对撞机物理唯象学基础与前沿

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目录

The history of electroweak theory

Beta decay

原子核衰变的能谱：

Z：质子数
N：中子数

$$A \to B + e^-$$

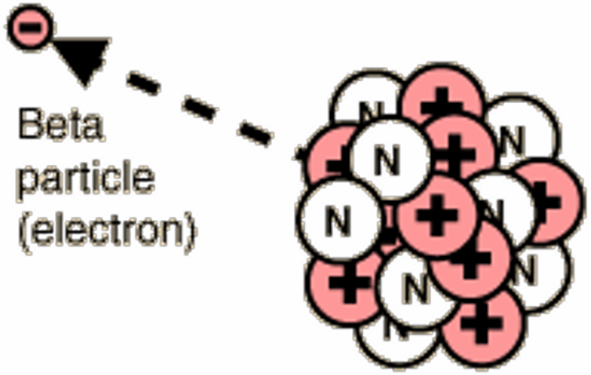
$$(Z, N) \to (Z+1, N-1) + e^-$$

N $m_n = 939.5656\ MeV$

+ $m_p = 938.2723\ MeV$

− $m_e = 0.510999\ MeV$

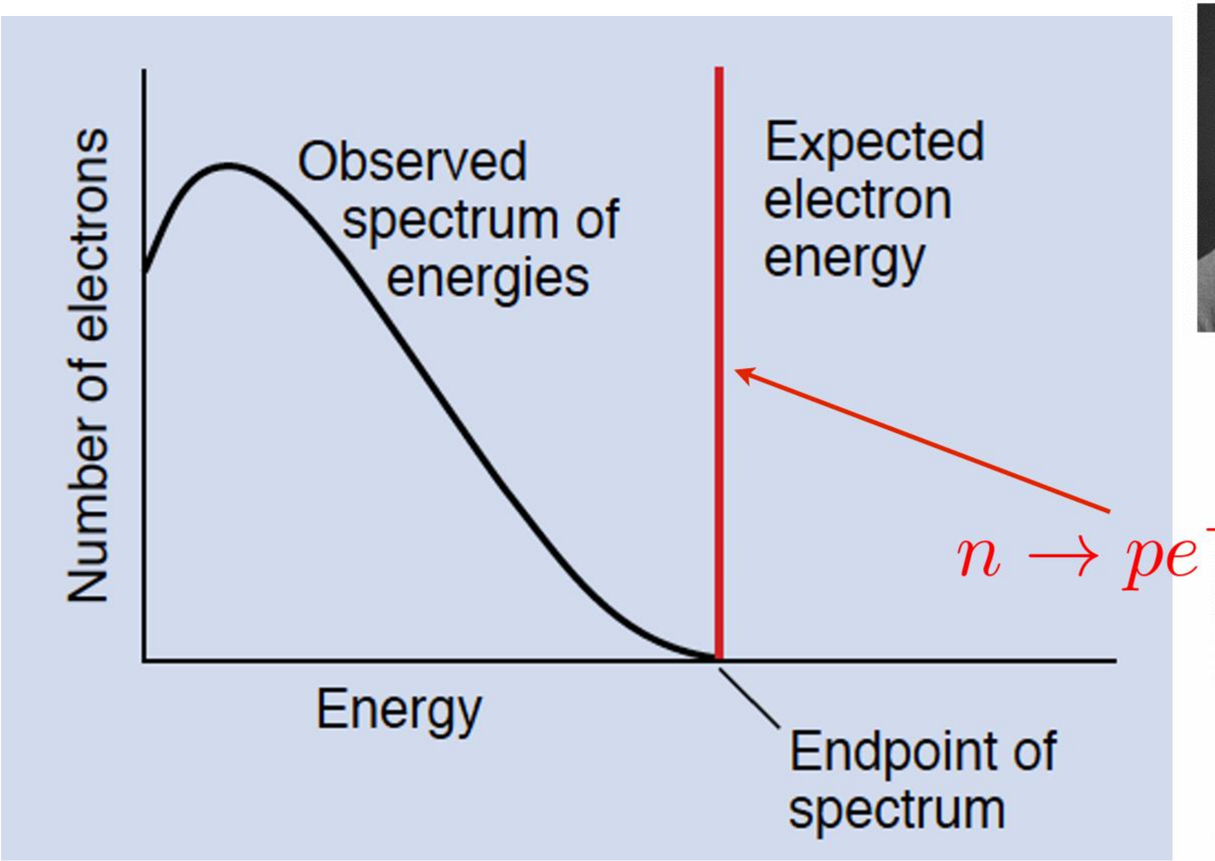
$0.7823\ MeV = Q\ \ for\ \ n \to p + e^-$



The conservation of Energy and momentum requires the electron have a single value of energy.

Beta decay

1914, Chadwick

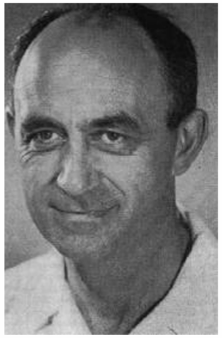


1924, Neil Bohr
放弃能量守恒，
只需要考虑统计
意义上的守恒

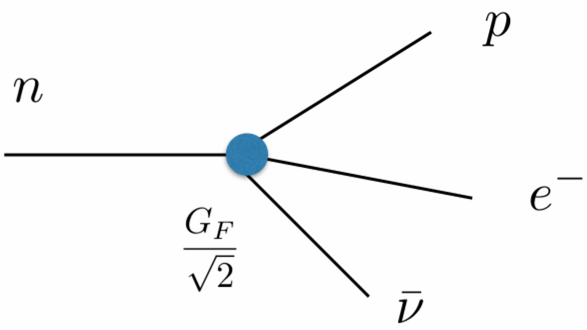
1930, Pauli
存在一个无法探
测的粒子（中微
子）

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}$$

Fermi Theory



1934：费米提出描述beta衰变的有效理论



$$M_{fi} = G_F \left[\overline{\psi_n}\gamma^\mu\psi_p\right]\left[\overline{\psi_e}\gamma^\mu\psi_\nu\right]$$

$$G_F \sim 10^{-5}\,(\mathrm{GeV})^{-2}$$

- 不可重整理论，费米理论是低能有效理论
- 在极高能情况下破坏幺正性

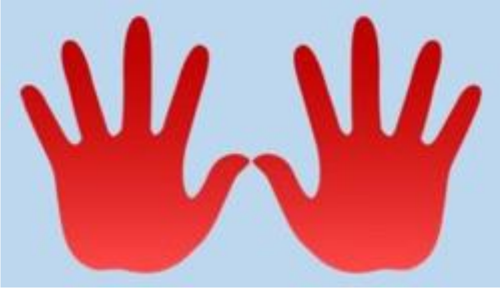
$$\Psi_i \propto \sqrt{E} \qquad \sigma \propto G_F^2 s$$

- 费米理论是宇称守恒理论

宇称破坏和弱相互作用

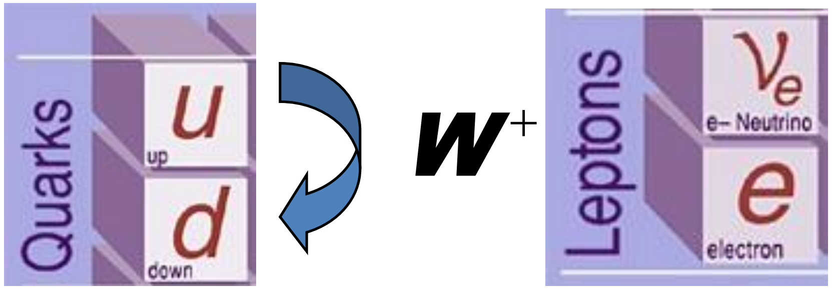
- $\theta - \tau$ 疑难

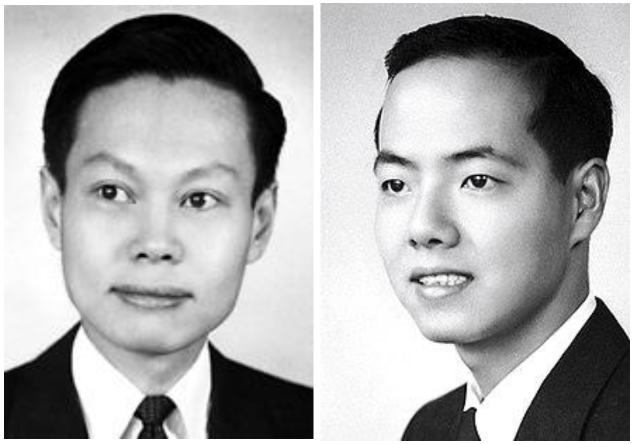
$\theta \rightarrow \pi\pi$，$\tau \rightarrow \pi\pi\pi$ ，质量、寿命、电荷均相同，但是宇称不同？



同一粒子还是不同粒子？

- Parity Violation



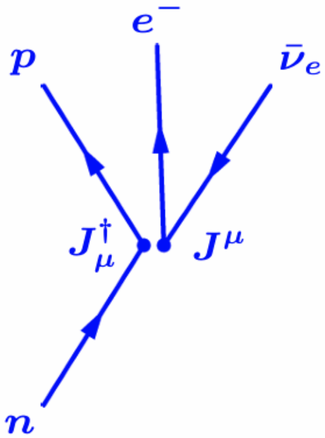


(Lee and Yang, Nobel prize 1957)

Chien-Shiung Wu

V-A theory

Feynman & Gell-man; Sudarshan, Marshak (1958)



$$\mathcal{H} = \frac{G_F}{\sqrt{2}} J^\dagger_\mu J^\mu \qquad J_\mu = \underbrace{J^\ell_\mu}_{\text{leptonic}} + \underbrace{J^h_\mu}_{\text{hadronic}}$$

$$J^\ell_\mu = \bar{e}^- \gamma_\mu \left(1 - \gamma^5\right) \nu_e + \bar{\mu} \gamma_\mu \left(1 - \gamma^5\right) \nu_\mu$$
$$= 2 \left[\bar{e}_L \gamma_\mu \nu_{eL} + \bar{\mu}_L \gamma_\mu \nu_{\mu L}\right]$$

- $\psi_L = P_L \psi = \frac{1-\gamma^5}{2} \psi$ (vector - axial)
- $G_F \simeq 1.17 \times 10^{-5}\ \mathrm{GeV}^{-2}$ (Fermi constant)

V-A theory: 幺正性破坏问题

The optical theorem

考虑S矩阵元：$(S = 1 + i\,T)$ 其中 T为S矩阵中非平庸的部分

$$\langle f|T|i\rangle = (2\pi)^4\delta^4(p_i - p_f)M(i \to f)$$

S矩阵幺正性：$S^+S = 1$ ⇒ $i(T^+ - T) = T^+T$

S矩阵元关系：$\langle f|i(T^+ - T)|i\rangle = i\,\langle i|T|f\rangle^* - i\,\langle f|T|i\rangle$

$$= i(2\pi)^4\delta^4(p_i - p_f)(M^*(f \to i) - M(i \to f))$$

$$\langle f|T^+T|i\rangle = \sum_X \int d\Pi_X\,\langle f|T^+|X\rangle\langle X|T|i\rangle$$

$$= \sum_X (2\pi)^4\delta^4(p_f - p_X)(2\pi)^4\delta^4(p_i - p_X)\int d\Pi_X M(i \to X)M^*(f \to X)$$

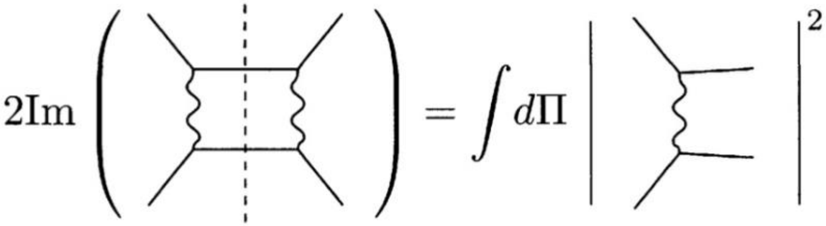
光学定理将散射振幅和散射截面关联起来

$$M(i \to f) - M^*(f \to i) = i\sum_X \int d\Pi_X (2\pi)^4\delta^4(p_i - p_X)M(i \to X)M^*(f \to X)$$

The optical theorem

初末态相同情况

$$2ImM(A\to A)=\sum_X\int d\Pi_X(2\pi)^4\delta^4(p_A-p_X)|M(A\to X)|^2$$



振幅级别圈图　　　　振幅模方树图

考虑两粒子态，在质心系的散射截面

$$\sigma(A\to X)=\frac{1}{4E_{\mathrm{CM}}|\vec{p}_i|}\int d\Pi_X(2\pi)^4\,\delta^4(p_A-p_X)|\mathcal{M}(A\to X)|^2.$$

$$\mathrm{Im}\mathcal{M}(A\to A)=2E_{\mathrm{CM}}|\vec{p}_i|\sum\nolimits_X\sigma(A\to X)$$

散射振幅的虚部正比于总散射截面

分波幺正性

考虑散射过程： $A(p_1)+B(p_2)\to A(p_3)+B(p_4)$

$$\sigma(AB\to AB)=\frac{1}{32\pi E_{\rm cm}^2}\int d\cos\theta|M(\theta)|^2$$

散射振幅分波展开：

$$M(\theta)=16\pi\sum_{j=0}^{\infty}a_j(2j+1)\underline{p_j(\cos\theta)}$$

Legendre Polynomials

正交性：

$$\int_{-1}^{1}p_j(\cos\theta)p_k(\cos\theta)d\cos\theta=\frac{2}{2j+1}\delta_{jk},\quad p_j(1)=1$$

总截面：

$$\sigma(AB\to AB)=\frac{16\pi}{E_{\rm cm}^2}\sum_{j=0}^{\infty}(2j+1)|a_j|^2$$

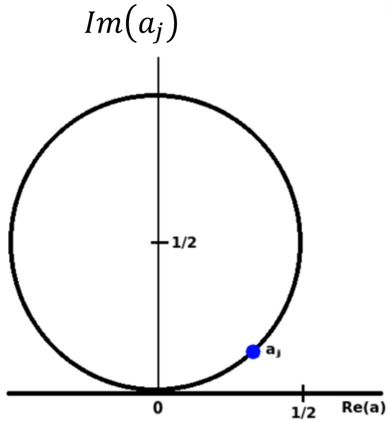
分波幺正性

考虑向前散射过程 $\theta = 0$，光学定理为：

$$Im M(AB \to AB, \theta = 0) = 2E_{\mathrm{cm}}|\vec{p}_i| \sum_X \sigma(AB \to X) \geq 2E_{\mathrm{cm}}|\vec{p}_i| \sum_X \sigma(AB \to AB)$$

利用分波展开：
$$\sum_{j=0}^{\infty}(2j+1)Im(a_j) \geq \frac{2|\vec{p}_i|}{E_{\mathrm{cm}}}\sum_{j=0}^{\infty}(2j+1)|a_j|^2 \qquad |a_j|^2 \geq Im(a_j)$$

考虑极高能情况：
$$\sum_{j=0}^{\infty}(2j+1)Im(a_j) \geq \sum_{j=0}^{\infty}(2j+1)|a_j|^2 \quad \Rightarrow \quad |a_j|^2 = Im(a_j)$$



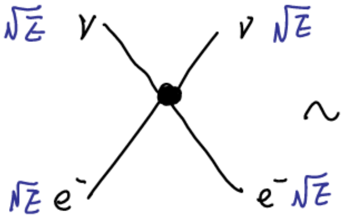
分波幺正性条件：

$$|a_j| \leq 1, \quad 0 \leq Im(a_j) \leq 1, \quad |Re(a_j)| \leq \frac{1}{2}$$

V-A theory: 幺正性破坏问题

- Feynman - Gell-mann V-A 理论

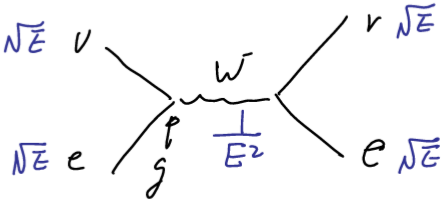
$$G_F \bar{\Psi}_n \gamma^\mu (1-\gamma_5) \psi_p \bar{\Psi}_{e^-} \gamma^\mu (1-\gamma_5) \psi_\nu$$



$$\sim G_F (\sqrt{E})^4 \sim G_F s \qquad s=(2E)^2$$

$$G_F = 常数 \Rightarrow \sigma(e^-\nu \to e^-\nu) \xrightarrow{s\to\infty} 发散$$

- 中间玻色子模型 (intermediate gauge boson model)

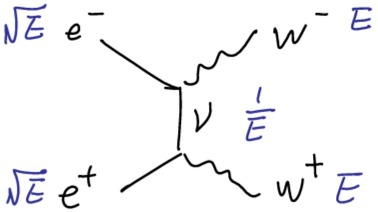


$$m \sim g^2 \frac{(\sqrt{E})^4}{E^2} \sim (E)^0$$

ok

高能情况下下，规范玻色子纵向极化主导

但是



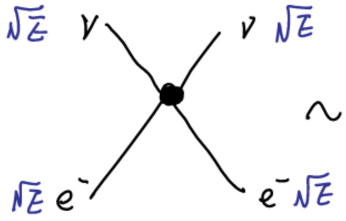
$$m \sim g^2 \frac{E^2 \cdot (\sqrt{E})^2}{E} \sim E^2$$

bad

V-A theory: 幺正性破坏问题

- Feynman - Gell-mann V-A 理论

$$G_F \bar{\psi}_n \gamma^\mu (1-\gamma_5) \psi_p \bar{\psi}_{e^-} \gamma^\mu (1-\gamma_5) \psi_\nu$$



$$\sim G_F (\sqrt{E})^4 \sim G_F s \qquad s = (2E)^2$$

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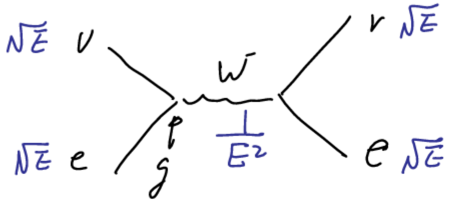
- 中间玻色子模型 (intermediate gauge boson model)



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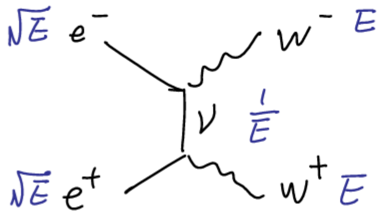
ok

但是



$$m \sim g^2 \frac{E^2 \cdot (\sqrt{E})^2}{E} \sim E^2$$

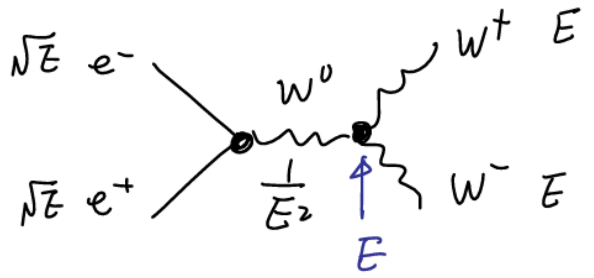
bad

高能情况下下，规范玻色子纵向极化主导

V-A theory: 幺正性破坏问题

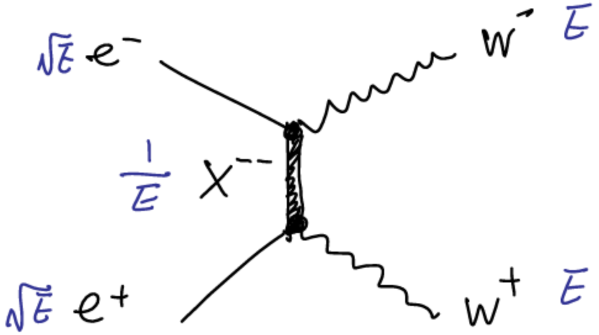
解决方案

(1) 中性流



$$m \sim g^2 \frac{(\sqrt{E})^2 E^2 \times E}{E^2} \sim E^2$$

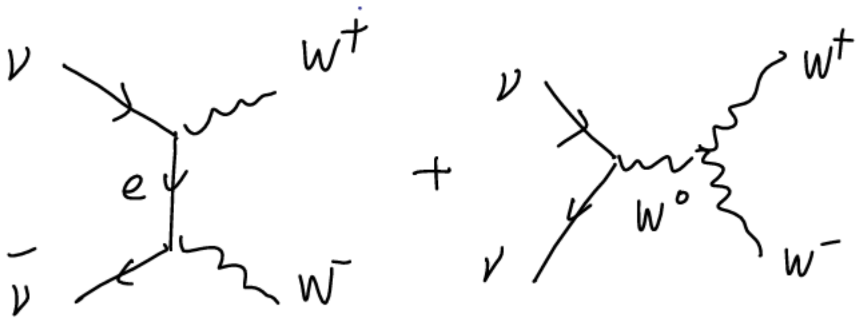
(2)



$$m \sim \frac{g^2 (\sqrt{E})^2 E^2}{E} \sim E^2$$

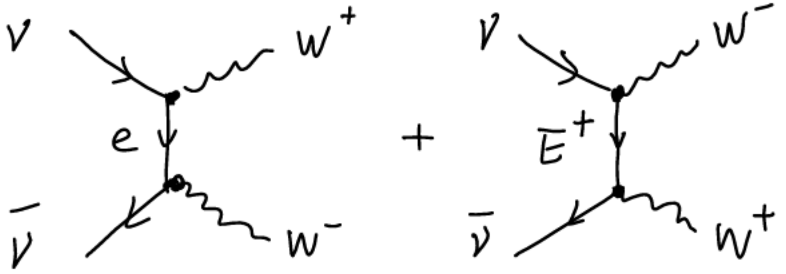
Exp says NO!

V-A theory: 幺正性破坏问题



$\sim (E)^0$

$\Rightarrow$ 中性流要和中微子相互作用



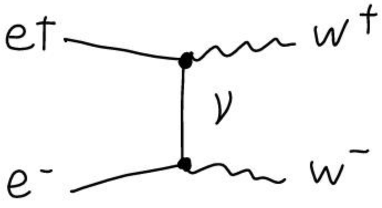
$\sim (E)^0$

$\Rightarrow$ Paraleption E^+

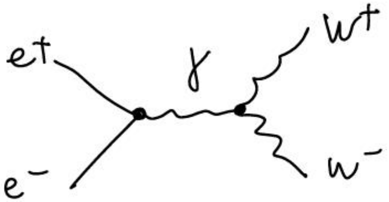
H. Georgi, Glashow
Phys. Rev. Lett. 28, 1494 (1972)
Unified Weak and EM INTerations
without Neutral currents

V-A theory: 幺正性破坏问题

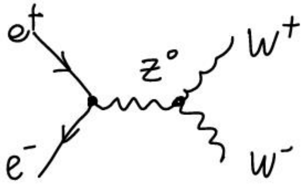
$e^+e^- \to W^+W^-$



①

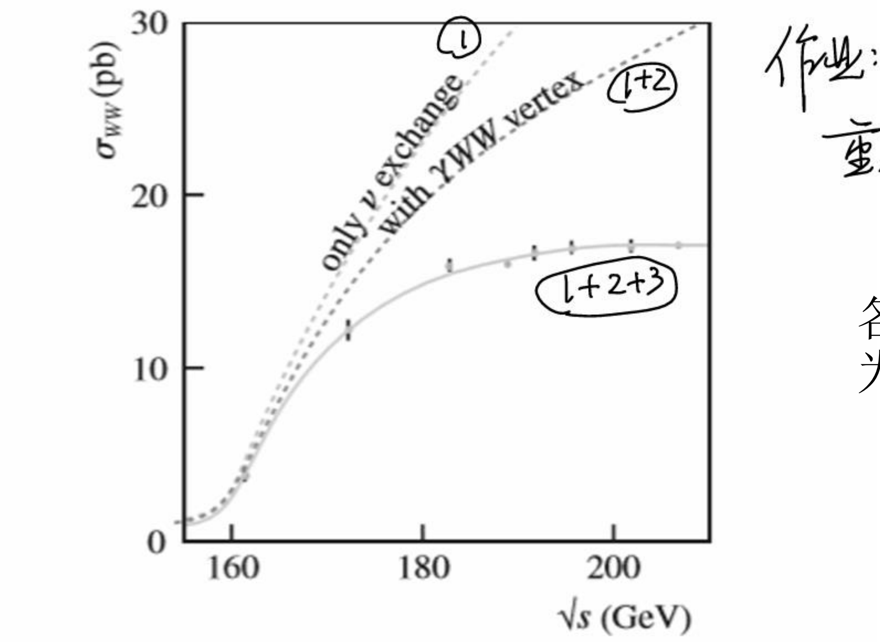


②



③

主要散射通过p-波来进行（s道的传播子是光子或Z玻色子 $J=1$）



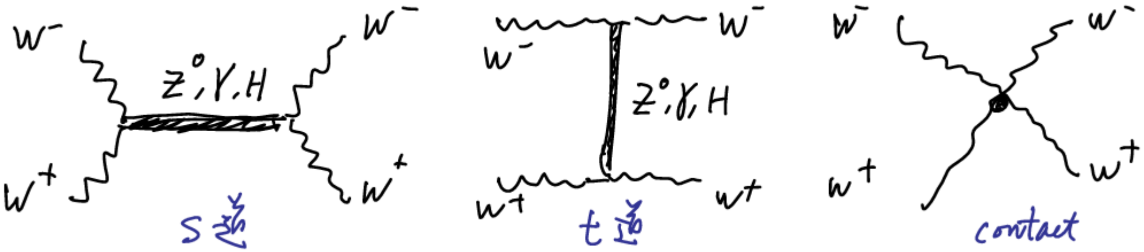
作业：使用CALCHEP
重复此条曲线

各种图的高能破坏行为彼此抵消

幺正性破坏问题

- 幺正性检验成为理论自洽性的关键检验
- WW scattering: 能量破坏效应最强的过程

b) $W_0^+ W_0^- \rightarrow W_0^+ W_0^-$



$$M(s,t) = 16\pi \sum_J (2J+1)\, a_J(s)\, P_J(\cos\theta)$$

$$a_J = A\left(\frac{g}{M_W}\right)^4 + B\left(\frac{g}{M_W}\right)^2 + C$$

W^+W^- 系统的总角动量为 $J = 0, 1, 2$

幺正性破坏问题

① A-term (E^4):

J=2: (contact 图) + (t道Z.γ 图) = 0

J=1: (contact 图) + (s道Zγ 图) + (t道Zγ 图) = 0

J=0: (contact 图) + (t道Zγ 图) = 0

② B-term

J=2: (contact 图) + (t道Zγ 图) = 0

J=1: (contact 图) + (t道Zγ 图) + (s道Zγ 图) + (t道H图) = 0

J=0: (contact 图) + (t道Zγ 图) + (s道H图) + (t道H图) = 0

J=0 分波:

$$a_0(w_0^+ w_0^- \to w_0^+ w_0^-) = \frac{-G_F M_H^2}{8\pi\sqrt{2}}\left[2 + \frac{M_H^2}{s-M_H^2} - \frac{M_H^2}{s}\ln\left(1+\frac{s}{M_H^2}\right)\right]$$

$$\xrightarrow[s \gg M_H^2]{} -\frac{G_F M_H^2}{4\pi\sqrt{2}}$$

幺正限:

$$\frac{G_F M_H^2}{4\pi\sqrt{2}} \le 1 \Rightarrow M_H^2 \le \frac{4\pi\sqrt{2}}{G_F} \le 1.5\,\mathrm{TeV}^2$$

$$(M_H \le 1.2\,\mathrm{TeV})$$

- 希格斯与规范玻色子的相互作用保证了散射过程的幺正性
- LHC的主要使命
- 实验和理论要求存在：带电流+中性流+希格斯粒子
- 规范对称性

Electroweak gauge couplings

费米子规范相互作用： $E_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$, $Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$ $T^{\pm} = \frac{1}{2}(\sigma^1 \pm i\sigma^2) = \sigma^{\pm}$

$$\mathcal{L} = \overline{E}_L(i\not{D})E_L + \bar{e}_R(i\not{D})e_R + \overline{Q}_L(i\not{D})Q_L + \bar{u}_R(i\not{D})u_R + \bar{d}_R(i\not{D})d_R$$

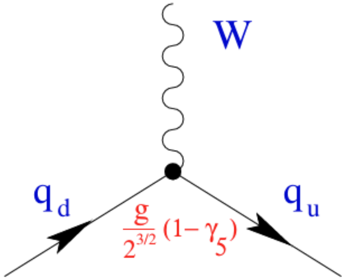
协变导数： $D_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}(W_\mu^+ T^+ + W_\mu^- T^-) - i\frac{g}{\cos\theta_w} Z_\mu (T^3 - \sin^2\theta_w Q) - ieA_\mu Q$

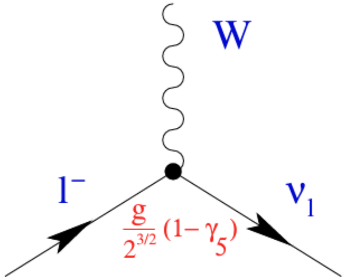
标准模型规范相互作用：

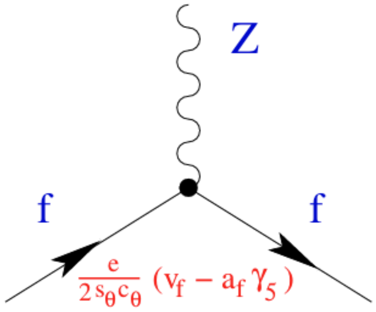
$$a_f = T_3^f \text{ and } v_f = T_3^f\,(1 - 4|Q_f|\sin^2\theta_W).$$

$$\mathcal{L}_{\rm CC} = \frac{g}{2\sqrt{2}}\left\{W_\mu^\dagger\,[\bar{u}\gamma^\mu(1-\gamma_5)d + \bar{\nu}_e\gamma^\mu(1-\gamma_5)e] + \text{h.c.}\right\}$$

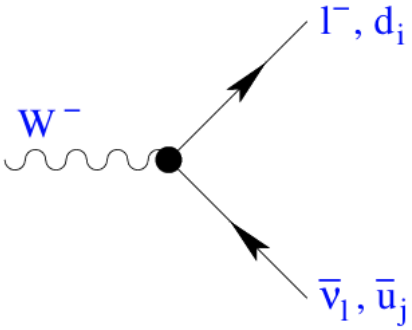
$$\mathcal{L}_{\rm NC}^Z = \frac{e}{2\sin\theta_W\cos\theta_W} Z_\mu \sum_f \bar{f}\gamma^\mu(v_f - a_f\gamma_5)\,f$$

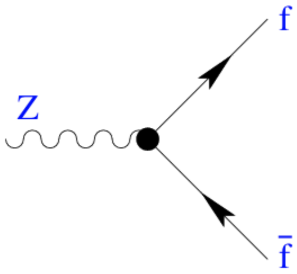






W/Z decay branching ratios





$$\Gamma\left(W^- \to \bar{\nu}_l l^-\right) = \frac{G_F M_W^3}{6\pi\sqrt{2}}$$

$$\Gamma\left(Z \to \bar{f} f\right) = N_f \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left(|v_f|^2 + |a_f|^2\right)$$

$$\Gamma\left(W^- \to \bar{u}_i d_j\right) = N_C \, |\mathbf{V}_{ij}|^2 \frac{G_F M_W^3}{6\pi\sqrt{2}}$$

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22501 \pm 0.00068 & 0.003732^{+0.000090}_{-0.000085} \\ 0.22487 \pm 0.00068 & 0.97349 \pm 0.00016 & 0.04183^{+0.00079}_{-0.00069} \\ 0.00858^{+0.00019}_{-0.00017} & 0.04111^{+0.00077}_{-0.00068} & 0.999118^{+0.000029}_{-0.000034} \end{pmatrix}$$

$$\mathrm{Br}(W^- \to \bar{\nu}_l \, l^-) = \frac{1}{3 + 2N_C} = 11.1\%$$

轻子相互作用普适性？

矢量流和轴矢流相互作用的符号？

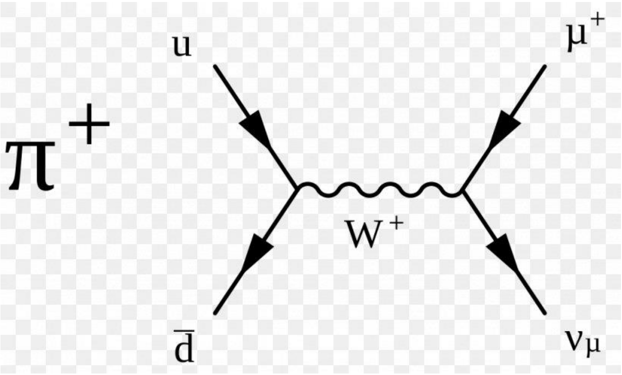
$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \, ,$$

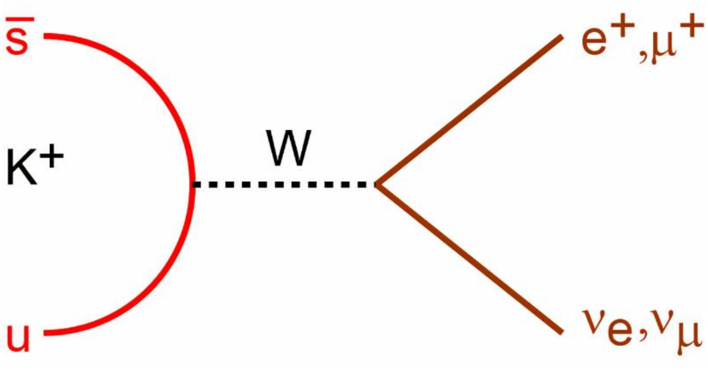
$$M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\, G_F}$$

$$a_f = T_3^f \text{ and } v_f = T_3^f \left(1 - 4|Q_f| \sin^2\theta_W\right).$$

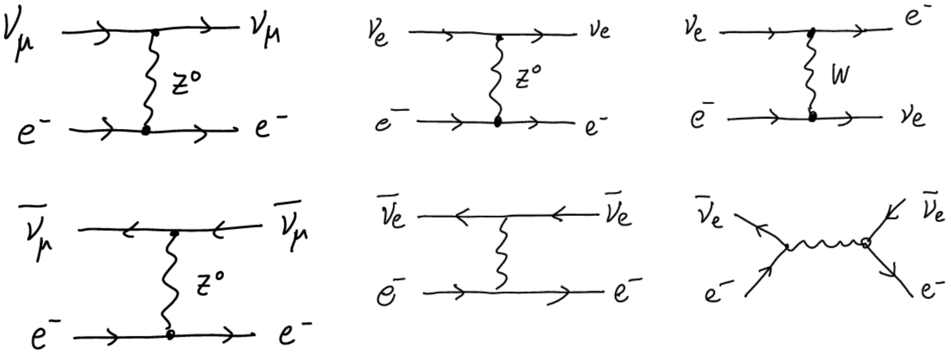
轻子普适性检验

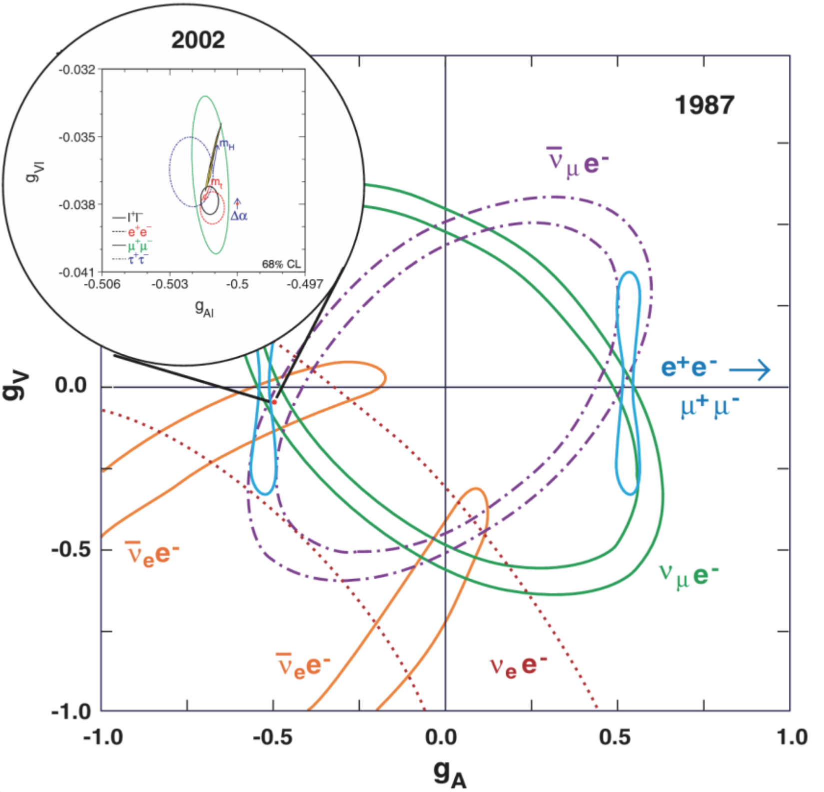
	$\Gamma_{\tau\to\nu_\tau\mu\bar{\nu}_\mu}/\Gamma_{\tau\to\nu_\tau e\bar{\nu}_e}$	$\Gamma_{\pi\to\mu\bar{\nu}_\mu}/\Gamma_{\pi\to e\bar{\nu}_e}$	$\Gamma_{W\to\mu\bar{\nu}_\mu}/\Gamma_{W\to e\bar{\nu}_e}$	
$\lvert g_\mu/g_e\rvert$	0.9999 ± 0.0020	1.0017 ± 0.0015	0.997 ± 0.010	
	$\Gamma_{\tau\to\nu_\tau e\bar{\nu}_e}/\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e}$	$\Gamma_{\tau\to\nu_\tau\pi}/\Gamma_{\pi\to\mu\bar{\nu}_\mu}$	$\Gamma_{\tau\to\nu_\tau K}/\Gamma_{K\to\mu\bar{\nu}_\mu}$	$\Gamma_{W\to\tau\bar{\nu}_\tau}/\Gamma_{W\to\mu\bar{\nu}_\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0004 ± 0.0023	0.9999 ± 0.0036	0.979 ± 0.017	1.037 ± 0.014
	$\Gamma_{\tau\to\nu_\tau\mu\bar{\nu}_\mu}/\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e}$	$\Gamma_{W\to\tau\bar{\nu}_\tau}/\Gamma_{W\to e\bar{\nu}_e}$		
$\lvert g_\tau/g_e\rvert$	1.0002 ± 0.0022	1.034 ± 0.014		





中性流相互作用





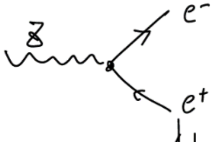
$$\sigma(\nu_\mu e \to \nu_\mu e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2+av+v^2}{3}\right)$$

$$\sigma(\bar{\nu}_\mu e \to \bar{\nu}_\mu e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2-av+v^2}{3}\right)$$

$$\sigma(\nu_e e \to \nu_e e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2+av+v^2}{3}+a+v+1\right)$$

$$\sigma(\bar{\nu}_e e \to \bar{\nu}_e e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2-av+v^2+a+v+1}{3}\right)$$

其中 $a \equiv a_e$, $v \equiv v_e$



$i\gamma^\mu(v_e + a_e\gamma_5)$

$v_e = \frac{1}{2}(L_e + R_e)$

$a_e = \frac{1}{2}(L_e - R_e)$

标准模型中 $a_e = -\frac{1}{2}$, $v_e = -\frac{1}{2} + 2x_W$, $x_W = \sin^2\theta_W$

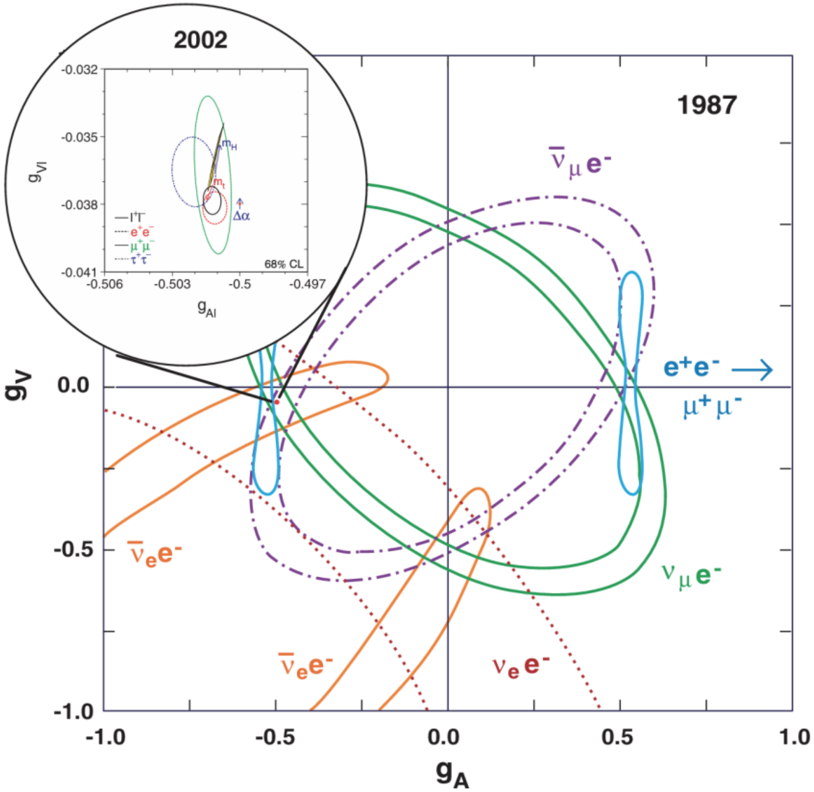
只涉及弱相互作用

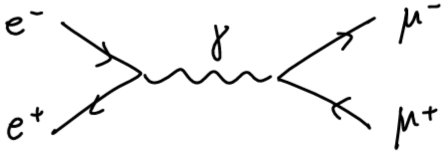
中性流相互作用

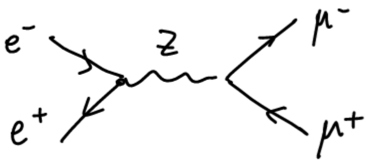
- 中微子散射截面具有$v \leftrightarrow a$ 对称性
- $\bar{\nu}_\mu e$ 和 $\nu_\mu e$具有正负号任意性
- $\bar{\nu}_e e$ 和 $\nu_e e$ 可消除此不确定性
- 综合所有中微子实验

  $a = 0, v = -0.5$ 或者 $a = -0.5, v = 0$

破除 $v \leftrightarrow a$ 对称性对于检验标准模型规范相互作用直观重要

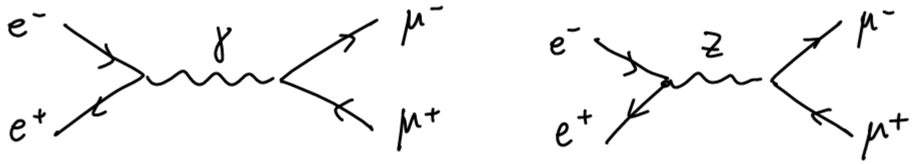




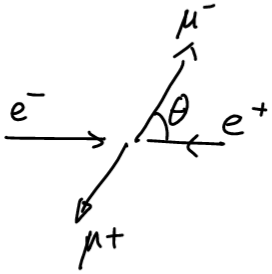


存在弱相互作用与电磁相互作用的干涉

中性流相互作用



在正负电子对撞机上的微分截面

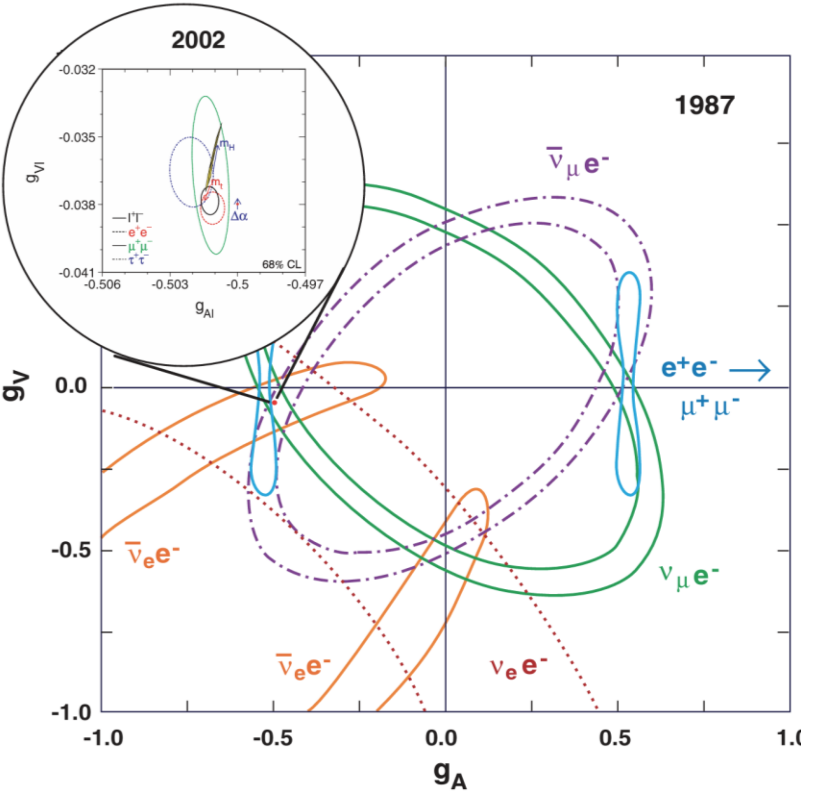


$$\frac{d\sigma}{d\cos\theta}(e^+e^-\to\mu^+\mu^-)$$

$$=\frac{\pi\alpha^2Q_\mu^2}{2s}(1+\cos^2\theta)$$

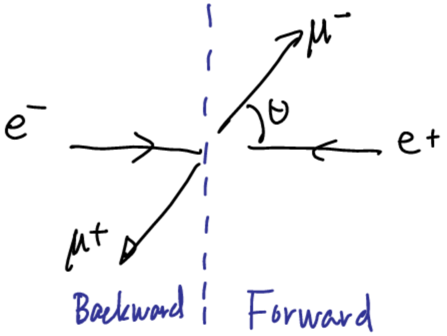
$$-\frac{\alpha Q_\mu G_F M_Z^2(s-m_Z^2)}{8\sqrt{2}\left[(s-m_Z^2)^2+m_Z^2\Gamma_Z^2\right]}\left[(R_e+L_e)(R_\mu+L_\mu)(1+\cos^2\theta)+2(R_e-L_e)(R_\mu-L_\mu)\cos\theta\right]$$

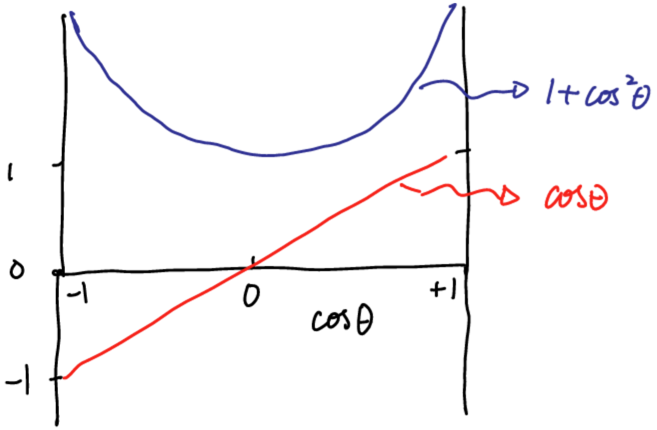
$$+\frac{G_F^2M_Z^4s}{64\pi\left[(s-m_Z^2)^2+m_Z^2\Gamma_Z^2\right]}\left[(R_e^2+L_e^2)(R_\mu^2+L_\mu^2)(1+\cos^2\theta)+2(R_e^2-L_e^2)(R_\mu^2-L_\mu^2)\cos\theta\right]$$



v和a对标准模型的截面贡献不同

中性流相互作用





$$A_{FB} \equiv \frac{\int_0^1 d\cos\theta \, \frac{d\sigma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \, \frac{d\sigma}{d\cos\theta}}{\int_0^1 d\cos\theta \, \frac{d\sigma}{d\cos\theta} + \int_{-1}^0 d\cos\theta \, \frac{d\sigma}{d\cos\theta}} = \frac{\sigma_F(\cos\theta>0) - \sigma_F(\cos\theta<0)}{\sigma_{total}}$$

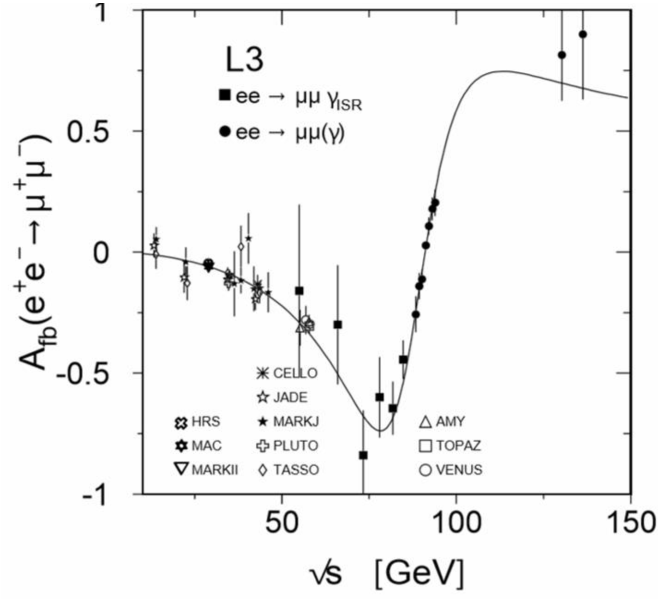
由于宇称破坏效应将产生前后不对称性

$$\frac{d\sigma}{d\cos\theta} \sim a + b\cos^2\theta + c\cos\theta$$

$$\Rightarrow \sigma_{tot} \sim 2a + \frac{2b}{3} \, , \quad \sigma_F - \sigma_B \sim c$$

$$\Rightarrow A_{FB} \sim \frac{c}{2a + \frac{2b}{3}}$$

中性流相互作用



从一系列实验中，人们可以得到 $a_e a_\mu$

例，$\sqrt{s}=29$ GeV，　$a_e a_\mu = 0.23 \pm 0.03$

$a_e a_\tau = 0.21 \pm 0.05$

In SM

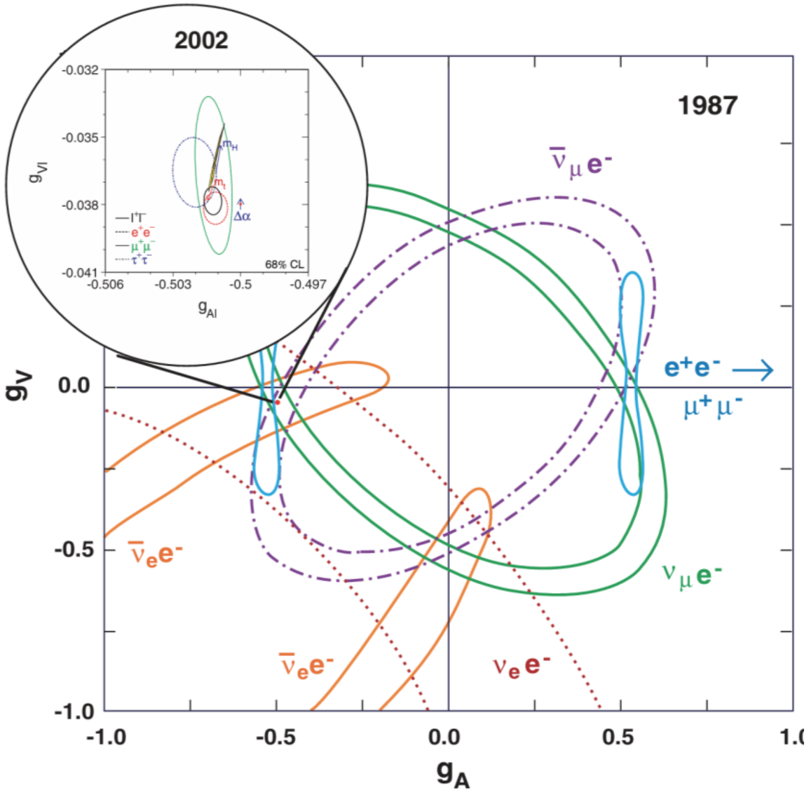
$a_e a_\mu = a_e a_\tau = 0.25$

假设弱相互作用是 universal 的，

则有　$a_\ell \approx \sqrt{a_e a_\mu} \sim \sqrt{a_e a_\tau} \approx \pm 0.5$

$\Rightarrow$ 和 νe 实验结果相比较，可得

$a \approx -\frac{1}{2}$, $v \approx 0$



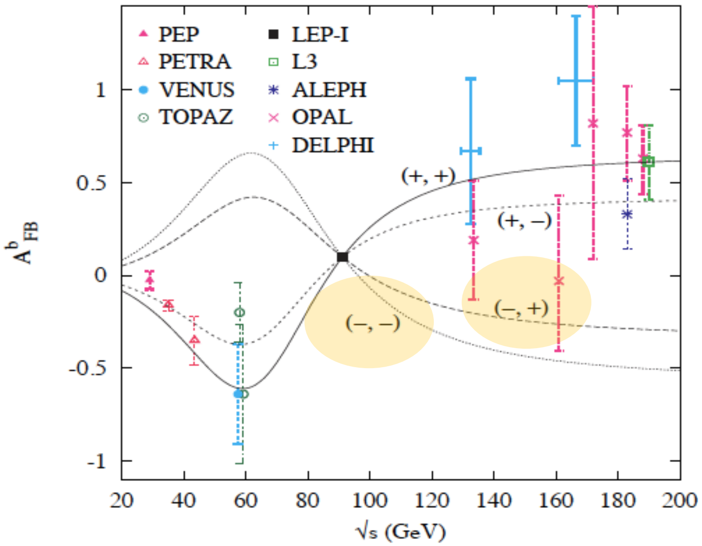
结合中微子散射以及正负电子对撞机实验，完全确定中性流相互作用

电弱精确检验

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}, \qquad R_\ell^0 \equiv \mathit{\Gamma}_{\mathrm{had}}/\mathit{\Gamma}_{\ell\ell}$$

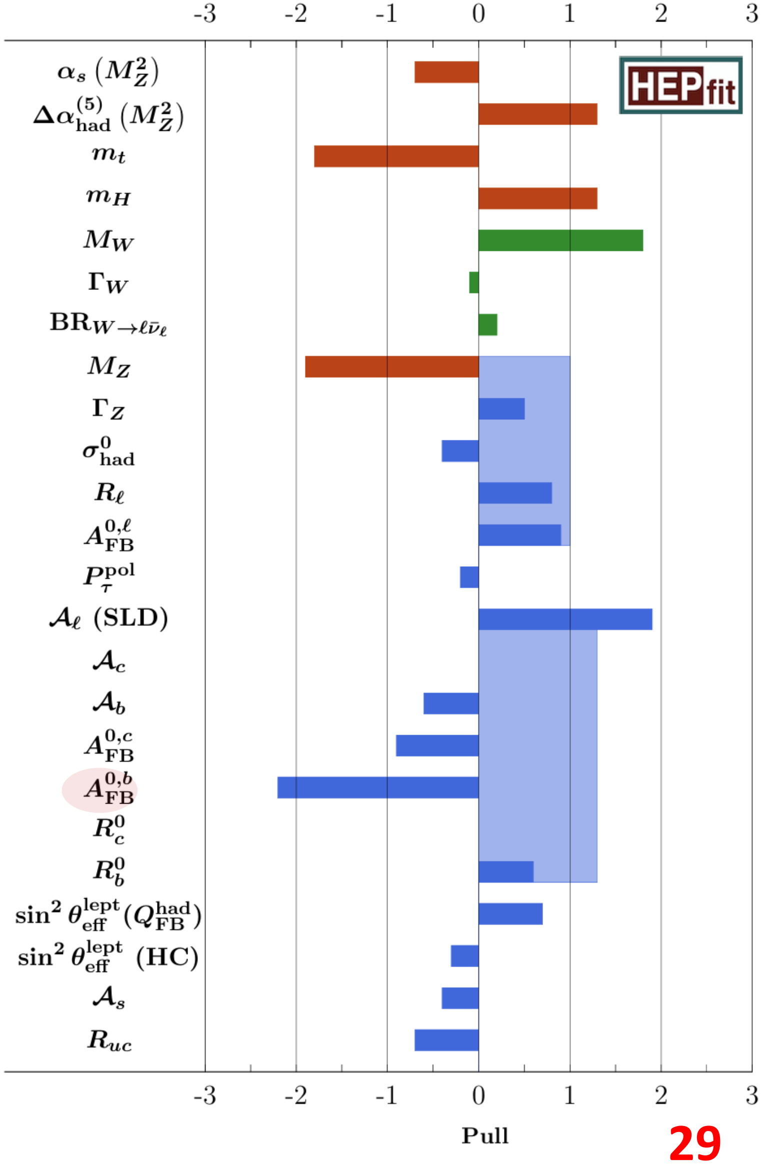
$$A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} \frac{1}{\langle|\mathscr{P}_{\mathrm{e}}|\rangle}, \quad R_{\mathrm{q}}^0 \equiv \mathit{\Gamma}_{\mathrm{q\bar{q}}}/\mathit{\Gamma}_{\mathrm{had}}$$

电弱精确检验与标准模型预言高度一致，除了bottom quark 前后不对称性？



$g_{Lb} < 0$ ✗

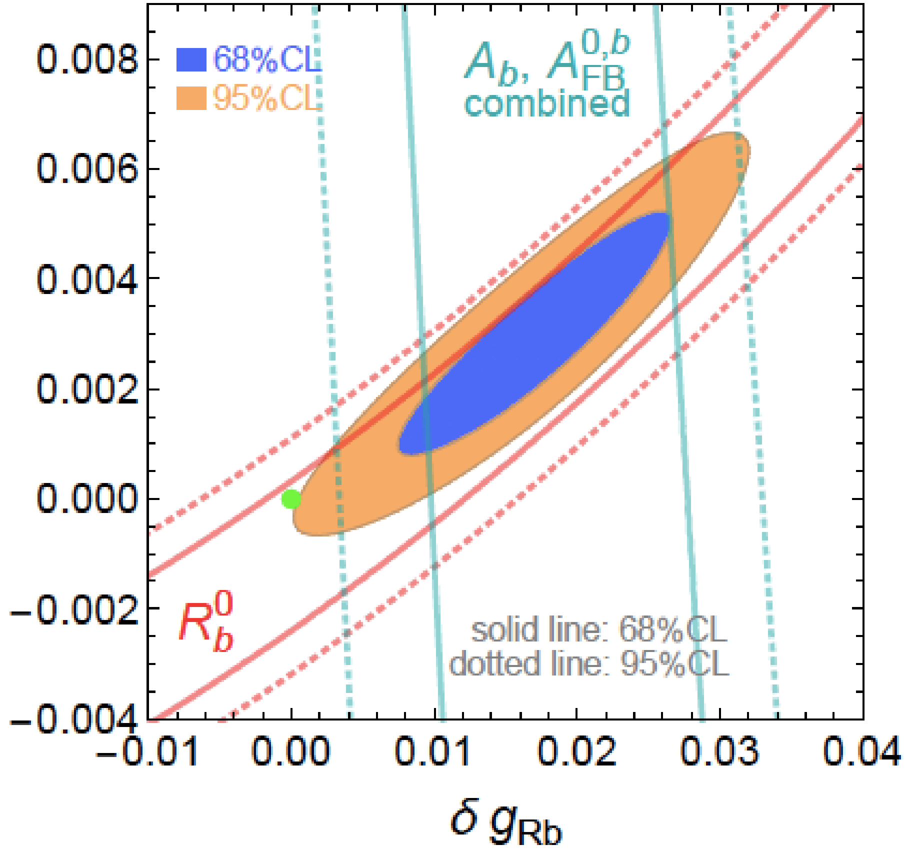
$g_{Rb} > 0 \ or < 0$



Status of Zbb couplings

$$\mathcal{L} \supset \frac{g}{c_W} Z_\mu (g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R)$$

S. Gori, J. Gu, L. T. Wang, JHEP04(2016)062



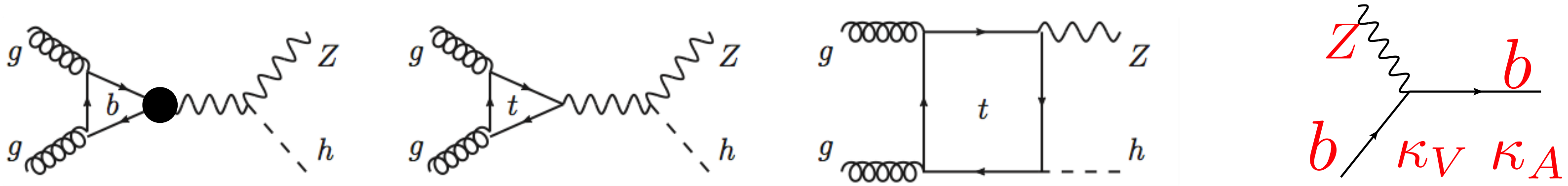
$\mathcal{O}(10^{-3})$

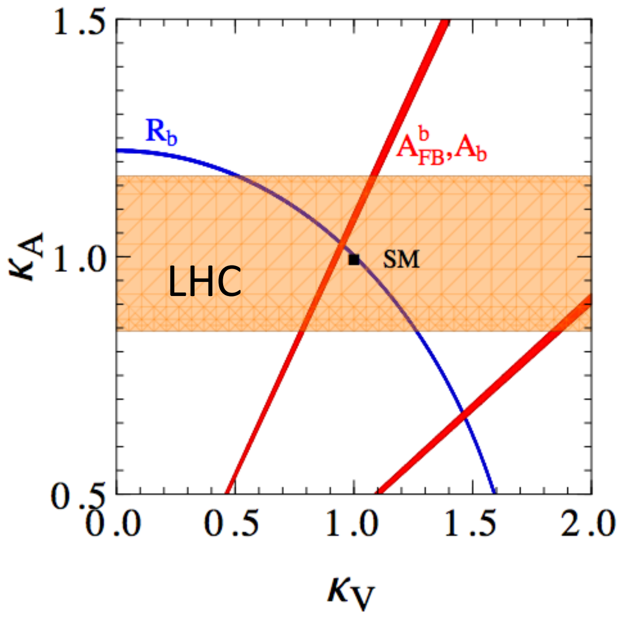
$\mathcal{O}(10^{-2})$

Strong constraint for the left-handed Zbb coupling and large deviation of the right-handed Zbb coupling

电弱精确检验

The precisely measurements for the SM Higgs production can also test the electroweak properties of the SM





Bin Yan, C.-P. Yuan, PRL 127 (2021) 5, 051801

$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5) b Z_\mu$$

The degeneracy of the anomalous Zbb could be resolved by the LHC data

The other possible methods:

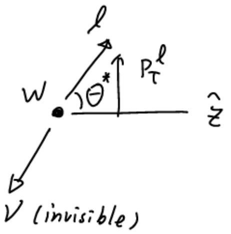
Bin Yan, C.-P. Yuan, Shu-Run Yuan, PRD 108 (2023) 5, 053001
F. Bishara, Zhuoni Qian, JHEP 10 (2023) 088
Hongxin Dong, Peng Sun, Bin Yan, C.-P. Yuan, PLB 829 (2022) 137076
Hai Tao Li, Bin Yan, C.-P. Yuan, PLB 833 (2022) 137300
Bin Yan, Zhite Yu, C.-P. Yuan, PLB 822 (2021) 136697

W boson mass measurement

*) M_W 测量

a) Jacobian peak technique

在W静止系中



$$\frac{d\sigma}{dp_T^\ell} = \frac{d\sigma}{d\cos\theta} \times \frac{d\cos\theta}{dp_T^\ell}$$

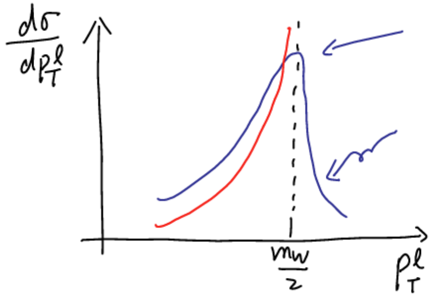
$$P_T^\ell = \left(\frac{M_W}{2}\right)\sin\theta \Rightarrow \frac{d\cos\theta}{dp_T^\ell} = \frac{1}{\frac{dP_T^\ell}{d\cos\theta}} = \frac{-2}{M_W}\frac{\sin\theta}{\cos\theta}$$

$$\left(dP_T = \frac{m_W}{2}\cos\theta\, d\theta = \frac{m_W}{2}\frac{\cos\theta}{\sin\theta}\sin\theta\, d\theta = -\frac{M_W}{2}\frac{\cos\theta}{\sin\theta}\, d\cos\theta\right)$$

$$\cos\theta = \sqrt{1-\left(\frac{2P_T^\ell}{m_W}\right)^2} = \frac{2}{m_W}\sqrt{\left(\frac{m_W}{2}\right)^2-\left(P_T^\ell\right)^2}$$

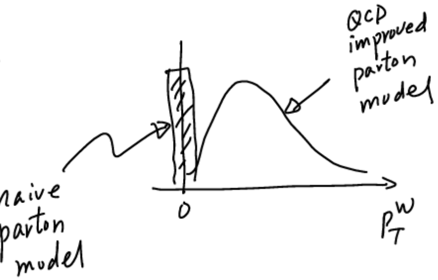
所以, $$\frac{d\cos\theta}{dP_T} = \frac{2P_T^\ell}{m_W}\frac{1}{\sqrt{\left(\frac{m_W}{2}\right)^2-\left(P_T^\ell\right)^2}}$$ (Jacobian 变换因子)

$$\Rightarrow \frac{d\sigma}{dP_T^\ell} = \underbrace{\frac{d\sigma}{d\cos\theta}}_{\text{无发散行为}} \times \frac{2P_T^\ell}{m_W}\frac{1}{\sqrt{\left(\frac{m_W}{2}\right)^2-\left(P_T^\ell\right)^2}}$$



$\frac{d\sigma}{dP_T}$ peaks at $P_T^\ell = \frac{m_W}{2}$

Non-zero P_T^W 和 Γ_W spread the curve out



W boson mass measurement

2) Transverse mass (M_T)

在强子对撞机上，我们无法探测中微子，也就无法得到其四动量 P_ν^μ. 从而传统的利用不变质量谱方法来测量共振态的方法不再适用。但我们可以得到中微子的横向动量

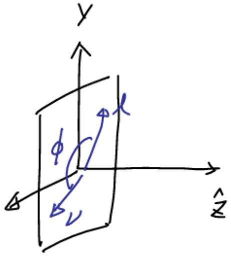
$$\vec{P}_T(W) = \vec{P}_T(l) + \vec{P}_T(\nu) \Rightarrow \vec{P}_T(\nu) = -\vec{P}_T(l)$$

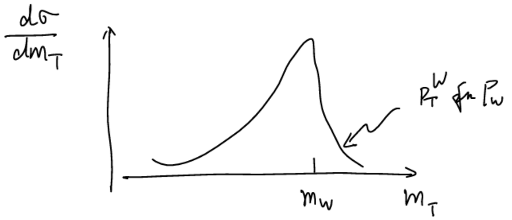
↳ 0 in parton model

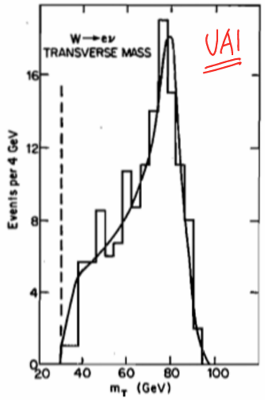
定义横向质量 (transverse mass) 如下

$$M_T^2 = 2\underbrace{P_T(l)}_{|\vec{P}_T(l)|}\underbrace{P_T(\nu)}_{\not{E}_T}[1-\cos\phi_{e\nu}]$$

separation angle in azimuthal angle







作业：使用 CALCHEP 重复 $\frac{d\sigma}{dM_T}$ 微分分布

$p\bar{p}$ 对撞 $E_p = E_{\bar{p}} = 270\,\text{GeV}$

$$\frac{d\hat{\sigma}}{dm_T^2} = \frac{1}{4\pi}\left(\frac{G_F m_W^2}{\sqrt{2}}\right)^2 \frac{1}{(s-m_W^2)^2+(m_W\Gamma_W)^2}\,\frac{2-\frac{m_T^2}{\hat{s}}}{\sqrt{1-\frac{m_T^2}{\hat{s}}}}$$

W boson mass measurement

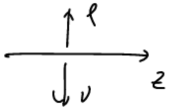
M_T的物理意义

定义M_T的动机如下:

如果 ℓ和ν都只有横向动量而无沿beam方向动量

$\eta_\ell = \eta_\nu = 0, \quad P_z(\ell) = P_z(\nu) = 0$

$\Rightarrow P_T(\ell) = \not{E}_T = \frac{m_W}{2}$



那么 $m_T = m_W$

一般情况下, 单粒子的运动学状态可表述如下

$E = m_\perp \cosh y, \quad P_z = m_\perp \sinh y, \quad P_x, P_y$

$\cosh y = \frac{1}{2}(e^{-y} + e^{y}) \quad \sinh y = \frac{1}{2}(e^{y} - e^{-y})$

$m_\perp^2 = m^2 + P_x^2 + P_y^2 = E^2 - P_z^2 = m^2 + P_\perp^2$

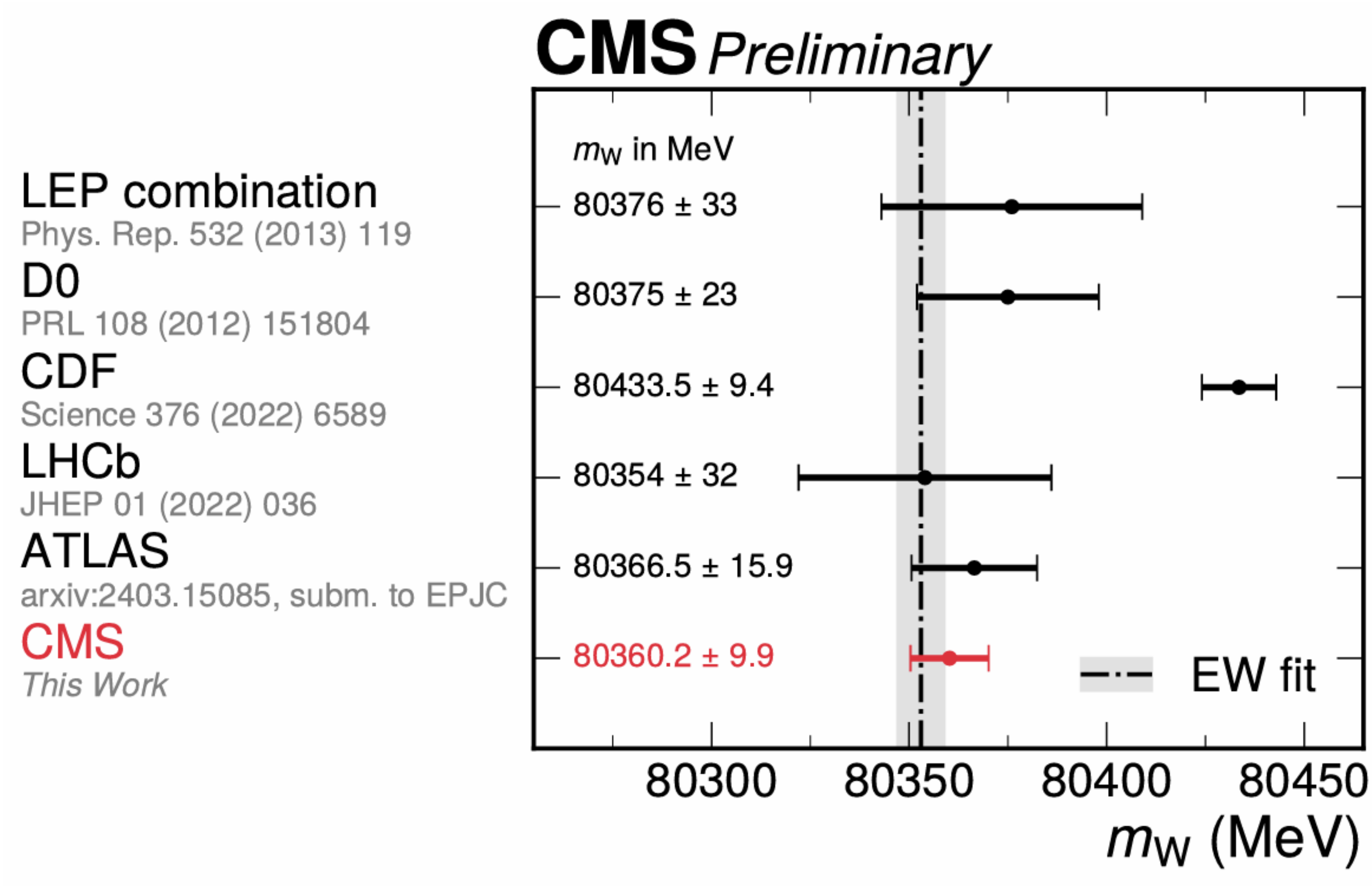
当 $m=0$ 时 $m_\perp = P_\perp$

$$
\begin{aligned}
M_W^2 &= (P_\ell + P_\nu)^2 = P_\ell^2 + P_\nu^2 + 2P_\ell \cdot P_\nu \\
&= 2\left(E_\ell \cdot E_\nu - P_z(\ell)P_z(\nu) - P_x(\ell)P_x(\nu) - P_y(\ell)P_y(\nu)\right] \\
&= 2P_T(\ell)P_T(\nu)\left[\cosh y_\ell \cosh y_\nu - \sinh y_\ell \sinh y_\nu - \cos\phi_{\ell\nu}\right] \\
&= 2P_T(\ell)P_T(\nu)\left[\cosh(y_\ell - y_\nu) - \cos\phi_{\ell\nu}\right] \\
&\geq 2P_T(\ell)P_T(\nu)\left[1 - \cos\phi_{\ell\nu}\right]
\end{aligned}
$$

↳ for $y_\ell = y_\ell$

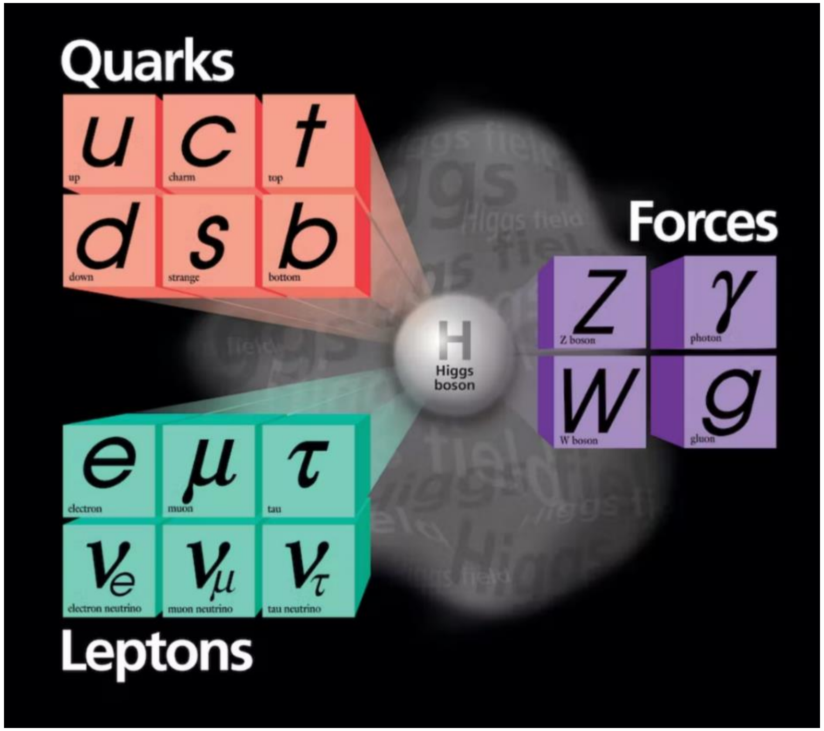
- 对于每个事例($\vec{P}(\ell)$和$\vec{\not{E}}_T$), 我们都可得到一个 m_T 此m_T数值给出m_W的下限 ($m_T \leq m_W$)
- $P_T(\ell) = \frac{m_W}{2}$ 时 $m_T = m_W \Rightarrow \frac{d\sigma}{dm_T}$ peaks at $m_T = m_W$.

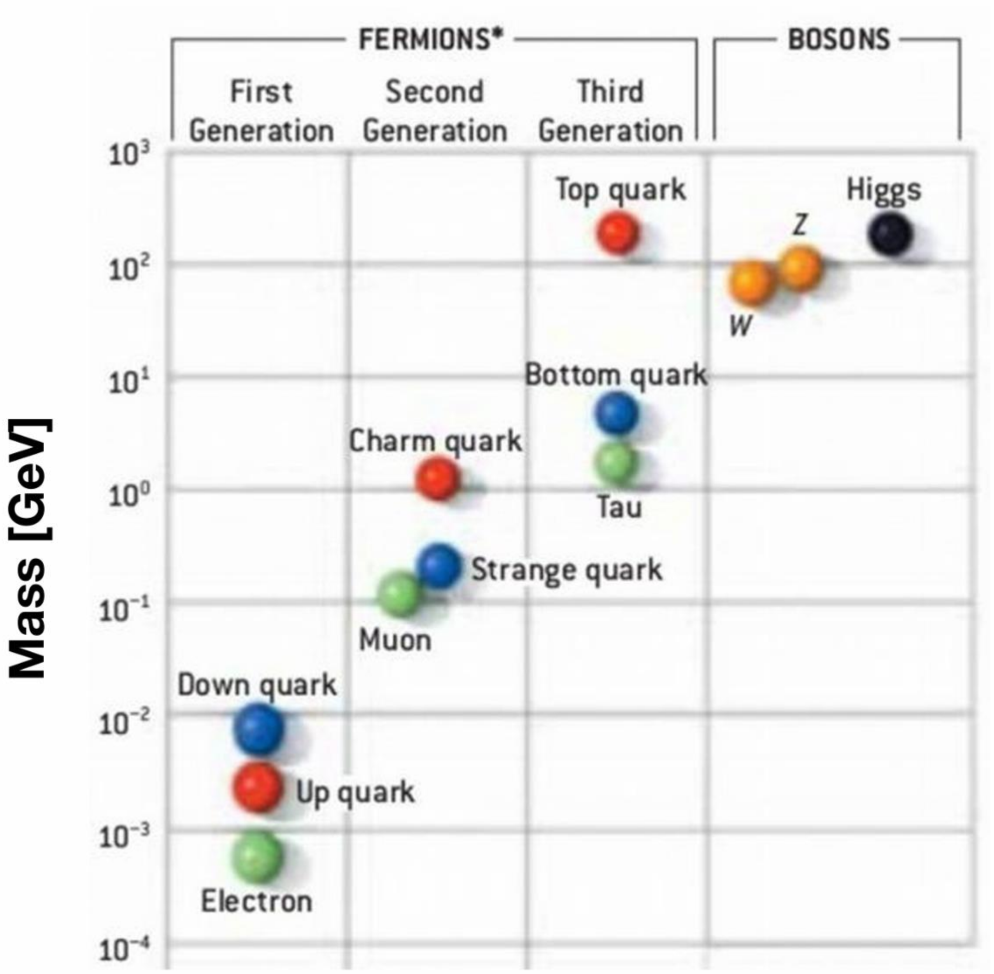
W boson mass measurement



Top quark physics

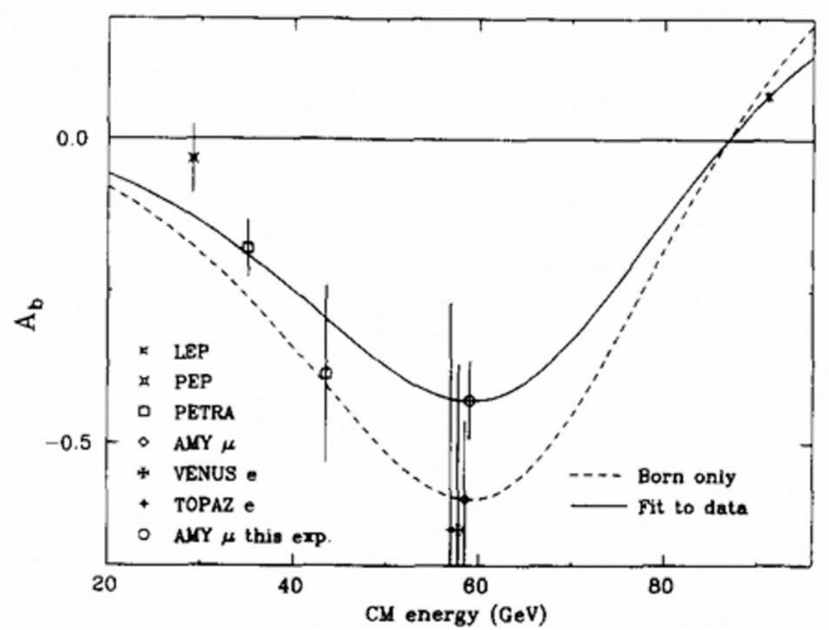
Top quark





Top quark： 172 GeV
Higgs boson: 125 GeV

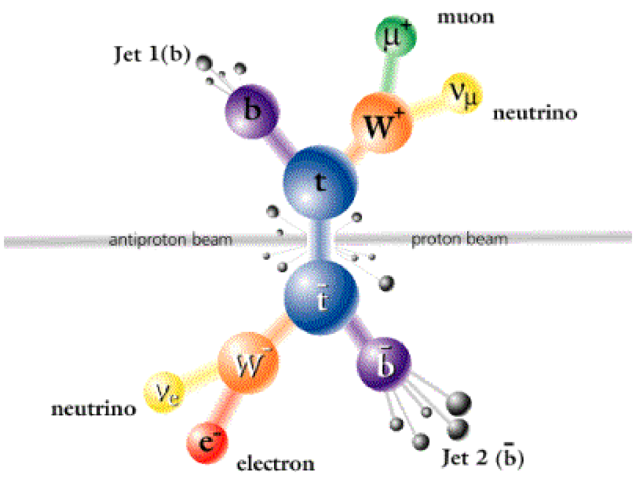
Top quark



1977: Forward-Backward Asymmetry of bottom quark $e^+e^- \to b\bar{b}$

Weak isospin of bottom quark $T_3 = -\frac{1}{2}$

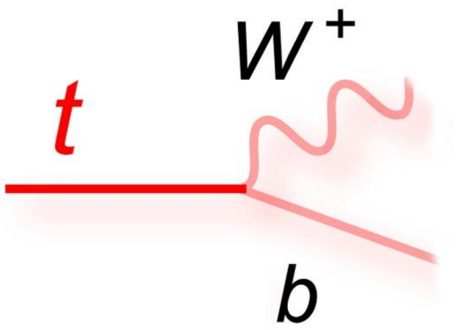
$T_3 = \frac{1}{2}$ state must exit: Top quark



Top quark discovered
in 1995 by CDF and D0

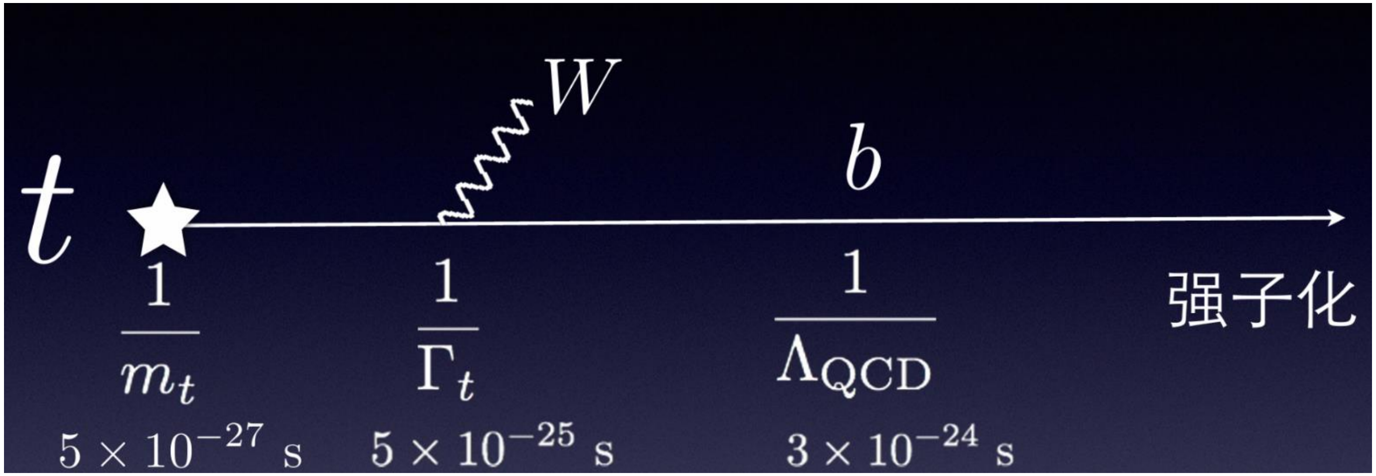
~20 years

Top quark Properties



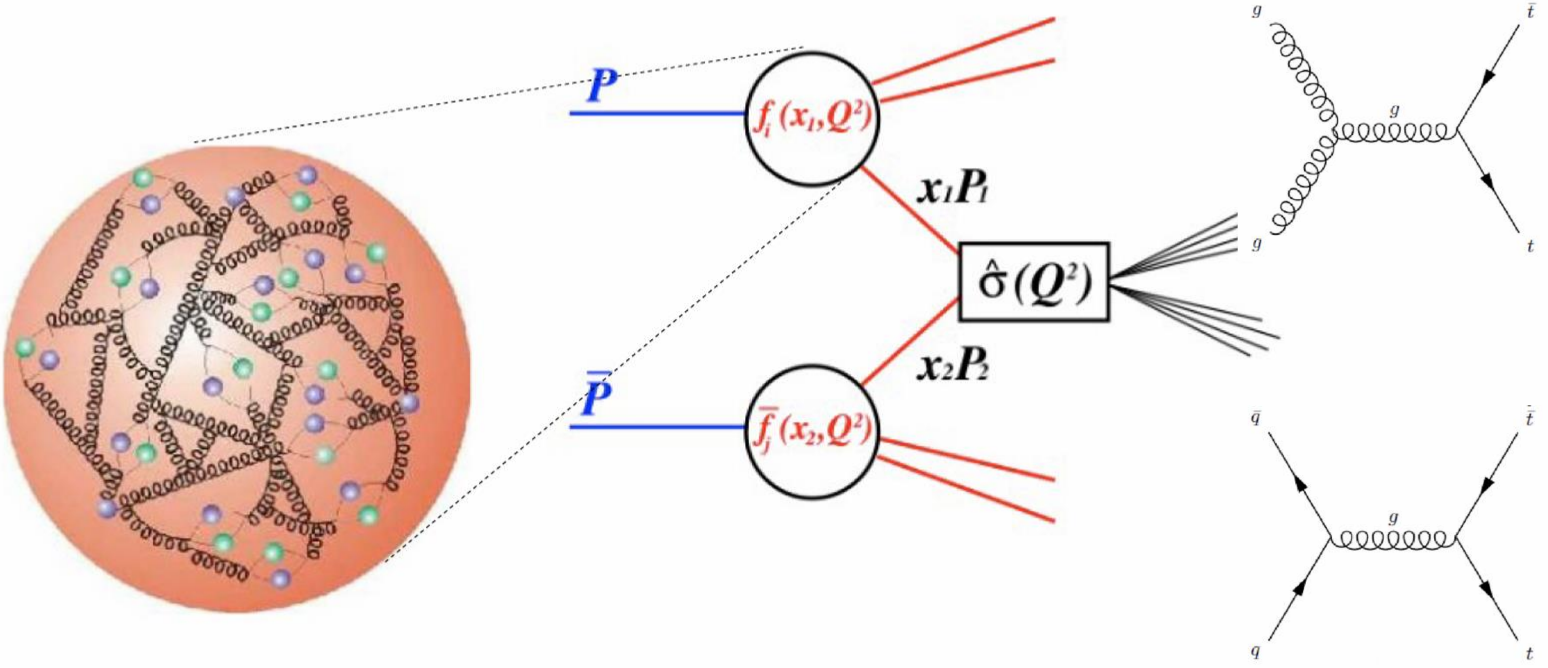
$$\Gamma_t = \frac{G_\mu}{8\pi\sqrt{2}} m_t^3 \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + \frac{2m_W^2}{m_t^2}\right) \qquad \Gamma_t = 1.4\ \text{GeV}$$

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22501 \pm 0.00068 & 0.003732^{+0.000090}_{-0.000085} \\ 0.22487 \pm 0.00068 & 0.97349 \pm 0.00016 & 0.04183^{+0.00079}_{-0.00069} \\ 0.00858^{+0.00019}_{-0.00017} & 0.04111^{+0.00077}_{-0.00068} & 0.999118^{+0.000029}_{-0.000034} \end{pmatrix}$$



- 顶夸克寿命极短，在强子化之前已经衰变
- 标准模型中唯一的裸夸克
- 顶夸克的极化可以通过末态产物进行重构

Top quark Production at hadron colliders



$$\underbrace{\sigma^{t\bar t}(\sqrt{s}, m_t)}_{\text{Cross section}} = \underbrace{\sum_{i,j=q,\bar q,g}\int dx_i\, dx_j}_{\text{Sum over all parton type and momenta}} \underbrace{f_i(x_i,\mu^2)\cdot \bar f_j(x_j,\mu^2)}_{\text{PDF}} \cdot \underbrace{\hat\sigma^{ij\to t\bar t}\left(\rho, m_t^2, \alpha_s(\mu^2), \mu^2\right)}_{\text{Partonic cross section}}$$

Top quark Production at hadron colliders

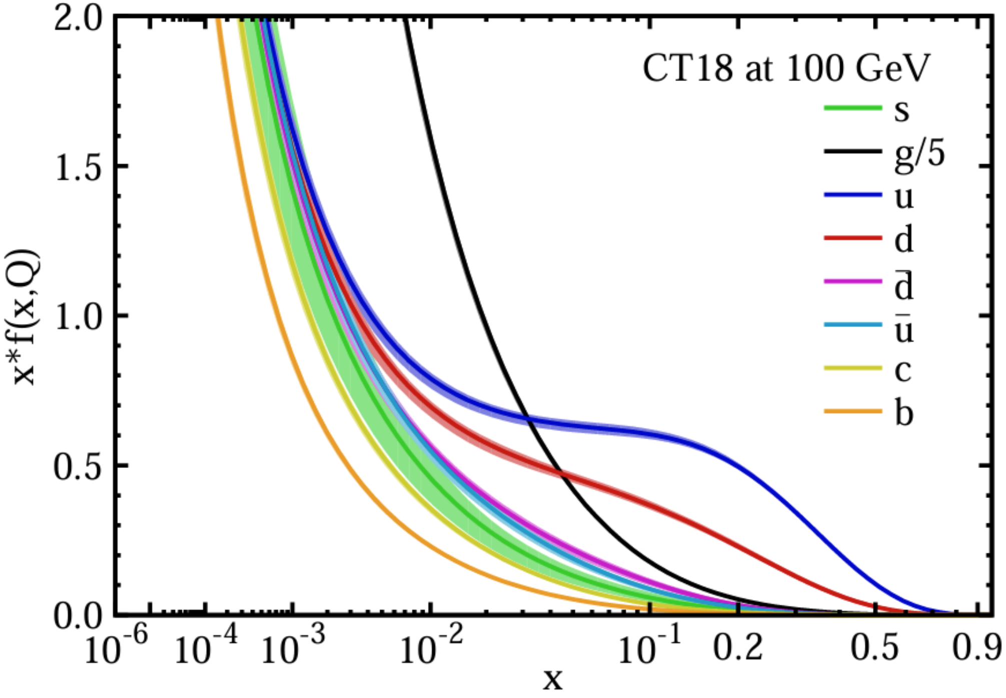
有效 Bjorken x: $\langle x \rangle = \frac{2m_t}{\sqrt{s}}$

- Tevatron: $\langle x \rangle \sim 0.2$ 价夸克主导

$$\sigma(q\bar{q} \to t\bar{t}) \gg \sigma(gg \to t\bar{t})$$

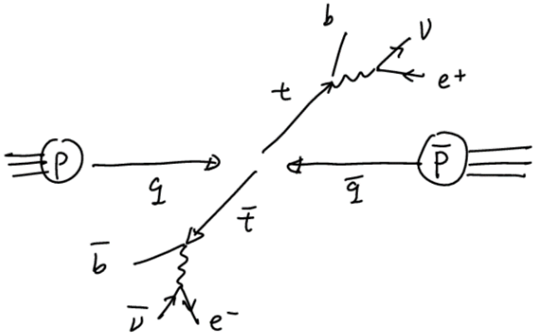
- LHC: 8 TeV $\langle x \rangle \sim 0.04$ 胶子主导
- LHC: 14 TeV $\langle x \rangle \sim 0.02$

$$\sigma(gg \to t\bar{t}) \gg \sigma(q\bar{q} \to t\bar{t})$$



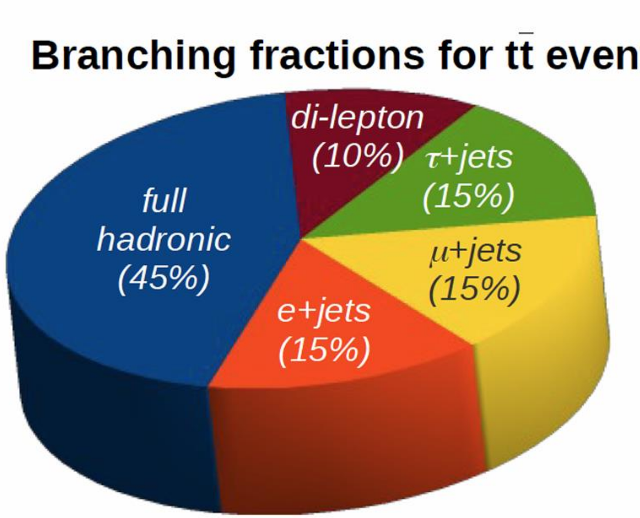
Top quark Production at hadron colliders

c) 顶夸克对产生的实验信号 (1995年 CDF)



实验信号：

2 b-jets,
2 charged leptons
large $\not{E}_T$ ($\nu\bar{\nu}$)

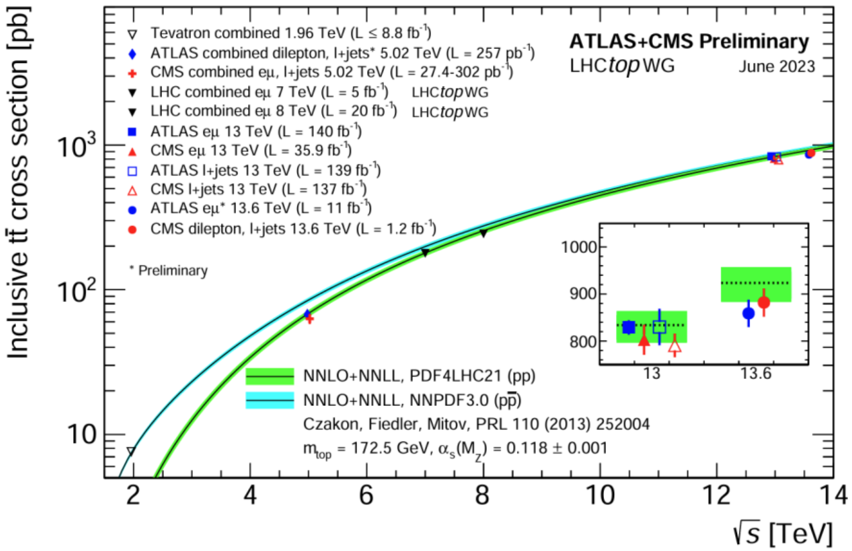


Note:

1) 顶夸克对产生过程是所有新物理的背景。
顶夸克对产生过程中含有最容易探测的实验信号

- ⊗ Heavy flavor jets
- ⊗ charged leptons
- ⊗ $\not{E}_T$

} The usual New Physics signal



2) 顶夸克对产生过程是强相互作用诱导的

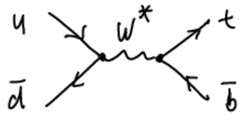
$m_t \gg \Lambda_{QCD} \sim 300$ MeV

⇒ $t\bar{t}$过程是检验pQCD的完美过程

Single top quark at hadron colliders

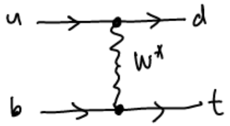
顶夸克也可以通过弱相互作用来单独产生。

(1) s-channel



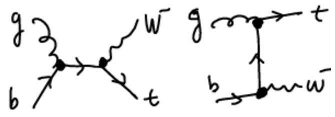
$Q_W^2>0$

(2) t-channel



$Q_W^2<0$

(3) tW 联合产生



$Q_W^2=m_W^2$

此三种分类可依据W粒子的运动学性质分类

- 截面正比于Vtb CKM 矩阵元，检验CKM矩阵幺正性
- 弱作用产生的顶夸克具有极化
- 直接敏感于tbW 反常相互作用

产生截面

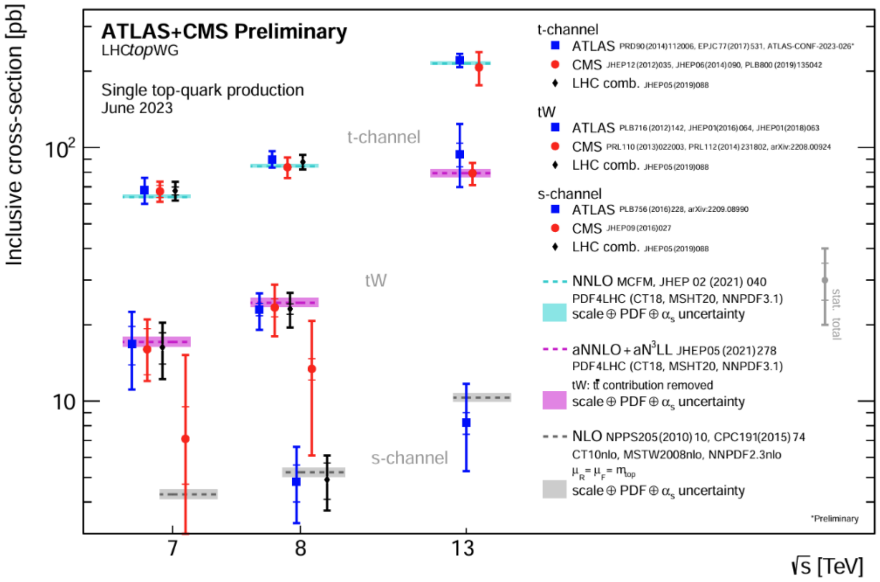
有效 Bjorken-x

Tevatron $\langle x\rangle \simeq \frac{m_t}{\sqrt{s}} = \frac{172\,\mathrm{GeV}}{1960\,\mathrm{GeV}} \sim 0.1$

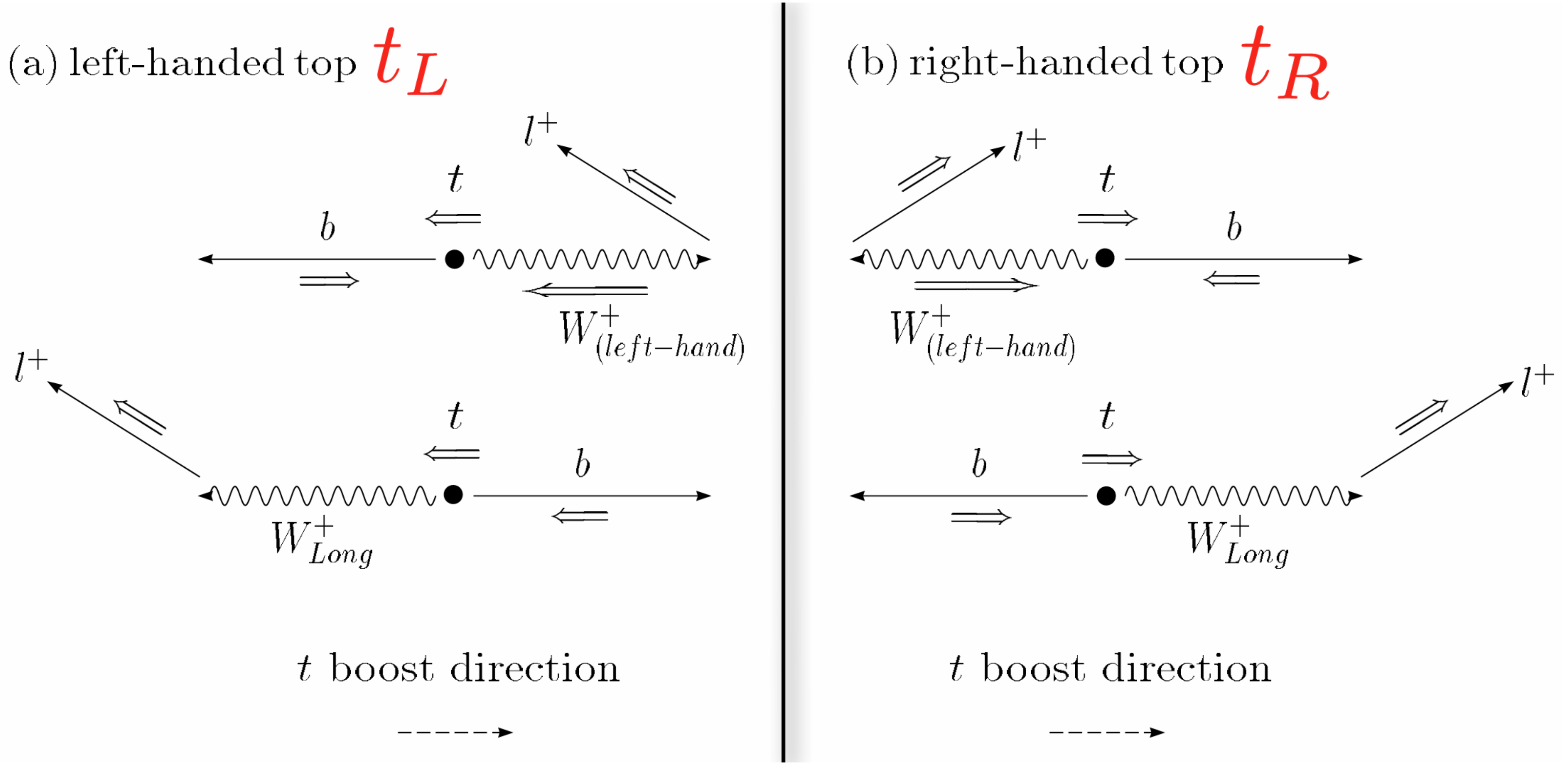
$\Rightarrow$ 价夸克占主导

LHC $\langle x\rangle \simeq \frac{m_t}{\sqrt{s}} = \frac{172\,\mathrm{GeV}}{8000\,\mathrm{GeV}} \sim 0.03$

$\Rightarrow$ 海夸克和胶子占主导



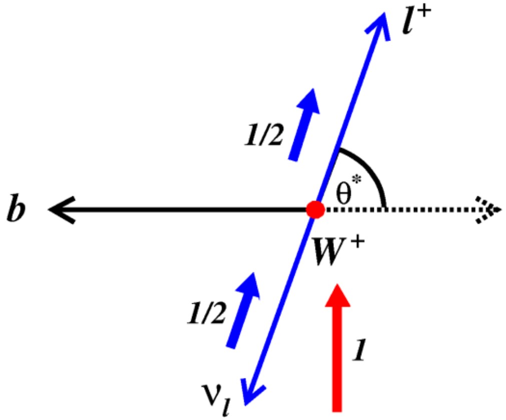
Charged Lepton: Spin Analyzer



Charged Lepton tends to follow the direction of Top-quark spin.

Helicity fractions

在顶夸克静止系下，带电轻子在W静止系下的夹角：



$$d^1_{1,-1} = \frac{1-\cos\theta}{2}, d^1_{1,1} = \frac{1+\cos\theta}{2}$$

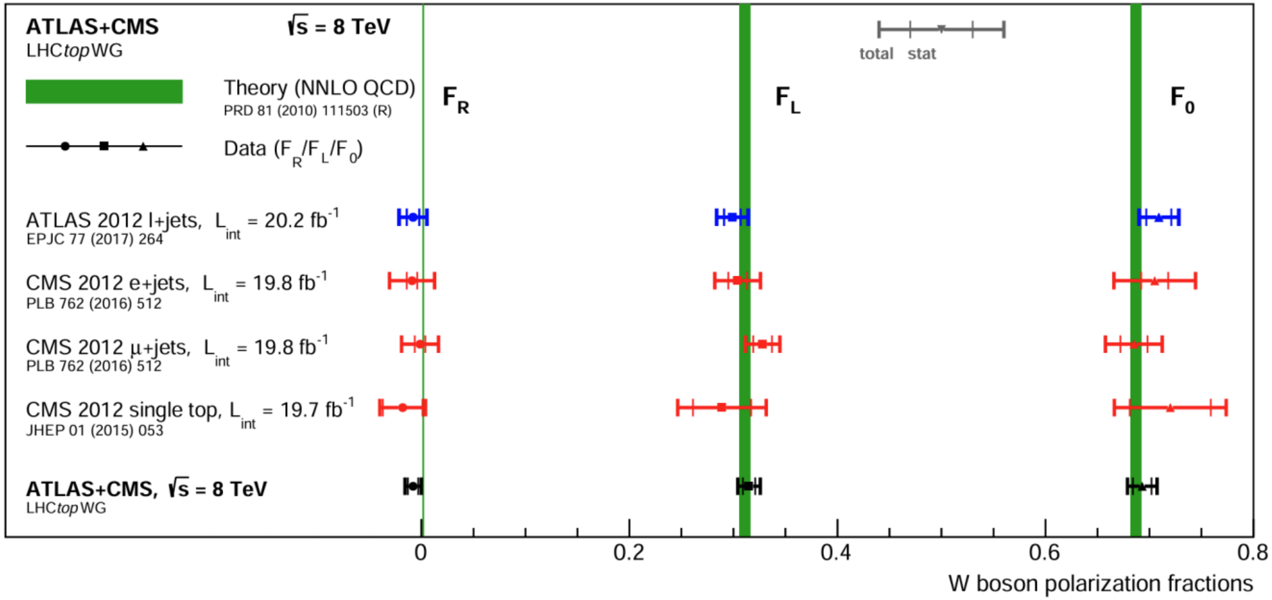
$$d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{8}(1-\cos\theta)^2 F_L + \frac{3}{8}(1+\cos\theta)^2 F_R + \frac{3}{4}\sin\theta^2 F_0$$

W boson helicity fractions 敏感 tbW 有关的相互作用

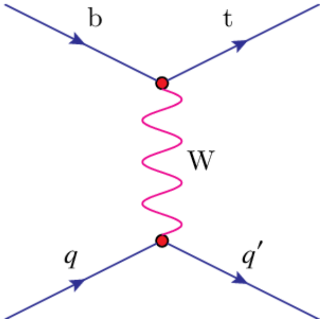
$$\begin{aligned}\mathcal{L}_{Wtb} \quad = \quad & -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\,(V_L P_L + V_R P_R)\,t\,W^-_\mu \\ & -\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\,(g_L P_L + g_R P_R)\,t\,W^-_\mu + \text{h.c.}\end{aligned}$$

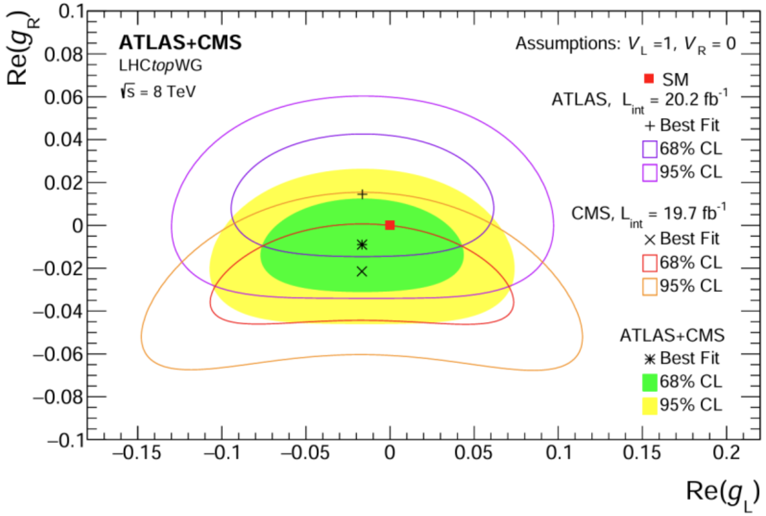
Top quark anomalous couplings

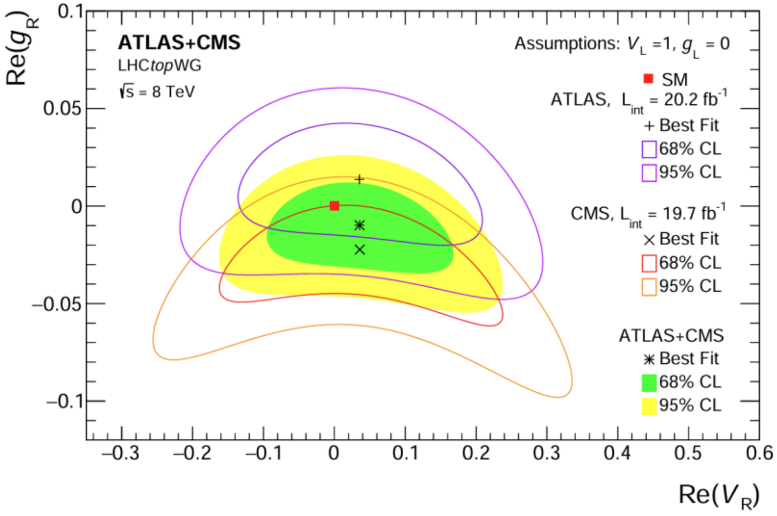


JHEP 08 (2020) 08, 051

结合顶夸克的电弱产生截面，我们将得到更严格的限制

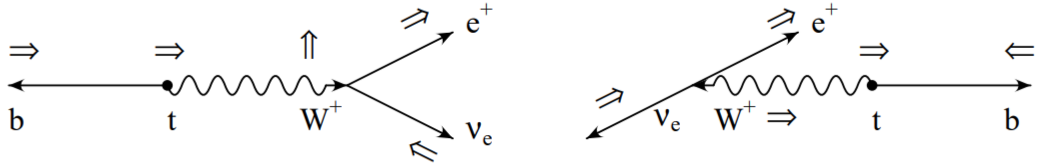


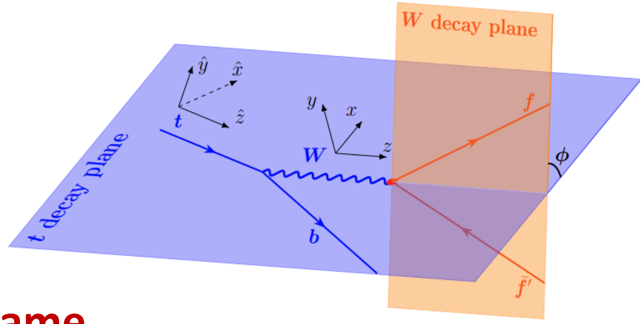




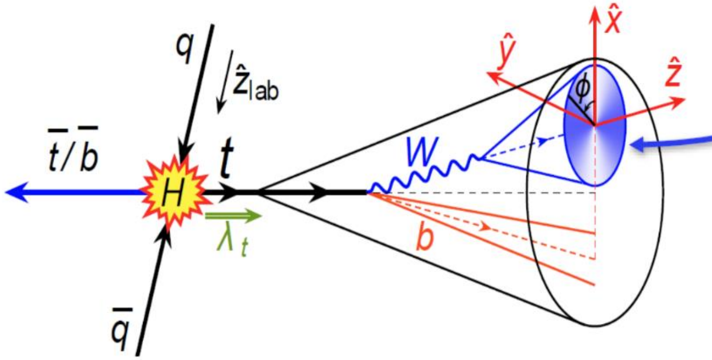
Linear polarization of W boson

Zhite Yu, C.-P. Yuan, PRL 129 (2022) 11,11





W boson is not linearly polarized in top quark rest frame



$$\frac{\mathrm{d}E}{\mathrm{d}\phi} = \frac{E_{\mathrm{tot}}}{2\pi}\left[1 + \xi \cos 2\phi\right]$$ **Infrared safe**

Boosted limit: $\xi = \xi(\lambda_t) = 0.145(\lambda_t - 1)$

[Assuming SM tbW coupling]

Azimuthal correlation

Boosted top polarization

- Measuring longitudinal polarization of boosted top
- New top tagger against QCD jets

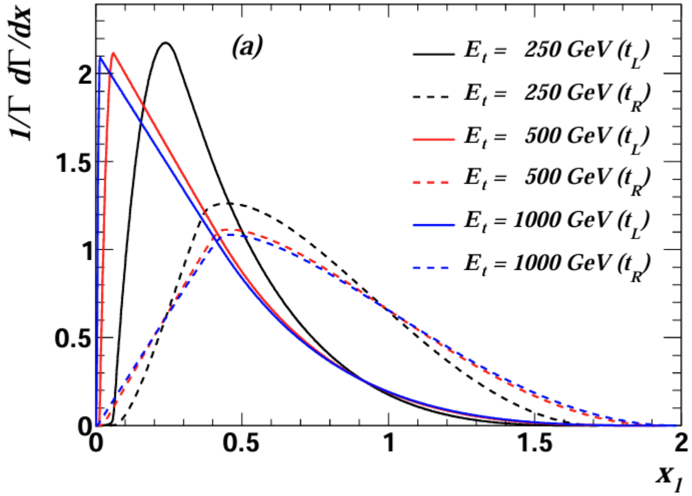
A new tool to probe the NP effects,
e.g. the CP violation in top quark decay

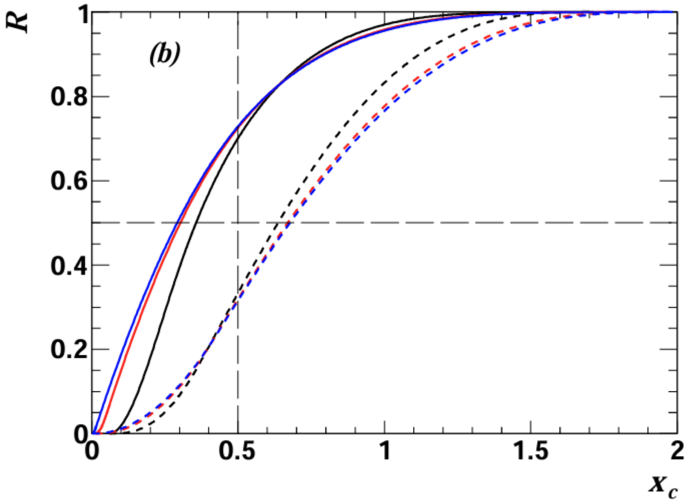
Lepton energy

Charged Lepton tends to follow the direction of Top-quark spin.

$x_\ell \equiv 2E_\ell/E_t$

E. L. Berger. Q. H. Cao, J. H. Yu, H. Zhang, PRL 109 (2012) 152004



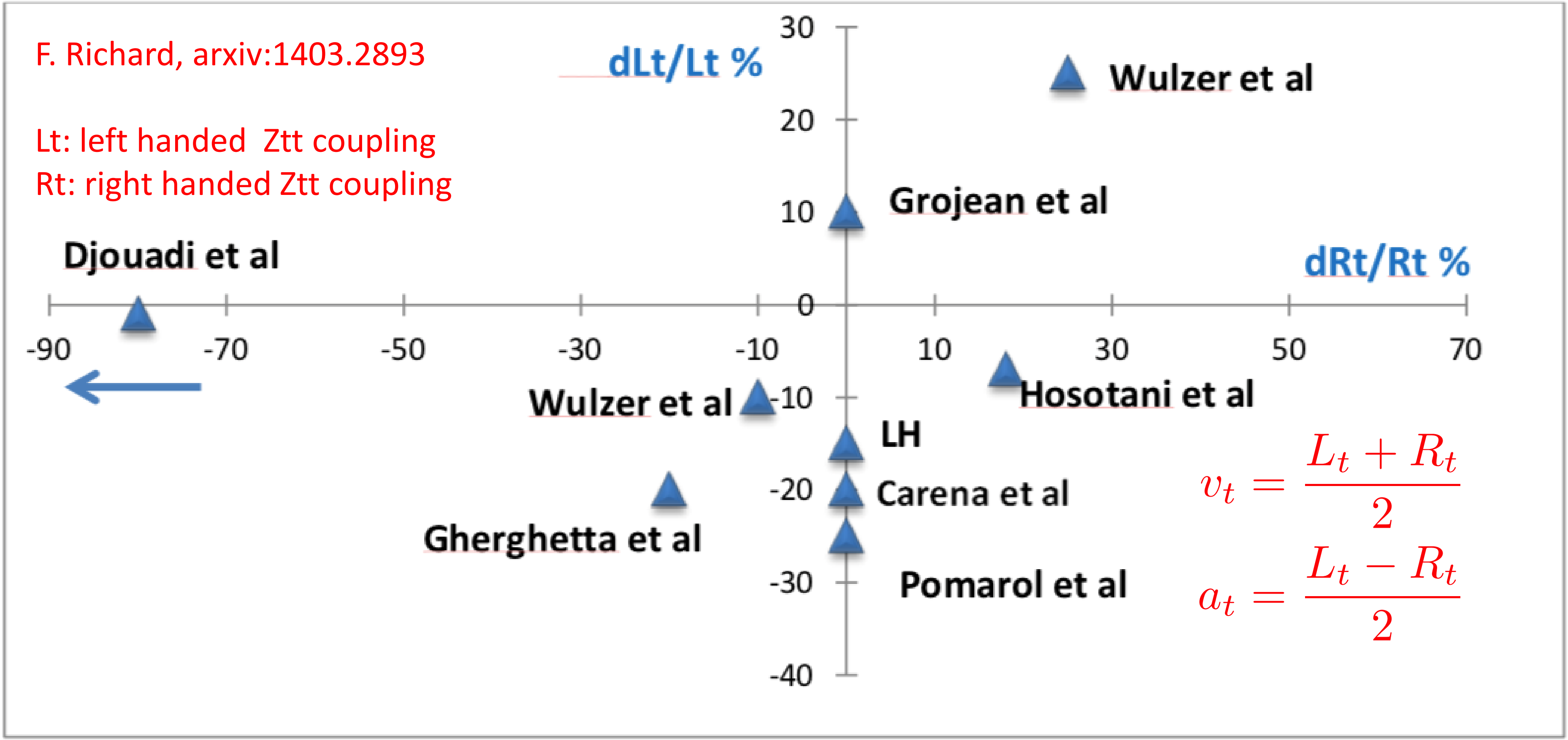


$$\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB} \int_{z_{\min}}^{z_{\max}} x\gamma^2[1 - x\gamma^2(1 - z\beta)] \left(1 + \hat{s}_t \frac{z - \beta}{1 - z\beta}\right) \mathrm{Arctan}\left[\frac{Ax\gamma^2(1 - z\beta)}{B - x\gamma^2(1 - z\beta)}\right] dz.$$

$$\mathcal{R}(x_c) = \frac{1}{\Gamma} \int_0^{x_c} \frac{d\Gamma}{dx_\ell} dx_\ell \equiv \frac{\Gamma(x_\ell < x_c)}{\Gamma}$$

右手顶夸克产生的轻子能量比左手大

Top quark Neutral current & NP



F. Richard, arxiv:1403.2893

Lt: left handed Ztt coupling
Rt: right handed Ztt coupling

$$v_t = \frac{L_t + R_t}{2}$$

$$a_t = \frac{L_t - R_t}{2}$$

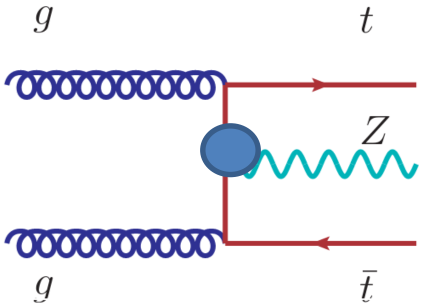
Distinguishing the vector and axial vector components of Ztt coupling=> different NP models

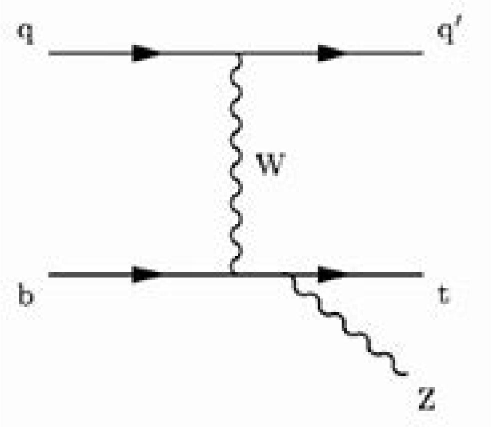
Top quark Neutral current

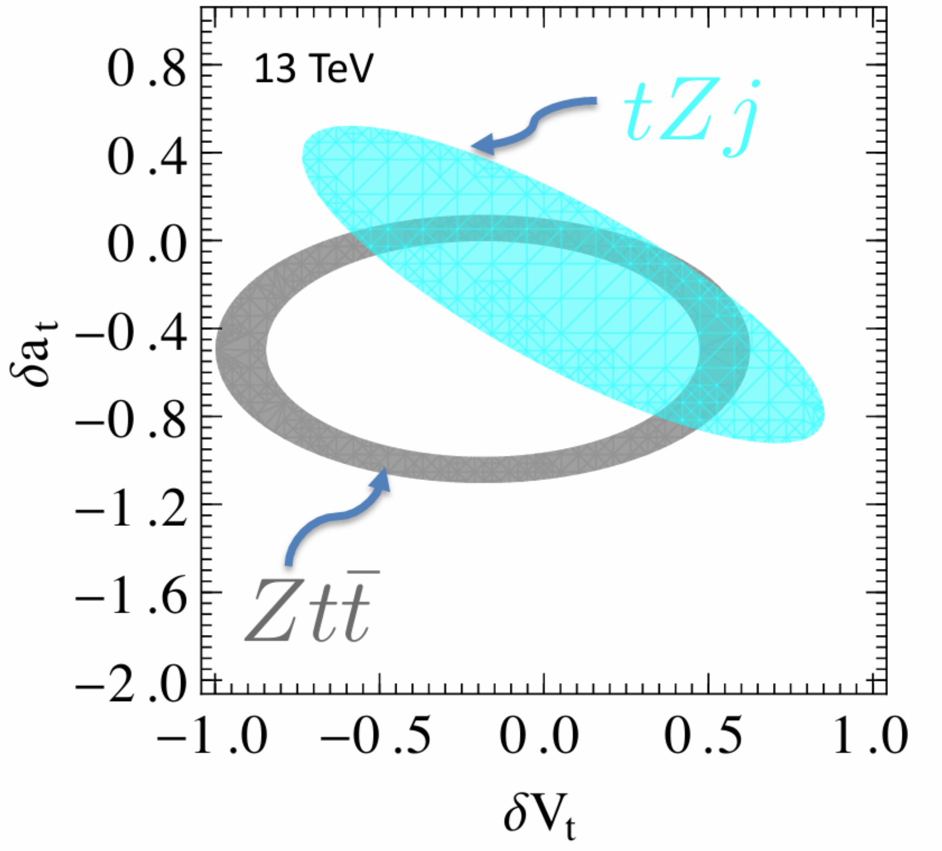
$$\mathcal{L} = \frac{g_W}{2c_W}\bar{t}(v_t - a_t\gamma_5)\gamma_\mu t Z^\mu$$

$$v_t^{\rm SM} = 0.35, \quad a_t^{\rm SM} = \frac{1}{2}$$

E.L. Berger, Q.-H. Cao and I. Low, PRD80,074020(2009)
R. Rontsch and M. Schulze, JHEP07,091(2014)
O. Bessidskaia Bylund et al, JHEP05,052(2016)



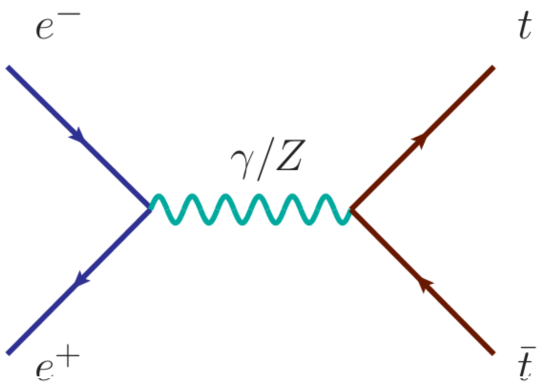




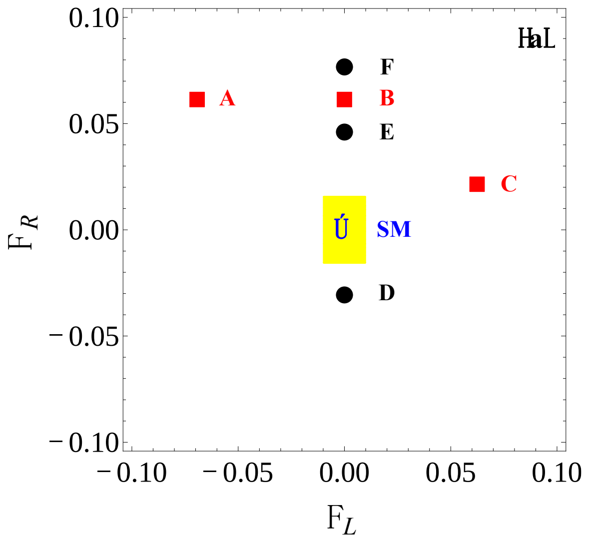
How to distinguish the top quark couplings

A, B and C: extra dimensional models

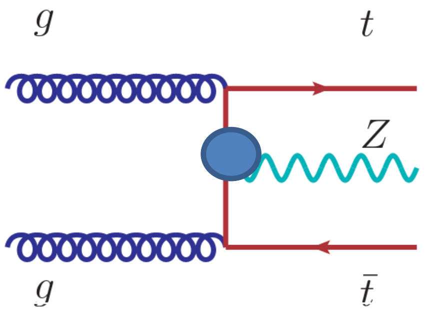
D, E and F: the composite models



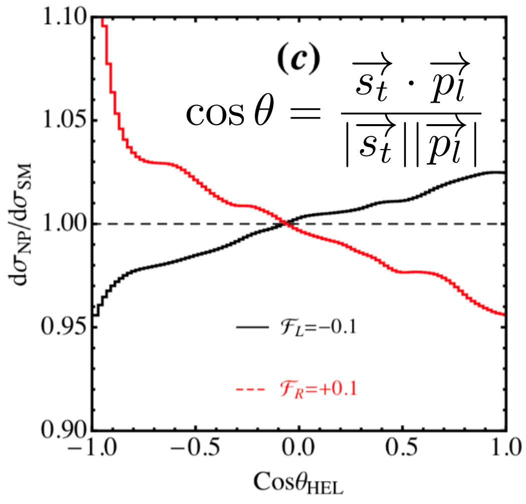
Q. H. Cao and **B. Yan**, PRD92,094018(2015)



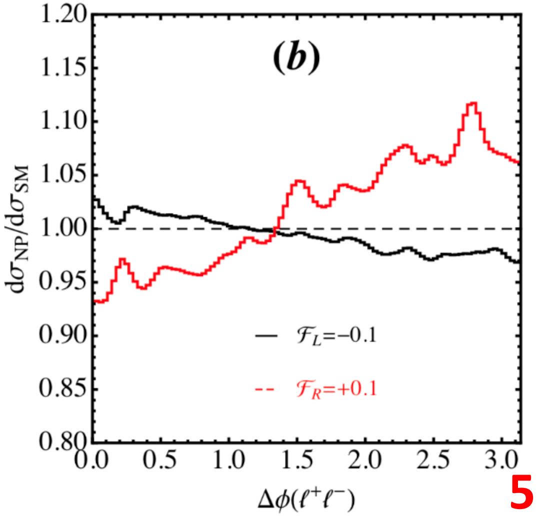
E. L. Berger, Q. H. Cao, I. Low, PRD80(2009)074020



A. Top quark Spin correlation



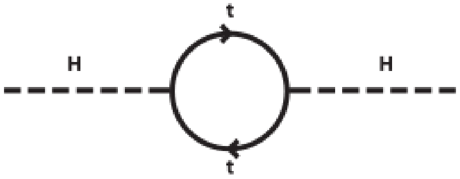
B. $\Delta\phi(\ell^+\ell^-)$

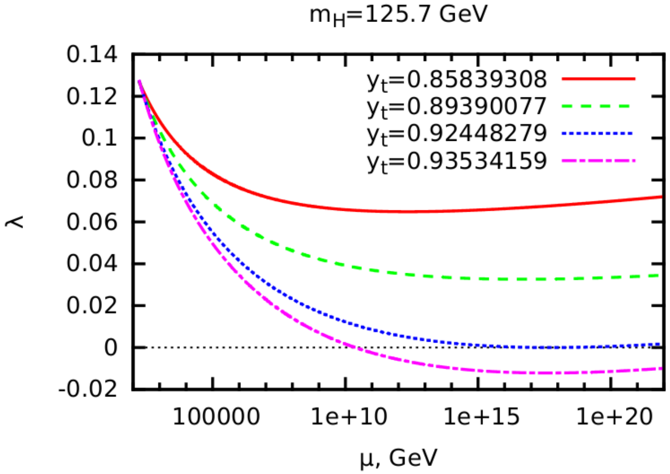


Top quark Yukawa coupling

- Theoretically, it connects to various new physics directly

F. Bezrukov, M. Shaposhnikov, J.Exp.Theor.Phys. 120 (2015) 335





1. Vacuum stability
2. Hierarchy problem (Naturalness problem)
3. Nature of electroweak symmetry breaking
4. Deviation from SM prediction can lead to many new physics models

Weak interacting?

Strongly interacting?

SUSY

Little Higgs

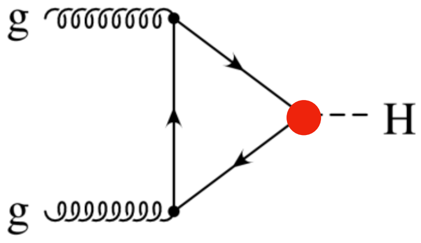
Composite

- Experimentally, it can be measured in many processes at colliders

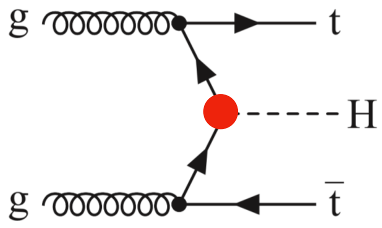
Top Yukawa coupling at LHC

$$\mu = \frac{\sigma_{obs.}}{\sigma_{exp.}} \sim |y_t|^2$$

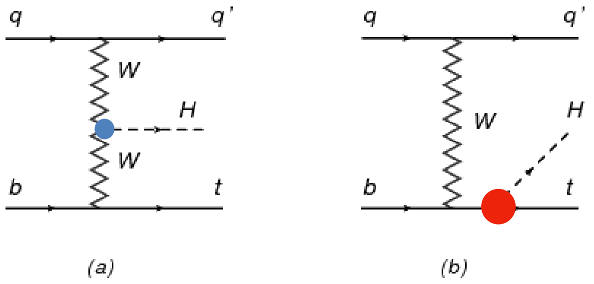
- Indirect probe: gluon fusion



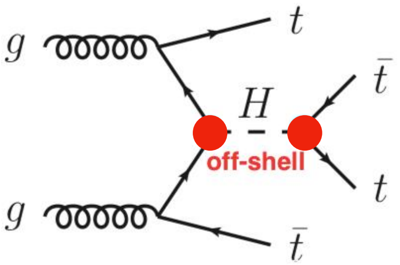
- Htt associated production



- Htj associated production



- Multi-top production

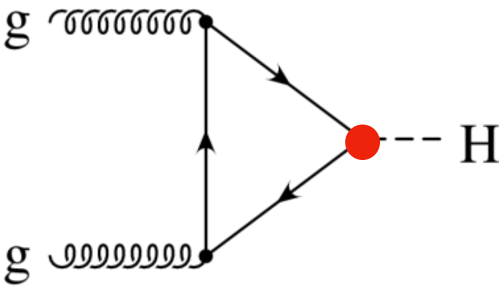


Q-H. Cao, S-L. Chen, Y. Liu, 17’
Q-H. Cao, S-L. Chen, Y. Liu, R. Zhang, Y. Zhang, 19’

Indirect and direct measurements at 13 TeV LHC

$$\mu = \frac{\sigma_{obs.}}{\sigma_{exp.}} \sim |y_t|^2$$

- Indirect probe: gluon fusion



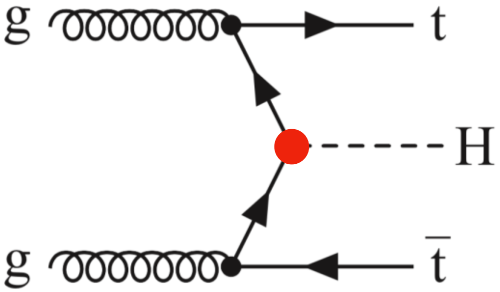
$\mu(gg \rightarrow h) = 1.07 \pm 0.09$

ATLAS-CONF-2018-031

$\mu(gg \rightarrow h) = 1.23 \pm 0.13$

CMS-PAS-HIG-17-031

- Htt associated production



$\mu(gg \rightarrow t\bar{t}h) = 1.32^{+0.28}_{-0.26}$

1806.00425

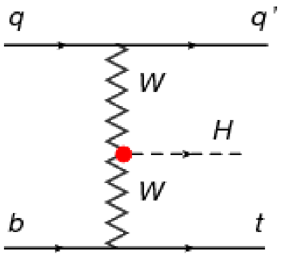
$\mu(gg \rightarrow t\bar{t}h) = 1.26^{+0.31}_{-0.26}$

1804.02610

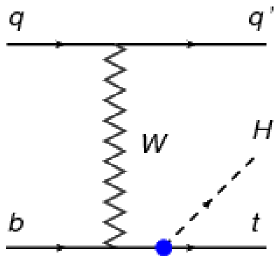
Indirect and direct measurements at 13 TeV LHC

$$\mu = \frac{\sigma_{obs.}}{\sigma_{exp.}} \sim |y_t|^2$$

- Htj associated production



(a)

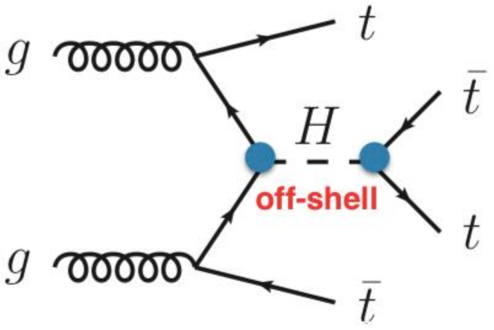


(b)

CMS: 1811.09696

the data favor a positive value of the top quark Yukawa coupling

- Multi-top production



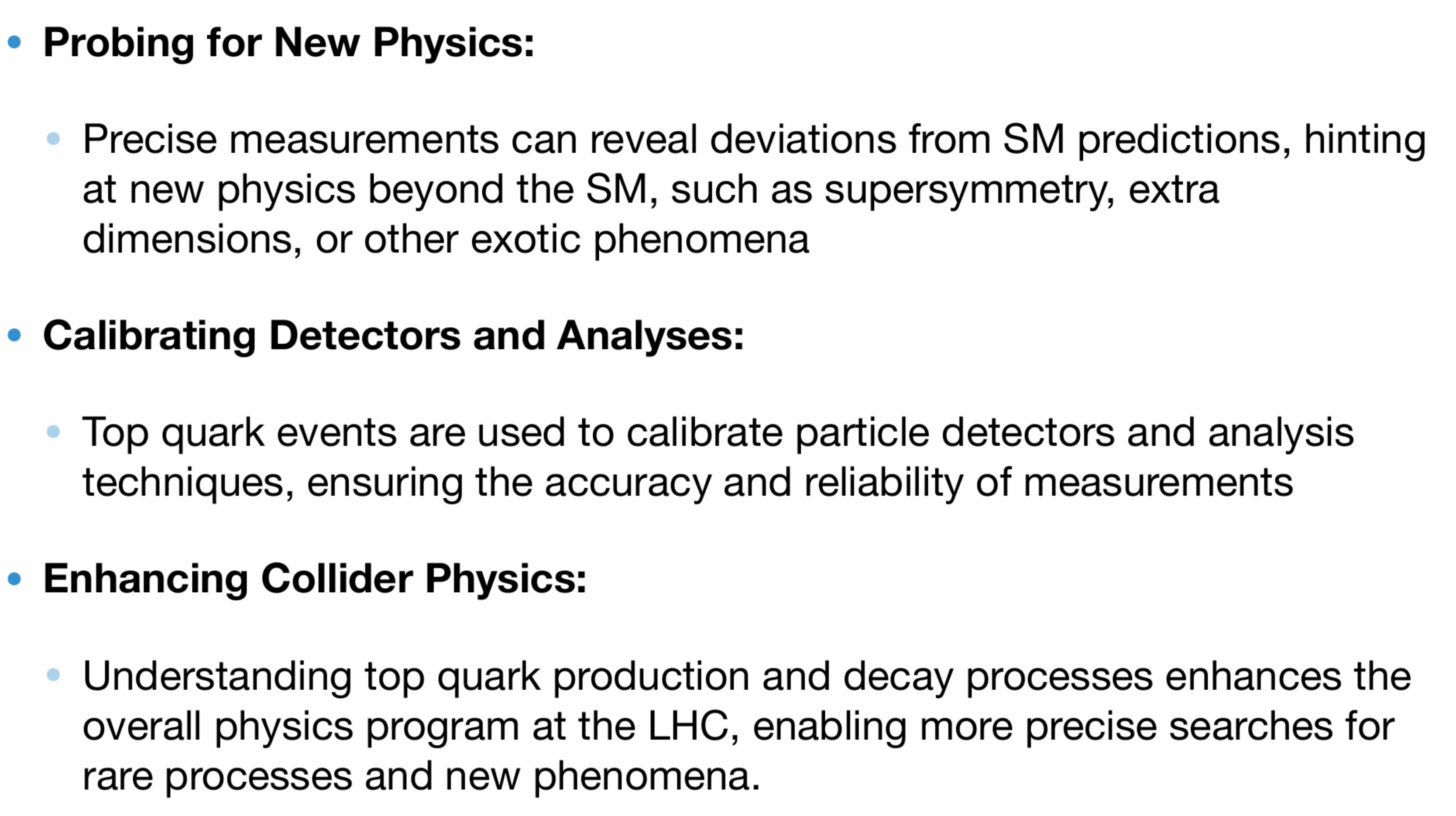
Evidence by ATLAS: 2007.14858

Q-H. Cao, S-L. Chen, Y. Liu, 17’
Q-H. Cao, S-L. Chen, Y. Liu, R. Zhang, Y. Zhang, 19’

Top quark Properties

- **Fundamental Parameter of the SM**:
  - The top quark plays a critical role in the SM of particle physics. Its properties, such as **mass**, **charge**, and **spin**, are fundamental parameters that influence predictions and calculations within the SM
- **Electroweak Symmetry Breaking**:
  - The top quark's mass is close to the electroweak scale. It could have a significant role in electroweak symmetry breaking
- **Higgs Boson Interactions:**
  - The top quark **interacts strongly** with the Higgs boson, affecting Higgs production and decay rates. Accurate measurements of top quark properties are essential to refine our understanding of the Higgs boson and its properties
- **Testing Quantum Chromodynamics (QCD):**
  - As the **heaviest quark**, the top quark decays before it hadronizes, providing a unique opportunity to study QCD in a relatively clean environment. This helps in testing and refining QCD predictions

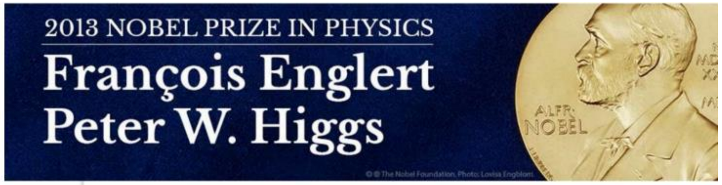
Top quark Properties

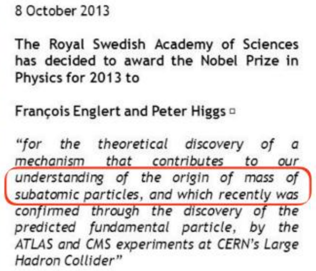


- **Probing for New Physics:**
  - Precise measurements can reveal deviations from SM predictions, hinting at new physics beyond the SM, such as supersymmetry, extra dimensions, or other exotic phenomena
- **Calibrating Detectors and Analyses:**
  - Top quark events are used to calibrate particle detectors and analysis techniques, ensuring the accuracy and reliability of measurements
- **Enhancing Collider Physics:**
  - Understanding top quark production and decay processes enhances the overall physics program at the LHC, enabling more precise searches for rare processes and new phenomena.

The Era of the Higgs Physics

The Era of the Higgs Physics



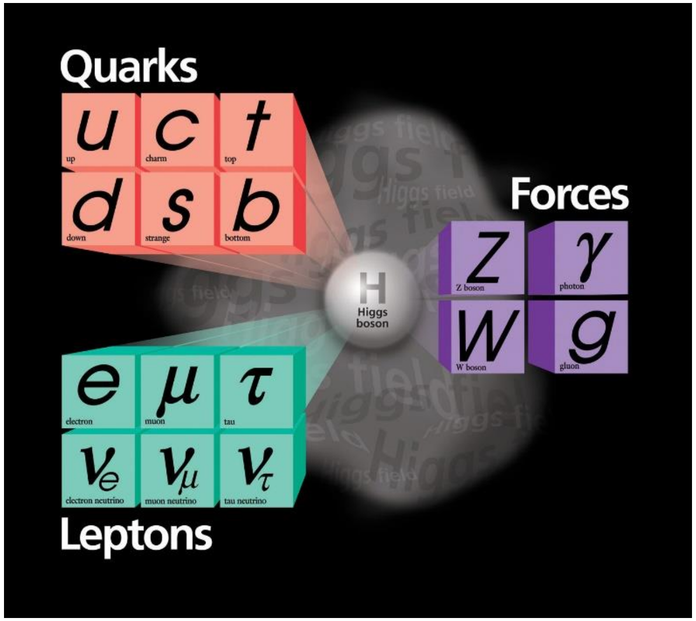


8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

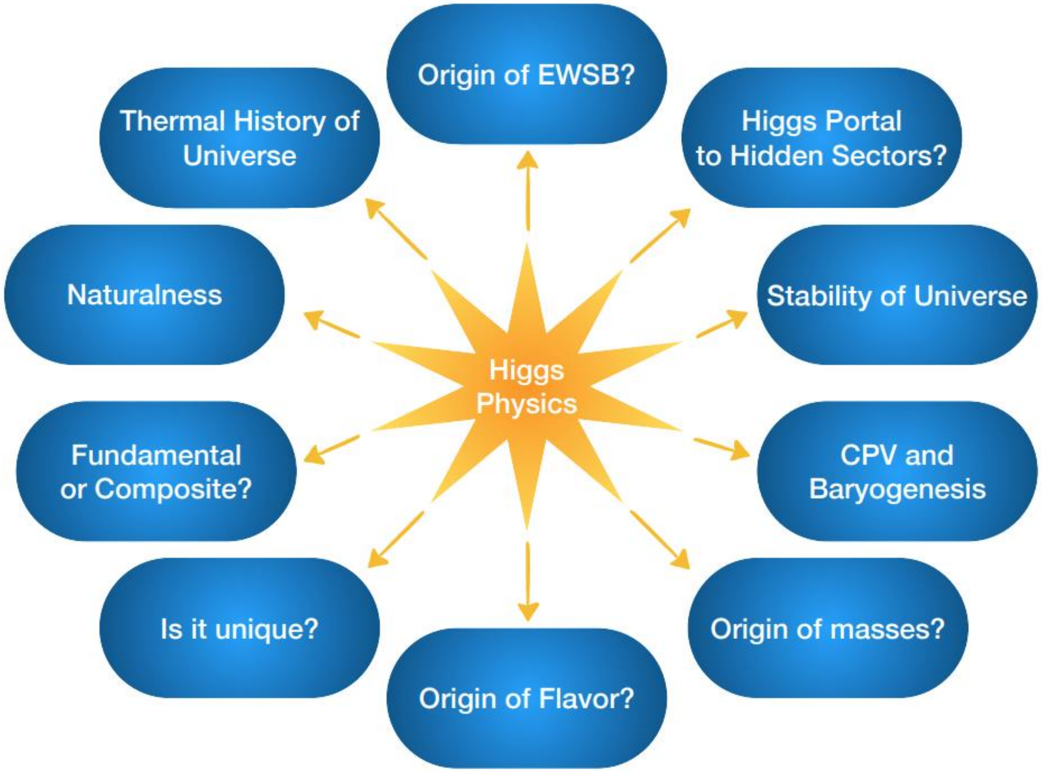
François Englert and Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



Understanding of origin of mass of subatomic particles

Snowmass 2021, 2209.07510



Higgs Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

Is it unique?

Fundamental or Composite?

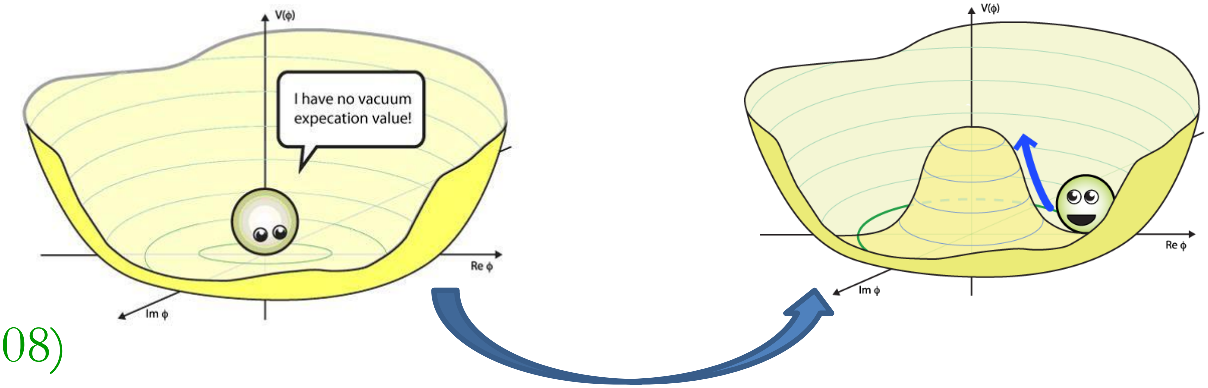
Naturalness

Thermal History of Universe

Brout-Englert-Higgs Mechanism

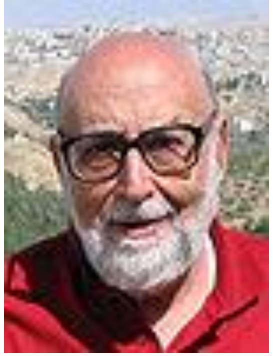
- **Spontaneous broken symmetry**: the Lagrangian is invariant under the symmetry, but the ground state of the theory is not

Nambu (Nobel Prize 2008)



- Brout-Englert-Higgs Mechanism (1964)

Brout



Englert

Peter Higgs

- **Goldstone's theorem:** Spontaneous breaking of continuous global symmetries implies the existence of massless particles

Englert, Higgs
2013 Nobel Prize

Example: Linear sigma model

复标量场：U(1) global symmetry $\phi(x) \to e^{i\alpha}\phi(x)$

$$\mathcal{L} = (\partial_\mu \phi^\star)(\partial_\mu \phi) + m^2 \phi\phi^\star - \frac{\lambda}{4}\phi^2\phi^{\star 2}$$

势能项：

$$V(\phi) = -m^2|\phi|^2 + \tfrac{\lambda}{4}|\phi|^4$$

$$\langle v \rangle = \sqrt{\frac{2m^2}{\lambda}}$$

将标量场进行重新参数化：

$$\phi(x) = \left(\sqrt{\frac{2m^2}{\lambda}} + \frac{1}{\sqrt{2}}\sigma(x)\right) e^{i\frac{\pi(x)}{F_\pi}}$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\sigma)^2 + \left(\sqrt{\frac{2m^2}{\lambda}} + \frac{1}{\sqrt{2}}\sigma(x)\right)^2 \frac{1}{F_\pi^2}(\partial_\mu\pi)^2$$

$$- \left(-\frac{m^4}{\lambda} + m^2\sigma^2 + \frac{1}{2}\sqrt{\lambda}m\sigma^3 + \frac{1}{16}\lambda\sigma^4\right)$$

只有动能项，
而无质量项
Goldstone

Brout-Englert-Higgs Mechanism

An Abelian Example: 电磁场+复标量场

$$D_\mu \;=\; \partial_\mu \;+\; ieA_\mu$$

$$V(\phi) = -\mu^2\phi^*\phi + \frac{\lambda}{2}(\phi^*\phi)^2$$

$$\mathcal{L} = -\tfrac{1}{4}(F_{\mu\nu})^2 + |D_\mu\phi|^2 - V(\phi)$$

U(1) 规范变换：

$$\phi(x) \to e^{i\alpha(x)}\phi(x), \qquad A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)$$

对称性自发破缺：

$$\phi(x) = \phi_0 + \frac{1}{\sqrt{2}}(\phi_1(x) + i\phi_2(x)) \qquad \langle\phi\rangle = \phi_0 = \left(\frac{\mu^2}{\lambda}\right)^{1/2}$$

$$|D_\mu\phi|^2 = \tfrac{1}{2}(\partial_\mu\phi_1)^2 + \tfrac{1}{2}(\partial_\mu\phi_2)^2 + \sqrt{2}e\phi_0 \cdot A_\mu\partial^\mu\phi_2 + \boxed{e^2\phi_0^2 A_\mu A^\mu} + \cdots$$

Goldstone boson to disappear from the spectrum and the gauge boson to become massive

Brout-Englert-Higgs Mechanism

标准模型电弱规范对称性 $\mathcal{L} = \left|D_\mu\phi\right|^2 + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$

$$D_\mu\phi = \left(\partial_\mu - igA^a_\mu\tau^a - i\tfrac{1}{2}g'B_\mu\right)\phi$$

电弱规范玻色子质量项：

$$\Delta\mathcal{L} = \frac{1}{2}\frac{v^2}{4}\left[g^2(A^1_\mu)^2 + g^2(A^2_\mu)^2 + (-gA^3_\mu + g'B_\mu)^2\right]. \tag{20.62}$$

There are three massive vector bosons, which we will notate as follows:

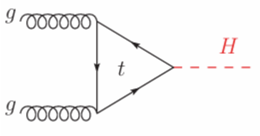
$$\begin{aligned} W^\pm_\mu &= \frac{1}{\sqrt{2}}(A^1_\mu \mp iA^2_\mu) \qquad \text{with mass} \quad m_W = g\frac{v}{2}; \\ Z^0_\mu &= \frac{1}{\sqrt{g^2+g'^2}}(gA^3_\mu - g'B_\mu) \qquad \text{with mass} \quad m_Z = \sqrt{g^2+g'^2}\,\frac{v}{2}. \end{aligned} \tag{20.63}$$

The fourth vector field, orthogonal to Z^0_μ, remains massless:

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'A^3_\mu + gB_\mu) \qquad \text{with mass} \quad m_A = 0. \tag{20.64}$$

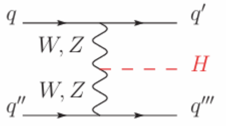
Higgs production at the LHC

- Gluon Fusion



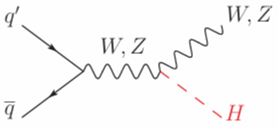
Loop suppressed, but large top quark Yukawa coupling, large gluon PDF enhancement

- VBF production



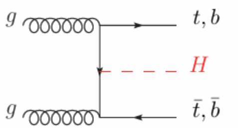
Forward & backward jet=> helps to identify Higgs event
Direct probe of HVV couplings

- VH associated production

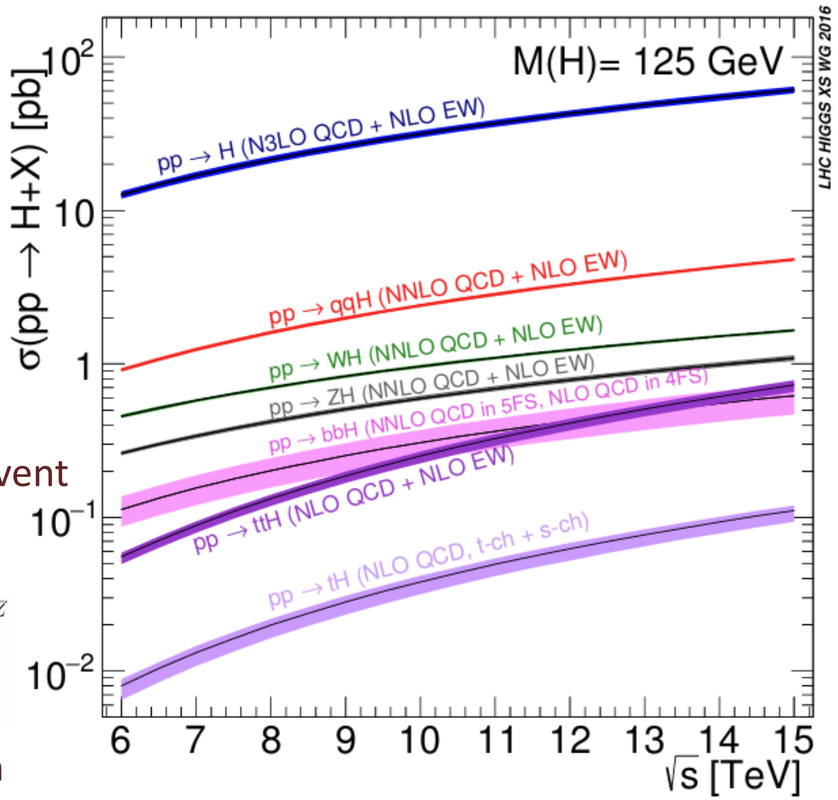


Leptons from V decay help with event identification
Direct probe of HVV couplings

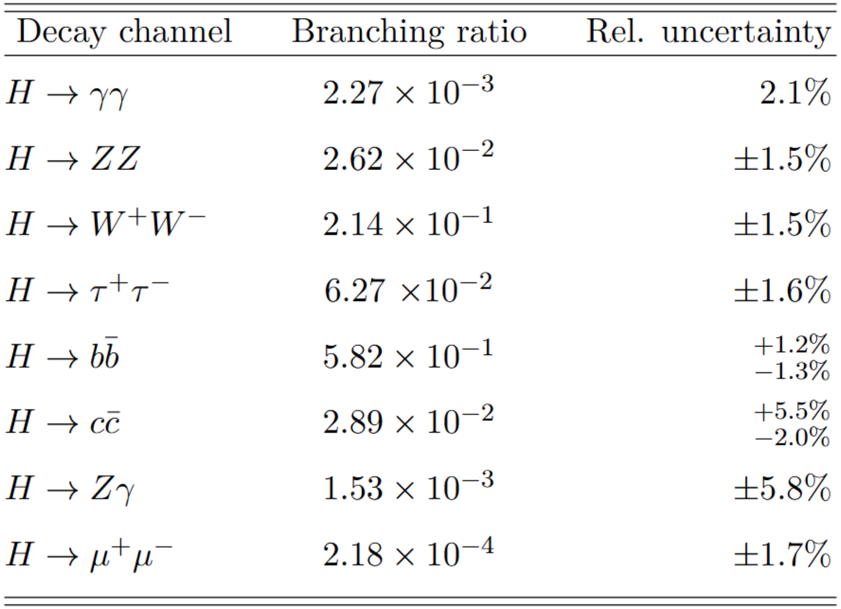
- ttH production



Challenging final state; direct probe of ttH coupling



Higgs decays



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	2.1%
$H \to ZZ$	2.62×10^{-2}	±1.5%
$H \to W^+W^-$	2.14×10^{-1}	±1.5%
$H \to \tau^+\tau^-$	6.27×10^{-2}	±1.6%
$H \to b\bar{b}$	5.82×10^{-1}	$^{+1.2\%}_{-1.3\%}$
$H \to c\bar{c}$	2.89×10^{-2}	$^{+5.5\%}_{-2.0\%}$
$H \to Z\gamma$	1.53×10^{-3}	±5.8%
$H \to \mu^+\mu^-$	2.18×10^{-4}	±1.7%

- Bottom quark (58%)

  B quark form short-lived B hadrons, can be identified by displaced tracks; large QCD background

- Vector bosons (Z: 3%, W: 21%)

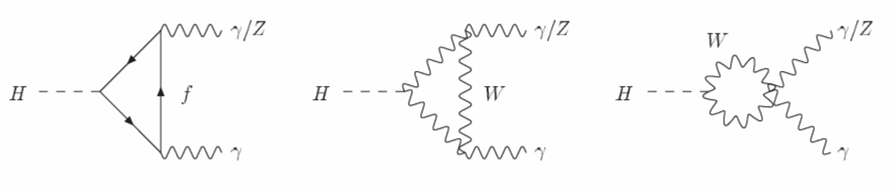
  One of the V has to be off-shell; small event rates when including decays to leptons, but clean detector signature

- Gluons (8.2%)

  Huge QCD backgrounds at LHC

- Photons ($Z\gamma$,$\gamma\gamma$ 0.2%)

  Small BR, but clear detector signature; destructive interferences

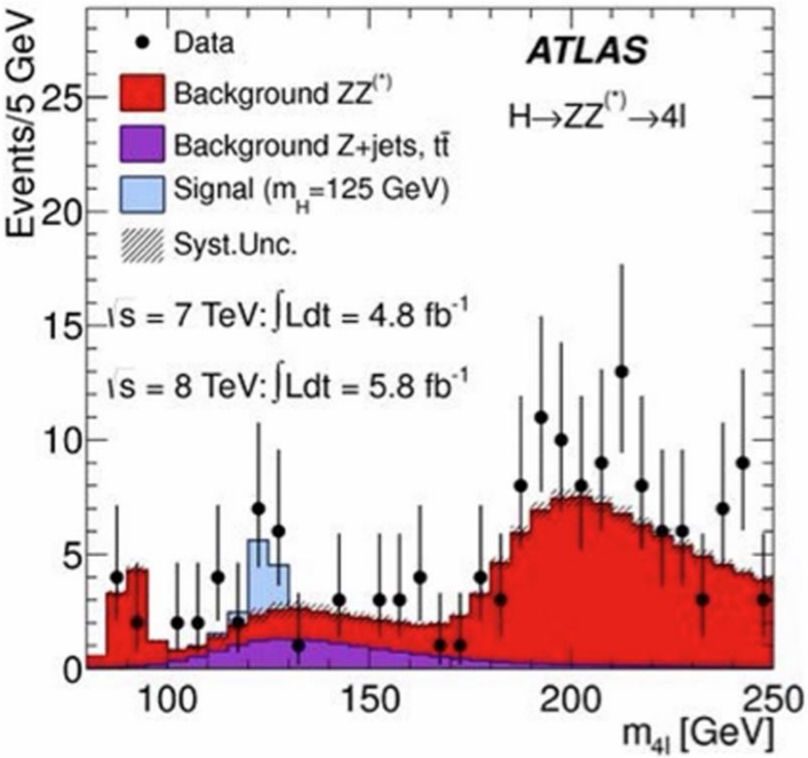


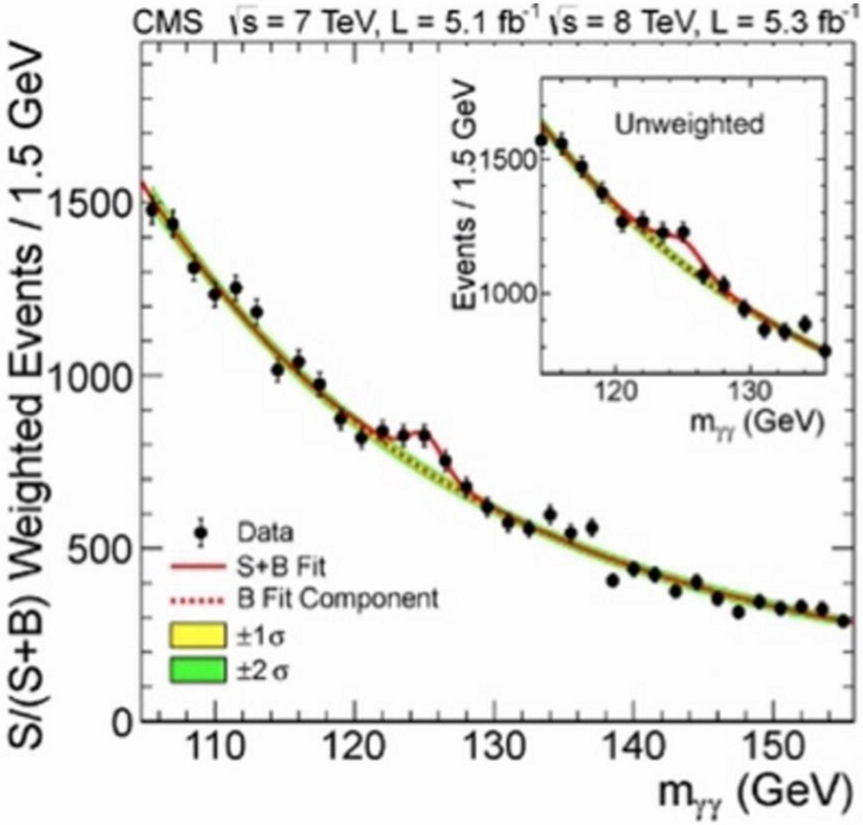
Higgs Discovery

From Matthias Kerner

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

→ resonance in the m_{4l} $(H \to ZZ^* \to 4l)$ and $m_{\gamma\gamma}$ $(H \to \gamma\gamma)$ spectrum





Higgs Discovery

From Matthias Kerner

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

→ many happy faces ...

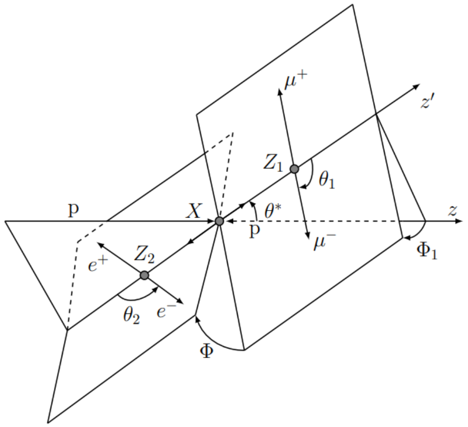
SM Higgs boson?

- ➢ Spin, Parity?
- ➢ Couplings to other SM particles?
- ➢ Higgs potential?

... and a year later:

Nobel Prize awarded to François Englert & Peter Higgs
(*1932) (1929-2024)

Higgs spin and CP properties



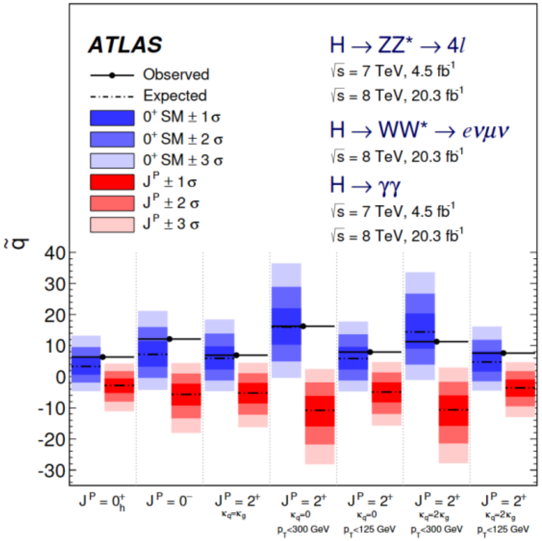
- ➢ Spin ½ and 1 (due to $H \to \gamma\gamma$: Landau-Yang theorem) excluded
- ➢ Only real contender: spin 0 & 2

☐ Spin 0: $f^{*(i)}_{\mu\nu} = \varepsilon^{\mu}_{i} q^{\nu} - \varepsilon^{\nu}_{i} q^{\mu}$ $\quad \tilde{f}^{*(i)}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} f^{*(i)\rho\sigma}$

$$m^2_{V_1}\varepsilon^*_{V_1}\varepsilon^*_{V_2} + a_2^{VV} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + \boxed{a_3^{VV} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2)\mu\nu}}$$

CP-odd interaction

$\frac{d\sigma}{d\phi} \propto \cos^2\phi$	CP-even	$\vec{\varepsilon}_{Z_1} \cdot \vec{\varepsilon}_{Z_2}$
$\frac{d\sigma}{d\phi} \propto \sin^2\phi$	CP-odd	$\vec{\varepsilon}_{Z_1} \times \vec{\varepsilon}_{Z_2}$



☐ Spin 2 : θ^* distributions is different for spin 2 and spin 0, $d^{J}_{m1,m2}(\theta^*)$

e.g. Bolognesi, Gao, Gritsan, Melnikov, Schulze, 2012

实验数据与标准模型一致，$J^p = 0^+$

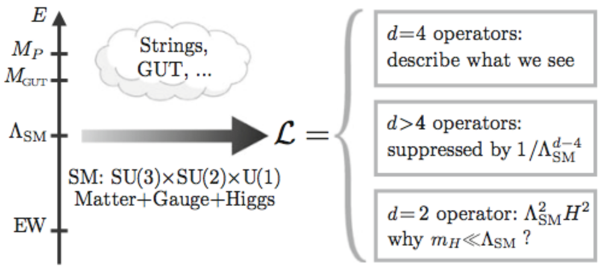
Higgs coupling measurements

The Framework for the Higgs physics

1. The κ framework for the couplings:

BSM physics is expected to affect the production modes and decay channels by a SM like interactions

2. The Standard Model Effective Field Theory



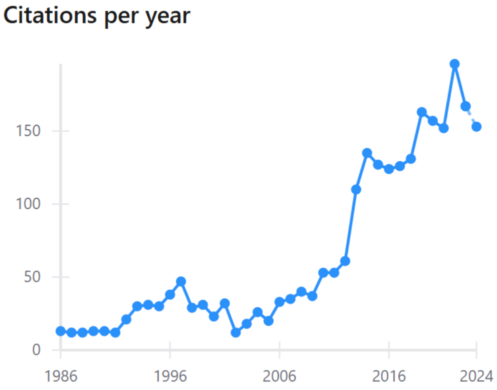
W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020
Murphy, 2020

$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

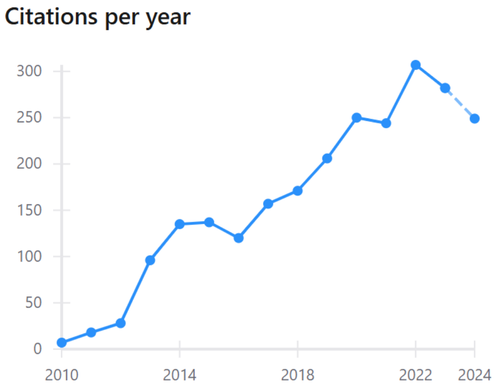
Linear realized EFT

Higgs is a fundamental particle
Weak interacting

W. Buchuller, D. wyler 1986



B. Grzadkowski et al, 2010

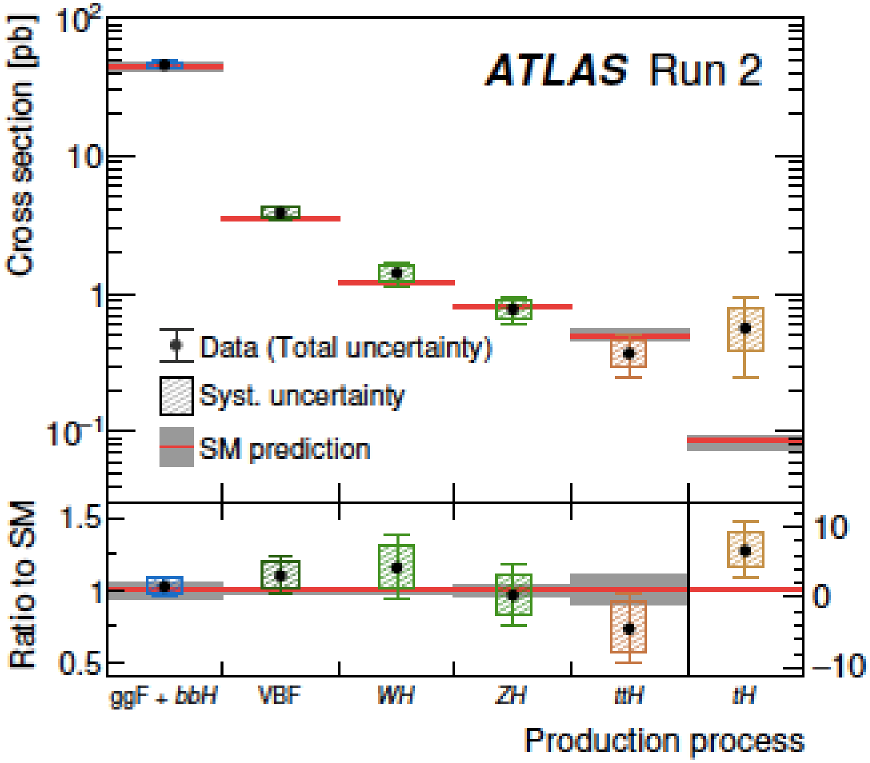


3. Higgs Effective Field Theory

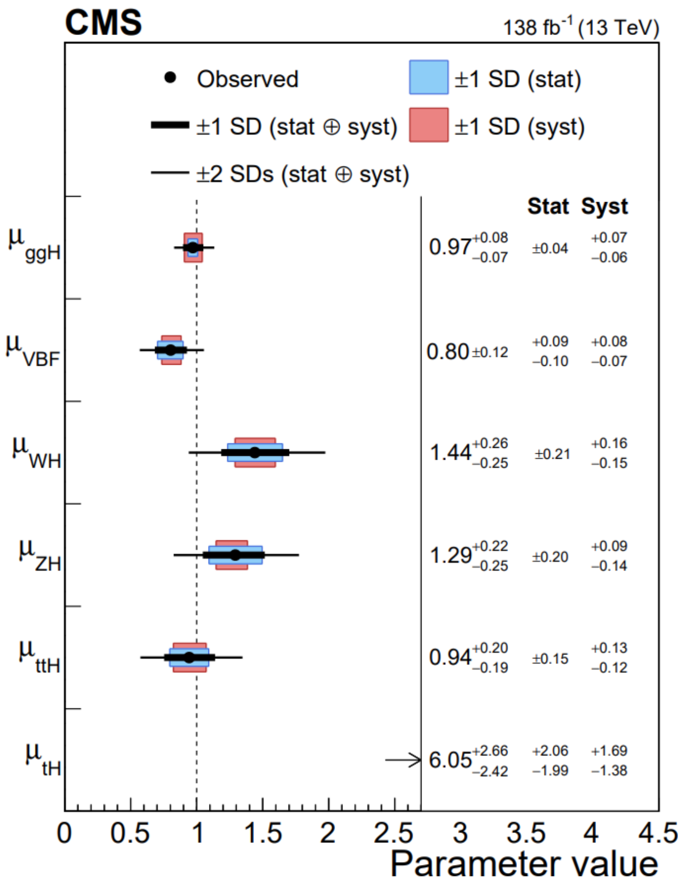
Callan, Coleman, Wess, Zumino, 1969
The electroweak chiral Lagrangian+light Higgs, A.C. Longhitano, 1980,….

The measurements @ LHC

Nature 607 (2022)7917,52-59



Nature 607 (2022)7917,60-68

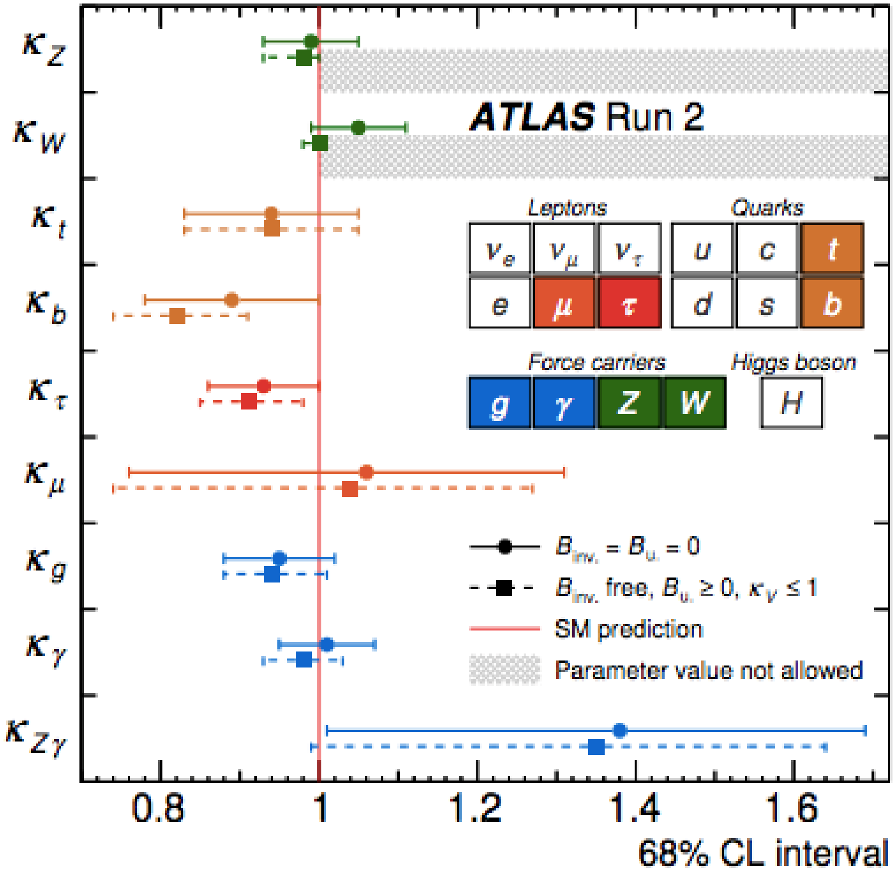


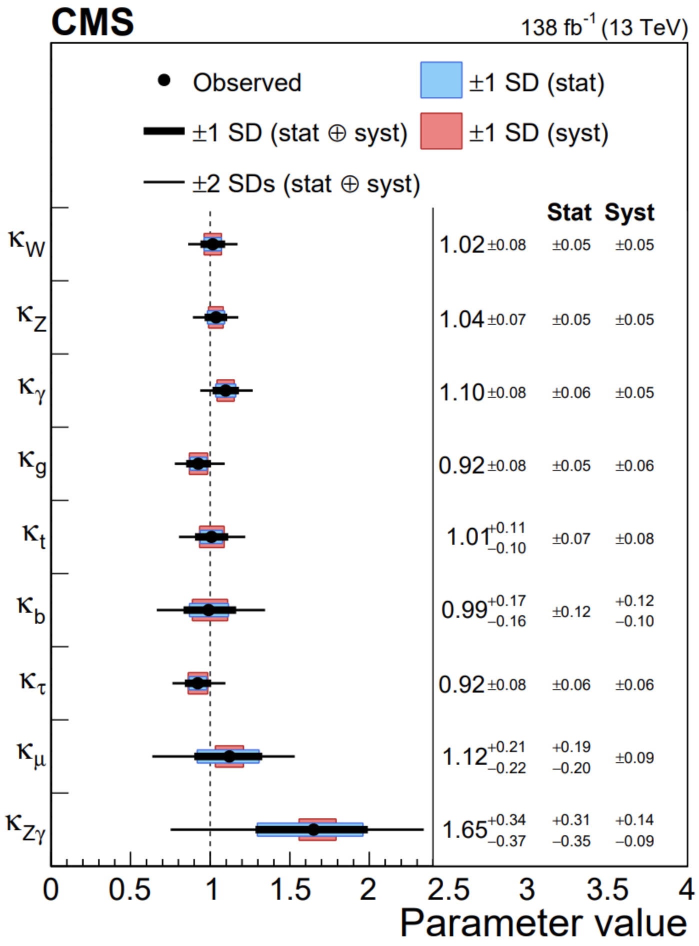
截面与信号强度测量结果

Higgs couplings @LHC

Nature 607 (2022)7917,52-59

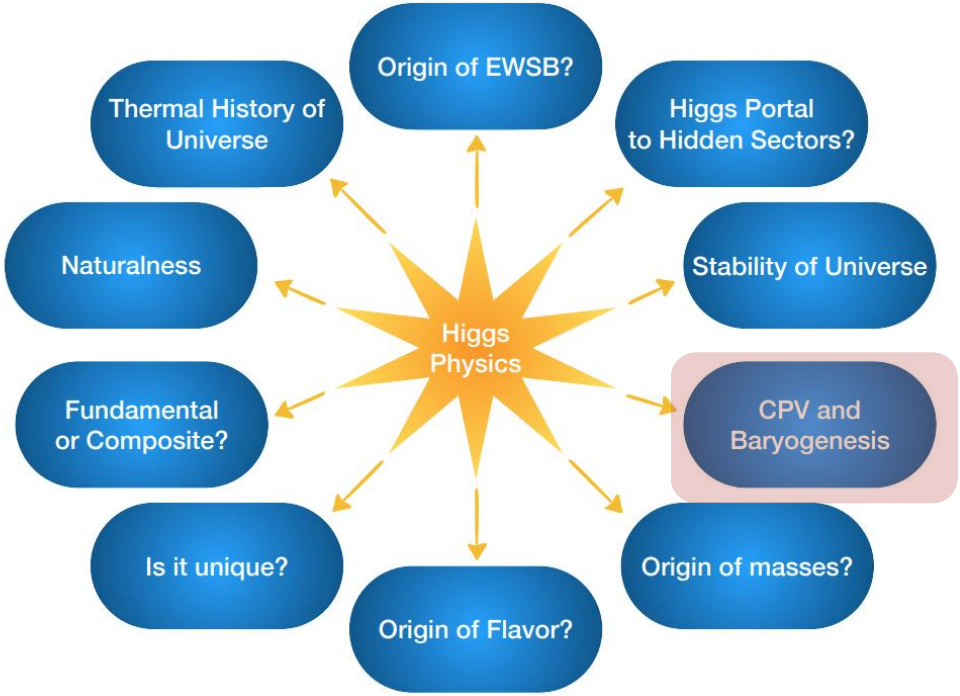
Nature 607 (2022)7917,60-68





$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

Higgs CP violation



Origin of EWSB?

Thermal History of Universe

Higgs Portal to Hidden Sectors?

Naturalness

Stability of Universe

Higgs Physics

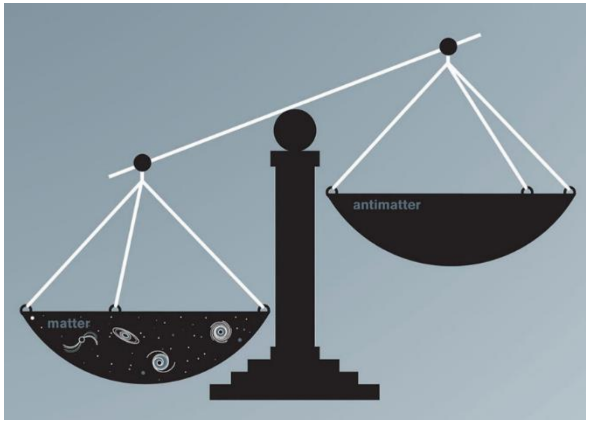
Fundamental or Composite?

CPV and Baryogenesis

Is it unique?

Origin of masses?

Origin of Flavor?



Sakharov Criteria (1967)

- ➢ B violation
- ➢ C & CP violations
- ➢ Departure from the equilibrium

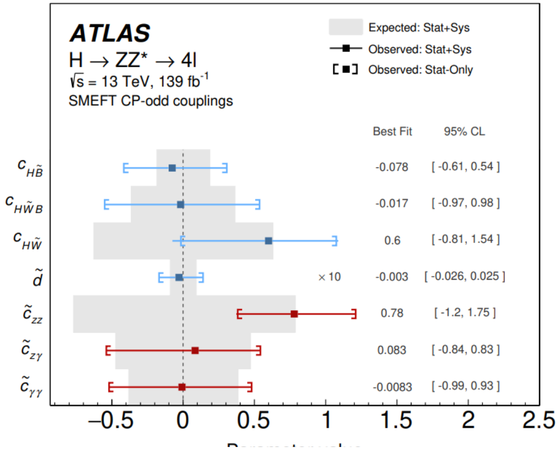
- ➢ A purely CP-odd Higgs has been excluded
- ➢ A CP-mixture Higgs boson is still possible

Higgs CP violation

- CP-odd interactions with gauge bosons (loop induced operators)

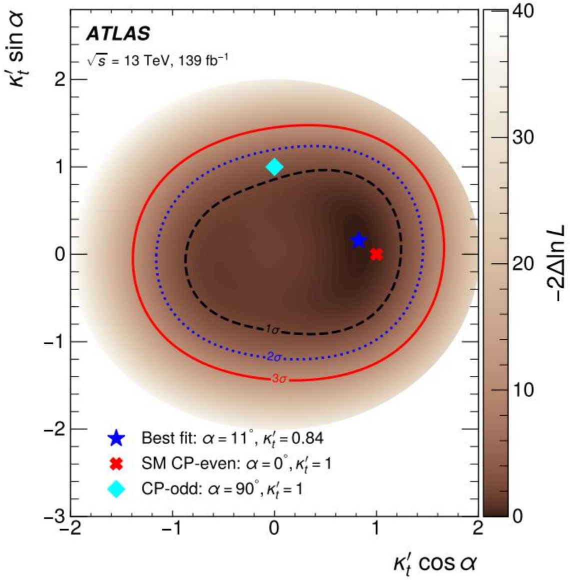
ATLAS,2304.09612

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



- CP-odd interactions with fermions

Gunion, He, PRL. 76, 4468 (1996)
Boudjema, Godbole, Guadagnolo, Mohan, PRD 92, 015019 (2015)
Mileo, Kiers, Szynkman, Crane, Gegner, JHEP 07, 056 (2016)
Gritsan, Rntsch, Schulze, Xiao, PRD 94, 055023 (2016)
S. Amor Dos Santos et al, PRD 96, 013004 (2017)
Kobakhidze, Liu, Wu, Yue, PRD 95 (2017) 1, 015016
Gouveia et al, 1801.04954
Gonalves, Kong, Kim, JHEP 06, 079 (2018)
Ren, Wu, Yang, 1901.05627
ATLAS, PRL 125 (2020) 6,061802
CMS, PRL 125 (2020) 6,061801
Q.-H. Cao, K.-P. Xie, H. Zhang , R. Zhang,CPC45 (2021)2,023117
Zhite Yu and C.-P. Yuan, 2211.00845
…

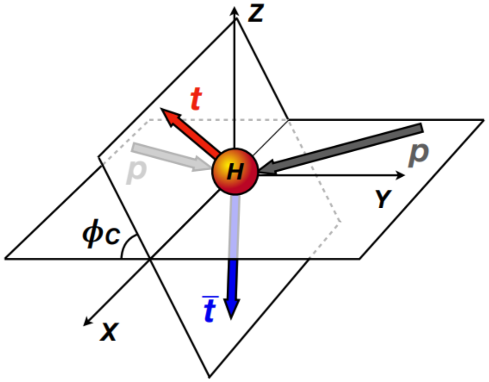


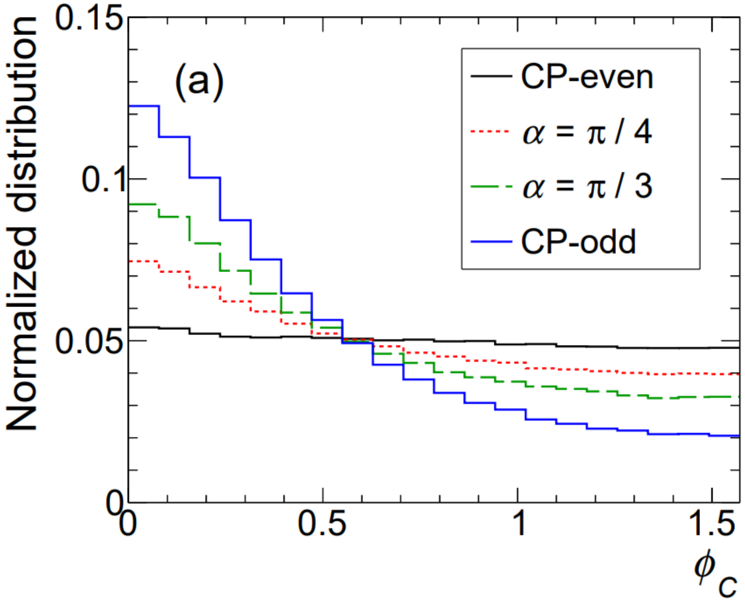
ATLAS：2303.05974
CMS：2208.02686

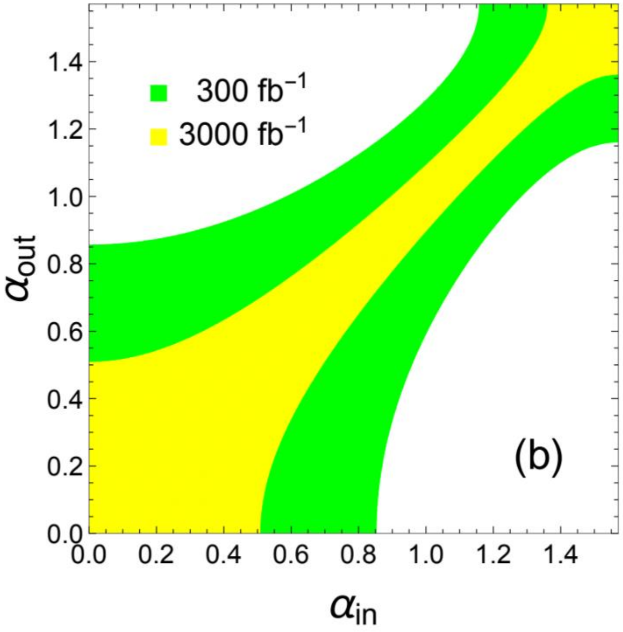
Higgs CP violation

$$\mathscr{L} = y_f h \bar{f}(\cos\alpha_f + i\gamma_5 \sin\alpha_f) f$$

$$\phi_C = \arccos\left|(\mathbf{n}_{p_1} \times \mathbf{n}_{p_2}) \cdot (\mathbf{n}_t \times \mathbf{n}_{\bar{t}})\right|$$







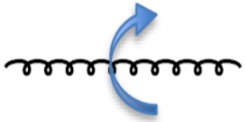
Q.-H. Cao, K.-P. Xie, H. Zhang , R. Zhang,CPC45 (2021)2,023117

New polarization observables

☐ Linear polarization vs. helicity/circular polarization

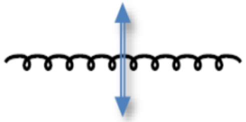
$$M \propto e^{i(\lambda_1-\lambda_2)\phi} d^J_{\lambda_1,\lambda_2}$$

helicity pol.



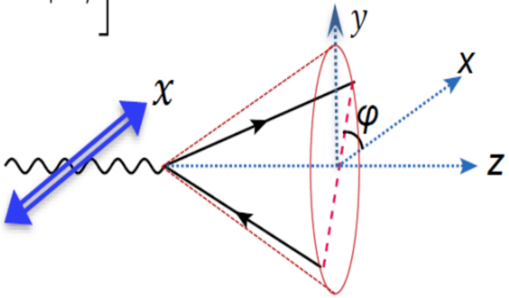
$|\pm 1\rangle$

linear pol.



$$|x\rangle = -\frac{1}{\sqrt{2}}\Big[|+\rangle - |-\rangle\Big], \quad |y\rangle = \frac{i}{\sqrt{2}}\Big[|+\rangle + |-\rangle\Big]$$

$$\Rightarrow \quad |e^{+i\phi} \pm e^{-i\phi}|^2 \rightarrow 2(1 \pm \cos 2\phi)$$



Interference of helicity λ_1 and λ_2 causes azimuthal distributions

$$\cos(\lambda_1 - \lambda_2)\phi, \quad \sin(\lambda_1 - \lambda_2)\phi$$

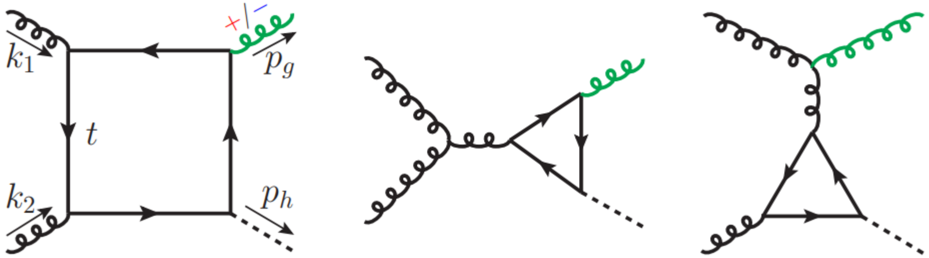
CP even **CP odd**

⇒ **Useful probes of new physics**

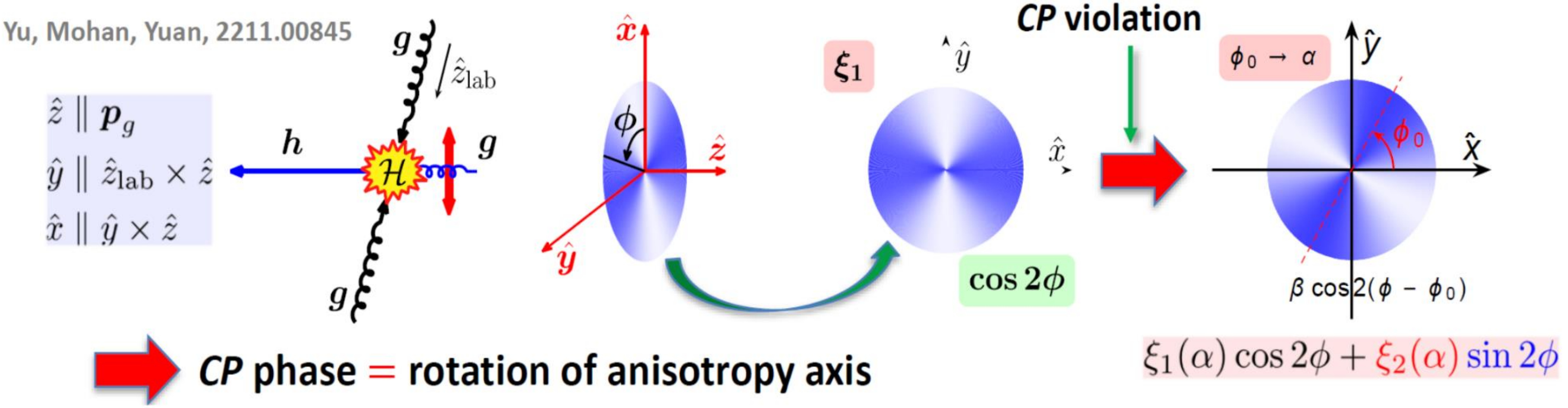
C.-P. Yuan's talk @ MBI 2023

New polarization observables

Linear polarization of gluon



$$\rho_{\lambda\lambda'} = \frac{1}{2}(1+\boldsymbol{\xi}\cdot\boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{pmatrix}$$



Yu, Mohan, Yuan, 2211.00845

$\hat{z} \parallel \boldsymbol{p}_g$

$\hat{y} \parallel \hat{z}_{\mathrm{lab}} \times \hat{z}$

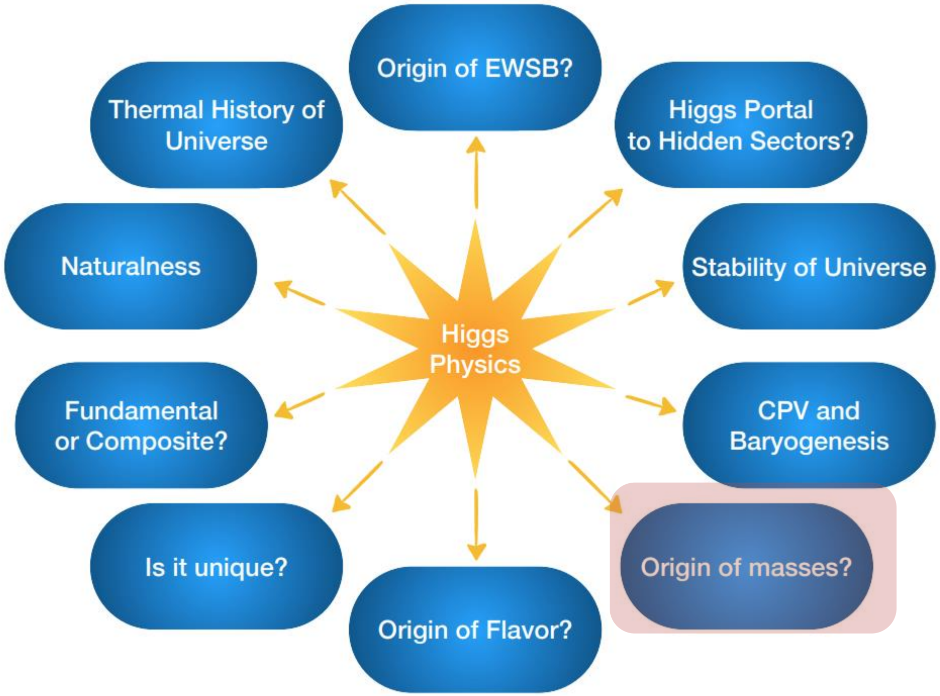
$\hat{x} \parallel \hat{y} \times \hat{z}$

CP phase = rotation of anisotropy axis

$\xi_1(\alpha)\cos 2\phi + \xi_2(\alpha)\sin 2\phi$

C.-P. Yuan’s talk @ MBI 2023

Higgs Yukawa couplings



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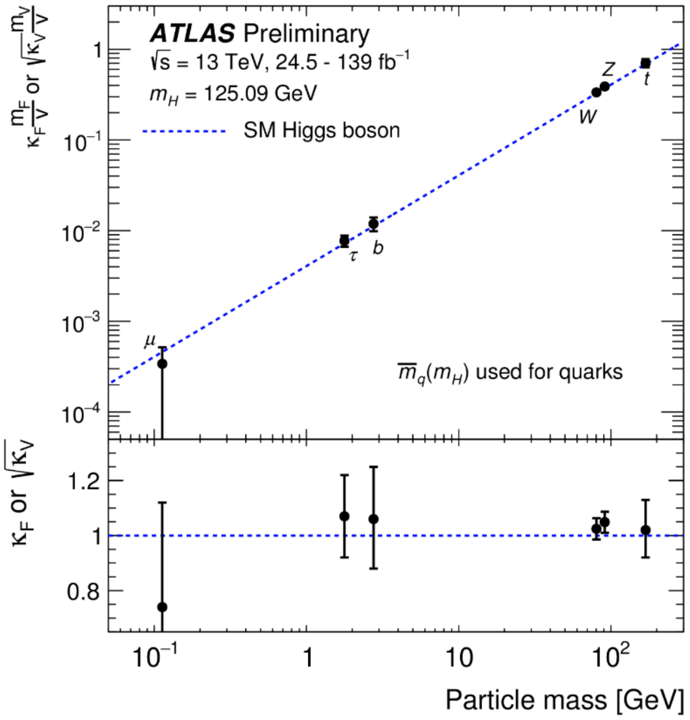


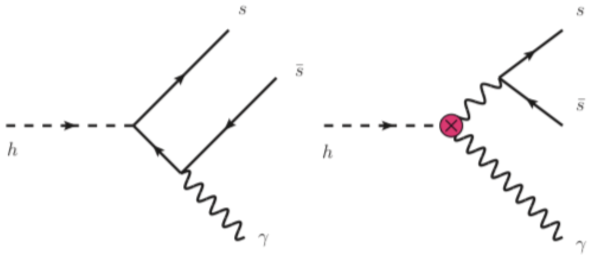
All fundamental particles get their mass from Higgs boson vev

How about light quarks?

Does Higgs mechanism still work?

Light quark Yukawa couplings@LHC

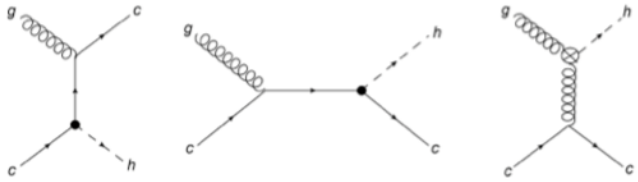
A. Rare decay: $h \to J/\Psi\gamma \ (\phi\gamma, \rho\gamma, \omega\gamma)$



G. T. Bodwin, F. Petriello, S. Stoynev, M. Velasco, PRD88 (2013) 5, 053003
A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev, PRL114 (2015) 10,101802

e.g. 14 TeV HL-LHC $y_s/y_b < 0.39$ $y_c/y_c^{\rm SM} < 220$

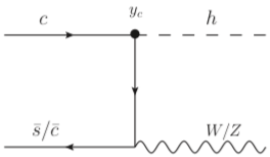
B. Higgs+charm production



I. Brivio, F. Goertz, G. Isidori, PRL115 (2015)21,211801

e.g. 14 TeV HL-LHC $y_c/y_c^{\rm SM} < 2.5$

C. Higgs data global analysis:



G. Perez, Y. Soreq, E. Stamou, K. Tobioka, PRD92(2015)3, 033016, PRD93(2016)1,013001
Y. Zhou, PRD93(2016) 1,013019

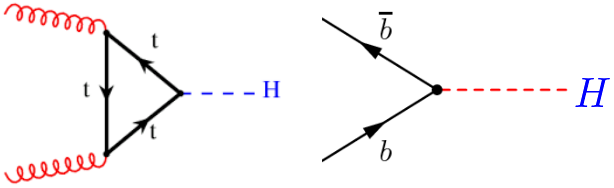
e.g. 14 TeV HL-LHC $y_c/y_c^{\rm SM} < 6.2$

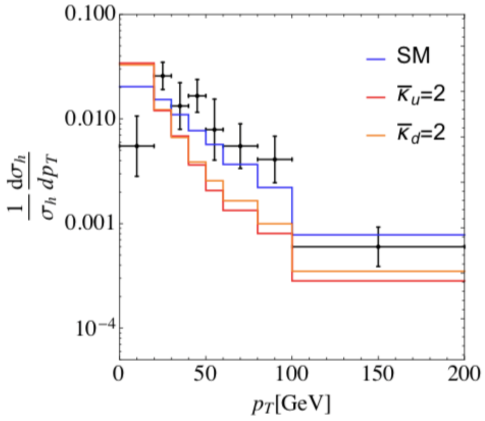
D. Higgs p_T analysis:

Y. Soreq, H.X. Zhu, J. Zupan, JHEP 12(2016)045
F. Bishara, U. Haisch, P. F. Monni, E. Re, PRL 118(2017)12,121801
G. Bonner, H. E. Logan, 1608.04376

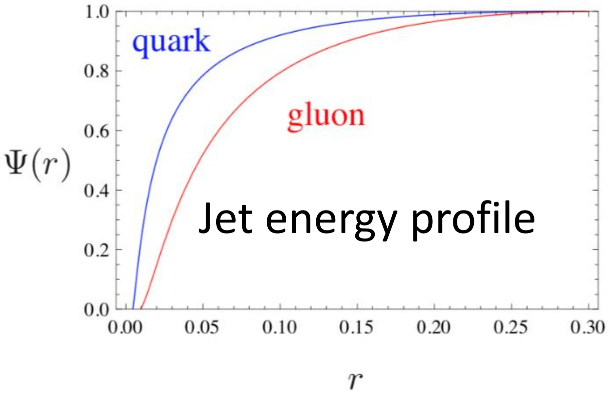
$y_{u,d}/y_b < 0.4 \sim 0.5$

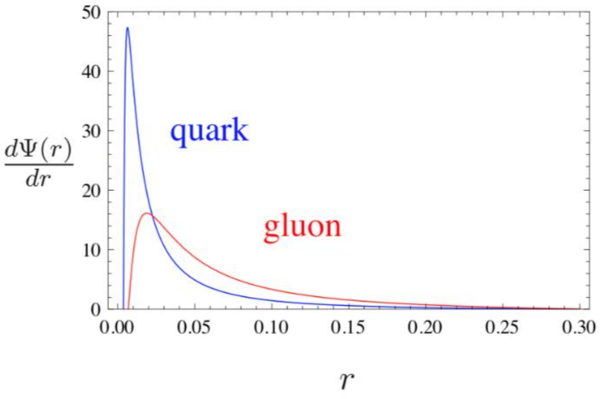
Soft gluon radiation



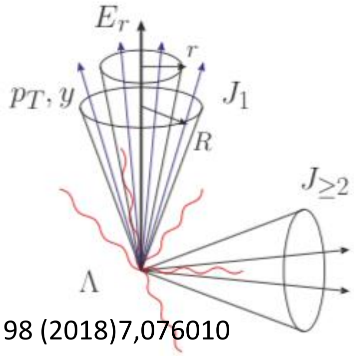


Light quark Yukawa couplings@ e^+e^-

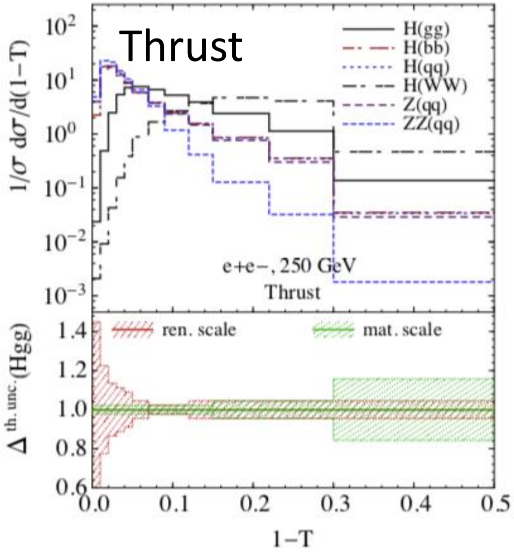


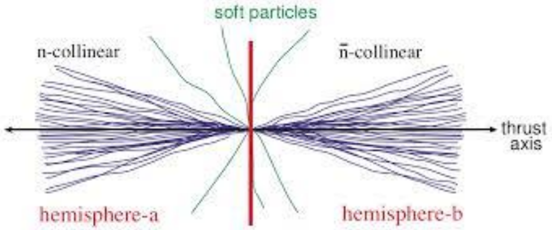


$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$



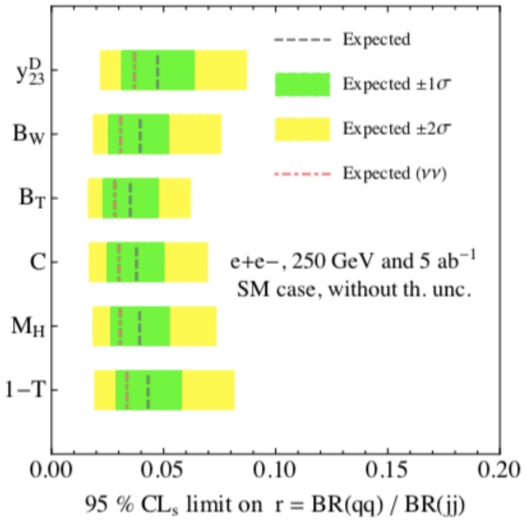
H. N. Li, Z. Li and C.-P. Yuan, PRL 107 (2011)152001;   Y. T. Chien, I. Vitev, JHEP 12(2014)061
J. Isaacson, H.N. Li, Z. Li and C.-P. Yuan, PLB 771 (2017)619-623; G. X. Li, Z. Li, Y.D. Liu, Y. Wang, X. R. Zhao, PRD 98 (2018)7,076010





$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$

$y_{u,d,s}/y_b < 0.091$



J. Gao, JHEP 01 (2018) 038

Event shapes

One class of event shapes:

$$e(X) = \frac{1}{Q}\sum_{i\in X} |p_\perp^i| f_e(\eta_i)$$

Examples:

Thrust $f_{1-T}(\eta) = e^{-|\eta|}$ Brandt, Peyrou, Sosnowski, Wroblewski,64; Farhi, 77

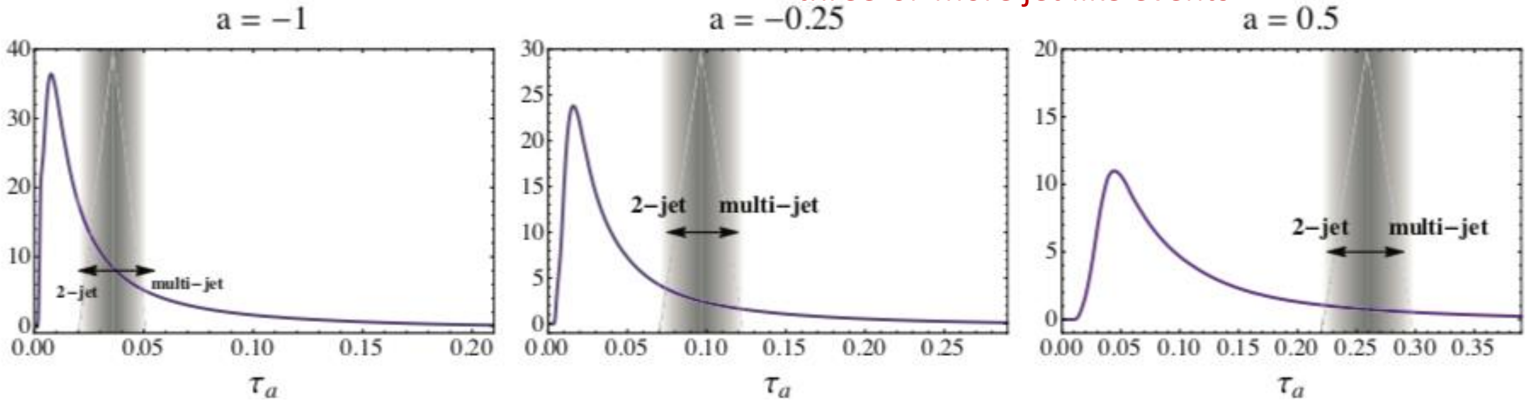
Jet broadening $f_B(\eta) = 1$ Catani, Turnock, Webber, 92

C-Parameter $f_C(\eta) = \frac{3}{\cosh(\eta)}$ Ellis, Ross, Terrano, 81

Angularities $f_{\tau_a}(\eta) = e^{-|\eta|(1-a)}$ Berger, Kucs, Sterman, 03 (relatively new)

G. Bell, A. Hornig, C. Lee, J. Talbert, JHEP01(2019)147

The proportions of two jet-like and three-or-more jet like events

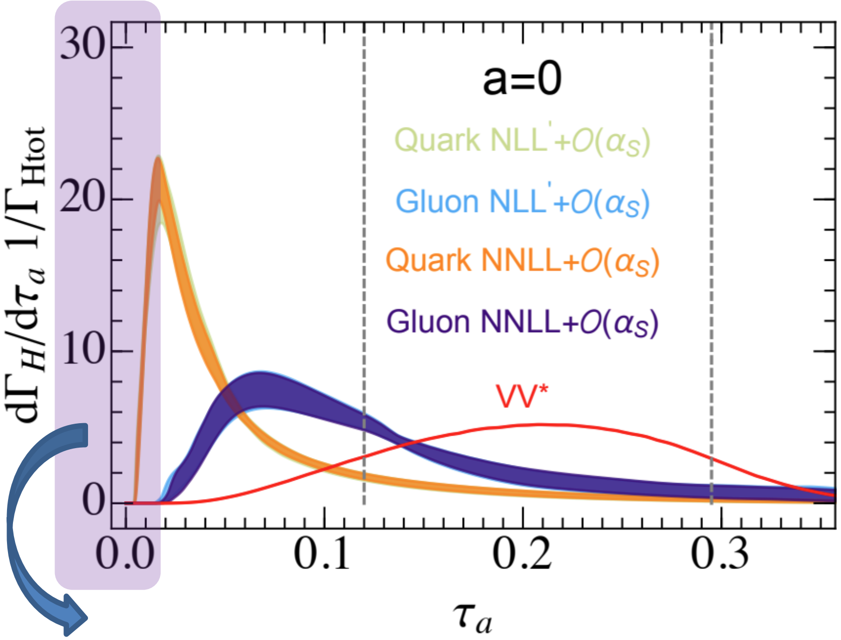


Higgs Yukawa couplings

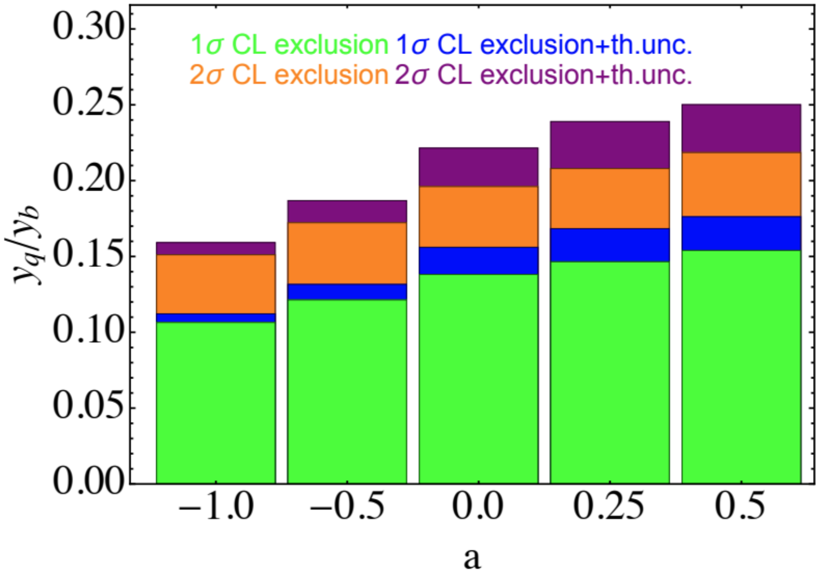
J. Gao, Y. Gong, W.-L. Ju and L. L. Yang, JHEP 03 (2019) 030
J. Zhu, J. Gao, D. Kang, T. Maji, 2311.07282
Bin Yan, C. Lee, JHEP 03 (2024) 123

Angularity distributions are very different for quark and gluon final state

Analysis Region



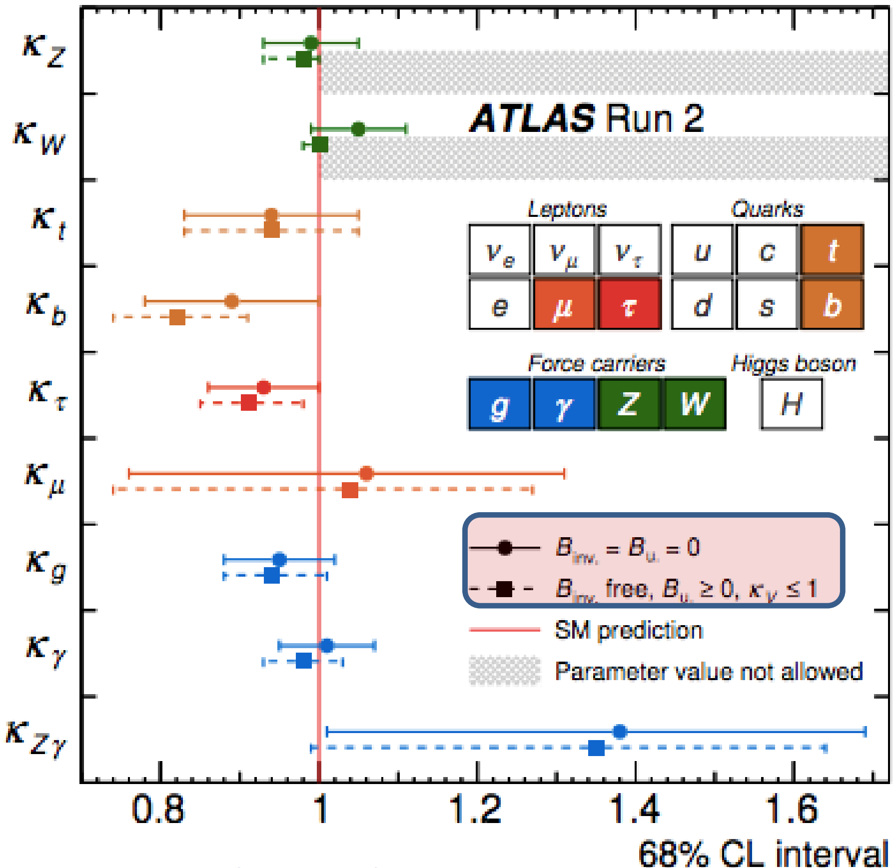
Sensitive to non-perturbative assumptions

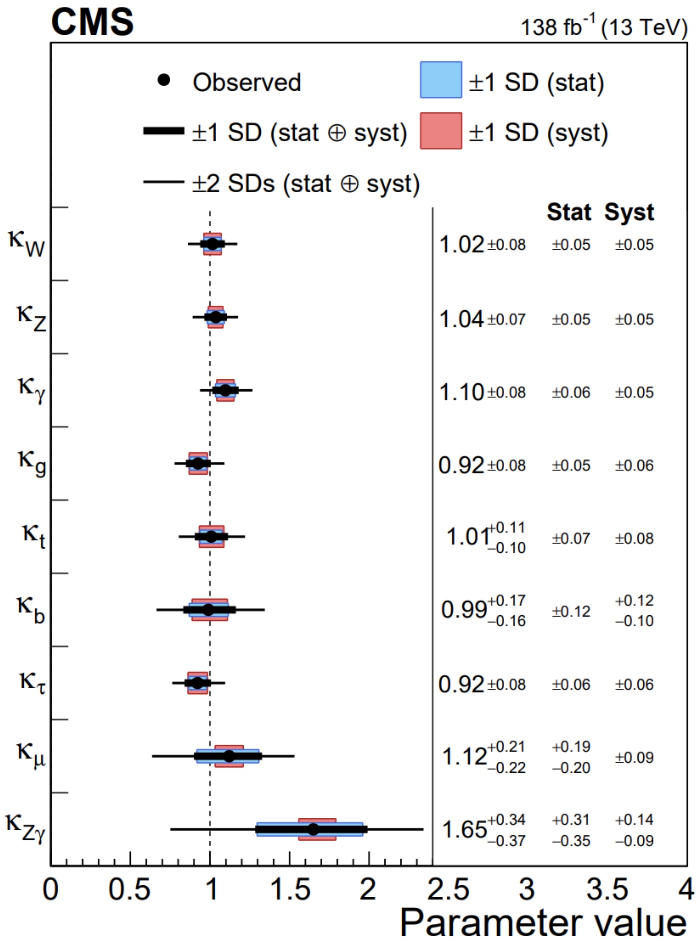


Higgs couplings @LHC

Nature 607 (2022)7917,52-59

Nature 607 (2022)7917,60-68





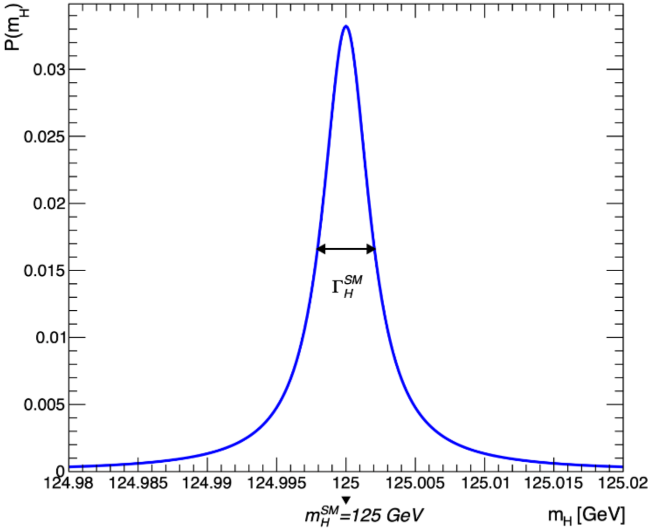
$$\mu = \frac{(\sigma_p \times BR_d)_{\rm obs}}{(\sigma_p \times BR_d)_{\rm SM}}$$

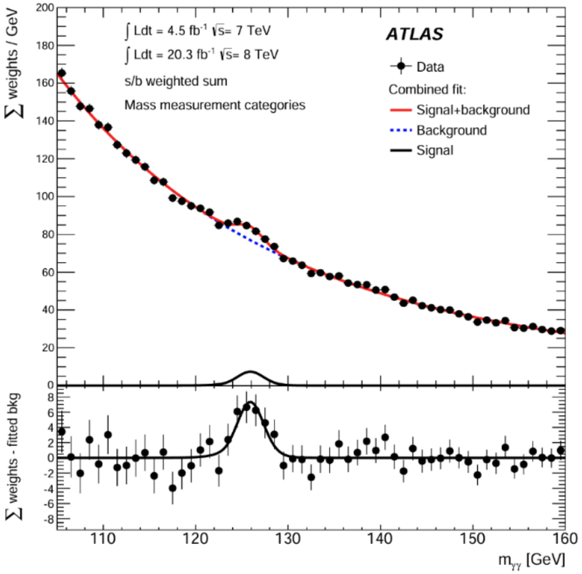
全局拟合结果依赖对希格斯宽度的假设 ➡ 直接测量希格斯宽度至关重要

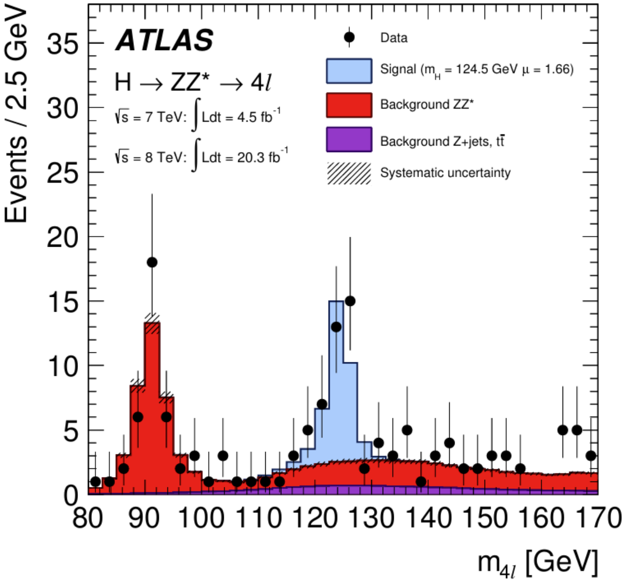
Higgs width measurements

Direct constraints: reconstructed mass line-shape

The intrinsic mass resolution: 1-2 GeV, Higgs width (SM): 4.1 MeV



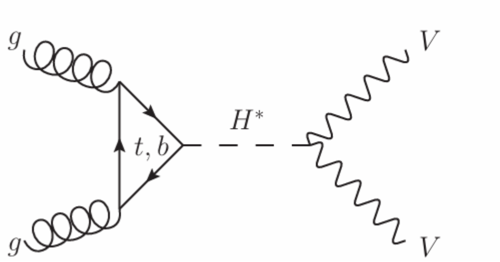


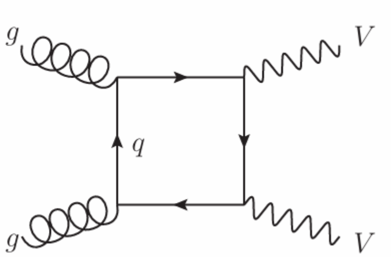


- ➢ the modelling of resolution uncertainties
- ➢ the modelling of the interference between the signal and the background which can be sizeable for large widths
- ➢ CMS: 330 MeV

Higgs width measurements

Indirect constraints from off-shell couplings





$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

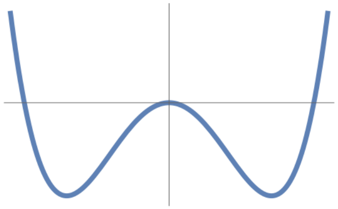
$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

Assuming the couplings are same for the on-shell and off-shell regions

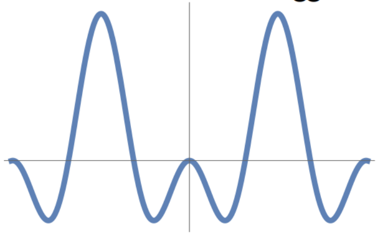
$$\begin{aligned} (\text{ATLAS})\ \ \Gamma_H &= 4.5^{+3.3}_{-2.5}\ \ [4.1^{+3.8}_{-3.8}\ (\text{exp})]\ \text{MeV}, \\ (\text{CMS})\ \ \Gamma_H &= 3.2^{+2.4}_{-1.7}\ \ [4.1^{+4.0}_{-3.5}\ (\text{exp})]\ \text{MeV}. \end{aligned}$$

$\Gamma_H = 4.1^{+0.7}_{-0.8}\,\text{MeV}$ (HL-LHC)

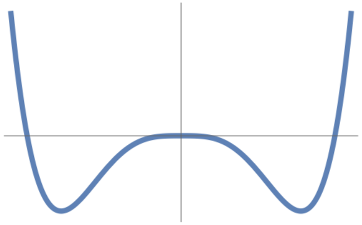
Higgs potential


Landau-Ginzburg Higgs

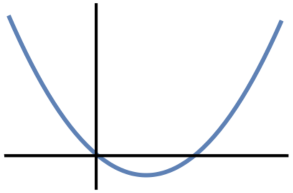
$$V(\phi) = -m^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$


Pseudo-Goldstone Higgs

$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

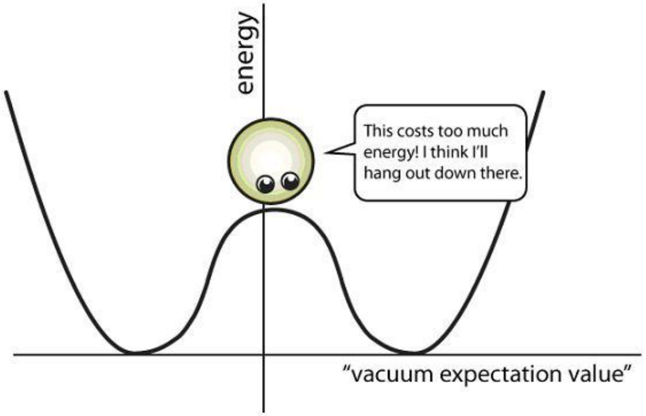

Coleman Weinberg Higgs

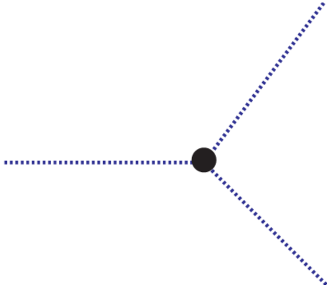
$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$


Tadpole-induced Higgs

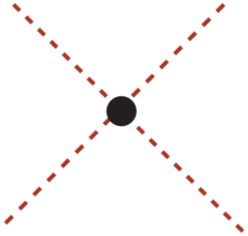
$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

Agrawal, Saha, Xu, Yu, Yuan, PRD 101 (2020) 075023





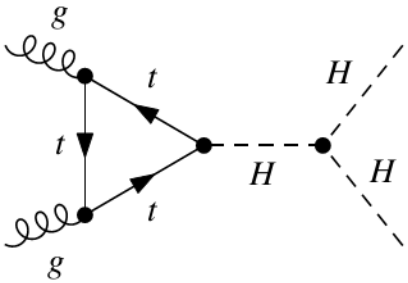
$$\lambda_{HHH} = \frac{3m_H^2}{v}$$

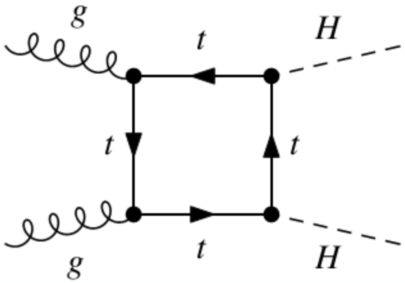


$$\lambda_{HHHH} = \frac{3m_H^2}{v^2}$$

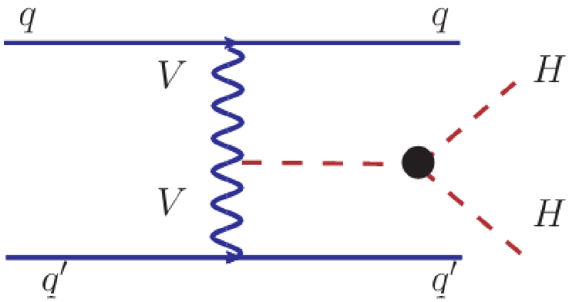
Higgs pair production

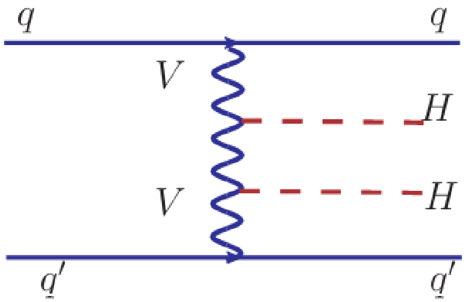
E. W. N.Glover et al (1988)
U. Baur et al (2002)
A.Papaefstathuou et al (2013)
J. Baglio et al (2013)
Q. Li et al (2015) …..

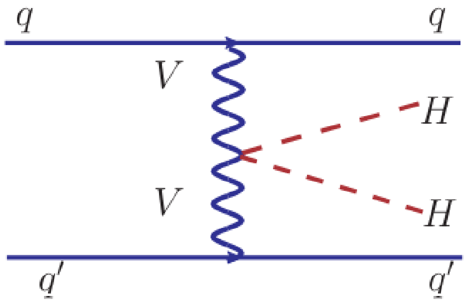


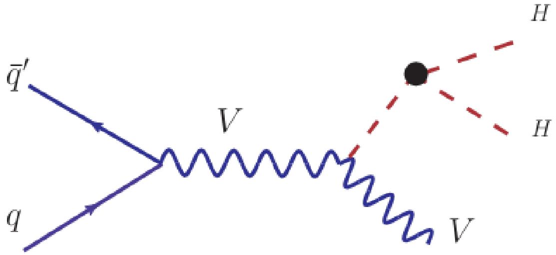


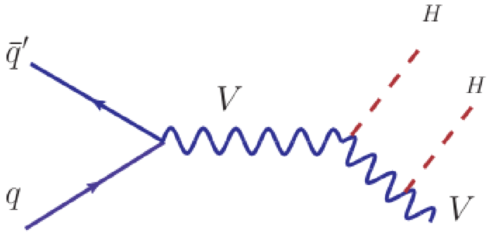
M. J. Dolan et al (2014,2015)

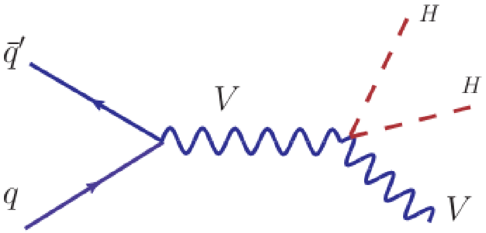








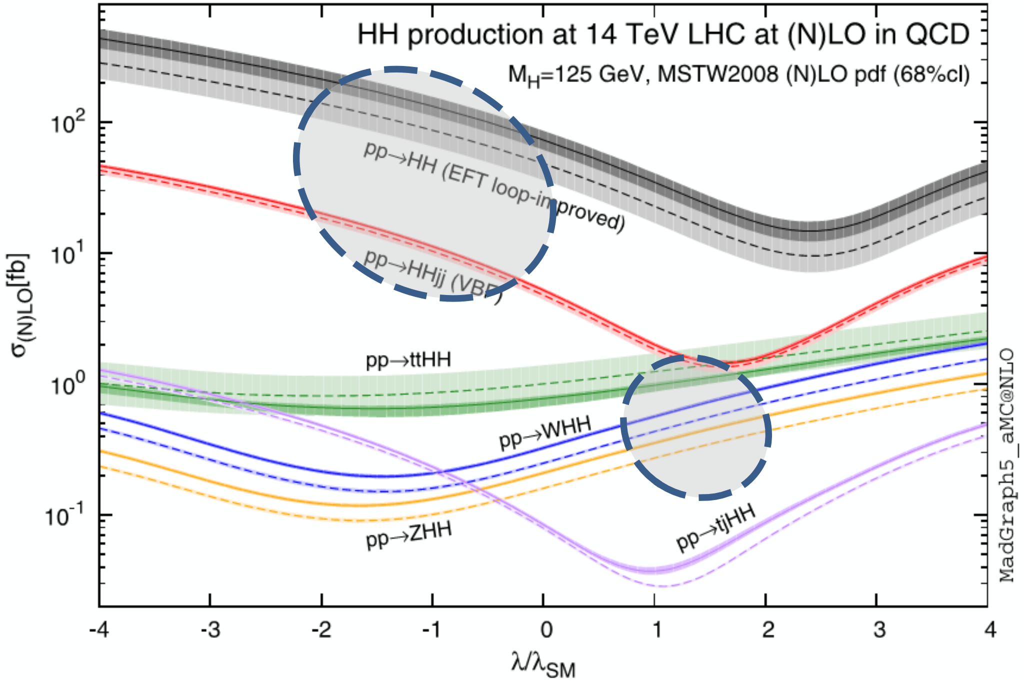




M. Moretti et al (2005), Q. H. Cao et al (2017)

Higgs pair production

$\sqrt{s}[TeV]$	$\sigma^{NLO}_{gg\to HH}$[fb]	σ^{NLO}_{HHjj}[fb]	σ^{NLO}_{WHH}[fb]	σ^{NLO}_{ZHH}[fb]
8	8.16	0.49	0.21	0.14
14	33.89	2.01	0.57	0.42
100	1417.83	79.55	8.00	8.27



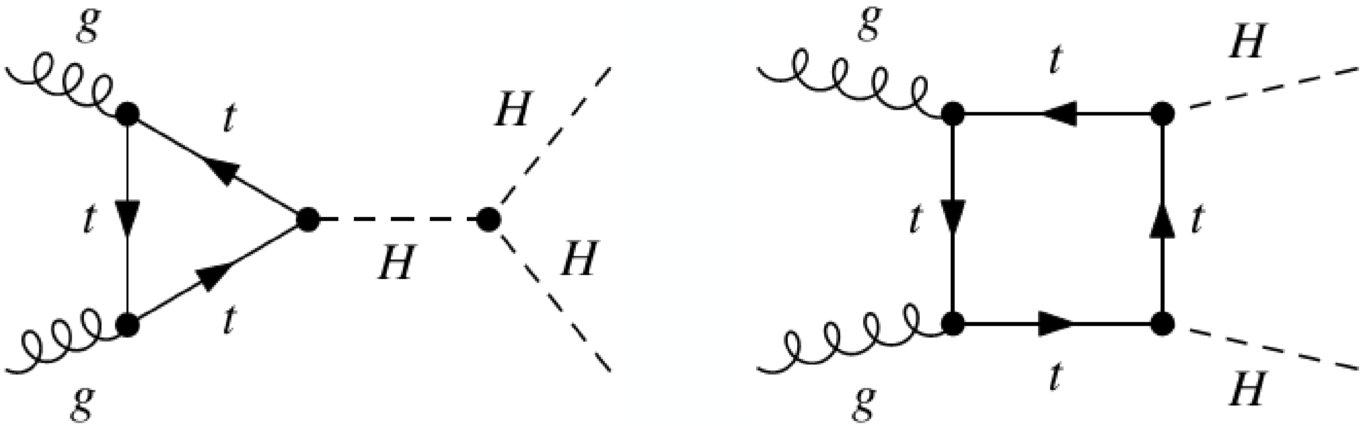
J. Baglio, A. Djouadi et al.
JHEP 1304(2013)51

- GGF and VBF 敏感于负区间
- VHH敏感于正区间

Higgs pair production

Low-energy theorem: Dawson and Haber (1989)

$$\eta = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$



$$-\frac{\alpha_s}{24\pi} G^{a,\mu\nu} G^a_{\mu\nu} \sum_n \frac{y_t^n h^n}{n!} \frac{\partial^n}{\partial m_t^n} \log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right)$$

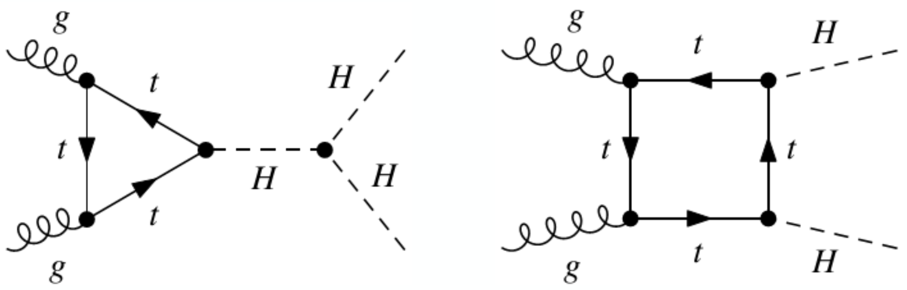
n=1

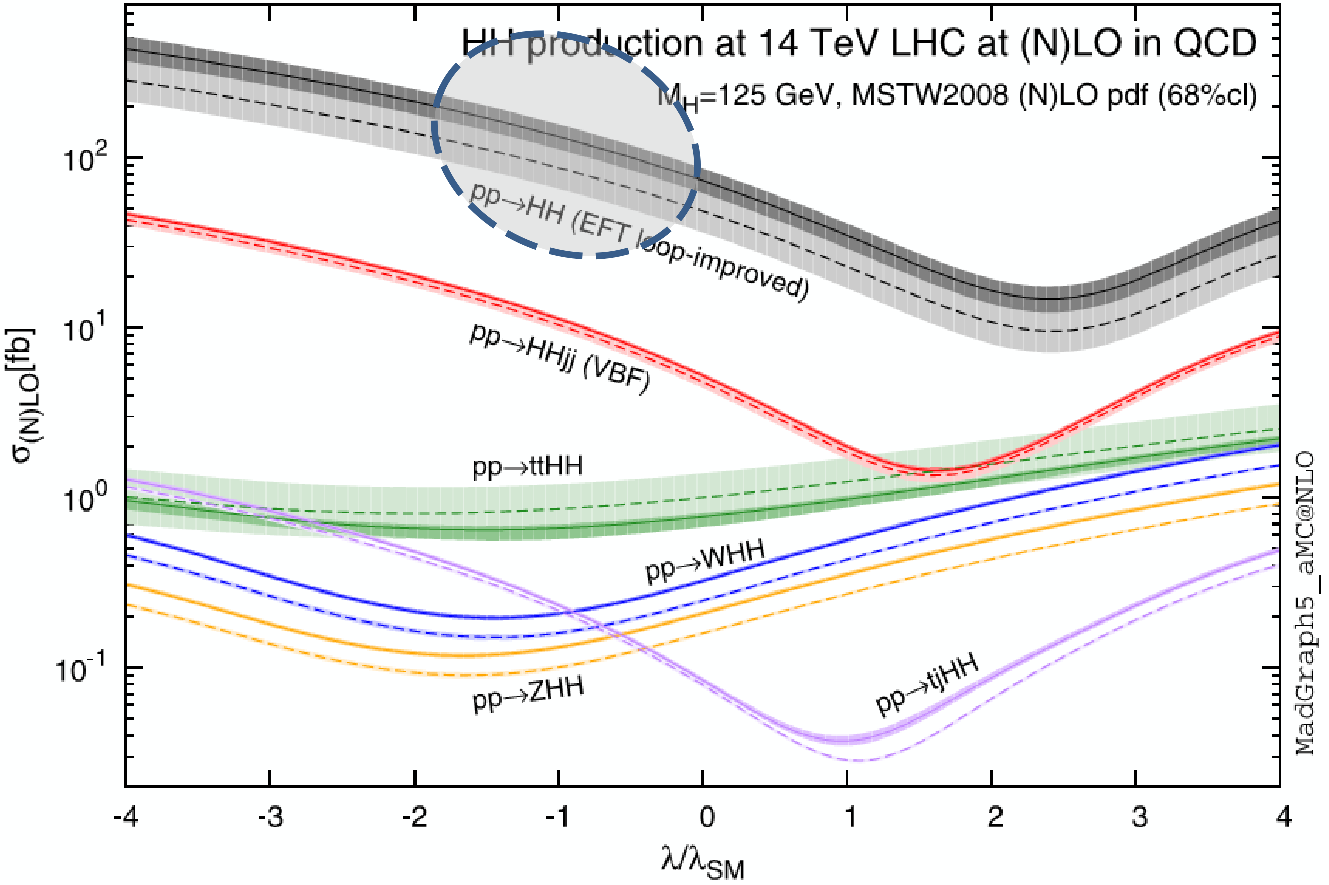
$$\eta \frac{\alpha_s}{12\pi v} G^{a,\mu\nu} G^a_{\mu\nu} h$$

n=2

$$- \frac{\alpha_s}{24\pi v^2} G^{a,\mu\nu} G^a_{\mu\nu} h^2$$

Higgs pair production

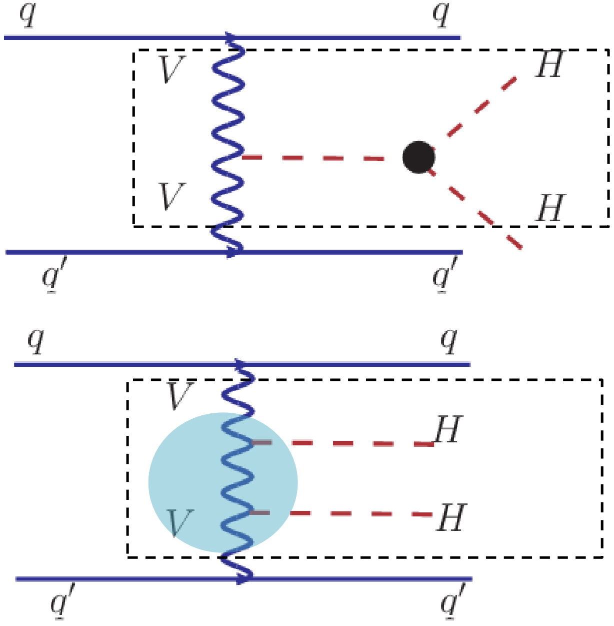




在标准模型中两个图贡献相互抵消，从而敏感依赖负的希格斯自相互作用

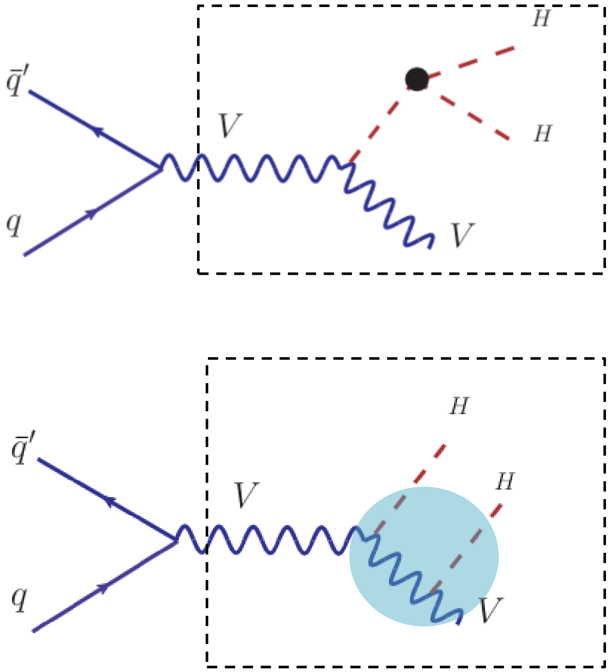
Higgs pair production

VBF Higgs pair

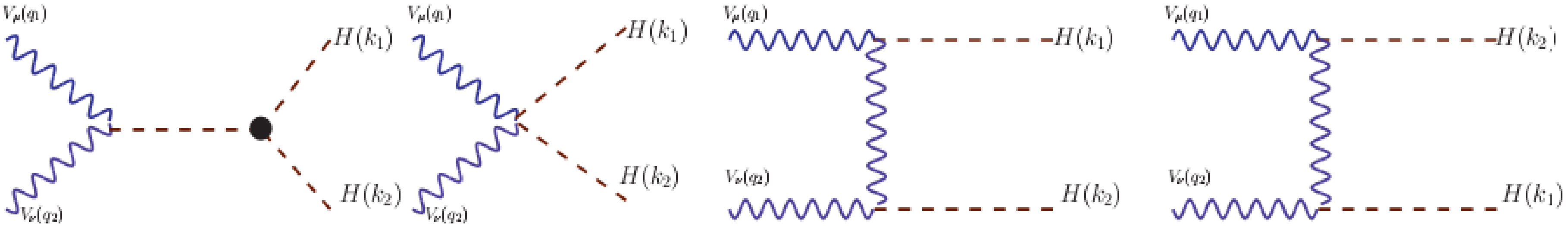


$Q^2 < 0$

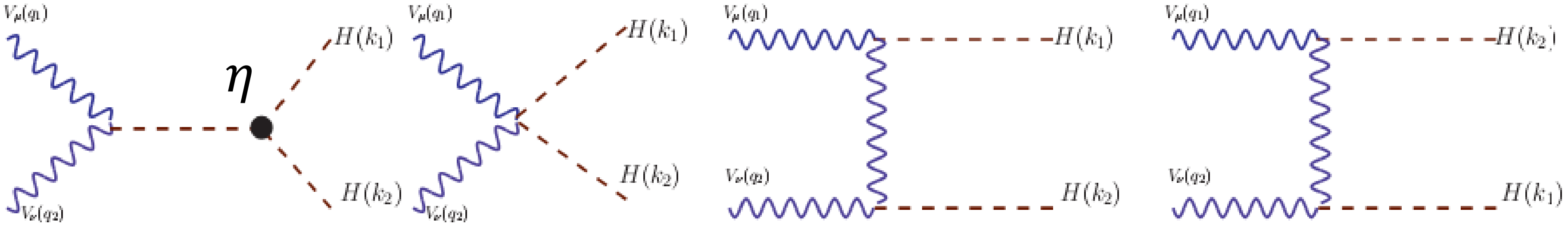
VHH Higgs pair



$Q^2 > 0$



Higgs pair production



$$M^{\mu\nu} = \left[\frac{m_W^2}{v^2}\frac{6m_H^2\eta}{s-m_H^2} + \frac{2m_W^2}{v^2} + \frac{4m_W^4}{v^2}\left(\frac{1}{t-m_W^2} + \frac{1}{u-m_W^2}\right)\right] g^{\mu\nu}$$

$$+A^{\mu\nu}(q_1, k_1, k_2)$$

$$\eta = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

Near the Threshold:

$s = 4m_H^2, t = u = 0$ For VBF

$$M^{\mu\nu} = \frac{2m_W^2}{v^2}(\eta - 3)g^{\mu\nu} + \ldots$$

$s = 4m_H^2, t = u = (m_H + m_V)^2$ For VHH

$$M^{\mu\nu} = \frac{2m_W^2}{v^2}(\eta + 1)g^{\mu\nu} + \ldots$$

Higgs pair production

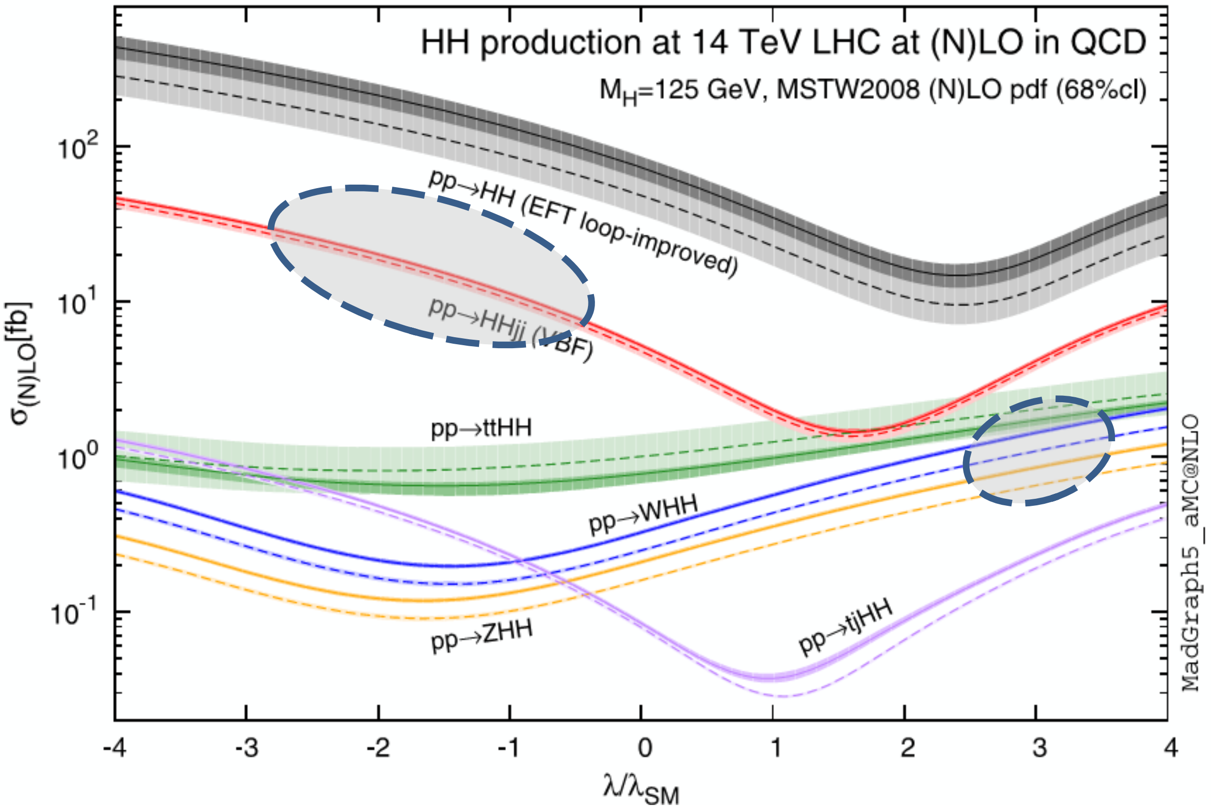
Near the Threshold:

VBF Higgs pair:

$$M^{\mu\nu}=\frac{2m_W^2}{v^2}(\eta-3)g^{\mu\nu}+\ldots$$

VHH Higgs pair:

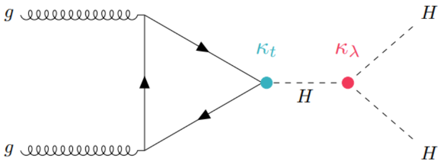
$$M^{\mu\nu}=\frac{2m_W^2}{v^2}(\eta+1)g^{\mu\nu}+\ldots$$

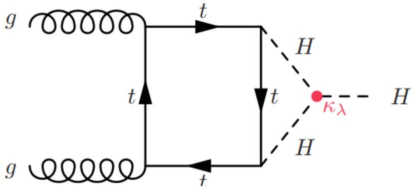


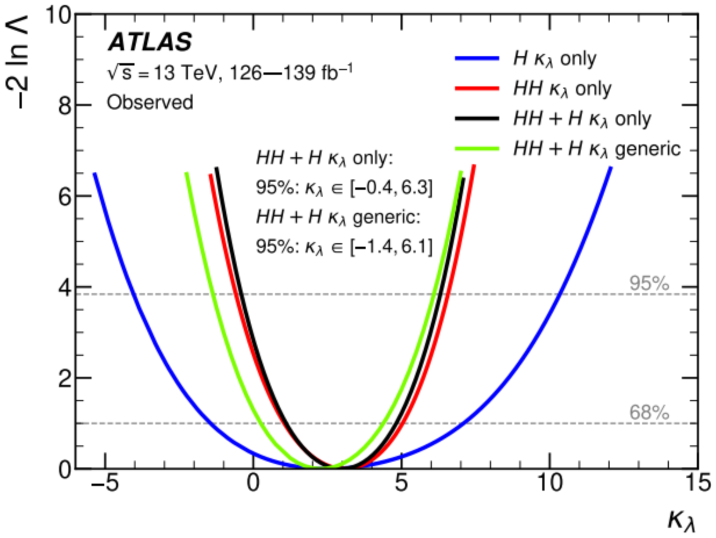
VBF 过程敏感负参数区间， VHH 过程敏感正的参数区间

Higgs potential

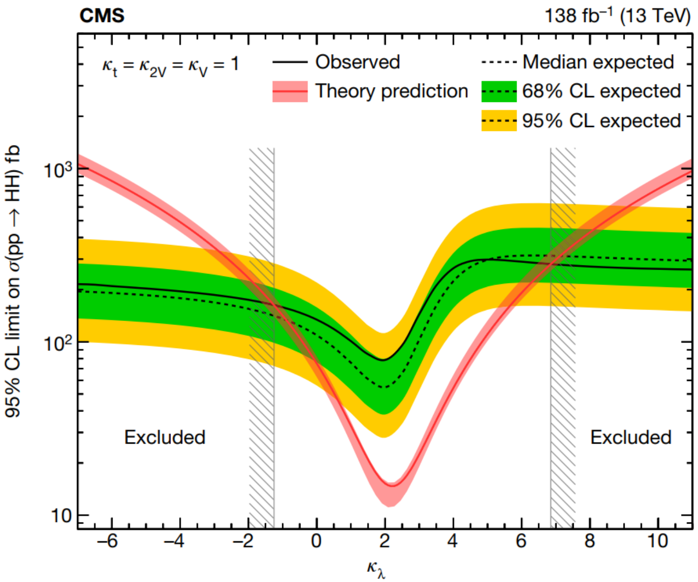
To determine the Higgs potential shape is challenge!







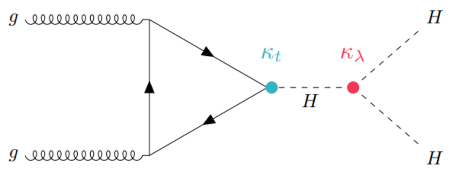
ATLAS, PRD108 (2023)5, 052003

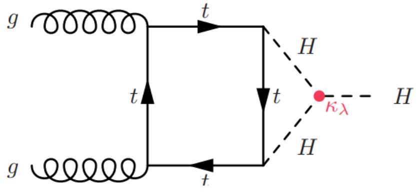


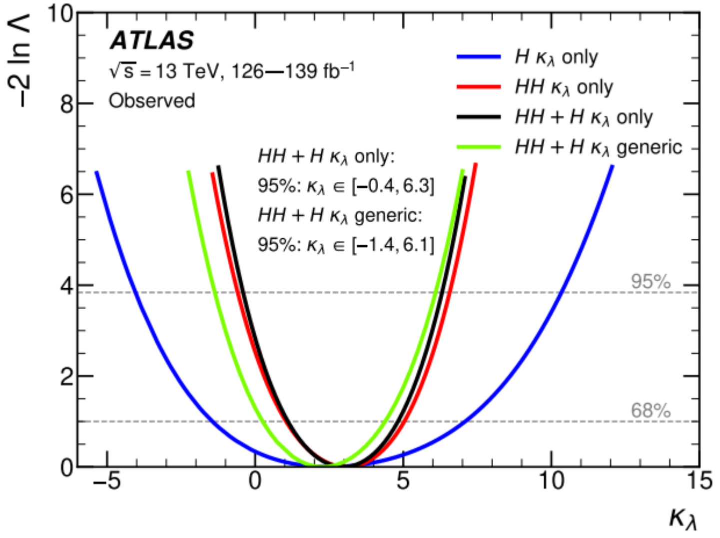
Nature 607 (2022) 60

Higgs potential

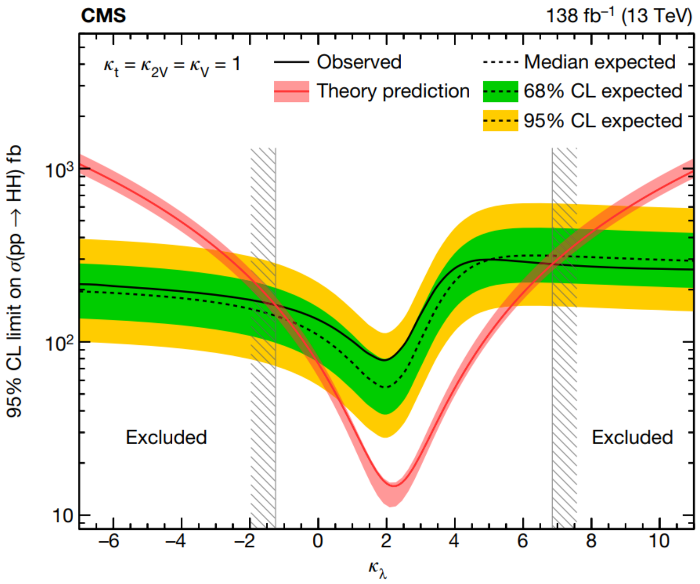
To determine the Higgs potential shape is challenge!







ATLAS, PRD108 (2023)5, 052003

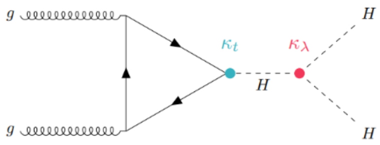


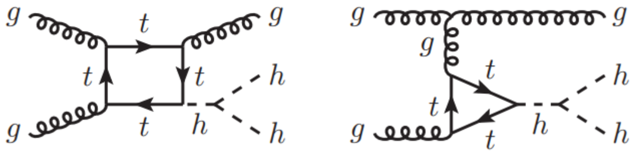
Nature 607 (2022) 60

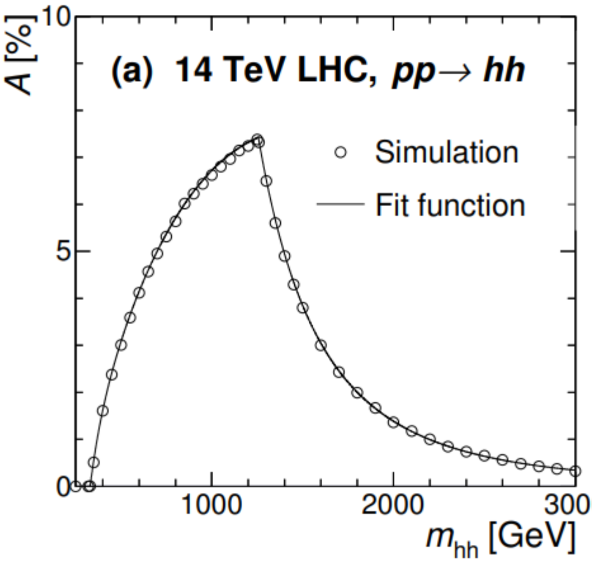
Higgs potential@ LHC

Current experimental searches mainly focus on the high di-Higgs invariant mass region

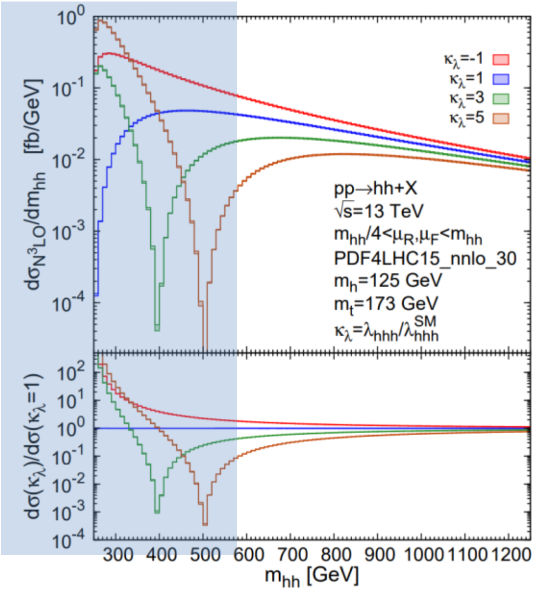
The low di-Higgs invariant mass region is more sensitive to the Higgs shape



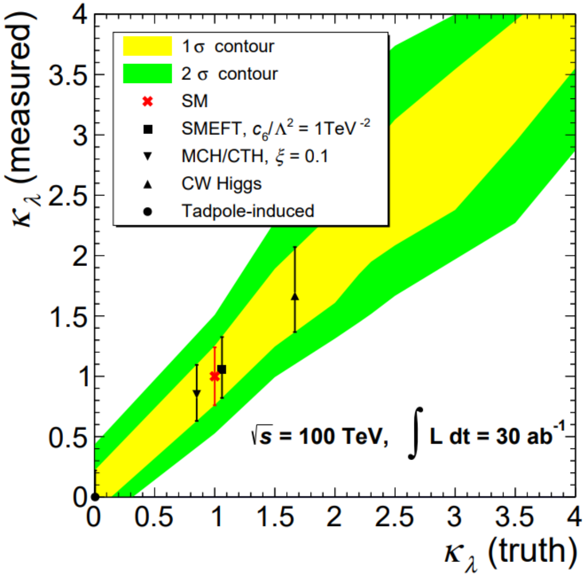




Q.-H. Cao, Bin Yan, D.-M. Zhang, H. Zhang, PLB 752 (2016) 285-290

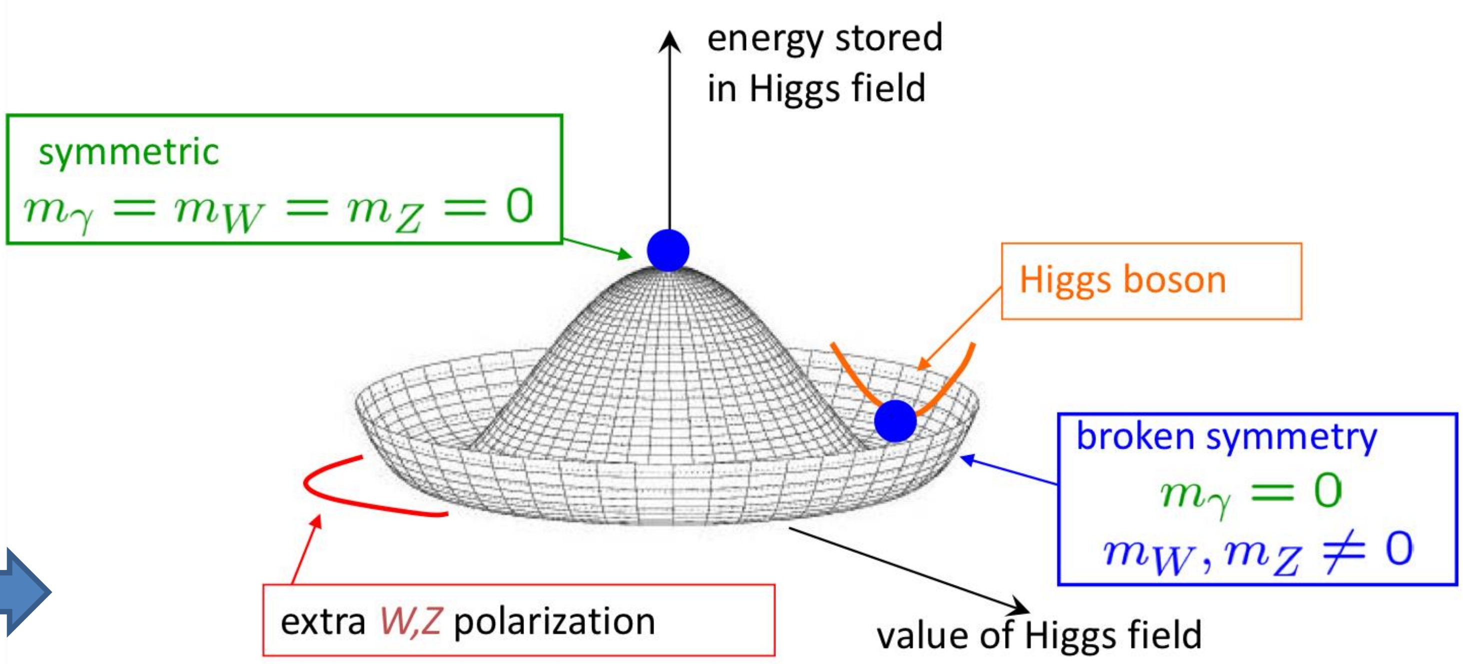


L. B. Chen, H. T. Li, H. S. Shao, J. Wang, PLB 803 (2020) 135292, JHEP 03 (2020) 072



K. Chai, J.-H. Yu, H. Zhang, PRD 107(2023) 5,055031

Testing the EWSB @ LHC



energy stored
in Higgs field

symmetric
$m_\gamma = m_W = m_Z = 0$

Higgs boson

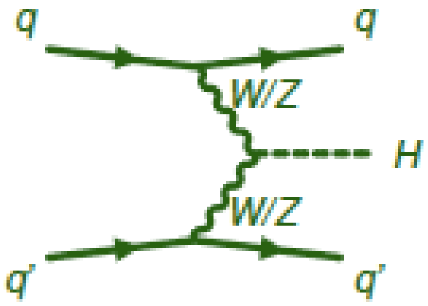
broken symmetry
$m_\gamma = 0$
$m_W, m_Z \neq 0$

extra *W,Z* polarization

value of Higgs field

Precisely determine the Higgs gauge couplings are also important for testing the EWSB

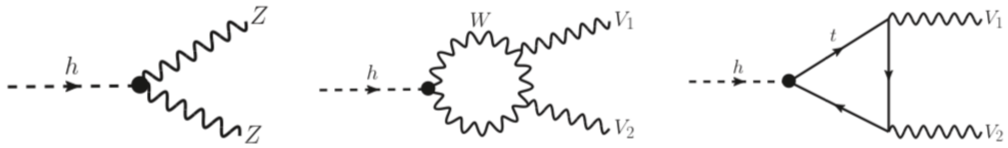
$$\mathscr{L}_{hVV} = \kappa_W g_{hWW}^{\mathrm{SM}} h W_\mu^+ W^{-\mu} + \frac{\kappa_Z}{2} g_{hZZ}^{\mathrm{SM}} h Z_\mu Z^\mu$$



Higgs couplings and EWSB

- ➢ The magnitude of the Higgs gauge couplings
- ➢ The relative sign between hWW and hZZ couplings

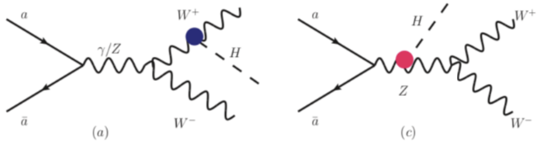
Y. Chen et al, PRL 2016



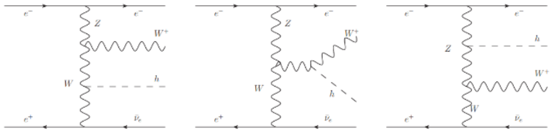
- ☐ Interference between tree and loop level in Higgs decay

- ☐ Lepton Colliders

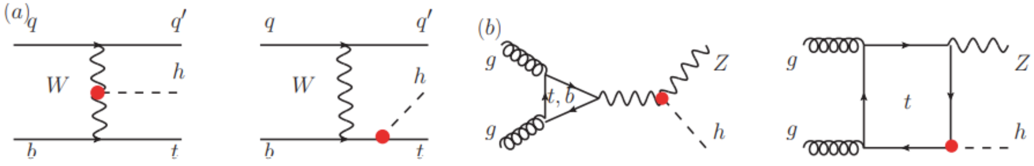
  C.W Chiang, X. G. He and G. Li, JHEP08(2018) 126



  D. Stolarski, Y. Wu, PRD 102 (2020)3, 033006



- ☐ th and Zh production

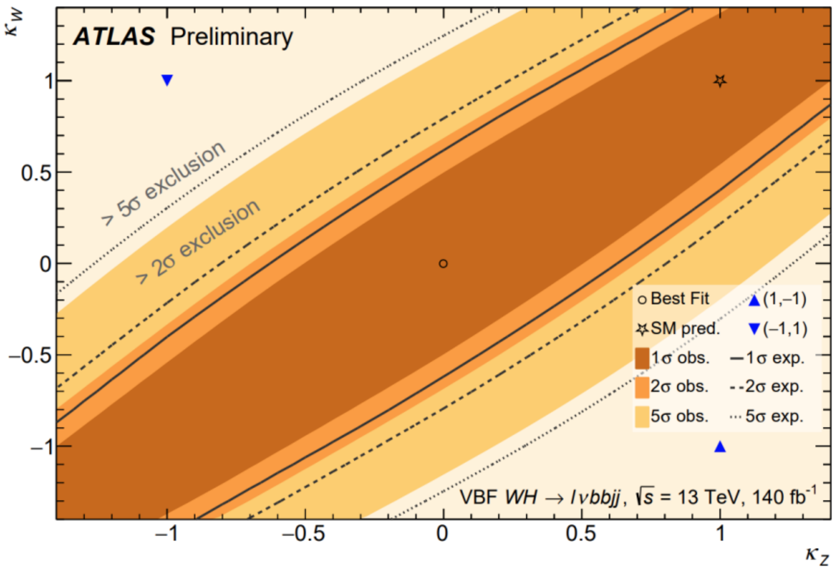


The data favors the same sign

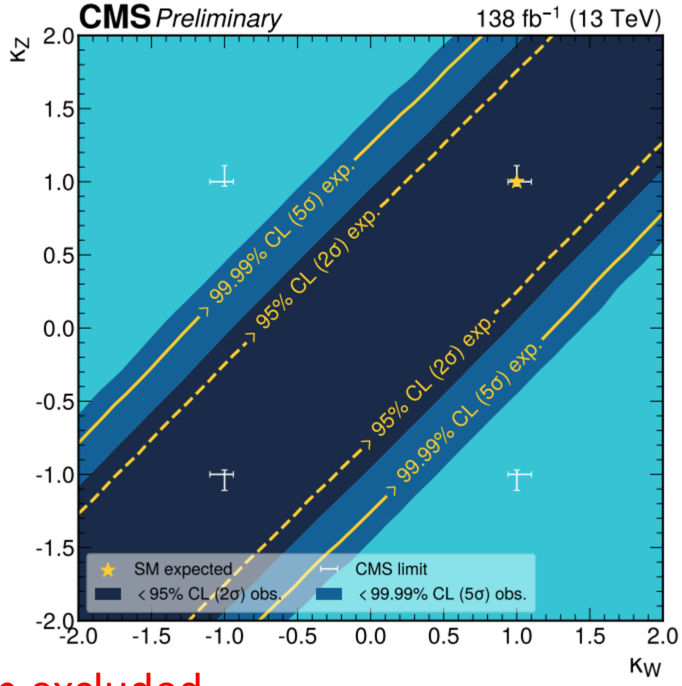
K. P. Xie and Bin Yan, PLB 820 (2021) 136515

Higgs couplings and EWSB

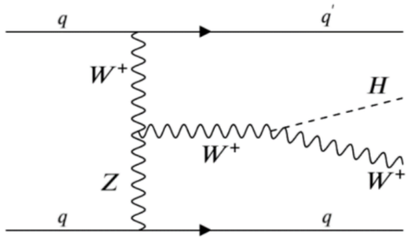
ATLAS-CONF-2023-057

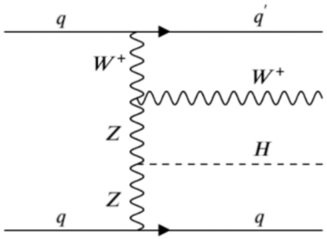


CMS-PAS-HIG-23-007



The opposite-sign coupling hypothesis has been excluded

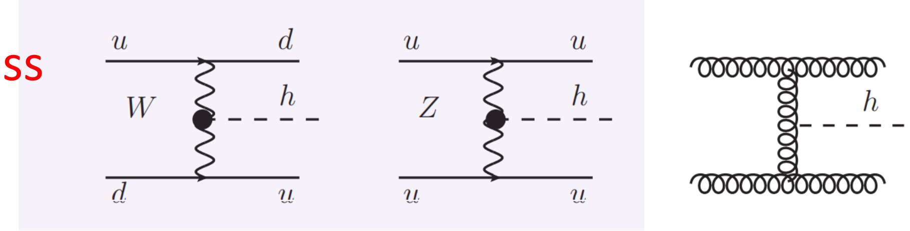




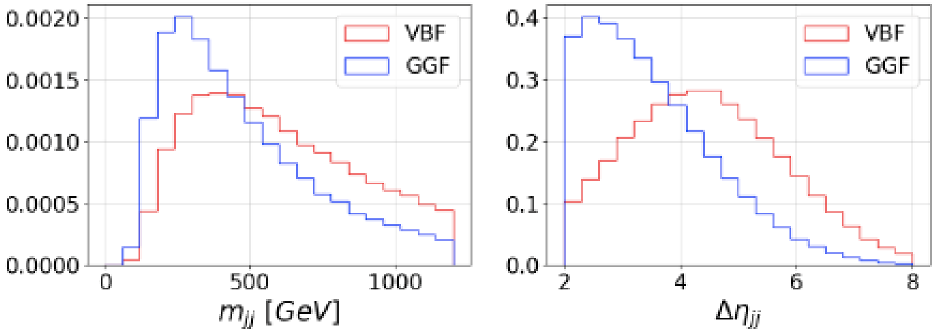
The magnitude of the Higgs gauge couplings would be the key task for testing EWSB

Higgs production mechanisms

VBF Higgs production is the main process to verify the Higgs gauge couplings

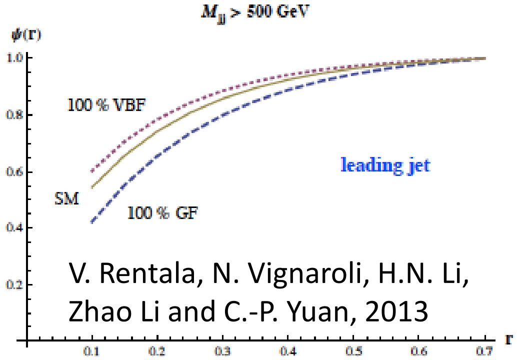


- ➢ The rapidity gap and the invariant mass of the two jets



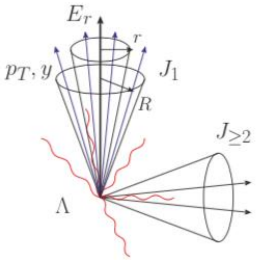
V.D. Bargeer, K.m.Cheung. T. Han, J. Ohnemus and D. Zeppenfeld, 1991
N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, 2001
……

- ➢ Soft gluon radiation effects: Jet energy profile, TMD effects

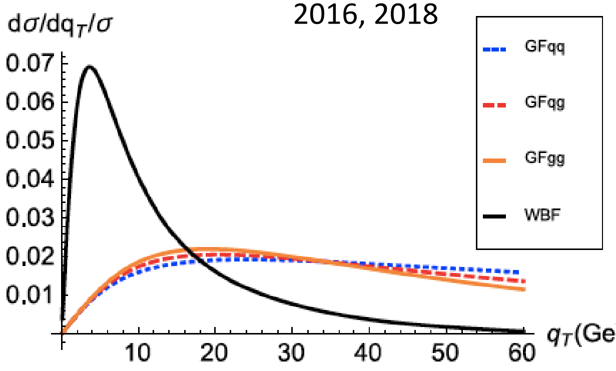


V. Rentala, N. Vignaroli, H.N. Li, Zhao Li and C.-P. Yuan, 2013

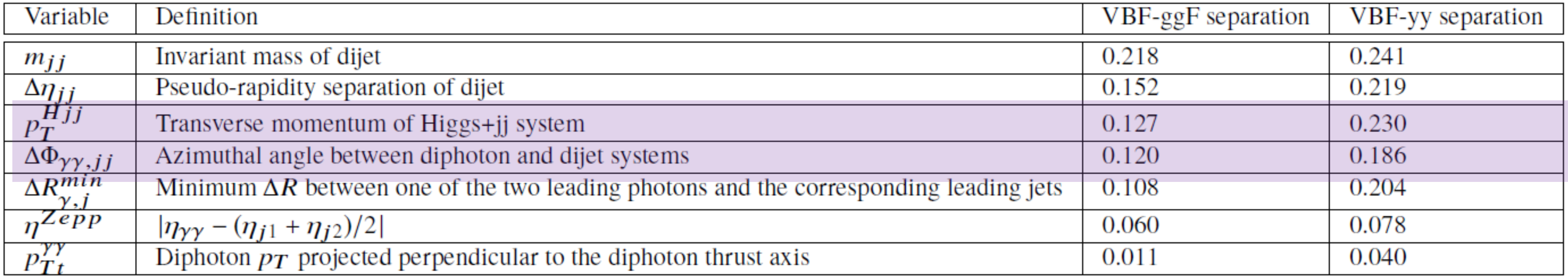
$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$



P. Sun, C.-P. Yuan and F. Yuan, 2016, 2018



Higgs production mechanisms

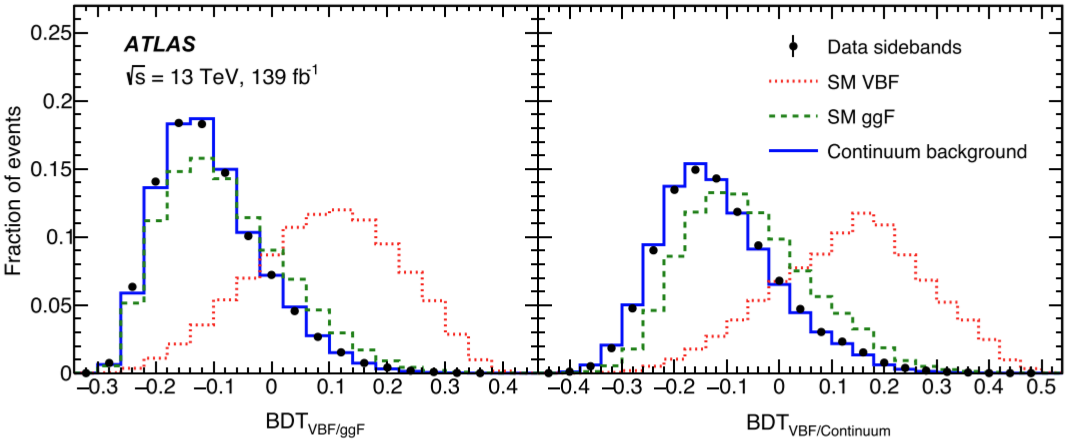


Variable	Definition	VBF-ggF separation	VBF-yy separation
m_{jj}	Invariant mass of dijet	0.218	0.241
$\Delta\eta_{jj}$	Pseudo-rapidity separation of dijet	0.152	0.219
p_T^{Hjj}	Transverse momentum of Higgs+jj system	0.127	0.230
$\Delta\Phi_{\gamma\gamma,jj}$	Azimuthal angle between diphoton and dijet systems	0.120	0.186
$\Delta R^{min}_{\gamma,j}$	Minimum ΔR between one of the two leading photons and the corresponding leading jets	0.108	0.204
η^{Zepp}	$\|\eta_{\gamma\gamma} - (\eta_{j1} + \eta_{j2})/2\|$	0.060	0.078
$p_{Tt}^{\gamma\gamma}$	Diphoton p_T projected perpendicular to the diphoton thrust axis	0.011	0.040

Table 7: Variables used for VBF categorization and their separation power.

Soft gluon radiation effects: TMD effects

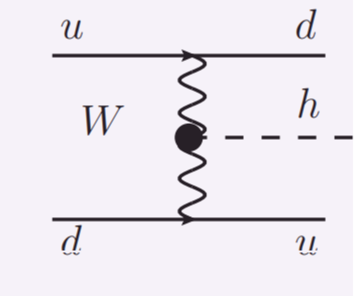
ATLAS, Phys.Rev.Lett. 131 (2023) 6, 061802

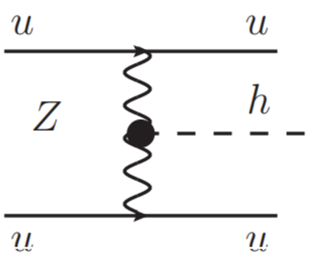


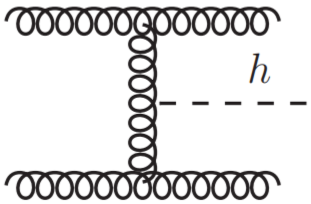
The VBF Higgs production can be well seperated from the GGF process

Higgs production mechanisms

Discriminating W-boson fusion, Z-boson fusion and gluon fusion Higgs production





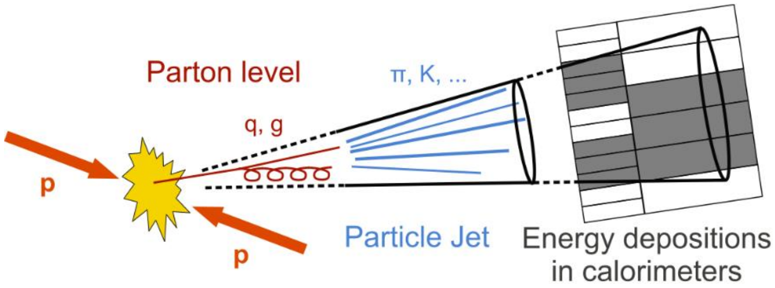


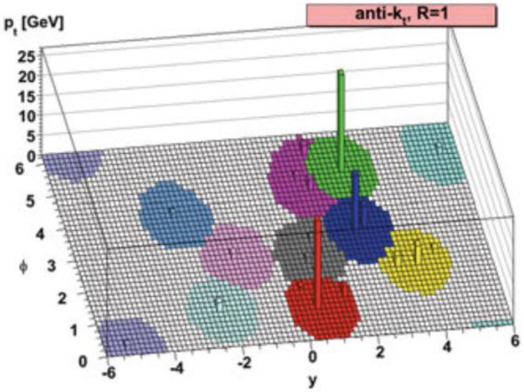
H. T. Li, Bin Yan, C.-P. Yuan, PRL 131 (2023) 4, 041802

Separating the W boson’s contribution from the VBF Higgs production is an important task for determining the Higgs gauge coupling

The key observable: Jet Charge
W: opposite sign for the two jet charges
Z: same or opposite sign for the two jet charges
G: the sign of the jet charge is arbitrary

Jet charge definition





Transverse-momentum-weighting scheme:

$$Q_J = \frac{1}{(p_T^j)^\kappa} \sum_{i \in jet} Q_i (p_T^i)^\kappa, \ \kappa > 0$$

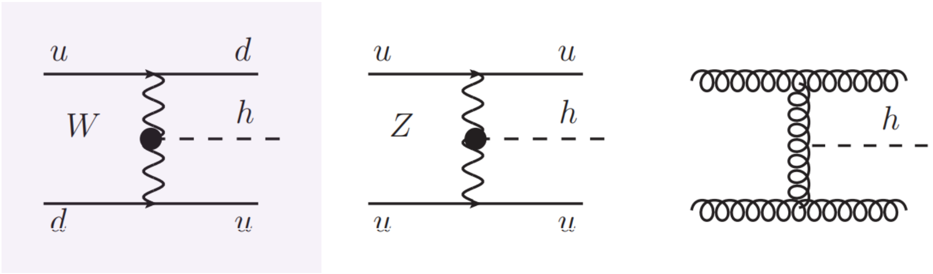
R.D. Field and R.P. Feynman, NPB136,1(1978)

κ: To regulate the sensitivity of the soft gluon radiation

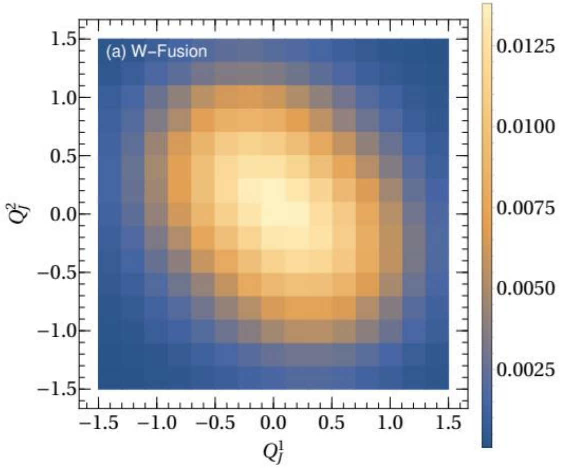
➢ SCET calculation	D. Krohn et al, PRL, 2013, W.J.Waalewijn, PRD, 2012
➢ Quark/gluon jet discrimination	K.Fraser and M.D. Schwartz, JHEP, 2018, Zhong-Bo Kang, Xiaohui Liu, et al, PRD, 2021
➢ Nuclear medium effects	H. T. Li and I. Vitev, PRD, 2020, PRL, 2021
➢ Quark flavor structure	Zhong-Bo Kang, Xiaohui Liu, et al, PRD, 2021, + Ding Yu Shao,PRL, 2020
➢ Non-perturbative model	Zhong-Bo Kang et al, PRL, 2023
➢ Electroweak and Higgs physics	H. T. Li, Bin Yan and C.-P. Yuan, PLB 2022, PRL 2023 Xiao-Rui Wang, Bin Yan, PRD 2023 H. Cui, M. Zhao, Y. Wang, H. Liang, Manqi Ruan, 2023

Higgs coupings @ VBF

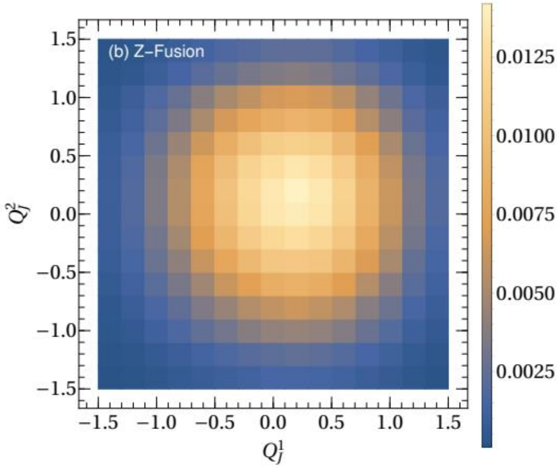
The key observable: Jet Charge



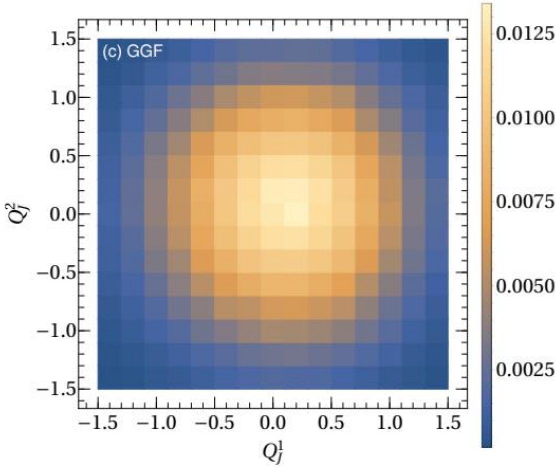
H. T. Li, Bin Yan, C.-P. Yuan,
PRL 131 (2023) 4, 041802



opposite sign for the two jet charges



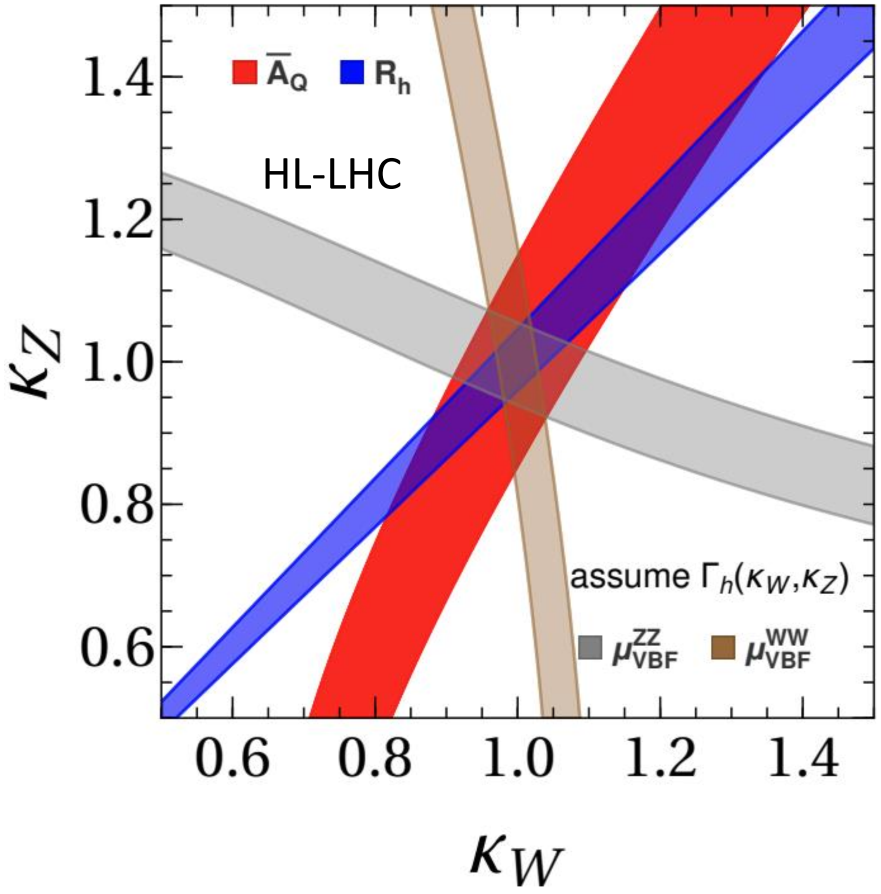
same or opposite sign



the sign of the jet charge is arbitrary

Higgs couplings @ VBF

$$h \to 4\ell/2\ell 2v_\ell$$



$$Q^{(\pm)} = |Q_J^1 \pm Q_J^2|$$

$$\overline{A}_Q^{\rm tot} = \frac{f_W\langle Q^{(-)}\rangle_W + f_Z\langle Q^{(-)}\rangle_Z + f_G\langle Q^{(-)}\rangle_G}{f_W\langle Q^{(+)}\rangle_W + f_Z\langle Q^{(+)}\rangle_Z + f_G\langle Q^{(+)}\rangle_G}$$

$$R_h = \frac{\mu(gg \to h \to WW^*)}{\mu(gg \to h \to ZZ^*)} = \frac{\kappa_W^2}{\kappa_Z^2}$$

$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\rm SM}}$$

H. T. Li, Bin Yan, C.-P. Yuan,
PRL 131 (2023) 4, 041802

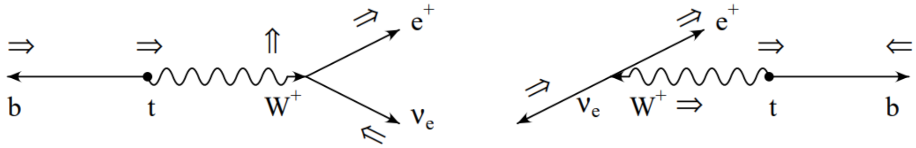
The limits from Rh and jet charge asymmetry are not depending on the assumption of the Higgs width

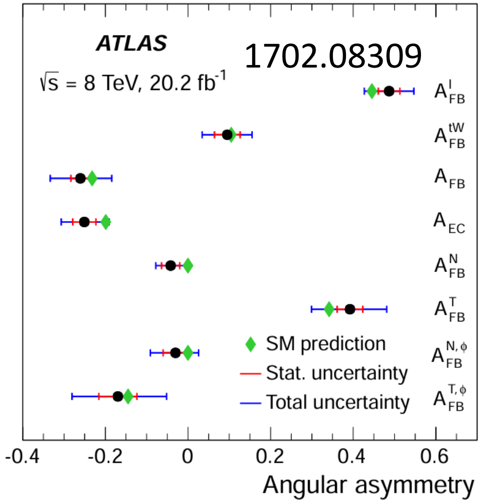
对撞机物理前沿进展

横向极化效应

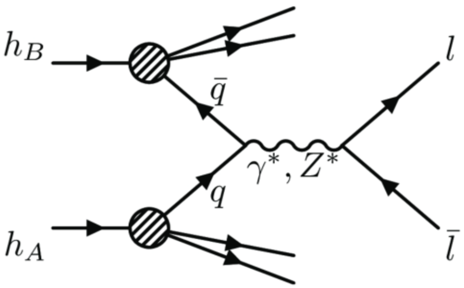
Spin effects and New Physics

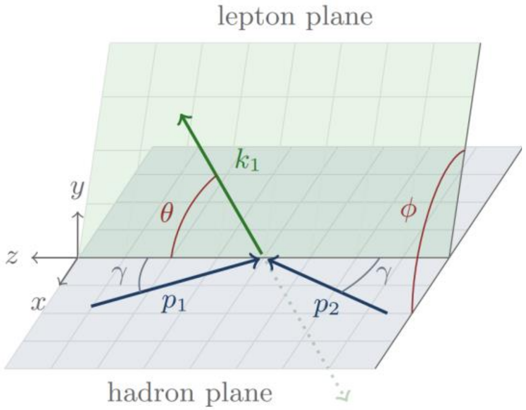
- Top quark polarization:



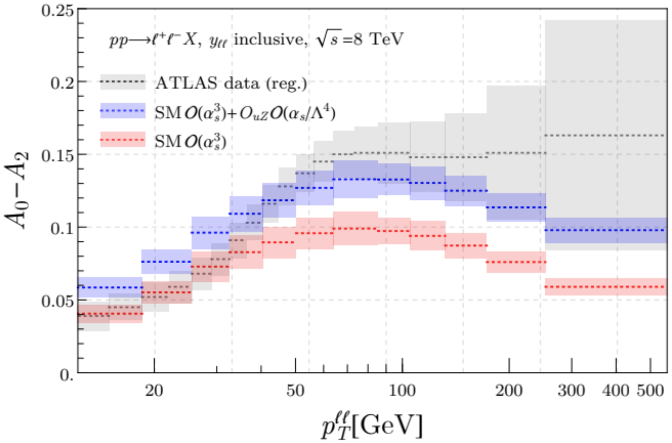


- Gauge boson polarization





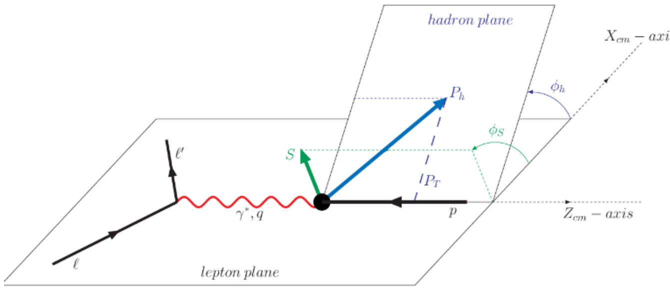
$$A_0(1 - 3\cos^2\theta) + A_2 \sin^2\theta\cos(2\phi)$$

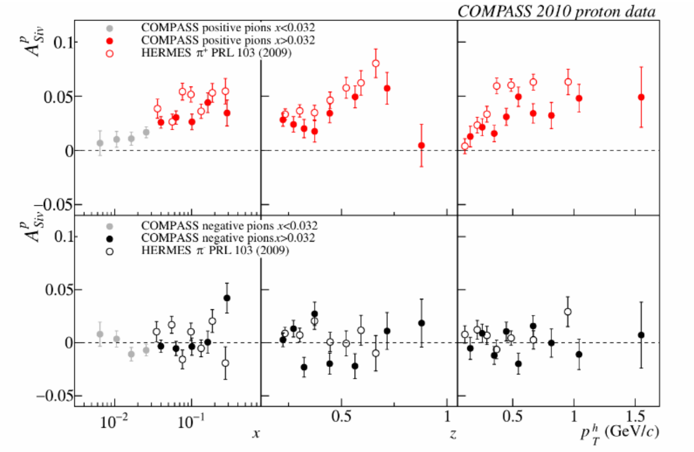


Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

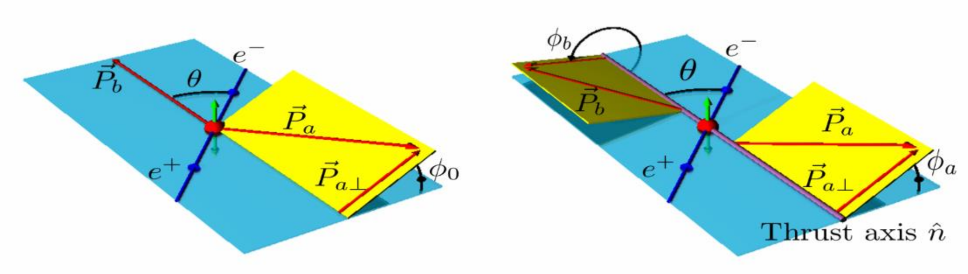
Spin effects in QCD

- Nucleon structure: PDFs

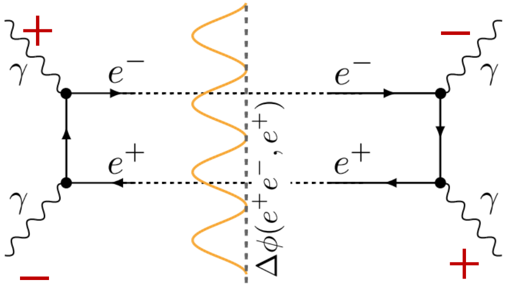


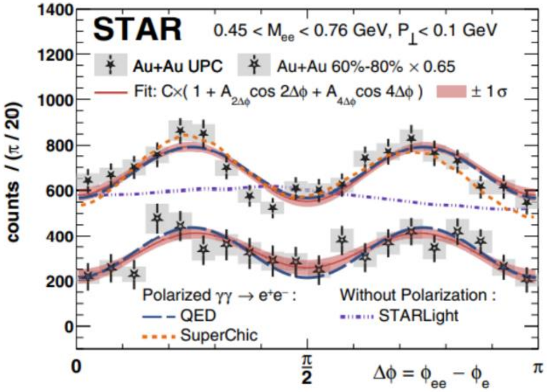


- Nucleon structure: FFs



- UPCs





QCD Spin effects and New physics

- **What type of new physics would exhibit sensitivity to the effects of QCD spin?**

Dipole moments

$$-\mu_e \frac{\vec{S}}{\left|\vec{S}\right|}\cdot\vec{B} \quad \Leftrightarrow \quad e\left(\bar{e}\gamma_\mu e\right)A^\mu + a_e \frac{e}{4m_e}\left(\bar{e}\sigma_{\mu\nu}e\right)F^{\mu\nu}$$

$$-d_e \frac{\vec{S}}{\left|\vec{S}\right|}\cdot\vec{E} \quad \Leftrightarrow \quad +d_e \frac{i}{2}\left(\bar{e}\sigma_{\mu\nu}\gamma_5 e\right)F^{\mu\nu}$$

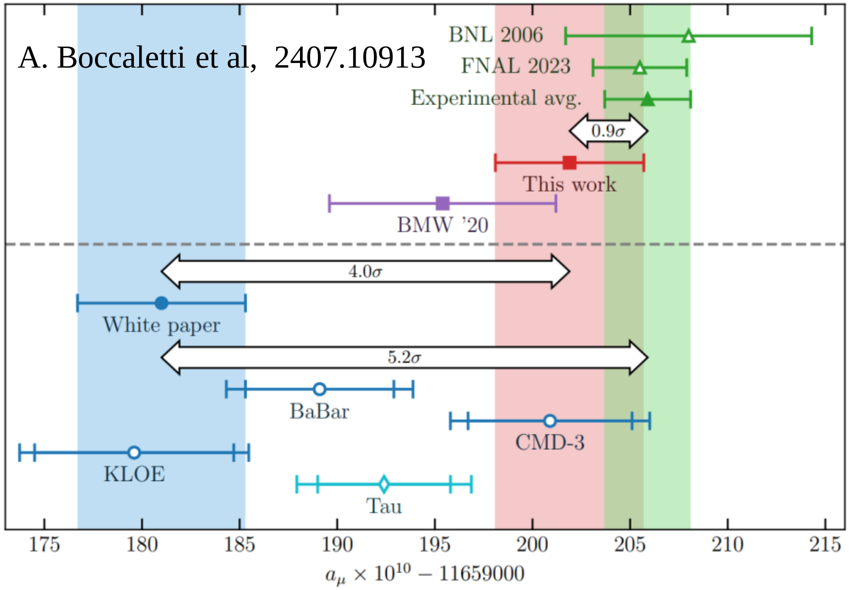
$$\mu_e = g_e \frac{e}{2m_e} \quad \text{and} \quad \left(g_e - 2\right) = 2a_e$$

New physics and Dipole Operator

- Magnetic dipole moments: probing the internal structures of particles

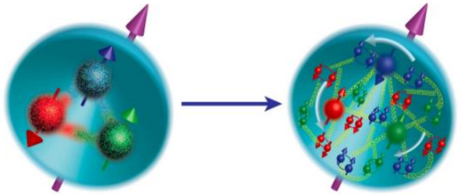
☐ Elementary particle:

Electron: g/2=1.001159…
Muon: g/2=1.0011659..



☐ Composite particle:

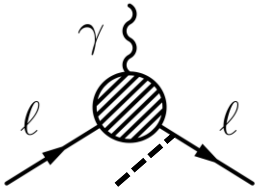
Proton: g/2=2.7928444..
Neutron: g/2=-1.91394308..



☐ Quarks: any internal structures?

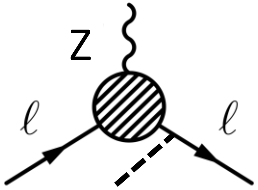
☐ From MDM and EDM to weak dipole moments?

$$\bar{\ell}\,\sigma^{\mu\nu} e \tau^I \varphi W^I_{\mu\nu}\,,\; \bar{\ell}\,\sigma^{\mu\nu} e \varphi B_{\mu\nu}$$



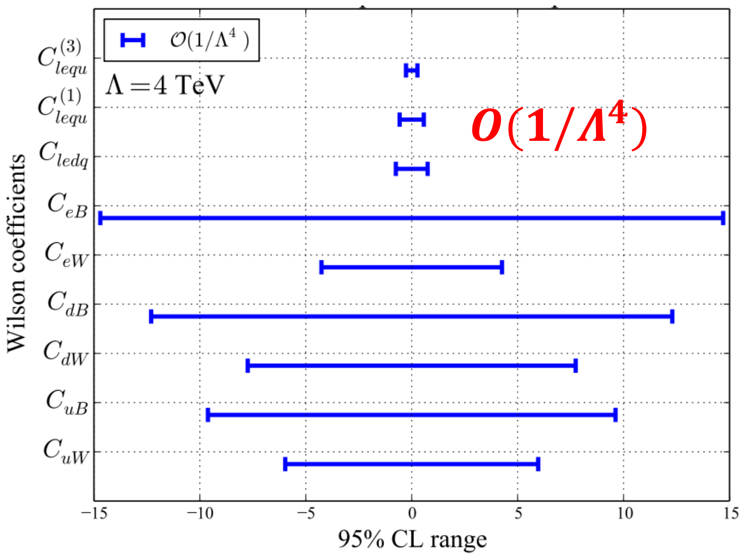
May have same physics source

$B_{\mu\nu}, W_{\mu\nu}$



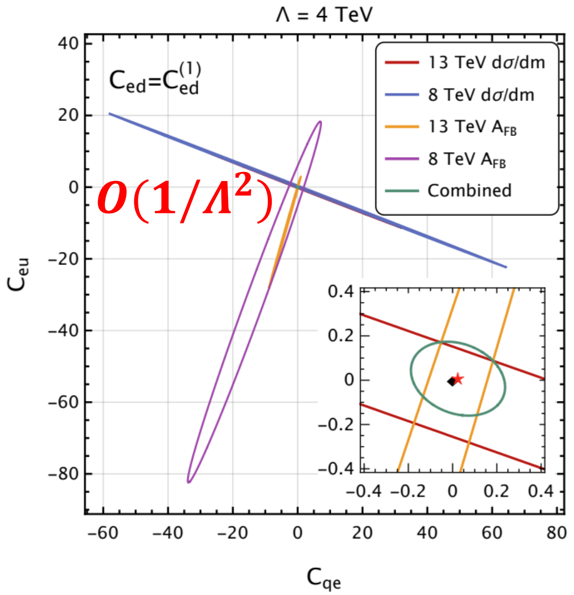
Example: Electroweak Dipole Operator

Single-Parameter-Analysis: EW dipole couplings are poorly constrained by Drell-Yan data



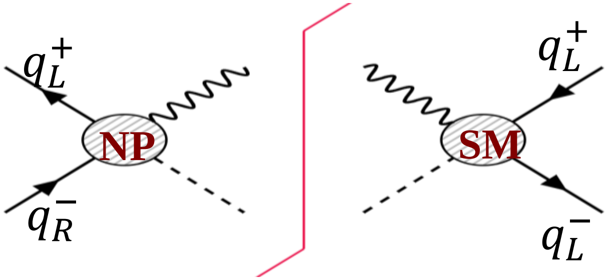
$O(1/\Lambda^4)$

R. Boughezal et al, PRD 104 (2021) 095022



$O(1/\Lambda^2)$

R. Boughezal et al, 2303.08257



=0 for the cross section

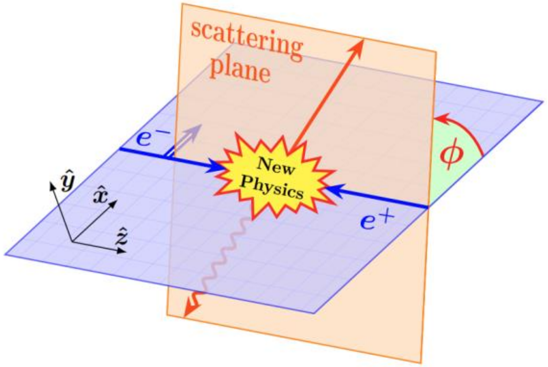
Leading contribution: $\left|\frac{c_{dipole}}{\Lambda^2}\right|^2$

- It is difficult to probe the electroweak dipole interactions at colliders

Electroweak dipole moments of leptons

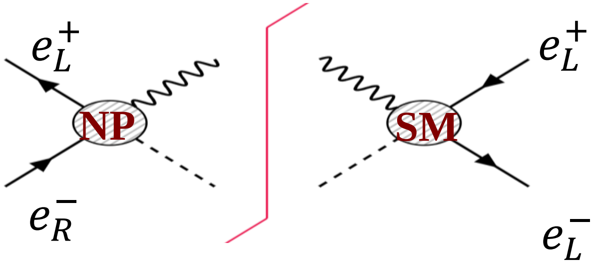
- Transversely polarized effect of beams @ lepton collider

The interference between the different helicity states



$$\boldsymbol{s} = (b_1, b_2, \lambda) = \underline{(b_\mathrm{T}\cos\phi_0, b_\mathrm{T}\sin\phi_0}, \lambda)$$

$$\rho = \frac{1}{2}(1+\boldsymbol{\sigma}\cdot\boldsymbol{s}) = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_\mathrm{T}e^{-i\phi_0} \\ b_\mathrm{T}e^{i\phi_0} & 1-\lambda \end{pmatrix}$$



Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801

$$\bar{e}_L\sigma_{\mu\nu}e_R A^{\mu\nu}, \bar{e}_L\sigma_{\mu\nu}e_R Z^{\mu\nu}$$

$$M\infty e^{i(\alpha1-\alpha2)\phi}d(\theta)$$

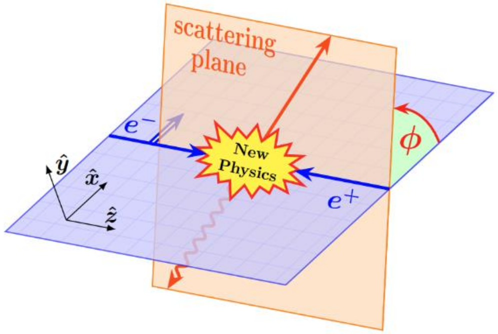
	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

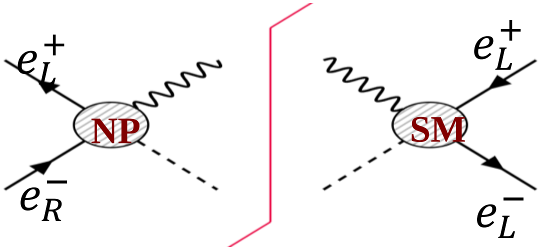
Breaking the rotational invariance & A nontrivial azimuthal behavior

Electroweak dipole moments of leptons

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

PRL 131 (2023) 241801





$M \propto e^{i(\alpha 1-\alpha 2)\phi} d(\theta)$

$e^{i\phi * 0}$

$e^{i\phi}$

	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

$$\frac{2\pi\, d\sigma^i}{\sigma^i\, d\phi} = 1 + \underline{A_R^i(b_T, \bar{b}_T)} \cos\phi + \underline{A_I^i(b_T, \bar{b}_T)} \sin\phi + \underline{b_T\, \bar{b}_T\, B^i} \cos 2\phi + \mathcal{O}(1/\Lambda^4)$$

Re[C_{dipole}]

Im[C_{dipole}]

SM & other NP

CP-conserving

CP-violation

- Linearly dependent on the dipole couplings C_{dipole} and spin b_T
- Without depending on other NP operators

Single Transverse Spin Asymmetries

$$A^i_{LR} = \frac{\sigma^i(\cos\phi > 0) - \sigma^i(\cos\phi < 0)}{\sigma^i(\cos\phi > 0) + \sigma^i(\cos\phi < 0)} = \frac{2}{\pi} A^i_R$$

$$A^i_{UD} = \frac{\sigma^i(\sin\phi > 0) - \sigma^i(\sin\phi < 0)}{\sigma^i(\sin\phi > 0) + \sigma^i(\sin\phi < 0)} = \frac{2}{\pi} A^i_I,$$

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

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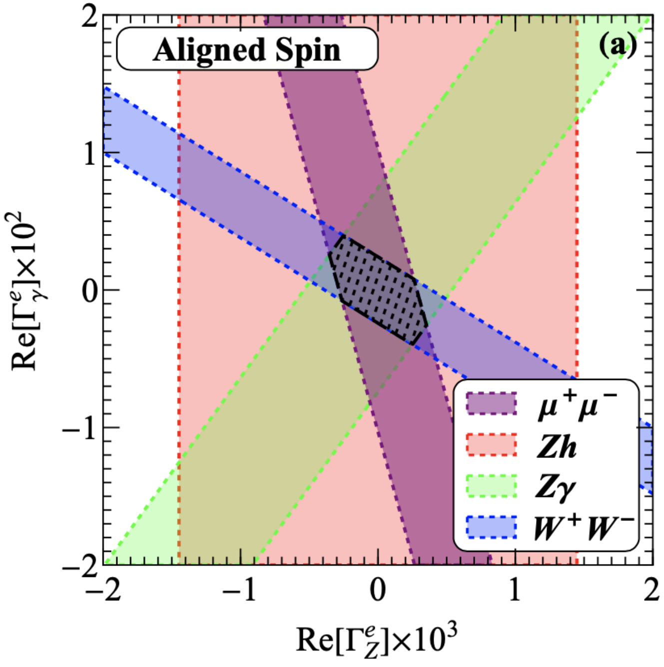
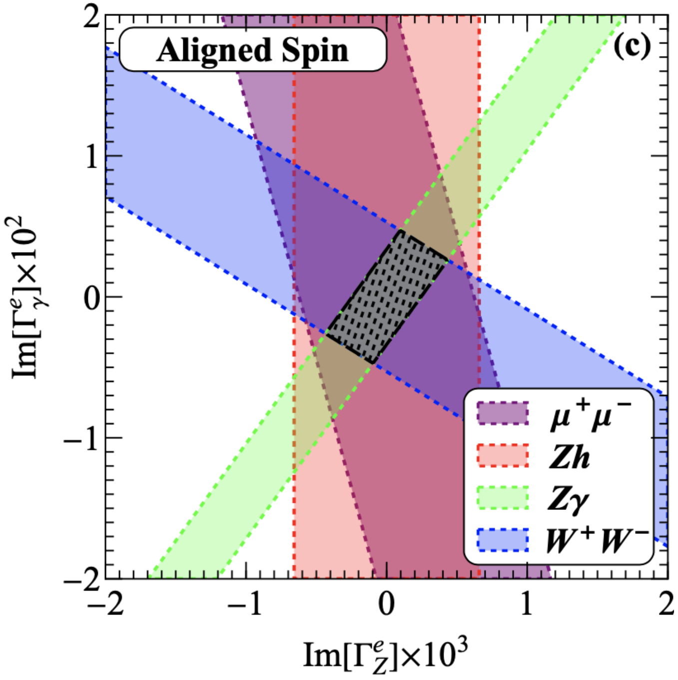
$\sqrt{s} = 250\ \mathrm{GeV}, \mathcal{L} = 5\ \mathrm{ab}^{-1}$ $\quad (b_T, \bar{b}_T) = (0.8, 0.3)$



CP-conserved dipole operator

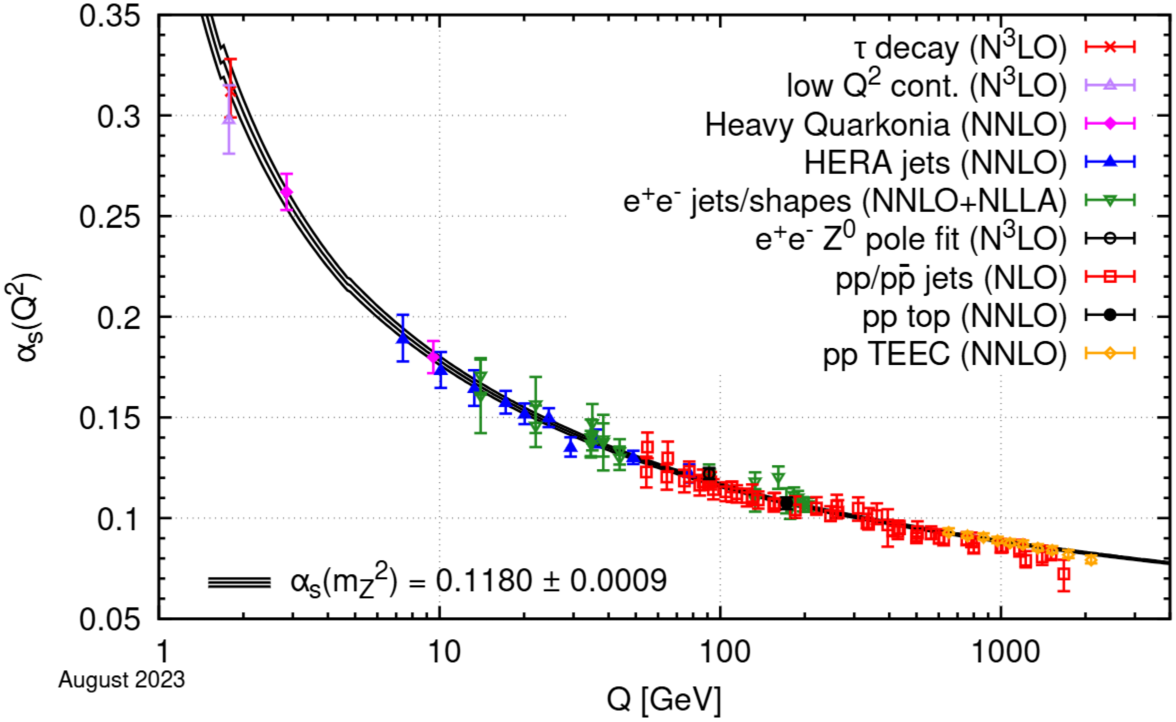


CP-violated dipole operator

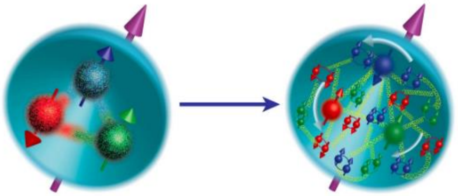
- Our bounds are much stronger than other approaches by 1~2 orders of magnitude
- Weak dipole coupling, SSA: 0.01%, LHC: 1%

Electroweak dipole moments of quarks

- ➢ The quark can not be a free particle due to the QCD confinement



Asymptotic freedom of QCD theory



- ➢ How to probe the spin information of quarks?

The non-perturbative functions, i.e., the parton distirbuion functions and the fragmentation functions

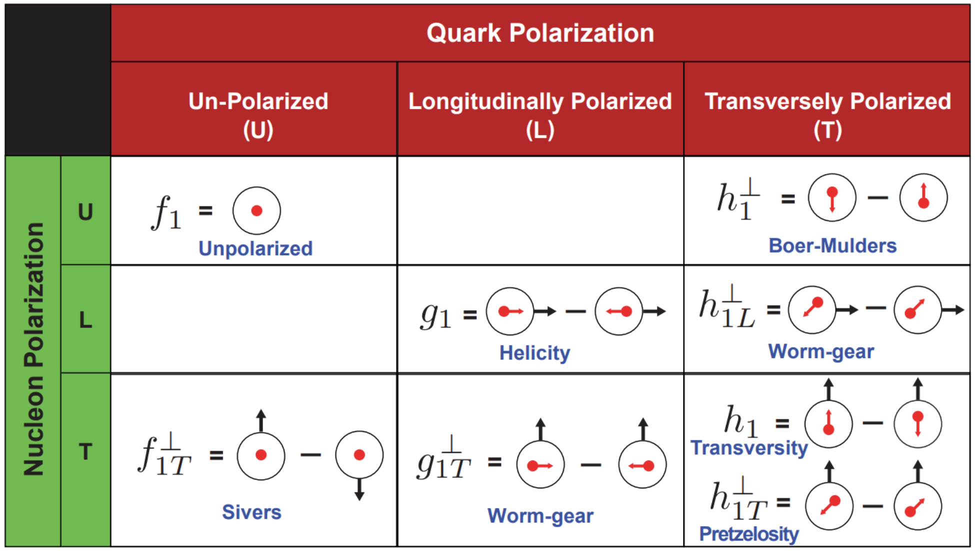
Transverse spin effects of quark @ EIC

- Quark dipole operators

R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, PRD 107 (2023) 7, 075028
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025

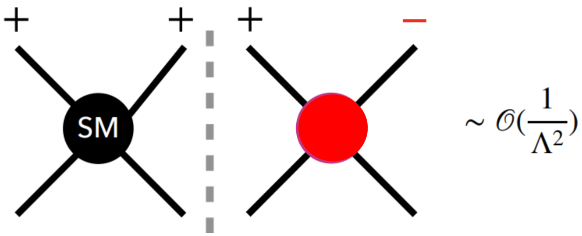
Leading Quark TMDPDFs

Nucleon Spin   Quark Spin



		Quark Polarization		
		Un-Polarized (U)	**Longitudinally Polarized (L)**	**Transversely Polarized (T)**
Nucleon Polarization	**U**	f_1 = **Unpolarized**		$h_1^\perp$ = − **Boer-Mulders**
	L		g_1 = − **Helicity**	$h_{1L}^\perp$ = − **Worm-gear**
	T	$f_{1T}^\perp$ = − **Sivers**	$g_{1T}^\perp$ = − **Worm-gear**	h_1 = − **Transversity** $h_{1T}^\perp$ = − **Pretzelosity**

$$
\begin{aligned}
\mathcal{O}_{uW} &= (\bar{q}\sigma^{\mu\nu}u)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{uB} &= (\bar{q}\sigma^{\mu\nu}u)\varphi B_{\mu\nu},\\
\mathcal{O}_{dW} &= (\bar{q}\sigma^{\mu\nu}d)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{dB} &= (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}.
\end{aligned}
$$



- The transversity is difficult to be constrained: chiral-odd

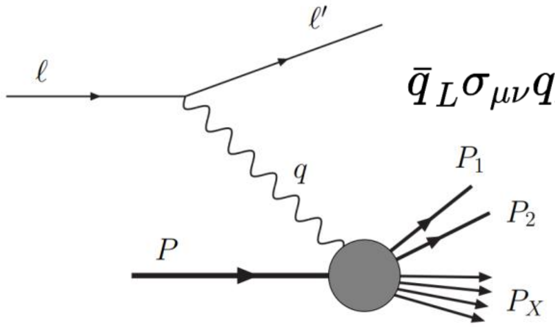
$$A_{UT} = \frac{\sigma\left(e^U p^\uparrow\right) - \sigma\left(e^U p^\downarrow\right)}{\sigma\left(e^U p^\uparrow\right) + \sigma\left(e^U p^\downarrow\right)}$$

- ☐ Collins Azimuthal Asymmetries in SIDIS, Collins function
- ☐ Low energy Drell-Yan process
- ☐ Dihadron production in SIDIS, Interference dihadron fragmentation

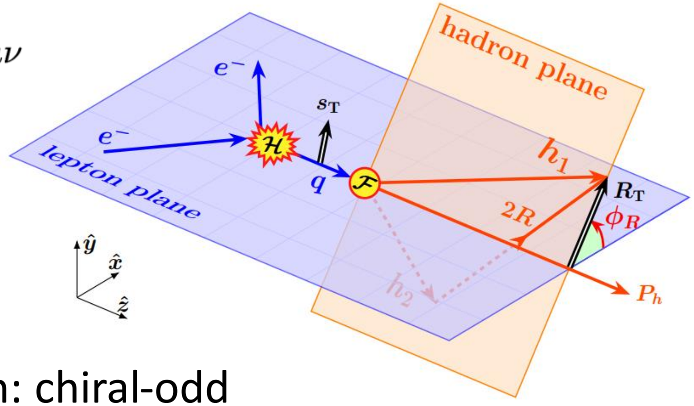
Kang, Prokudin, Sun, Yuan, PRD 93 (2016) 014009; Zeng, Dong, Liu, Sun, Zhao, PRD 109 (2024) 056002;
JAM Collaboration, PRD 106 (2022) 034014

Transverse spin effects of quark @ EIC

- The transverse spin of quarks can be generated by the quark dipole moments



$\bar{q}_L\sigma_{\mu\nu}q_R A^{\mu\nu}, \bar{q}_L\sigma_{\mu\nu}q_R Z^{\mu\nu}$



- The interference dihadron fragmentation function: chiral-odd

$$\frac{d\sigma}{dx\,dy\,dz\,dM_h\,d\phi_R} = \frac{N}{2\pi}\sum_q f_q(x,Q)\big[D_{h_1h_2/q}(z,M_h;Q)$$

$$-\,(\boldsymbol{s}_{T,q}(x,Q)\times\hat{\boldsymbol{R}}_T)^z H_{h_1h_2/q}(z,M_h;Q)\big]C_q(x,Q)$$

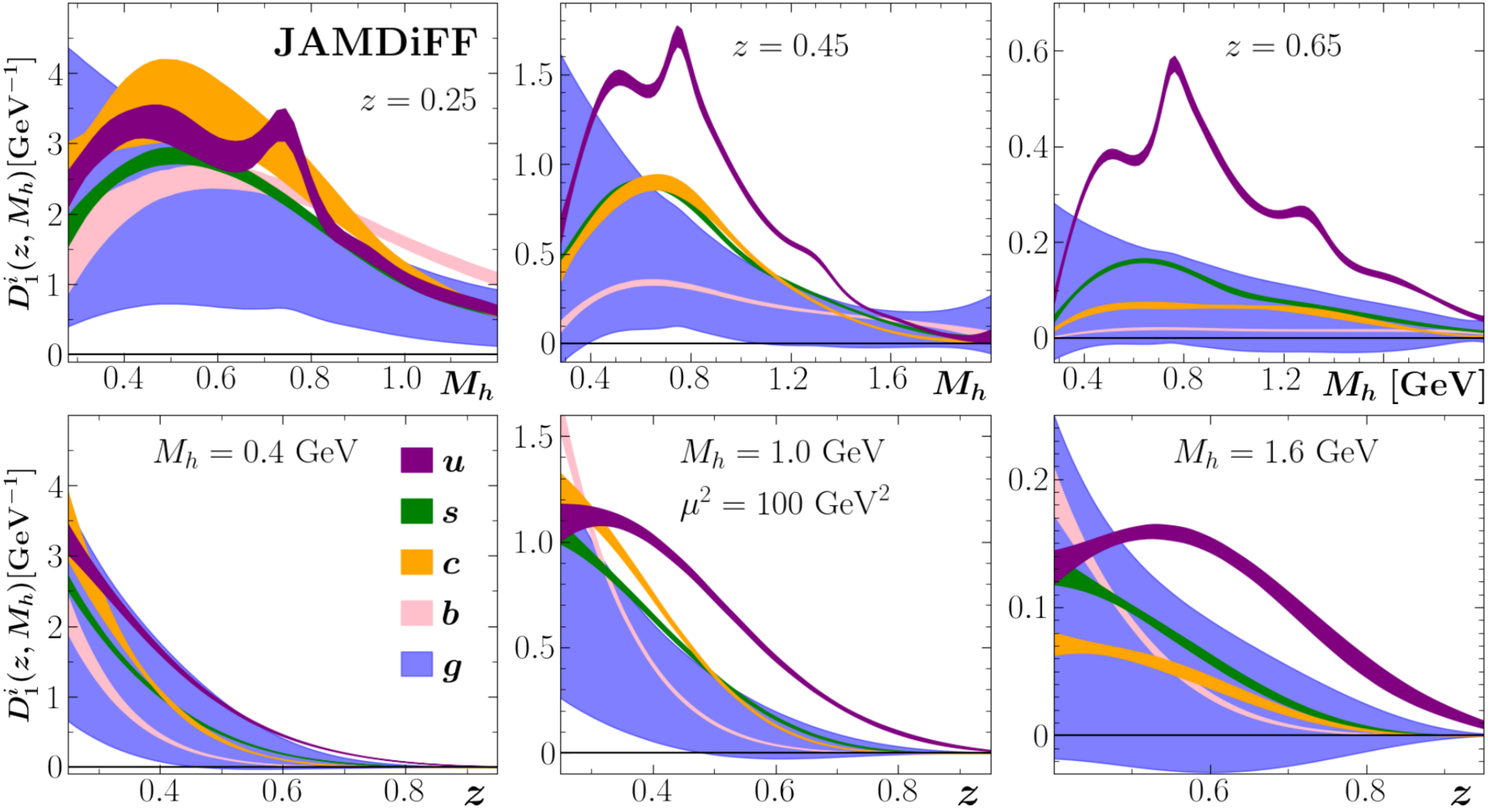
$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Re}\,\Gamma_Z^q\right)$$

$$(\boldsymbol{s}_{T,q}\times\hat{\boldsymbol{R}}_T)^z = s_q^x\sin\phi_R - s_q^y\cos\phi_R$$

$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Im}\,\Gamma_Z^q\right)$$

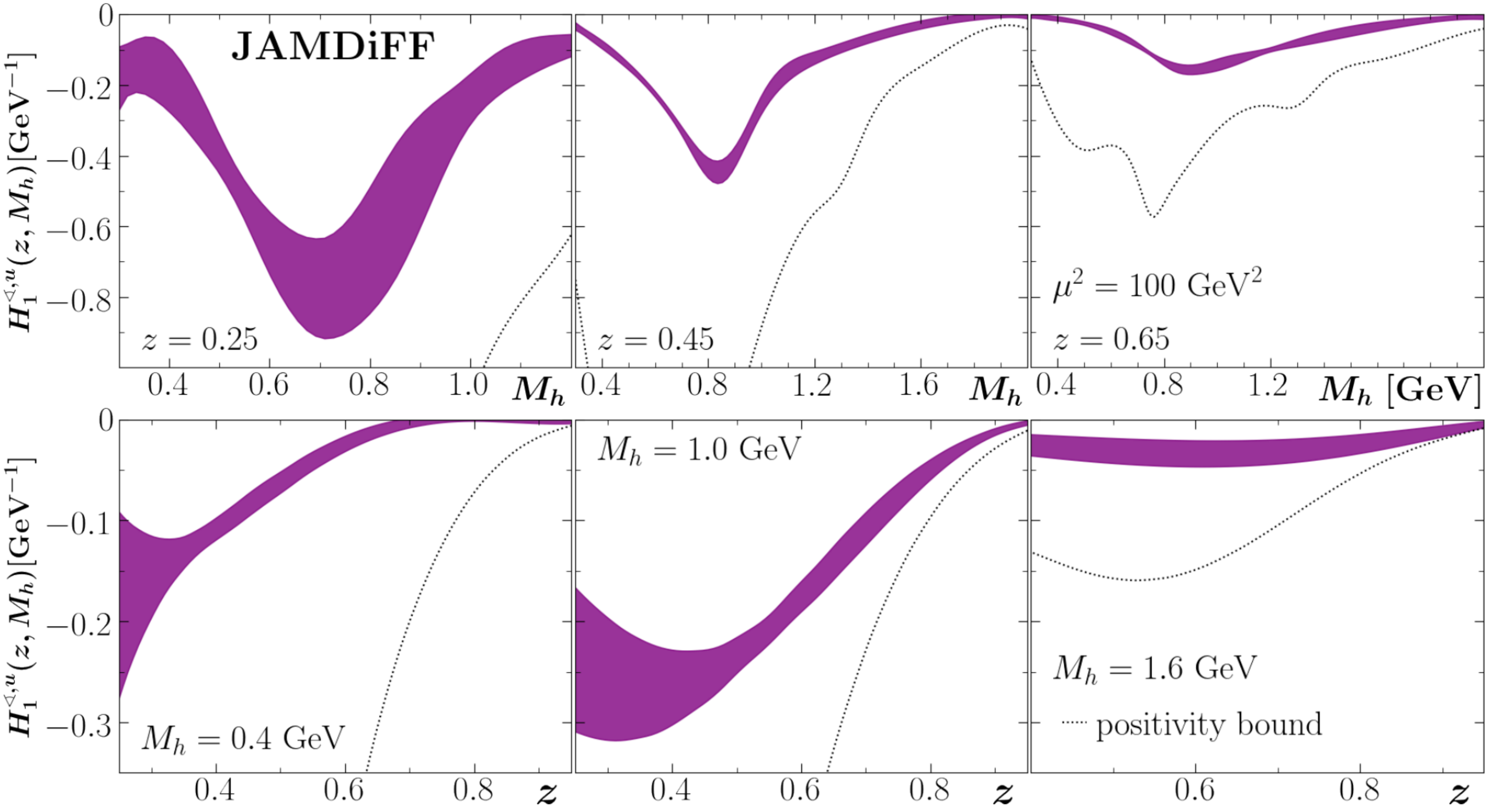
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

$\pi^+\pi^-$ Dihadron fragmentation functions



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

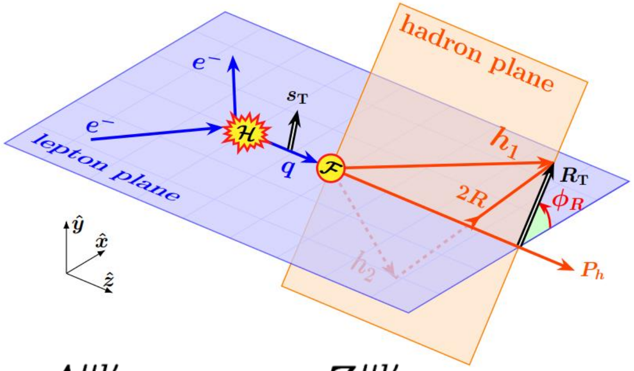
$\pi^+\pi^-$ Dihadron fragmentation functions



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

Transverse spin effects of quark @ EIC

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255



The non-trivial azimuthal distribution requires parity-violation effects:

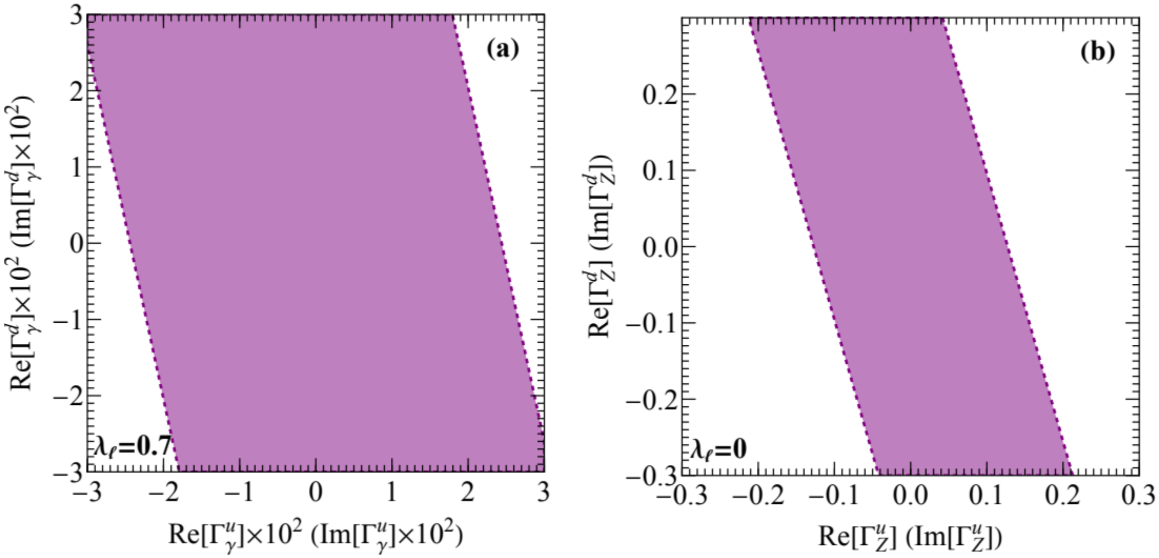
☐ the longitudinal polarization of the electron

☐ the parity-violating Z interactions

$$(\boldsymbol{s}_{T,q} \times \hat{\boldsymbol{R}}_T)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R$$

$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

$$A_{LR} = \frac{\sigma(\cos\phi_R > 0) - \sigma(\cos\phi_R < 0)}{\sigma(\cos\phi_R > 0) + \sigma(\cos\phi_R < 0)} = \frac{2}{\pi} A_I \qquad A_{UD} = \frac{\sigma(\sin\phi_R > 0) - \sigma(\sin\phi_R < 0)}{\sigma(\sin\phi_R > 0) + \sigma(\sin\phi_R < 0)} = \frac{2}{\pi} A_R$$



$$\sqrt{s} = 105\ \mathrm{GeV}, \mathcal{L} = 1\ \mathrm{ab}^{-1}$$

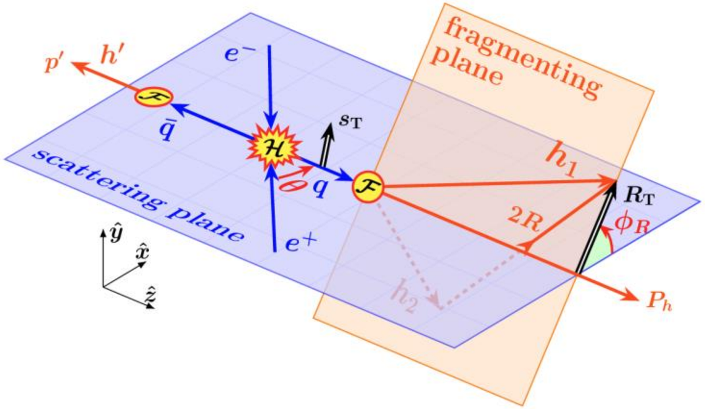
☐ Photon dipole: O(0.01)

☐ Z-boson dipole: O(0.1)

The flat direction in dipole couplings?

Transverse spin effects of quark @ CEPC

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 24011.13845



$$\frac{d\sigma}{dy\,dz\,d\bar{z}\,dM_h\,d\phi_R} = \frac{1}{32\pi^2 s}\sum_{q,\,q\to\bar{q}} C_q(y)\,D_{\bar{q}}^{h'}(\bar{z})$$

$$\times\left[D_q^{h_1h_2}(z,M_h) - (\boldsymbol{s}_{T,q}(y)\times\hat{\boldsymbol{R}}_T)^z H_q^{h_1h_2}(z,M_h)\right]$$

$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Re}\,\Gamma_Z^q\right)$$

$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Im}\,\Gamma_Z^q\right)$$

$$\bar{q}_L\sigma_{\mu\nu}q_R A^{\mu\nu},\, \bar{q}_L\sigma_{\mu\nu}q_R Z^{\mu\nu}$$

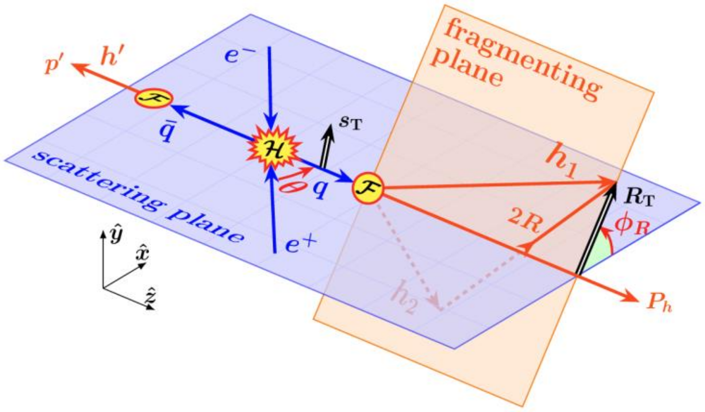
Isospin and charge conjugation symmetries:

$$D_u^{\pi^+\pi^-} = D_d^{\pi^+\pi^-},\quad H_u^{\pi^+\pi^-} = -H_d^{\pi^+\pi^-},\quad H_{s,\bar{s},c,\bar{c},b,\bar{b}}^{\pi^+\pi^-} = 0$$

$$D_q^{\pi^+\pi^-} = D_{\bar{q}}^{\pi^+\pi^-},\quad H_q^{\pi^+\pi^-} = -H_{\bar{q}}^{\pi^+\pi^-}$$

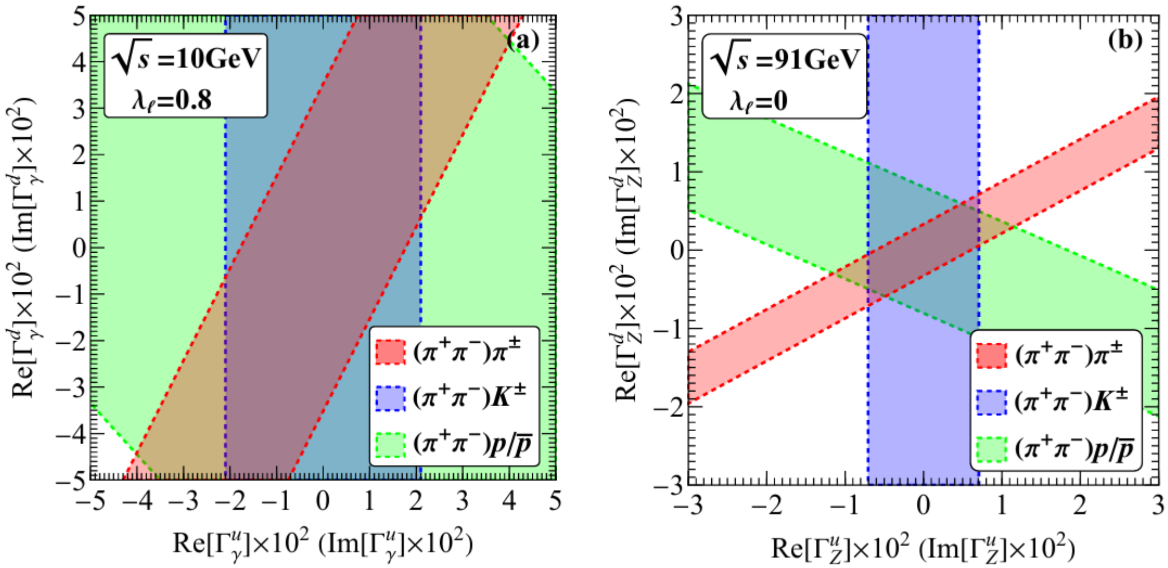
Transverse spin effects of quark @ CEPC

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 24011.13845



$$\frac{d\sigma}{dz\, d\bar{z}\, dM_h\, d\phi_R} = \frac{B^0 - B^x \sin\phi_R + B^y \cos\phi_R}{32\pi^2 s}$$

$$B^0 = \sum_q \langle C_q \rangle\, D_q^{\pi^+\pi^-} \left(D_q^{h'} + D_{\bar{q}}^{h'}\right) \qquad B^i = H_u^{\pi^+\pi^-} \left[\langle S_u^i \rangle \left(D_{\bar{u}}^{h'} - D_u^{h'}\right) - \langle S_d^i \rangle \left(D_{\bar{d}}^{h'} - D_d^{h'}\right)\right]$$



$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu},\ \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

$$\mathcal{L} = 1\ \mathrm{ab}^{-1}$$

- ☐ The flat direction can be closed by combing more processes
- ☐ Photon dipole: O(0.01)
- ☐ Z-boson dipole: O(0.001)

总结

- 粒子物理研究物质最深层次的结构和最基本的相互作用
- 当前粒子物理最成功的理论是粒子物理标准模型
- 粒子物理目前仍然面临众多挑战

  暗物质的性质

  中微子的质量起源

  宇宙中观测到的正反物质不对称性

  电弱对称性的自发破缺机制
- 标准模型电弱精确检验、顶夸克和希格斯物理等将是寻找超出标准模型新物理的重要探针