COMPLEMENTARY CONSTRAINTS ON $Zb\bar{b}$ COUPLING AT THE LHC

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arXiv: 2306.15109

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Background: A persistent discrepancy in $Zb\bar{b}$ coupling

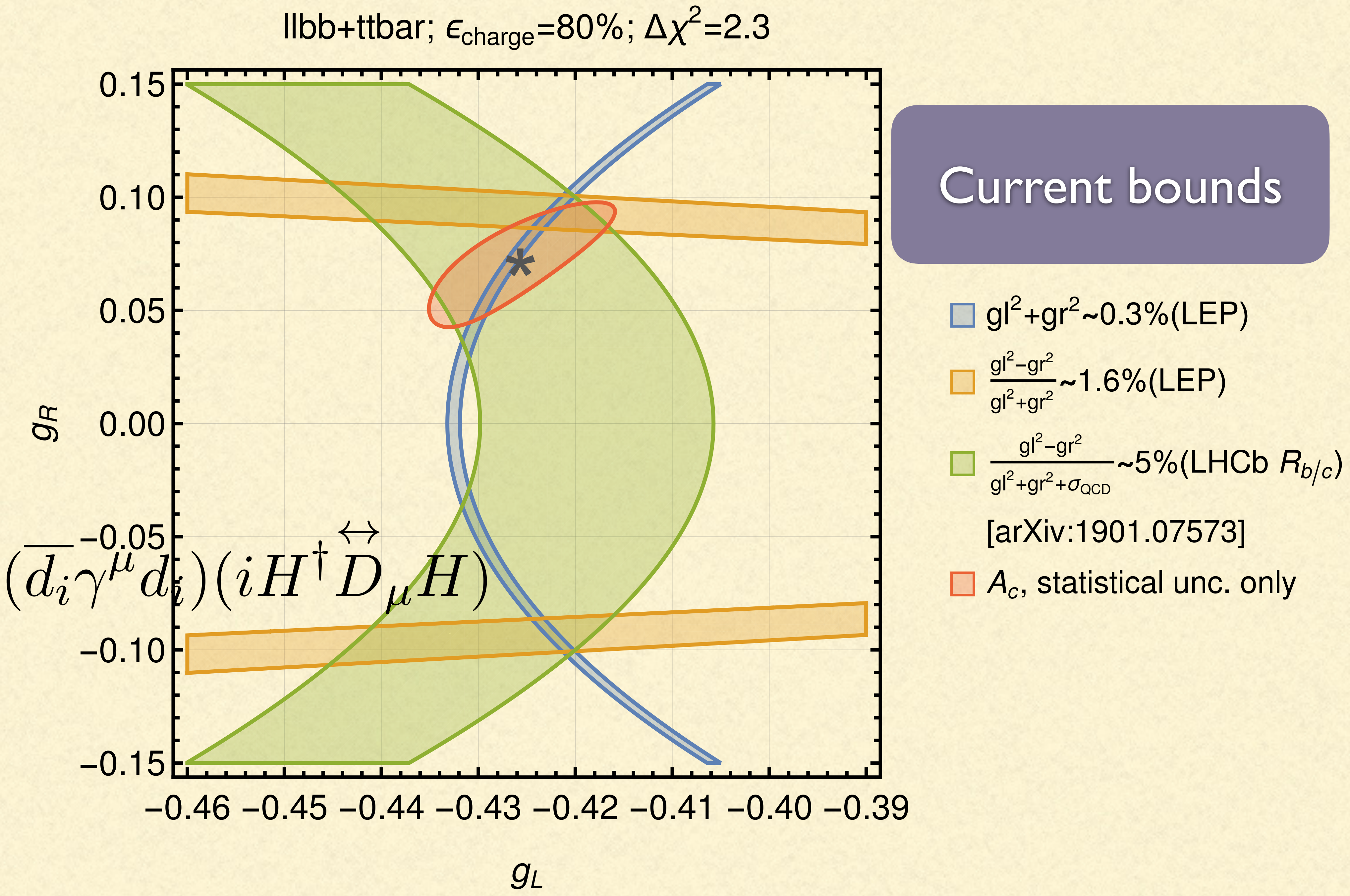
L,R $Zb\bar{b}$ Coupling and the SM prediction:

$$\mathcal{L}_{Zb\bar{b}} = \frac{-e}{s_W c_W} Z_\mu (g_L \bar{b}_R \gamma^\mu b_L + g_R \bar{b}_L \gamma^\mu b_R)$$

$$g_{L,SM} = -1/2 + s_W^2/3 \qquad g_{R,SM} = s_W^2/3$$

$$\mathscr{L} \supset c^{(1)}_{\varphi q,i}\,(\overline{Q}_i\gamma^\mu Q_i)(iH^\dagger \overleftrightarrow{D}_\mu H) + c^{(3)}_{\varphi q,i}\,(\overline{Q}_i\sigma^a\gamma^\mu Q_i)(iH^\dagger \overleftrightarrow{D}^a_\mu H) + c_{\varphi d,i}\,(\overline{d}_i\gamma^\mu d_i)(iH^\dagger \overleftrightarrow{D}_\mu H)$$

$$\delta g_{b,L} = -\frac{1}{2\sqrt{2}G_F}\left(c^{(1)}_{\varphi q,3} + c^{(3)}_{\varphi q,3}\right), \quad \delta g_{b,R} = -\frac{1}{2\sqrt{2}G_F} c_{\varphi d,3}$$



Current bounds

Symmetric / asymmetric observable

$$(\text{LEP}) \quad \frac{\sigma_Q^{inc}}{\sigma_q^{inc}} = R_Q \propto (g_{Q,L}^2 + g_{Q,R}^2)$$

$$(\text{LEP}) \quad \frac{\sigma^A}{\sigma^{inc}} = A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)(g_{e,L}^2 - g_{e,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2)(g_{e,L}^2 + g_{e,R}^2)}$$

$$(\text{Tevatron, LHCb}) \quad A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2) + \sigma_{\text{QCD}}}$$

$$\delta R_Q \sim g_{Q,L}\delta g_{Q,L} + g_{q,R}\delta g_{q,R}$$

$$\delta A_{FB}(\text{LEP}) \sim \frac{4g_{Q,L}^2 g_{Q,R}^2}{g_{Q,L}^2 + g_{Q,R}^2}\left(\frac{\delta g_{Q,L}}{g_{Q,L}} - \frac{\delta g_{q,R}}{g_{q,R}}\right)$$

$$\delta A_{FB}(\text{LHCb}) \sim \frac{2}{\sigma_{\text{QCD}}}(g_{Q,L}\delta g_{Q,L} - g_{q,R}\delta g_{q,R}) \ (\text{for } \sigma_{\text{QCD}} \gg \sigma_Z),$$

For small deviation, R_Q and A_{FB} give orthogonal bounds

Background: A persistent discrepancy in $Zb\bar{b}$ coupling?

- discrepancy evolution over the years

	SM fit	EXP. EXTRACTION	PULL
LEP, SLD EWPD 2011	0.1038	0.0992 ± 0.0016	2.9
JHEP 01 (2017) 053	0.1038	0.0996 ± 0.0016	2.6
EUR.PHYS.J.C 78 (2018) GFITTER	0.1030	0.0992 ± 0.0016	2.4
PHYS.REV.D 106 (2022) HEPFIT	0.10315	0.0996 ± 0.0016	2.2
PDG2022 REV	0.1029	0.0996 ± 0.0016	2.0

- New physics interpretations over the years

D. Choudhury, T. M. P. Tait and C. E. M. Wagner, *Beautiful mirrors and precision electroweak data*, *Phys. Rev. D* **65** (2002) 053002 [hep-ph/0109097].

X.-G. He and G. Valencia, *A**b(FB) and R(b) at LEP and new right-handed gauge bosons*, *Phys. Rev. D* **68** (2003) 033011 [hep-ph/0304215].

K. Cheung, W.-Y. Keung, C.-T. Lu and P.-Y. Tseng, *Vector-like Quark Interpretation for the CKM Unitarity Violation, Excess in Higgs Signal Strength, and Bottom Quark Forward-Backward Asymmetry*, *JHEP* **05** (2020) 117 [2001.02853].

A. Crivellin, C. A. Manzari, M. Alguero and J. Matias, *Combined Explanation of the Zbb Forward-Backward Asymmetry, the Cabibbo Angle Anomaly, and* $\tau \to \mu\nu\nu$ *and* $b \to s\ell\ell$ *Data*, *Phys. Rev. Lett.* **127** (2021) 011801 [2010.14504].

K. Agashe, R. Contino, L. Da Rold and A. Pomarol, *A Custodial symmetry for* $Zb\bar{b}$, *Phys. Lett. B* **641** (2006) 62 [hep-ph/0605341].

D. Liu, J. Liu, C. E. M. Wagner and X.-P. Wang, *Bottom-quark Forward-Backward Asymmetry, Dark Matter and the LHC*, *Phys. Rev. D* **97** (2018) 055021 [1712.05802].

L. Da Rold, *Solving the* A^b_{FB} *anomaly in natural composite models*, *JHEP* **02** (2011) 034 [1009.2392].

E. Alvarez, L. Da Rold and A. Szynkman, *A composite Higgs model analysis of forward-backward asymmetries in the production of tops at Tevatron and bottoms at LEP and SLC*, *JHEP* **05** (2011) 070 [1011.6557].

E. C. Andrés, L. Da Rold and I. A. Davidovich, *Beautiful mirrors for a pNGB Higgs*, *JHEP* **03** (2016) 152 [1509.04726].

- QCD higher order with m_b effects
- Including LHC data drives the main input α_s and m_t accurate (down)

Background: A persistent discrepancy in $Zb\bar{b}$ coupling

LEP(2.9σ) SLD(1σ) @ Z-pole: $e^-e^+ \to Z^* \to b\bar{b}$
[hep-ex/0509008] ,1407.3792

Tevatron/LHCb: $q\bar{q} \to Z^* \to b\bar{b}$
1504.06888,1505.02429, 1504.02493, 1901.07573

Future Proposal e^-e^+ collider:1508.07010, 2107.02134
HL-LHC processes: 2101.06261 ($gg \to Zh$)

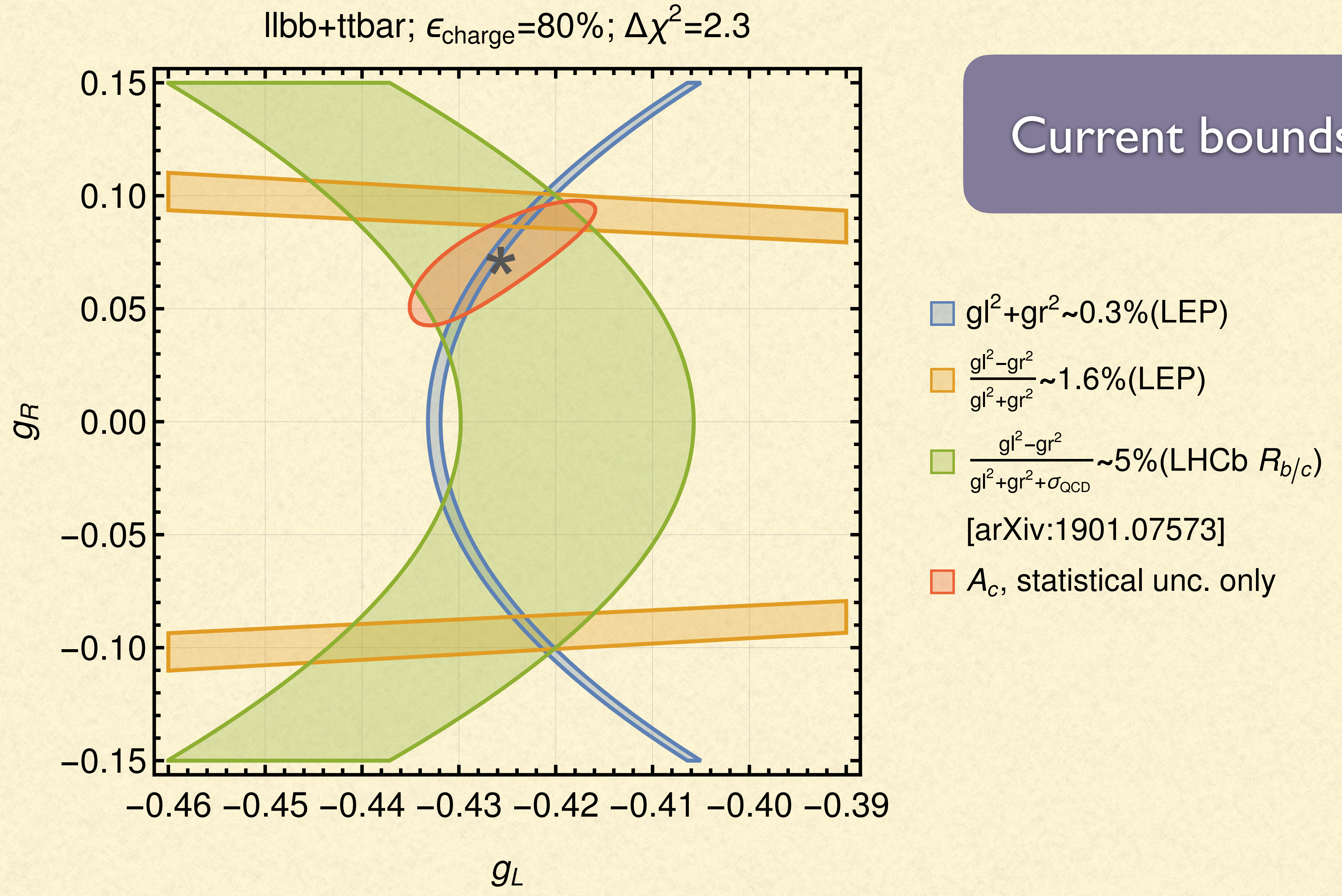
Symmetric / Asymmetric observable @$\sqrt{s} \approx m_z$

$$\text{(LEP)} \quad \frac{\sigma_Q^{inc}}{\sigma_q^{inc}} = R_Q \propto (g_{Q,L}^2 + g_{Q,R}^2)$$

$$\text{(LEP)} \quad \frac{\sigma^A}{\sigma^{inc}} = A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)(g_{e,L}^2 - g_{e,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2)(g_{e,L}^2 + g_{e,R}^2)}$$

$$\text{(Tevatron, LHCb)} \quad A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2) + \sigma_{\rm QCD}}$$

$$\text{(LHCb)} \quad R_{b/c} \propto A_b/A_c$$



Current bounds

With Z-pole data only, gL, gR sign degeneracy is unbroken.

Existing Bounds and Limitation:

Sign determination of (g_L^b , g_R^b) at LEP

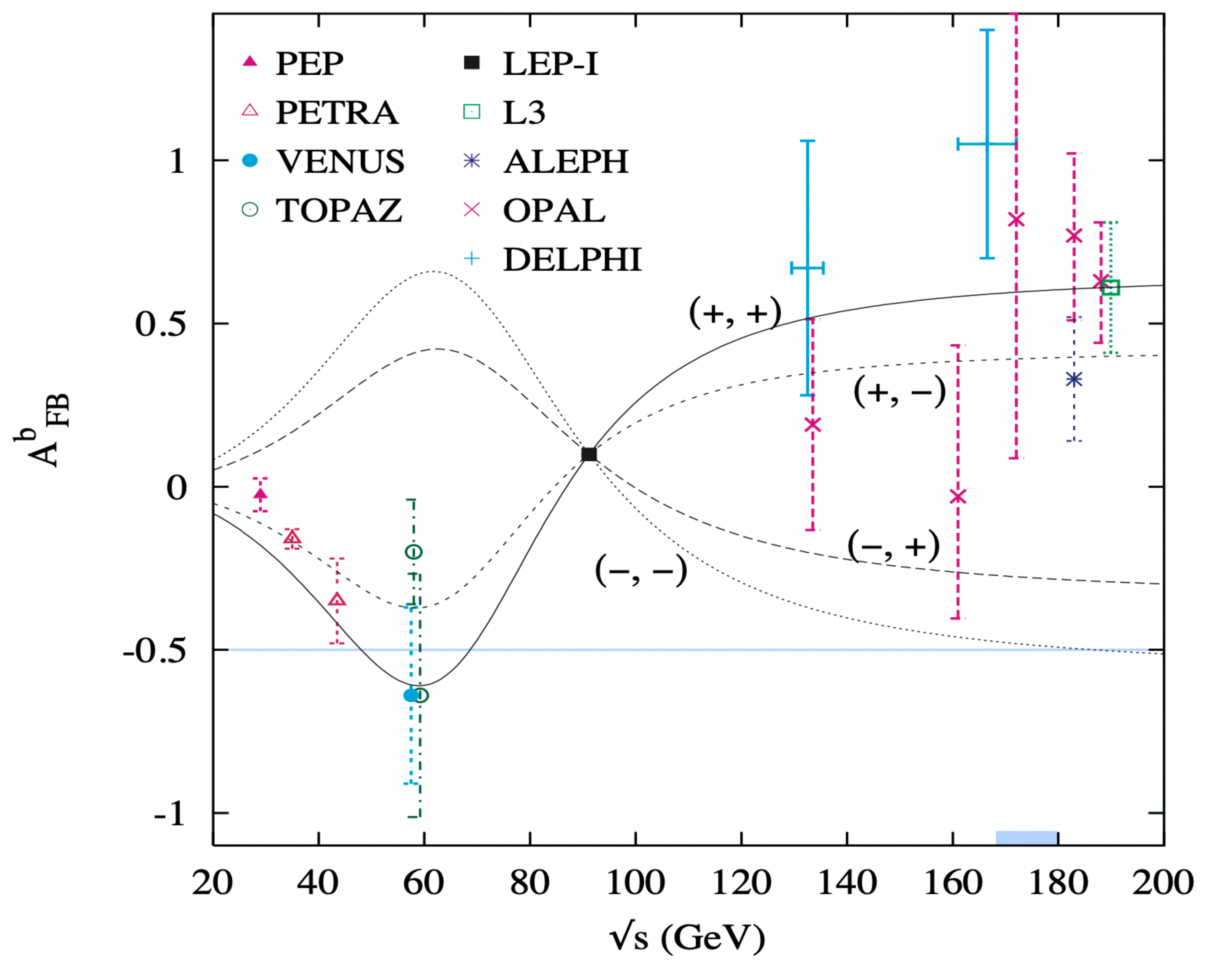
LEP/SLD (e^+e^- collider): A_{FB} ($\sim 3\sigma$) , A_b ($\sim 1\sigma$)

- limited off-Z-pole data
- g_L sign determined, g_R sign degenerate

A_{FB}^b : forward-backward asymmetry

A_b: charge asymmetry from longitudinal polarized beams that mix g_L^e and g_R^e coupling.

$$\mathcal{A}_b = \frac{g_{Lb}^2 - g_{Rb}^2}{g_{Lb}^2 + g_{Rb}^2}\,, \qquad A_{\rm FB}^{0,b} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b = \frac{3}{4}\frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2}\frac{g_{Lb}^2 - g_{Rb}^2}{g_{Lb}^2 + g_{Rb}^2}\,.$$



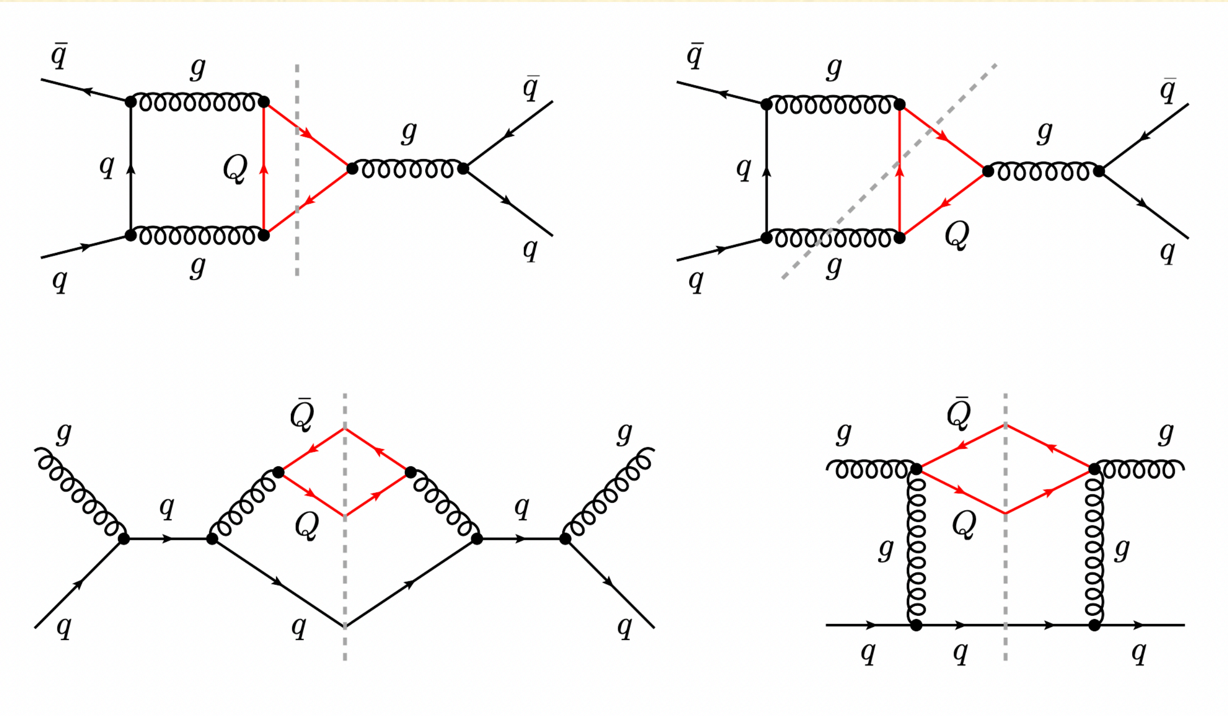
Hep-ph/0109097

Existing Bounds and Limitation:

Tevatron ($p\bar{p}$ collision): $A_{FB}^{b\bar{b}}$

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad \Delta y = y_b - y_{\bar{b}}$$

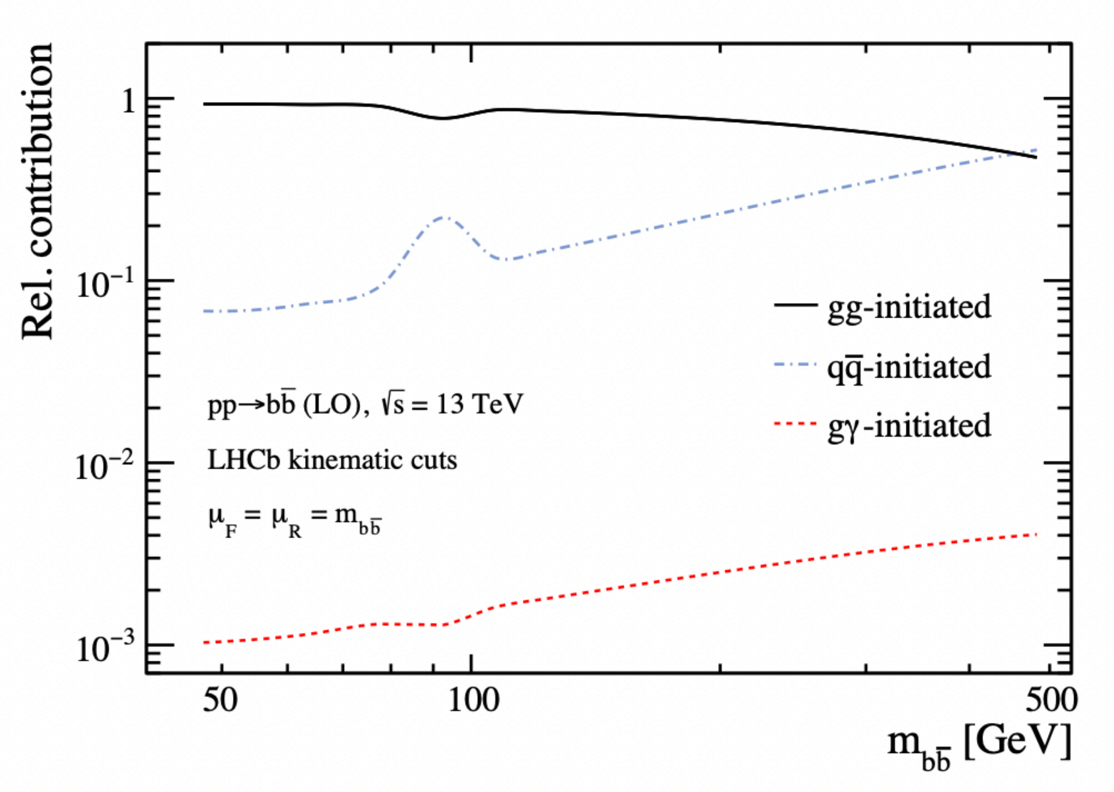
- $q\bar{q} \to b\bar{b}$ dominated,
- NLO QCD contribution at high mass bins $\longrightarrow$ $A_{FB}^{Q\bar{Q}}$ arise at NLO QCD $\longrightarrow$
- Negligible QCD-EW interference

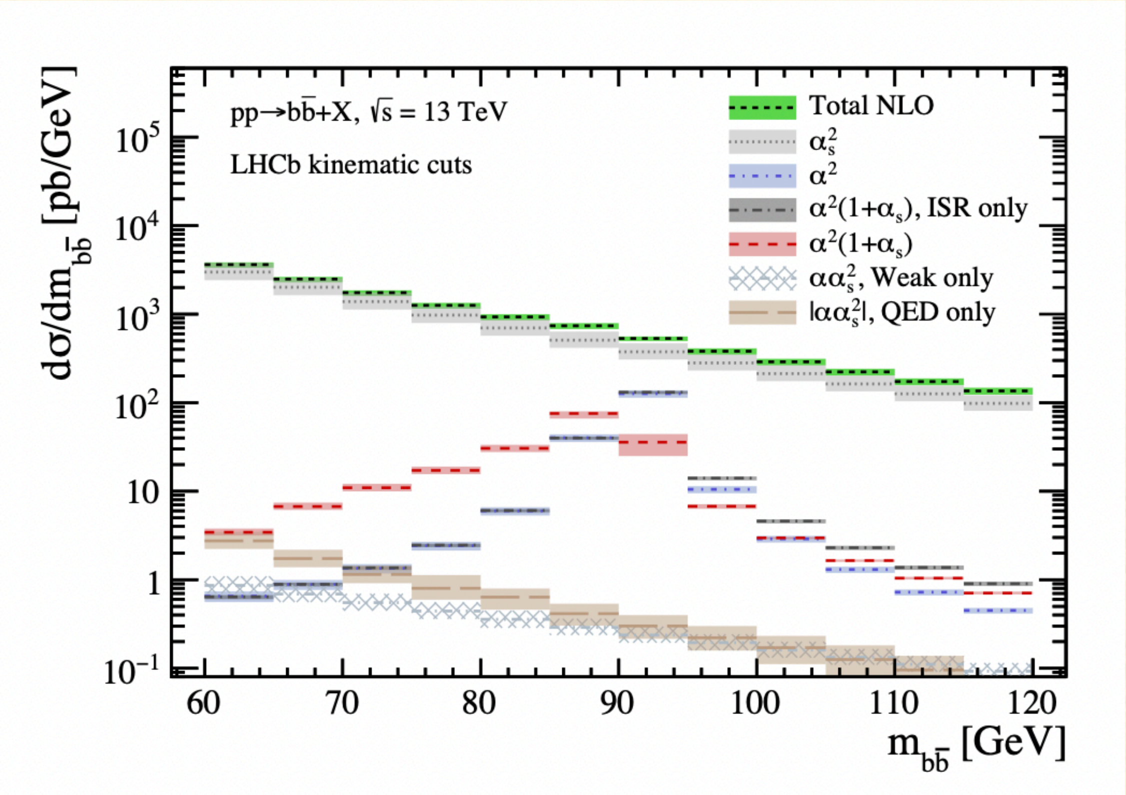


Bin	$\mathcal{O}(\alpha^2/\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha)$	$A_{FB}^{b\bar{b}}[\%]$
$35 \le M_{b\bar{b}}/\mathrm{GeV} < 75$	$0.00^{+0.00}_{-0.00}$	$0.20^{-0.01}_{+0.01}$	-0.01	$0.19 \pm 0.06\ ^{-0.01}_{+0.01}$
$75 \le M_{b\bar{b}}/\mathrm{GeV} < 95$	$2.01^{+0.54}_{-0.47}$	$0.52^{-0.02}_{+0.03}$	-0.05	$2.49 \pm 0.16\ ^{+0.52}_{-0.44}$
$95 \le M_{b\bar{b}}/\mathrm{GeV} < 130$	$0.56^{+0.17}_{-0.14}$	$0.89^{-0.02}_{+0.02}$	-0.01	$1.44 \pm 0.27\ ^{+0.16}_{-0.12}$
$130 \le M_{b\bar{b}}/\mathrm{GeV}$	$0.15^{+0.05}_{-0.04}$	$2.11^{-0.07}_{+0.08}$	-0.13	$2.14 \pm 0.63\ ^{-0.01}_{+0.03}$

C. Murphy 2015

Bin	$\mathcal{O}(\alpha^2/\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	$A_{FB}^{b\bar{b}}[\%]$
$40 \le M_{b\bar{b}}/\mathrm{GeV} < 75$	$0.00^{+0.00}_{-0.00}$	$0.46^{-0.03}_{+0.04}$	$0.46 \pm 0.14\ ^{-0.03}_{+0.04}$
$75 \le M_{b\bar{b}}/\mathrm{GeV} < 105$	$2.48^{+0.59}_{-0.52}$	$1.02^{-0.07}_{+0.08}$	$3.50 \pm 0.31\ ^{+0.52}_{-0.43}$
$105 \le M_{b\bar{b}}/\mathrm{GeV}$	$0.25^{+0.07}_{-0.06}$	$1.53^{-0.06}_{+0.09}$	$1.79 \pm 0.46\ ^{+0.01}_{+0.03}$





LHCb: $pp \to b\bar{b}$ R. Gauld et al 2019

LHCb (pp collision): $A_{FC}^{b\bar{b}}$ ($A_{C}^{b\bar{b}}$) $\quad \Delta y \equiv |y_b| - |y_{\bar{b}}|$

- $gg \to b\bar{b}$ dominated,
- Relatively larger $q\bar{q}$-initiated contribution in forward region
- Limited with systematics (missing higher order theory calc.)

$$\begin{aligned} A_{FB} &= A_u F_u + A_d F_d\,, \\ A_C &= A_u F_u D_u + A_d F_d D_d \end{aligned}$$

Sufficient off the Z-pole data, yet overwhelmed by QCD background.

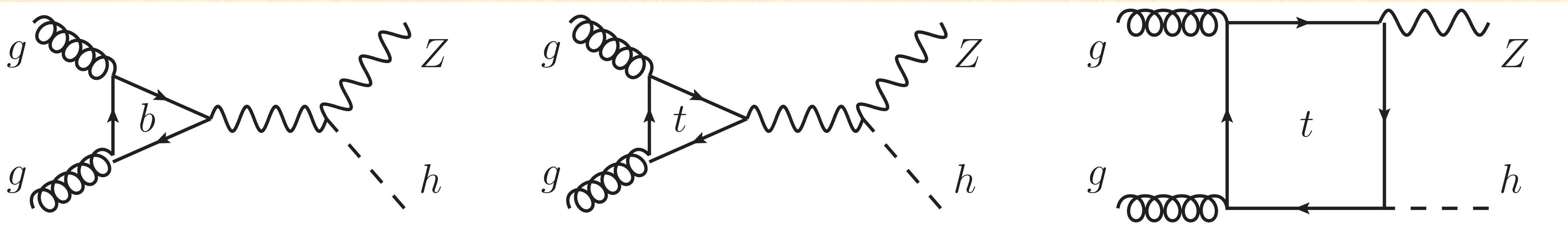
Existing Bounds and Limitation:

- S. Gori, J. Gu and L.-T. Wang, The Zbb couplings at future $e^+ e^-$ colliders, JHEP 04 (2016) 062 [1508.07010].

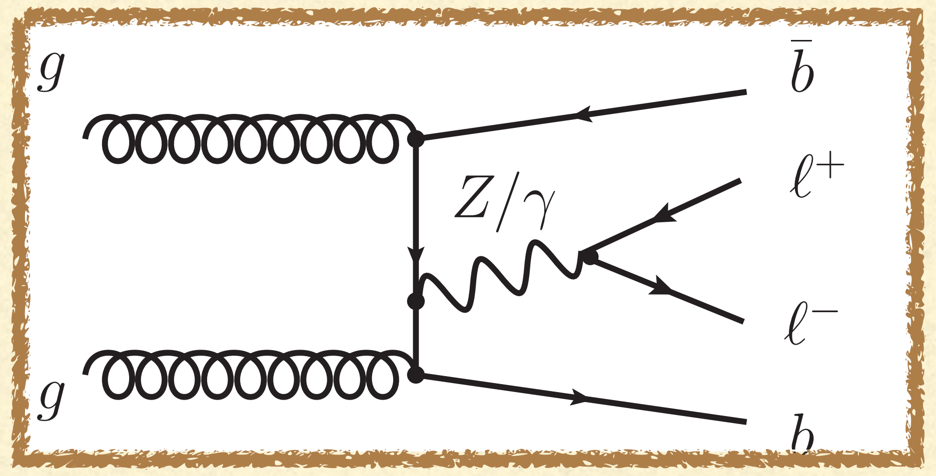
- B. Yan, Z. Yu and C. P. Yuan, The anomalous $Z b\bar{b}$ couplings at the HERA and EIC, Phys. Lett. B 822 (2021) 136697 [2107.02134].

- H. T. Li, B. Yan and C. P. Yuan, Jet Charge: A new tool to probe the anomalous $Z b\bar{b}$ couplings at the EIC, 2112.07747.

- B. Yan and C. P. Yuan, Anomalous $Zb\bar{b}$ Couplings: From LEP to LHC, Phys. Rev. Lett. 127 (2021) 051801 [2101.06261].
  (through b-quark loop contribution to $gg \to Zh$ rate)

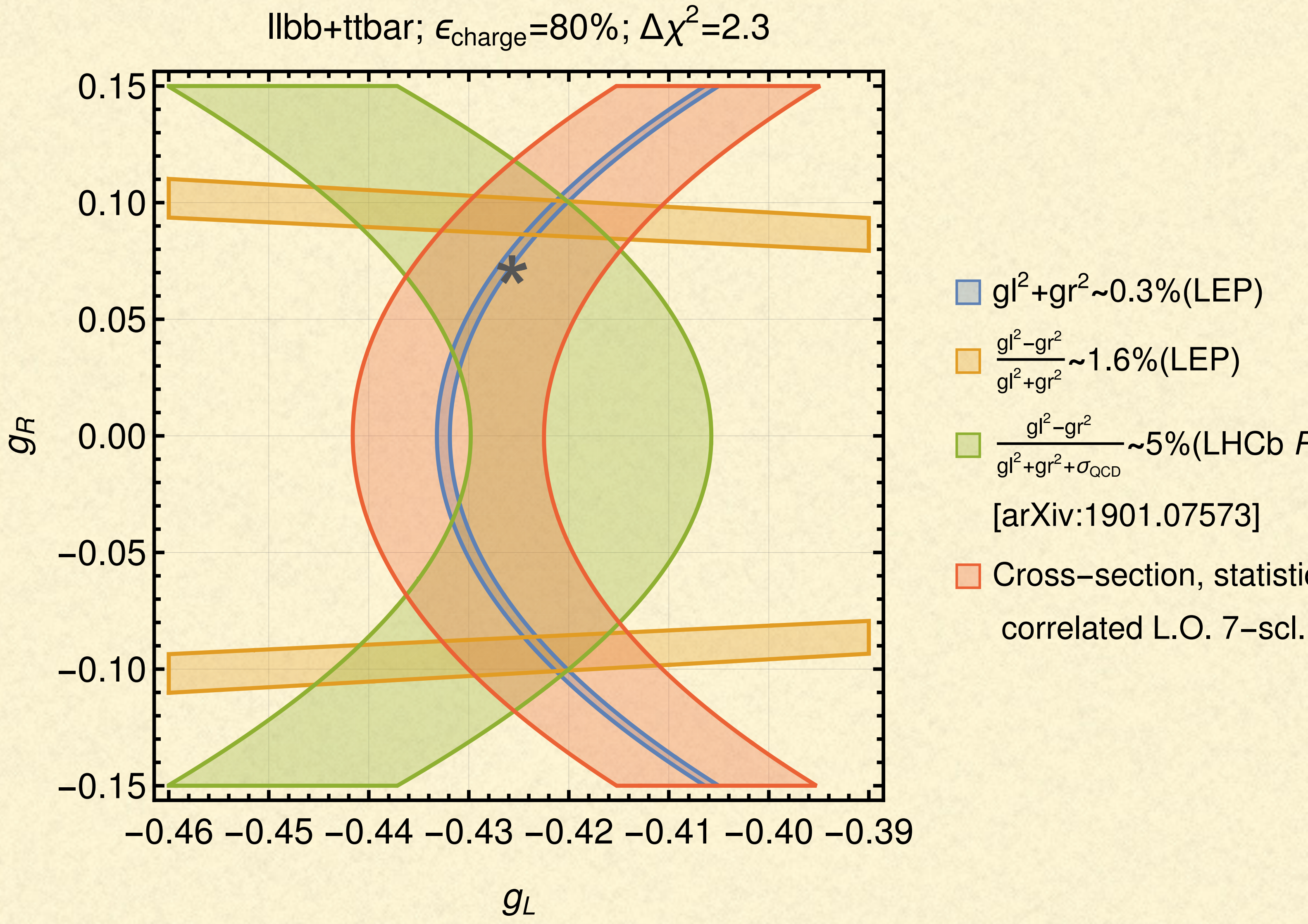


$gg \to b\bar{b}\ell^-\ell^+$ Process and Observable:



Symmetric cross section:

- $\sigma^{inc} \propto g_L^2 + g_R^2$
- Systematics dominant (>2-3%) not competitive with LEP (0.3%)



Asymmetric observable:

- In the $m_b \to 0$ limit, the Z-mediated channel:

$$g_L \to b_L, \bar{b}_R \to b(-), \bar{b}(+);\ \ g_R \to b_R, \bar{b}_L \to b(+), \bar{b}(-)$$

Chirality of the coupling $\{g_L, g_R\}$ flips with helicity/charge flipping

(* helicity is even harder to determine):

$$\mathcal{M}_L^{-+}(b, \bar{b}) = \mathcal{M}_R^{-+}(\bar{b}, b)$$

So, $\{g_L, g_R\}$ asymmetry <=> $\{b, \bar{b}\}$ charge asymmetric observable

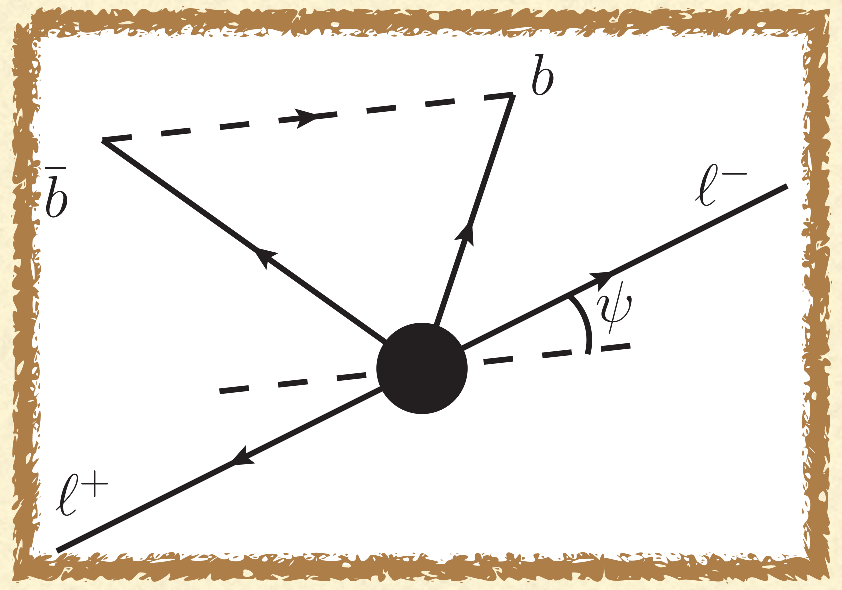
$\mathbf{gg \to b\bar{b}\ell^-\ell^+}$ Process and Observable:

- Similar to the LEP process: Polarisation summed $\overline{|\mathscr{M}|}^2(\ell^-\ell^+ \to Z^*/\gamma^* \to b\bar{b})$:

$$|\mathcal{M}|^2 = |\mathcal{M}_S|^2(p_b, p_{\bar{b}}, p_{\ell^-}, p_{\ell^+})$$
$$\left(\frac{1}{m_{\ell\ell}^4} + \frac{9/4}{\sin\theta_W^4 \cos\theta_W^4}\frac{(g_{Q,L}^2+g_{Q,R}^2)(g_{e,L}^2+g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2} + \frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}+g_{Q,R})(g_{e,L}+g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}\right)$$
$$+ |\mathcal{M}_A|^2(p_b, p_{\bar{b}}, p_{\ell^-}, p_{\ell^+})$$
$$\left(\frac{9/4}{\sin\theta_W^4 \cos\theta_W^4}\frac{(g_{Q,L}^2-g_{Q,R}^2)(g_{e,L}^2-g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2} + \frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}-g_{Q,R})(g_{e,L}-g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}\right).$$

- After integrating over gluons, the $\{g_L, g_R\}$ asymmetric term is proportional to,

$$(p_b - p_{\bar{b}}).(p_{l^-} - p_{l^+})$$



- Define Asym in the Z^* $(m_{\ell\ell})$ rest frame: $sign(cos\psi)$ between $\vec{p}_b - \vec{p}_{\bar{b}}$ and $\vec{p}_{\ell^-}$

$sign(cos\psi)$: whether $b/\bar{b}$ is closer to ℓ^-(Forward) direction

$\mathbf{gg \to b\bar{b}\ell^-\ell^+}$ Process and Observable:

- Off-shell through $m_{\ell\ell}$ spectra

$$\frac{d\sigma_\gamma}{dm_{\ell\ell}} = F(m_{\ell\ell})\frac{1}{m_{\ell\ell}^4}$$

$$\frac{d\sigma_Z}{dm_{\ell\ell}} = F(m_{\ell\ell})\frac{9/4}{(\sin\theta_W^2\cos\theta_W^2)^2}\frac{(g_{Q,L}^2+g_{Q,R}^2)(g_{e,L}^2+g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2}$$

$$\frac{d\sigma_{\rm int}}{dm_{\ell\ell}} = F(m_{\ell\ell})\frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}+g_{Q,R})(g_{e,L}+g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}.$$

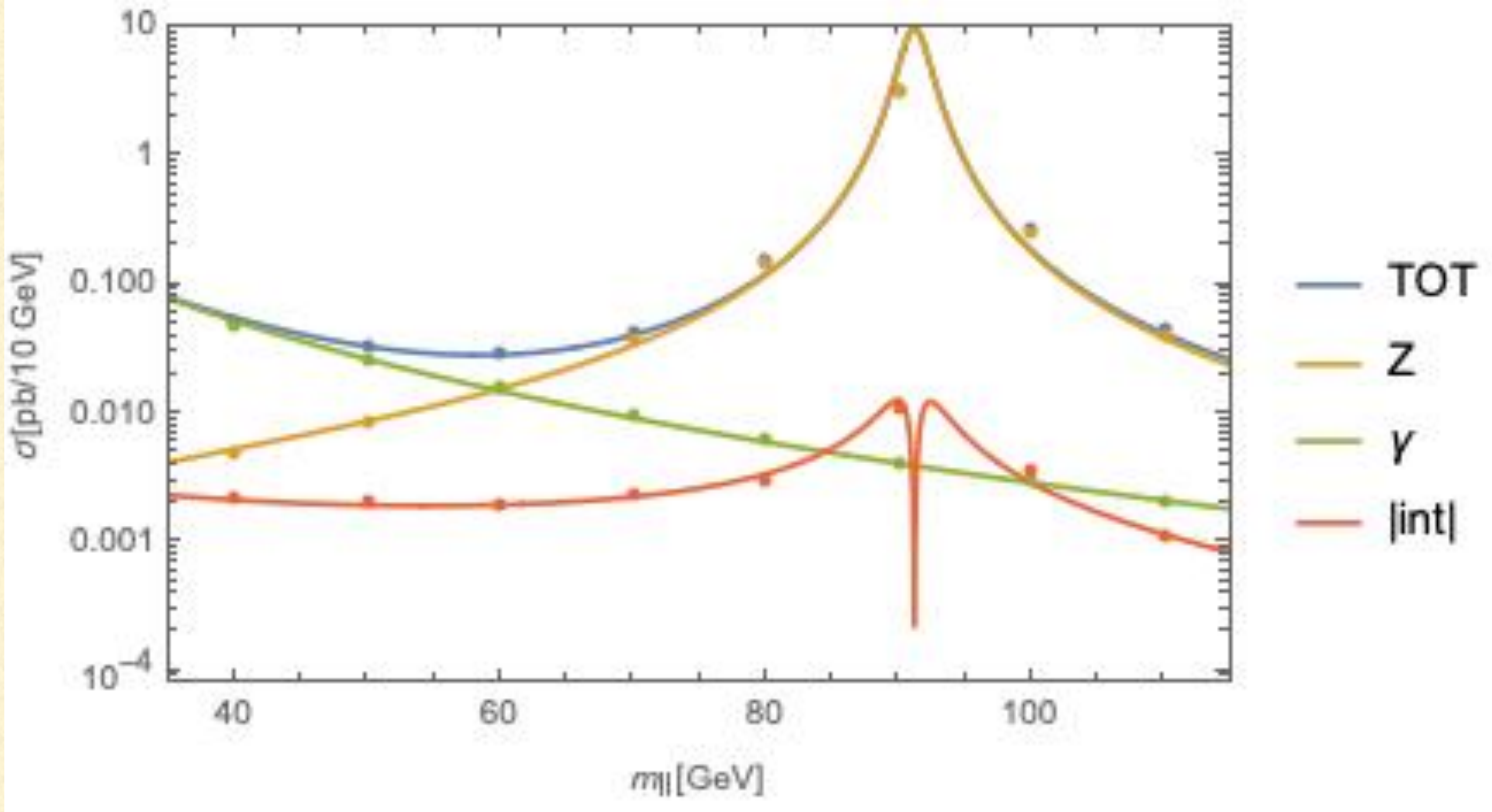
$$\frac{d\sigma_\gamma^A}{dm_{\ell\ell}} = 0$$

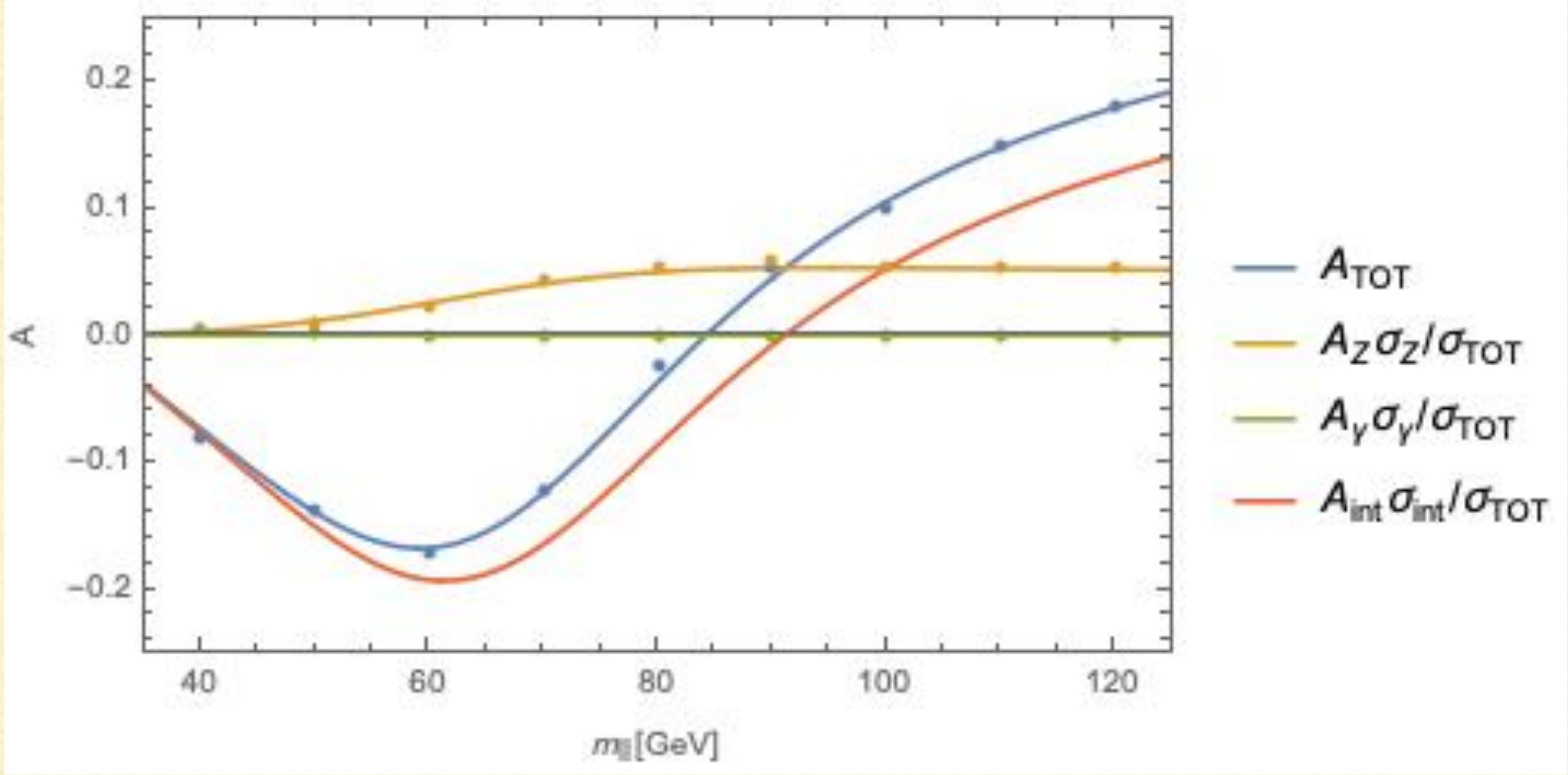
$$\frac{d\sigma_Z^A}{dm_{\ell\ell}} = G(m_{\ell\ell})\frac{9/4}{(\sin\theta_W^2\cos\theta_W^2)^2}\frac{(g_{Q,L}^2-g_{Q,R}^2)(g_{e,L}^2-g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2}$$

$$\frac{d\sigma_{\rm int}^A}{dm_{\ell\ell}} = G(m_{\ell\ell})\frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}-g_{Q,R})(g_{e,L}-g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}$$

$$A(m_{\ell\ell}) = \frac{d\sigma_{tot}^A}{d\sigma_{tot}} = \frac{d\sigma_\gamma^A+d\sigma_Z^A+d\sigma_{\rm int}^A}{d\sigma_\gamma+d\sigma_Z+d\sigma_{\rm int}},$$

$\boxed{\gamma, Z \text{ and int contribution } gg \to Zb\bar{b}, Z \to \ell^-\ell^+}$





Simulation and Fits

- Benchmark fit $pp \to b\bar{b}\ell^-\ell^+$ with LO simulation

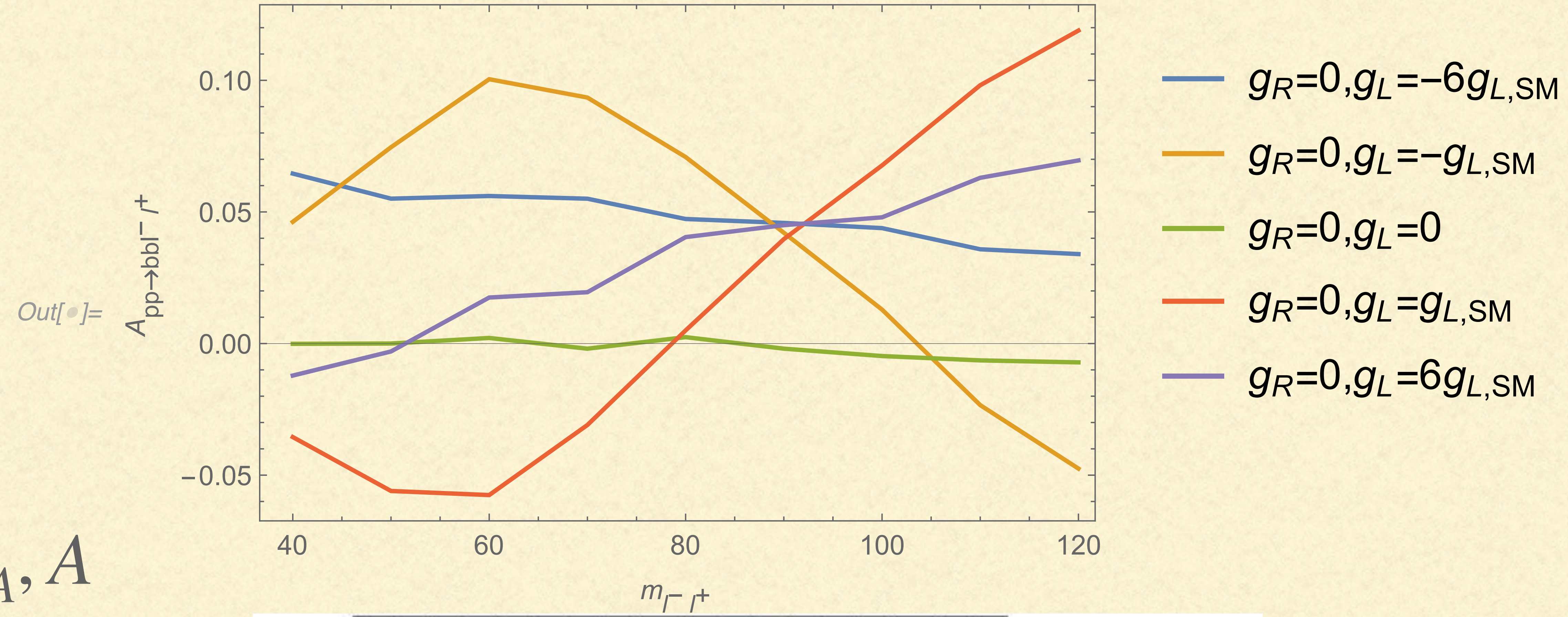
$$\sigma = A + B(g_L + g_R) + C(g_L^2 + g_R^2)$$
$$\sigma^A = D + E(g_L + g_R) + F(g_L^2 + g_R^2)$$

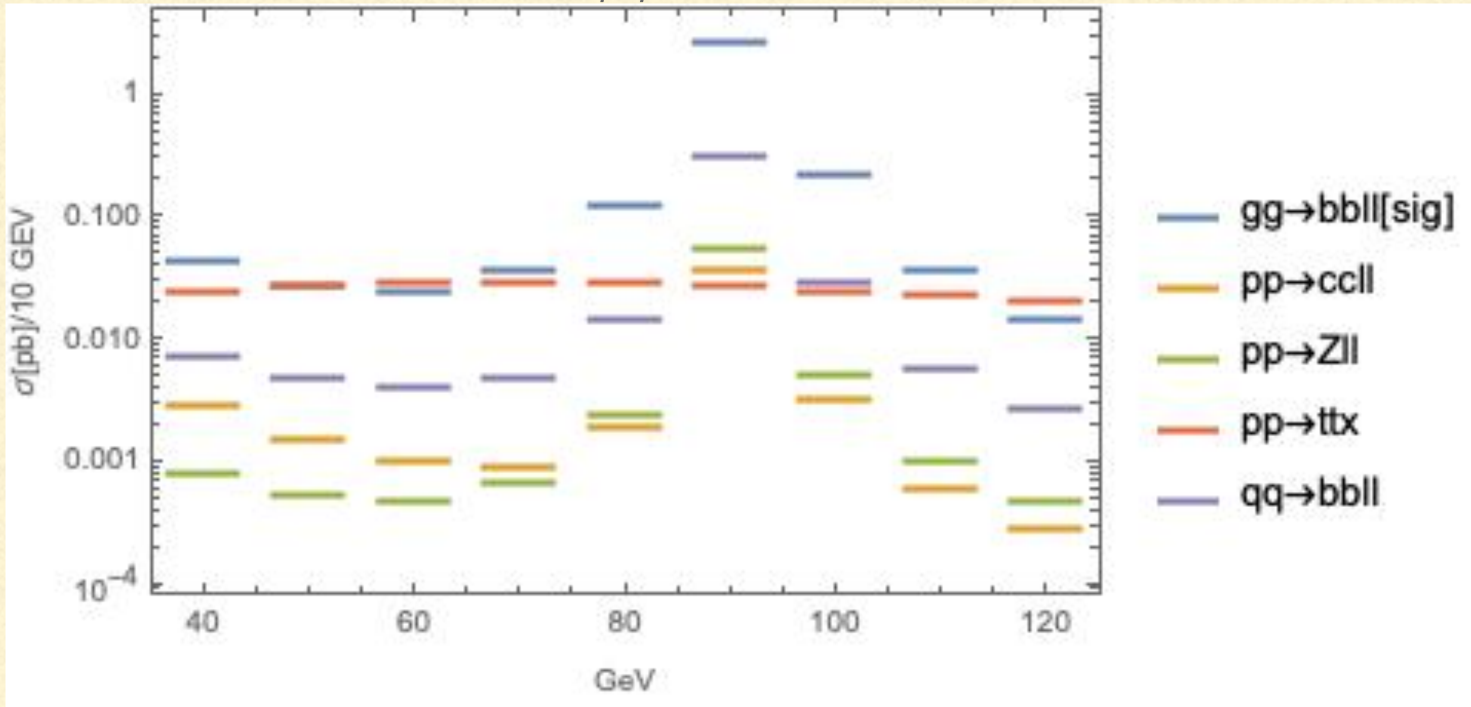
- Parton analysis for 10 GeV bin from 35-125 GeV: σ, σ_A, A
- Total Asymmetry contribution $\quad A_p = \dfrac{\sum_c A_c \sigma_c}{\sum_c \sigma_c}$
- (Charge) Tagging efficiency: $\quad A_{obs} = \dfrac{2\varepsilon_{charge} - 1}{1 - 2\varepsilon_{charge} + 2\varepsilon_{charge}^2} A_p$
- Basic Selection Cuts:

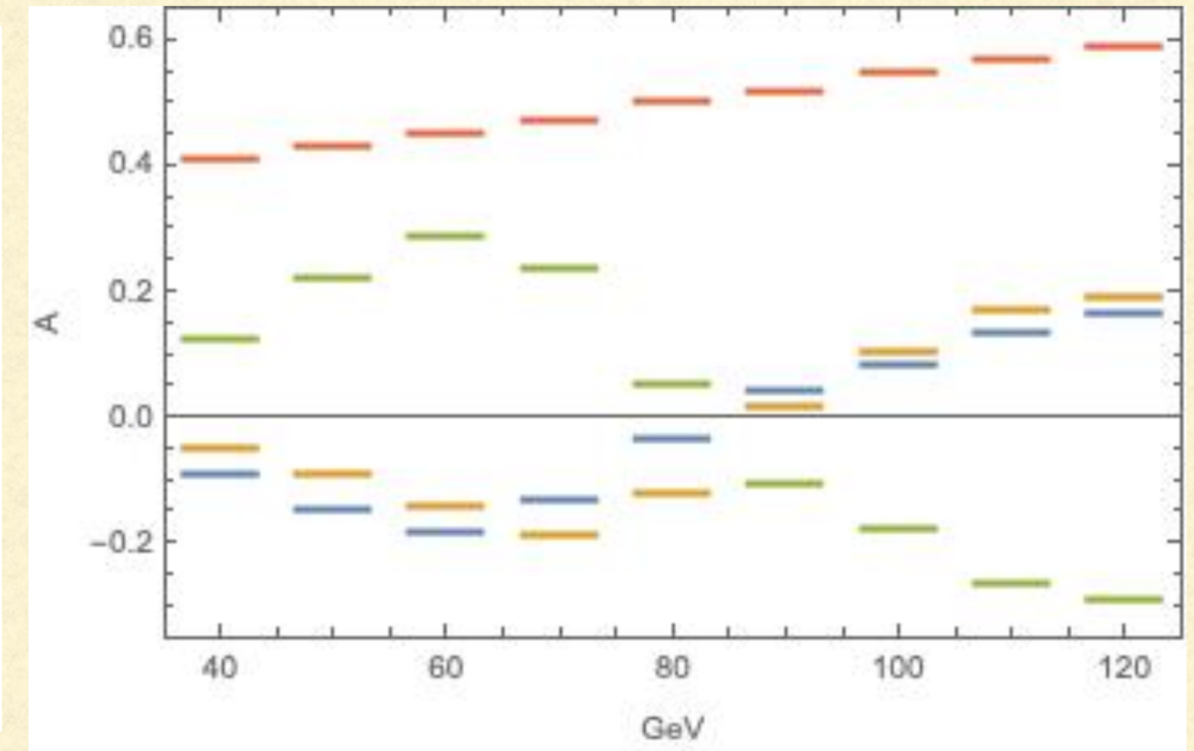
$$p_{T,bjet} > 20, p_\ell > 10 \text{ GeV and } |\eta|_{bjet,\ell} < 2.5$$

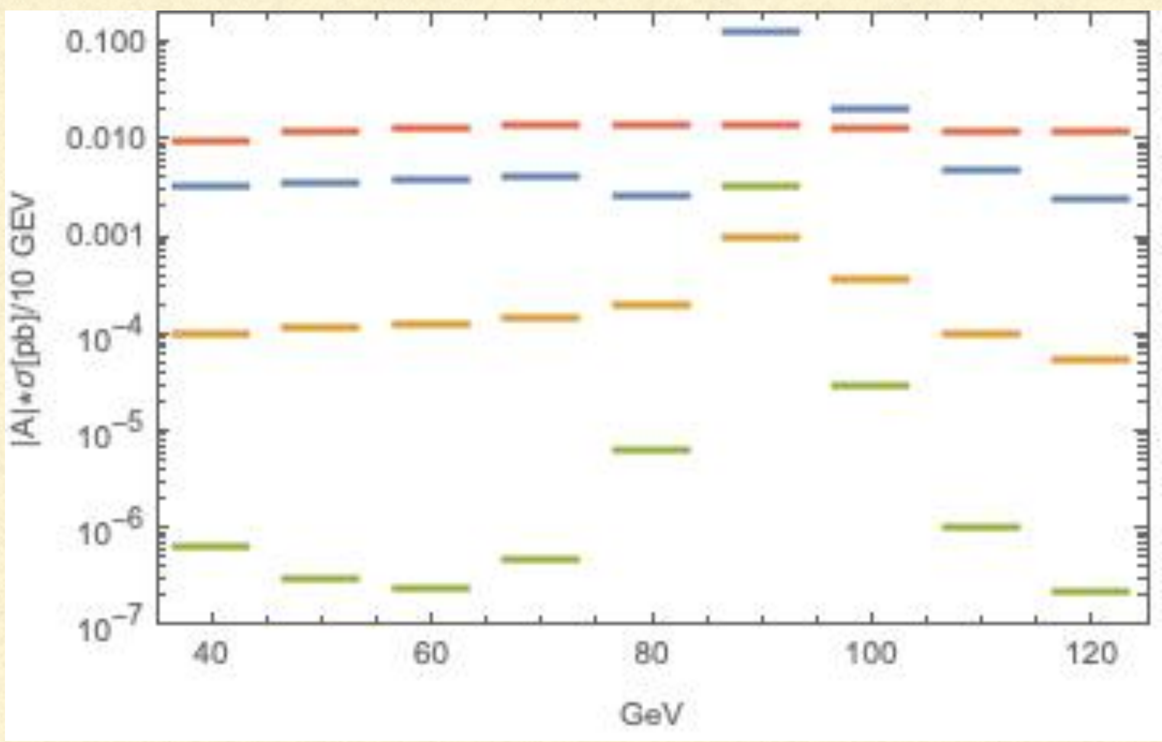
MET>30 GeV (for reducing $t\bar{t}$ background)

$t\bar{t}$ same flavor decay background is non-negligible!









Simulation and Fits

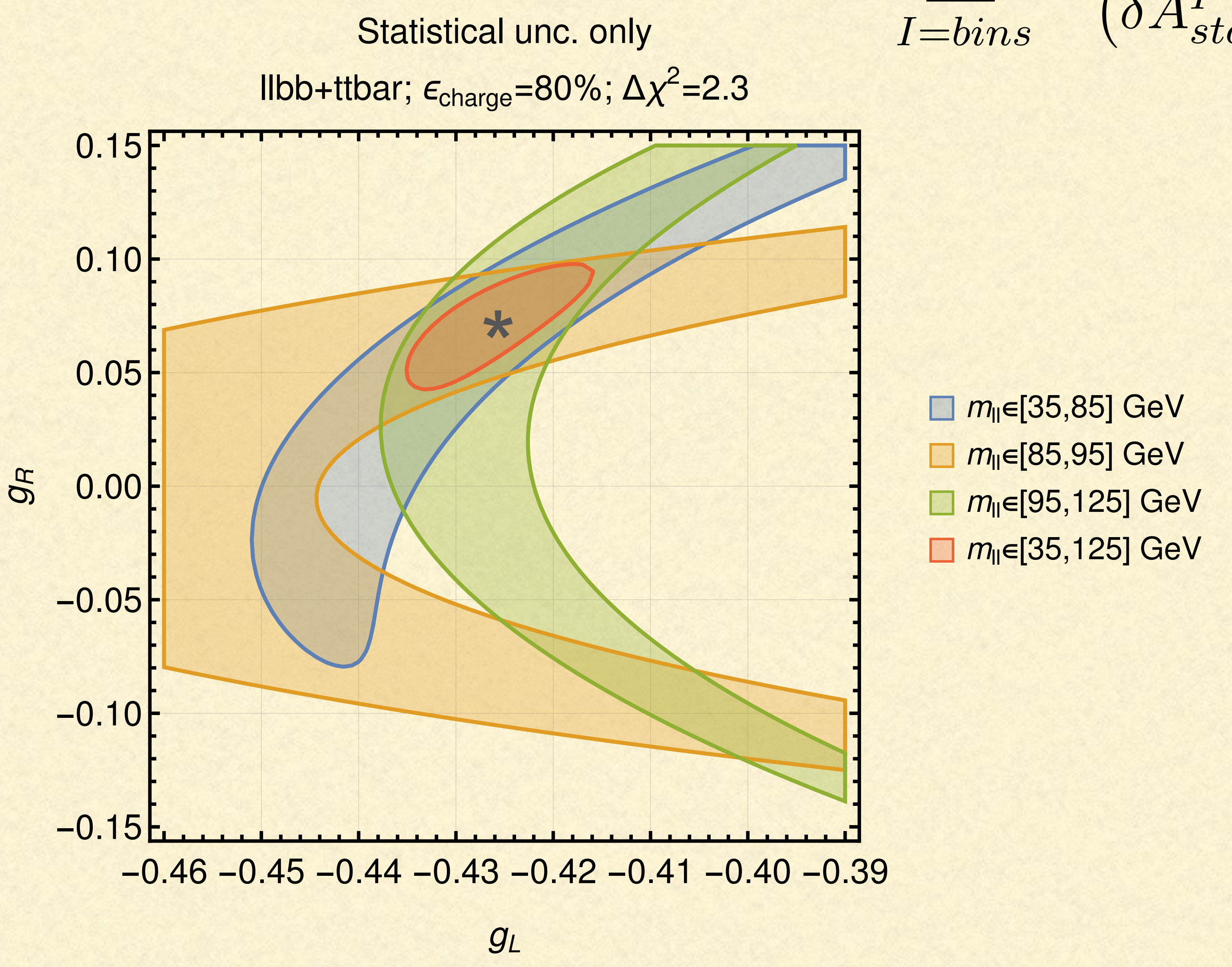
$$\chi^2 = \sum_{I=bins} \frac{\left(A^I_{obs}(g_L, g_R) - A^{I,SM}_{obs}\right)^2}{\left(\delta A^I_{stat}\right)^2 + \left(\delta A^I_{syst}\right)^2}.$$

Statistic error and results: A_{tot}

$$(\delta\sigma^{stat})^2 = \frac{(\sigma_{bbZ} + \sigma^{\rm SF}_{t\bar{t}})^2}{N}$$

$$A_{\rm SF} = \frac{\sigma^A_{\rm SF}}{\sigma_{\rm SF}} = \frac{A_{Zb\bar{b}}\sigma_{Zb\bar{b}} + A_{t\bar{t}}\sigma_{t\bar{t}}}{\sigma_{Zb\bar{b}} + \sigma_{t\bar{t}}}$$

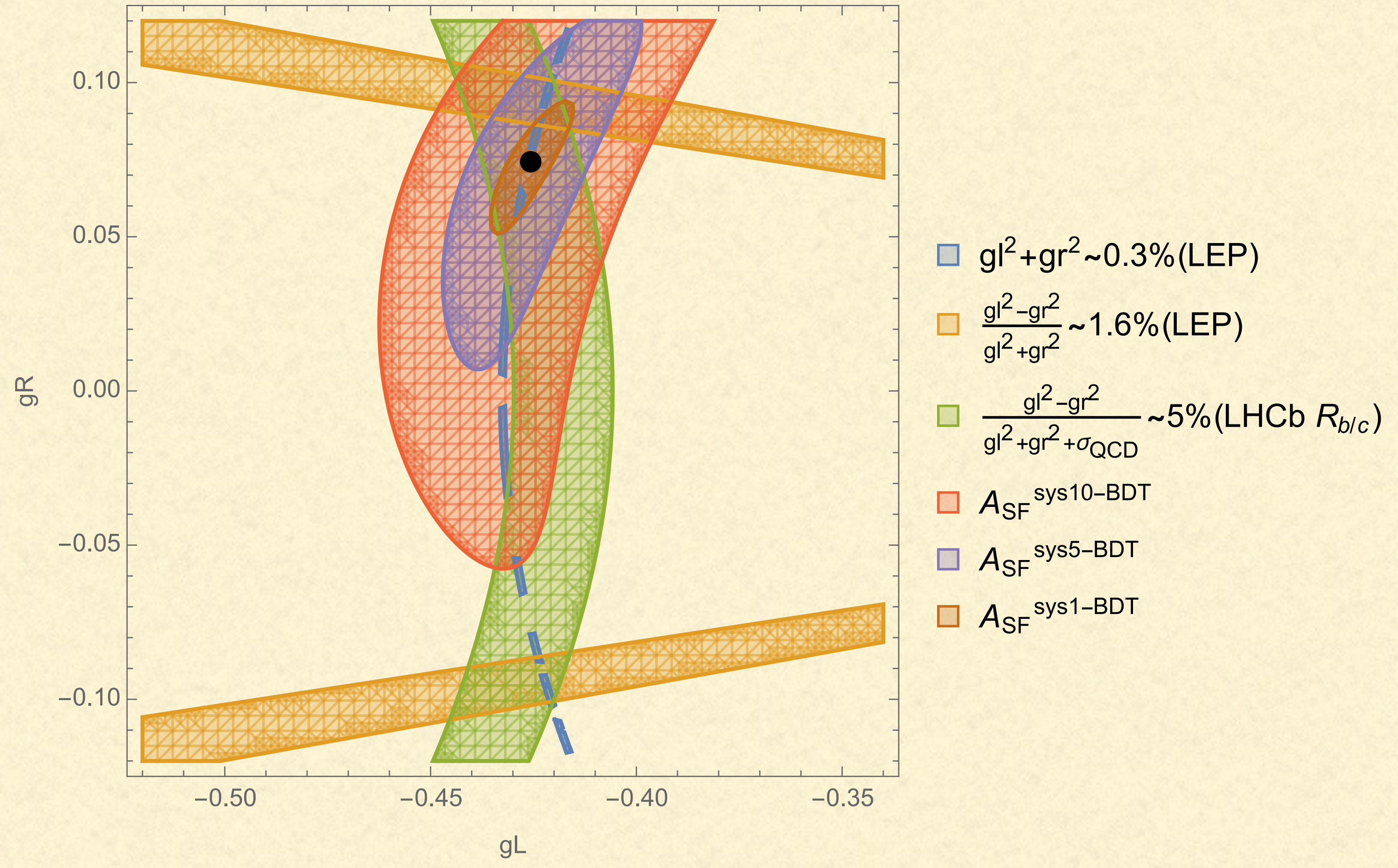
$$(\delta A^{\rm stat}_{\rm SF})^2 = \frac{1 - A^2_{SF}}{N_{SF}}$$



Low, High, Z-pole bins give complementary constraints

Including systematic error: A_{tot}

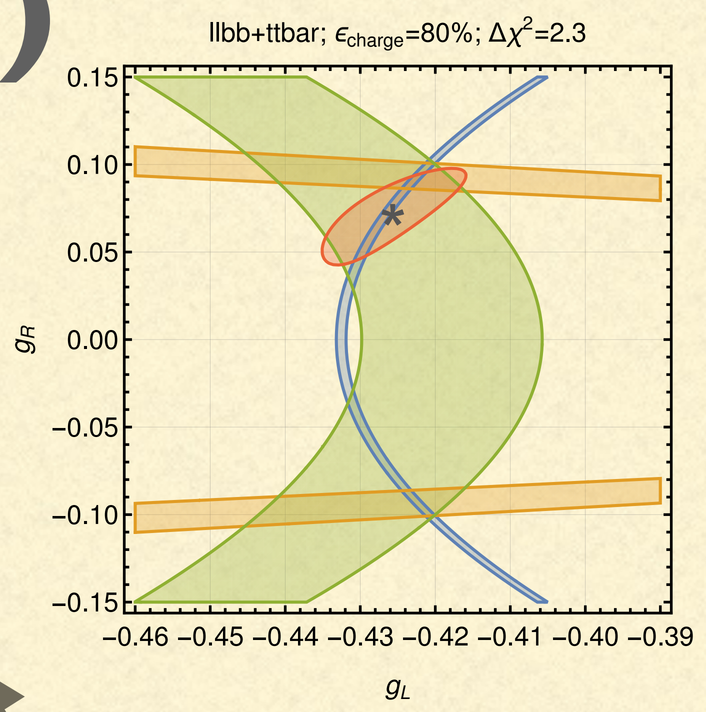
- Higher order correction ~5%,
- PDF ~4%, m_b correction <1%,
- Experimental (jet energy scale, tagging) ~6%

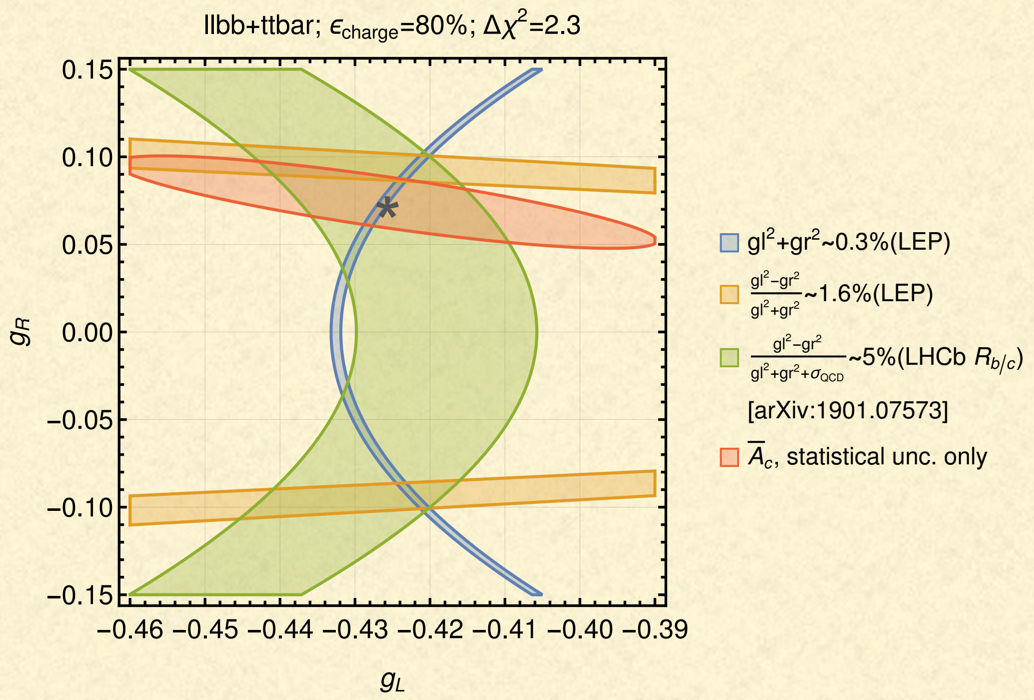


Alternative observable: subtracting $t\bar{t}$ (DF)

Different flavor $t\bar{t}$ ($b\bar{b}e\mu\nu\nu$: DF) as "sideband": $\bar{A}$

(Subtracting $t\bar{t}$-SF with $t\bar{t}$-DF)





$$\bar{\sigma} = \sigma_{\mathrm{SF}} - \sigma_{\mathrm{DF}} \approx \sigma_{bbZ} \quad (\delta\bar{\sigma}^{\mathrm{stat}})^2 = (\delta\sigma_{\mathrm{SF}}^{\mathrm{stat}})^2 + (\delta\sigma_{\mathrm{DF}}^{\mathrm{stat}})^2 = \frac{\sigma_{SF}^2}{N_{SF}} + \frac{\sigma_{DF}^2}{N_{DF}}$$

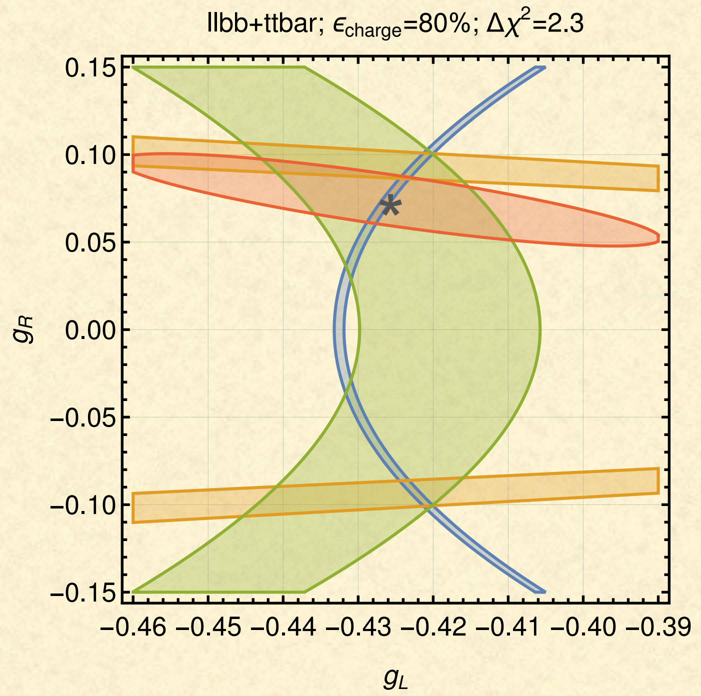
$$\bar{A} = \frac{\bar{\sigma}^A}{\bar{\sigma}} = \frac{(\sigma_{\mathrm{SF}}^+ - \sigma_{\mathrm{DF}}^+) - (\sigma_{\mathrm{SF}}^- - \sigma_{\mathrm{DF}}^-)}{(\sigma_{\mathrm{SF}}^+ + \sigma_{\mathrm{SF}}^-) - (\sigma_{\mathrm{DF}}^+ + \sigma_{\mathrm{DF}}^-)} \approx A_{Zb\bar{b}}$$

Worsened statistic

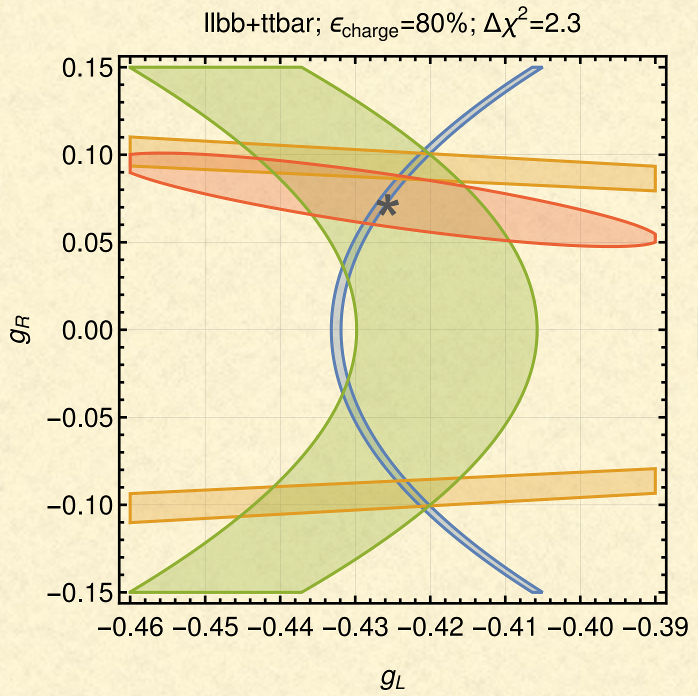
$$(\delta\bar{A}^{\mathrm{stat}})^2 = \frac{1}{N_{Zbb}} \frac{\sigma_{Zbb}(1 - A_{Zbb}^2) + \sigma_{t\bar{t}}(2 - 4A_{t\bar{t}}A_{Zbb} + 2A_{Zbb}^2)}{\sigma_{Zbb}}$$

Improved systematics

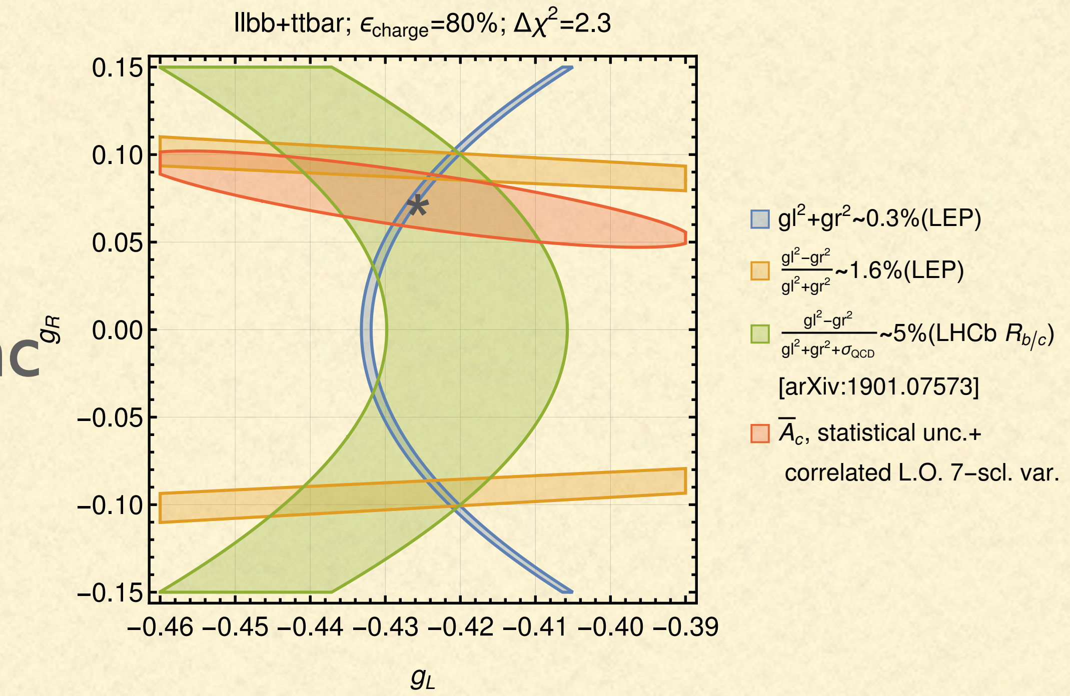
$$\delta\bar{\sigma}^{\mathrm{sys}} \approx \delta\sigma_{bbZ}^{\mathrm{sys}} \gg \delta\bar{\sigma}^{\mathrm{stat}} \qquad \delta\bar{A}^{sys} = \delta A_Z^{sys}$$



Stat. Only



LO Sys/2. Inc

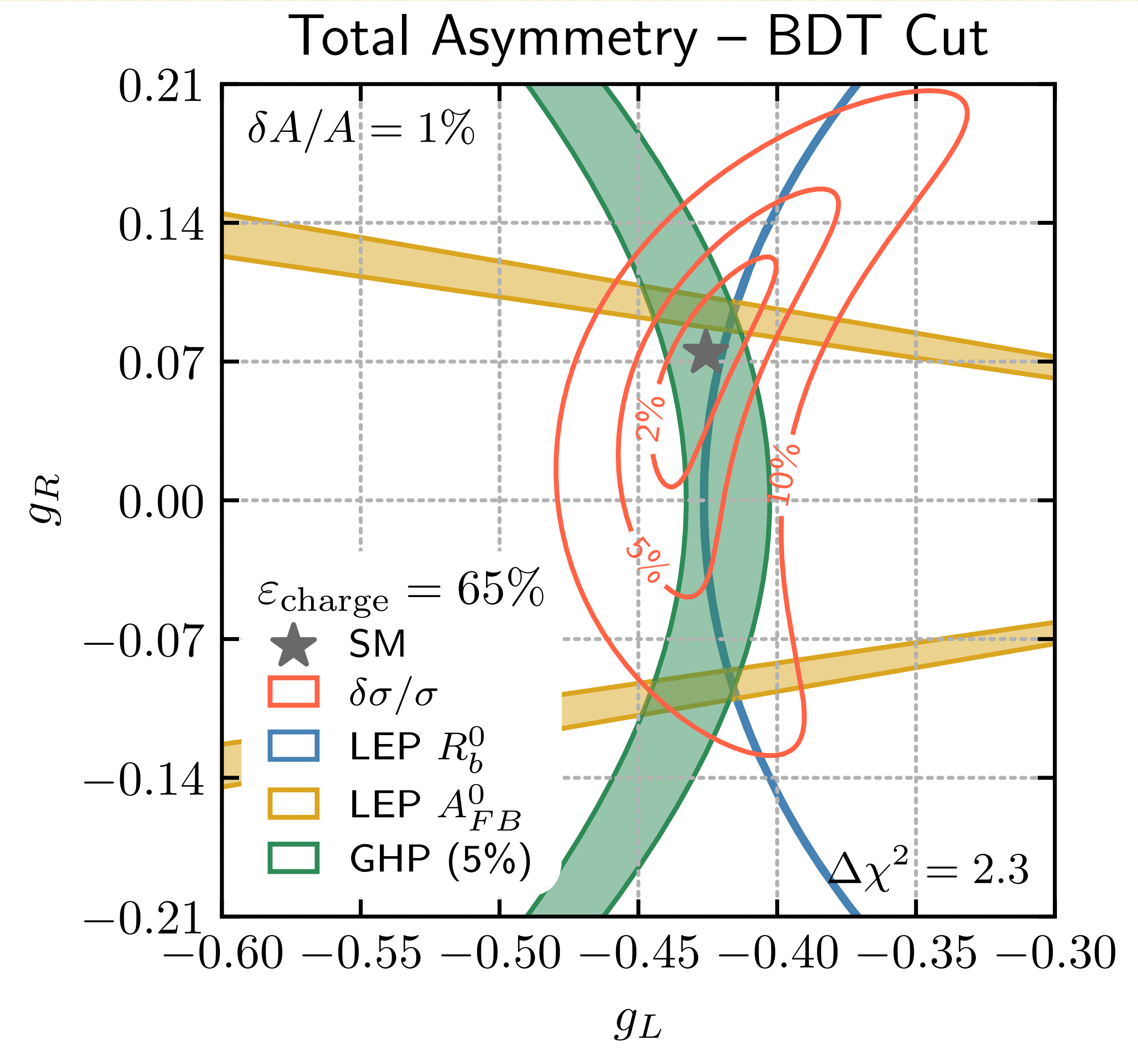


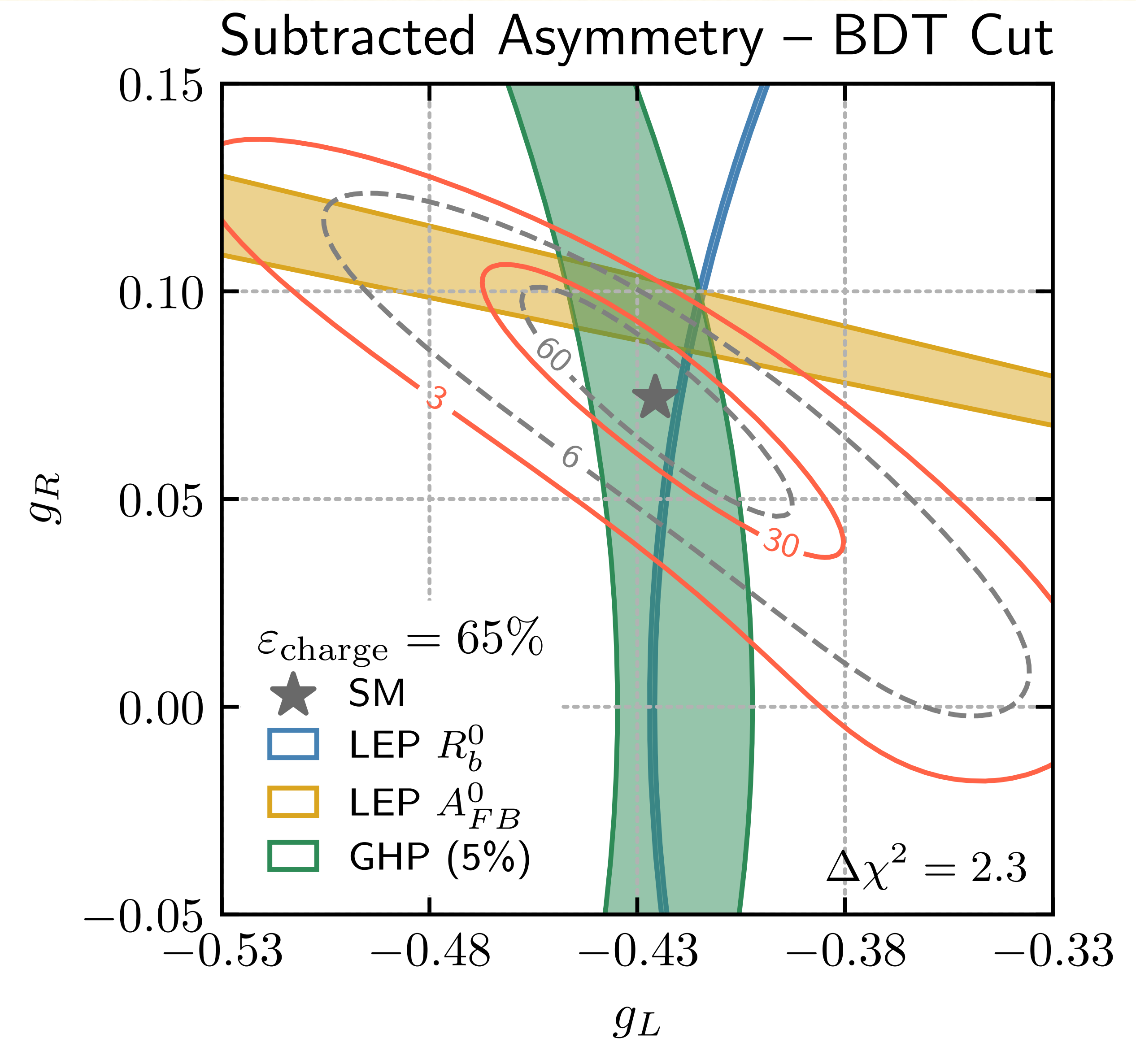
LO Sys. Inc.

Main Results:

* Further Improvement with “careful” BDT: +20～+30% (off-shell)

σ (fb)	$b\bar{b}\ell\ell$	35–85	85–95	95–125	$t\bar{t}$	35–85	85–95	95–125
Selection w/o $\not{E}_T$	700	72.9	565	62.1	1312	802	151	359
$\not{E}_T < 30$ GeV	605	63.9	488	53.2	225	132	26.3	67.1
BDT cut	632	51.9	548	46.5	156	24.8	43.2	18.4





- The result sensitively depend on flavor and charge tagging efficiency
- g_R sign degeneracy is resolved.

$$g^Z_{b,R} \in [0.05, 0.09]$$

- “Anomaly” be conclusively resolved at HL-LHC when

A_{tot}: theory calc. Improved $\lesssim$1%

$\bar{A}$: doubled statistics, tagging eff. improved

Conclusion

- The $Zb\bar{b}$ coupling: a declining anomaly, but a sign degeneracy remains
- Asymmetric observable $\mathscr{O}_{[b,\bar{b}]}$ provide orthogonal information
- $b\bar{b}\ell^-\ell^+$ study at LHC provides complimentary probe through $m_{\ell\ell}$ spectra
- Independent and competitive HL-LHC constraints