"Who Ordered That?"
Muons For New Physics

缪子束加速和对撞技术及其应用论坛
2021年12月3日

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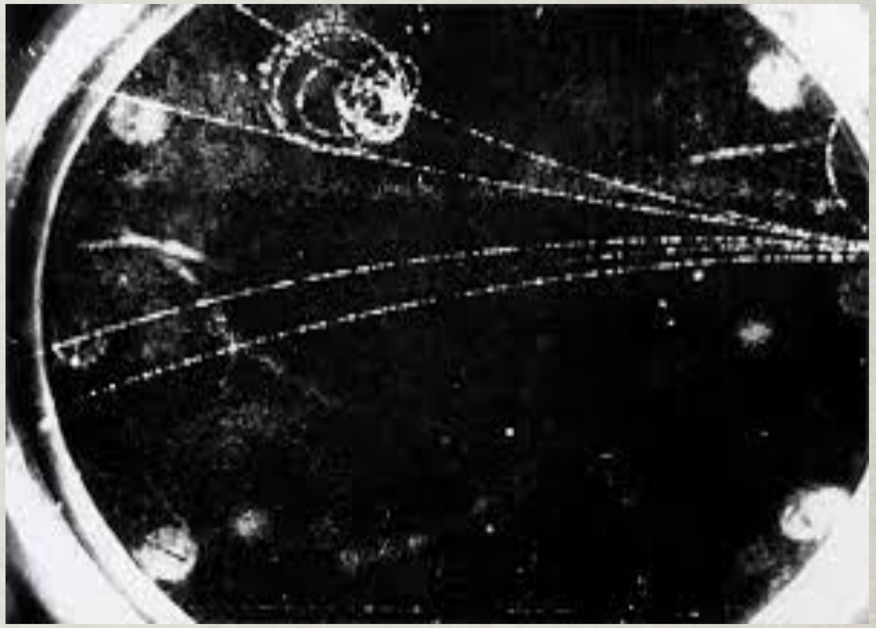
Who Ordered That?!

• A surprising discovery



In 1936, Anderson & Neddermeyer used a cloud chamber and found ± charged particle in the cosmic ray: $m_{e-} < M < m_{p+}$

It was NOT Yukawa's "meson" (1935) to mediate p^{+}, n strong nuclear force:

- Pair production from γ^{*}
- Highly penetrating: no strong interactions
- Highly ionizing: a slow-motion $M \sim 200\ m_{e-}$
- Decaying to electron with a lifetime $\tau \sim 2 \times 10^{-6}$ s

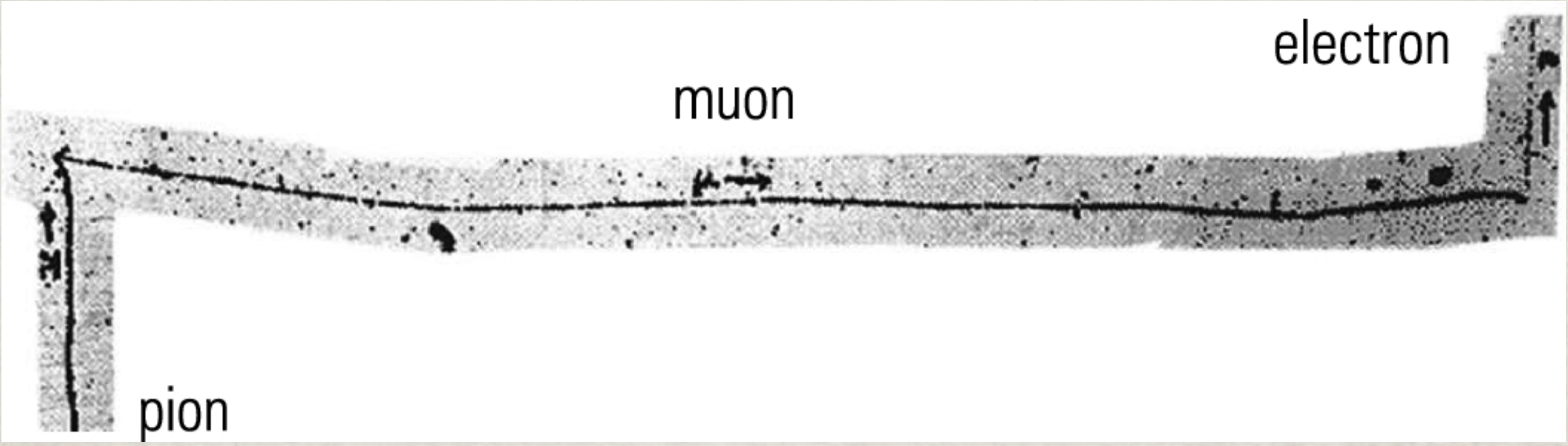
"Who ordered THAT?!"
(谁点的这道菜？！)

-- I. I. Rabi (1944 Nobel Laureate)

• There are two "mesons"!

In 1948, Lattes et al. used a photographic emulsion detector, observing two charged particles:

$$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$$



Both named by Lattes,
the discovery of $\mu^{\pm}$ led to another discovery of $\pi^{\pm}$!

The $\pi^{\pm,0}$ are the Yukawa mesons mediating the strong force!

(1949)

• Parity violation in muon decay

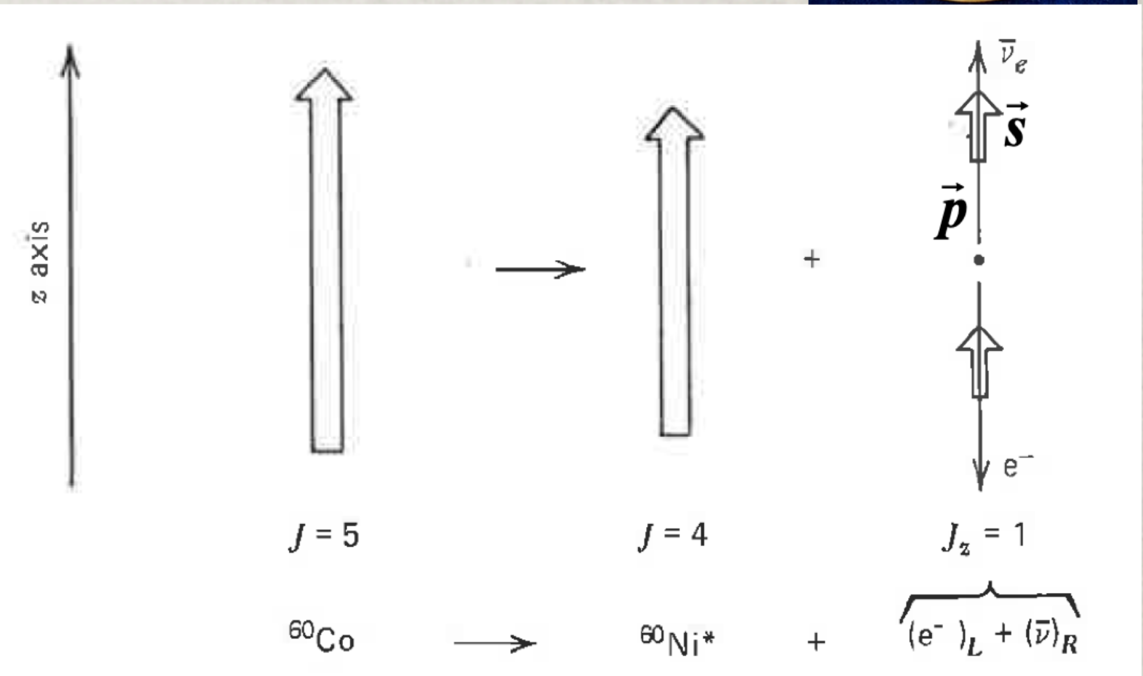
(1957)

Following Prof. Wu's experiment:

$$^{60}_{27}\mathrm{Co} \to {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$$

$$\frac{dN_e}{d\cos\theta} \propto a + b\,\vec{J}\cdot\vec{p}_e$$

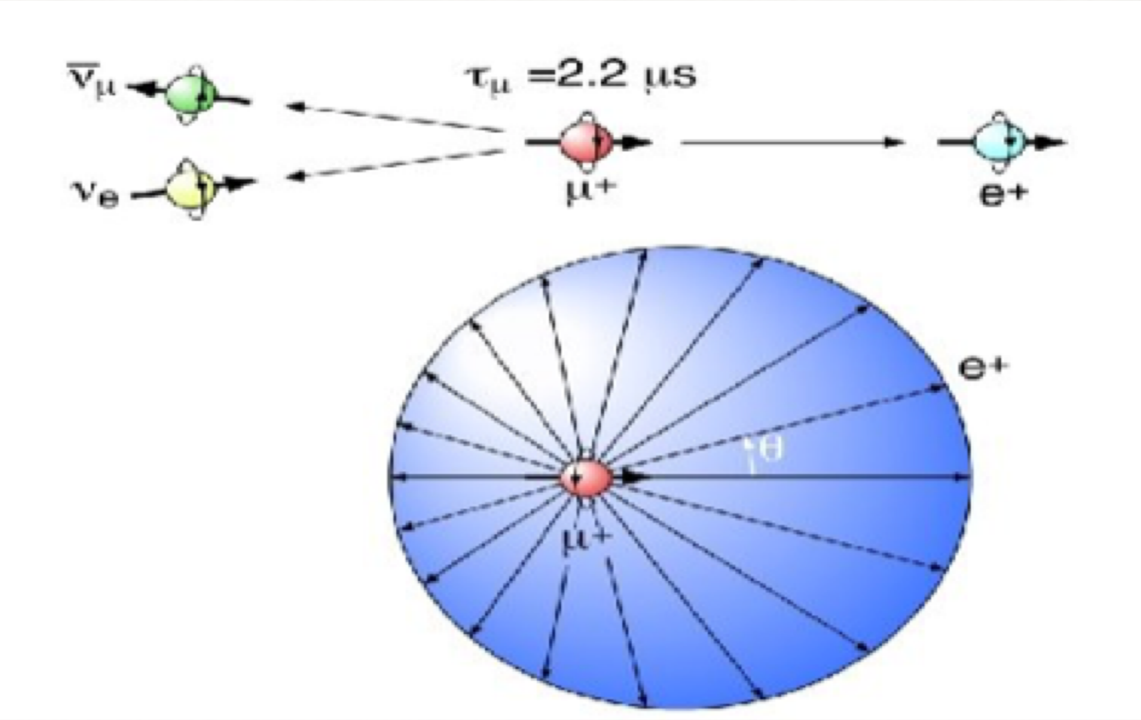
Phys. Rev. 105, 1413 (1957)



Lederman et al. & Friedman et al. made it with polarized muons:

$$\frac{dN_e}{d\cos\theta} \propto 1 + \vec{p}_e\cdot\vec{n}_\mu \sim 1 - \frac{1}{3}\cos\theta_e$$

Phys. Rev. 105, 1415 (1957);
Phys. Rev. 106, 1290 (1957)



• Heavy Quark Onia:

"Lederman's shoulder":
1968-1969@BNL di-muon expt:
ushered the $J/\psi(c\bar{c})$ Discovery

"Ooops-leon"
(Leon Lederman)
the $\Upsilon(b\bar{b}) \rightarrow \mu^{+}\mu^{-}$ Discovery

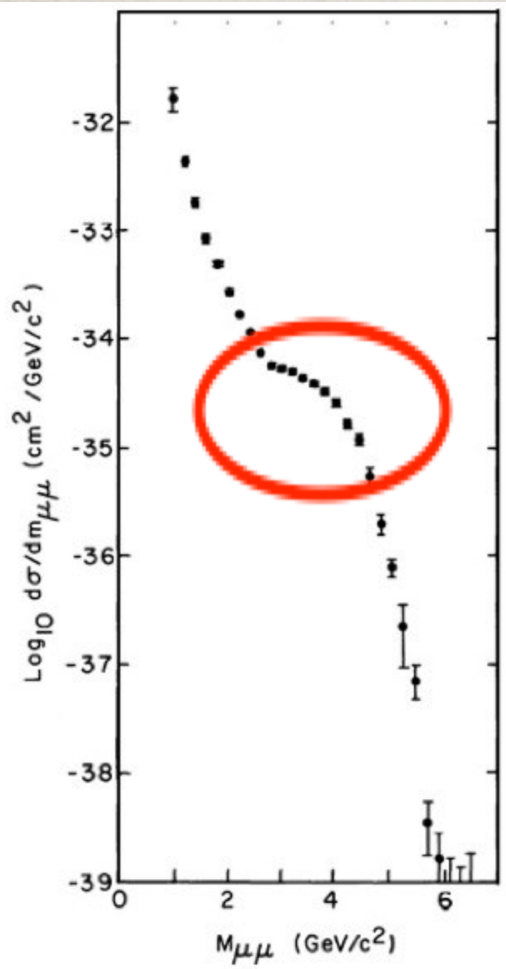
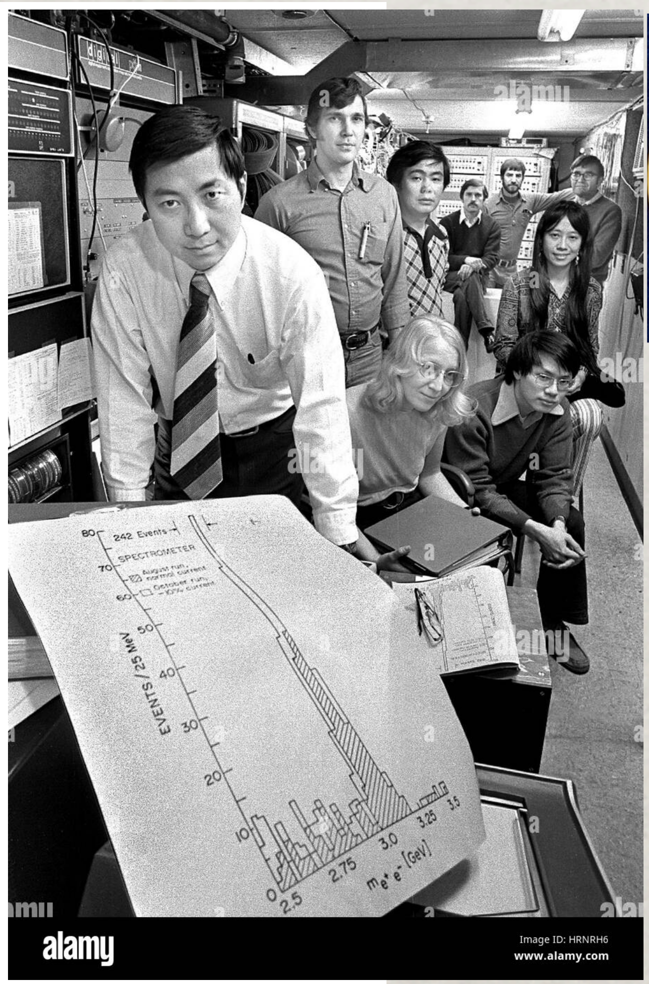
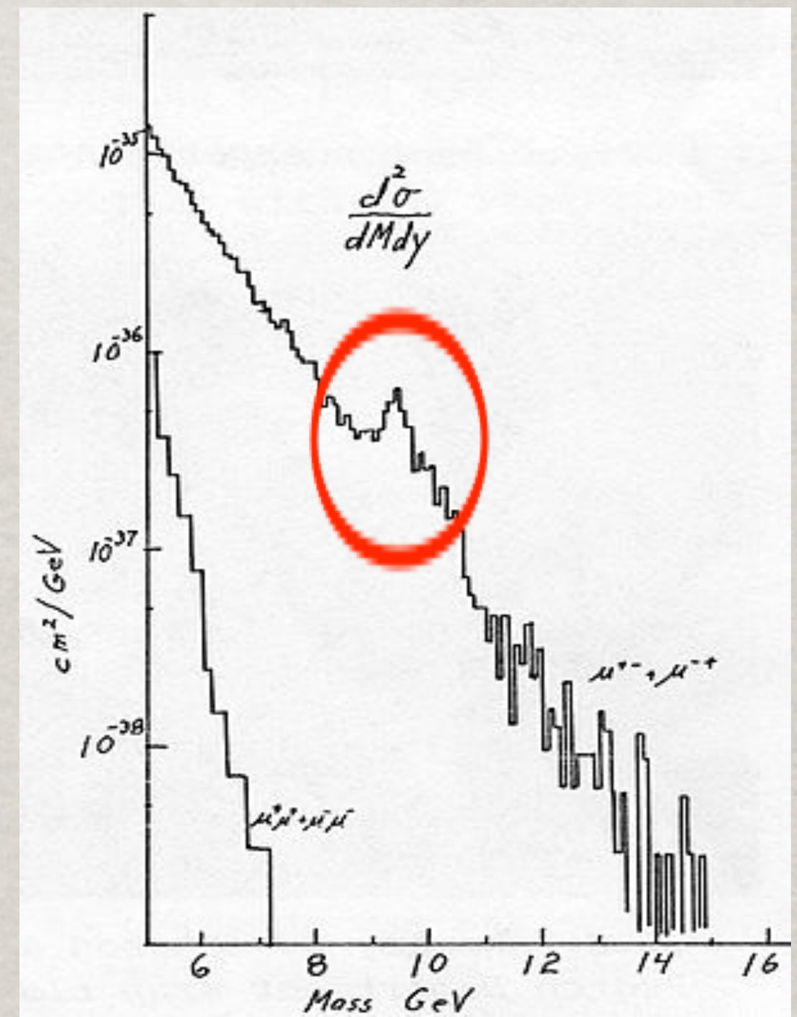


Fig. 1 - Dimuon yield from the 1968 BNL experiment. Source: J. H. Christenson, et al. (1970). Observation of massive muon pairs in hadron collisions. Physical Review Letters, 25(21), 1523.



(1976)



• Two flavors of neutrinos:

Lederman-Schwartz-Steinberger made the ν_μ beam!

$$\pi^\pm \to \mu^\pm + \nu \;\Rightarrow\; \nu + N \to \mu^\pm + N'$$

And there "ν" is NOT ν_e!

Phys. Rev. Lett. 9, 36 (1962)

(1988)

(1). Muon flavor identified: Lepton flavor physics!

(2). Neutrino beam and scattering opens a new avenue

• Neutrino Deeply Inelastic Scattering

In addition to $e^\pm + N \to^{(\gamma^*)} e^\pm + \text{hadrons}:$

$$F_2^e(x) = 2xF_1^e(x) = x\sum_q e_q^2[q(x) + \bar{q}(x)]$$

(1990)

We have

$$\nu_\mu + N \to^{(W^*)} \mu^\pm + \text{hadrons}:$$

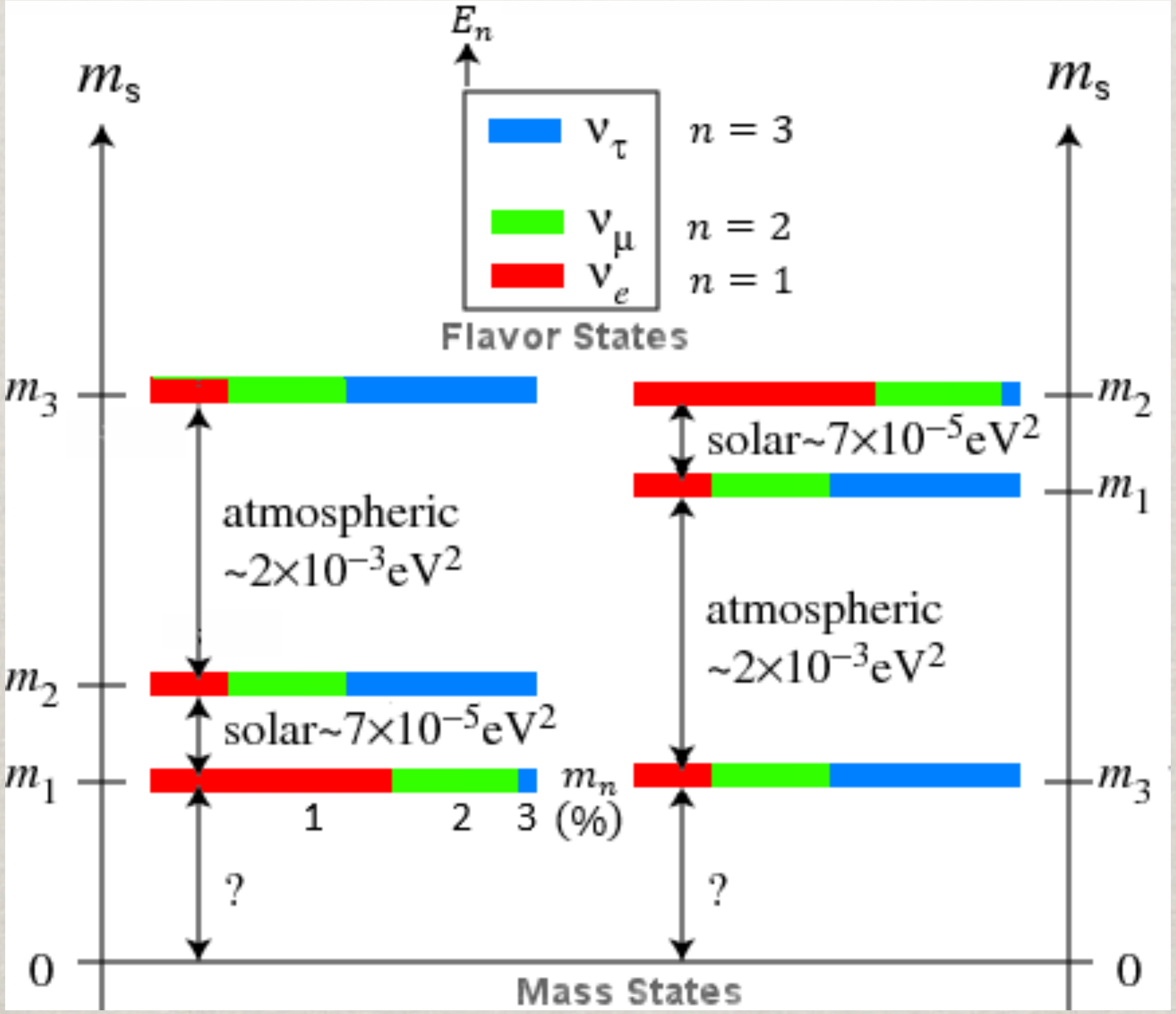
$$F_2^\nu(x) = 2xF_1^\nu(x) = x\sum_{u,d}[d(x) + \bar{u}(x)], \quad F_3^\nu(x) = 2[d(x) - \bar{u}(x)]$$

Precision measurements: $s(x) - \bar{s}(x),\ V_{cd},\ V_{cs},\ \sin\theta_W$

- Muons as sources of atmospheric $\nu_{\mu,e}$

$$\pi^{\pm},\ K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$
$$\mu^{\pm} \rightarrow \nu_{\mu} + \nu_{e} + e^{\pm}$$

The Super-Kamiokande experiment provided
a very precise measurement of neutrino oscillation



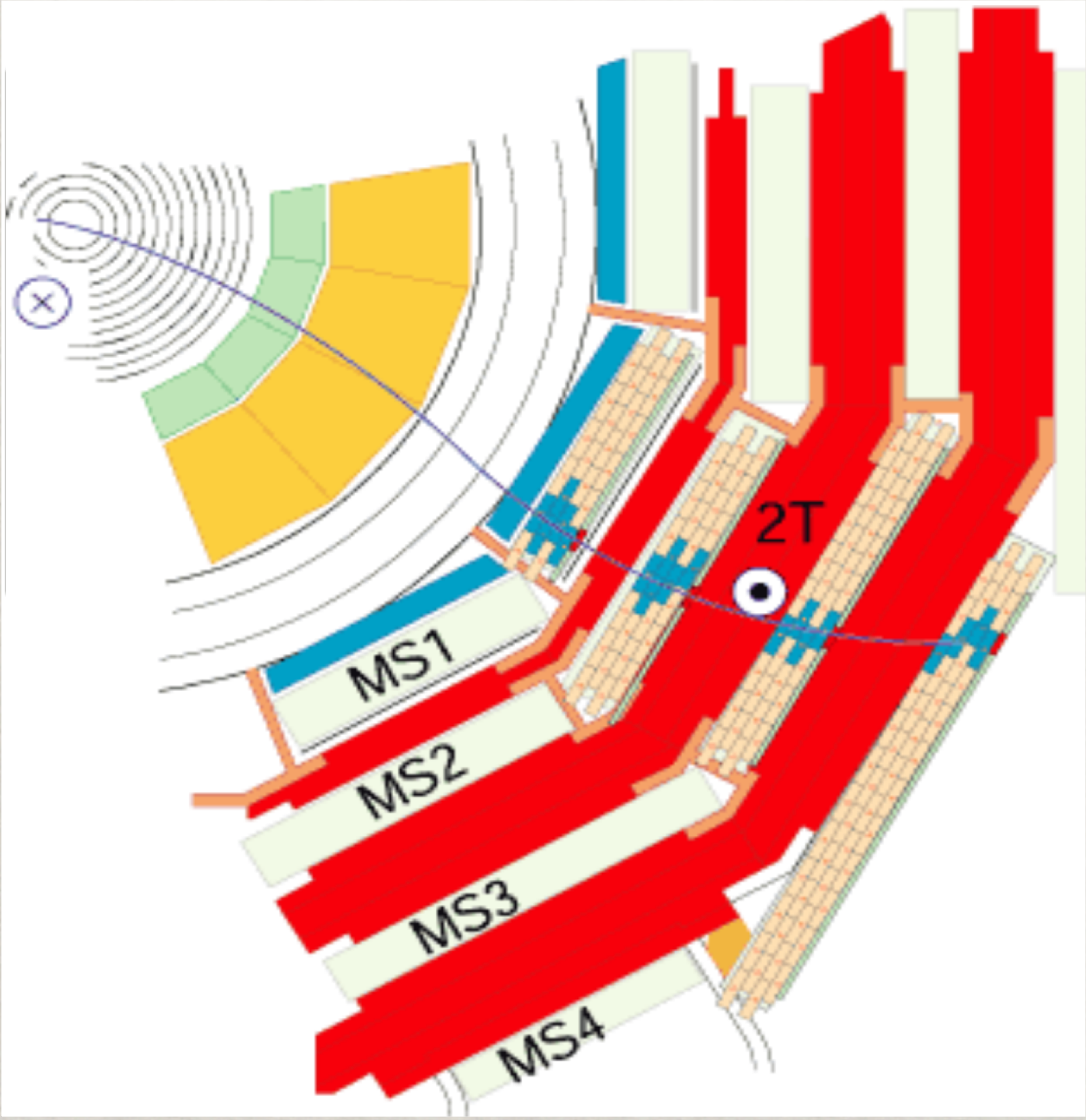
(2015)

• Muons for discovery @ Colliders

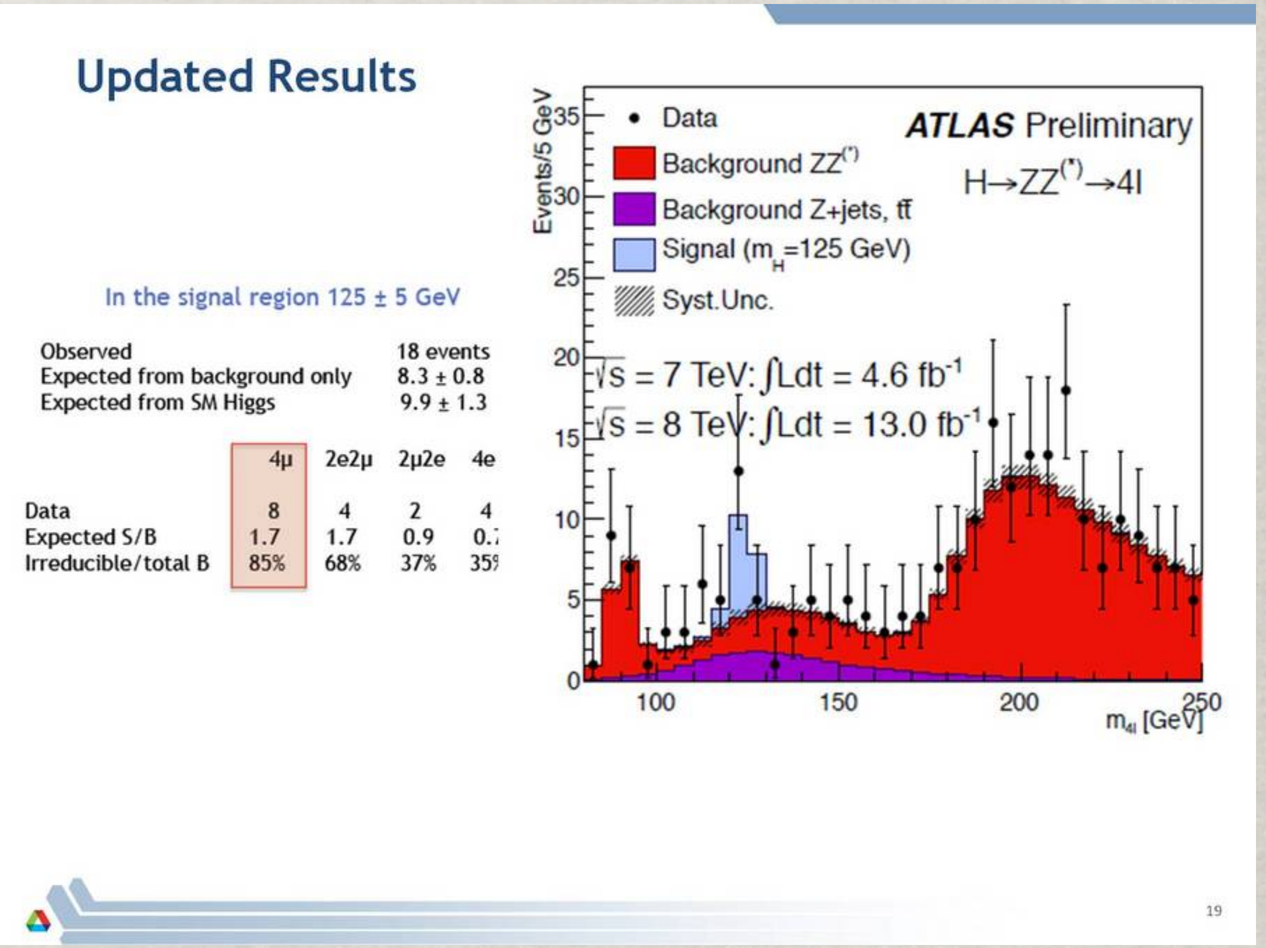
Muons are the most penetrating particle,
and thus most “visible” at the LHC.

(2013)

“Compact Muon Solenoid”



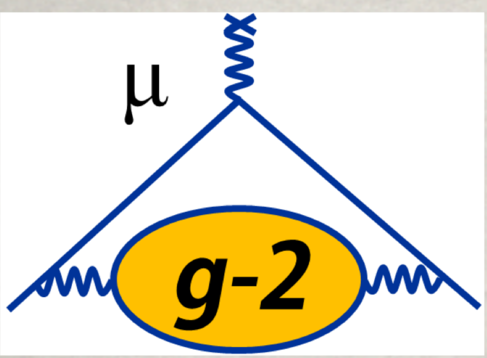
The Higgs boson discovery:



Continuing Explorations

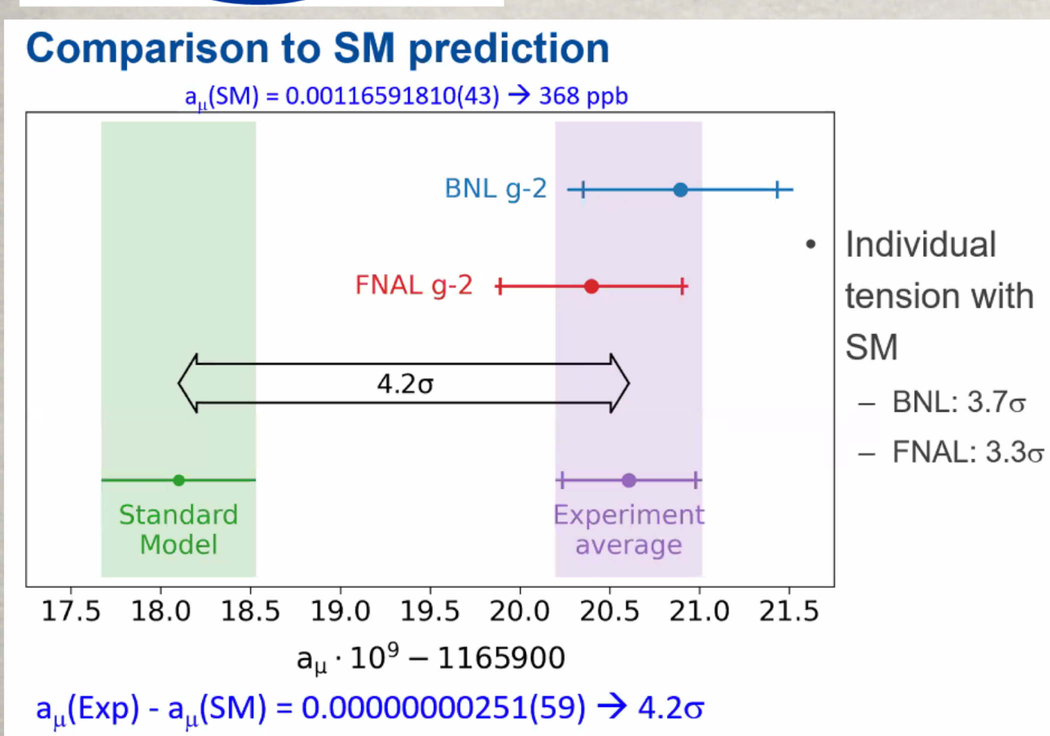
Fermilab Muon Department

"the muon campus"



Sensitivity:

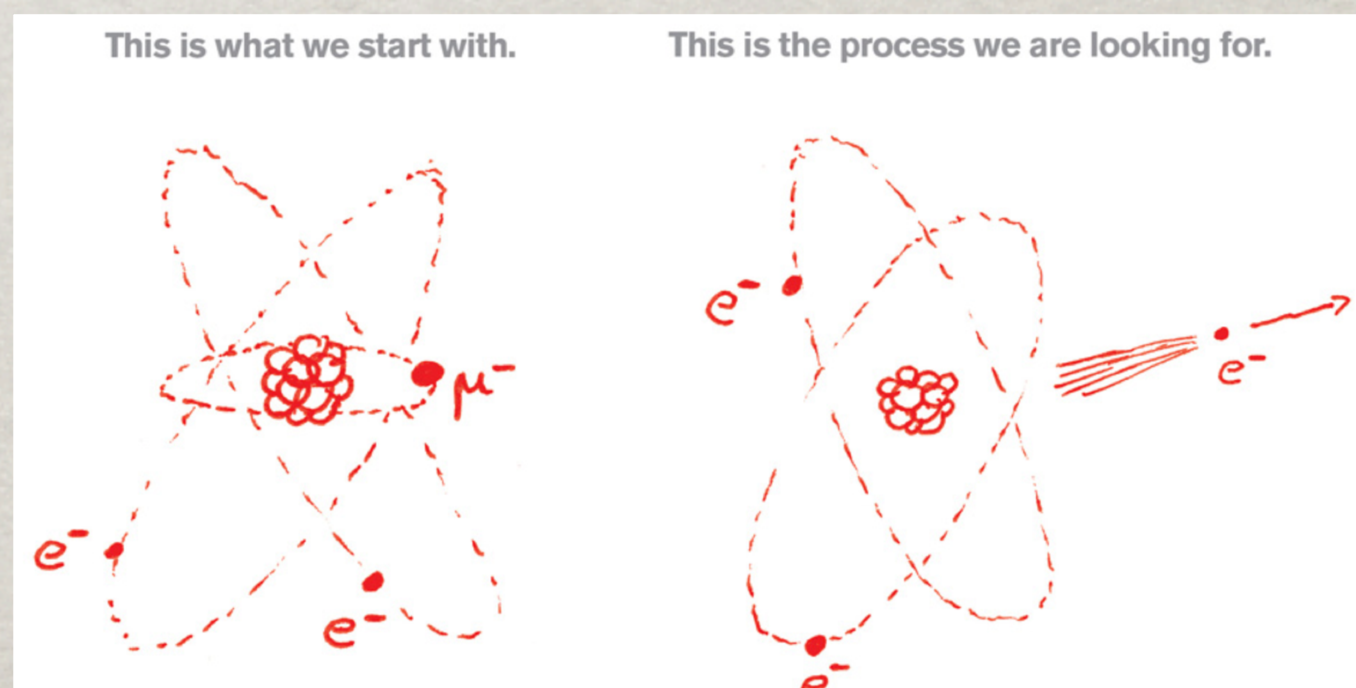
$(m_\mu/m_e)^2 \sim 42{,}000$



Fermi National Accelerator Laboratory

The Mu2e Experiment at Fermilab

And COMET @ J-PARC



• Nu-Storm @ FNAL / PIP-II

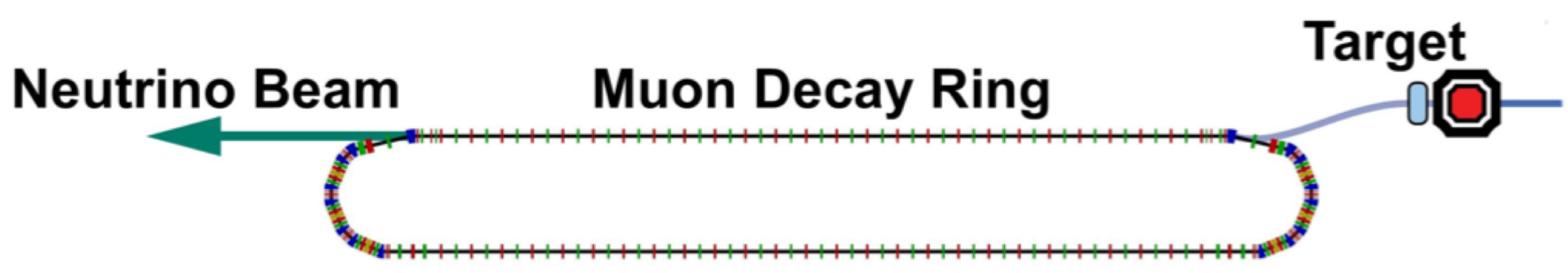


Figure 1

Schematic layout of the nuSTORM facility

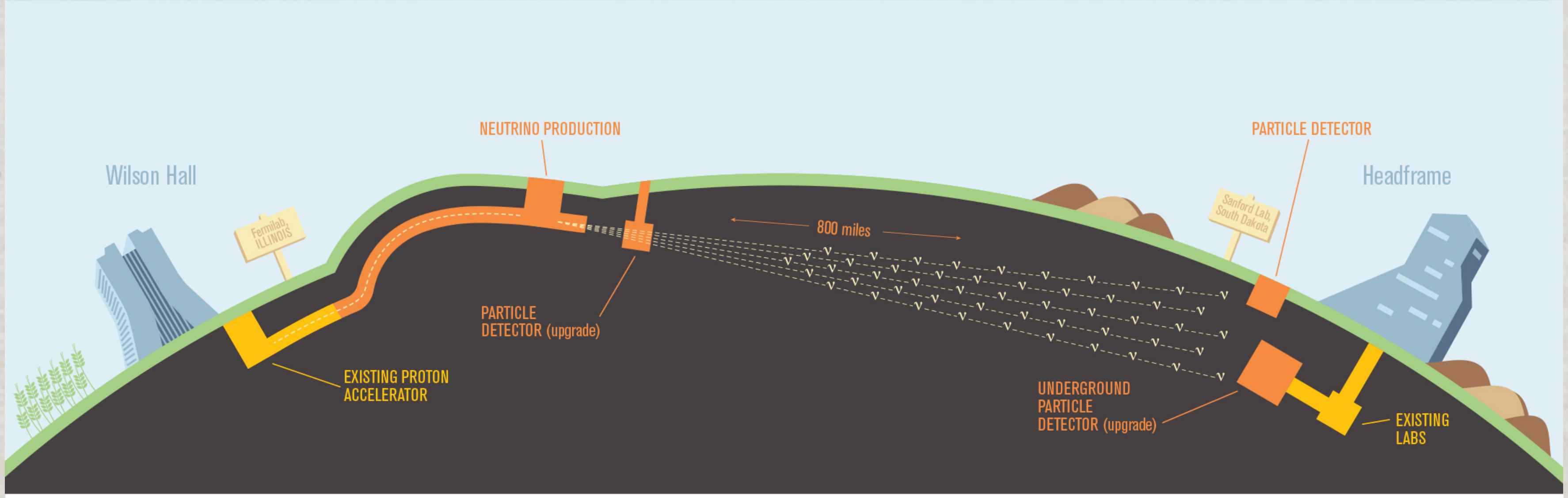
nuSTORM's physics program: Three themes

The physics program for the nuSTORM facility encompasses three central themes.

1. The neutrino beams produced at the nuSTORM facility will enable short-baseline (SBL) oscillation searches for light-sterile neutrinos with unprecedented sensitivity over a wide parameter space and, if sterile neutrinos are discovered, offers the opportunity to carry out an extremely comprehensive study of their properties.
2. These same beams may be exploited to make detailed studies of neutrino-nucleus scattering over the neutrino-energy range of interest to present and future long-baseline (LBL) neutrino oscillation experiments such as T2HK (7), LBNE (8) and LBNO (9).
3. The storage ring itself, and the muon beam it contains, can be used to carry out a R&D program that can facilitate the implementation of the next step in the incremental development of muon accelerators for particle physics.

• LBNE: Long-Baseline Neutrino Experiments

DUNE: Deep Underground Neutrino Experiment, the "ultimate" neutrino experiment



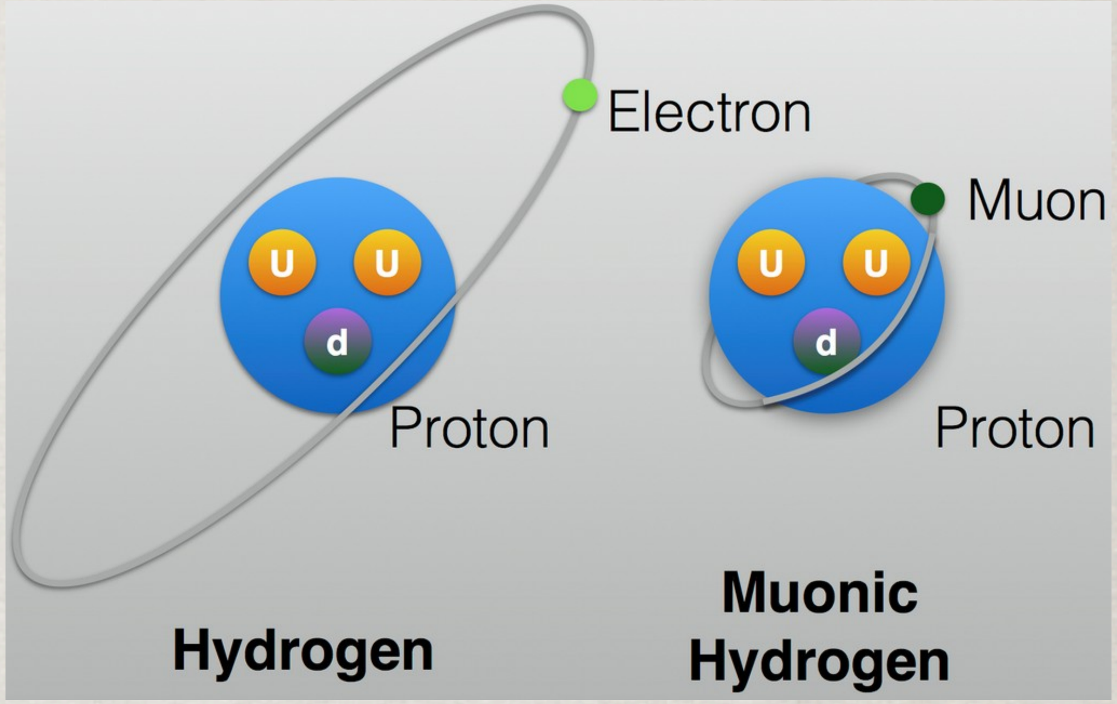
Neutrinos can travel long distances through rock and other matter without a scratch. The LBNE neutrino beam will travel 800 miles straight through the earth from Batavia, Illinois, to the Sanford Lab in Lead, South Dakota—no tunnel necessary. The trip will take less than one-hundredth of a second, enough time for some of the muon neutrinos to transform into electron neutrinos and tau neutrinos. Scientists call this process neutrino oscillation.

DUNE will pursue major science goals:

- Leptonic CP violation, precision measurements of θ_{13}, Δm^2_{13}
- Dark matter searches
- Proton decay
- Supernova, formation of neutron star/black holes

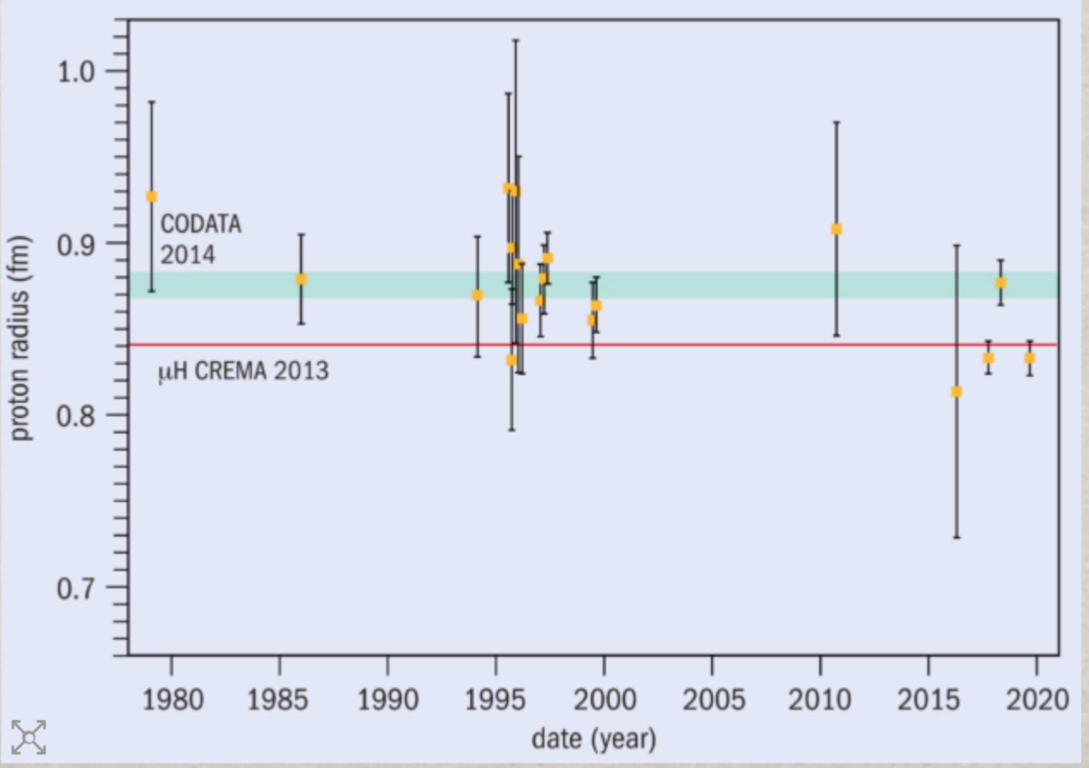
MUONS BEYOND HEP

- Muonic atom for precision physics



- $r_B = (\alpha\, m)^{-1}$: $r_B(\mu^-) = r_B(e^-)/207 = 2.2 \times 10^{-5}$ nm
- Wavefunction overlap: $(m_\mu/m_e)^3 \sim 10^7$ stronger
- Lamb shift: 10^5 larger

More sensitive to probe the proton size/properties:
PSI, CREMA
Nature09250: July 8, 2010



• Muons for material science

PSI, Zurich

SμS: Swiss Muon Source

μSR - Muon Spin Rotation, Relaxation or Resonance: A research tool using muons as sensitive local magnetic probes in matter.
Research at the LMU focuses mainly on magnetic properties of materials and on positive muons or muonium (bound state of a positive muon and an electron) as light protons or hydrogen substitutes in matter.

Worldwide unique: The Low-Energy Muon Beam and μSR Spectrometer for the study of thin films, layers and surfaces, the possibility to perform high-field μSR with a field up to 9.5 Tesla, and the Extraction of Muons On Request for high frequency resolution and slow relaxation measurements.

KEK, Japan:

Muon Science Laboratory
MSL
Institute of Materials Structure Science
High Energy Accelerator Research Organization,KEK

One important experimental technique which the team uses is called Muon Spin Rotation / Relaxation / Resonance (μSR). μSR is used to map magnetic fields inside matter on a nanometer scale by means of muons shot into samples. Using this technique, scientists can examine the magnetic properties of materials. For example, they can examine the magnetic flux through type-II superconductors, and [determine][simulate][?] the location of the trace amounts of hydrogen atoms contained in some materials. Other examples include studies of muon-catalyzed fusion and the non-destructive analysis of the interior of solids, which takes advantage of the fact that negatively charged muons behave as heavy electrons.

• Muon Tomography: Cosmic muons

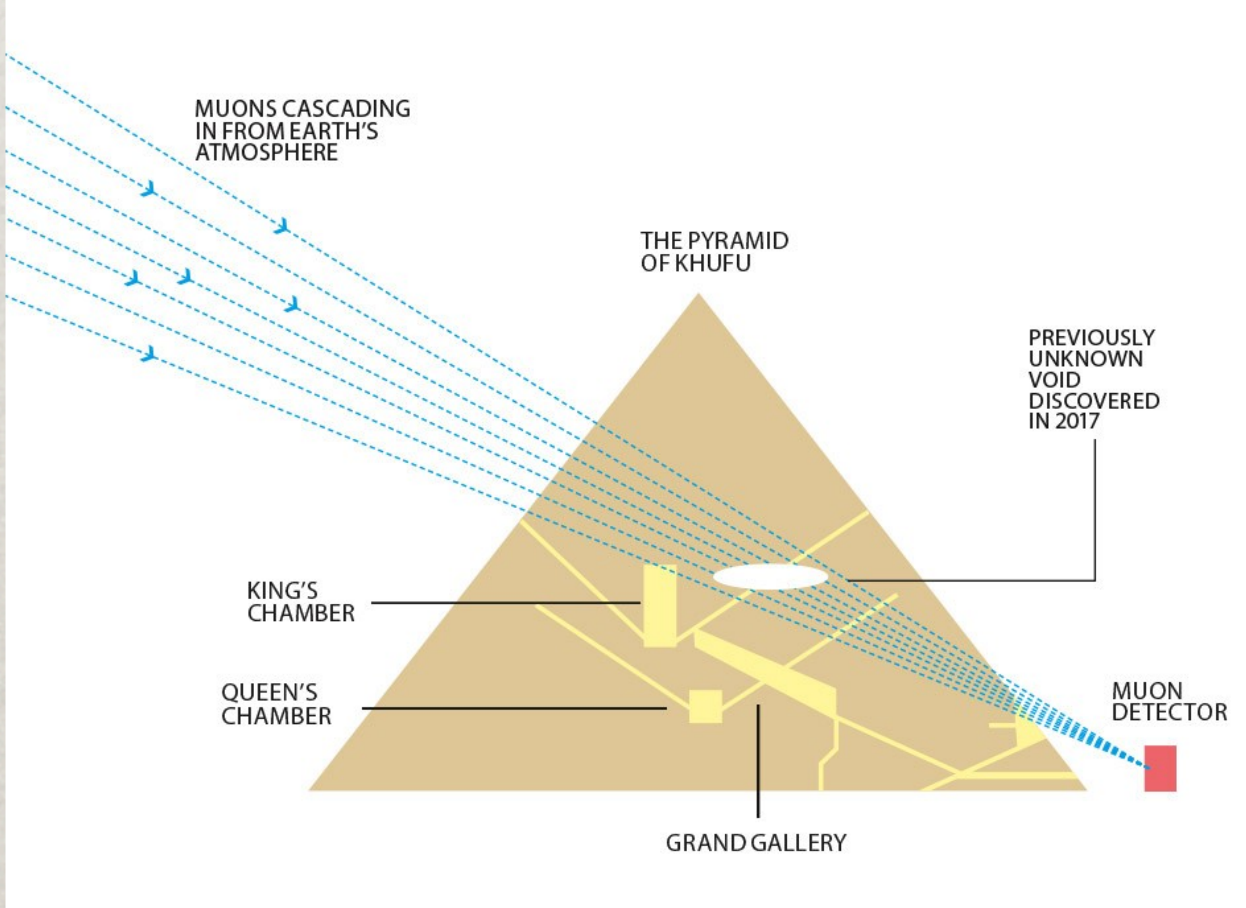
Atmospheric muon flux ~ 200/m^2/s

Muons are penetrating!

nature (November 2, 2017)

Cosmic-ray particles reveal secret chamber in Egypt's Great Pyramid

A previously unknown chamber has been found in the largest of the pyramids in Giza, Egypt. Credit: Tomasz Tomaszewski/VISUM creativ/eyevine



A Muon Collider

Why muons?

Although sharing the same EW interactions,
it isn't another electron:

$$m_\mu \approx 207\ m_e$$
$$\tau(\mu \to e\bar{\nu}_e\nu_\mu) \approx 2.2\ \mu s$$
$$c\tau \approx 660\ m.$$

It is these features: heavy mass, short lifetime
that dictate the physics.

Some early work:

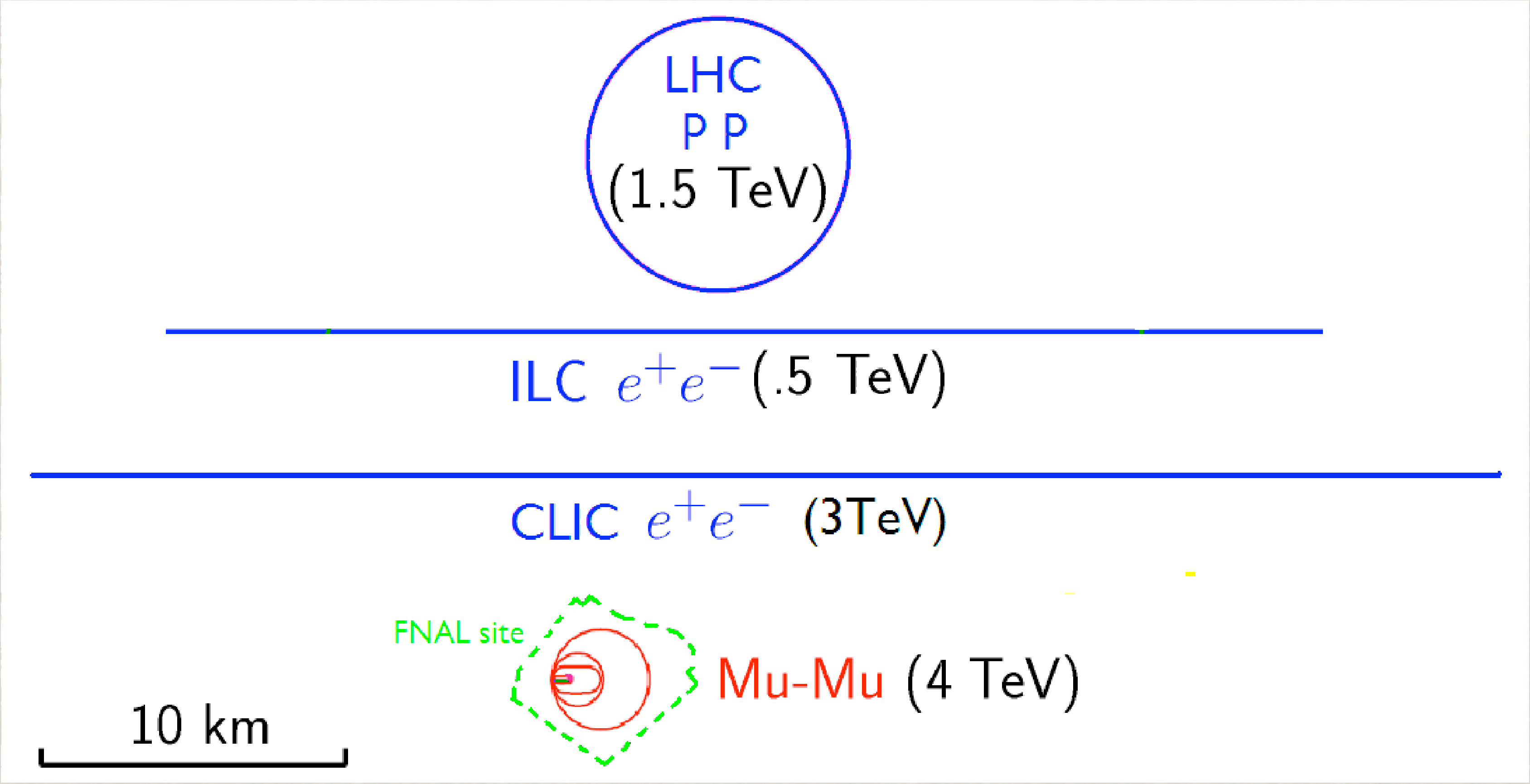
- *S-channel Higgs boson production at a muon collider,* Barger et al., PRL75 (1995).
- ***$\mu^+ \mu^-$*** *Collider: Feasibility study,* Muon collider collaboration (July, 1996).
- *Higgs boson physics in the s-channel muon collider,* Barger et al., Phys Rep. 186 (1997).
- *Status of muon collider research,* Muon collider collaboration (Aug., 1999).
- *Recent progress on neutrino factory and muon collider research,*
  Muon collider collaboration (July, 2003).

• Advantages of a muon collider

- Much less synchrotron radiation energy loss than e's:

$$\Delta E \sim \gamma^4 = (\frac{E}{m_\mu})^4$$

which would allow a smaller and a circular machine:



- Unlike the proton as a composite particle, E_{CM} efficient in $\mu^+\mu^-$ annihilation
- Much smaller beam-energy spread:

  ΔE/E ~ 0.01% - 0.001%

• Disadvantages of a muon collider

- Production: Protons on target → pions → muons:

Require sophisticated scheme for **μ** capture & transport

"Never play with an unstable thing!"

- Very short lifetime: in micro-second,

Muons cooling in (x,p) 6-dimensions

→ Difficult to make quality beams and a high luminosity

[Note: $E_\mu \sim 1$ TeV → $\gamma \sim 10^4$ → $\gamma\tau = 0.02$ s → d=6,000 km]

- Beam Induced Backgrounds (BIB)

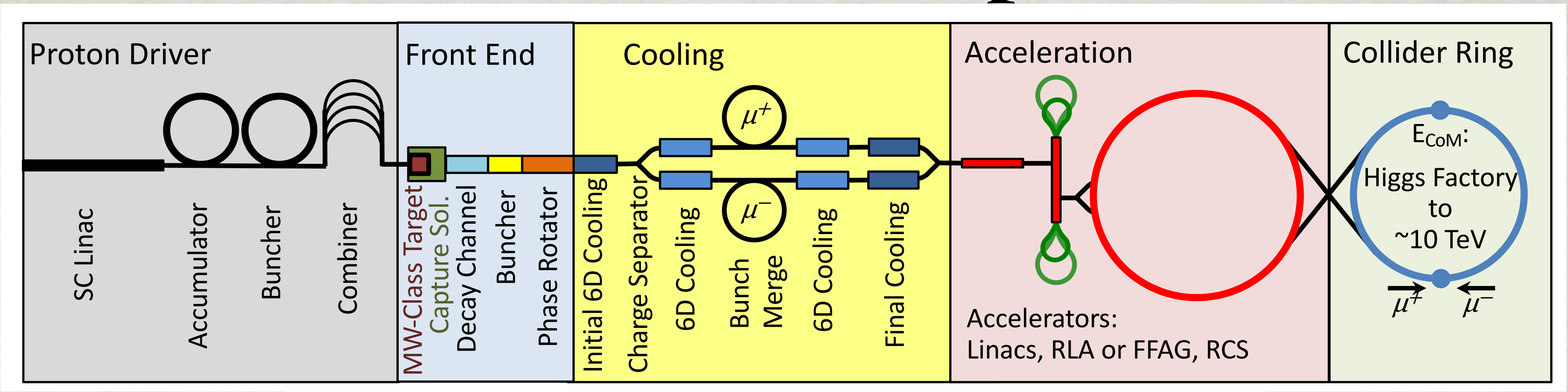
from the decays in the ring at the interacting point,

[Note: σ_{pp}(total)~100 mb; $\sigma_{\mu\mu}$(total)~100 nb]

- Neutrino beam dump (environmental hazard)

$\sigma_\nu \sim G_F^2 E^2$ → Shielding?

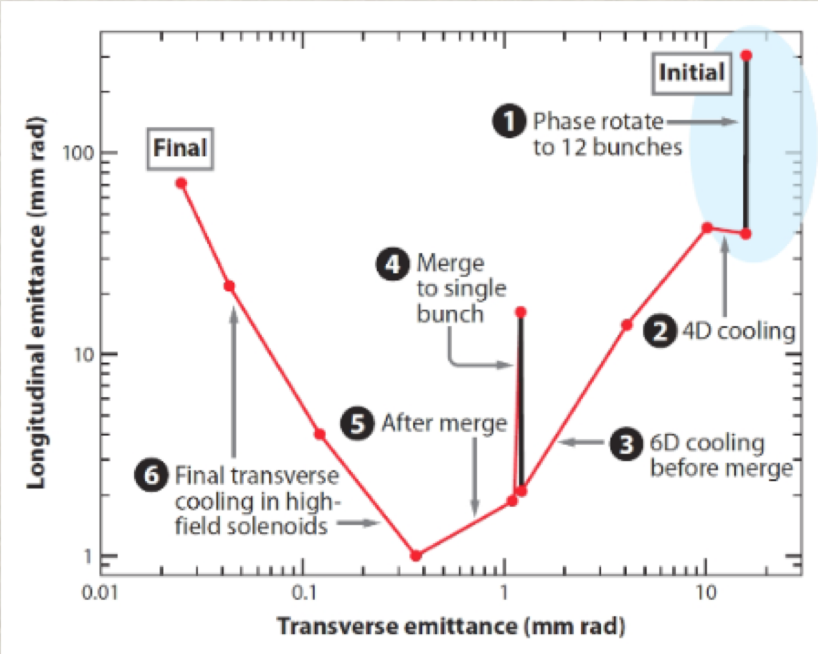
Proton Driver Option:



Muon Accelerator Program
map.fnal.gov

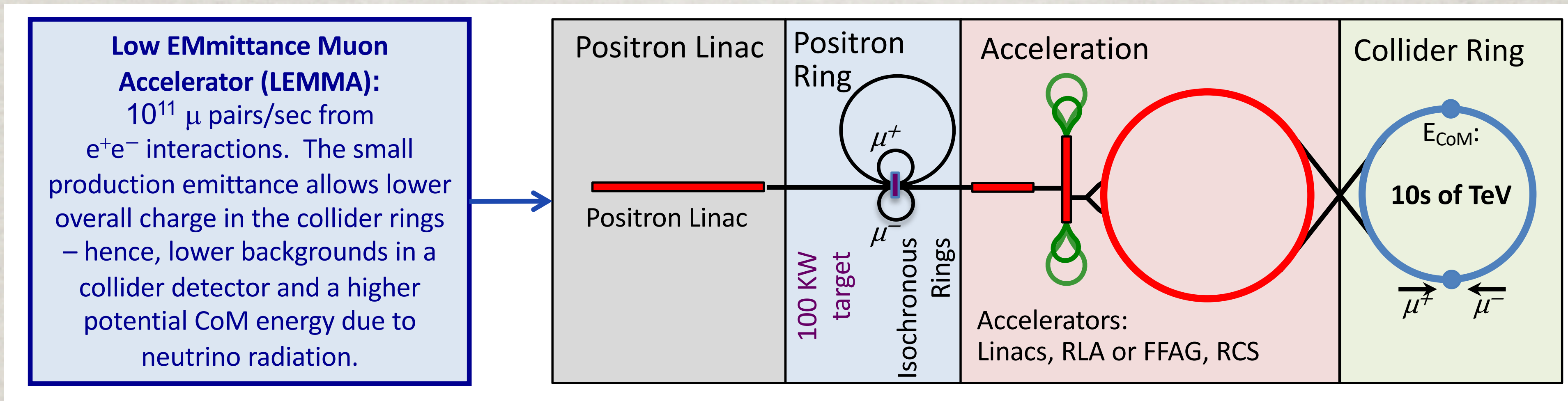
During 2011-2016, MAP collaboration formed:
to address key feasibility issues for **μ**C

- Protons → pions → muons
- Transverse ionization cooling achieved by MICE
- Muon emittance exchange demonstrated at FNAL/RAL
- 6D cooling of 5-6 orders needed



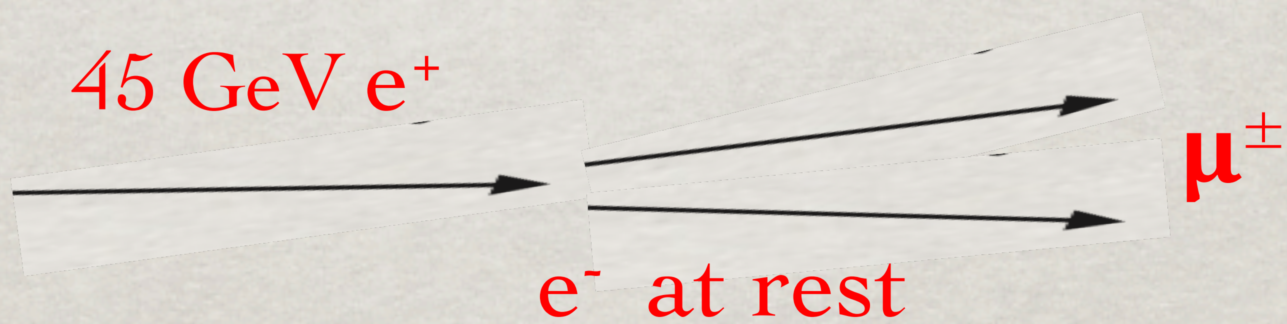
https://arxiv.org/abs/1907.08562
J.P. Delahauge et al., arXiv:1901.06150

LEMMA: e^+e^- (at rest) → $\mu^+\mu^-$ (at threshold)



Low EMittance Muon Accelerator

web.infn.it/LEMMA



Cooling is not a problem;

but high luminosity is challenging!

J.P. Delahauge et al., arXiv:1901.06150

Collider benchmark points:

- The Higgs factory:

$E_{cm} = m_H$

$L \sim 1\ \mathrm{fb}^{-1}/\mathrm{yr}$

$\Delta E_{cm} \sim 5$ MeV

Parameter	**Units**	**Higgs**
CoM Energy	TeV	0.126
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.008
Beam Energy Spread	%	0.004
Higgs Production/10^7 sec		13'500
Circumference	km	0.3

Current Snowmass 2021 point: 4 fb^{-1} / yr

- Multi-TeV colliders:

Lumi-scaling scheme: **σ** $L \sim$ const.

$$L \gtrsim \frac{5\ \text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\ \text{TeV}}\right)^2 2 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

1 ab^{-1} /yr

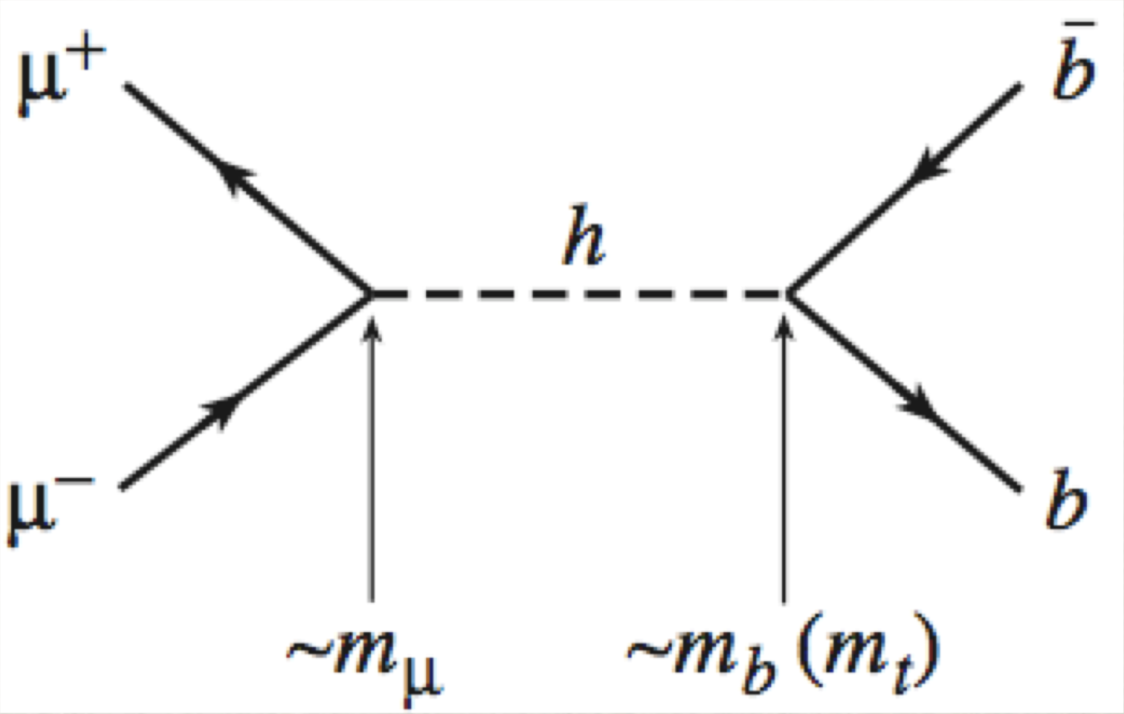
The aggressive choices:

$$\sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30 \text{ and } 100 \text{ TeV}, \quad \mathcal{L} = 1,\ 4,\ 10,\ 20,\ 90, \text{ and } 1000\ \mathrm{ab}^{-1}$$

European Strategy, arXiv:1910.11775; arXiv:1901.06150; arXiv:2007.15684.

A Higgs Factory

Resonant Production:



$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

$$\sigma_{peak}(\mu^+\mu^- \to h) = \frac{4\pi}{m_h^2} BR(h \to \mu^+\mu^-)$$

$$\approx 71 \text{ pb at } m_h = 125 \text{ GeV}.$$

About O(70k) events produced per fb^{-1}

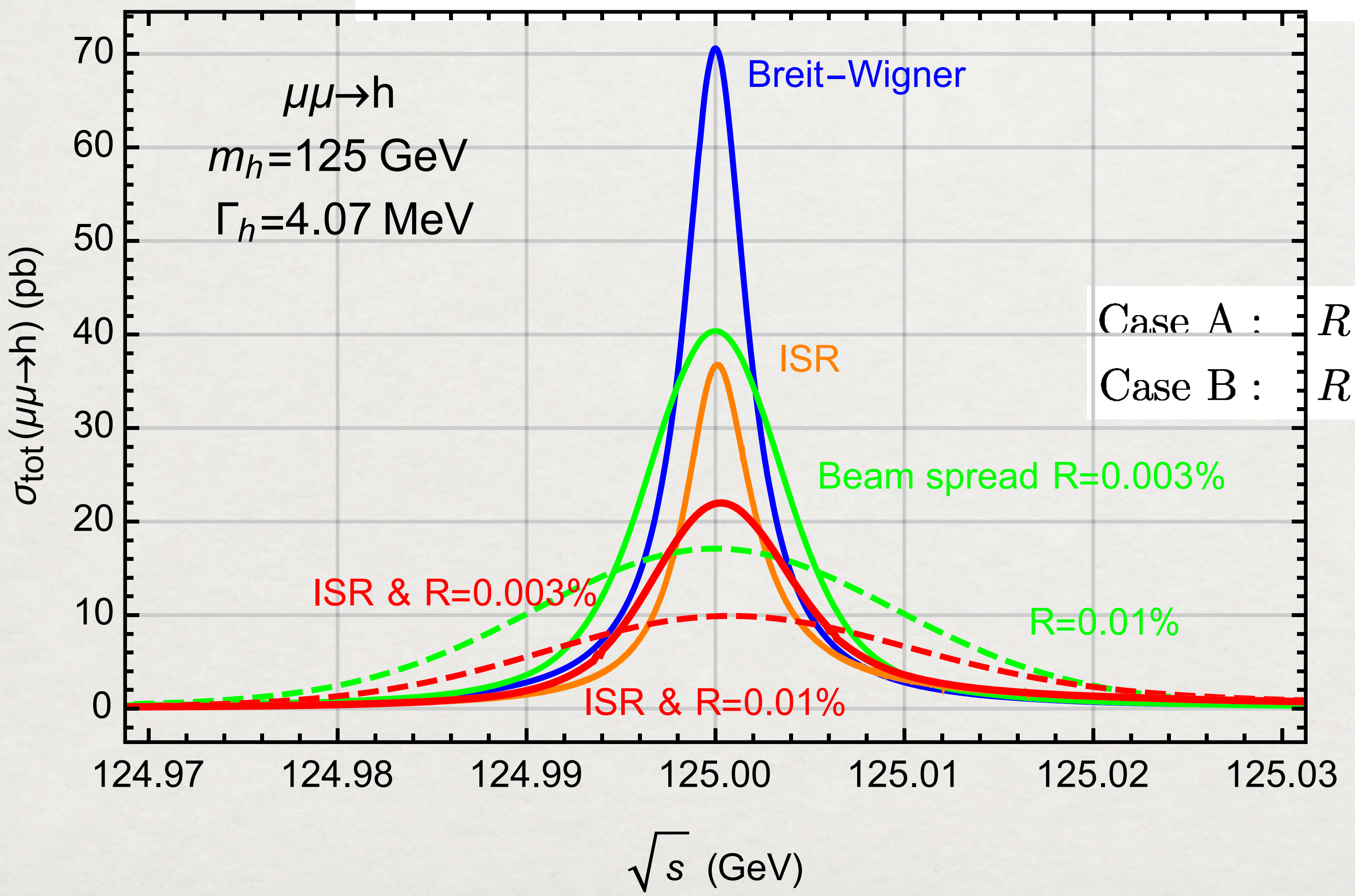
At m_h=125 GeV, Γ_h = 4.2 MeV

$$\frac{\exp[-(\sqrt{\hat{s}}-\sqrt{s})^2/(2\sigma^2_{\sqrt{s}})]}{\sqrt{2\pi}\sigma_{\sqrt{s}}}$$

$$\frac{4\pi\Gamma(h\to\mu\mu)\,\Gamma(h\to X)}{(\hat{s}-m_h^2)^2+m_h^2[\Gamma_h^{\rm tot}]^2}$$

$$\sigma_{\rm eff}(s) = \int d\sqrt{\hat{s}}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^-\to h\to X)$$

$$\propto \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2+\Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B\exp[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

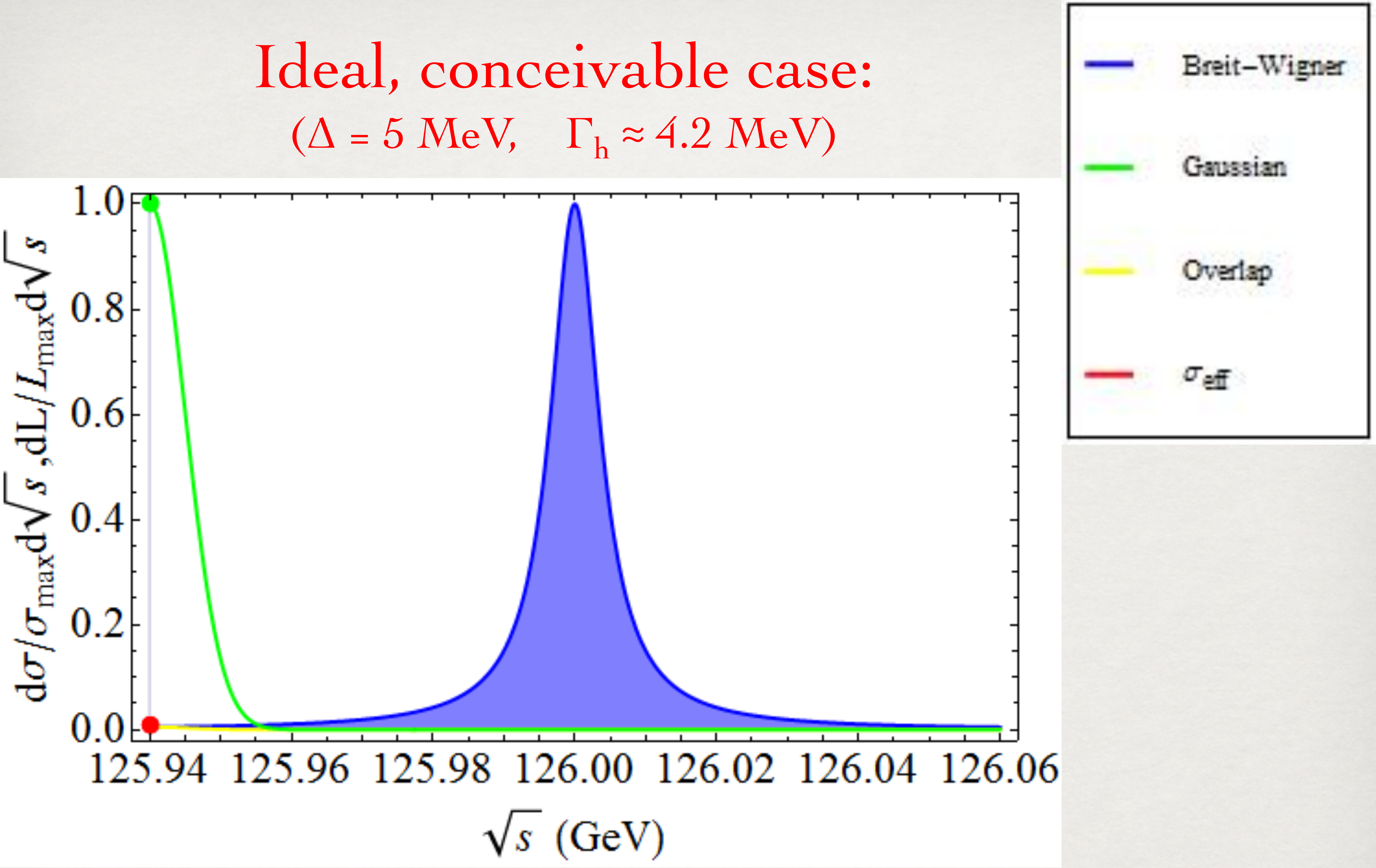


"Muon Collider Quartet":
Barger-Berger-Gunion-Han
PRL & Phys. Report (1995)

Case A : $R = 0.01\%$ ($\Delta = 8.9$ MeV), $L = 0.5$ fb^{-1},
Case B : $R = 0.003\%$ ($\Delta = 2.7$ MeV), $L = 1$ fb^{-1}.

TH, Liu: 1210.7803;
Greco, TH, Liu: 1607.03210

Ideal, conceivable case:
($\Delta = 5$ MeV, $\Gamma_h \approx 4.2$ MeV)



An optimal fitting would reveal Γ_h

Achievable accuracy at the Higgs factory:

TABLE I. Effective cross sections (in pb) at the resonance $\sqrt{s} = m_h$ for two choices of beam energy resolutions R and two leading decay channels, with the SM branching fractions $\mathrm{Br}_{b\bar{b}} = 56\%$ and $\mathrm{Br}_{WW^*} = 23\%$ [9]. a cone angle cut: $10^o < \theta < 170^o$

	$\mu^+\mu^- \to h$	$h \to b\bar{b}$		$h \to WW^*$	
R (%)	σ_{eff} (pb)	σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
0.01	16	7.6		3.7	
0.003	38	18	15	5.5	0.051

Good S/B>1, S/√B → % accuracies

Table 3

Fitting accuracies for one standard deviation of Γ_h, B and m_h of the SM Higgs with the scanning scheme for two representative luminosities per step and two benchmark beam energy spread parameters.

$\Gamma_h = 4.07$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.05	0.79	3.0%	0.36
	0.2	0.39	1.1%	0.18
$R = 0.003\%$	0.05	0.30	2.5%	0.14
	0.2	0.14	0.8%	0.07

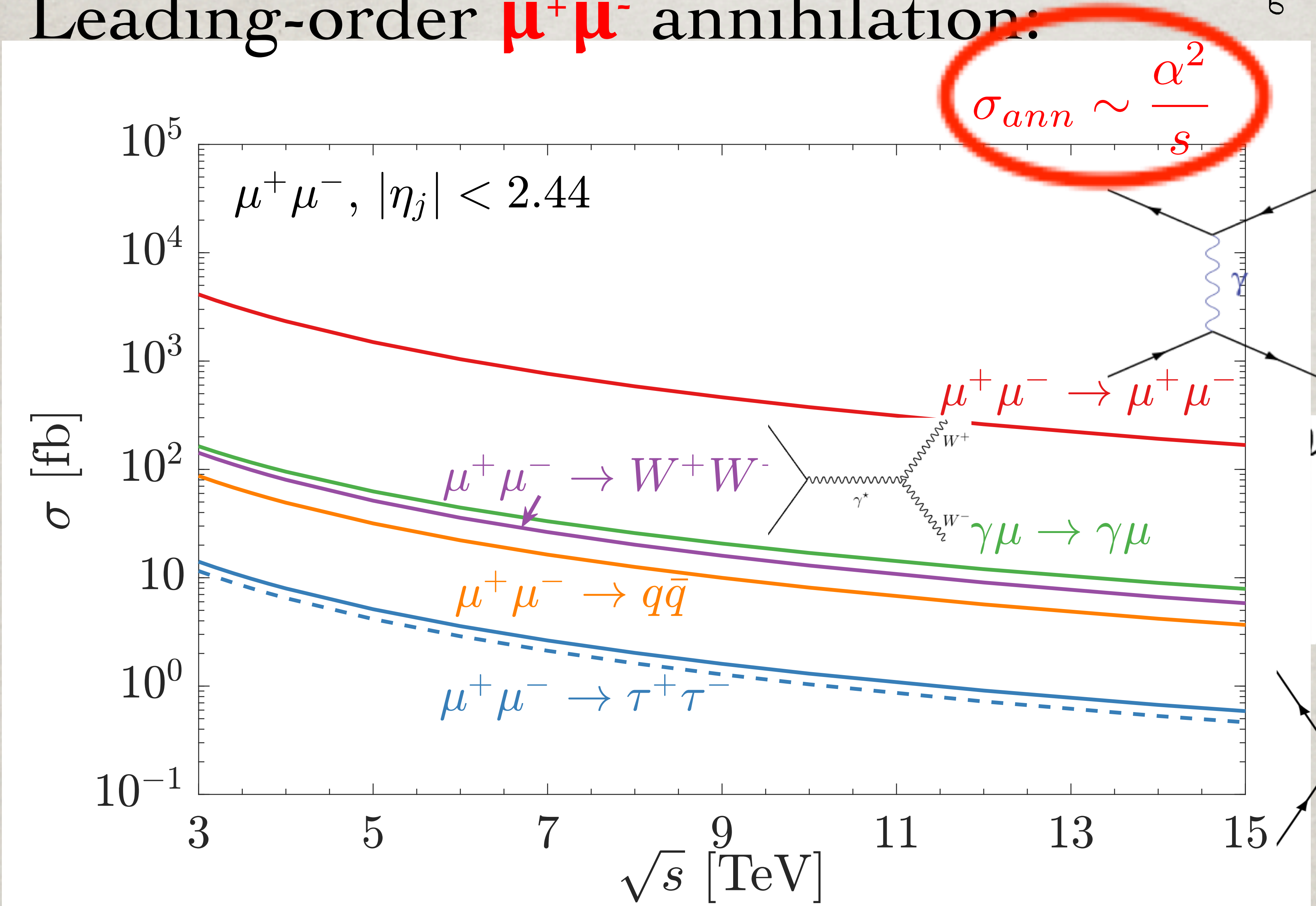
~ 3.5%

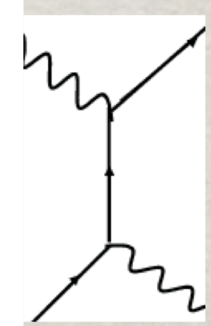
TH, Liu: 1210.7803;
Greco, TH, Liu: 1607.03210

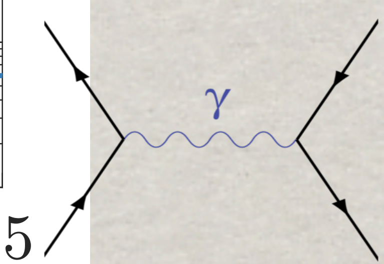
A Multi-TeV Muon Collider

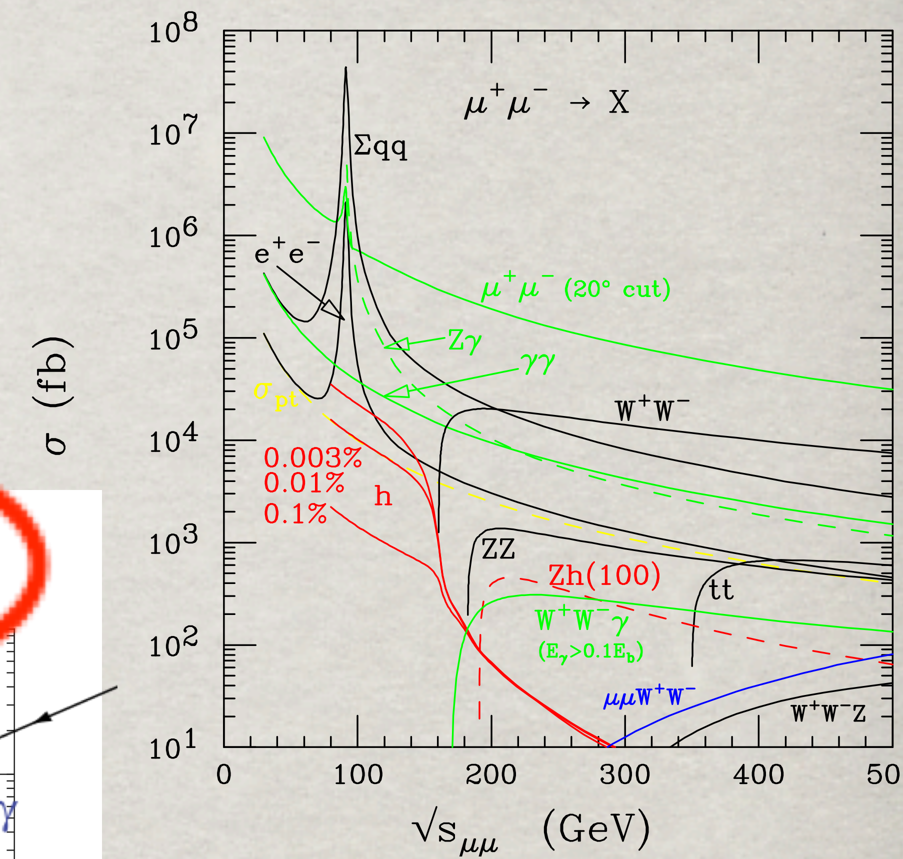
Exciting energy-frontier! What will happen when you turn on a $\mu^+\mu^-$ Smasher?

Leading-order $\mu^+\mu^-$ annihilation:



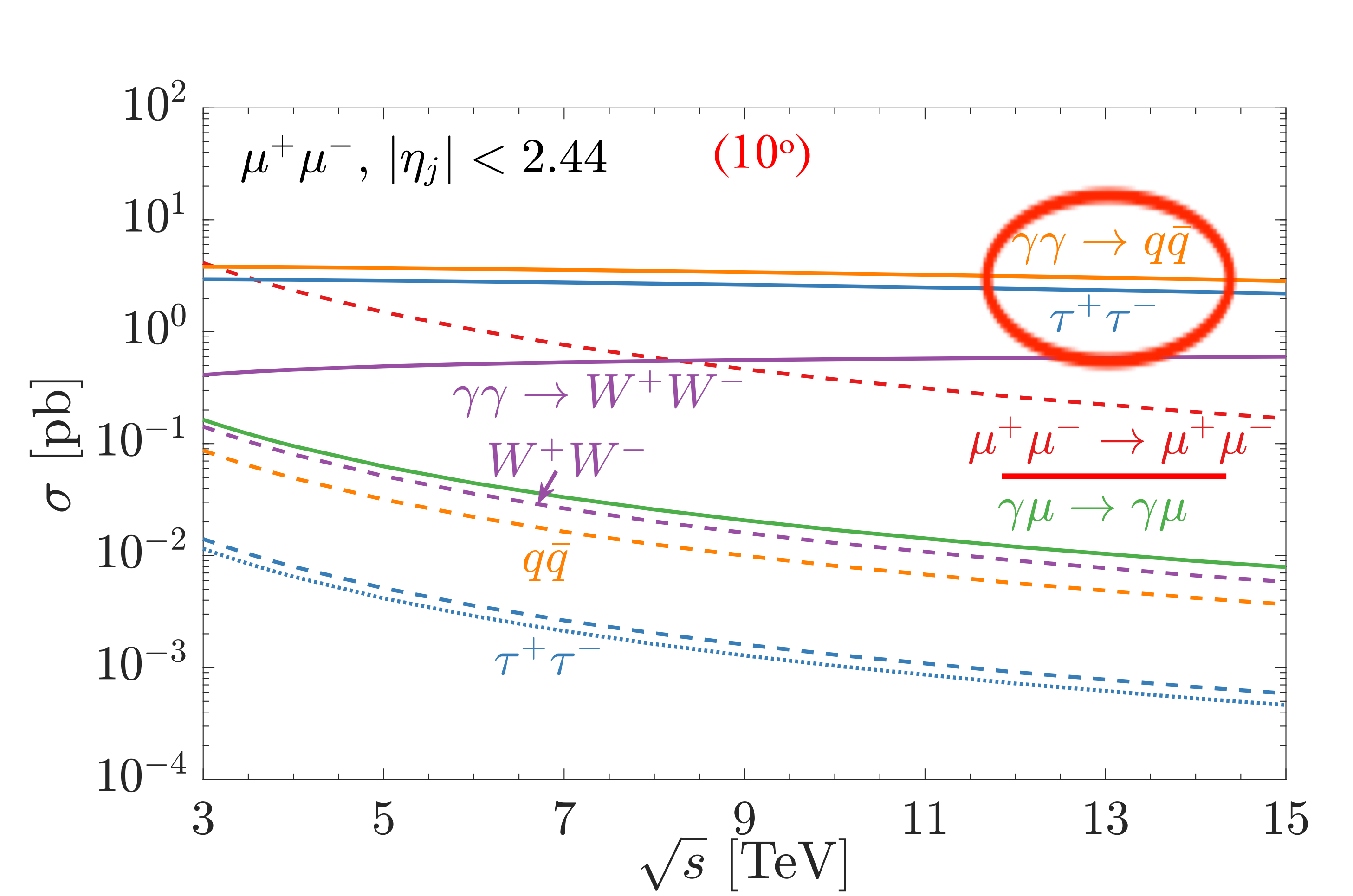


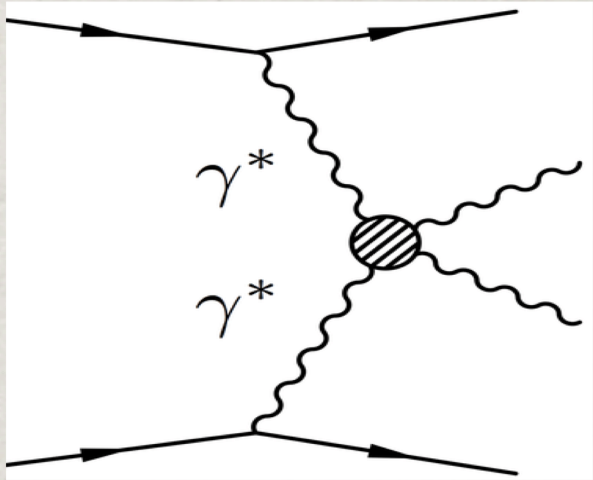




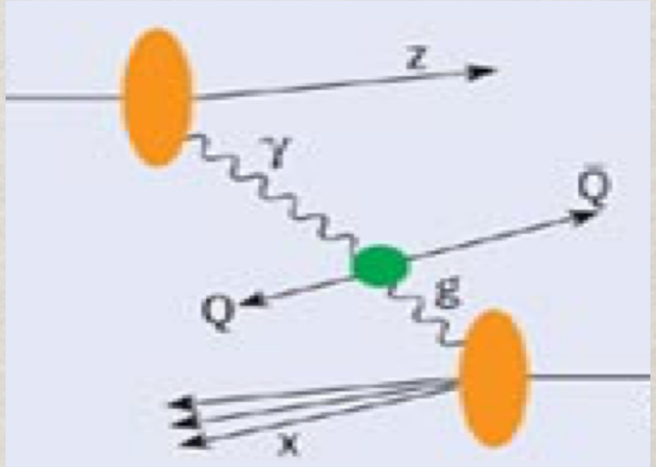
- # Photon-induced QED cross sections

large rates $\sigma_{fusion} \sim \frac{\alpha^2}{m_{jj}^2} \log^2(\frac{Q^2}{m^2})$





m_{jj}

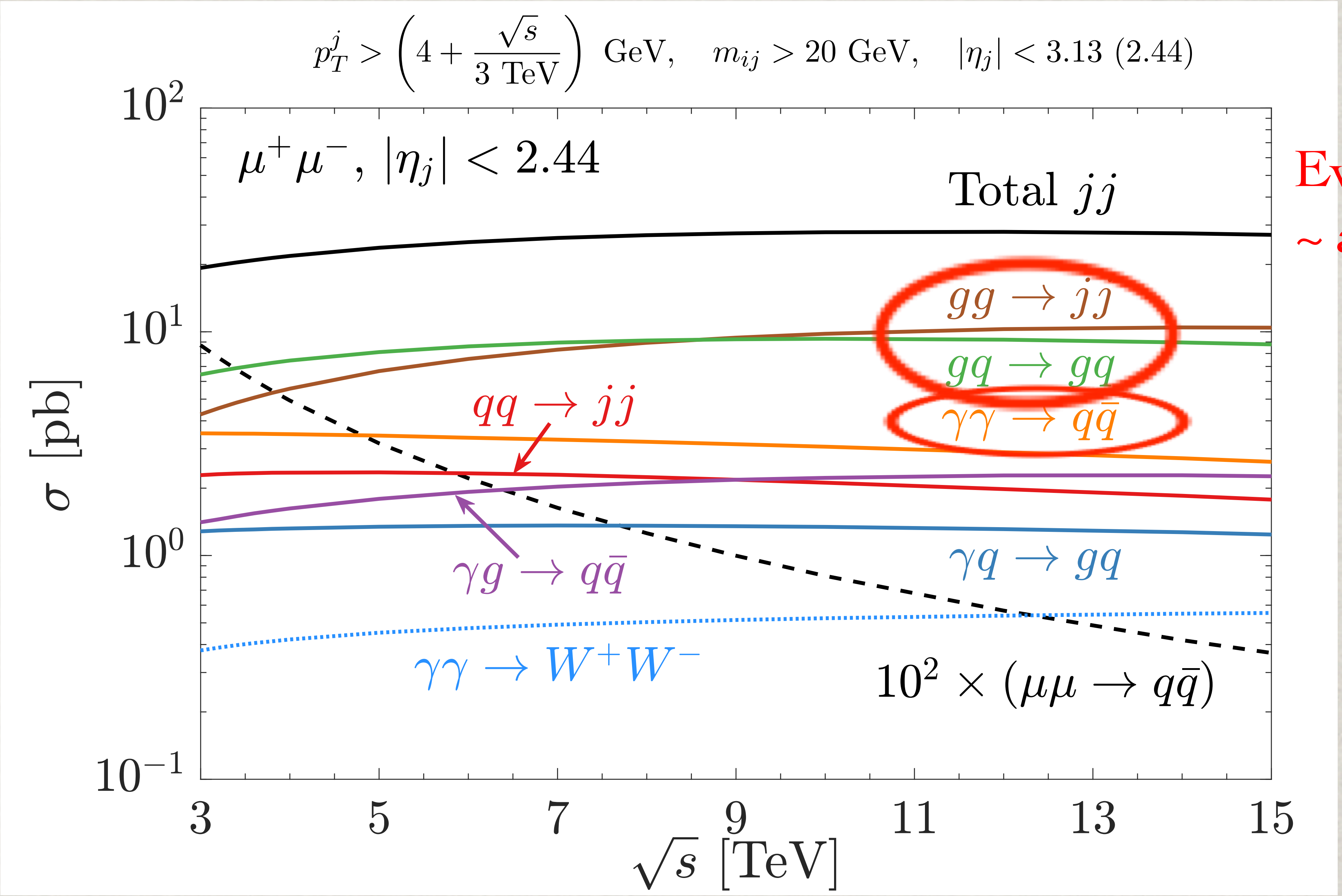


$$p_T^j > \left(4 + \frac{\sqrt{s}}{3\ \text{TeV}}\right)\ \text{GeV}, \quad m_{ij} > 20\ \text{GeV}, \quad |\eta_j| < 3.13\ (2.44)$$

Quarks/gluons come into the picture via SM DGLAP:

$$\frac{\mathrm{d}}{\mathrm{d}\log Q^2}\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \begin{pmatrix} P_{\ell\ell} & 0 & 0 & 2N_\ell P_{\ell\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma\ell} & P_{\gamma u} & P_{\gamma d} & P_{\gamma\gamma} & 0 \\ 0 & P_{gu} & P_{gd} & 0 & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix}$$

Di-jet production: $\gamma\gamma \to q\bar{q},\ \gamma g \to q\bar{q},\ \gamma q \to gq,$ $qq \to qq(gg),\ gq \to gq,$ and $gg \to gg(q\bar{q})$



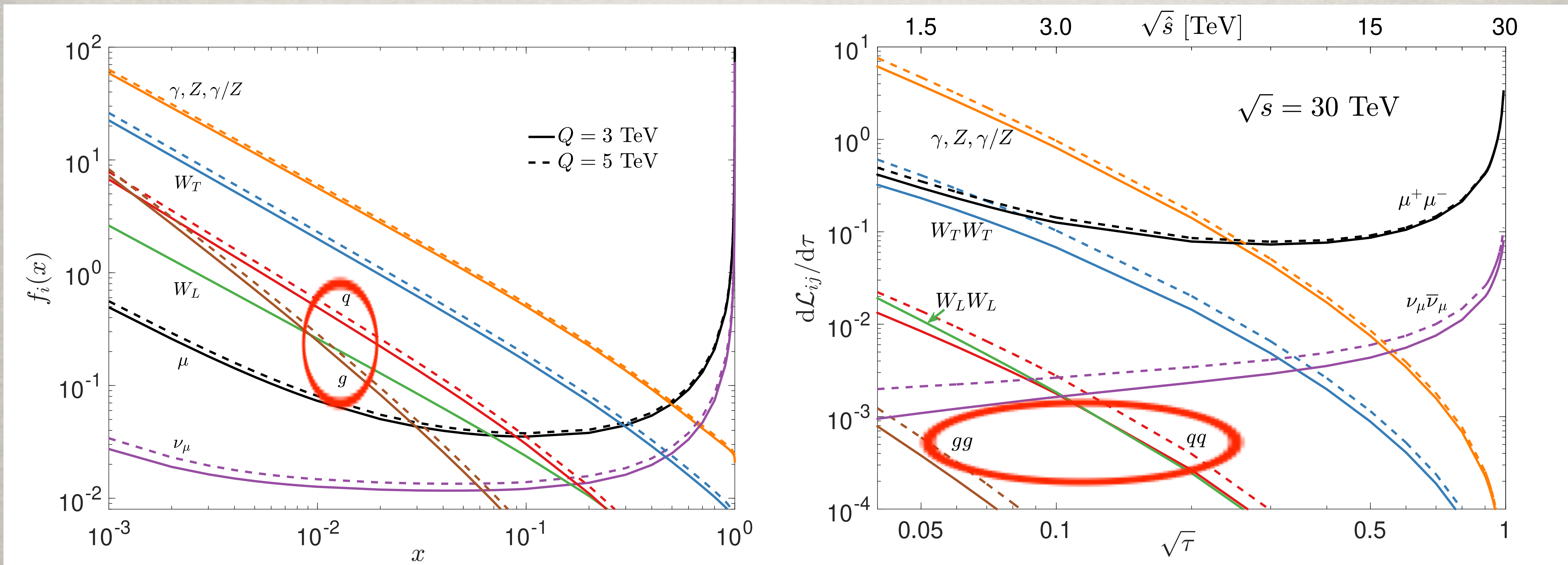
Event rate
~ a few Hz

- Jet production dominates at low energies
- EW processes take over for $p_T > 60$ GeV

TH, Yang Ma, Keping Xie, arXiv:2103.09844.

• EW PDFs at a muon collider:

"partons" dynamically generated $\frac{\mathrm{d} f_i}{\mathrm{d}\ln Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P^I_{i,j} \otimes f_j$



$\mu^\pm$: the valance. $\ell_R,\ \ell_L,\ \nu_L$ and $B, W^{\pm,3}$: LO sea.

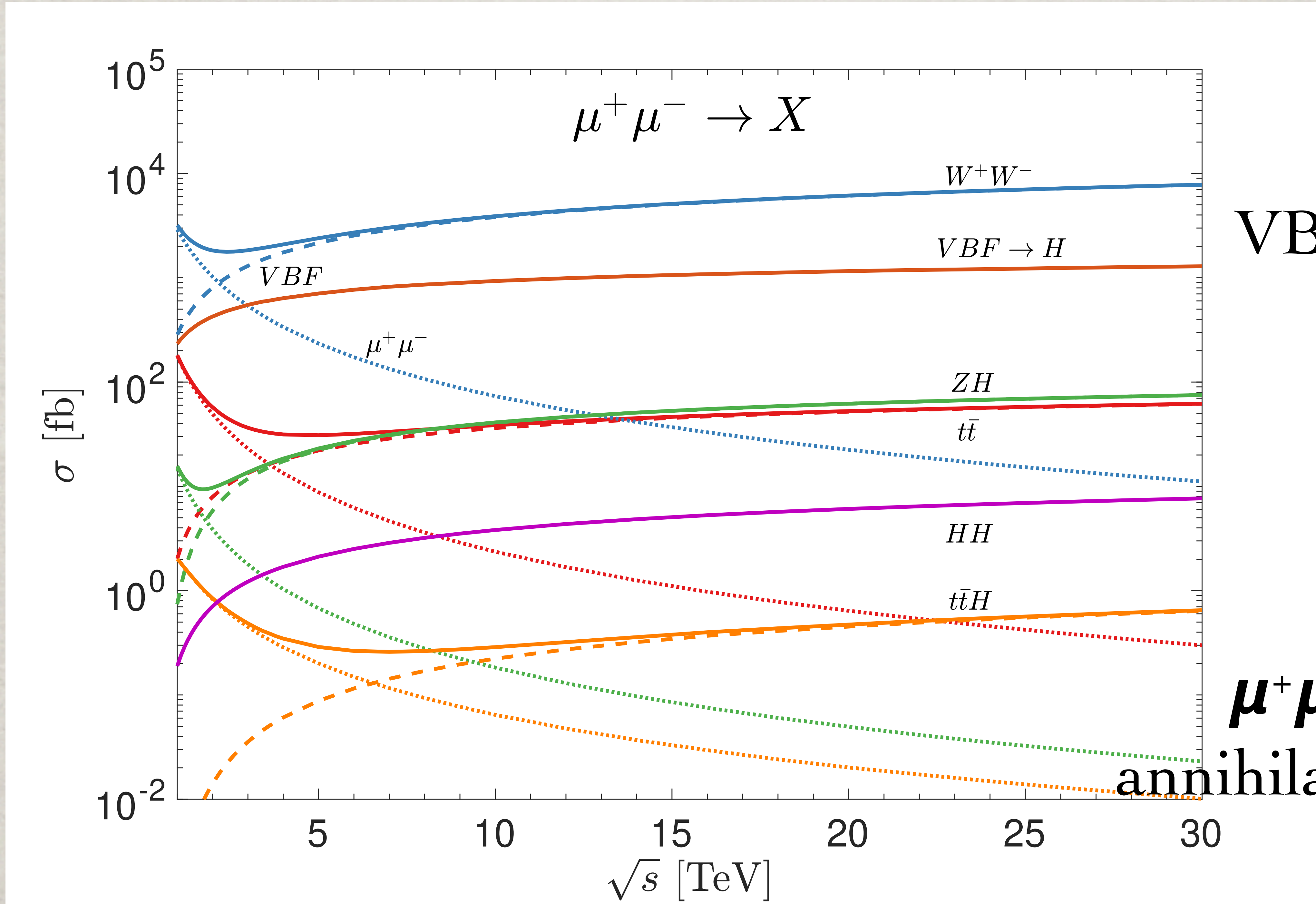
Quarks: NLO; gluons: NNLO.

TH, Yang Ma, Keping Xie, arXiv:2007.14300

- **"Semi-inclusive" processes**

Just like in hadronic collisions:

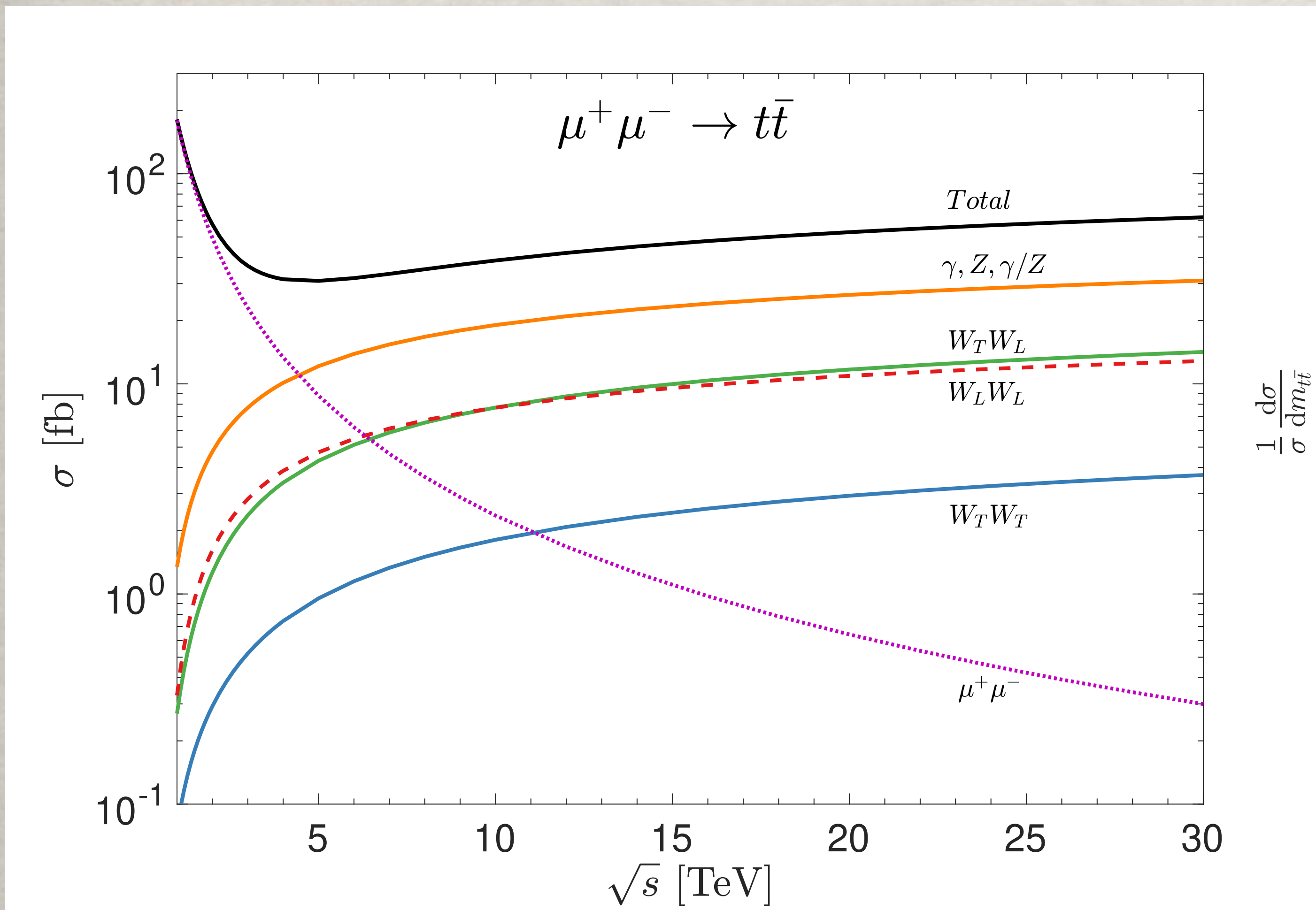
$\mu^+\mu^-$ → exclusive particles + remnants

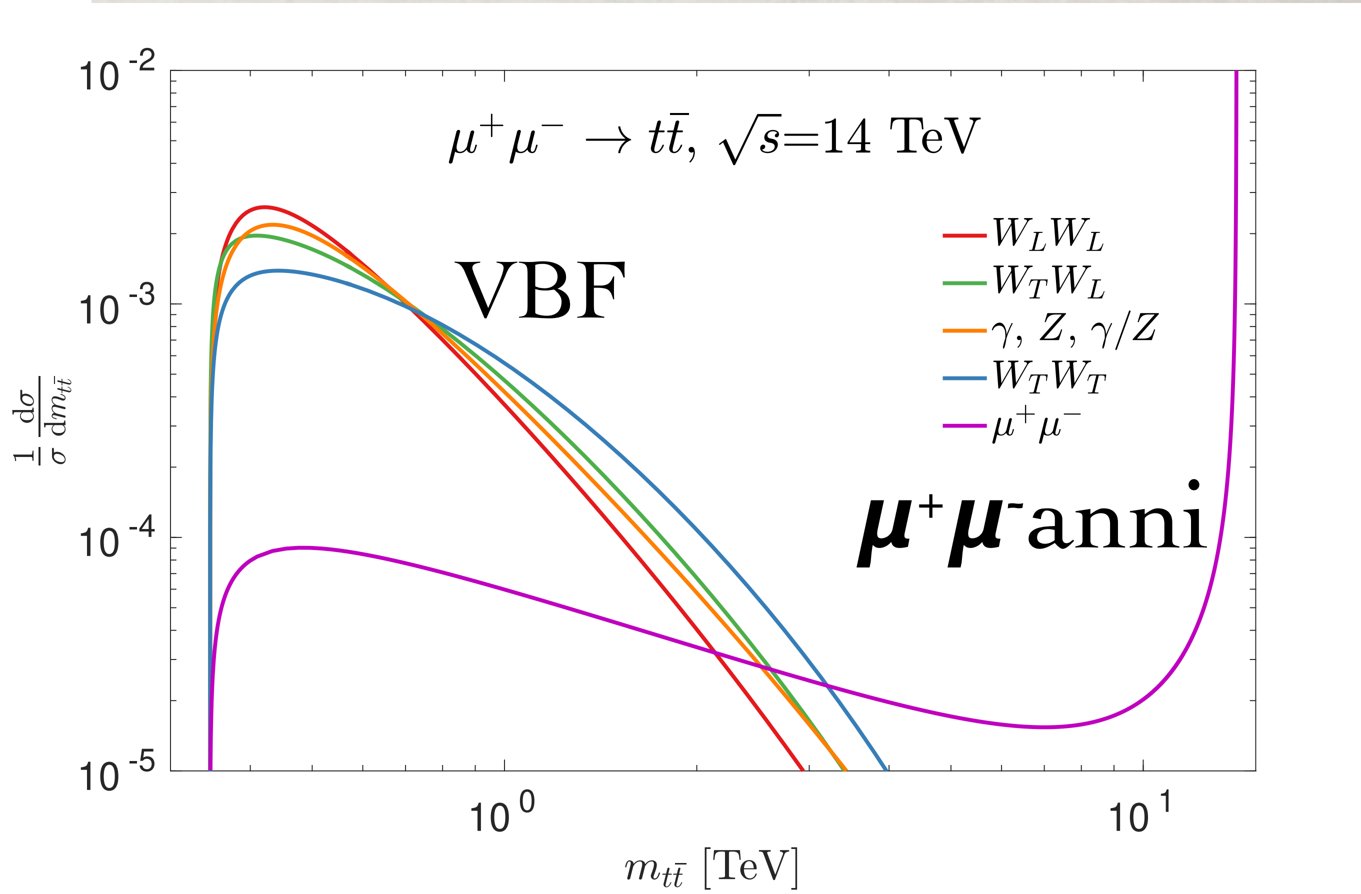


VBF

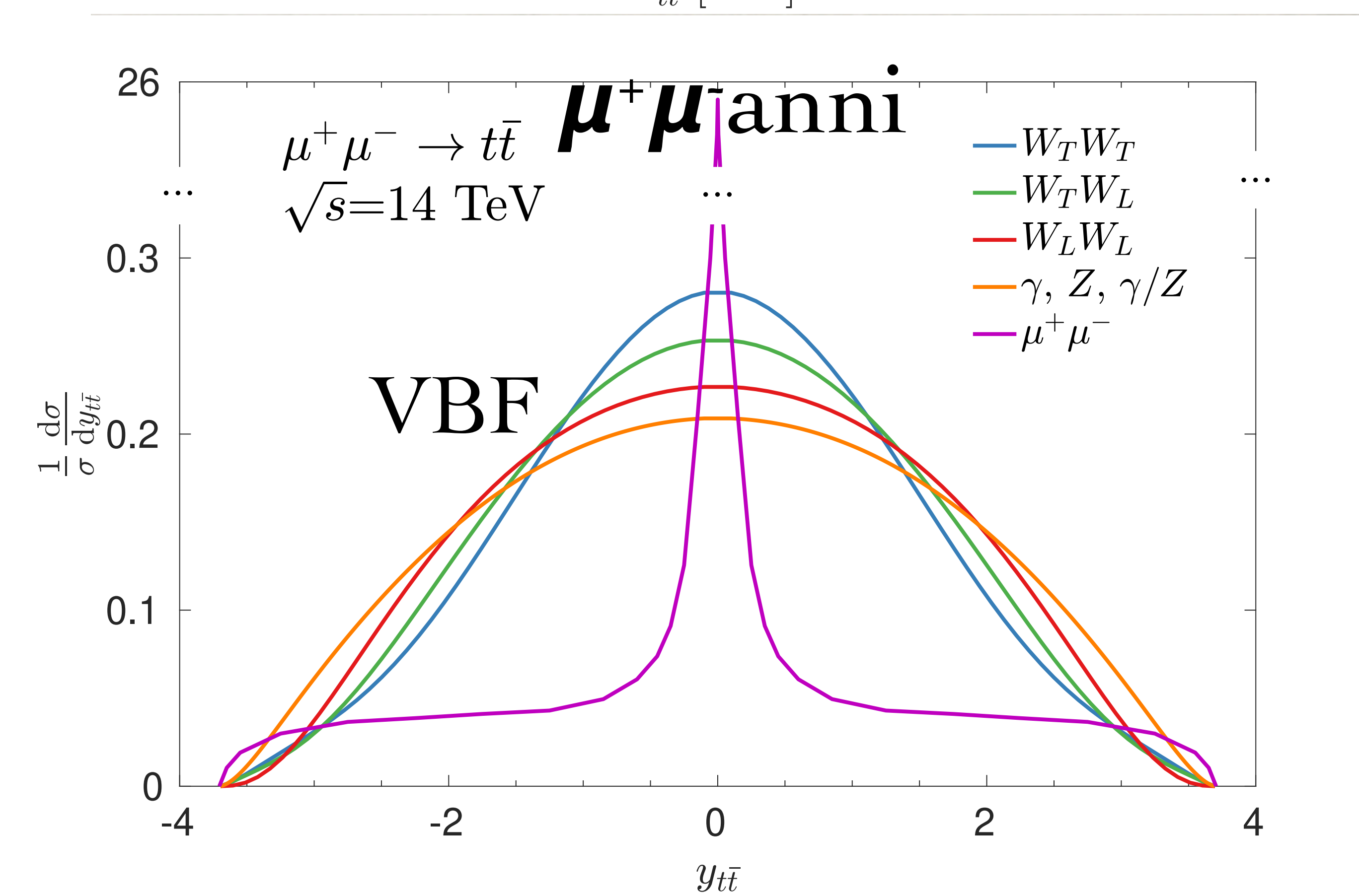
$\mu^+\mu^-$ annihilations

• Underlying sub-processes:





Partonic contributions



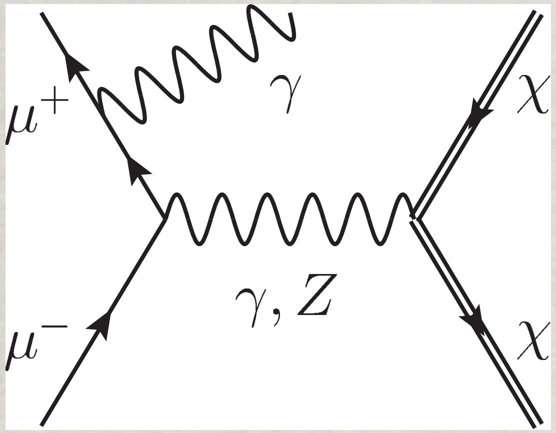
$\mu^+\mu^-$ Collider:
"Buy one, get one free"
Annihilation + VBF

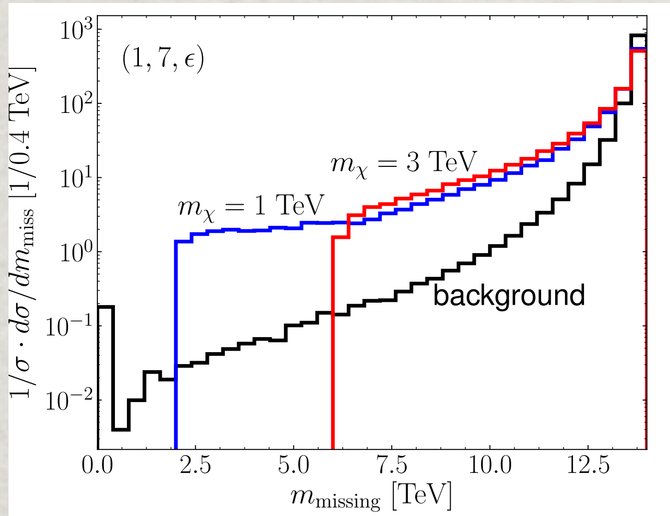
• Unique kinematic features:

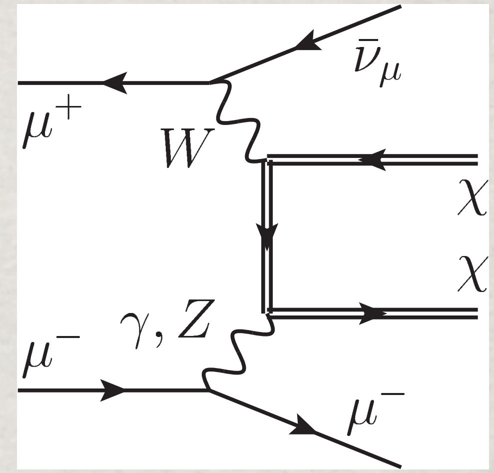
• “Recoil mass” → “missing mass”: $m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$

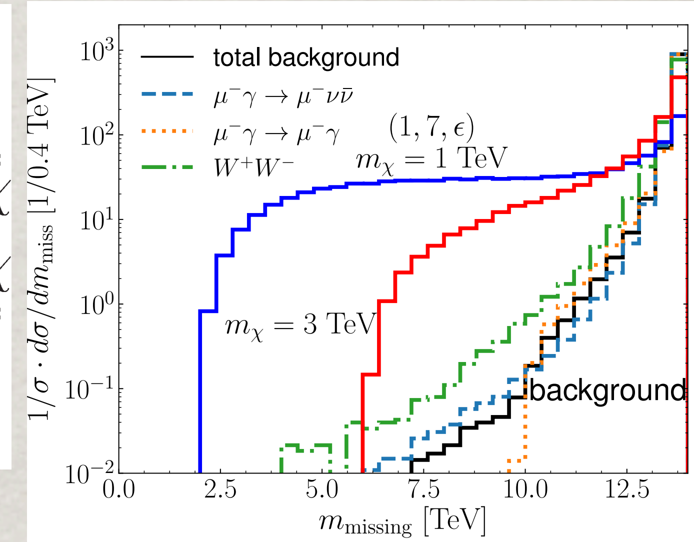
$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4m_\chi^2$

$m^2_{\text{missing}} = (p^{\text{in}}_{\mu^+} + p^{\text{in}}_{\mu^-} - p^{\text{out}}_{\mu^\pm})^2 > 4m_\chi^2.$



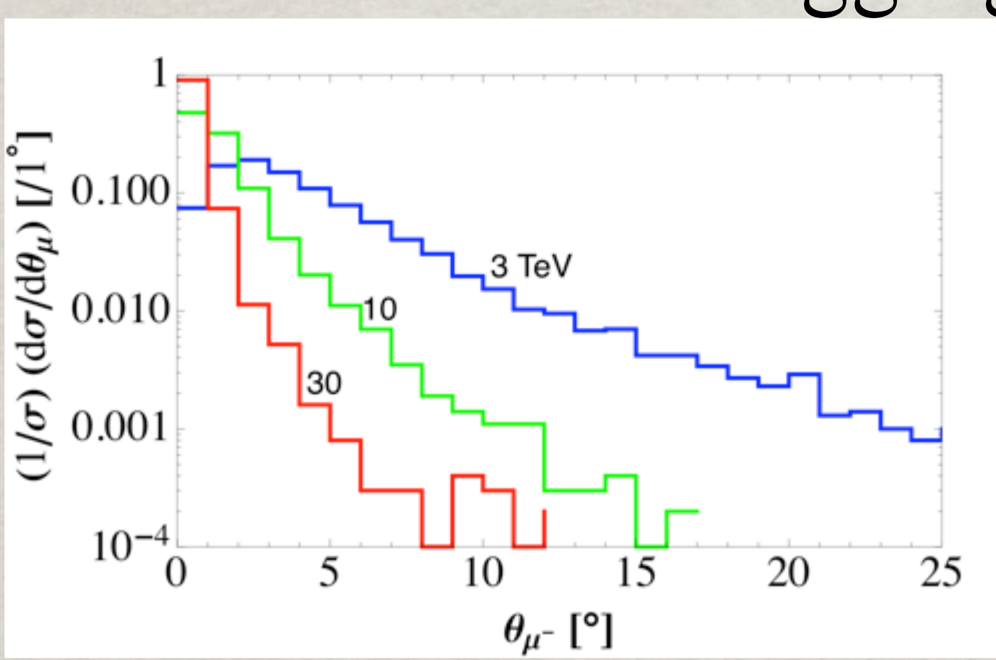


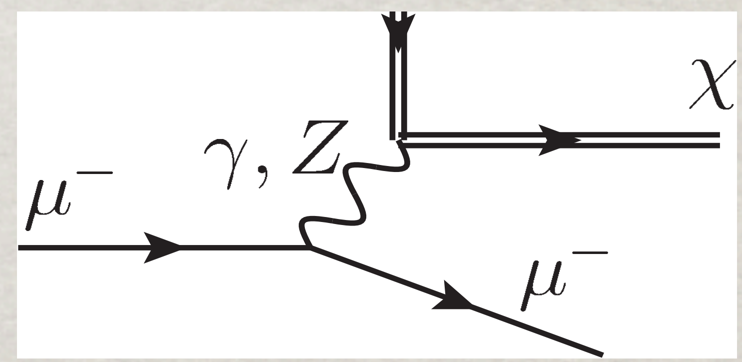




Unavailable in hadronic collisions!

• Forward tagging:





$\theta_\mu \approx M_Z/E_\mu \quad \theta_\mu \sim 0.02 \approx 1.2^\circ$ at 10 TeV.

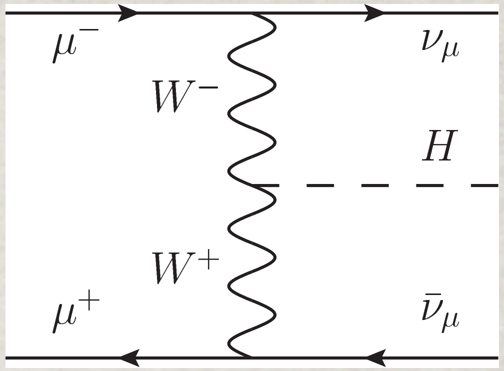
Tagging is costly:
forward detector ?

TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

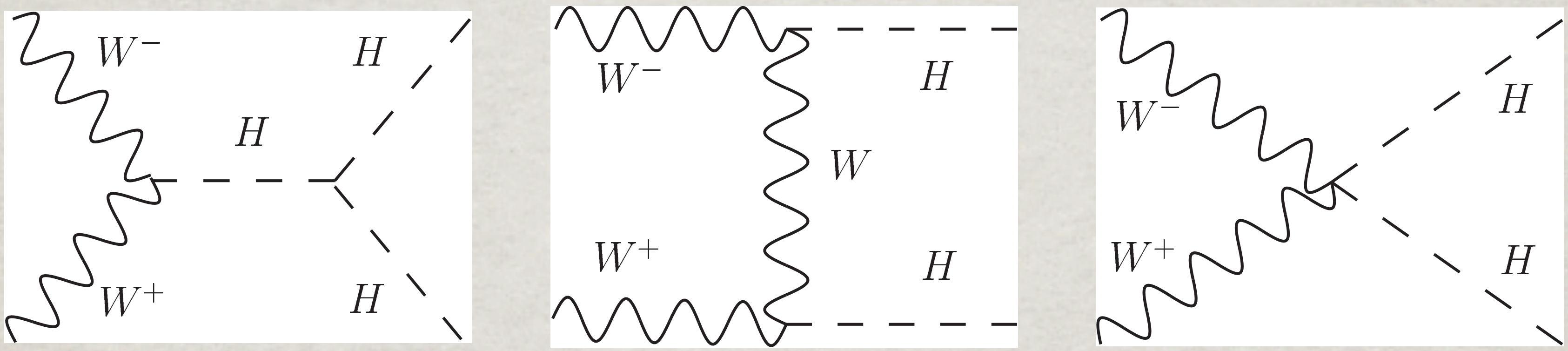
• Precision Higgs Physics

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu \; H \qquad (WW \text{ fusion}),$$
$$\mu^+\mu^- \to \mu^+\mu^- \; H \qquad (ZZ \text{ fusion}).$$



WWH / ZZH couplings

HHH / WWHH couplings:



(a) (b) (c)

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZH$	9.5	22	33	42	67
$WW \to t\bar{t}H$	0.012	0.046	0.090	0.14	0.28
$WW \to Z$	2200	3100	3600	4200	5200
$WW \to ZZ$	57	130	200	260	420

10M H

500k HH

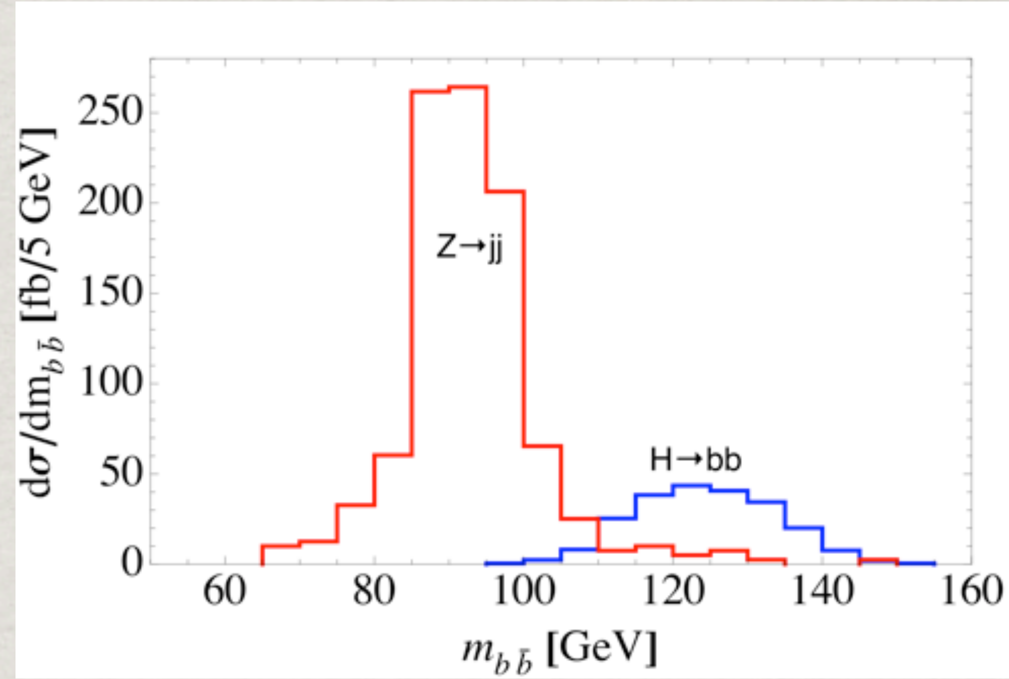
TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

Achievable accuracies

Leading channel H → bb:

$$\Delta E/E = 10\%.$$

$$10^\circ < \theta_{\mu^\pm} < 170^\circ.$$



$$\mathcal{L} \supset \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left(\kappa_V \frac{2H}{v} + \kappa_{V_2}\frac{H^2}{v^2}\right) - \frac{m_H^2}{2v}\left(\kappa_3 H^3 + \frac{1}{4v}\kappa_4 H^4\right)$$

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Table 7: Summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

 TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

• WIMP Dark Matter (a conservative SUSY scenario)

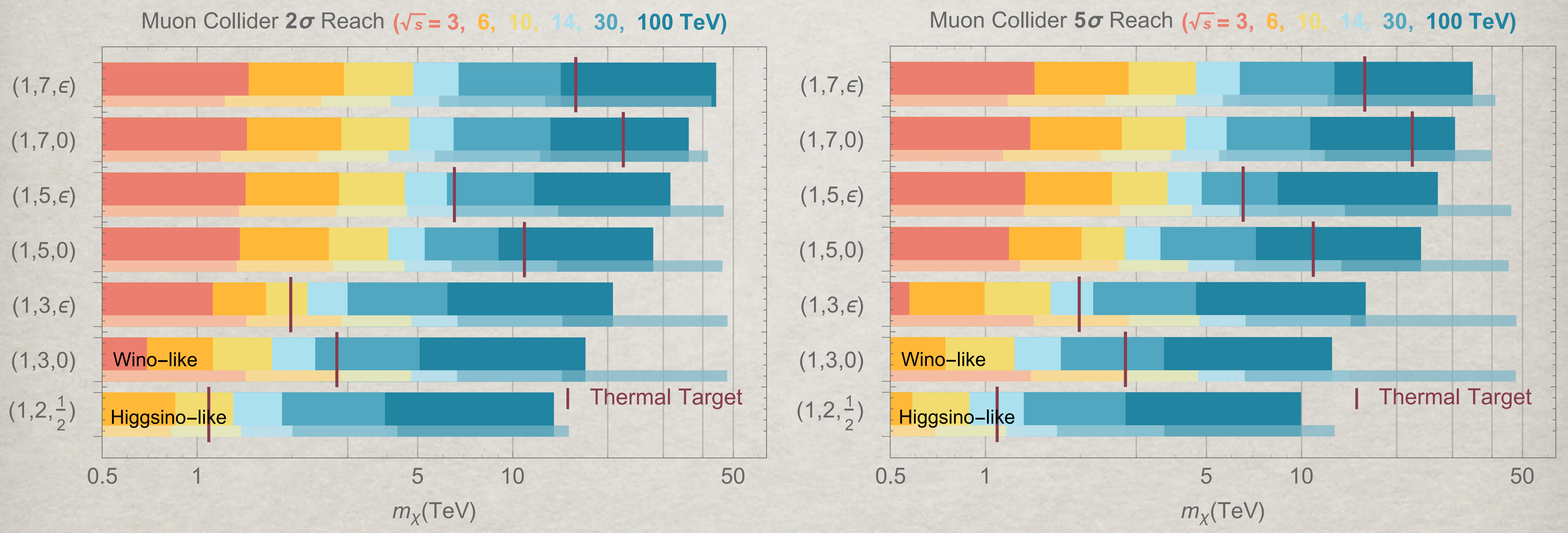
Consider the "minimal EW dark matter": an EW multi-plet

- The lightest neutral component as DM
- Interactions well defined → pure gauge
- Mass upper limit predicted → thermal relic abundance

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

Cirelli, Fornengo and Strumia: hep-ph/0512090, 0903.3381;
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

The mass reach for minimal WIMP DM:



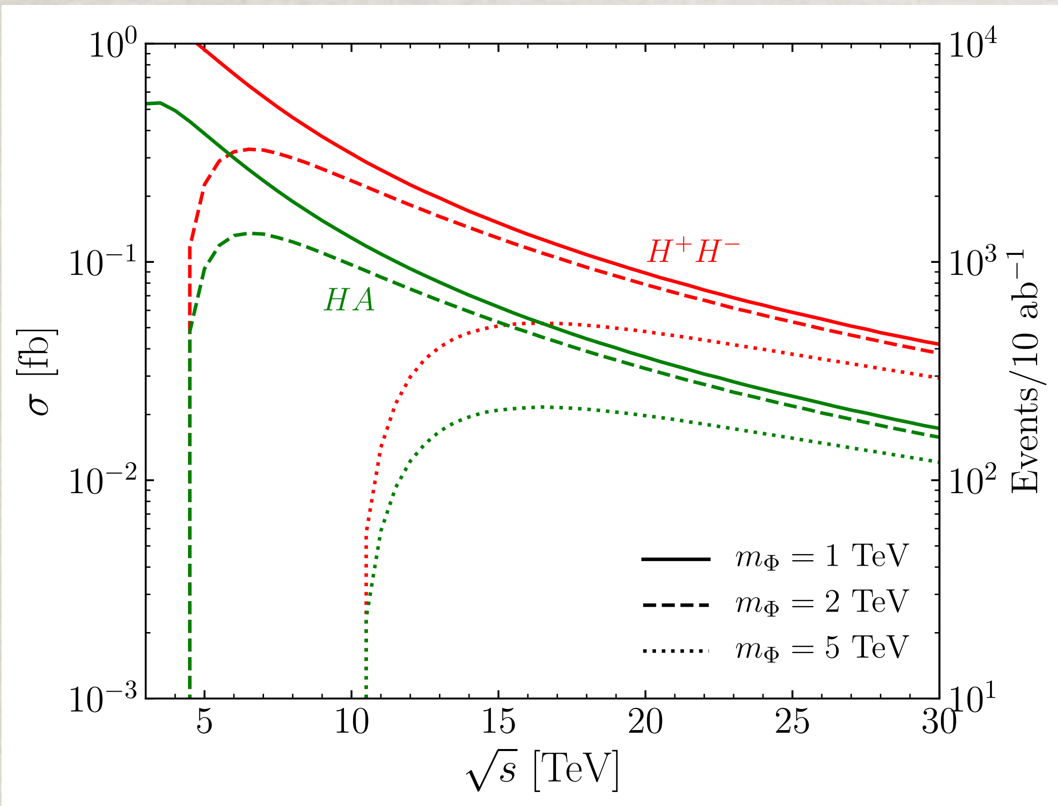
$E_{CM} \approx 14$ TeV enough to cover n≤3 multiplets.

Higher energy needed to cover higher multiplets.

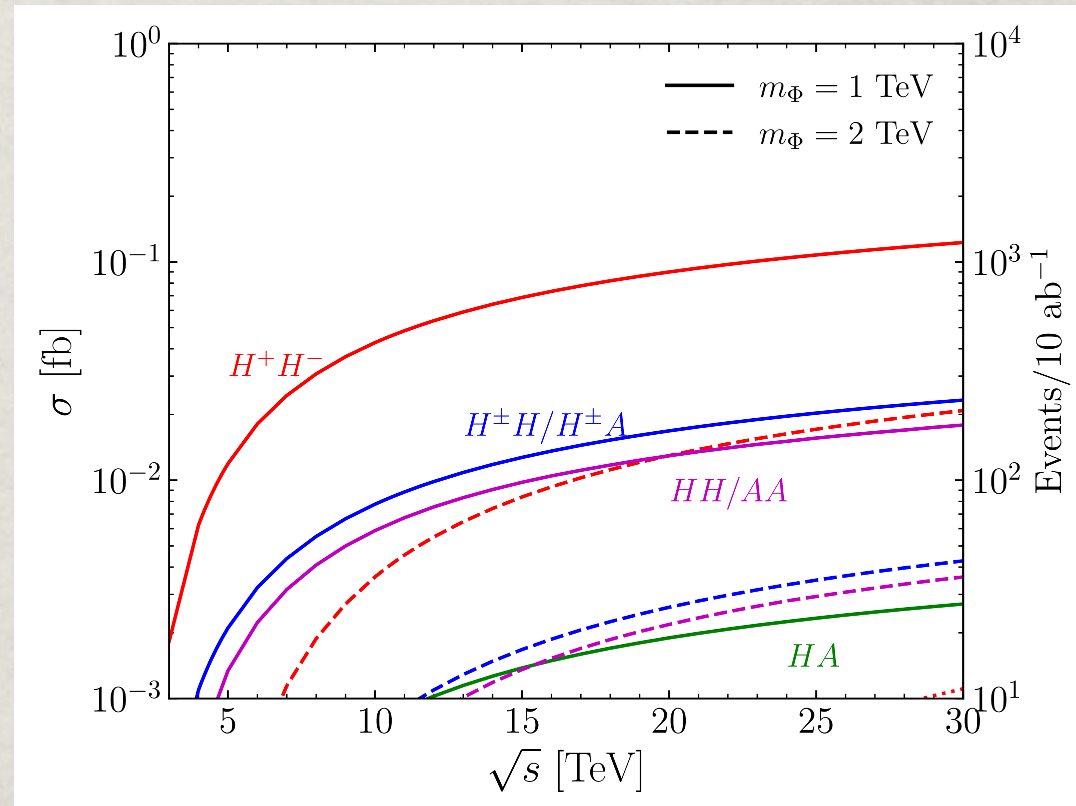
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

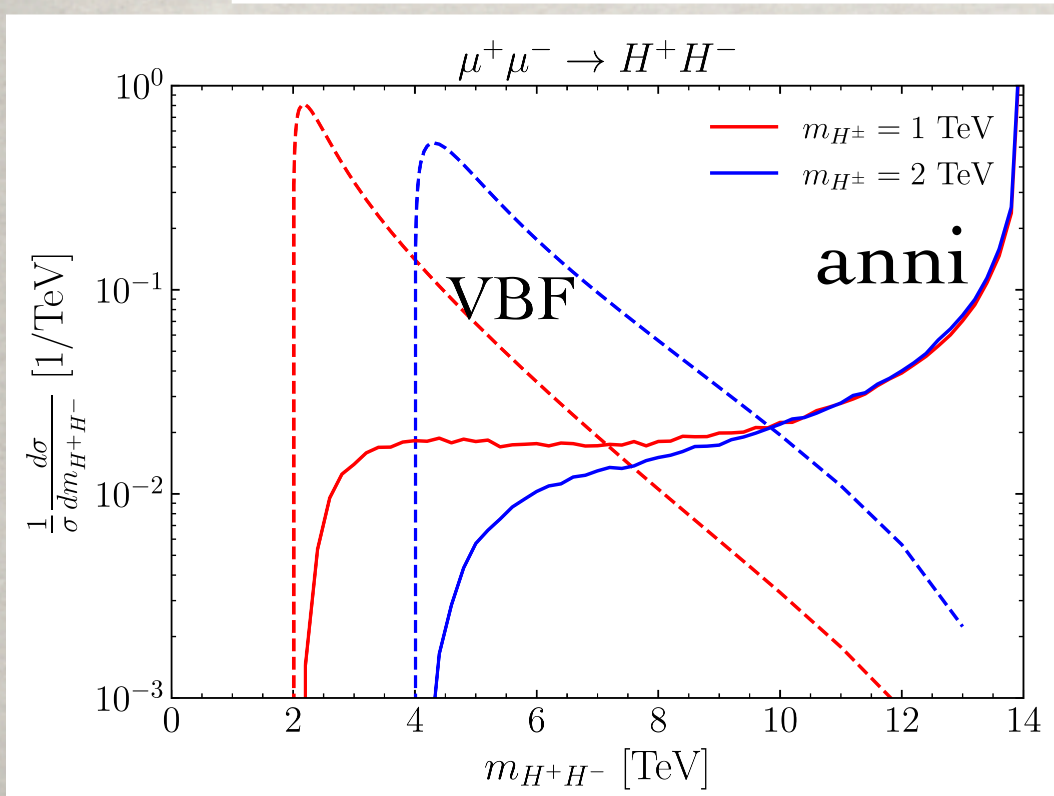
• Heavy Higgs Bosons Production

annihilation



VBF

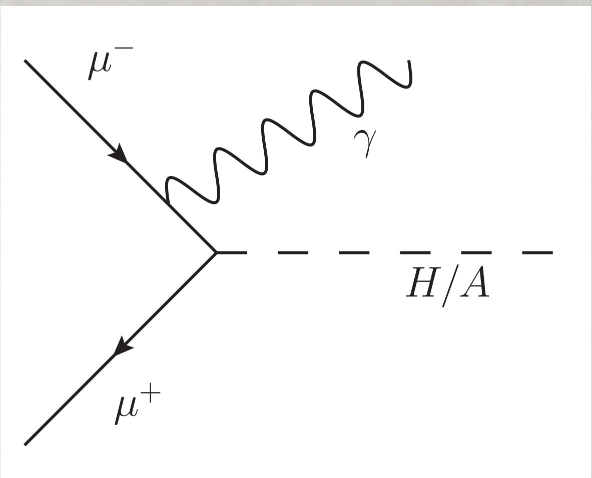


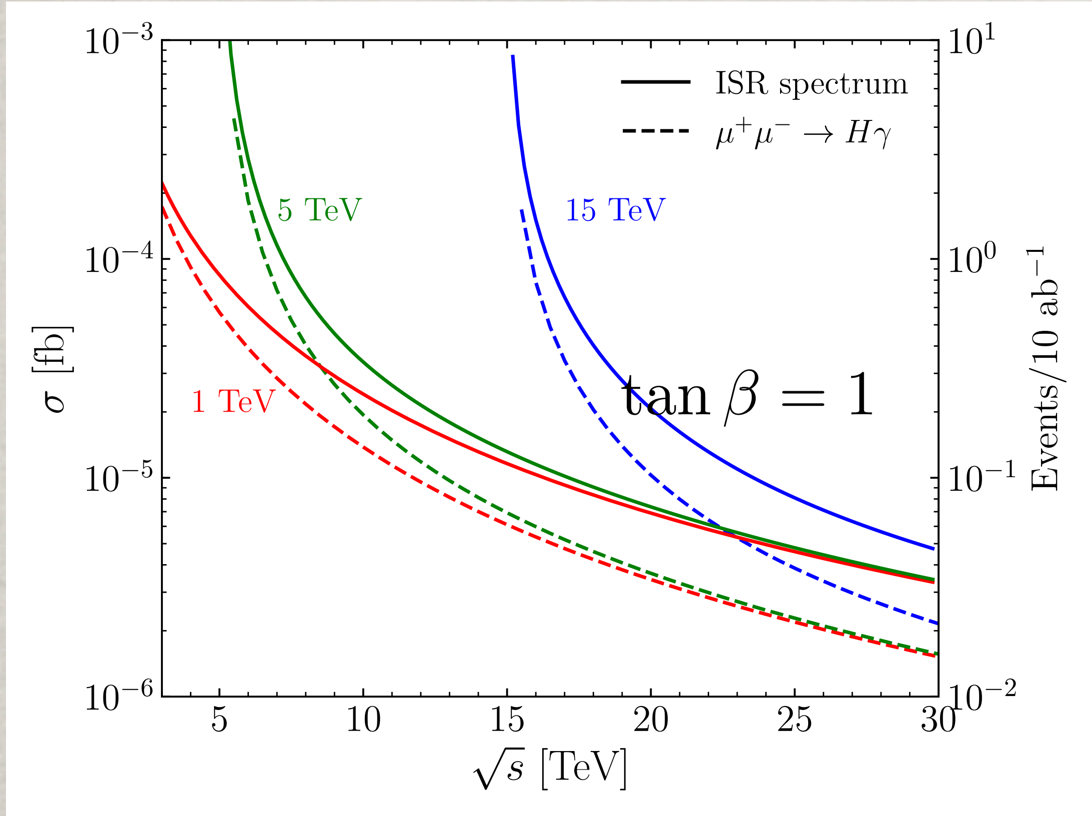


	production	Type-I	Type-II	Type-F	Type-L
small $\tan\beta < 5$	H^+H^-	$t\bar{b}, \bar{t}b$			
	$HA/HH/AA$	$t\bar{t}, t\bar{t}$			
	$H^\pm H/A$	$tb, t\bar{t}$			
intermediate $\tan\beta$	H^+H^-	$t\bar{b}, \bar{t}b$			$tb, \tau\nu_\tau$
	$HA/HH/AA$	$t\bar{t}, t\bar{t}$	$t\bar{t}, b\bar{b}$		$t\bar{t}, \tau^+\tau^-$
	$H^\pm H/A$	$tb, t\bar{t}$	$tb, t\bar{t}$; $tb, b\bar{b}$		$tb, t\bar{t}$; $tb, \tau^+\tau^-$; $\tau\nu_\tau, t\bar{t}$; $\tau\nu_\tau, \tau^+\tau^-$
large $\tan\beta > 10$	H^+H^-	$t\bar{b}, \bar{t}b$	$tb, tb(\tau\nu_\tau)$	$t\bar{b}, \bar{t}b$	$\tau^+\nu_\tau, \tau^-\nu_\tau$
	$HA/HH/AA$	$t\bar{t}, t\bar{t}$	$b\bar{b}, b\bar{b}(\tau^+\tau^-)$	$b\bar{b}, b\bar{b}$	$\tau^+\tau^-, \tau^+\tau^-$
	$H^\pm H/A$	$tb, t\bar{t}$	$tb(\tau\nu_\tau), b\bar{b}(\tau^+\tau^-)$	$tb, b\bar{b}$	$\tau^\pm\nu_\tau, \tau^+\tau^-$

TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386.

Radiative returns:

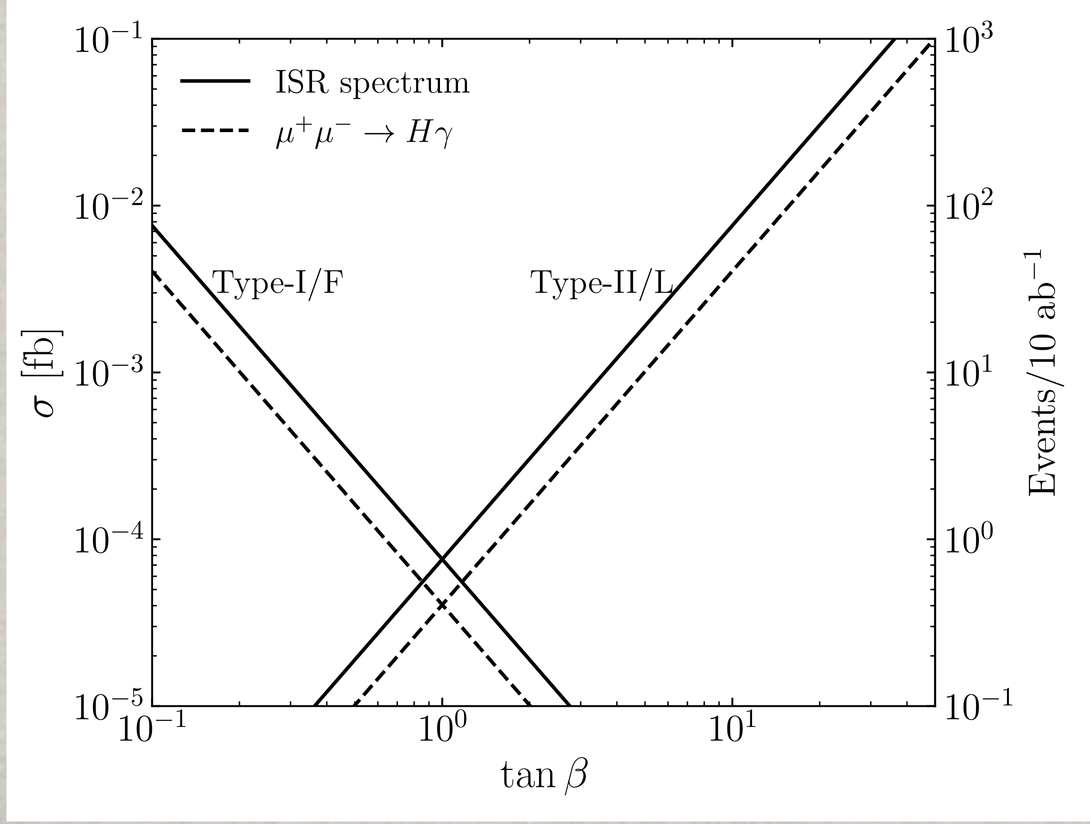




$$\hat{\sigma}(\mu^+\mu^- \to H) = \frac{\pi Y_\mu^2}{4}\delta(\hat{s} - m_H^2) = \frac{\pi Y_\mu^2}{4s}\delta(\tau - \frac{m_H^2}{s})$$

$$f_{\ell/\ell}(x) = \frac{\alpha}{2\pi}\frac{1+x^2}{1-x}\log\frac{s}{m_\mu^2}$$

$$\sigma = 2\int dx_1 f_{\ell/\ell}(x_1)\hat{\sigma}(\tau = x_1) = \frac{\alpha Y_\mu^2}{4s}\frac{s + m_H^4/s}{s - m_H^2}\log\frac{s}{m_\mu^2}$$



Depending on the coupling,

$M_H \sim E_{cm}$

TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386;
TH, Z. Liu et al., arXiv:1408.5912.

Lots of recent works!
-- my apologies not to cover properly

D. Buttazzo, D. Redogolo, F. Sala, arXiv:1807.04743 (VBF to Higgs)
A. Costantini, F. Maltoni, et al., arXiv:2005.10289 (VBF to NP)
M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini, and X. Zhao, arXiv:2005.10289 (SM Higgs)
R. Capdevilla, D. Curtin, Y. Kahn, G. Krnjaic, arXiv:2006.16277; arXiv:2101.10334 (g-2, flavor)
P. Bandyopadhyay, A. Costantini et al., arXiv:2010.02597 (Higgs)
D. Buttazzo, P. Paradisi, arXiv:2012.02769 (g-2)
W. Yin, M. Yamaguchi, arXiv:2012.03928 (g-2)
R. Capdevilla, F. Meloni, R. Simoniello, and J. Zurita, arXiv:2012.11292 (MD)
D. Buttazzo, F. Franceschini, A. Wulzer, arXiv:2012.11555 (general)
G.-Y. Huang, F. Queiroz, W. Rodejohann, arXiv:2101.04956; arXiv:2103.01617 (flavor)
W. Liu, K.-P. Xie, arXiv:2101.10469 (EWPT)
H. Ali, N. Arkani-Hamed, et al, arXiv:2103.14043 (Muon Smasher's Guide)
Richard Ruiz et al., arXiv:2111.02442 (MadGraph5)
… …

Summary: "Who ordered That?"

The muon is such a pleasant surprise Nature offers us!

- **Leads to many discoveries**
- **Provides deeper understanding of Nature**
- **Continues to play a key role in going forward**

Based on Snowmass 2013, the 2014 P5 summary list:

all involves with muon physics →

	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown
Large Projects					
Muon program: Mu2e, Muon g-2					✓
HL-LHC	✓		✓		✓
LBNF + PIP-II		✓			✓
ILC	✓		✓		✓
NuSTORM		✓			
Medium Projects					
MAP	✓	✓	✓		✓

Muon physics has taken many spot-lights at Snowmass 2021!

Look forward to more surprises with muons!