Why building a muon collider

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Ideology

HEP before the LHC

HEP before the F.C.

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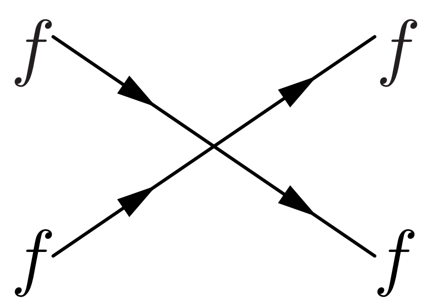
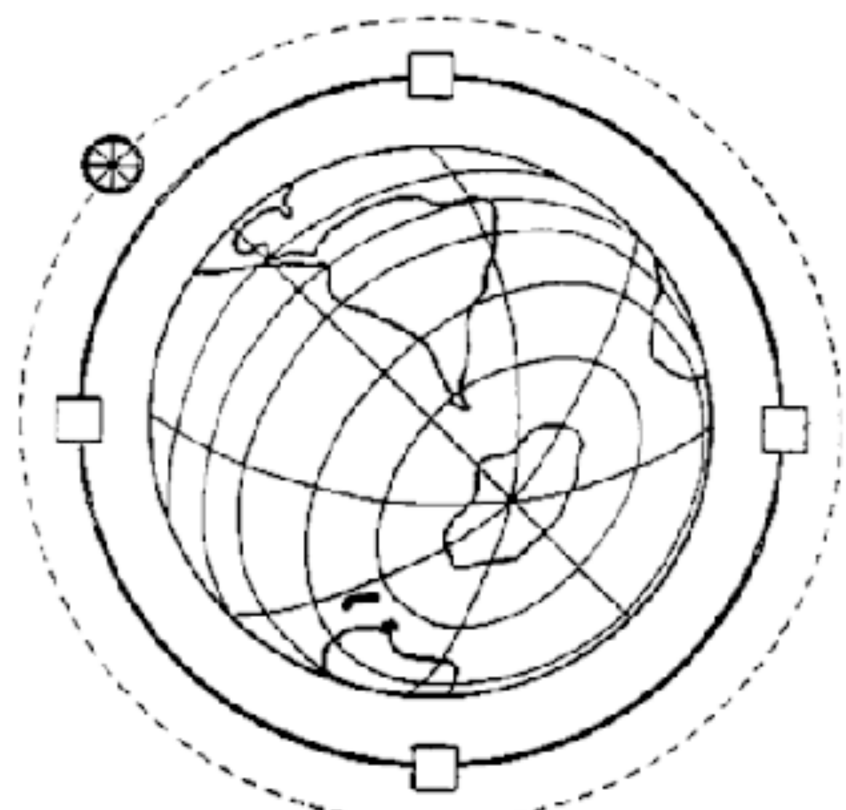


$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v$$

Ultimate Accelerator.

Drawn by Fermi in the ’50 to reach 3 TeV.

The manifesto of HEP!



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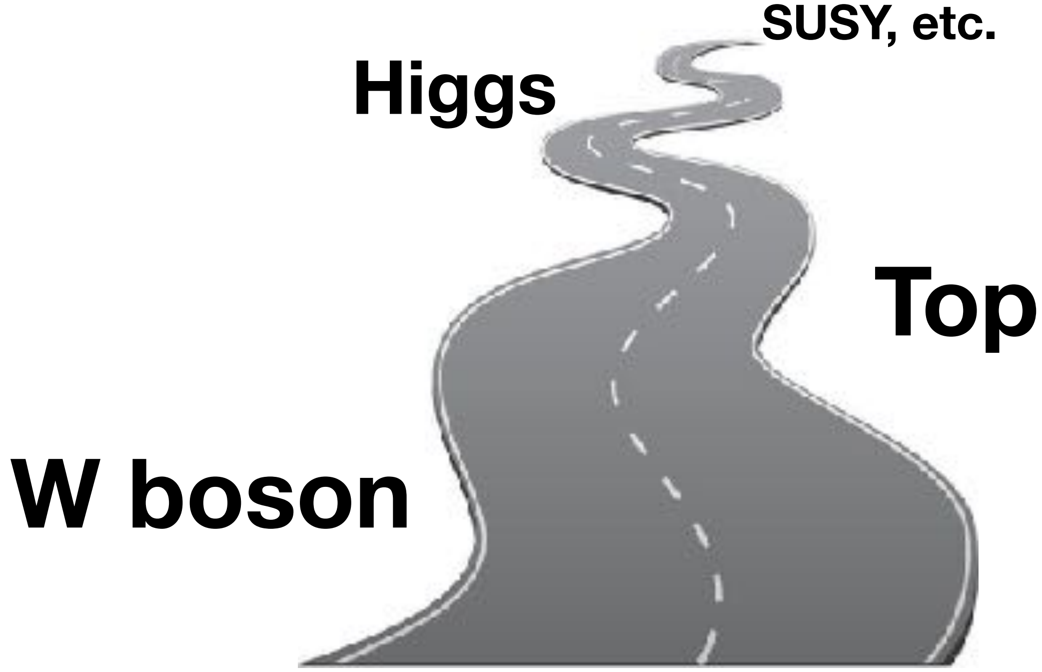

HEP before the F.C.

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories** *

* Not necessarily a bad thing. Columbus left for his trip just because he had no idea of where he was going !!

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The next big FC **will exist only if** capable to **explore many directions**, and be **conclusive** on some of those

Naturalness

"Is m_H Unnatural?" $=$ "Is m_H Unpredictable?"

$$\left(m_H^2\right)_{Phys.} = \int_0^{\infty} F_{true}(E;\, g_{true})$$

UV Contribution
$c\,\Lambda_{\rm SM}{}^2$

$$= \int_0^{\Lambda_{\rm SM}} (\ldots) + \int_{\Lambda_{\rm SM}}^{\infty} (\ldots)$$

SM Contribution
$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda_{\rm SM}{}^2$$

Fine Tuning: $\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\rm SM}}{500\,\mathrm{GeV}}\right)^2$

Measures how much Unpredictable m_H is.

Unnaturalness is a challenge to **Reductionism**

Dramatic paradigm shift. E.g. Anthropic or Dynamical

Naturalness

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LHC may push conventional Natural models to

$$\Lambda_{\mathrm{SM}} \gtrsim 2\ \mathrm{TeV} \longrightarrow \Delta \gtrsim 10$$

Still Naturalness might be there in the form of:

Partial Unnaturalness

$$\Delta \sim 100$$

$$\downarrow$$

$$\Lambda_{\mathrm{SM}} \sim 5\ \mathrm{TeV}$$

Neutral Naturalness

$$\Delta \sim \text{few} \longrightarrow \Lambda_{\mathrm{SM}}^{\mathrm{col.}} \sim 5\ \mathrm{TeV}$$

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$$\Lambda_{\mathrm{SM}}^{\mathrm{neut.}} \lesssim 1\ \mathrm{TeV}$$

Need **5 TeV** reach on ordinary Top Partners

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Still, the higher the reach, the better

Dark Matter

The FC should be capable to tell if DM is **WIMP** *

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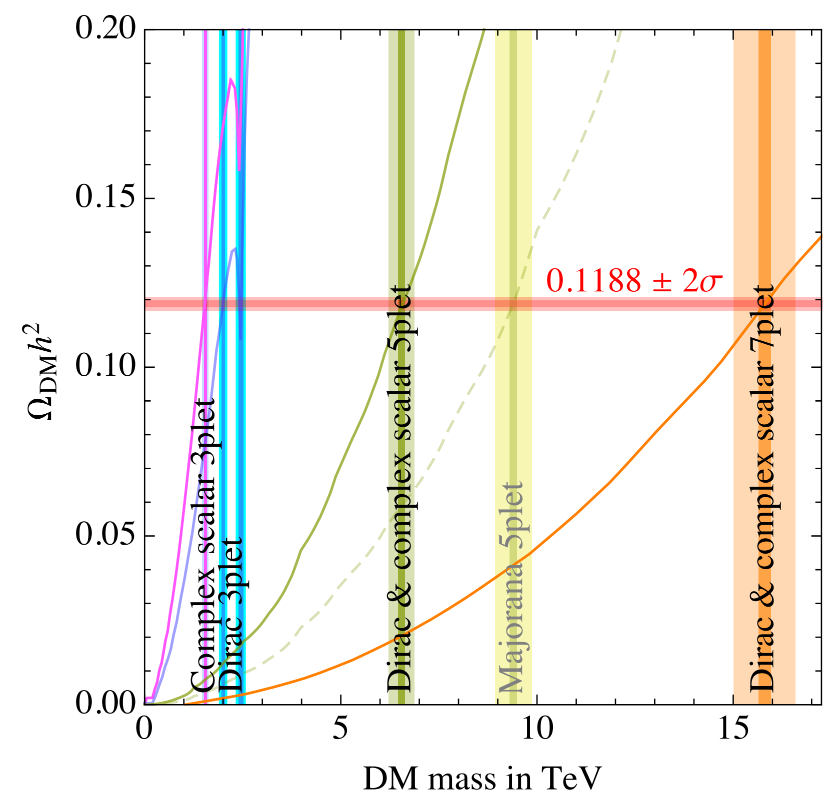
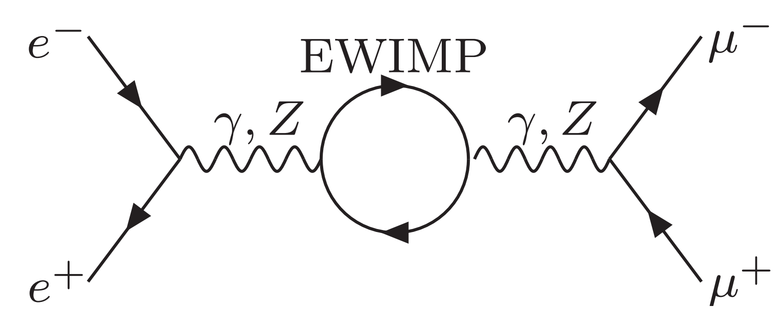
Accidental DM: stability from **accidental symmetries**

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$ *	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$ **	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16



Searched for directly, but also indirectly



EW Baryogenesis

Our knowledge of the Higgs sector is so **limited** that **we cannot tell** if EW phase transition was first order

This requires BSM states (possibly neutral) coupled to Higgs. Typically connected with trilinear Higgs.

The FC must be conclusive on this possibility.

If Everything Fails

The FC must have indirect reach superior to direct one, on BSM scale, by at least a few

EFT

$\mathcal{L}^{d=6}$

Low-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\rm EW}^2/\Lambda^2$

- require **accuracy:** large lumi, low syst. and th. err

High-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- benefit from high **energy and** high **accuracy**

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Measurements also **characterise new physics**, if discovered.

Muon Colliders

Much better direct reach than hadron colliders !

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Lepton coll. operating at energy $\sqrt{s_L}$.
Cross section for reaction at $E \sim \sqrt{s_L}$
(e.g., production of BSM with $M \sim \sqrt{s_L}$)

$$\sigma_L(s_L) = \frac{1}{s_L}\left[\hat{s}\hat{\sigma}\right]_L$$

Hadron coll. operating at energy $\sqrt{s_H}$.
Cross section for reaction at E.
Parton Luminosity suppression

$$\sigma_H(E, s_H) = \frac{1}{s_H}\int_{E^2/s_H}^{1}\frac{d\tau}{\tau}\frac{dL}{d\tau}\left[\hat{s}\hat{\sigma}\right]_H$$

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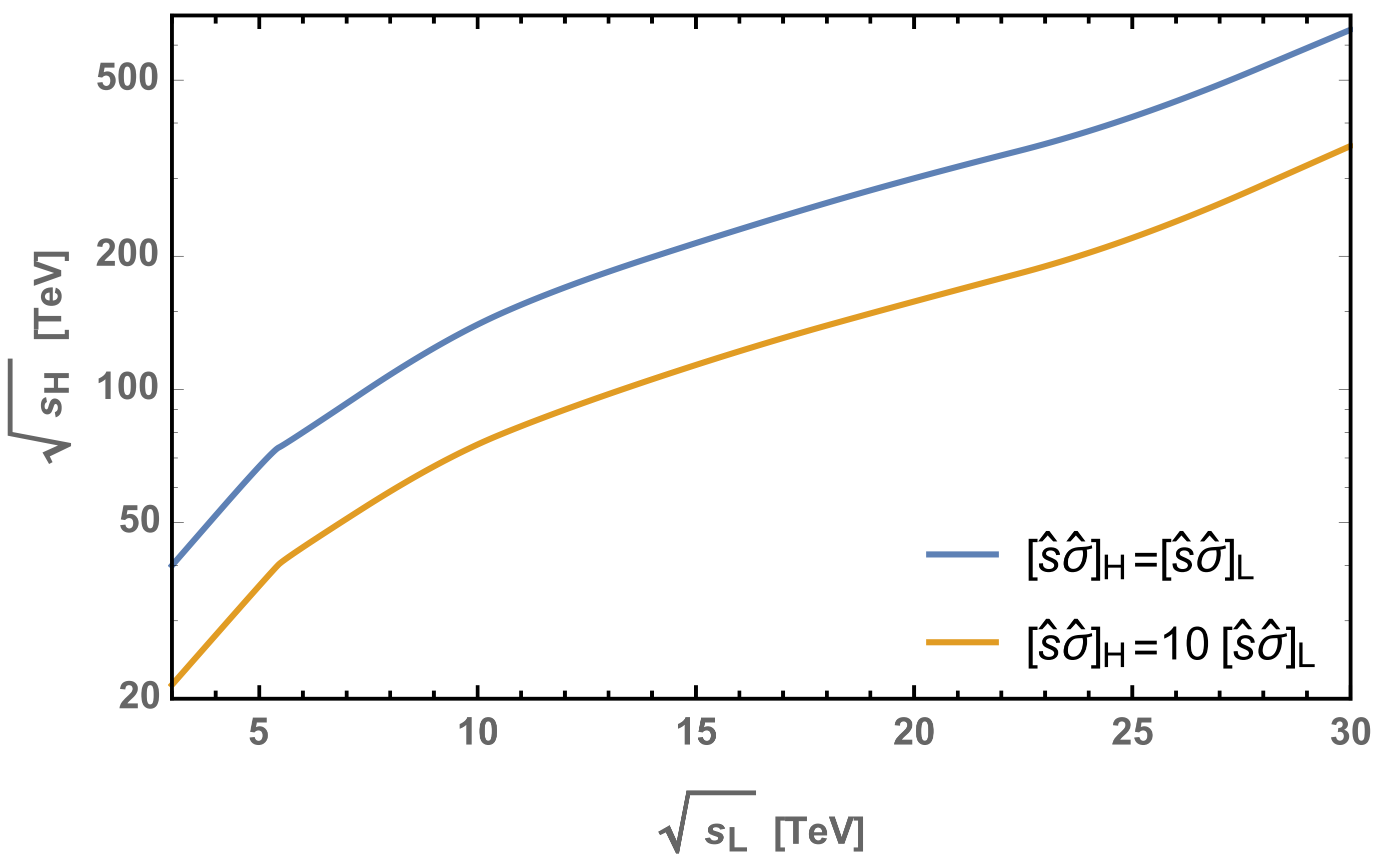
Find **equivalent $\sqrt{s_H}$** for Had. Coll. have **same cross-section** as Lep. Coll. for reactions at E~$\sqrt{s_L}$. Use that $[\hat{s}\hat{\sigma}]$ is nearly constant in τ.



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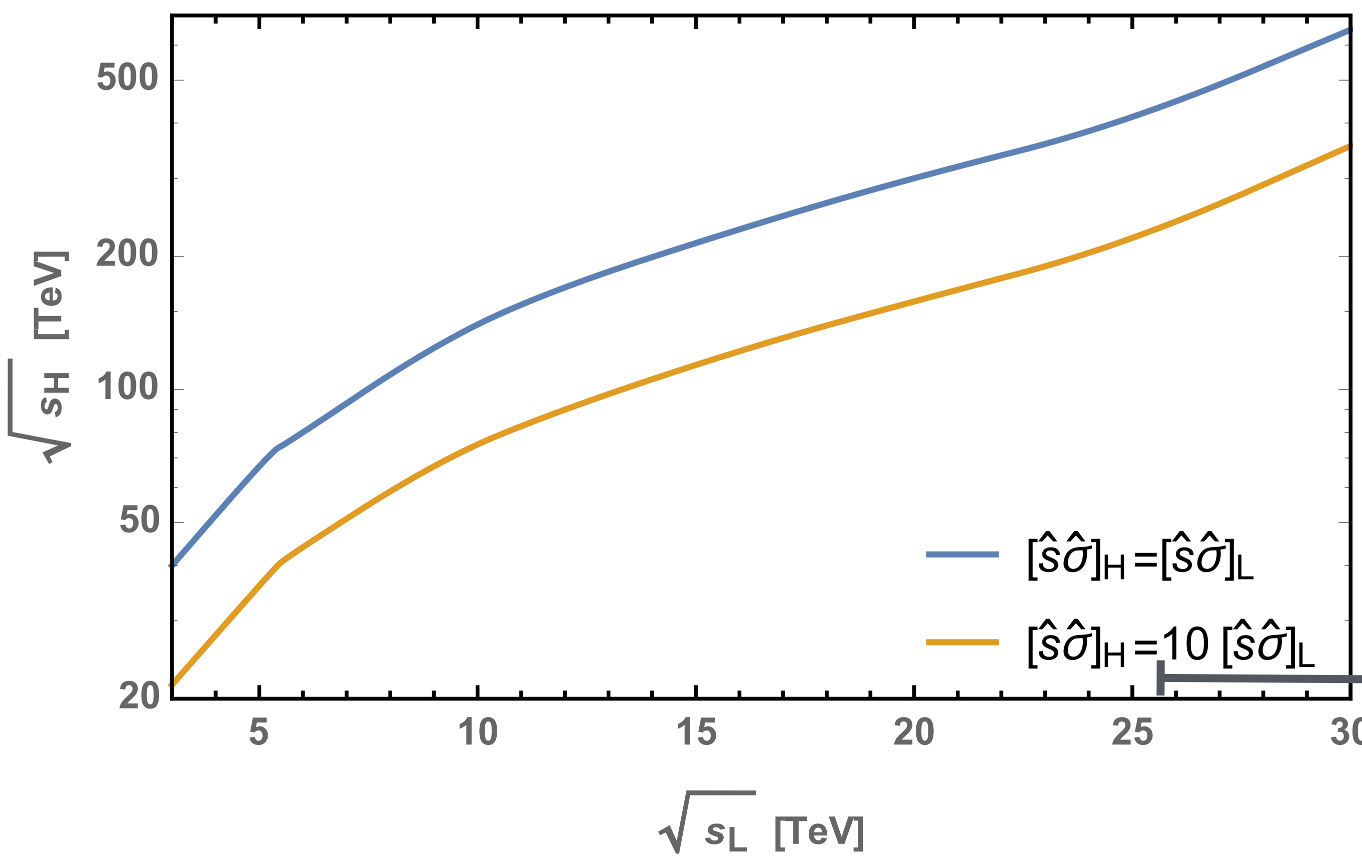

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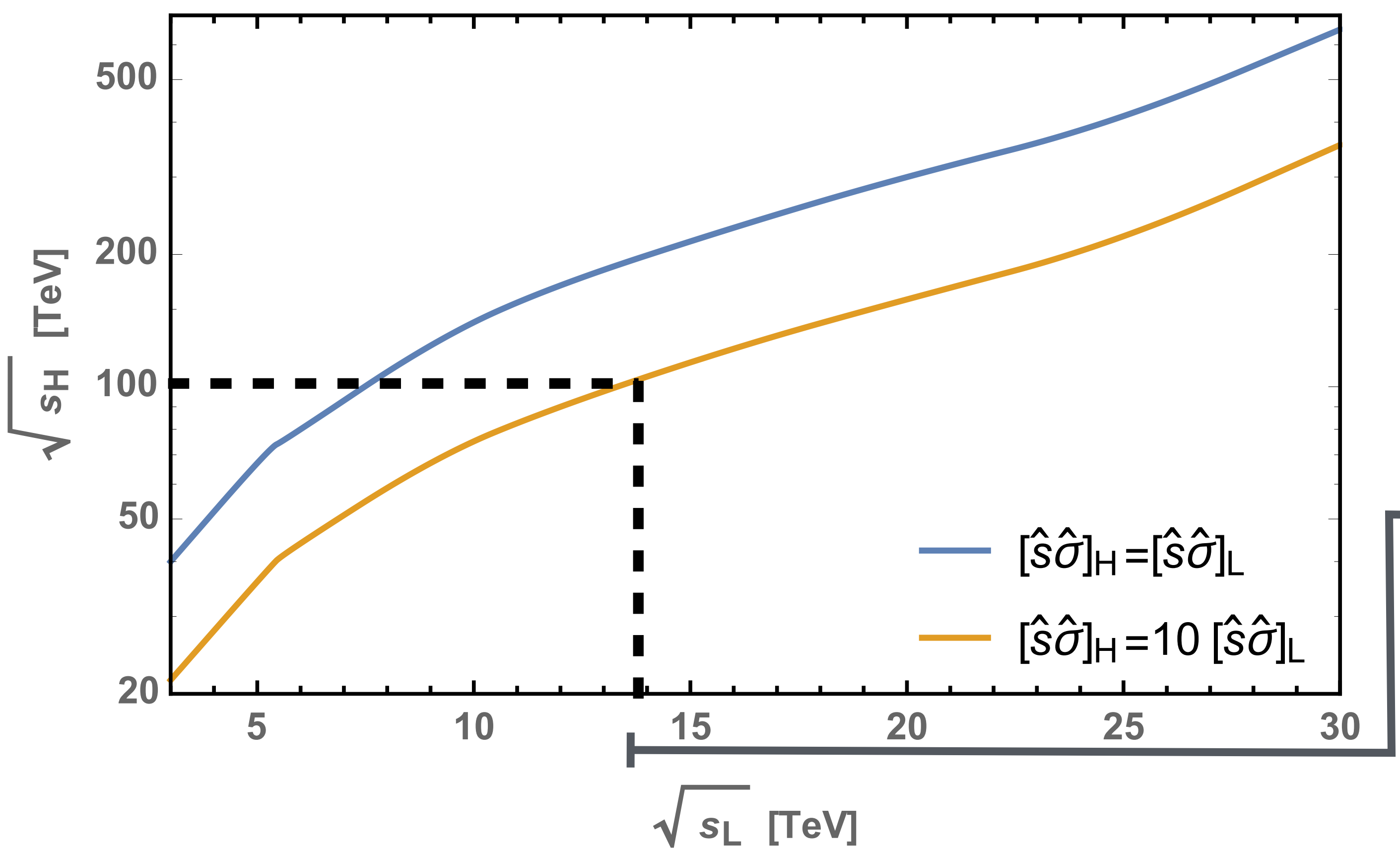

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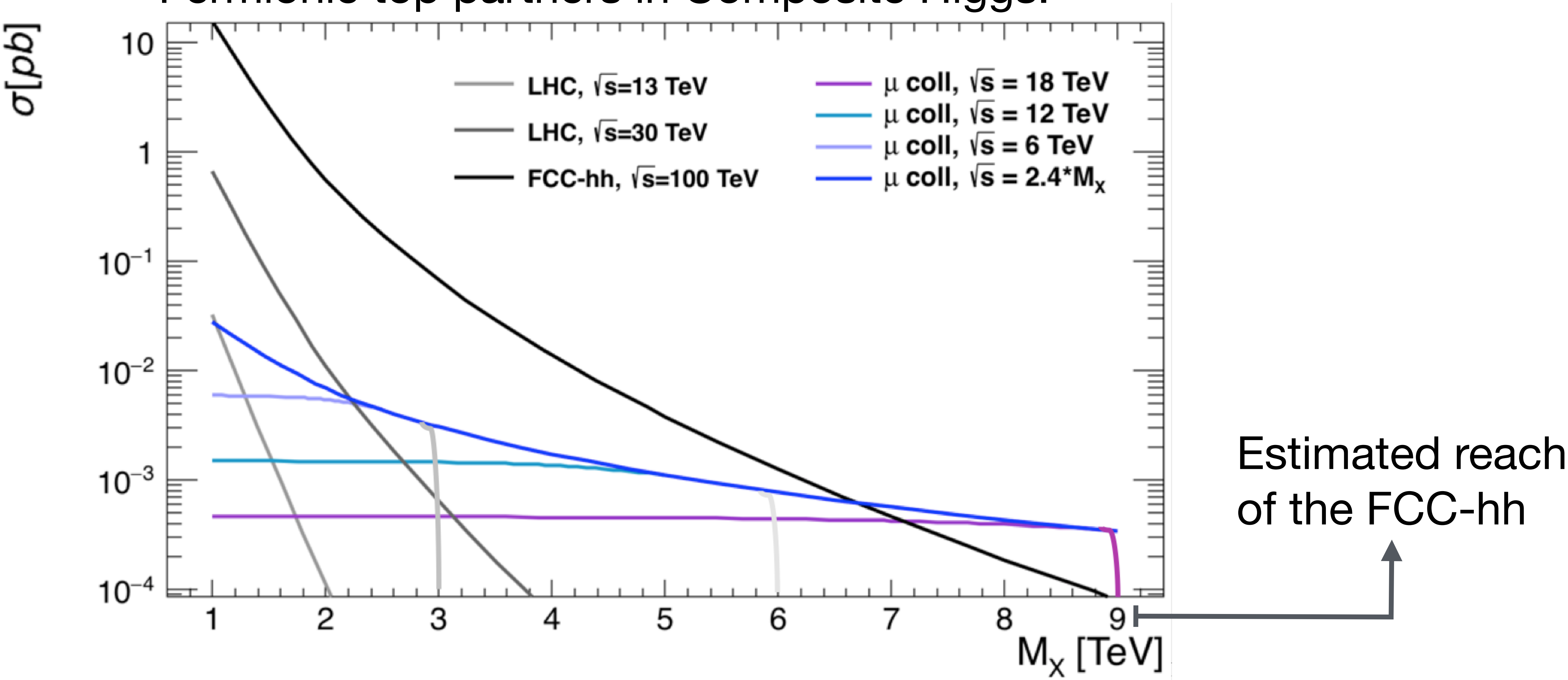
14 TeV μ-collider nearly as good as the FCC at 100 TeV?

Muon Colliders

Plenty of examples can be made to refine the claim

Fermionic top partners in Composite Higgs:



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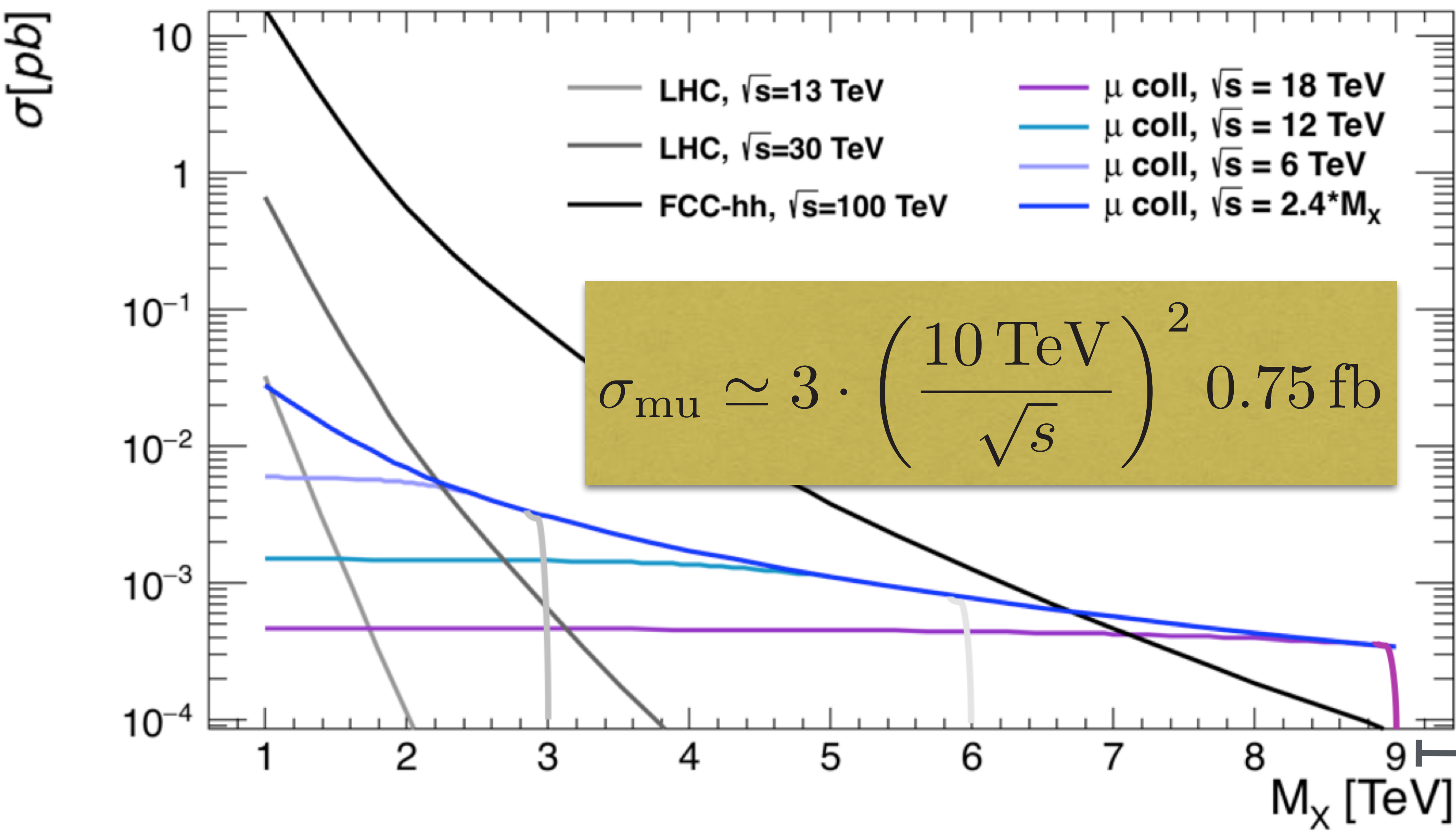

$$\sigma_{\mathrm{mu}} \simeq 3 \cdot \left(\frac{10\,\mathrm{TeV}}{\sqrt{s}}\right)^2 0.75\,\mathrm{fb}$$

Estimated reach of the FCC-hh

Analogous results for **SUSY Stops/Squarks.**

Muon Colliders Requirements Specification

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$$N = 400\,\frac{\text{yrs}}{5}\left(\frac{10\,\text{TeV}}{\sqrt{s}}\right)^2 \frac{L}{10^{34}\text{cm}^{-2}s^{-1}} \quad \Rightarrow \quad L > \frac{1}{4}\,\frac{5}{\text{yrs}}\left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2 10^{34}\text{cm}^{-2}s^{-1}$$

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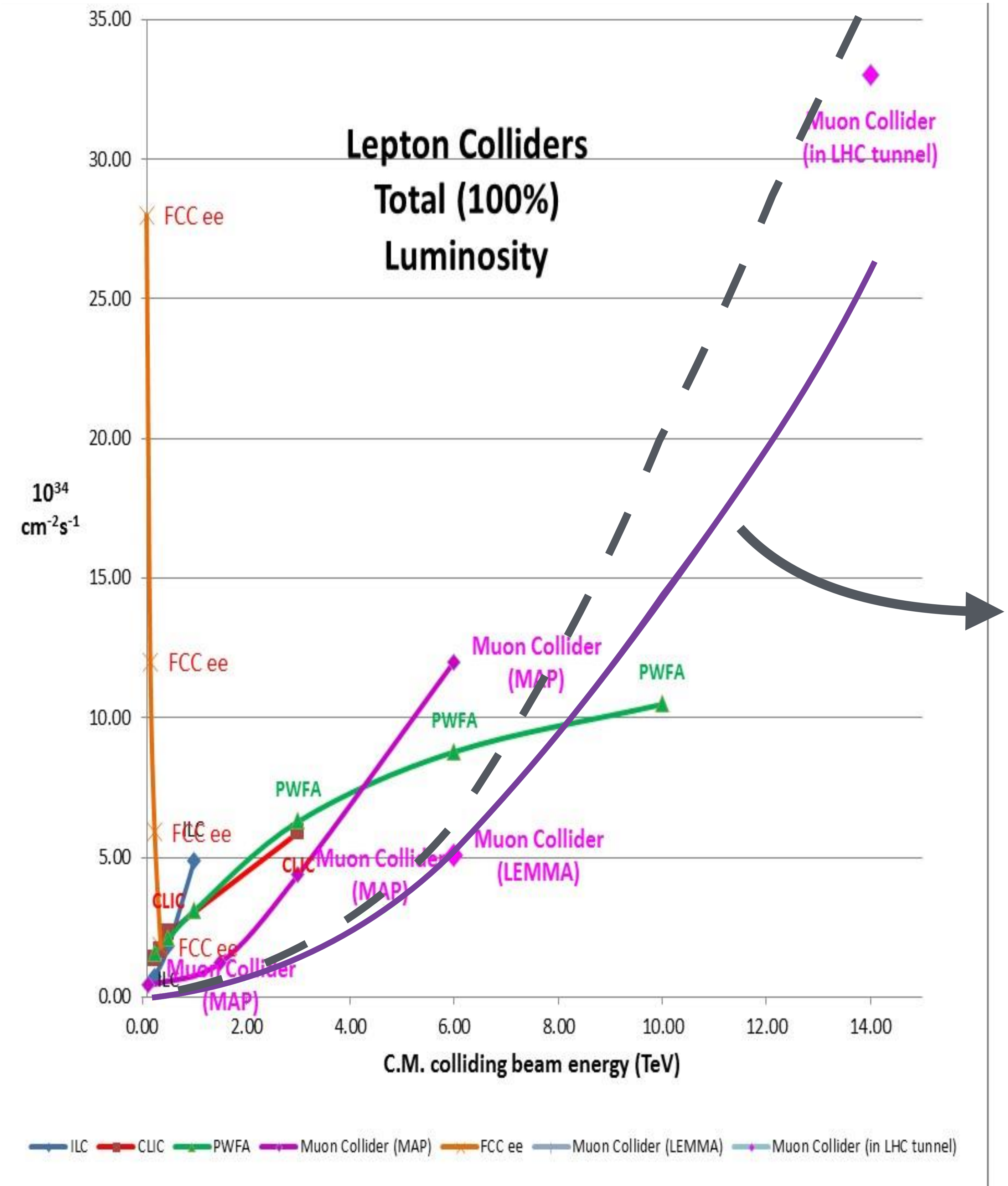
4) Probe DM in mono-γ/W/Z, EW singlets, **L>**?

Muon Colliders Requirements Specification



Both MAP and LEMMA claim they can make it

Low
Emittance
Muon
Muon
Accelerator

Muon Colliders Requirements Specification

But also:

5) Comply with radiation limit from neutrino flux
   must be possible to bound emittance as function of energy and lumi

6) Produce low enough background level
   again pointing towards low emittance

Conclusions

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Higgs pole (see backup) could be a **demonstrator**, but:

1. Decent physics case only if no other lepton collider is built before
2. Poses significant extra challenges
3. Impossible with LEMMA. On the other hand, LEMMA requires ~45GeV=$m_Z/2$ high intensity positron beam …

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Muon collider: dream or reality?

Backup

Result of the coupling (a.k.a. κ) fit

- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

13	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	5	6	7	3	+4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	+1.5
δm_H (MeV)	0.1	t.b.a.	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$(%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.70
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	1.9	4.2	1.9	1.4	1.4	0.82
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	4.2
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
Br$_{invis}$ (%)$_{95\%CL}$	SM	<0.3	<0.6	<0.5	<0.15	<0.3	<0.25
BR$_{EXO}$ (%)$_{95\%CL}$	–	<1.8	<3.0	<1.6	<1.2	<1.2	<1.1

Patrick Janot — Higgs properties @ Circular Lepton Colliders, 1 June 2018

(*) Green = best, Red = worst

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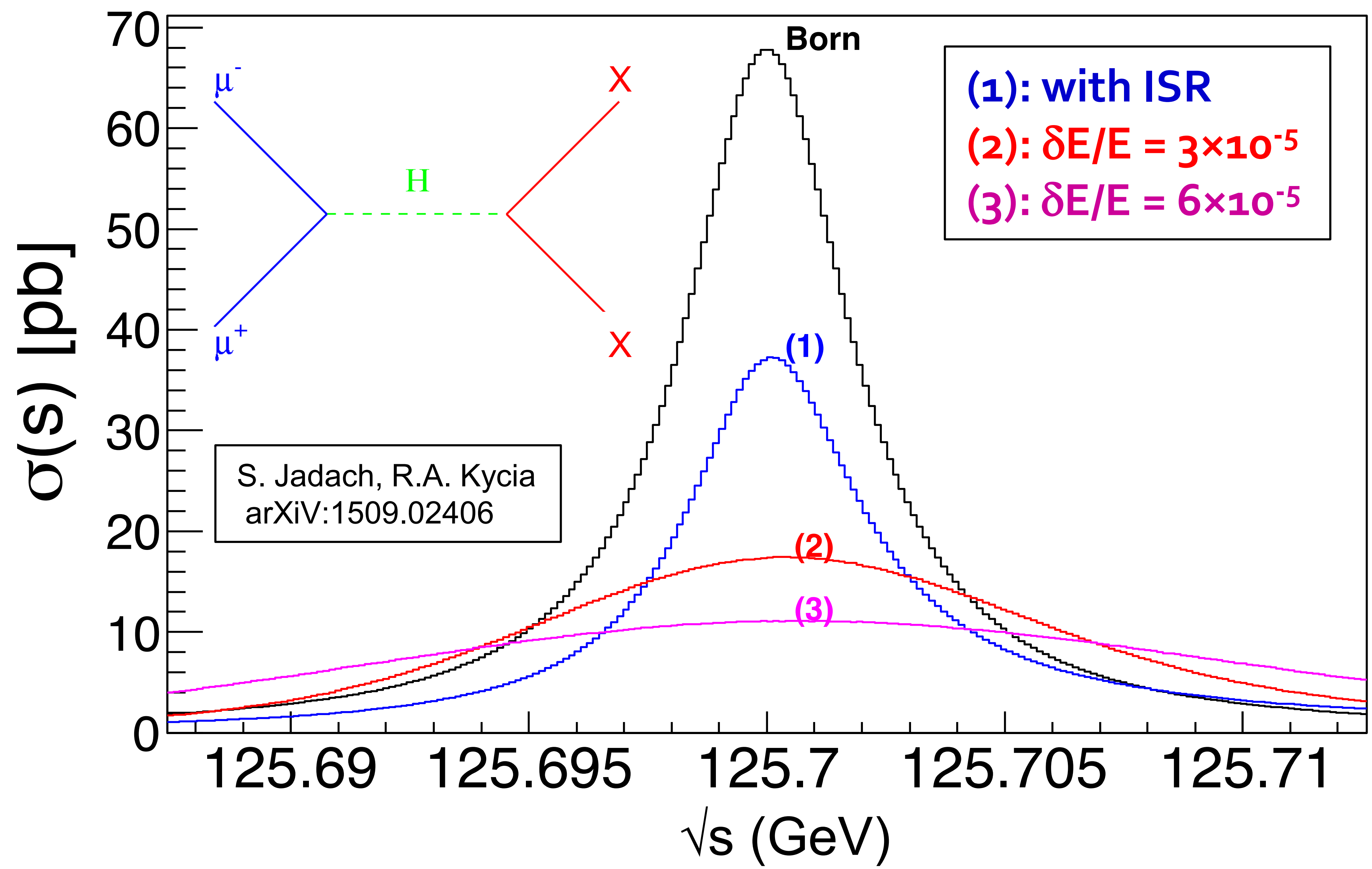
Backup



σ(s) [pb]
0
10
20
30
40
50
60
70
125.69
125.695
125.7
125.705
125.71
√s (GeV)
Born
(1)
(2)
(3)
μ-
μ+
H
X
X
(1): with ISR
(2): δE/E = 3×10-5
(3): δE/E = 6×10-5
S. Jadach, R.A. Kycia
arXiV:1509.02406