Physics Potential of a Muon Collider

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Muon Collider Explorations, Dec 10, 2020

Energy frontier: what colliders after the LHC?

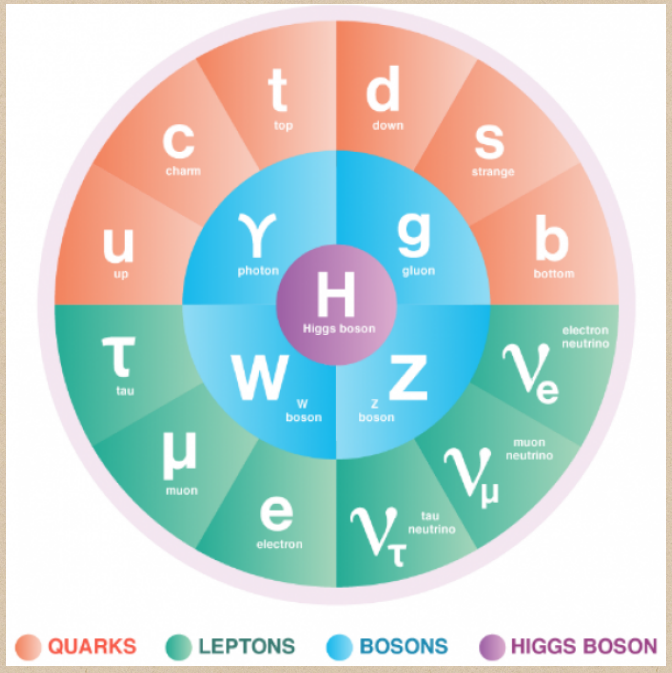
Energy frontier (collider) is ***irreplaceable*** in fundamental particle physics.

The Unique Higgs Target

Higgs couplings to gauge bosons

Higgs couplings to fermions

Higgs self-coupling

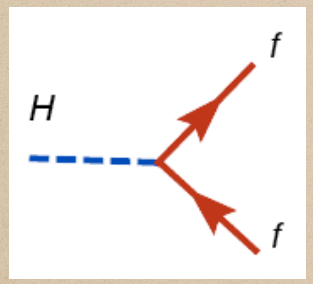


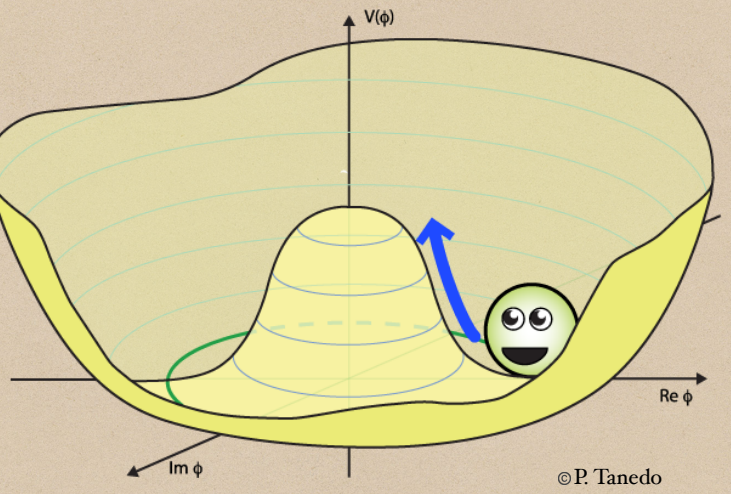
How to explain the Higgs mass?

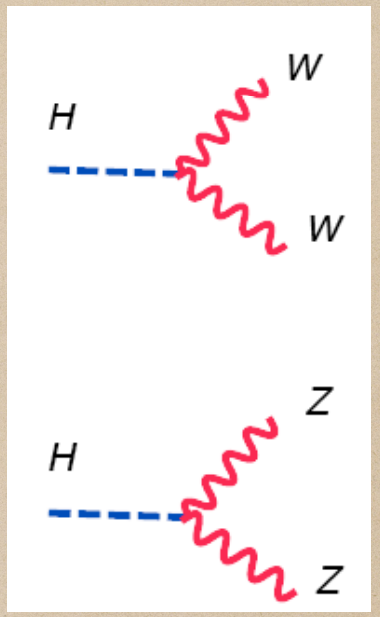
Higgs decay width

Higgs compositeness?

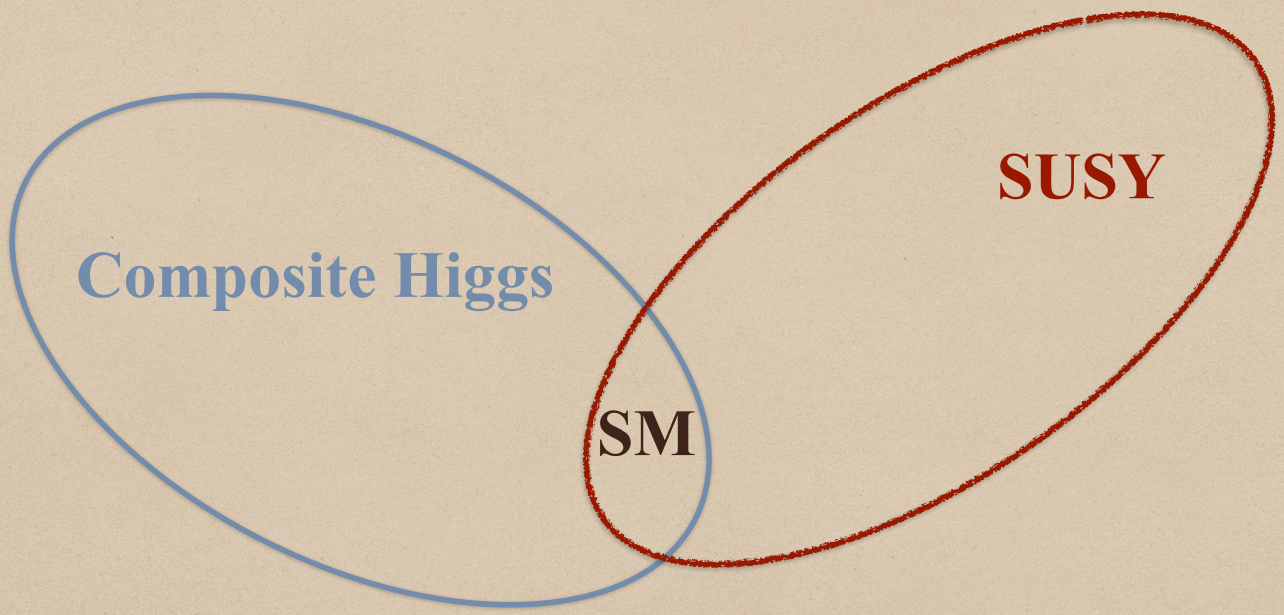
How to explain the Higgs mass?







We do ***not*** have an explanation for the Higgs mass itself in the standard model! One has to rely on ***BSM*** to explain the Higgs mass.



Other ideas: neutral naturalness, cosmic relaxion …..

Traditional strict naturalness requirement $\Longrightarrow$ new physics close to weak scale (~ 1TeV).

Cornered by data and leads to more complicated models: more difficult signals but still new physics at (1- 10) TeV.

Loose naturalness requirement: i.e. ~(0.1 -1)% fine tuning: same level as the fine-tunings we have encountered in nuclear physics and Nature.

O(10-100) TeV ———— SUSY scalars: stops

a few TeV ———— SUSY fermions

split SUSY, Arkani-Hamed, Dimopoulos, Giudice, Romanino 2004….

Explaining the Higgs mass (aka the naturalness/fine-tuning puzzle) has been a major drive for BSM physics for the past 40 years.

No matter what your tolerance level of fine-tuning is, ***we need an explanation for the Higgs mass!***

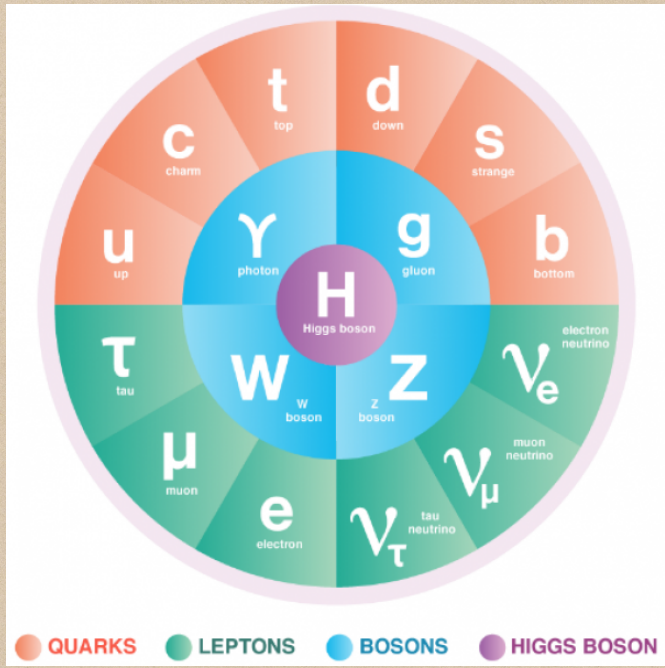
The emergence of some ***"folk-lore" knowledge***: new physics at O(10 - 100) TeV in a broad range of BSM models aiming at explaining the Higgs mass.

The Unique Higgs target

Higgs couplings to gauge bosons (precision/ energy)

Higgs couplings to fermions (precision/ energy)

Higgs self-coupling (energy)



How to explain Higgs mass? (energy)

Higgs decay width (precision)

Higgs compositeness? (energy)

Precision

Lepton Colliders

ILC, FCC-ee, CEPC, CLIC

Energy

Hadron Colliders

SppC, FCC-hh

Precision

Lepton Colliders

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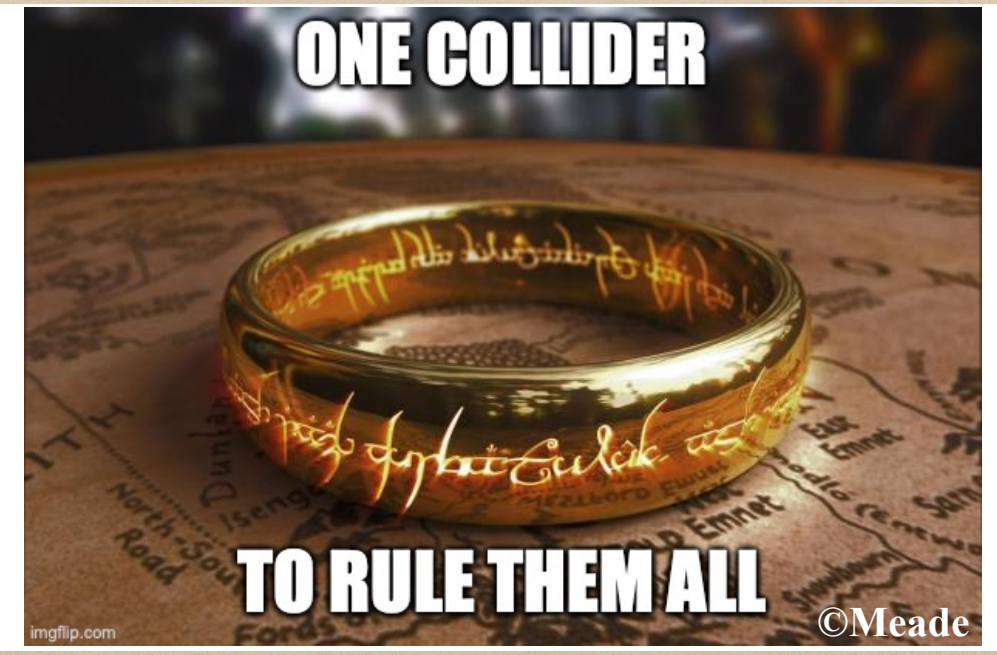
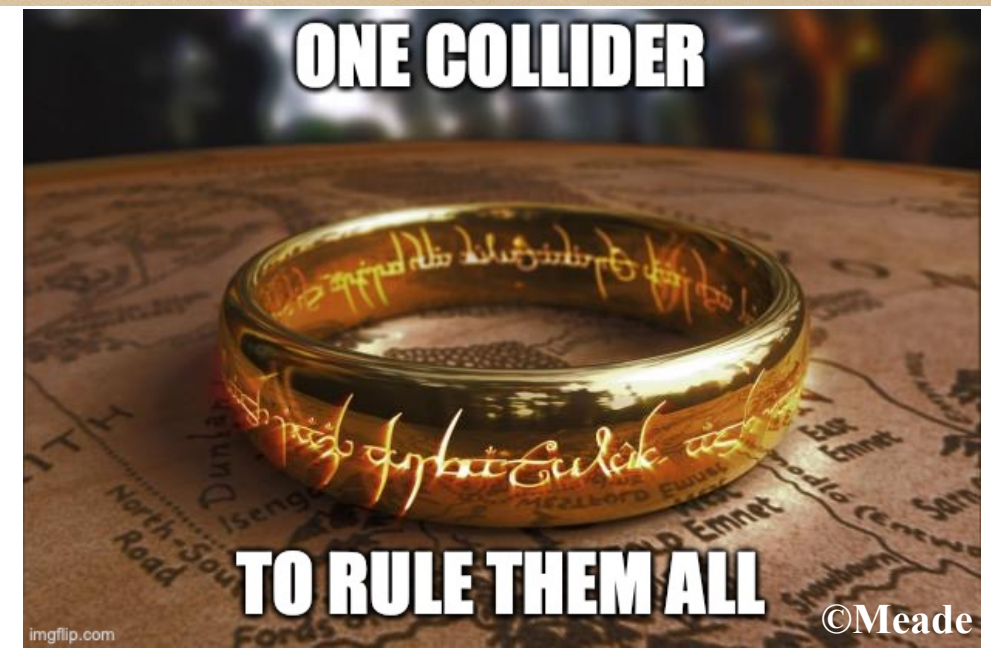
Energy

Hadron Colliders

SppC, FCC-hh





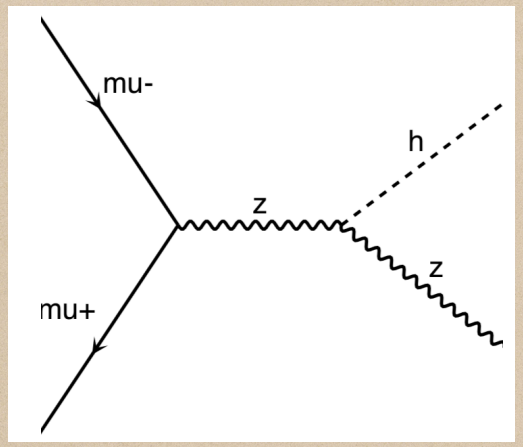
High Energy Muon Collider = Precision + Energy;

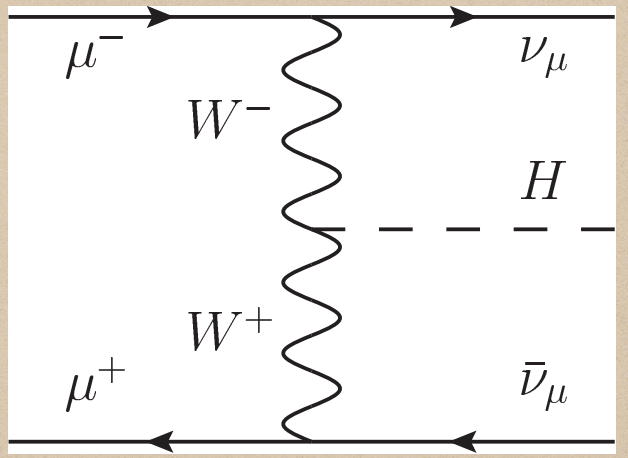
Erode the precision/energy dichotomy!

Muon Collider Pirate Ship

High Energy muon colliders as vector gauge boson colliders

Large EW Sudakov factor $\frac{\alpha_W}{\pi}\log^2\frac{E}{m_\mu}\sim 1$



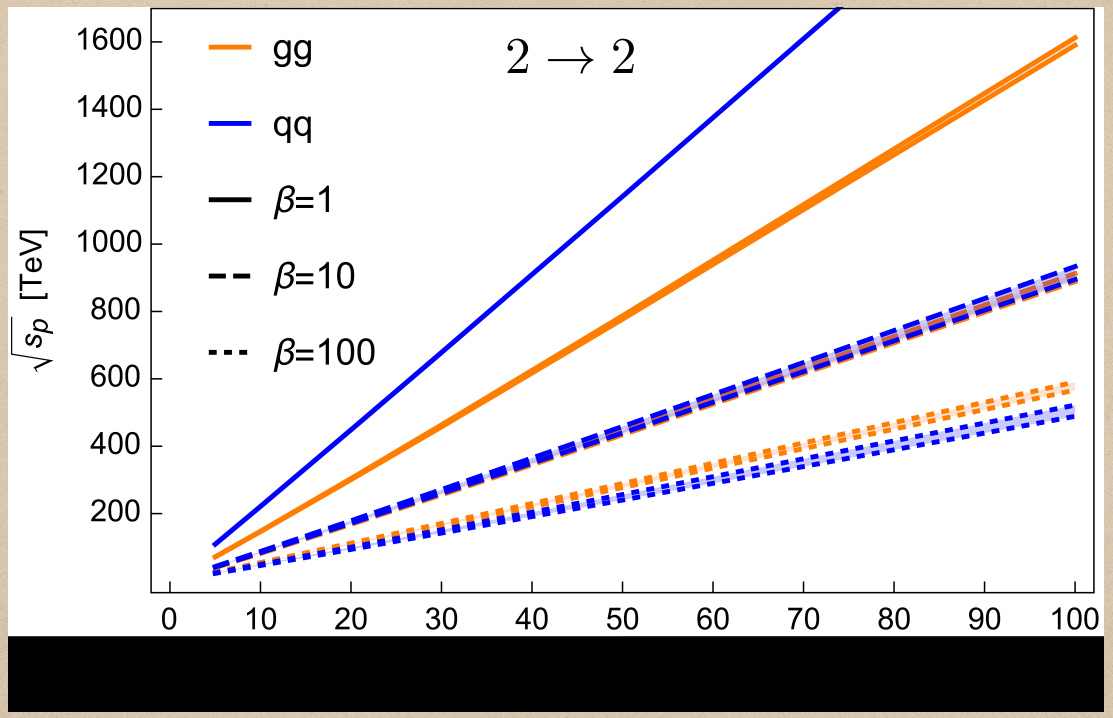


Vector boson fusion: with bosons as initial state (just as PDF for hadron collider); always **wins** at moderately high energies.

Muons vs Protons

Muon: probe all values of $\sqrt{\hat{s}}$;

Proton: probe $\sqrt{\hat{s}} \ll \sqrt{s}$

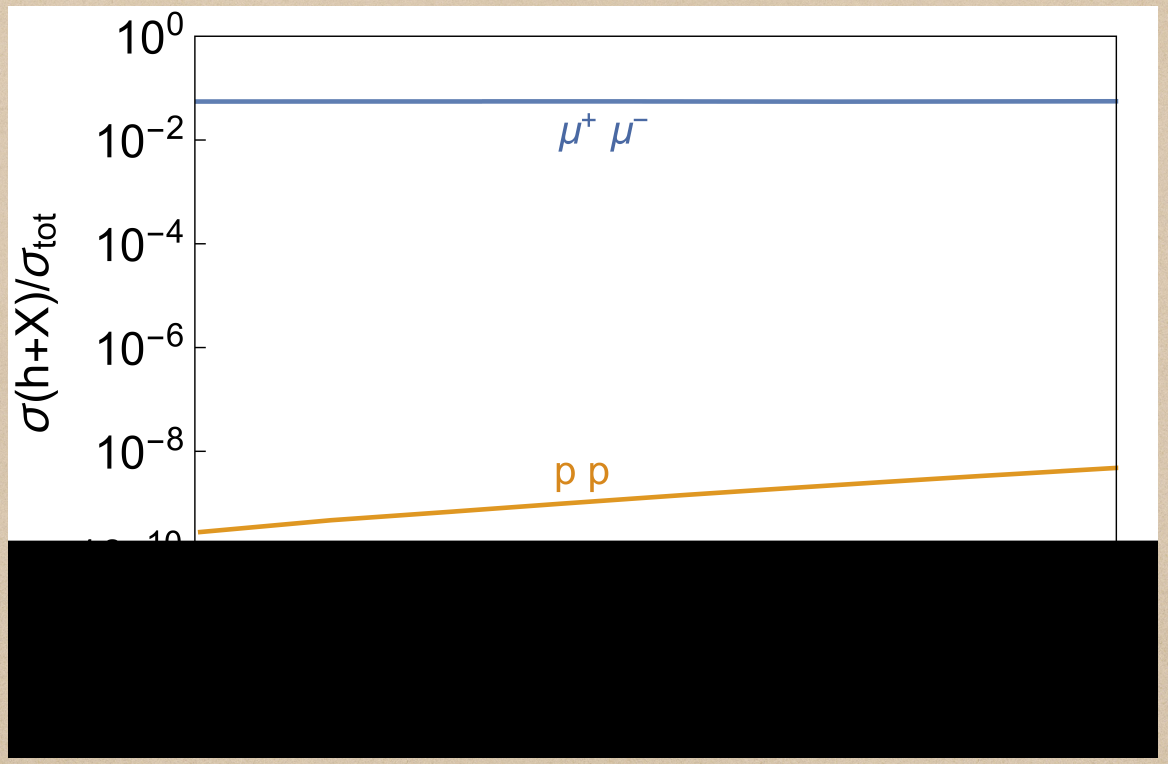


$\beta \equiv [\hat{\sigma}]_p / [\hat{\sigma}]_\mu$

Costantini et.al 2005.10289; reprise in white paper from the muon pirate ship group, to appear.

100 TeV pp collider ⇔ 12 TeV muon collider (β = 100)

Much cleaner background



Higgs Couplings to Bosons

$10^6 \rightarrow 10^8$ Higgses

Precision

Energy

$\sqrt{s}$ (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.)

Electron Collider
(~10^6 Higgses)

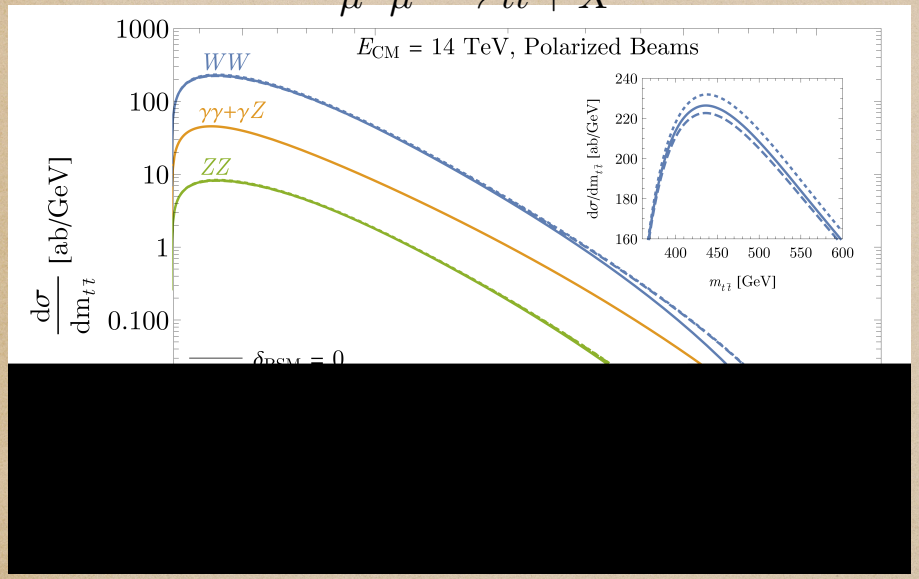
Hadron Collider
(~10^{10} Higgses)

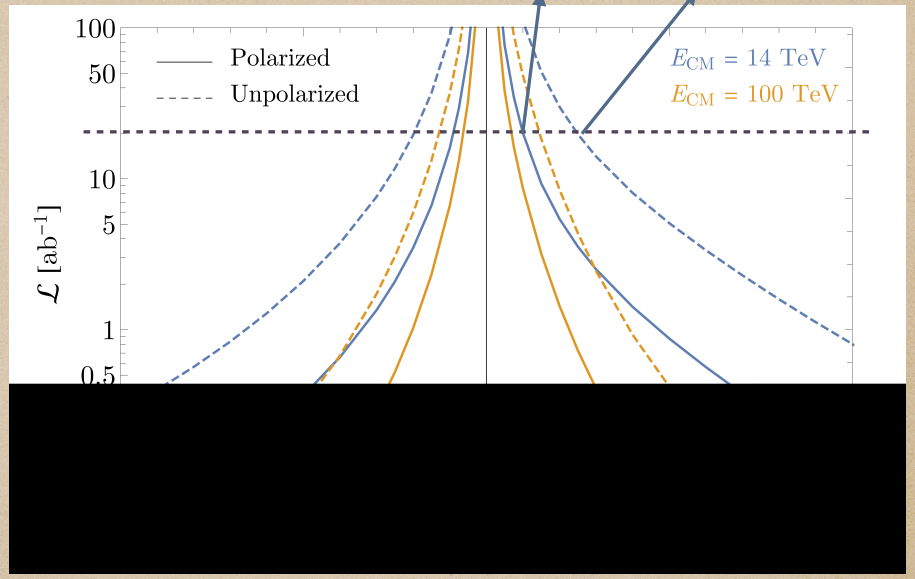
Han, Liu, Low, Wang 2008.12204

Top Yukawa

$$\mathcal{M}(W_L^+ W_L^- \to t\bar{t}) \approx -\frac{m_t}{v^2}\delta_{\rm BSM}\sqrt{\hat{s}}, \quad \sqrt{\hat{s}} \gg m_t.$$

$\mu^+\mu^- \to t\bar{t} + X$





HL-LHC: 6%

Fan and Reece, part of the white paper from the muon pirate ship group, to appear

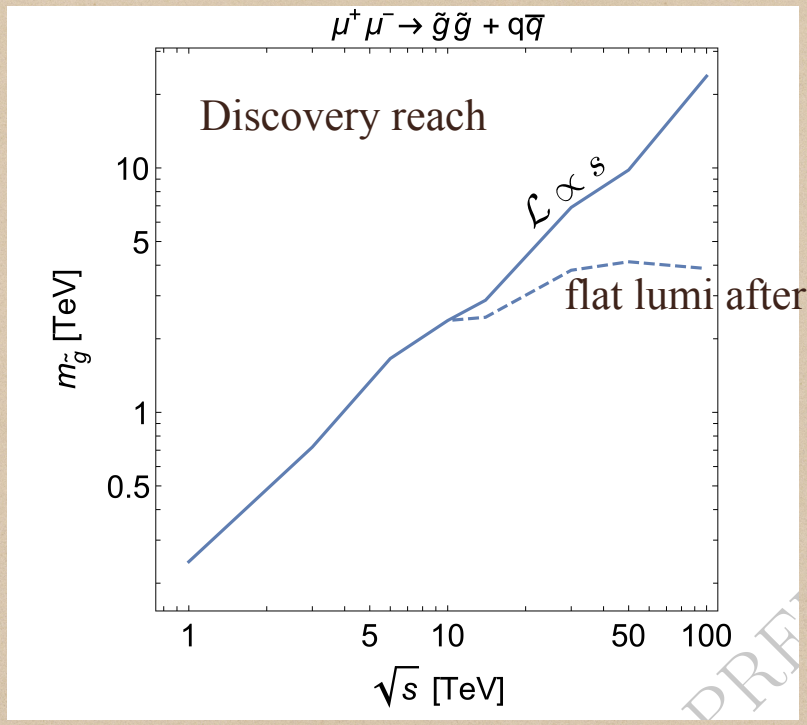
Explaining the Higgs mass: supersymmetric tops

Fine-tuning	Stop mass	$(\sqrt{s})_{\min}$
~1%	~ 3 TeV	6 TeV
10^{-3}	~ 10 TeV	20 TeV
10^{-4}	~ 30 TeV	66 TeV

$$\tilde{m} \sim 0.9\sqrt{s}/2$$

For comparison, a 100 TeV proton collider (3 ab^{-1}) could potentially discover up to 6 TeV stop and ~10^{-3} level fine-tuning.

Gluino: affecting Higgs mass at two-loop order in SUSY



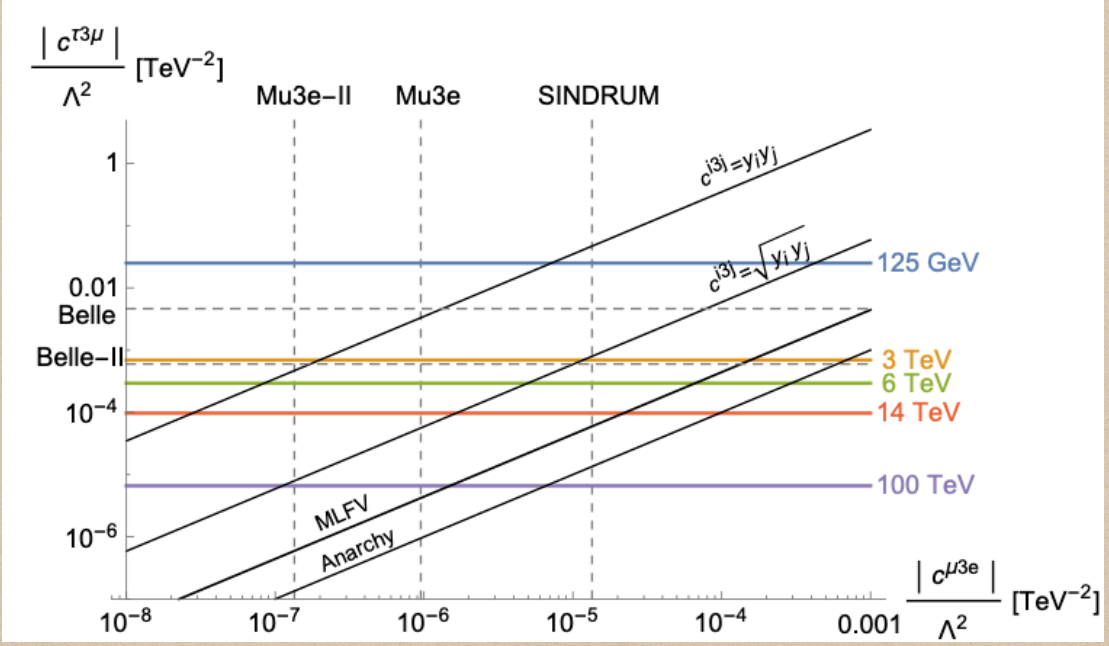
UCSB group led by Craig, part of the white paper from the muon pirate ship group, to appear

En route to the muon collider, possible discoveries from other complementary experiments, hinting the energy scales of new physics:

- Flavor violation
- EDM
- g-2 Capdevilla, Curtin, Kahn, Krnjaic 2006.16277
- DM: galactic center GeV excess?
- gravity waves?
- …..

Lepton flavor violation

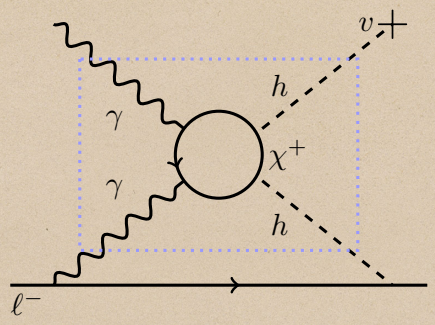
$$\mu^+\mu^- \to \mu\tau$$

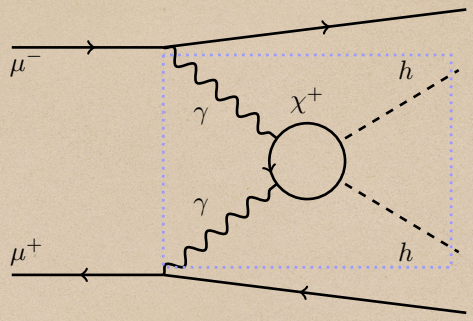


$1\,\mathrm{ab}^{-1}$

Qianshu Lu, part of the white paper from the muon pirate ship group, to appear

CP violation: EDM





$$d_e \sim \sin(\delta_{\rm CP}) \frac{e m_e}{M^2} \left(\frac{\alpha}{4\pi}\right)^2 \sim 10^{-32} e \cdot {\rm cm} \sin(\delta_{\rm CP}) \left(\frac{20\,{\rm TeV}}{M}\right)^2$$

current: ACME $|d_e| \leq 1.1 \times 10^{-29}\, e\,{\rm cm}$ at 90% CL;

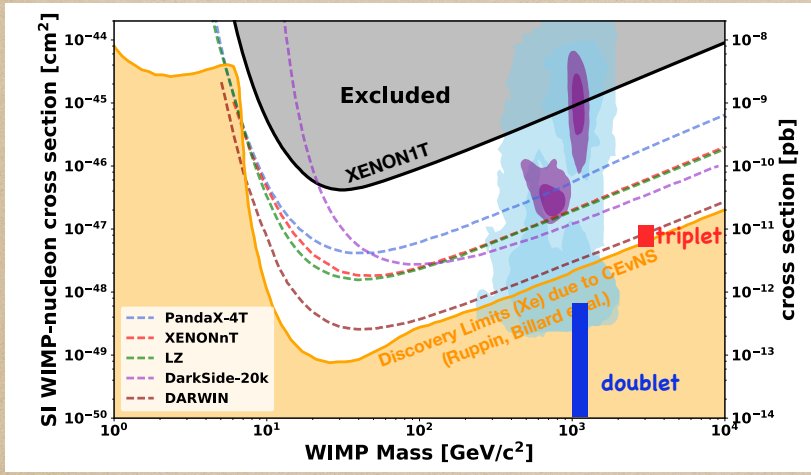
In the coming decade, $|d_e| \sim 10^{-32} e\,{\rm cm}$

Cesarotti, Lu, Nakai, Parikh, Reece 2018

Simplest WIMP DM *Alive*: fermionic electroweak states

Direct detection

Hill and Solon 2013

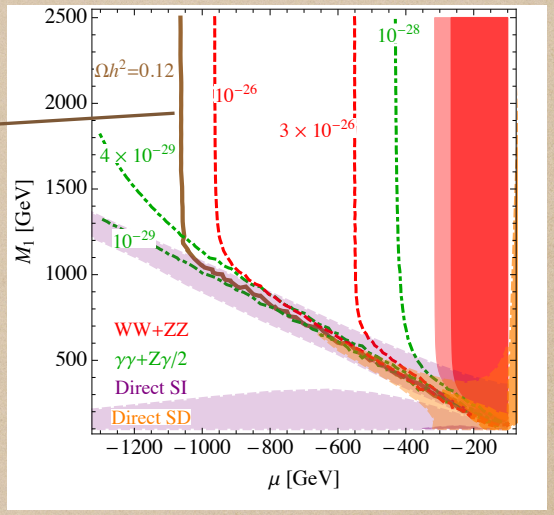


Indirect detection

Powerful for triplet; weak for doublet:

Cohen, Lisanti, Pierce, Slayter; Fan, Reece 2013;

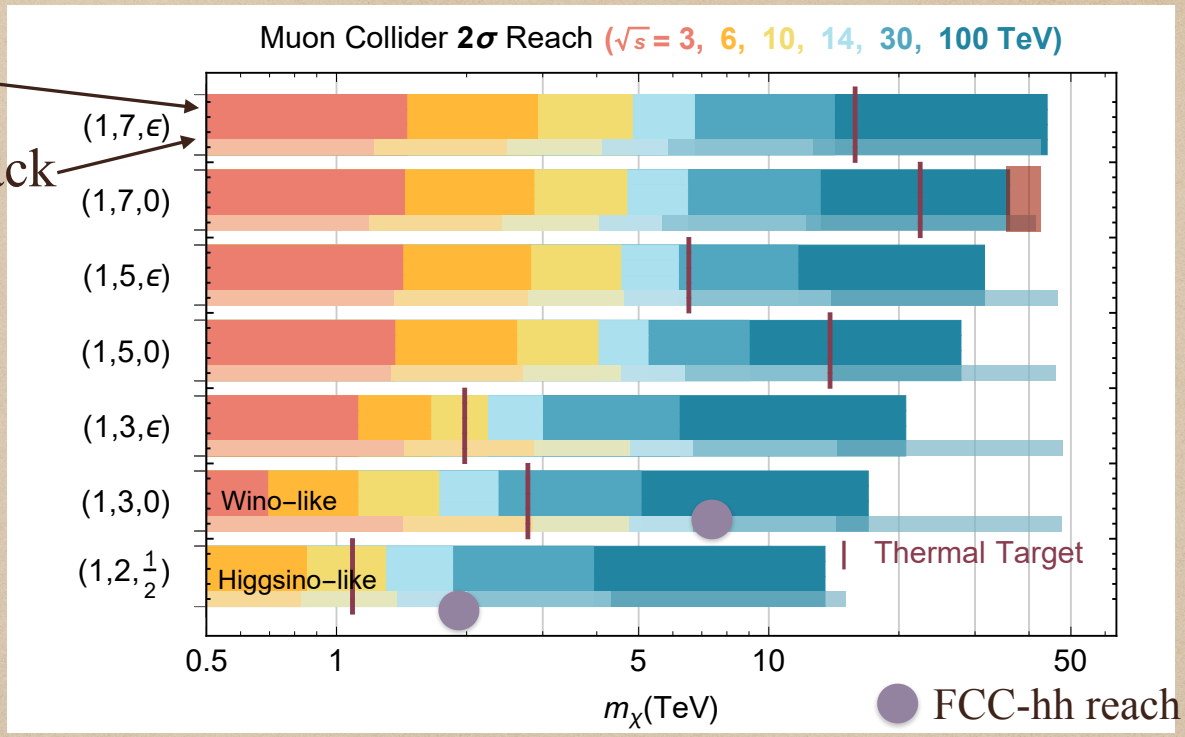
thermal doublet



Future Colliders are definitely needed!

mono-X

disappearing-track

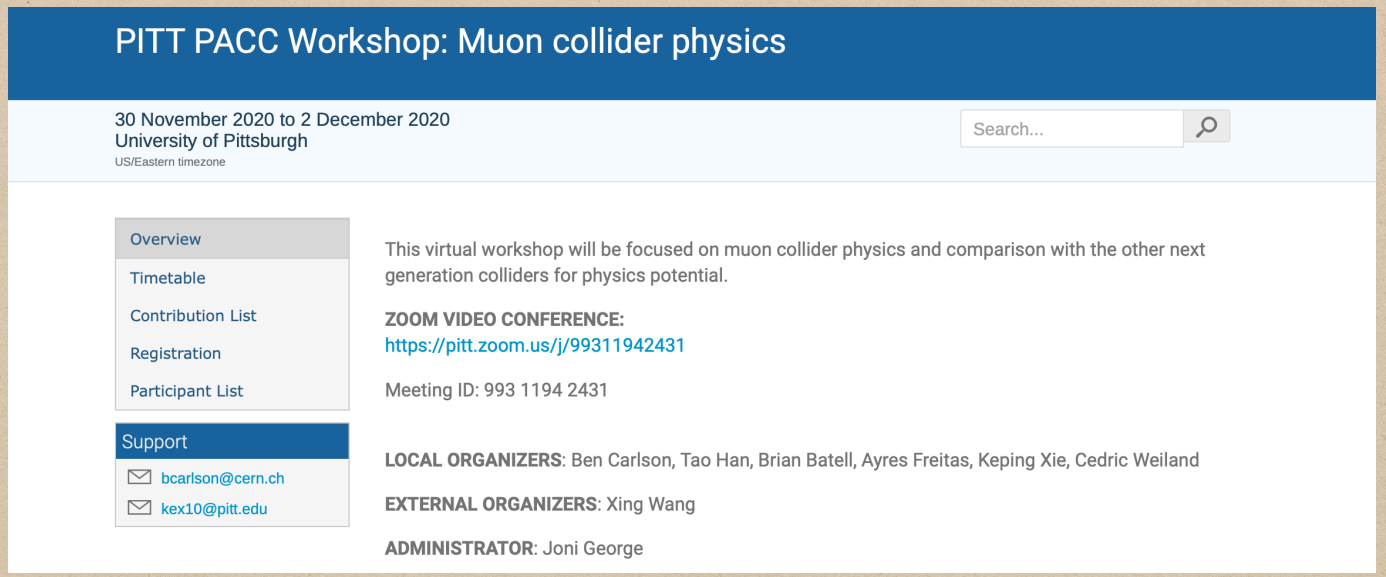


Han, Liu, Wang and Wang, 2009.11287

A lot of other (recent) theoretical efforts:

Tao will tell us more in a latter talk;

More than one muon collider physics white papers for snowmass: e.g., Buttazzo et.al;



Conclusion

Muon Collider: an ***all in one*** machine;

A big challenge but comes with ***big opportunities*** for high energy physicists in the current and coming generations!

A long-term project that could eventually explore a plethora of deep physics questions with capabilities ***comparable to***/***beyond*** future electron and hadron colliders being discussed.

Time is now to build up resonance between different groups and the excitement needs to be broadcast to P5!

Thank you!