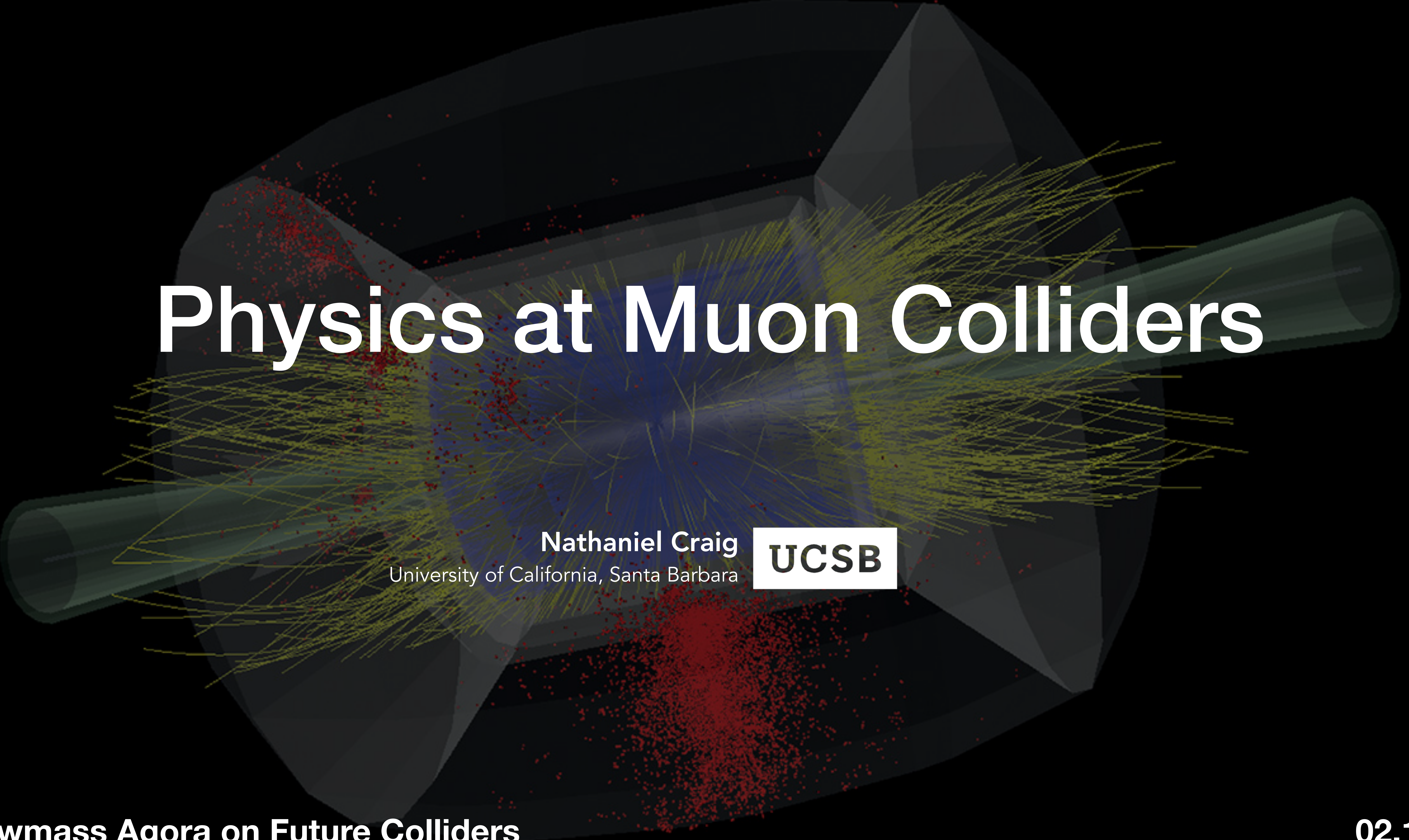
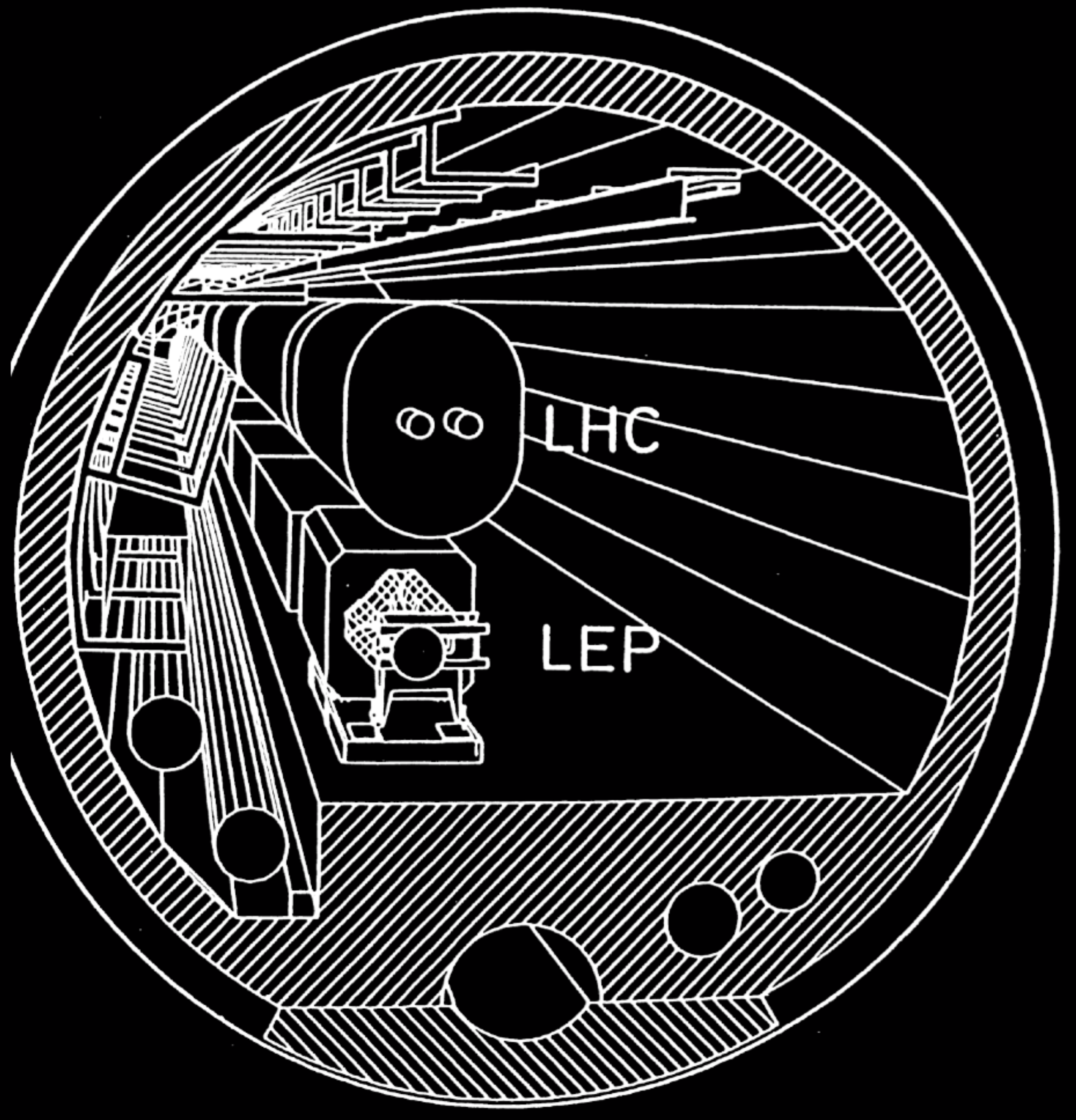


Physics at Muon Colliders

Nathaniel Craig
University of California, Santa Barbara
UCSB

Theory vision circa 1984

ECFA 84/85
CERN 84-10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

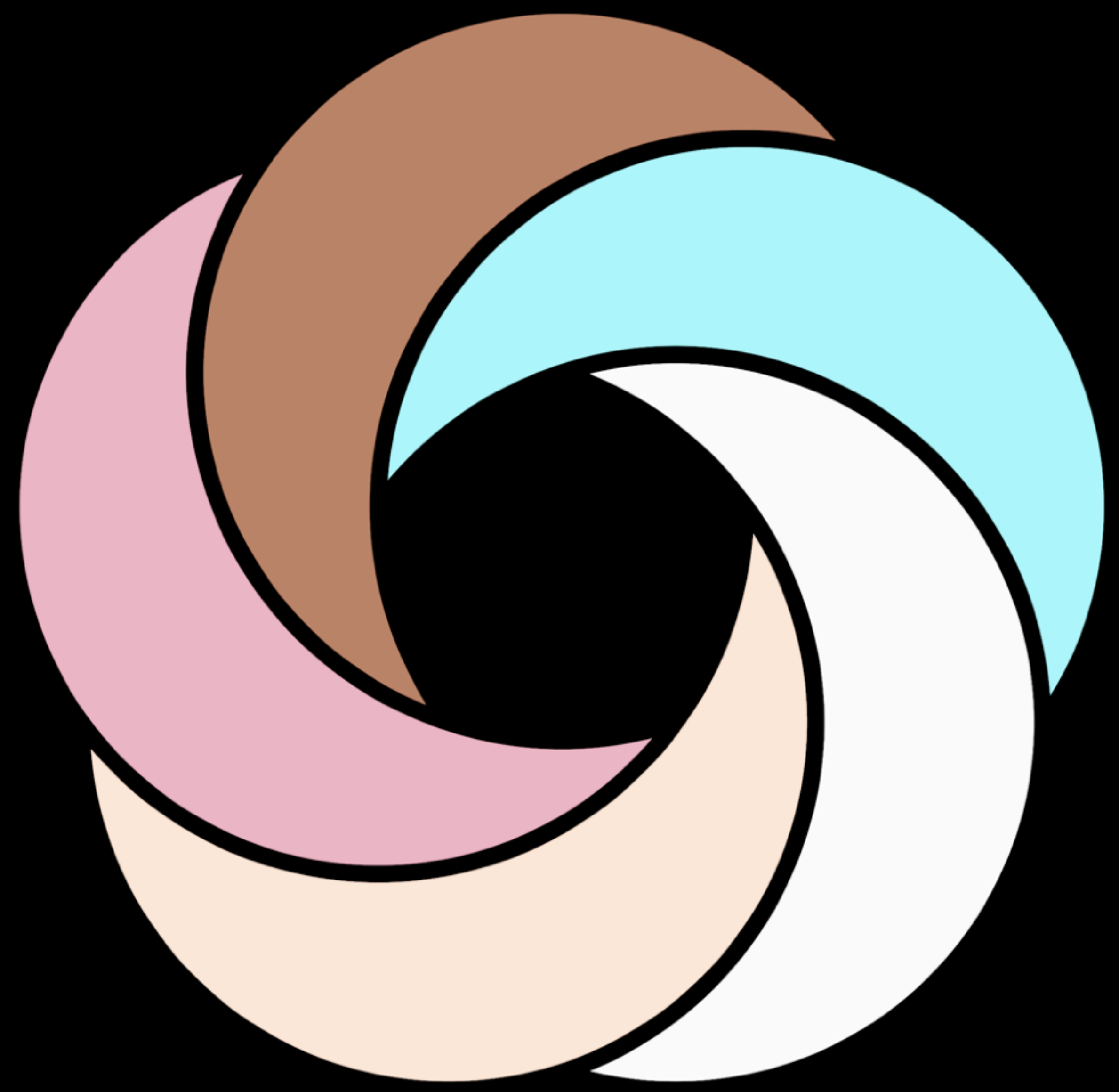
held at Lausanne and Geneva,
21-27 March 1984

Satisfied with these successes, we have now to face deeper questions such as:

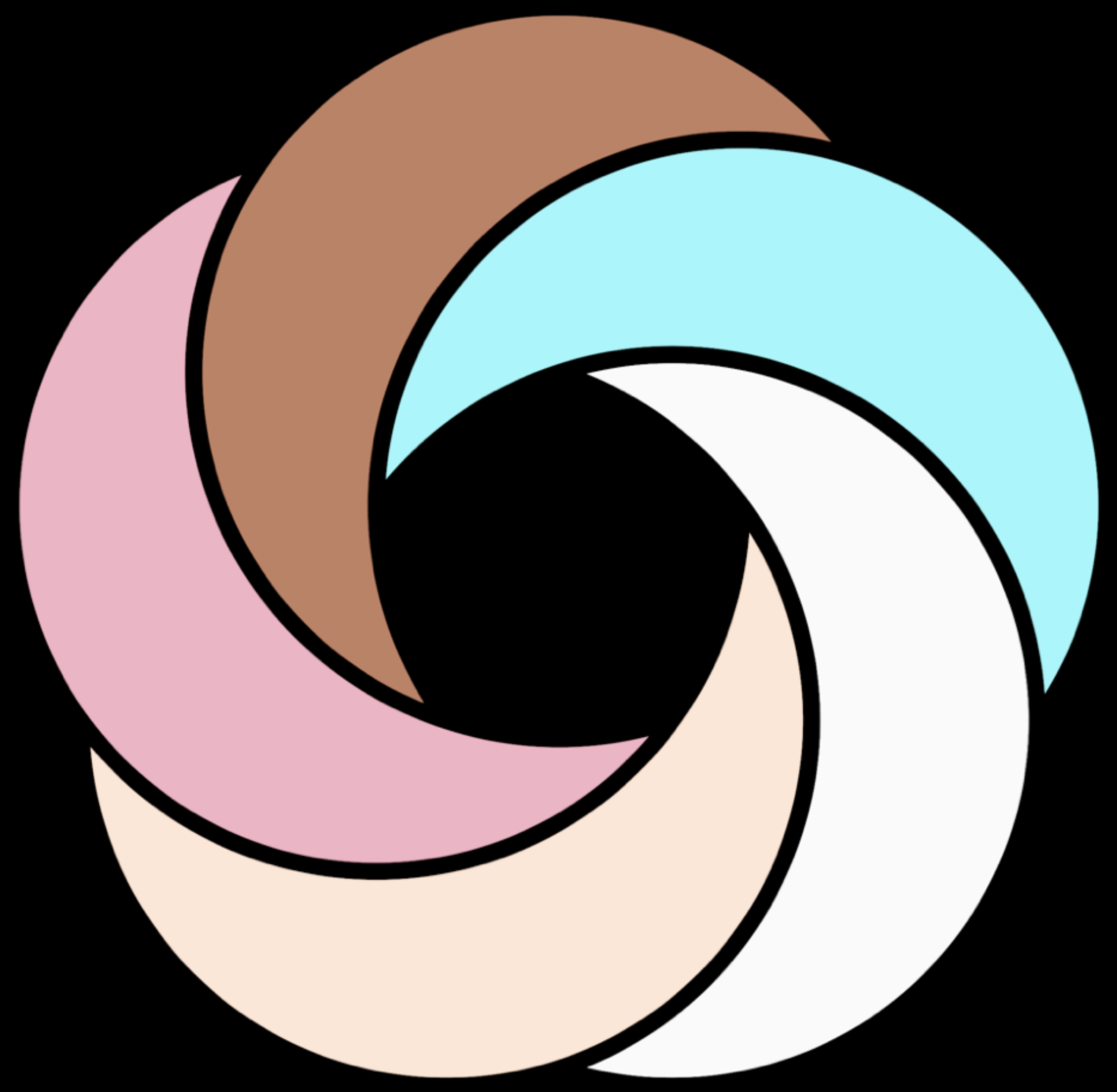
what is the origin of mass?
what kind of unification may exist beyond the standard model?
what is the origin of flavour?
is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

Theory vision circa 2022

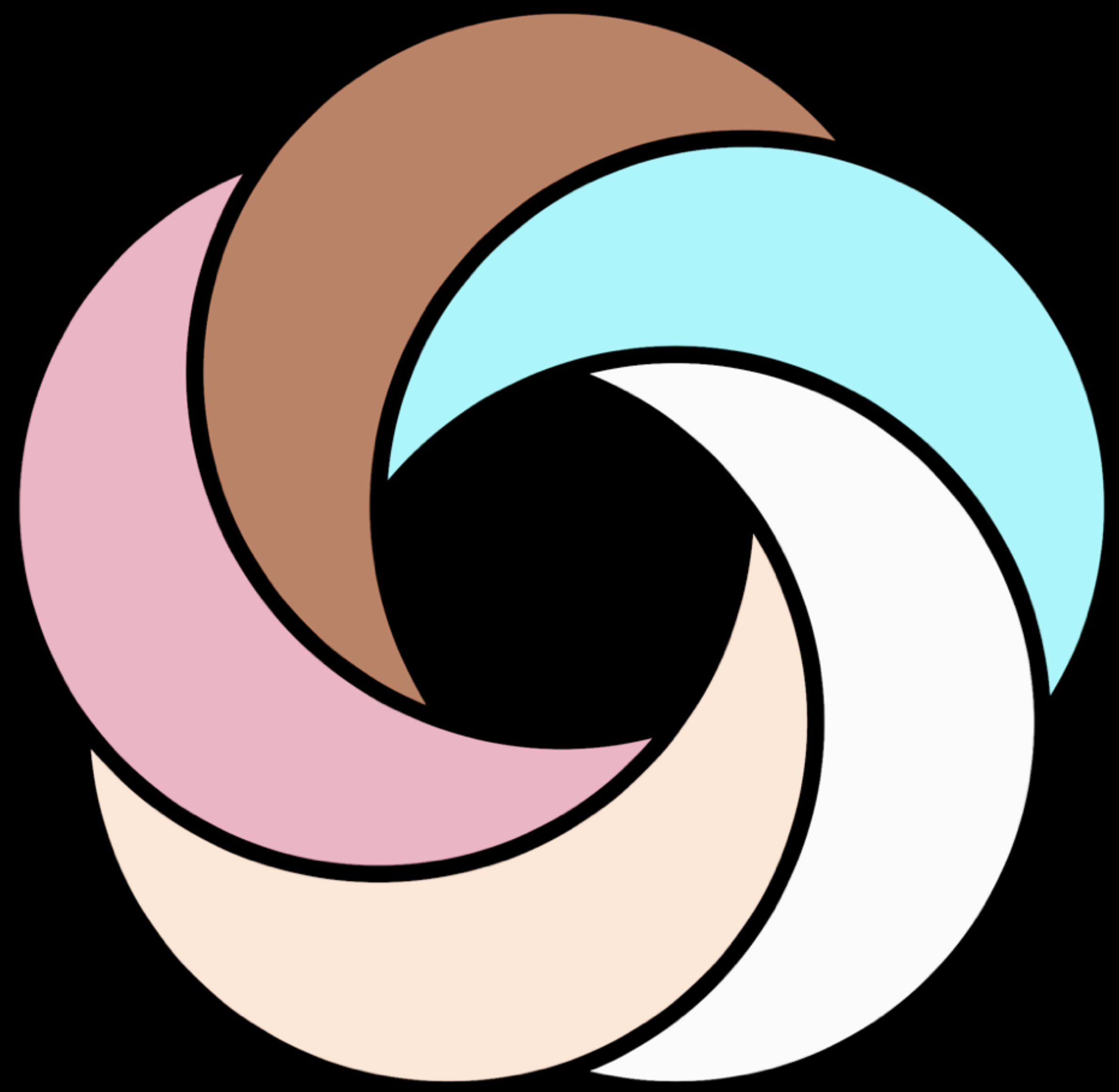


Theory vision circa 2022



✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?

Theory vision circa 2022



✓ What is the origin of mass?
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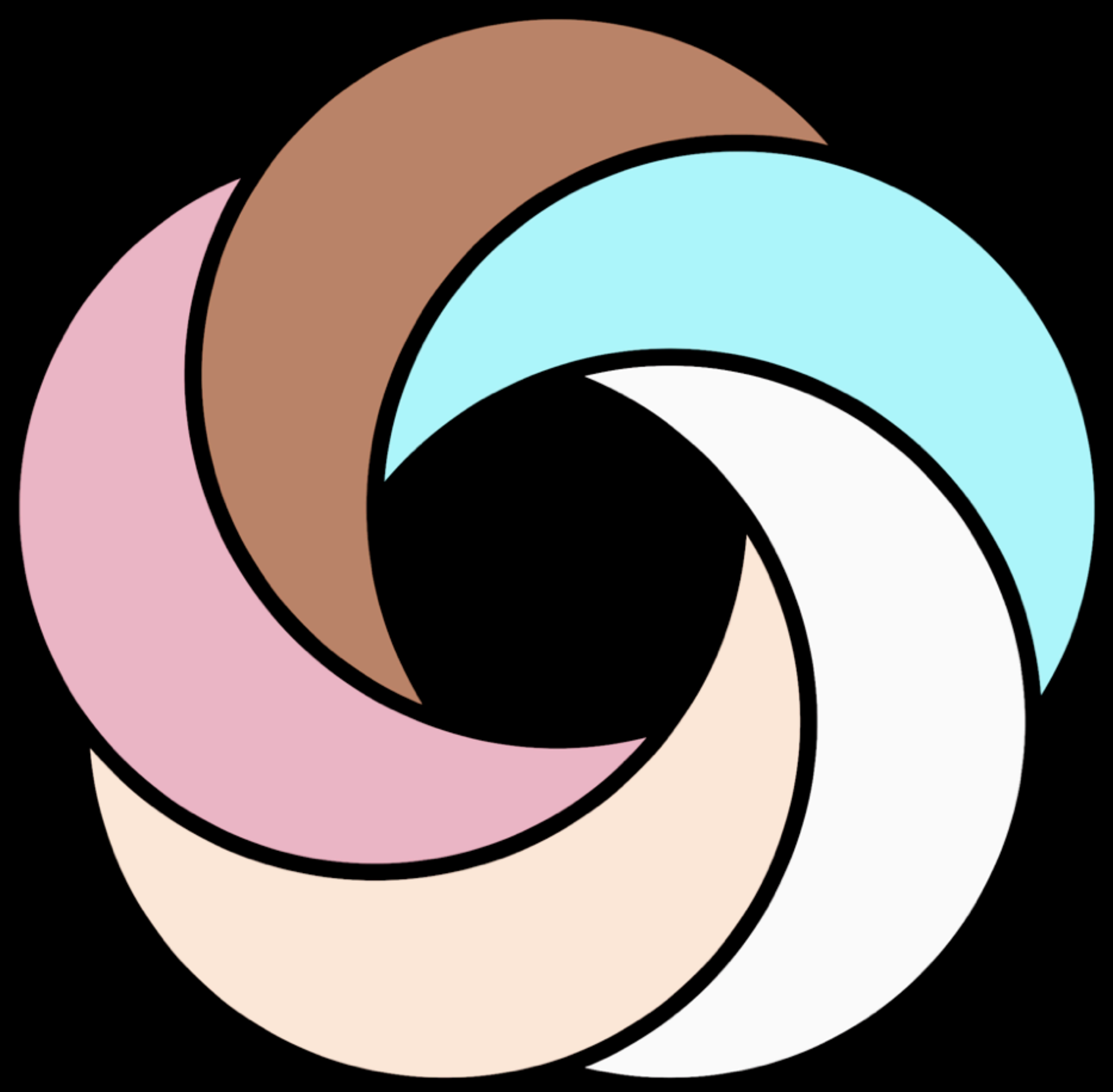
Is there a deeper reason for gauge symmetry?
+ What is the nature of dark matter?

Theory vision circa 2022



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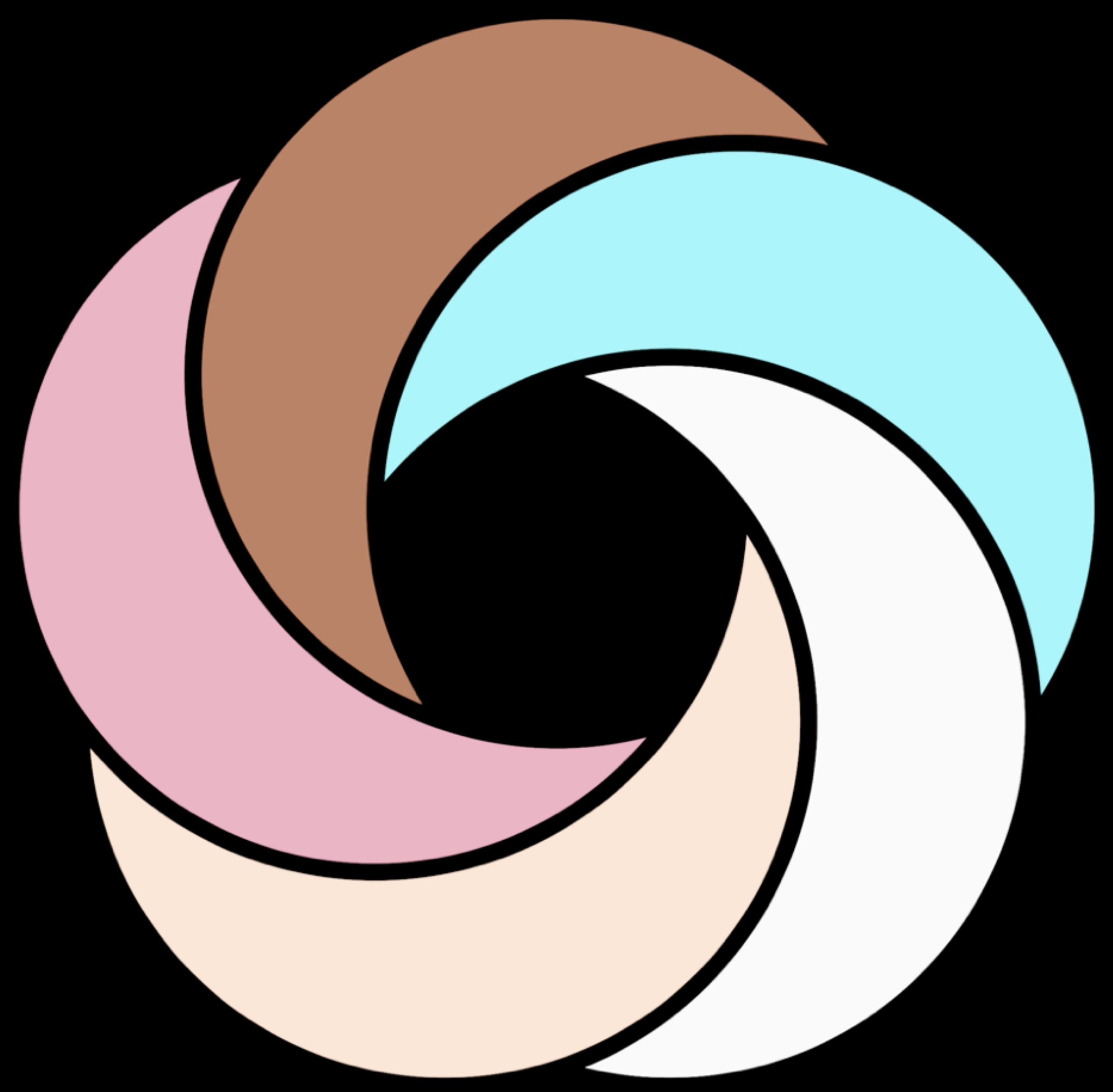
+ What is the nature of dark matter?
+ What is the nature of the neutrino sector?

Theory vision circa 2022



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+ What is the nature of dark matter?
+ What is the nature of the neutrino sector?

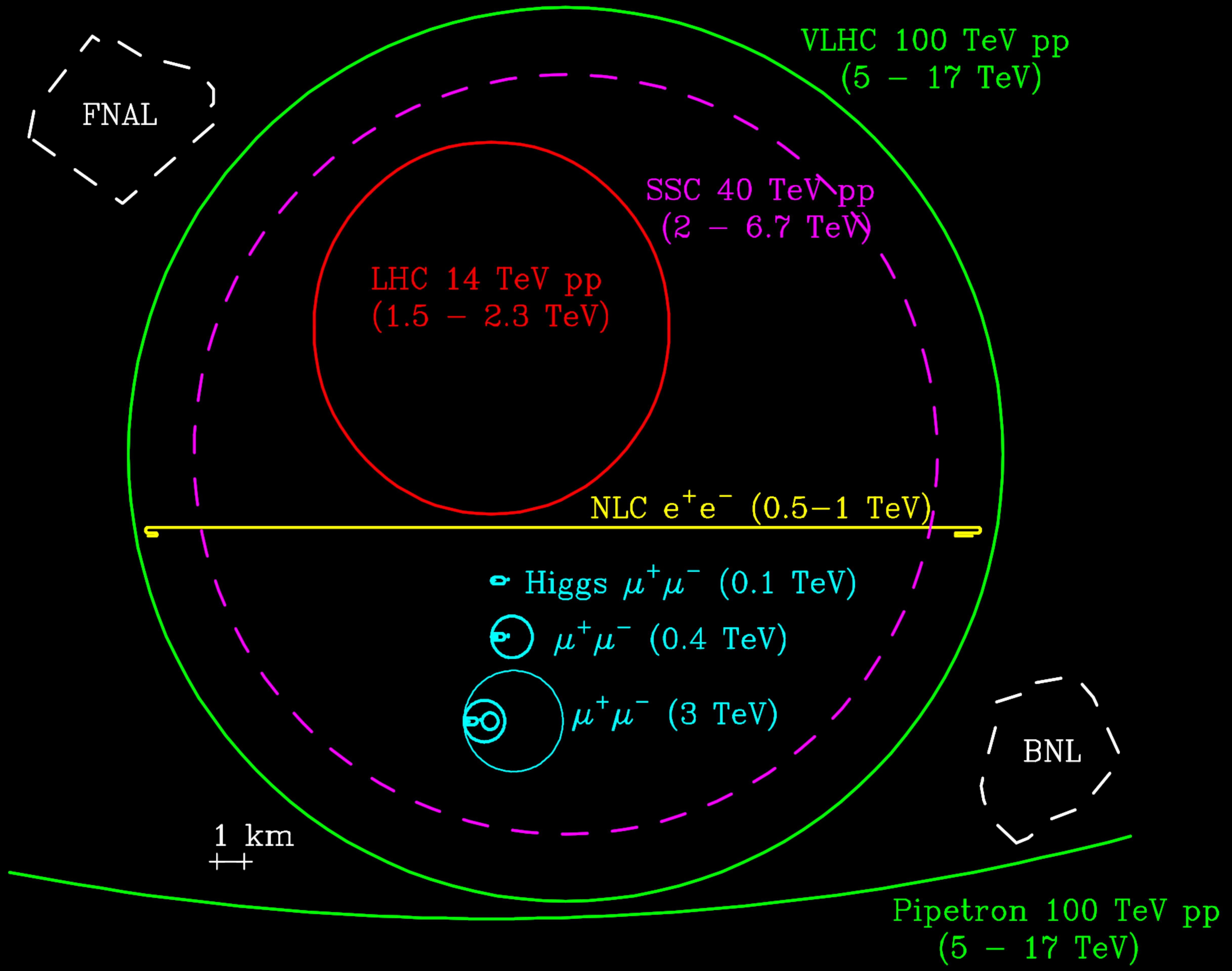
A Higgs! Yet:
Is it the SM Higgs?
Is it the only one?
Why is there EWSB?
What sets the scale?

The path to shorter distances

Conventionally: pursue these questions by probing shorter distances with either **precision** (indirect) or **energy** (direct).

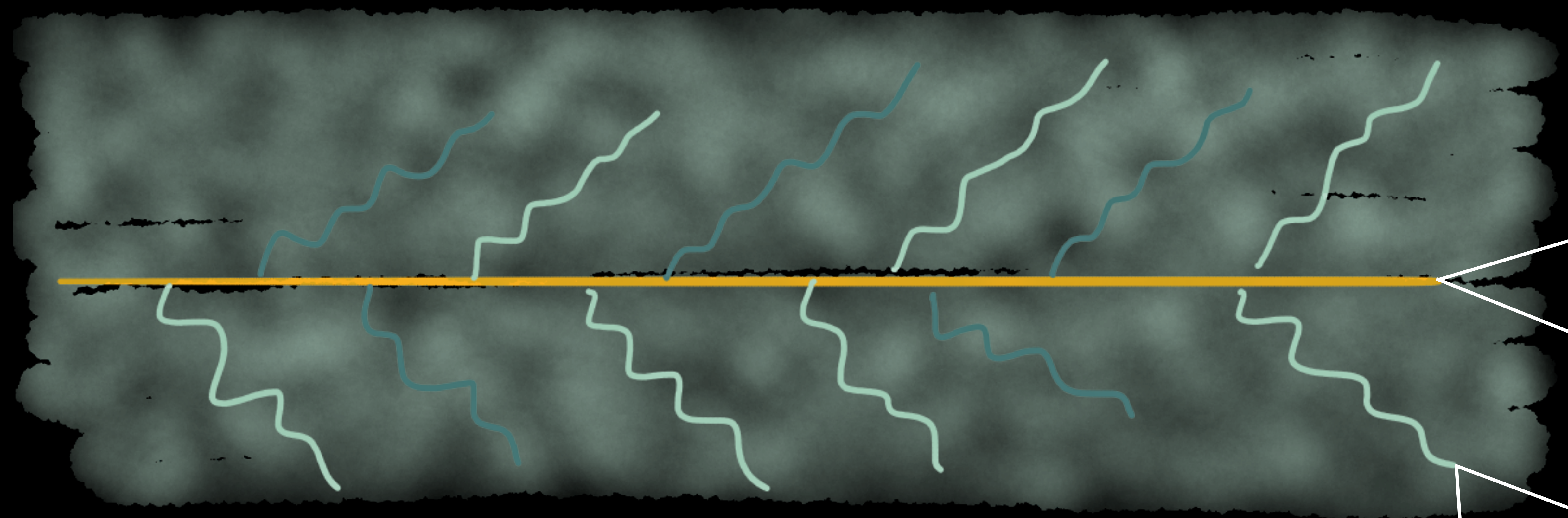
Muon colliders blur this dichotomy.

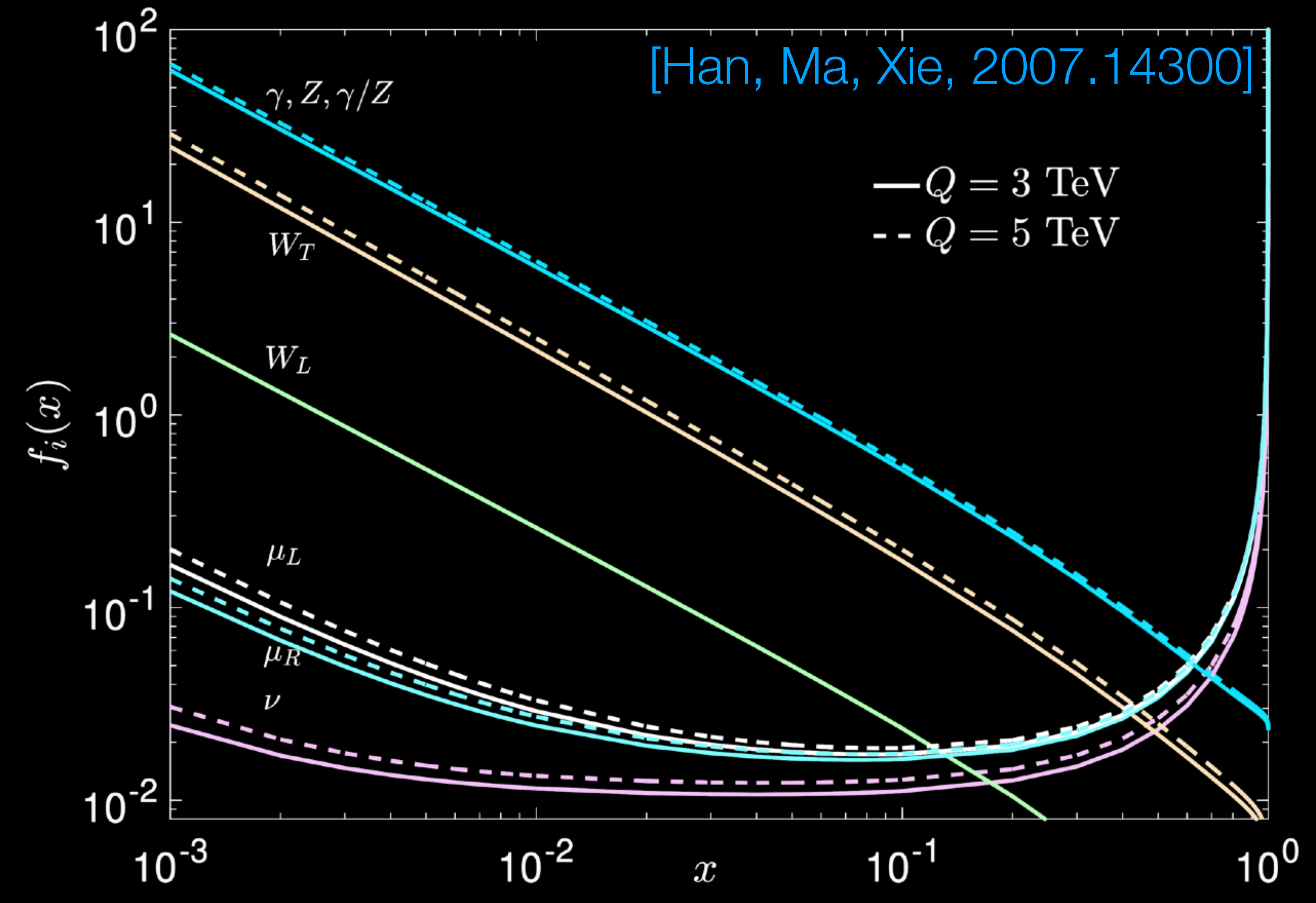
- Colliding elementary particles leverages the **full energy** of the accelerator, with a (relatively) **clean environment.**
- Larger mass of the muon allows a **smaller footprint** & **higher energies** compared to e^+e^- counterparts.
- **Major challenges:** finite lifetime, cooling

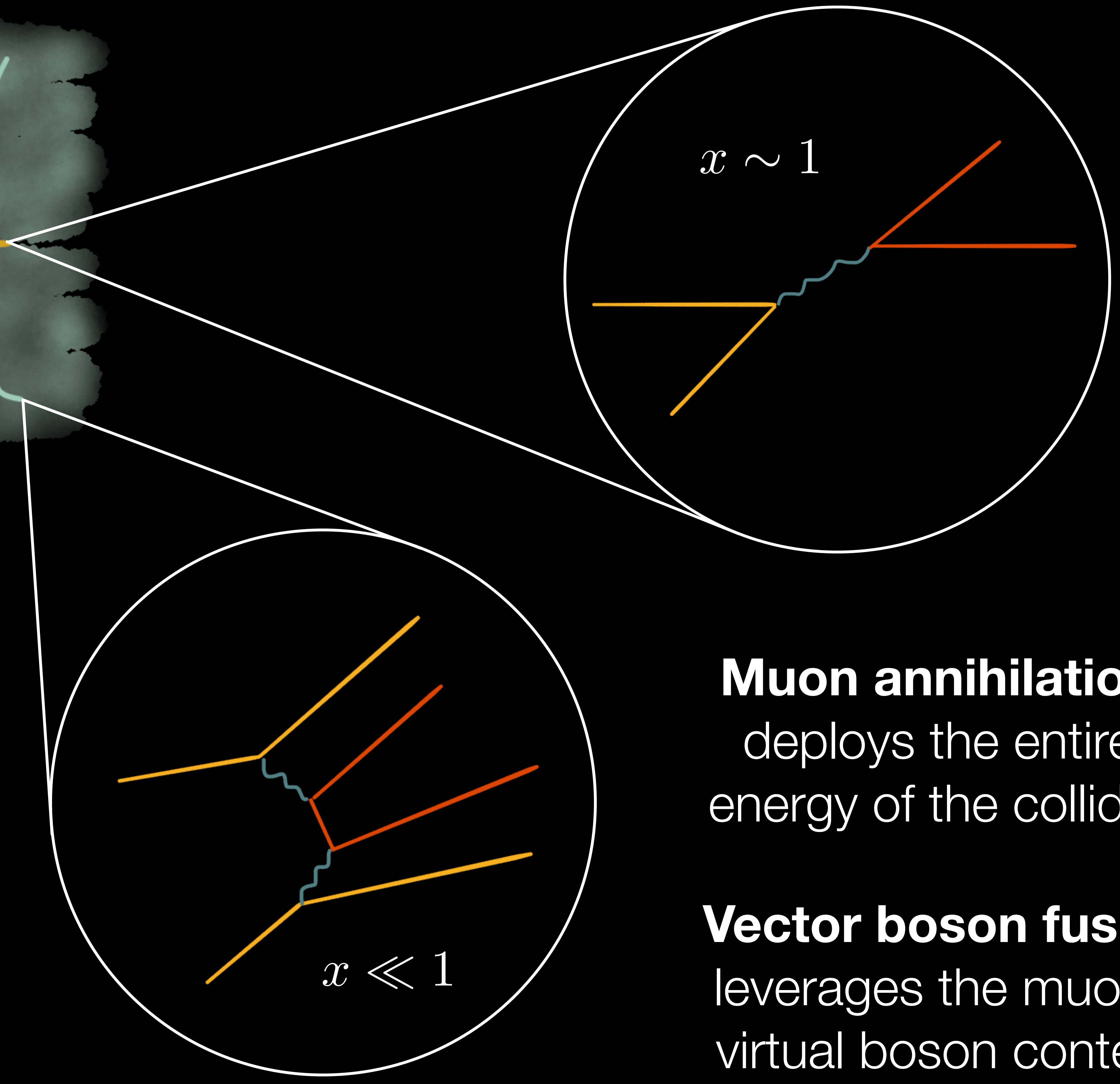


[Ankenbrandt et al. arXiv:physics/9901022]

The Quantum Muon







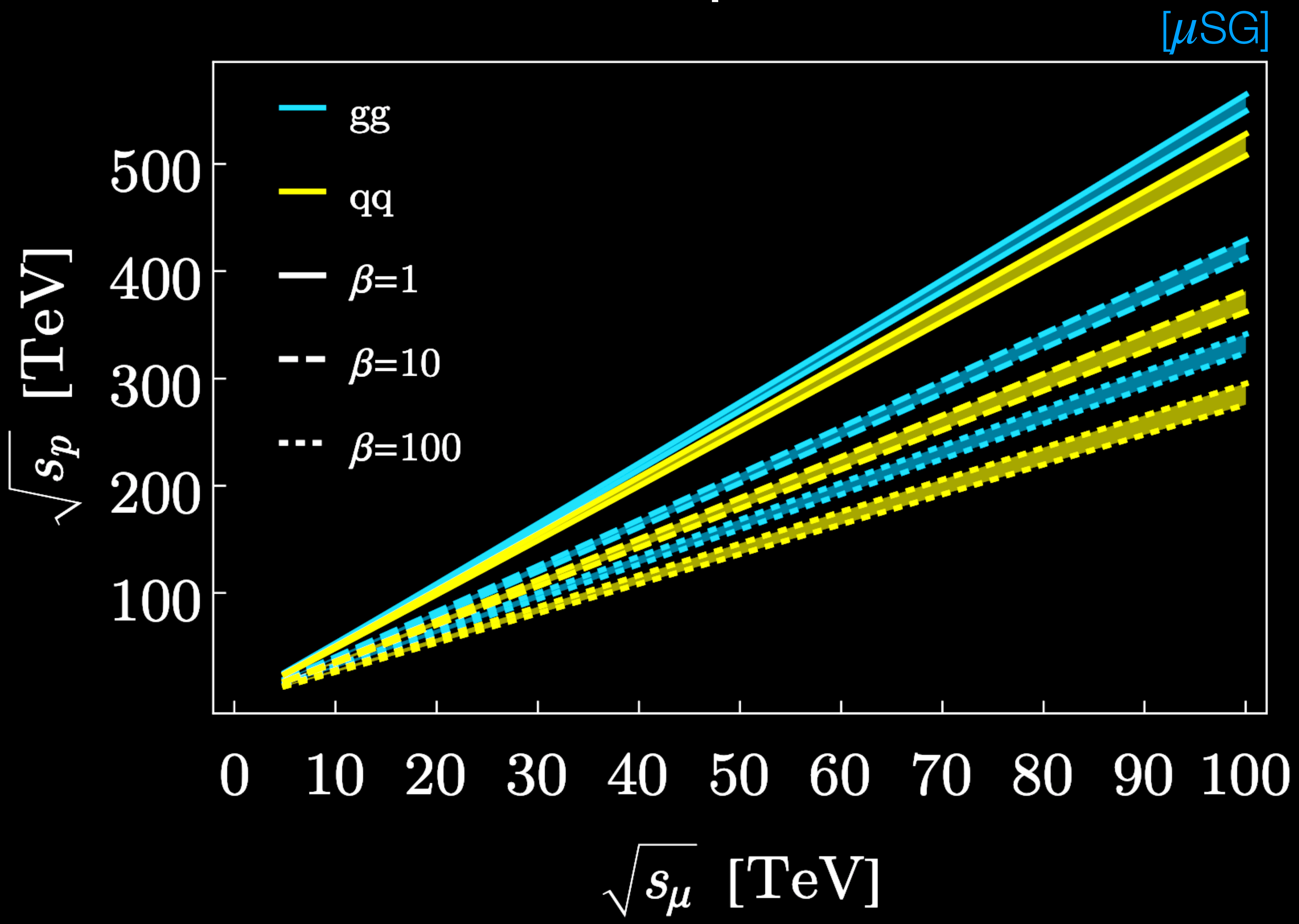
Muon annihilation deploys the entire energy of the collider

Vector boson fusion leverages the muon's virtual boson content

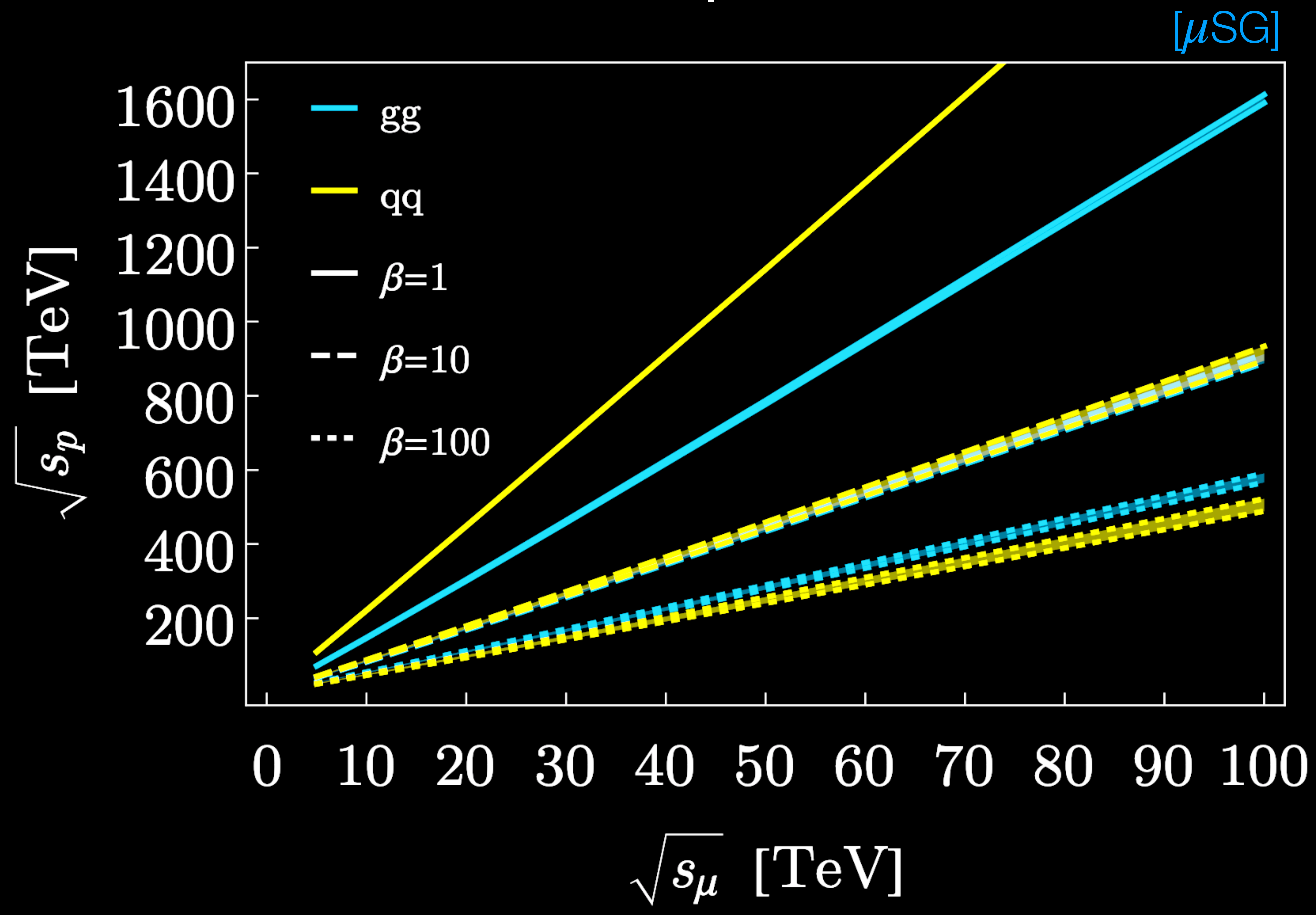
Muon annihilation & pp equivalents

In the spirit of [Delahaye et al. 1901.06150, Costantini et al. 2005.10289]

2-to-1 production



2-to-2 production

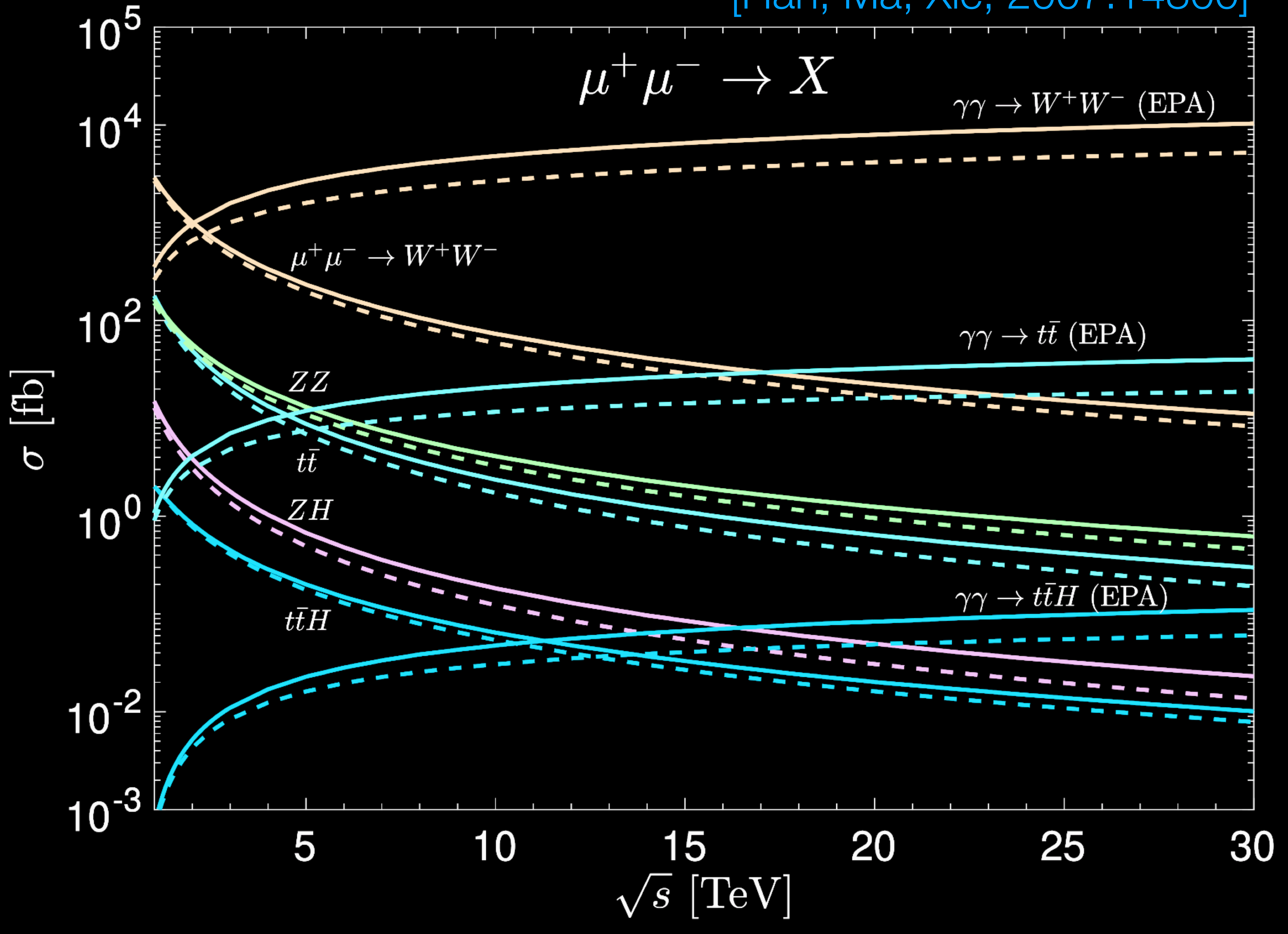


(Bands are NNPDF3.0 LO vs. CT18NNLO)

Comparison favorable to MC in that $\hat{s} = s_\mu = M^2$ for 2-to-1 and $\hat{s} = s_\mu = 4M^2$ for 2-to-2

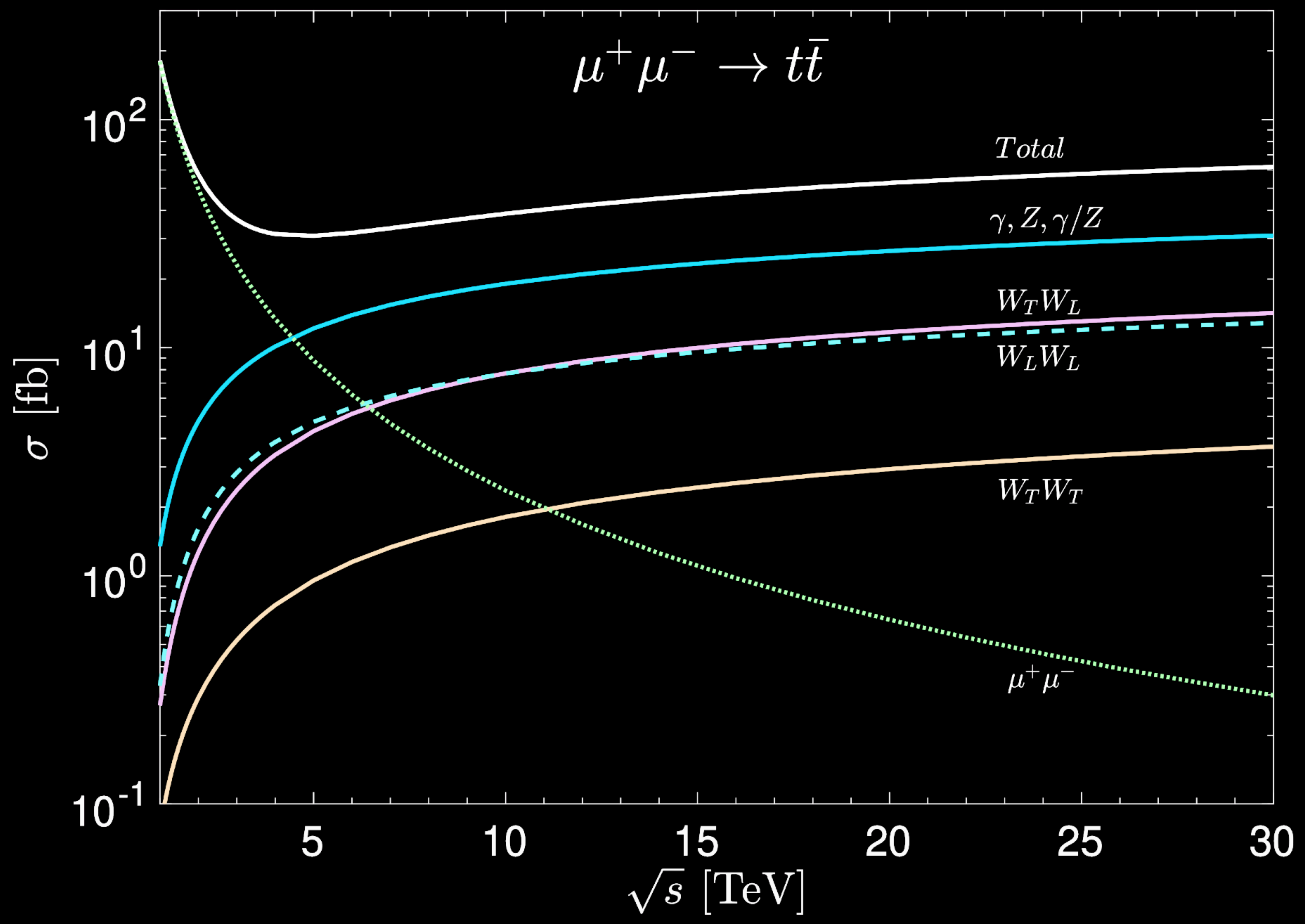
VBF: μCs as Vector Factories

[Han, Ma, Xie, 2007.14300]



VBF dominates well above threshold due to logarithmic growth with E_{CM}

[Han, Ma, Xie, 2007.14300]



Longitudinal polarizations play a key role, making an extraordinary laboratory for EWSB

c.f. [Costantini et al. 2005.10289]

What is the origin of mass?

```
A Higgs! Yet:
Is it the SM Higgs?
Is it the only one?
Why is there EWSB?
What sets the scale?
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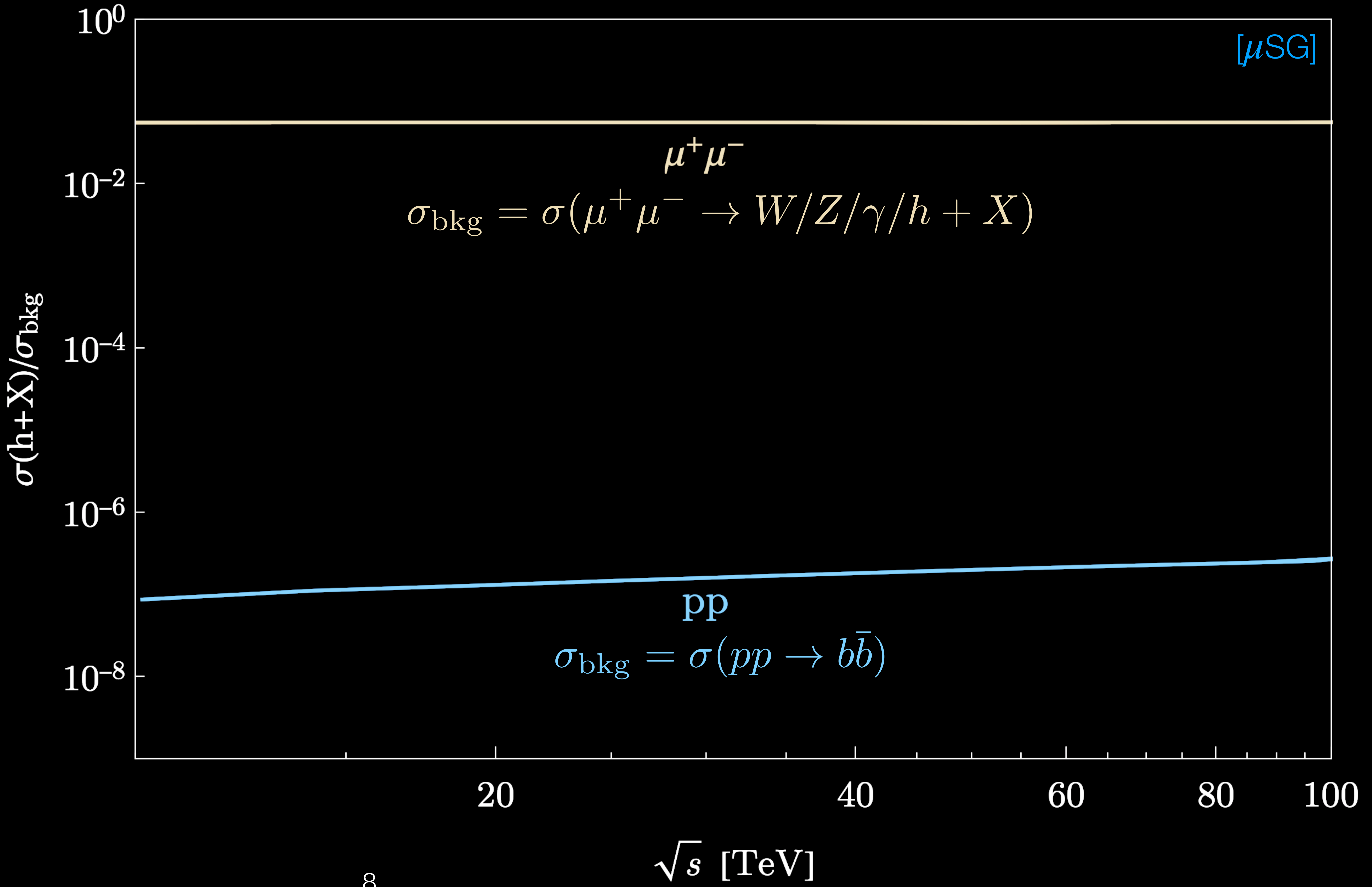
The Higgs itself is key.

Any deviation in its properties from SM predictions is a telltale sign of new physics.

S/B favorable at a μC.



Is it the SM Higgs?

Coupling	HLLHC	HLLHC + 125 GeV μ-coll. 5 fb^{-1}	HLLHC + 3 TeV μ-coll. 1 ab^{-1}	HLLHC + 10 TeV μ-coll. 10 ab^{-1}	HLLHC + 10 TeV μ-coll. + e^+e^- H fact (240/365 GeV)
κ_W	1.7	1.3	0.4	0.1	0.1
κ_Z	1.5	1.3	0.9	0.4	0.1
κ_g	2.3	1.7	1.4	0.7	0.6
κ_γ	1.9	1.6	1.3	0.8	0.8
κ_c	-	12	7.4	2.3	1.1
κ_t	3.3	3.2	3.1	3.1	3.1
κ_b	3.6	1.6	0.9	0.4	0.4
κ_μ	4.6	0.6	4.3	3.4	3.2
κ_τ	1.9	1.4	1.3	0.6	0.4
$\kappa_{Z\gamma}^\dagger$	10.4	10.3	10.3	10.3	10.1

† No input used for μ collider.

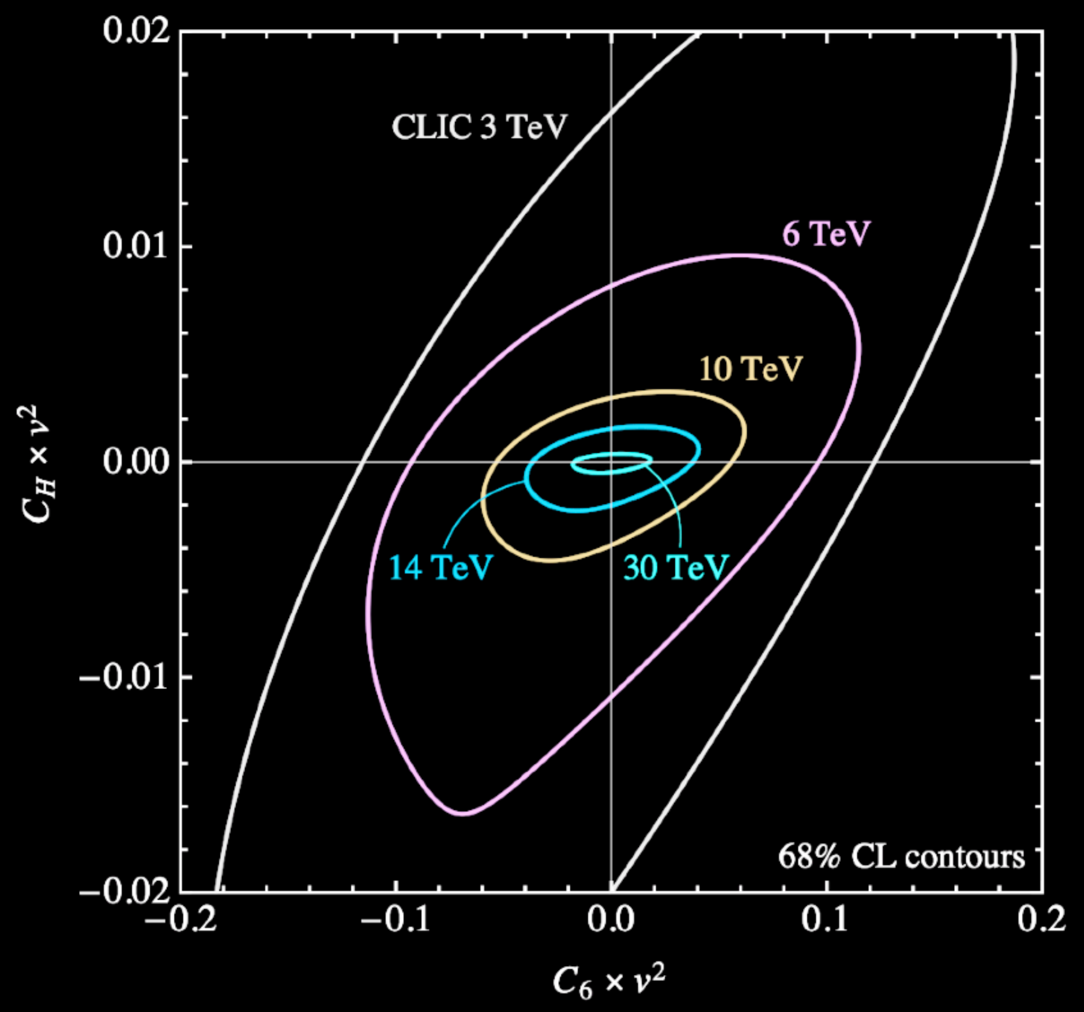
Courtesy P. Meade, from [Forslund & Meade, *to appear*] and [de Blas, Gu, Liu, *to appear*]

Is it the SM Higgs?

Higgs cubic self-coupling

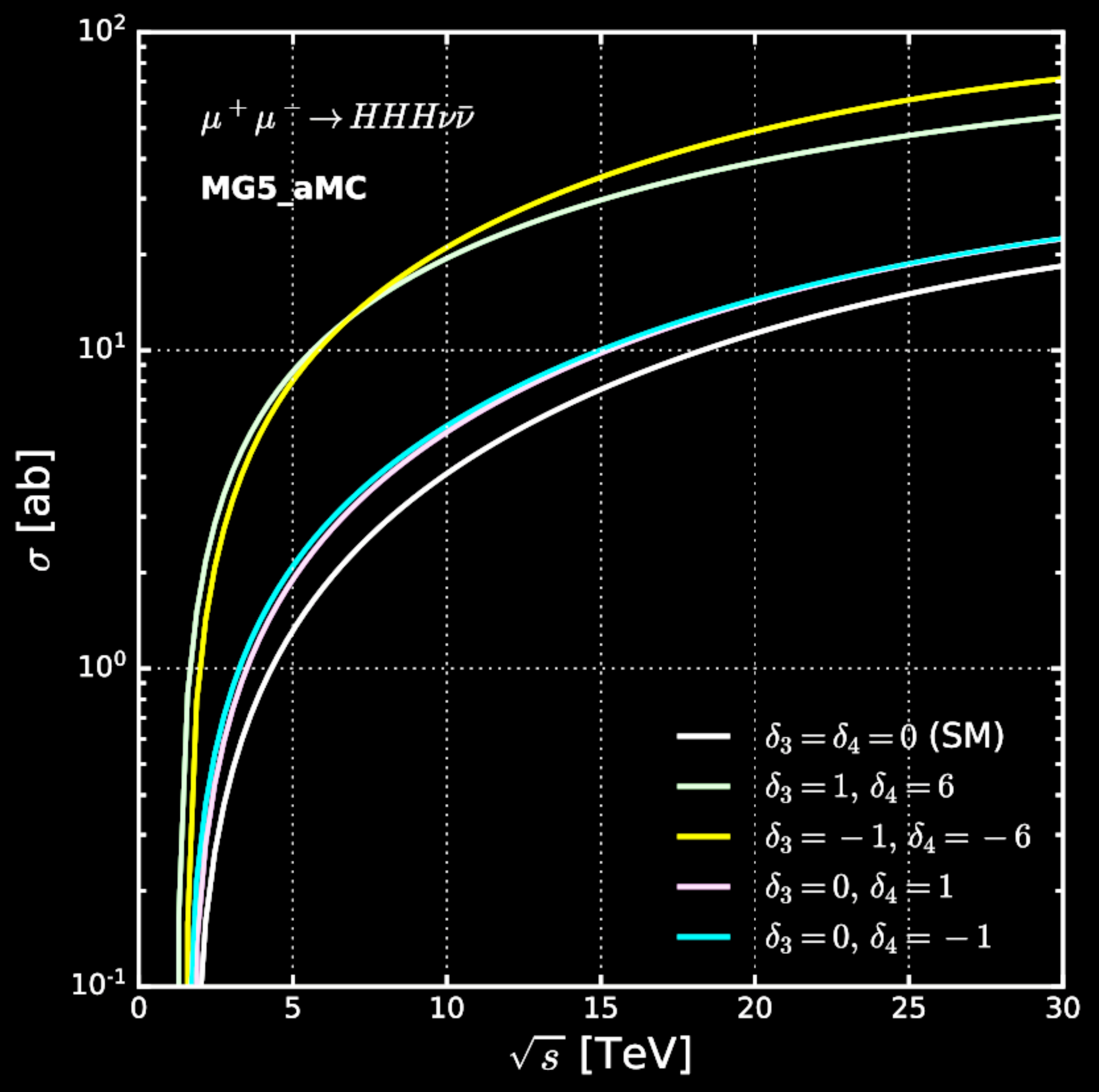
[Han, Liu, Low, Wang 2008.12204]

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_3)_{in}$	25%	10%	5.6%	3.9%	2.0%



[Buttazzo, Franceschini, Wulzer, 2012.11555]

Higgs quartic self-coupling



[Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao 2003.13628]

$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only, acceptance cuts 1 σ	2 σ	3 σ
6	12	$[-0.50, 0.70]$	$[-0.74, 0.95]$	$[-0.93, 1.15]$
10	20	$[-0.37, 0.54]$	$[-0.55, 0.72]$	$[-0.69, 0.85]$
14	33	$[-0.28, 0.43]$	$[-0.42, 0.58]$	$[-0.52, 0.68]$
30	100	$[-0.15, 0.30]$	$[-0.24, 0.38]$	$[-0.30, 0.45]$
3	100	$[-0.34, 0.64]$	$[-0.53, 0.82]$	$[-0.67, 0.97]$

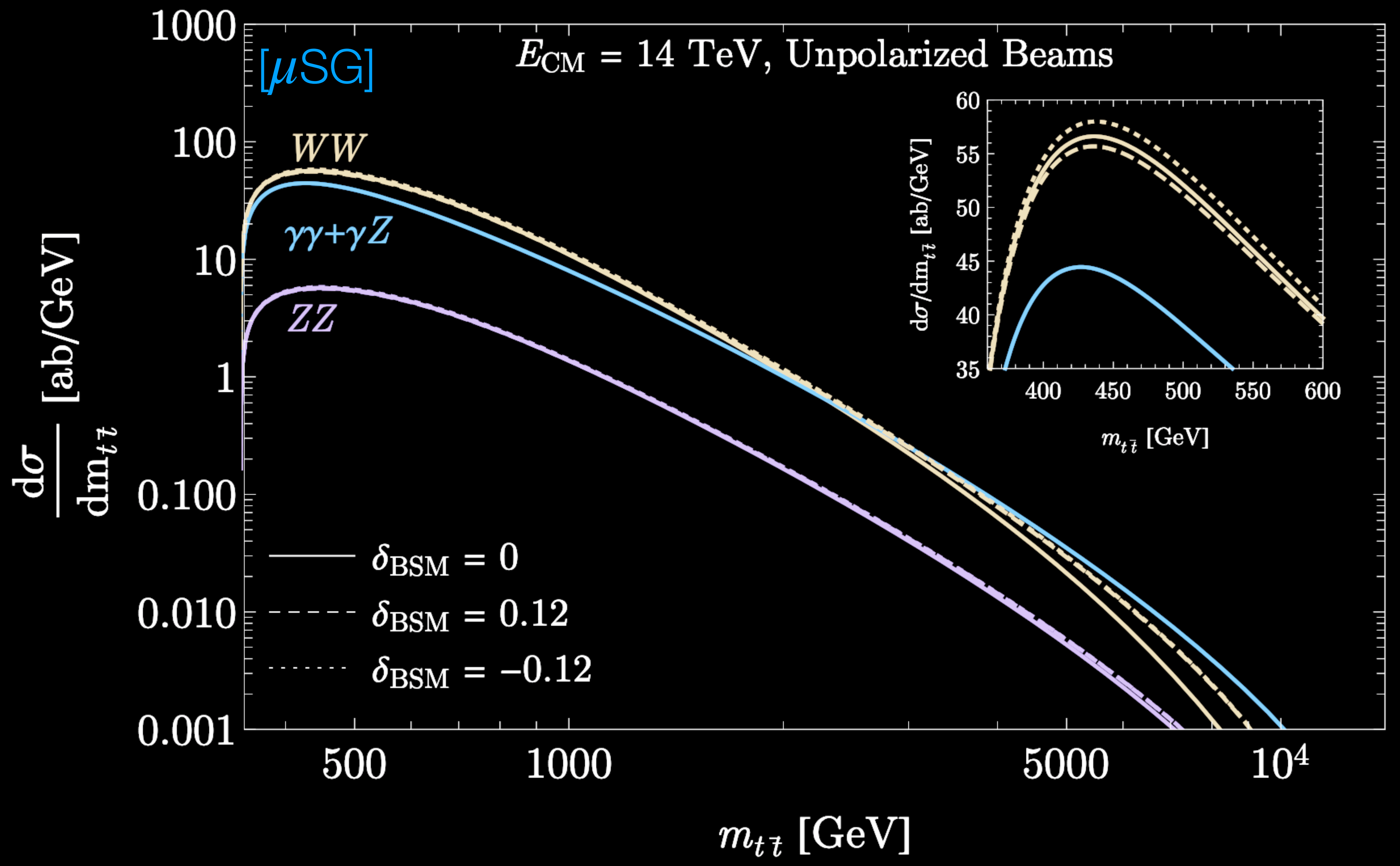
Is it the SM Higgs?

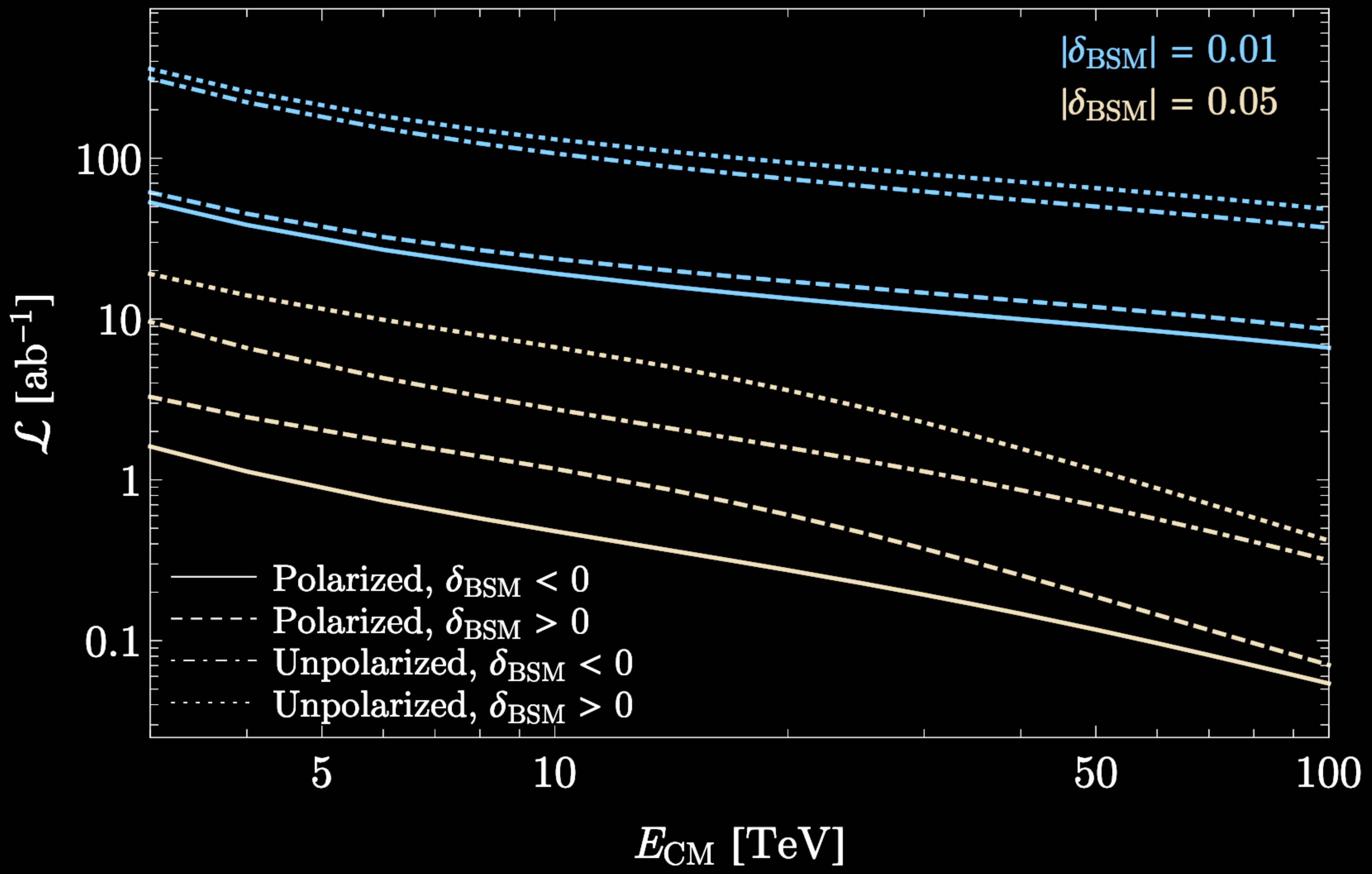
High-energy measurements equally powerful [Buttazzo, Franceschini, Wulzer, 2012.11555]

For example: measuring Higgs-top coupling in high-energy $t\bar{t}$

Expect to remain an interesting target after HL-LHC/Higgs factory ($|\delta_{\mathrm{BSM}}| < 0.06$)

$$y_t \to y_t(1+\delta_{\mathrm{BSM}}) \qquad \mathcal{M}(W_L^+ W_L^- \to t\bar{t}) \approx -\frac{m_t}{v^2}\delta_{\mathrm{BSM}}\sqrt{\hat{s}} \qquad \sqrt{\hat{s}} \gg m_t$$





Is our Higgs the only one?

Many possible extensions of the scalar sector…

For illustration: a Standard Model singlet mixing with the Higgs.

$$h = h^0 \cos\gamma + S \sin\gamma$$
$$\phi = S\cos\gamma - h^0 \sin\gamma$$

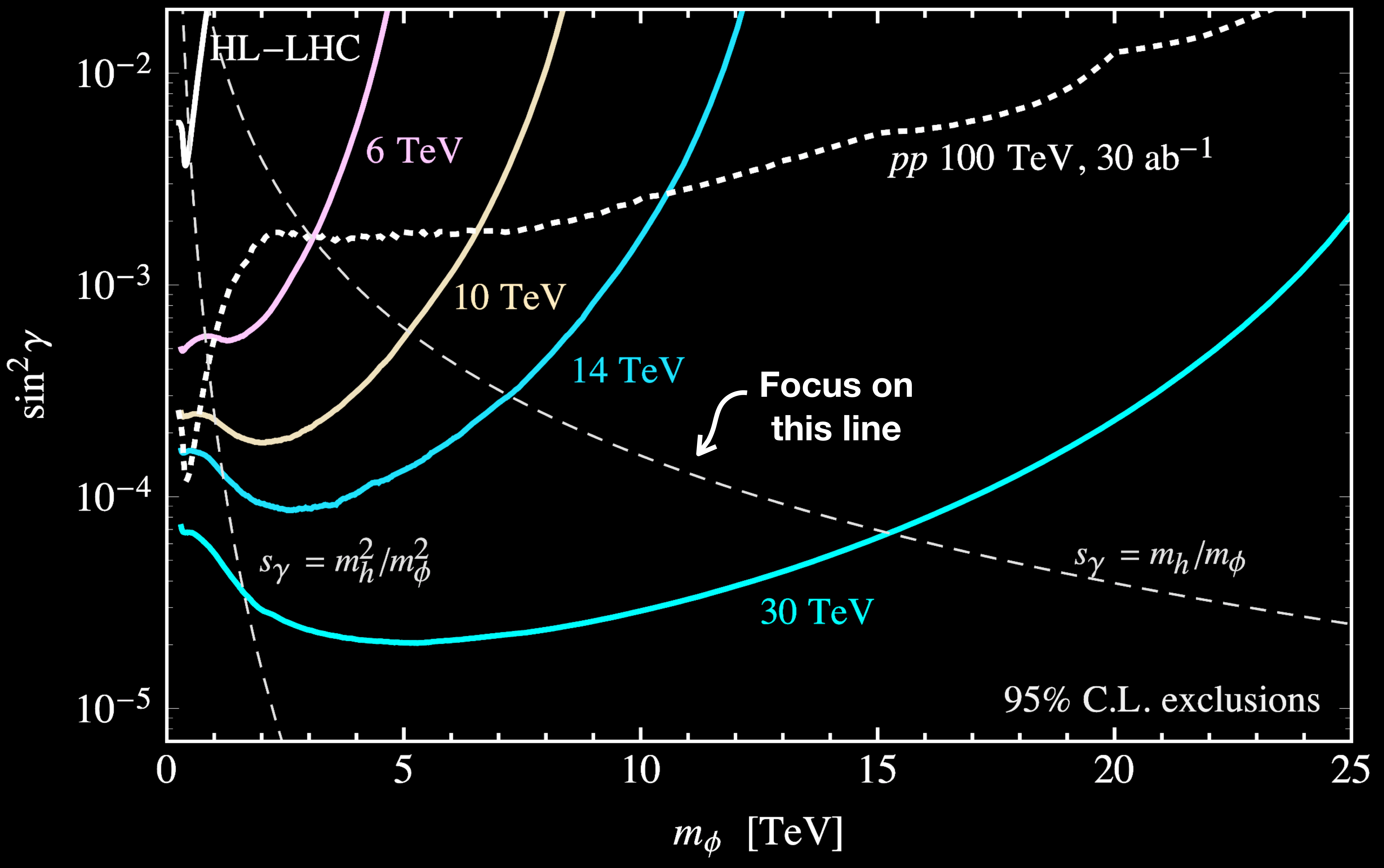
Production:

$$\sigma_\phi = \sin^2\gamma \cdot \sigma_h(m_\phi)$$

Decay:

$$\mathrm{BR}_{\phi\to f\bar{f},VV} = \mathrm{BR}_{h\to f\bar{f},VV}(1-\mathrm{BR}_{\phi\to hh})$$
$$\mathrm{BR}_{\phi\to hh} \sim 25\%$$

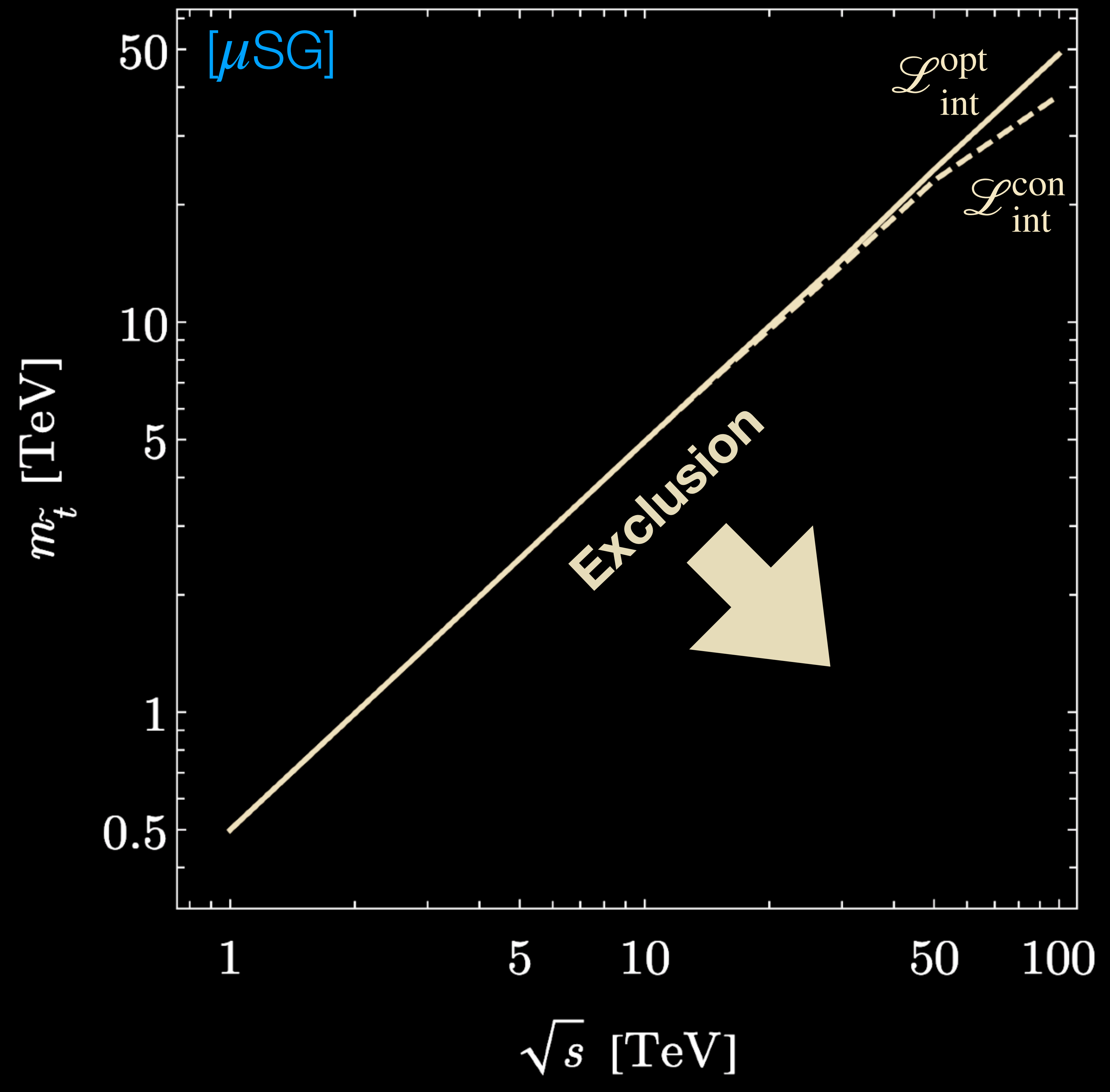
[Buttazzo, Redigolo, Sala, Tesi, 1807.04743; updated for μSG]



Why EWSB? What sets the scale?

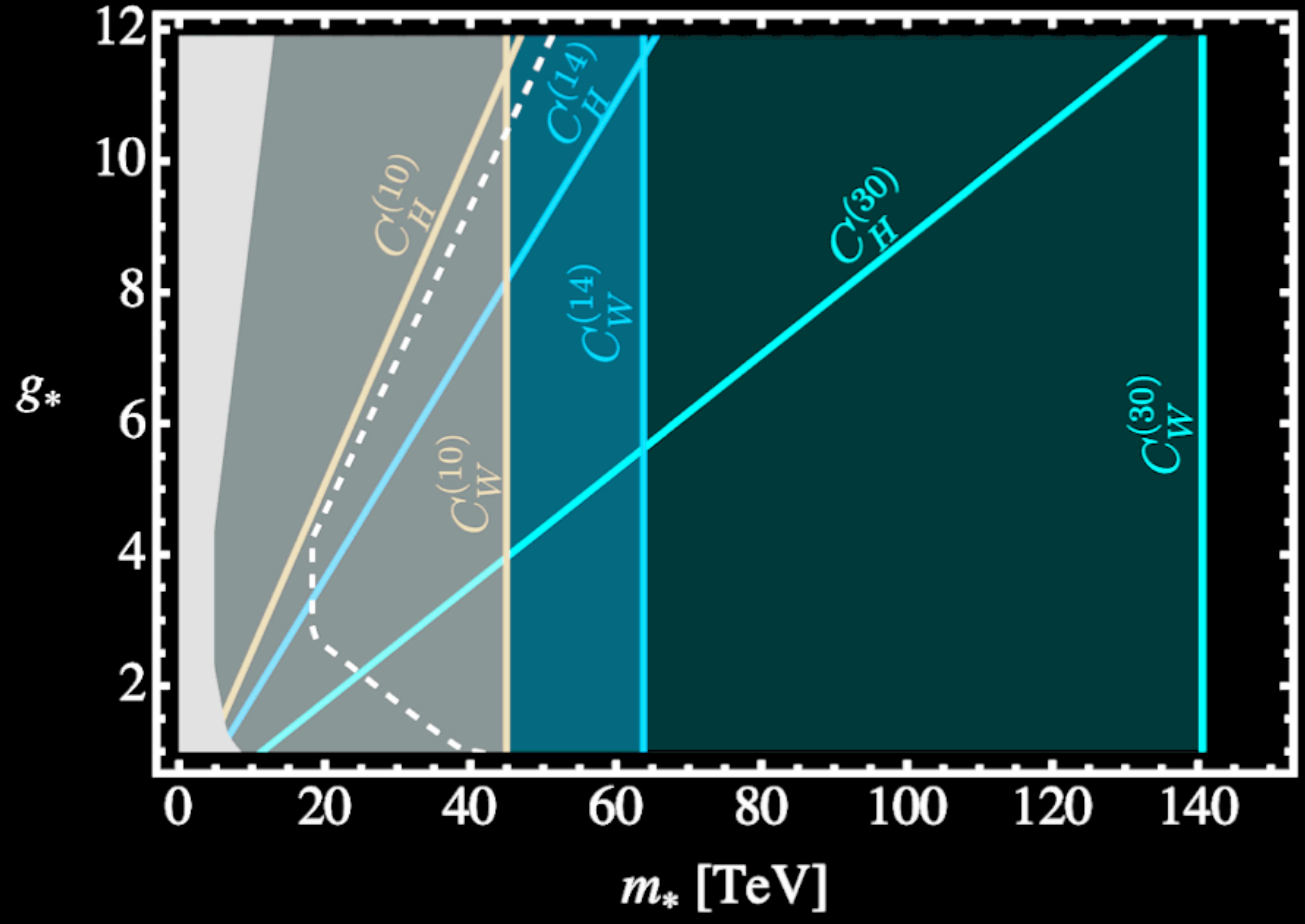
Supersymmetry

$\mu^+\mu^- \to \tilde{t}_R\tilde{t}_R \to t\bar{t} + \chi\chi$



Composite Higgs

Indirect $\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$, $\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$



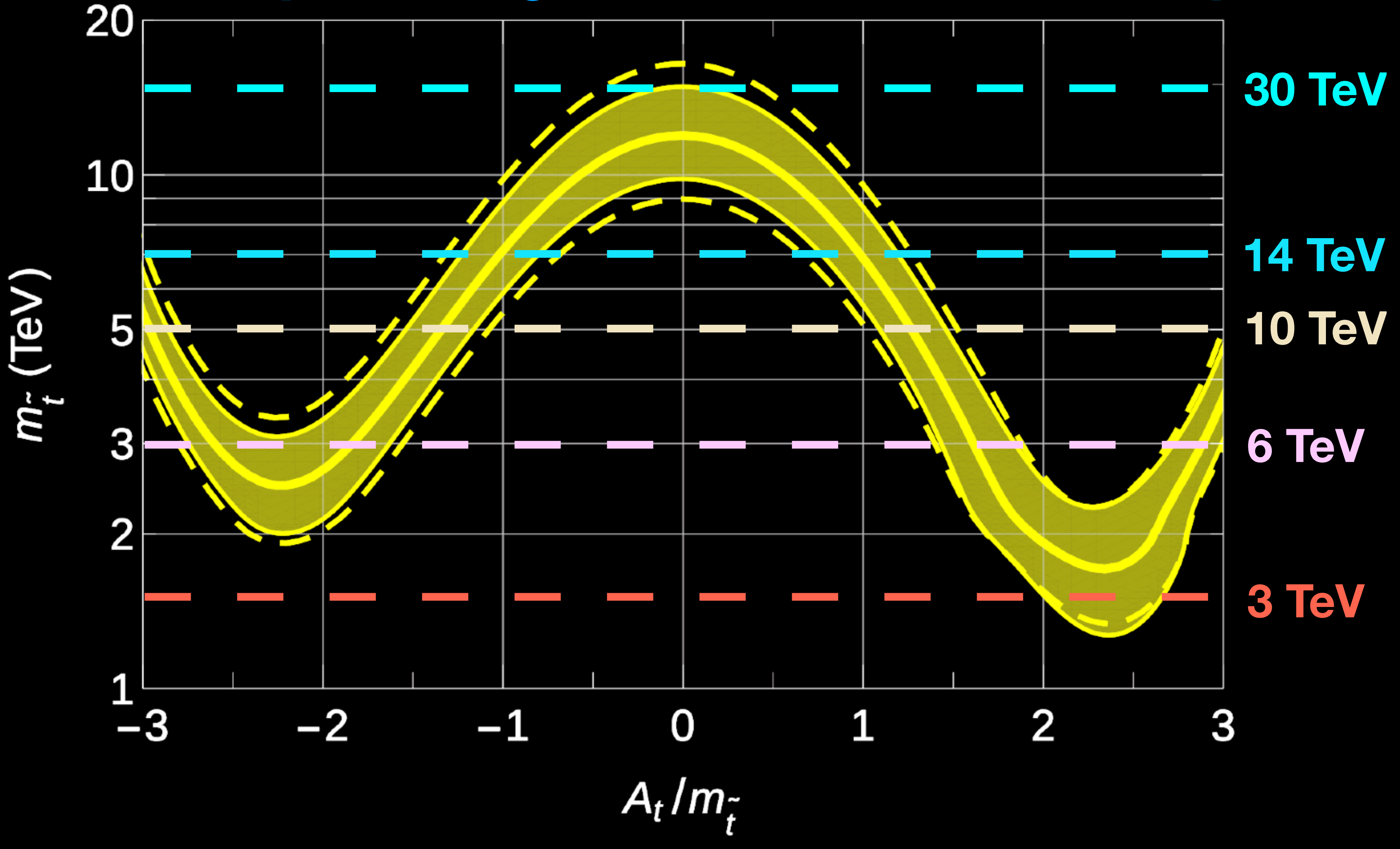
[Buttazzo, Franceschini, Wulzer 2012.11555]

Why EWSB? What sets the scale?

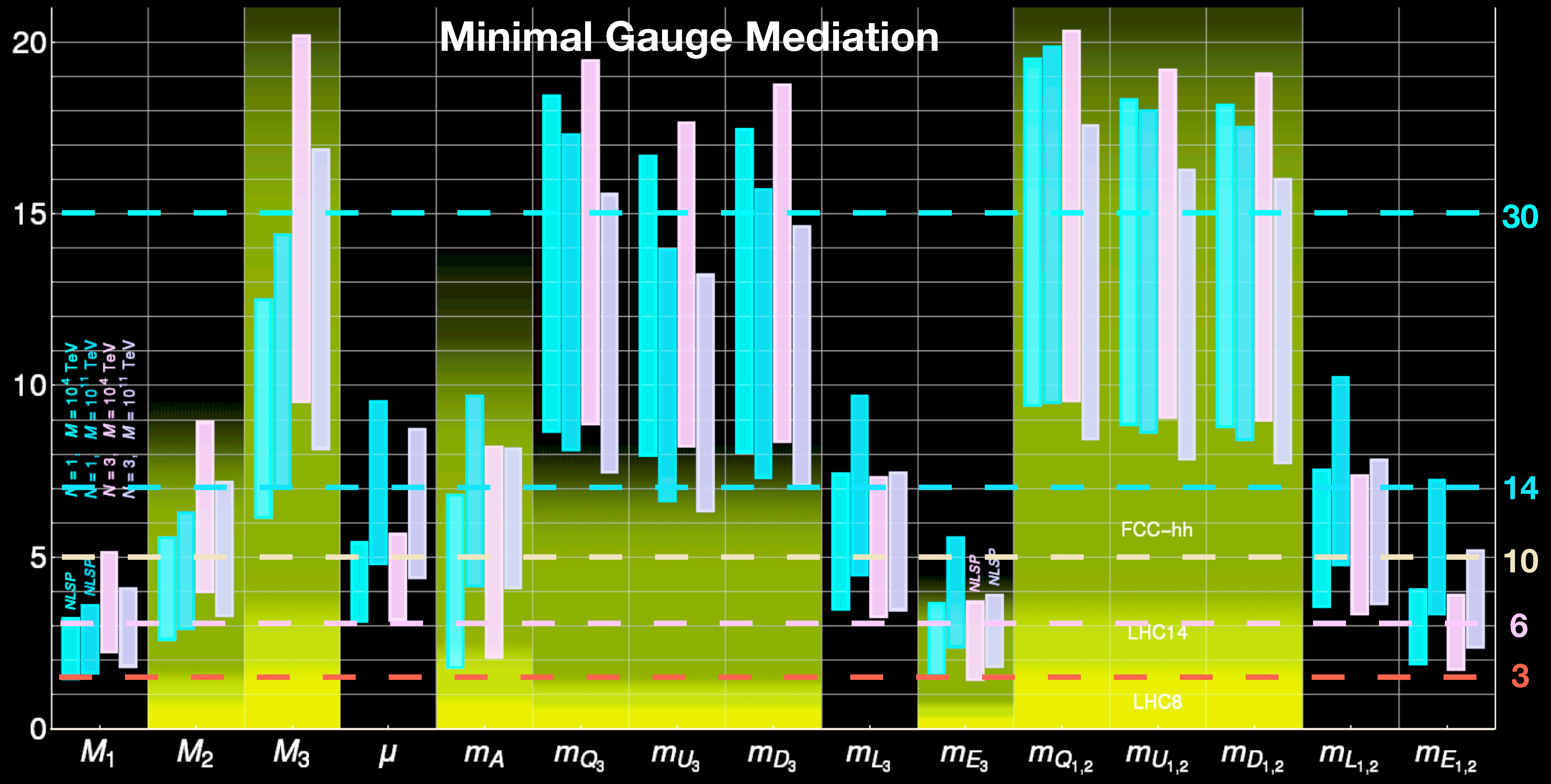
Theories that predict the Higgs mass provide sharp targets for the scale of new physics.

Direct targets set by the observed Higgs mass (e.g. supersymmetry)

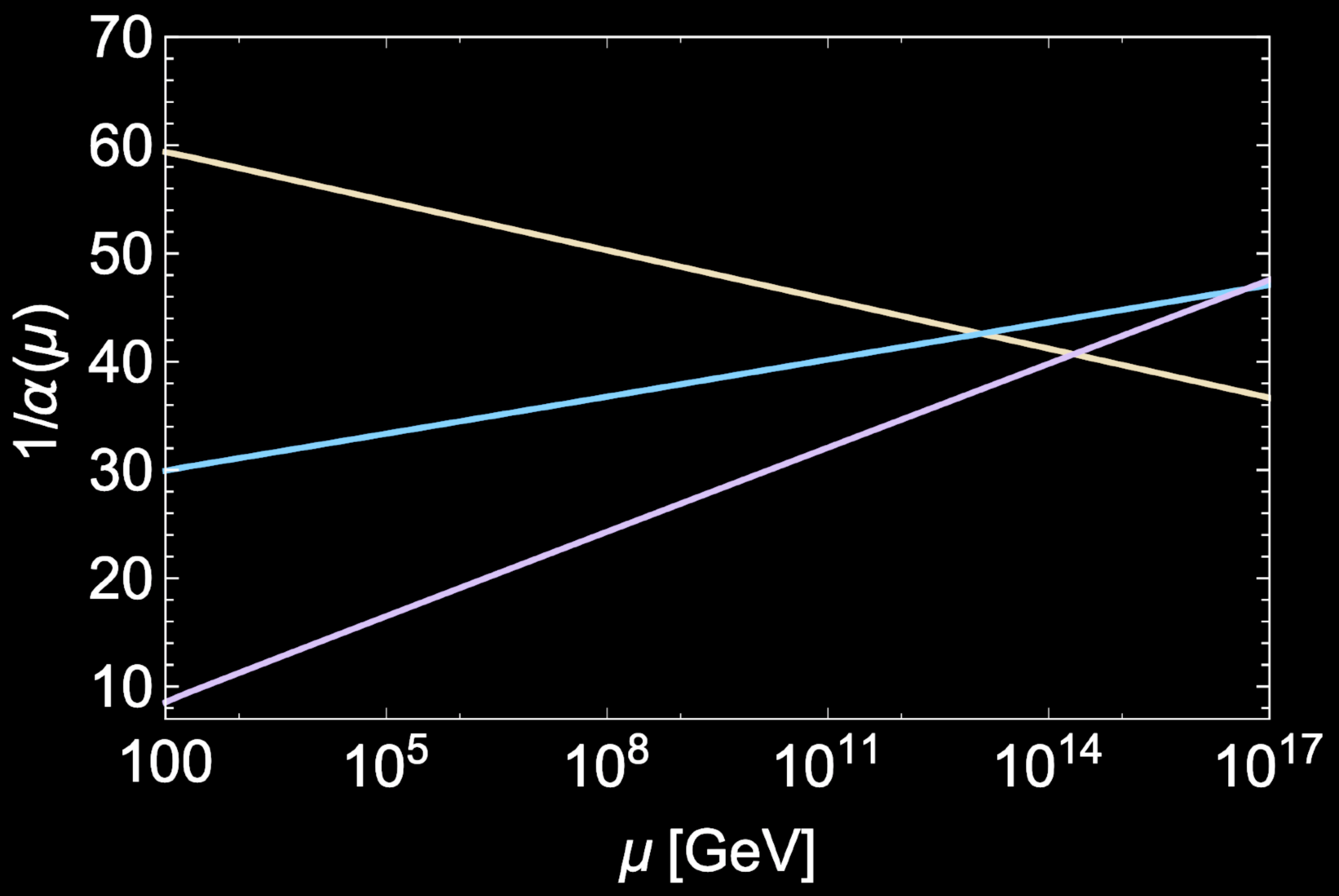
[Pardo Vega & Villadoro, 1504.05200]



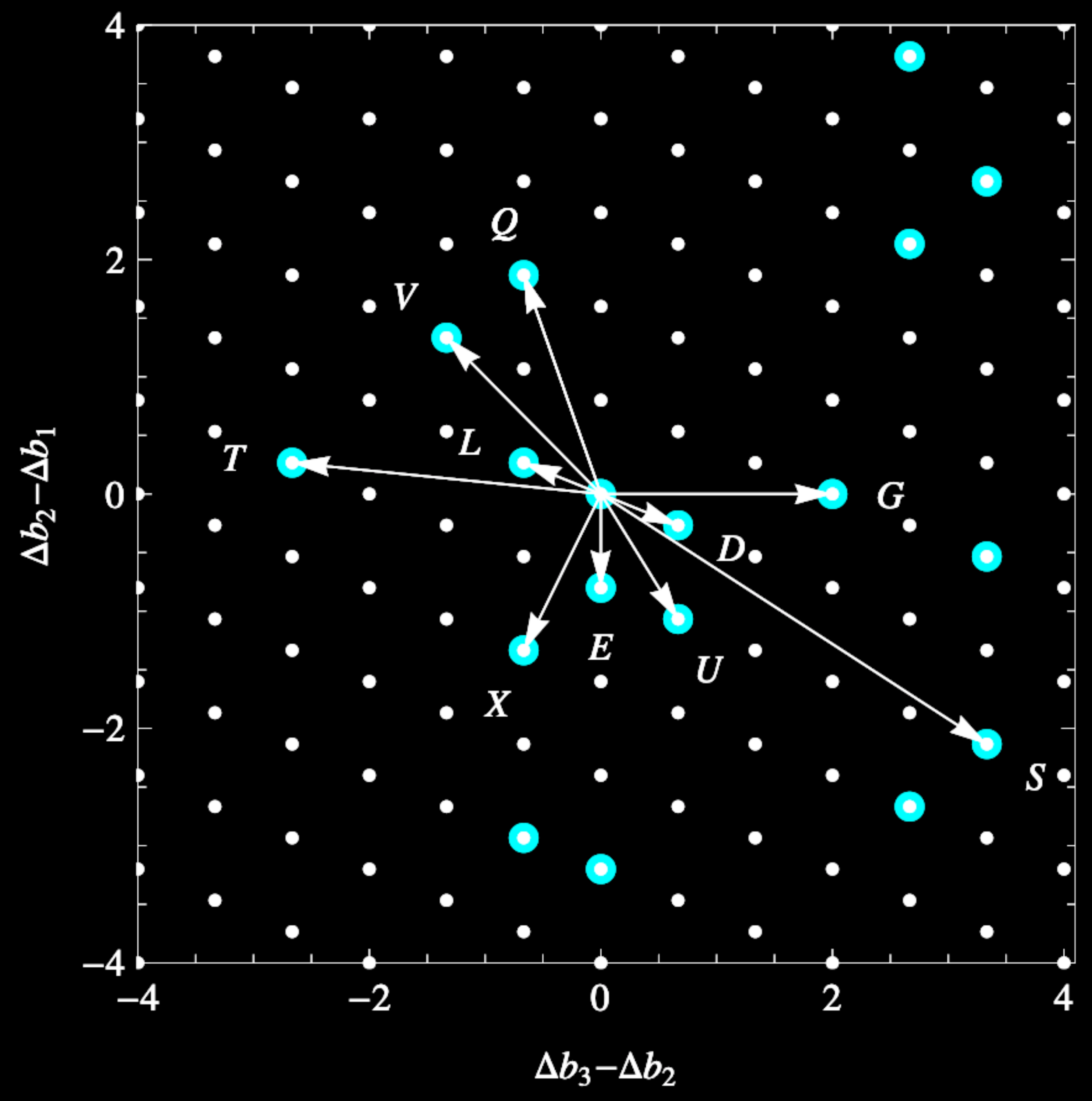
Correlated opportunities in minimal frameworks

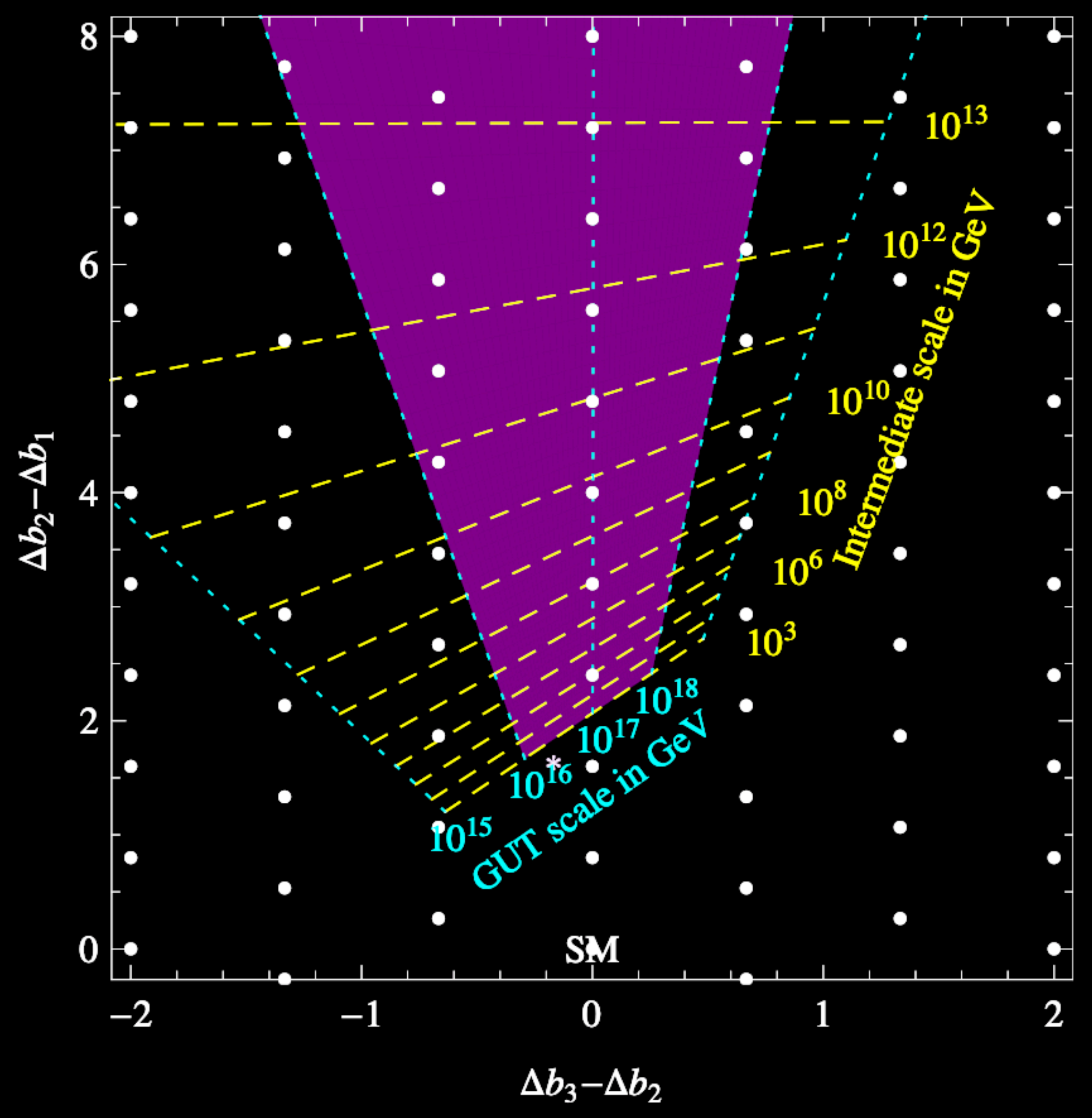


Unification beyond the Standard Model?



[Giudice et al 1204.5465]





Running of couplings in the Standard Model tantalizingly hints at unification, but the intersection is imperfect & scale too low.

New particles at TeV energies sharpen the prediction & raise the scale: clear targets for a high-energy muon collider, reach to $\sim\sqrt{s}/2$.

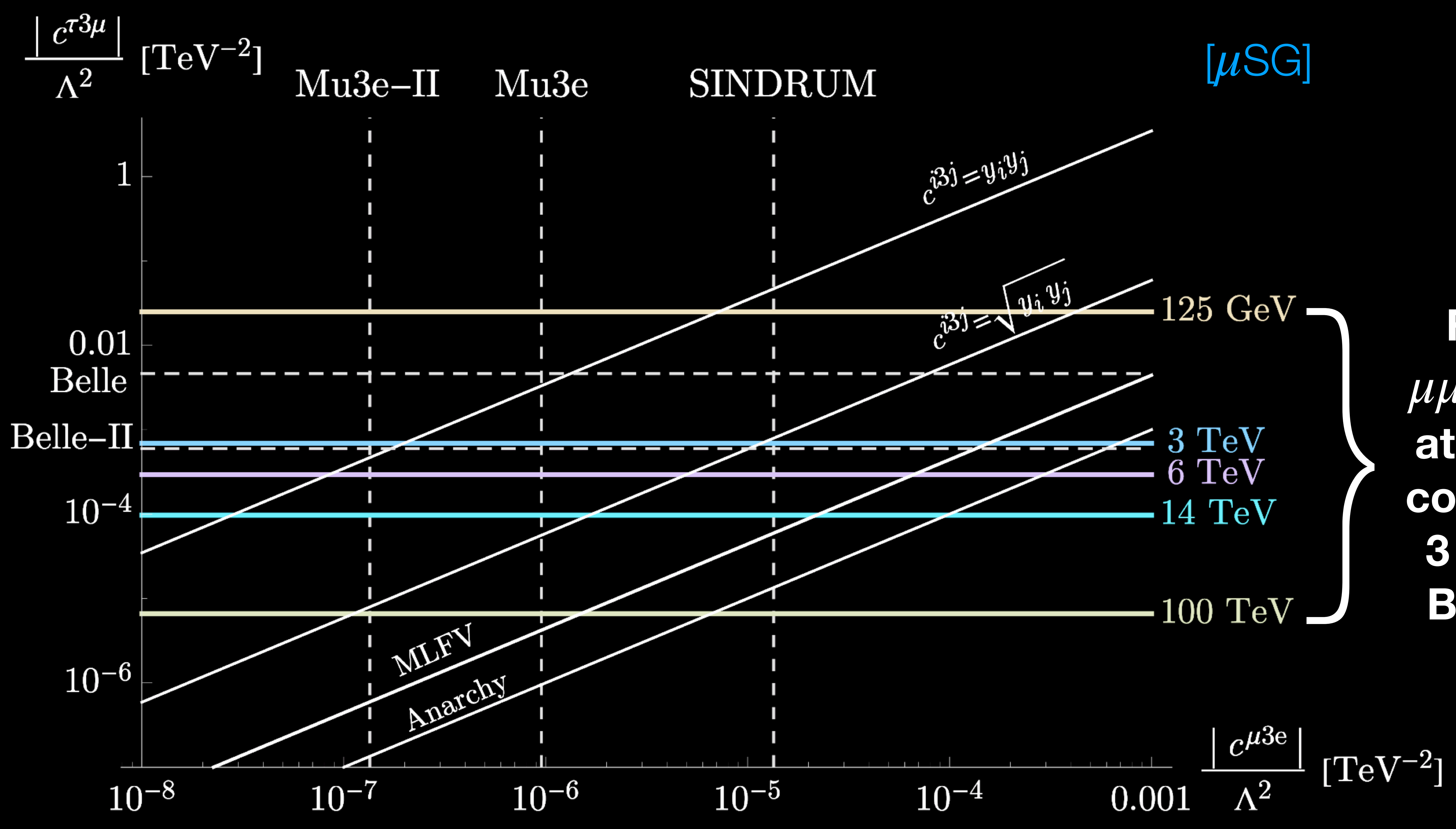
What is the origin of flavor?

First high-energy accelerator to primarily collide second-generation fermions.

High collision energies provide:

Direct access to hypothetical new particles associated with flavor structure

Indirect access to flavor structure via lepton flavor violating operators



From $\mu\mu \to \mu\tau$ at muon colliders, 3 TeV ~ Belle-II

Muon colliders an outstanding probe of explanations for **B flavor anomalies**
[Huang, Queiroz, Rodejohann, 2101.04956; Huang, Sana, Queiroz, Rodejohann, 2103.01617, Asadi, Capdevilla, Cesarotti, Homiller 2104.05720]

Is there ~~a deeper reason for~~ gauge symmetry?

We increasingly assume, but **do not know**, that *h* is* part of an electroweak doublet *H*, i.e. that $SU(2)_L x U(1)_Y$ is linearly realized by the known fields.

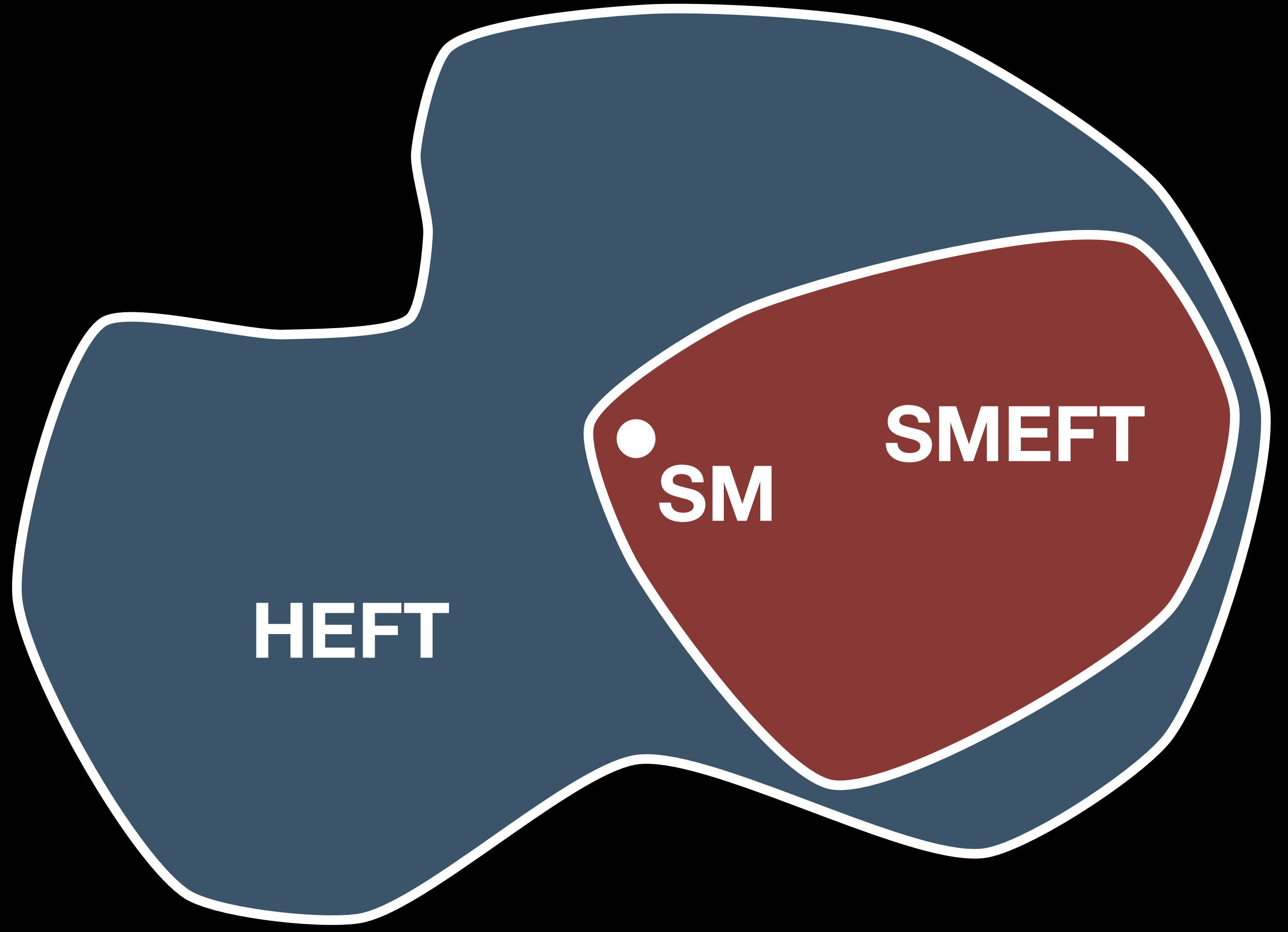
*"is" = low-energy theory suitably well behaved when *h* packaged into *H*

Equivalently: is the appropriate EFT

SMEFT: $SU(2)_L x U(1)_Y$, *H*

or

HEFT: $U(1)_{em}$, *h* & $\vec{\pi}$



Easy to obtain $U(1)_{em}$-symmetric EFT from $SU(2)_L x U(1)_Y$-symmetric UV theories.
Showing that the linearly realized gauge symmetry of known particles is $SU(2)_L x U(1)_Y$ ↔ ruling out the coset "HEFT/SMEFT", which necessarily violates unitarity by $4\pi v$ a la [Lee, Quigg, Thacker '77]

Is there ~~a deeper reason for~~ gauge symmetry?

Decisive test:

Measuring 2-to-2 scattering at high energy not optimal [Chang, Luty '19; Falkowski, Rattazzi '19].

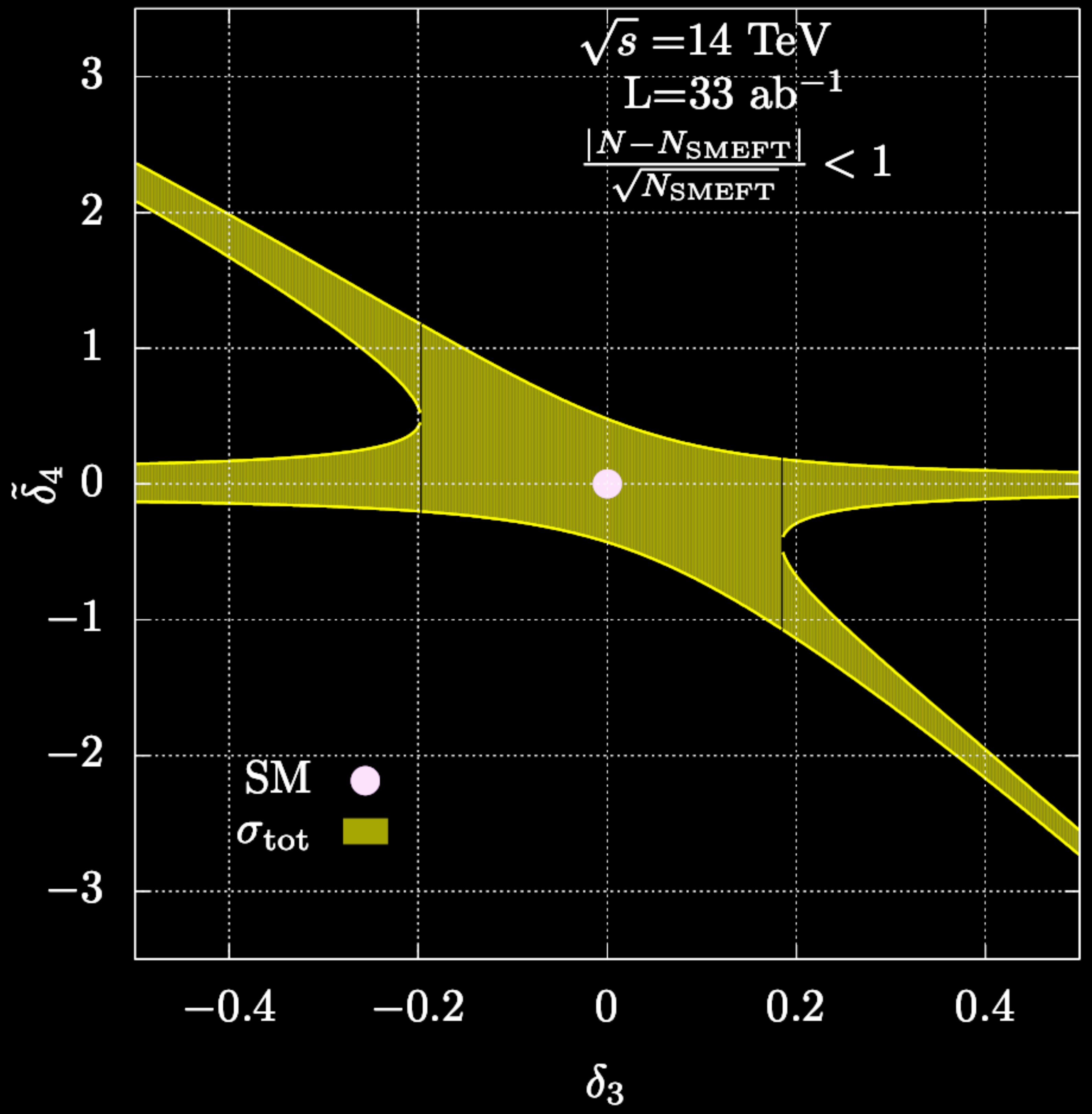
Instead: measure comprehensive set of 2-to-2 and 2-to-few processes w/ longitudinal vectors & Higgs bosons at partonic energies above $4\pi v \sim$ 3 TeV.

- Beyond reach of the HL-LHC.
- *Ideal for multi-TeV μC.*

Not comprehensively studied yet, but relevant results encouraging, e.g. [Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao 2003.13628]

Deviation from SMEFT correlation between Higgs cubic and quartic

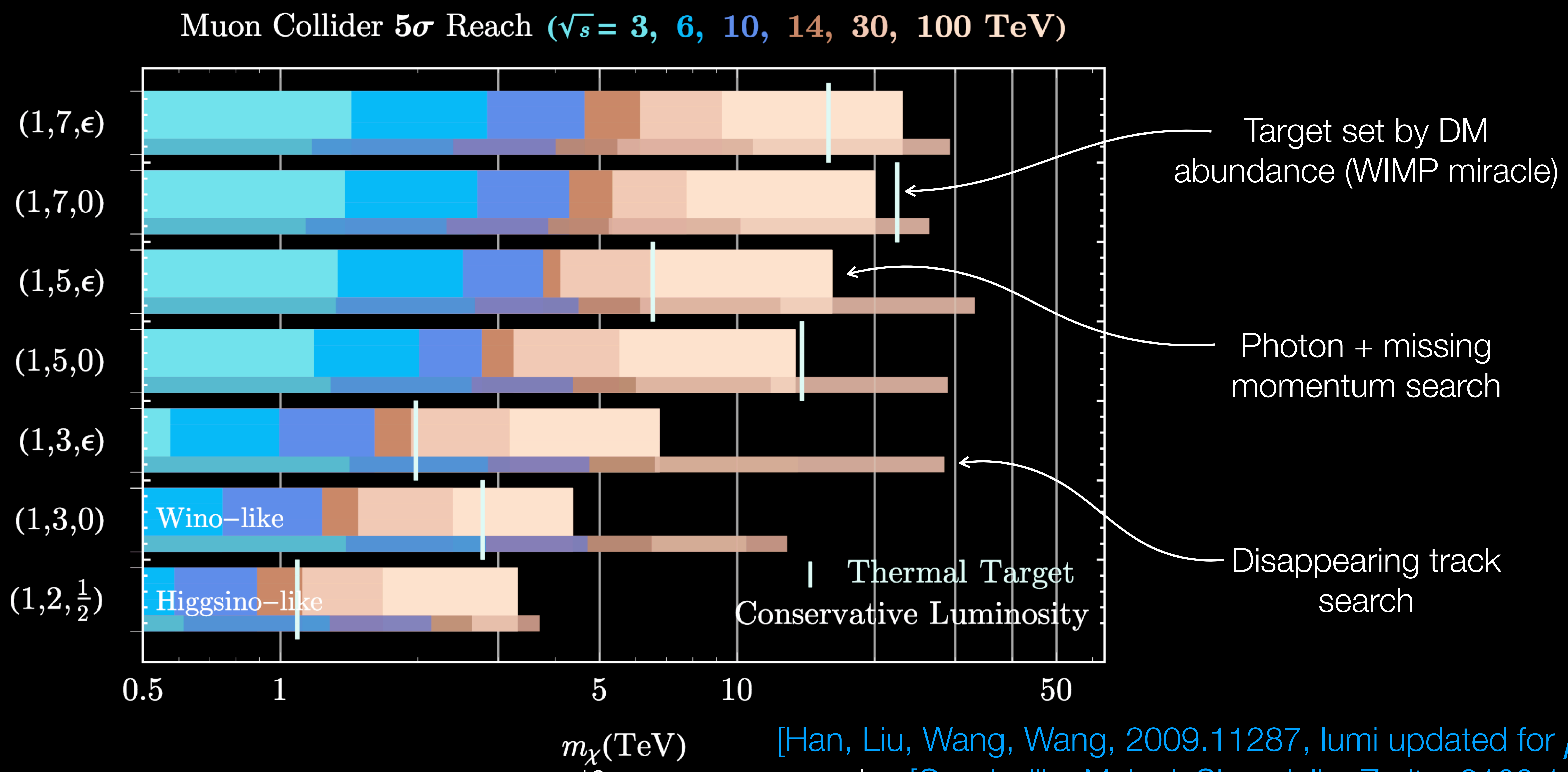
$$\tilde{\delta}_4 \equiv \delta_4 - 6\delta_3$$



What is the nature of dark matter?

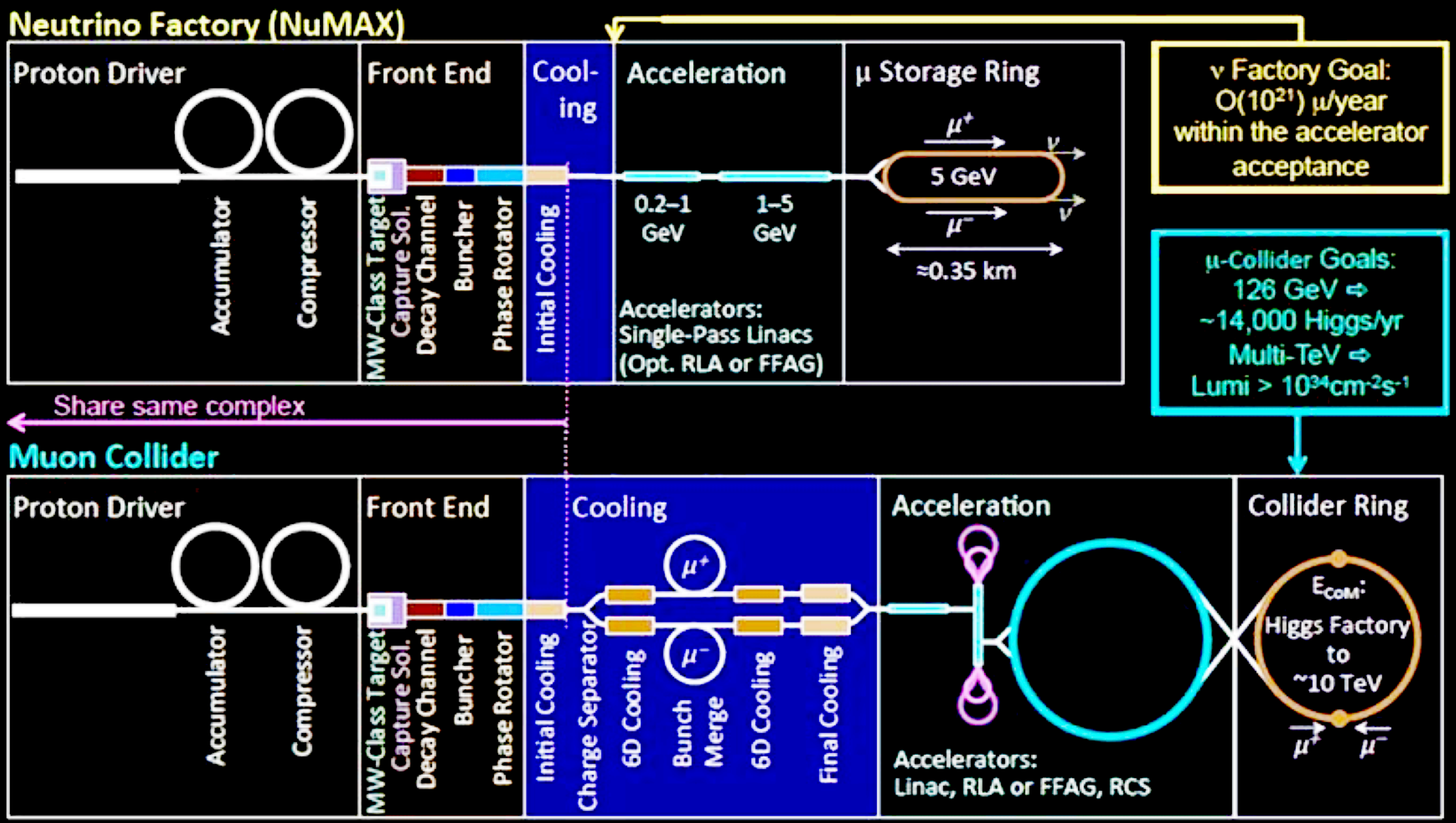
Powerful prospects for a μC in final states with missing energy:
large electroweak production rates, low backgrounds compared to hadron colliders

"Minimal dark matter"
(Electroweak multiplets with neutral lightest particle, abundance set by SM interactions)



[Han, Liu, Wang, Wang, 2009.11287, lumi updated for μSG]
see also [Capdevilla, Meloni, Simoniello, Zurita 2102.11292]

What is the nature of the neutrino sector?

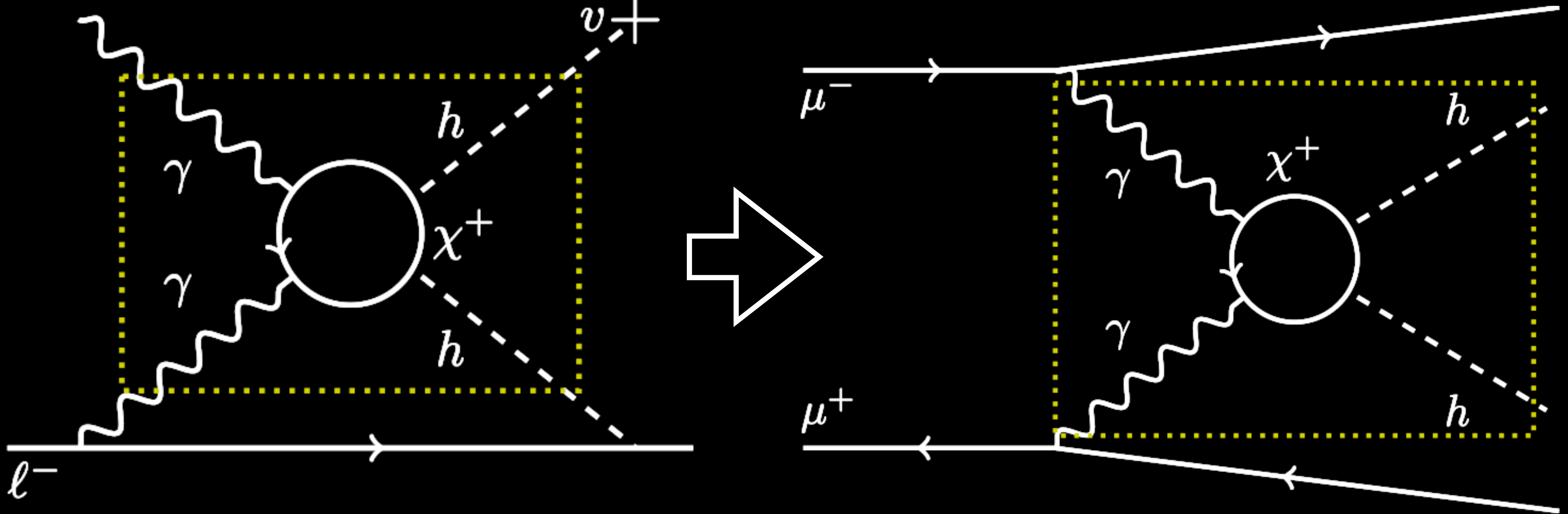


[Delahaye et al. 1803.07431]

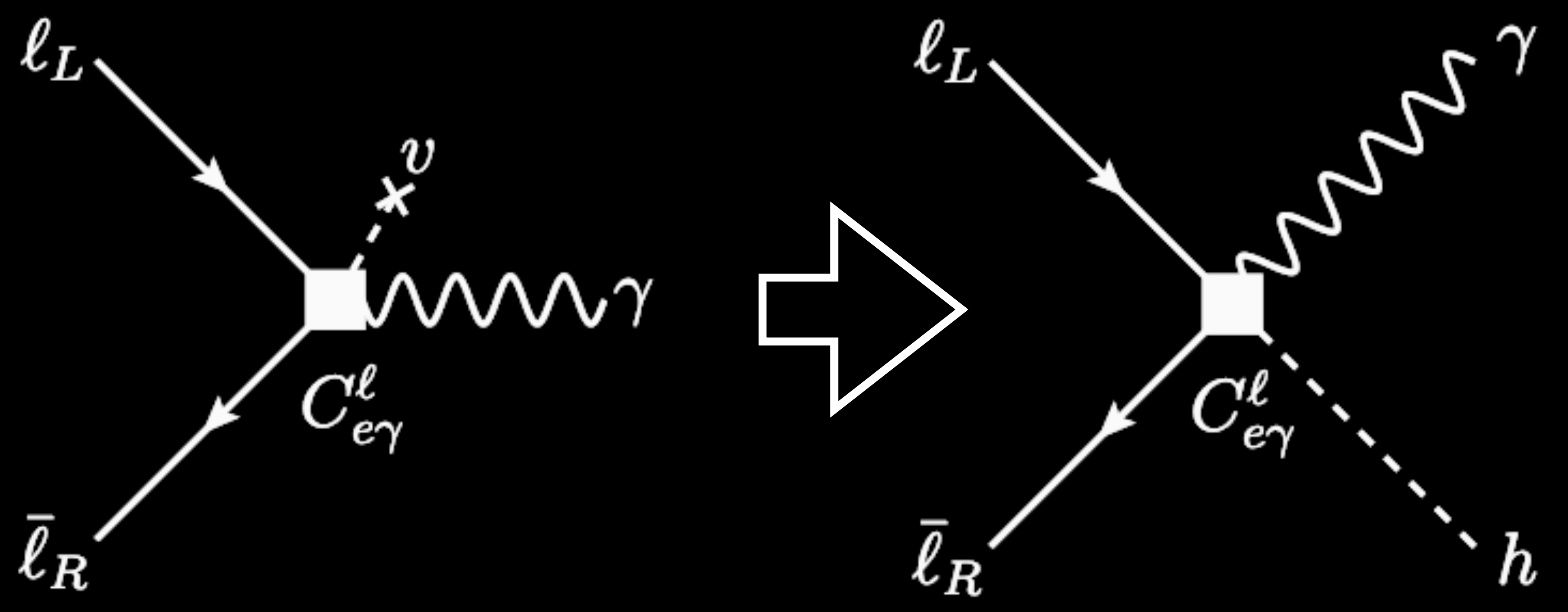
- Muon storage ring-based neutrino factory synergistic w/ development of high-energy muon beams.
- Physics opportunities in neutrino radiation, mu-nu collisions, or nu-nu collisions at high-energy muon collider itself? [de Gouvêa, Muon Collider Forum 09/21/21]

Compelling complementarity

E.g. next-gen. **electron EDM** experiments sensitive to ~20 TeV particles in Barr-Zee diagrams; same diagram probed in muon colliders



Any new physics contributions to **Muon g-2** efficiently probed at muon colliders [Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277; Buttazzo & Paradisi, 2012.02769; Capdevilla, Curtin, Kahn, Krnjaic, 2101.10334; Chen, Wang, Yao 2102.05619; Yin, Yamaguchi 2012.03928]



[Buttazzo & Paradisi, 2012.02769]

Theory vision circa 2022

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A Higgs! Yet:

- ✓ Is it the SM Higgs?
- ✓ Is it the only one?
- ✓ Why is there EWSB?
- ✓ What sets the scale?

The muons are calling, and we must go.

Thank you!