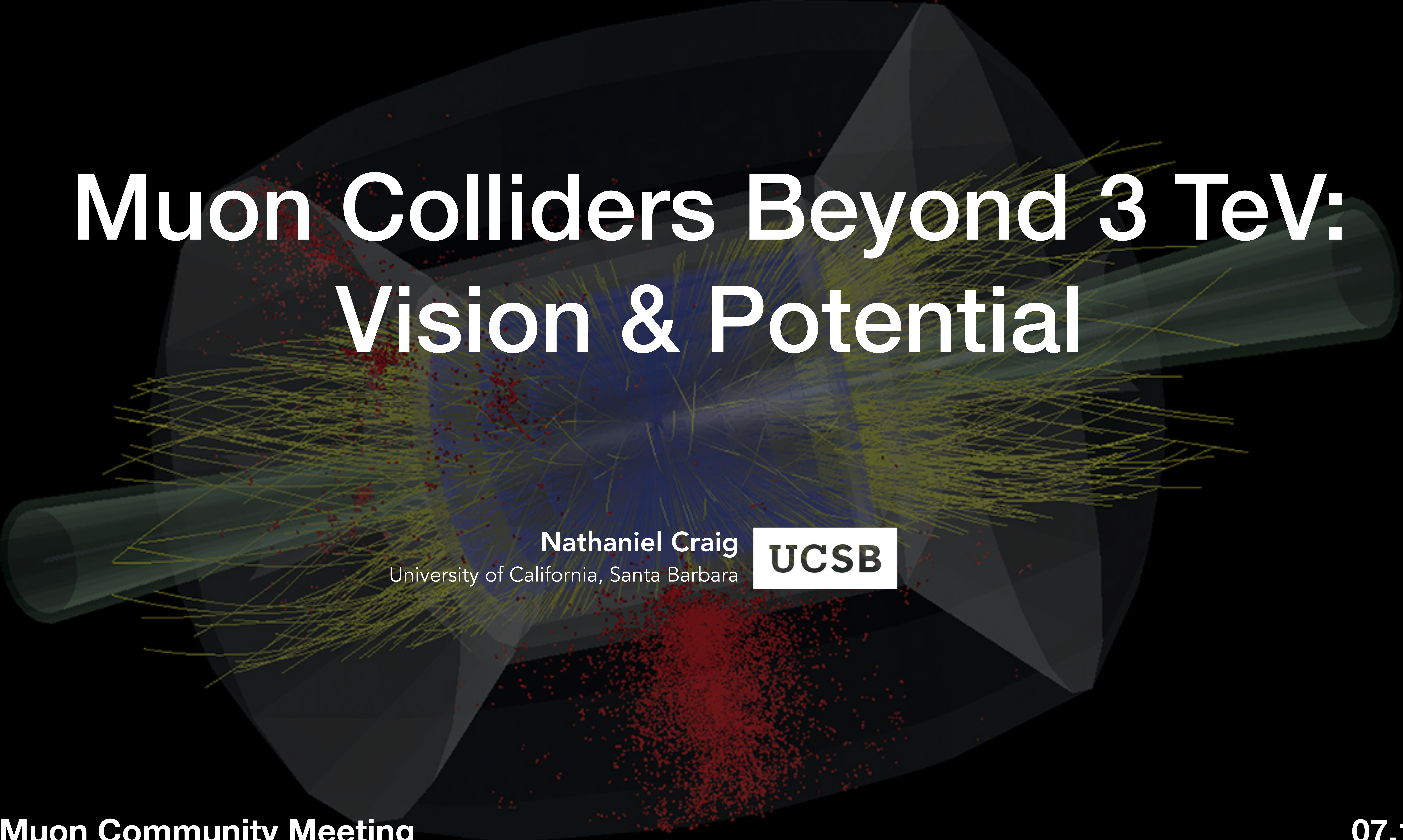


Muon Colliders Beyond 3 TeV: Vision & Potential

Nathaniel Craig
University of California, Santa Barbara
UCSB

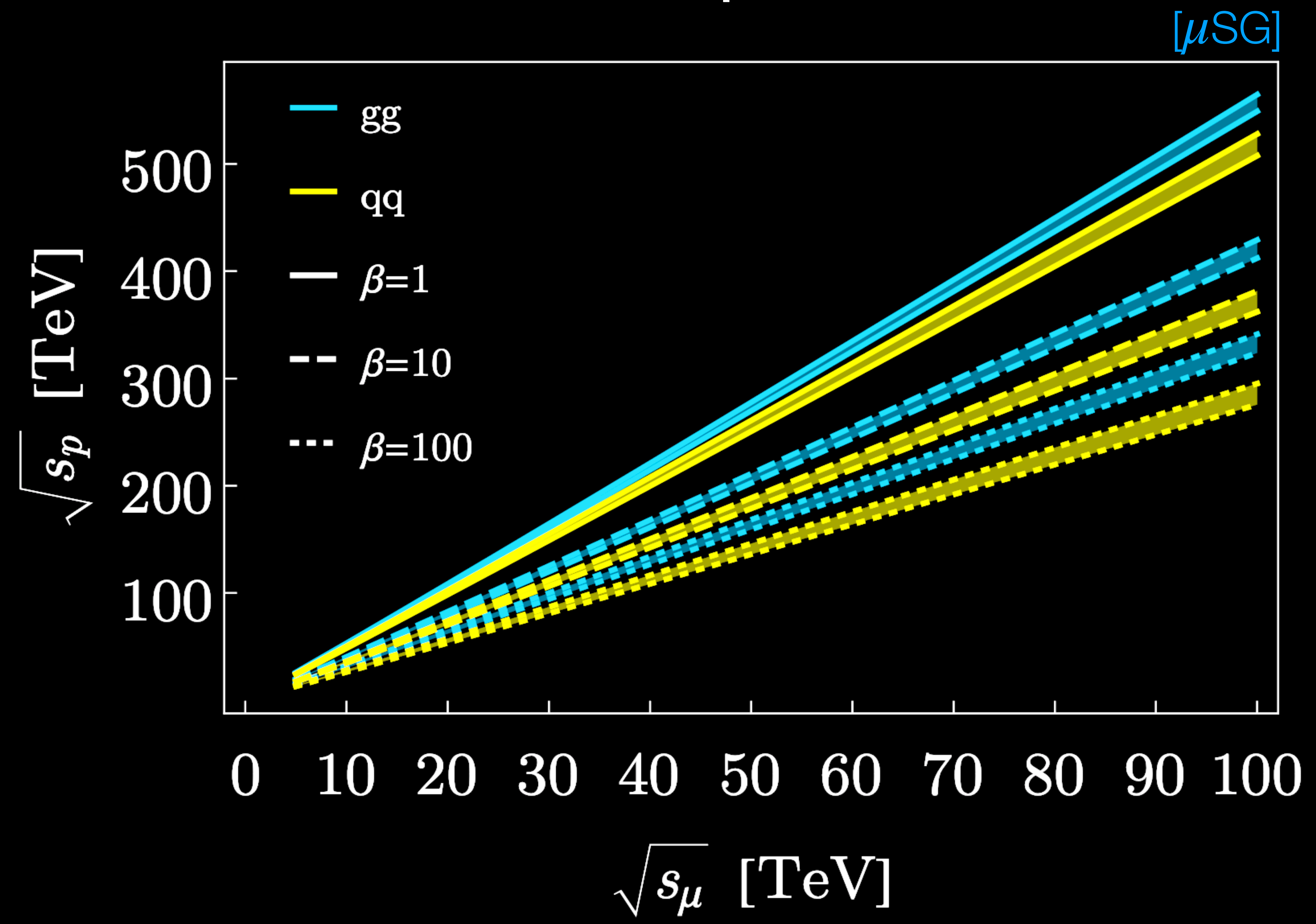
3rd Muon Community Meeting

07.10.21

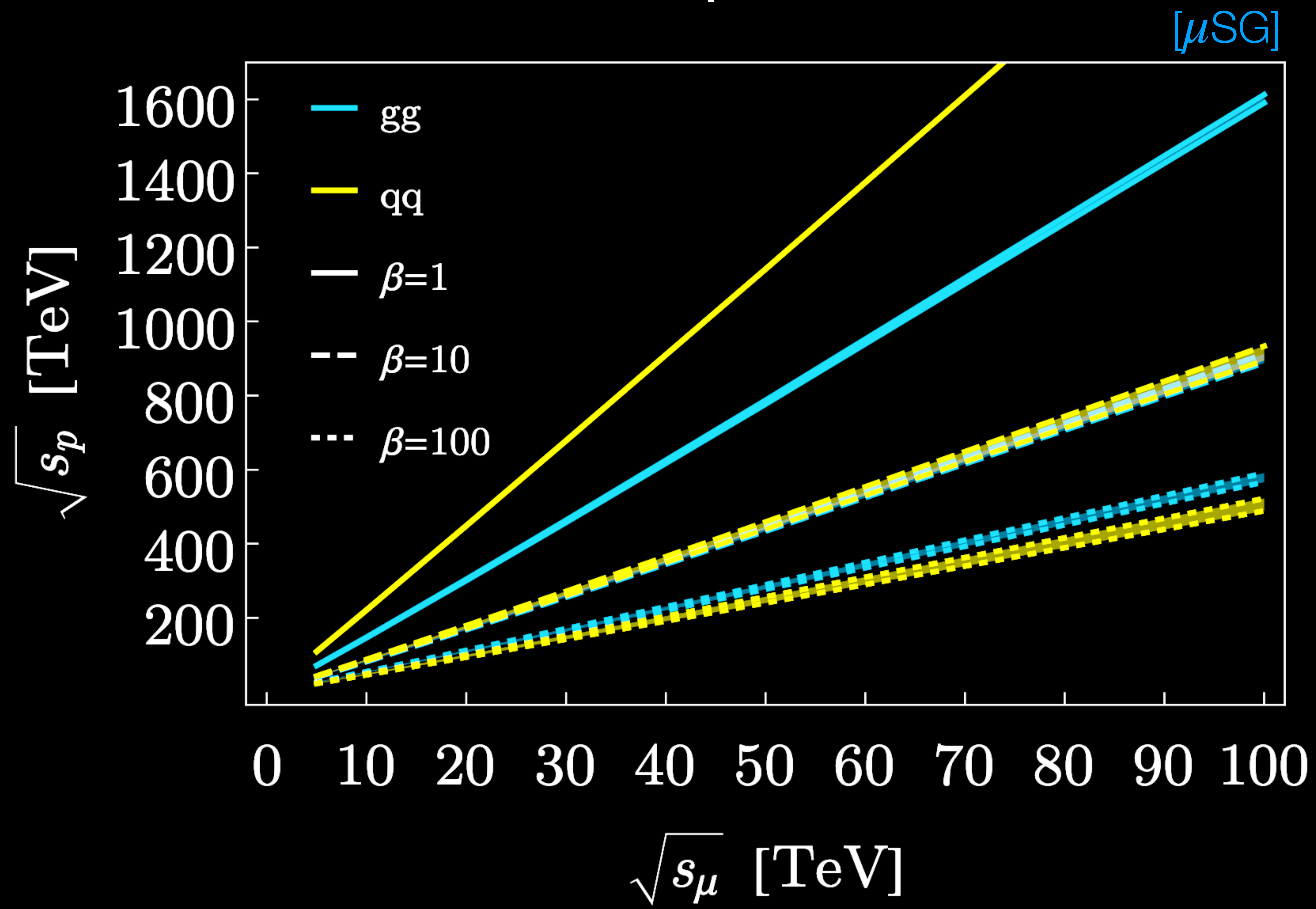
Why go beyond 3 TeV?

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

2-to-1 production



2-to-2 production

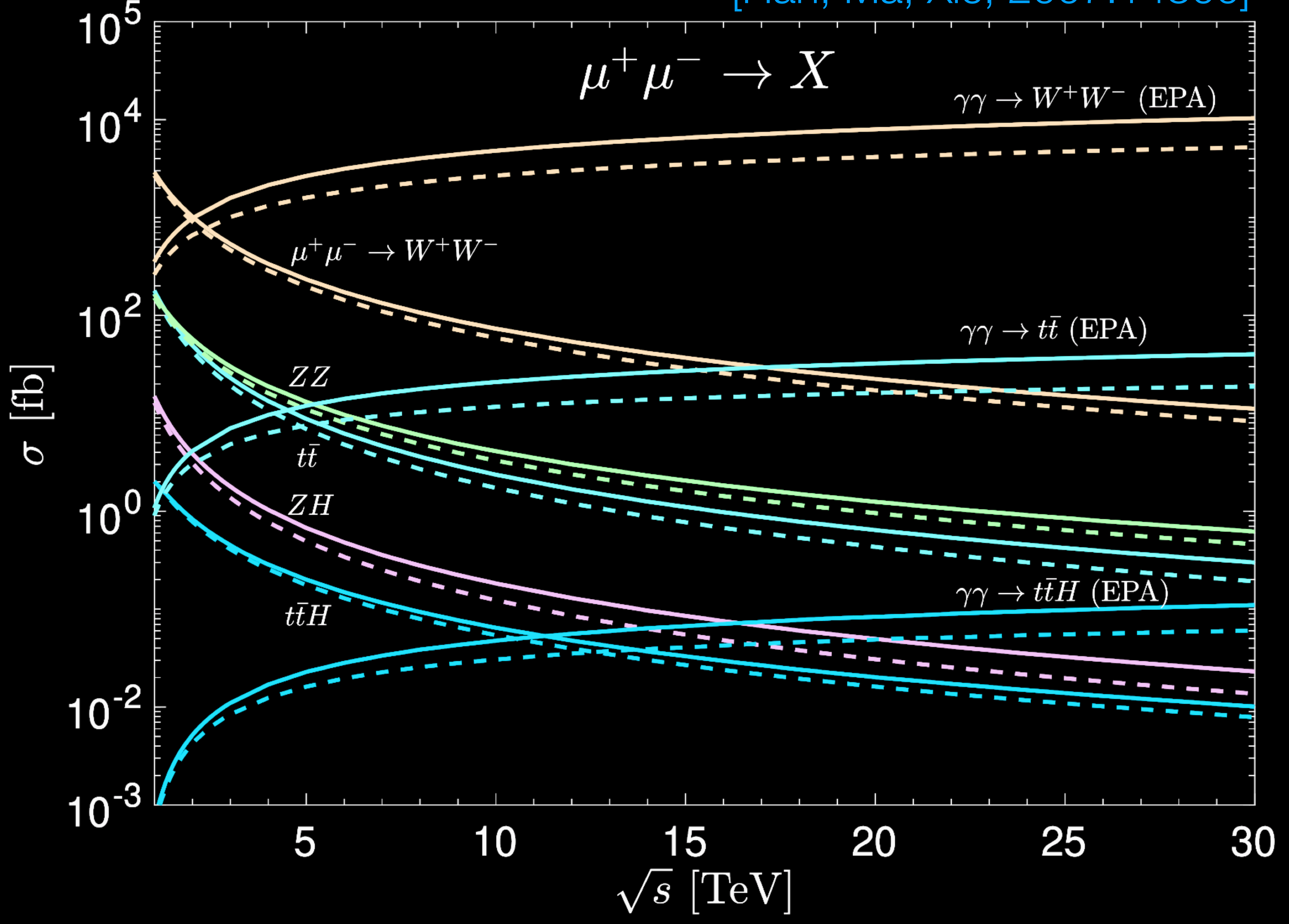


(Bands are NNPDF3.0 LO vs. CT18NNLO)

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

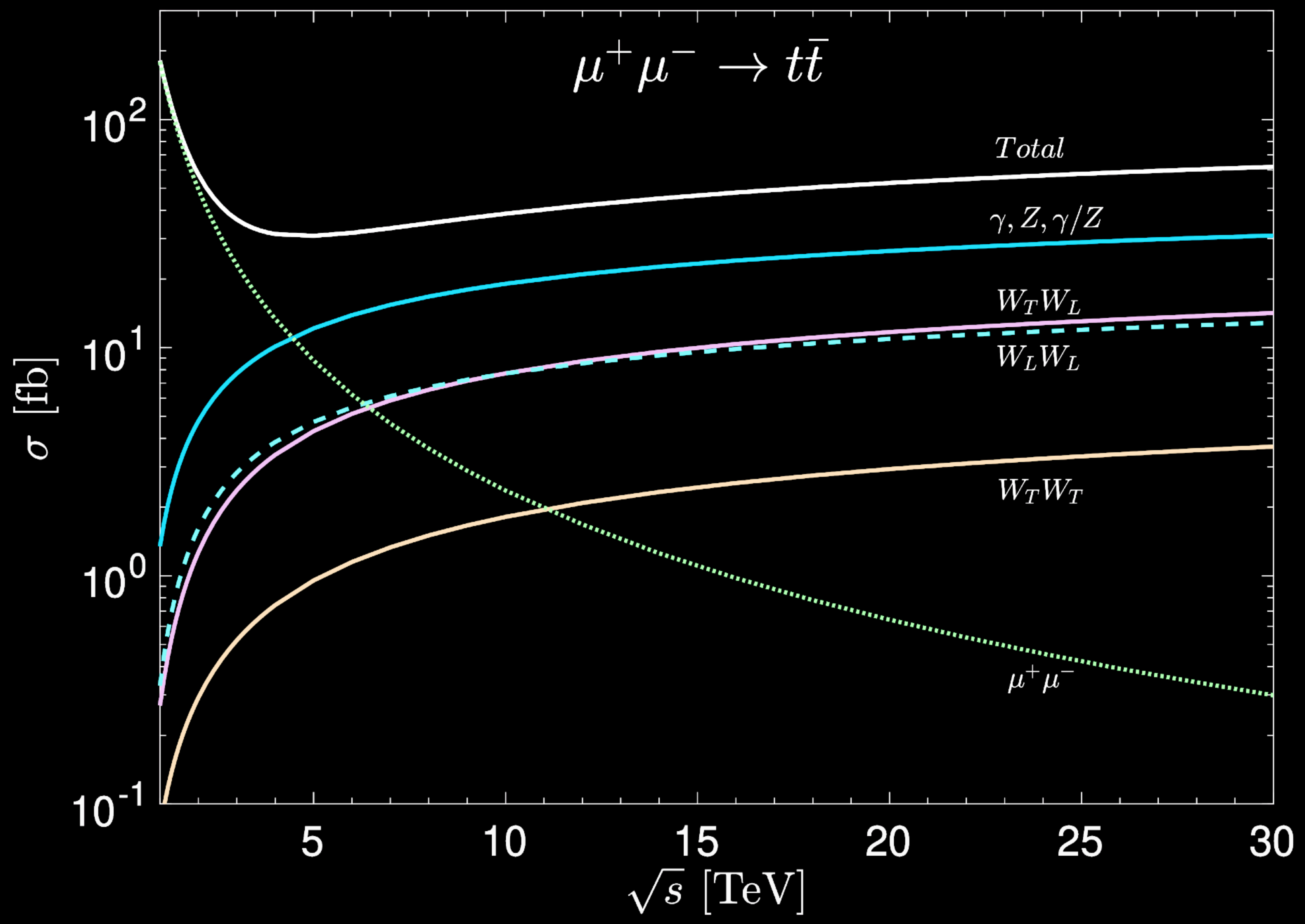
Why go beyond 3 TeV?

[Han, Ma, Xie, 2007.14300]



Crossover from annihilation to VBF dominance takes place around 2-3 TeV

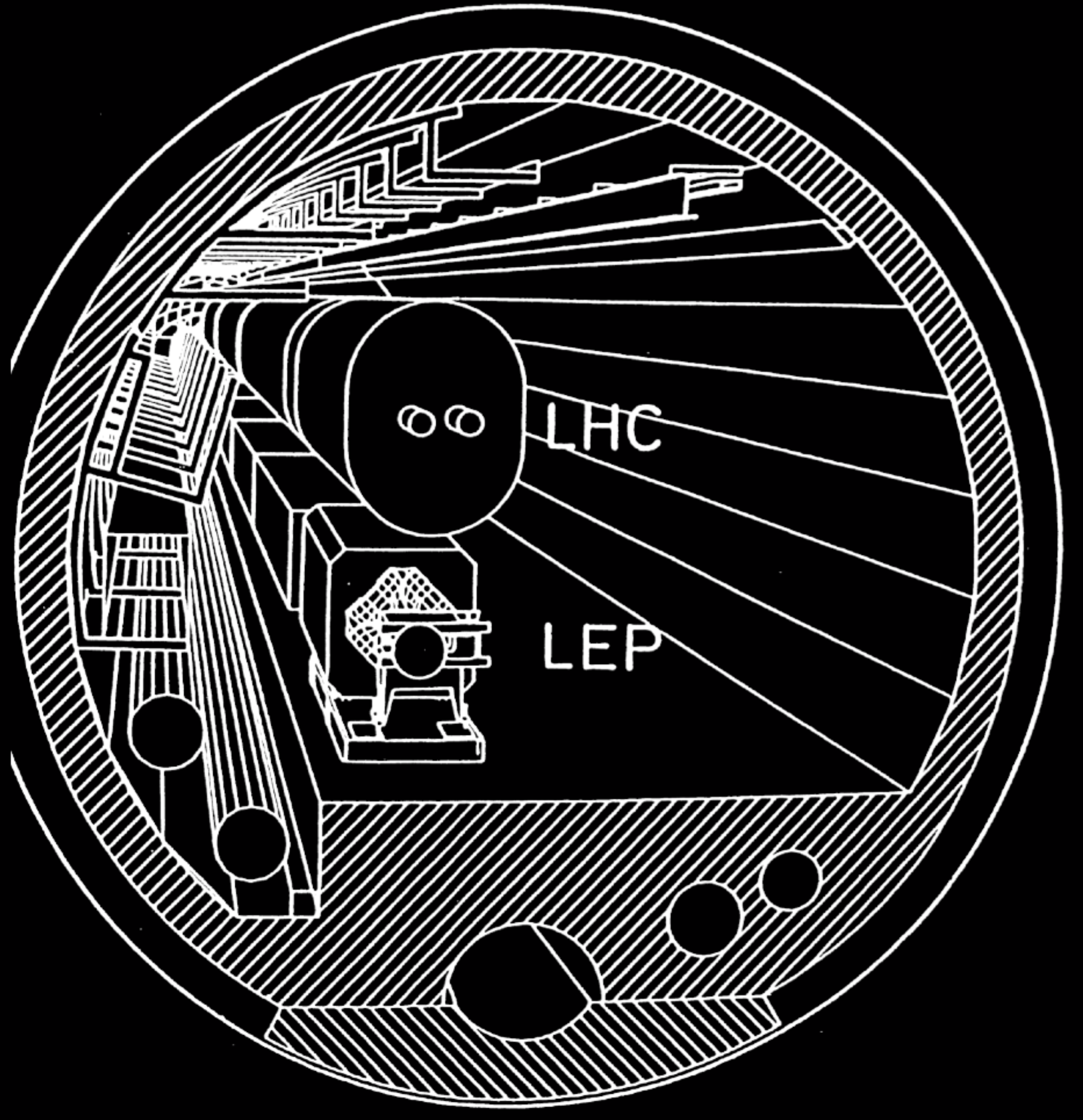
[Han, Ma, Xie, 2007.14300]



Longitudinal polarizations increasingly important above 3 TeV, an extraordinary laboratory for EWSB

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 2021

International
MUON Collider
Collaboration

Theory vision circa 2021

International
MUON Collider
Collaboration

✓ 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 2021

International
MUON Collider
Collaboration

✓ 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?
+ What is the nature of dark matter?

Theory vision circa 2021

International MUON Collider Collaboration

✓ 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?
\+ What is the nature of dark matter?

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

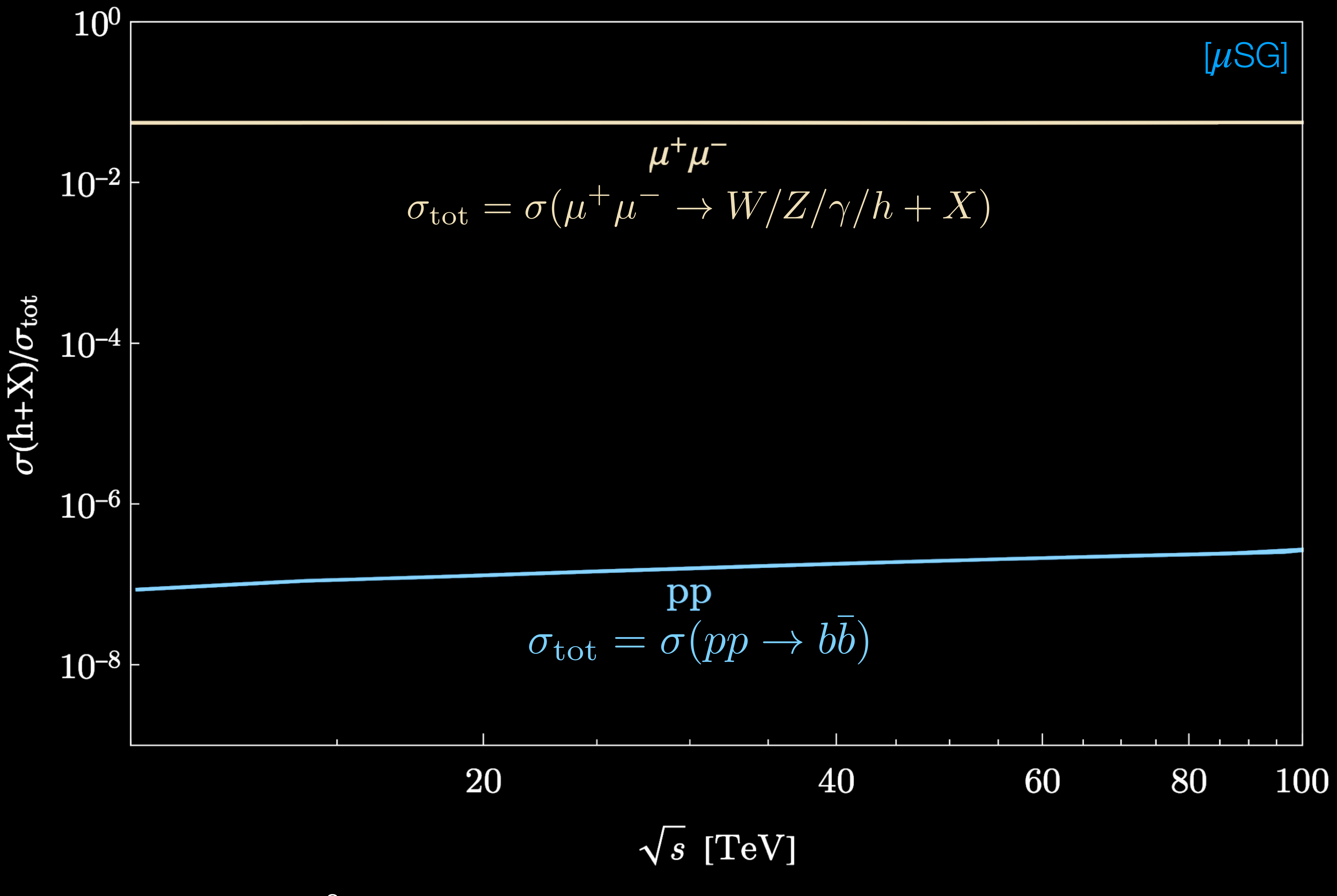
What is the origin of mass?

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

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?

κ fit in "κ-0" scenario (no invisible/untagged BR, no HL-LHC combination)

For illustration only: Muon collider projections for $\sqrt{s} = 10$ TeV, 10/ab using fast sim, DELPHES μC detector card, minimal cuts/tagging. No physics backgrounds or BIB, though latter under control [Bartosik et al. 2001.04431]

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69	1.0
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	7.49
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41	1.95
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.27

Other entries: [de Blas et al. 1905.03764].

3 TeV: see L. Sestini's talk

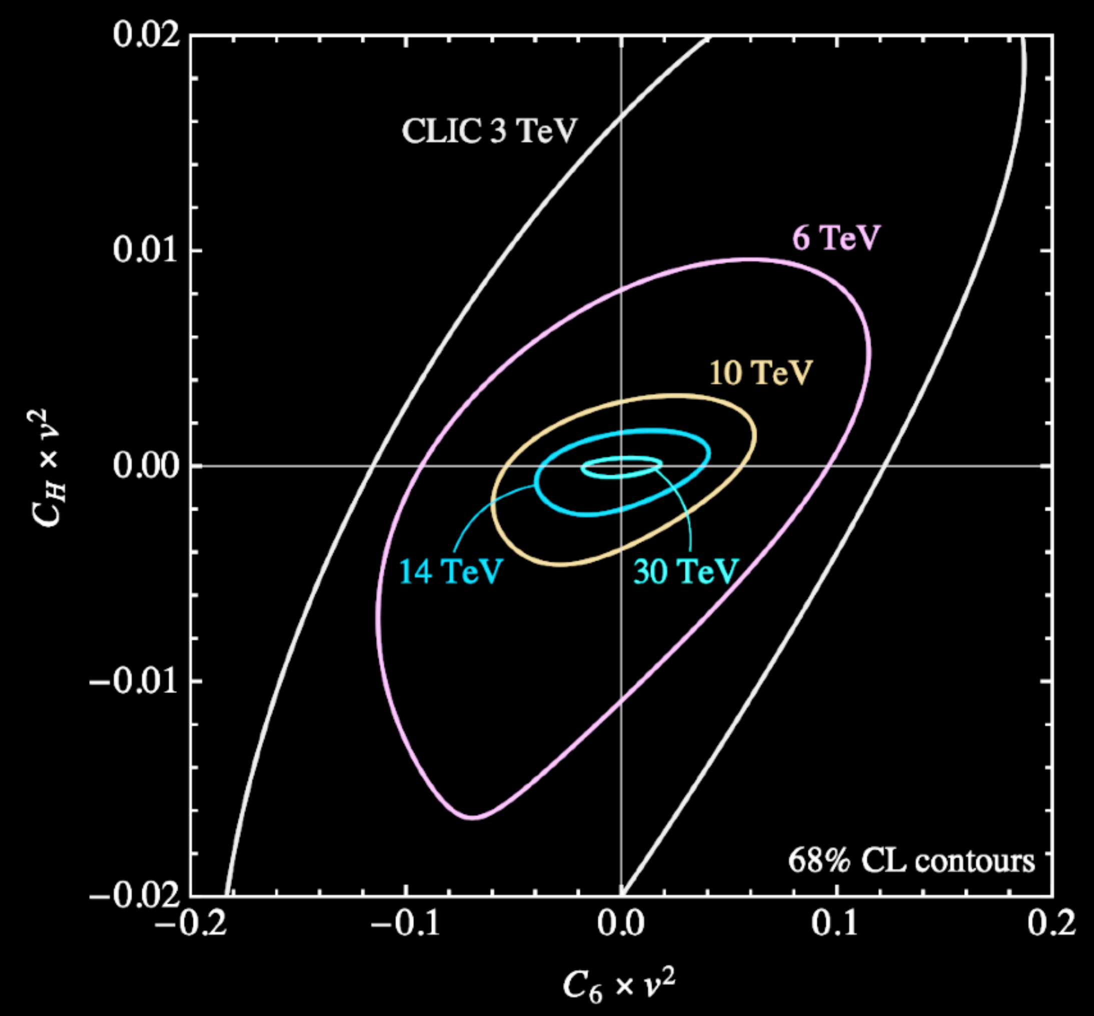
Is it the SM Higgs?

Higgs cubic self-coupling

[Han, Liu, Low, Wang 2008.12204]

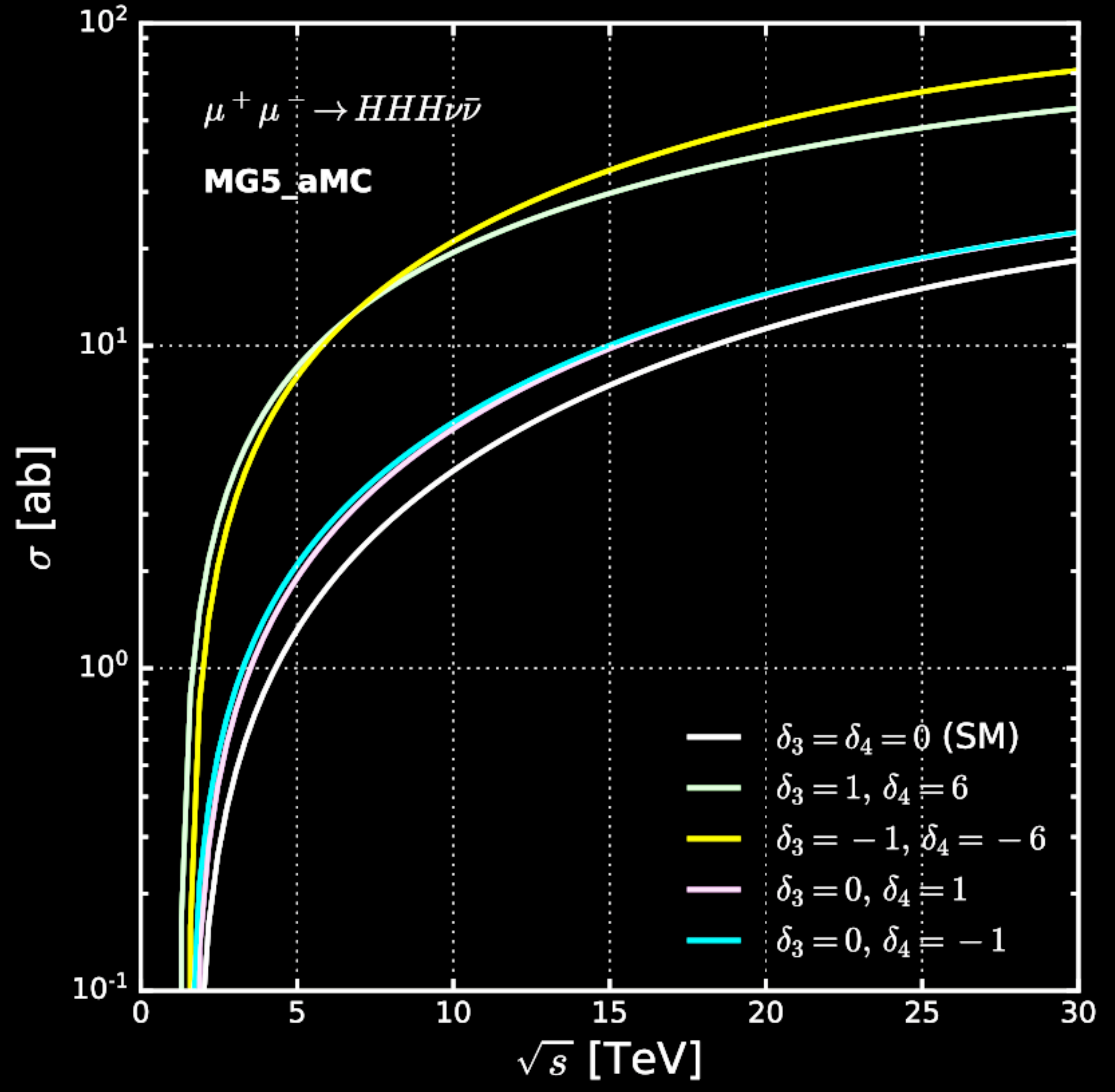
$\sqrt{s}$ (TeV) benchmark lumi (ab^{-1})	3 1	6 4	10 10	14 20	30 90
$(\Delta\kappa_3)_{\text{in}}$	25%	10%	5.6%	3.9%	2.0%

See L. Sestini's talk



[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	$[-0.34, 0.64]$	$[-0.53, 0.82]$	$[-0.67, 0.97]$

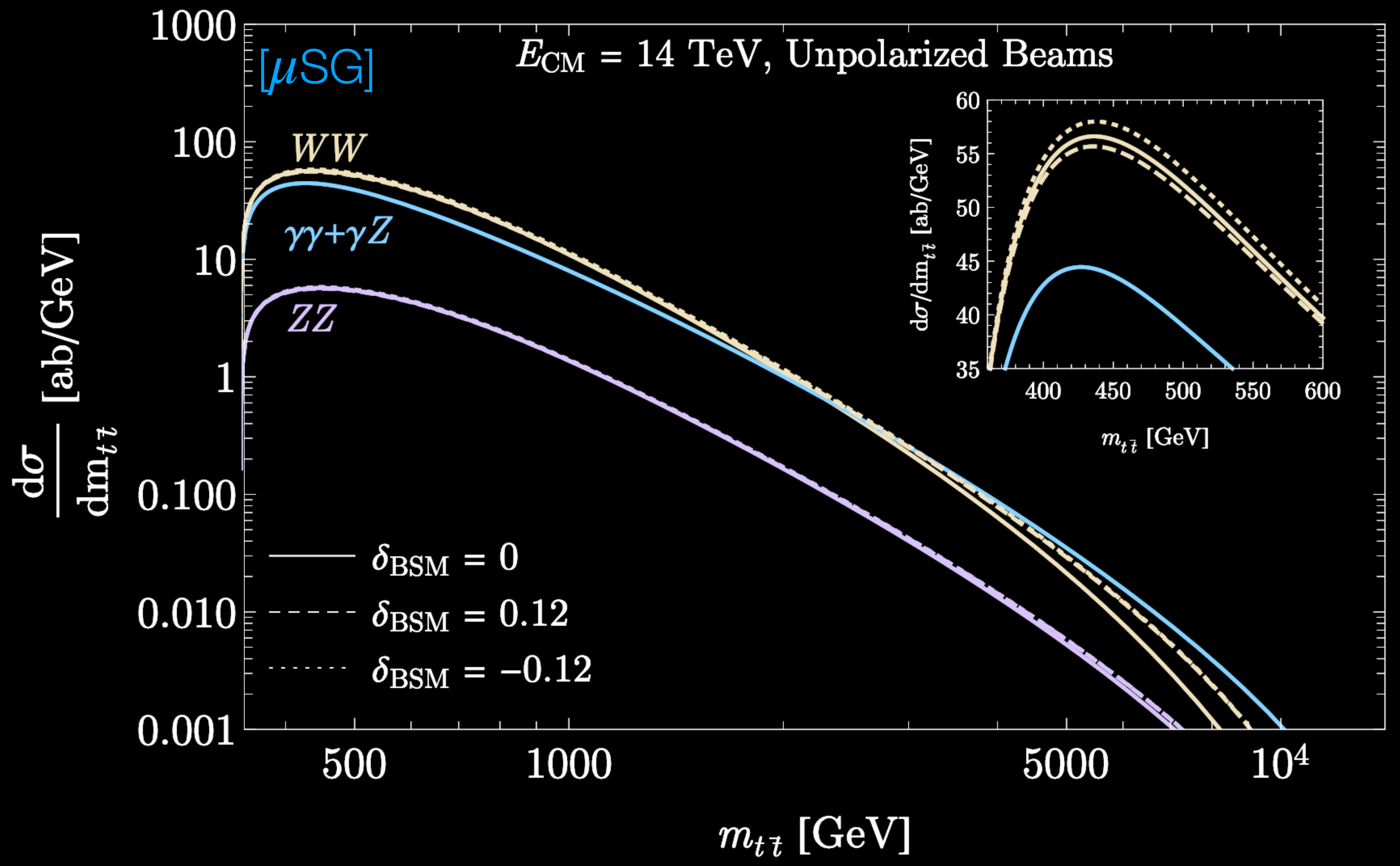
Is it the SM Higgs?

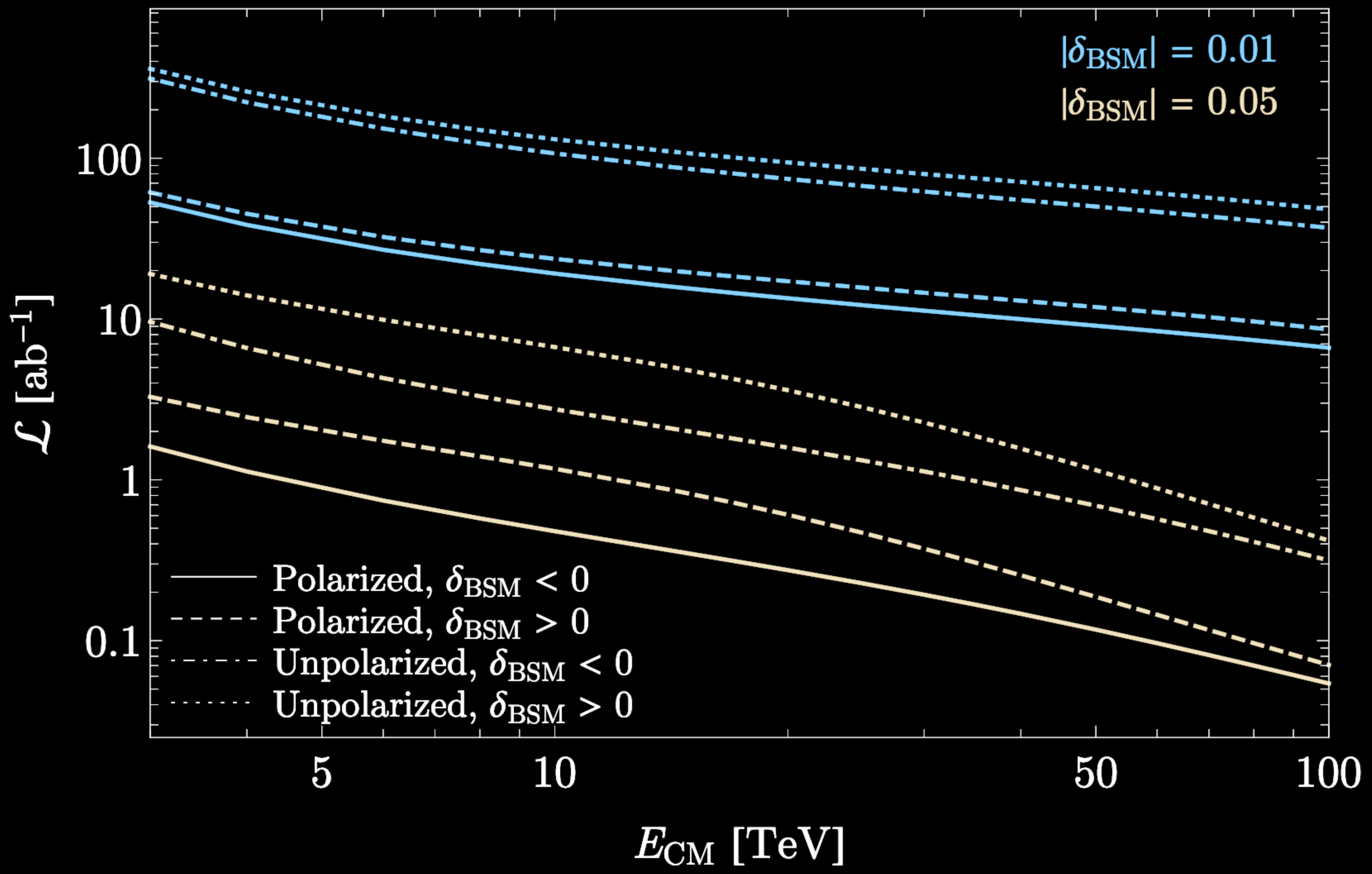
High-energy measurements equally powerful [Buttazzo, Franceschini, Wulzer, 2012.11555]

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

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

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





Is our Higgs the only one?

Many possible extensions of the scalar sector…

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

See R. Franceschini's talk

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

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

Production:

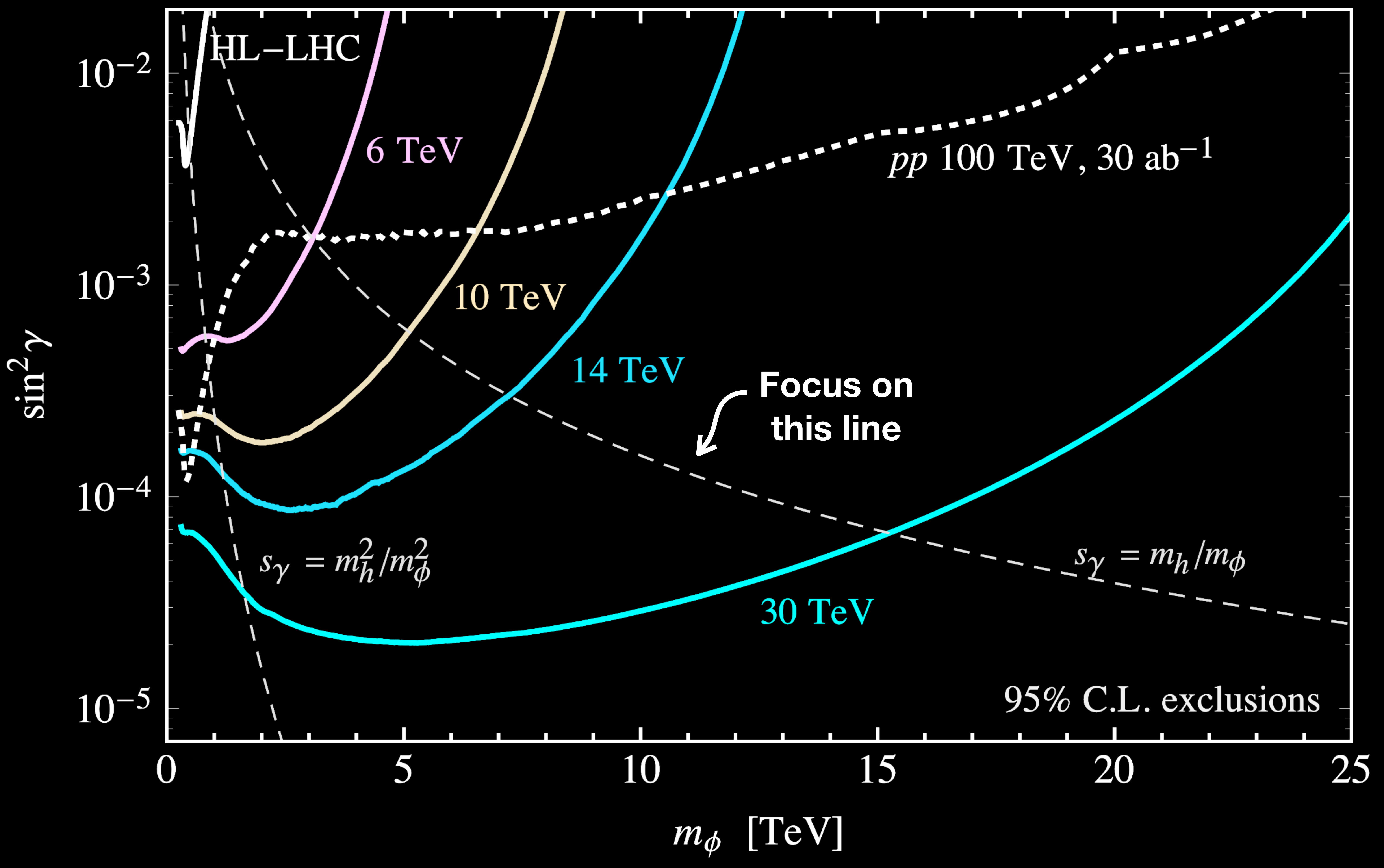
$$\sigma_\phi = \sin^2\gamma \cdot \sigma_h(m_\phi)$$

Decay:

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

$$\mathrm{BR}_{\phi\to hh} \sim 25\%$$

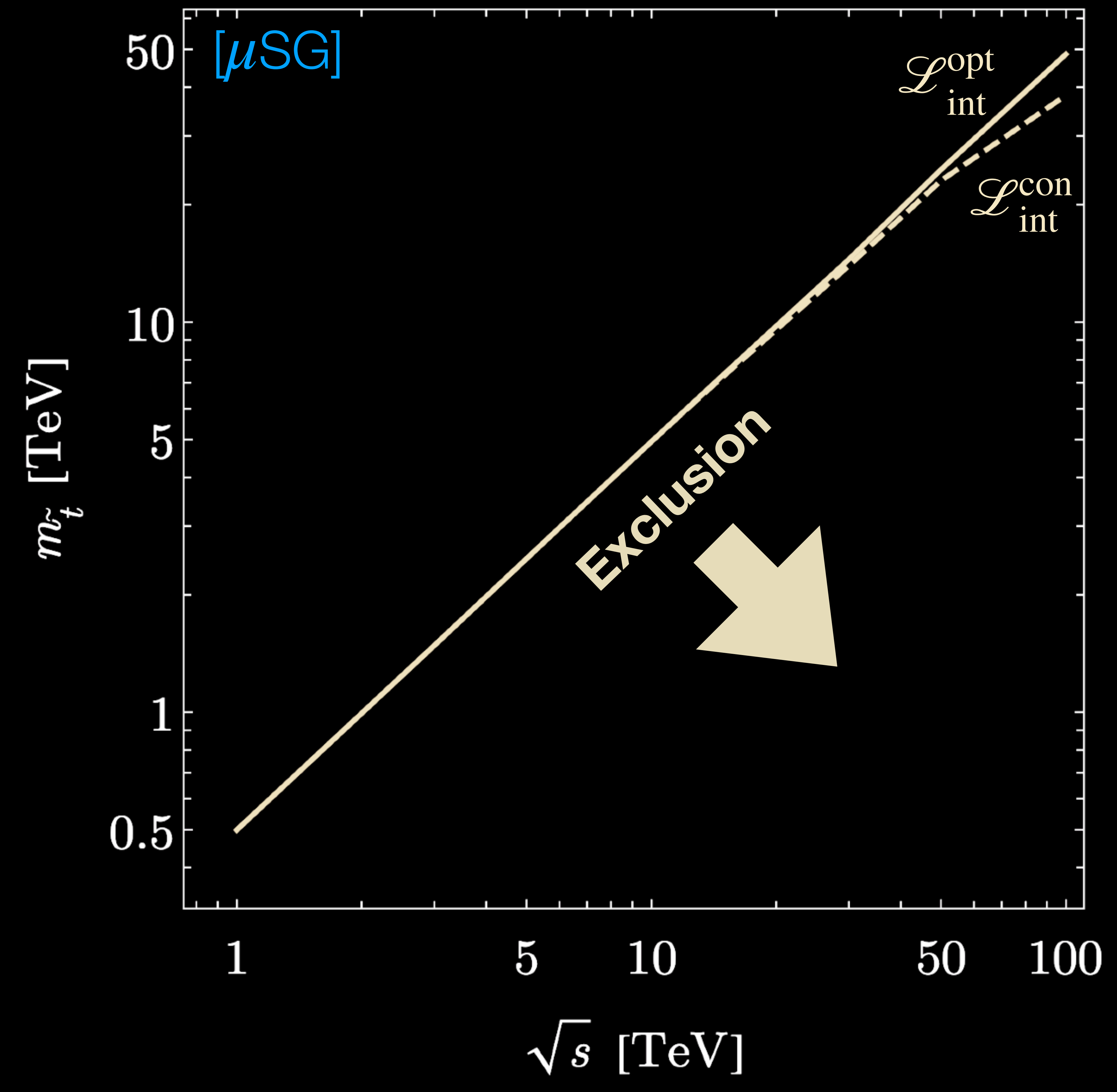
[Buttazzo, Redigolo, Sala, Tesi, 1807.04743; updated for μSG]



Why EWSB? What sets the scale?

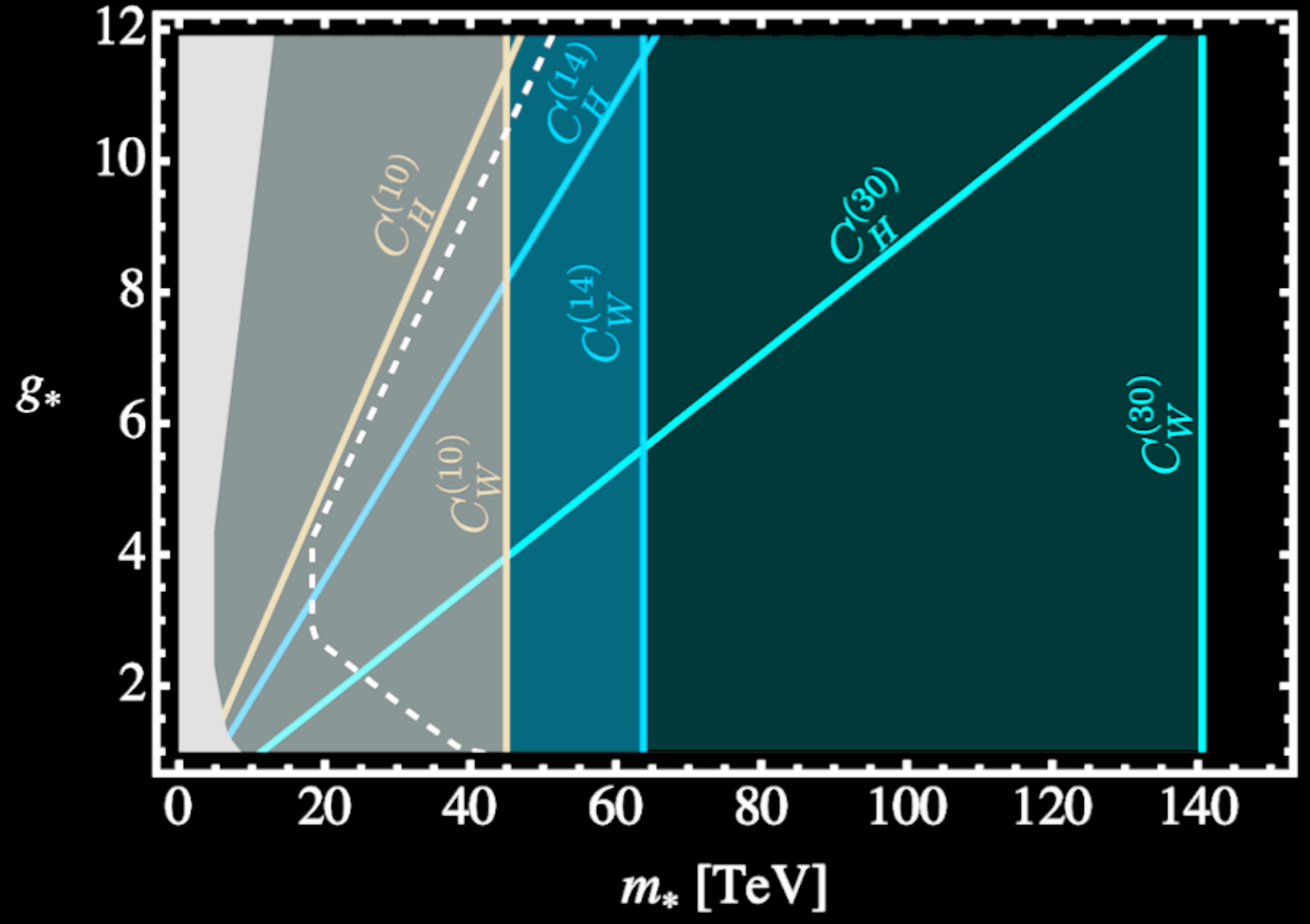
Supersymmetry

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



Composite Higgs

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



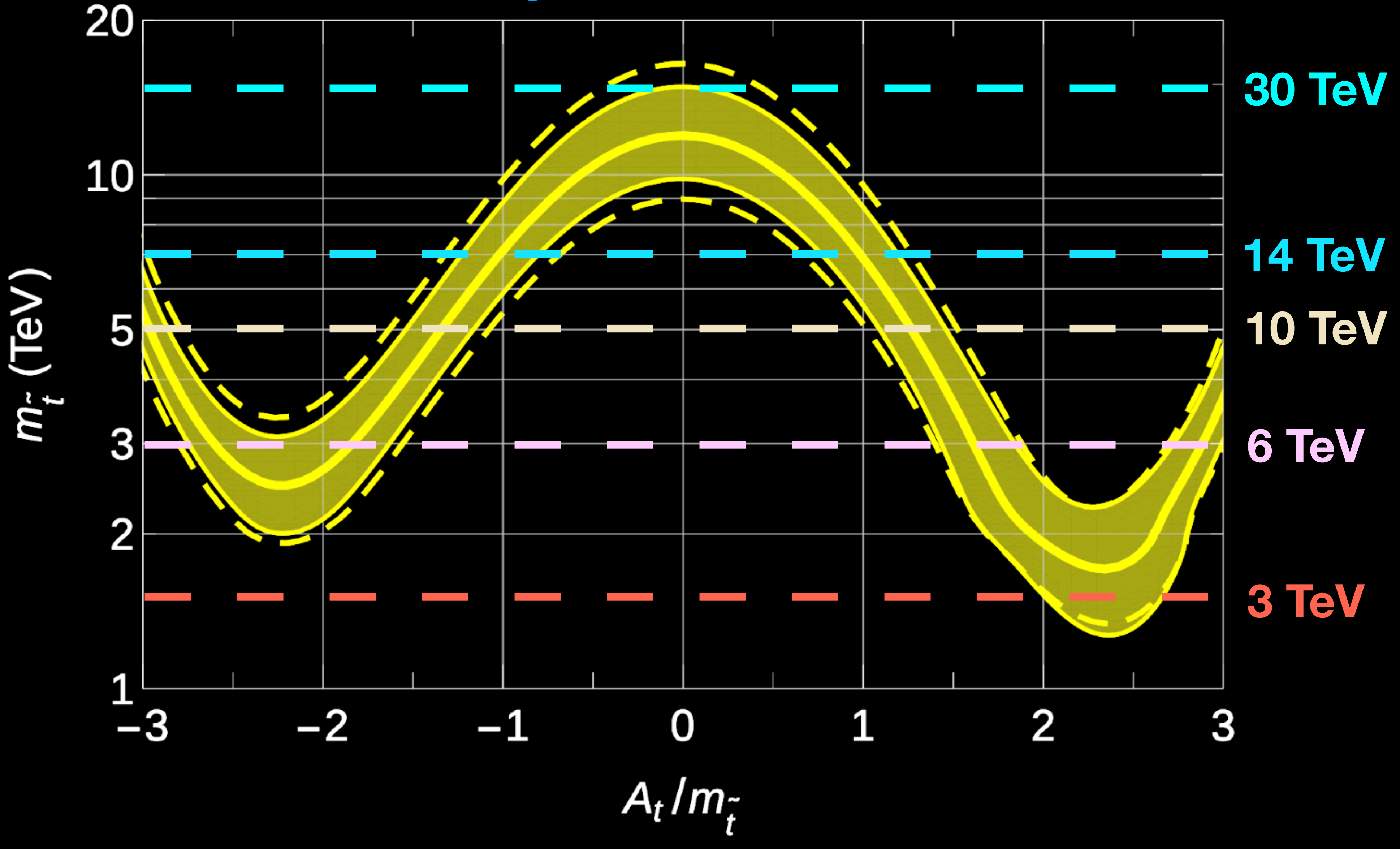
[Buttazzo, Franceschini, Wulzer 2012.11555]

Why EWSB? What sets the scale?

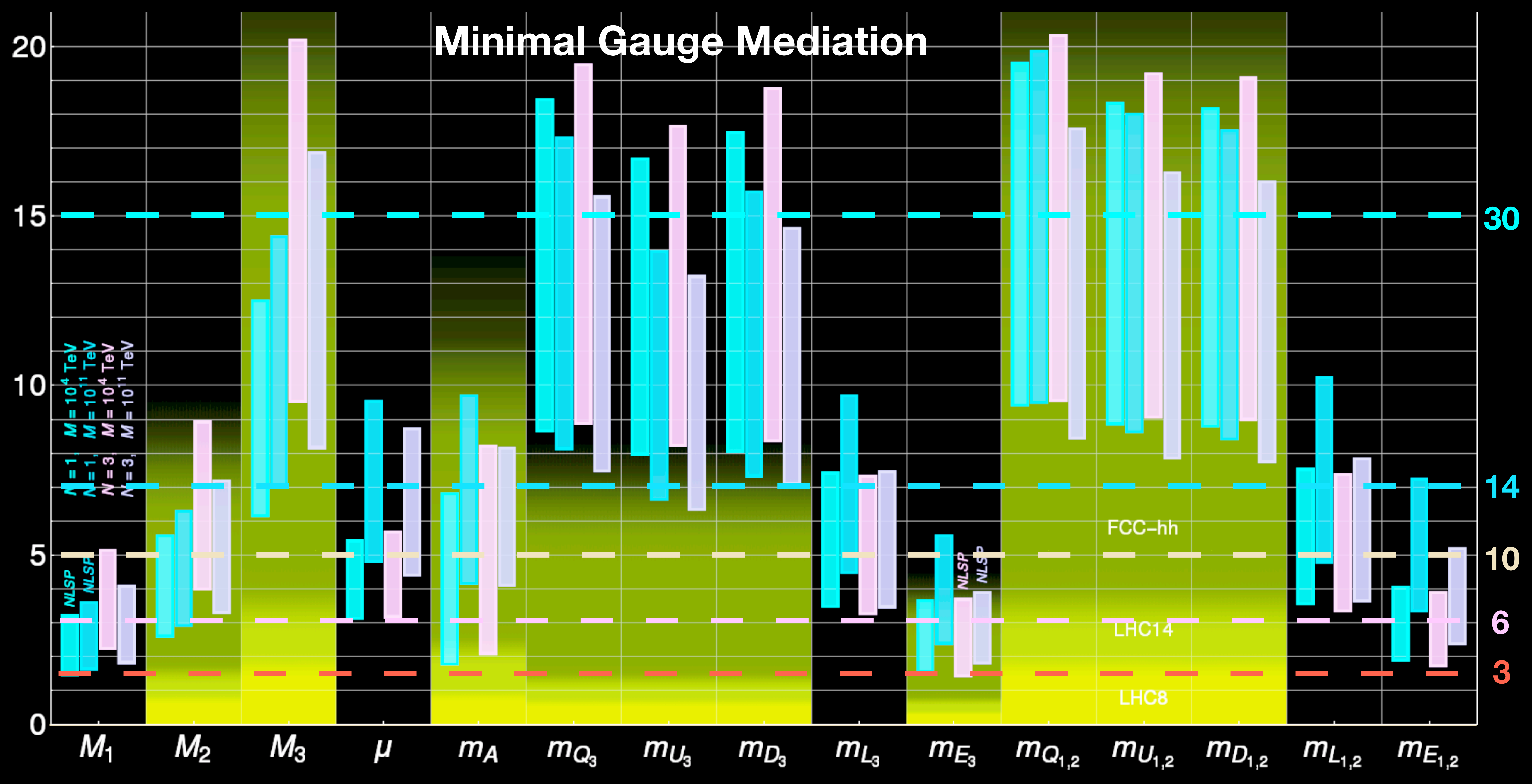
Theories that predict the Higgs mass provide sharp targets for the scale of new physics.

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

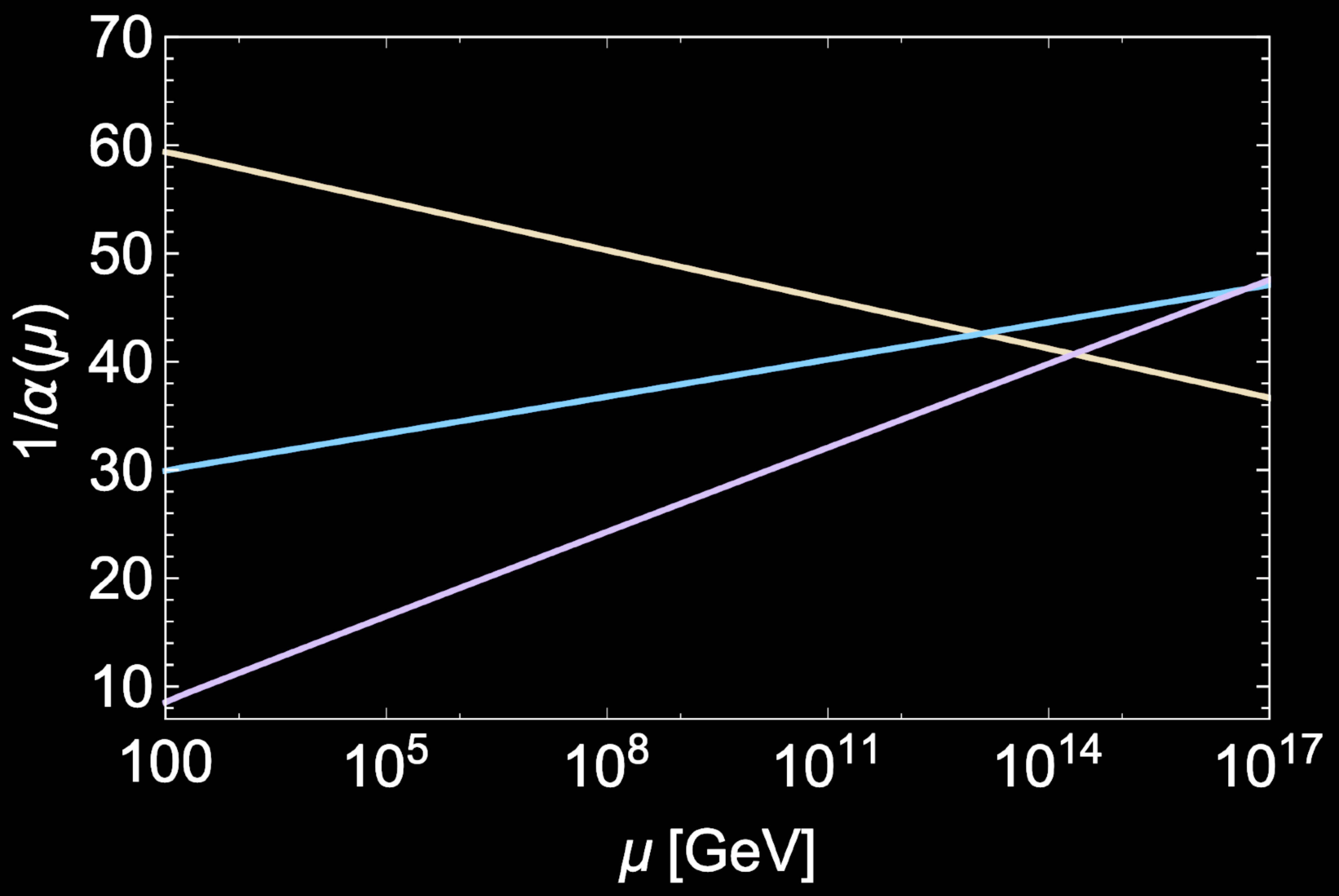
[Pardo Vega & Villadoro, 1504.05200]



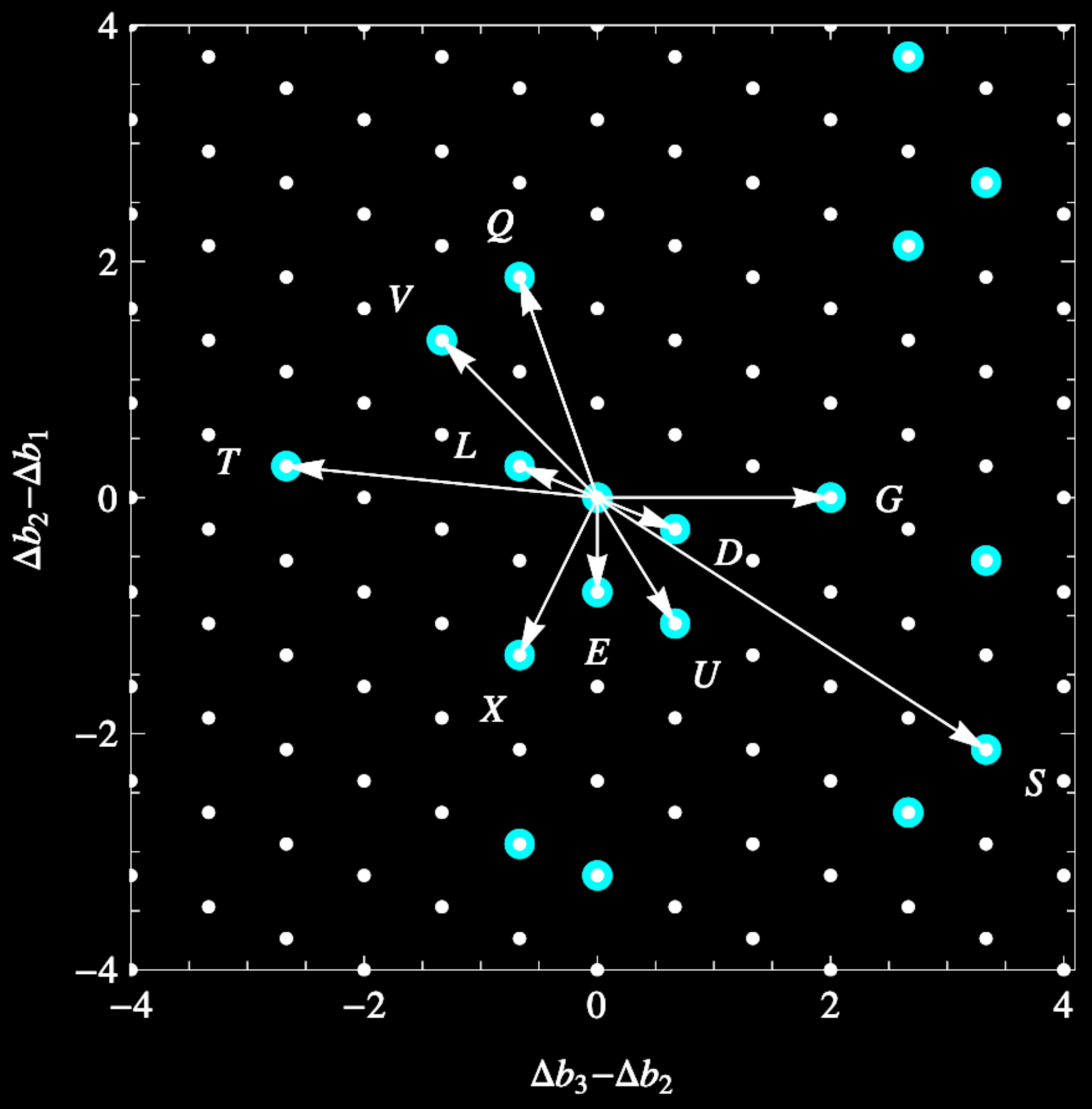
Correlated opportunities in minimal frameworks

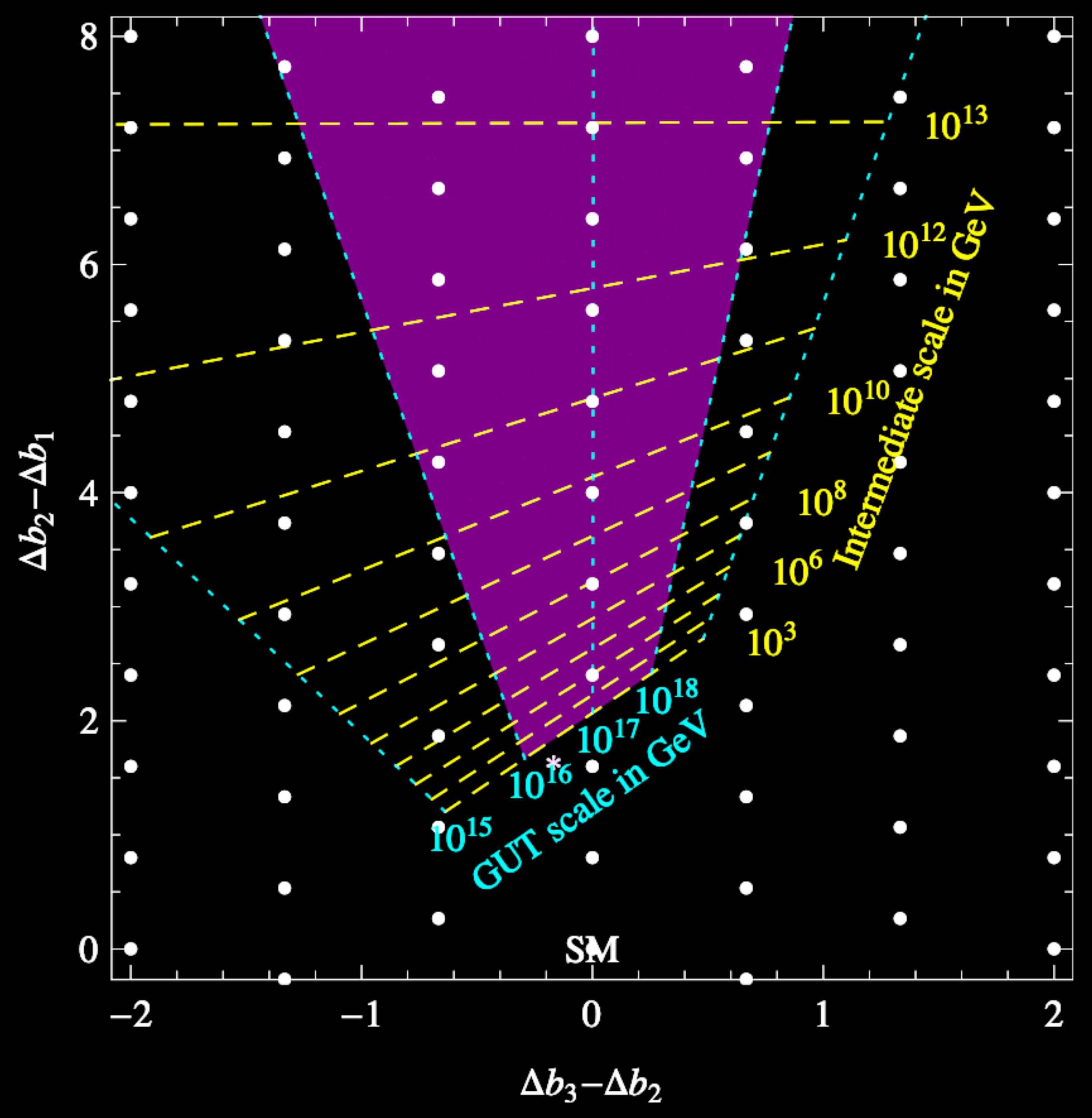


Unification beyond the Standard Model?



[Giudice, Rattazzi, Strumia 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 $\sim\sqrt{s}/2$.

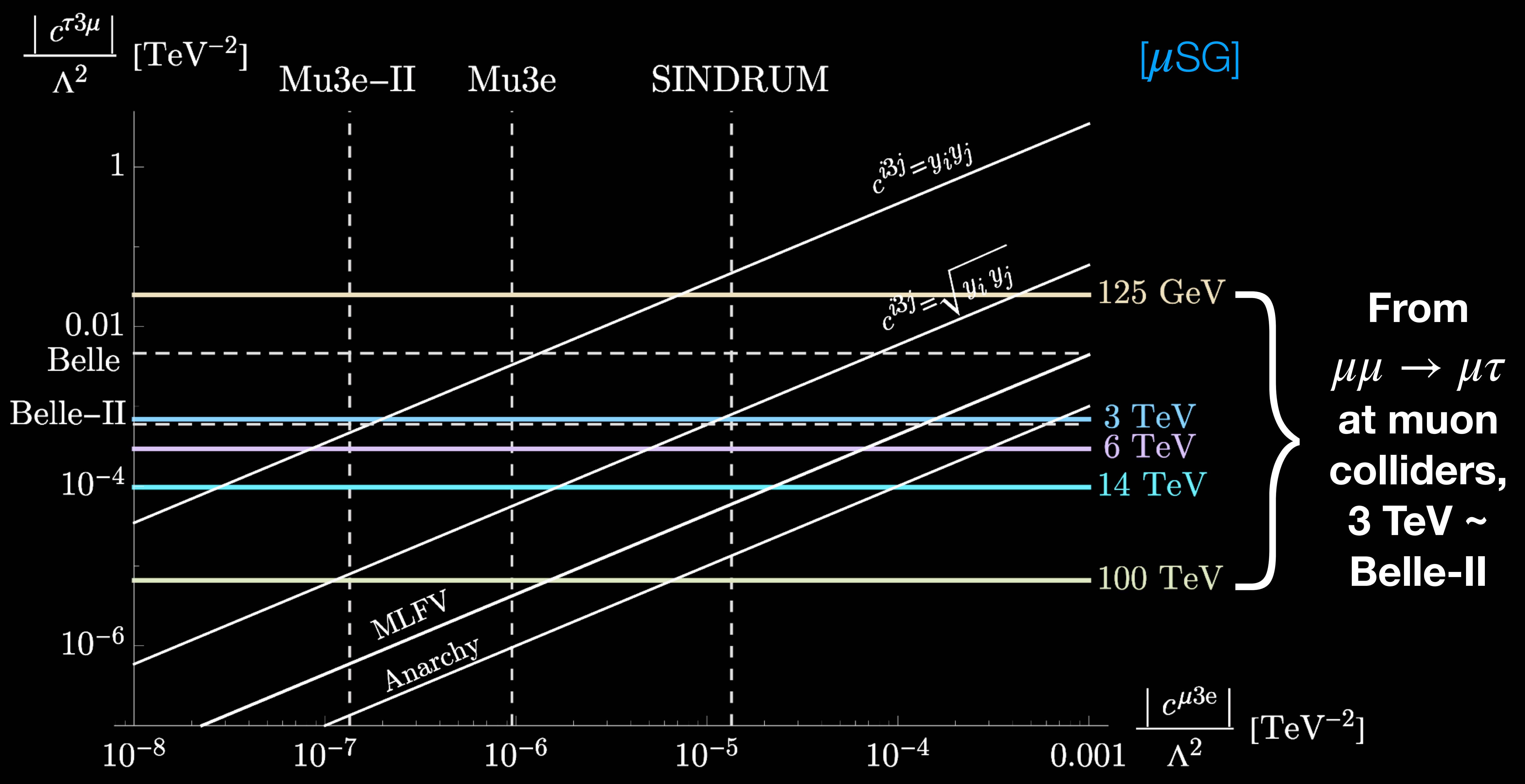
What is the origin of flavor?

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



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.

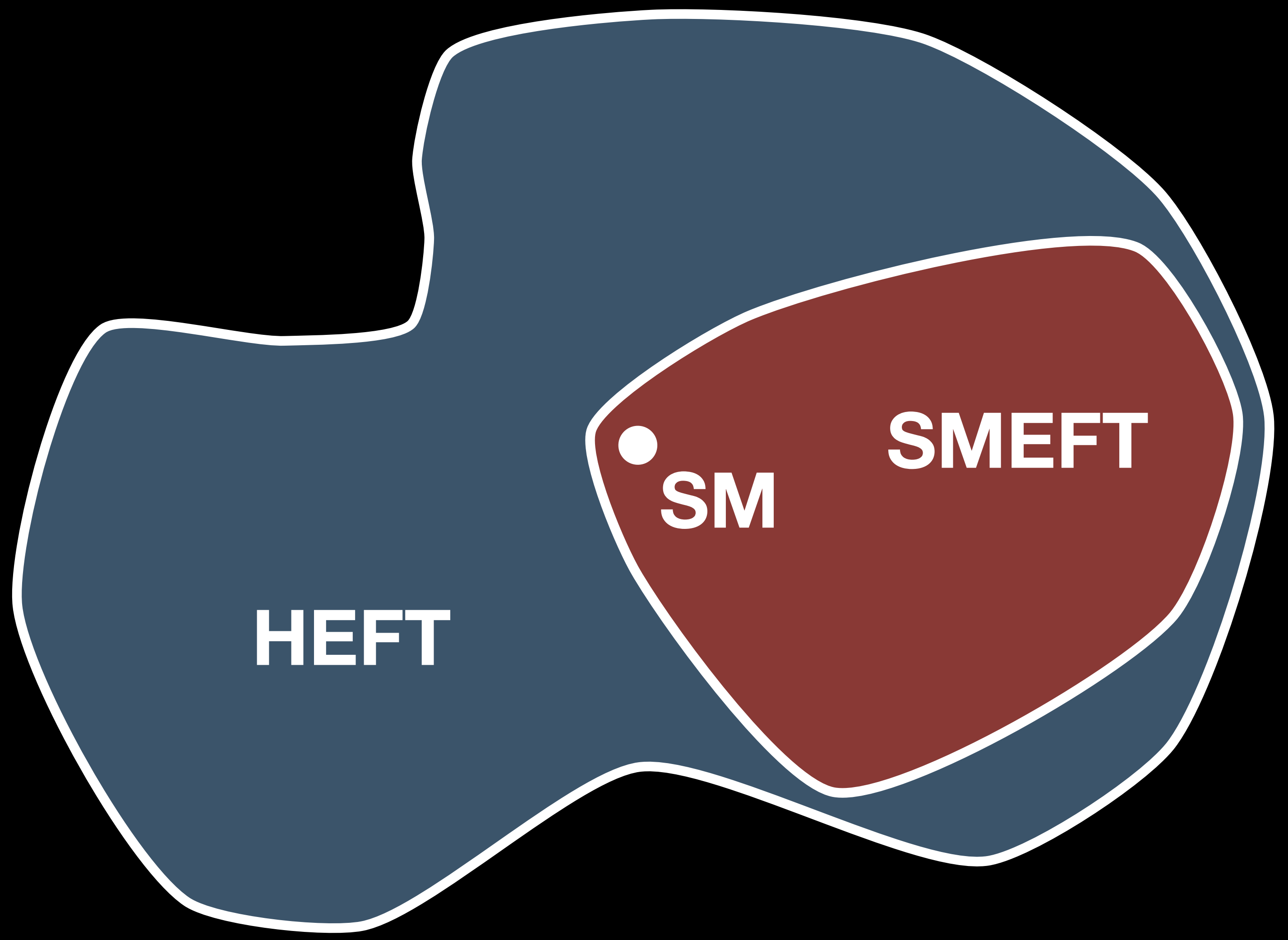
*"is" = theory suitably well behaved when *h* packaged into *H*

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 $4\pi v$.

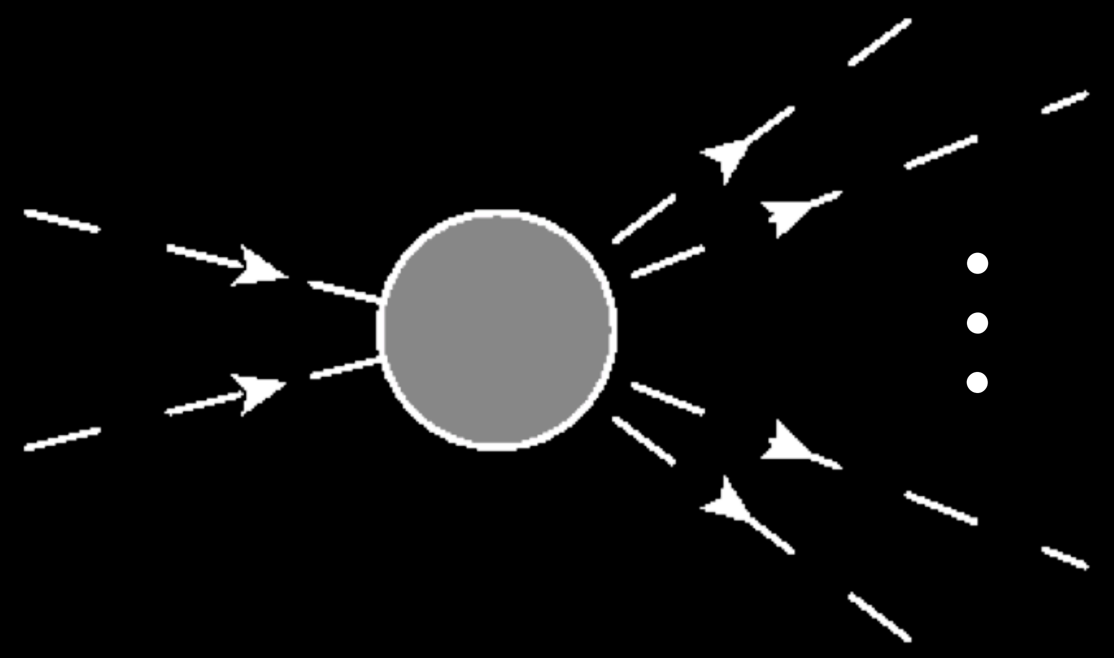
Is there ~~a deeper reason for~~ gauge symmetry?

Long history of unitarity bounds in electroweak sector, a la [Lee, Quigg, Thacker '77]

Might expect HEFT vs. SMEFT is easy to settle by measuring $2 \to 2$ processes out to $4\pi v$.
Alas, for some instances of HEFT (e.g. Higgs trilinear-only), requires $2 \to \text{many}$

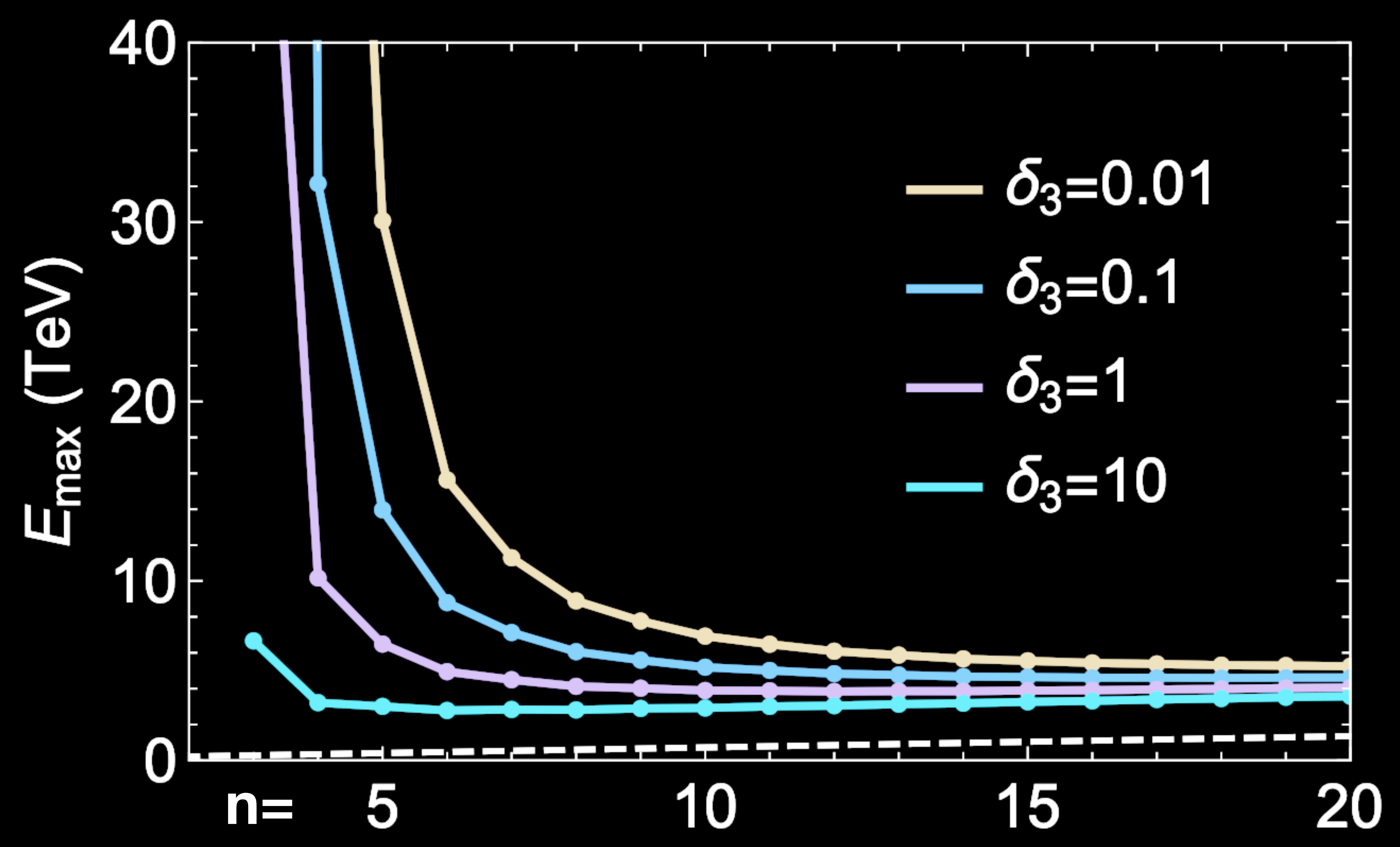
For example, trilinear-only modification δ_3 (HEFT only)

Perturbative unitarity violation in $V_L V_L \to$ multi-h at $\sqrt{s} \sim 4\pi v$ [Falkowski & Rattazzi '19]



$$\sigma(\pi_i \pi_j \to X) \propto \delta_3{}^2 \exp\left(\frac{s}{(4\pi v)^2}\right)$$

Scale of unitarity violation in $Z_L^2 h^n$ [Chang, Luty '19]



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

Decisive test:

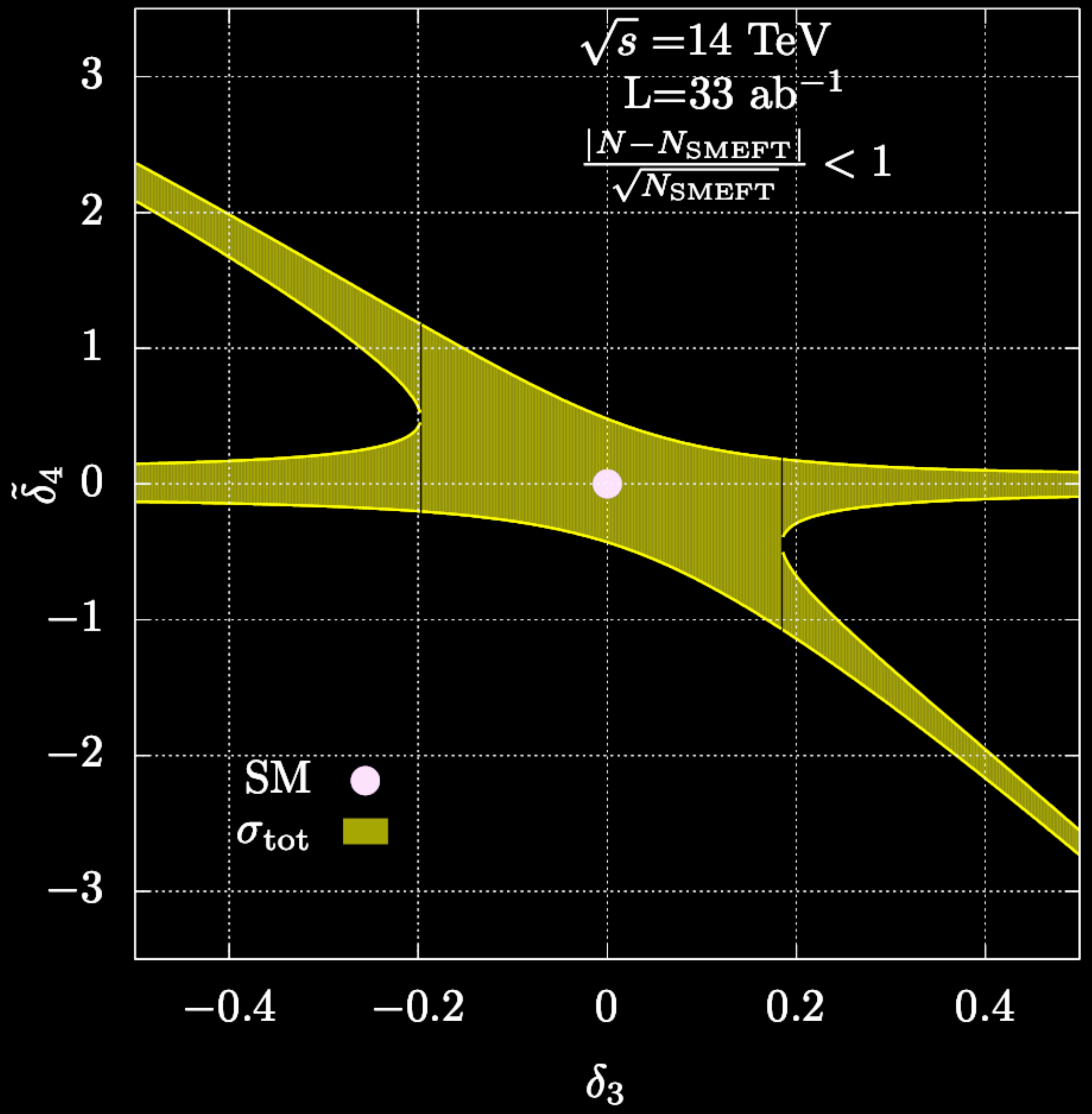
Measure comprehensive set of 2-to-2 and 2-to-few processes w/ longitudinal vectors & Higgs bosons at partonic energies above $4\pi v \sim$ 3 TeV.

- Beyond reach of the HL-LHC.
- Beyond reach of 3 TeV μC.
- *Ideal for 10-14 TeV μC.*

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

Deviation from SMEFT correlation (assuming dim-6 dominated)

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



What is the nature of dark matter?

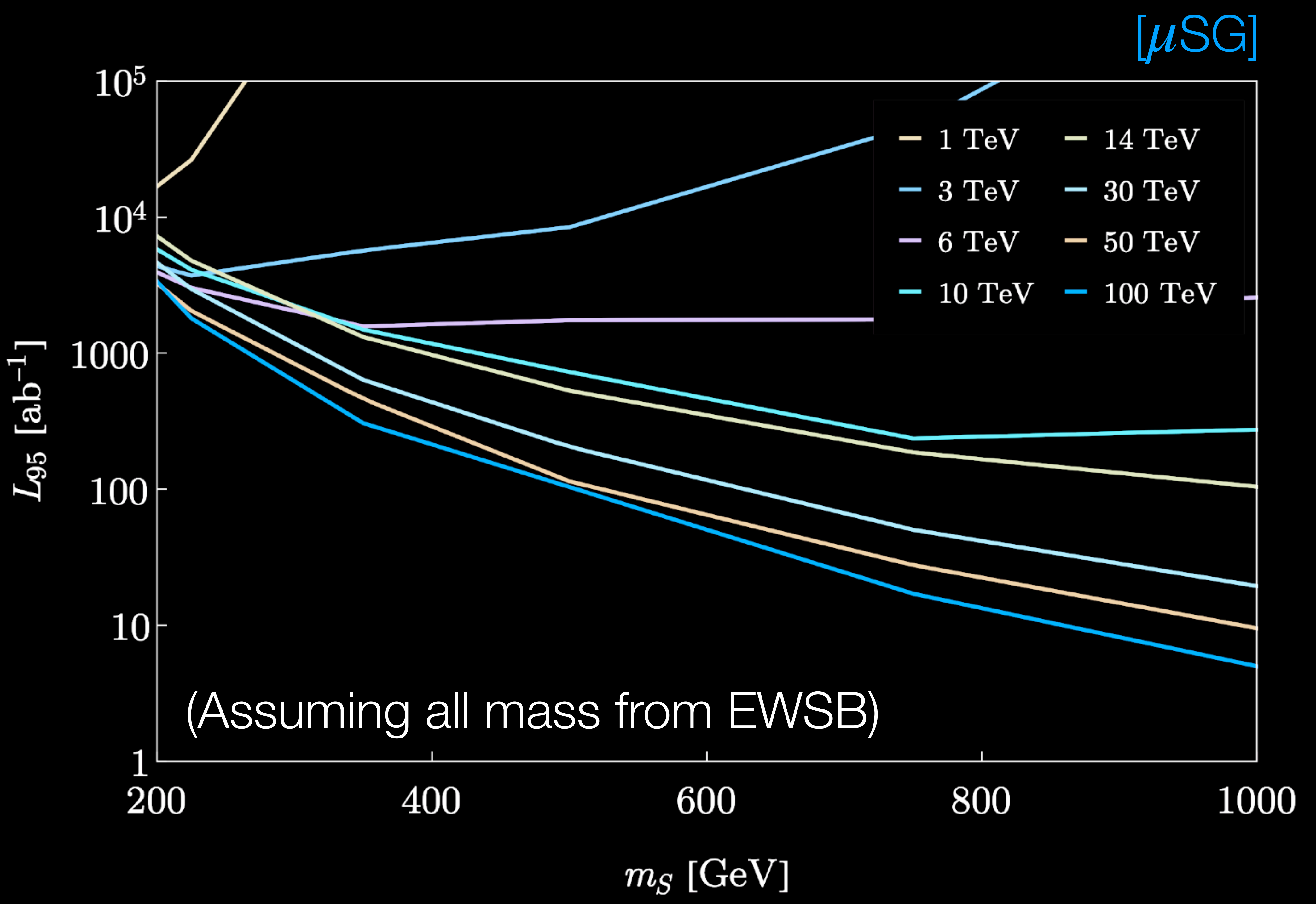
3 TeV muon collider ideal for probing minimal electroweak DM

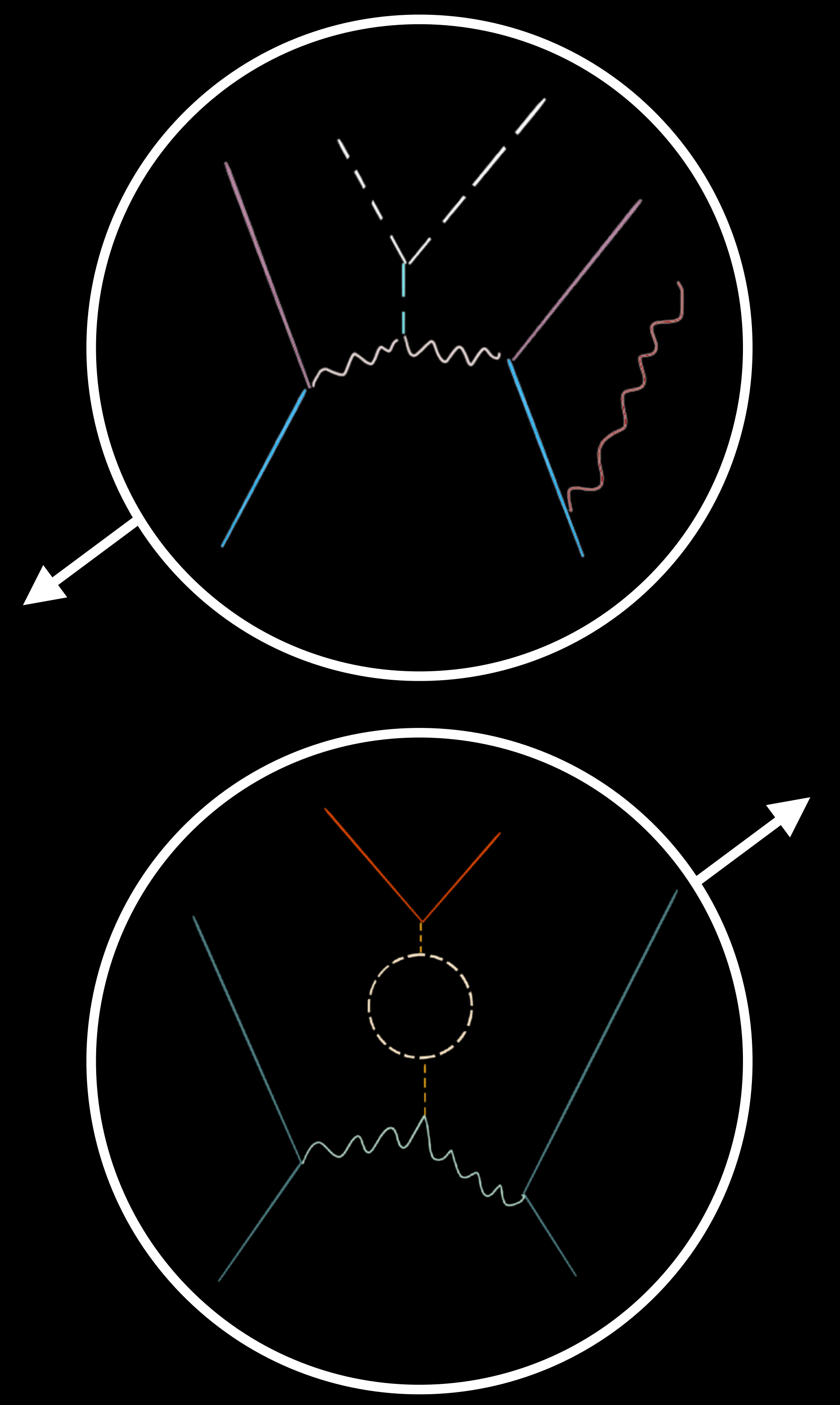
See R. Franceschini's talk

Another candidate: Z_2-symmetric singlet coupling to Higgs (also interesting for EW phase transition, naturalness,…), the "nightmare scenario"

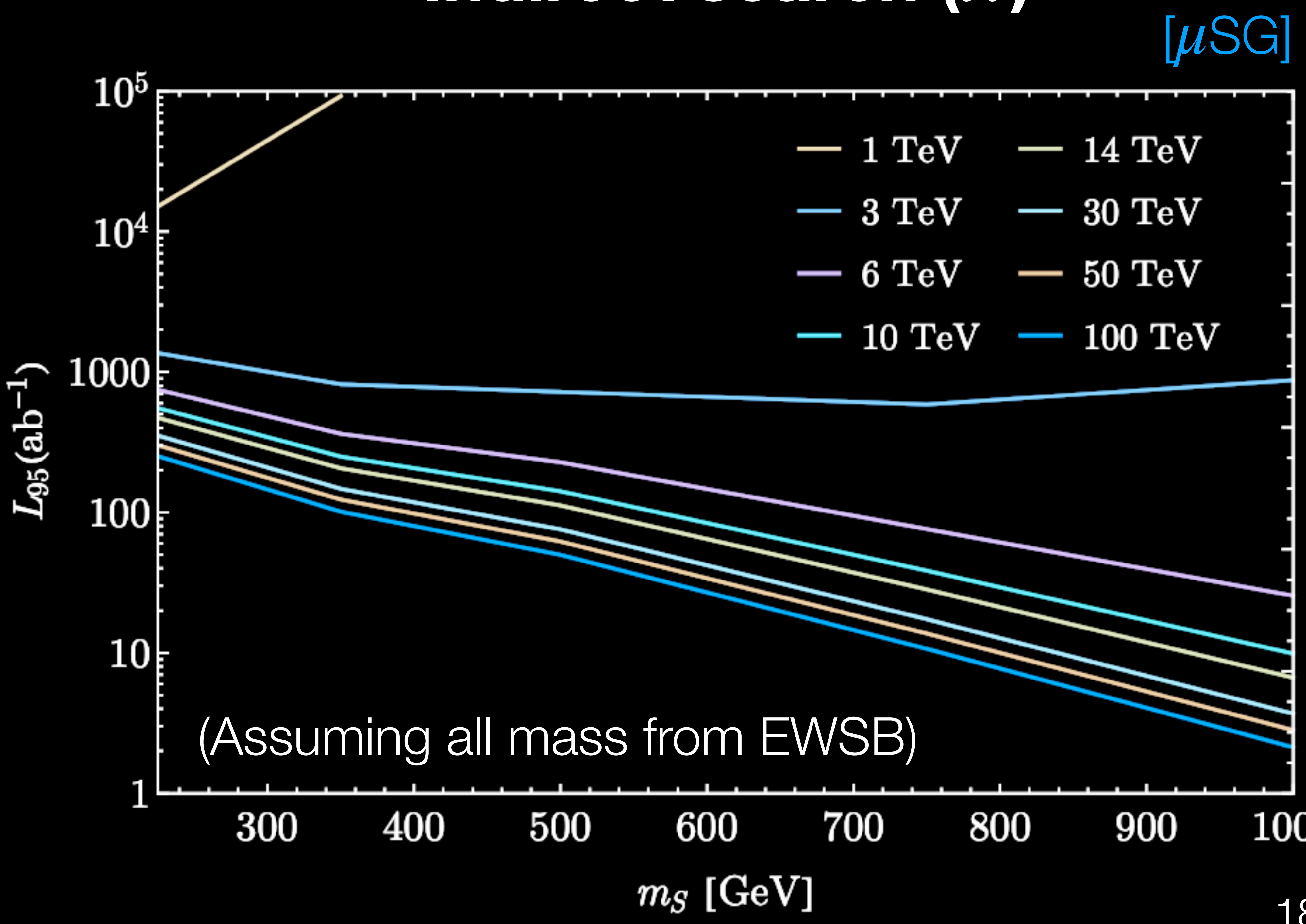
$$\mathcal{L} \supset -\lambda_{HS} S^2 |H|^2$$

Direct searches



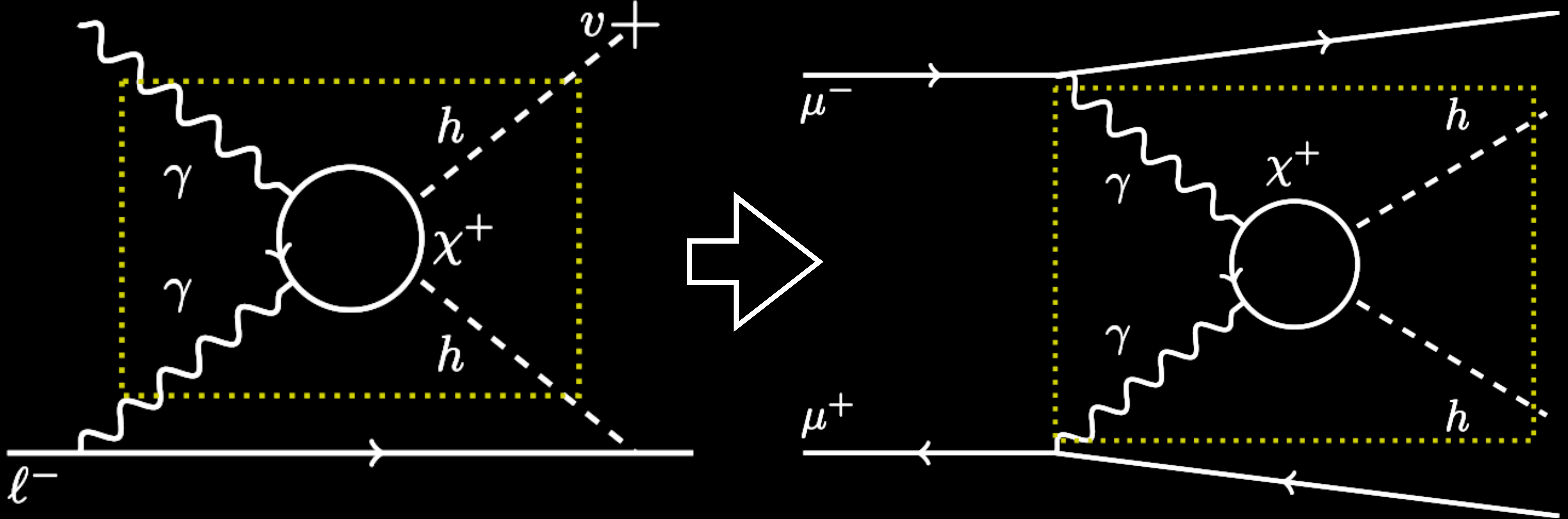


Indirect search ($t\bar{t}$)

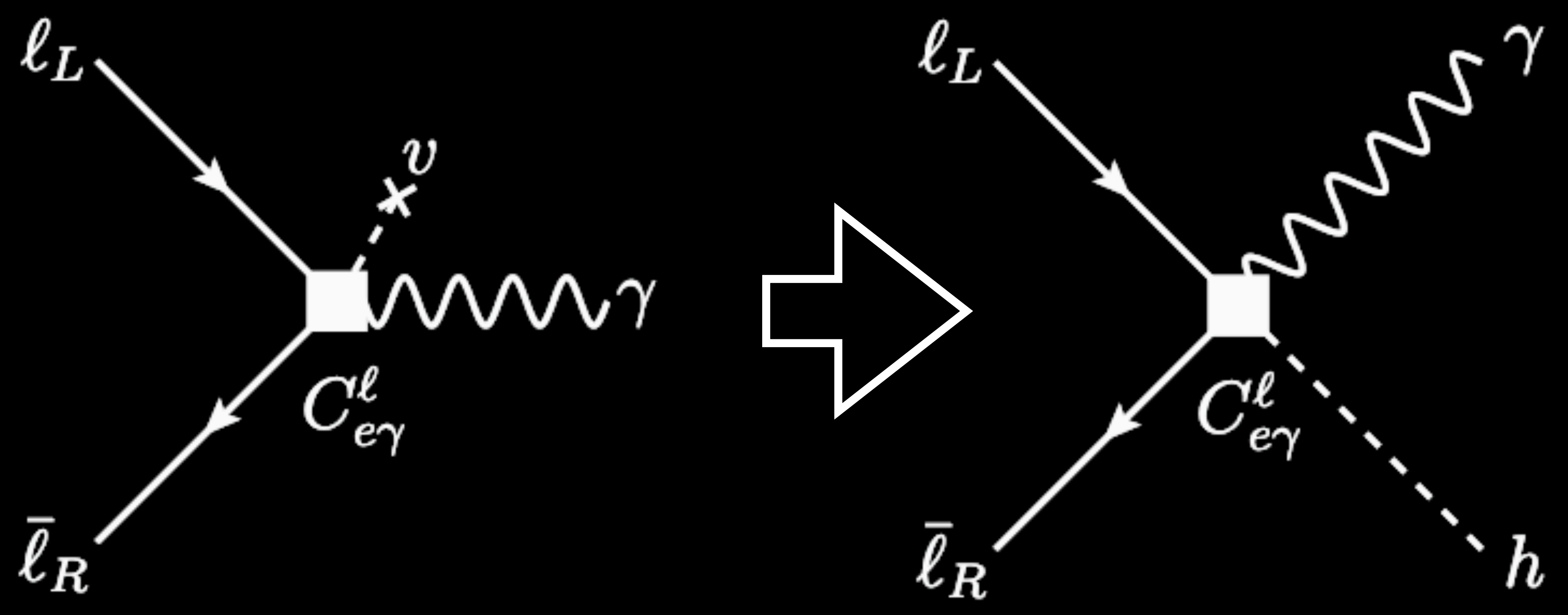


Compelling complementarity

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 2021

International
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Collaboration

- ✓ What is the origin of mass?
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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!