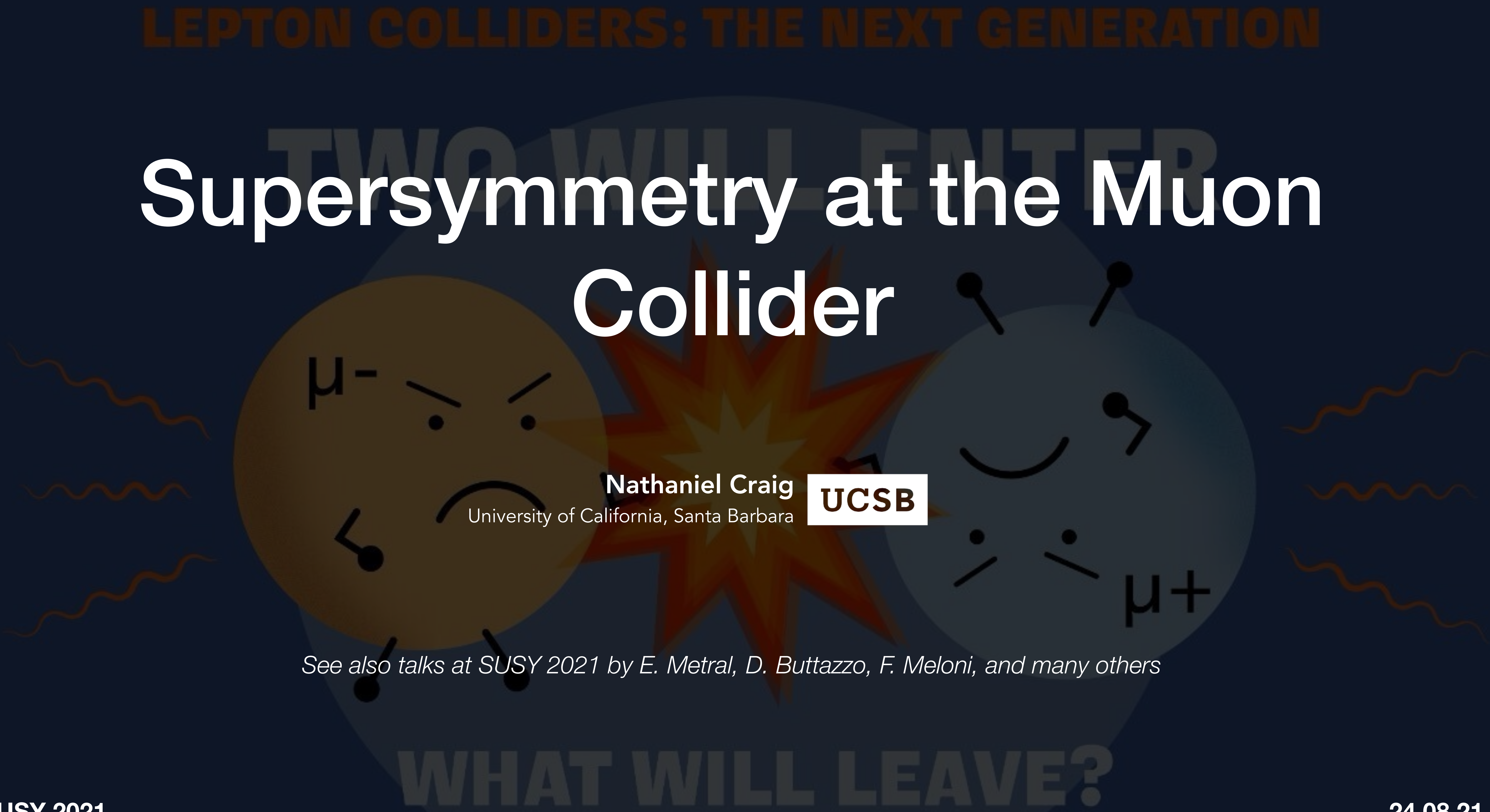


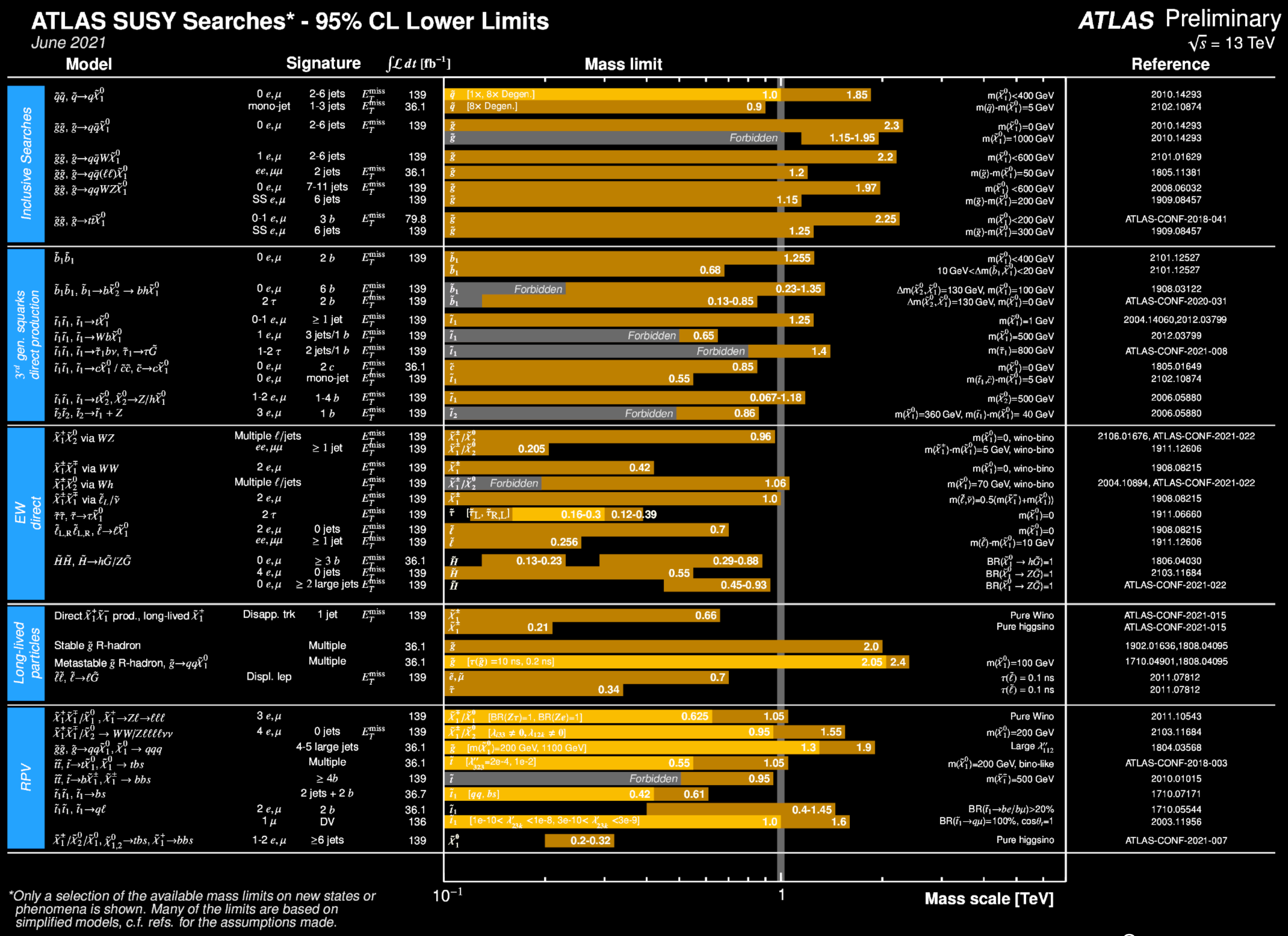
Supersymmetry at the Muon Collider

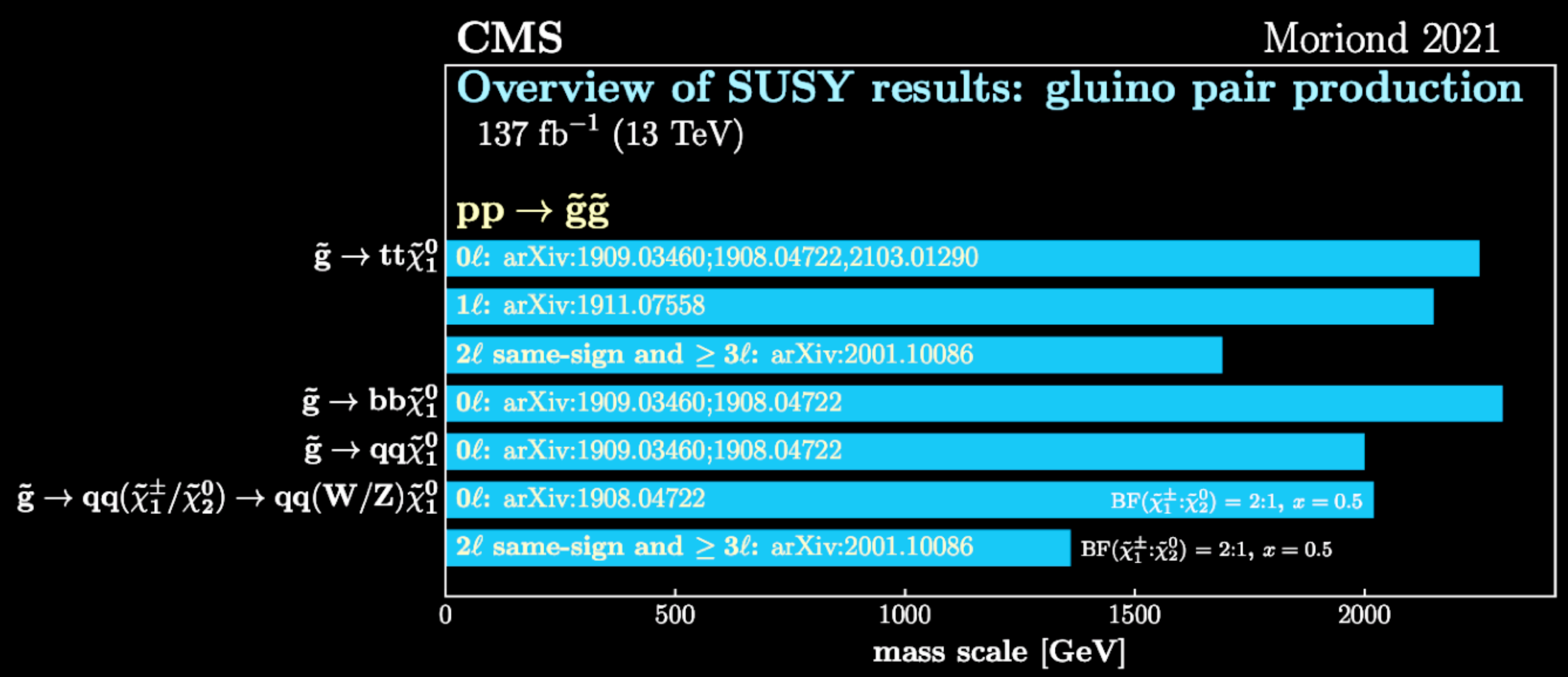
Nathaniel Craig
University of California, Santa Barbara
UCSB

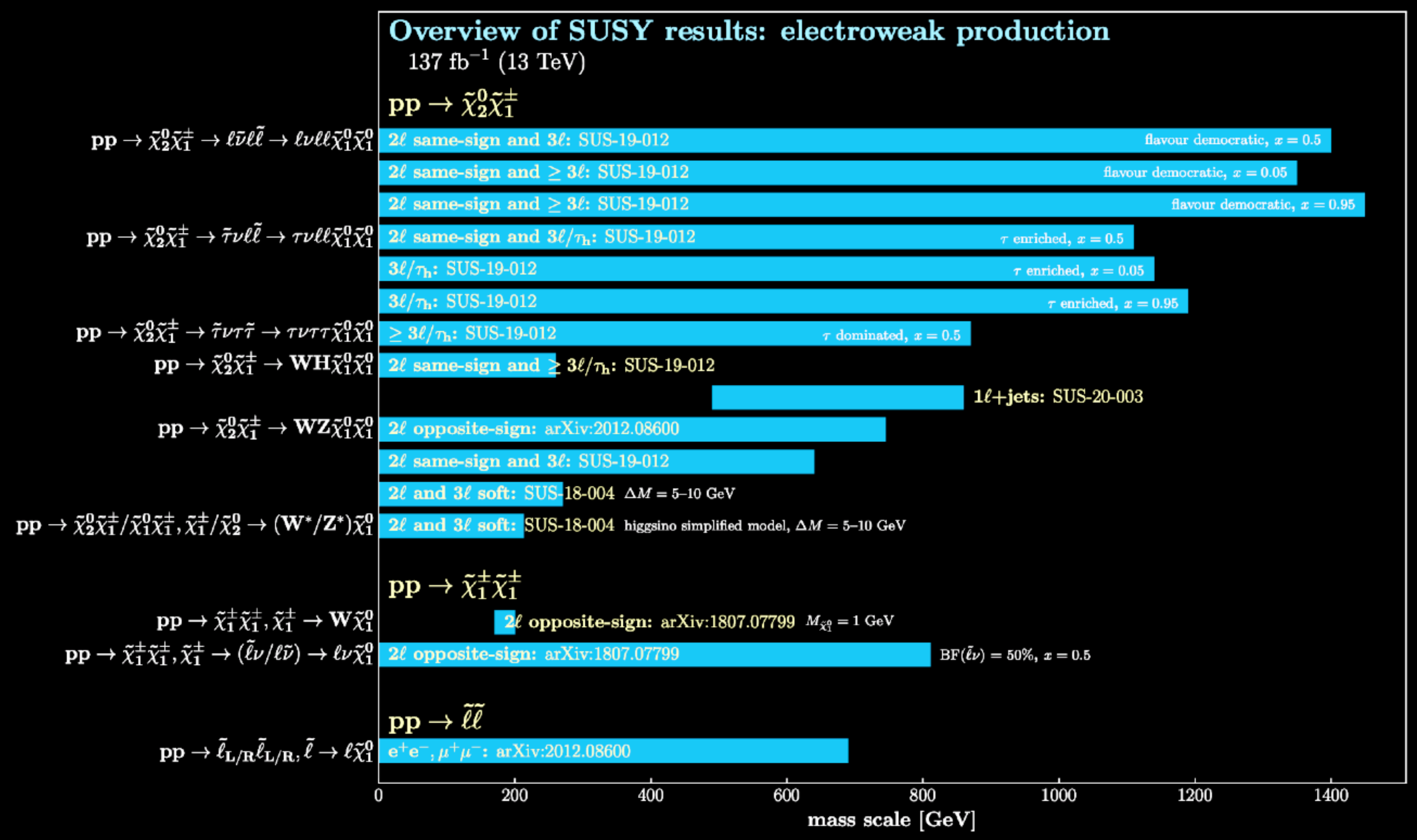
See also talks at SUSY 2021 by E. Metral, D. Buttazzo, F. Meloni, and many others

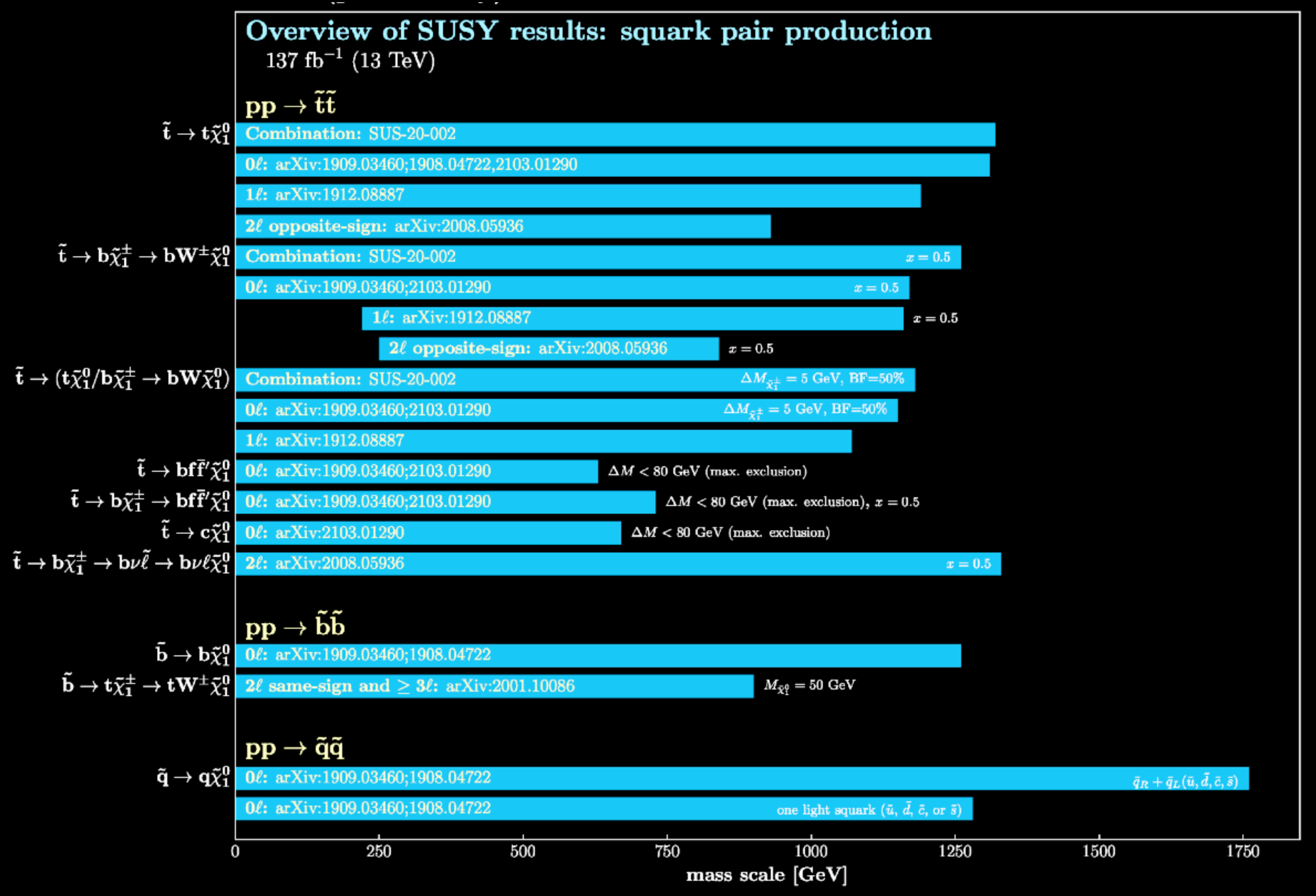
SUSY Reality

…which is essential to recognize in any discussion of future experiments.









Why SUSY (in the future)?

Quadratic pressure for sparticles as close to the weak scale as possible.
(Perhaps the least compelling argument at present, but still worth keeping in mind)

Higgsinos (tree level)

$$\Delta_{\tilde{h}} \simeq \frac{2m_{\tilde{h}}^2}{m_h^2}$$

↑

Fairly UV independent

Stops (one loop)

$$\Delta_{\tilde{t}} \simeq \frac{3y_t^2}{4\pi^2}\frac{m_{\tilde{t}}^2}{m_h^2}\log\frac{\Lambda}{m_{\tilde{t}}}$$

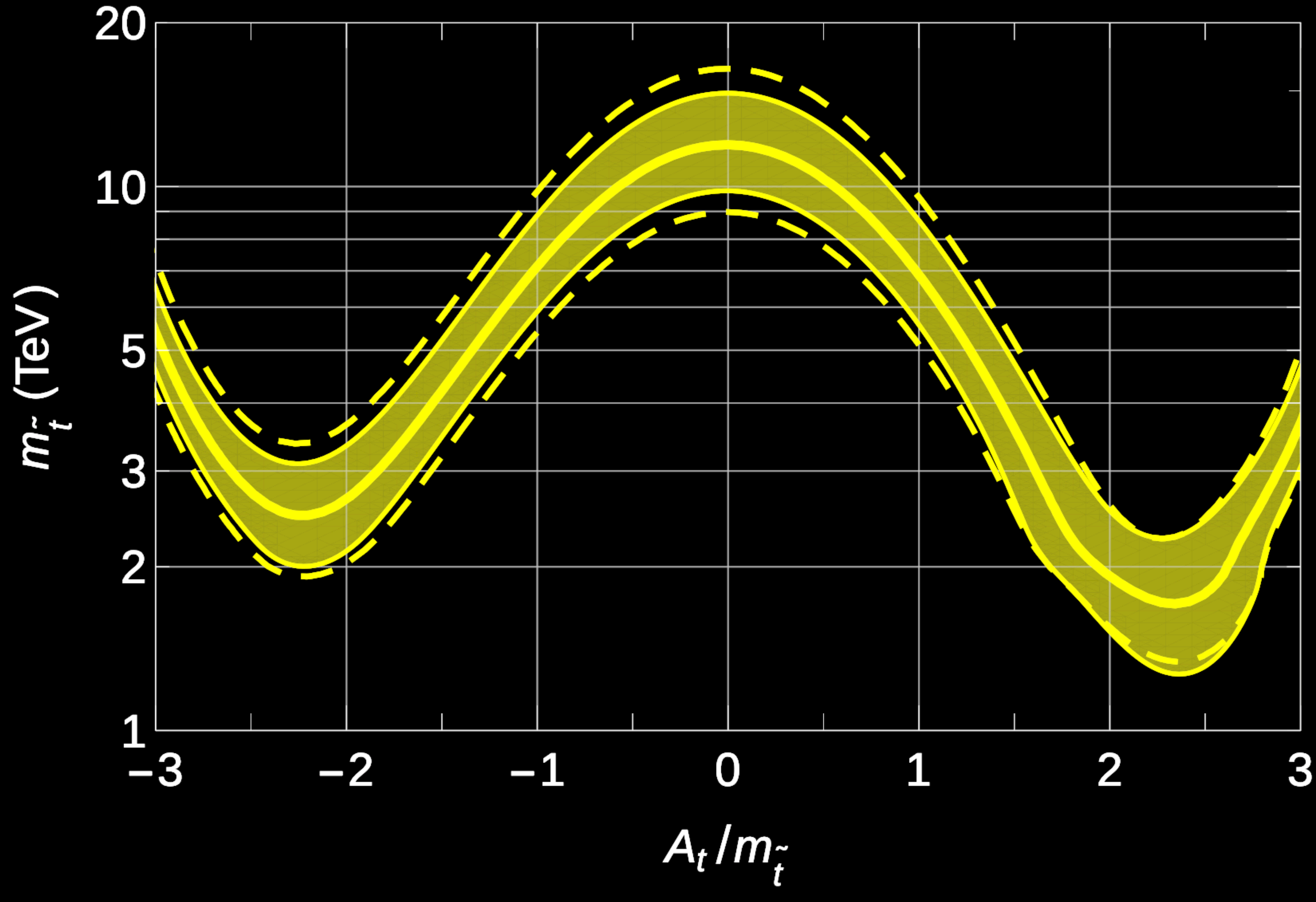
Gluinos (two loops)

$$\Delta_{\tilde{g}} \simeq \frac{\alpha_s y_t^2}{\pi^3}\frac{m_{\tilde{g}}^2}{m_h^2}\log^2\frac{\Lambda}{m_{\tilde{g}}}$$

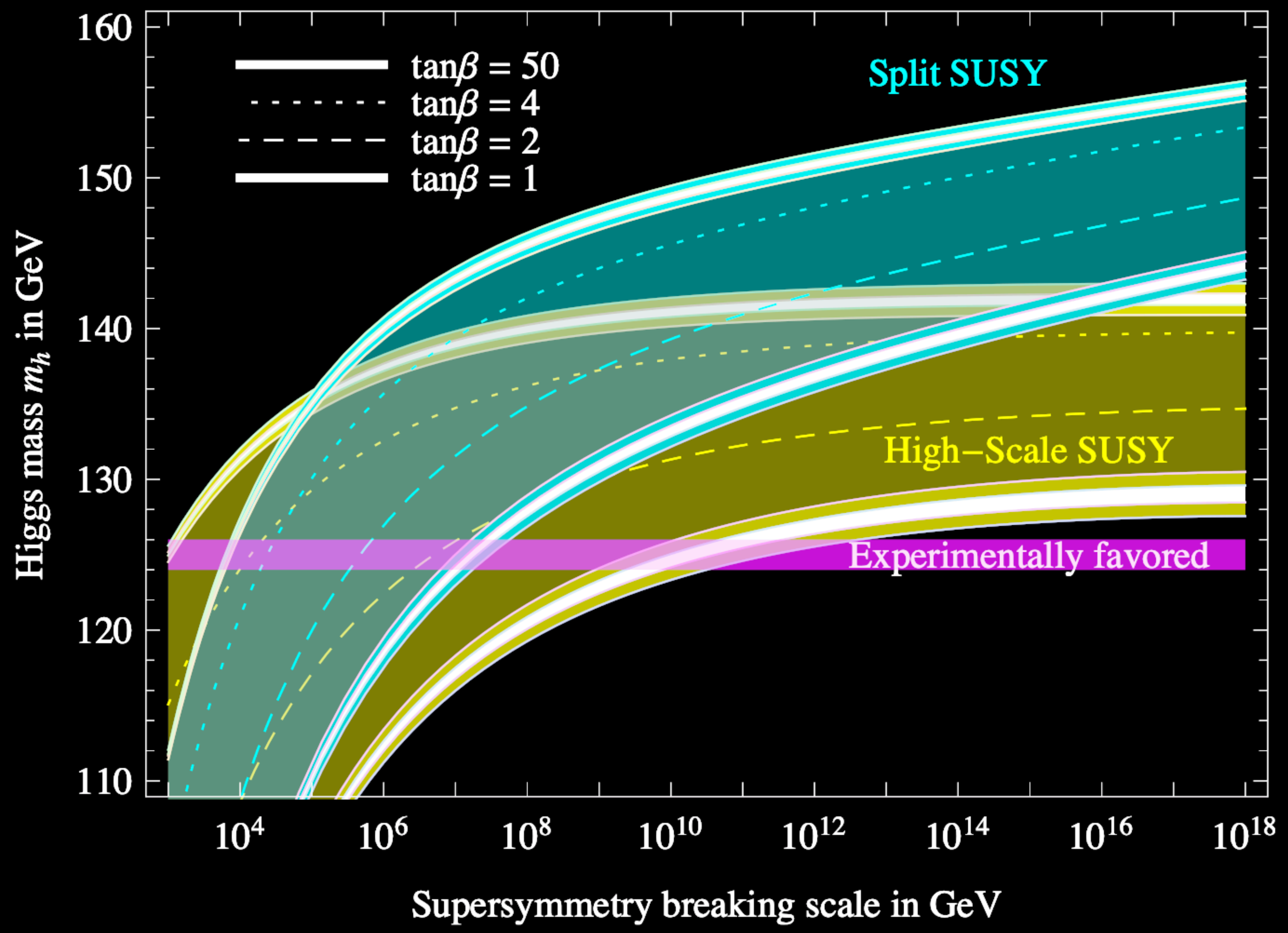
Some UV dependence

Why SUSY (in the future)?

Predicts the Higgs mass.



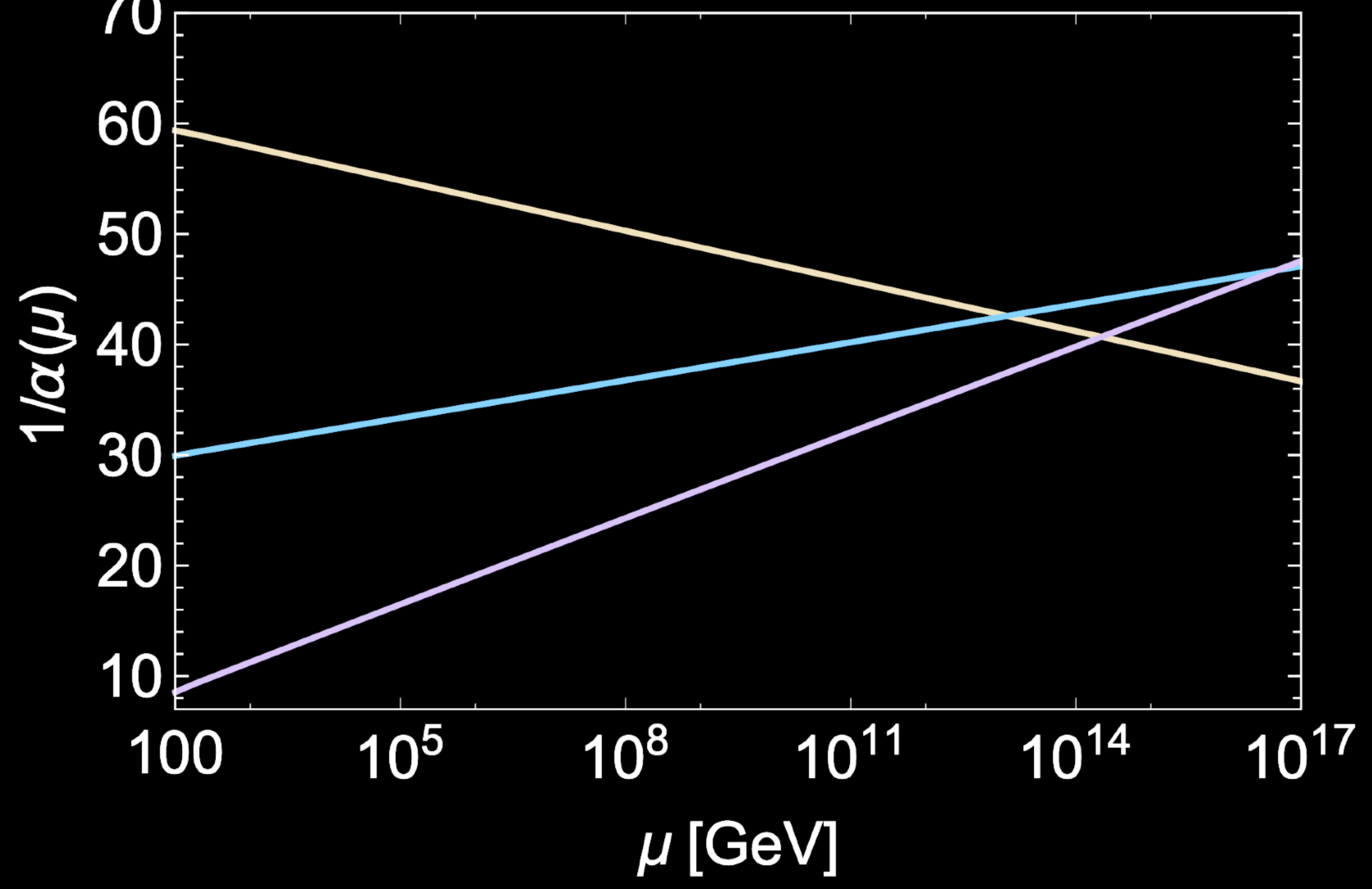
[Pardo Vega & Villadoro, 1504.05200]



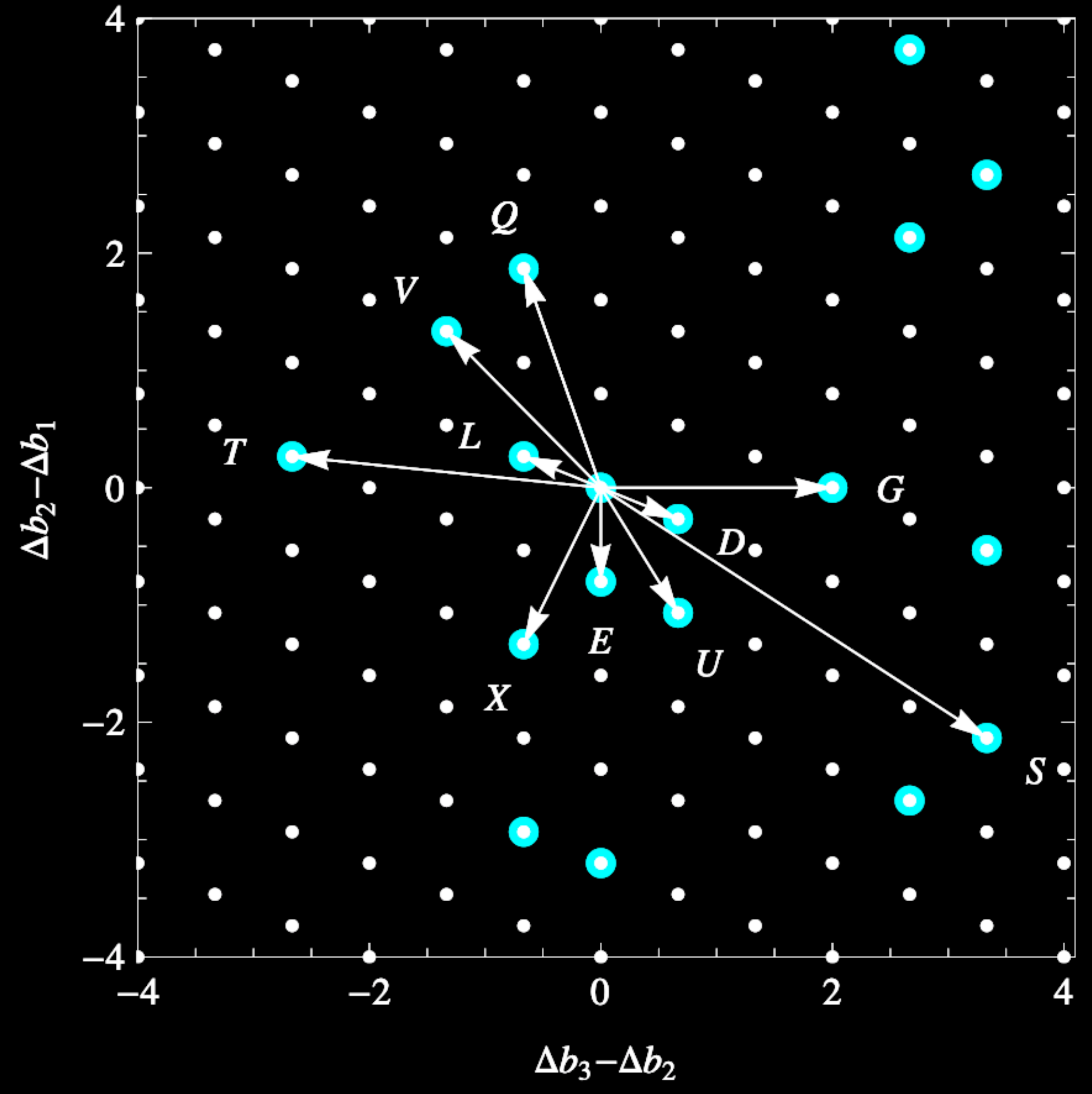
[Degrassi et al., 1205.6497]

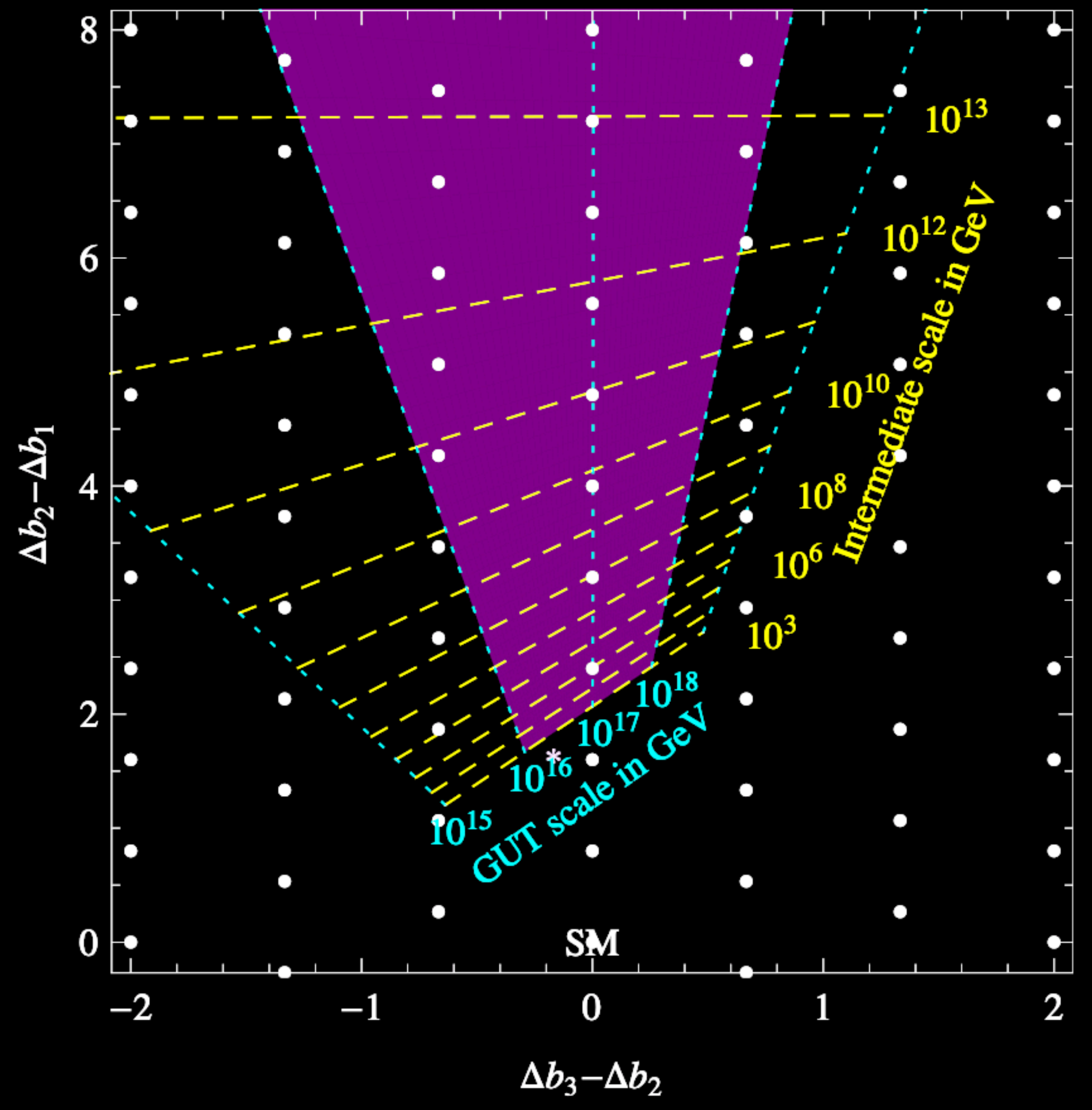
Why SUSY (in the future)?

Unification.



[Giudice, Rattazzi, Strumia 1204.5465]





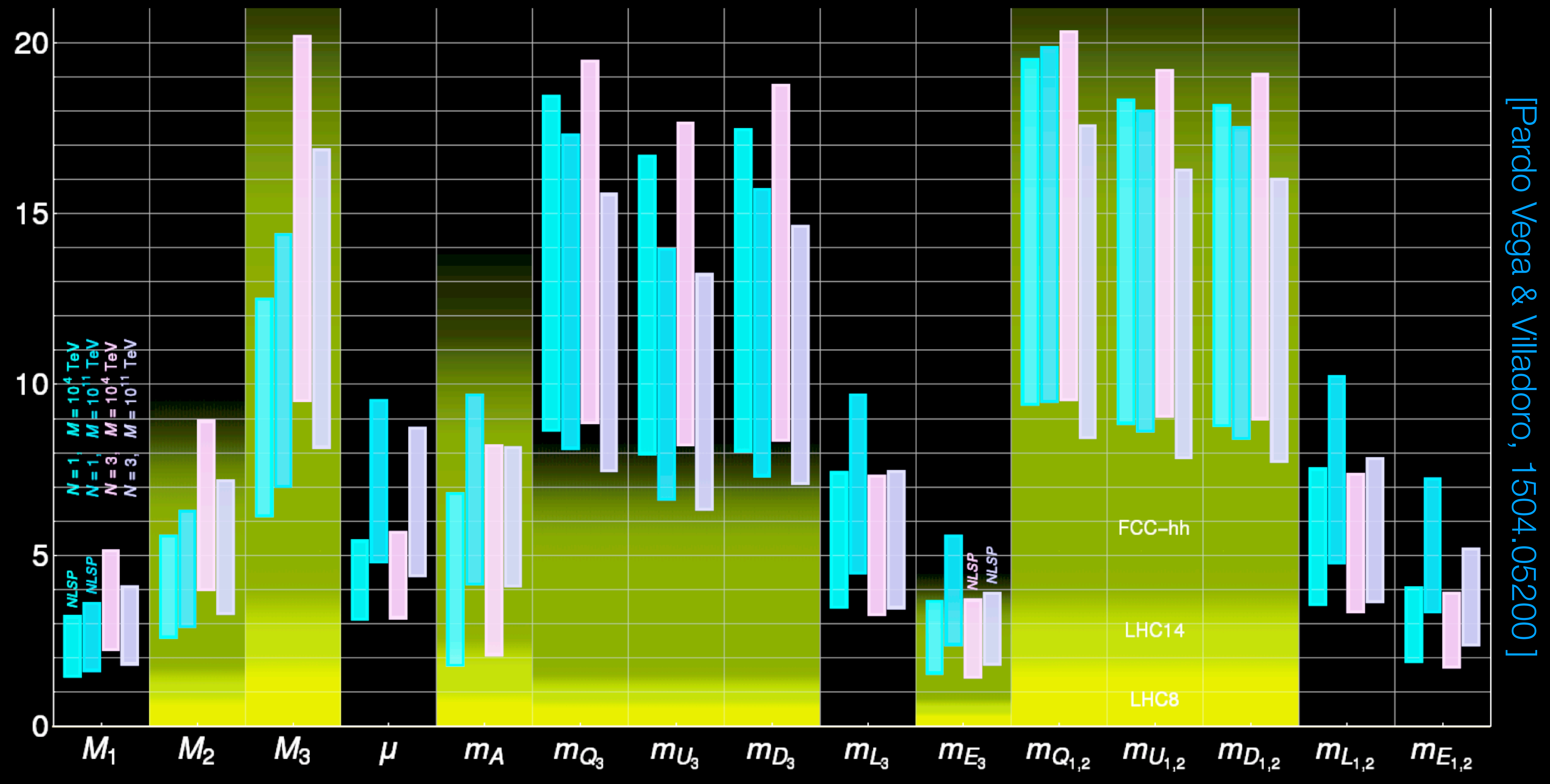
Running of couplings in the Standard Model tantalizingly hints at unification, but the intersection is imperfect & scale too low.

New particles at TeV energies sharpen the prediction & raise the scale; SUSY furnishes natural candidates in higgsinos & gauginos

Why SUSY (in the future)?

Highly predictive, bounded scenarios that can be discovered or decisively excluded.

e.g. **Minimal Gauge Mediation**



Why SUSY (in the future)?

SUSY is a phenomenal signal generator

	γ	ℓ	τ	j	t	W	Z	h	E_T
γ	H,A						H		$\chi^0{}_1$
ℓ		RPV	RPV	RPV	RPV				$\tilde{\ell}$
τ			H,A	RPV	RPV				$\tilde{\tau}$
j				H,A	RPV				$\tilde{q}$
t					H,A				$\tilde{t}$
W						H		$H^\pm$	$\chi^\pm$
Z							H	A	$\tilde{h}$
h								H	$\tilde{h}$
E_T									h

- *disappearing tracks*
- *R-hadrons*
- *HSCPs*
- *displaced photons*
- *....*

SUSY at a Muon Collider?

Supersymmetry vis-à-vis Muon Colliders

V. Barger

Physics Department, University of Wisconsin, Madison, WI 53706, USA

CP435, *Workshop on the Front End of a Muon Collider*
edited by S. Geer and R. Raja

The Muon Smasher's Guide

Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dario Buttazzo[3], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid Ekhterachian[5], JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9], Seth Koren[10], Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Alberto Mariotti[13], Amara McCune[1], Patrick Meade[7], Isobel Ojalvo[14], Umut Oktem[1], Diego Redigolo[15,16], Matthew Reece[9], Filippo Sala[17], Raman Sundrum[5], Dave Sutherland[18], Andrea Tesi[16,19], Timothy Trott[1], Chris Tully[14], Lian-Tao Wang[10], and Menghang Wang[1]

[1] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ, 08540, USA*
[3] *INFN, Sezione di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*
[4] *Institute for Fundamental Science, University of Oregon, Eugene, OR 97403, USA*
[5] *Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA*
[6] *Department of Physics, Brown University, Providence, RI 02912, USA*
[7] *C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA*
[8] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[9] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[10] *Department of Physics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[11] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*
[12] *Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong S.A.R., P.R.C*
[13] *Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, and International Solvay Institutes, Pleinlaan 2, B-1050 Brussels, Belgium*
[14] *Princeton University, Princeton, NJ 08540, USA*
[15] *CERN, Theoretical Physics Department, Geneva, Switzerland*
[16] *INFN Sezione di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy*
[17] *LPTHE, CNRS & Sorbonne Universite, 4 Place Jussieu, F-75252 Paris, France*
[18] *INFN Sezione di Trieste, via Bonomea 265, 34136 Trieste, Italy*
[19] *Department of Physics and Astronomy, University of Florence, Italy*

[arXiv: 2103.14043]

Coarse-grained approach to phenomenology: interested in rates, simple parton-level analyses, setting aside beam-induced background & reconstruction issues.

Broad goal: to figure out what energies & luminosities might provide a comprehensive physics case, bring new targets into focus.

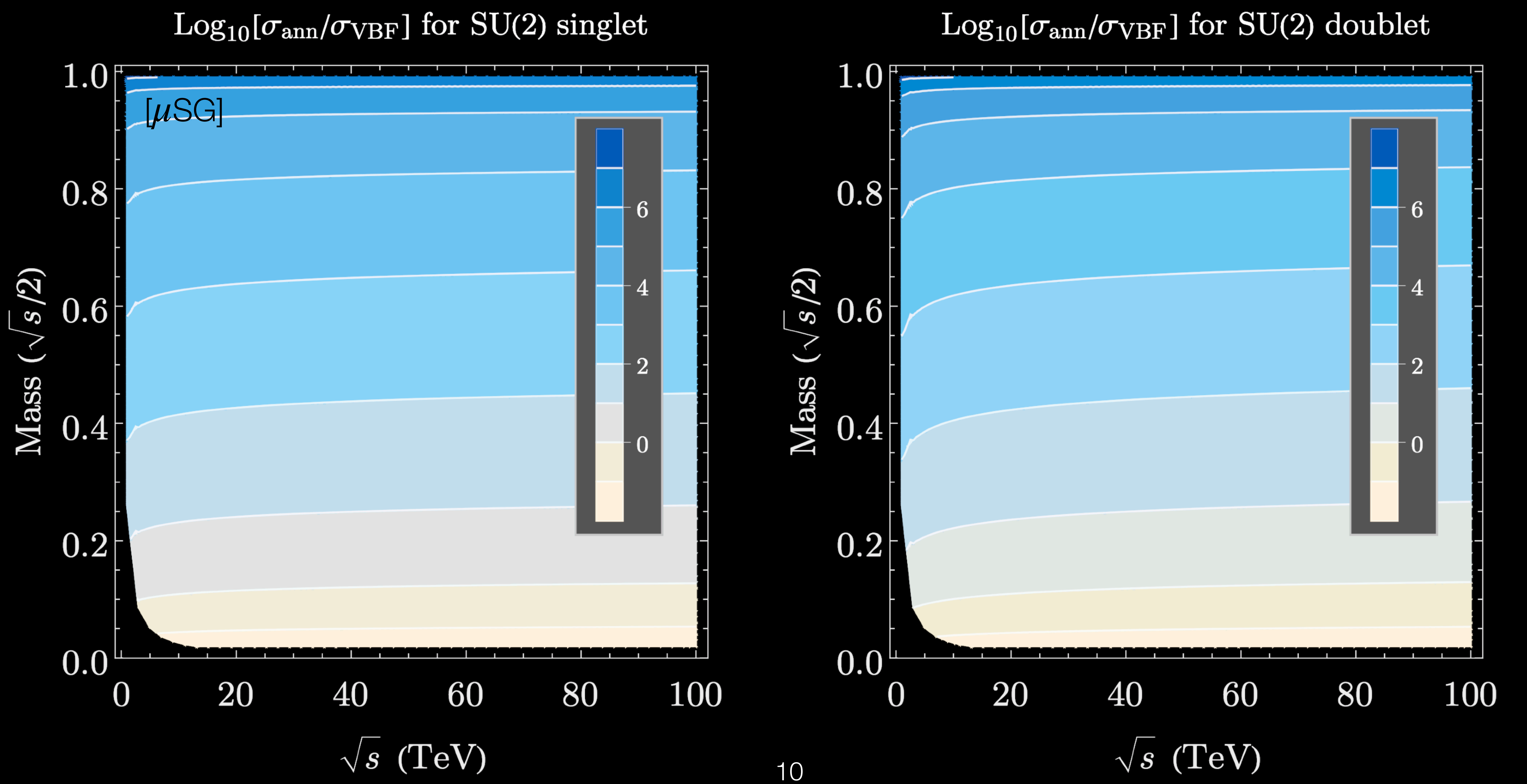
Various luminosity assumptions & energies:

$\sqrt{s}$ [TeV]	1	3	6	10	14	30	50	100
$\mathcal{L}_{\rm int}^{\rm opt}$ [ab^{-1}]	0.2	1	4	10	20	90	250	1000
$\mathcal{L}_{\rm int}^{\rm con}$ [ab^{-1}]	0.2	1	4	10	10	10	10	10

Two channels for new physics

Combination of annihilation and VBF offers kinematic reach and considerable rate

c.f. [Costantini et al. 2005.10289]

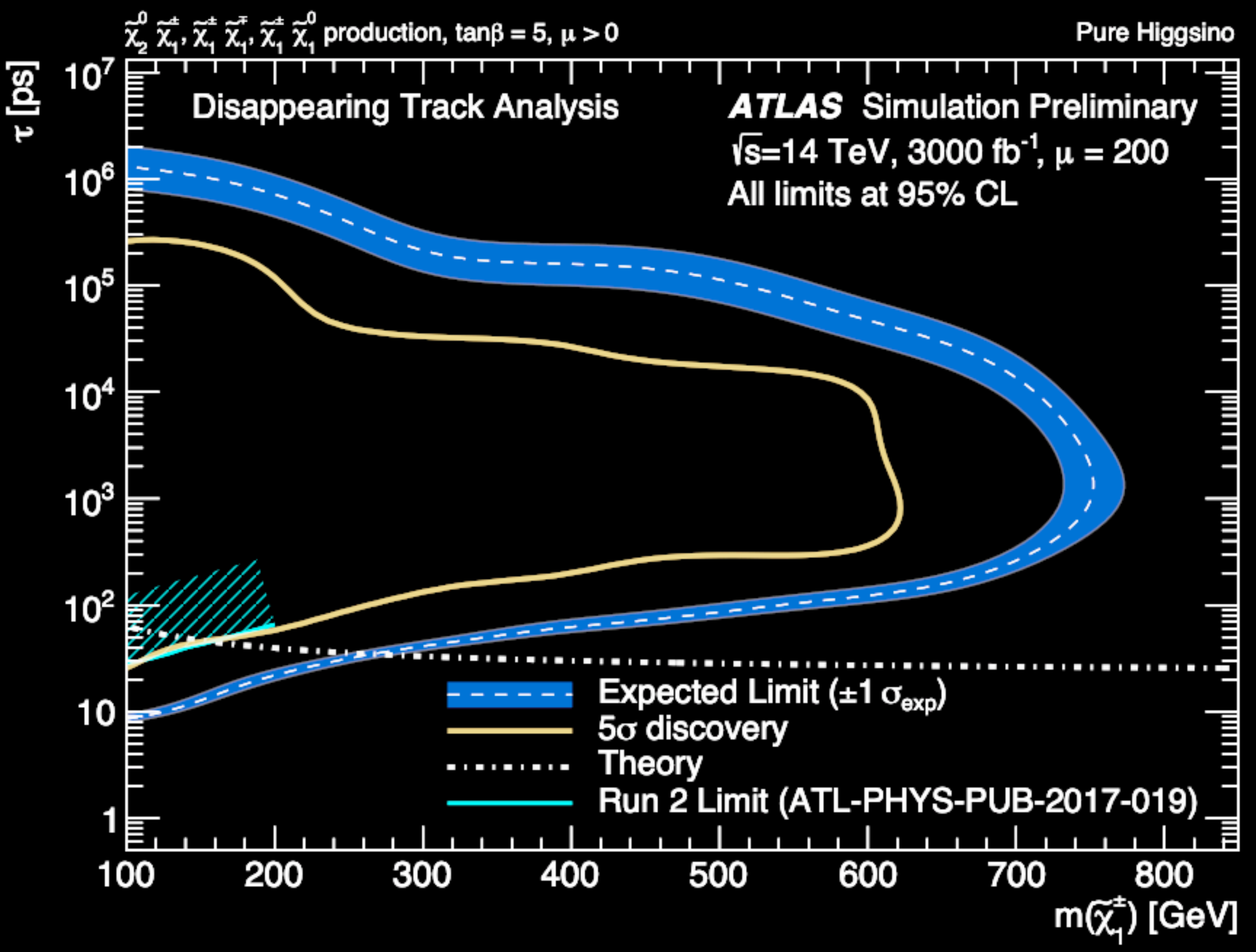


Higgsinos

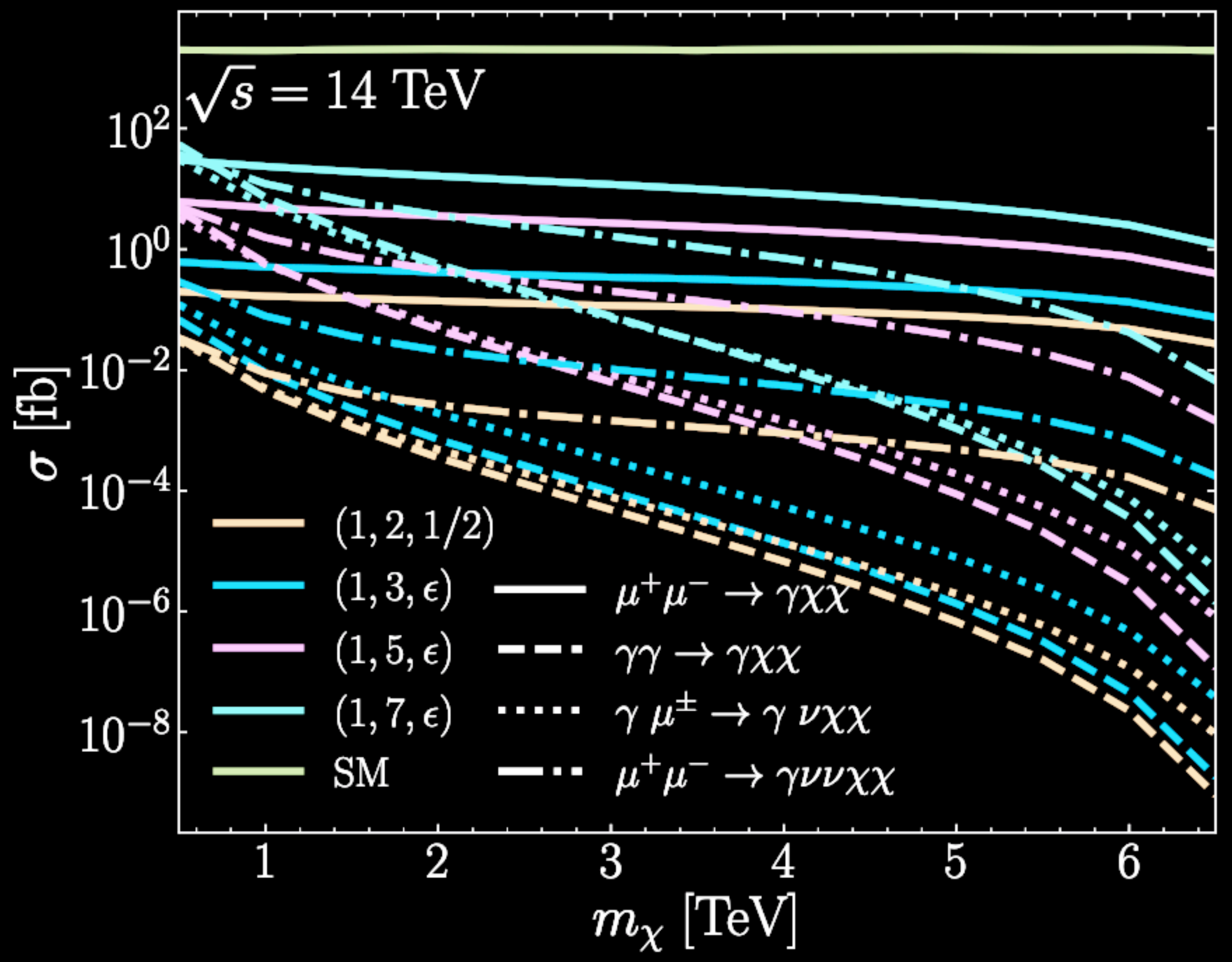
Sharp **target**

Pure Higgsino poorly constrained by HL-LHC

$$\Delta_{\tilde{h}} \simeq \frac{2m_{\tilde{h}}^2}{m_h^2}$$



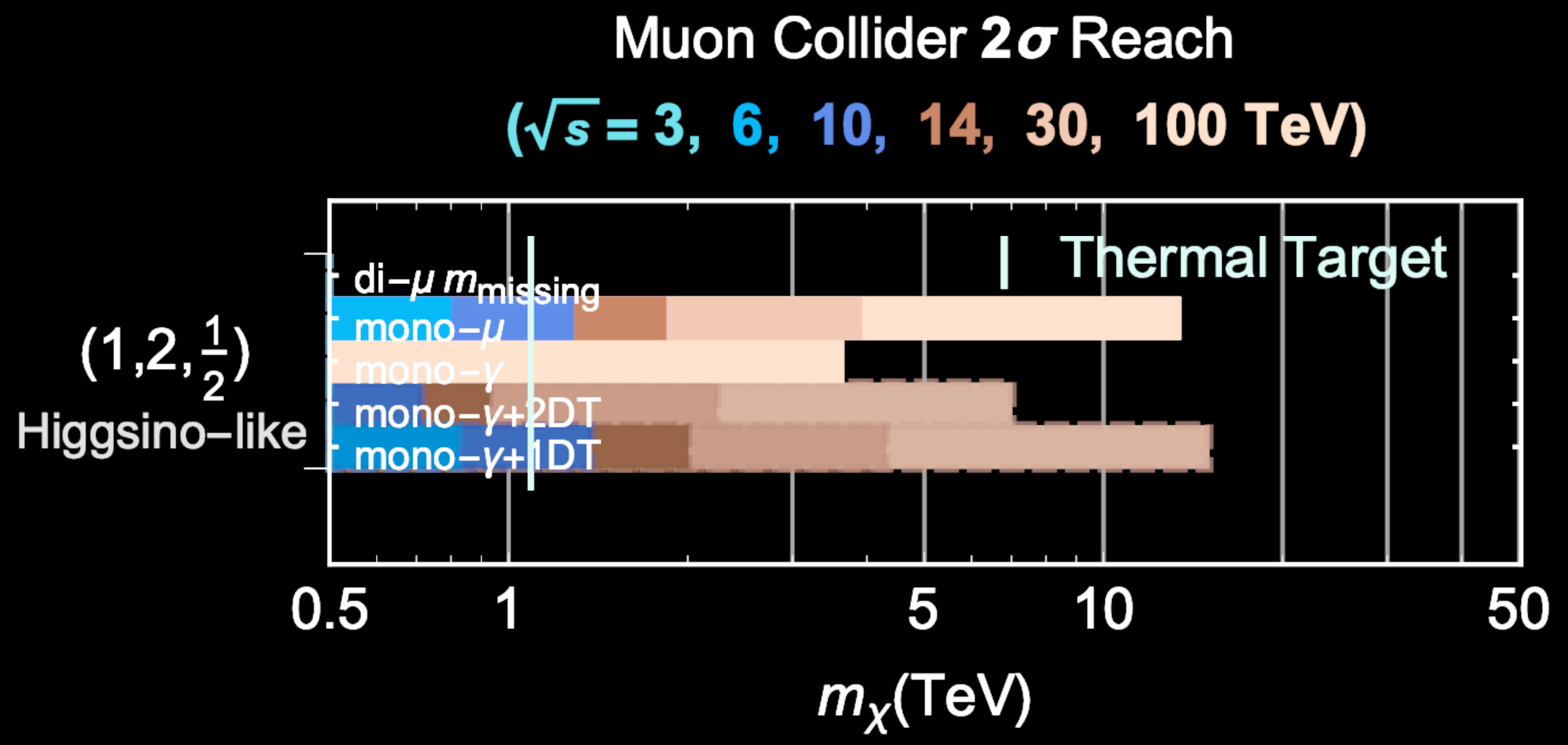
Nontrivial background @ Muon Collider

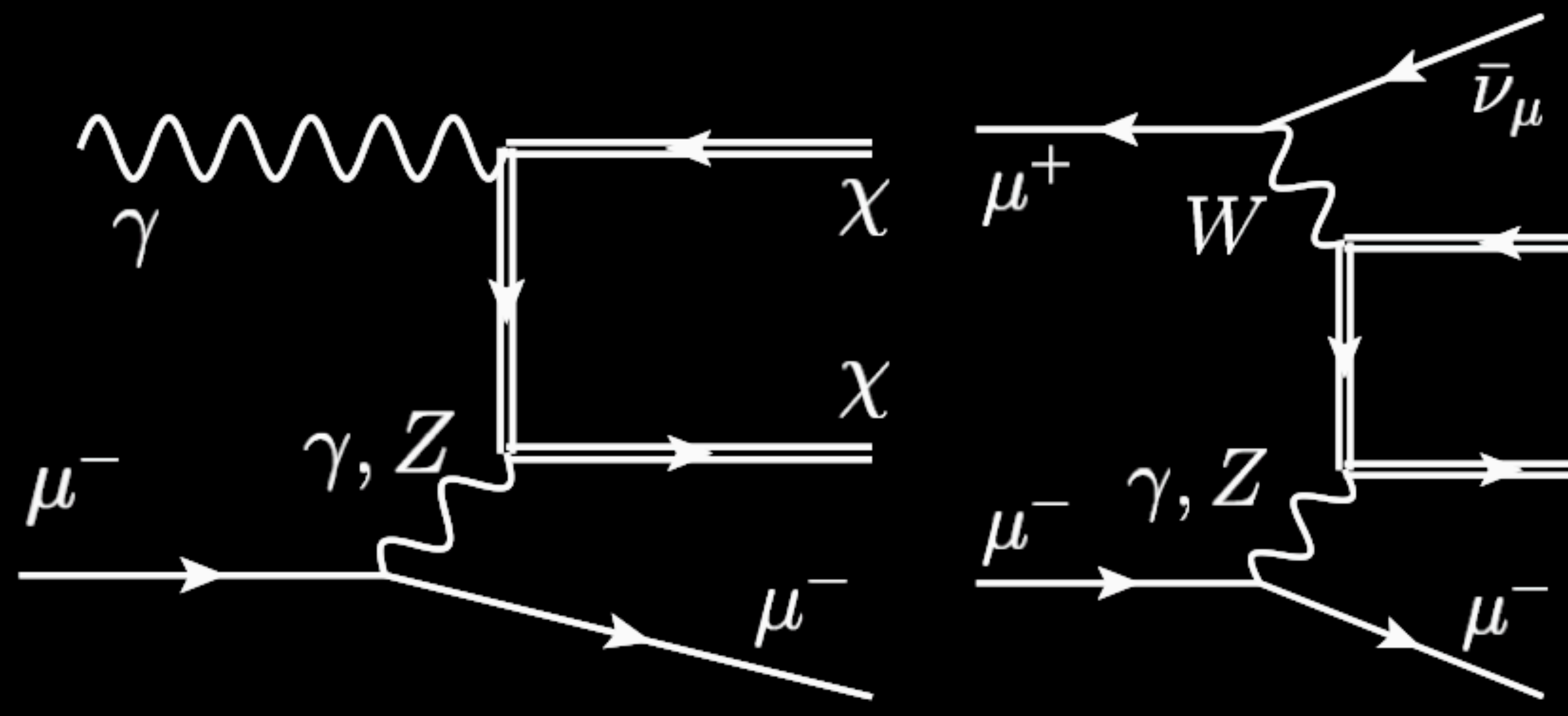


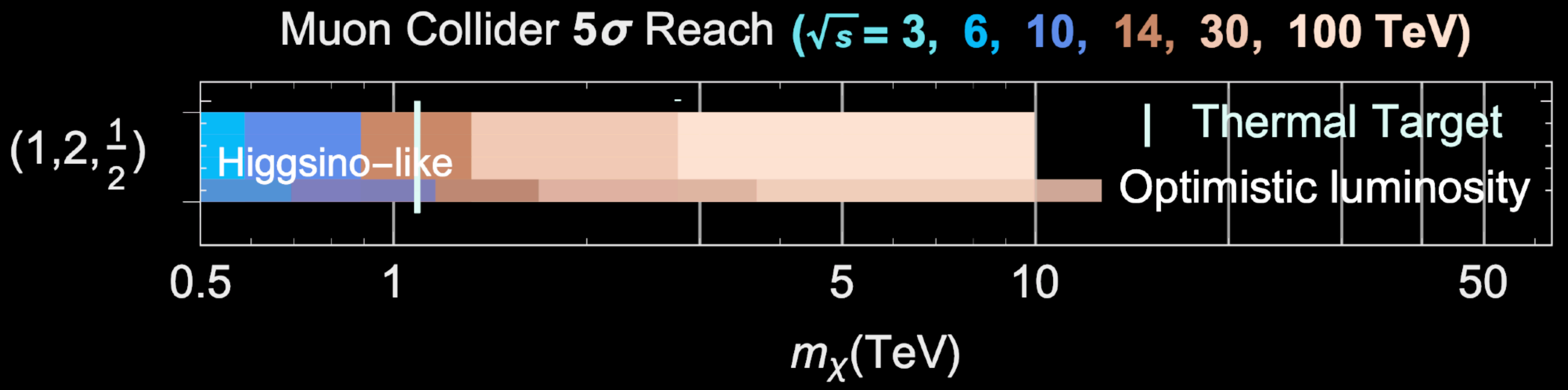
[Han, Liu, Wang, Wang, 2009.11287]

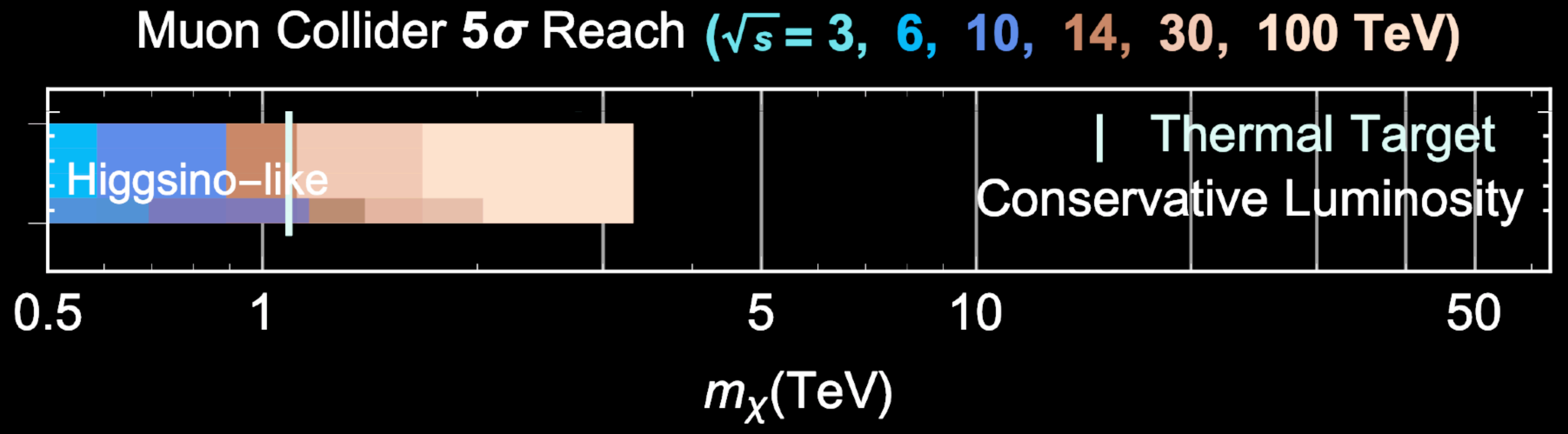
[Han, Liu, Wang, Wang, 2009.11287, updated for μSG]

Higgsinos









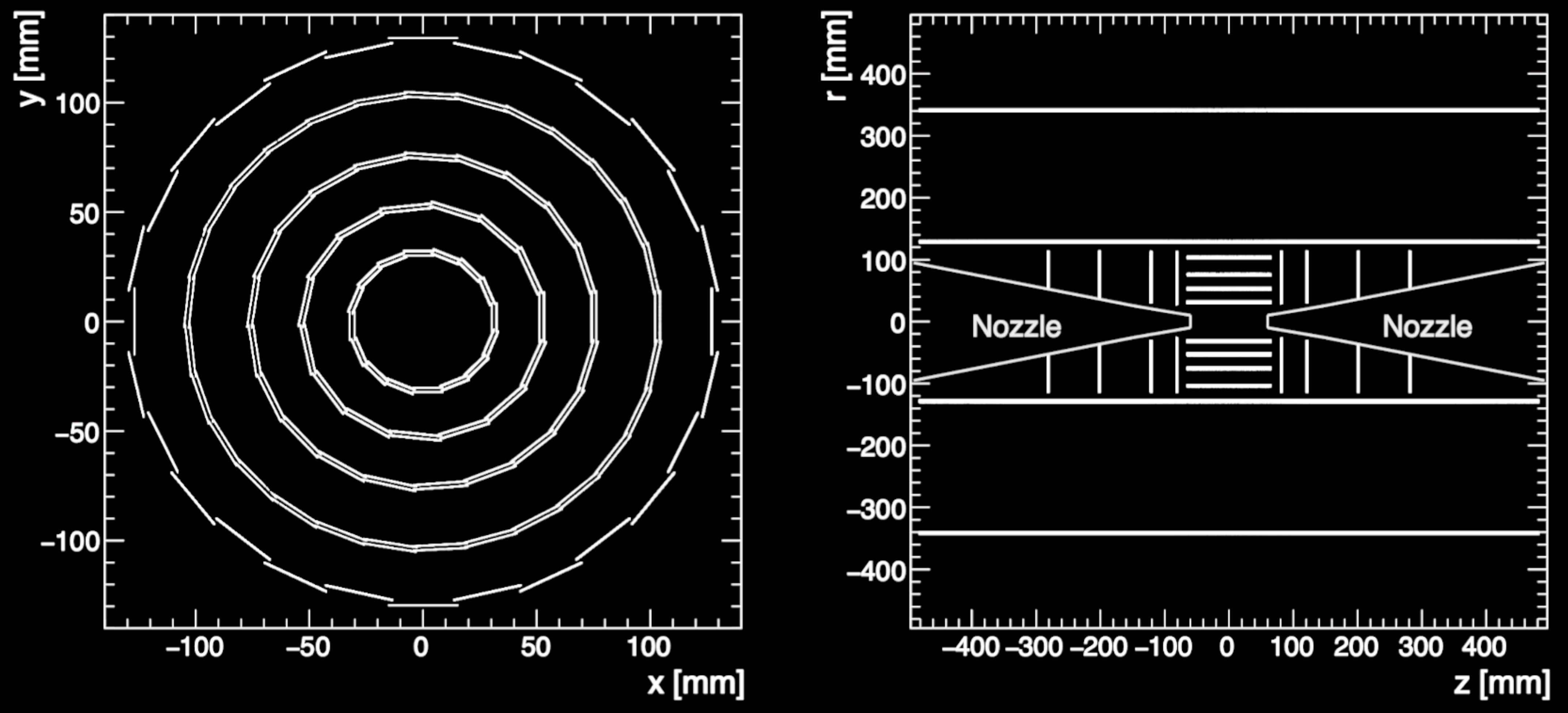
* Pure Higgsino case may be overly conservative, if other gauginos are light then signals become more striking.

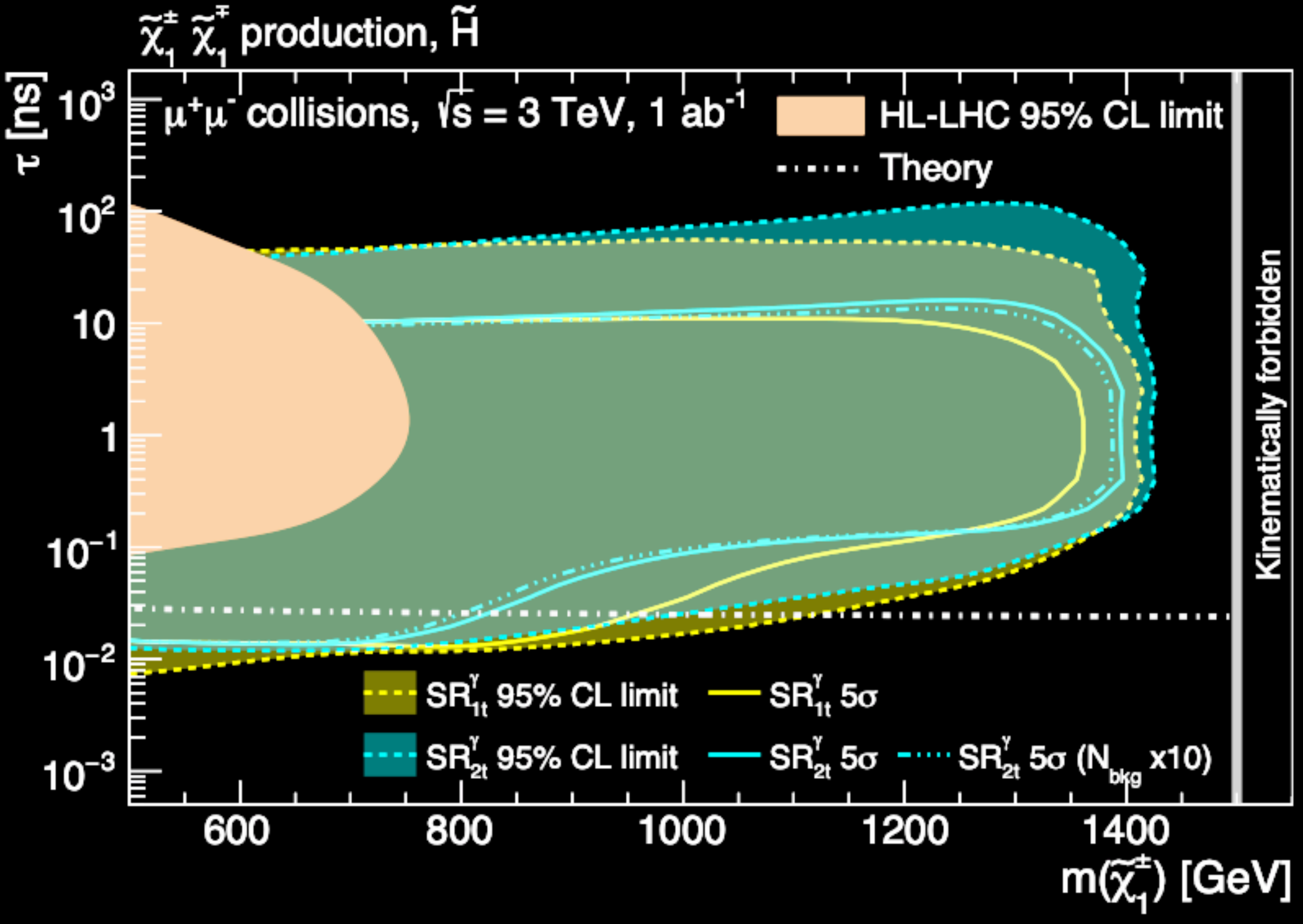
Higgsinos

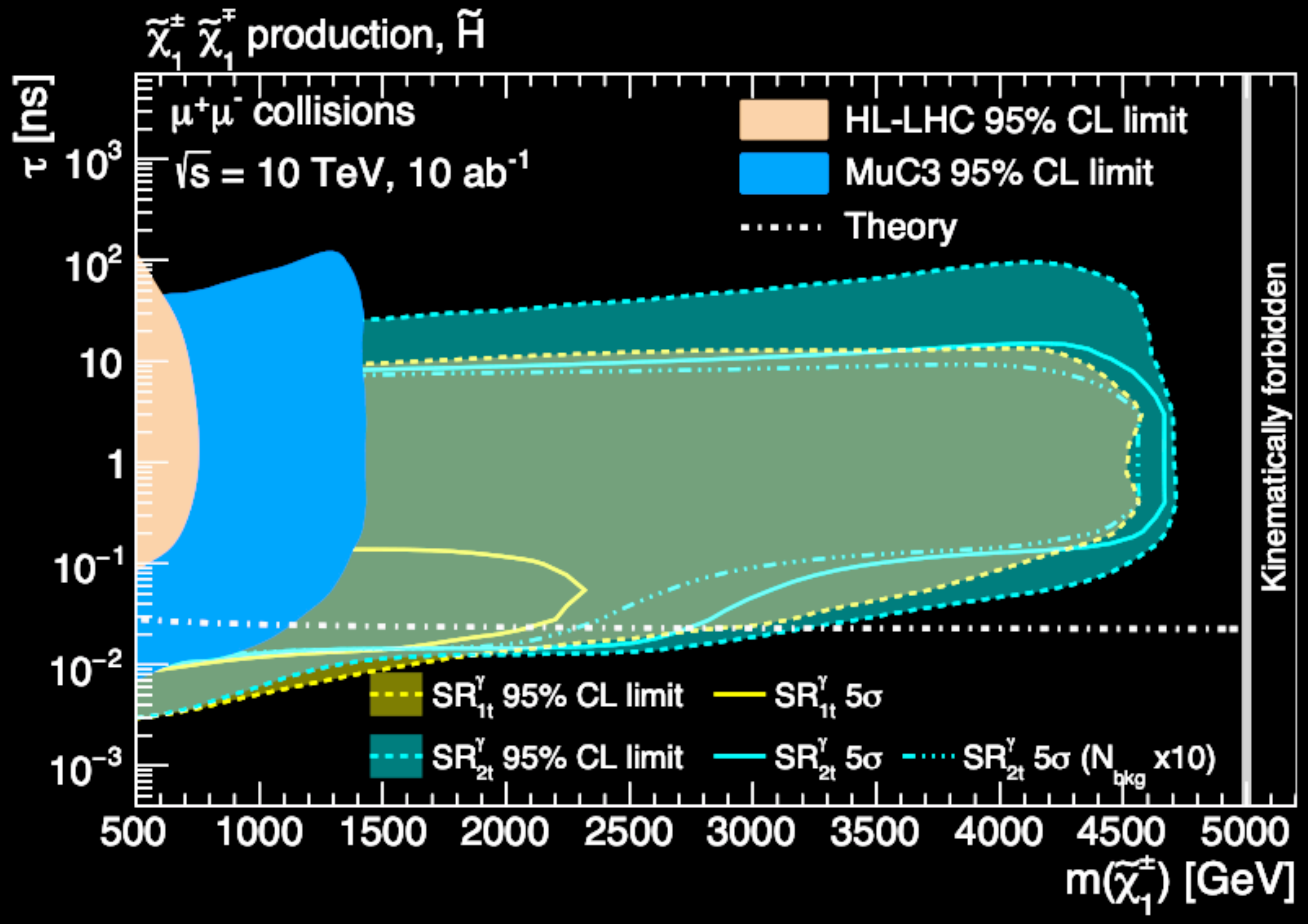
[Capdevilla, Meloni, Simoniello, Zurita 2102.11292]

Detailed treatment of reco & BIB

Conclusions somewhat more optimistic.



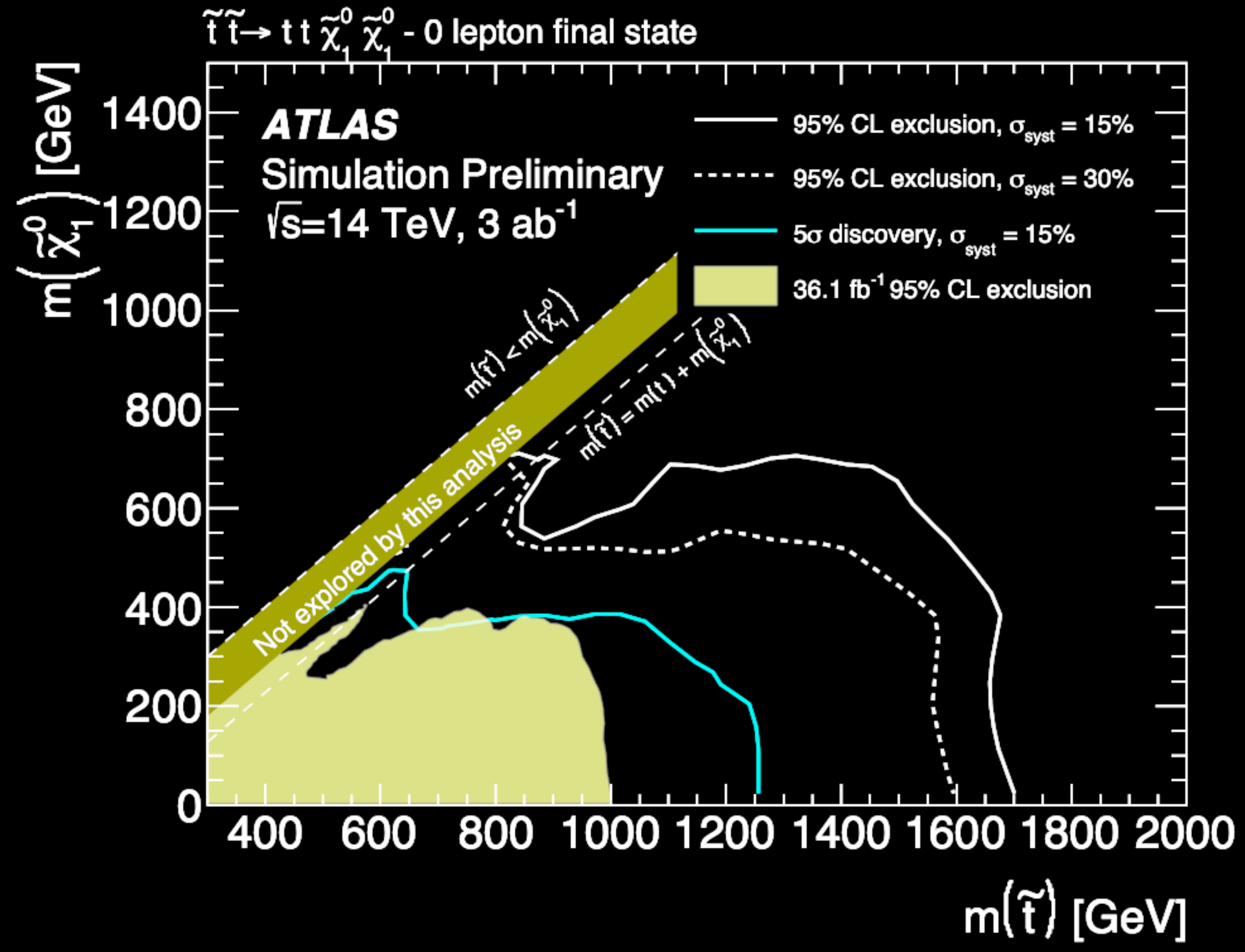


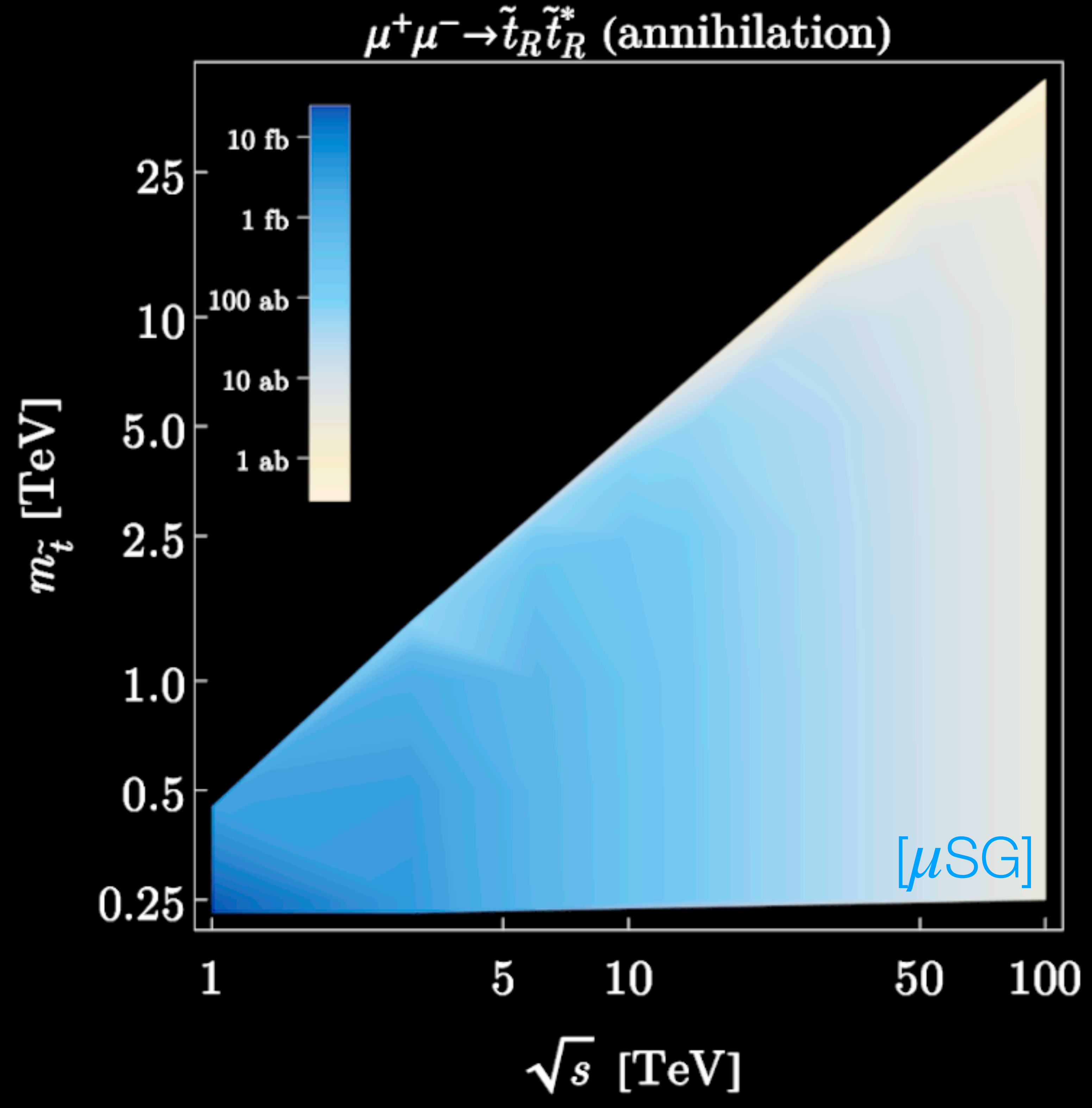


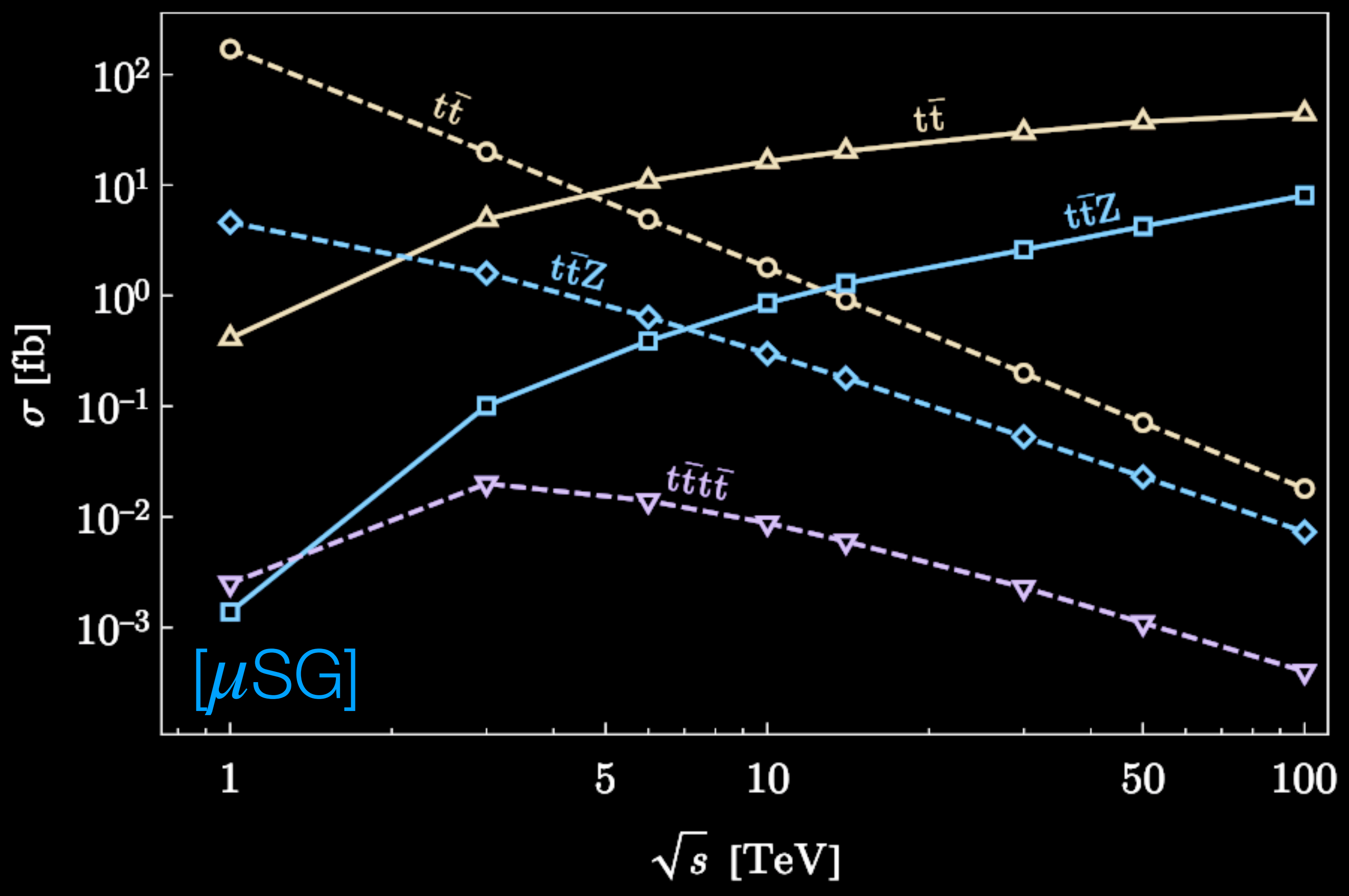
Stops

The flagship LHC SUSY search…

$$\Delta_{\tilde{t}} \simeq \frac{3y_t^2}{4\pi^2}\frac{m_{\tilde{t}}^2}{m_h^2}\log\frac{\Lambda}{m_{\tilde{t}}}$$

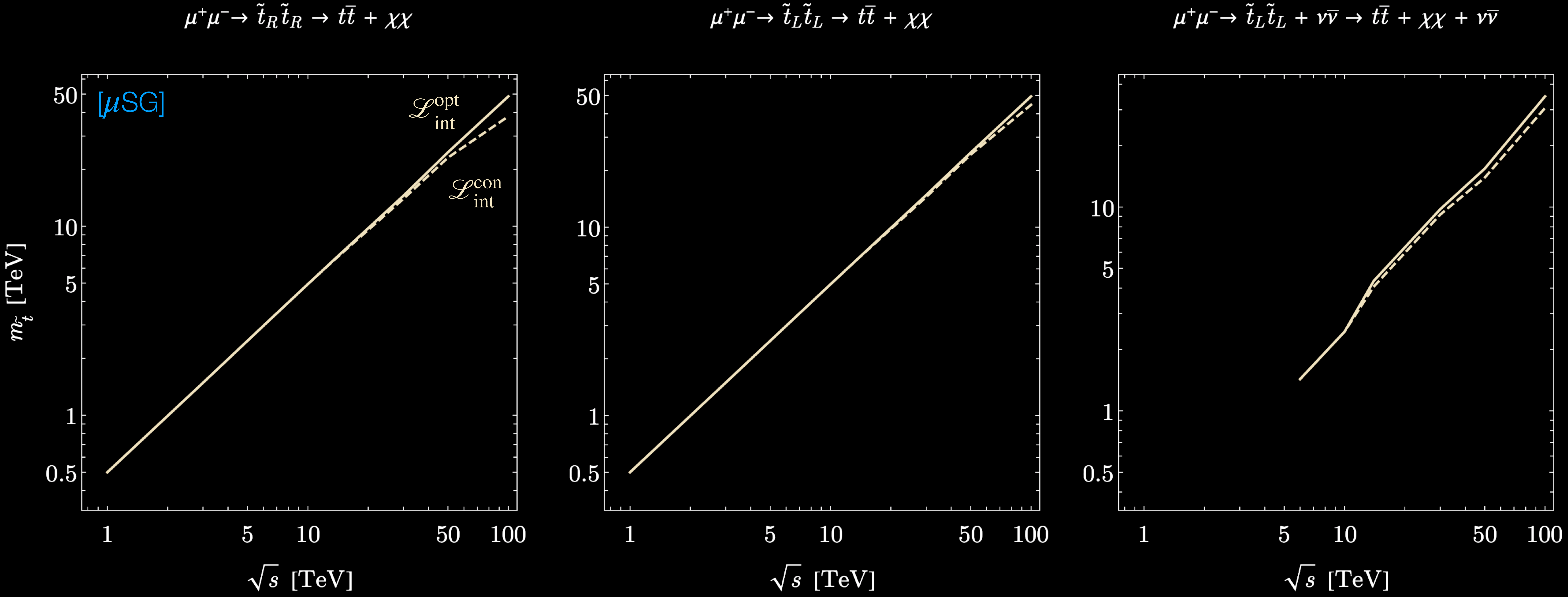






Stops

95% CL exclusion in simplified parton-level analysis w/ optimized invisible p_T cut, VBF $t\bar{t}$ background

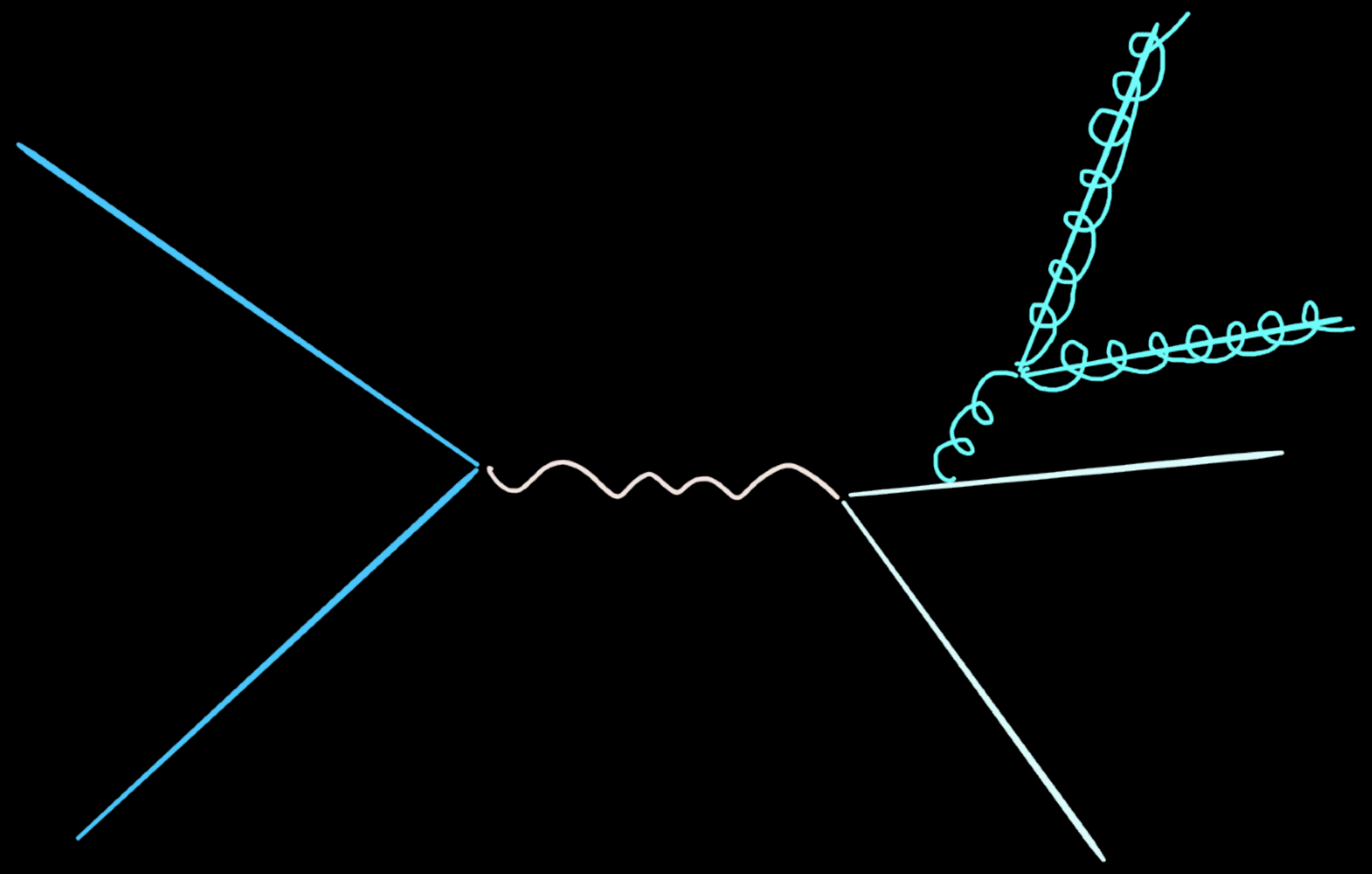


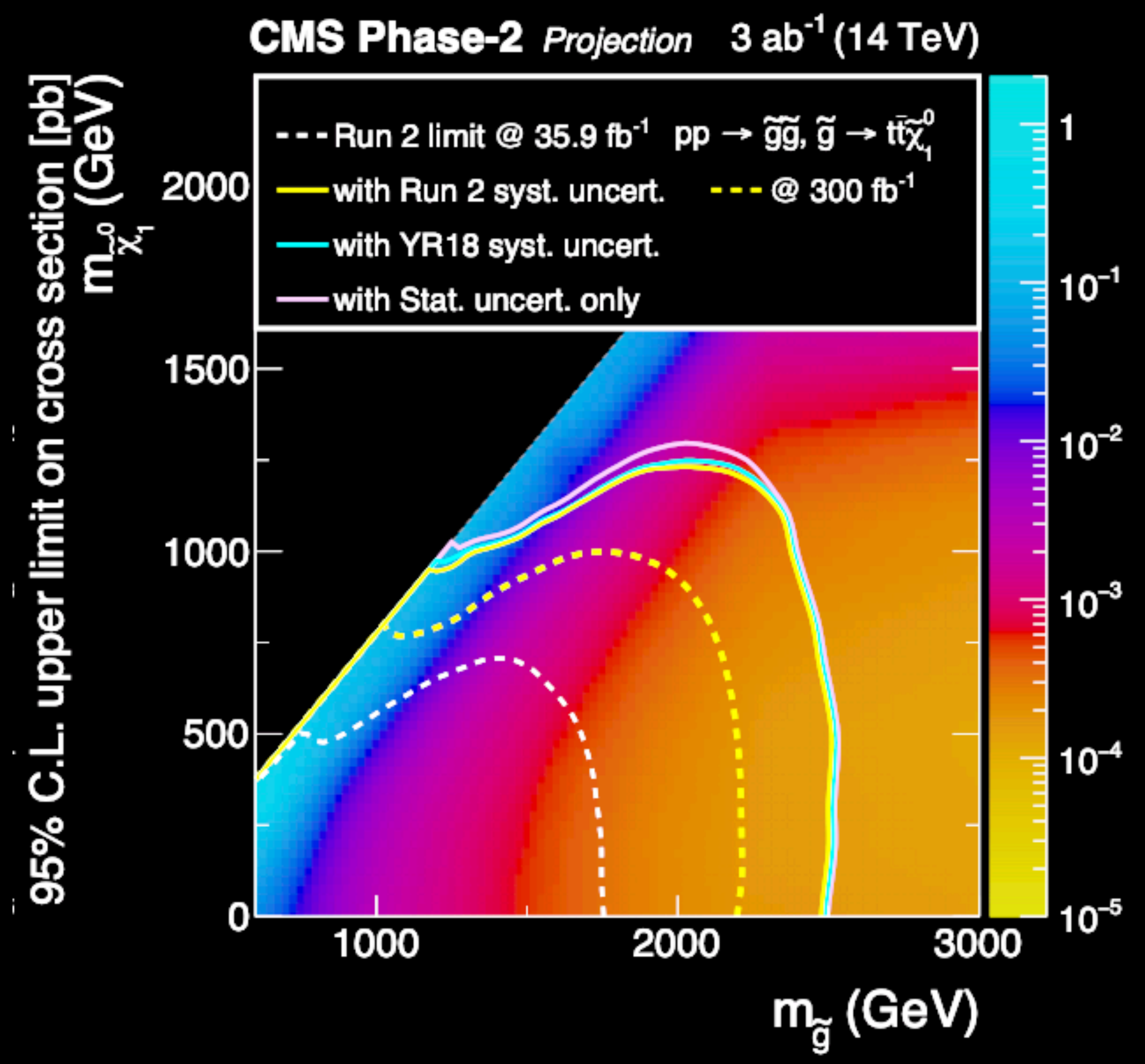
For sufficiently distinctive final states, production in muon annihilation ~sufficient to give limit at kinematic threshold

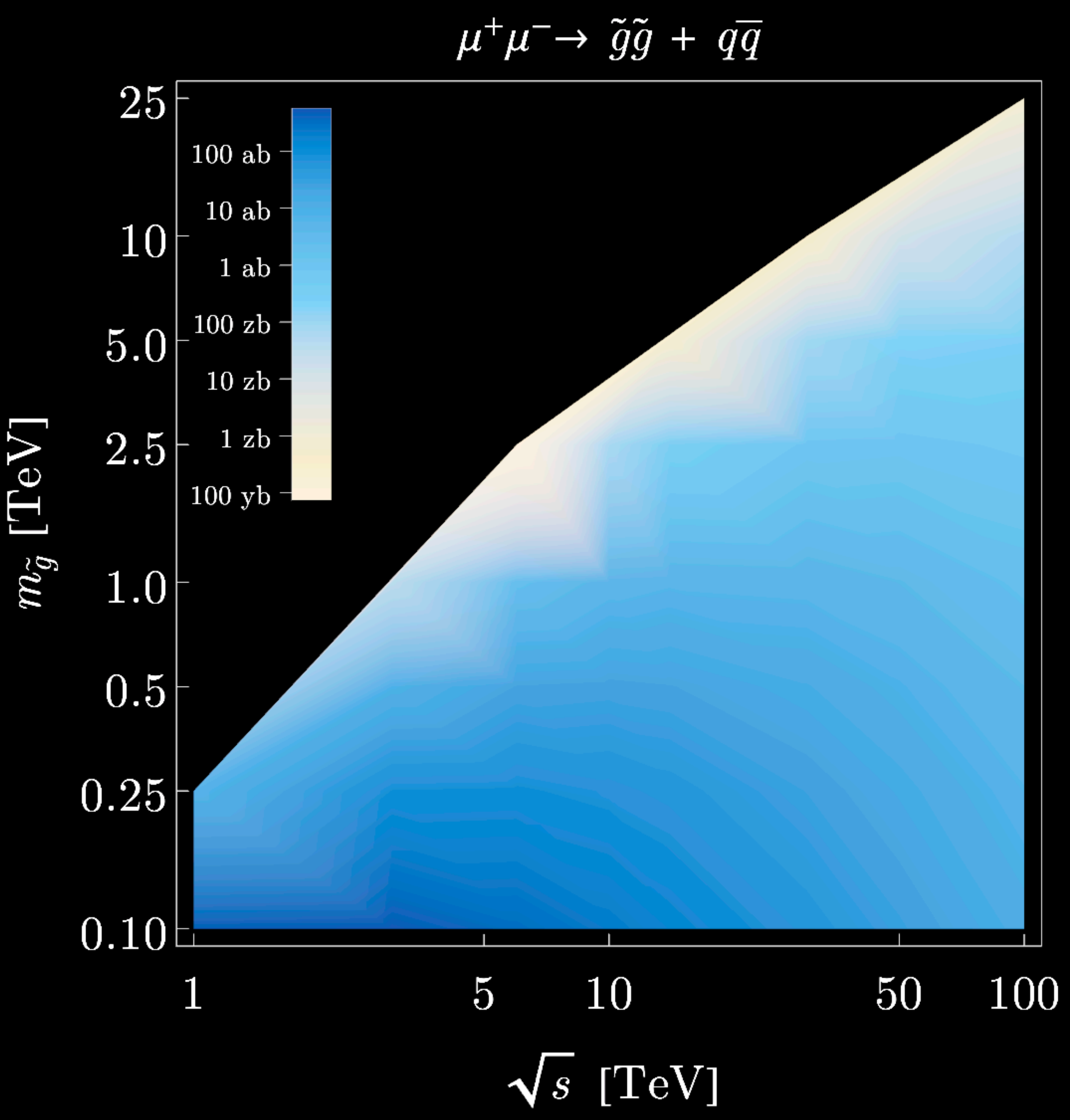
Gluinos

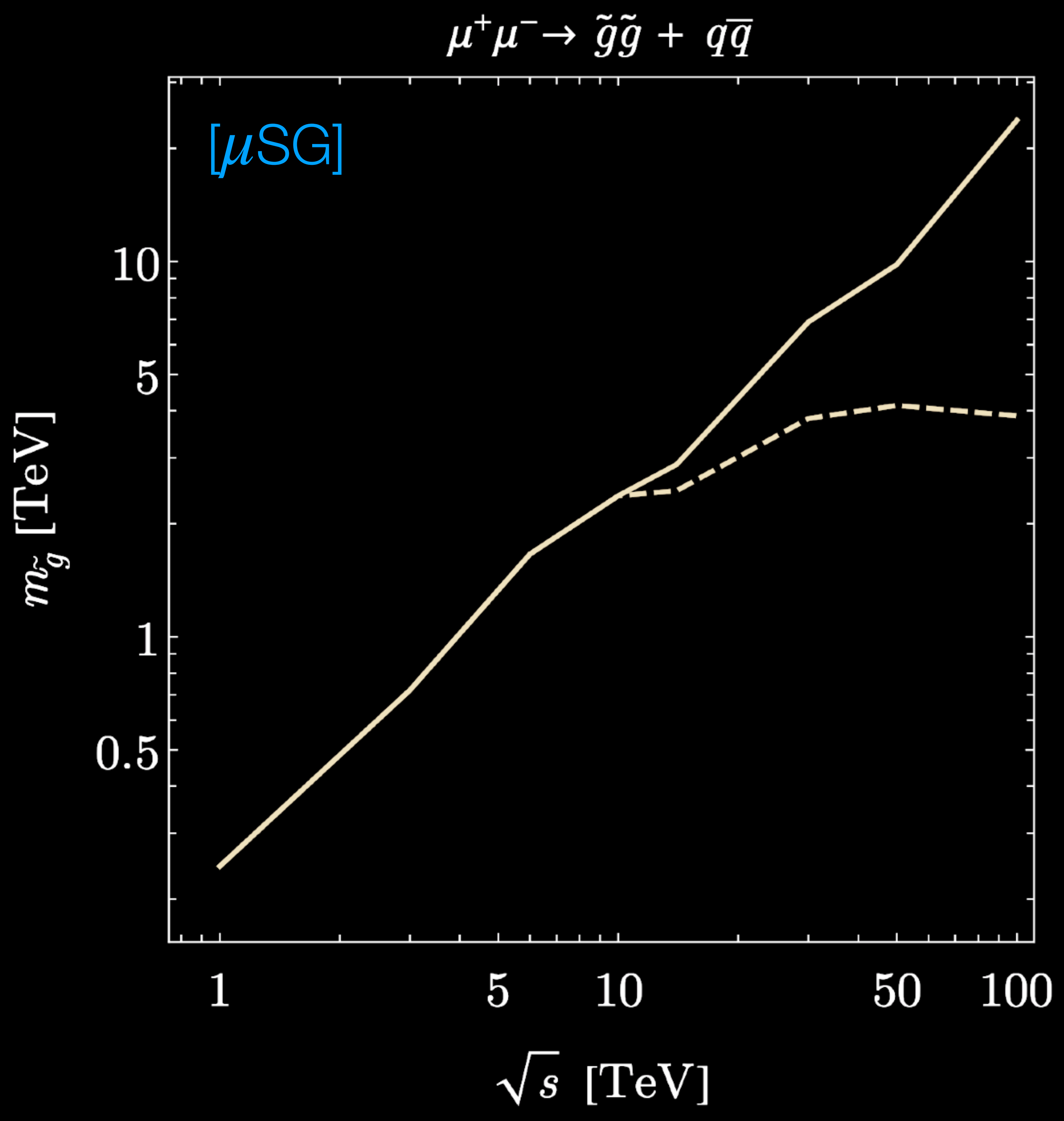
$$\Delta_{\tilde{g}} \simeq \frac{\alpha_s y_t^2}{\pi^3} \frac{m_{\tilde{g}}^2}{m_h^2} \log^2 \frac{\Lambda}{m_{\tilde{g}}}$$

Absence of electroweak quantum #s requires higher-order production (revisit w/ hadronic PDFs? [Han, Ma, Xie, 2103.09844])





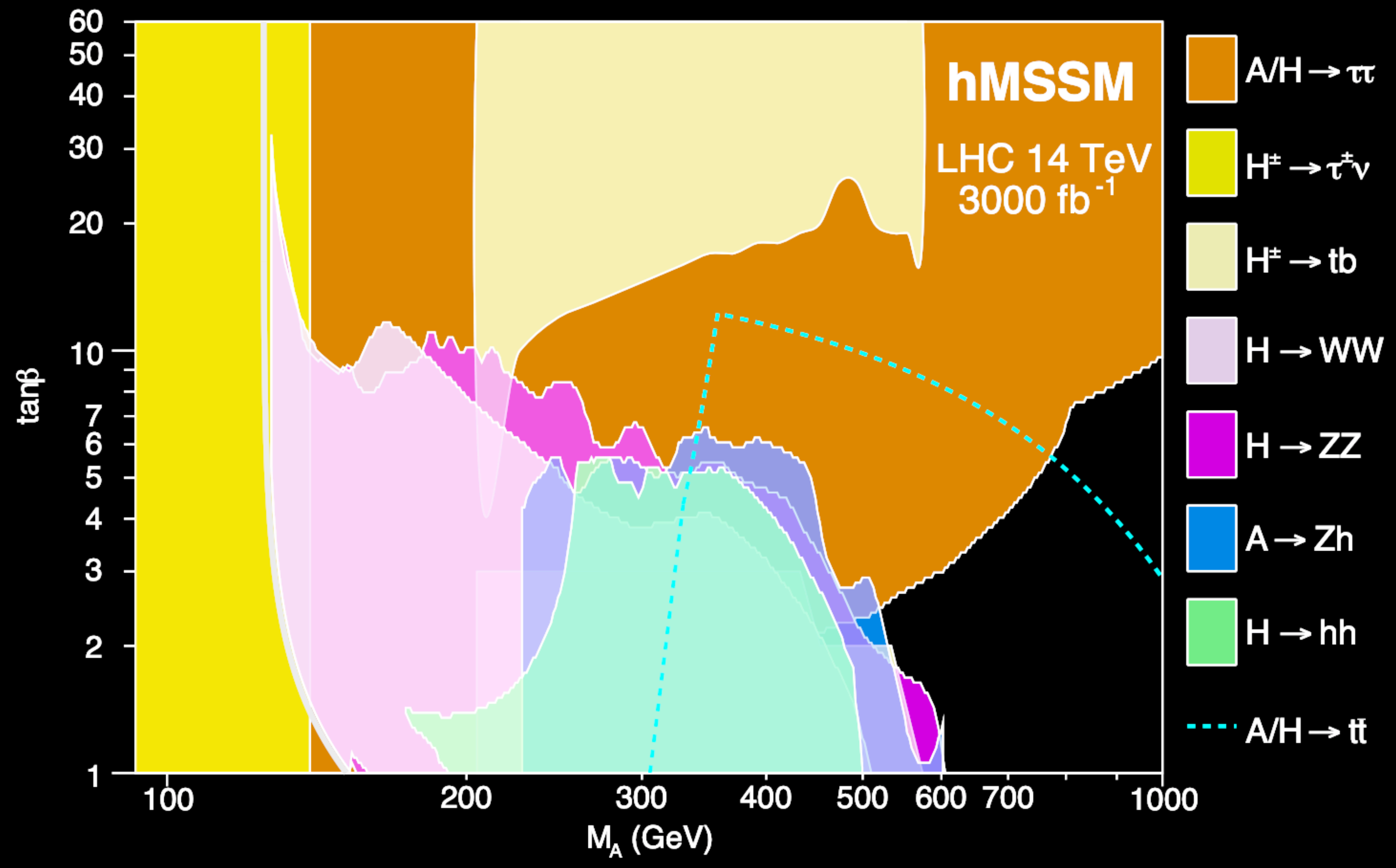




Higgs Sector

Remains largely open after HL-LHC (especially at moderate/low $\tan\beta$), due to S/B and difficulties of $t\bar{t}$ final state

[Djouadi, Maiani, Polosa, Quevillon, Riquer, 1502.05653]



2HDM at muon colliders

[Han, Li, Su, Su, Wu 2102.08386]

Charged Higgs pair production in muon annihilation sufficiently distinctive up to ~kinematic threshold

Signal after cuts

Signal Rate	$\sqrt{s}$ (TeV)	σ (fb)	$t\bar{t}b\bar{b}$
H^+H^-	6	0.32	70%
	14	0.14	79%
	30	0.04	87%
HA	6	0.13	69%
	14	0.06	79%
	30	0.02	87%

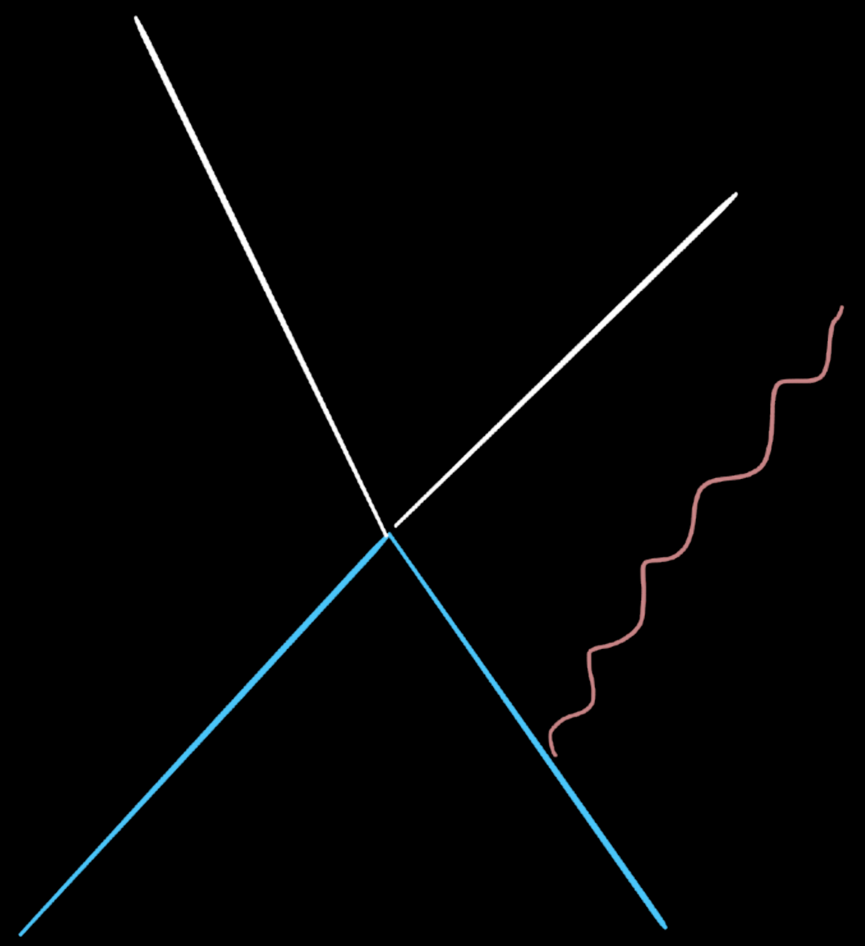
Background after cuts

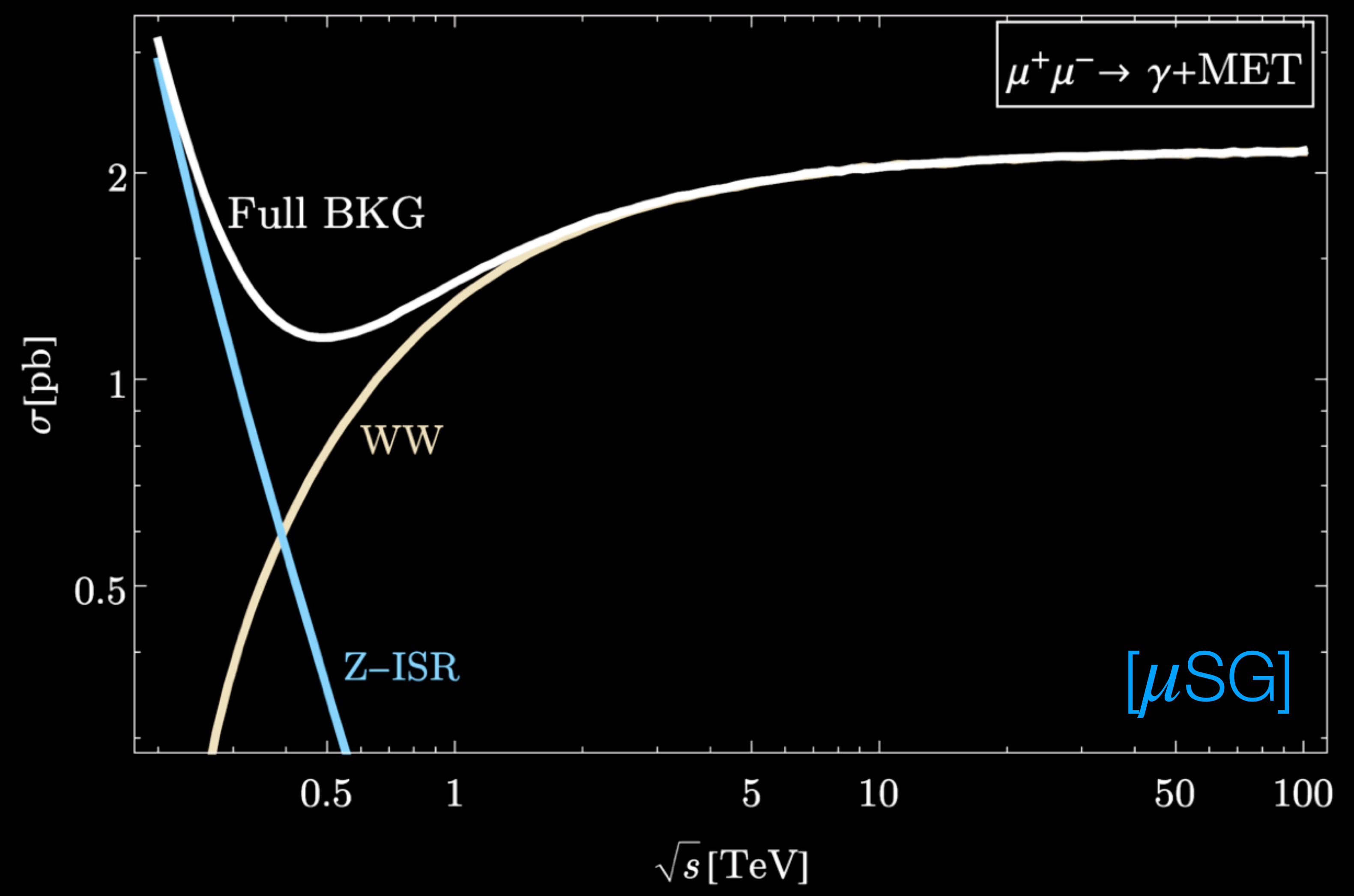
σ (fb)	$\sqrt{s}$ (TeV)	$t\bar{t}b\bar{b}$ $\mu^+\mu^-$	$t\bar{t}b\bar{b}$ VBF
H^+H^-	6	6.7×10^{-4}	$\lesssim 10^{-13}$
	14	2.3×10^{-3}	1.1×10^{-4}
	30	1.4×10^{-3}	5.2×10^{-4}
HA	6	1.4×10^{-3}	4.0×10^{-8}
	14	1.7×10^{-3}	1.7×10^{-4}
	30	7.9×10^{-4}	6.8×10^{-4}

The Gravitino

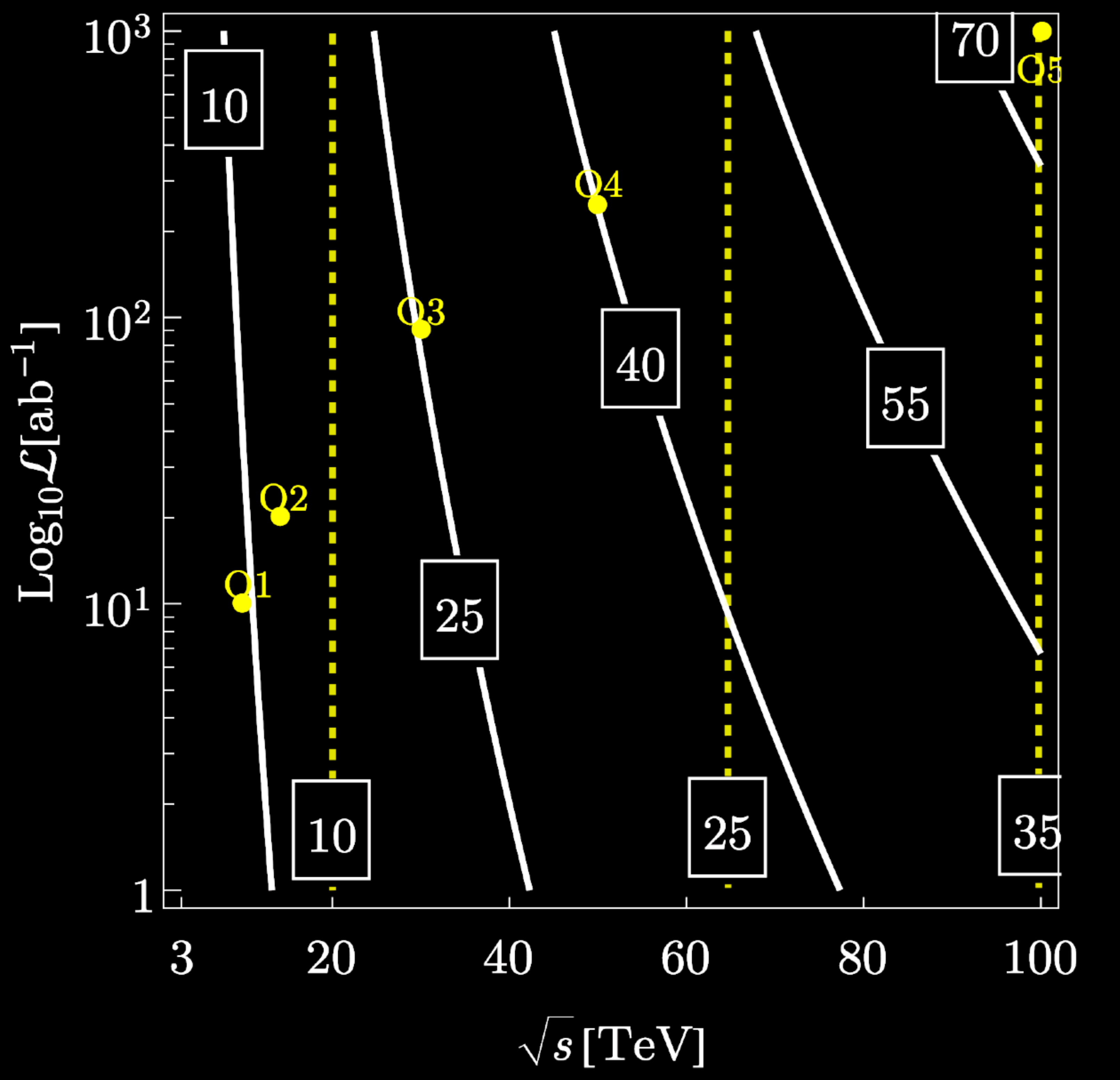
Never interesting at pp machines compared to MSSM searches.

Cross section $\propto s^3/F^4$ makes it much more promising at μC.





Reach in $\sqrt{F}$ [TeV]



$$\sigma(\mu^+\mu^- \to \tilde{G}\tilde{G}\gamma) = \frac{\alpha s^3}{160\pi^2 F^4}\left[\frac{247}{60} + 2\log\left(\frac{2E^{\gamma}_{\rm min}}{\sqrt{s}}\right)\right]\log\left(\frac{1-\cos\theta_{\rm min}}{1+\cos\theta_{\rm min}}\right)$$

$$\sqrt{F} \lesssim 61.7\ \text{TeV}\left(\frac{\mathcal{L}}{1000\ \text{ab}^{-1}}\right)^{1/16}\left(\frac{\sqrt{s}}{100\ \text{TeV}}\right)^{3/4}\left(4.8+\log\left[\frac{\sqrt{s}}{100\ \text{TeV}}\right]\right)^{1/8}$$

Sensitive to “strong” low-scale SUSY-breaking

Discover SUSY via SUSY breaking

Conclusions

- We must be **realistic** about the implications of LHC SUSY searches and **careful** in framing SUSY motivation for a high-energy muon collider.
- **Abundant motivation remains**: prediction of Higgs mass, unification, bounded scenarios, signal generation (and dark matter…).
- Suggests **new particles around ~few TeV scale**, naturalness considerations aside. (Similar things can be said about composite Higgs models.)
- Many places where a muon collider at ~10-14 TeV **significantly improves** upon LHC sensitivity, hits targets in the ~few TeV range.
- Some places where a muon collider covers **entirely new ground** (gravitino).
- Current studies give a decent sketch of sensitivity, with **room for improvement**.

Thank you!