

# Supersymmetry at the Muon Collider

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*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.

## ATLAS SUSY Searches\* - 95% CL Lower Limits

June 2021

| Model                                                                                                                                                   | Signature                                                                                                                         | $\int \mathcal{L} dt$ [fb $^{-1}$ ]    | Mass limit                                    | Reference                                    |                    |                                                                            |                                                  |                                 |                                                                                                                                                                                      |                                                  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|-----------------------------------------------|----------------------------------------------|--------------------|----------------------------------------------------------------------------|--------------------------------------------------|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|
| Inclusive Searches                                                                                                                                      | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$                                                                     | 0 $e, \mu$<br>mono-jet                 | 2-6 jets<br>1-3 jets                          | $E_T^{miss}$<br>$E_T^{miss}$                 | 139<br>36.1        | $\tilde{q}$ [1x, 8x Degen.]<br>$\tilde{q}$ [8x Degen.]                     | 1.0<br>0.9                                       | 1.85                            | $m(\tilde{\chi}_1^0) < 400$ GeV<br>$m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV                                                                                                      | 2010.14293<br>2102.10874                         |
|                                                                                                                                                         | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$                                                            | 0 $e, \mu$                             | 2-6 jets                                      | $E_T^{miss}$                                 | 139                | $\tilde{g}$<br>$\tilde{g}$                                                 | Forbidden<br>1.15-1.95                           | 2.3                             | $m(\tilde{\chi}_1^0) = 0$ GeV<br>$m(\tilde{g}) = 1000$ GeV                                                                                                                           | 2010.14293<br>2010.14293                         |
|                                                                                                                                                         | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$                                                           | 1 $e, \mu$                             | 2-6 jets                                      | $E_T^{miss}$                                 | 139                | $\tilde{g}$                                                                | Forbidden                                        | 2.2                             | $m(\tilde{\chi}_1^0) < 600$ GeV                                                                                                                                                      | 2101.01629                                       |
|                                                                                                                                                         | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$                                                  | $ee, \mu\mu$                           | 2 jets                                        | $E_T^{miss}$                                 | 36.1               | $\tilde{g}$                                                                | Forbidden                                        | 1.2                             | $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50$ GeV                                                                                                                                        | 1805.11381                                       |
|                                                                                                                                                         | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$                                                          | 0 $e, \mu$                             | 7-11 jets                                     | $E_T^{miss}$                                 | 139                | $\tilde{g}$                                                                | Forbidden                                        | 1.97                            | $m(\tilde{\chi}_1^0) < 600$ GeV                                                                                                                                                      | 2008.06032                                       |
|                                                                                                                                                         | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$                                                            | SS $e, \mu$                            | 6 jets                                        | $E_T^{miss}$                                 | 139                | $\tilde{g}$                                                                | Forbidden                                        | 1.15                            | $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV                                                                                                                                       | 1909.08457                                       |
| 3 <sup>rd</sup> gen. squarks direct production                                                                                                          | $\tilde{b}_1\tilde{b}_1$                                                                                                          | 0 $e, \mu$                             | 2 $b$                                         | $E_T^{miss}$                                 | 139                | $\tilde{b}_1$<br>$\tilde{b}_1$                                             | Forbidden<br>0.68                                | 1.255                           | $m(\tilde{\chi}_1^0) < 400$ GeV<br>10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV                                                                                       | 2101.12527<br>2101.12527                         |
|                                                                                                                                                         | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 \rightarrow b\tilde{h}\tilde{\chi}_1^0$                        | 0 $e, \mu$                             | 6 $b$<br>2 $\tau$                             | $E_T^{miss}$<br>$E_T^{miss}$                 | 139<br>139         | $\tilde{b}_1$<br>$\tilde{b}_1$                                             | Forbidden<br>0.13-0.85                           | 0.23-1.35                       | $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV<br>$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV | 1908.03122<br>ATLAS-CONF-2020-031                |
|                                                                                                                                                         | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$                                                               | 0-1 $e, \mu$                           | $\geq 1$ jet                                  | $E_T^{miss}$                                 | 139                | $\tilde{t}_1$                                                              | Forbidden                                        | 1.25                            | $m(\tilde{\chi}_1^0) = 1$ GeV                                                                                                                                                        | 2004.14060, 2012.03799                           |
|                                                                                                                                                         | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$                                                              | 1 $e, \mu$                             | 3 jets/1 $b$                                  | $E_T^{miss}$                                 | 139                | $\tilde{t}_1$                                                              | Forbidden                                        | 0.65                            | $m(\tilde{\chi}_1^0) = 500$ GeV                                                                                                                                                      | 2012.03799                                       |
|                                                                                                                                                         | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$                   | 1-2 $\tau$                             | 2 jets/1 $b$                                  | $E_T^{miss}$                                 | 139                | $\tilde{t}_1$                                                              | Forbidden                                        | 1.4                             | $m(\tilde{\tau}_1) = 800$ GeV                                                                                                                                                        | ATLAS-CONF-2021-008                              |
|                                                                                                                                                         | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{e}\tilde{e}, \tilde{e} \rightarrow e\tilde{\chi}_1^0$ | 0 $e, \mu$<br>0 $e, \mu$               | 2 $c$<br>mono-jet                             | $E_T^{miss}$<br>$E_T^{miss}$                 | 36.1<br>139        | $\tilde{t}_1$<br>$\tilde{t}_1$                                             | Forbidden<br>0.55                                | 0.85                            | $m(\tilde{\chi}_1^0) = 0$ GeV<br>$m(\tilde{t}_1, \tilde{e}) - m(\tilde{\chi}_1^0) = 5$ GeV                                                                                           | 1805.01649<br>2102.10874                         |
| EW direct                                                                                                                                               | $\tilde{\chi}_1^+\tilde{\chi}_2^0$ via WZ                                                                                         | Multiple $\ell$ /jets<br>$ee, \mu\mu$  | $\geq 1$ jet                                  | $E_T^{miss}$<br>$E_T^{miss}$                 | 139<br>139         | $\tilde{\chi}_1^+/\tilde{\chi}_2^0$<br>$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ | 0.96<br>0.205                                    | 1.06                            | $m(\tilde{\chi}_1^0) = 0$ , wino-bino<br>$m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino                                                                              | 2106.01676, ATLAS-CONF-2021-022<br>1911.12606    |
|                                                                                                                                                         | $\tilde{\chi}_1^+\tilde{\chi}_1^+$ via WW                                                                                         | 2 $e, \mu$                             |                                               | $E_T^{miss}$                                 | 139                | $\tilde{\chi}_1^+$                                                         | 0.42                                             | 1.0                             | $m(\tilde{\chi}_1^0) = 0$ , wino-bino                                                                                                                                                | 1908.08215                                       |
|                                                                                                                                                         | $\tilde{\chi}_1^+\tilde{\chi}_2^0$ via Wh                                                                                         | Multiple $\ell$ /jets                  |                                               | $E_T^{miss}$                                 | 139                | $\tilde{\chi}_1^+/\tilde{\chi}_2^0$                                        | Forbidden                                        | 1.06                            | $m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino                                                                                                                                            | 2004.10894, ATLAS-CONF-2021-022                  |
|                                                                                                                                                         | $\tilde{\chi}_1^+\tilde{\chi}_1^+$ via $\tilde{\ell}_L/\tilde{\nu}$                                                               | 2 $e, \mu$                             |                                               | $E_T^{miss}$                                 | 139                | $\tilde{\chi}_1^+$                                                         | 0.16-0.3                                         | 0.12-0.39                       | $m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\ell}_1^0))$                                                                                                      | 1908.08215                                       |
|                                                                                                                                                         | $\tilde{\tau}_1\tilde{\tau}_1, \tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$                                                   | 2 $\tau$                               |                                               | $E_T^{miss}$                                 | 139                | $\tilde{\tau}_1$                                                           | Forbidden                                        | 0.7                             | $m(\tilde{\chi}_1^0) = 0$                                                                                                                                                            | 1911.06660                                       |
|                                                                                                                                                         | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$                                             | 2 $e, \mu$<br>$ee, \mu\mu$             | 0 jets<br>$\geq 1$ jet                        | $E_T^{miss}$<br>$E_T^{miss}$                 | 139<br>139         | $\tilde{\ell}$<br>$\tilde{\ell}$                                           | 0.256                                            | 0.7                             | $m(\tilde{\chi}_1^0) = 0$<br>$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV                                                                                                        | 1908.08215<br>1911.12606                         |
| Long-lived particles                                                                                                                                    | $\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$                                                                 | 0 $e, \mu$<br>4 $e, \mu$<br>0 $e, \mu$ | $\geq 3$ $b$<br>0 jets<br>$\geq 2$ large jets | $E_T^{miss}$<br>$E_T^{miss}$<br>$E_T^{miss}$ | 36.1<br>139<br>139 | $\tilde{H}$<br>$\tilde{H}$<br>$\tilde{H}$                                  | 0.13-0.23<br>0.55<br>0.45-0.93                   | 0.29-0.88                       | $BR(\tilde{H} \rightarrow h\tilde{G}) = 1$<br>$BR(\tilde{H} \rightarrow Z\tilde{G}) = 1$<br>$BR(\tilde{H} \rightarrow Z\tilde{G}) = 1$                                               | 1806.04030<br>2103.11684<br>ATLAS-CONF-2021-022  |
|                                                                                                                                                         | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^+$ prod., long-lived $\tilde{\chi}_1^+$                                                    | Disapp. trk                            | 1 jet                                         | $E_T^{miss}$                                 | 139                | $\tilde{\chi}_1^+$                                                         | 0.66                                             | 0.21                            | Pure Wino<br>Pure higgsino                                                                                                                                                           | ATLAS-CONF-2021-015<br>ATLAS-CONF-2021-015       |
|                                                                                                                                                         | Stable $\tilde{g}$ R-hadron                                                                                                       | Multiple                               |                                               |                                              | 36.1               | $\tilde{g}$                                                                | 2.0                                              | 2.05 2.4                        | $m(\tilde{\chi}_1^0) = 100$ GeV                                                                                                                                                      | 1902.01636, 1808.04095<br>1710.04901, 1808.04095 |
| RPV                                                                                                                                                     | Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$                                               | Multiple                               |                                               |                                              | 36.1               | $\tilde{g}$                                                                | [ $\tau(\tilde{g}) = 10$ ns, 0.2 ns]             | 0.7                             | $\tau(\tilde{g}) = 0.1$ ns<br>$\tau(\tilde{g}) = 0.1$ ns                                                                                                                             | 2011.07812<br>2011.07812                         |
|                                                                                                                                                         | $\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$                                                                | Displ. lep                             |                                               | $E_T^{miss}$                                 | 139                | $\tilde{\ell}, \tilde{\mu}$<br>$\tilde{\tau}$                              | 0.34                                             | 0.625 1.05                      |                                                                                                                                                                                      |                                                  |
|                                                                                                                                                         | $\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell \rightarrow \ell\ell\ell$                  | 3 $e, \mu$                             |                                               | $E_T^{miss}$                                 | 139                | $\tilde{\chi}_1^+/\tilde{\chi}_1^0$                                        | [BR(Z $\tau$ )=1, BR(Z $e$ )=1]                  | 0.95 1.55                       | Pure Wino                                                                                                                                                                            | 2011.10543                                       |
|                                                                                                                                                         | $\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_2^0 \rightarrow WWZ\ell\ell\ell\nu\nu$                                             | 4 $e, \mu$                             | 0 jets                                        | $E_T^{miss}$                                 | 139                | $\tilde{\chi}_1^+/\tilde{\chi}_2^0$                                        | [ $\lambda_{333} \neq 0, \lambda_{133} \neq 0$ ] | 1.3 1.9                         | $m(\tilde{\chi}_1^0) = 200$ GeV                                                                                                                                                      | 2103.11684                                       |
|                                                                                                                                                         | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$                           | 4-5 large jets                         |                                               | $E_T^{miss}$                                 | 36.1               | $\tilde{g}$                                                                | [ $m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV]     | 0.55 1.05                       | Large $\lambda'_{12}$                                                                                                                                                                | 1804.03568                                       |
|                                                                                                                                                         | $\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow b\tilde{s}$                                 | Multiple                               |                                               | $E_T^{miss}$                                 | 36.1               | $\tilde{t}_1$                                                              | [ $\lambda'_{323} = 2e-4, 1e-2$ ]                | 0.42 0.61                       | $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like                                                                                                                                           | ATLAS-CONF-2018-003                              |
| $\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow b\tilde{s}$                                                       | $\geq 4b$                                                                                                                         |                                        | $E_T^{miss}$                                  | 139                                          | $\tilde{t}_1$      | Forbidden                                                                  | 0.95                                             | $m(\tilde{\chi}_1^0) = 500$ GeV | 2010.01015                                                                                                                                                                           |                                                  |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$                                                                                                    | 2 jets + 2 $b$                                                                                                                    |                                        | $E_T^{miss}$                                  | 36.7                                         | $\tilde{t}_1$      | [ $qq, bs$ ]                                                               | 0.4 1.45                                         | 1.6                             | $BR(\tilde{t}_1 \rightarrow b\tilde{e}/b\tilde{\mu}) > 20\%$<br>$BR(\tilde{t}_1 \rightarrow q\tilde{u}) = 100\%$ , $\cos\theta = 1$                                                  | 1710.07171<br>1710.05544<br>2003.11956           |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$                                                                                         | 2 $e, \mu$                                                                                                                        | 2 $b$                                  |                                               | 36.1                                         | $\tilde{t}_1$      | [ $1e-10 < \lambda'_{234} < 1e-8, 3e-10 < \lambda'_{334} < 3e-9$ ]         | 1.0                                              | Pure higgsino                   | ATLAS-CONF-2021-007                                                                                                                                                                  |                                                  |
| $\tilde{\chi}_1^+\tilde{\chi}_2^0/\tilde{\chi}_1^0/\tilde{\chi}_1^+, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s, \tilde{\chi}_1^+ \rightarrow b\tilde{s}$ | 1-2 $e, \mu$                                                                                                                      | $\geq 6$ jets                          |                                               | 139                                          | $\tilde{\chi}_1^+$ | 0.2-0.32                                                                   |                                                  |                                 |                                                                                                                                                                                      |                                                  |

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

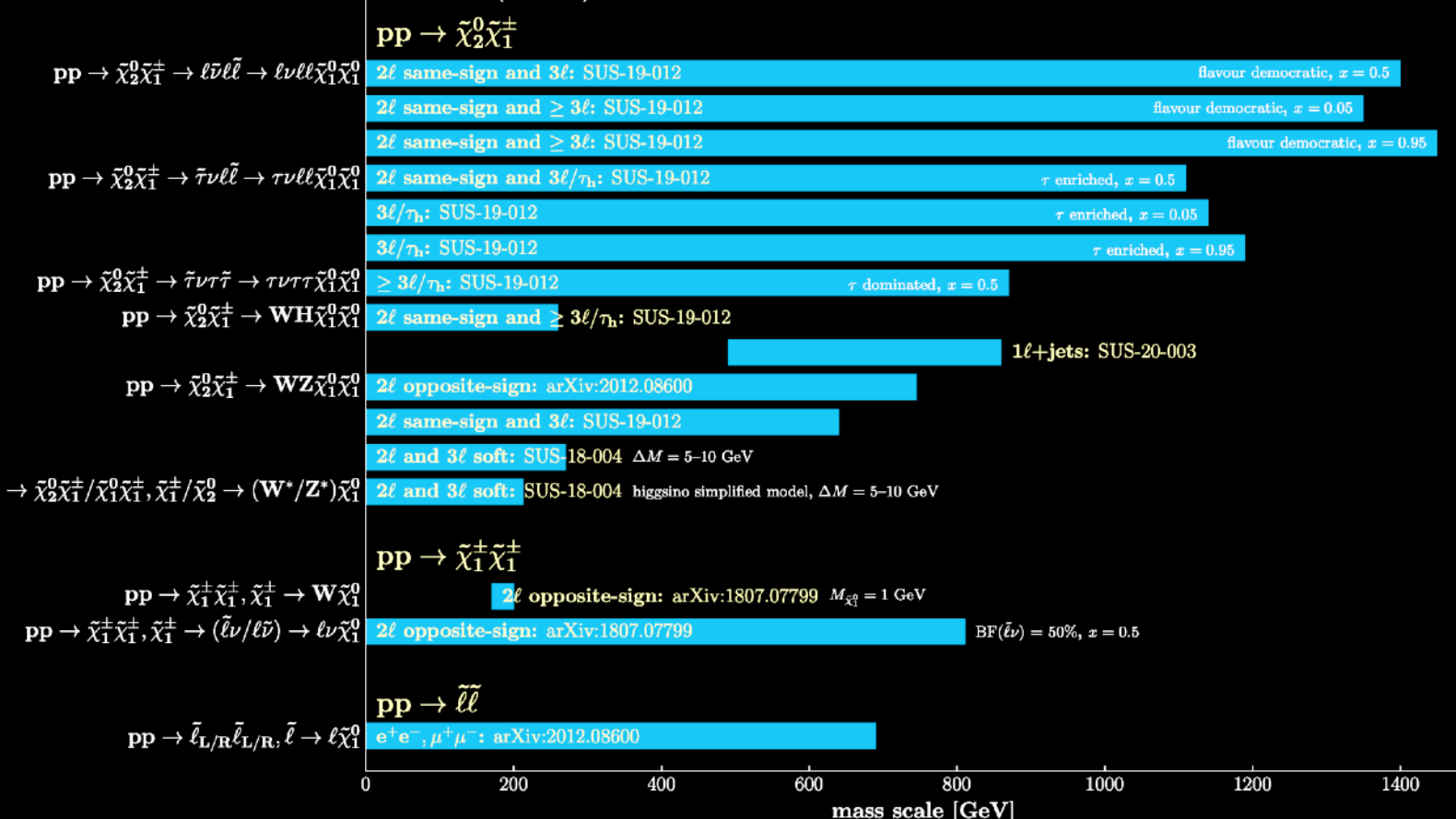
## Overview of SUSY results: gluino pair production

137 fb $^{-1}$  (13 TeV)



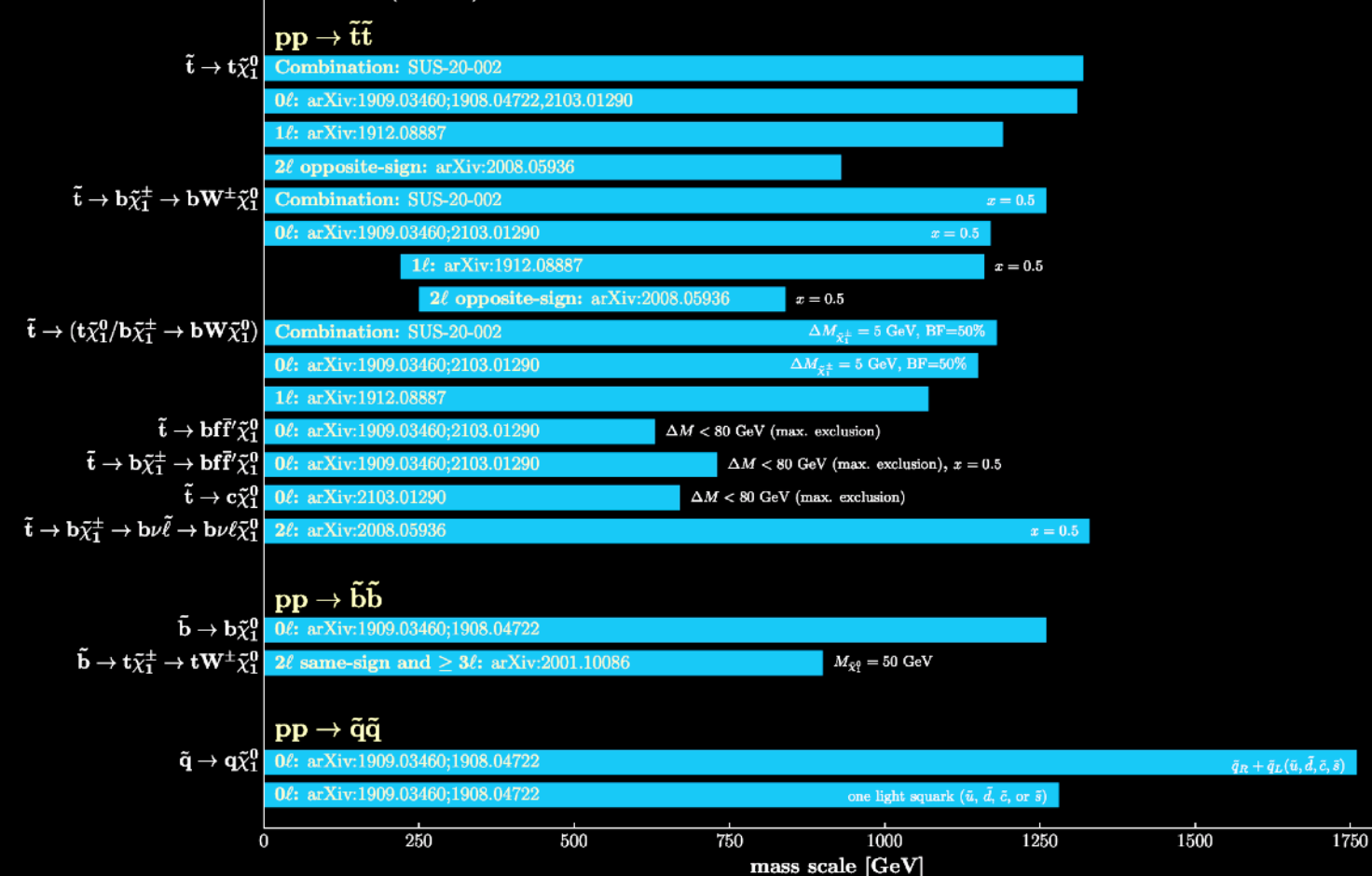
## Overview of SUSY results: electroweak production

137 fb $^{-1}$  (13 TeV)



## Overview of SUSY results: squark pair production

137 fb $^{-1}$  (13 TeV)



# 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)**

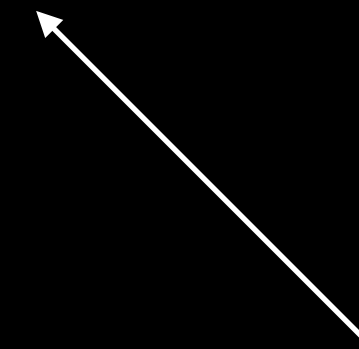
$$\Delta_{\tilde{h}} \simeq \frac{2m_{\tilde{h}}^2}{m_h^2}$$



**Fairly UV independent**

**Stops (one loop)**

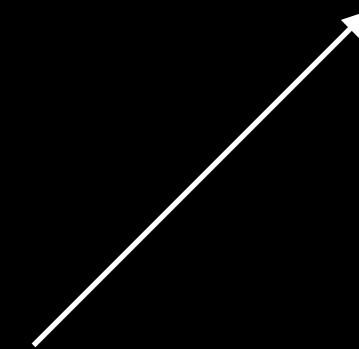
$$\Delta_{\tilde{t}} \simeq \frac{3y_t^2}{4\pi^2} \frac{m_{\tilde{t}}^2}{m_h^2} \log \frac{\Lambda}{m_{\tilde{t}}}$$



**Some UV dependence**

**Glueinos (two loops)**

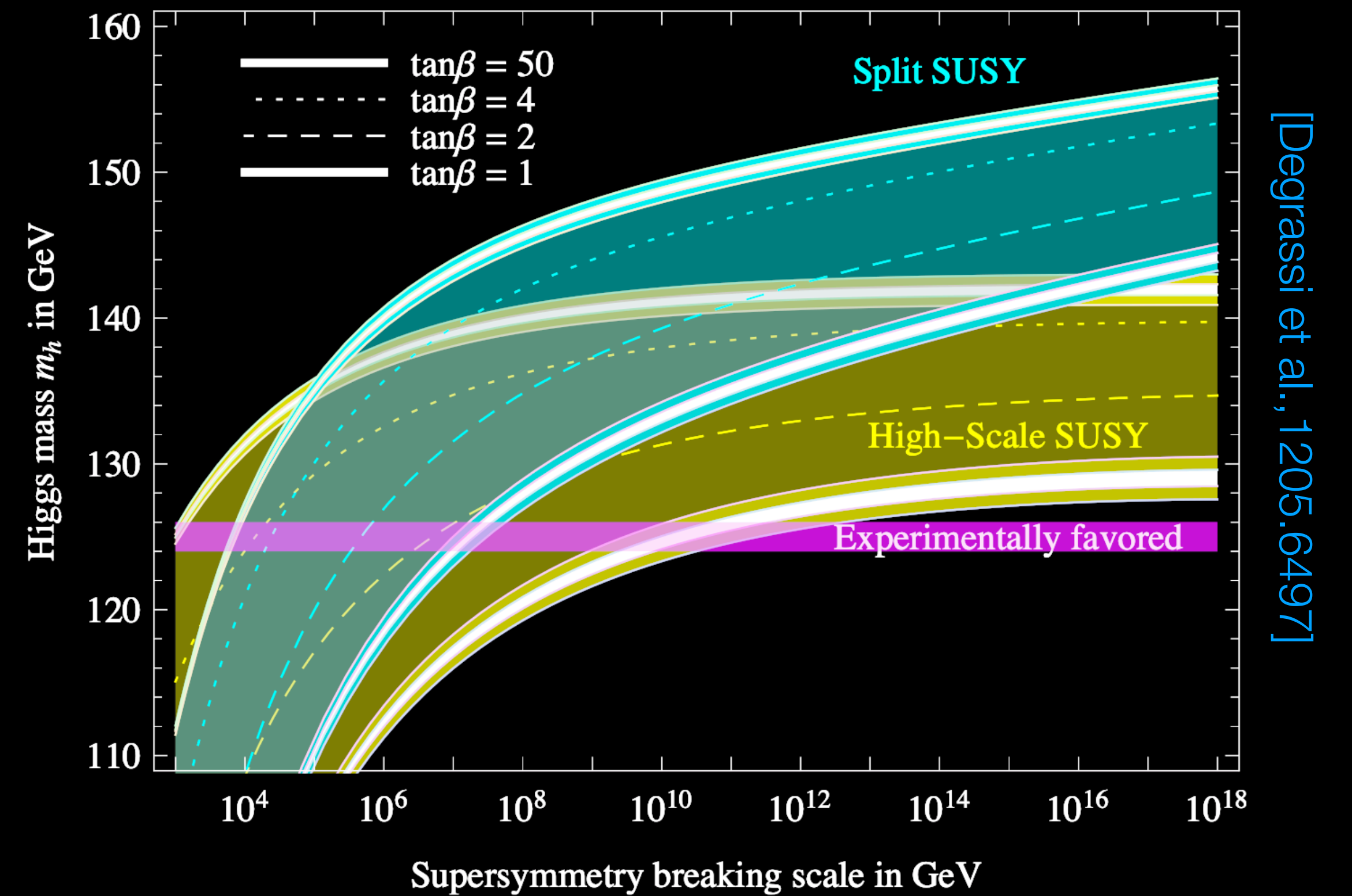
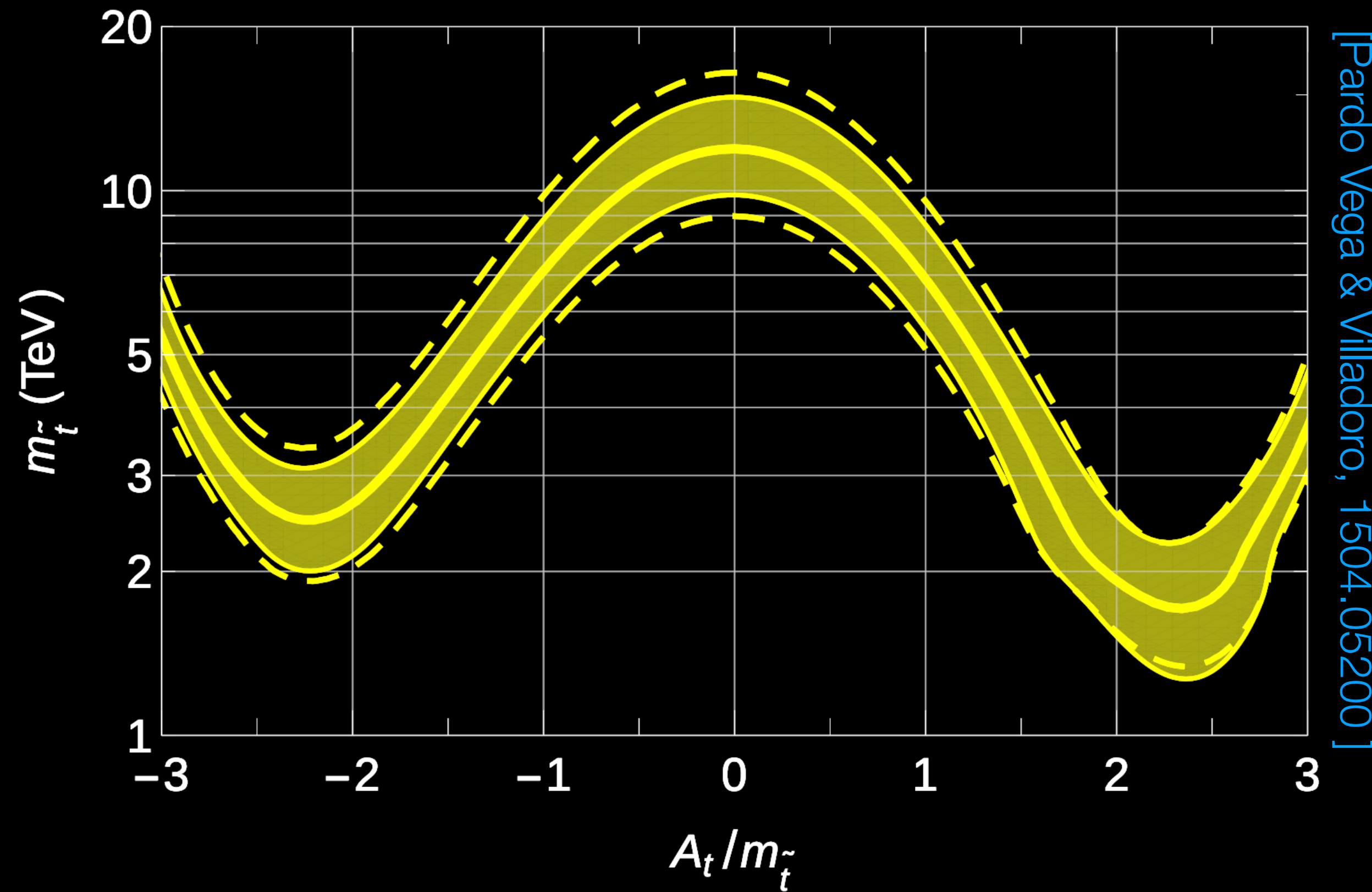
$$\Delta_{\tilde{g}} \simeq \frac{\alpha_s y_t^2}{\pi^3} \frac{m_{\tilde{g}}^2}{m_h^2} \log^2 \frac{\Lambda}{m_{\tilde{g}}}$$





# Why SUSY (in the future)?

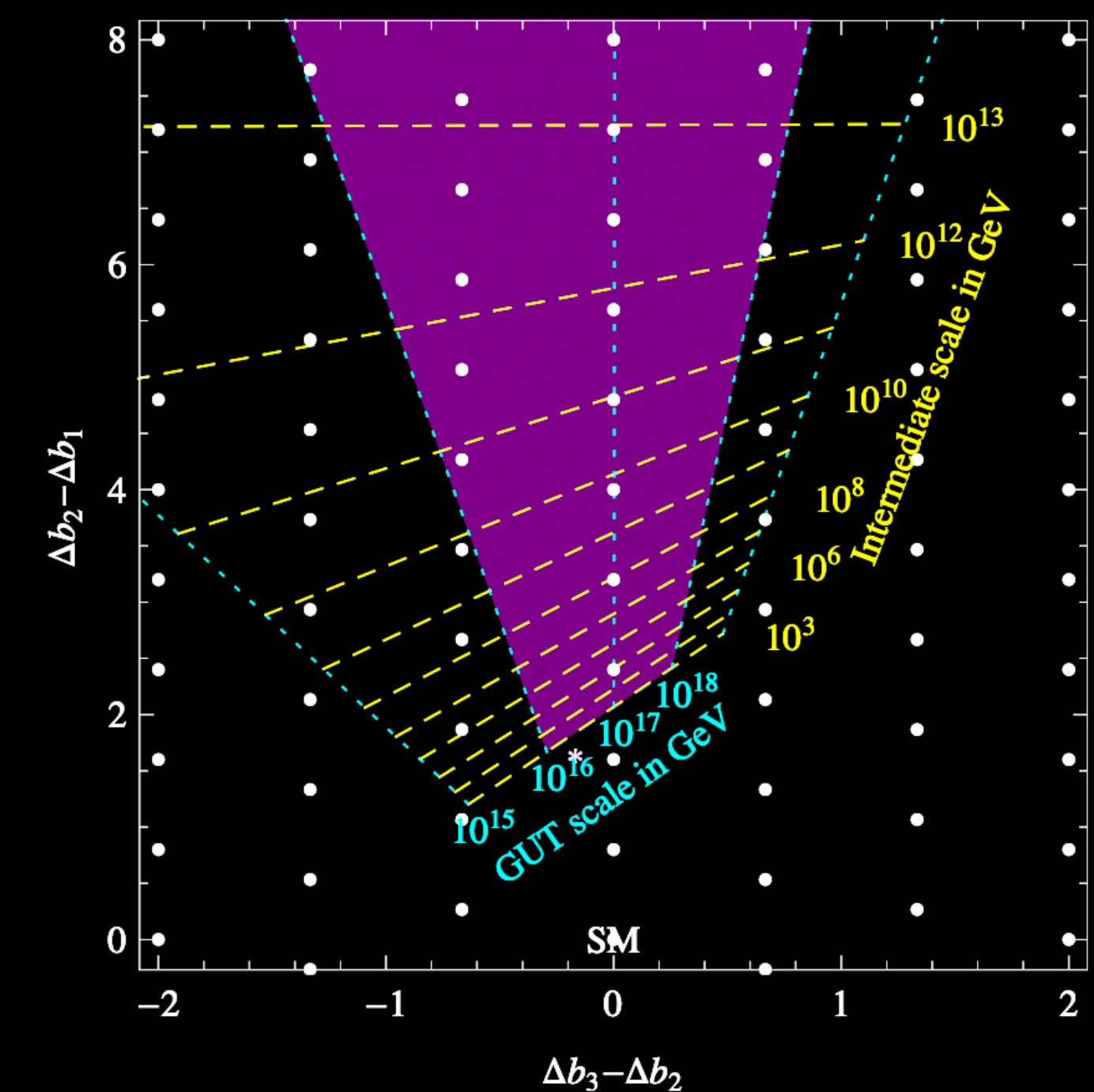
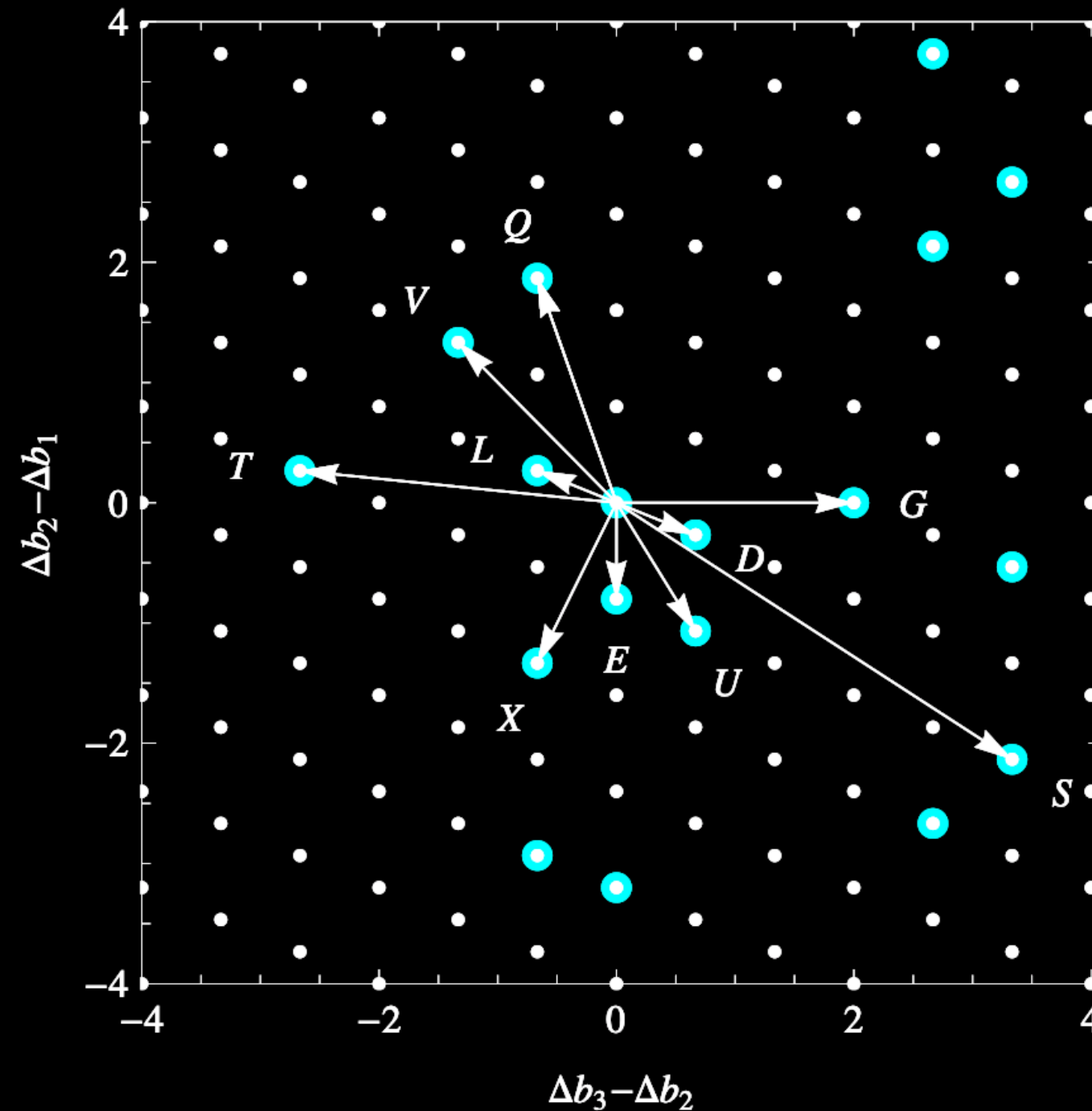
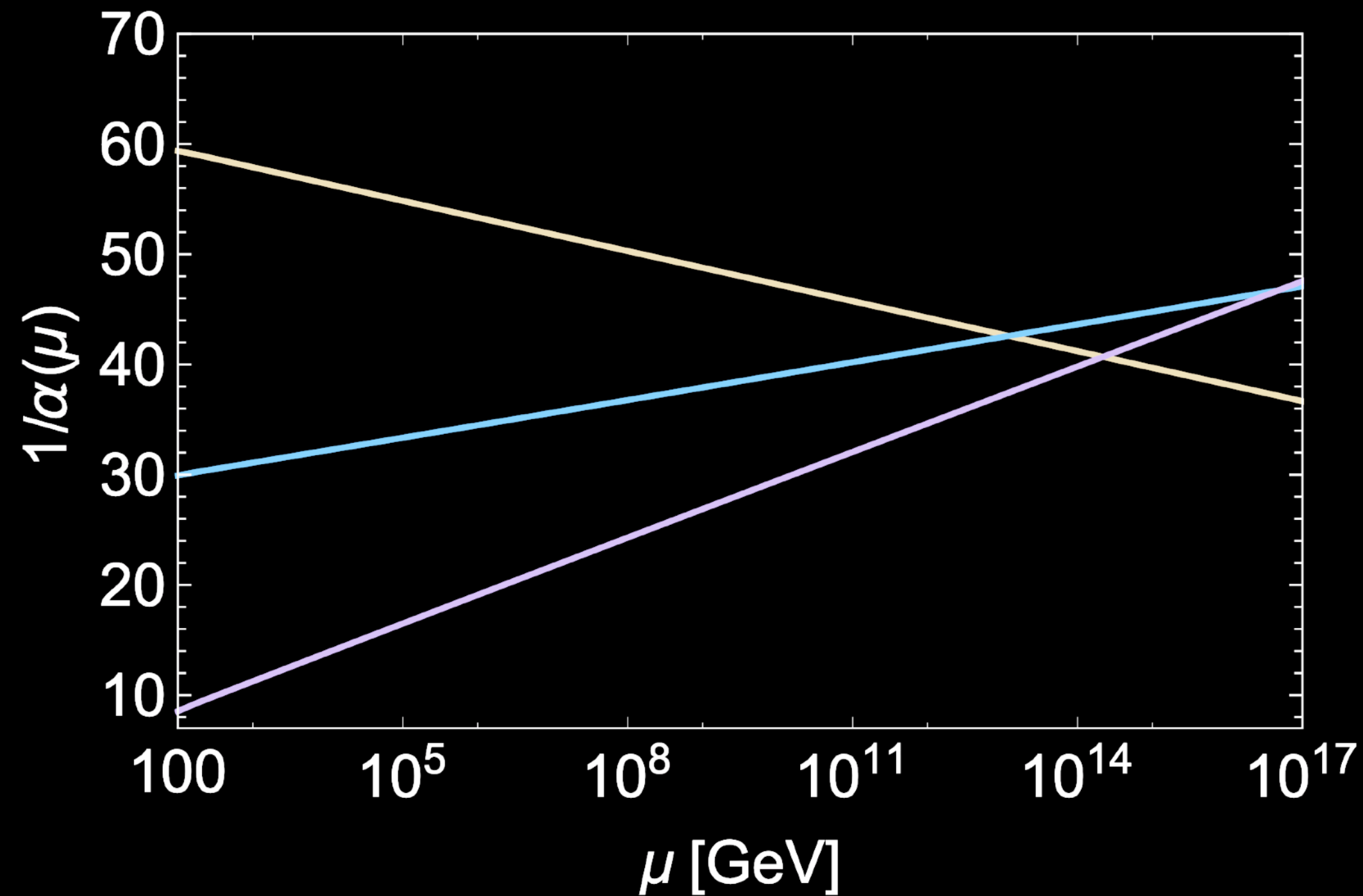
*Predicts the Higgs mass.*



# Why SUSY (in the future)?

*Unification.*

[Giudice, Rattazzi, Strumia 1204.5465]



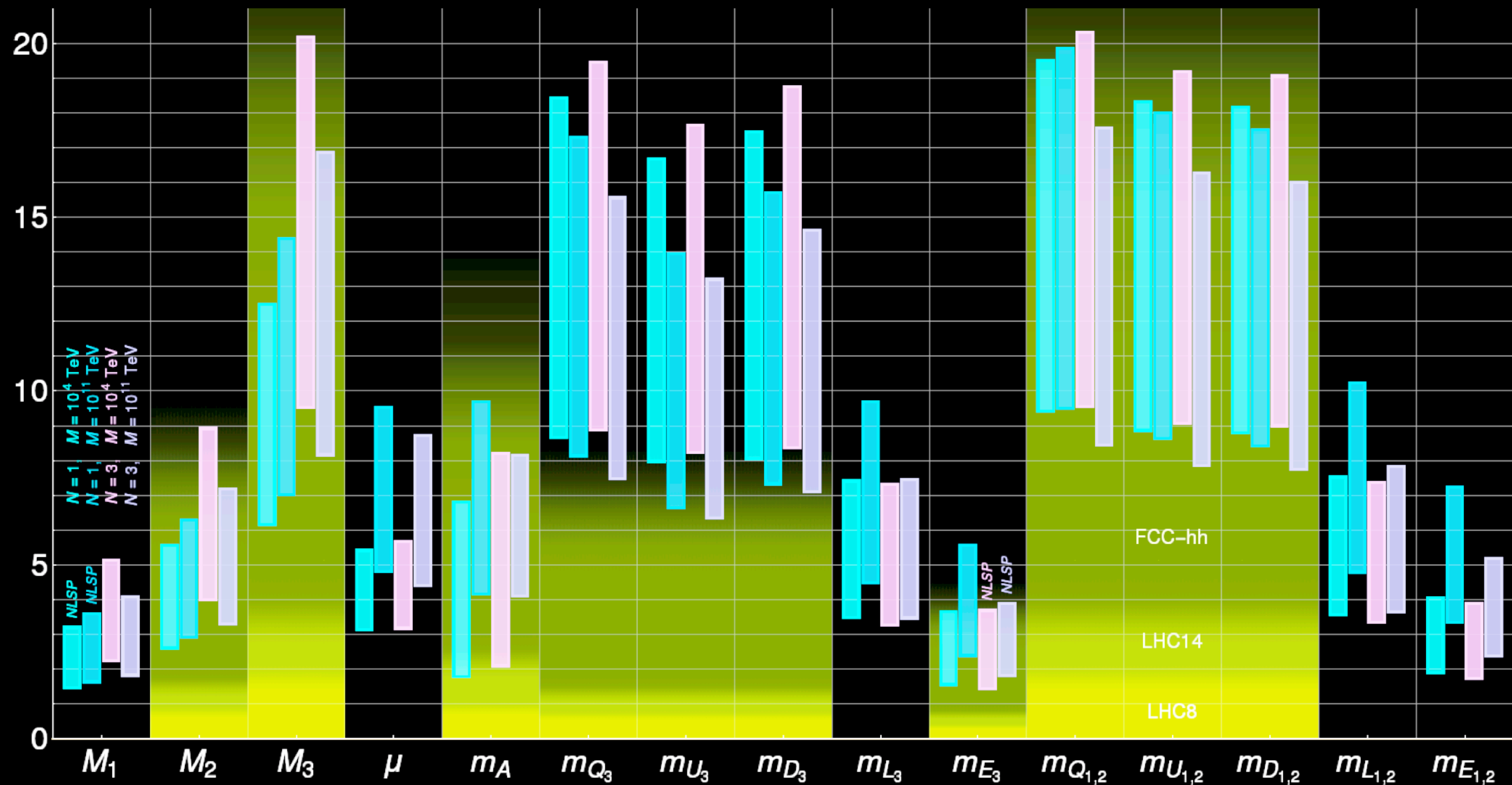
Running of couplings in the Standard Model tantalizingly hints at unification, but the intersection is imperfect & scale too low.

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



[Pardo Vega & Villadoro, 1504.05200]



# Why SUSY (in the future)?

*SUSY is a phenomenal signal generator*

|          | $\gamma$ | $\ell$ | $\tau$ | $j$ | $t$ | $W$ | $Z$ | $h$     | $E_T$          |
|----------|----------|--------|--------|-----|-----|-----|-----|---------|----------------|
| $\gamma$ | H,A      |        |        |     |     |     | H   |         | $\chi^0_1$     |
| $\ell$   |          | RPV    | RPV    | RPV | RPV |     |     |         | $\tilde{\ell}$ |
| $\tau$   |          |        | 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

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

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# The Muon Smasher's Guide

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

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[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.

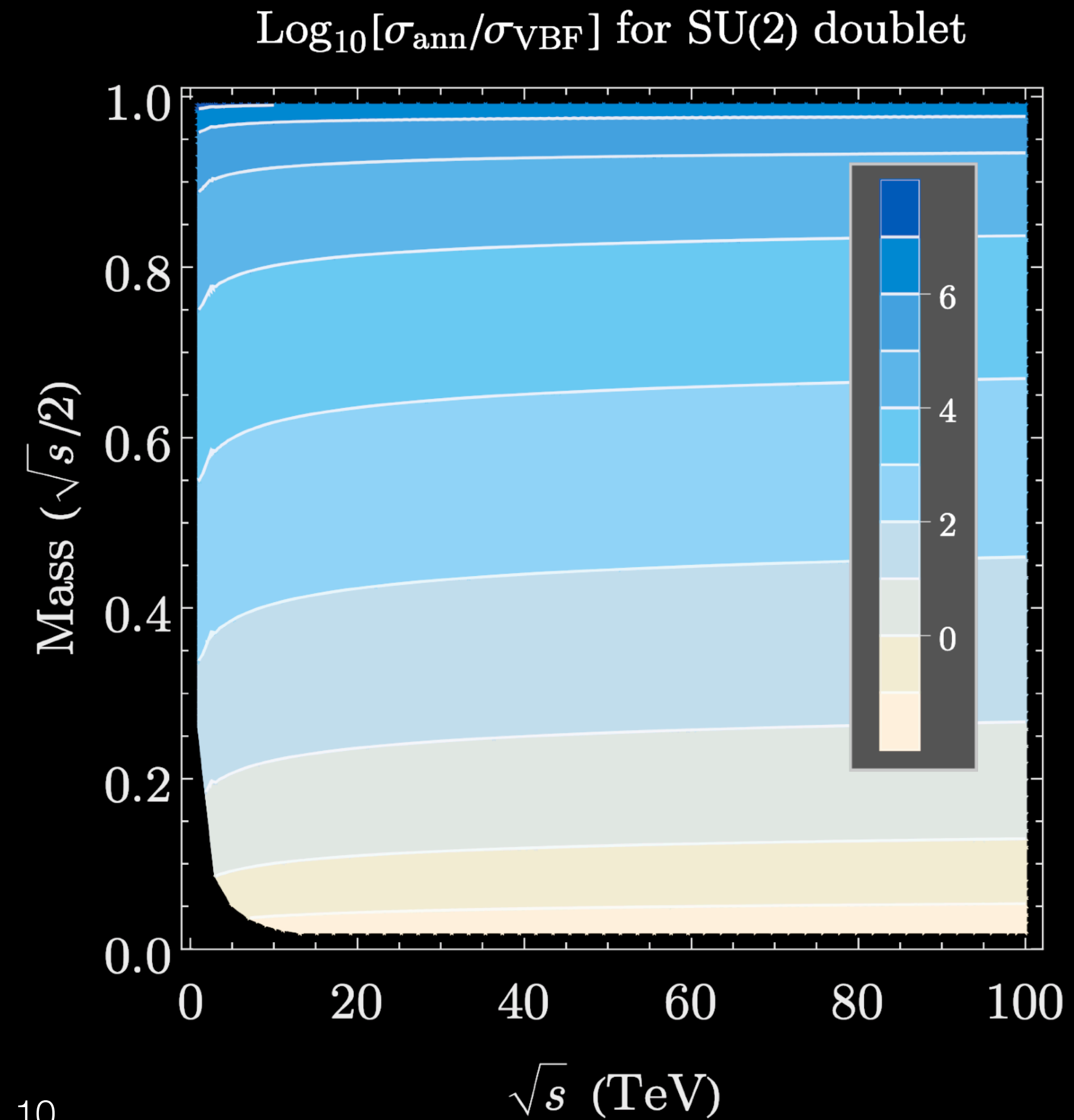
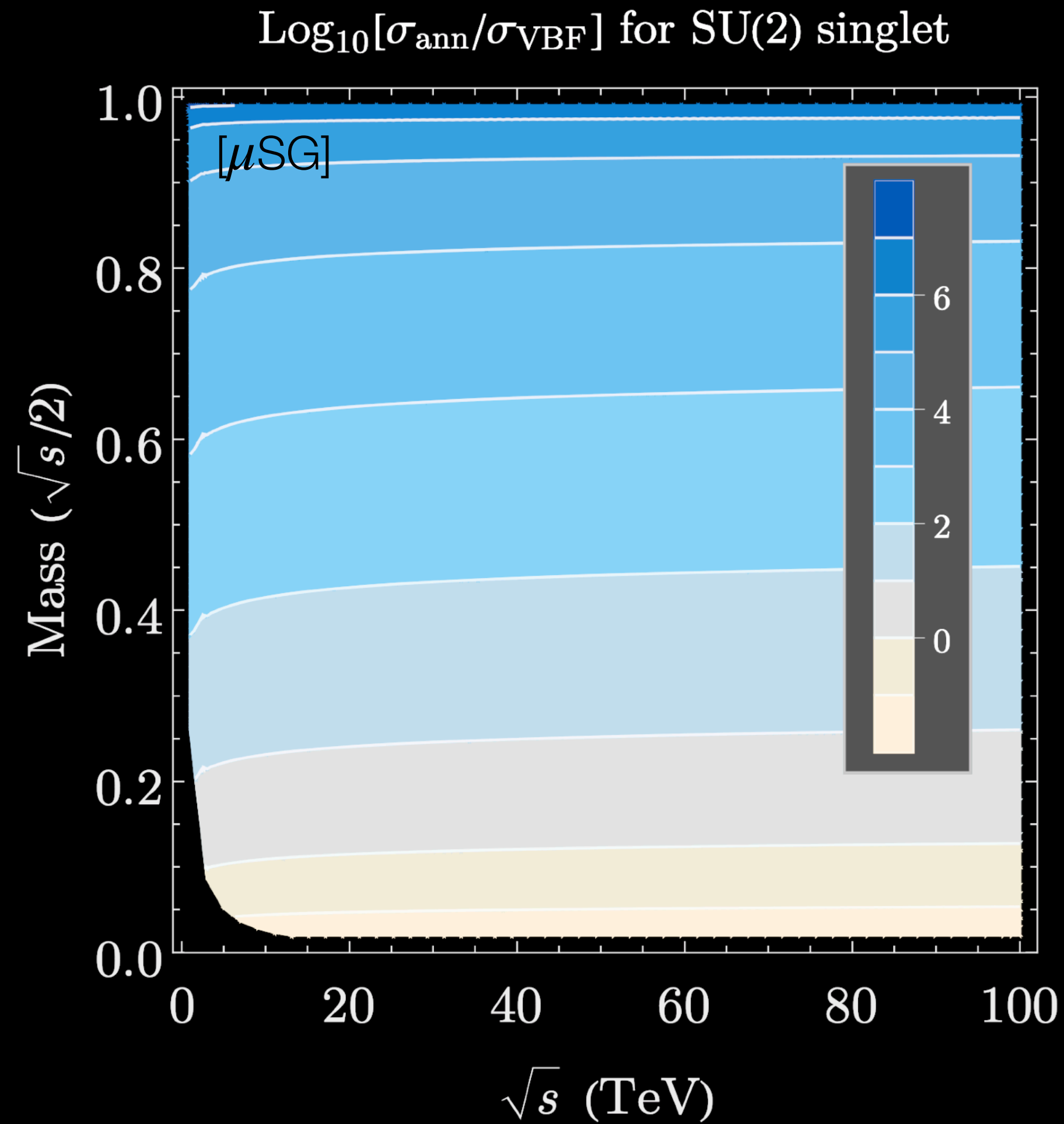
Various luminosity assumptions & energies:

| $\sqrt{s}$ [TeV]                                             | 1   | 3 | 6 | 10 | 14 | 30 | 50  | 100  |
|--------------------------------------------------------------|-----|---|---|----|----|----|-----|------|
| $\mathcal{L}_{\text{int}}^{\text{opt}}$ [ $\text{ab}^{-1}$ ] | 0.2 | 1 | 4 | 10 | 20 | 90 | 250 | 1000 |
| $\mathcal{L}_{\text{int}}^{\text{con}}$ [ $\text{ab}^{-1}$ ] | 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. [\[Costantini et al. 2005.10289\]](#)



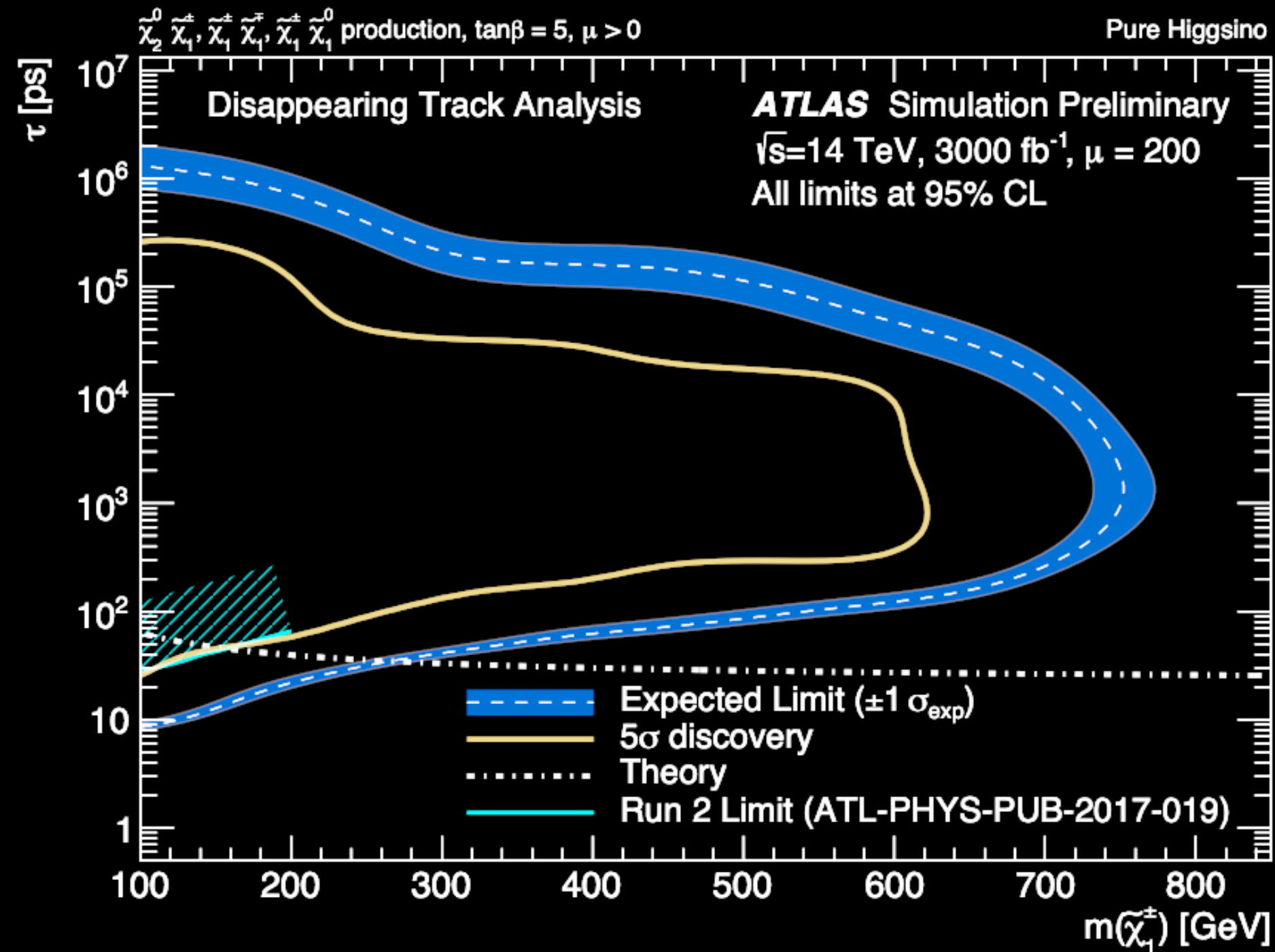


# Higgsinos

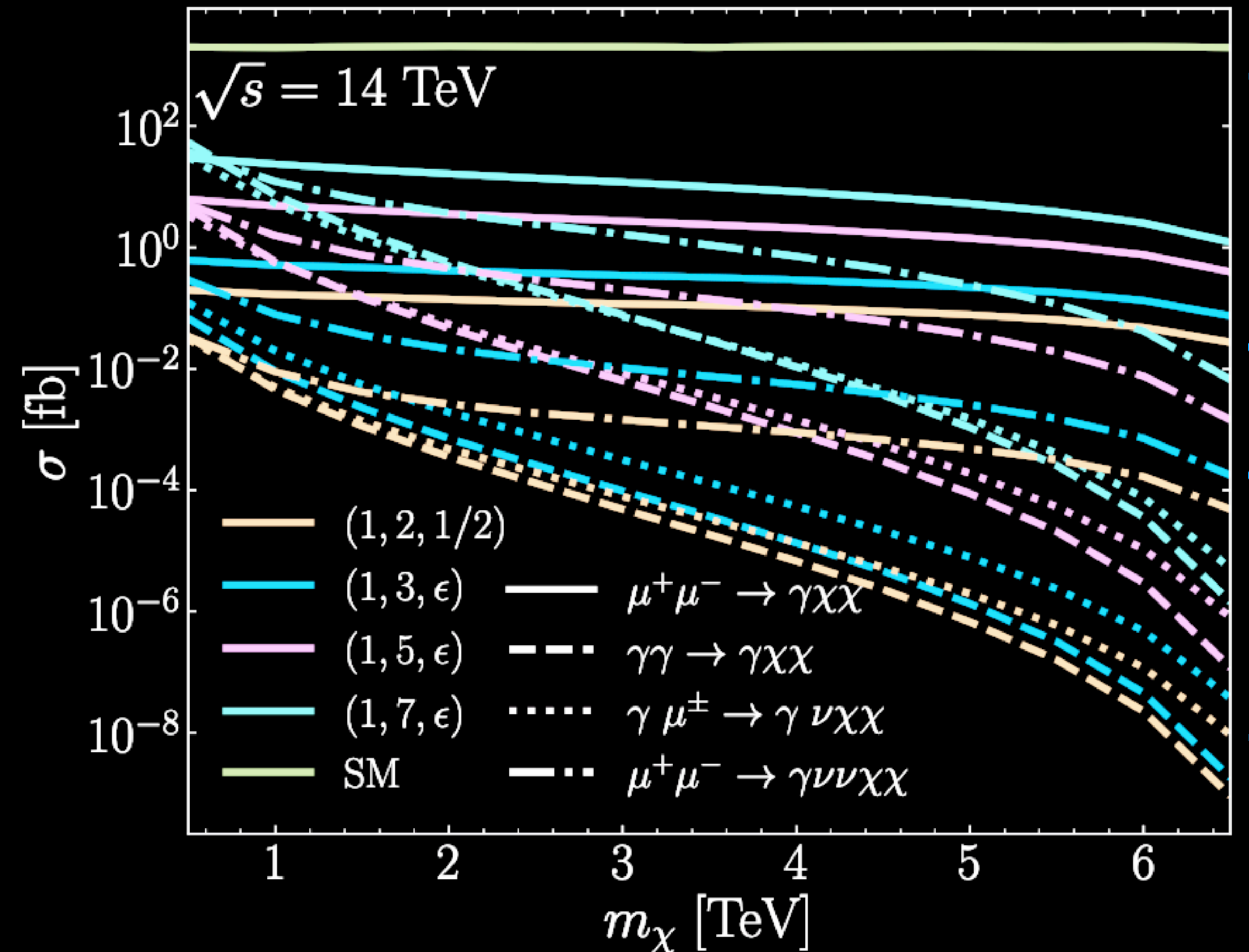
## Sharp target

Pure Higgsino poorly constrained by HL-LHC

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



## Nontrivial background @ Muon Collider



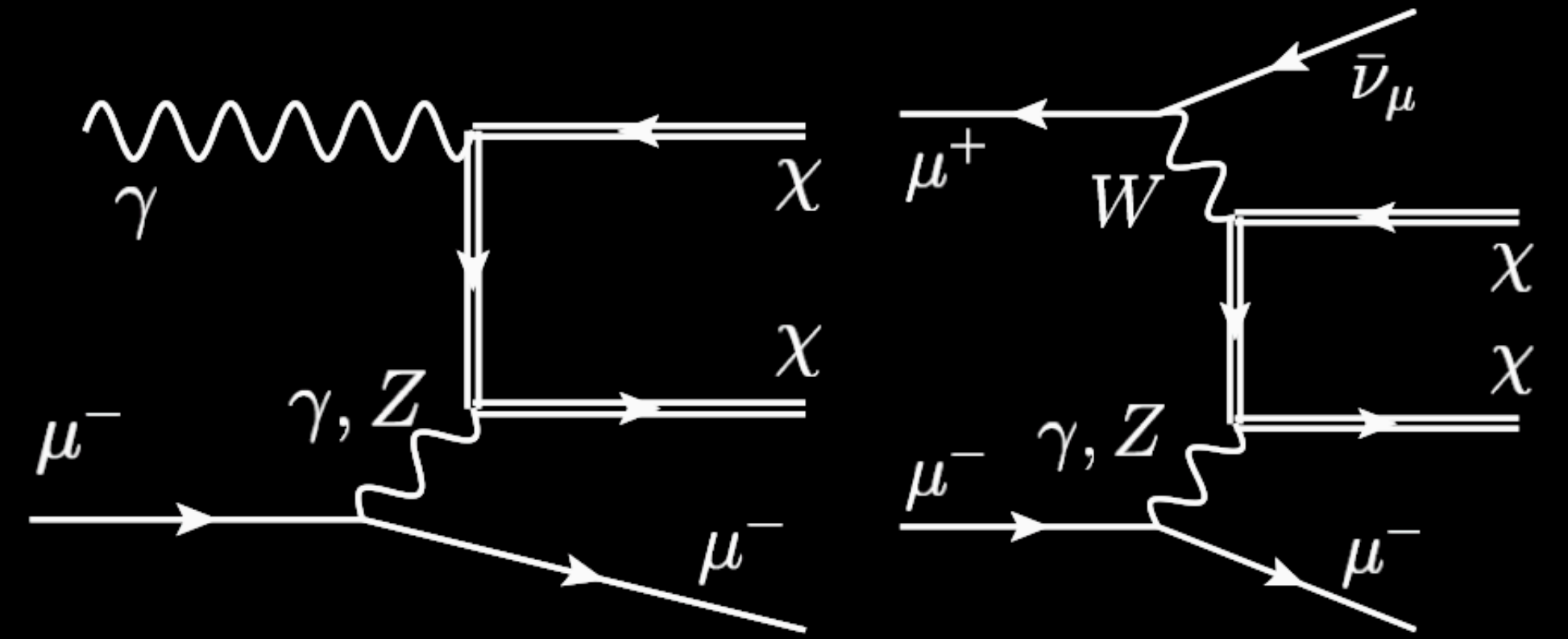
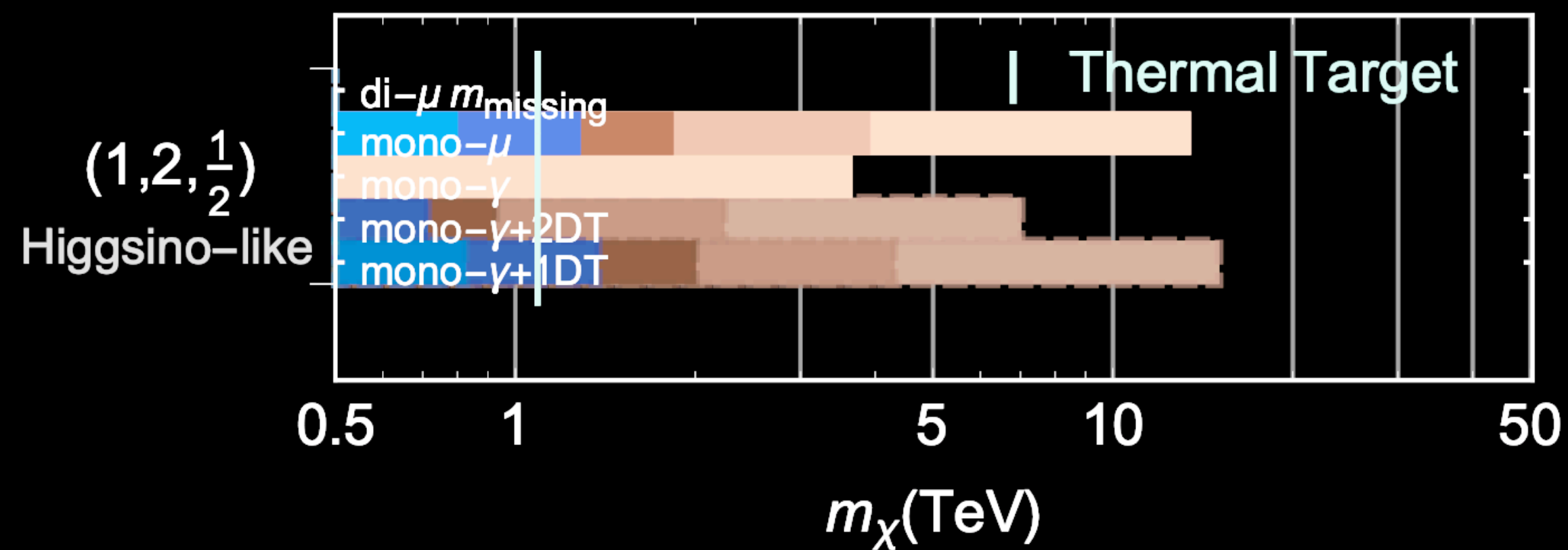
[Han, Liu, Wang, Wang, 2009.11287]



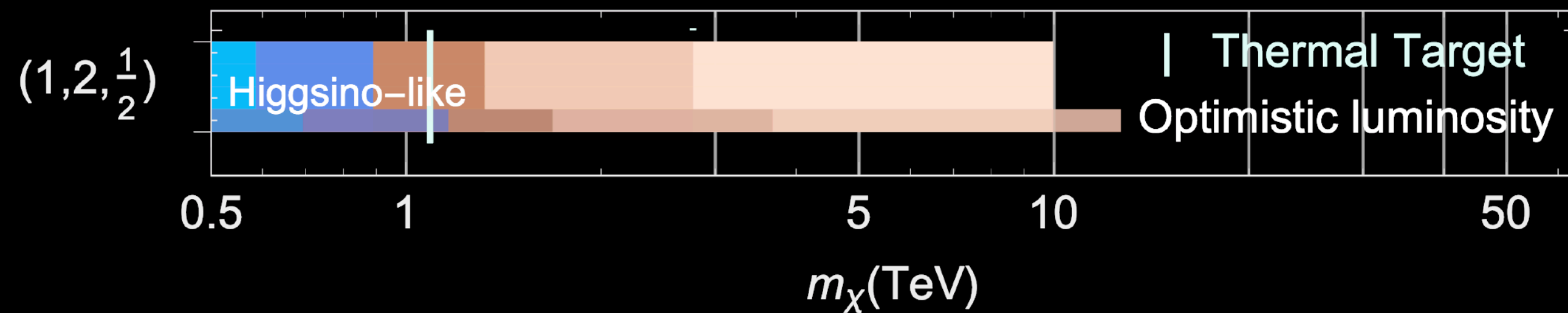
# Higgsinos

Muon Collider  $2\sigma$  Reach

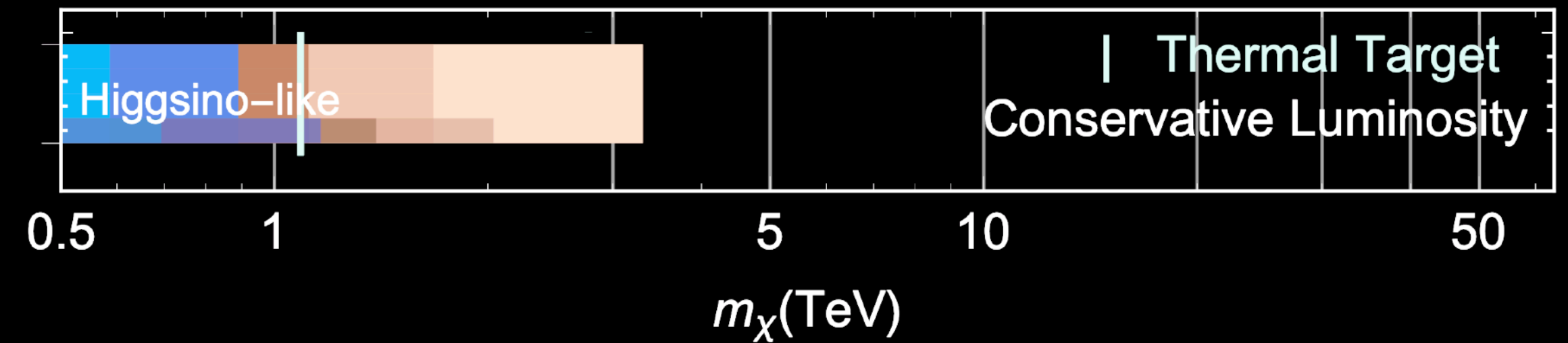
( $\sqrt{s} = 3, 6, 10, 14, 30, 100$  TeV)



Muon Collider  $5\sigma$  Reach ( $\sqrt{s} = 3, 6, 10, 14, 30, 100$  TeV)



Muon Collider  $5\sigma$  Reach ( $\sqrt{s} = 3, 6, 10, 14, 30, 100$  TeV)



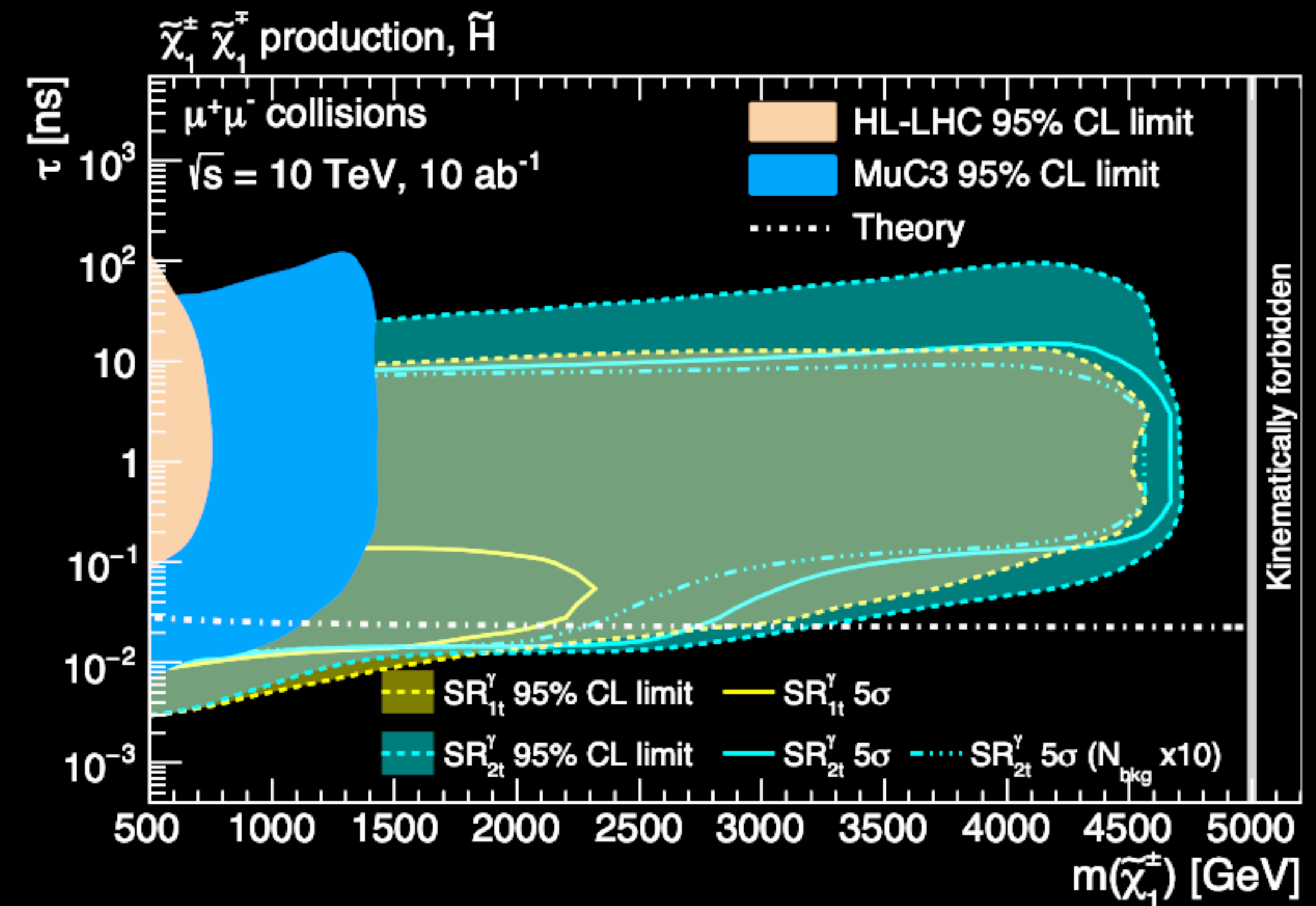
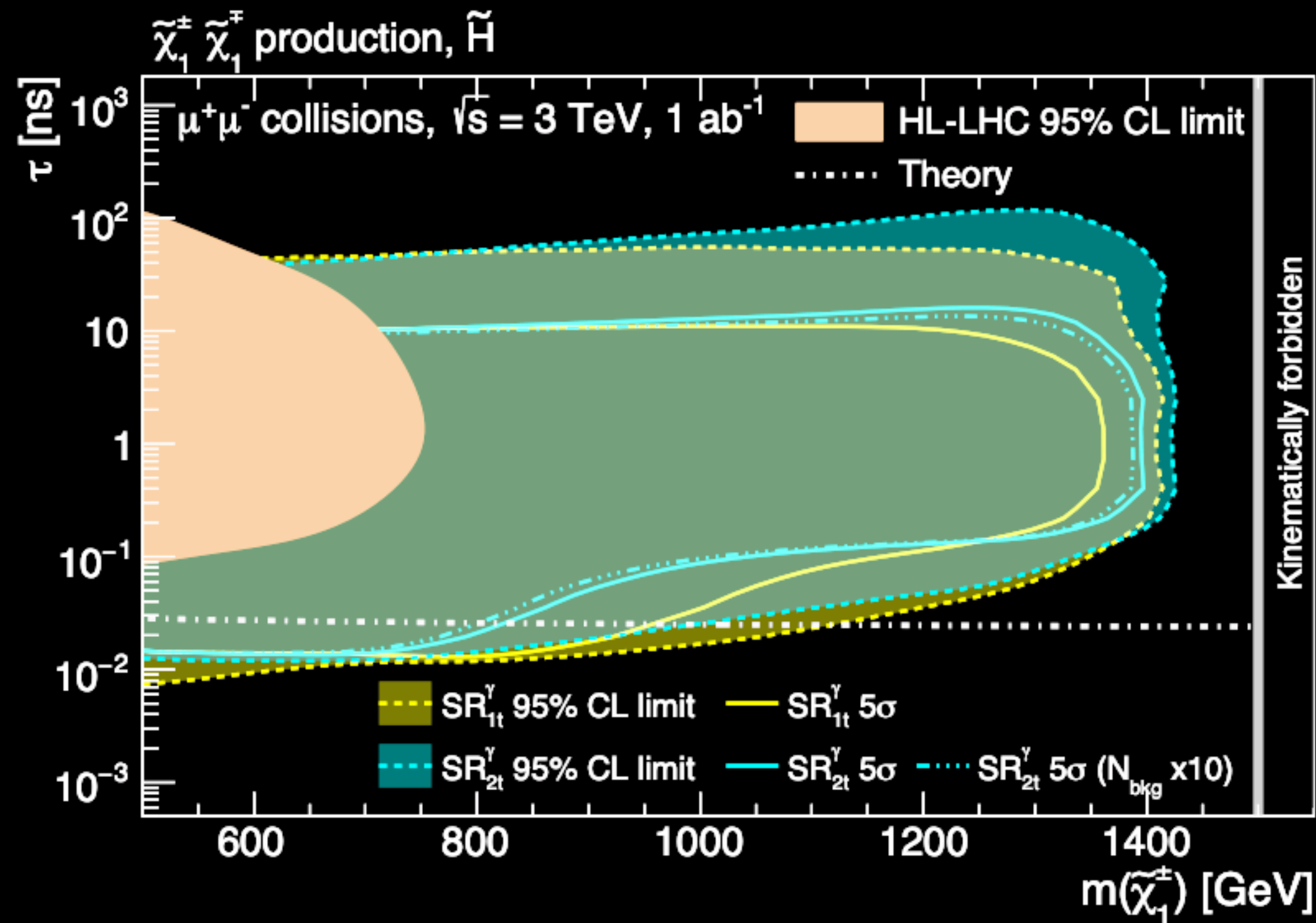
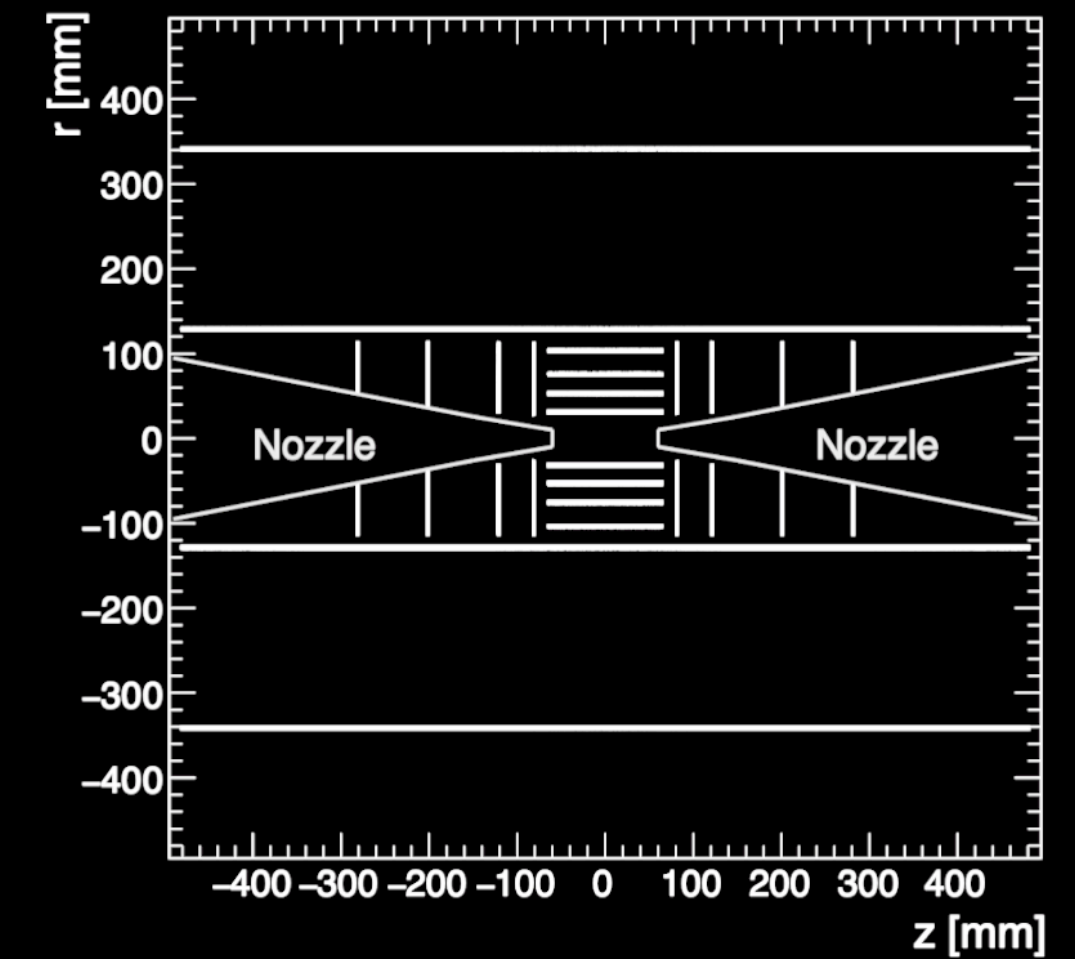
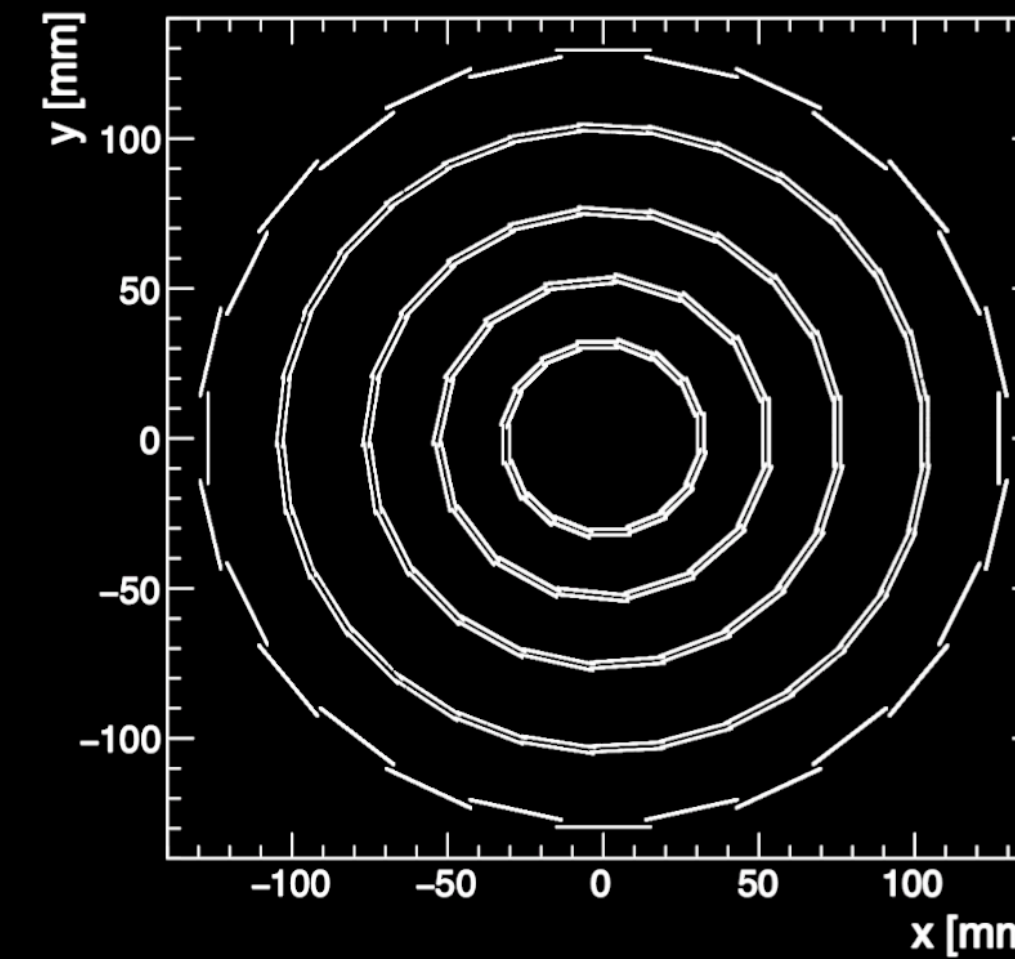
\* Pure Higgsino case may be overly conservative, if other gauginos are light then signals become more striking.

# Higgsinos

[Capdevilla, Meloni, Simoniello, Zurita 2102.11292]

Detailed treatment of reco & BIB

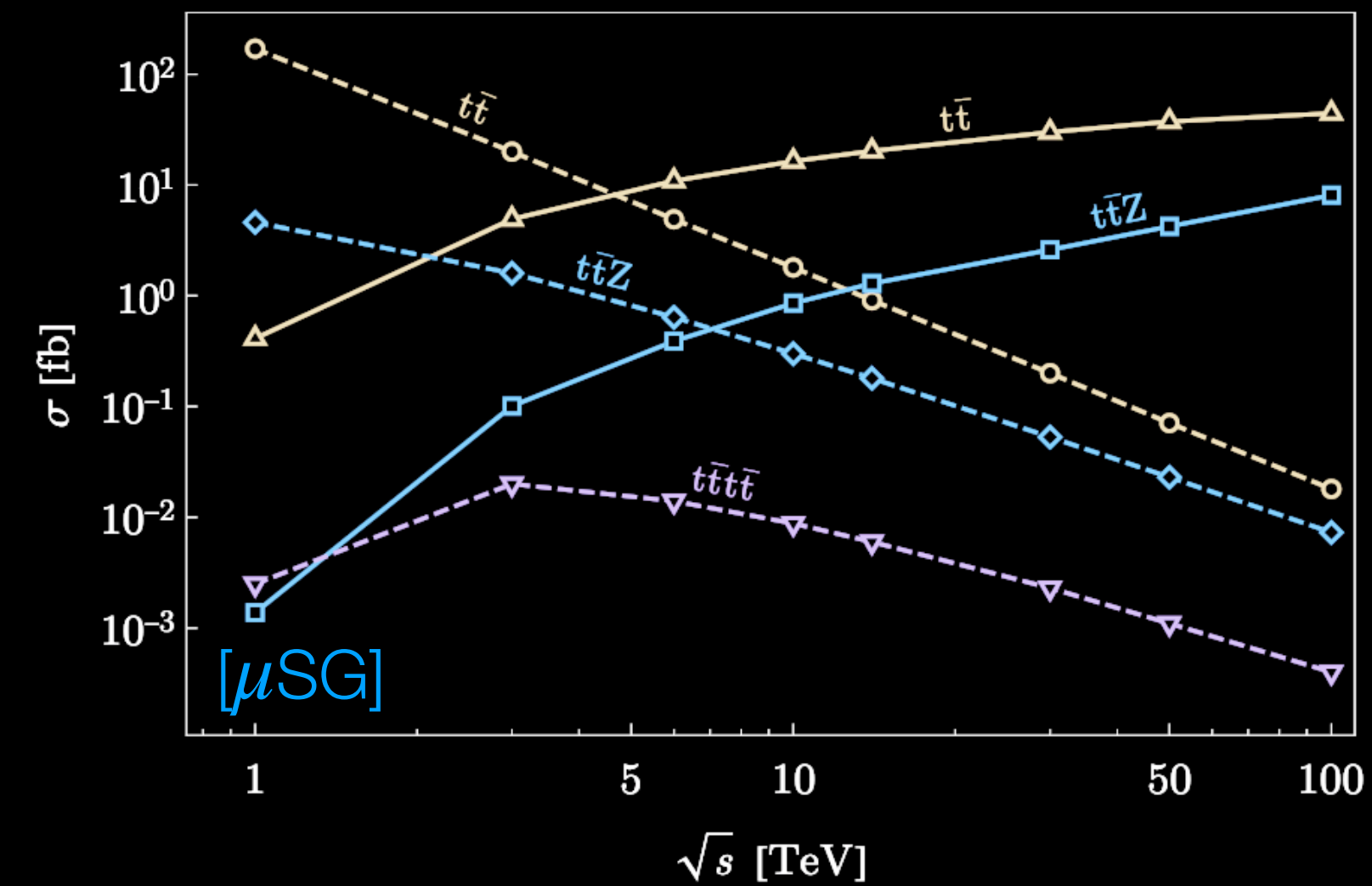
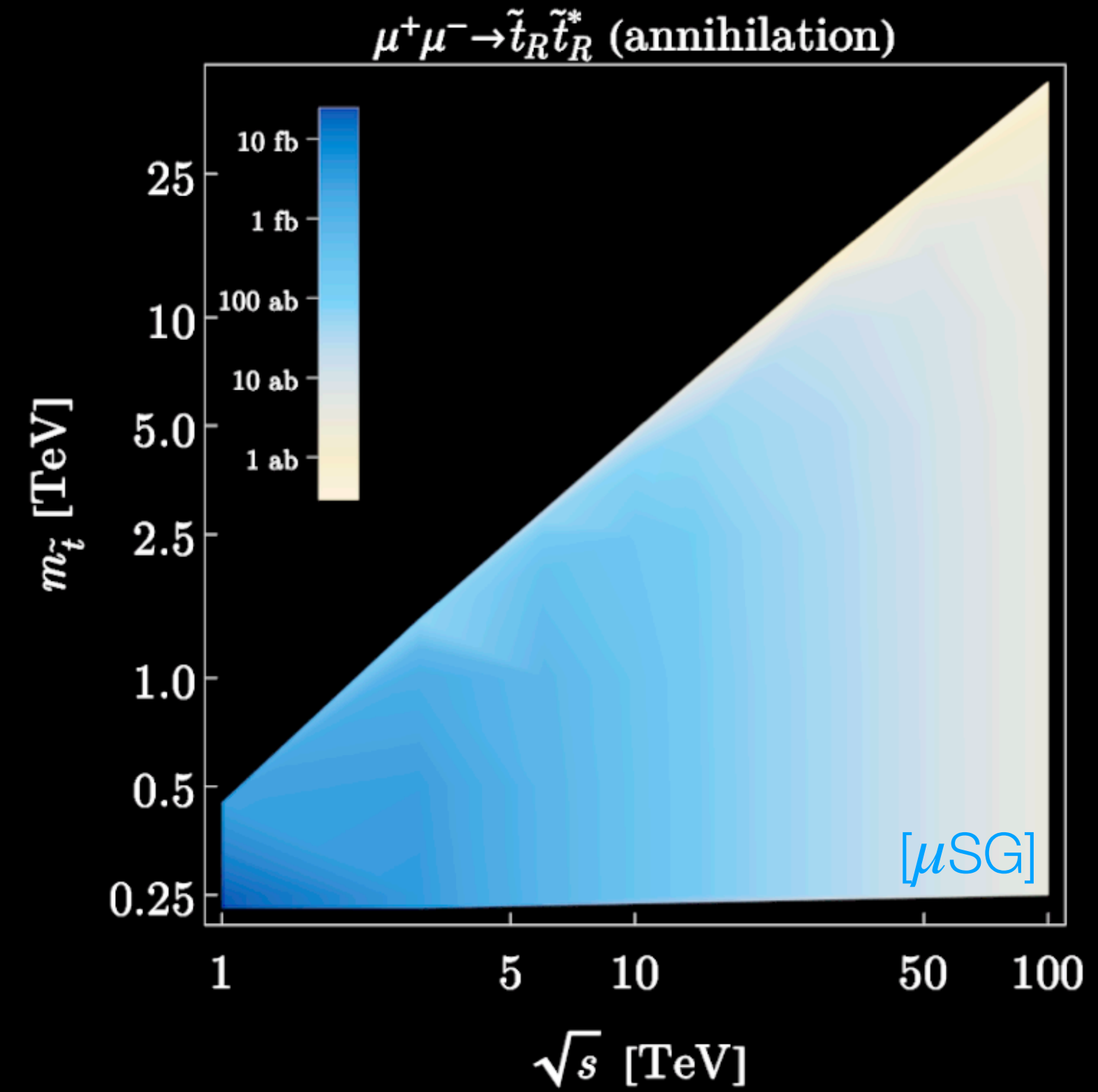
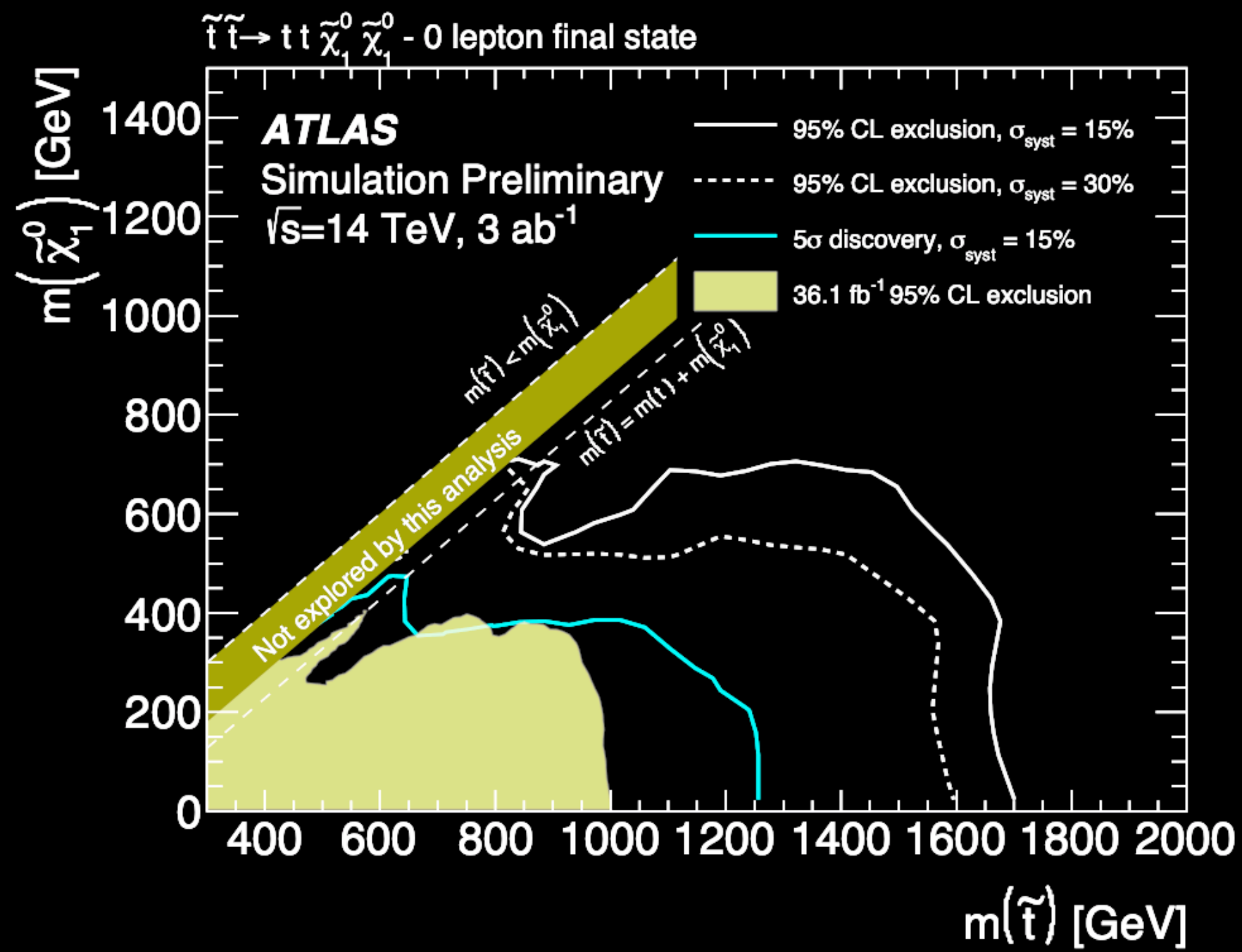
Conclusions somewhat more optimistic.



# Stops

The flagship LHC SUSY search...

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





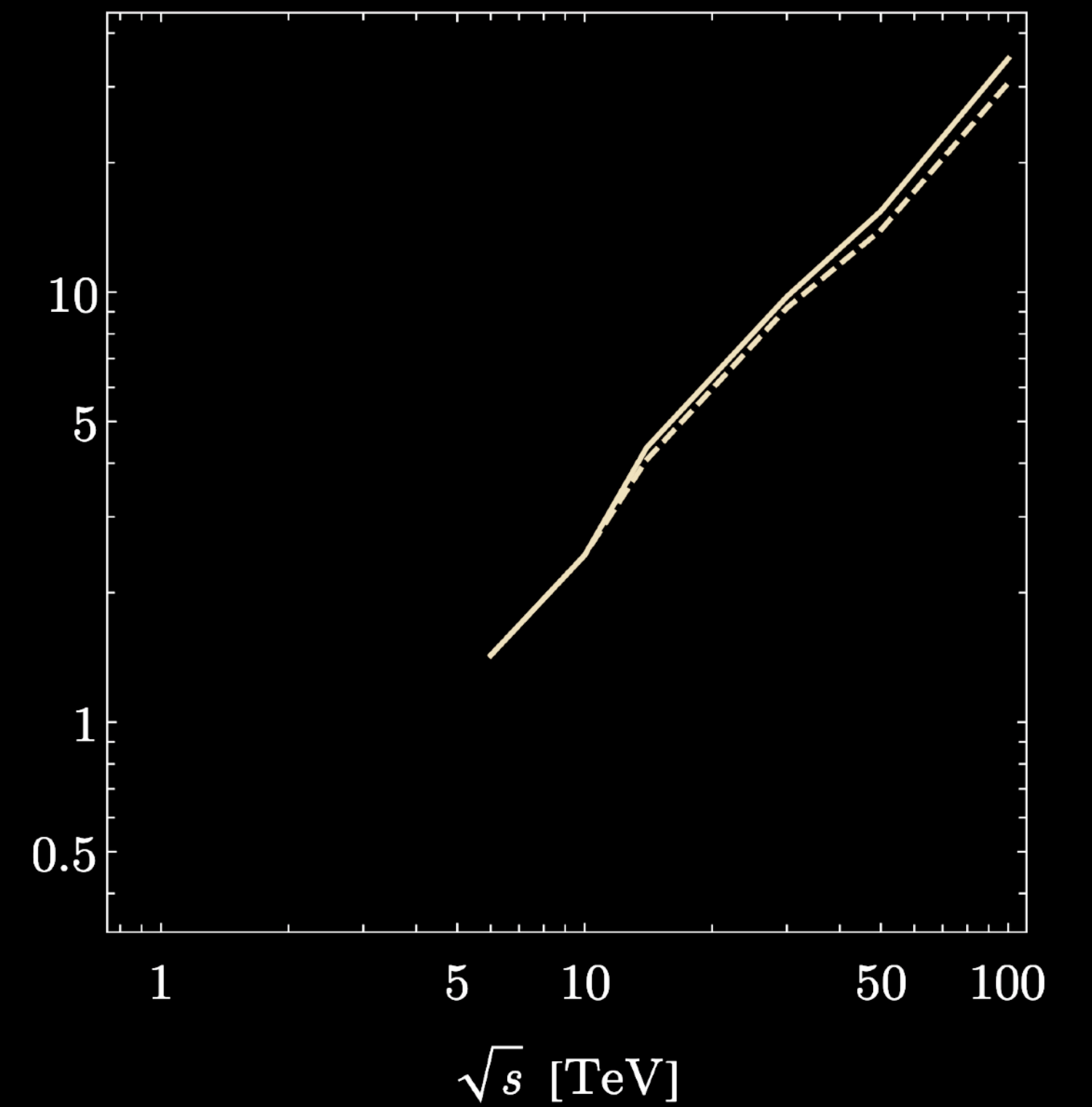
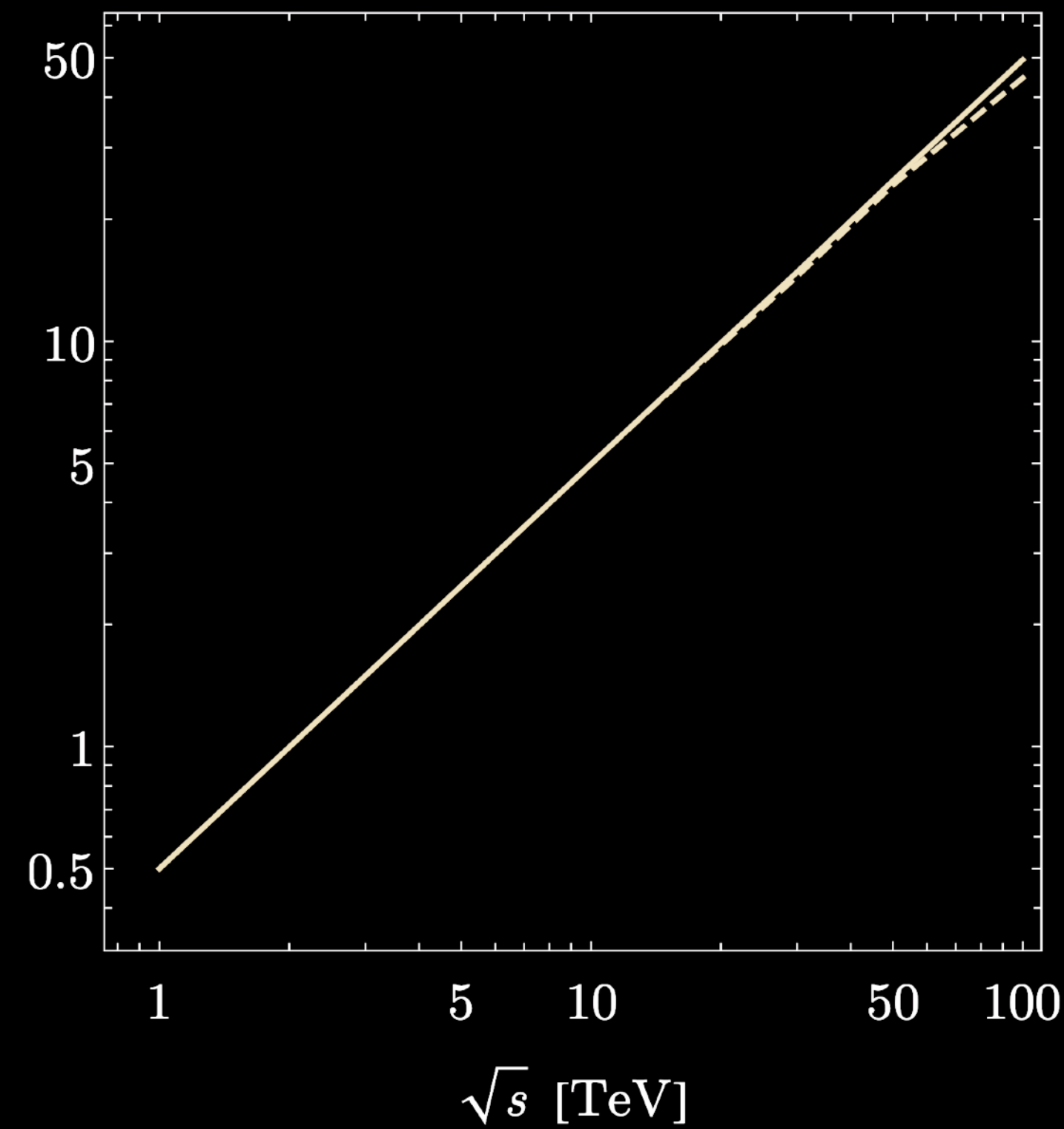
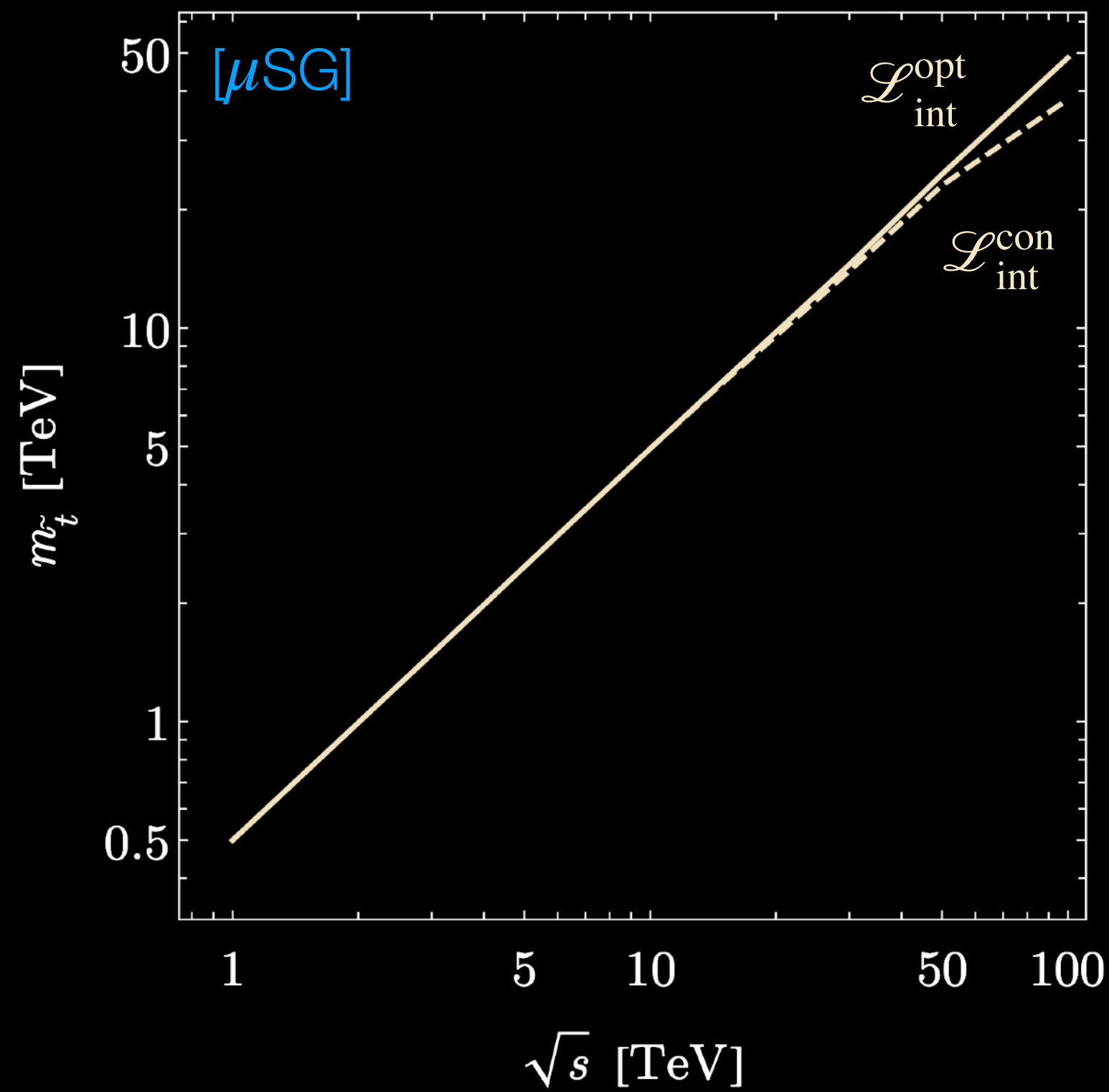
# Stops

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

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

$$\mu^+\mu^- \rightarrow \tilde{t}_L \tilde{t}_L \rightarrow t\bar{t} + \chi\chi$$

$$\mu^+\mu^- \rightarrow \tilde{t}_L \tilde{t}_L + \nu\bar{\nu} \rightarrow t\bar{t} + \chi\chi + \nu\bar{\nu}$$

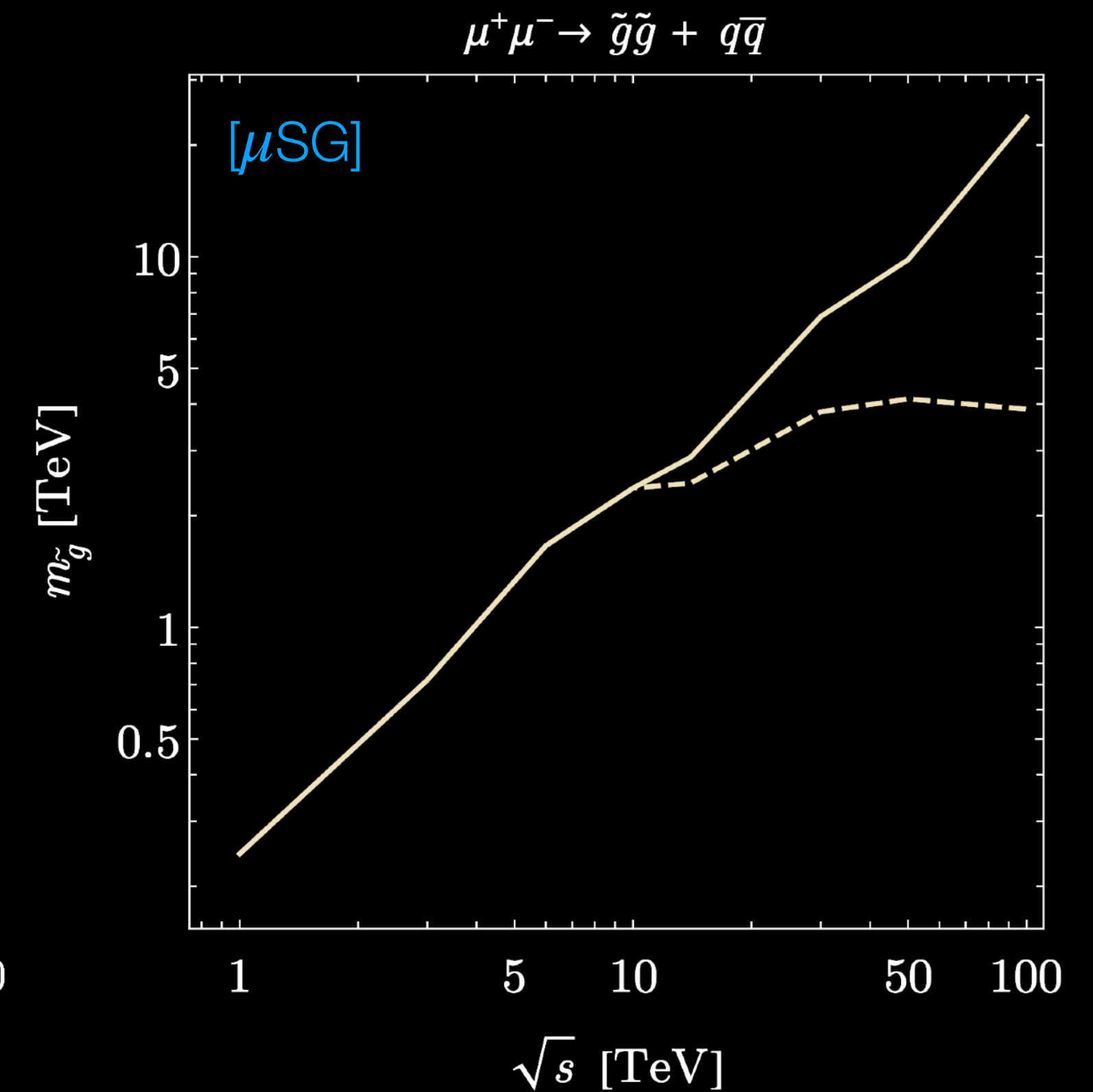
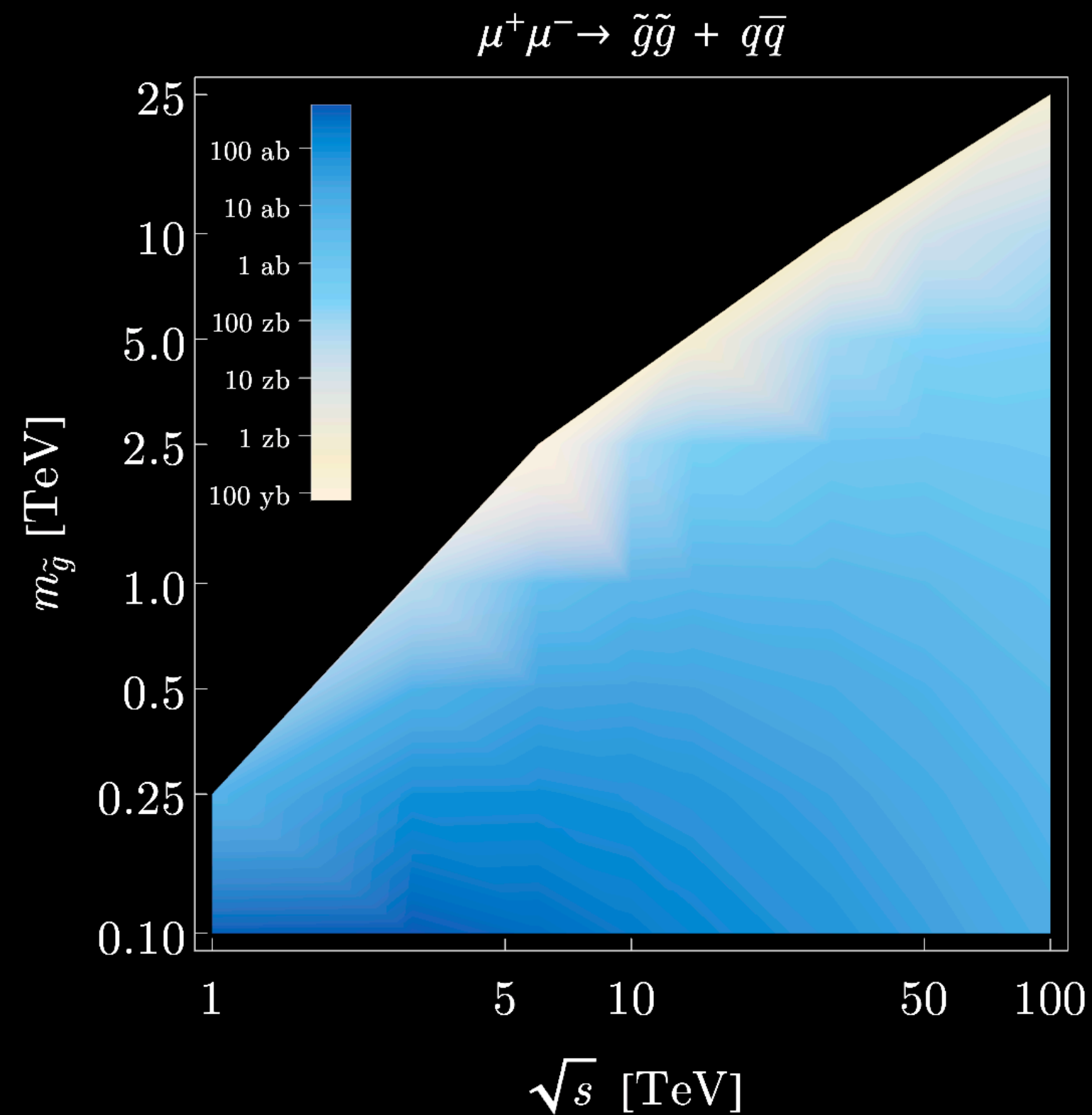
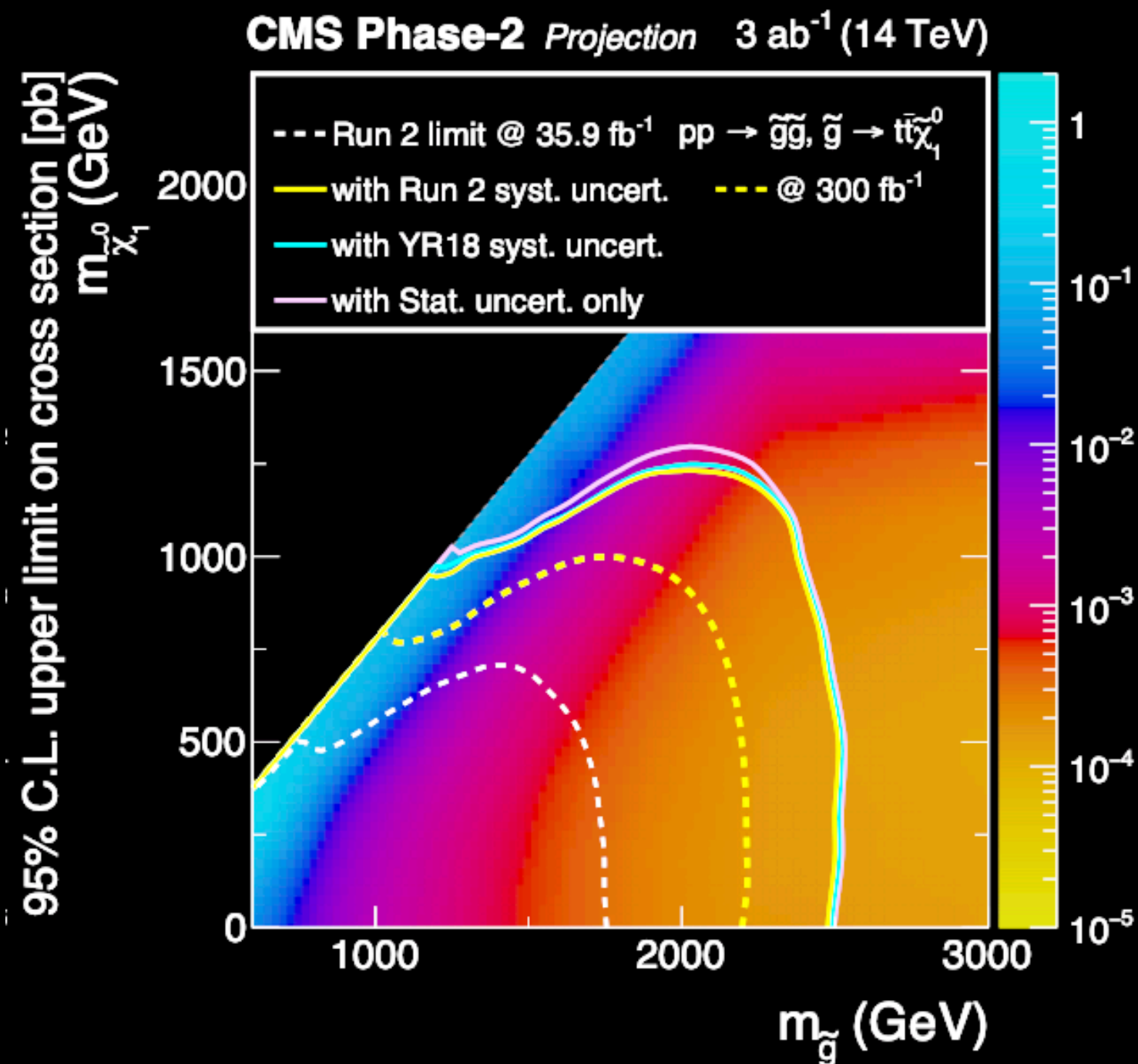
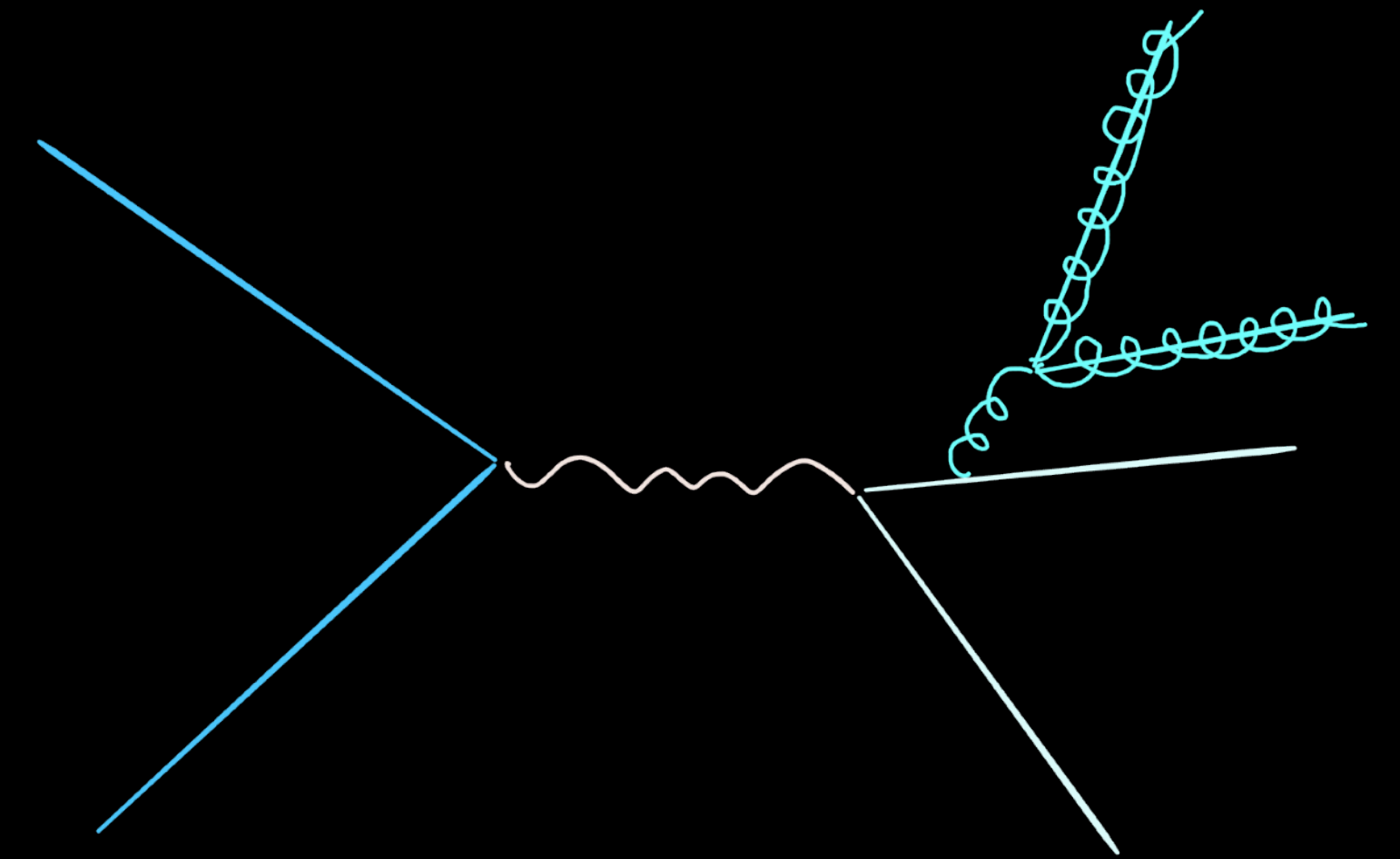


*For sufficiently distinctive final states, production in muon annihilation ~sufficient to give limit at kinematic threshold*

# Gluginos

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

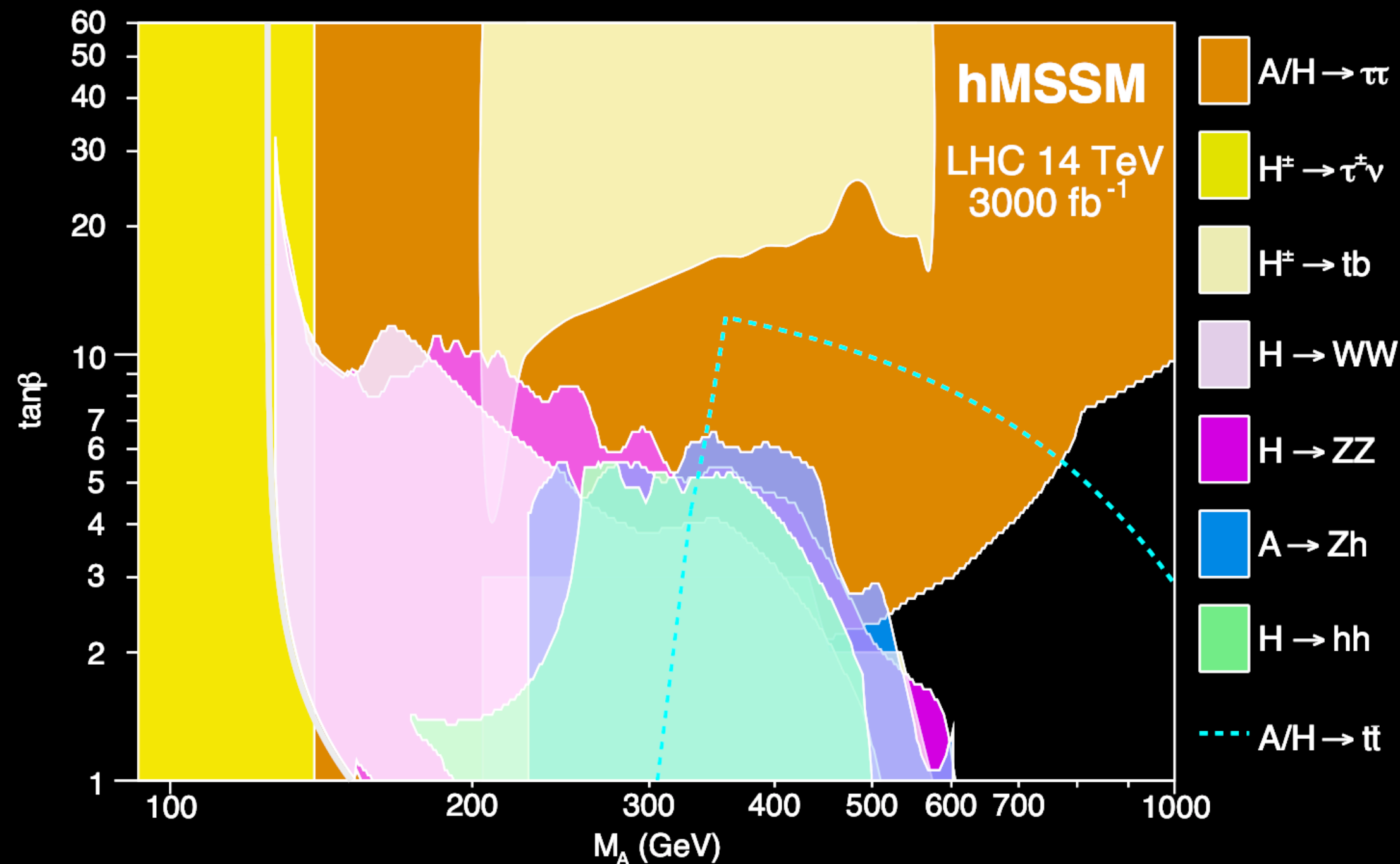
Absence of electroweak quantum #s requires higher-order production  
(revisit w/ hadronic PDFs?  
[Han, Ma, Xie, 2103.09844])



# 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  $\sim$ kinematic threshold

### Signal after cuts

| Signal Rate | $\sqrt{s}$ (TeV) | $\sigma$ (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

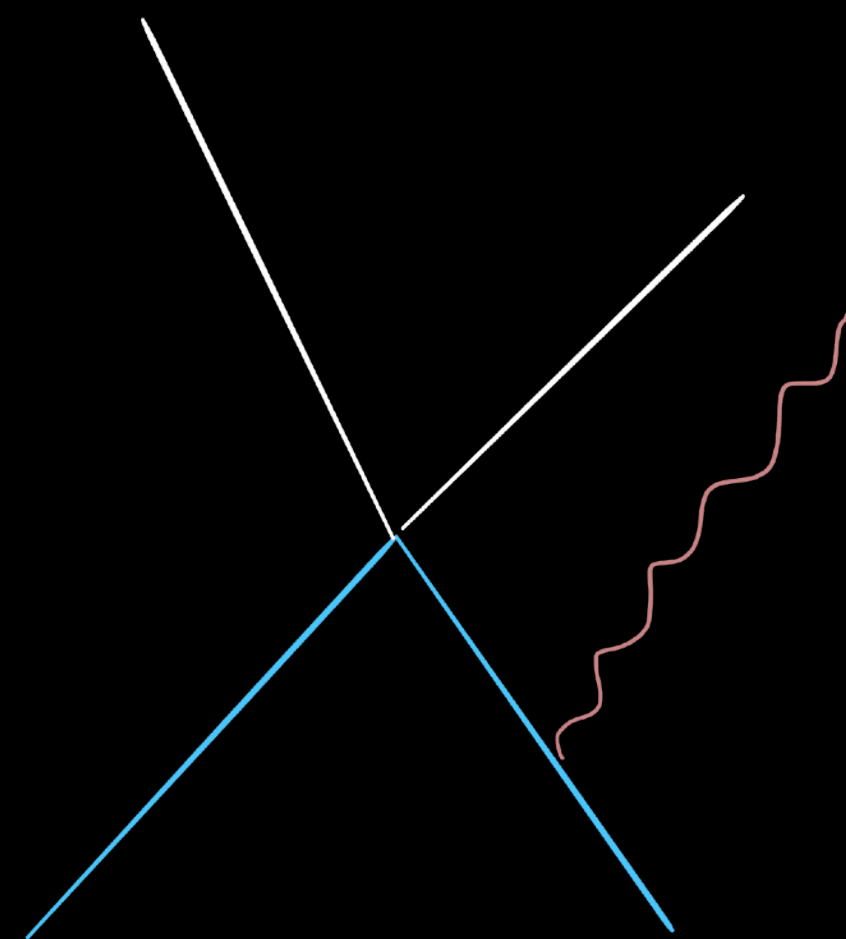
| $\sigma$ (fb) | $\sqrt{s}$ (TeV) | $t\bar{t}b\bar{b}$   |                      |
|---------------|------------------|----------------------|----------------------|
|               |                  | $\mu^+\mu^-$         | VBF                  |
| $H^+H^-$      | 6                | $6.7 \times 10^{-4}$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



# The Gravitino

Never interesting at pp machines compared to MSSM searches.

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

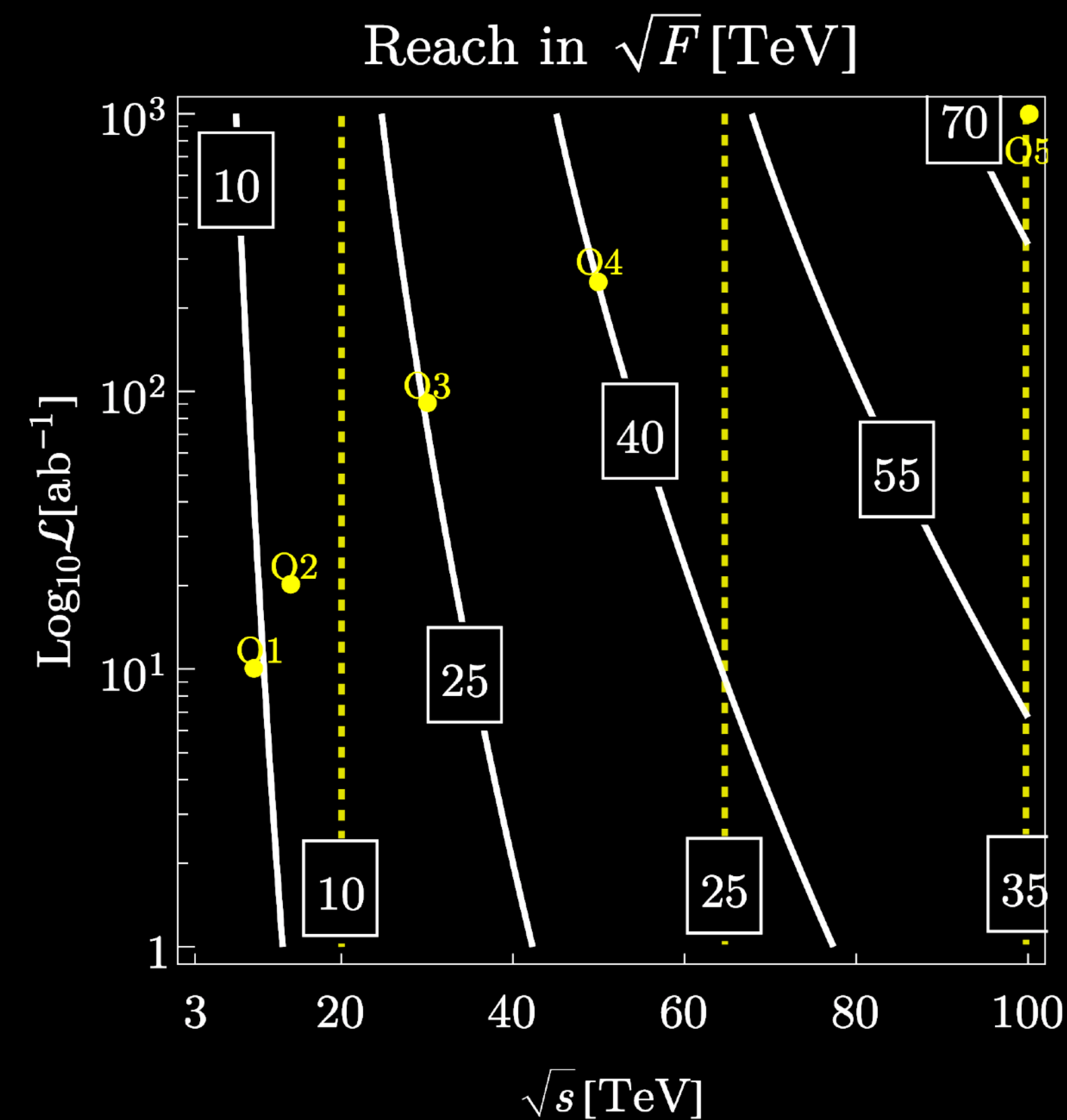
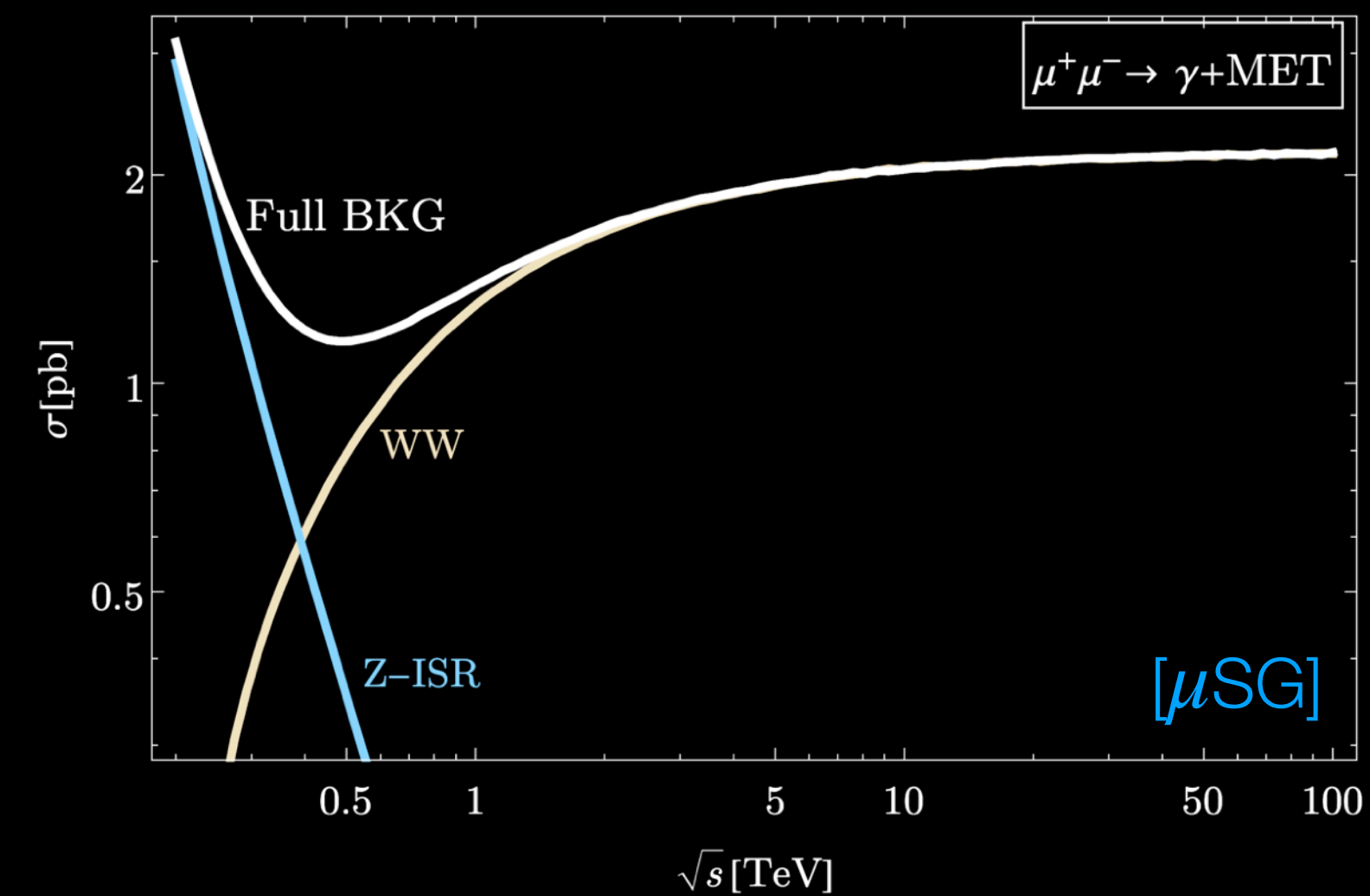


$$\sigma(\mu^+ \mu^- \rightarrow \tilde{G}\tilde{G}\gamma) = \frac{\alpha s^3}{160\pi^2 F^4} \left[ \frac{247}{60} + 2 \log \left( \frac{2E_{\min}^\gamma}{\sqrt{s}} \right) \right] \log \left( \frac{1 - \cos \theta_{\min}}{1 + \cos \theta_{\min}} \right)$$

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

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  $\sim 10\text{-}14$  TeV **significantly improves** upon LHC sensitivity, hits targets in the  $\sim$ 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!**