Supersymmetry 2014: μ-collider implications

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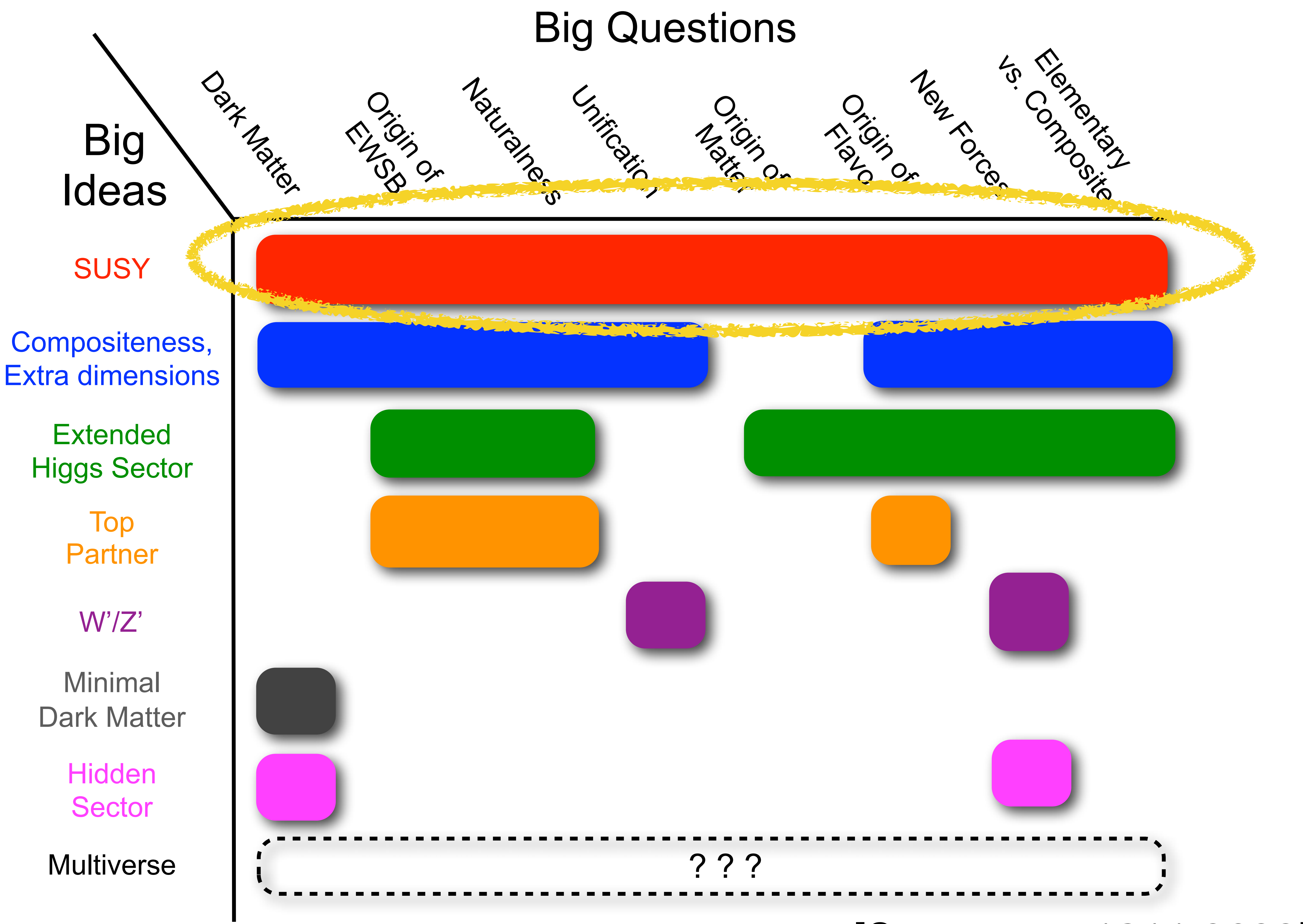
Outline

SUSY as we knew it, pre-LHC

SUSY after 20 fb^{-1}, 8 TeV + a ~126 GeV Higgs

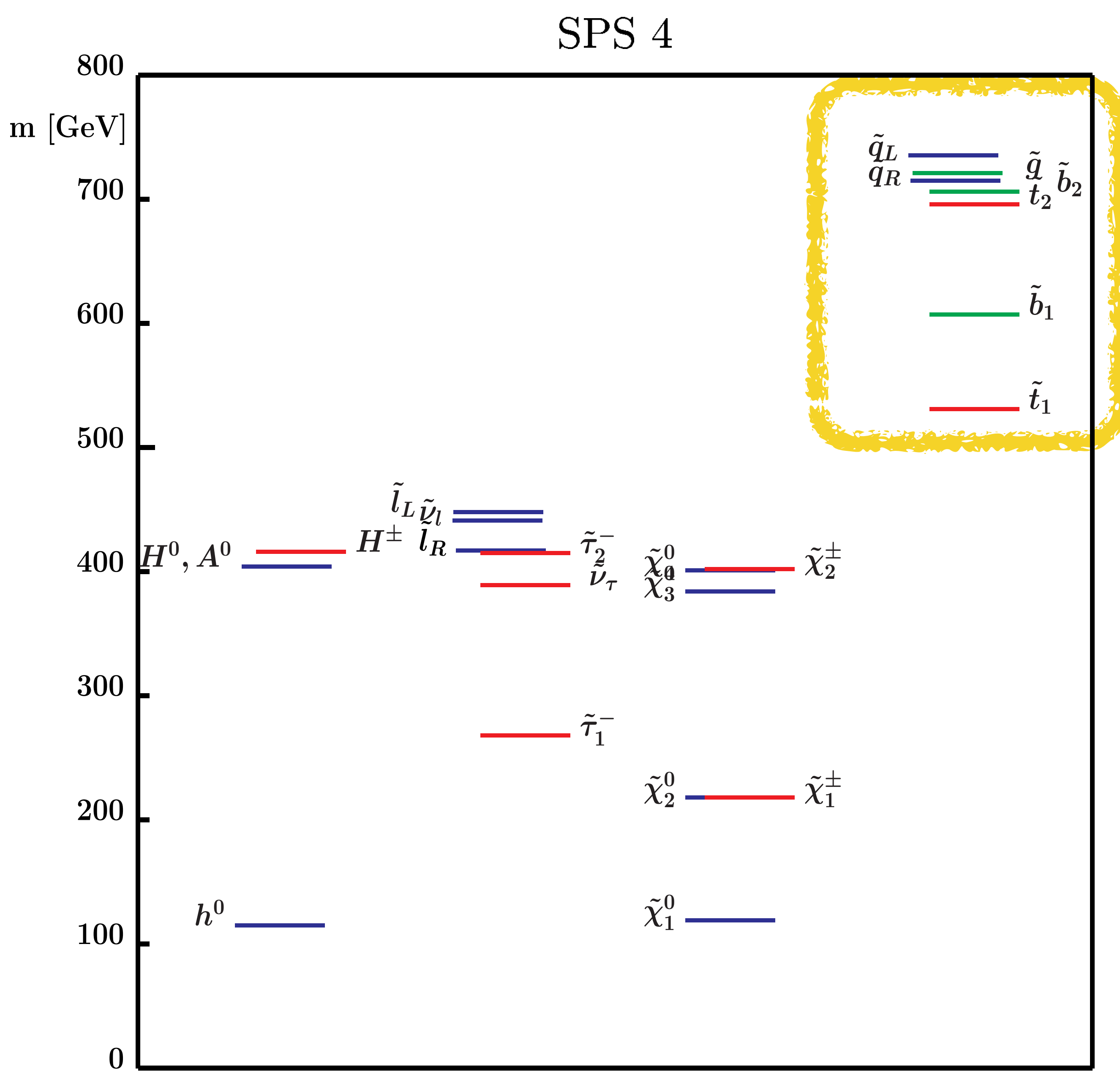
where we go from here

why supersymmetry?



[Snowmass 1311.0299]

what was possible in SUSY, a la 2010



[LesHouches 2011]

CMSSM-style spectra

colored sparticles ≲ 1000 GeV,

similar mass for all squark generations & gluino

color neutral particles hovering right at the 100-200

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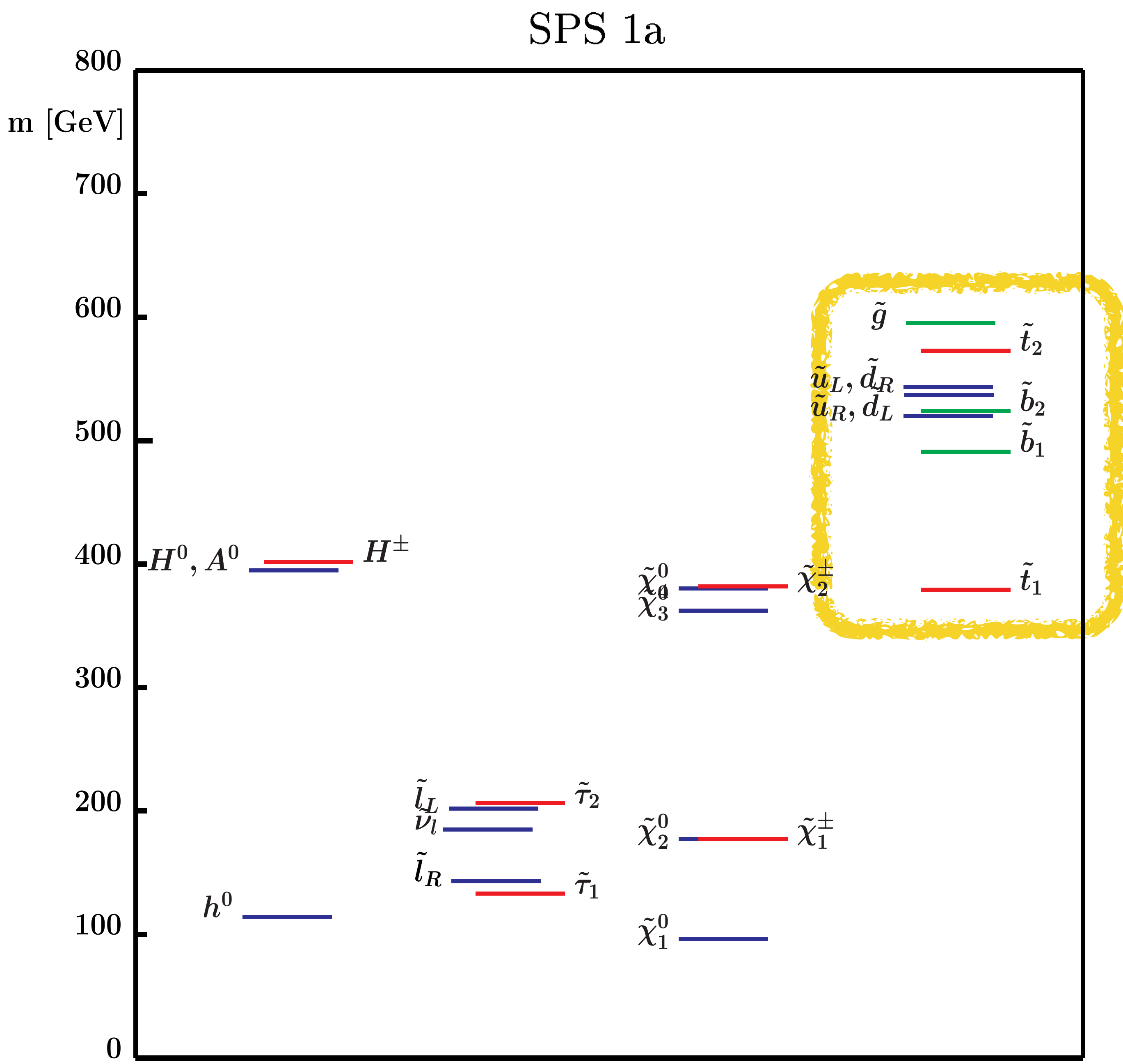

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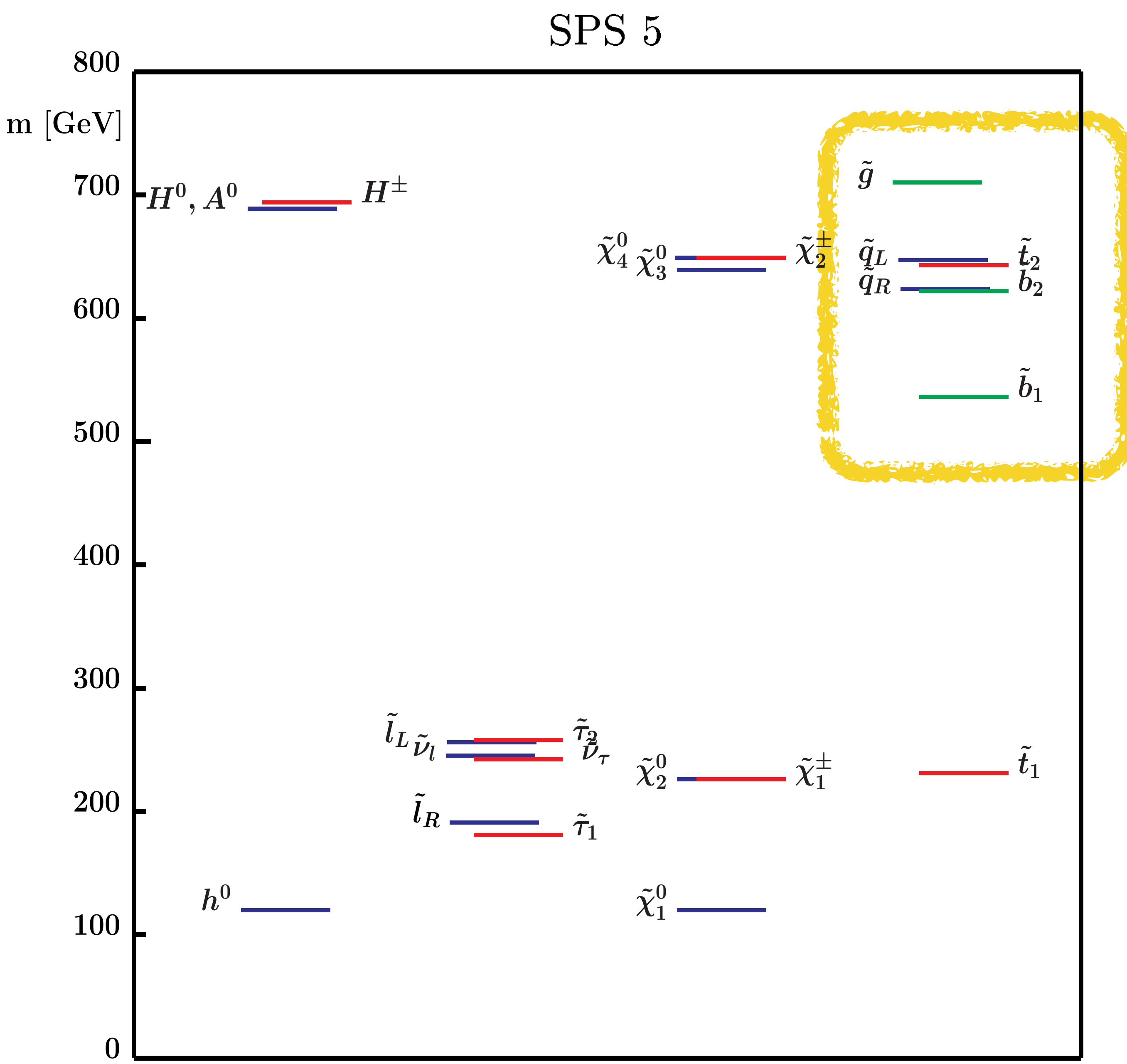

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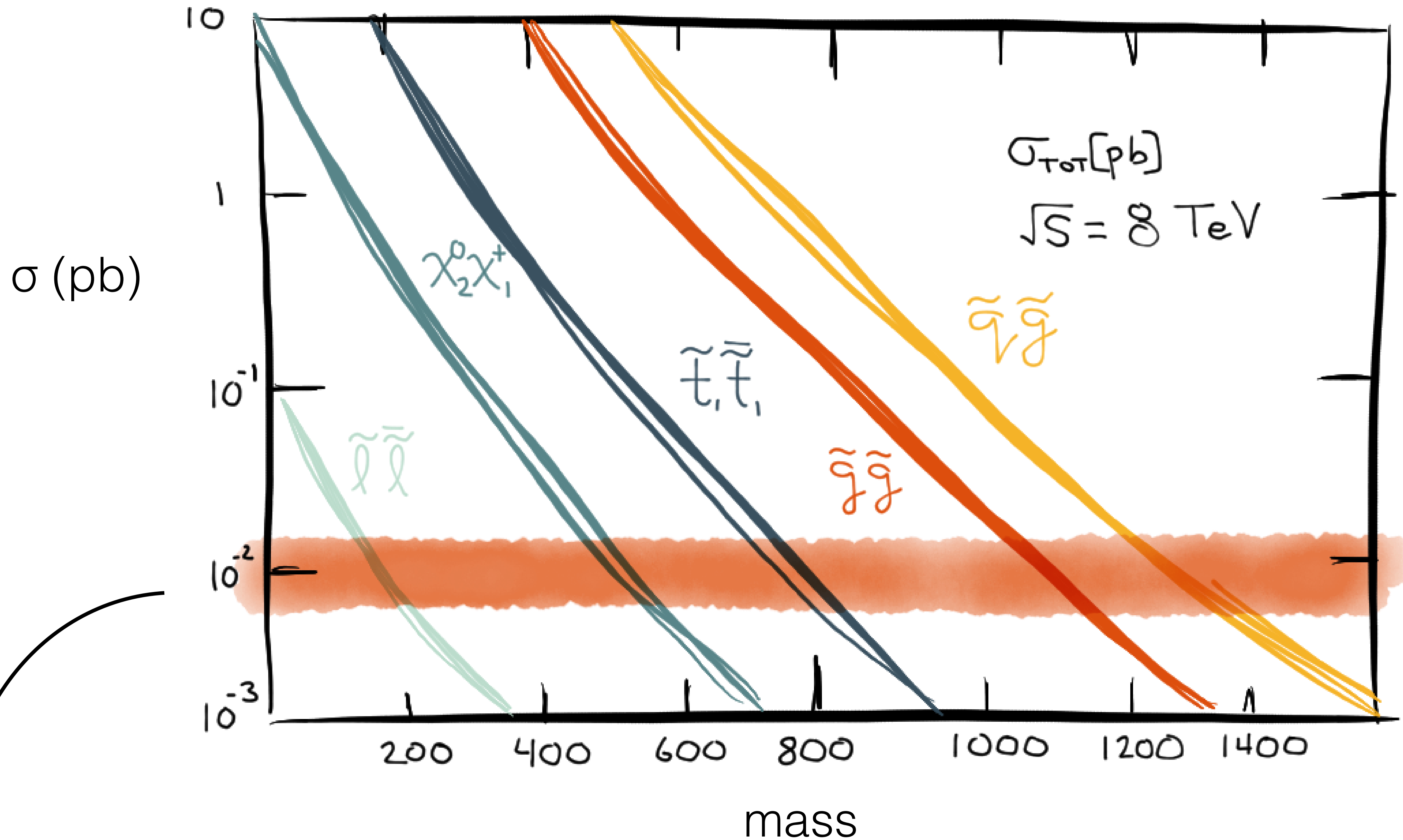
what the LHC sees, so far

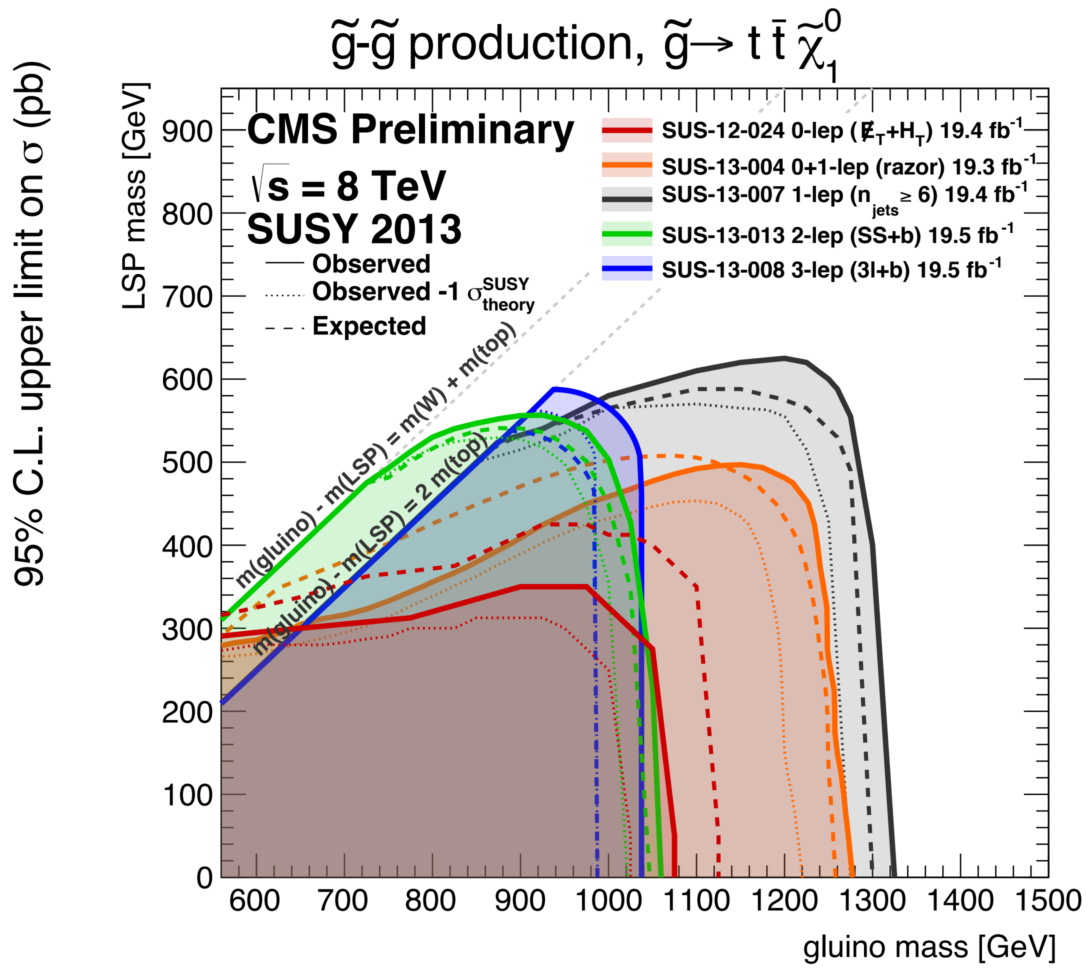


‘typical’ cross sections for supersymmetry processes

rough limits after LHC_8 : σ~ 10 fb

[from N. Craig]

more detailed limits: some dependence on decays



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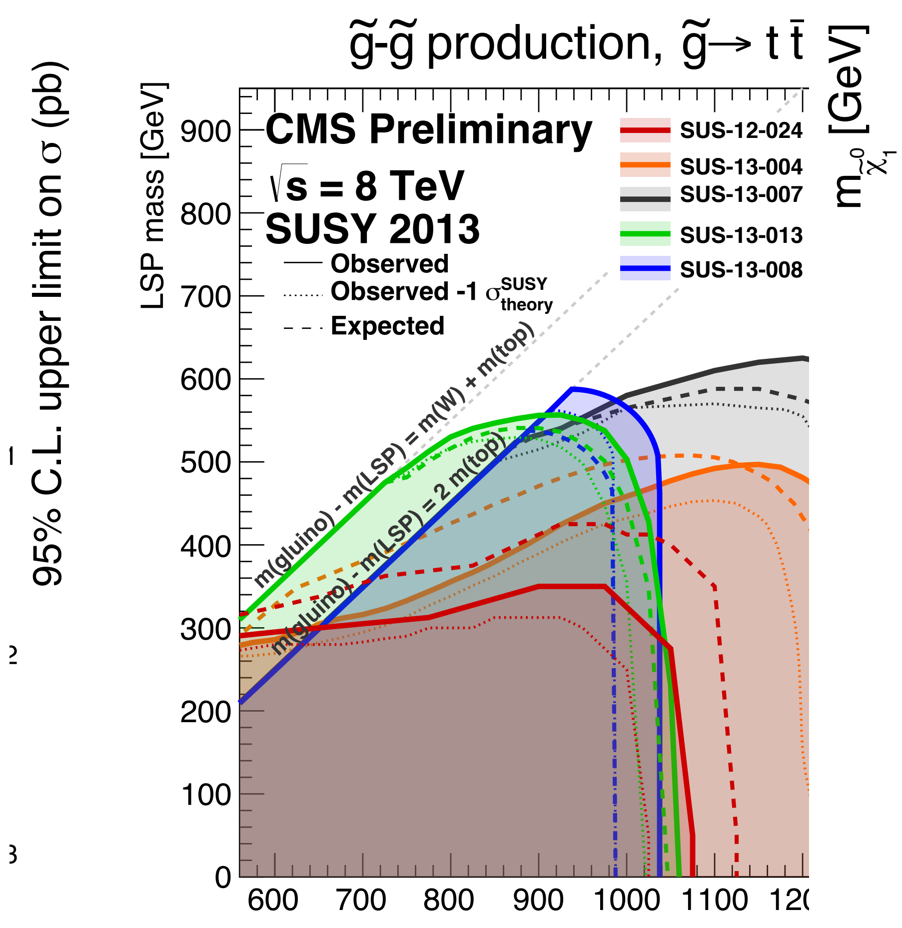

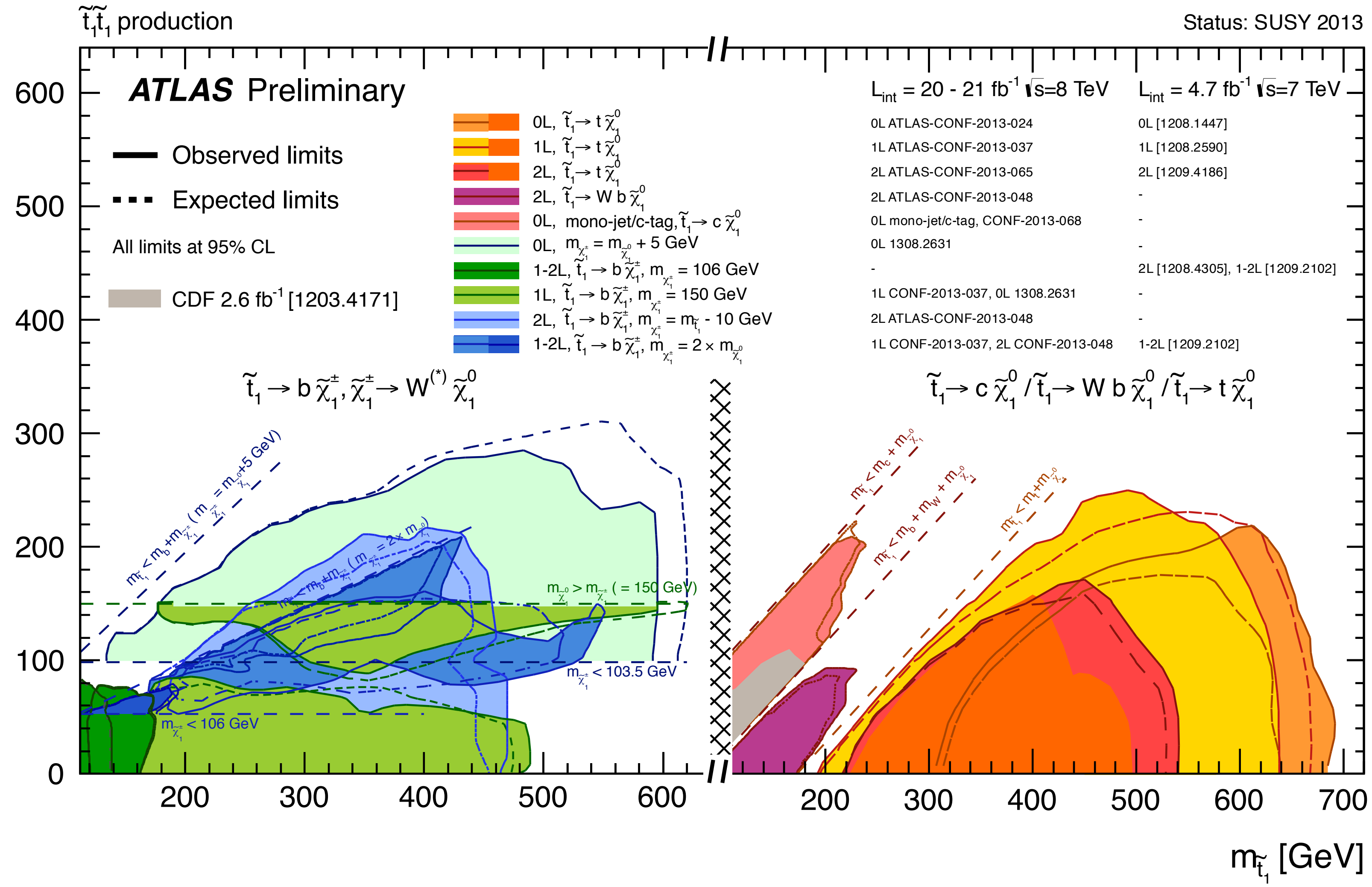

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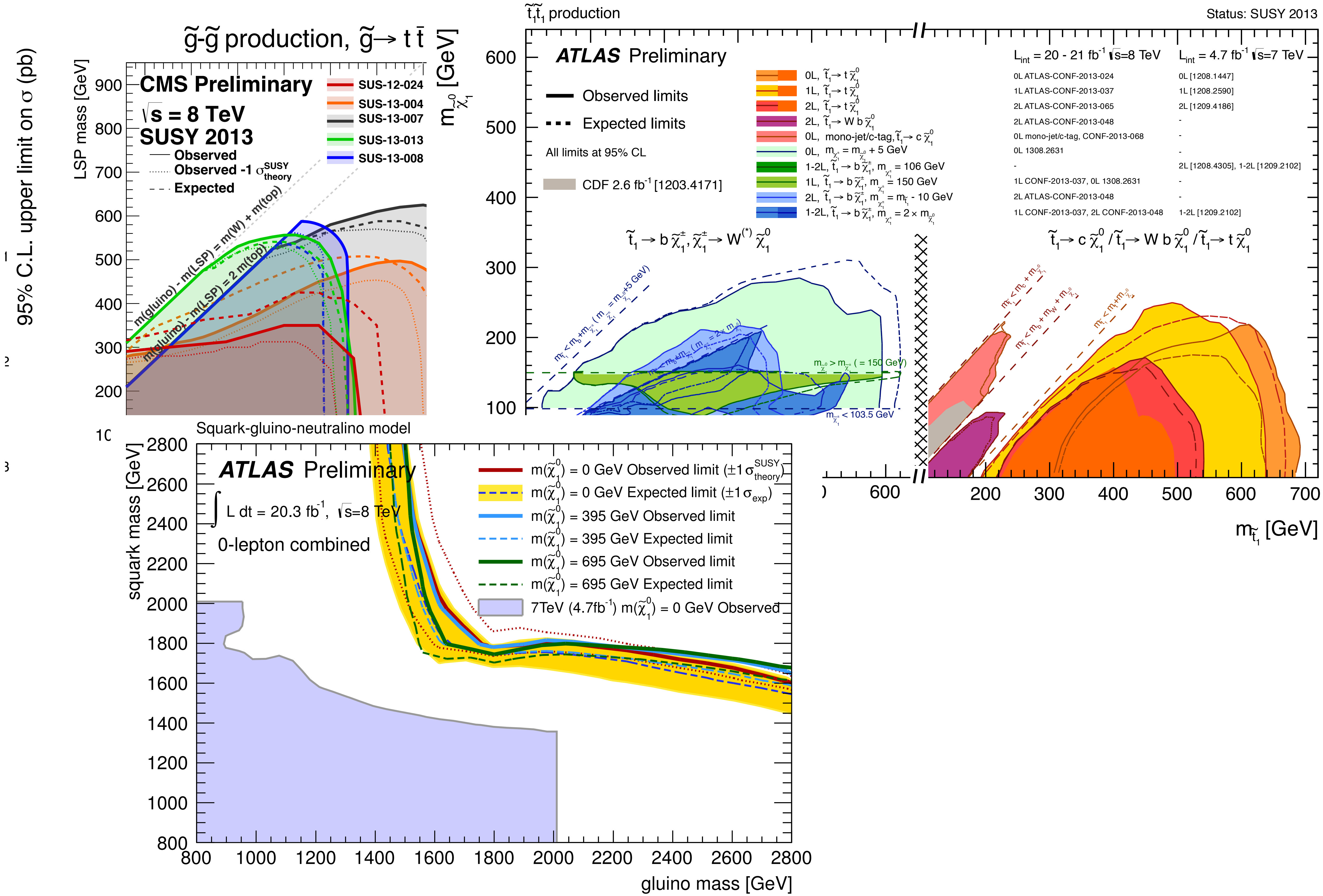

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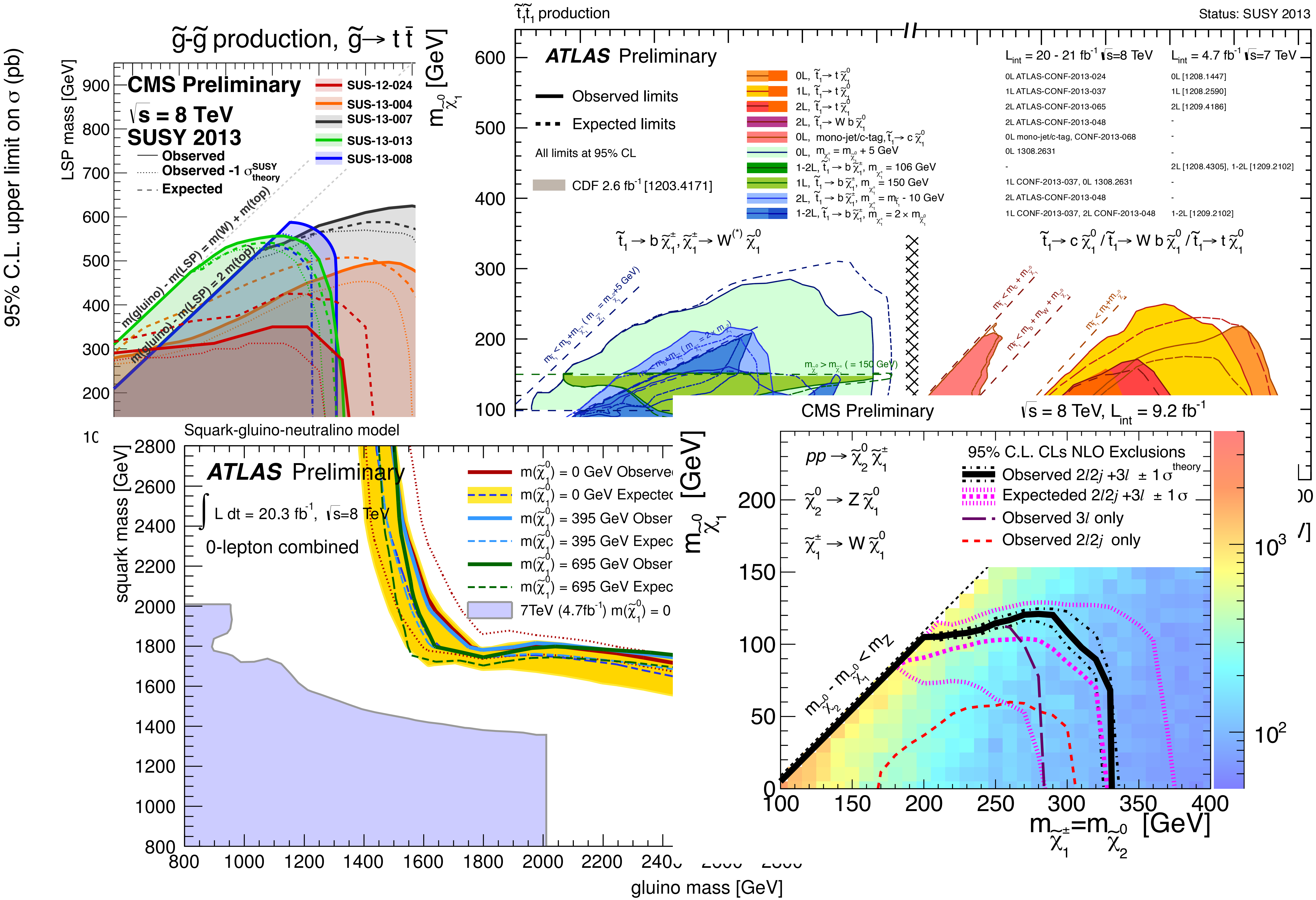

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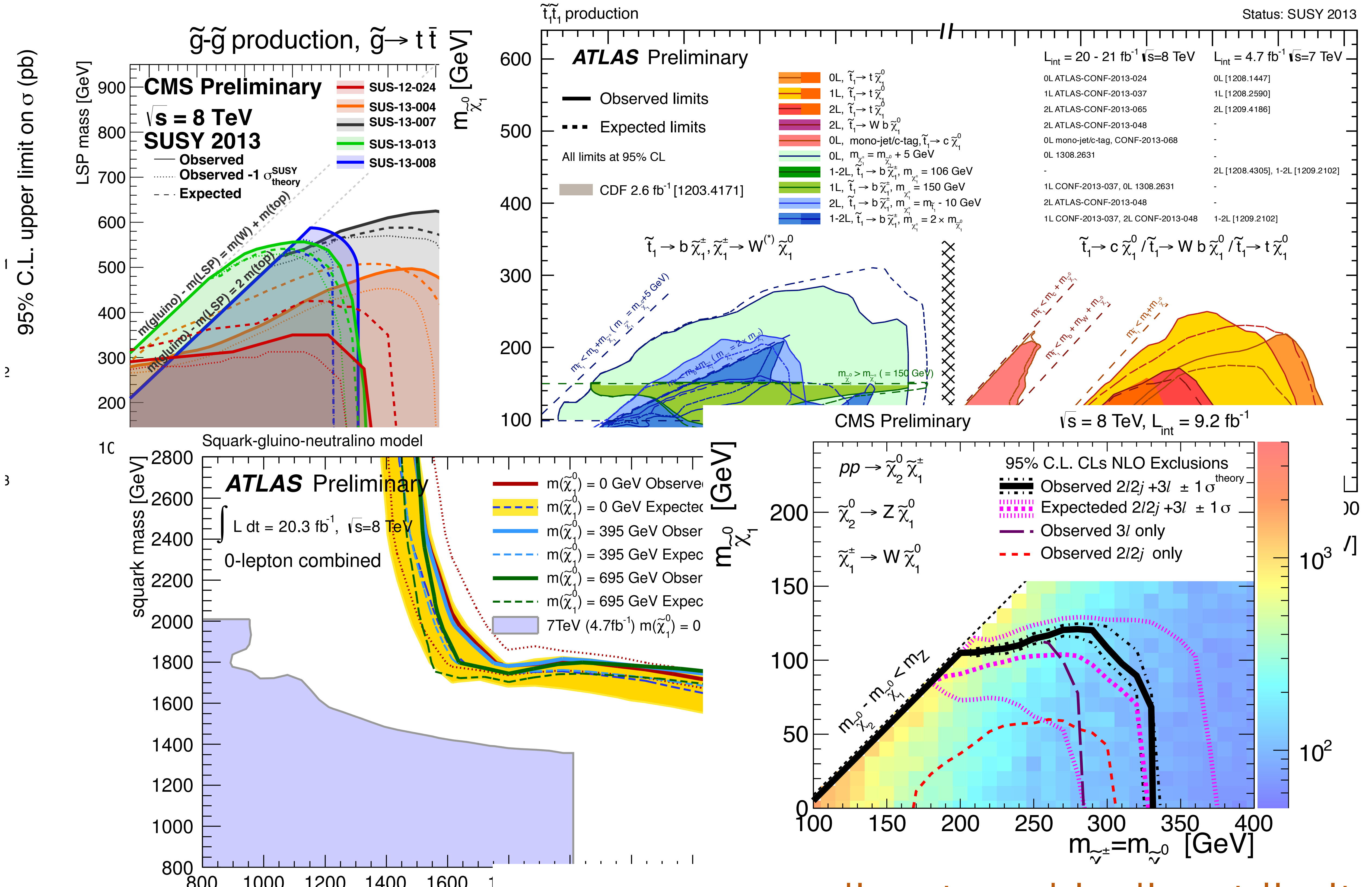
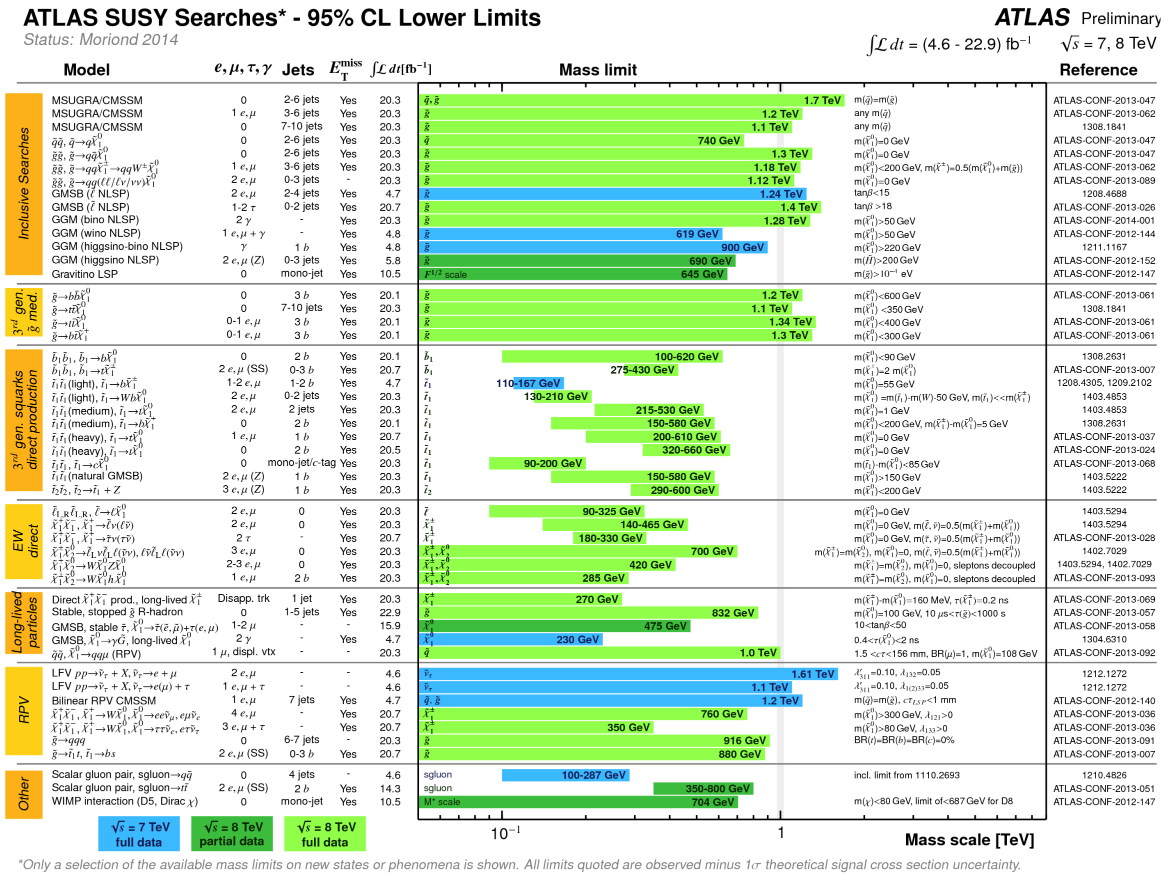


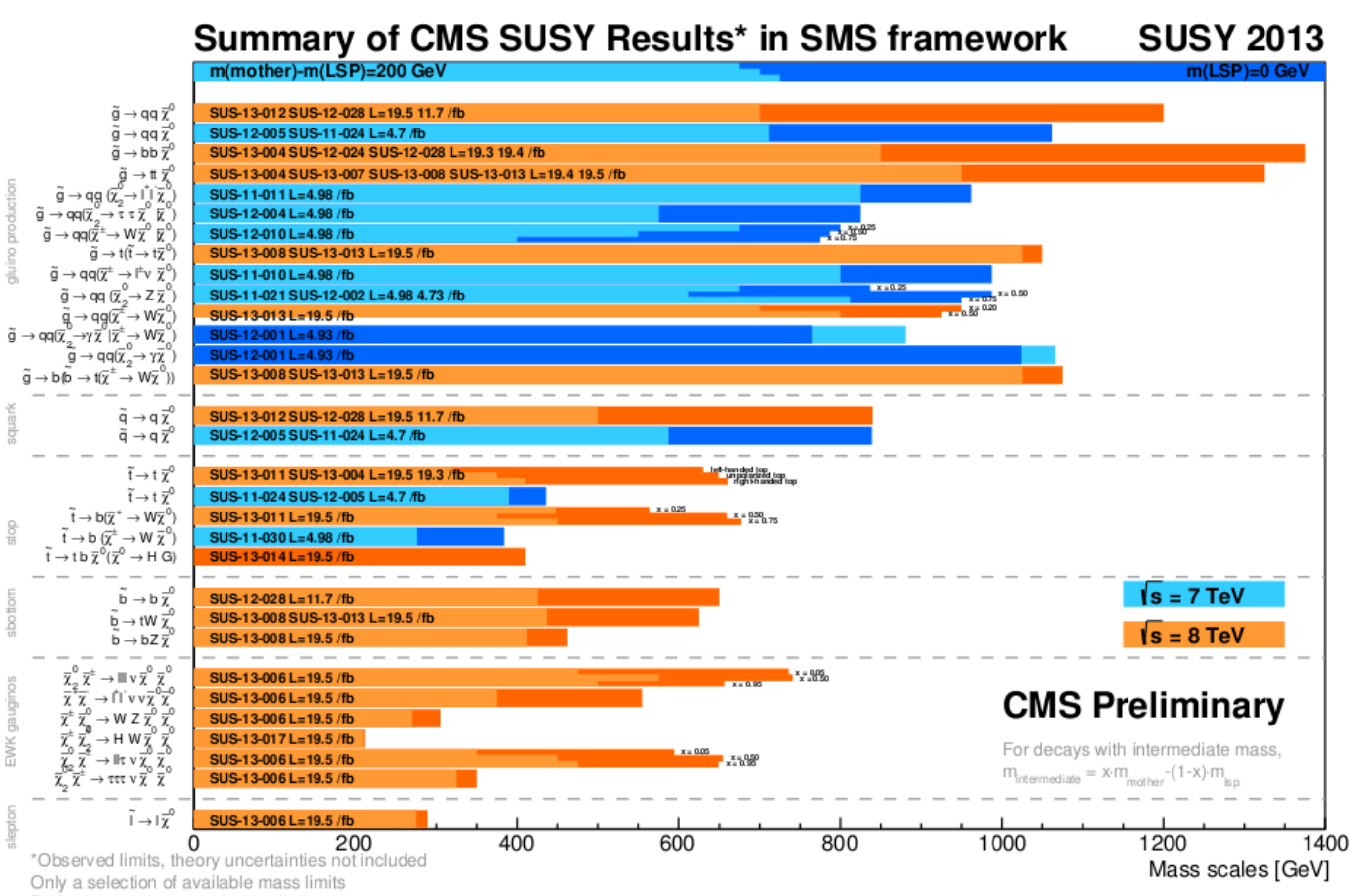
+ many more direct and indirect limits

the only stop seen at CERN



BUT:

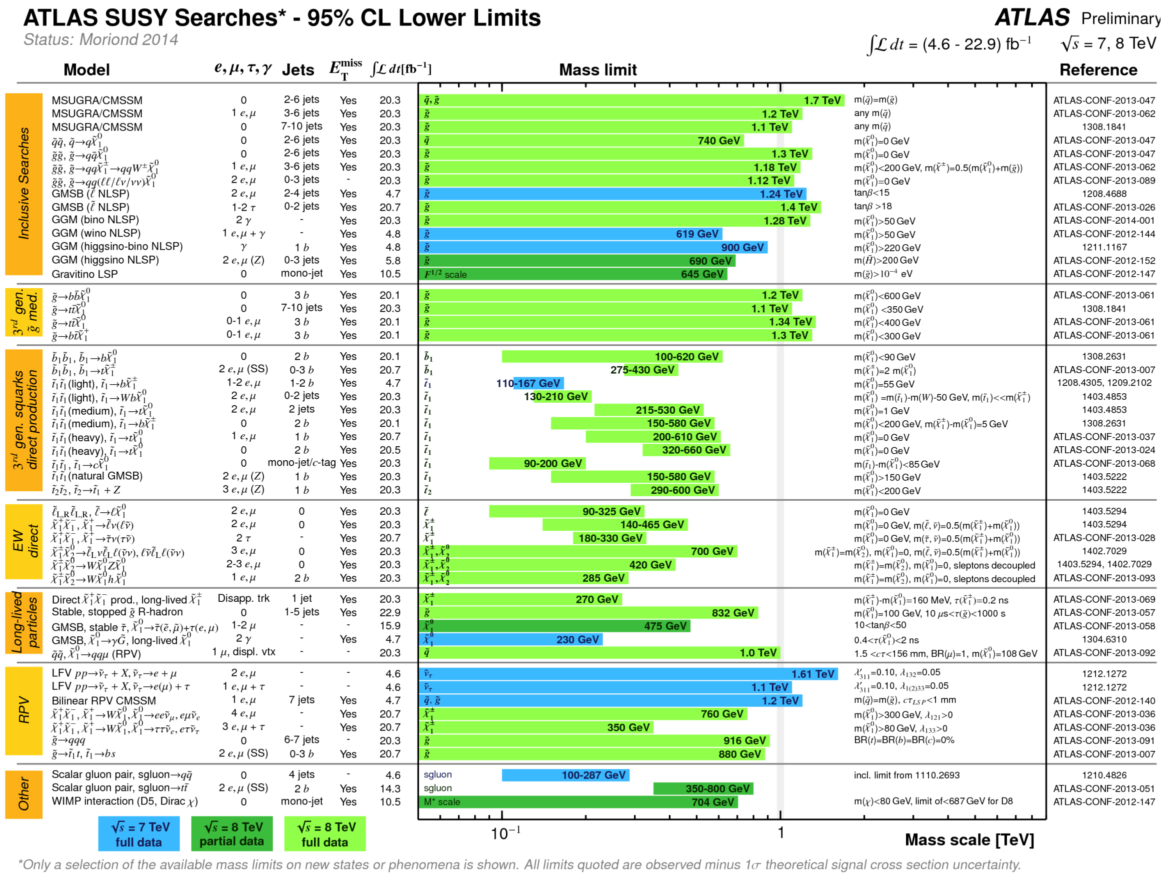
limits are driven by first generation squarks… not the most important states for EWSB



what do we need to be light?

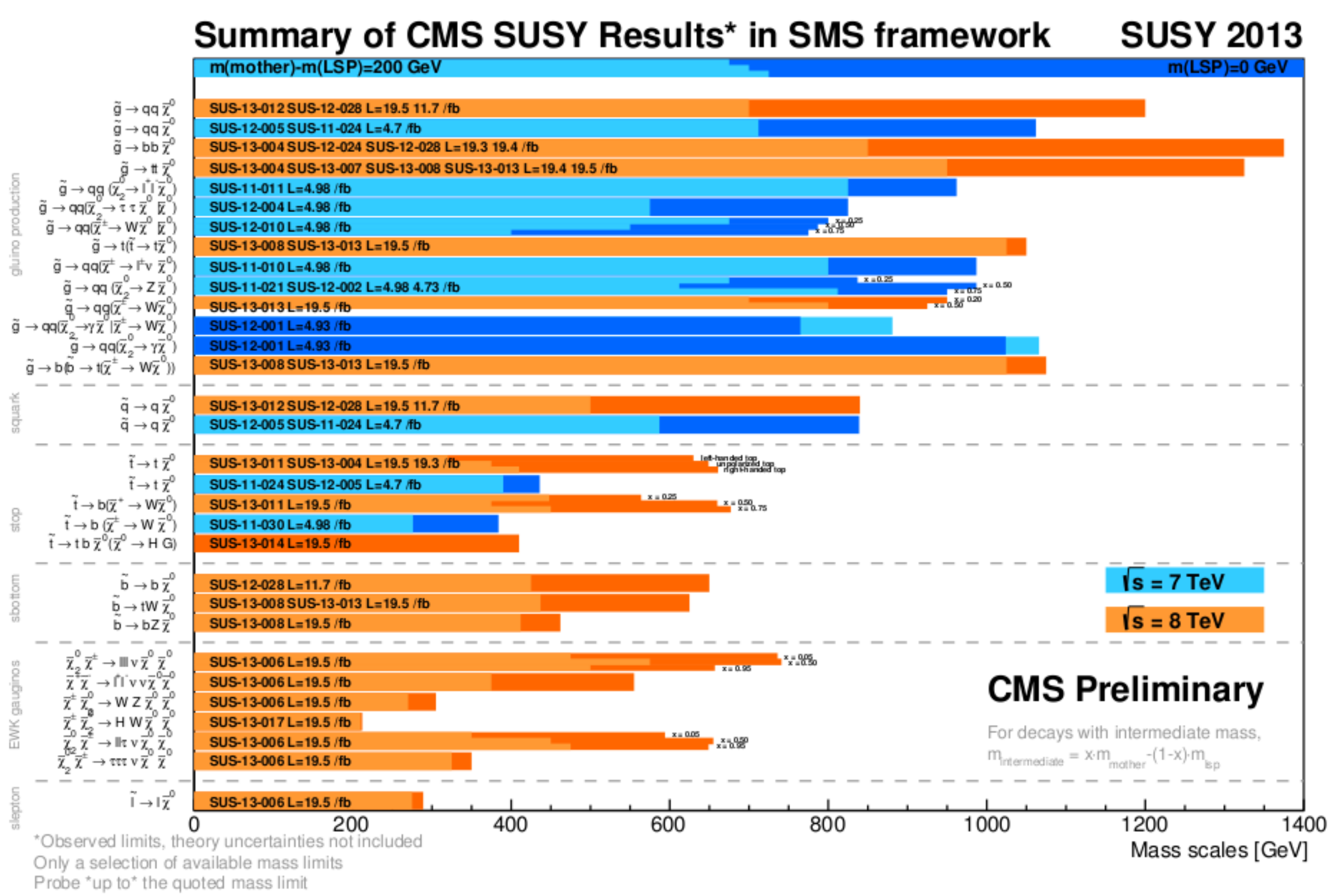
and

what do we need (analysis-wise, machine wise) to see those states?



BUT:

limits have holes



what do we need (analysis-wise, machine wise) to fill these gaps

Naturalness

$$\frac{1}{2}M_Z^2 = -m_{H_u}^2 - |\mu|^2 + O\Big(\frac{1}{\tan^2\beta}\Big)$$

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$$\Delta(|\mu|^2) = 10 \times \frac{|\mu|^2}{(200\ \mathrm{GeV})^2}$$

"tree-level"

$$\Delta(\delta m_{H_u}^2|_{\mathrm{stop}}) = \frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\log\frac{\Lambda_{\mathrm{mess}}}{(m_{\tilde{t}_1}m_{\tilde{t}_2})^{1/2}}$$

$$\simeq 10 \times \frac{m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2}{2\times(450\ \mathrm{GeV})^2}\,\frac{\log\Lambda_{\mathrm{mess}}/(m_{\tilde{t}_1}m_{\tilde{t}_2})^{1/2}}{3}\ .$$

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"loop-level"

small Δ pushes for

$\mu \sim$ 100-200 GeV

$m_{\mathrm{stop}} \sim$ 400 GeV

Naturalness

scale where SUSY-breaking communicated

$$\Delta(\delta m_{H_u}^2|_{\rm wino}) = \frac{3g_2^2}{8\pi^2}|M_2|^2 \log\frac{\Lambda_{\rm mess}}{|M_2|}$$

$$\simeq 10\times\frac{|M_2|^2}{(930\ {\rm GeV})^2}\,\frac{\log\Lambda_{\rm mess}/|M_2|}{3}$$

$$\Delta(\delta m_{H_u}^2|_{\rm gluino}) = \frac{2\alpha_s y_t^2}{\pi^3}|M_3|^2 \log\frac{\Lambda_{\rm mess}}{(m_{\tilde t_1} m_{\tilde t_2})^{1/2}}\log\frac{\Lambda_{\rm mess}}{|M_3|}$$

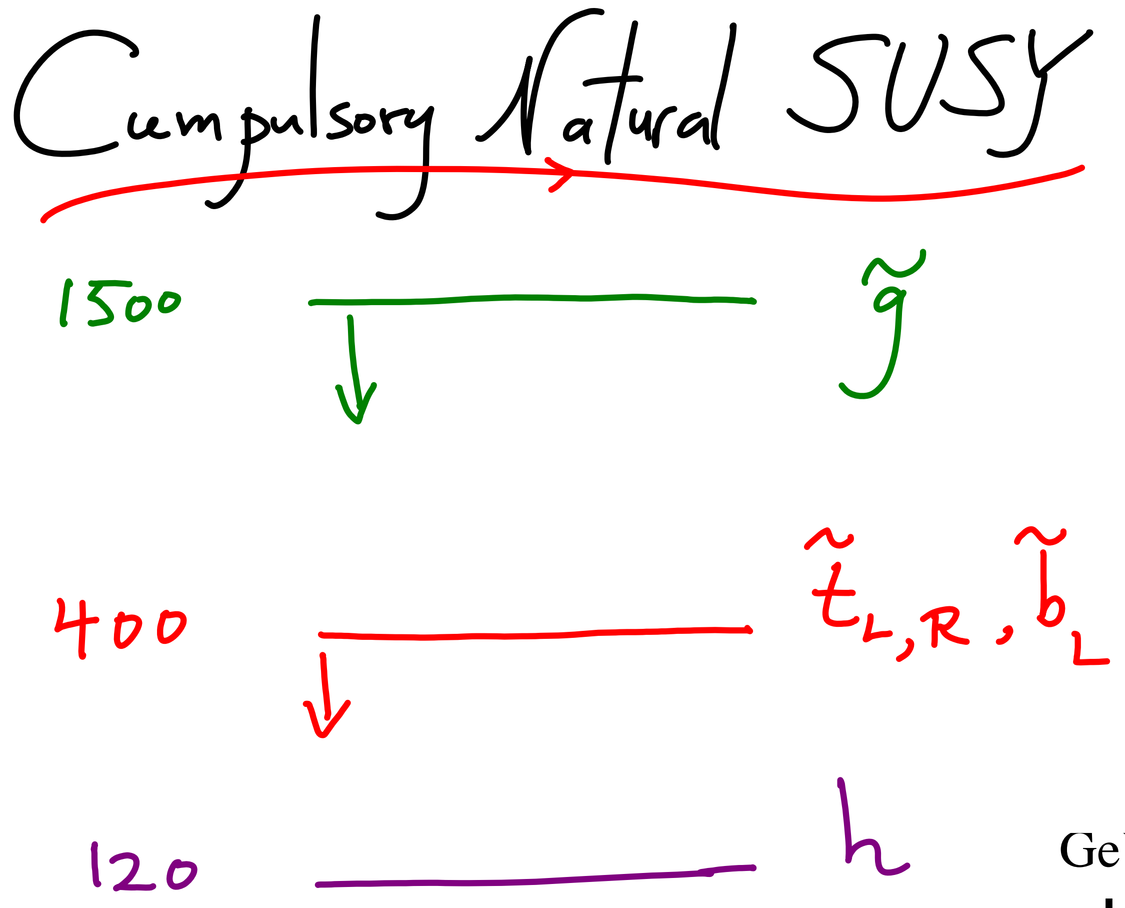
$$= 10\times\frac{|M_3|^2}{(1200\ {\rm GeV})^2}\,\frac{\log\Lambda_{\rm mess}/(m_{\tilde t_1} m_{\tilde t_2})^{1/2}}{3}\,\frac{\log\Lambda_{\rm mess}/|M_3|}{1.5}$$

wino: $\lesssim$ TeV

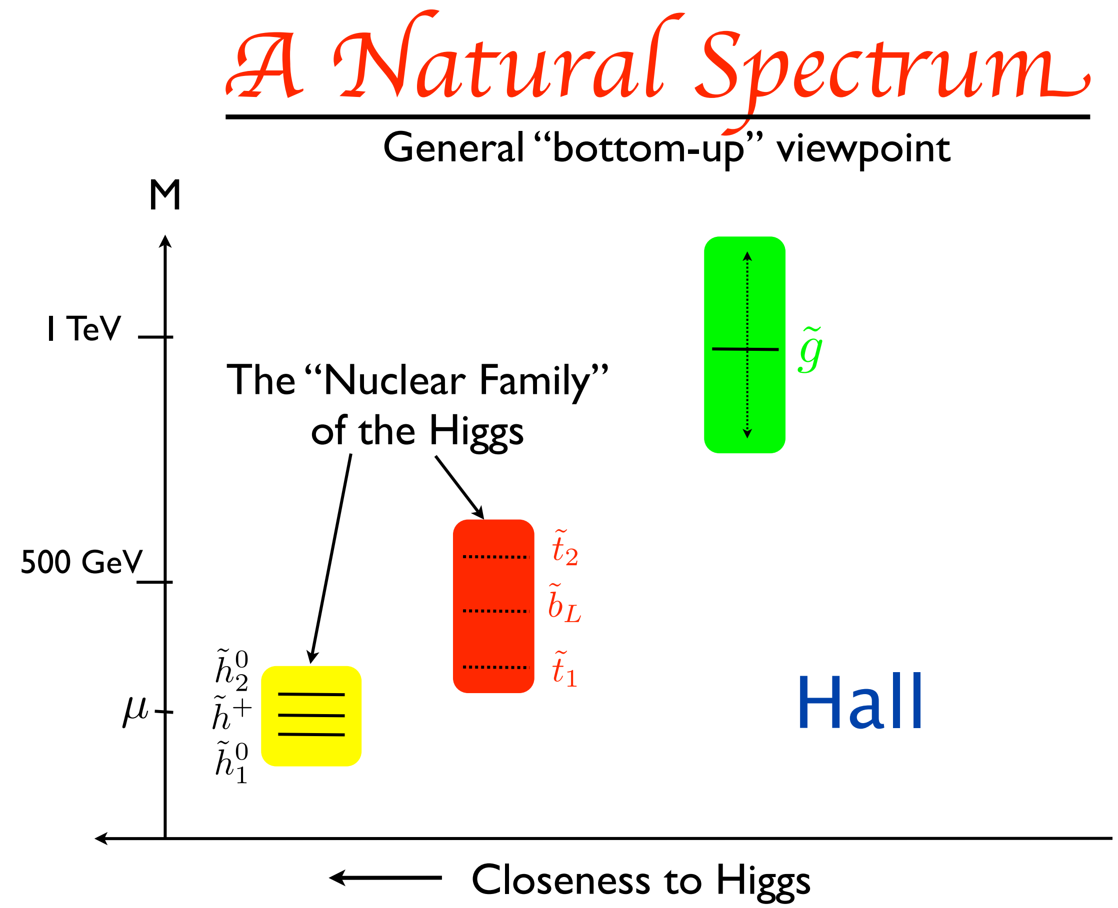
gluino: $\lesssim$ 1.3 TeV, comes from stop running

same sparticles affect Higgs mass, but weaker dependence

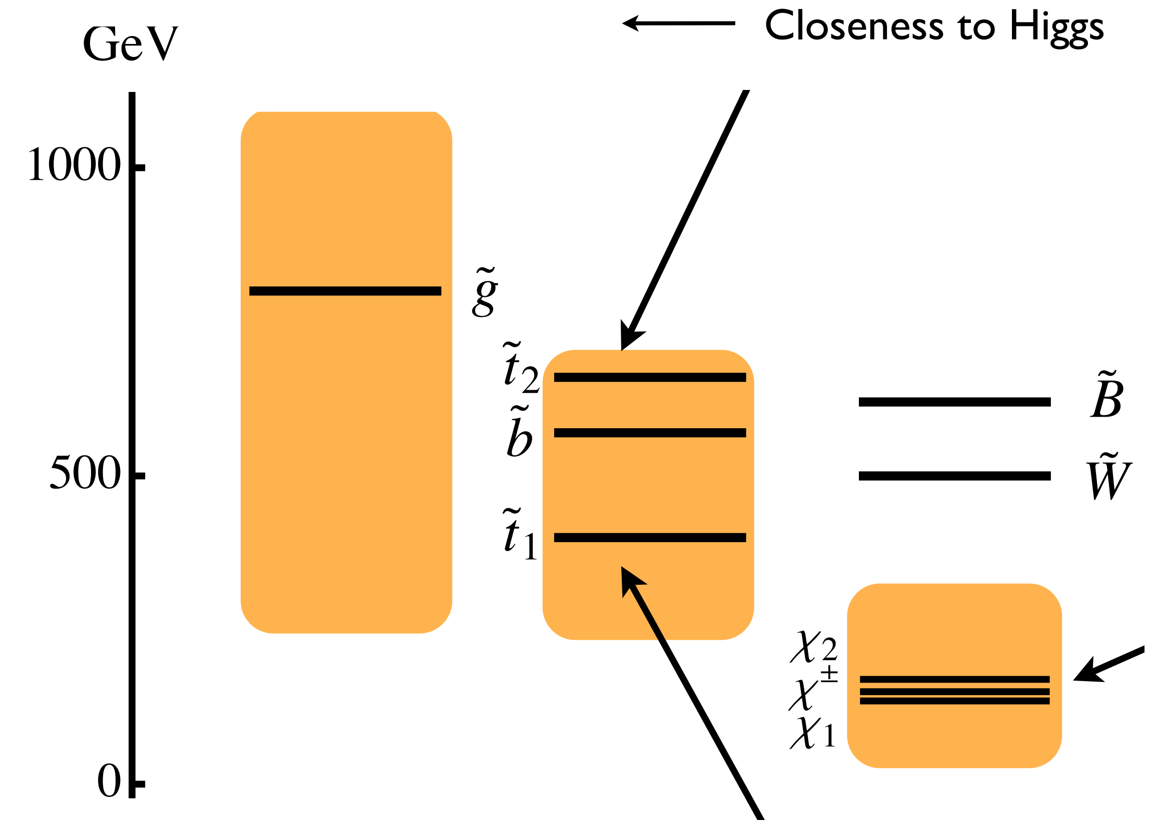
Naturalness



Arkani-Hamed



Hall



Barbieri

even without direct limits, a dose of reality

Higgs mass forces **MSSM** supersymmetry to shift expectations

$$m_{h^0}^2 = m_Z^2\cos^2(2\beta) + \frac{3}{4\pi^2}\sin^2\beta\, y_t^2\Big[m_t^2\ln\Big(m_{\tilde t_1}m_{\tilde t_2}/m_t^2\Big) + c_{\tilde t}^2 s_{\tilde t}^2(m_{\tilde t_2}^2 - m_{\tilde t_1}^2)\ln(m_{\tilde t_2}^2/m_{\tilde t_1}^2)$$
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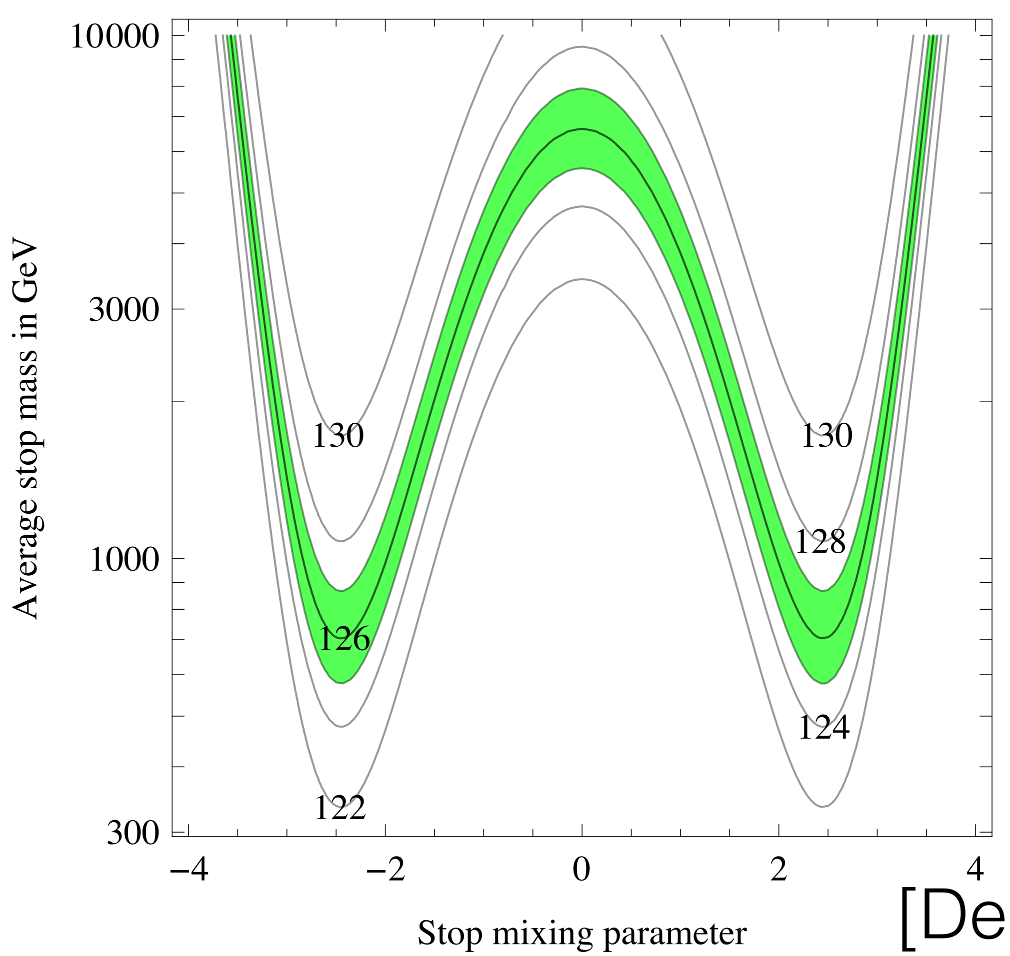

only log-sensitive to superpartner masses

large increase in stop mass
-> small m_h increase,
but **large** increase in Δ

[Delgado et al '12]

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though fairly easy to accommodate in extended setups

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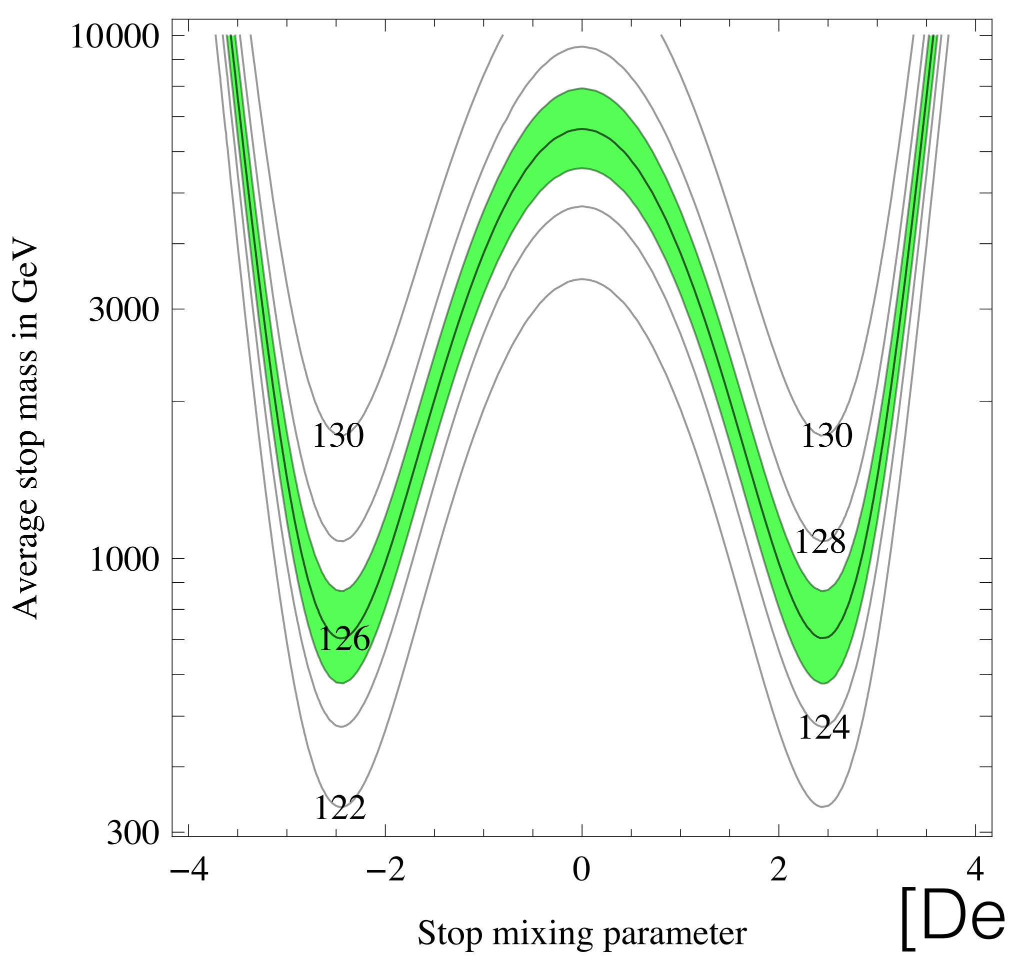

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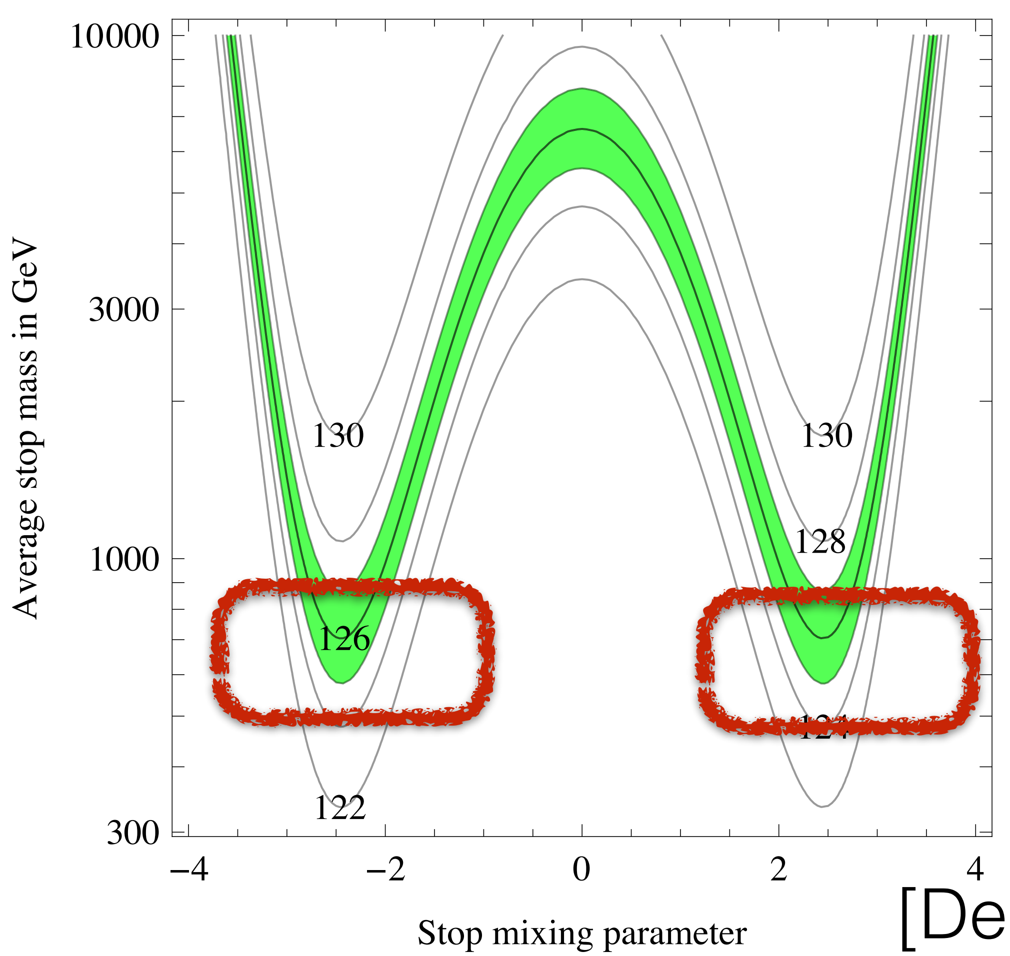

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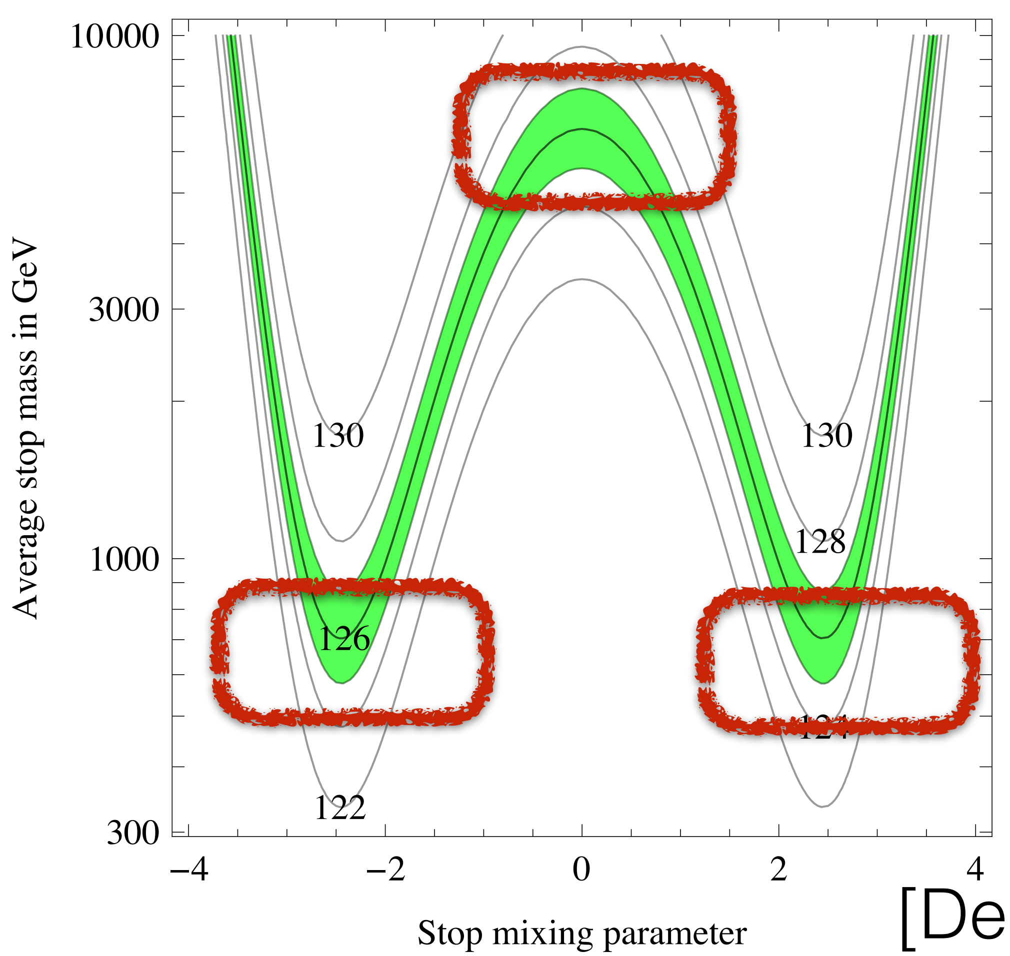

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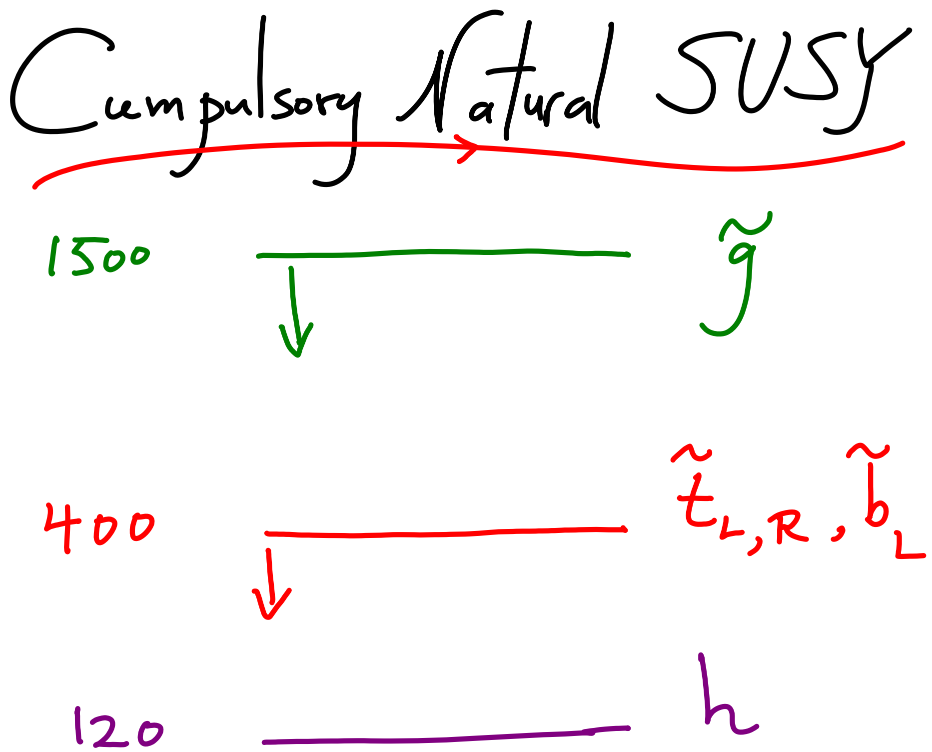
targeting natural SUSY

Higgs mass makes us accept more tuning, but the natural paradigm remains relatively unconstrained

Number 1 SUSY target for LHC_{14} + beyond



model building efforts well underway

[Craig et al ’11, ’12], [Delgado et al ’11]

lightest states are the Higgsinos (μ) and stops

(gluino contribution more model dependent.. (e.g. Dirac SUSY))

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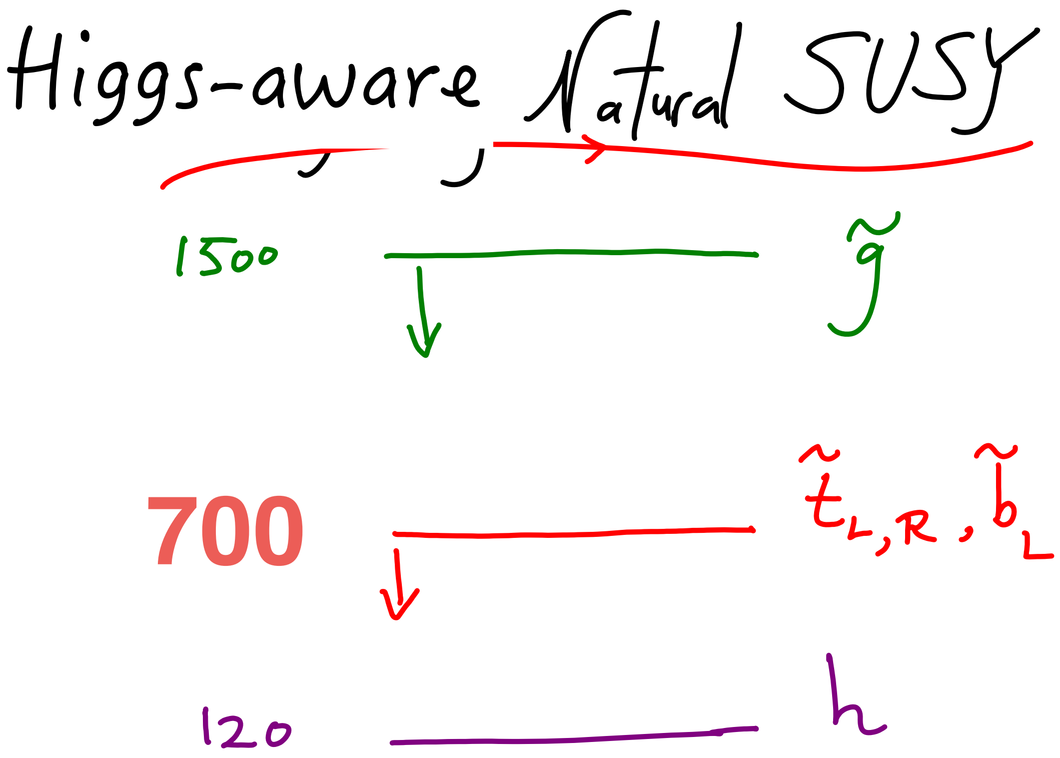

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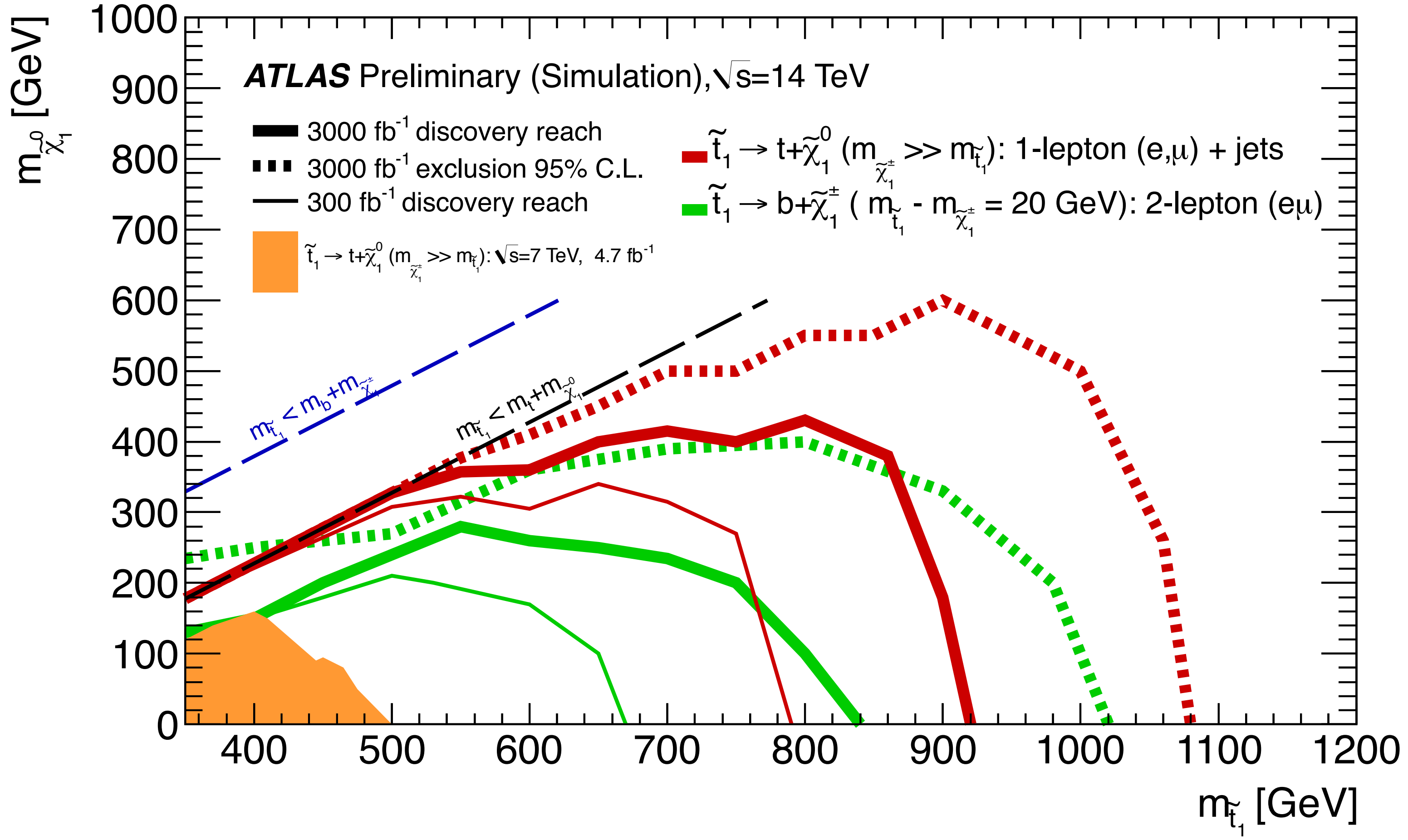
LHC reach estimate [Eur. Strategy book, 2013]



region where we need to get is where the LHC is running out of steam…

future collider should have **this** region in its sights

want to study the stop, not just discover it!!

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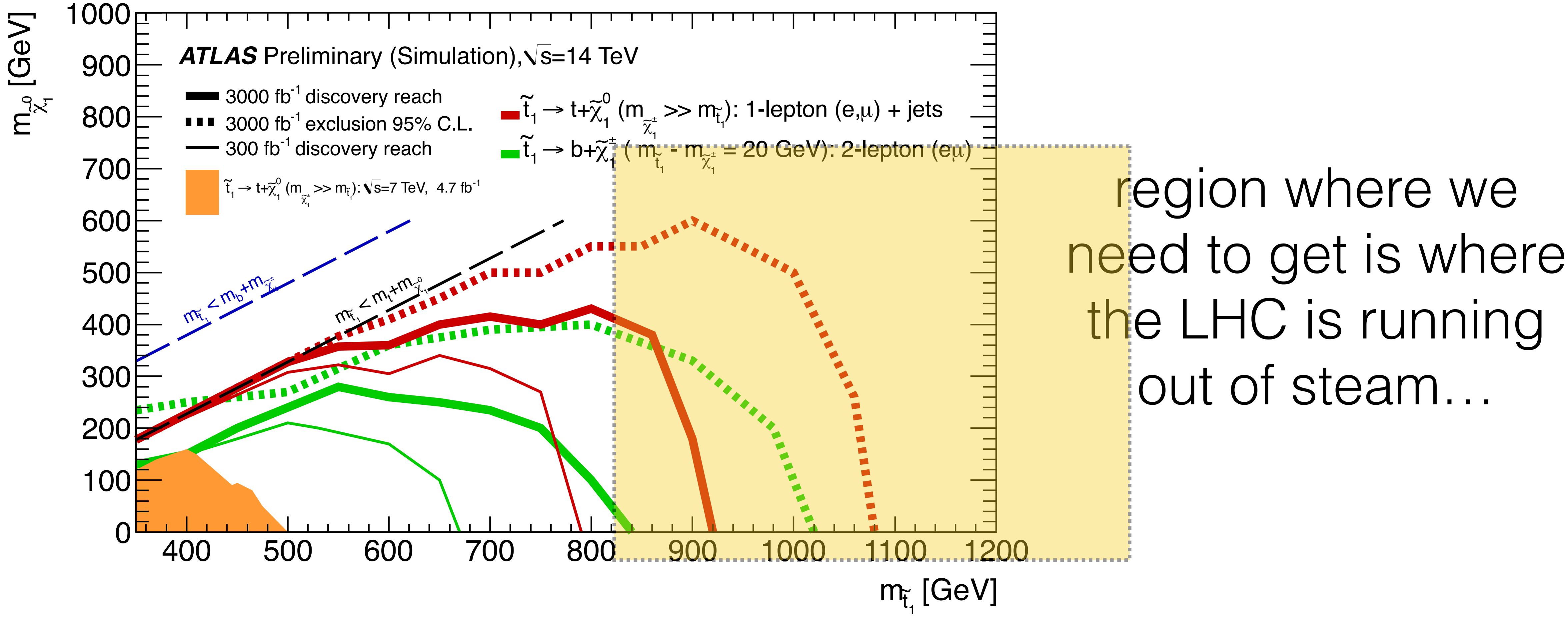

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- long cascade decays
- compressed spectra

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- long cascade decays
- compressed spectra

kills the MET signal by having the LSP decay to SM

spreads out energy over multiple final state objects, making them too soft for cuts

limits the phase space for decay particles, lowering the average energy and the MET

lots of tricks that allow lighter stops (and other states) to remain valid

- R-parity violation
- long cascade decays
- compressed spectra

clean environment and knowledge of initial state means lepton colliders are not confused by these tricks: 'loophole free'

[Berggren 1308.1461]

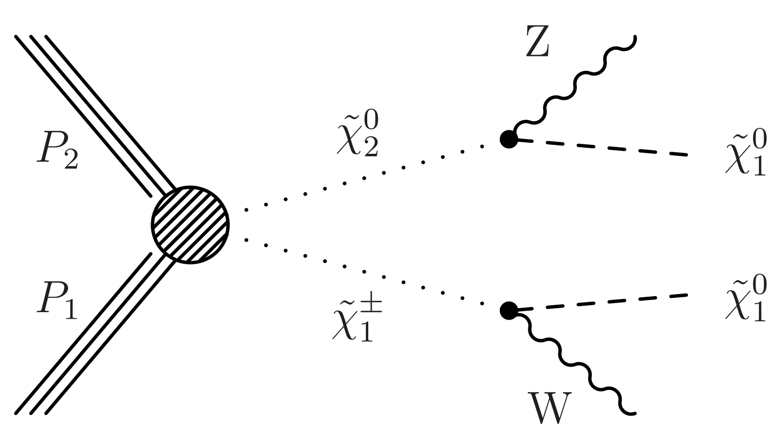
plus offer unparalleled precision in mass/mass-difference/spin/coupling measurements (though fewer recent/detailed studies done for μ-collider)

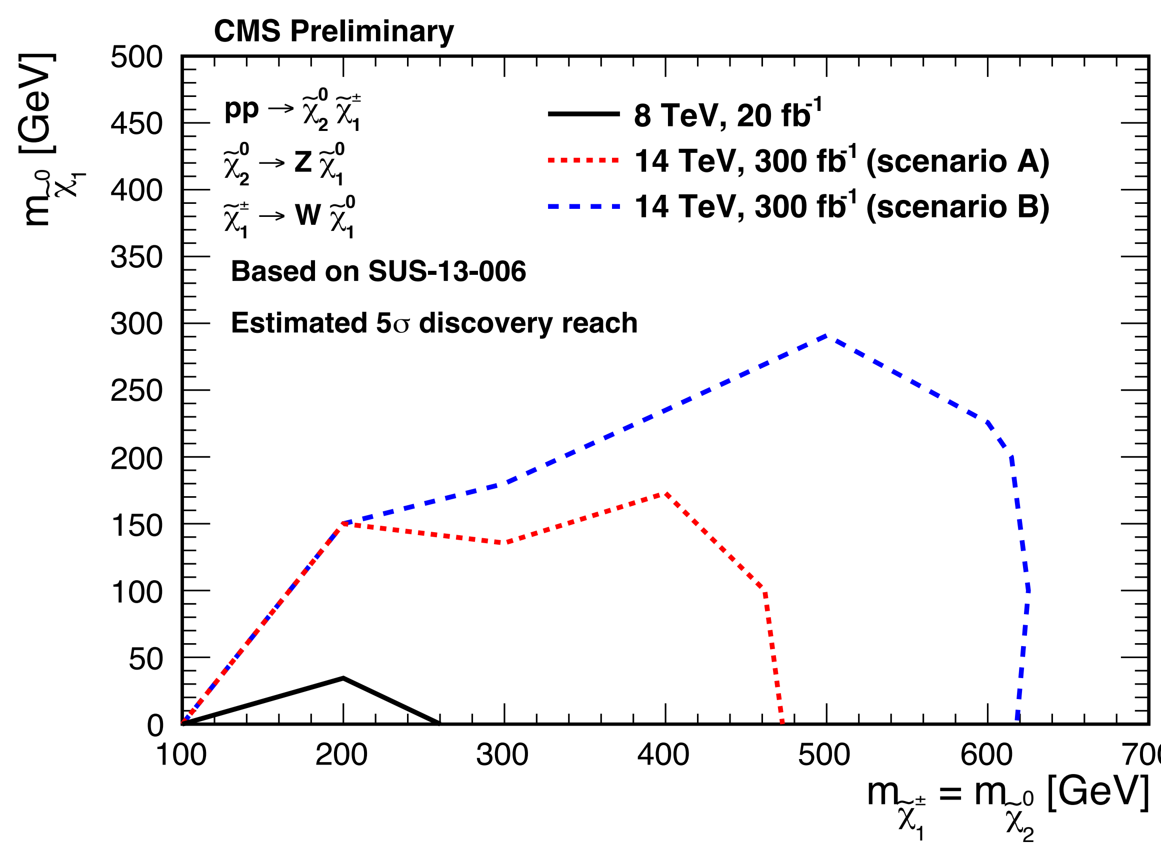
to take advantage of these benefits, need the energy to make the sparticles: μ-collider

light electroweakinos (Higgsinos/Winos/Bino)

μ must be light for naturalness → **prime** target for LHC/future collider studies

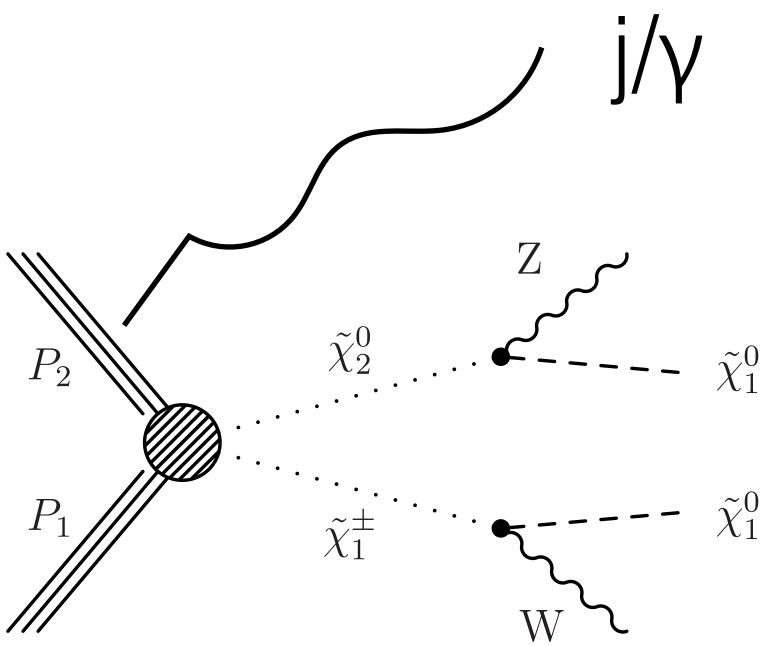
in some SUSY setups, i.e **split SUSY**, electroweakinos are the only TeV-scale particles, **motivated by DM & unification**





[CMS 1307.7135]

electroweakino mixtures can be as heavy as **~3 TeV** while remaining viable DM candidates… well beyond reach of LHC/ILC chargino searches lose sensitivity as mass increases or mass splitting decreases



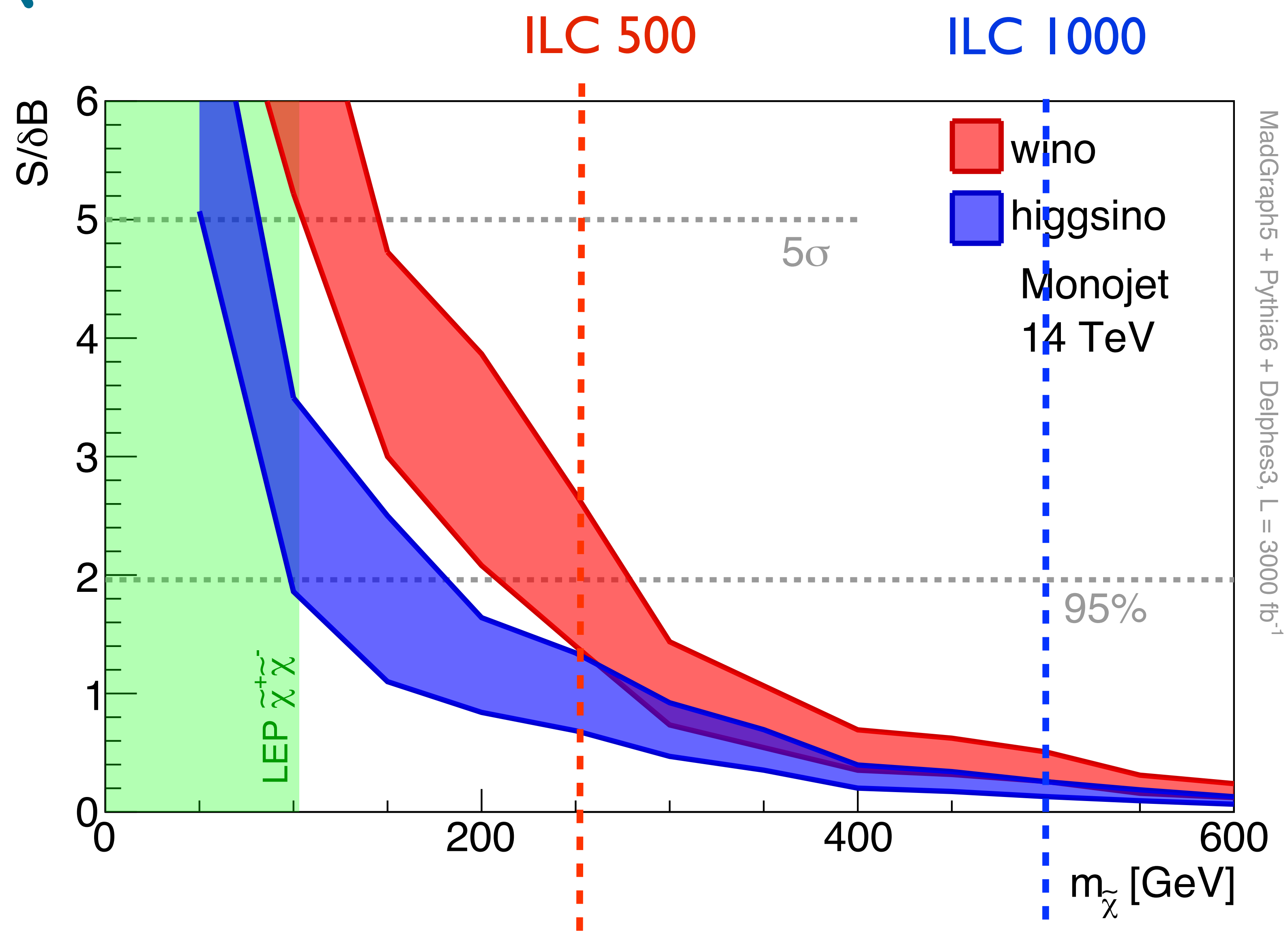
when states are nearly degenerate, must rely on ISR-assisted signals

tricky at LHC due to systematics on $Z(\nu\bar{\nu})$+j/γ background,

- ~ no limit at LHC_8
- limited reach even after several ab^{-1}, LHC_{14}

chargino searches lose sensitivity as mass increases or mass splitting decreases

Mono-X



[LT Wang]

ILC sensitivity near √s/2.. no μ-collider study I know of neutralino/chargino spectrum contains a lot of information about the theory (μ, M_1, M_2, $\tan\beta$)

full sector must be observed to distinguish between models

current 'standard' searches focus on $\chi^{\pm}\chi^{0}_{2}$

many extensions of the MSSM (i.e NMSSM) leave their most visible imprint in the EW-ino sector as extra states or modified interactions

precision, high energy studies necessary s-channel advantage:

all SUSY models contain extra Higgses H/A

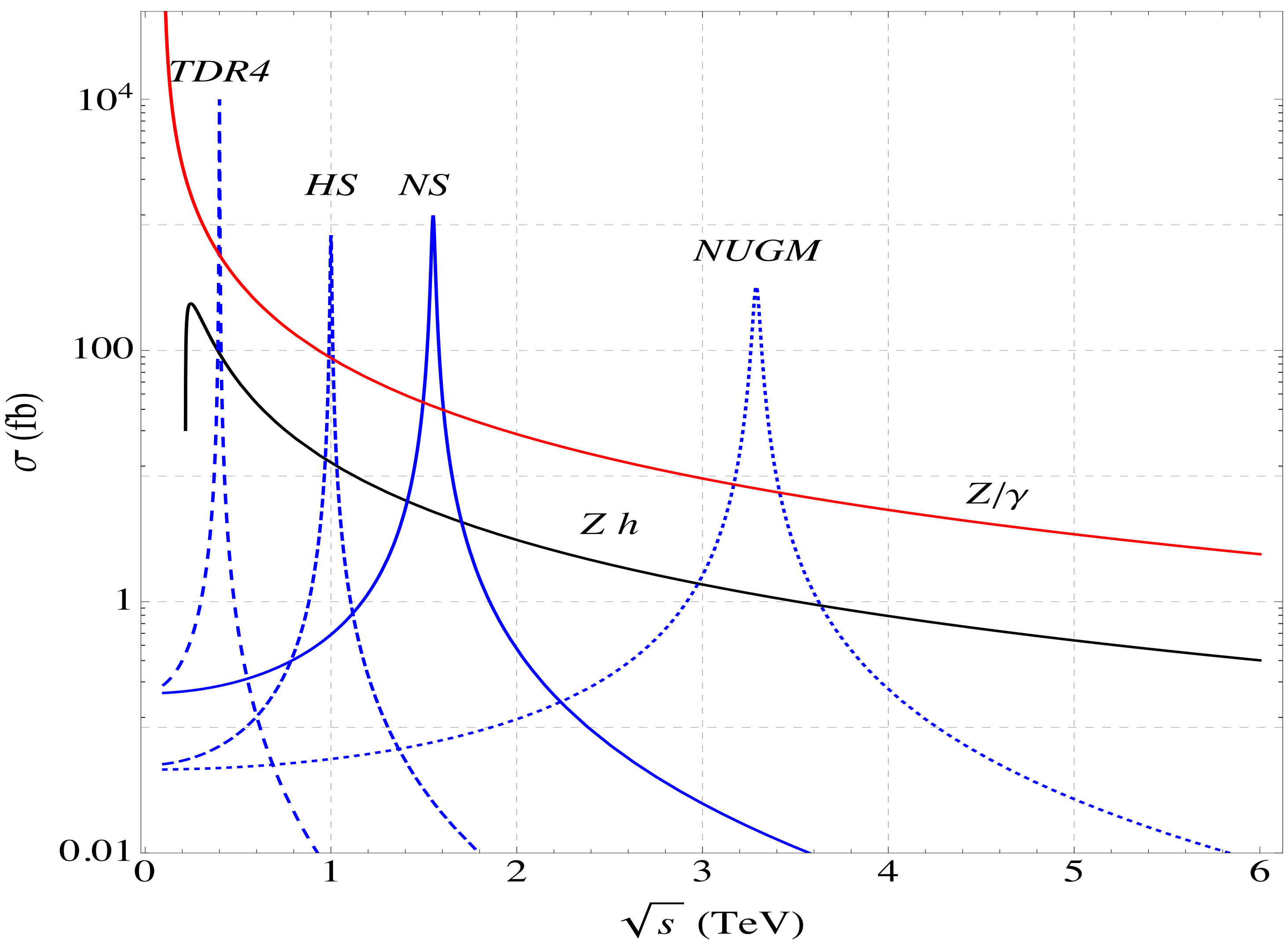
from Higgs (h) coupling measurements, we know H/A are essentially decoupled from WW/ZZ and are **narrow**

$m_H \sim m_A$ not pinpointed by naturalness, but also not tightly bounded at LHC

H/A can be produced as s-channel resonances at a μ-collider. Tuning $\sqrt{s} \sim m_H$, rate becomes enormous

$$\text{Events/year} = 1.54 \times 10^5 \times \left(\frac{\mathcal{L}}{10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}} \right) \left(\frac{1\,\text{TeV}}{m_{H/A}} \right)^2 \left(\frac{BR(H/A \to \mu^+\mu^-)}{10^{-4}} \right)$$

[Eichten, AM ’13]



depending on H/A separation, width, and energy resolution, two distinct peaks may be seen

if $m_H > 2\ m_X$ for some superpartner (electroweakinos!), pp → H/A is a new SUSY source

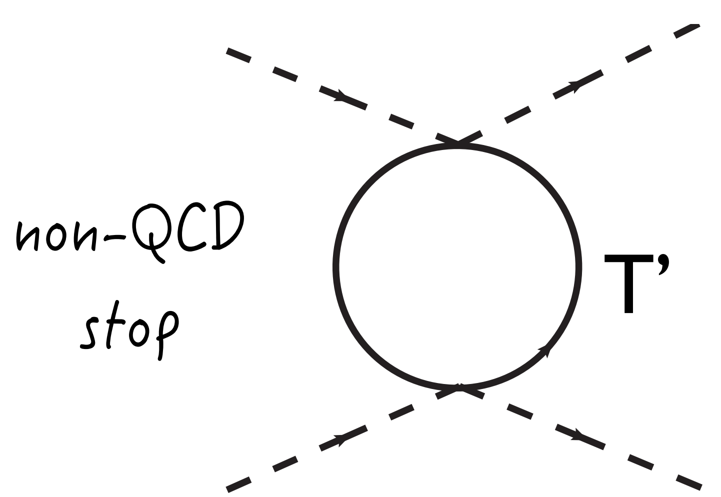
even at ~few % BR, pp → H/A → XX can far exceed other X production modes nasty scenarios still exist…

cancellation of quadratic sensitivity of Higgs mass does not require top-partner has QCD color, just the same # of d.o.f.

could have a SUSY where the stop is not colored under our QCD!

'Folded Supersymmetry' [Burdman, Chacko et al '06]

little studied, but best option is likely precision Higgs



→ $\#|DH|^2$, so acts as a wave-function renormalization & shifts all Higgs couplings

[Craig, Englert, McCullough '13]

Conclusions

direct LHC constraints and m_h = 126 GeV have cut a swath out of SUSY parameter space

`Natural' spectra remain the least constrained and are a main goal for LHC14 + beyond (m_{stop}, m_{inos} < few TeV)

to thoroughly search for &, if found, measure SUSY, a **high-energy, high precision** lepton collider is the best tool

if μ-collider is the best combination of these traits, its the machine to use (added bonus of s-channel H/A factory)

updated, detailed studies of μ-collider capabilities for precision SUSY/DM studies motivated

EXTRAS

more detailed limits