Natural Susy Endures

Andreas Weiler
(DESY)

NPKI workshop, Seoul
27/2/12

With
Michele Papucci & Josh Ruderman
arXiv:1110.6926

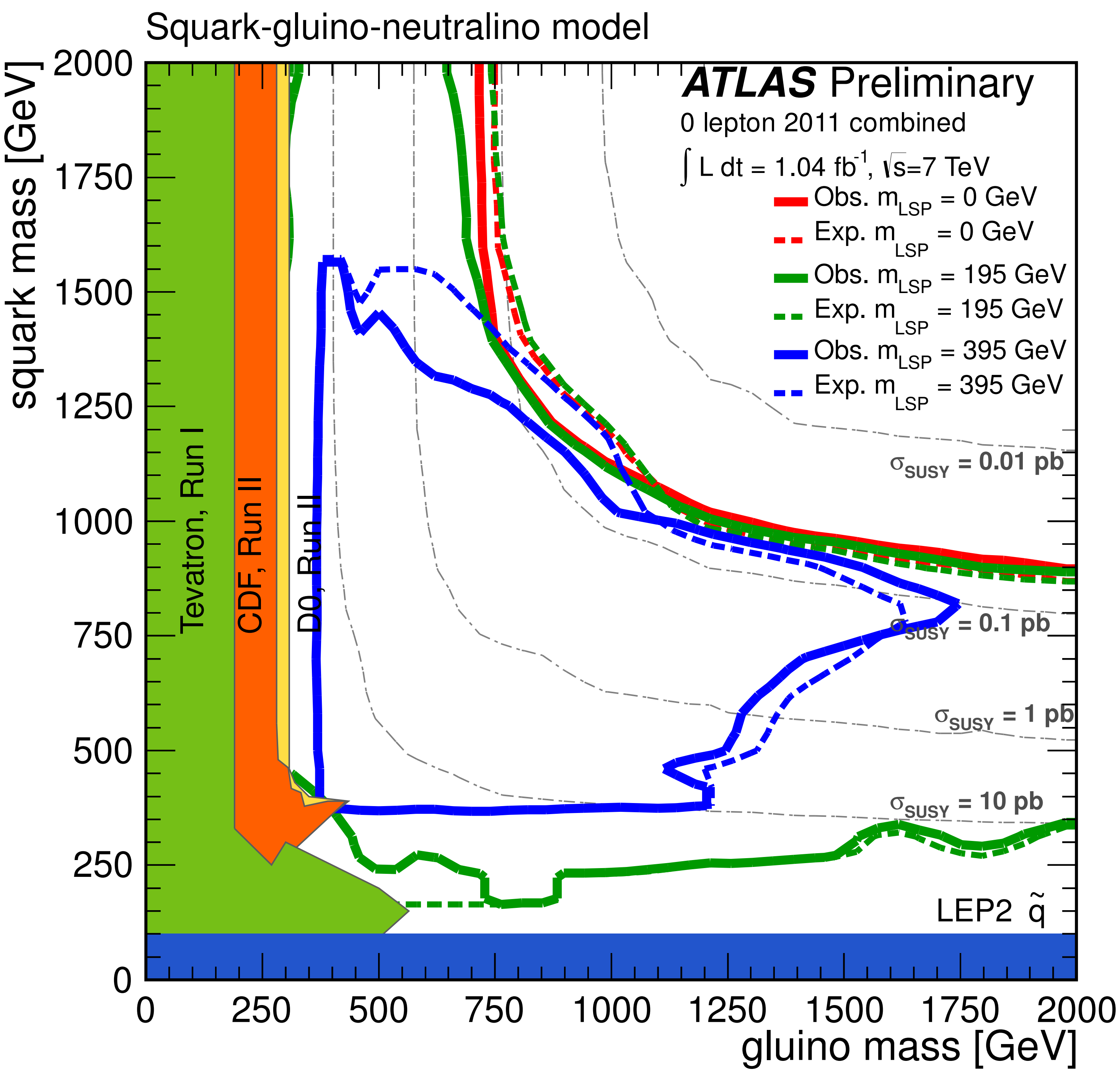
Related papers

R. Essig, E. Izaguirre, J. Kaplan, J. G. Wacker, arXiv:1110.6443.
Y. Kats, P. Meade, M. Reece, D. Shih, arXiv:1110.6444.
C. Brust, A. Katz, S. Lawrence, R. Sundrum, arXiv:1110.6670.

Everything is natural; if it weren’t, it wouldn’t be.

M. Bateson

1/fb Susy, pre-Moriond



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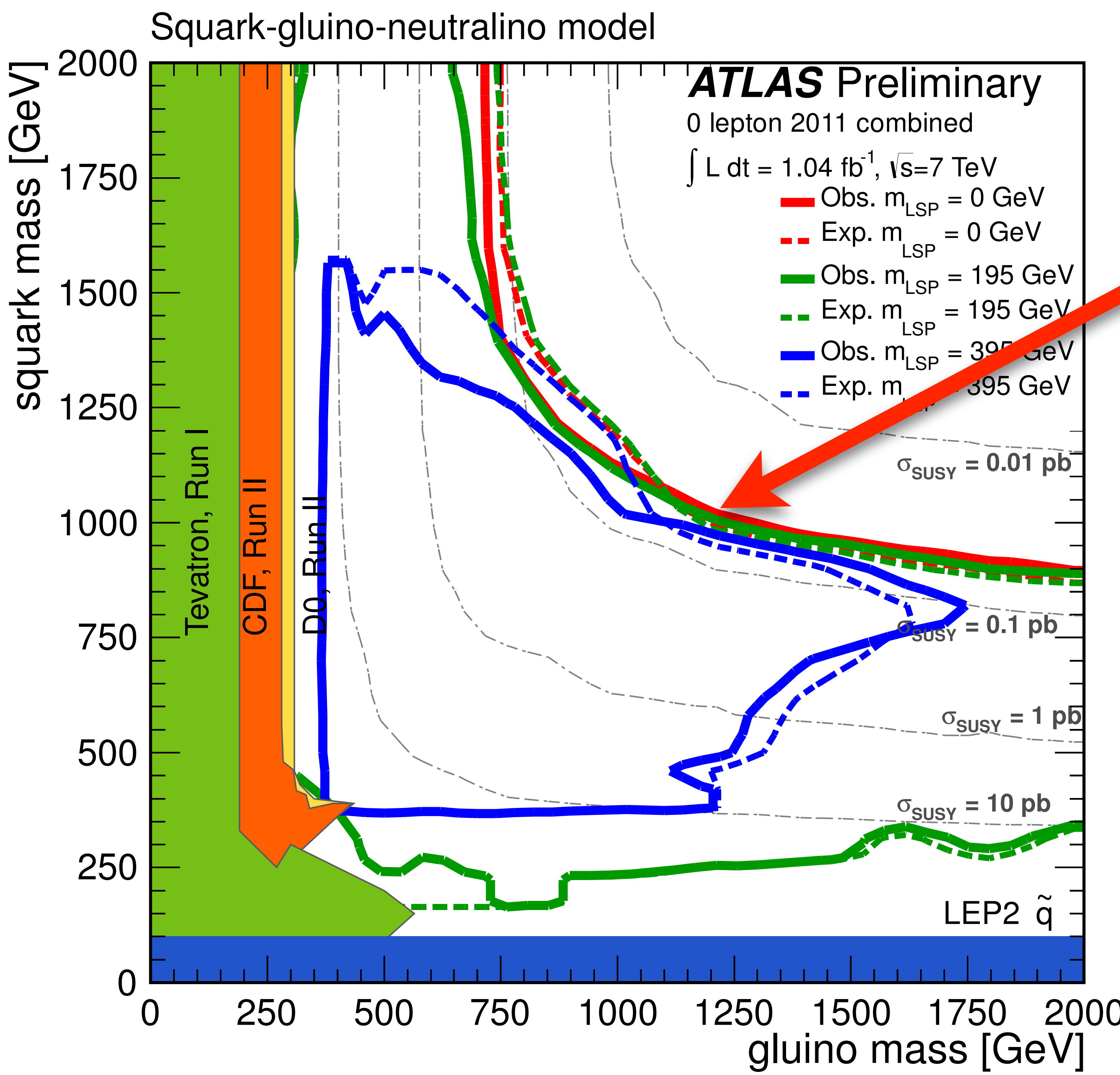
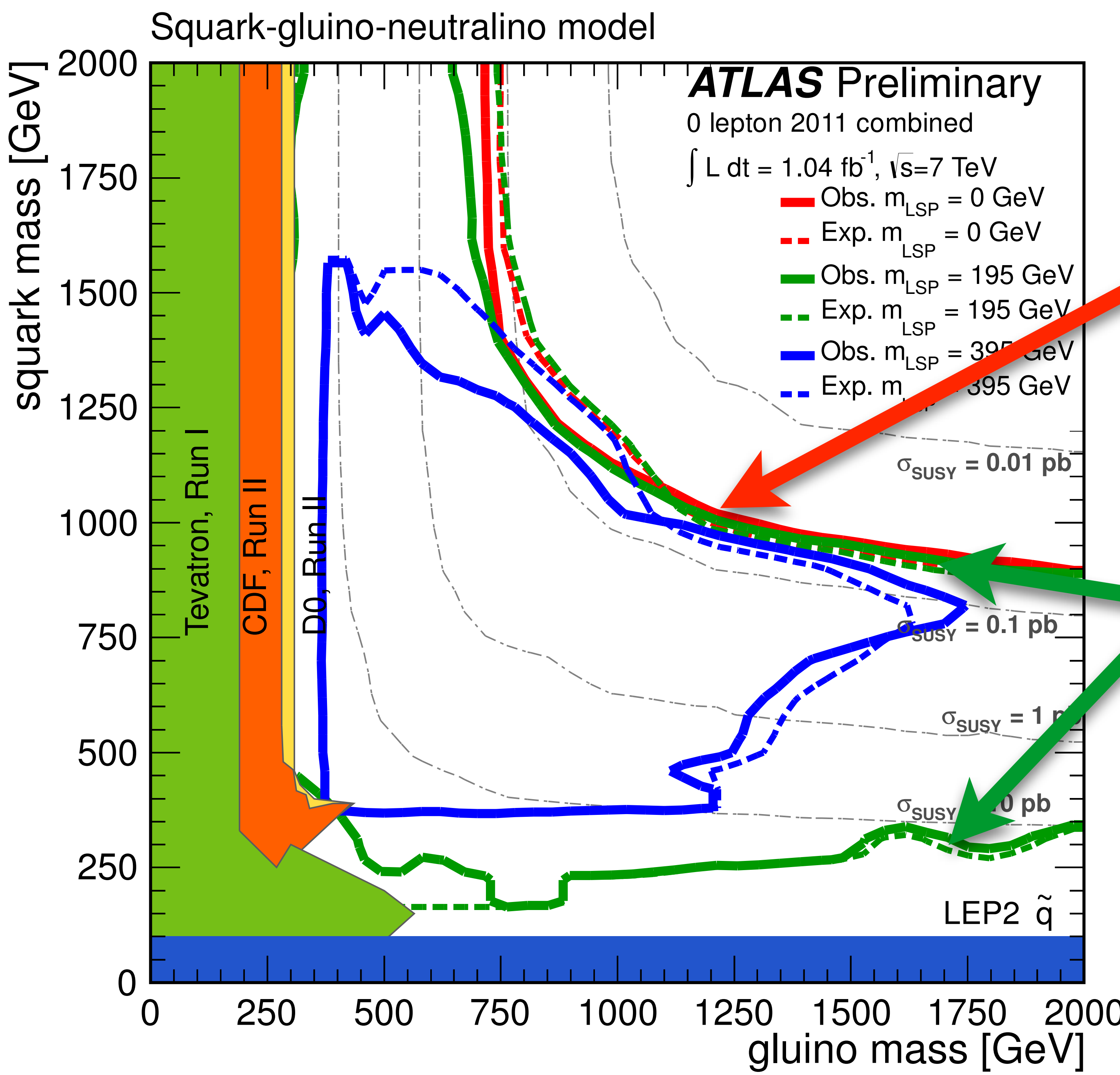


$m_{LSP} = 0$ GeV

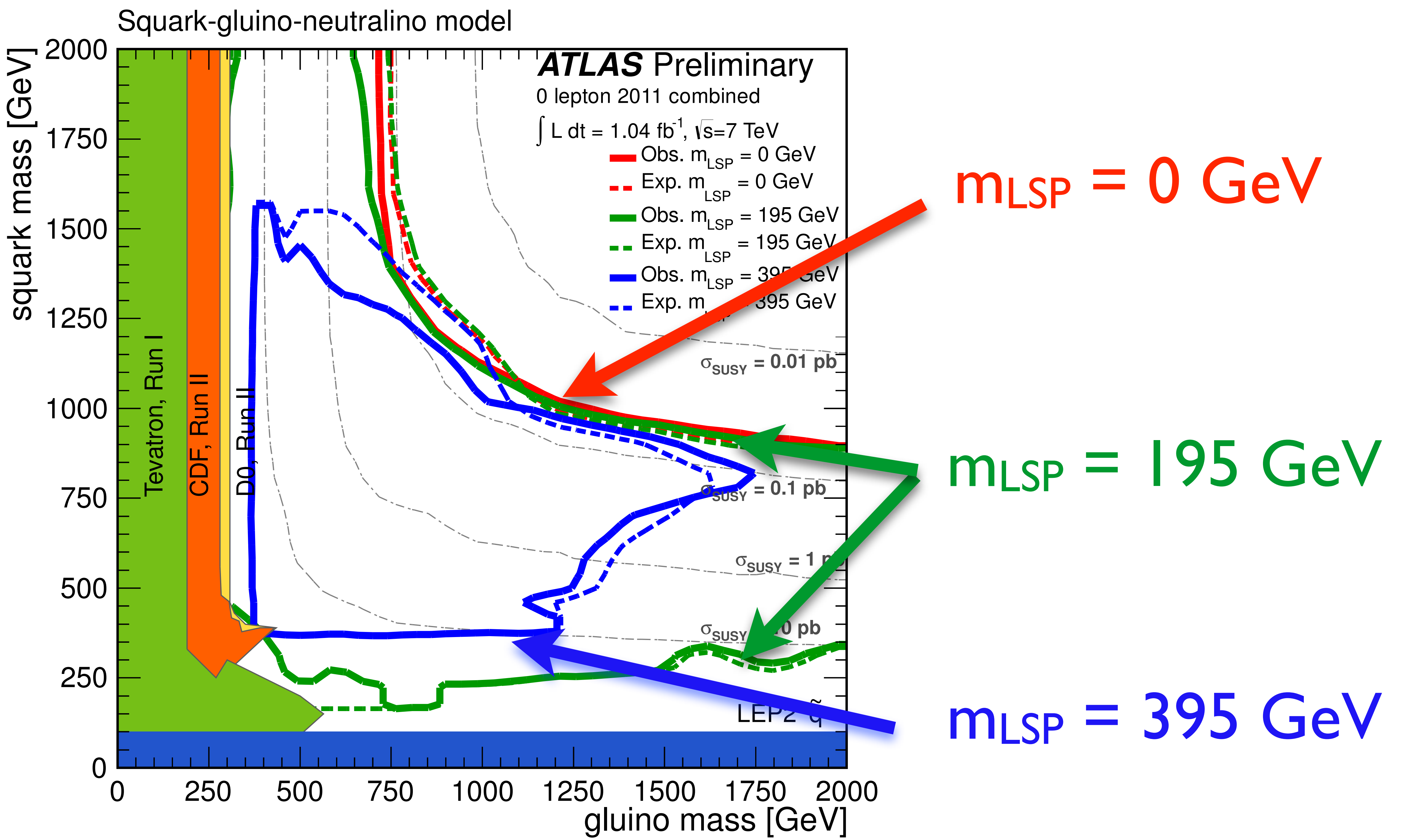
1/fb Susy, pre-Moriond



mLSP = 0 GeV

mLSP = 195 GeV

1/fb Susy, pre-Moriond



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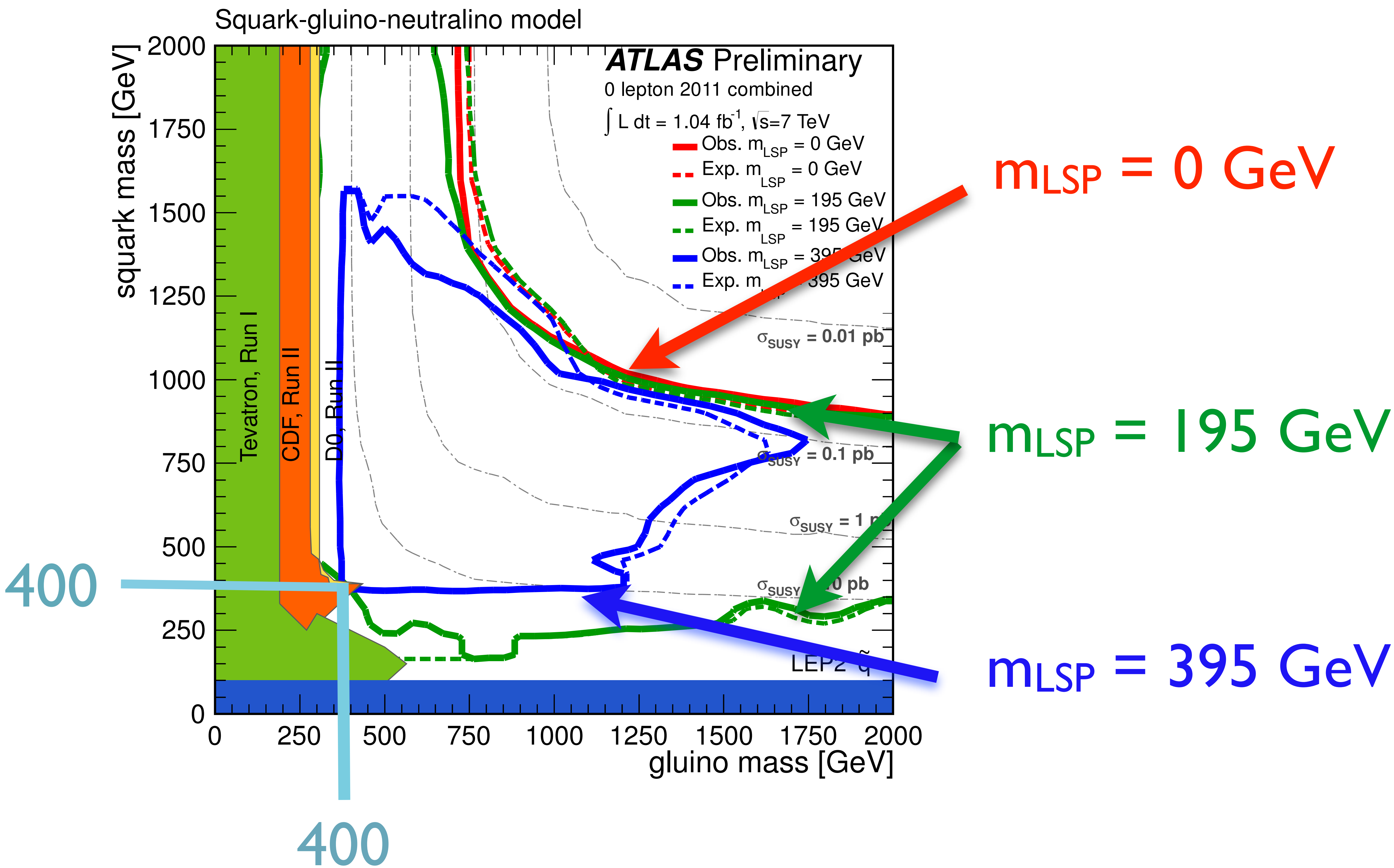

Avoiding m_{SUSY} > TeV

- R-parity violation? → Csaba's talk
- Stealth susy? → Matt's talk
- Compressed susy? (ISR?)
- bottom-up natural spectrum! → this talk

- Bottom-up naturalness reminder
- What are the limits?

h = linear combination of fields whose vev breaks EW symmetry

$$V = m_H^2 |h|^2 + \frac{\lambda}{4} |h|^4 \qquad m_h^2 = \lambda v^2 = -2 m_H^2$$

$$\Delta = \frac{2|\delta m_H^2|}{m_h^2}$$

measures fine-tuning

Natural EWSB & MSSM

Fine-tuning of (Higgs mass)^2

$$\frac{m_Z^2}{2} = -|\mu|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}$$

$$\approx -|\mu|^2 - m_{H_u}^2 - \delta m_{H_u}^2$$

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H$$

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

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Higgsinos

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

Higgsinos

1loop $\delta m_H^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2 \right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$

stops, sbottom$_L$

2loop $\delta m_H^2|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$

gluino

EW-inos:

$$\delta M_H^2|_{bino} = \frac{3}{8\pi^2}\frac{g'^2}{3}M_1^2 \ln\frac{\Lambda}{\mathrm{TeV}}$$

$$\delta M_H^2|_{wino} = \frac{3}{8\pi^2}g^2 M_2^2 \ln\frac{\Lambda}{\mathrm{TeV}}$$

Bottom-up natural spectrum

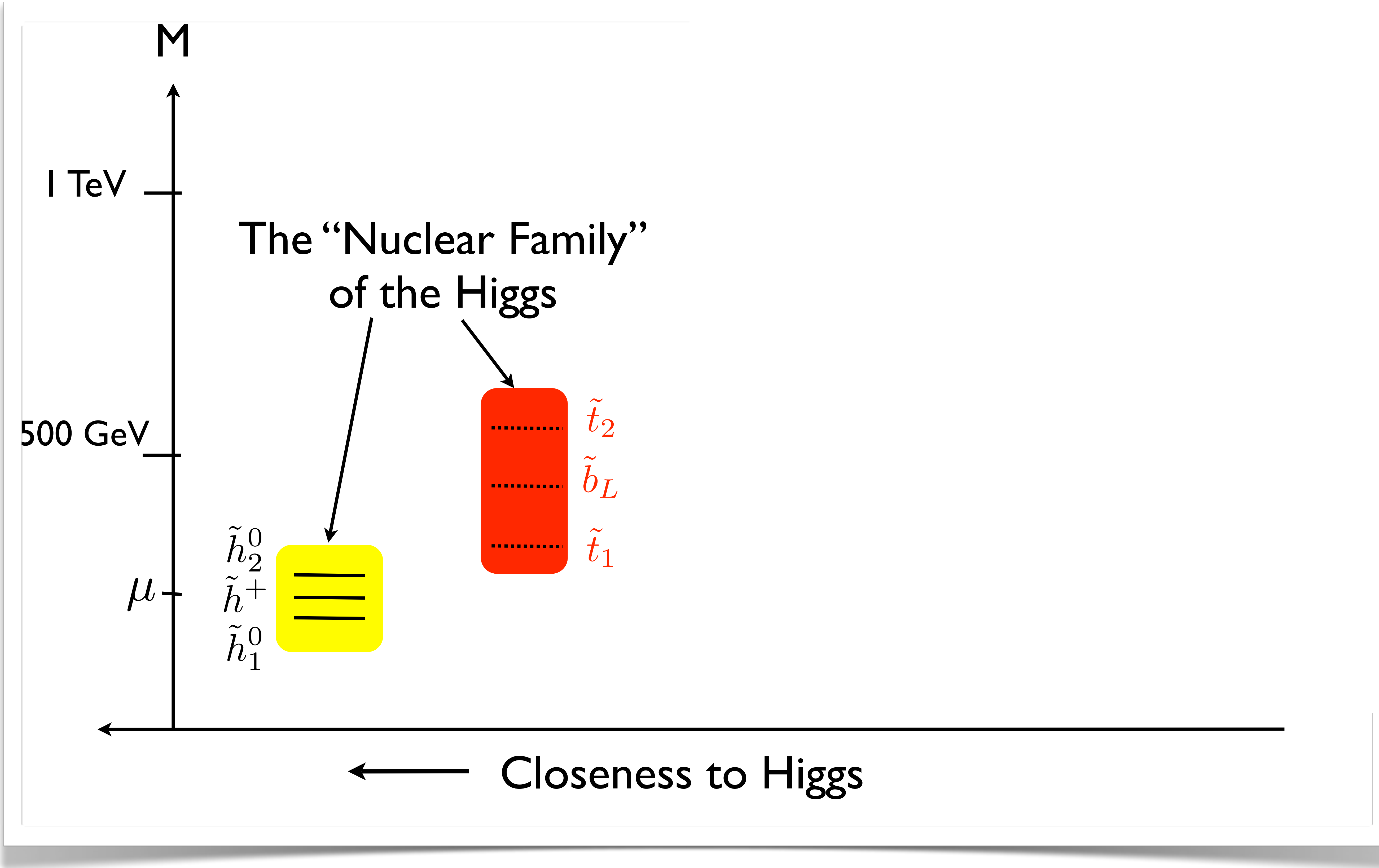
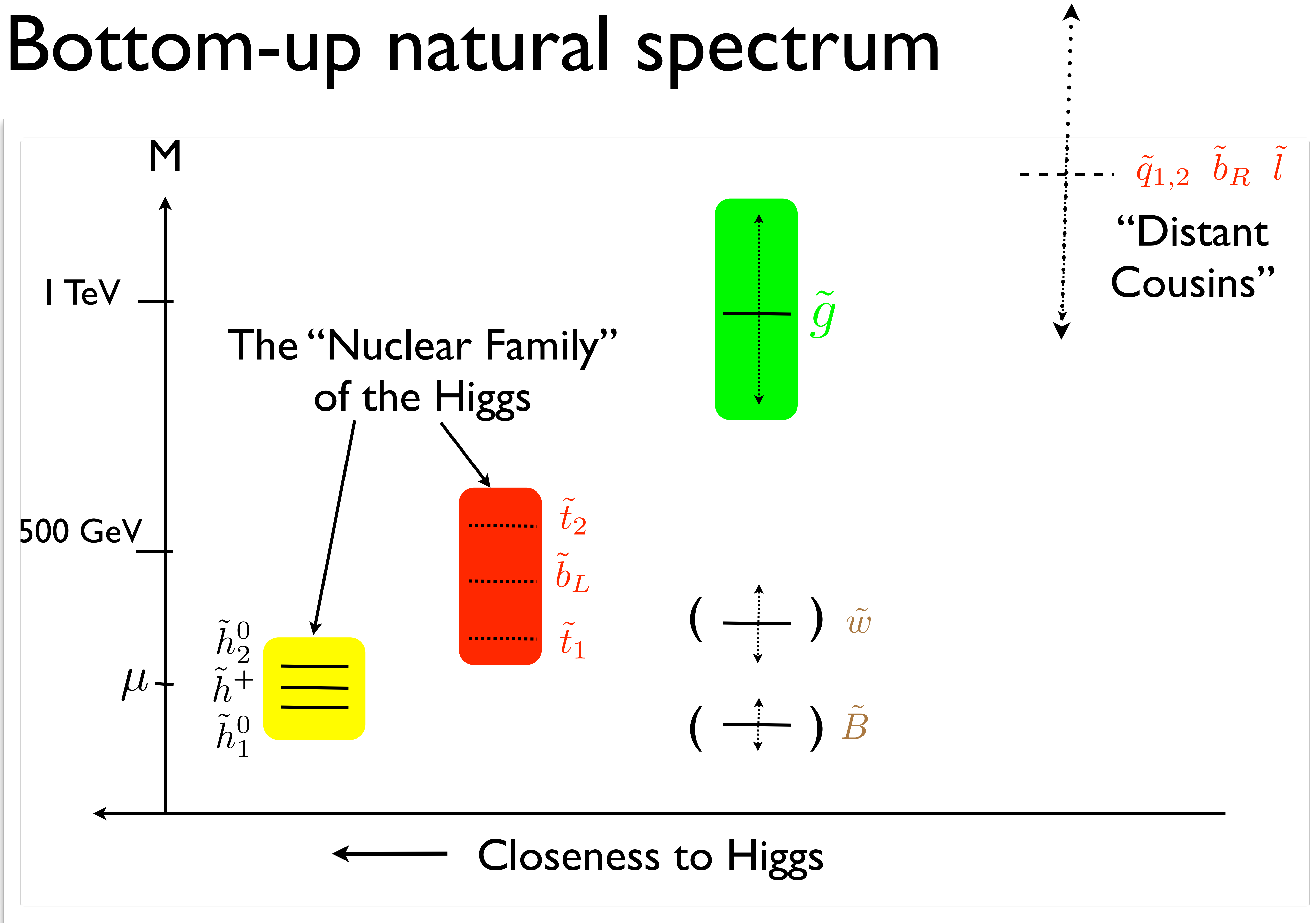


Fig. from L.Hall's talk

Bottom-up natural spectrum



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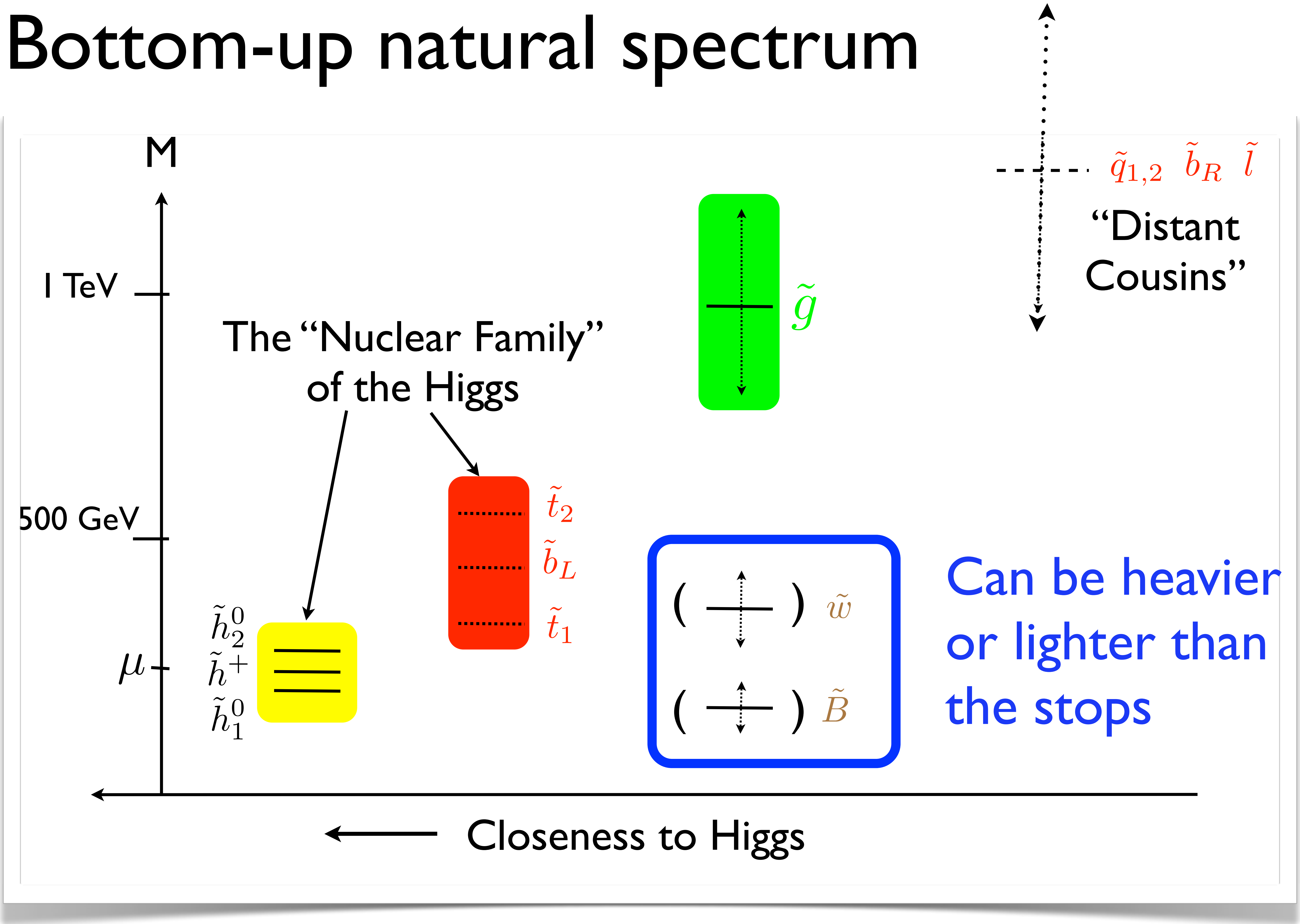


Fig. from L.Hall's talk

bottom up naturalness quantified

$$m_{\tilde{t}}^2 \lesssim (400\ \text{GeV})^2 \frac{1}{1 + A_t^2/2m_{\tilde{t}}^2} \left(\frac{20\%}{\Delta^{-1}}\right) \left(\frac{3}{\log \Lambda/m_{\tilde{t}}}\right) \left(\frac{m_{\text{higgs}}}{120\ \text{GeV}}\right)^2$$

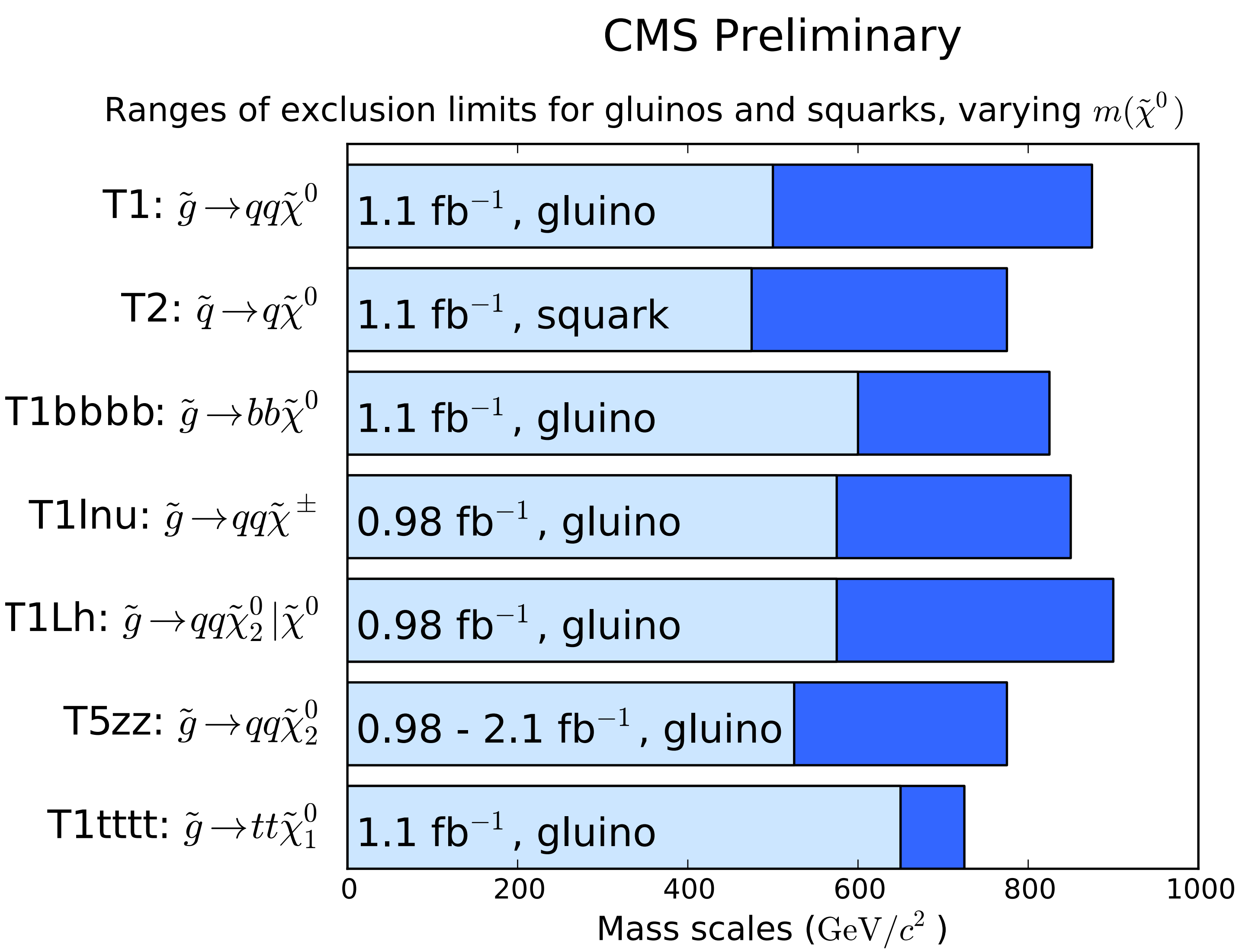
Kitano and Nomura 2006.

$$\mu^2 \lesssim (200\ \text{GeV})^2 \left(\frac{20\%}{\Delta^{-1}}\right) \left(\frac{m_{\text{higgs}}}{120\ \text{GeV}}\right)^2$$

$$M_3^2 \lesssim (700\ \text{GeV})^2 \frac{1}{1 - A_t/2M_3} \left(\frac{20\%}{\Delta^{-1}}\right) \left(\frac{3}{\log \Lambda/m_{\tilde{t}}}\right)^2 \left(\frac{m_{\text{higgs}}}{120\ \text{GeV}}\right)^2$$

Kagan, Dine, Leigh ’93; Dimopoulos, Giudice ’95; Cohen, Kaplan, Nelson ’96; … Perelstein/Spethman ’07

Current status



For limits on $m(\tilde{g}),m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{\mathrm{prod}} = \sigma^{\mathrm{NLO-QCD}}$.

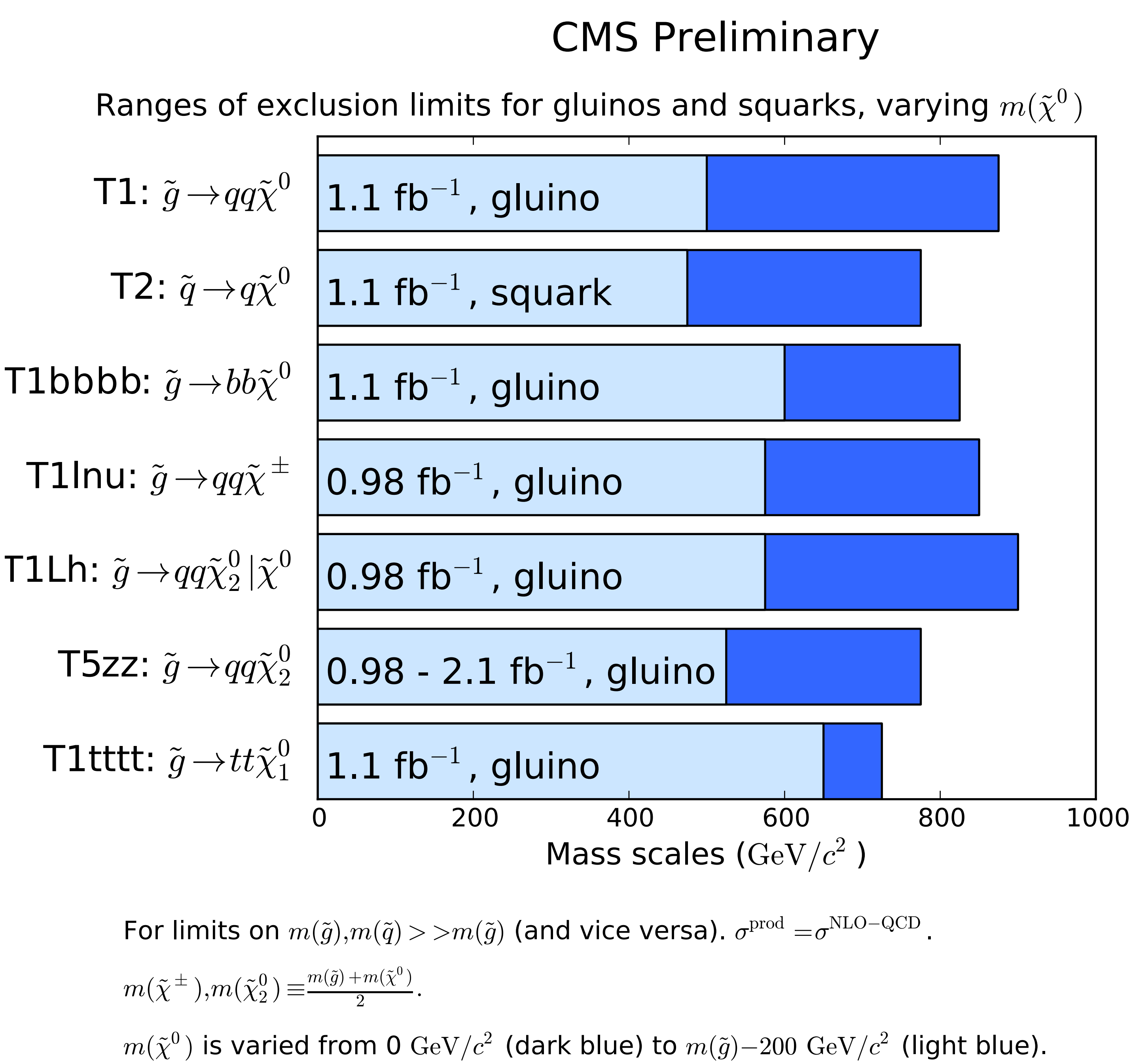
$m(\tilde{\chi}^{\pm}),m(\tilde{\chi}^0_2) \equiv \frac{m(\tilde{g})+m(\tilde{\chi}^0)}{2}$.

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})-200$ GeV/c^2 (light blue).

Gluino $\gtrsim$ 0.7-0.9 TeV

Squarks$_{1,2}$ $\gtrsim$ 0.8 -1 TeV

Current status



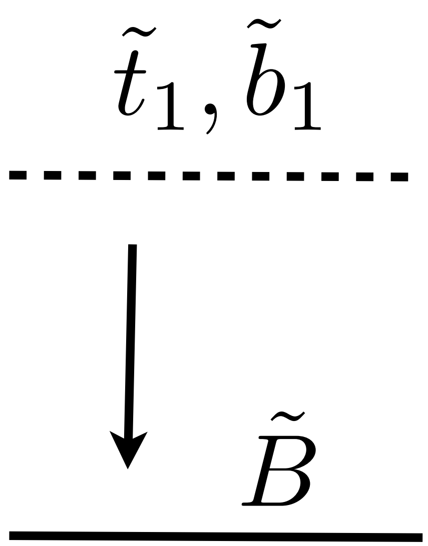
Gluino $\gtrsim$ 0.7-0.9 TeV

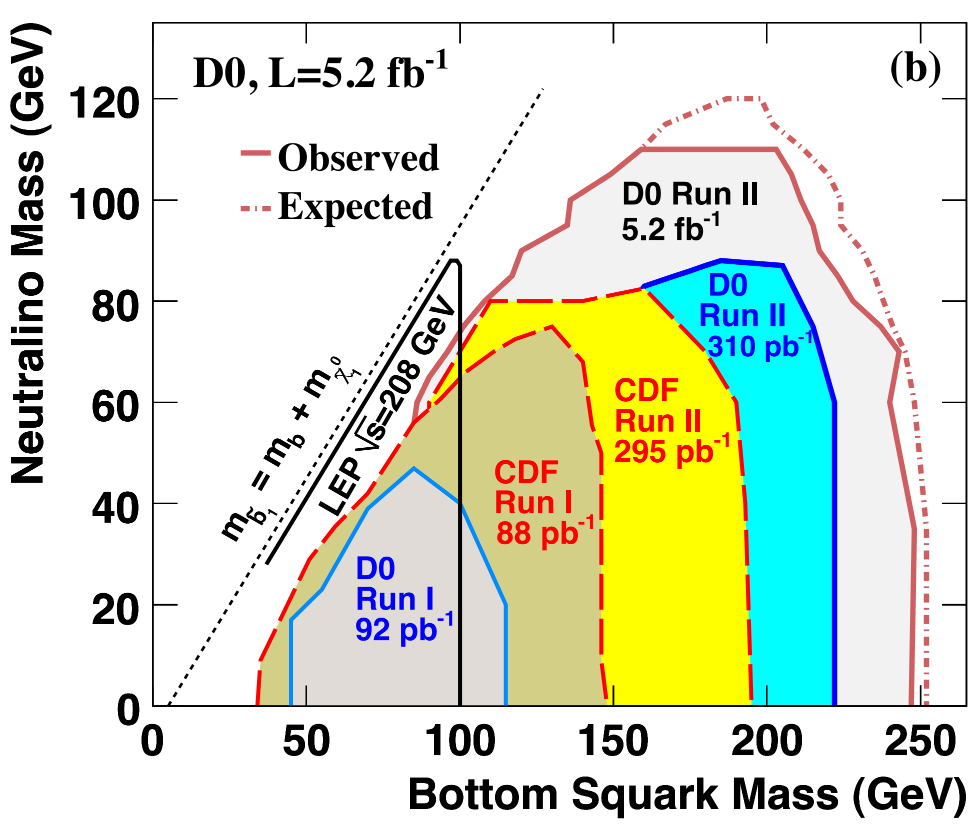
Squarks$_{1,2}$ $\gtrsim$ 0.8 -1 TeV

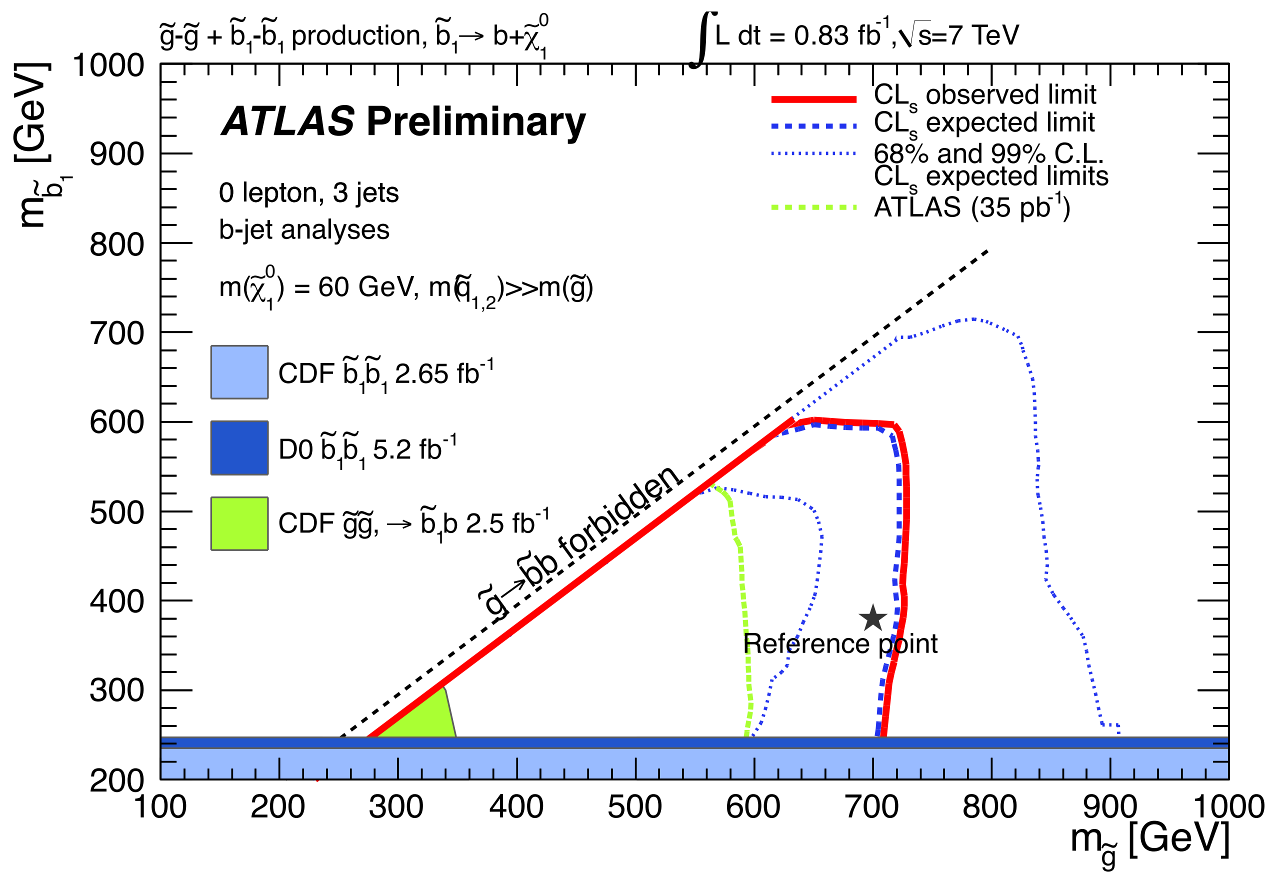
For natural spectrum need to split 1,2 vs. 3rd generation squarks

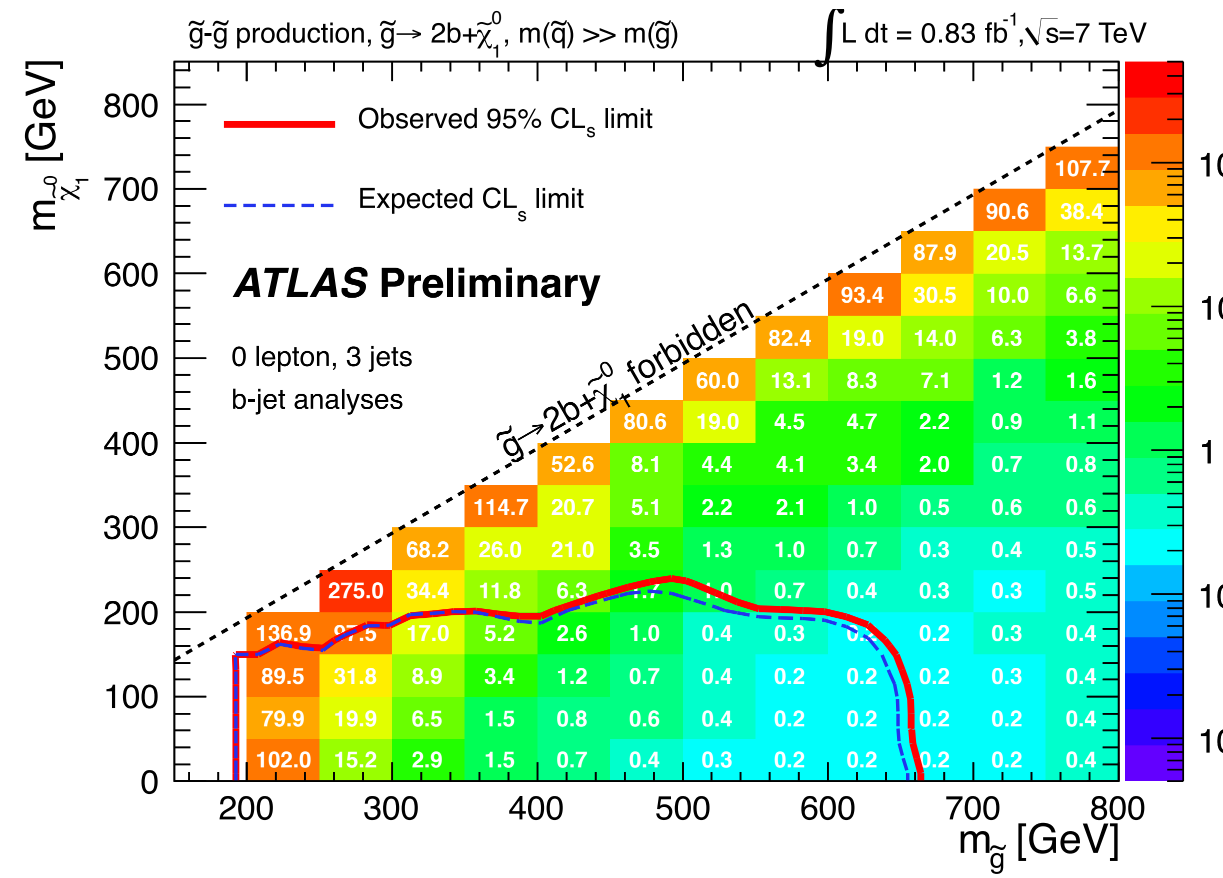
Existing limits on Stops and sbottoms

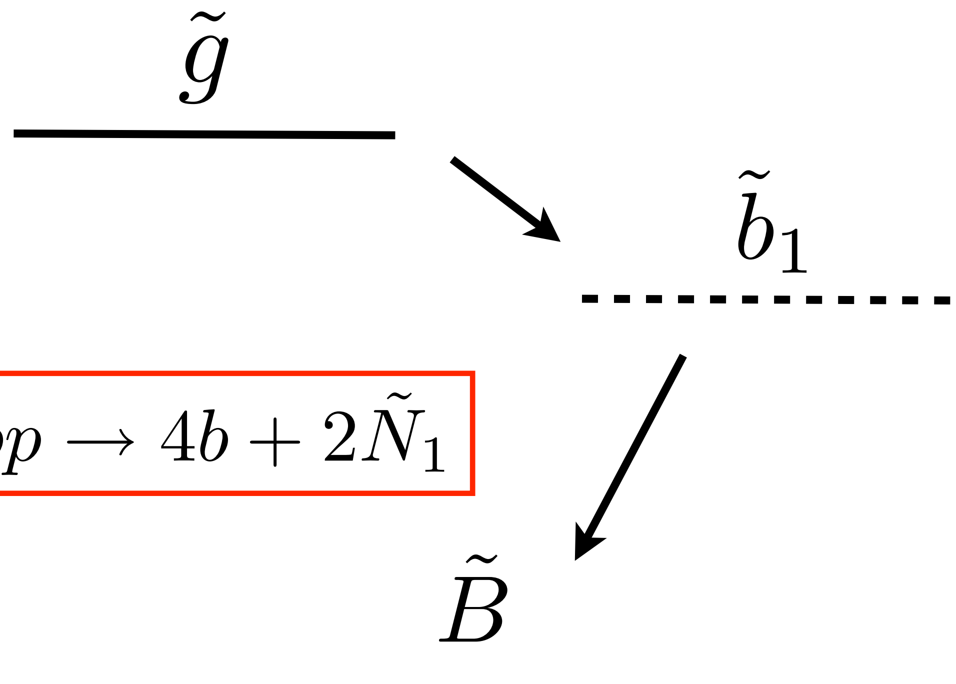
- Tevatron:
  - Stops can still be light (even 120-180 GeV)
  - Sbottoms should be > 250 GeV





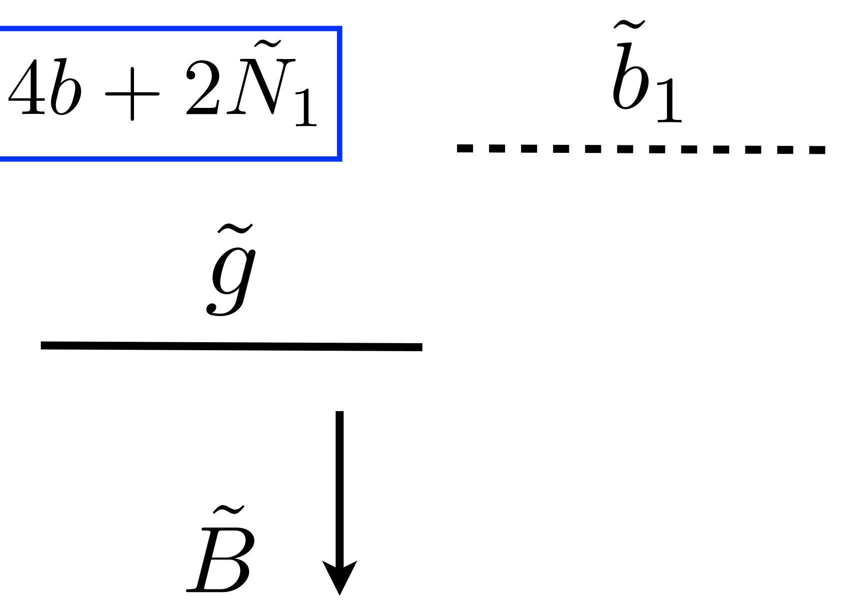




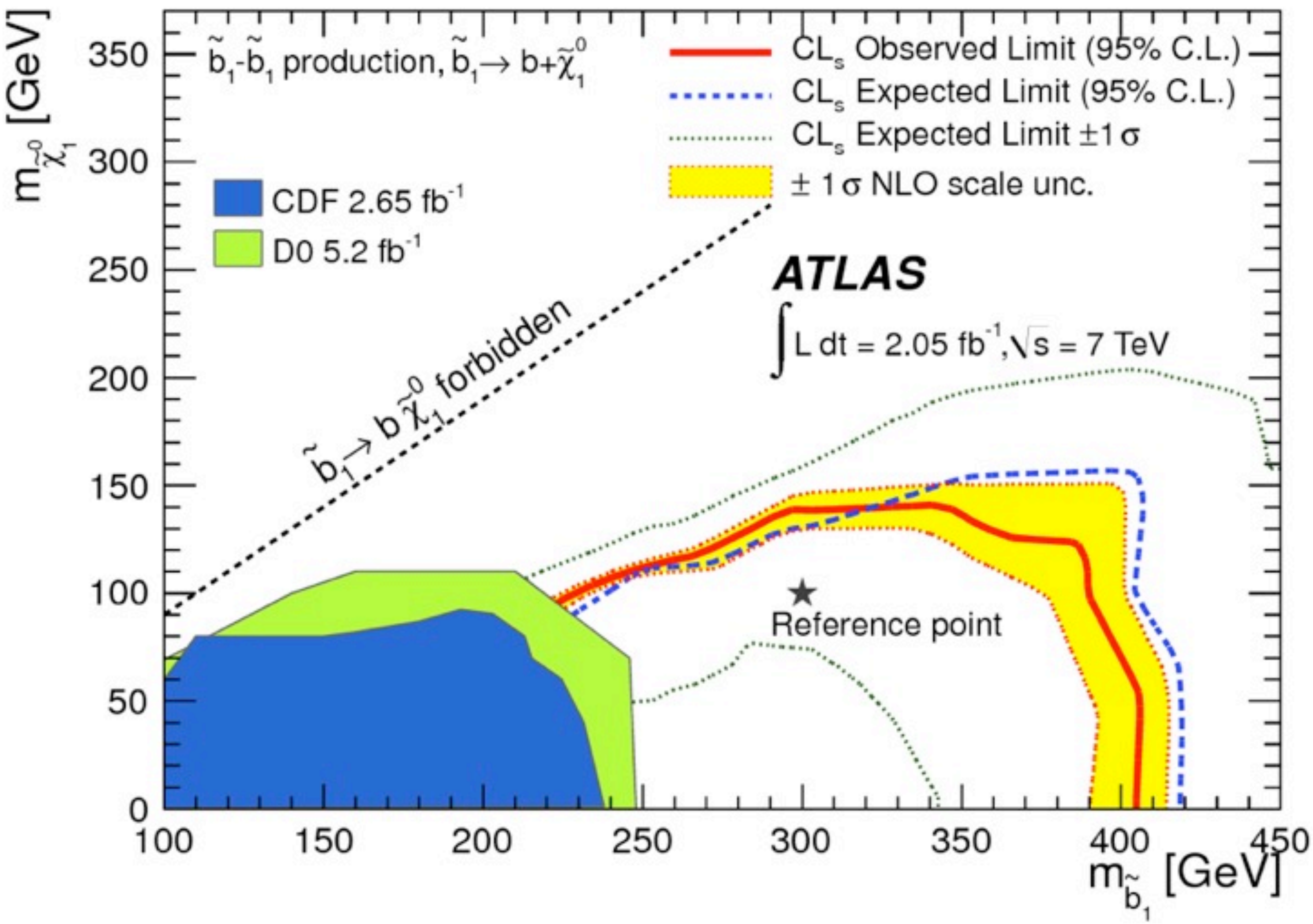


$$pp \to 4b + 2\tilde{N}_1$$

$$pp \to 4b + 2\tilde{N}_1$$

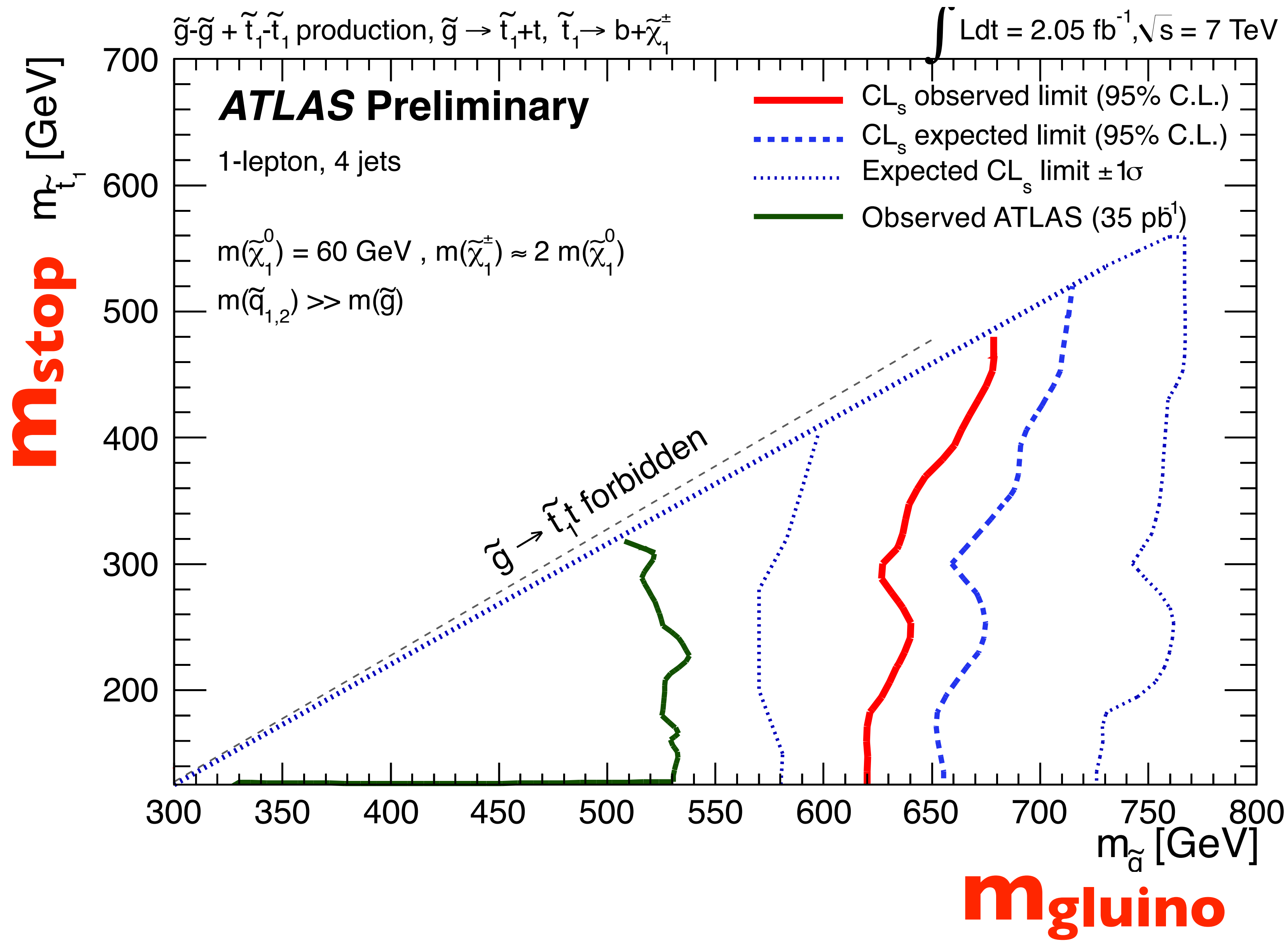


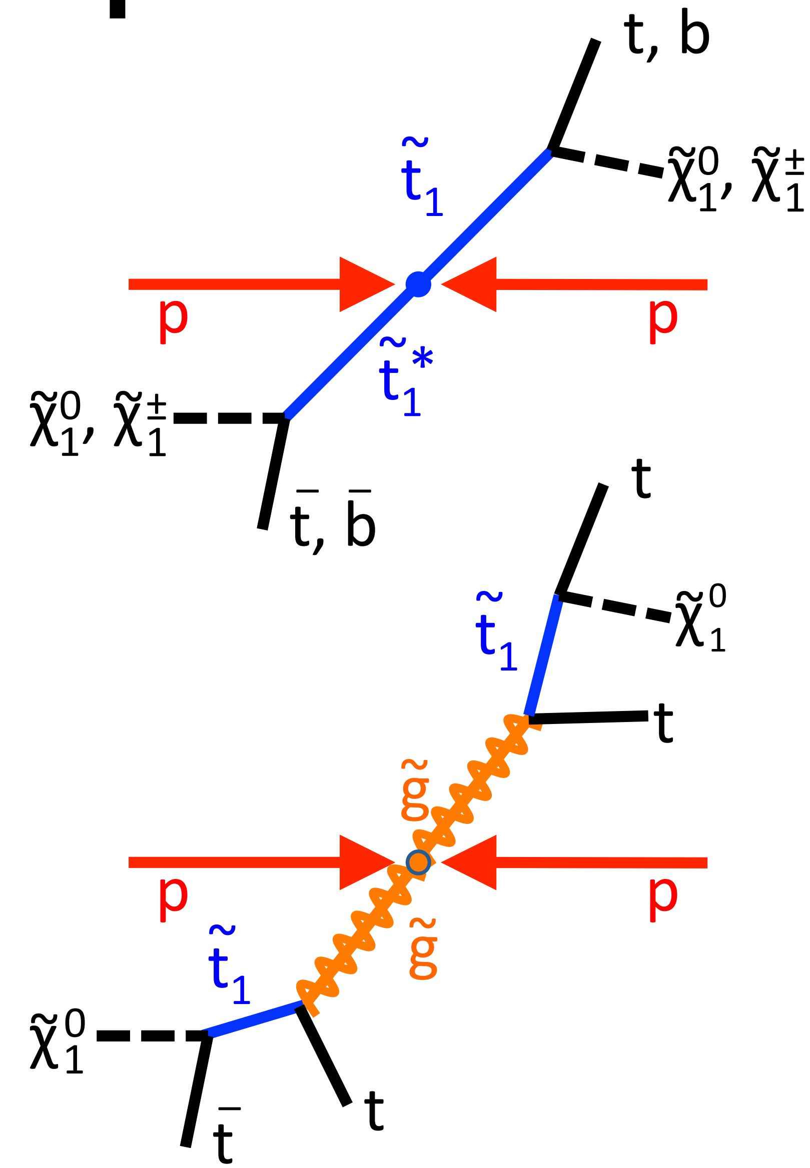
Latest on direct sbottoms



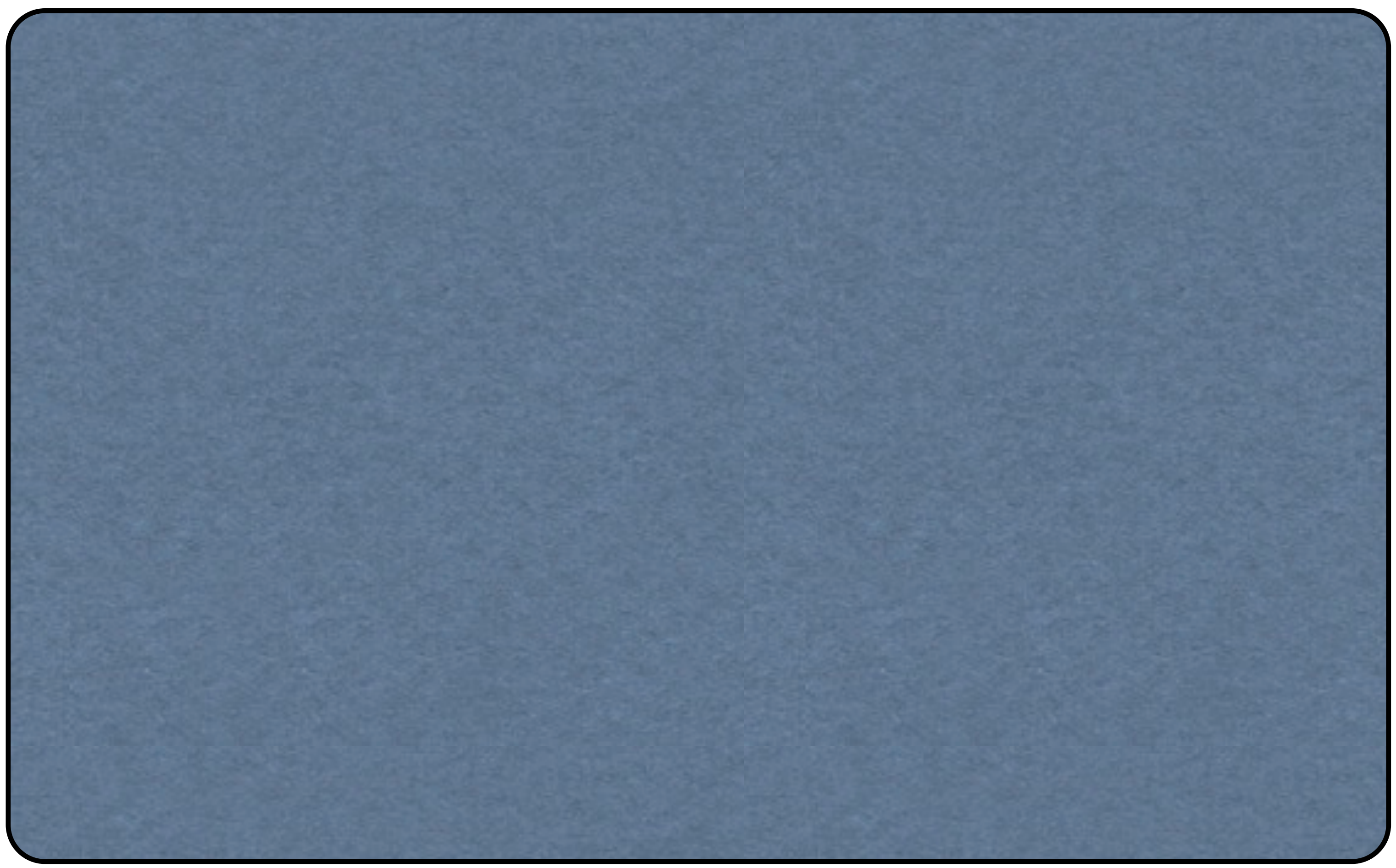
→ Tommaso's talk

Latest limits on stops

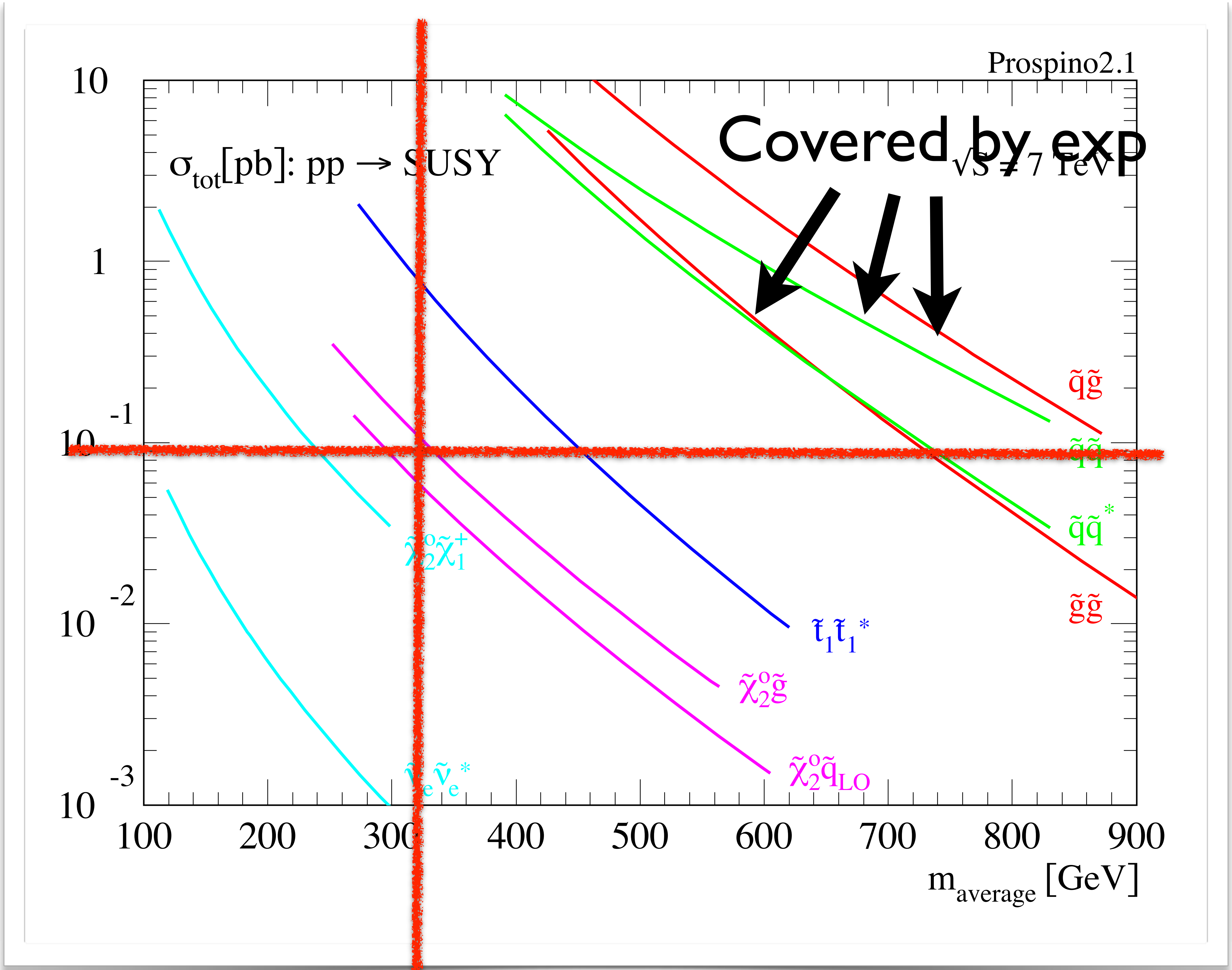




?? σ excess in stop search



Direct stop prod. with 1/fb ?



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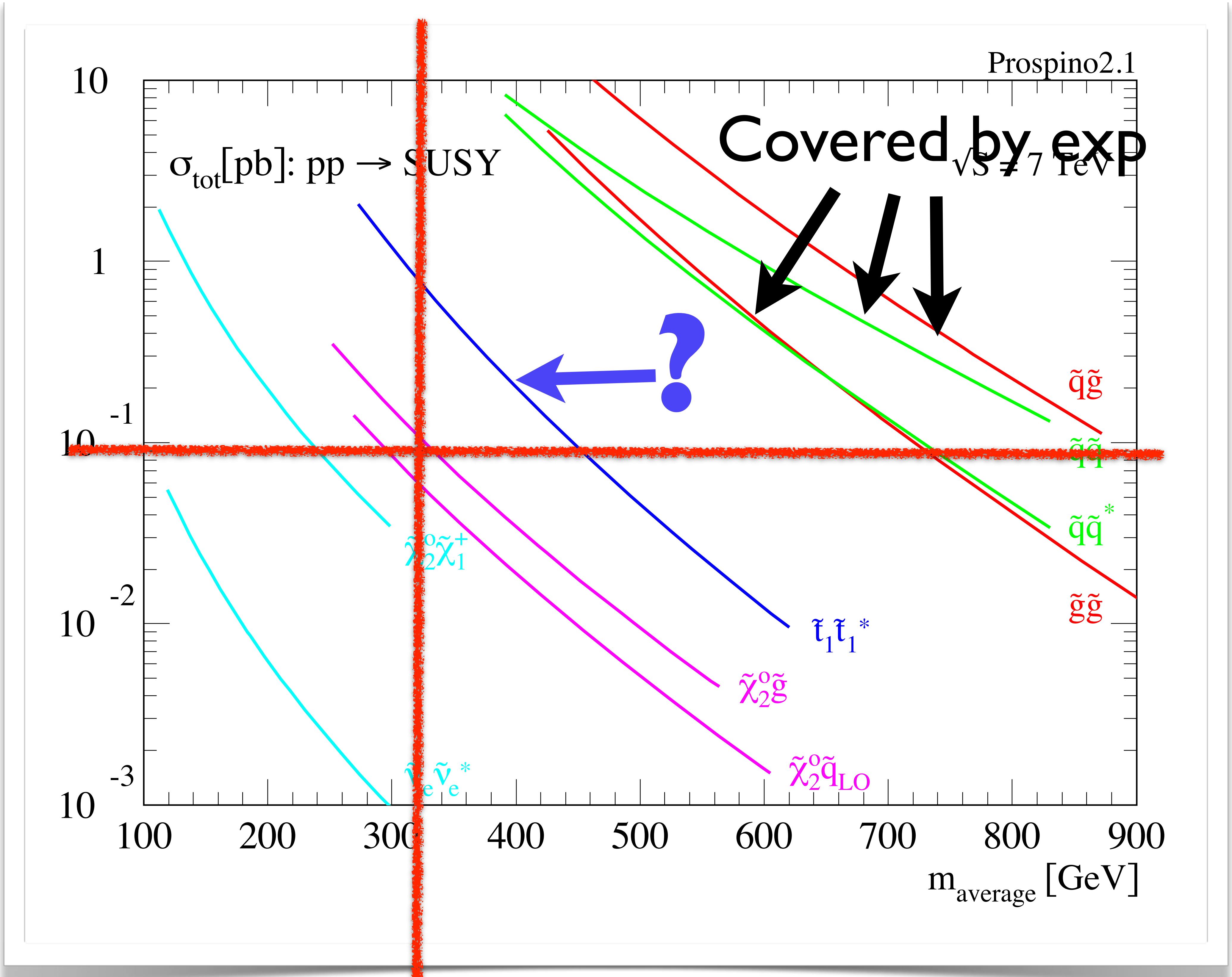


“The experiments haven’t covered my favorite model”

Relax & Wait?

vs.

* not his real attitude.

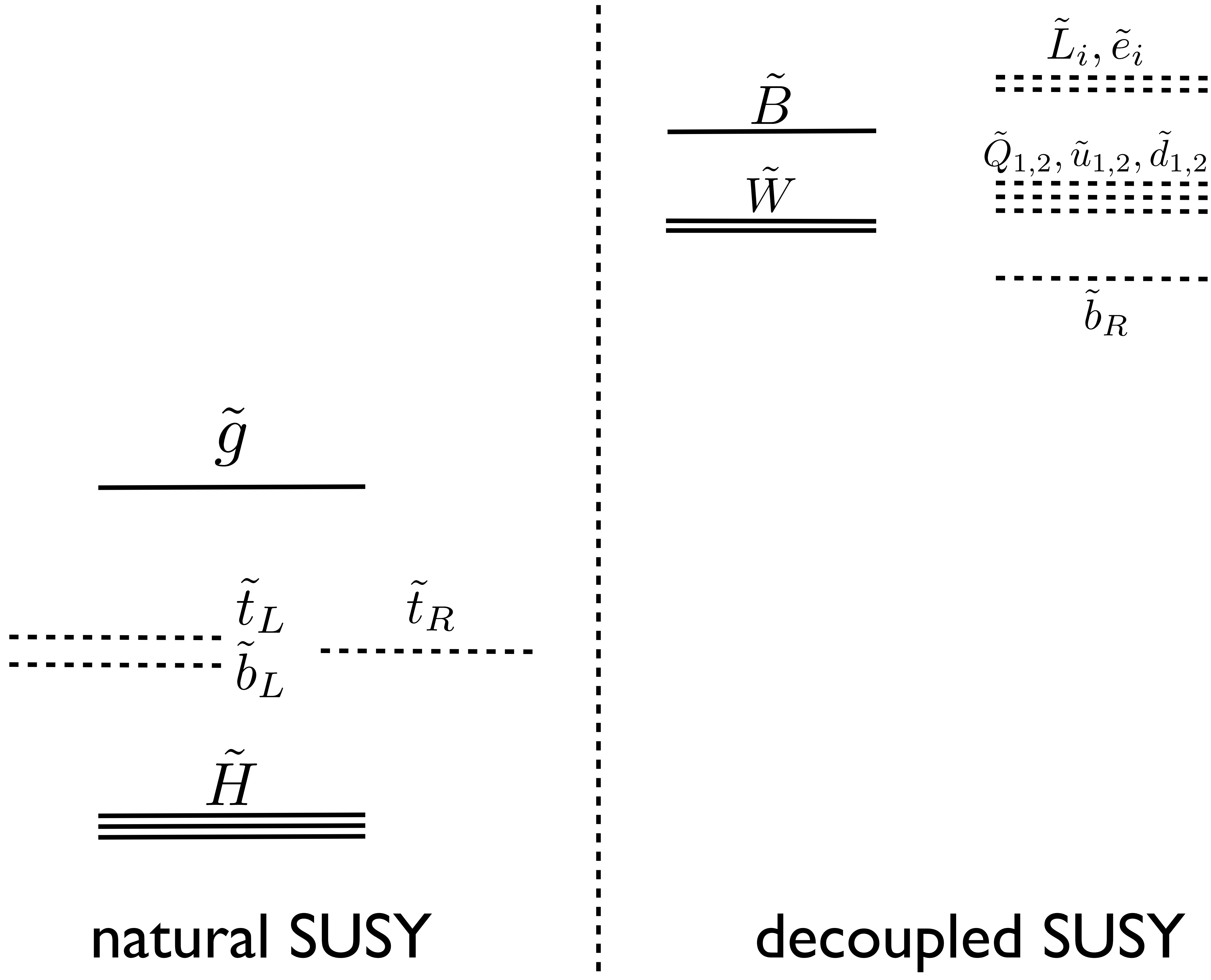
“The experiments haven’t covered my favorite model”

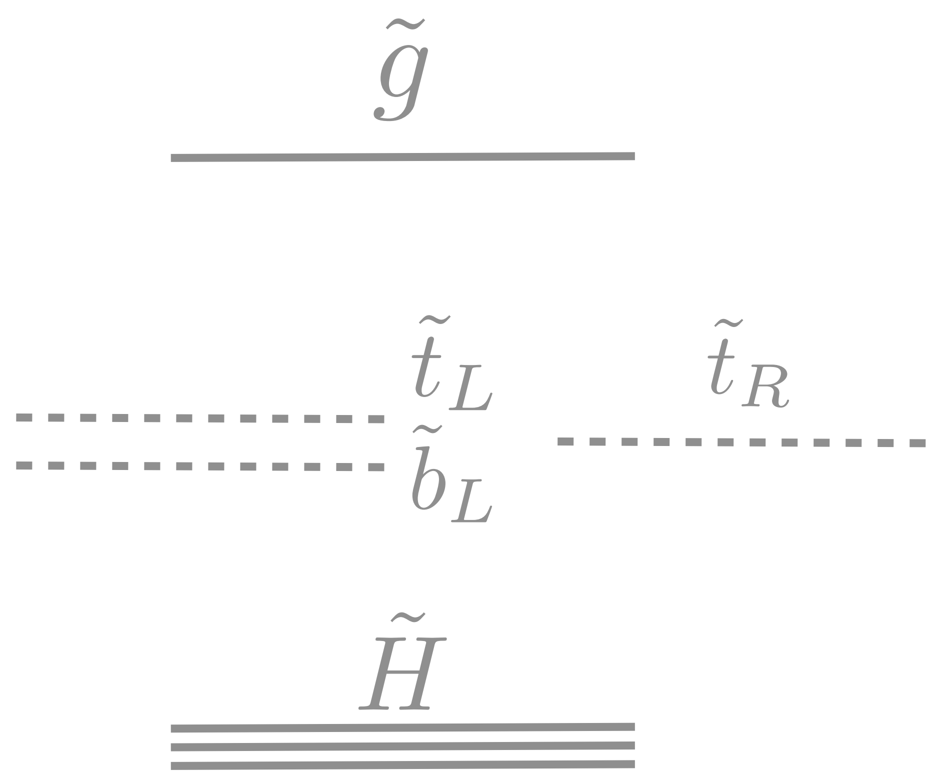
Relax & Wait?

vs.

Let’s check!

* not his real attitude.


$\tilde{L}_i, \tilde{e}_i$
$\tilde{B}$
$\tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2}$
$\tilde{W}$
$\tilde{b}_R$
$\tilde{g}$
$\tilde{t}_L$
$\tilde{t}_R$
$\tilde{b}_L$
$\tilde{H}$
natural SUSY
decoupled SUSY



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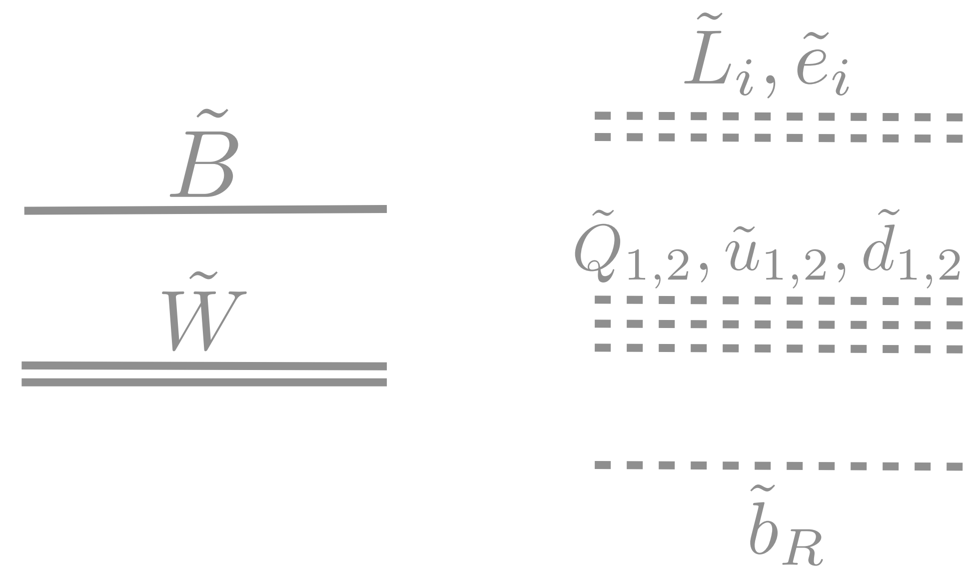

Our Limits

today: *arXiv:1110.6926*

M. Papucci, J. Ruderman, AW

decoupled SUSY

Large signature space

arXiv:1110.6926

	ATLAS			CMS		
	channel	$\mathcal{L}$ [fb^{-1}]	ref.	channel	$\mathcal{L}$ [fb^{-1}]	ref.
jets + $\not\!\!E_T$	2-4 jets	1.04	[1]	α_T	1.14	[11]
	6-8 jets	1.34	[2]	H_T, $\not\!\!H_T$	1.1	[12]
b-jets (+ l's + $\not\!\!E_T$)	$1b, 2b$	0.83	[3]	m_{T2} $(+b)$	1.1	[13]
	$b + 1l$	1.03	[4]	$1b, 2b$	1.1	[14]
				$b'b' \to b + l^\pm l^\pm, 3l$	1.14	[15]
				$t't' \to 2b + l^+l^-$	1.14	[16]
multilepton (+ $\not\!\!E_T$)	$1l$	1.04	[5]	$1l$	1.1	[17]
	$\mu^\pm\mu^\pm$	1.6	[6]	SS dilepton	0.98	[18]
	$t\bar{t} \to 2l$	1.04	[7]	OS dilepton	0.98	[19]
	$t\bar{t} \to 1l$	1.04	[8]	$Z \to l^+l^-$	0.98	[20]
	$4l$	1.02	[9]	$3l, 4l + \not\!\!E_T$	2.1	[21]
	$2l$	1.04	[10]	$3l, 4l$	2.1	[22]

non susy analyses

Large signature space

arXiv:1110.6926

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non susy analyses

too recent

DYI limits?

CERN-PH-EP-2011-145

Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions

The ATLAS Collaboration

Example:

jets+ MET 1.041/fb

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Example:
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Signal Region	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	$> 500/1000$	> 1100

signal bins

Bgd's are left to the experimentalists… stay out of control regions!

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{\text{eff}} > 500$ GeV	$\geq$ 4-jet, $m_{\text{eff}} > 1000$ GeV	High mass
Z/γ+jets	$32.3 \pm 2.6 \pm 6.9$	$25.5 \pm 2.6 \pm 4.9$	$209 \pm 9 \pm 38$	$16.2 \pm 2.2 \pm 3.7$	$3.3 \pm 1.0 \pm 1.3$
W+jets	$26.4 \pm 4.0 \pm 6.7$	$22.6 \pm 3.5 \pm 5.6$	$349 \pm 30 \pm 122$	$13.0 \pm 2.2 \pm 4.7$	$2.1 \pm 0.8 \pm 1.1$
$t\bar{t}$+ single top	$3.4 \pm 1.6 \pm 1.6$	$5.9 \pm 2.0 \pm 2.2$	$425 \pm 39 \pm 84$	$4.0 \pm 1.3 \pm 2.0$	$5.7 \pm 1.8 \pm 1.9$
QCD multi-jet	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.73 \pm 0.14 \pm 0.50$	$2.10 \pm 0.37 \pm 0.82$
Total	$62.4 \pm 4.4 \pm 9.3$	$54.9 \pm 3.9 \pm 7.1$	$1015 \pm 41 \pm 144$	$33.9 \pm 2.9 \pm 6.2$	$13.1 \pm 1.9 \pm 2.5$
Data	58	59	1118	40	18

Table 2: Fitted background components in each SR, compared with the number of events observed in data. The Z/γ+jets background is constrained with co regions CR1a and CR1b, the QCD multi-jet, W and top quark backgrounds by control regions CR2, CR3 and CR4, respectively. In each case the first (sec quoted uncertainty is statistical (systematic). Background components are partially correlated and hence the uncertainties (statistical and systematic) on the background estimates do not equal the quadrature sums of the uncertainties on the components.

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[5] has improved the ATLAS reach at large m_0. The five signal regions are used to set limits on $\sigma_{new} = \sigma A \epsilon$, for non-SM cross-sections (σ) for which ATLAS has an acceptance A and a detection efficiency of ϵ [44]. The excluded values of σ_{new} are 22 fb, 25 fb, 429 fb, 27 fb and 17 fb, respectively, at the 95% confidence level.

upper bound on signal xsec

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upper bound on signal xsec

"Only" need efficiency x Acceptance of the signal bins for your model…

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QCD multi-jet	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.73 \pm 0.14 \pm 0.50$	$2.10 \pm 0.37 \pm 0.82$
Total	$62.4 \pm 4.4 \pm 9.3$	$54.9 \pm 3.9 \pm 7.1$	$1015 \pm 41 \pm 144$	$33.9 \pm 2.9 \pm 6.2$	$13.1 \pm 1.9 \pm 2.5$
Data	58	59	1118	40	18

Table 2: Fitted background components in each SR, compared with the number of events observed in data. The Z/γ+jets background is constrained with co regions CR1a and CR1b, the QCD multi-jet, W and top quark backgrounds by control regions CR2, CR3 and CR4, respectively. In each case the first (sec quoted uncertainty is statistical (systematic). Background components are partially correlated and hence the uncertainties (statistical and systematic) on the background estimates do not equal the quadrature sums of the uncertainties on the components.

[5] has improved the ATLAS reach at large m_0. The five signal regions are used to set limits on $\sigma_{new} = \sigma A \epsilon$, for non-SM cross-sections (σ) for which ATLAS has an acceptance A and a detection efficiency of ϵ [44]. The excluded values of σ_{new} are 22 fb, 25 fb, 429 fb, 27 fb and 17 fb, respectively, at the 95% confidence level.

upper bound on signal xsec

"Only" need efficiency x Acceptance of the signal bins for your model…

LIMIT!

Bgd's are left to the experimentalists…

stay out of control regions!

Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, $m_{\mathrm{eff}} > 500$ GeV	≥ 4-jet, $m_{\mathrm{eff}} > 1000$ GeV	High mass
Z/γ+jets	32.3 ± 2.6 ± 6.9	25.5 ± 2.6 ± 4.9	209 ± 9 ± 38	16.2 ± 2.2 ± 3.7	3.3 ± 1.0 ± 1.3
W+jets	26.4 ± 4.0 ± 6.7	22.6 ± 3.5 ± 5.6	349 ± 30 ± 122	13.0 ± 2.2 ± 4.7	2.1 ± 0.8 ± 1.1
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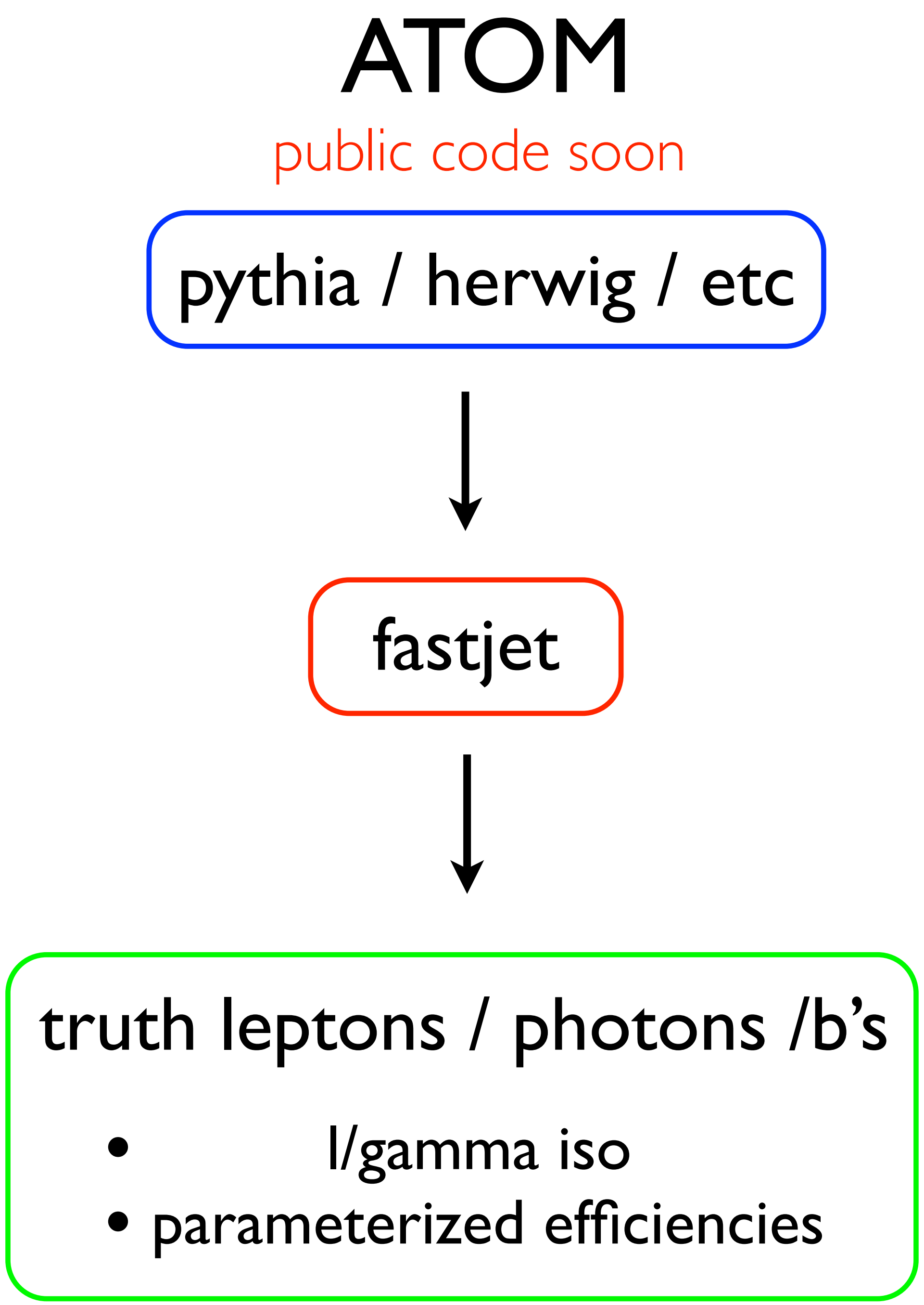
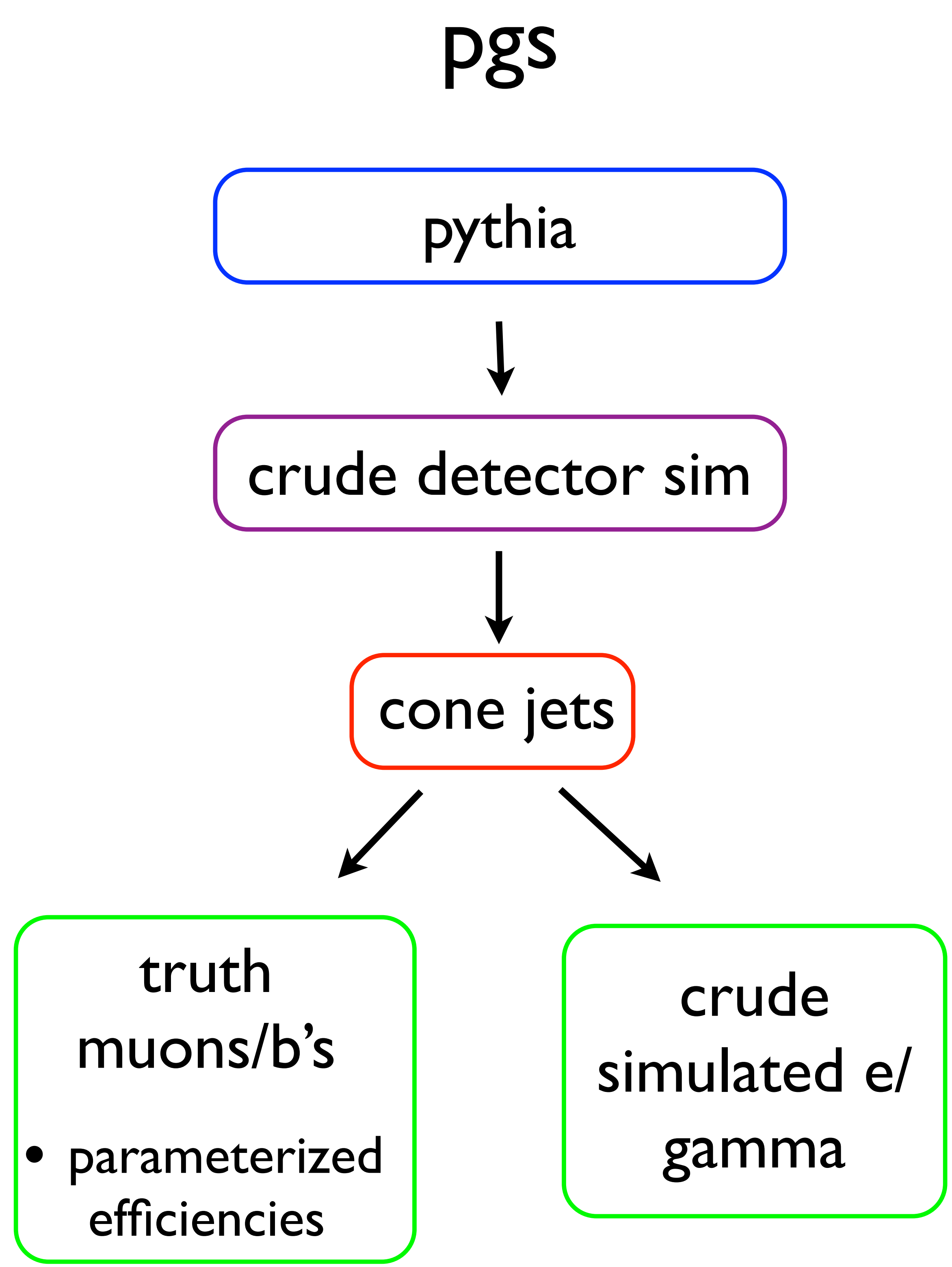
LIMIT!

our pipelines



checks sensitivity of cut & leakage in control region

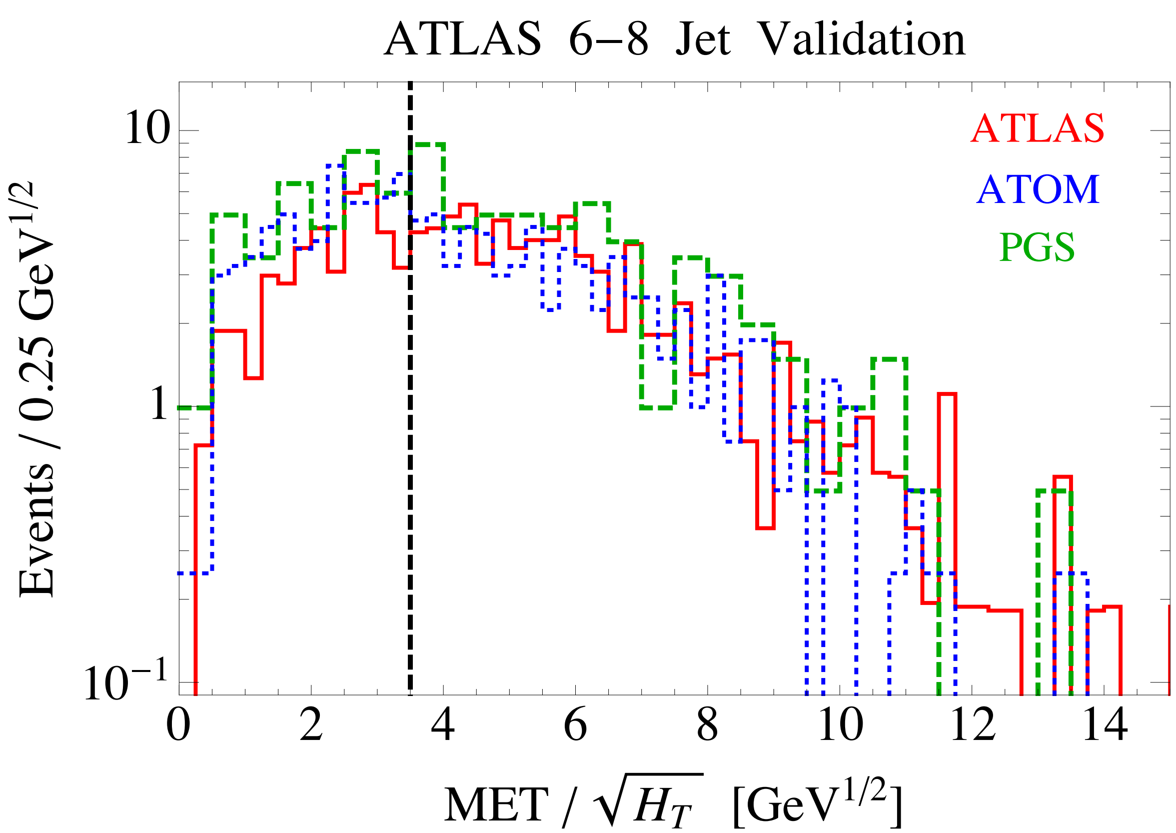


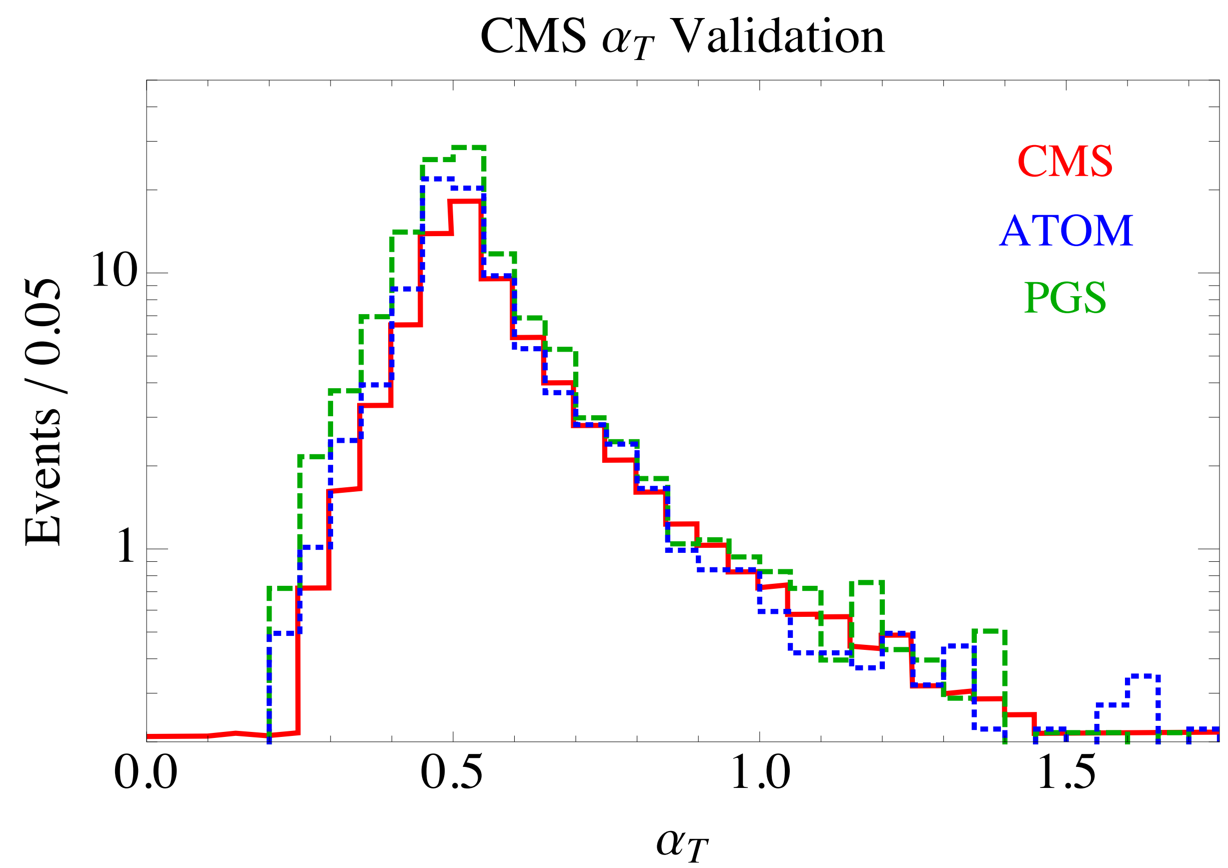
Calibration

"theorist limits"

To calibrate compare:

1) key kinematical distributions
2) limits





Check:

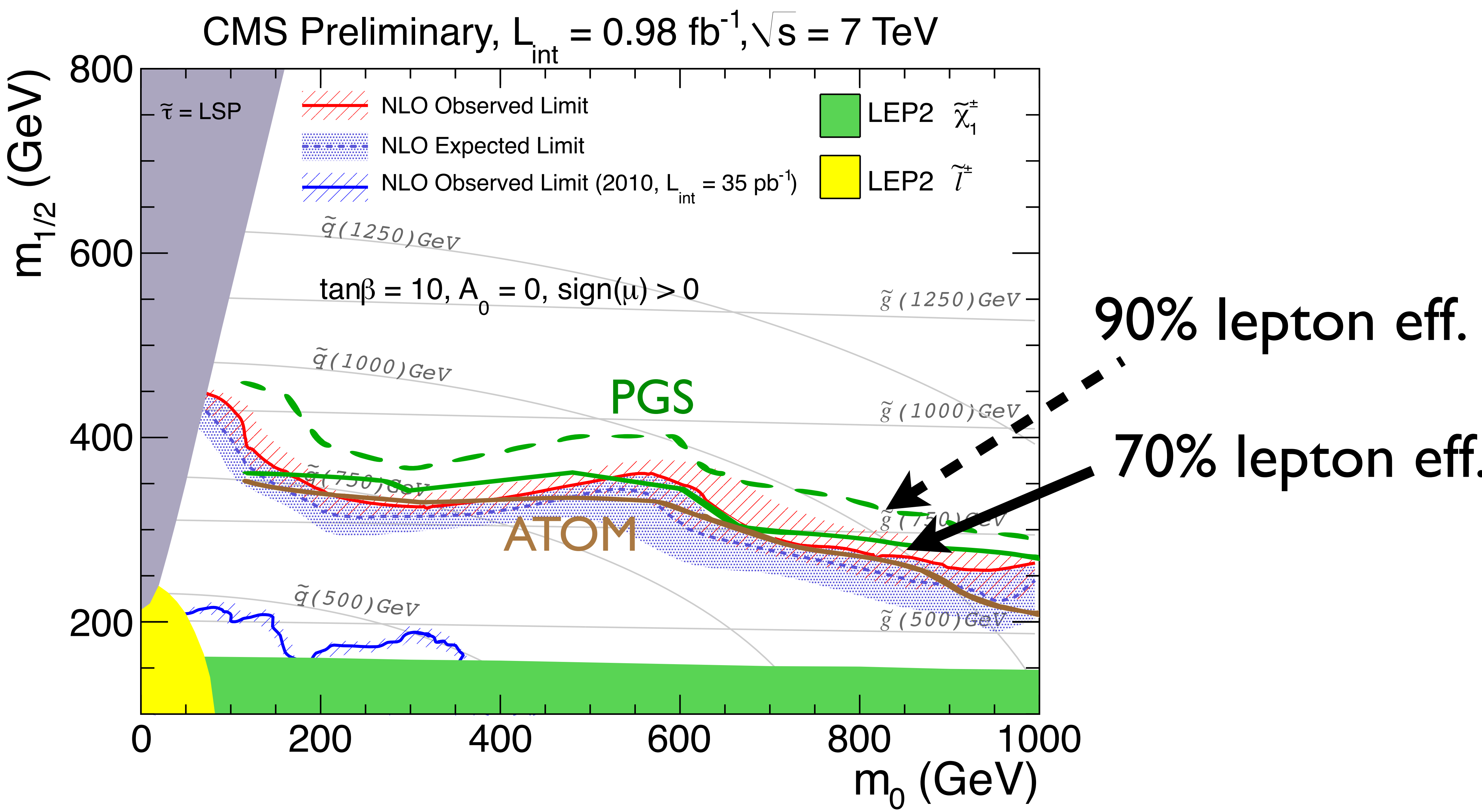
- kinematic distortions (shape)
- signal $\epsilon \times \mathcal{A}$ (normalization)

+ compare to all available limit plots…

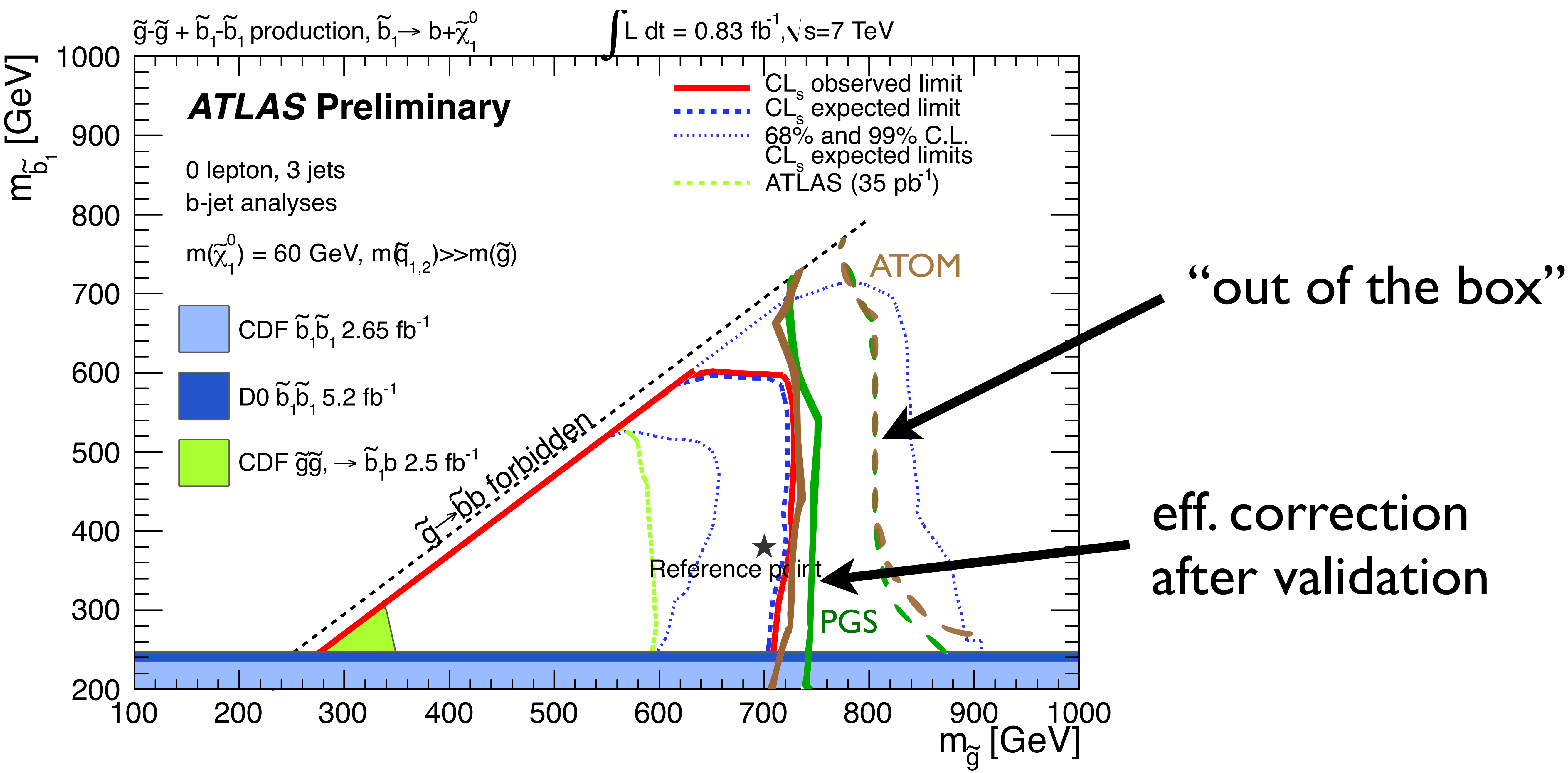
~ 50 GeV accuracy (usually better)

Compare limits

Example: Same-Sign dilepton by CMS



Validation using Limits



Les Houches recommendations

Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results

Coordinators: S. Kraml[1], S. Sekmen[2,3];
B.C. Allanach[4], P. Bechtle[5], G. Belanger[6], K. Benslama[7], C. Balazs[8], A. Belyaev[9,10], M. Dolan[11], B. Fuks[12], M. Campanelli[13], K. Cranmer[14], J. Ellis[3,15], M. Felcini[16], D. Guadagnoli[17], J.F. Gunion[18], S. Heinemeyer[16], M. Kadastik[19], M. Krämer[20], J. Lykken[21] F. Mahmoudi[3,22], M. Mangano[3], S.P. Martin[23,24,25], H. Prosper[2], T. Rizzo[26], T. Robens[27], M. Tytgat[28], A. Weiler[5]
underlined: editors

Abstract
We present a draft set of recommendations for the presentation of LHC results on searches for new physics, which are aimed at providing a more efficient flow of scientific information between the experimental collaborations and the rest of the high energy physics community, and facilitating the interpretation of the results in a wide class of models. Implementing these recommendations would aid the full exploitation of the physics potential of the LHC.

Please comment and consider signing the document.

https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=173341

Large signature space

arXiv:1110.6926

	ATLAS			CMS		
	channel	$\mathcal{L}$ [fb^{-1}]	ref.	channel	$\mathcal{L}$ [fb^{-1}]	ref.
jets + $\not{E}_T$	2-4 jets	1.04	[1]	α_T	1.14	[11]
	6-8 jets	1.34	[2]	H_T, $\not{H}_T$	1.1	[12]
b-jets (+ l's + $\not{E}_T$)	$1b, 2b$	0.83	[3]	m_{T2} $(+b)$	1.1	[13]
	$b + 1l$	1.03	[4]	$1b, 2b$	1.1	[14]
				$b'b' \to b + l^\pm l^\pm, 3l$	1.14	[15]
				$t't' \to 2b + l^+ l^-$	1.14	[16]
multilepton (+ $\not{E}_T$)	$1l$	1.04	[5]	$1l$	1.1	[17]
	$\mu^\pm \mu^\pm$	1.6	[6]	SS dilepton	0.98	[18]
	$t\bar{t} \to 2l$	1.04	[7]	OS dilepton	0.98	[19]
	$t\bar{t} \to 1l$	1.04	[8]	$Z \to l^+ l^-$	0.98	[20]
	$4l$	1.02	[9]	$3l, 4l + \not{E}_T$	2.1	[21]
	$2l$	1.04	[10]	$3l, 4l$	2.1	[22]

non susy analyses

Large signature space

arXiv:1110.6926

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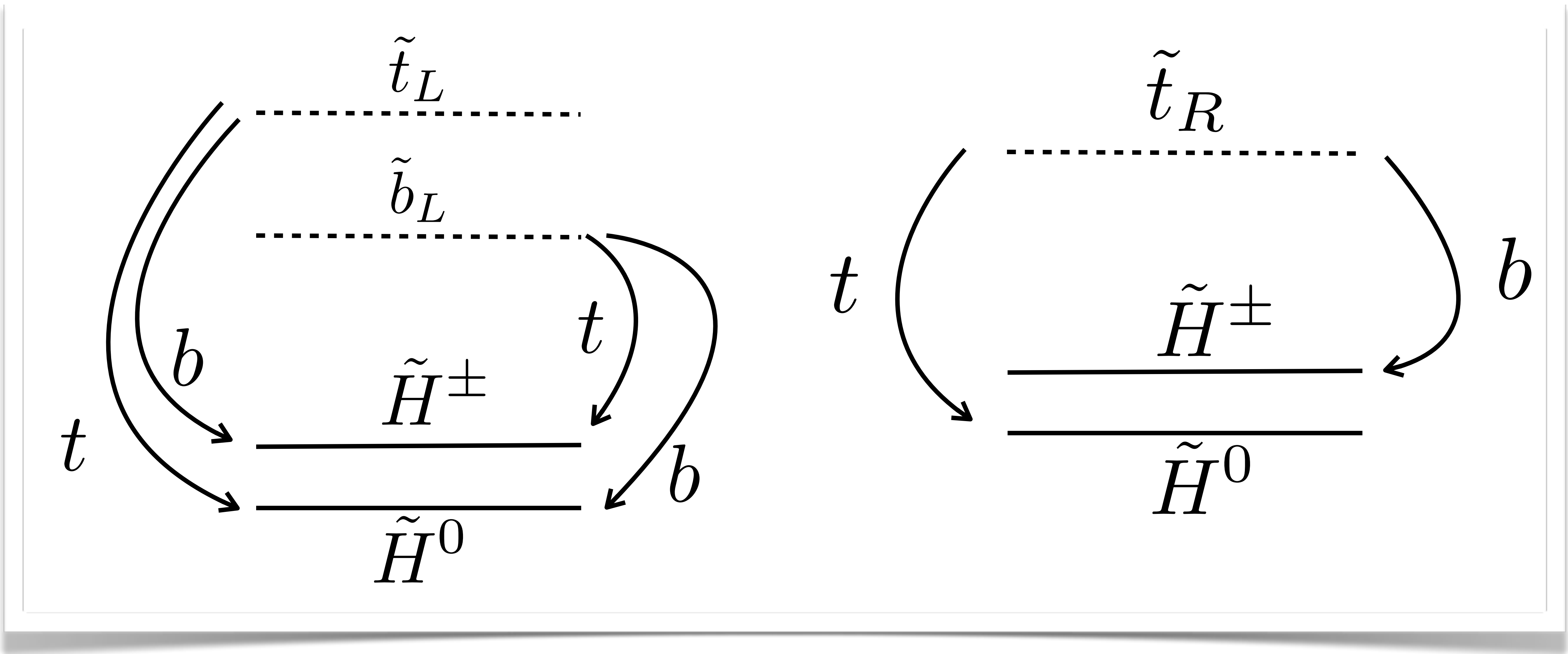
	~~$2l$~~	1.04	[10]	~~$3l, 4l$~~	2.1	[22]

non susy analyses

too recent

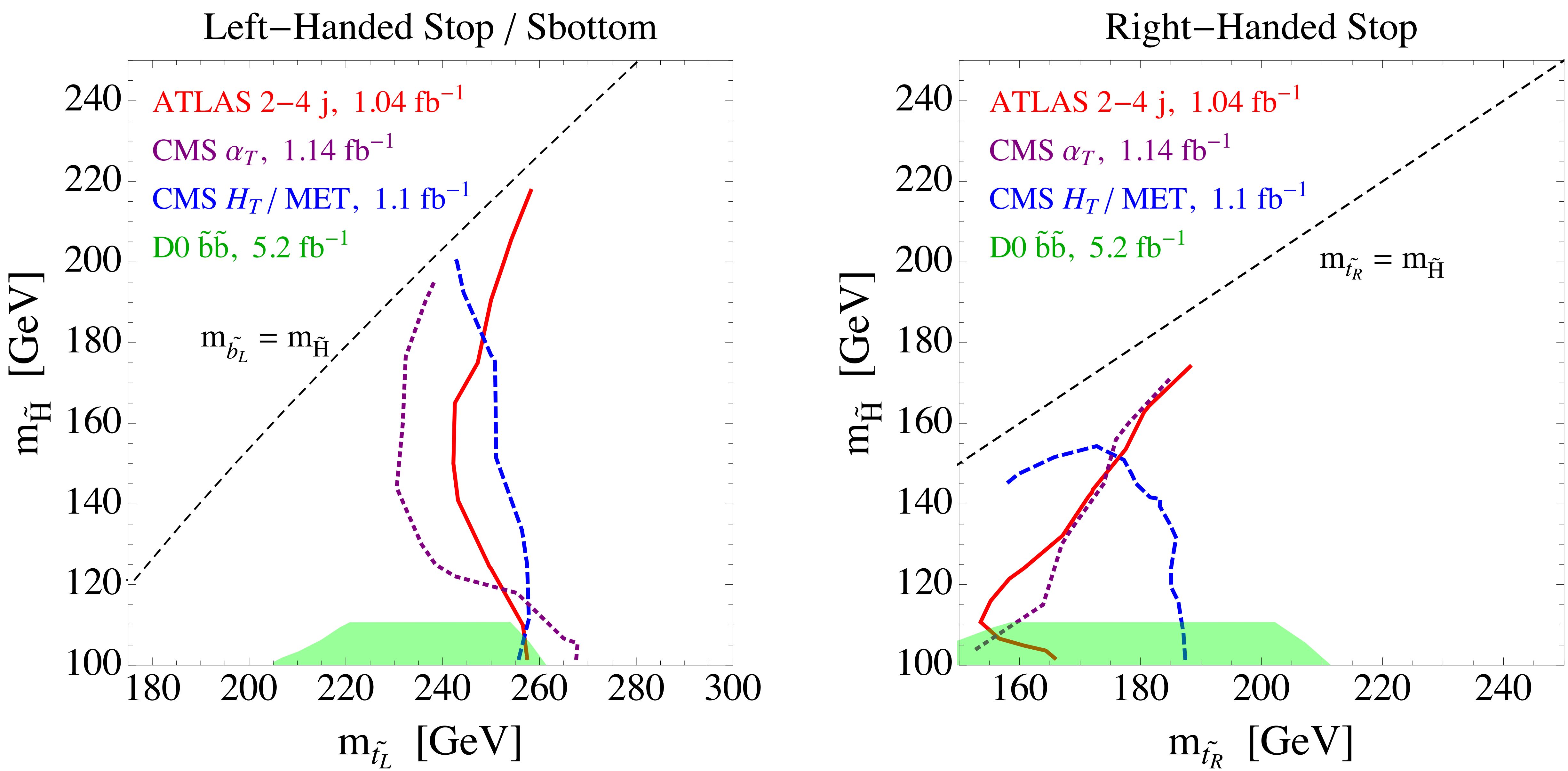
Stops (sbottom) + Higgsinos



Stops can act as "sbottom" (bjet+χ) !

Chargino-neutralino splitting irrelevant for present searches

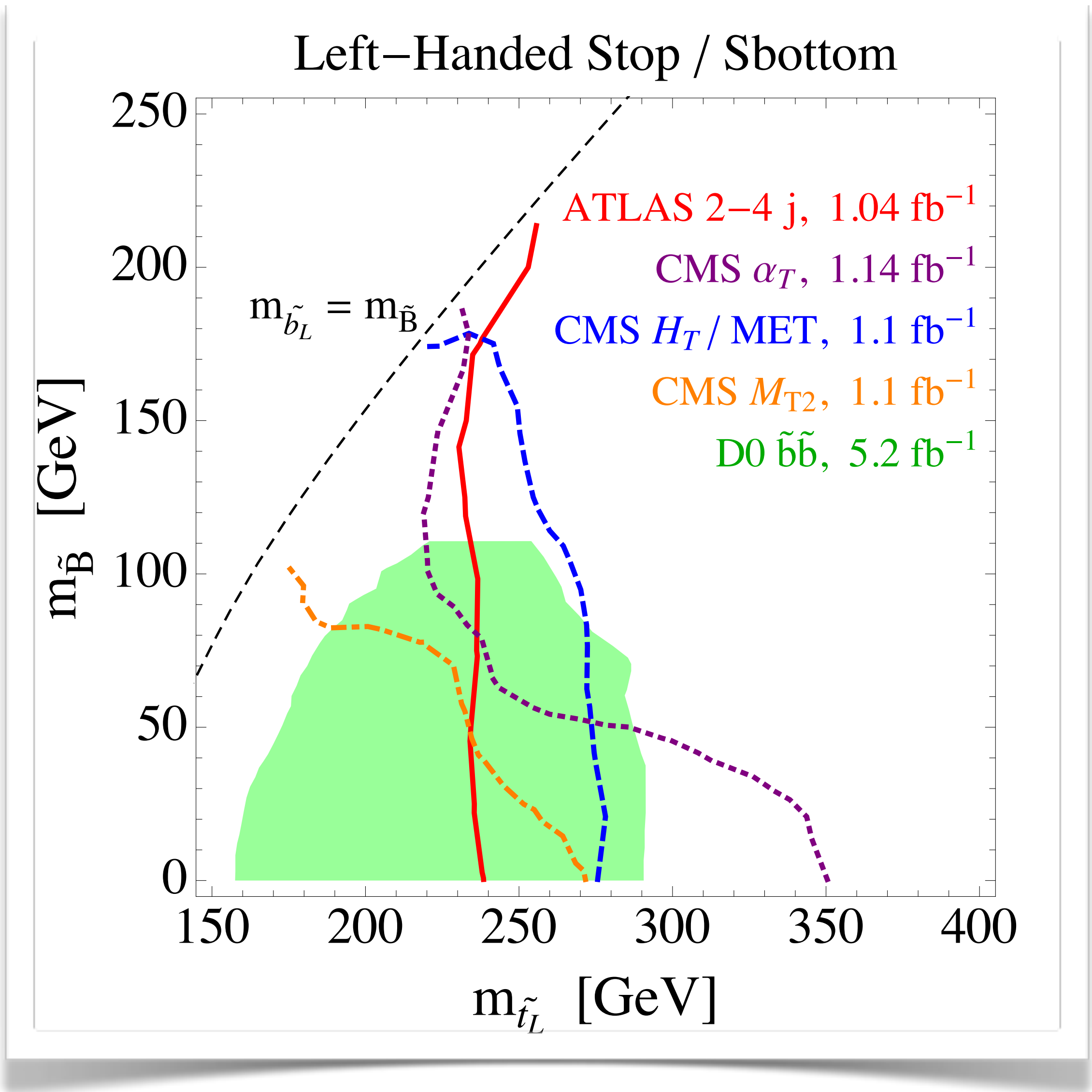
Stops (sbottom) + Higgsinos

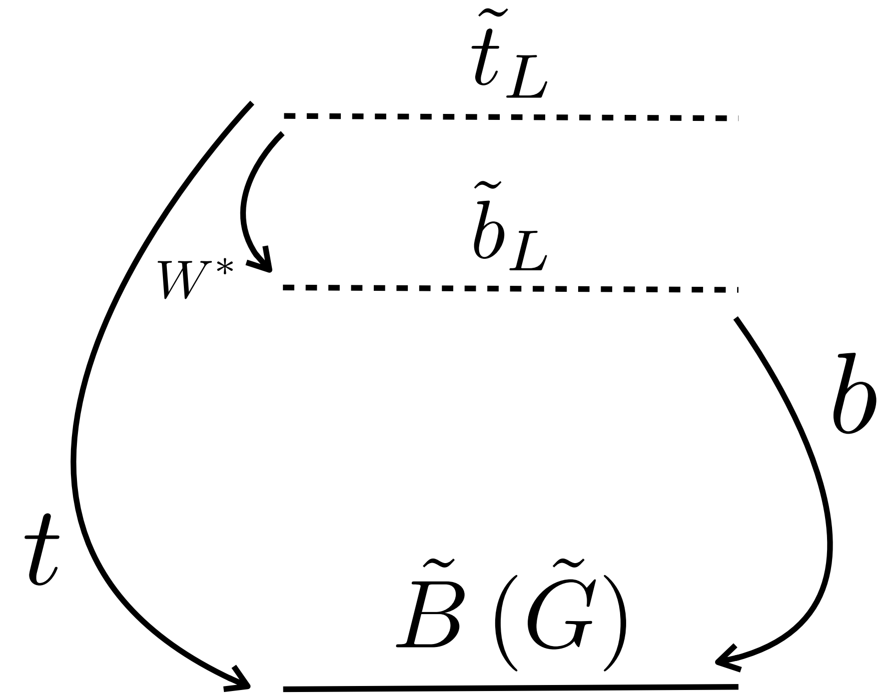


LHC surpasses Tevatron:

Strongest bounds from jets + MET

Stops (sbottom) + Bino

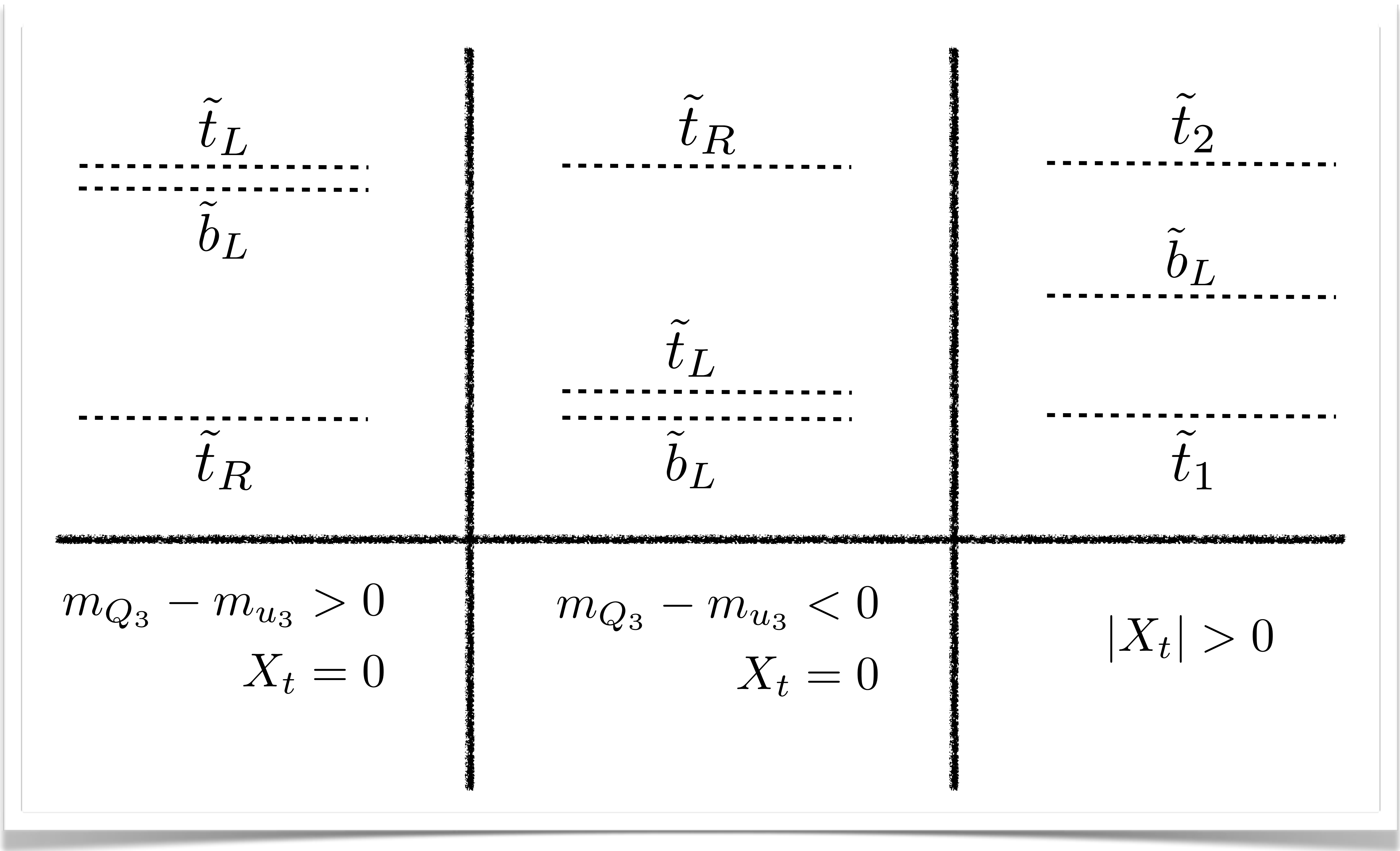




jets+MET searches powerful here too

- RH stop→Bino: top-like final state. Weak bound around 200GeV, but we don't trust it too much. Further (exp') study needed...

Un-Splitting the spectrum



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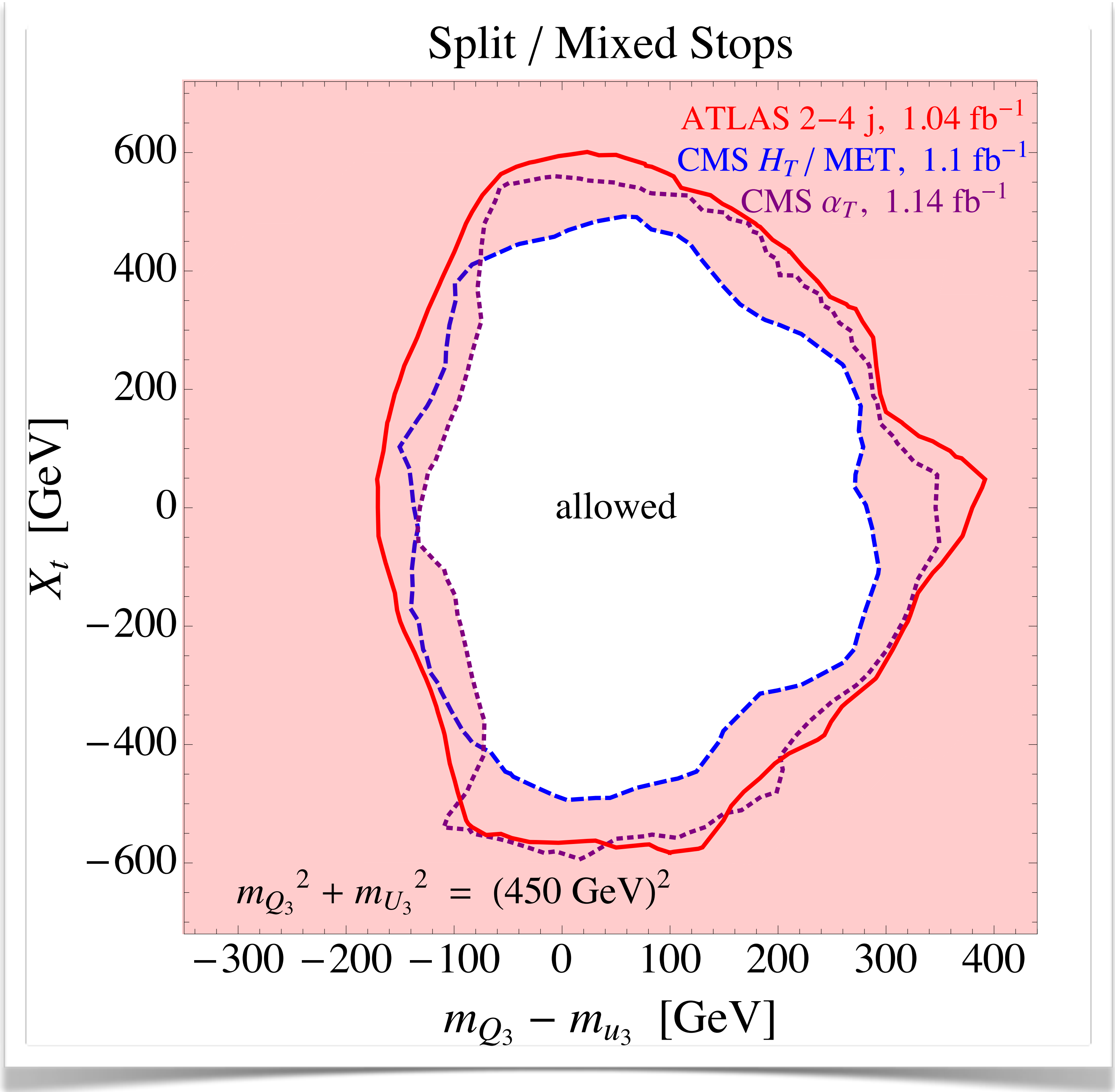
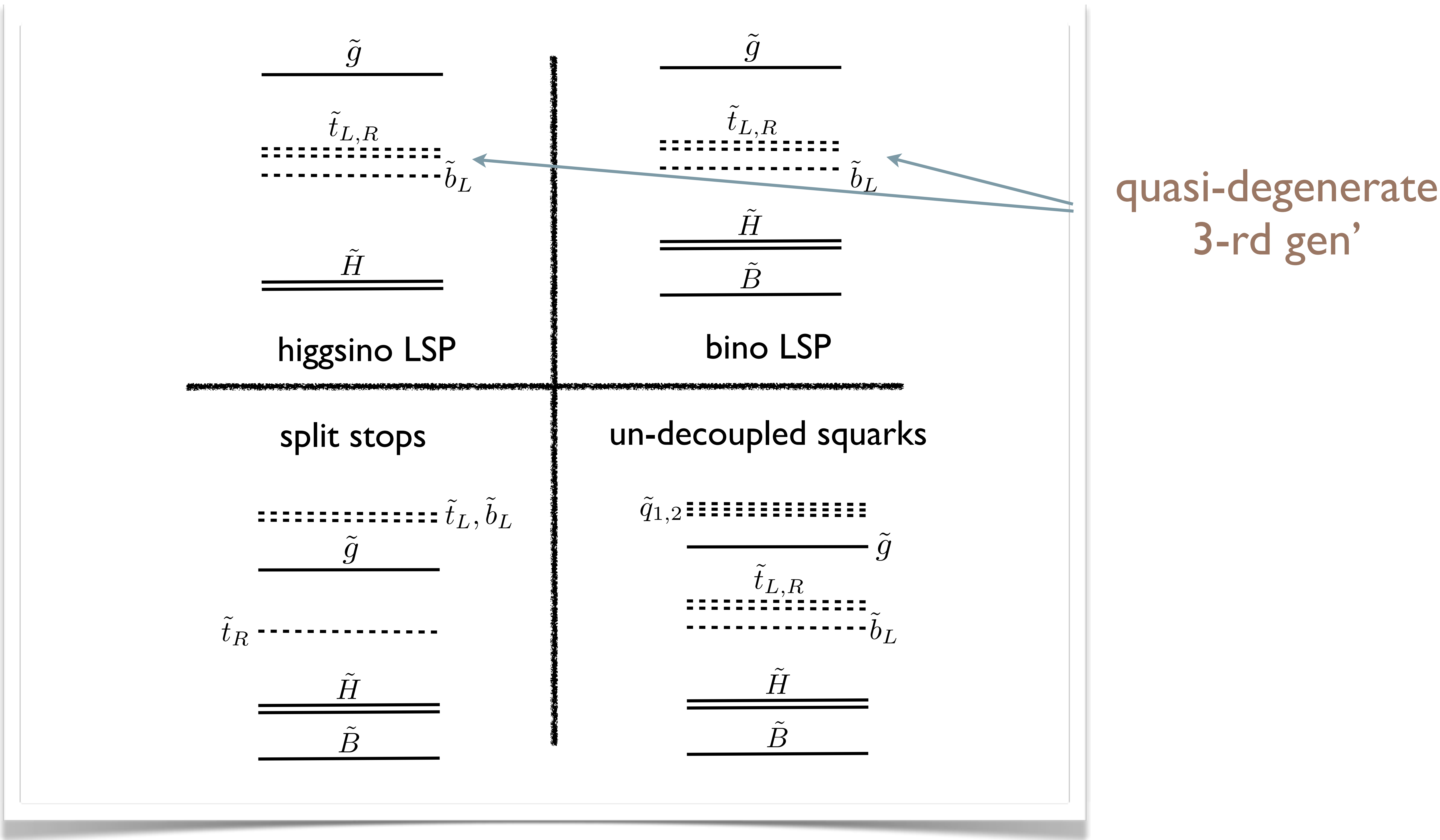


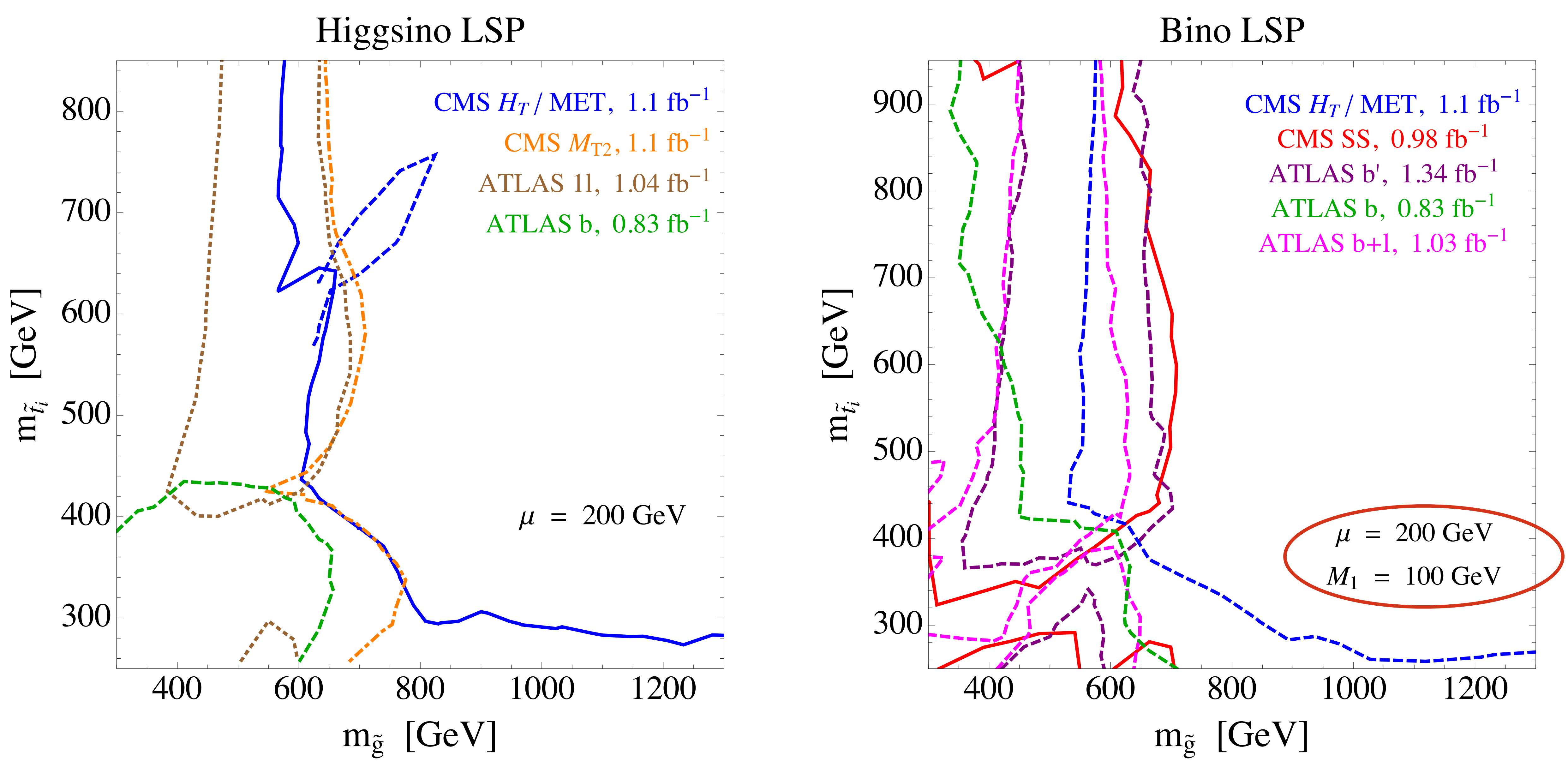
stronger bound on the left due to light sbottom

TeVatron bounds not shown b/c they have no sensitivity for m_{LSP} >110GeV

Adding gluinos



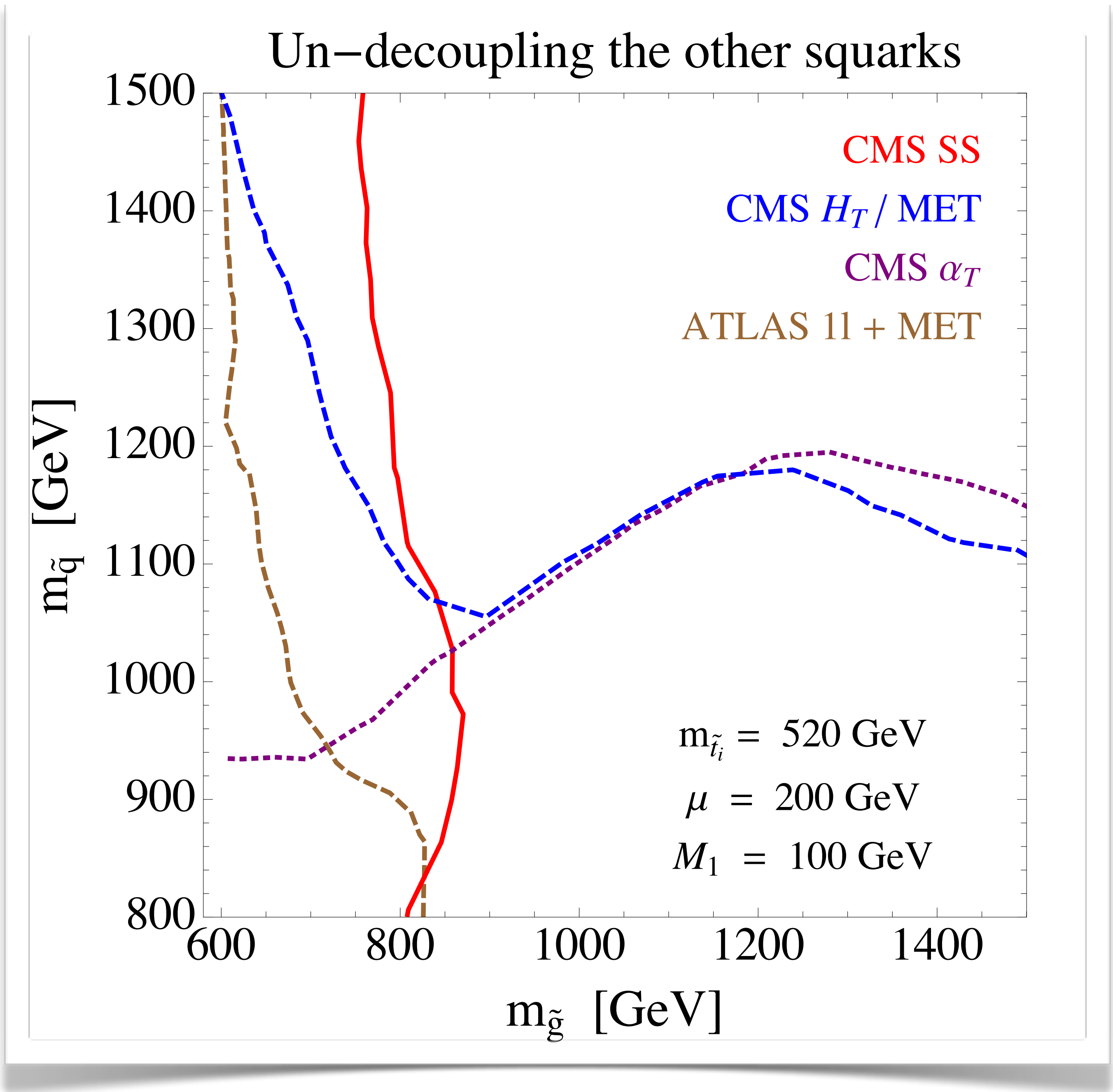
Adding the gluinos



Gluino bounded (again) by jets+MET, and 1lep searches

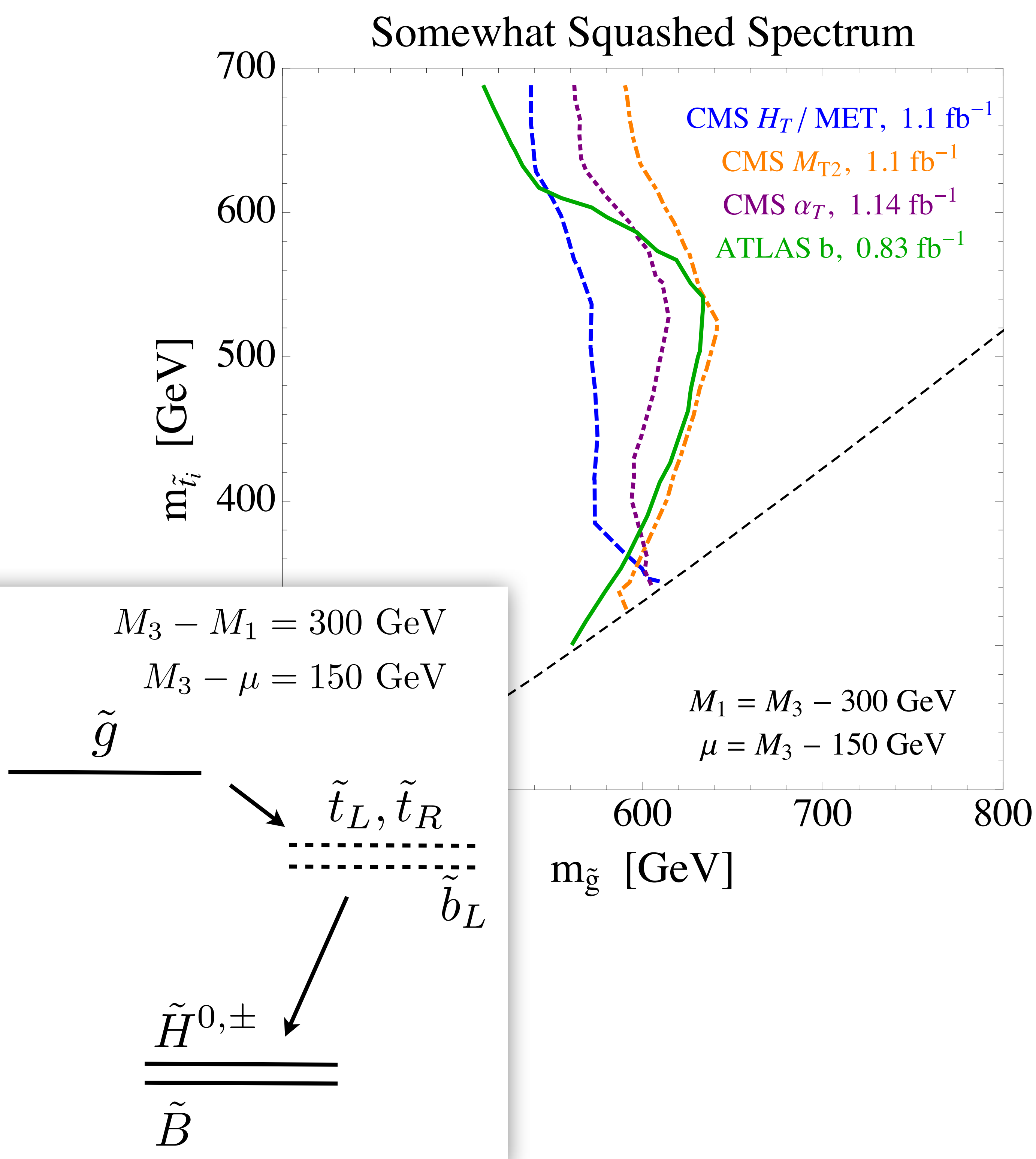
Gluino mostly bounded by Same Sign searches

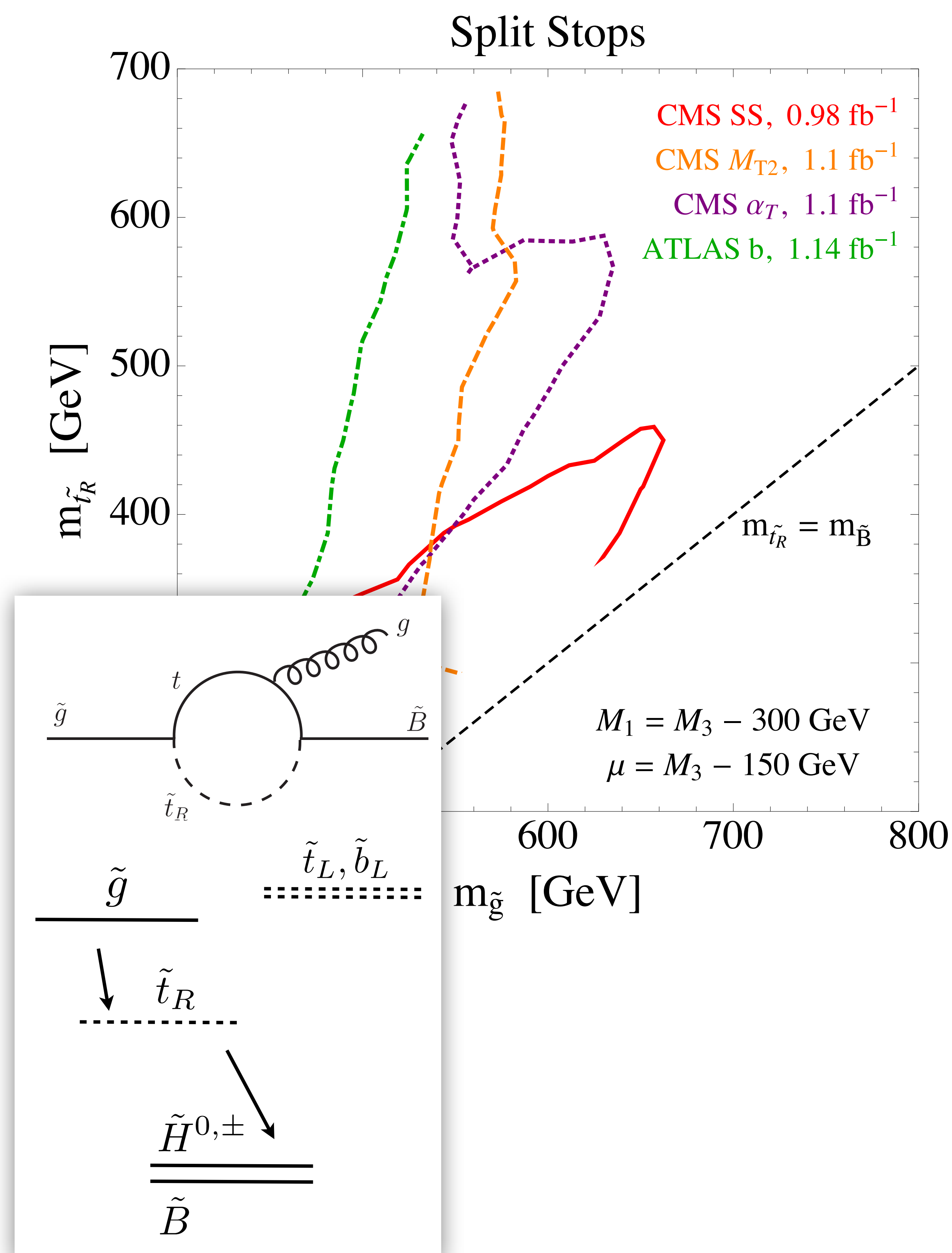
Adding the squarks, too



- Bounds similar to the ATLAS/CMS plots (800GeV-1TeV)
- Decoupling not effective until 1.2-1.4 TeV

Squashed spectrum

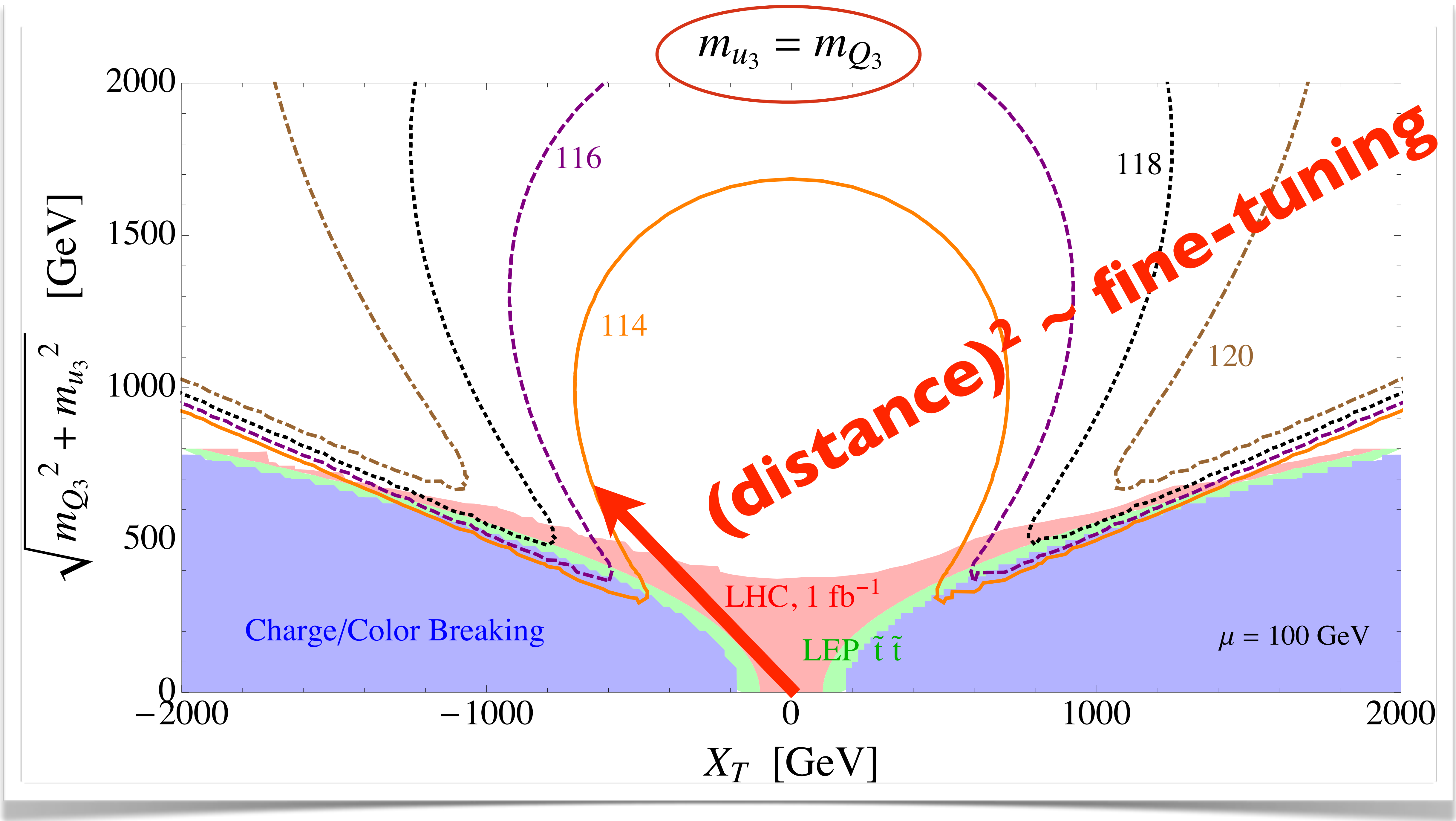




MSSM little hierarchy problem

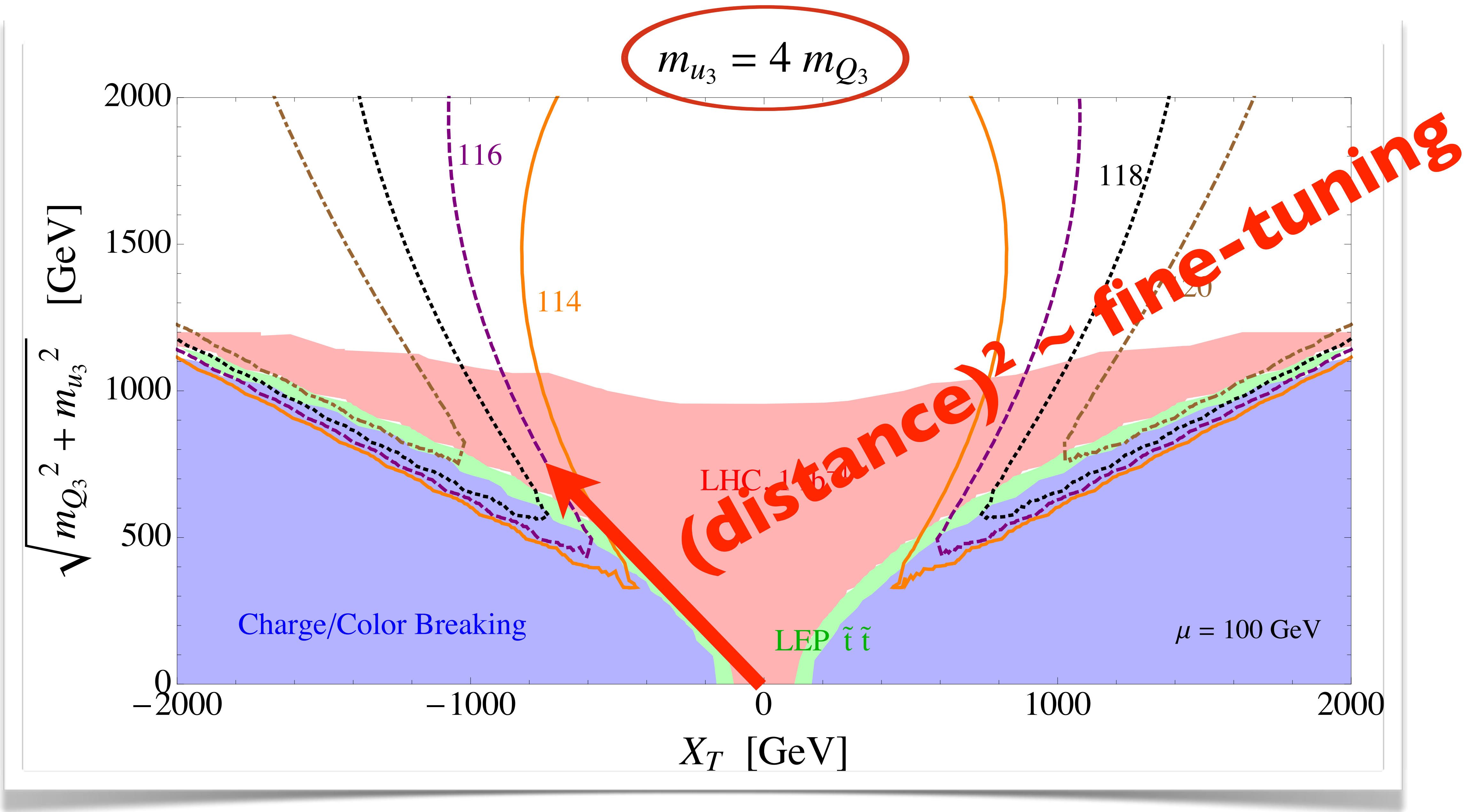
- Higgs mass lifted by large A-terms → split stop spectrum, | stop may be light and constrained by searches
- Compare to constraints from the Higgs mass bound?
- CAVEAT: only for higgsinos (higgsinos+binos) lighter than stops...

MSSM higgs: LEP2 tuning vs. direct stop



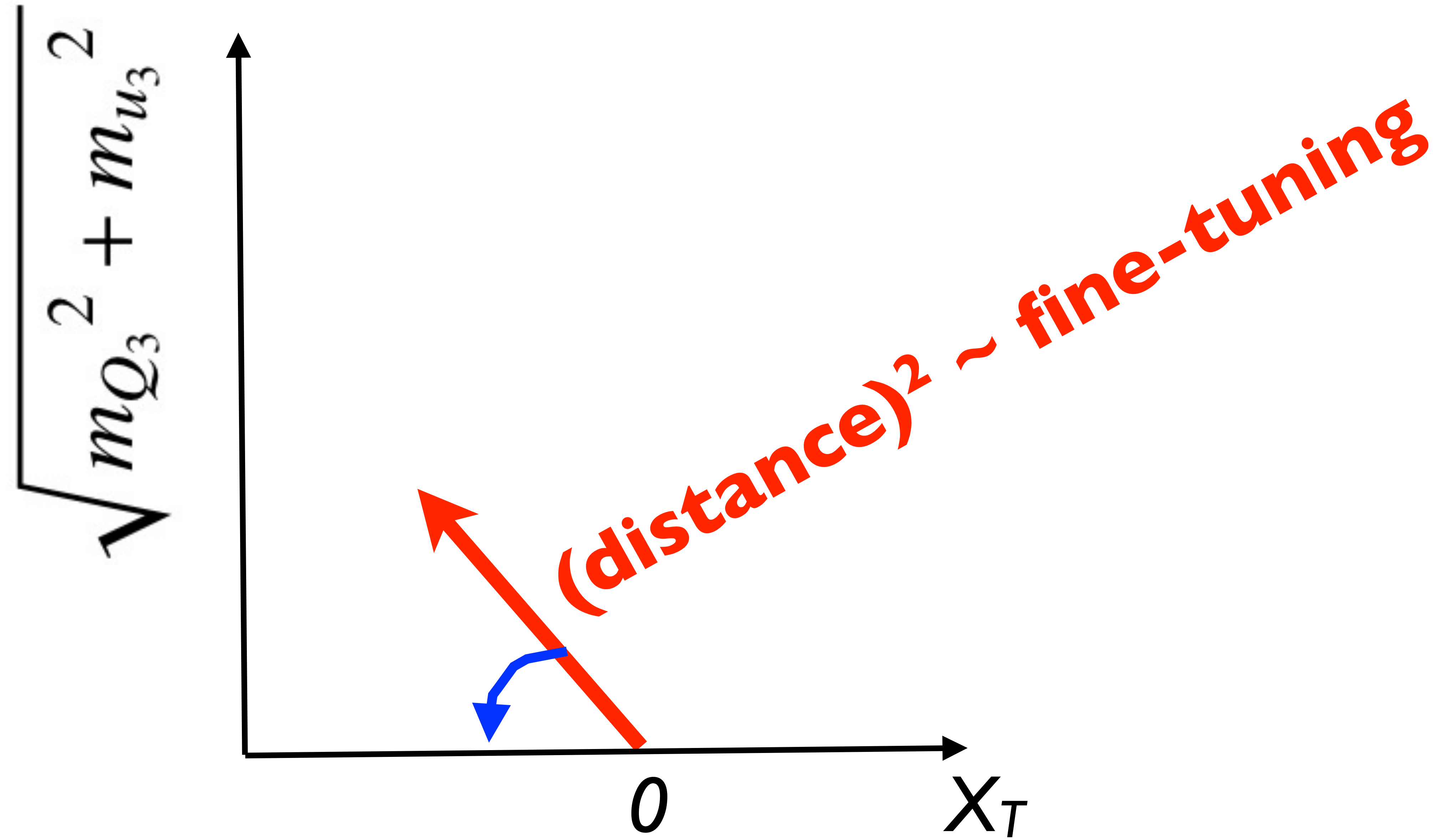
$$\delta m_H^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

MSSM higgs: LEP2 tuning vs. direct stop



Maximal mixing (for light Higgsino case) probed by the LHC… interesting interplay with Higgs searches.

Tuning to get maximal mixing required



"angle" not RGE stable →

Comment on max. mixing in MSSM

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

RGE focussing

$$m_{\tilde{t}}^2(M_Z) \simeq 5.0 M_3^2(M_G) + 0.6 m_{\tilde{t}}^2(M_G)$$
$$A_t(M_Z) \simeq -2.3 M_3(M_G) + 0.2 A_t(M_G)$$

→ Dermisek/H. D. Kim '06

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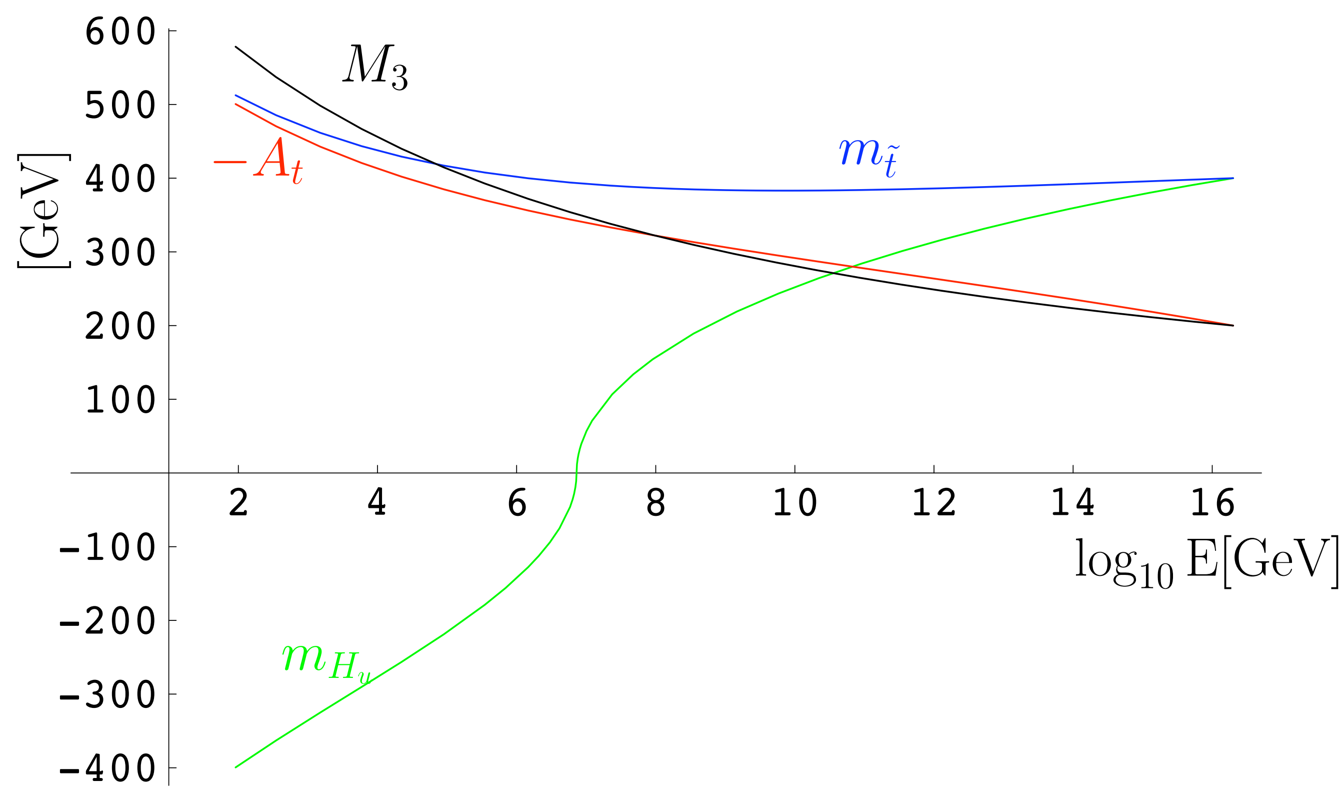


max. mixing requires engineering, usually: $|A_t/m_{\tilde{t}}| \lesssim 1$

→ Dermisek/H. D. Kim '06

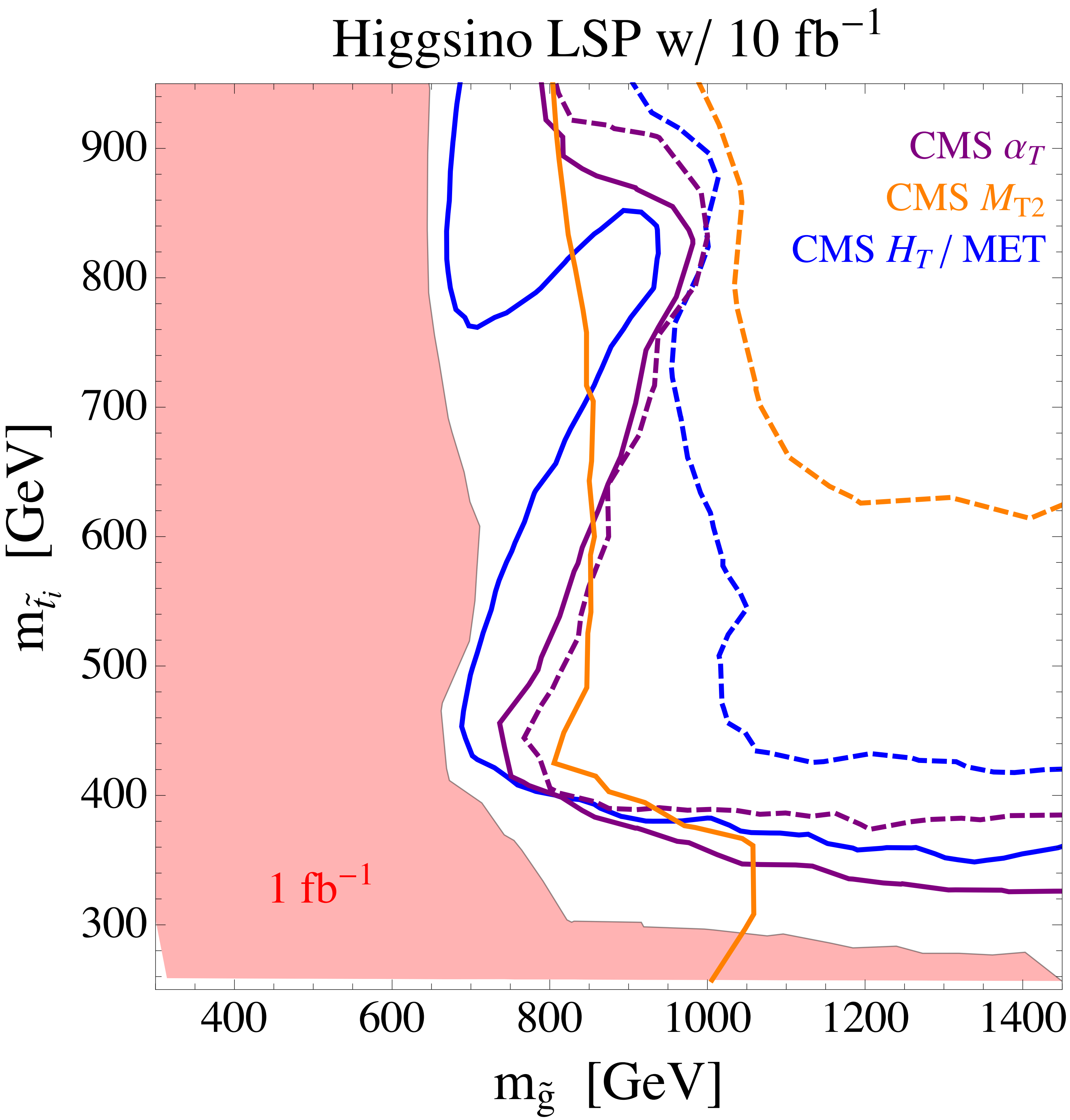
Summary

production	LSP	$\tilde{t}$ limit [GeV]	figure
$\tilde{t}_L + \tilde{b}_L$	$\tilde{H}$	~ 250	3
$\tilde{t}_R$	$\tilde{H}$	~ 180	3
$\tilde{t}_L + \tilde{b}_L$	$\tilde{B}$	$\sim 250 - 350$	5

scenario	$\tilde{g}$ limit [GeV]	$\tilde{t}$ limit [GeV]	figure
$\tilde{H}$ - LSP	$\sim 650 - 700$	~ 280	10
$\tilde{B}$ - LSP	~ 700	~ 270	10
somewhat squashed	$\sim 600 - 700$	–	11
split $\tilde{t}$	$\sim 550 - 650$	–	11
flavor degen.	1200 (fixed)	$600 - 900$	16
gaugino unify	$\sim 750 - 800$	~ 260	16

arXiv:1110.6926

Projections?



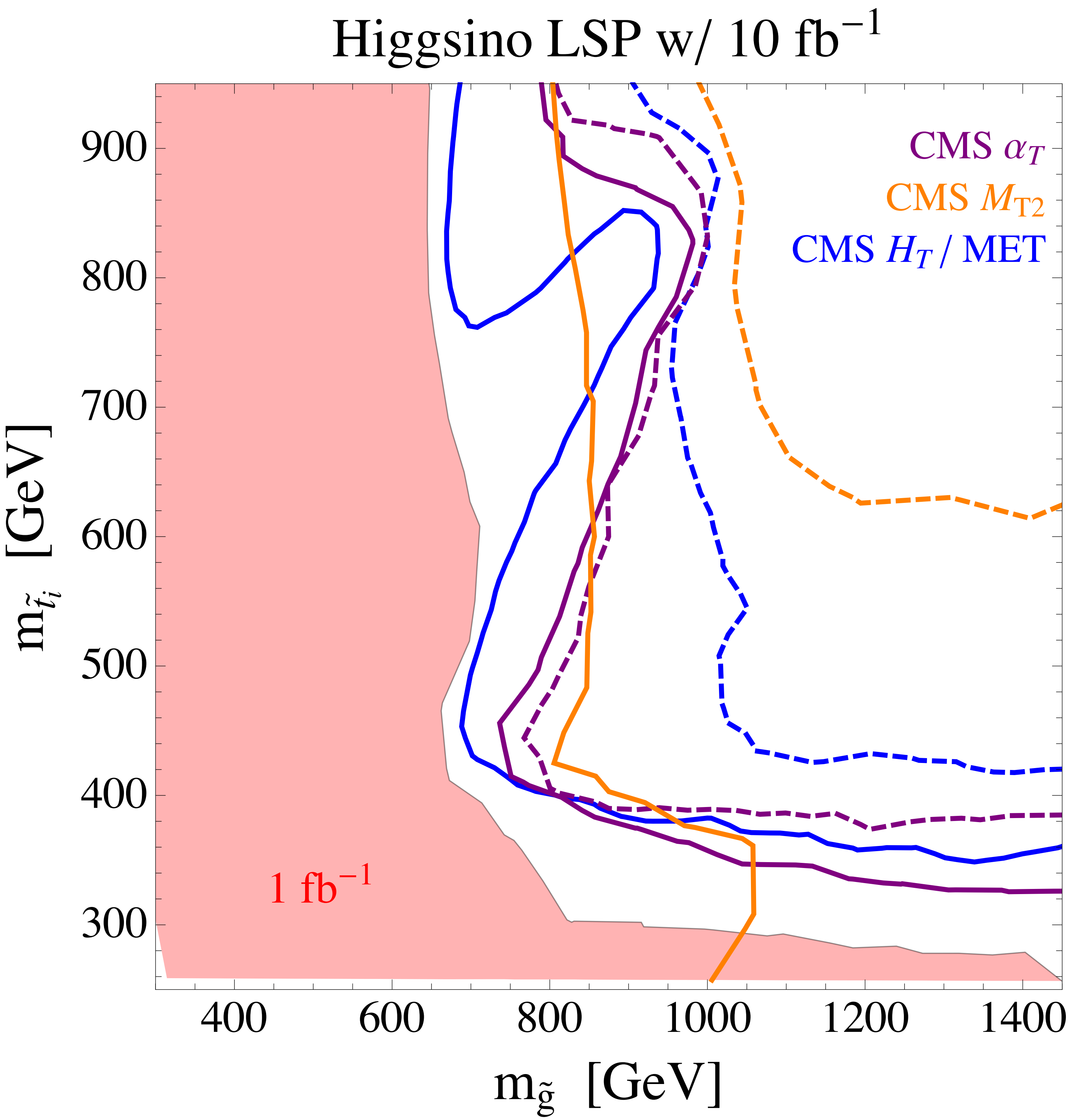
dashed - perfect bgd's

solid - statistics improves, systematics same fraction

* Large uncertainty
* Targeted searches do likely better.

Backup

Projections?



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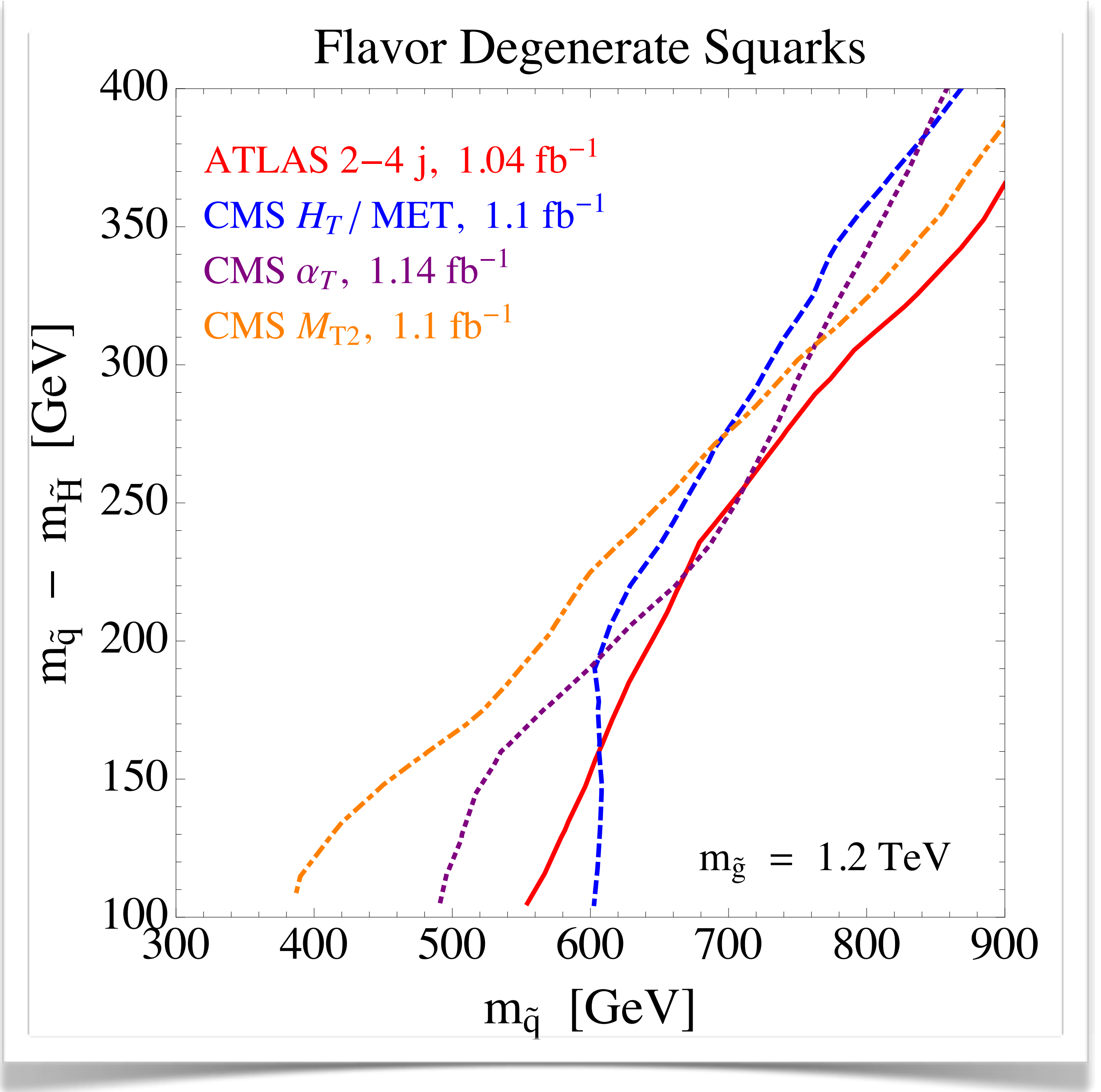
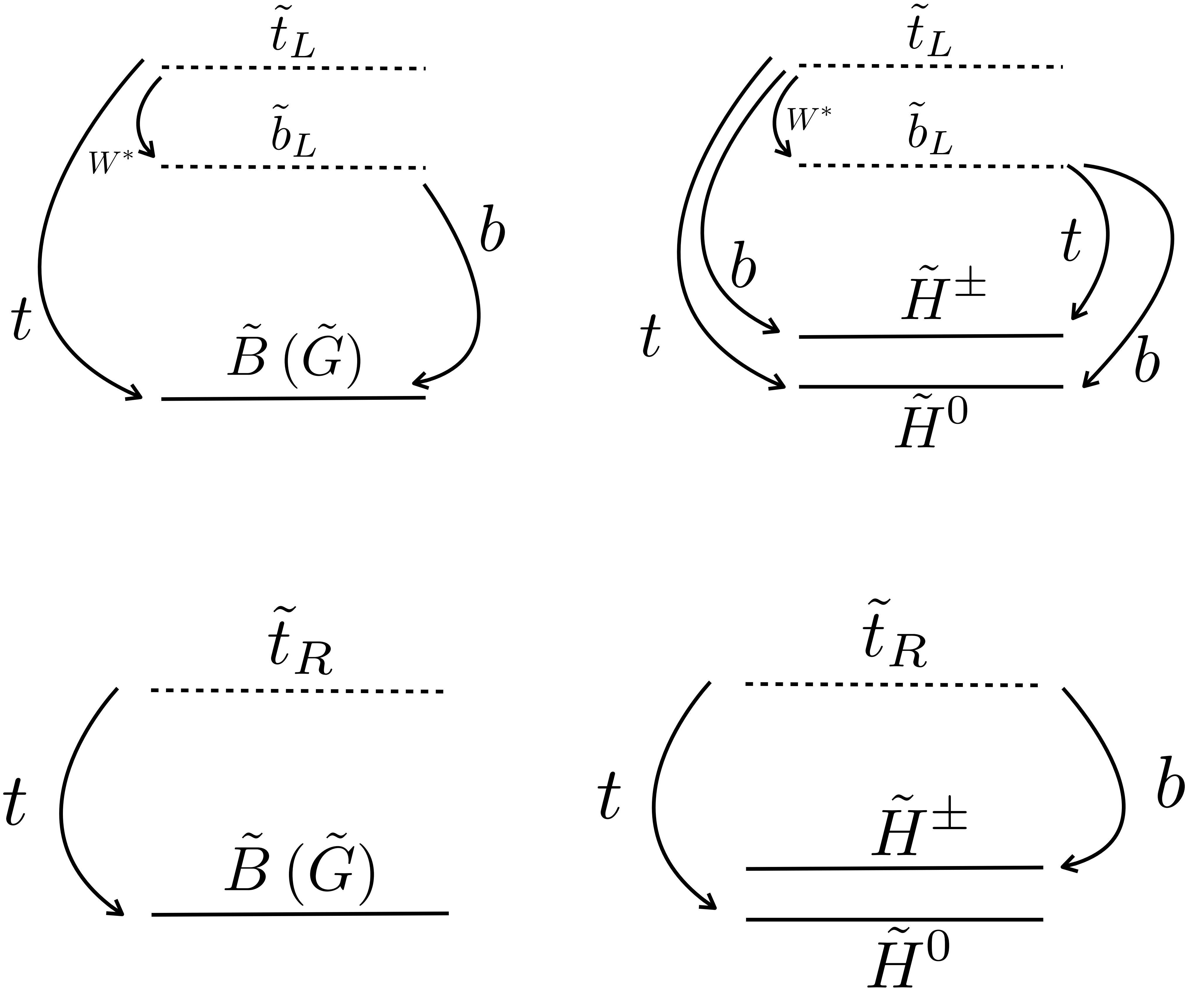
* Targeted searches do likely better.

Back to the flavor degenerate case



Hard to investigate more squashed spectra
(+ additional tuning due to squashing…)



$\tilde{t}_L$
$\tilde{b}_L$
W^*
t
b
$\tilde{B}\,(\tilde{G})$
$\tilde{t}_L$
$\tilde{b}_L$
W^*
t
b
t
b
$\tilde{H}^{\pm}$
$\tilde{H}^0$
$\tilde{t}_R$
t
$\tilde{B}\,(\tilde{G})$
$\tilde{t}_R$
t
b
$\tilde{H}^{\pm}$
$\tilde{H}^0$