Natural Susy Endures

Andreas Weiler
(DESY)

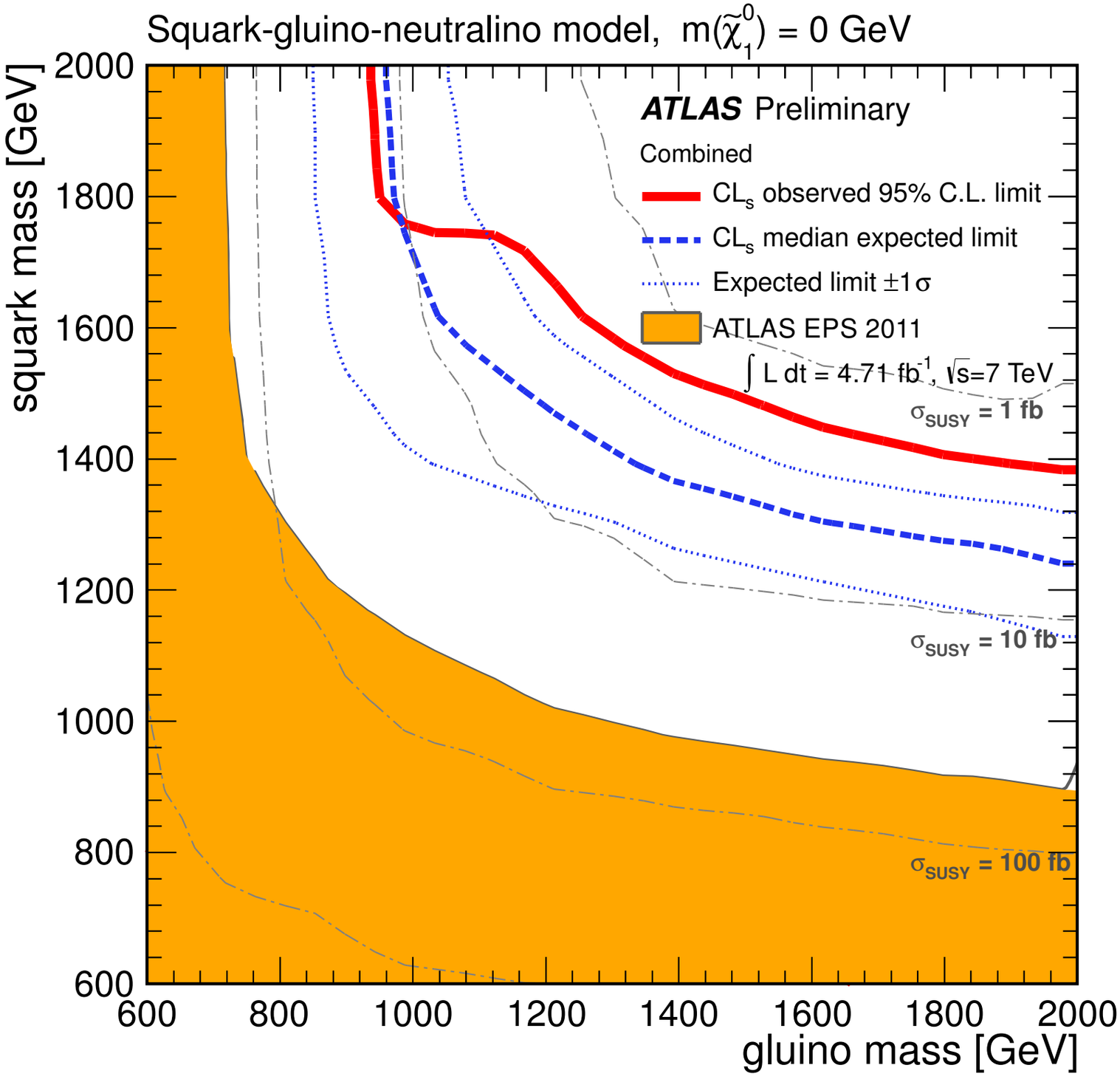
CERN LHC2TSP
28/3/12

With
Michele Papucci & Josh Ruderman
arXiv:1110.6926

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

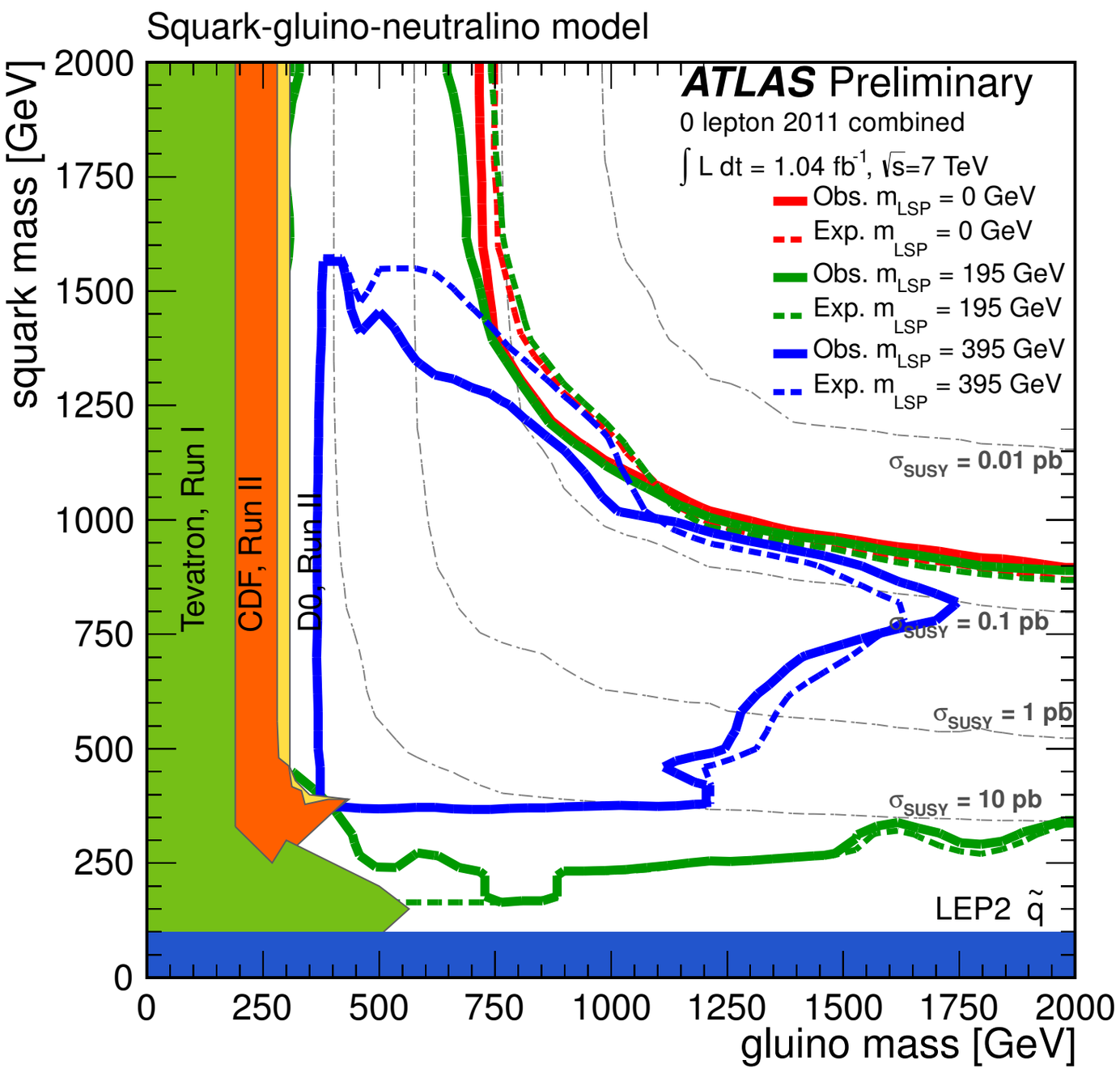
M. Bateson

4.7 /fb Susy, post-Moriond

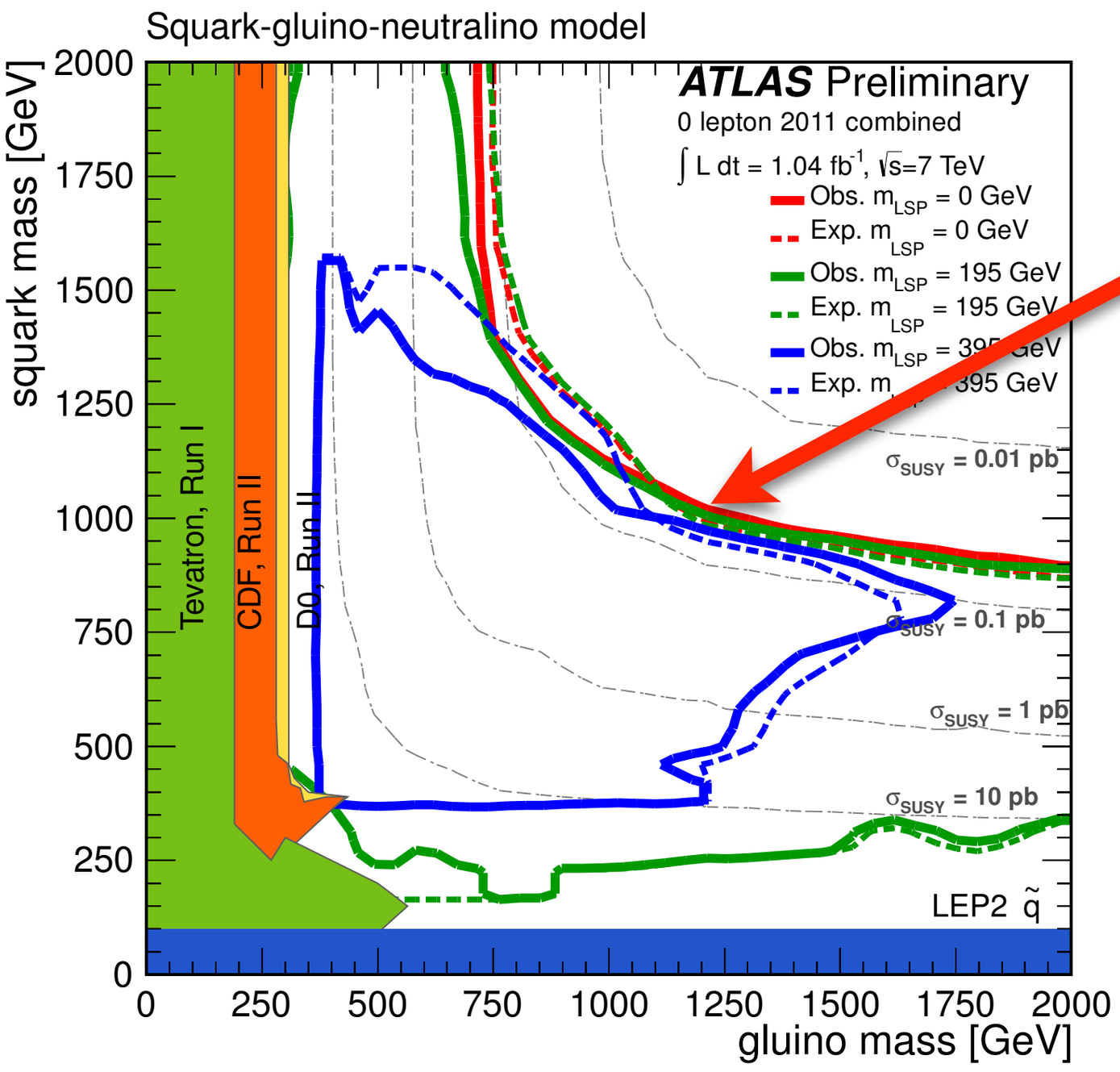


Will's talk

1/fb Susy, pre-Moriond

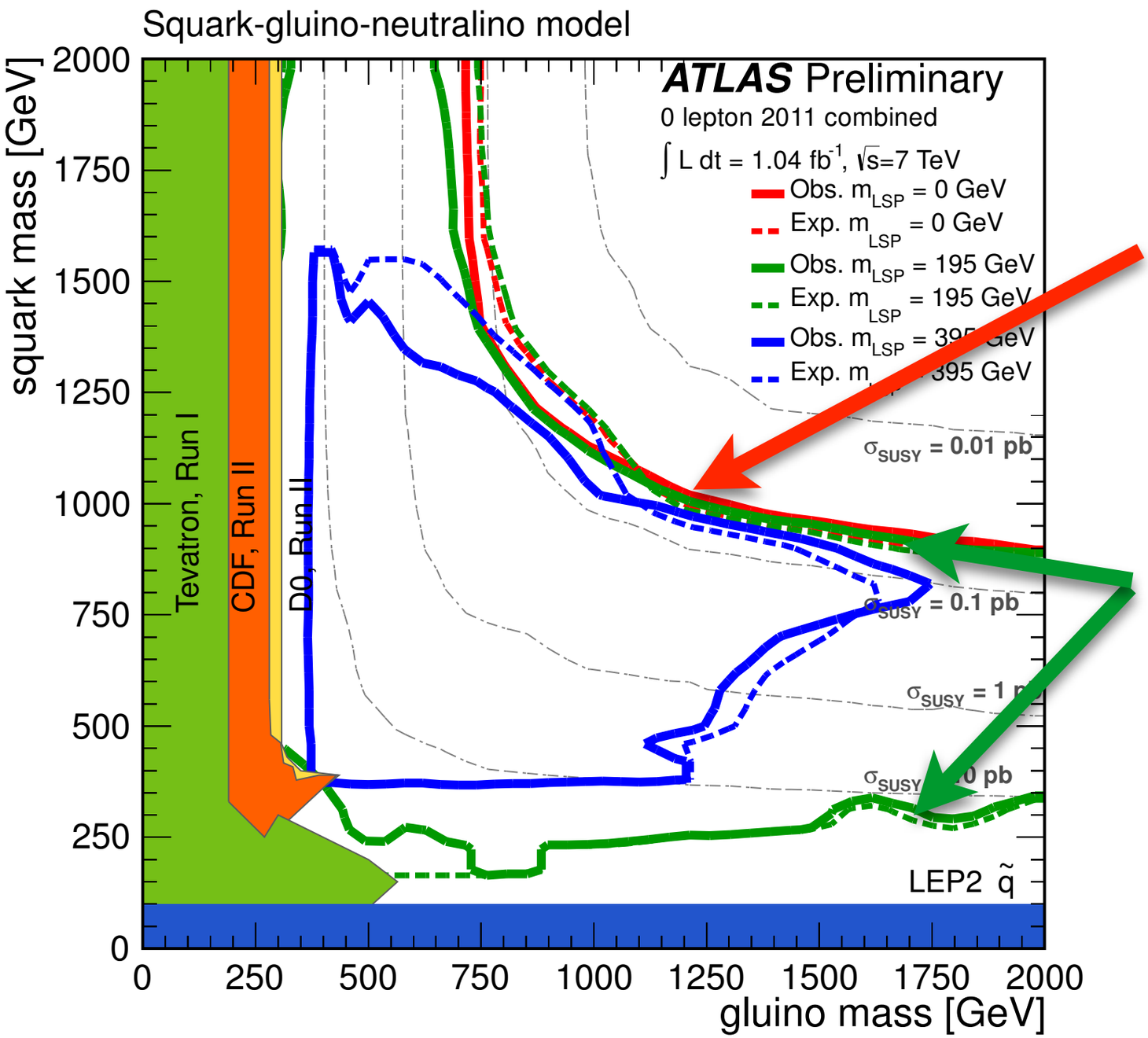


1/fb Susy, pre-Moriond



m_{LSP} = 0 GeV

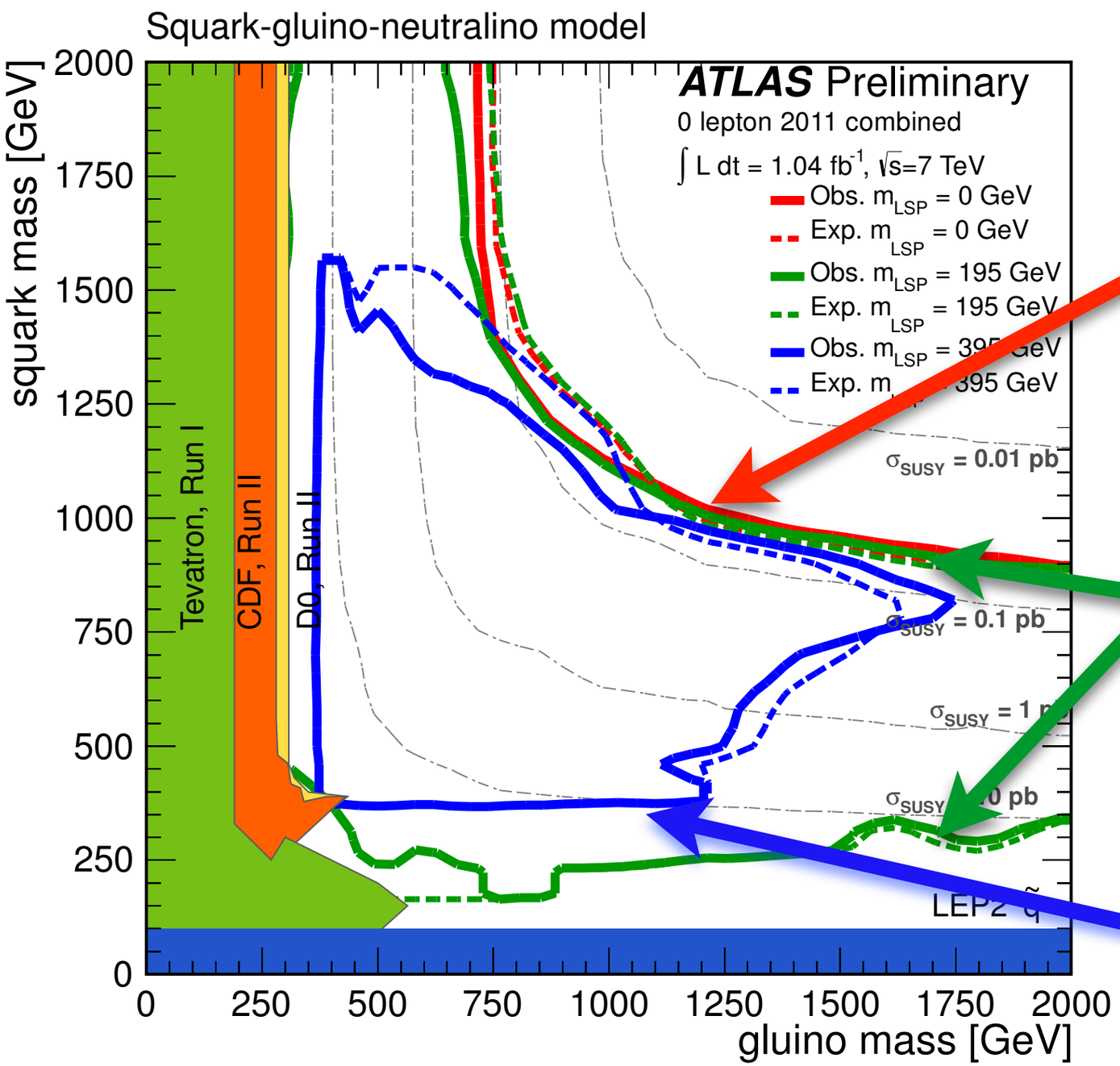
1/fb Susy, pre-Moriond



m_{LSP} = 0 GeV

m_{LSP} = 195 GeV

1/fb Susy, pre-Moriond

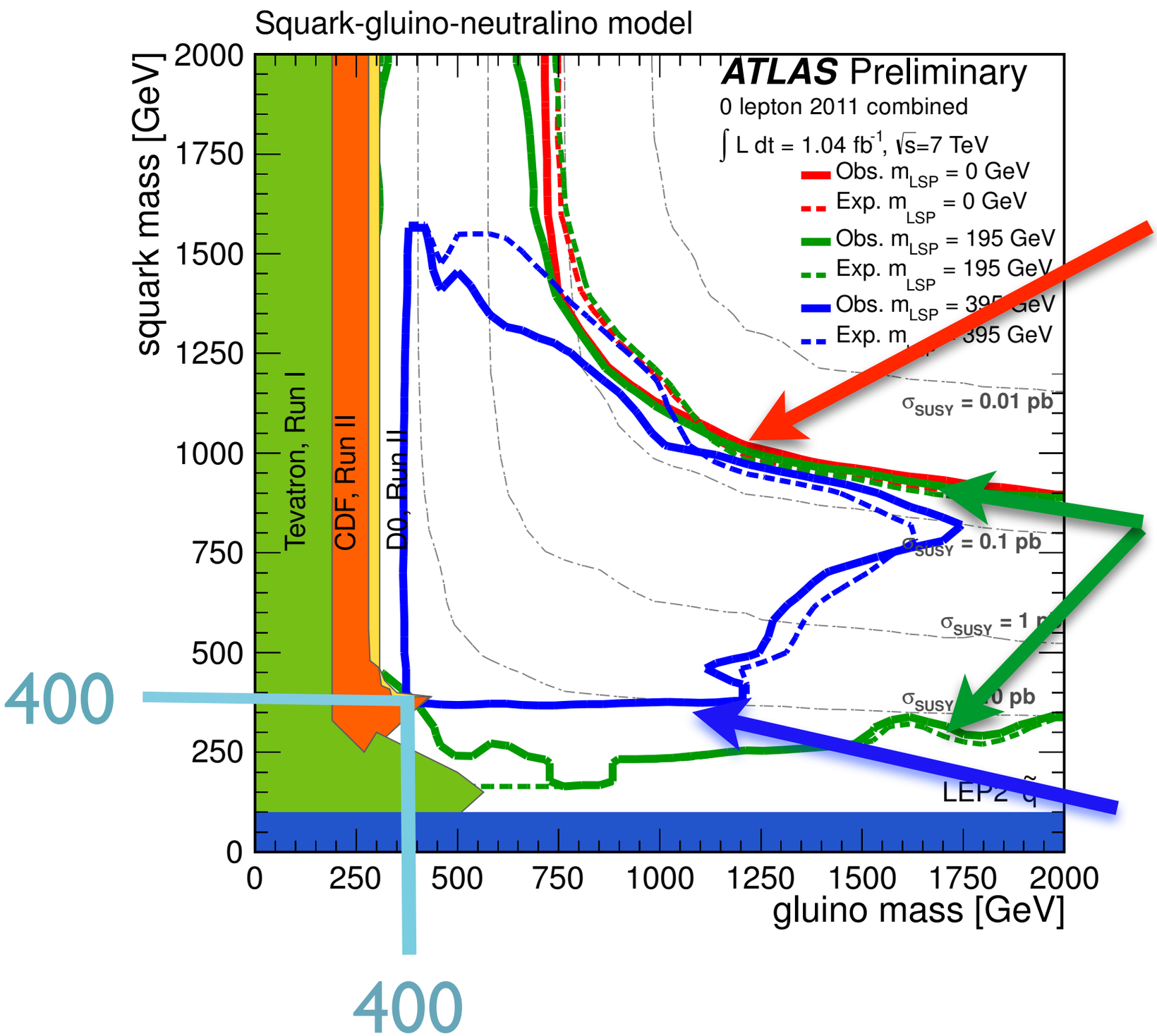


m_{LSP} = 0 GeV

m_{LSP} = 195 GeV

m_{LSP} = 395 GeV

1/fb Susy, pre-Moriond



m_{LSP} = 0 GeV

m_{LSP} = 195 GeV

m_{LSP} = 395 GeV

400

400

Avoiding m_{SUSY} > TeV

- R-parity violation?
- Stealth susy?
- Compressed susy? (ISR?)
- bottom-up natural spectrum! → this talk
- other options?

- Bottom-up naturalness reminder
- Current limits?

h = linear combination of fields whose vev breaks EW symmetry

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

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

measures fine-tuning

Natural EWSB & MSSM

Fine-tuning of (Higgs mass)^2

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

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

Natural EWSB & SUSY

MSSM,NMSSM, DMSSM, ...

Fine-tuning of (Higgs mass)^2

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

Natural EWSB & SUSY

MSSM,NMSSM, DMSSM, ...

Fine-tuning of (Higgs mass)^2

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Higgsinos

Natural EWSB & SUSY

MSSM,NMSSM, DMSSM, ...

Fine-tuning of (Higgs mass)^2

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

Higgsinos

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

stops, sbottom$_L$

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

gluino

EW-inos:

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

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

→ can be heavier (or lighter…) than stop

Bottom-up natural spectrum

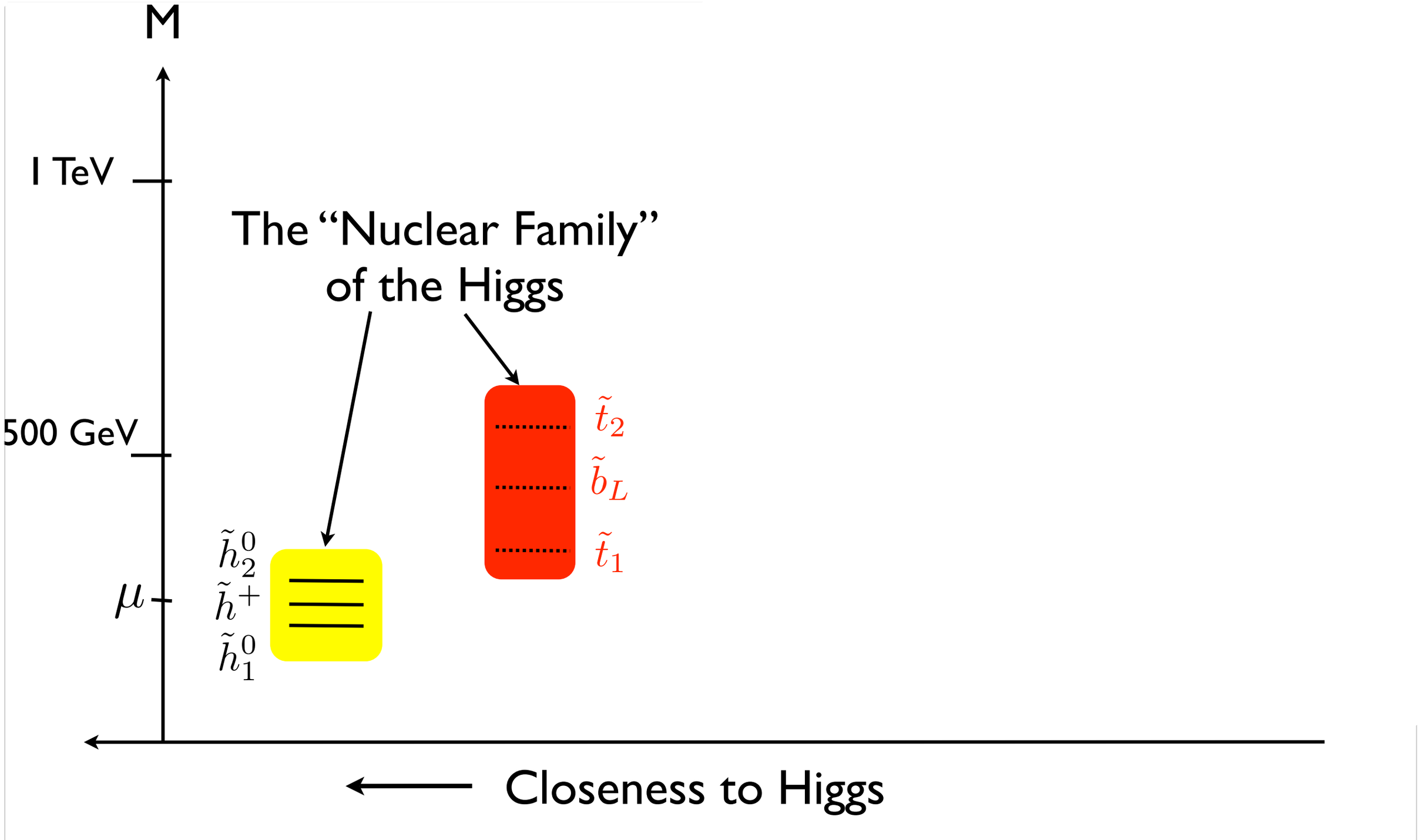
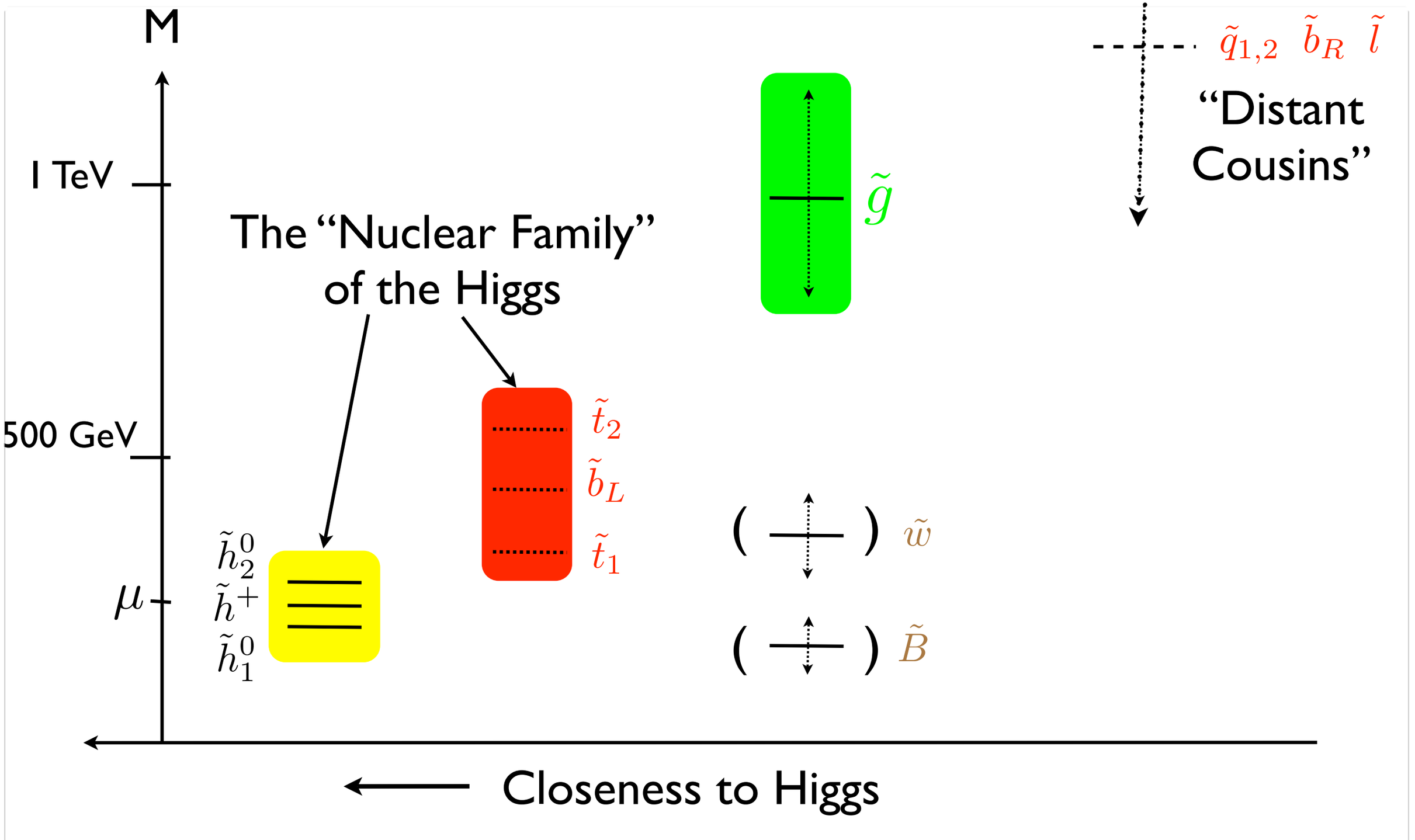


Fig. from L.Hall's talk

Bottom-up natural spectrum



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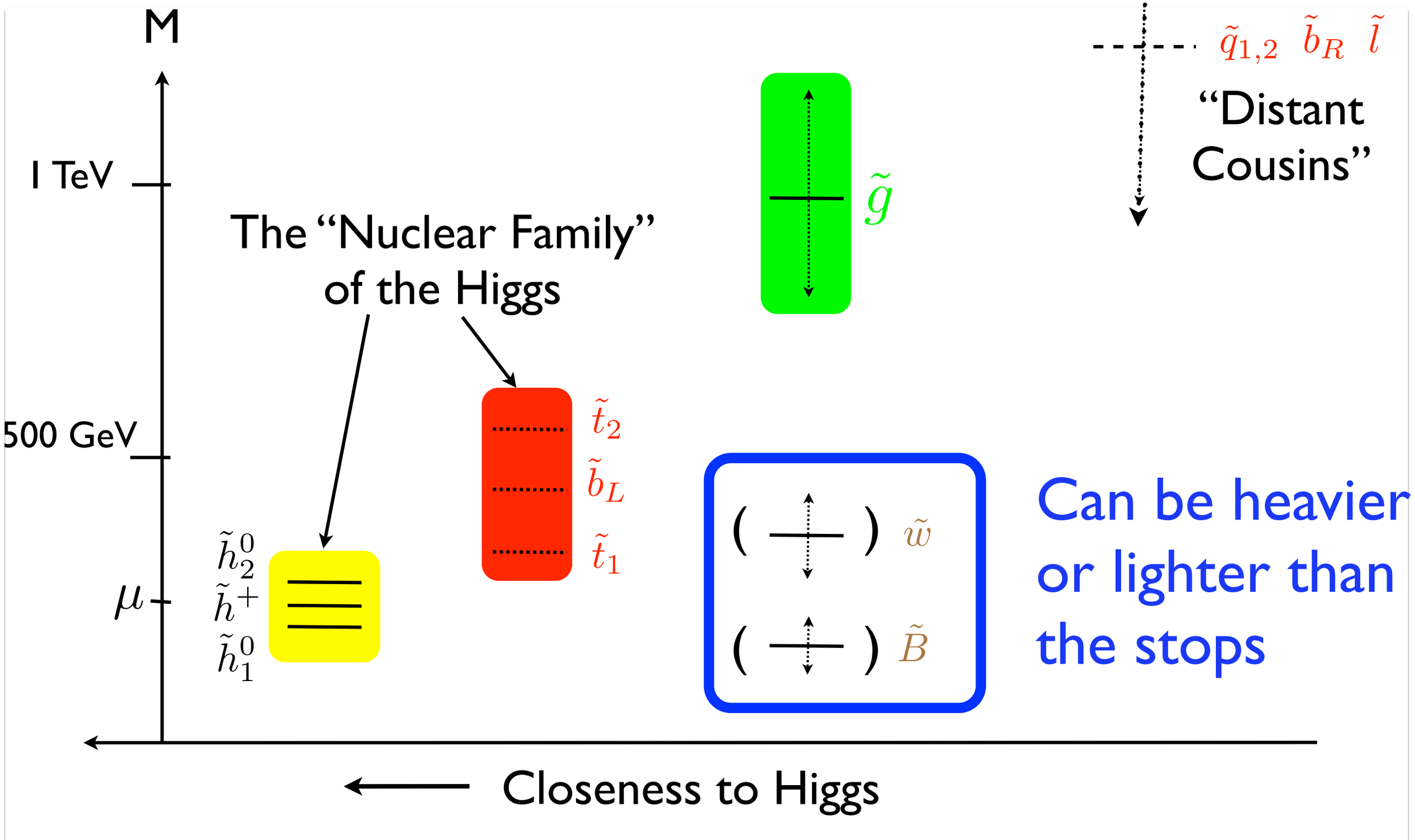


Fig. from L.Hall's talk

bottom up naturalness quantified

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

Kitano and Nomura 2006.

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

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

Kagan, Dine, Leigh ’93; Dimopoulos, Giudice ’95; Cohen, Kaplan, Nelson ’96; … Perelstein/Spethman ’07; Barbieri et al. … (many many more)

A natural spectrum naturally (in a full model)?

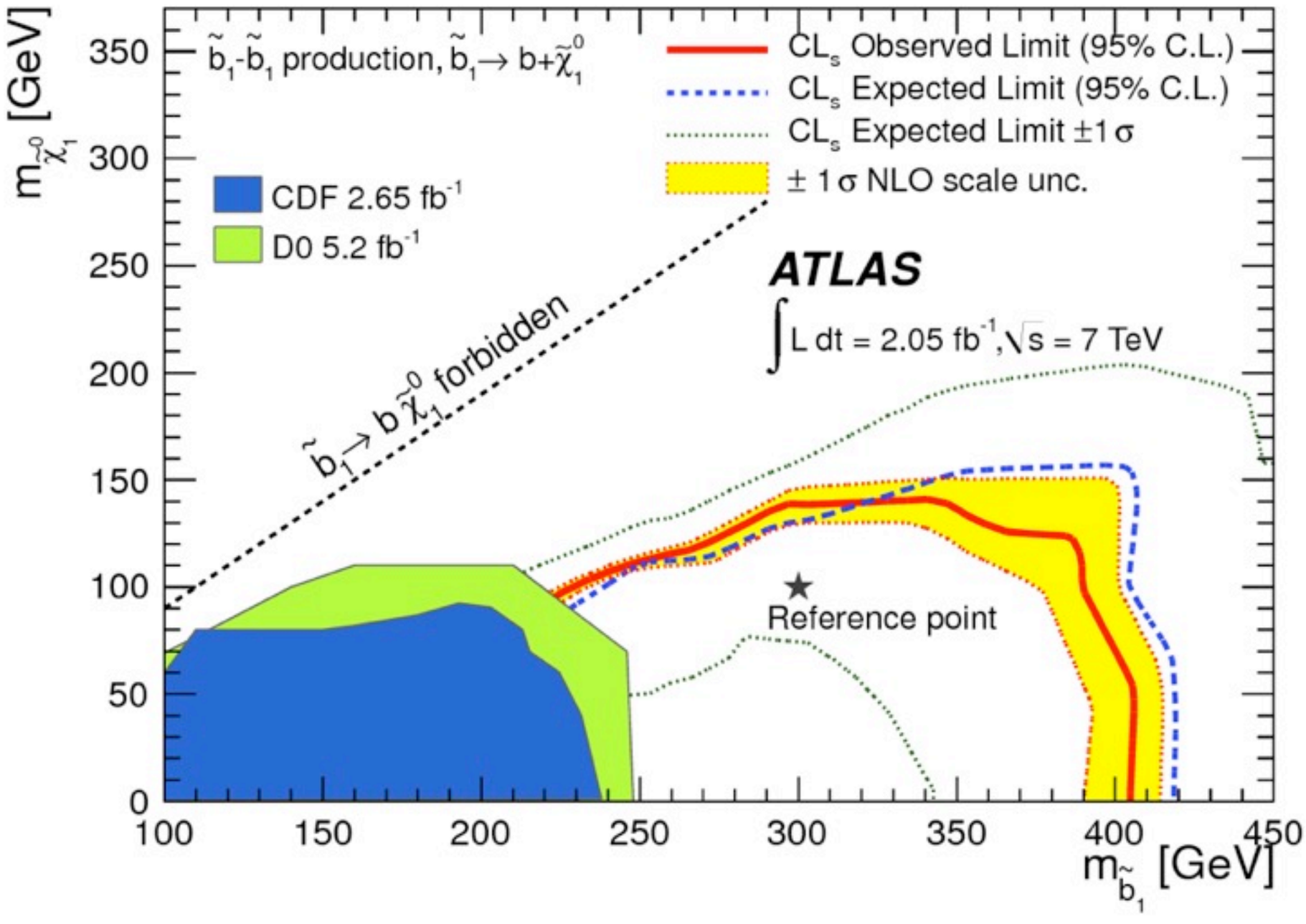
Many examples in the recent literature

…

Csaki et al [1201.1293] (seiberg'ology),
Krippendorf et. al [1201.4857] (strings),
Craig et. al [1203.1622] (flavor mediation),

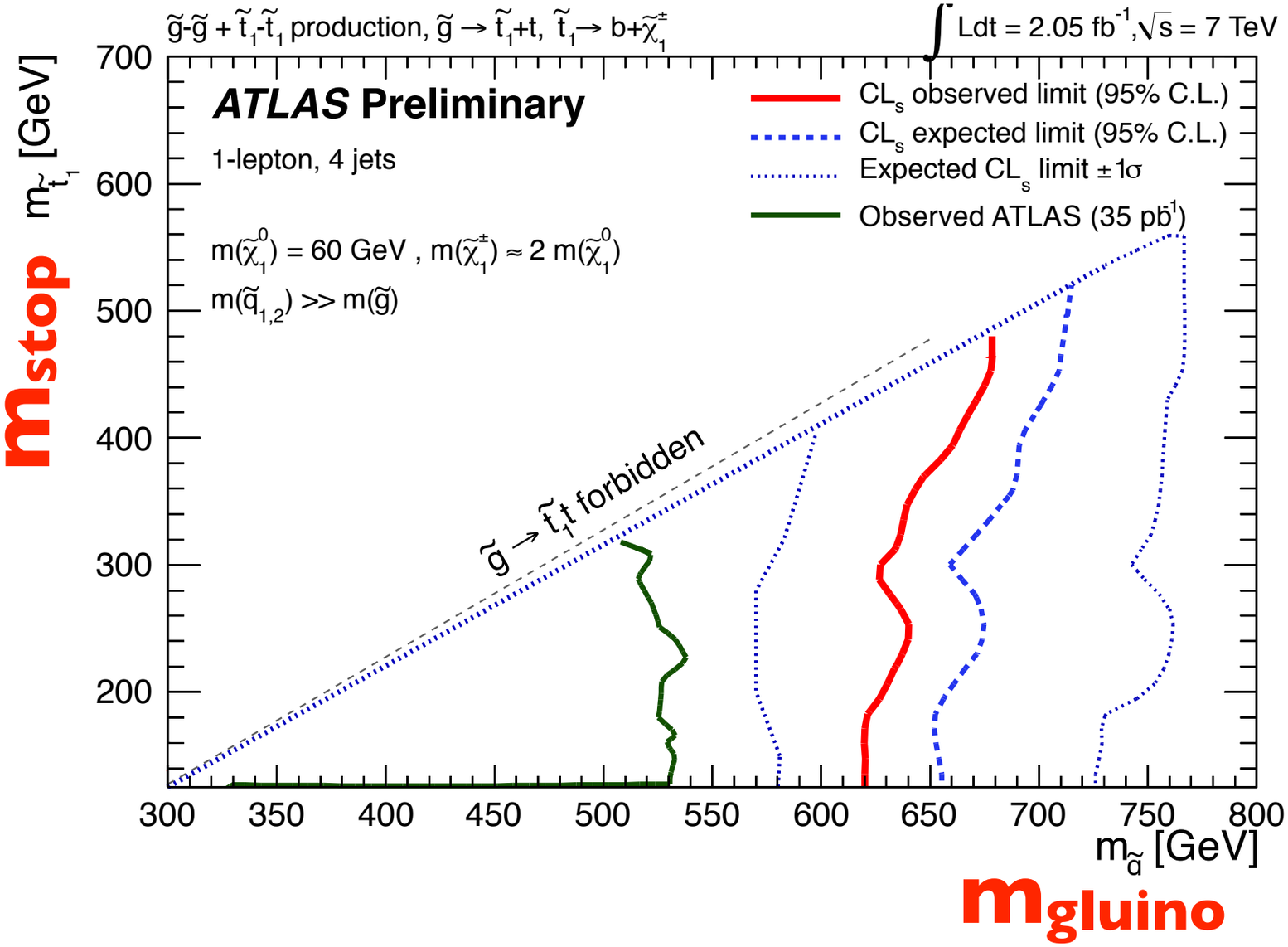
…

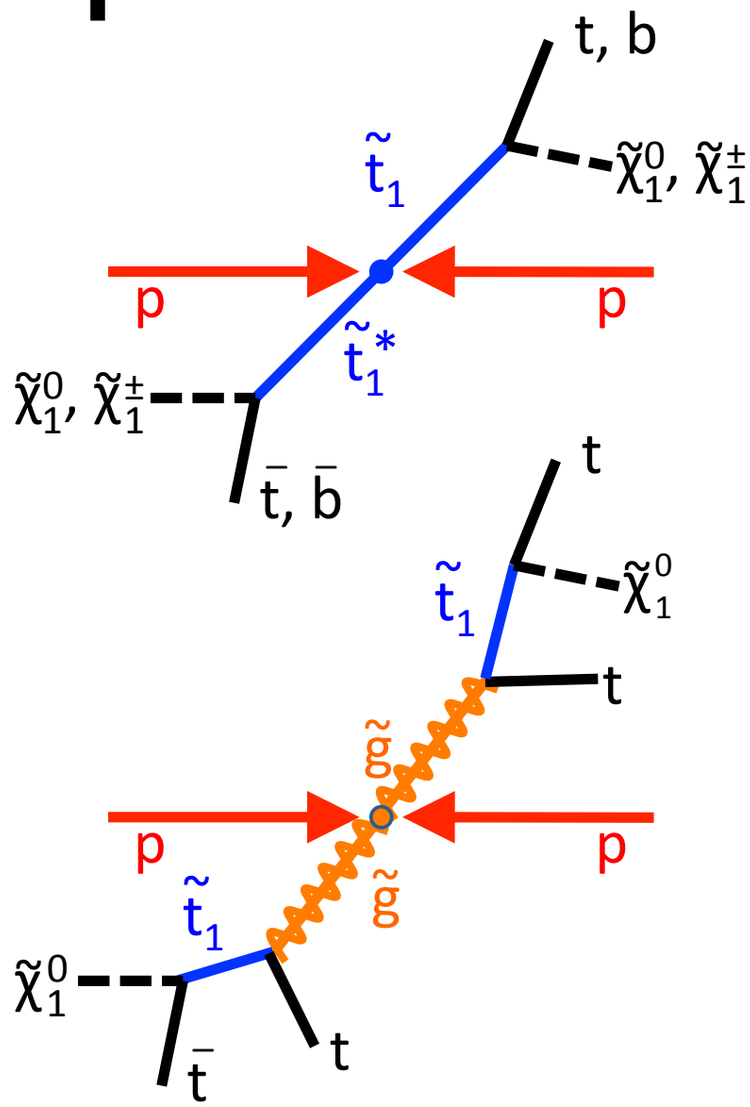
Latest on direct sbottoms



→ Alan's talk

Latest limits on stops





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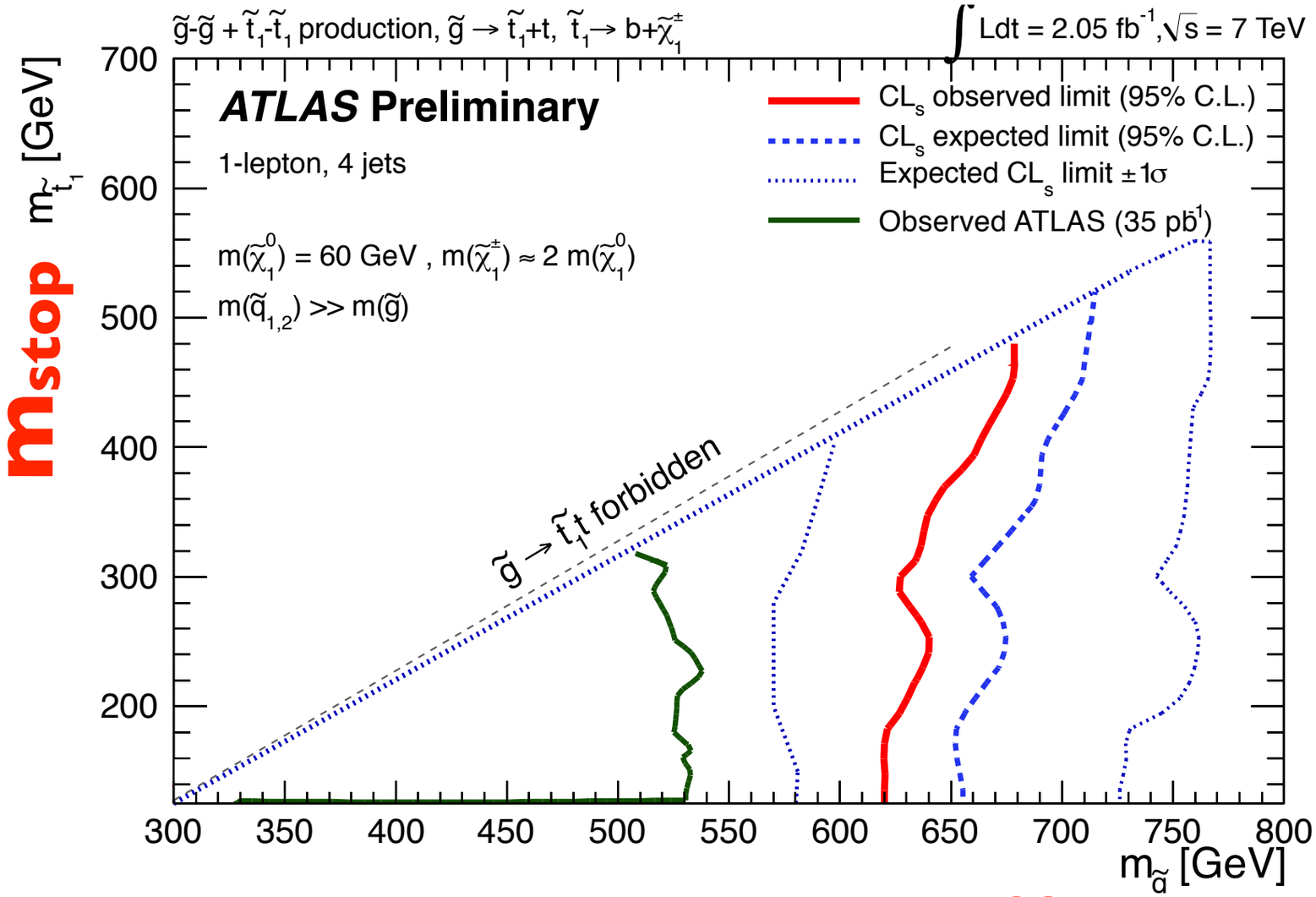
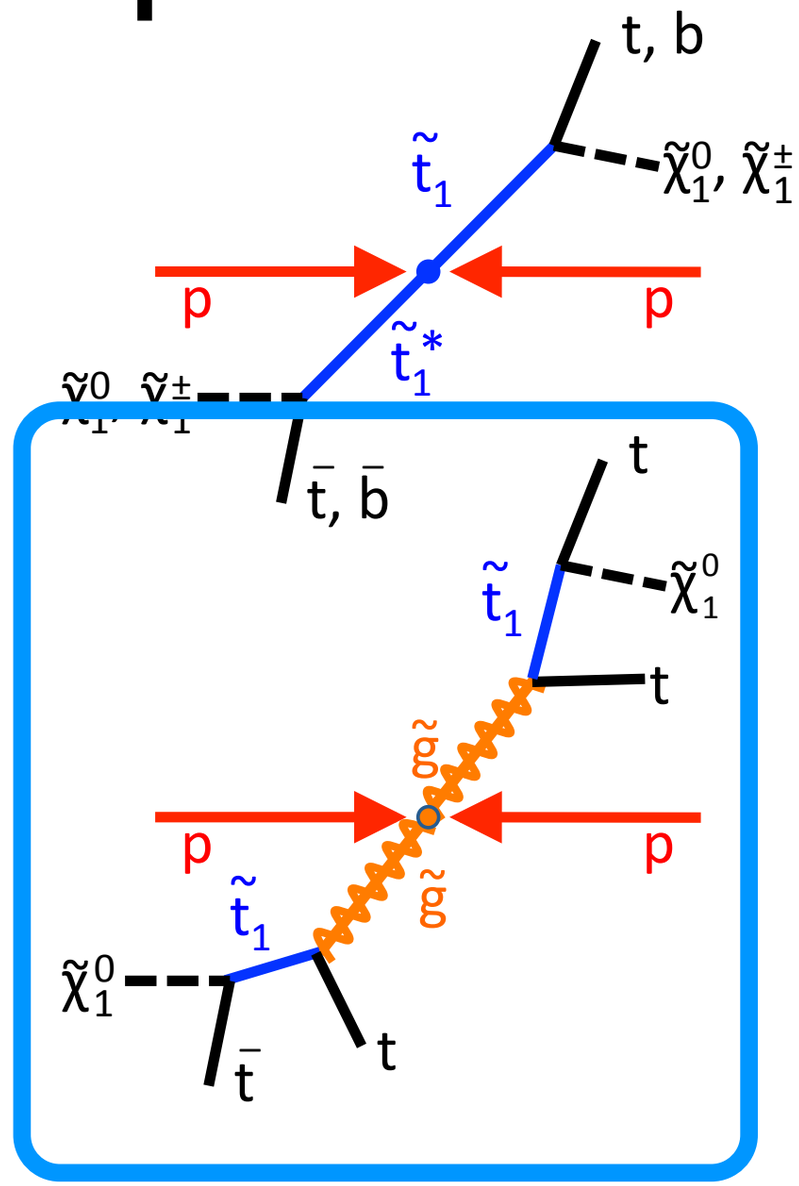


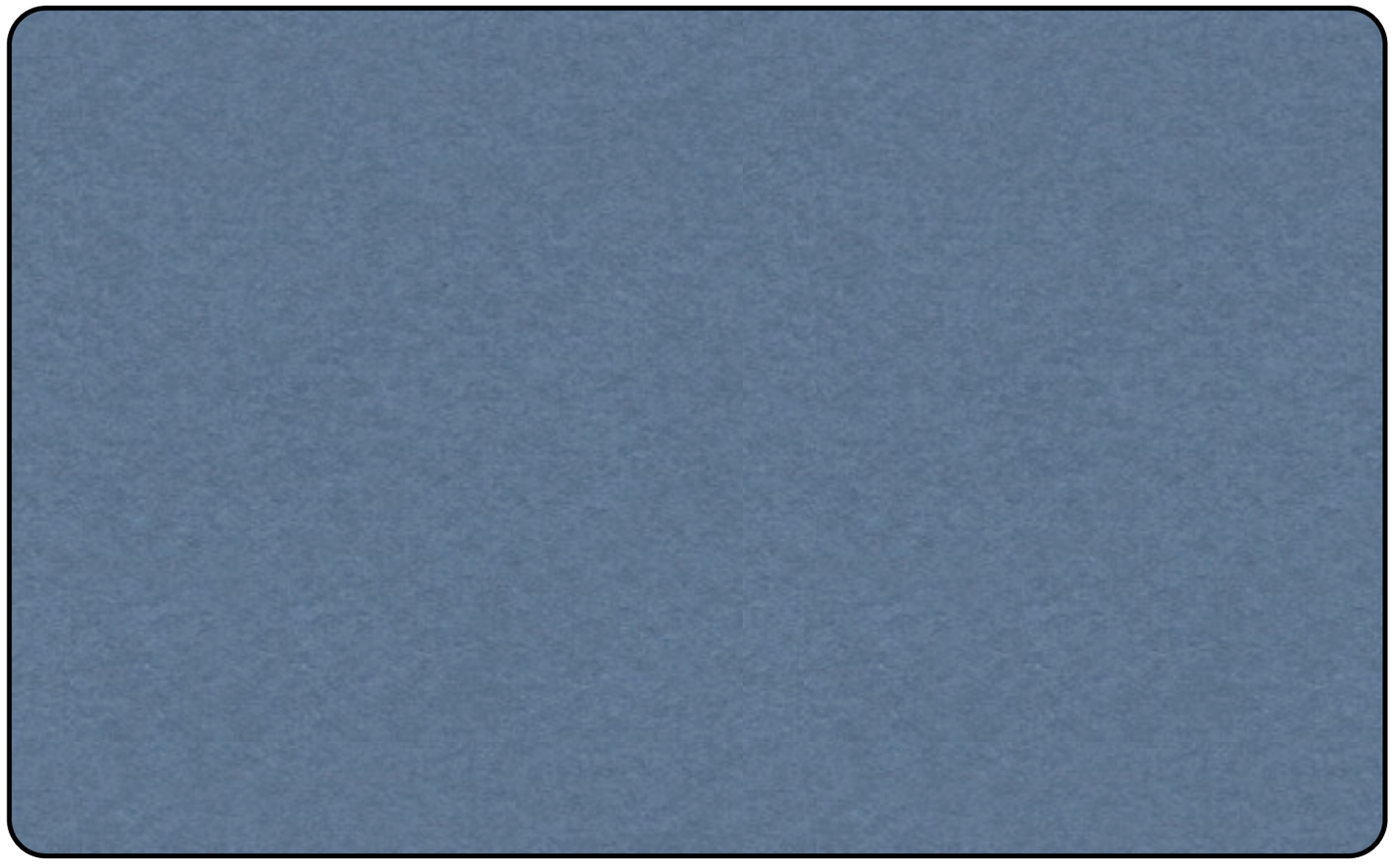
m_{stop}

m_{gluino}

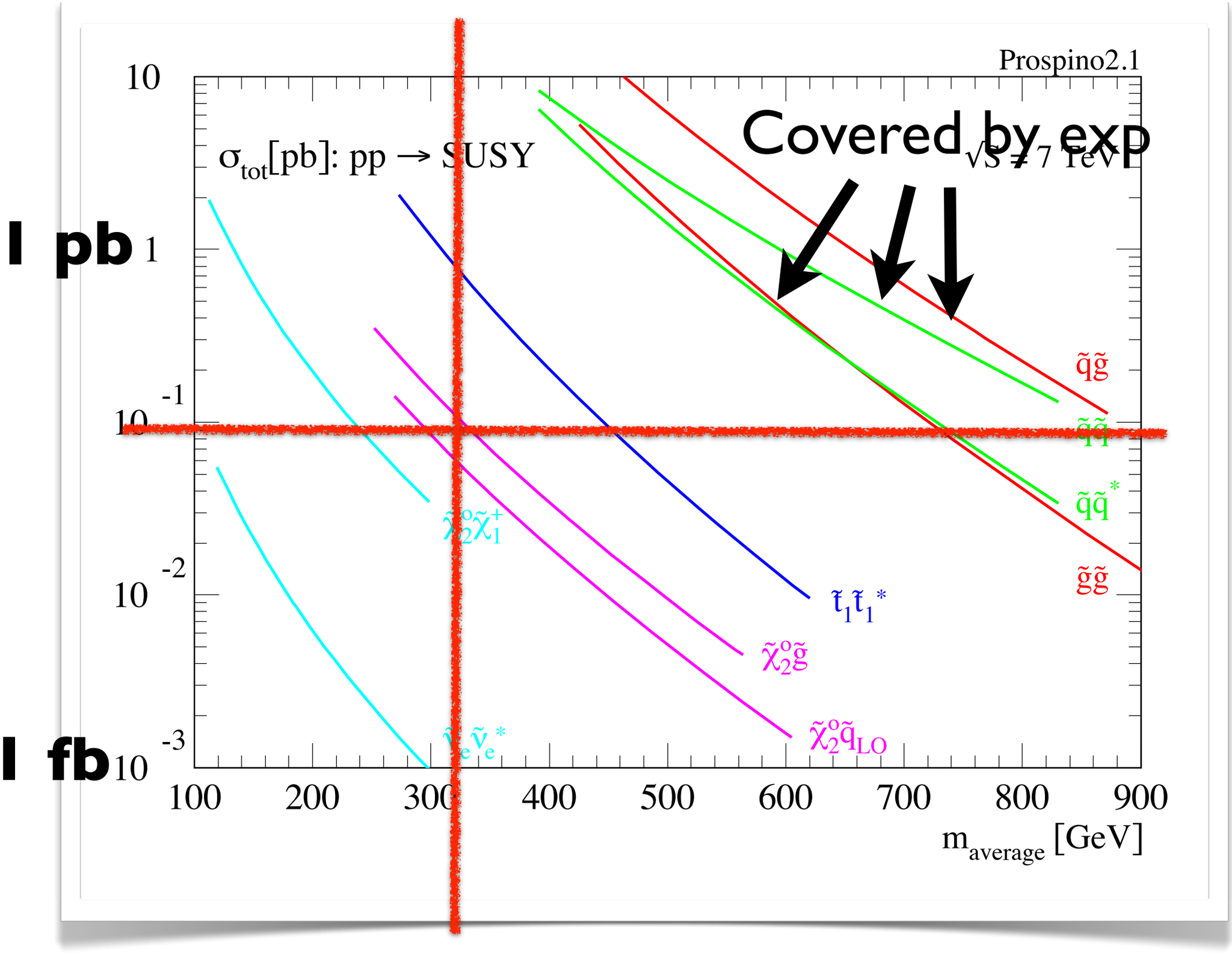


dominates

?? σ excess in direct stop search



Direct stop prod. with O(1/fb) ?



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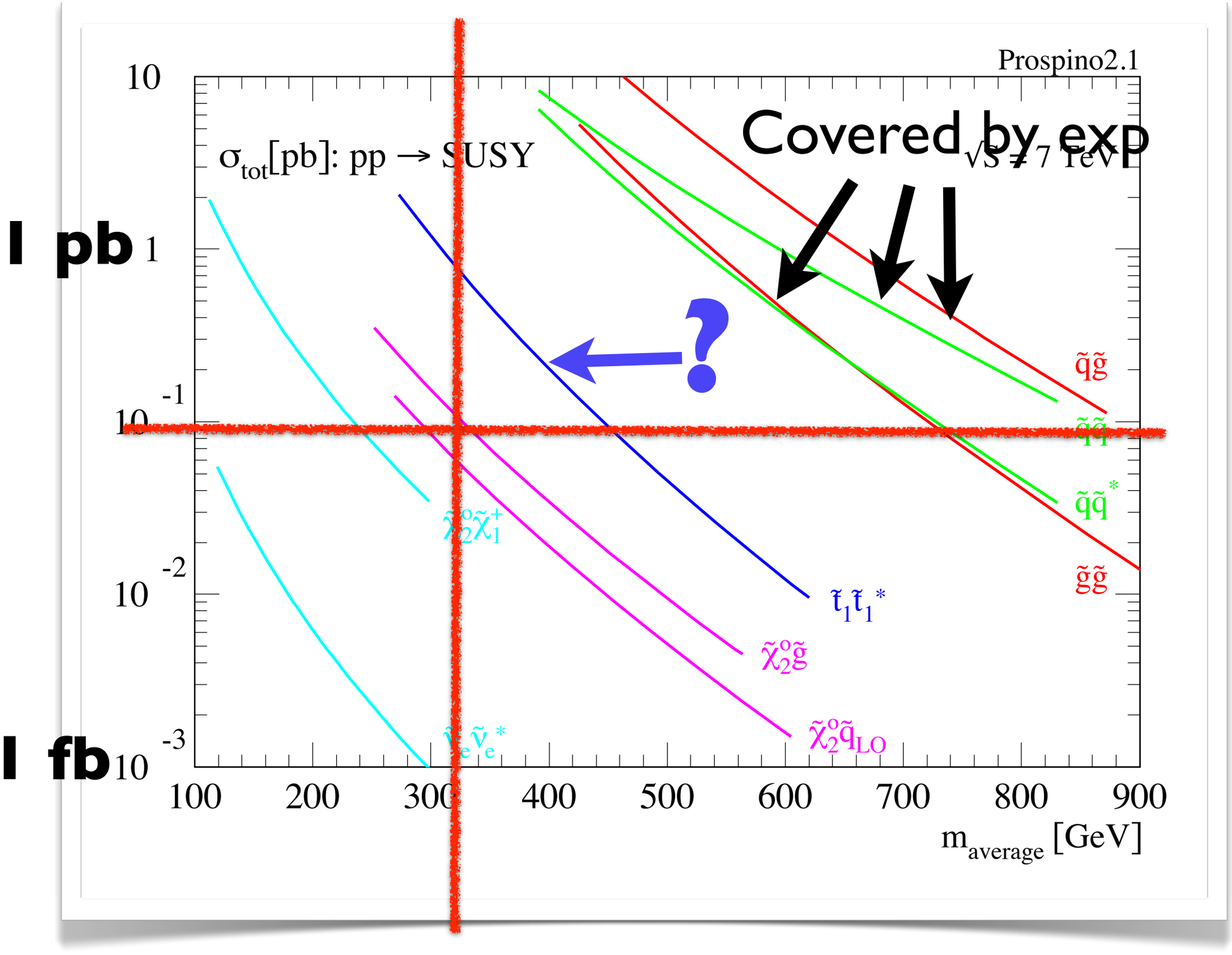


"The experiments haven't covered my favorite model"

Relax & Wait?

vs.

* not his real attitude.

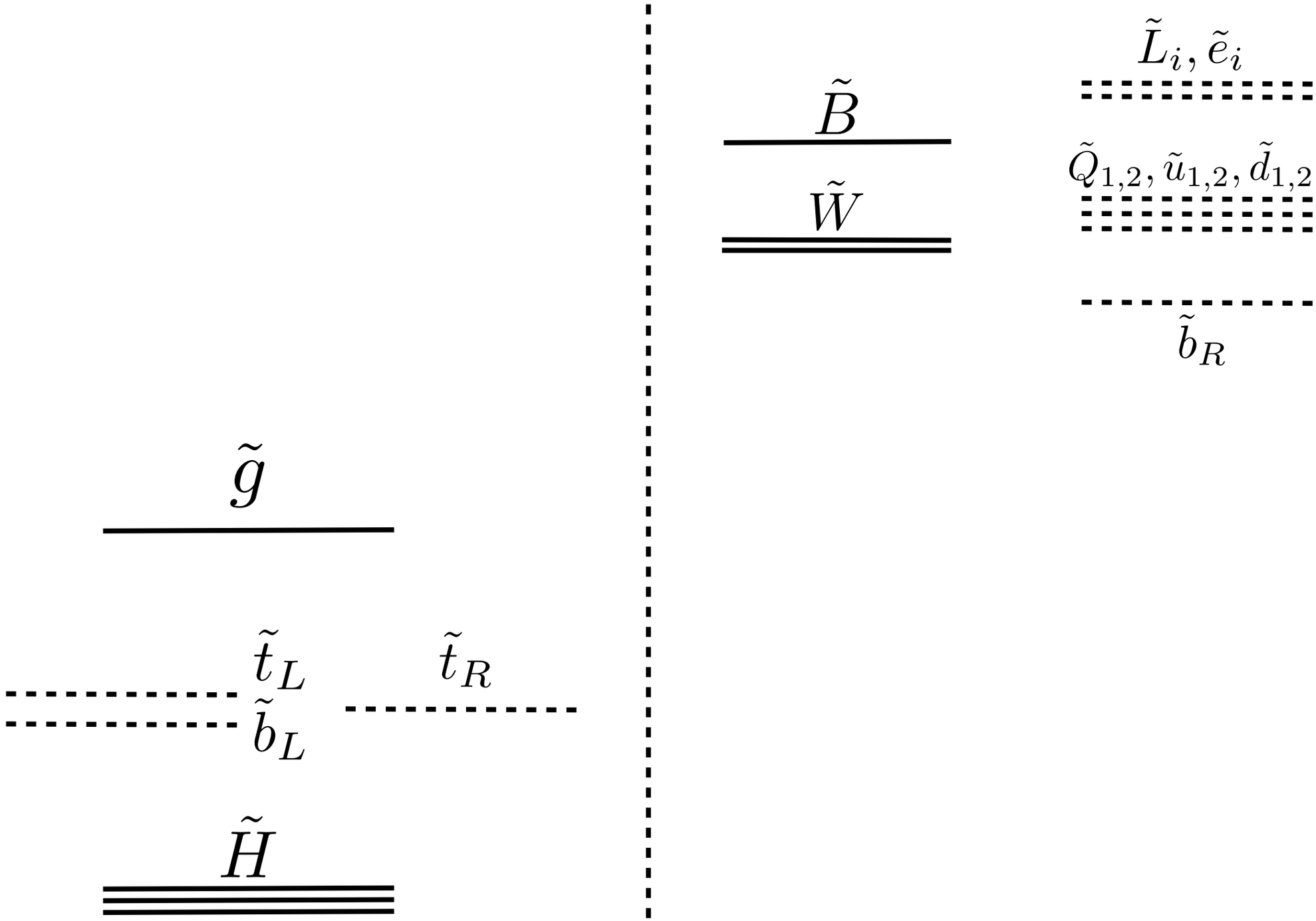
"The experiments haven't covered my favorite model"

Relax & Wait?

vs.

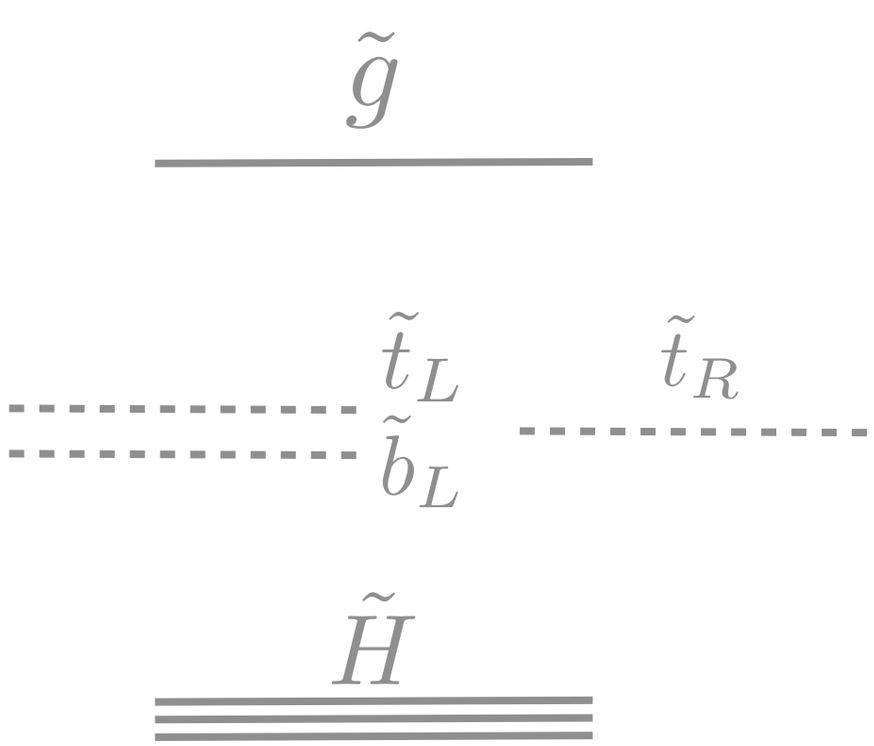
Let's check!

* not his real attitude.



natural SUSY

decoupled SUSY



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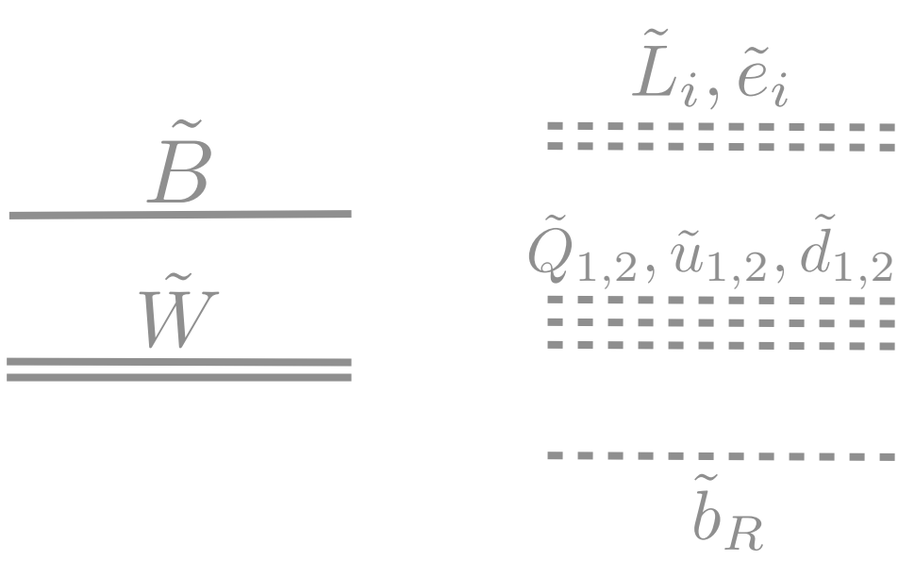

Our Limits

today: *arXiv:1110.6926*

M. Papucci, J. Ruderman, AW

decoupled SUSY

Large signature space

	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]

arXiv:1110.6926

non susy analyses

Large signature space

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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

DY1 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

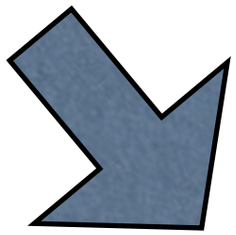
The ATLAS Collaboration

Example:
jets+ MET 1.041/fb

Signal Region	≥ 2-jet	≥ 3-jet	≥ 4-jet	High mass
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 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
$\Delta\phi(\mathrm{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$	> 0.4	> 0.4	> 0.4	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 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				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, $m_{\text{eff}} > 500$ GeV	≥ 4-jet, $m_{\text{eff}} > 1000$ 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
tt+ single top	3.4 ± 1.6 ± 1.6	5.9 ± 2.0 ± 2.2	425 ± 39 ± 84	4.0 ± 1.3 ± 2.0	5.7 ± 1.8 ± 1.9
QCD multi-jet	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.73 ± 0.14 ± 0.50	2.10 ± 0.37 ± 0.82
Total	62.4 ± 4.4 ± 9.3	54.9 ± 3.9 ± 7.1	1015 ± 41 ± 144	33.9 ± 2.9 ± 6.2	13.1 ± 1.9 ± 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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LIMIT!

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

Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, $m_{\text{eff}} > 500$ GeV	≥ 4-jet, $m_{\text{eff}} > 1000$ 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
tt+ single top	3.4 ± 1.6 ± 1.6	5.9 ± 2.0 ± 2.2	425 ± 39 ± 84	4.0 ± 1.3 ± 2.0	5.7 ± 1.8 ± 1.9
QCD multi-jet	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.73 ± 0.14 ± 0.50	2.10 ± 0.37 ± 0.82
Total	62.4 ± 4.4 ± 9.3	54.9 ± 3.9 ± 7.1	1015 ± 41 ± 144	33.9 ± 2.9 ± 6.2	13.1 ± 1.9 ± 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!

our pipelines

ATOM

public code soon

pythia / herwig / etc

+prospino

fastjet

truth leptons / photons /b's

- l/gamma iso
- parameterized efficiencies

checks sensitivity of cut & leakage in control region

pgs

pythia

+prospino

crude detector sim

cone jets

truth muons/b's

- parameterized efficiencies

crude simulated e/ gamma

ATOM

an **A**utomated **T**ester **O**f **M**odels

(soon to be) Public Tool developed by

QCD/Jets: C. Bauer (Berkeley), C. Vermillion (Berkeley)

BSM: M. Papucci (Berkeley),
T. Volansky (Tel Aviv), A. W. (DESY)

Calibration

"theorist limits"

To calibrate compare:

1) key kinematical distributions
2) limits

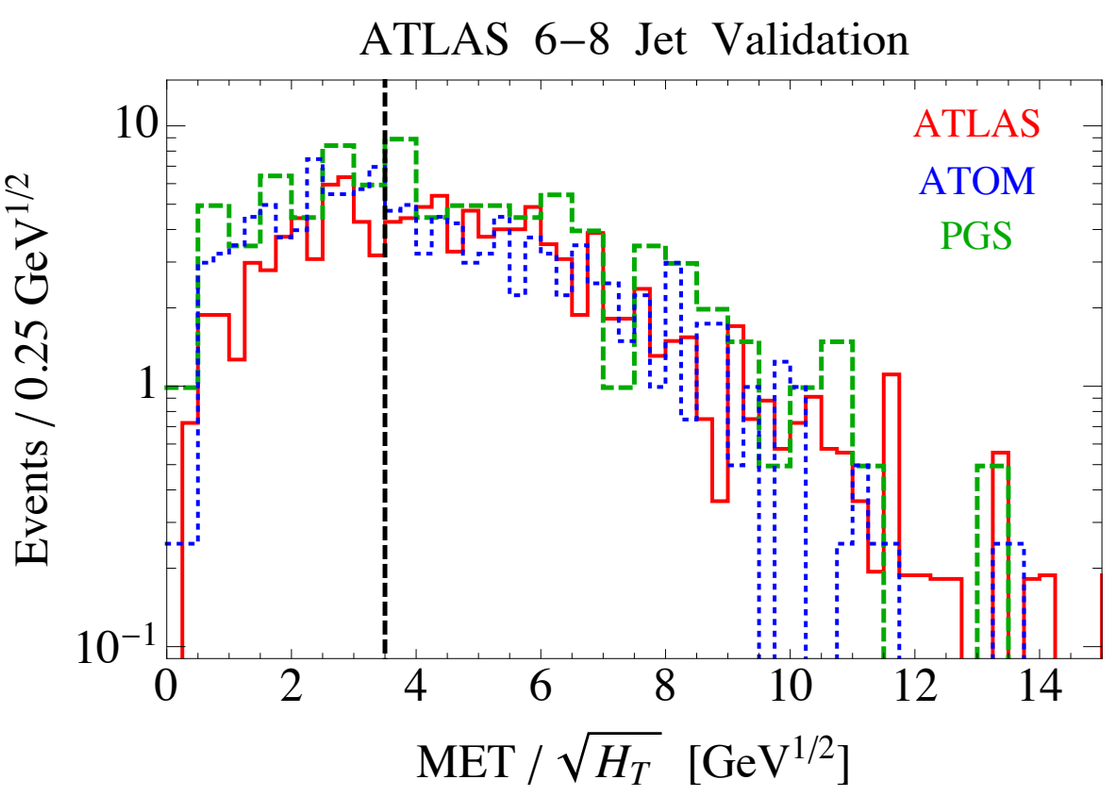
Calibration

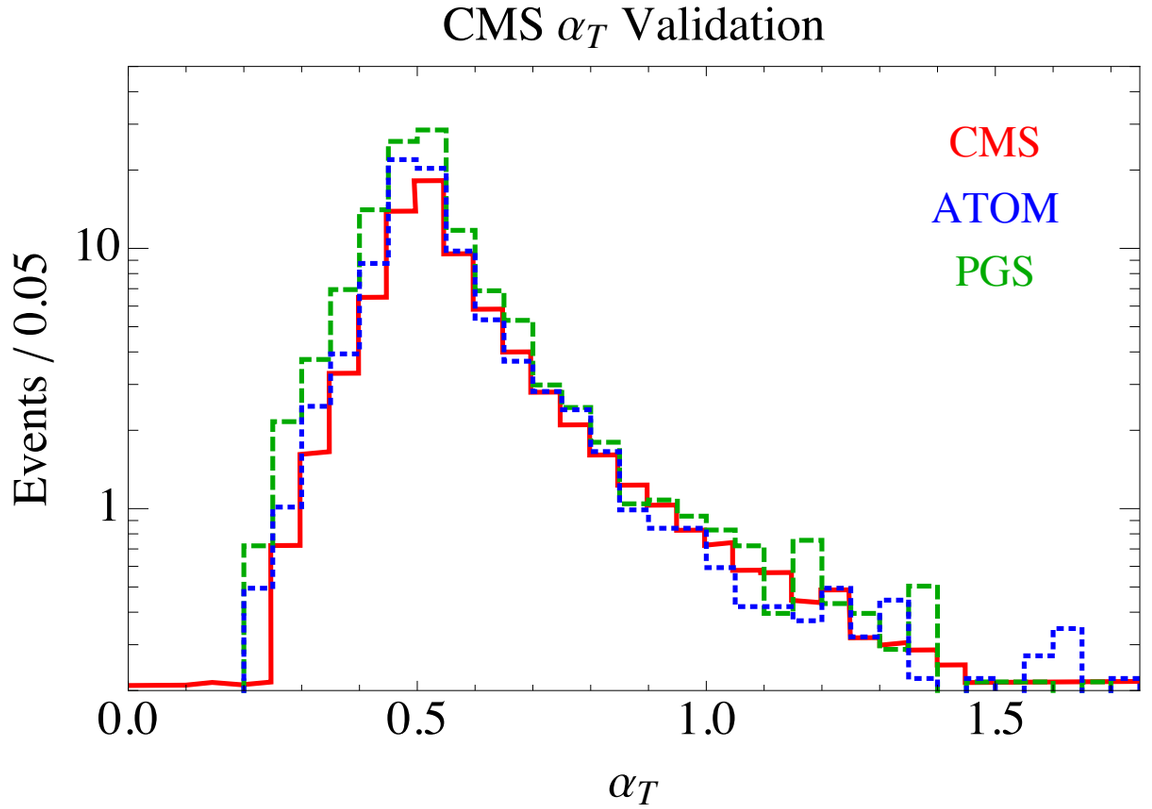
"theorist limits"

To calibrate compare:

1) key kinematical distributions
2) limits

simplified models work best!





Check:

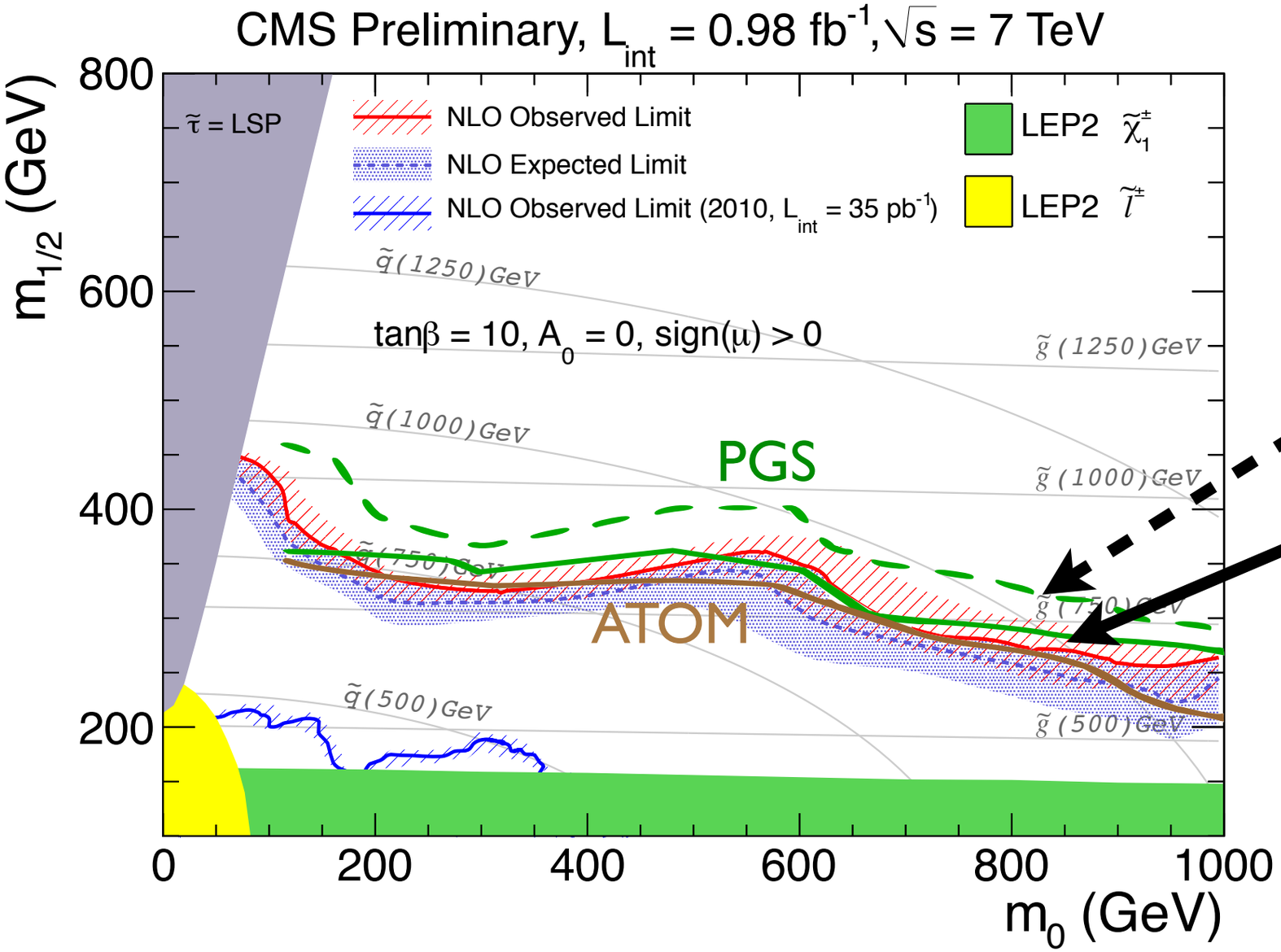
- kinematic distortions (shape)
- signal $\epsilon \times \mathcal{A}$ (normalization)

+ compare to all available limit plots…

~ 50 GeV accuracy (usually better)

Compare limits

Example: Same-Sign dilepton by CMS



90% lepton eff.

70% lepton eff.

Large signature space

	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

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	channel	$\mathcal{L}$ [fb^{-1}]	ref.	channel	$\mathcal{L}$ [fb^{-1}]	ref.
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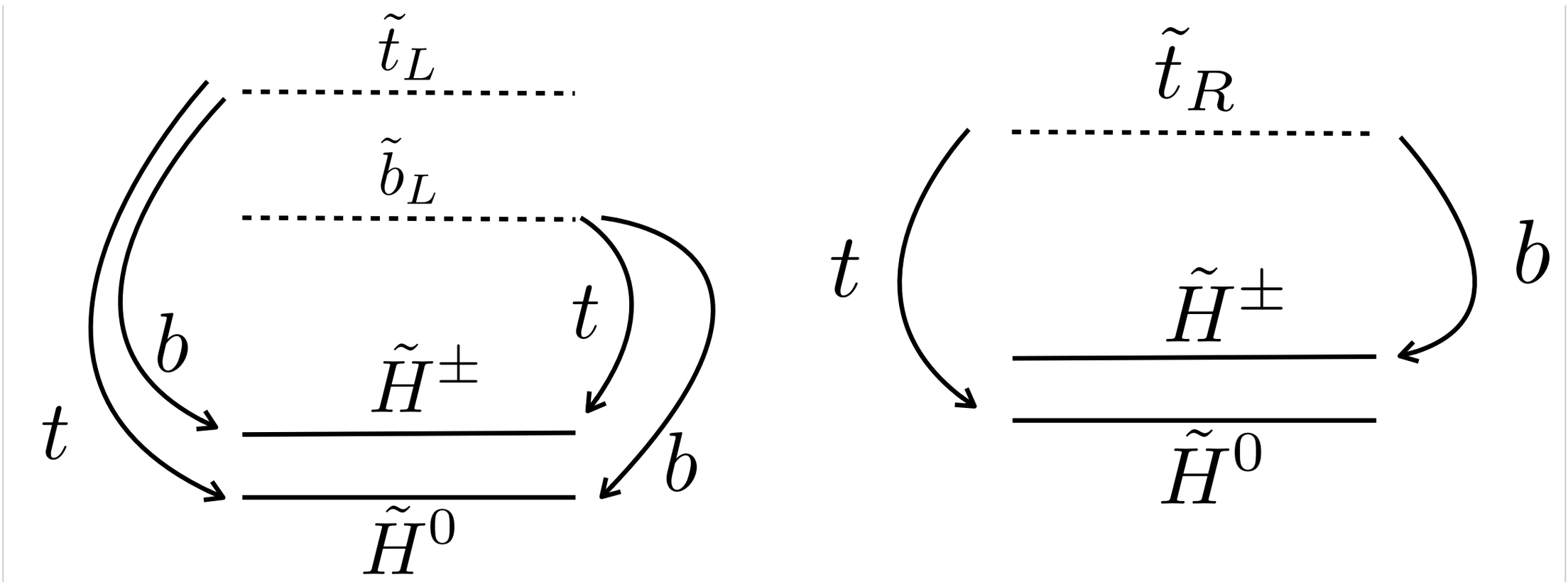
	~~$2l$~~	1.04	[10]	~~$3l, 4l$~~	2.1	[22]

arXiv:1110.6926

non susy analyses

too recent

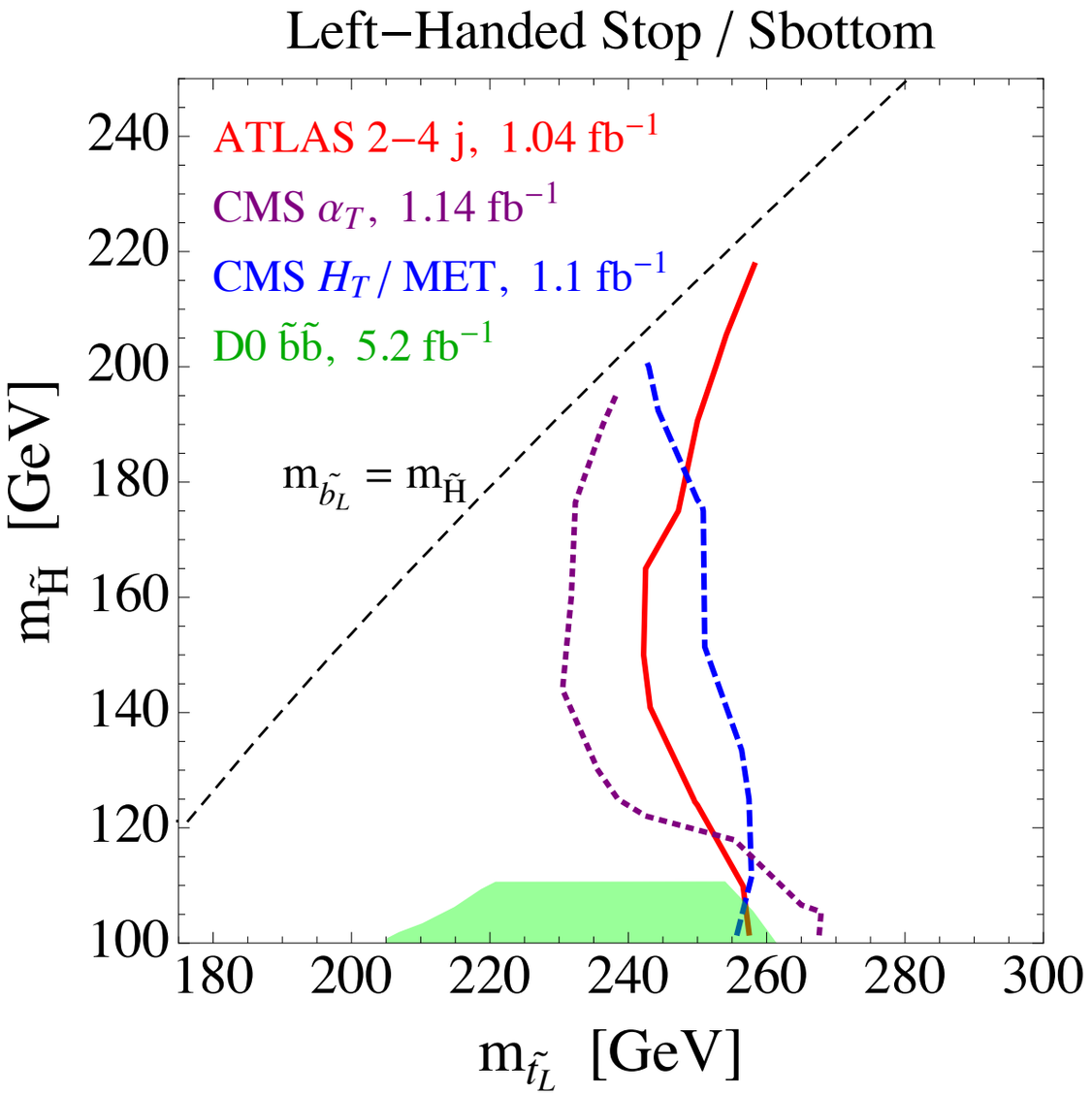
Stops (sbottom) + Higgsinos

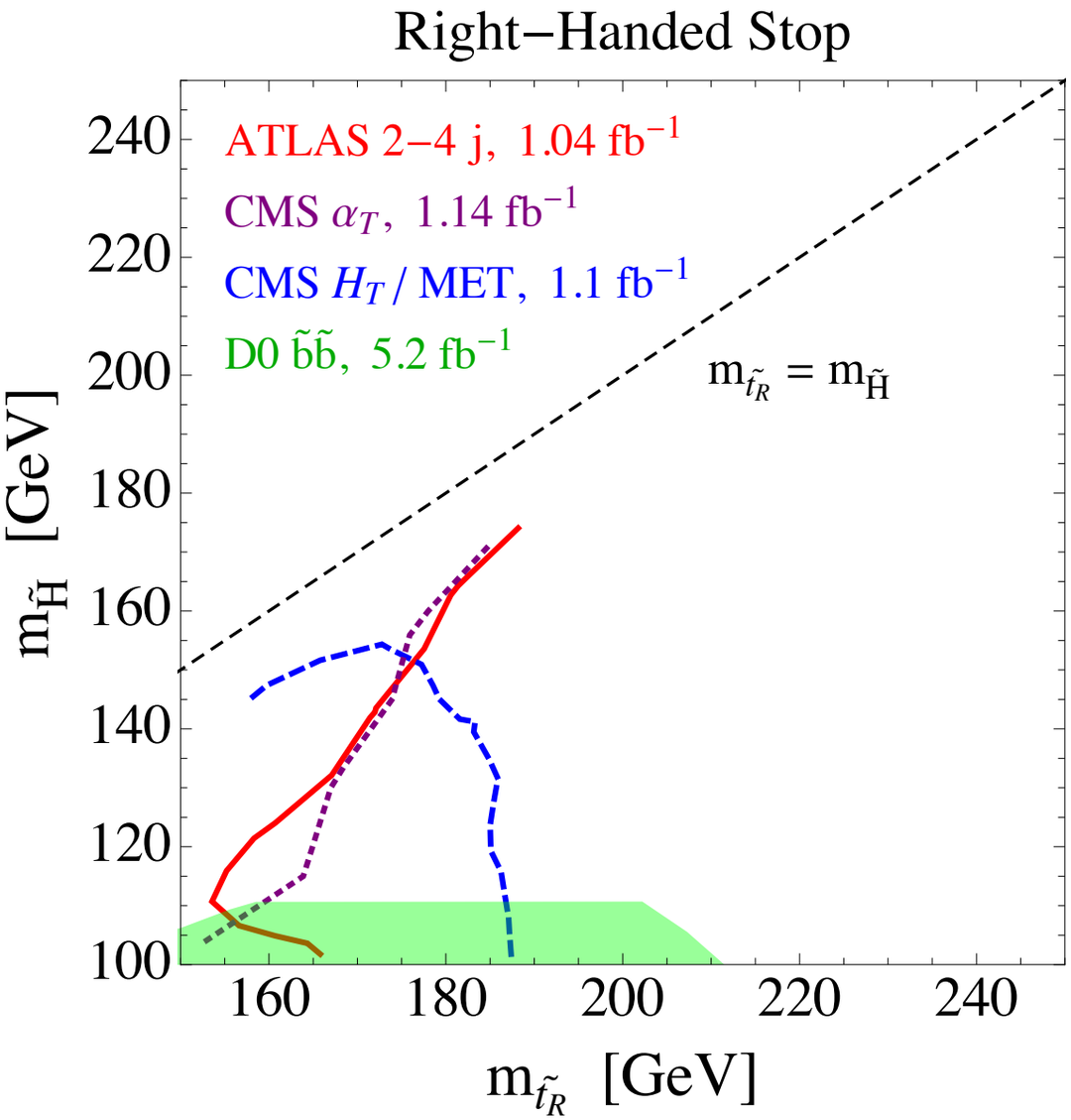


Stops can act as "sbottom" (bjet+χ) !

Chargino-neutralino splitting irrelevant for present searches

Stops (sbottom) + Higgsinos

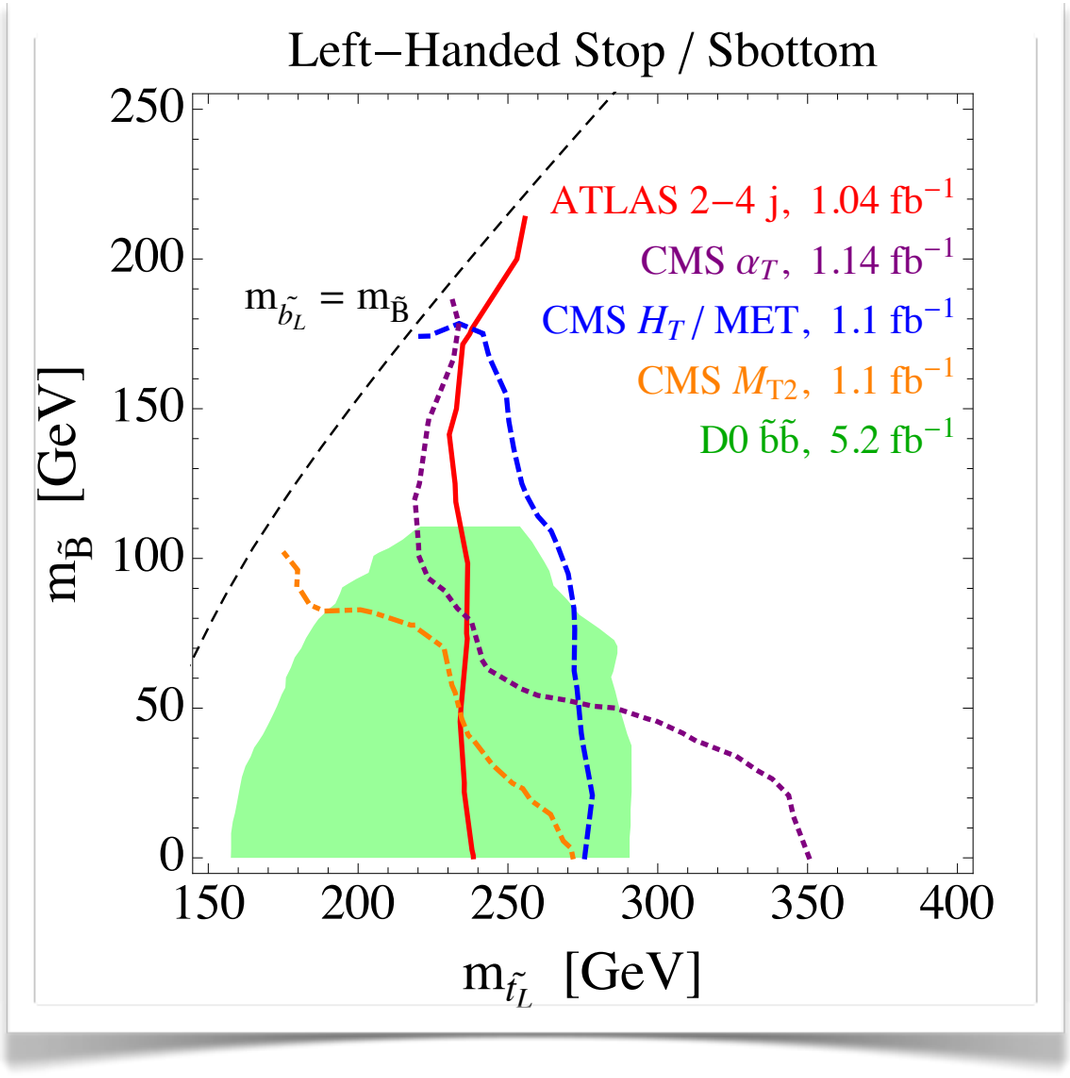


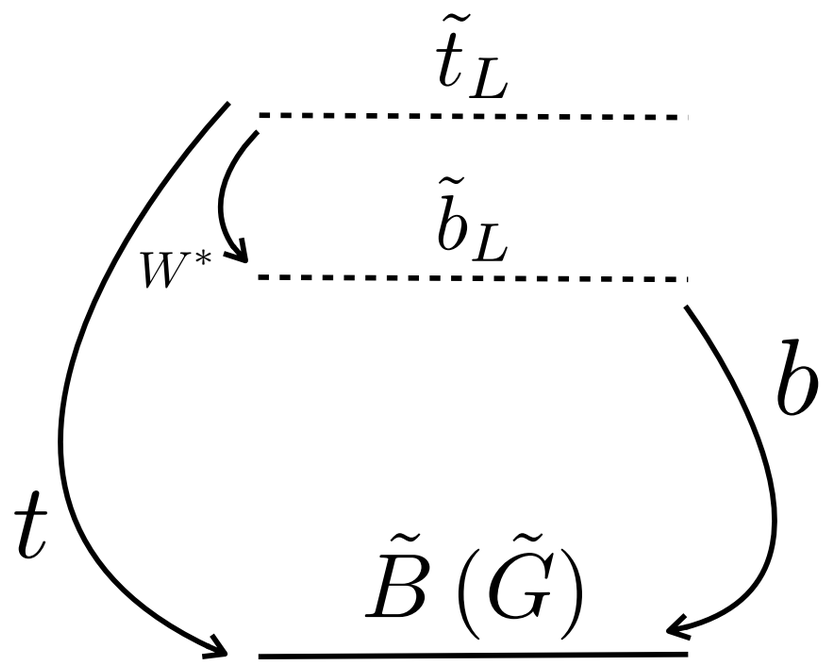


LHC surpasses Tevatron:

Strongest bounds from jets + MET

Stops (sbottom) + Bino





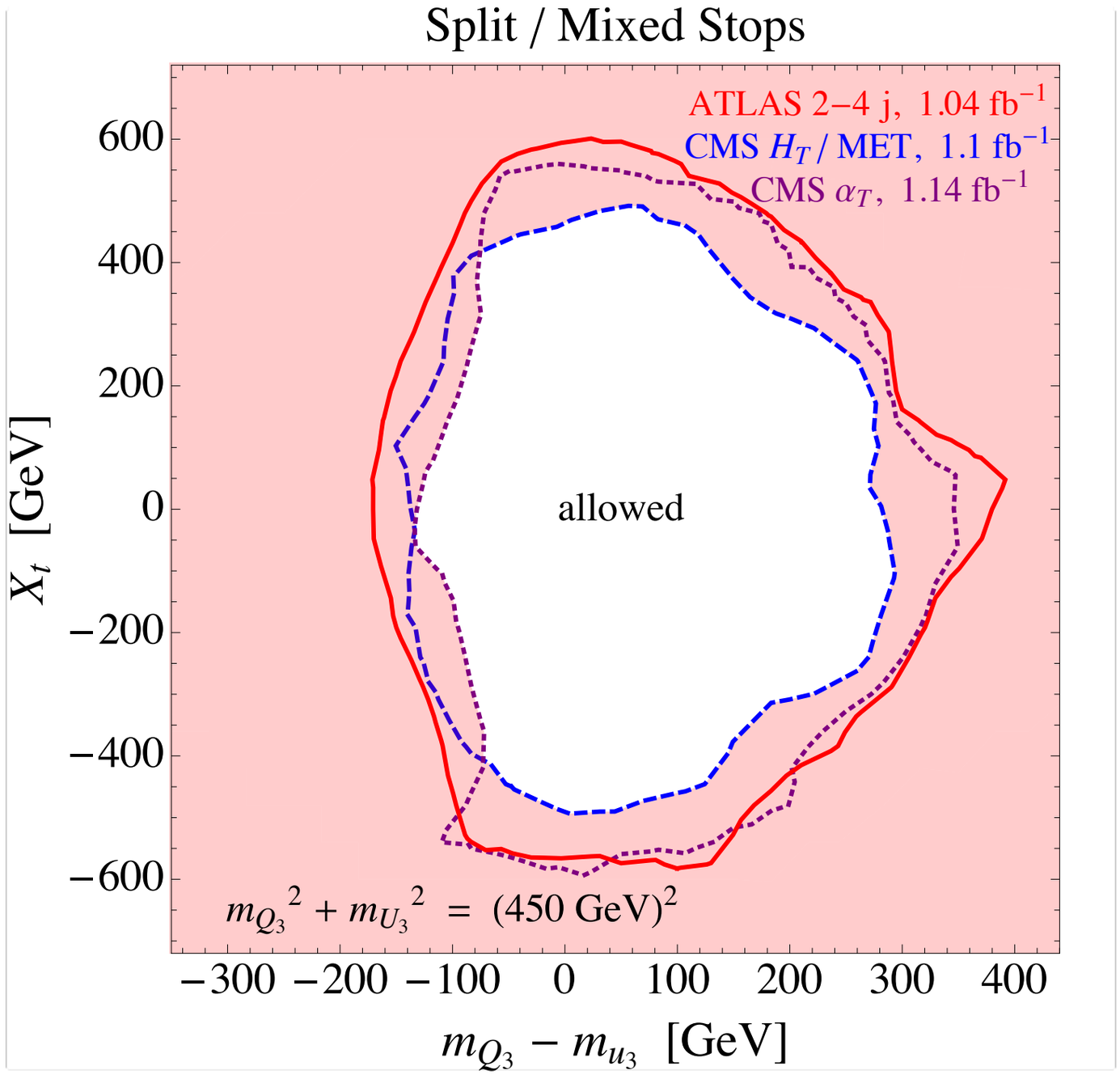
jets+MET searches powerful here too

- 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

$\tilde{t}_L$ $\tilde{b}_L$ $\tilde{t}_R$	$\tilde{t}_R$ $\tilde{t}_L$ $\tilde{b}_L$	$\tilde{t}_2$ $\tilde{b}_L$ $\tilde{t}_1$
$m_{Q_3} - m_{u_3} > 0$ $X_t = 0$	$m_{Q_3} - m_{u_3} < 0$ $X_t = 0$	$\lvert X_t \rvert > 0$

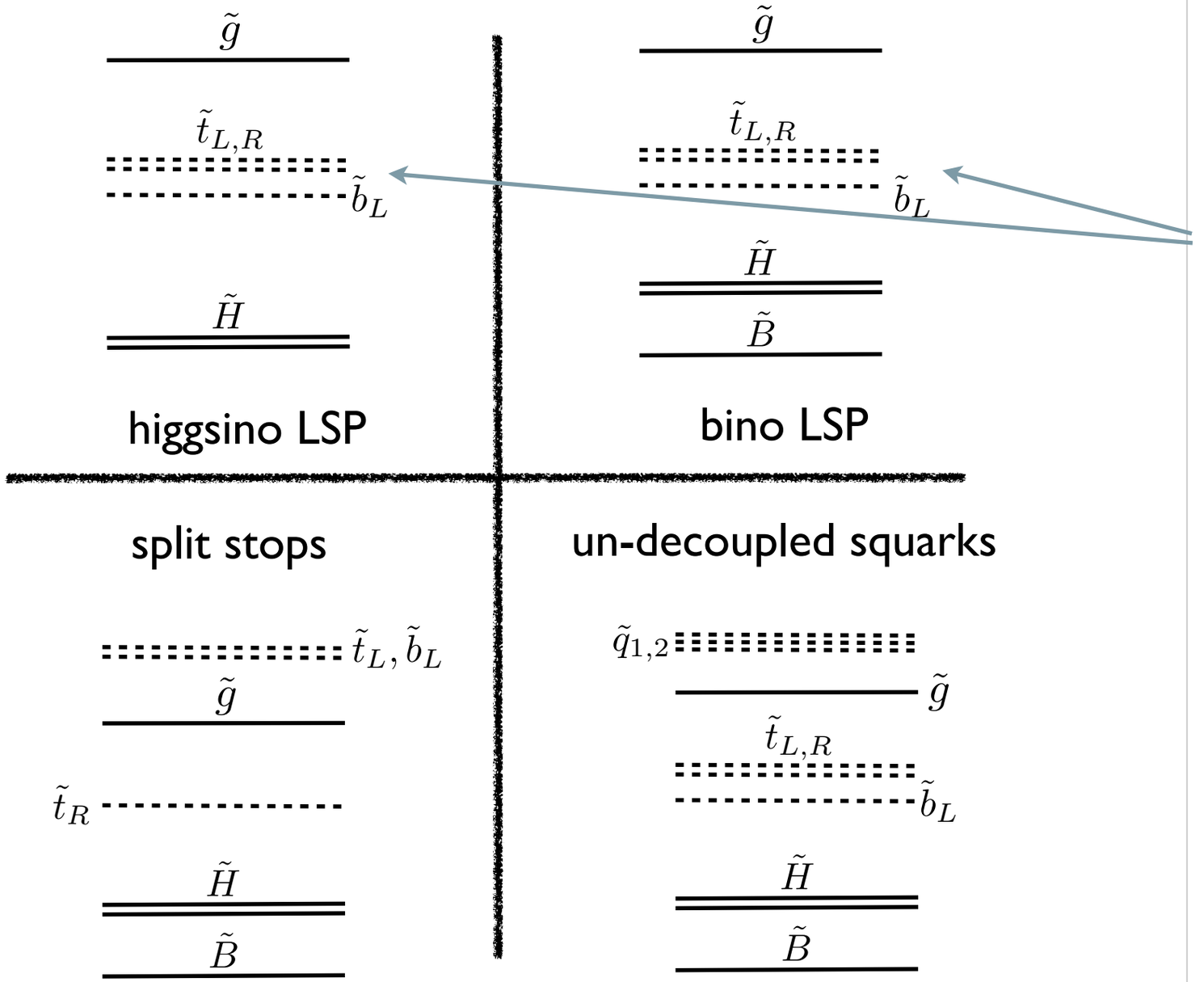
Un-Splitting the spectrum



stronger bound on the left due to light sbottom

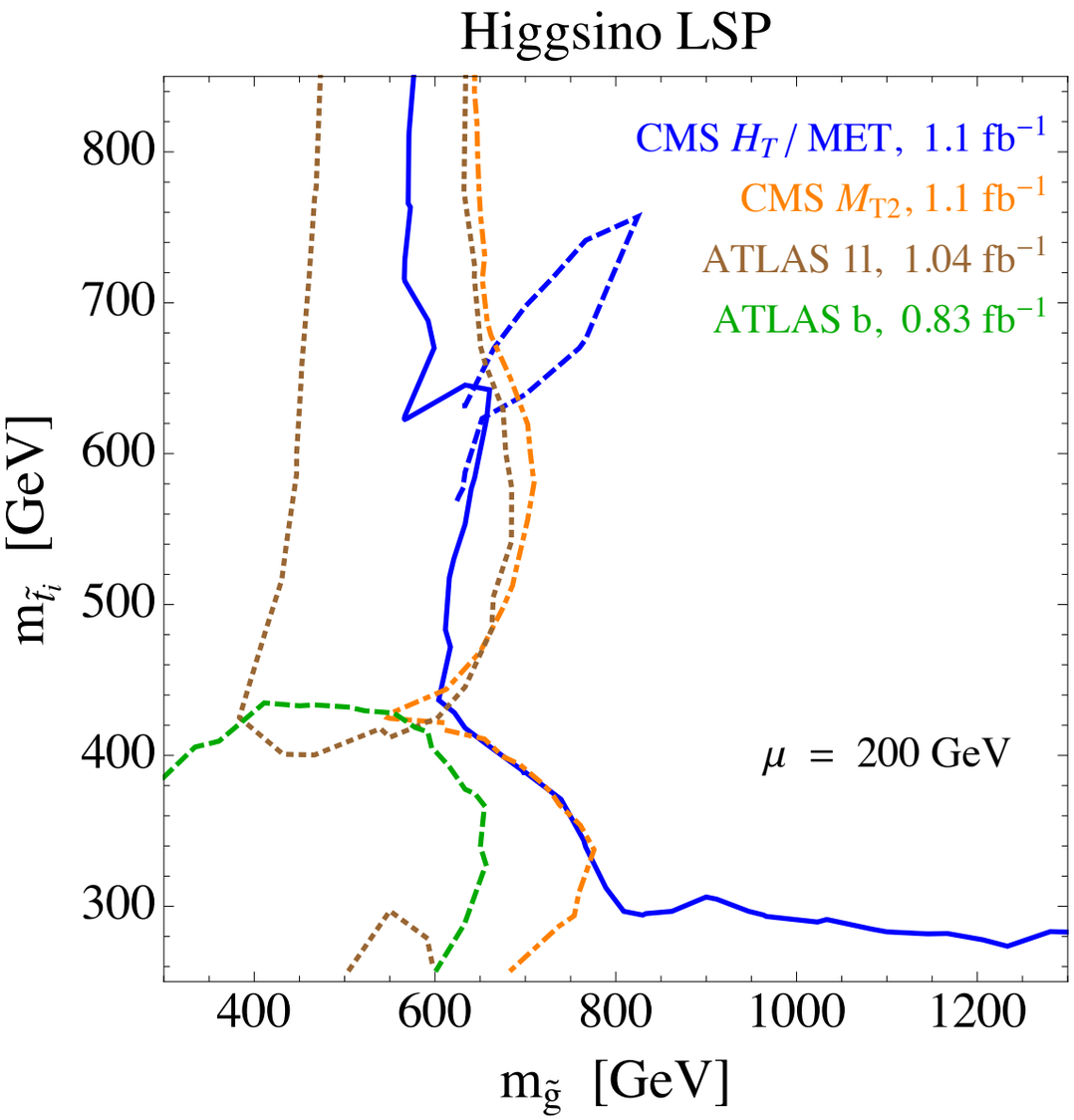
TeVatron bounds not shown b/c they have no sensitivity for $m_{LSP} > 110$GeV

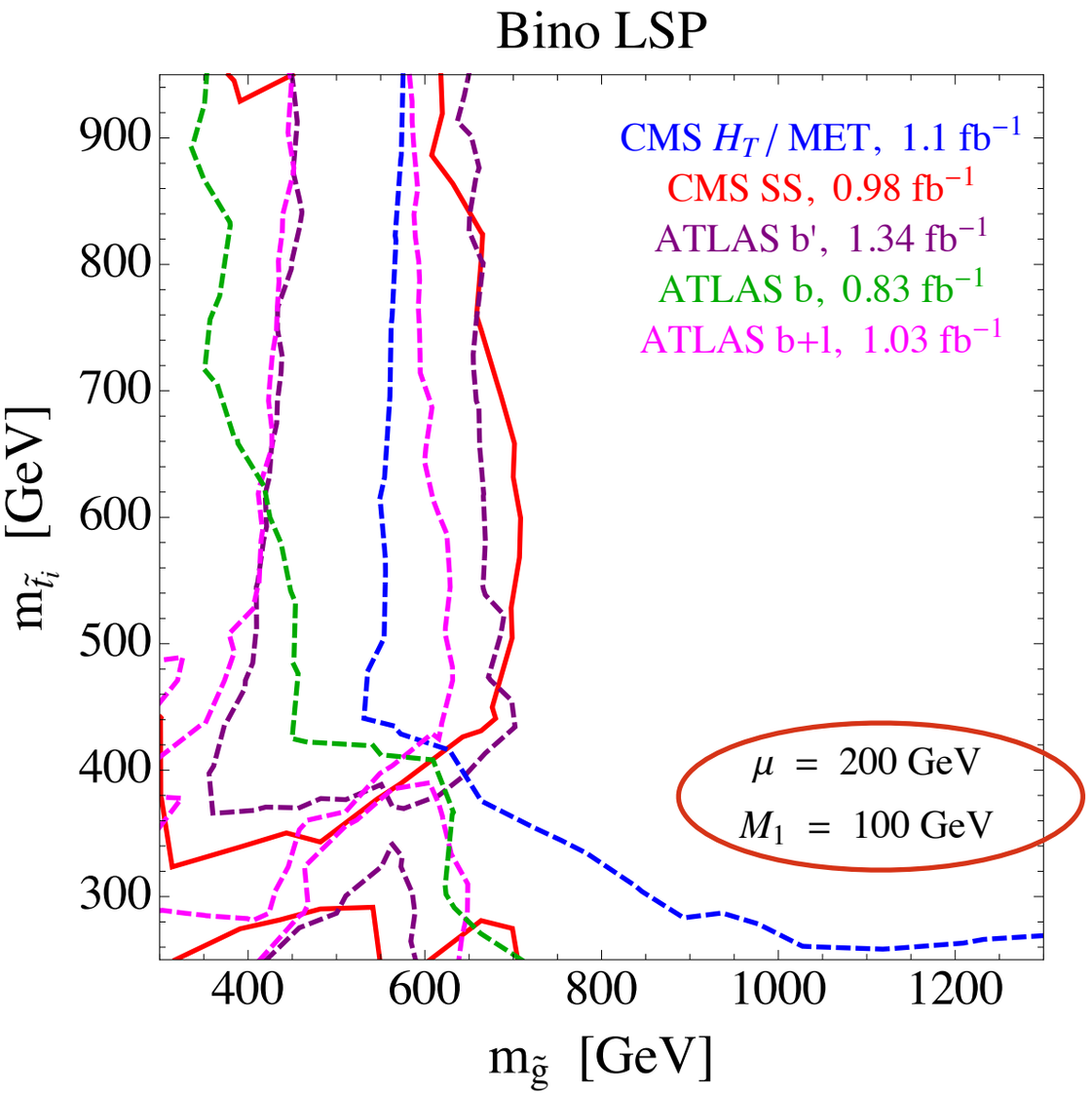
Adding gluinos



quasi-degenerate
3-rd gen'

Adding the gluinos

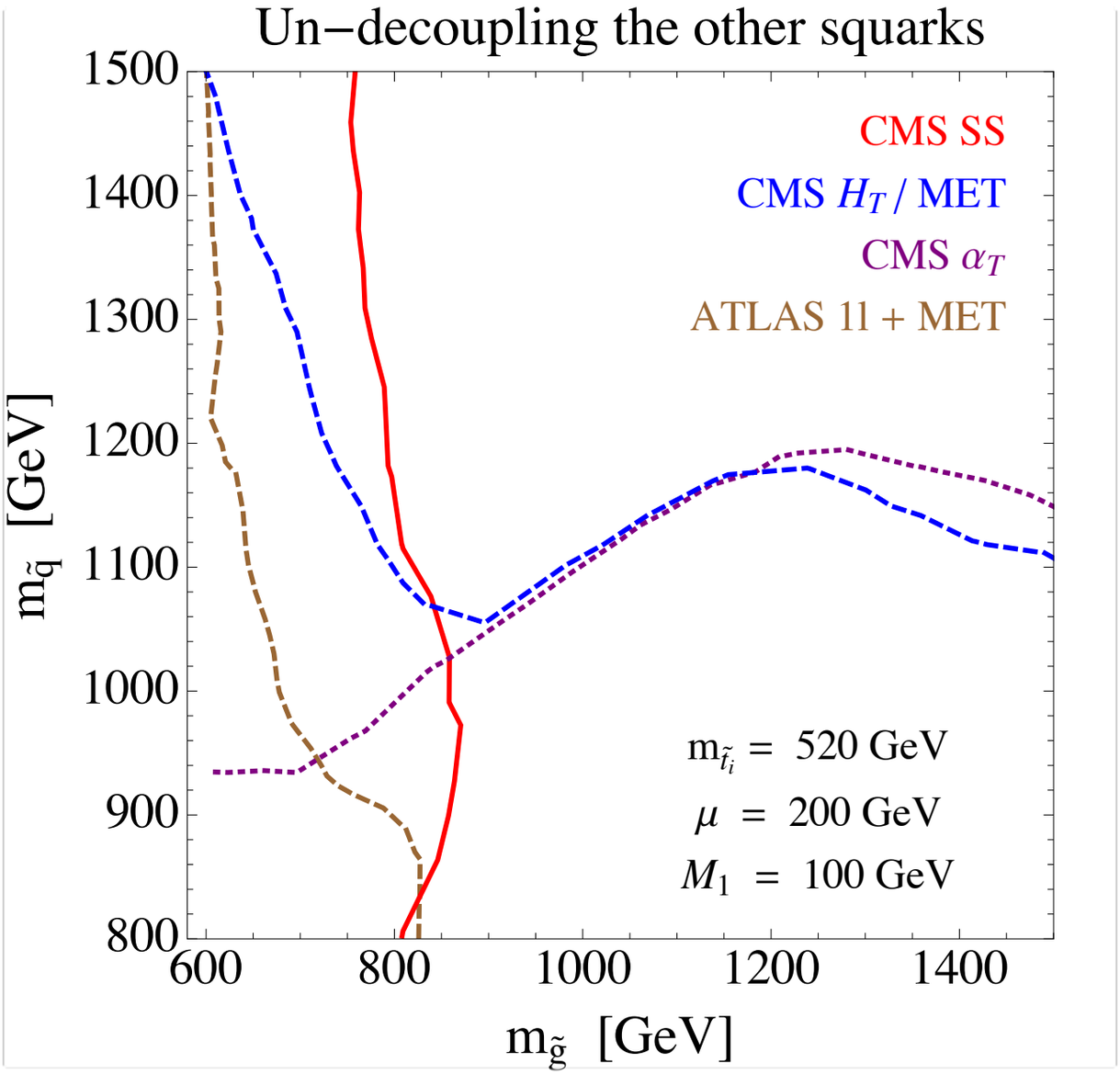




Gluino bounded (again) by jets+MET, and 1lep searches

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

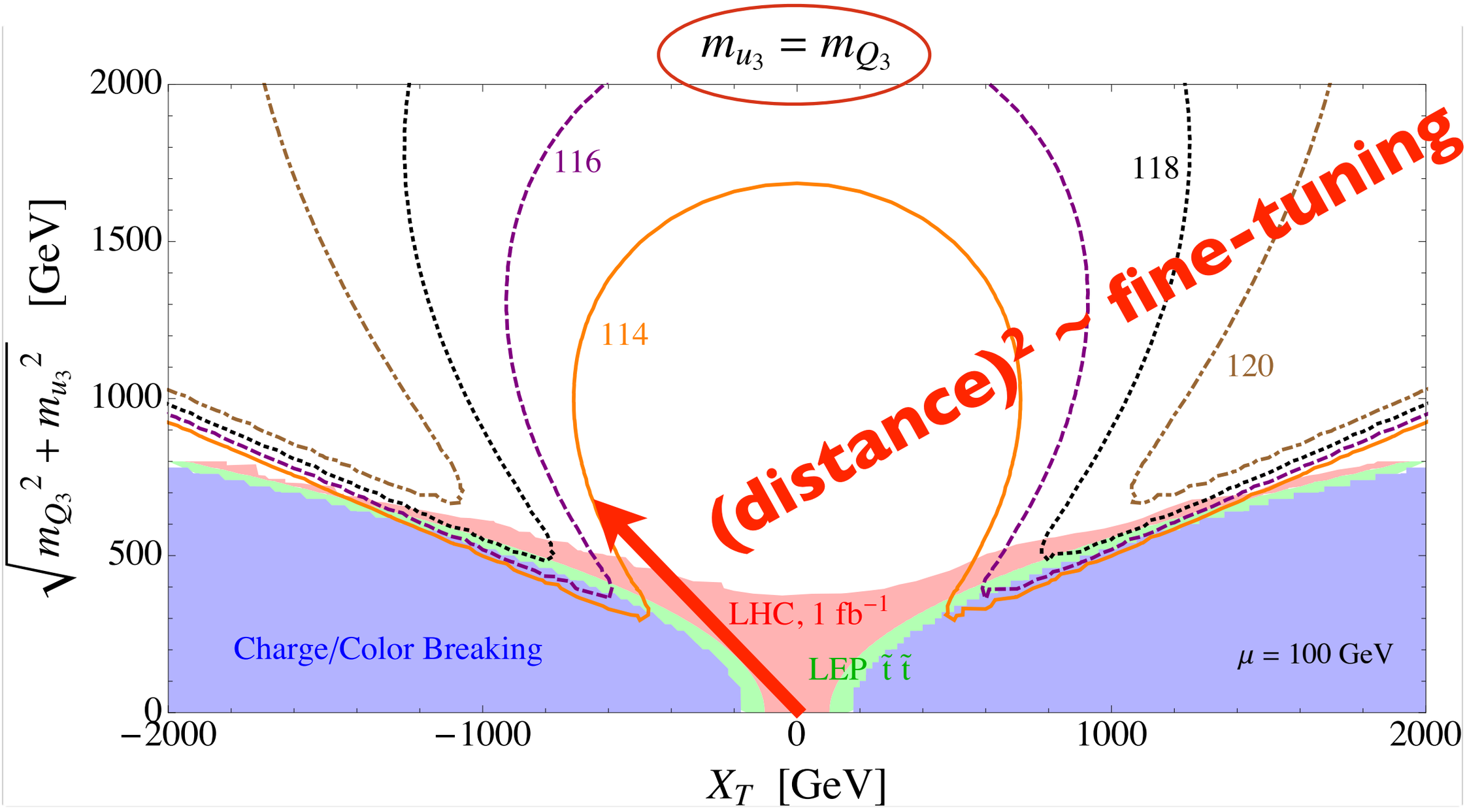
MSSM little hierarchy problem

- 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?

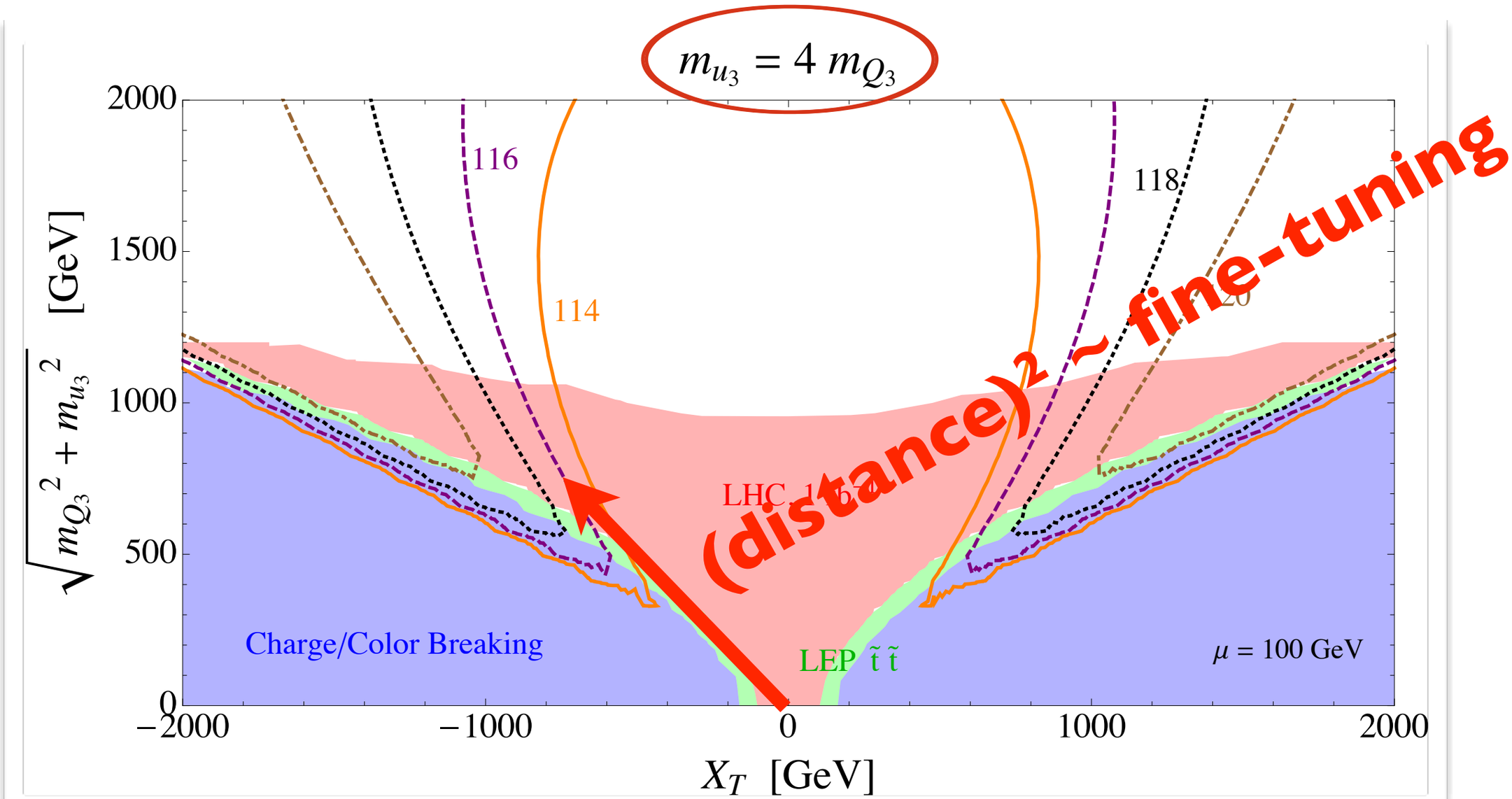
- CAVEAT: only for higgsinos (higgsinos+binos) lighter than stops...

MSSM higgs: LEP2 tuning vs. direct stop



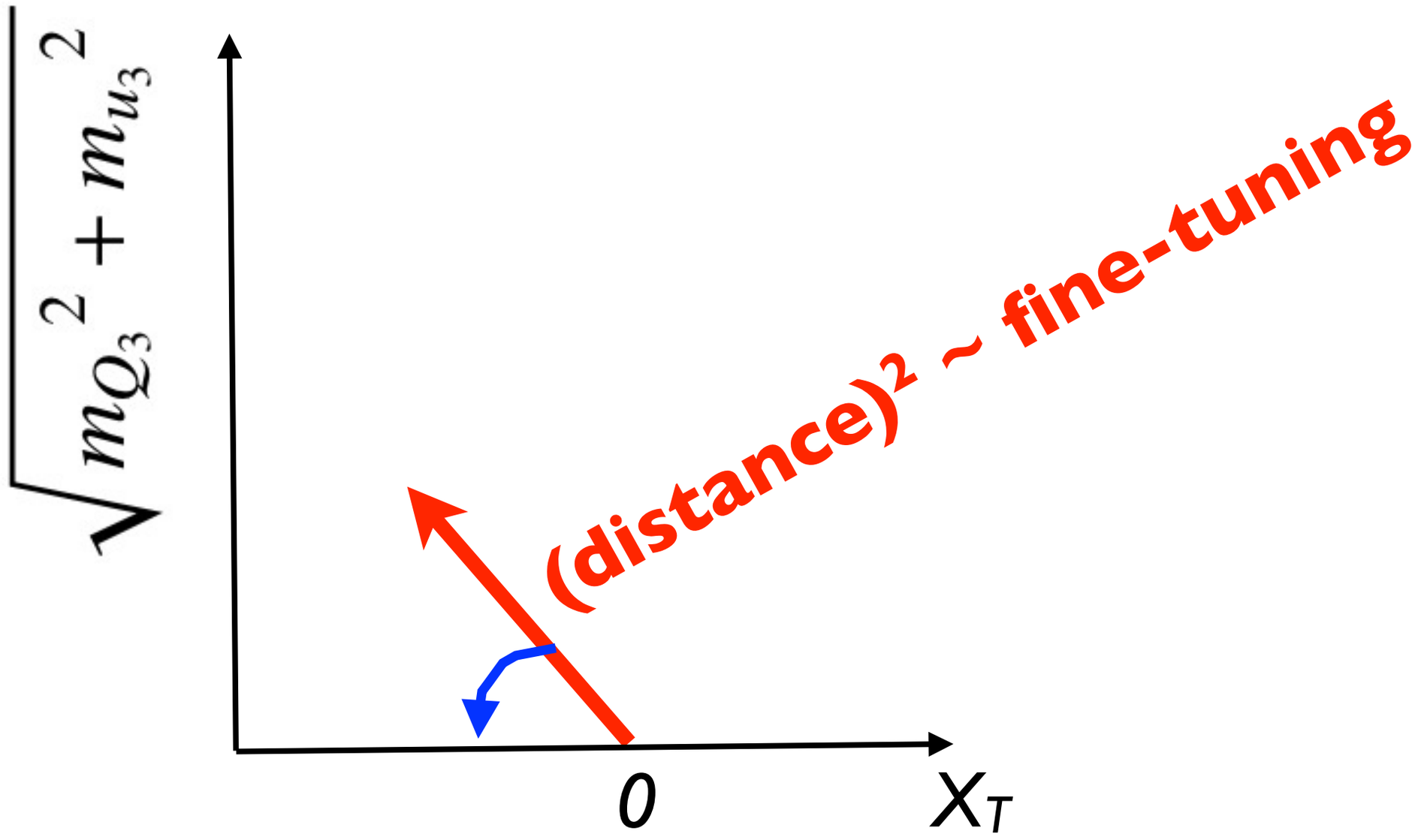
$$\delta m_H^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2 \right) \log\left(\frac{\Lambda}{\text{TeV}} \right)$$

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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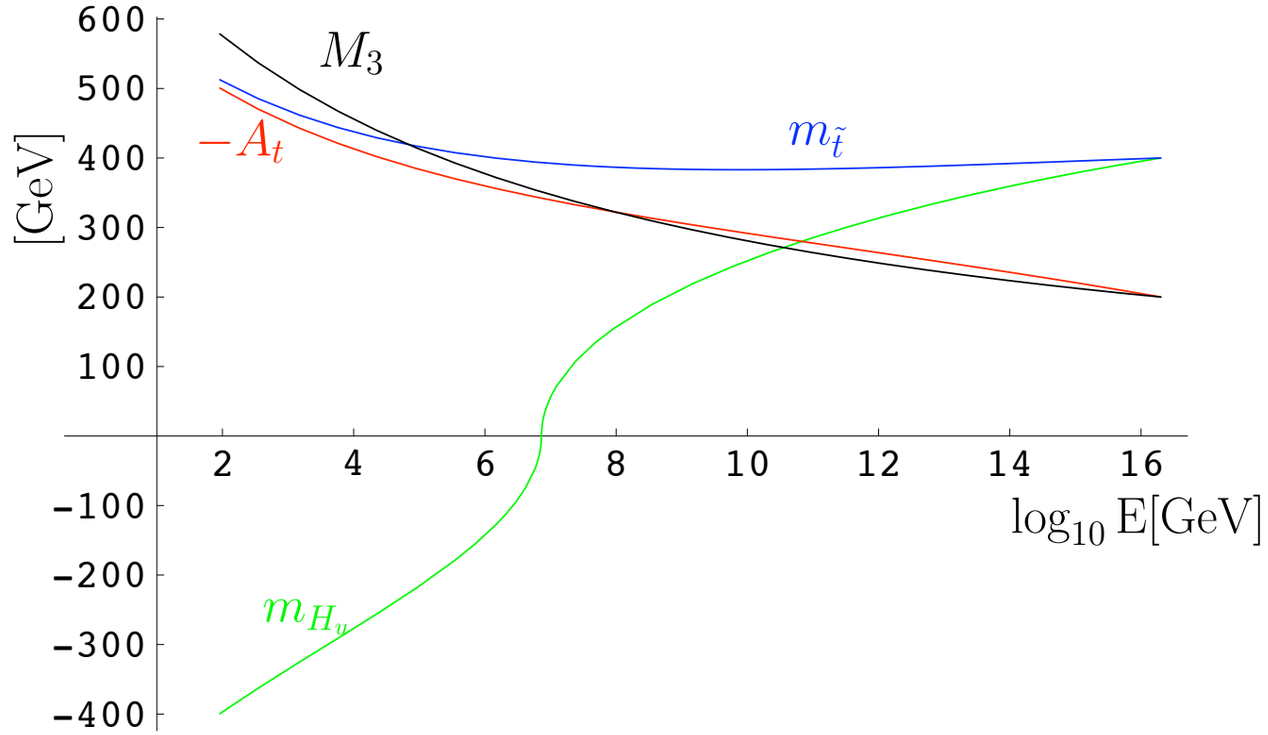


max. mixing requires engineering, usually: $|A_t/m_{\tilde{t}}| \lesssim 1$

→ 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

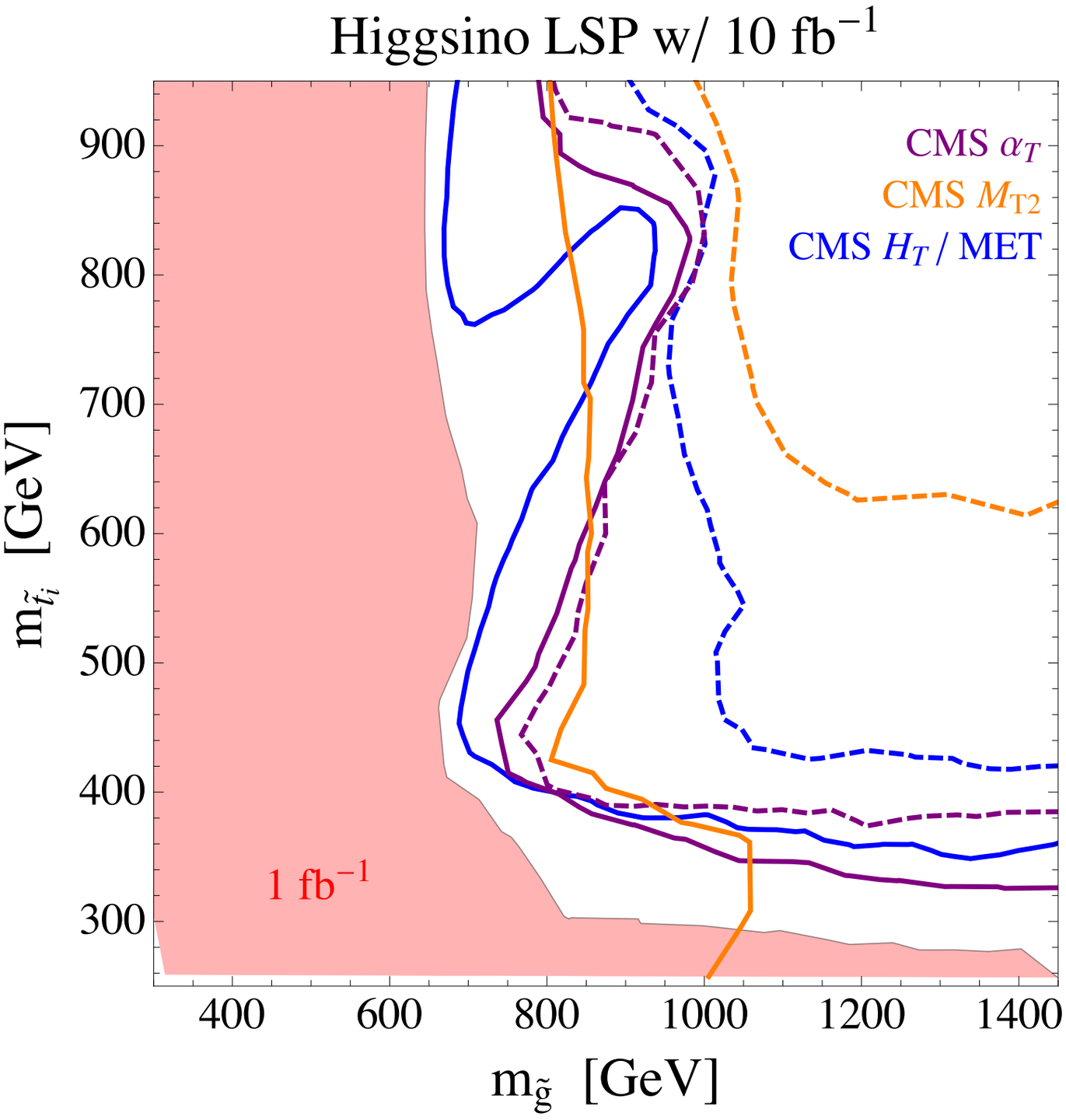
scenario	$\tilde{g}$ limit [GeV]	$\tilde{t}$ limit [GeV]	figure
$\tilde{H}$ - LSP	$\sim 650 - 700$	~ 280	10
$\tilde{B}$ - LSP	~ 700	~ 270	10
somewhat squashed	$\sim 600 - 700$	–	11
split $\tilde{t}$	$\sim 550 - 650$	–	11
flavor degen.	1200 (fixed)	$600 - 900$	16
gaugino unify	$\sim 750 - 800$	~ 260	16

arXiv:1110.6926

Outlook

- Next frontier: Heavy flavor themed naturalness, EW-inos
- Natural SUSY not in trouble yet (and won't be before shutdown).
- LHC will cover interesting ground in the coming years (obviously)

Projections?



dashed - perfect bgd's

solid - statistics improves, systematics same fraction

* Large uncertainty
* Targeted searches do likely better.

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

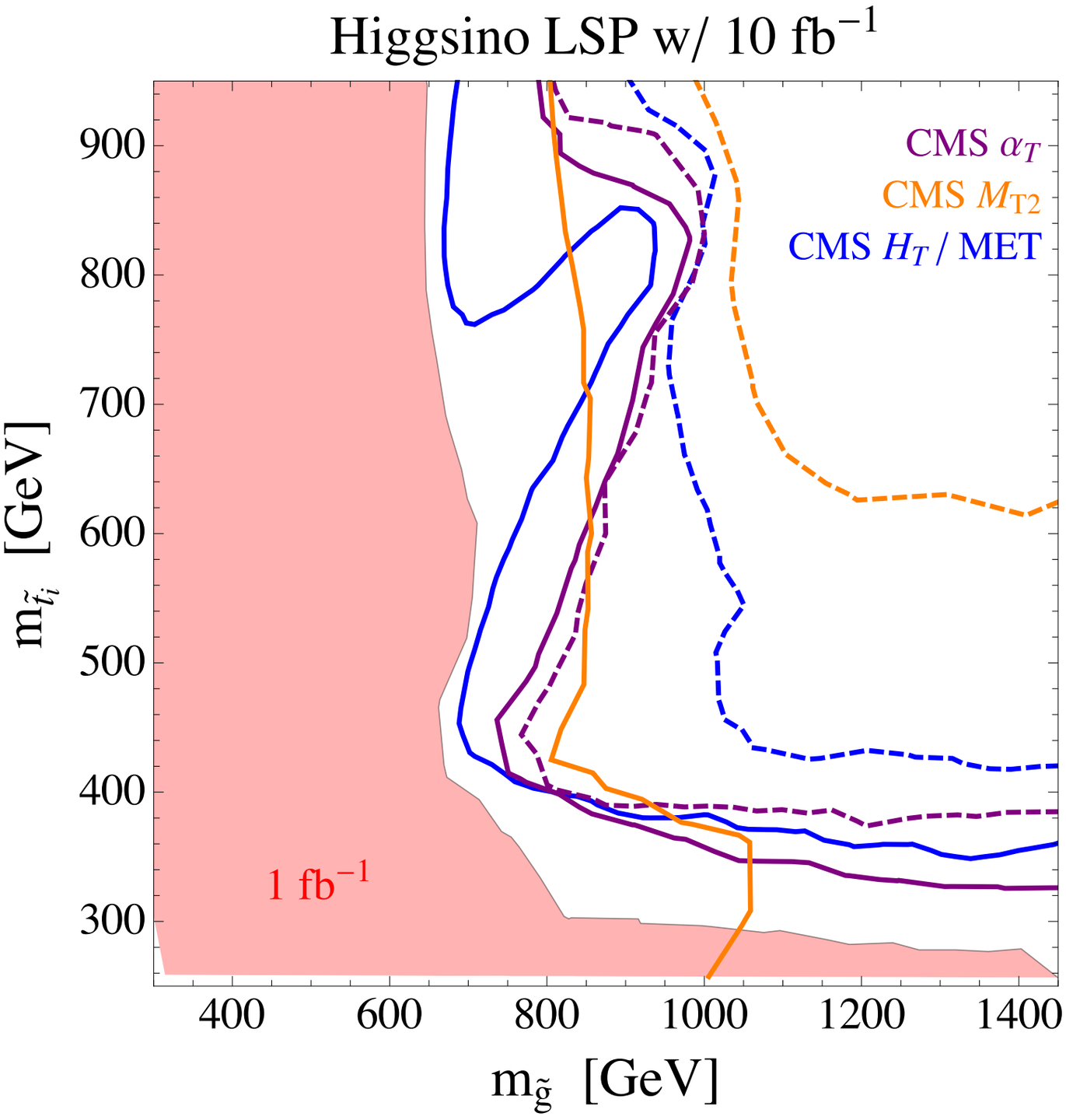
We present a draft set of recommendations for the presentation of LHC results on searches for new physics, which are aimed at providing a more efficient flow of scientific information between the experimental collaborations and the rest of the high energy physics community, and facilitating the interpretation 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

Backup

Projections?



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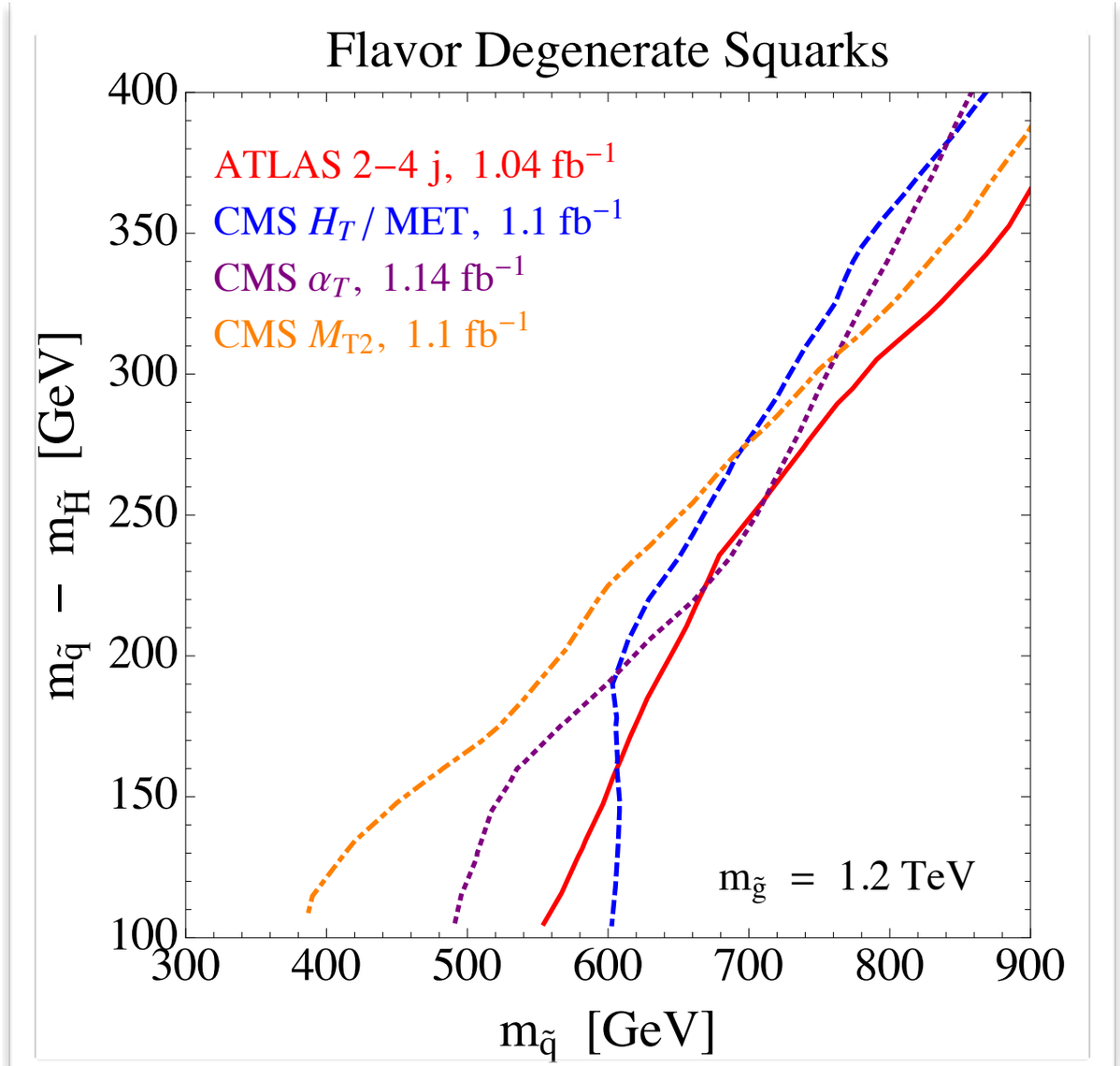
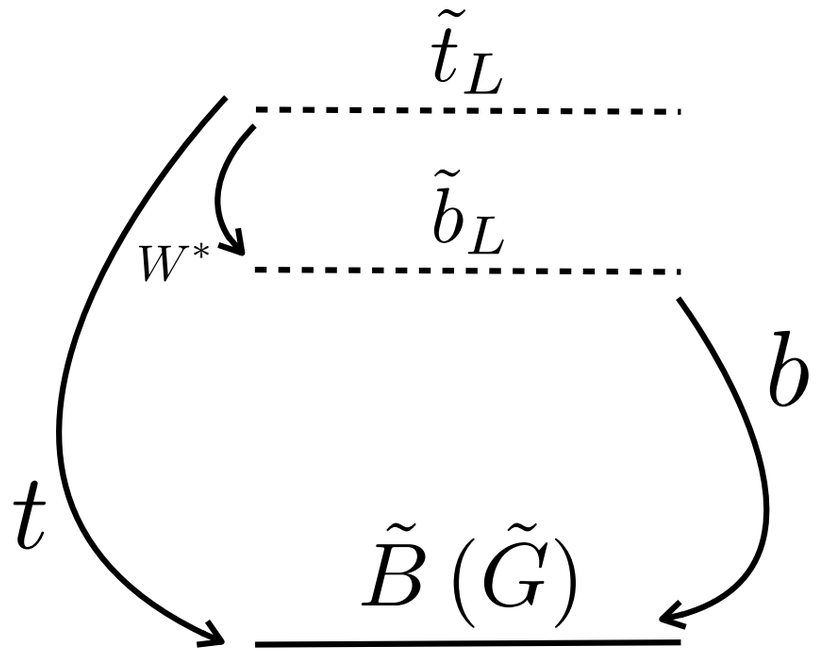
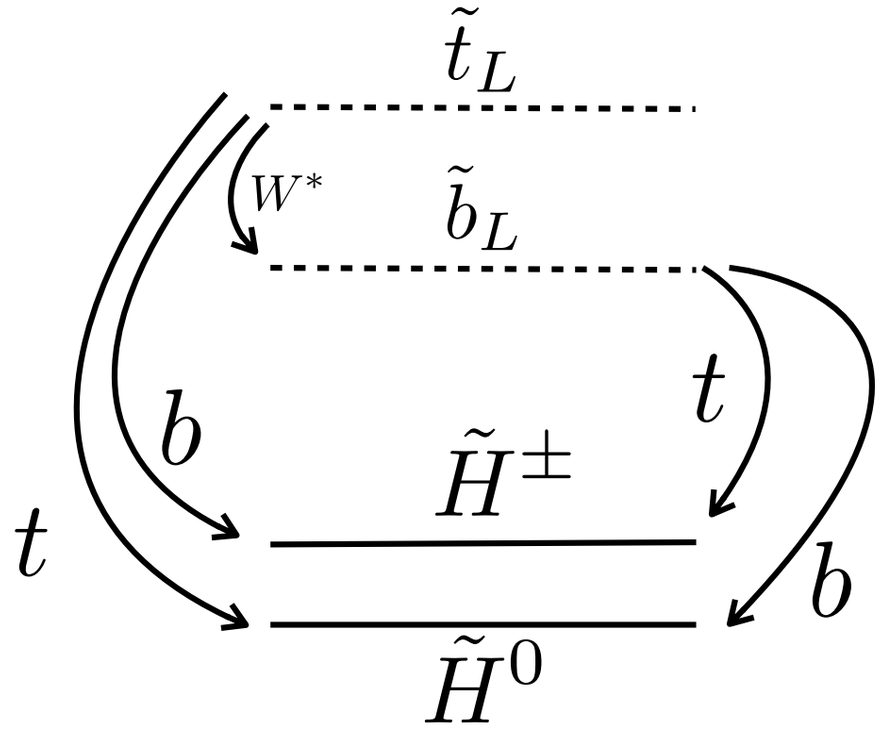
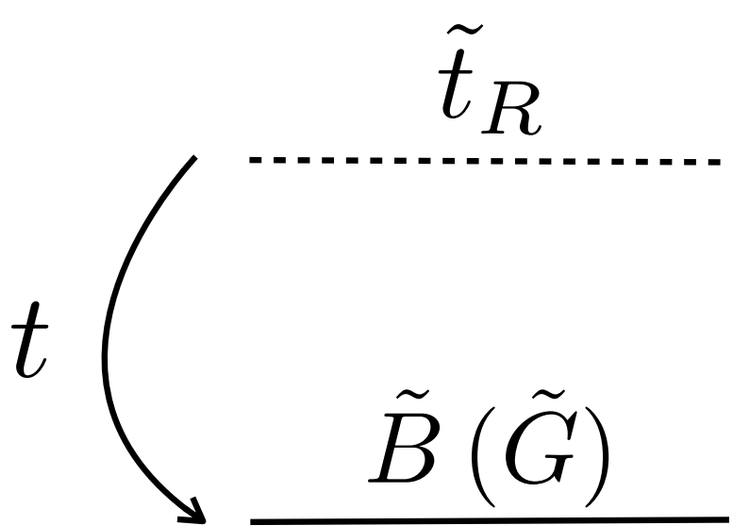
Back to the flavor degenerate case



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


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


$\tilde{t}_L$
W^*
$\tilde{b}_L$
t
b
$\tilde{H}^{\pm}$
t
b
$\tilde{H}^0$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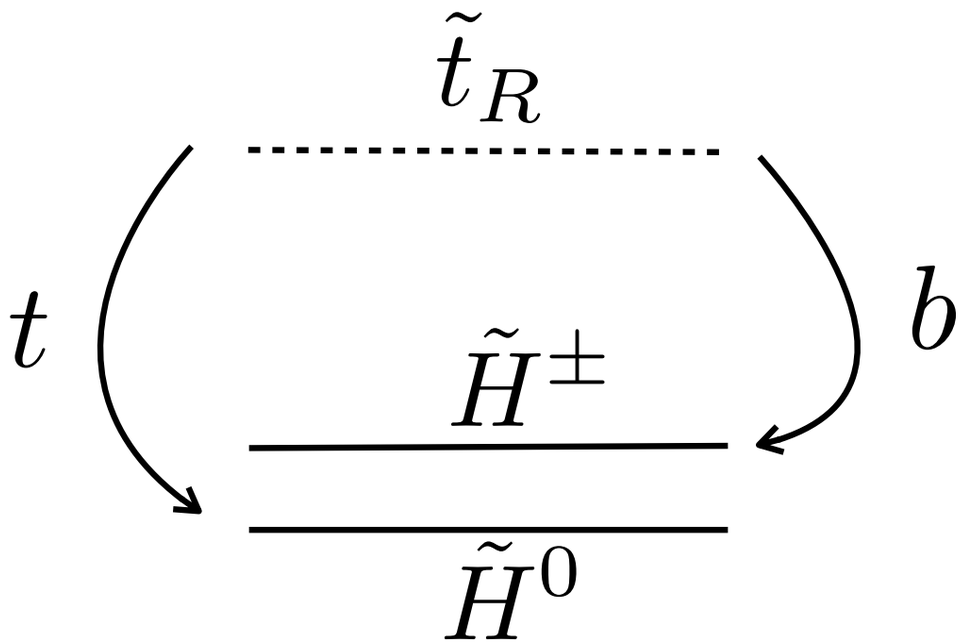
$\tilde{t}_R$
t
$\tilde{H}^{\pm}$
b
$\tilde{H}^0$