

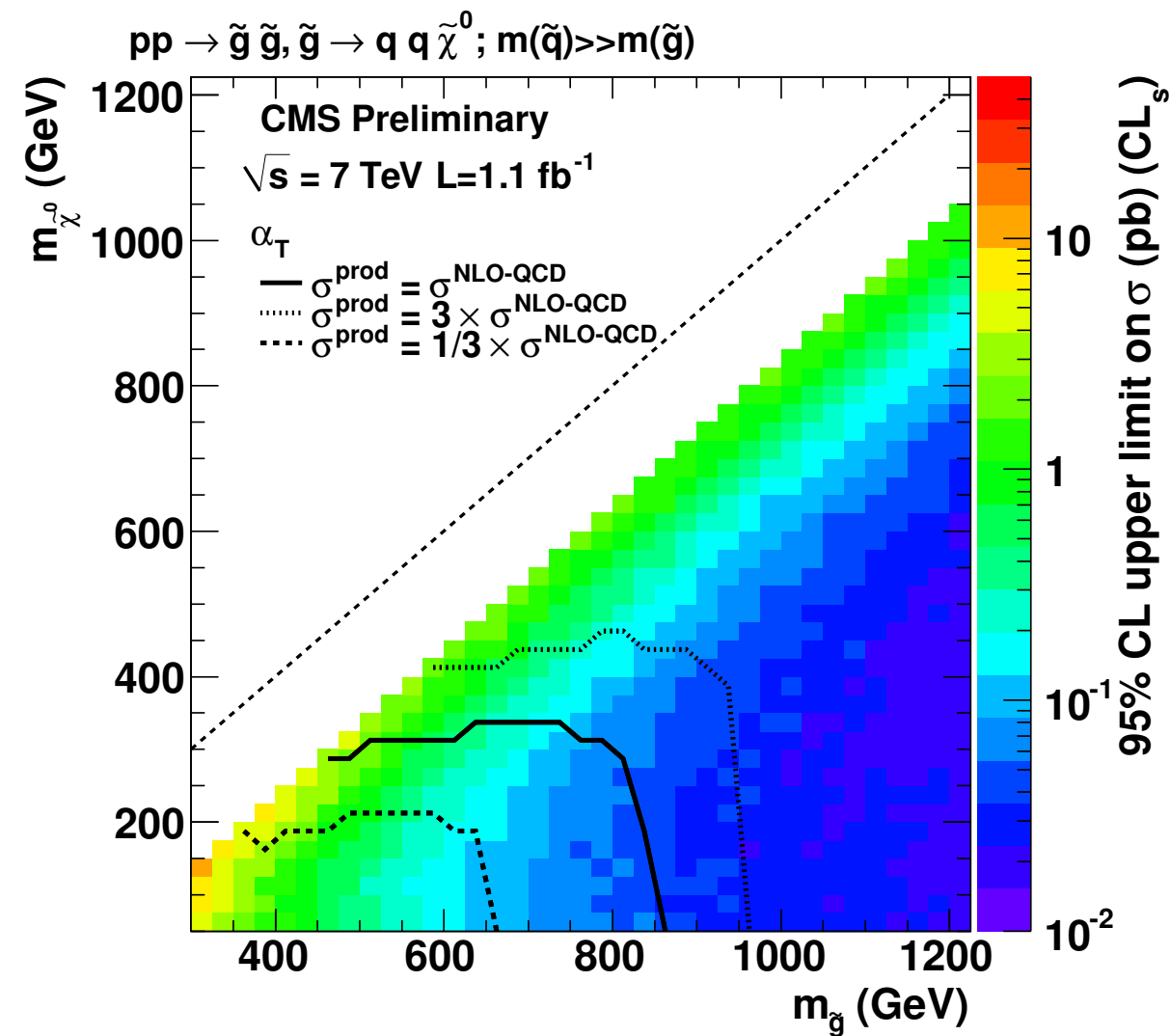
Natural Susy after $>1/\text{fb}$

Andreas Weiler
(DESY)

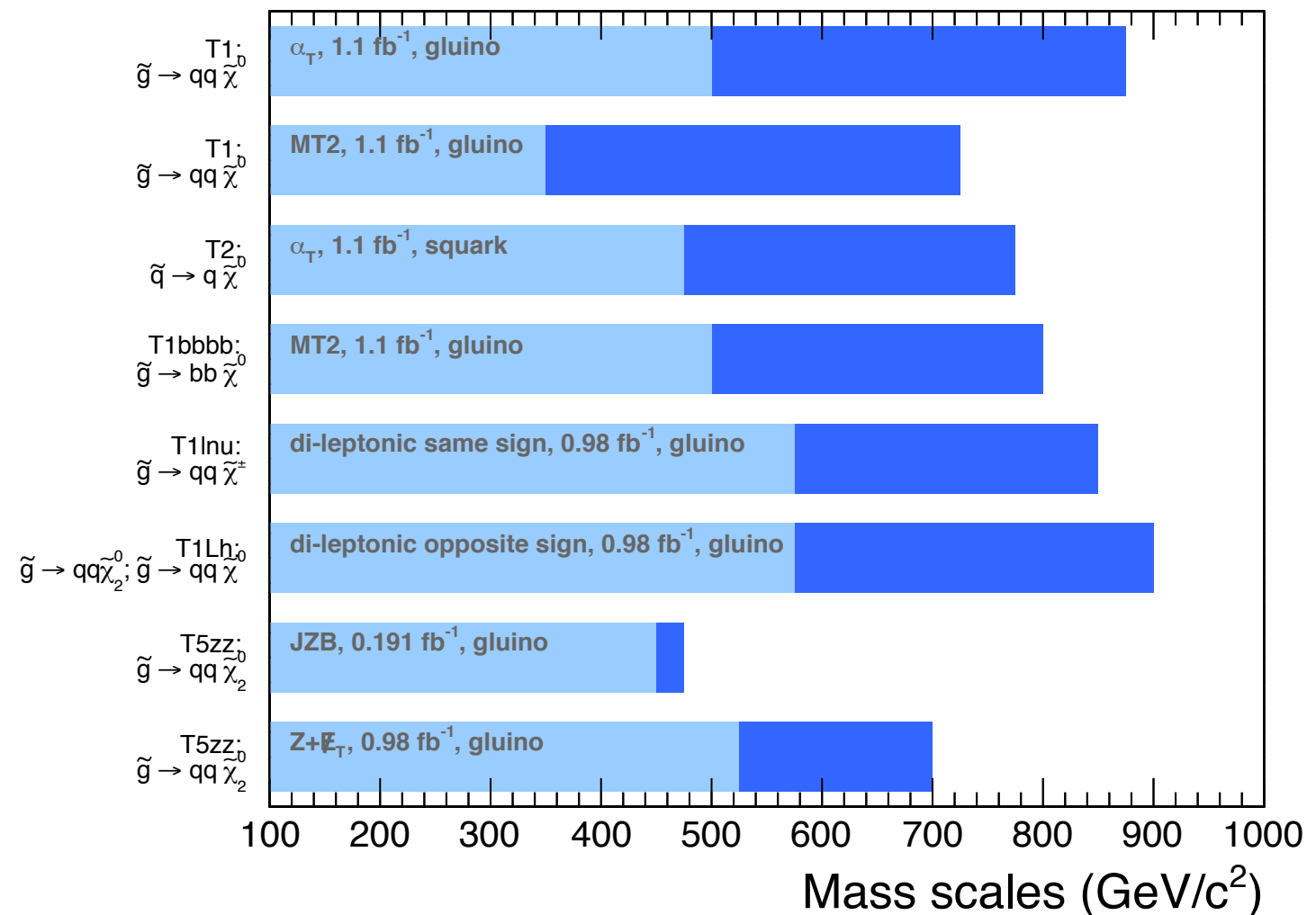
LHC physics discussions
24/10/11

*in progress w/
M. Papucci & Josh Ruderman (Berkeley)
{N. Toro (Perimeter)}*

CMS jets + MET + X



Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0)$
 CMS preliminary



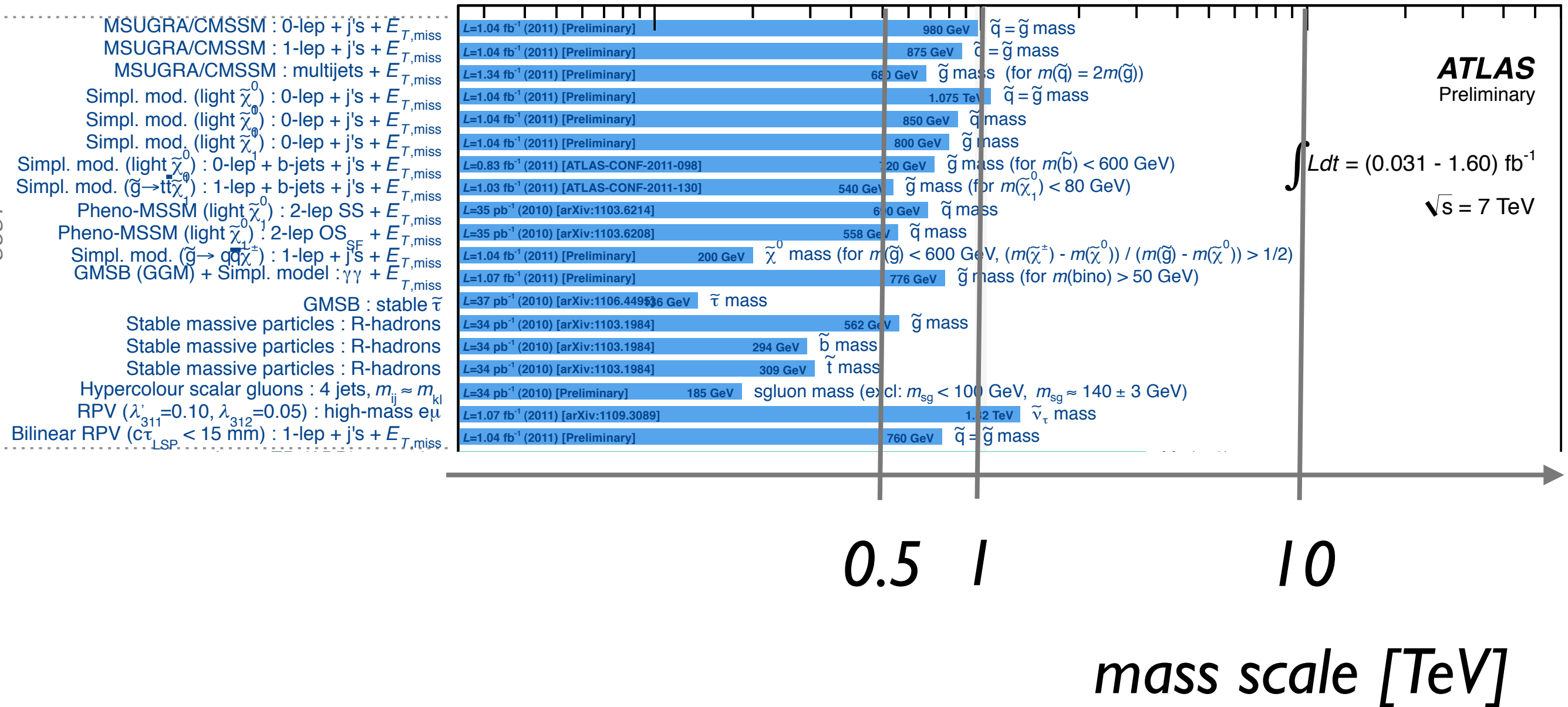
For limits on $m(\tilde{g}), m(\tilde{q}) \gg m(\tilde{g})$ (and vice versa). $\sigma^{\text{prod}} = \sigma^{\text{NLO-QCD}}$.

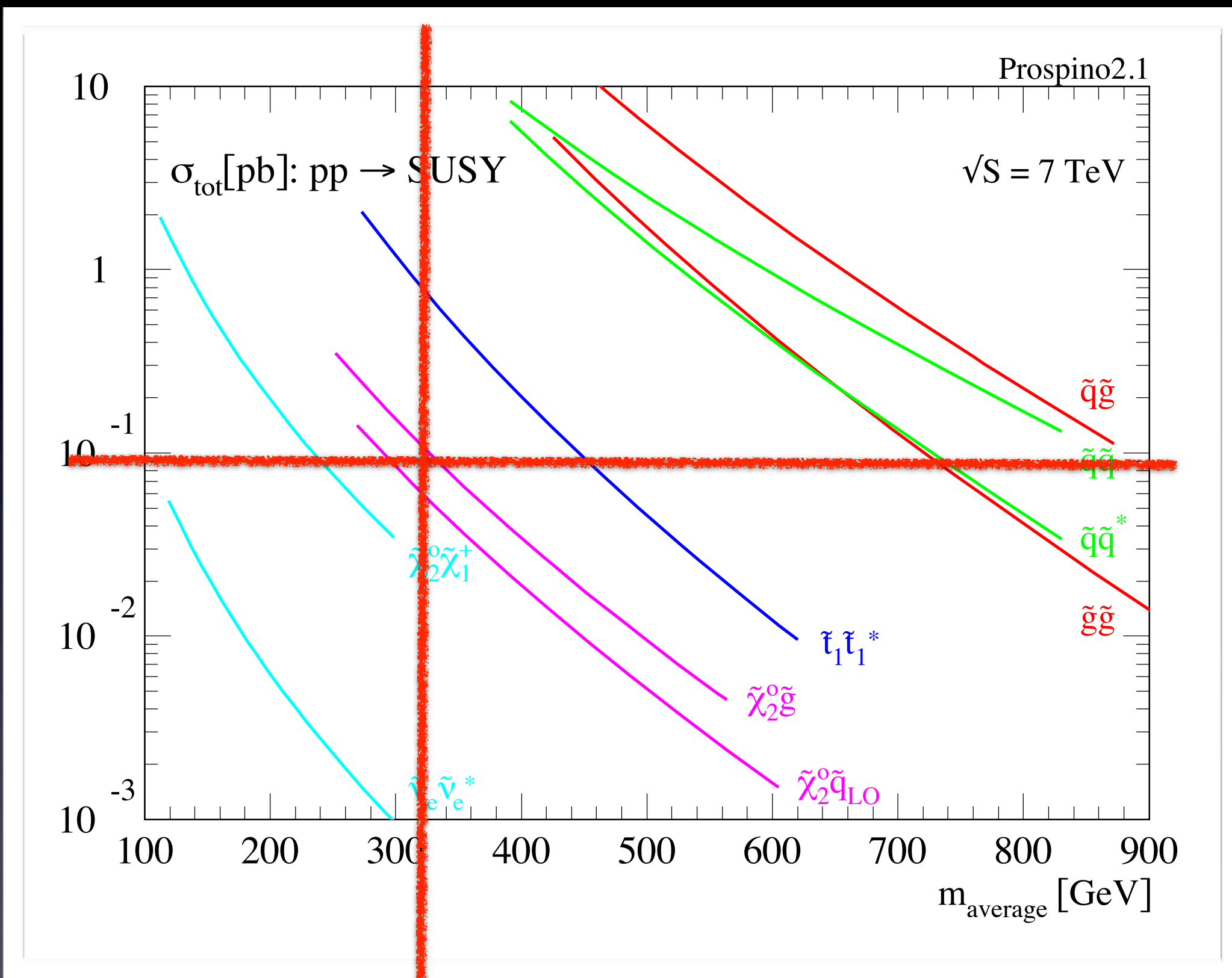
$$m(\tilde{\chi}^\pm), m(\tilde{\chi}_2^0) = \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}.$$

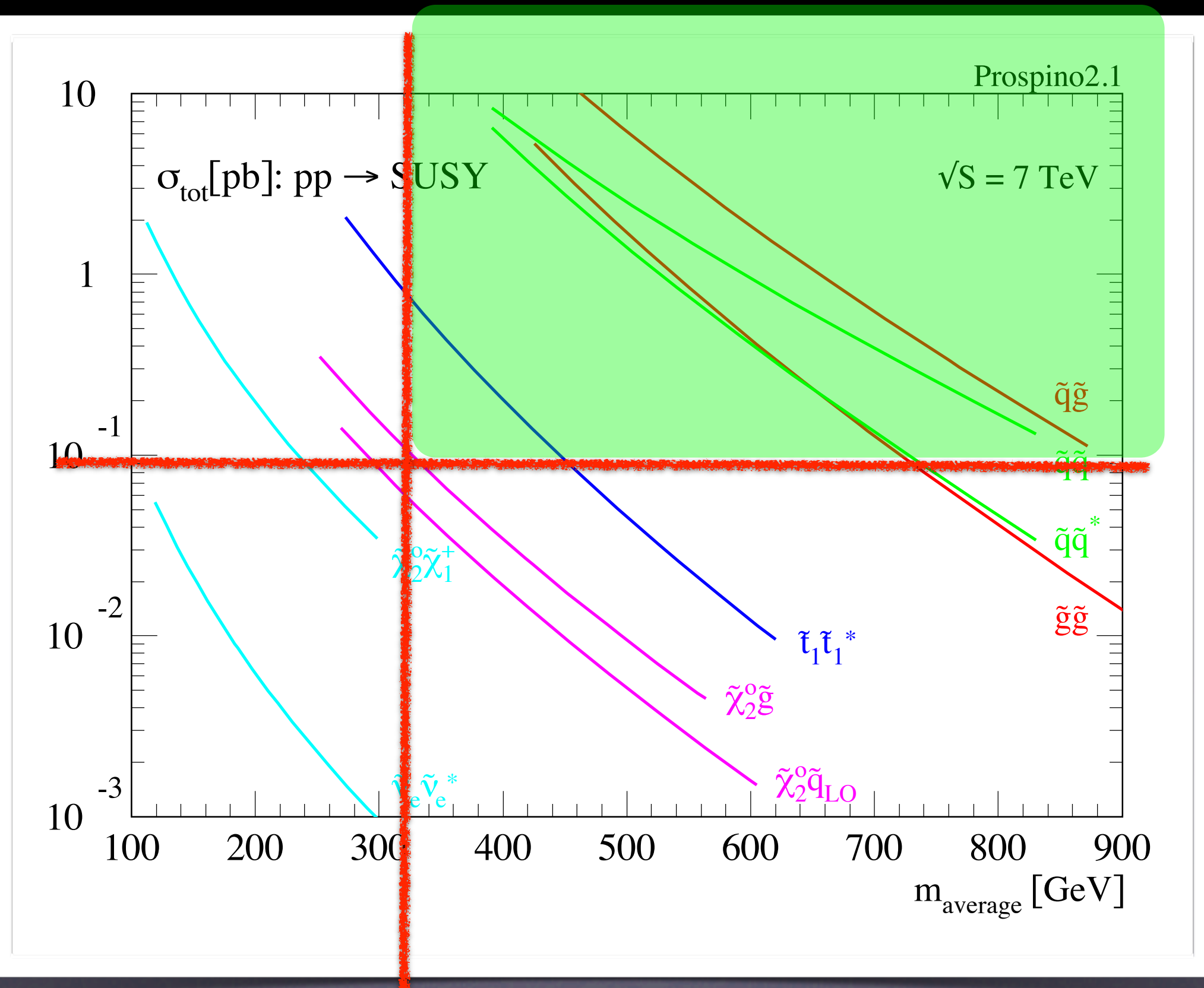
$m(\tilde{\chi}^0)$ is varied from 0 GeV/c² (dark blue) to $m(\tilde{g})-200 \text{ GeV/c}^2$ (light blue).

ATLAS SUSY searches

ATLAS Searches* - 95% CL Lower Limits (Status: BSM-LHC 2011)







Should you be worried?

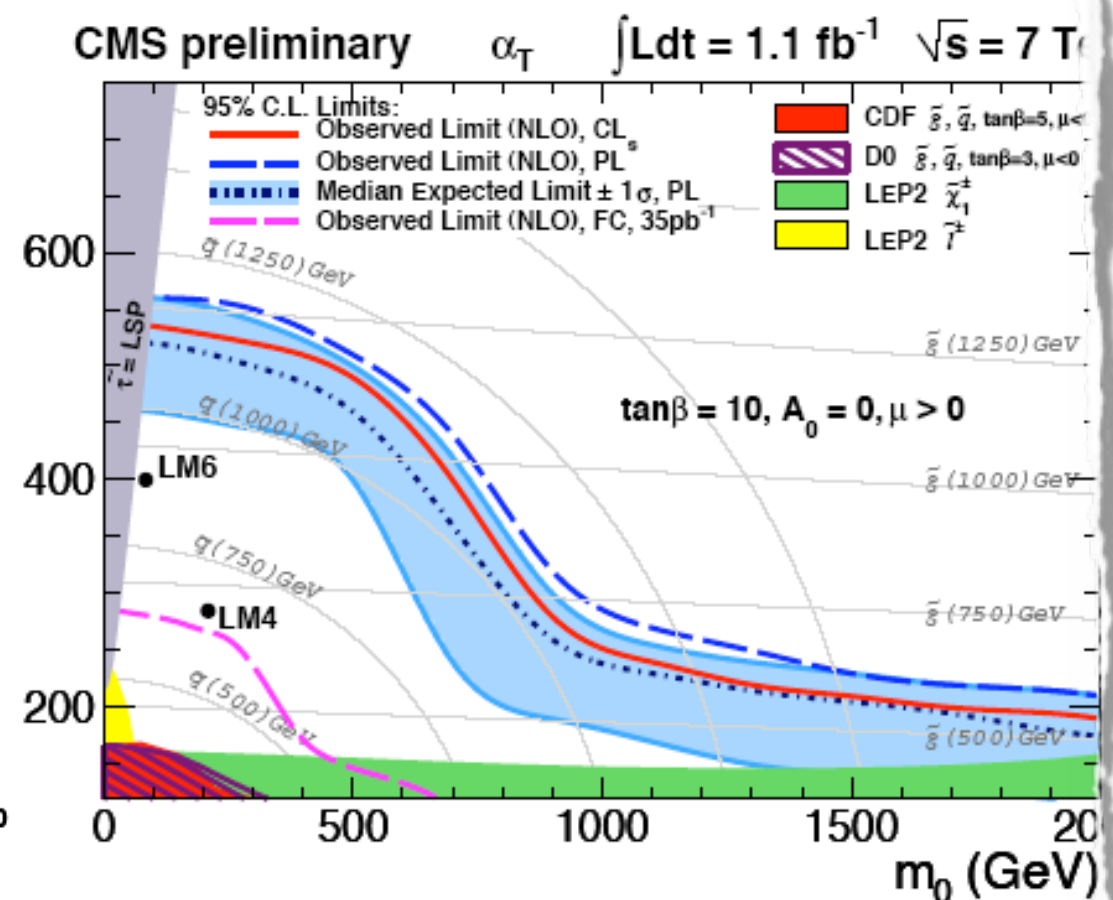
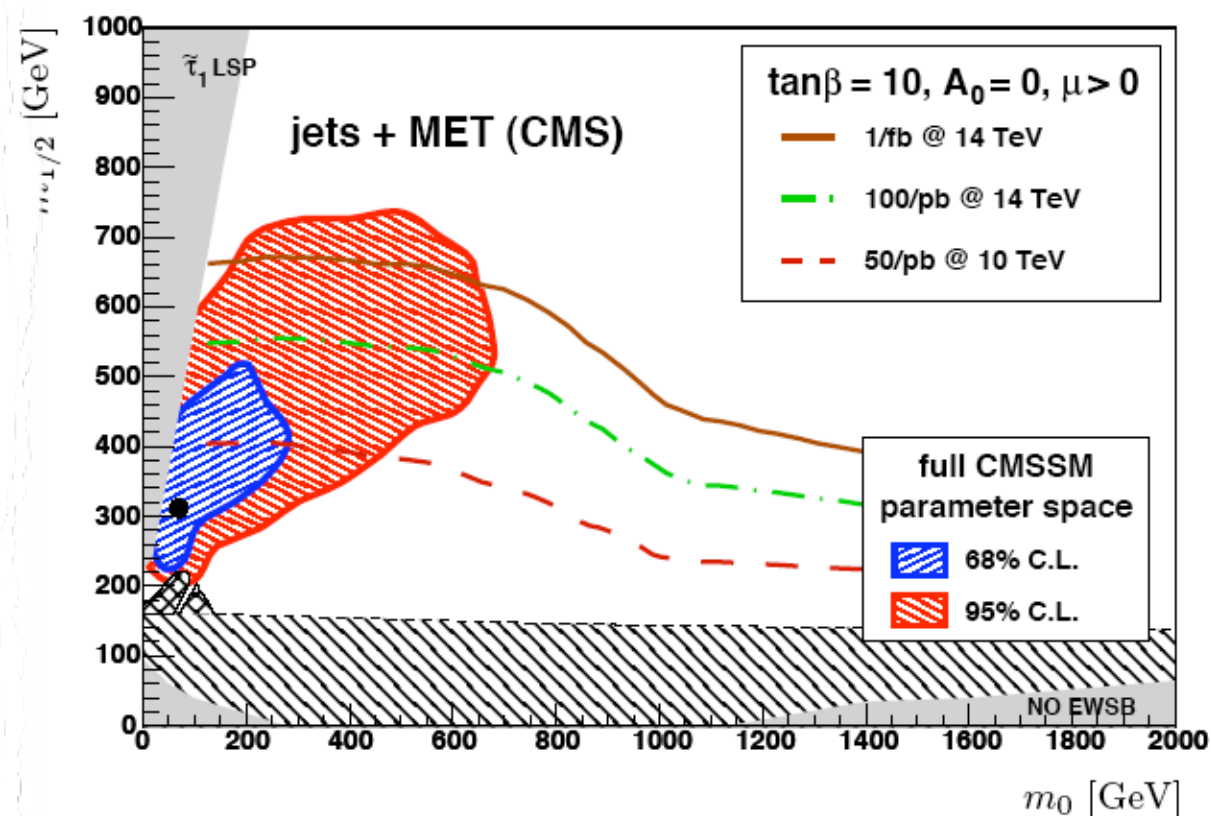
→ Michael Peskin (@LPII)

Before the start of LHC, I expected early discovery of supersymmetry in the jets+MET signature. Many other theorists also had this belief. But, it was not correct.

Georg

Buchmuller, ... , DeRoeck, Ellis ...
2008

CMS LP11 α_T analysis



→ Michael Peskin (@LP11)

I expected supersymmetry at a lower energy for a good reason. We postulate supersymmetry to provide a natural explanation of the mass scale of electroweak symmetry breaking.

In supersymmetry,

$$m_Z^2 = 2 \frac{M_{Hd}^2 - \tan^2 \beta M_{Hu}^2}{\tan^2 \beta - 1} - 2\mu^2$$

It is hard to understand how m_Z can be as small as 90 GeV ($v = 250$ GeV), if parameters of the SUSY spectrum such as μ are even as large as 1 TeV.

The simplest possibility is that all SUSY masses are at the few hundred GeV scale.

→ Michael Peskin (@ LPTI)

It is time to give up on the cMSSM. But what should replace it ?

Here are two options:

1. Find a type of SUSY model in which the mass scale is least constrained by the condition of naturalness.
2. Accept that the theory of electroweak symmetry breaking might involve strong interactions.

Where do these ideas lead ?

→ Michael Peskin (@ L P I I)

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Here are two options:

This talk!

1. Find a type of SUSY model in which the mass scale is least constrained by the condition of naturalness.
2. Accept that the theory of electroweak symmetry breaking might involve strong interactions.

Where do these ideas lead ?

→ Michael Peskin (@ LPI I)

Susy & naturalness

tree

$$\frac{m_Z^2}{2} = -|\mu|^2 + \dots + \delta m_H^2$$

loop

$$\delta m_H^2 \simeq -\frac{3y_t^2}{8\pi^2} (m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2) \ln \left(\frac{M}{m_{\tilde{t}}} \right)$$

$$\delta m_{\tilde{t}}^2 \simeq \frac{8\alpha_s}{3\pi} M_3^2 \ln \left(\frac{\Lambda_M}{m_{\tilde{t}}} \right)$$

Susy & naturalness

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(sbottom_L) stop_{1,2}

$$\delta m_{\tilde{t}}^2 \simeq \frac{8\alpha_s}{3\pi} M_3^2 \ln \left(\frac{\Lambda_M}{m_{\tilde{t}}} \right)$$

gluino

higgsinos

bottom up naturalness

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

Kitano and Nomura 2006.

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

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

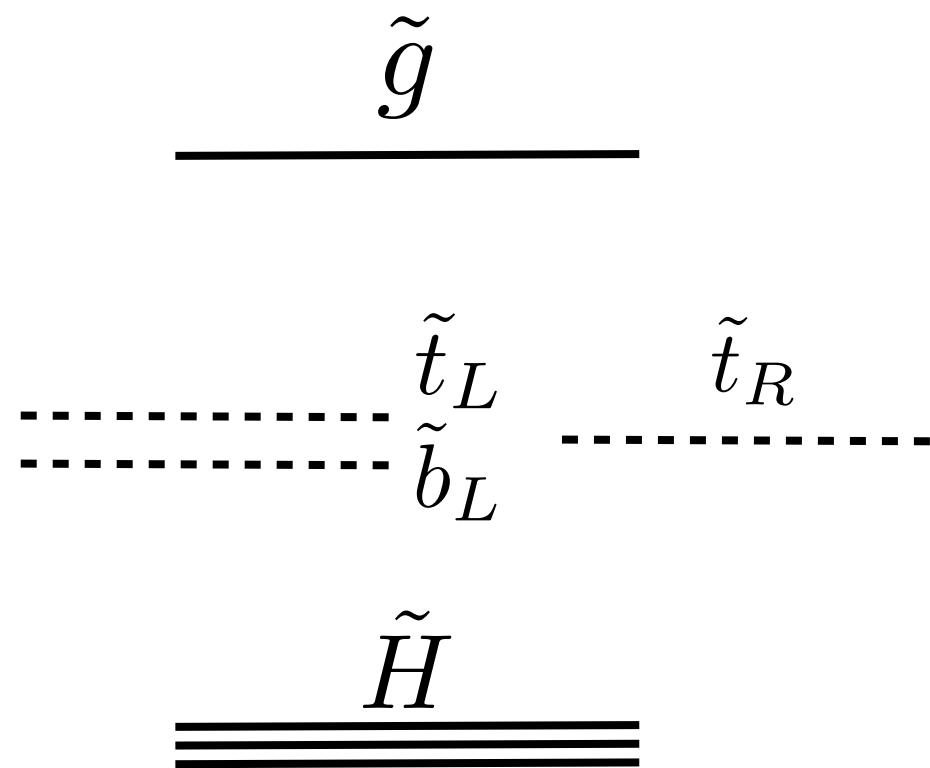
This naturalness criterium is **independent** of the *little hierarchy problem* of the MSSM Higgs. This is at the core of susy solution to fine-tuning.

Model **dependent**:

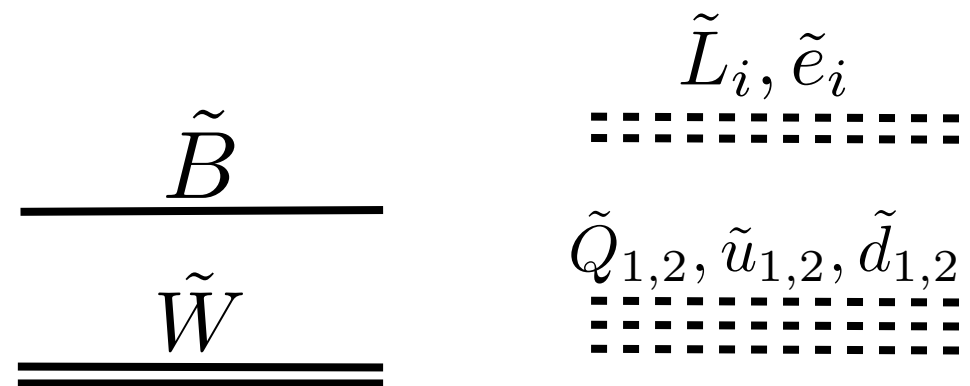
physics beyond MSSM (NMSSM,...) can

1) raise m_{higgs}

2) change decays (hide the Higgs)



natural SUSY



decoupled SUSY

$$\begin{array}{c}
 \hline \tilde{g} \\
 \\
 \begin{array}{cc}
 \cdots \tilde{t}_L & \tilde{t}_R \cdots \\
 \cdots \tilde{b}_L & \cdots
 \end{array} \\
 \hline \hline \tilde{H} \\
 \hline \hline
 \end{array}$$

natural SUSY

$$\begin{array}{c}
 \tilde{L}_i, \tilde{e}_i \\
 \cdots \cdots \cdots \\
 \hline \tilde{B} \\
 \hline \tilde{W} \\
 \hline \hline \\
 \tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2} \\
 \cdots \cdots \cdots \\
 \cdots \cdots \cdots \tilde{b}_R \cdots \cdots \cdots
 \end{array}$$

this part of the spectrum
does not matter much for
naturalness & can be heavier

decoupled SUSY

parameters: $\mu, \tan \beta$
 m_{Q_3}, m_{u_3}, A_t
 M_3

$\tilde{g}$

$\tilde{t}_L \quad \tilde{t}_R$
 $\tilde{b}_L$

$\tilde{H}$

natural SUSY

$\tilde{B}$

$\tilde{W}$

$\tilde{L}_i, \tilde{e}_i$

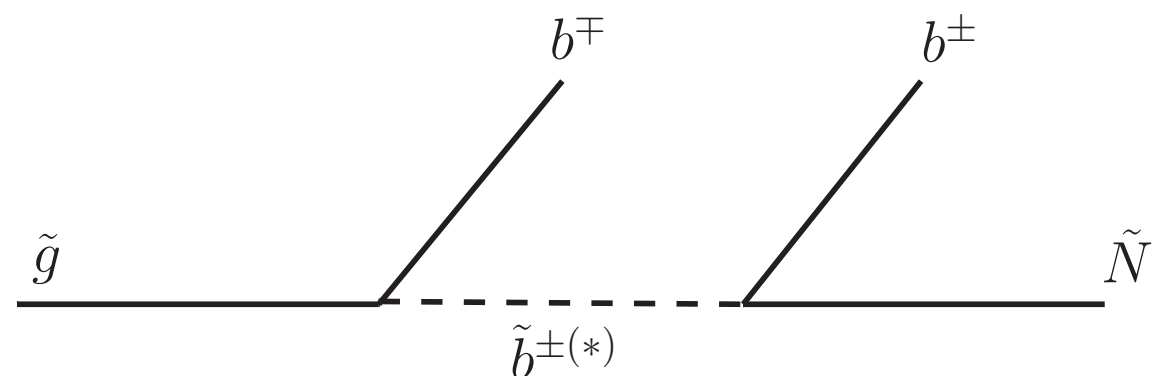
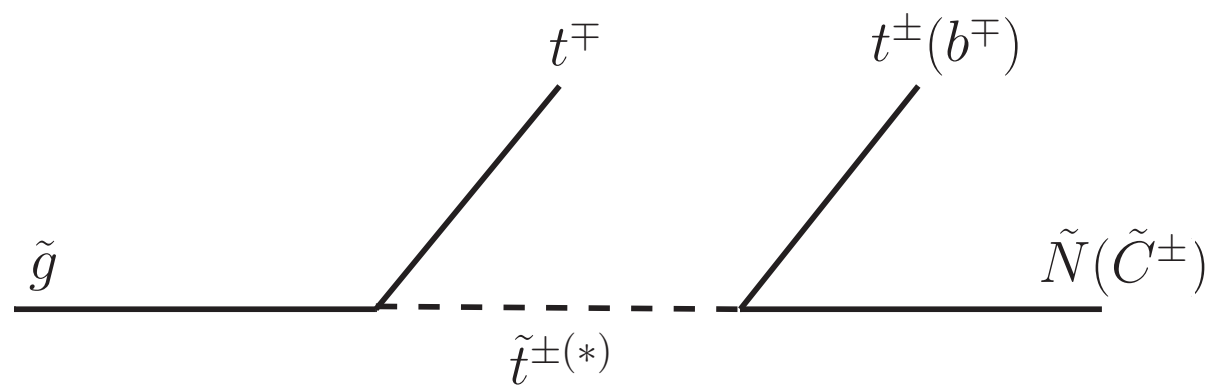
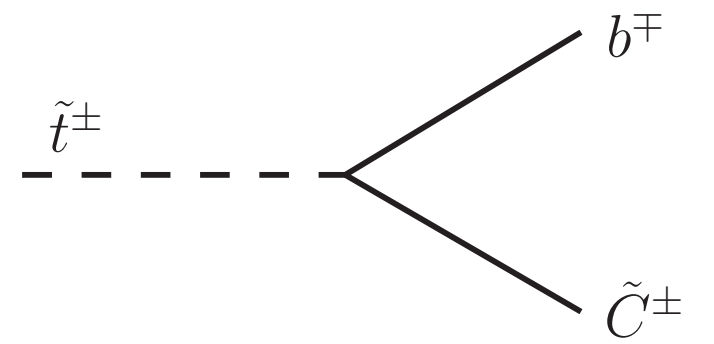
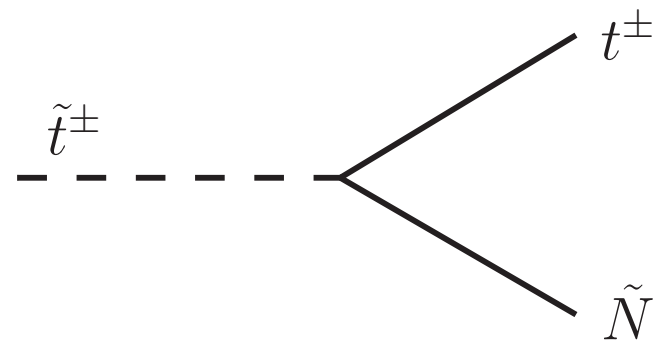
$\tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2}$

$\tilde{b}_R$

this part of the spectrum
 does not matter much for
 naturalness & can be heavier

decoupled SUSY

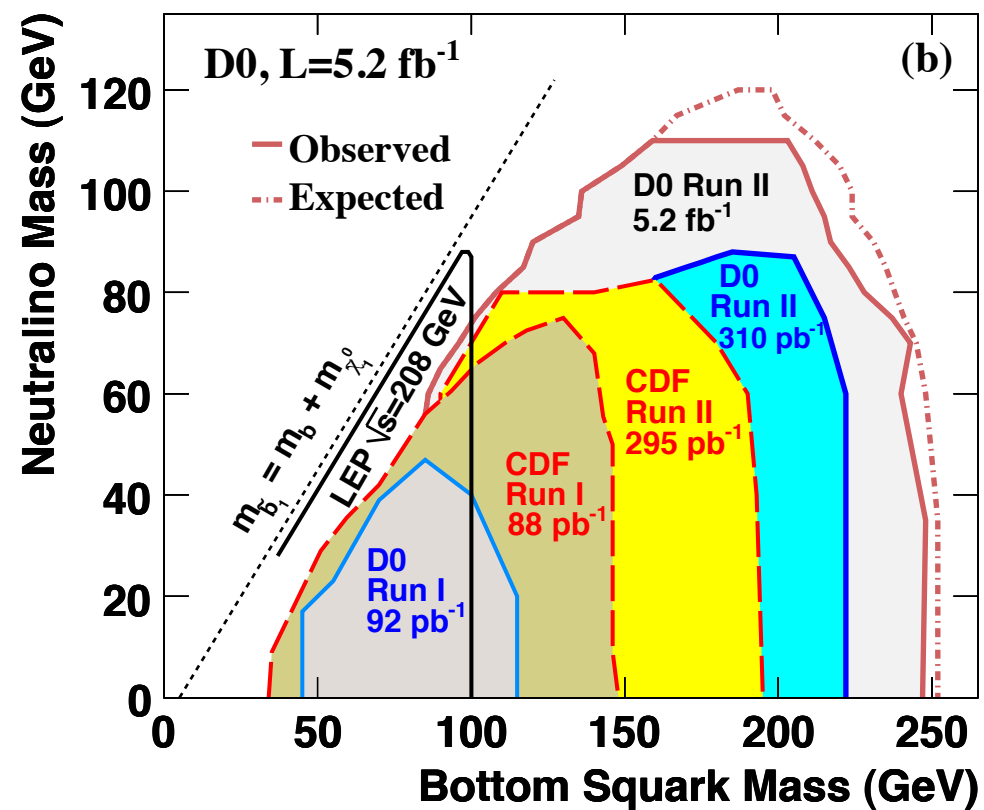
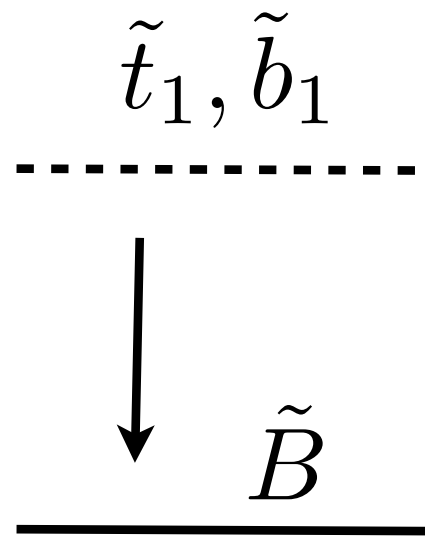
squark decays



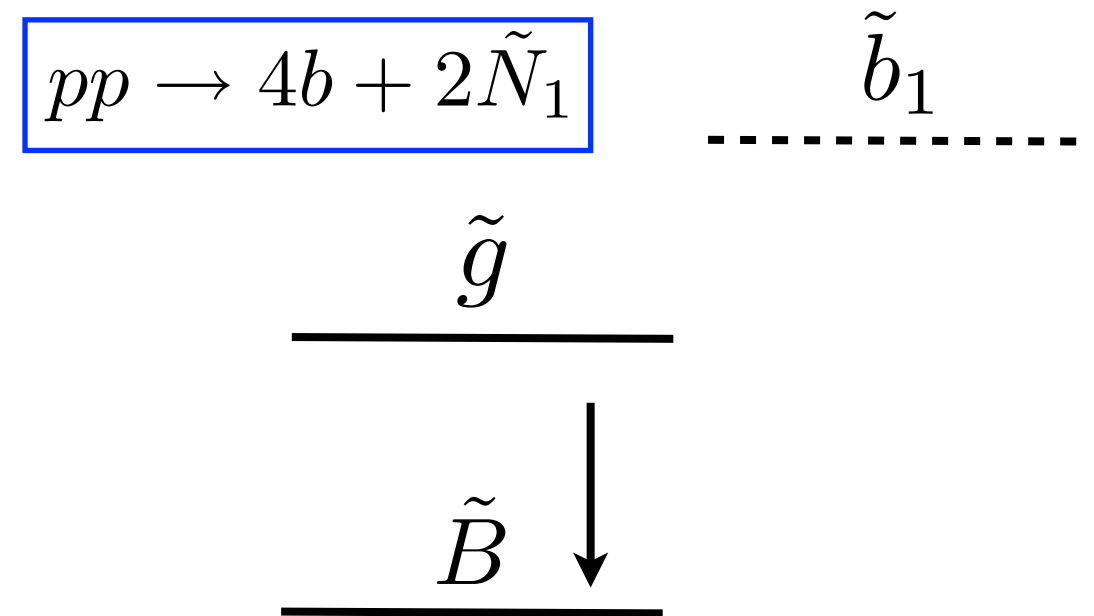
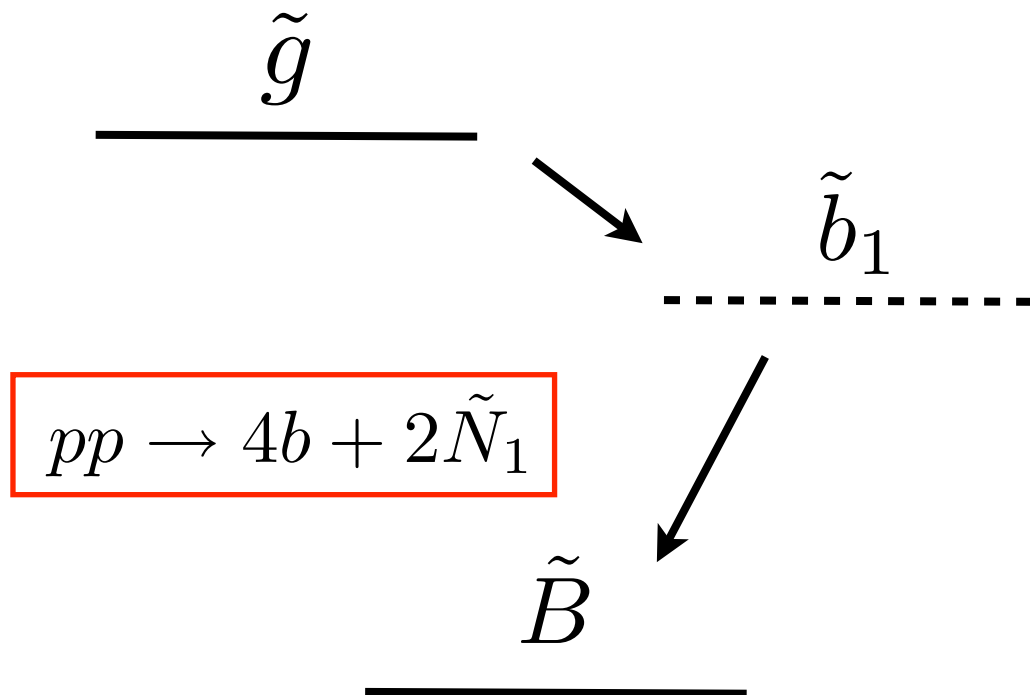
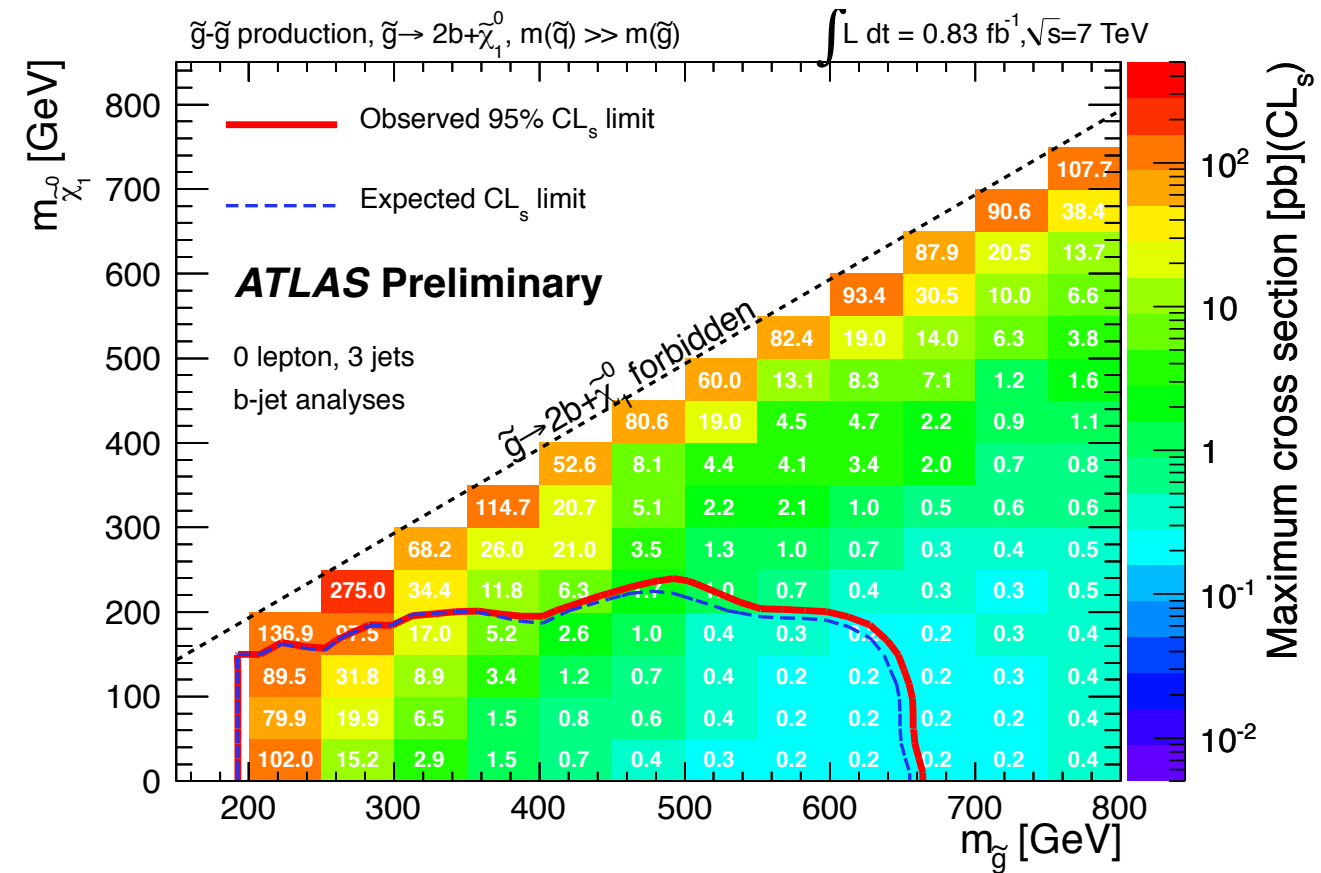
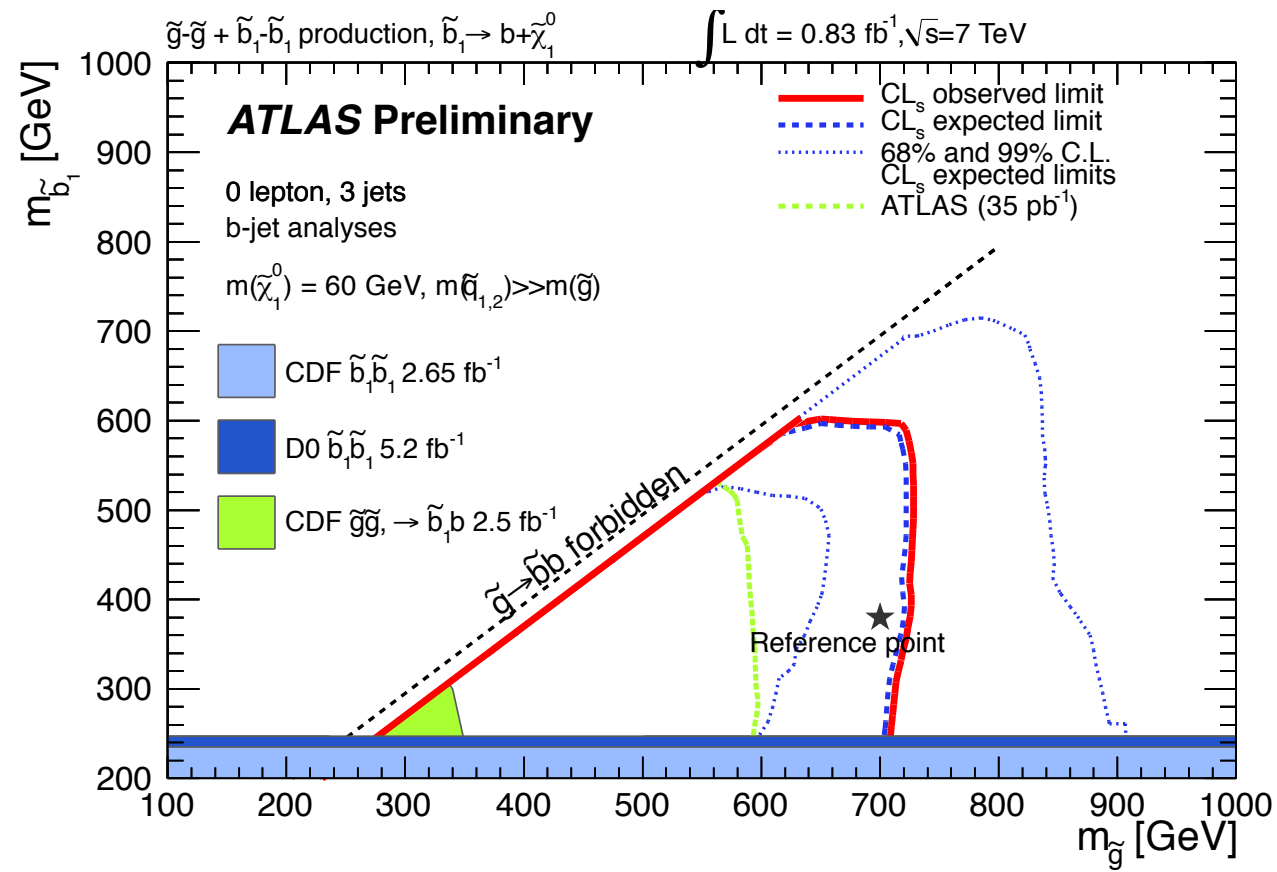
gluino decays

weak limits from Tevatron

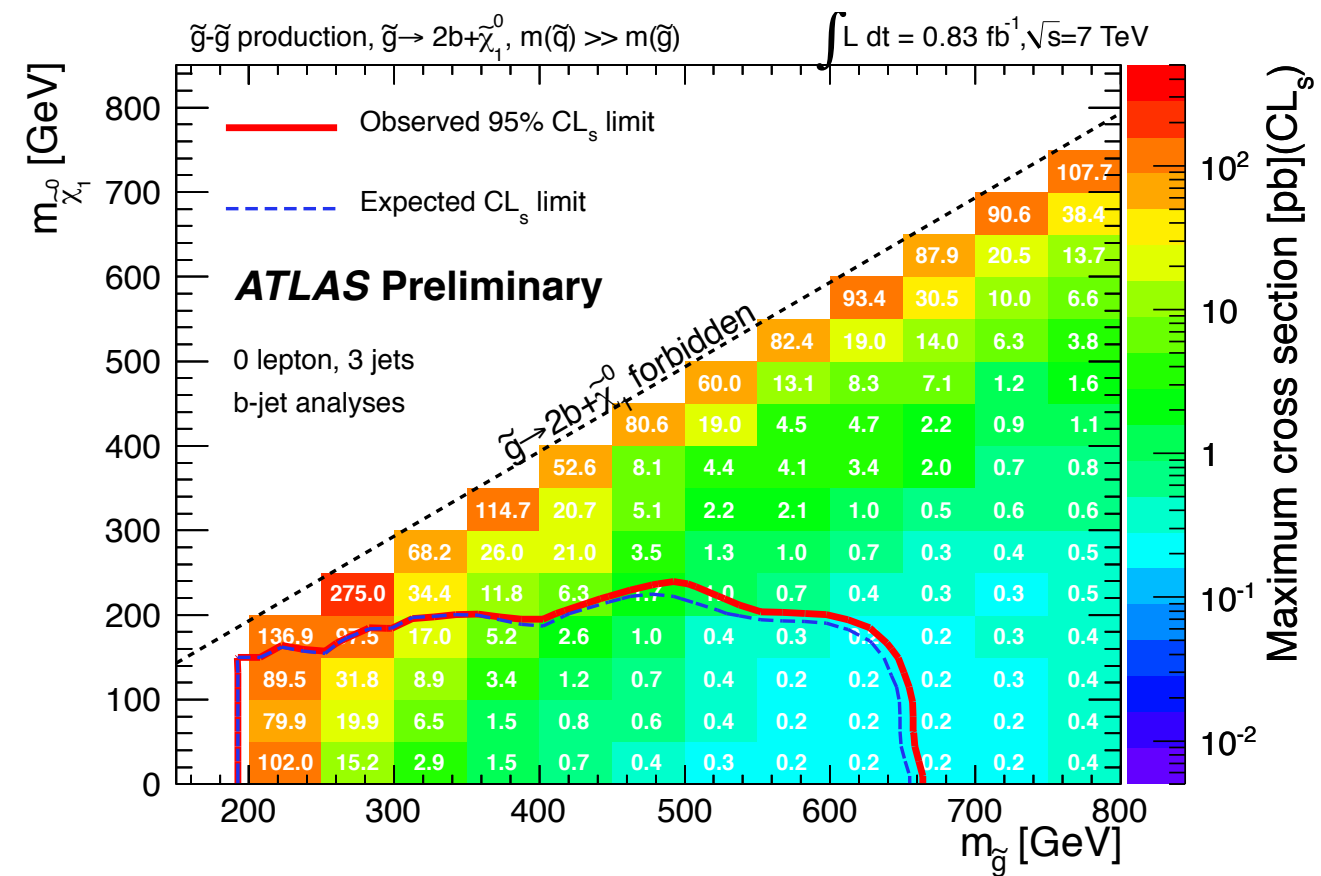
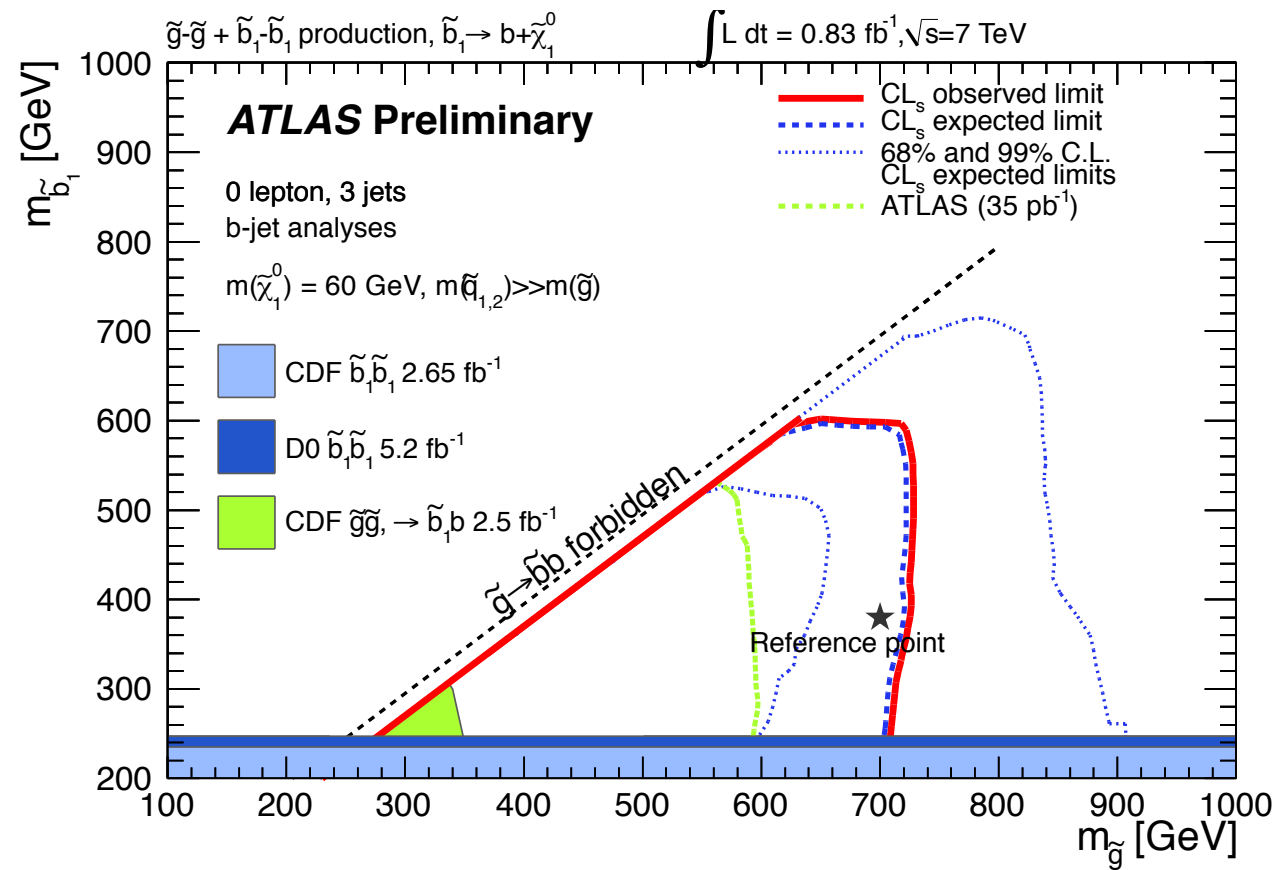
$m_{\tilde{b}_1} > 250 \text{ GeV}$ (prompt decaying)
stops can still be light (even 120-180 GeV)



Atlas b-jet + MET



Atlas b-jet + MET



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

Exclusions mostly driven by gluinos !

$\tilde{g}$

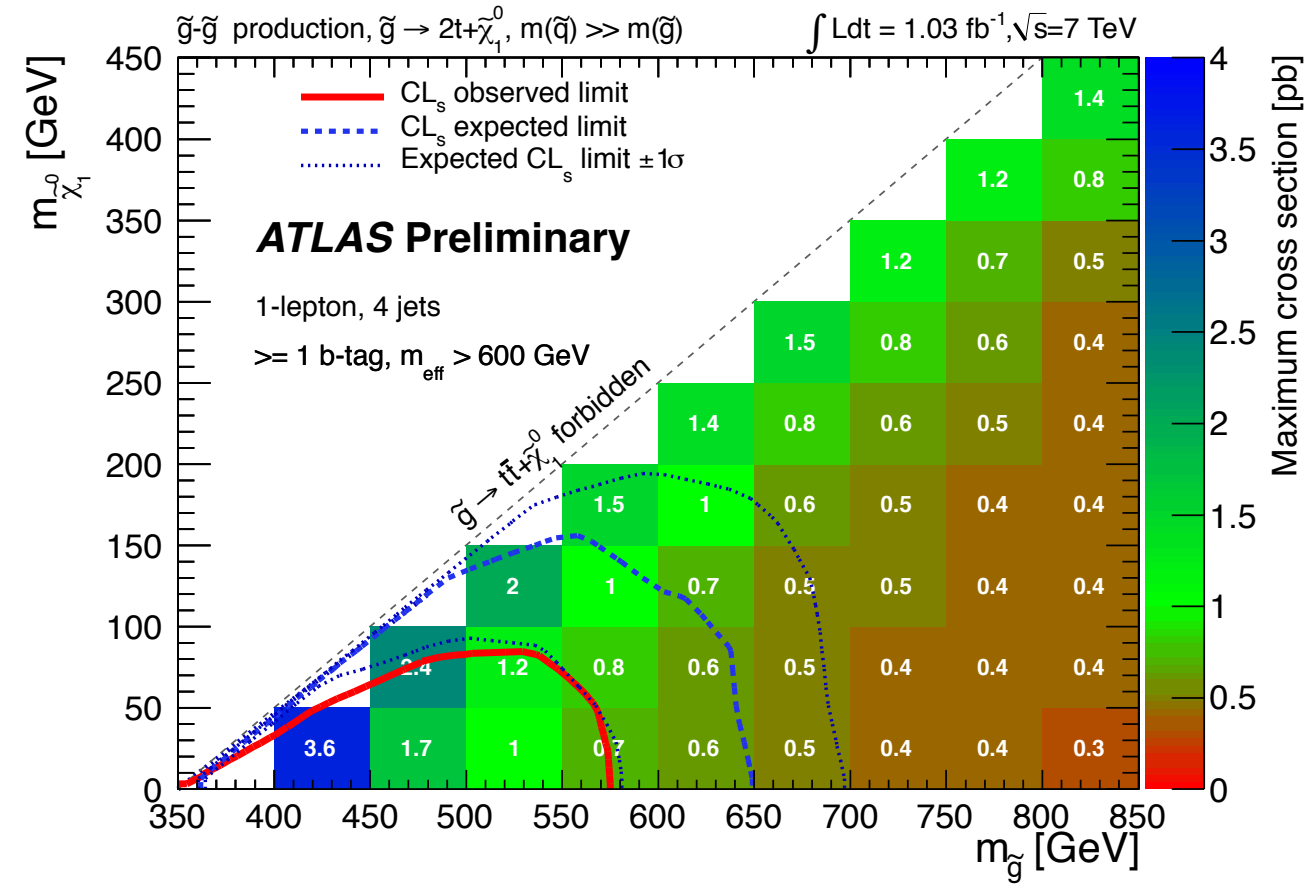
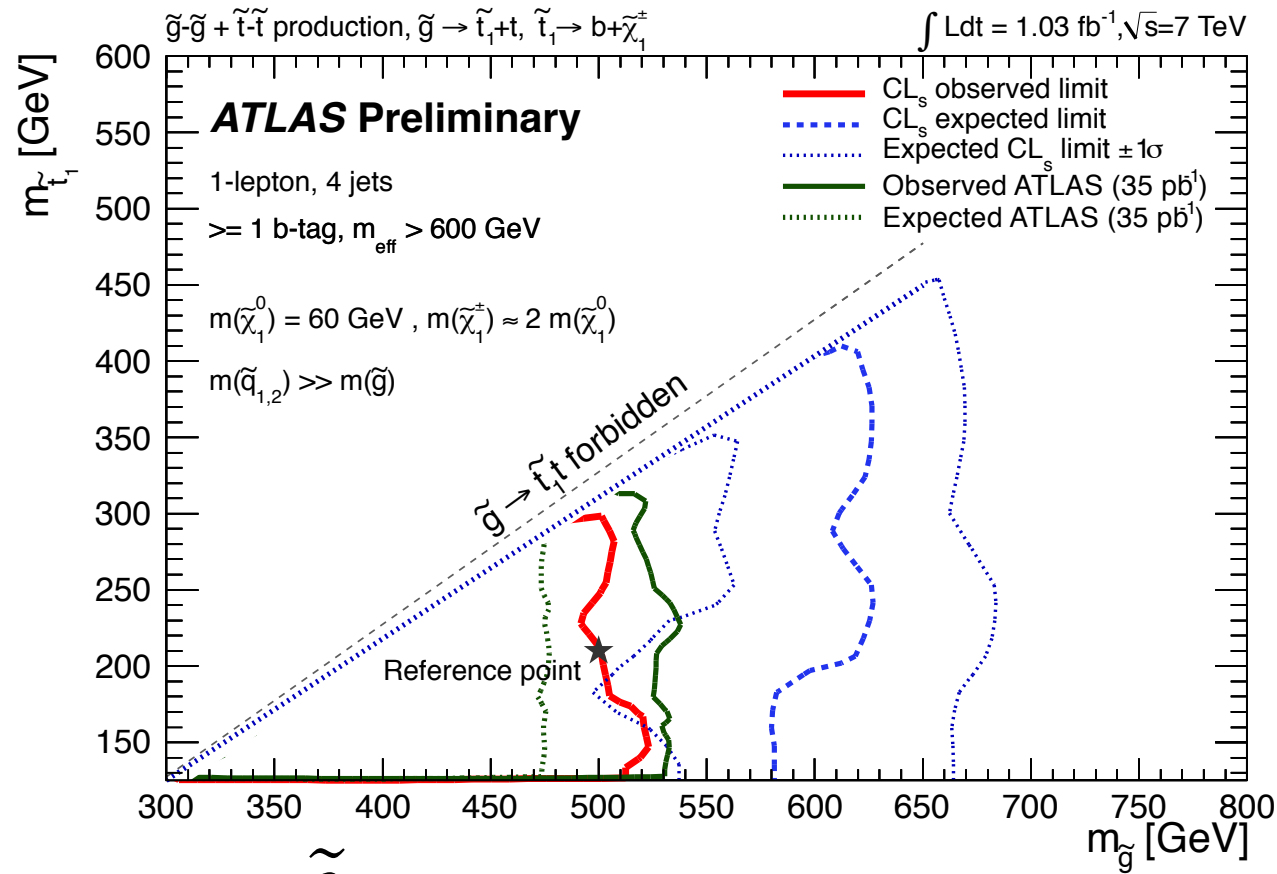
$\tilde{t}$

$\tilde{b}_1$

$\tilde{B}$

$\tilde{B}$

Atlas b-jet + l + MET



$$pp \rightarrow 4t + 2\tilde{N}_1$$

$\tilde{t}_1$

$\tilde{C}_1^\pm$

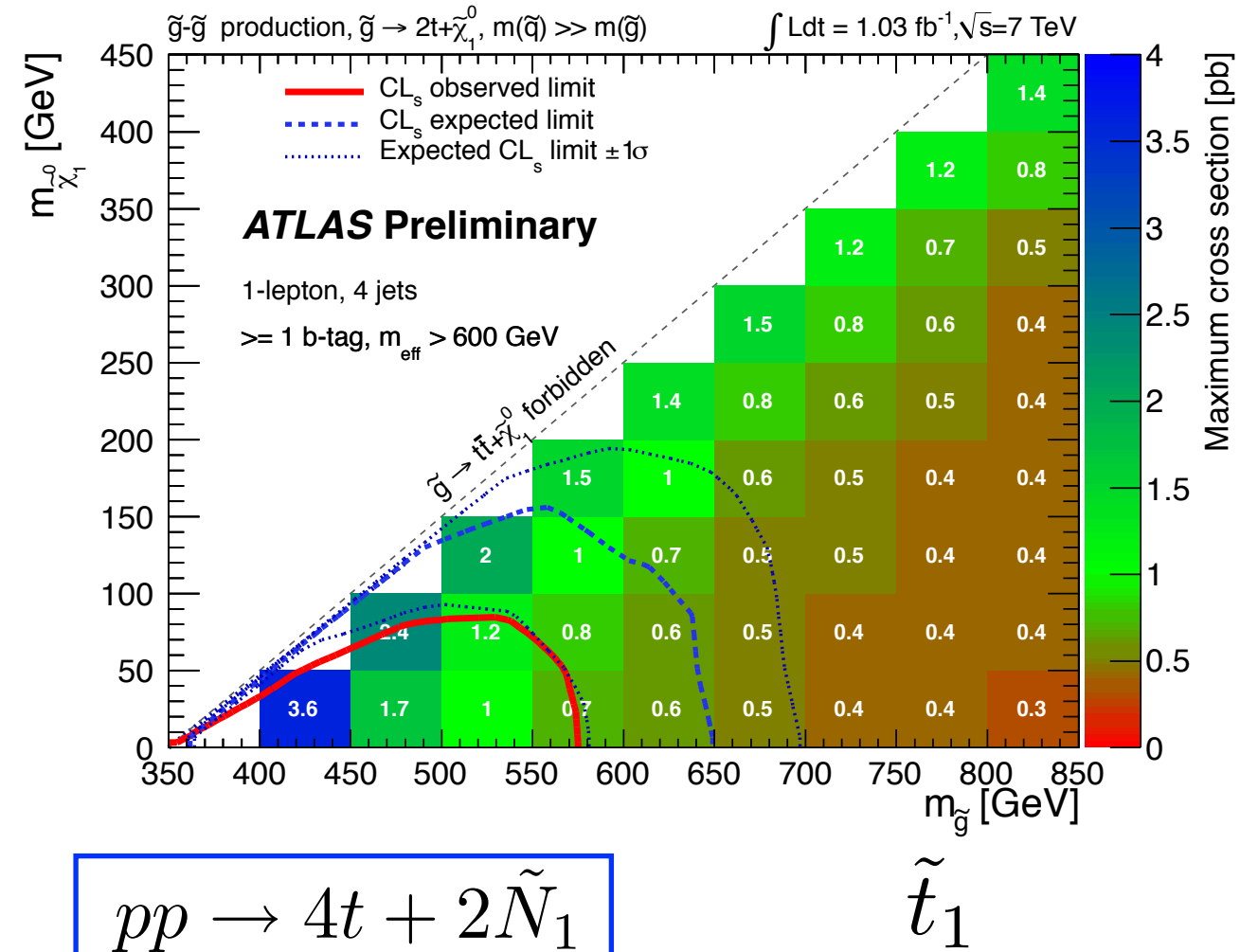
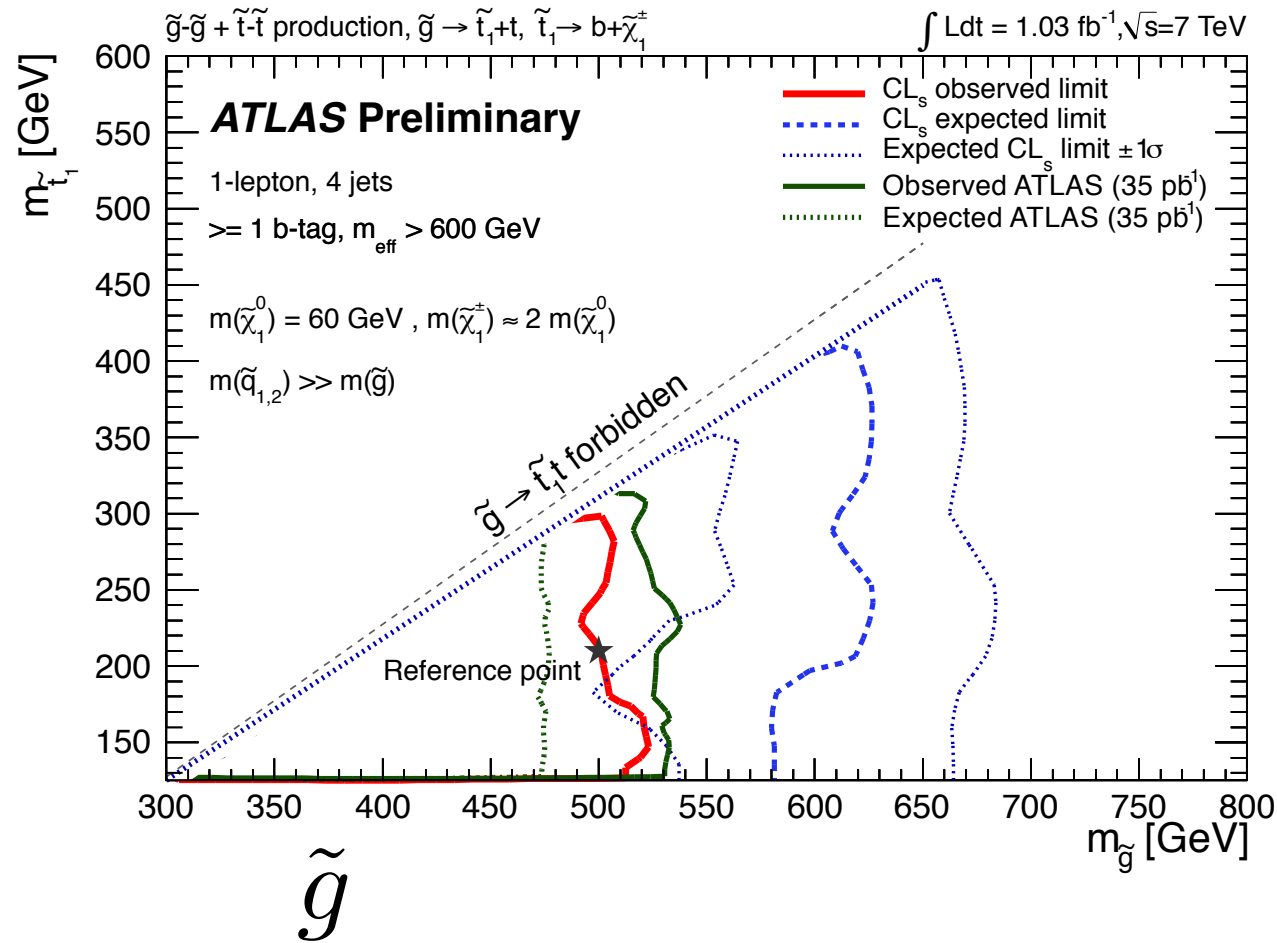
$\tilde{N}_1$

$$pp \rightarrow 2t + 2b + 2W + 2\tilde{N}_1$$

$\tilde{g}$

$\tilde{B}$

Atlas b-jet + l + MET



$$pp \rightarrow 4t + 2\tilde{N}_1$$

$\tilde{t}_1$

Exclusions mostly driven by gluinos !

$C_1^\pm$



$\tilde{N}_1$

$$pp \rightarrow 2t + 2b + 2W + 2\tilde{N}_1$$

$\tilde{B}$



our pipelines

ATOM

pythia / herwig / etc



fastjet



truth leptons / photons /b's

- l/gamma iso
- parameterized efficiencies

pgs

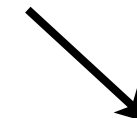
pythia



crude detector sim



cone jets



truth
muons/b's

- parameterized efficiencies

crude
simulated e/
gamma

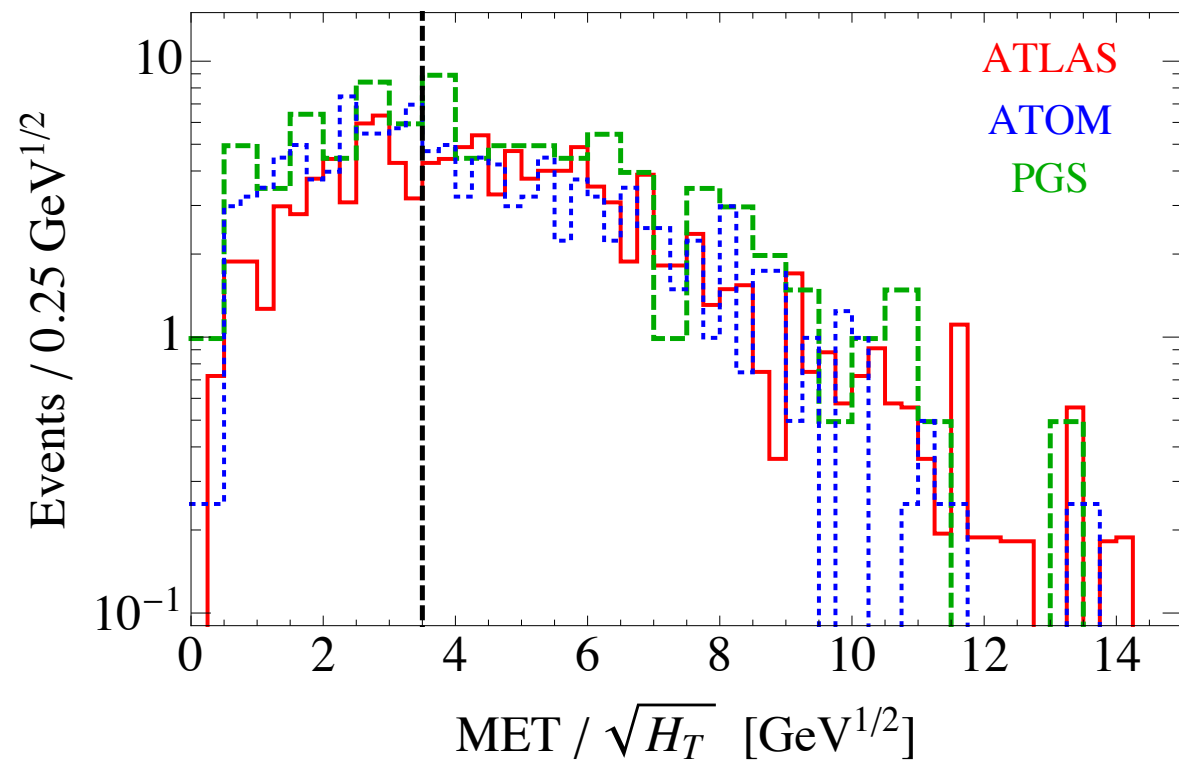
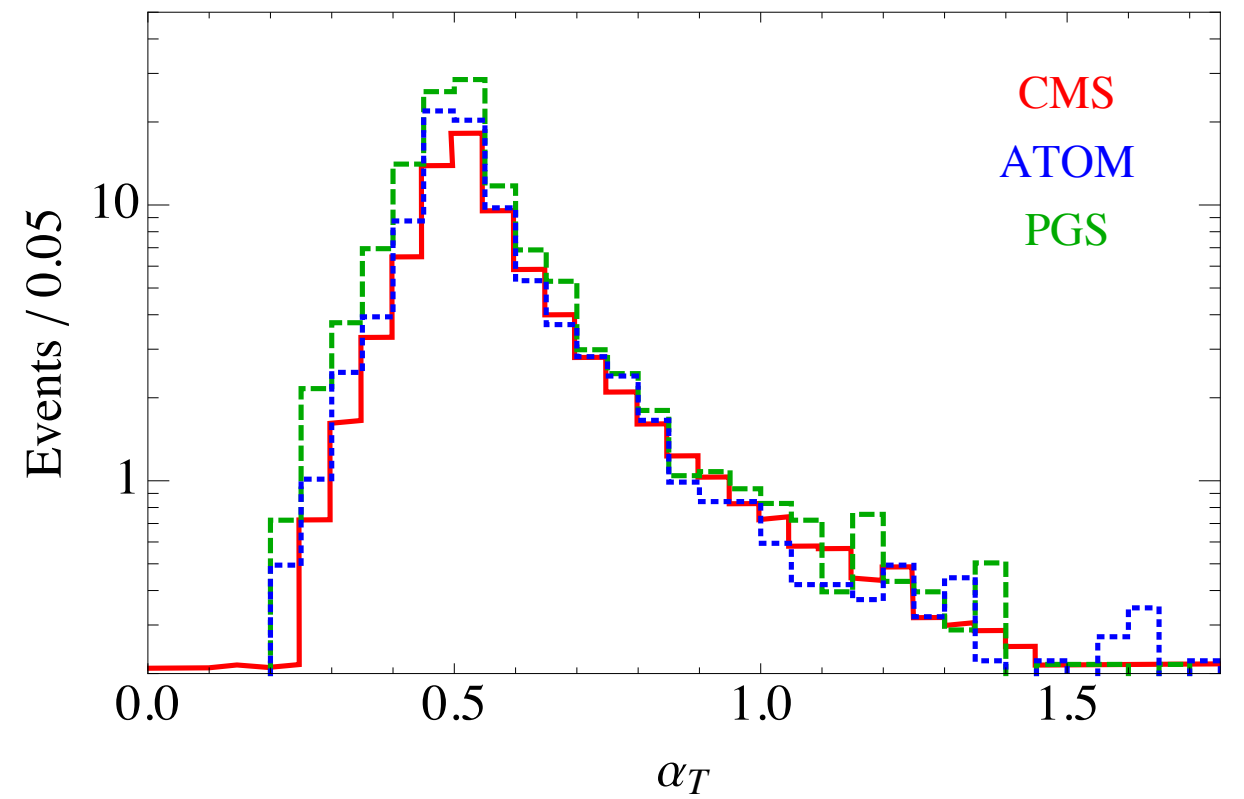
Calibration

“theorist limits”

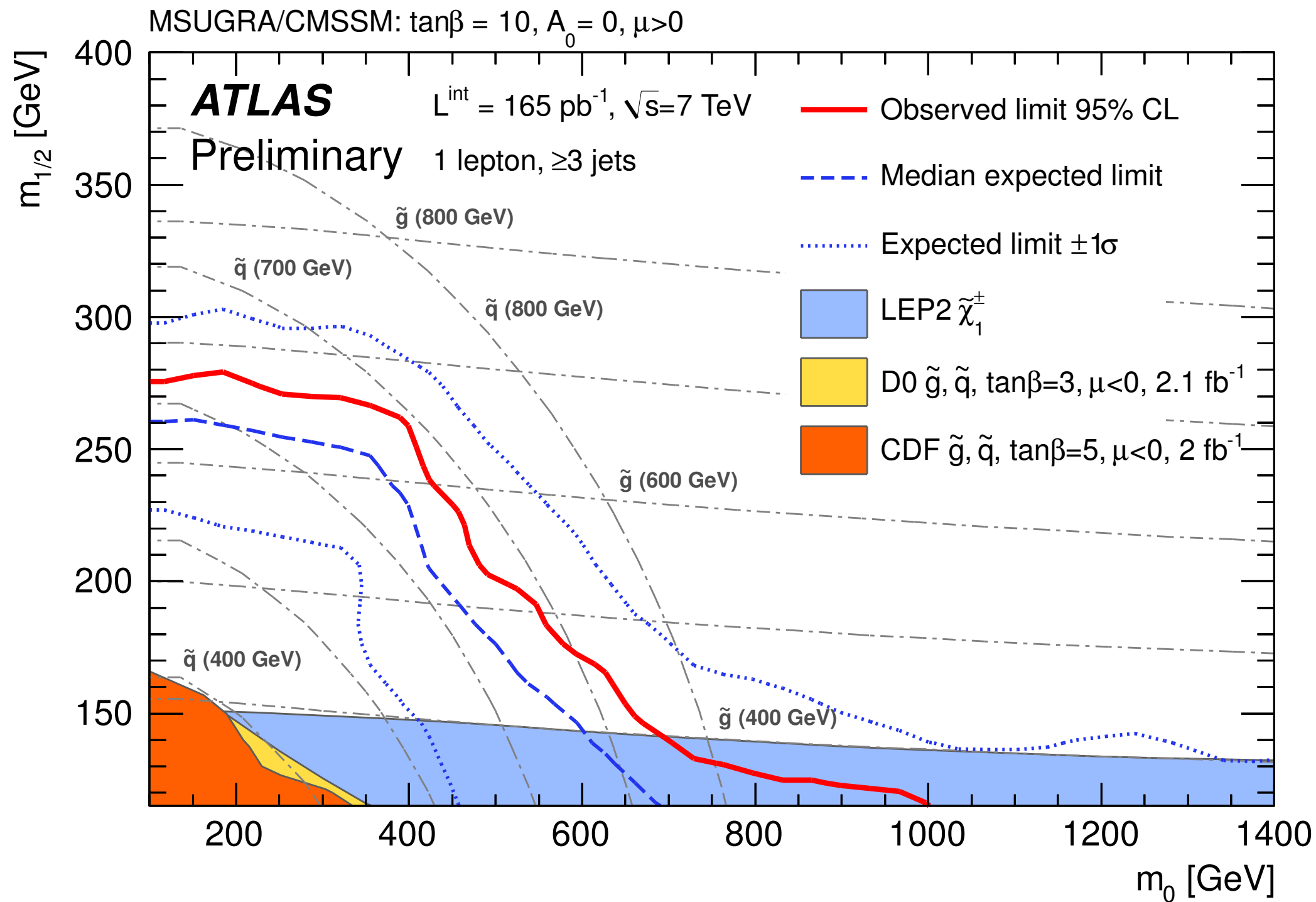
To calibrate compare:

- 1) key kinematical distributions
- 2) limits

ATLAS 6–8 Jet Validation

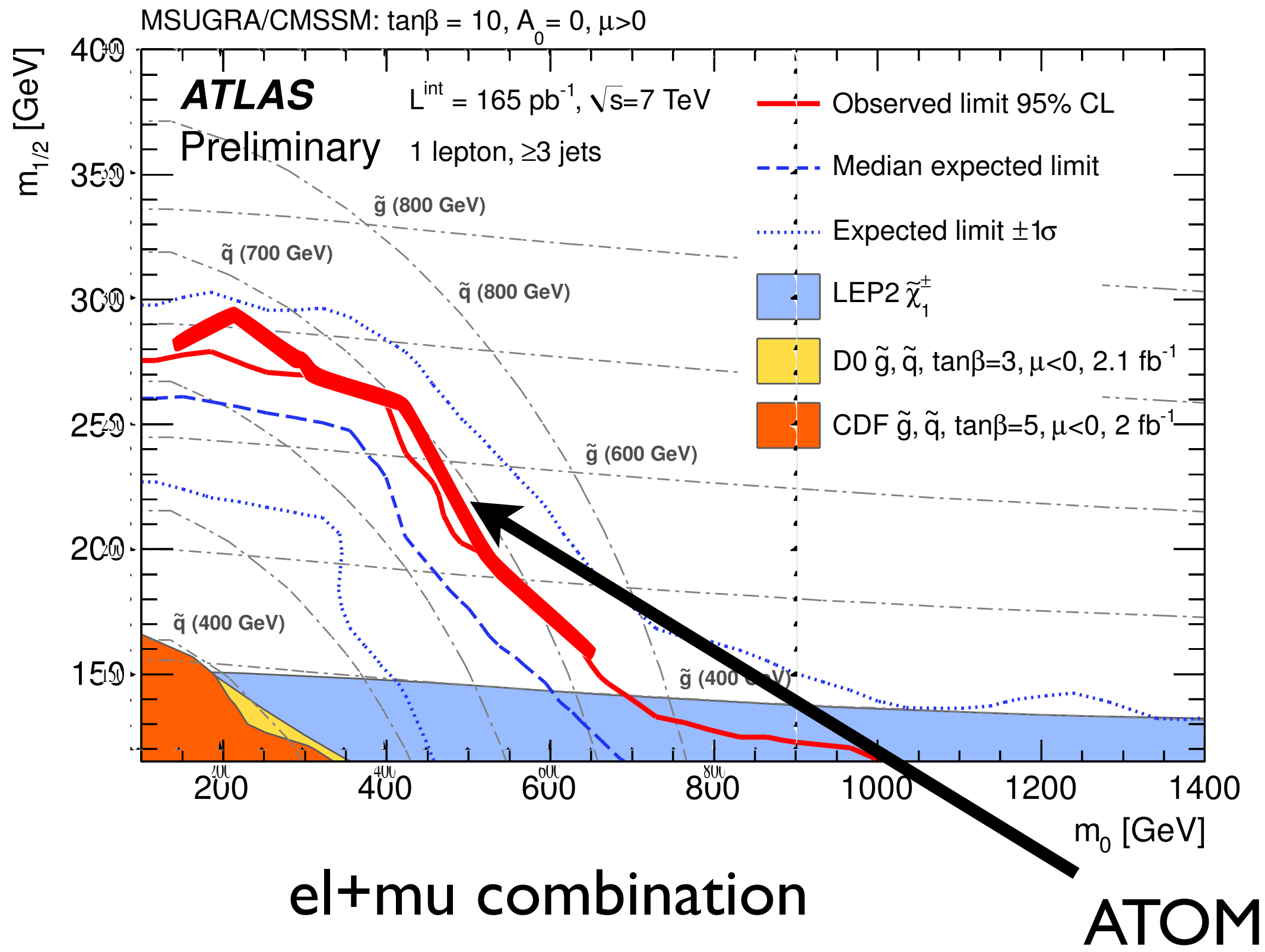
CMS α_T Validation

ATLAS-CONF-2011-090 (Jets + MET + l (e,mu)) 161 1/pb



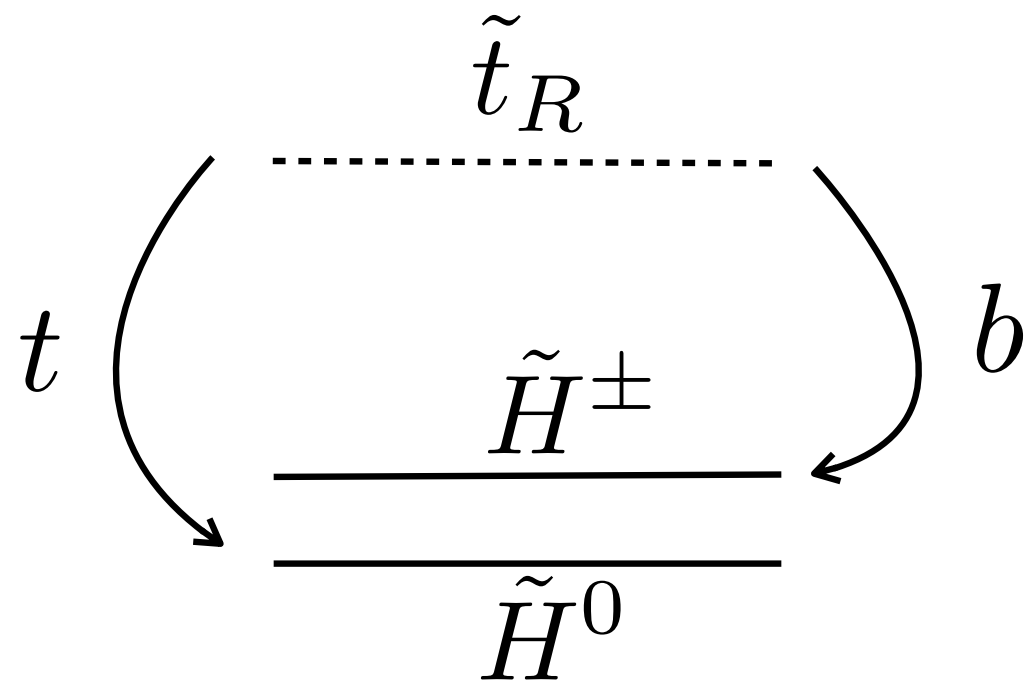
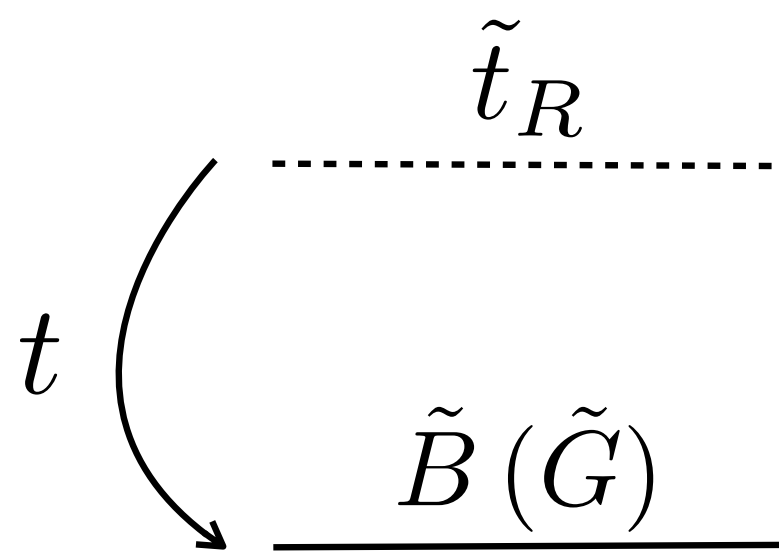
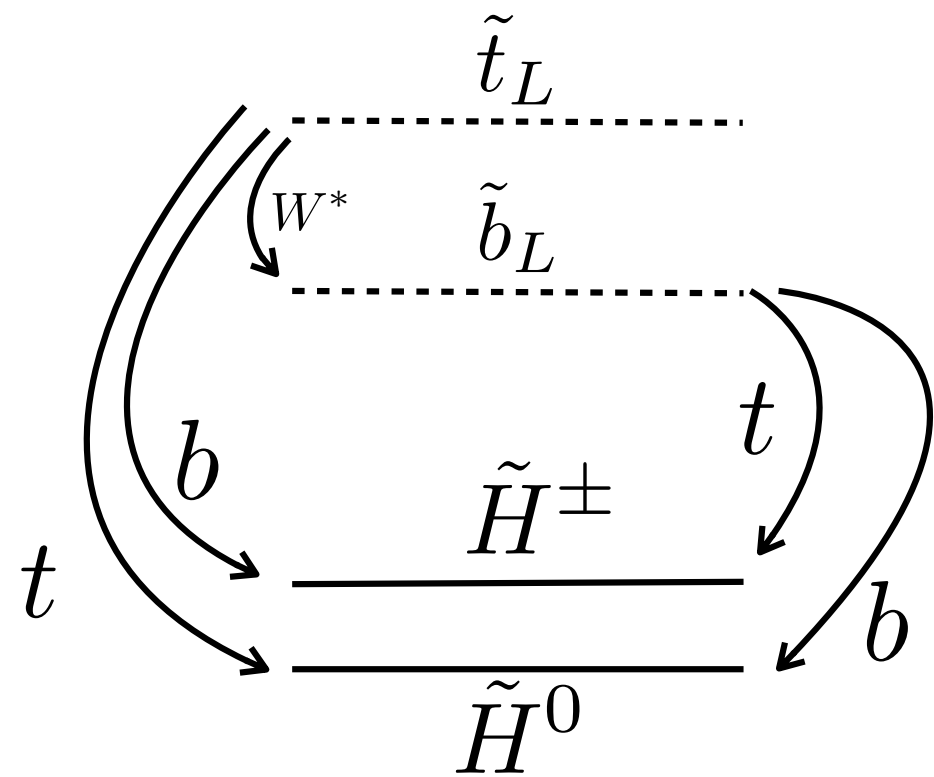
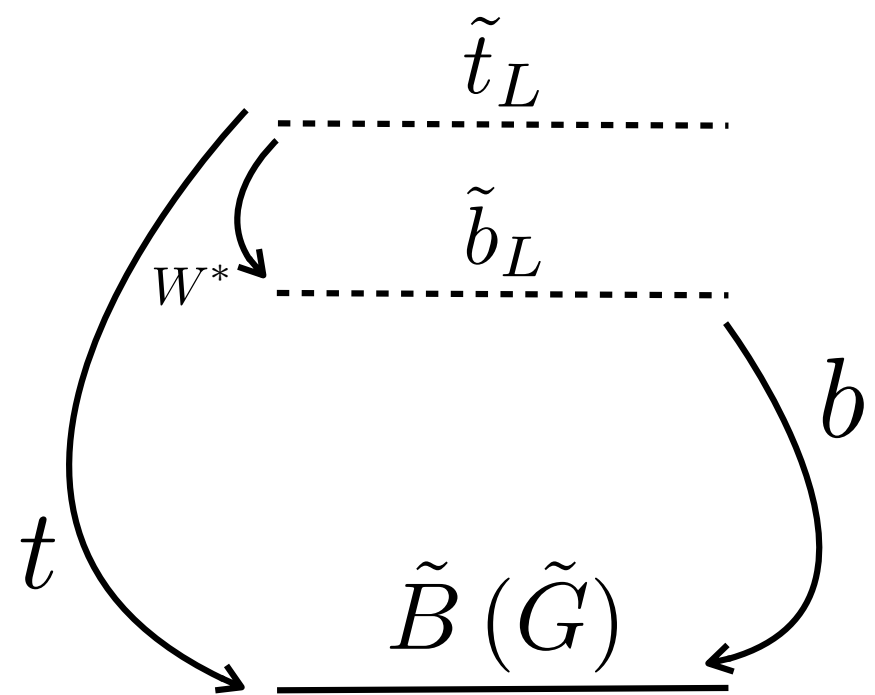
el+mu combination

ATLAS-CONF-2011-090 (Jets + MET + l (e,mu)) 161 1/pb



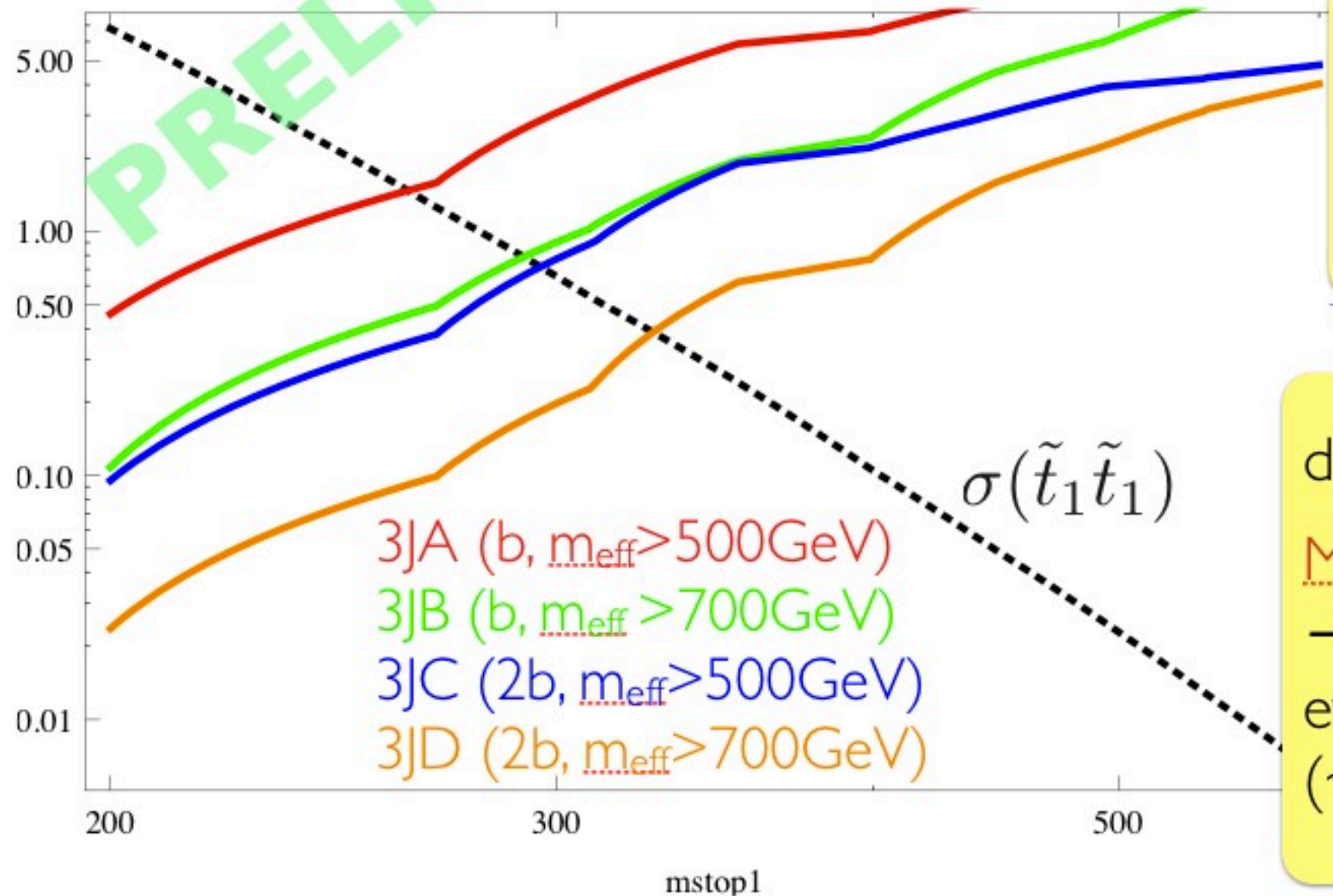
LHC Susy searches

	ATLAS			CMS		
	channel	$\mathcal{L}$ [fb ⁻¹]	ref.	channel	$\mathcal{L}$ [fb ⁻¹]	ref.
jets + $\cancel{E}_T$	2-4 jets	1.04	[1, 2]	α_T	1.1	[9, 10]
	6-8 jets	1.34	[2]	$H_T, \cancel{H}_T$	1.1	[11]
b -jets + $\cancel{E}_T$	$b + 0l$	0.83	[3]	$m_{T2} (+b)$	1.1	[12]
	$b + 1l$	1.03	[4]			
multilepton + $\cancel{E}_T$	$1l$	1.04	[5]	$1l$	1.1	[13]
	$\mu^\pm \mu^\pm$	1.6	[6]	SS dilepton	0.98	[14]
	$t\bar{t} \rightarrow 2l$	1.04	[7]	OS dilepton	0.98	[15]
	$t\bar{t} \rightarrow 1l$	1.04	[8]	$Z \rightarrow l^\pm l^\mp$	0.98	[16]



ATLAS CONF 2011 - 098 (Jets + MET + b) 830 1/pb

$\sigma_{\text{production}}(pp \rightarrow t_1 t_1)$ [pb] vs estimated Efficiency (%)



direct **sbottom** prod':

$N_{\text{jet}} > 2$!

low acceptance

direct **stop** production:

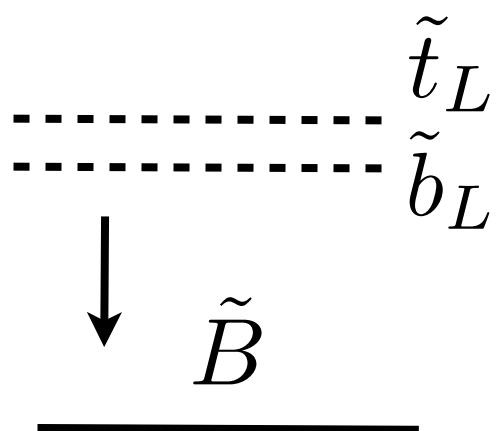
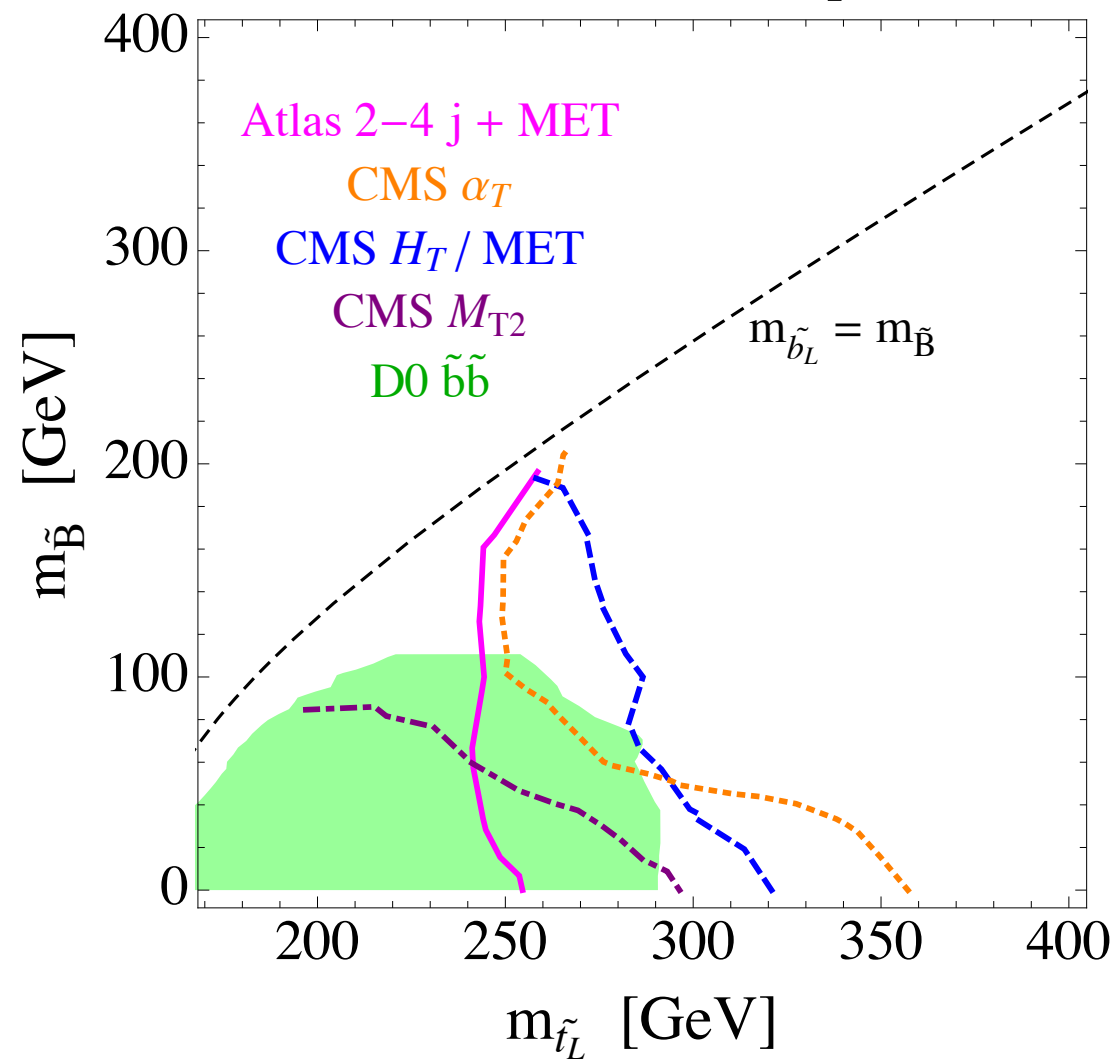
M_{eff} built from 3 leading jets

$\rightarrow M_{\text{eff}} < 2m_{\text{stop}} \rightarrow$ low $\epsilon \cdot A$
even for 300 GeV stops
($\sim 150 \text{ GeV}$ "lost")

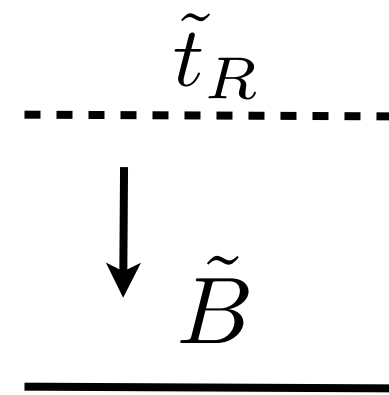
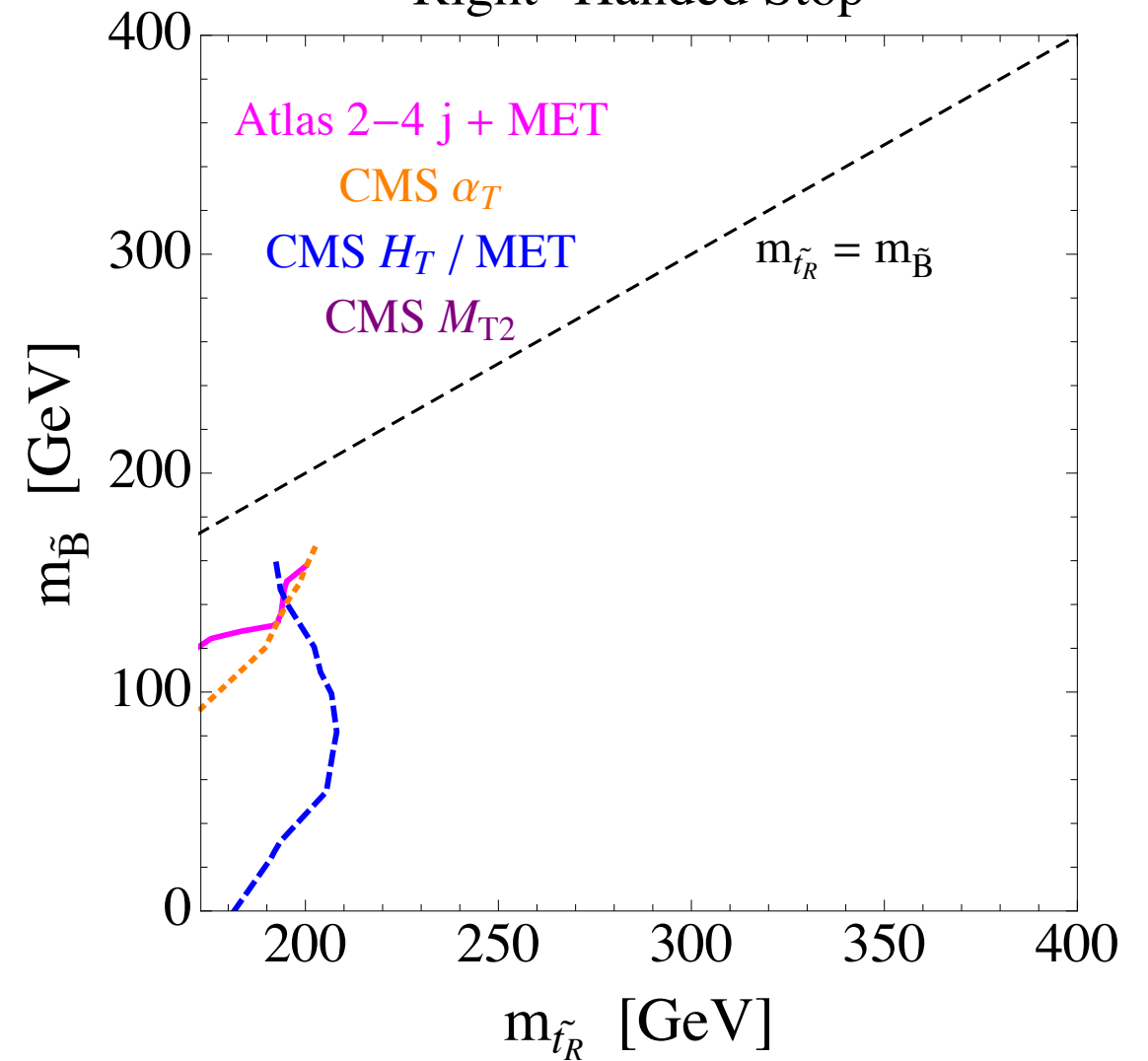
stop_l = stop_R, $\chi_0 = 50 \text{ GeV}$, $\mu = 200 \text{ GeV}$

stop limits

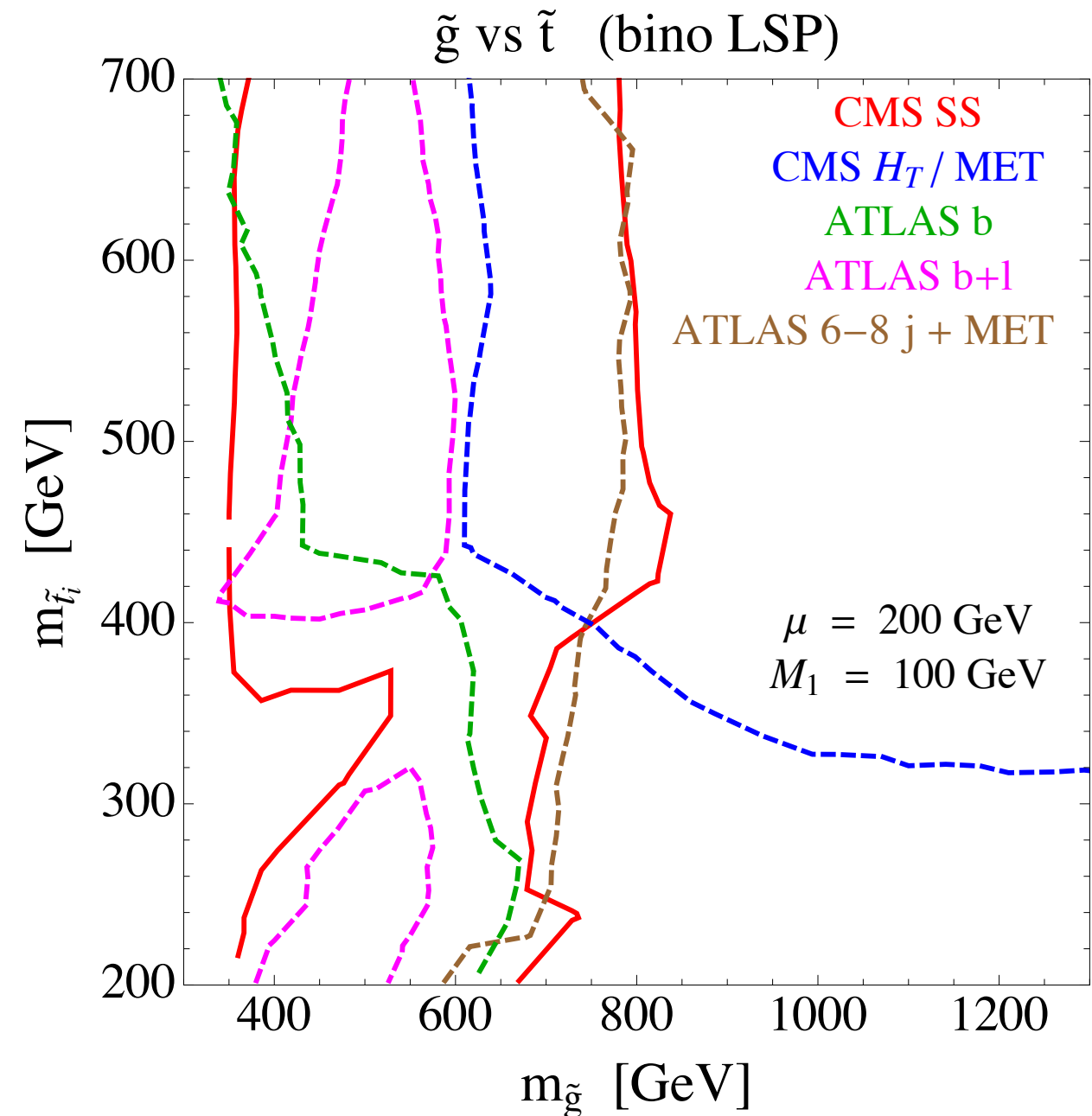
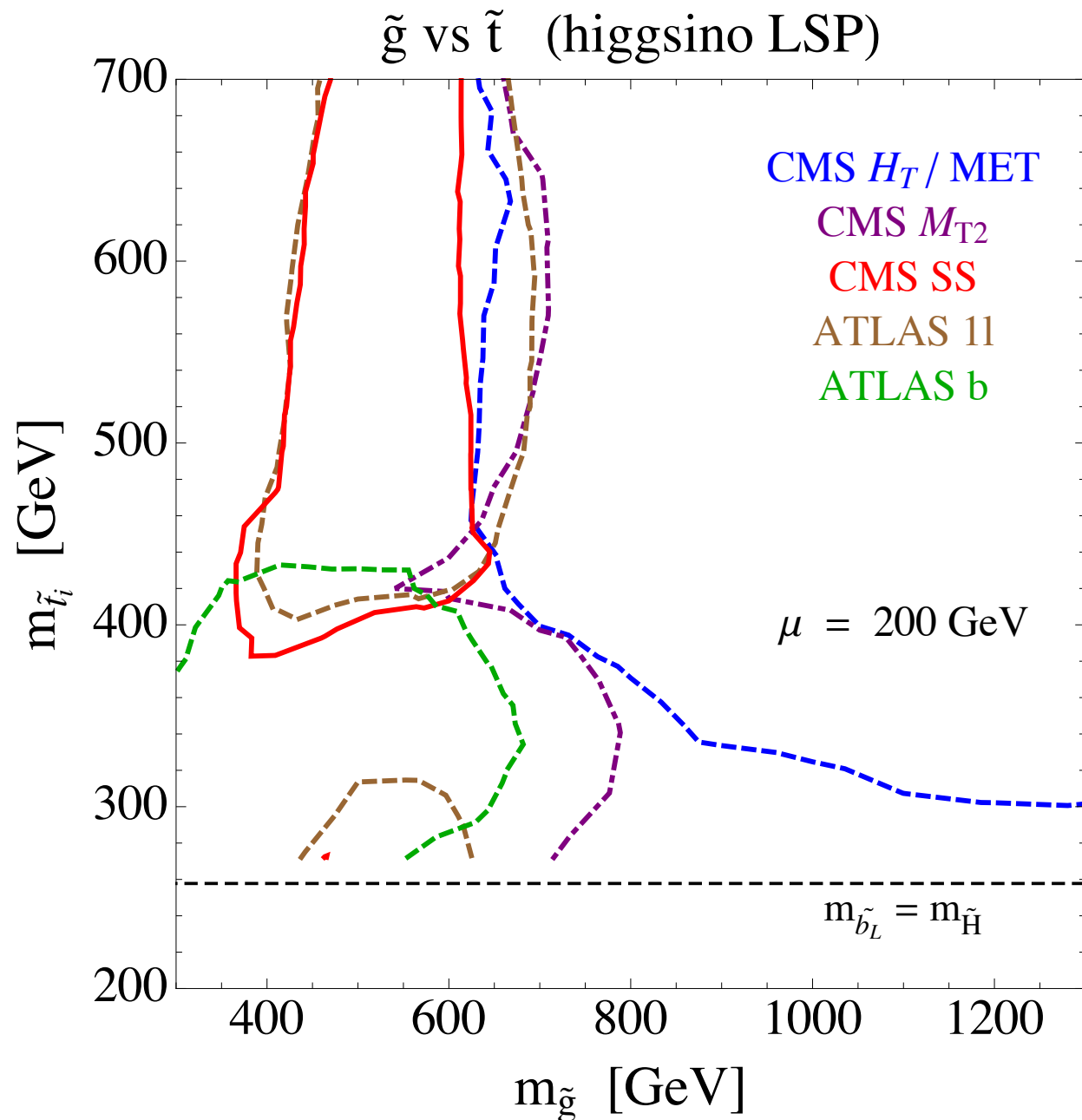
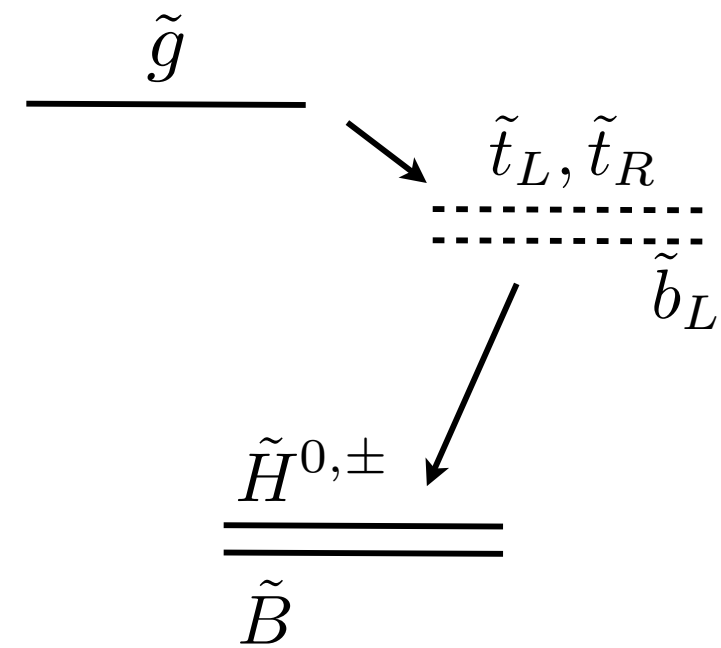
Left-Handed Stop



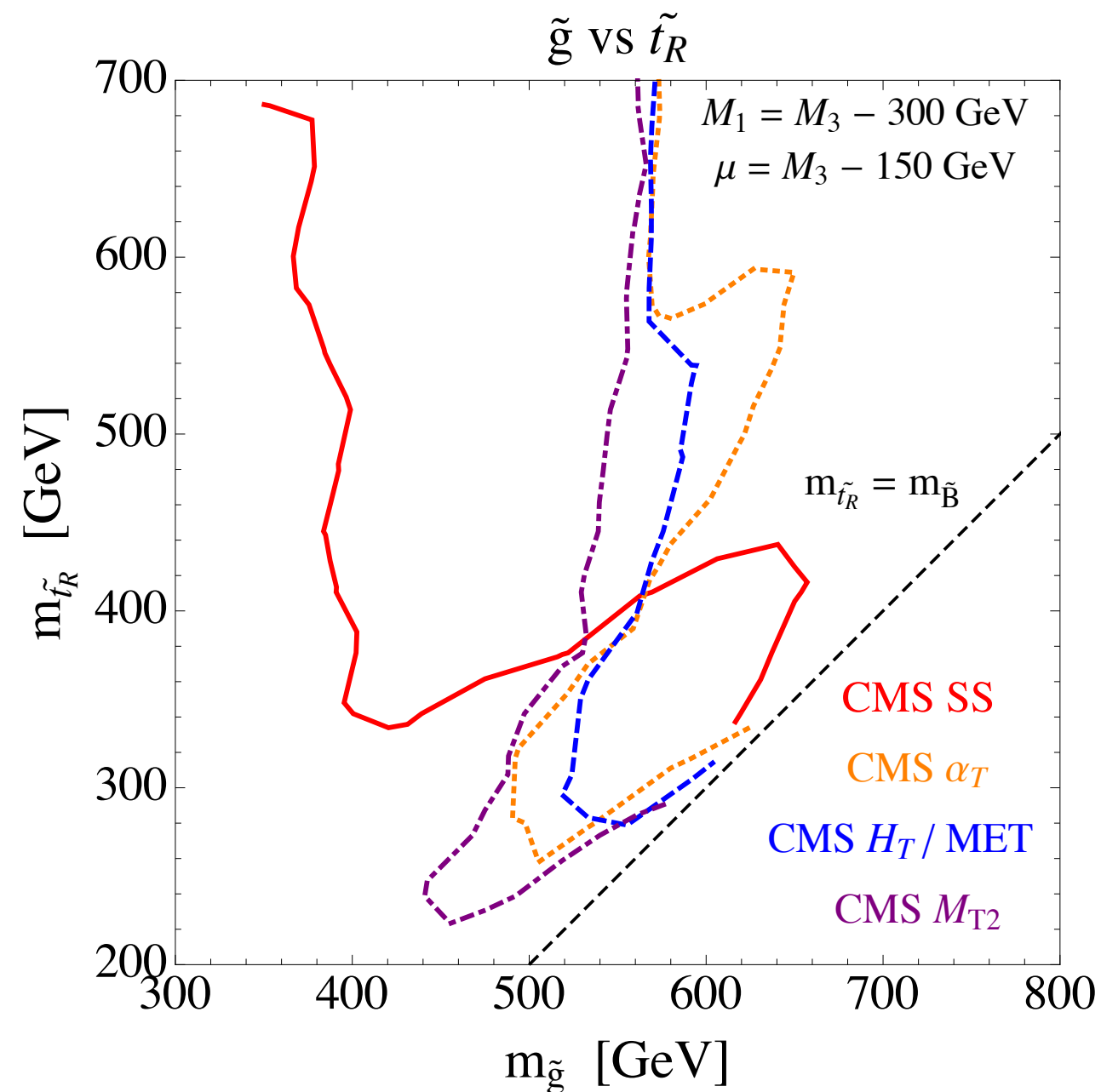
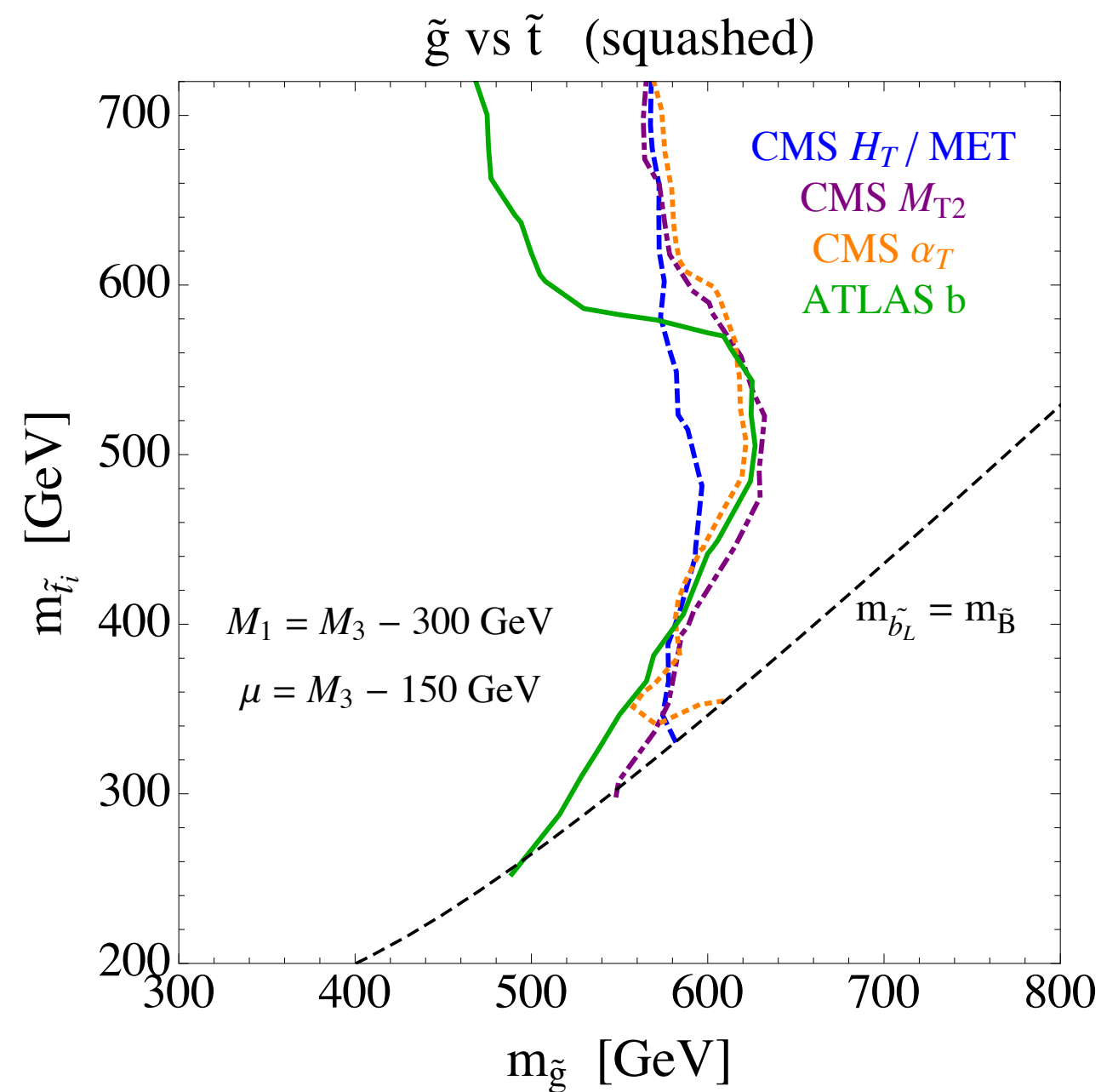
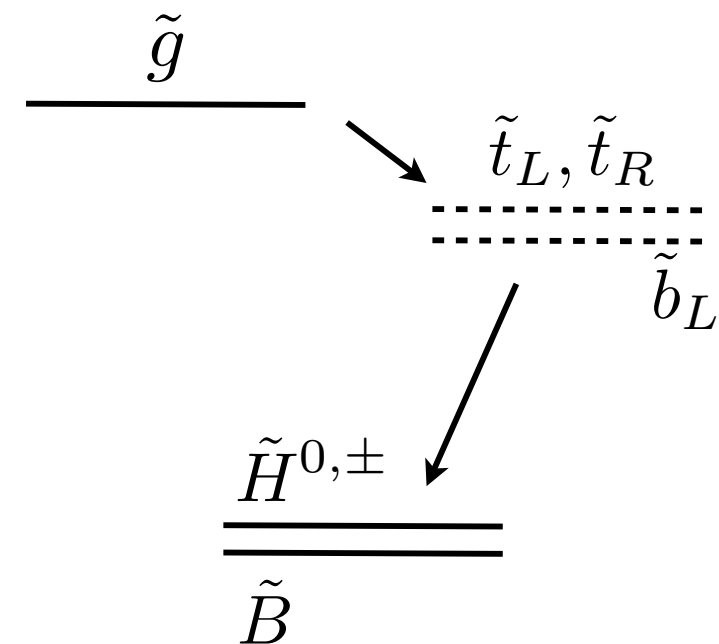
Right-Handed Stop



stop vs. gluino



Squashed spectrum



Some requests/remarks

Please

- Always publish digital representation of results (root macros), see eg. <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS11006>
- Always define your kinematical variables H_T , M_{eff} , ... in the paper/website
- include slha files (+ generator parameters) for the shown benchmarks
- find something.

Simplified models

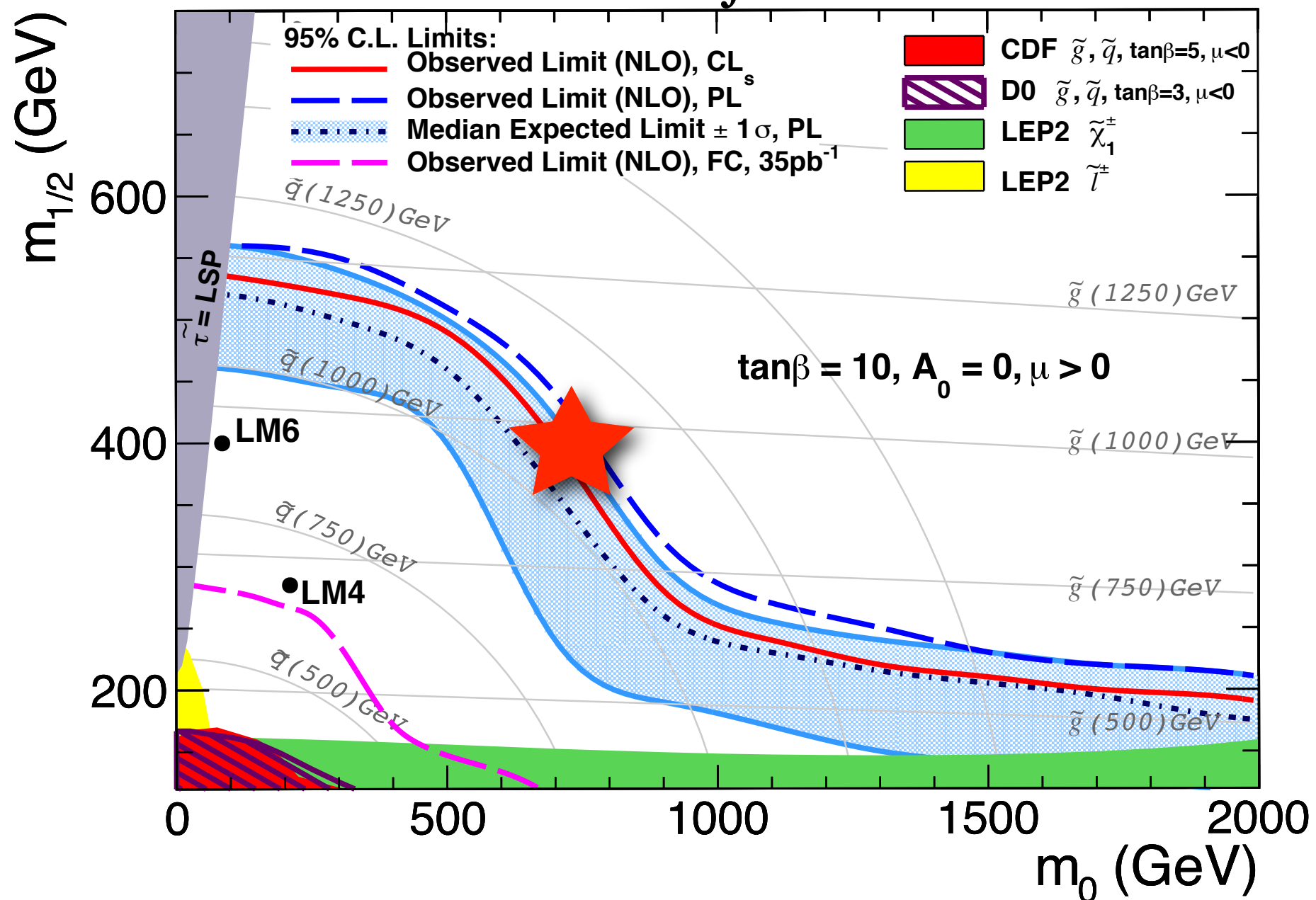
- Good for theorists that can't run MC's
- Works against model prejudice in e.g. susy parameter space
- Very good to calibrate (see next slides)

CMS preliminary

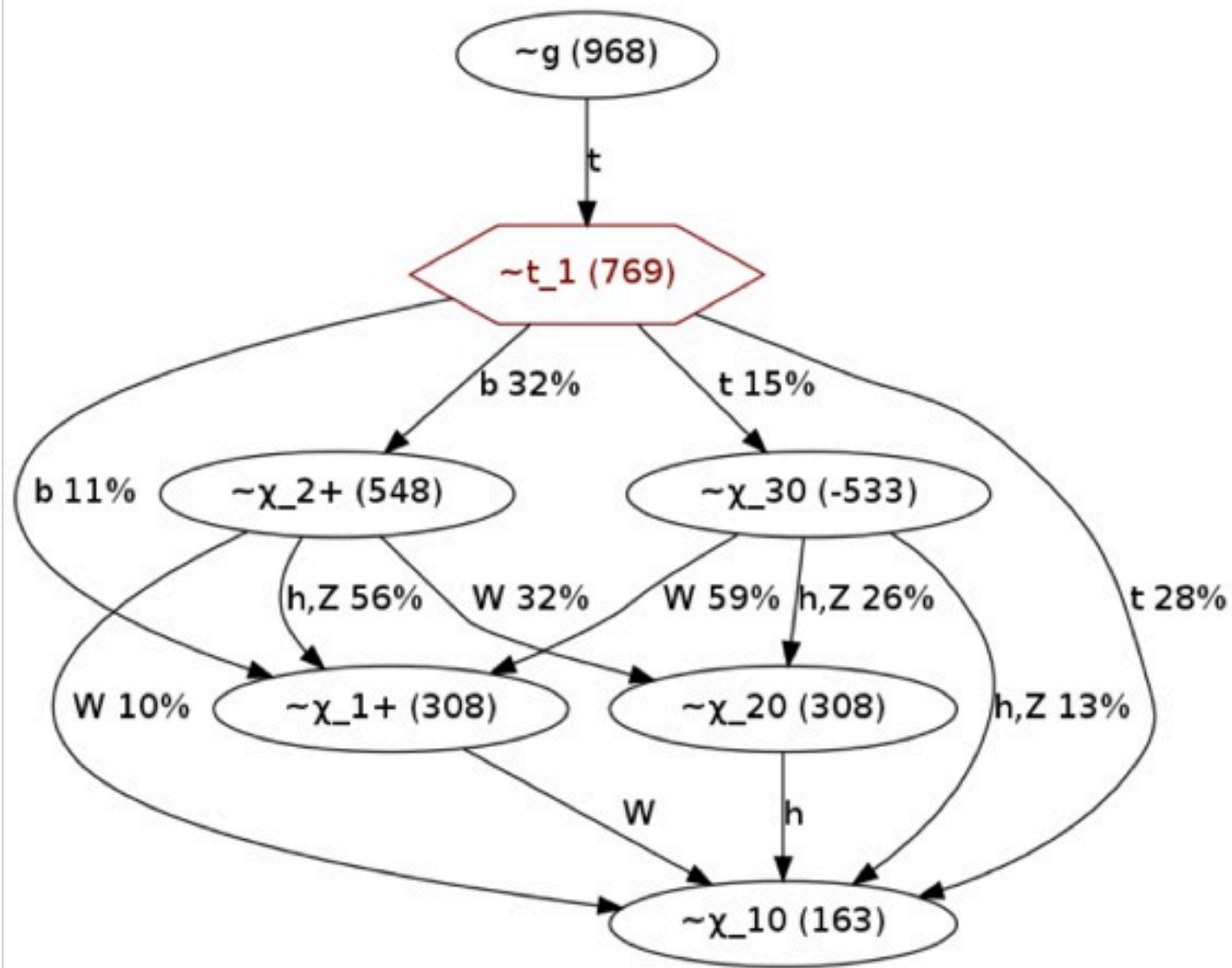
α_T

$\int \mathcal{L} dt = 1.1 \text{ fb}^{-1}$

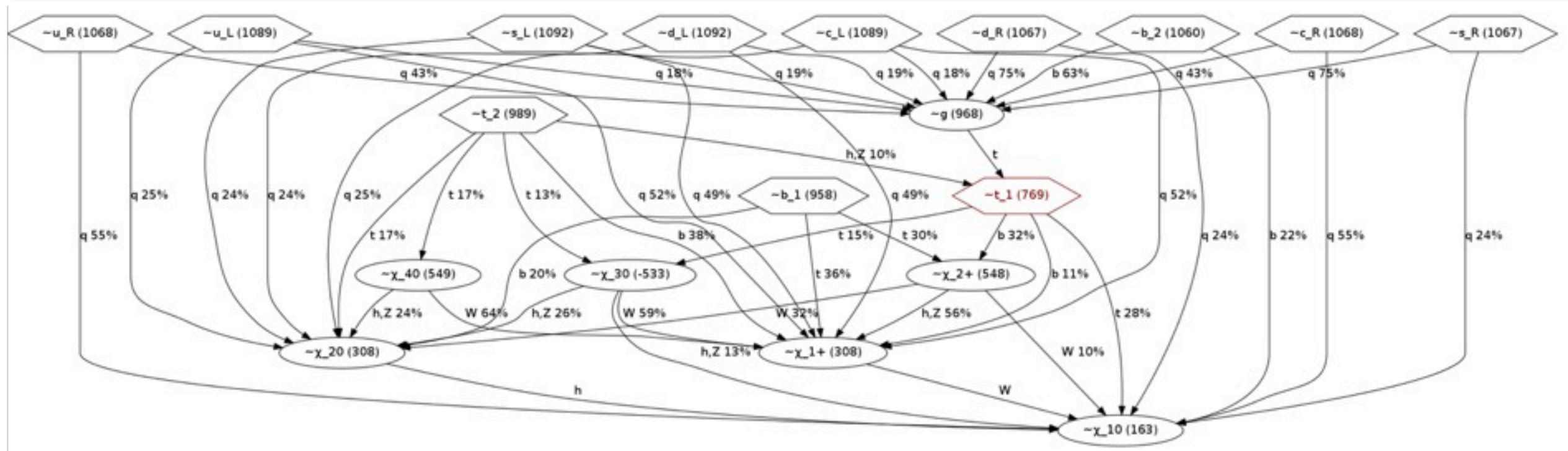
$\sqrt{s} = 7 \text{ TeV}$



Implications beyond CMSSM?



!?



http://www.hephy.at/user/walten/msugra/html/400_700_0_10_1_1.html

What happened here?

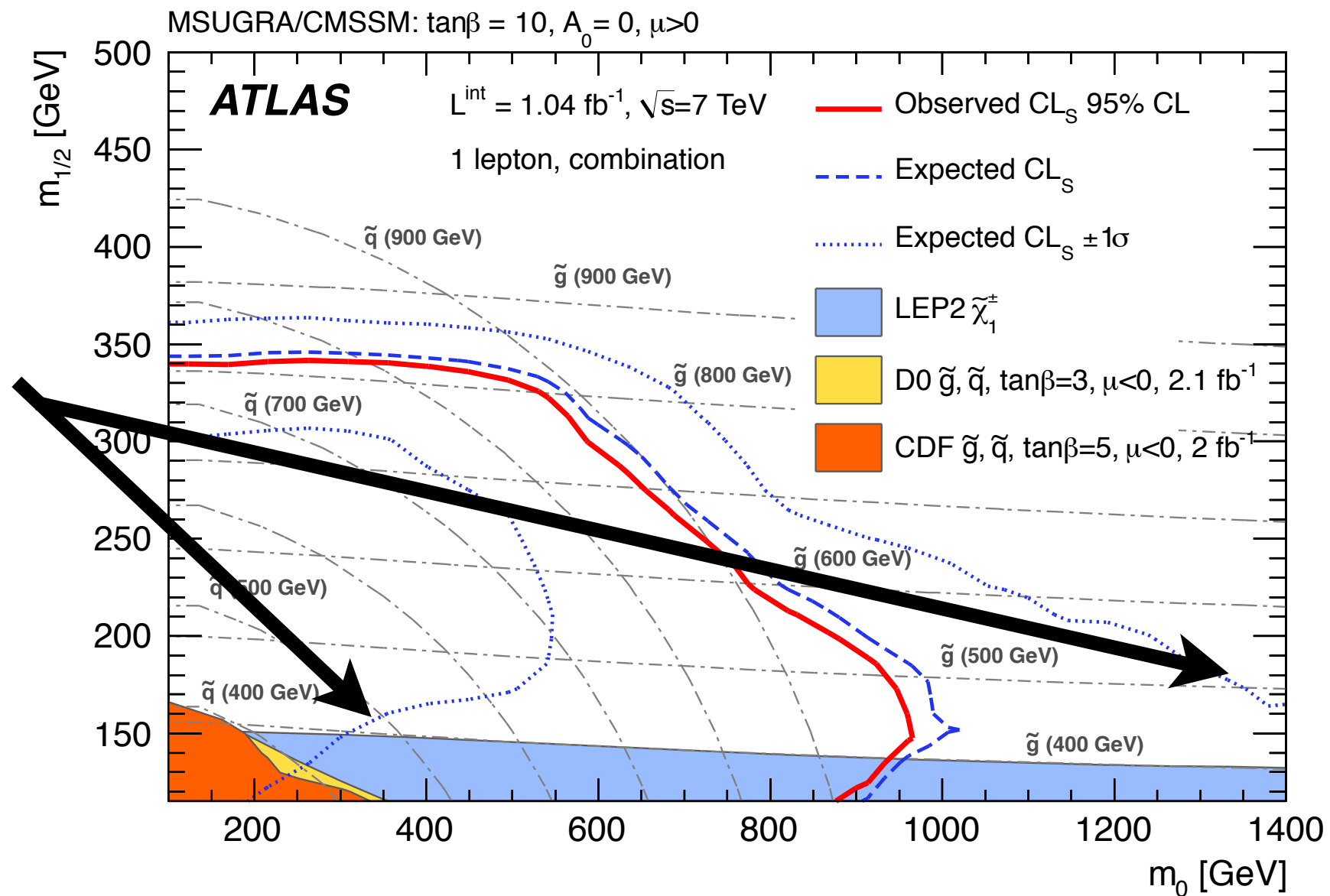
$1\sigma?$ 

FIG. 7: Observed and expected 95% CL exclusion limits, as well as the $\pm 1\sigma$ variation on the median expected limit, in the combined electron and muon channels. The plots also show the published limits from CDF [60], D0 [61], and the results from the LEP experiments [62].

- When multiple channels contribute to an exclusion and you take the best one for each parameter point to derive the limit -- is it the best observed or best expected?

Tuning in the MSSM

$$m_{h^0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\text{stop}}^2}{m_t^2}$$

Tuning in the MSSM

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Negative search at LEP: $m_H > 114 \text{ GeV}$

Therefore need $m_{\text{stop}} \sim \mathcal{O}(1 \text{ TeV})$.

But at minimum,

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But at minimum,

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

Tuning in the MSSM

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$$\delta m_{H_u}^2(\text{loop}) = -\frac{3y_t^2}{8\pi^2} m_{\text{stop}}^2 \ln \frac{\Lambda^2}{m_{\text{stop}}^2} \approx 600 \cdot \frac{m_Z^2}{2}$$

Tuning in the MSSM

$$m_{h^0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\text{stop}}^2}{m_t^2}$$

Negative search at LEP: $m_H > 114 \text{ GeV}$

Therefore need $m_{\text{stop}} \sim \mathcal{O}(1 \text{ TeV})$.

But at minimum,

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

Little Hierarchy problem

$$\delta m_{H_u}^2(\text{loop}) = -\frac{3y_t^2}{8\pi^2} m_{\text{stop}}^2 \ln \frac{m_{\text{stop}}^2}{m_t^2} \approx 600 \cdot \frac{m_Z^2}{2}$$

$$\delta m_{H_u}^2(\text{loop}) = -\frac{3y_t^2}{8\pi^2} m_{\text{stop}}^2 \ln \frac{\Lambda^2}{m_{\text{stop}}^2}$$

o Raise tree-level Higgs mass ? m_{stop} reduced !

a) F-Term (NMSSM)

b) D-term (extended gauge structure)

$$\delta m_{H_u}^2(\text{loop}) = -\frac{3y_t^2}{8\pi^2} m_{\text{stop}}^2 \ln \frac{\Lambda^2}{m_{\text{stop}}^2}$$

- o Raise tree-level Higgs mass ? m_{stop} reduced !
 - a) F-Term (NMSSM)
 - b) D-term (extended gauge structure)
- o Lower the cut-off ?
 - c) NMSSM (large SH_uH_d coupling $\Rightarrow \Lambda_{\text{Landau}} \ll M_{\text{Gut}}$)
 - d) Find rationale why $\Lambda = (\text{protection scale } f) \sim O(\text{TeV})$
(i.e. little Higgs like protection)