Directions for New Physics

Ben Allanach[a] (University of Cambridge)

[a] BCA, Gripaios, 1202.6616; BCA, Sridhar 1205.5170; BCA, Parker 1211.3231.

Hierarchy problem solved

The supersymmetric copies *cancel* the quantum fluctuations. (This is a *very* difficult problem to solve). Not only that, the model contains a dark matter candidate the neutralino χ_1^0:

- Weakly interacting
- Stable
- Massive

To predict how much of it is around today, we must make assumptions on our *cosmology*, and on the *particle physics*. If we can measure the particle physics, we have a handle on the cosmology.

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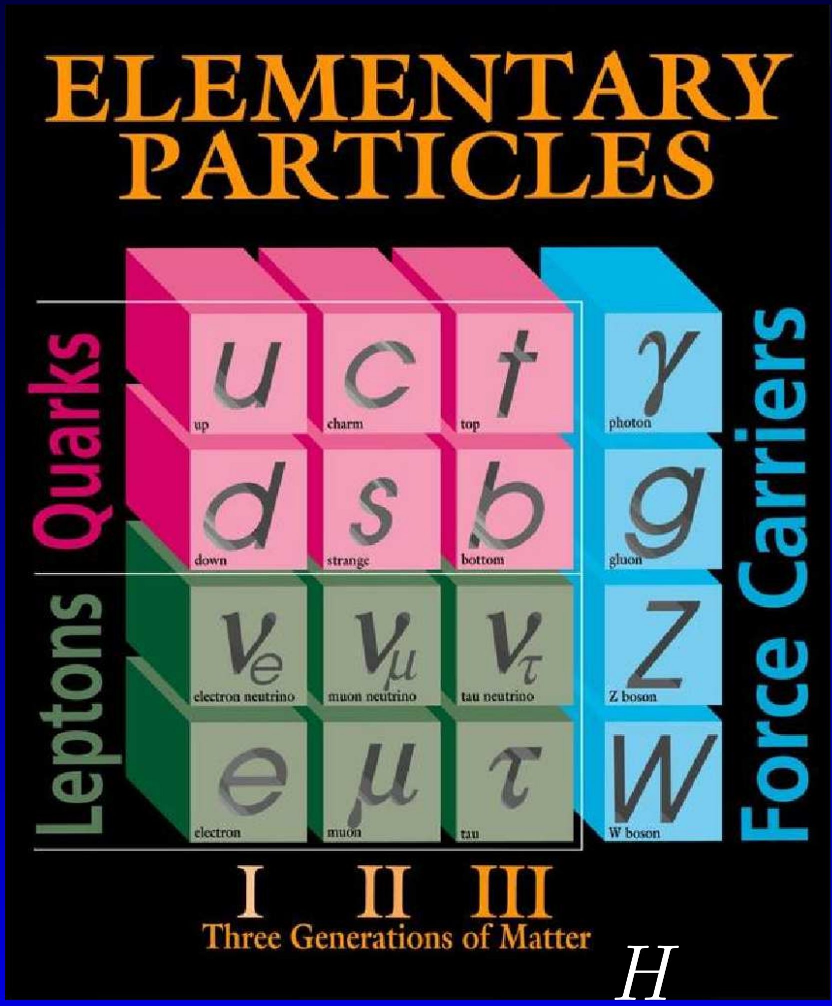
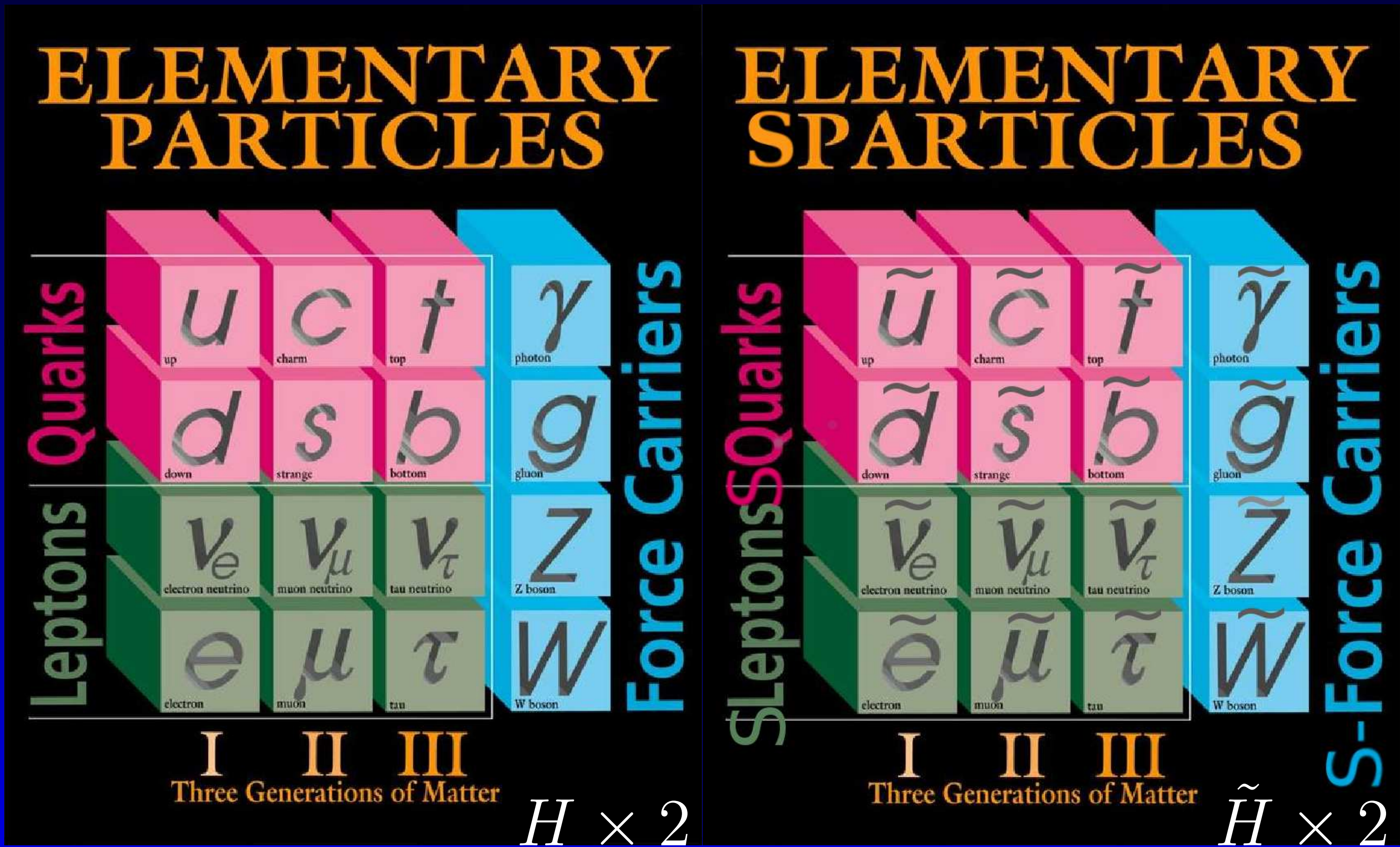


Supersymmetric Copies



Review of R-Parity

The superpotential of the MSSM can be seperated into two parts:

$$
\begin{aligned}
W_{R_p} &= h^e_{ij} L_i H_1 \bar{E}_j + h^d_{ij} Q_i H_1 \bar{D}_j \\
&\quad + h^u_{ij} Q_i H_2 \bar{U}_j + \mu H_1 H_2, \\
W_{\not{R}_P} &= \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k \\
&\quad + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2.
\end{aligned}
$$

W_{R_p} is what is usually meant by the MSSM.

$\mathcal{Q}$: Why ban $W_{\not{R}_P}$?

$\mathcal{A}$: "Proton decay"

Definition of R-Parity

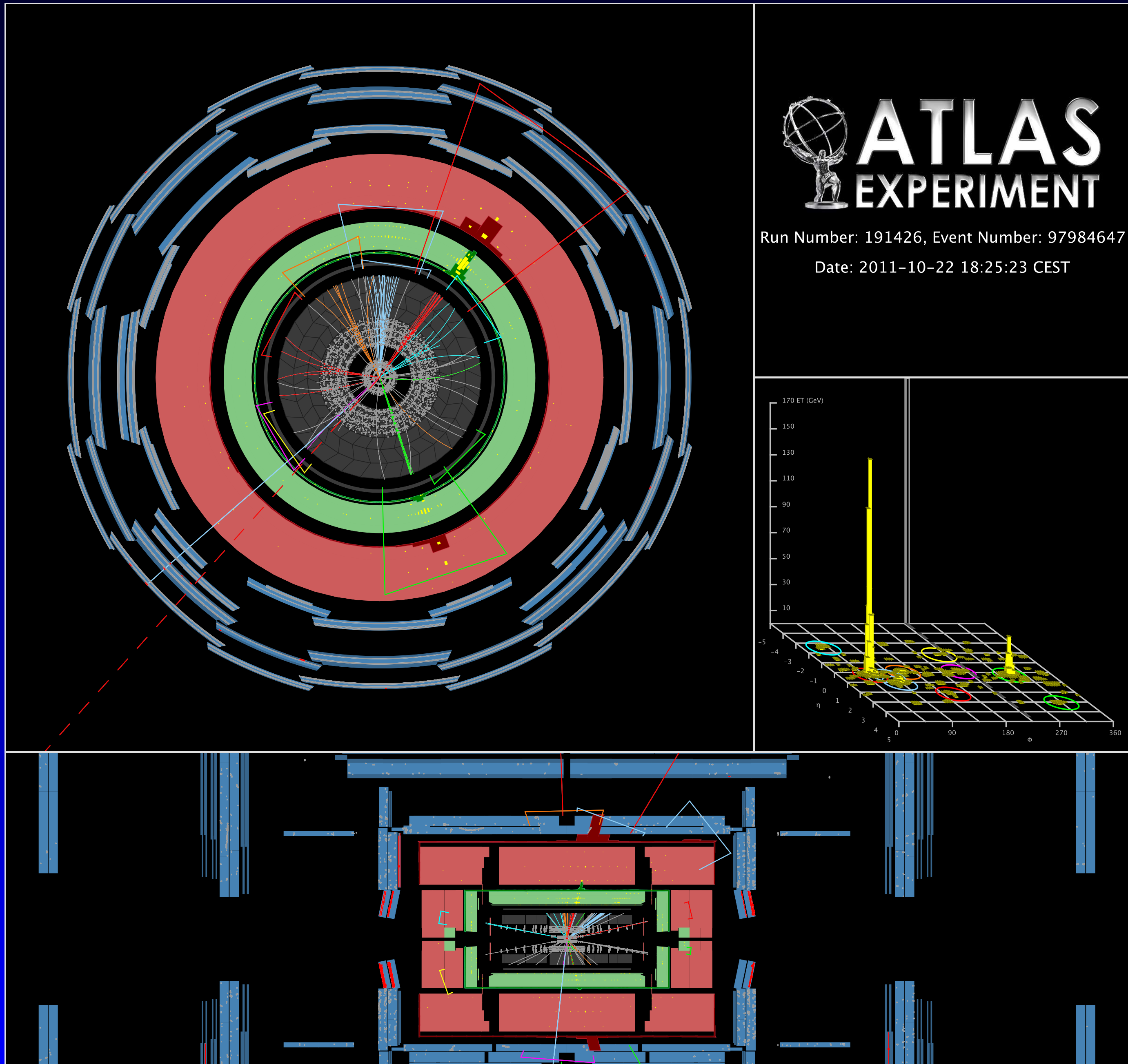
$\mathcal{Q}$: How is $W_{\not R_P}$ normally banned?
$\mathcal{A}$: By defining discrete symmetry R_p

$$R_p = (-\mathbf{1})^{3B+L+2S}.$$

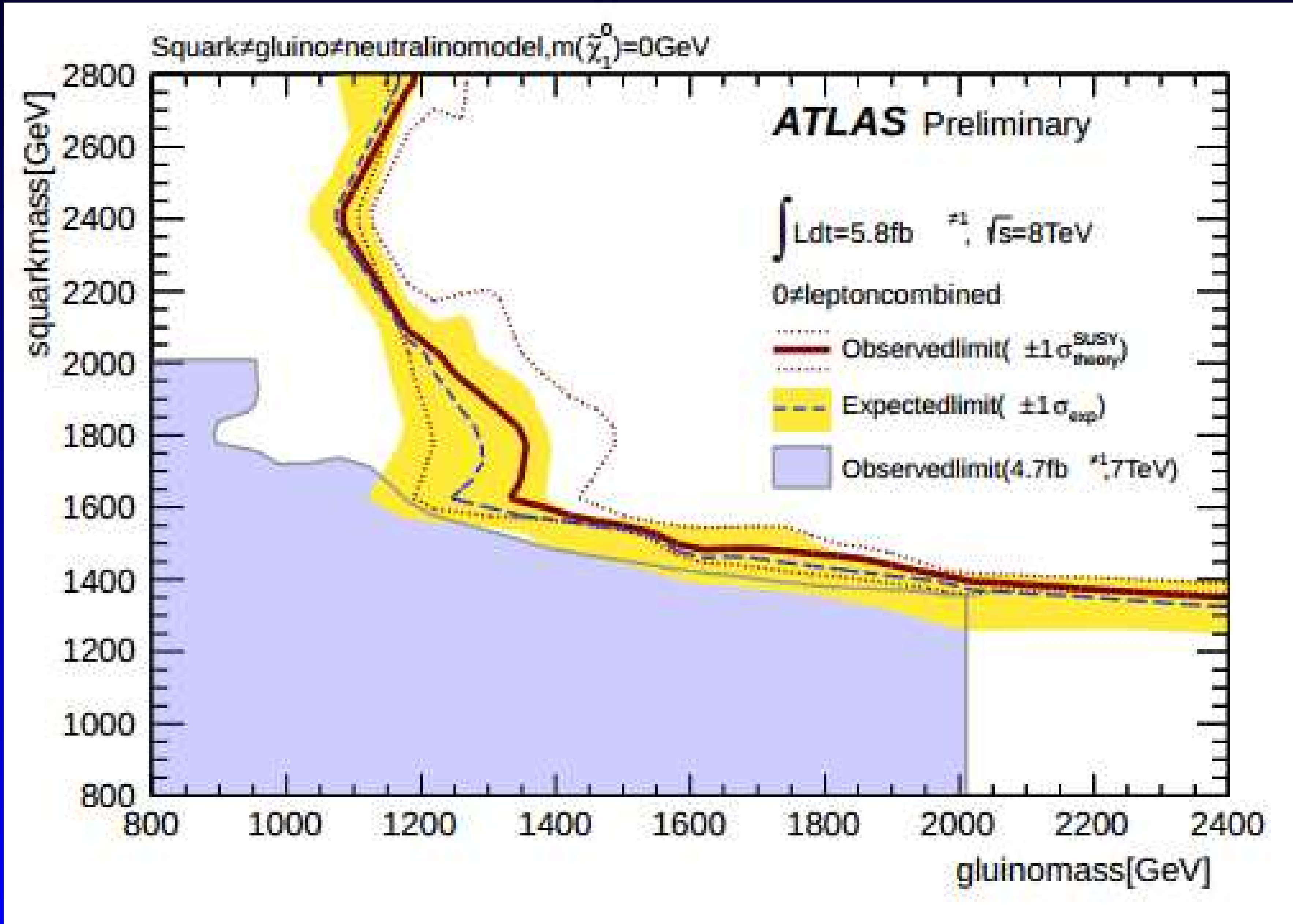
$\rightarrow$ SM fields have $R_p = +1$ and superpartners have $R_p = -1$. There are two important consequences:

- Because initial states in colliders are R_p EVEN, we can only pair produce SUSY particles
- The *lightest superpartner is stable*

Candidate Event: High $E_T(j)$



Jets Plus $\not\!\!E_T$ Search



EWSB in the MSSM

Minimisation of MSSM Higgs potential yields the constraint:

$$\mu^2 = \frac{\tan 2\beta}{2} \left[m_{H_2}^2 \tan\beta - m_{H_1}^2 \cot\beta \right] - \frac{M_Z^2}{2}.$$

For successful EWSB, $\mu^2 > 0$, i.e.

$$\left[m_{H_2}^2 (M_{SUSY}) \tan\beta - m_{H_1}^2 (M_{SUSY}) \cot\beta \right] < \frac{M_Z^2}{\tan 2\beta}.$$

RGEs of EWSB

$$16\pi^2\frac{\partial m^2_{H_2}}{dt} = 6\left[(m^2_{H_2}+m^2_{\tilde{Q}_3}+m^2_{\tilde{u}_3}+A_t^2)h_t^2\right] - 6g_2^2M_2^2$$
$$-\frac{6}{5}g_1^2M_1^2+\frac{3}{5}g_1^2\left(m^2_{H_2}-m^2_{H_1}+\right.$$
$$\left.\mathrm{Tr}[m^2_{\tilde{Q}}-m^2_{\tilde{L}}-2m^2_{\tilde{u}}+m^2_{\tilde{d}}+m^2_{\tilde{e}}]\right),$$

where $t=\ln Q$.

$$h_t(M_Z) = \frac{\sqrt{2}\,m_t(M_Z)}{v(M_Z)\sin\beta(M_Z)},$$

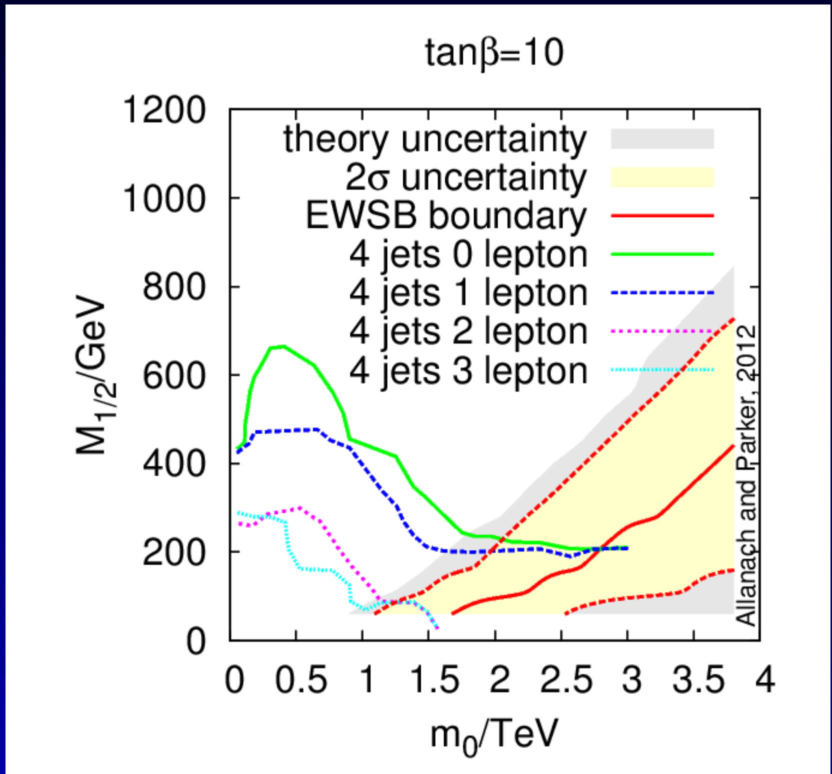
Approximate Solution

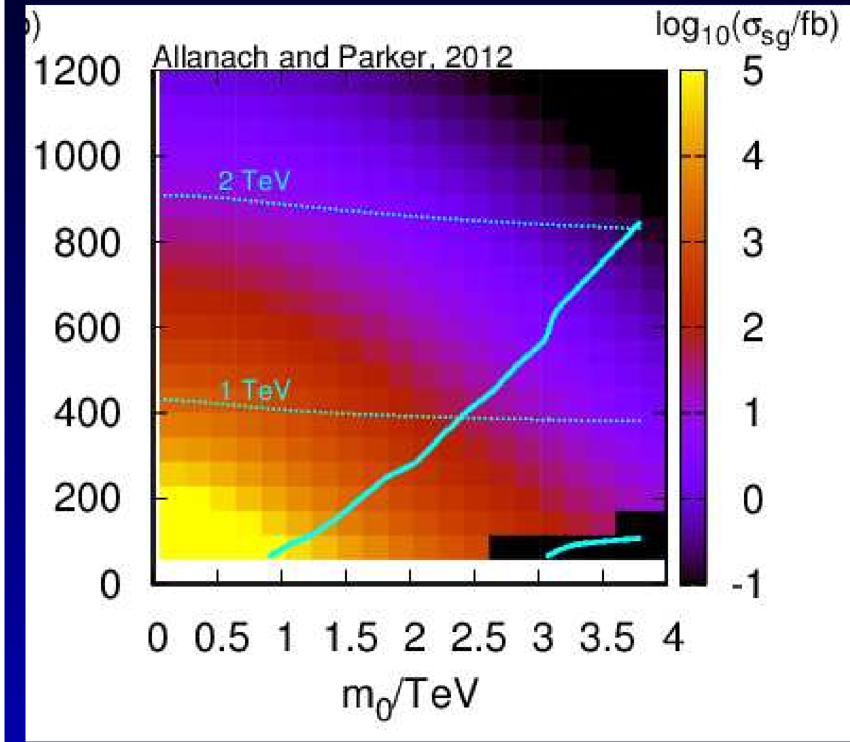
$$
\begin{aligned}
m_{H_2}^2(M_{SUSY}) &= m_{H_2}^2(M_X) - A\left(6\left[m_{H_2}^2(M_X)\right.\right. \\
&\quad + m_{\tilde{Q}_3}^2(M_X) + m_{\tilde{u}_3}^2(M_X) + \\
&\quad \left.\left. A_t^2(M_X)\right] h_t^2(M_X)\right),
\end{aligned}
$$

where $A = \log(M_X/M_{SUSY})/(16\pi^2)$. Plug into our $\mu^2 > 0$ condition, then at M_X:

$$
\begin{aligned}
m_{H_2}^2 &< \frac{1}{1-6Ah_t^2}\left\{6Ah_t^2\left(m_{\tilde{Q}_3}^2 + m_{\tilde{u}_3}^2 + A_t^2\right) + \frac{M_Z^2}{\tan\beta\ \mathrm{ta}\ldots}\right. \\
&\quad \left. \frac{1}{\tan^2\beta}\left[m_{H_1}^2 - 6Ah_b^2(m_{\tilde{Q}_3}^2 + m_{\tilde{d}_3}^2 + A_b^2)\right]\right\},
\end{aligned}
$$

EWSB in the CMSSM at 14 TeV, $1\ \mathrm{fb}^{-1}$, $5\ \sigma$





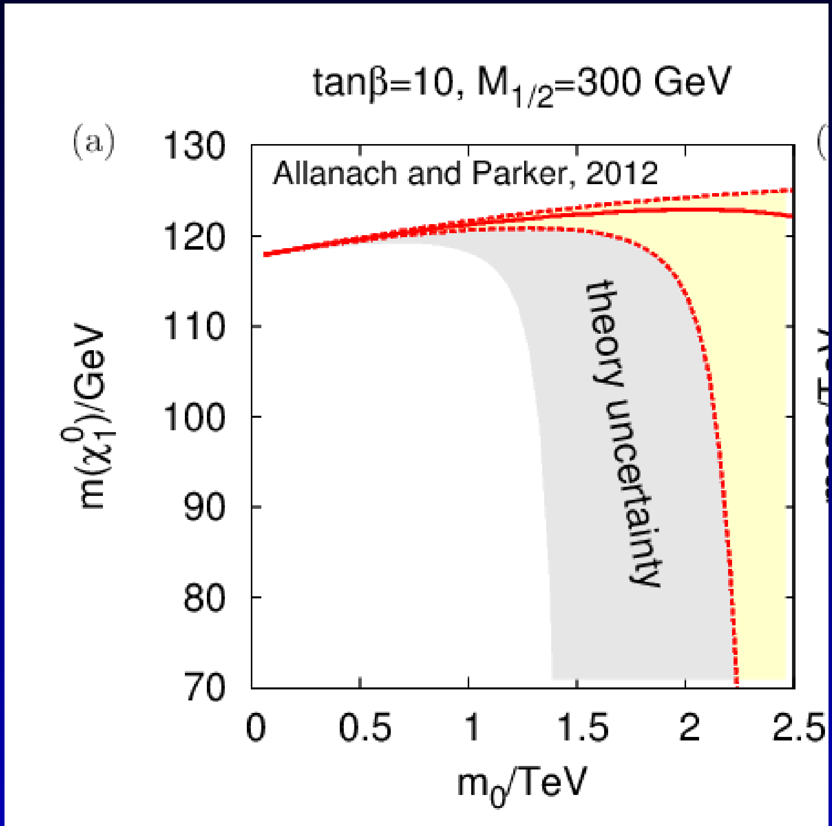
The position of the EWSB boundary is extremely uncertain due to the error in $m_t = 172.5 \pm 1$ GeV. *Experiments should use the higher value (plus theory error) when making grids of MSSM spectra*[a]

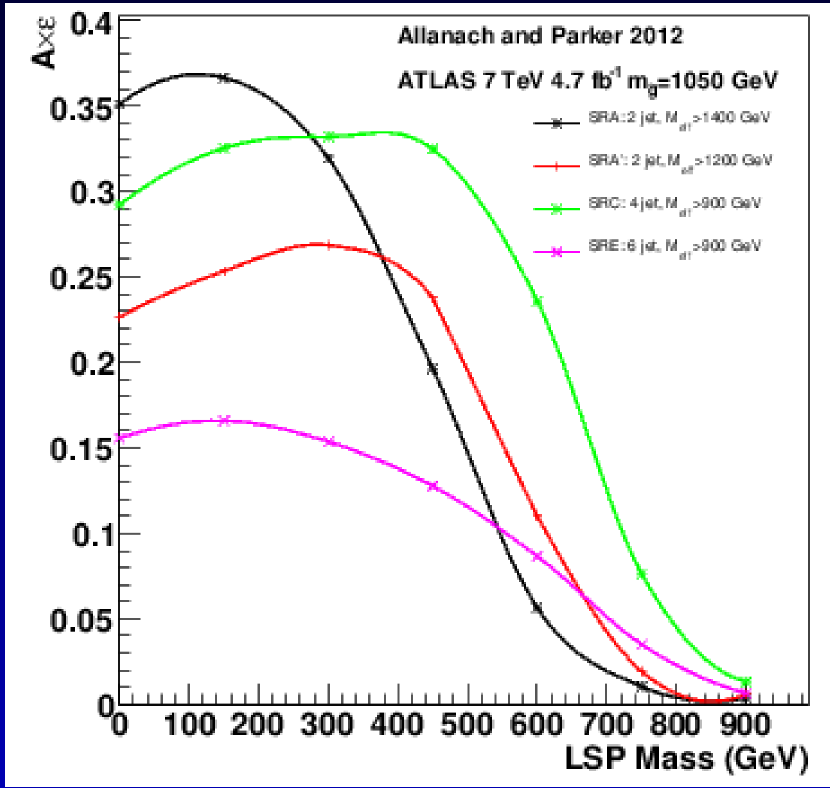
[a] BCA, Parker 1211.3231

Extreme Dependence on m_t

- This extreme dependence on m_t can happen in *models with high scale boundary conditions* - not just the CMSSM.
- It affects particle masses, and hence theoretical uncertainties etc.
- However, this uncertainty does not affect low-scale models such as the pMSSM (or simplified models).

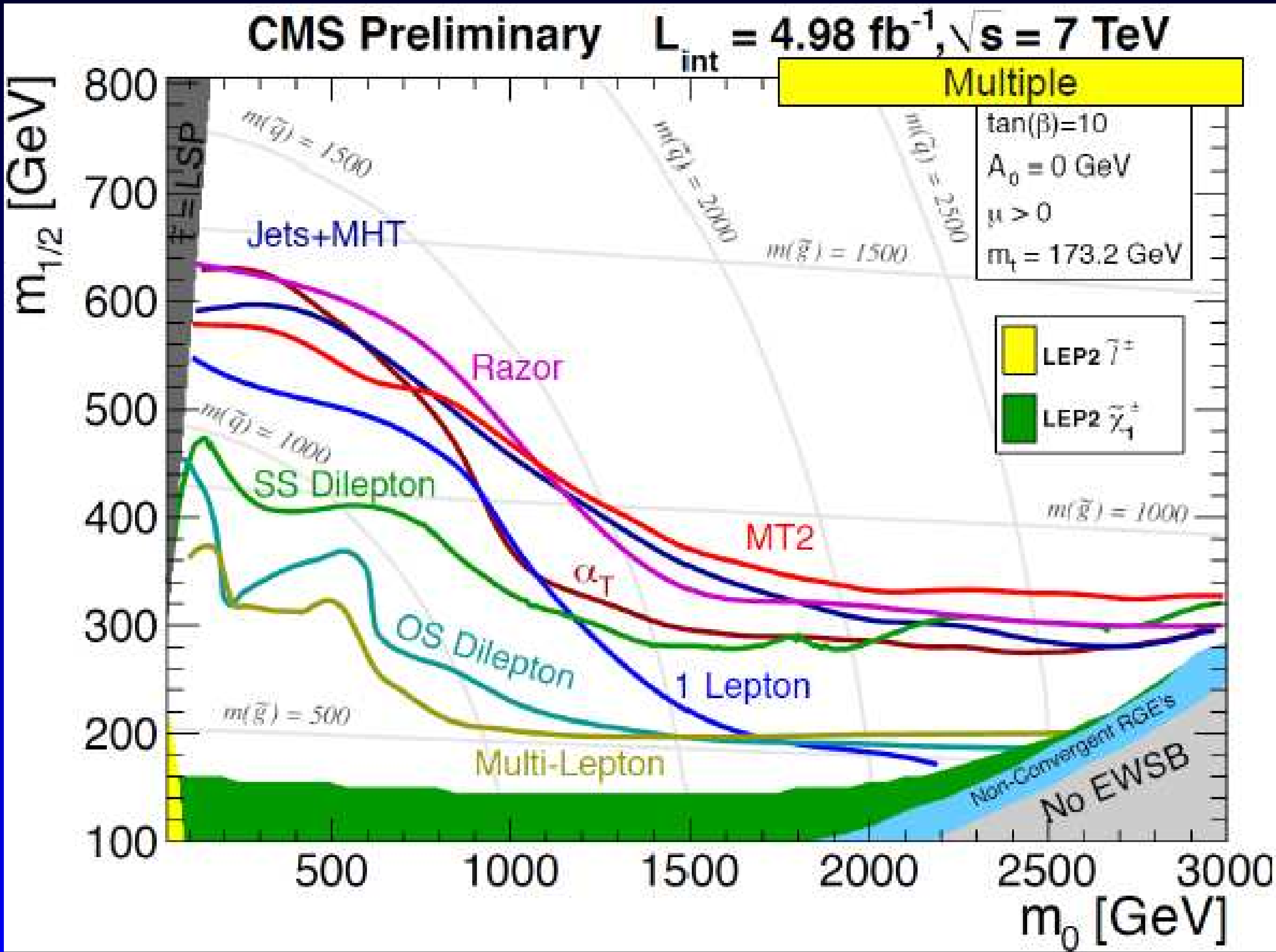
Neutralino Mass





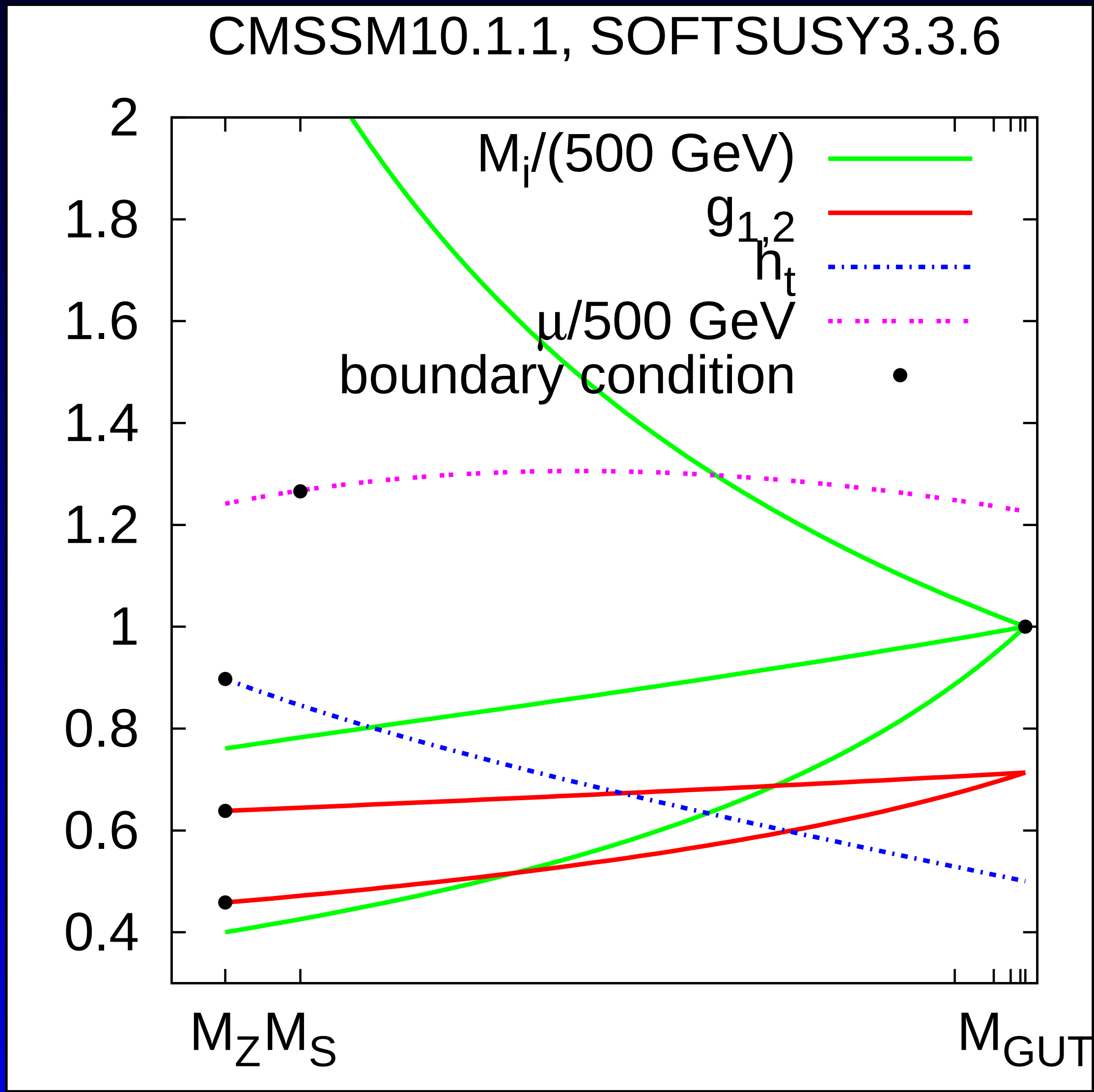
For a given value of m_t, on the boundary the LSP mass goes to 0. Therefore, for a given point in parameter space in the dodgy region, there is a 100% uncertainty in its mass $\Rightarrow$a theoretical error.

Bad convergence?



What is the "Non-convergent RGE region"?

2 Boundary Problem



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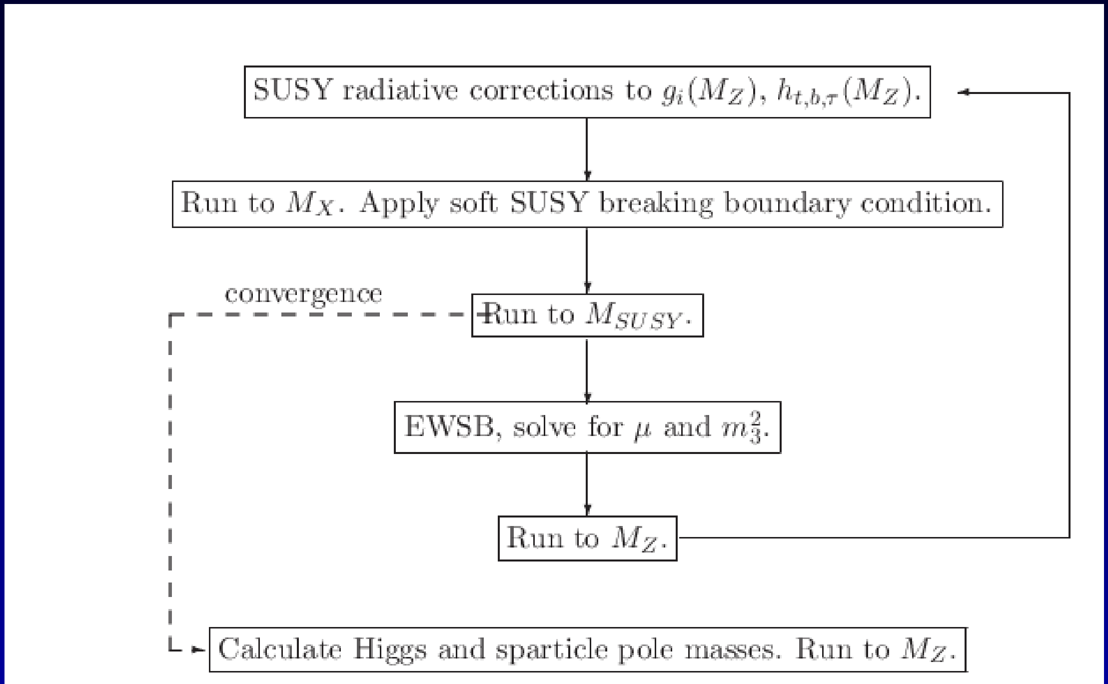
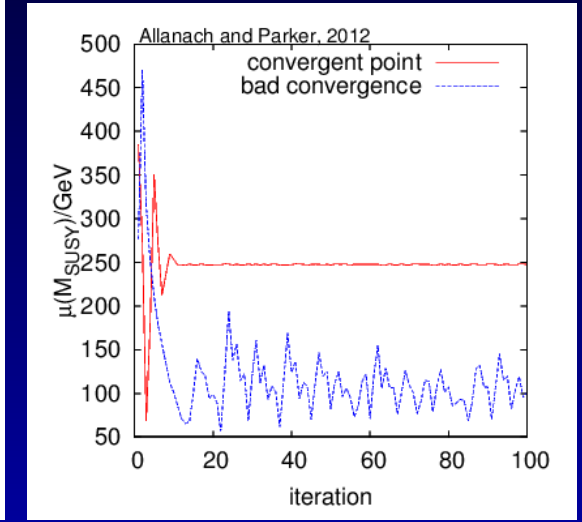
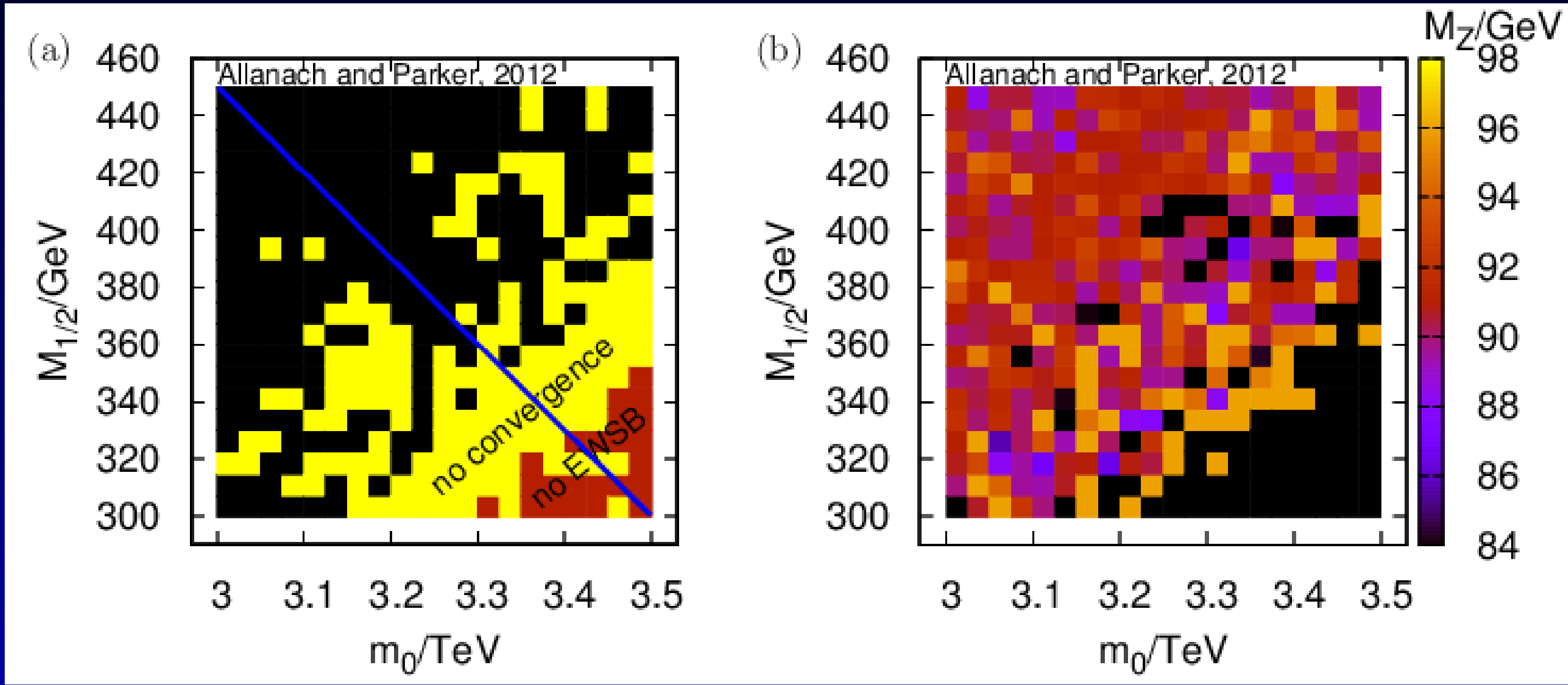


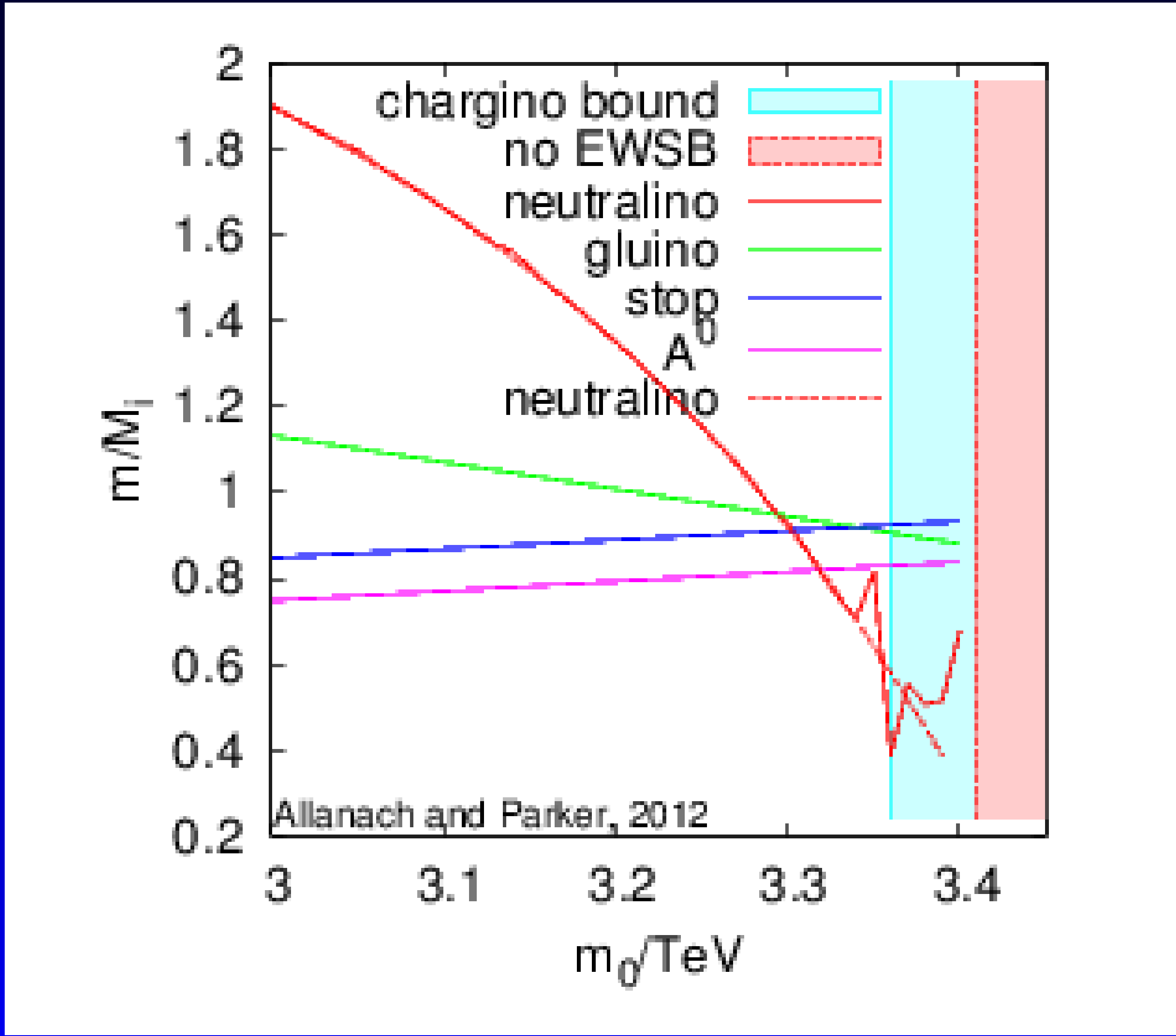


Previously, convergence criteria based on SUSY parameters converging iteration by iteration. But there is an absolute criterion: M_Z^2.

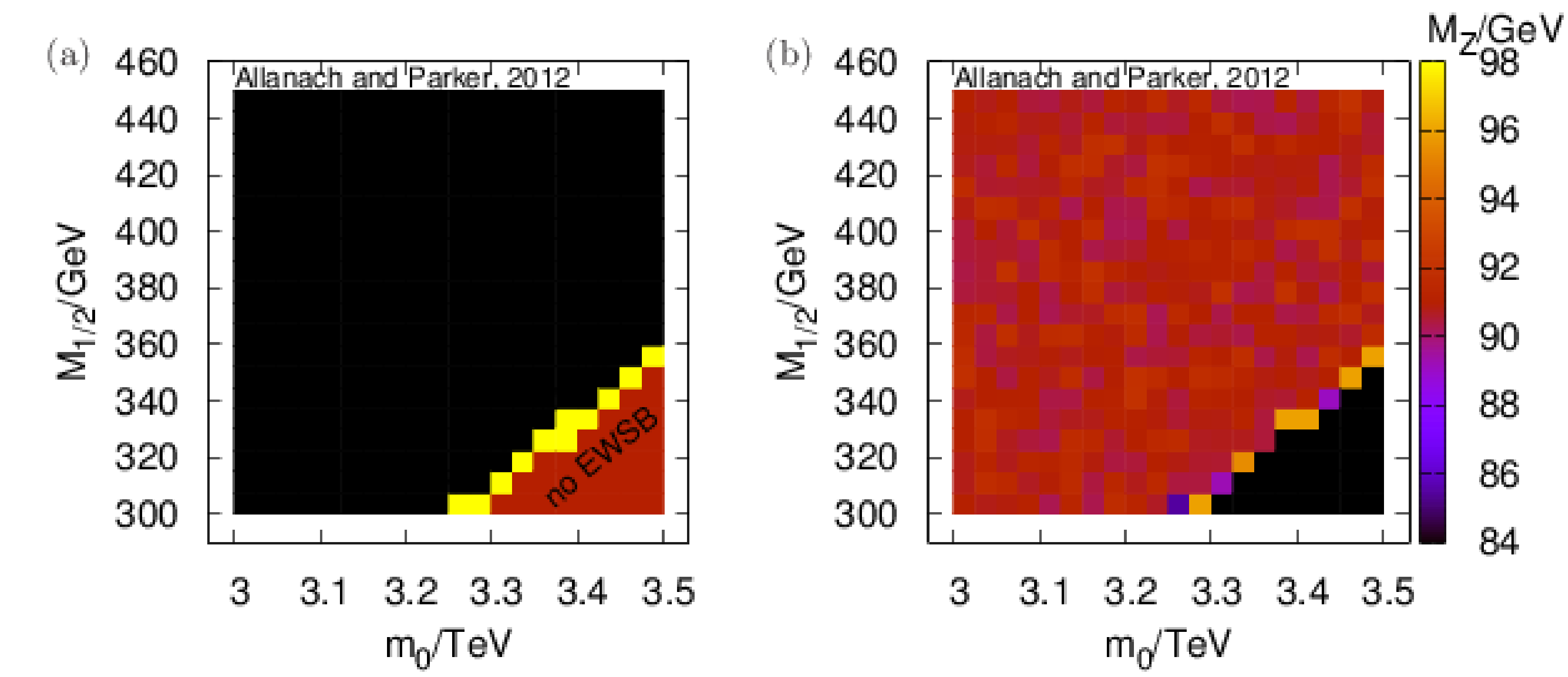
Bad convergence region



Masses On The Blue Line



Tweaked up convergence



Iteration proceeds also until M_Z converges.
Sub-iterations made more accurate, and iteration of μ is damped.

Recommendations for searches

- When devising grids of SUSY particle masses for exclusions, generate the masses at $m_t + 2\sigma$.
- Include a parameteric variation of m_t when estimating theory errors in SUSY in (or near) the uncertain region.
- Use the more recent version of SOFTSUSY with improved convergence criteria.

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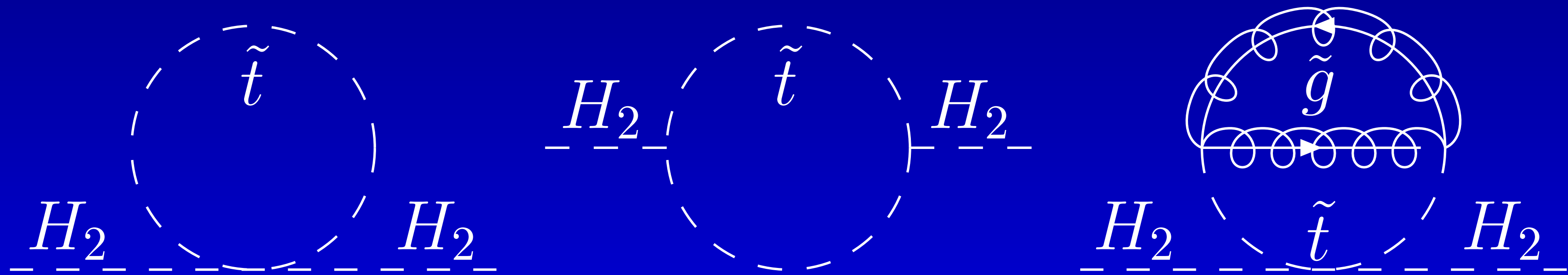
Natural SUSY

The particles coupling the most strongly to the higgs are the *stops*[a]. Minimising the MSSM Higgs potential,

$$-\frac{M_Z^2}{2} \approx |\mu|^2 + m_{H_2}^2,$$

$$\delta m_{H_2}^2 \approx \frac{-3h_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda_{UV}}{m_{\tilde{t}}}\right)$$



[a] M. Papucci, J. T. Ruderman and A. Weiler, `arXiv:1110.6926`; C. Brust, A. Katz, S. Lawrence and R. Sundrum, `arXiv:1110.6670`

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\delta m_{H_2}^2 &\approx \frac{-3h_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda_{UV}}{m_{\tilde{t}}}\right)
\end{aligned}
$$

No cancellation⇒

$$m_{\tilde{t}} \lesssim 700 \text{ GeV}, \qquad m_{\tilde{g}} \lesssim 1000 \text{ GeV}.$$

Experimental $\not{E}_T$ searches are probing this parameter space!

[a] M. Papucci, J. T. Ruderman and A. Weiler, `arXiv:1110.6926`; C. Brust, A. Katz, S. Lawrence and R. Sundrum, `arXiv:1110.6670`

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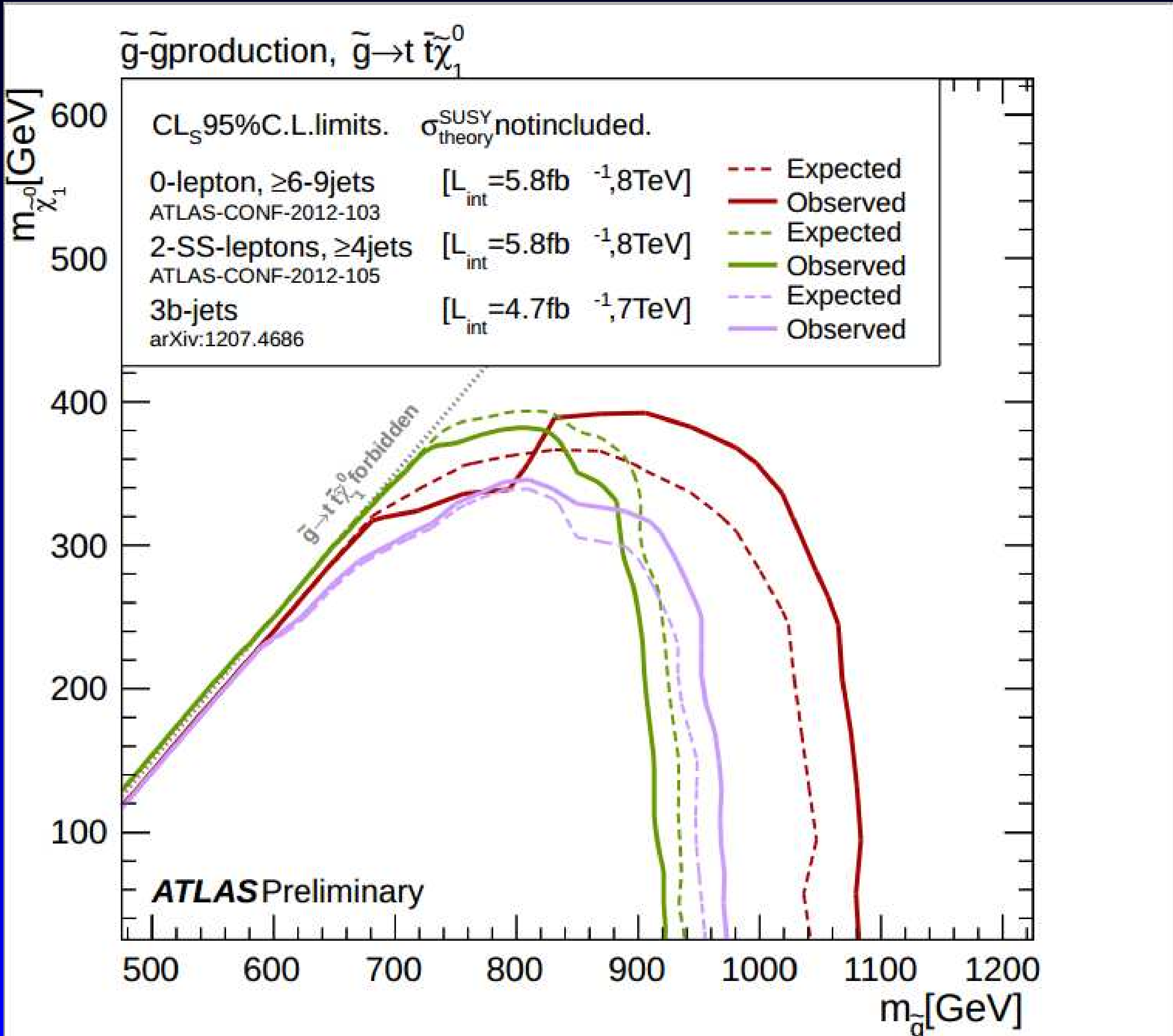
gt: $\not{E}_T > 50/120$ GeV, $N_b \geq 2$, $\#j \geq 2$, $H_T > 320$ GeV



Bottom Up Implications of 2012 Data

Naturalness is under pressure. Ways to get around it:

- First two generation squarks > 1.8 TeV, $m_{\tilde{t}} = 0.5 - 0.7$ TeV, $m_{\tilde{g}} = 0.9 - 1$ TeV, $m_{\chi_1^0} < 0.5$ TeV. Ruled out soon?
- Compressed spectra[a]: ISR monojets/$\not{E}_T$ searches give you $m_{\tilde{g}} > 500$ GeV only.
- RPV decreases/removes the $\not{E}_T$[b].
  - Explains why natural SUSY hasn't been found yet
  - Like-sign dileptons is a generic signature, as we'll see

[a] Dreiner, Kramer, Tattersall `arxiv:1207.1613`

[b] BCA, Gripaios `arXiv:1202.6616`

RPV and Dark Matter

If one gives up $R-$parity, χ_1^0 is no longer a good dark matter candidate, since it decays. One then has to have something else, eg:

- *Gravitino* - still decays, but lifetime may be much longer than the age of the universe
- *Hidden sector matter*
- Axion/axino

The implications of each of these is that (in-)direct dark matter searches shouldn't find anything.

Upper Bounds on λ''_{ijk}

λ''_{11k}			$(10^{-8} - 10^{-7})(10^{8}\mathrm{s}/\tau_{osc})\tilde{m}^{5/2}$ $[n\bar{n}]$ (6.128)
λ''_{112}			10^{-6} $[NN]$ $(\tilde{m} = 300$ GeV$)$ (6.131) $6 \times 10^{-17}\, \tilde{s}_R^2\, (m_{3/2}/1$ eV$)$ $[p \to K^+\tilde{G}]$ (6.121) $8 \times 10^{-17}\, C_q^{-1}\, \tilde{s}_R^2\, (F_a/10^{10}$ GeV$)$ $[p \to K^+\tilde{a}]$ (6.122)
λ''_{113}			10^{-3} $[NN]$ $(\tilde{m} = 300$ GeV$)$ (6.131)
λ''_{123}			1.25 $[RG]$
λ''_{212}			1.25 $[RG]$
λ''_{213}			1.25 $[RG]$
λ''_{223}			1.25 $[RG]$
λ''_{312}		1.45 $[R_l]$ (6.41) $(\tilde{m} = 100$ GeV$)$	4.28 $[RG]$ 2.1×10^{-3} $[n\bar{n}]$ (6.129)
λ''_{313}		1.46 $[R_l]$ (6.41) $(\tilde{m} = 100$ GeV$)$	1.12 $[RG]$ 2.6×10^{-3} $[n\bar{n}]$ (6.129)
λ''_{323}		1.46 $[R_l]$ (6.41) $(\tilde{m} = 100$ GeV$)$	1.12 $[RG]$
λ''_{ijk}			$(10^{-11}\, \tilde{m}^3 - 10^{-8}\, \tilde{m}^2)$ $\times(m_{3/2}/1$ eV$)$ $[p \to K^+\tilde{G}]$ (6.123) $\times(F_a/10^{10}$ GeV$)$ $[p \to K^+\tilde{a}]$ (6.124)

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Bottom up thinking

We are not assuming

- MSSM: don't put higgs constraints - there might be higher dimension operators coming from heavier fields.
- Some specific (or even generic) string model.
- We only put in the particles important for our analysis. Others may be decoupled, or light: it shouldn't matter.

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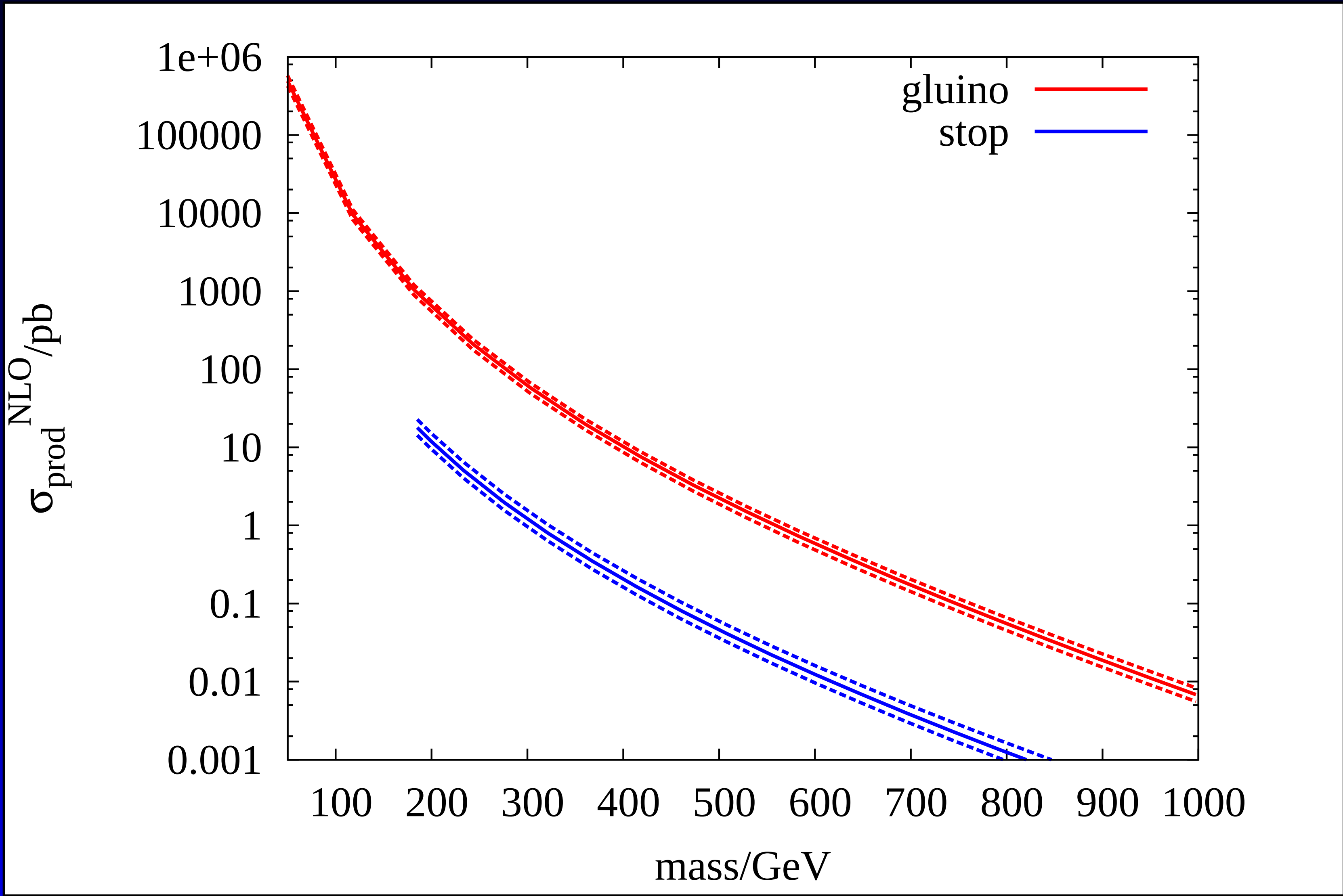
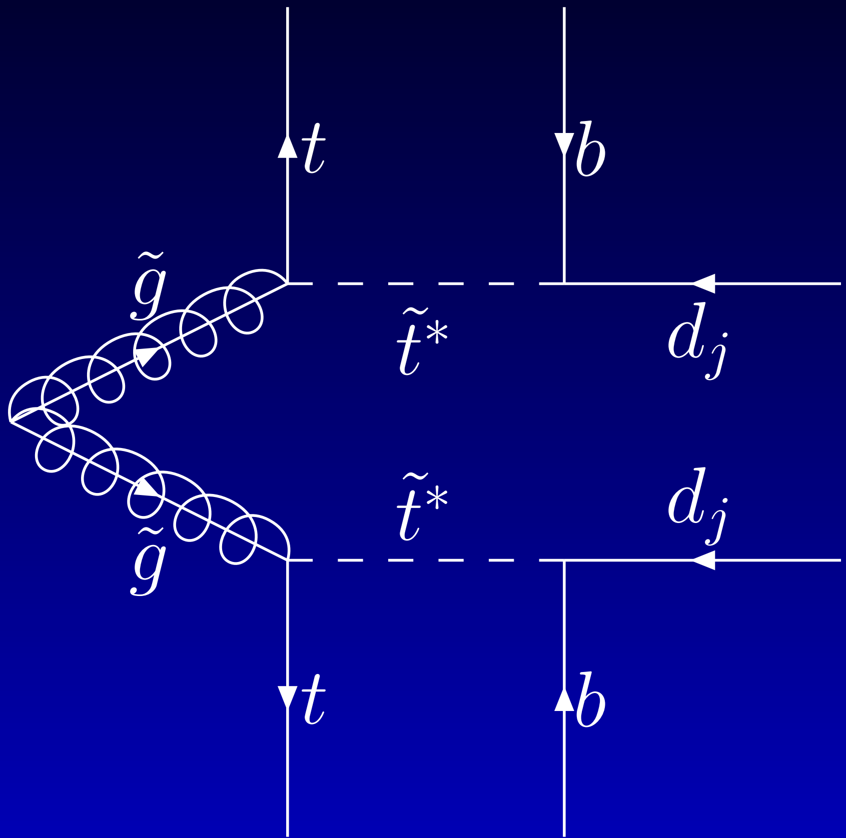
Gluino/stop production at LHC7



Gluinos With R_p Violation

- We assume lightish $\tilde{g}$, $\tilde{t}_R$. If one has lepton number violating LLE or LH_1 operators, the gluinos decay producing various leptons. These cases ought to be easy to find, and are good candidates for searches. Get same-sign leptons.
- With LQD operators, the stops will again decay into leptons, easy to see. Flavour constraints imply that L_3QD operators are likely to be the largest. Get same-sign leptons in $\sim \frac{7}{9}$ of $\tilde{g}\tilde{g}$ events.
- With UDD operators, the (right-handed) top decays direcly into jets.

Baryon Number Violating Example



Can lead to natural SUSY with light stops and gluinos that hasn't been excluded yet. *A difficult case*[a]: $W \supset \lambda''_{ijk} U_i D_j D_k$.

[a] BCA and Ben Gripaios, `arXiv:1202.6616`

$\tilde{g}\tilde{g}$ production dominates. Here, you can look for like-sign di-leptons since gluinos decay into t and $\bar{t}$ with equal branching ratios.

Other Light States

How robust is the same-sign dilepton signature in the case that other states are also light?

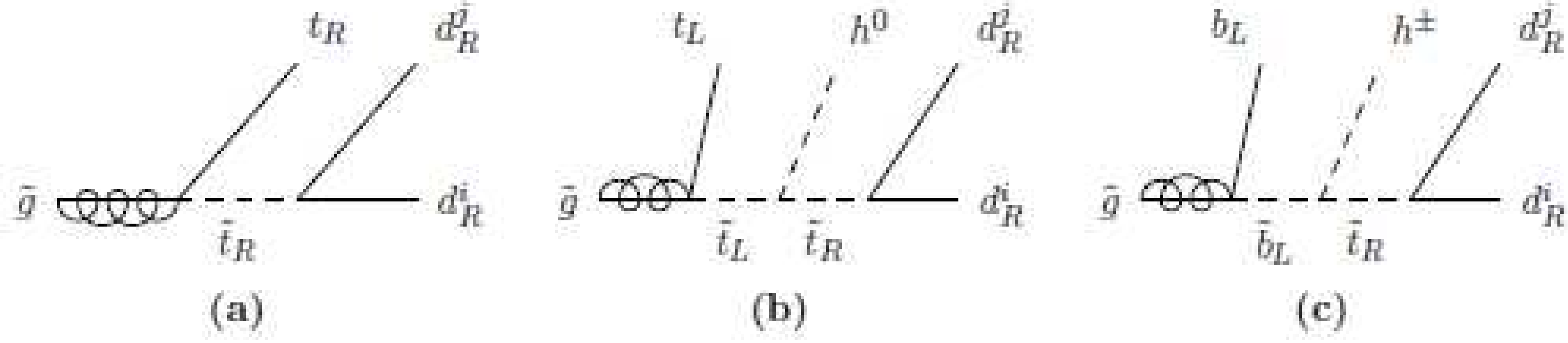


Figure 1. Gluino decays without right-handed bottom squarks in the presence of $W \supset U_3 D_i D_j$, via (a) right-handed top, (b) left-handed top, and (c) left-handed bottom. Same sign leptons are obtained in (c) only if the charged Higgs subsequently decays to $t\bar{b}$ or to leptons.

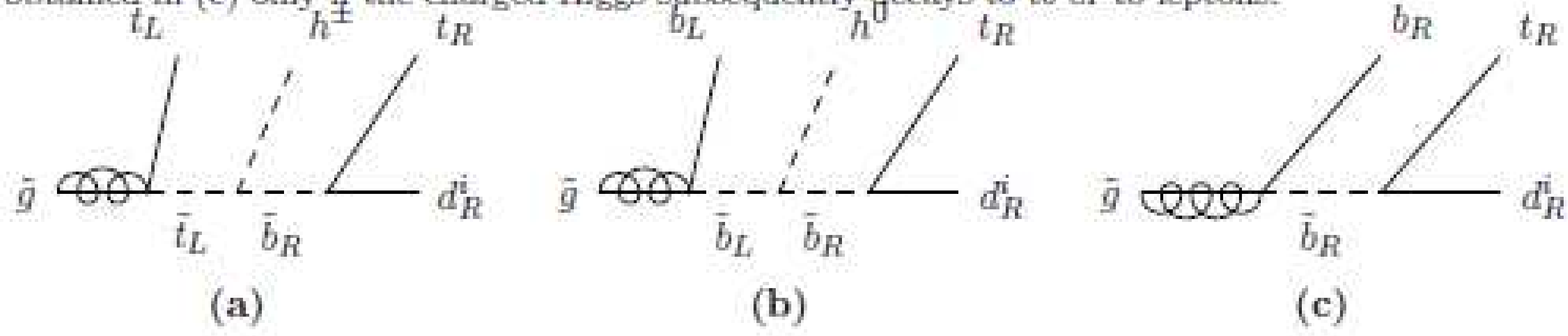
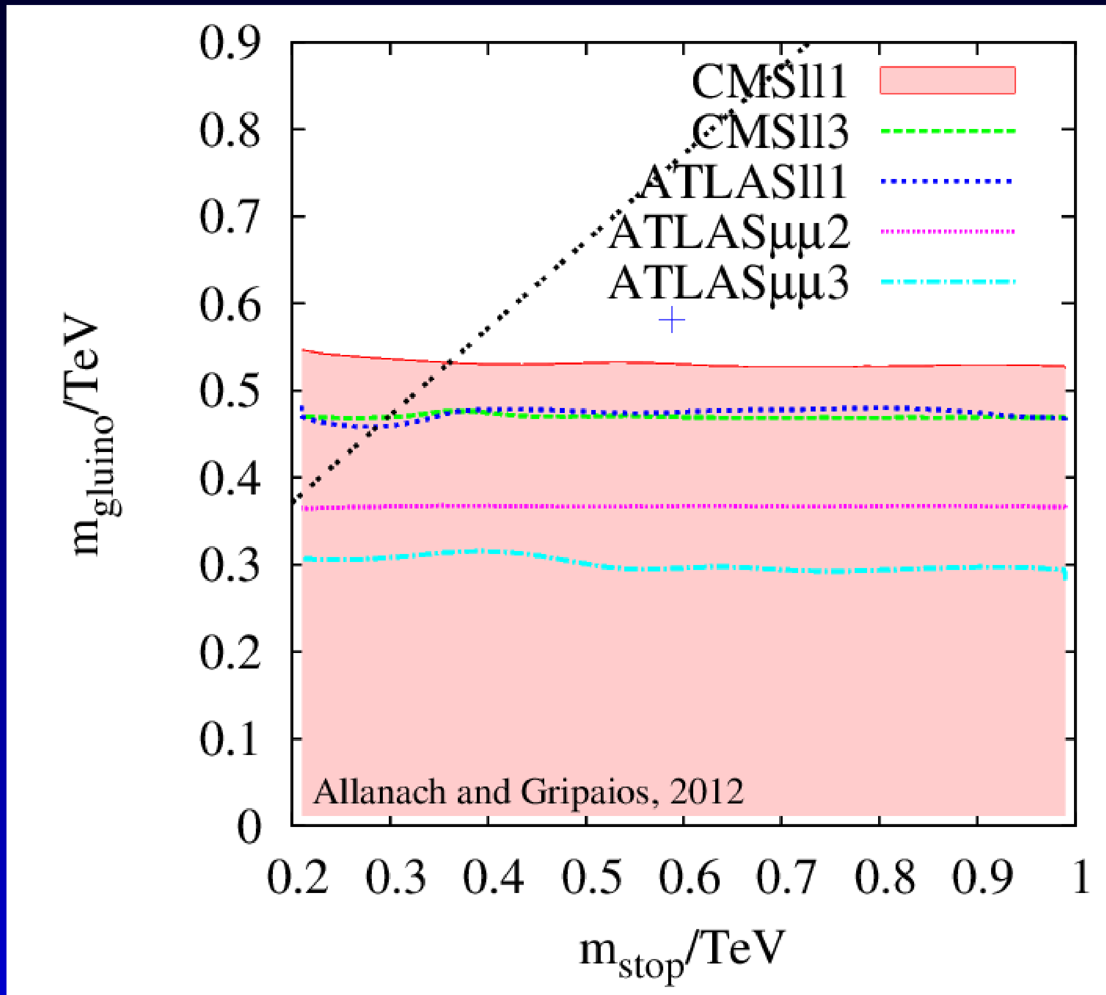


Figure 2. Gluino decays with right-handed bottom squarks in the presence of $W \supset U_3 D_i D_3$, via (a) left-handed top squark, (b) left-handed bottom squark, and (c) right-handed bottom squark.

Can we avoid SS dileptons?

- For $m_{H^\pm} > m_t + m_b$, $H^+ \to t\bar{b}$ dominates, which again will yield same-sign dileptons.
- $H^+ \to \tau^+\nu_\tau$ is also OK, since we'll get like-sign di-taus.
- Only fly in the ointment comes from Fig. 1c: when $H^+ \to c\bar{b}$ (but only happens when $\tan\beta \ll m_t V_{cb}/m_\tau \sim 3$, which seems unlikely).

Same-sign $\not{E}_T$ Limits



$\text{CMSS}ll1^a$: $H_T > 400$ GeV, $|\not{E}_T| > 120$ GeV

[a] CMS-PAS-SUS-010; ATLAS-CONF-2012-004

A_{FB} in the Standard Model

EVIDENCE FOR A MASS DEPENDENT FORWARD- . . .

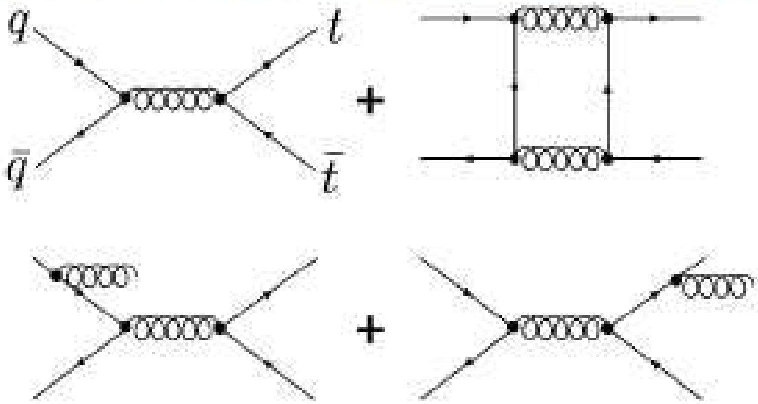


FIG. 1. Interfering $q\bar{q} \to t\bar{t}$ (above) and $q\bar{q} \to t\bar{t}j$ (below) amplitudes.

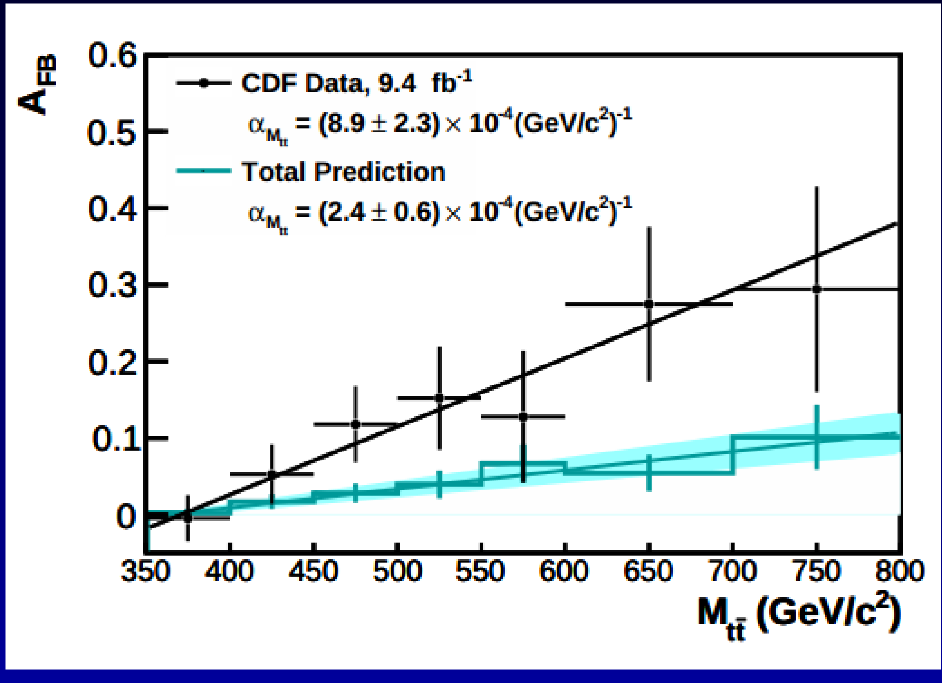
1.96 TeV $p\bar{p}$ collisions at the Tevatron.

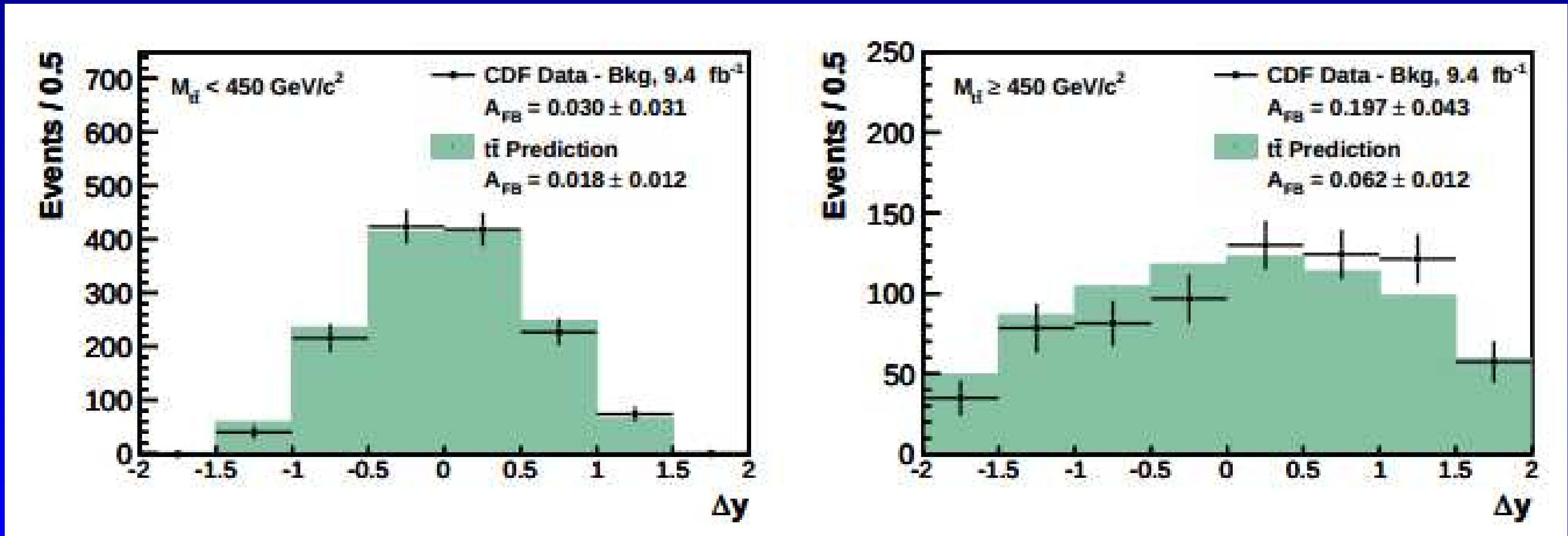
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, c = \cos\theta.$$

NLO QCD+NLNLL SM Prediction[a]: 7.2±1.0%.

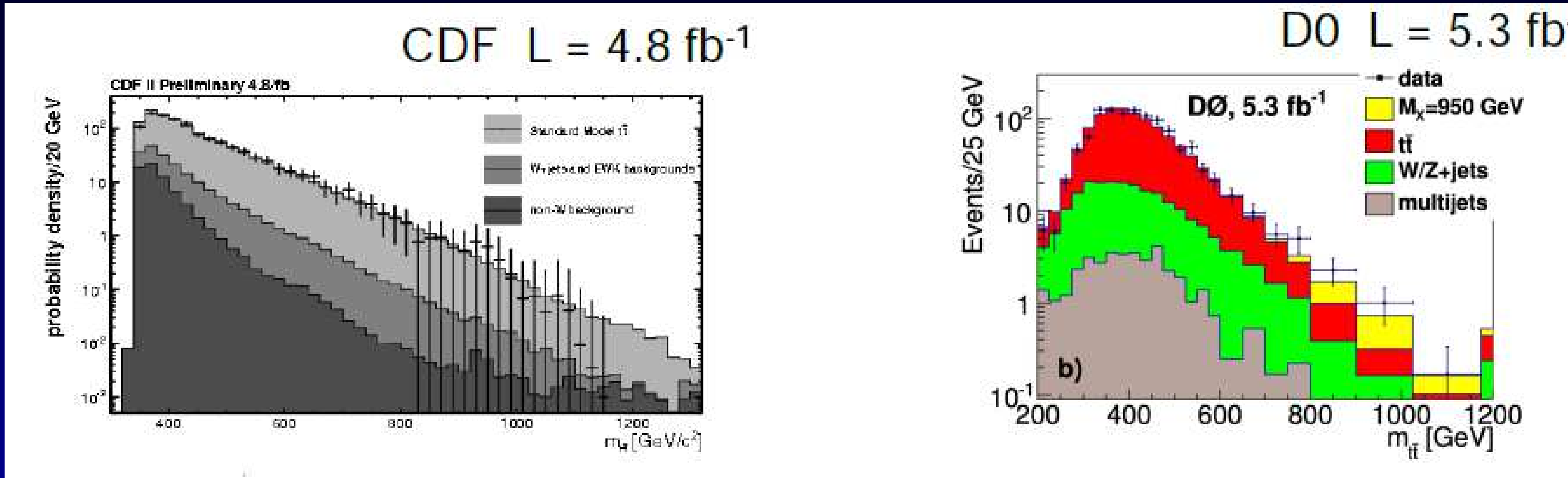
[a] Ahrens et al, PRD84 (2011) 074004

Measurements of A_{FB}





Other Constraints



$$\sigma_{t\bar{t}}^{LHC7} = 173.4 \pm 10.6 \text{ pb}, \qquad \sigma_{t\bar{t}}^{SM} = 163 \pm 10 \text{ pb}$$

$$A_C^y = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_{\bar{t}}| > |y_t|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_{\bar{t}}| > |y_t|)} = -0.015 \pm 0.04,$$

where $y_i = 1/2 \ln(E_i - p_{i_z})/(E_i + p_{i_z})$ is the rapidity of particle i. ${A_C^y}^{SM} = 0.006 \pm 0.002$.

ΔA_{FB}

Many models of random particles have been proposed, but most don't fit all the data. However, this one does:

$$W = \frac{\lambda''_{313}}{2} t_R d_R b_R$$

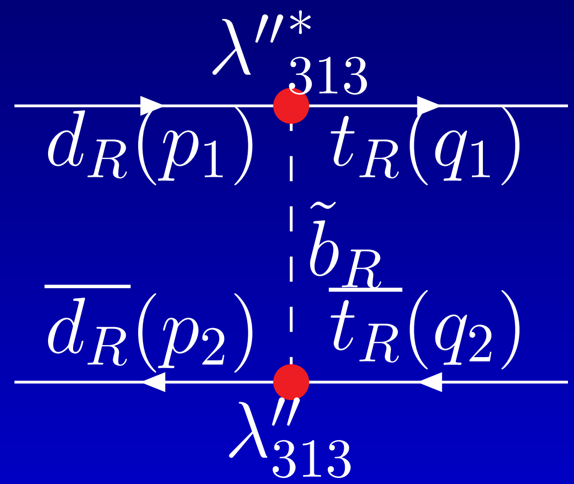


Figure 1: SUSY contribution to A_{FB}[a]

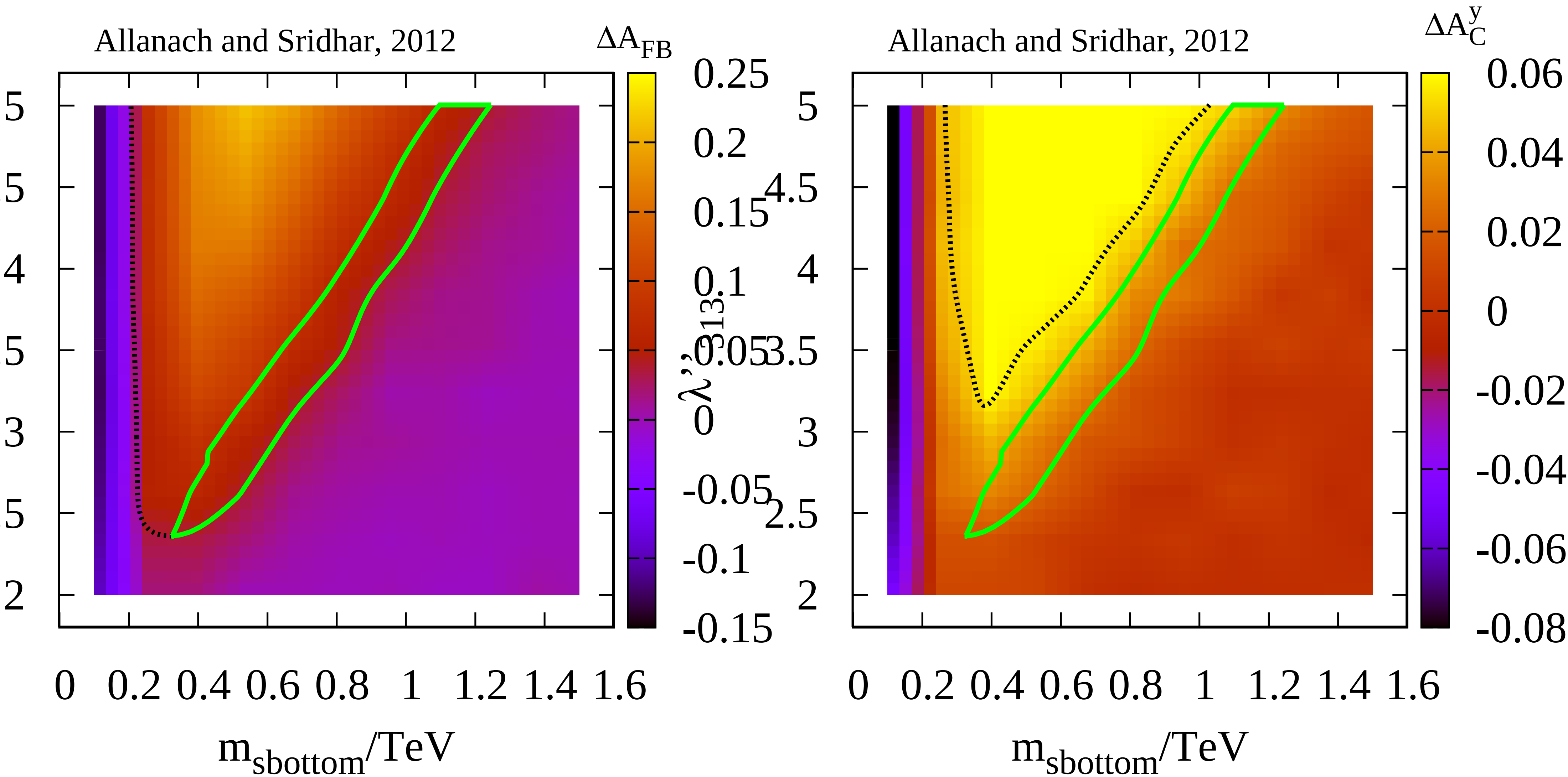
[a] BCA, Sridhar `arXiv:1205.5170`

New Physics Contribution

$$\frac{d\Delta\sigma}{dc} = \frac{|\lambda''_{313}|^4 \beta \hat{s}}{384\pi} \left[\frac{(\beta c - 1)}{\hat{s}(\beta c - 1) + 2m_t^2 - 2m_{\tilde{b}_R}^2} \right]^2 +$$
$$\frac{\alpha_s |\lambda''_{313}|^2 \beta}{72\hat{s}} \frac{4m_t^2 + \hat{s}(\beta c - 1)^2}{\hat{s}(\beta c - 1) + 2m_t^2 - 2m_{\tilde{b}_R}^2},$$

where $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$, $\hat{s} = (p_1 + p_2)^2$, α_s is the strong coupling constant and m_t is the top quark mass.

Calculate observables with MadGraph arXiv:1205.5170



Constraints and Predictions

$0.037 < \Delta A_{FB} < 0.205$	$-0.079 < \Delta A_C^y < 0.061$
$-0.65 < \Delta\sigma_{t\bar{t}}^{TEV}/\text{pb} < 1.51$	$4 < \Delta\sigma_{t\bar{t}}^{TEV}(\text{bin})/\text{fb} < 156$
$-0.38 < \Delta A_{FB}^l < 0.23$	$0.062 < \Delta A_{FB}^h < 0.33$
$-19.2 < \Delta\sigma_{t\bar{t}}^{LHC7}/\text{pb} < 39.2$	

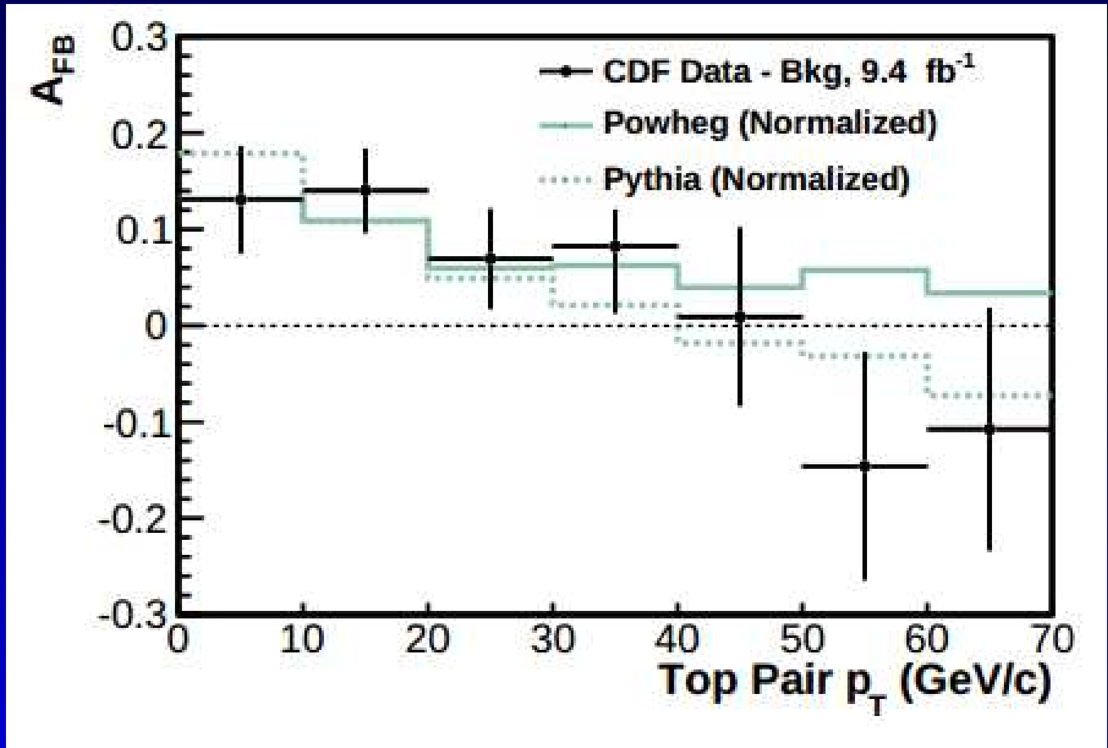
Table 1: 95% CL constraints

$0.037 < \Delta A_{FB} < 0.09$	$0.02 < \Delta A_C^y < 0.06$
$0 < \Delta\sigma_{t\bar{t}}^{TEV}/\text{pb} < 1.8$	$110 < \Delta\sigma_{t\bar{t}}^{TEV}(\text{bin})/\text{fb} < 156$
$0.005 < \Delta A_{FB}^l < 0.04$	$0.062 < \Delta A_{FB}^h < 0.14$
$8 < \Delta\sigma_{t\bar{t}}^{LHC7}/\text{pb} < 25$	$13 < \Delta\sigma_{t\bar{t}}^{LHC8}/\text{pb} < 33$

Table 2: Predicted values in good fit region

More Tests

We are now checking to see if the most recent data from the LHC (eg $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$) rule our model out. Also,



Summary

- Need to scan over m_t when doing CMSSM searches!
- R_p violation allows natural SUSY with lightish gluinos and squarks that have not yet been ruled out by searches.
- Same-sign dilepton searches *without* huge $\not{E}_T$ cut will be interesting. It covers almost all possible cases of RPV operator.
- In case of $U_i D_j D_k$ operators, current searches[a] $\Rightarrow m_{\tilde{g}} > 800$ GeV.
- Anomalous A_{FB} measurements can *also* be explained by $U_i D_j D_k$ type operator - fits data as of May 2012

Backup

Sets of Cuts

Signal Region	$m_{\mu\mu}$/GeV	$\sigma^{test}_{SS\mu\mu}$/fb	$A/10^{-3}$	$\sigma^{95}_{SS\mu\mu}$/fb
ATLAS$\mu\mu 1$	$>$15	12	1.3	58
ATLAS$\mu\mu 2$	$>$100	7.5	0.86	16
ATLAS$\mu\mu 3$	$>$200	2.1	0.29	8.4
ATLAS$\mu\mu 4$	$>$300	0.41	0.077	5.3

Table 3: The ATLAS same-sign di-muon analysis search regions.

Sets of Cuts

Signal Region	$\|\vec{p}_{\rm T}^{\rm miss}\|$/GeV	$m_T(l_1)/GeV$	$A/10^{-3}$	σ^{95}_{SSll}/fb
ATLAS$ll1$	> 150	> 0	1.0	1.6
ATLAS$ll2$	> 150	> 100	0.6	1.5

Table 4: ATLAS same sign-di lepton analysis search regions.

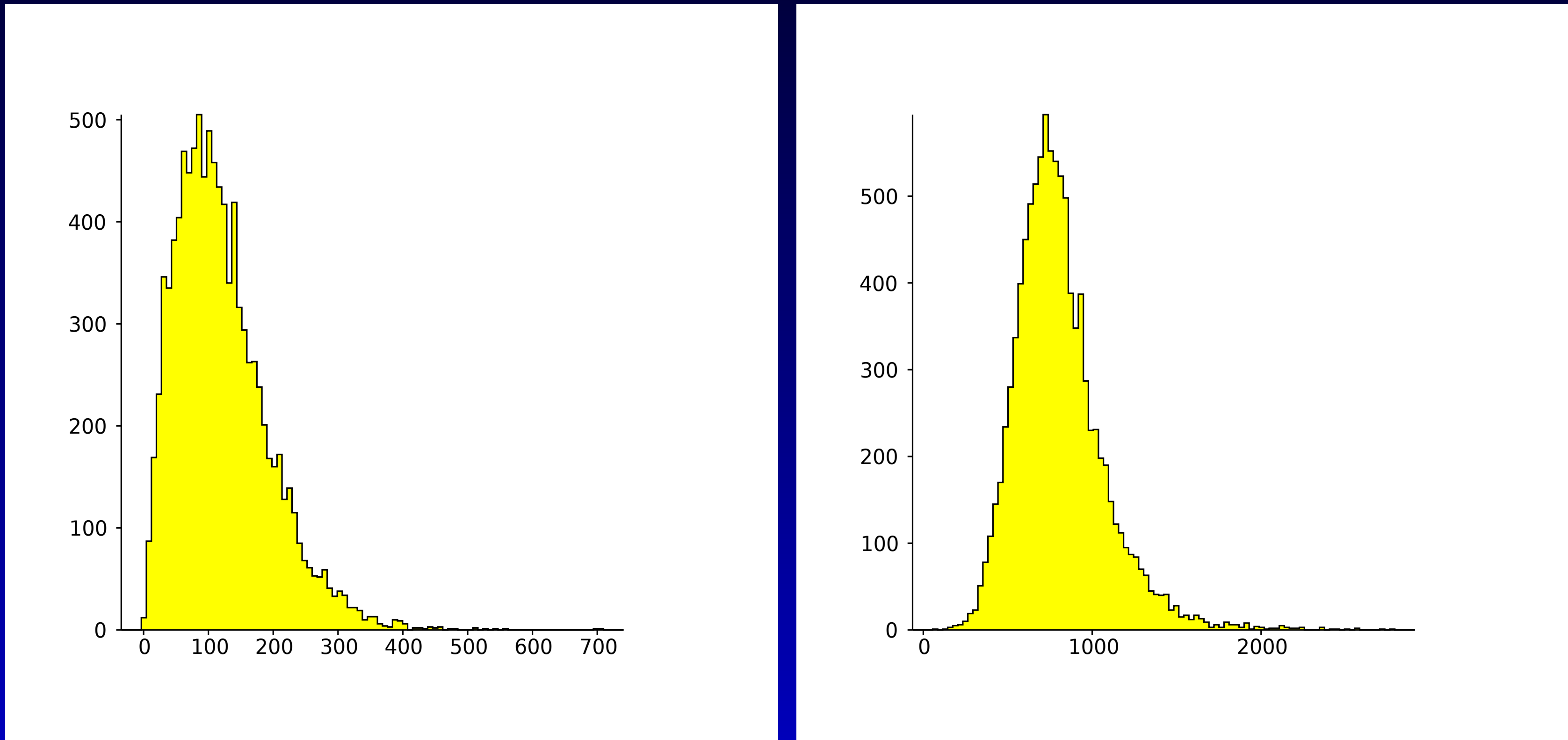
Sets of Cuts

Signal Region	H_T/GeV	$\|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}\|$/GeV	N_{ll}/fb	$A \times \epsilon/10^{-3}$	N_{ll}^{95}
CMSll1	$>$400	$>$120	2.4	3.5	$<$3.7
CMSll2	$>$400	$>$ 50	4.6	6.8	$<$8.9
CMSll3	$>$200	$>$120	2.5	3.7	$<$7.3

Table 5: Number of events past cuts for the CMS same sign-di lepton analysis N_{ll} predicted by our test point over SM backgrounds, and acceptance A times efficiency ϵ of the signal selection, for the test point.

Test Point

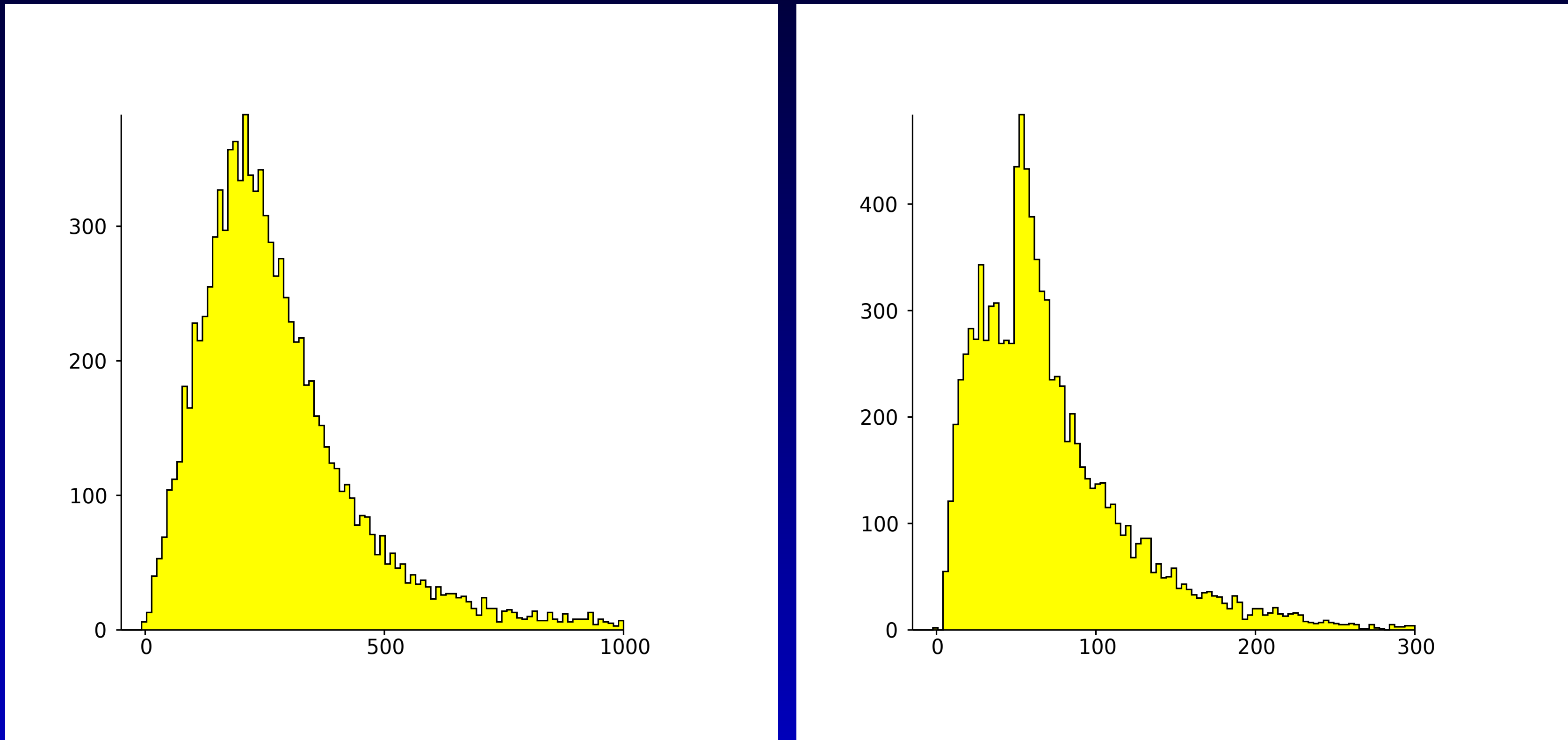
$$m_{\tilde{g}} = 588 \text{ GeV}, m_{\tilde{t}} = 581 \text{ GeV}.$$



LH panel: $\not{E}_T/GeV$, RH panel: H_T/GeV

Test Point

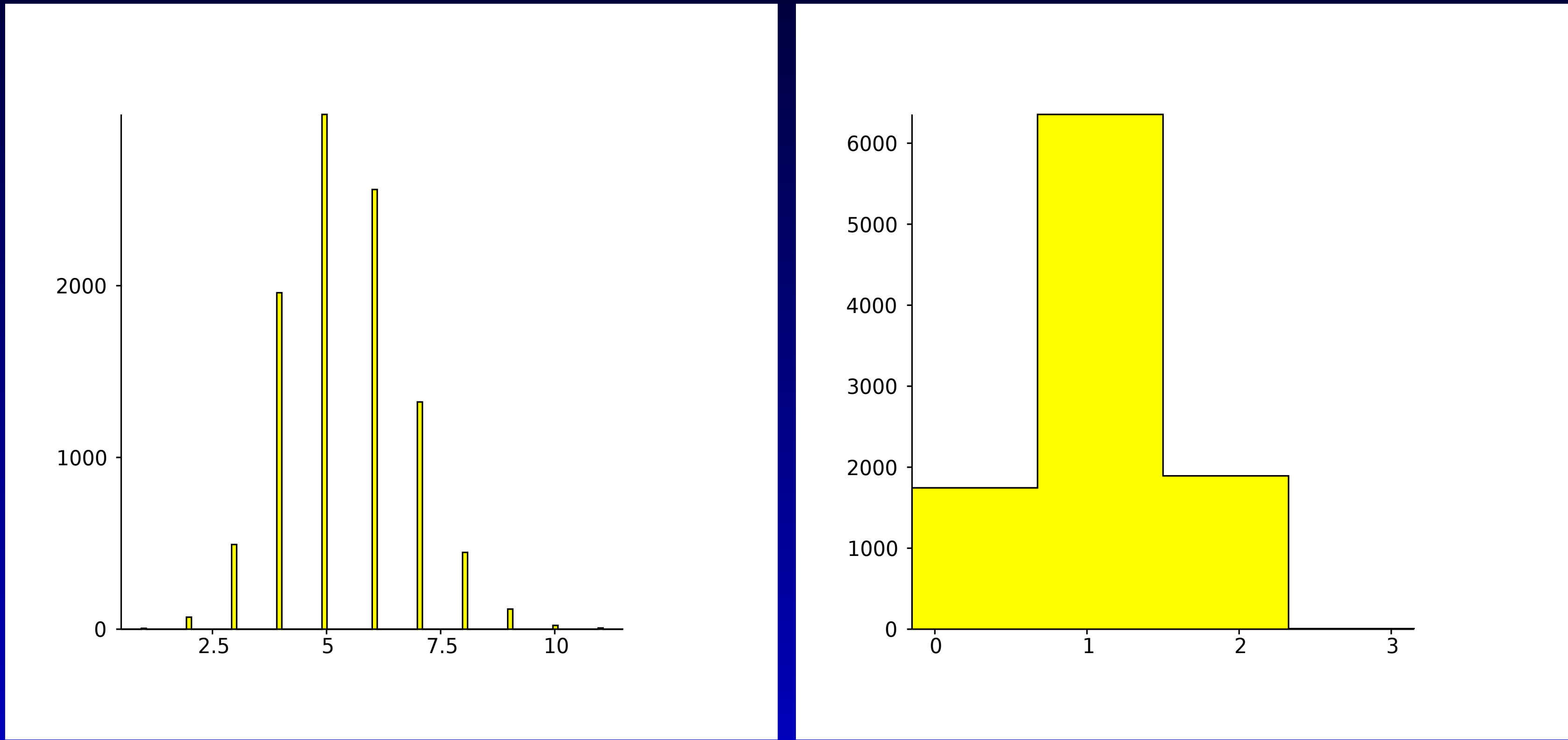
$m_{\tilde{g}} = 588$ GeV, $m_{\tilde{t}} = 581$ GeV.



LH panel: $p_T(j_1)/GeV$, RH panel: $p_T(l_1)/GeV$

Test Point

$$m_{\tilde{g}} = 588 \text{ GeV}, m_{\tilde{t}} = 581 \text{ GeV}.$$



LH panel: N_J, RH panel: $N_{isol\ e,\mu}$

Efficiencies of CMS $ll\not{E}_T$

$$\epsilon = \frac{\text{SUSY events past cuts}}{\text{SUSY events}}$$

You pay for the di-leptonic tt branching ratio.