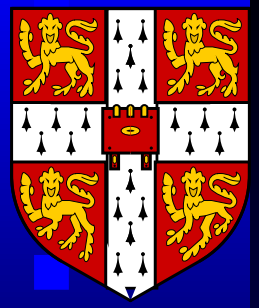
Hide and Seek With SUSY

Ben Allanach[a] (University of Cambridge)

[a]BCA, Grab, Haber, 1010.4261; BCA, Gripaios, 1202.6616; BCA, Sridhar 1205.5170; BCA, Parker 1211.3231.



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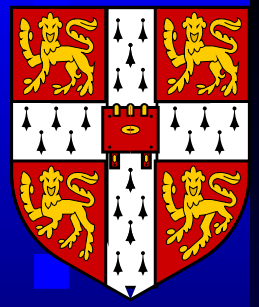
A Long Time Ago in a Galaxy Far, Far Away. . .

In the early 1980s, CERN $p\bar{p}$ collisions resulting in single jets ('monojet') in the UA1 experiment were famously interpreted in terms of supersymmetric particle production[a]. One example of such a process was squark photino production, followed by decay of the squark into a quark and photino. Later, it was calculated that the monojet events would predict more di-jet missing transverse momentum events than were observed[b]. Finally, backgrounds (particularly W production, where $W \to \tau\nu$, followed by $\tau \to \nu_\tau j$), and Zj production[c], where $Z \to \nu\bar{\nu}$ were seen to adequately account for the monojet events.

[a] Haber, Kane; Barger, Hagiwara, Woodside, Keung; Barnett, '84-85

[b] Barnett, Haber, Kane '86

[c] Ellis, Kleiss, Stirling '86



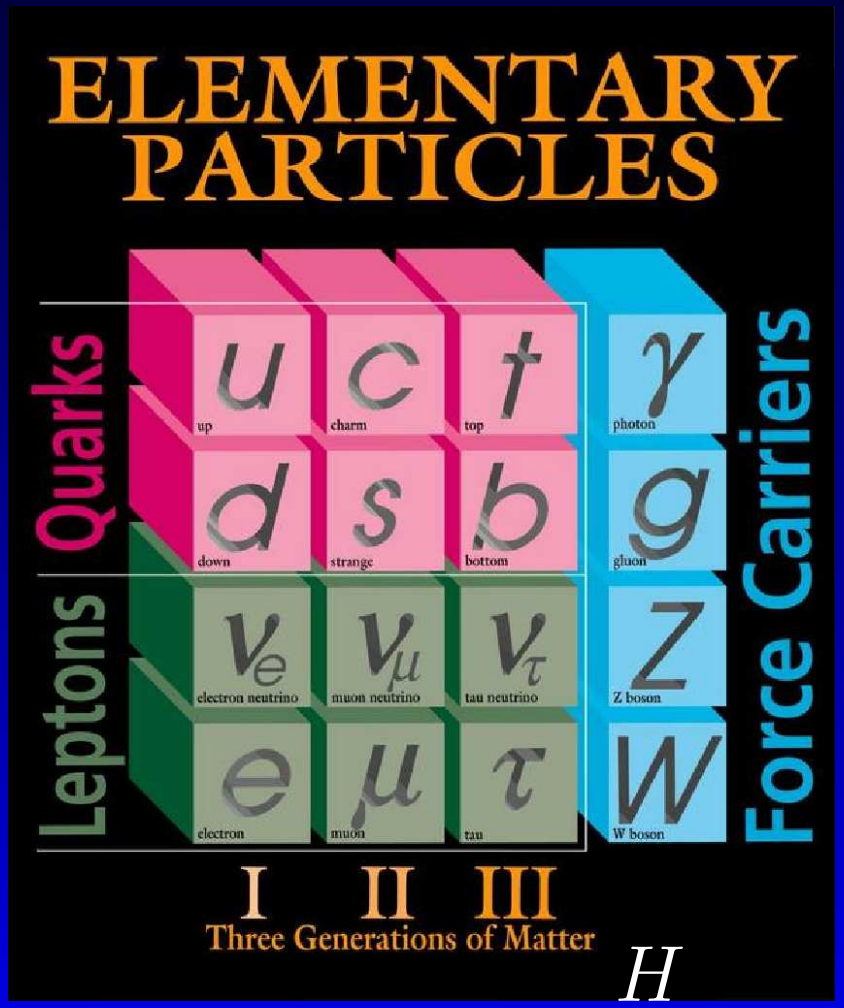
Hierarchy problem solved

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:

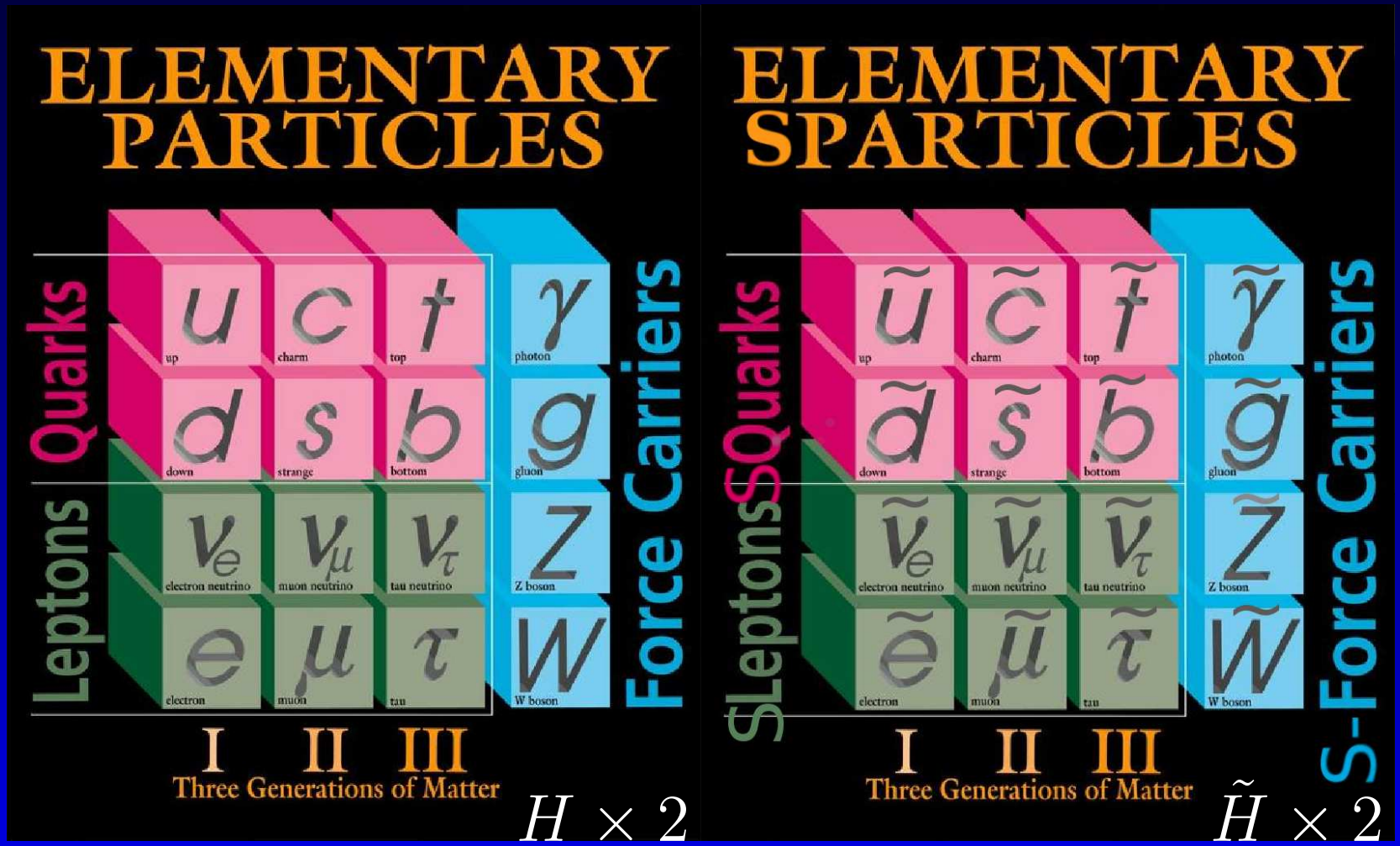
- Weakly interacting
- Stable
- Massive

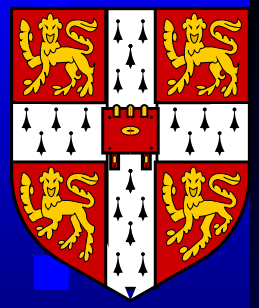
To predict how much of it is around today, we must make assumptions on our *cosmology*, and on the *particle physics*. If we can measure the particle physics, we have a handle on the cosmology.

Supersymmetric Copies



Supersymmetric Copies





Warm-up: Neutralino Mixing

Neutralino masses measured: $\chi^0_{1,2,4}$ but need mixing matrix to determine couplings. Left with $\tan\beta$.

$\mathcal{L} = \ldots - \frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0$ + h.c., where

$\tilde{\psi}^0 = \{-i\tilde{B}, -i\tilde{W}^3, \tilde{H}_u, \tilde{H}_d\}^T$ and $\mathcal{M}_{\tilde{\psi}^0} =$

$$\begin{bmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{bmatrix}$$

This matrix is diagonalised by $N\mathcal{M}_{\tilde{\psi}^0}N^T$

$\Rightarrow \chi^0_1 = N_{1B}\tilde{B} + N_{1W}\tilde{W} + N_{1d}\tilde{H}_d + N_{1u}\tilde{H}_u$

Motivation to Measure $\tilde{q} - q - \chi_1^0$

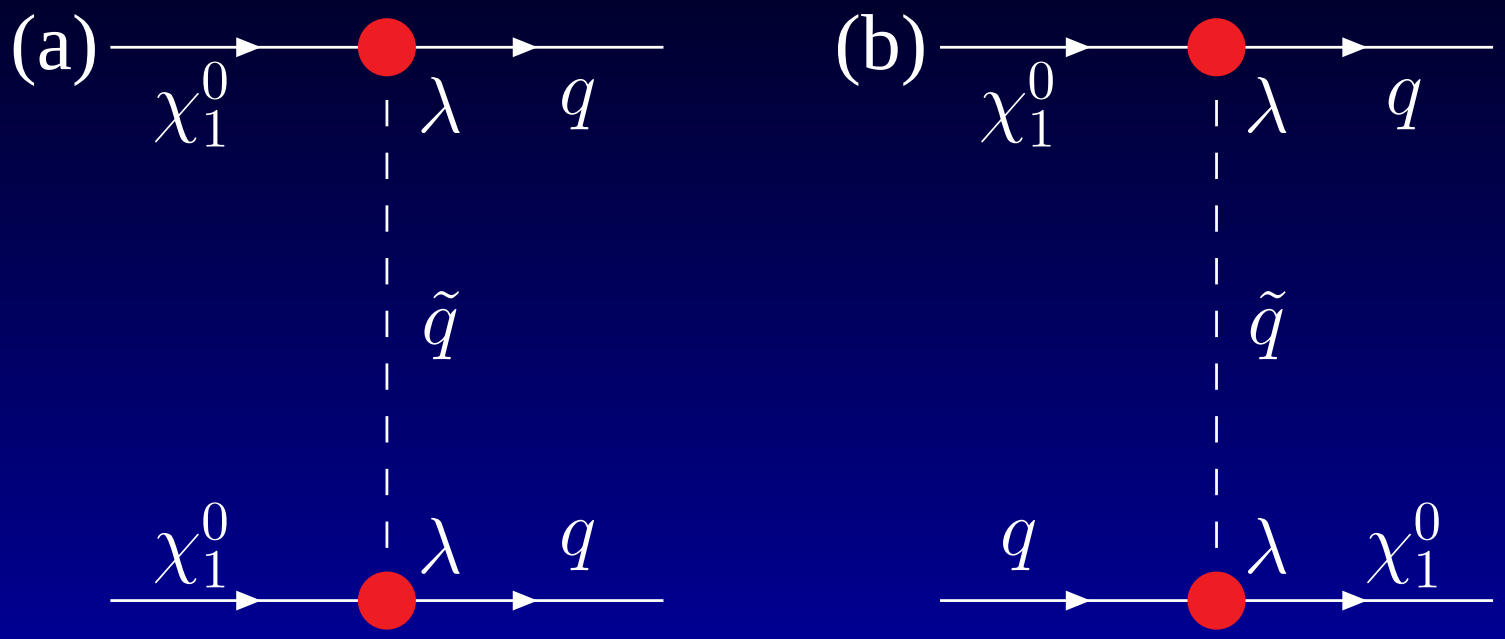
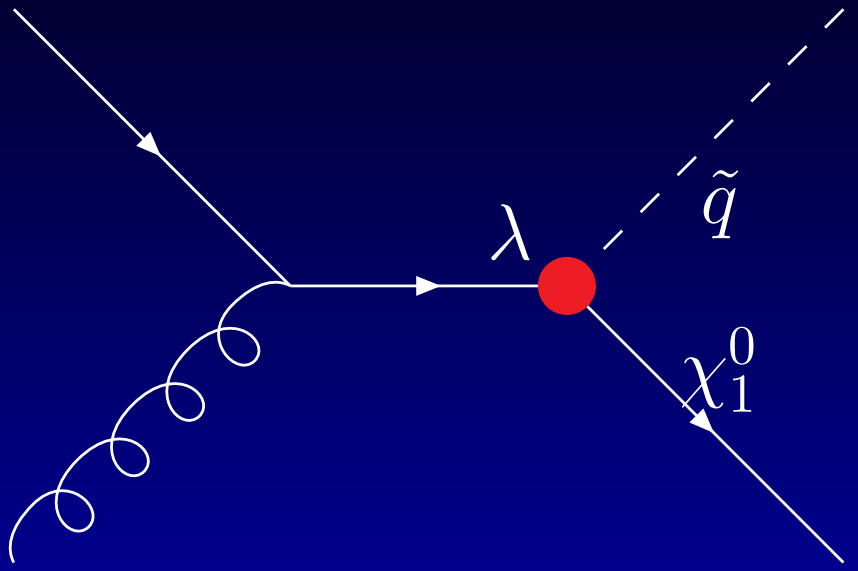
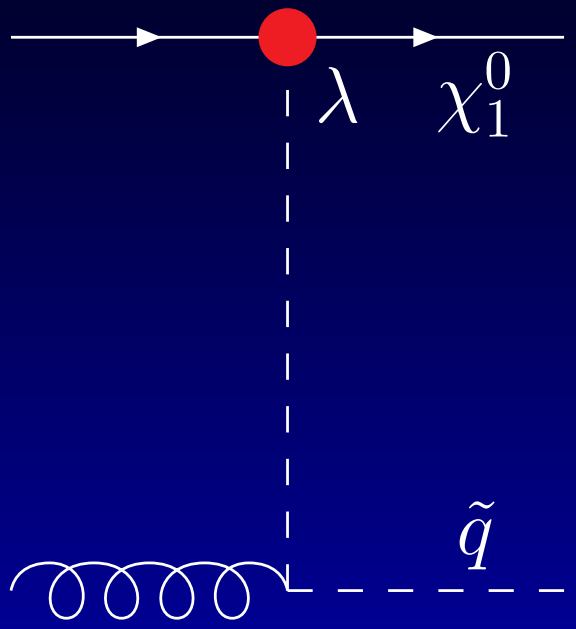


Figure 1: Tree-level Feynman diagrams contributing to (a) dark matter annihilation and (b) dark matter direct detection.

Signal Process

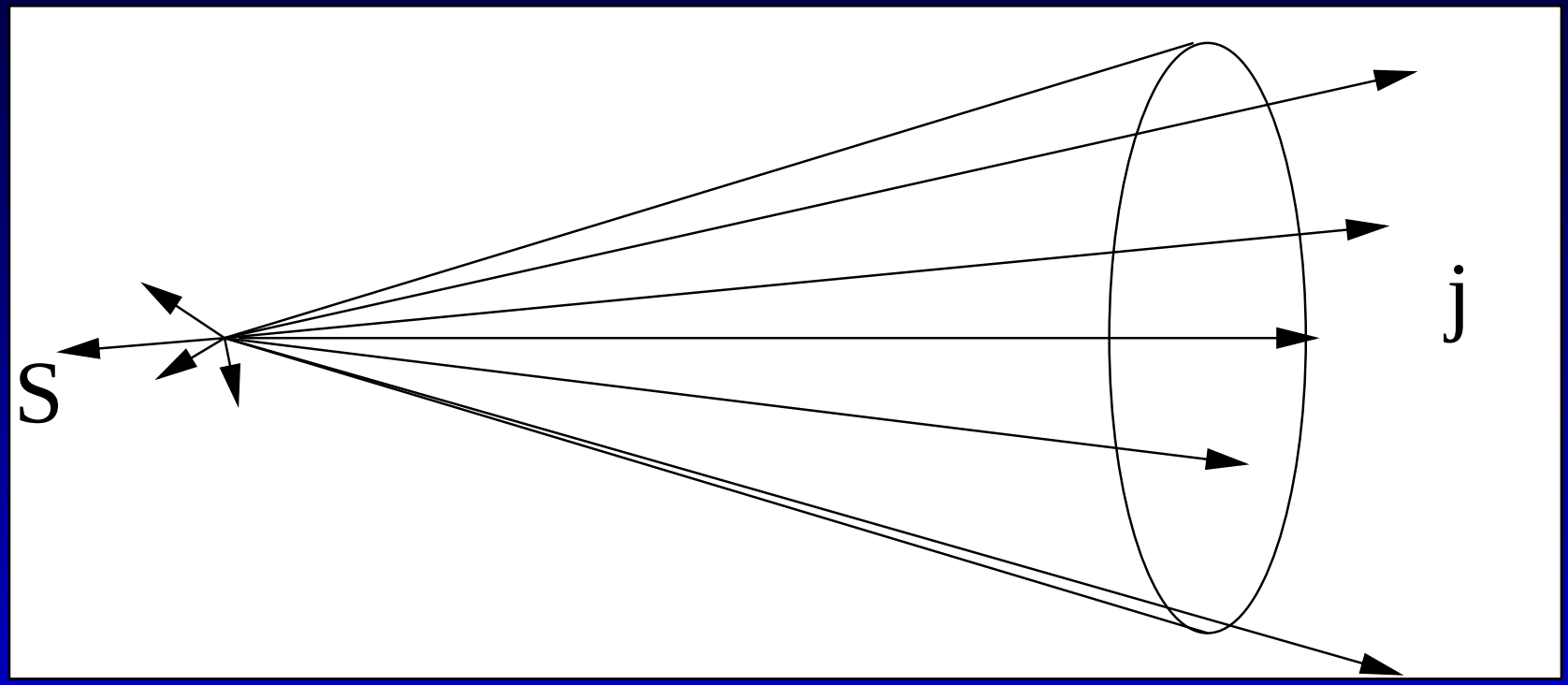




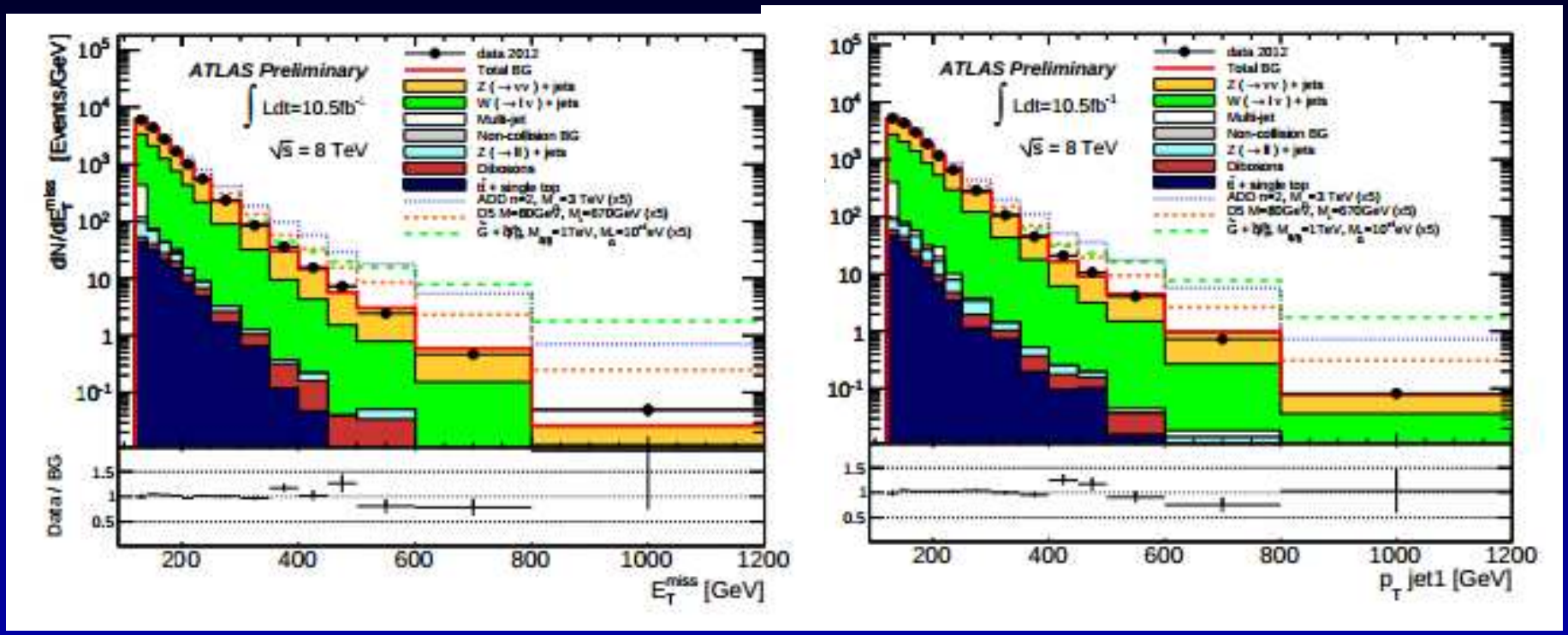
- Not a search channel! Get $\tilde{q} \to q\chi_1^0$.
- Can get at identity of χ_1^0 via λ:
  $\chi_1^0 = N_{1B}\tilde{B} + N_{1W}\tilde{W} + N_{1d}\tilde{H}_d + N_{1u}\tilde{H}_u$
- $\lambda = \{g', g, 0\}$ for $\{\tilde{B}, \tilde{W}, \tilde{H}_{u,d}\}$, respectively

Monojet Kinematics

$$\not{E}_T \neq -p_T(j)$$

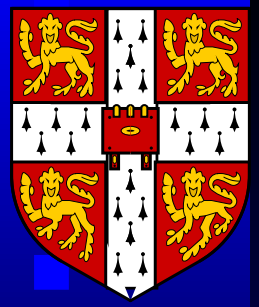


Data



- Anti-k_T algorithm with $R = 0.4$
- Multi-jet veto[a] for $p_T > 30$ GeV (max 2)

[a] ATLAS-CONF-2012-147



SUSY Monojet Backgrounds

- $Z(\to \nu\,\bar{\nu})$+jet: measure it with $Z(\to e^+e^-/\mu^+\mu^-)$+jet then subtract it
- $W(\to \nu l)$+jet: lepton veto: $E < 10$ GeV in a cone of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.2$. Measure the vetoed events and extrapolate to ones that get past the cut.
- QCD dijets, where one of the jets is badly mismeasured
- eg $\tilde{q}\tilde{q}$ production, and all decay products of the q's go in the same direction
- $\chi_1^0\chi_1^0$ production plus ISR jet

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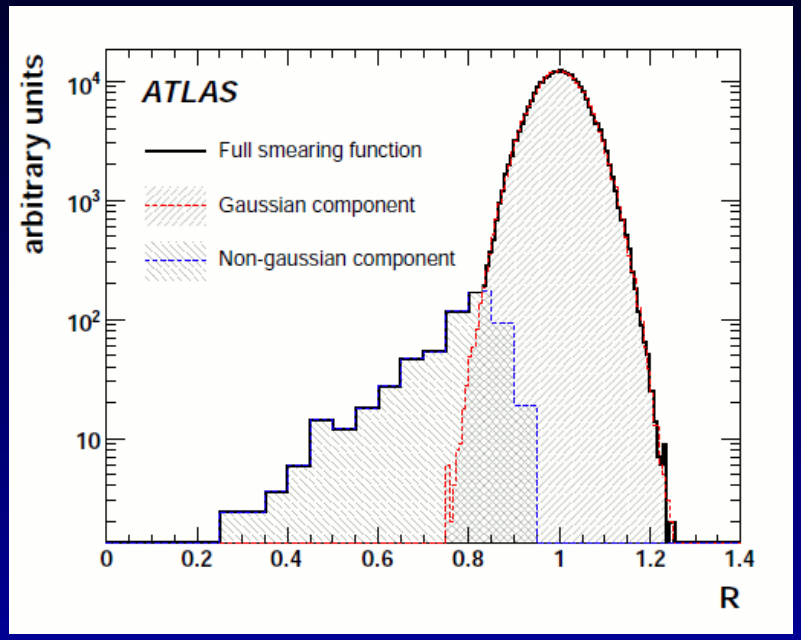
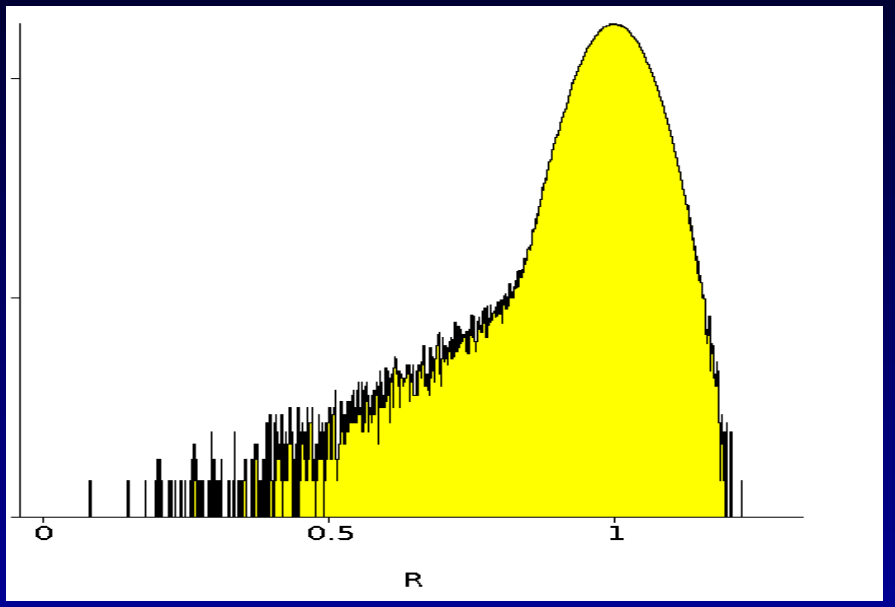
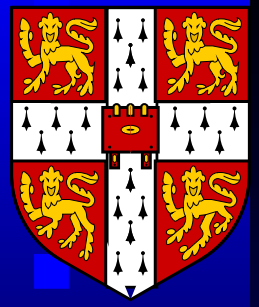
Modelling QCD Background





$$p(R) = \frac{0.99}{\sqrt{2\pi\sigma^2}}\, e^{\frac{(1-R)^2}{2\sigma^2}} + 0.01\, A\, e^{7.32R}\, \Theta(0.9 - R),$$

$$\sigma = \frac{0.6}{\sqrt{E/GeV}} \oplus 0.03.$$ *Background will be measured by looking at momentum imbalance in di-jet events etc*



What's Expected of χ_1^0?

- In most models of SUSY breaking, Higgsino component is small.
- GUT relations (eg CMSSM) imply
  $M_1 \approx 0.5 M_2 \Rightarrow \tilde{B}$ domination.
  $\mathrm{BR}(\widetilde{q}_R \to q\chi_1^0) \simeq 100\%$.
- Anomaly mediated SUSY breaking
  $M_i \approx \beta_i \frac{g_i^2}{16\pi^2} m_{3/2}$, where
  $\beta_i = \{\frac{33}{5}, 1, -3\} \Rightarrow M_1 \approx 2.8 M_2 \Rightarrow \tilde{W}$ domination. $\mathrm{BR}(\widetilde{q}_L \to q\chi_1^0) \simeq 100\%$.
  $\chi_1^\pm - q - \tilde{q}'$ coupling=λ.

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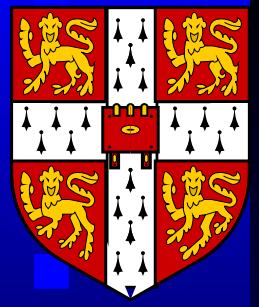

Simulation

`Herwig++2.4.2, HepMC-2.04.02, fastjet-2.4.1`. Jets are defined with $p_T > 30$ GeV, $\sqrt{s} = 14$ TeV, anti-kt algorithm with $R = 0.7$. SUSY spectrum determined with `SOFTSUSY3.0.13`.
e.g. in the $\tilde{W}$ LSP case,

$$\lambda_{\tilde{u}_L} = -\lambda_{\tilde{d}_L} = \frac{g}{\sqrt{2}}$$

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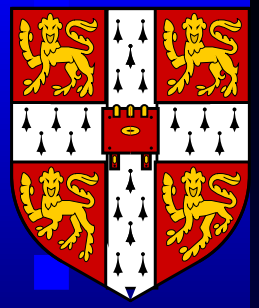

Wino Case Study

$$m_{\chi_1^\pm} - m_{\chi_1^0} \approx 0.2 \text{ GeV}$$

$\tilde{W}$: $g + q \to \tilde{\chi}_1^0 + \tilde{q}_L$ and $g + q \to \tilde{\chi}_1^+ + \tilde{q}'_L$, where $\tilde{q}_L \to q\tilde{\chi}_1^0$, and $\tilde{\chi}_1^+ \to \chi_1^0$+soft stuff. $\mu > 0$,

$$m_{3/2} = 33\,\text{TeV},\ \ m_0 = 200\,\text{GeV},\ \ \tan\beta = 10.$$

The lightest chargino, which will be included in our signal, couple with strength $0.98g$ to $\tilde{d}_L - u$ because of a small higgsino admixture and with $1.00g$ to $\tilde{u}_L - d$. $\lambda = 0.99g$.

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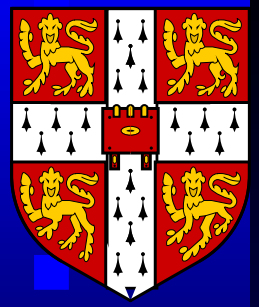

$\tilde{W}$: Cuts

cut	B_{SM}	B_{SUSY}	signal	$S/\sqrt{B}$
trigger	$3.8\ 10^7$	$1.0\ 10^6$	$4.4\ 10^4$	-
lepton veto	$2.5\ 10^7$	$6.2\ 10^5$	$4.4\ 10^4$	-
p_T(j2) < 50 GeV	$1.7\ 10^7$	$1.1\ 10^5$	$1.6\ 10^4$	3.9 (1.5)
$\not{E}_T > 300$ GeV	$1.7\ 10^5$	$1.1\ 10^4$	$8.4\ 10^3$	20 (7.7)
m(j1) < 80 GeV	$1.5\ 10^5$	$6.0\ 10^3$	$6.4\ 10^3$	17 (6.5)
tau veto	$1.2\ 10^5$	$5.8\ 10^3$	$6.4\ 10^3$	18 (7.0)
b-jet veto	$1.1\ 10^5$	$5.3\ 10^3$	$6.3\ 10^3$	19 (7.0)

Table 1: $\mathcal{L} = 100$ fb^{-1} at $\sqrt{s} = 14$ TeV. 'Trigger': $p_T(j), \not{E}_T > 100$ GeV.

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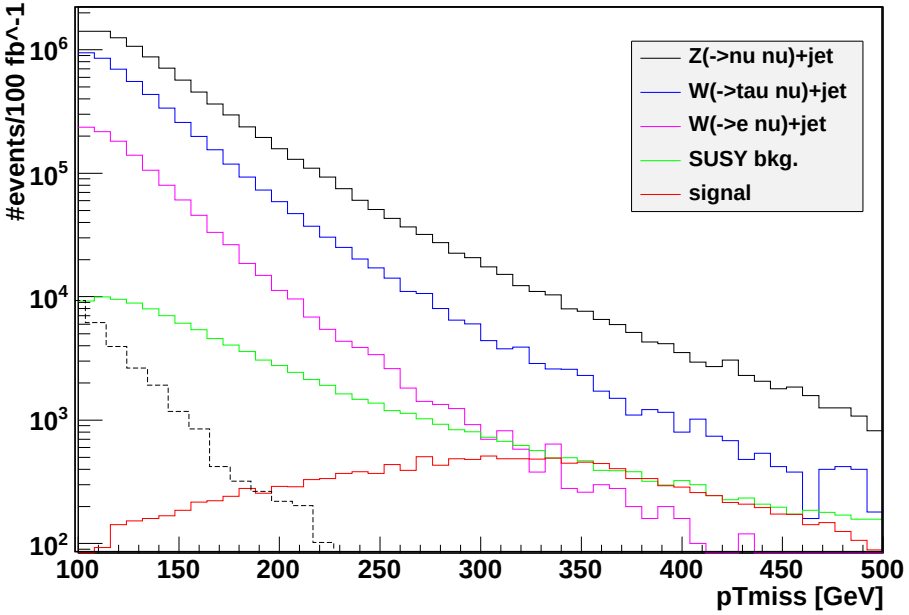
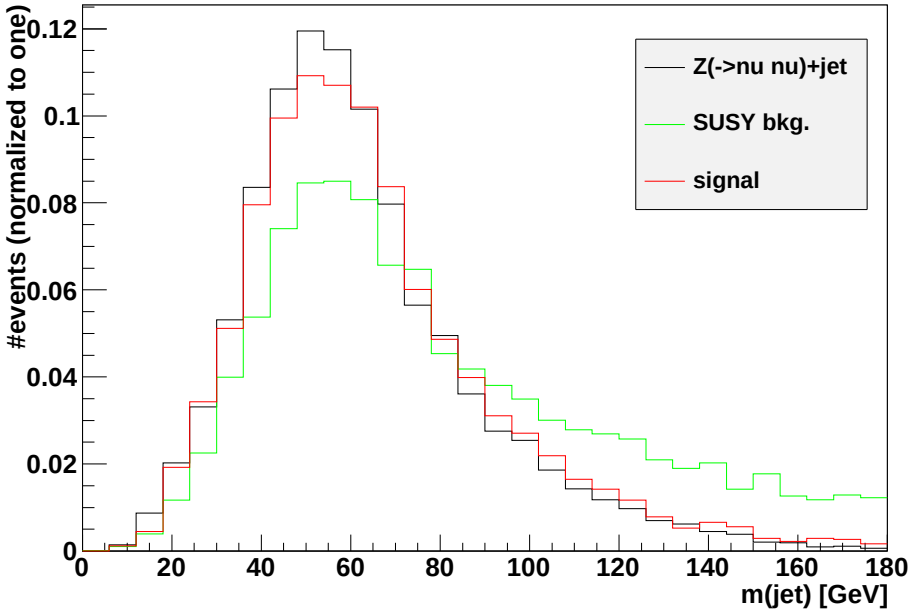
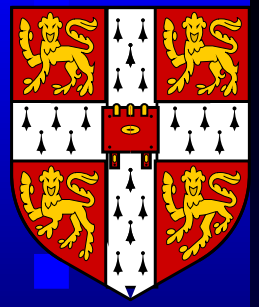
$\tilde{W}$ Distributions





$Z + j$ background is better - only need to know it to $\sim 10\%$! 100 fb^{-1}.

$m(jet)$ cut less effective because $\chi_1^{0,\pm}\chi_1^{0,\mp}$+ISR is a large background



$\tilde{W}$: Coupling Errors

error	$\Delta\sigma_{\rm mono}/\sigma_{\rm mono}$	$\Delta\lambda/\lambda$
luminosity	3%	1.5%
PDF	17%	8.2%
NLO	18%	9%
$\Delta\tilde{m} = 10$ GeV	7.3%	3.7%
stats (optimistic)	5.8%	2.9%
stats (conservative)	15%	7.7%
total (optimistic)	26%	13%
total (conservative)	30%	15%

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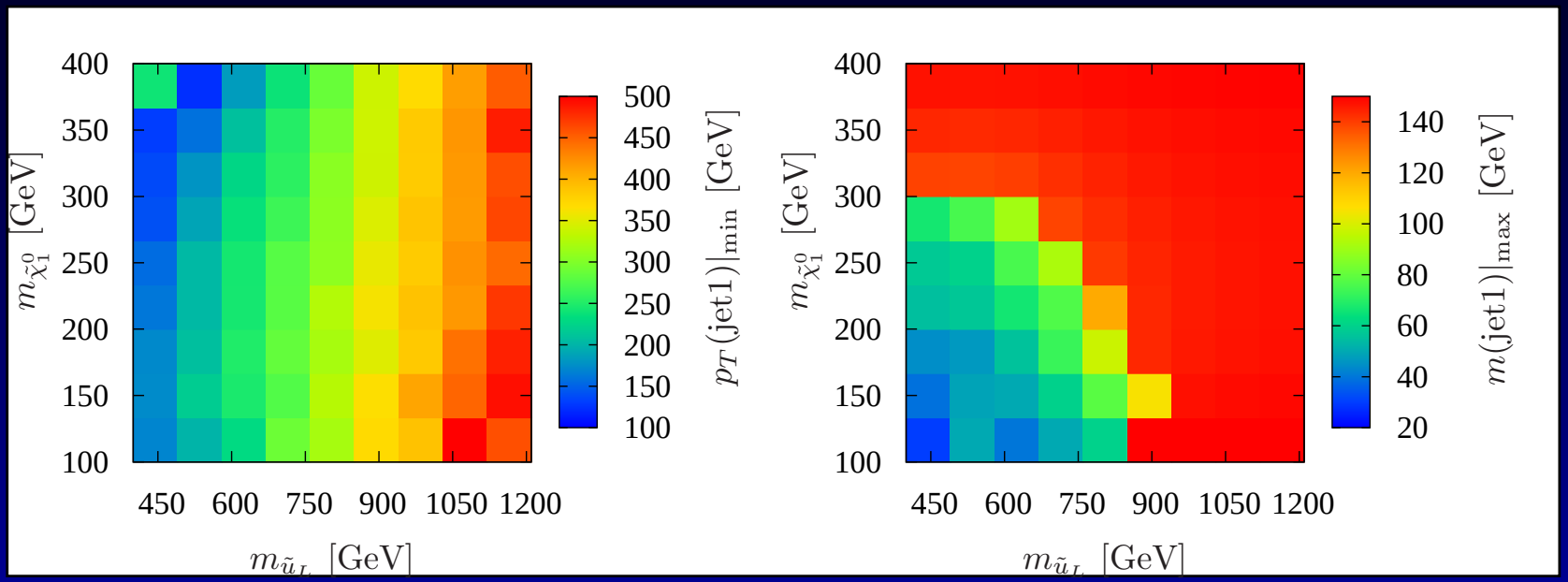
Best Cuts Over Parameter Space



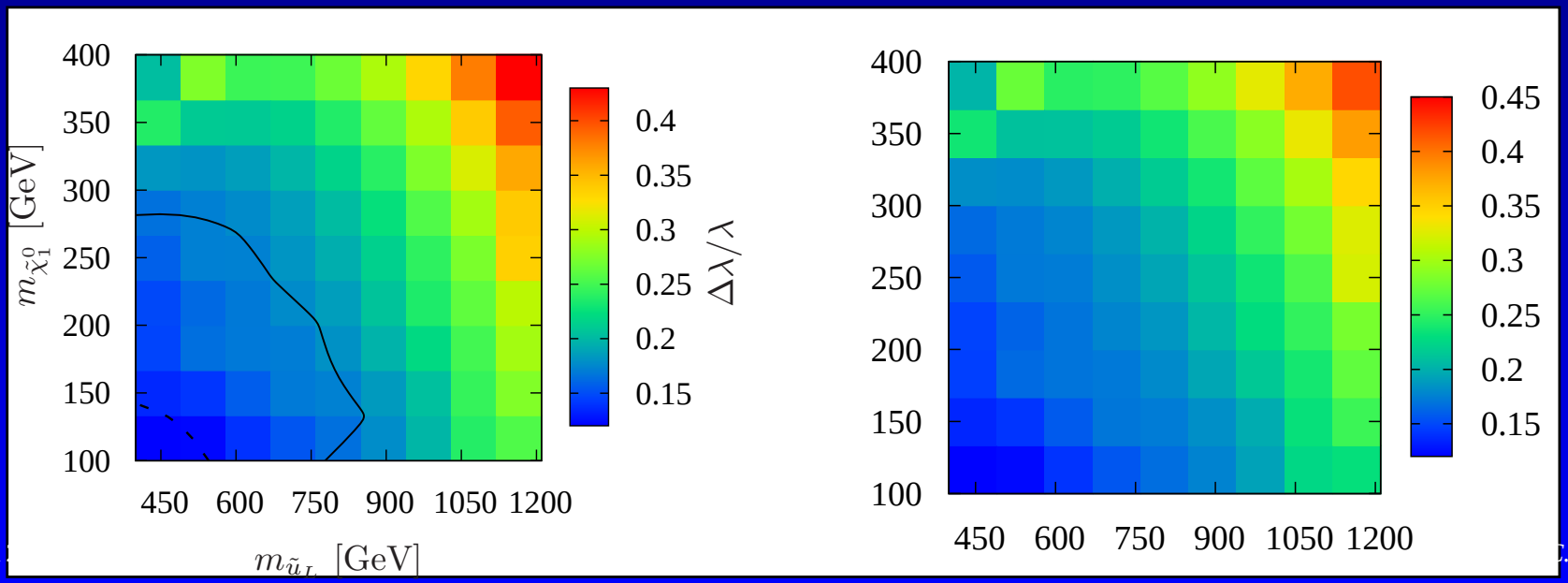
We now look at how well we might do over $\tilde{W}$-LSP parameter space. Search in steps of 10 GeV for the p_T cut that provides the highest $S/\sqrt{S+B}$, and the $m(j)$ cut. Best significance is near Jacobian peak.

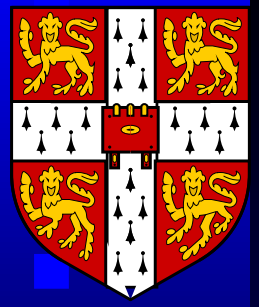
Red region: where $S/\sqrt{7B} \leq 5$.

Accuracy Over Parameter Space

- NLO uncertainties - log fit.
- PDF uncertainties - linear fit.
- Assume

$$\frac{\Delta m_{\tilde{q}}}{m_{\tilde{q}}} \propto \sqrt{\frac{1}{\sigma(PP \to \tilde{q}\tilde{q})}}.$$





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"

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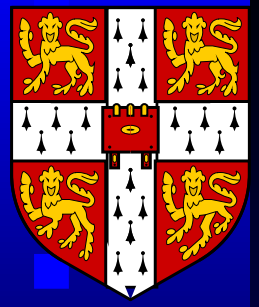

Definition of R-Parity

$\mathcal{Q}$: How is $W_{\not R_P}$ normally banned?

$\mathcal{A}$: By defining discrete symmetry R_p

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

$\rightarrow$ 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*

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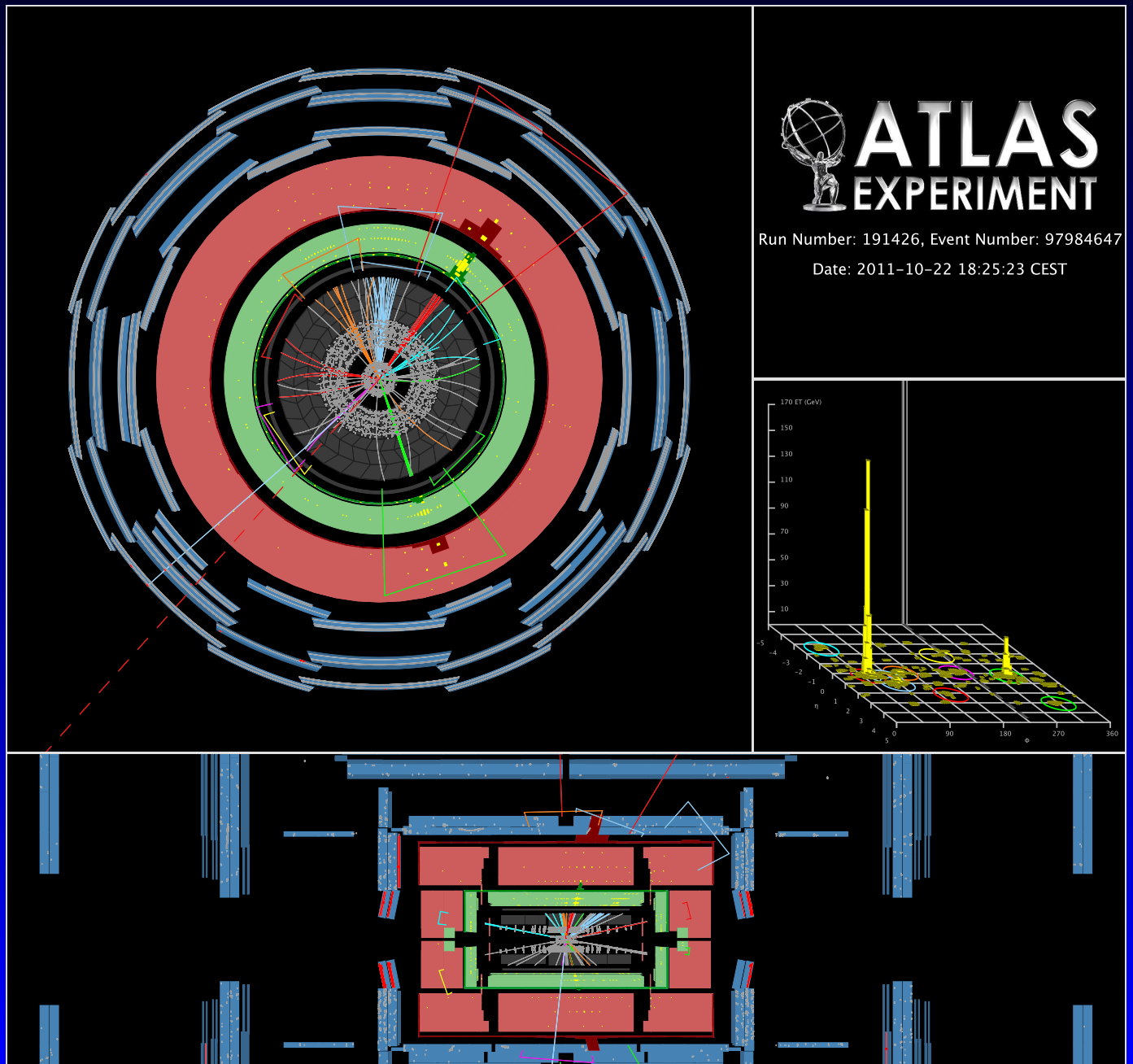
Candidate Event: High $E_T(j)$



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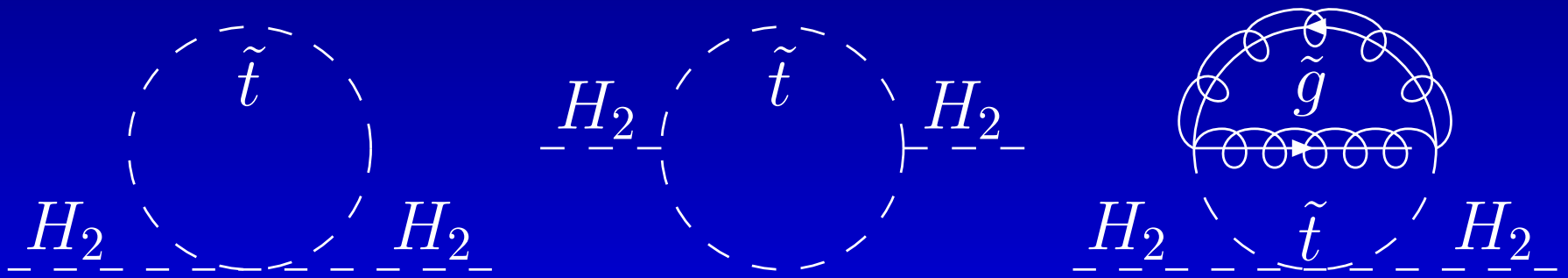
Natural SUSY

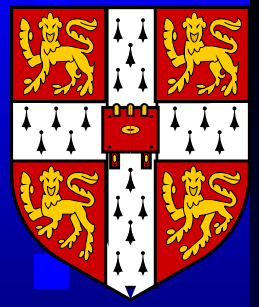
The particles coupling the most strongly to the higgs are the *stops*[a]. Minimising the MSSM Higgs potential,

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

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



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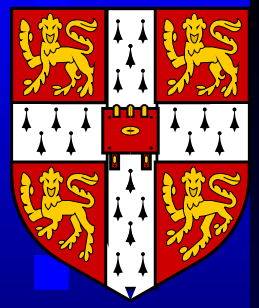
$$\delta m_{H_2}^2 \approx \frac{-3h_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda_{UV}}{m_{\tilde{t}}}\right)$$

No cancellation$\Rightarrow$

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

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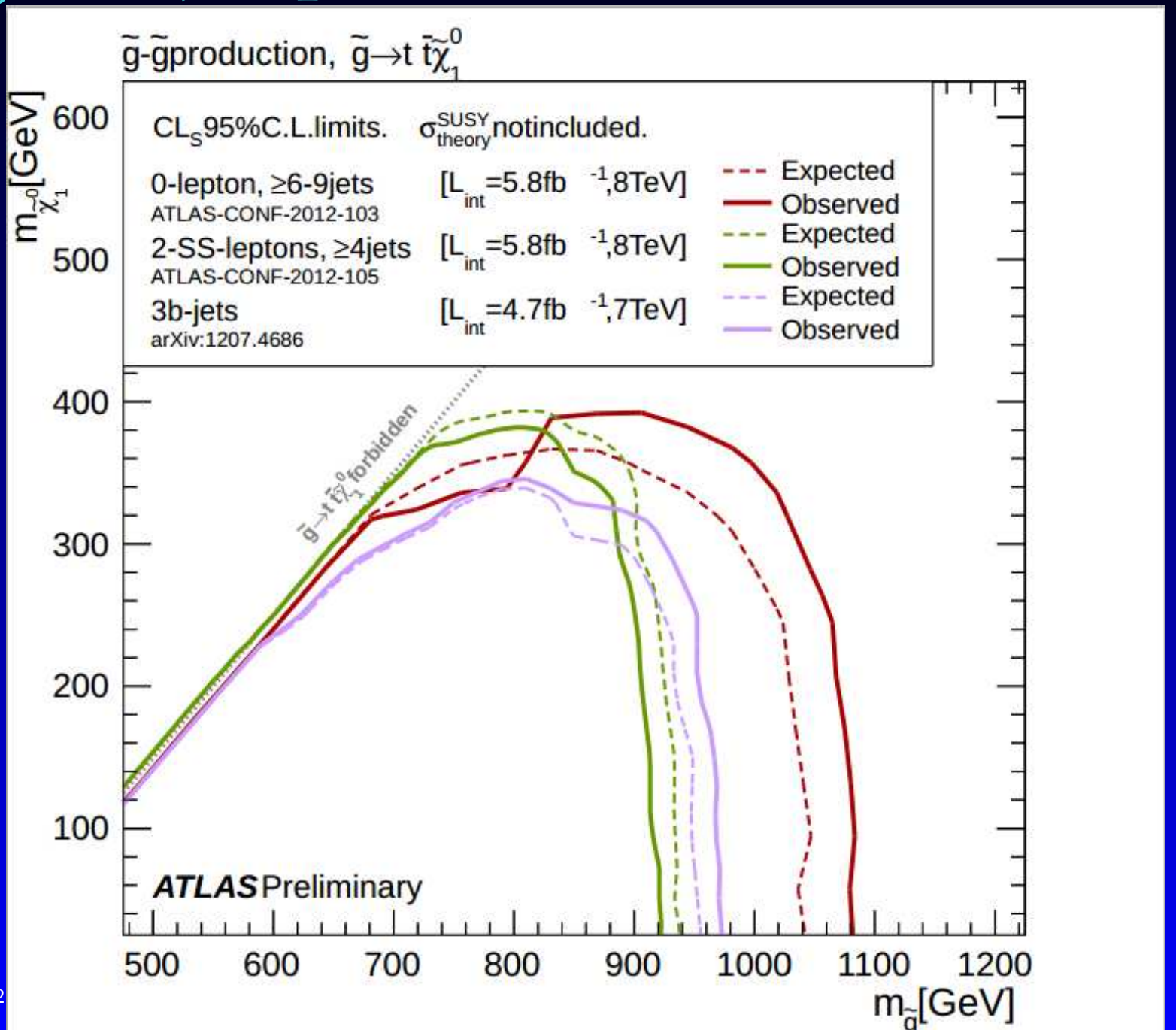
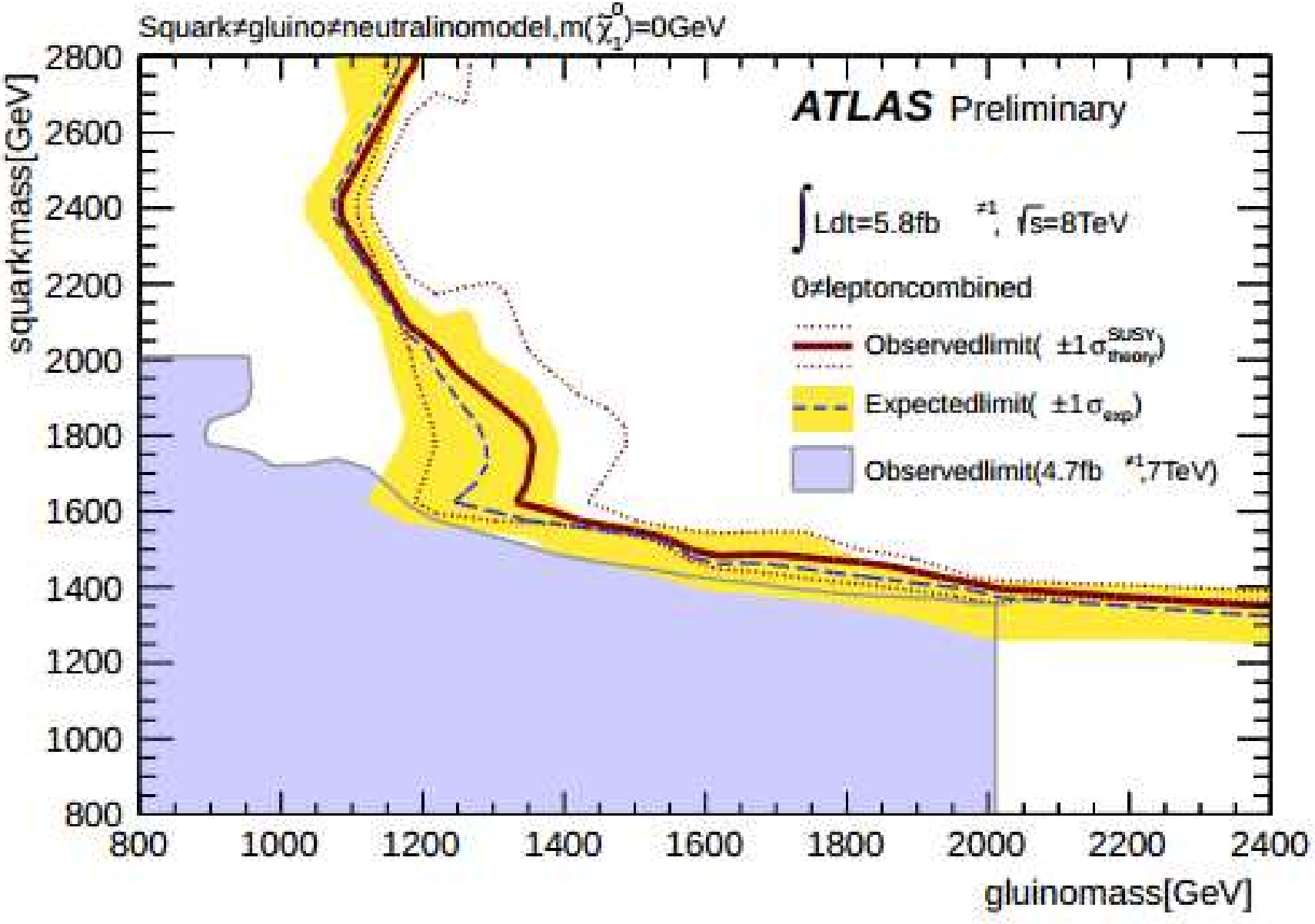
gt: $\not{E}_T > 50/120$ **GeV,** $N_b \geq 2$, $\#j \geq 2$, $H_T > 320$ **GeV**



Jets Plus $\not{E}_T$ Search



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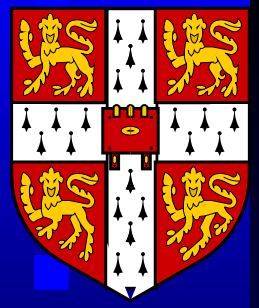


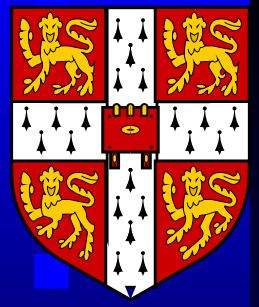
Bottom Up Implications of 2012 Data

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.

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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) $6\times10^{-17}\,\tilde{s}_R^2\,(m_{3/2}/1$ eV) $[p\to K^+\tilde{G}]$ (6.121) $8\times10^{-17}\,C_q^{-1}\,\tilde{s}_R^2\,(F_a/10^{10}$ 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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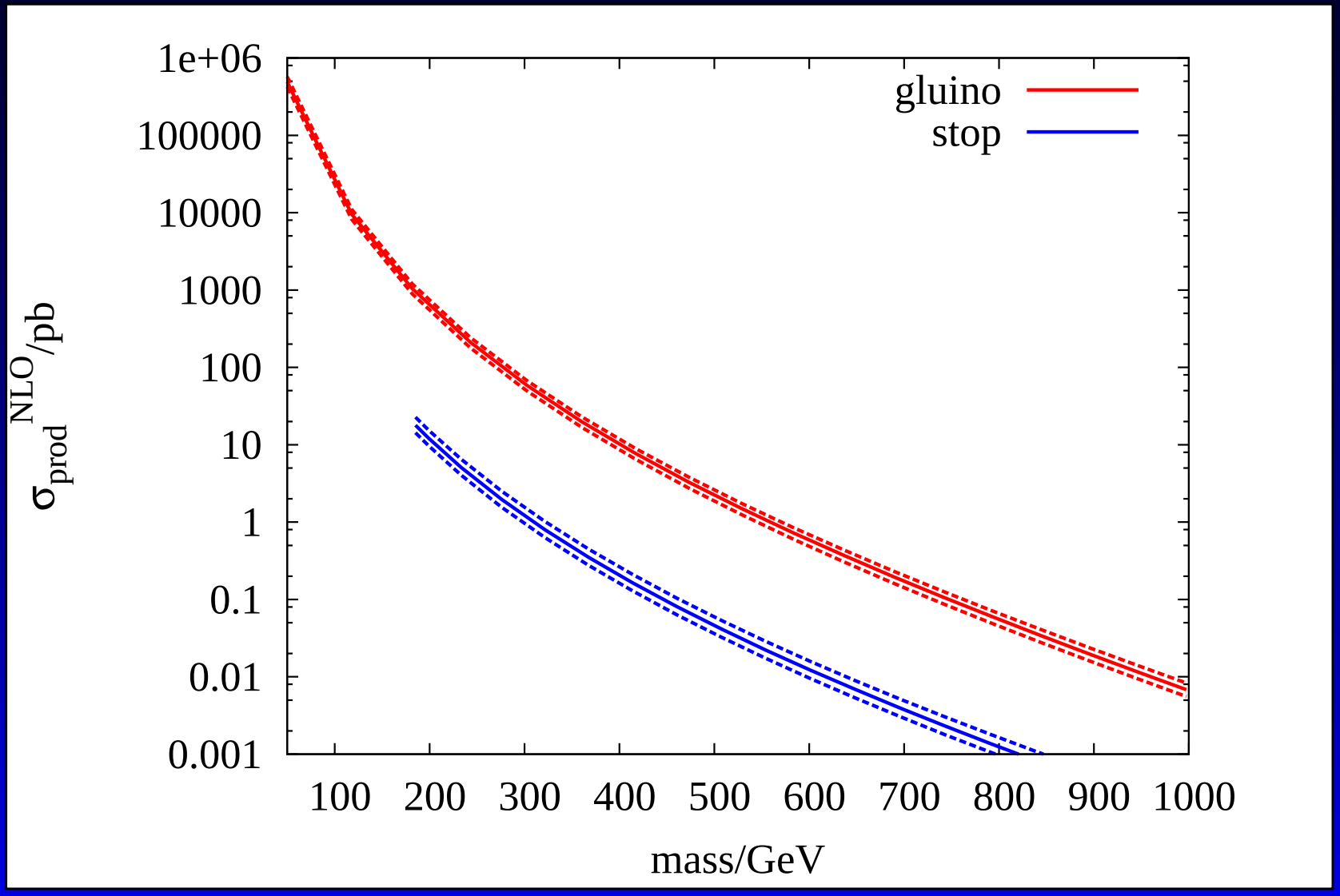
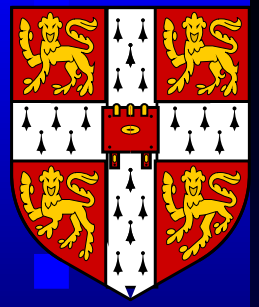
Bottom up thinking

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.

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.

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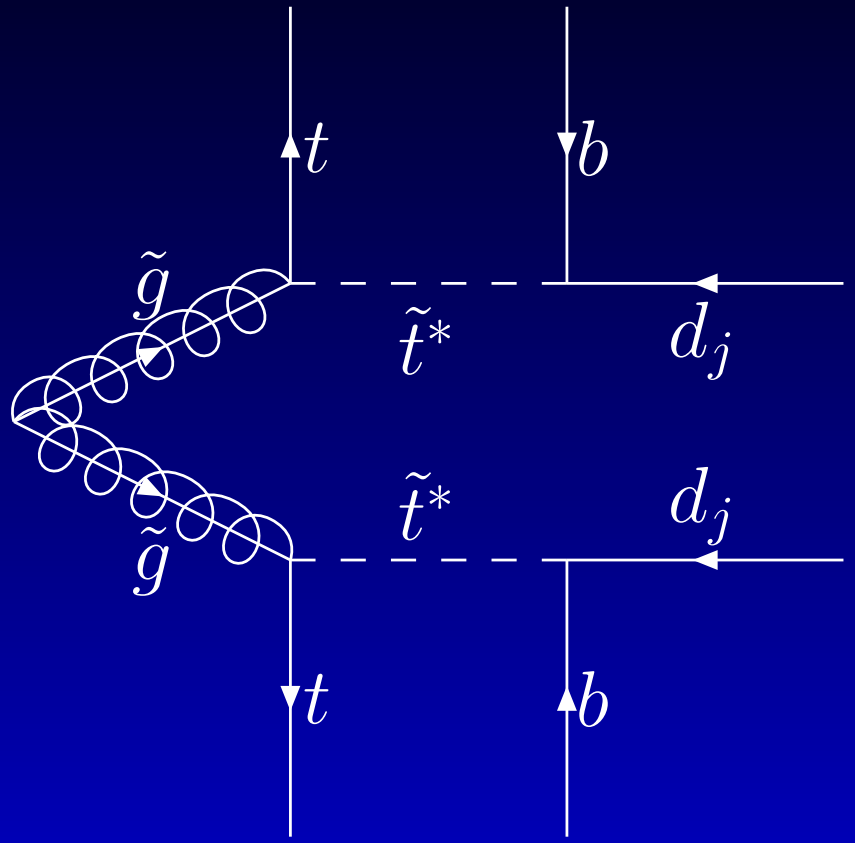
Baryon Number Violating Example



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?

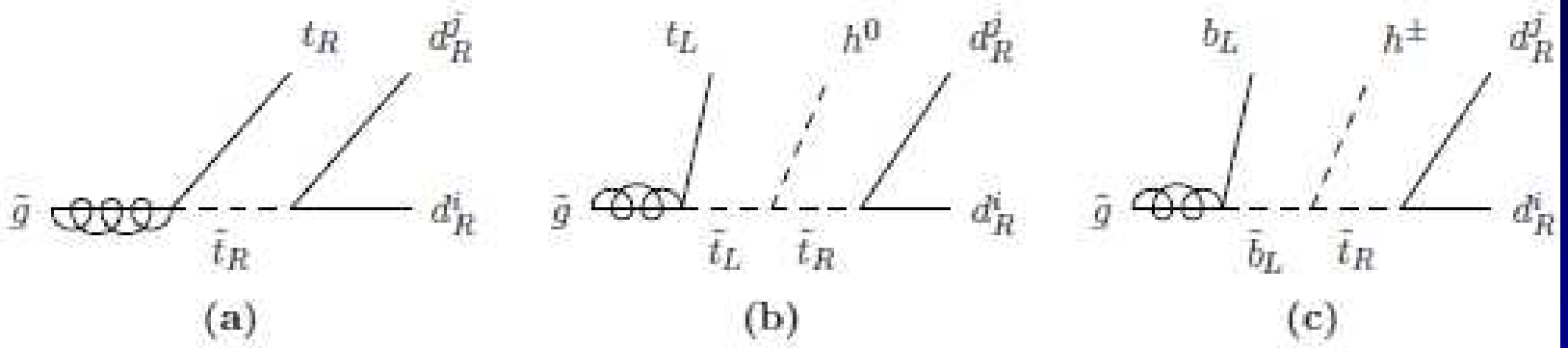


Figure 1. Gluino decays without right-handed bottom squarks in the presence of $W \supset U_3 D_i D_j$, via (a) right-handed top, (b) left-handed top, and (c) left-handed bottom. Same sign leptons are obtained in (c) only if the charged Higgs subsequently decays to $t\bar{b}$ or to leptons.

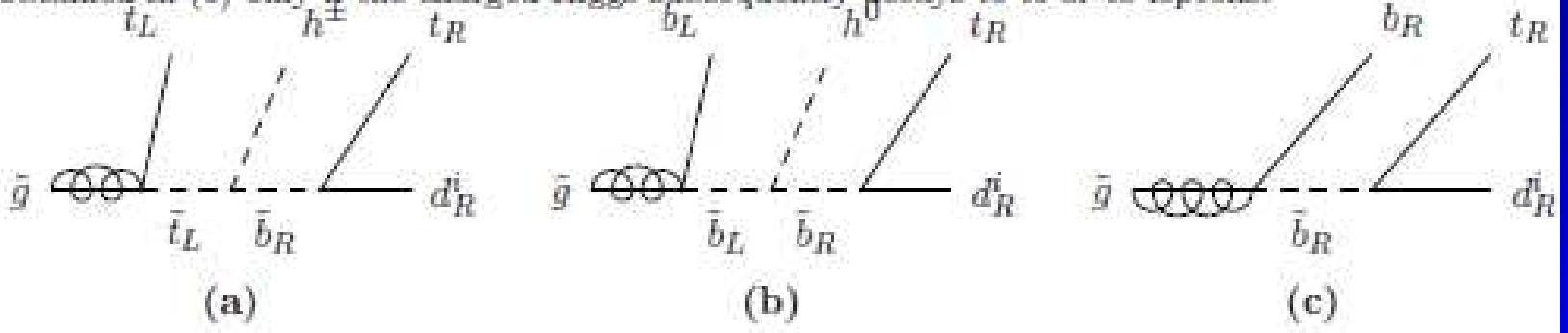
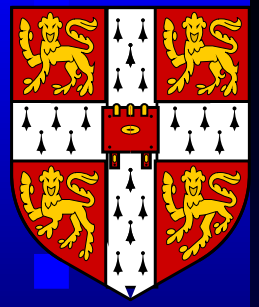


Figure 2. Gluino decays with right-handed bottom squarks in the presence of $W \supset U_3 D_i D_3$, via (a) left-handed top squark, (b) left-handed bottom squark, and (c) right-handed bottom squark.



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).

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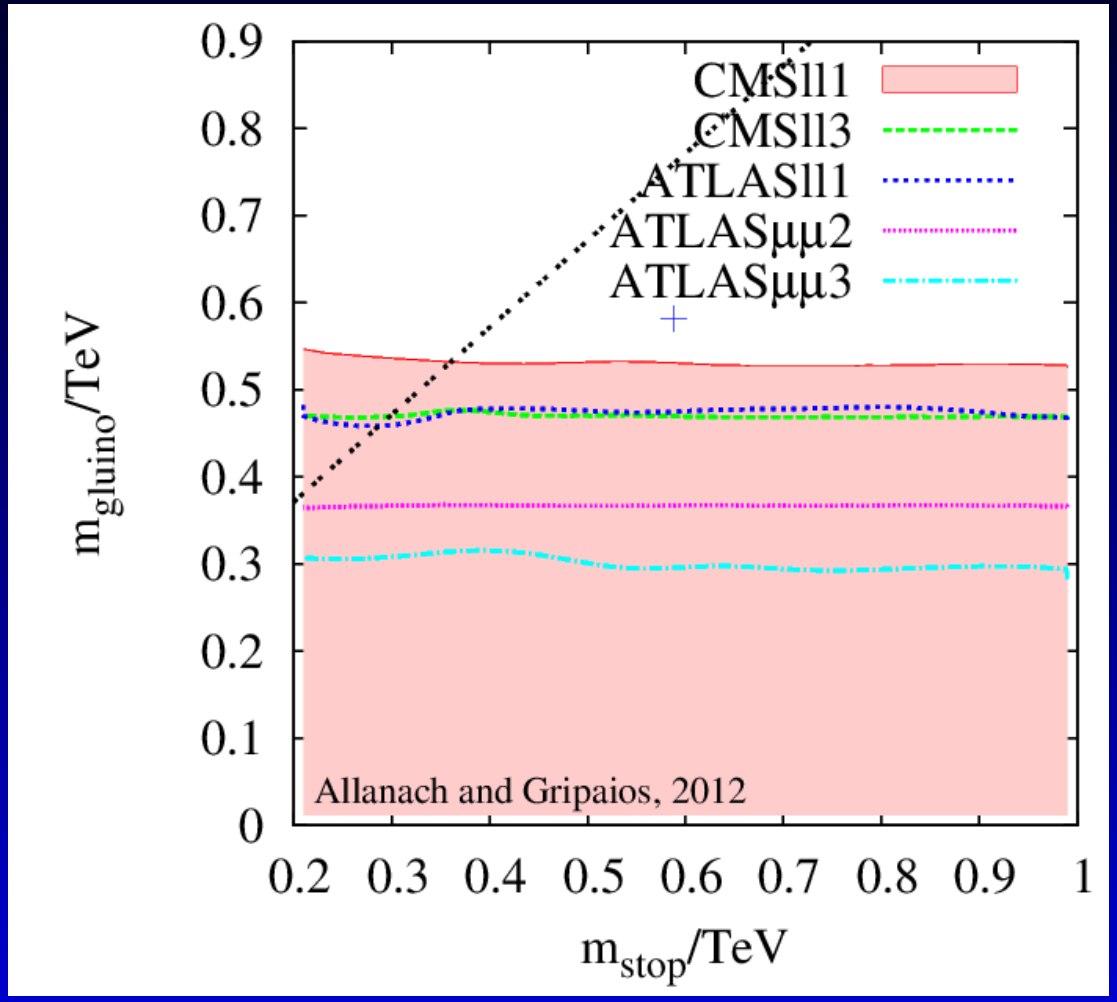
Same-sign $\not{E}_T$ Limits



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

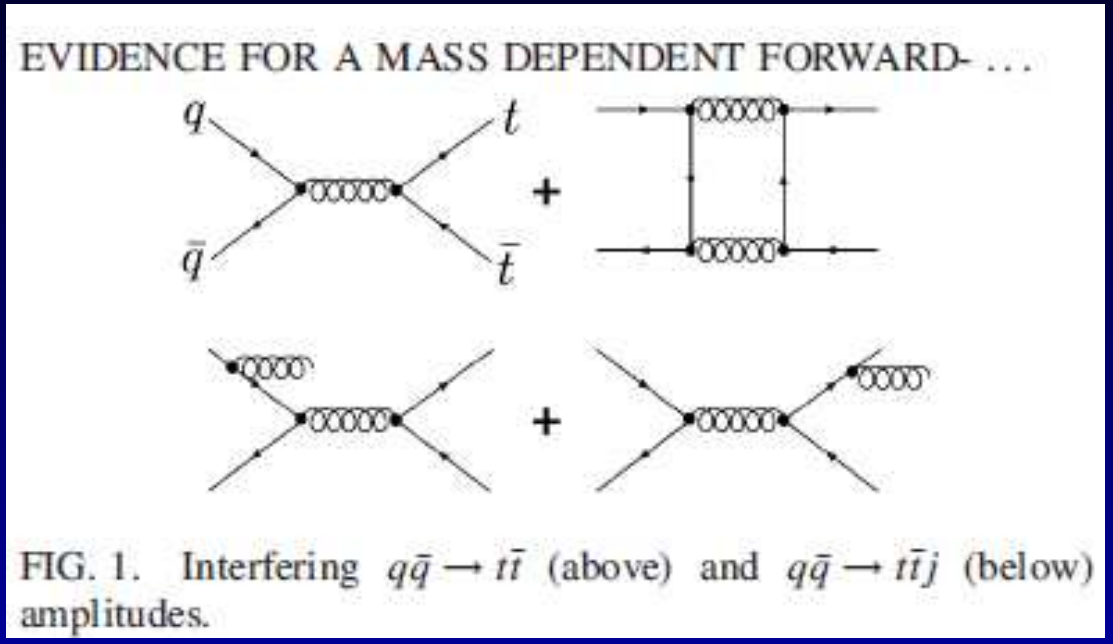

EVIDENCE FOR A MASS DEPENDENT FORWARD- . . .

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

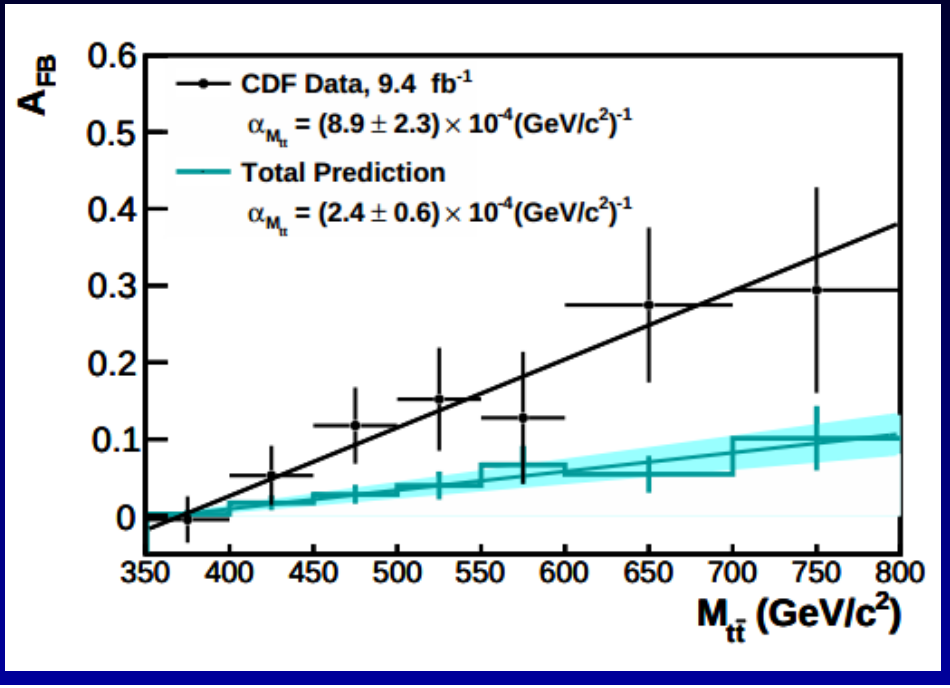
1.96 TeV $p\bar{p}$ collisions at the Tevatron.

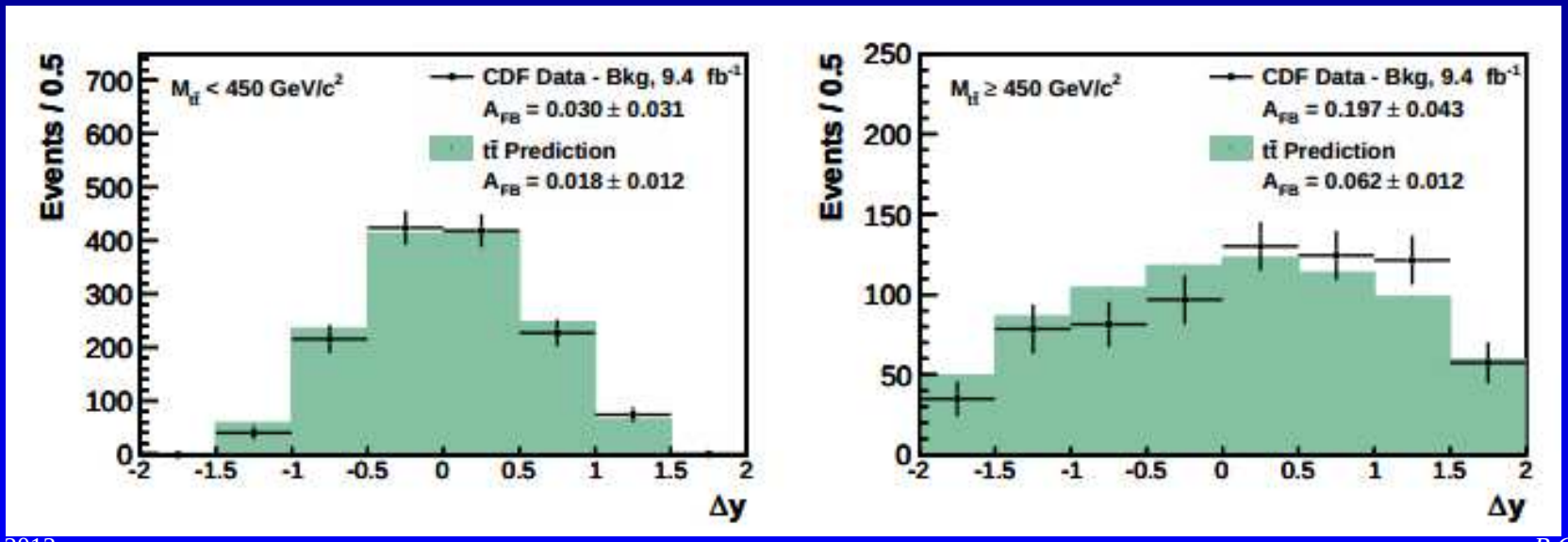
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, c = \cos\theta.$$

NLO QCD+NLNLL SM Prediction[a]: $7.2 \pm 1.0\%$.

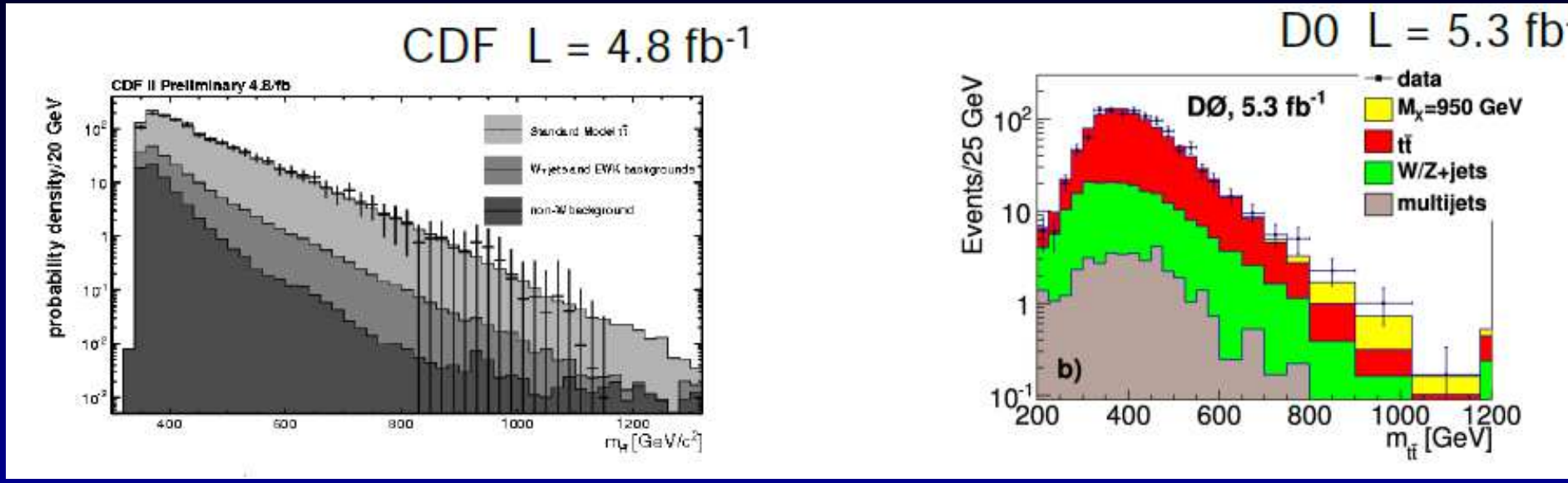
[a] Ahrens et al, PRD84 (2011) 074004

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

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ΔA_{FB}

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

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

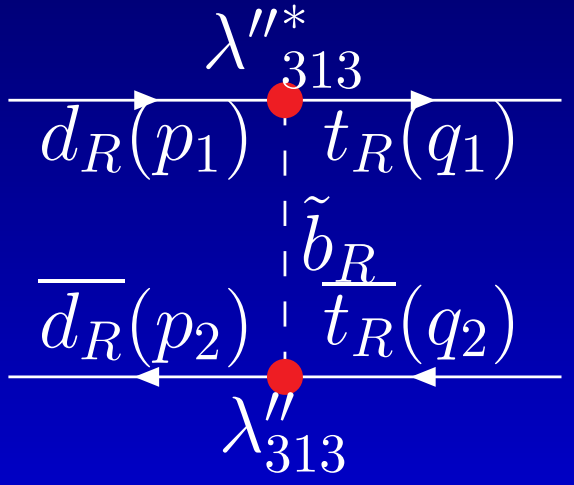


Figure 2: SUSY contribution to A_{FB}[a]

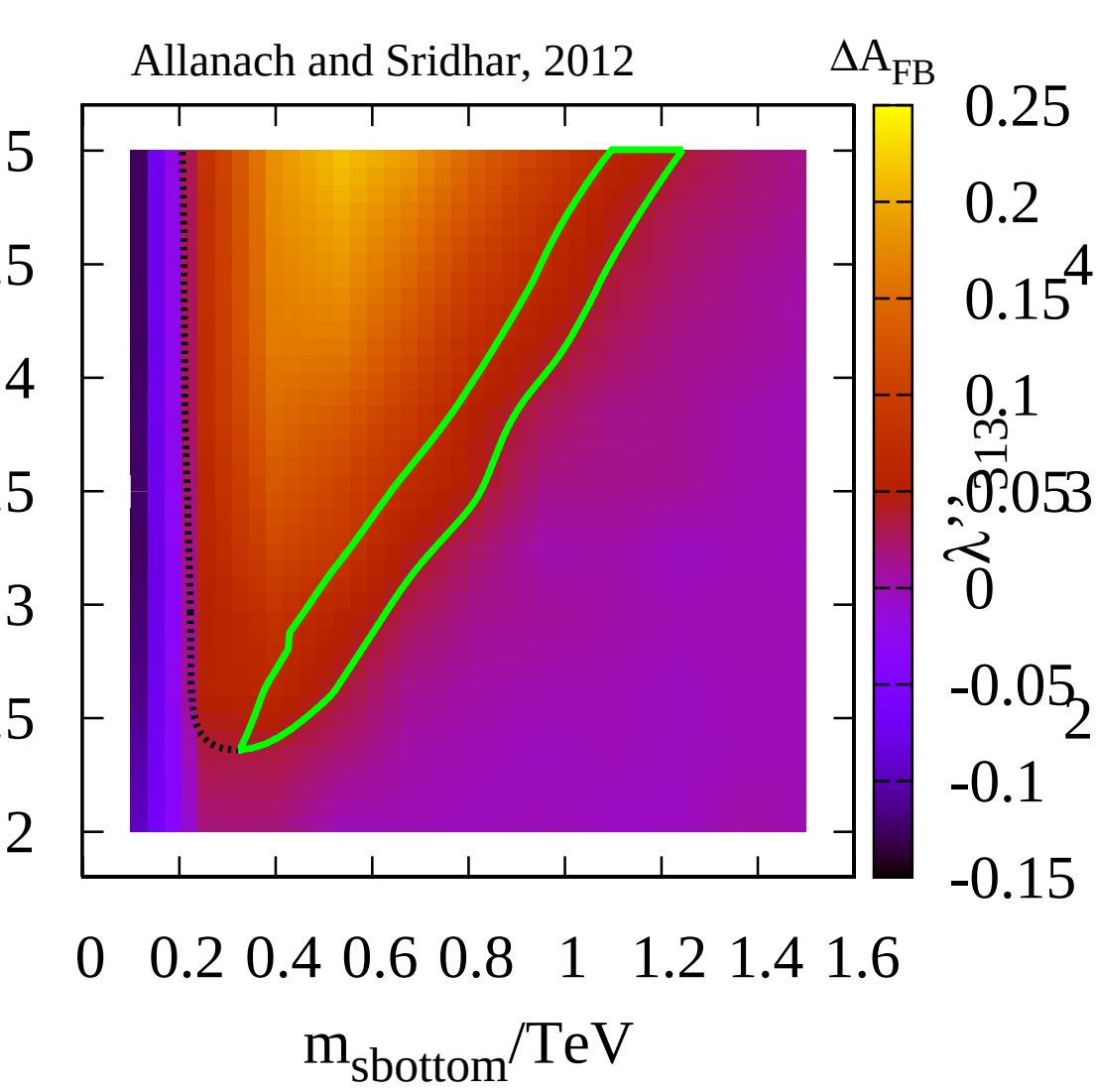
[a] BCA, Sridhar arXiv:1205.5170

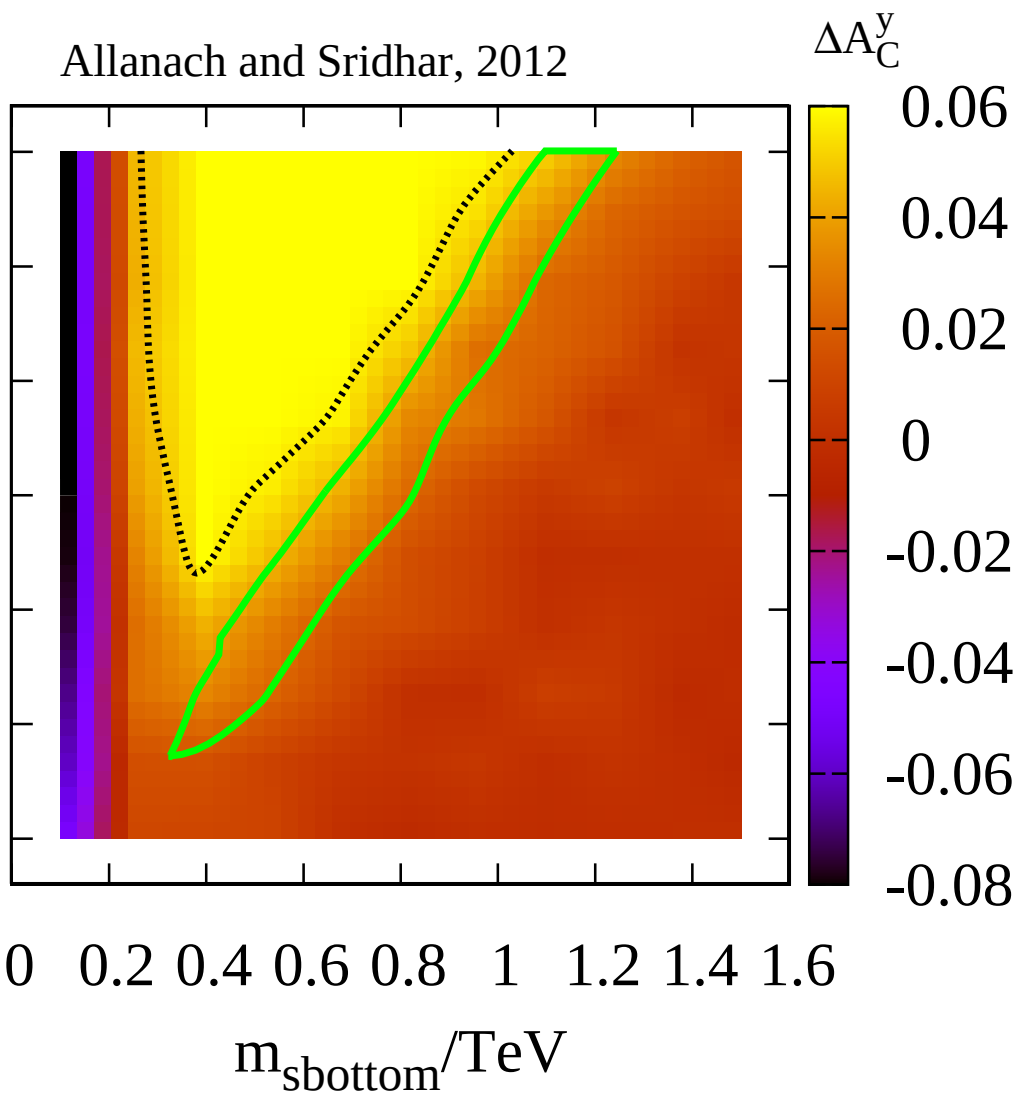
New Physics Contribution

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

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

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

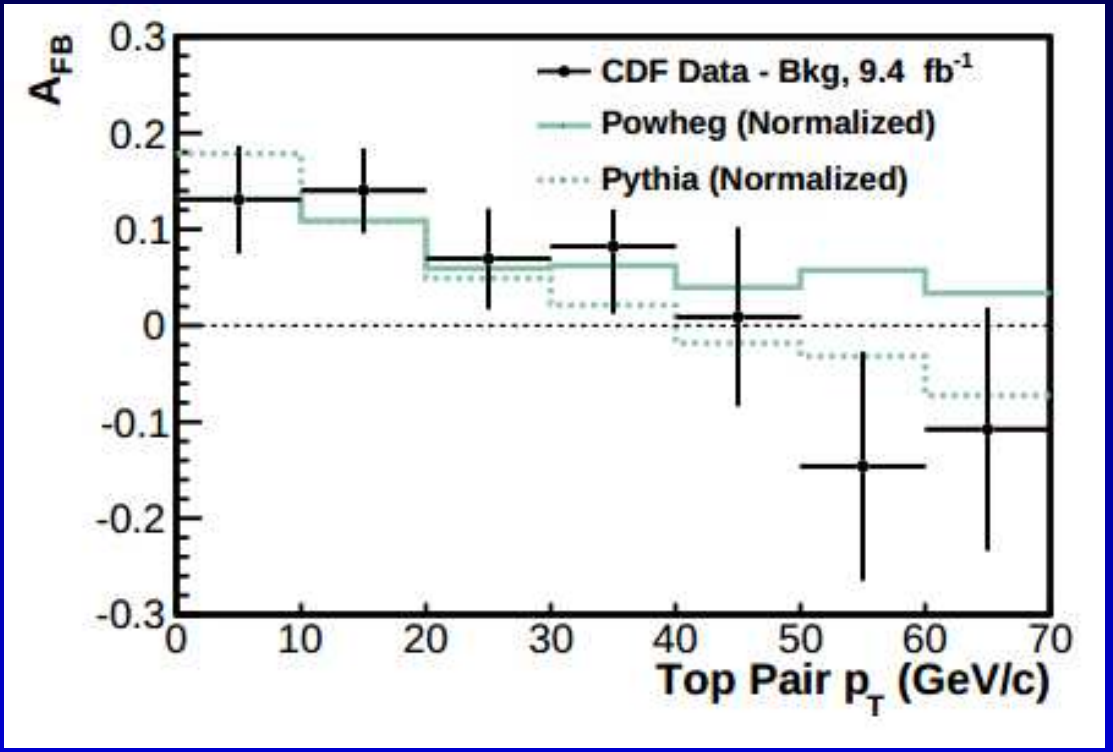
Table 2: 95% CL constraints

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

Table 3: 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,



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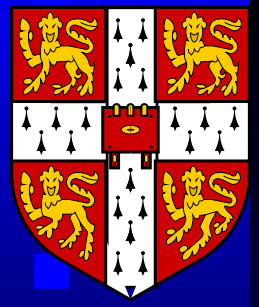

EWSB in the MSSM

Minimisation of MSSM Higgs potential yields the constraint:

$$(1)\quad \mu^2 = \frac{\tan 2\beta}{2}\left[m_{H_2}^2 \tan\beta - m_{H_1}^2 \cot\beta\right] - \frac{M_Z^2}{2}.$$

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

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

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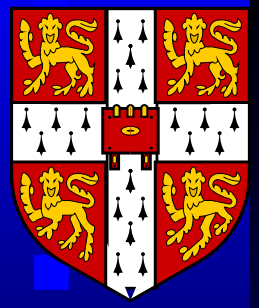
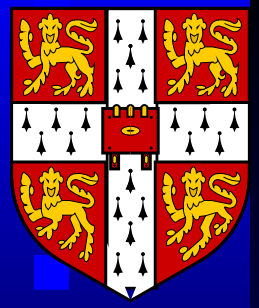


RGEs of EWSB

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

where $t=\ln Q$.

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



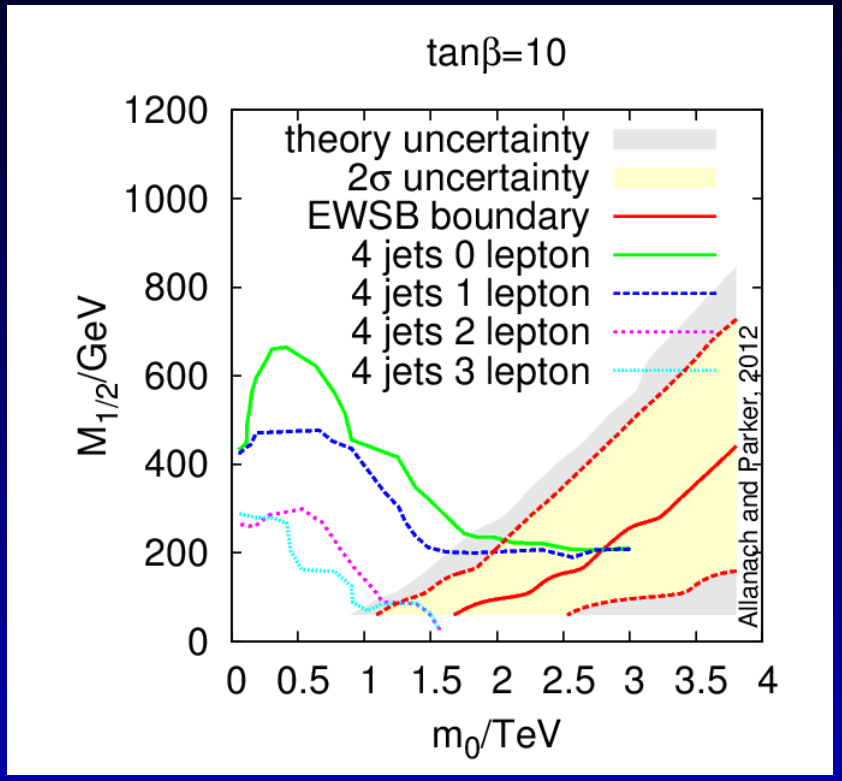
Approximate Solution

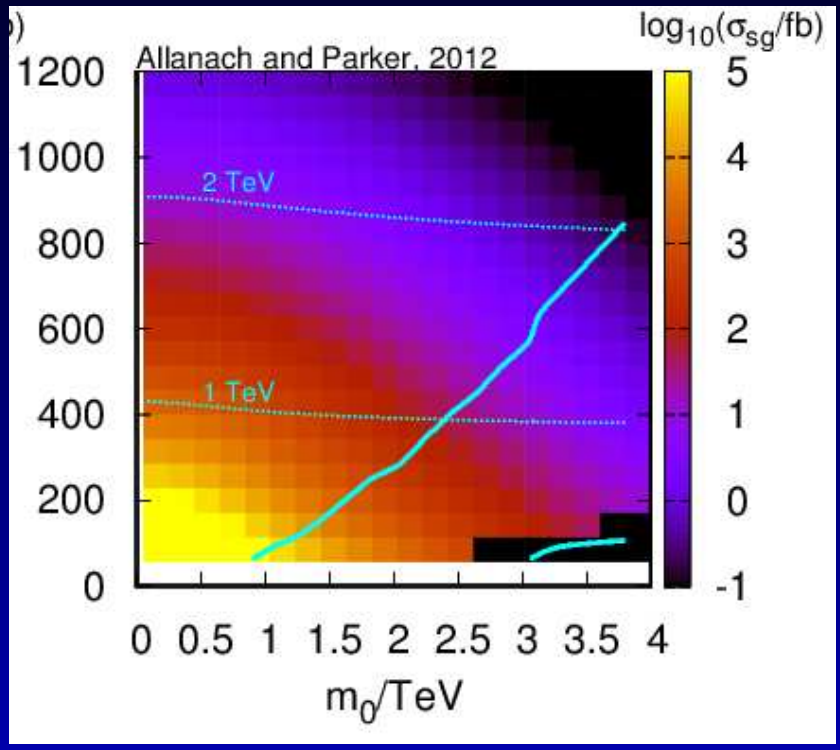
$$m^2_{H_2}(M_{SUSY}) = m^2_{H_2}(M_X) - A\left(6\left[m^2_{H_2}(M_X) + m^2_{\tilde{Q}_3}(M_X) + m^2_{\tilde{u}_3}(M_X) + A^2_t(M_X)\right]h^2_t(M_X)\right),$$

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

$$m^2_{H_2} < \frac{1}{1-6Ah_t^2}\left\{6Ah_t^2\left(m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + A_t^2\right) + \frac{M_Z^2}{\tan\beta\,\text{ta}} \right.$$
$$\left. \frac{1}{\tan^2\beta}\left[m^2_{H_1} - 6Ah_b^2(m^2_{\tilde{Q}_3} + m^2_{\tilde{d}_3} + A_b^2)\right]\right\},$$

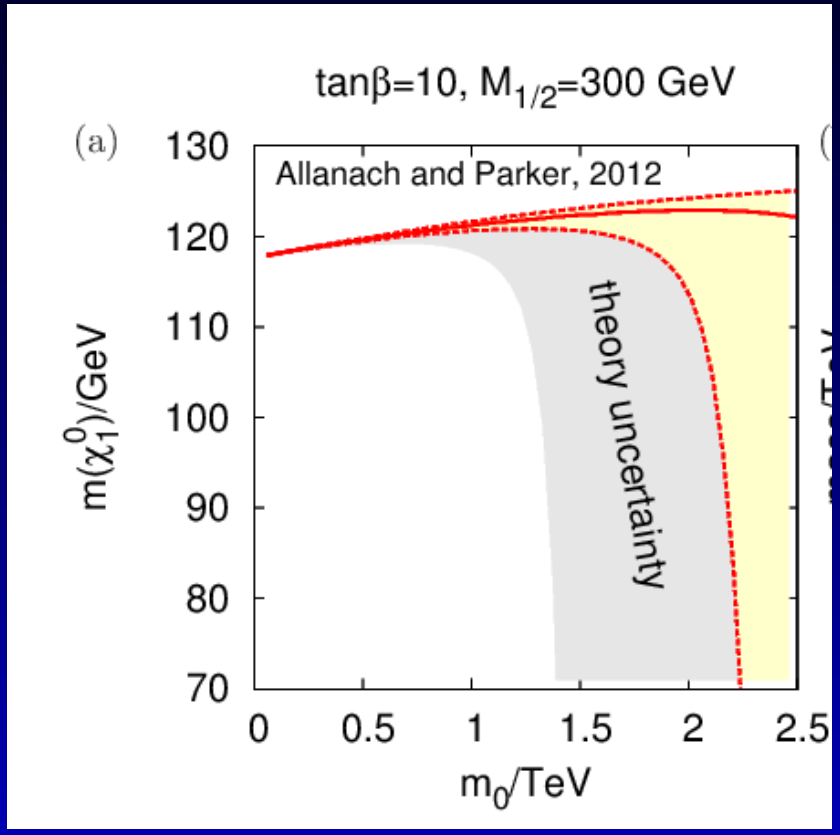
EWSB in the CMSSM at 14 TeV, 1 fb^{-1}, 5 σ

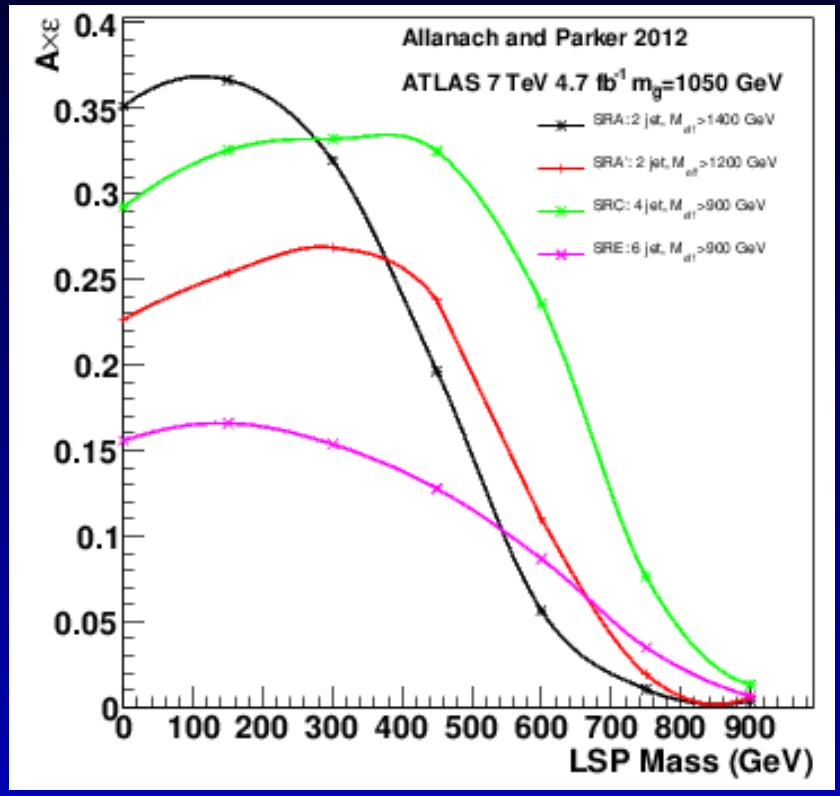




The position of the EWSB boundary is extremely uncertain due to the error in $m_t = 172.5 \pm 1$ GeV. *Experiments should use the higher value (plus theory error) when making grids of MSSM spectra*

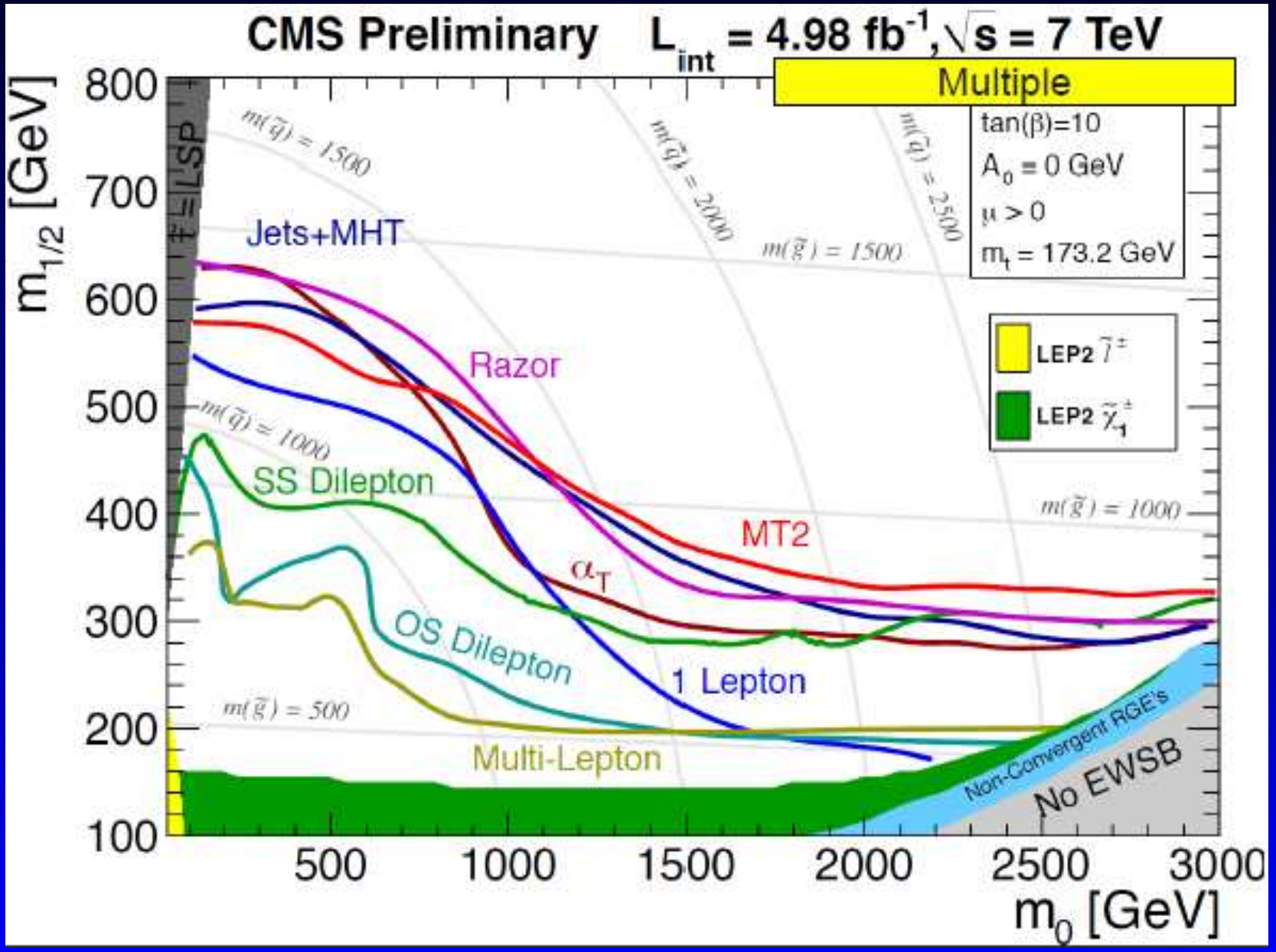
Neutralino Mass





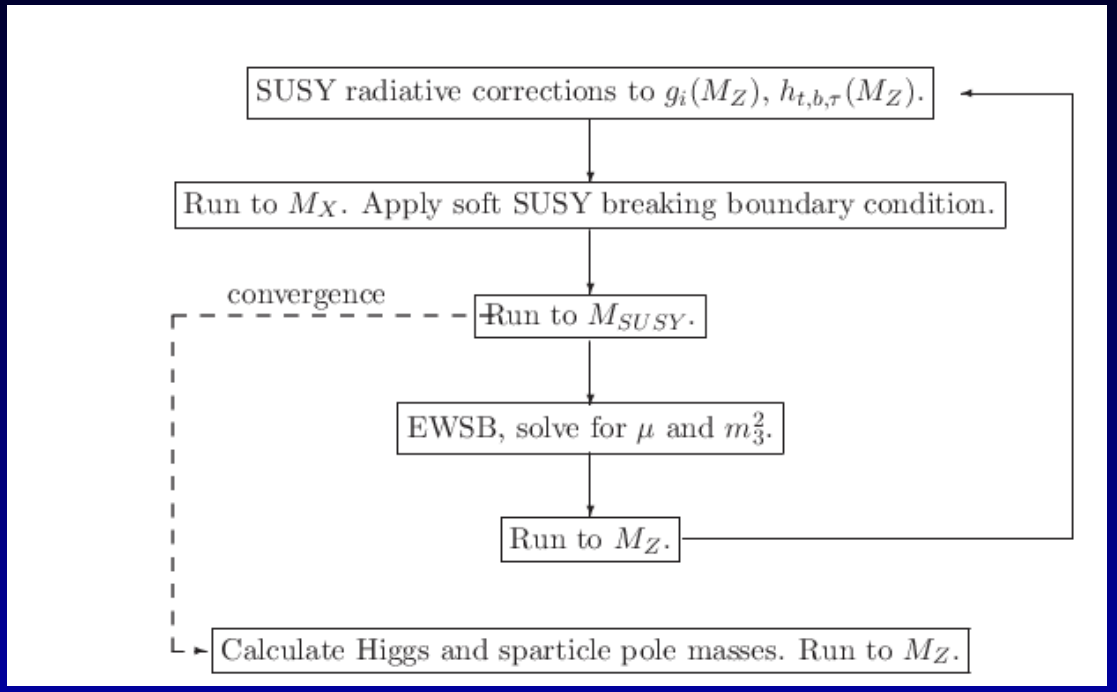
For a given value of m_t, on the boundary the LSP mass goes to 0. Therefore, for a given point in parameter space in the dodgy region, there is a 100% uncertainty in its mass $\Rightarrow$a theoretical error.

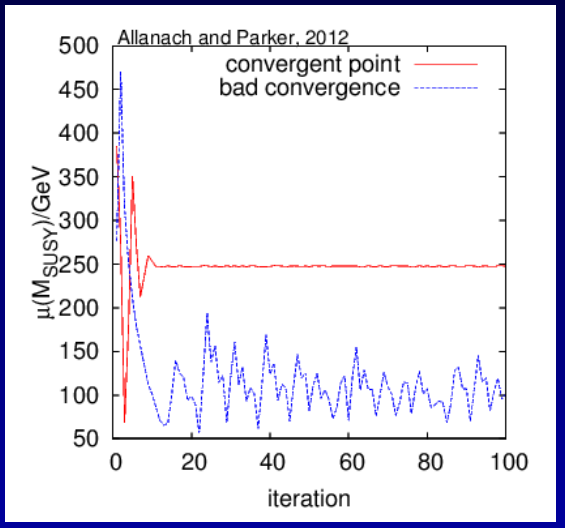
Bad convergence?



What is the "Non-convergent RGE region"?

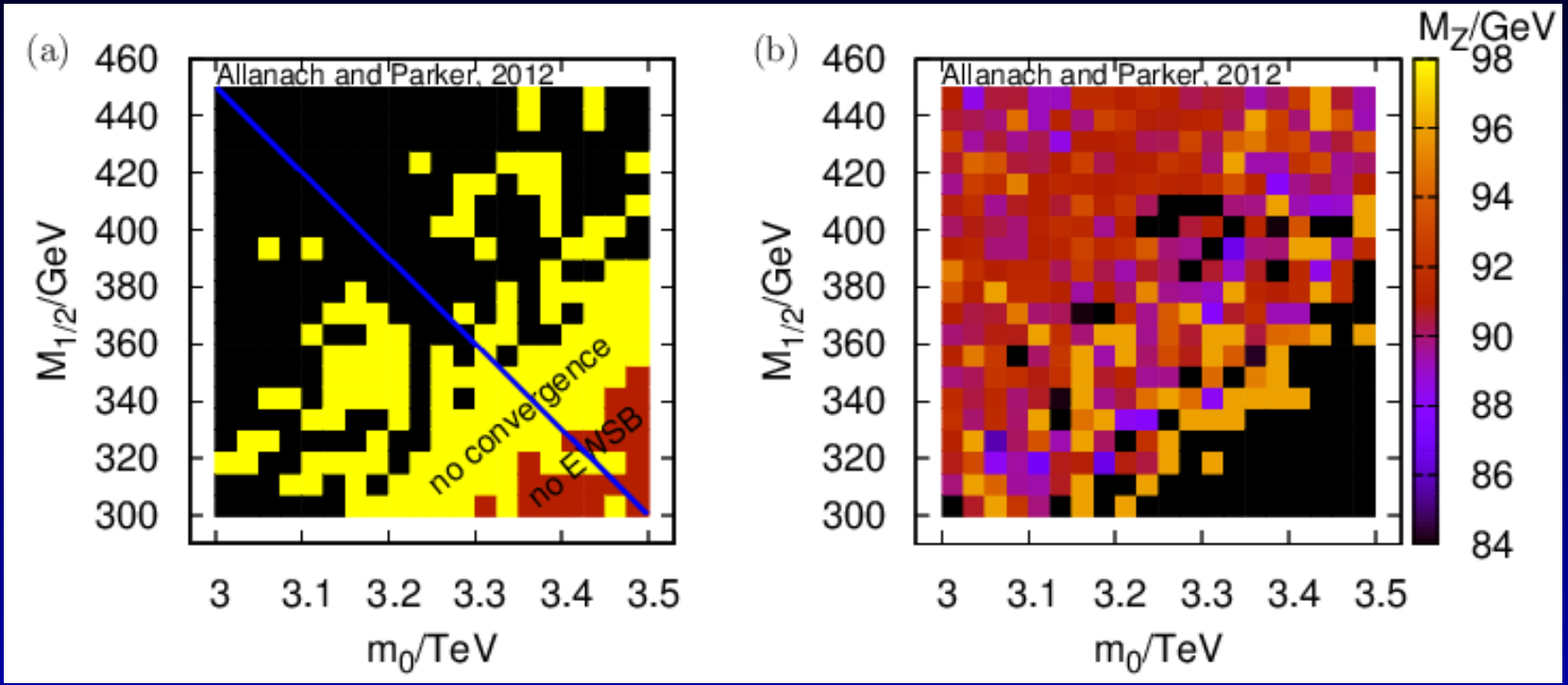
Bad convergence





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

Bad convergence region



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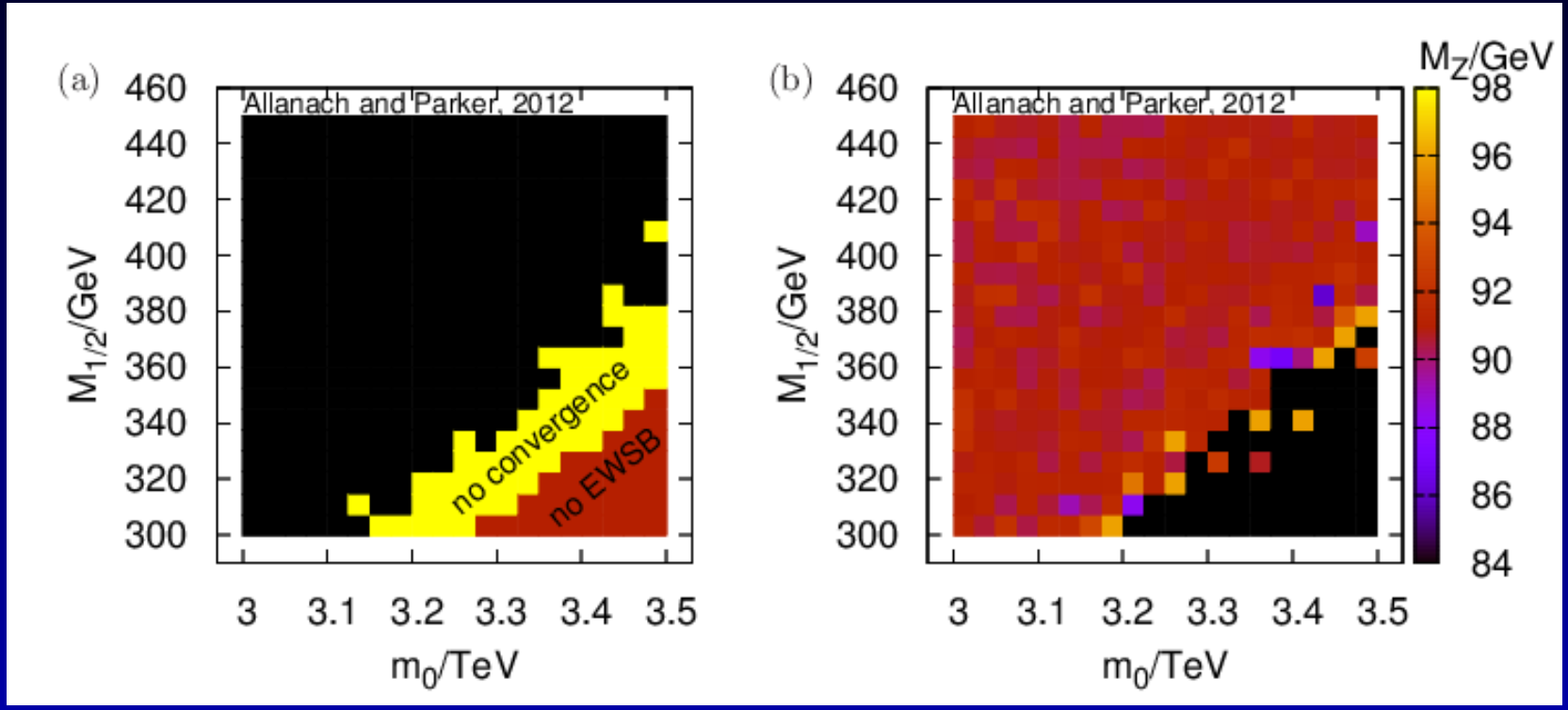
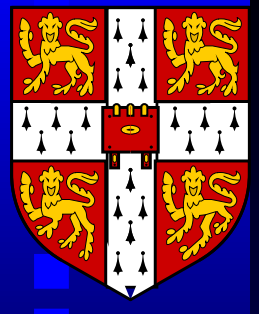
Tweaked up convergence



Iteration proceeds also until M_Z converges.
Sub-iterations made more accurate.



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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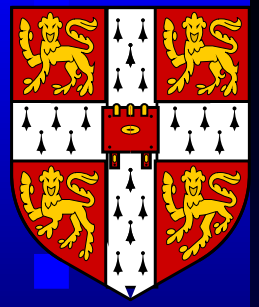

Summary

- 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.
- Paper by Brust, Katz, Sundrum, `arXiv:1206.2353` looks at $\tilde{b} \to l\nu jj$
- In case of $U_i D_j D_k$ operators, current searches $\Rightarrow m_{\tilde{g}} > 550$ GeV.
- Anomalous A_{FB} measurements can *also* be explained by $U_i D_j D_k$ type operator - fits all data
- Other models tend to fail one or more checks

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HAPPY BIRTHDAY HOWIE AND MICHAEL

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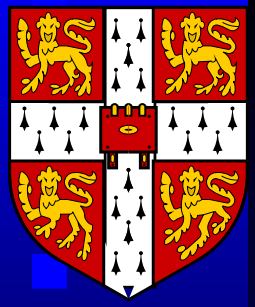

Backup

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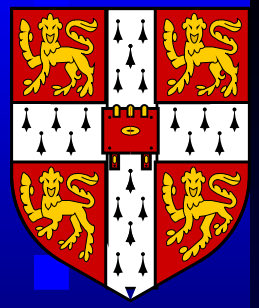

Sets of Cuts

Signal Region	$m_{\mu\mu}$/GeV	$\sigma^{test}_{SS\mu\mu}$/fb	$A/10^{-3}$	$\sigma^{95}_{SS\mu\mu}$/fb
ATLAS$\mu\mu1$	$>$15	12	1.3	58
ATLAS$\mu\mu2$	$>$100	7.5	0.86	16
ATLAS$\mu\mu3$	$>$200	2.1	0.29	8.4
ATLAS$\mu\mu4$	$>$300	0.41	0.077	5.3

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

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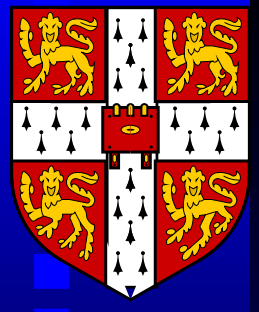

Sets of Cuts

Signal Region	$\lvert\vec{p}_{\rm T}^{\rm miss}\rvert$/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 5: ATLAS same sign-di lepton analysis search regions.

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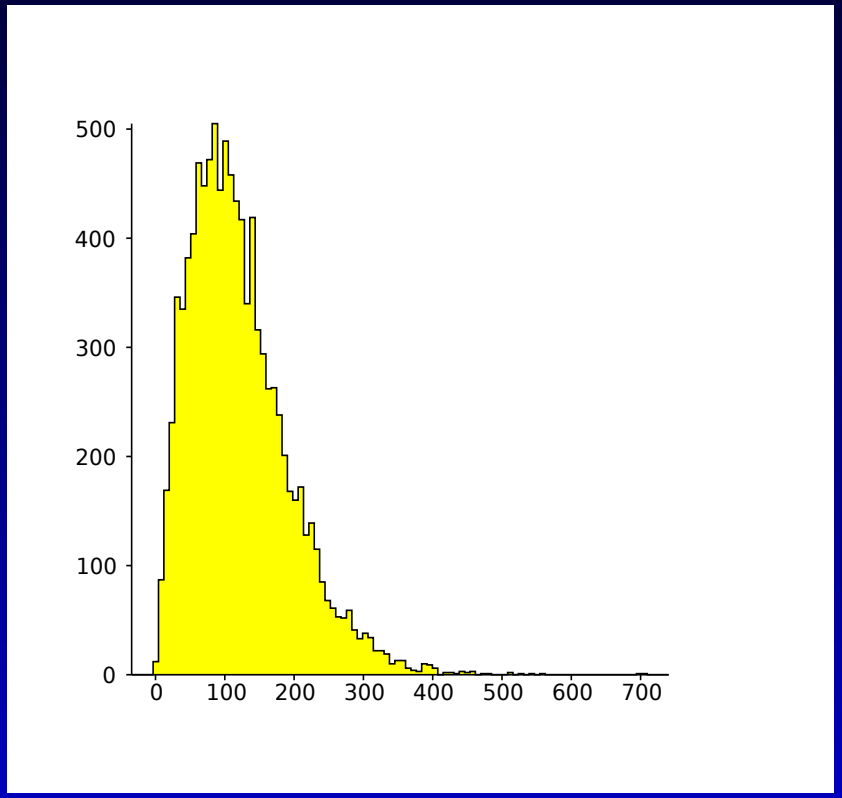
Sets of Cuts

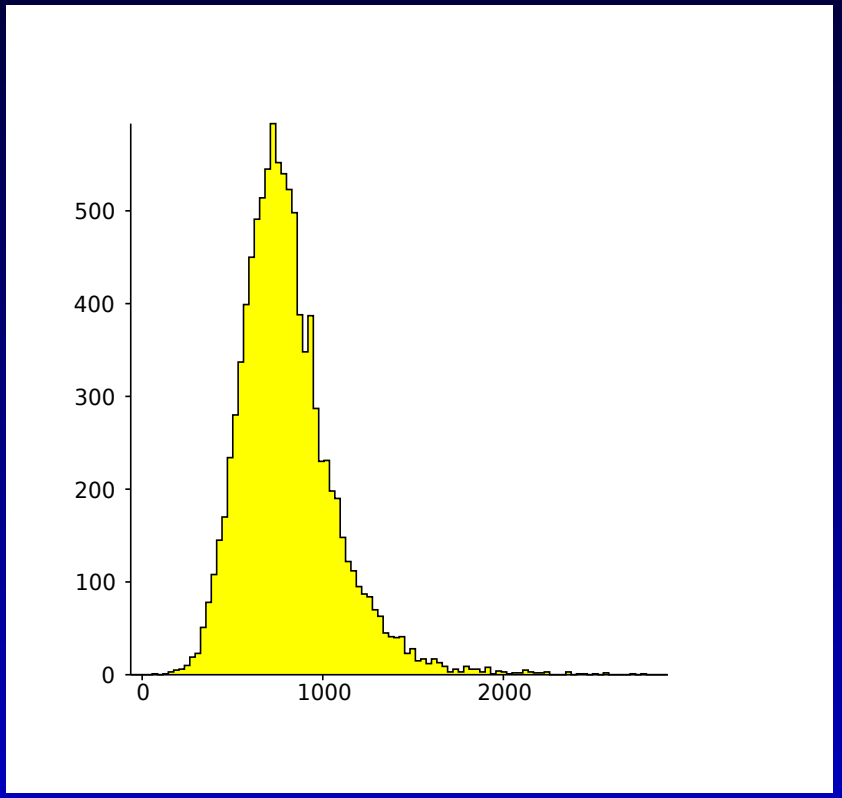
Signal Region	H_T/GeV	$\vert\vec{p}_{\rm T}^{\rm miss}\vert$/GeV	N_{ll}/fb	$A \times \epsilon / 10^{-3}$	N_{ll}^{95}
CMS$ll1$	$>$400	$>$120	2.4	3.5	$<$3.7
CMS$ll2$	$>$400	> 50	4.6	6.8	$<$8.9
CMS$ll3$	$>$200	$>$120	2.5	3.7	$<$7.3

Table 6: 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

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

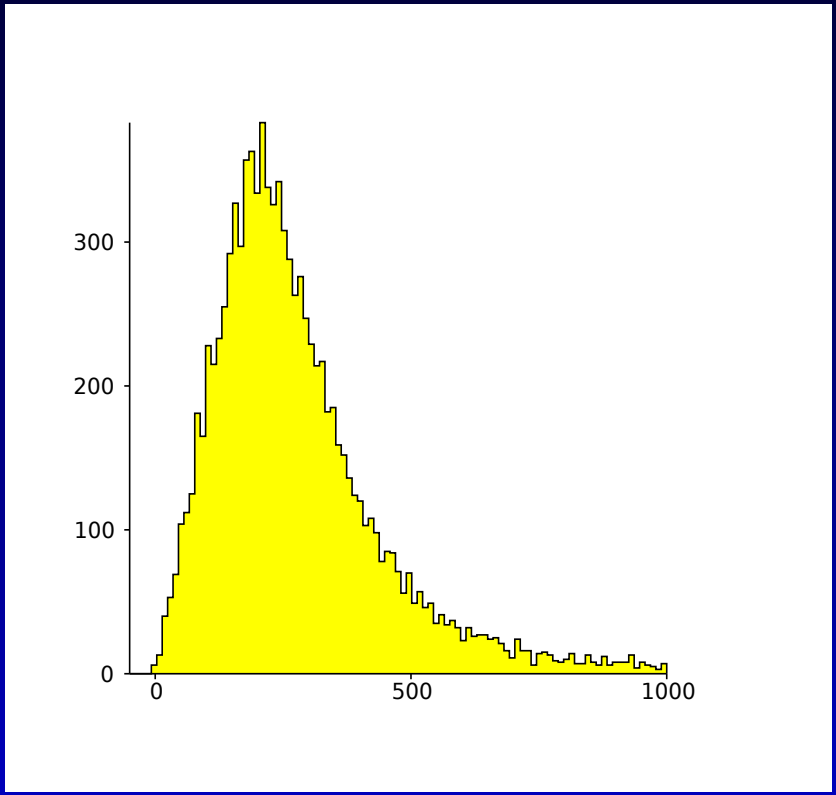


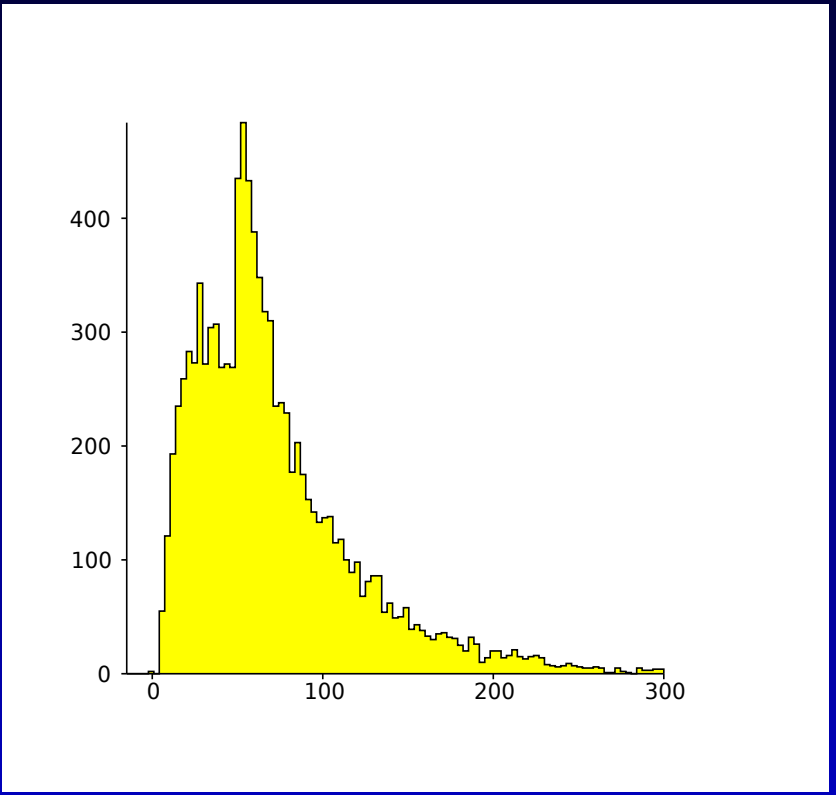


LH panel: $\not{E}_T/GeV$, RH panel: H_T/GeV

Test Point

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

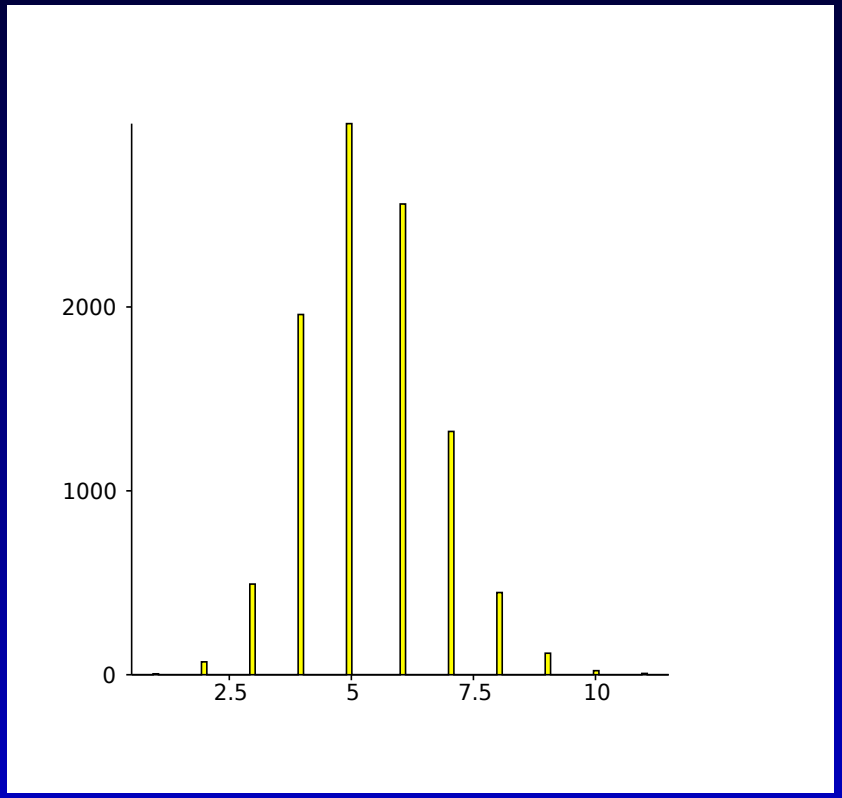


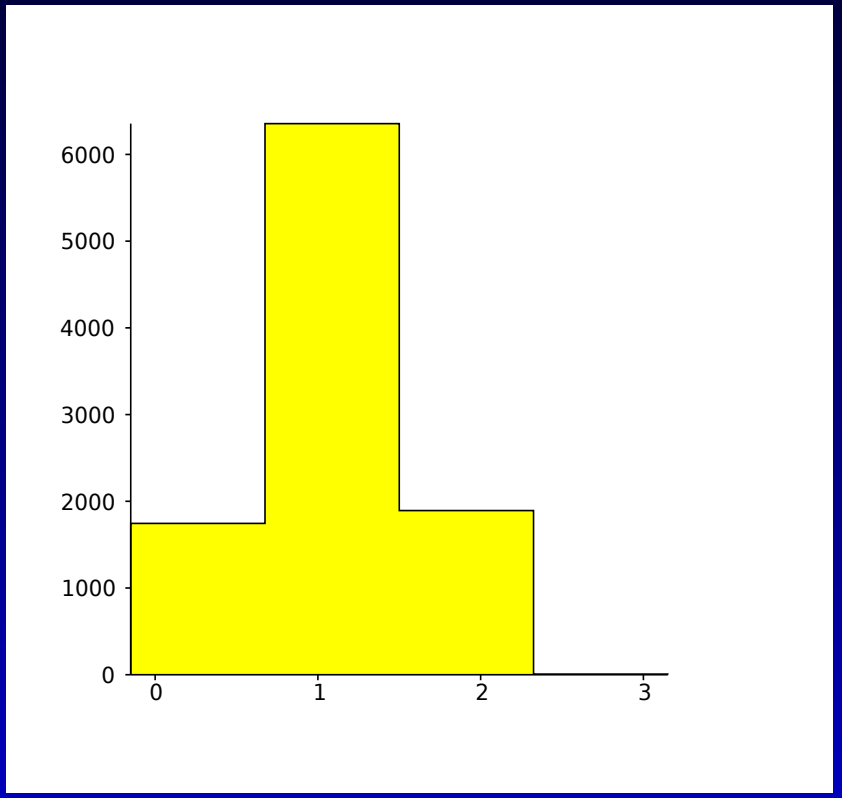


LH panel: $p_T(j_1)/GeV$, RH panel: $p_T(l_1)/GeV$

Test Point

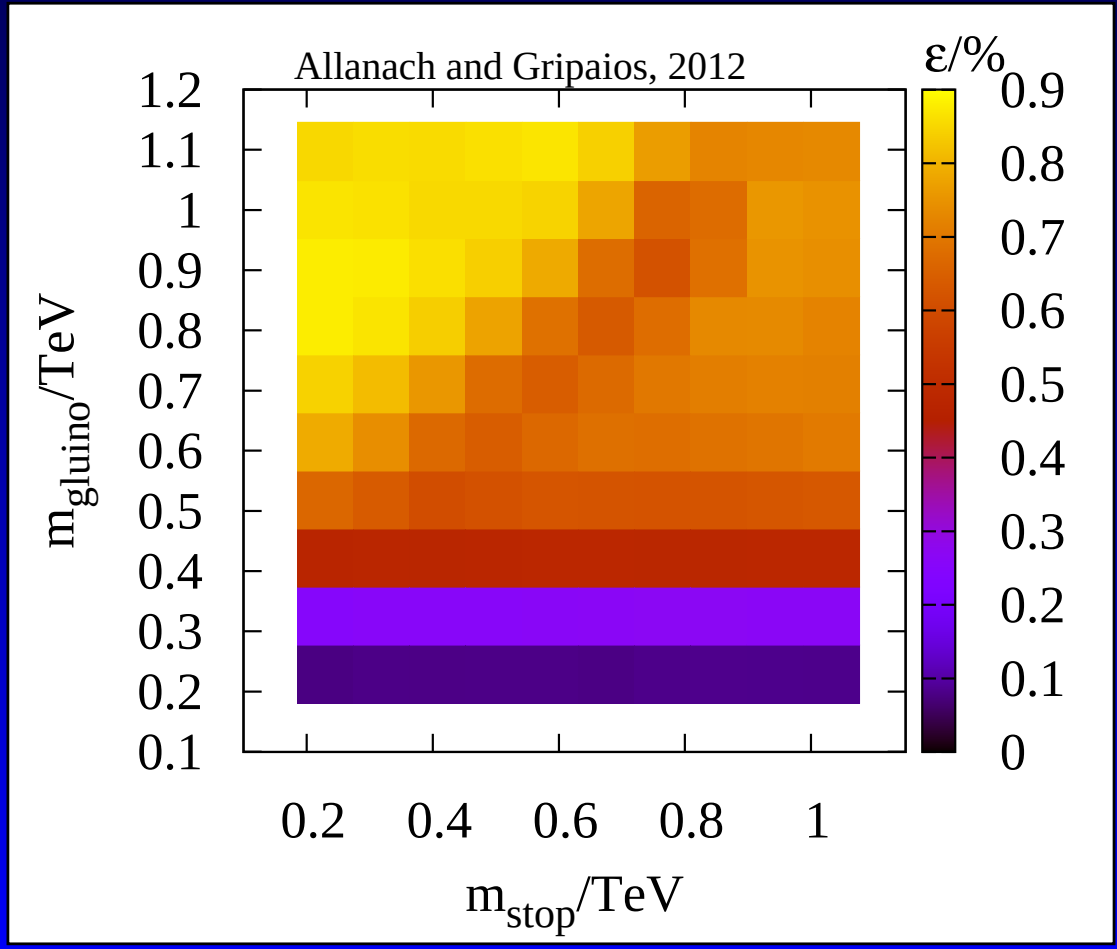
$$m_{\tilde{g}} = 588 \text{ GeV}, m_{\tilde{t}} = 581 \text{ GeV}.$$





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.