Phenomenological Targets for String Model Building

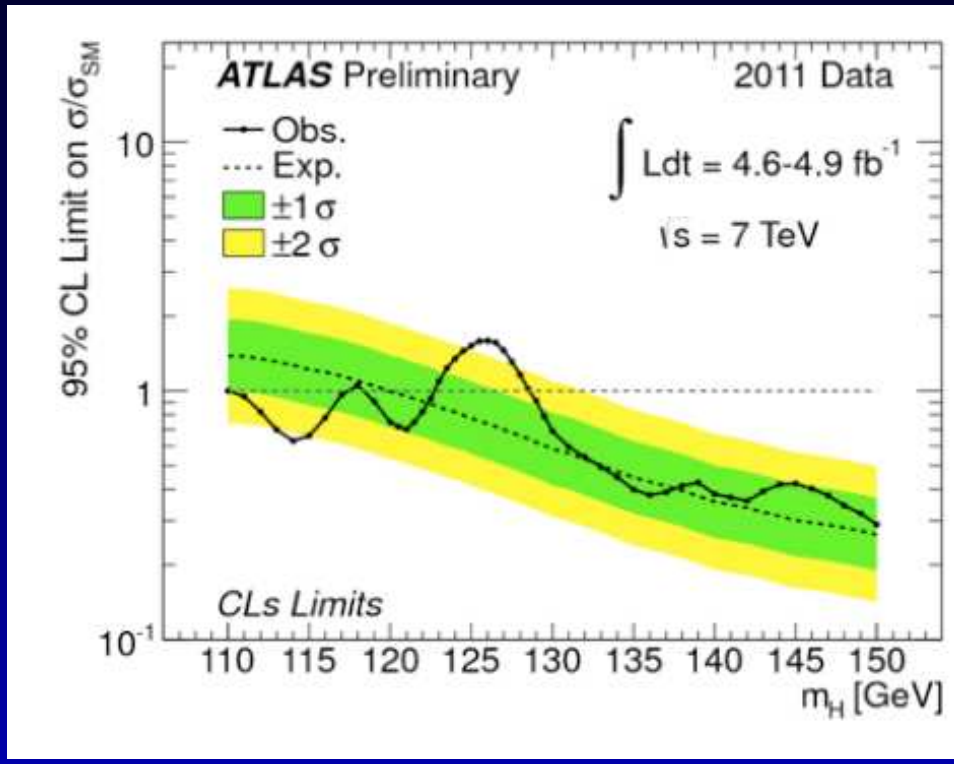
Ben Allanach (University of Cambridge)

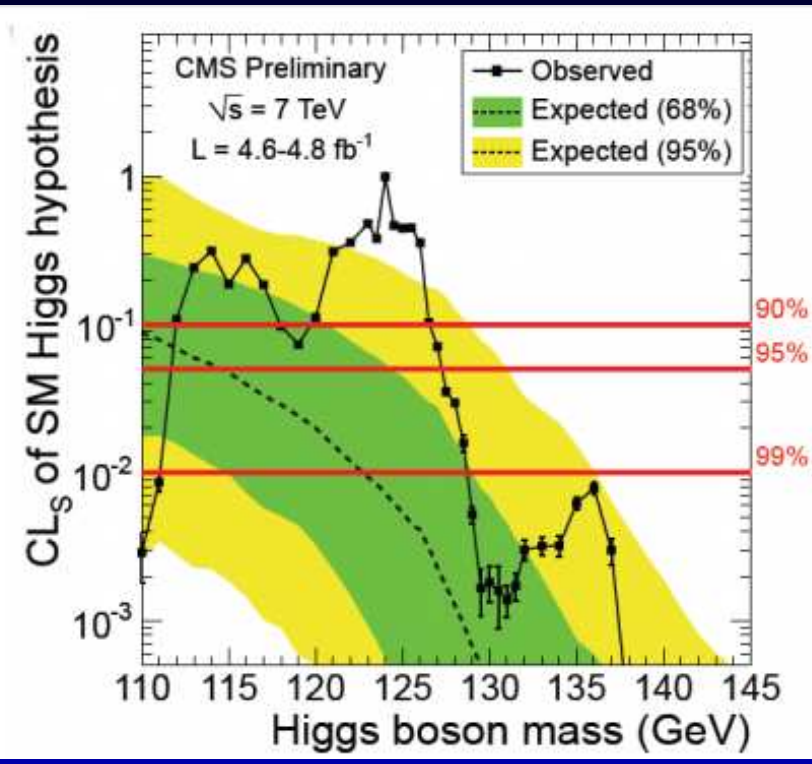
Please ask questions while I'm talking

Targets

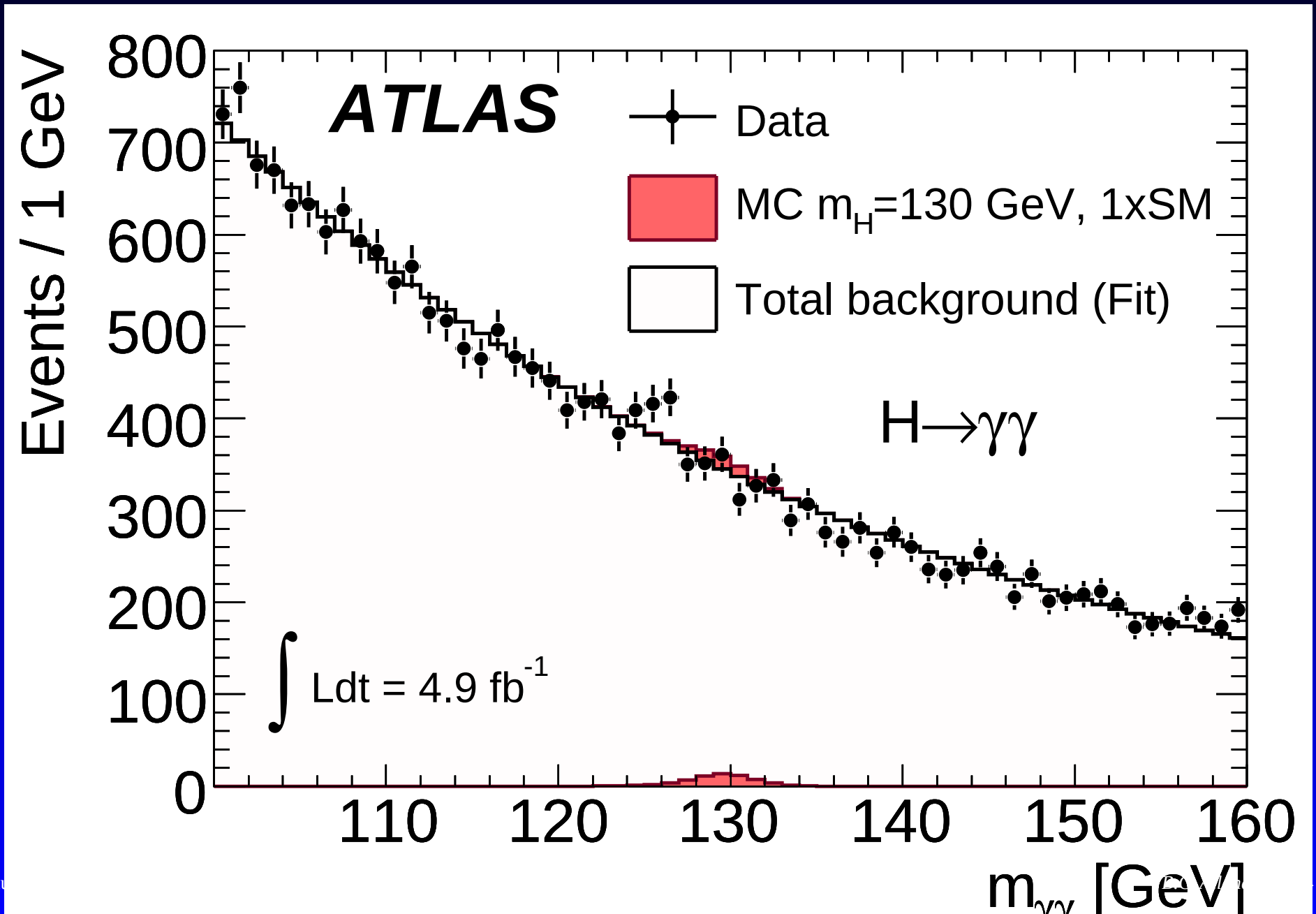
- Higgs
- Supersymmetry
- $t\bar{t}$ asymmetry
- b results
- 130 GeV dark matter line
- Neutrino masses/mixings

2011 Higgs Exclusion

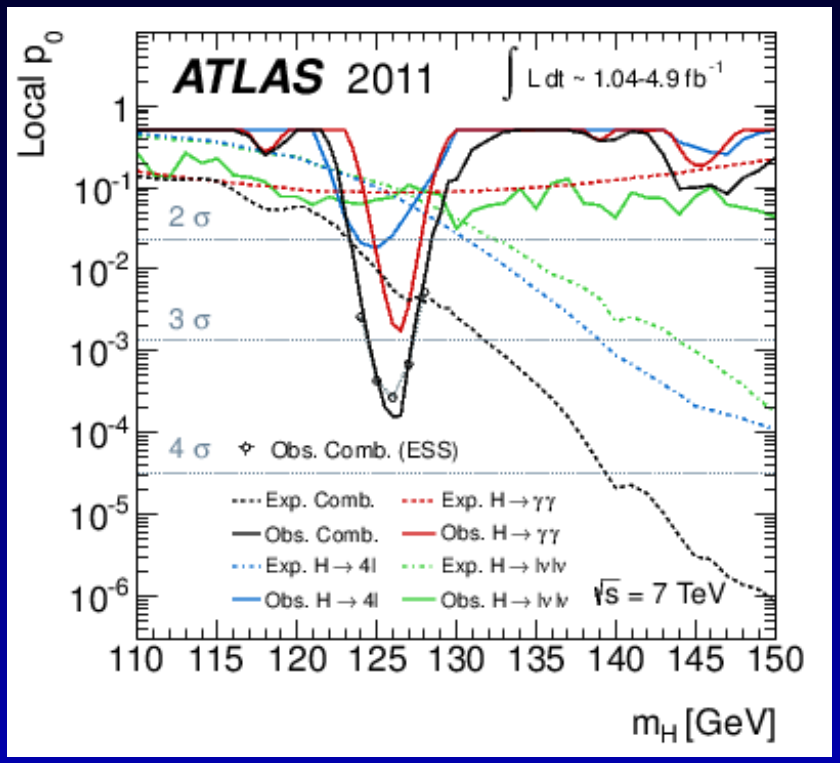


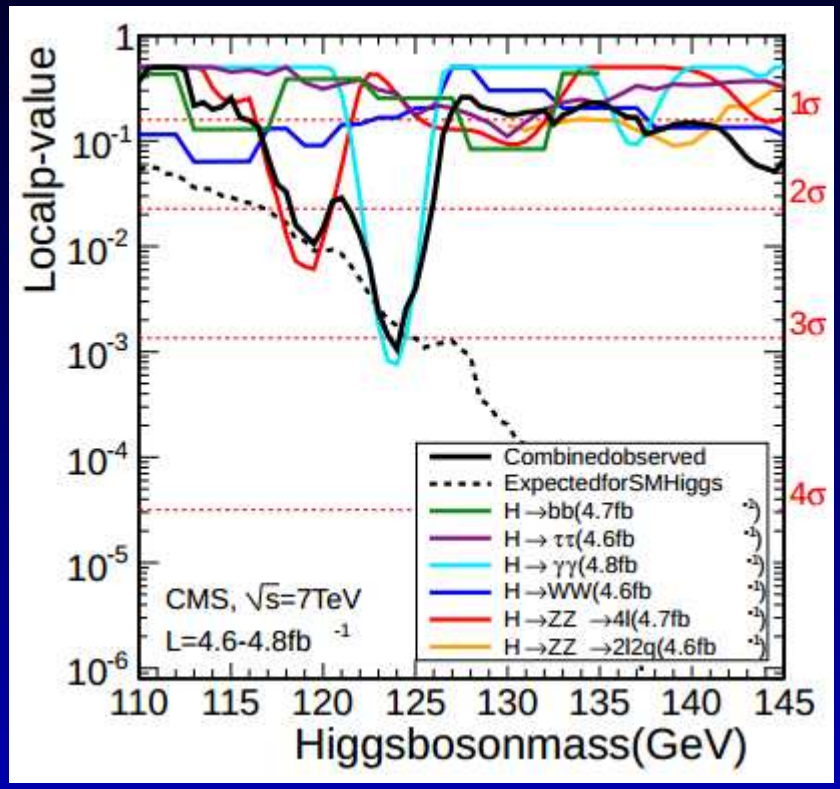


2011 Higgs Signal



2011 Higgs Signal

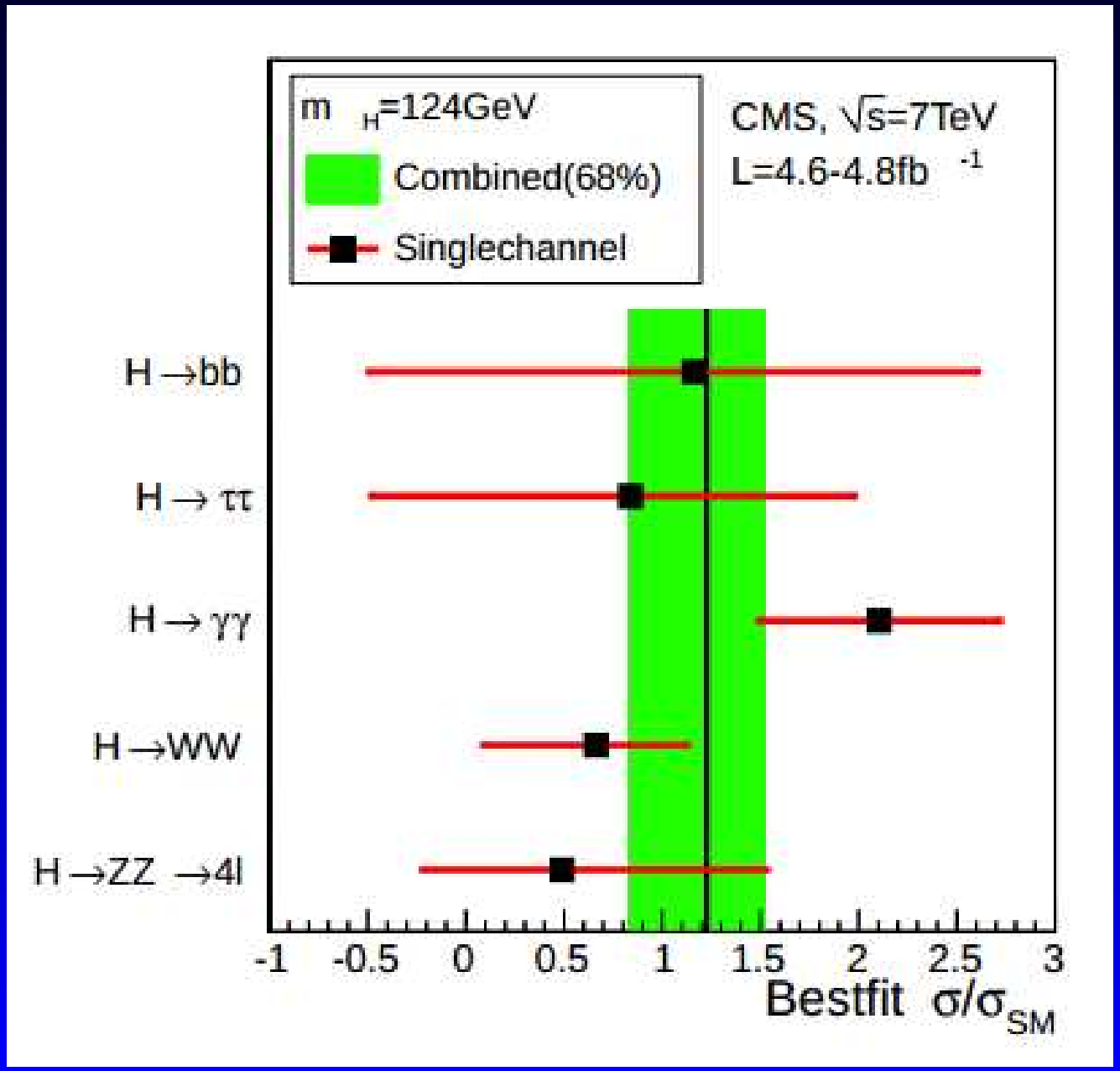




ATLAS: $H \to \gamma\gamma$: 2.8σ
$H \to ZZ \to llll$: 2.1σ
$H \to WW^*$: 1.4σ.
combined LEE: 2.2σ

CMS: $H \to \gamma\gamma$: 3.1σ
$H \to ZZ \to llll$: 2.4σ.
combined LEE: 1.5σ

Branching ratios



2012 Higgs

NNLO+NNLL QCD+2 loop EW predictions

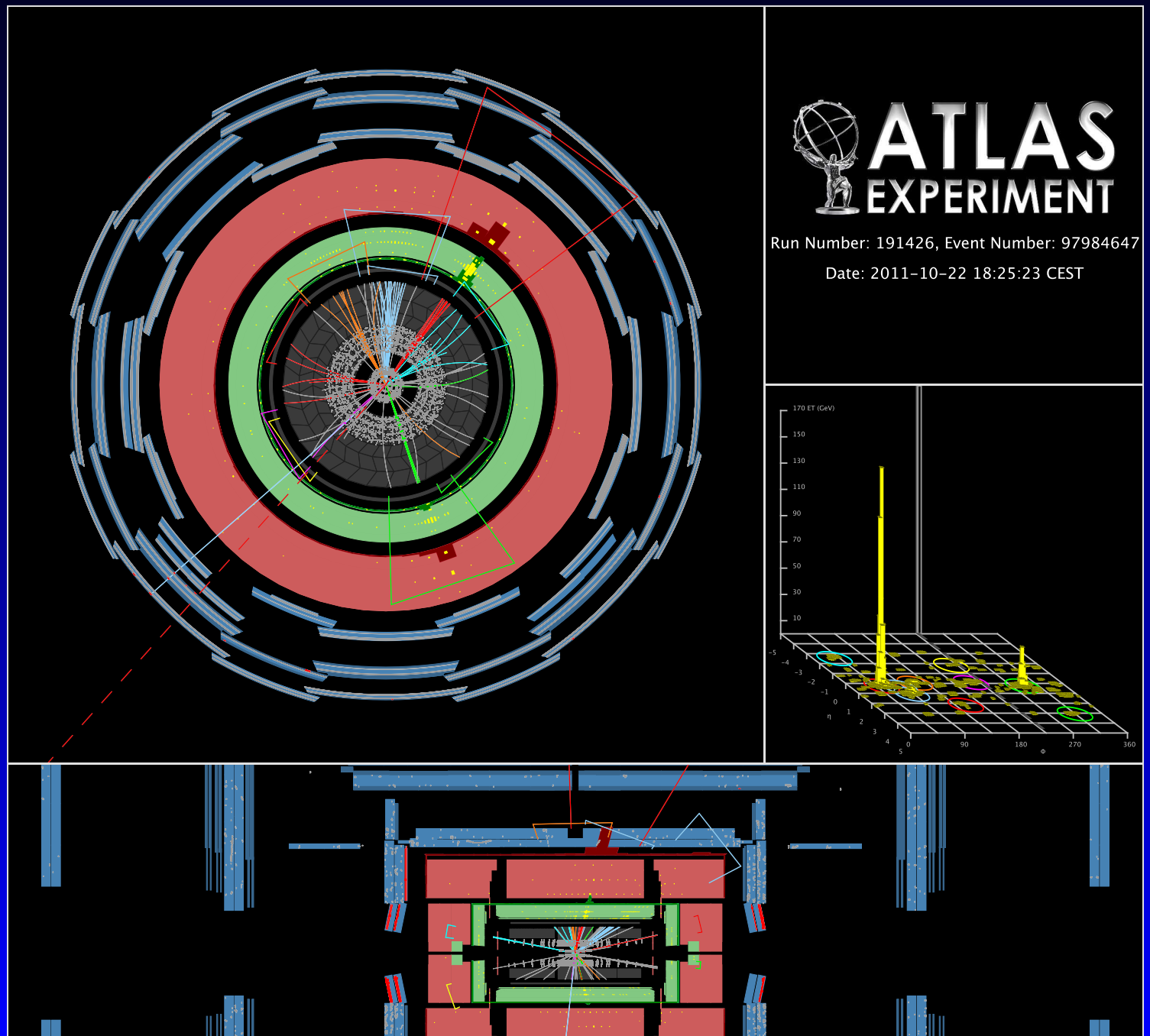
$$\sigma_H(7\text{ TeV}) = 15\pm3\pm1\text{ pb},\ \sigma_H(8\text{ TeV}) = 20\pm3\pm1\text{ pb}.$$

Backgrounds also go up, but overall an increase of 10-20% sensitivity is expected for the same luminosity.
If it goes away, you'll need to build *invisible higgs* models, or *models with suppressed cross-sections*.
Implications for MSSM SUSY breaking:

A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
$M_h^{\max}$	121.0	121.5	128.0	123.0	123.5	124.5	128.5

$\not{E}_T = 984, p_T = 974, 276, 146, 61$

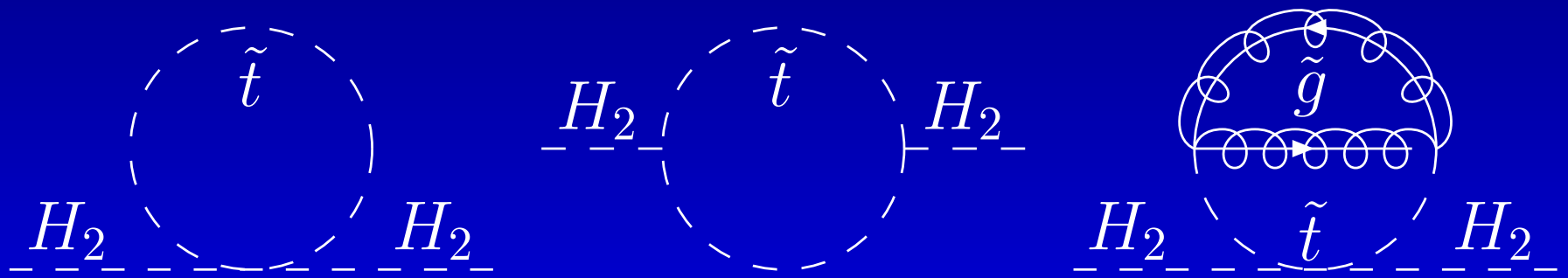


Natural SUSY

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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No cancellation$\Rightarrow$

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

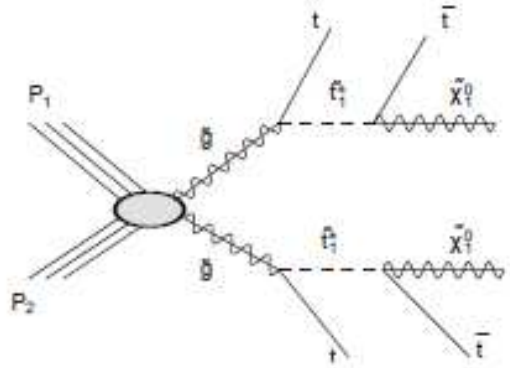
Experimental $\not{E}_T$ searches$\Rightarrow$

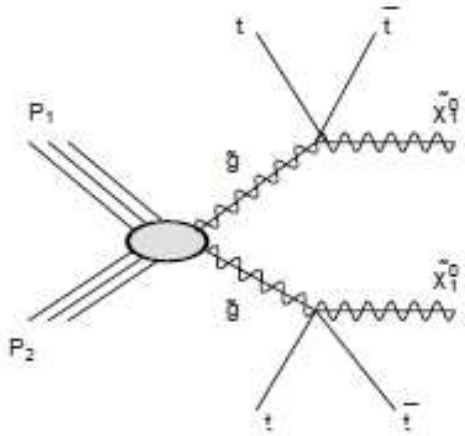
$$m_{\tilde{t}} > 500 \text{ GeV}, \qquad m_{\tilde{g}} > 900 \text{ GeV}.$$

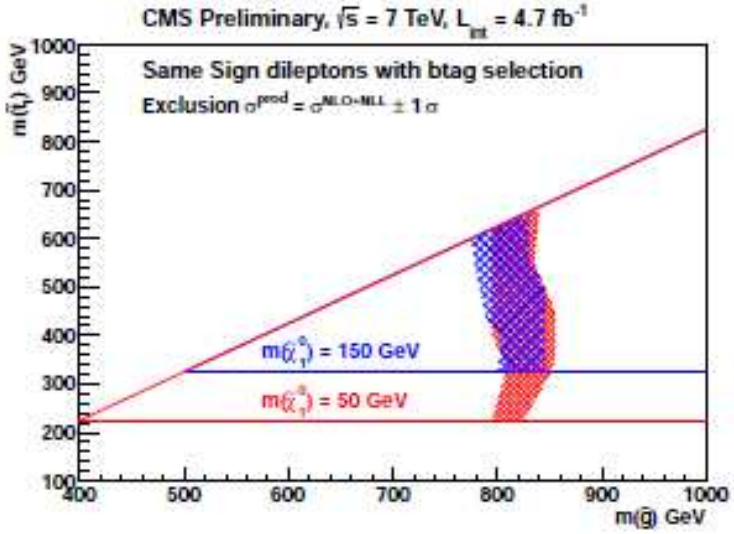
[a] M. Papucci, J. T. Ruderman and A. Weiler, `arXiv:1110.6926`; C. Brust, A. Katz, S. Lawrence and R. Sundrum, `arXiv:1110.6670`

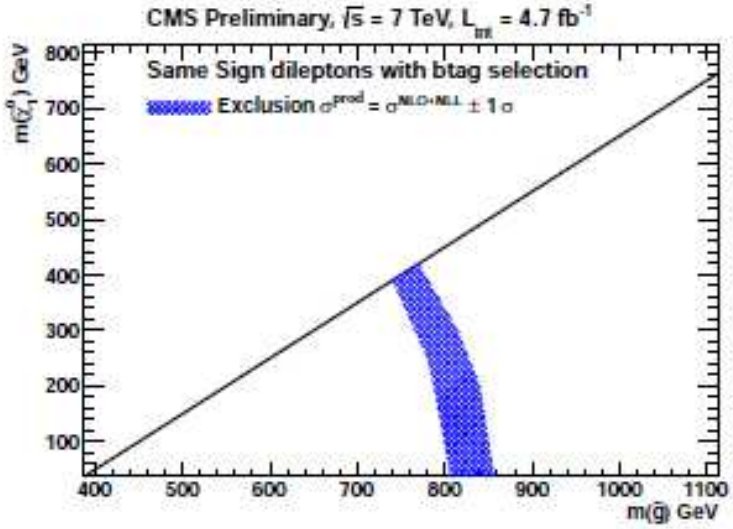
gt: $\not{E}_T > 50/120$ **GeV**, $N_b \geq 2$, $\#j \geq 2$, $H_T > 320$ **GeV**

Interpret in a gluino-mediated stop scenario with on-shell (left) or off-shell stops (right)



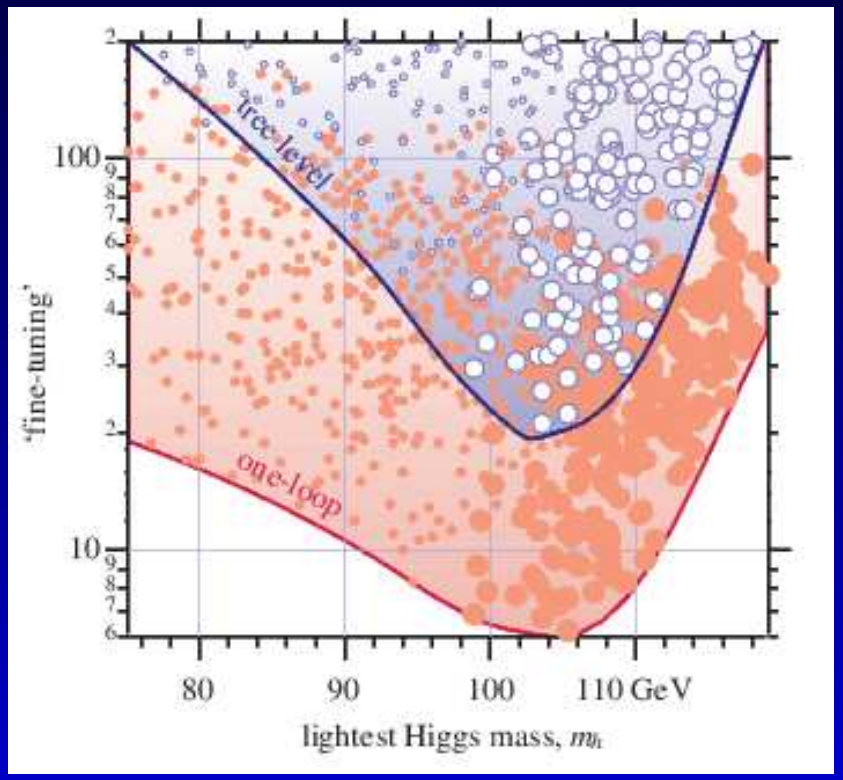






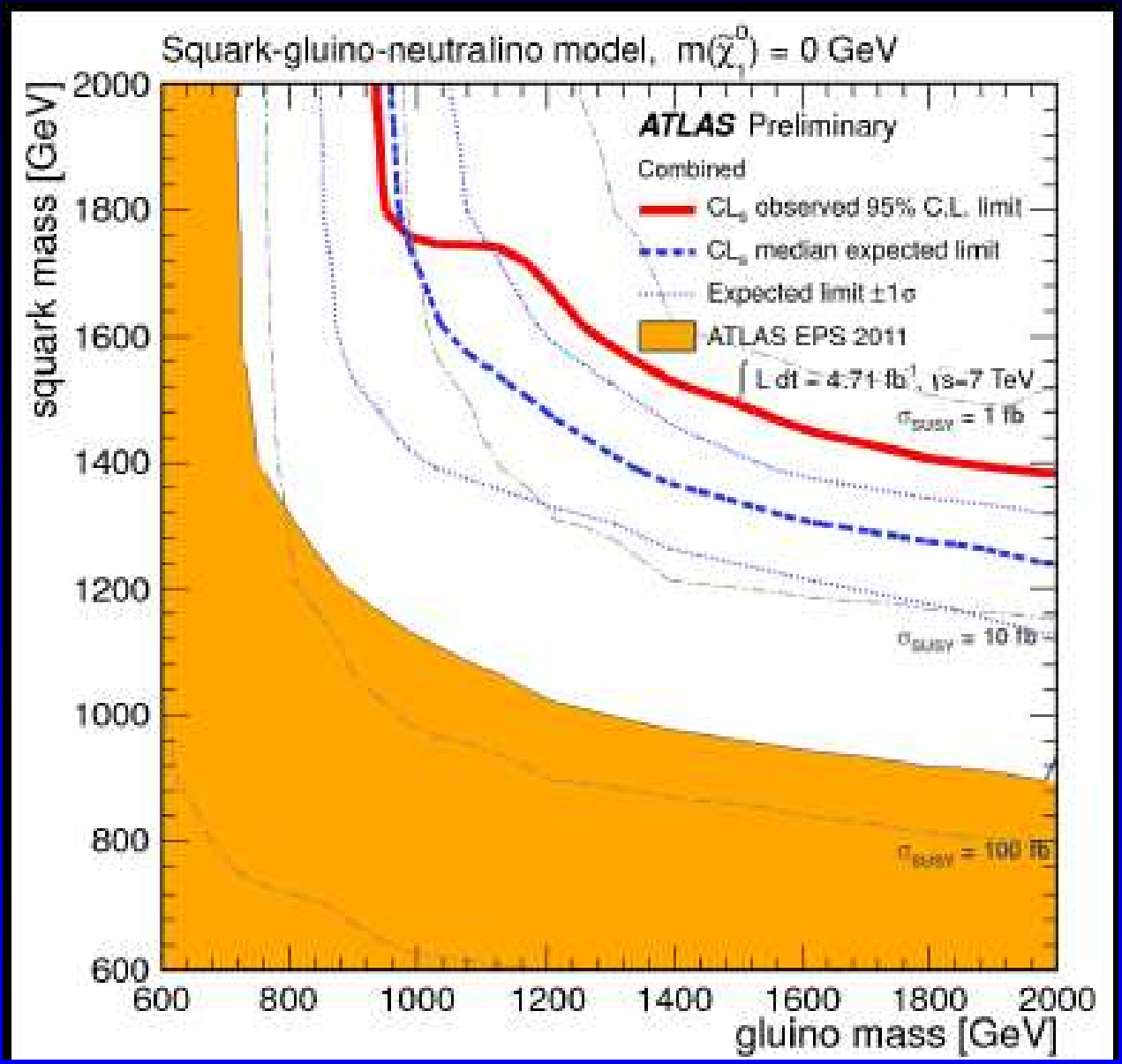
Higgs and SUSY Implications

Getting a high enough m_h may require heavy stops in the MSSM, which is usually *un-natural*. Solutions:



- High energy correlations between parameters in your string model
- Build in a singlet: the NMSSM, or other structure on top of the MSSM, raising the Higgs mass

Jets Plus $\not{E}_T$ Search



Bottom Up Implications of 2011 Data

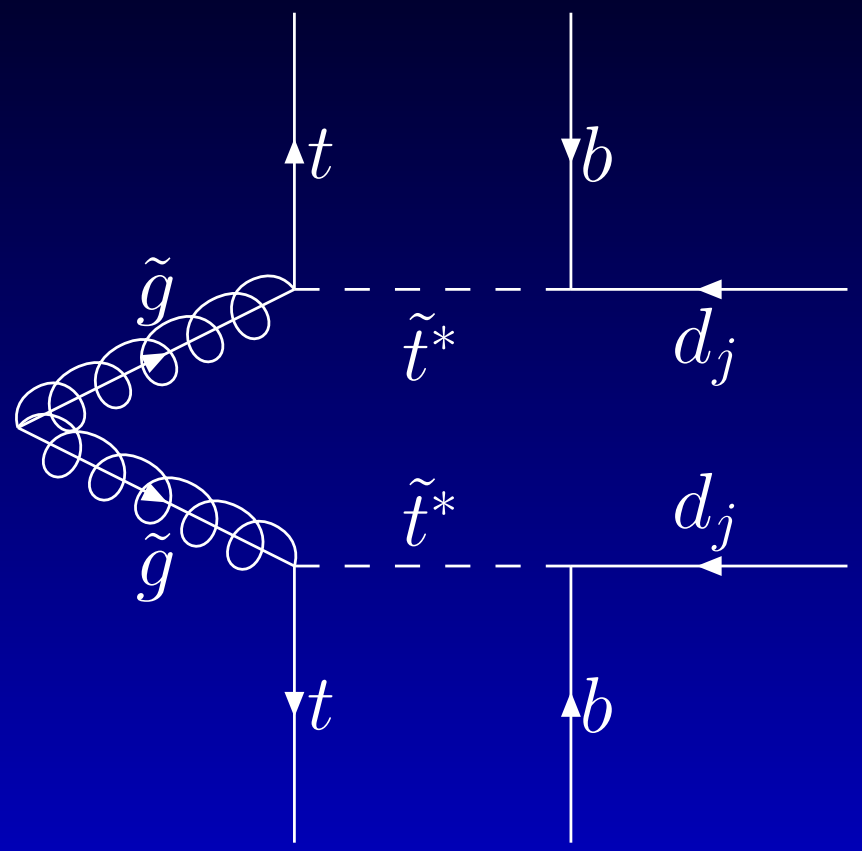
Naturalness is under pressure. Ways to get around it:

- 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] bounds from current jets plus $\not{E}_T$ searches become less stringent
- 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] LeCompte, Martin `arXiv:1111.6897`

[b] BCA, Gripaios `arXiv:1202.6616`

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.

A_{FB} in the Standard Model

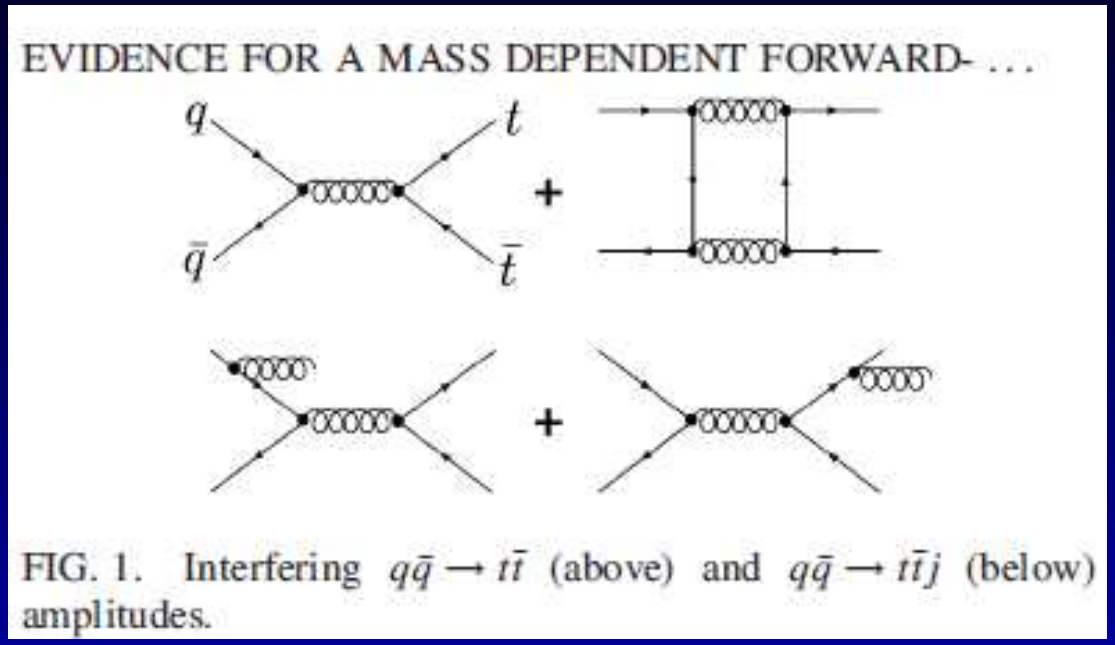


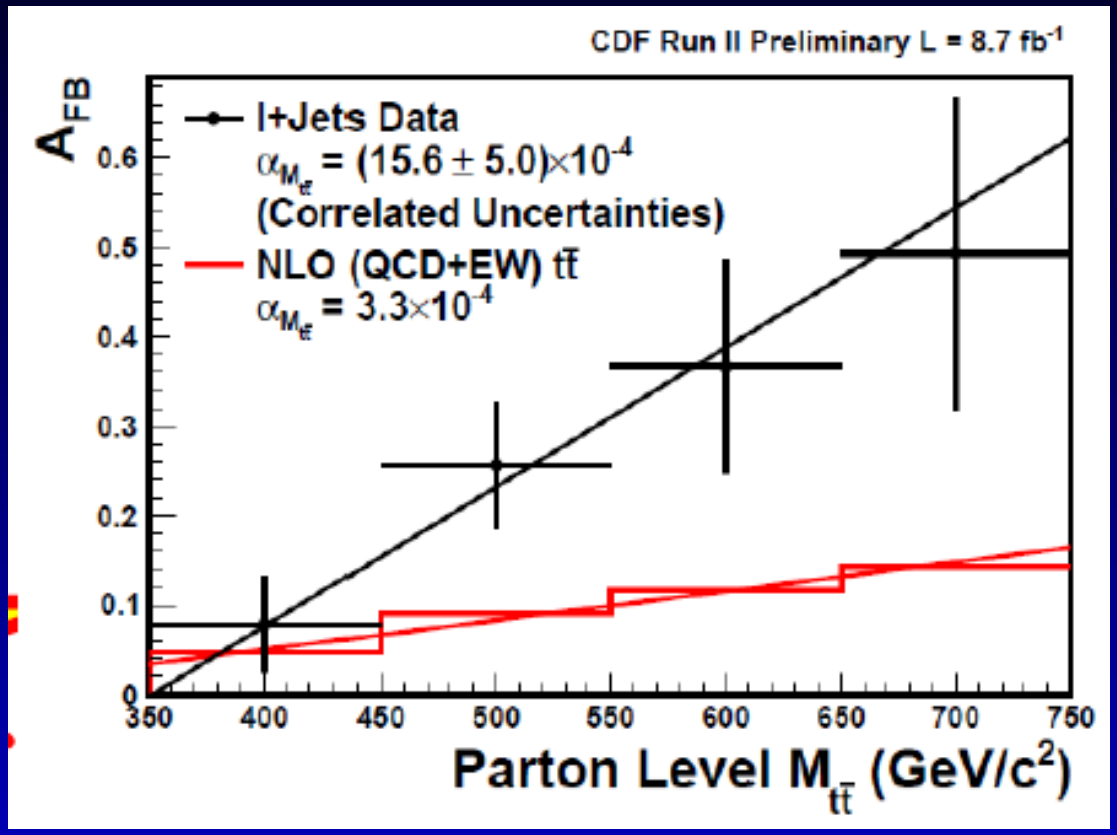
FIG. 1. Interfering $q\bar{q} \to t\bar{t}$ (above) and $q\bar{q} \to t\bar{t}j$ (below) amplitudes.

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

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

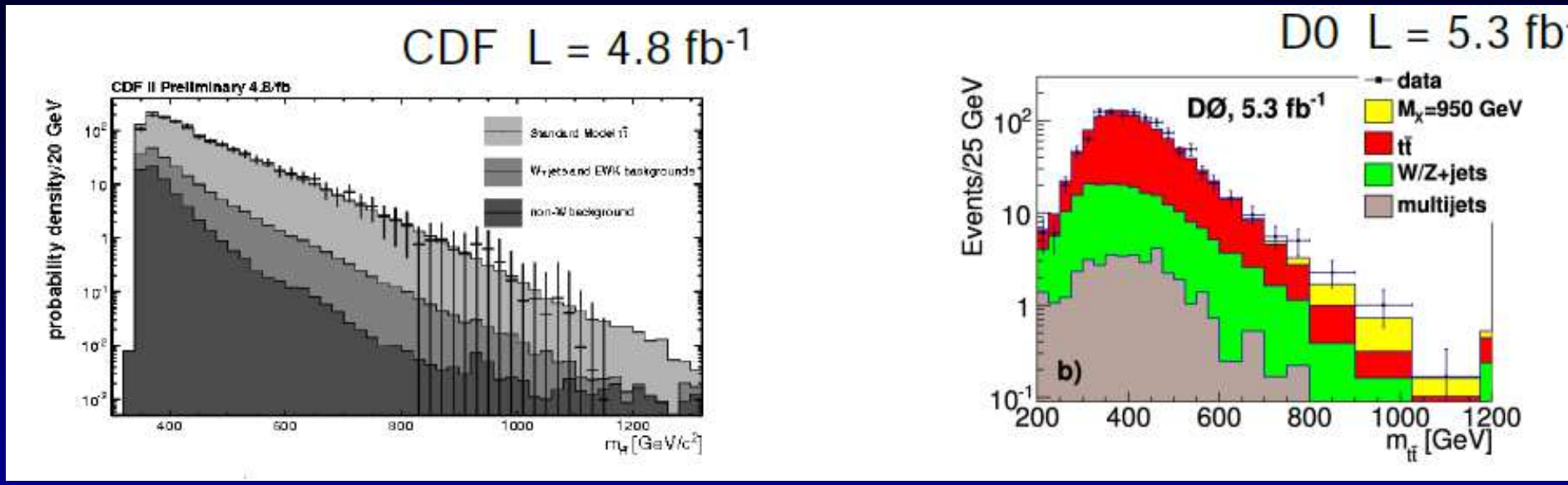
SM Prediction: 0.066.

Measurements of A_{FB}



S Leone (CDF) talk at Electroweak session of Rencontres de Moriond 2012.

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. ${A_C^y}^{SM} = 0.006 \pm 0.002$.

ΔA_{FB}

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

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

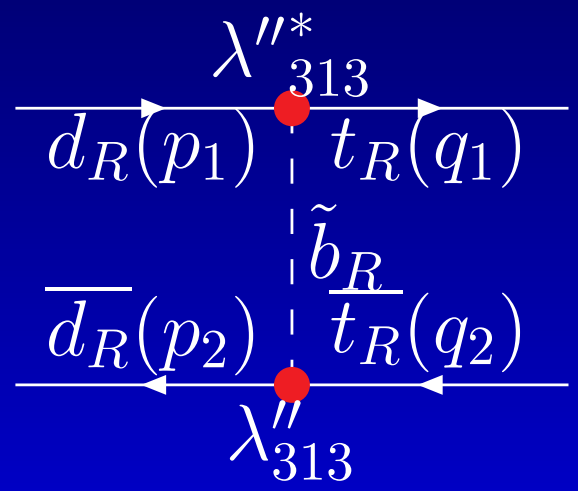
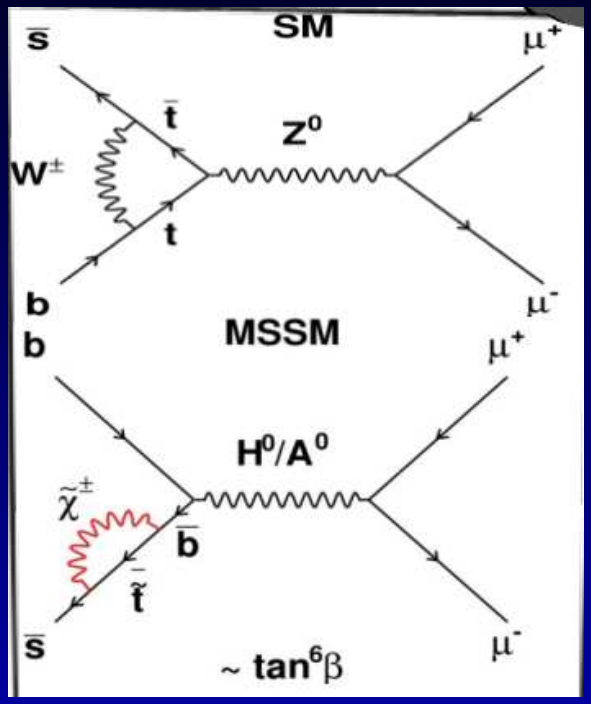
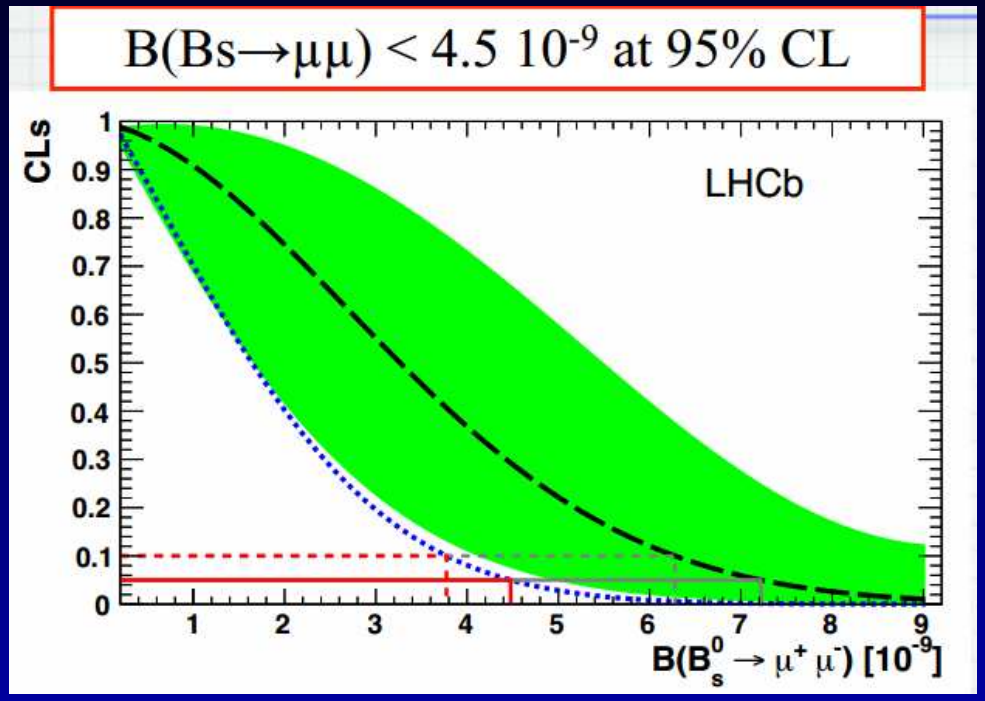


Figure 1: SUSY contribution to A_{FB}[a]

[a] BCA, Sridhar `arXiv:1205.5170`

$B_s \to \mu^+\mu^-$: LHCb 1 fb^{-1}





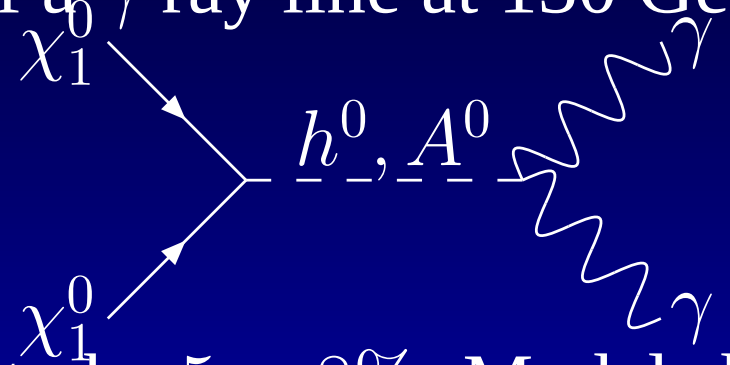
$$BR(B_s \to \mu^+\mu^-) = 0.8^{+1.8}_{-1.3} \times 10^{-9}$$

$$BR(B_s \to \mu^+\mu^-)^{SM} = 3.2 \pm 0.2 \times 10^{-9}$$

Morata, Moriond 2012: better not have too large $\tan^6\beta/M_A^4$ for light $\tilde{t}$!

130 GeV Fermi/LAT line

Fermi/LAT measures galactic γs. Weniger[a] analysed their data with optimised regions of the sky and found 3.3σ evidence of a γ ray line at 130 GeV. Rates

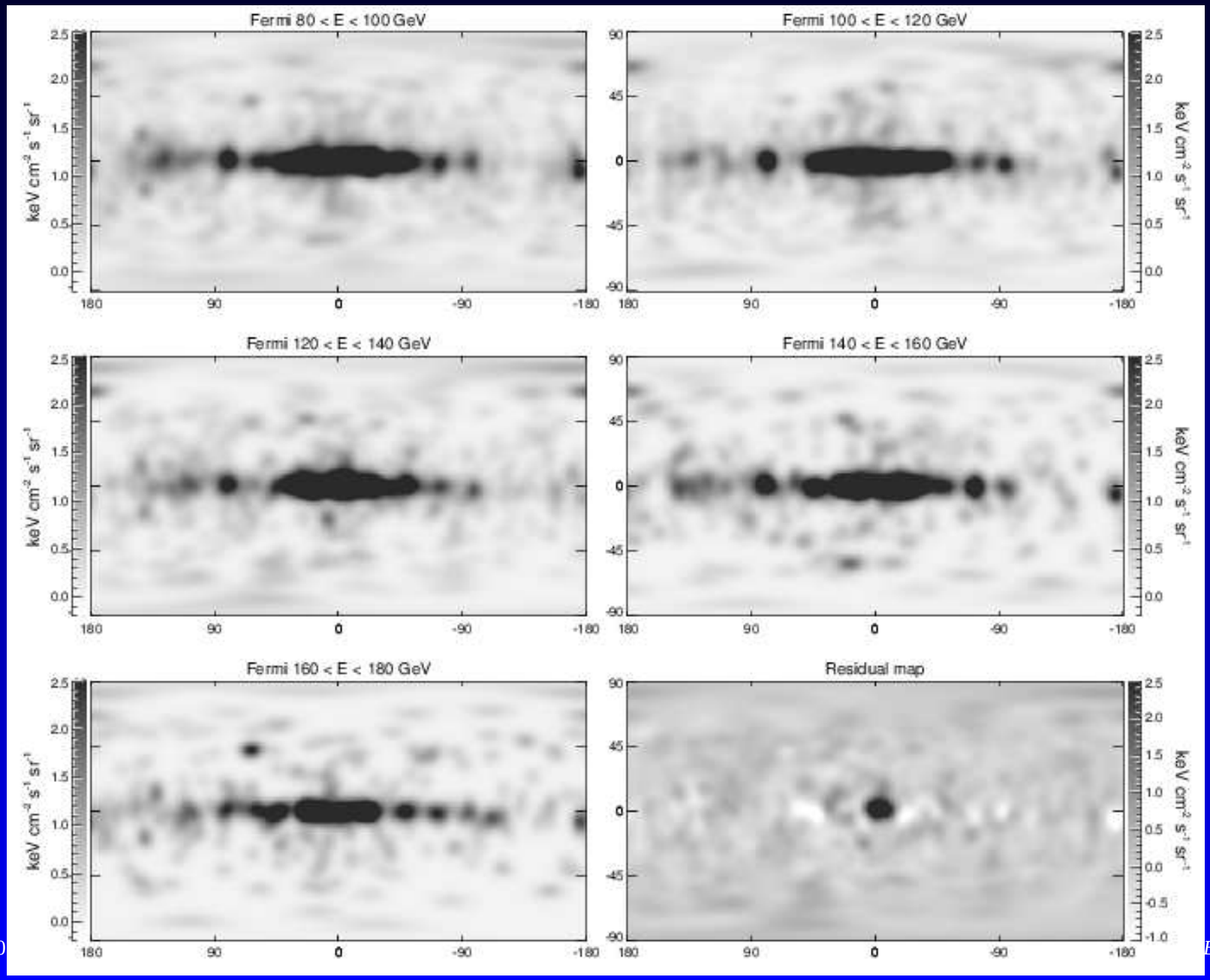


predicted by eg are too low: BR would need to be $5-8\%$. Models have been built where dark matter annihilates to heavy states which then decay to approximately mono-energetic photons, however.

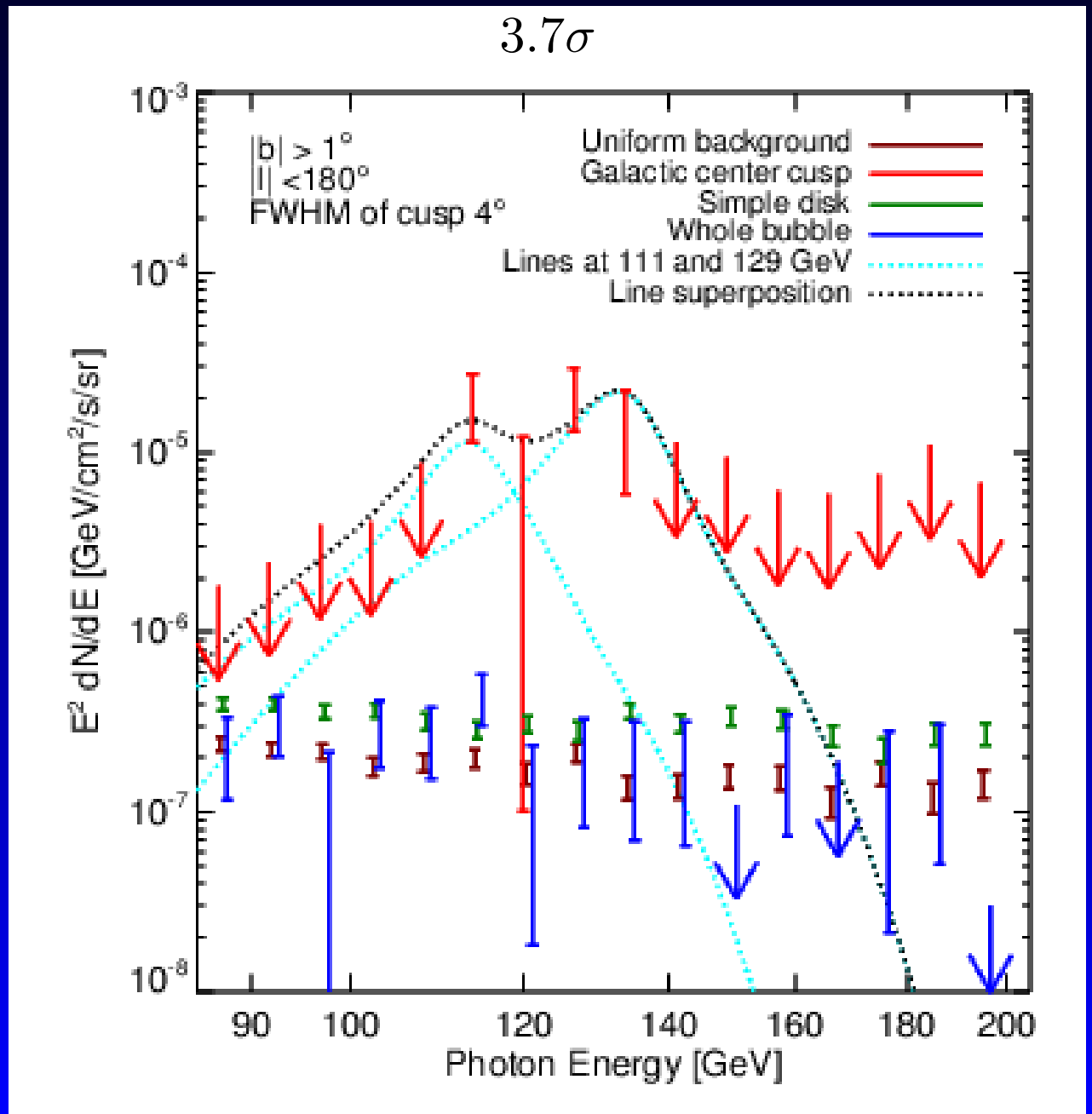
[a] Weniger, `arXiv:1204.2797`

Residual Map

Su, Finkbeiner arXiv:1206.1616



Energy Spectrum in Cusp



Daya Bay and Neutrino Oscillations

Previous oscillation results for 3 neutrino flavours imply:

$$\begin{aligned} |\Delta m^2_{21}| &= 7.6 \times 10^{-5}\mathrm{eV}^2, \quad |\Delta m^2_{31}| = 2.3 \times 10^{-3}\mathrm{eV}^2 \\ \sin^2 2\theta_{12} &= 0.86 \end{aligned}$$

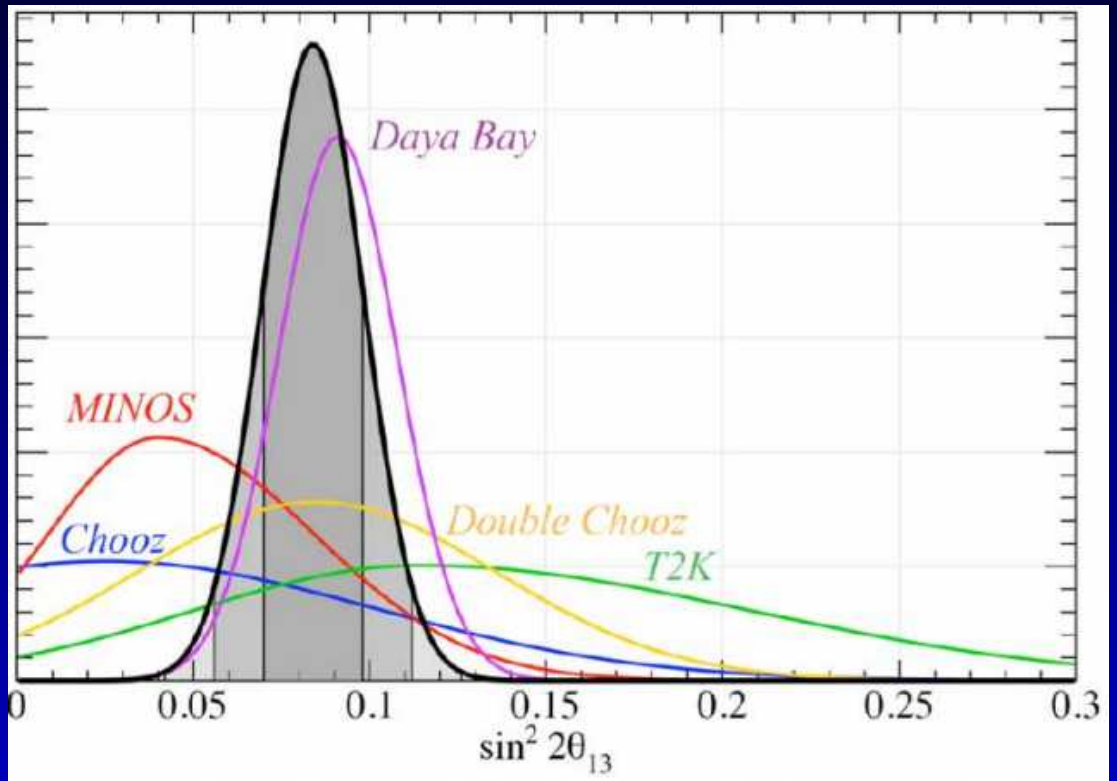
Measure $\bar{\nu}_e$ survival probability

$$\begin{aligned} P &= 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.267\Delta m^2_{31}}{E}\right) \\ &\quad - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.267\Delta m^2_{21} L}{E}\right) \end{aligned}$$

by measuring total reactor flux from near/far detectors. Know everything expect for θ_{13}.

Neutrino mixing

Good prospects to measure CP violation.



Ideogram of recent θ_{13} results for normal hierarchy, $\delta_{CP}=0$, and maximal θ_{23}

Models: Strict Tri-bimaximal is *out*

$$\begin{bmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{bmatrix}.$$

Summary

- All eyes on the Higgs boson this (apparently 4th) July
- MSSM is under *naturalness pressure* from Higgs results: oppurtunity for stringy model builders
- SUSY is natural only if one has: compressed spectra, $R-$parity violation, or a split spectrum with certain particles light (i.e. sub-TeV): gluino, stop, neutralino, chargino, first two generations of sleptons
- Tevatron $t\bar{t}$ forward backward asymmetry stands out
- As does a potential 130 GeV gamma ray line in Fermi-LAT data: keep an eye on it

Backup

Other Light States

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

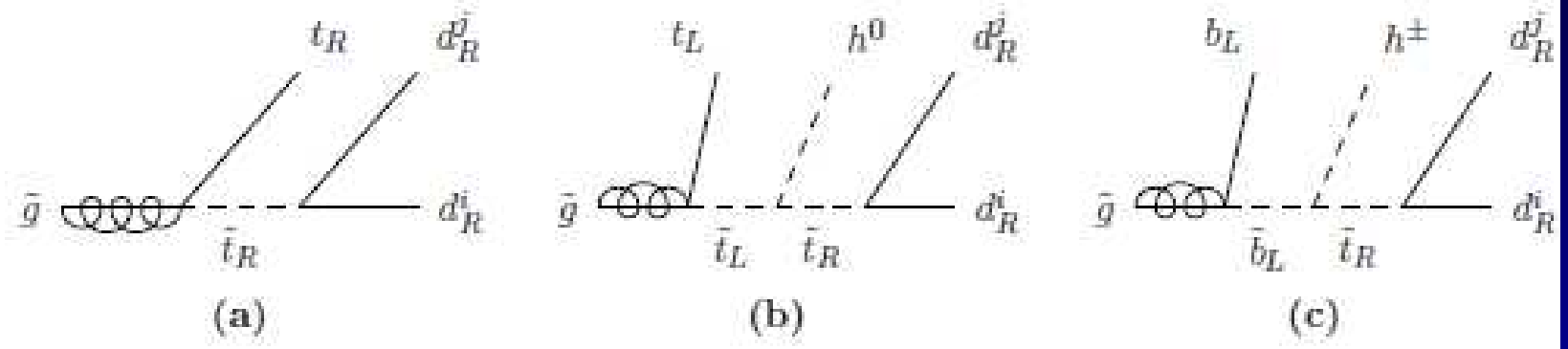


Figure 1. Gluino decays without right-handed bottom squarks in the presence of $W \supset U_3 D_i D_j$, via (a) right-handed top, (b) left-handed top, and (c) left-handed bottom. Same sign leptons are obtained in (c) only if the charged Higgs subsequently decays to $t\bar{b}$ or to leptons.

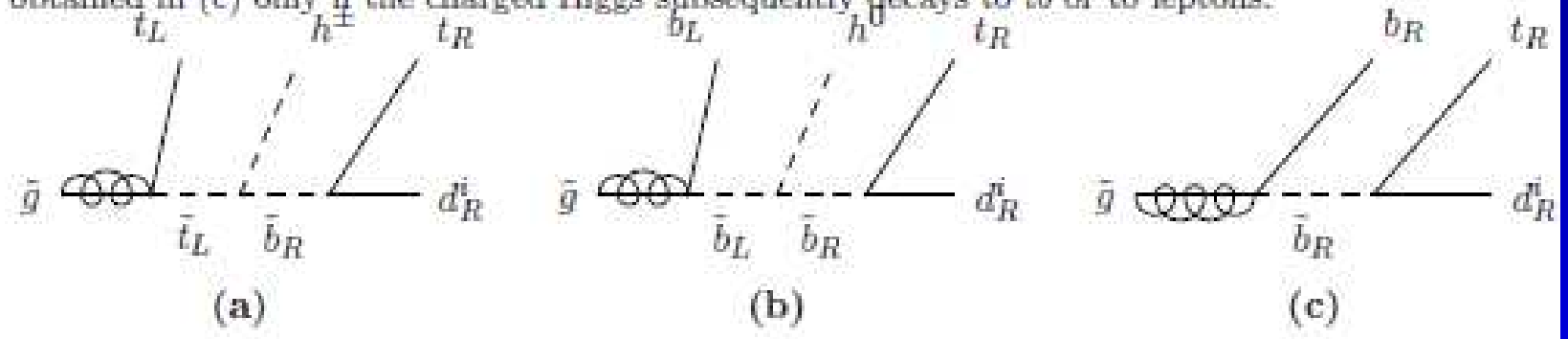
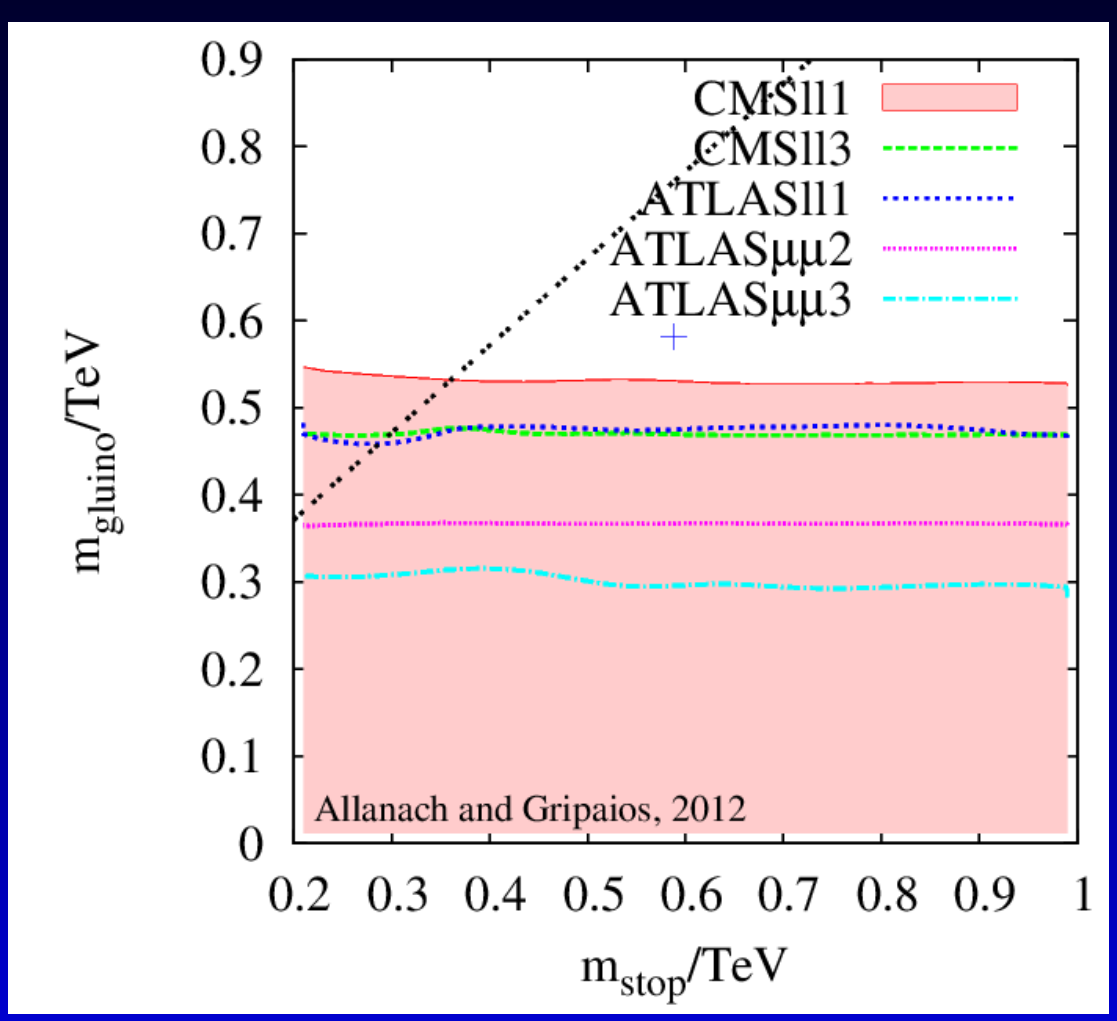


Figure 2. Gluino decays with right-handed bottom squarks in the presence of $W \supset U_3 D_i D_3$, via (a) left-handed top squark, (b) left-handed bottom squark, and (c) right-handed bottom squark.

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



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

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

ΔA_{FB}

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

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

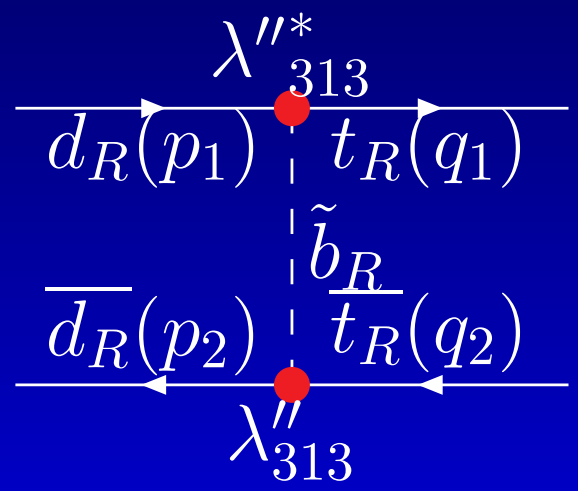


Figure 2: SUSY contribution to A_{FB}[a]

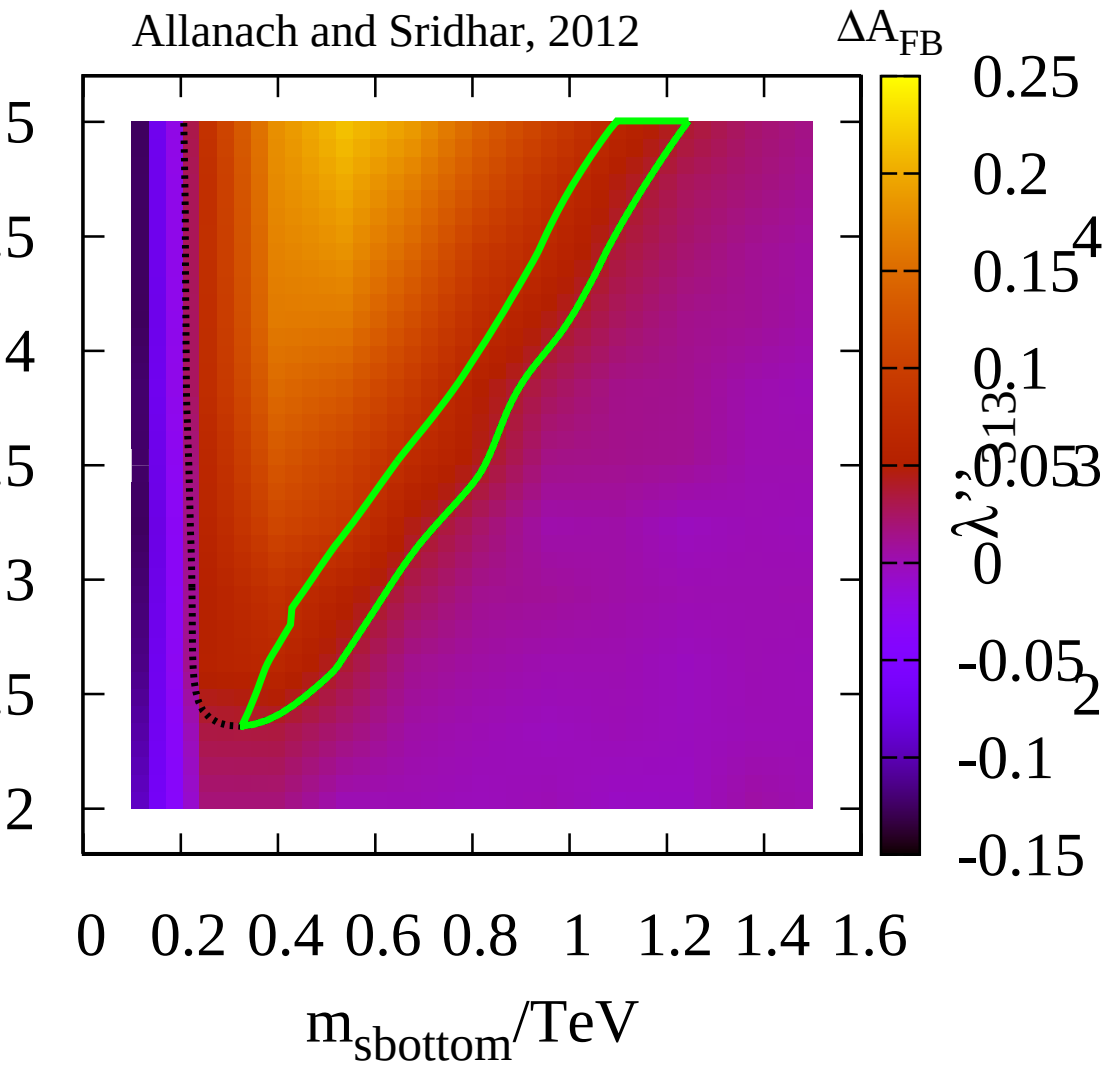
[a] BCA, Sridhar `arXiv:1205.5170`

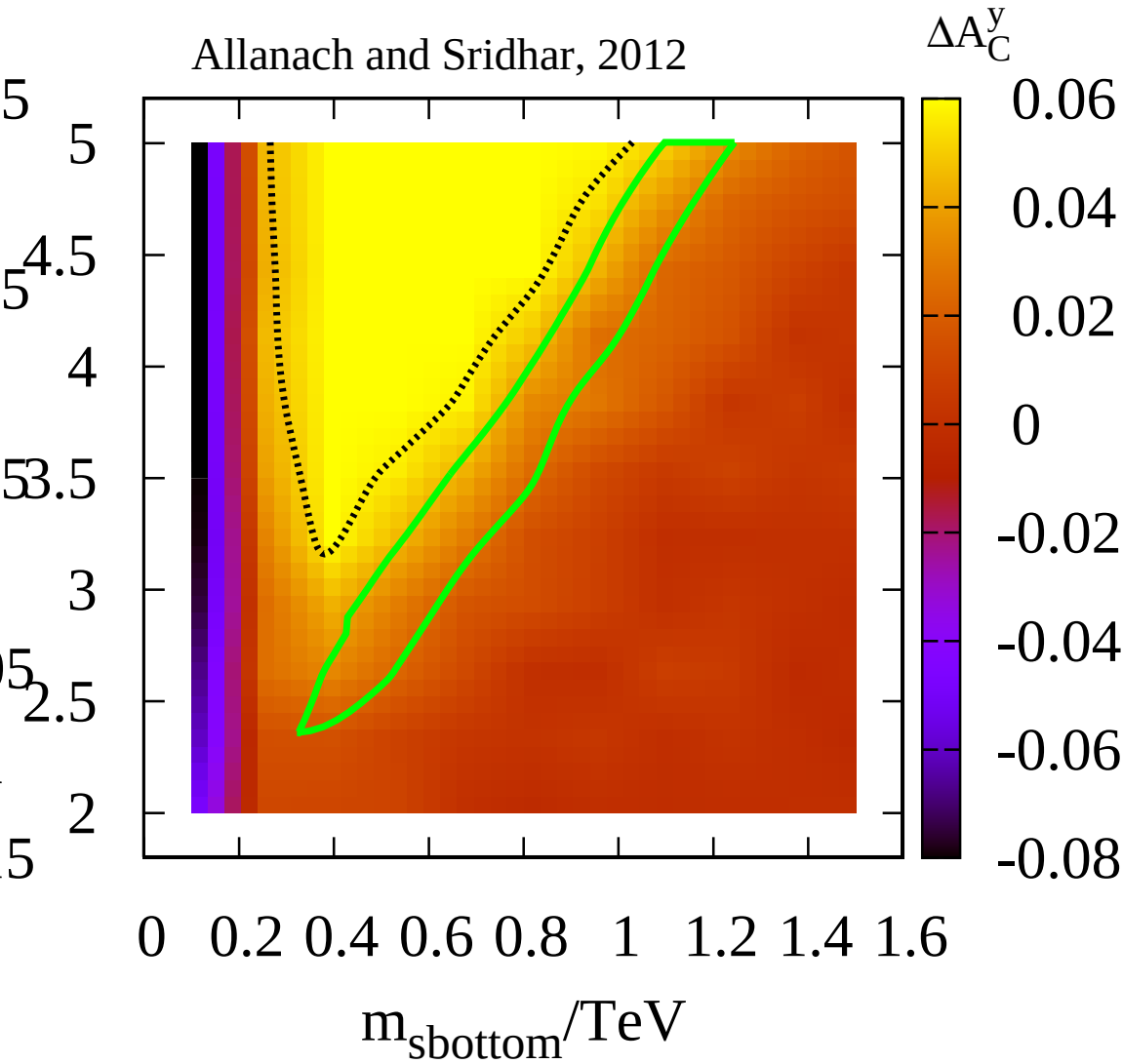
New Physics Contribution

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

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

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:

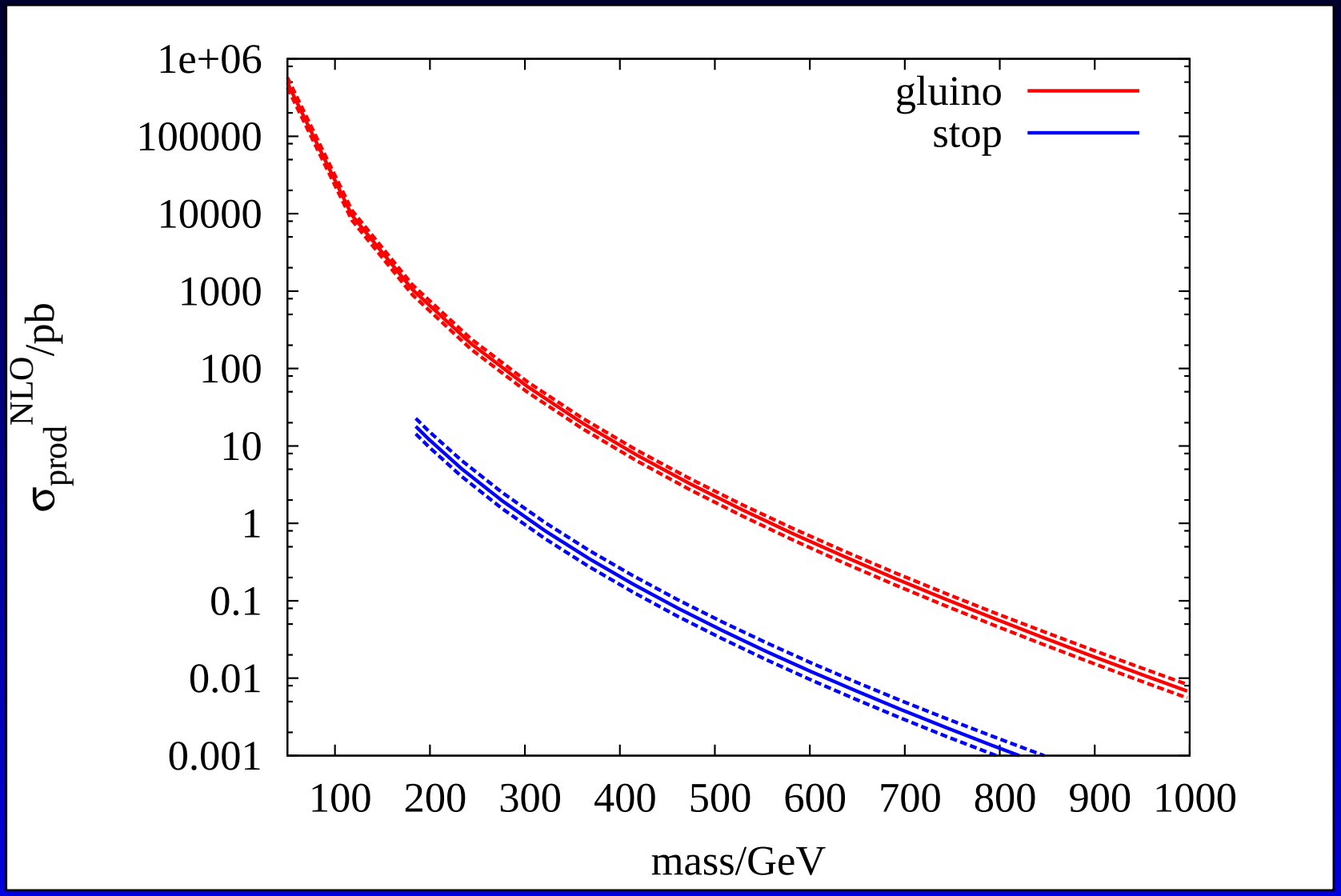
- *Gravitino* - still decays, but lifetime may be much longer than the age of the universe
- *Hidden sector matter*
- Axion/axino

The implications of each of these is that direct dark matter search 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)

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.

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	$\lvert\vec{p}_{\mathrm{T}}^{\mathrm{miss}}\rvert$/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 4: ATLAS same sign-di lepton analysis search regions.

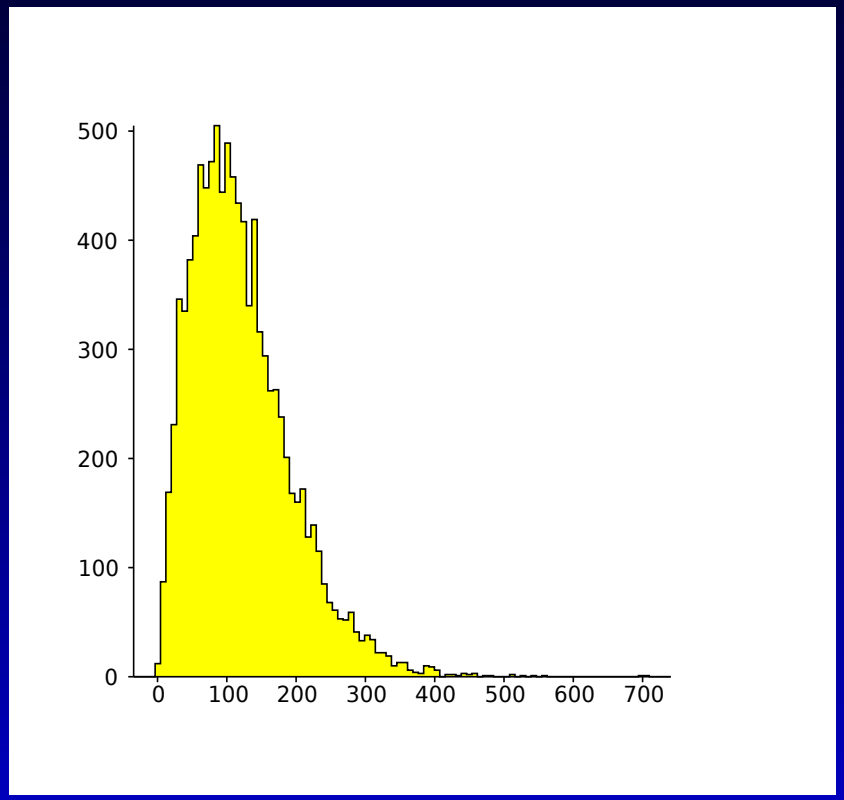
Sets of Cuts

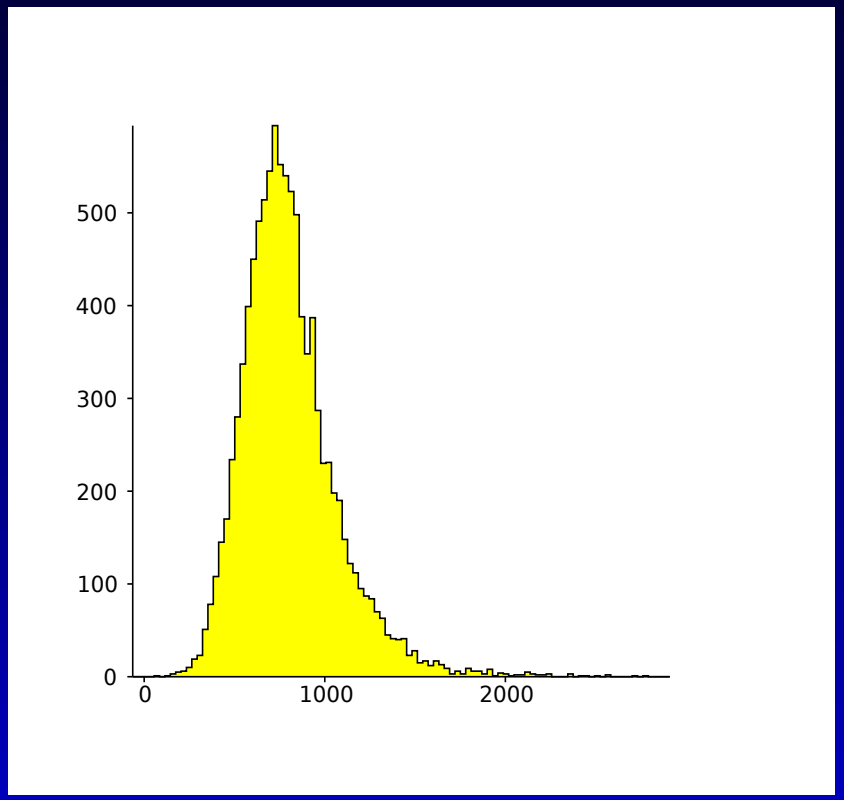
Signal Region	H_T/GeV	$\lvert\vec{p}_{\rm T}^{\rm miss}\rvert$/GeV	N_{ll}/fb	$A \times \epsilon/10^{-3}$	N_{ll}^{95}
CMS$ll1$	$>$400	$>$120	2.4	3.5	$<$3.7
CMS$ll2$	$>$400	> 50	4.6	6.8	$<$8.9
CMS$ll3$	$>$200	$>$120	2.5	3.7	$<$7.3

Table 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

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

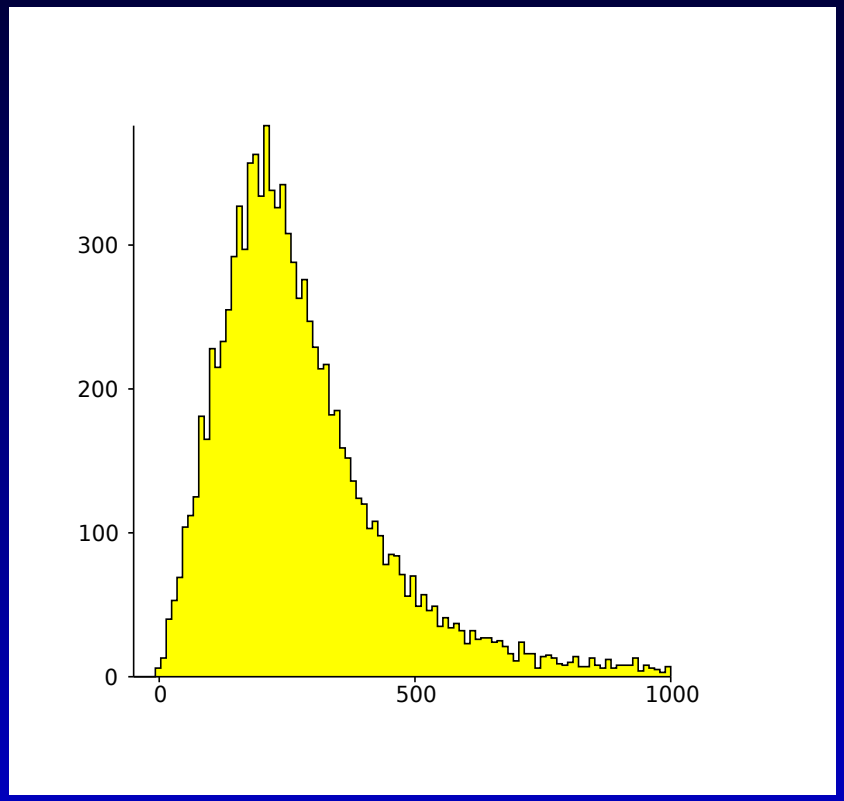


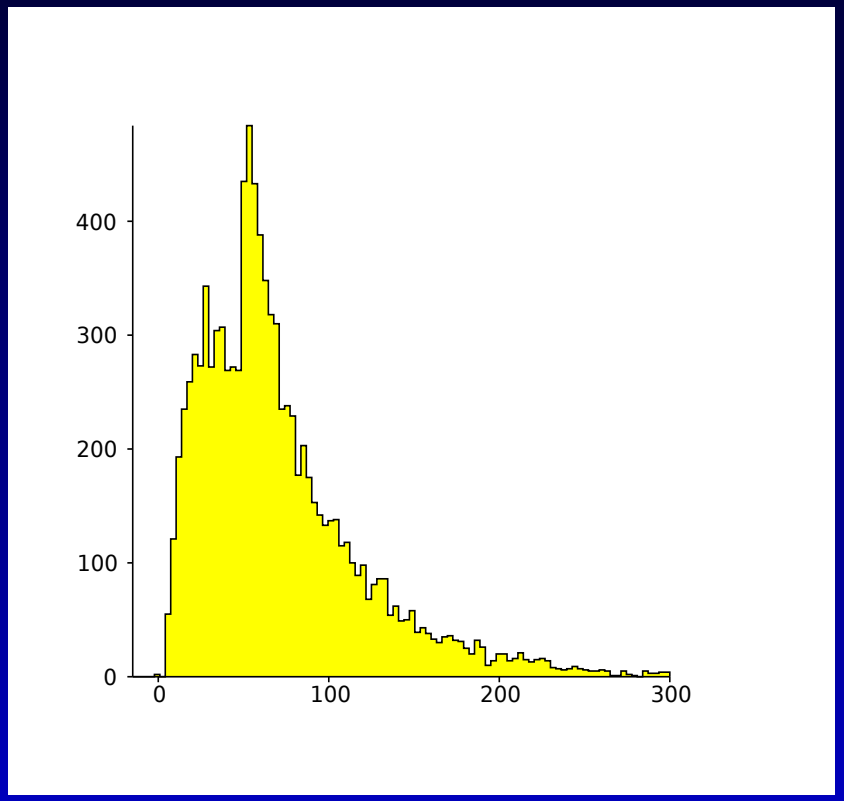


LH panel: $\not{E}_T/GeV$, RH panel: H_T/GeV

Test Point

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

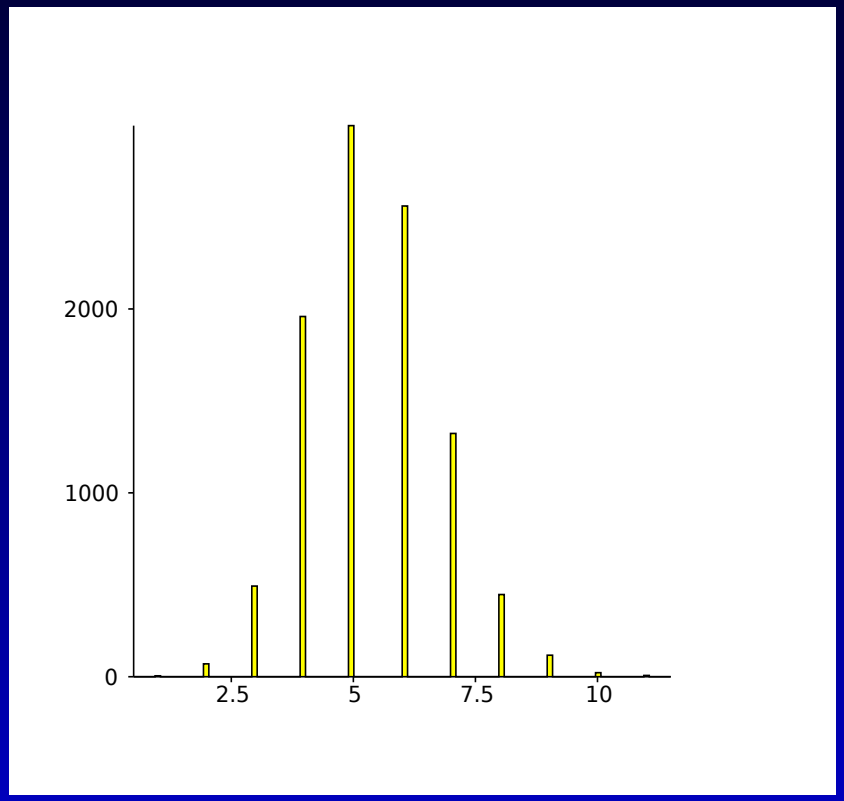


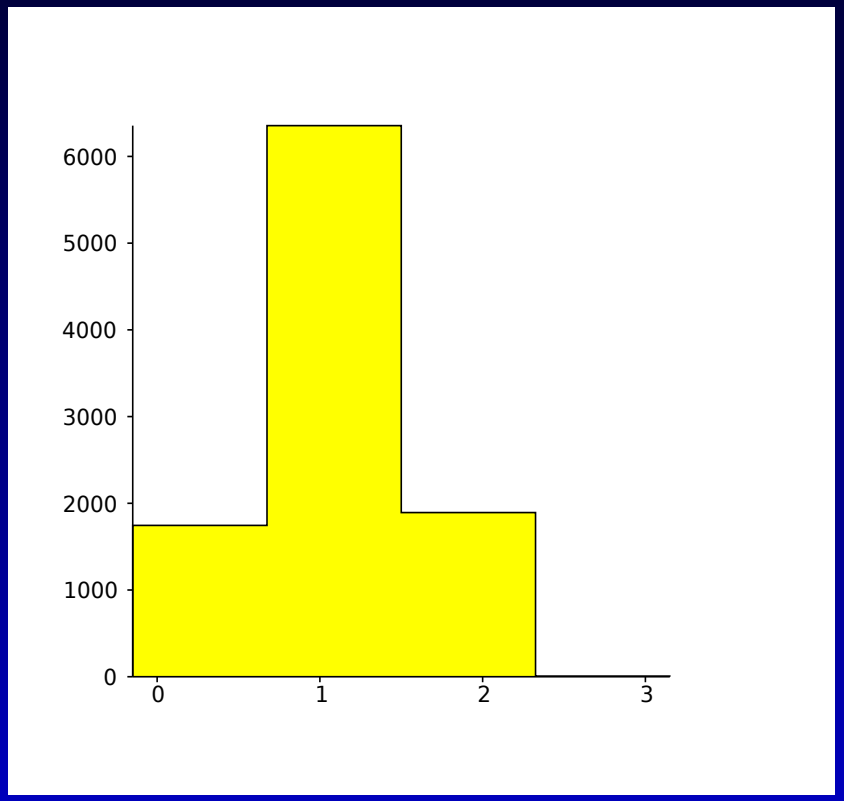


LH panel: $p_T(j_1)/GeV$, RH panel: $p_T(l_1)/GeV$

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.