SUSY and Exotica

by

Ben Allanach (University of Cambridge)

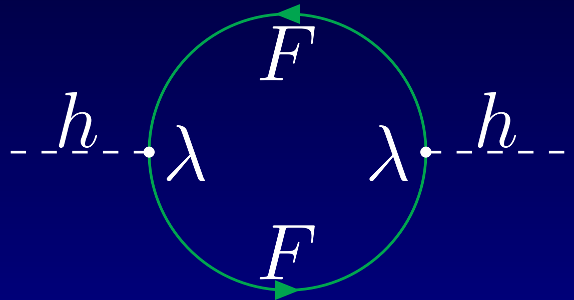
Talk outline

- SUSY Fits
- Impact of LHC data
- SUSY Tactics
- Exotica and $A_{FB}(t\bar{t})$

Please ask questions while I'm talking

A Problem With the Higgs Boson

The Higgs boson mass receives quantum corrections from heavy particles in the theory:



$$\sim -\frac{a\lambda^2}{16\pi^2}\int \frac{d^n k}{k^2 - m_F^2} + \ldots$$

Quantum correction to Higgs mass:

$$m_h^{phys} = 126 \text{ GeV}/c^2 = m_h^{tree} + \mathcal{O}(m_F/100).$$

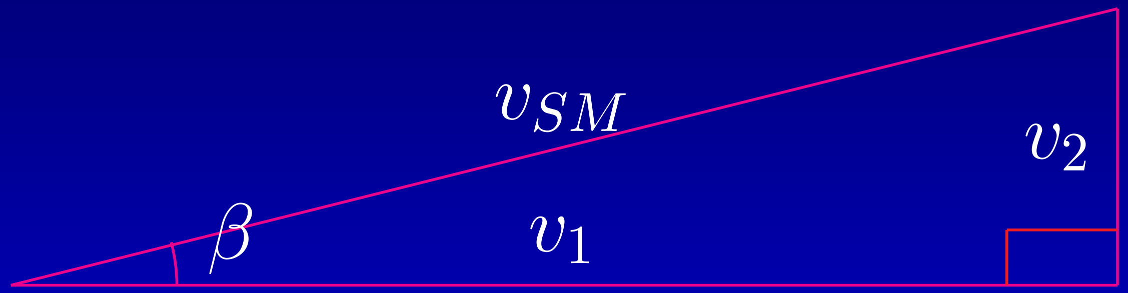
$m_F \sim 10^{19}$ GeV$/c^2$ is *heaviest mass scale* present.

Electroweak Breaking

Both Higgs get vacuum expectation values:

$$\begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \to \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \to \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

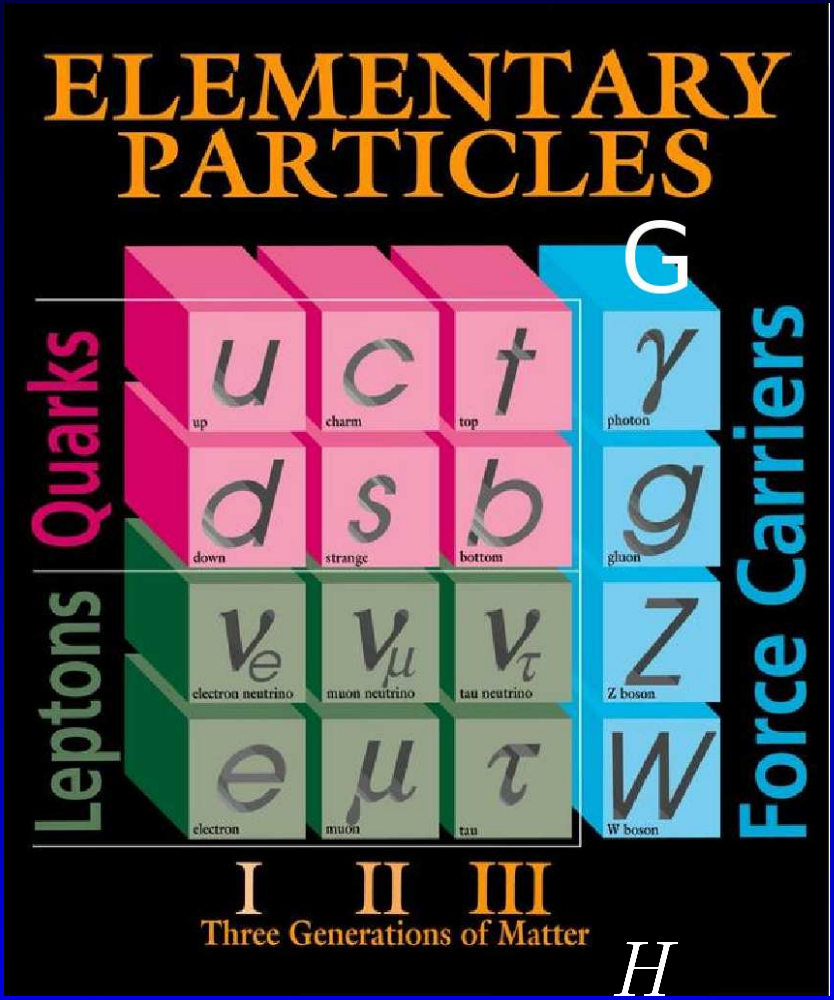
and to get M_W correct, match with $v_{SM} = 246$ GeV:



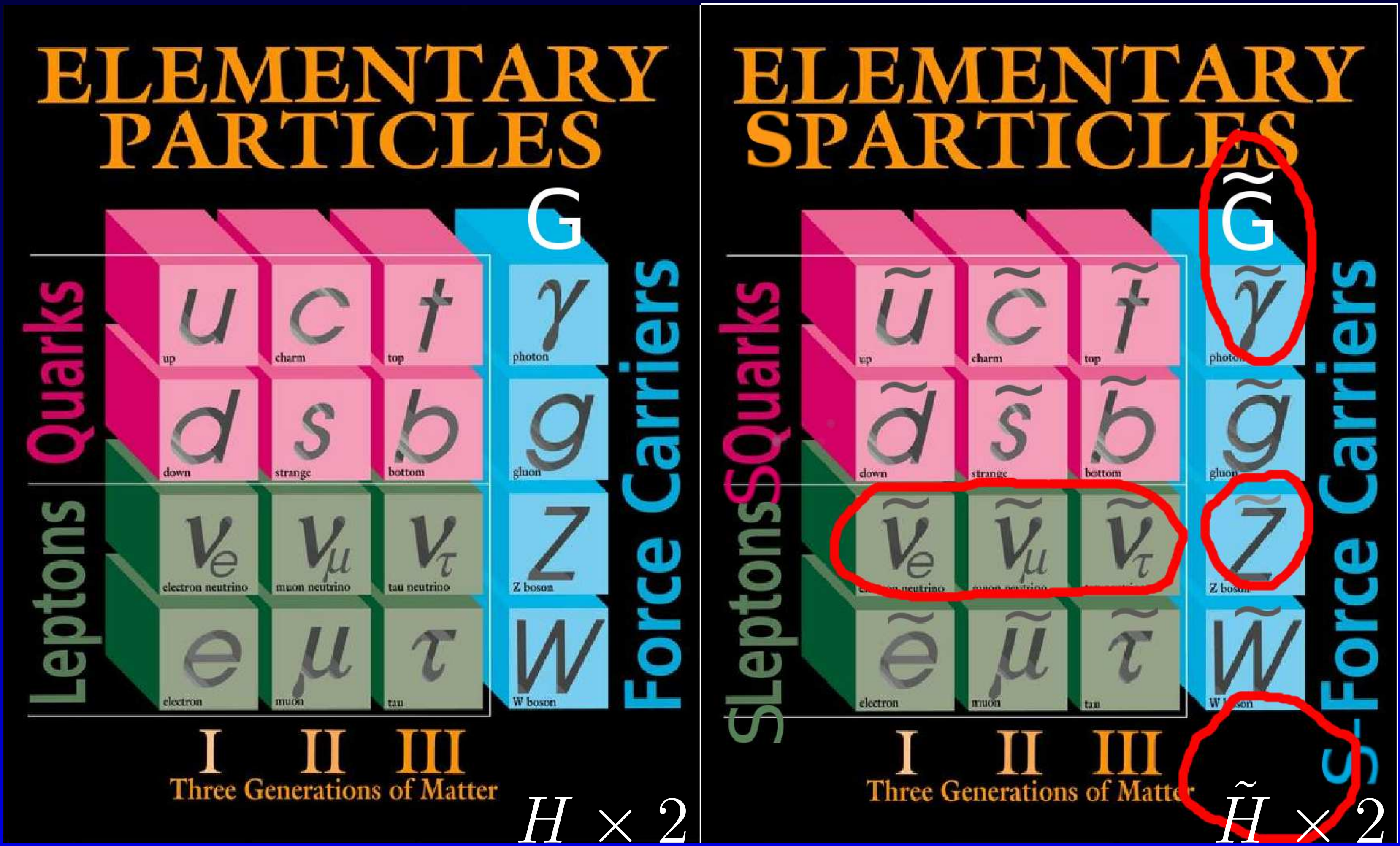
$\tan\beta = \frac{v_2}{v_1}$

$$\begin{aligned} \mathcal{L} &= h_t \bar{t}_L H_2^0 t_R + h_b \bar{b}_L H_1^0 b_R + h_\tau \bar{\tau}_L H_1^0 \tau_R \\ \Rightarrow \frac{m_t}{\sin\beta} &= \frac{h_t v_{SM}}{\sqrt{2}}, \qquad \frac{m_{b,\tau}}{\cos\beta} = \frac{h_{b,\tau} v_{SM}}{\sqrt{2}}. \end{aligned}$$

Supersymmetric Copies



Supersymmetric Copies



Implementation

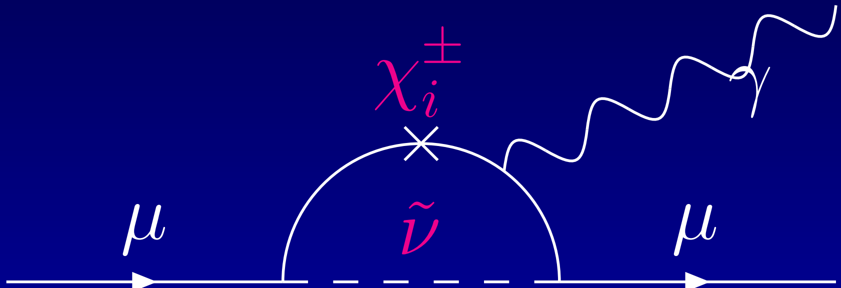
We use

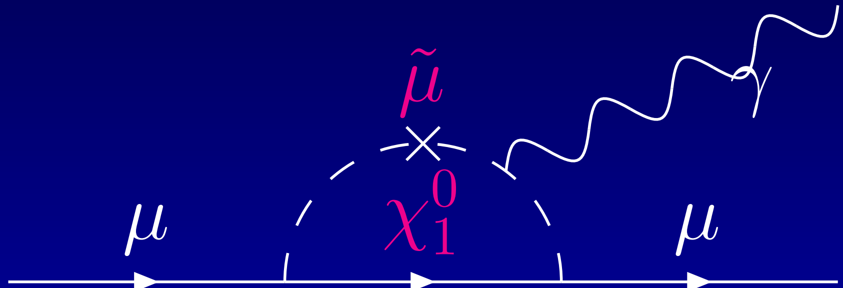
- *95% C.L. direct search constraints*
- $\Omega_{DM} h^2 = 0.1143 \pm 0.02$ `micrOMEGAs`
- $\delta(g-2)_\mu/2 = (29.5 \pm 8.8) \times 10^{-10}$ Stöckinger *et al*
- $B-$physics observables including `SusyBSG` $BR[b \to s\gamma]_{E_\gamma > 1.6 \text{ GeV}} = (3.52 \pm 0.38) \times 10^{-4}$, $\text{BR}(B_s \to \mu\mu) < 1.1 \times 10^{-8}$ `micrOMEGAs`
- Electroweak data W Hollik, A Weber *et al*

$$2 \ln \mathcal{L} = -\sum_i \chi_i^2 + c = \sum_i \frac{(p_i - e_i)^2}{\sigma_i^2} + c$$

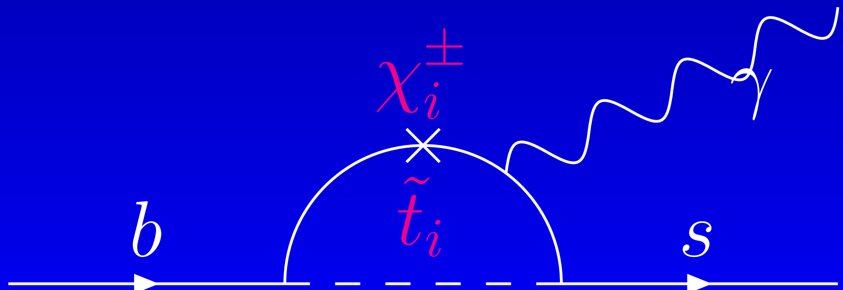
Additional observables

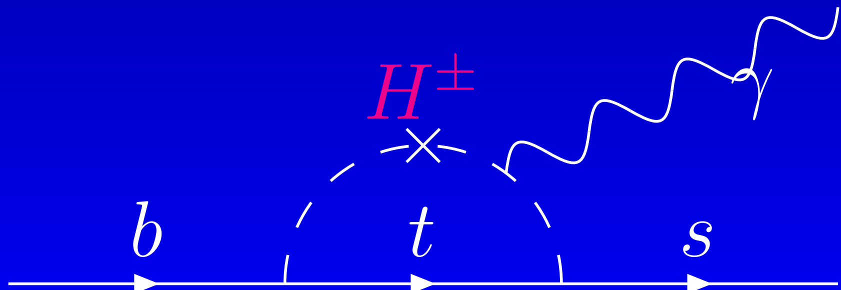
$$\delta\frac{(g-2)_\mu}{2} \sim 13\times 10^{-10}\left(\frac{100\text{ GeV}}{M_{SUSY}}\right)^2 \tan\beta$$



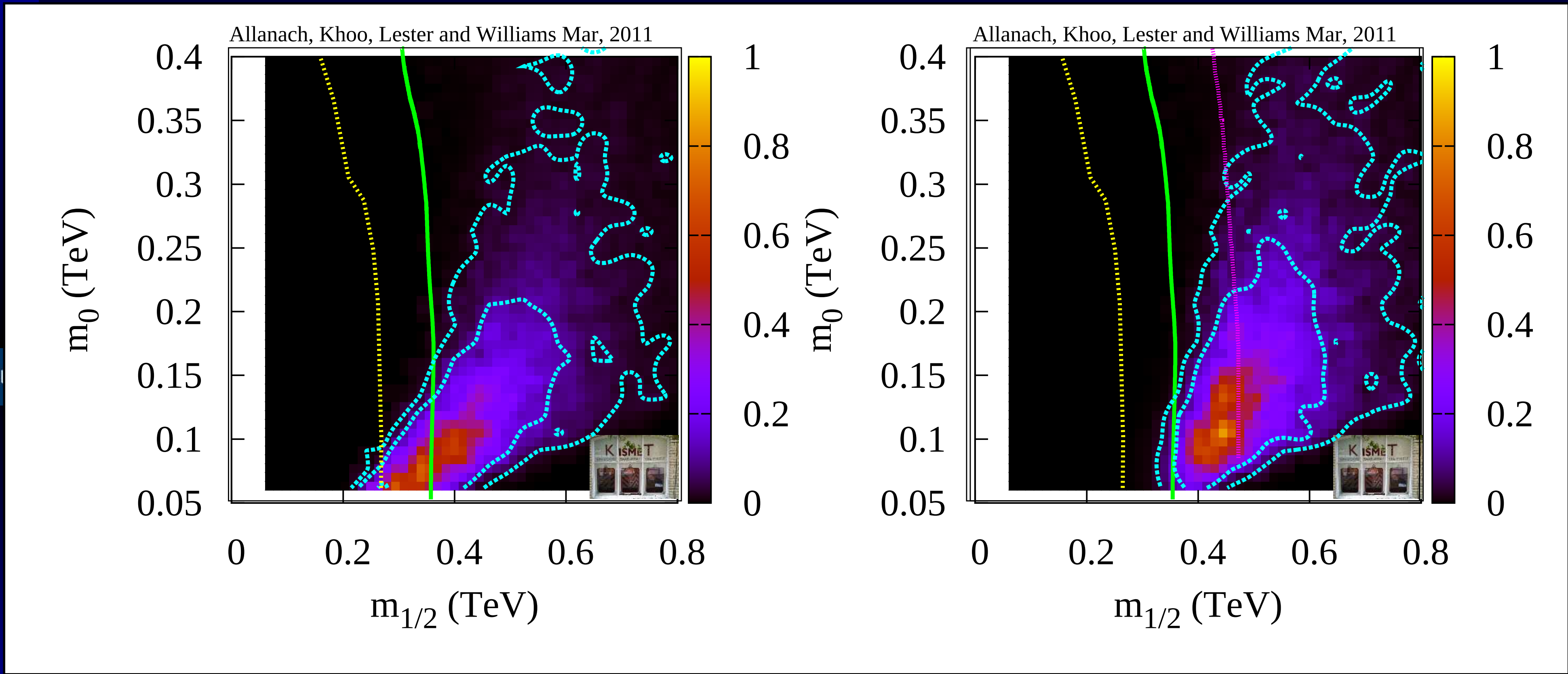


$$BR[b\to s\gamma] \propto \tan\beta (M_W/M_{SUSY})^2$$



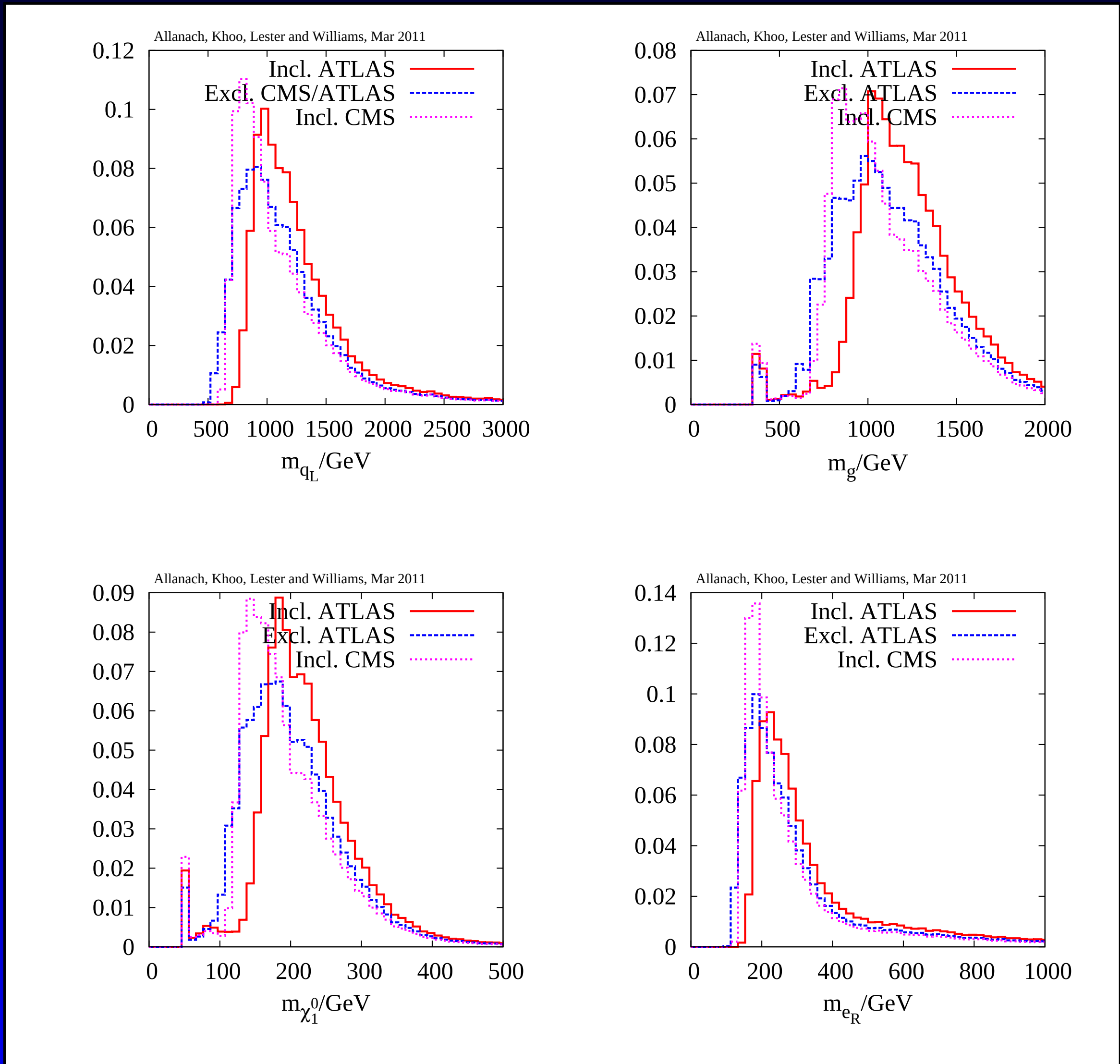


ATLAS Weighted Fits



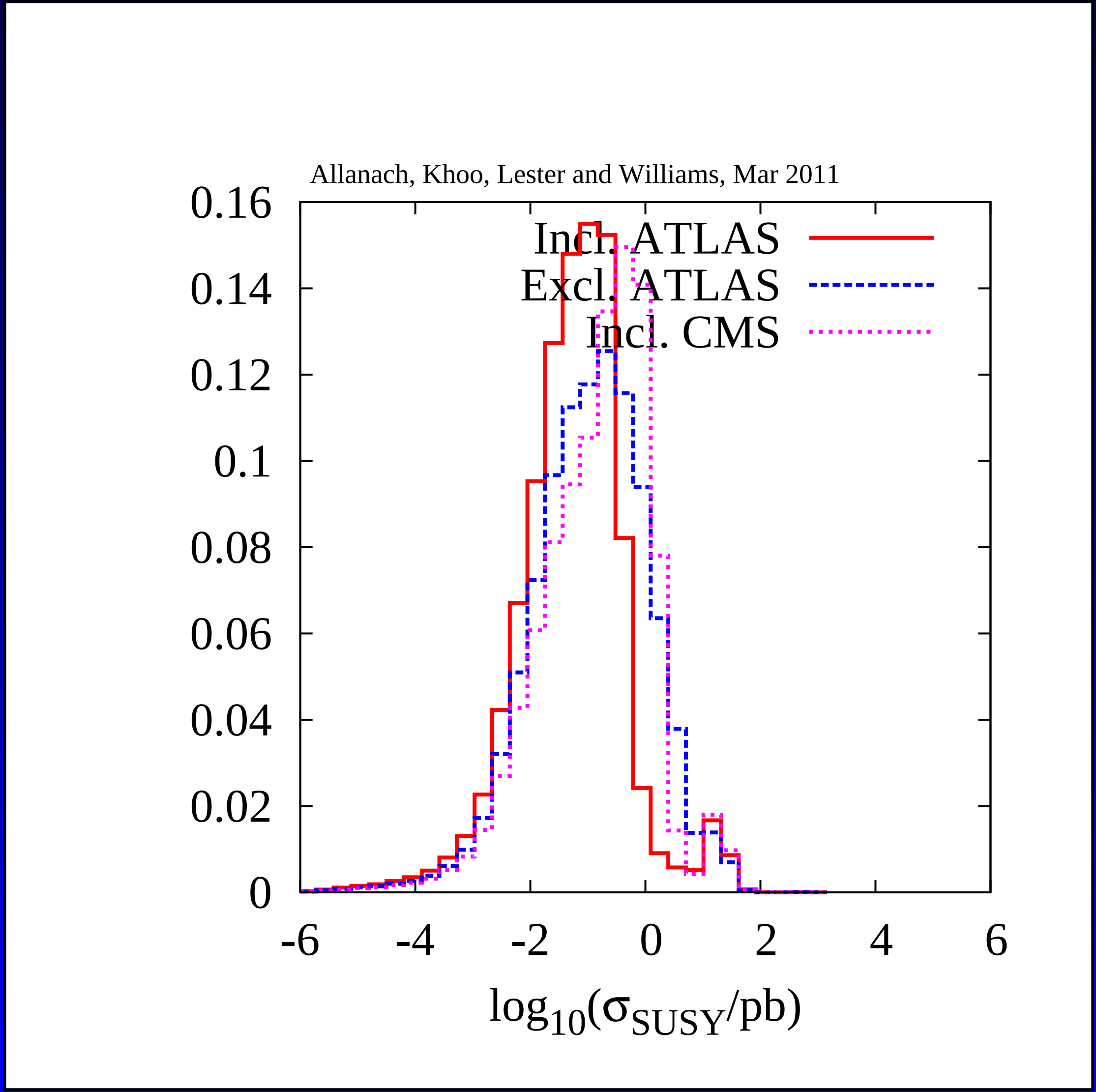
Again, we assume A_0-$\tan\beta$ independence and interpolate across m_0 and $m_{1/2}$. CMS 35 pb^{-1}, ATLAS 35 pb^{-1}, CMS 1 fb^{-1}

CMS/ATLAS Weighted Fits



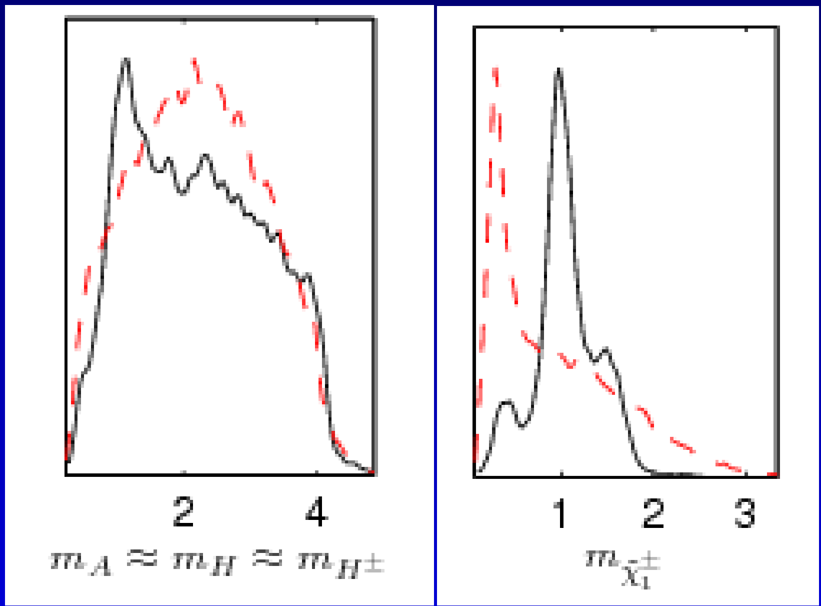
Prospects for SUSY

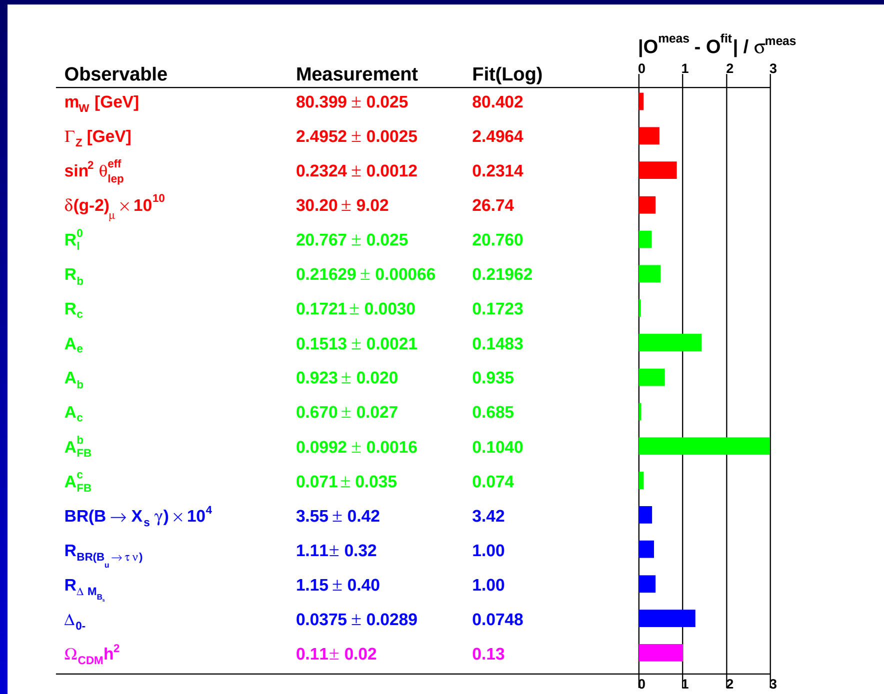
Still look good! 5fb^{-1} expected before christmas



pMSSM Fits

25 pMSSM input parameters are: $M_{1,2,3}$, $A_{t,b,\tau,\mu}$, $m_{H_{1,2}}$, $\tan\beta$, $m_{\tilde{d}_{R,L}} = m_{\tilde{s}_{R,L}}$, $m_{\tilde{u}_{R,L}} = m_{\tilde{c}_{R,L}}$, $m_{\tilde{e}_{R,L}} = m_{\tilde{\mu}_{R,L}}$, $m_{\tilde{t},\tilde{b},\tilde{\tau}_{R,L}}$ m_t, $m_b(m_b)$ $\alpha_s(M_Z)^{\overline{MS}}$, $\alpha^{-1}(M_Z)^{\overline{MS}}$, M_Z. Combined Bayesian fit[a]:

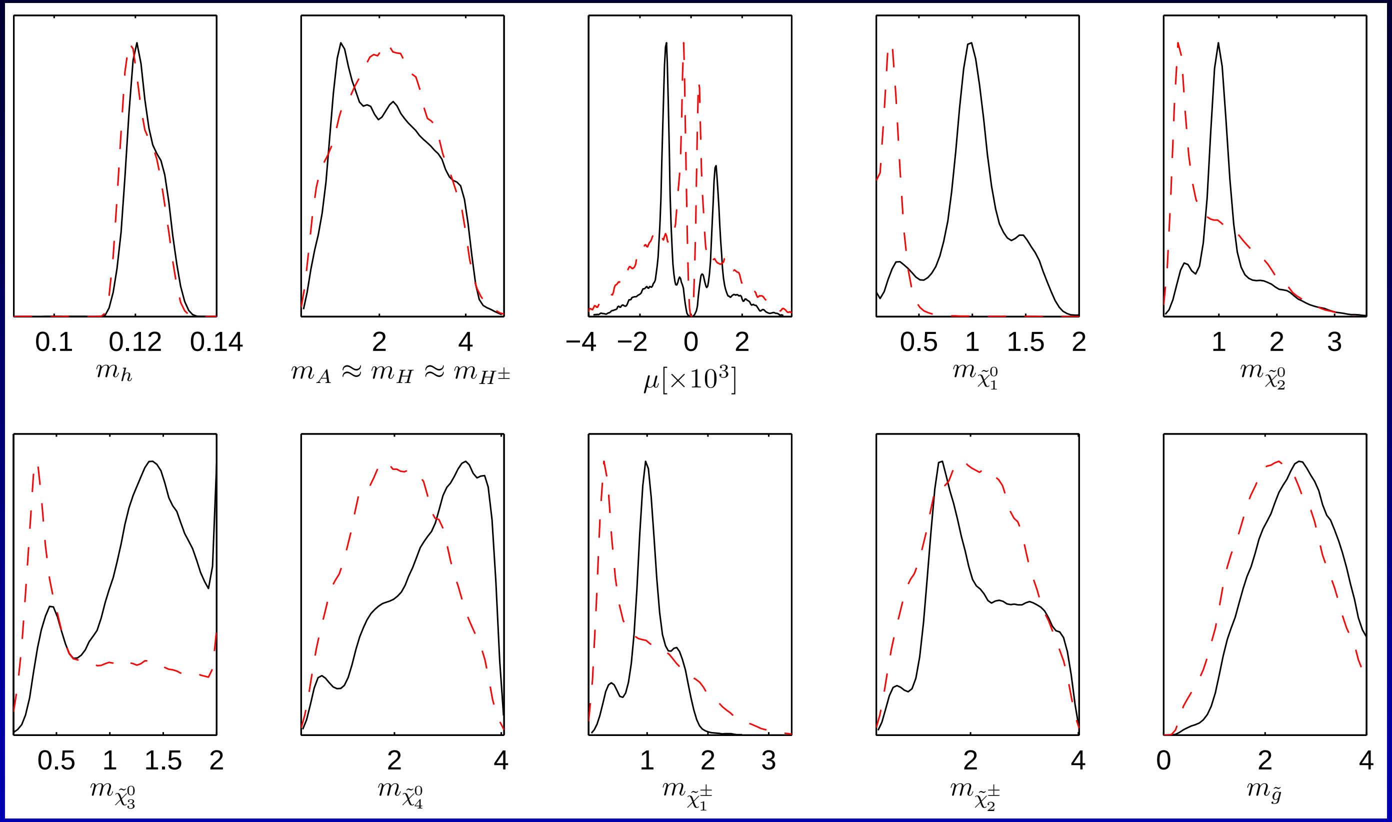




Observable	Measurement	Fit(Log)
m_W [GeV]	80.399 ± 0.025	80.402
Γ_Z [GeV]	2.4952 ± 0.0025	2.4964
$\sin^2\theta^{eff}_{lep}$	0.2324 ± 0.0012	0.2314
$\delta(g-2)_\mu \times 10^{10}$	30.20 ± 9.02	26.74
R_l^0	20.767 ± 0.025	20.760
R_b	0.21629 ± 0.00066	0.21962
R_c	0.1721 ± 0.0030	0.1723
A_e	0.1513 ± 0.0021	0.1483
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.685
A^b_{FB}	0.0992 ± 0.0016	0.1040
A^c_{FB}	0.071 ± 0.035	0.074
$BR(B \to X_s\gamma) \times 10^4$	3.55 ± 0.42	3.42
$R_{BR(B_u \to \tau\nu)}$	1.11 ± 0.32	1.00
$R_{\Delta M_{B_s}}$	1.15 ± 0.40	1.00
Δ_{0-}	0.0375 ± 0.0289	0.0748
$\Omega_{CDM}h^2$	0.11 ± 0.02	0.13

[a] S.S. AbdusSalam, BCA, F. Quevedo, F. Feroz, M. Hobson, PRD81 (2010) 985012, `arXiv:0904.2548`

Spectrum

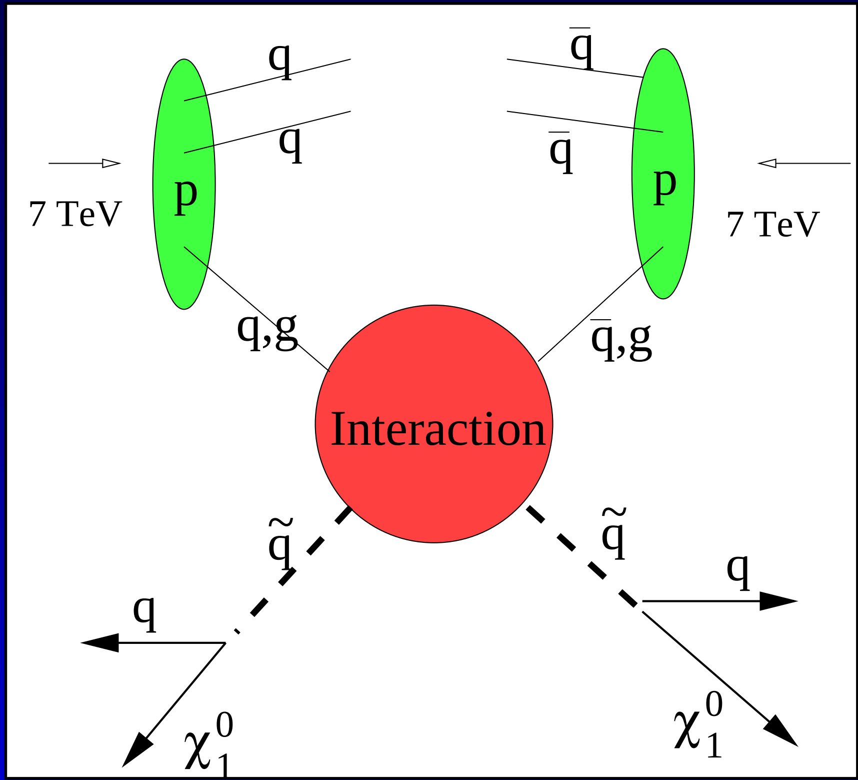


Obtained with `MultiNest`[a] algorithm in 16 CPU years. Prior dependence is *useful*: which predictions are robust?

[a] Feroz, Hobson `arxiv:0704.3704`

Collider SUSY Production

Strong sparticle production and decay to dark matter particles.



Any (light enough) dark matter candidate that couples to hadrons can be produced at the LHC

α_T, MET, M_{T_2} Searches

CMS: jets and missing energy `arXiv:1101.1628`

$\mathcal{L} = 35$ pb^{-1}. $H_T = \sum_{i=1}^{N_{jet}} |\mathbf{p}_T^{j_i}| > 350$ GeV.

$$\Delta H_T \equiv \sum_{j_i \in A} |\mathbf{p}_T^{j_i}| - \sum_{j_i \in B} |\mathbf{p}_T^{j_i}|. \qquad (1)$$

One then calculates

$$\alpha_T = \frac{H_T - \Delta H_T}{2\sqrt{H_T^2 - \not{H}_T^2}} > 0.55 \qquad (2)$$

where $\not{H}_T = \sqrt{(\sum_{i=1}^{N_{jet}} p_x^{j_i})^2 + (\sum_{i=1}^{N_{jet}} p_y^{j_i})^2}$.

Cue M_{T_2}

$$m_T^{(i)^2}(\mathbf{p}_T{}^{(i)}, \not{\mathbf{q}}_T{}^{(i)}) \equiv 2\left|\mathbf{p}_T{}^{(i)}\right|\left|\not{\mathbf{q}}_T{}^{(i)}\right| - 2\mathbf{p}_T{}^{(i)} \cdot \not{\mathbf{q}}_T{}^{(i)}$$

where $\not{\mathbf{q}}_T{}^{(i)}$ is the missing transverse momentum from i. The variable M_{T2} is defined by:

$$M_{T2}(\mathbf{p}_T{}^{(1)}, \mathbf{p}_T{}^{(2)}, \not{\mathbf{p}}_T) \equiv \min_{\sum \not{\mathbf{q}}_T = \not{\mathbf{p}}_T} \left\{ \max\left(m_T^{(1)}, m_T^{(2)} \right) \right\}$$

The minimization is over all values of $\not{\mathbf{q}}_T{}^{(1,2)}$ consistent with $\sum \not{\mathbf{q}}_T = \not{\mathbf{p}}_T$. For the SUSY search, the unknown undetected particle masses are set to zero in M_{T2}.

M_{T_2} Search

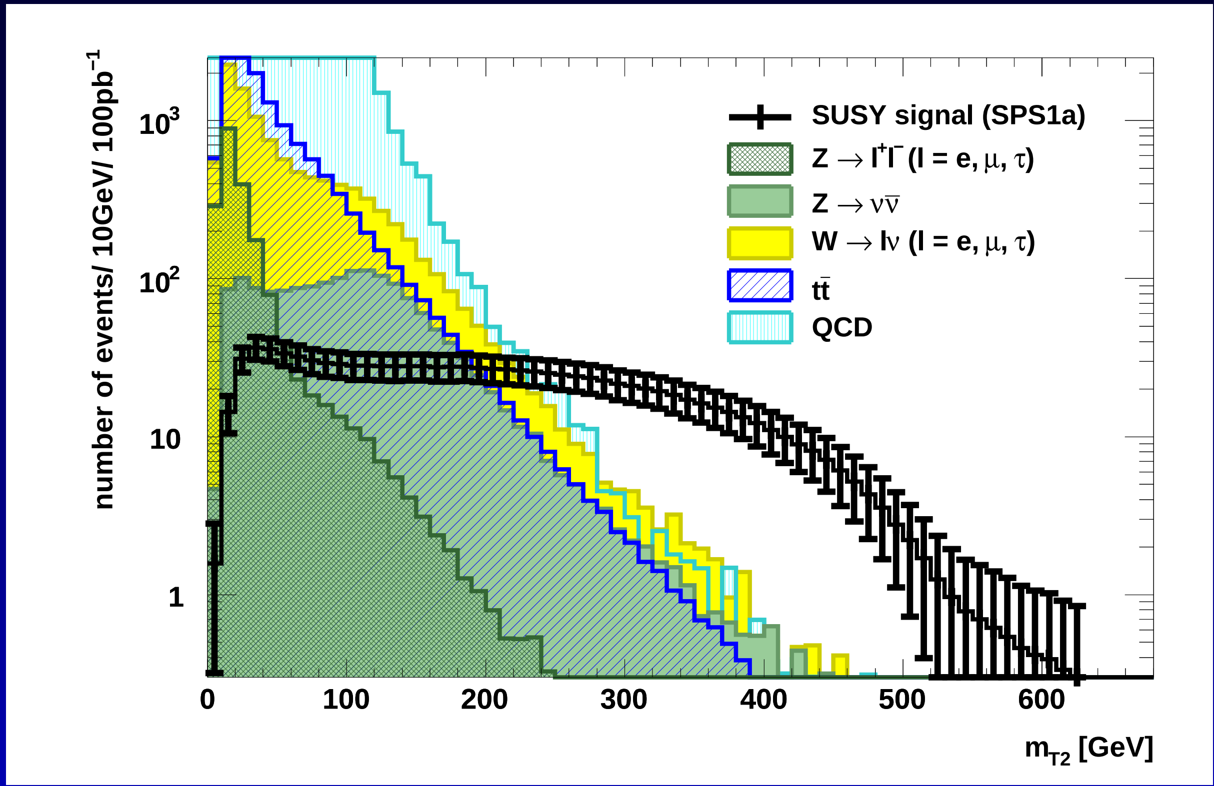


Figure 1: Only cuts: $N_j > 1$, $p_T > 50$ GeV, $\mathcal{L} = 100 pb^{-1}$ at $\sqrt{s} = 7$ TeV. Barr, Gwenlan PRD80 (2009) 074007.

M_{T2} v E_T^{miss}

BCA, Barr, Dafinca, Gwenlan, JHEP 1107 (2011) 104,

arXiv:1105.1024

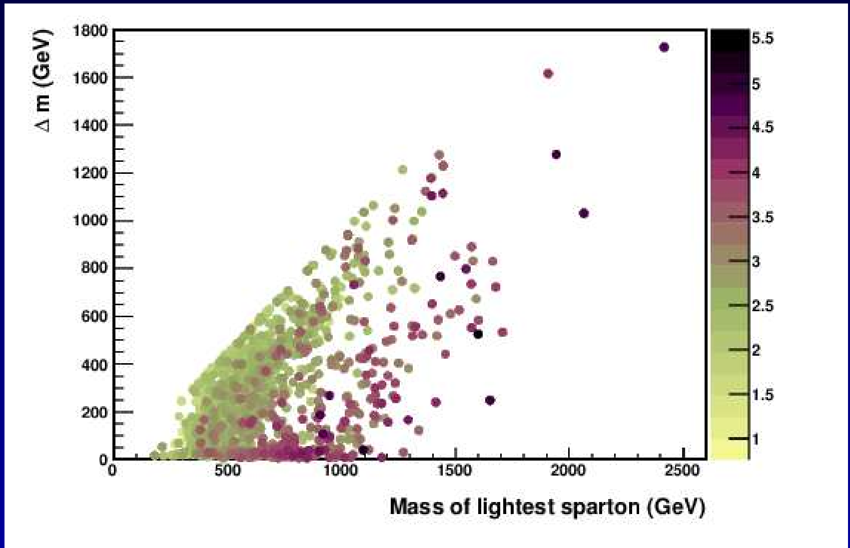
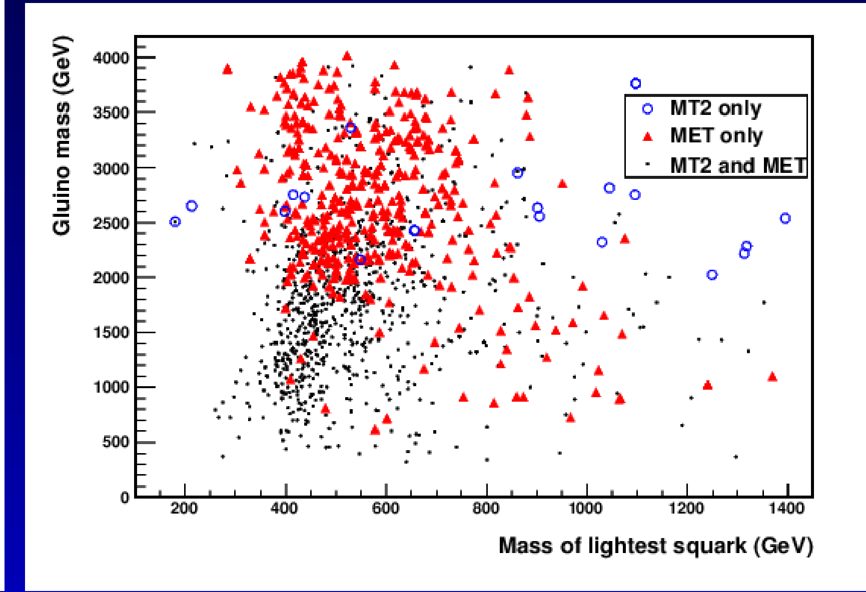


Figure 6: $\log_{10}$[luminosity $(\text{pb})^{-1}$ needed for discovery] with the combined optimal M_{T2} and MET based strategy at $\sqrt{s}$ = 14 TeV in the $(\Delta m, m_{\text{lightest sparton}})$ plane. Δm is the mass difference between the lightest sparton and the LSP. The M_{T2} based strategy was optimized for an integrated luminosity of 1 fb^{-1}. Systematic uncertainties in the background have been neglected.



Compressed Spectra

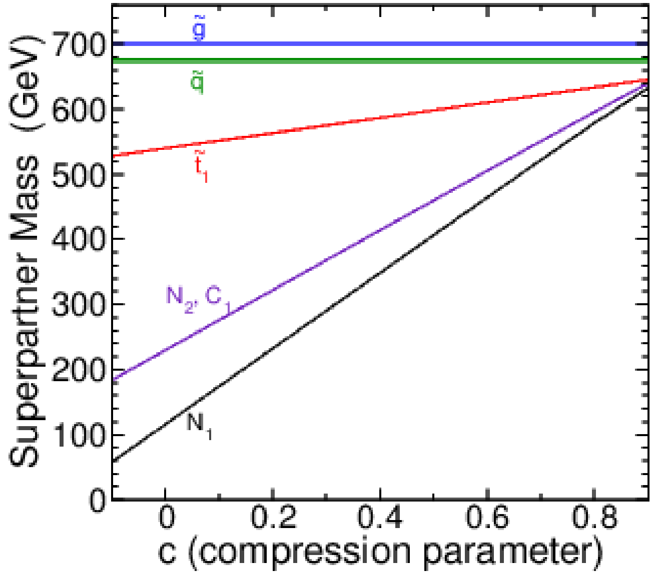


FIG. 1: The masses of the most relevant superpartners for the class of models defined in subsection III A, as a function of the compression parameter c, for fixed $M_{\tilde{g}} = 700$ GeV. The case $c = 0$ corresponds to an mSUGRA-like model.

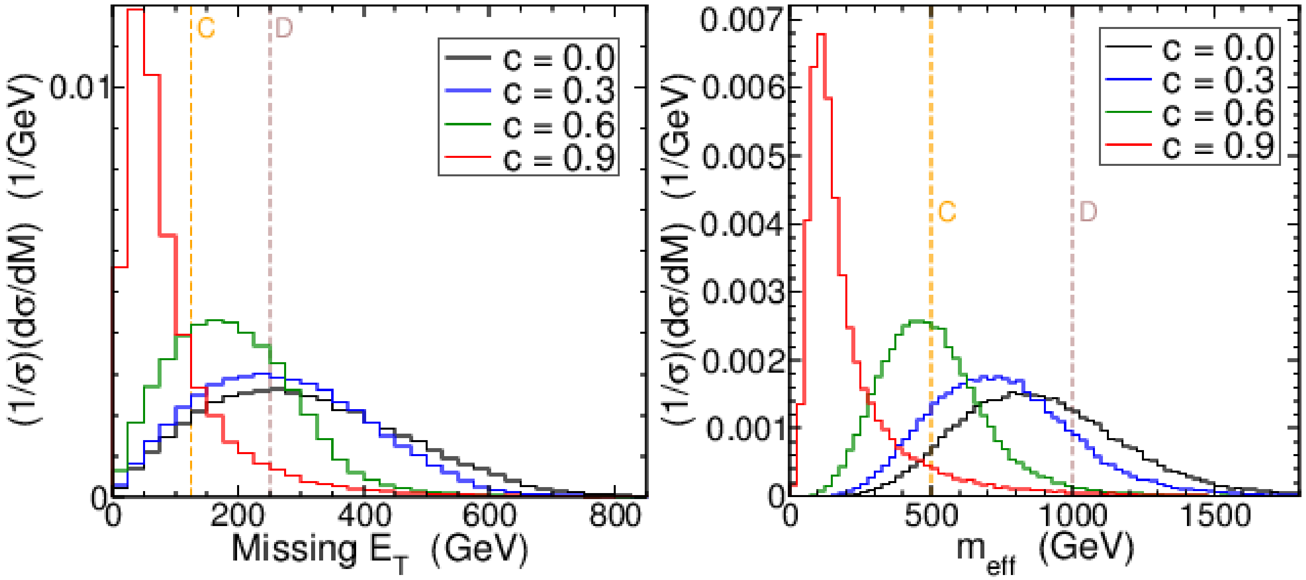
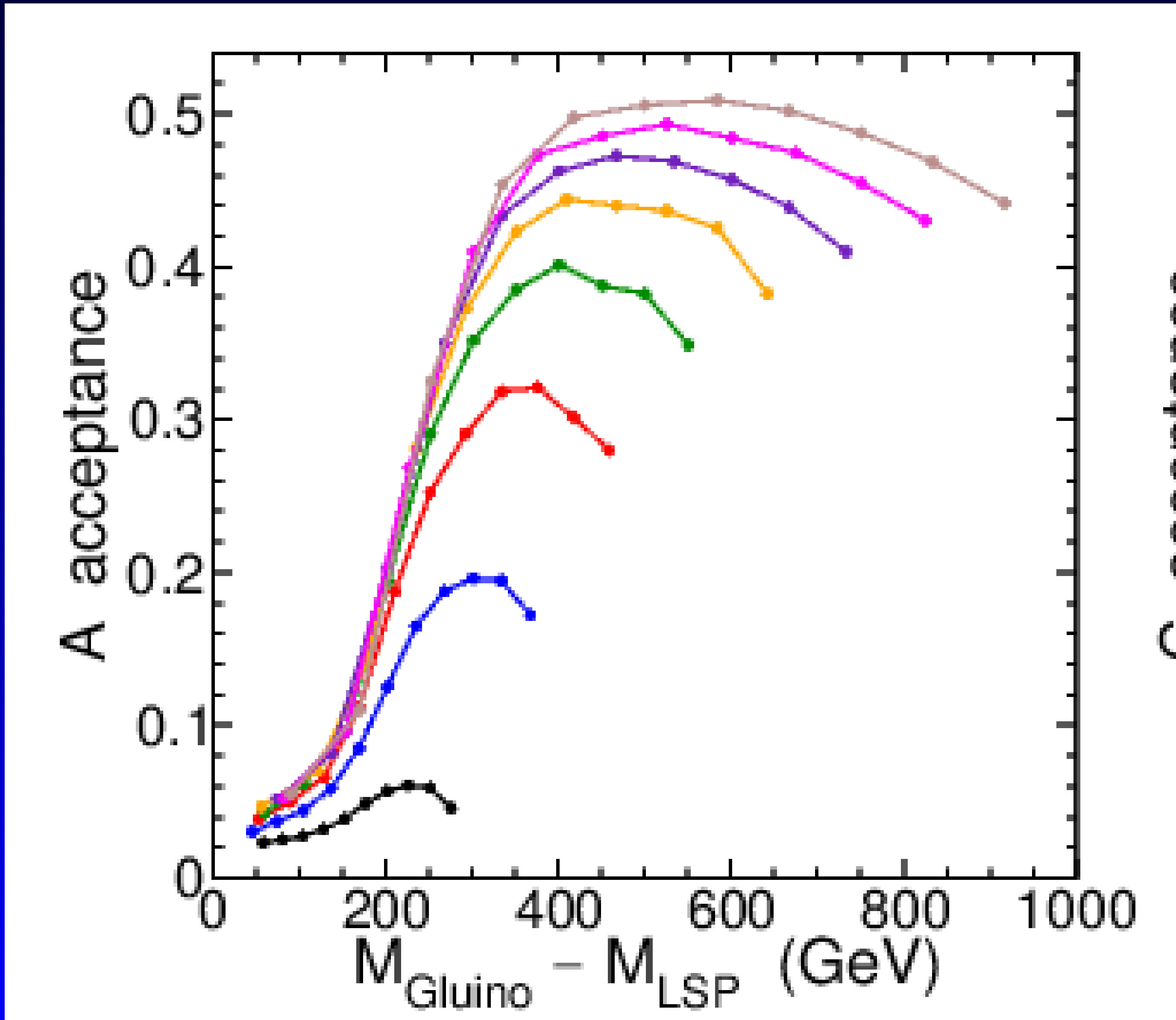


FIG. 2: The distributions before cuts of $E_T^{\rm miss}$ (left panel) and $m_{\rm eff}$ with 3 jets included (right panel) for models described in subsection III A with $M_{\tilde{g}} = 700$ GeV and $c = 0.0, 0.3, 0.6$, and 0.9, from right to left.

Compressed Spectra II

LeCompte, Martin, arXiv:1105.4304



Benchmarks

Currently we[a] are devising SUSY benchmark models. It's *imminent*.

- CMSSM, NUHM, mAMSB, mGMSB, RPV and some simplified models (via pMSSM) are defined.
- Defining interesting parameter planes: identifying important parameters which control the masses of sparticles in each case.
- Discrete set of points along monotonic lines: next point for the experiments to study is defined as the lightest one that is not ruled out to 95% CL.

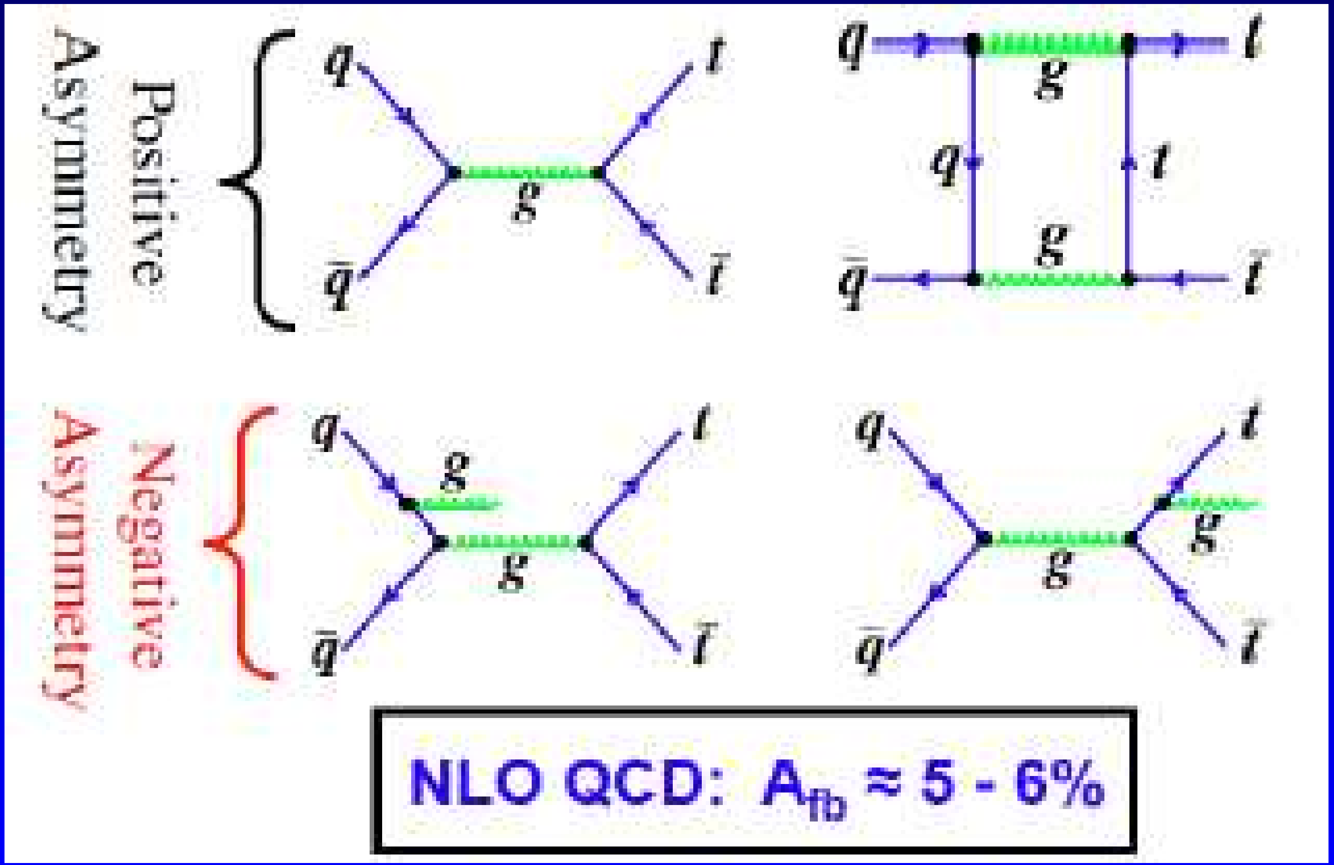
[a] S.S. AbdusSalam, BCA H. Dreiner, J. Ellis, S. Heinemeyer, M. Krämer, M. Mangano, K.A. Olive, S. Rogerson, L. Roszkowski, M. Schlaffer, G. Weiglein

Science & Technology Facilities Council

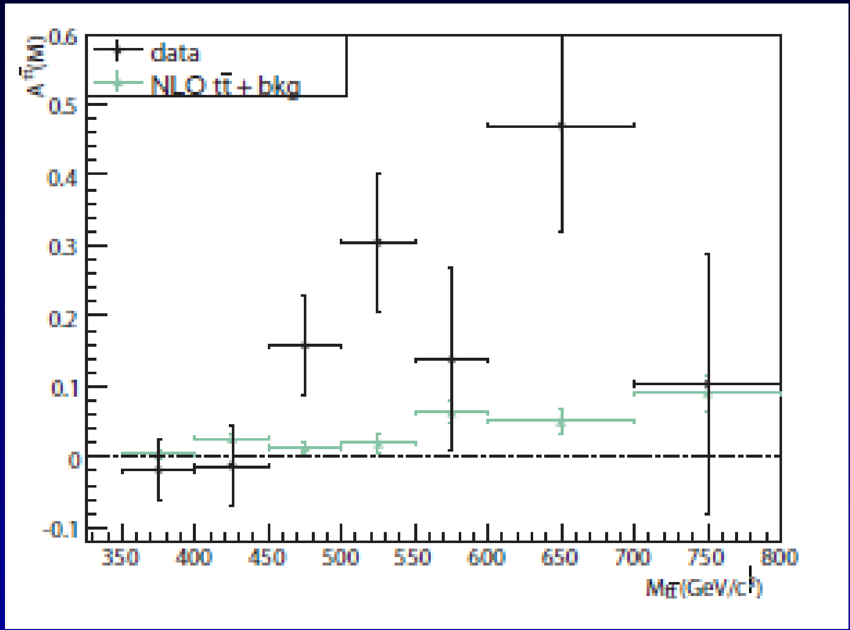
Supersymmetry Cambridge Working group

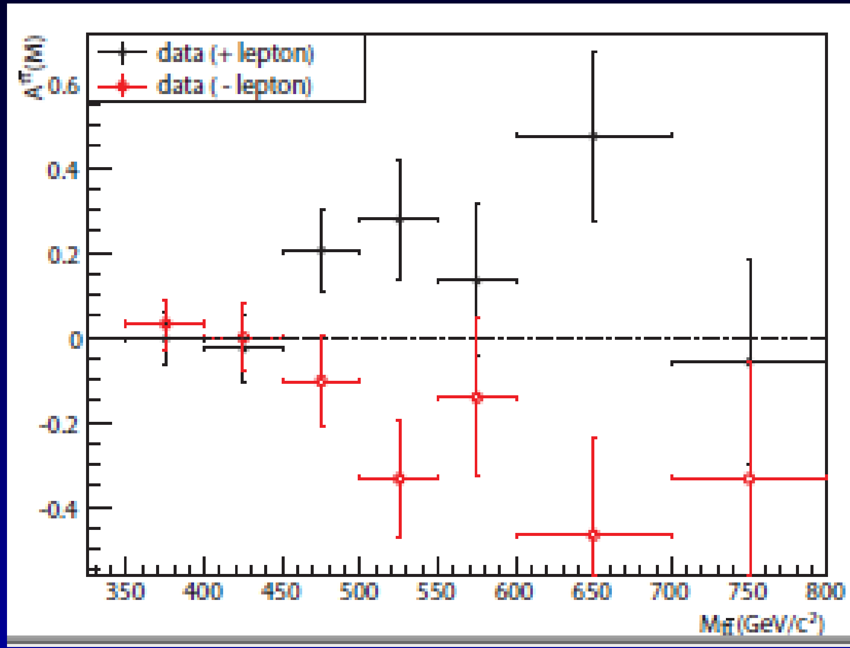
$A_{FB}(t\bar{t})$

$$
\begin{aligned}
A_{FB} &= \frac{N(y_t > y_{\bar{t}}) - N(y_{\bar{t}} > y_t)}{N(y_t > y_{\bar{t}}) + N(y_{\bar{t}} > y_t)} \\
A_{FB}(CDF)_{lj+ll} &= (20.9 \pm 6.6)\%, \\
A_{FB}(D0)_{lj} &= (19.6 \pm 6.5)\%,
\end{aligned}
$$



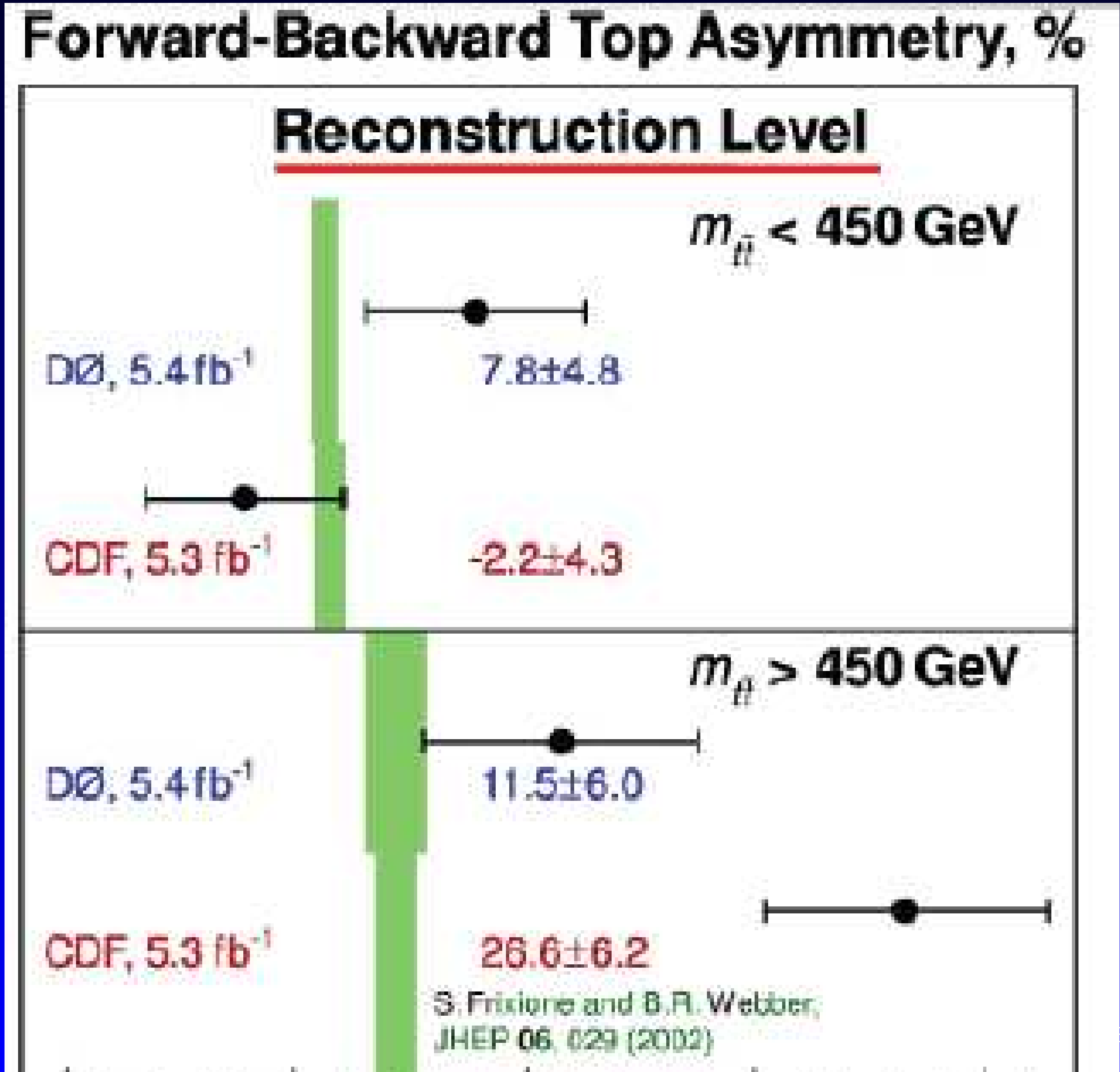
CDF





Seems to be increasing with mass. Lepton charge is nice verification.

$M_{t\bar{t}}$



Forward-Backward Top Asymmetry, %
Reconstruction Level
$m_{t\bar{t}}$ < 450 GeV
DØ, 5.4 fb⁻¹
7.8±4.8
CDF, 5.3 fb⁻¹
-2.2±4.3
$m_{t\bar{t}}$ > 450 GeV
DØ, 5.4 fb⁻¹
11.5±6.0
CDF, 5.3 fb⁻¹
26.6±6.2
S. Frixione and B.R. Webber,
JHEP 06, 029 (2002)

A_{FB} Exotica

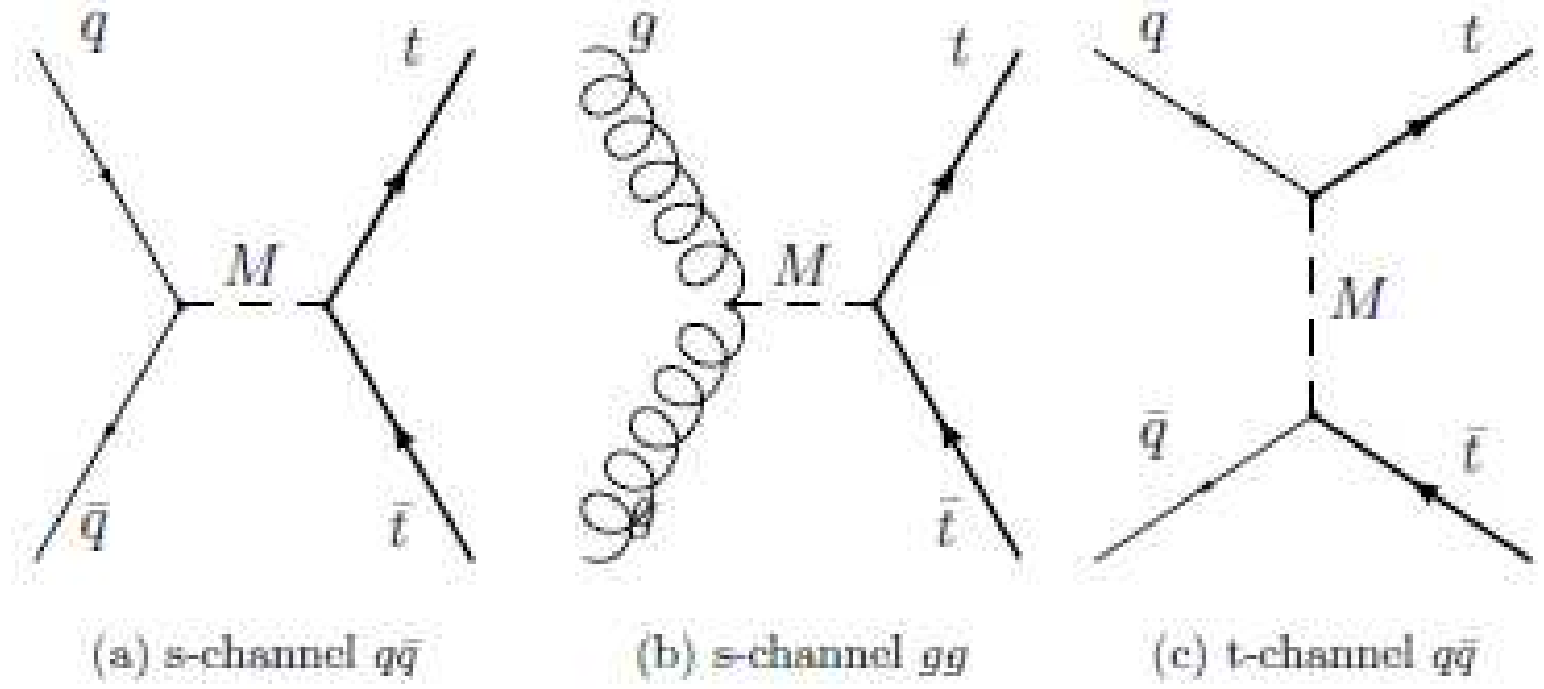


Figure 1: Tree level $t\bar{t}$ production diagram with mediator M exchange.

Must not disturb $\sigma_{t\bar{t}}$ or $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$

- axigluons[a]
- Z'/W'[b]

LHC Asymmetry

Defined LHC charge asym

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(y_{\bar{t}} > |y_t|)}{N(|y_t| > |y_{\bar{t}}|) + N(y_{\bar{t}} > |y_t|)}$$

SM discovery would take 60 fb^{-1} at 5σ, but new physics quicker (Z' takes 2 fb^{-1})

$A_C^{CMS} = -1.6 \pm 3 \pm 1\%$ $A_C^{ATLAS} = -2.4 \pm 1.6 \pm 2.3\%$

Models

- Z' model is rather odd: only contains a vertex coupling utZ', eg $M_{Z'} = 800$ GeV, $g_Z = 3.4$: predicts significant *same sign tops*.
- W' models also covered by LHC experiments by now.
- Heavy axigluon models eg 2 TeV, g_q=-g_t=2.4 are ruled out by LHC m_{jj} searches
- Recent proposal[a]: axigluons $g =$0.4-0.8, $M = 50 - 90$ GeV. They evade jet data because the have masses *below* current limits. Non-resonant production suppresses new physics contribution to $\sigma_{t\bar{t}}$.

[a] Krnjaic, `arXiv:1109.0648`

Shopping List

Things that the CMS/ATLAS always provide that we need:

- Cuts and numbers of events observed past them
- Expected background numbers with systematic errors

We could really do with:

- Keeping in mind: we can't combine analyses that use the same events: much better to keep the events disjoint. Doesn't preclude fully inclusive analysis, but make the others as disjoint as possible.
- Likelihood versus predicted number of events past cuts (before efficiency correction). Ideally, sanitized `RooStats`

Shopping List II

Failing that, then we must calculate the likelihood:

- Systematic errors on signals: perhaps at least a range over parameter space in one model. Ideally, it would be parameterised in terms of important quantities.
- Other contours (eg 1/5 sigma exclusion contours) so we can check our likelihood away from 95% excluded region.
- Numbers in histogram plots attached to `arXiv` publication

Summary

- LHC analyses providing a nice amount of information for interpretation of data. There's always room for improvement...
- SUSY is late to the party, but not late enough to be reported missing
- CMSSM *could well be discovered this/next year*
- Current searches reach squark and gluino masses of 980 GeV. This will be extended to ~ 1100 GeV next year, covering much of the good-fit region.
- $t\bar{t}$ asymmetry situation extremely murky. Many heavy axigluon models now ruled out.

Supplementary Material

CMS α_T Search

CMS: jets and missing energy `arXiv:1101.1628`

$\mathcal{L} = 35$ pb^{-1}. $H_T = \sum_{i=1}^{N_{jet}} |\mathbf{p}_T^{j_i}| > 350$ GeV.

(3) $$\Delta H_T \equiv \sum_{j_i \in A} |\mathbf{p}_T^{j_i}| - \sum_{j_i \in B} |\mathbf{p}_T^{j_i}|.$$

One then calculates

(4) $$\alpha_T = \frac{H_T - \Delta H_T}{2\sqrt{H_T^2 - \not{H}_T^2}} > 0.55$$

where $\not{H}_T = \sqrt{(\sum_{i=1}^{N_{jet}} p_x^{j_i})^2 + (\sum_{i=1}^{N_{jet}} p_y^{j_i})^2}$.

Results

ATLAS 0-lepton, jets and $\not{p}_T$

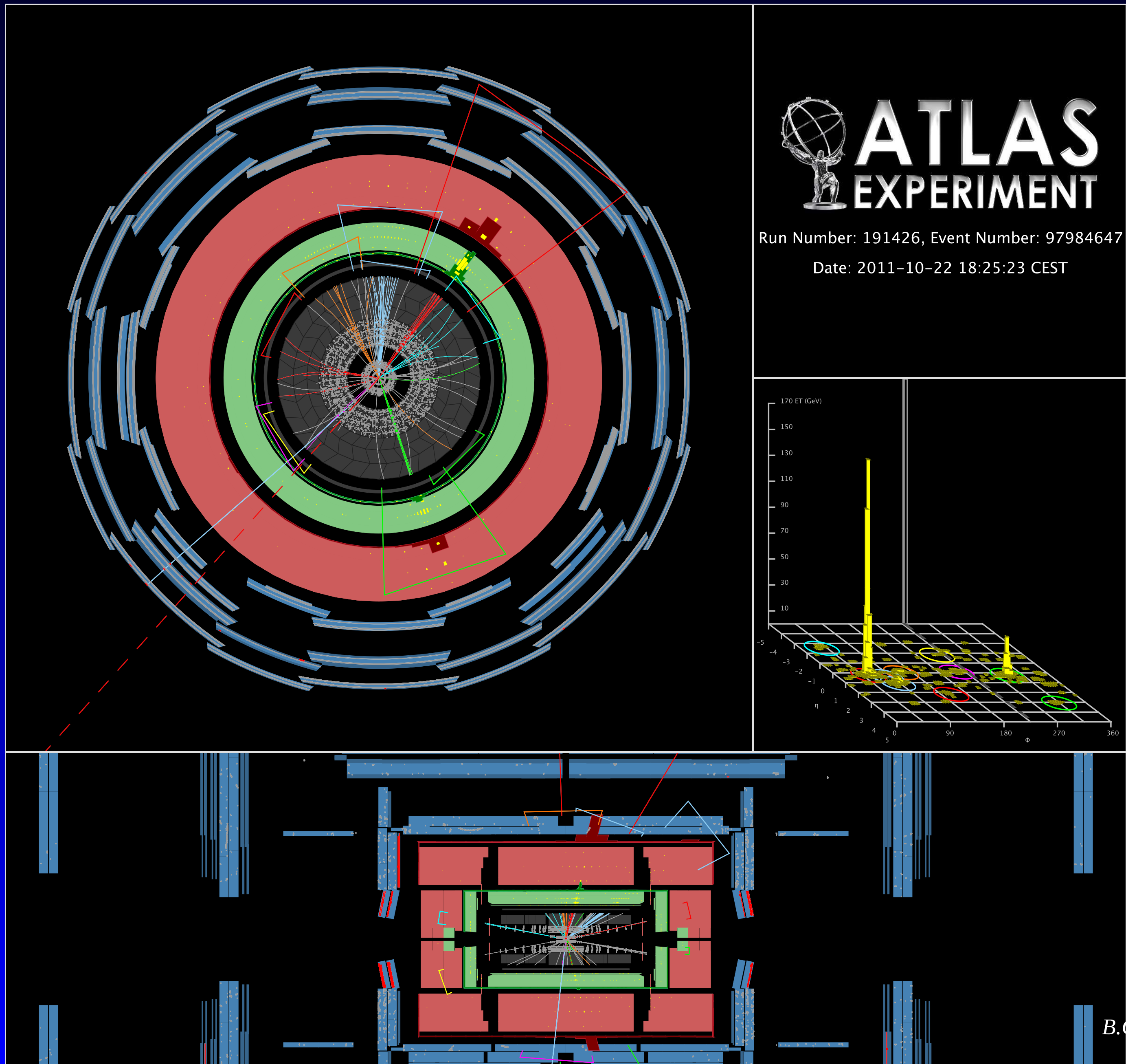
$$m_{eff} = \sum p_T^{(j)} + \not{p}_T,$$

$$m_T^{(i)\,2}(\mathbf{p}_T{}^{(i)}, \not{\mathbf{q}}_T{}^{(i)}) \equiv 2\left|\mathbf{p}_T{}^{(i)}\right| \left|\not{\mathbf{q}}_T{}^{(i)}\right| - 2\mathbf{p}_T{}^{(i)} \cdot \not{\mathbf{q}}_T{}^{(i)}$$

where $\not{\mathbf{q}}_T{}^{(i)}$ is the transverse momentum of particle (i). For each event, it is a lower bound on $m(NLSP)$.

$$M_{T2}(\mathbf{p}_T{}^{(1)}, \mathbf{p}_T{}^{(2)}, \not{\mathbf{p}}_T) \equiv \min_{\sum \not{\mathbf{q}}_T = \not{\mathbf{p}}_T} \left\{ \max\left(m_T^{(1)}, m_T^{(2)} \right) \right\}$$

Candidate Event: High $E_T(j)$



MSSM Exclusion: Simplified Model

	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\ ^{+8}_{-7}$[u+j]	$0.6\ ^{+0.7}_{-0.6}$[u+j]	$9\ ^{+10}_{-9}$[u+j]	$0.2\ ^{+0.4}_{-0.2}$[u+j]
W+jets	50 ± 11[u] $^{+14}_{-10}$[j] $\pm\ 5[\mathcal{L}]$	4.4 ± 3.2[u] $^{+1.5}_{-0.8}$[j] $\pm 0.5[\mathcal{L}]$	$35 \pm\ 9$[u] $^{+10}_{-8}$[j] $\pm 4[\mathcal{L}]$	1.1 ± 0.7[u] $^{+0.2}_{-0.3}$[j] $\pm 0.1[\mathcal{L}]$
Z+jets	52 ± 21[u] $^{+15}_{-11}$[j] $\pm\ 6[\mathcal{L}]$	4.1 ± 2.9[u] $^{+2.1}_{-0.8}$[j] $\pm 0.5[\mathcal{L}]$	27 ± 12[u] $^{+10}_{-6}$[j] $\pm 3[\mathcal{L}]$	0.8 ± 0.7[u] $^{+0.6}_{-0.0}$[j] $\pm 0.1[\mathcal{L}]$
$t\bar{t}$ and t	$10 \pm\ 0$[u] $^{+3}_{-2}$[j] $\pm\ 1[\mathcal{L}]$	0.9 ± 0.1[u] $^{+0.4}_{-0.3}$[j] $\pm 0.1[\mathcal{L}]$	$17 \pm\ 1$[u] $^{+6}_{-4}$[j] $\pm 2[\mathcal{L}]$	0.3 ± 0.1[u] $^{+0.2}_{-0.1}$[j] $\pm 0.0[\mathcal{L}]$
Total SM	118 ± 25[u] $^{+32}_{-23}$[j] $\pm 12[\mathcal{L}]$	10.0 ± 4.3[u] $^{+4.0}_{-1.9}$[j] $\pm 1.0[\mathcal{L}]$	88 ± 18[u] $^{+26}_{-18}$[j] $\pm 9[\mathcal{L}]$	2.5 ± 1.0[u] $^{+1.0}_{-0.4}$[j] $\pm 0.2[\mathcal{L}]$
Data	87	11	66	2

Table 2: Expected and observed numbers of events in the four signal regions. Uncertainties shown are due to "MC statistics, statistics in control regions, other sources of uncorrelated systematic uncertainty, and also the jet energy resolution and lepton efficiencies" [u], the jet energy scale [j], and the luminosity [$\mathcal{L}$].