

# Supersymmetric Flavour and Selectron Smuon splitting

by

Ben Allanach (University of Cambridge)

## Talk outline<sup>a</sup>

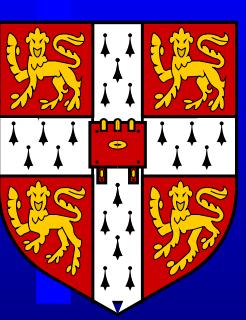
- SUSY kinematic edges at the LHC
- Selectron-smuon splitting: generation
- Measurement and interpretation

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<sup>a</sup>Based on work with J Conlon, C Lester arXiv: 0801.3666, PRD77

(2008) 076006



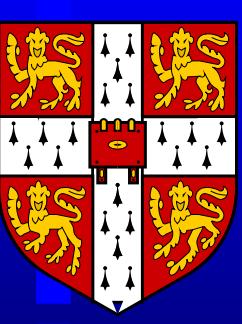


# SUSY flavour tools



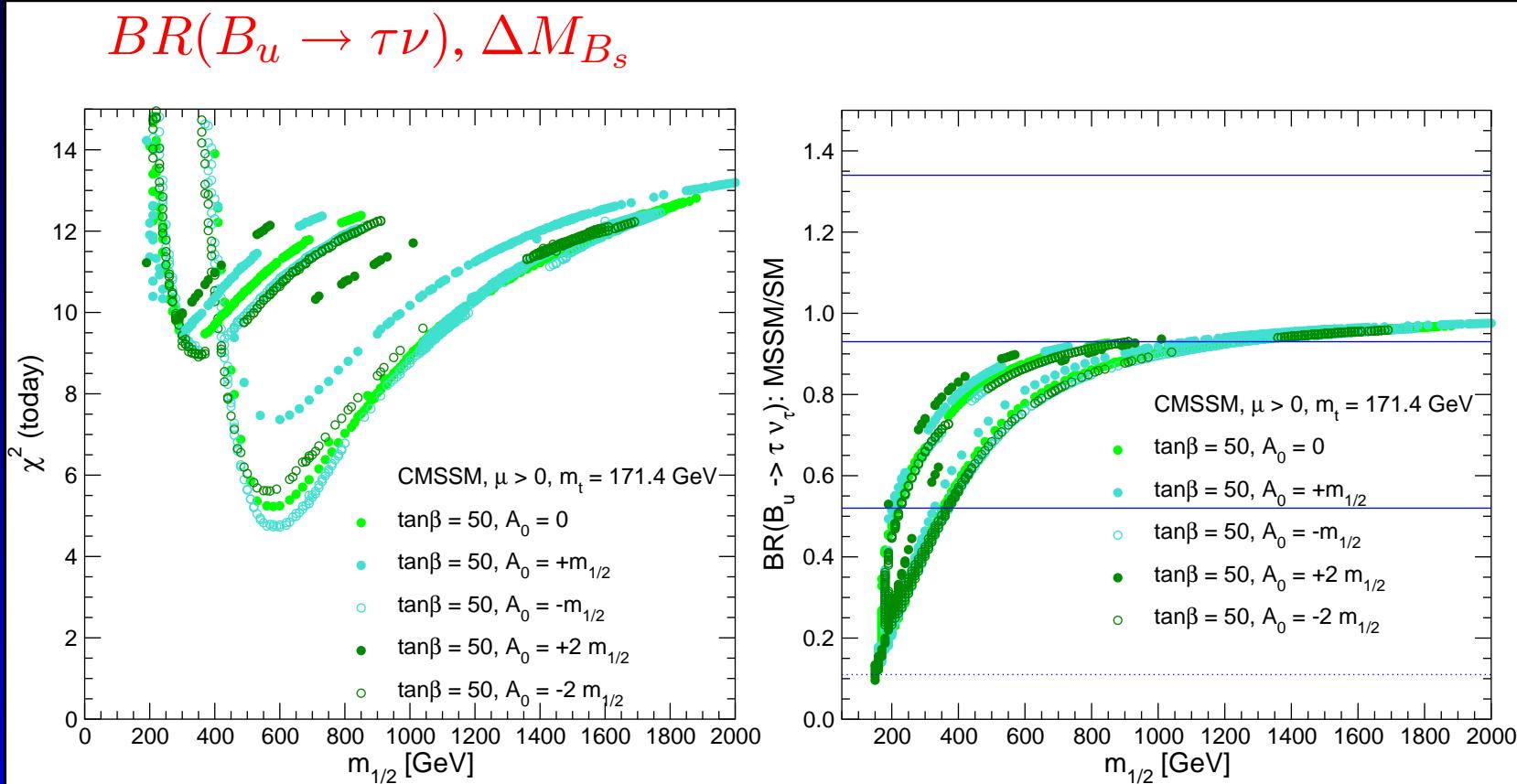
There's been a lot of progress lately:

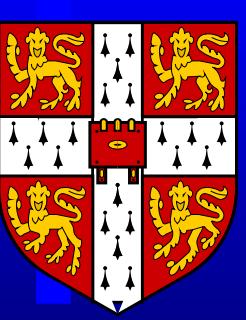
- $\Delta_{0-}$ ,  $BR(B_s \rightarrow \mu\mu)$   
*talk by A Dedes,*  
 $\Delta M_{B_s}$ ,  $B_u \rightarrow \tau\nu$ .  
SUSY tools review  
0805.2088
- SLHA2 does **flavour violating** MSSM,  
0801.0045
- *See talk this afternoon by Sven Heinemeyer*



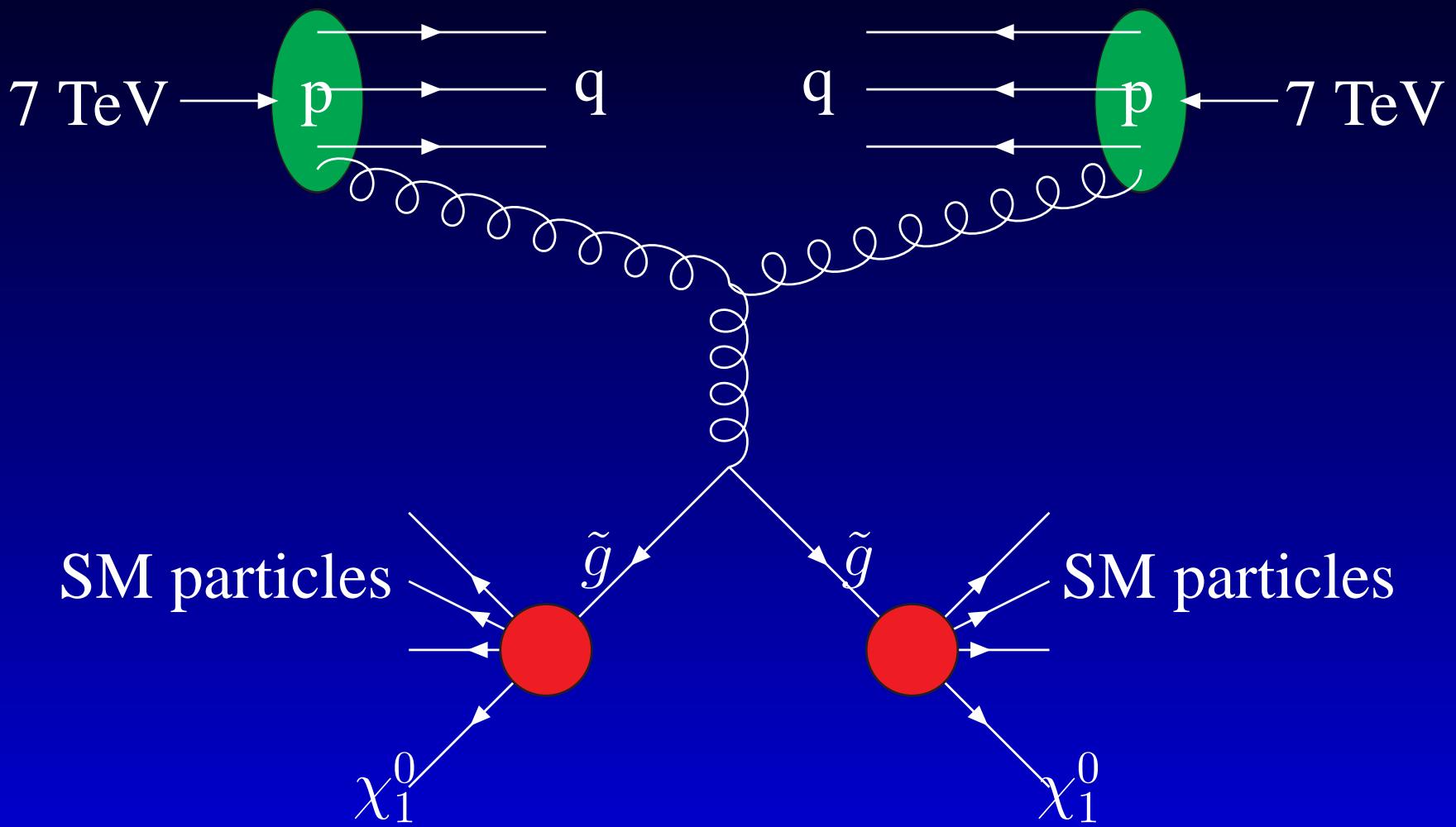
# b Observables

CMSSM: Ellis, Heinemeyer, Olive, Weber, Weiglein, arXiv:0706.0652

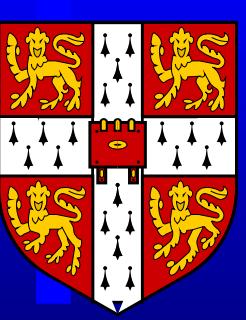




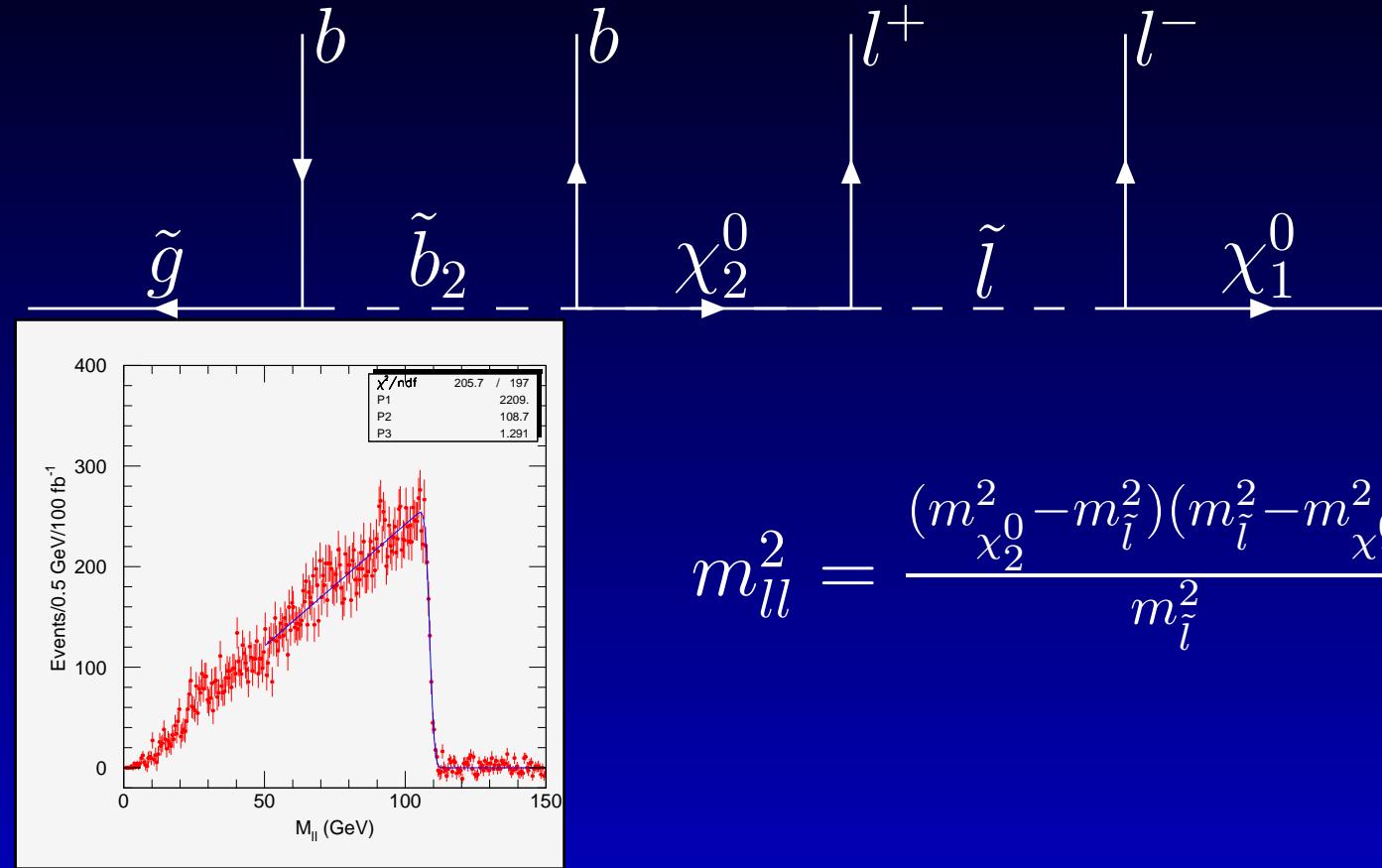
# LHC sparticle production



*Hard SM particles.  $R_P \Rightarrow$  large missing  $E_T$*



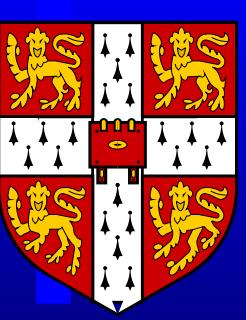
# LHC SUSY Measurements



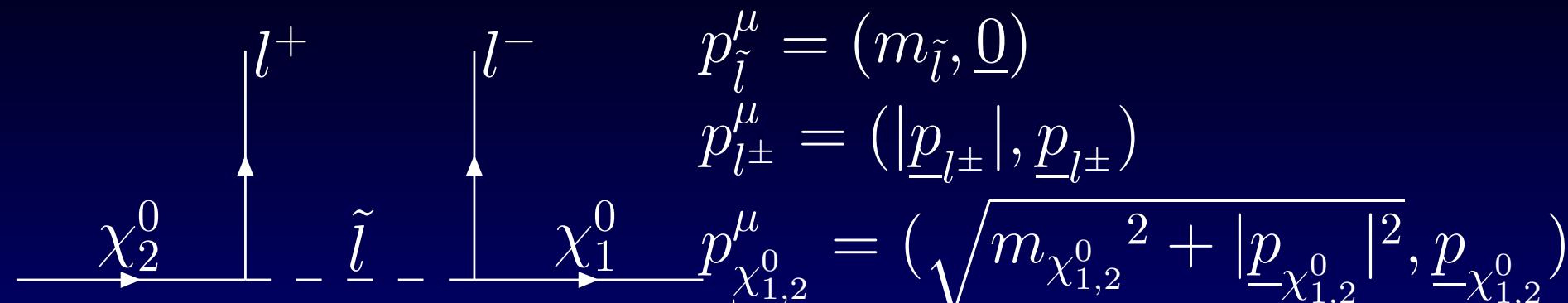
$$m_{ll}^2 = \frac{(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)}{m_{\tilde{l}}^2}$$

Q: Can we measure enough of these to pin SUSY<sup>a</sup> down?

<sup>a</sup>BCA, Lester, Parker, Webber, hep-ph/0007009; Bachacou, Hinchliffe, Paige, hep-ph/9907518; ...



# Cascade Decay



The invariant mass of the  $l^+ l^-$  pair is

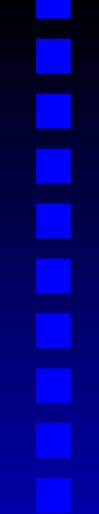
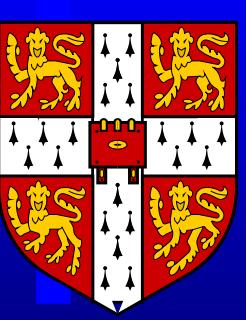
$$\begin{aligned} m_{ll}^2 &= (p_{l^+} + p_{l^-})^\mu (p_{l^+} + p_{l^-})_\mu = p_{l^+}^2 + p_{l^-}^2 + 2 p_{l^+} \cdot p_{l^-} \\ &= 2 |\underline{p}_{l^+}| |\underline{p}_{l^-}| (1 - \cos \theta) \leq 4 |\underline{p}_{l^+}| |\underline{p}_{l^-}|. \end{aligned}$$

Momentum conservation:

$$\Rightarrow \underline{p}_{\chi_2^0} + \underline{p}_{l^+} = \underline{0}, \quad \underline{p}_{l^-} + \underline{p}_{\chi_1^0} = \underline{0}.$$

Energy conservation:  $\sqrt{{m_{\chi_2^0}}^2 + |\underline{p}_{l^+}|^2} = m_{\tilde{l}} + |\underline{p}_{l^+}|,$

$$\Rightarrow |\underline{p}_{l^+}| = \frac{{m_{\chi_2^0}}^2 - m_{\tilde{l}}^2}{2 m_{\tilde{l}}}. \text{ Similarly } |\underline{p}_{l^-}| = \frac{m_{\tilde{l}}^2 - {m_{\chi_1^0}}^2}{2 m_{\tilde{l}}}.$$



# Other Observables

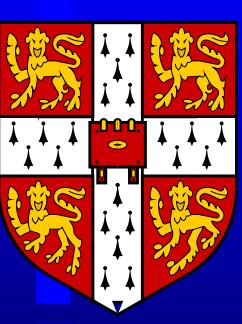
Often more complicated, eg  $m_{llq}$  edge:

$$\max \left[ \frac{(m_{\tilde{q}}^2 - m_{\chi_2^0}^2)(m_{\chi_2^0}^2 - m_{\chi_1^0}^2)}{m_{\chi_2^0}^2}, \frac{(m_{\tilde{q}}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)}{m_{\tilde{l}}^2}, \right. \\ \left. \frac{(m_{\tilde{q}} m_{\tilde{l}} - m_{\chi_2^0} m_{\chi_1^0})(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)}{m_{\chi_2^0} m_{\tilde{l}}} \right]$$

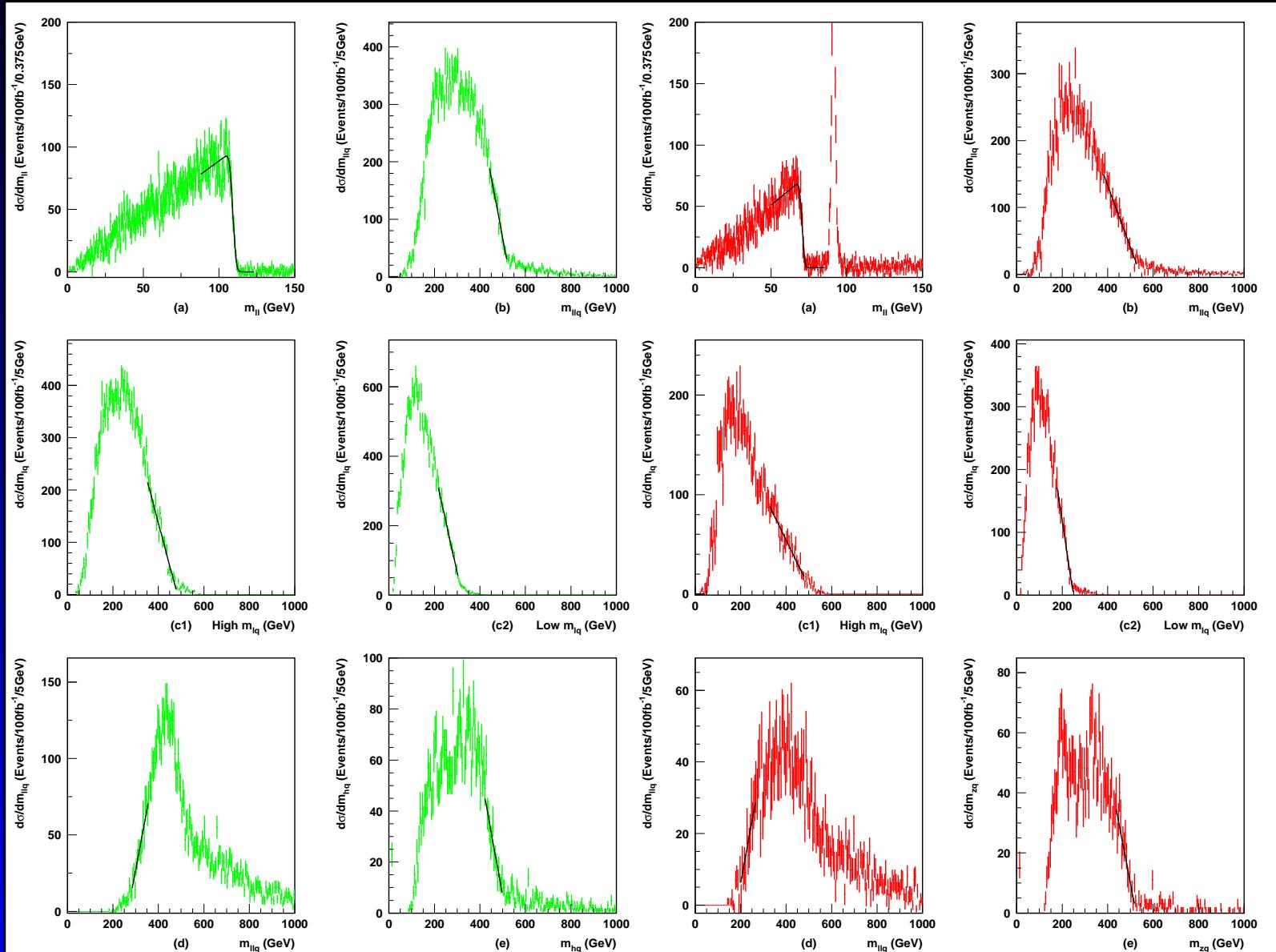
Also  $m_{lq}^{high}$ ,  $m_{lq}^{low}$ ,  $llq$  *threshold*<sup>a</sup>,  $M_{T_2}^2(m) =$

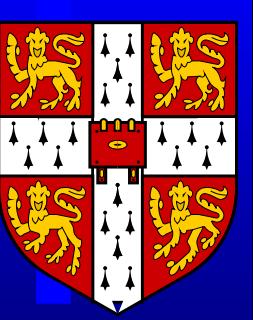
$$\min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[ \max \left\{ m_T^2(p_T^{l_1}, \not{p}_1, \textcolor{red}{m}), m_T^2(p_T^{l_2}, \not{p}_2, \textcolor{red}{m}) \right\} \right],$$

$\max[M_{T_2}(m_{\chi_1^0})] = m_{\tilde{l}}$  for di-slepton production.  
CERN flavour workshop



# Edge Fitting at S5 and O1



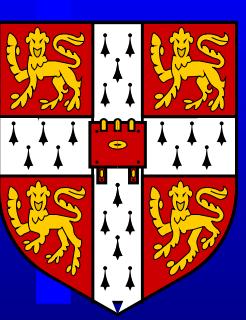


# Edge Positions

endpoint	S5 fit	O1 fit
$m_{ll}$	$109.10 \pm 0.13$	$70.47 \pm 0.15$
$m_{llq}$ edge	$532.1 \pm 3.2$	$544.1 \pm 4.0$
$lq$ high	$483.5 \pm 1.8$	$515.8 \pm 7.0$
$lq$ low	$321.5 \pm 2.3$	$249.8 \pm 1.5$
$llq$ thresh	$266.0 \pm 6.4$	$182.2 \pm 13.5$

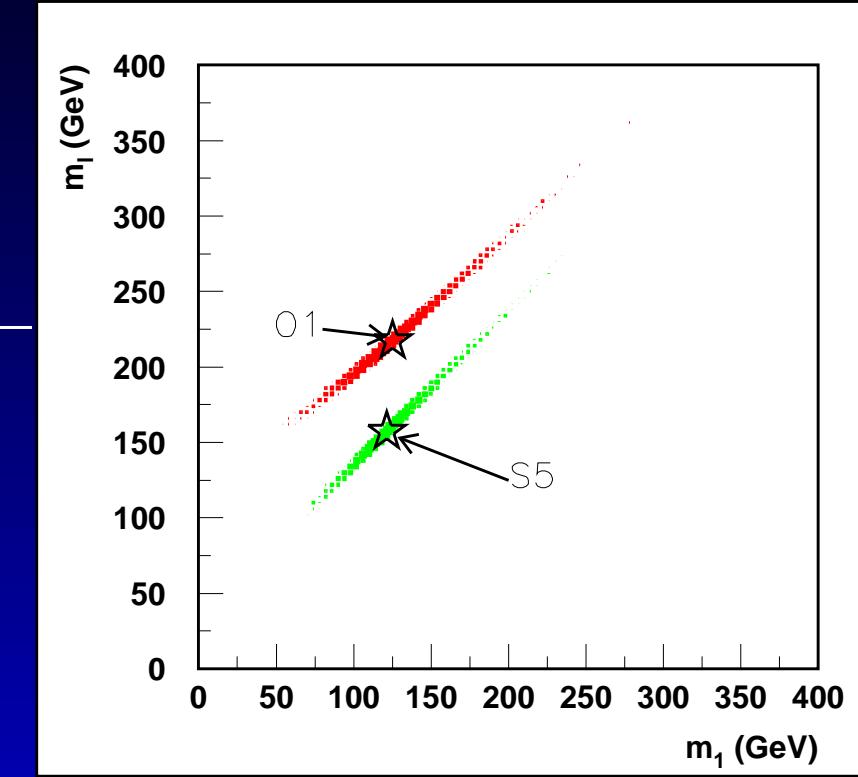
*Best case lepton mass measurements can be as accurate as 1 per mille, but jets are a few percent*





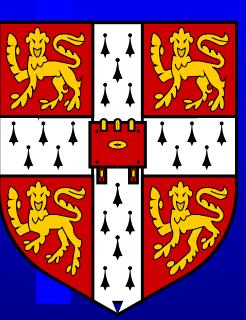
# Edge to Mass Measurements

	width S5	width O1
$\chi_1^0$	17	22
$\tilde{l}_R$	17	20
$\chi_2^0$	17	20
$\tilde{q}$	22	20

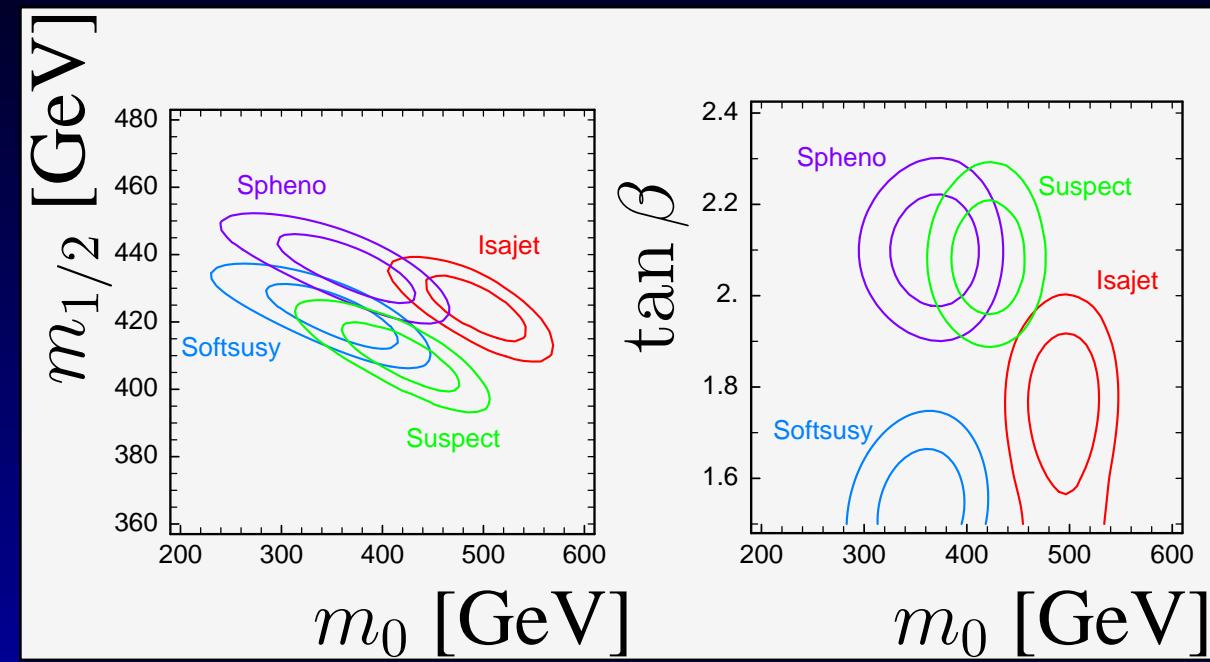


*differences well constrained, but overall mass scale  
not so well constrained by LHC*



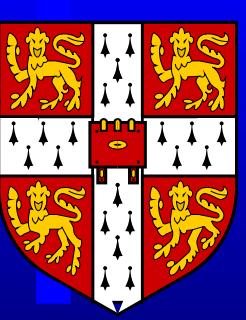


# Fitting to SUSY Breaking Model



- Experimenters pick a SUSY breaking point
- They derive observables and errors after detector simulation
- We fit<sup>a</sup> this “data” with our codes

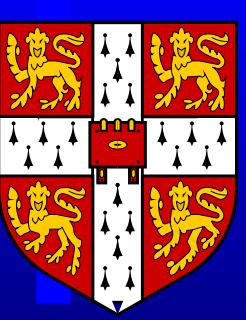
<sup>a</sup>BCA, S Kraml, W Porod, hep-ph/0302102



# Caveat

All of these edge studies *average* over the  $e$ ,  $\mu$  assuming their masses to be equal but here we are interested in *differences between them*.





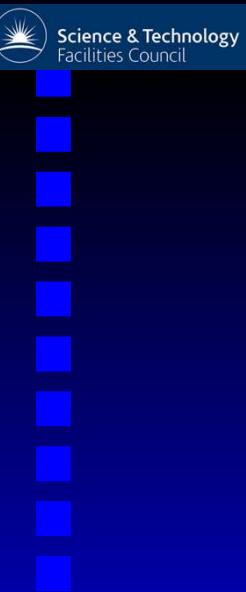
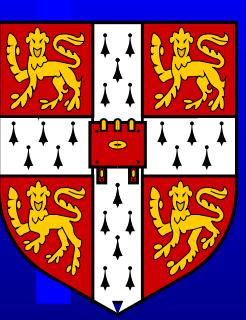
# Constraints

$\mathcal{L}_{MSSM}$  strongly constrained by absence of new physics contributions to FCNCs, eg  
 $BR(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$  by MEGA. Constrains off-diagonal propagator mixing between selectron and smuon flavour eigenstates to

$$(1) \quad \frac{m_{\tilde{L}_{12}}^2}{m_{\tilde{L}_{11}}^2 + m_{\tilde{L}_{22}}^2} \lesssim 6 \times 10^{-4}.$$

$RR$  constraints similar over most of parameter space, but there are possible cancellations.





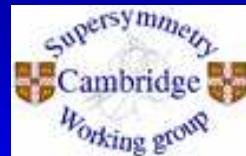
# Unconstraints

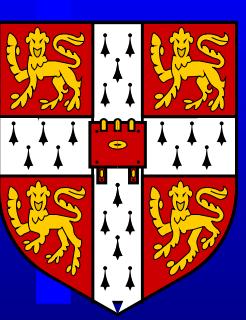
However, these constraints do *not* constrain selectron-smuon mass splitting

$$(2) \quad \Delta m^2 \equiv m_{\tilde{\mu}_R}^2 - m_{\tilde{e}_R}^2$$

in the absence of lepton flavour violation (**LFV**).  
Some other work on SUSY **LFV** at LHC:

Agashe, Graesser hep-ph/9904422; Hinchliffe, Paige hep-ph/0010086;  
Hisano, Kitano, Nojiri hep-ph/0202129; Carvallo, Ellis, Gomez, Lola,  
Romao hep-ph/0206148; Bartl, Hidaka, Hohenwarter-Sodek,  
Kernreiter, Majerotto, Porod 0510074; Grossman, Nir, Thaler,  
Volansky, Zupan 0706.1845; Feng, Lester, Nir, Shadmi 0712.0674

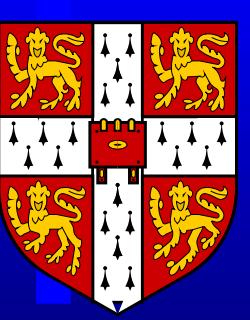




# RGEs

$\Delta m^2$  is generated by universal models by RGE running (see following talk by Colangelo):

$$\begin{aligned} 16\pi^2 \frac{d\Delta m^2}{d \ln \mu} &= 4 \left[ Y_\mu^2 (m_{\tilde{\mu}_R}^2 + m_{\tilde{\mu}_L}^2) - Y_e^2 (m_{\tilde{e}_R}^2 + m_{\tilde{e}_L}^2) \right. \\ &\quad \left. + m_{H1}^2 (Y_\mu^2 - Y_e^2) + Y_\mu^2 h_\mu^2 - Y_e^2 h_e^2 \right], \\ \Rightarrow \Delta m^2(M_Z) &\approx \Delta m^2(M_X) + \frac{8m_\mu^2}{16\pi^2 v^2} \left[ m_{\tilde{\mu}_R}^2(M_X) \right. \\ &\quad \left. + m_{\tilde{\mu}_L}^2(M_X) + m_{H1}^2(M_X) + \right. \\ &\quad \left. A_\mu^2(M_X) \right] \tan^2 \beta \ln \left( \frac{M_X}{M_Z} \right), \end{aligned}$$



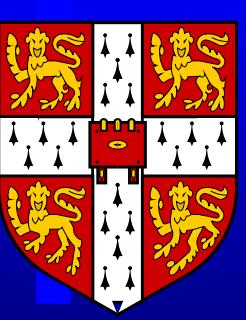
# Enhancement factor

$$m_{ll}^2 = \frac{(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)}{m_{\tilde{l}}^2}$$

$$\Rightarrow \frac{dm_{ll}^2}{dm_{\tilde{l}}^2} = \frac{m_{\chi_1^0}^2 m_{\chi_2^0}^2}{m_{\tilde{l}}^4} - 1,$$

$$\Rightarrow \frac{\Delta m_{ll}}{m_{ll}} = \frac{\Delta m_{\tilde{l}}}{m_{\tilde{l}}} \left( \frac{m_{\chi_1^0}^2 m_{\chi_2^0}^2 - m_{\tilde{l}}^4}{(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)} \right)$$

( ) can be large for somewhat compressed spectra, meaning for a given experimental error, we get very accurate slepton mass splitting.



# Enhancement Factor

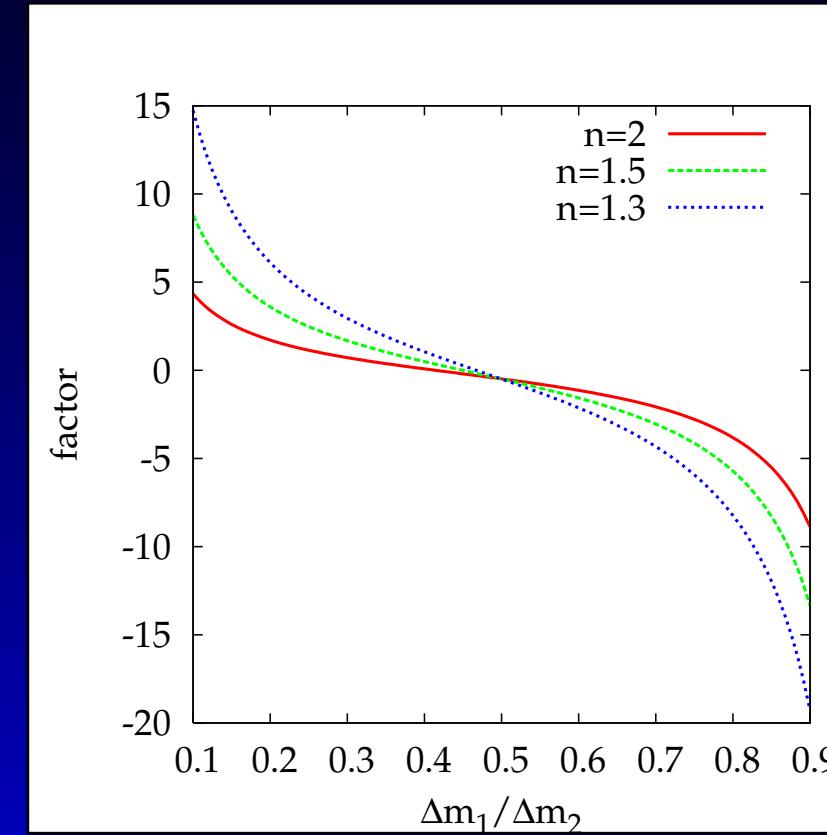
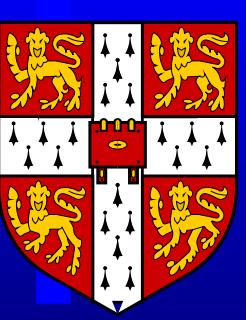


Figure 1:  $(\Delta m_{ll}/m_{ll})/(\Delta m_{\tilde{l}}/m_{\tilde{l}})$  as a function of  $\Delta m_1/\Delta m_2 \equiv (m_{\tilde{l}} - m_{\chi_1^0})/(m_{\chi_2^0} - m_{\chi_1^0})$  for three different values of  $n \equiv m_{\chi_2^0}/m_{\chi_1^0}$ .



# Energy calibration

Can subtract opposite sign different flavour di-leptons in order to subtract backgrounds from tops or  $W$ -pairs, just like in the *summed* sample!

Use muons/electrons from  $Z^0$  pole to calibrate energies/efficiencies by extrapolation: for SPS1a,3,5,9  
 $m_{ll} = 80, 118, 99, 122, 343$  GeV. Best guess

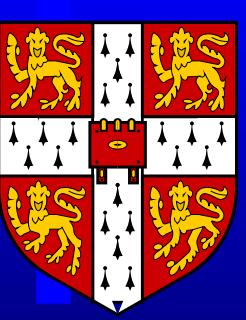
$$\Delta E/E = 0.1\%$$

*a*

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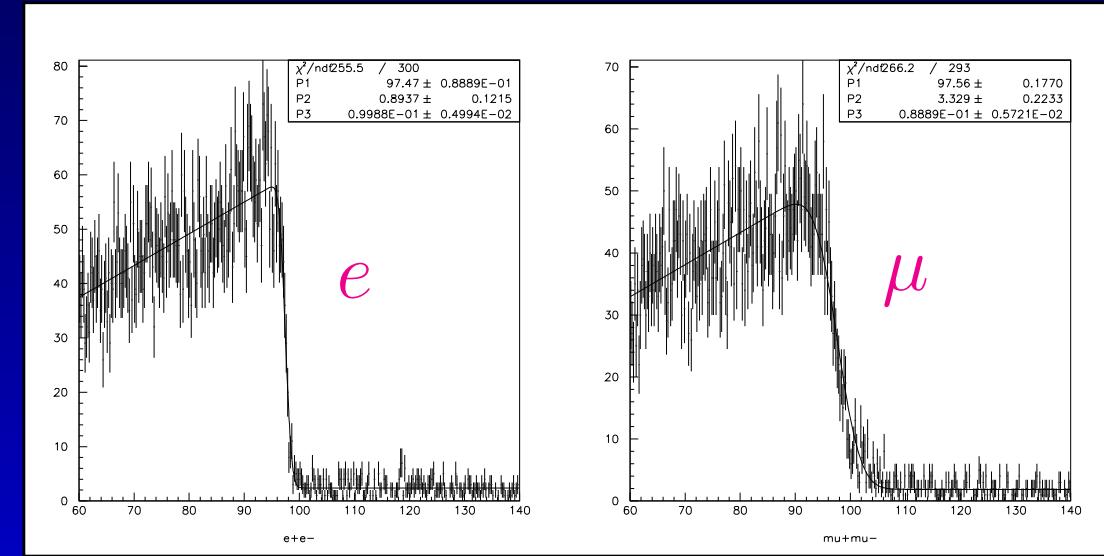
<sup>a</sup>ATLAS performance chapter



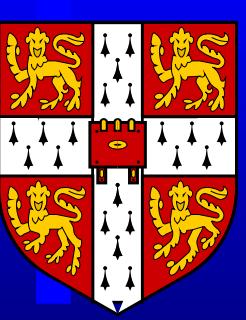


# Experimental Precision

SUGRA point 5:  $m_0 = 100 \text{ GeV}$ ,  $m_{1/2} = 300 \text{ GeV}$ ,  
 $A_0 = 300 \text{ GeV}$ ,  $\tan \beta = 2.1$ . Total SUSY  
cross-section from HERWIG6 .510 is 24 pb. Pass  
through AcerDet minimal rough detector sim,



$16 \text{ fb}^{-1}$ . Require 2 OSSF isolated leptons with  
 $p_T > 10 \text{ GeV}$ , missing  $E_T > 100 \text{ GeV}$ . Perform log  $L$   
fit to Gaussian-smeared  $\Delta$  and number of events.



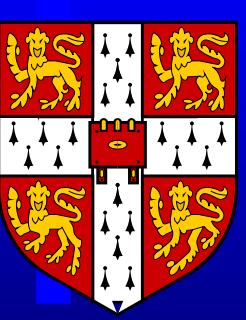
# Luminosity Dependence

Integrated Luminosity ( $fb^{-1}$ )	Events below 100 GeV	Electron Endpoint (GeV)	Muon Endpoint (GeV)
16.0	22145	$97.47 \pm 0.09$	$97.56 \pm 0.18$
8.0	11131	$97.41 \pm 0.13$	$97.83 \pm 0.23$
4.0	5520	$97.54 \pm 0.19$	$97.63 \pm 0.35$
2.0	2707	$97.52 \pm 0.28$	$97.56 \pm 0.50$

Fractional fit error

$\Sigma = \sqrt{(0.002\sqrt{22145/N})^2 + 0.001^2}$  defined by  
 $\Delta E/E$  and largest endpoint error.





# Splitting Discovery

Define splitting discovery significance

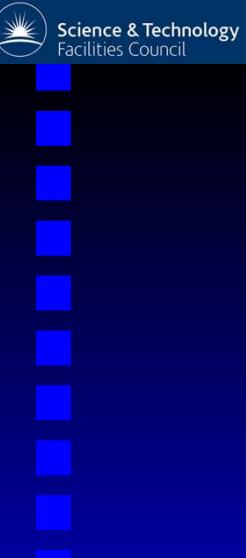
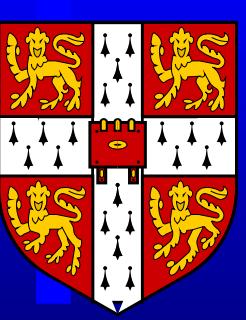
$$S_1 = \left| \frac{\Delta m_{ll}}{m_{ll}} \right| \div \Sigma$$

In mSUGRA,  $S_1(\max) = 0.5$ . If trigger and reconstruction efficiencies could be controlled, one could also use

$$(3) \quad S_2 = \frac{N_{ee} - N_{\mu\mu}}{\sqrt{N}}.$$

*(we won't)*

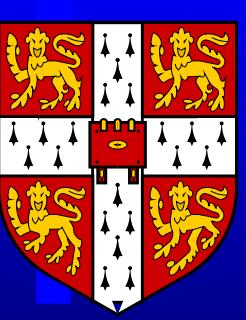




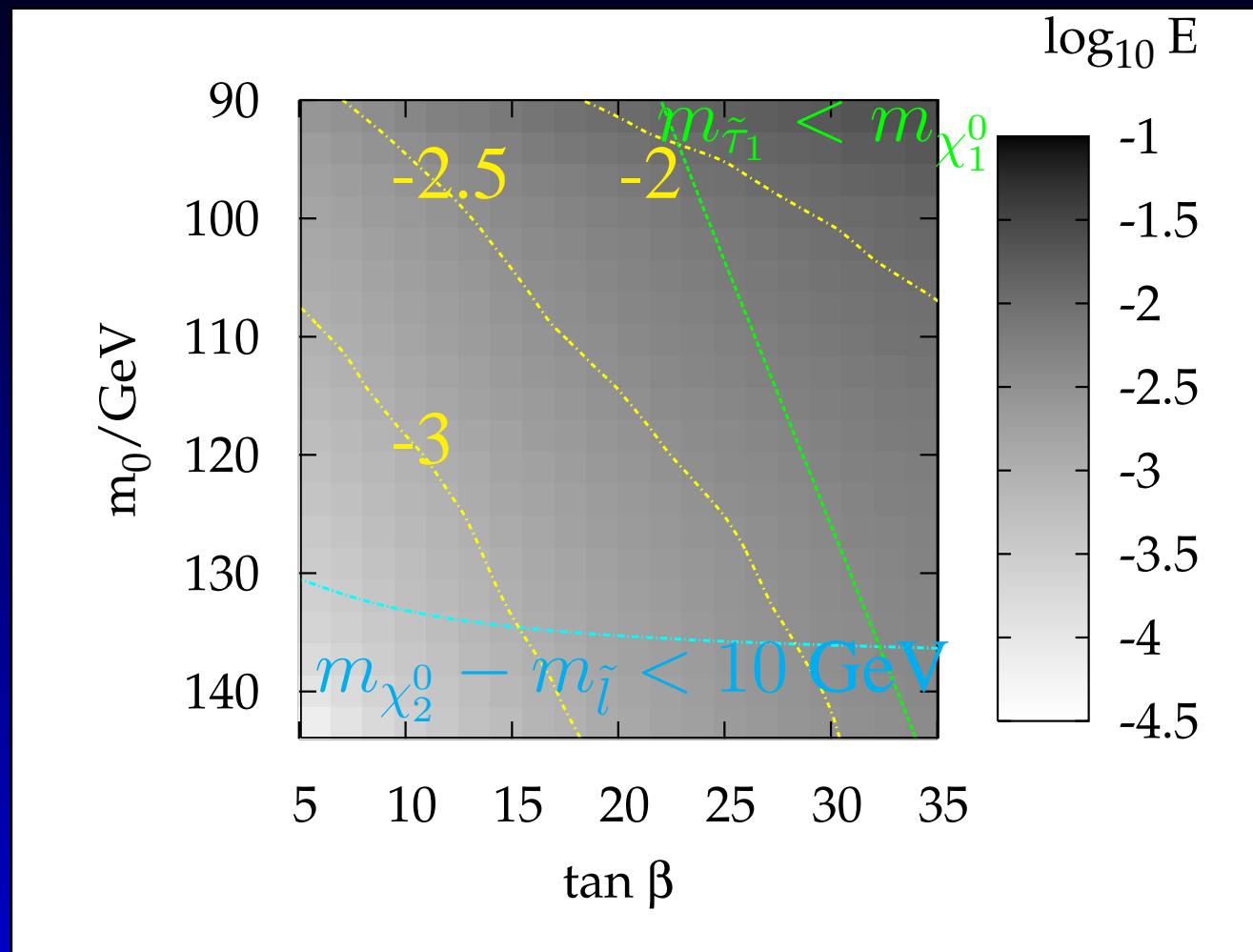
# mSUGRA Degeneracy

In fact, mSUGRA splittings at large  $\tan \beta$  can often be **several %**. But at large  $\tan \beta$ ,  $\tilde{\tau}_R$  is light and dominates decay modes with  $BR(\chi_2^0 \rightarrow \tilde{l}_R l) \ll 1$ ,  $BR(\chi_2^0 \rightarrow \tilde{\tau}_1 \tau) \approx 1$ .

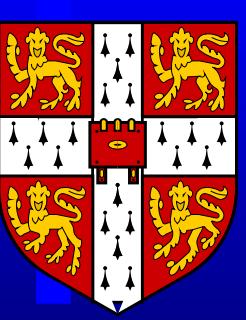
If we depart from mSUGRA by making  $\tilde{\tau}$ s heavy, one might easily discriminate from smuon-selectron universality:  $m_0 = 148$  GeV,  $m_{1/2} = 250$  GeV,  $A_0 = -600$  GeV,  $\tan \beta = 40$  but  $m_{\tilde{\tau}_{L,R}} = 950$  GeV:  $\Delta m_{\tilde{l}}/m_{\tilde{l}} = 2.3 \times 10^{-3}$  and  $\Delta m_{ll}/m_{ll} = 1.5\%$  whereas  $\Sigma = 0.27\%$ , allowing an ( $S_1 > 5$ )-sigma discovery.



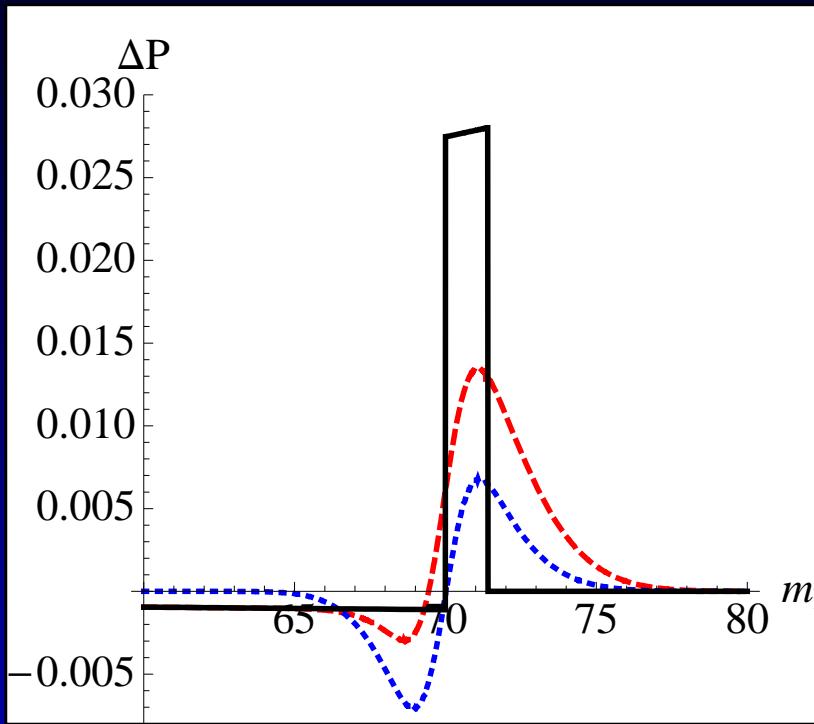
# $1\sigma$ Sensitivity to $\tilde{e}$ - $\tilde{\mu}$ Universality



$$\mathcal{L} = 30 \text{ fb}^{-1} \text{ SPS1a. } E \equiv \left. \frac{\Delta m_{\tilde{l}}}{m_{\tilde{l}}} \right|_{S_1=1}.$$



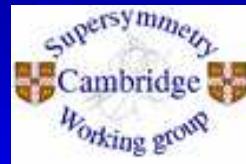
# Difference in mass distributions

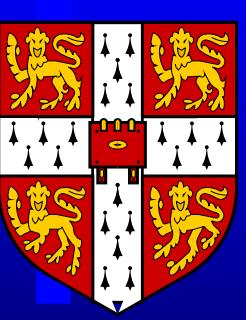


$\Delta m/m = 2\%$  and  
(black) no energy resolution

Red: Energy resolution  
Blue:  $\Delta m/m = 0$  with  
energy resolution

Thus we could be fooled by the difference: best to fit both  $\tilde{e}$ ,  $\tilde{\mu}$  separately.

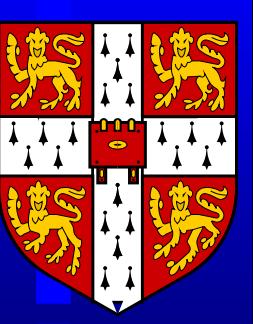




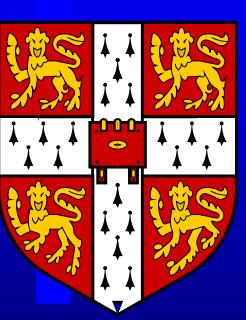
# Summary

- Selectron-smuon mass splitting not ruled out by flavour constraints
- RGEs/large  $\tan \beta$  can give mass splittings of several % even in mSUGRA
- However, a positive signal with  $30\text{fb}^{-1}$  would rule mSUGRA out and imply primordial mass splittings.
- Should *not* forget to perform analysis with **separate**  $m_{\tilde{e}}$ ,  $m_{\tilde{\mu}}$  if we're lucky enough to see such a signal





# Supplementary Material



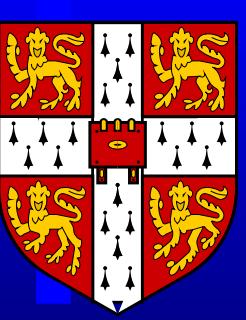
# Implementation

Input parameters are:  $m_0$ ,  $A_0$ ,  $M_{1/2}$ ,  $\tan \beta$ ,

- $m_t = 171.4 \pm 2.9$ ,  $m_b(m_b) = 4.24 \pm 0.11$  GeV,
- $\alpha_s(M_Z)^{\overline{MS}} = 0.1176 \pm 0.002$ ,
- $\alpha^{-1}(M_Z)^{\overline{MS}} = 127.918 \pm 0.018$

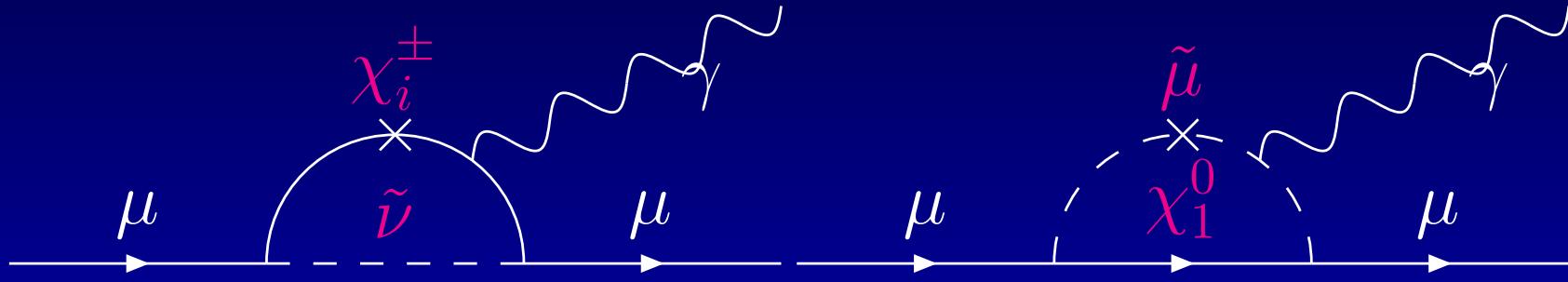
For the likelihood, we also use

- $\Omega_{DM} h^2 = 0.104^{+0.0073}_{-0.0128}$  expand errors to 0.002  
*Boudjema et al*
- $\delta(g - 2)_\mu/2 = (22 \pm 10) \times 10^{-10}$  *Stöckinger et al*
- $BR[b \rightarrow s\gamma] = (3.55 \pm 0.38) \times 10^{-4}$  (old)
- $\sin^2 \theta_w^l(\text{eff}) = 0.23153 \pm 0.000175$
- $M_W = 80.392 \pm 0.031$  GeV *W Hollik, A Weber et al*

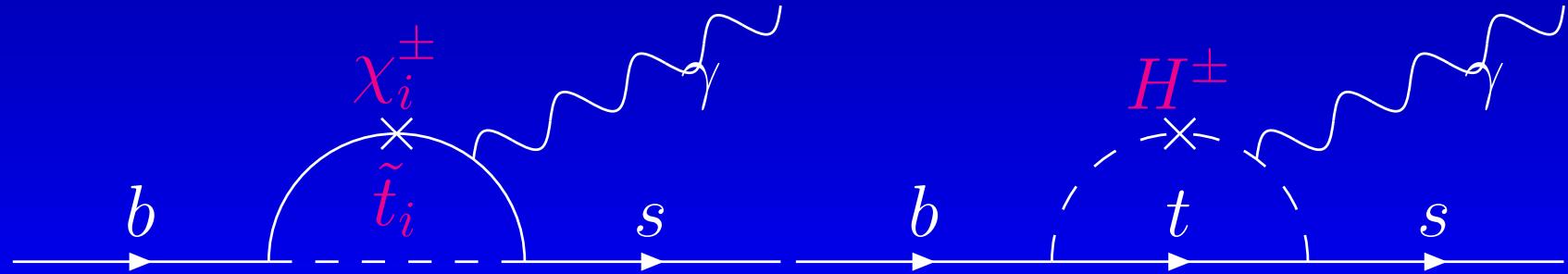


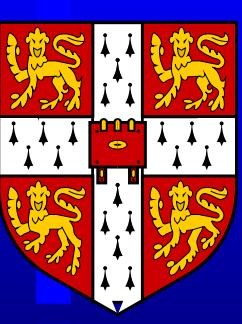
# Additional observables

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



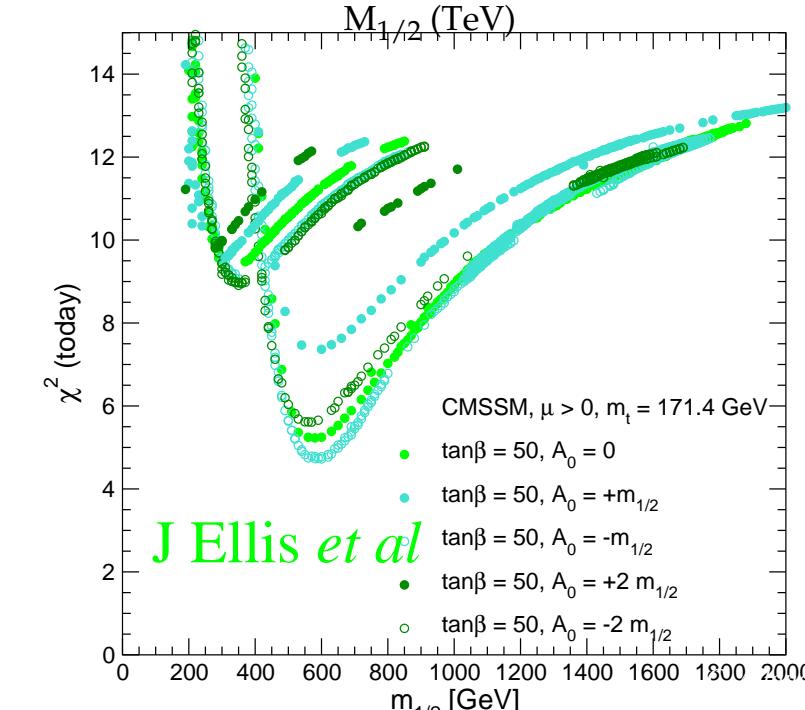
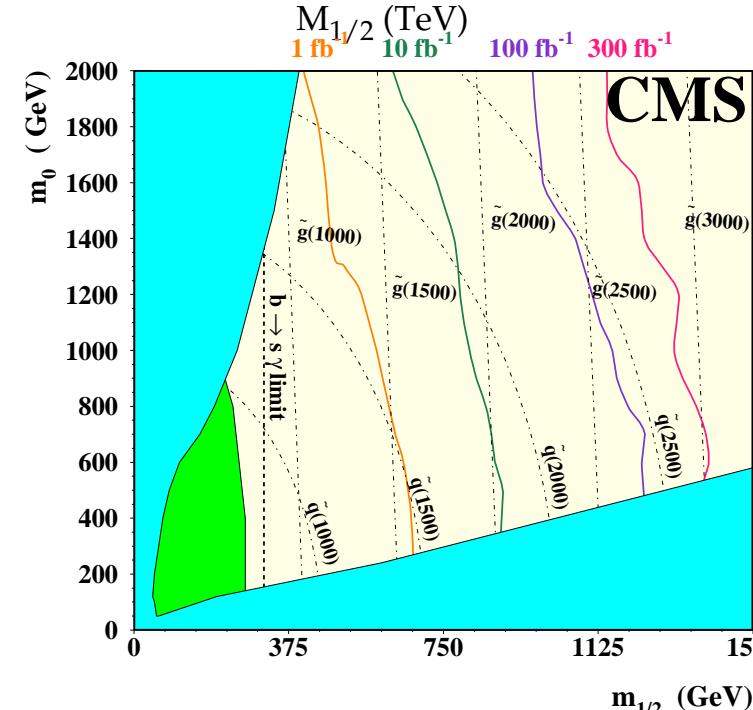
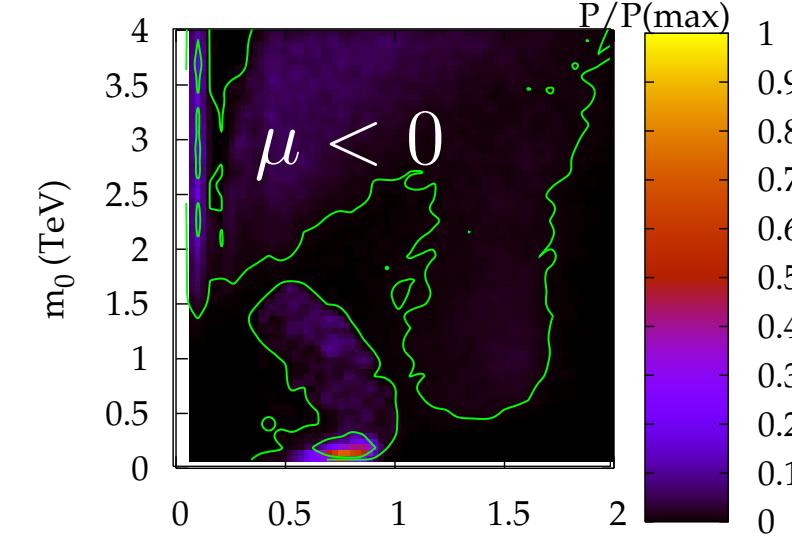
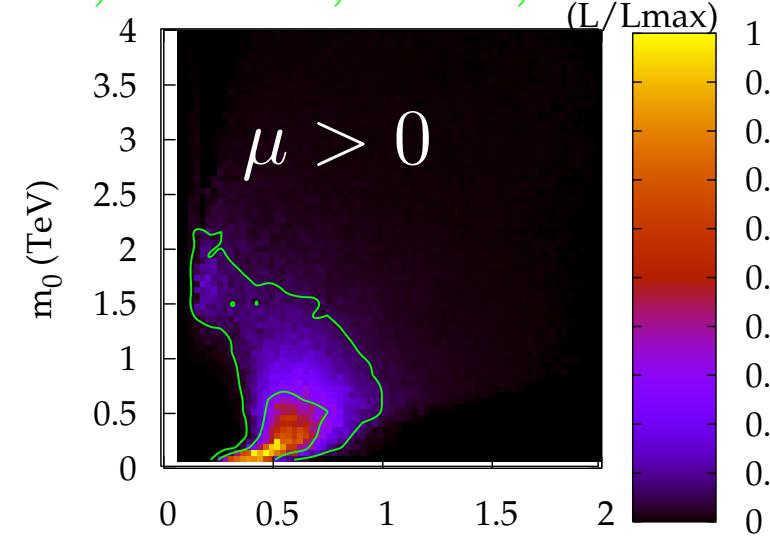
$$BR[b \rightarrow s\gamma] \propto \tan \beta (M_W/M_{SUSY})^2$$

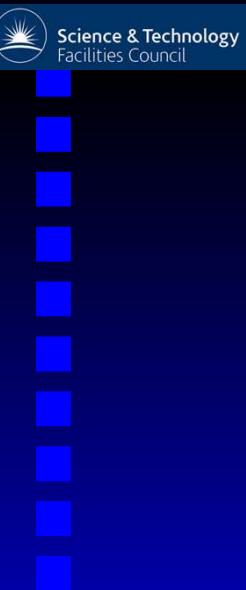
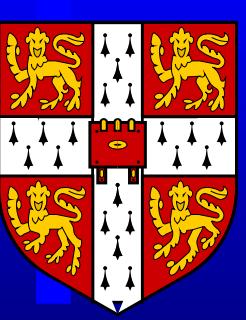




# $\chi^2$ Global Fit

BCA, Cranmer, Weber, Lester





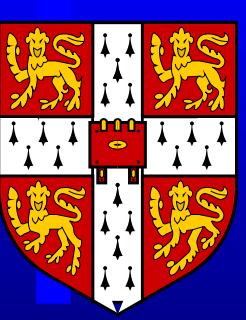
# Fit Development

- Typically only 2d scans, but in general we have  $\alpha(M_Z)$ ,  $\alpha_s(M_Z)$ ,  $m_t$ ,  $m_b$ ,  $m_0$ ,  $M_{1/2}$ ,  $A_0$ ,  $\tan \beta$  to vary
- Effective 3d type scan done<sup>a</sup> which parametrises a 2d surface of correct  $\Omega h^2$
- Baltz *et al* managed to perform a 4d scan, but lost the likelihood interpretation. They used the impressive *Markov Chain Monte Carlo technique*.
- Really, would like to combine likelihoods from different measurements<sup>b</sup>: Bayesian fit

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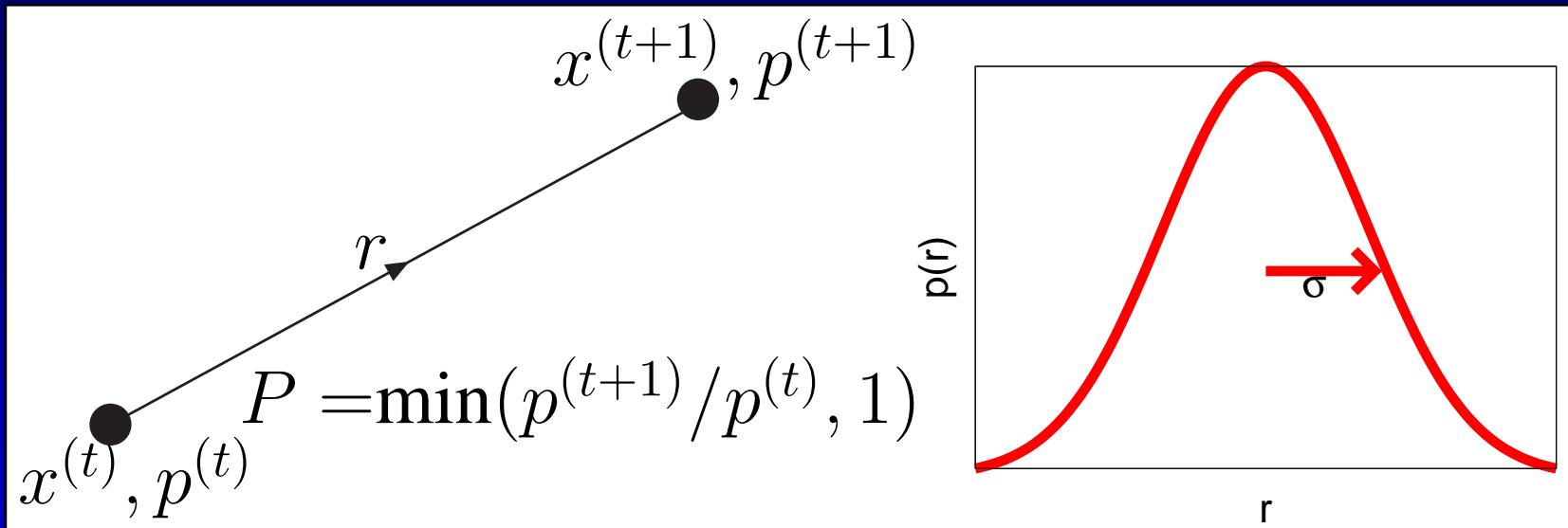
<sup>a</sup>Ellis *et al*, hep-ph/0411218

<sup>b</sup>Done in 2d in Ellis *et al*, hep-ph/0310356

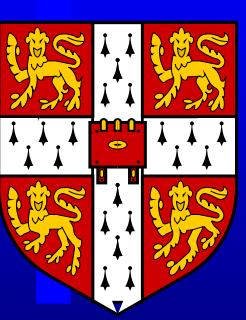


# Markov-Chain Monte Carlo

Metropolis-Hastings Markov chain sampling consists of list of parameter points  $x^{(t)}$  and associated posterior probabilities  $p^{(t)}$ .



Final density of  $x$  points  $\propto p$ . Required number of points goes *linearly* with number of dimensions.



# Application of Bayes'

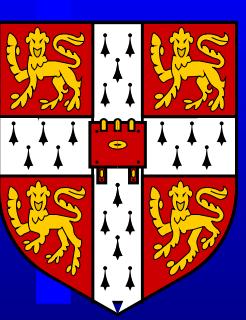
$\mathcal{L} \equiv p(d|m, H)$  is pdf of reproducing data  $d$  assuming CMSSM hypothesis  $H$  and parameter point  $m$

$$p(m|d, H) = p(d|m, H) \frac{p(m, H)}{p(d, H)}$$

$$\frac{p(m_1|d, H)}{p(m_2|d, H)} = \frac{p(d|m_1, H)p(m_1, H)}{p(d|m_2, H)p(m_2, H)}$$

$p(m|d, H)$  is called the **posterior** pdf. We will compare  $p(m_i, H) = 1$  with a ***different*** prior.

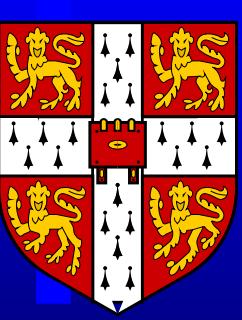




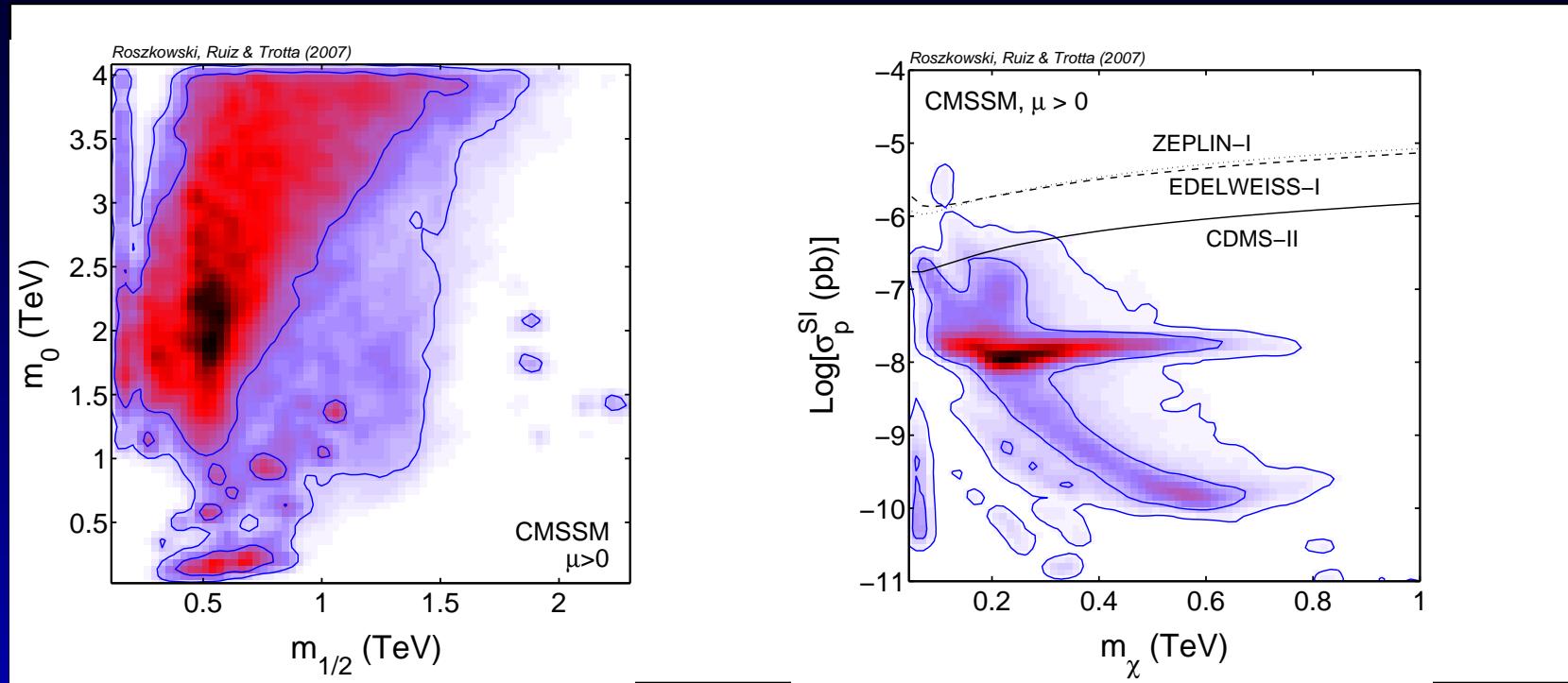
# CMSSM Regions

After WMAP+LEP2, **bulk region** diminished. Need specific mechanism to reduce overabundance:

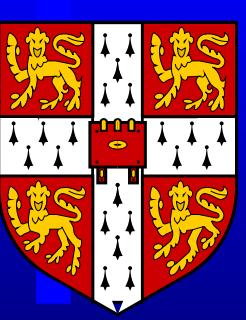
- $\tilde{\tau}$  co-annihilation: small  $m_0$ ,  $m_{\tilde{\tau}_1} \approx m_{\chi_1^0}$ . Boltzmann factor  $\exp(-\Delta M/T_f)$  controls ratio of species.  $\tilde{\tau}_1 \chi_1^0 \rightarrow \tau \gamma$ ,  $\tilde{\tau}_1 \tilde{\tau}_1 \rightarrow \tau \bar{\tau}$ .
- Higgs Funnel:  $\chi_1^0 \chi_1^0 \rightarrow A \rightarrow b\bar{b}/\tau\bar{\tau}$  at large  $\tan \beta$ . Also via<sup>a</sup>  $h$  at large  $m_0$  small  $M_{1/2}$ .
- Focus region: Higgsino LSP at large  $m_0$ :  $\chi_1^0 \chi_1^0 \rightarrow WW/ZZ/Zh/t\bar{t}$ .
- $\tilde{t}$  co-annihilation: high  $-A_0$ ,  $m_{\tilde{t}_1} \approx m_{\chi_1^0}$ .  $\tilde{t}_1 \chi_1^0 \rightarrow gt$ ,  $\tilde{t}\tilde{t} \rightarrow tt$



# Other literature



R. R. de Austri, R. Trotta and L. Roszkowski,  
arXiv:0705.2012, including some NNLO  
 $b \rightarrow s\gamma$  pieces.



# Cuts Example

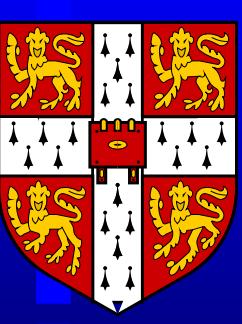
We use ATLFAST2.16, HERWIG6.0, ISAWIG and ISAJET7.42. Assume  $100 \text{ fb}^{-1}$  of LHC data.

- $|\eta_j| \leq 5, p_T^j \geq 15 \text{ GeV}$
- $p_T^e \geq 5, p_T^\mu \geq 6, |\eta_l| \leq 2.5$
- $l$  isolation:  $10 \text{ GeV}$  in  $\Delta R = 0.2, \Delta R(lj) \geq 0.4$ .

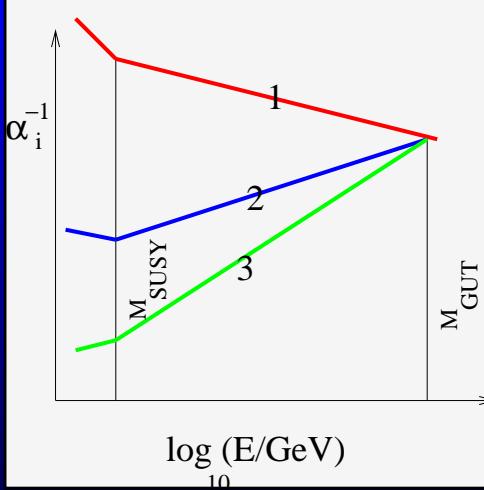
eg for  $m_{ll}$ :

- 2 OSSF leptons,  $p_T^{l_1} \geq p_T^{l_2} \geq 10 \text{ GeV}$ .
- $n_{jets} \geq 2, p_T^{j_1} \geq p_T^{j_2} \geq 150 \text{ GeV}, \not{p}_T > 300 \text{ GeV}$

OSSF-OSDF subtracts well the Standard Model background.



# SOFTSUSY



Get  $g_i(M_Z)$ ,  $h_{t,b,\tau}(M_Z)$ .

Run to  $M_S$ .



REWSB, iterative solution of  $\mu$



$M_X$ . Soft SUSY breaking BC.



Run to  $M_S$ . Calculate<sup>a</sup> sparticle pole masses.



Run to  $M_Z$

<sup>a</sup>BCA, Comp. Phys. Comm. 143 (2002) 305.