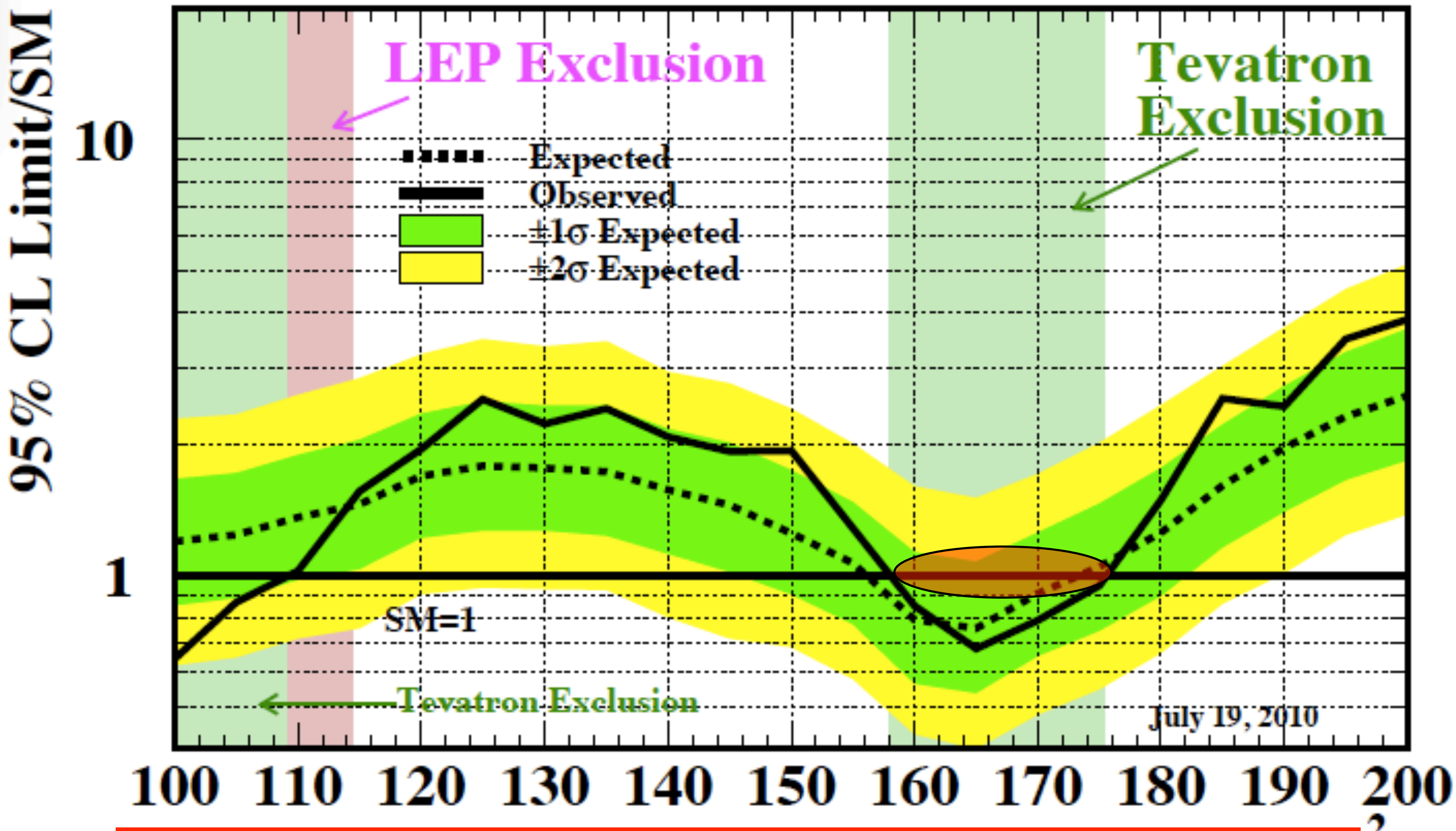
Prospects for Supersymmetry in the LHC Era

John ELLIS,
CERN, Geneva, Switzerland
& King's College London

Open Questions beyond the Standard Model

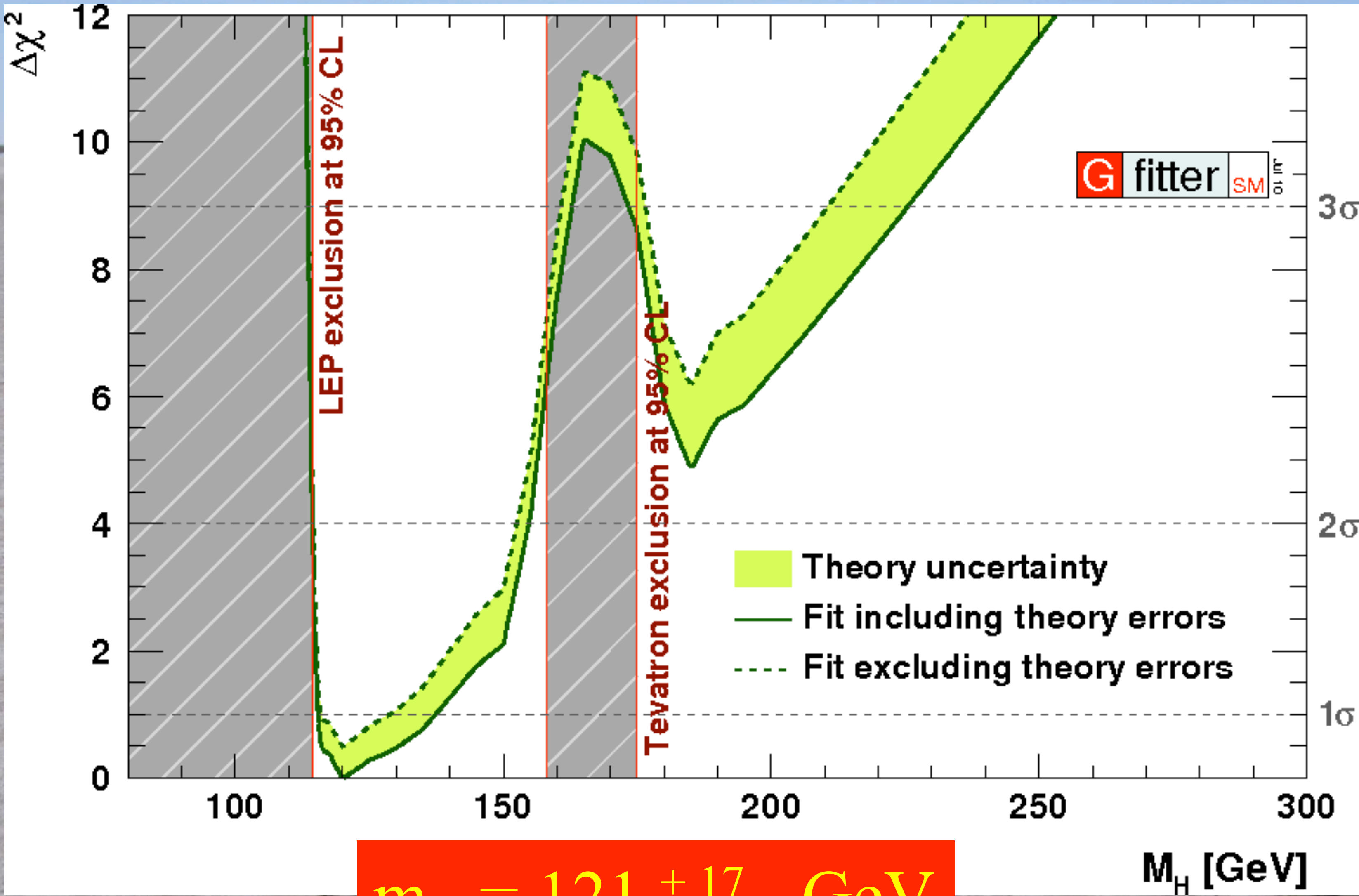
- What is the origin of particle masses? due to a Higgs boson? SUSY
- Why so many types of matter particles?
- What is the dark matter in the Universe SUSY
- Unification of fundamental forces? SUSY
- Quantum theory of gravity? SUSY

Higgs Search @ Tevatron



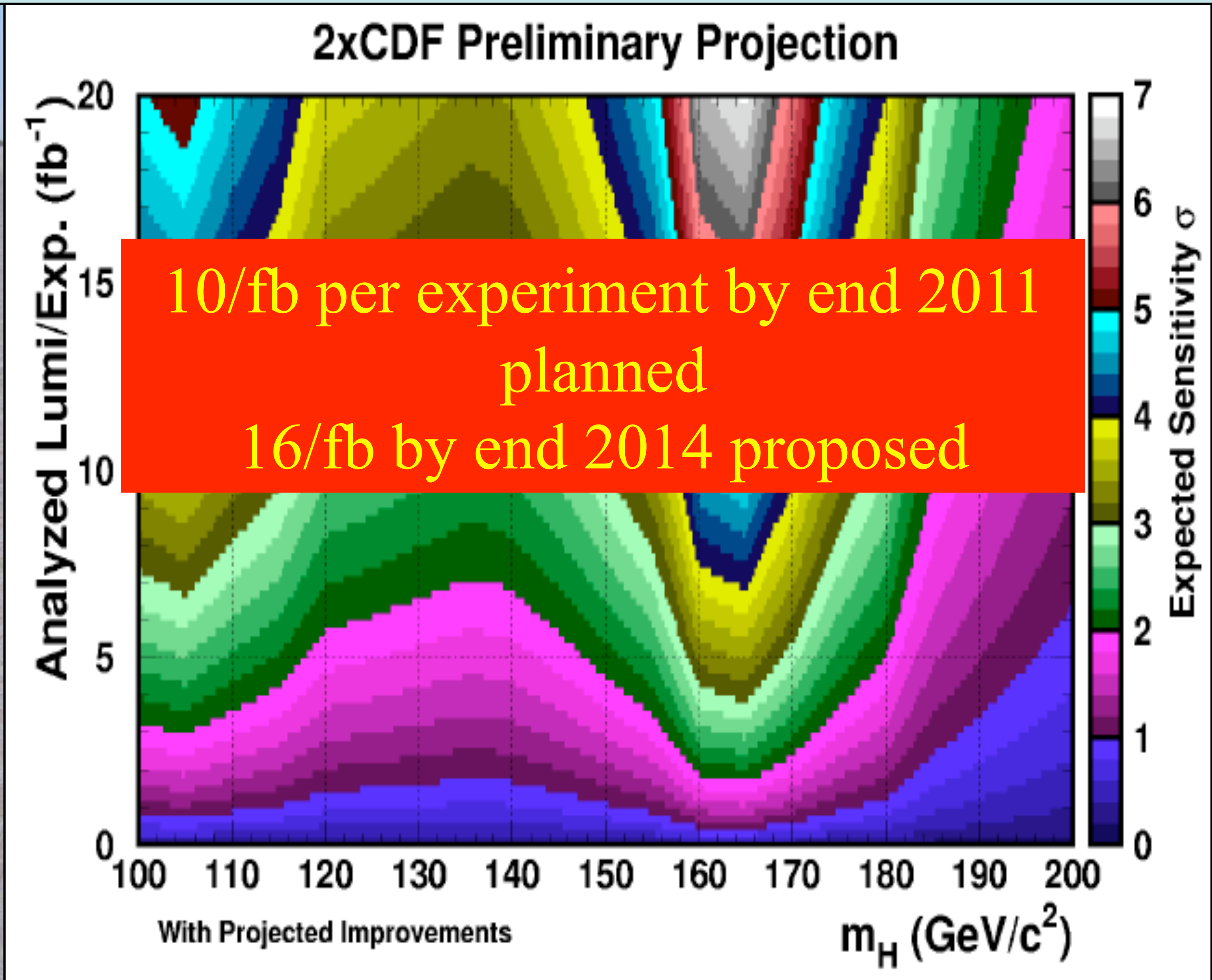
Tevatron excludes Higgs between 158 & 175 GeV

Combining the Higgs Information



$m_H = 121^{+17}_{-6}$ GeV

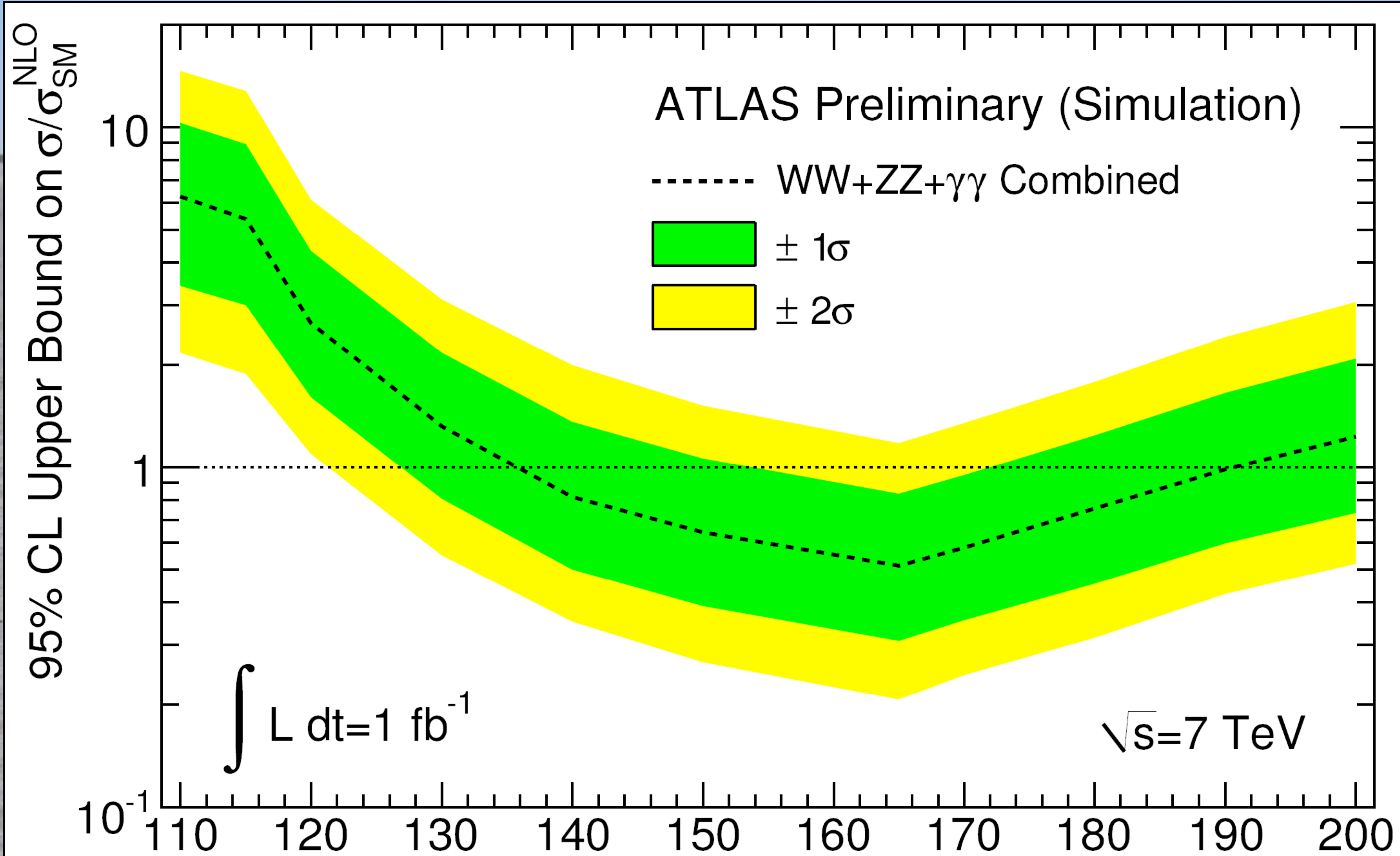
Prospects for Tevatron Higgs Search



10/fb per experiment by end 2011 planned

16/fb by end 2014 proposed

Higgs Search @ 7 TeV

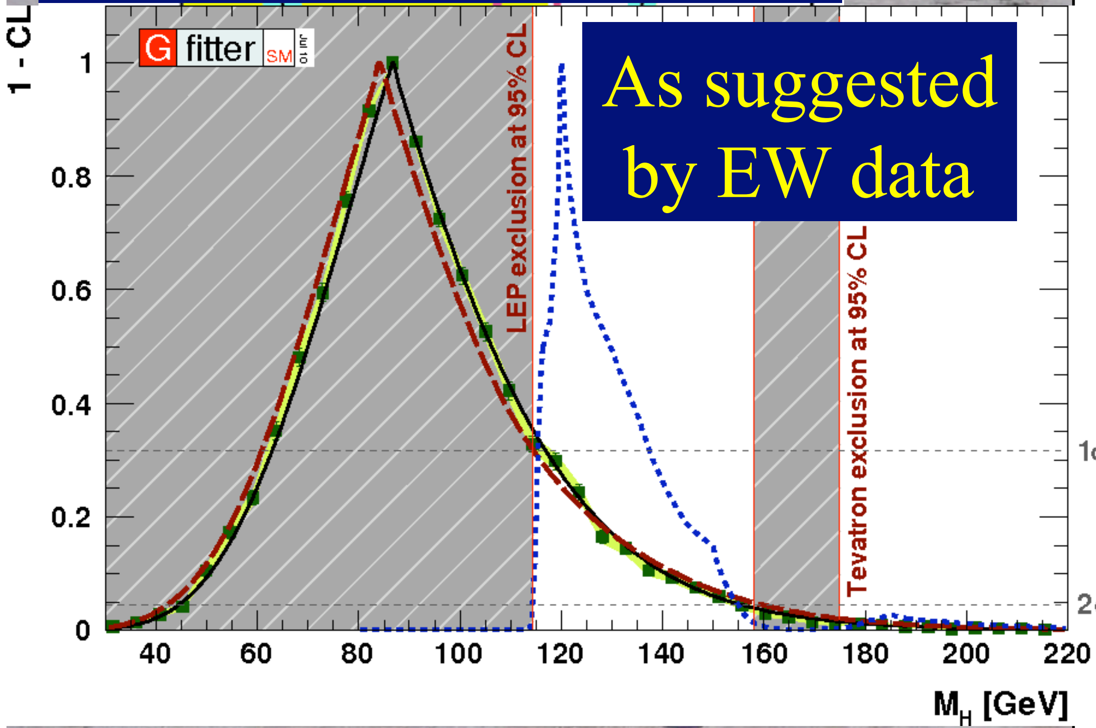


Expected 95 % CL excluded region is 135 GeV < M_H < 188 GeV

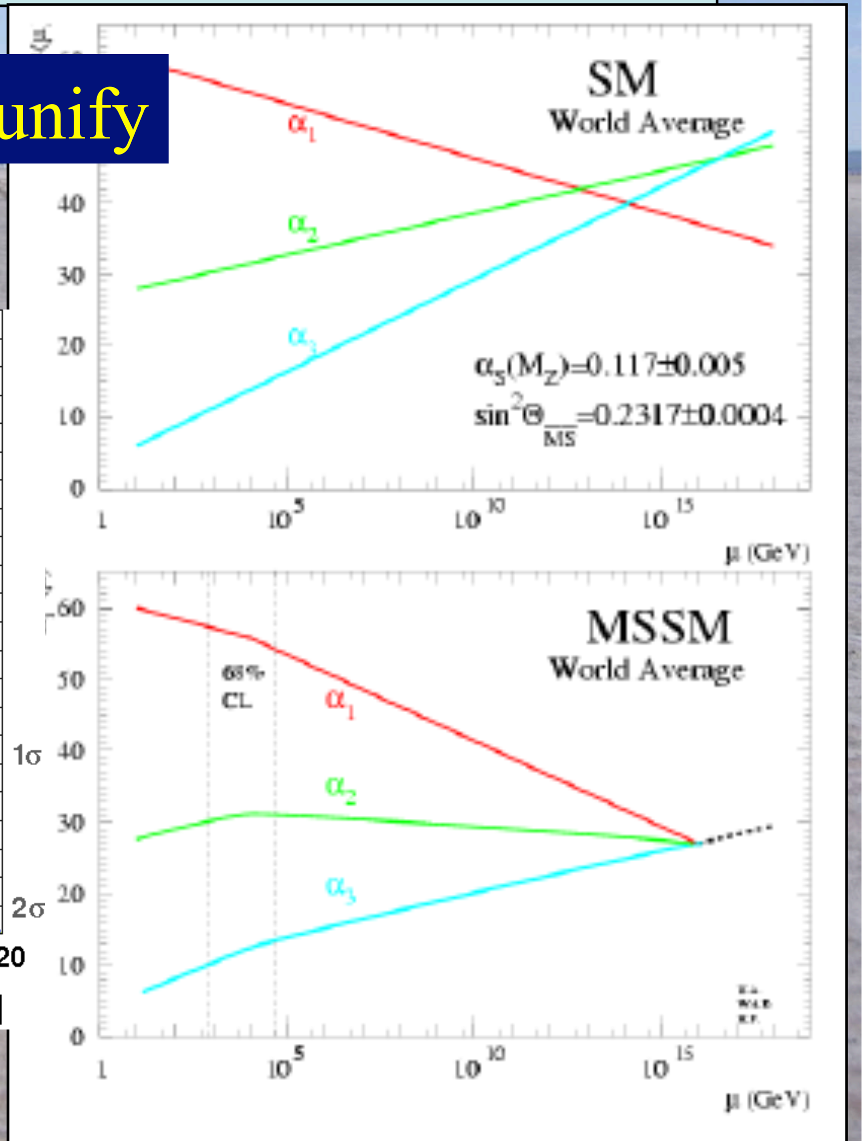
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV

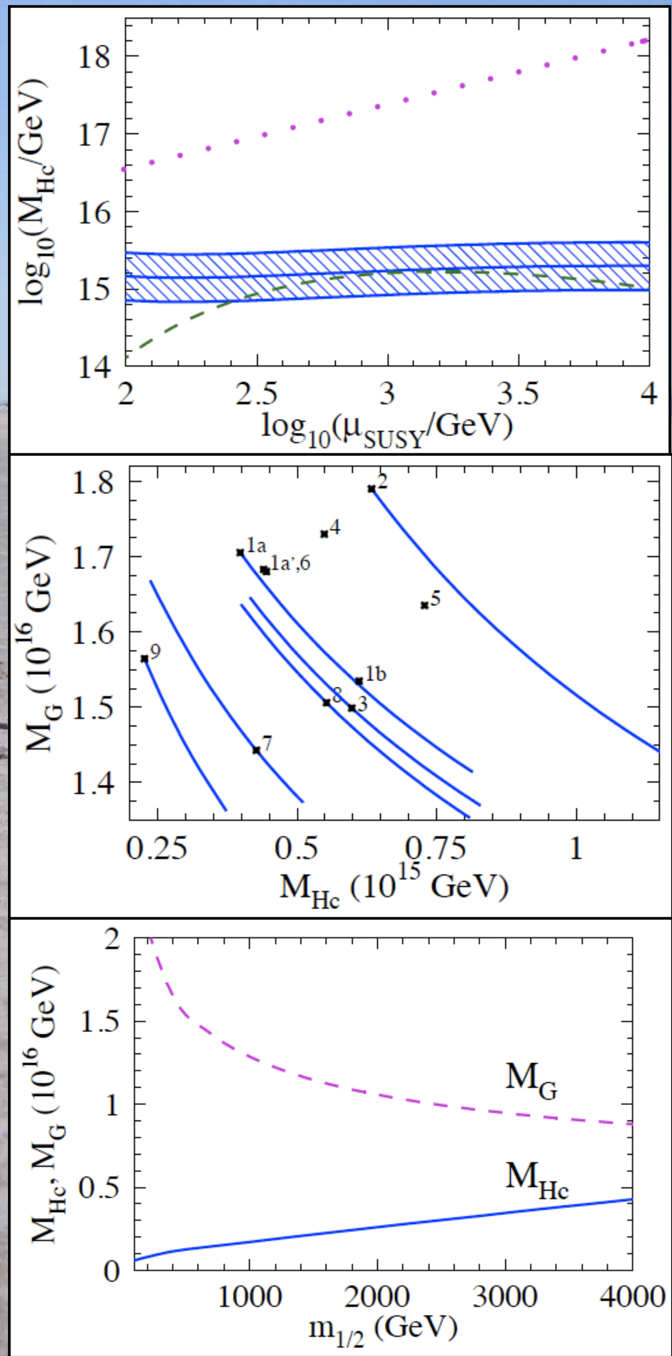


As suggested by EW data



3-Loop SUSY SU(5) GUT

- Stable prediction for coloured Higgs H_c @ 3 loops
- Sensible M_{Hc} & M_{GUT} for different benchmarks
- Sensible M_{Hc} & M_{GUT} for different $m_{1/2}$



Martens, Mihaila, Salomon & Steinhauser: arXiv:1008.3070

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:

  Scalar masses m_0, gaugino masses $m_{1/2}$,
  trilinear soft couplings A_λ, bilinear soft coupling B_μ
- Often assume universality:

  Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Called constrained* MSSM = CMSSM (* at what scale?)
- Minimal supergravity (mSUGRA) predicts gravitino mass: $m_{3/2} = m_0$ and relation: $B_\mu = A_\lambda - m_0$

Non-Universal Scalar Masses

- Different sfermions with same quantum #s?

  e.g., d, s squarks?

  disfavoured by upper limits on flavour-changing neutral interactions

- Squarks with different #s, squarks and sleptons?

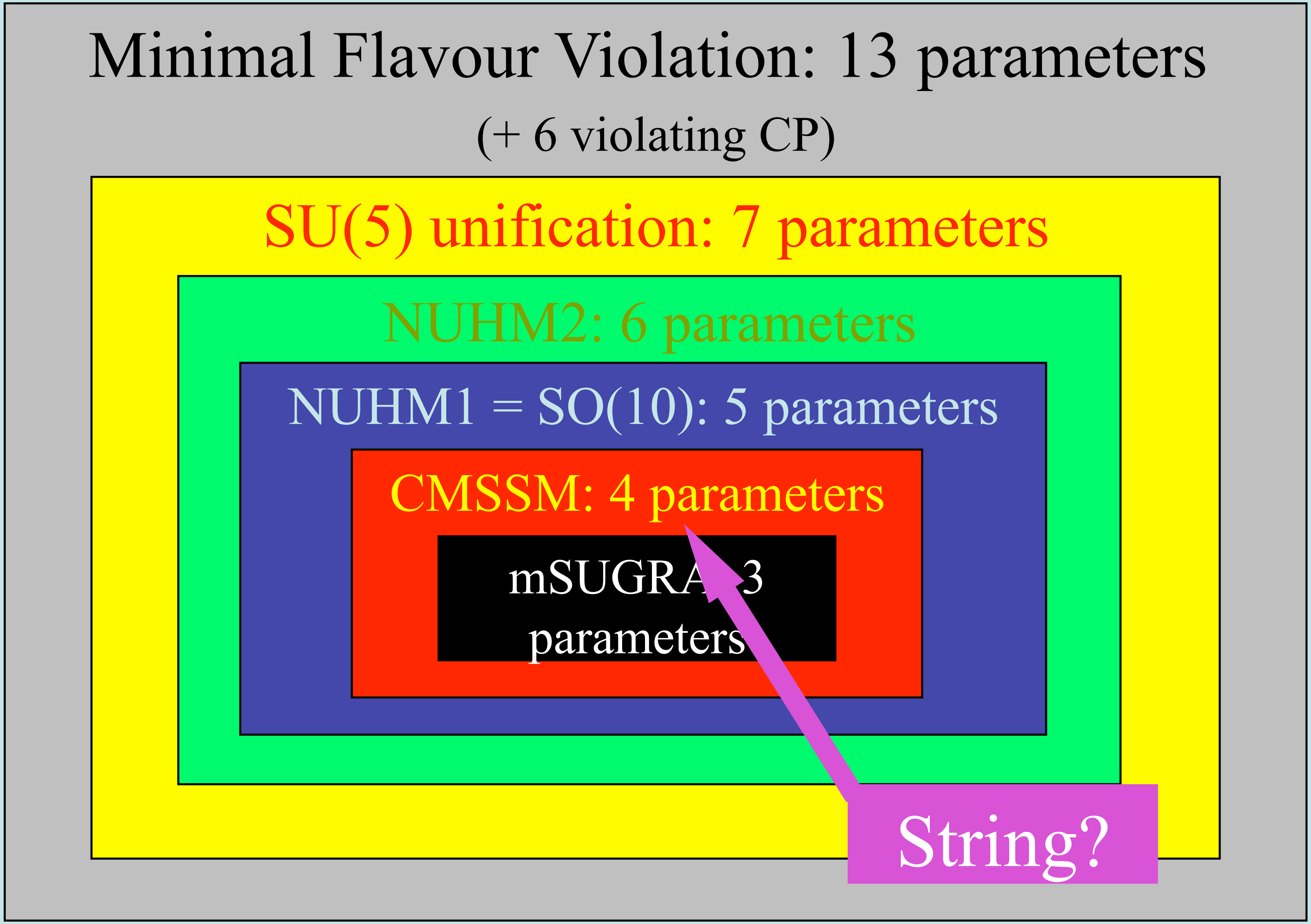
  disfavoured in various GUT models

  e.g., $d_R = e_L$, $d_L = u_L = u_R = e_R$ in SU(5), all in SO(10)

- Non-universal susy-breaking masses for Higgses?

  No reason why not! NUHM

MSSM: > 100 parameters



Current Constraints on CMSSM

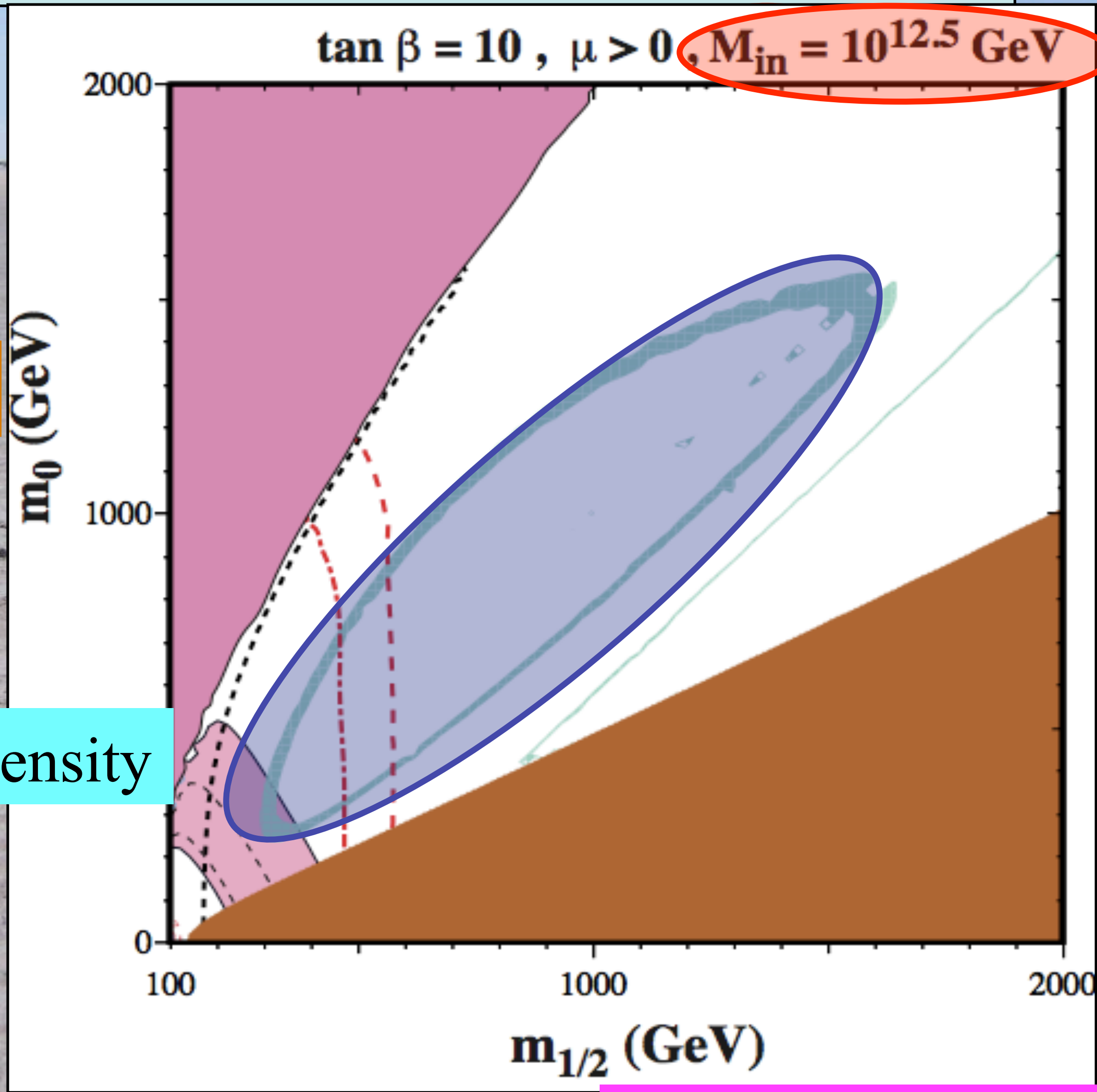
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

Preferred (?) by latest g - 2



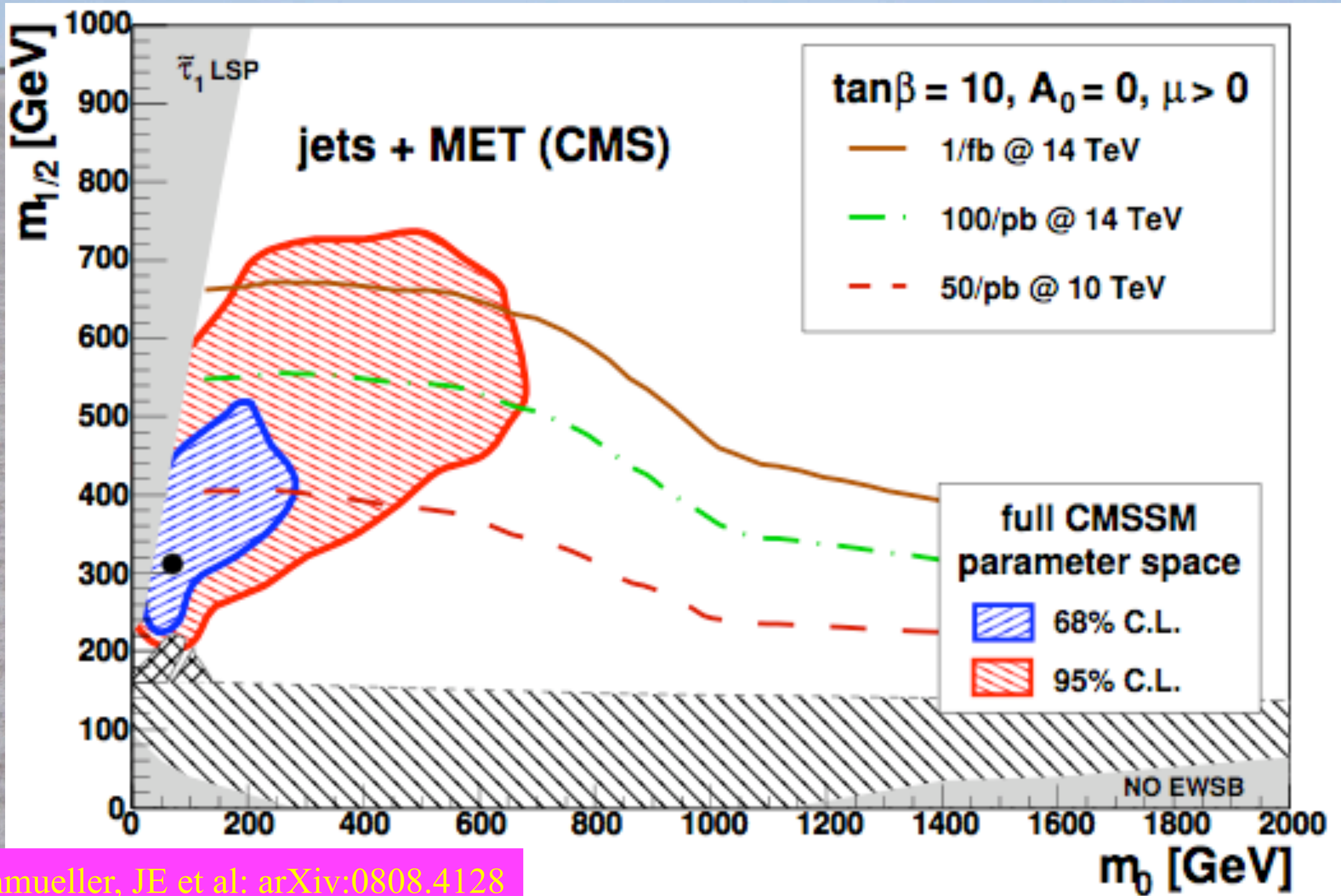
JE + Olive + Sandick

Global Supersymmetric Fit

- Frequentist approach
- Data used:
  - Precision electroweak data
  - Higgs mass limit
  - cold dark matter density
  - B decay data ($b \rightarrow s\,\gamma$, $B_s \rightarrow \mu^+\mu^-$)
  - g_μ - 2 (optional)
- Combine likelihood functions
- Analyze CMSSM, NUHM1 (VCMSSM, mSUGRA)

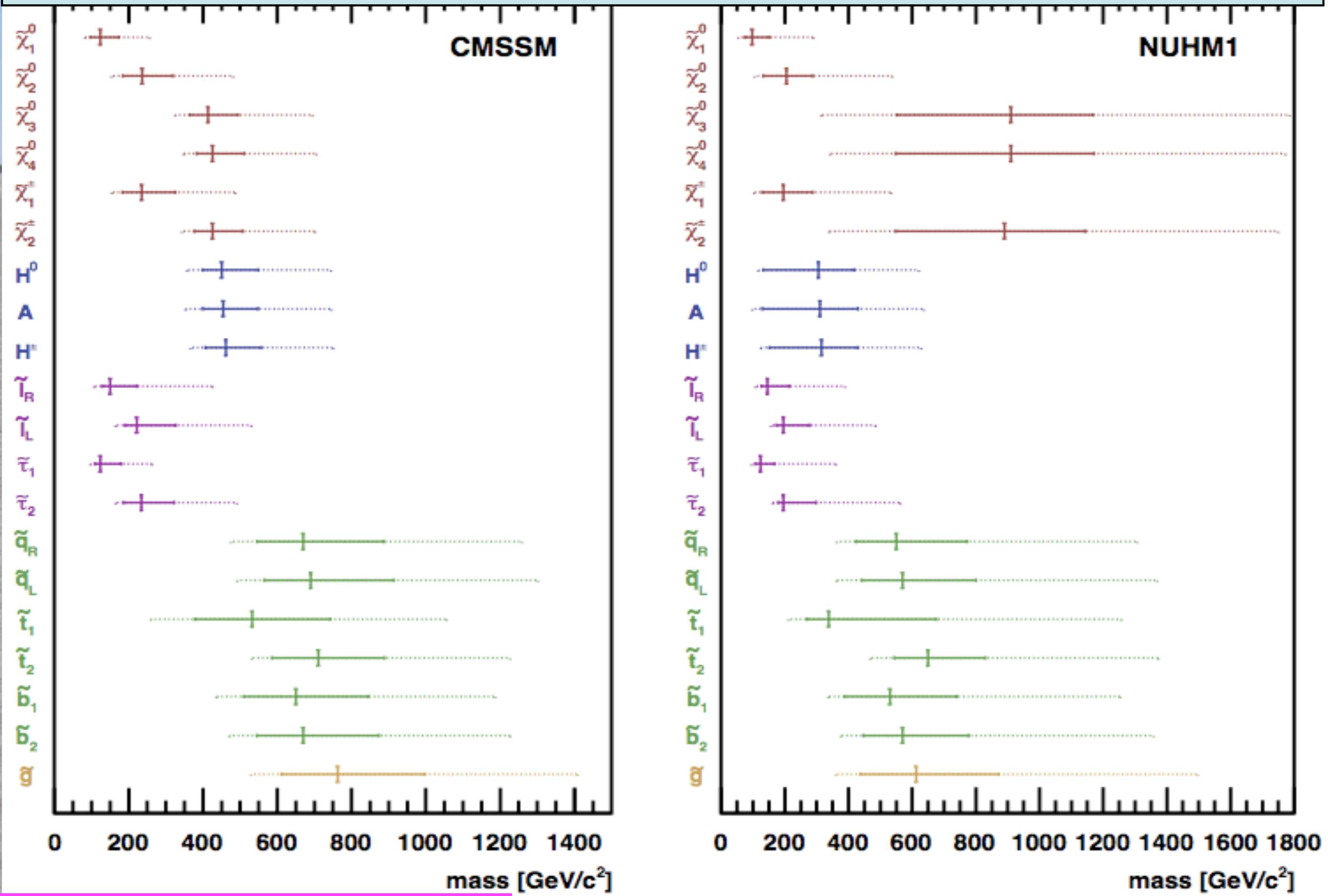
O.Buchmueller, JE et al: arXiv:0808.4128, 0907.5568, 0912.1036

How Soon Might the CMSSM be Detected?



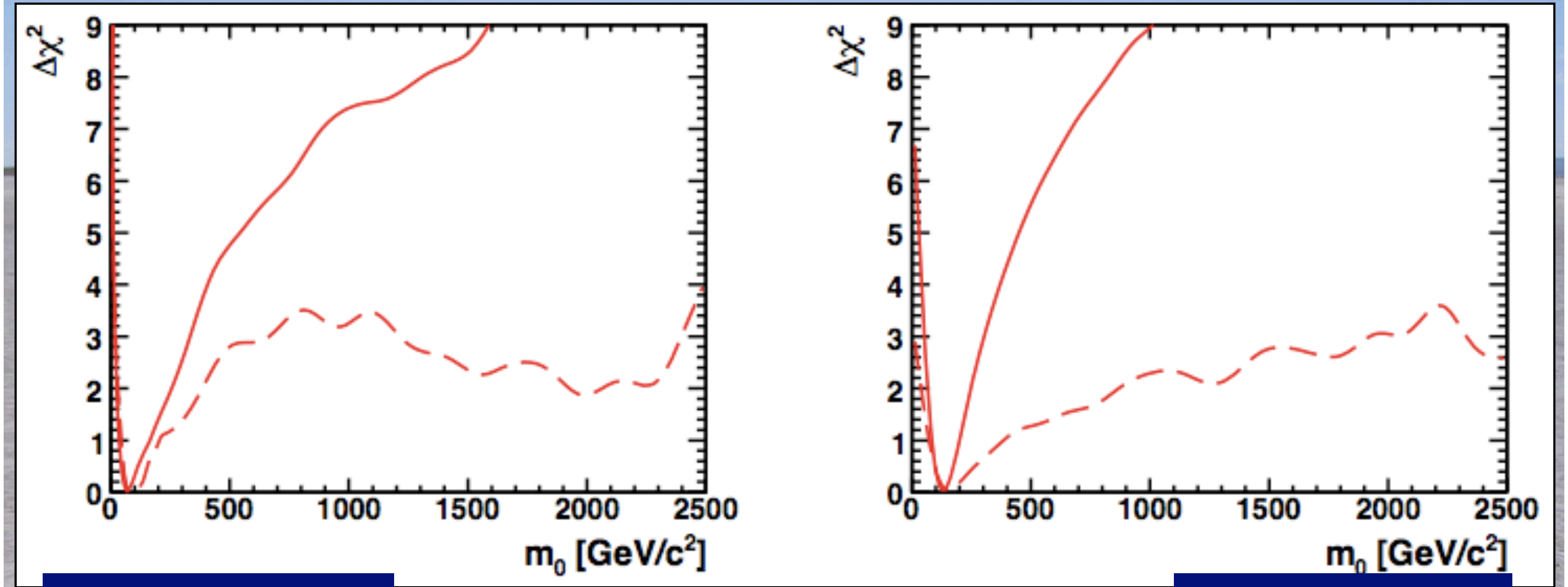
O.Buchmueller, JE et al: arXiv:0808.4128

Spectra with likely Ranges



O.Buchmueller, JE et al: arXiv:0907.5568

What Happens if g_μ - 2 Dropped?



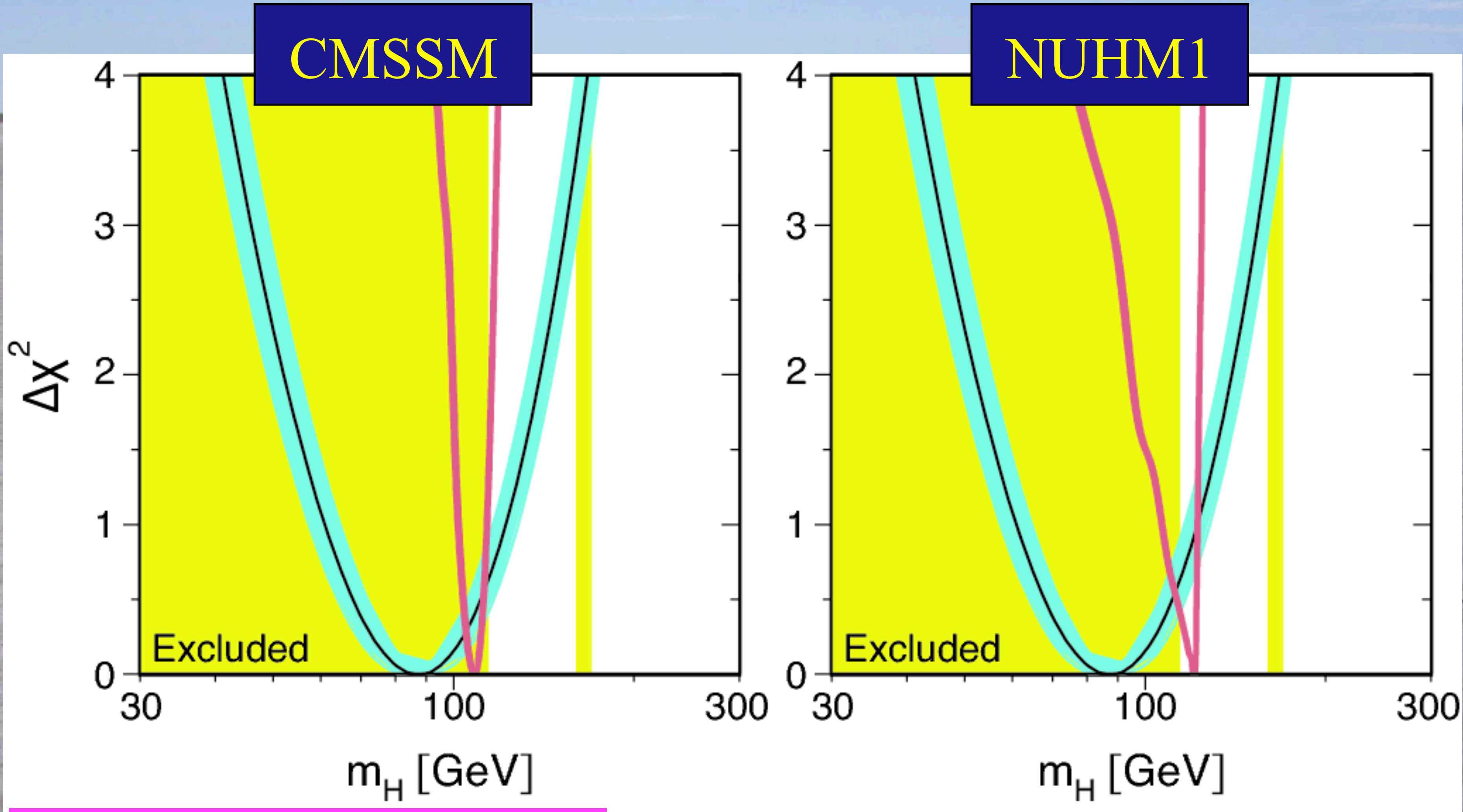
CMSSM

NUHM1

Solid lines: with g_μ - 2
Dashed lines: without g_μ - 2
Focus-point still disfavoured, e.g., by m_W

O.Buchmueller, JE et al: arXiv:0907.5568

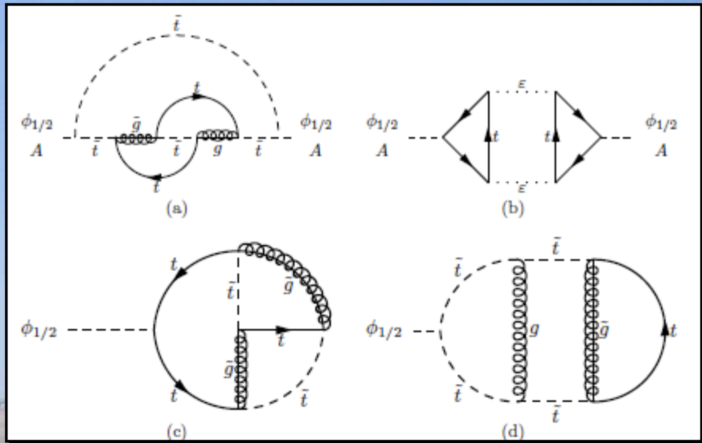
Likelihood Function for Higgs Mass

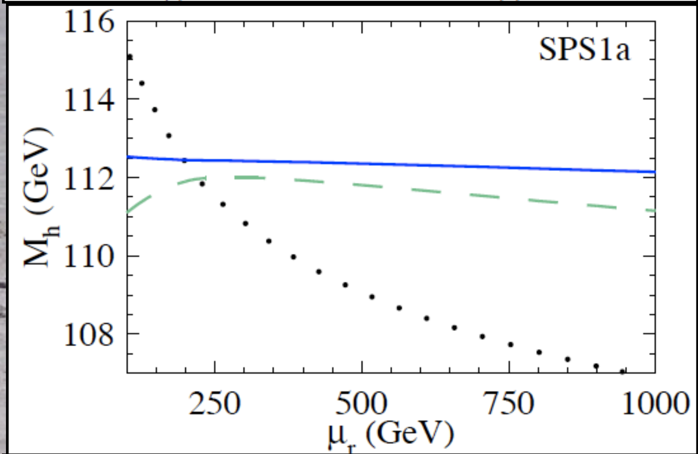


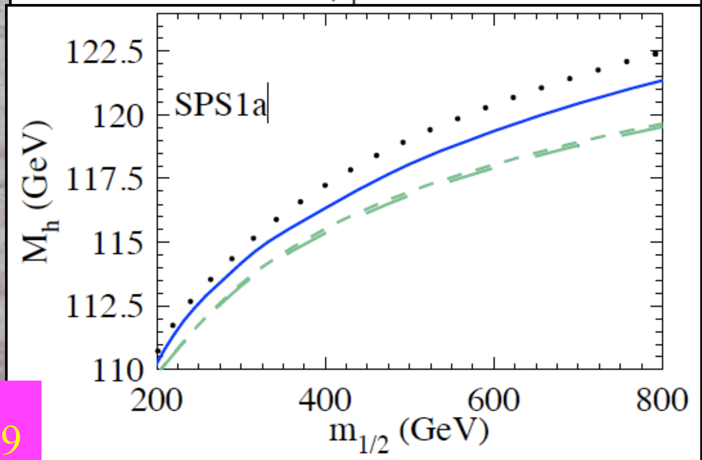
O.Buchmueller, JE et al: arXiv:0907.5568

SUSY Higgs Mass @ 3 Loops

- Sample diagrams
- Renormalization-scale dependences @ 1, 2, 3 loops
- Results @
  - 1 Loop: dotted ……
  - 2 Loops: dashed ---------
  - 3 Loops: solid



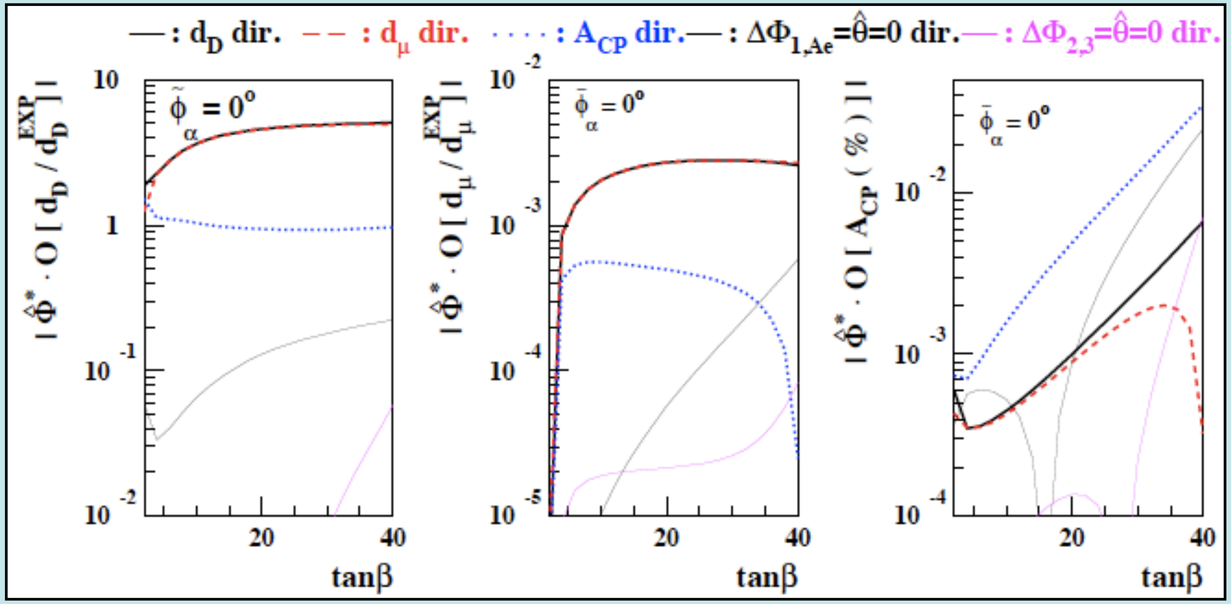




Kant, *Harlander*, Mihaila & Steinhauser: arXiv:1005.5709

Geometric Approach to Maximizing CP-Violating Observables

- Maximal CP-violating minimal flavour-violating (MCPMFV) SUSY model has 6 phases (+ θ_{QCD})
- Maximize CP-violating observables compatibly with EDM constraints by systematic construction
  - Techniques of differential geometry
- Observables may be >> experimental sensitivity

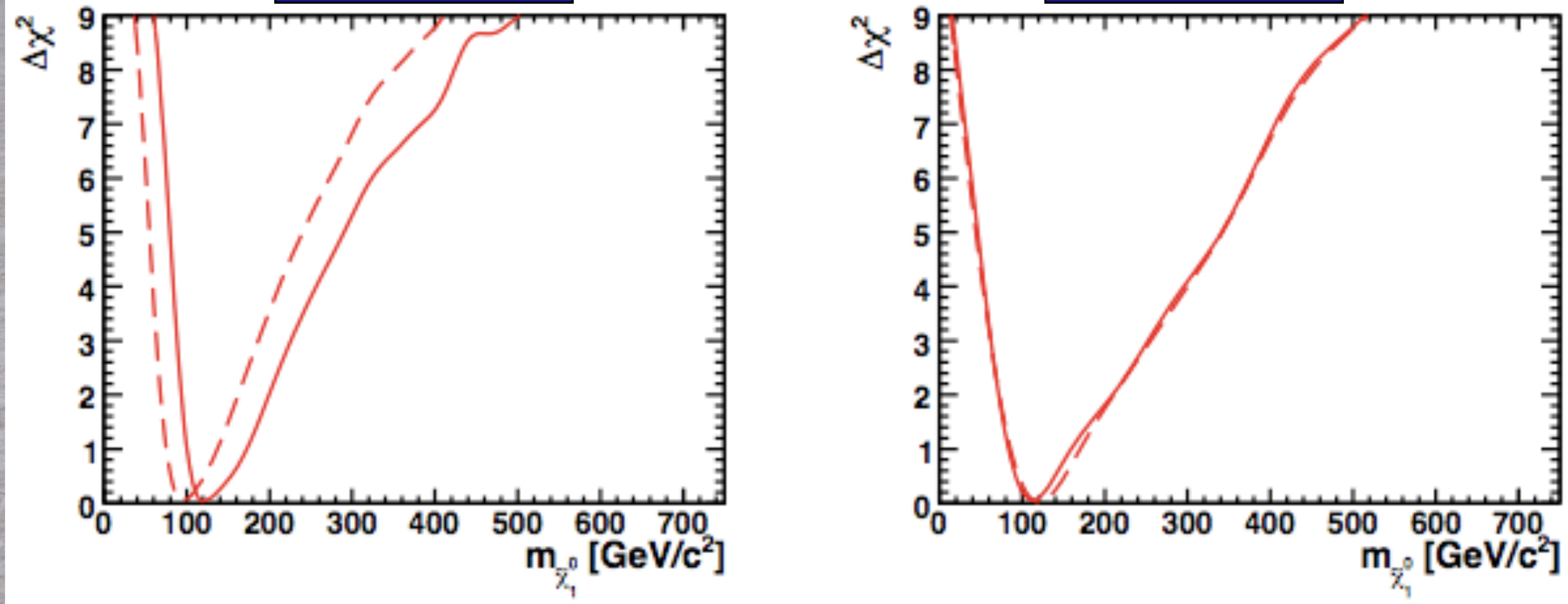


JE, Lee & Pilaftsis: arXiv:1006.3087

Likelihood Function for Neutralino Mass

CMSSM

NUHM1

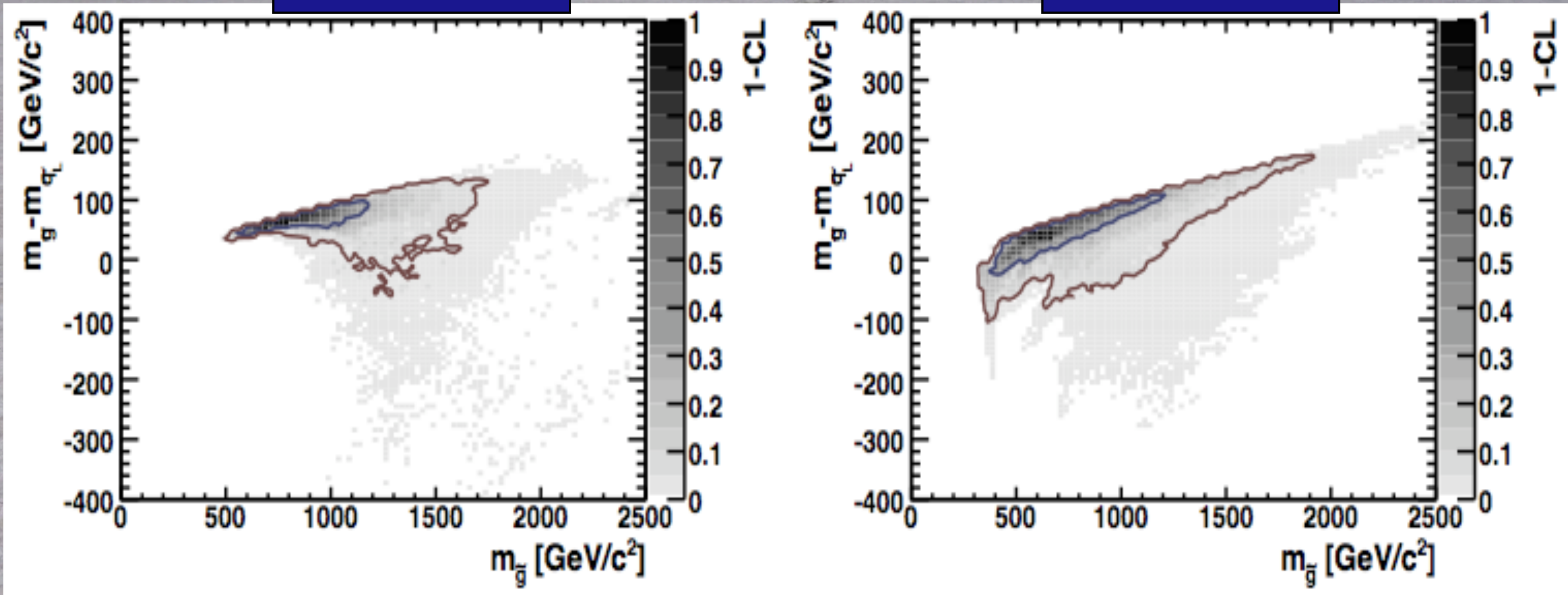


O.Buchmueller, JE et al: arXiv:0907.5568

Correlation between Gluino & Squark Masses

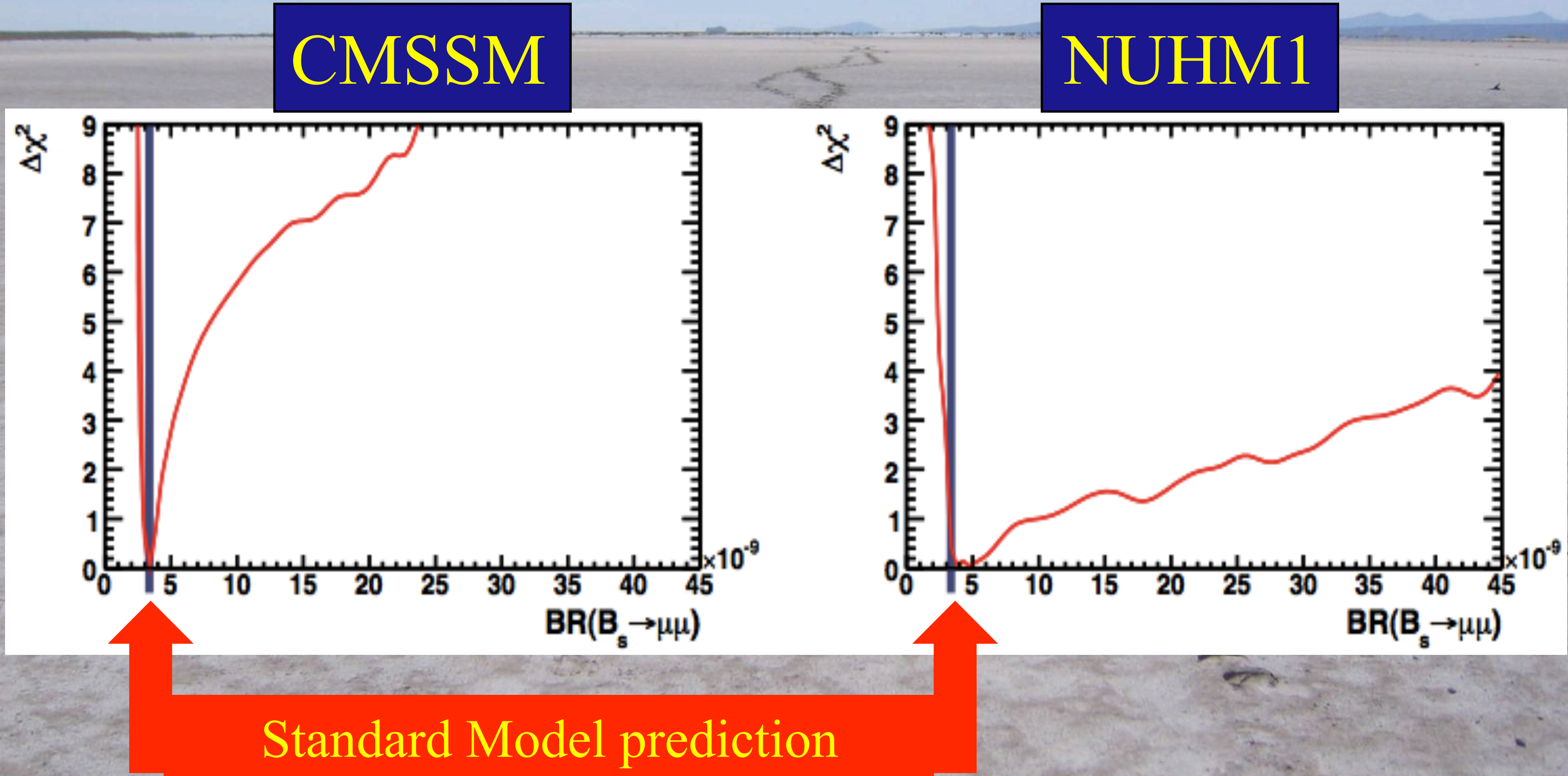
CMSSM

NUHM1



O.Buchmueller, JE et al: arXiv:0907.5568

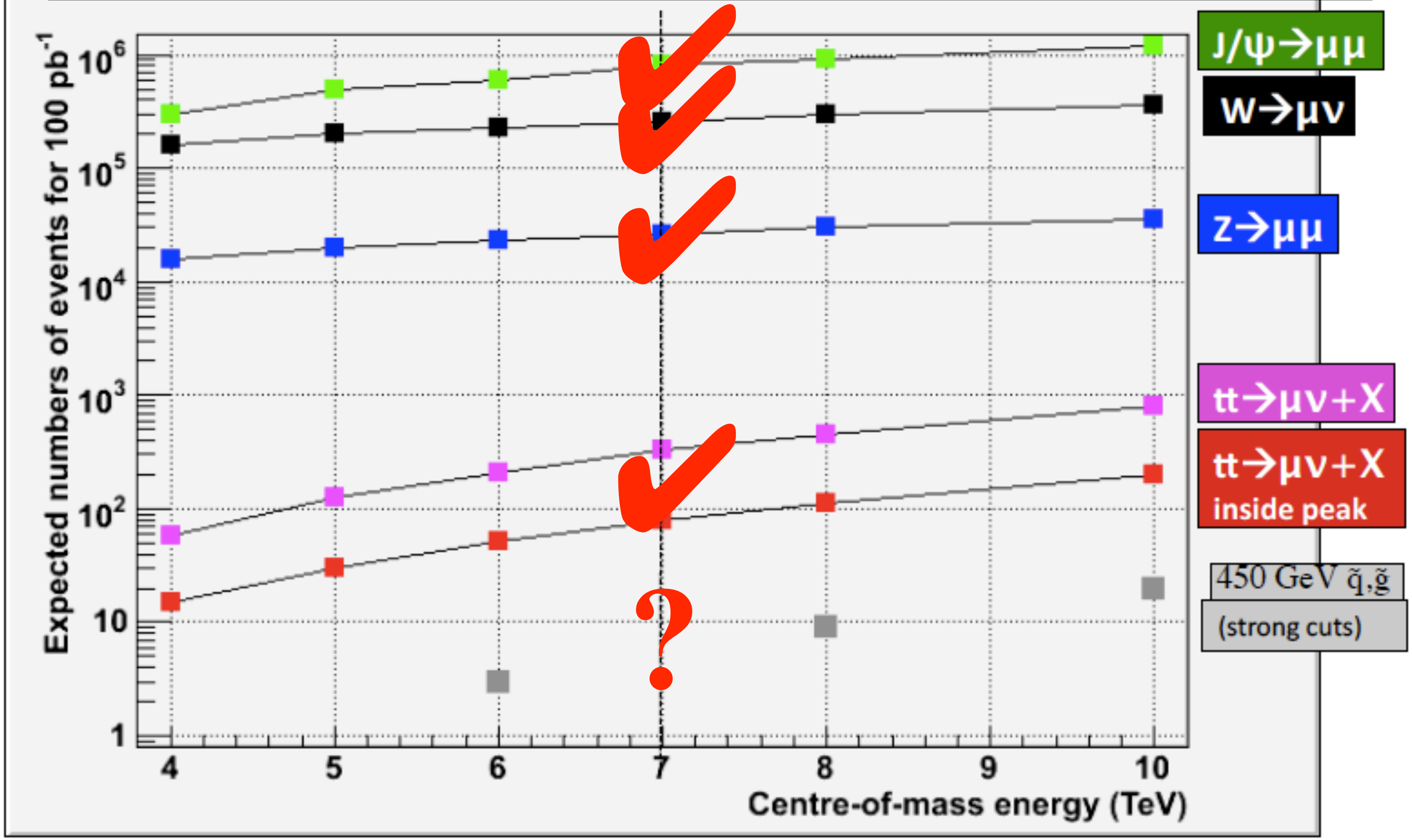
Likelihood Function for $B_s \to \mu^+\mu^-$



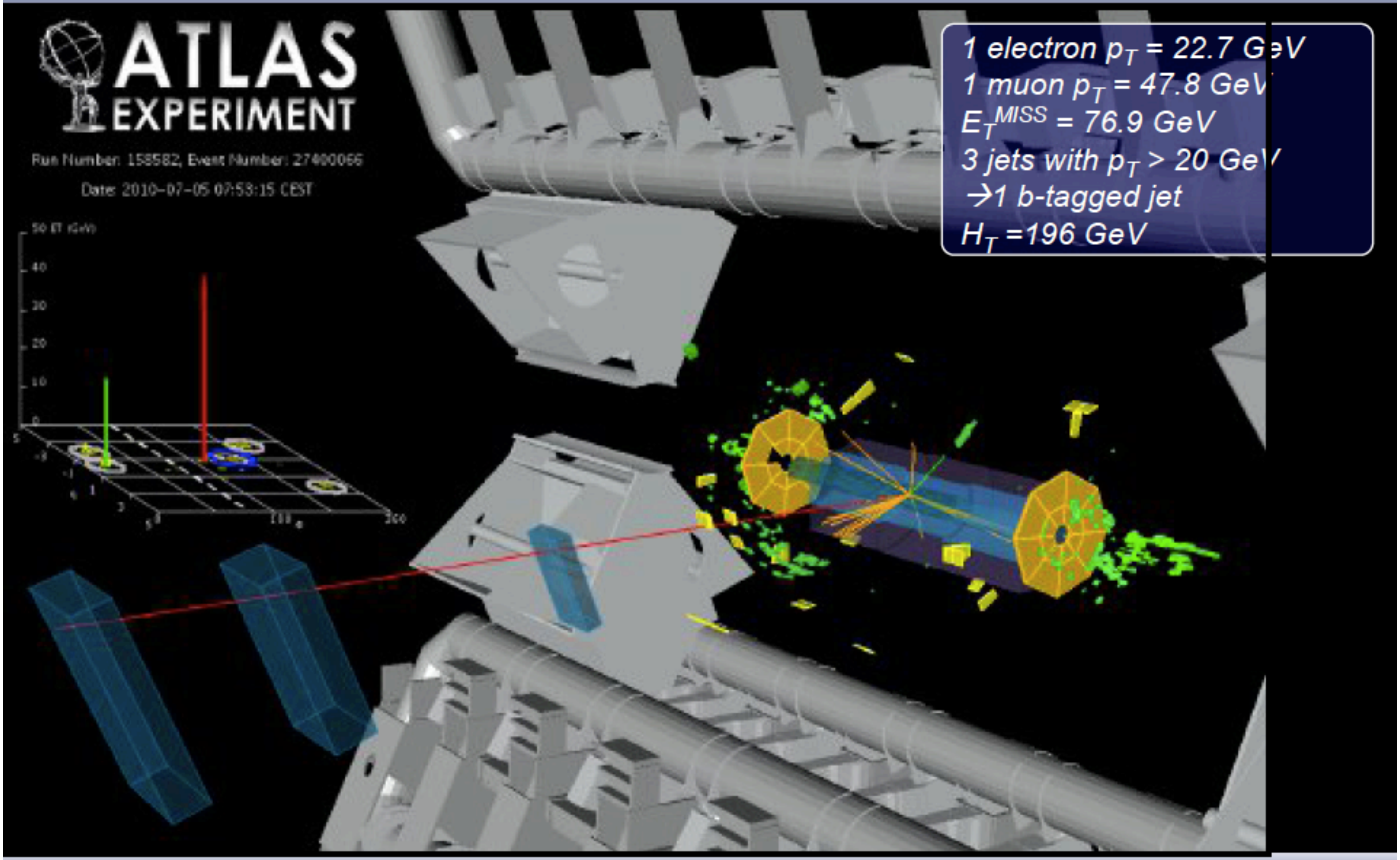
O.Buchmueller, JE et al: arXiv:0907.5568

Nov. 20th 2009: Jubilation

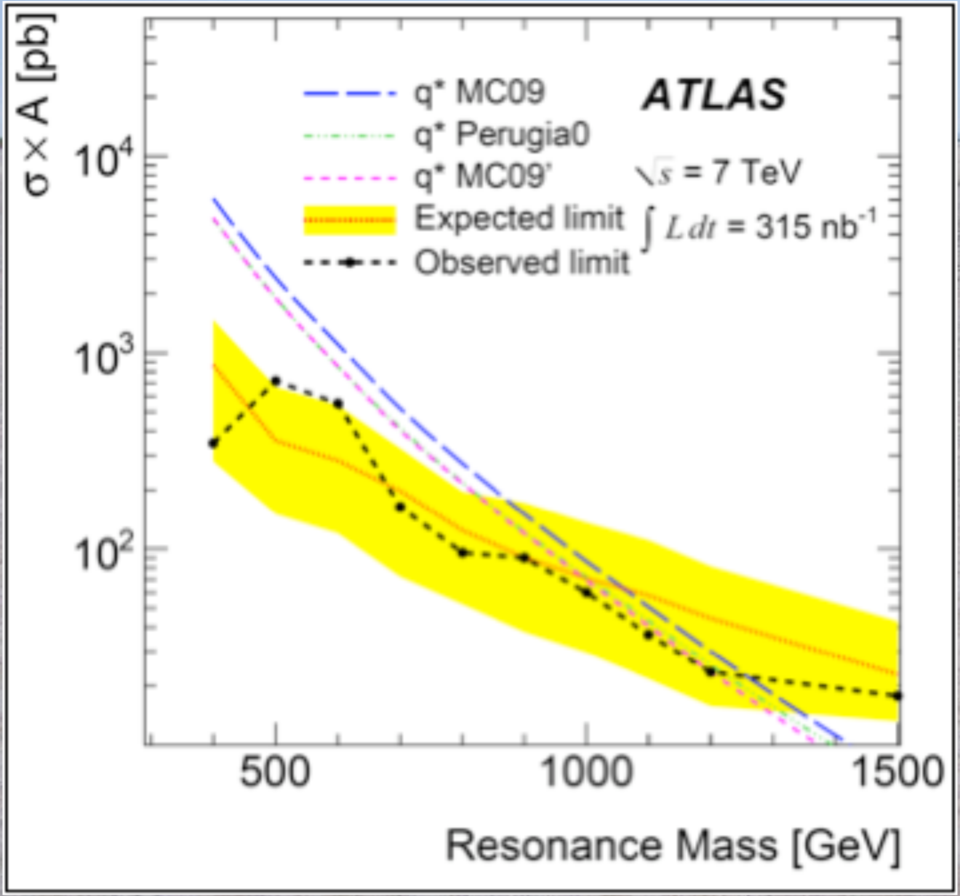
The Story so far – and to come

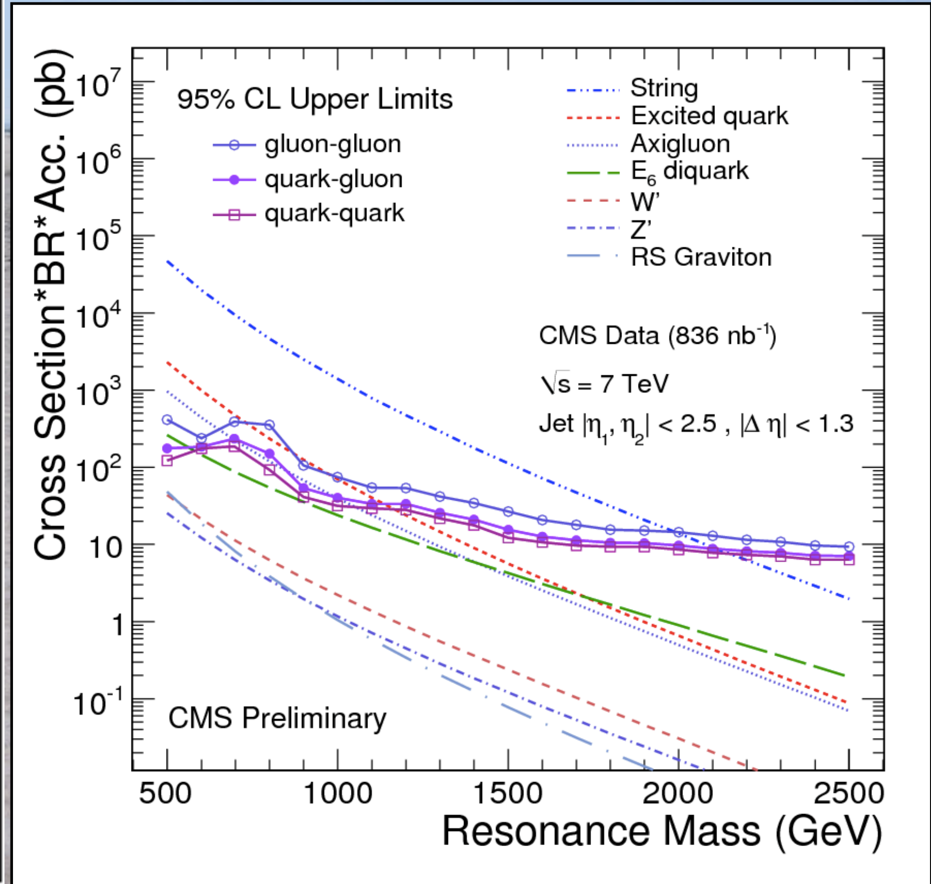


Top Pair Candidate in ATLAS



The LHC Sensitivity Starts to Extend Beyond the Tevatron





Excited quark mass > 1.20 TeV (ATLAS), 1.16 TeV (CMS)

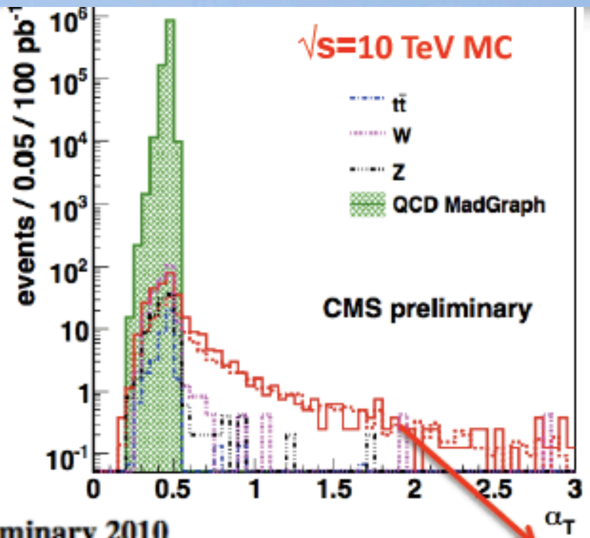
cf 0.87 TeV (CDF)

Supersymmetry Search in CMS

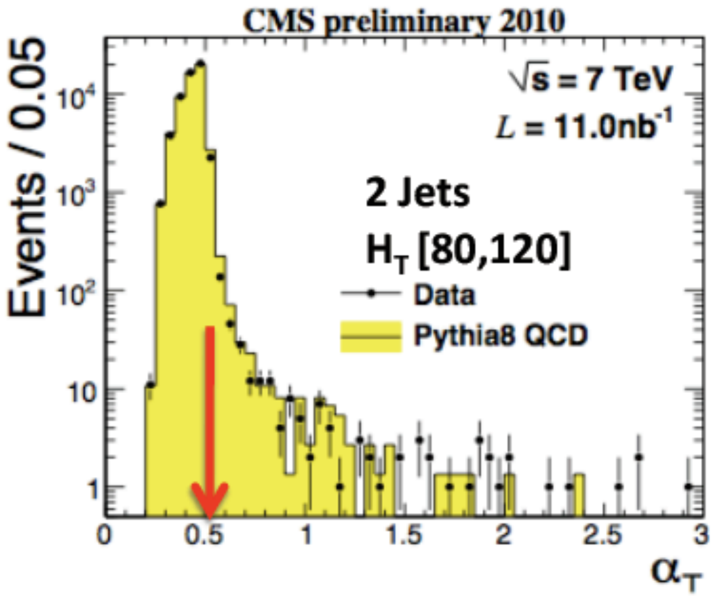
- A powerful variable for suppressing mis-measured QCD

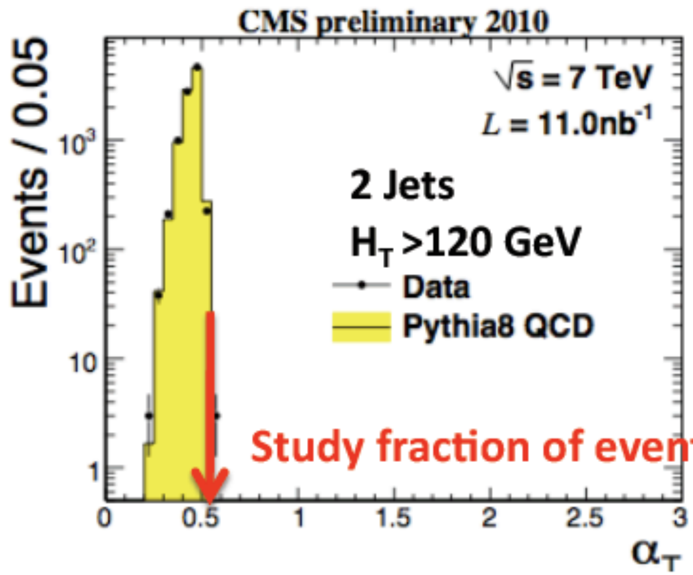
$$\alpha_T \equiv \frac{p_{T2}}{M_T} \qquad \alpha_T = \frac{\sqrt{p_{T2}/p_{T1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$

- Well measured back-to-back di-jet system $\alpha_T \approx 0.5$, if one jet is mis-measured $\alpha_T < 0.5$



SUSY





$$H_T = \sum_i p_T(\mathrm{jet}_i)$$

Study fraction of events with $\alpha_T > 0.55$

Supersymmetry Search in ATLAS

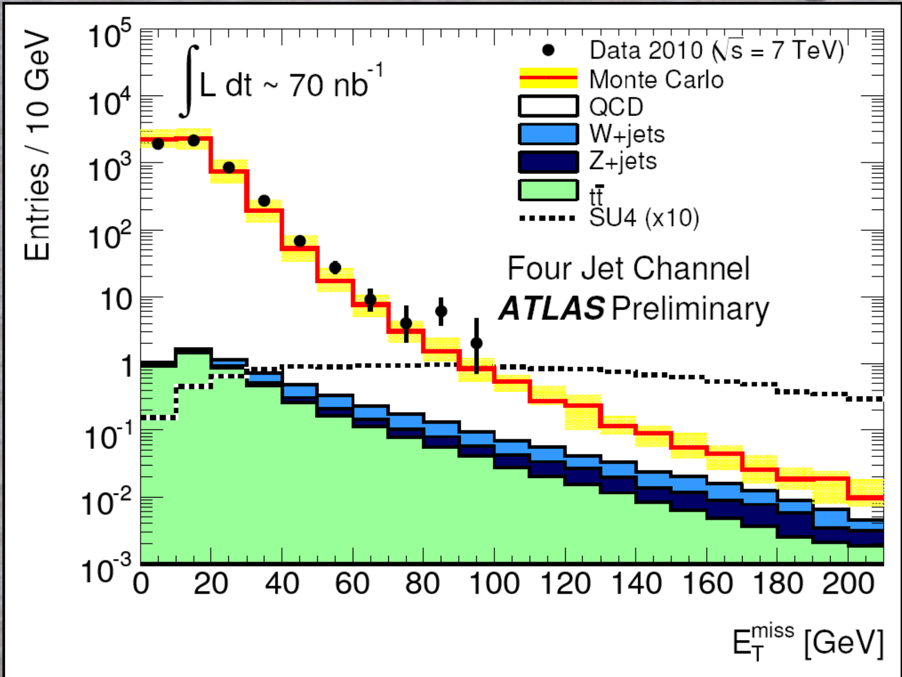
Highest discovery potential: in jets + $E_{T,miss}$ + 0 lepton channel

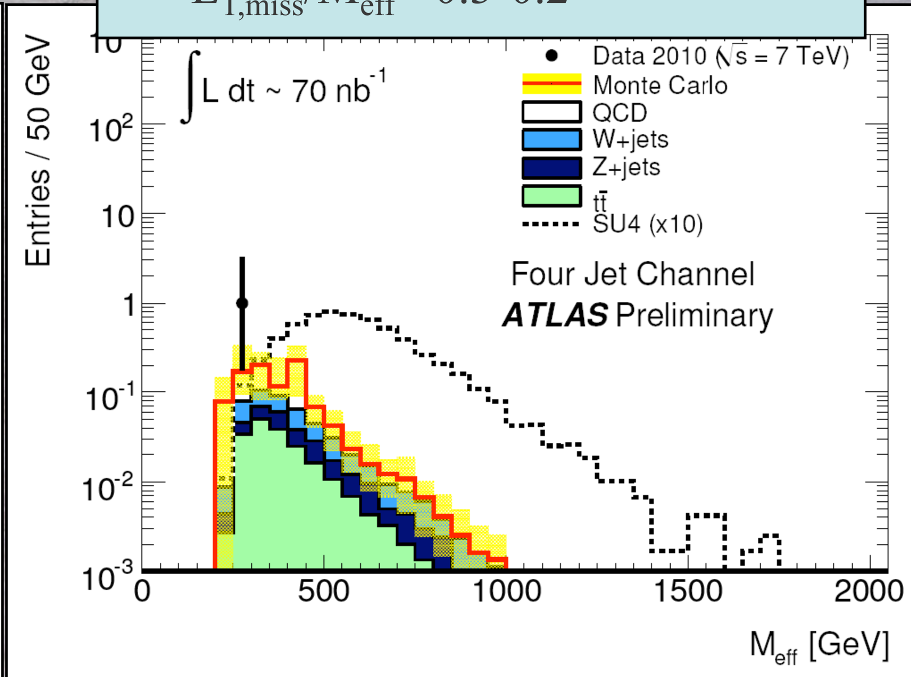
pre-selection: (~70nb^{-1},L1 jet trigger)

- =1, ≥2, ≥3, ≥4 jets with p_T>70 (30) GeV

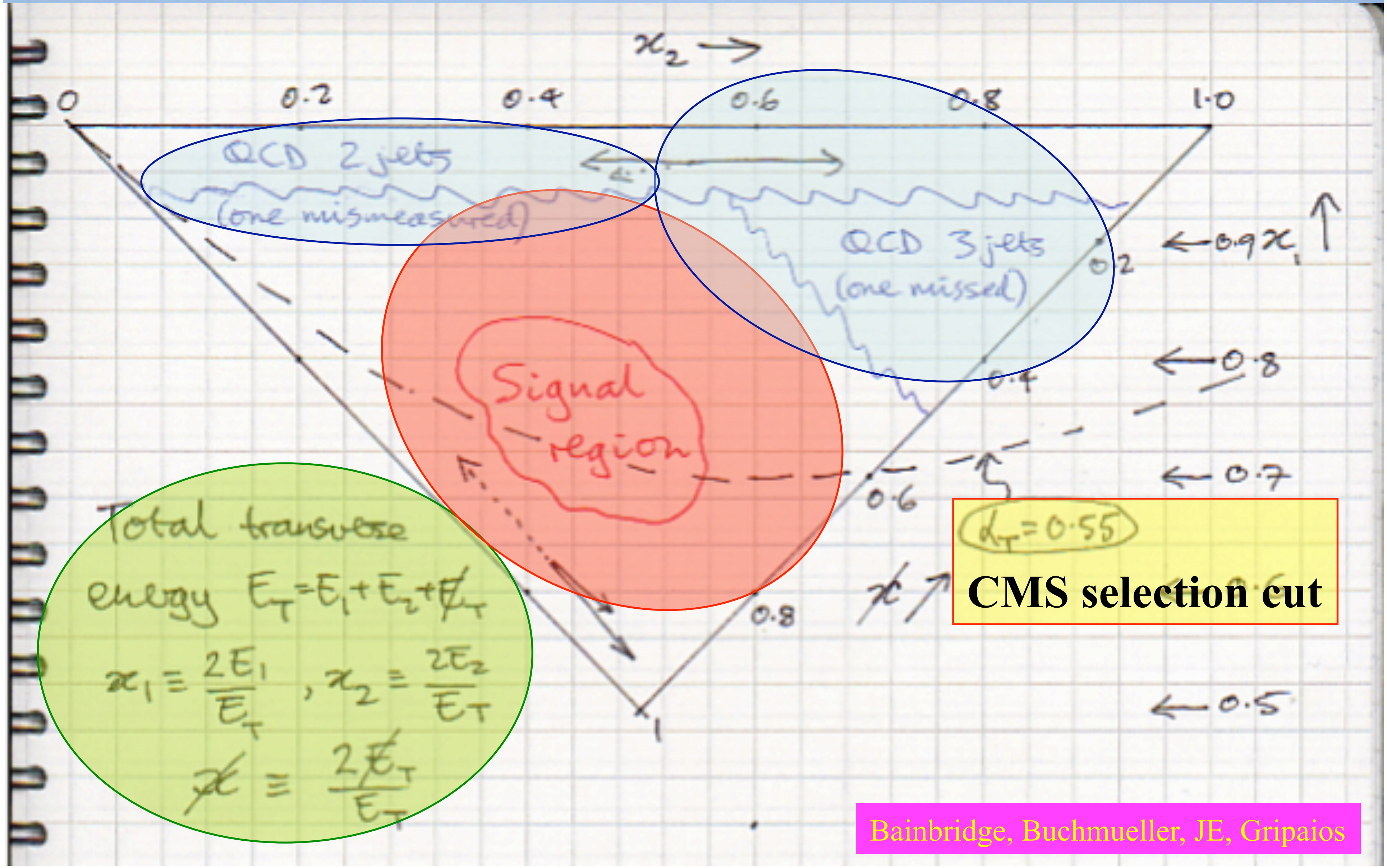
final selection:

- $E_{T,miss}$>40GeV, $\Delta\Phi(j_i, E_{T,miss})$>0.2
- $E_{T,miss}/M_{eff}$> 0.3-0.2

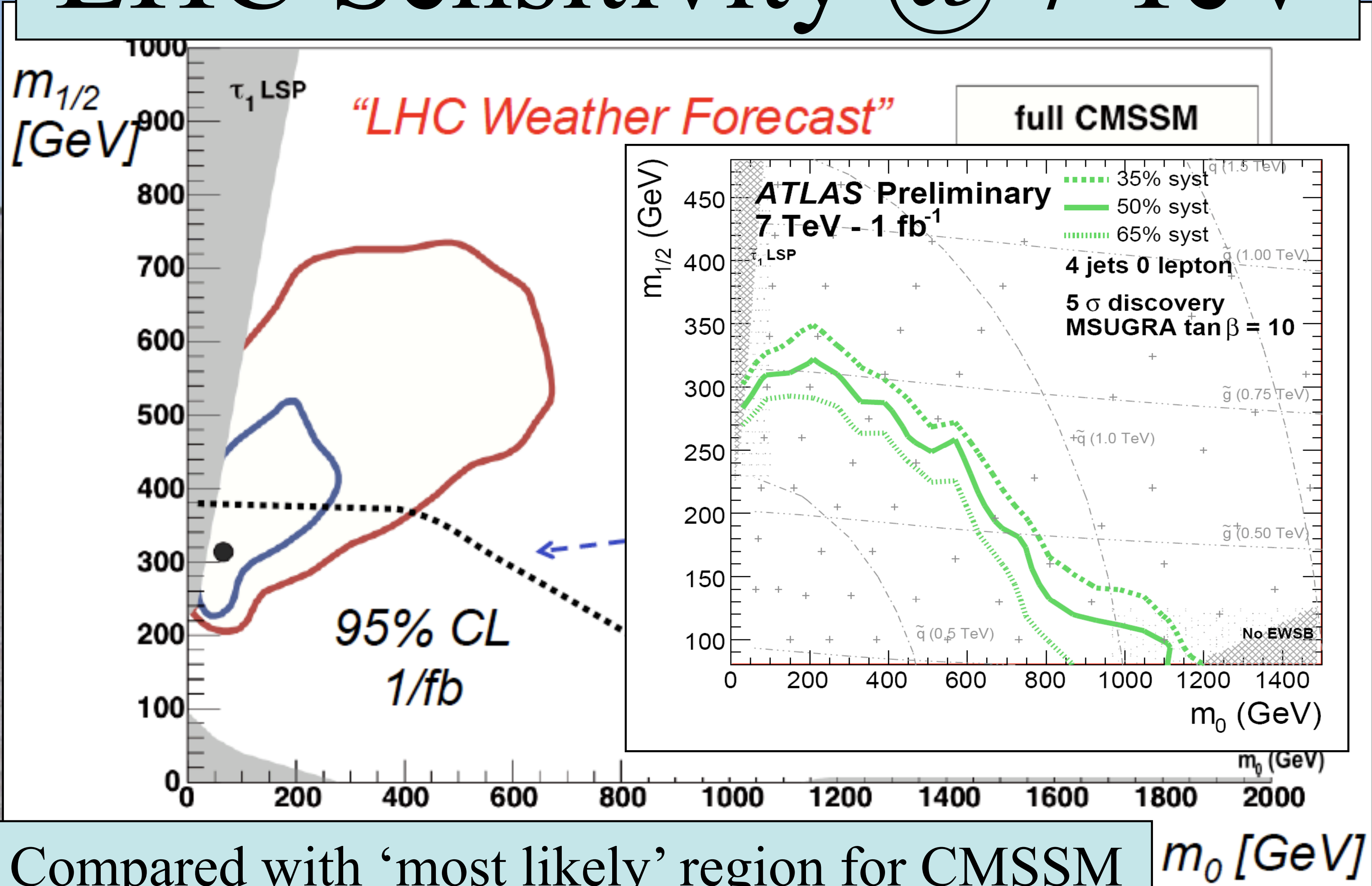




'Dalitz Plot' for Supersymmetric Dijets



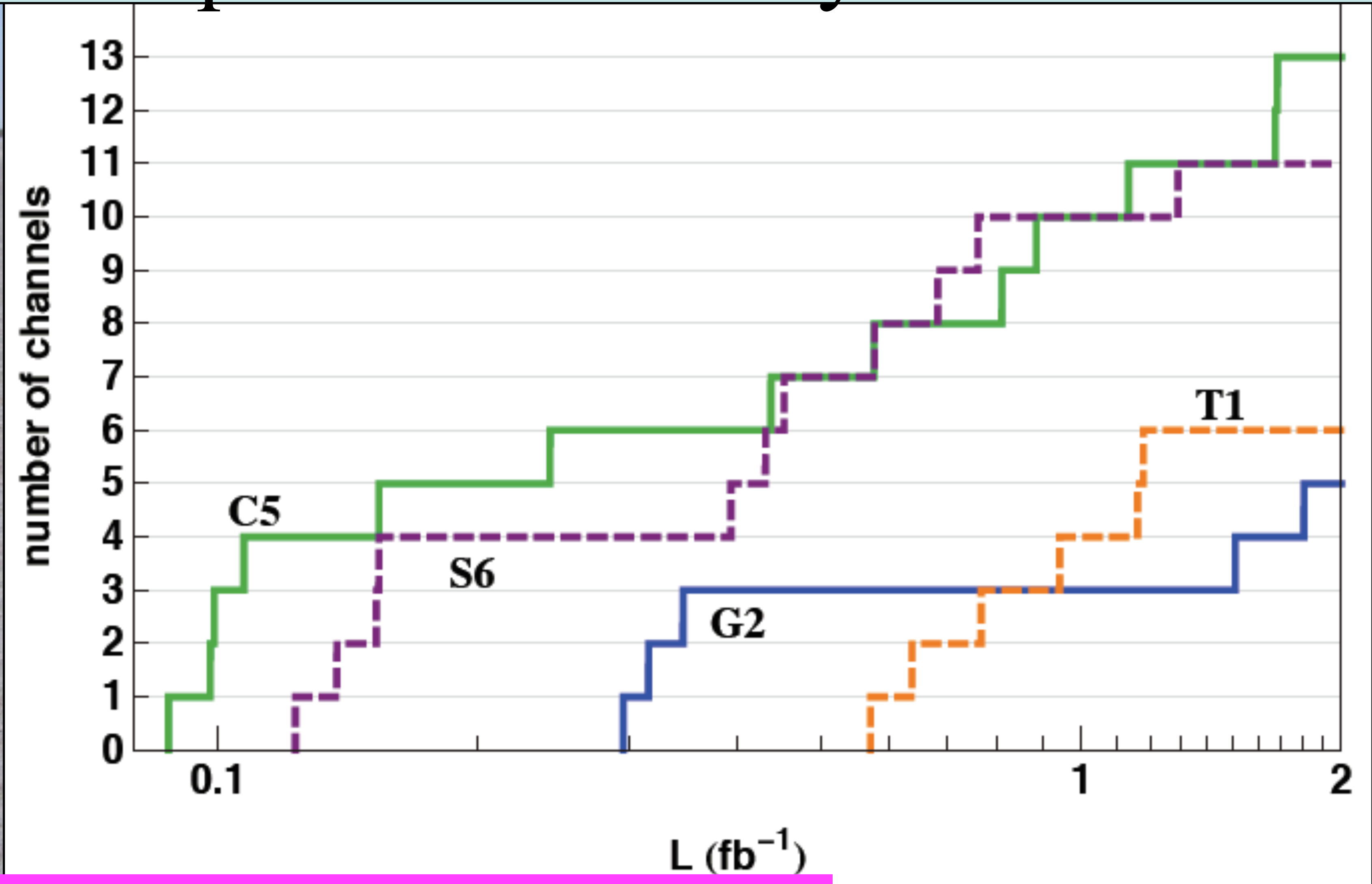
LHC Sensitivity @ 7 TeV



Compared with 'most likely' region for CMSSM

O.Buchmueller, JE et al: arXiv:0808.4128

The LHC may Detect Many Sparticles in Many Channels

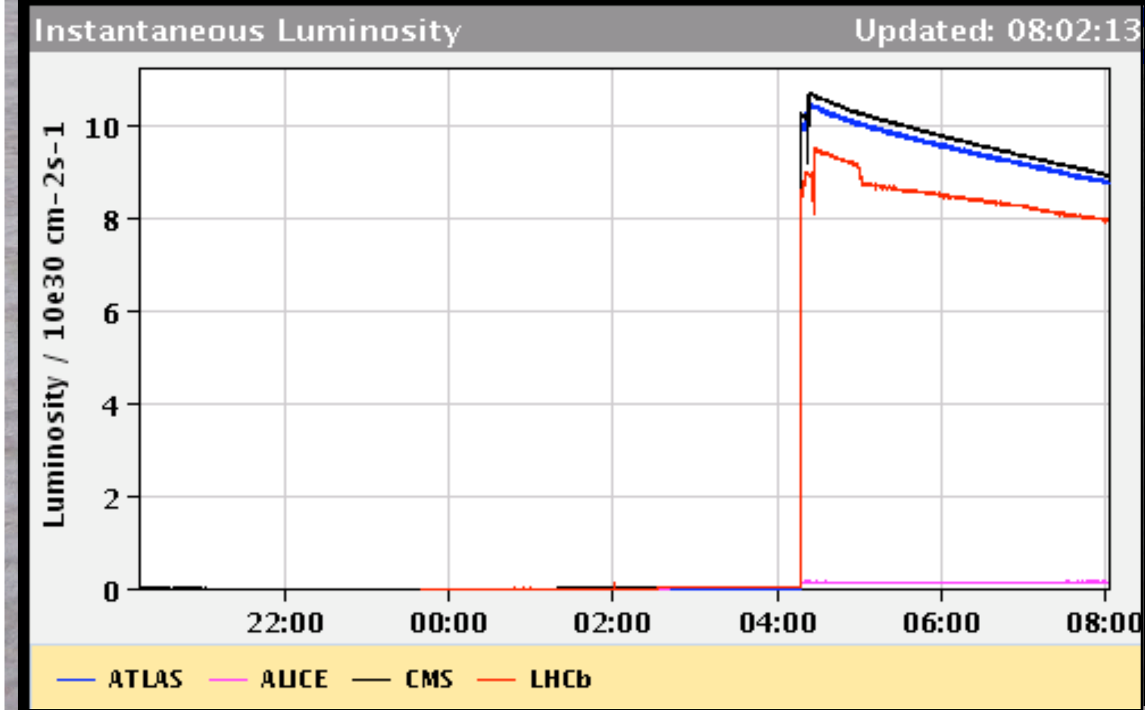


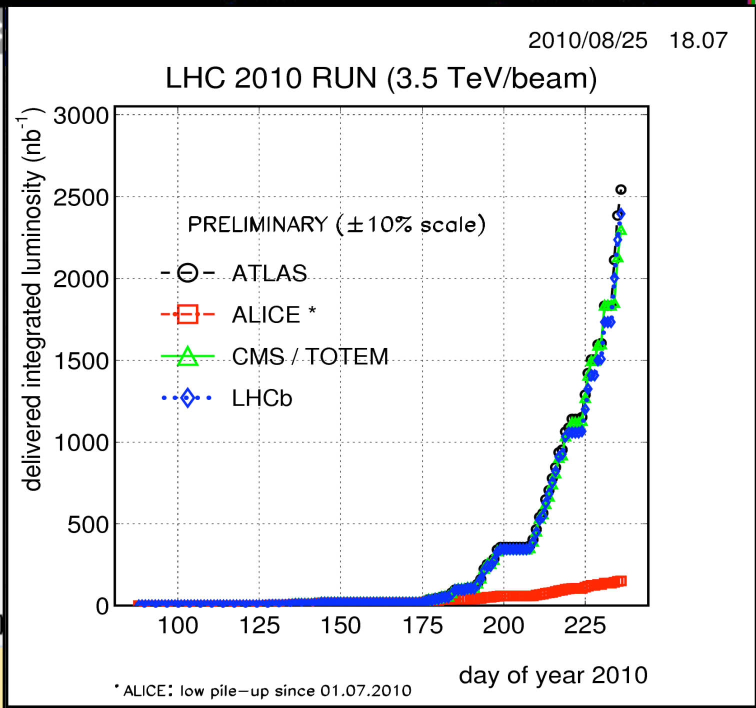
Altunkaynak, Holmes, Nath, Nelson & Peim: arXiv:1008.3423

LHC Luminosity Reaches $10^{31}/cm^2s$

26-Aug-2010 04:24:46 Fill #: 1303 Energy: 3500 GeV I(B1): 5.51e+12 I(B2): 5.23e+12

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	NOT READY	STANDBY	PHYSICS
Instantaneous Lumi (ub.s)^-1	10.456	0.138	10.719	8.882
BRAN Luminosity (ub.s)^-1	9.573	0.137	7.914	7.327
Fill Lumiosity (nb)^-1	2.0	0.0	2.0	1.7
BKGD 1	0.018	0.019	20.644	0.197
BKGD 2	16.000	0.290	0.002	4.773
BKGD 3	5.000	0.008	0.003	0.106





Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?

- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots ?$

- Annihilation in core of Sun or Earth

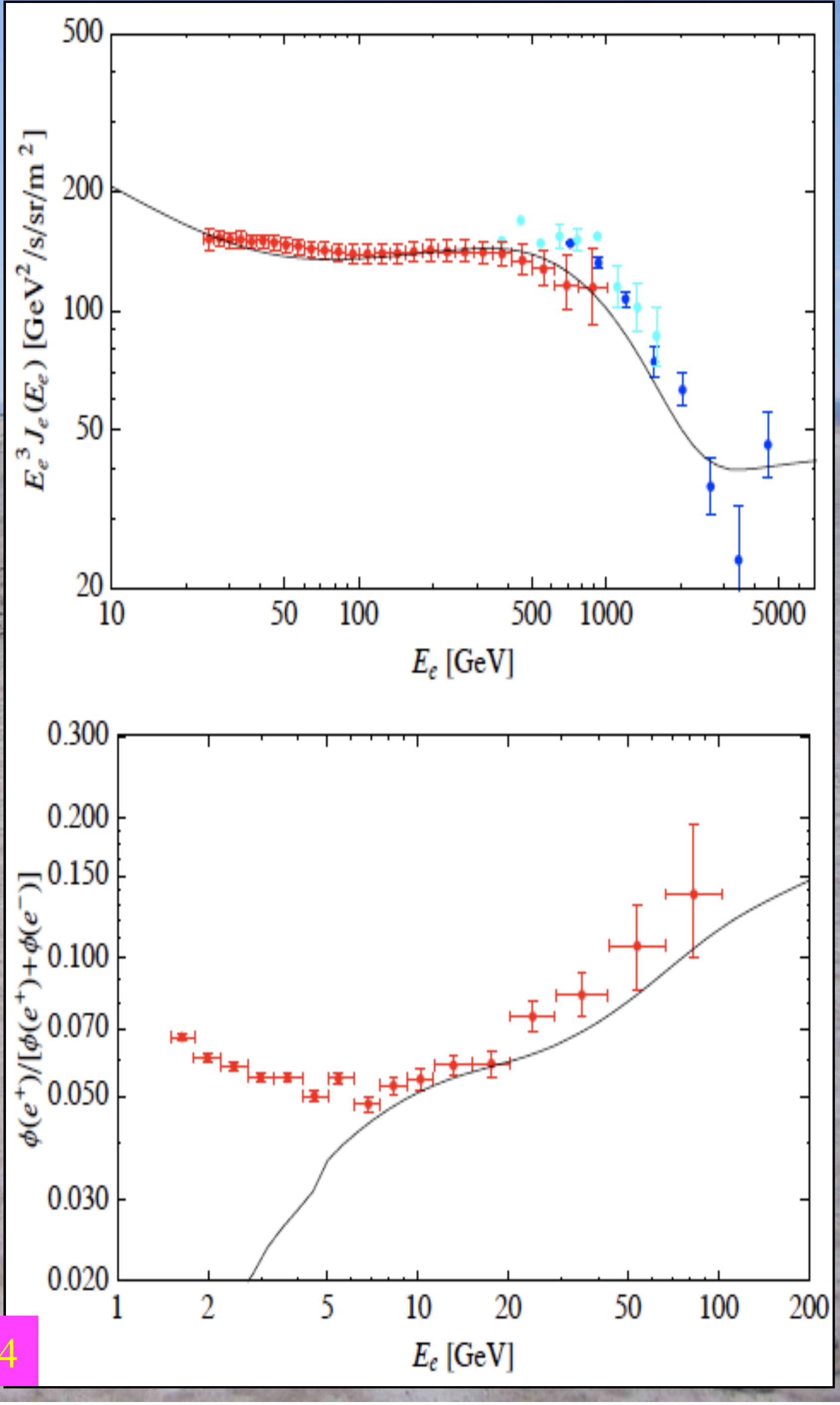
  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

- Scattering on nucleus in laboratory

  $\chi + A \rightarrow \chi + A$

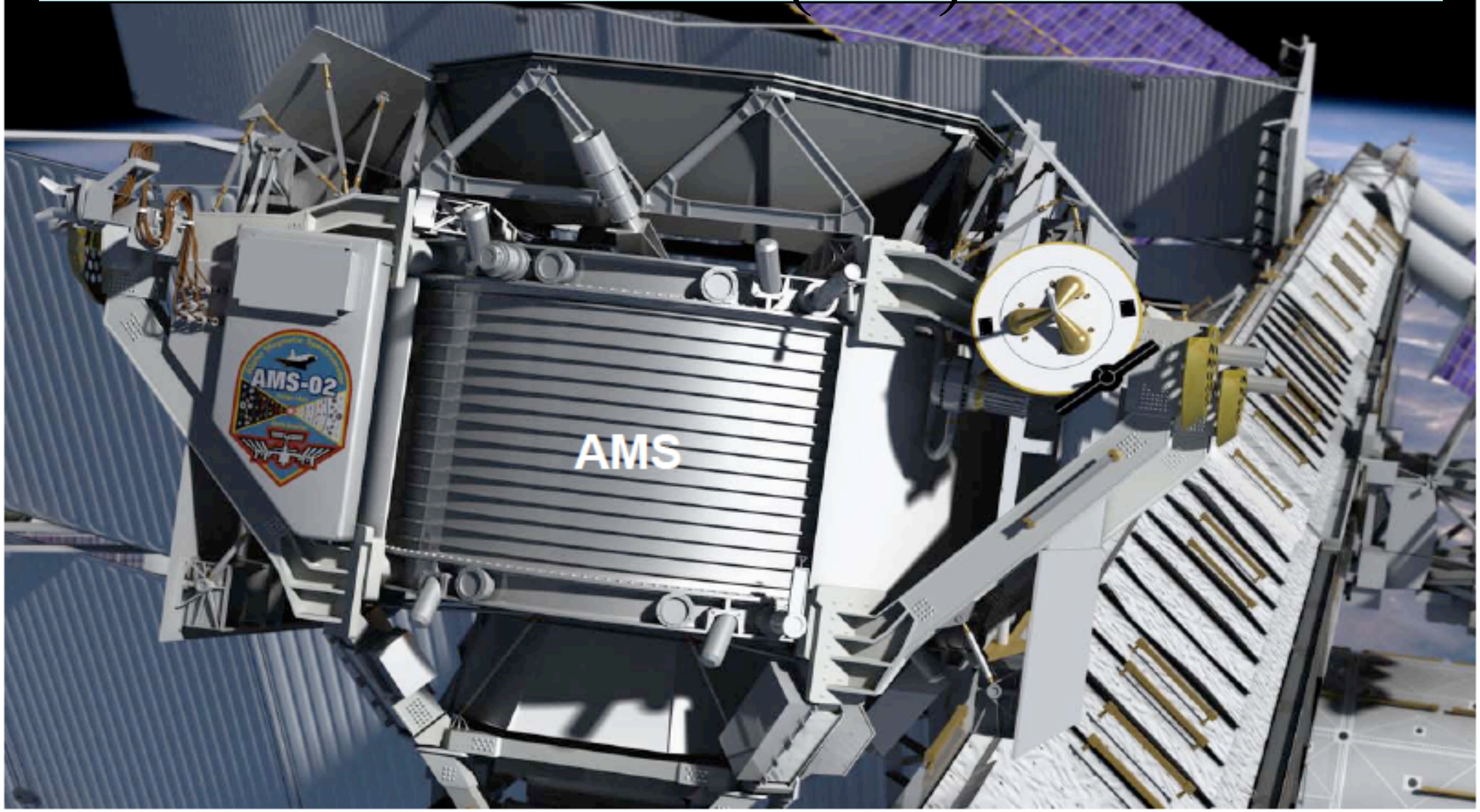
Anomalies in e^+/e^- Spectra?

- Shoulder in $e^+ + e^-$ spectrum?
- Rising e^+/e^- ratio
- Can be accommodated within uncertainties in cosmic-ray production, propagation
- SUSY interpretation difficult, unnecessary



Stawarz, Petrosian & Blandford: arXiv:0908.1094

AMS on the International Space Station (ISS)

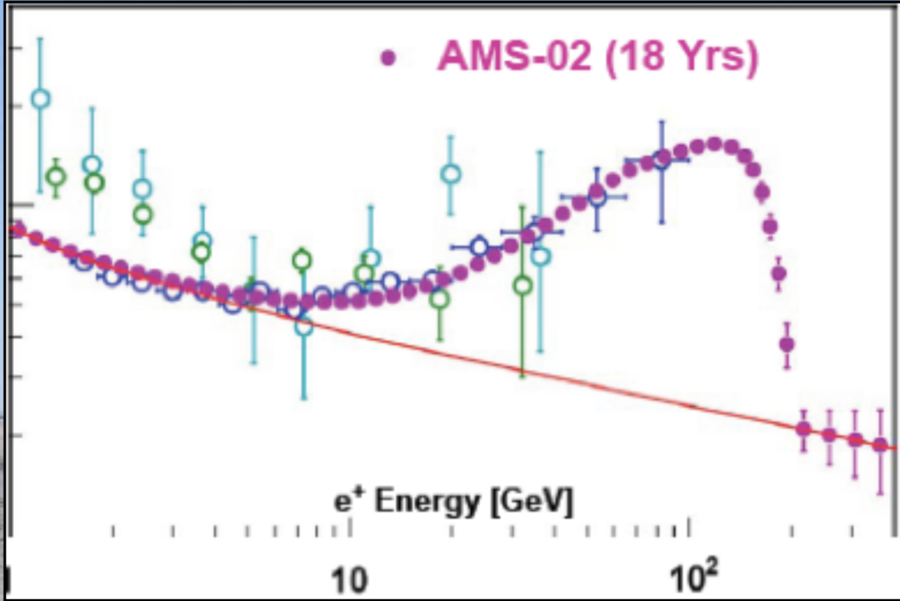


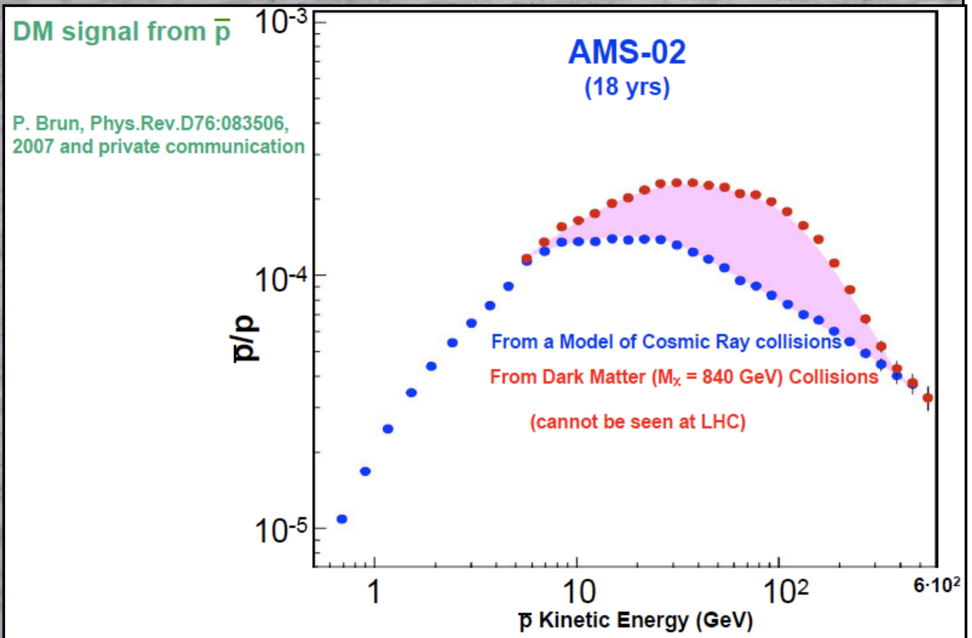
AMS on ISS for the lifetime of ISS: 18 or more years

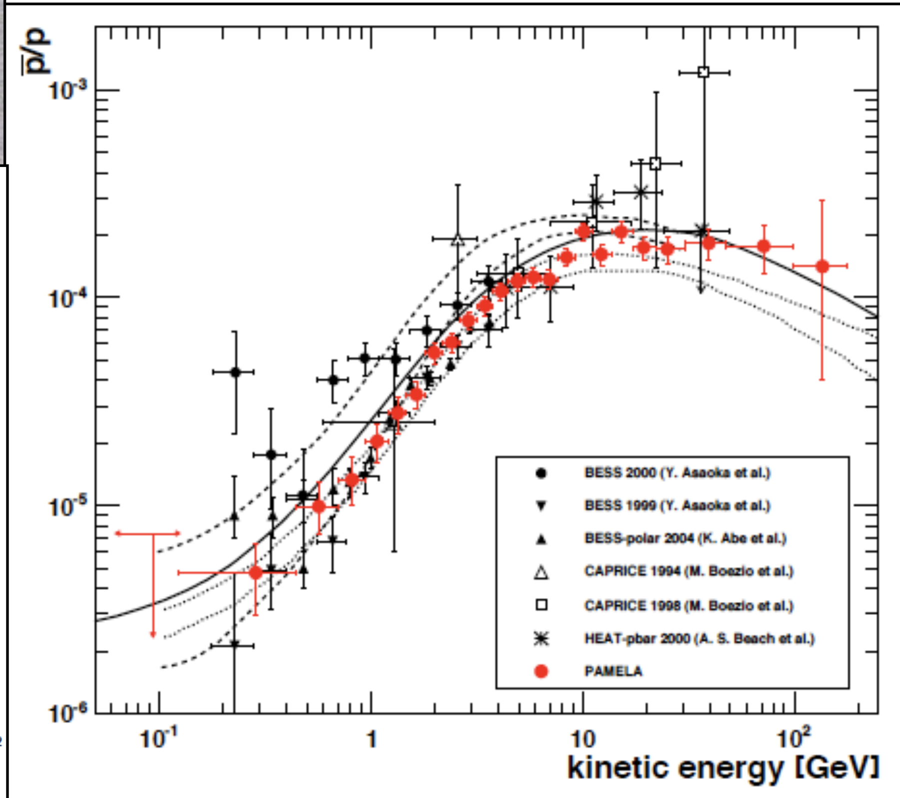
AMS on its way to the ISS

AMS and Dark Matter

- Measurement of e^+ spectrum to higher E
- Precision measurement of antiproton spectrum

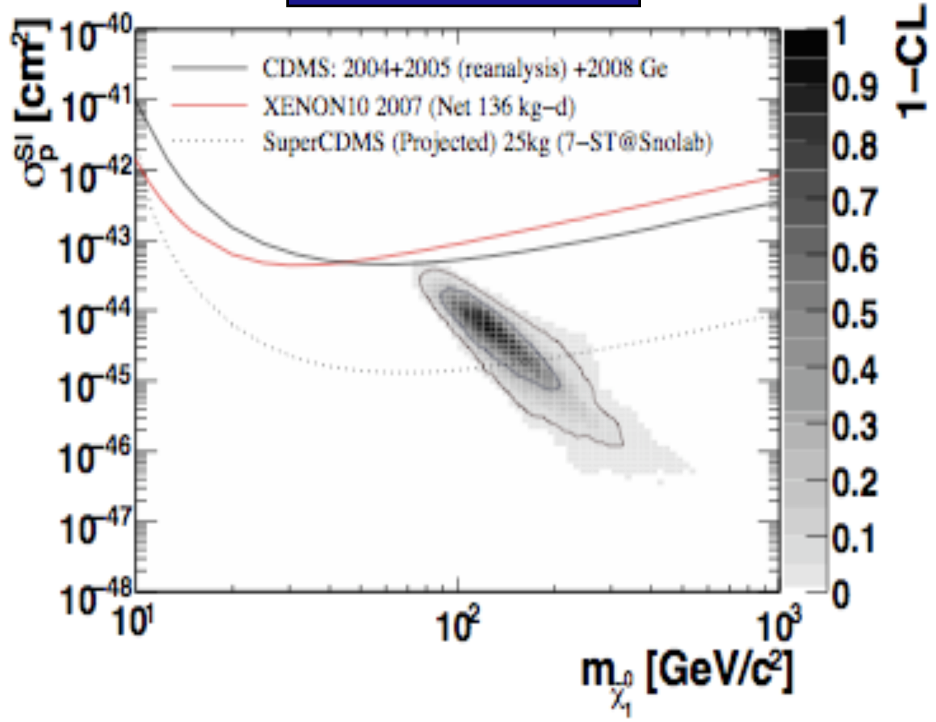




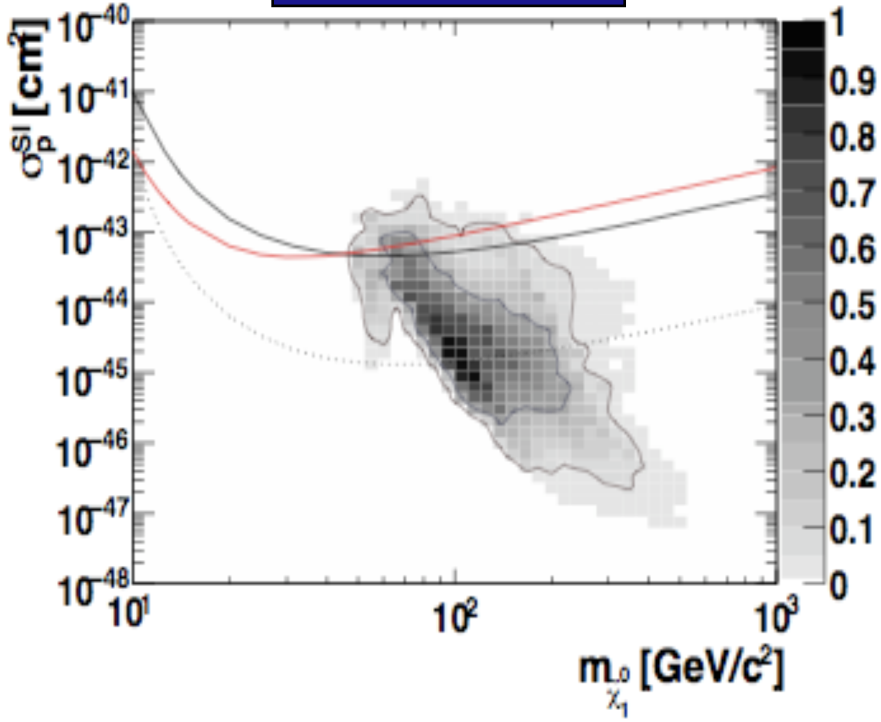


Elastic Scattering Cross Sections

CMSSM



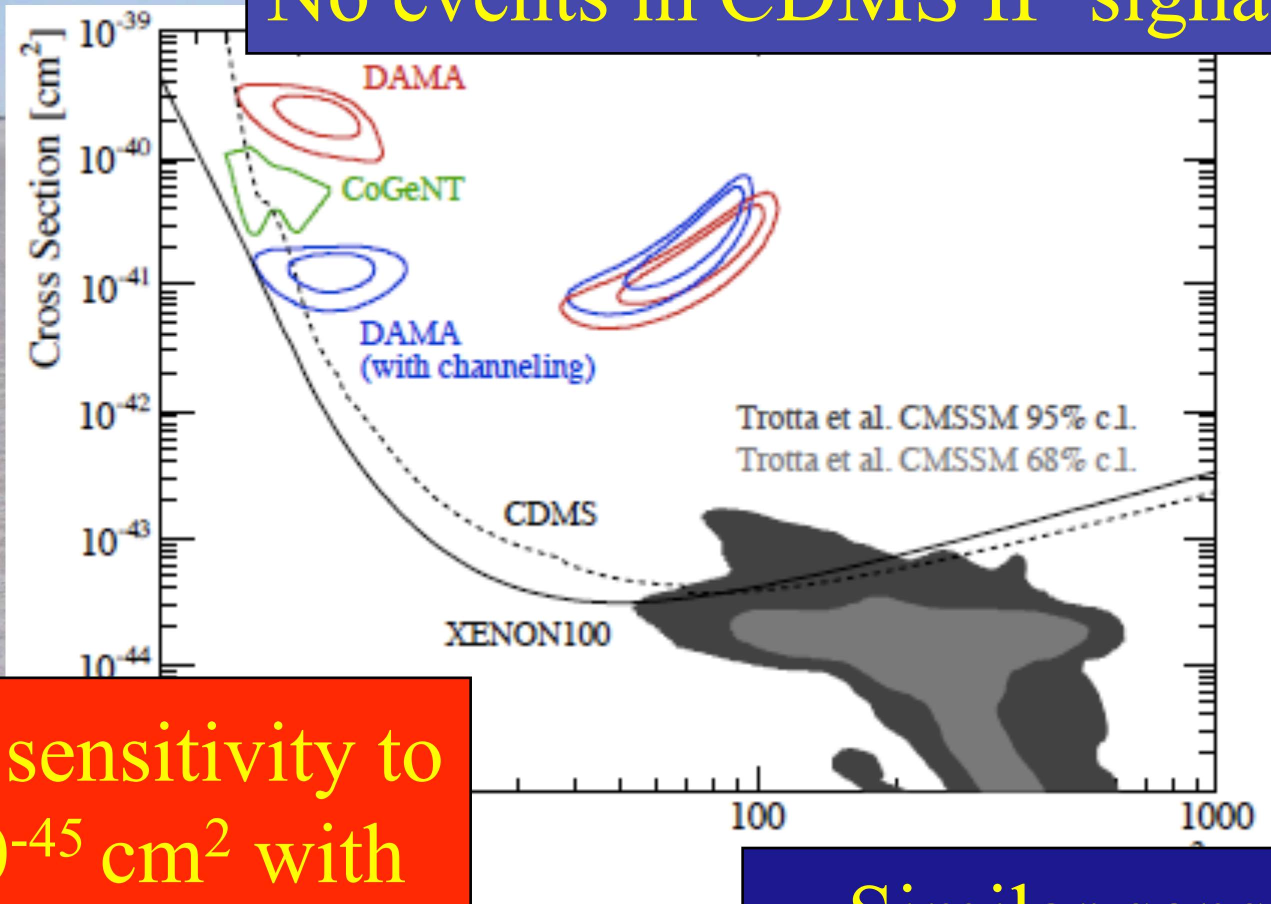
NUHM1



O.Buchmueller, JE et al: arXiv:0907.5568

Xenon100 Experiment

No events in CDMS II ‘signal’ region



Expect sensitivity to $\sim 10^{-45}$ cm^2 with 200 days of data

Aprile et al: arXiv:1005.0380

Similar sensitivity with 11 days of data

Long-Lived Gravitino & BBN

- Conventional Big-Bang Nucleosynthesis calculations agree well with D, 3He, 4He data
- Constraints on abundance of long-lived relic
  - Apparent discrepancy for Lithium:

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{halo}\star} = (1.23^{+0.34}_{-0.16}) \times 10^{-10}$$

  - Globular clusters: $(2.34 \pm 0.05) \times 10^{-10}$
  - BBN calculation: $(5.12^{+0.71}_{-0.62}) \times 10^{-10}$
- **Can discrepancy be removed by decays of long-lived relic, e.g., gravitino?**

Cyburt, JE, Fields, Luo, Olive & Spanos: arXiv:1007.4173

Nuclear Reactions

- Relevant interactions of non-thermal particles from relic decay showers
- Incorporate errors in measurements
- Make global likelihood analysis

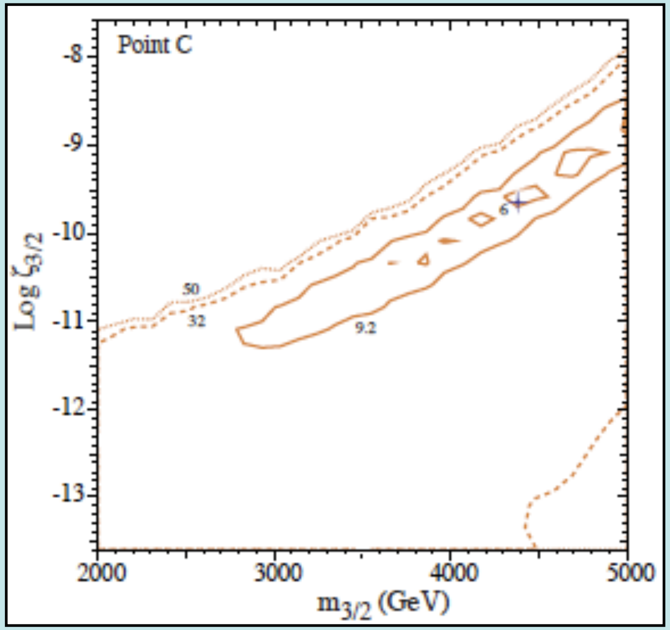
Table 1: Nuclear reactions of non-thermal particles, including the most important of the estimated uncertainties in the cross sections.

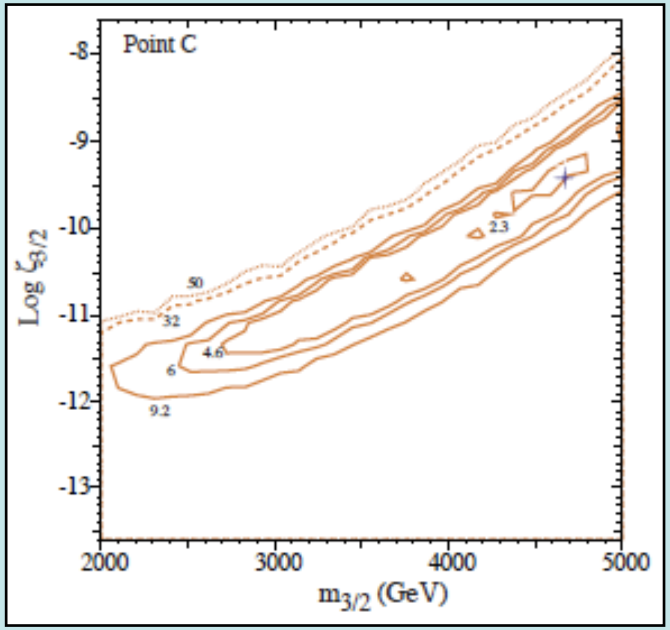
Code	Reaction	Uncertainty ϵ	Reference
1	$p^4\mathrm{He} \to d^3\mathrm{He}$		Meyer [34]
2	$p^4\mathrm{He} \to np^3\mathrm{He}$	20%	Meyer [34]
3	$p^4\mathrm{He} \to ddp$	40%	Meyer [34]
4	$p^4\mathrm{He} \to dnpp$	40%	Meyer [34]
5	$d^4\mathrm{He} \to {}^6\mathrm{Li}\gamma$		Mohr [35]
6	$t^4\mathrm{He} \to {}^6\mathrm{Li}n$	20%	Cyburt et al. [14]
7	${}^3\mathrm{He}^4\mathrm{He} \to {}^6\mathrm{Li}p$	20%	Cyburt et al. [14]
8	$t^4\mathrm{He} \to {}^7\mathrm{Li}\gamma$		Cyburt [27]
9	${}^3\mathrm{He}^4\mathrm{He} \to {}^7\mathrm{Be}\gamma$		Cyburt and Davids [36]
10	$p^6\mathrm{Li} \to {}^3\mathrm{He}^4\mathrm{He}$		Cyburt et al. [14]
11	$n^6\mathrm{Li} \to t^4\mathrm{He}$		Cyburt et al. [14]
12	$pn \to d\gamma$		Ando, Cyburt, Hong, and Hyun [37]
13	$pd \to {}^3\mathrm{He}\gamma$		Cyburt et al. [14]
14	$pt \to n^3\mathrm{He}$		Cyburt [27]
15	$p^6\mathrm{Li} \to {}^7\mathrm{Be}\gamma$		Cyburt et al. [14]
16	$p^7\mathrm{Li} \to {}^8\mathrm{Be}\gamma$		Cyburt et al. [14]
17	$p^7\mathrm{Be} \to {}^8\mathrm{B}\gamma$		Cyburt et al. [32]
18	$np \to d\gamma$		Ando, Cyburt, Hong, and Hyun [37]
19	$nd \to t\gamma$		Cyburt et al. [14]
20	$n^4\mathrm{He} \to dt$		Meyer [34]
21	$n^4\mathrm{He} \to npt$	20%	Meyer [34]
22	$n^4\mathrm{He} \to ddn$	40%	Meyer [34]
23	$n^4\mathrm{He} \to dnnp$	40%	Meyer [34]
24	$n^6\mathrm{Li} \to {}^7\mathrm{Li}\gamma$		Cyburt et al. [14]
25	n (thermal)		—
26	$n^7\mathrm{Be} \to p^7\mathrm{Li}$		Cyburt et al. [14]
27	$n^7\mathrm{Be} \to {}^4\mathrm{He}^4\mathrm{He}$		Cyburt et al. [32]
28	$p^7\mathrm{Li} \to {}^4\mathrm{He}^4\mathrm{He}$		Cyburt et al. [14]
29	$n\pi^+ \to p\pi^0$		Meyer [34]
30	$p\pi^- \to n\pi^0$		Meyer [34]
31	$p^4\mathrm{He} \to ppt$	20%	Meyer [34]
32	$n^4\mathrm{He} \to nn^3\mathrm{He}$	20%	Meyer [34]
33	$n^4\mathrm{He} \to nnnpp$		Meyer [34]
34	$p^4\mathrm{He} \to nnppp$		Meyer [34]
35	$p^4\mathrm{He} \to N^4\mathrm{He}\pi$		Meyer [34]
36	$n^4\mathrm{He} \to N^4\mathrm{He}\pi$		Meyer [34]

Cyburt, JE, Fields, Luo, Olive & Spanos: arXiv:1007.4173

Improvements in Fit to BBN Data

- Standard BBN: $\chi^2 = 31.7$
- Best fit to halo Li data: $\chi^2 \sim 5.5$





- Best fit to globular cluster Li data: $\chi^2 \sim 2.7$
- Allowing for higher D/H error: $\chi^2 \sim 1.1$

Cyburt, JE, Fields, Luo, Olive & Spanos: arXiv:1007.4173

Conversation with Mrs Thatcher: 1982