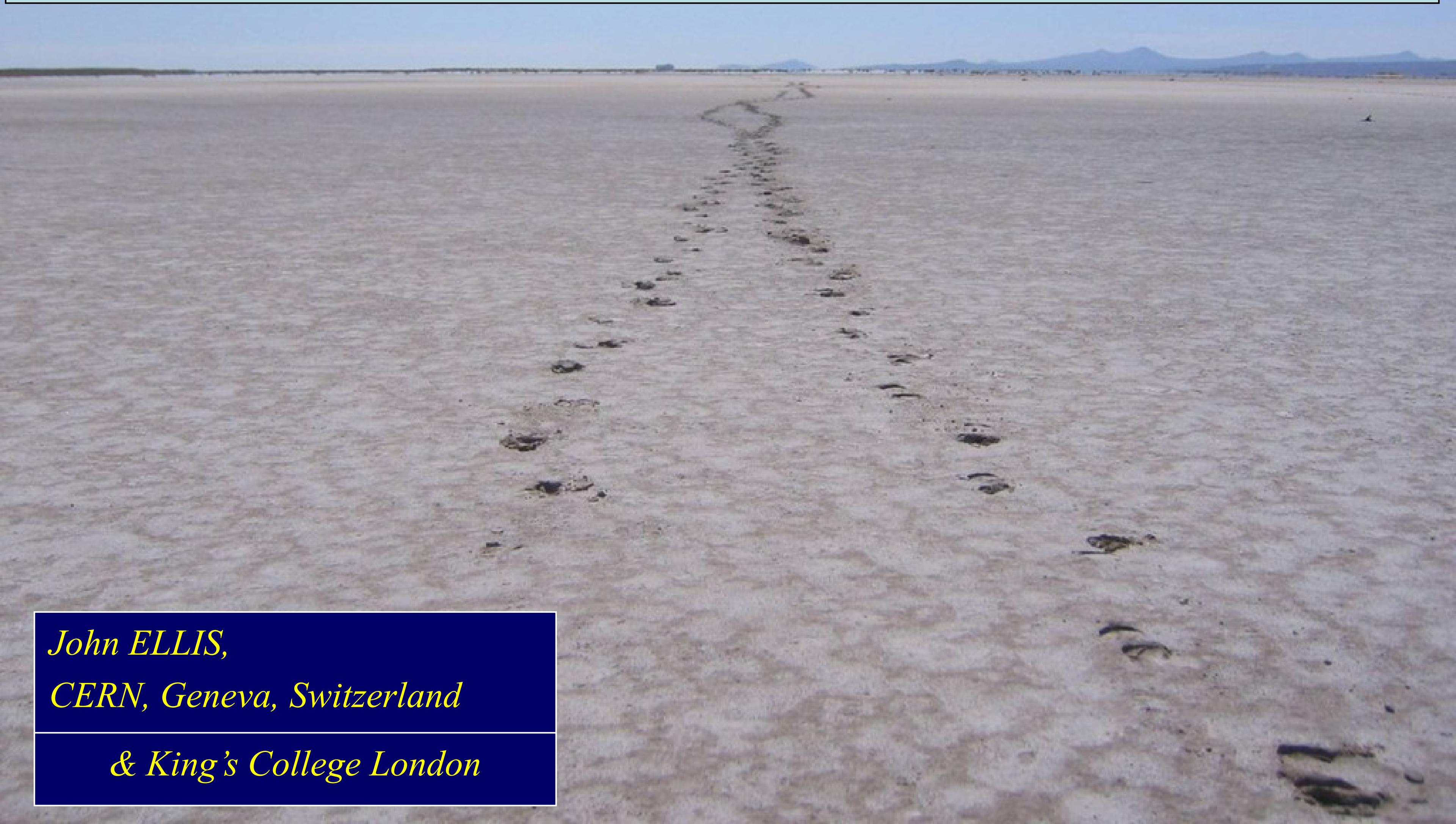
Outstanding Questions:
Physics beyond the Standard Model



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

The ‘Standard Model’

= Cosmic DNA

The matter particles

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L E_R	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $e_R^- , \mu_R^- , \tau_R^-$	$(\mathbf{1},\mathbf{2},-1)$ $(\mathbf{1},\mathbf{1},-2)$
Q_L U_R D_R	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$ u_R , c_R , t_R d_R , s_R , b_R	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} \\ &+ i\bar{\psi} \not{D}\psi + h.c. \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

gauge interactions

matter fermions

No direct

Experimental evidence

Parameters of the Standard Model

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase
- Yukawa interactions:
  - 3 charged-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ
- **Total: 19 parameters**

Unification?

Flavour?

Neutrino masses?

Mass?

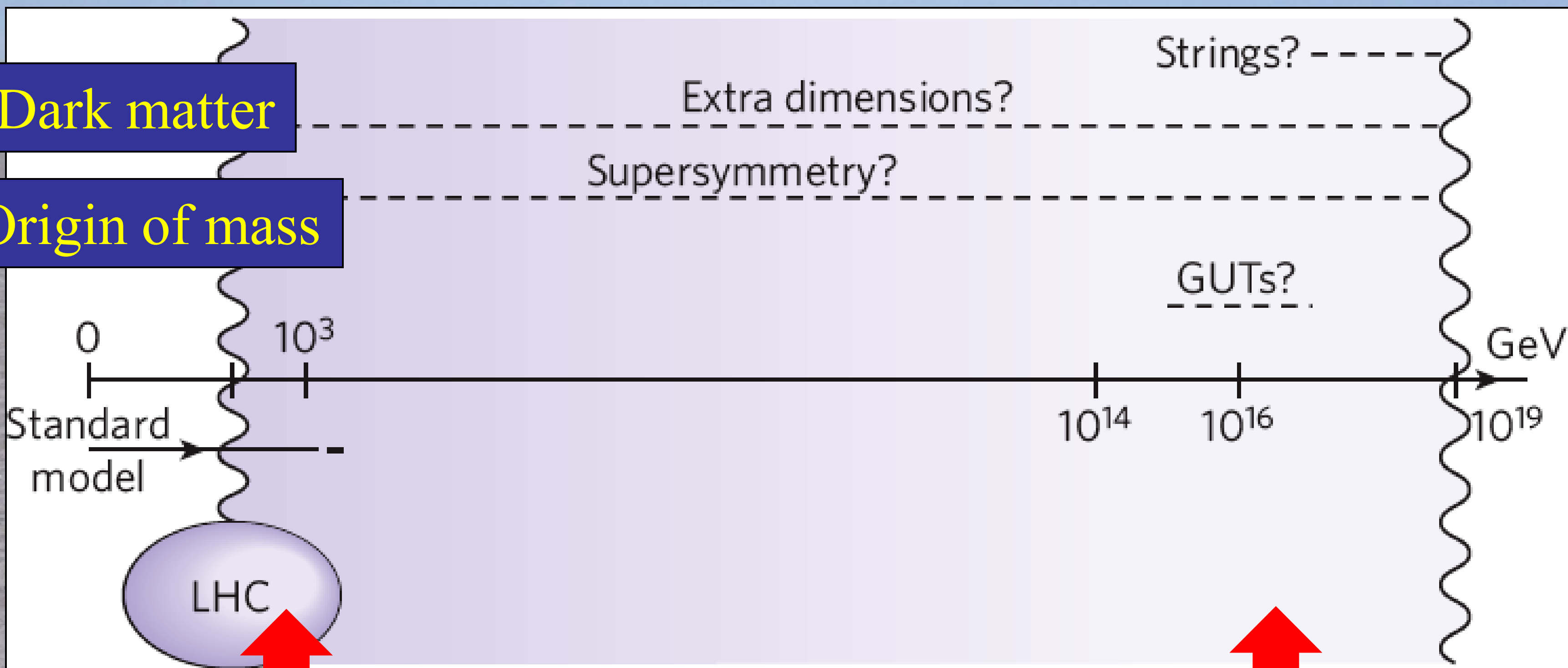
Open Questions beyond the Standard Model

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

At what Energy is the New Physics?

Dark matter

Origin of mass



A lot accessible to the LHC

Some accessible only via astrophysics & cosmology

Why do Things Weigh?

Newton:

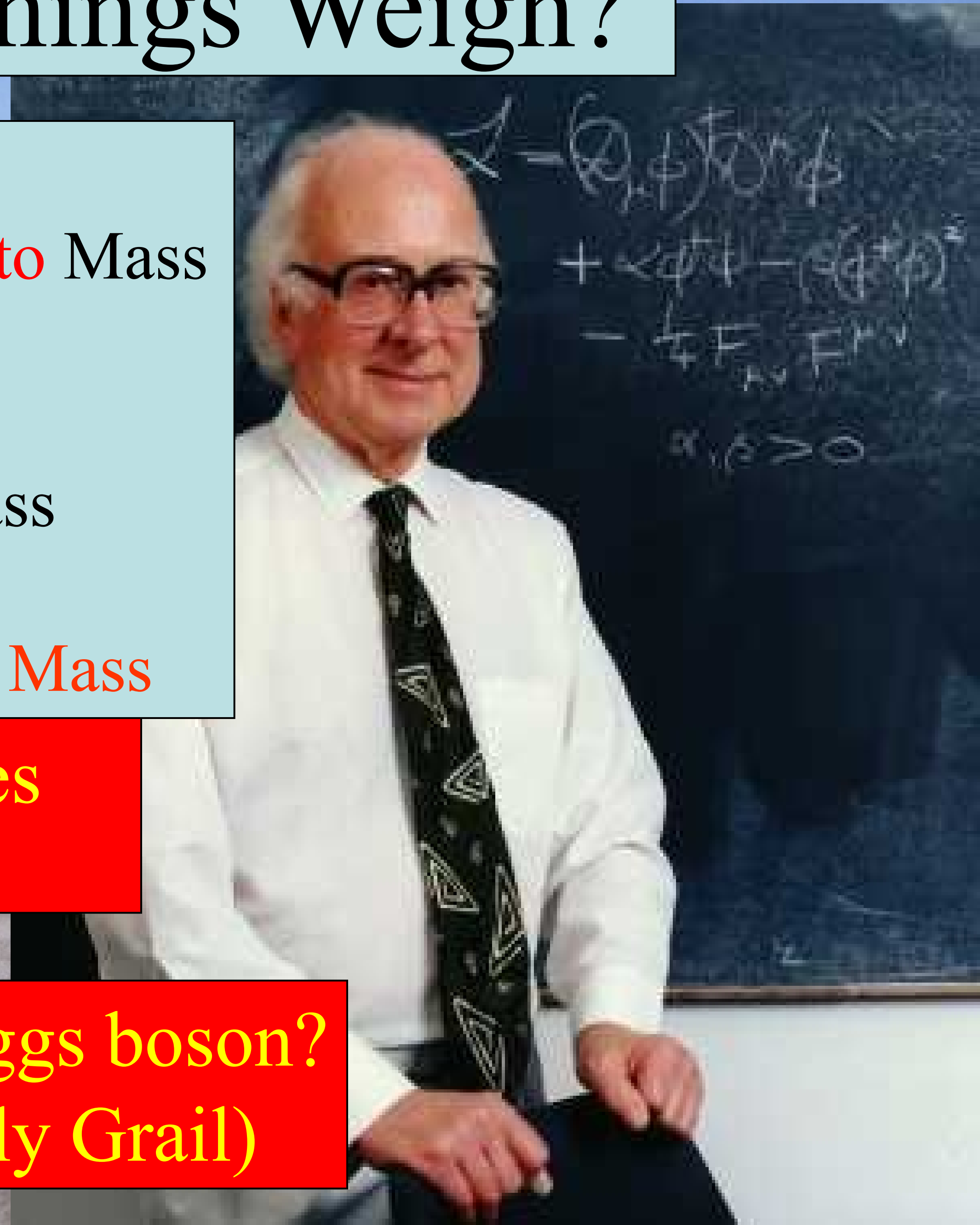
Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?



Are masses due to Higgs boson?
(the physicists' Holy Grail)

Think of a Snowfield

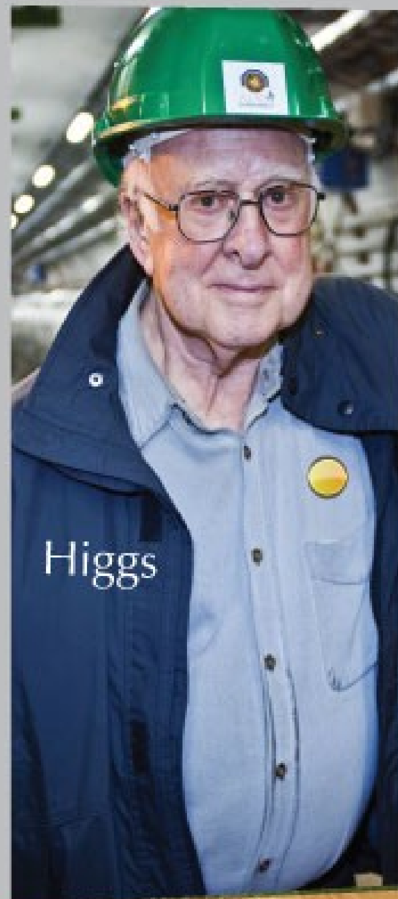
Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

The LHC will look for the snowflake: The Higgs Boson

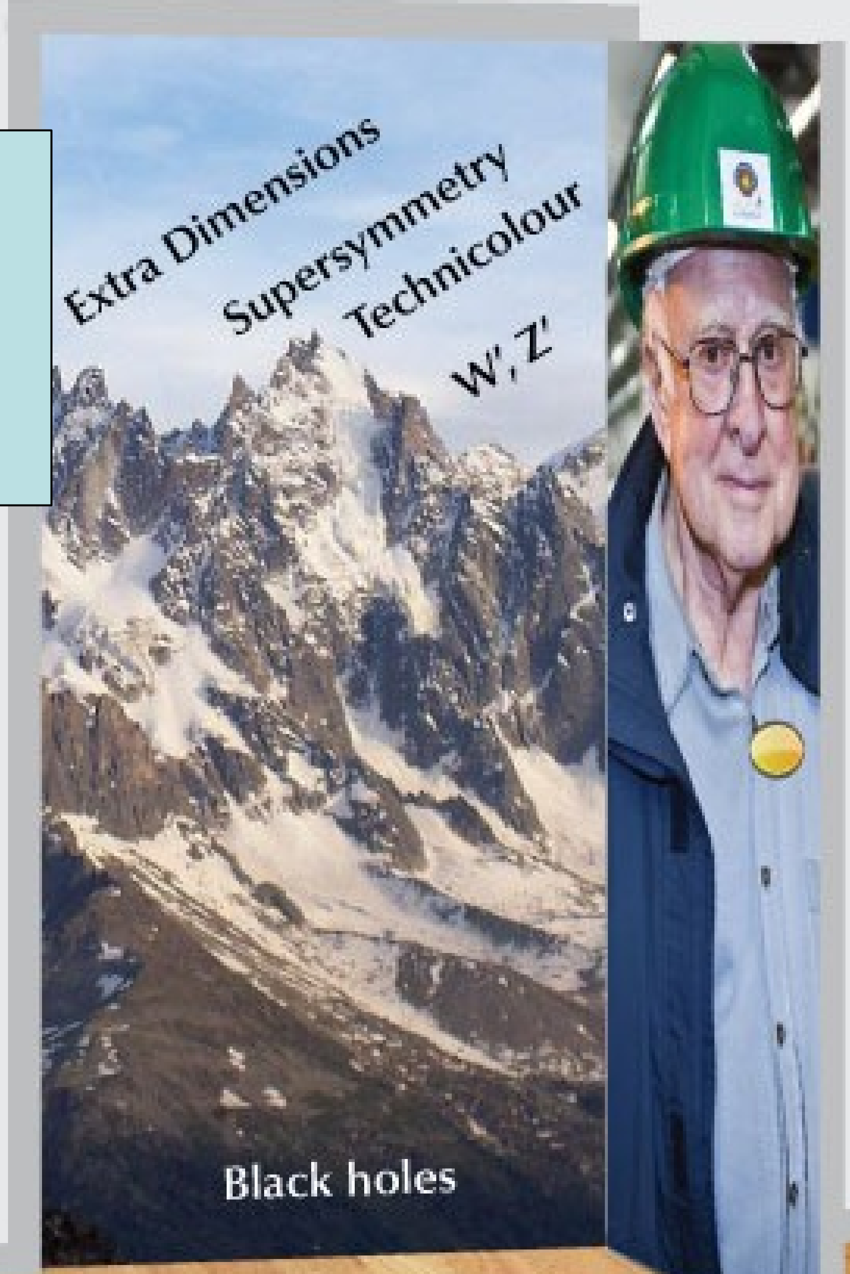
Hiker sinks deep,
moves very slowly:
Particle with large mass

What lies Beyond?

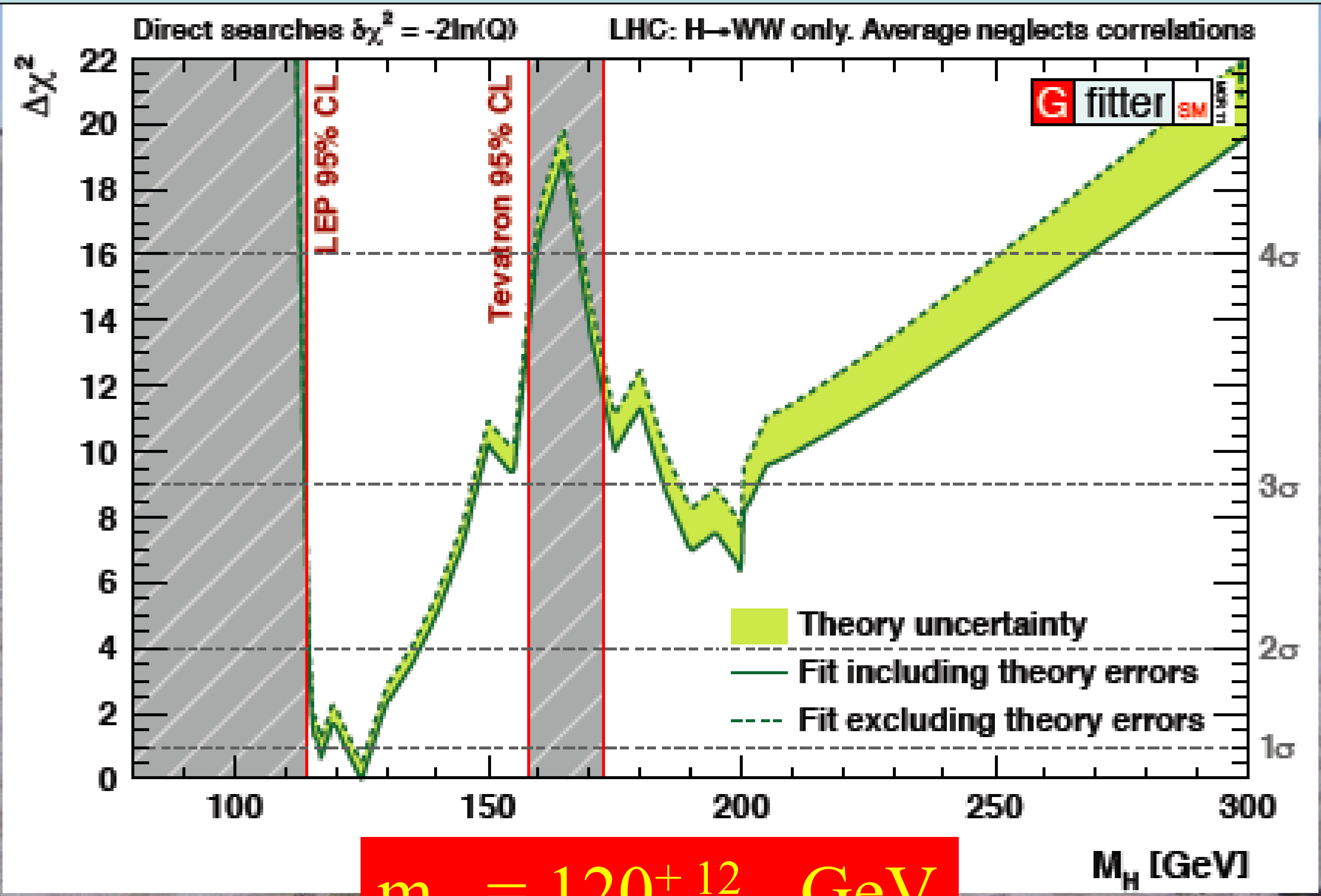


… Open The Door

What lies Beyond?



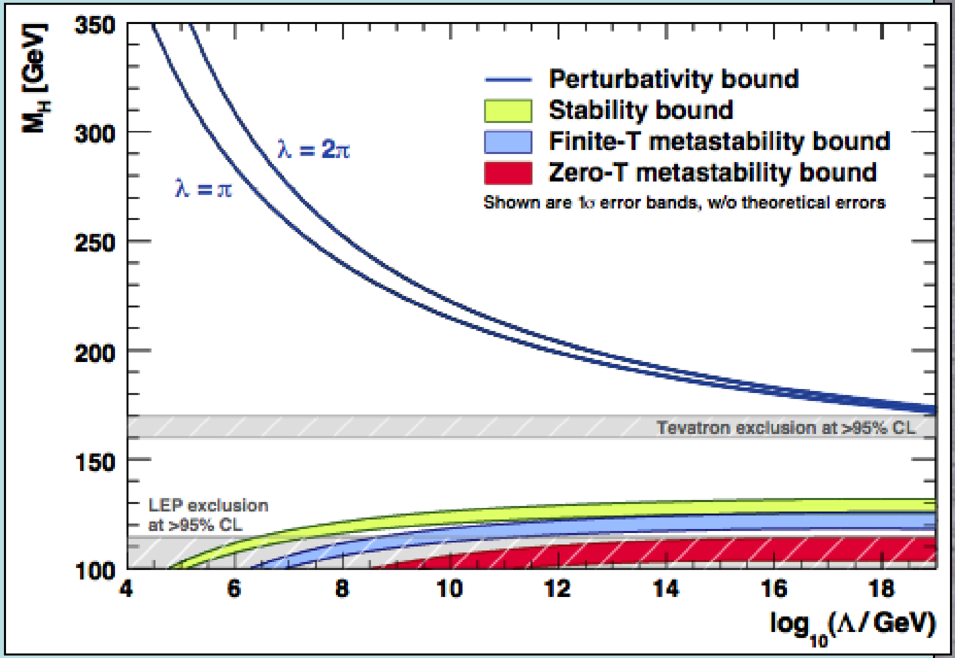
Combining the Information from High-Energy and Precision Data



$m_H = 120^{+12}_{-5}$ GeV

Theoretical Constraints on Higgs Mass

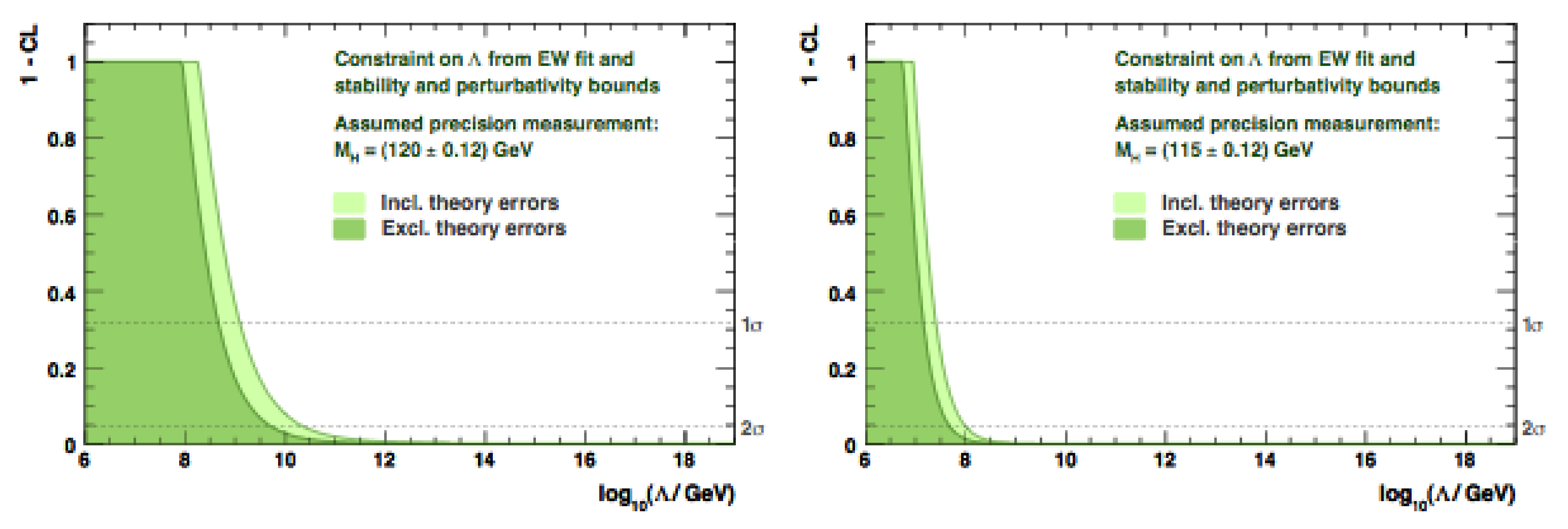
- Large → large self-coupling → blow up at low energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable



- Bounds on Higgs mass depend on Λ

The LHC will Tell the Fate of the SM

Examples with LHC measurement of m_H = 120 or 115 GeV



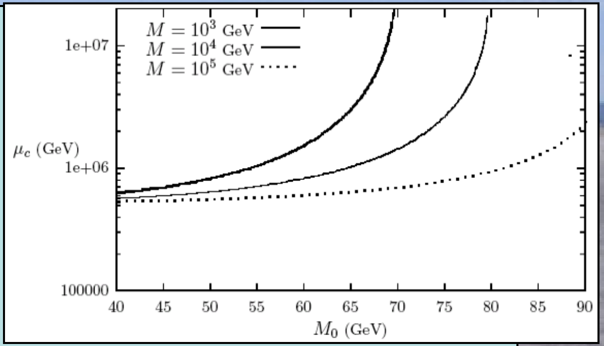
Espinosa, JE, Giudice, Hoecker, Riotto

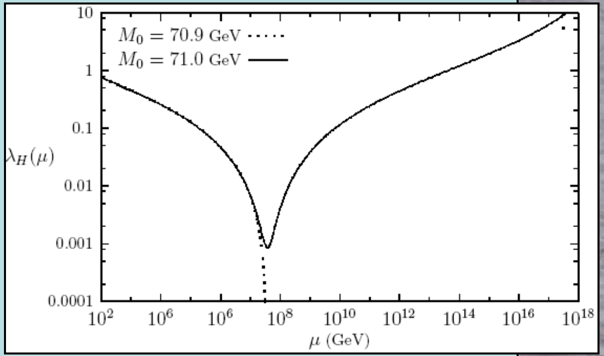
How to Stabilize a Light Higgs Boson?

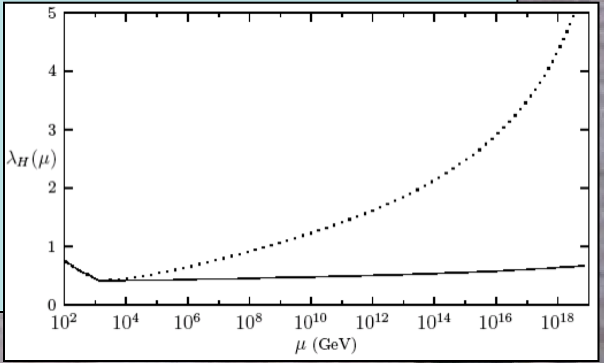
- Top quark destabilizes potential: introduce stop-like scalar:

$$\mathcal{L} \supset \; M^2|\phi|^2 + \frac{M_0}{v^2}|H|^2\,|\phi|^2$$

- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  – just like Higgsinos
- Very like **Supersymmetry!**







JE & D. Ross

The Stakes in the Higgs Search

- How is particle symmetry broken?
- Is there an elementary scalar field?
- What is the fate of the Standard Model?
- Did mass appear when the Universe was a picosecond old?
- Did Higgs help create the matter in the Universe?
- Did a related inflaton make the Universe so big and old?
- Why is there so little dark energy?

Open Questions beyond the Standard Model

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

Where does the Matter come from?

Dirac predicted existence of antimatter:
- **same mass**
- **opposite internal properties:**
  - **electric charge, …**

Discovered in cosmic rays
Studied using accelerators
Used in medical diagnosis

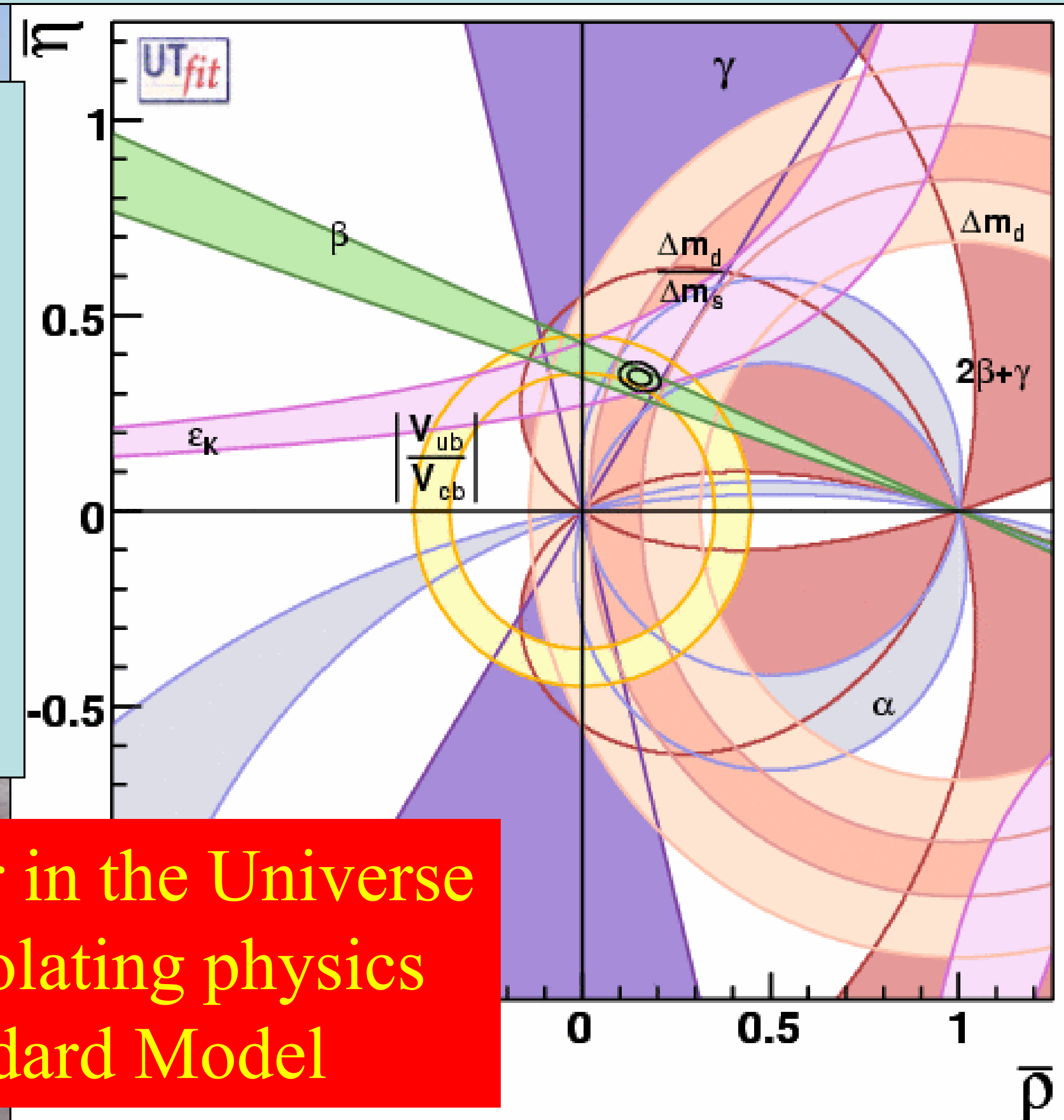
Matter and antimatter not quite equal and opposite: WHY

Is this why the Universe contains matter, not antimatter?

Will experiments reveal matter was created?

Matter-Antimatter Asymmetry

- Standard Model successful at present
- New physics is well hidden
- Search in rare K, D, B decays



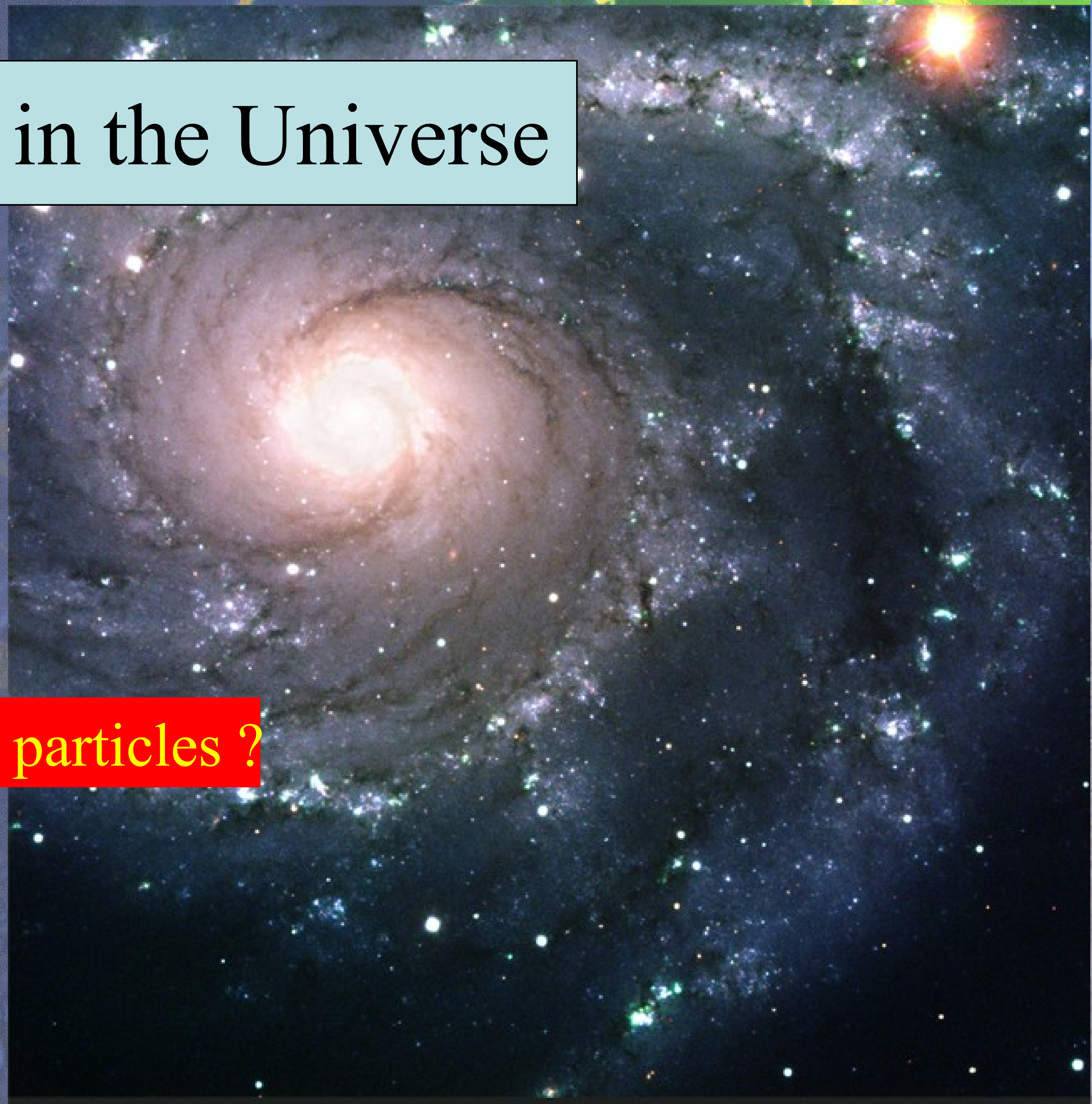
Generating the matter in the Universe requires new CP-violating physics beyond the Standard Model

Dark Matter in the Universe

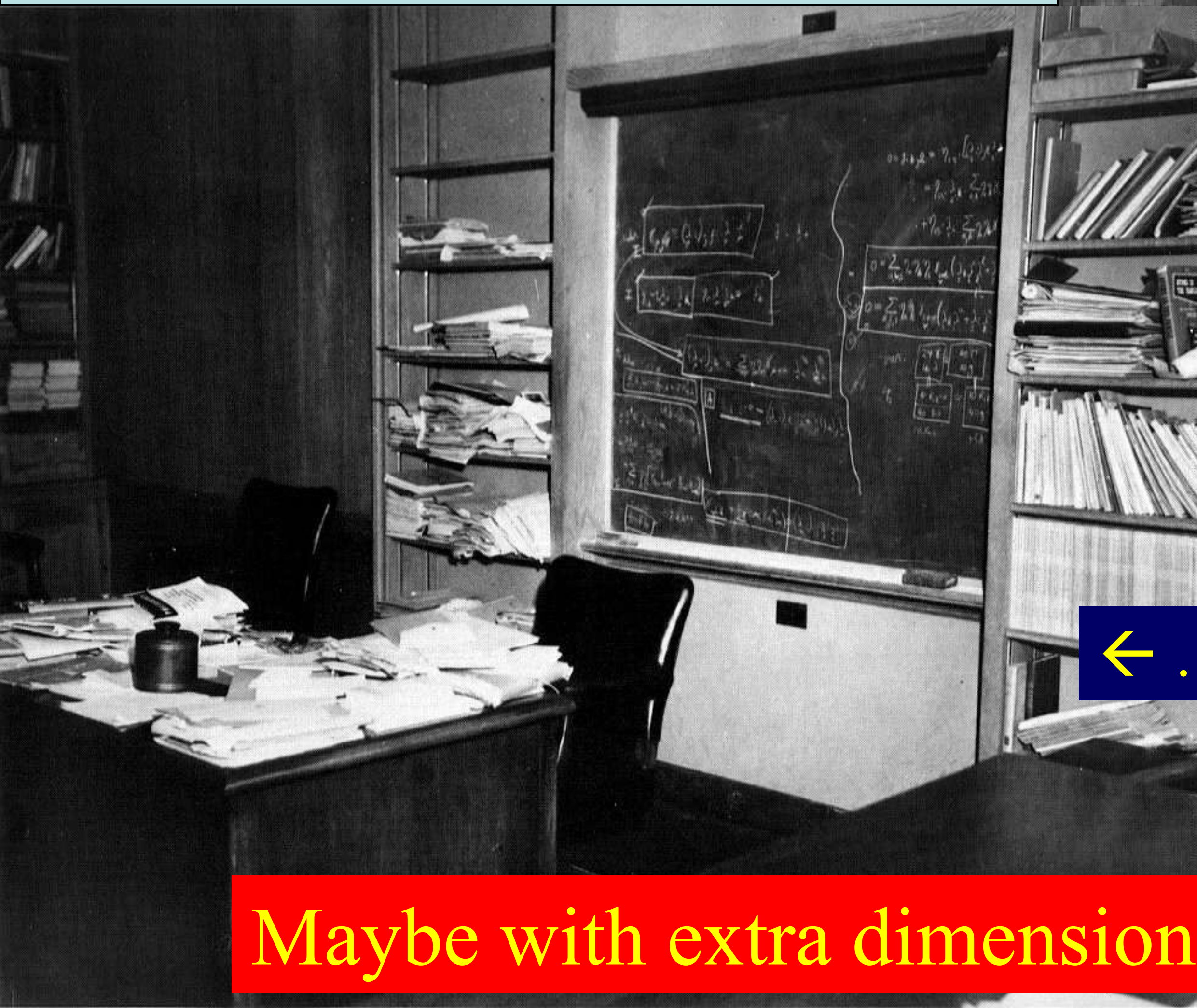
Astronomers say that most of the matter in the Universe is invisible
Dark Matter

'Supersymmetric' particles ?

We shall look for them with the LHC



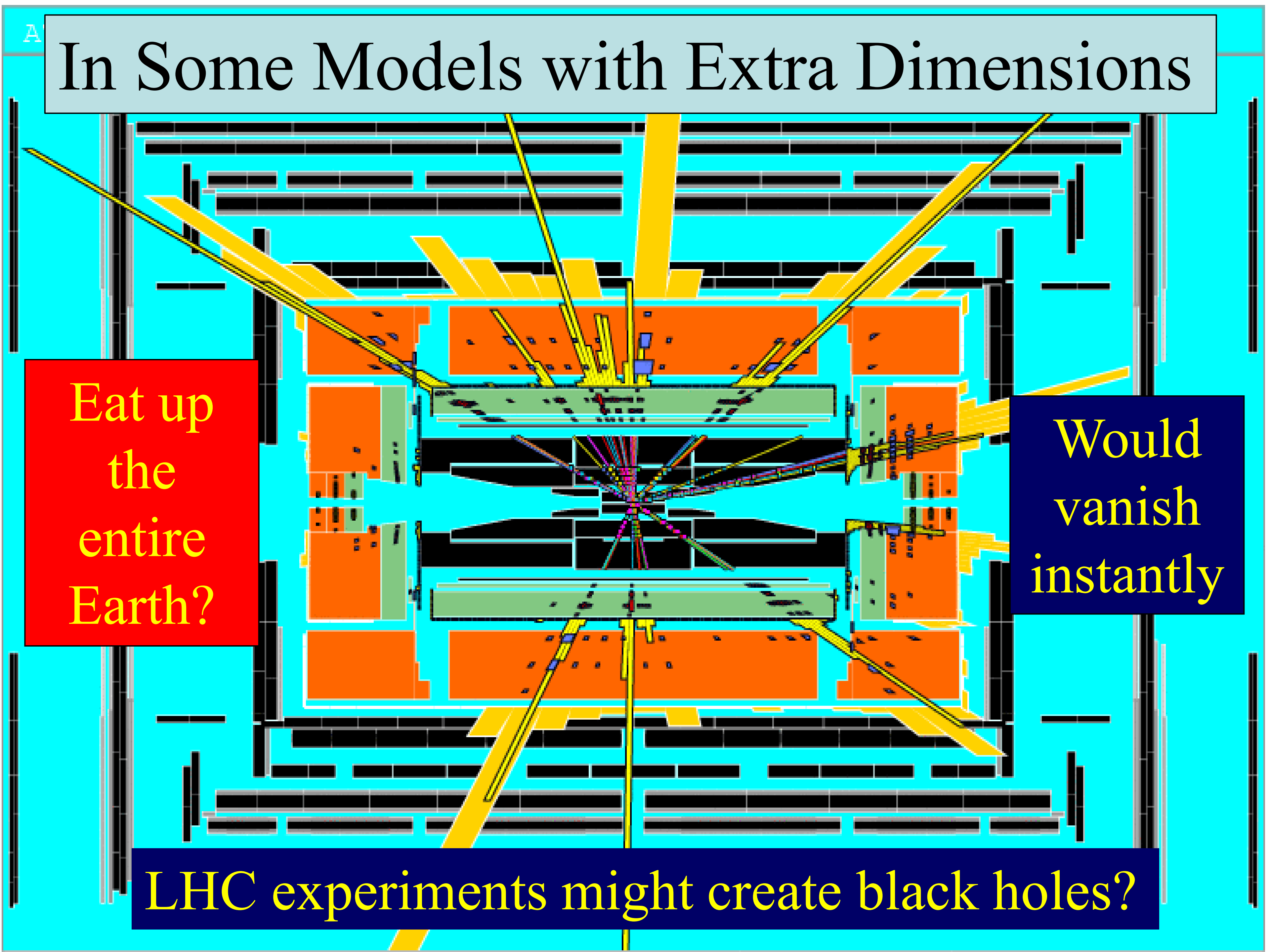
Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

Maybe with extra dimensions of space?

In Some Models with Extra Dimensions



Eat up the entire Earth?

Would vanish instantly

LHC experiments might create black holes?

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

Supersymmetry?

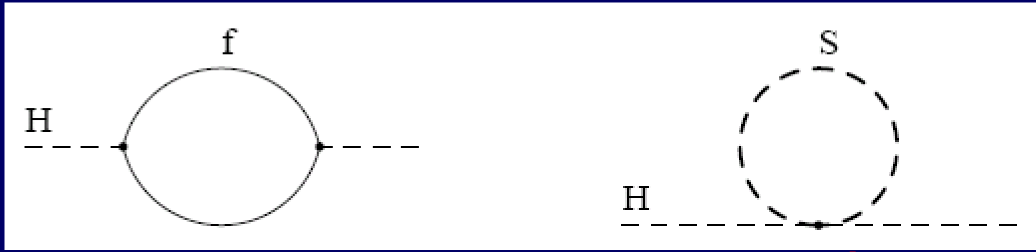
- Would unify matter particles and force particles
- Related particles spinning at different rates

  0 - ½ - 1 - 3/2 - 2

  Higgs - Electron - Photon - Gravitino – Graviton
- Many phenomenological motivations
  - Would help fix particle masses
  - Would help unify forces
  - Predicts light Higgs boson
  - Could fix discrepancy in $g_\mu - 2$
- **Could provide dark matter for the astrophysicists and cosmologists**

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

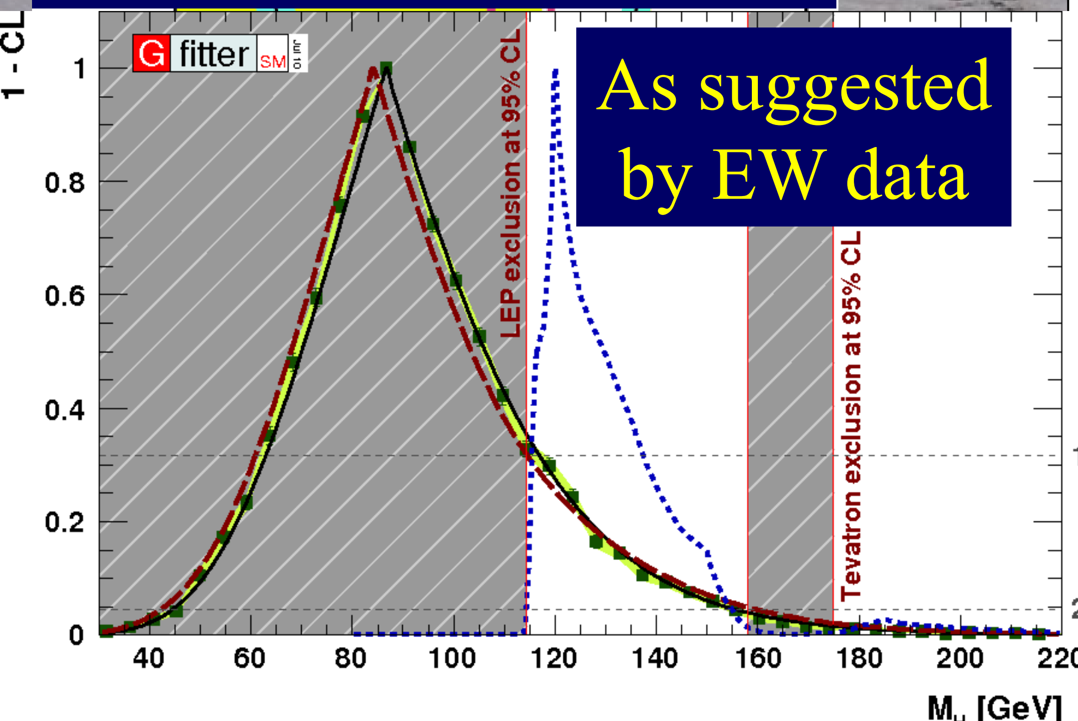
$\lambda_S = y_f^2$ x 2 **Supersymmetry!**

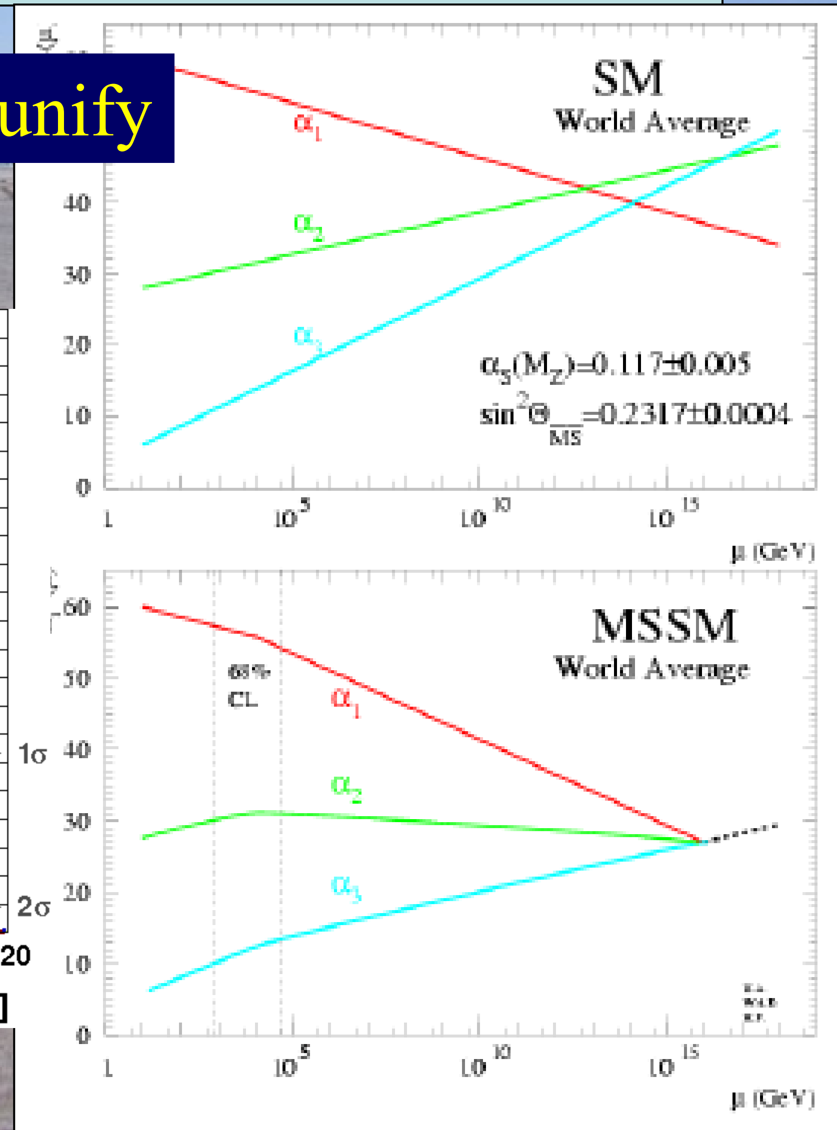
Reasons to like Supersymmetry

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV

As suggested by EW data





Lightest Sparticle as Dark Matter

- Stable in many models because of conservation of R parity:

  Fayet

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

  where S = spin, L = lepton #, B = baryon #
- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles
- Lightest supersymmetric particle (LSP) stable
- Present in Universe today as relic from Big Bang

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

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 400 GeV

- Indirect constraints

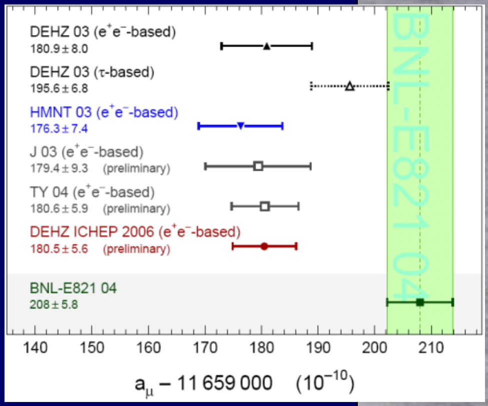
  Higgs > 114 GeV, $b \to s\,\gamma$

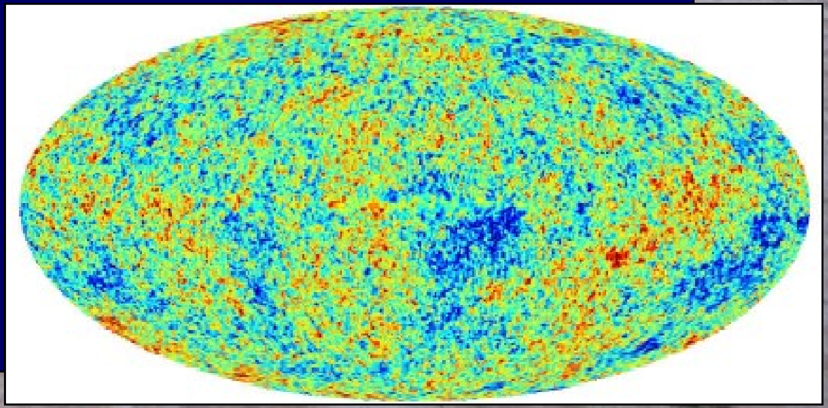
- Density of dark matter

  lightest sparticle χ:

  $0.094 < \Omega_\chi h^2 < 0.124$

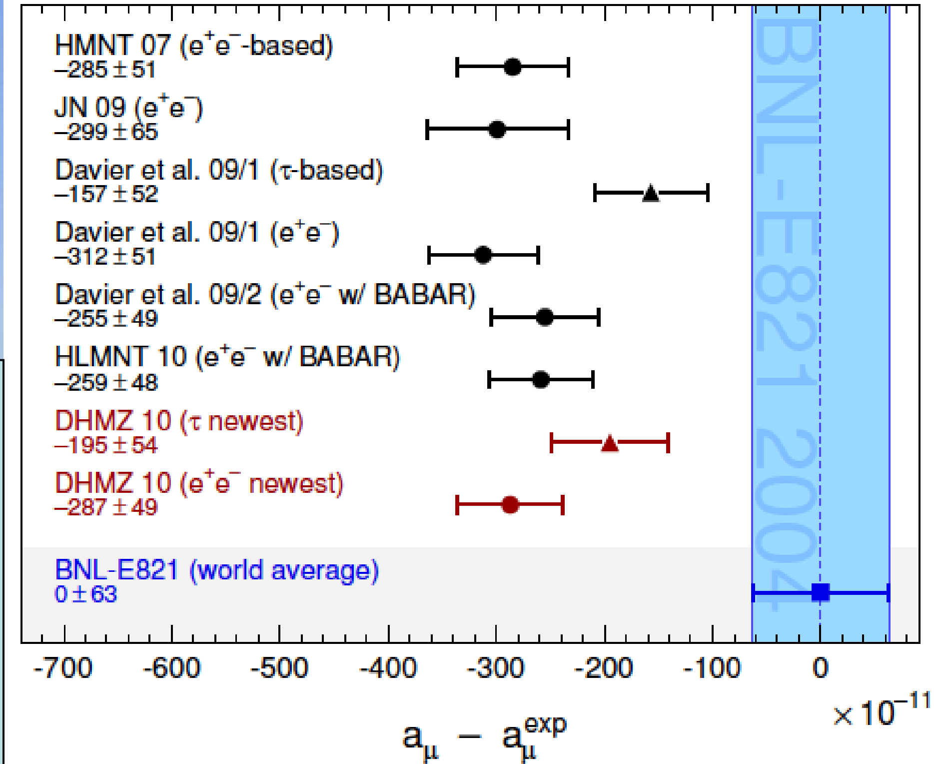
3 σ effect in $g_\mu - 2$?

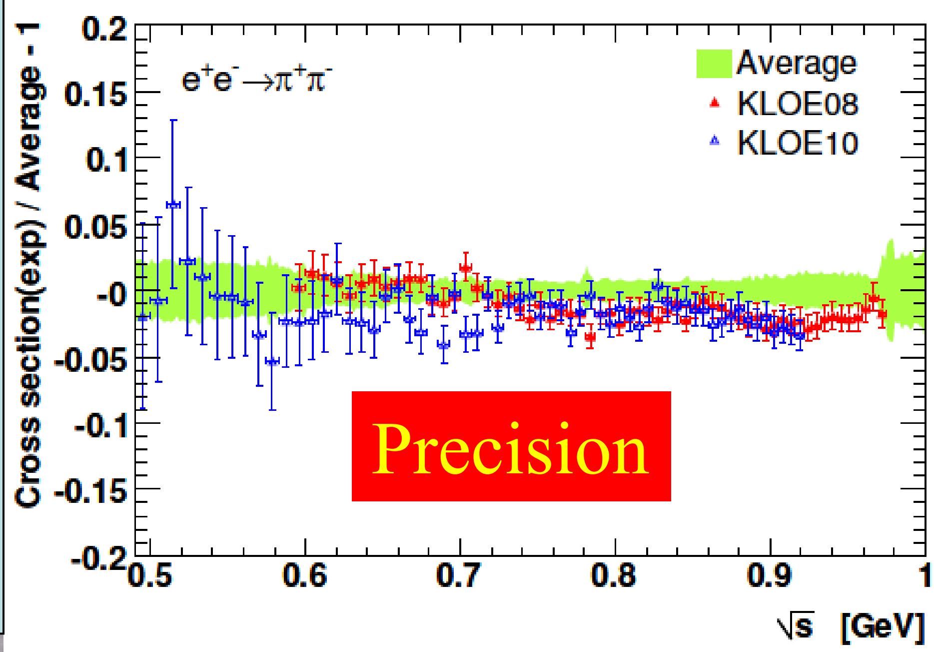




Quo Vadis g_μ - 2?

- Strong discrepancy between BNL experiment and e^+e^- data:
  - now ~ 3.6 σ
- Decent agreement between e^+e^- experiments
- Increased discrepancy between BNL experiment and τ decay data
  - now ~ 2.4 σ
- Convergence between e^+e^- experiments and τ decay data?
- **More credibility?**





Pre-LHC Constraints on CMSSM

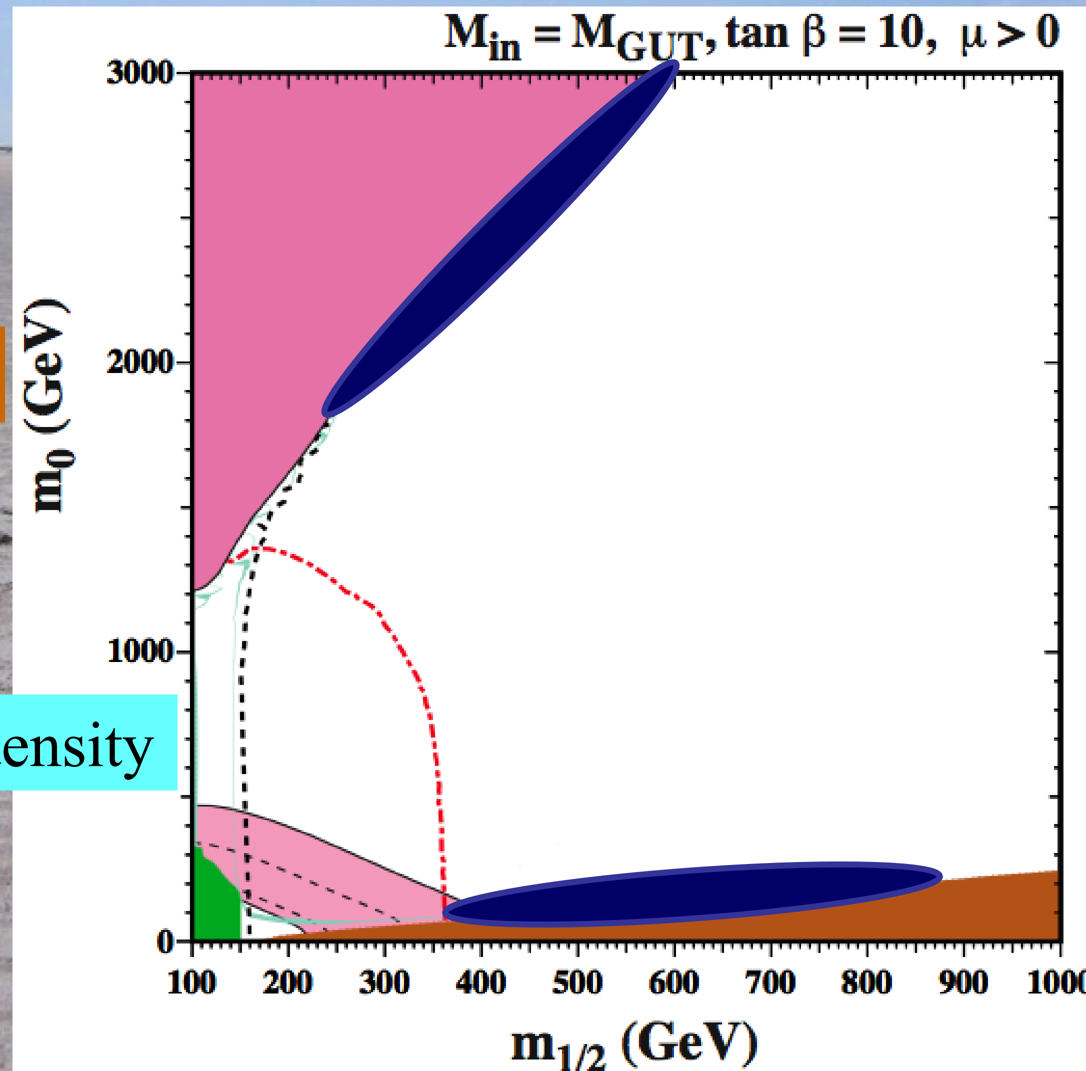
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

Preferred (?) by latest g - 2



JE + Olive + Santoso + Spanos

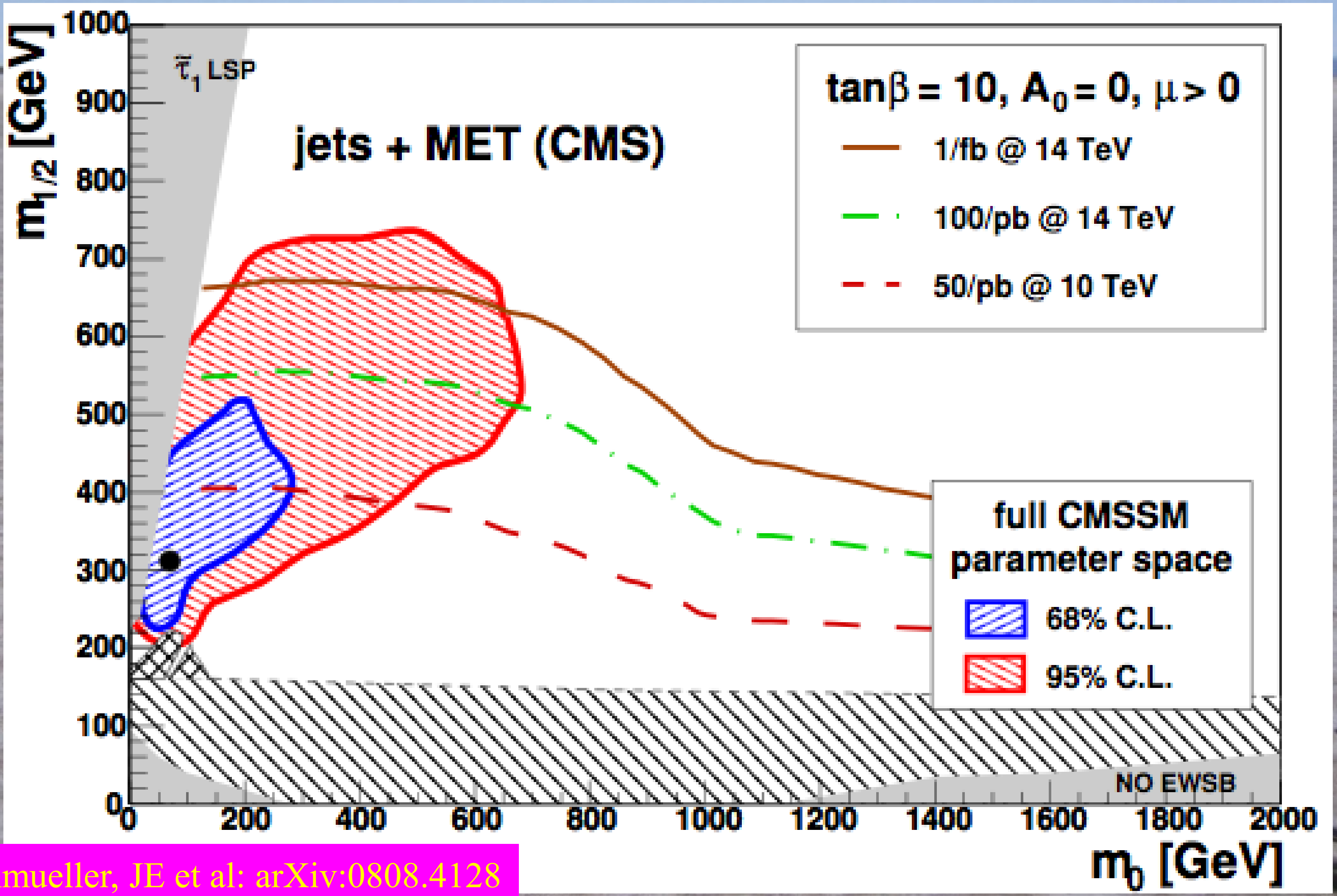
Global Supersymmetric Fits

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

O.Buchmueller, JE et al: arXiv:0808.4128, 0907.5568, 0912.1036, 1011.6118, 1102.4585

Pre-LHC

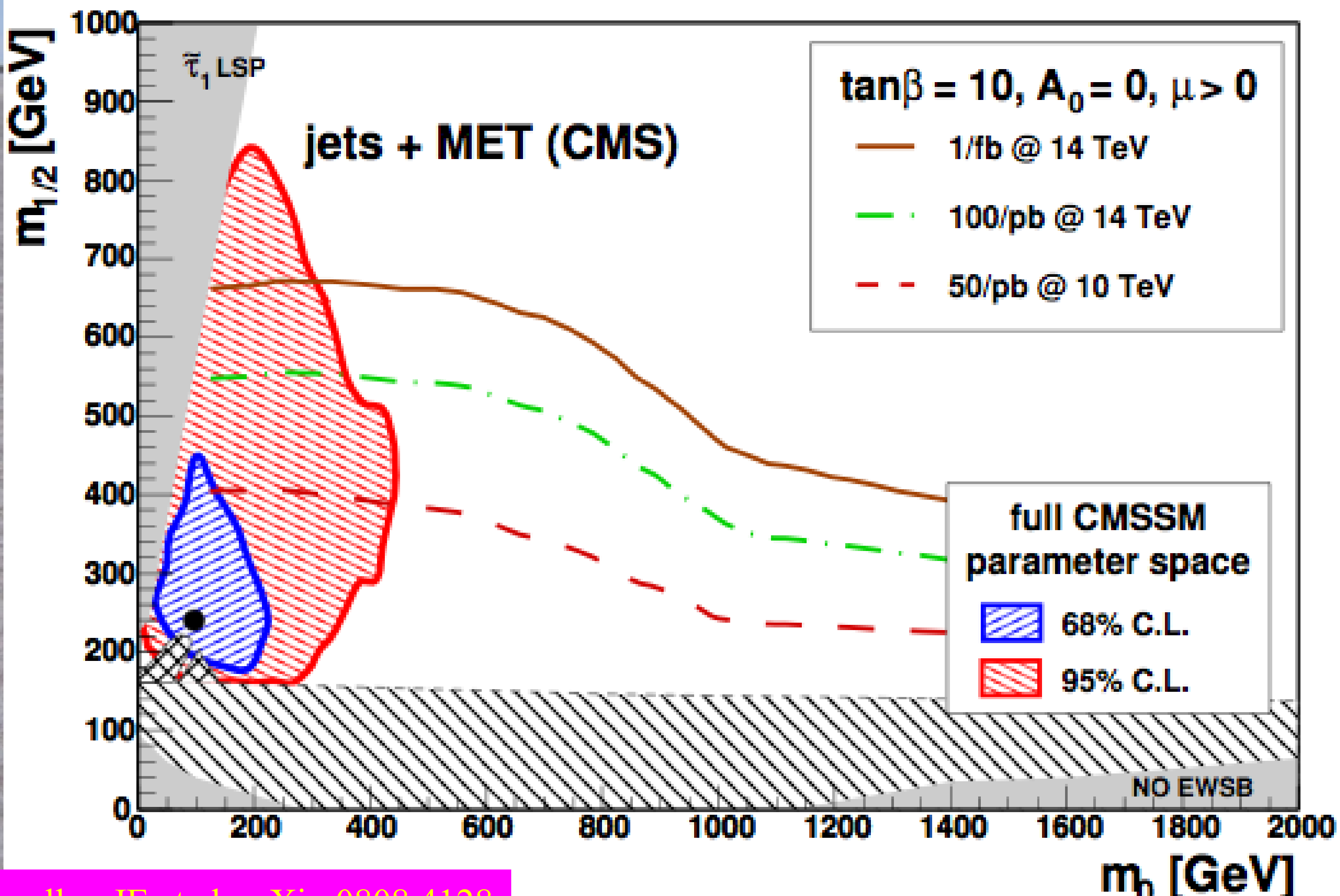
How Soon Might the CMSSM be Detected?



O.Buchmueller, JE et al: arXiv:0808.4128

Pre-LHC

How Soon Might the NUHM1 be Detected?



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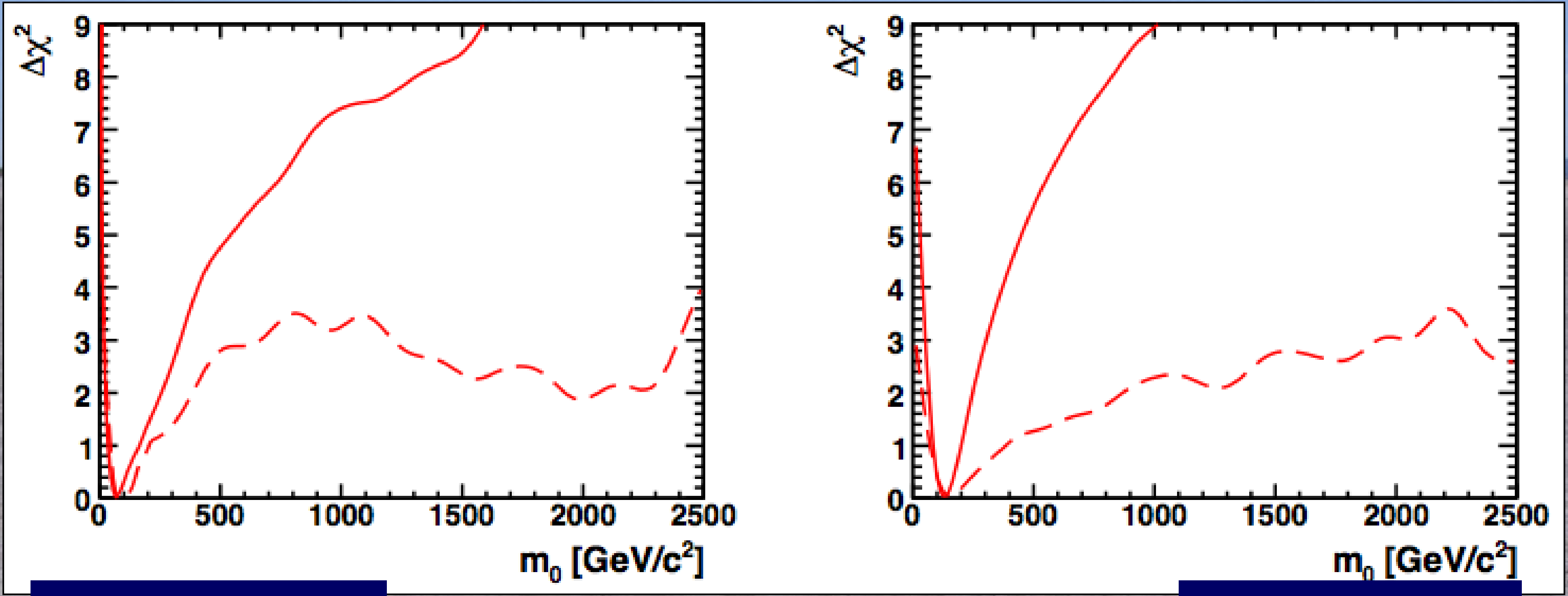
What Happens if g_μ - 2 Dropped?



CMSSM

NUHM1

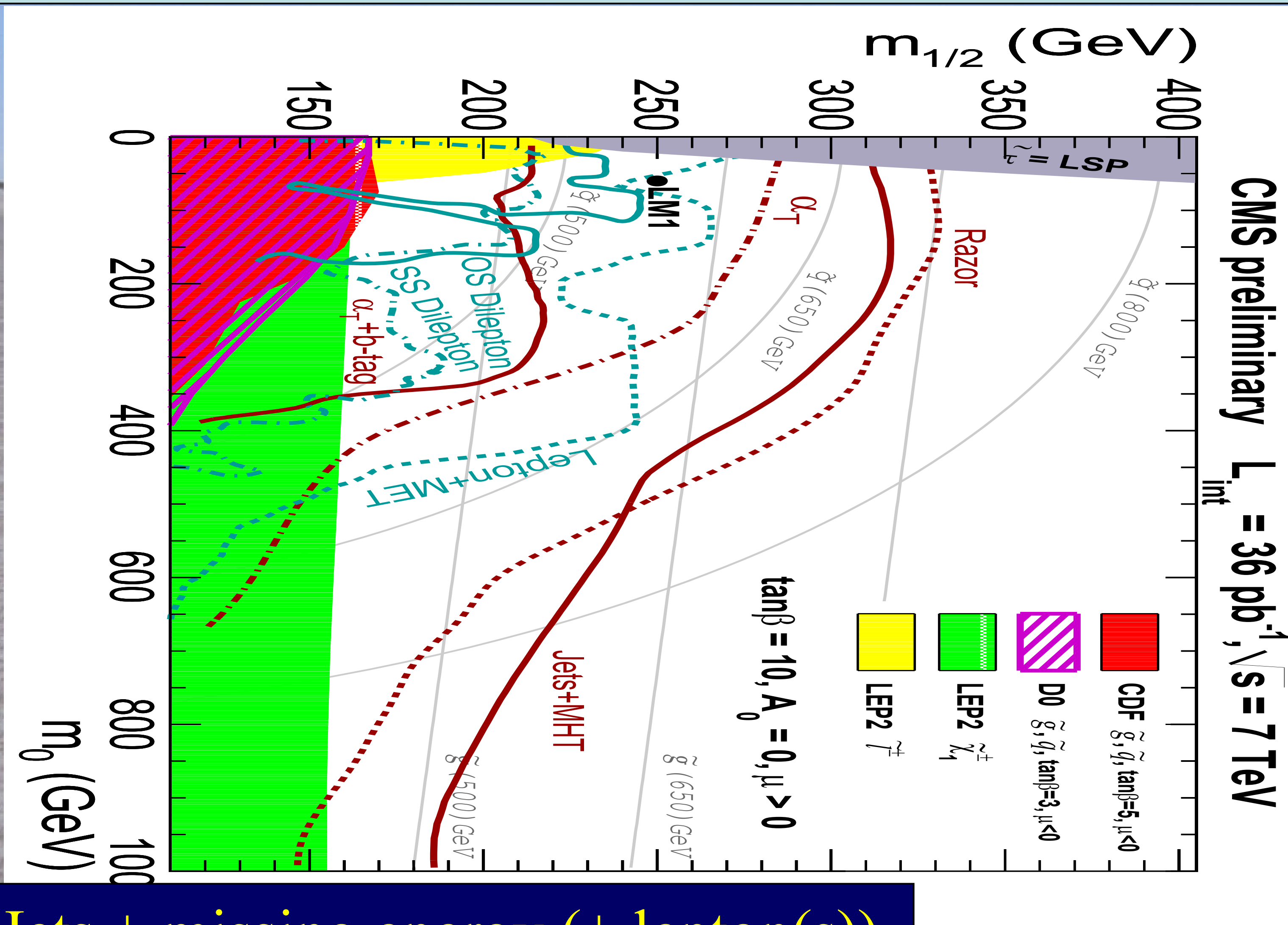
Solid lines: with g_μ - 2

Dashed lines: without g_μ - 2

Focus-point still disfavoured, e.g., by m_W

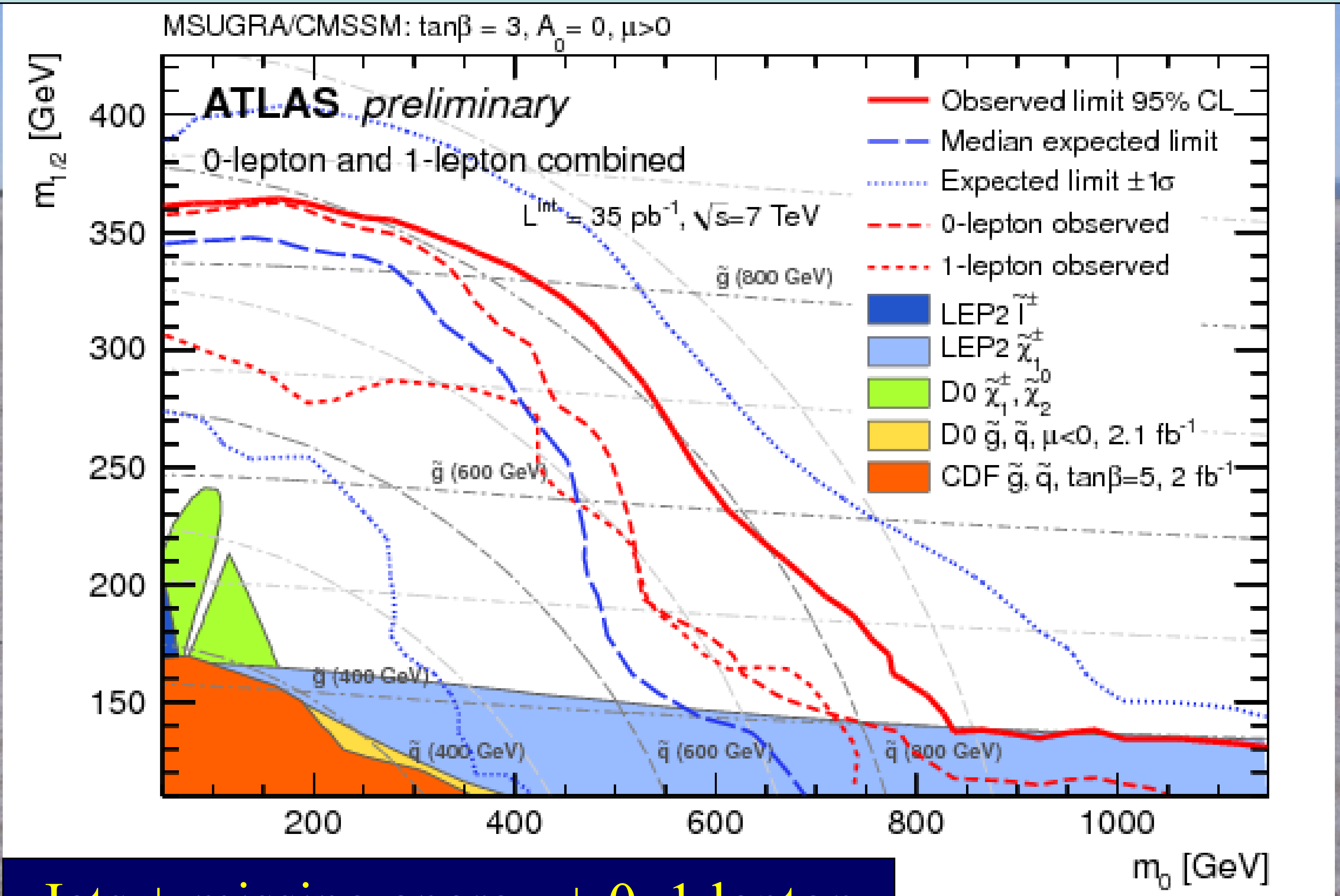
O.Buchmueller, JE et al: arXiv:0907.5568

Supersymmetry Searches in CMS



Jets + missing energy (+ lepton(s))

Supersymmetry Searches in ATLAS



Jets + missing energy + 0, 1 lepton

Impact of LHC on the CMSSM

Assuming the lightest sparticle is a neutralino

CMS MHT

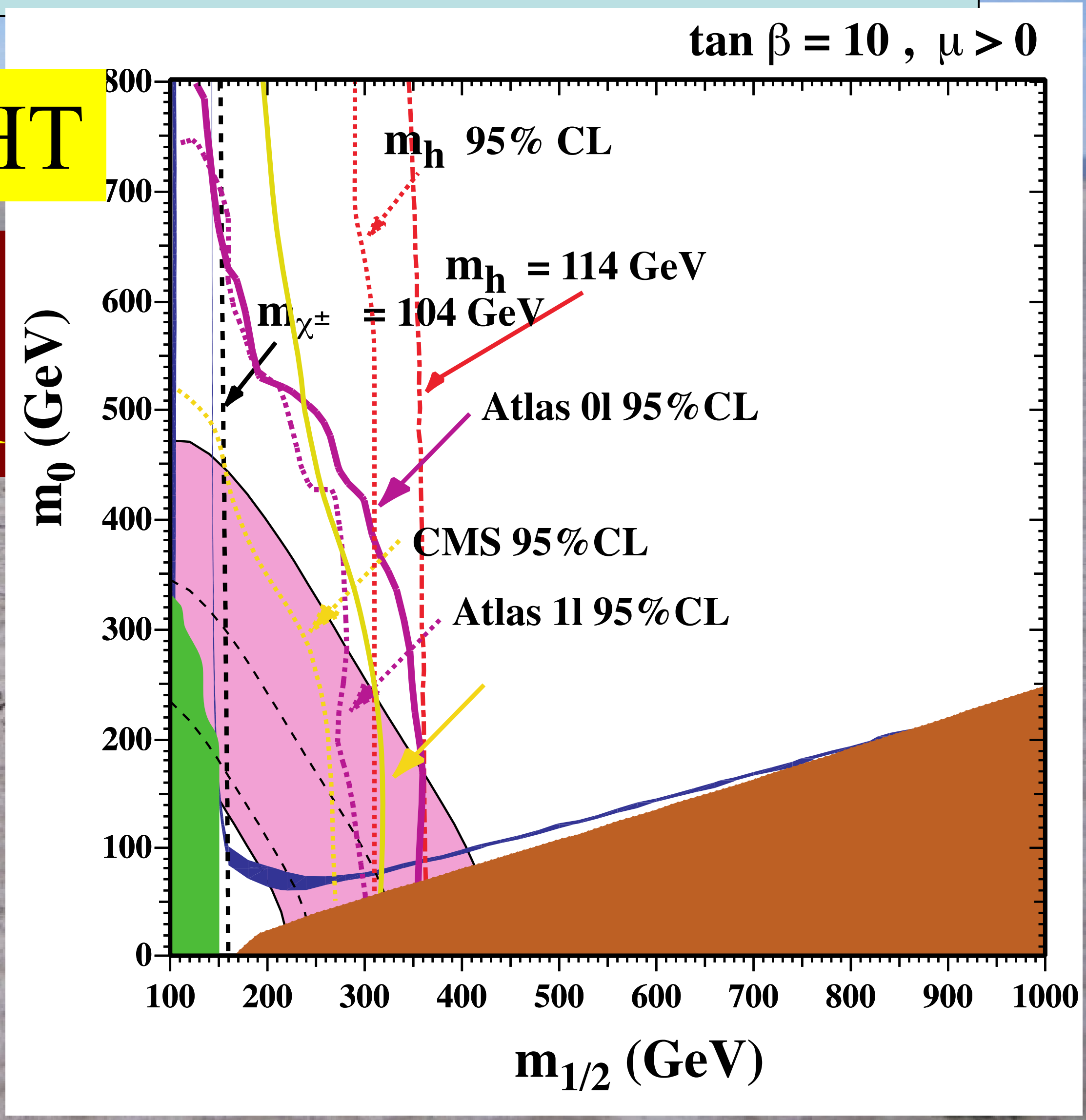
ATLAS 0 Lepton

Excluded because stau LSP

Excluded by b → s gamma

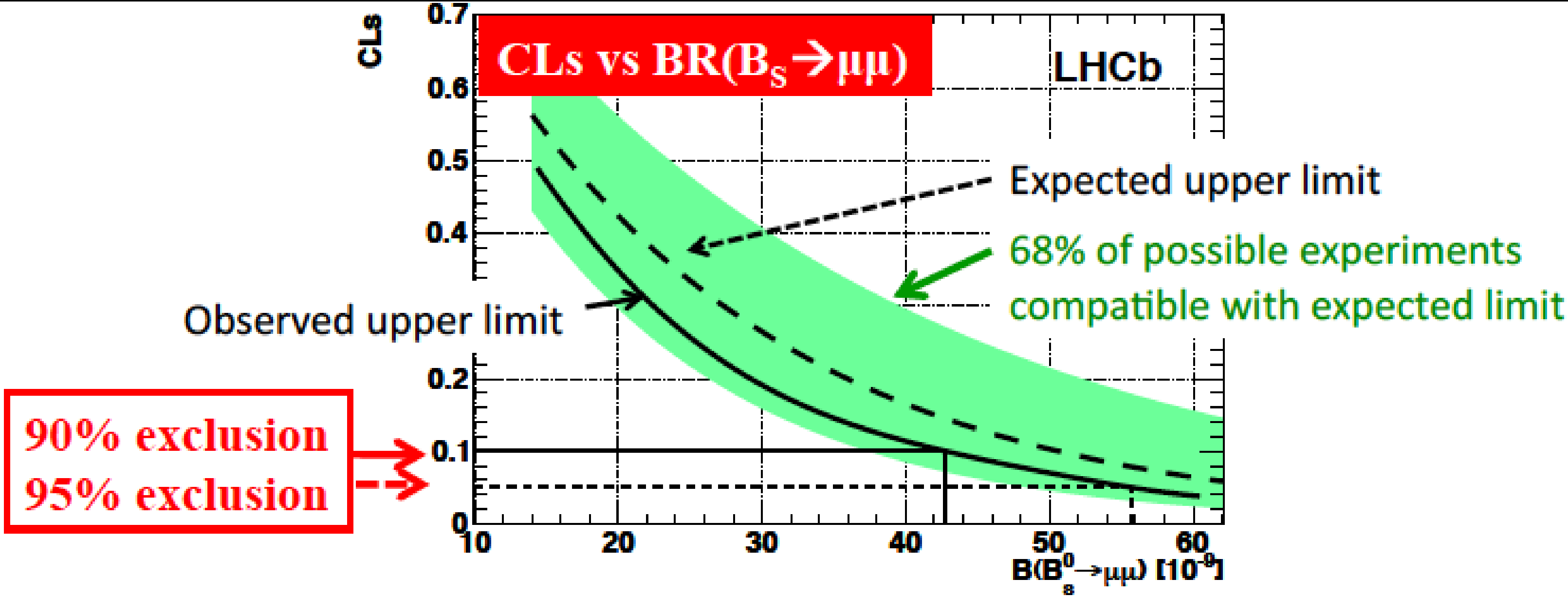
WMAP constraint on CDM density

Preferred (?) by latest g - 2



Rare decay

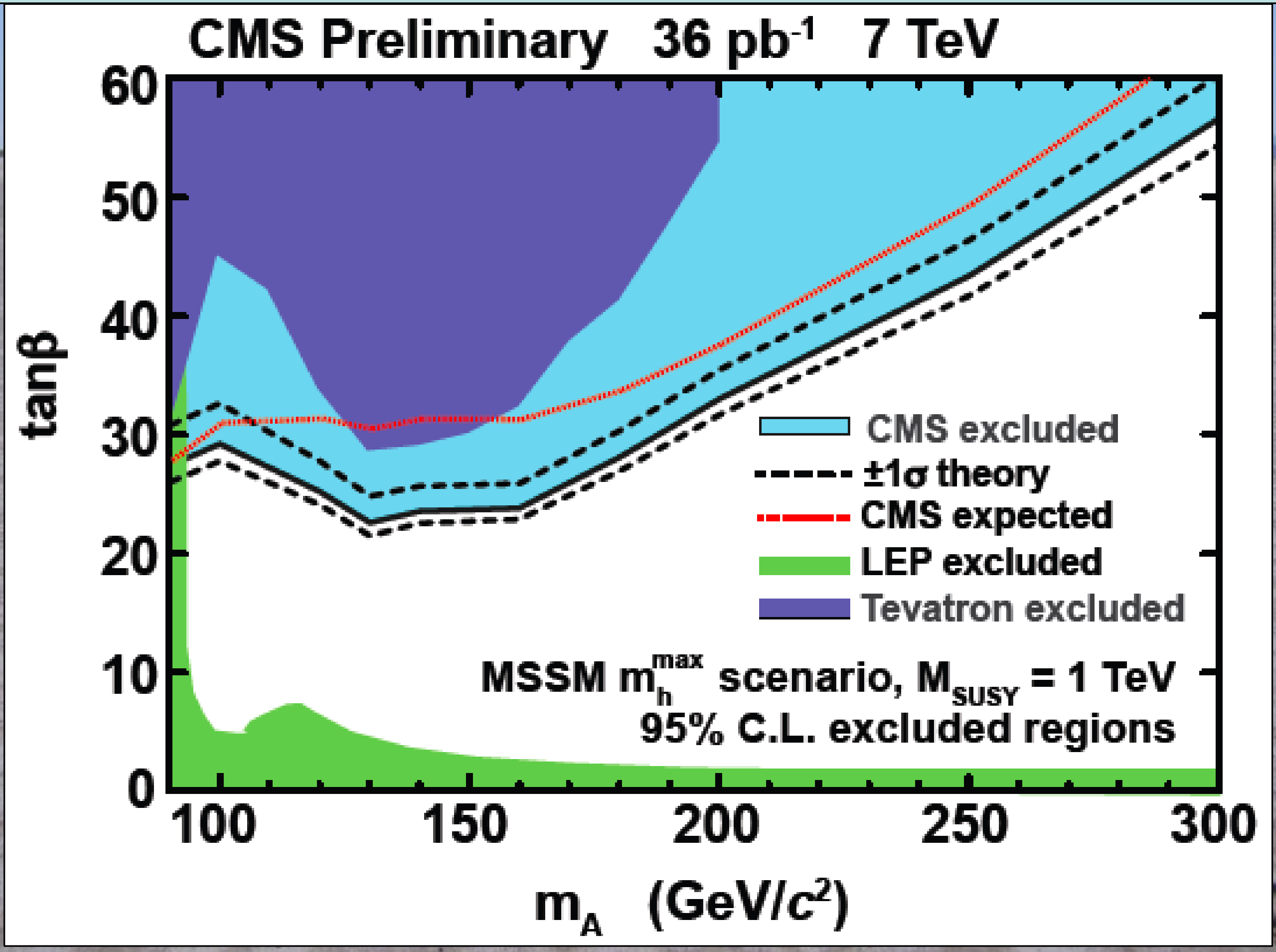
LHCb Upper Limit on BR($B_s \to \mu^+\mu^-$)



		@ 90% CL	@ 95% CL
LHCb	Observed (expected), 37 pb^{-1}	< 43 (51) $\times10^{-9}$	< 56 (65) $\times10^{-9}$
D0	World best published, 6.1 fb^{-1} PLB 693 539 (2010)	< 42 $\times10^{-9}$	< 51 $\times10^{-9}$
CDF	Preliminary, 3.7 fb^{-1} Note 9892	< 36 $\times10^{-9}$	< 43 $\times 10^{-9}$

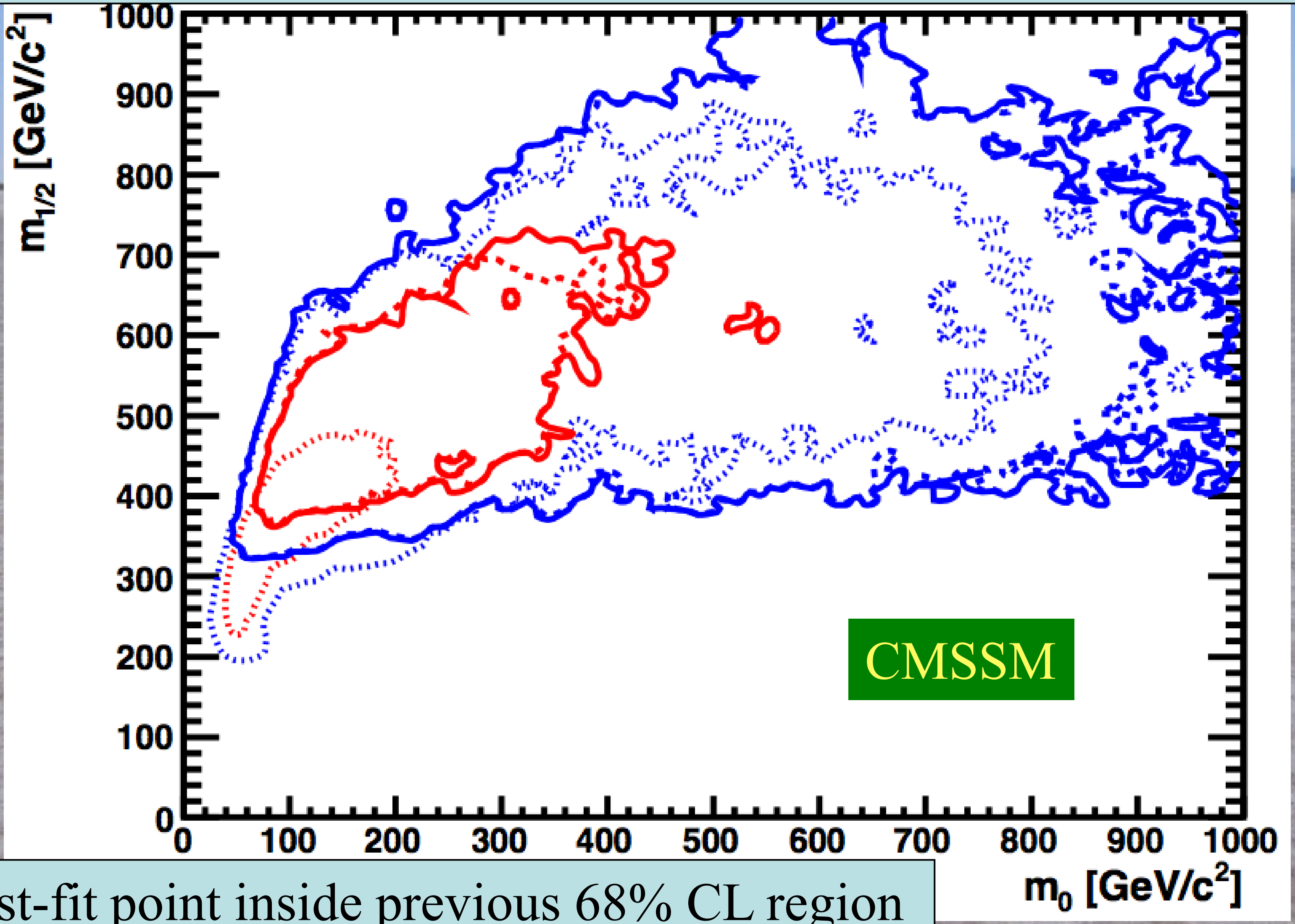
Potential impact of LHCb, CDF and D0

Limits on Heavy MSSM Higgses



Full LHC 2010 data

CMSSM $(m_0, m_{1/2})$ Plane Revisited



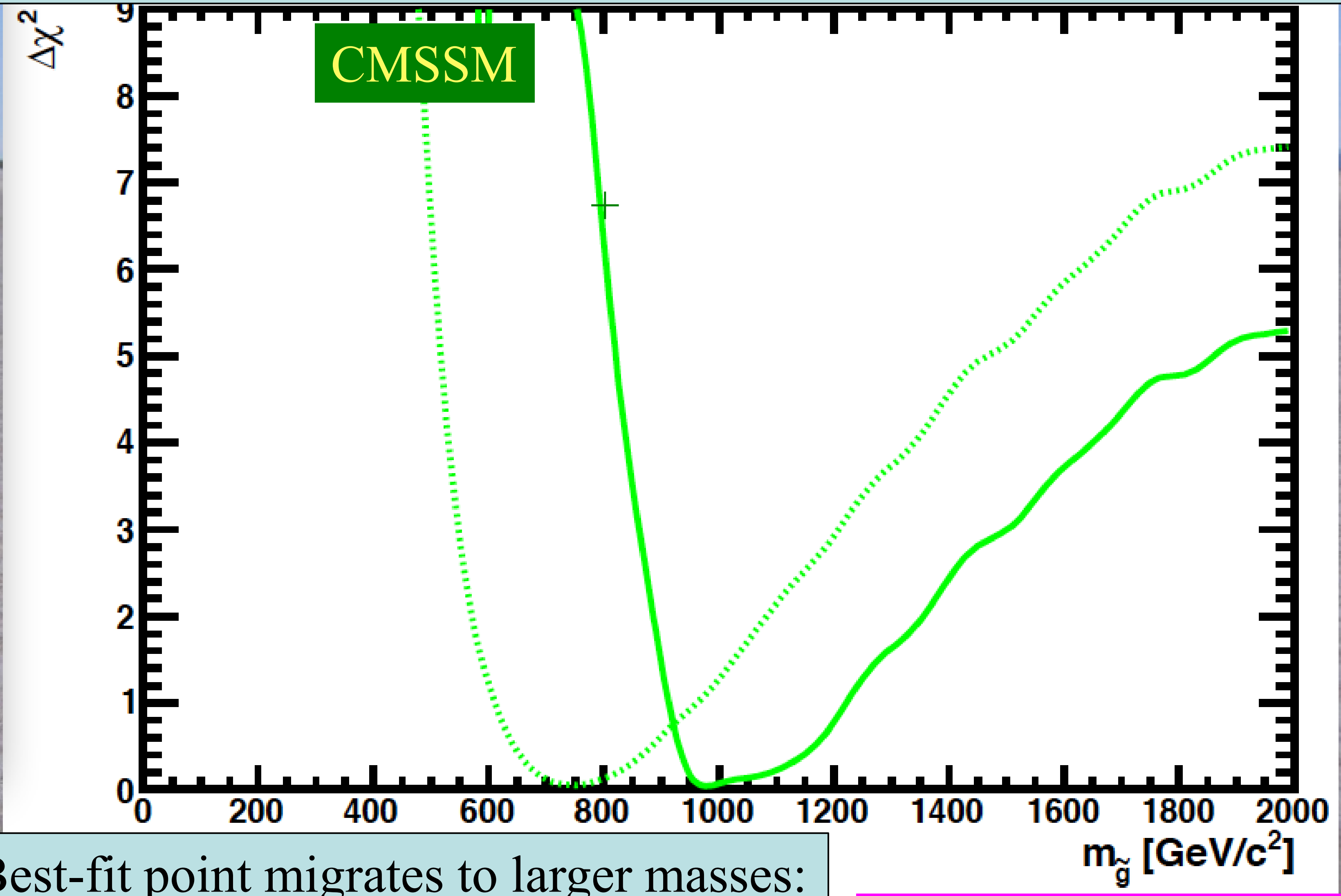
Best-fit point inside previous 68% CL region

➔ No significant tension or conflict

O.Buchmueller, JE et al: in preparation

Full LHC 2010 data

CMSSM Gluino Mass Revisited



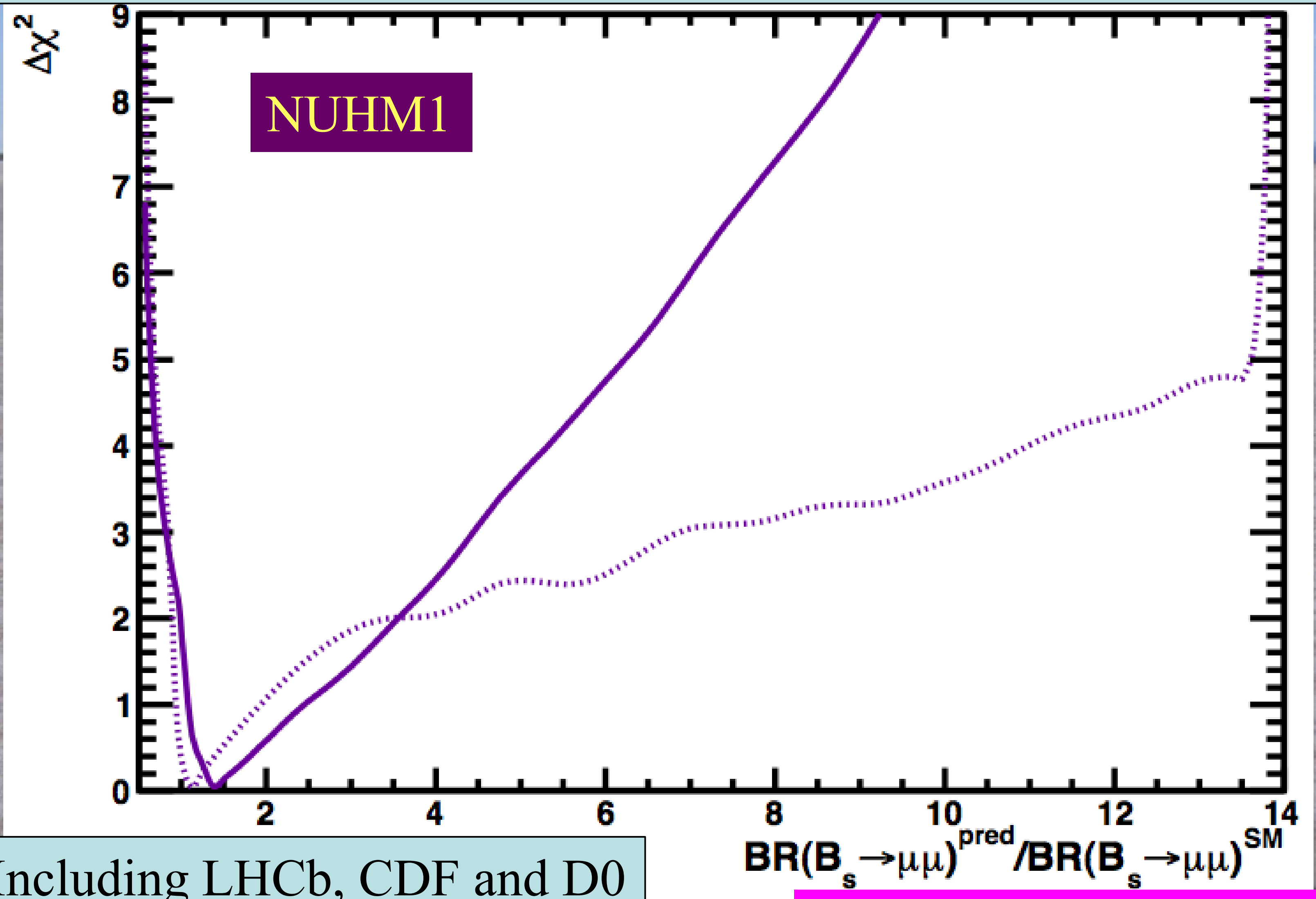
Best-fit point migrates to larger masses: within previous uncertainties

O.Buchmueller, JE et al: in preparation

Full LHC 2010 data

Rare decay

NUHM1 BR($B_s \rightarrow \mu^+\mu^-$) Revisited

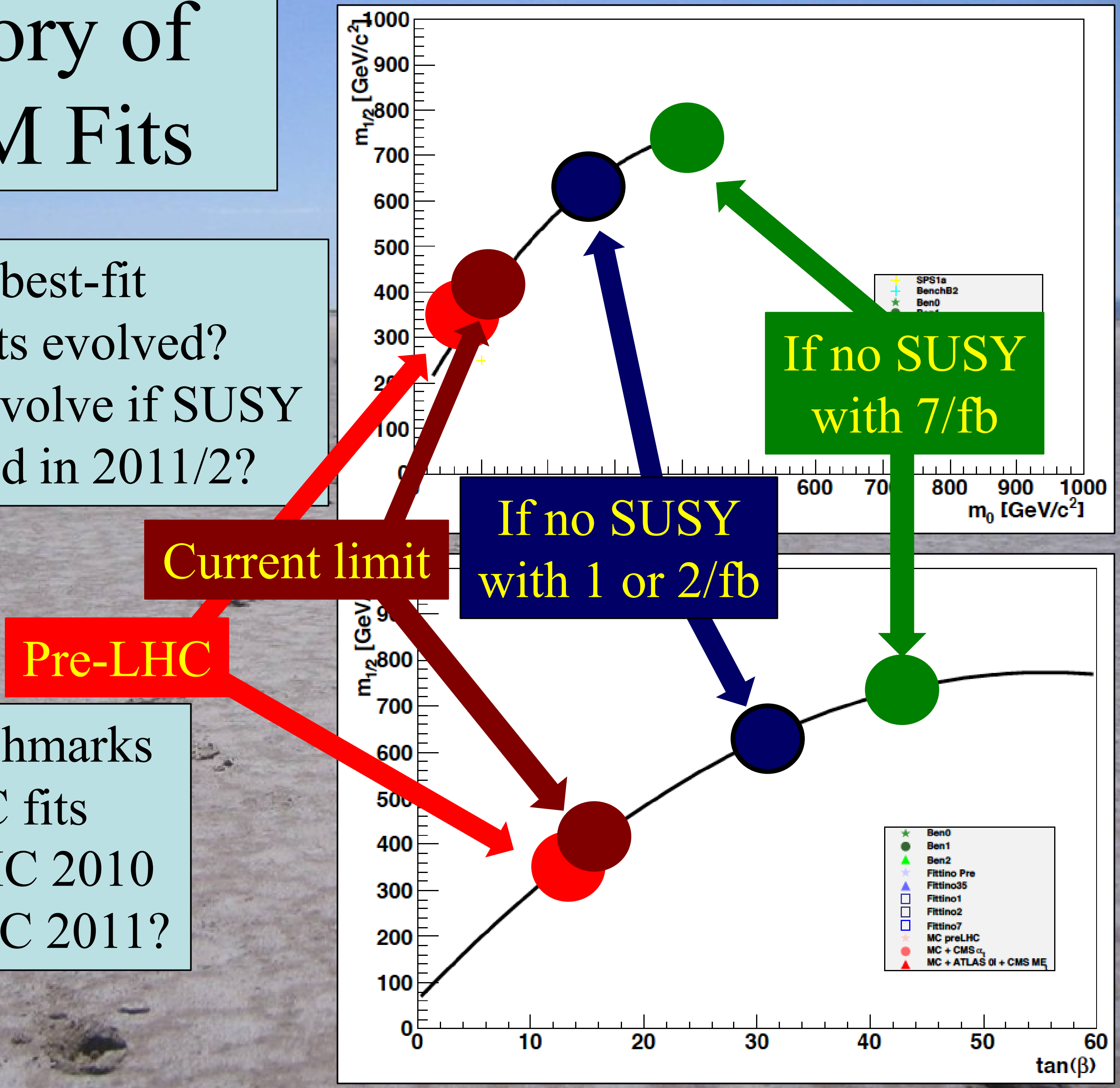


Including LHCb, CDF and D0

O.Buchmueller, JE et al: in preparation

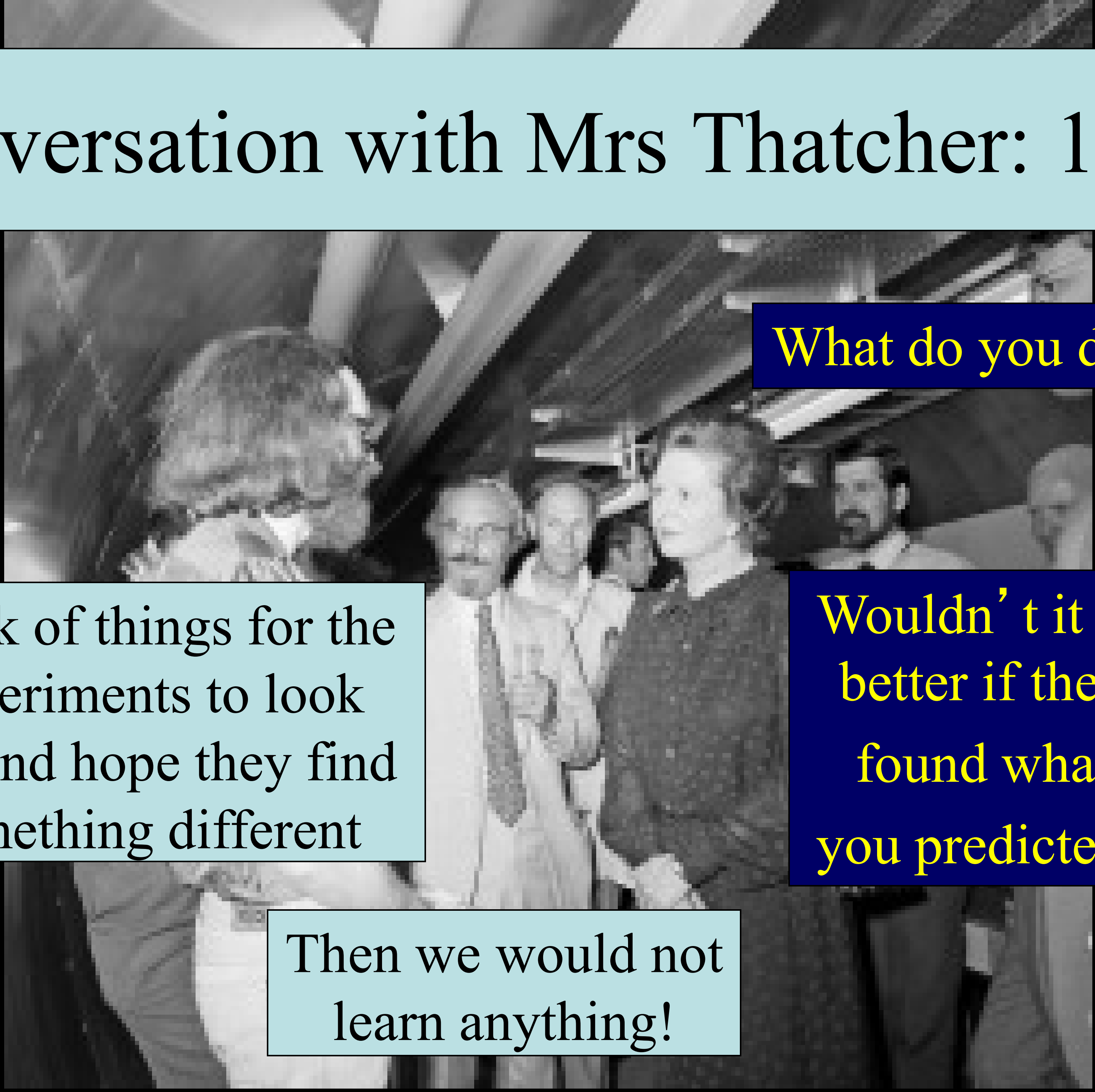
Trajectory of CMSSM Fits

How have best-fit CMSSM points evolved?
How would they evolve if SUSY is not discovered in 2011/2?



✚ Old benchmarks
★ Pre-LHC fits
□ After LHC 2010
■ After LHC 2011?

Conversation with Mrs Thatcher: 1982



What do you do?

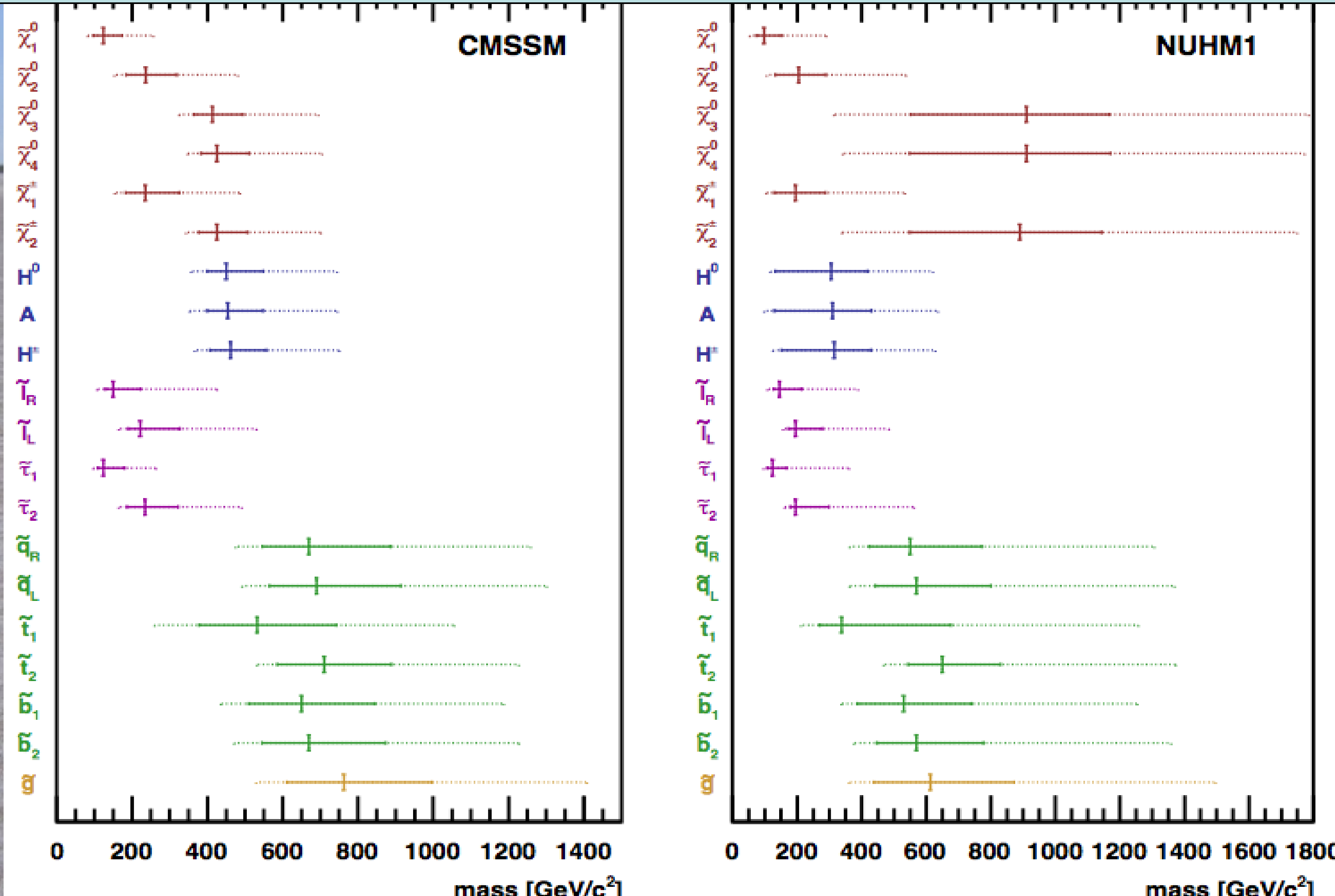
Think of things for the experiments to look for, and hope they find something different

Wouldn't it be better if they found what you predicted?

Then we would not learn anything!

Pre-LHC

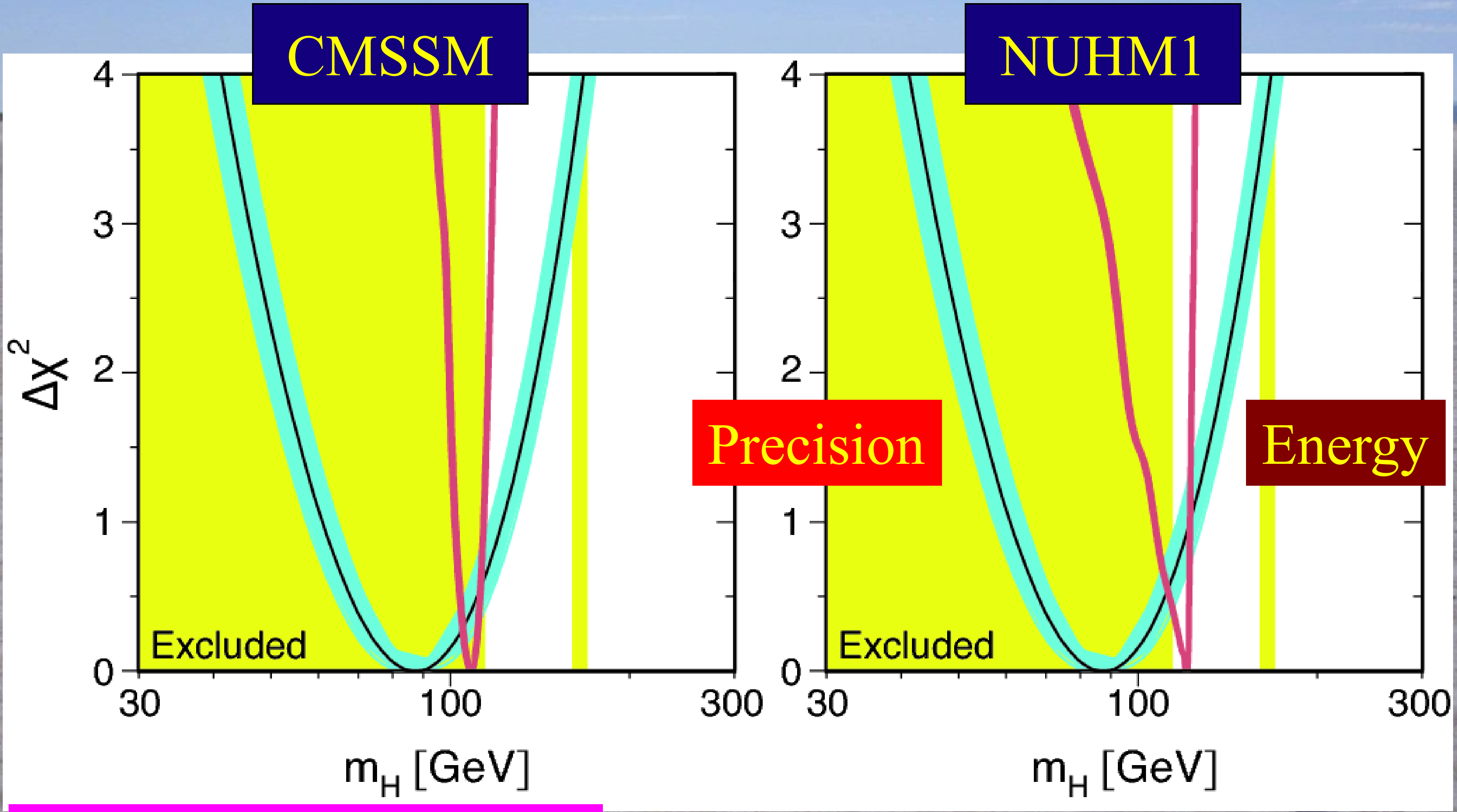
Spectra with Ranges: CMSSM & NUHM1



O.Buchmueller, JE et al: arXiv:0907.5568

Pre-LHC

Likelihood Function for Higgs Mass



O.Buchmueller, JE et al: arXiv:0907.5568

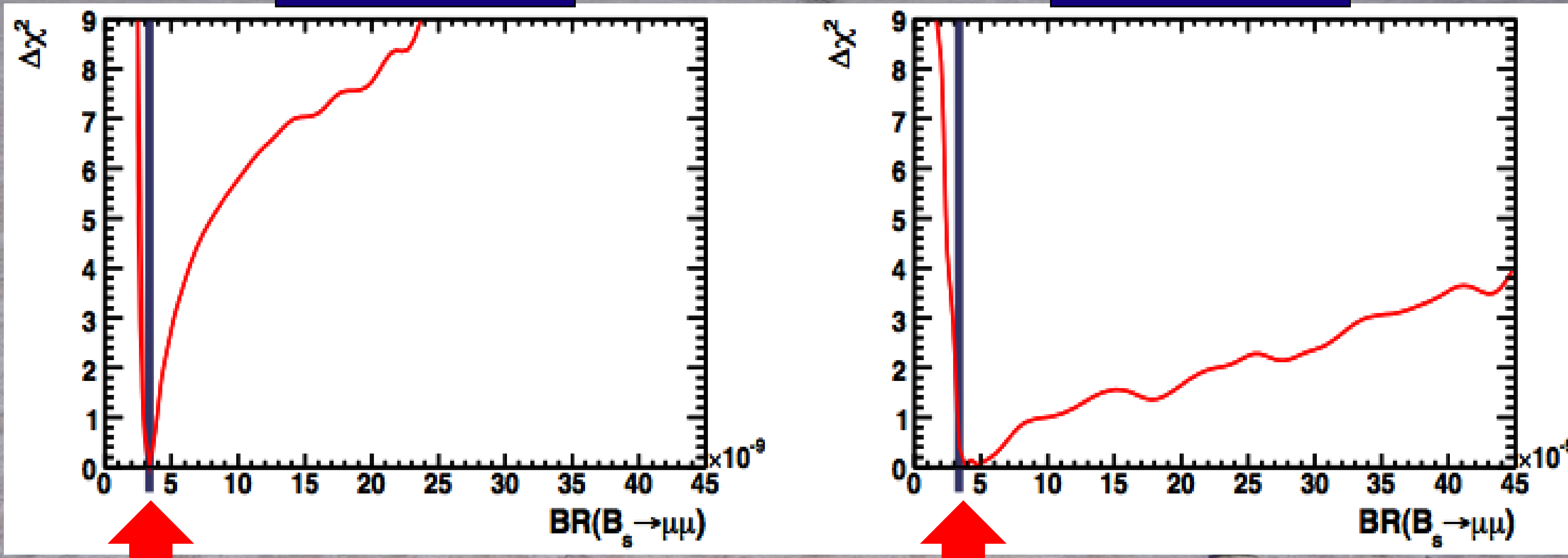
Pre-LHC

Rare decay

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

CMSSM

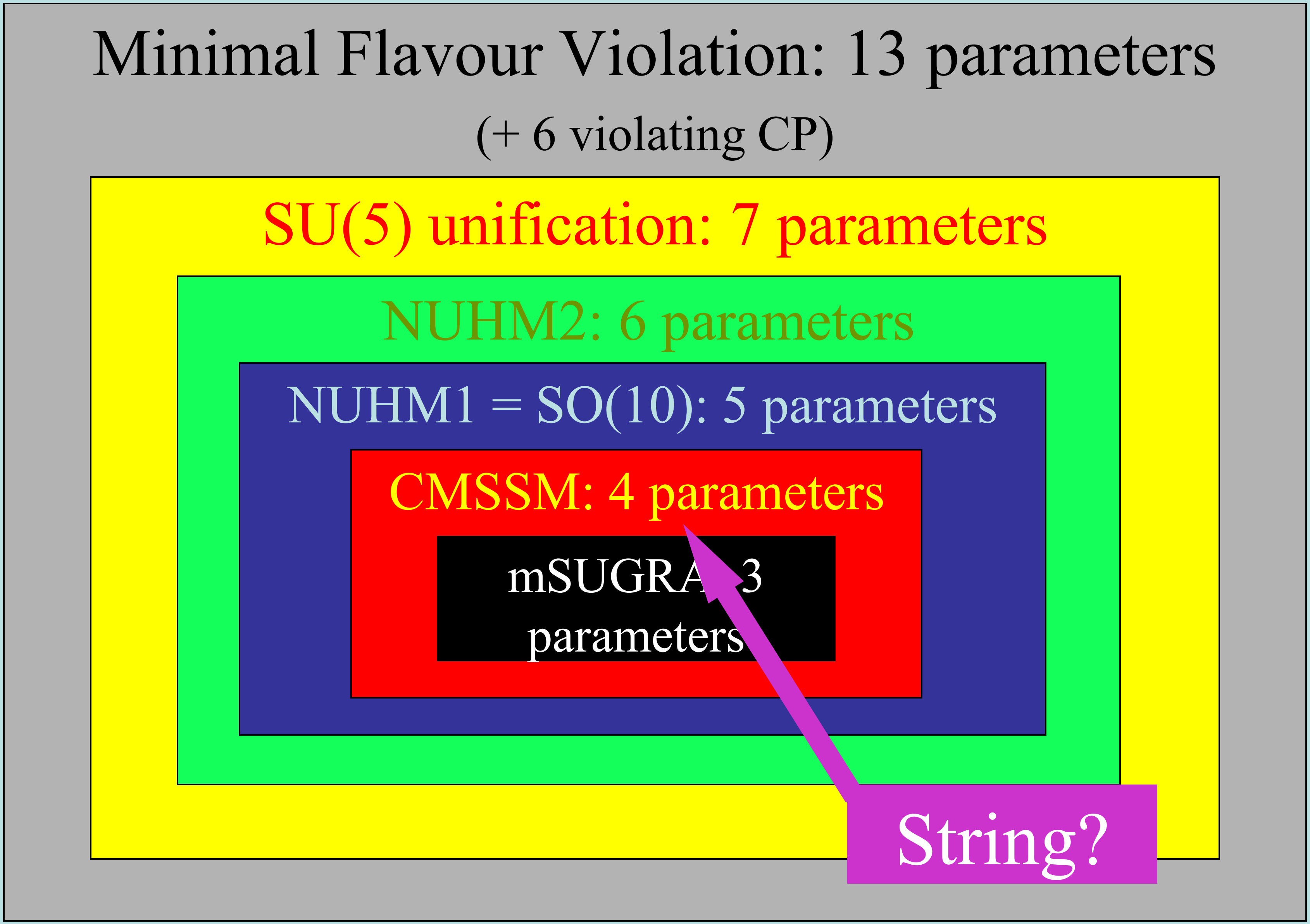
NUHM1



Standard Model prediction

O.Buchmueller, JE et al: arXiv:0907.5568

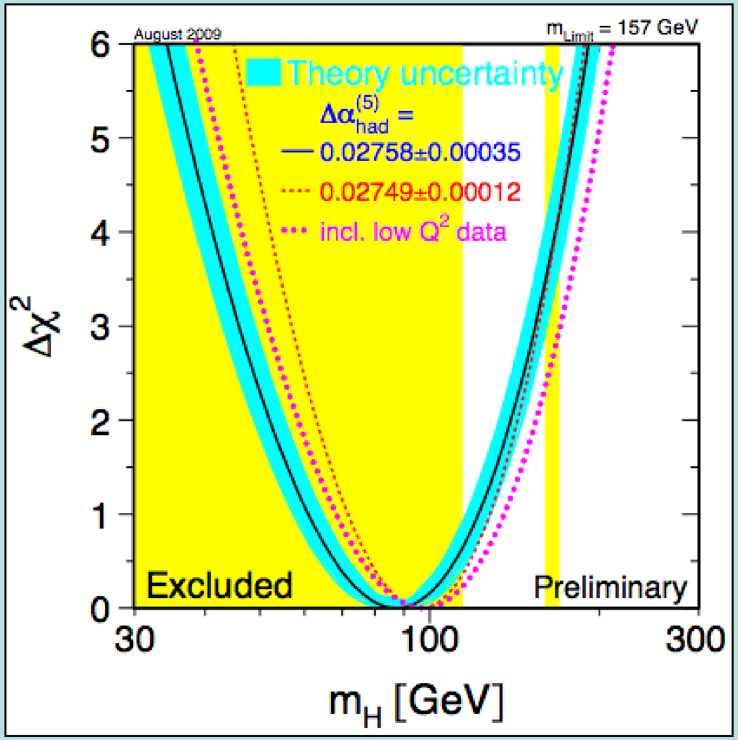
MSSM: > 100 parameters



The State of the Higgs: May 2011

- High-energy search:
  - Limit from LEP:

$$m_H > 114.4 \text{ GeV}$$



- High-precision electroweak data:
  - Sensitive to Higgs mass:

$$m_H = 96^{+30}_{-24} \text{ GeV}$$

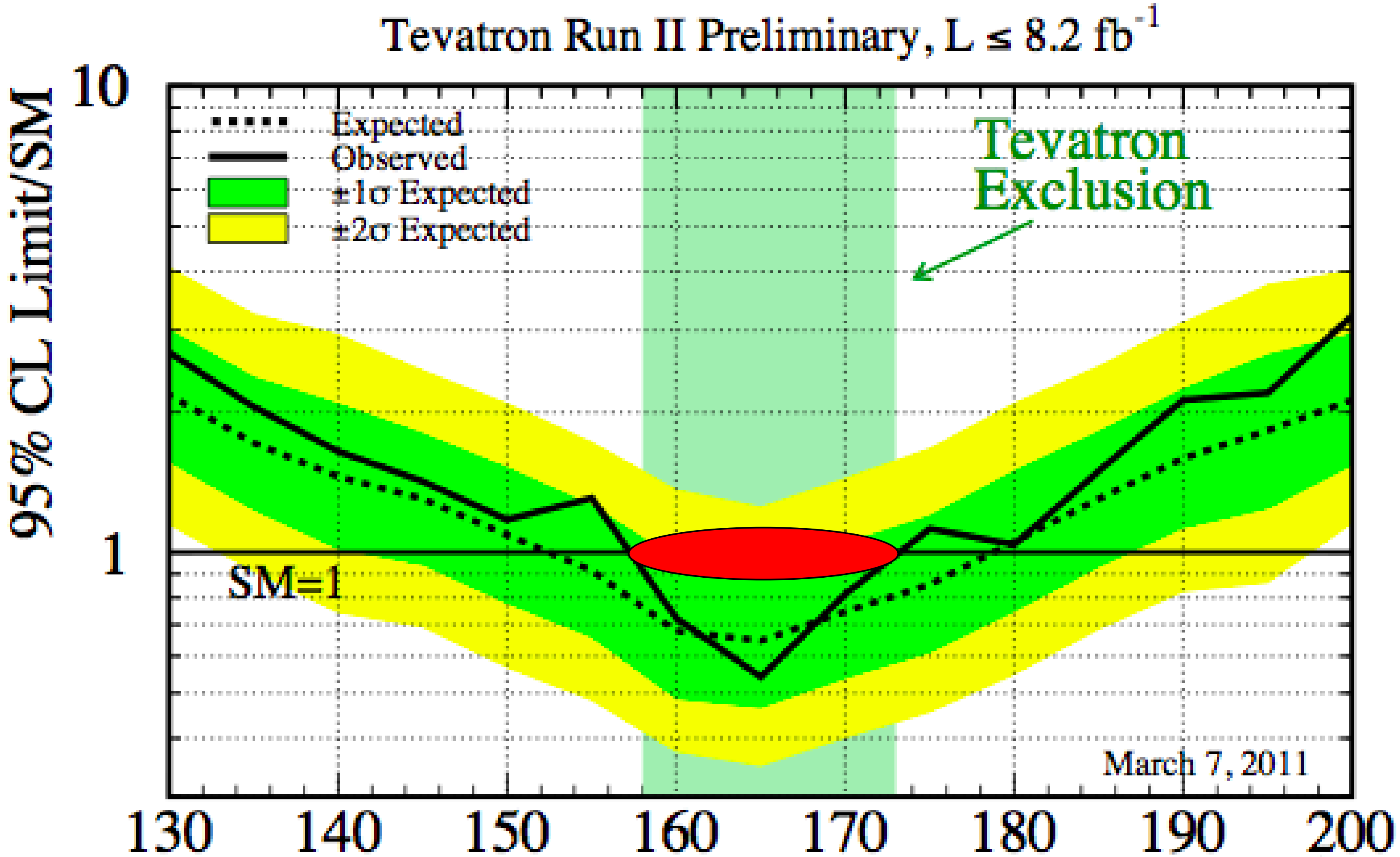
- Combined upper limit:

$m_H < 157$ GeV, or 186 GeV including direct limit

- Exclusion from high-energy search at Tevatron:

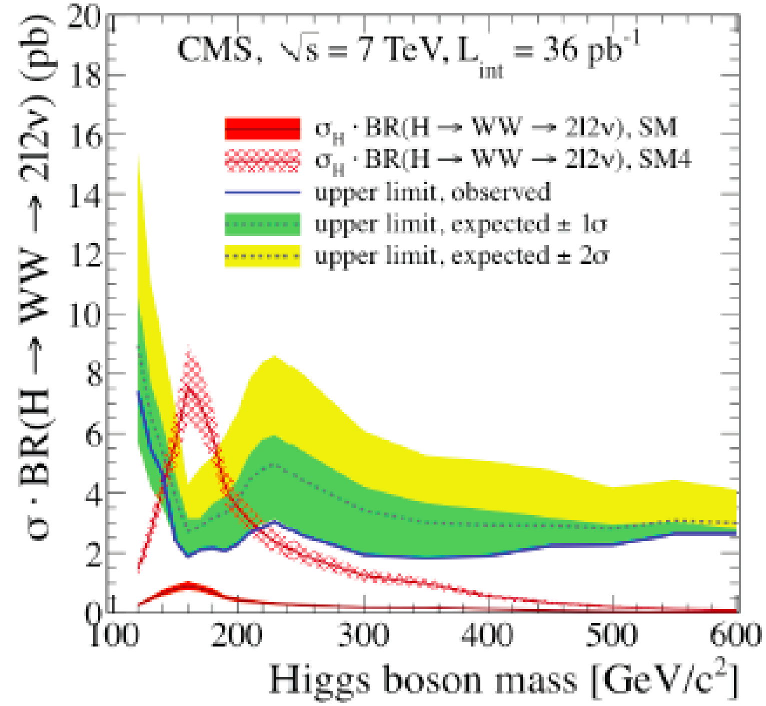
$m_H < 158$ GeV or > 173 GeV

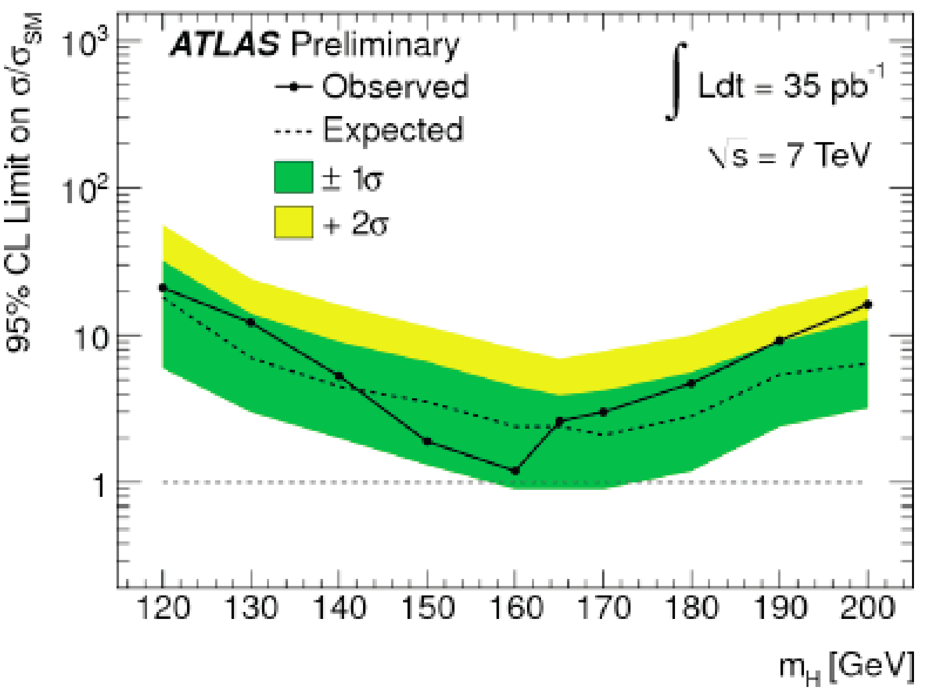
Higgs Search @ Tevatron



Tevatron excludes Higgs between 158 & 173 GeV

First Higgs Searches @ LHC

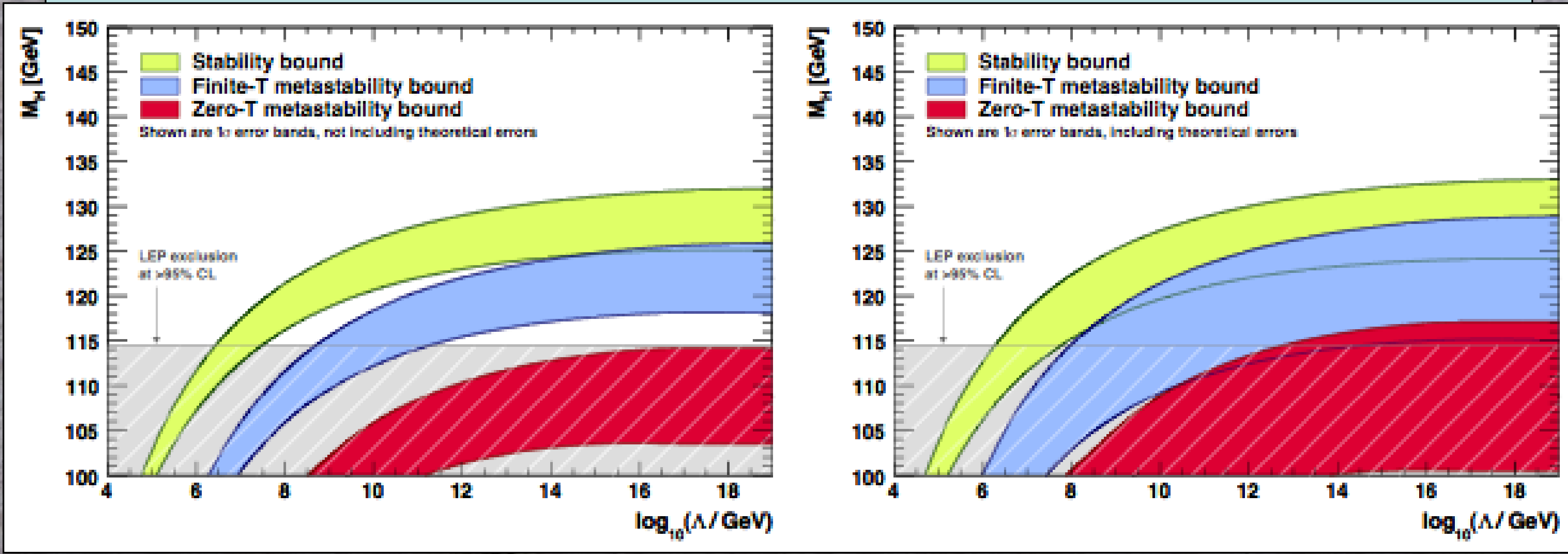




No exclusion yet, but significant contribution to global fit

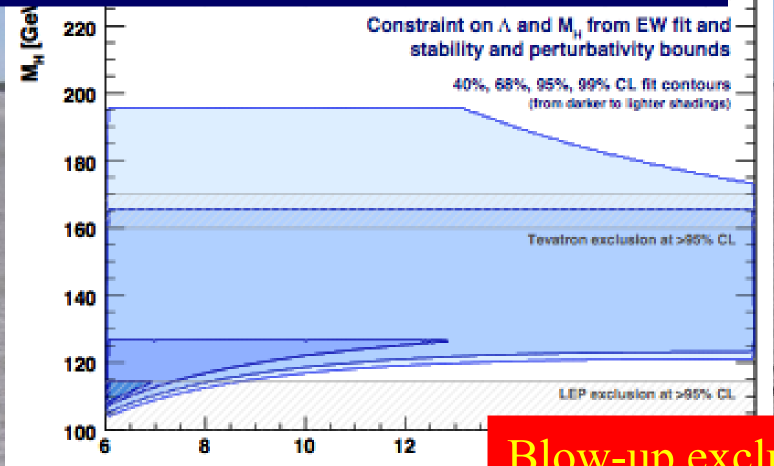
Vacuum Stability vs Metastability

- Dependence on scale up to which Standard Model remains
  - **Stable**
  - **Metastable at non-zero temperature**
  - **Metastable at zero temperature**

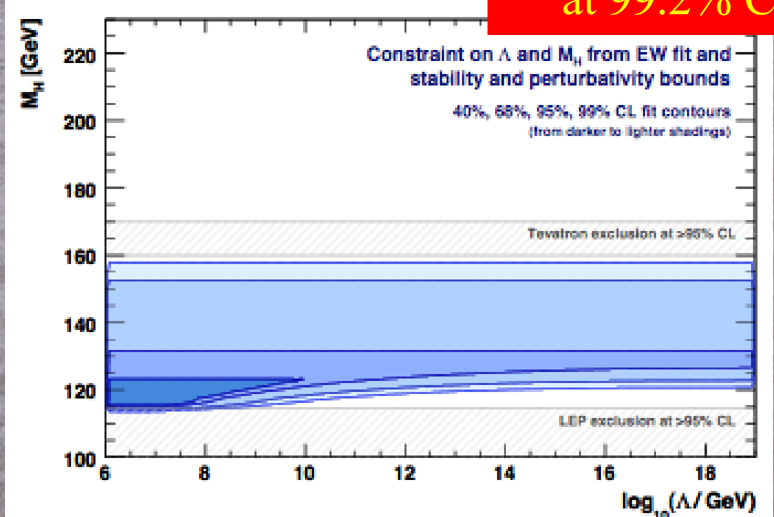


What is the probable fate of the SM?

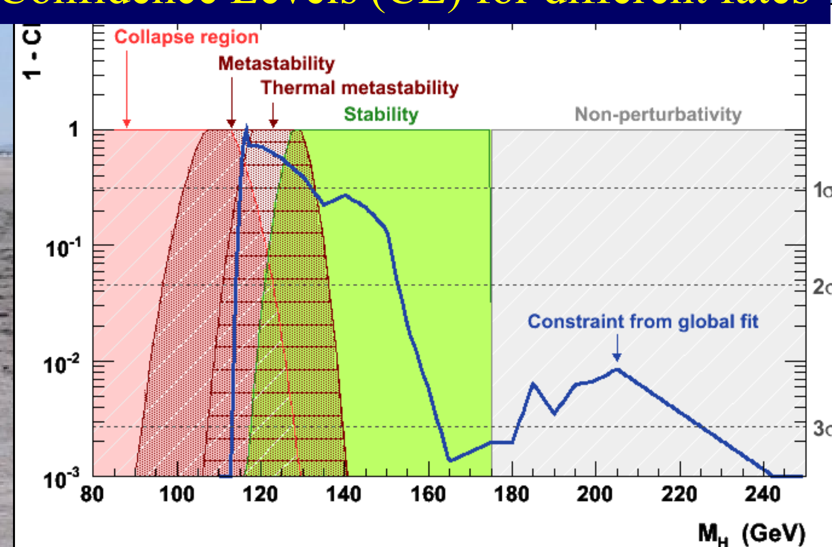
Confidence Levels (CL) without/with Tevatron exclusion

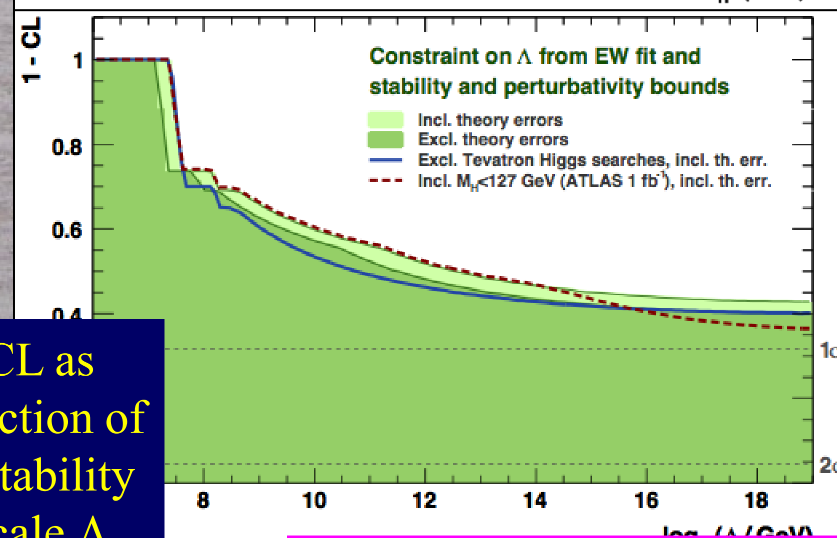


Blow-up excluded at 99.2% CL



Confidence Levels (CL) for different fates





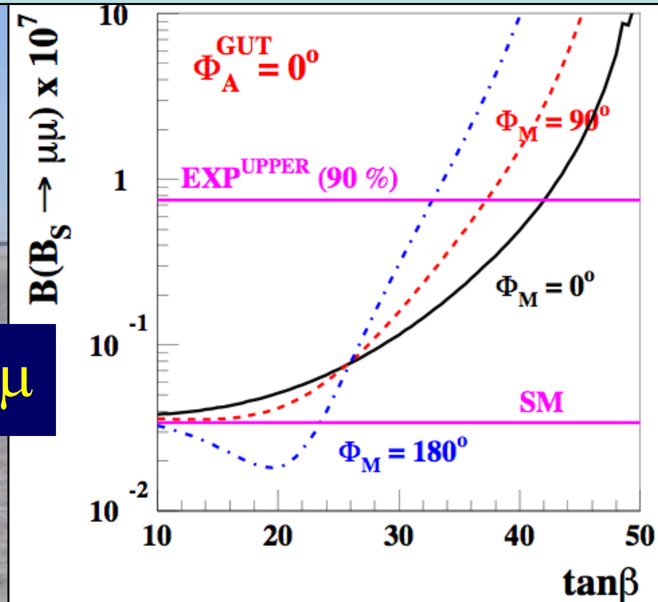
CL as function of instability scale Λ

Espinosa, JE, Giudice, Hoecker, Riotto

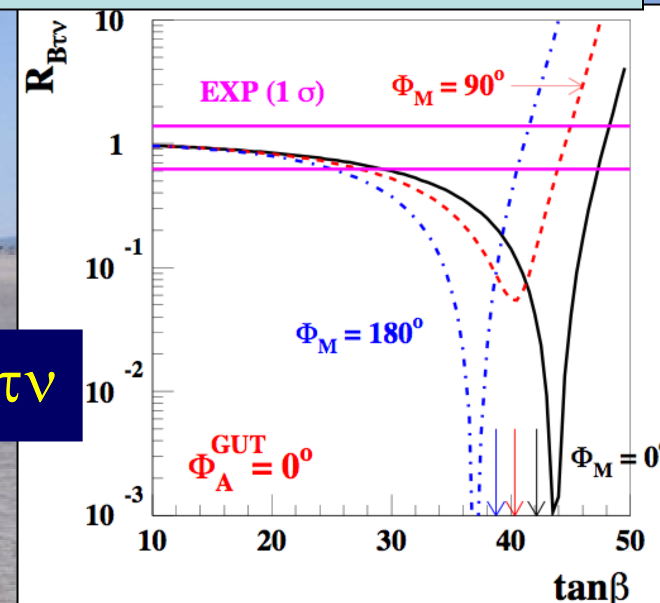
Possible Effects of CP-Violating Phases

Rare decays

$B_s \to \mu\mu$

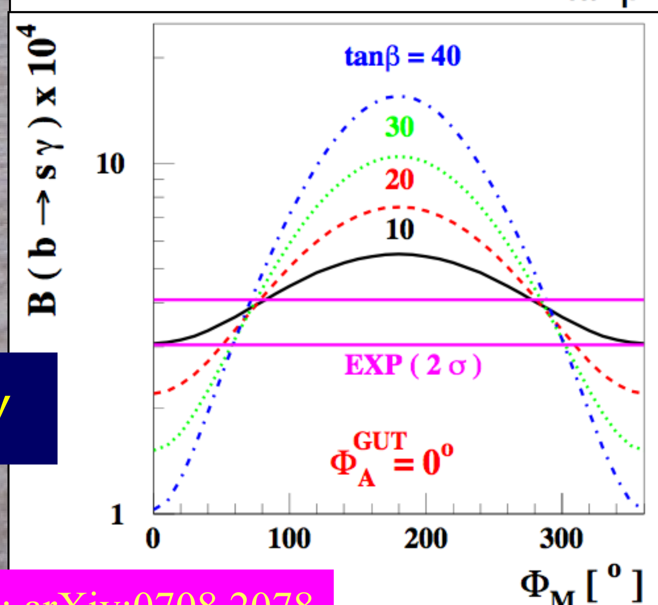


$B_u \to \tau\nu$

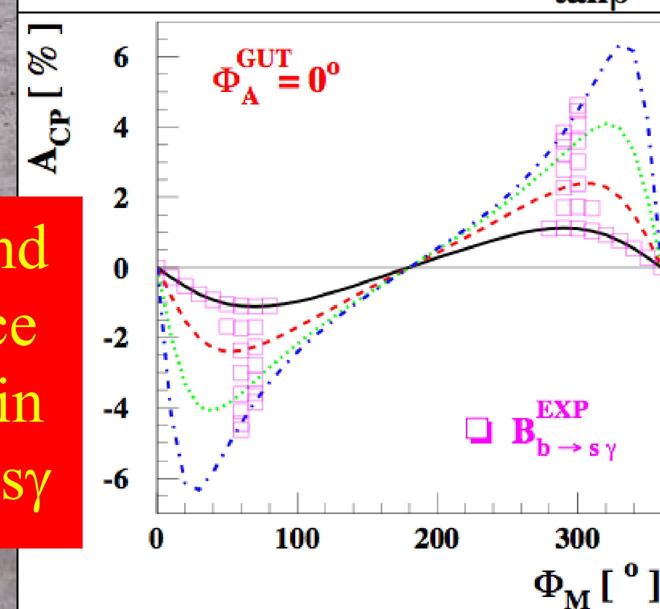


Different regions allowed for different phases …

$b \to s\gamma$



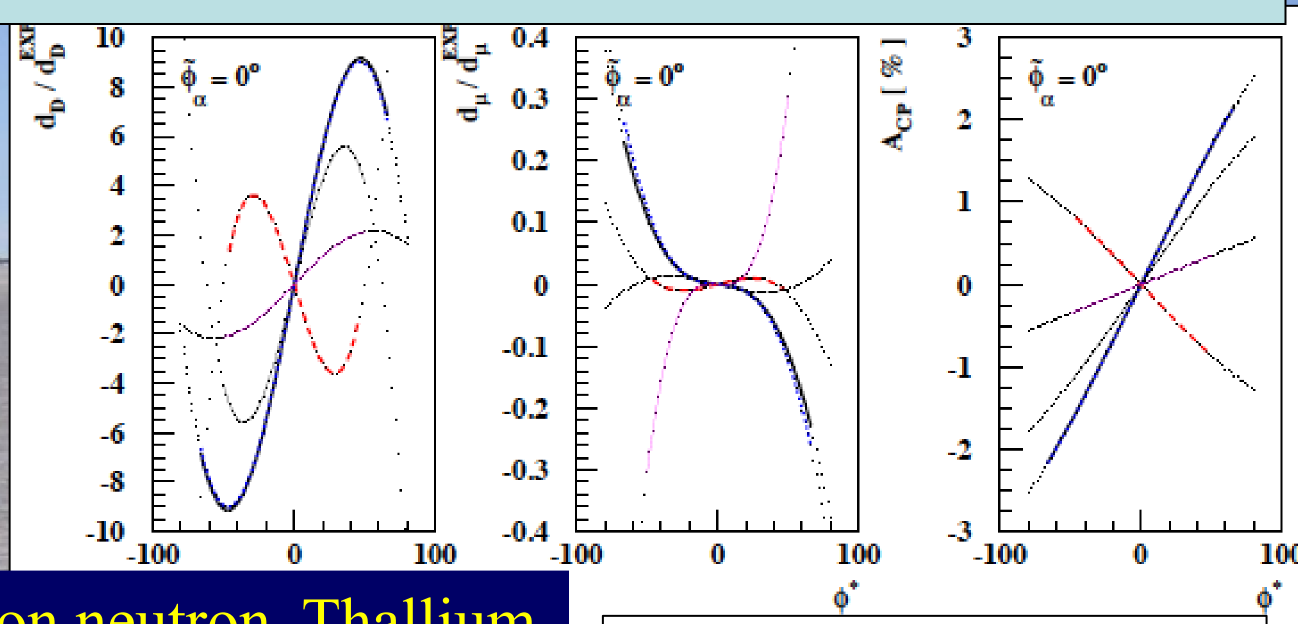
… and hence A_{CP} in $b \to s\gamma$



J.E. + Lee + Pilaftsis: arXiv:0708.2078

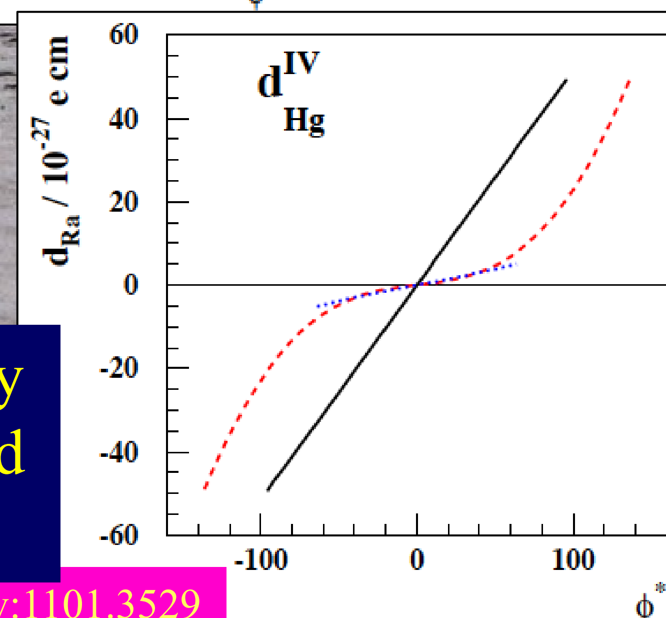
SUSY and Electric Dipole Moments

Precision



Present upper limits on neutron, Thallium and Mercury EDMs allow large EDMs for deuteron and proton

J.E. + Lee + Pilaftsis: arXiv:1006.3087



Another window of opportunity may be provided by nuclei with enhanced Schiff moments such as ^{225}Ra

J.E. + Lee + Pilaftsis: arXiv:1101.3529

Minimal Flavour Violation (MFV)

- All squark mixing due to CKM matrix
- Universal scalar masses at high scale for sparticles with same quantum numbers
- Parametrization:

$$M_{1,2,3}\,, \quad M^2_{H_{u,d}}\,, \qquad \widetilde{\mathbf{M}}^2_{Q,L,U,D,E} \;=\; \widetilde{M}^2_{Q,L,U,D,E}\,\mathbf{1}_3\,, \qquad \mathbf{A}_{u,d,e} \;=\; A_{u,d,e}\,\mathbf{1}_3$$

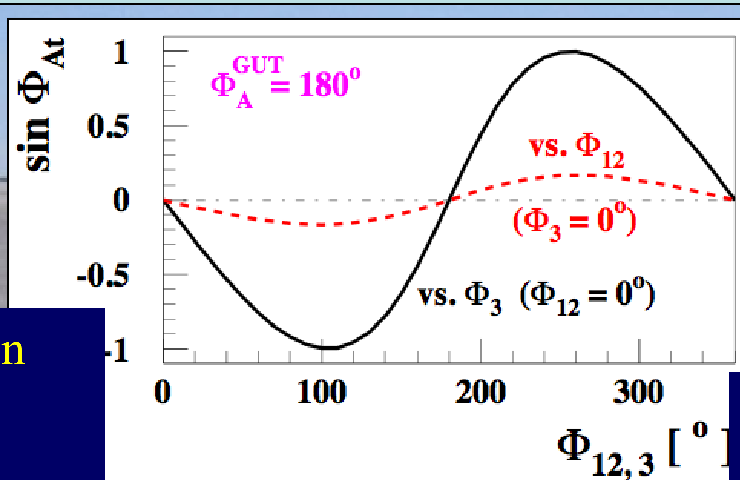
- Maximally CP-violating MFV (MCPMFV) model has 19 parameters, of which 6 violate CP:

$$\mathrm{Im}\, M_{1,2,3} \text{ and } \mathrm{Im}\, A_{u,d,e}$$

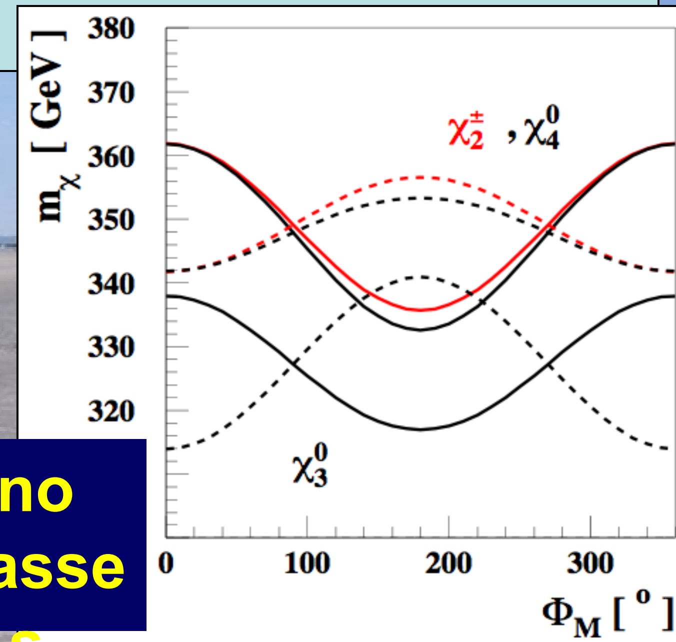
- Often assume universal ImM_a, ImA_f, but non-universality compatible with MFV: **MCPMFV**

JE + Lee + Pilaftsis: arXiv 0708.2079

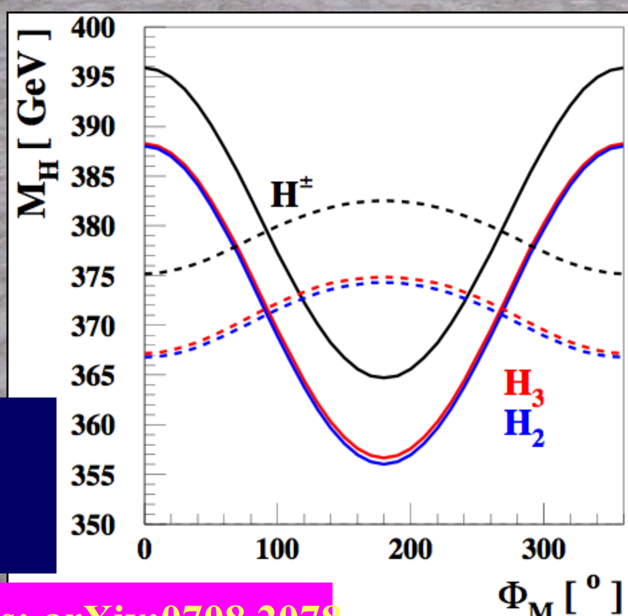
Effects of CP Phases in MCPMFV



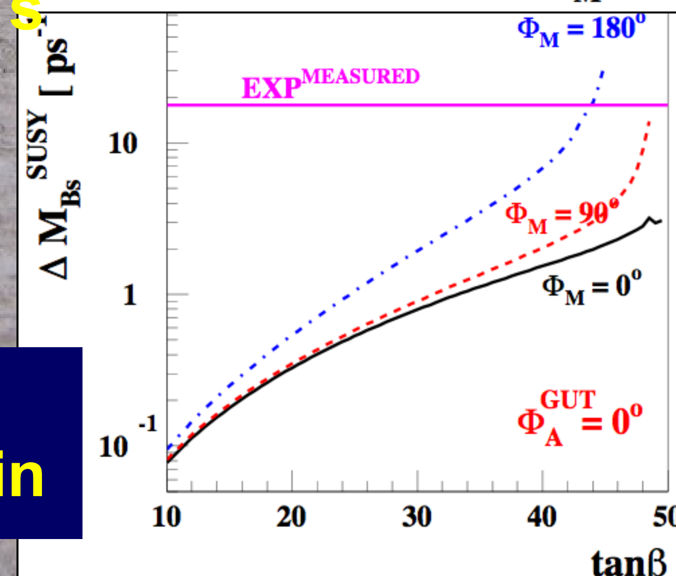
Renormalization of phases



Ino masses



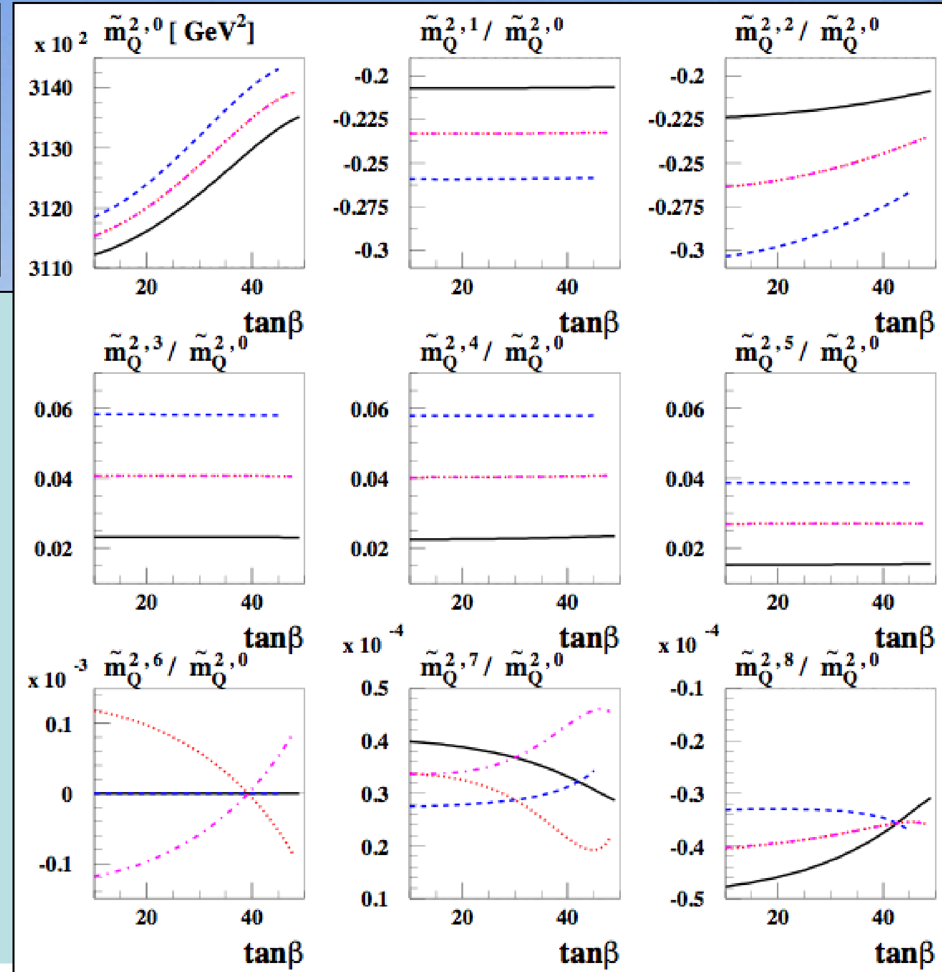
Heavy Higgs



B_s mixing

J.E. + Lee + Pilaftsis: arXiv:0708.2078

Supersymmetric Flavour Geometry



- Expand scalar mass^2 matrices in complete basis derived from Yukawa couplings:

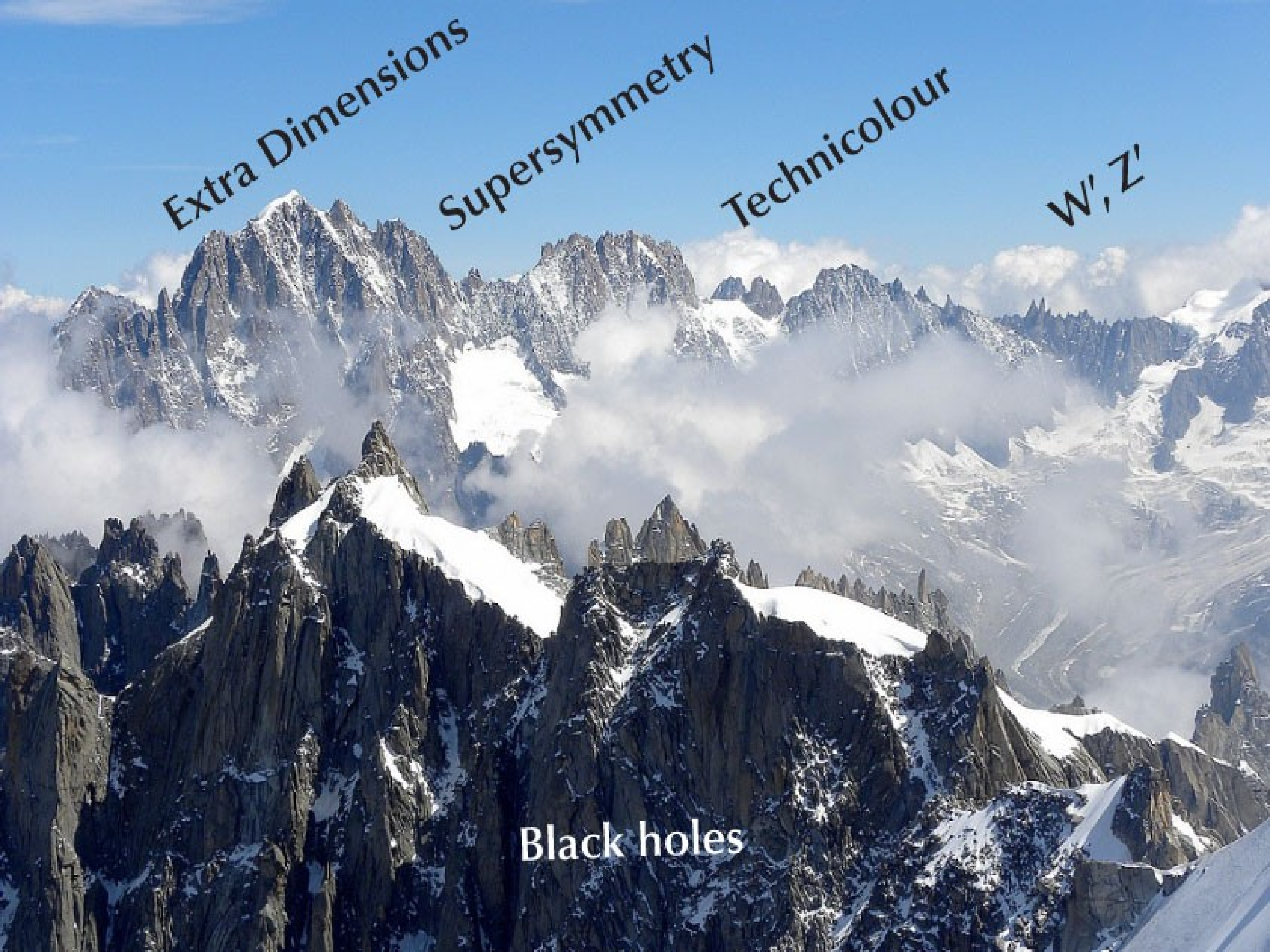
$$\widetilde{\mathbf{M}}^2_Q(M_X) \;=\; \sum_{I=0}^{8} \widetilde{m}^{2,I}_Q(M_X)\,\mathbf{H}^Q_I(M_X)$$

where:

$$\left\{\mathbf{H}^Q_I\right\} = \Big\{\mathbf{1}_3\,,\ \mathbf{h}_u^\dagger\mathbf{h}_u\,,\ \mathbf{h}_d^\dagger\mathbf{h}_d\,,\ (\mathbf{h}_u^\dagger\mathbf{h}_u)^2\,,\ (\mathbf{h}_d^\dagger\mathbf{h}_d)^2\,,\ [\mathbf{h}_u^\dagger\mathbf{h}_u\,,\mathbf{h}_d^\dagger\mathbf{h}_d]_+\,,\ i[\mathbf{h}_u^\dagger\mathbf{h}_u\,,\mathbf{h}_d^\dagger\mathbf{h}_d]_-\,,\ \mathbf{h}_u^\dagger\mathbf{h}_u\mathbf{h}_d^\dagger\mathbf{h}_d\mathbf{h}_u^\dagger\mathbf{h}_u\,,\ \mathbf{h}_d^\dagger\mathbf{h}_d\mathbf{h}_u^\dagger\mathbf{h}_u\mathbf{h}_d^\dagger\mathbf{h}_d\Big\}\,.$$

- Use RGEs to study magnitudes in MCPMFV
- **Use data to constrain coefficients**

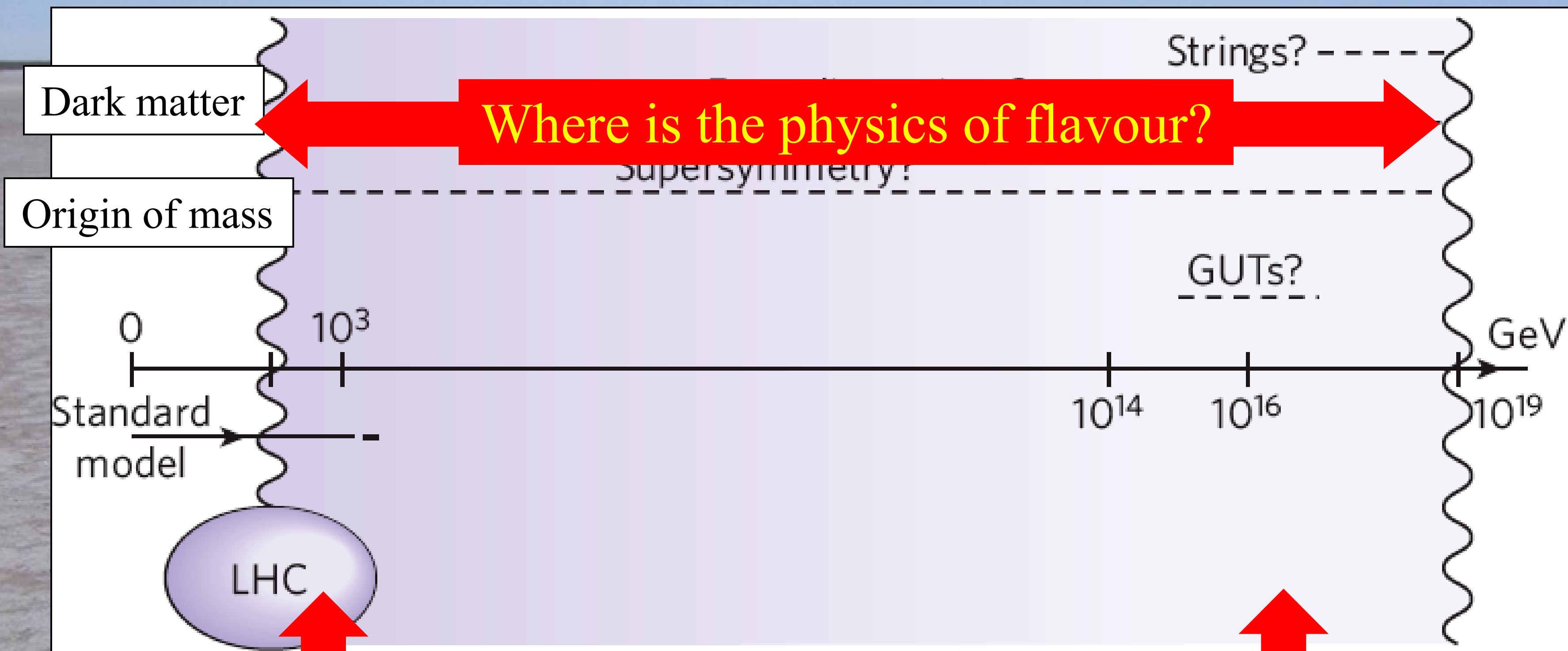
JE + Hodgkinson +Lee + Pilaftsis: arXiv 0911.3611


Extra Dimensions
Supersymmetry
Technicolour
W', Z'
Black holes

The Dogs that did (not) Bark

- In the quark sector:
  - CKM model describes perfectly (?) the available data on quark mixing and CP violation
  - Passes consistency tests
- In the lepton sector:
  - MNS model describes neutrino mixing
  - No consistency tests
  - Muon anomalous magnetic moment may suggest new physics at the TeV scale

At what Energy is the New Physics?



A lot accessible to the LHC

Some accessible only indirectly

Post-LHC

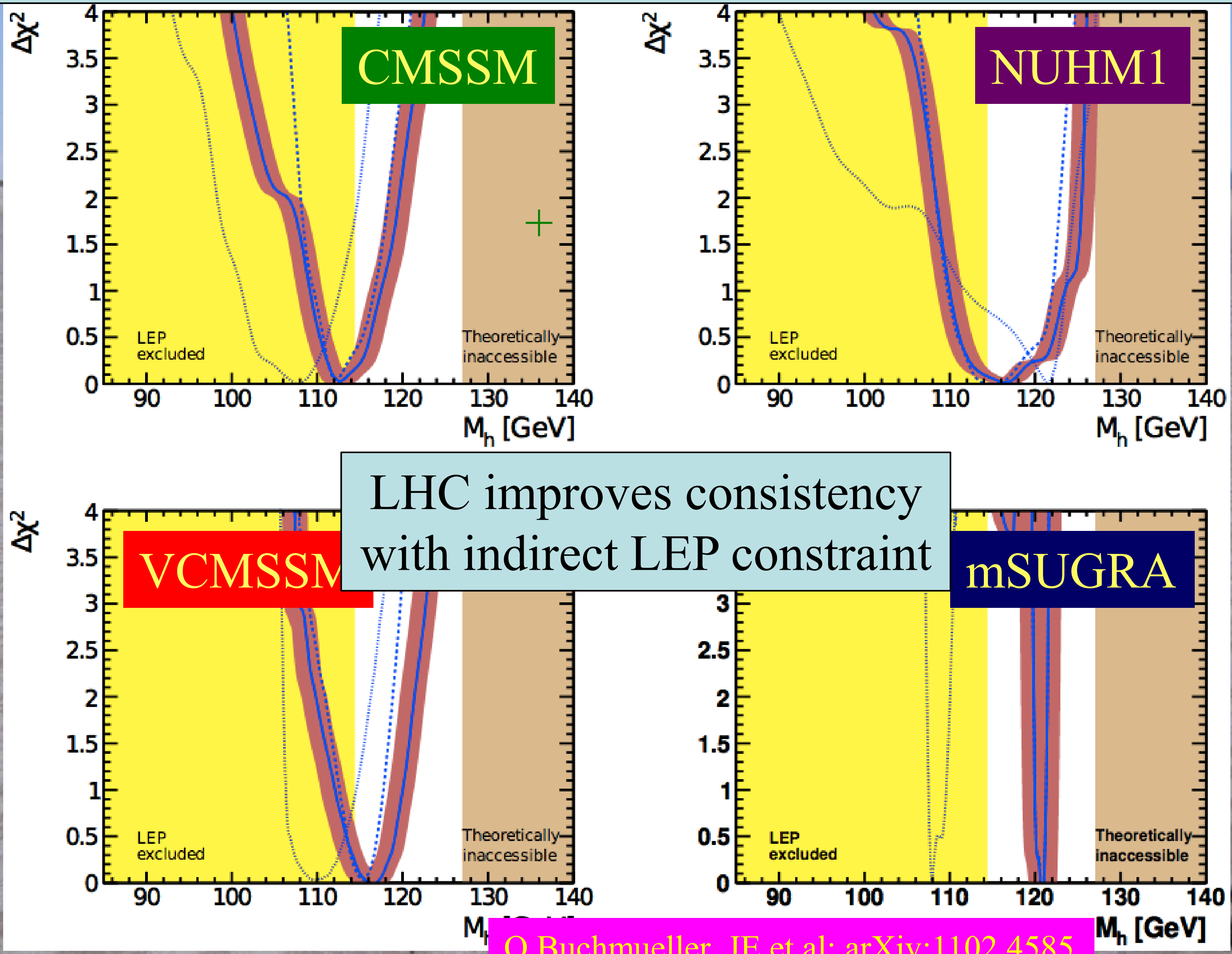
Best-Fit Points Compared

Model	Minimum χ^2	Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	M_h (no LEP) (GeV)
CMSSM	(21.3)	(32%)	(320)	(60)	(-170)	(11)	(107.9)
with CMS	22.0	29%	370	80	-340	14	112.6
with ATLAS	24.9	16%	400	100	-430	16	112.8
NUHM1	(19.3)	(31%)	(260)	(110)	(1010)	(8)	(121.9)
with CMS	20.9	28%	380	90	70	14	113.5
with ATLAS	23.3	18%	490	110	-630	25	116.5
VCMSSM	(22.5)	(31%)	(300)	(60)	(30)	(9)	(109.3)
with CMS	23.8	25%	340	70	50	9	115.5
with ATLAS	27.1	13%	390	90	70	11	117.0
mSUGRA	(29.4)	(6.1%)	(550)	(230)	(430)	(28)	(107.8)
with CMS	29.4	6.1%	550	230	430	28	121.2
with ATLAS	30.9	5.7%	550	230	430	28	121.2

No significant reductions in fit probabilities:
No significant tension or conflict

O.Buchmueller, JE et al: arXiv:1102.4585

Higgs Mass Revisited



LHC improves consistency with indirect LEP constraint

O.Buchmueller, JE et al: arXiv:1102.4585

No Issue of Fine-Tuning

- Standard measure of fine-tuning:

	Pre-LHC	After CMS, ATLAS 0l
CMSSM	100	120, 140
NUHM1	250	230, 310
VCMSSM	130	110, 140
mSUGRA	250	250, 250

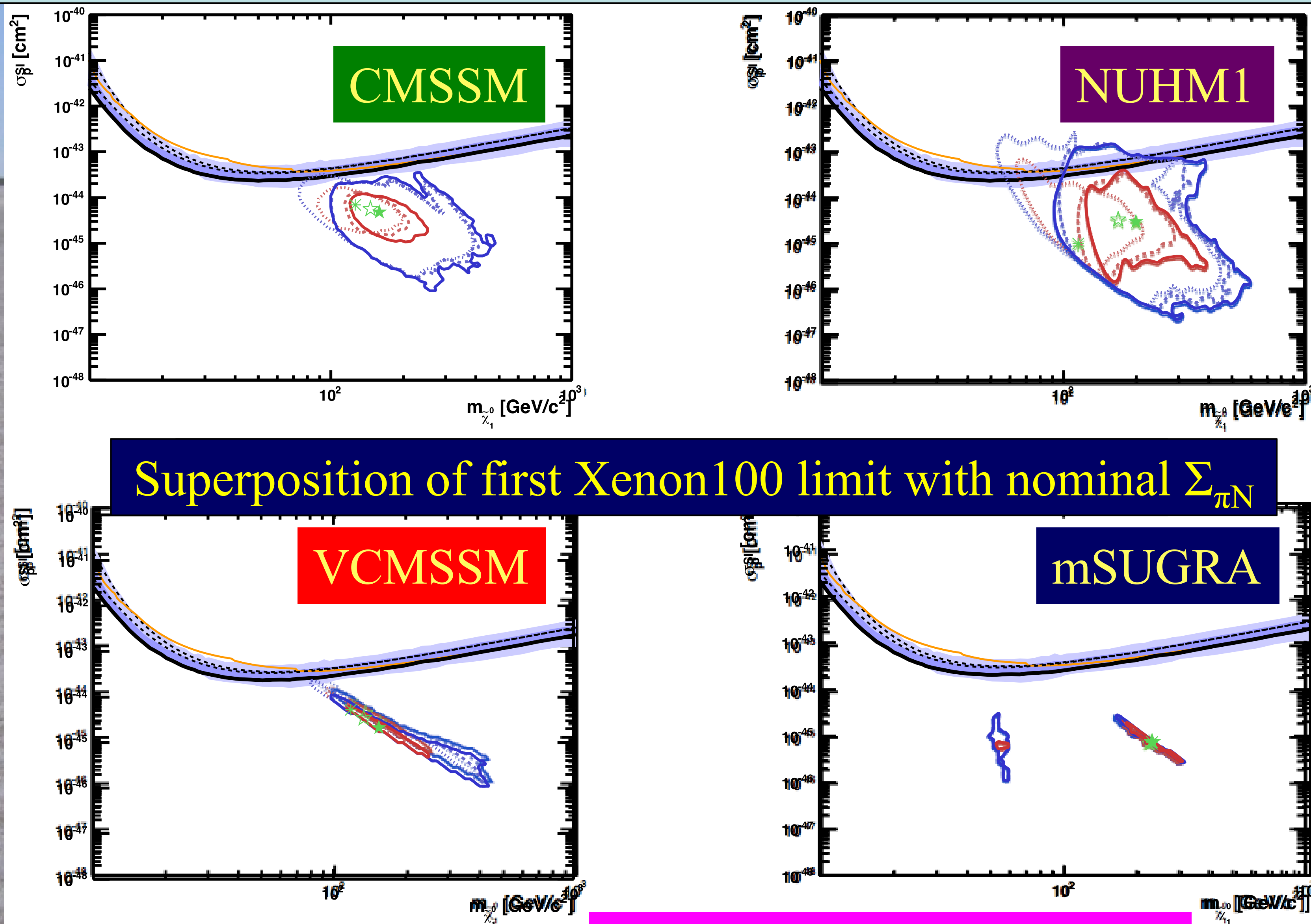
- **No significant increase**

O.Buchmueller, JE et al: arXiv:1102.4585

Contrast Strumia: arXiv:1101.2195

Post-LHC

Dark Matter Scattering Revisited



Superposition of first Xenon100 limit with nominal $\Sigma_{\pi N}$

O.Buchmueller, JE et al: arXiv:1102.4585

Importance of the π-N σ Term ($\Sigma_{\pi N}$)

- Higgs exchange important for spin-independent DM scattering
- **Sensitive to $\langle N|\bar{s}s|N\rangle$**
- Baryon masses: $\sigma_0 = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$

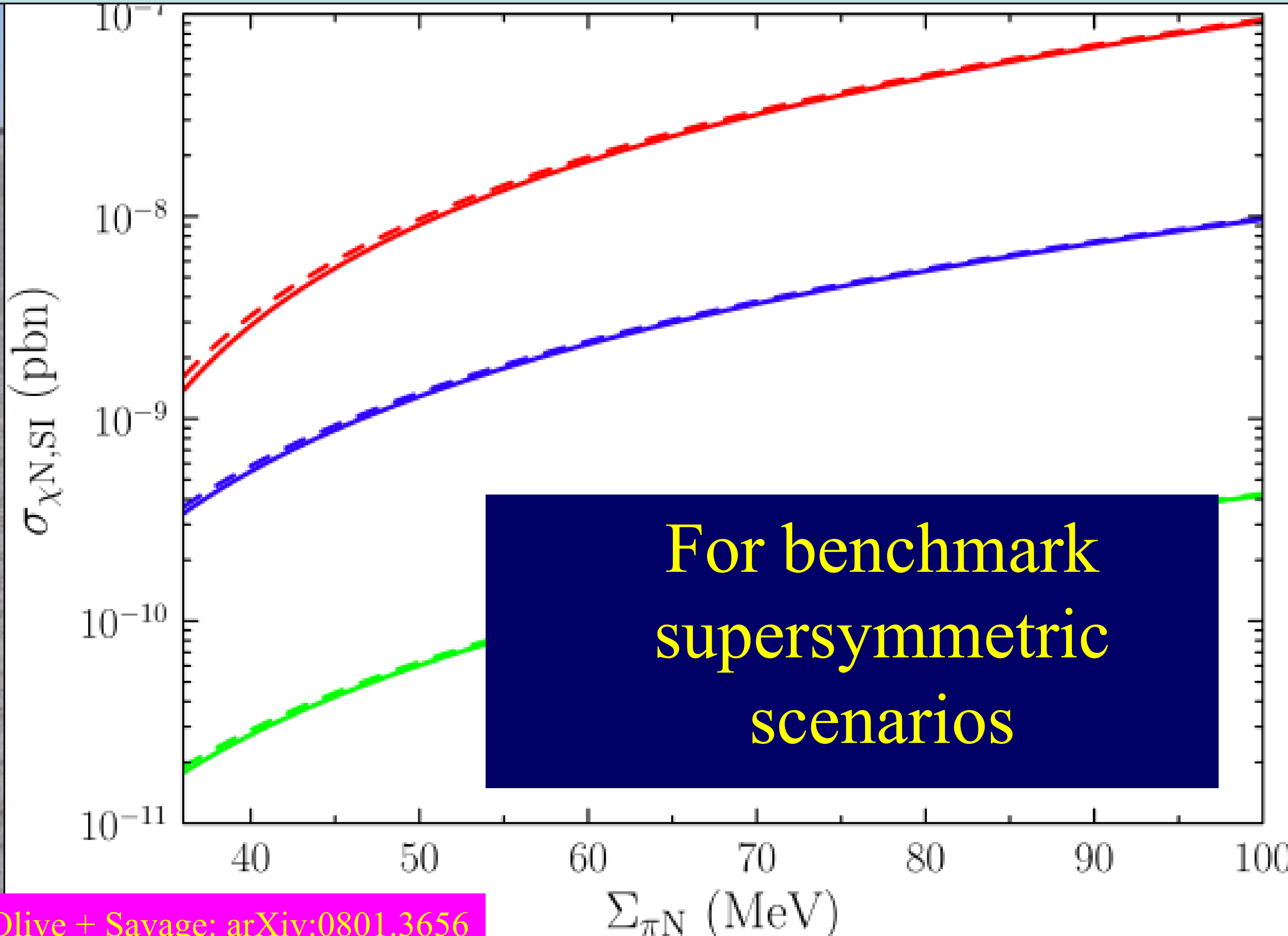
  $$= 36 \pm 7 \text{ MeV}$$

- Cf, $\Sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d|N\rangle$
- Strangeness ratio $y = \langle N|2\bar{s}s|N\rangle / \langle N|\bar{u}u + \bar{d}d|N\rangle$

  $$= 1 - \sigma_0/\Sigma_{\pi N}$$

- Some experiments suggest large value of $\Sigma_{\pi N} = 64 \pm 8$ MeV, hence y large
- Some lattice calculations suggest y small

Sensitivity to π-N Scattering σ Term

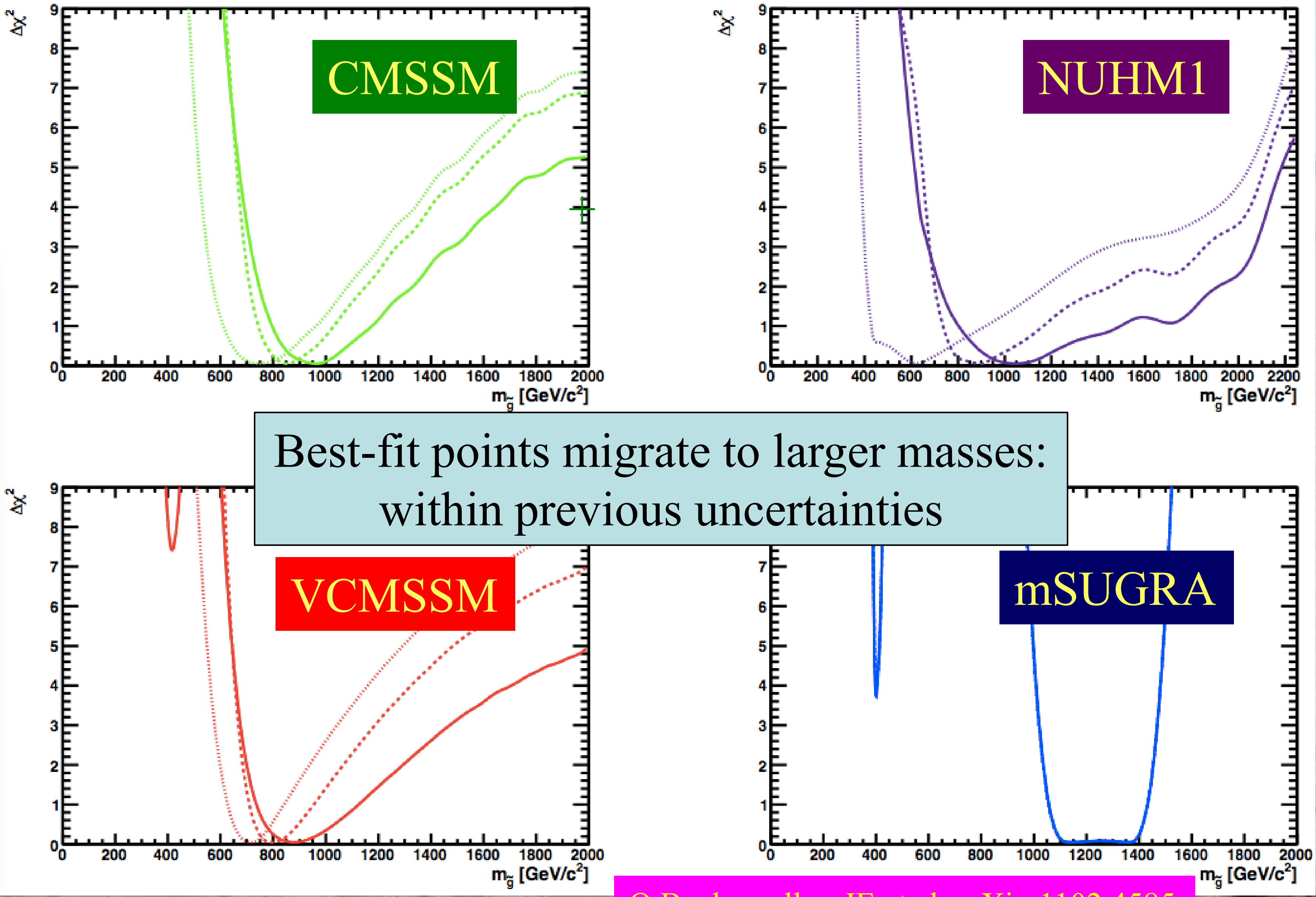


For benchmark supersymmetric scenarios

JE + Olive + Savage: arXiv:0801.3656

Post-LHC

Gluino Mass Revisited



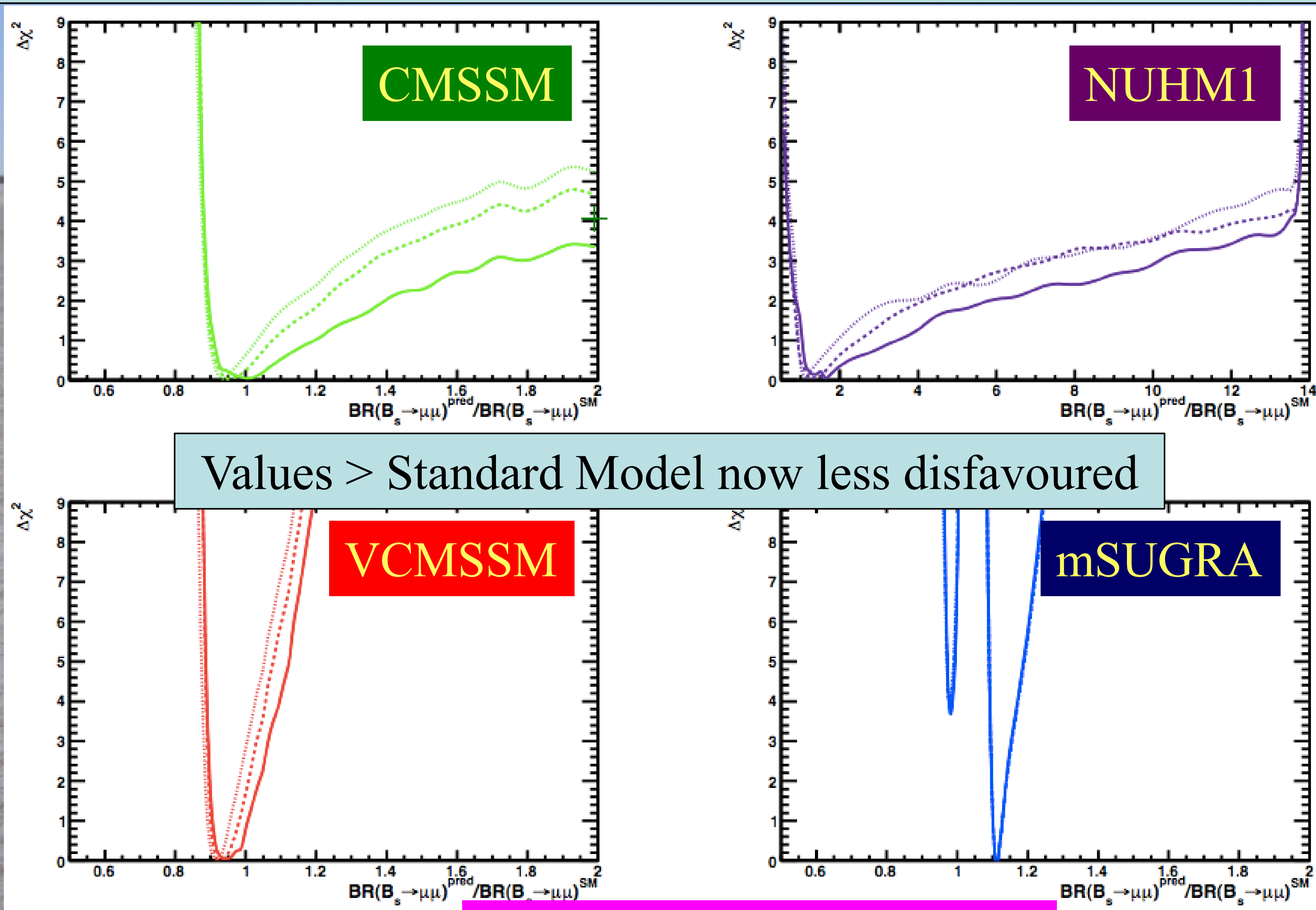
Best-fit points migrate to larger masses: within previous uncertainties

O.Buchmueller, JE et al: arXiv:1102.4585

Post-LHC

Rare decay

BR($B_s \rightarrow \mu^+\mu^-$) Revisited

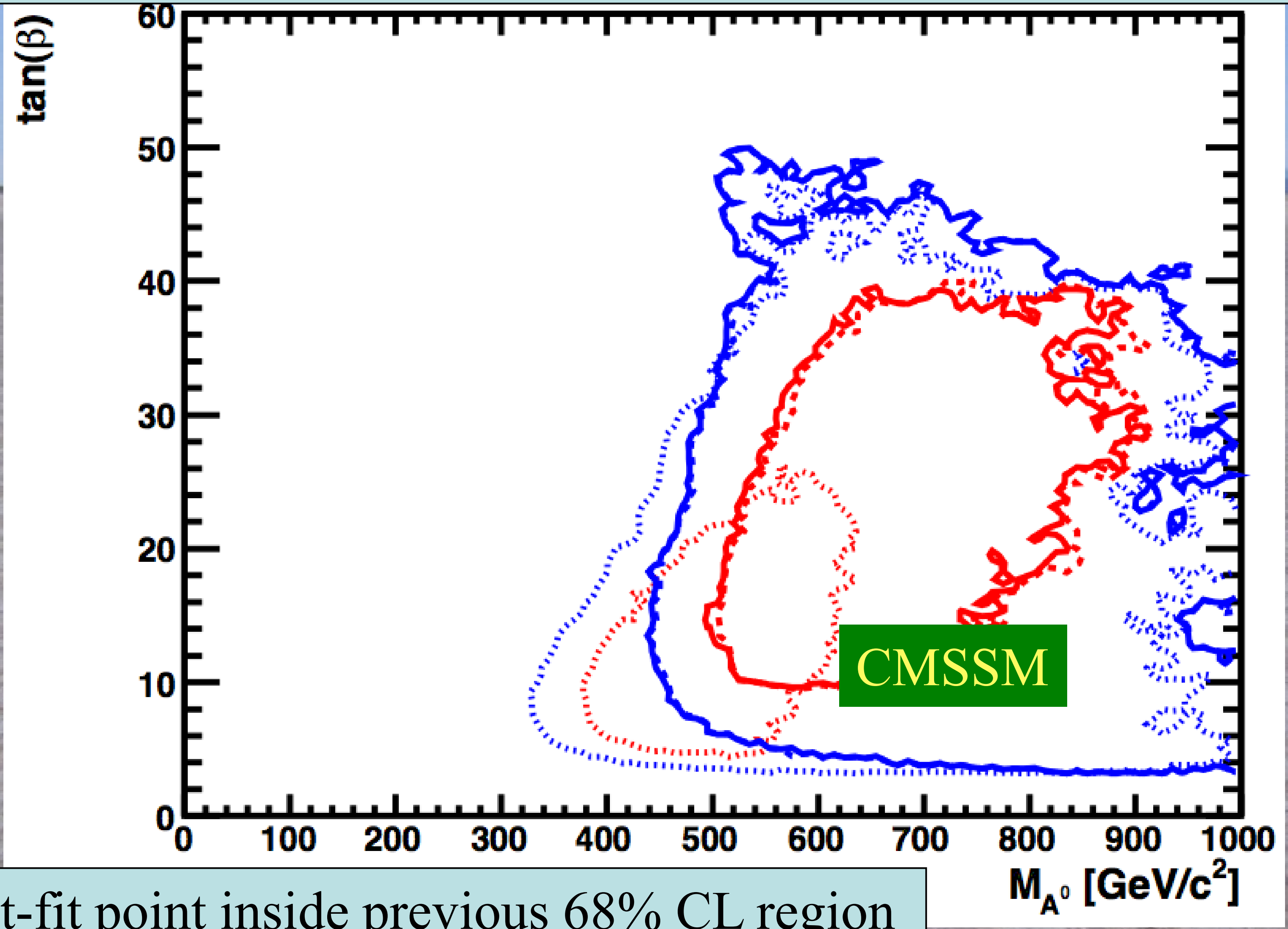


Values > Standard Model now less disfavoured

O.Buchmueller, JE et al: arXiv:1102.4585

Full LHC 2010 data

CMSSM (M_A, tan β) Plane Revisited

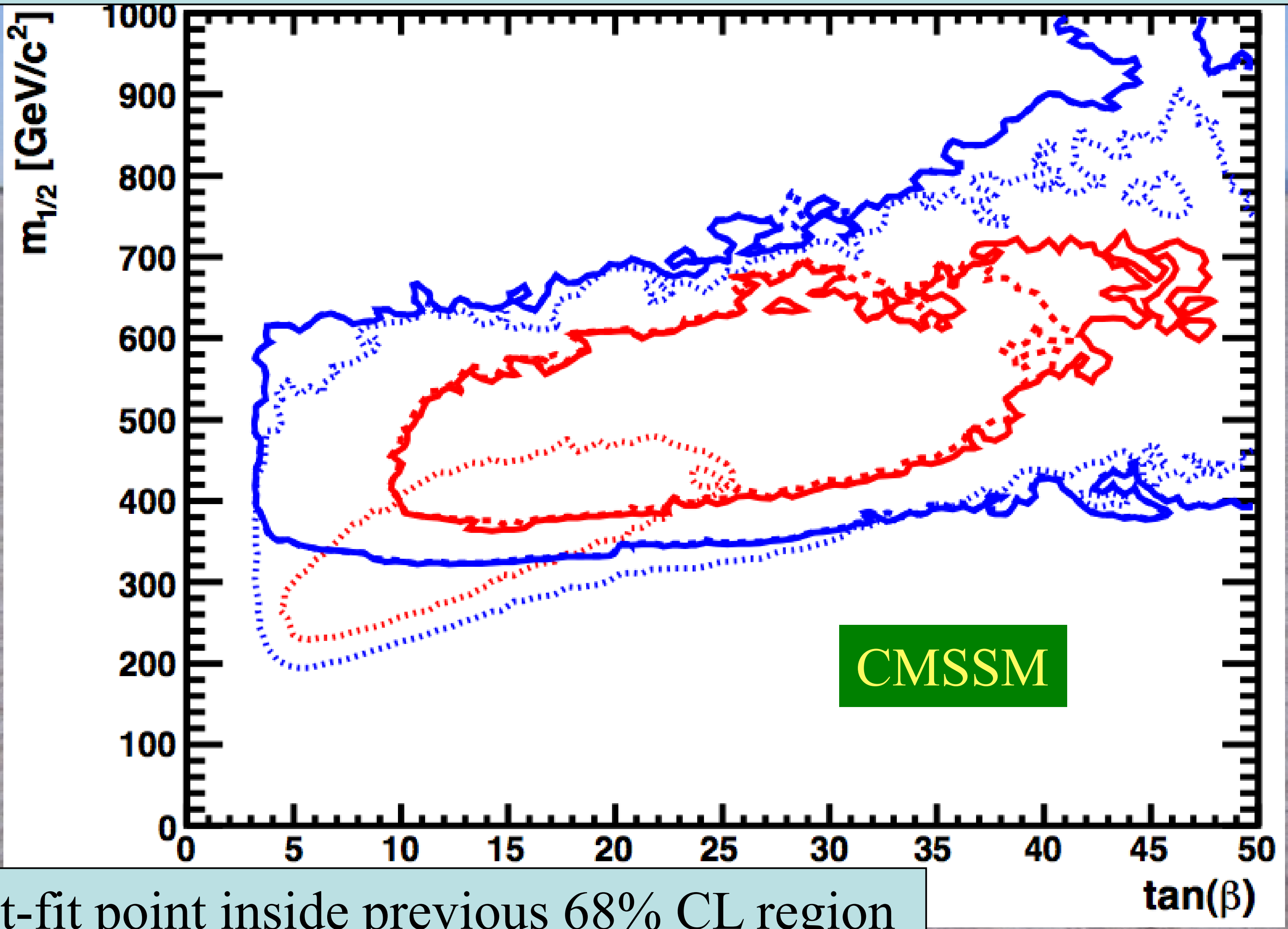


Best-fit point inside previous 68% CL region
➔ No significant tension or conflict

O.Buchmueller, JE et al: in preparation

Full LHC 2010 data

CMSSM ($\tan\beta$, $m_{1/2}$) Plane Revisited



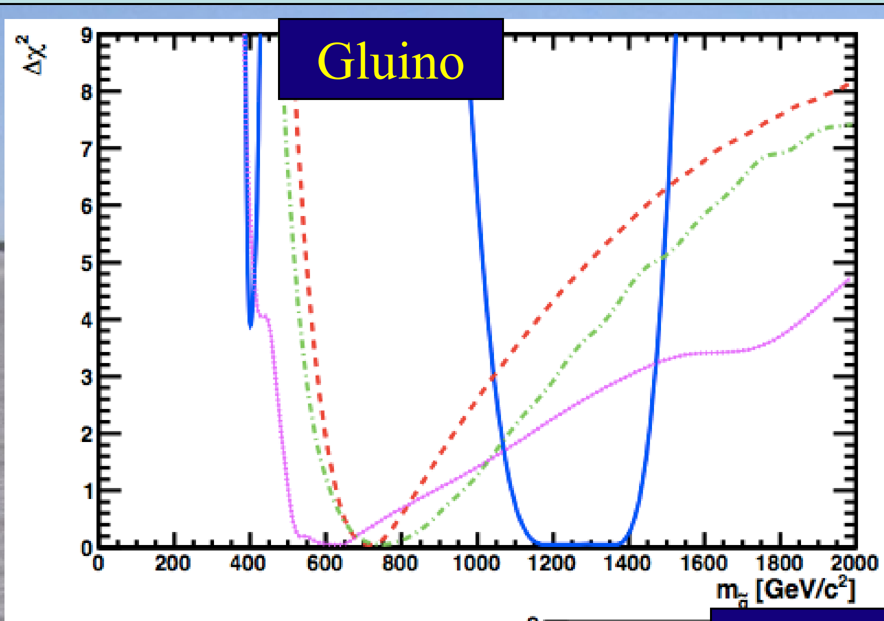
Best-fit point inside previous 68% CL region

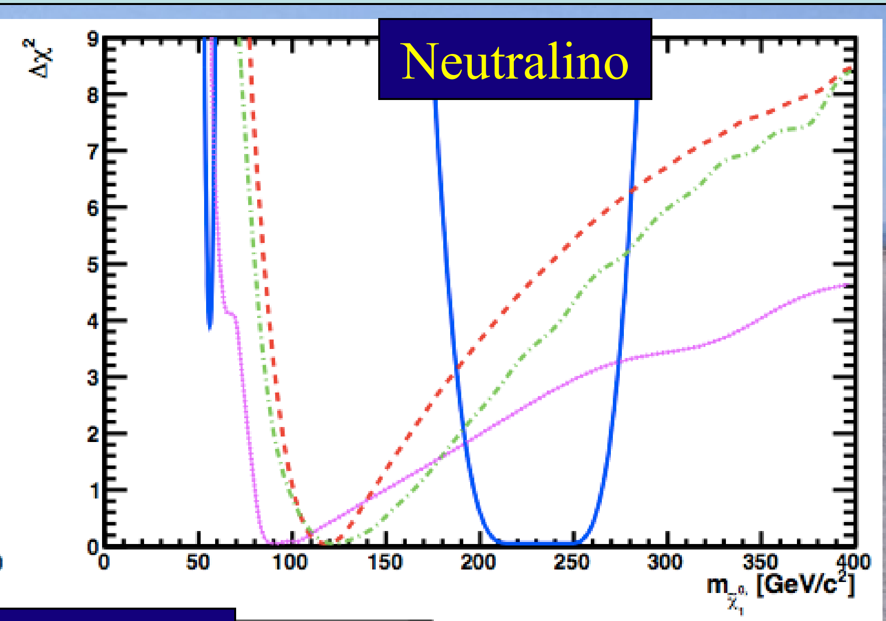
➔ No significant tension or conflict

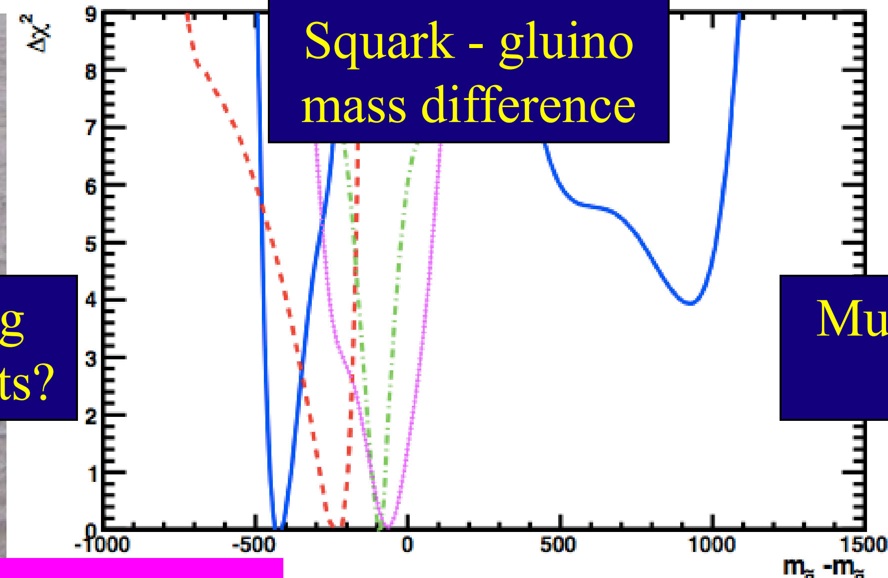
O.Buchmueller, JE et al: in preparation

Pre-LHC

Likelihood Functions for Sparticle Masses







Dijet + missing energy events?

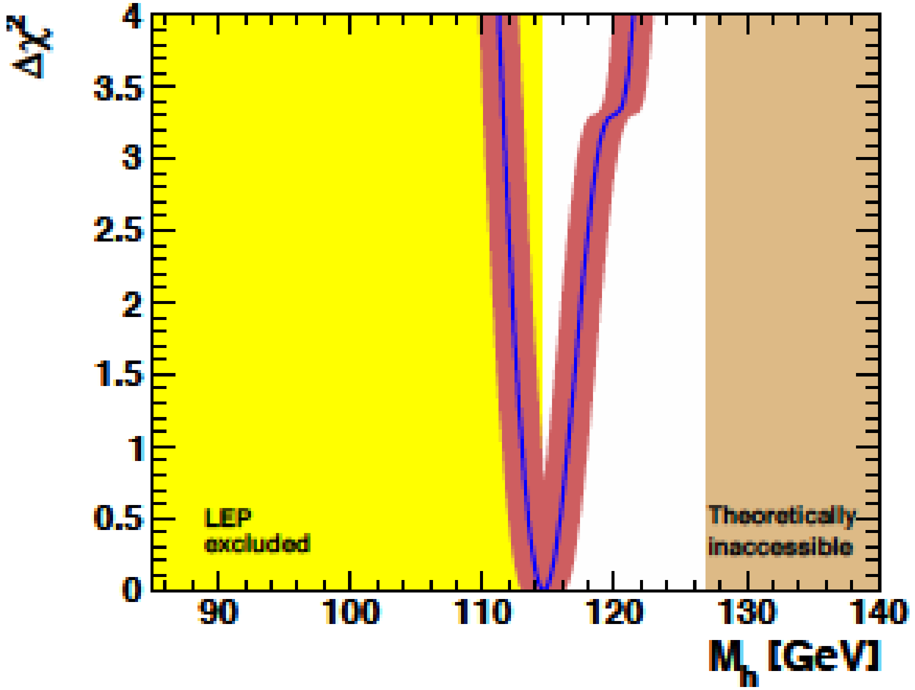
Multijet + missing energy events?

O.Buchmueller, JE et al: arXiv:1011.6118

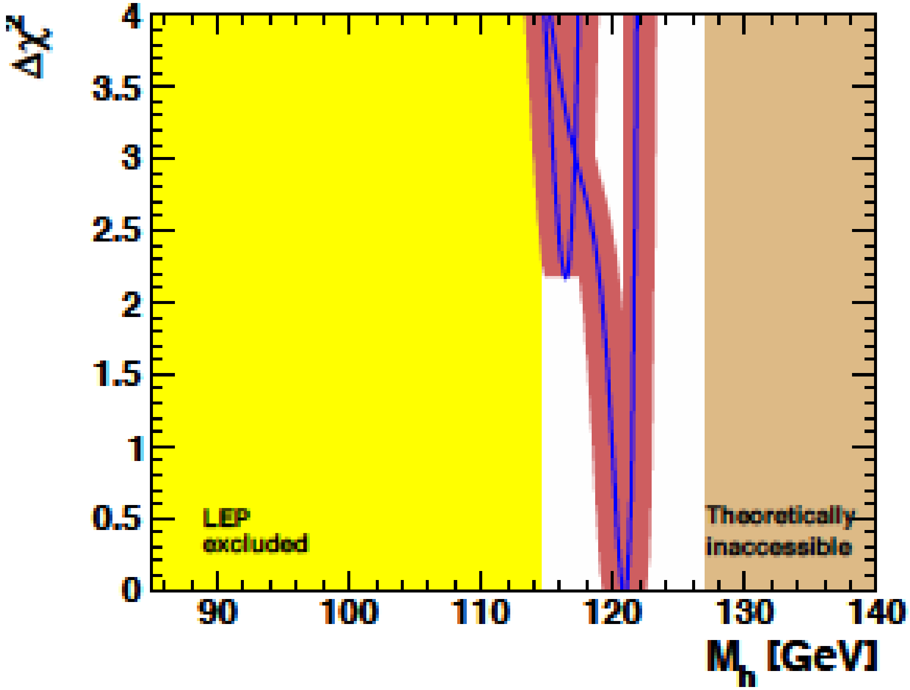
Pre-LHC

Likelihood Function for Higgs Mass

VCMSSM



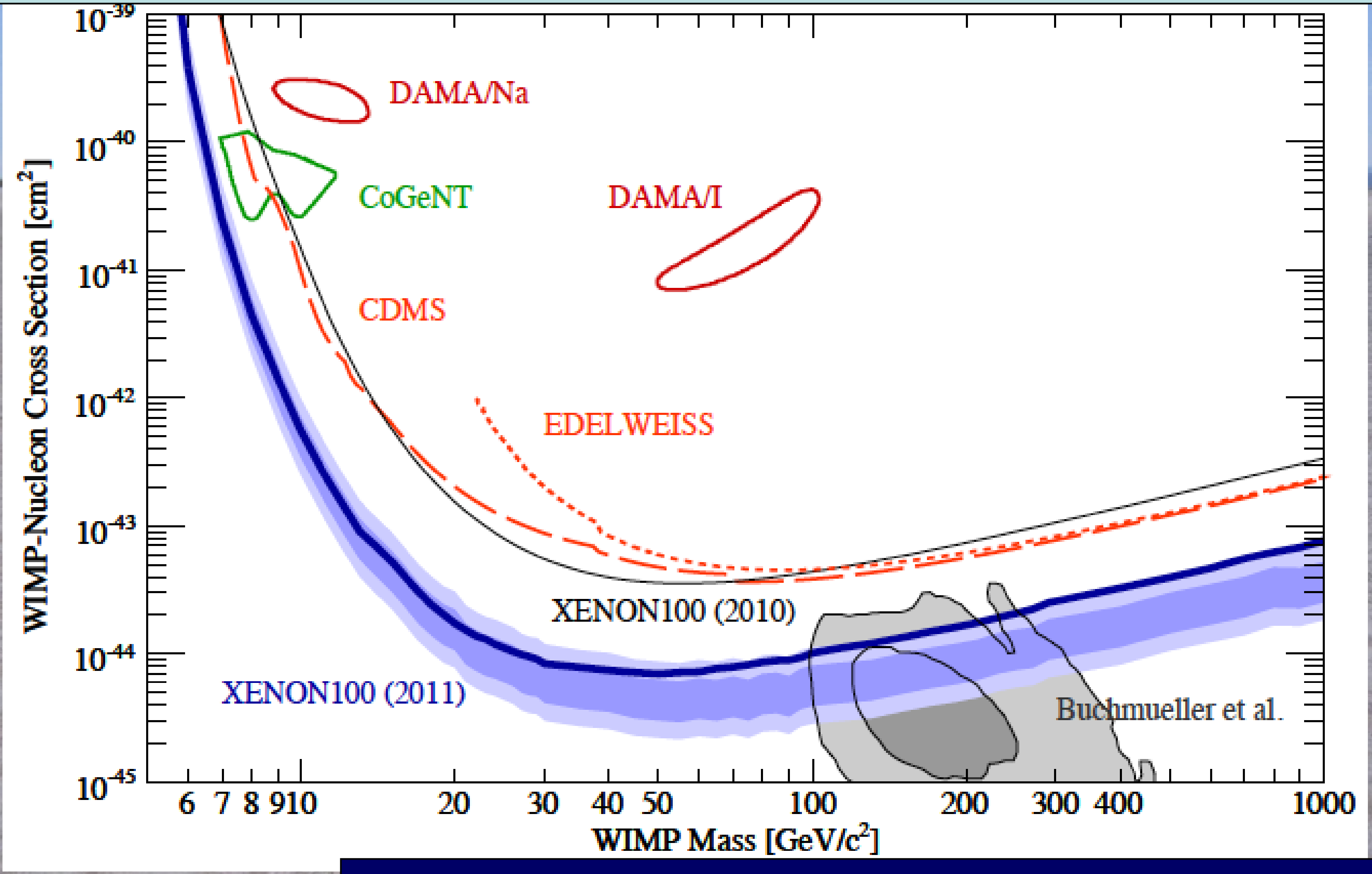
mSUGRA



With LEP constraint

O.Buchmueller, JE et al: arXiv:1011.6118

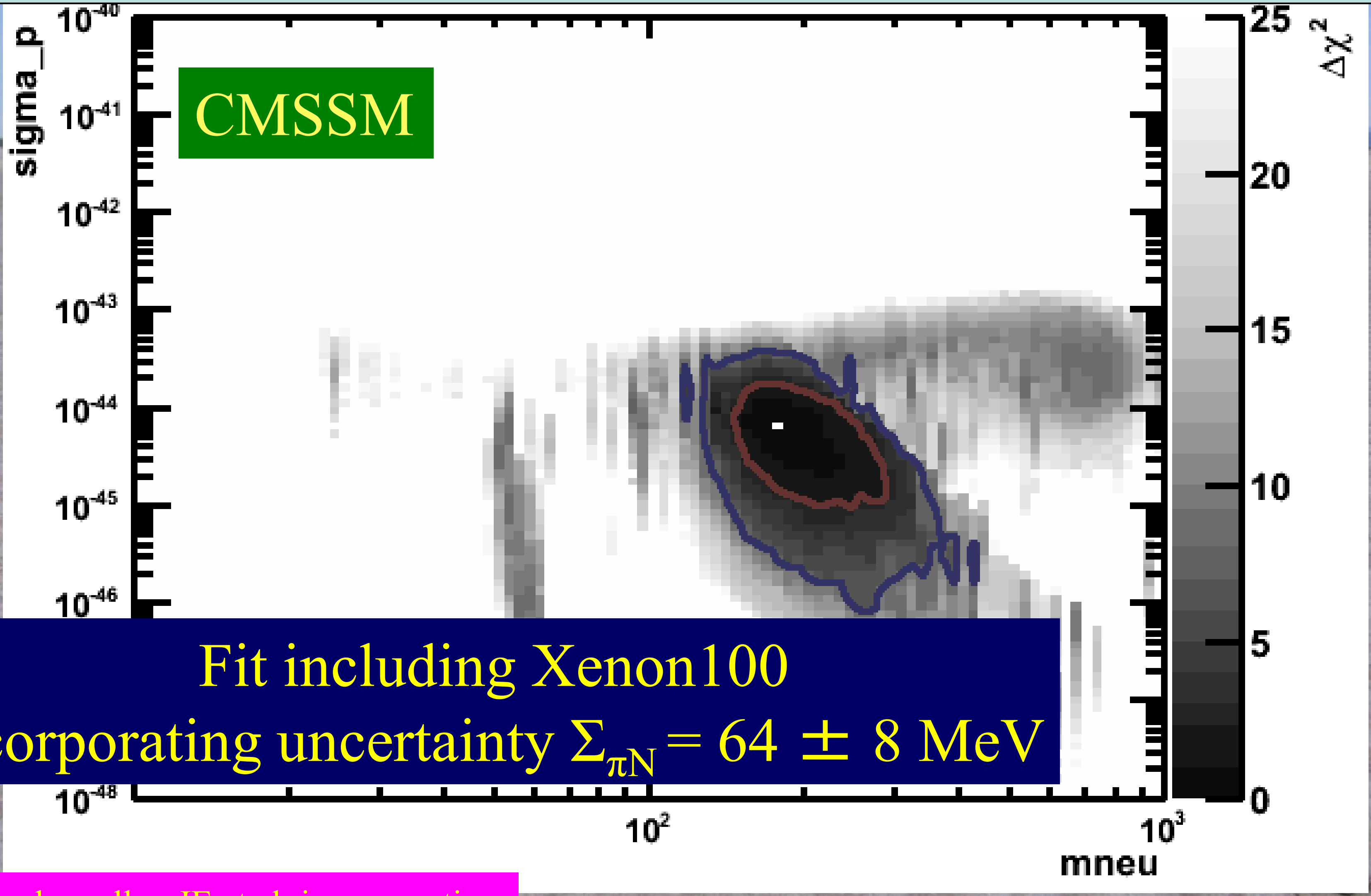
New Xenon100 Limit



Best available limit with 100 days of data

Aprile et al: arXiv:1104.2549

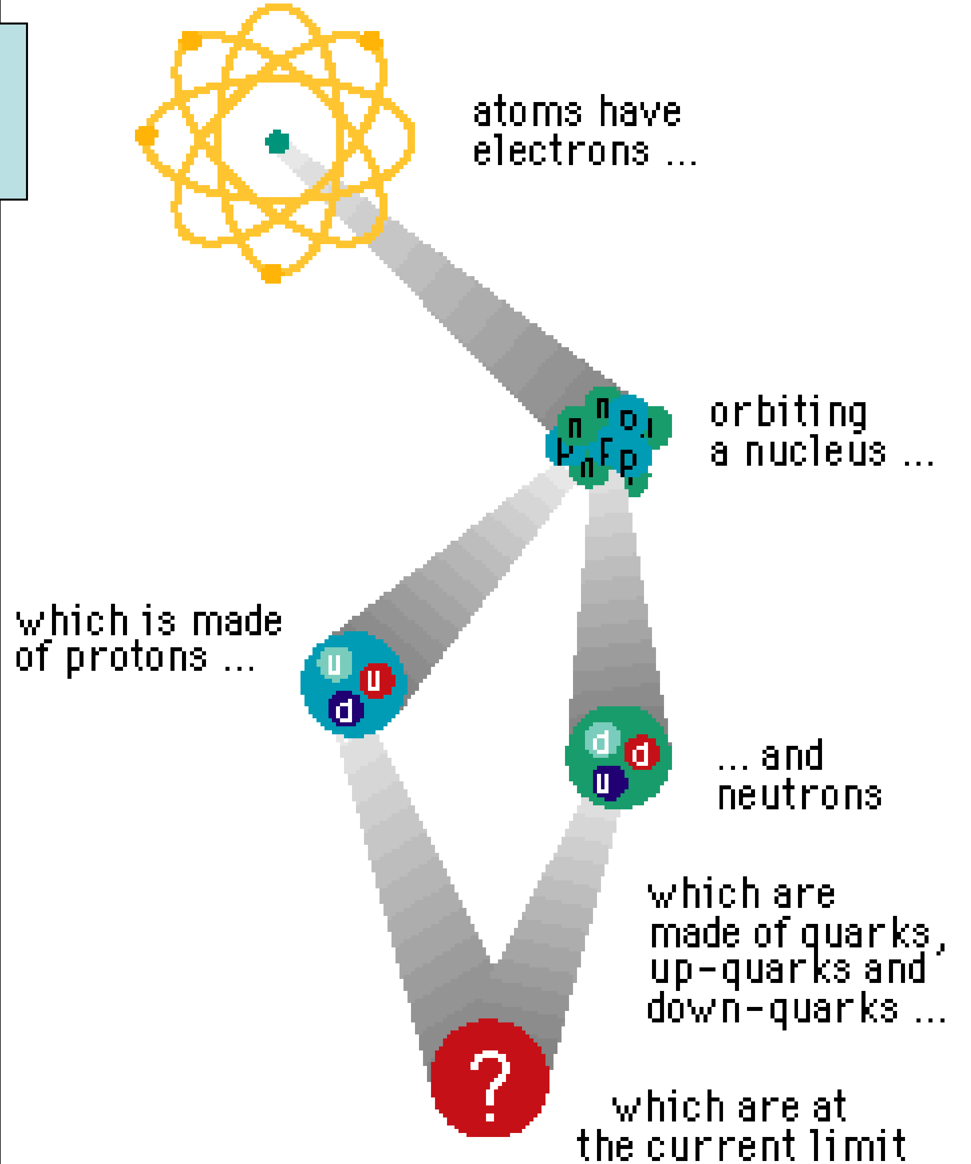
Impact of Xenon100 on LHC Fit



Fit including Xenon100
incorporating uncertainty $\Sigma_{\pi N} = 64 \pm 8$ MeV

O.Buchmueller, JE et al: in preparation

Inside Matter

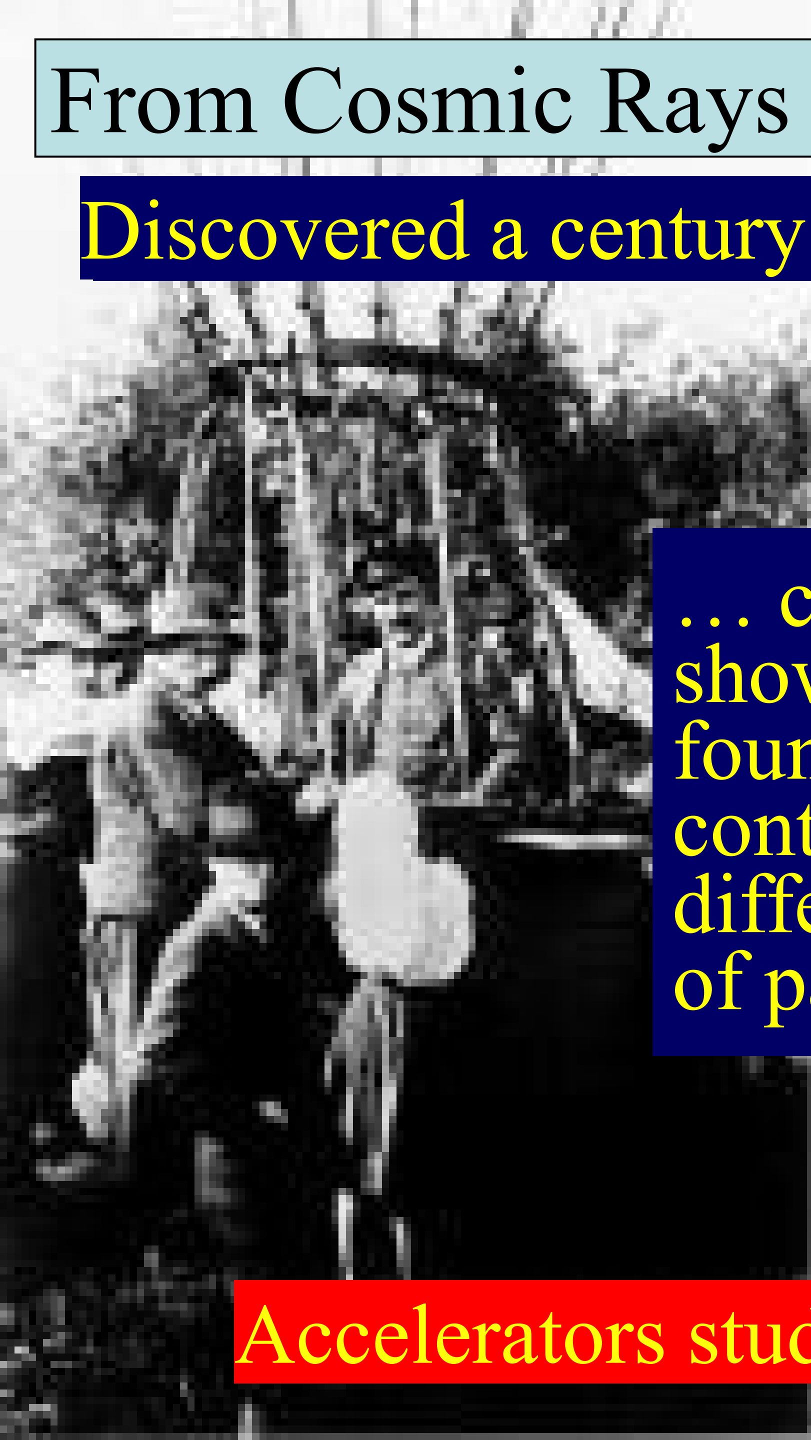


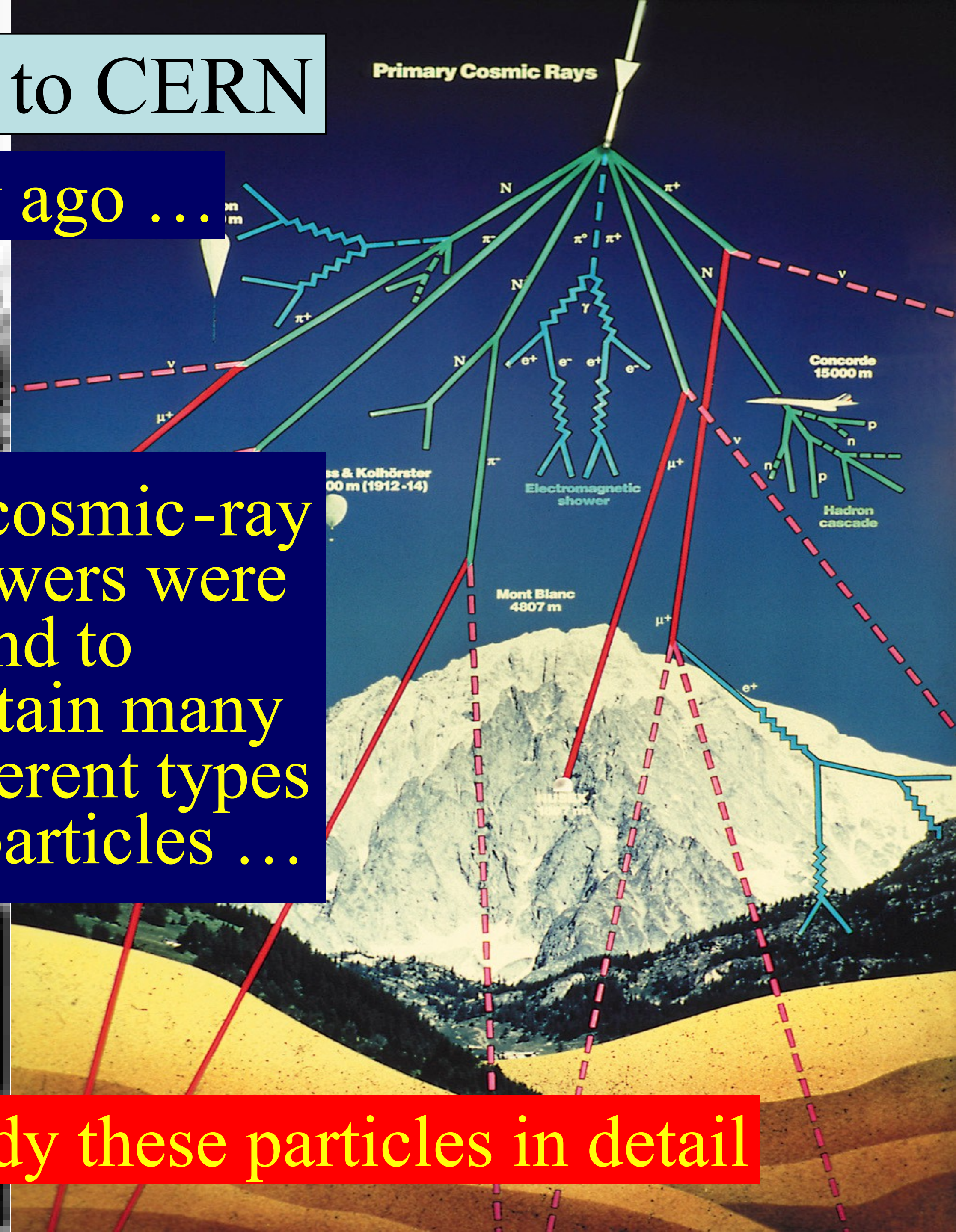
All matter is made of the same constituents

What are they?
What forces between them?

From Cosmic Rays to CERN

Discovered a century ago …

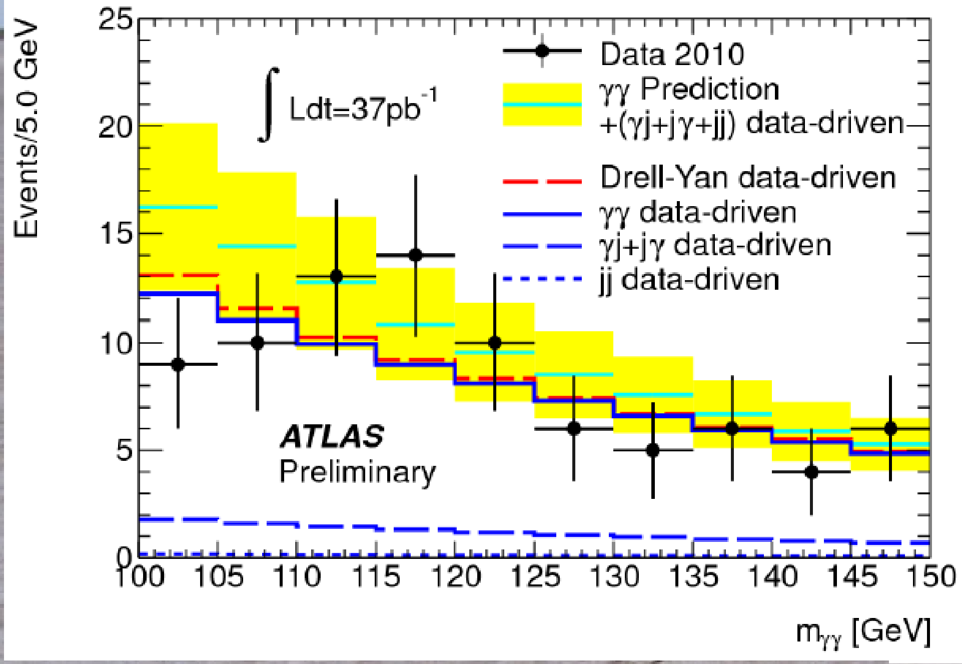


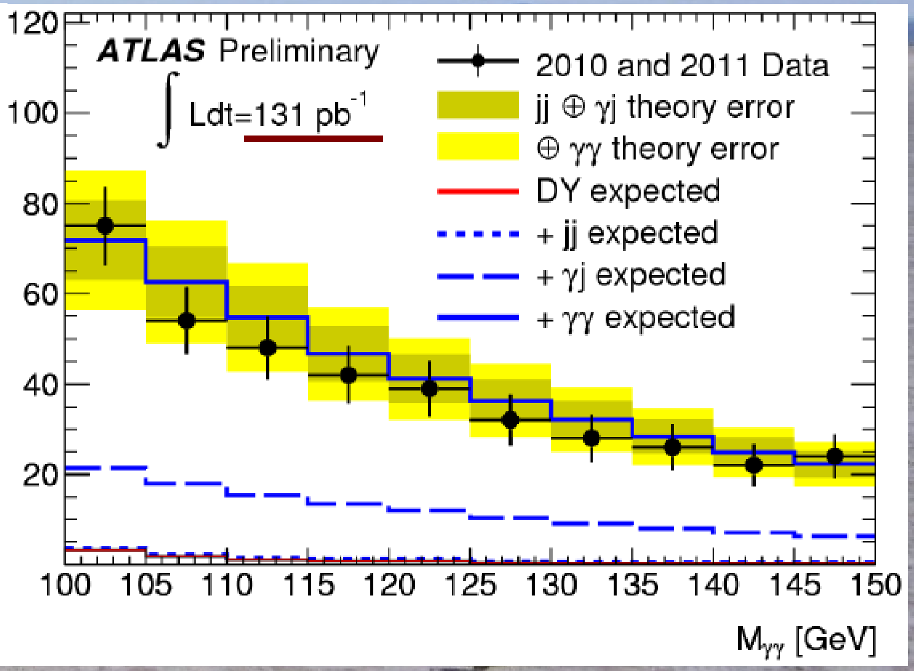


… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

Higgs ➔ γγ @ LHC

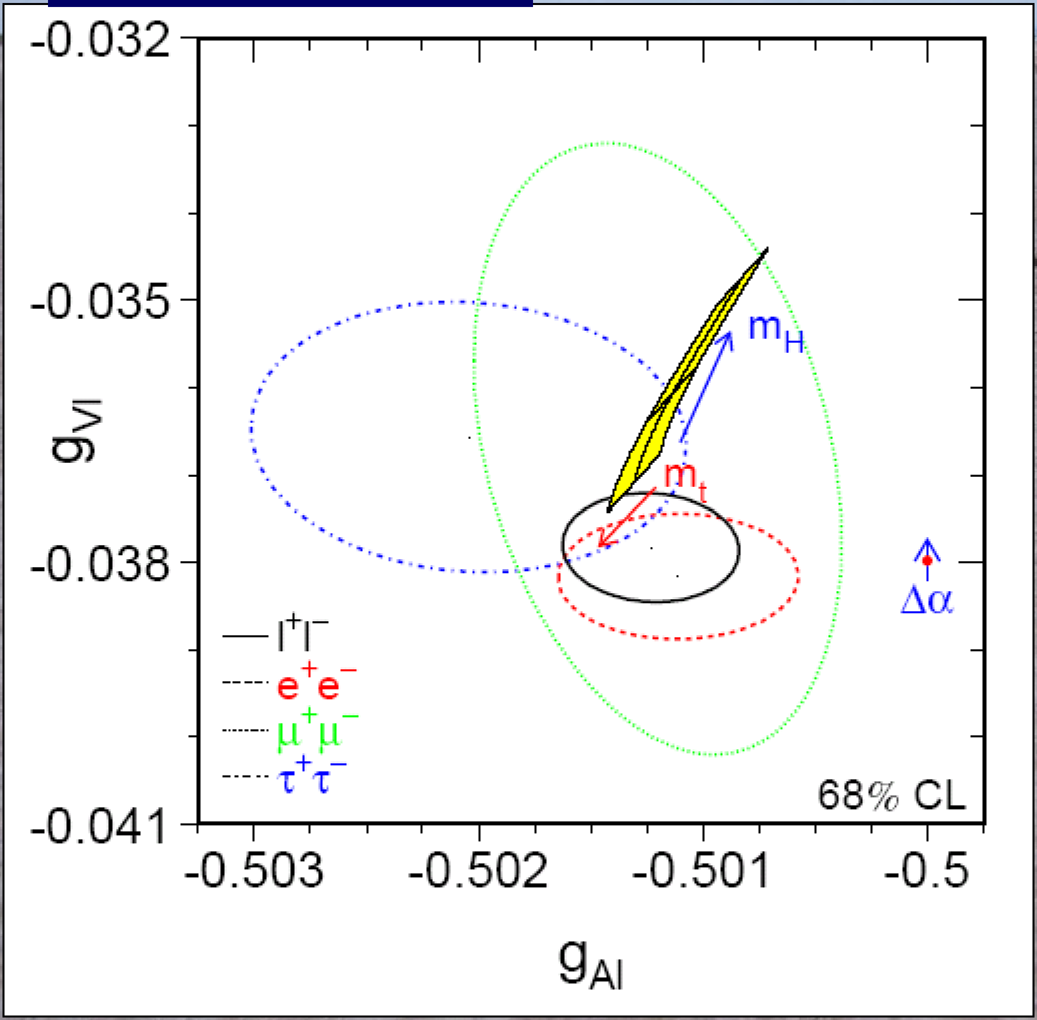




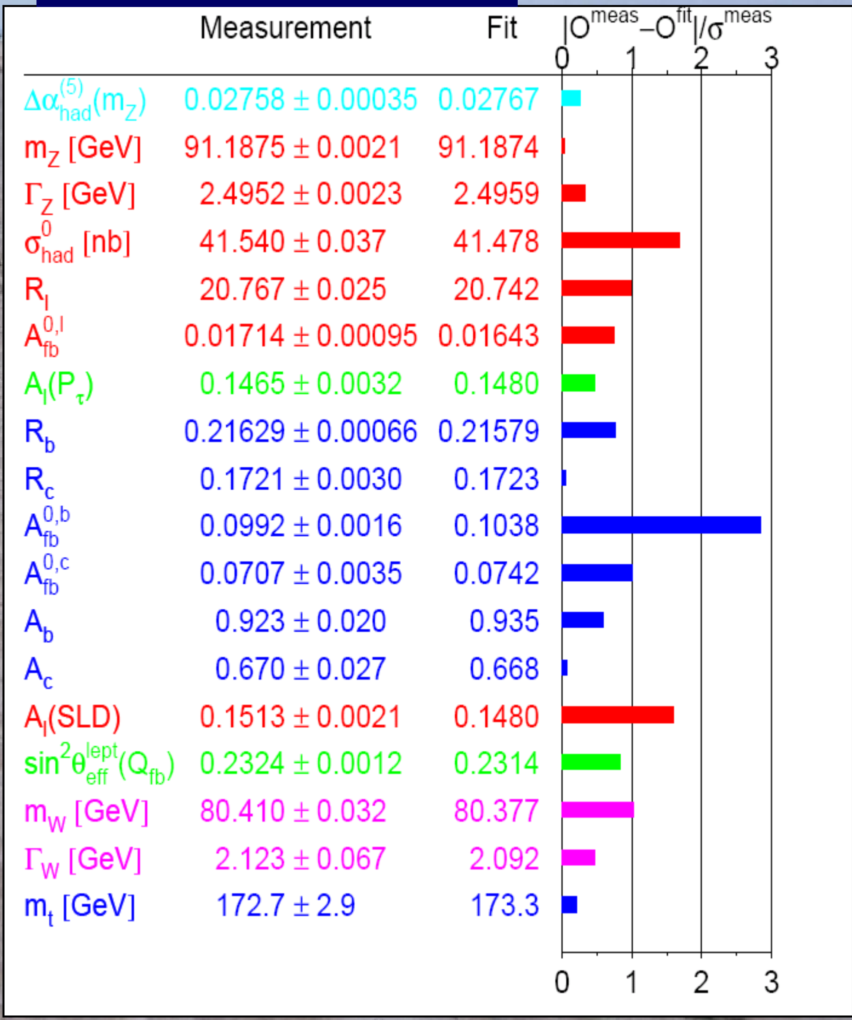
Last year's 'hint' has gone away

Precision Tests of the Standard Model

Lepton couplings



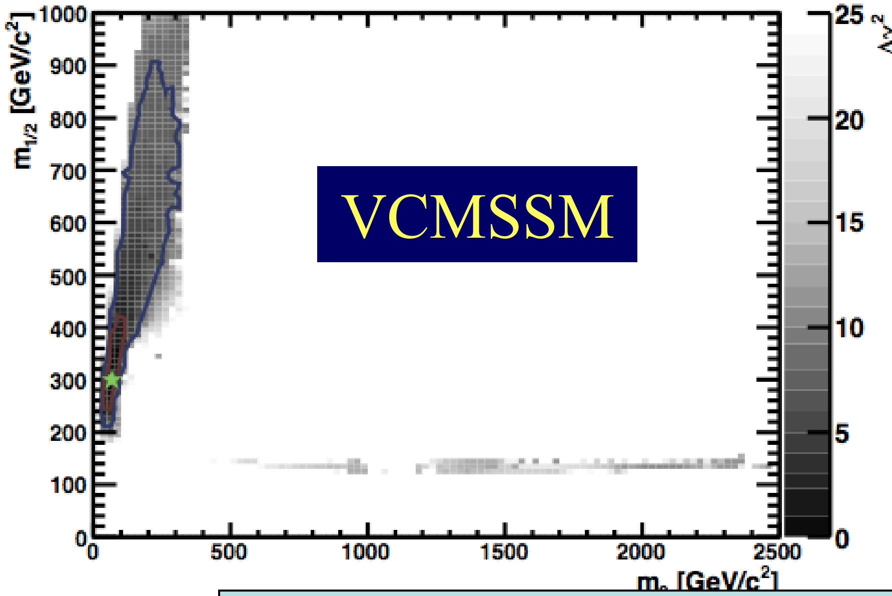
Pulls in global fit

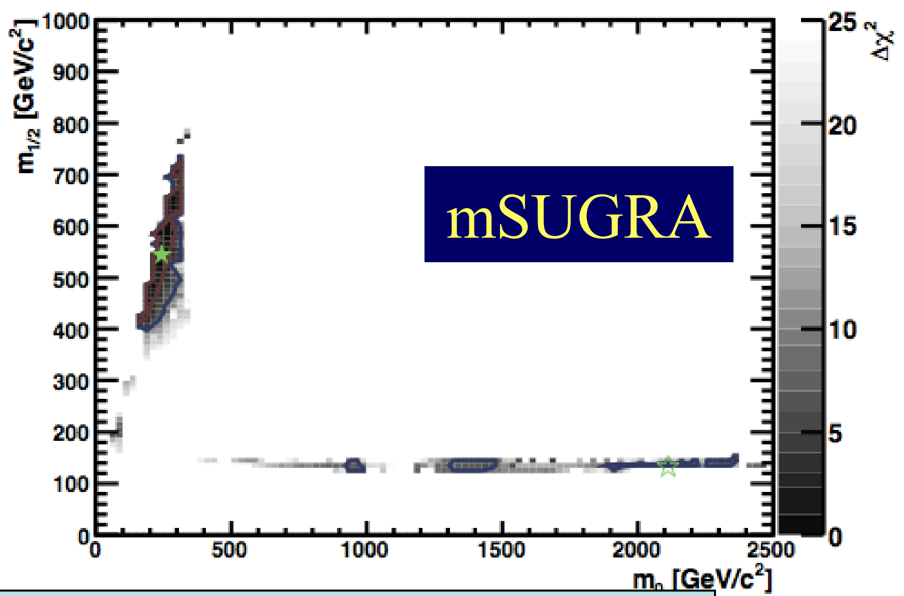


	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1480	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.410 ± 0.032	80.377	
Γ_W [GeV]	2.123 ± 0.067	2.092	
m_t [GeV]	172.7 ± 2.9	173.3	

Pre-LHC

Frequentist Fits to VCMSSM & mSUGRA





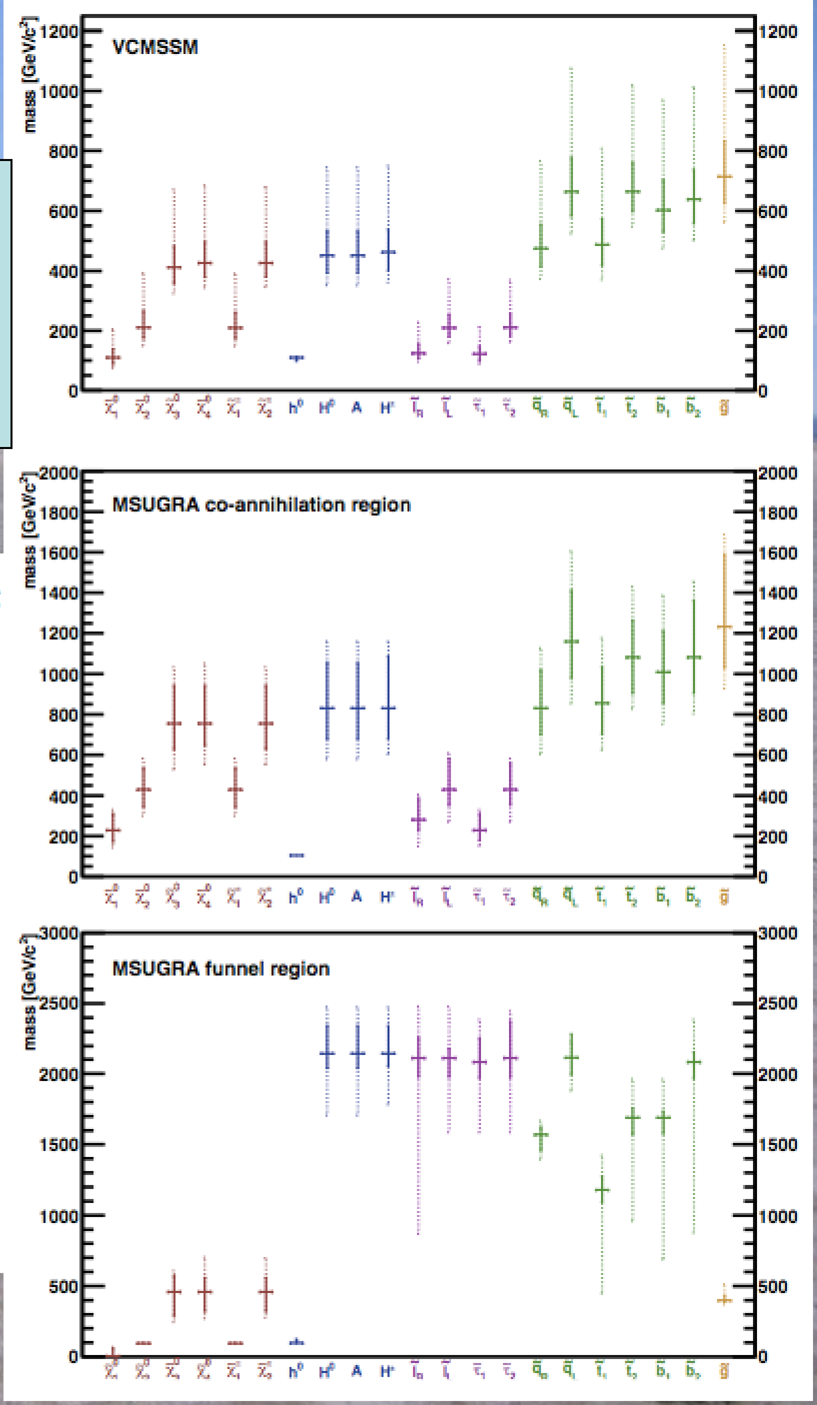
Best-fit parameters in different models

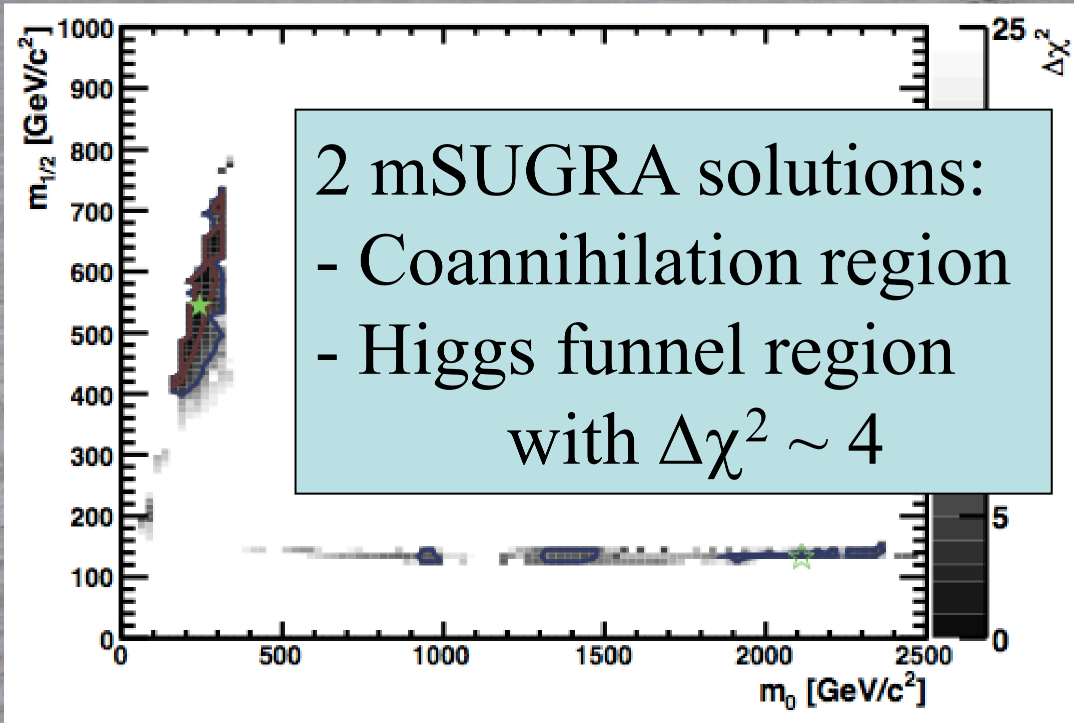
Model	Minimum χ^2	Probability	$m_{1/2}$	m_0	A_0	$\tan\beta$	M_h (no LEP)
mSUGRA	29.4	6.0%	550	230	430	28	107.7
	33.2	2.3%	130	2110	980	7	116.9
VCMSSM	22.5	31%	300	60	30	9	109.3
CMSSM	21.3	32%	320	60	-160	11	107.9
NUHM1	19.3	31%	260	100	1010	8	119.5

O.Buchmueller, JE et al: arXiv:1011.6118

Pre-LHC

Spectra with Ranges: VCMSSM, mSUGRA



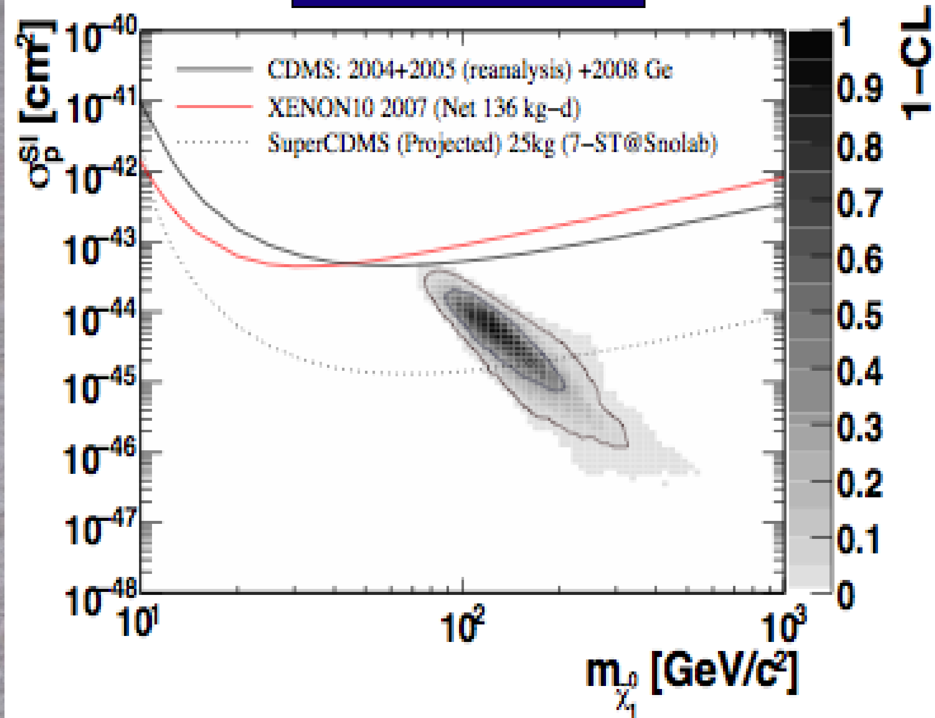


2 mSUGRA solutions:
- Coannihilation region
- Higgs funnel region with $\Delta\chi^2 \sim 4$

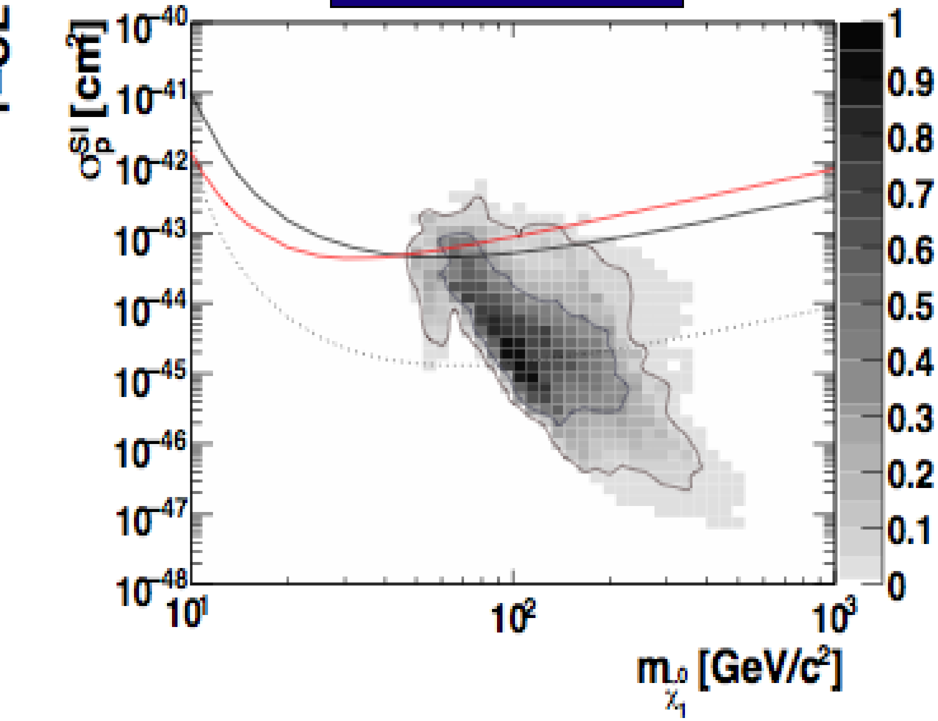
O.Buchmueller, JE et al: arXiv:1011.6118

Elastic Scattering Cross Sections

CMSSM



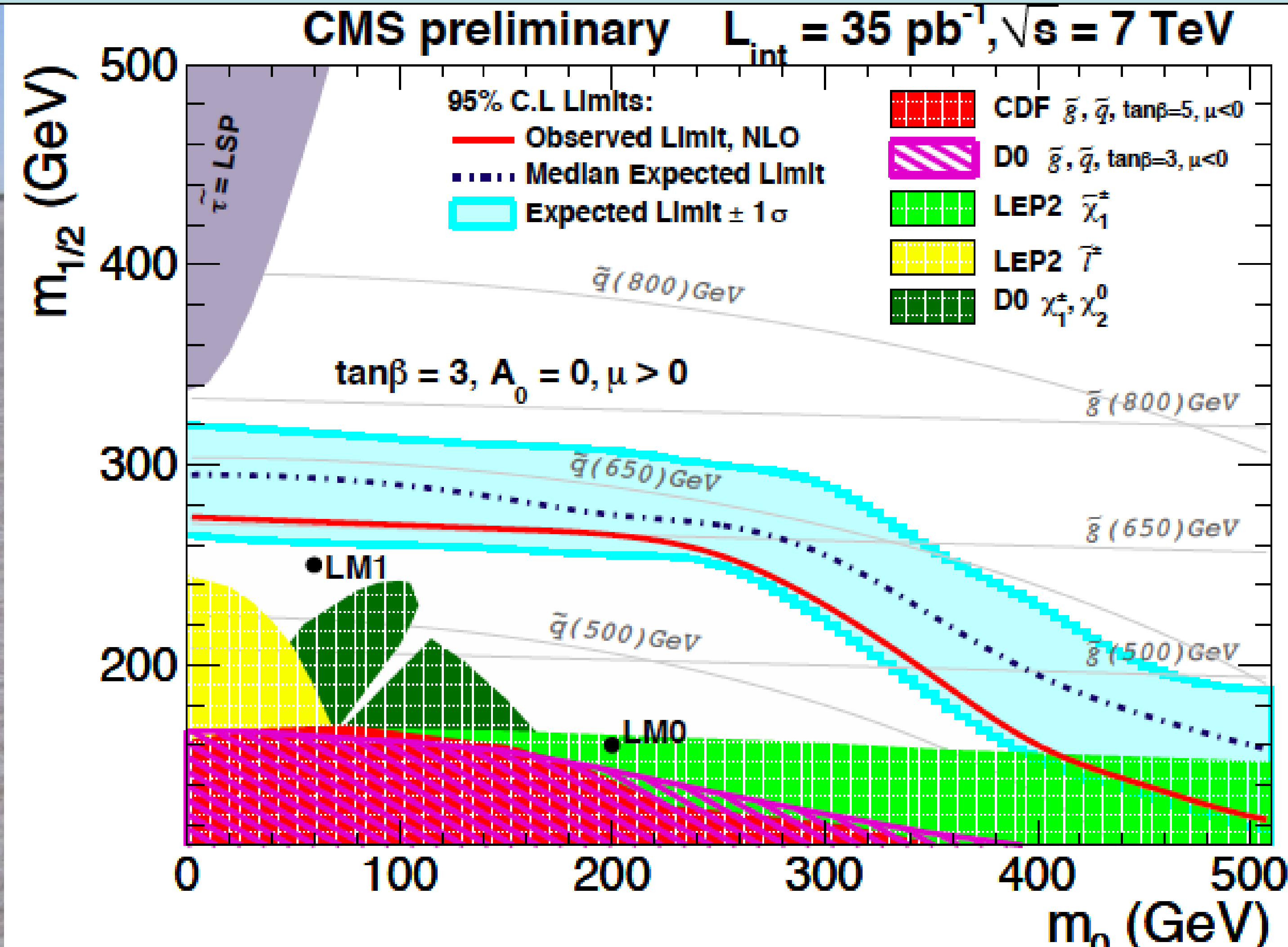
NUHM1



O.Buchmueller, JE et al: arXiv:0907.5568

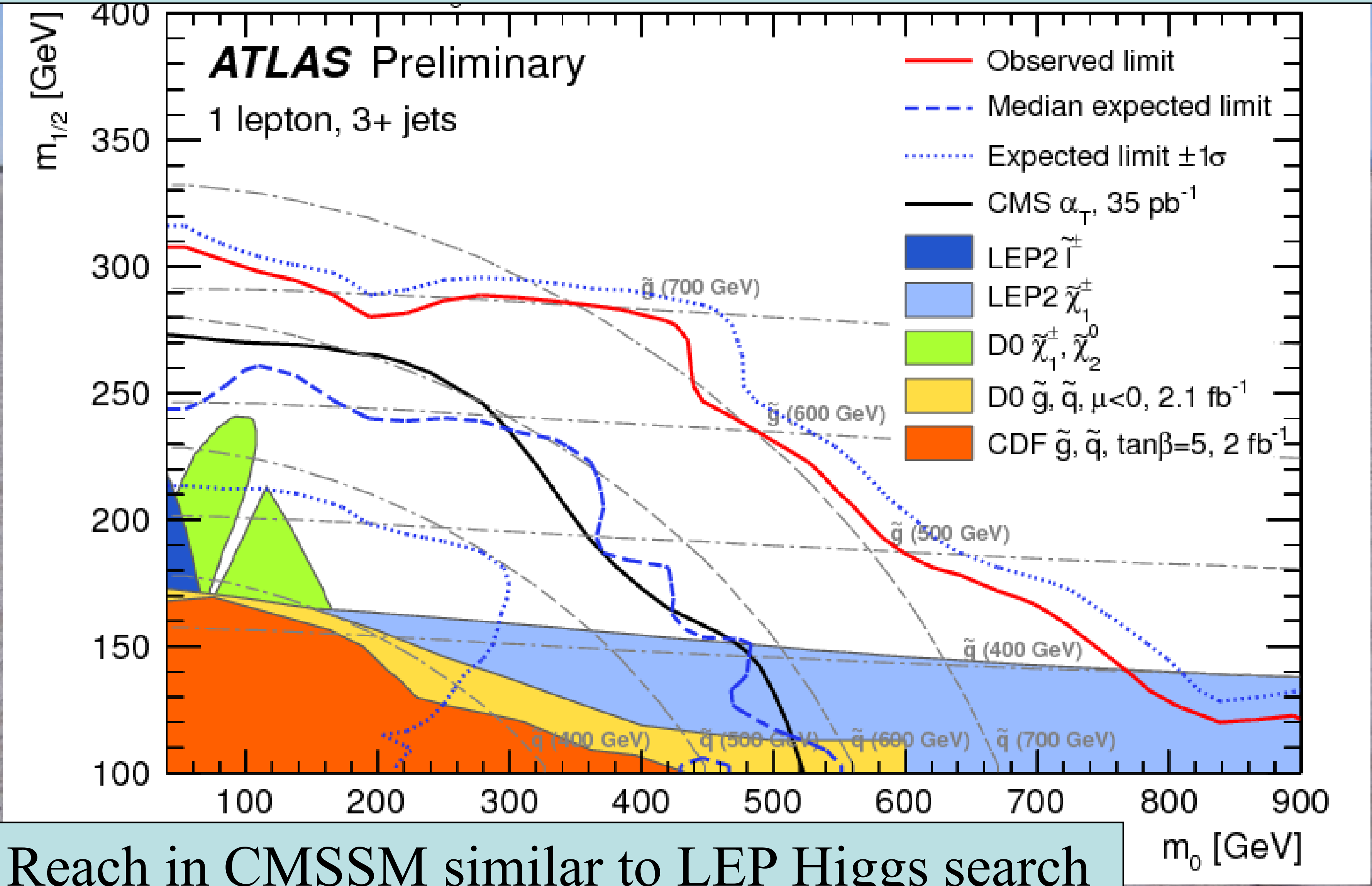
Nov. 20th 2009: Jubilation

Supersymmetry Search in CMS



Reach in CMSSM comparable to LEP Higgs search

Supersymmetry Search in ATLAS



Reach in CMSSM similar to LEP Higgs search

Impact of LHC on the CMSSM

Assuming the lightest sparticle is a neutralino

CMS

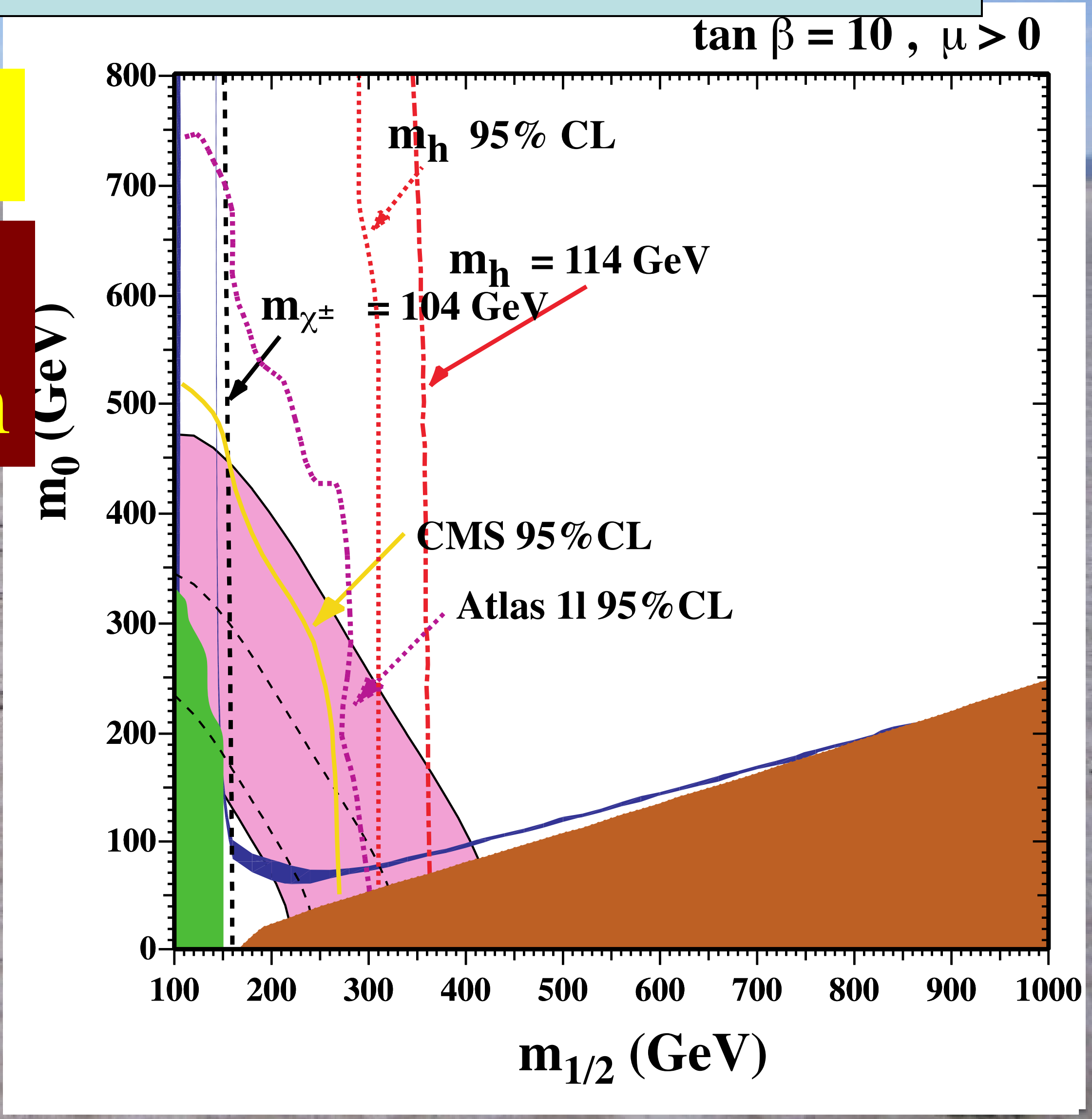
ATLAS 1 Lepton

Excluded because stau LSP

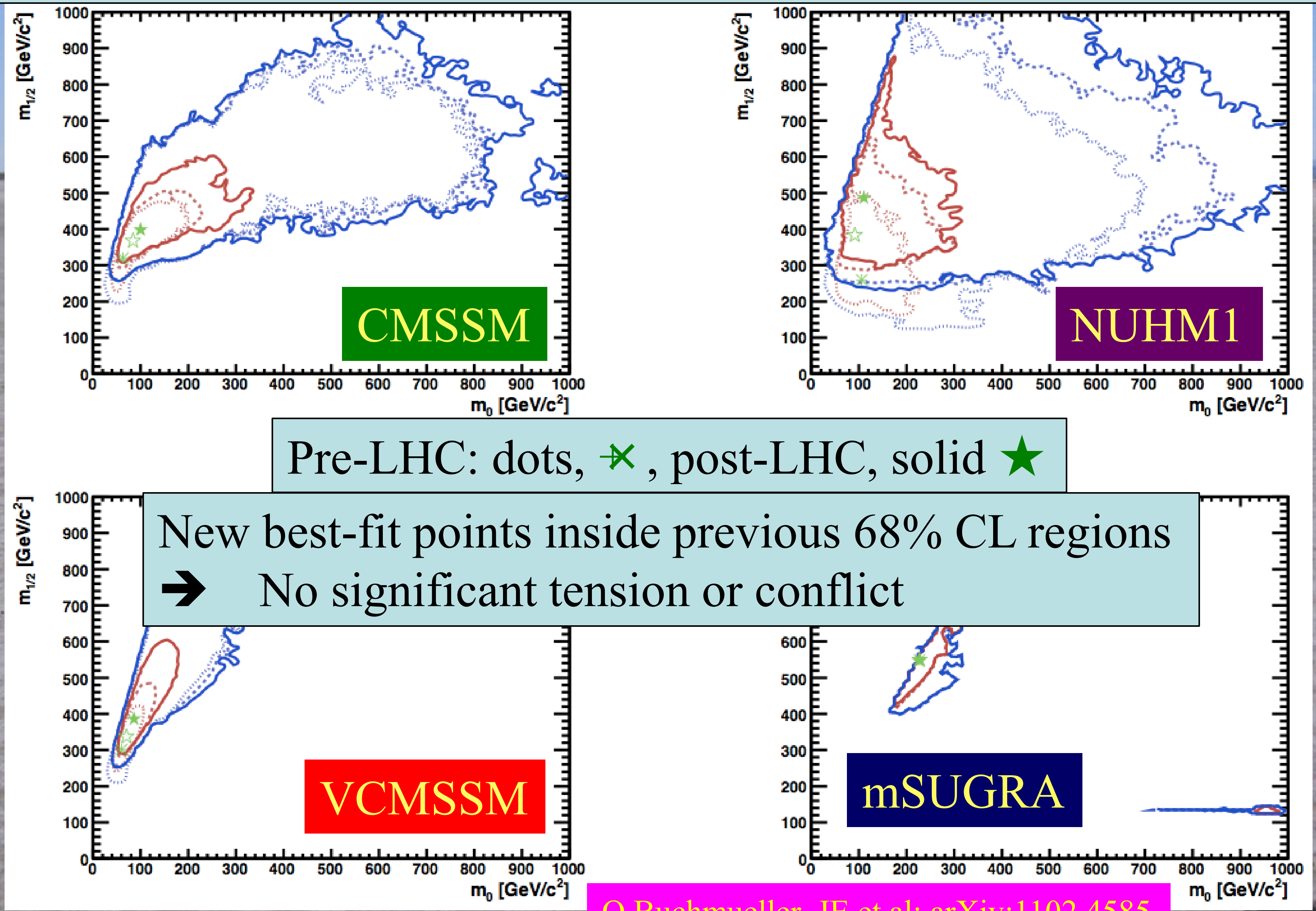
Excluded by b → s gamma

WMAP constraint on CDM density

Preferred (?) by latest g - 2



$(m_0, m_{1/2})$ Planes Revisited



Pre-LHC: dots, ✗, post-LHC, solid ★

New best-fit points inside previous 68% CL regions

➔ No significant tension or conflict

O.Buchmueller, JE et al: arXiv:1102.4585