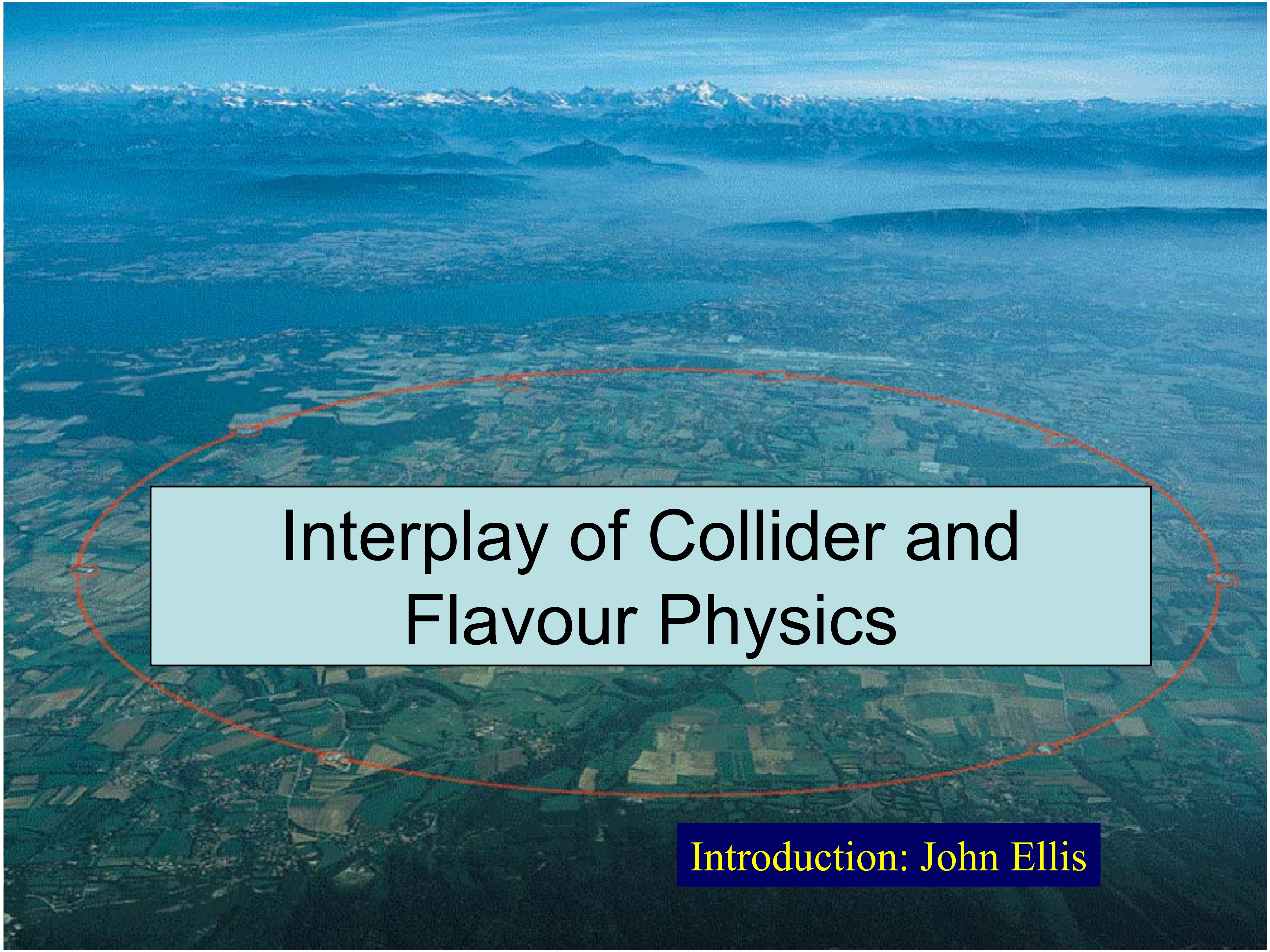

Interplay of Collider and Flavour Physics
Introduction: John Ellis

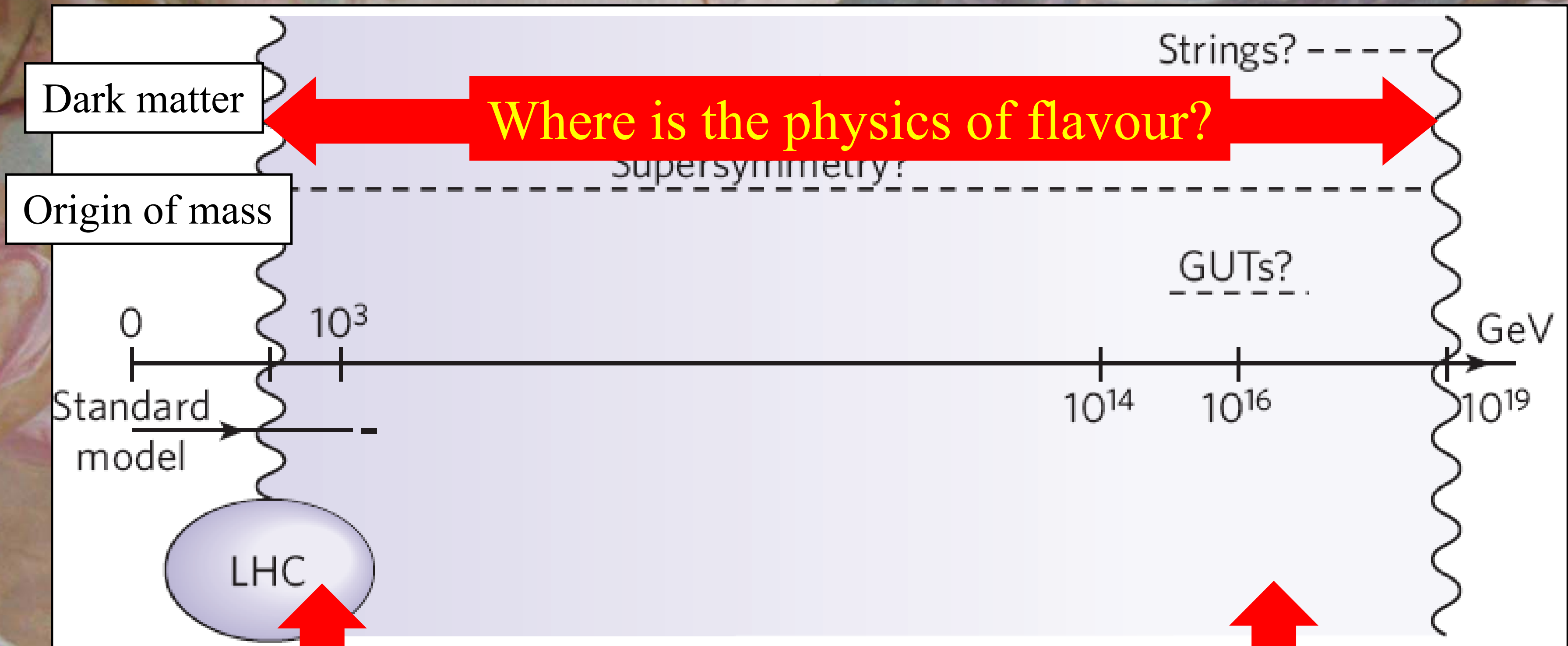
Open Questions beyond the Standard Model

- What is the origin of particle masses?
  due to a Higgs boson? + other physics?
  solution at energy < 1 TeV (1000 GeV) **LHC**
- Why so many flavours of matter particles?
  mixing and CP violation? **LHC**
- Unification of the fundamental forces?
  at very high energy ~ 10^{16} GeV?
  probe directly via neutrino physics, indirectly via masses, couplings **LHC**
- Quantum theory of gravity?
  (super)string theory: extra space-time dimensions? **LHC**

High-p_T Physics Meets Flavour

- The major particle physics objectives of the LHC
  - ATLAS, CMS, LHCb
- Good reasons to expect new physics at the TeV scale:
  - Higgs, naturalness, dark matter
- No clue where flavour physics originates
- What is flavour structure of TeV physics?
- How to reveal it?
  - Combine direct and indirect approaches

At what Energy is the New Physics?



A lot accessible to the LHC

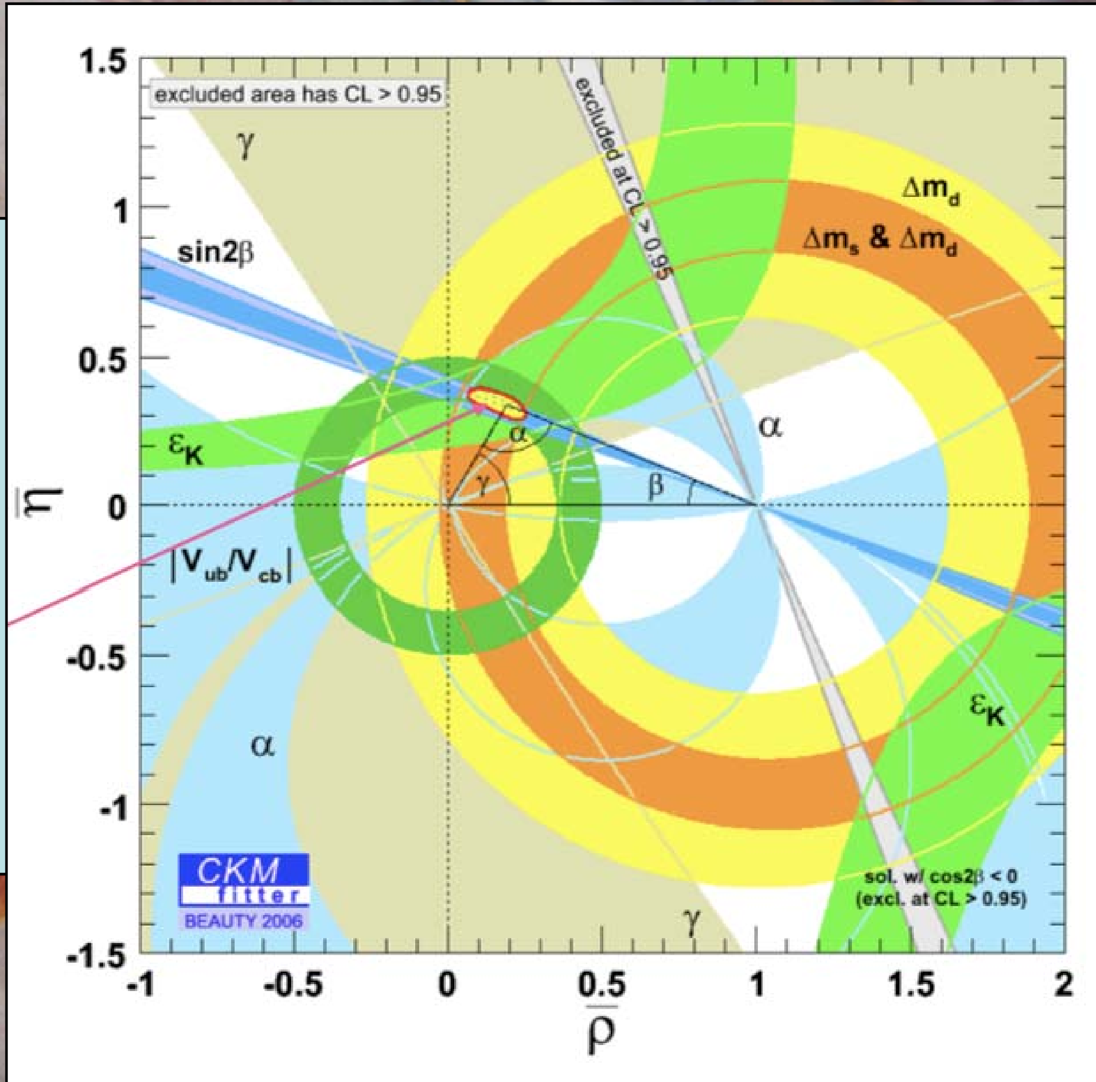
Some accessible only indirectly

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

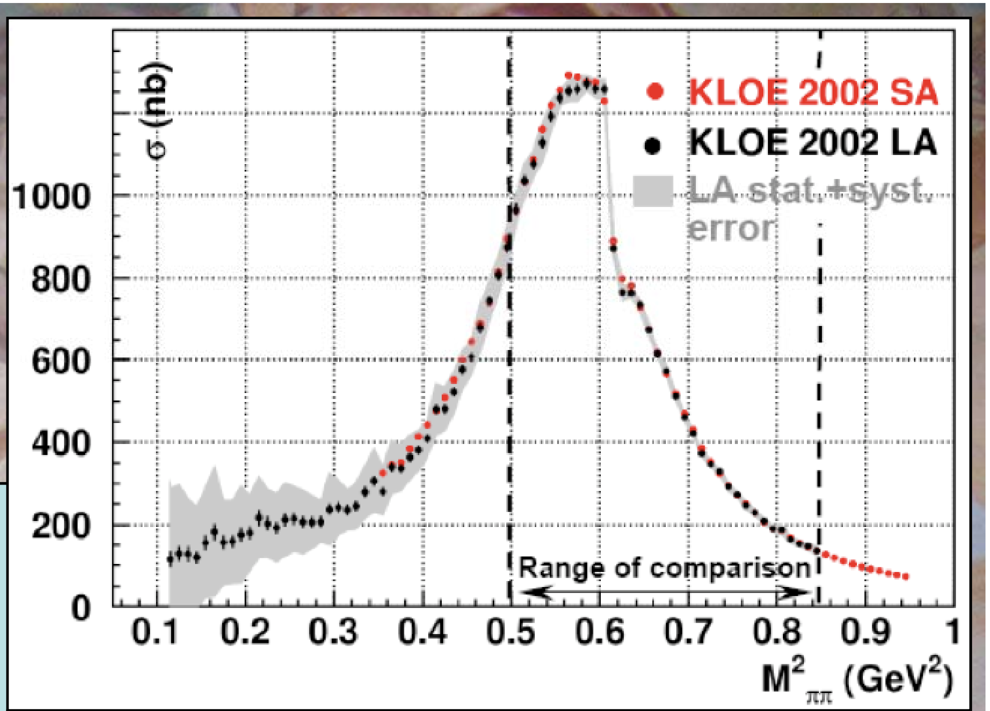
Flavour and CP Violation

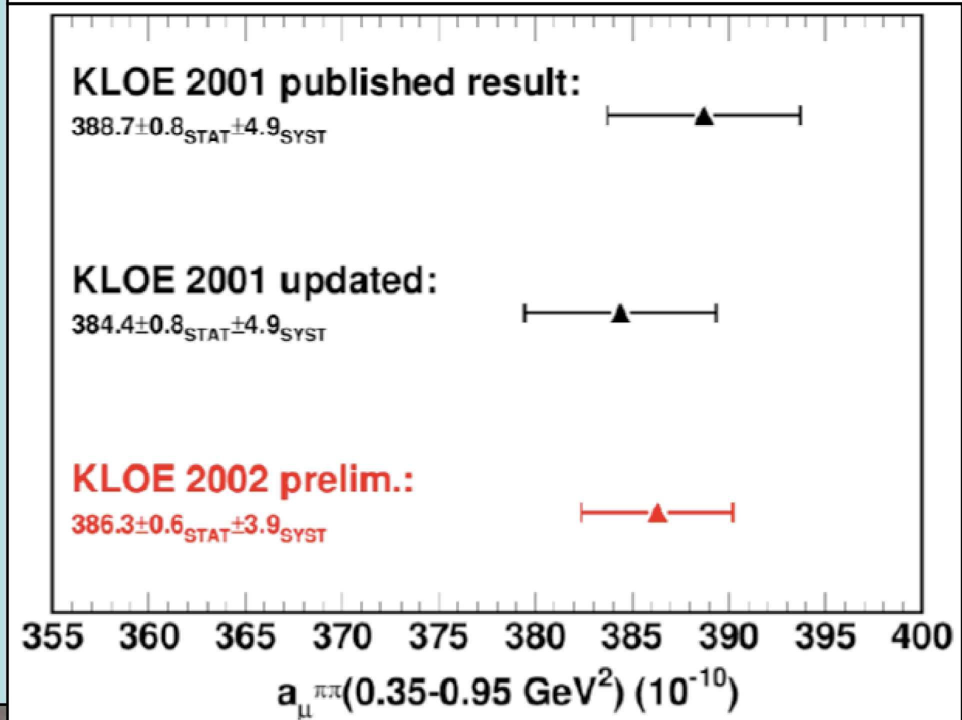
- CKM model successful at present
- A pillar of the Standard Model
- What lies beyond it?



Quo Vadis g_μ - 2?

- New e^+e^- data agree with previous
- Strengthen discrepancy
  - now 3.4 σ
- New τ decay analysis apparently disagrees with previous, consistent with e^+e^-





Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

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

- 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}
- Assume universality? constrained MSSM = CMSSM
  - Single m_0, single $m_{1/2}$, single A_{λ}, B_{μ}: not string?
- Not the same as minimal supergravity (mSUGRA)
- Gravitino mass, additional relations

$$m_{3/2} = m_0, \; B_{\mu} = A_{\lambda} - m_0$$

Mass Renormalizations

- **Assuming universality at the GUT scale**
- Gaugino masses:
  - $M_a = (\alpha_a / \alpha_{GUT})\ m_{1/2}$, e.g., $\rightarrow M_2 / M_3 = \alpha_2 / \alpha_3$
- Squark and slepton masses:
  - Squark mass^2: $m_0^2 + 6\ m_{1/2}^2$
  - Left-handed slepton mass^2: $m_0^2 + 0.5\ m_{1/2}^2$
  - Right-handed slepton mass^2: $m_0^2 + 0.15\ m_{1/2}^2$
- Minimal flavour violation (MFV):
  - Flavour mixing of squarks and sleptons induced by CKM, MNS mixing

Current Constraints on CMSSM

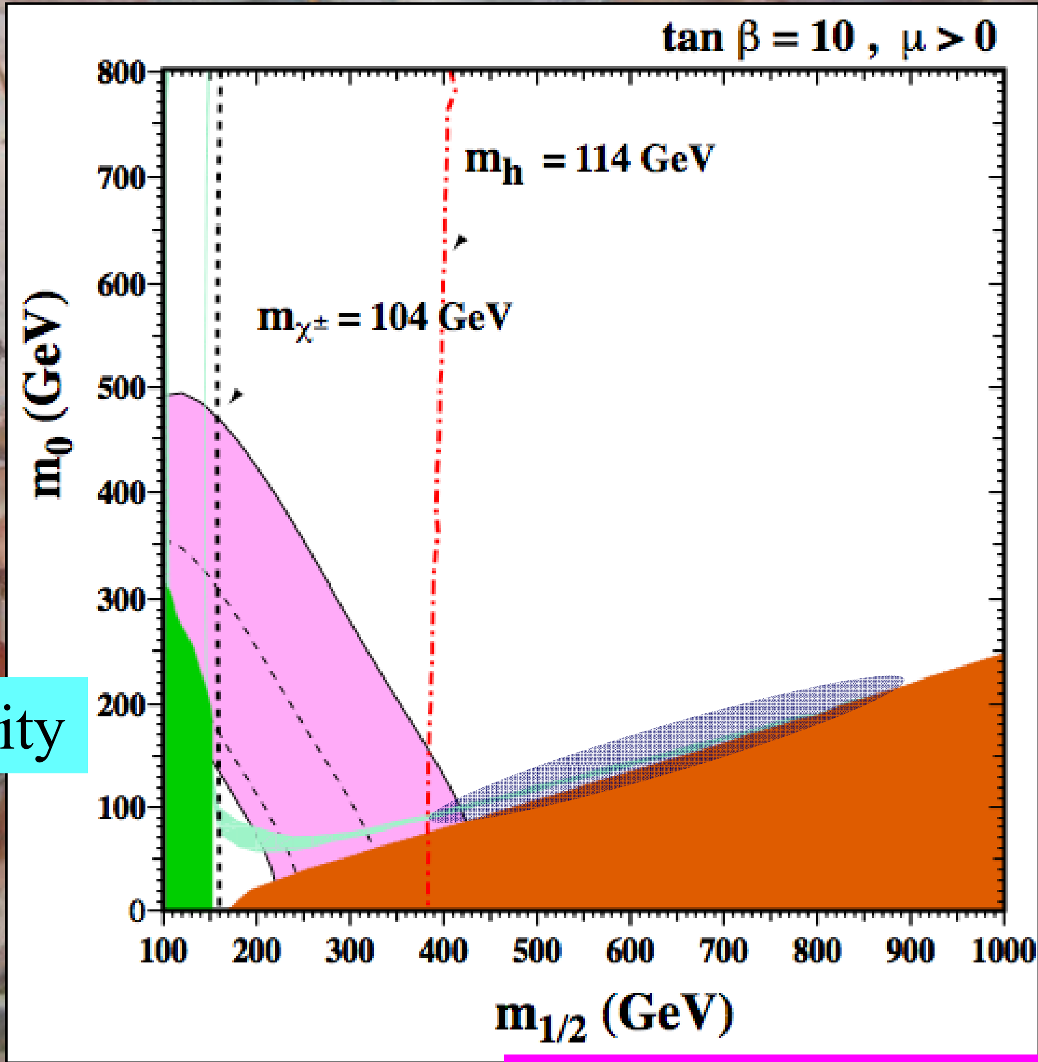
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

Preferred (?) by latest g - 2



JE + Olive + Santoso + Span

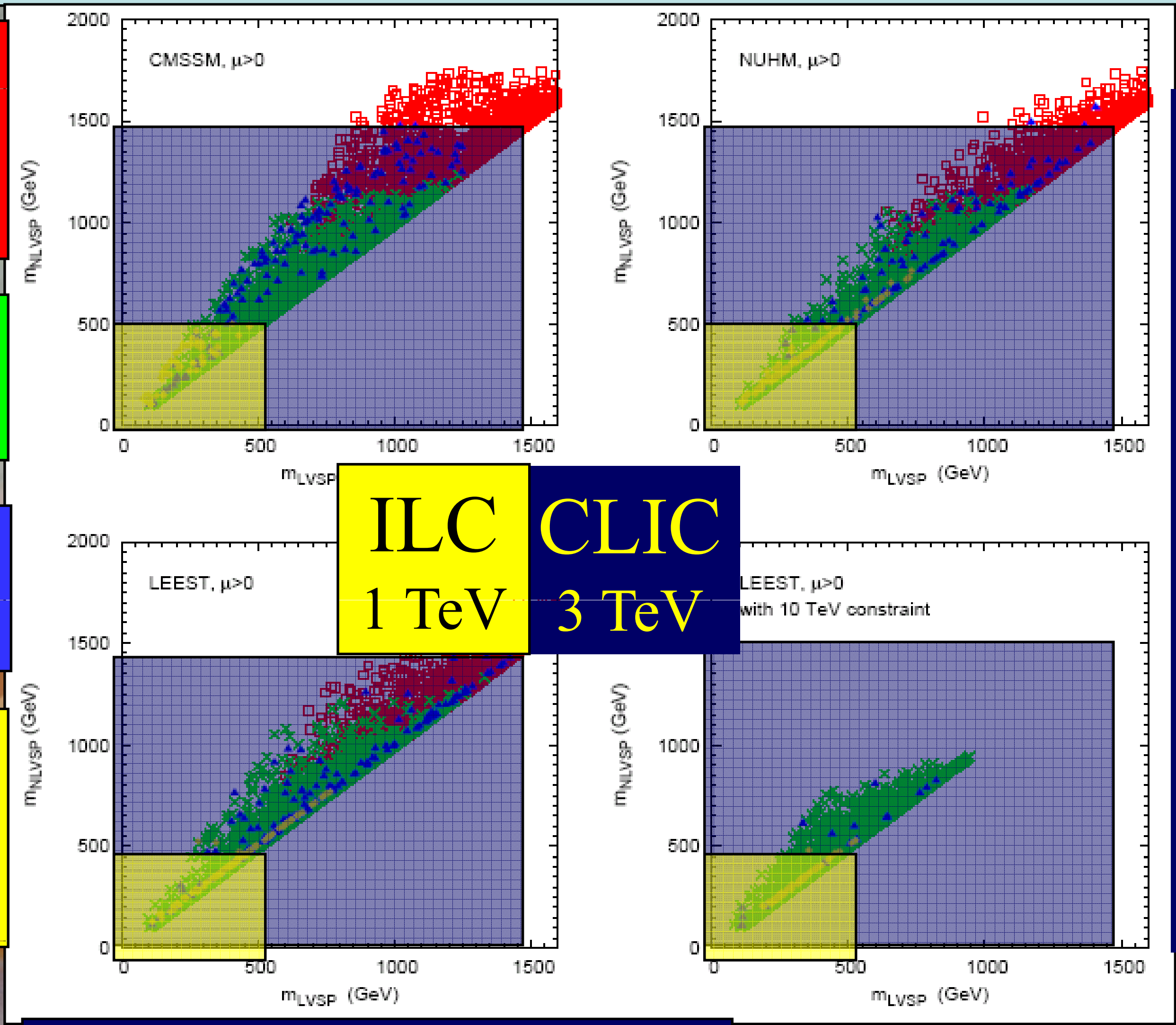
Sparticles may not be very light

Full Model samples

Detectable @ LHC

Provide Dark Matter

Dark Matter Detectable Directly



Lightest visible sparticle →

→ Second lightest visible sparticle

JE + Olive + Santoso + Span

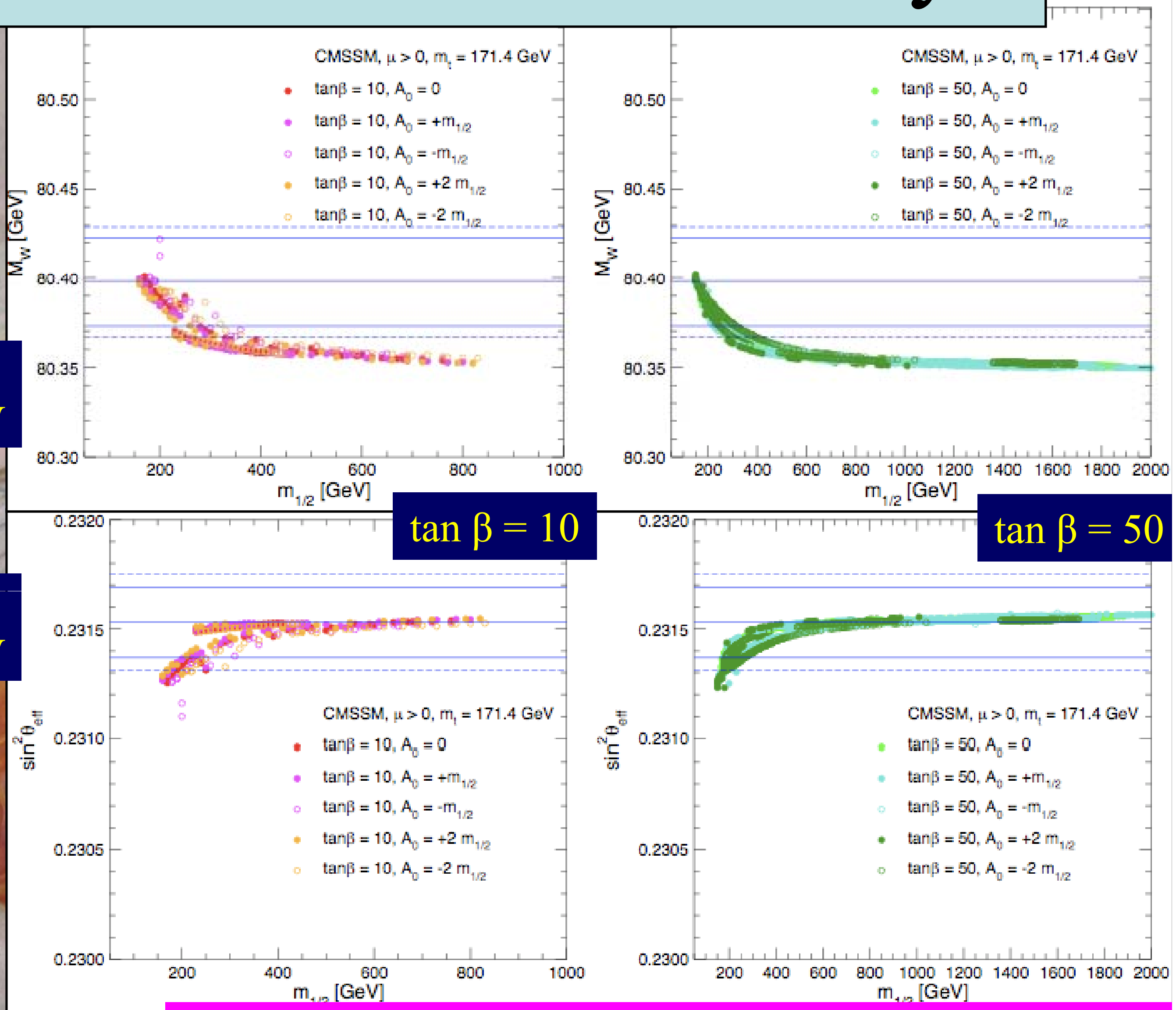
Can one estimate the scale of supersymmetry?

Precision Observables vs Susy

Sensitivity to $m_{1/2}$ in CMSSM along WMAP lines for different A

m_W

$\sin^2\theta_W$



tan β = 10

tan β = 50

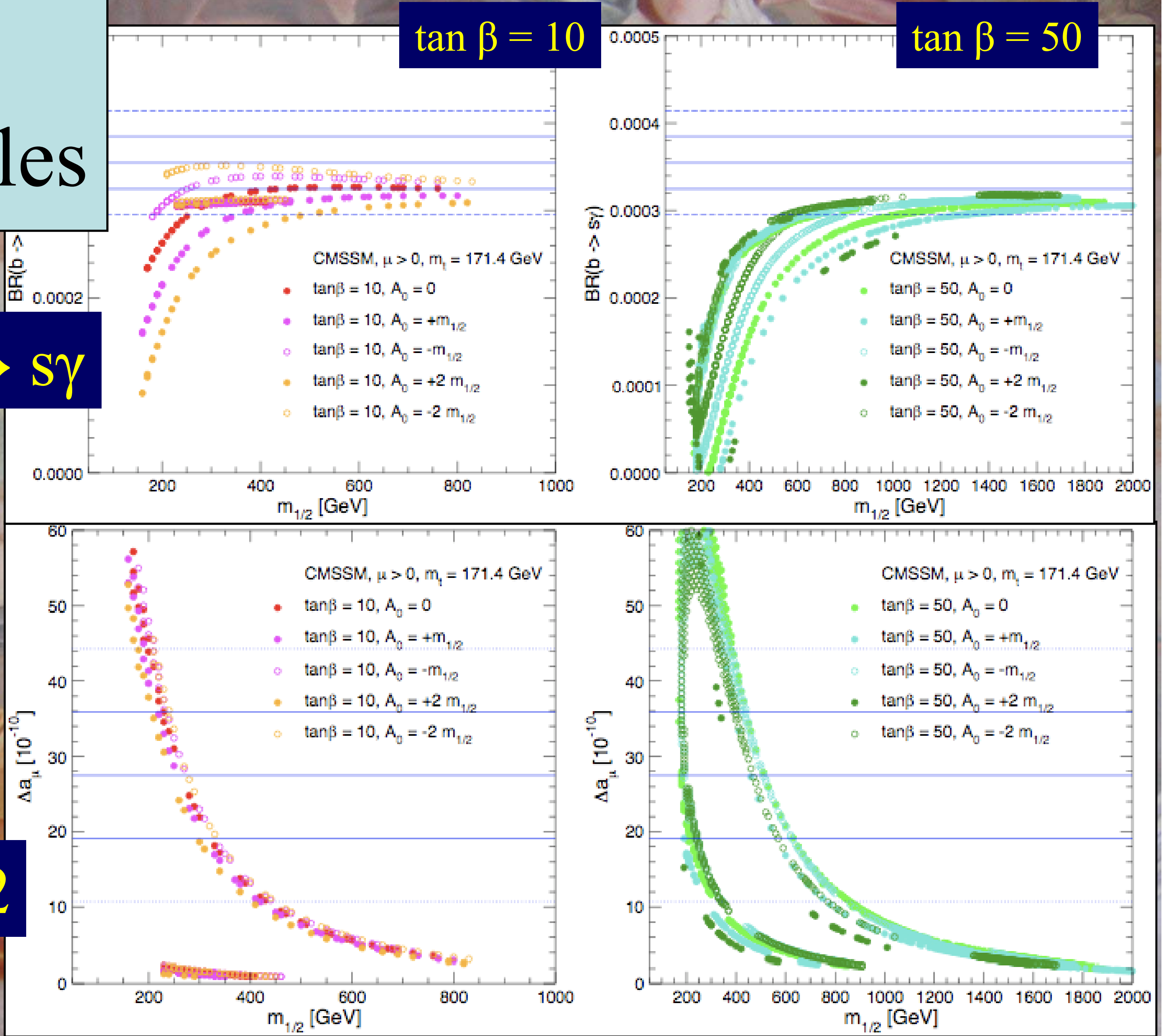
Present & possible future errors

JE + Heinemeyer + Olive + Weber + Weiglein, arXiv:0706.0652

More Observables

$b \rightarrow s\gamma$

$g_\mu - 2$



JE + Heinemeyer + Olive + Weber + Weiglein, arXiv:0706.0652

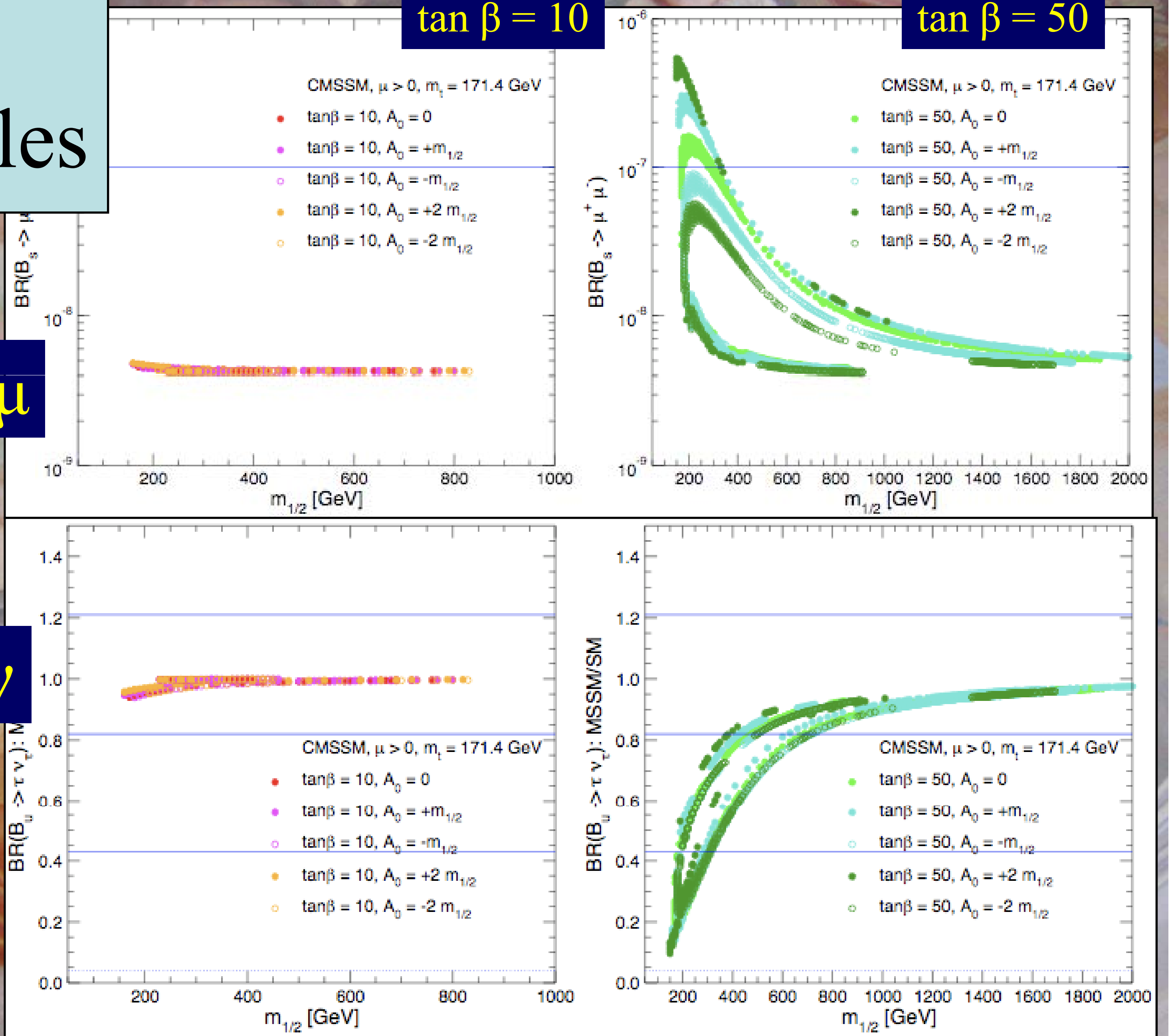
More Observables

tan β = 10

tan β = 50

$B_s \to \mu\mu$

$B_u \to \tau\nu$

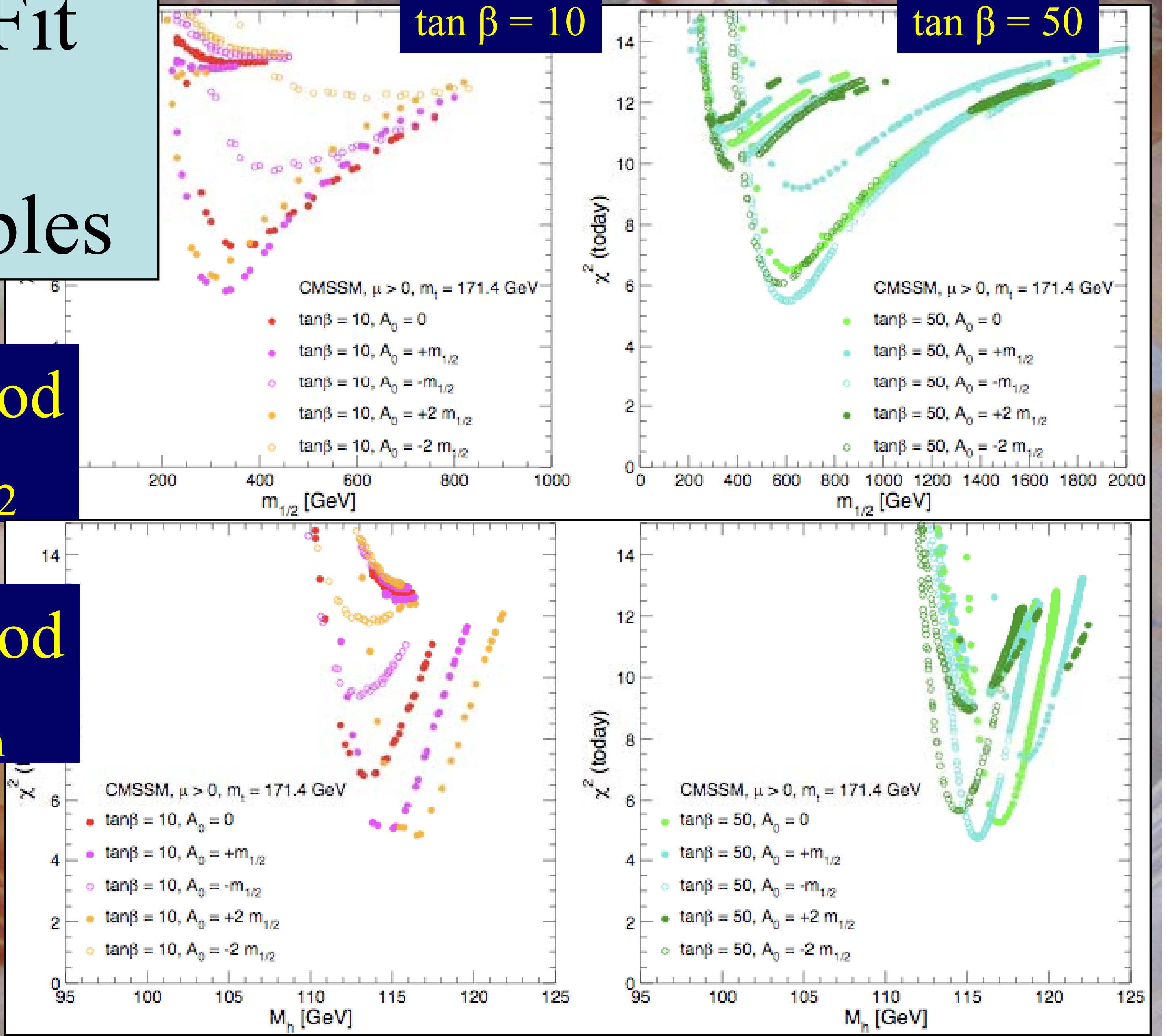


JE + Heinemeyer + Olive + Weber + Weiglein, arXiv:0706.0652

Global Fit to all Observables

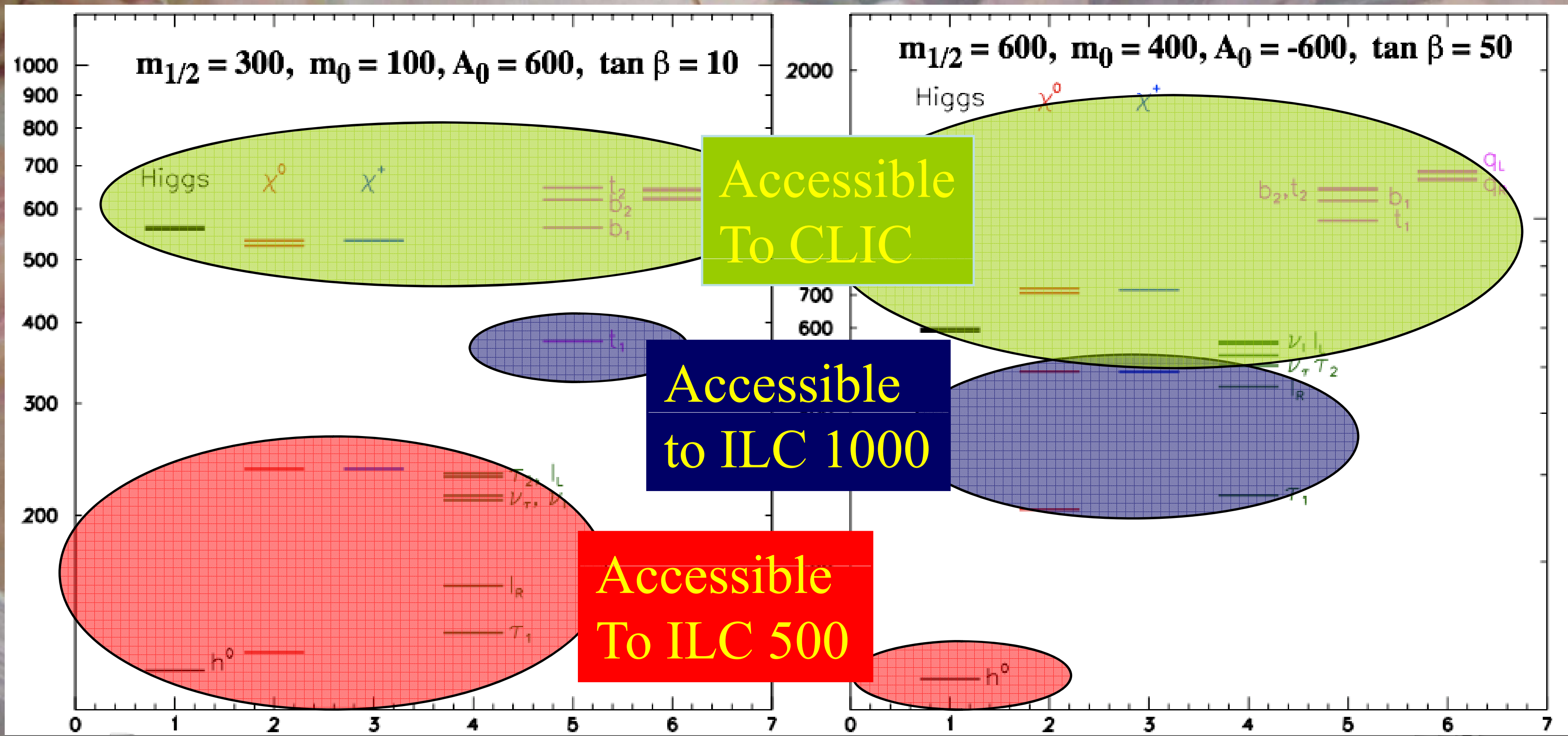
Likelihood for $m_{1/2}$

Likelihood for M_h



JE + Heinemeyer + Olive + Weber + Weiglein, arXiv:0706.0652

Spectra at Best-Fit Points

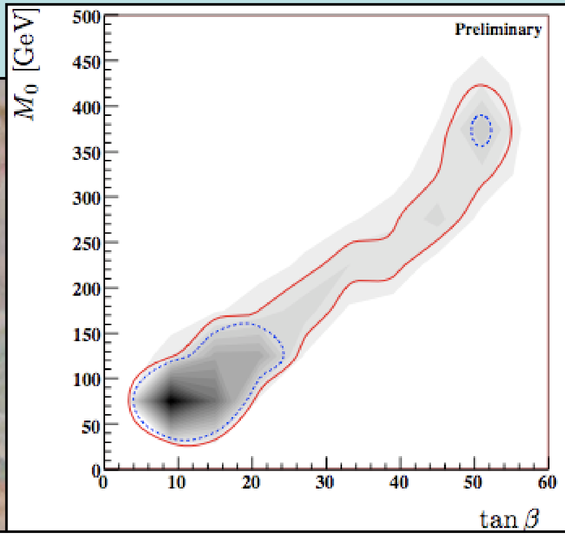


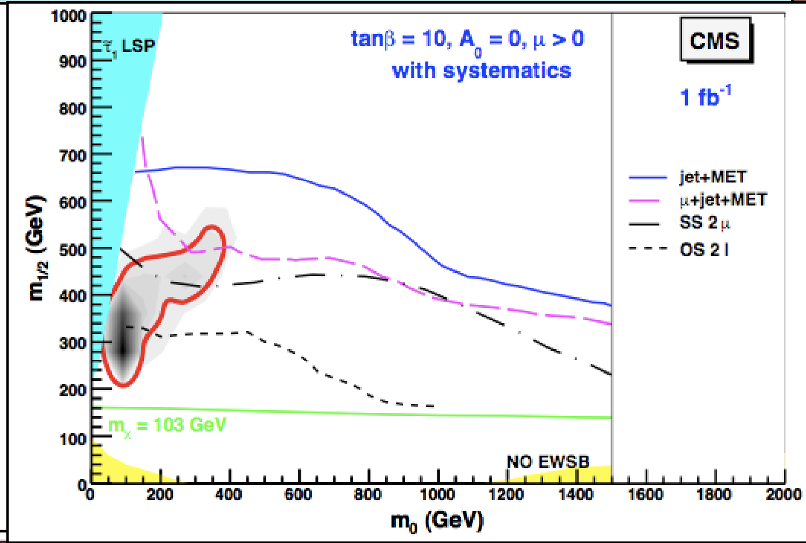
Markov Chain Monte Carlo Analysis of Electroweak B Observables

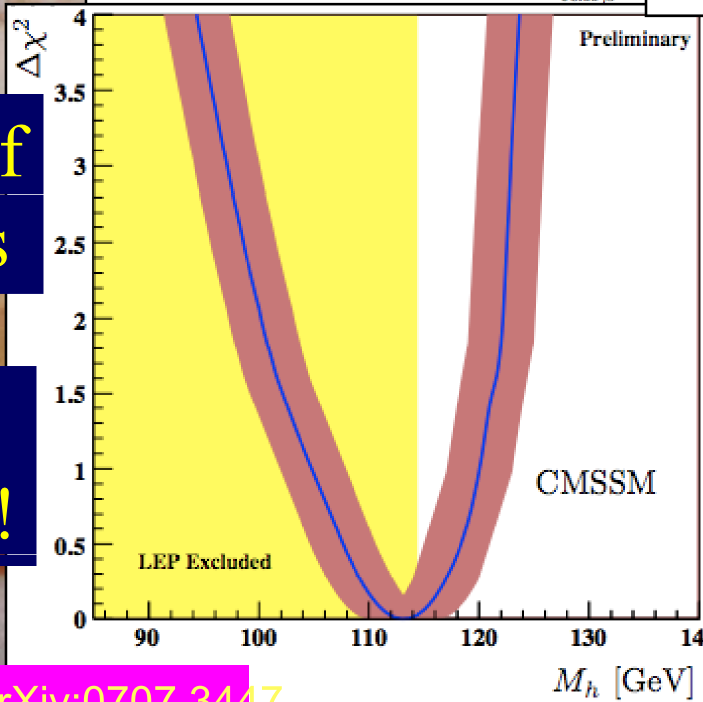
More complete analysis of parameter space

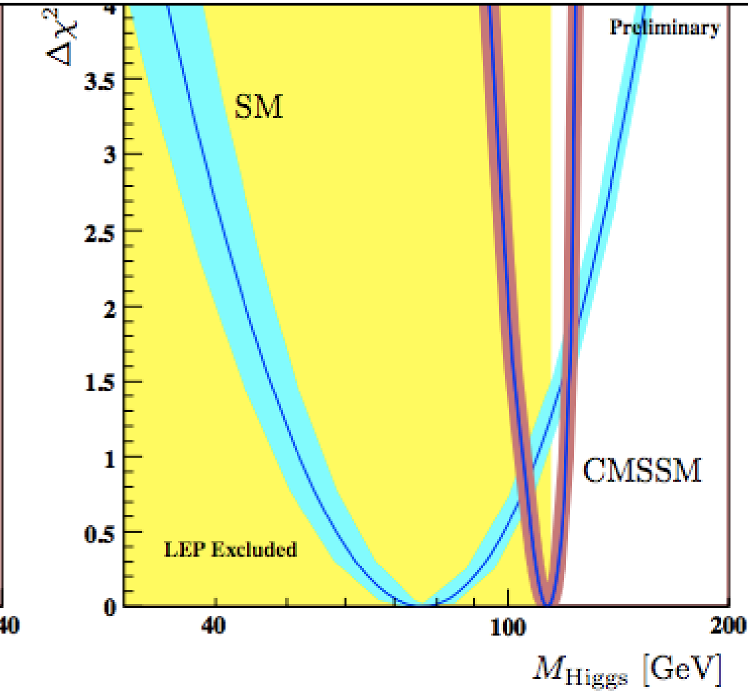
Larger set of observables

Better Graphics!



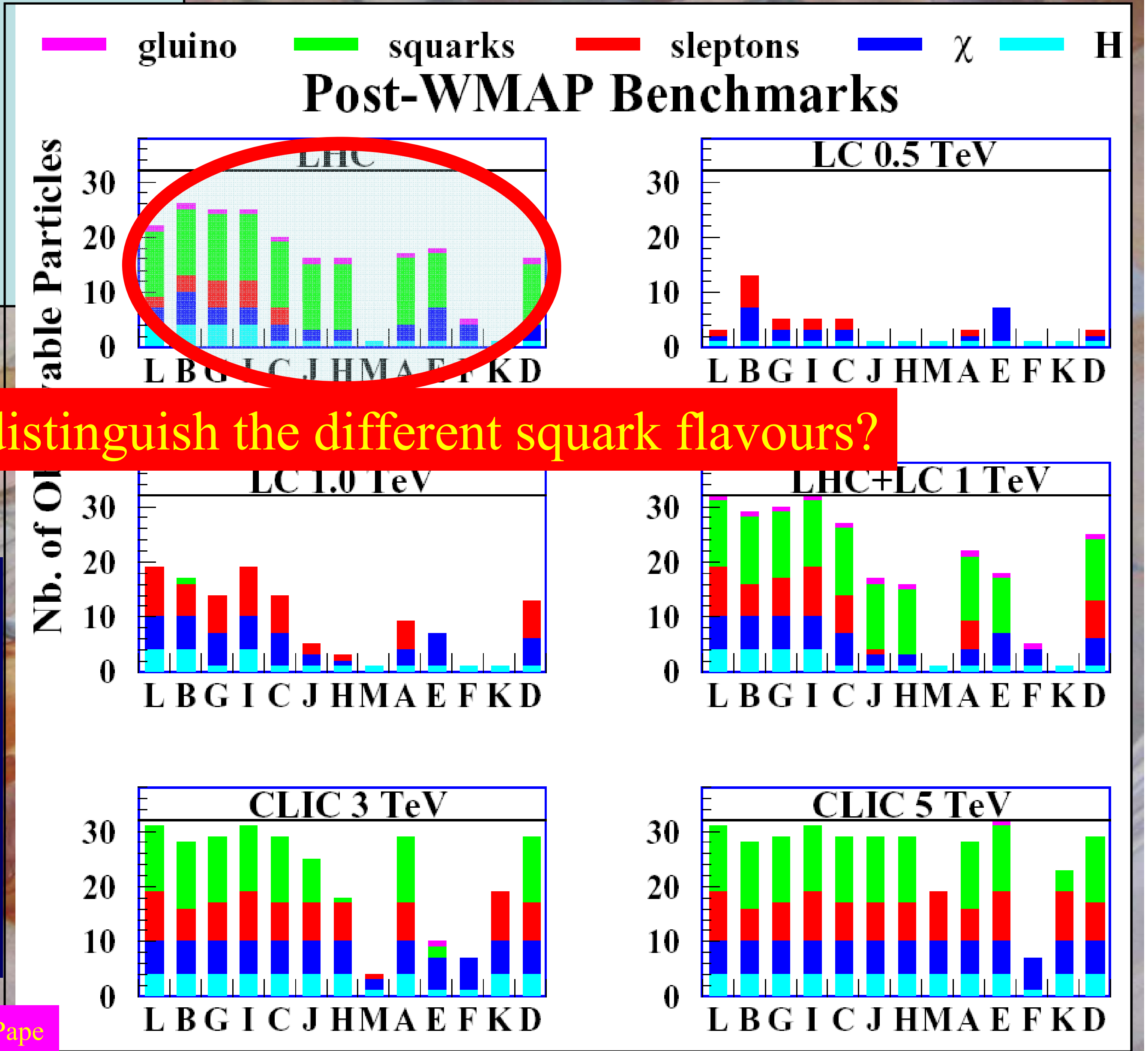






O. Buchmueller et al, arXiv:0707.3447

Summary of LHC Scapabilities … and Other Accelerators



How to distinguish the different squark flavours?

LHC almost 'guaranteed' to discover supersymmetry if it is relevant to the mass problem

Battaglia, De Roeck, Gianotti, JE, Olive, Pape

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!

Minimal Flavour Violation (MFV)

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

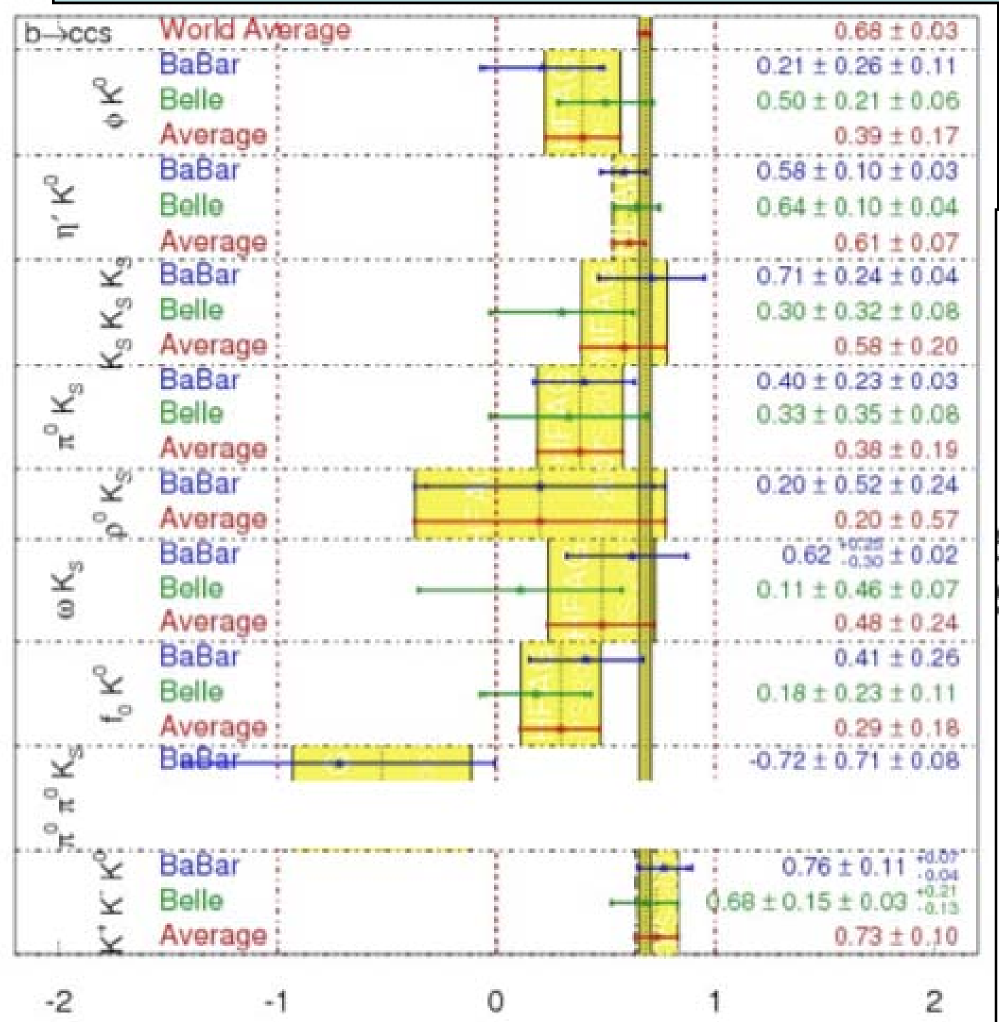
$$M_{1,2,3}\,, \quad M^2_{H_{u,d}}\,, \qquad \widetilde{\mathbf{M}}^2_{Q,L,U,D,E} = \widetilde{M}^2_{Q,L,U,D,E}\,\mathbf{1}_3\,, \qquad \mathbf{A}_{u,d,e} = A_{u,d,e}\,\mathbf{1}_3$$

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

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

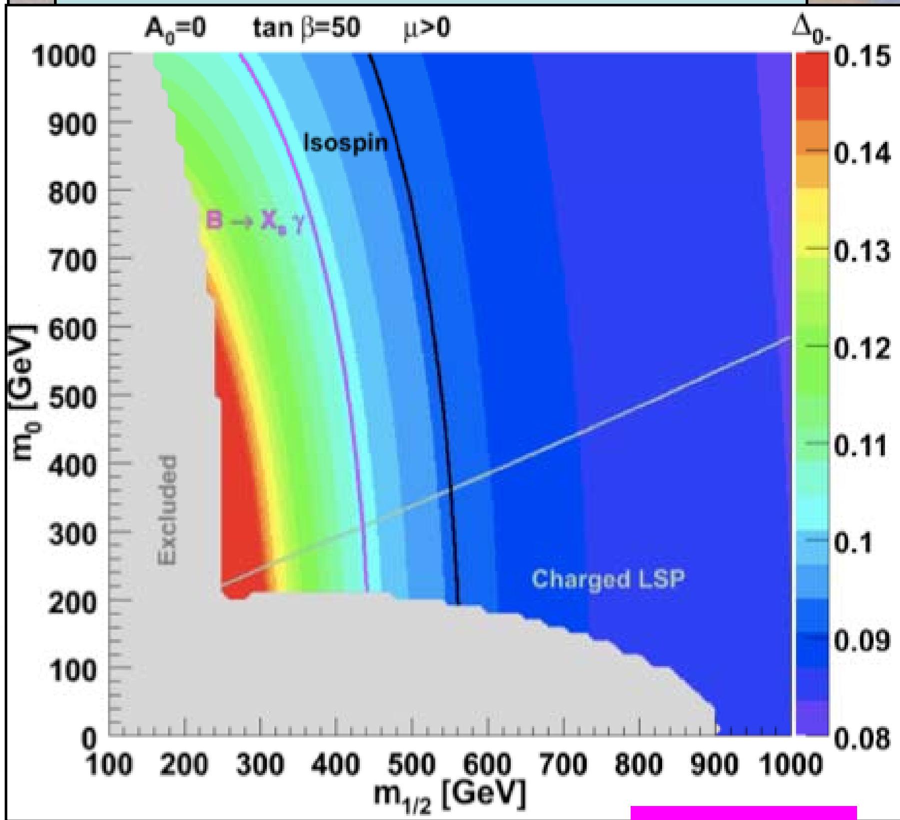
- Often assume universal ImM_a, ImA_f, but non-universality compatible with MFV: **MCPMFV**

Flavour in the LHC Era: Supersymmetric B Physics?



Discrepancies in B decays?

Isospin asymmetry in $B \to K^*\gamma$?

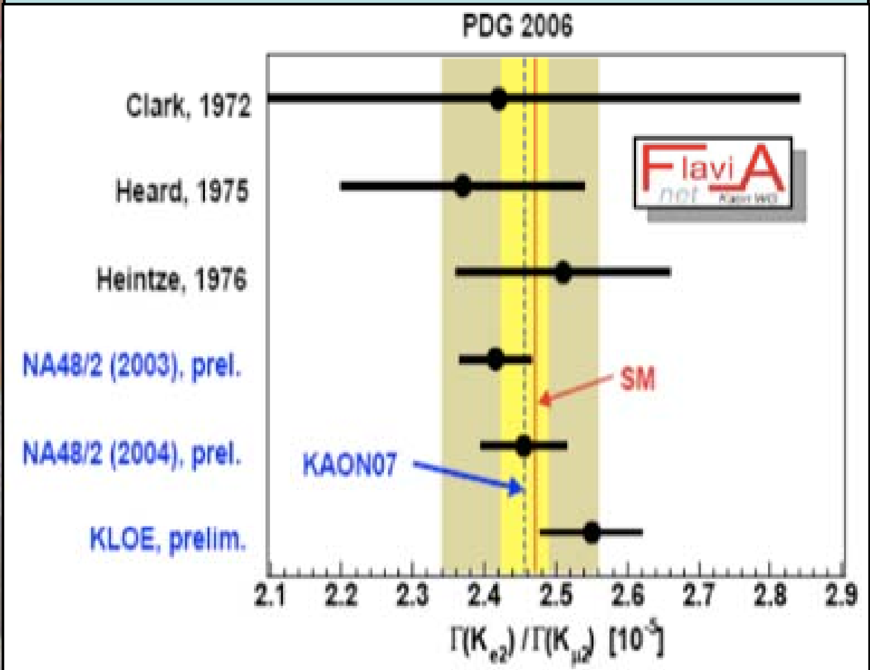


Mahmoudi

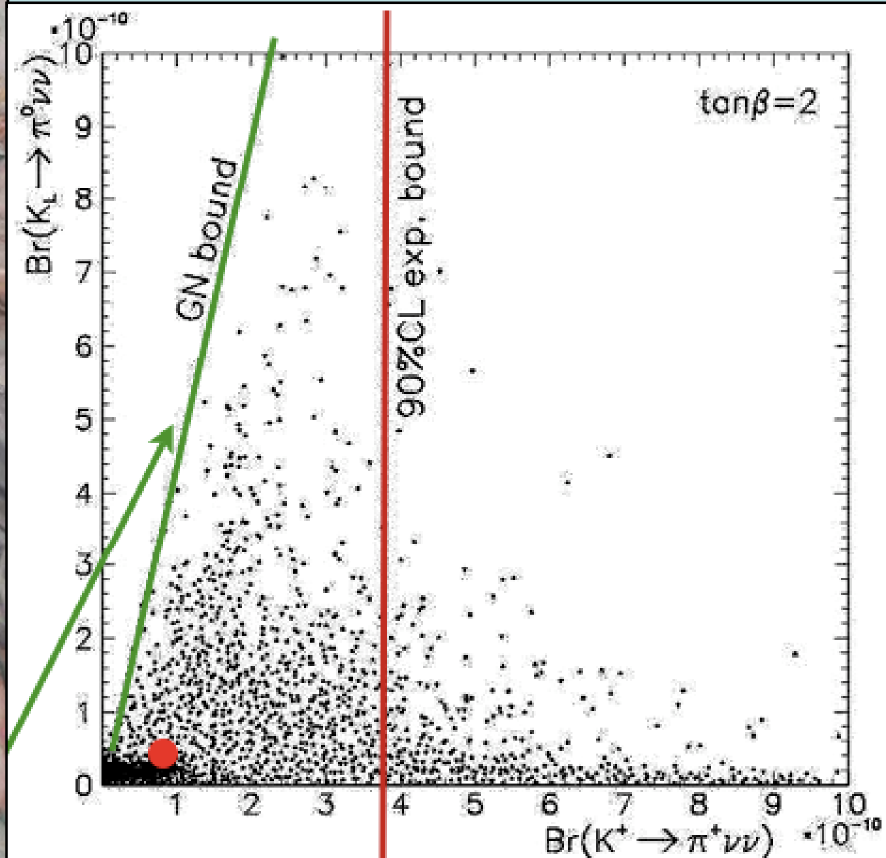
Flavour in the LHC Era: Supersymmetric K Physics?

- Violation of universality in $K \to e$

$$R_K^{LFV} \simeq R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_H^4} \right) \left(\frac{m_\tau^2}{m_e^2} \right) |\Delta_R^{31}|^2 \tan^6\beta \right]$$



- $K \to \pi\,\nu\nu$ decays?

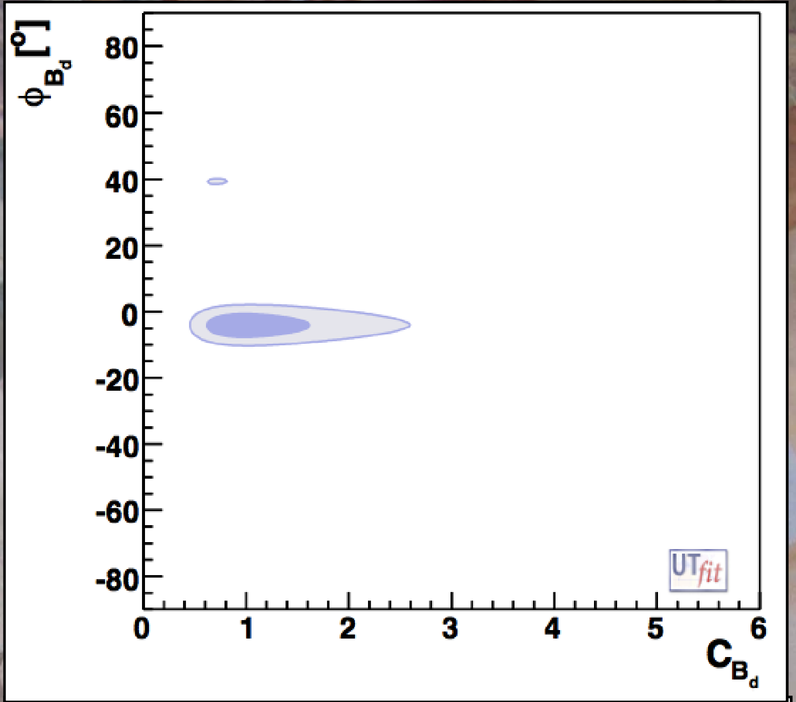


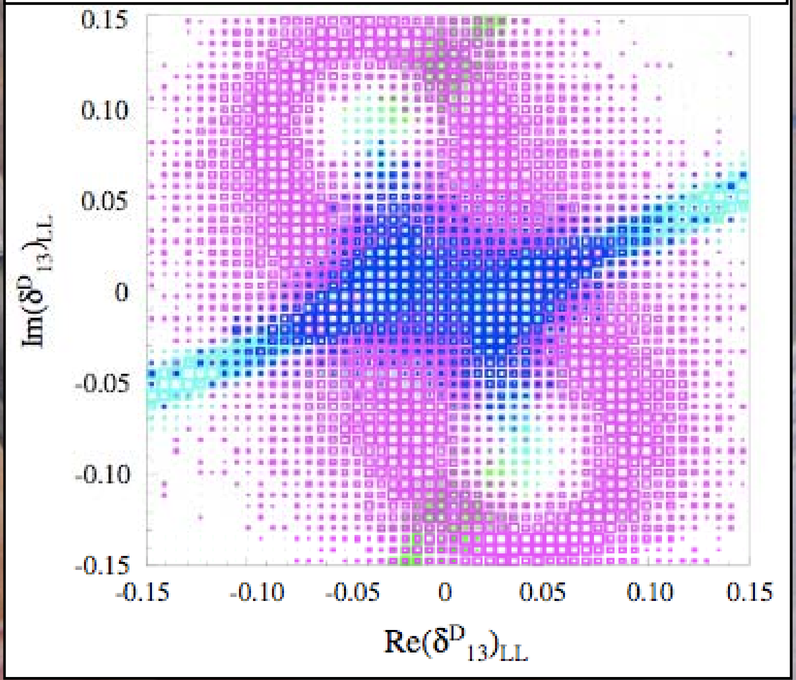
Constraints Imposed by Success of CKM

- Limits on new physics in B_d mixing
- Constraint on D_{LL} mixing in supersymmetry:

$$(\delta^D{}_{13})_{LL} = \frac{(M^D{}_{13})^2{}_{LL}}{\langle M^D{}_{11}\rangle \langle M^D{}_{33}\rangle}$$

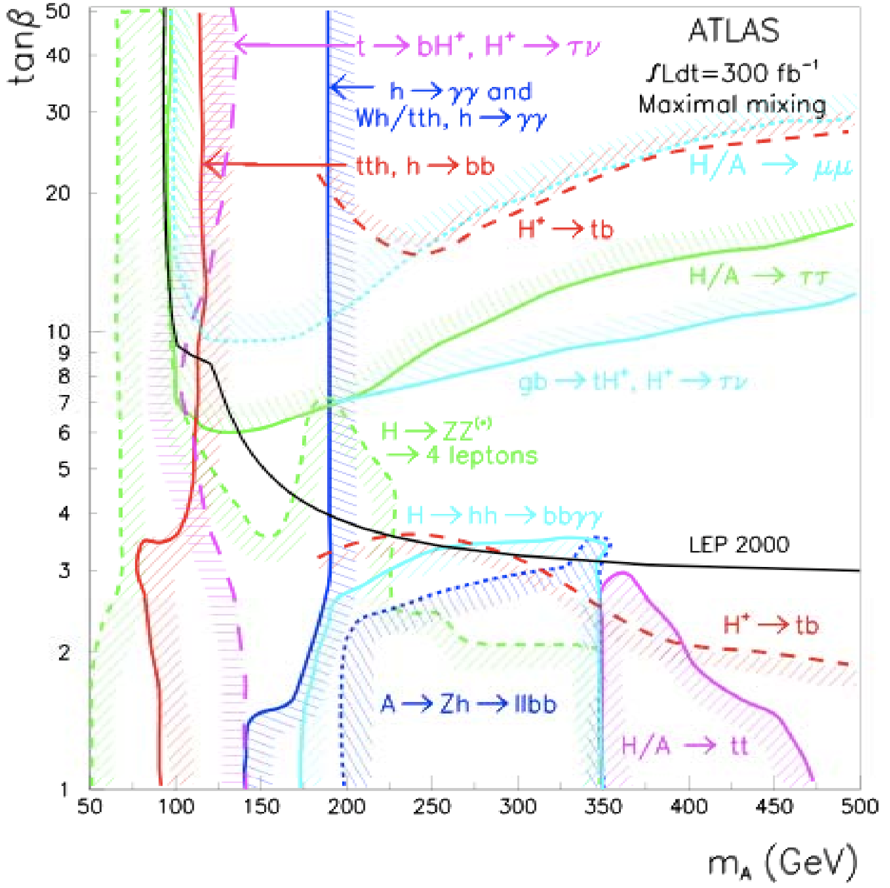
imposed by B_d mixing
- Analogous constraints on other mixing parameters

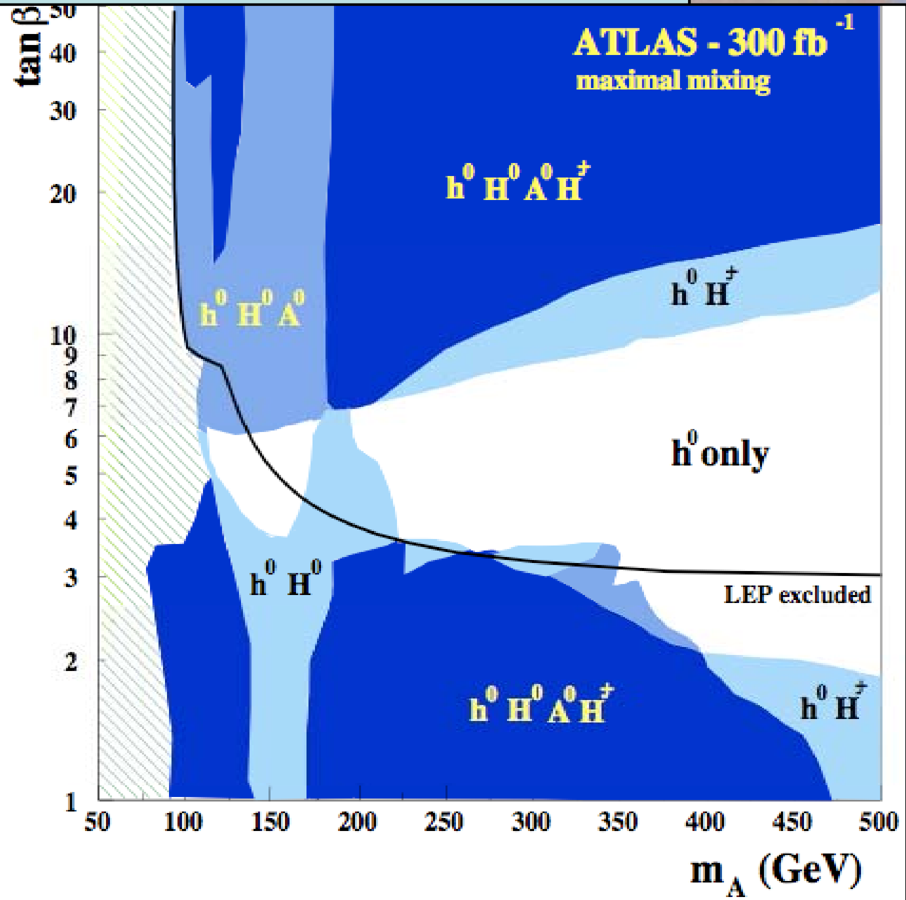




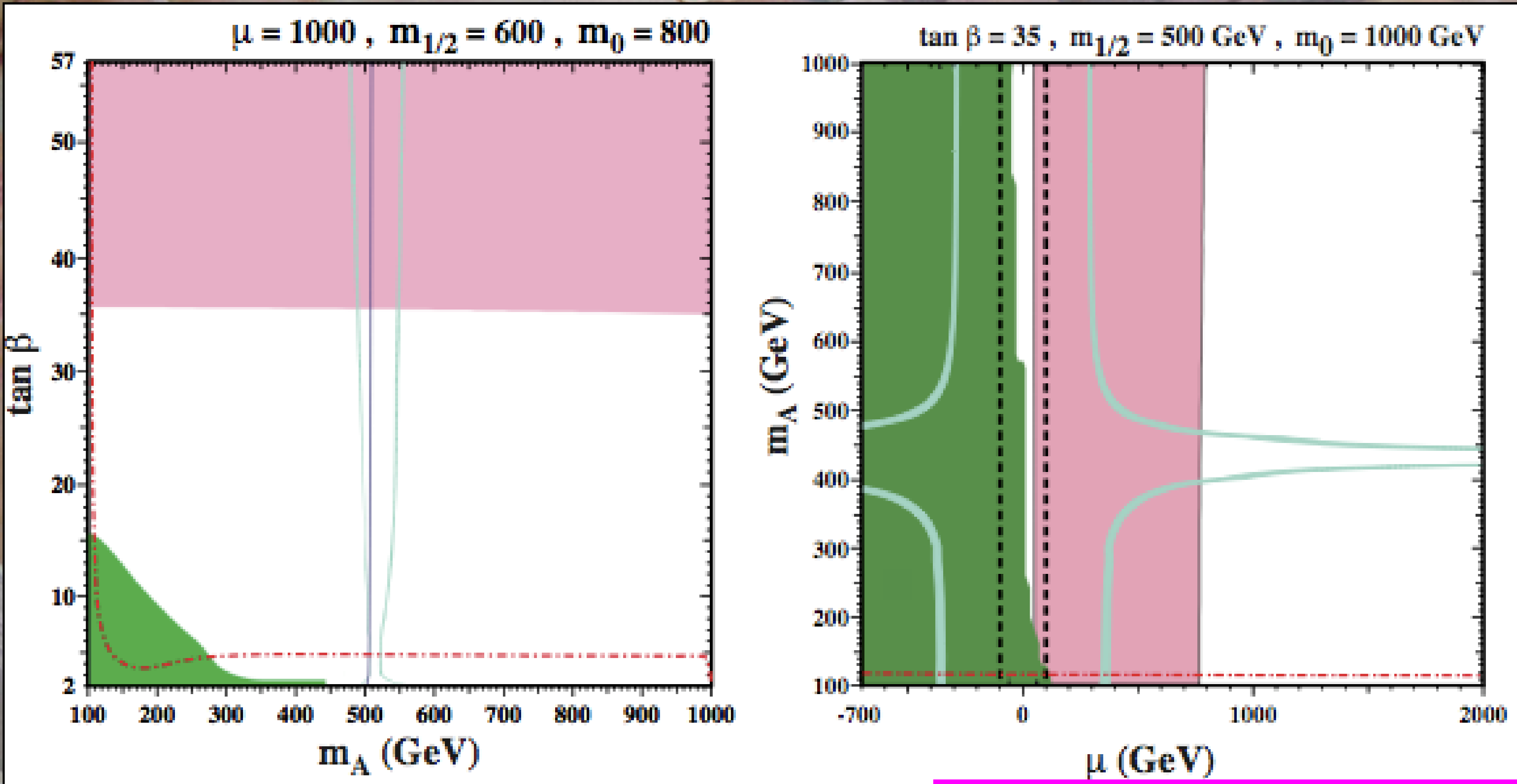
Prospects for SUSY Higgses @ LHC

Cover entire plane at least (only)





Most of (m_A, tan β) Planes **NOT** WMAP-Compatible



J.E., Hahn, Henemeyer, Olive + Weigle

Non-Universal Scalar Masses

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  e.g., d, s squarks?

  disfavoured by upper limits on flavour-changing neutral interactions

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  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?

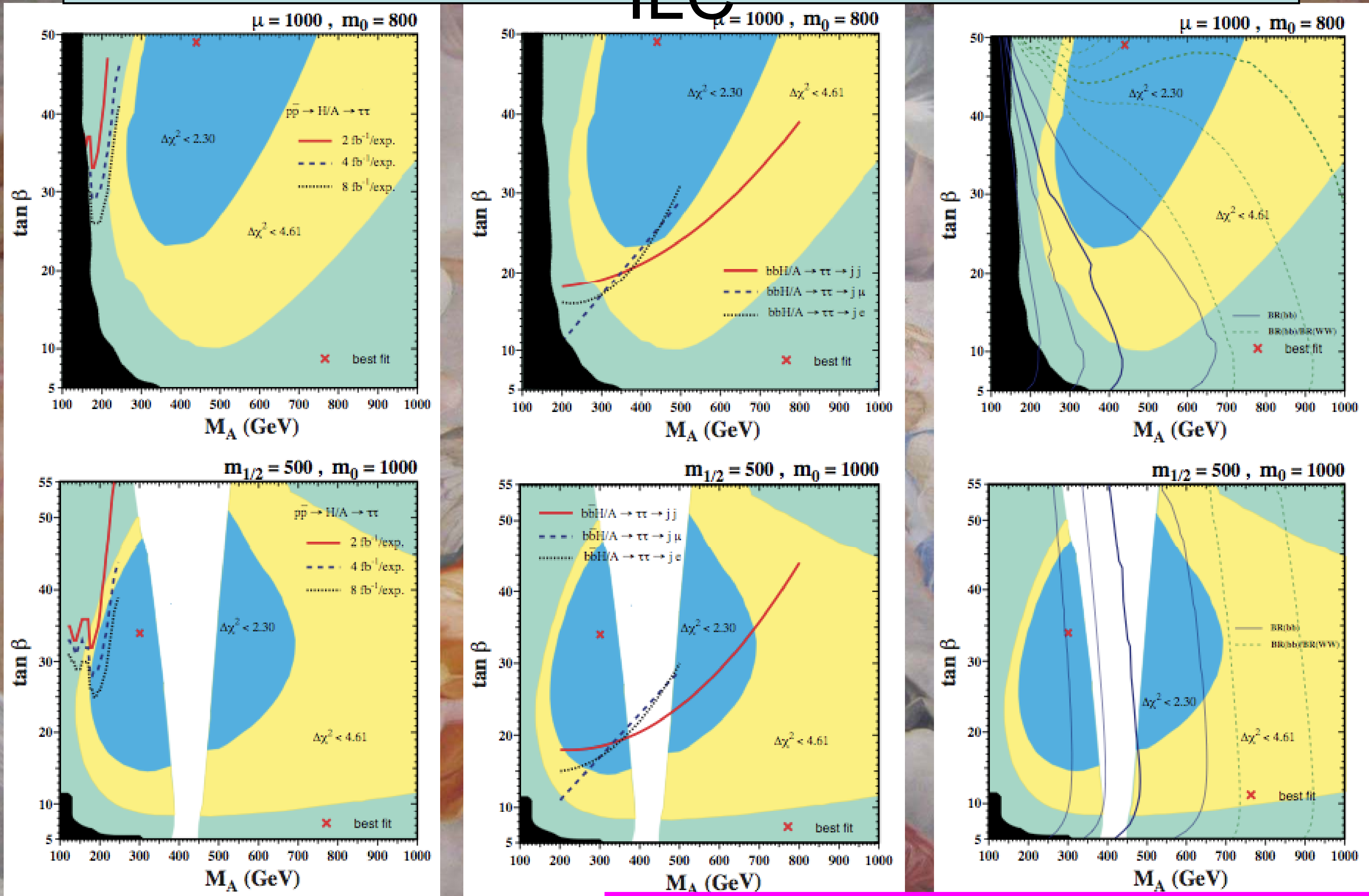
  No reason why not!

NUHM

WMAP-Compatible (m_A, tanβ) Surfaces in NUHM

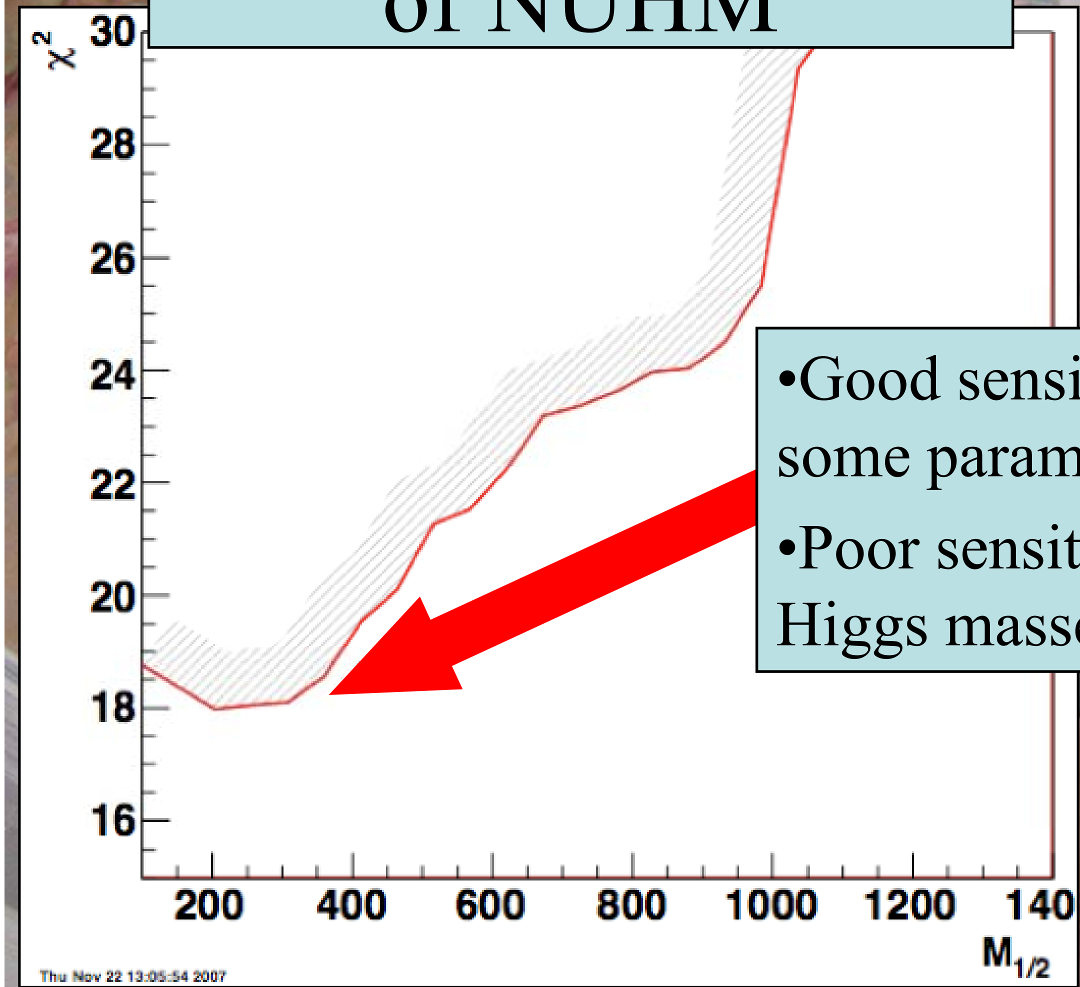
- Within CMSSM, generic choices of m_A, tanβ do not have correct relic density
- Use extra NUHM parameters to keep $\Omega_\chi h^2$ within WMAP range, e.g.,
  - m_0 = 800 GeV, μ = 1000 GeV, $m_{1/2} \sim 9/8\ m_A$
  - $m_{1/2}$ = 500, m_0 = 1000, $\mu \sim$ 250 to 400 GeV
- Make global fit to electroweak and B observables
- Analyze detectability @ Tevatron/LHC/ILC

WMAP Surfaces @ Tevatron, LHC, ILC

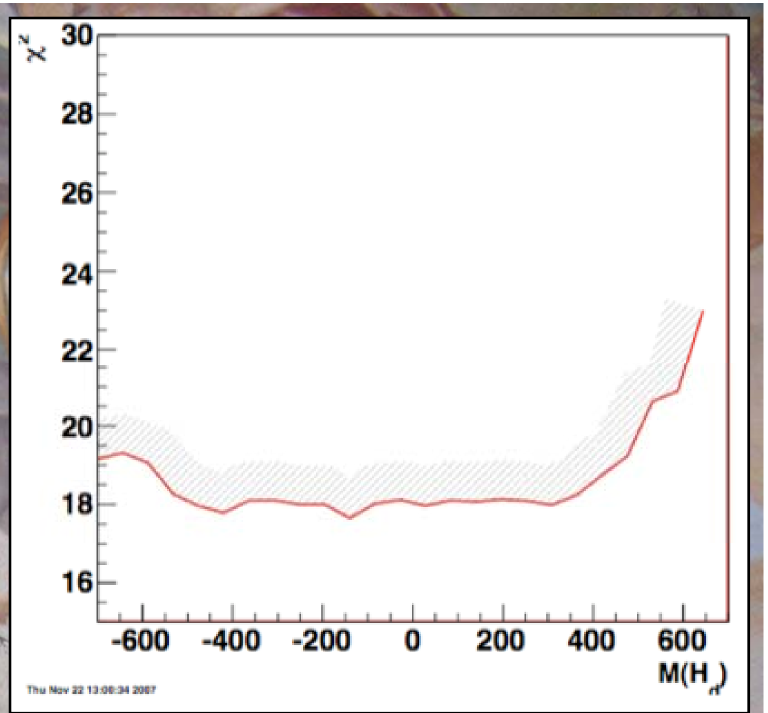


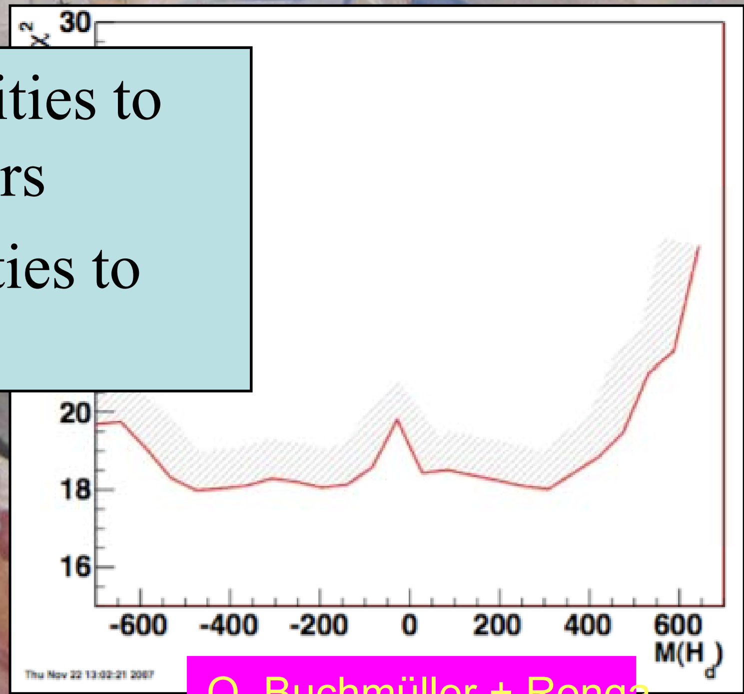
J.E., Hahn, Heinemeyer, Olive + Weiglein: arXiv:0709.0(

Markov Chain Monte Carlo (MCMC) Analysis of NUHM



- Good sensitivities to some parameters
- Poor sensitivities to Higgs masses

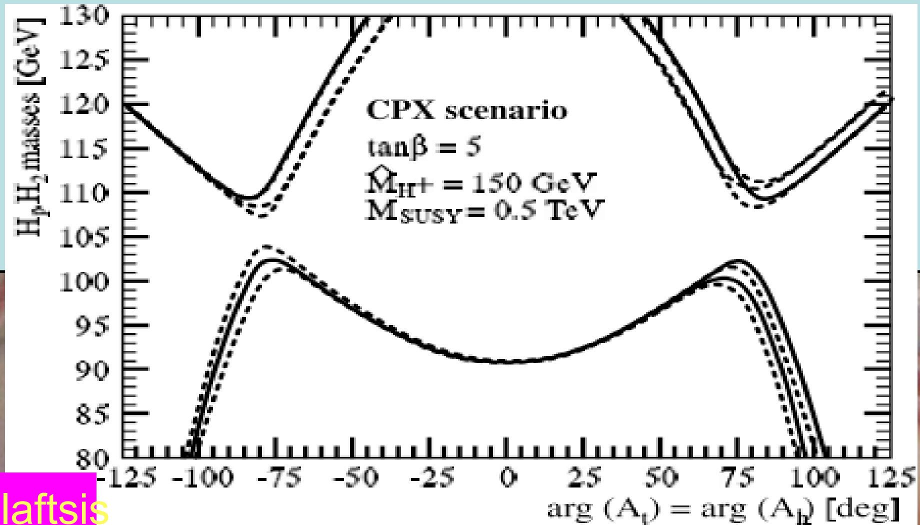


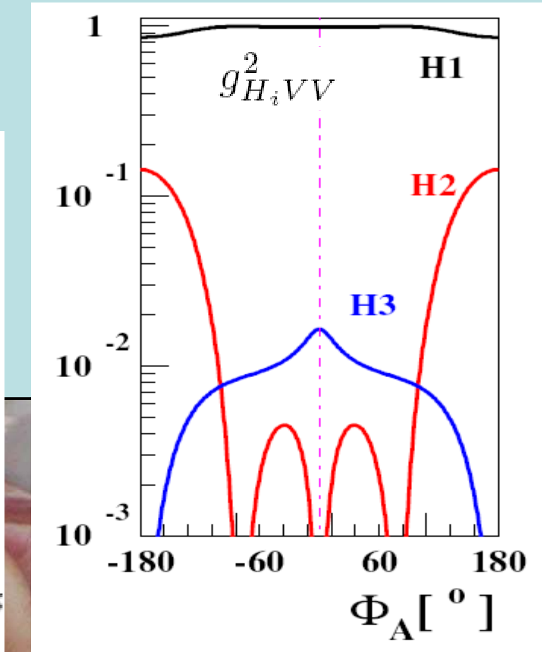


O. Buchmüller + Ronga

Complexification of CMSSM

- With universality, just two new CP-violating parameters:
  - Arg(M_a μ), Arg(A_f μ)
- Loop-induced mixing ~ $\frac{3}{16\pi^2}\frac{\mathrm{Im}\,(A_f\mu)}{m^2_{\tilde{f}_2}-m^2_{\tilde{f}_1}}$
  - (h,H,A) → (H_1,H_2,H_3) with indefinite CP
- Effects on masses, couplings

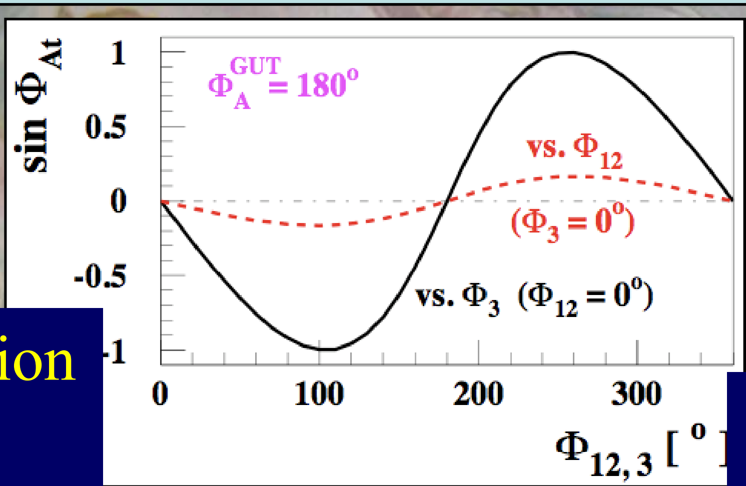




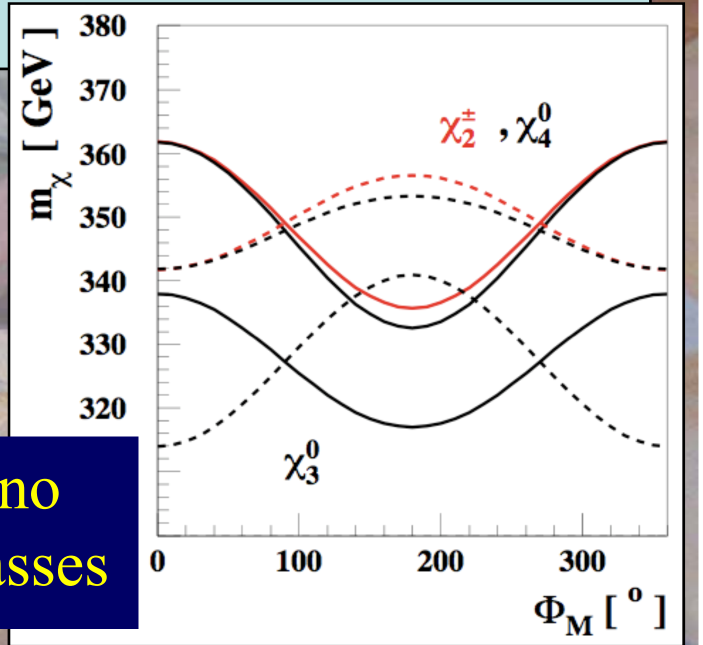
J.E. + Lee + Pilaftsis

Effects of CP Phases in MCPMFV

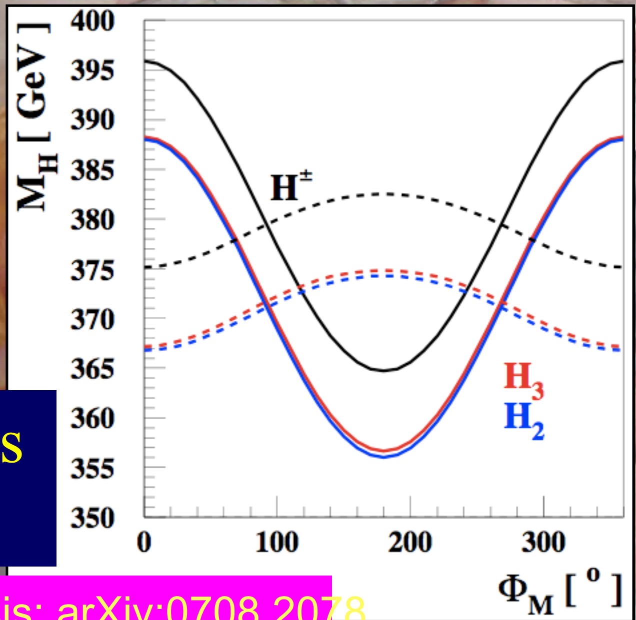
Renormalization of phases



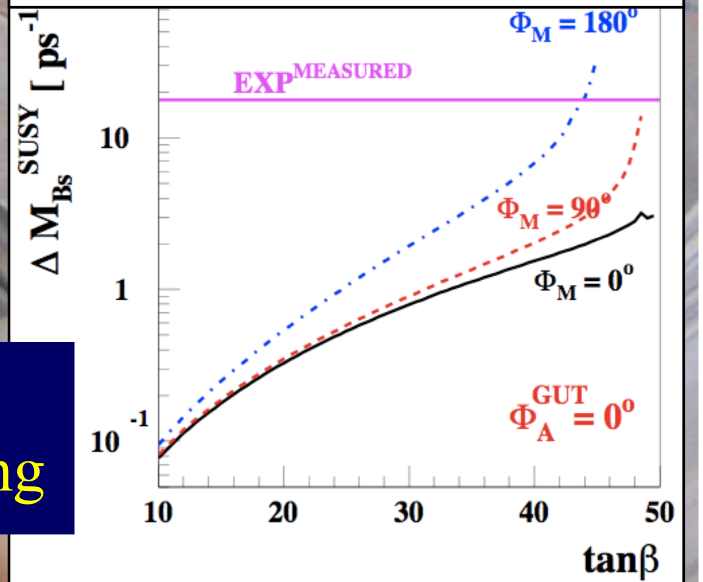
Ino masses



Heavy Higgs masses



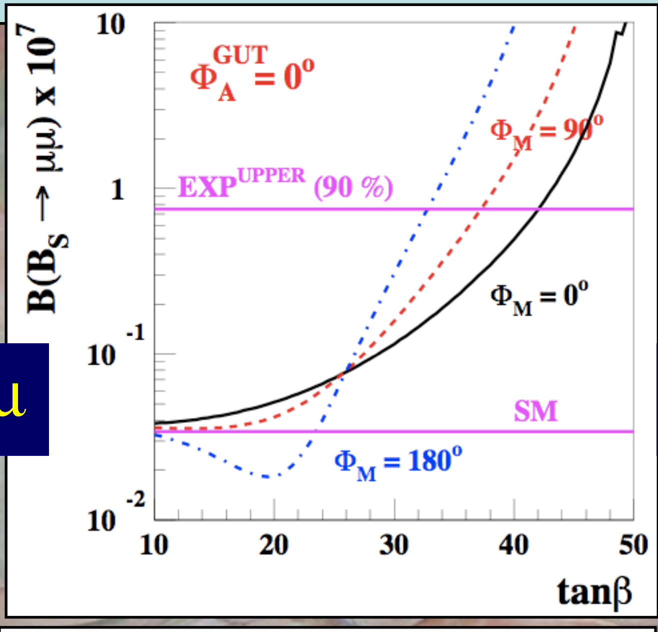
B_s mixing



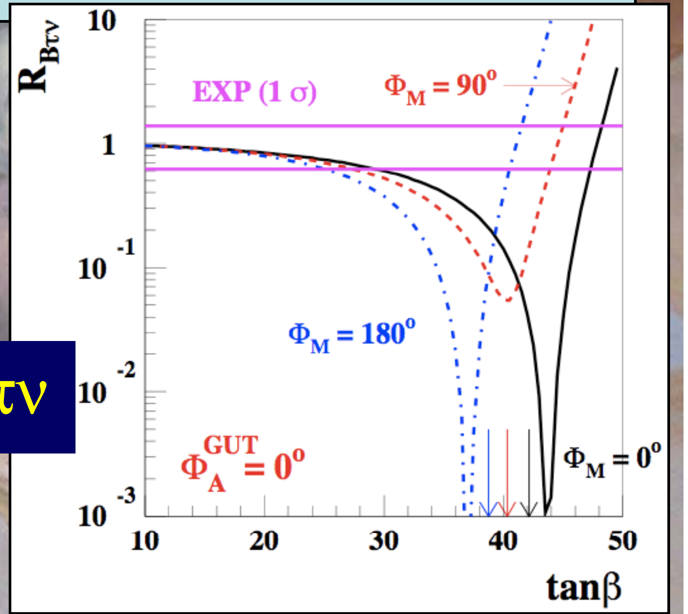
J.E. + Lee + Pilaftsis: arXiv:0708.2078

Effects of CP Phases in MCPMFV

$B_s \to \mu\mu$

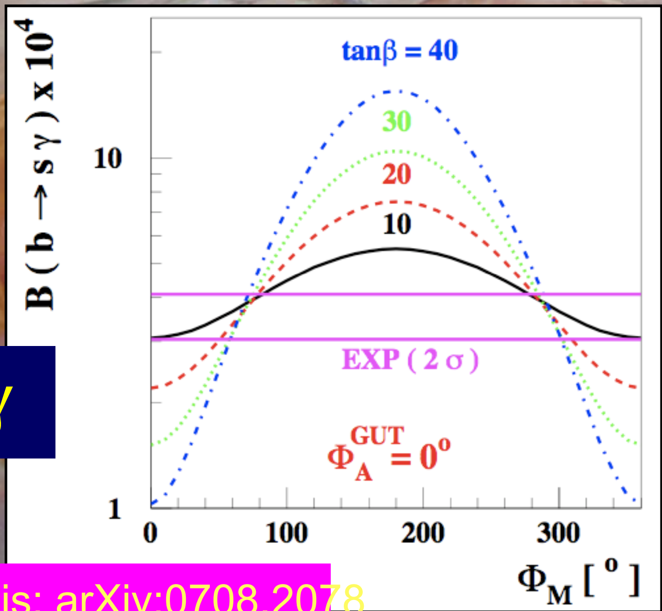


$B_u \to \tau\nu$

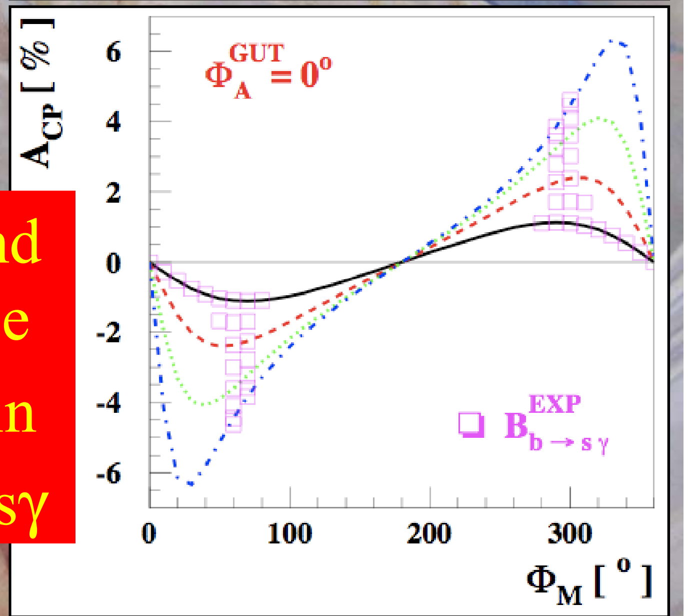


Different regions allowed for different phases …

$b \to s\gamma$



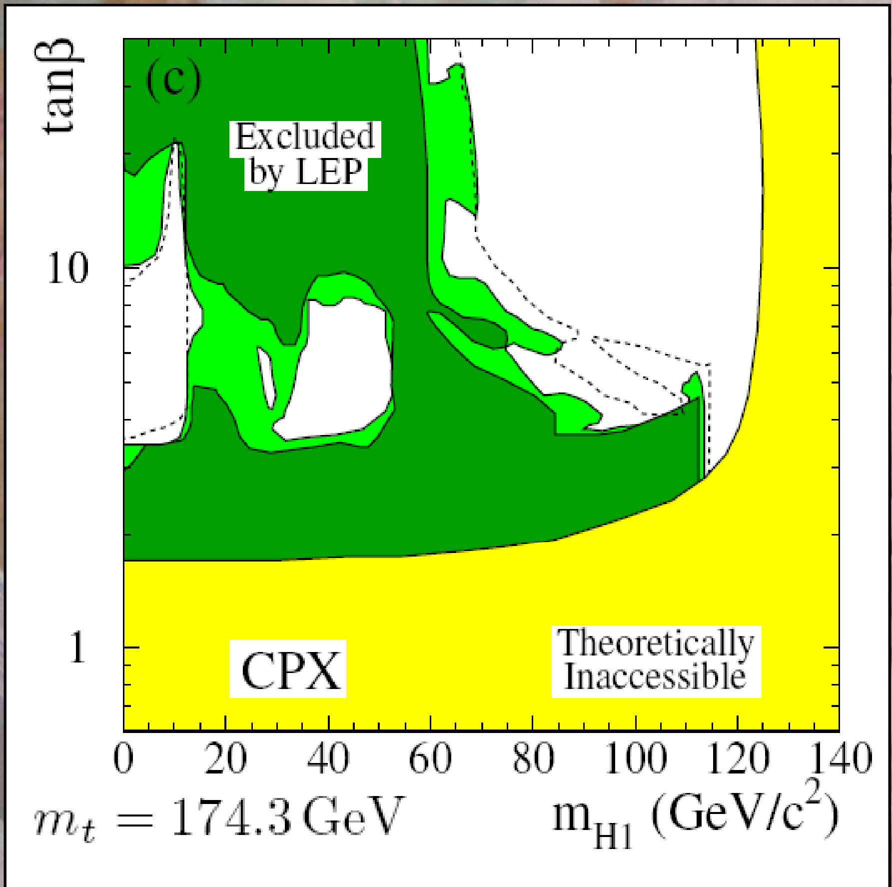
… and hence A_{CP} in $b \to s\gamma$

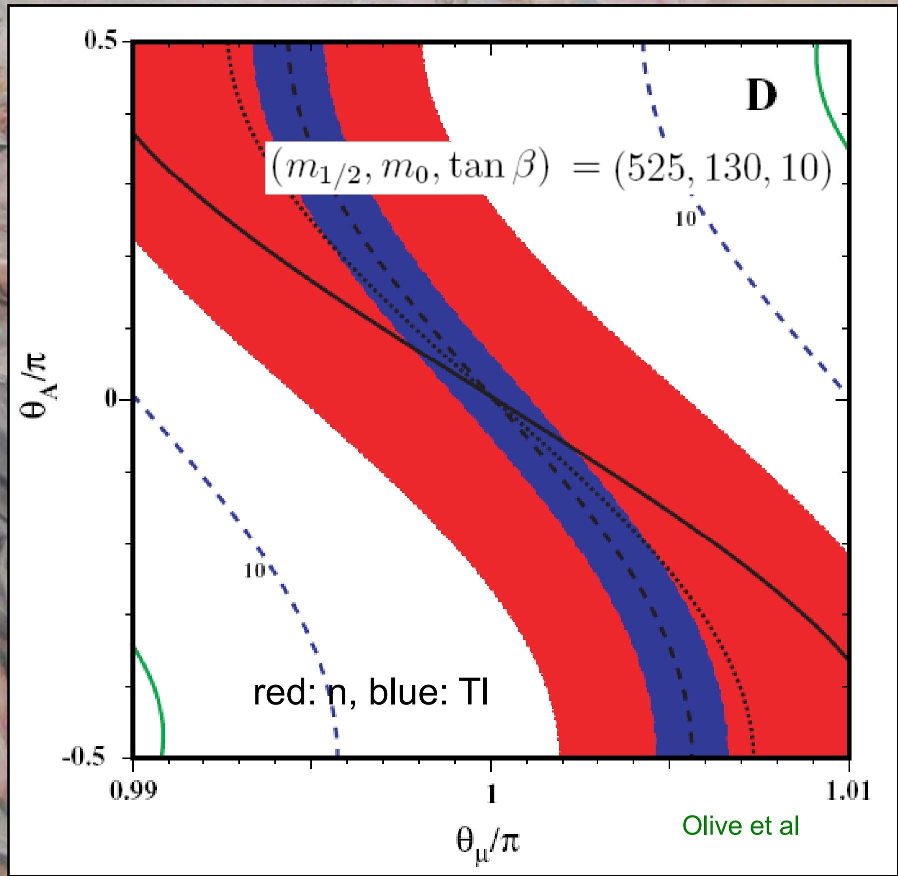


J.E. + Lee + Pilaftsis: arXiv:0708.2078

Experimental Constraints

From LEP, from electric dipole moments





Parameters in Minimal Seesaw Model

- Effective light-neutrino theory

$$-\mathcal{L}_\nu \supset \quad (Y_\nu)_{ij} \, H\bar{N}_i \begin{pmatrix} \nu \\ L \end{pmatrix}_j \quad + \quad \underbrace{\frac{1}{2}\bar{N}_i \mathcal{M}_{ij} \bar{N}_j}$$

- 3 masses, 3 mixing angles, 3 CP-violating phases
- Additional 9 parameters associated with heavy singlet 'right-handed' neutrinos:

  3 more masses, 3 more mixing angles,

  3 more CP-violating phases
- 12 contribute to leptogenesis, not MNS phase δ
- If supersymmetric, 16 parameters contribute to renormalization of soft susy-breaking m_0

How to Measure Neutrino Parameters?

7 measurable:

$m_{1,2,3}$, θ_{12}, θ_{13}, θ_{23}, δ

not $\varphi_{1,2}$?

Seesaw mechanism

M_ν

9 effective parameters

Y_ν , M_{N_i}

15+3 physical parameters

$$\epsilon_{ij} = \frac{1}{8\pi}\frac{1}{\left(Y_\nu Y_\nu^\dagger\right)_{ii}}\mathrm{Im}\left(\left(Y_\nu Y_\nu^\dagger\right)_{ij}\right)^2 f\left(\frac{M_j}{M_i}\right)$$

CP violation in decays of heavy neutrinos

Leptogenesis

$Y_\nu Y_\nu^\dagger$, M_{N_i}

9+3 parameters

$$\left(\delta m_{\tilde{L}}^2\right)_{ij} \ni -\frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(Y_\nu^\dagger Y_\nu\right)_{ij} \mathrm{Ln}\left(\frac{M_{GUT}}{M}\right),$$

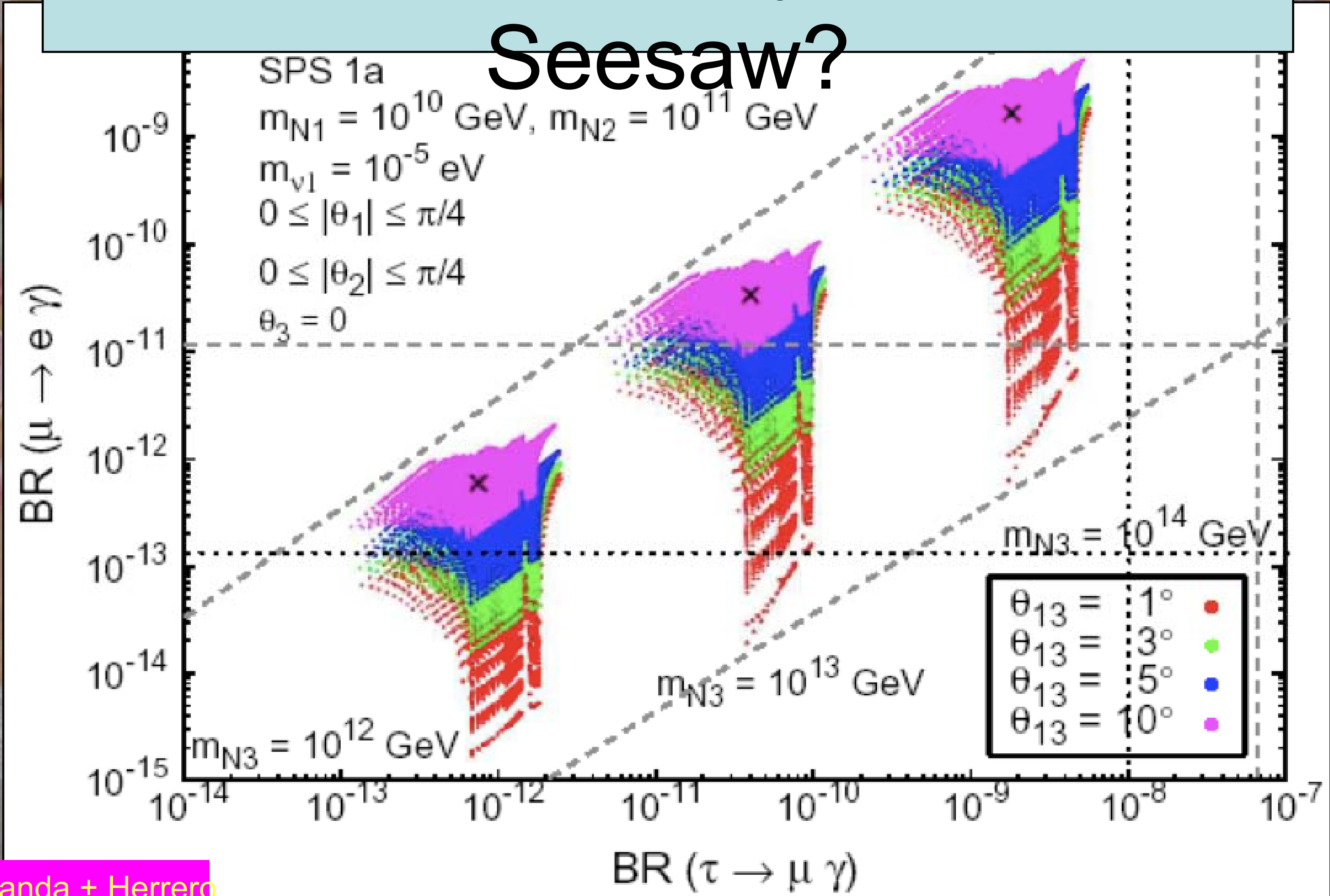
Induces flavour-changing decays of charged leptons, CP violation

Renormalization

$Y_\nu^\dagger L Y_\nu$, M_{N_i}

13+3 parameters

Flavour in the LHC Era: LFV in Supersymmetric Seesaw?

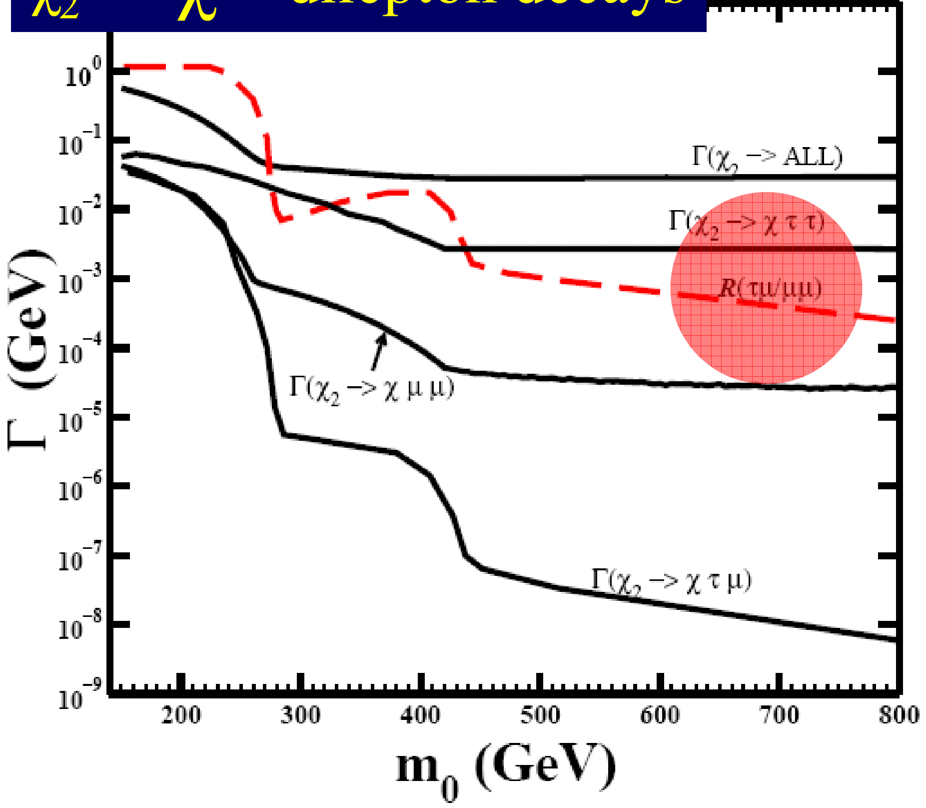


Arganda + Herrero

Flavour Violation in Sparticle Decays @ LHC?

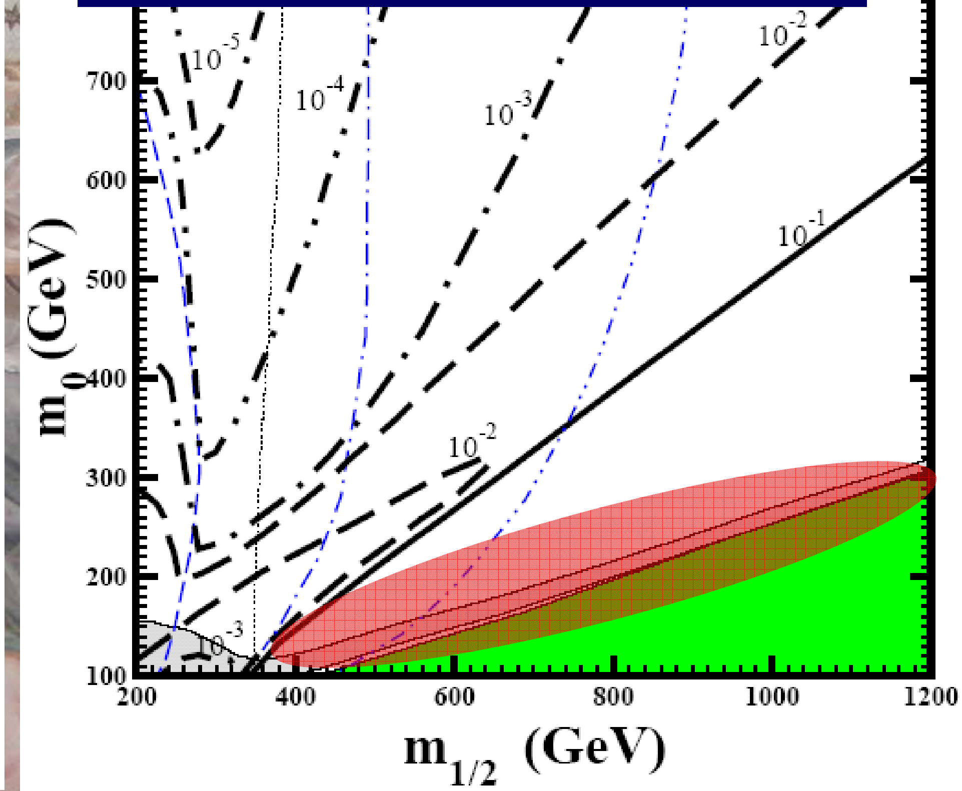
Possible rates for

$\chi_2 \to \chi$ + dilepton decays



Possible branching ratios for

$\chi_2 \to \chi + \tau\mu$ decays



Carvalho + J.E. + Gomez + Lola + Rom

Outlook

- Flavour is (perhaps) the most open problem in particle physics
  - The LHC will provide many flavour probes
- If the LHC discovers new physics at the TeV scale (supersymmetry, extra dimensions, …), flavour problem will become more acute
  - What is flavour structure of new physics?
  - Low-energy effects of this TeV flavour physics?
- **Plenty of collider ↔ flavour interplay to play with!**