Physics Beyond the Standard Model

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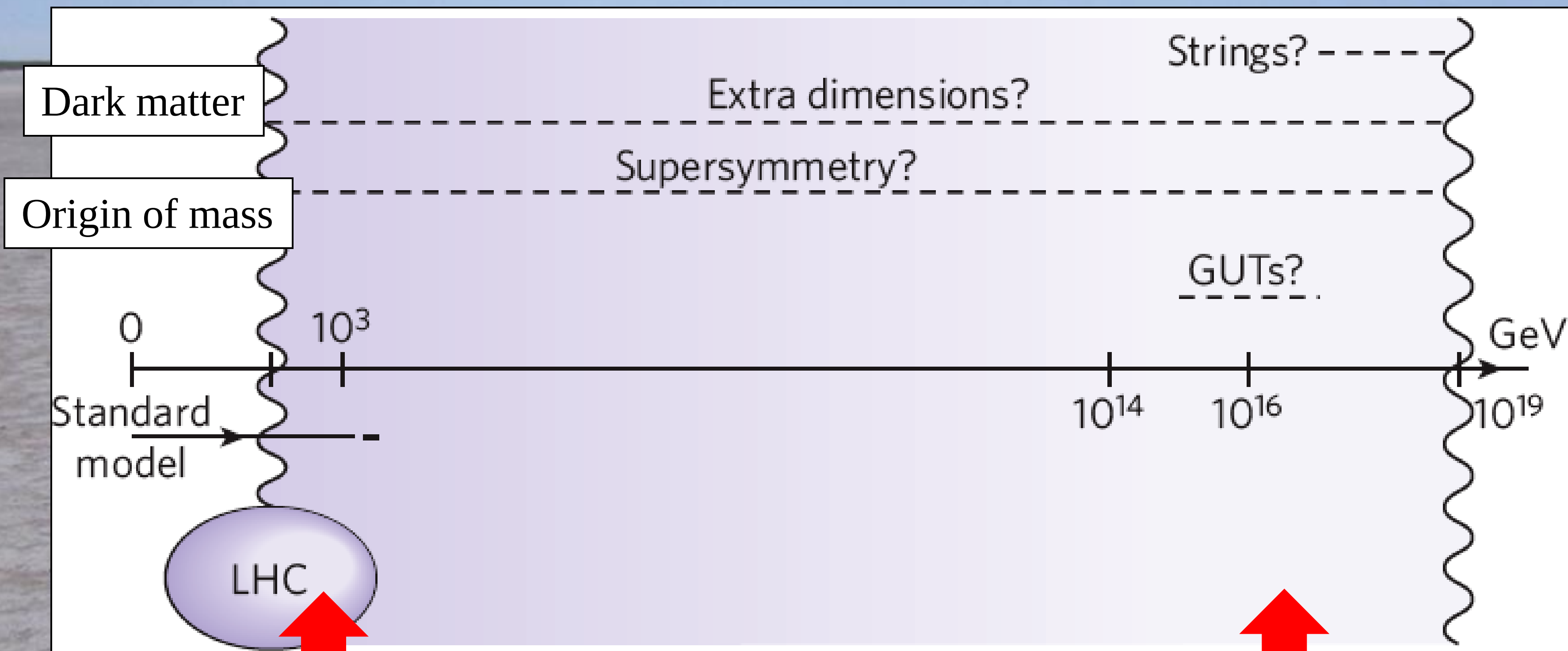
Open Questions beyond the Standard Model

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

At what Energy is the New Physics?

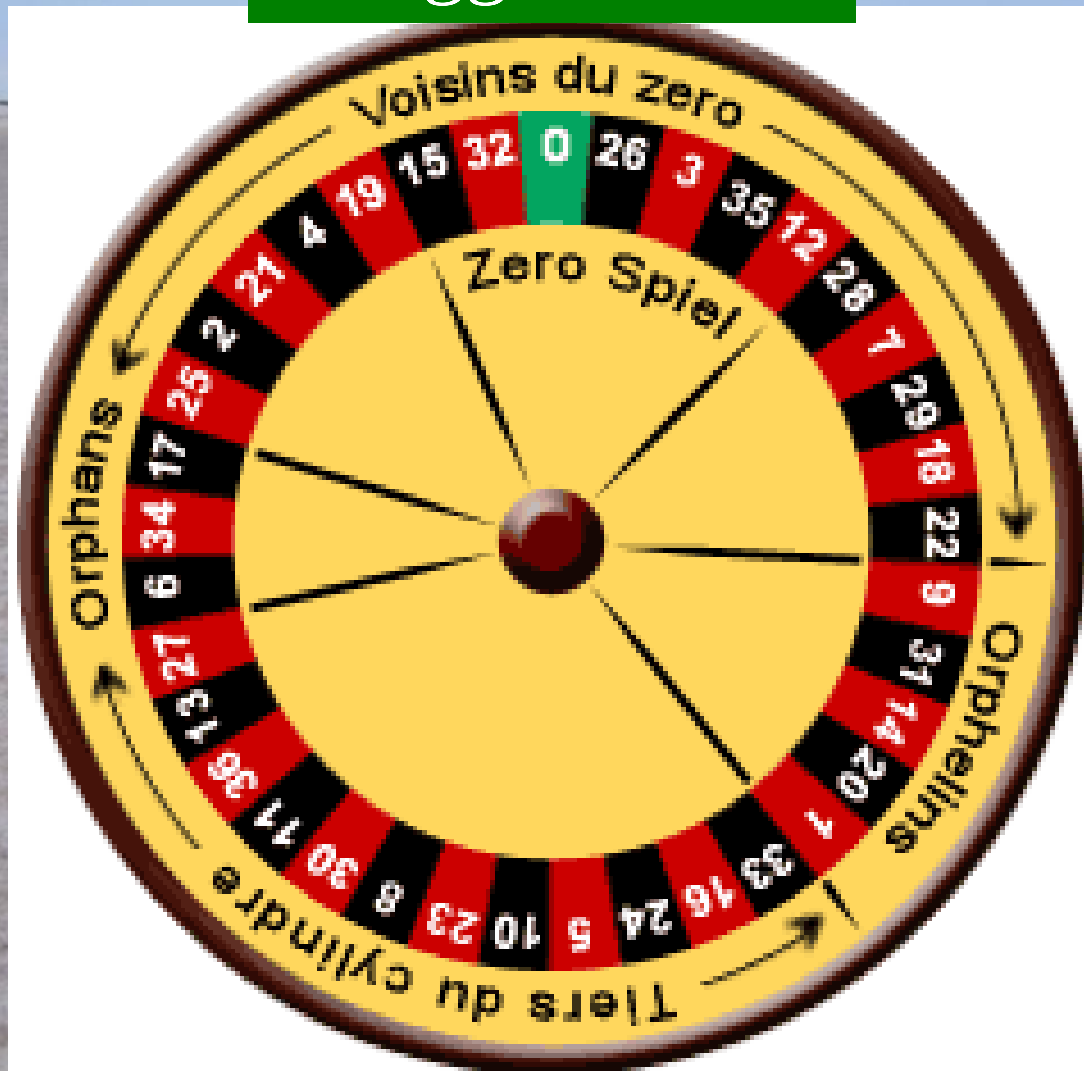


A lot accessible to the LHC

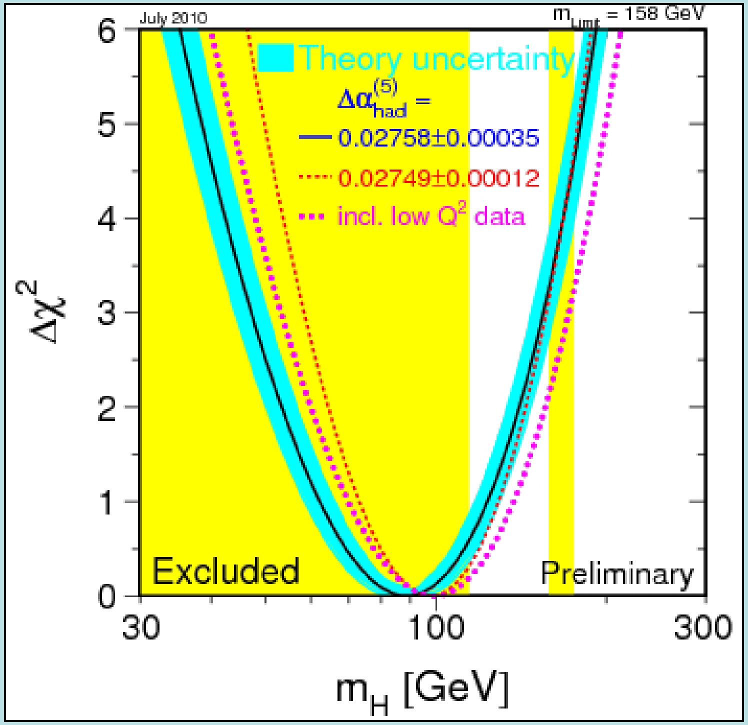
Some accessible only via astrophysics & cosmology

The LHC Roulette Wheel

Higgs boson



How Heavy is the Higgs Boson?



- Direct search limit from LEP:

  $m_H > 114.4$ GeV

- Electroweak fit sensitive to m_t

  (Now $m_t = 173.1 \pm 1.3$ GeV)

- Best-fit value for Higgs mass:

  $m_H = 89^{+35}_{-26}$ GeV

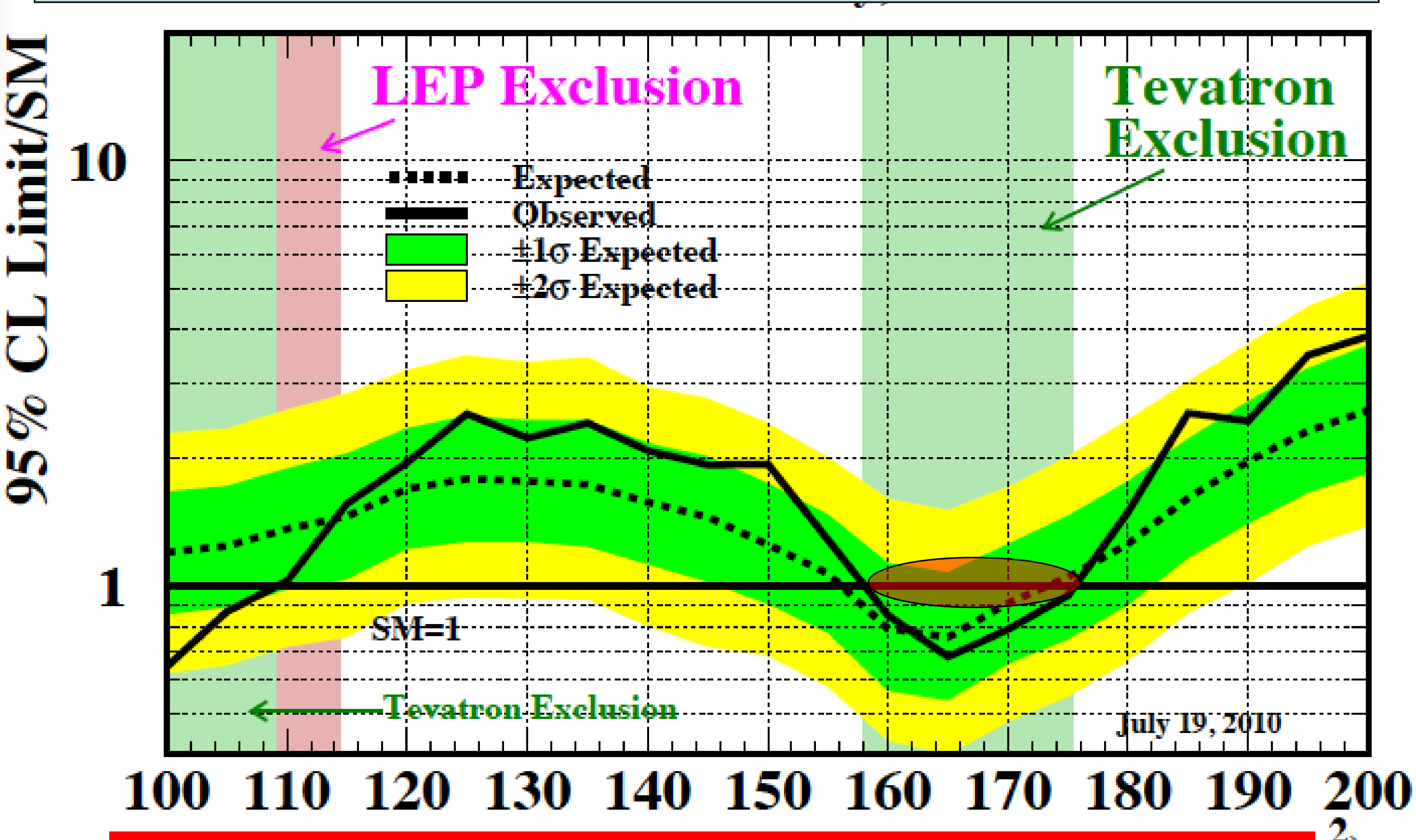
- 95% confidence-level upper limit:

  $m_H < 158$ GeV, or 185 GeV including LEP direct limit

- Tevatron exclusion:

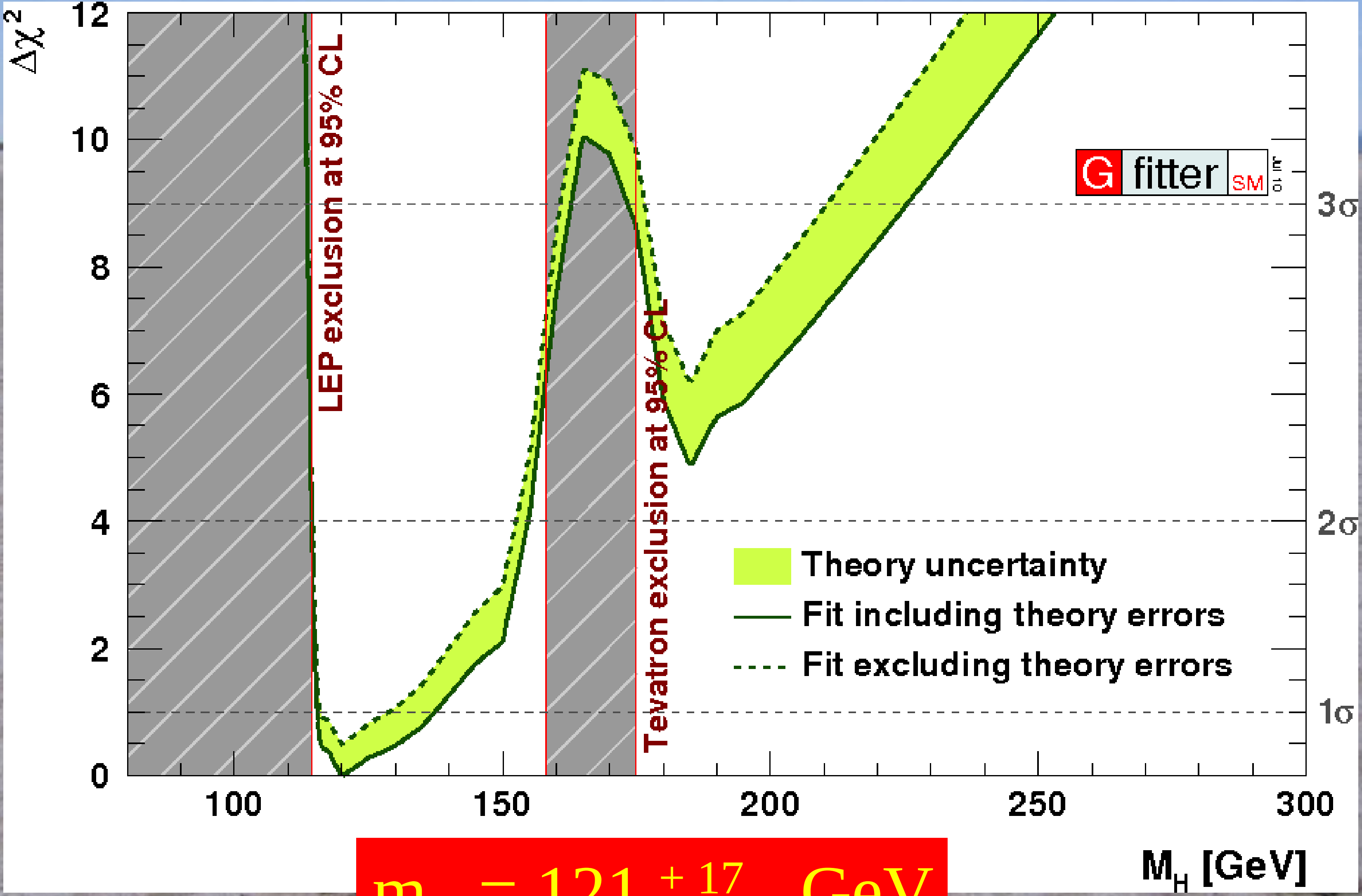
  $m_H < 158$ GeV or > 175 GeV

Higgs Search @ Tevatron



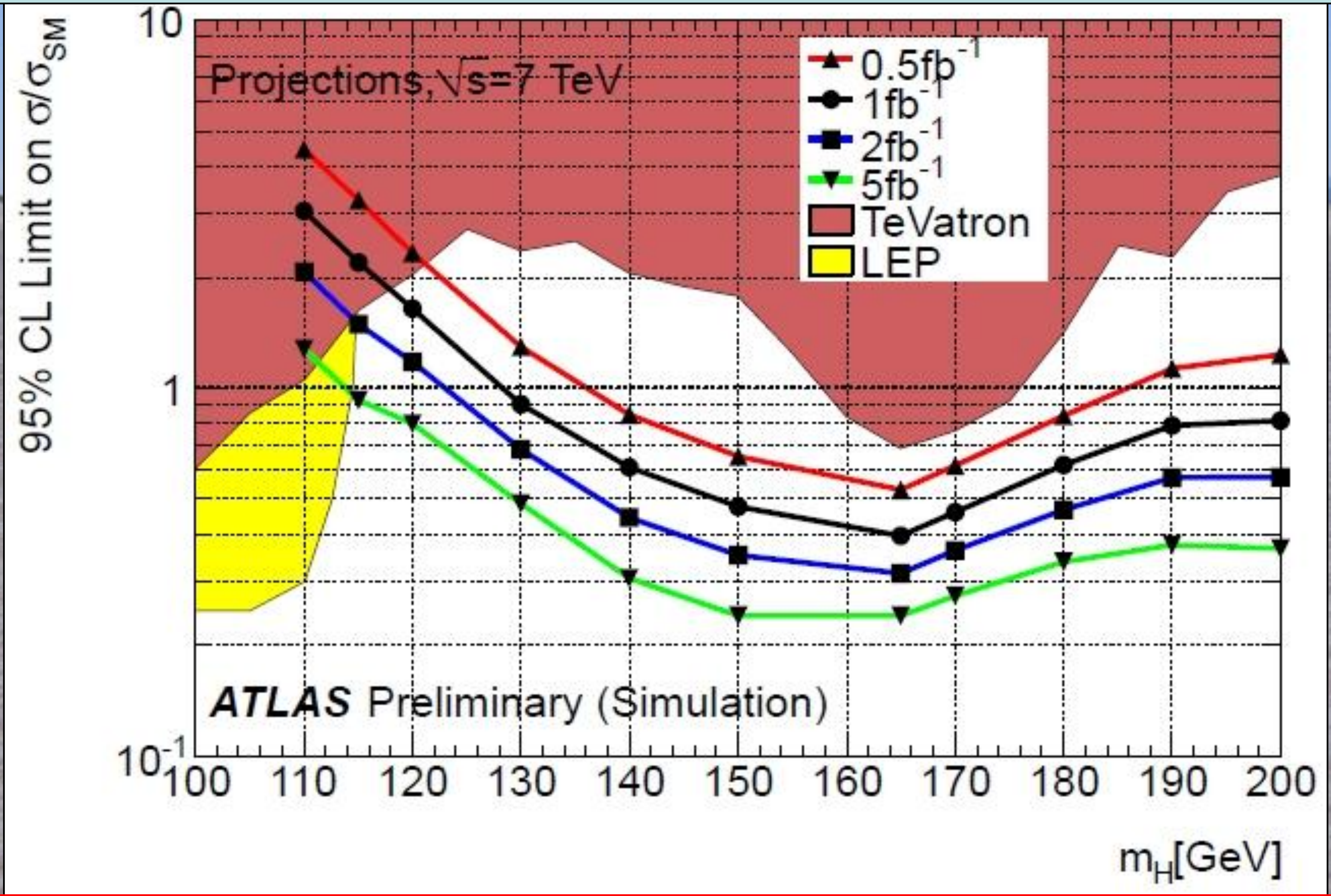
Tevatron excludes Higgs between 158 & 175 GeV

Combining the Higgs Information



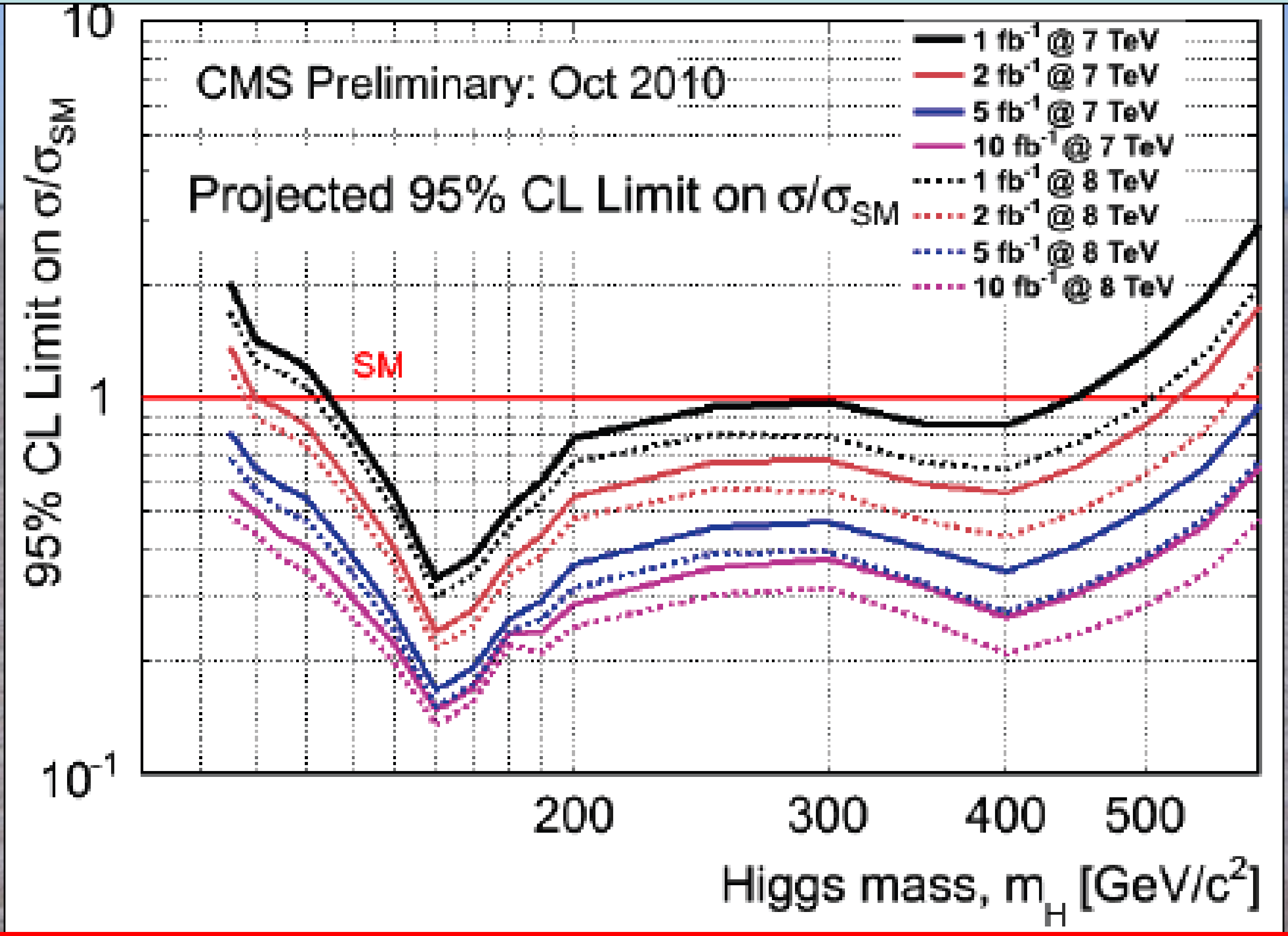
$m_H = 121^{+17}_{-6}$ GeV

Higgs Search @ 7 TeV



Expected 95 % CL excluded region is 128 GeV < M_H < 200+ GeV with 1/fb of integrated luminosity @ 7 TeV

Higgs Search @ 7 TeV

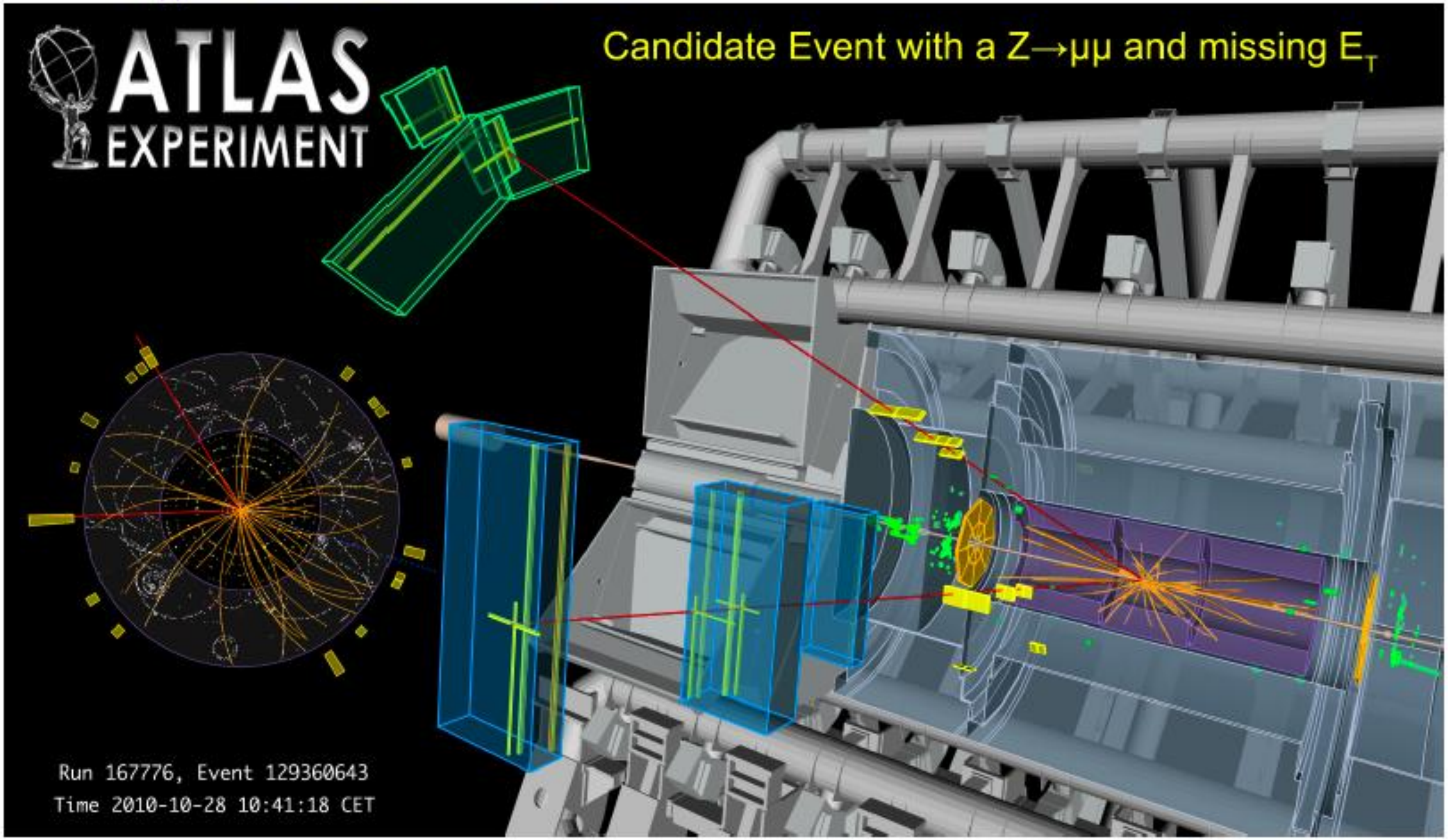


Expected 95 % CL excluded region is 135 GeV < M_H < 450 GeV with 1/fb of integrated luminosity @ 7 TeV

Interesting Events

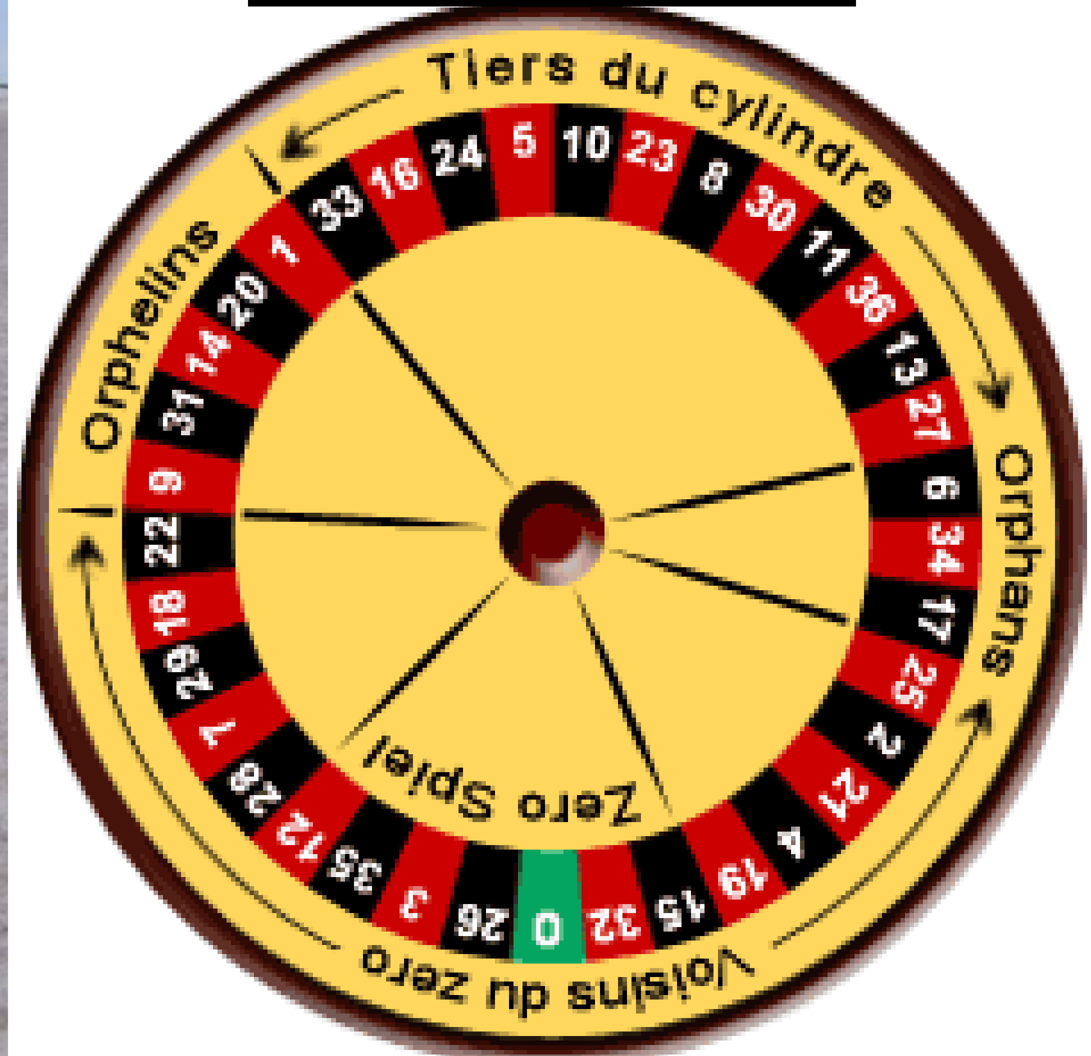
Candidate for ZZ→μμνν

$m_{\mu\mu}$ 94 GeV, E_T^{miss} = 161 GeV



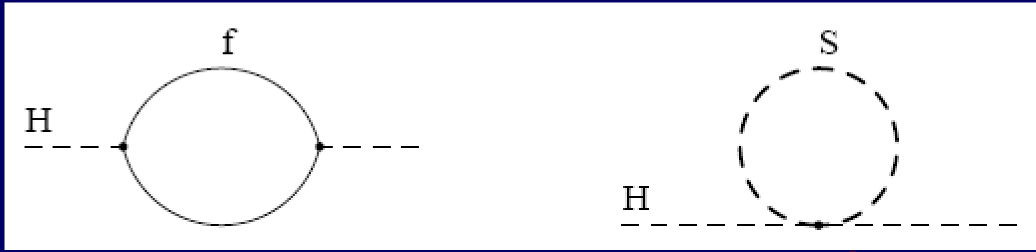
The LHC Roulette Wheel

Supersymmetry



Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



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

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

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

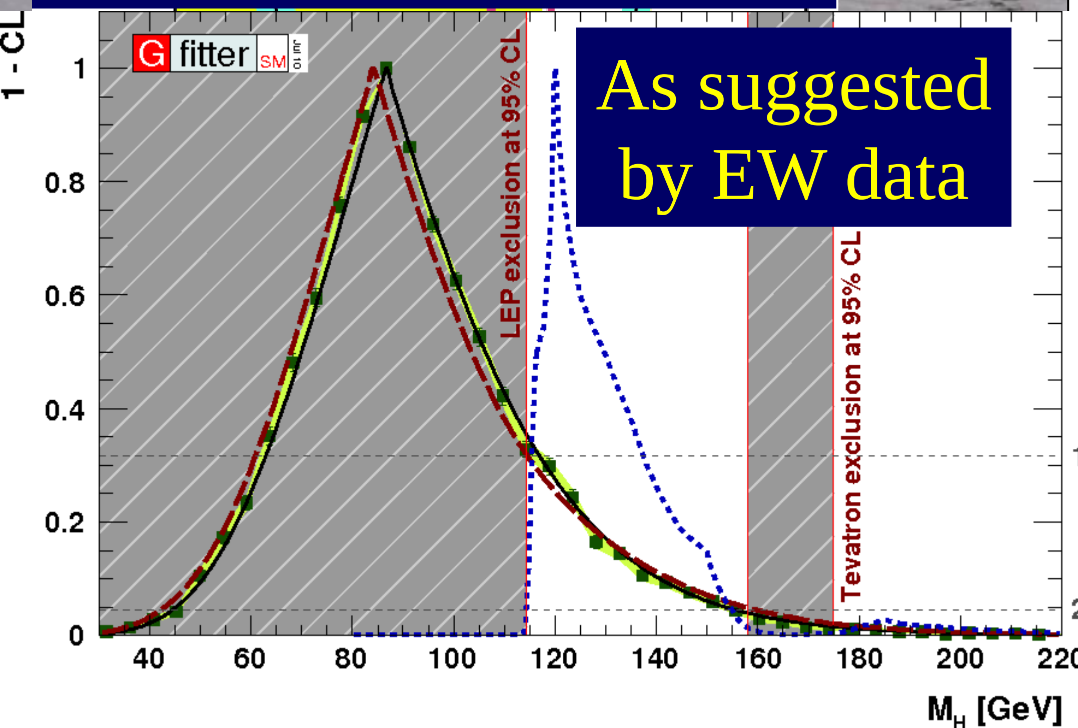
- Leading divergence cancelled if

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

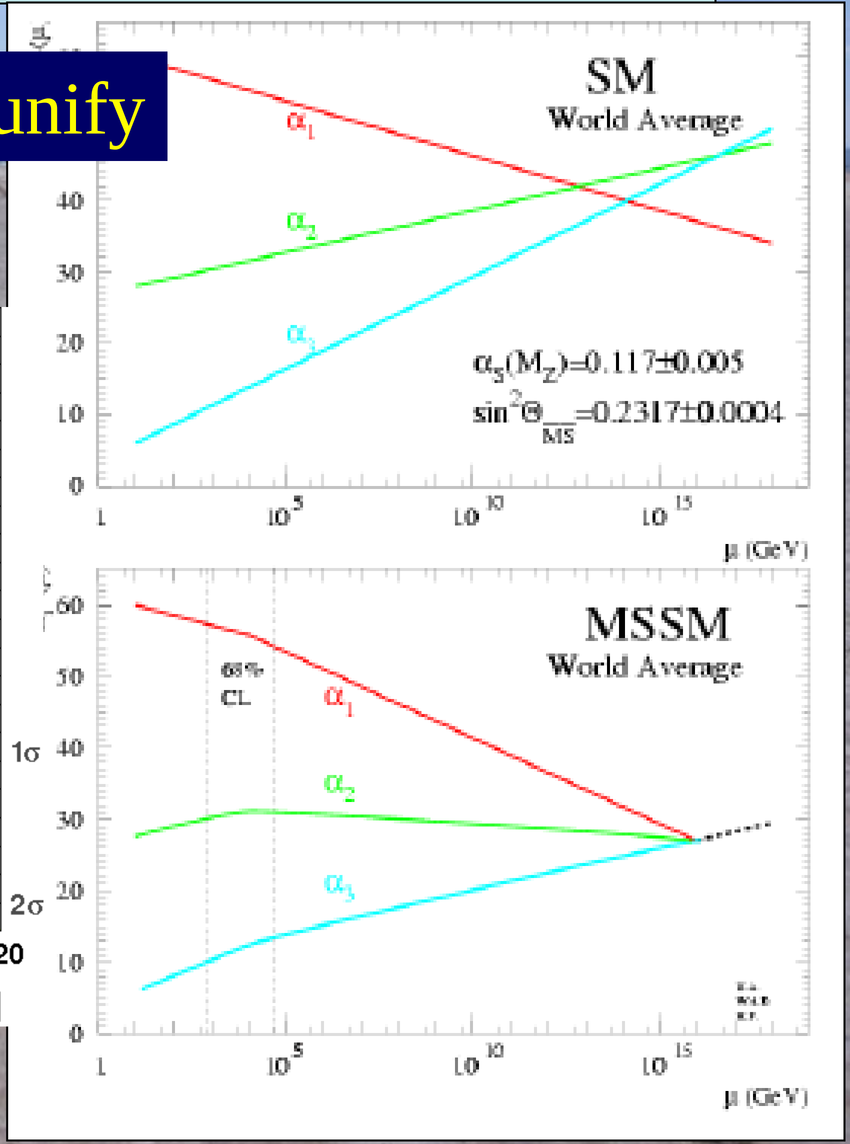
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV



As suggested by EW data



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

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 $A_{\lambda,}$ 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?

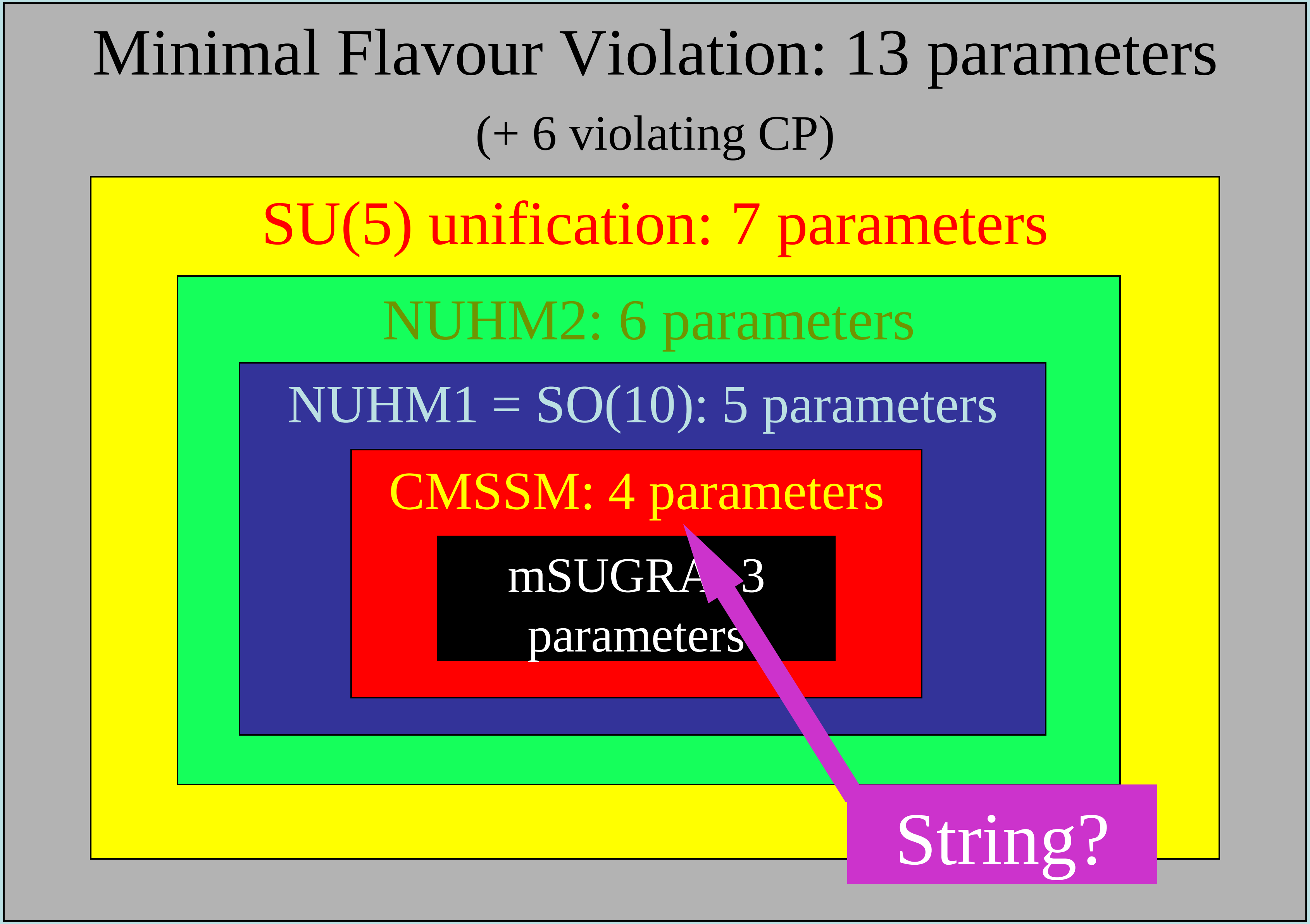
  disfavoured by upper limits on flavour-changing neutral interactions
- Squarks with different #s, squarks and sleptons?

  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



Lightest Supersymmetric Particle

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

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

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles

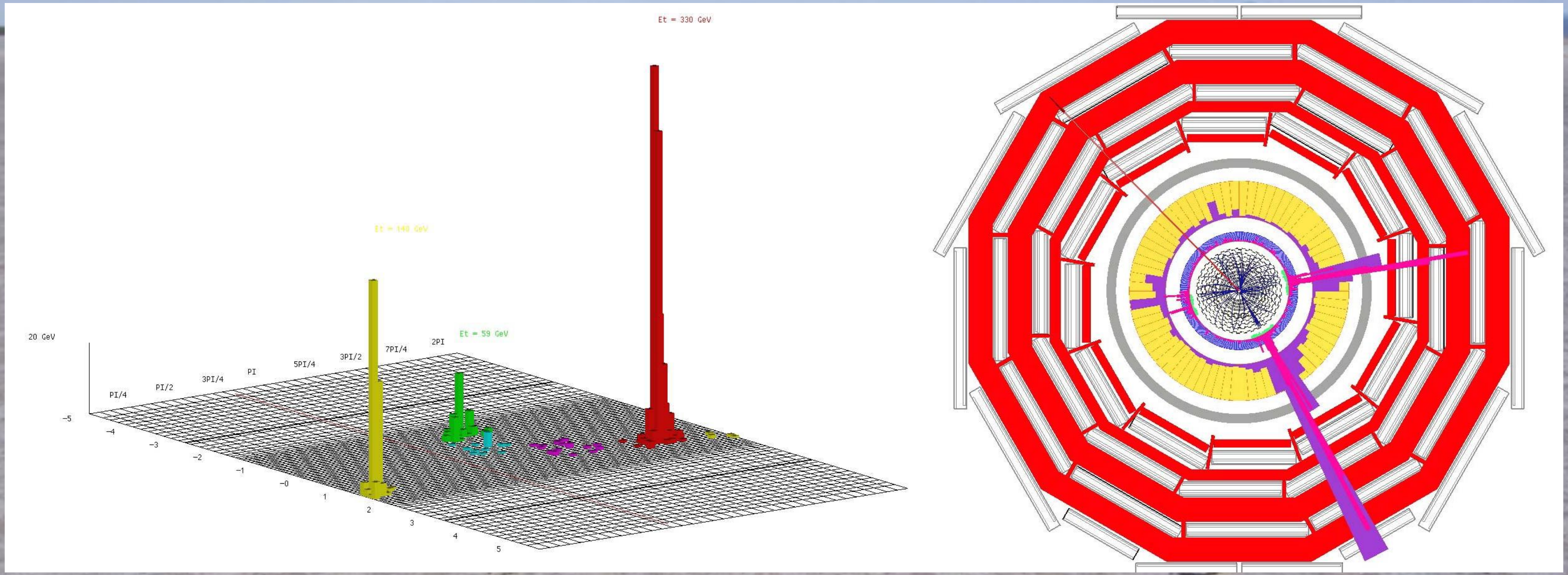
- Lightest supersymmetric particle (LSP) stable

Fayet

Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ (partner of Z, H, γ)
  - Gravitino
    - (nightmare for astrophysical detection)

Classic Supersymmetric Signature

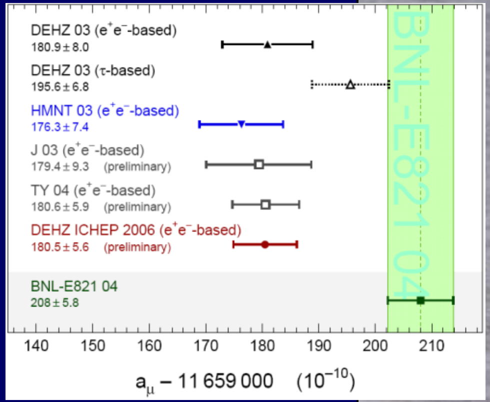


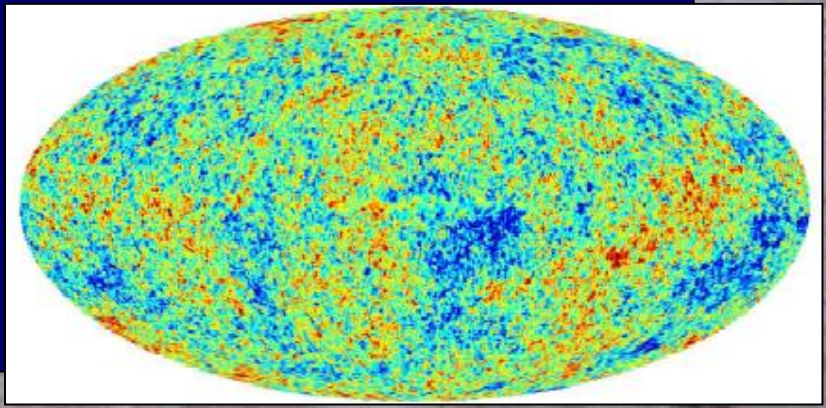
Missing transverse energy
carried away by dark matter particles

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron
  - selectron, chargino > 100 GeV
  - squarks, gluino > 300 GeV
- Indirect constraints
  - Higgs > 114 GeV, $b \to s \gamma$
- Density of dark matter
  - lightest sparticle χ:
  - $0.094 < \Omega_\chi h^2 < 0.124$

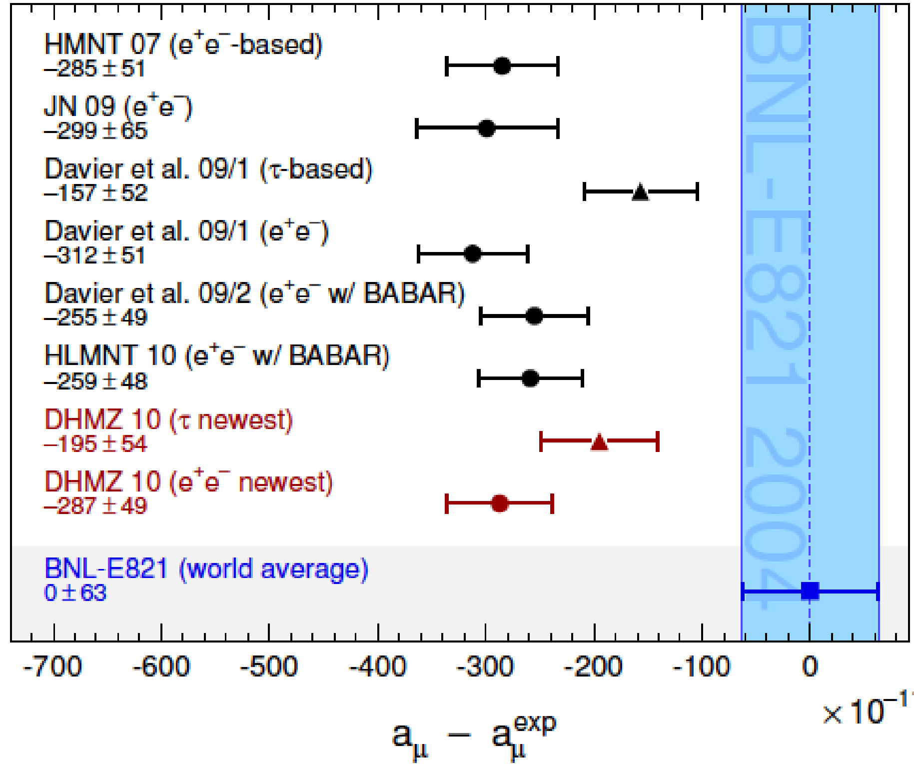
3.3 σ effect in $g_\mu - 2$?

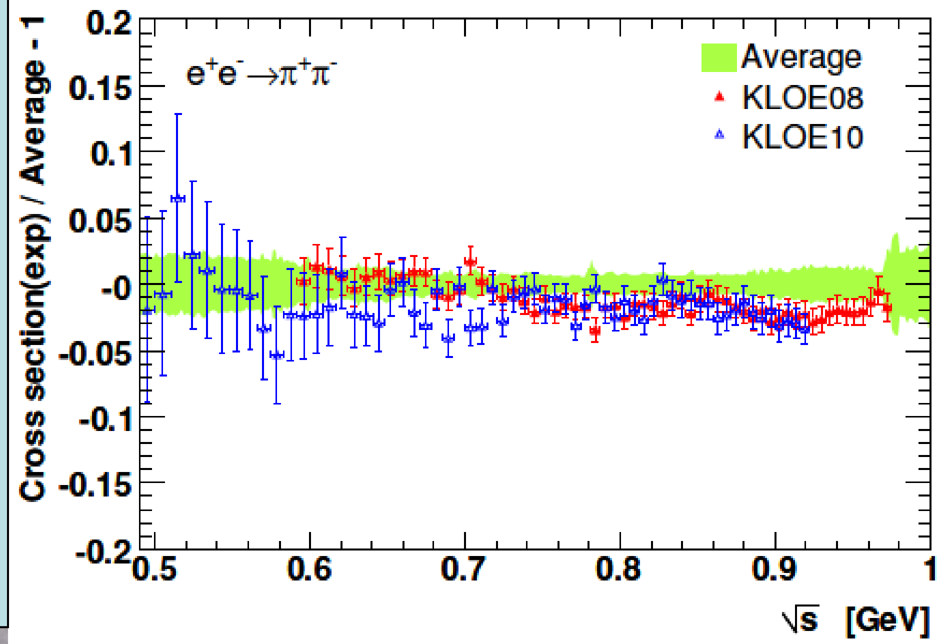




Quo Vadis g_μ - 2?

- 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?**





Current Constraints on CMSSM

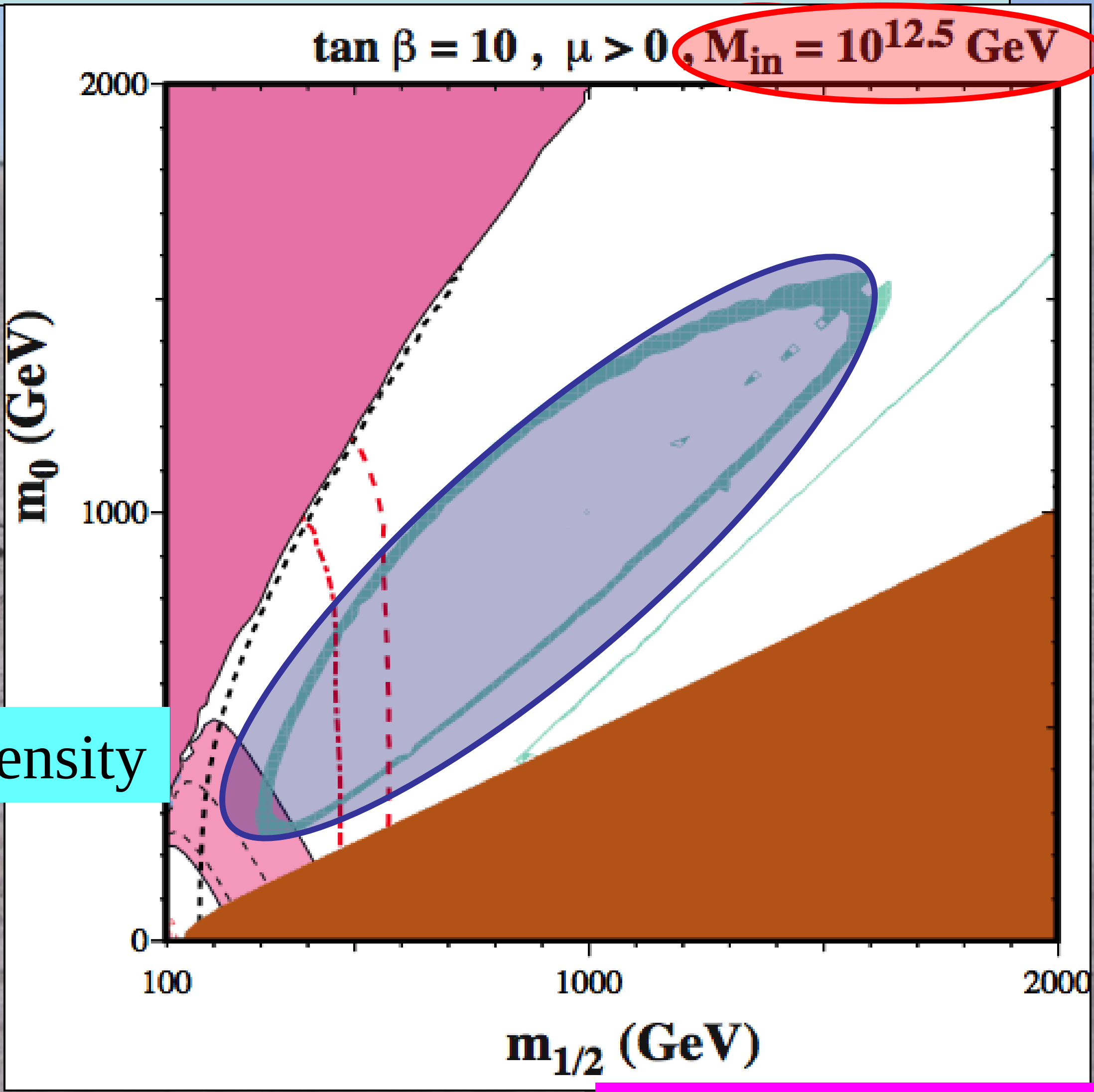
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

Preferred (?) by latest g - 2



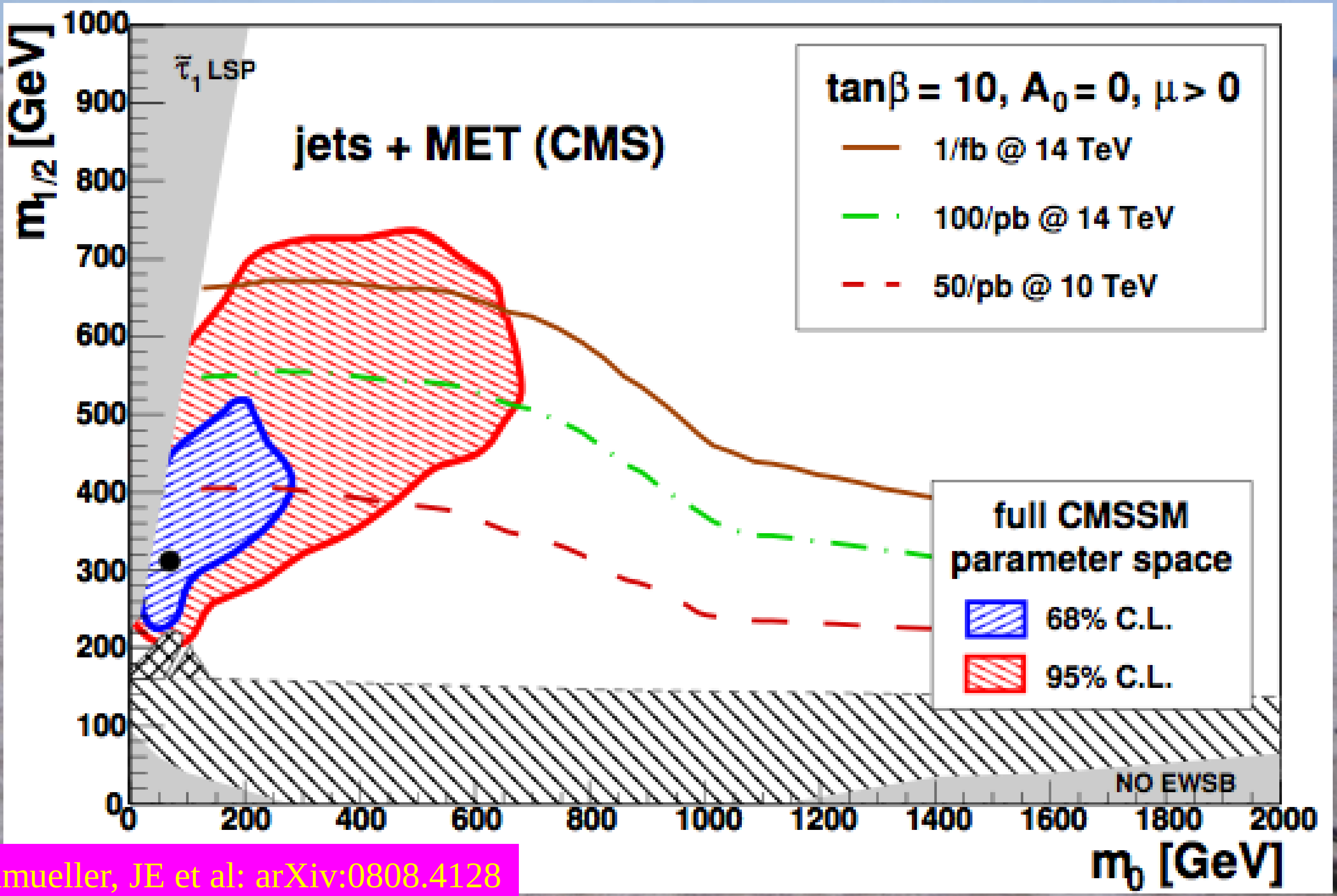
JE + Olive + Sandick

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)

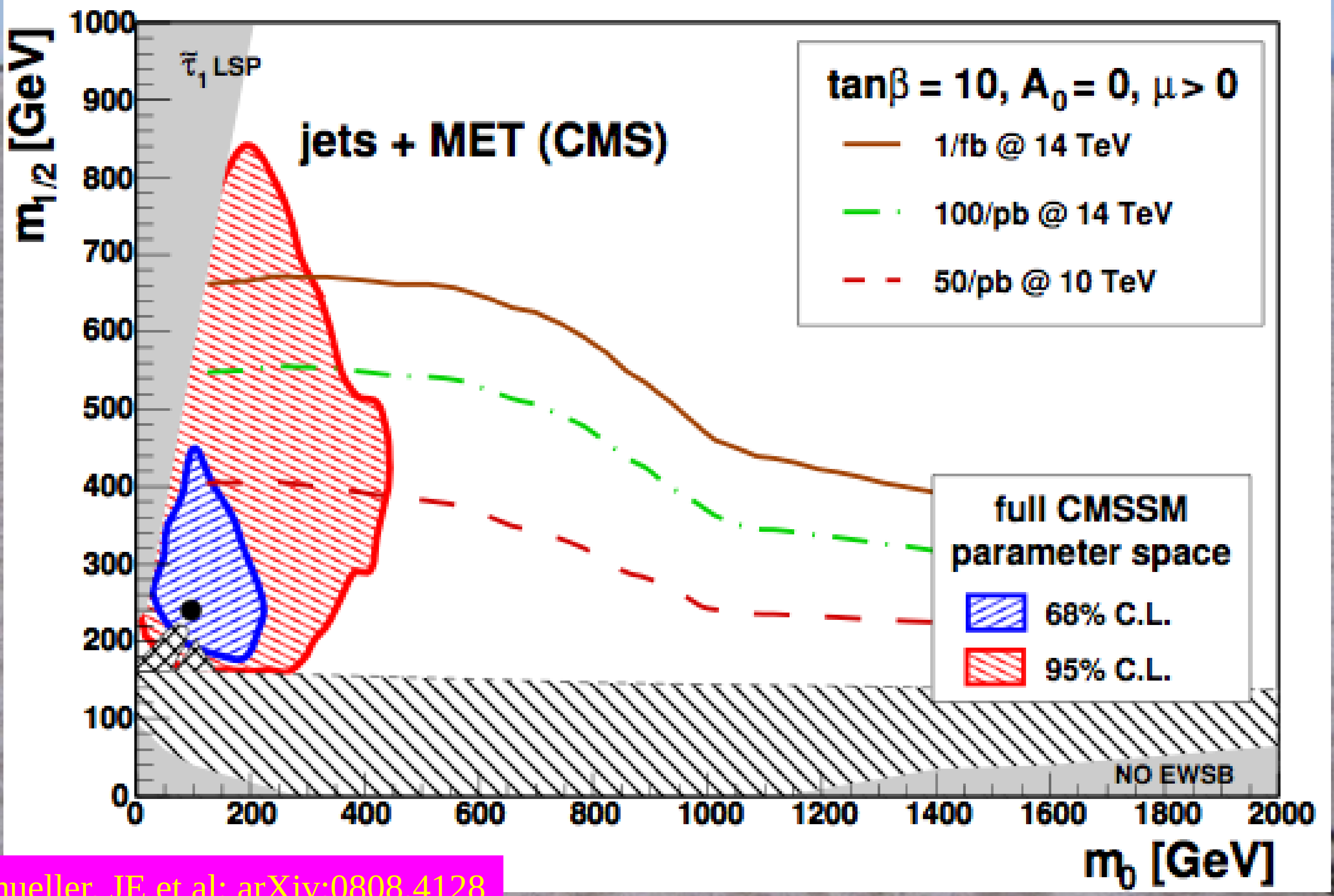
O.Buchmueller, JE et al: arXiv:0808.4128, 0907.5568, 0912.1036

How Soon Might the CMSSM be Detected?



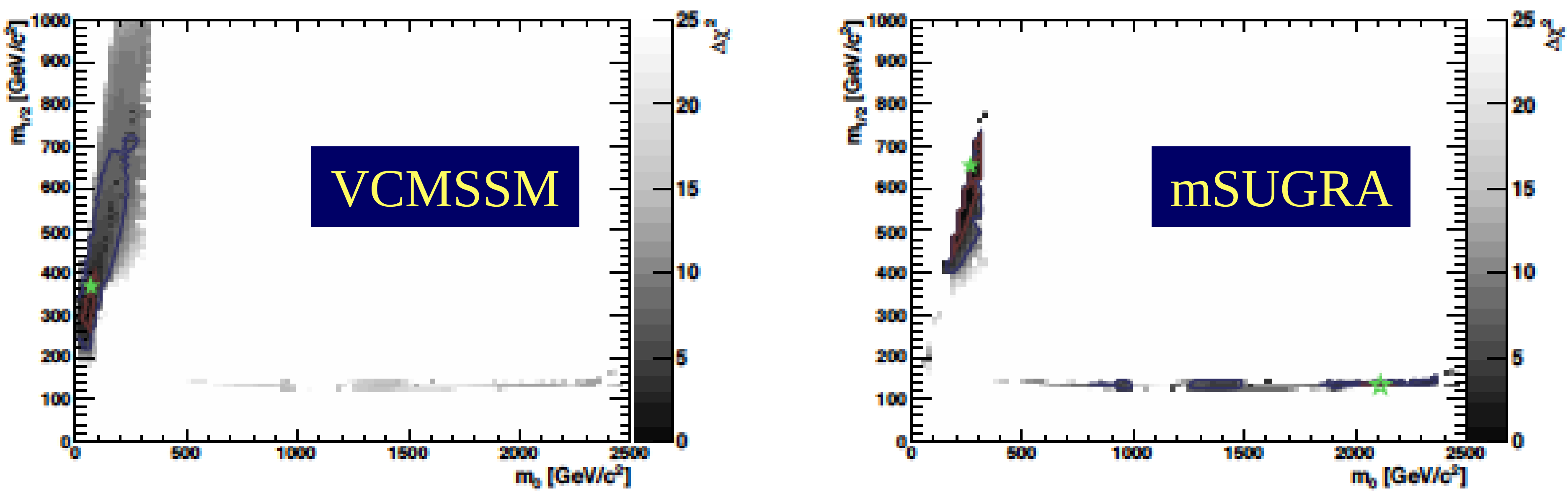
O.Buchmueller, JE et al: arXiv:0808.4128

How Soon Might the NUHM1 be Detected?



O.Buchmueller, JE et al: arXiv:0808.4128

Frequentist Fits to VCMSSM & mSUGRA



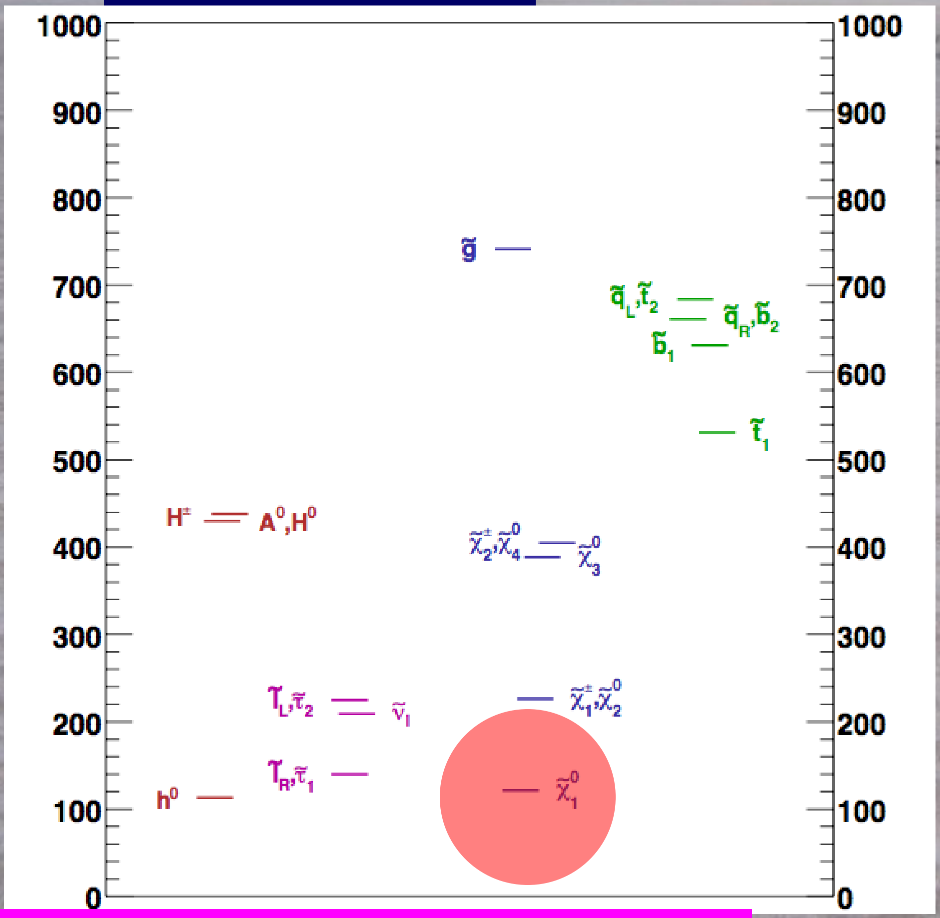
Best-fit parameters in different models

Model	Minimum χ^2	Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	M_h (GeV)
mSUGRA	29.3	6.0%	550	230	430	28	122.1
	33.2	2.2%	130	2110	980	7	116.9
VCMSSM	20.9	40%	370	70	-15	6	114.2
CMSSM	21.5	31%	320	60	-110	10	114.2
NUHM1	19.6	30%	260	100	930	7	120.7

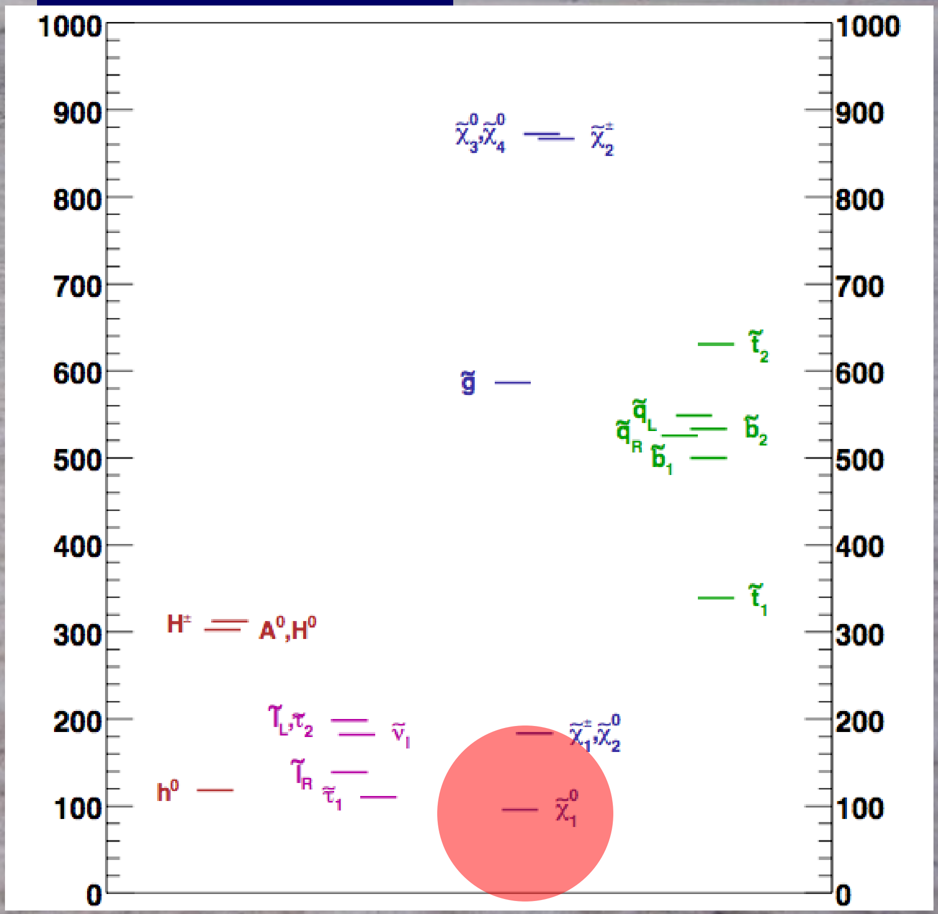
O.Buchmueller, JE et al: arXiv:1011.6118

Best-Fit Spectra

CMSSM

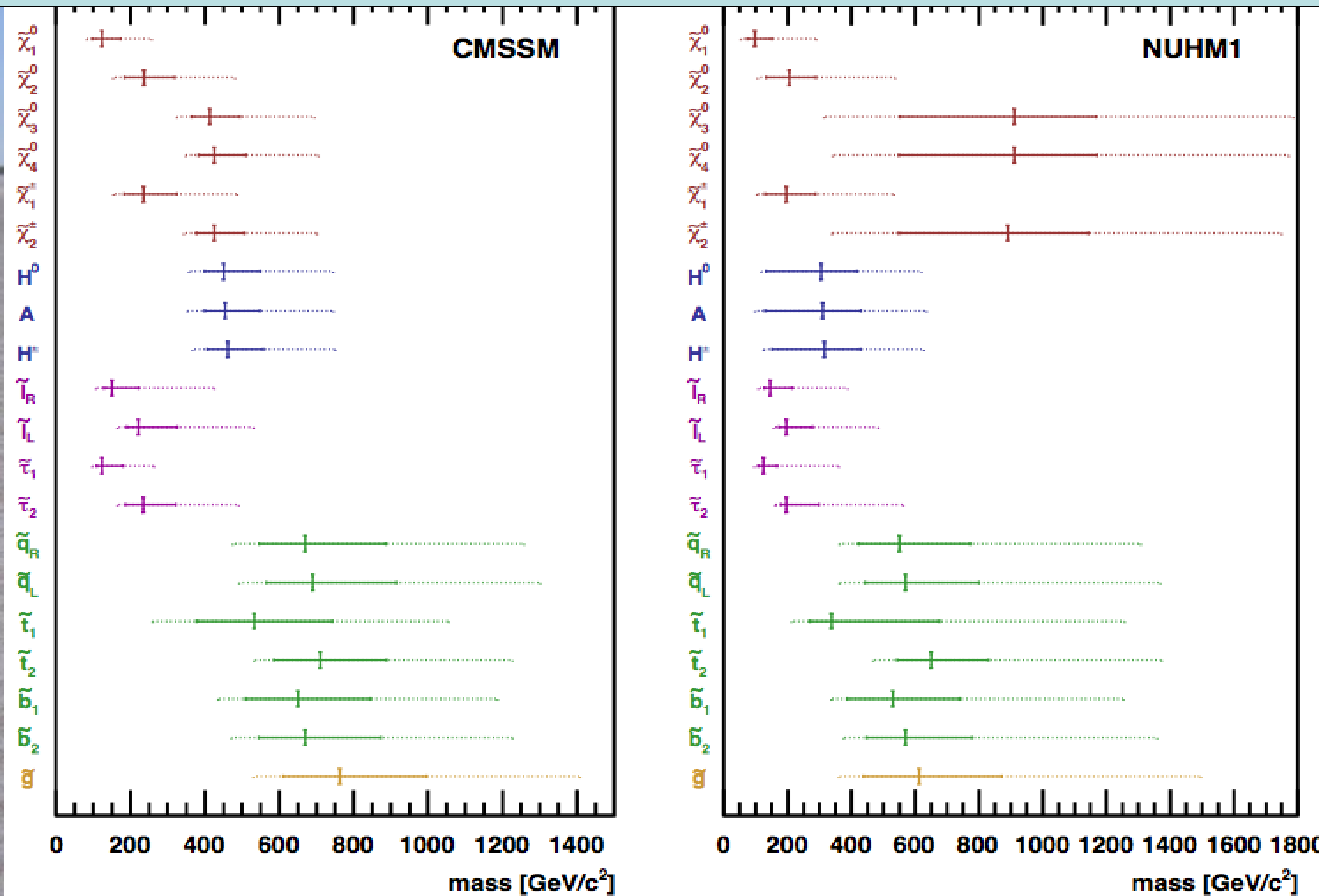


NUHM1



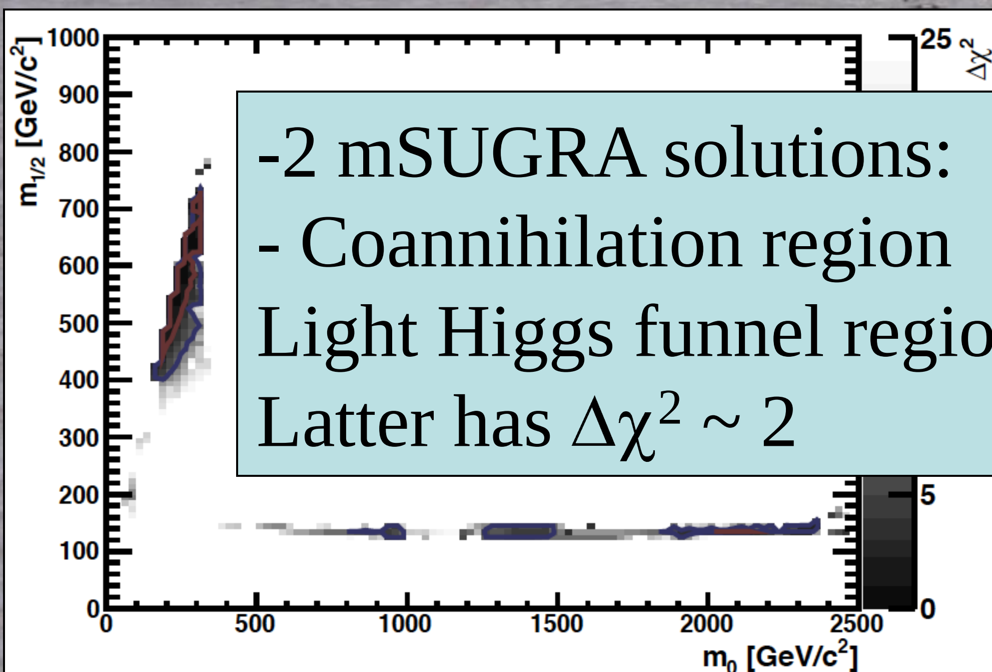
O.Buchmueller, JE et al: arXiv:0808.4128

Spectra with Ranges: CMSSM & NUHM1

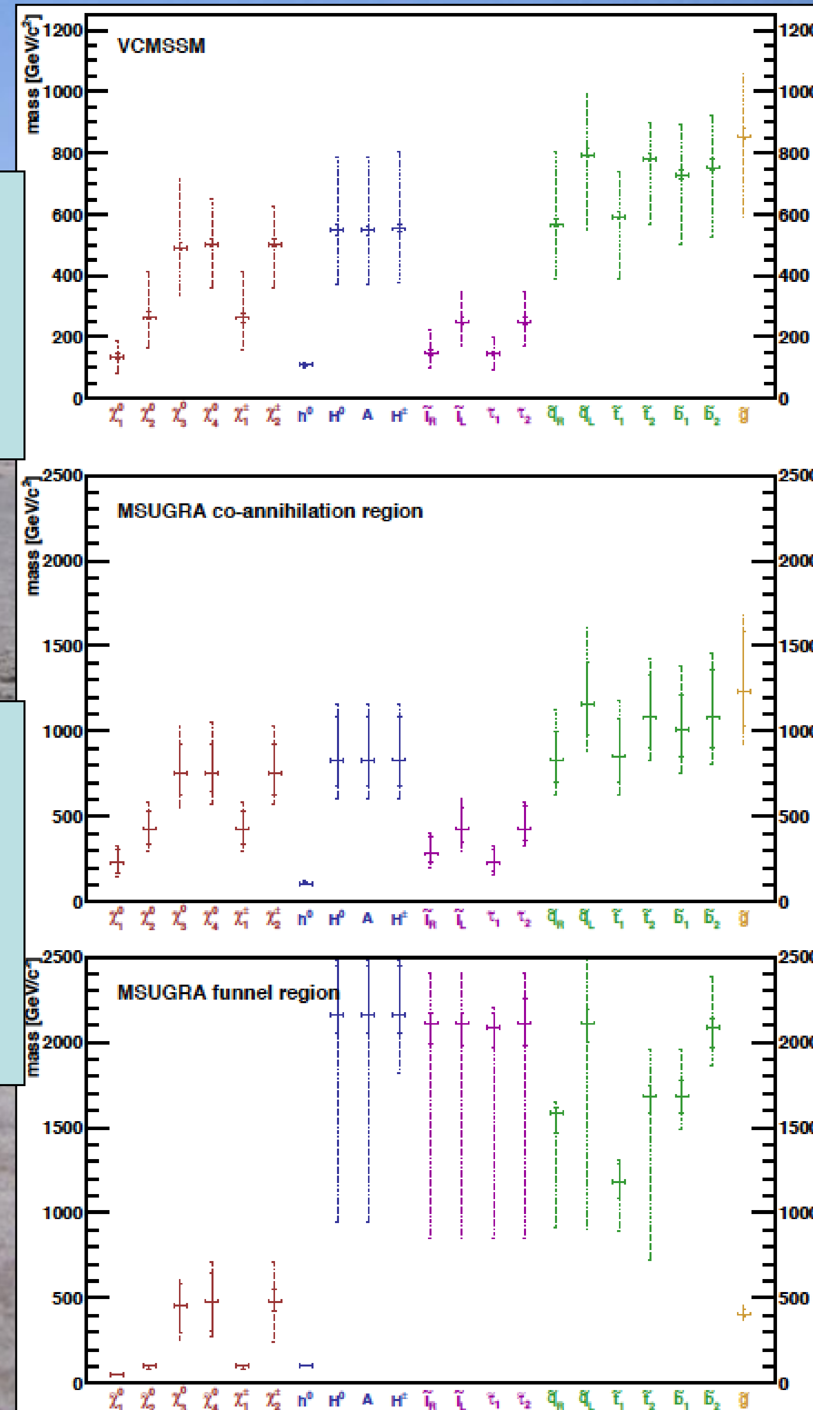


O.Buchmueller, JE et al: arXiv:0907.5568

Spectra with Ranges: VCMSSM, mSUGRA



-2 mSUGRA solutions:
- Coannihilation region
Light Higgs funnel region
Latter has $\Delta\chi^2 \sim 2$

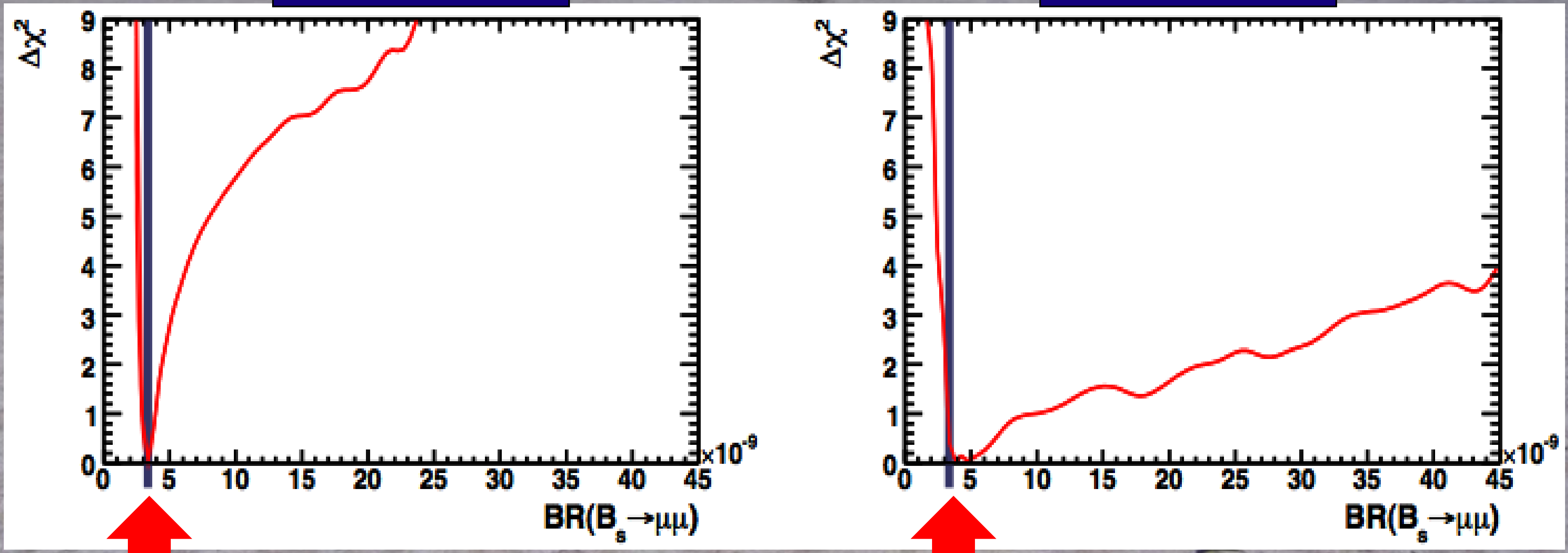


O.Buchmueller, JE et al: arXiv:1011.6118

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

CMSSM

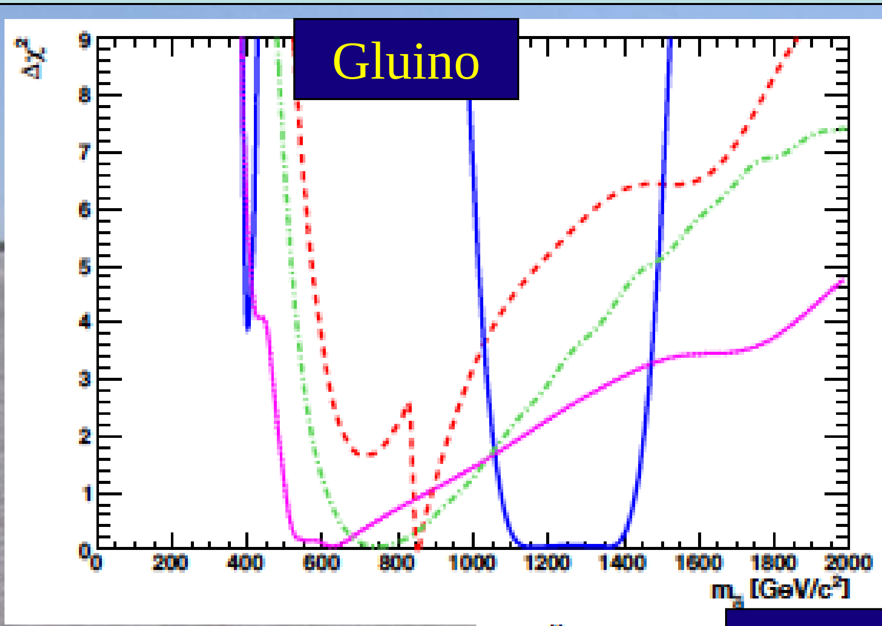
NUHM1

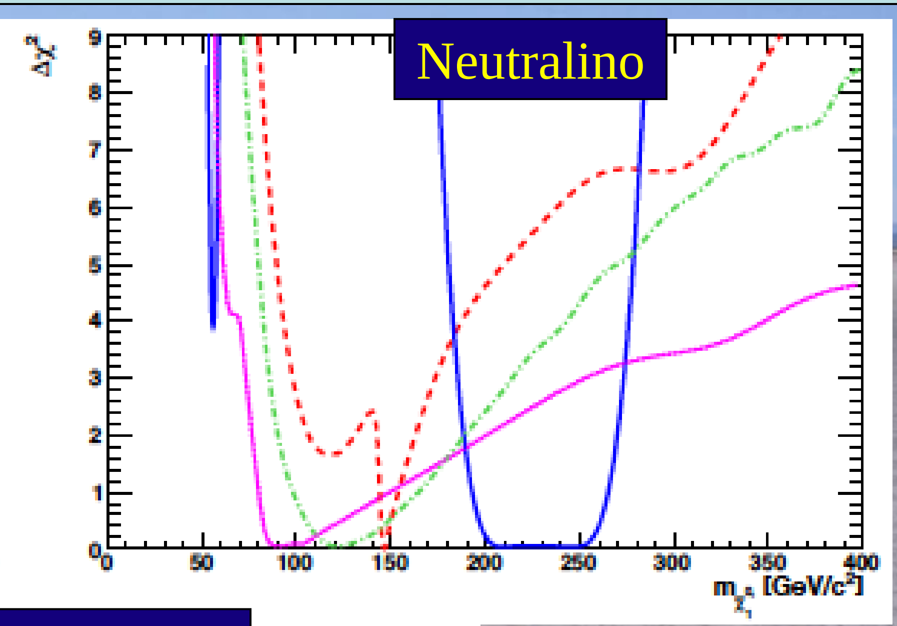


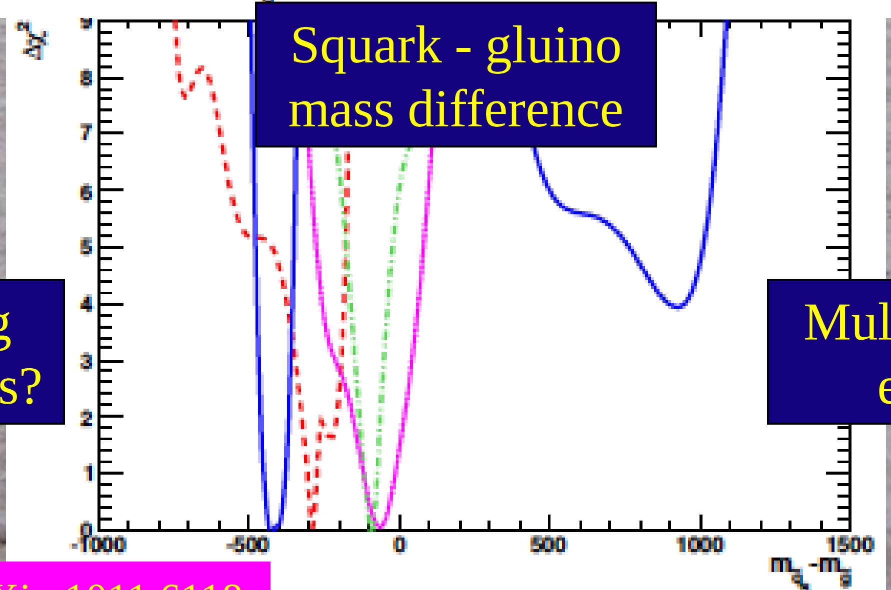
Standard Model prediction

O.Buchmueller, JE et al: arXiv:0907.5568

Likelihood Functions for Sparticle Masses





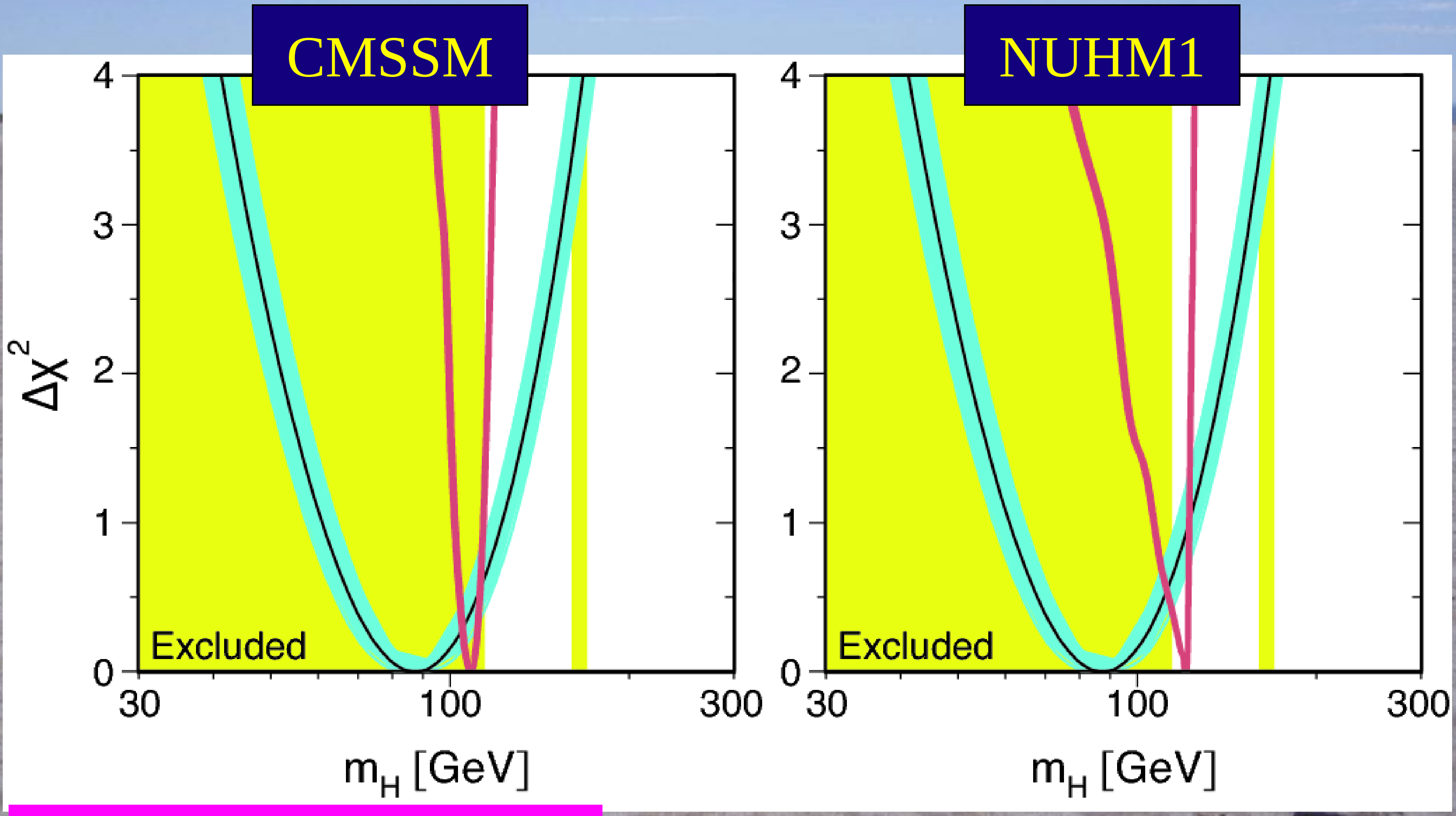


Dijet + missing energy events?

Multijet + missing energy events?

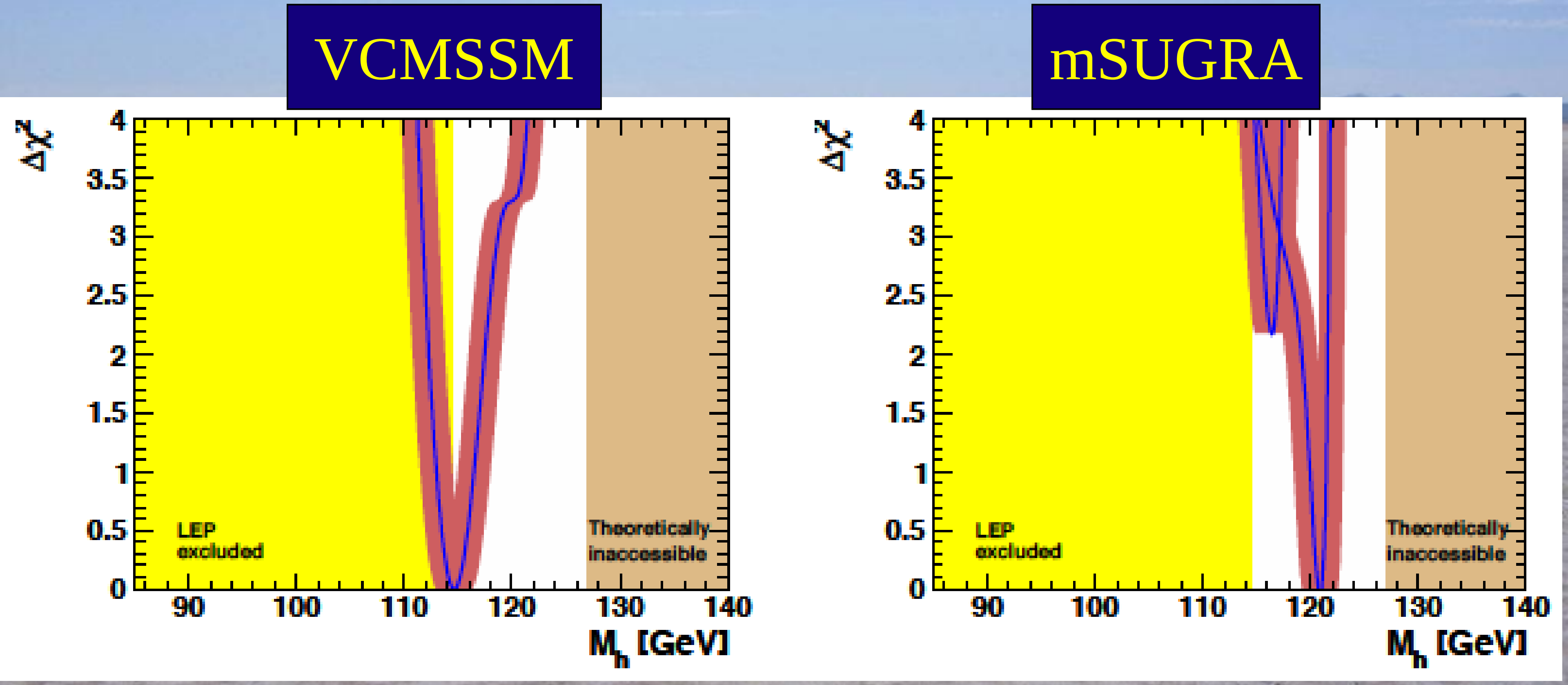
O.Buchmueller, JE et al: arXiv:1011.6118

Likelihood Function for Higgs Mass



O.Buchmueller, JE et al: arXiv:0907.5568

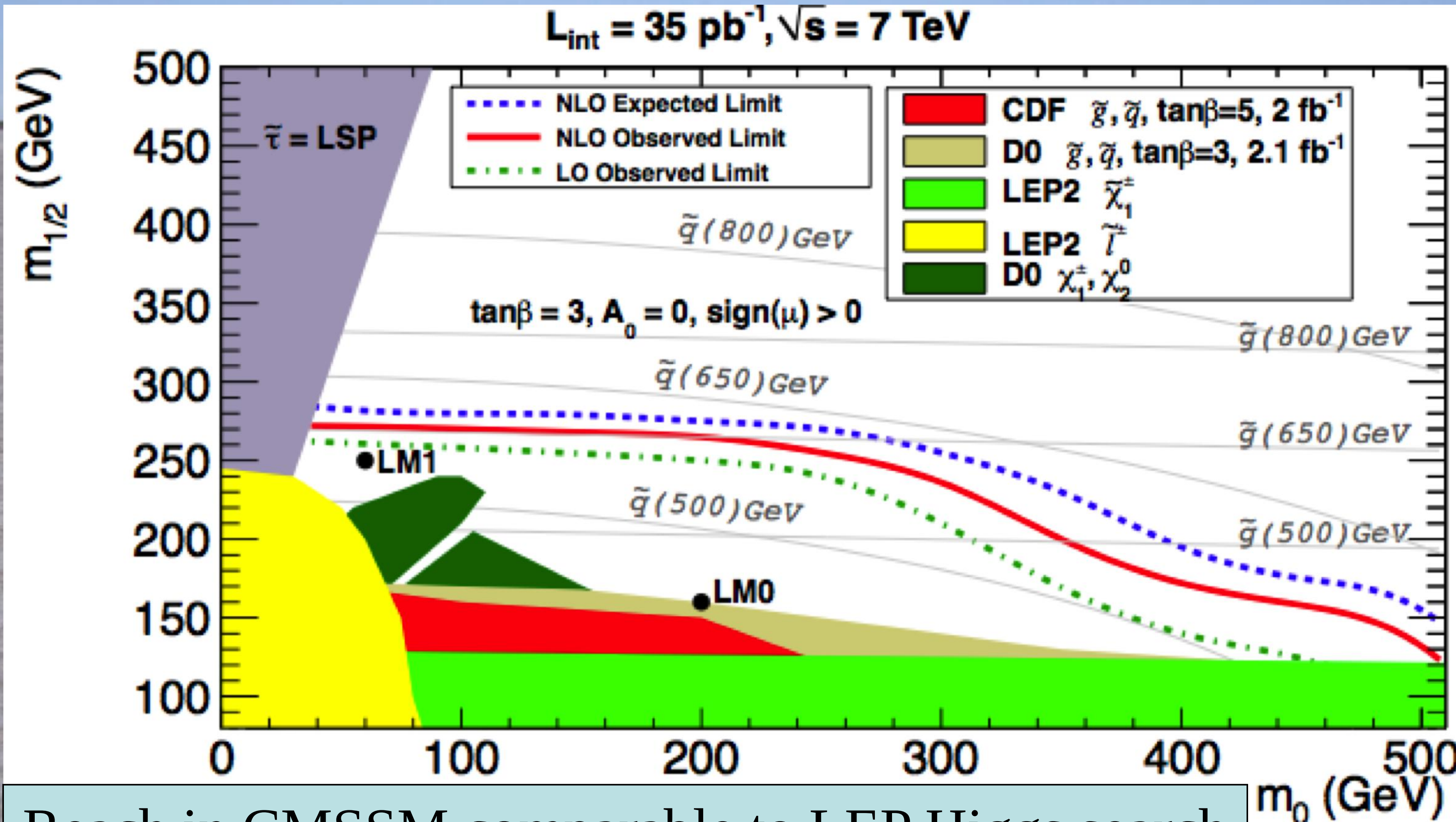
Likelihood Function for Higgs Mass



O.Buchmueller, JE et al: arXiv:1011.6118

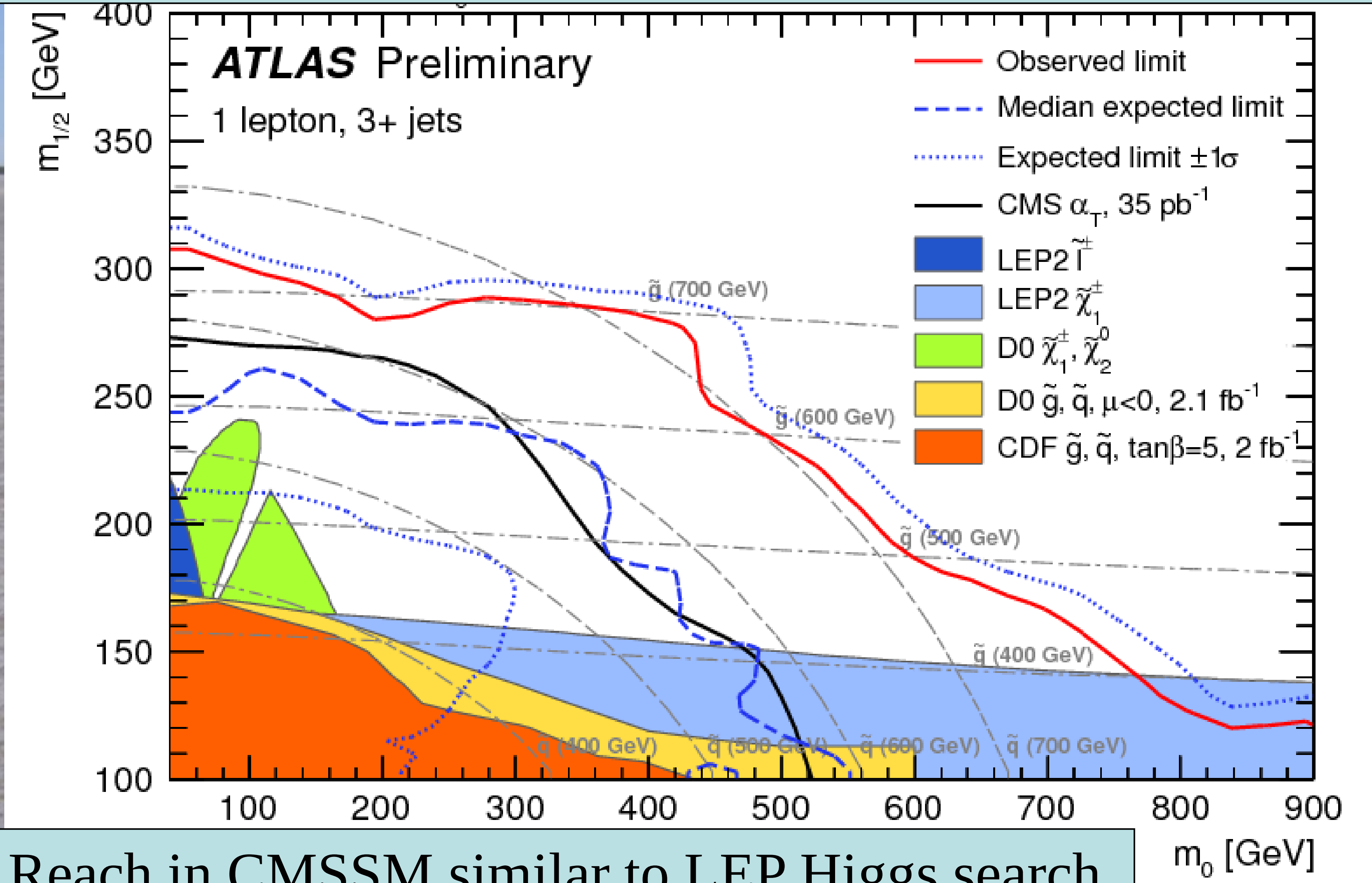
Nov. 20th 2009: Jubilation

Supersymmetry Search in CMS



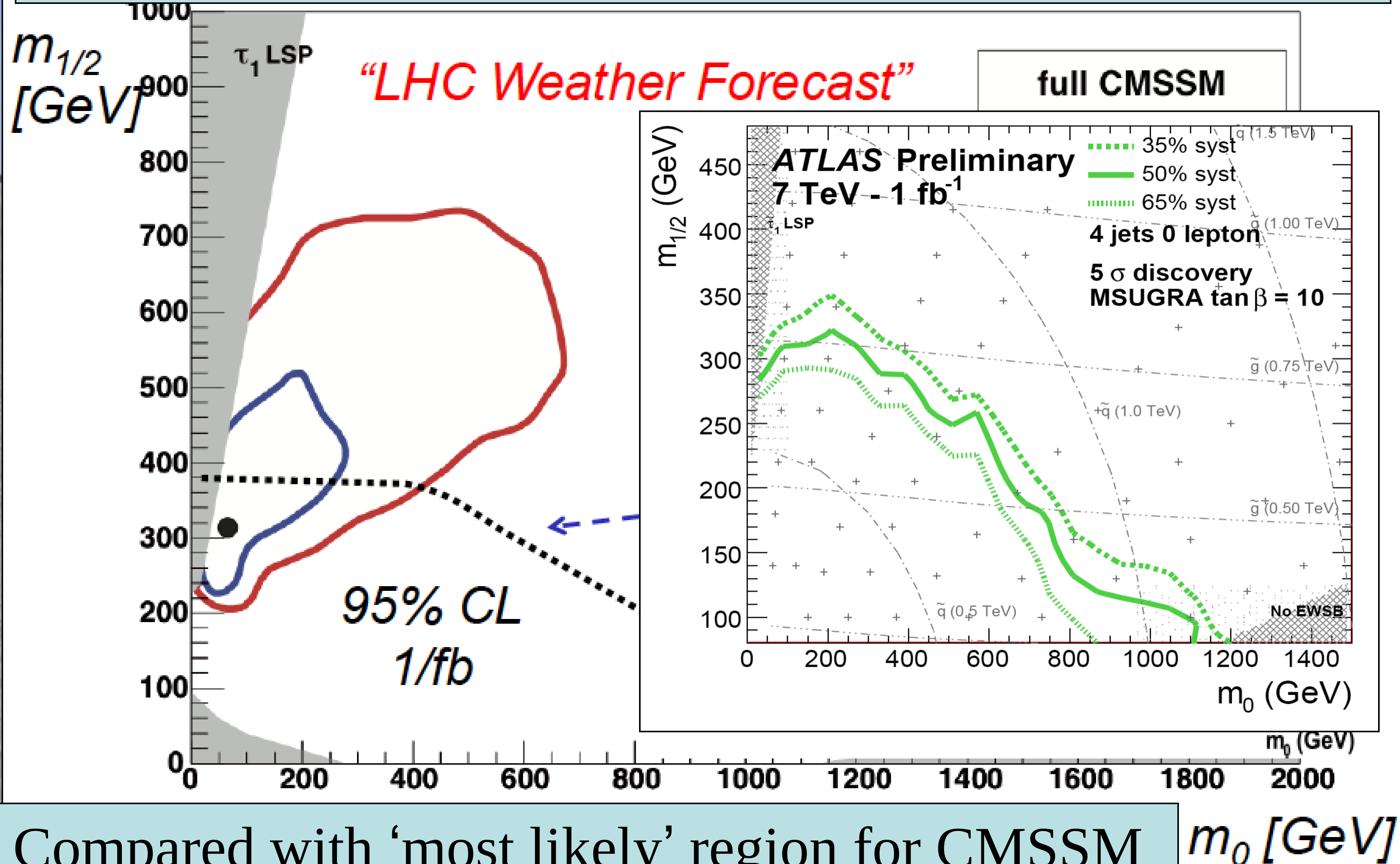
Reach in CMSSM comparable to LEP Higgs search

Supersymmetry Search in ATLAS



Reach in CMSSM similar to LEP Higgs search

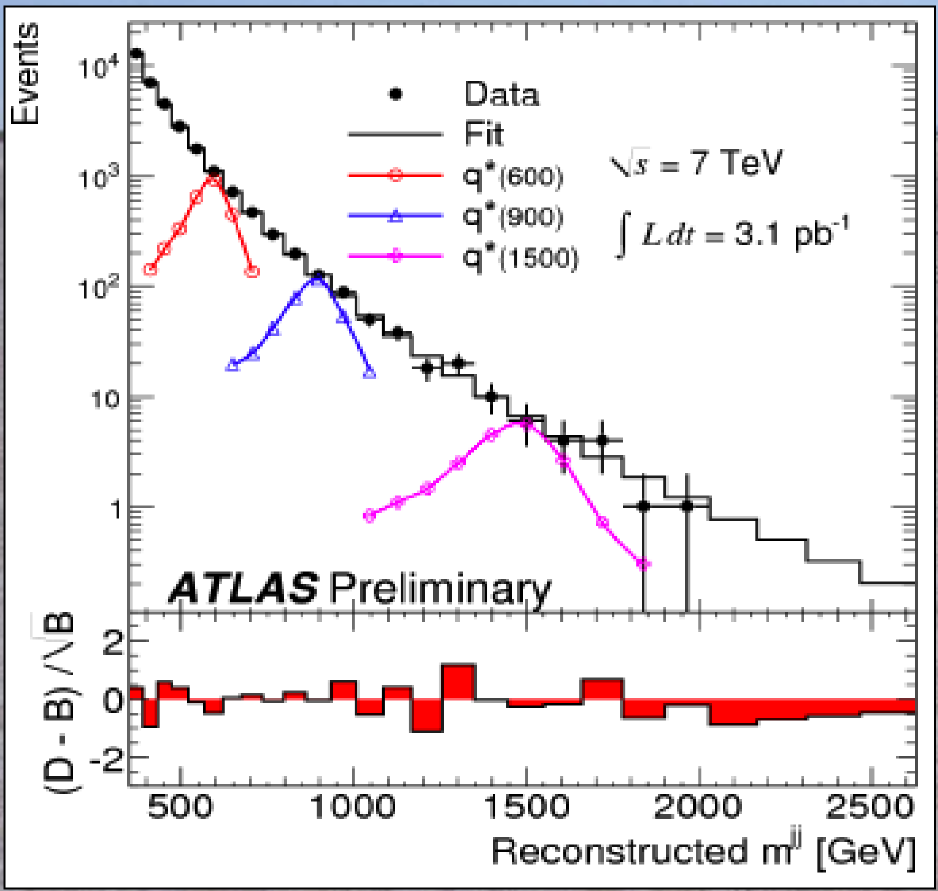
LHC Sensitivity @ 7 TeV

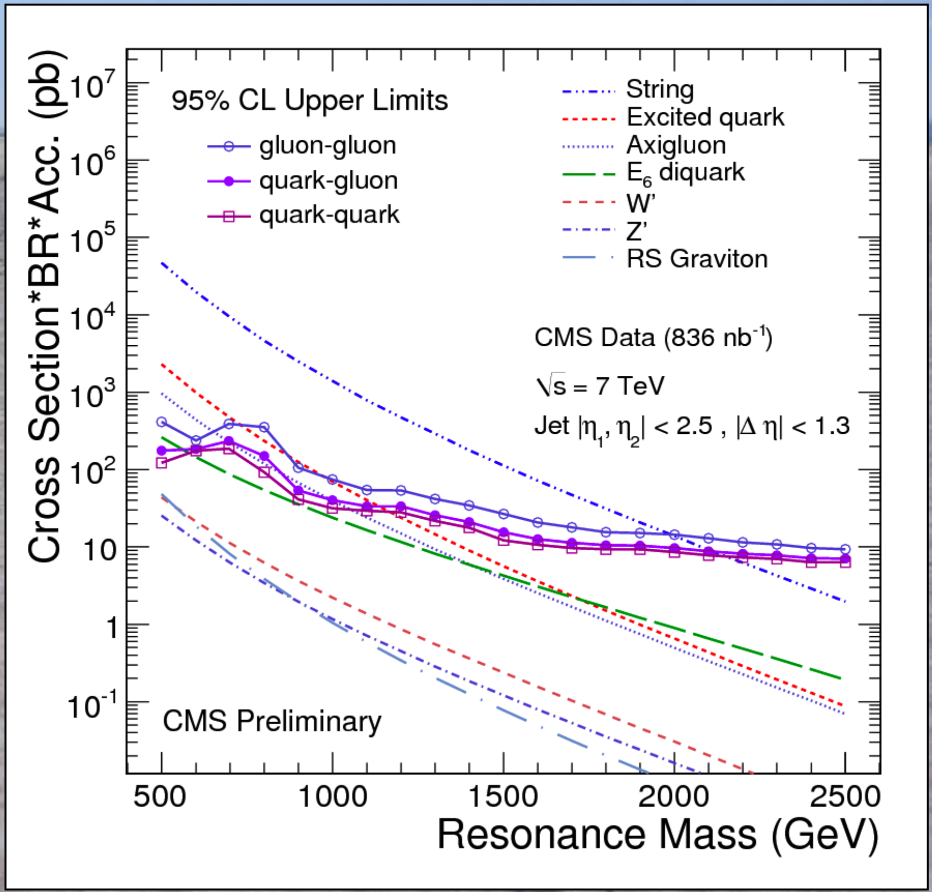


Compared with 'most likely' region for CMSSM

O.Buchmueller, JE et al: arXiv:0808.4128

The LHC Sensitivity Starts to Extend Beyond the Tevatron



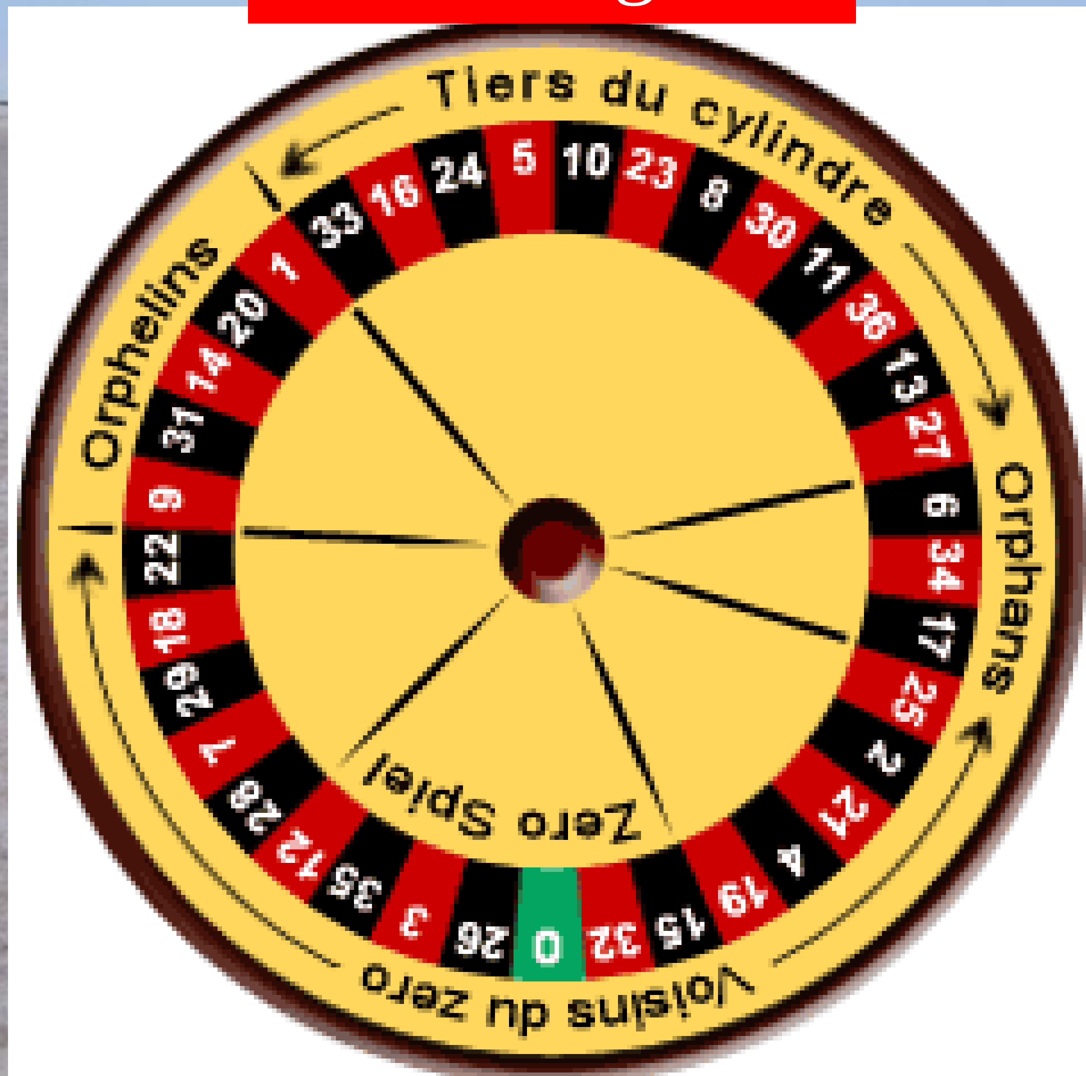


Excited quark mass > 1.53 TeV (ATLAS), 1.58 TeV (CMS)

cf 0.87 TeV (CDF)

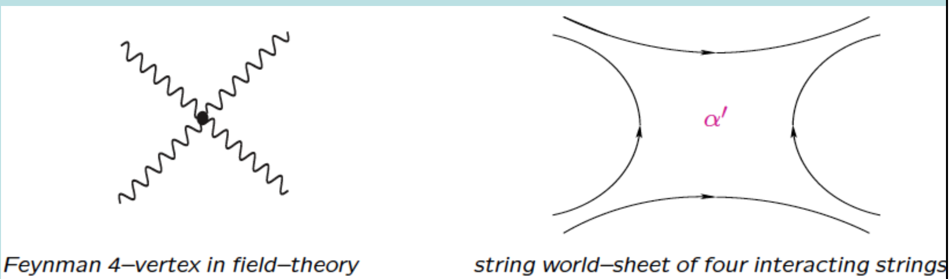
The LHC Roulette Wheel

String

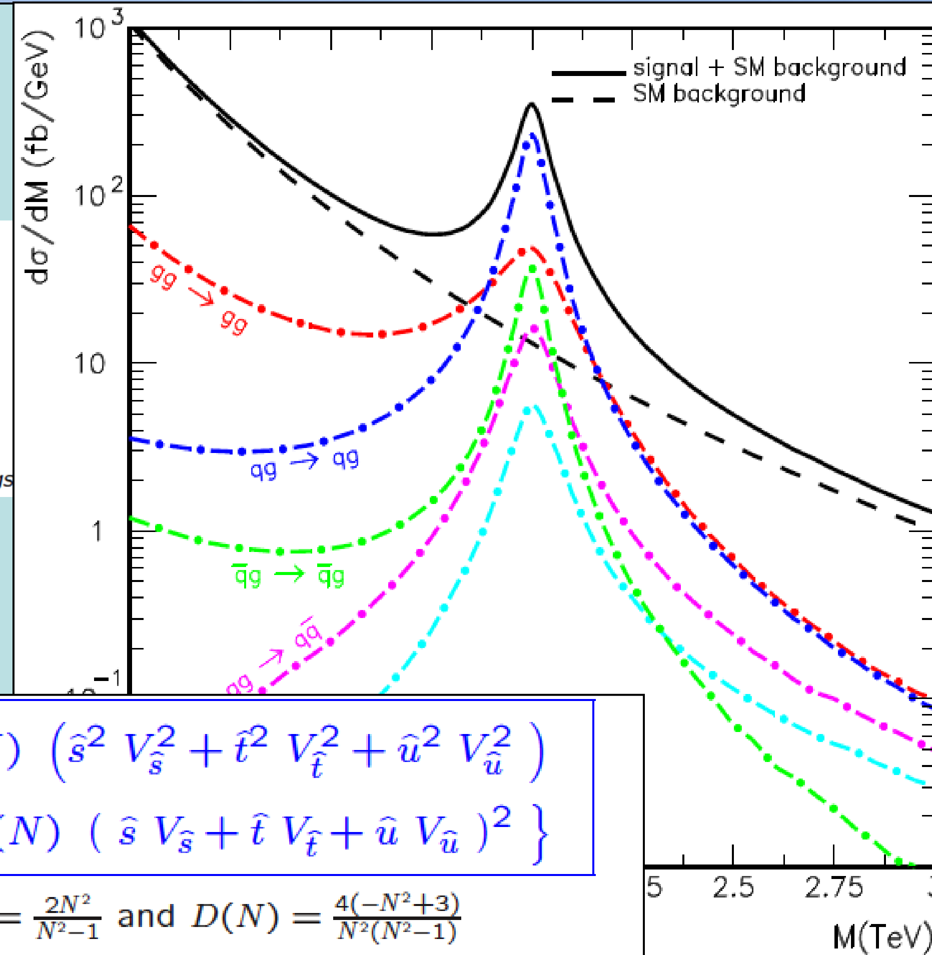


String Effects in 2-2 Scattering @ LHC?

- World-line becomes sheet:



- Modifications of scattering amplitudes:



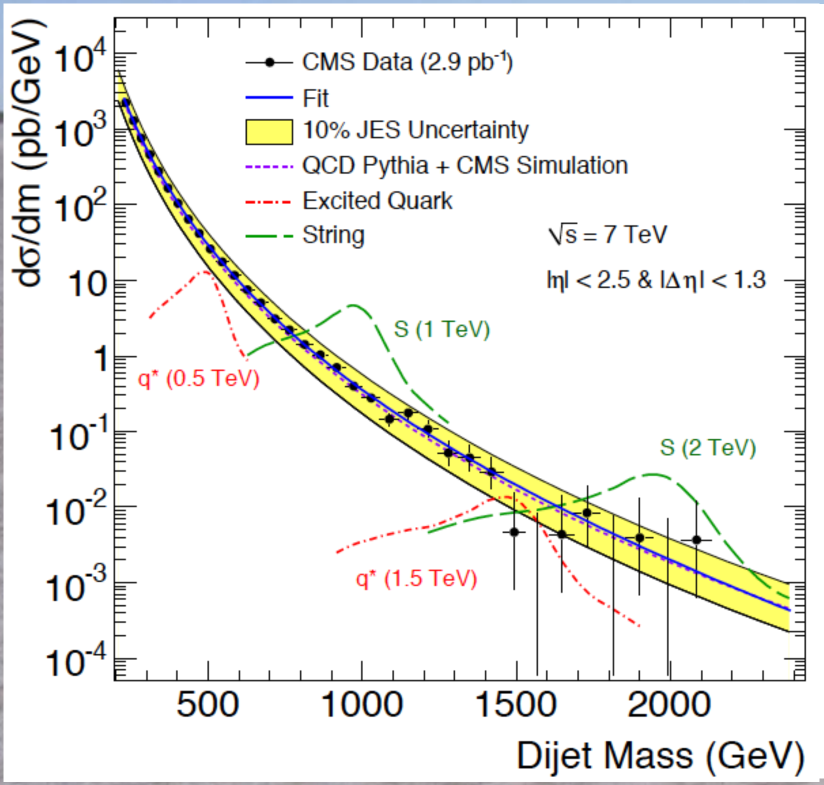
$$|\mathcal{M}(gg\to gg)|^2 \;=\; g_{Dpa}^4 \left(\frac{1}{\hat s^2}+\frac{1}{\hat t^2}+\frac{1}{\hat u^2}\right)\Big\{C(N)\;\left(\hat s^2\, V_{\hat s}^2+\hat t^2\, V_{\hat t}^2+\hat u^2\, V_{\hat u}^2\right) + D(N)\;\left(\hat s\, V_{\hat s}+\hat t\, V_{\hat t}+\hat u\, V_{\hat u}\right)^2\Big\}$$

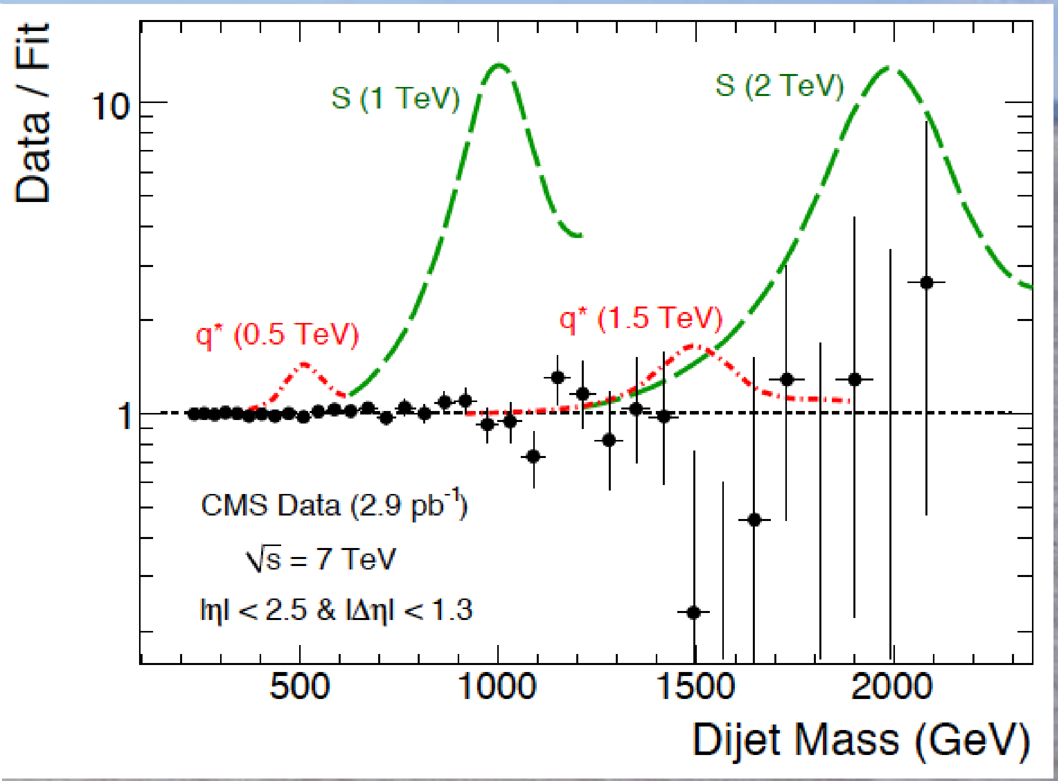
with $C(N)=\frac{2N^2}{N^2-1}$ and $D(N)=\frac{4(-N^2+3)}{N^2(N^2-1)}$

$$|\mathcal{M}(gg\to q\bar q)|^2 = g_{Dpa}^4\,\frac{N_f}{2N}\left\{\frac{\hat t^2+\hat u^2}{\hat u\hat t\hat s^2}\,(\hat t\, V_{\hat t}+\hat u\, V_{\hat u})^2-\frac{2N^2}{(N^2-1)}\,\frac{\hat t^2+\hat u^2}{\hat s^2}\,V_{\hat t}\, V_{\hat u}\right\}$$

Feng, Lust, Schlotterer, Stieberger & Taylor: arXiv:1007.5254

Search for String Resonances

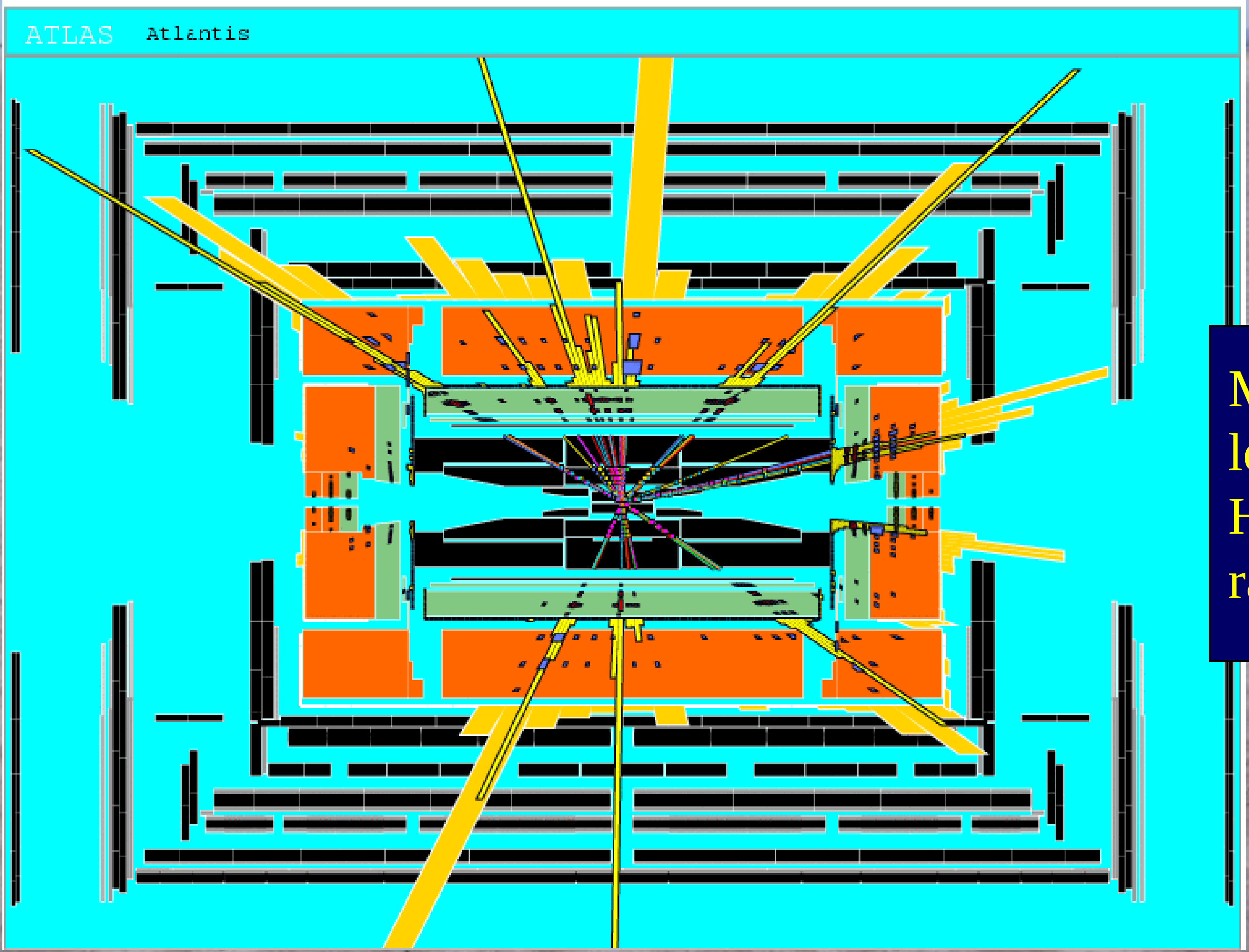




String resonance mass > 2.50 TeV (CMS)

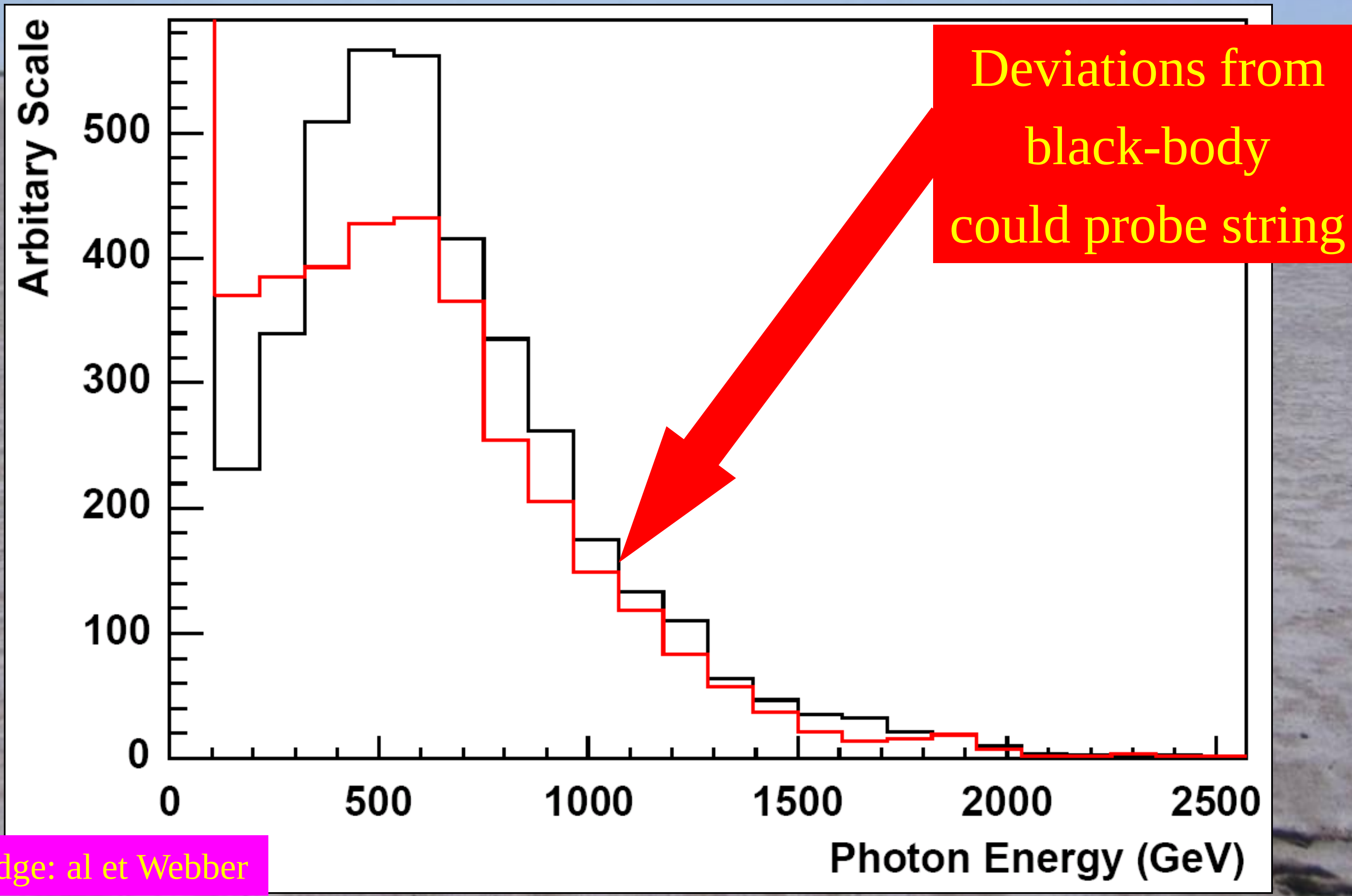
And if gravity becomes strong at the TeV scale …

Black Hole Production at LHC?



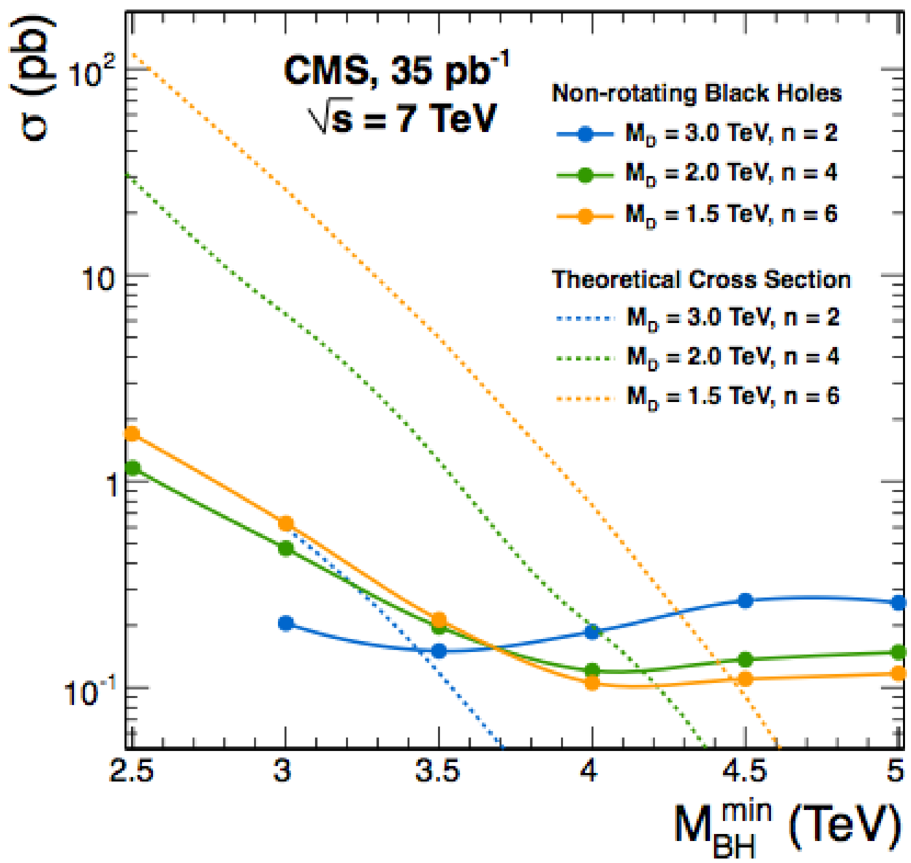
Multiple jets, leptons from Hawking radiation

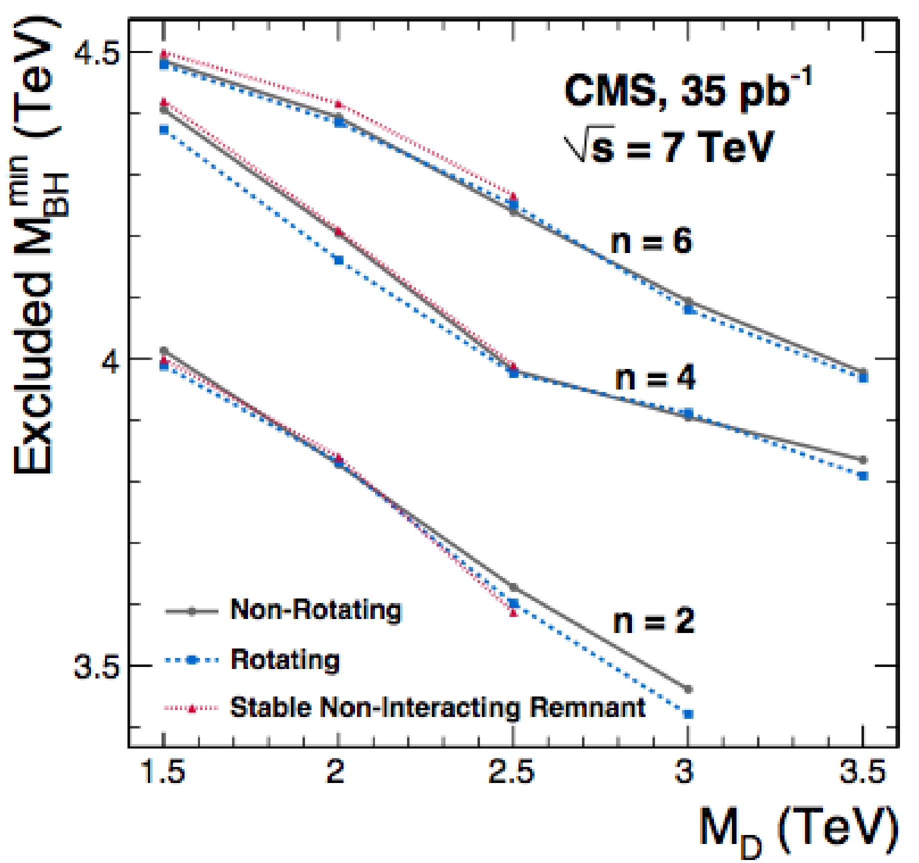
Black Hole Decay Spectrum



Cambridge: al et Webber

No Black Holes yet





Black holes excluded for masses up to 3.5 to 4.5 TeV

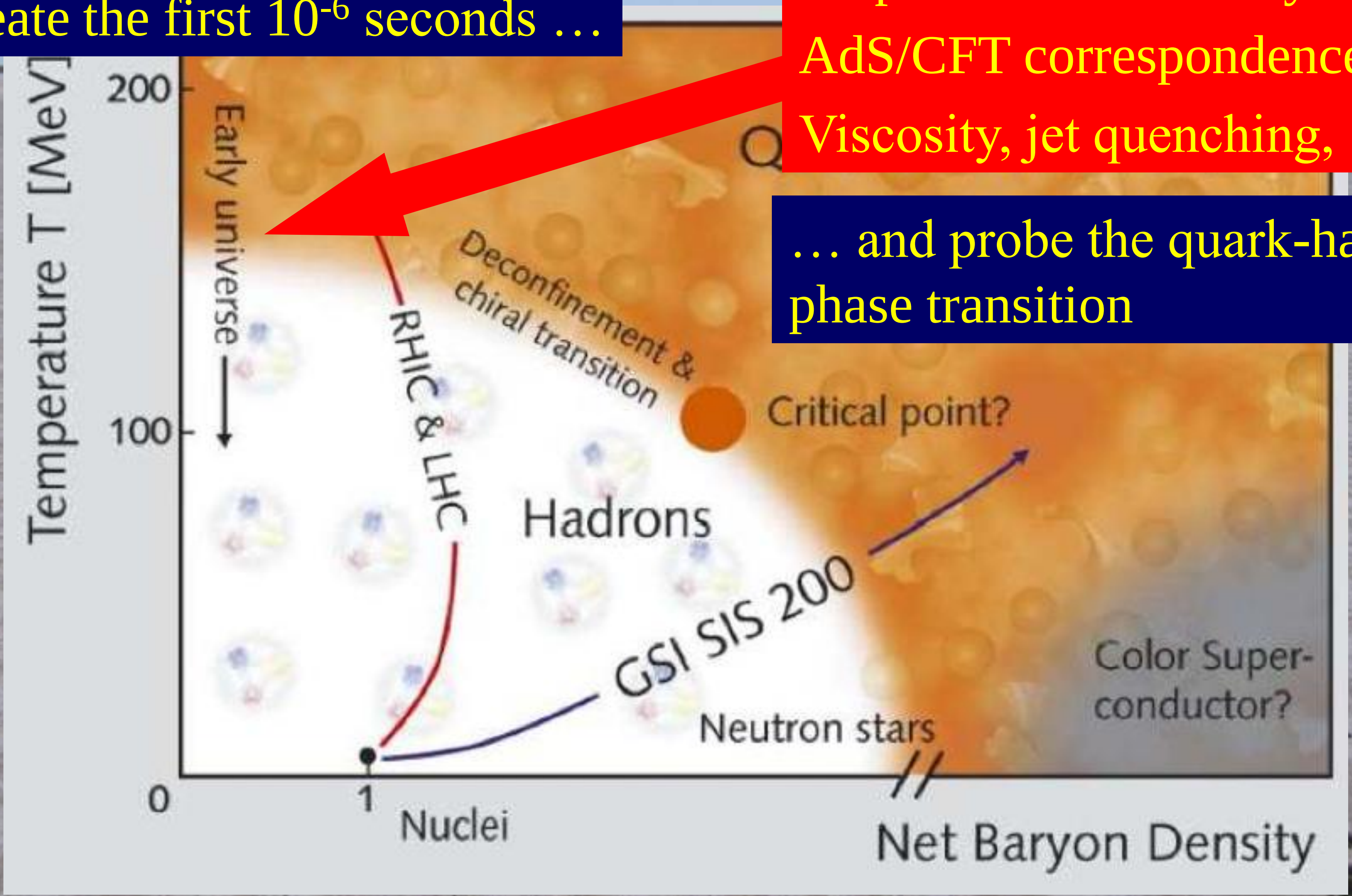
Collide heavy nuclei at high energies to create …

Hot and Dense Hadronic Matter

Recreate the first 10^{-6} seconds …

Properties described by AdS/CFT correspondence: Viscosity, jet quenching, …?

… and probe the quark-hadron phase transition



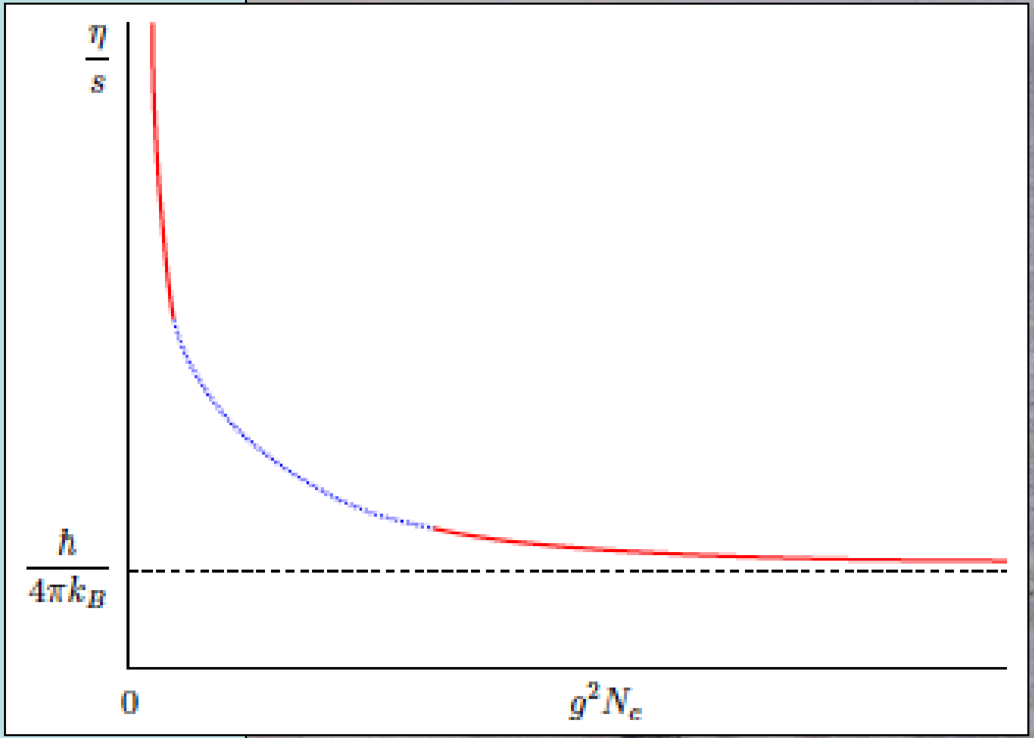
Viscosity of Quark-Gluon Matter

- Shear viscosity/entropy ratio [η/s] can be calculated in N=4 SUSY QCD:
- Lower limit from

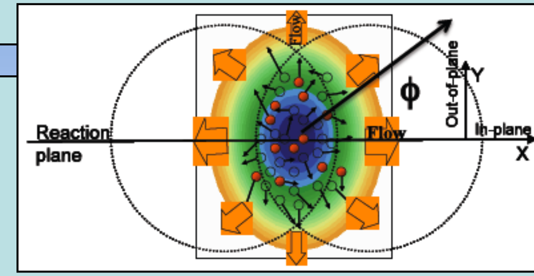
  AdS/CFT

  correspondence:

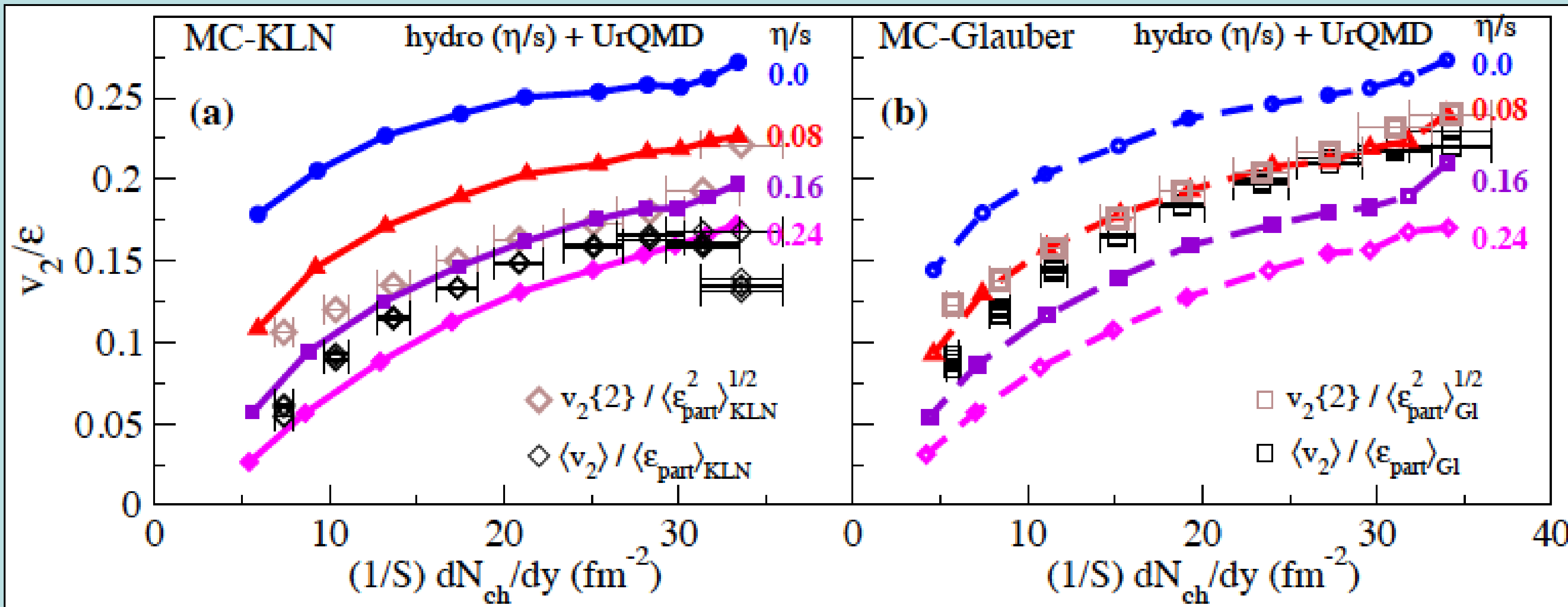
  $\eta/s \geq 1/4\pi$
- Intense experimental interest



Viscosity of Quark-Gluon Matter



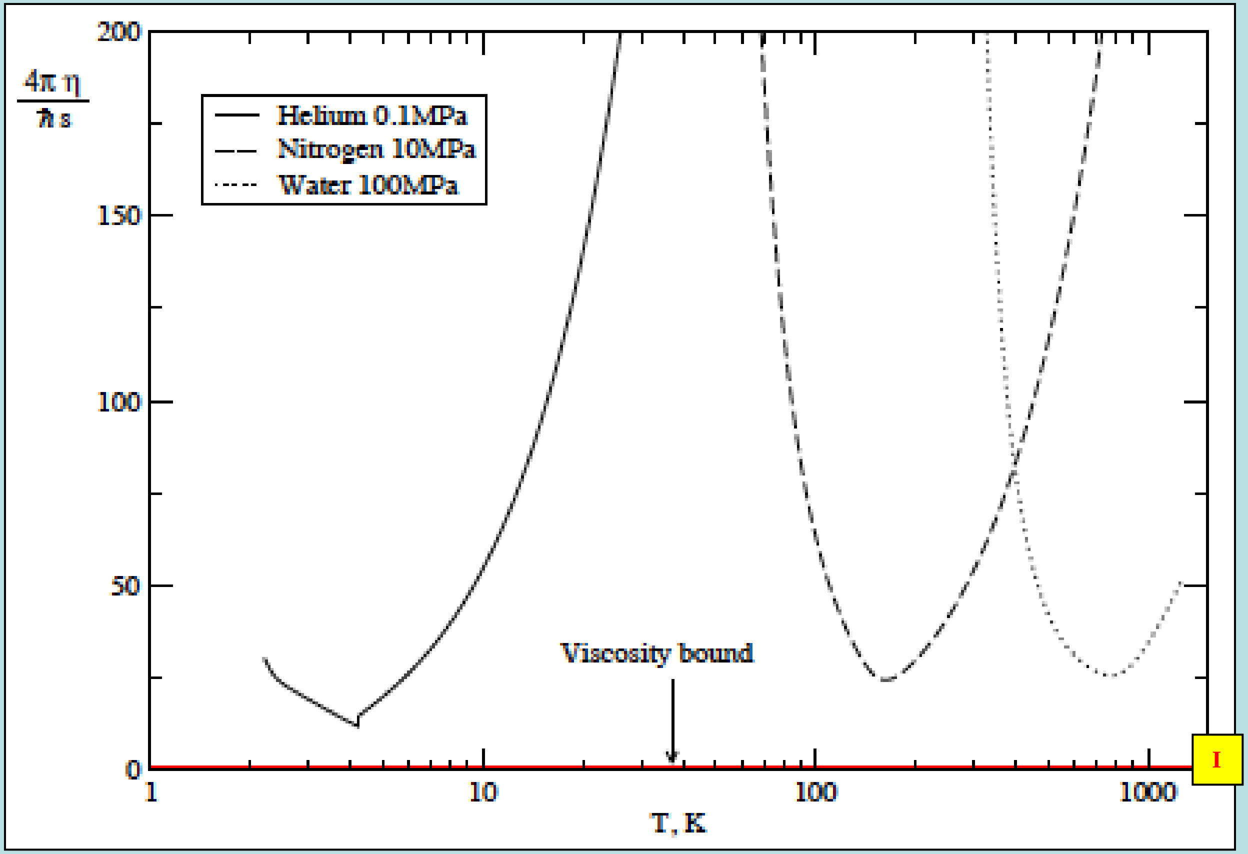
- η/s can be measured via elliptic flow of produced particles:



- $1 < 4\pi \times (\eta/s) < 3$

Viscosity of Quark-Gluon Matter

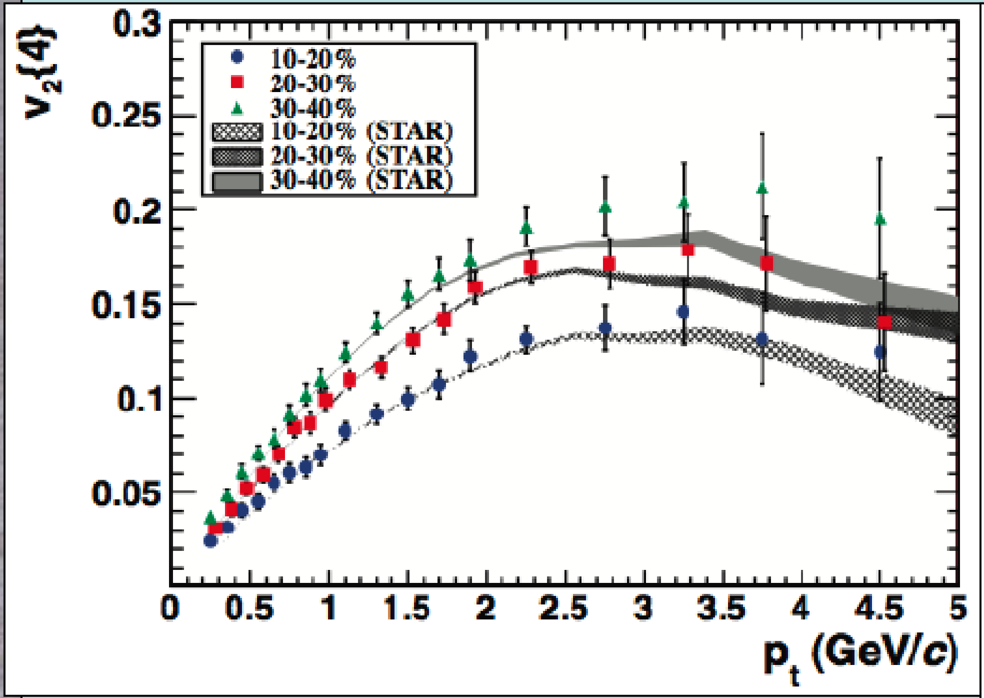
- η/s of quark-gluon matter compared with other fluids:

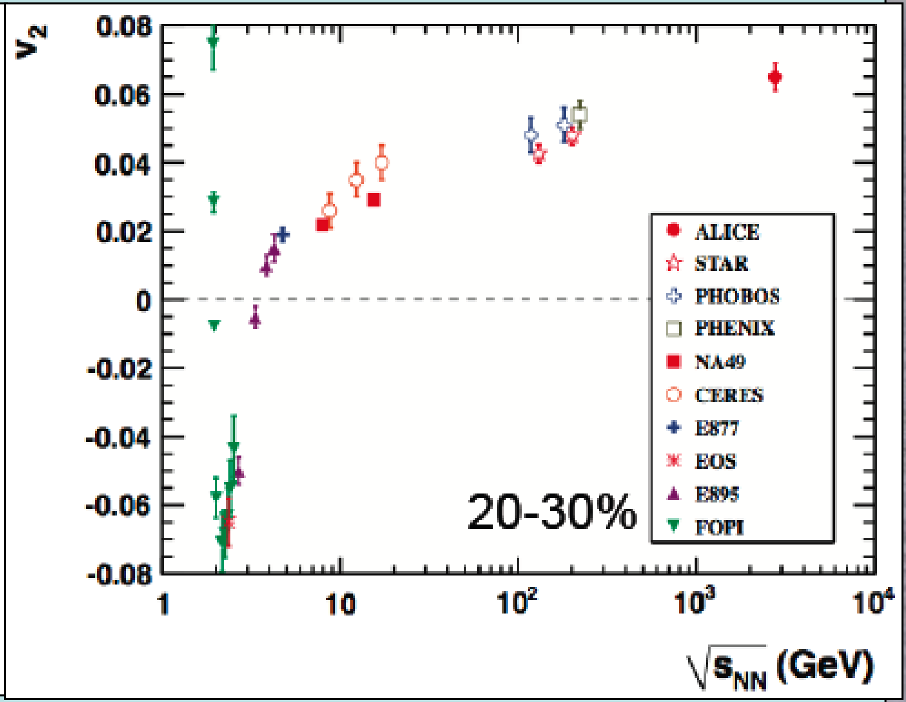


- The most perfect fluid known?

Elliptic Flow @ LHC

- In agreement with hydrodynamics with viscous corrections





- How far from a perfect fluid?

Seize this Apollo Moment!

- The LHC has the world’s attention
- Communicate the excitement
- Be ready when the big discoveries come
- Talk to your local newspapers
- Talk to engineering students
- Go back to your old school(s)
  - Help them get cosmic-ray detectors

- **Secure public and political support**
- **Lay basis for the future**
- **LHC upgrades**
- **New accelerator projects**