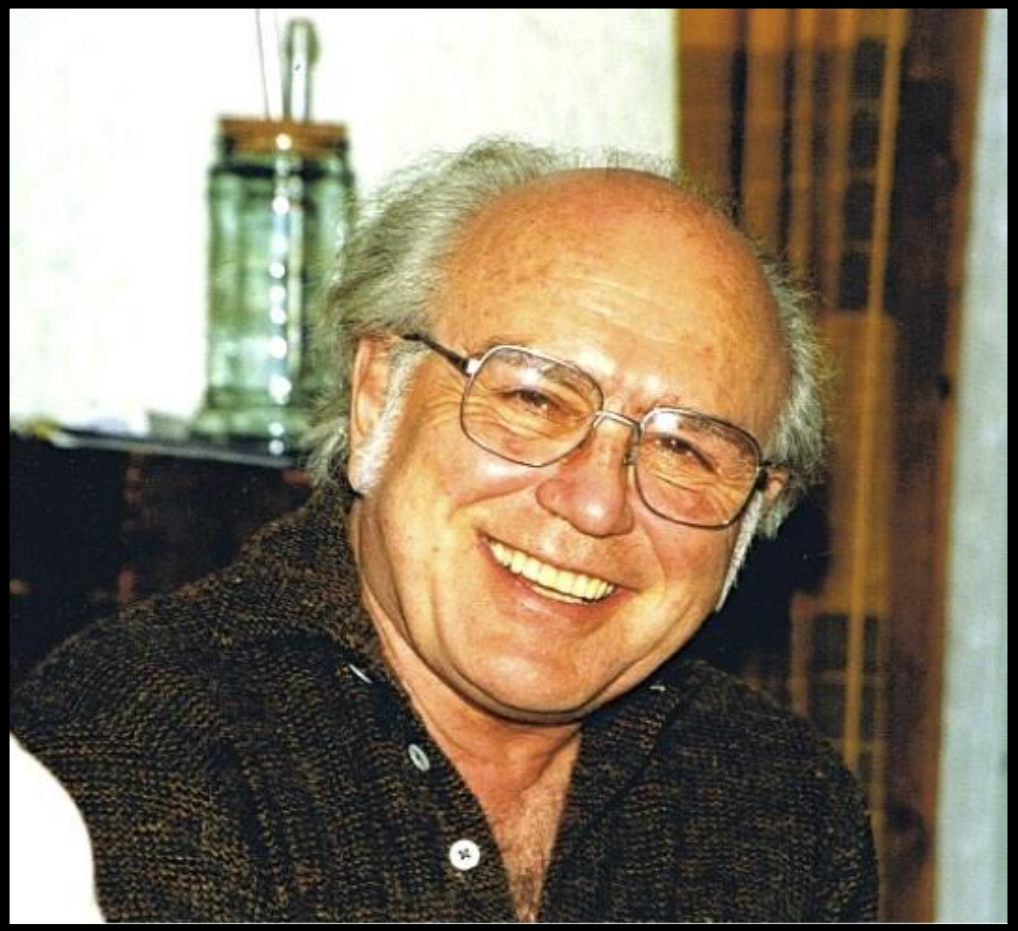
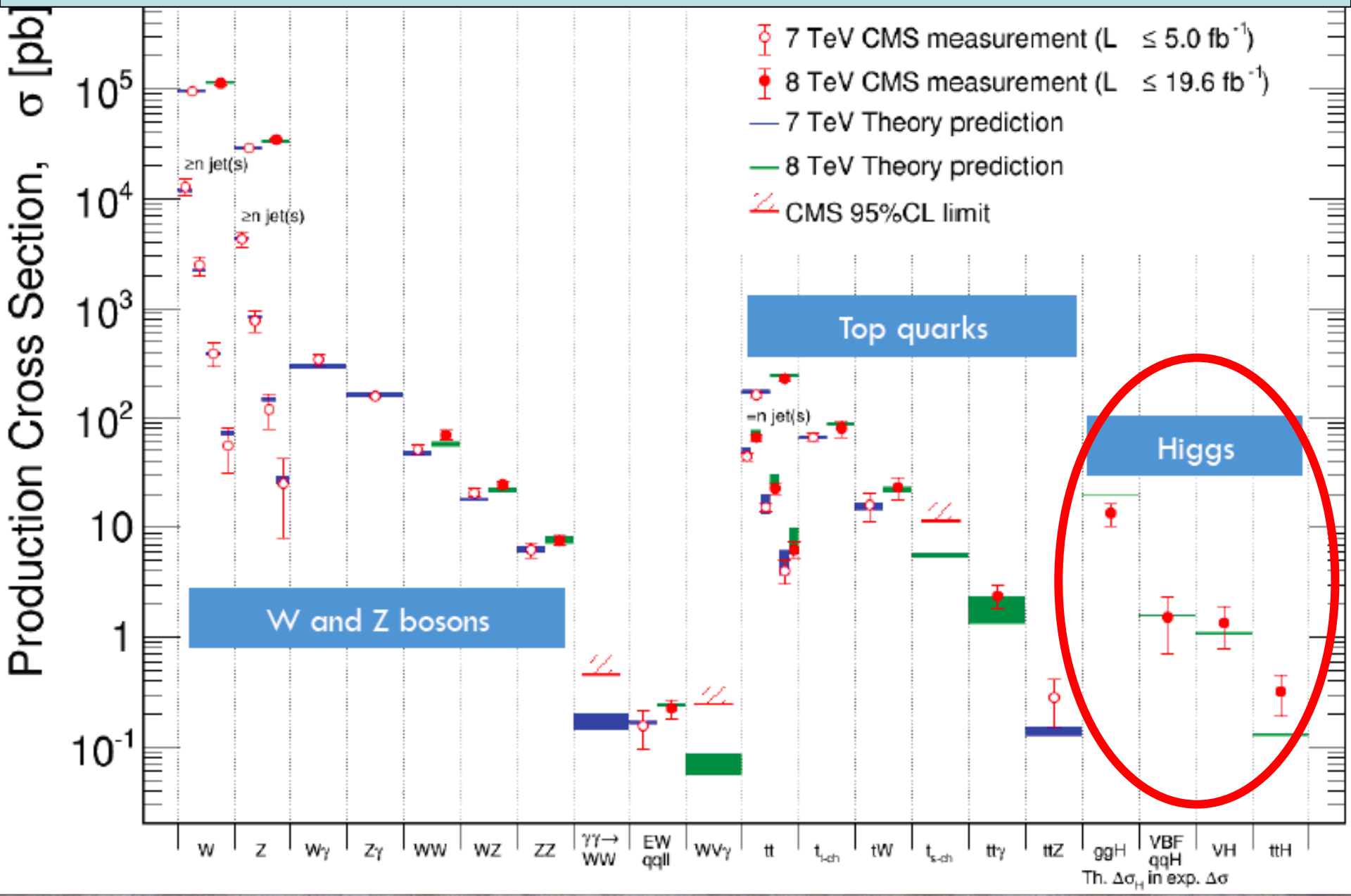
New Physics at LHC run II:

Perspectives & Visions



The second big LHC discovery?

Standard Model Cross-Sections @ LHC



Higgs Mass Measurements

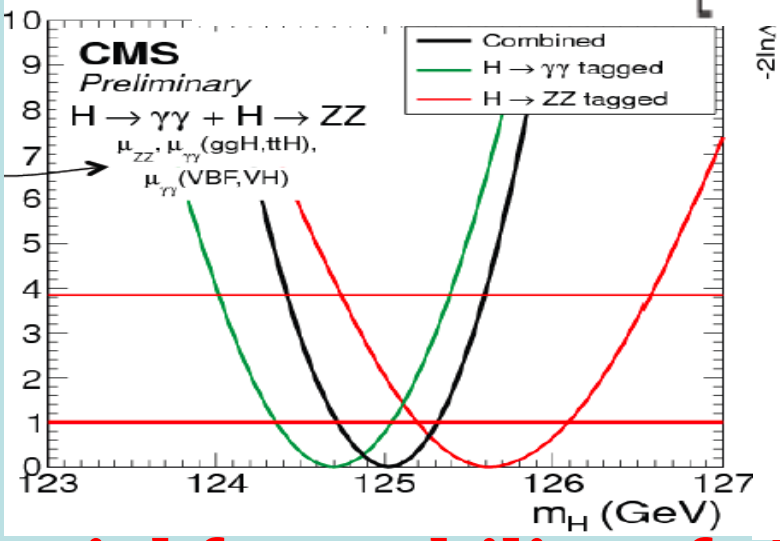
- ATLAS:

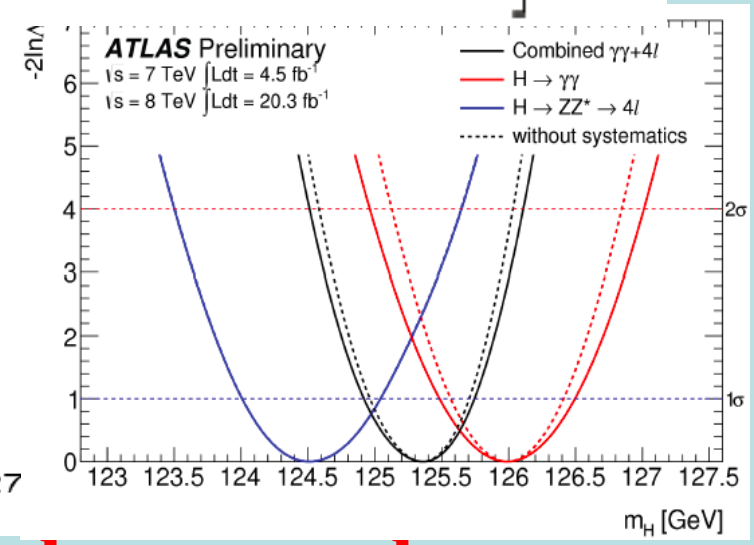
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{sys}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.04\,(\text{sys}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{sys}) = 125.36 \pm 0.41$

- CMS: $m_H = 125.6 \pm 0.4 \pm 0.2$ GeV from ZZ*

$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$ from $\gamma\gamma$

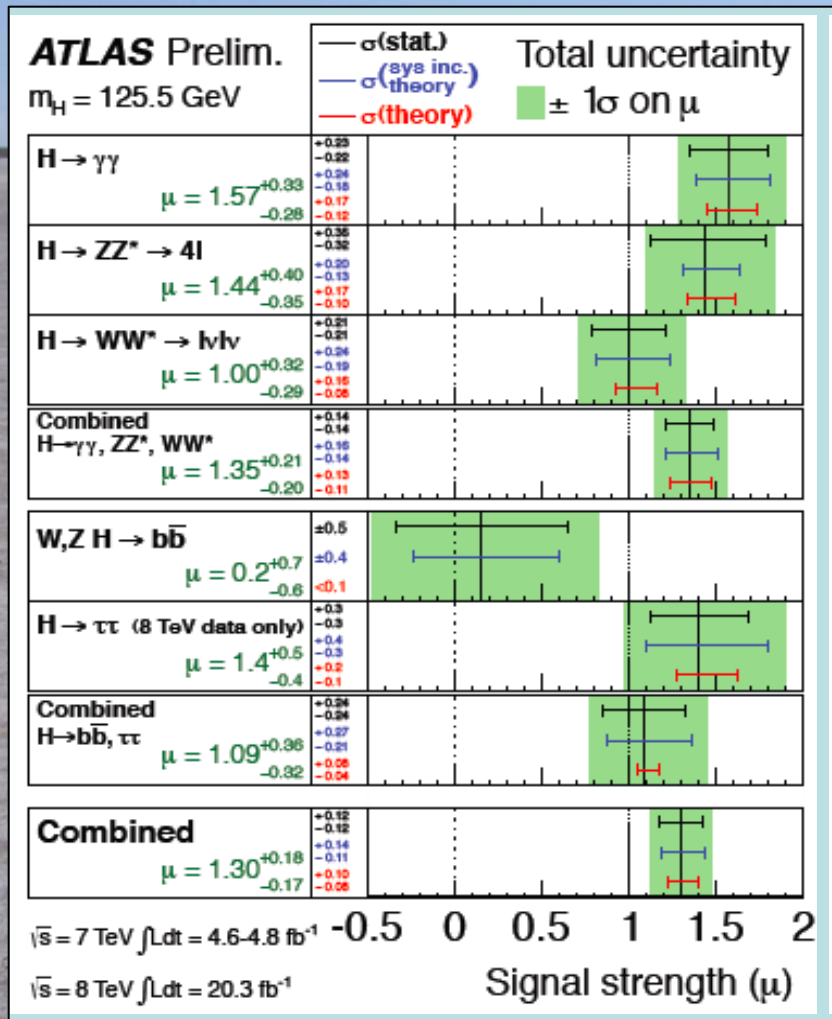
Combined: $$m_H = 125.03 \pm 0.30\ \left[^{+0.26}_{-0.27}(\text{stat.})^{+0.13}_{-0.15}(\text{syst.})\right]\ \text{GeV}$$



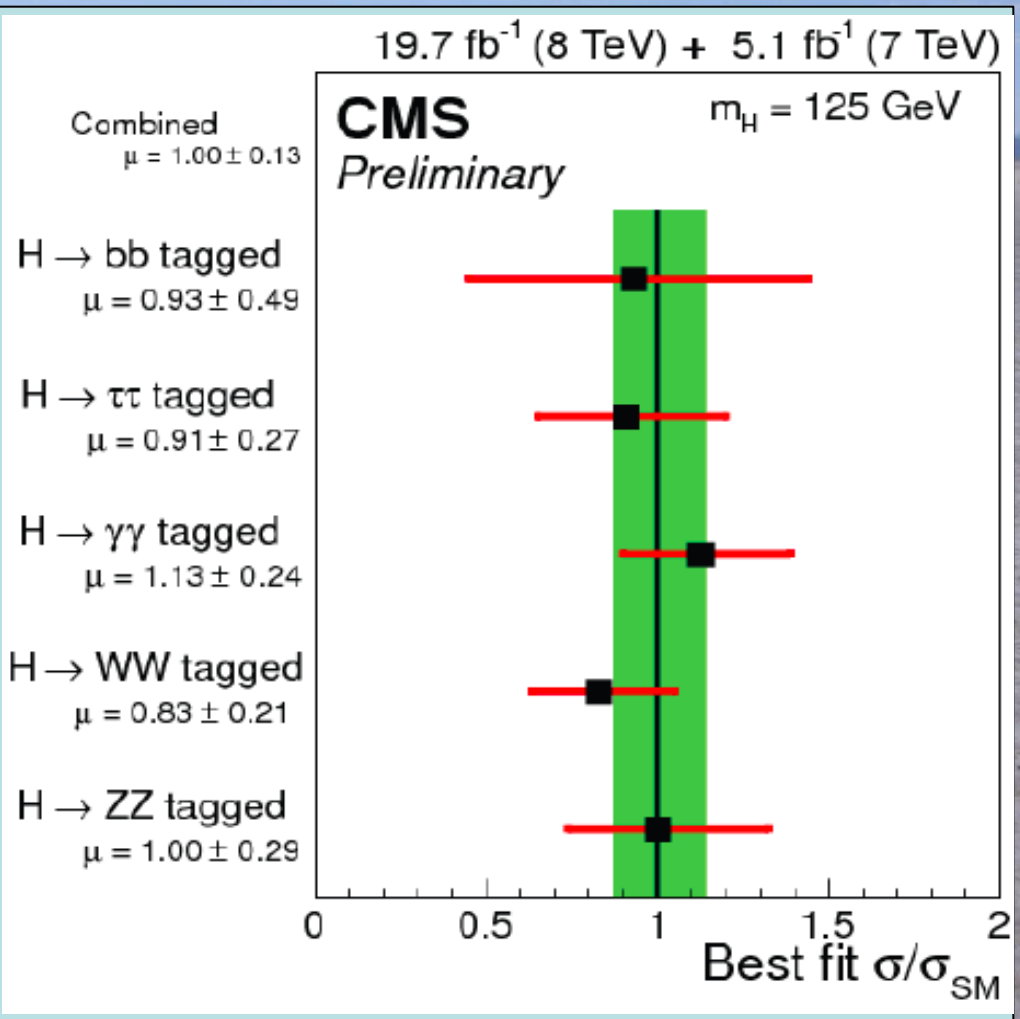


- **Crucial for stability of electroweak vacuum**

Higgs Signal Strengths



$\mu = 1.30 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{th}) \pm 0.09\,(\text{syst})$



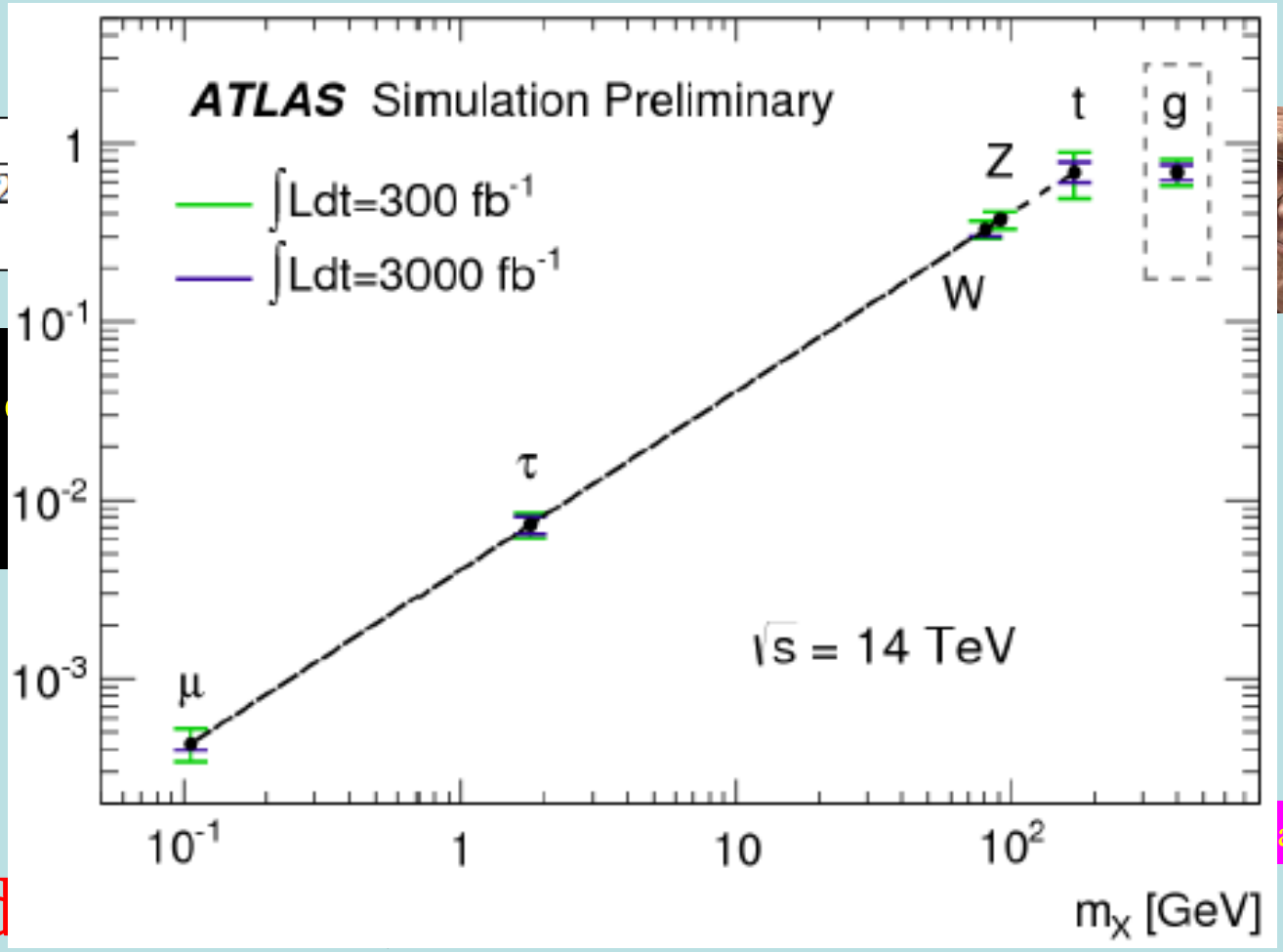
$\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$\lambda_f = \sqrt{2}$

Glob… fit



arXiv:1303.3879

- **Red…**

No BSM? Beware Historical Hubris

- ***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"* - Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, < 1492**
- *"The more important fundamental laws and facts of physical science have all been discovered"* – Albert Michelson, 1894
- *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"* - Lord Kelvin, 1900
- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, 1980

- « Empty » space is unsta SUSY
- Dark matter SUSY
- Origin of matter SUSY
- Masses of neutrinos
- Hierarchy problem SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …

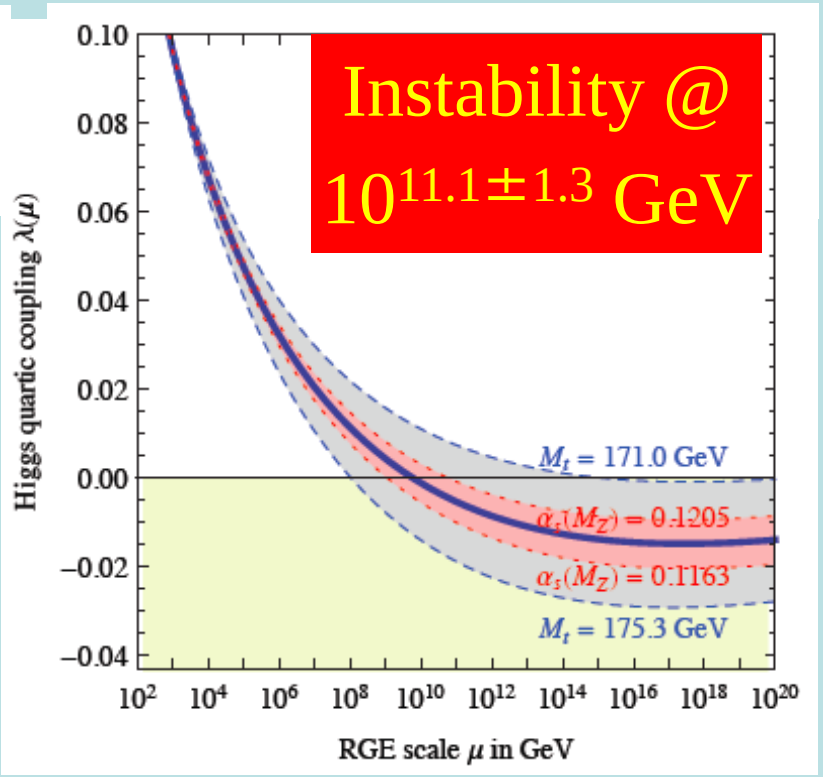
The Standard Model Is Not Enough

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$

- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable

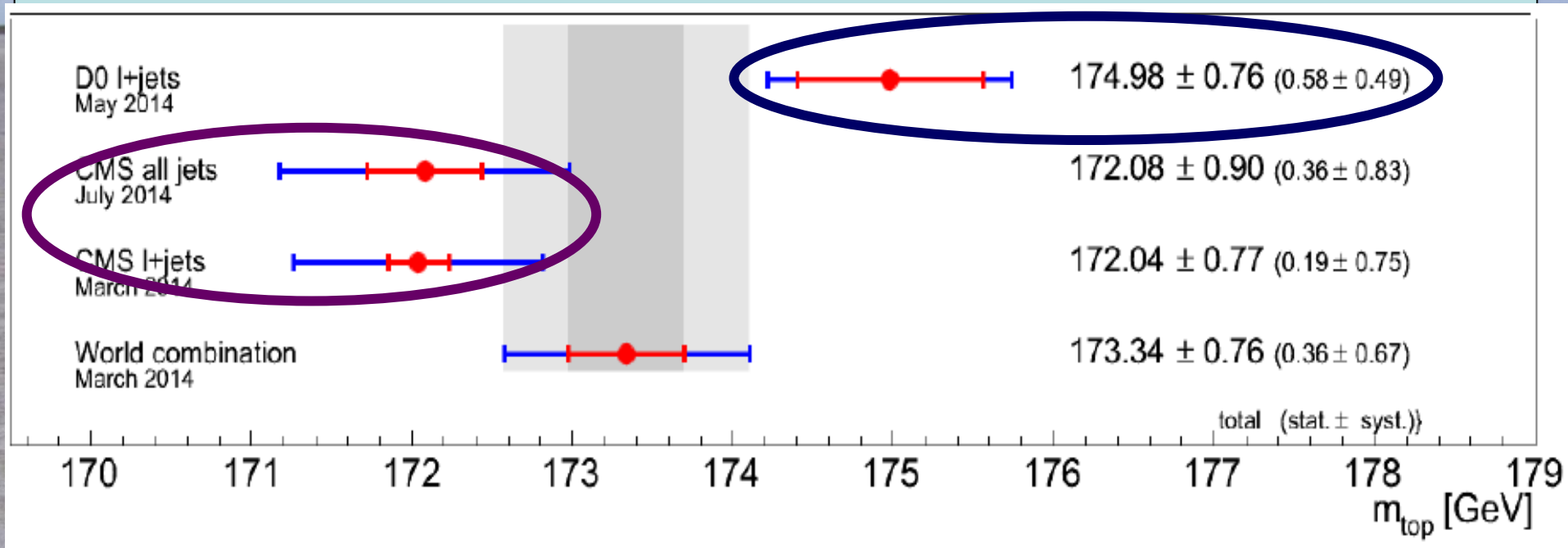


- Vacuum could be stabilized by **Supersymmetry**

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H



- Instability scale: Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

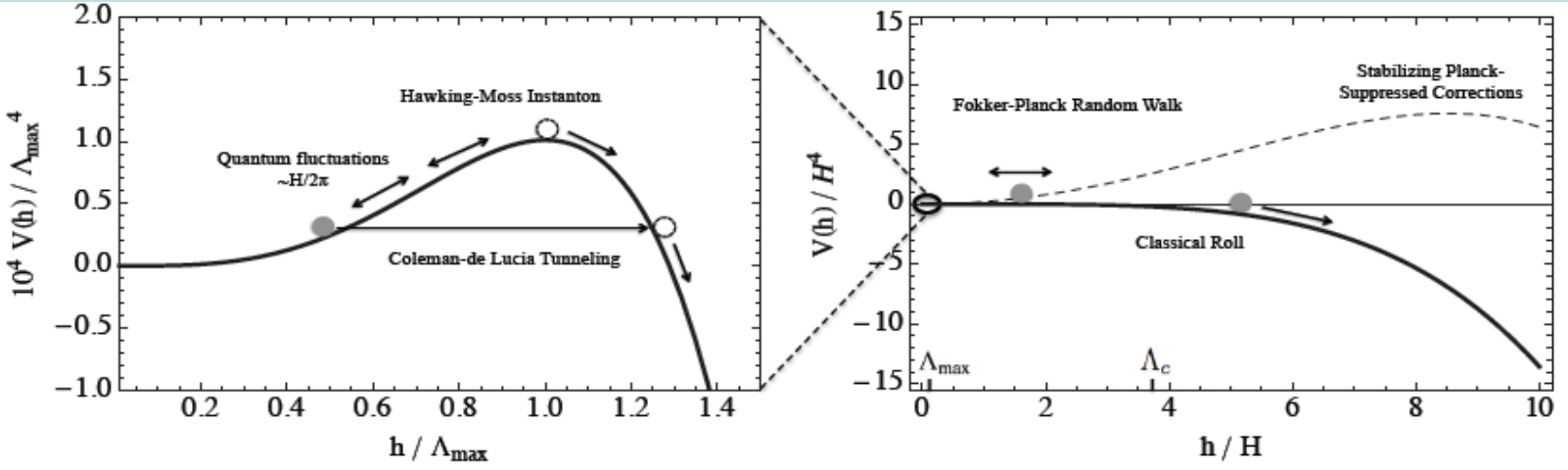
$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

m_t = 173.3 ± 1.0 GeV ➔ $\log_{10}(\Lambda/\text{GeV})$ = 11.1 ± 1.2

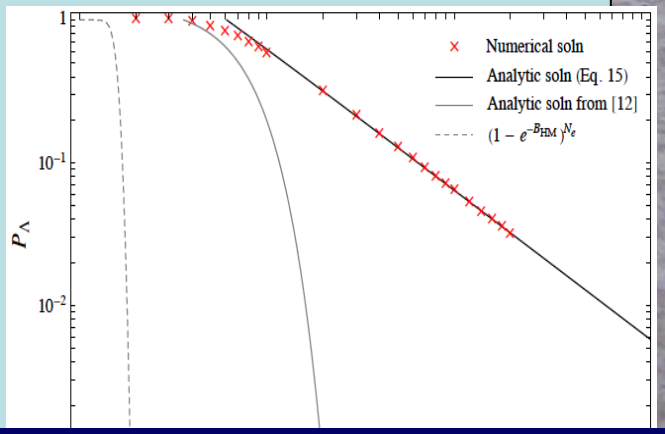
Instability during Inflation?

Hook, Kearns, Shakya & Zurek: arXiv:1404.5953

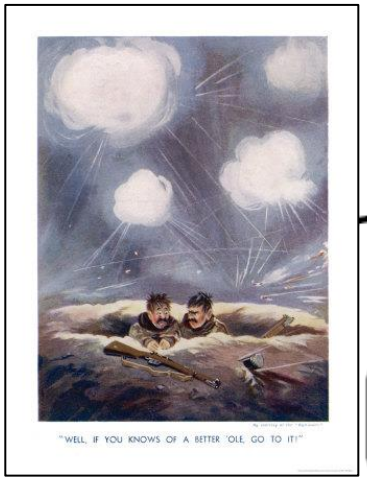
- Do inflation fluctuations drive us over the hill?



- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - Disaster if so
  - If not, OK if more inflation



OK if dim-6 operator? Non-minimal gravity coupling?



DECOUPLING

????????

NO PROBLEM

LARGE EXTRA DIMENSIONS

LOW CUTOFF

HIERARCHY PROBLEM

JUST SO

TUNED

WARPED EXTRA DIMENSIONS

NEW PHYSICS

ANTHROPIC

TECHNICOLOR

COMPOSITE HIGGS

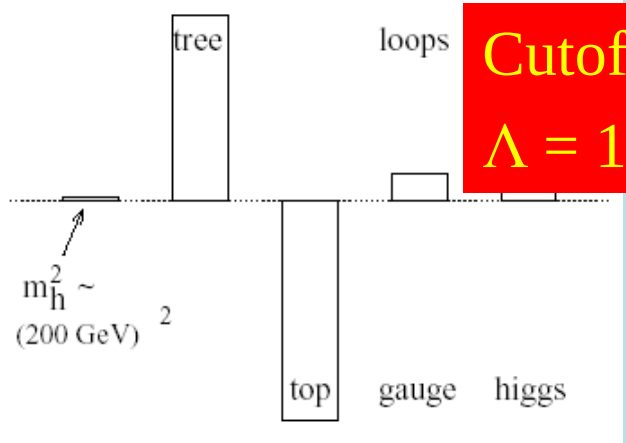
Craig

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff

Λ = 10 TeV

Cut-off Λ ~ 1 TeV with

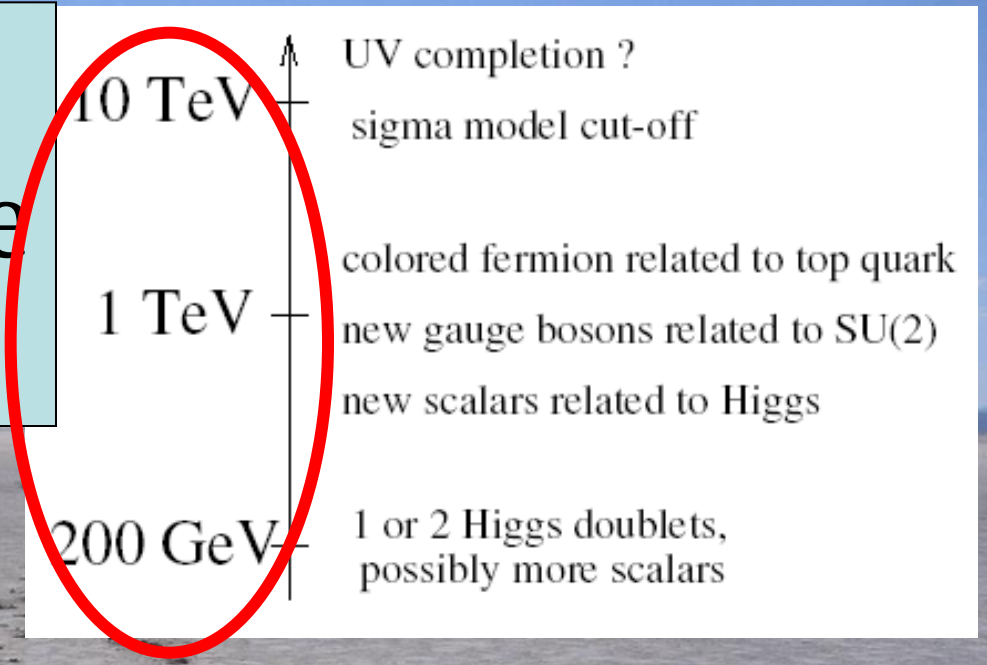
Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity

New technicolour force?

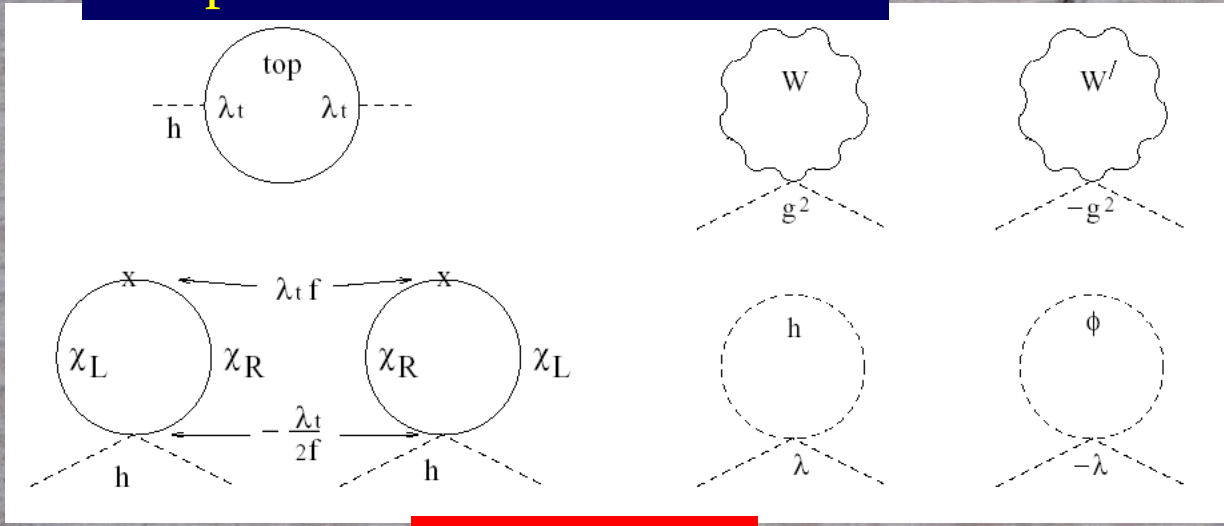
- Heavy scalar resonance?
- Pseudo-Nambu-Goldstone?

Higgs as a Pseudo-Goldstone Boson?

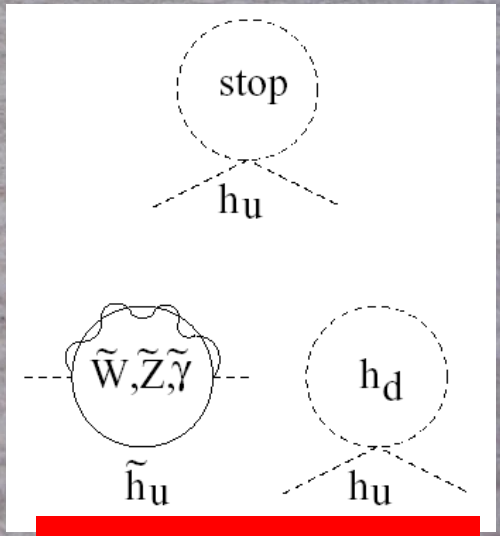


'Little Higgs' models
(breakdown of larger symmetry)

Loop cancellation mechanism



Little Higgs

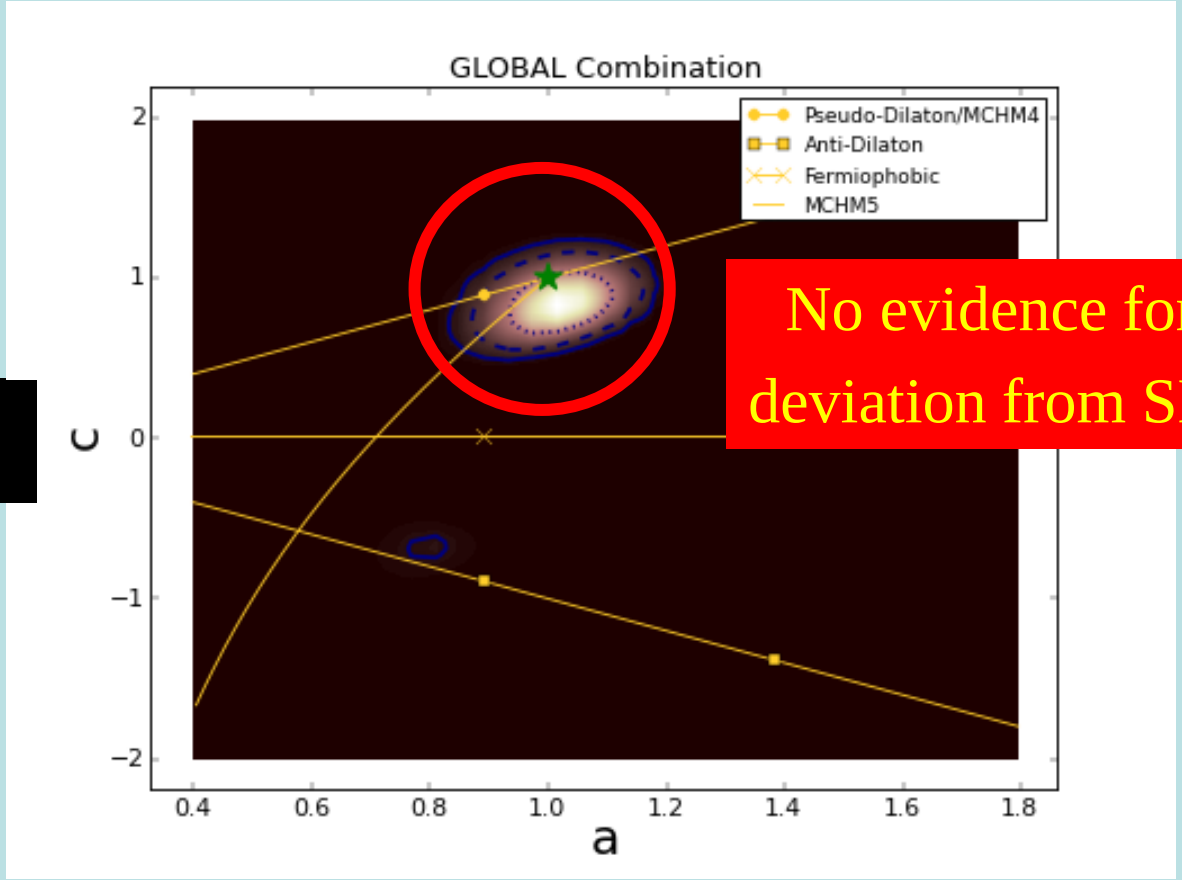


Supersymmetry

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

Global



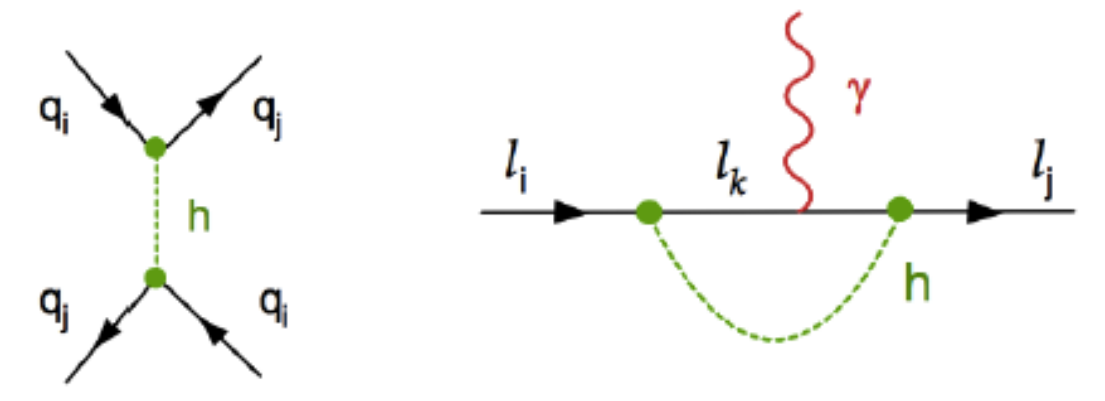
No evidence for deviation from SM

- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

BR(τμ) or BR(τe) could be O(10)%

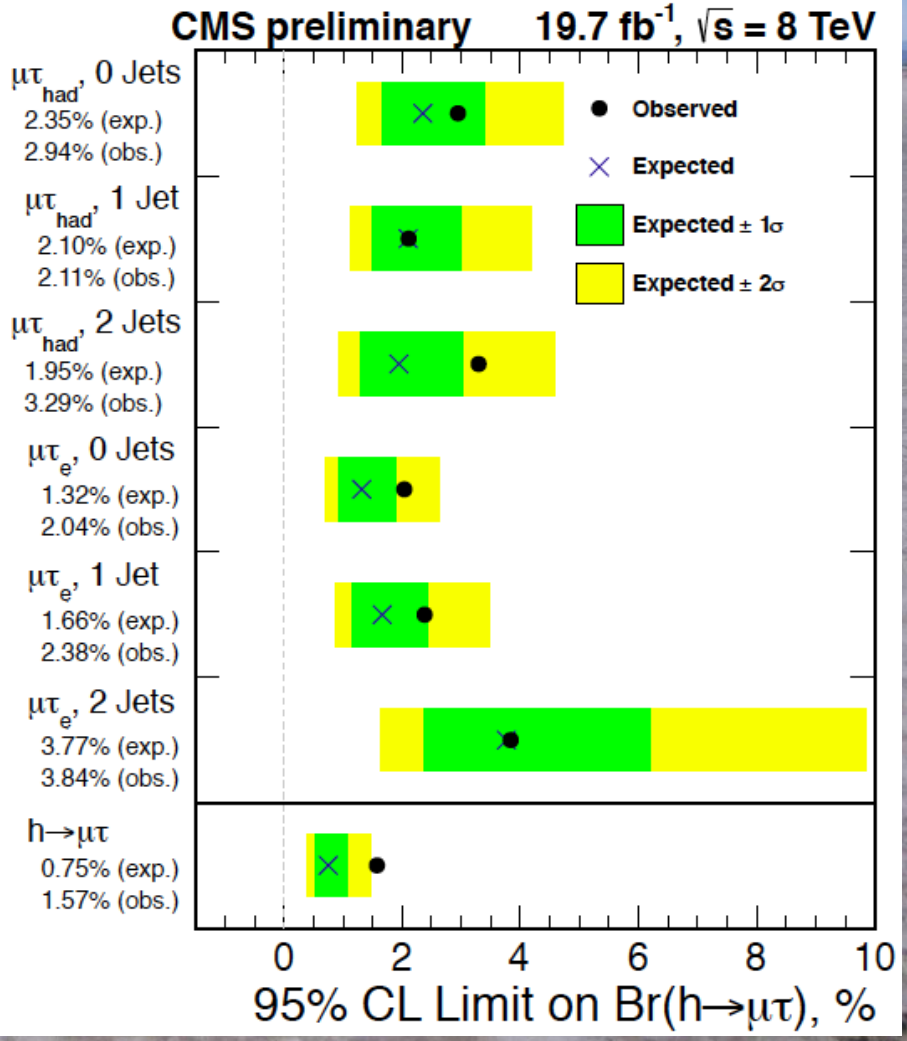
Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Couplings?

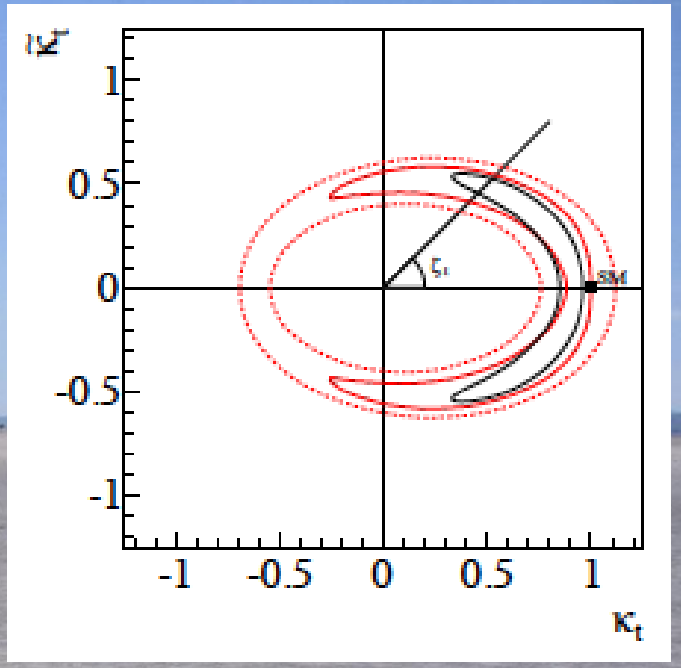
Limits on H→μτ branching ratio

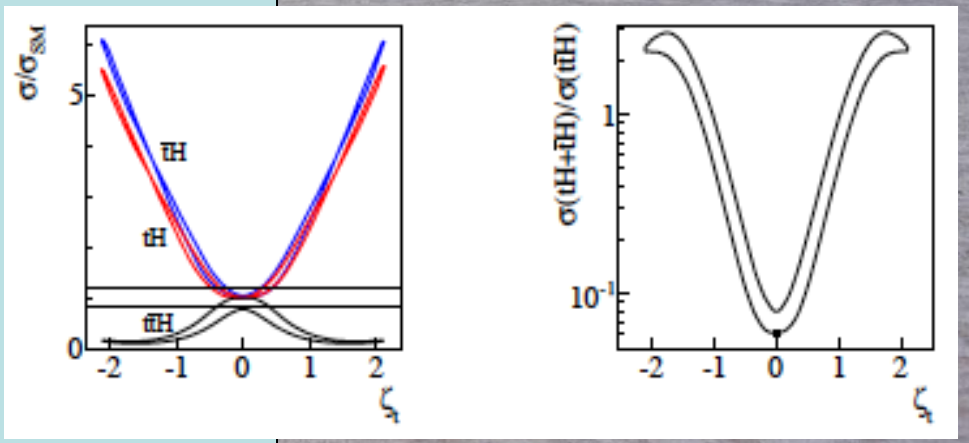
- Comparable sensitivity from all channels
- Observed limit 1.57% (exp. 0.75%)
- **Large improvement of previous limits**
- **Background-only p-value of 0.007 (2.46σ)**
  - Best-fit $B(H\to\mu\tau) = 0.89^{+0.40}_{-0.37}\%$

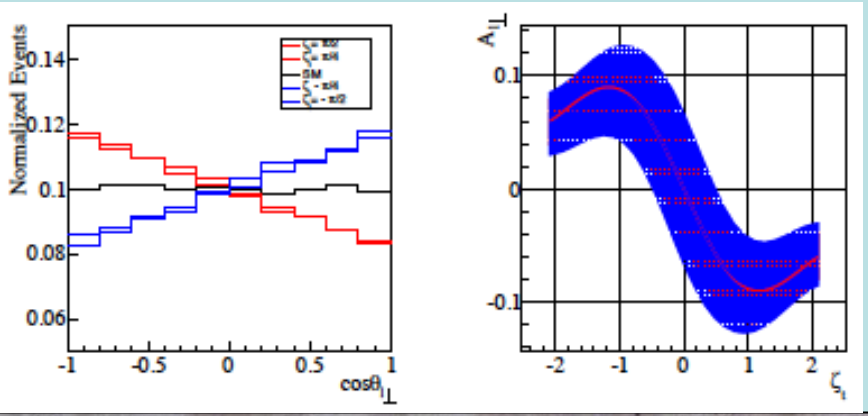


Constraining CP Violation in H-t couplings

- Present data constrain combination of CP-conserving, –violating H-t couplings
- Cross-sections for t-tbar-H and t-H depend on angle ζ_t
- CP violation if $\zeta_t \neq 0$



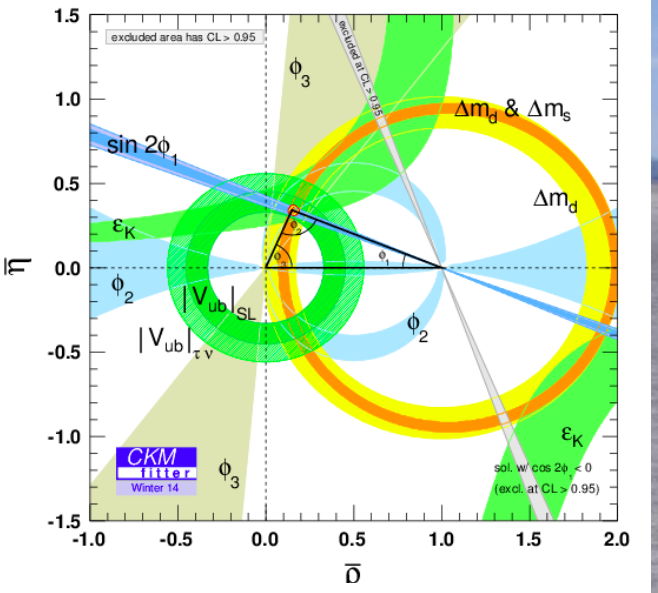


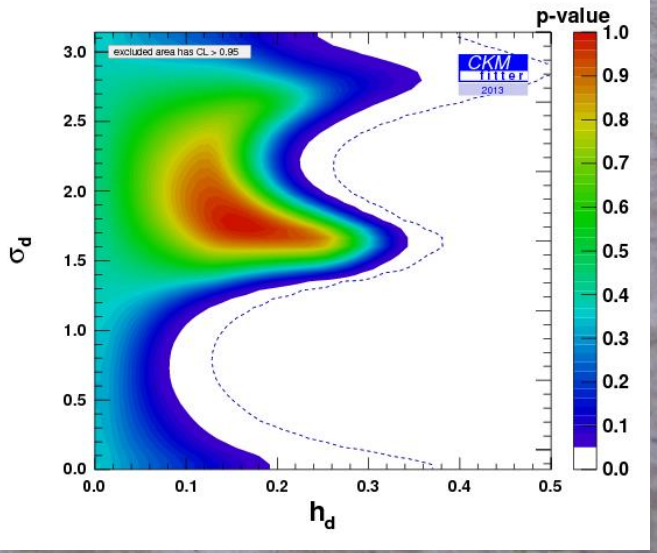


Opportunity for Run 2 and beyond

Flavour Physics

- CKM picture works very well
- Many successful predictions:
  - Many modes of CPV
  - In K^0, B^0, $B^{\pm}$, B_s systems
  - No sign of CPV in charm ☹
- Also rare decays: $B_{s,d}$ ➔ $\mu^+\mu^-$
- Could still be substantial BSM contribution
- Does new TeV physics copy CKM? Squarks non-



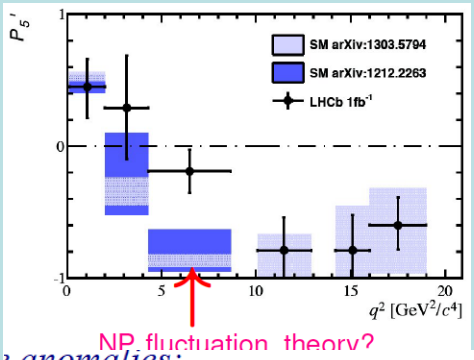


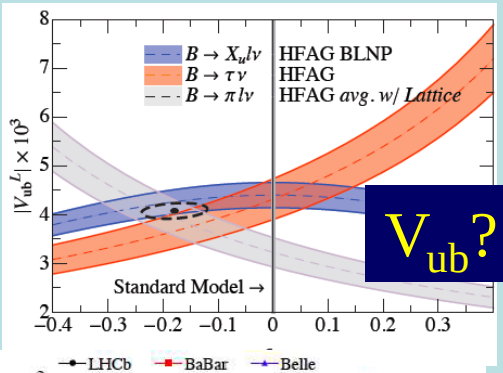
Flavour Puzzles

- CP asymmetries in B to Kπ?

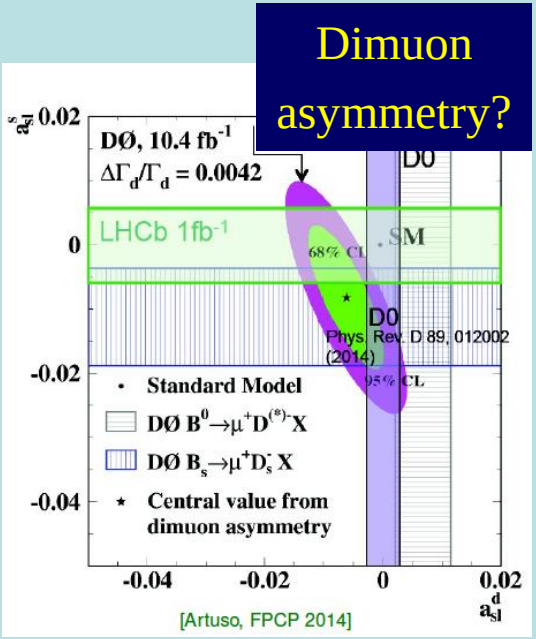
$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.122 \pm 0.022$$

- B^0 to $K^{*0}\,\mu^+\,\mu^-$ angular distribution: P_5' anomaly (3.7σ, 0.5% with LEE): explicable by Z'?
-





V_{ub}?



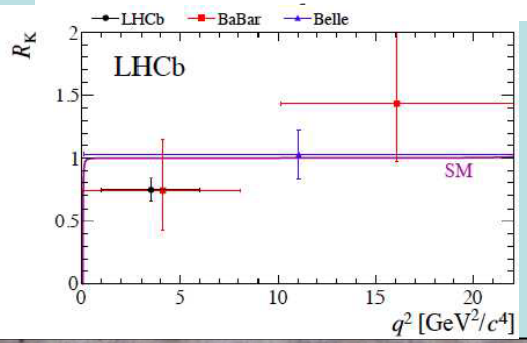
B to Kμμ/Kee ratio?

The lepton universality ratio

$d\Gamma(B^+ \to K^+\mu\mu)/d\Gamma(B^+ \to K^+ee)$

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat})^{+0.036}_{-0.036}(\text{syst})$$

2.6σ from SM



What else is there?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, dark matter, GUTs, string, …

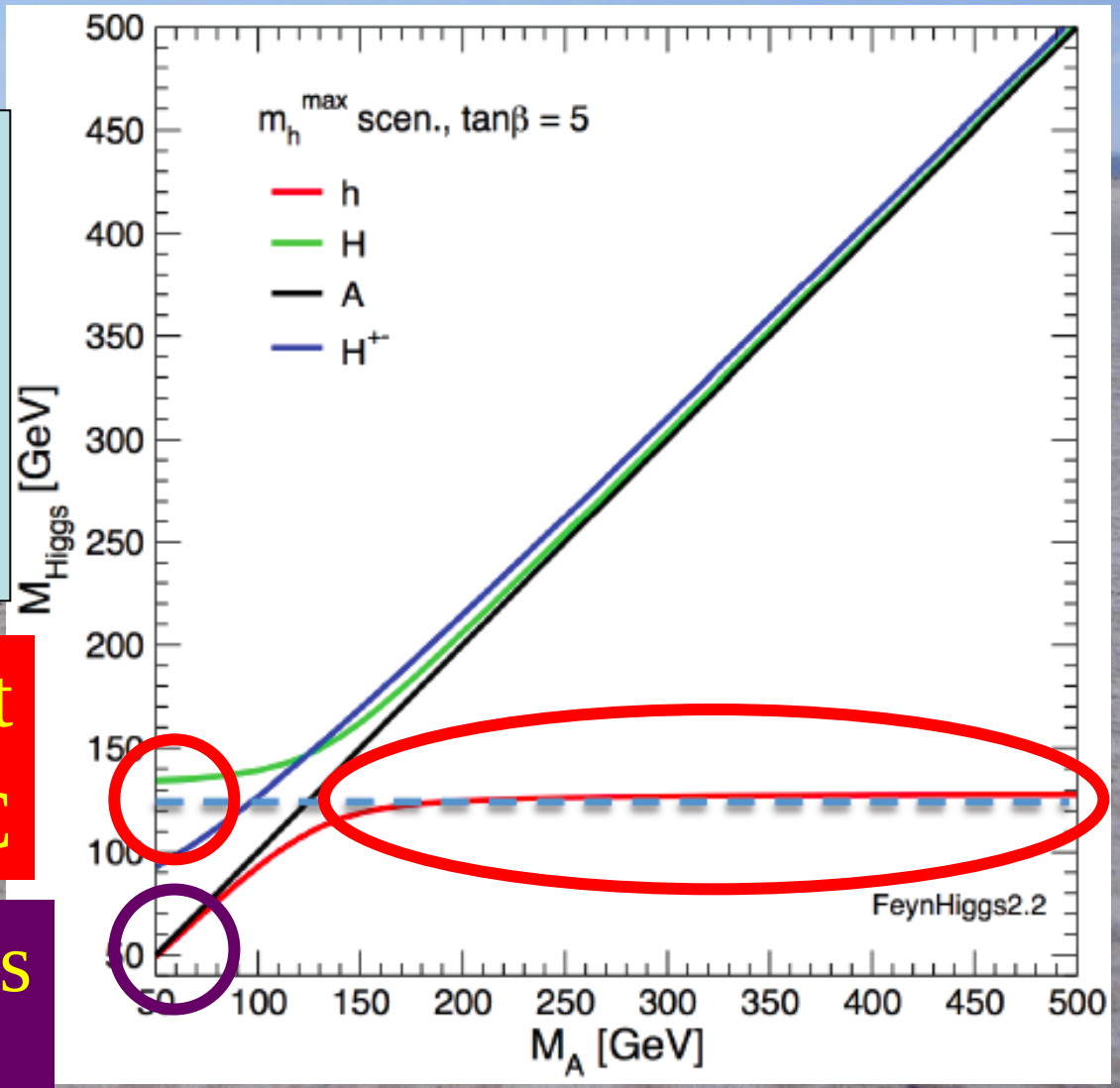
MSSM Higgs Masses & Couplings

Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close

Consistent With LHC

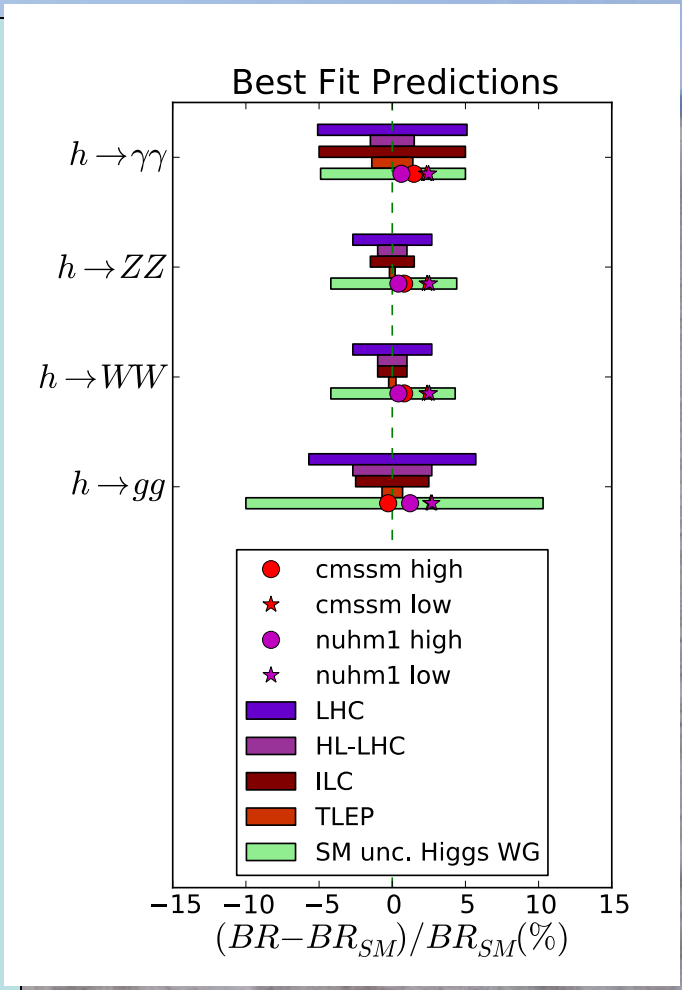
Is a lighter Higgs still waiting?

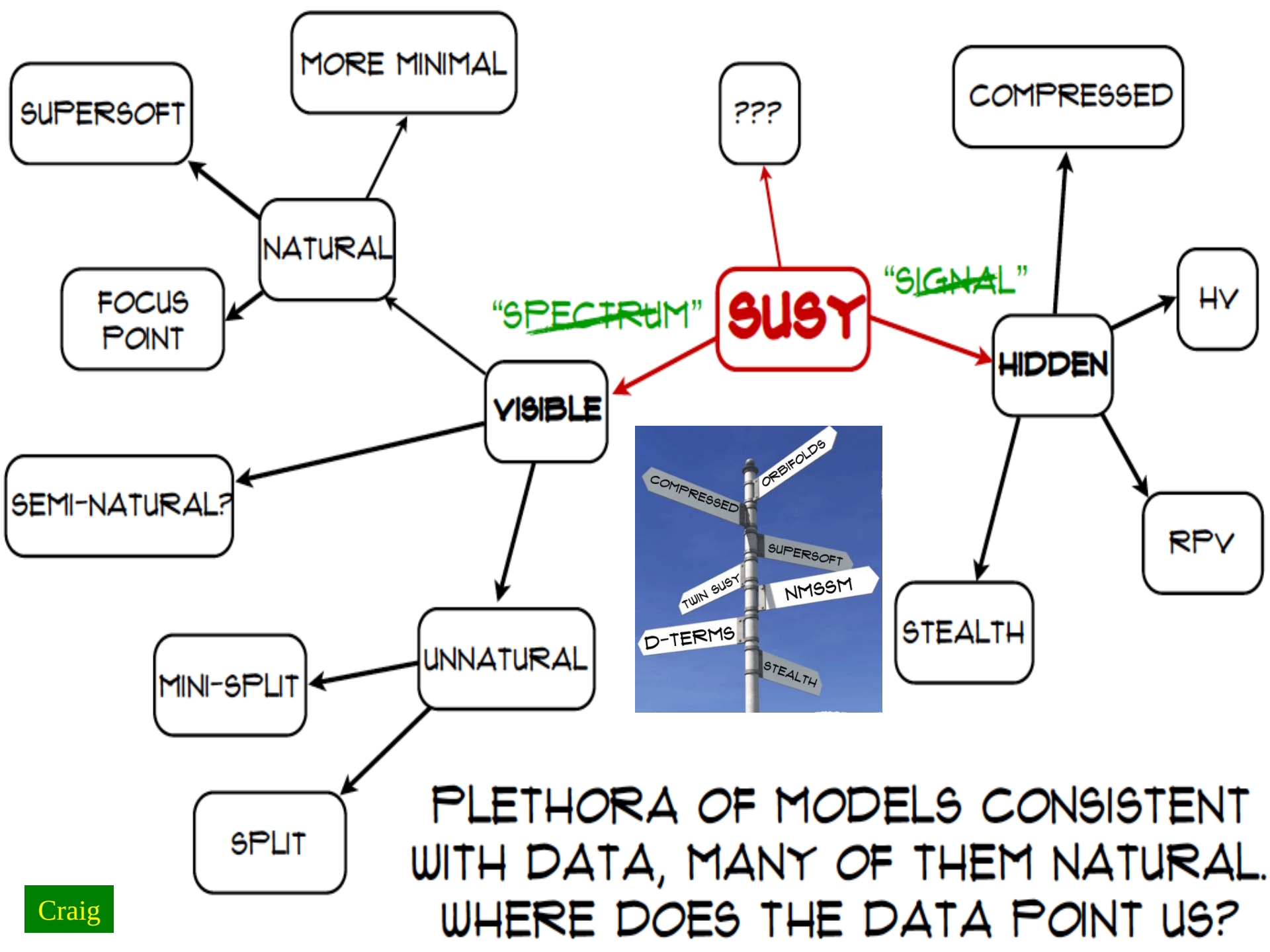


Higgs Coupling Measurements

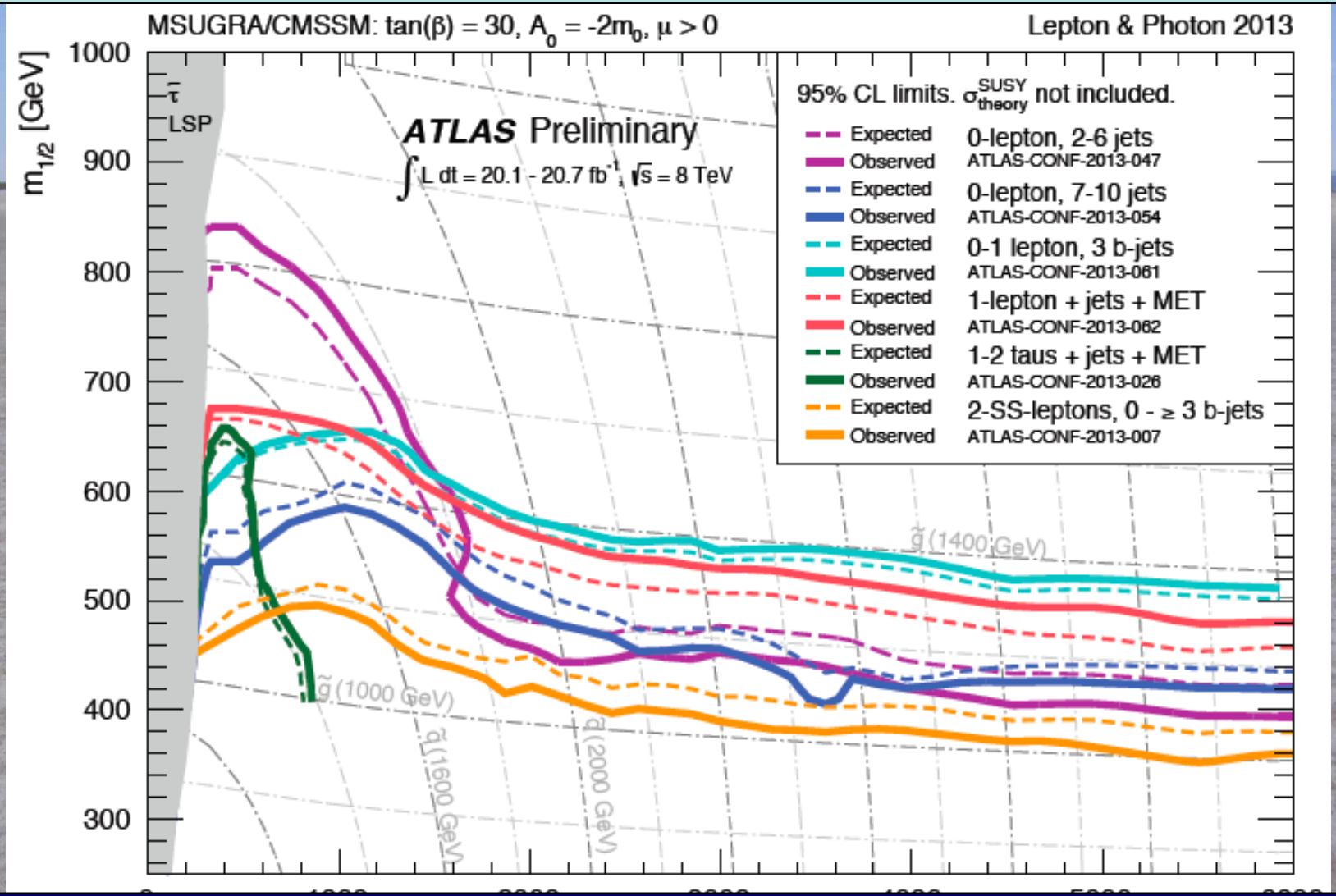
- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - **LHC**
  - **HL-LHC**
  - **ILC**
  - **TLEP (= FCC-ee)**

(Able to distinguish from SM)



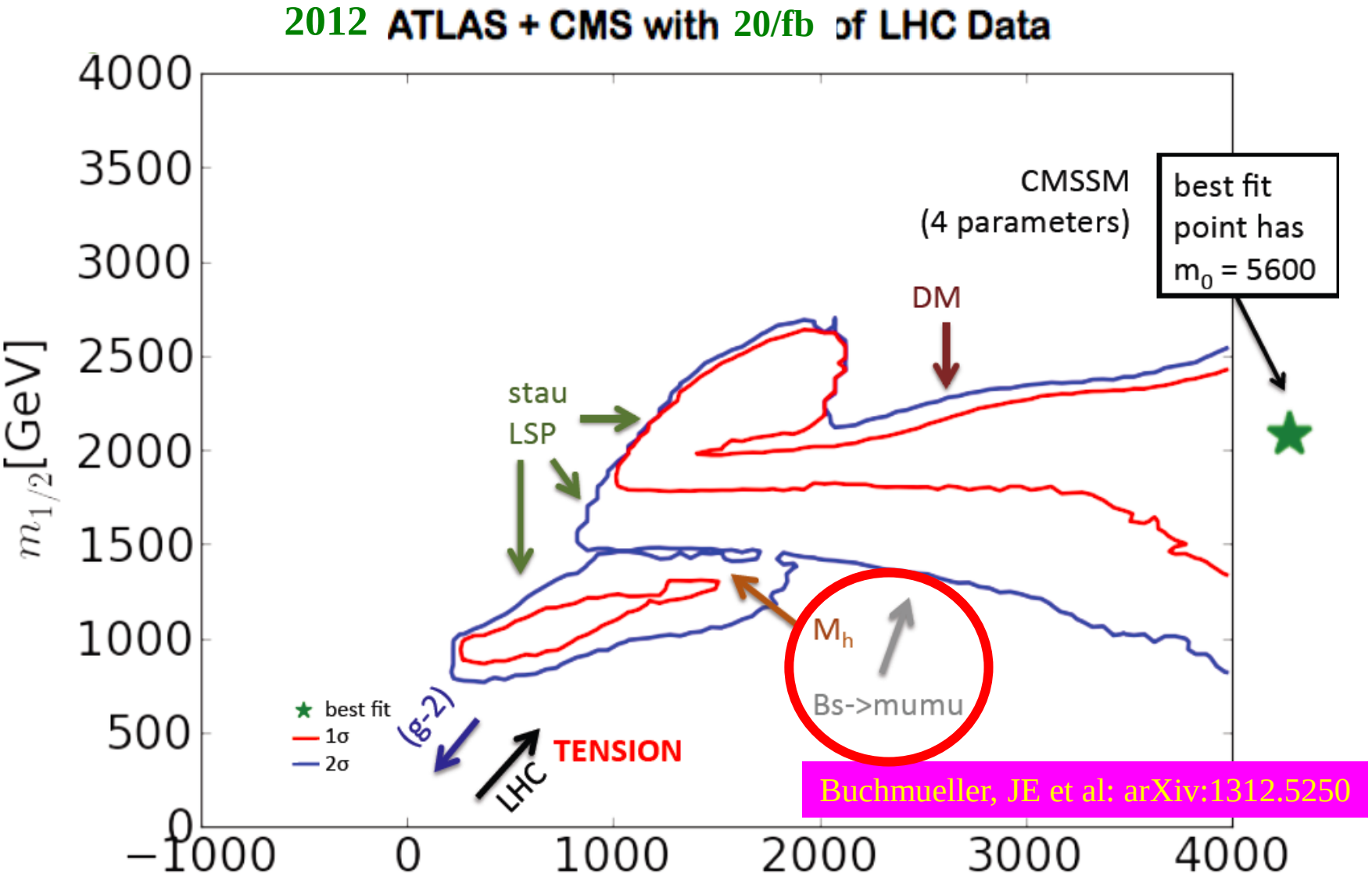

MORE MINIMAL
SUPERSOFT
???
COMPRESSED
NATURAL
FOCUS POINT
"SPECTRUM"
SUSY
"SIGNAL"
HV
HIDDEN
VISIBLE
SEMI-NATURAL?
ORBIFOLDS
COMPRESSED
SUPERSOFT
TWIN SUSY
NMSSM
D-TERMS
STEALTH
RPV
STEALTH
UNNATURAL
MINI-SPLIT
SPLIT
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?
Craig

Searches with ~ 20/fb @ 8 TeV



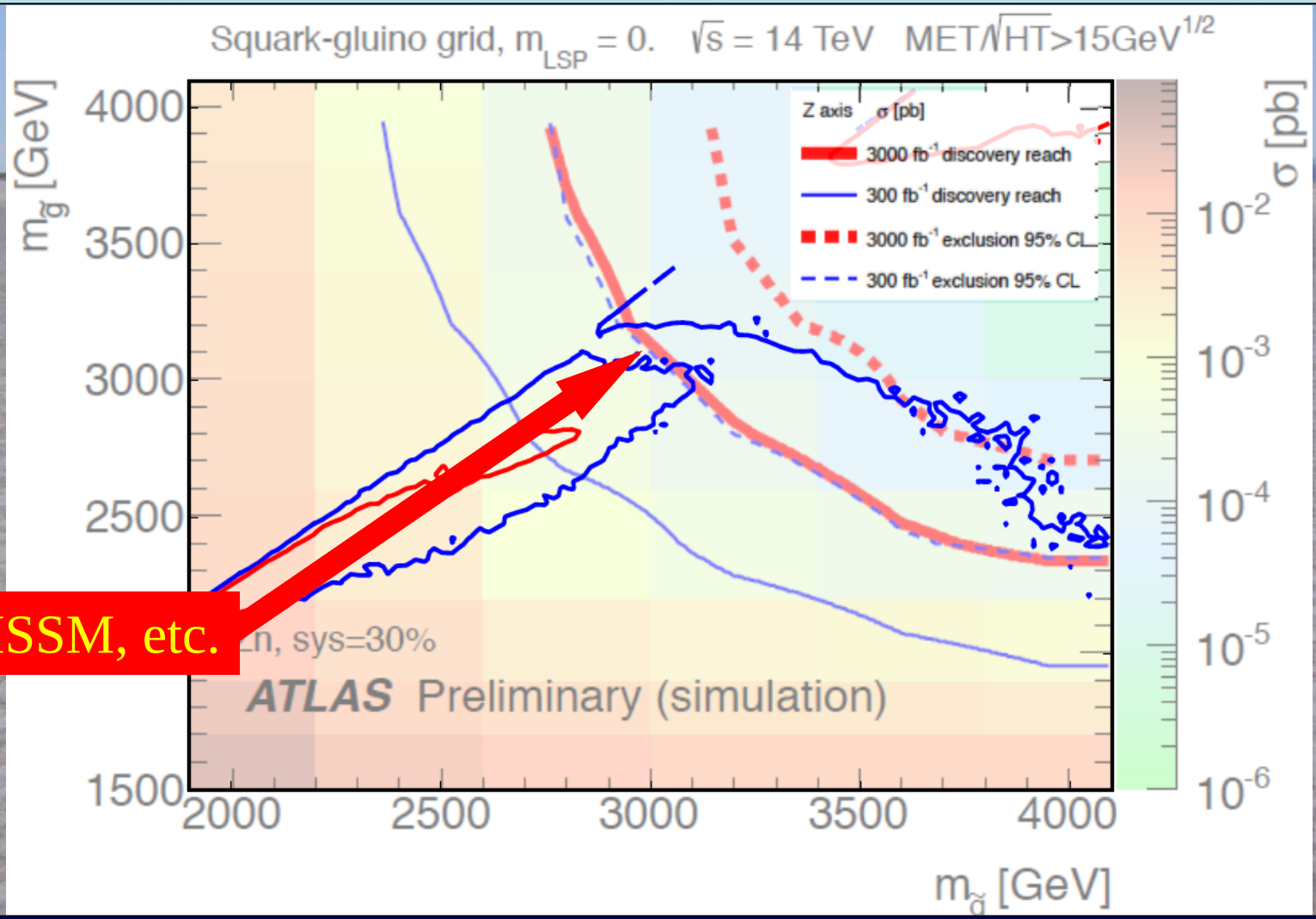
CMSSM = universal sparticle masses @ GUT scale

Constrained MSSM



p-value of simple models ~ 5% (also SM)

LHC Reach for CMSSM Susy

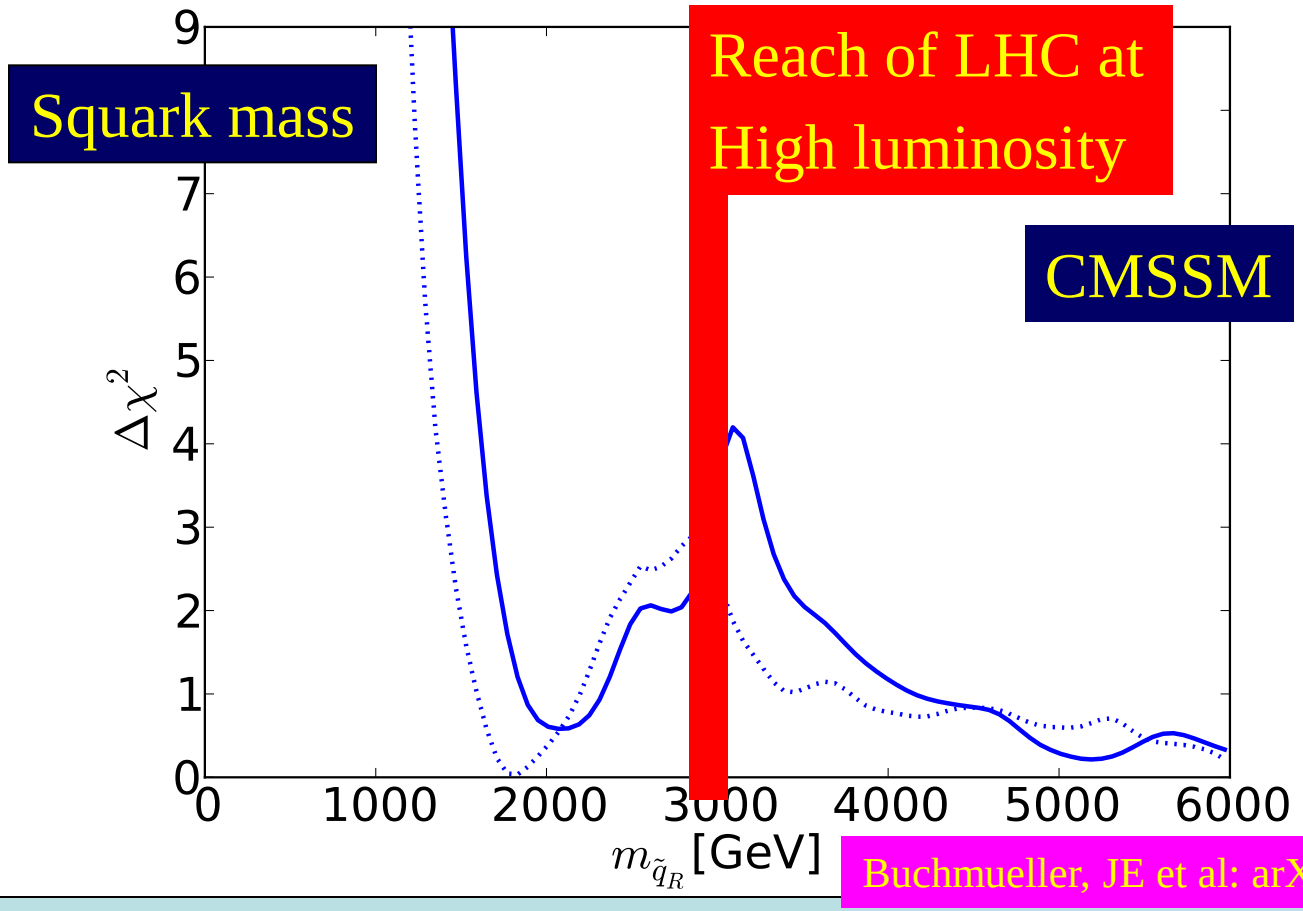


CMSSM, etc.

Confronted with likelihood analysis of CMSSM

Constrained MSSM

2012 ATLAS + CMS with 20/fb of LHC Data



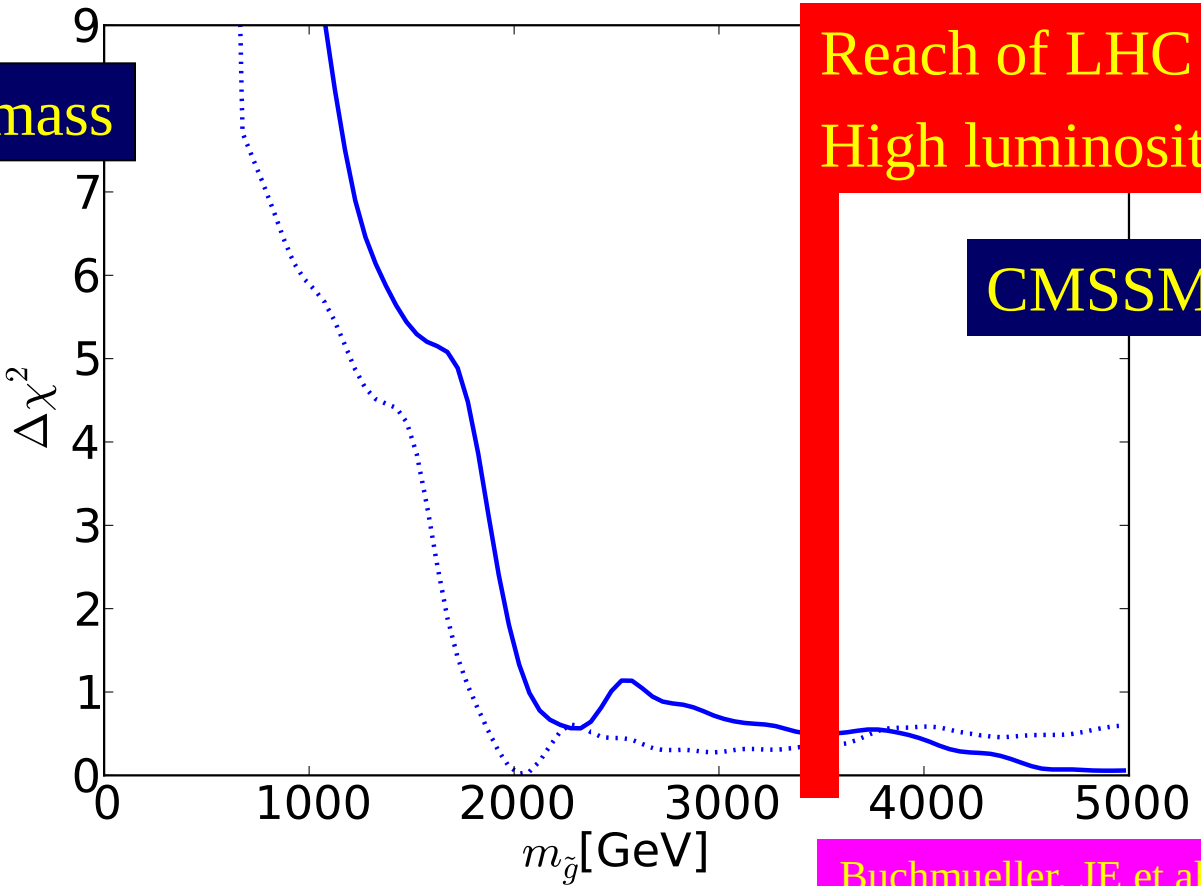
Buchmueller, JE et al: arXiv:1312.5250

Favoured values of squark mass also significantly above pre-LHC, > 1.6 TeV

Constrained MSSM

2012 ATLAS + CMS with 20/fb of LHC Data

Gluino mass



Reach of LHC at High luminosity

CMSSM

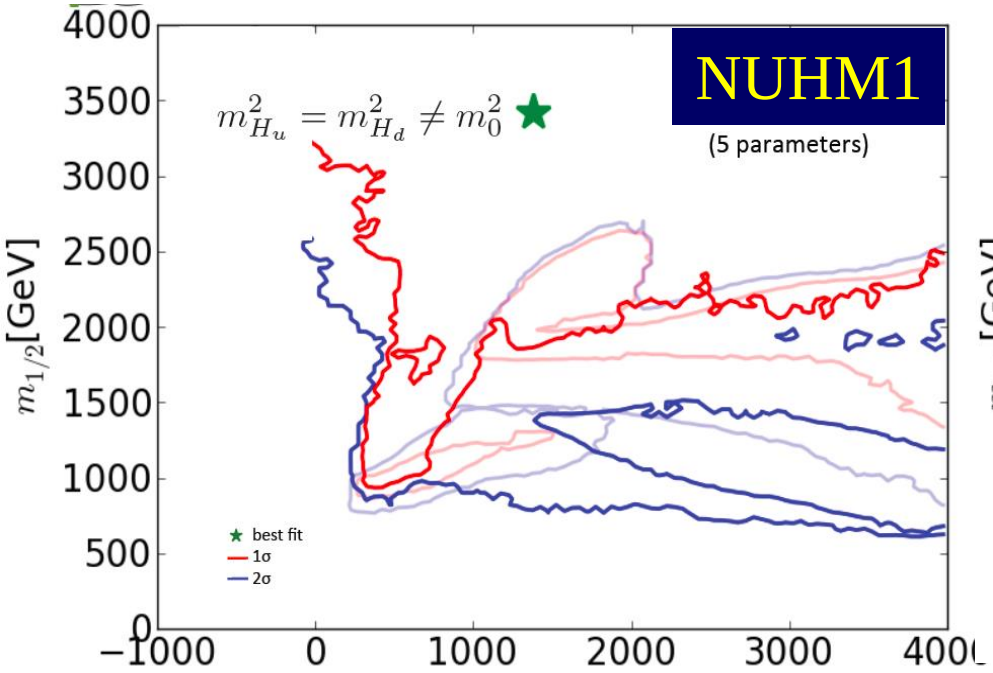
1

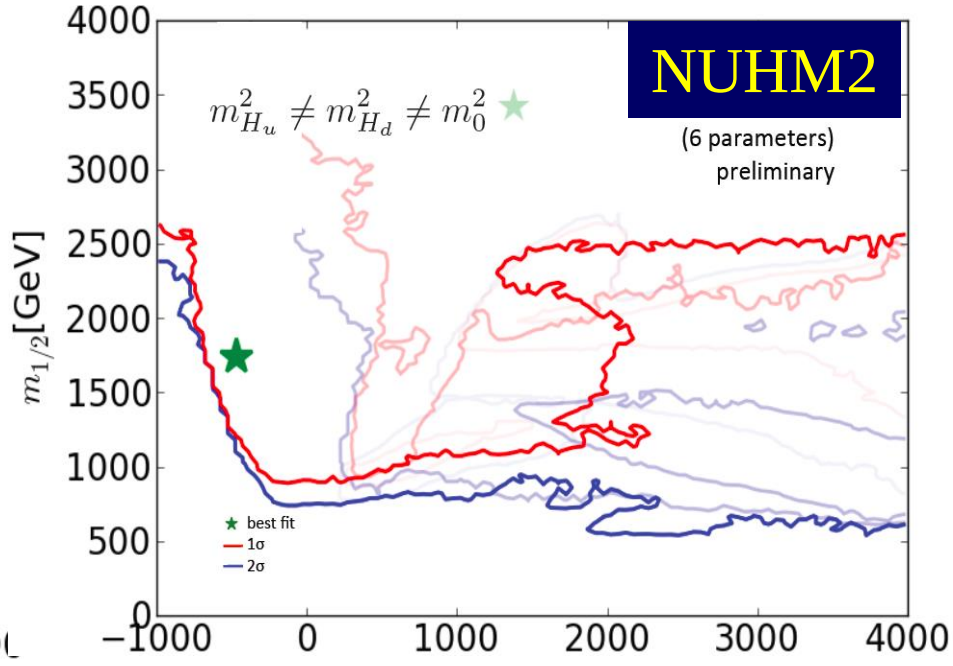
Buchmueller, JE et al: arXiv:1312.5250

Favoured values of gluino mass significantly above pre-LHC, > 1.8 TeV

Non-universal Higgs Mass Models

2012 ATLAS + CMS with 20/fb of LHC Data



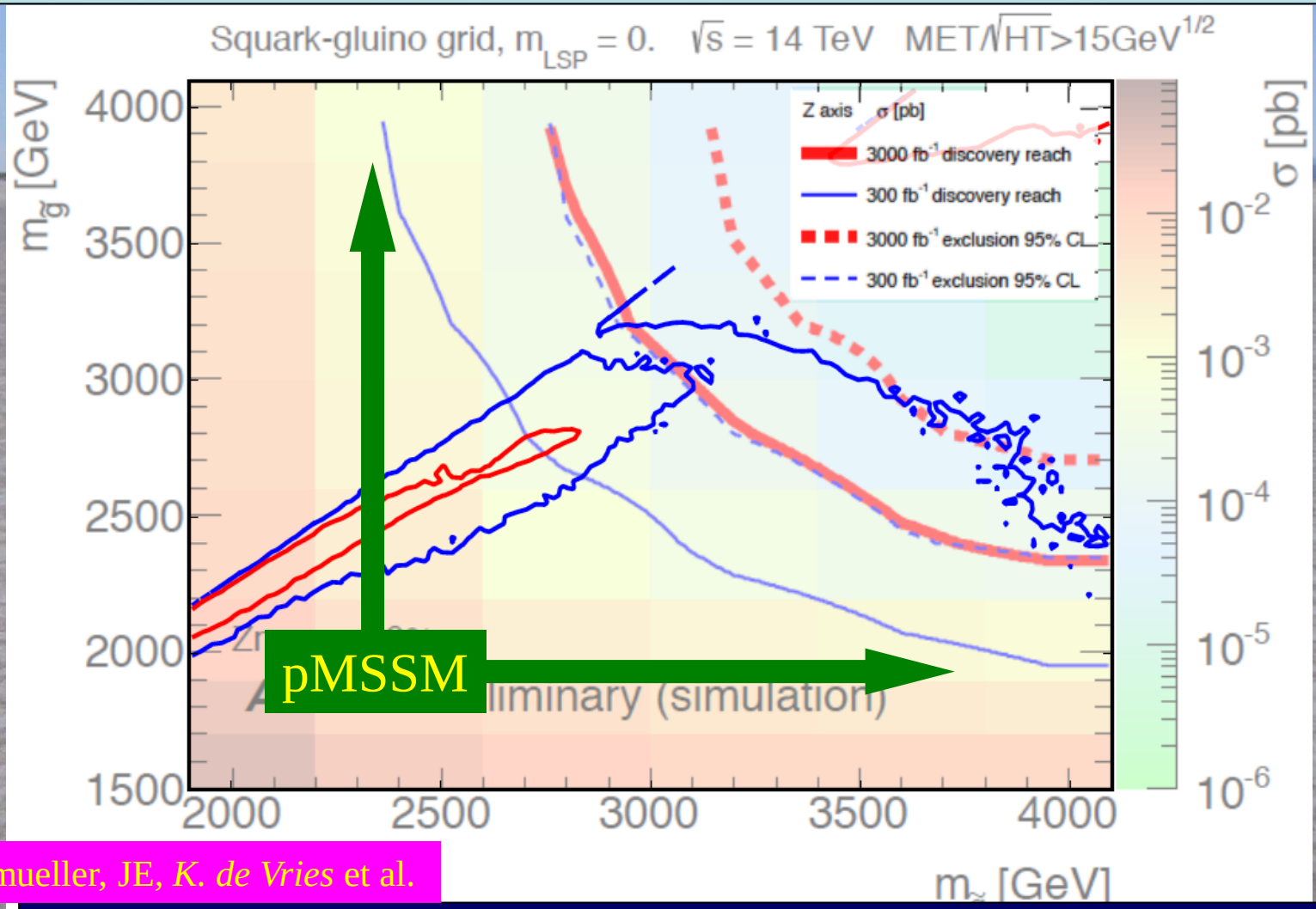


Buchmueller, JE et al: in preparation

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ★

Parameter space opens up at large masses

LHC Reach for Supersymmetry



O. Buchmueller, JE, *K. de Vries* et al.

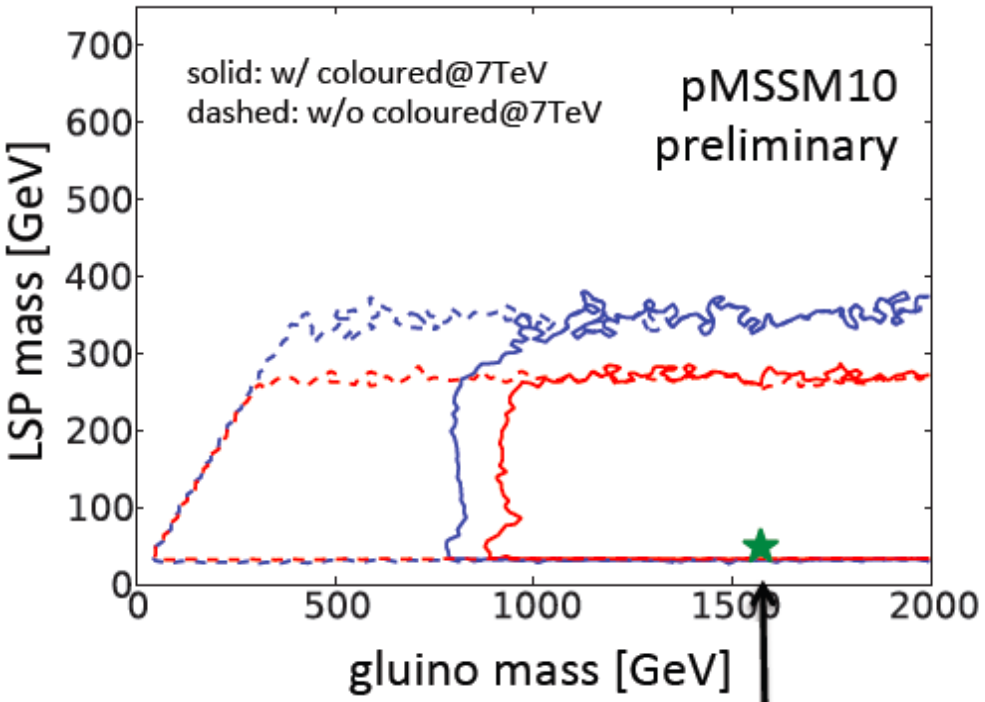
More possibilities in unconstrained pMSSM

Exploration of the pMSSM

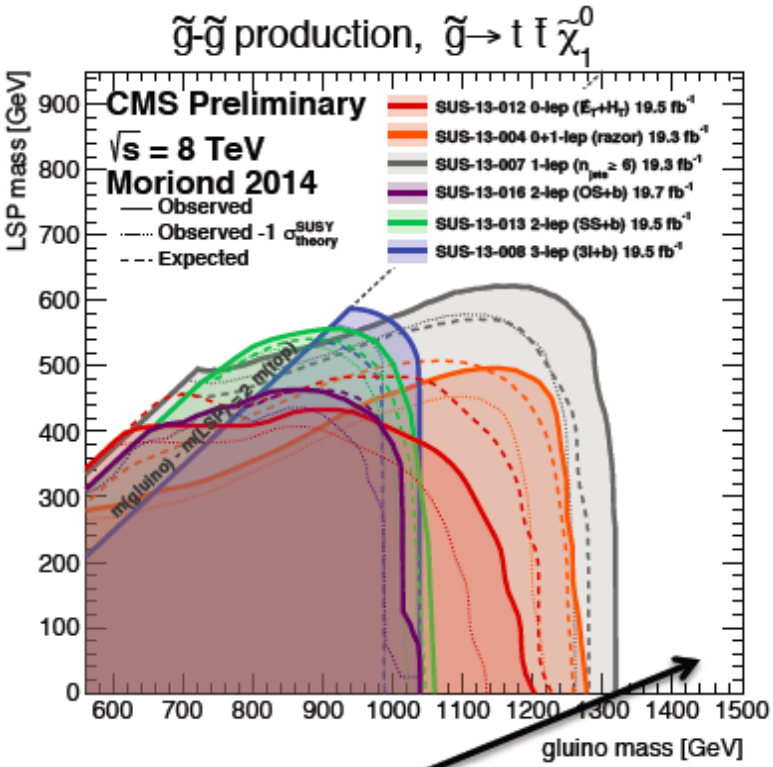
Gluino

2012 ATLAS + CMS with 20/fb of LHC Data

pMSSM10



searches today



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

A lot of the parameter space, including the current best fit point, lies outside the reach of 8 TeV searches. **Early Discovery?**

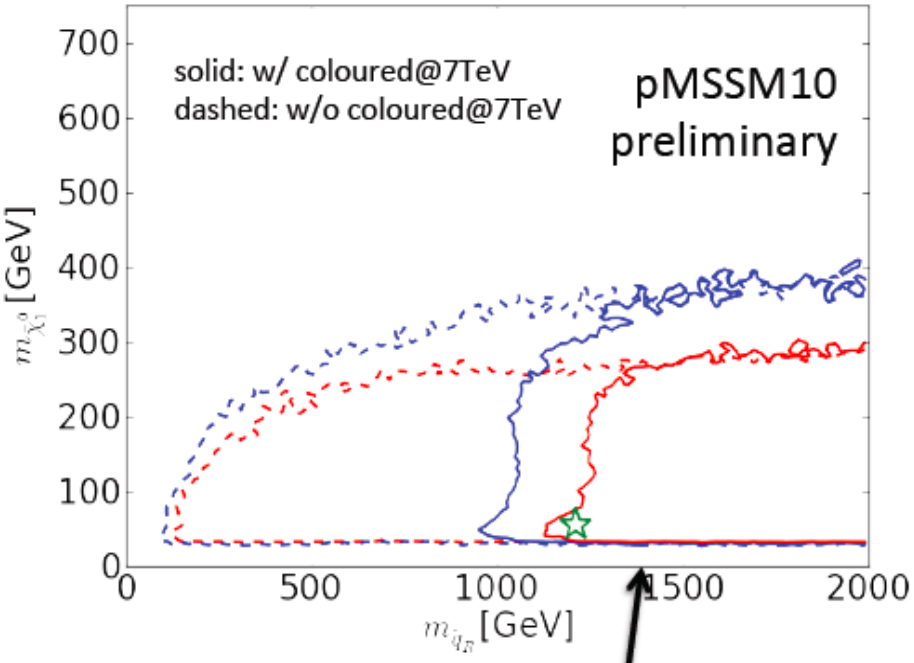
Buchmueller, JE et al: in preparation

Exploration of the pMSSM

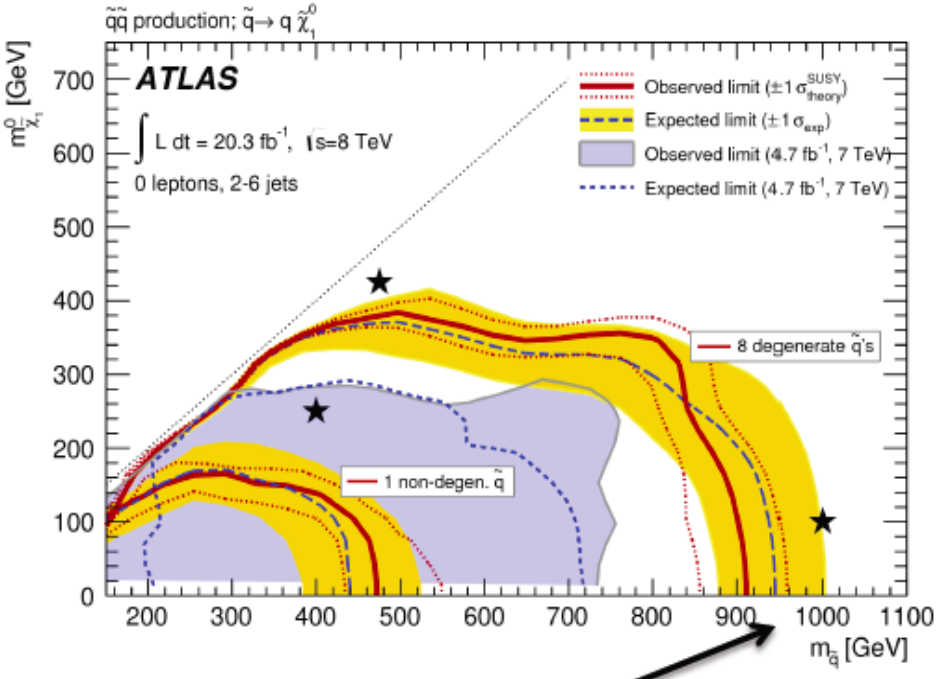
Squarks

2012 ATLAS + CMS with 20/fb of LHC Data

pMSSM10



searches today



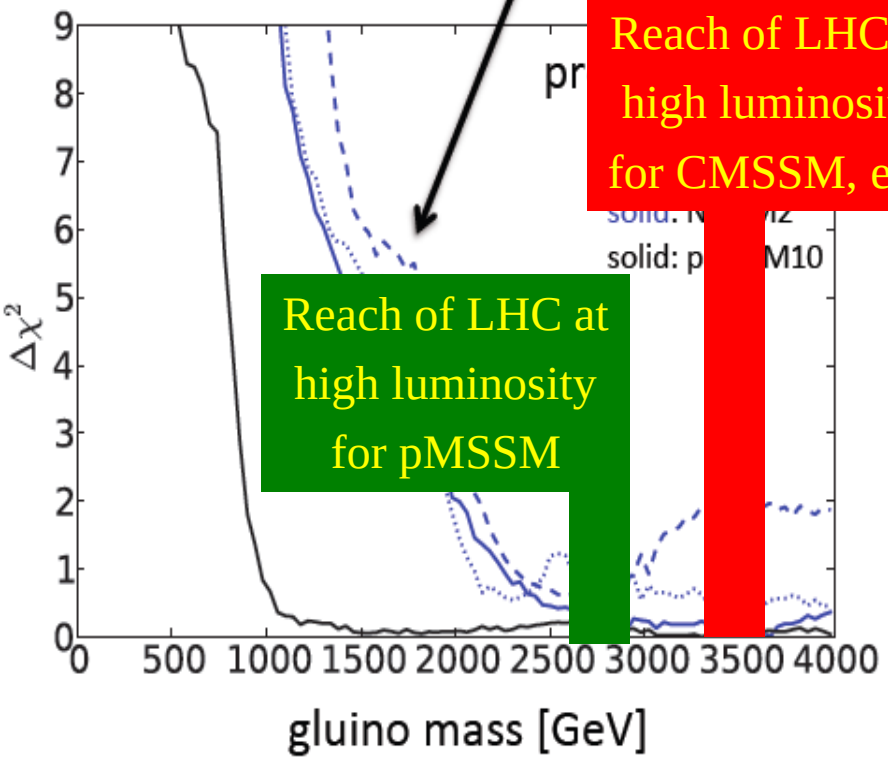
A lot of the parameter space, including the current best fit point, lies outside the reach of 8 TeV searches. **Early Discovery?**

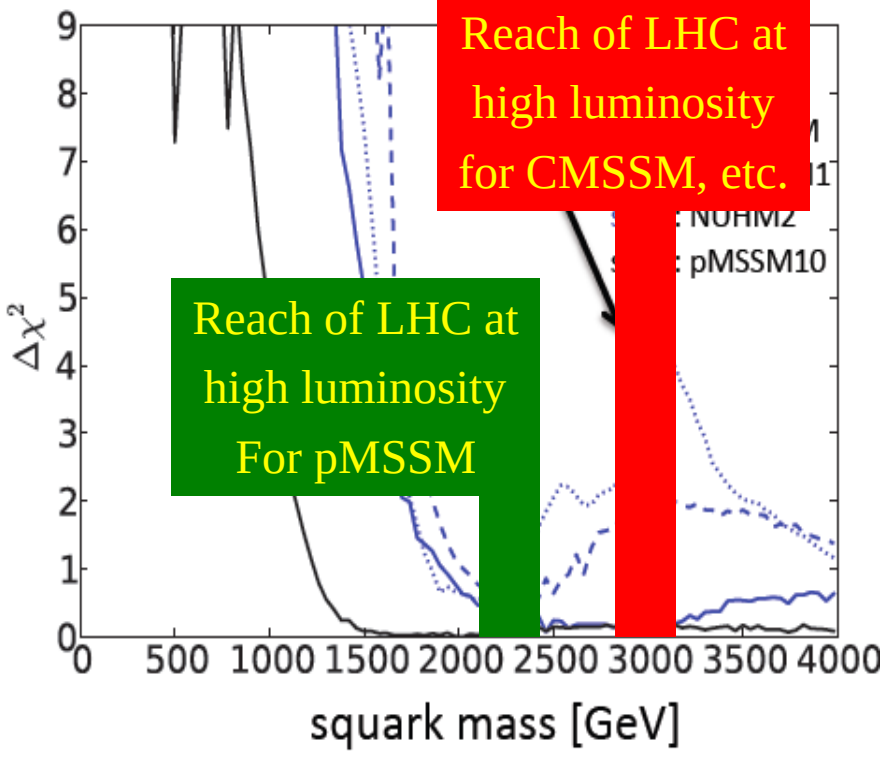
Buchmueller, JE et al: in preparation

Gluino, Squark Masses in Models

2012 ATLAS + CMS with 20/fb of LHC Data

The **CMSSM**, **NUHM1** and **NUHM2** give very **comparable** mass ranges. For the squark mass, the two-modal structure is quite visible in the CMSSM, and less so in the other models.

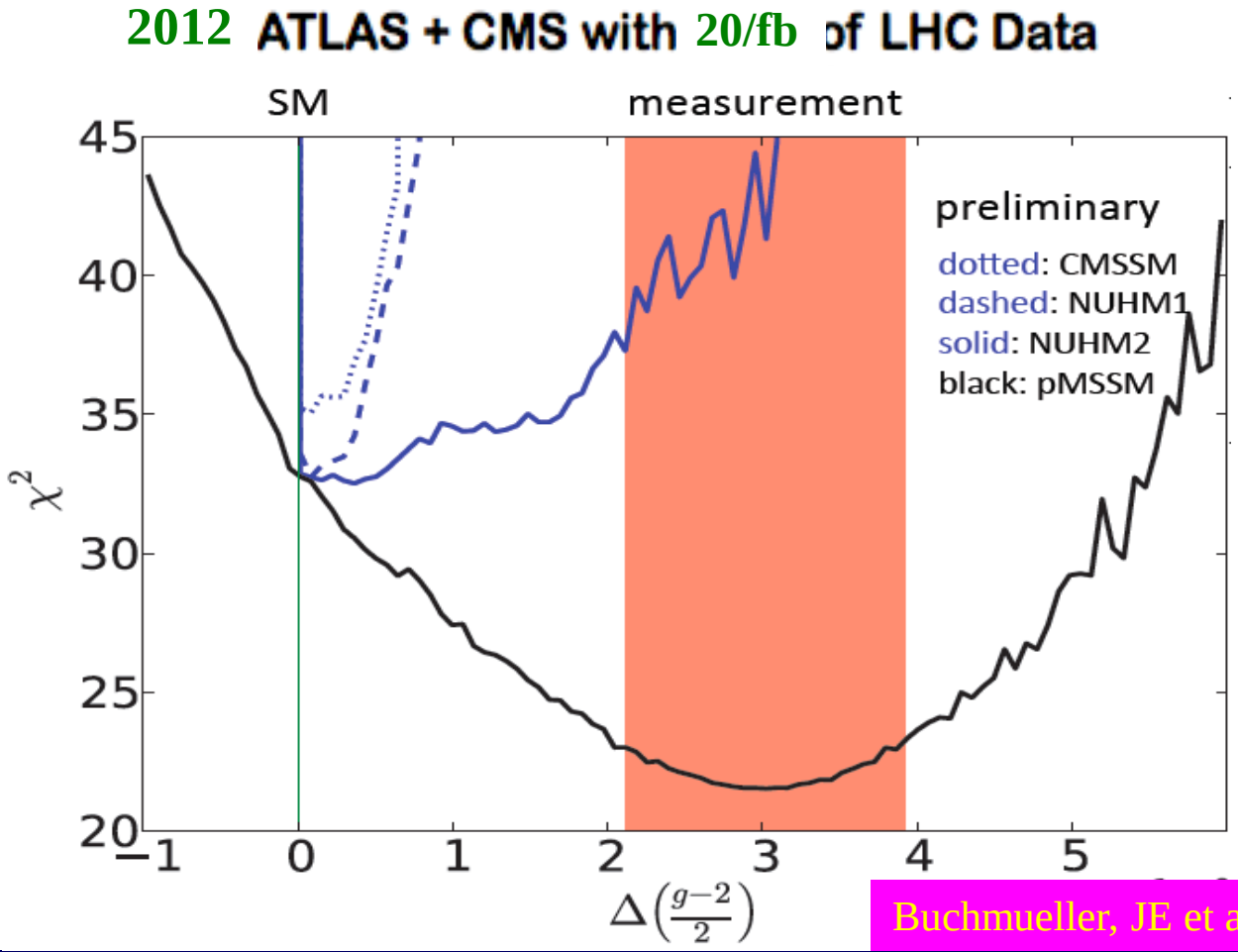




Buchmueller, JE et al: in preparation

Lower masses still allowed in pMSSM

Muon Anomalous Moment in Models



Buchmueller, JE et al: in preparation

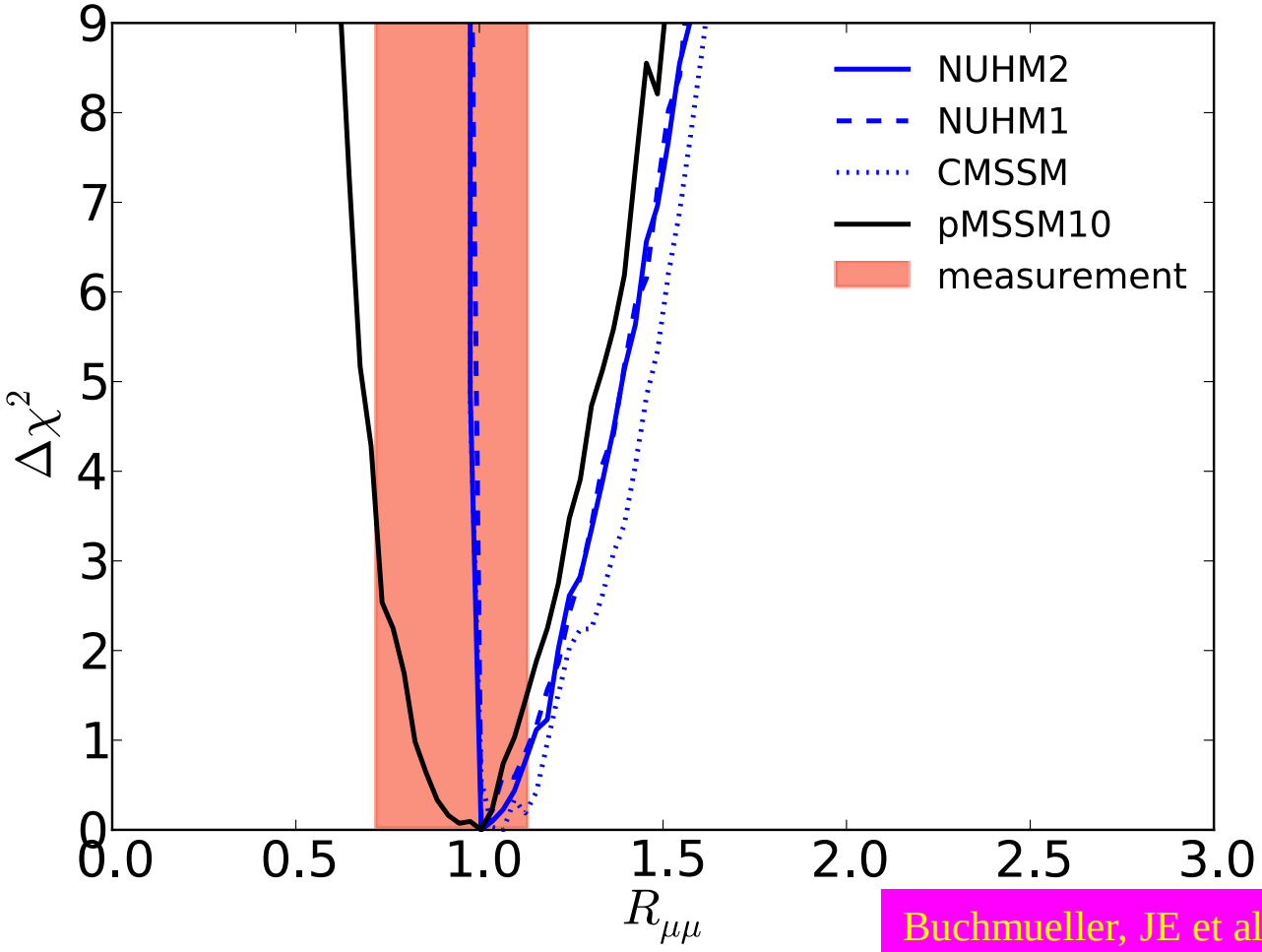
Strong tension in CMSSM and NUHM1

Less significant in NUHM1

Removed in pMSSM

$B_s \rightarrow \mu^+\mu^-$ Decays in Models

2012 ATLAS + CMS with 20/fb of LHC Data

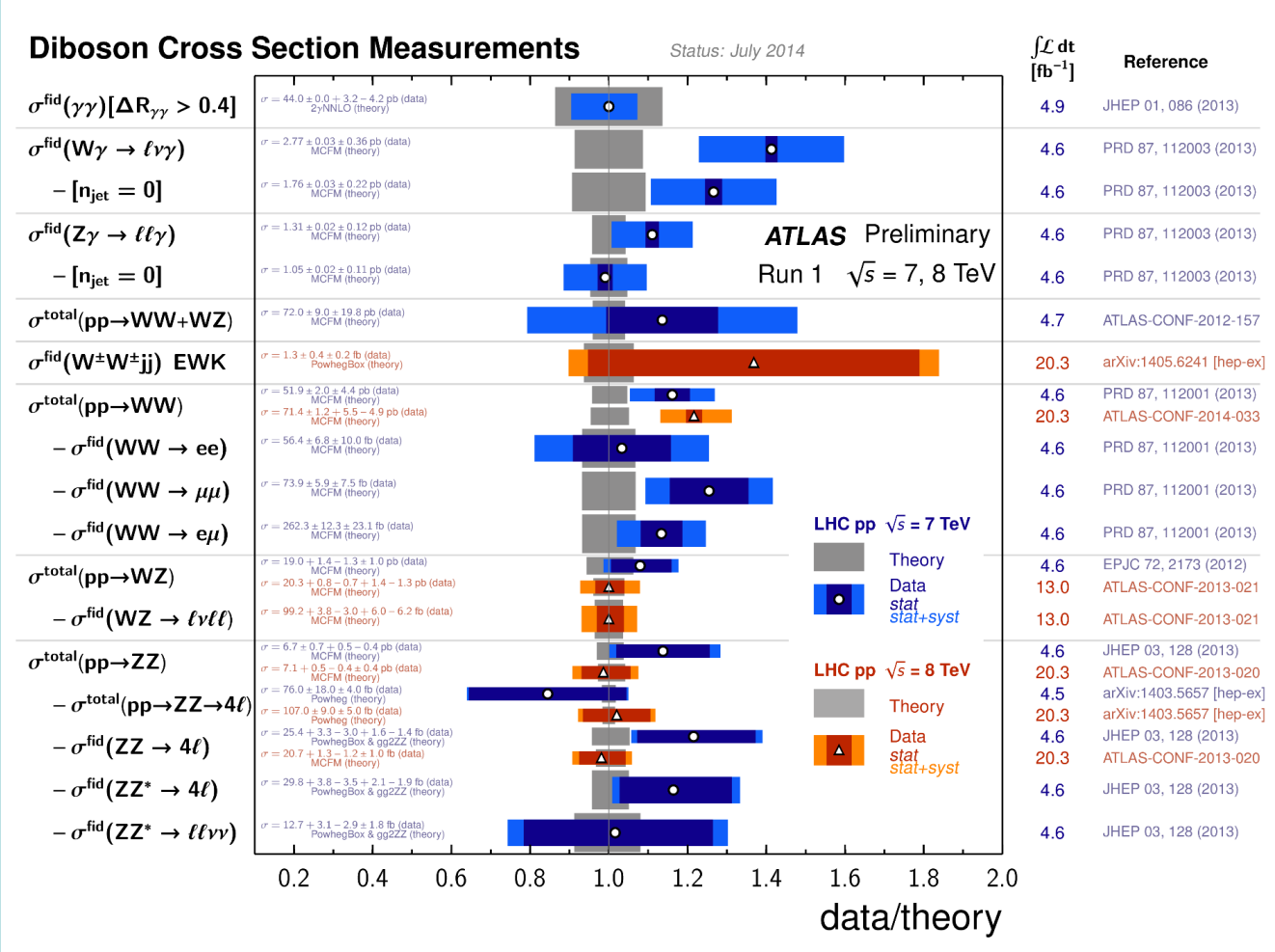


Buchmueller, JE et al: in preparation

Similar to Standard Model in all models

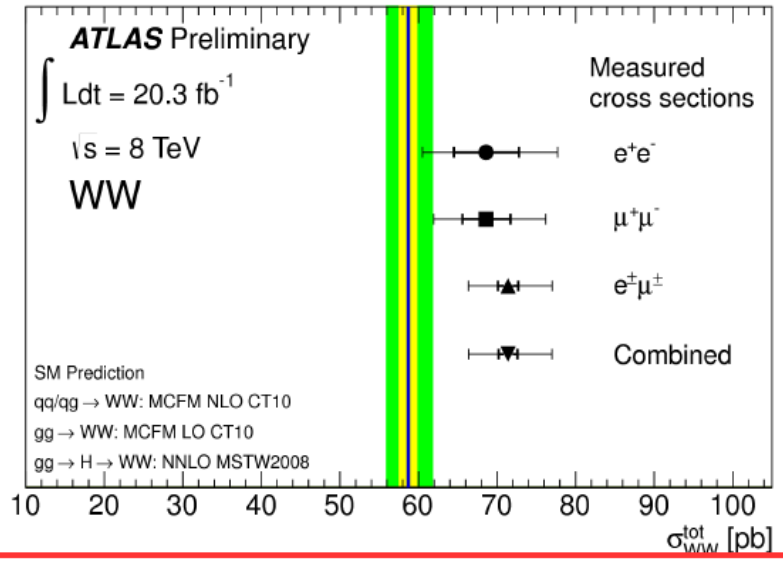
Large pp ➔ W^+W^- Cross-Section?

- No anomalies in other diboson channels



Large pp ➔ W^+W^- Cross-Section?

- σ larger than NLO SM calc's
- NNLO, NNLL, etc., corrections expected to be several %
- Other diboson cross-sections exhibit no anomalies
- Light sparticles?



$$\sigma_{WW}^{tot} = 71.4\ ^{+1.2}_{-1.2}(\text{stat})\ ^{+5.0}_{-4.4}(\text{syst})\ ^{+2.2}_{-2.1}(\text{lumi})\ \text{pb}$$

Standard Model prediction: $58.7^{+1.0}_{-1.1}$ (PDF) $^{+3.1}_{-2.7}$ (total) pb

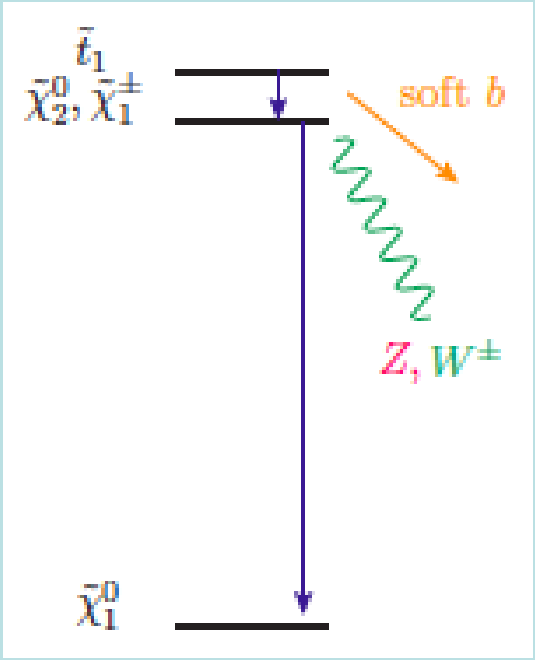
- $q\bar{q} \rightarrow WW$ (NLO → NNLO+NNLL k-factor) + 1.6 pb
- $gg \rightarrow WW$ (LO → NNLO+NNLL k-factor) + 1.4 up to +2.8 pb

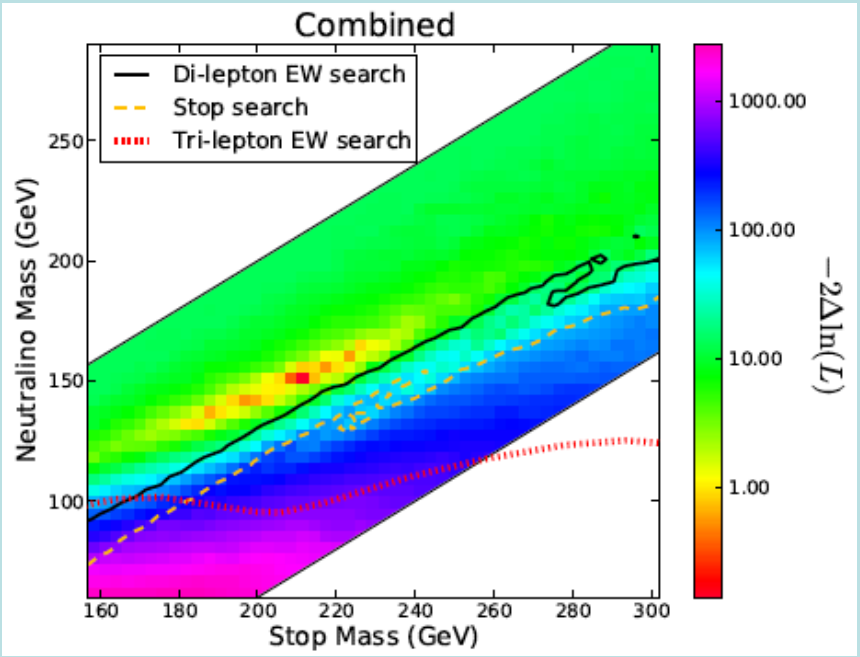
- Electroweak corrections – 0.5 pb
- γγ-induced WW + 0.5 pb
- Vector boson scattering + 0.5 pb
- Double parton interaction + 0.04 pb

Total sum of: + 3.5 to 4.9 pb

‘Natural’ Supersymmetric Explanation?

- Pair-production of light stops
- Cascade decays producing W’s
  - e.g., stop ➔b + ($\chi^{\pm}$ ➔W + χ^{0})





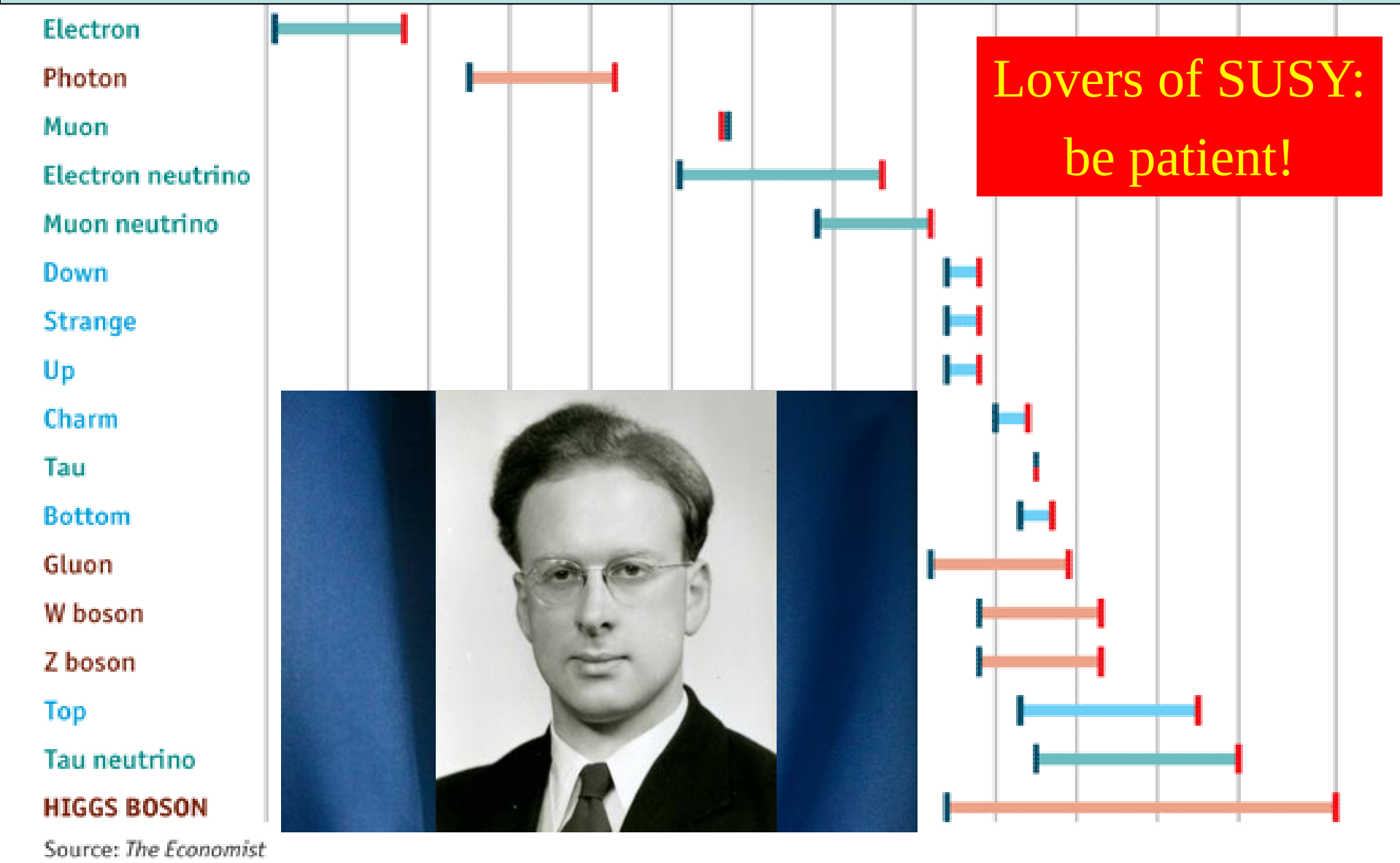
- Consistent with di-, tri-lepton, stop searches

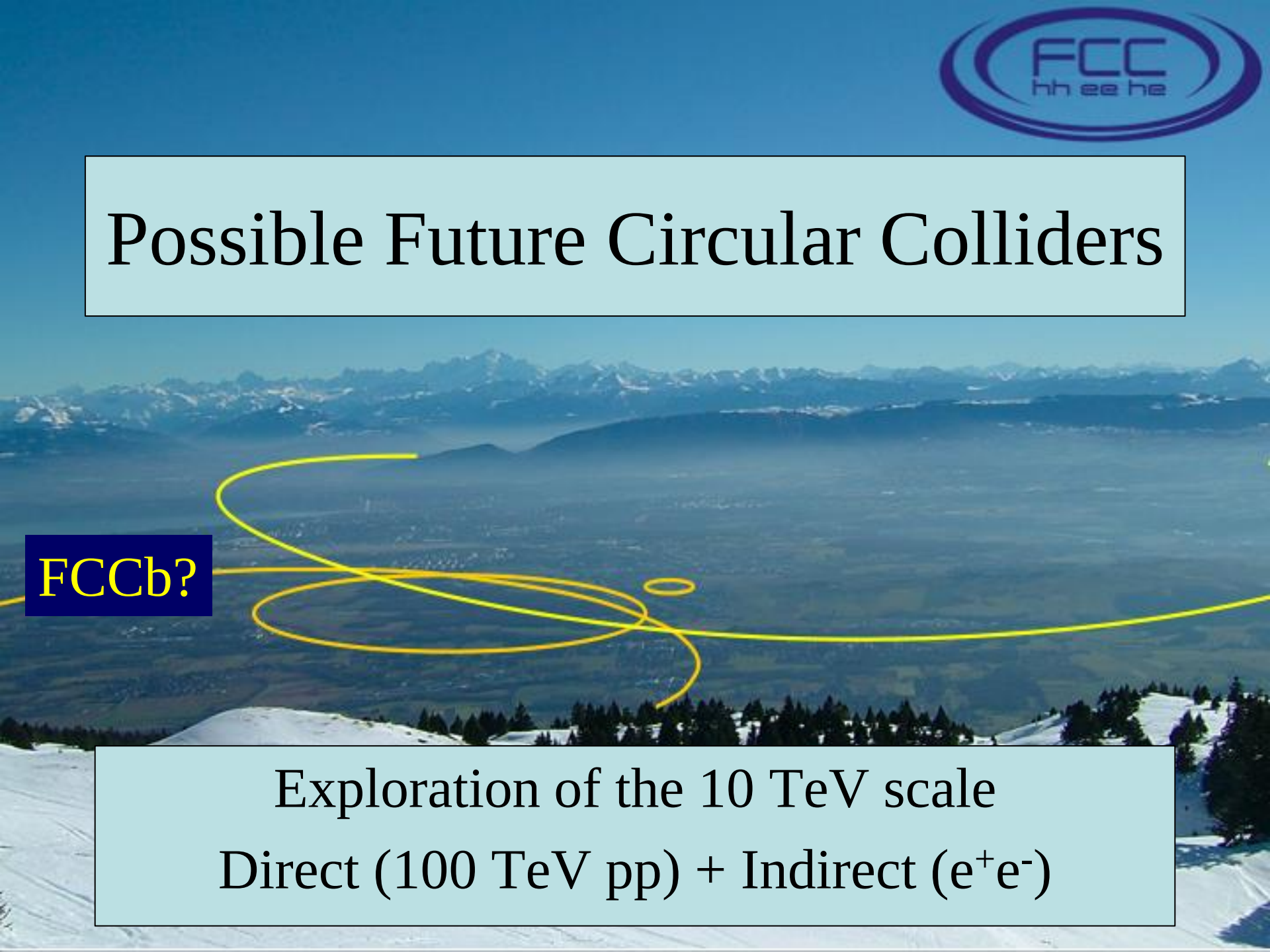
Theoretical Confusion

- High mortality rate among theories
- (M_H, M_t) close to stability bound
- Split SUSY? High-scale SUSY?
- Modify/abandon naturalness? Does Nature care?
- String landscape?
- SUSY anywhere better than nowhere
- SUSY could not explain the hierarchy
- **New ideas needed!**

"In ~~football as in watchmaking~~, talent and elegance mean nothing without rigour and precision."
particle theory
[Lionel Messi]

Standard Model Particles:
Years from Proposal to Discovery





Possible Future Circular Colliders

FCCb?

Exploration of the 10 TeV scale

Direct (100 TeV pp) + Indirect (e^+e^-)