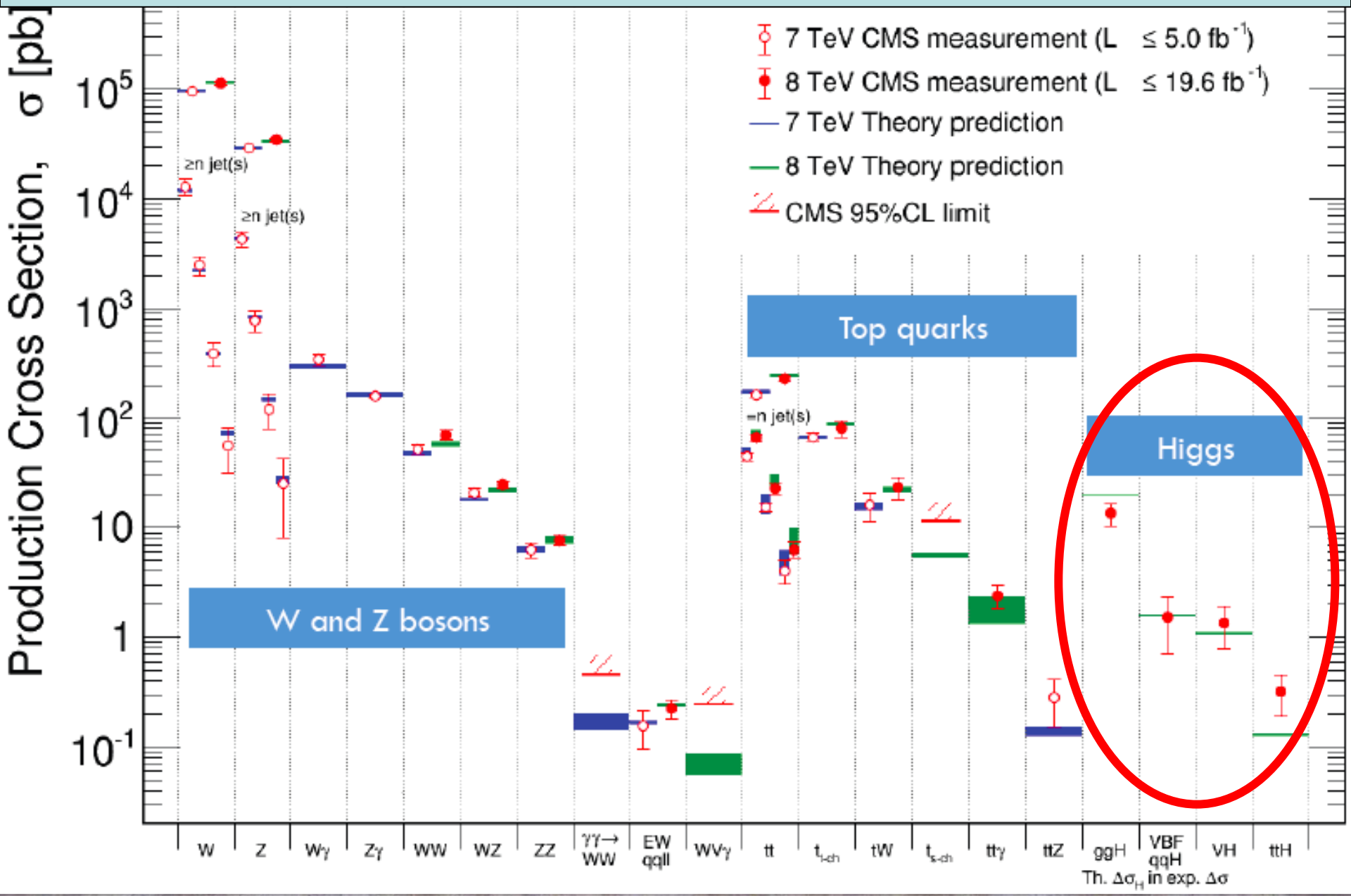
The Higgs Boson & Beyond

What is Higgs telling us?
What else is there?
How do we find it?

John Ellis
King's College London
(& CERN)

Standard Model Cross-Sections @ LHC



Higgs Mass Measurements

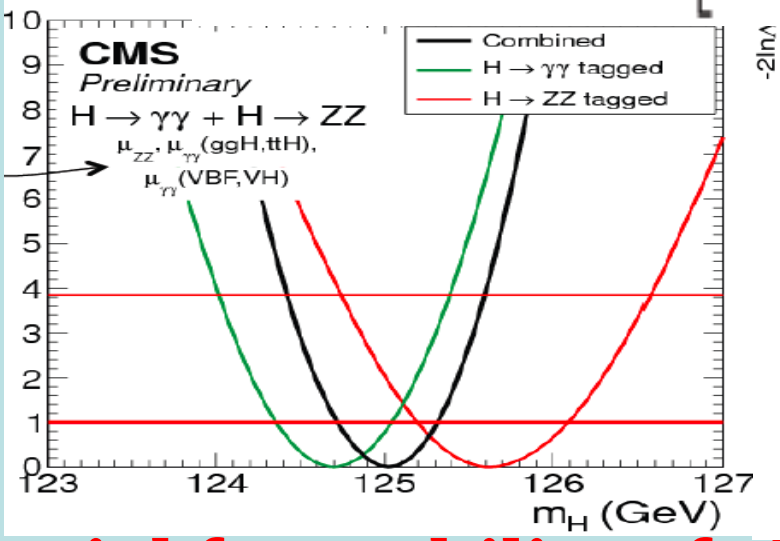
- ATLAS:

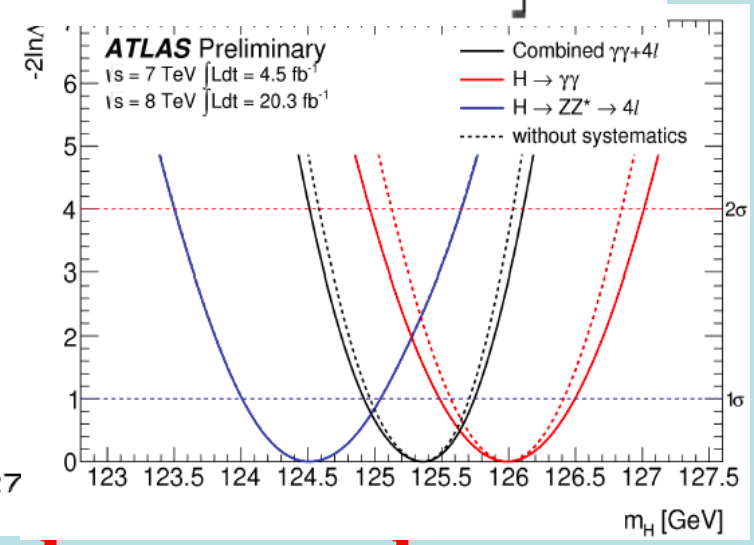
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{sys}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.04\,(\text{sys}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{sys}) = 125.36 \pm 0.41$

- 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 $\gamma\gamma$

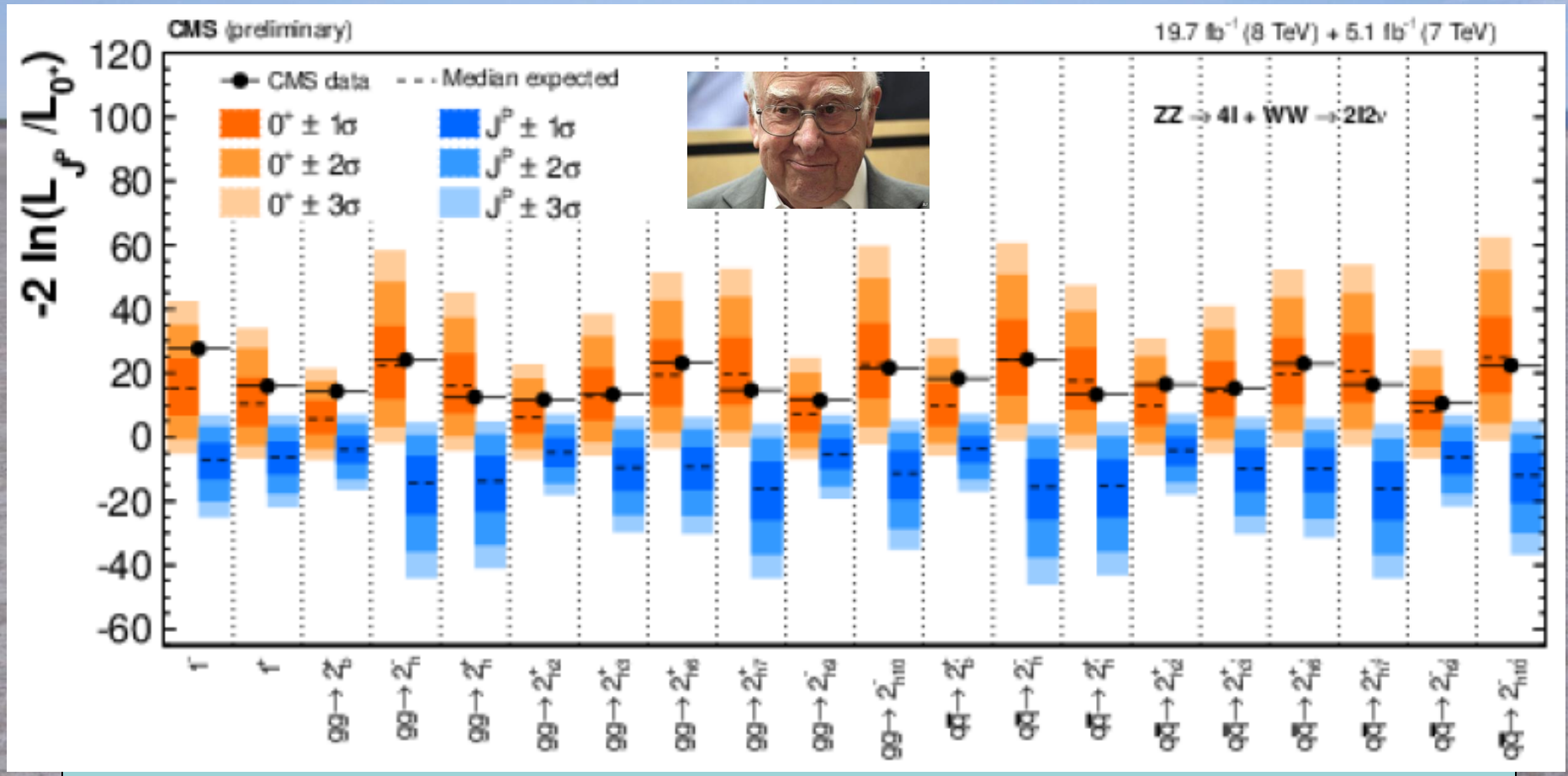
Combined: $$m_H = 125.03 \pm 0.30\ \left[^{+0.26}_{-0.27}(\text{stat.})^{+0.13}_{-0.15}(\text{syst.})\right]\ \text{GeV}$$





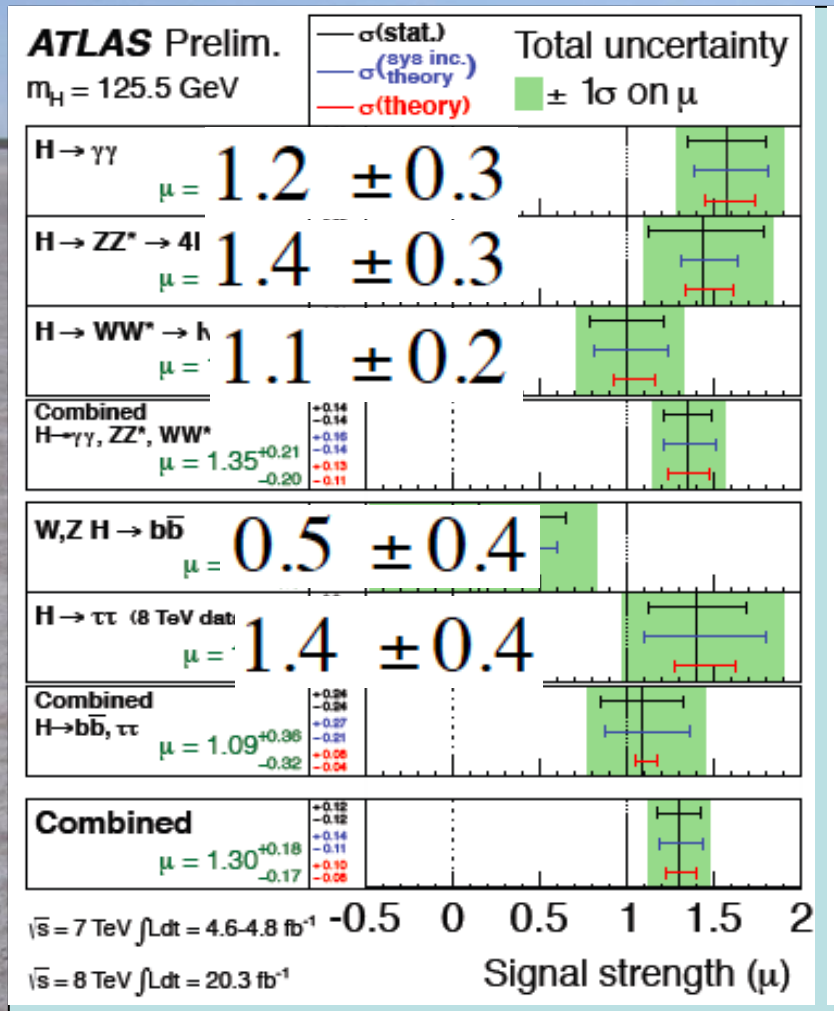
- **Crucial for stability of electroweak vacuum**

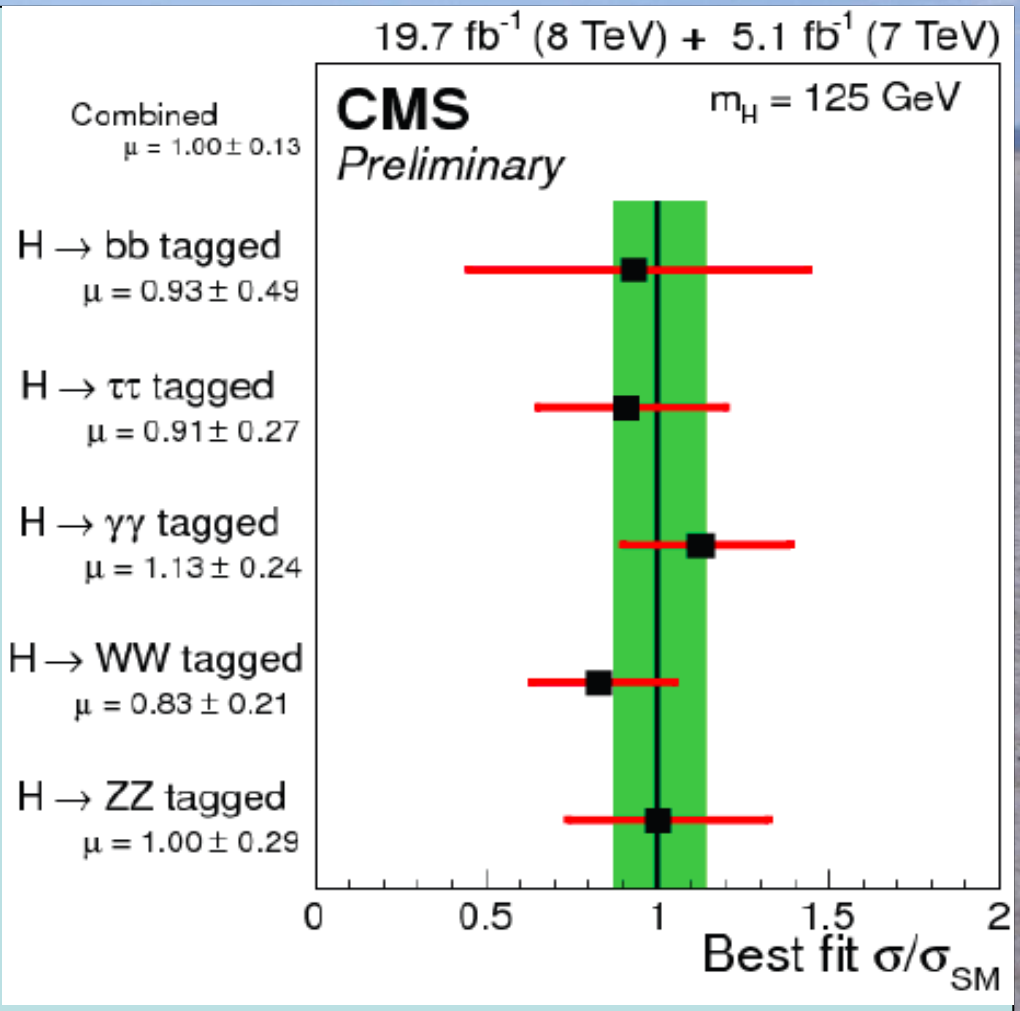
The ‘Higgs’ has Spin 0



- Alternative spin-parity hypotheses disfavoured

Higgs Signal Strengths





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

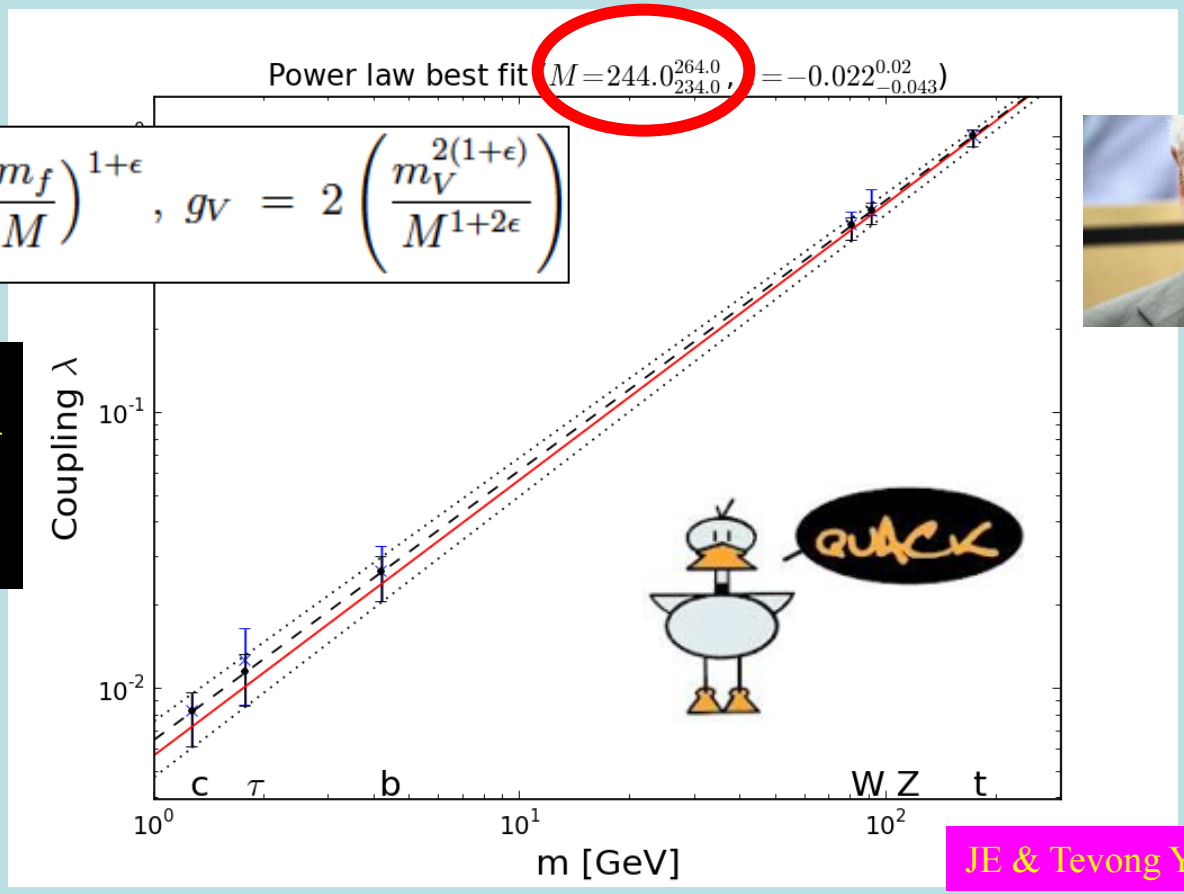
$\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$

It Walks and Quacks like a Higgs

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

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

Global fit

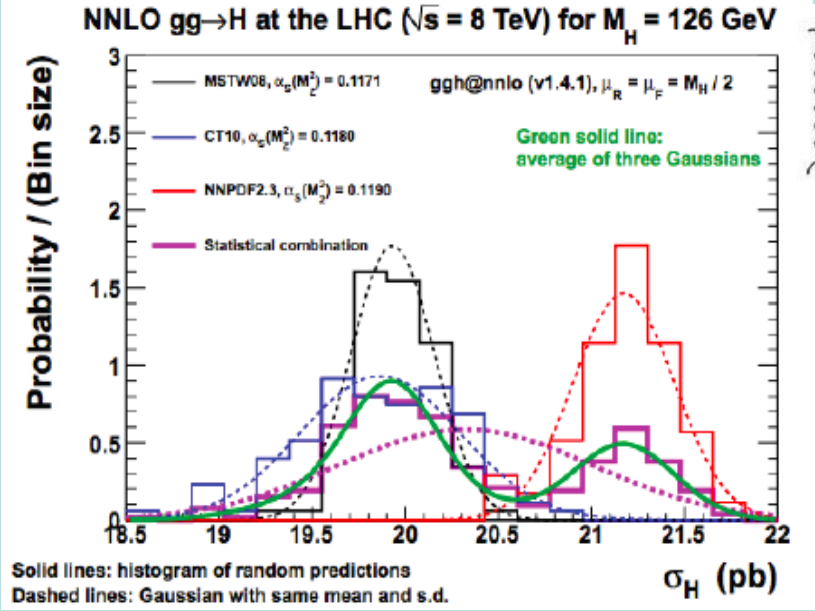


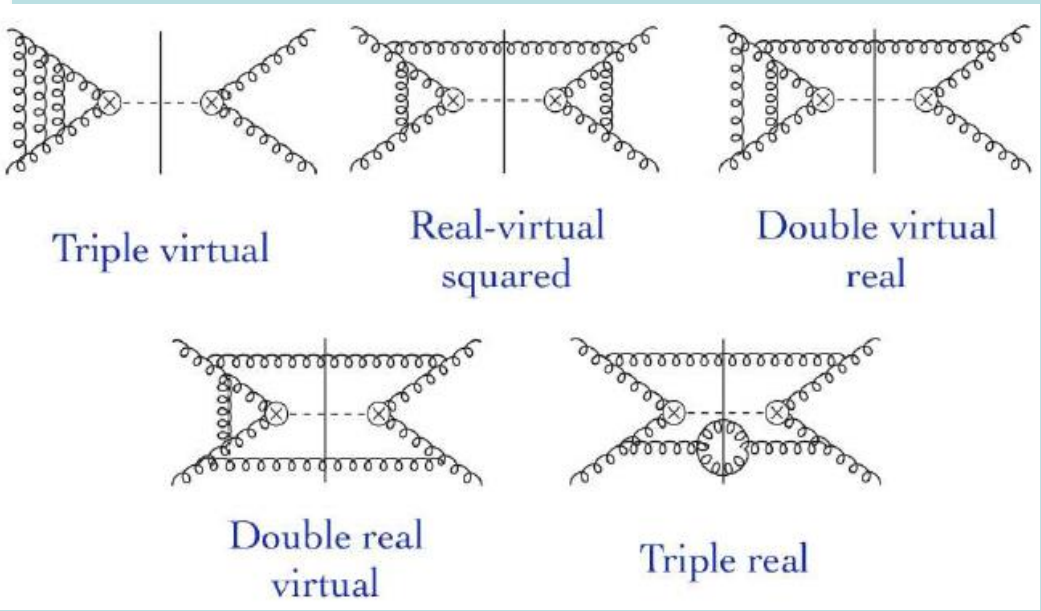
JE & Tevong You, arXiv:1303.3879

- **Red line = SM**, dashed line = best fit

QCD Uncertainties in Higgs Production

- Many perturbative QCD calculations to NNLO
- Issues in parton distributions
- E.g., gg to H: agreement unsatisfactory

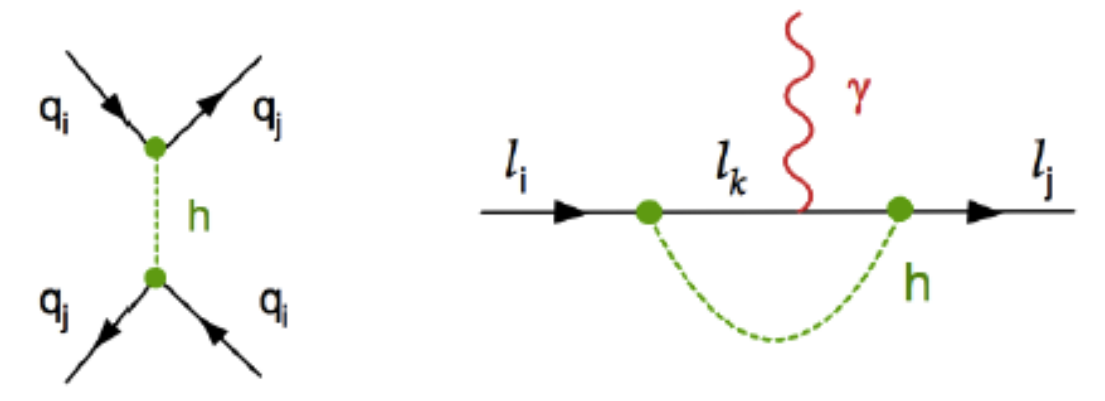




- Progress towards NNNLO calculation

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

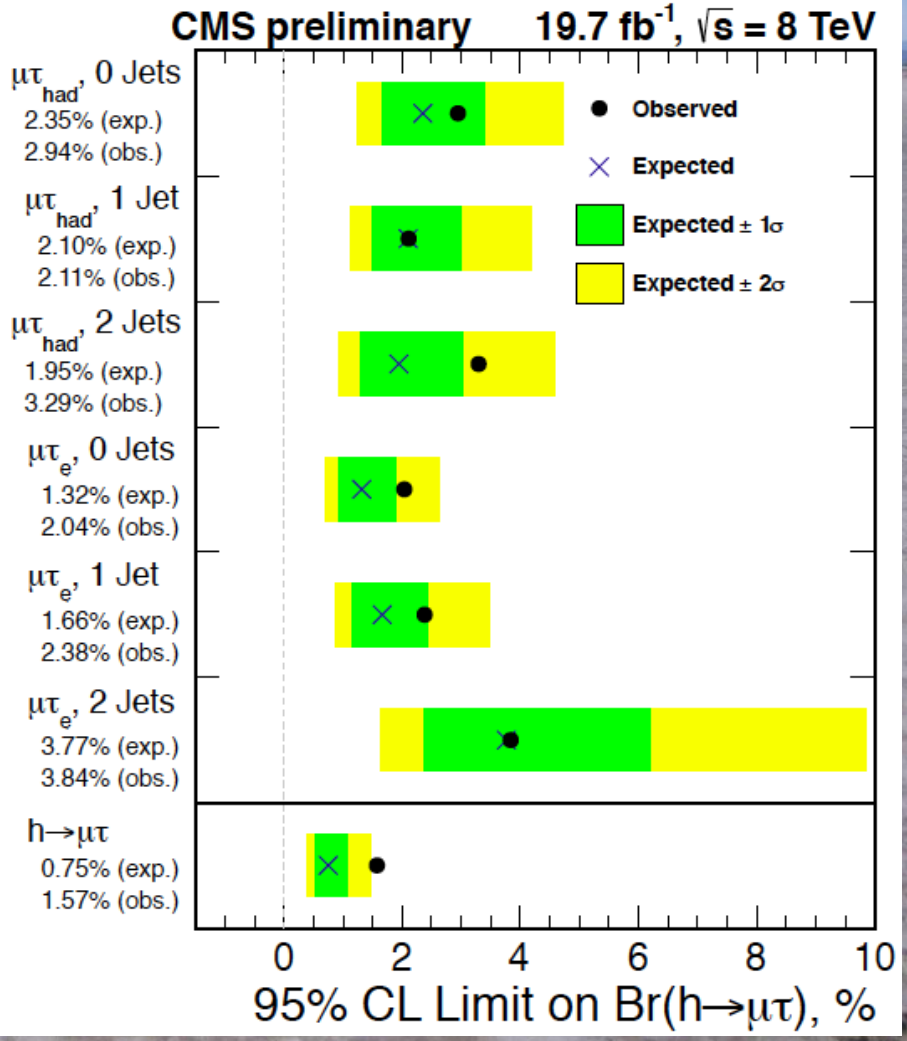
BR(μe) must be $< 2 \times 10^{-5}$

Flavour-Changing Higgs Couplings?

Limits on H→μτ branching ratio

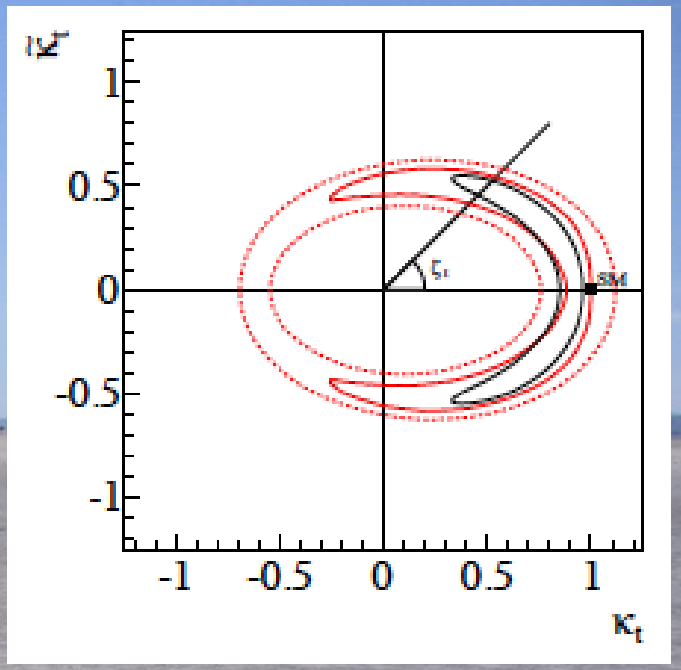
- Comparable sensitivity from all channels
- Observed limit 1.57% (exp. 0.75%)
- **Large improvement of previous limits**
- **Background-only p-value of 0.007 (2.46σ)**
  - Best-fit

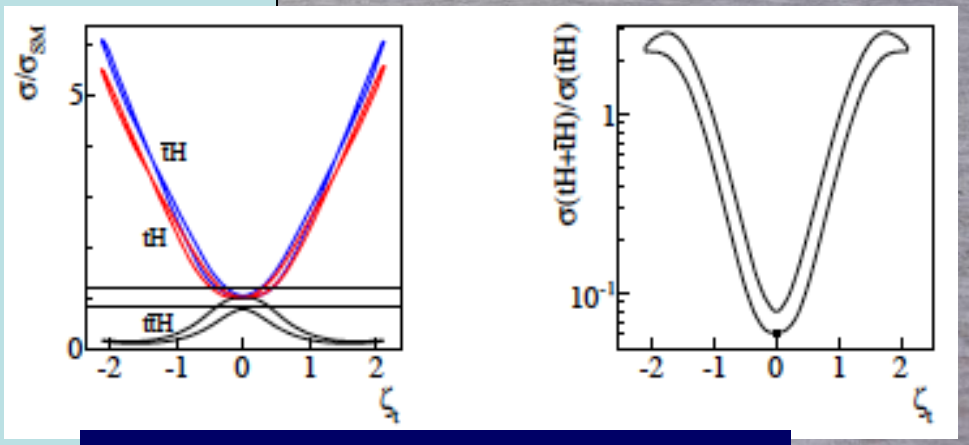
$$B(H\to\mu\tau) = 0.89^{+0.40}_{-0.37}\%$$

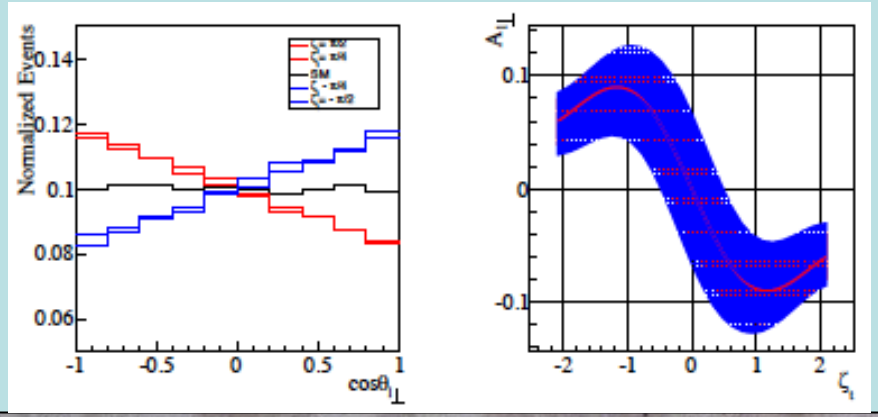


Probing CP Violation in H-t couplings

- ggH, Hγγ couplings 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?

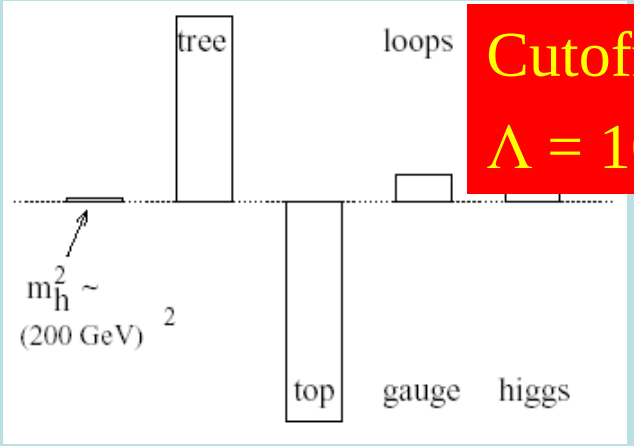
JE, Hwang, Sakurai, Takeuchi: arXiv:1312.5736

Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



Cutoff

Λ = 10 TeV

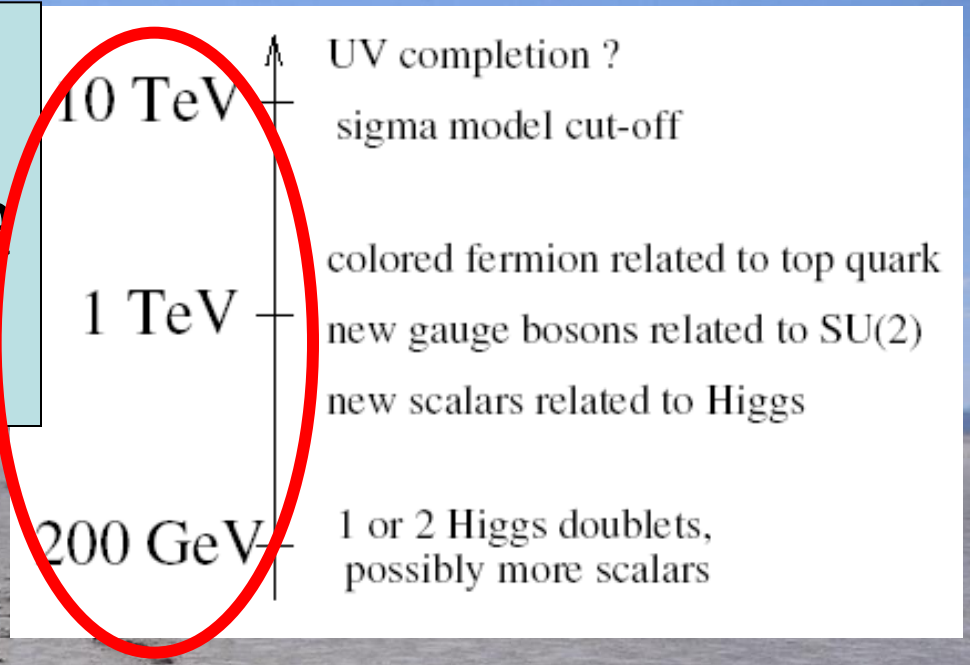
Cut-off Λ ~ 1 TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

New technicolour force?

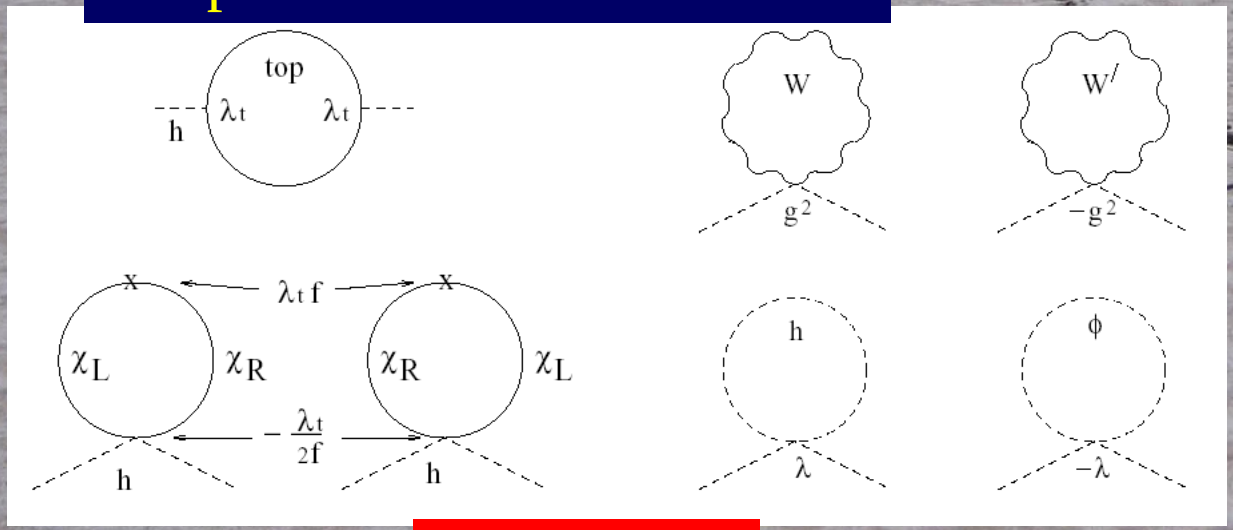
- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

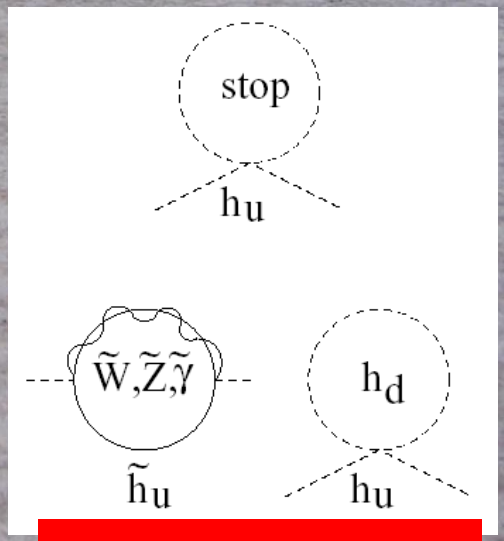
Higgs as a Pseudo-Goldstone Boson



'Little Higgs' models
(breakdown of larger symmetry)

Loop cancellation mechanism





Little Higgs

Supersymmetry

Phenomenological Framework

- Assume custodial symmetry:

$$SU(2) \times SU(2) \to SU(2)_V \qquad (\rho \equiv M_W/M_Z \cos\theta_w \sim 1)$$

- Parameterize gauge bosons by 2 × 2 matrix Σ:

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+\ldots\right) - m_i\bar{\psi}^i_L\Sigma\left(1+c\frac{h}{v}+\ldots\right)\psi^i_R + \mathrm{h.c.}$$
$$+\frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,$$

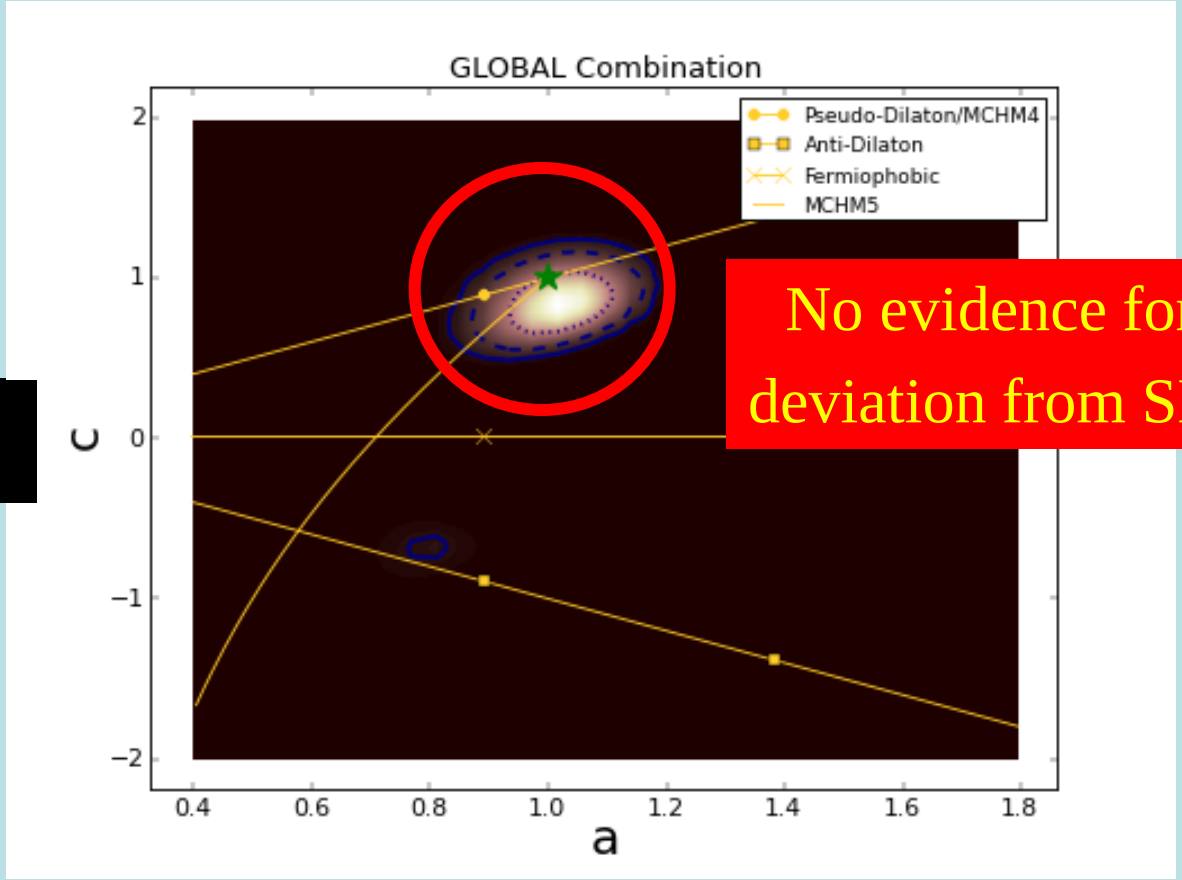
$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \qquad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

- Coefficients ***a = c = 1*** in Standard Model

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

Why is there Nothing rather than Something?

- Higher-dimensional operators as relics of higher-energy physics: $\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\,\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
& + \frac{2ig\,\bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\,\bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
& + \frac{ig\,\bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\,\bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
& + \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R
\end{aligned}
$$

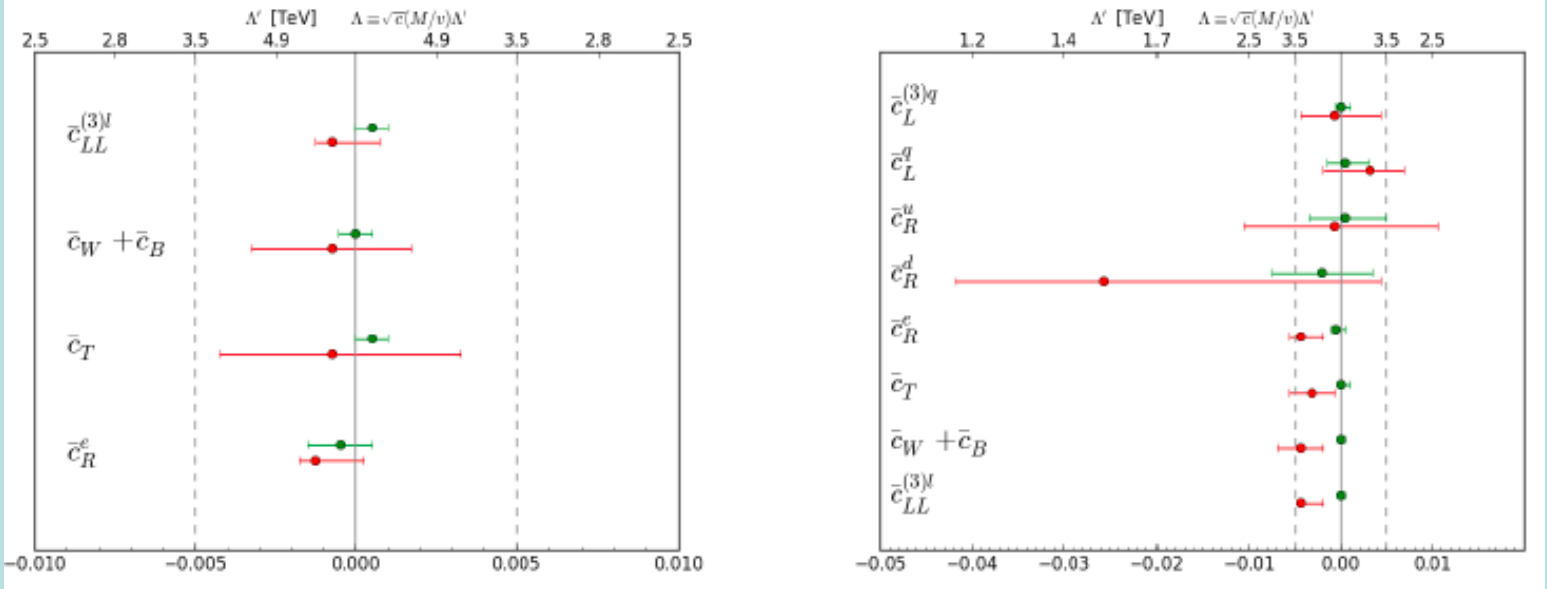
- Constrain with precision EW, Higgs data, TGCs ...

Electroweak Precision Data

- Operators affecting electroweak tests

$$\mathcal{L}_{\text{dim-6}} \subset \frac{\bar{c}_{WB}}{m_W^2}\mathcal{O}_{WB} + \frac{\bar{c}_W}{m_W^2}\mathcal{O}_W + \frac{\bar{c}_B}{m_W^2}\mathcal{O}_B + \frac{\bar{c}_T}{v^2}\mathcal{O}_T + \frac{\bar{c}_{2W}}{m_W^2}\mathcal{O}_{2W} + \frac{\bar{c}_{2B}}{m_W^2}\mathcal{O}_{2B}$$

- Contribute to oblique parameters, other tests
- Constraints from LEP et al. data



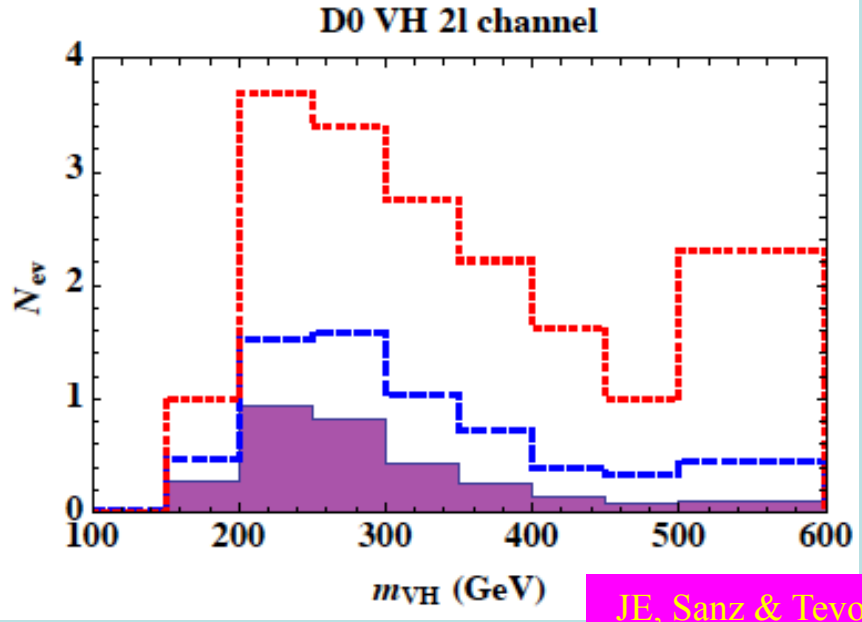
JE, Sanz & Tevong You, arXiv:1410.7703

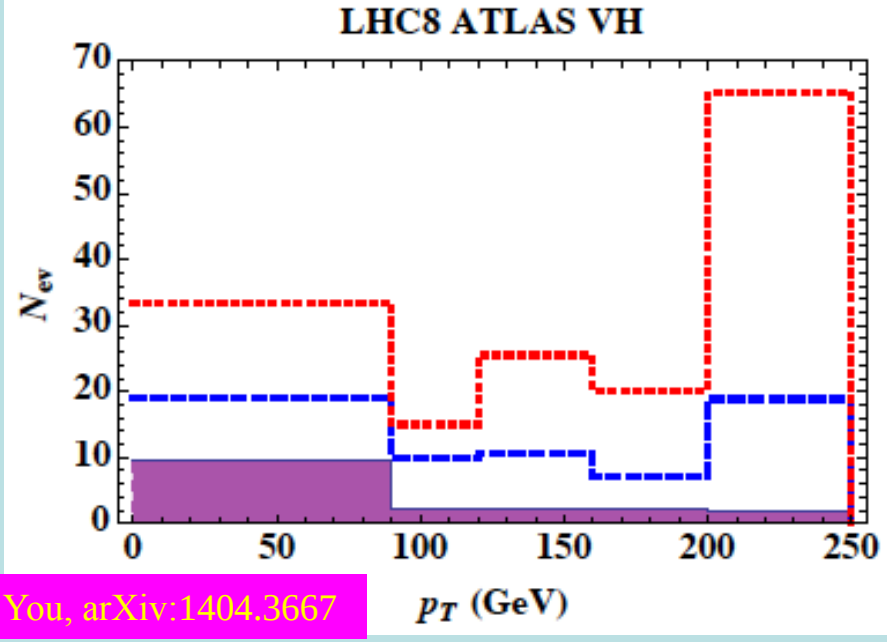
Information from Associated V+H Production

- Operators affecting Higgs physics

$$\bar{c}_i \equiv \left\{\bar{c}_H, \bar{c}_{t,b,\tau}, \bar{c}_W, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g\right\}$$

- Affect signal strengths μ, distributions in m_{VH}, p_T
- Sensitivity in Tevatron, LHC data

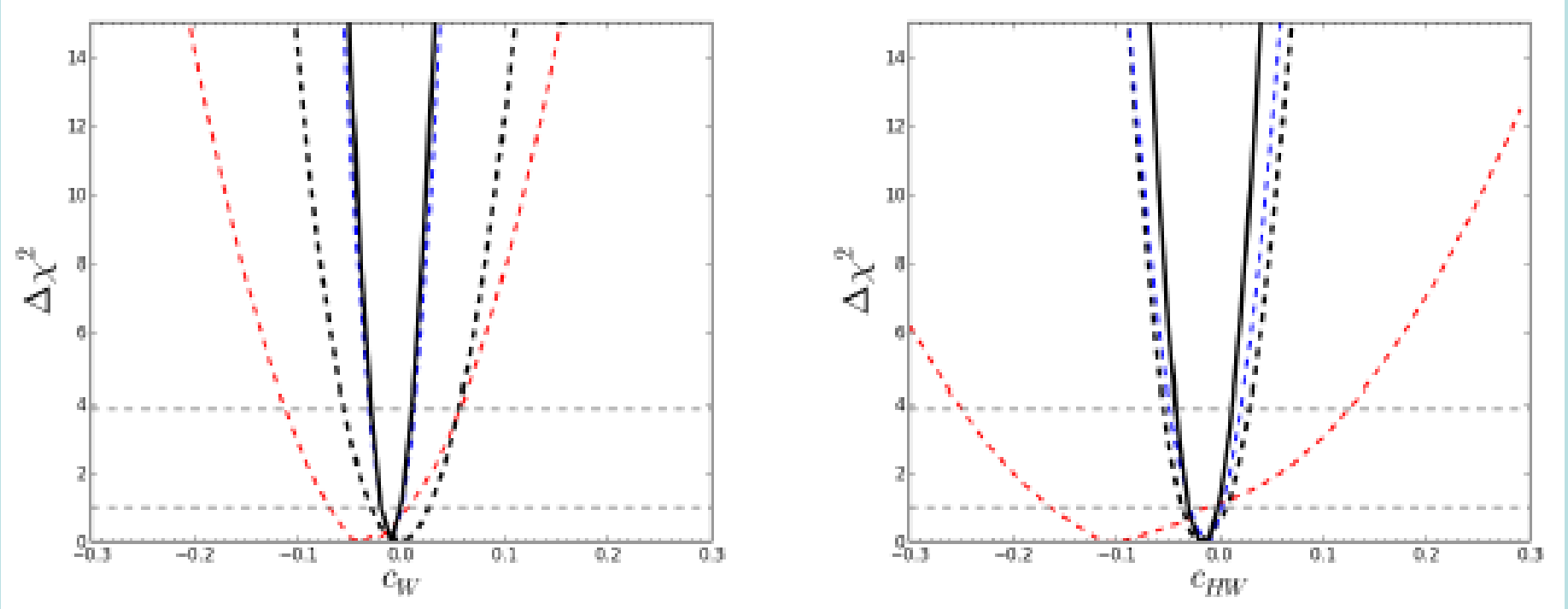




JE, Sanz & Tevong You, arXiv:1404.3667

Information from Associated V+H Production

- Impacts on determinations of coefficients

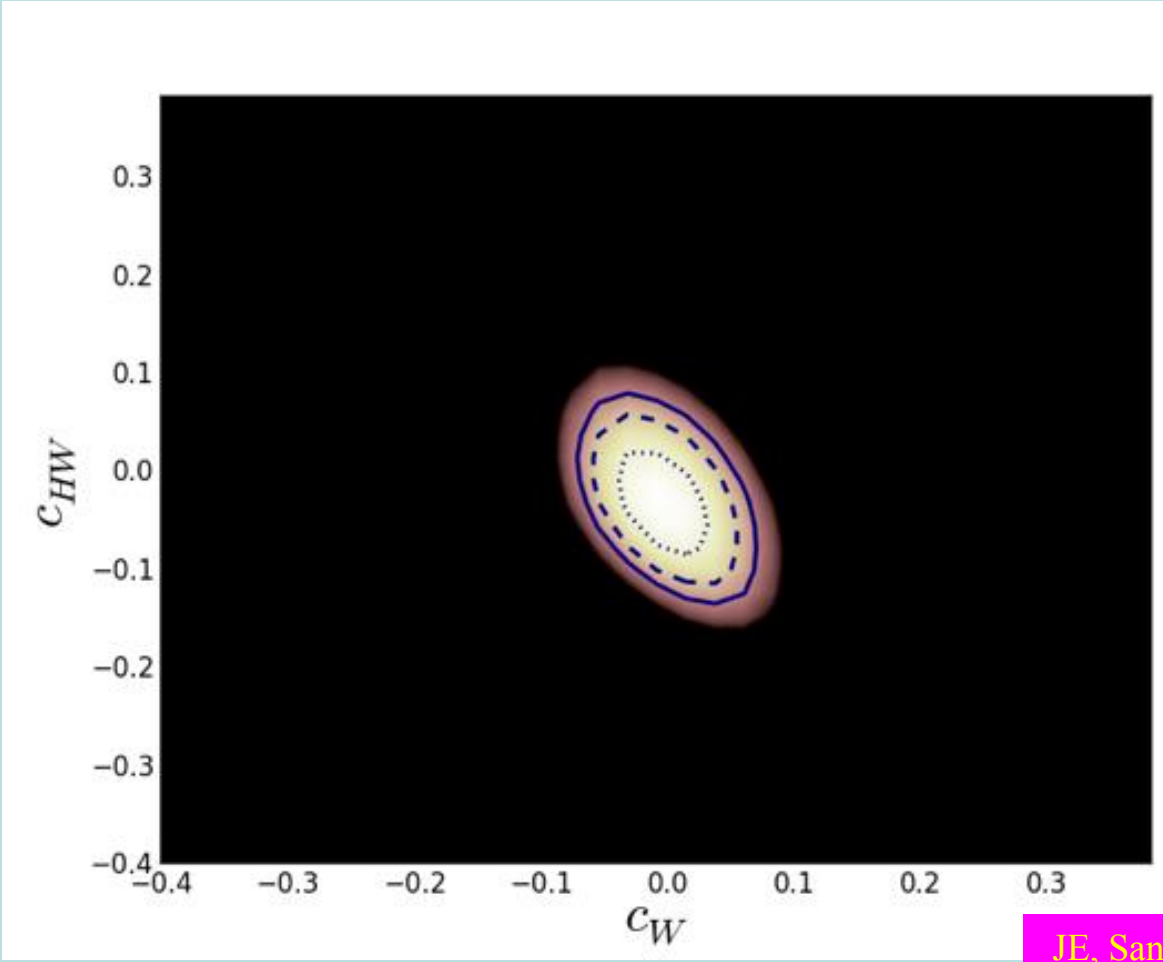


- **Dashed = D0, dashed = ATLAS, dashed = rates**
- **Solid = kinematics included**

JE, Sanz & Tevong You, arXiv:1404.3667

Information from Associated V+H Production

- Impacts on determinations of coefficients



Kinematics + strengths

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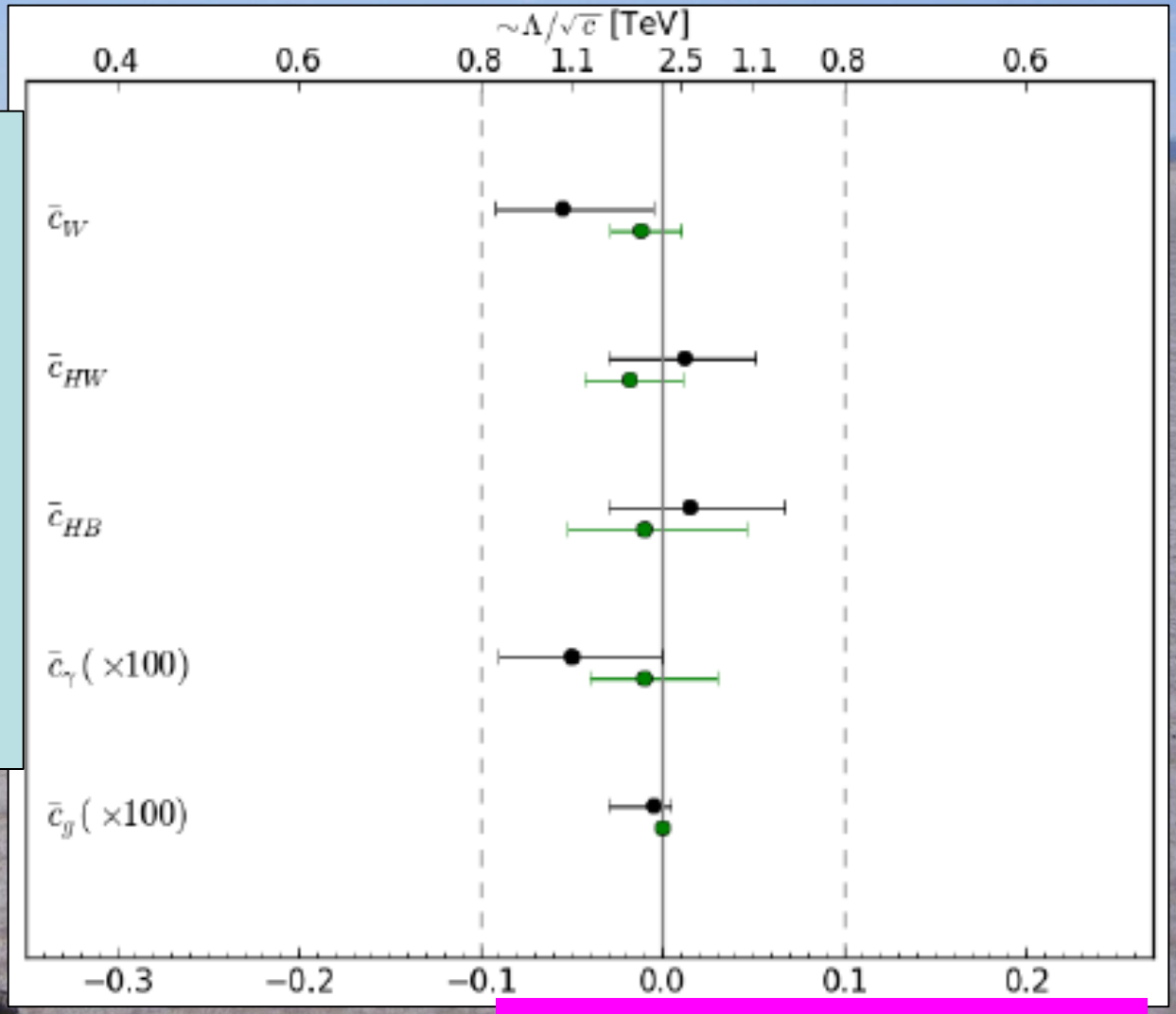
JE, Sanz & Tevong You, arXiv:1404.3667

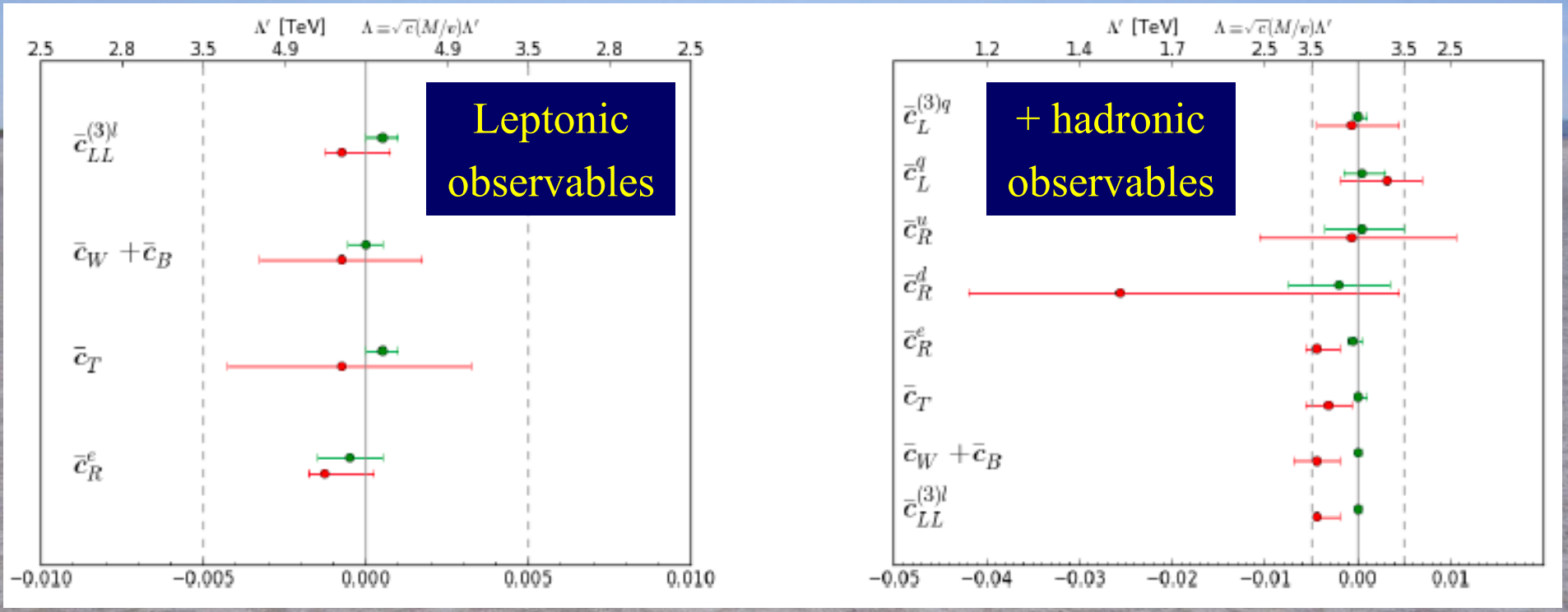
Fits including Associated Production

- Using signal strengths & VH kinematics in global fit
- **Single-parameter fits**



JE, Sanz & Tevong You, arXiv:1404.3667

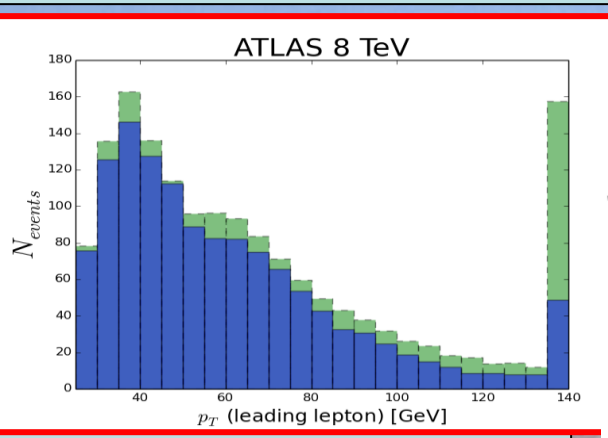
Constraints from Electroweak Precision Data



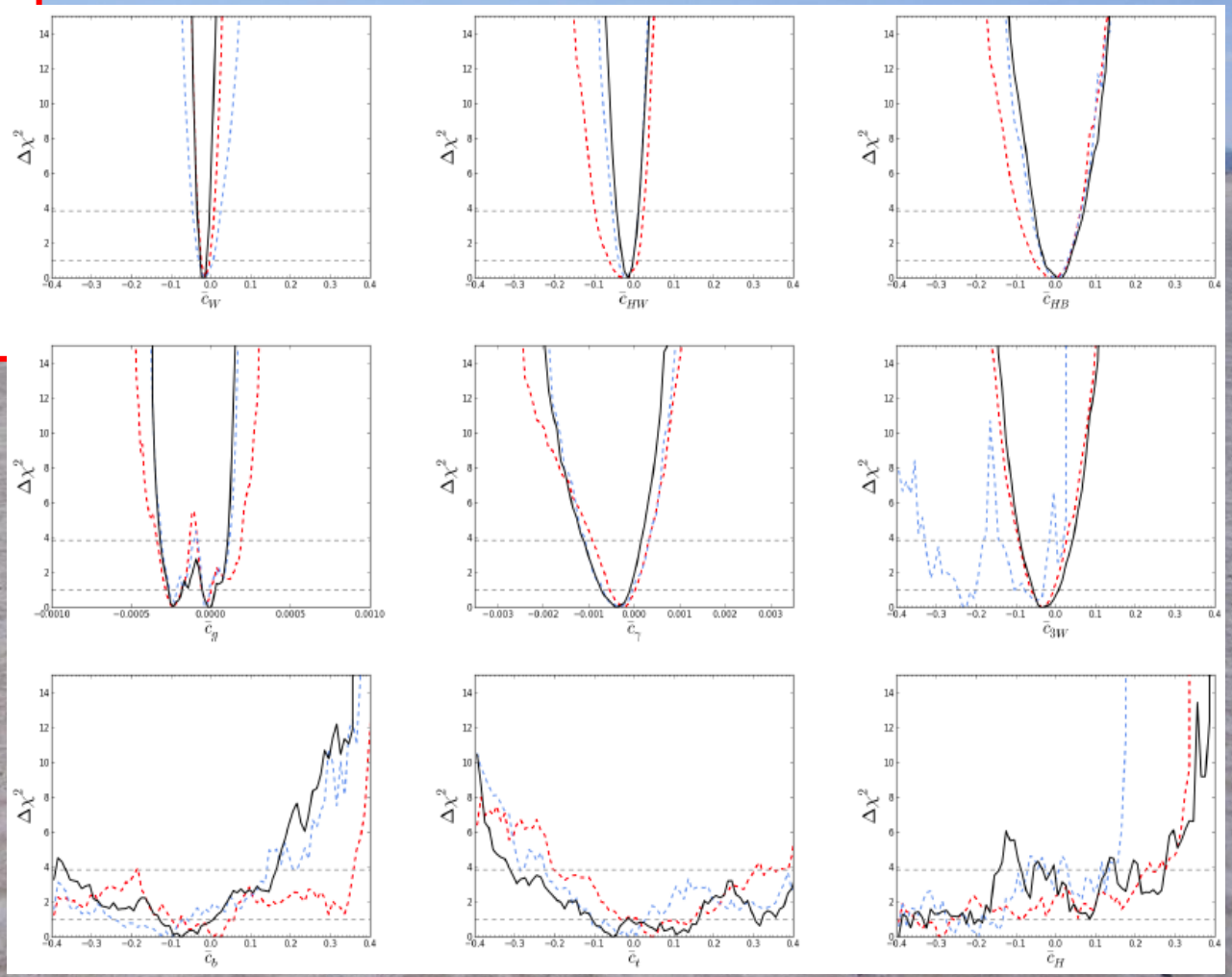
- **Fits to individual dimension-6 operators**
- **Global fit to dimension-6 operators**

JE, Sanz & Tevong You, arXiv:1410.7703
See also Falkowski & Riva, arXiv:1411.0669

Including LHC Triple-Gauge Couplings



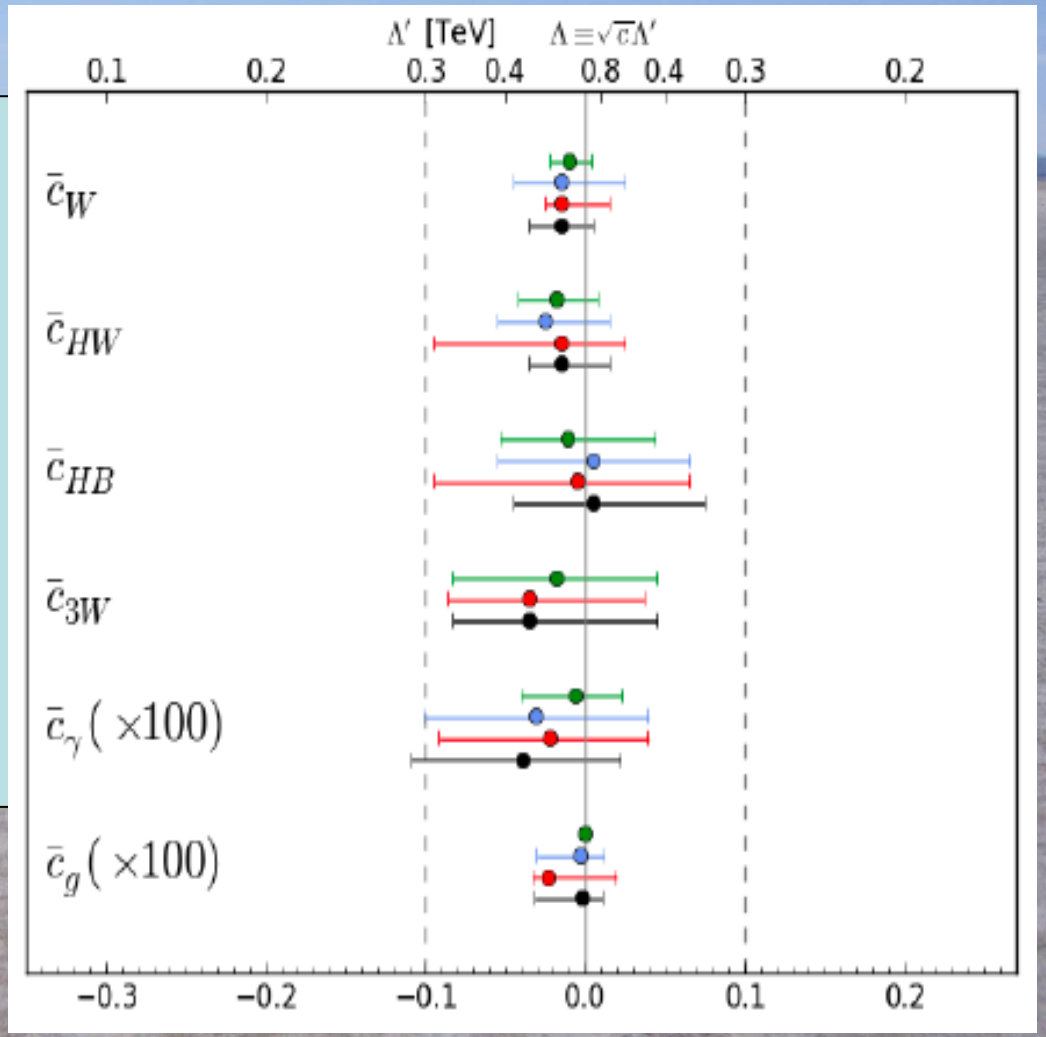
- **Associated production**
- **LHC Triple-gauge couplings**
- Global combination



JE, Sanz & Tevong You, arXiv:1410.7703

Including LHC Triple-Gauge Couplings

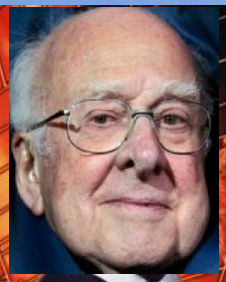
- **Associated production**
- **LHC Triple-gauge couplings**
- Global combination
- **Individual operators**



JE, Sanz & Tevong You, arXiv:1410.7703

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
- …

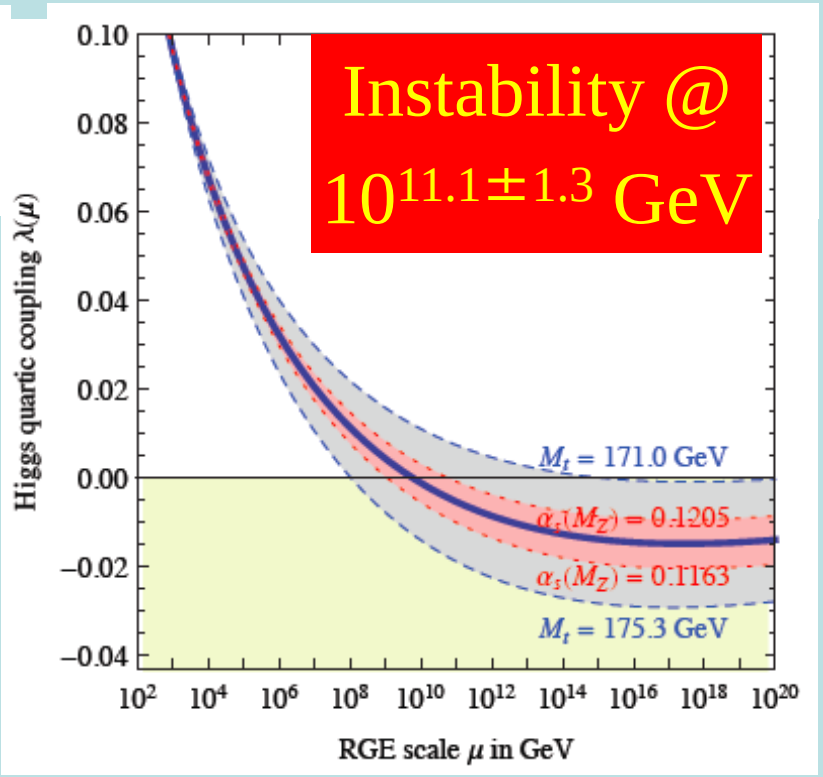
The Standard Model

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

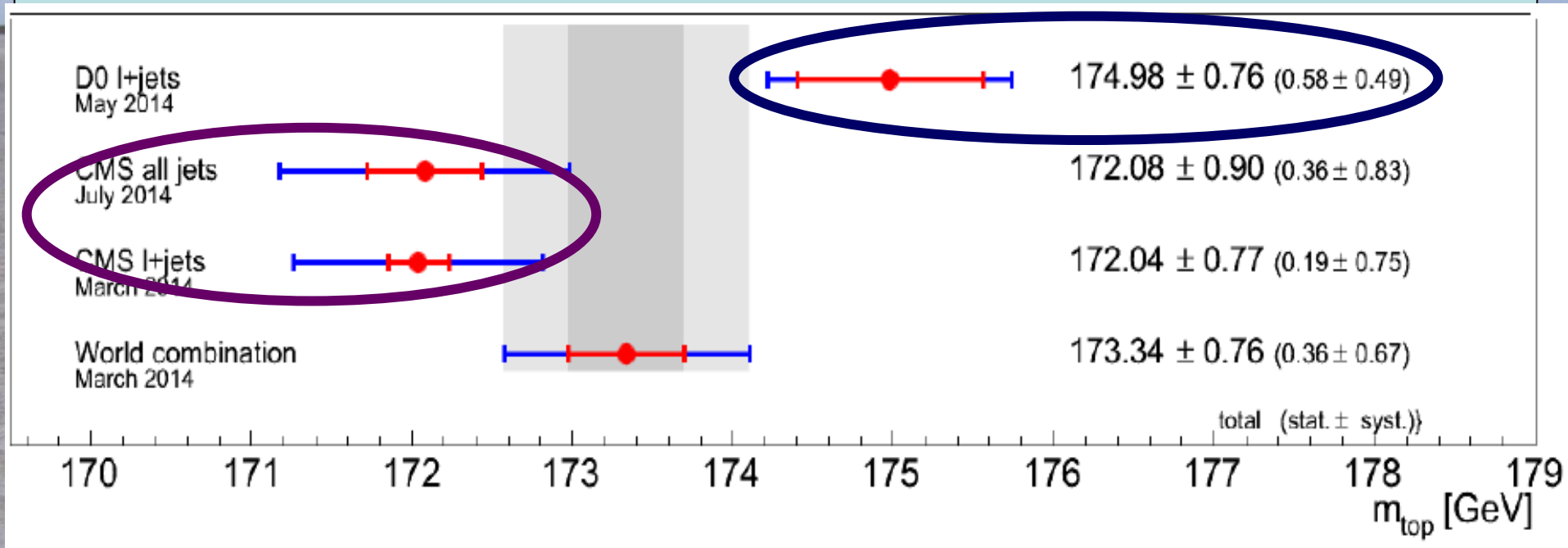


- Vacuum could be stabilized by **Supersymmetry**

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

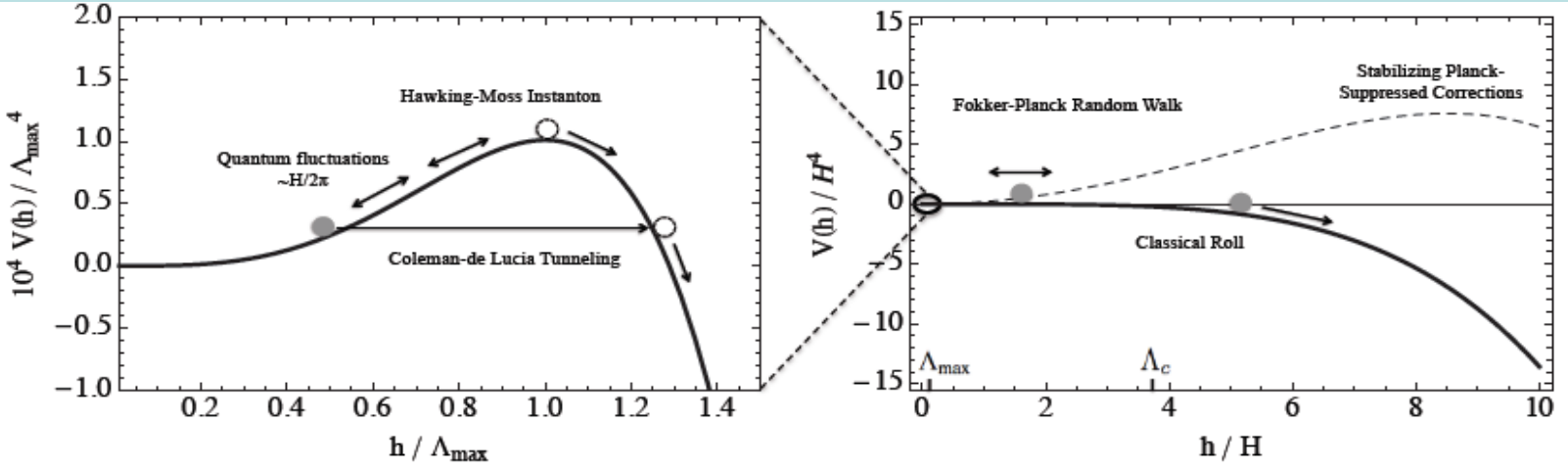
$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

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

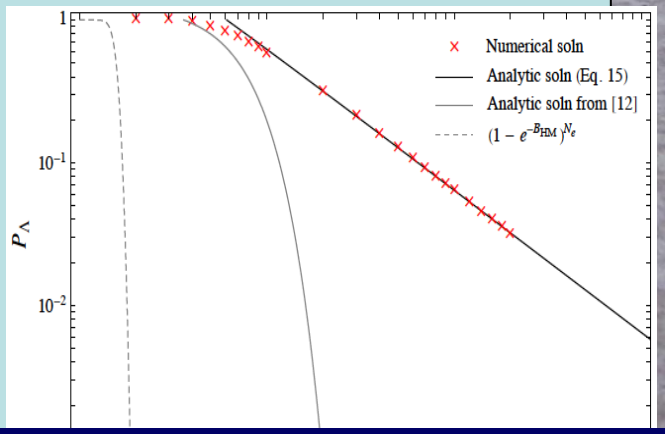
Instability during Inflation?

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



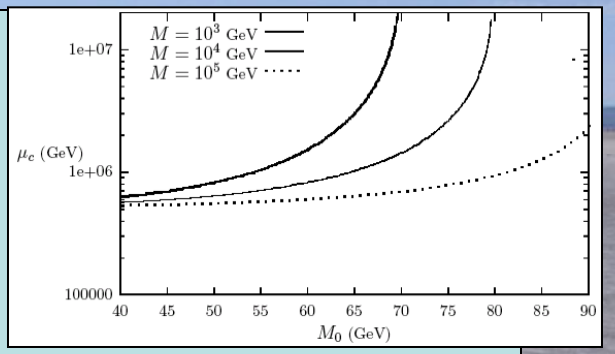
OK if dim-6 operator? Non-minimal gravity coupling?

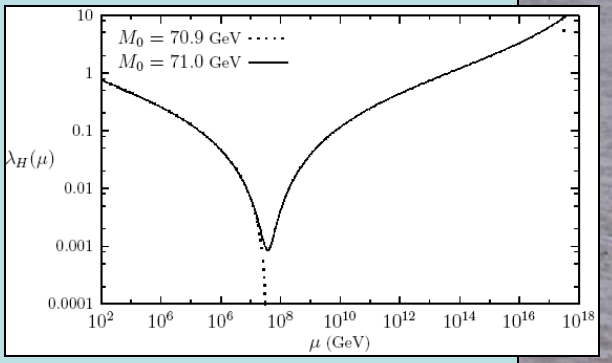
How to Stabilize a Light Higgs Boson?

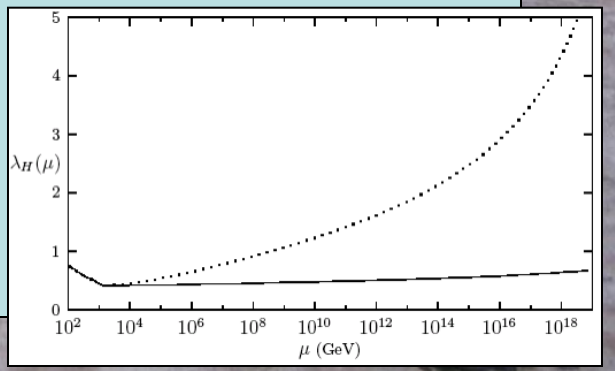
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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!**

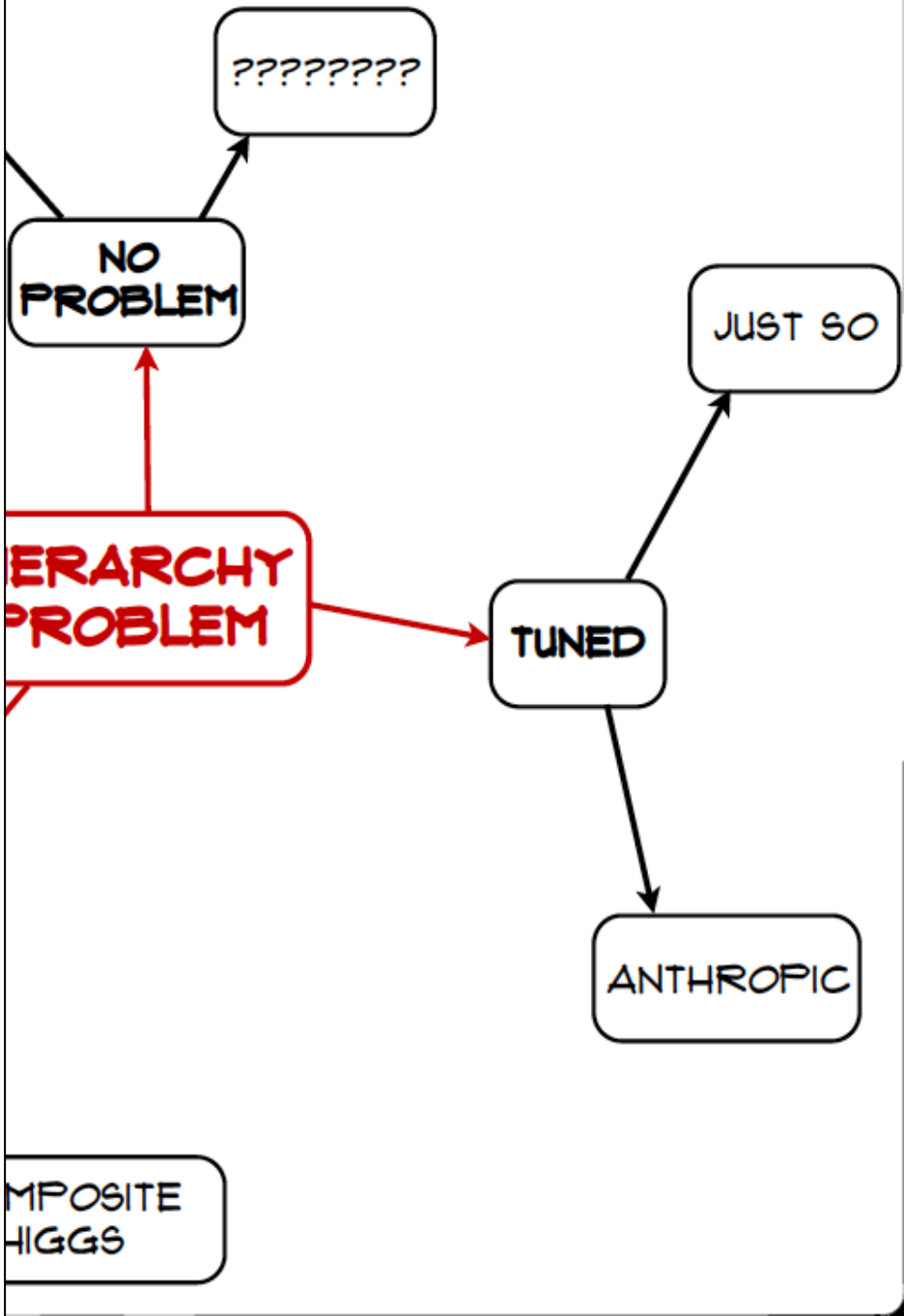






JE + D. Ross

"WELL, IF YOU KNOWS OF A BETTER 'OLE, GO TO IT!"

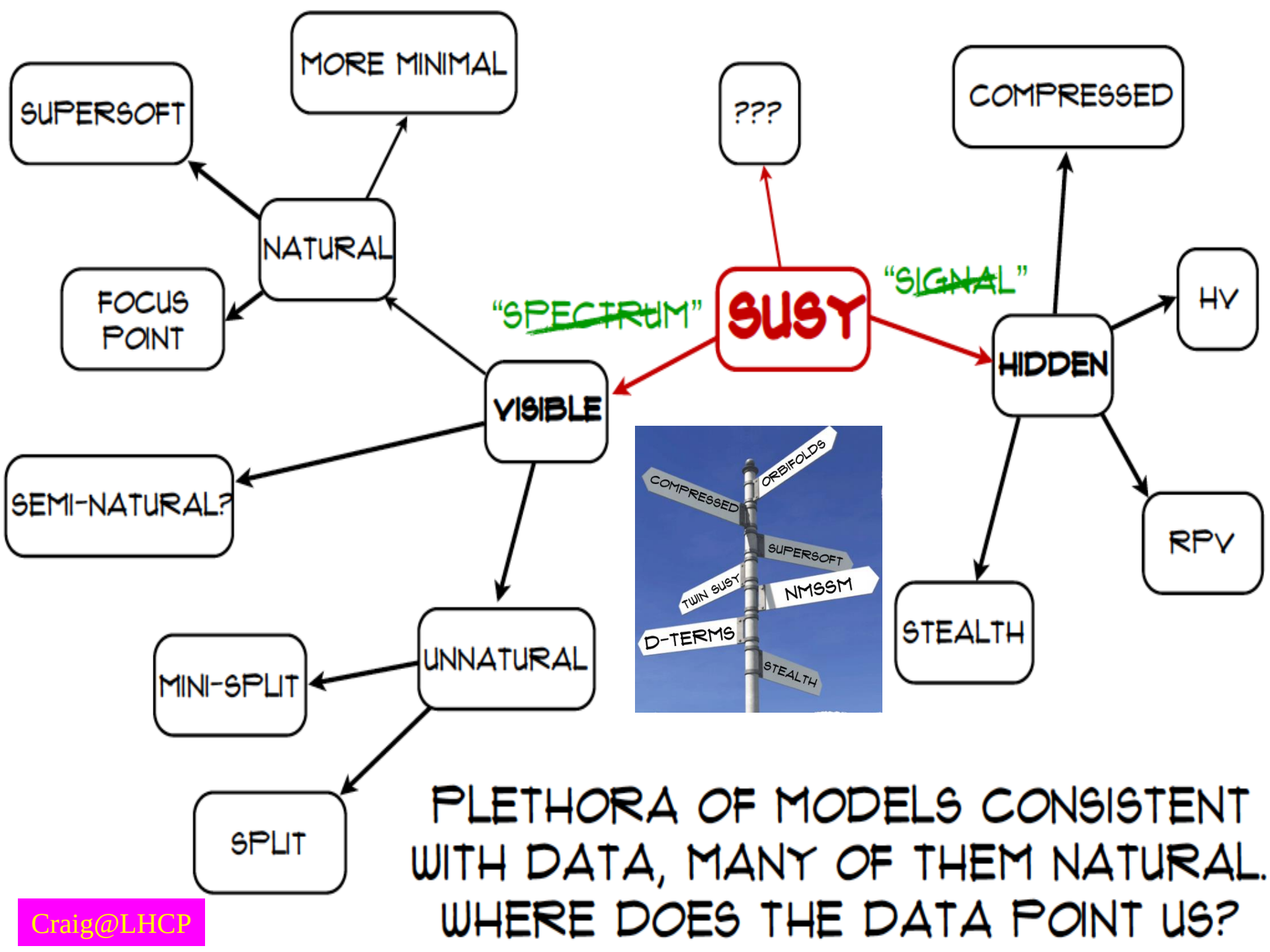


What else is there?

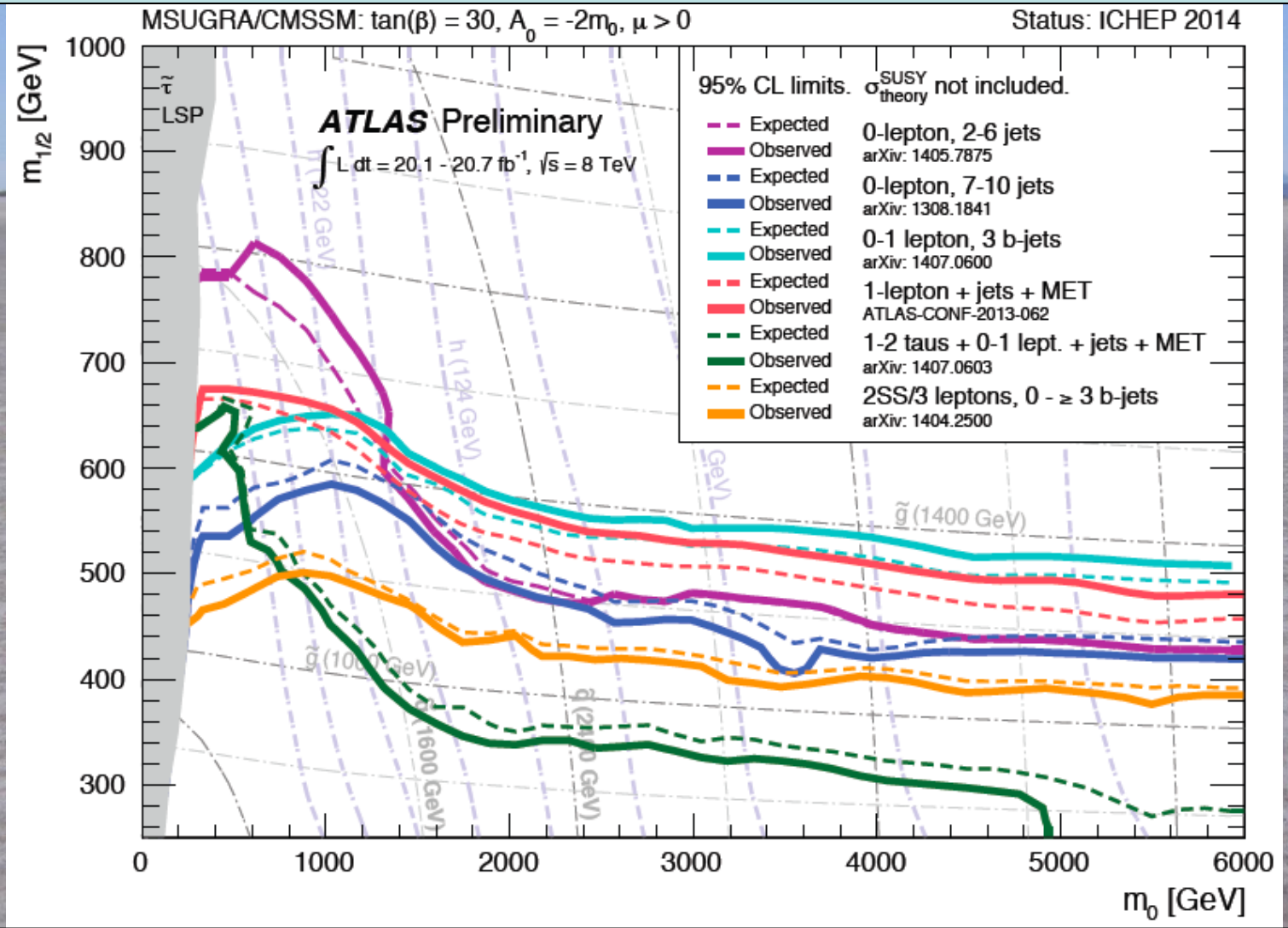
Supersymmetry

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, GUTs, string, …, **dark matter**

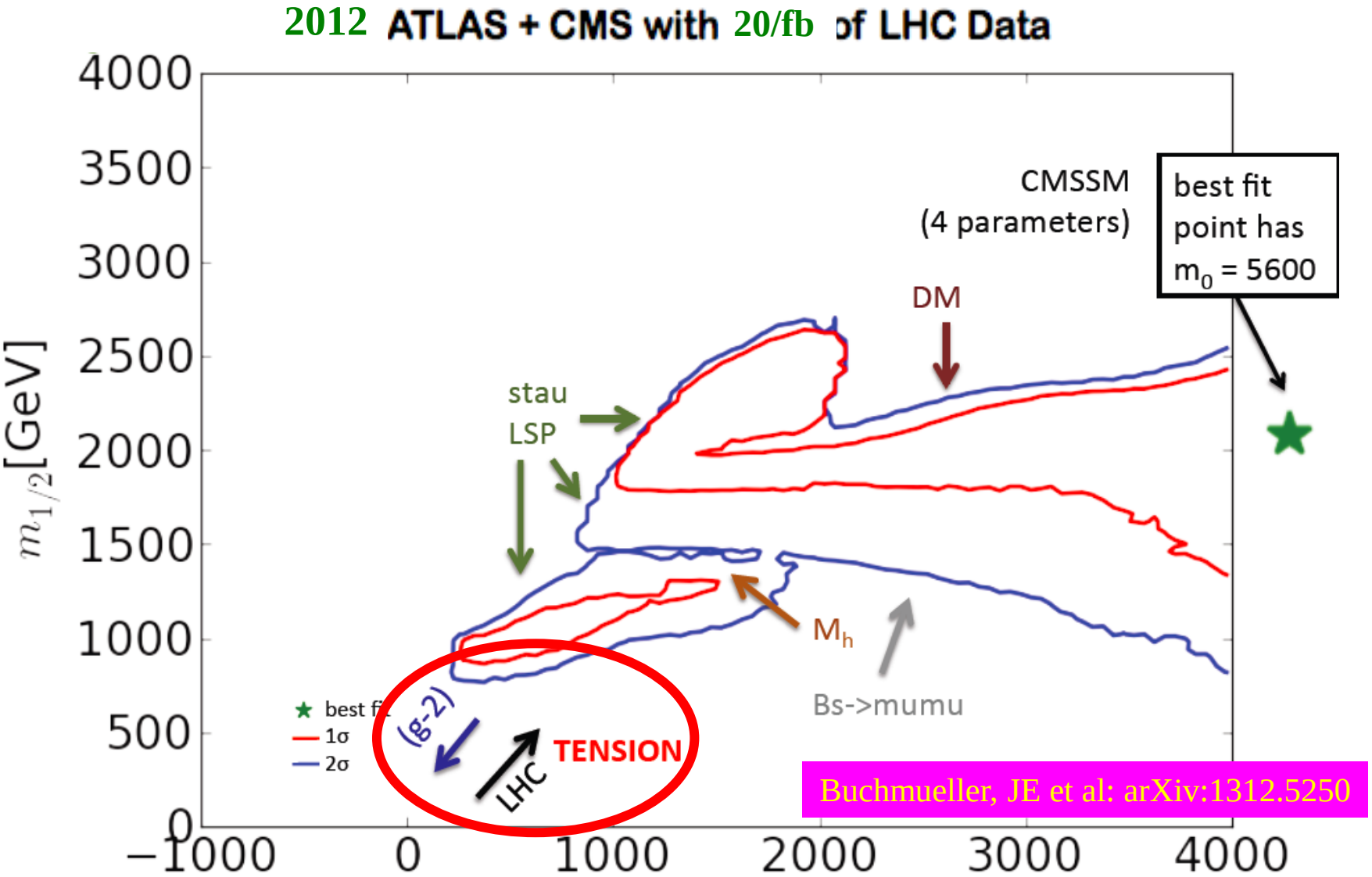

MORE MINIMAL
SUPERSOFT
???
COMPRESSED
NATURAL
FOCUS POINT
"SPECTRUM"
SUSY
"SIGNAL"
HV
HIDDEN
VISIBLE
SEMI-NATURAL?
ORBIFOLDS
COMPRESSED
SUPERSOFT
TWIN SUSY
NMSSM
D-TERMS
STEALTH
RPV
STEALTH
UNNATURAL
MINI-SPLIT
SPLIT
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL.
WHERE DOES THE DATA POINT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

Searches with ~ 20/fb @ 8 TeV



CMSSM = universal sparticle masses @ GUT scale

Constrained MSSM



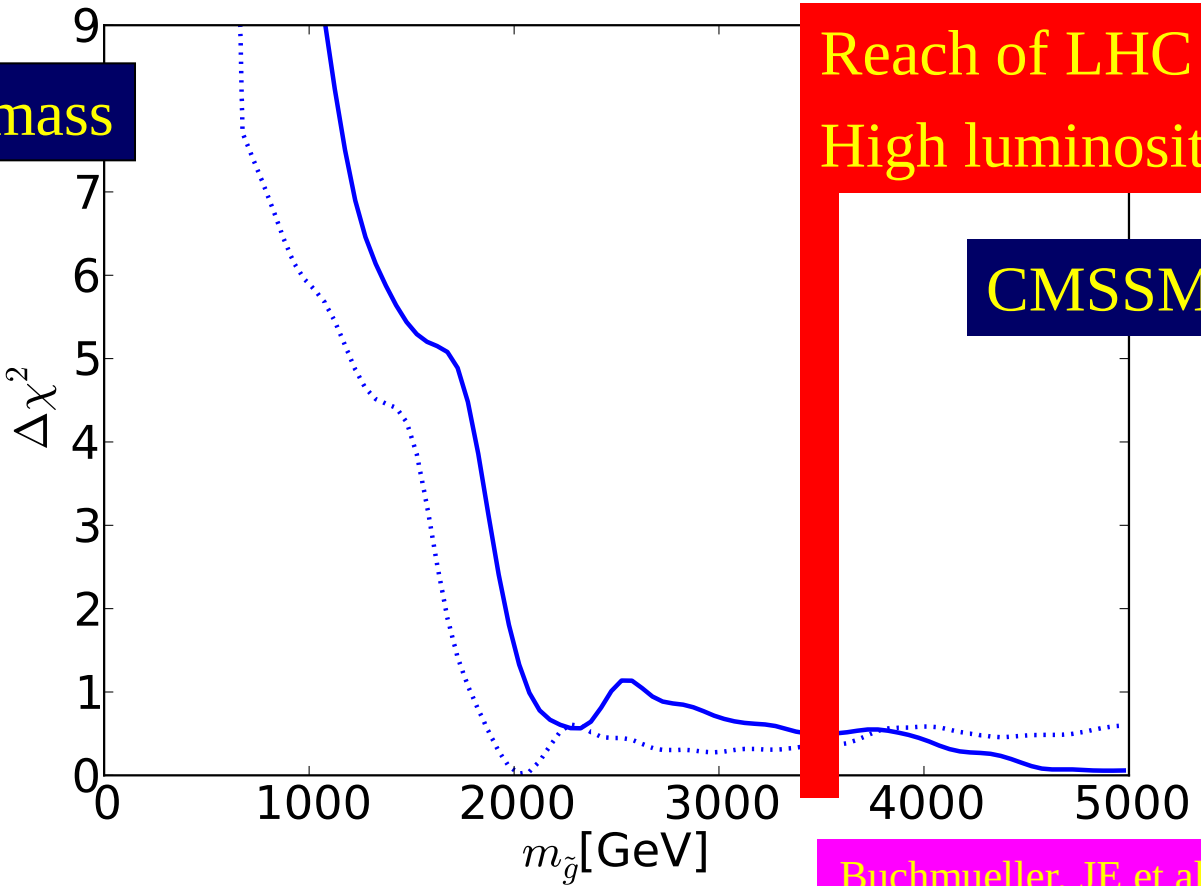
Buchmueller, JE et al: arXiv:1312.5250

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

Constrained MSSM

2012 ATLAS + CMS with 20/fb of LHC Data

Gluino mass



Reach of LHC at High luminosity

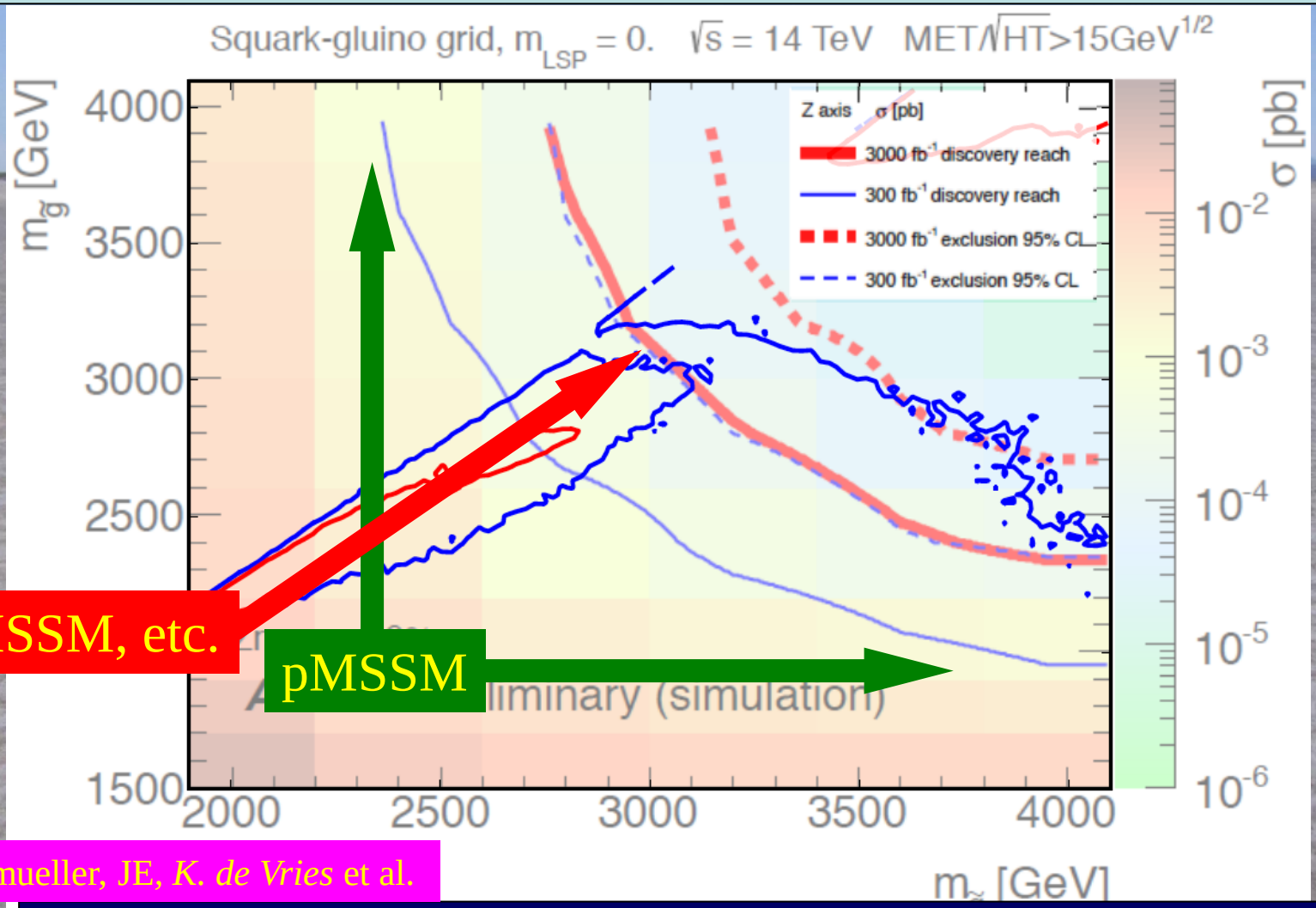
CMSSM

1

Buchmueller, JE et al: arXiv:1312.5250

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

LHC Reach for Supersymmetry



CMSSM, etc.

pMSSM

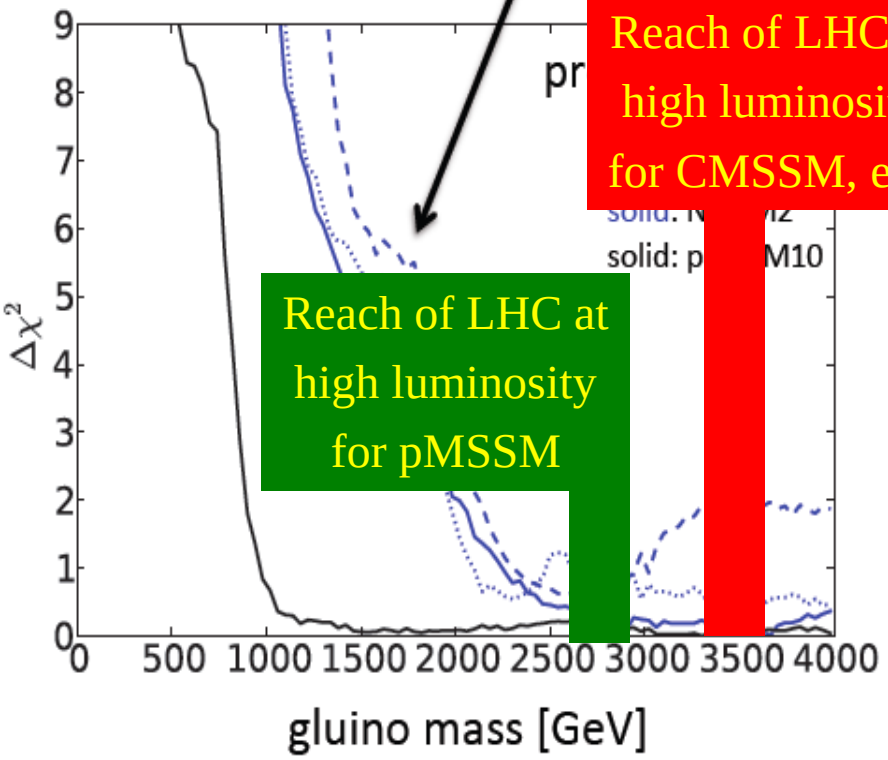
O. Buchmueller, JE, *K. de Vries* et al.

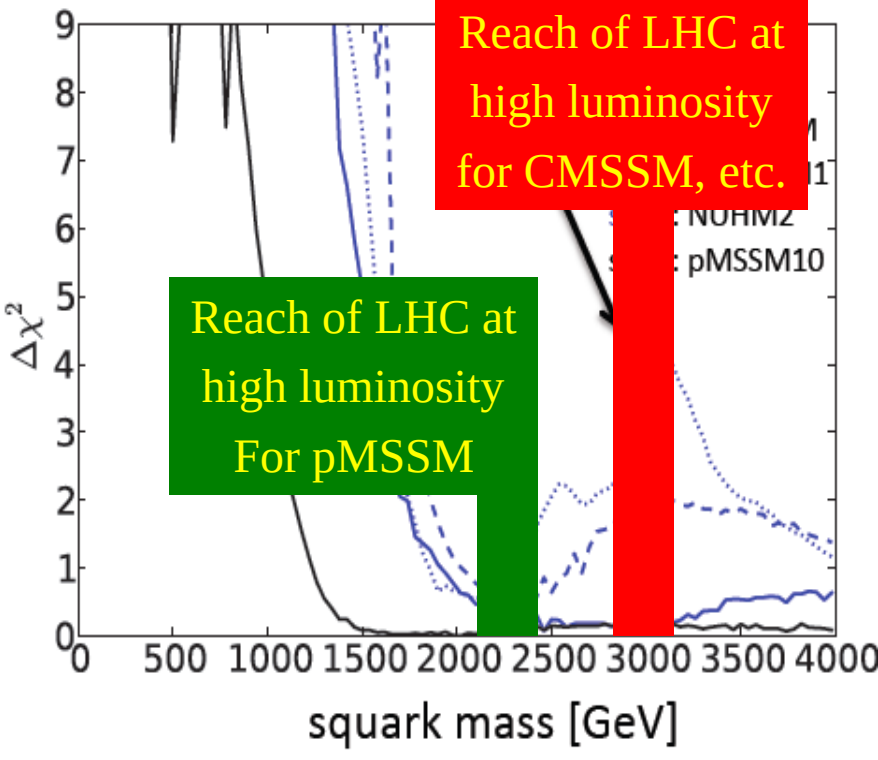
More possibilities in unconstrained pMSSM

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.

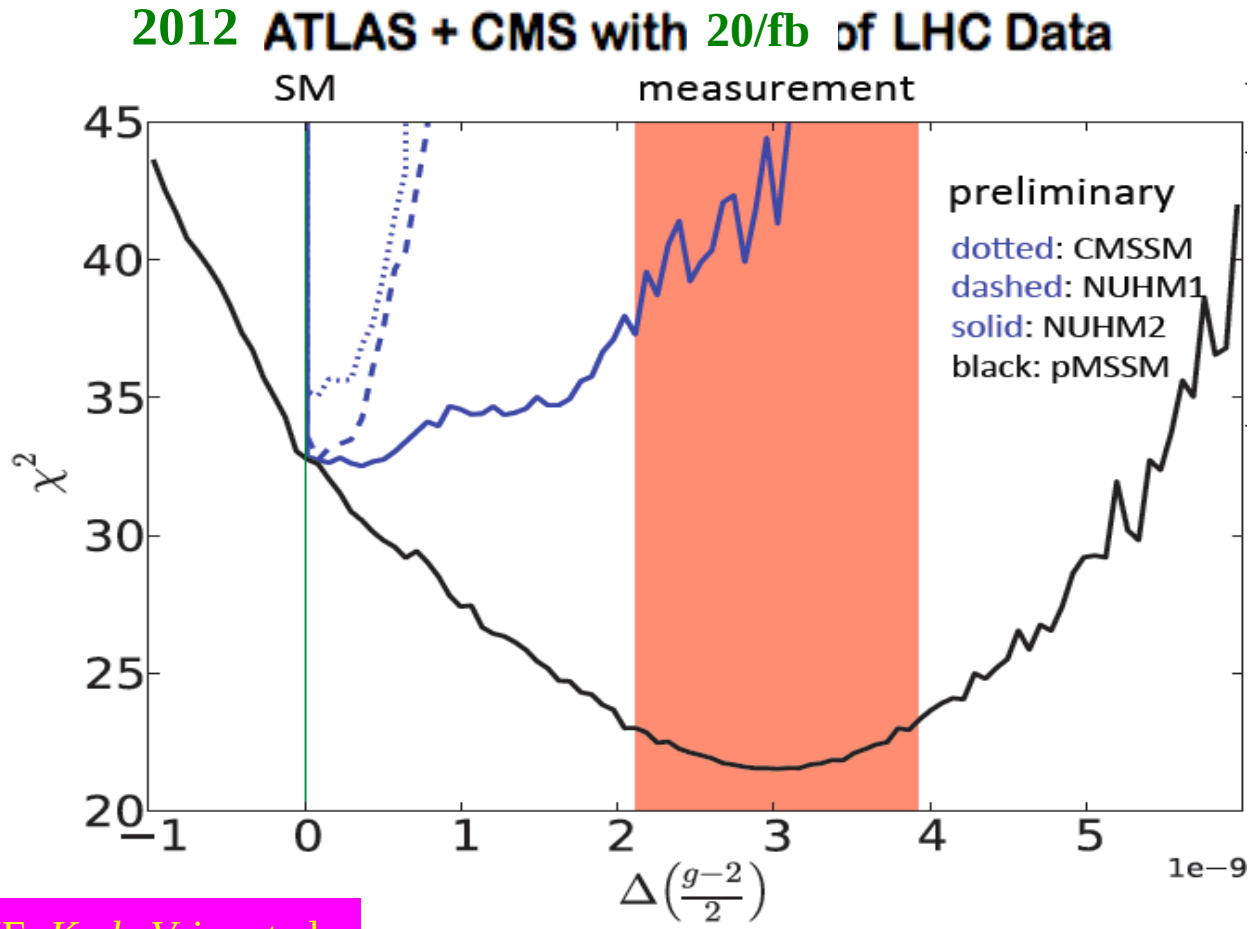




O. Buchmueller, JE, *K. de Vries* et al.

Lower masses still allowed in pMSSM

Muon Anomalous Moment in Models



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

Strong tension in CMSSM and NUHM1

Less significant in NUHM2

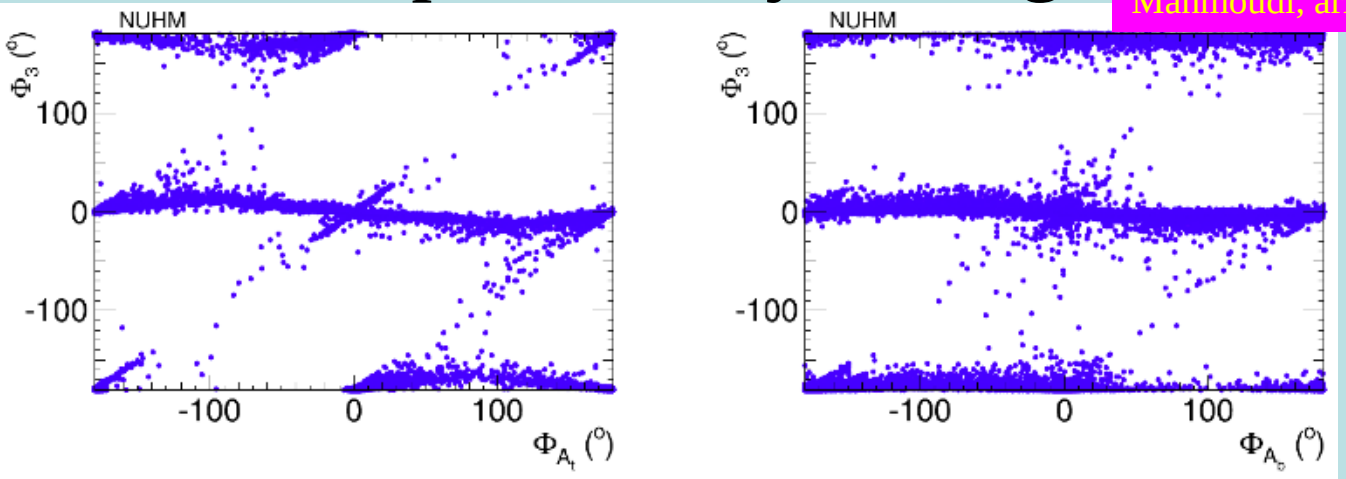
Removed in pMSSM

CP-Violating MSSM Scenarios

- 6 CP-violating phases even if assume minimal flavour violation:
  - phases in gaugino masses $M_{1,2,3}$, trilinear couplings $A_{t,b,\tau}$
- 4 strong EDM constraints:
  - **2-dimensional blind subspace**
- Combinations of phases may be large

EDM	Upper limit (e.cm)
Thallium	1.3×10^{-24}
Mercury	3.5×10^{-29}
Neutron	4.7×10^{-26}
Electron	1.1×10^{-28}

Arbey, JE, Godbolde & Mahmoudi, arXiv:1410.4824

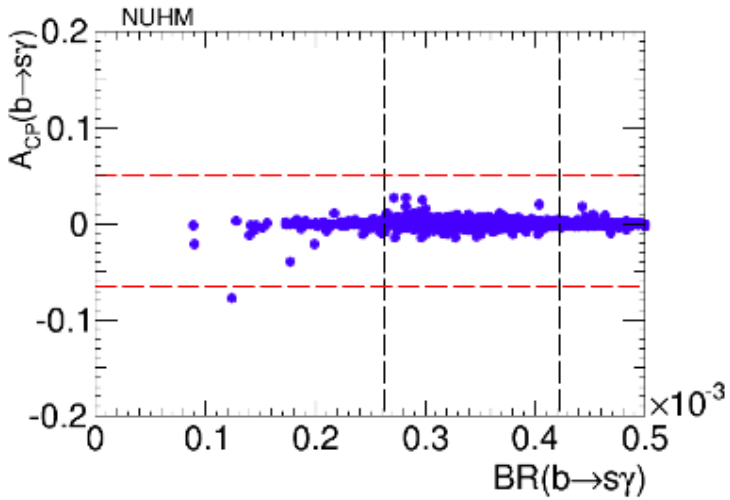


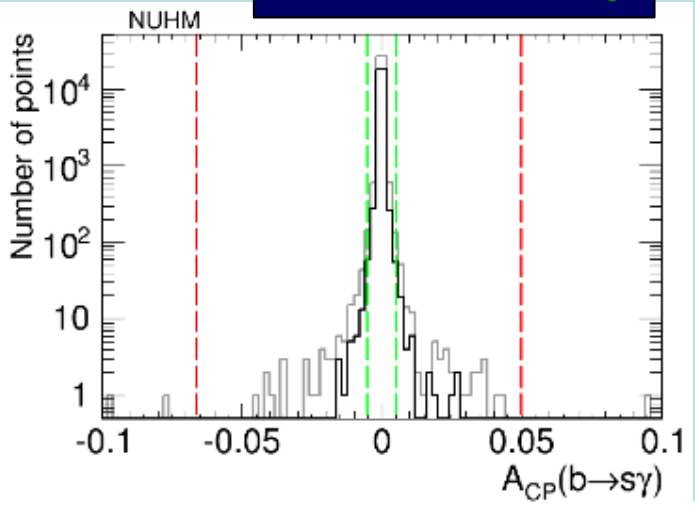
Possible Experimental Signature

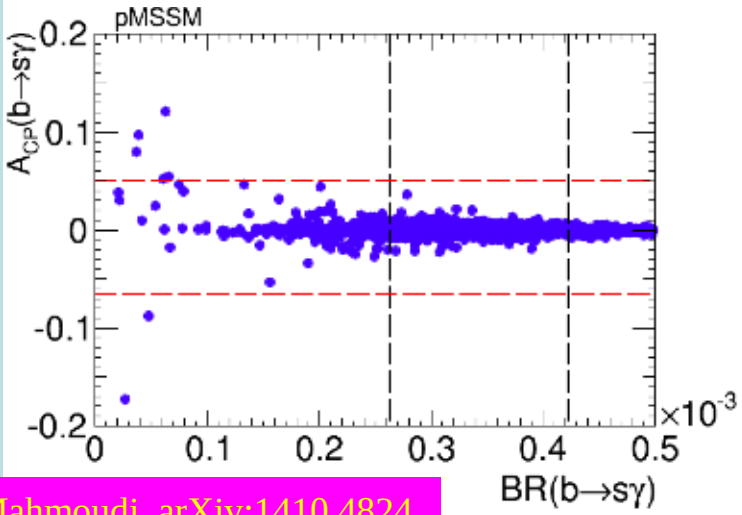
- CP-violating asymmetry in b to s γ:
- NUHM2
- pMSSM

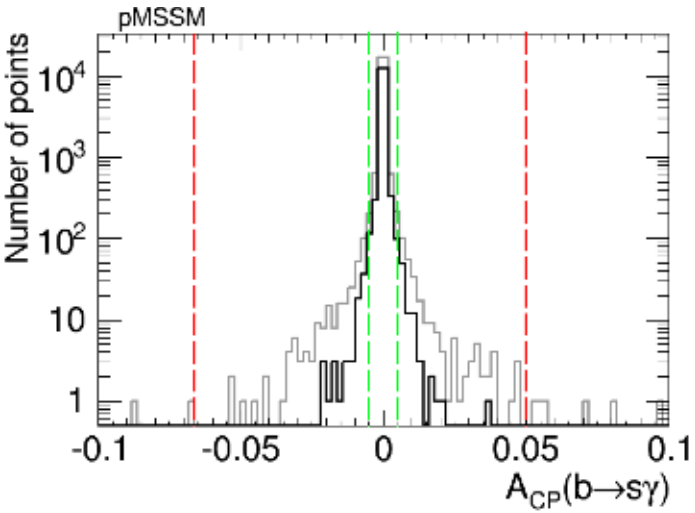
Present bounds

Future sensitivity





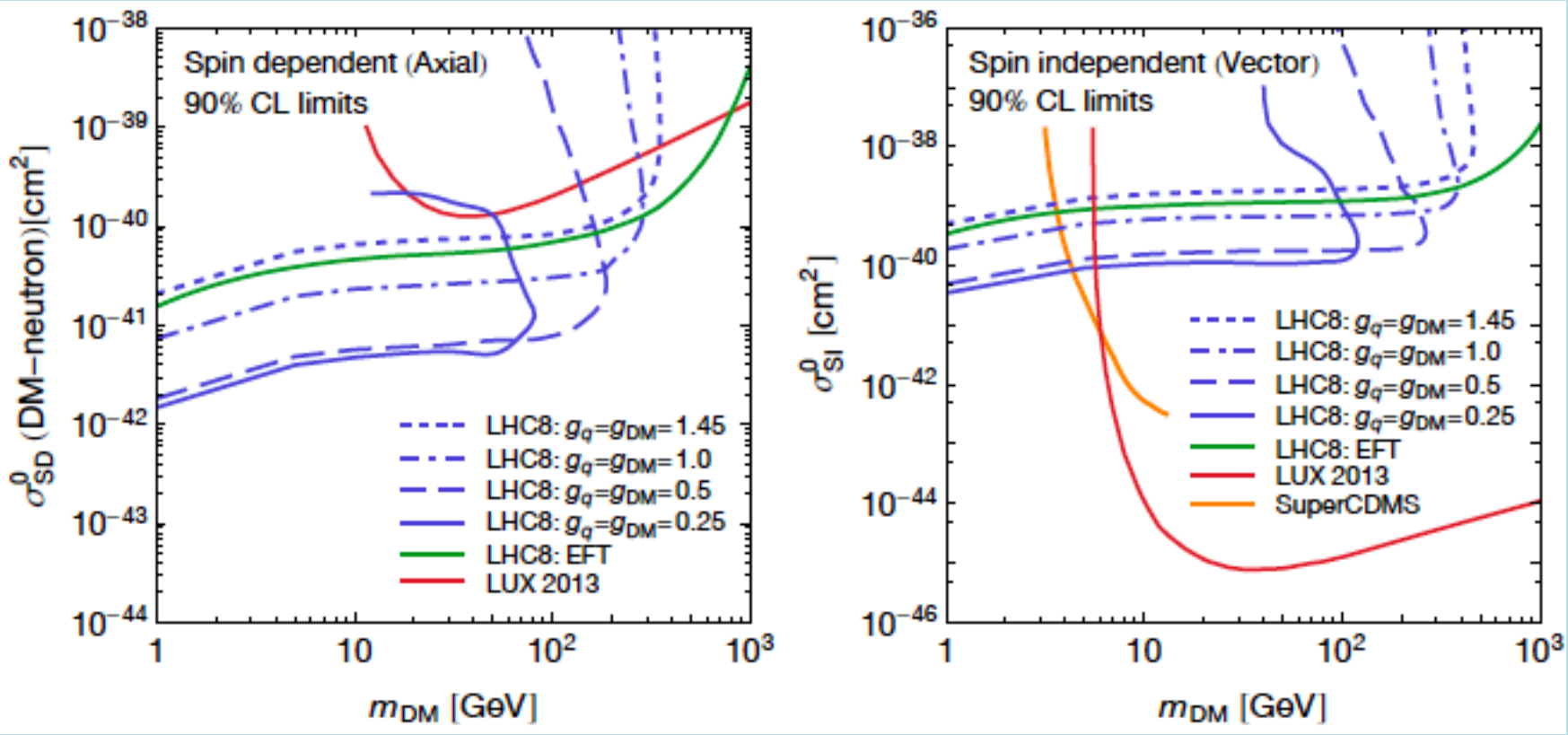




Arbey, JE, Godbolde & Mahmoudi, arXiv:1410.4824

LHC vs Dark Matter Searches

- Compilation of present and future sensitivities

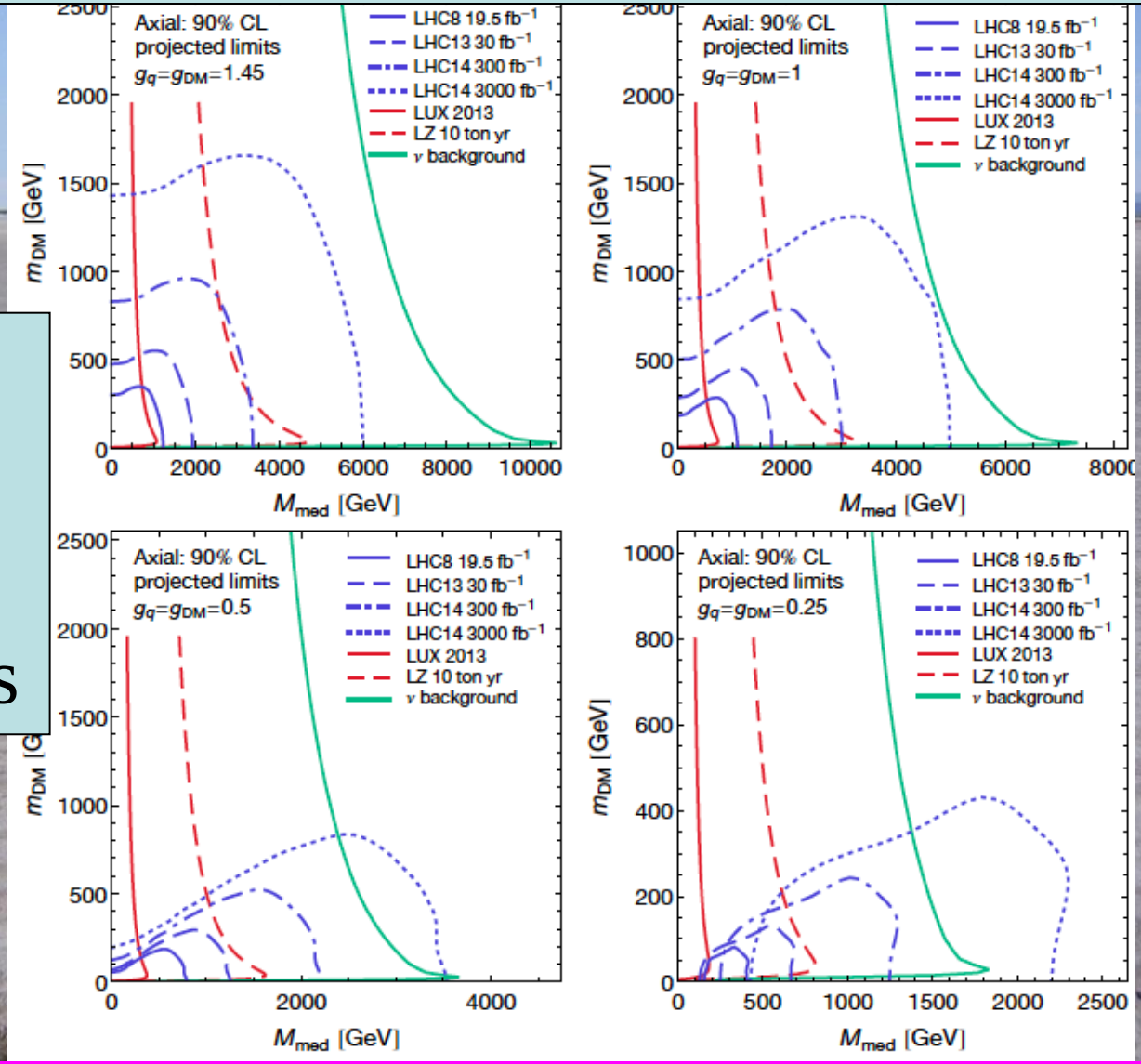


- LHC wins for spin-independent, except small m_{DM}

Buchmueller, Dolan, Malik & McCabe: arXiv:1407.8257; Malik, McCabe, …, JE et al: arXiv:1409.4075

Projections for Future

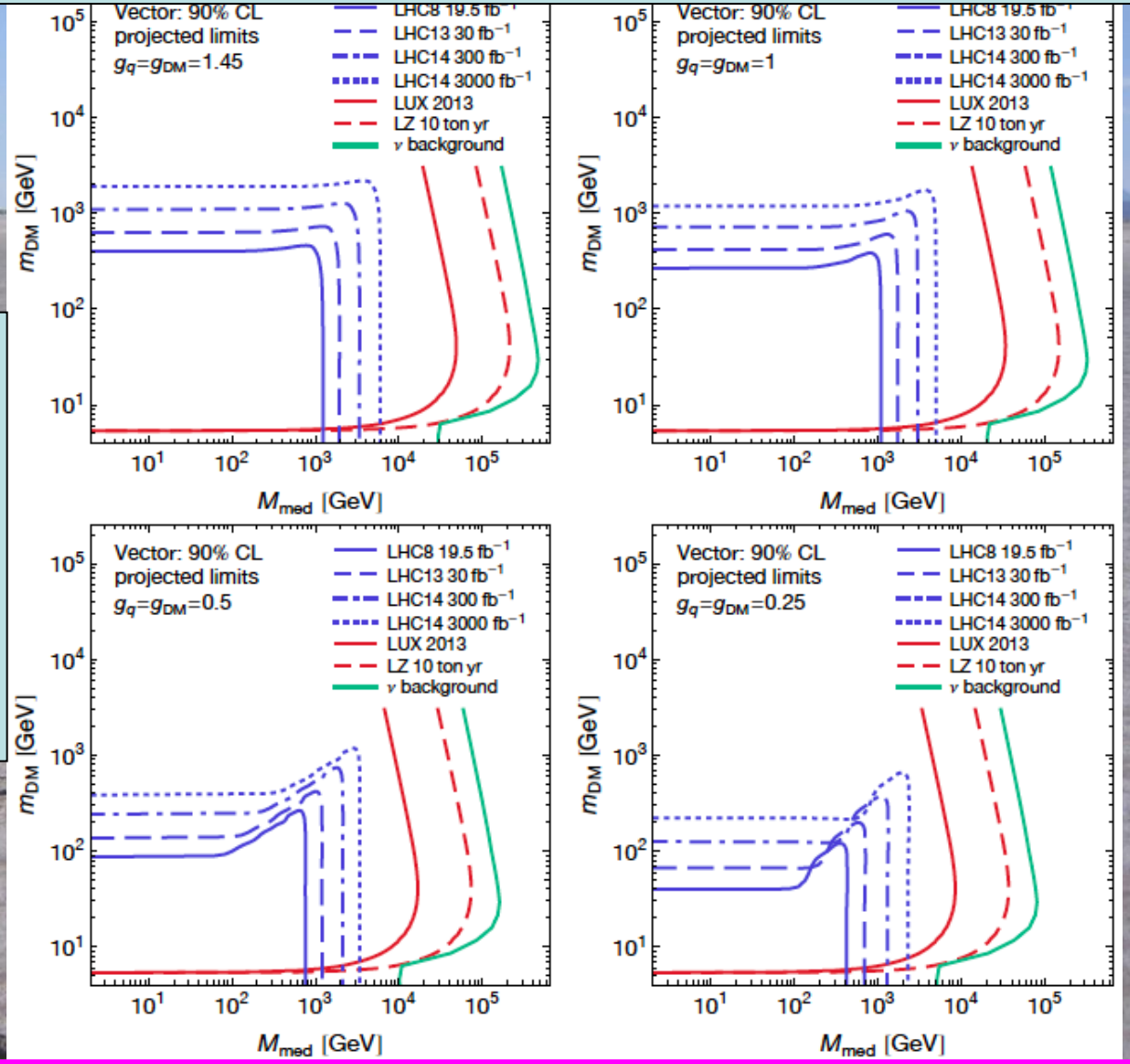
- Axial interaction
- Sensitive to mediator mass



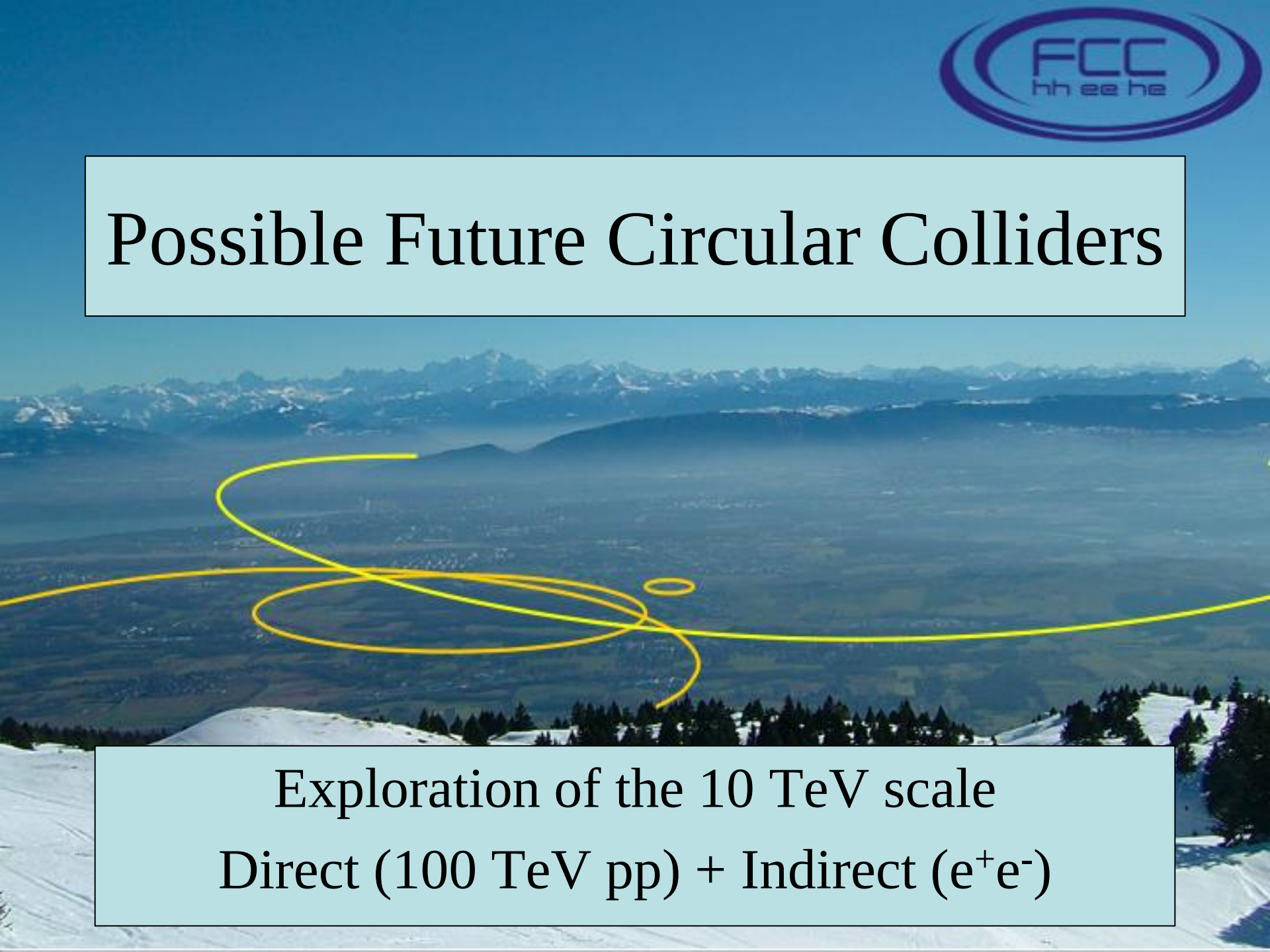
Buchmueller, Dolan, Malik & McCabe: arXiv:1407.8257; Malik, McCabe, …, JE et al: arXiv:1409.4075

Projections for Future

- Vector interaction
- Sensitive to mediator mass



Buchmueller, Dolan, Malik & McCabe: arXiv:1407.8257; Malik, McCabe, …, JE et al: arXiv:1409.4075



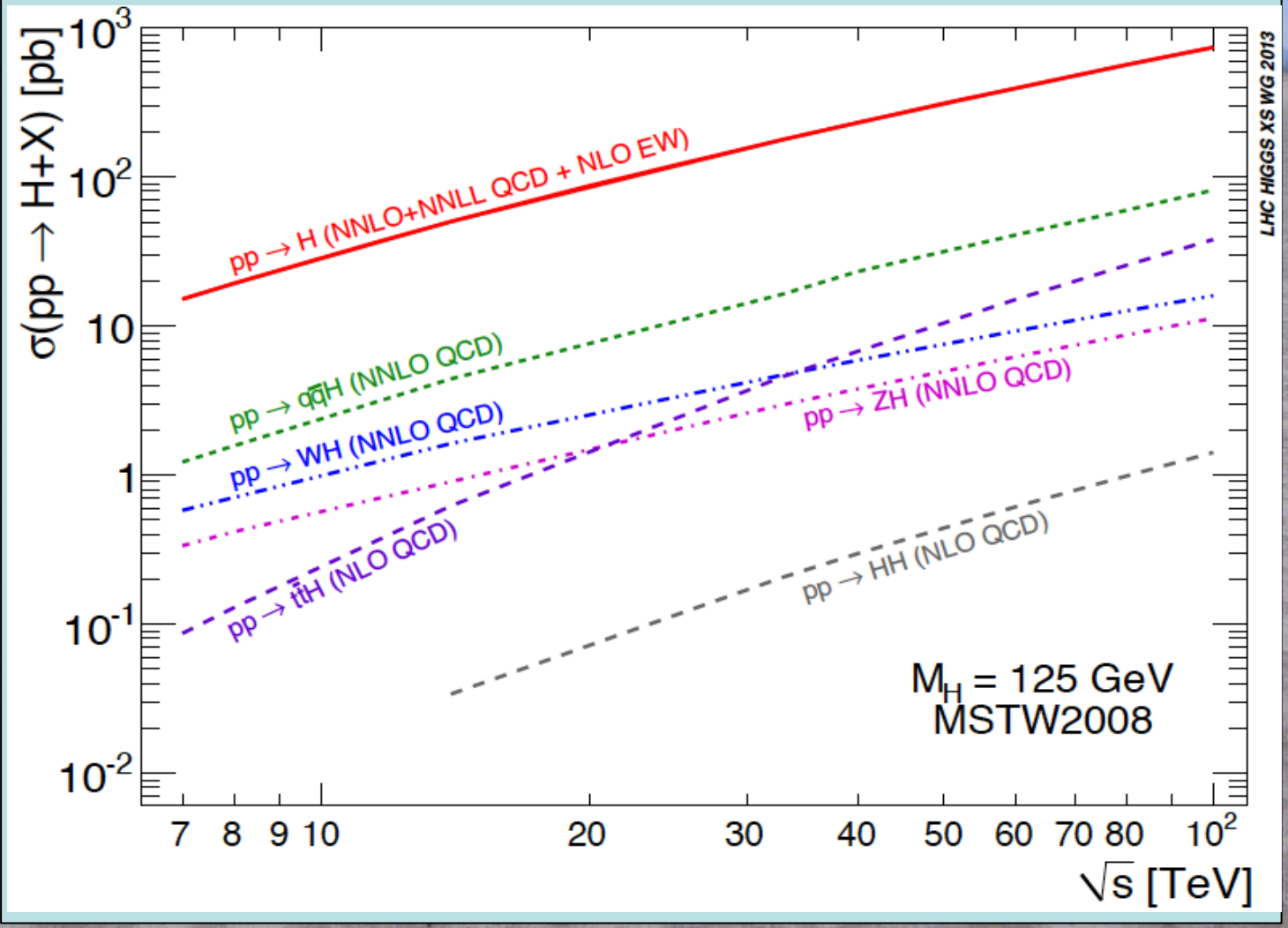
Possible Future Circular Colliders

Exploration of the 10 TeV scale

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

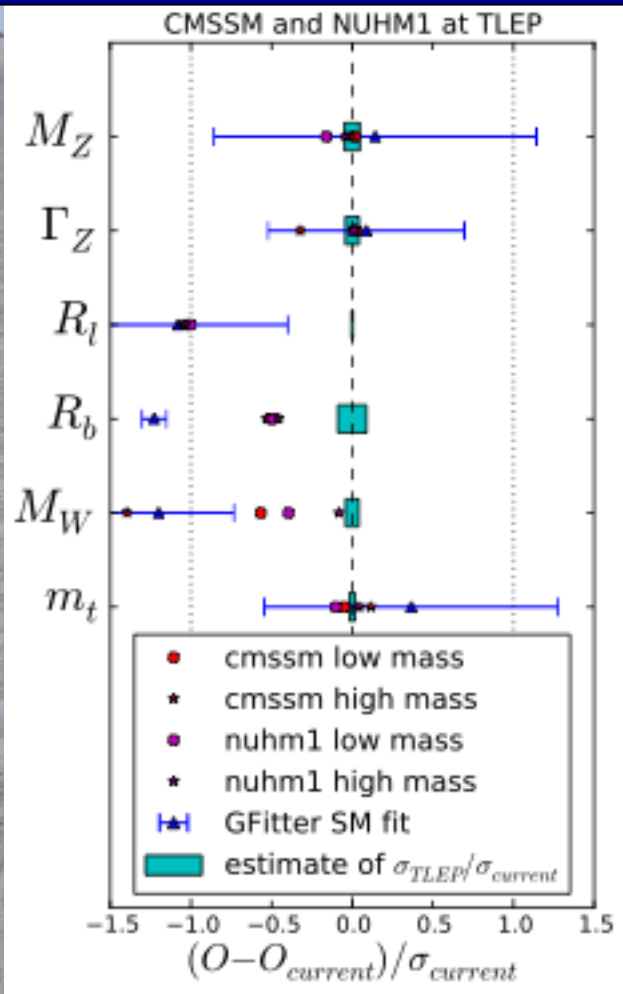
Higgs Cross Sections

- At the LHC and beyond:

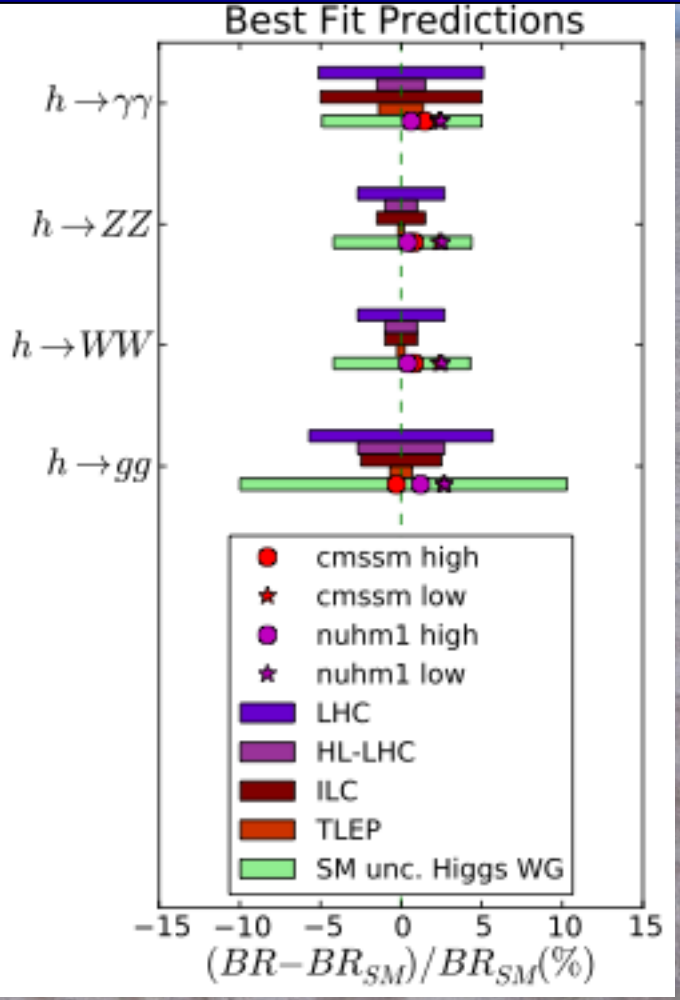


Precision **FCC-ee** Measurements

Precision Electroweak



Precision Higgs



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