

The Higgs Boson: Portal to what new physics?

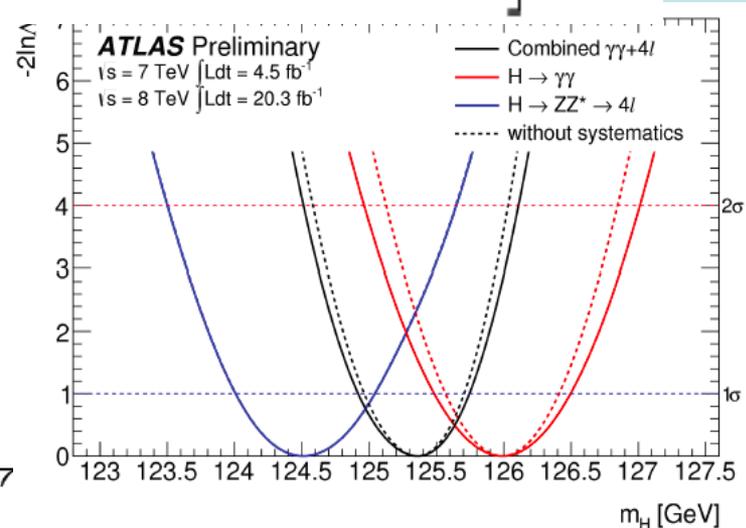
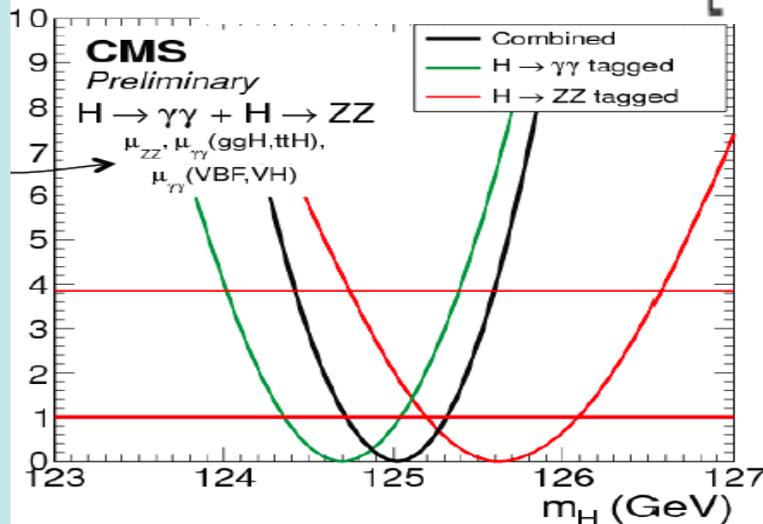


What will be the next big LHC discovery?

Higgs Mass Measurements

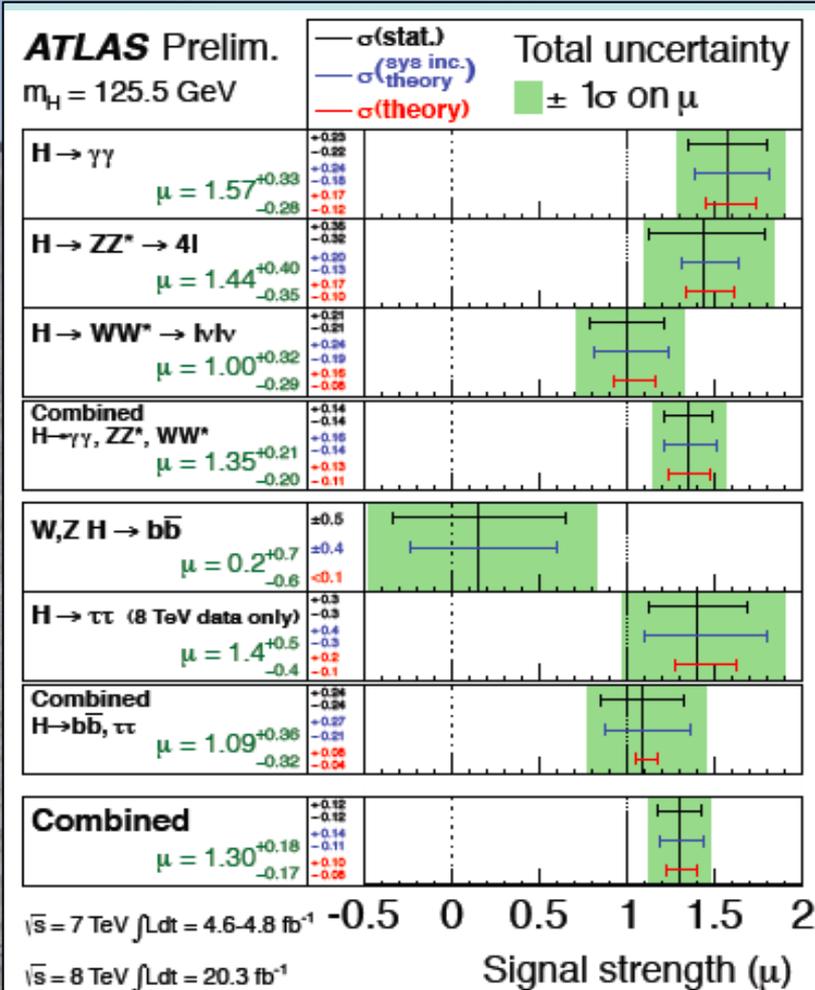
- ATLAS:**

$H \rightarrow \gamma\gamma$	125.98 ± 0.42 (stat) ± 0.28 (sys) = 125.98 ± 0.50
$H \rightarrow ZZ^* \rightarrow 4\ell$	124.51 ± 0.52 (stat) ± 0.04 (sys) = 124.51 ± 0.52
Combined	125.36 ± 0.37 (stat) ± 0.18 (sys) = 125.36 ± 0.41
- CMS:** $m_H = 125.6 \pm 0.4 \pm 0.2$ GeV from ZZ^*
 $m_H = 124.70^{+0.35}_{-0.34}$ [± 0.31 (stat.) ± 0.15 (syst.)] GeV from $\gamma\gamma$
Combined: $m_H = 125.03 \pm 0.30$ [$^{+0.26}_{-0.27}$ (stat.) $^{+0.13}_{-0.15}$ (syst.)] GeV

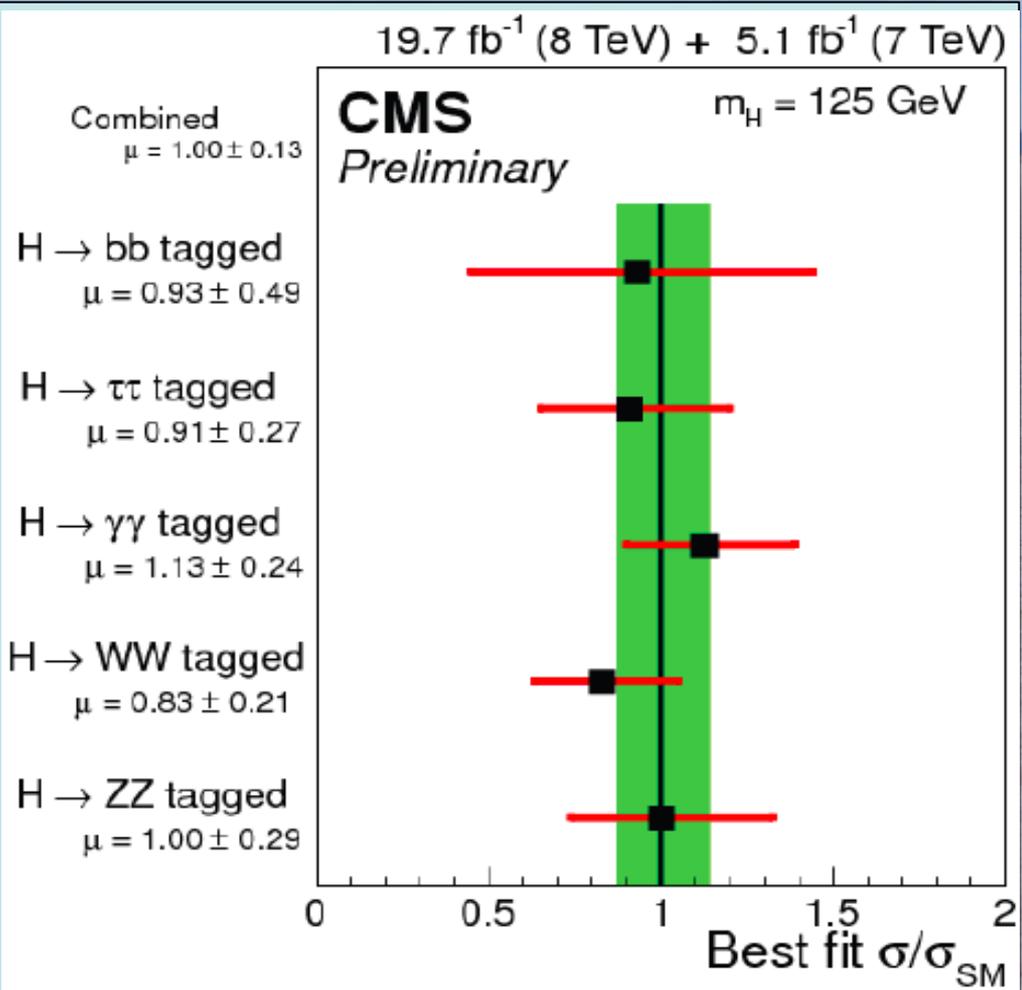


- Crucial for stability of electroweak vacuum**

Higgs Signal Strengths



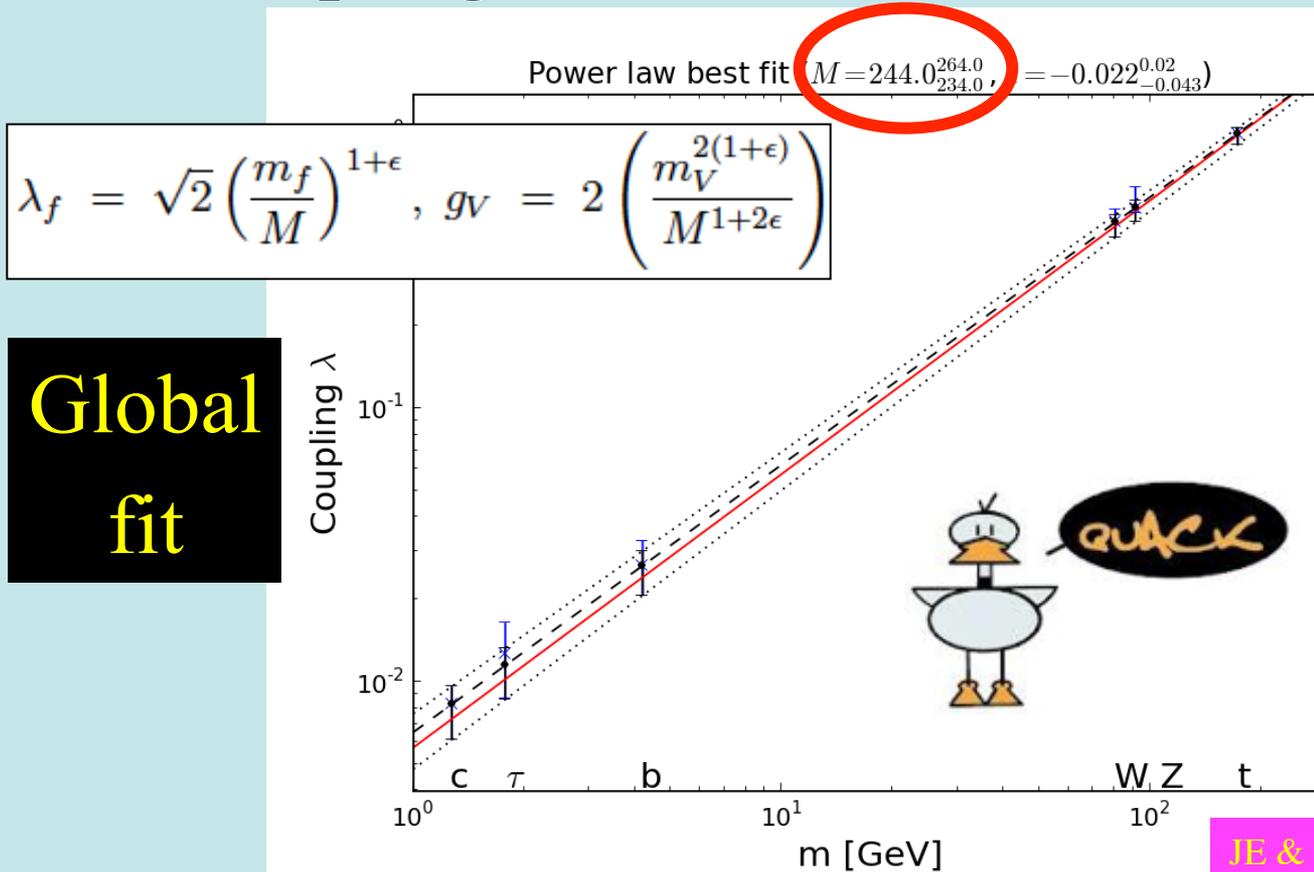
$$\mu = 1.30 \pm 0.12 \text{ (stat)} \pm 0.10 \text{ (th)} \pm 0.09 \text{ (syst)}$$



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

It Walks and Quacks like a Higgs

- Do couplings scale \sim mass? With scale = v ?



JE & Tevong You, arXiv:1303.3879

- Red line = SM, dashed line = best fit

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*

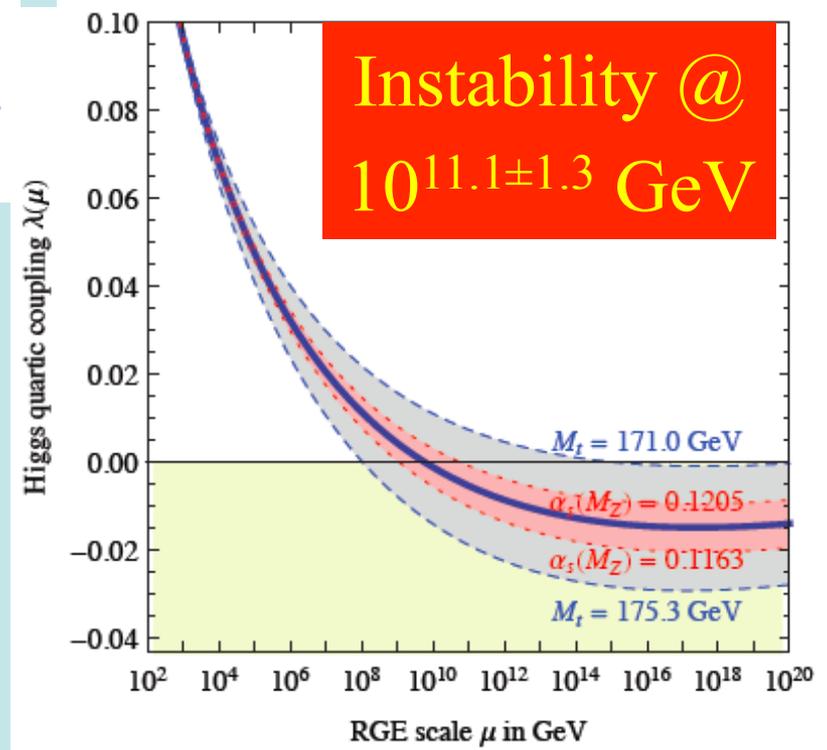
Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling \rightarrow 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
 \rightarrow vacuum unstable

- Vacuum could be stabilized by **Supersymmetry**



Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H

D0 l+jets
May 2014

174.98 ± 0.76 (0.58 ± 0.49)

CMS all jets
July 2014

172.08 ± 0.90 (0.36 ± 0.83)

CMS l+jets
March 2014

172.04 ± 0.77 (0.19 ± 0.75)

World combination
March 2014

173.34 ± 0.76 (0.36 ± 0.67)

total (stat. \pm syst.)



- Instability scale: [Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536](#)

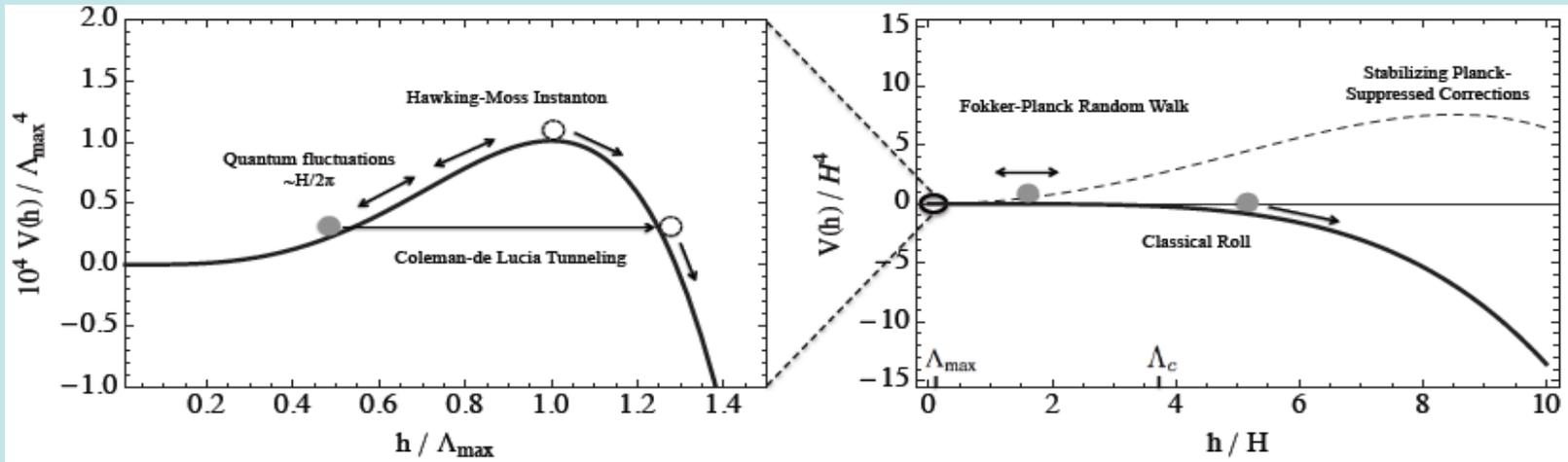
$$\log_{10} \frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0 \left(\frac{M_h}{\text{GeV}} - 125.66 \right) - 1.2 \left(\frac{M_t}{\text{GeV}} - 173.10 \right) + 0.4 \frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$$m_t = 173.3 \pm 1.0 \text{ GeV} \rightarrow \log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3$$

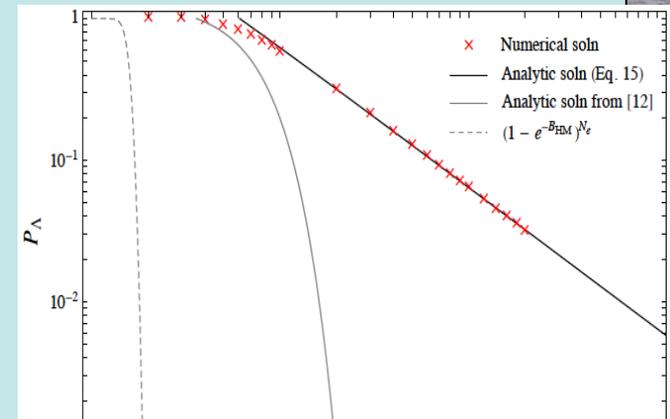
Instability during Inflation?

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?

SUSY UNITED Vs COMPOSITE CITY



THE BATTLE OF MANCHESTER

OLD TRAFFORD MANCHESTER



<http://jaffarjaffar.com>

BARCLAYS PREMIER LEAGUE

MANCHESTER UNITED - MANCHESTER CITY

OLD TRAFFORD 25TH MARCH 2014 - KICK OFF 20:45



Carena

DESIGN BY: JAFFAR

Phenomenological Framework

- Assume custodial symmetry:

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

- Parameterize gauge bosons by 2×2 matrix Σ :

$$\begin{aligned} \mathcal{L} = & \frac{v^2}{4} \text{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \dots \right) - m_i \bar{\psi}_L^i \Sigma \left(1 + c \frac{h}{v} + \dots \right) \psi_R^i + \text{h.c.} \\ & + \frac{1}{2} (\partial_\mu h)^2 + \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6} \left(\frac{3m_h^2}{v} \right) h^3 + d_4 \frac{1}{24} \left(\frac{3m_h^2}{v^2} \right) h^4 + \dots \quad , \end{aligned}$$

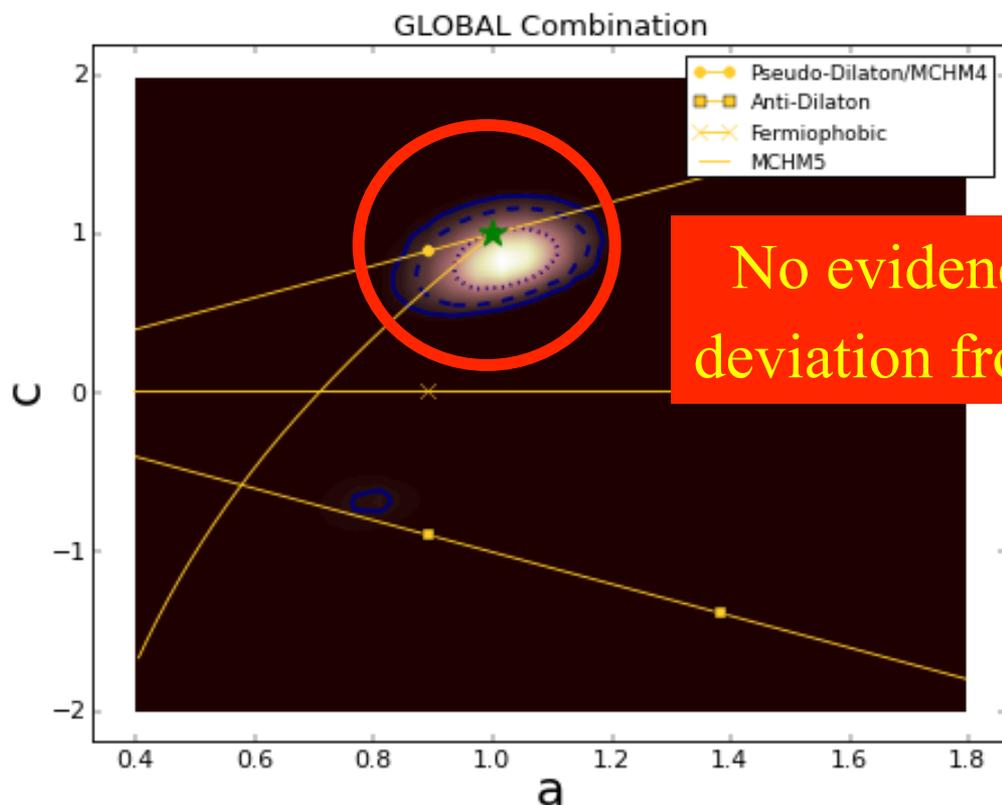
$$\Sigma = \exp \left(i \frac{\sigma^a \pi^a}{v} \right) \quad \mathcal{L}_\Delta = - \left[\frac{\alpha_s}{8\pi} b_s G_{a\mu\nu} G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi} b_{em} F_{\mu\nu} F^{\mu\nu} \right] \left(\frac{h}{V} \right)$$

- 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: $a = c = 1$

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 $SU(2) \times U(1)$ symmetry:

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

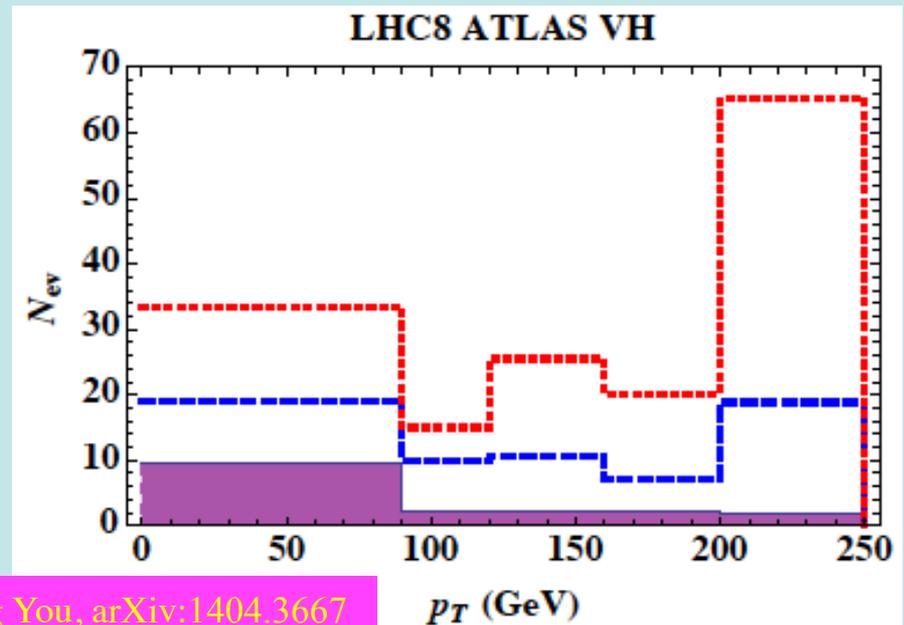
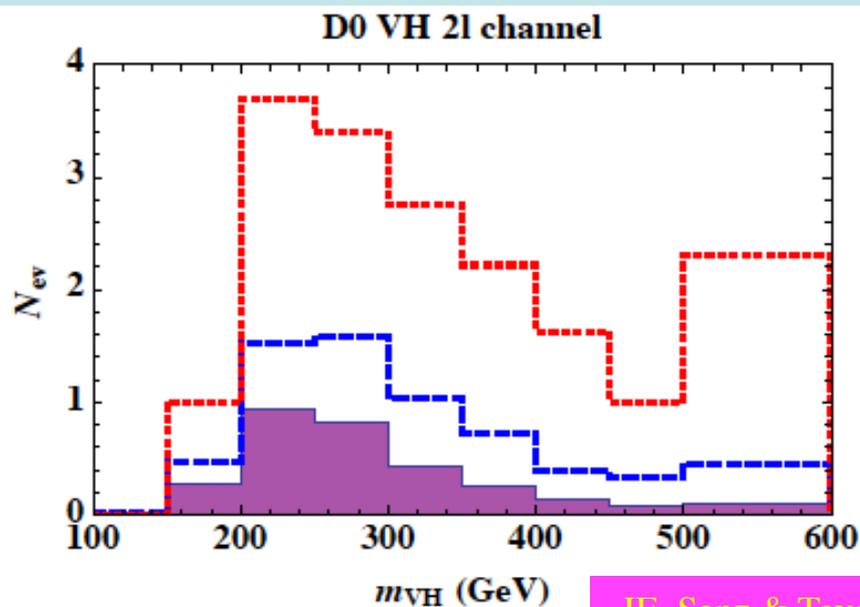
- Constrain with precision EW, Higgs data, TGCs ...

Information from Associated Production

- Operators affecting Higgs physics

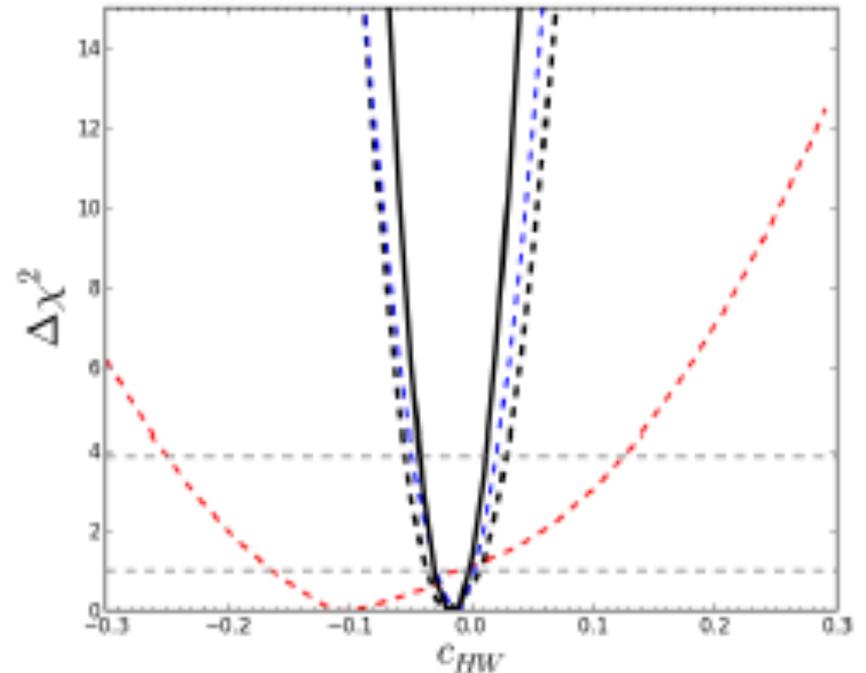
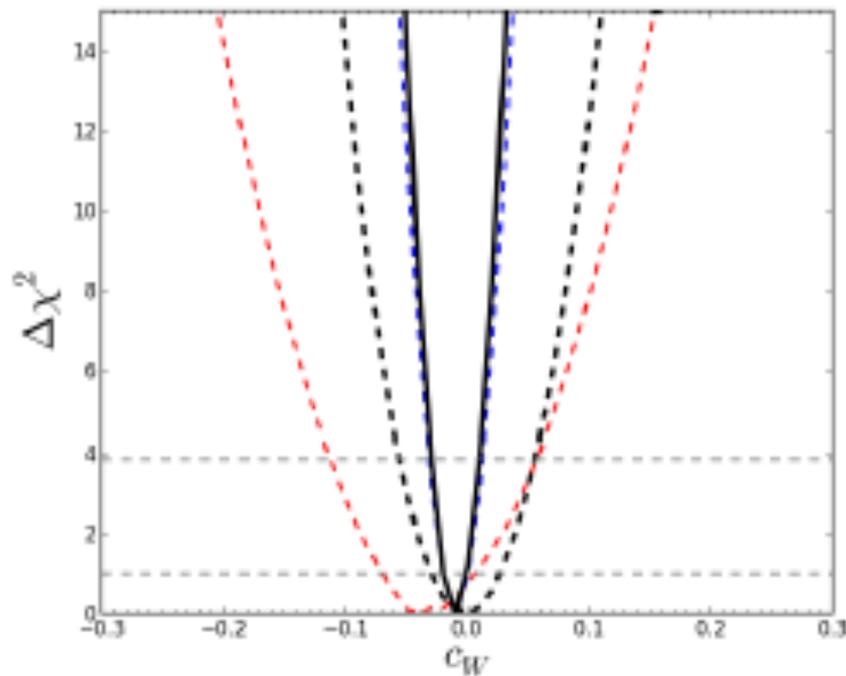
$$\bar{c}_i \equiv \{\bar{c}_H, \bar{c}_{t,b,\tau}, \bar{c}_W, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g\}$$

- Dimension-6 operators affect rates, distributions
- Sensitivity in Tevatron, LHC data



Information from Associated Production

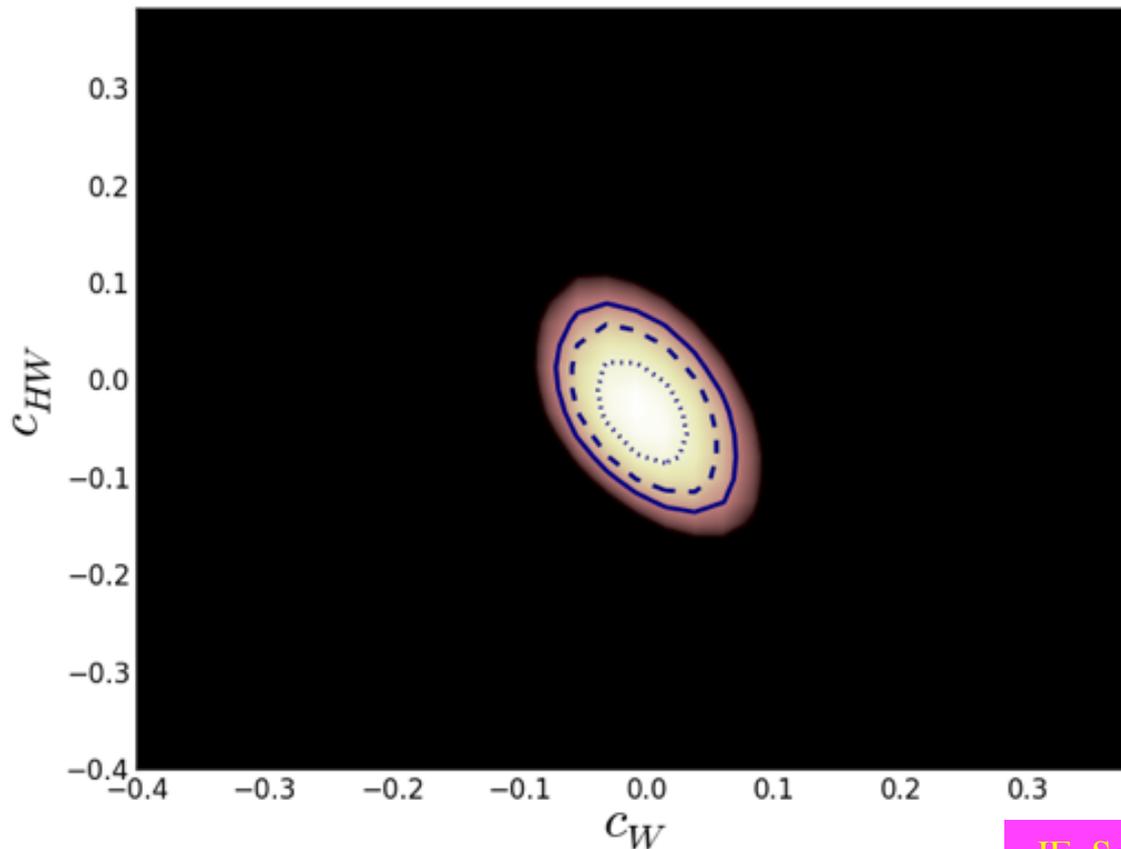
- Impacts on determinations of coefficients



- **Dashed = D0**, **dashed = ATLAS**, **dashed = rates**
- **Solid = combined**

Information from Associated Production

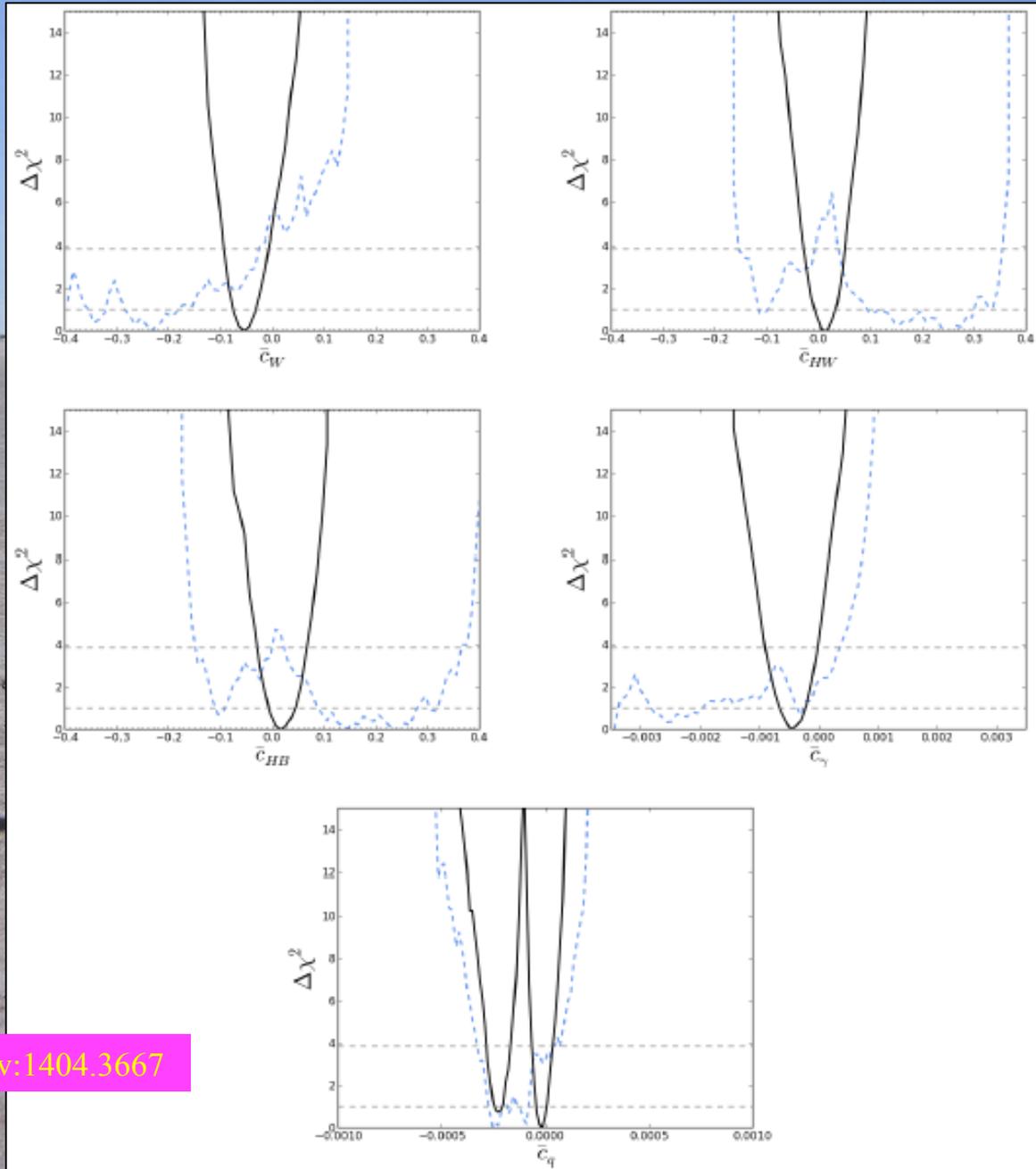
- Impacts on determinations of coefficients



**Kinematics
+ strengths**

Fits including Associated Production

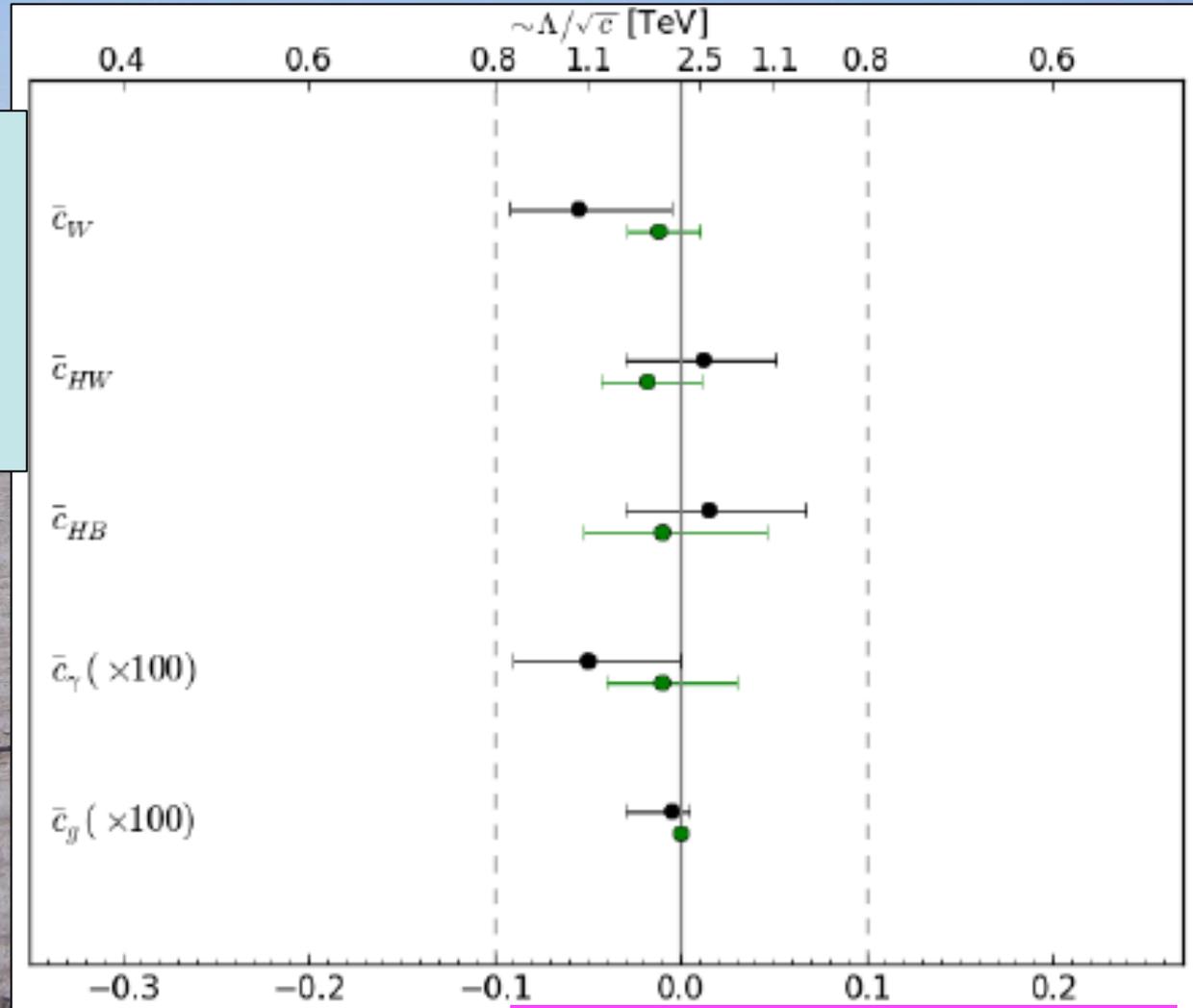
- Fits with
(without)
information from
kinematics



JE, Sanz & Tevong You, arXiv:1404.3667

Fits including Associated Production

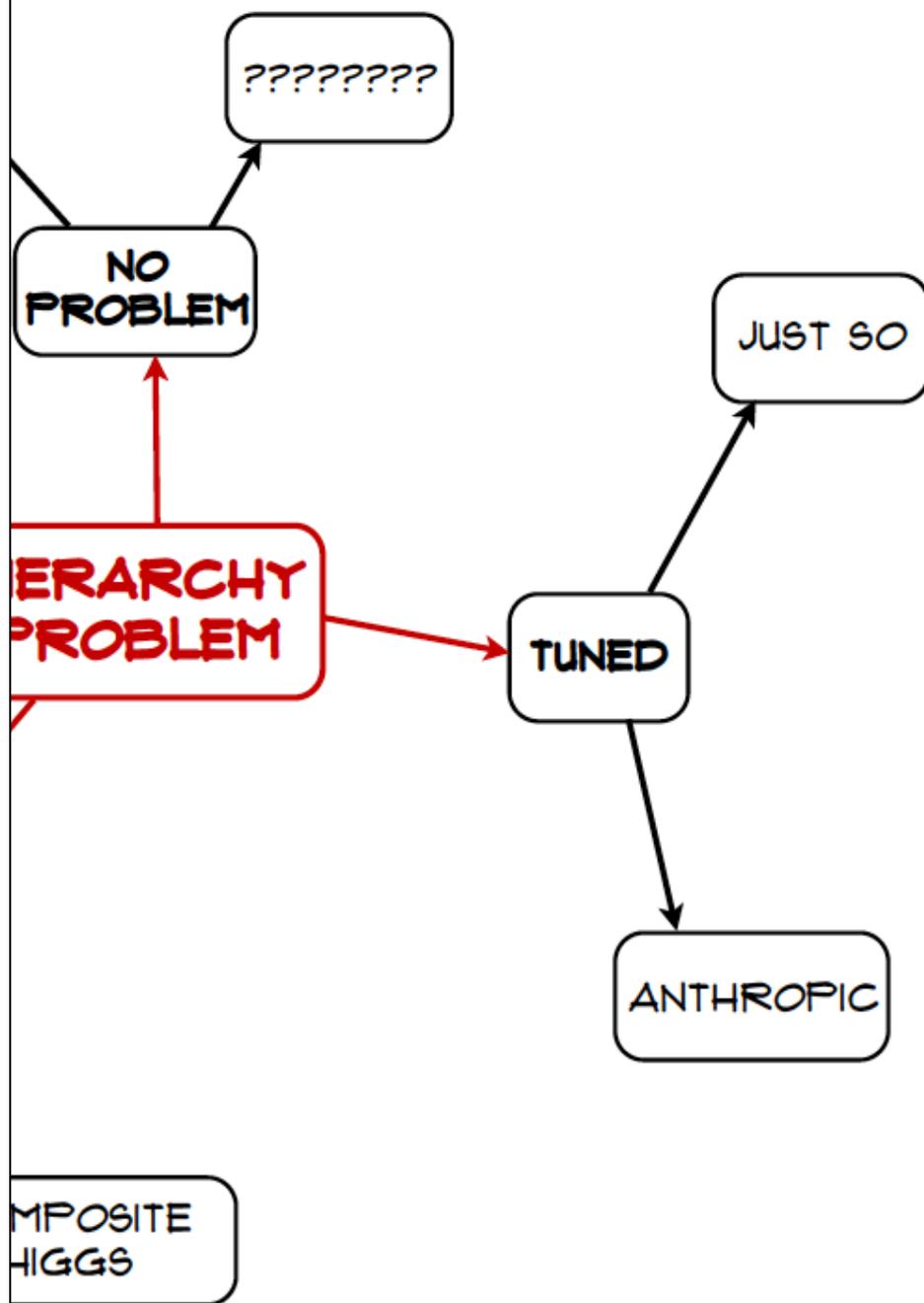
- Global fit
- **Single-parameter fits**





By courtesy of the "Barracks"

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

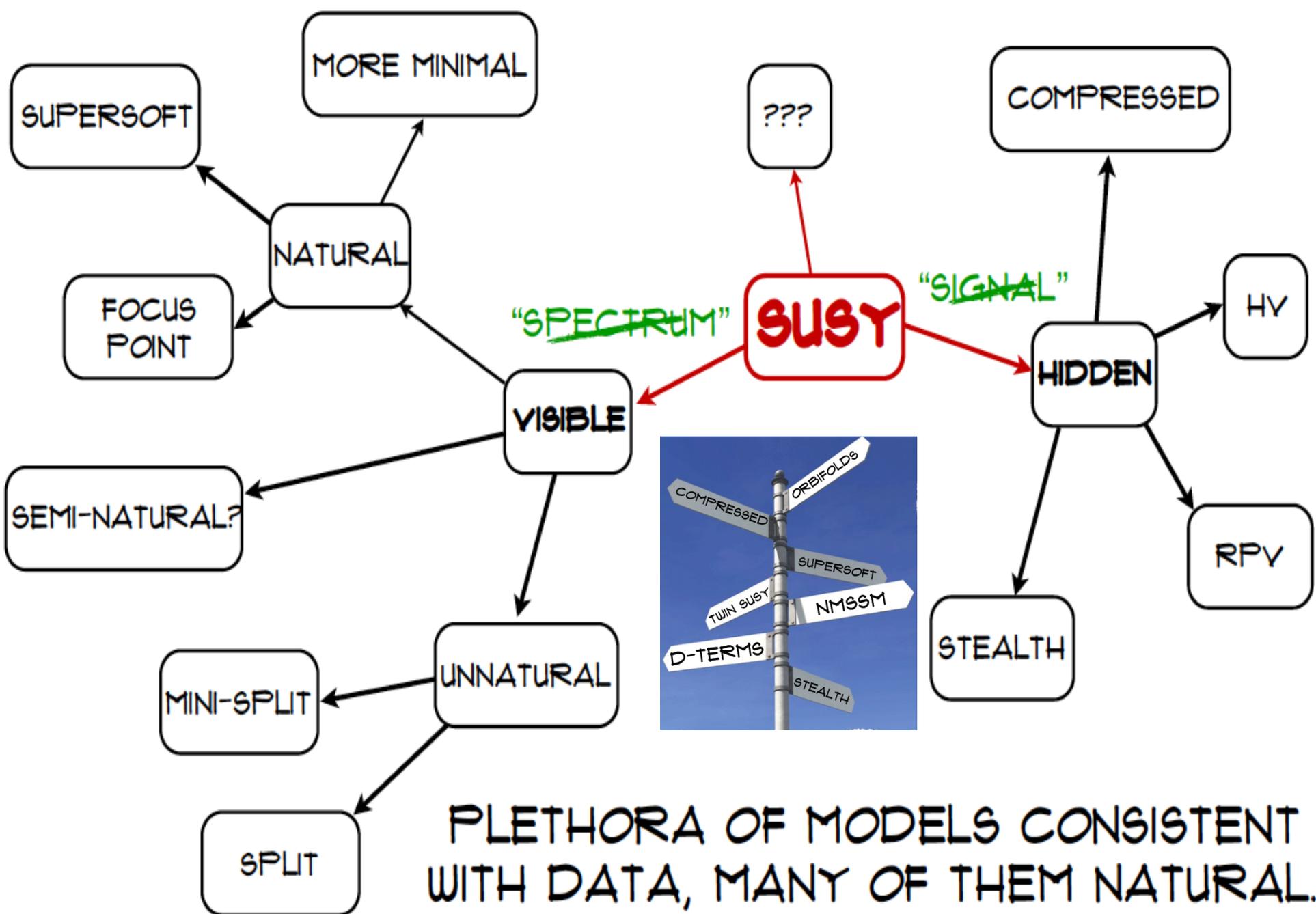


What else is there?

Supersymmetry

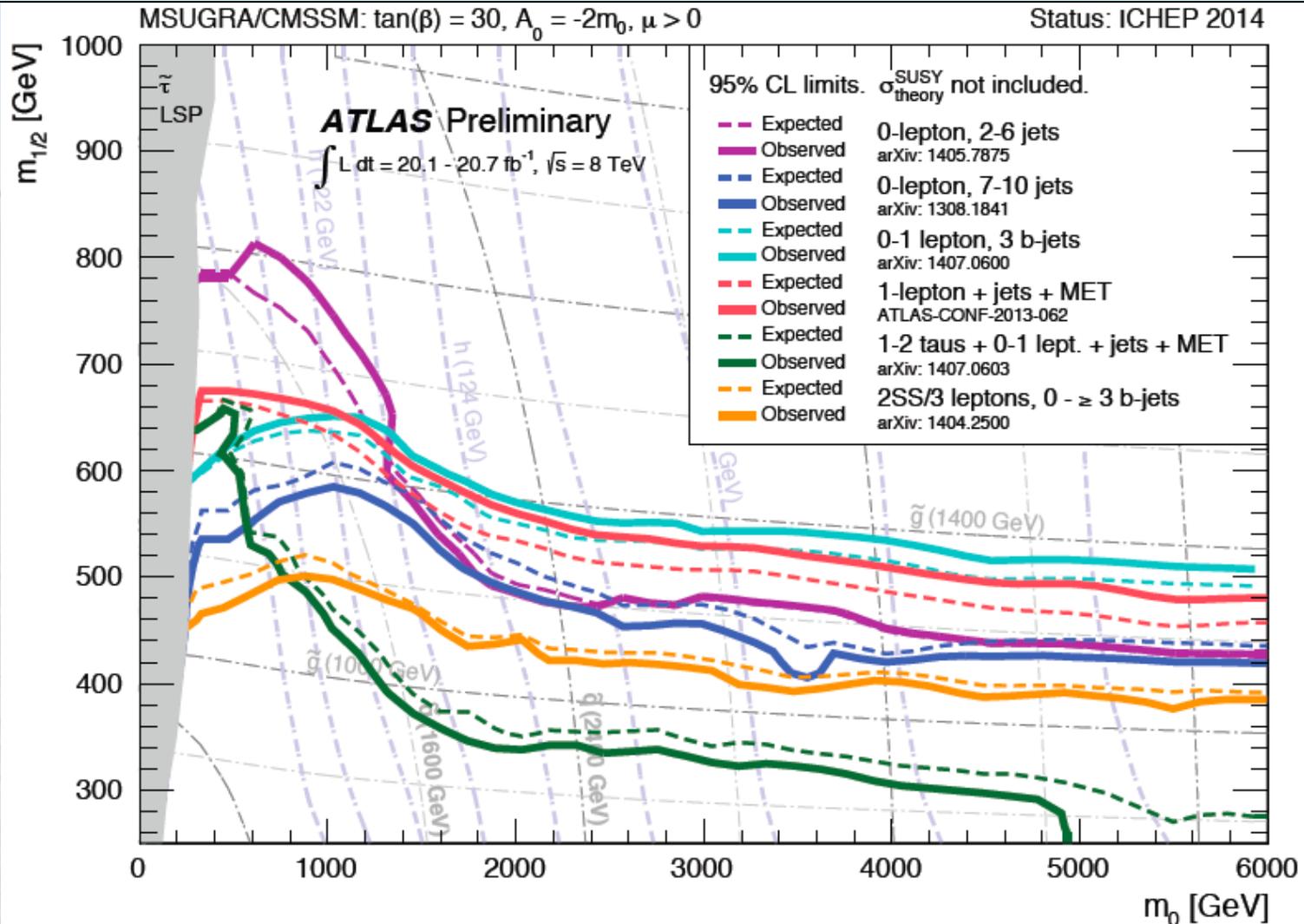
New motivations
From LHC Run 1

- **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, dark matter, GUTs, string, ...



PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?

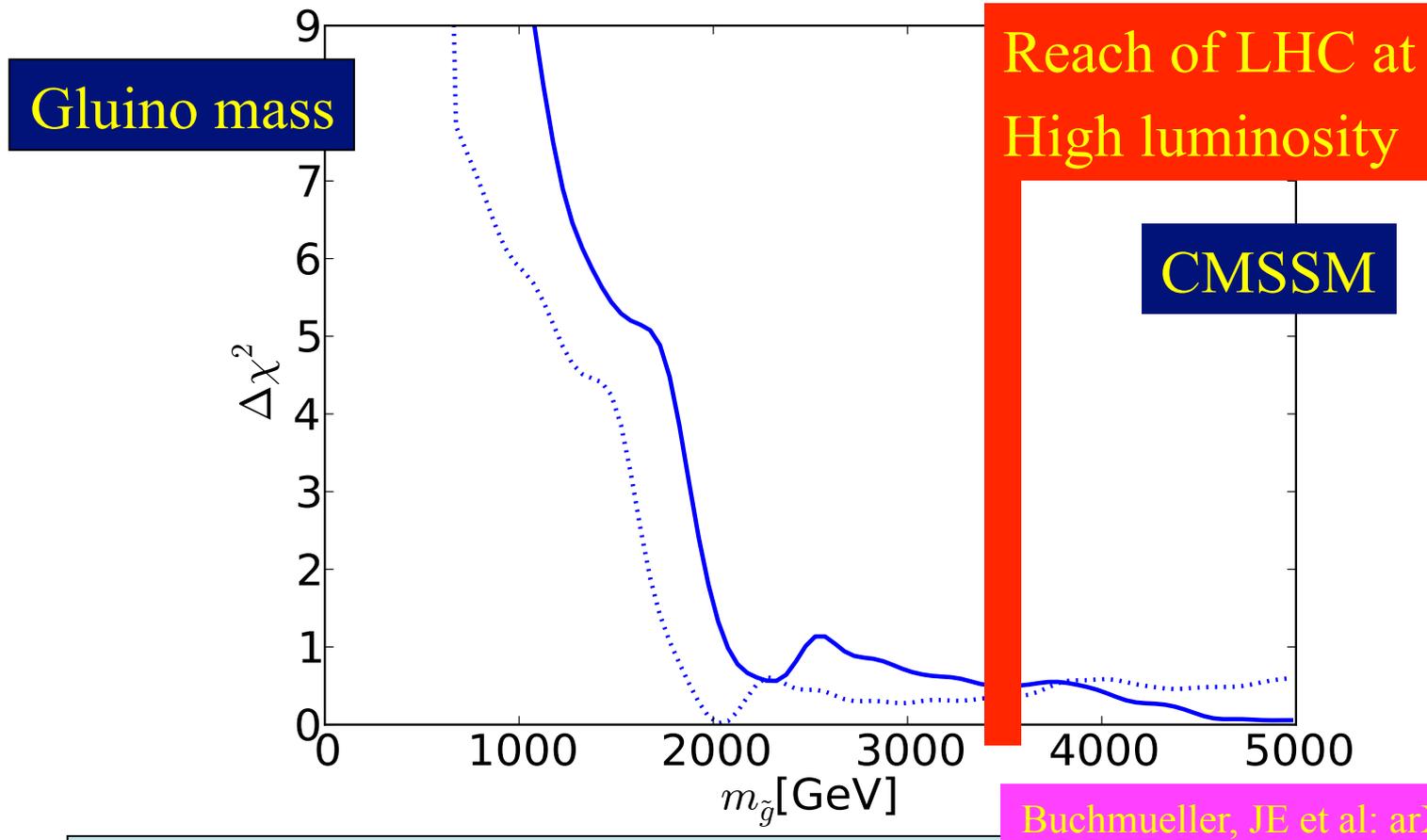
Searches with $\sim 20/\text{fb}$ @ 8 TeV



CMSSM = universal sparticle masses @ GUT scale

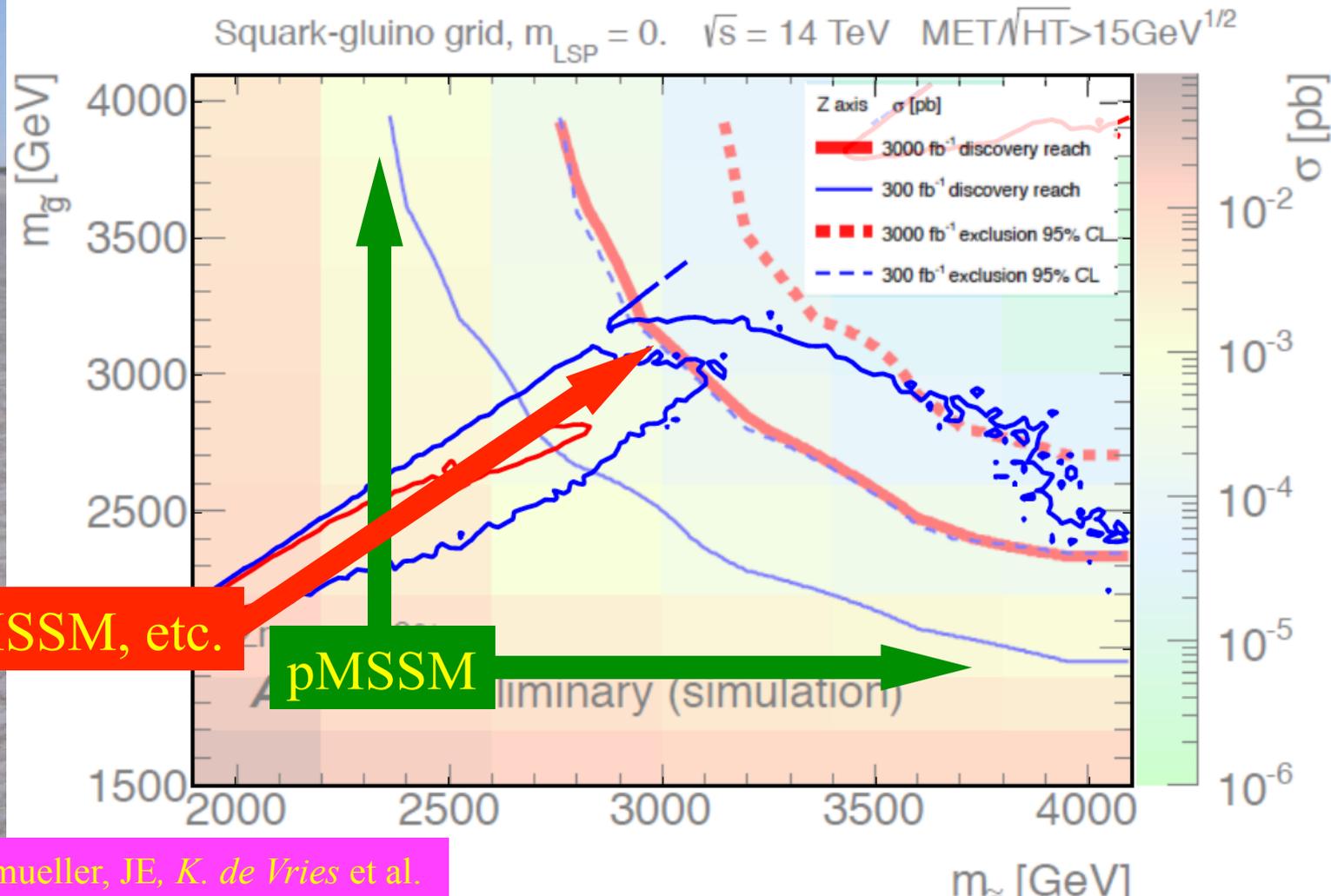
Constrained MSSM

2012 ATLAS + CMS with 20/fb of LHC Data



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

LHC Reach for Supersymmetry



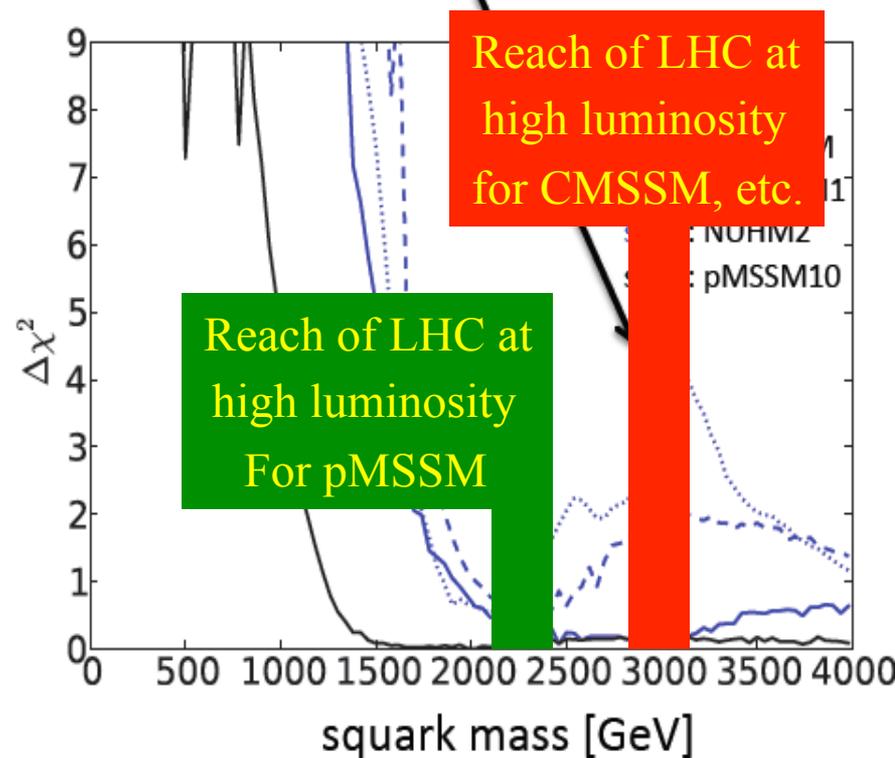
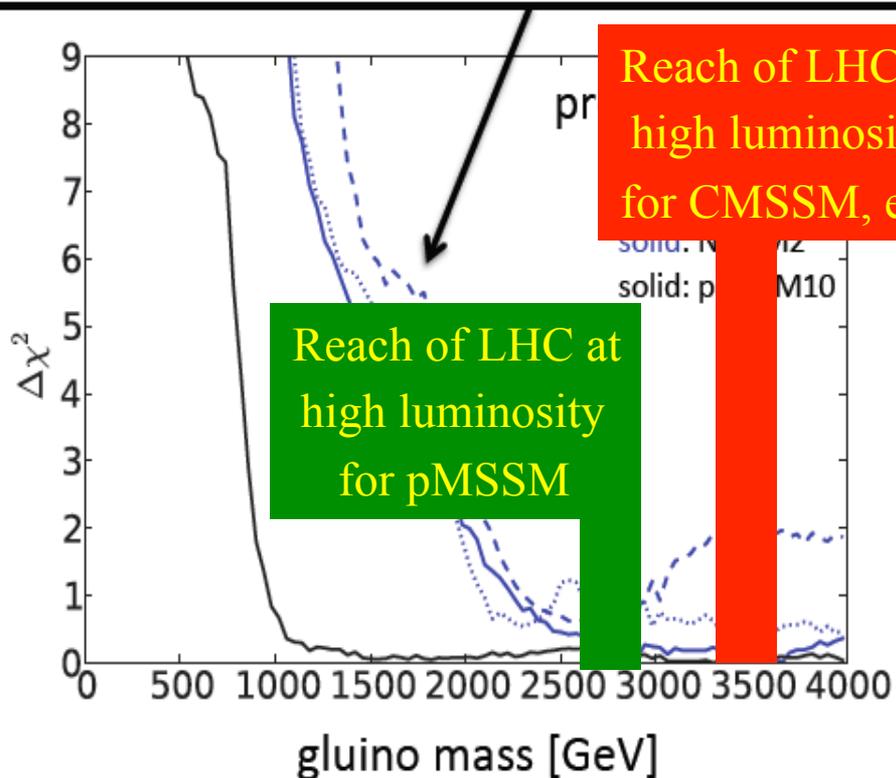
O. Buchmueller, JE, K. de Vries et al.

More possibilities in unconstrained pMSSM

Glino, Squark Masses in Models

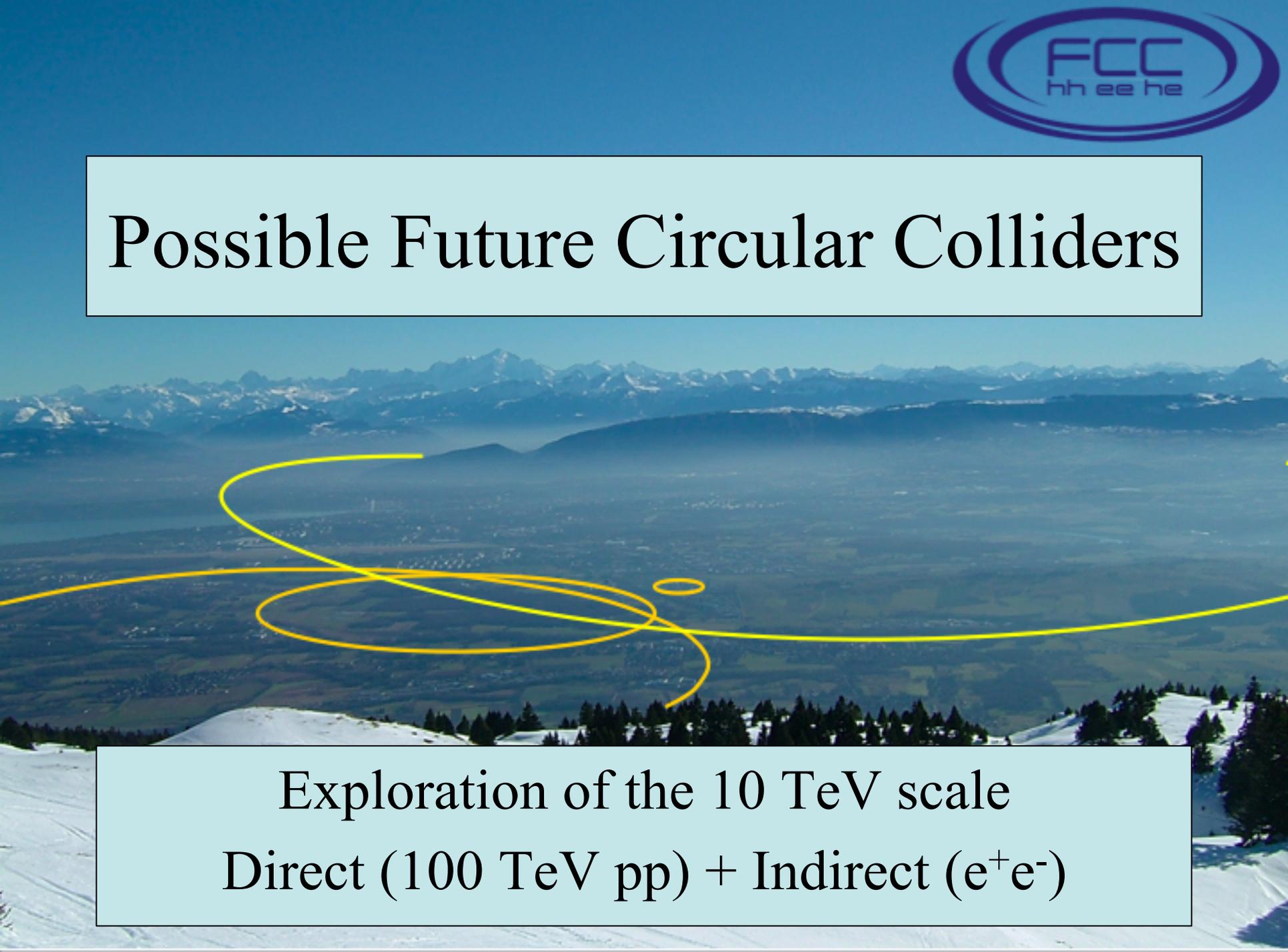
2012 ATLAS + CMS with 20/fb of LHC Data

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.



Lower masses still allowed in pMSSM

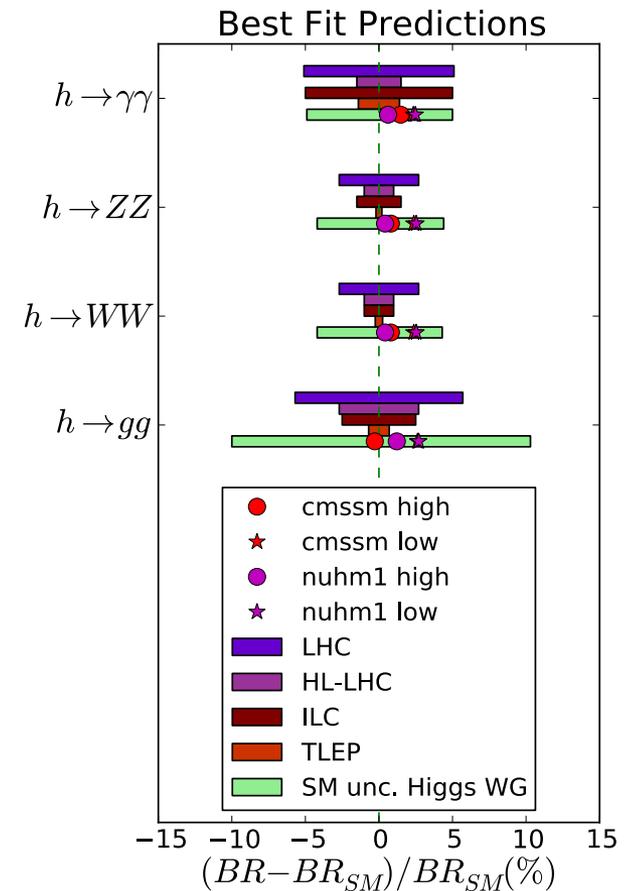
Possible Future Circular Colliders



Exploration of the 10 TeV scale
Direct (100 TeV pp) + Indirect (e^+e^-)

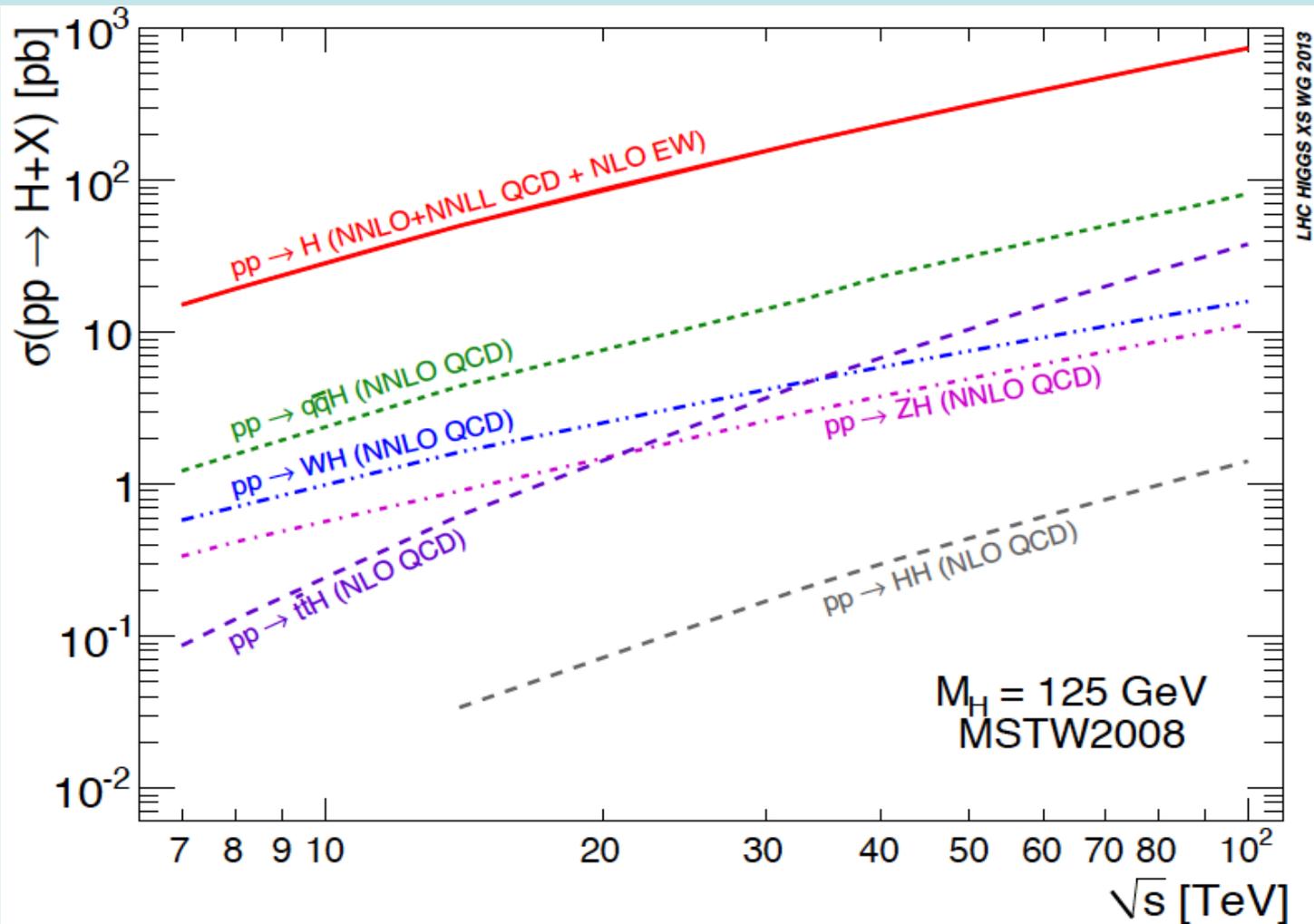
Higgs Coupling Measurements

- 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)**



Higgs Cross Sections

- At the LHC and beyond:



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]