

Phenomenology Overview

What is the Higgs boson
trying to tell us?

Is supersymmetry awaiting us?

Can LHC Run 2 find it?

What if X(750) exists?

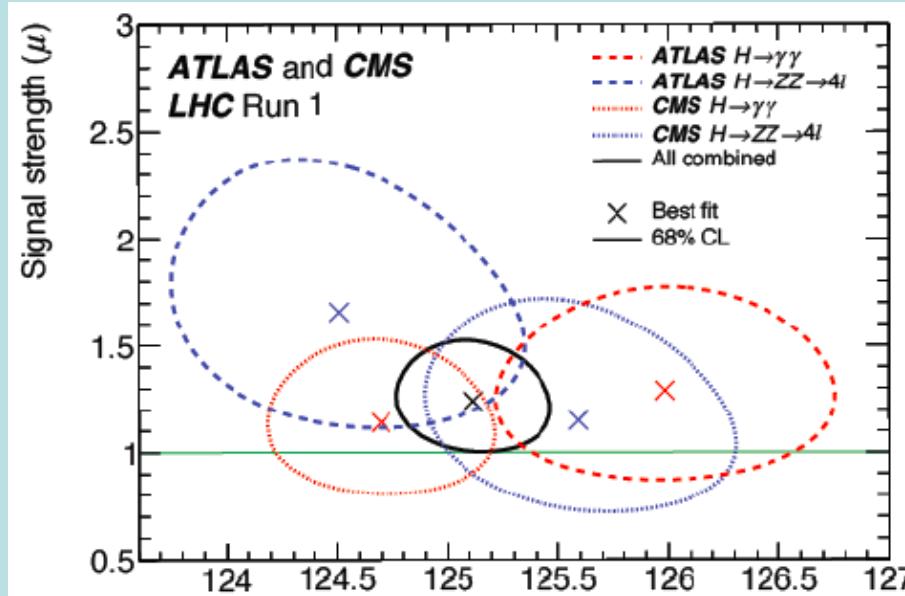
Beyond the LHC?

John Ellis

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College
LONDON

Higgs Mass Measurements

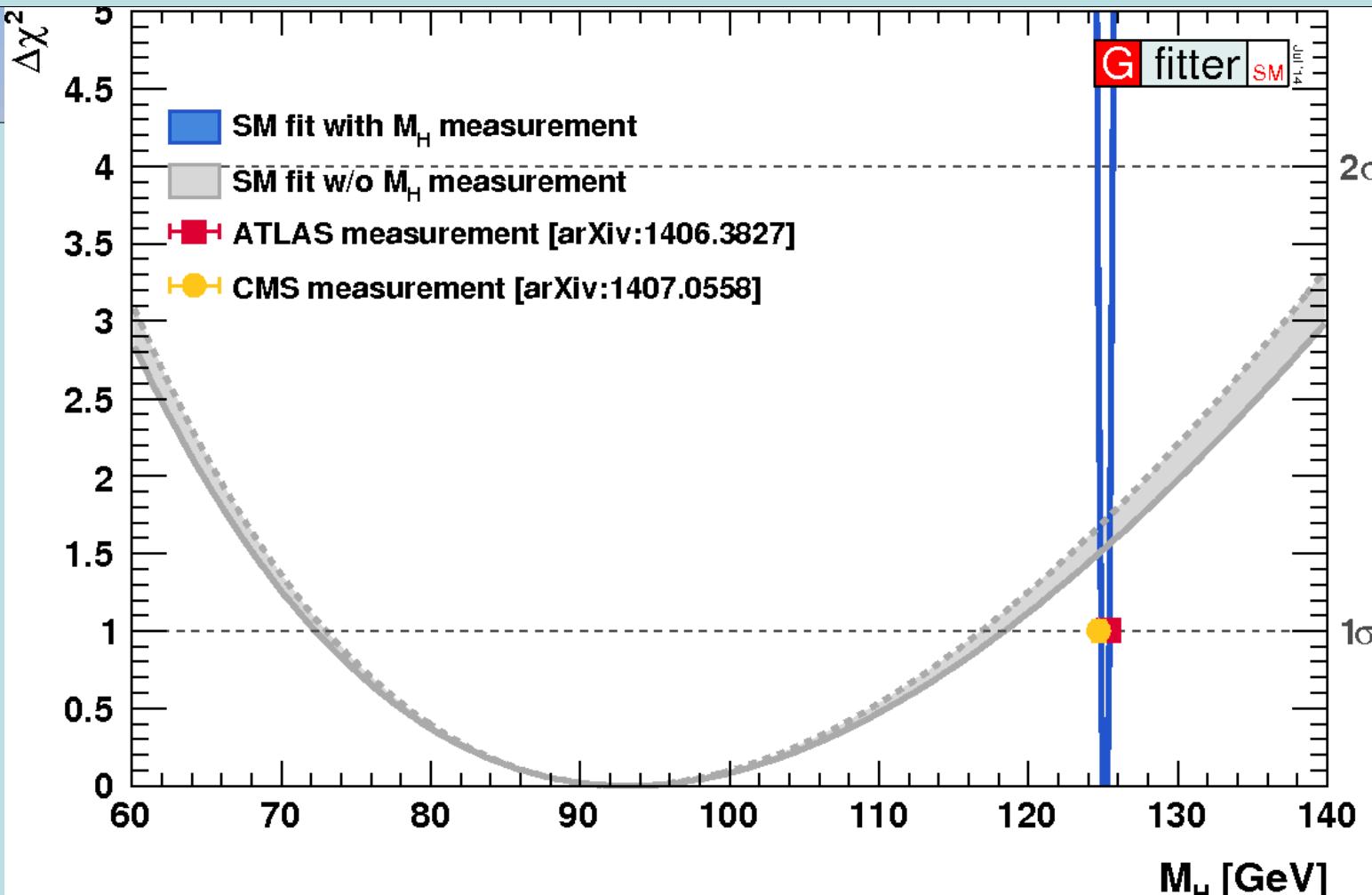
- ATLAS + CMS ZZ* and $\gamma\gamma$ final states



125.09 ± 0.21 (stat) ± 0.11 (syst)

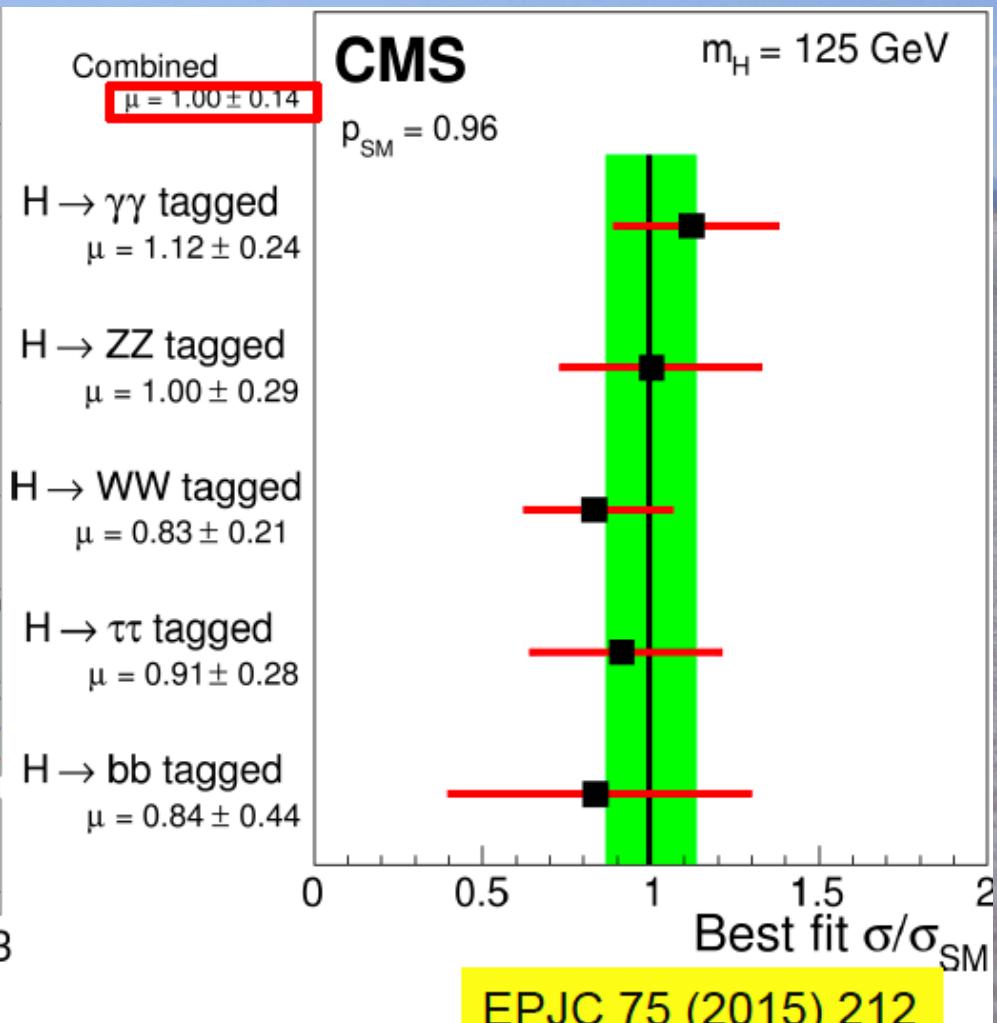
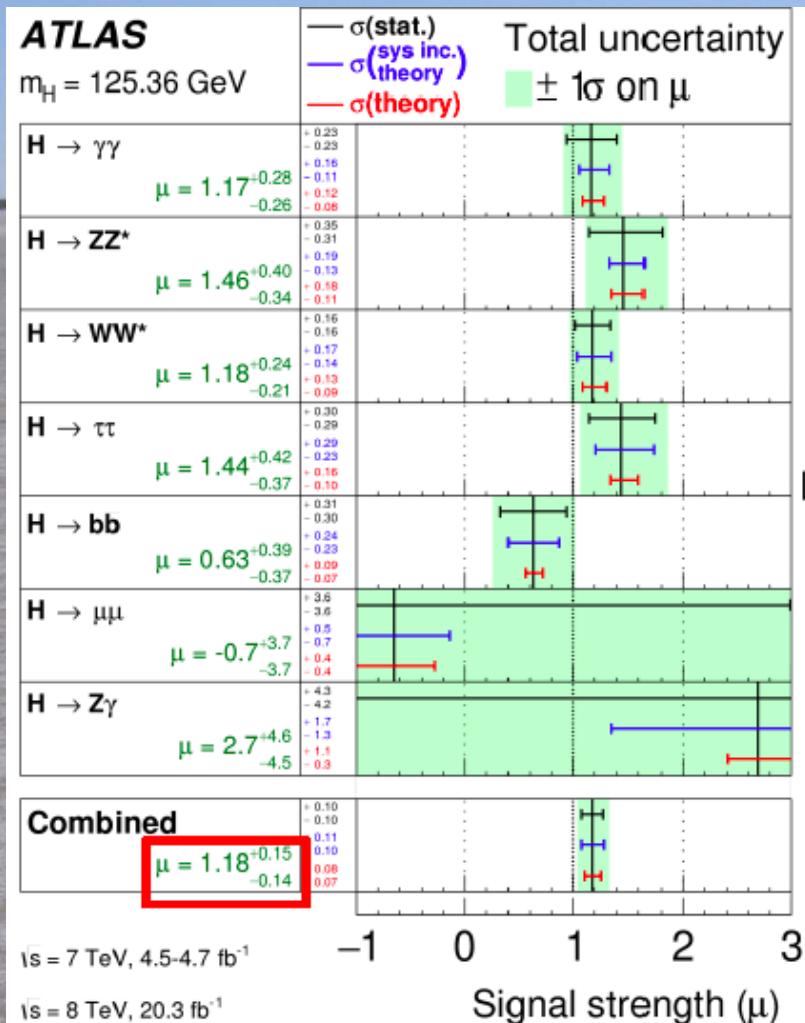
- Statistical uncertainties dominate
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

Measured m_H Compared with Electroweak Fit



Quite consistent: $\Delta\chi^2 \sim 1.5$

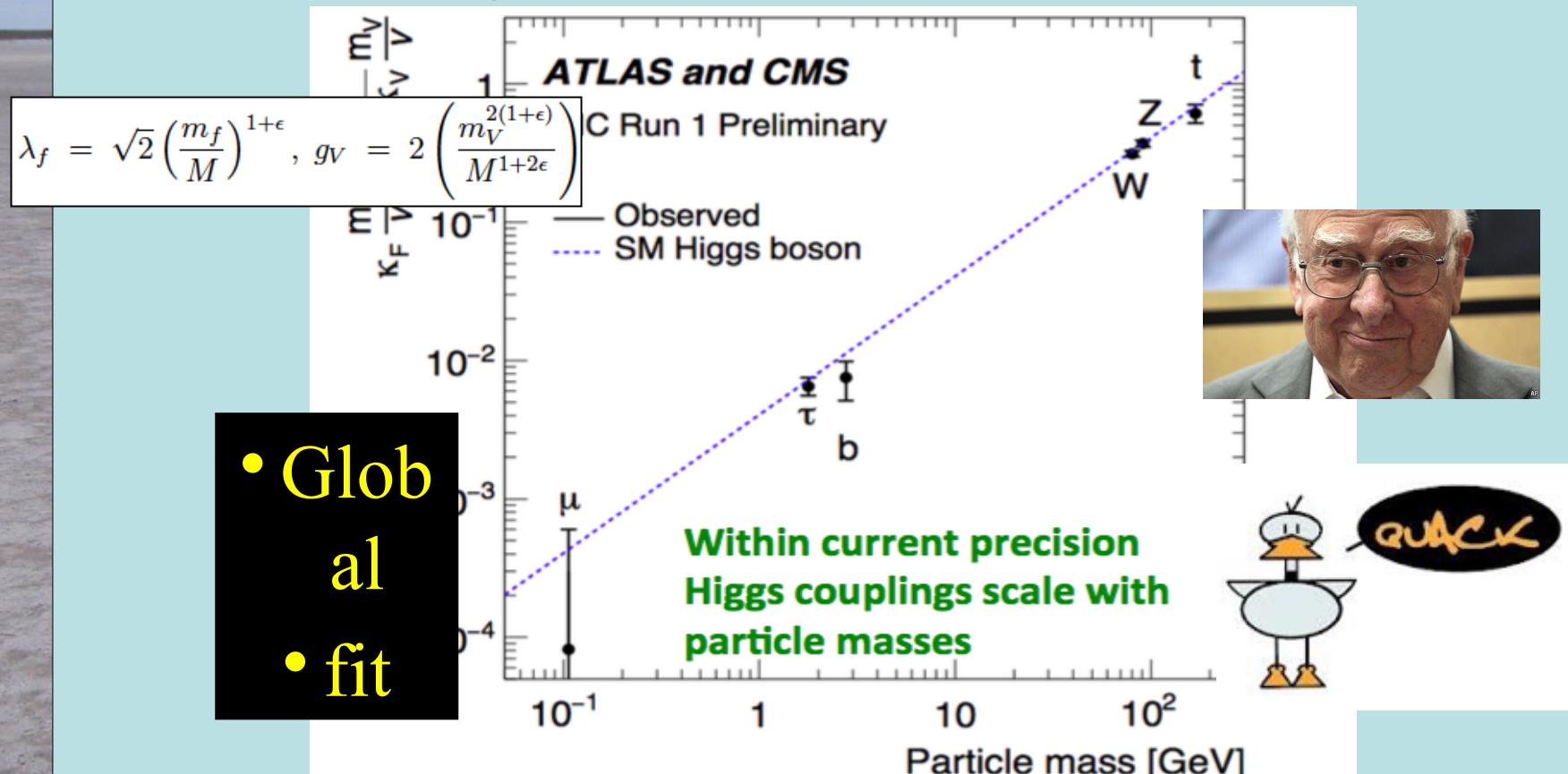
Higgs Signal Strengths



- Globally, Standard Model OK @ 10% level

It Walks and Quacks like a Higgs

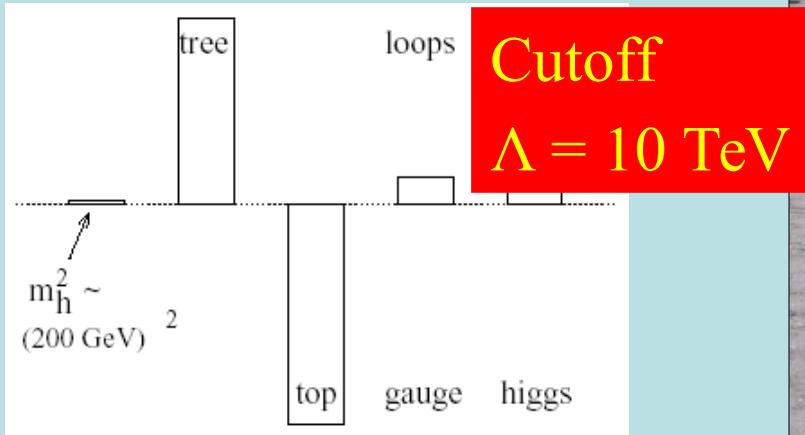
- Do couplings scale \sim mass? With scale = v?



- Blue dashed line = Standard Model

Elementary Higgs or Composite?

- Higgs field:
 $\langle 0|H|0 \rangle \neq 0$
- Quantum loop problems



Cut-off $\Lambda \sim 1 \text{ TeV}$ with
Supersymmetry?

Fermion-antifermion
condensate

Just like QCD, BCS
superconductivity
Top-antitop condensate?
needed $m_t > 200 \text{ GeV}$

New technicolour force?
- Heavy scalar resonance?
- Inconsistent with
precision electroweak data?
- Little Higgs, ...

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 :

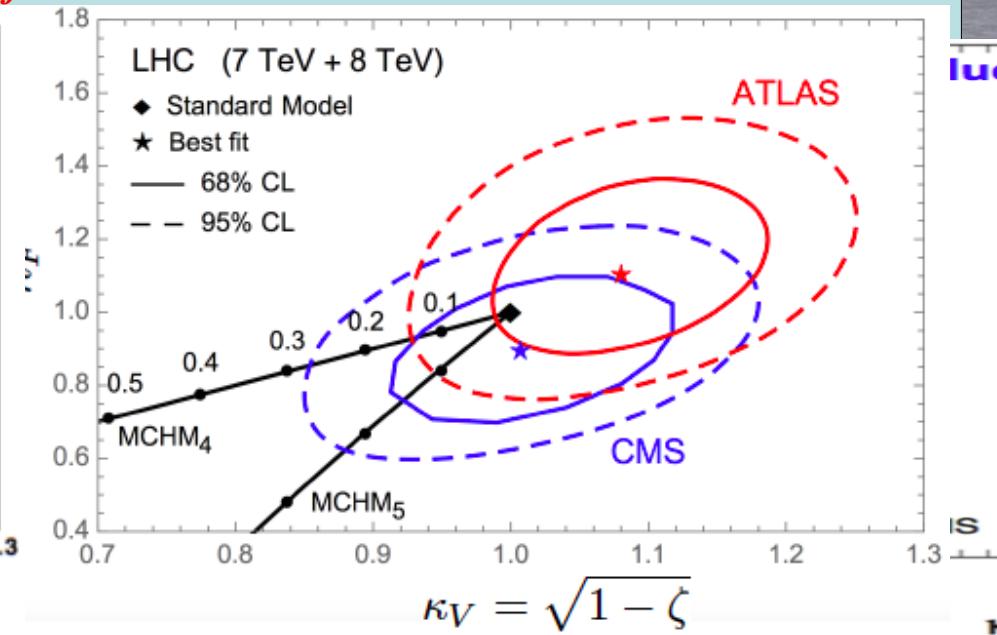
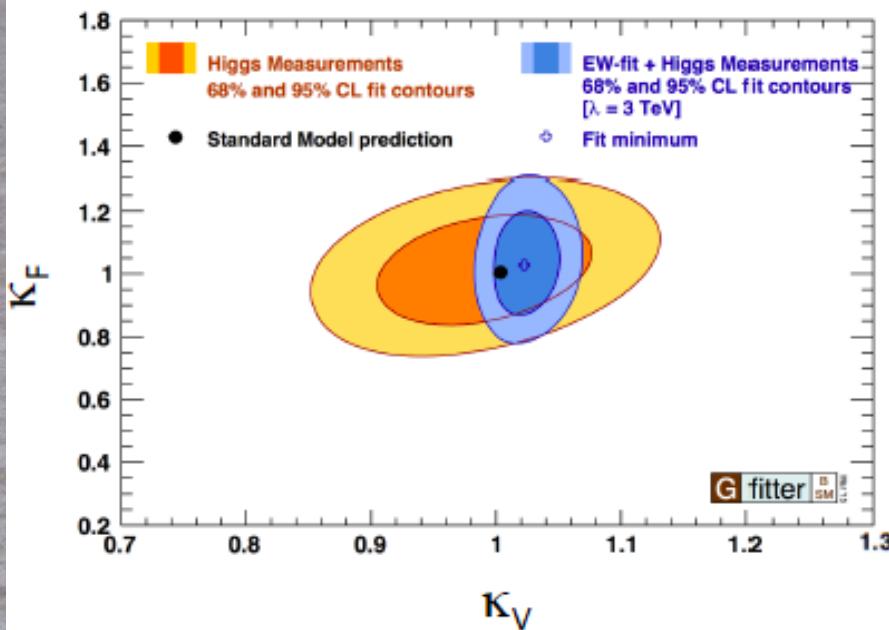
$$\begin{aligned} \mathcal{L} = & \frac{v^2}{4} \text{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma \left(1 + 2\textcolor{red}{a} \frac{h}{v} + \textcolor{red}{b} \frac{h^2}{v^2} + \dots \right) - m_i \bar{\psi}_L^i \Sigma \left(1 + \textcolor{red}{c} \frac{h}{v} + \dots \right) \psi_R^i + \text{h.c.} \\ & + \frac{1}{2} (\partial_\mu h)^2 + \frac{1}{2} m_h^2 h^2 + \textcolor{red}{d}_3 \frac{1}{6} \left(\frac{3m_h^2}{v} \right) h^3 + \textcolor{red}{d}_4 \frac{1}{24} \left(\frac{3m_h^2}{v^2} \right) h^4 + \dots , \end{aligned}$$

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

- Coefficients $\textcolor{red}{a} = \textcolor{red}{c} = 1$ in Standard Model

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by κ_V , to fermions by κ_f
- Standard Model: $\kappa_V = \kappa_f = 1$



- Consistency between Higgs and EW measurements
- **Must tune composite models to look like SM**

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:

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

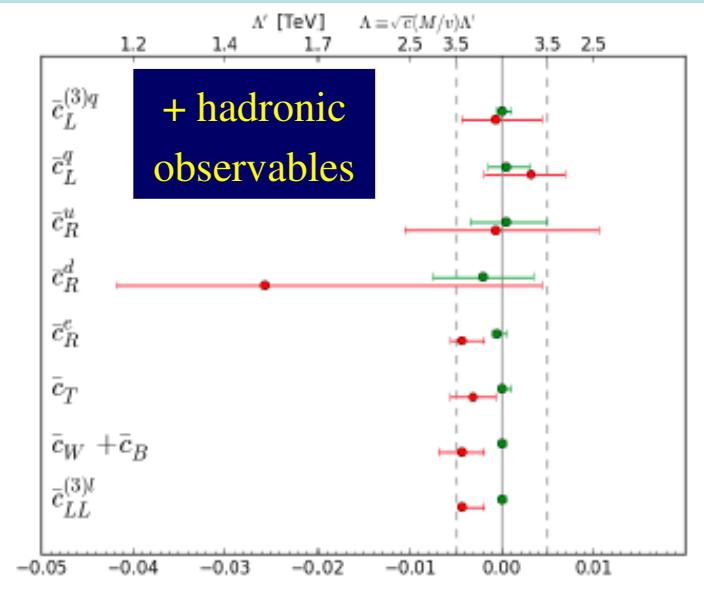
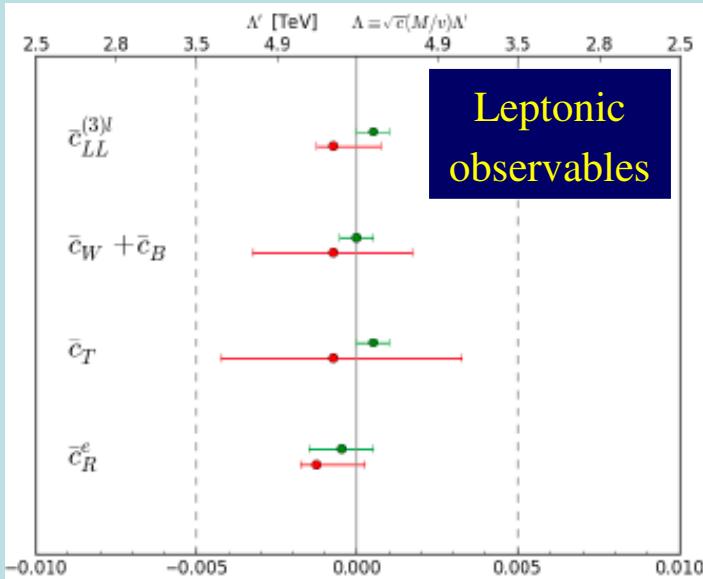
- Constrain with precision EW, Higgs data, TGCs ...

Electroweak Precision Data

- Operators affecting oblique parameters

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

- Also other electroweak tests
- Constraints from LEP et al. data

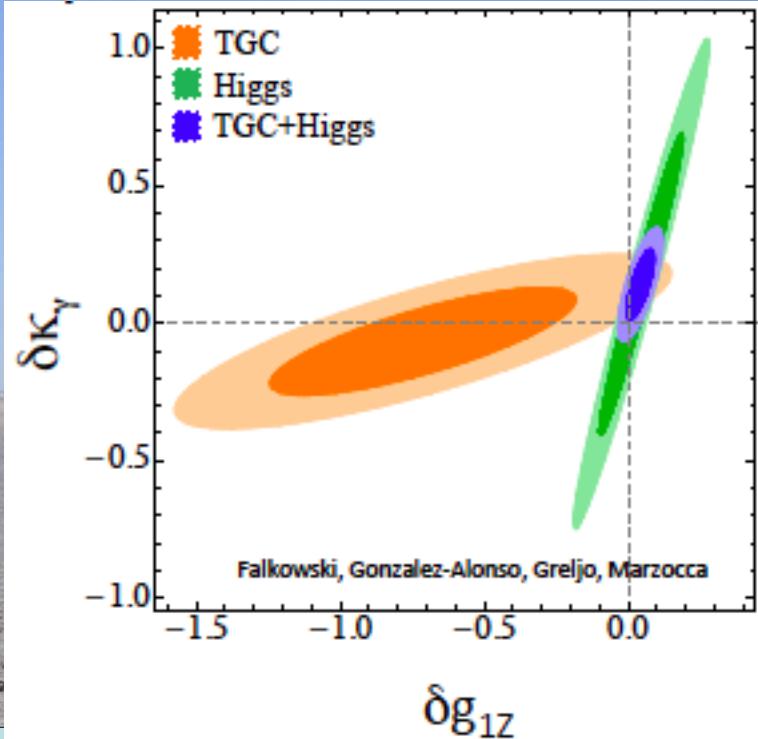
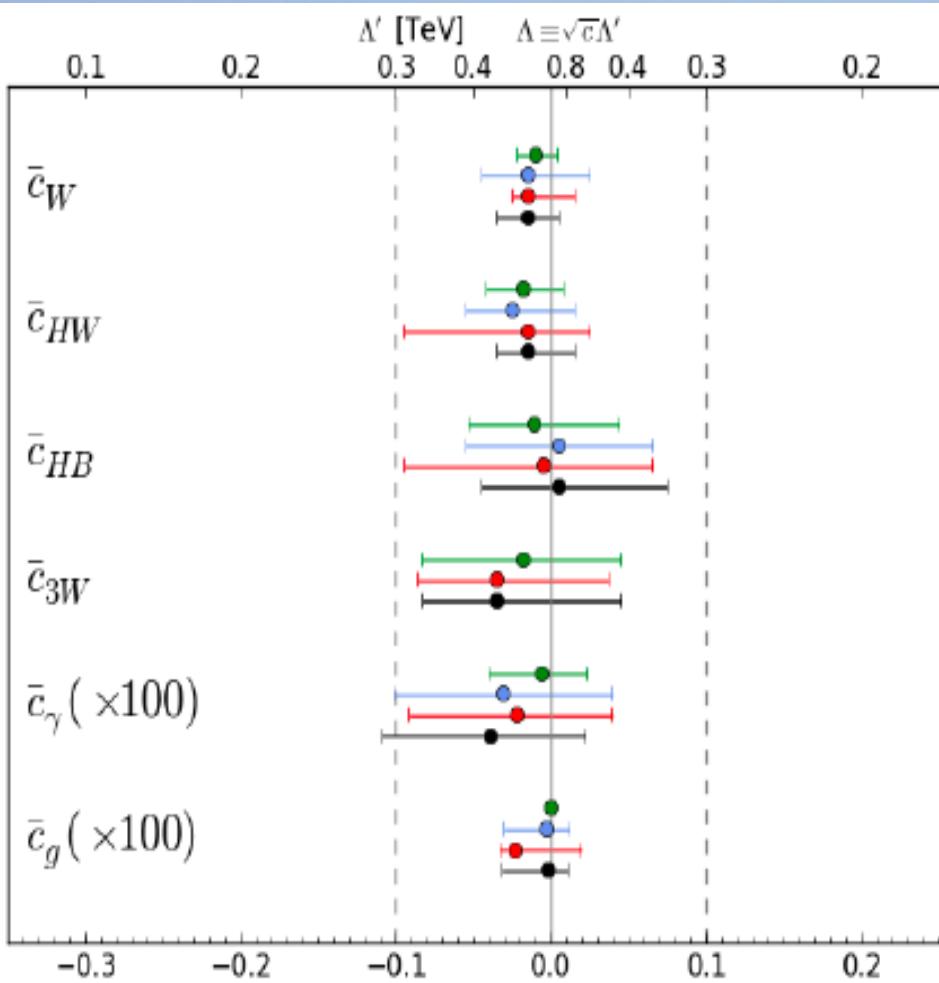


Fits to individual dimension-6 operators

Global fit to dimension-6 operators

JE, Sanz & Tevong You, arXiv:1410.7703

Global Fits including LHC TGCs



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



The Standard Model

- « Empty » space is unstable
- Dark matter
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity
- ...

SUSY

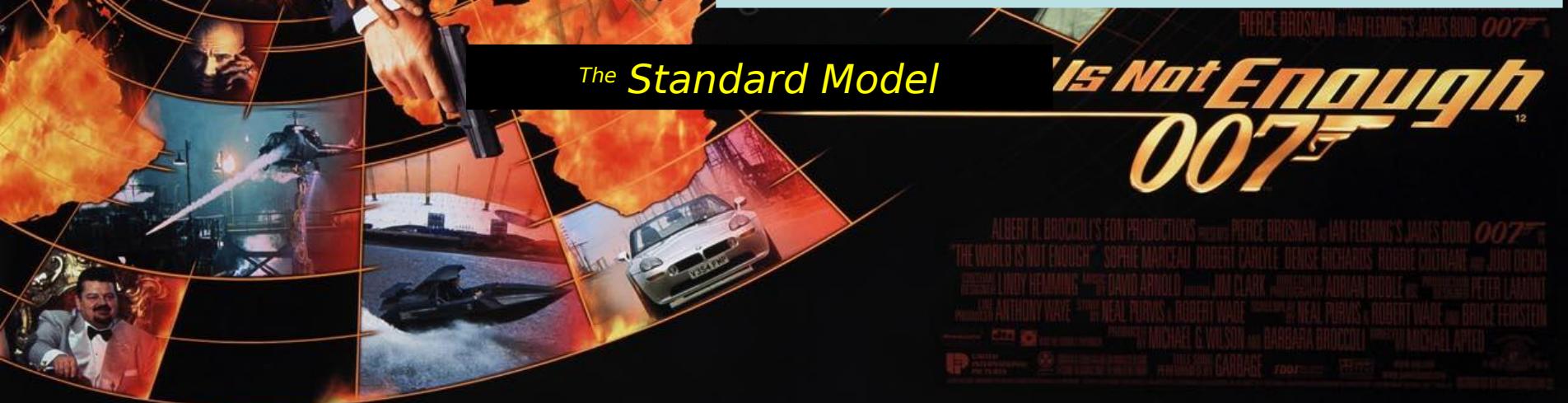
SUSY

SUSY

SUSY

SUSY

SUSY



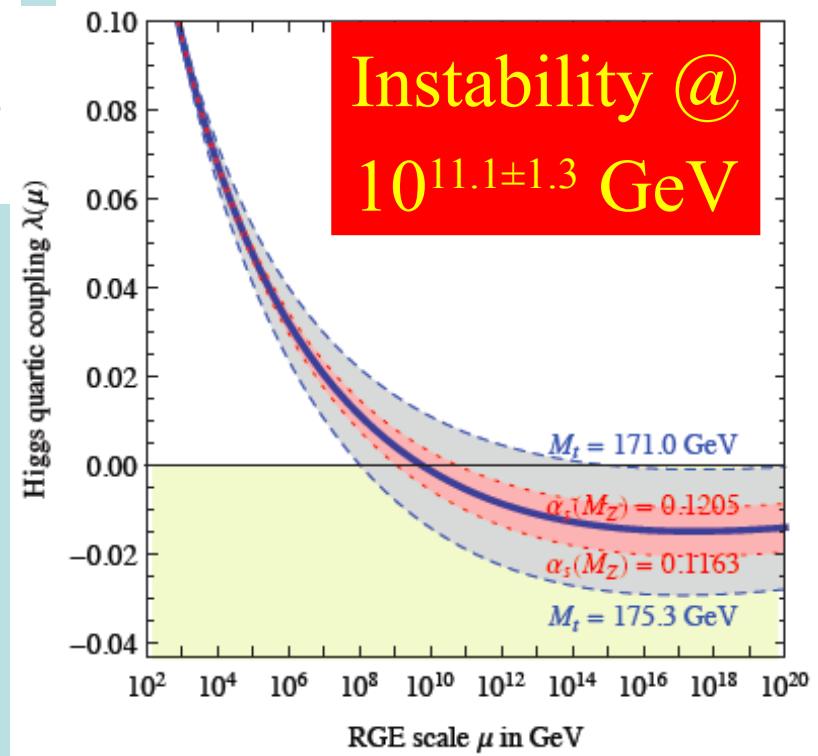
What lies beyond the Standard Model?

Supersymmetry

- **Stabilize electroweak vacuum** New motivations
From LHC Run 1
- **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**

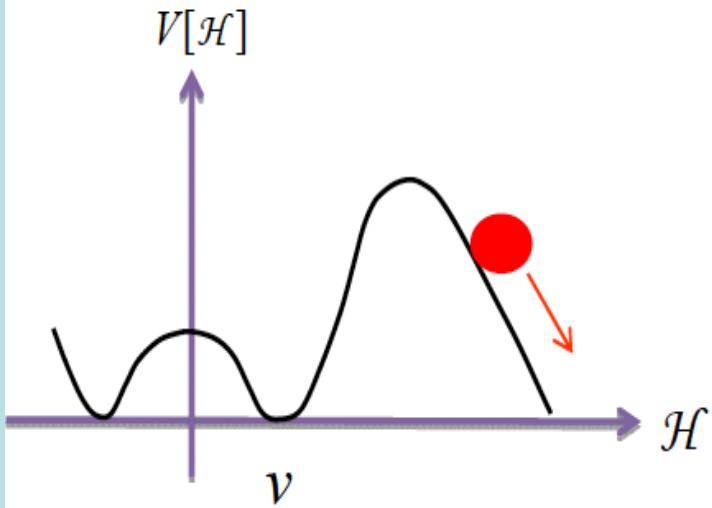
Theoretical Constraints on Higgs Mass

- Large $M_h \rightarrow$ large self-coupling λ \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**

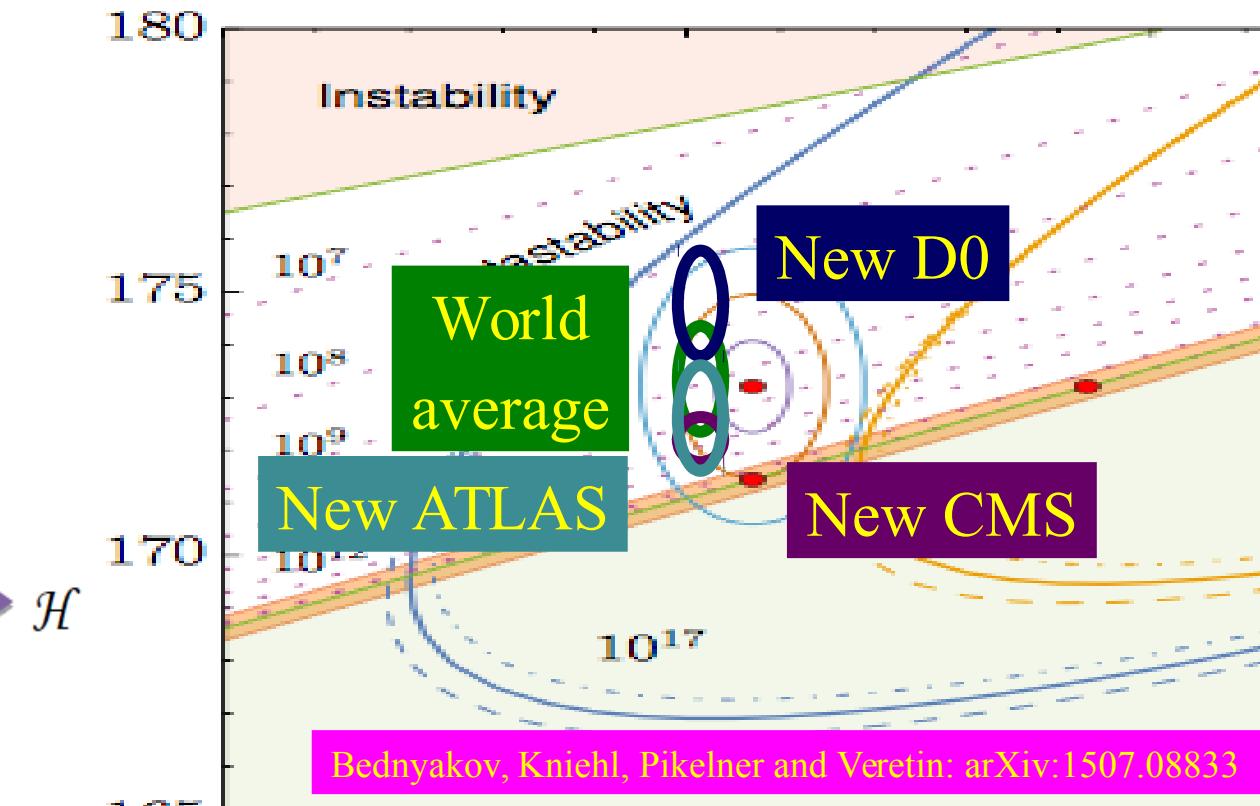


Vacuum Instability in the Standard Model

- Very sensitive to t



- Instability scale



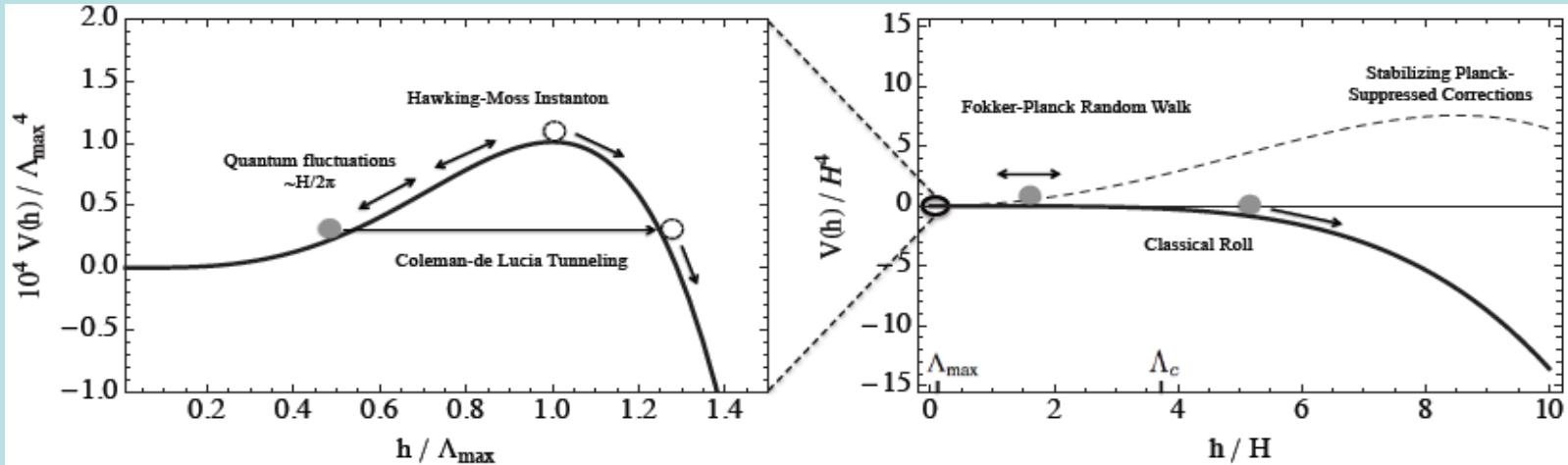
$$\log_{10} \frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0 \left(\frac{M_h}{\text{GeV}} - 125.66 \right) - 1.2 \left(\frac{M_t}{\text{GeV}} - 173.10 \right) + 0.4 \frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

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

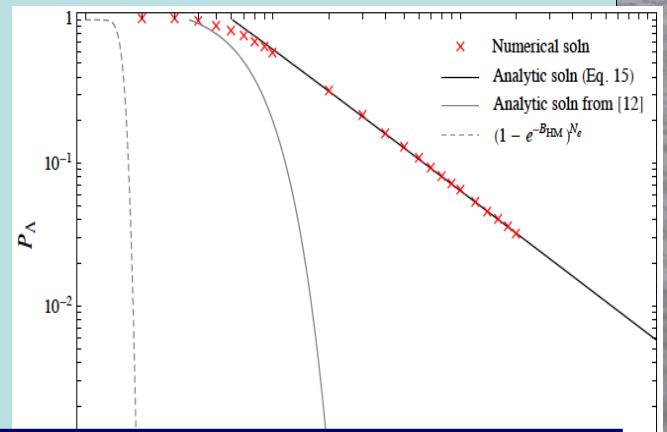
Instability during Inflation?

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



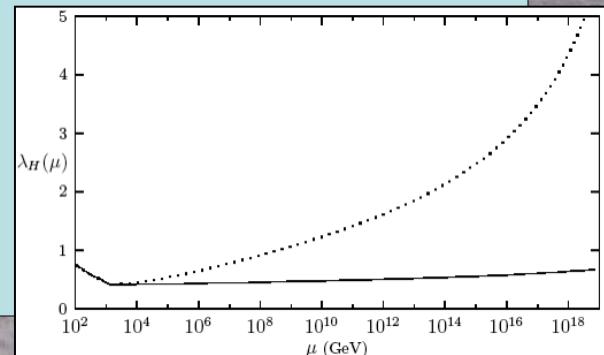
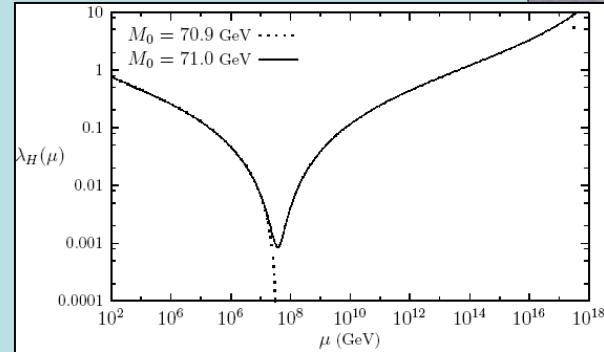
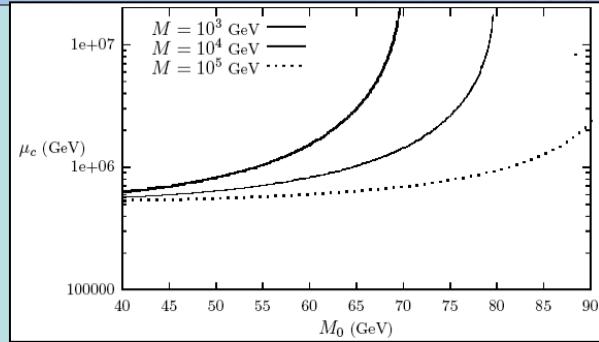
OK if some physics beyond the Standard Model?

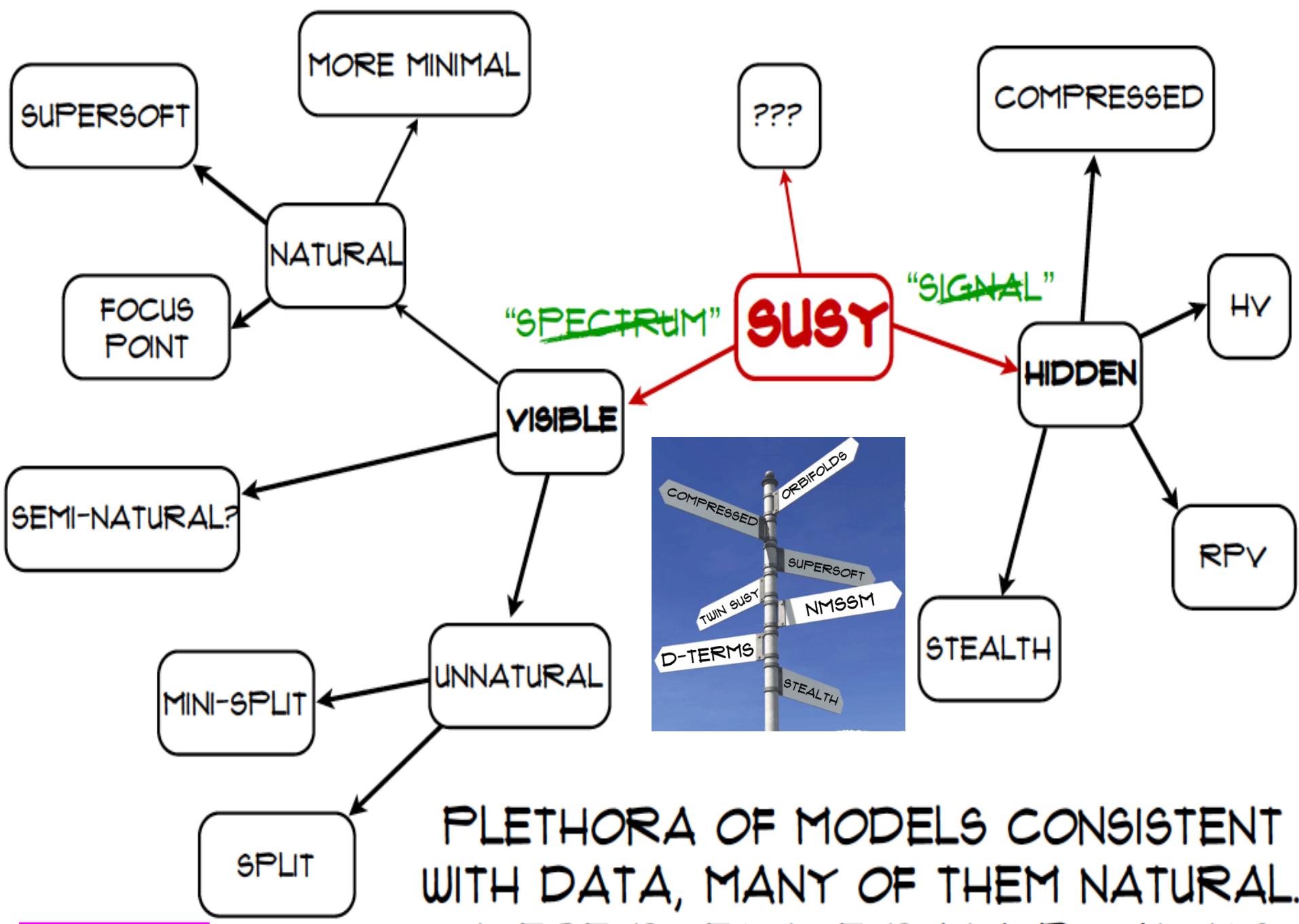
How to Stabilize a Light Higgs Boson?

- 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!**





Minimal Supersymmetric Extension of Standard Model (MSSM)

- Double up the known particles:

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \text{ e.g., } \begin{pmatrix} \ell \text{ (lepton)} \\ \tilde{\ell} \text{ (slepton)} \end{pmatrix} \text{ or } \begin{pmatrix} q \text{ (quark)} \\ \tilde{q} \text{ (squark)} \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \text{ e.g., } \begin{pmatrix} \gamma \text{ (photon)} \\ \tilde{\gamma} \text{ (photino)} \end{pmatrix} \text{ or } \begin{pmatrix} g \text{ (gluon)} \\ \tilde{g} \text{ (gluino)} \end{pmatrix}$$

- Two Higgs doublets
 - 5 physical Higgs bosons:
 - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

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 \rightarrow lighter sparticles
- **Lightest supersymmetric particle (LSP) stable**

LSP as Dark Matter?

- 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 detection)

Data

- Electroweak precision observables
- Flavour physics observables
- $g_\mu - 2$
- Higgs mass
- Dark matter
- LHC

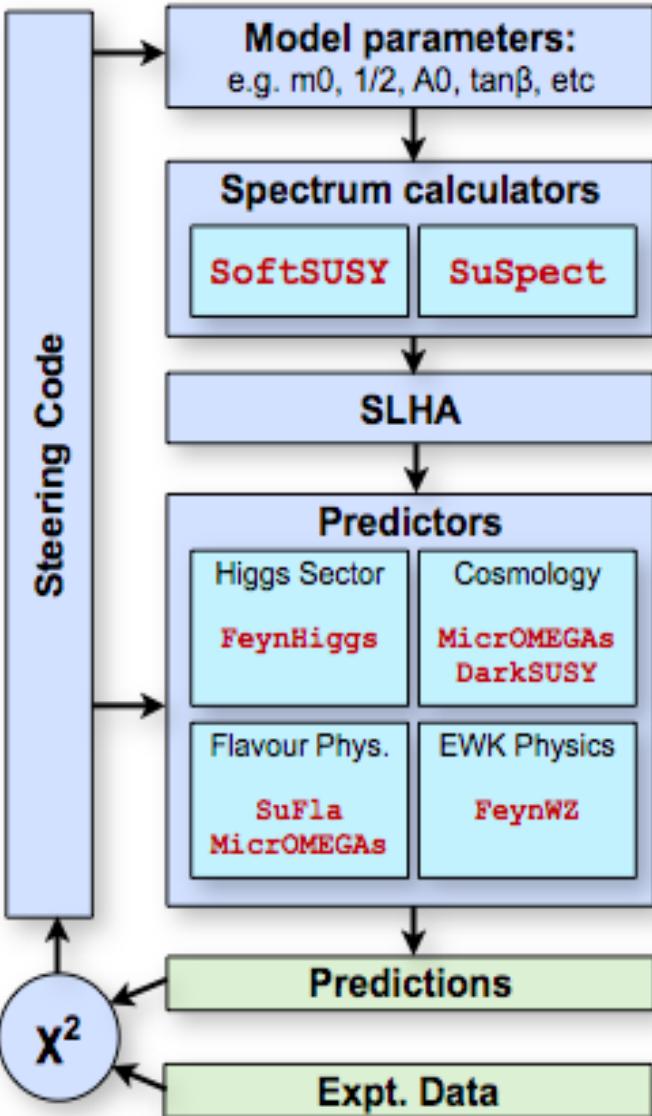
Deviation from Standard Model:
Supersymmetry at low scale, or ...?

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\text{SUSY}}$
σ_{had}^0 [nb]	[24] / [40]	41.540 ± 0.037
R_l	[24] / [40]	20.767 ± 0.025
$A_{\text{fb}}(\ell)$	[24] / [40]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[24] / [40]	0.1465 ± 0.0032
R_b	[24] / [40]	0.21629 ± 0.00066
R_c	[24] / [40]	0.1721 ± 0.0030
$A_{\text{fb}}(b)$	[24] / [40]	0.0992 ± 0.0016
$A_{\text{fb}}(c)$	[24] / [40]	0.0707 ± 0.0035
A_b	[24] / [40]	0.923 ± 0.020
A_c	[24] / [40]	0.670 ± 0.027
$A_\ell(\text{SLD})$	[24] / [40]	0.1513 ± 0.0021
$\sin^2 \theta_w^{\ell} (Q_{\text{fb}})$	[24] / [40]	0.2324 ± 0.0012
M_W [GeV]	[24] / [40]	$80.399 \pm 0.023 \pm 0.010_{\text{SUSY}}$
$\text{BR}_{b \rightarrow s\gamma}^{\text{EXP}} / \text{BR}_{b \rightarrow s\gamma}^{\text{SM}}$	[41] / [42]	$1.117 \pm 0.076_{\text{EXP}} \pm 0.082_{\text{SM}} \pm 0.050_{\text{SUSY}}$
	[27] / [37]	$(< 1.08 \pm 0.02_{\text{SUSY}}) \times 10^{-8}$
	[27] / [42]	$1.43 \pm 0.43_{\text{EXP+TH}}$
	[27] / [42]	$< (4.6 \pm 0.01_{\text{SUSY}}) \times 10^{-9}$
	[43] / [42]	0.99 ± 0.32
$\text{BR}_{K \rightarrow \mu\nu}^{\text{EXP}} / \text{BR}_{K \rightarrow \mu\nu}^{\text{SM}}$	[27] / [44]	$1.008 \pm 0.014_{\text{EXP+TH}}$
$\text{BR}_{K \rightarrow \pi\nu\bar{\nu}}^{\text{EXP}} / \text{BR}_{K \rightarrow \pi\nu\bar{\nu}}^{\text{SM}}$	[45] / [46]	< 4.5
$\Delta M_{B_s}^{\text{EXP}} / \Delta M_{B_s}^{\text{SM}}$	[45] / [47, 48]	$0.97 \pm 0.01_{\text{EXP}} \pm 0.27_{\text{SM}}$
$(\Delta M_{B_d}^{\text{EXP}} / \Delta M_{B_d}^{\text{SM}})$	[27] / [42, 47, 48]	$1.00 \pm 0.01_{\text{EXP}} \pm 0.13_{\text{SM}}$
$\Delta \epsilon_K^{\text{EXP}} / \Delta \epsilon_K^{\text{SM}}$	[45] / [47, 48]	$1.08 \pm 0.14_{\text{EXP+TH}}$
$a_s^{\text{EXP}} - a_s^{\text{SM}}$	[49] / [38, 50]	$(30.2 \pm 8.8 \pm 2.0_{\text{SUSY}}) \times 10^{-10}$
M_h	[23]	$125.09 \pm 0.24 \text{ GeV}$
Ω_C		$0.0056 \pm 0.012_{\text{SUSY}}$
σ_p		(m_{DM}, \vec{p}) plane
jets + E_T	[16, 18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan \beta)$ plane

MasterCode



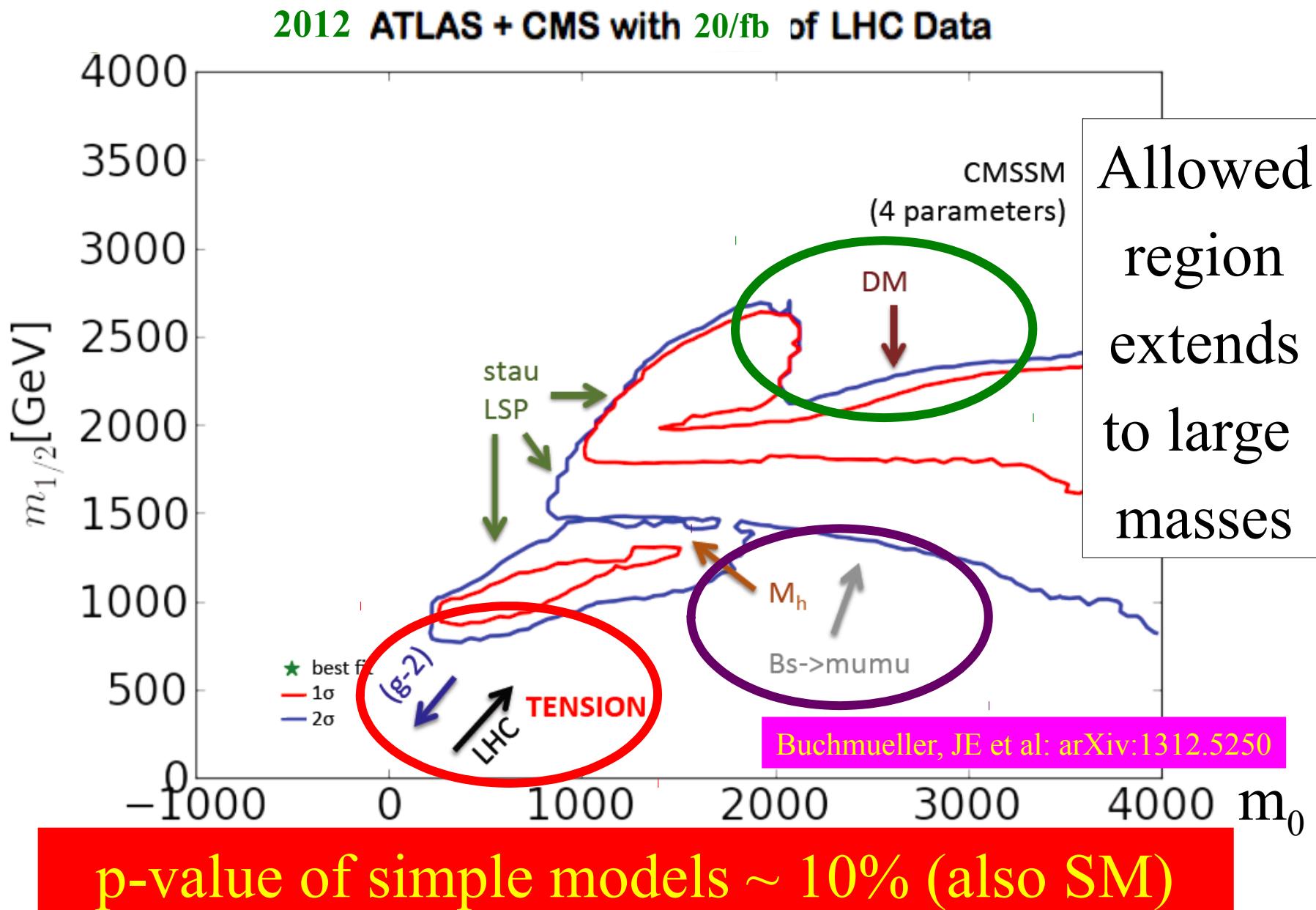
- Combines diverse set of tools
 - different codes : all state-of-the-art
 - Electroweak Precision (**FeynWZ**)
 - Flavour (**SuFla**, **micrOMEGAs**)
 - Cold Dark Matter (**DarkSUSY**, **micrOMEGAs**)
 - Other low energy (**FeynHiggs**)
 - Higgs (**FeynHiggs**) • LHC (**FastLim**, **Atom**, **Scorpion**)
 - different precisions (one-loop, two-loop, etc)
 - different languages (Fortran, C++, English, German, Italian, etc)
 - different people (theorists, experimentalists)
- Compatibility is crucial! Ensured by
 - close collaboration of tools authors
 - standard interfaces



Sample Supersymmetric Models

- Universal soft supersymmetry breaking at input GUT scale?
 - For gauginos and all scalars: CMSSM
 - Non-universal Higgs masses: NUHM1,2
- **Strong pressure from LHC ($p \sim 0.1$)**
- Treat soft supersymmetry-breaking masses as phenomenological inputs at EW scale
 - pMSSM n (n parameters)
 - With universality motivated by upper limits on flavour-changing neutral interactions: pMSSM10
- **Less strongly constrained by LHC ($p \sim 0.3$)**

Fit to Constrained MSSM (CMSSM)

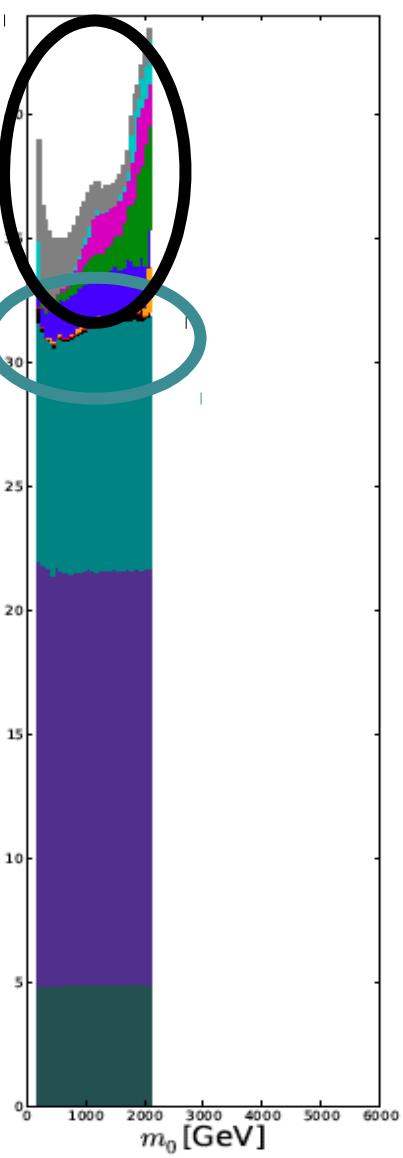
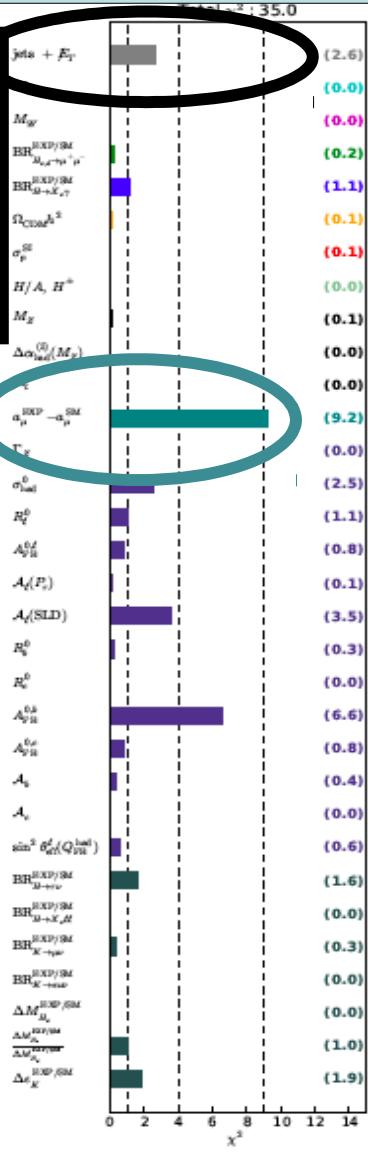


Constrained MSSM (CMSSM)

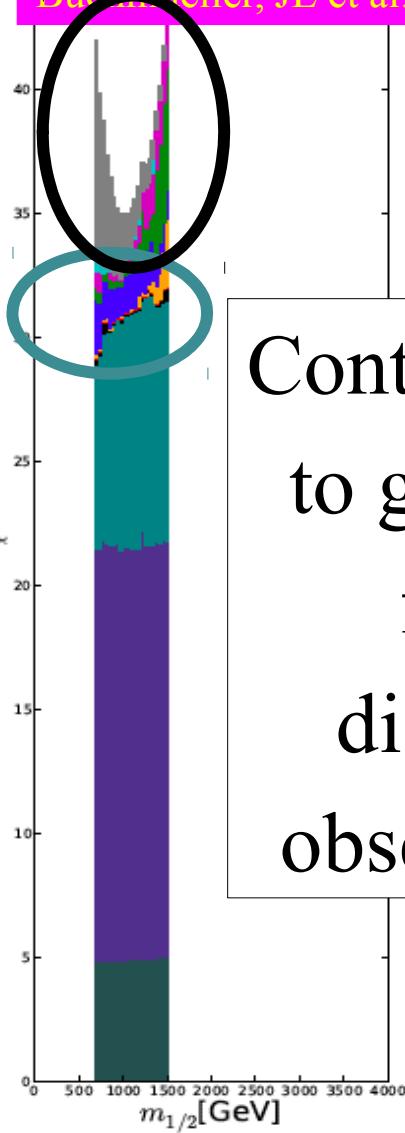


LHC
MET
searches

$g_\mu - 2$



Buchmueller, JE et al: arXiv:1312.5250



Contributions
to global χ^2
from
different
observables

$\text{jets} + E_T$	$BR(B_{s,d} \rightarrow \mu^+ \mu^-)$	σ_p^{SI}	$(g-2)_\mu$
M_h	$BR(B \rightarrow X_s \gamma)$	$H/A \rightarrow \tau^+ \tau^-$	$Z\text{-pole}$
$M_{\tilde{\chi}_1^0}$	$\Omega_{\text{CDMS}} h^2$	mischance	Other Flavour obs

Dark Matter Density Mechanisms



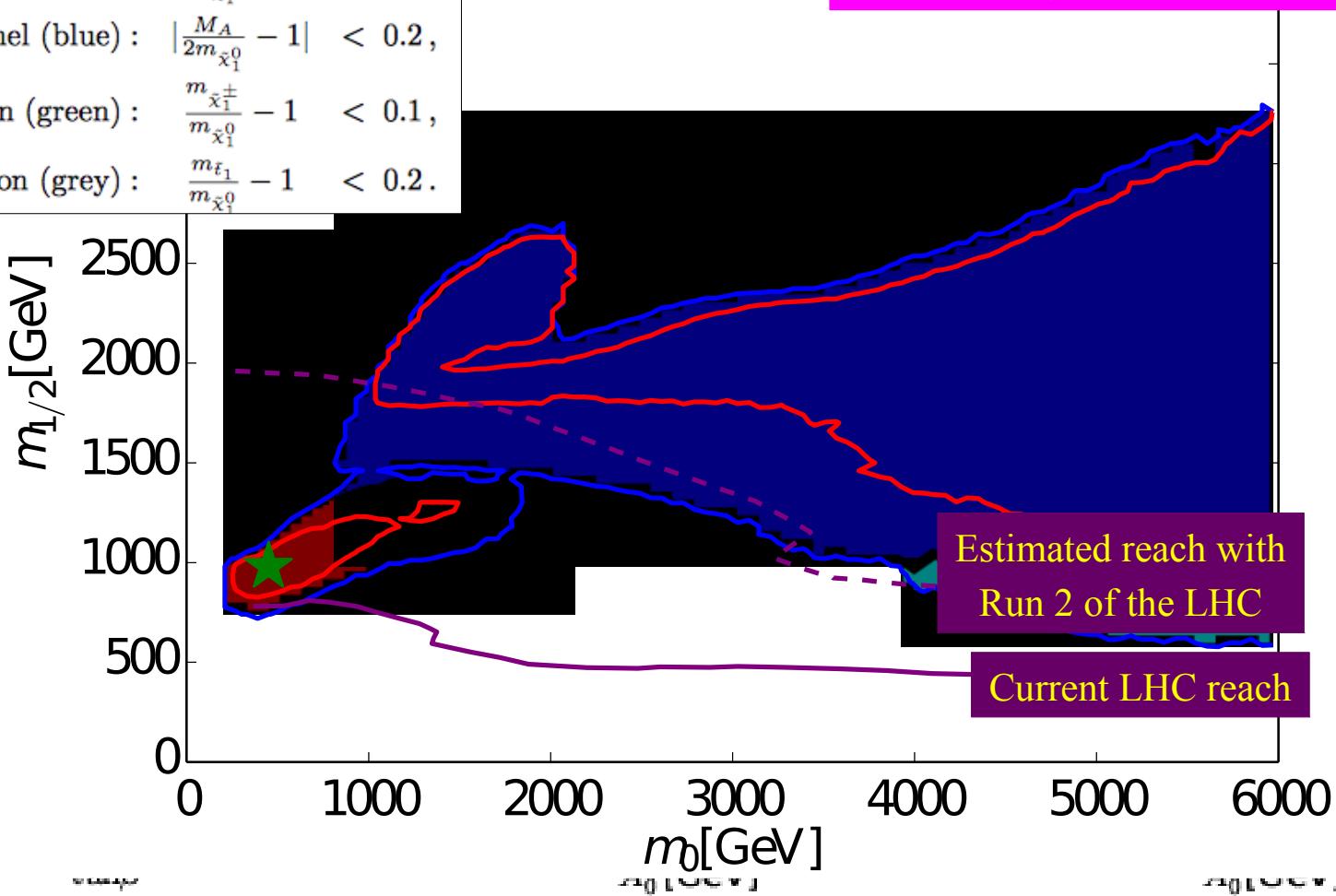
2012 ATLAS + CMS with 20/fb of LHC Data



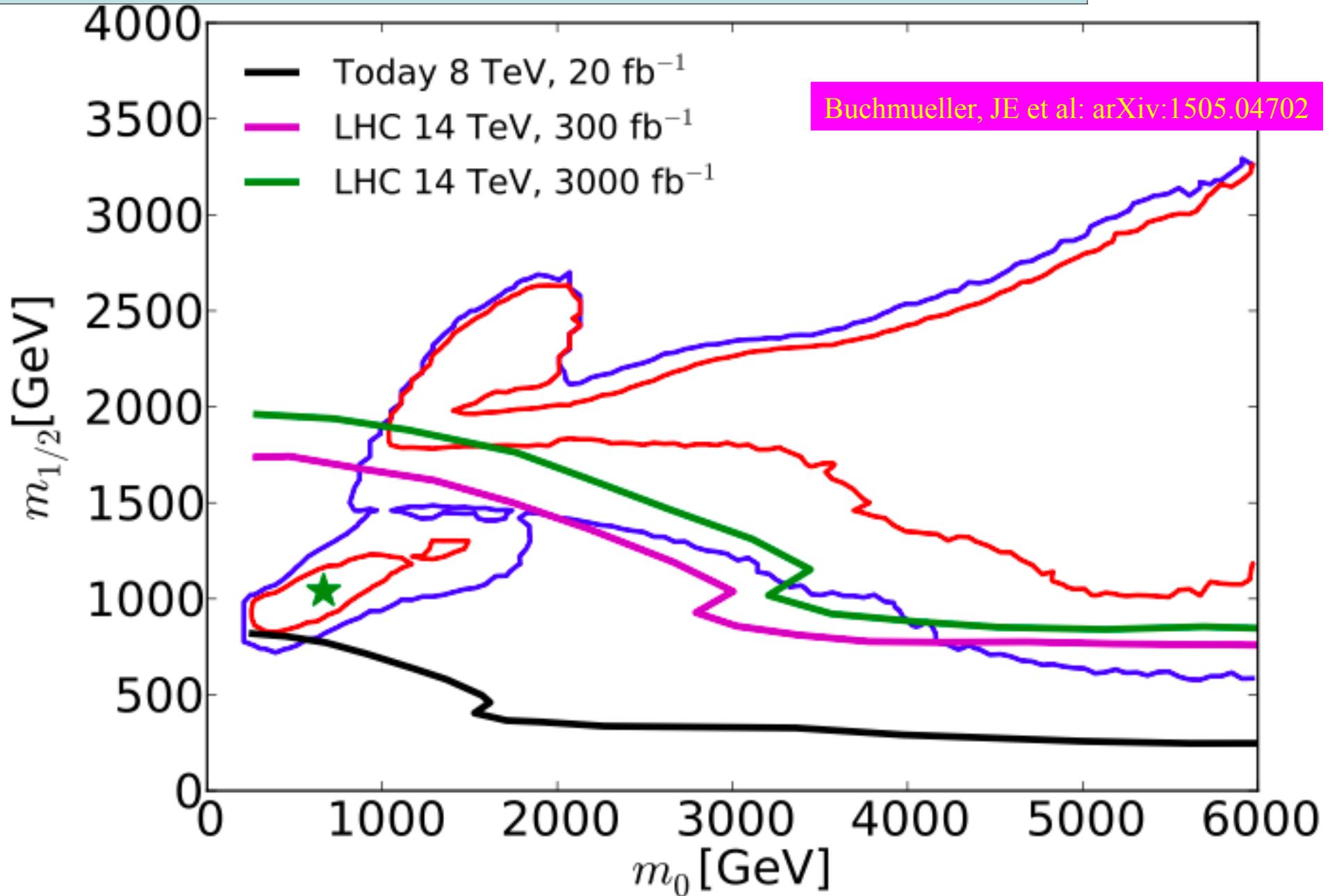
— CMSSM: best fit, 1σ , 2σ

$$\begin{aligned} \tilde{\tau}_1 \text{ coannihilation (pink)} : \quad & \frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} - 1 < 0.15, \\ A/H \text{ funnel (blue)} : \quad & \left| \frac{M_A}{2m_{\tilde{\chi}_1^0}} - 1 \right| < 0.2, \\ \tilde{\chi}_1^\pm \text{ coannihilation (green)} : \quad & \frac{m_{\tilde{\chi}_1^\pm}}{m_{\tilde{\chi}_1^0}} - 1 < 0.1, \\ \tilde{t}_1 \text{ coannihilation (grey)} : \quad & \frac{m_{\tilde{t}_1}}{m_{\tilde{\chi}_1^0}} - 1 < 0.2. \end{aligned}$$

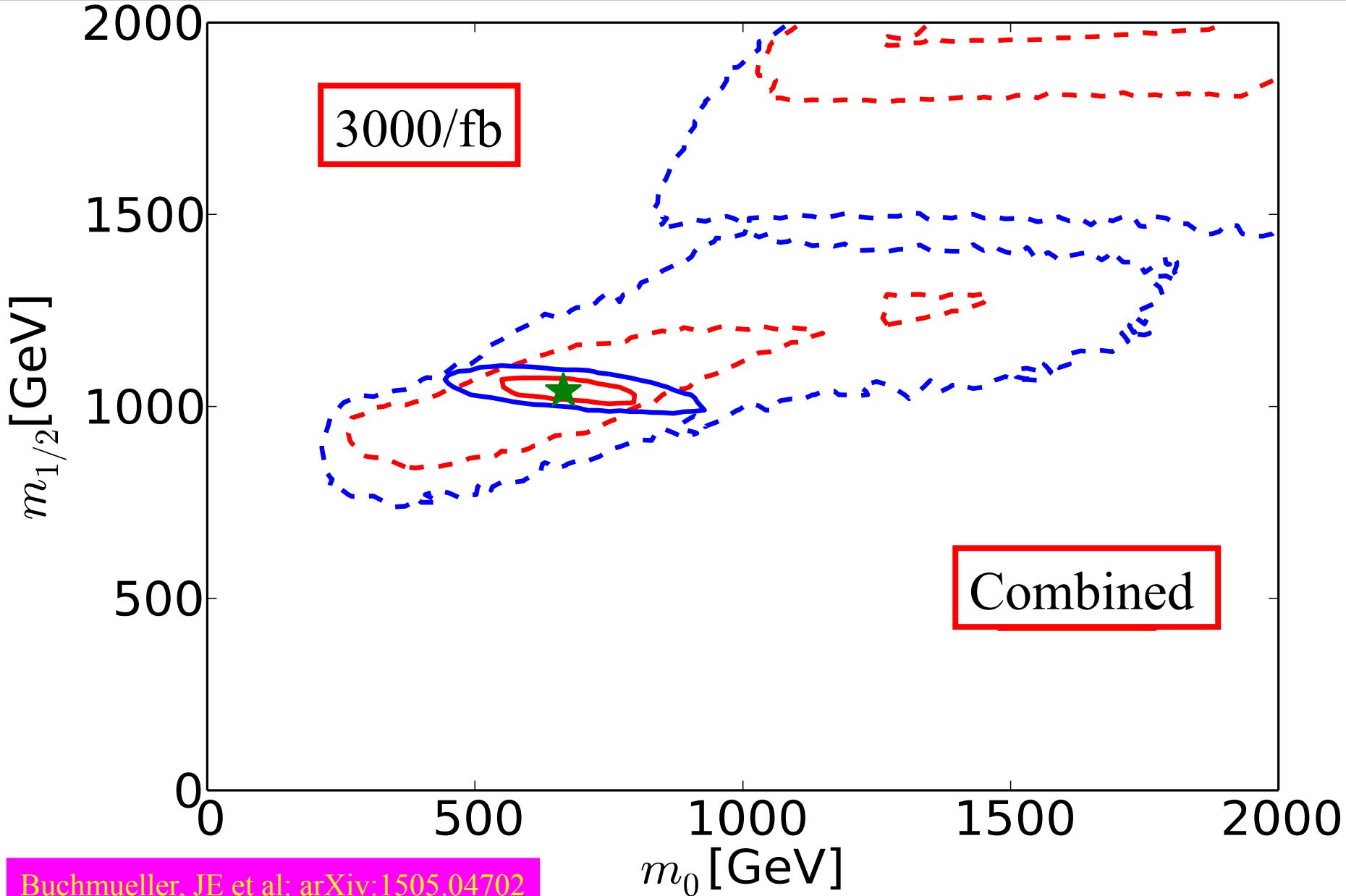
Buchmueller, JE et al: arXiv:1312.5250



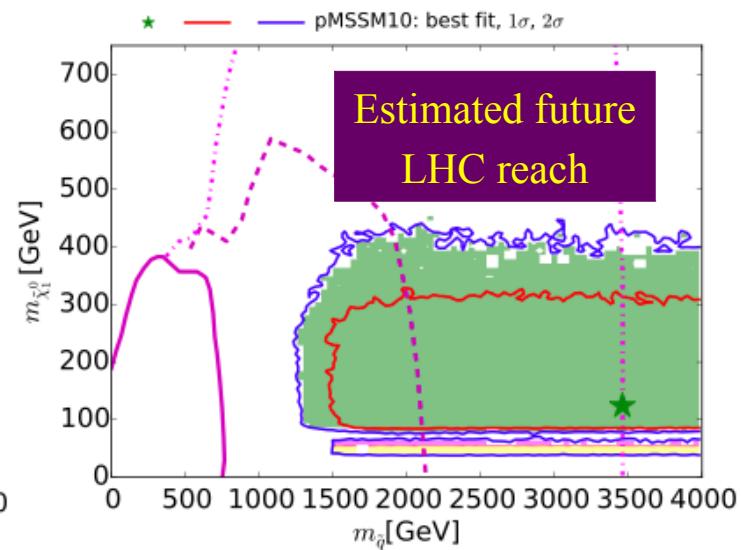
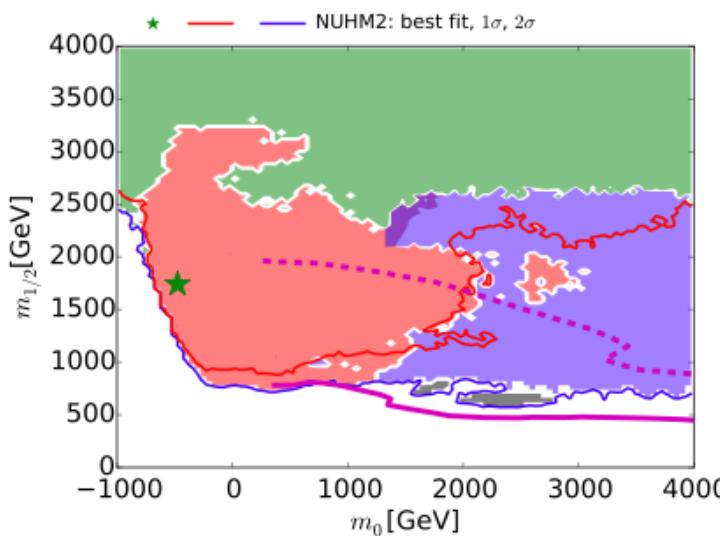
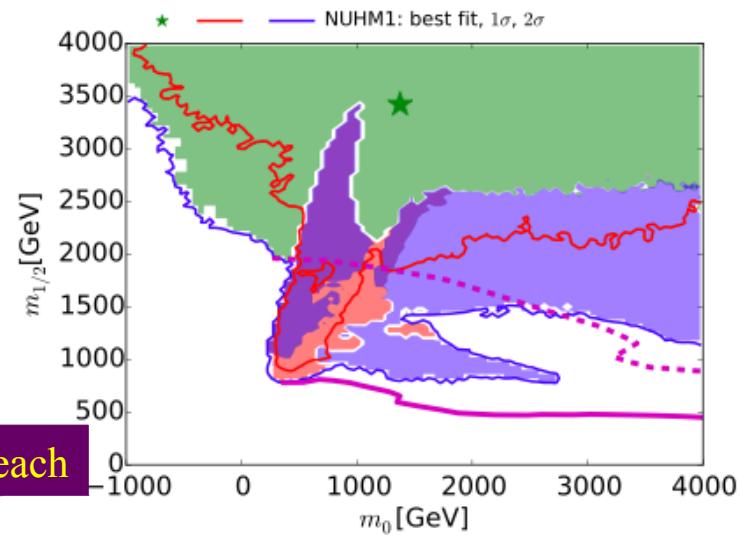
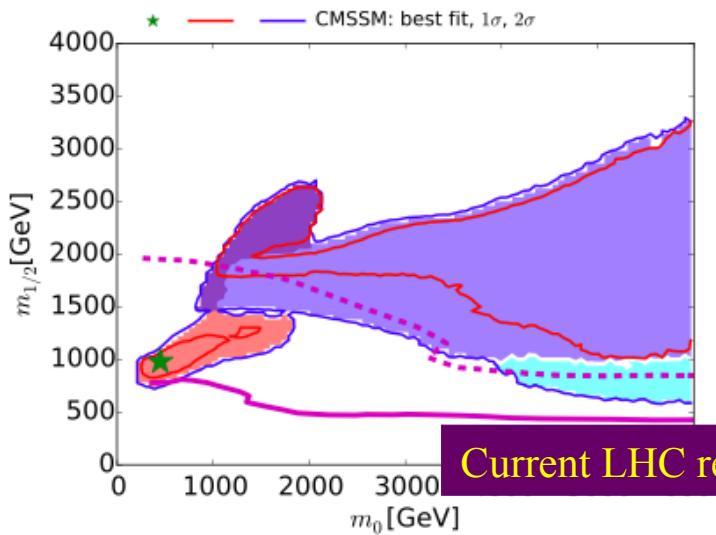
Probing the CMSSM with the LHC



Measuring the CMSSM with the LHC



Dark Matter in CMSSM, NUHM1/2, pMSSM10



stau coann.	hybrid
A/H funnel	$\tilde{\chi}_1^\pm$ coann.

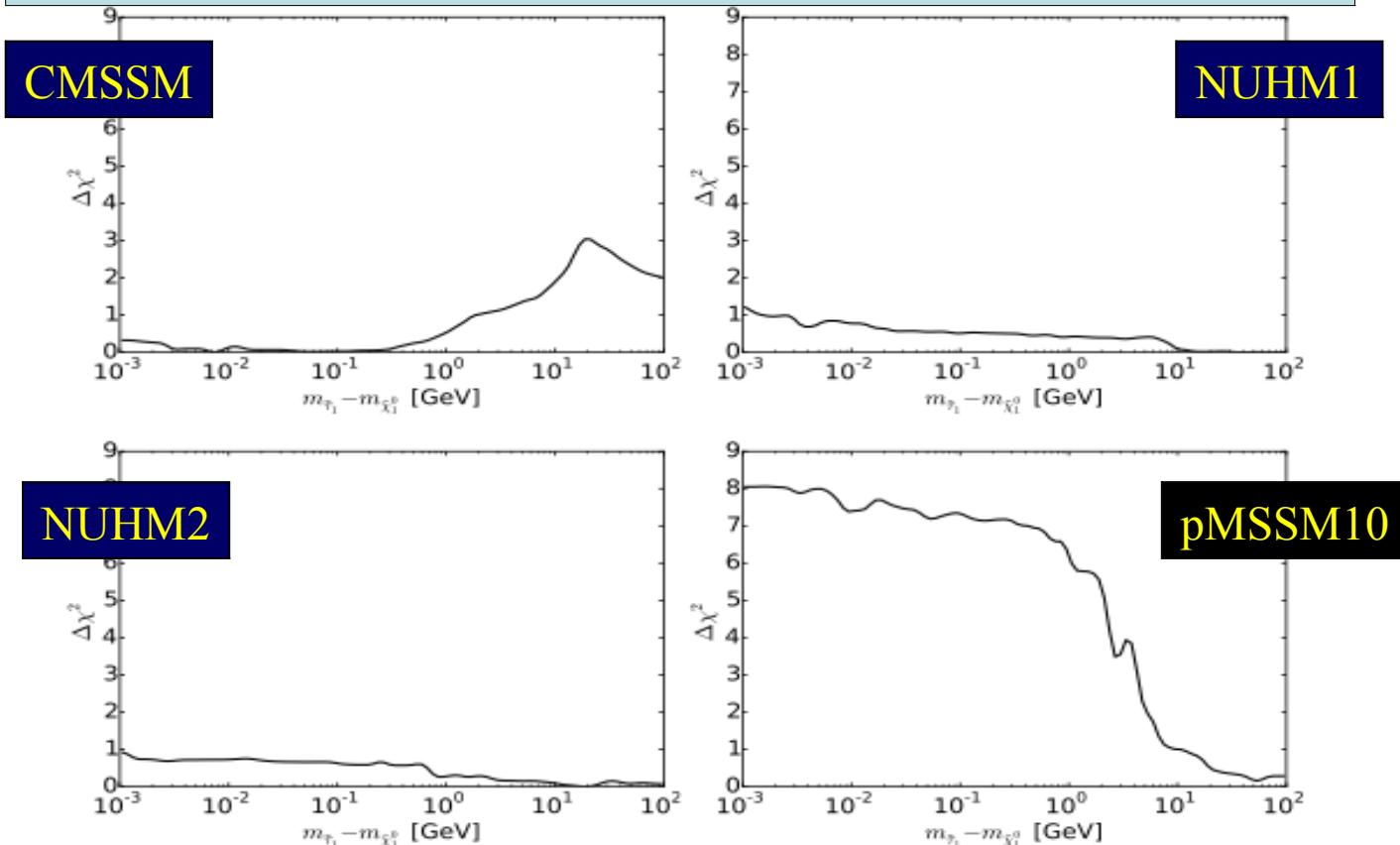
stop coann.	h funnel
focus point	Z funnel

Long-Lived Stau in CMSSM, NUHM?

Possible if $m_{\text{stau}} - m_{\text{LSP}} < m_\tau$

Generic possibility in CMSSM, NUHM1, NUHM2
(stau coannihilation region)

Bagnaschi, JE et al: arXiv:1508.01173

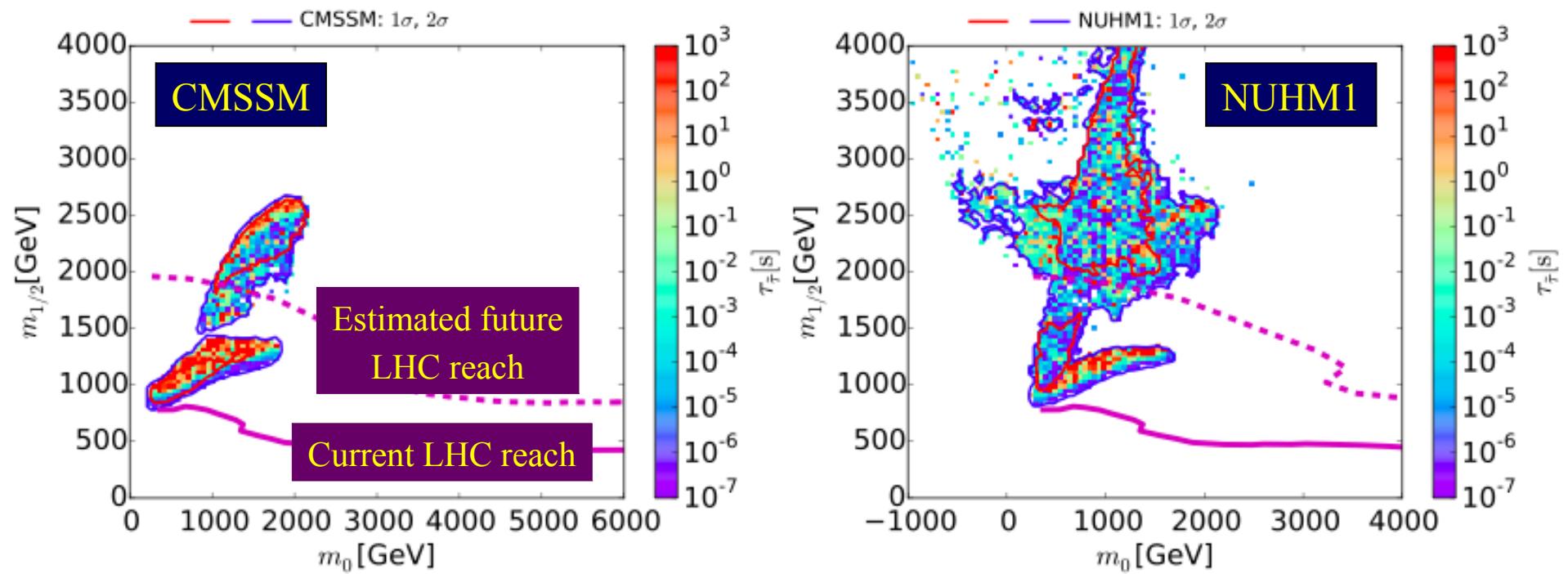


$\tau_{\text{stau}} > 10^3$ s gives problems with nucleosynthesis

$\tau_{\text{stau}} > 10^{-7}$ s gives separated vertex signature

Long-Lived Stau in CMSSM, NUHM?

Possible if $m_{\text{stau}} - m_{\text{LSP}} < m_\tau$
Generic possibility in CMSSM, NUHM
(stau coannihilation region)



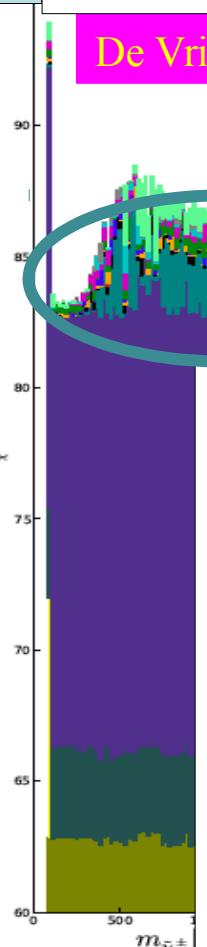
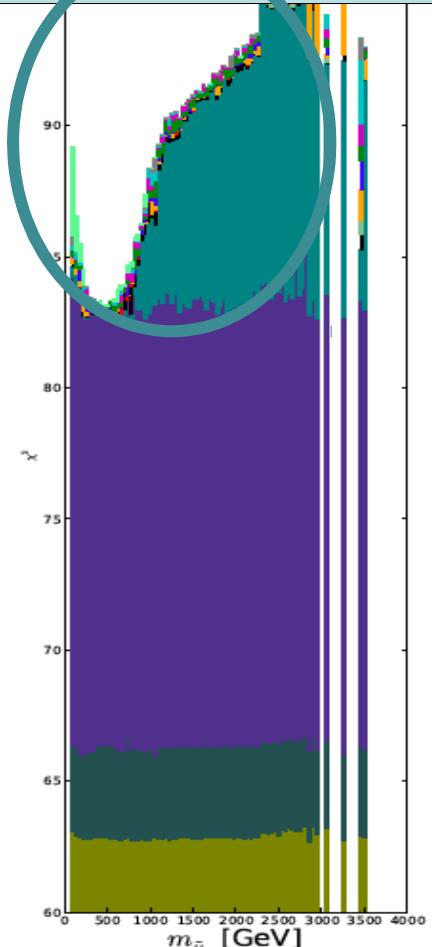
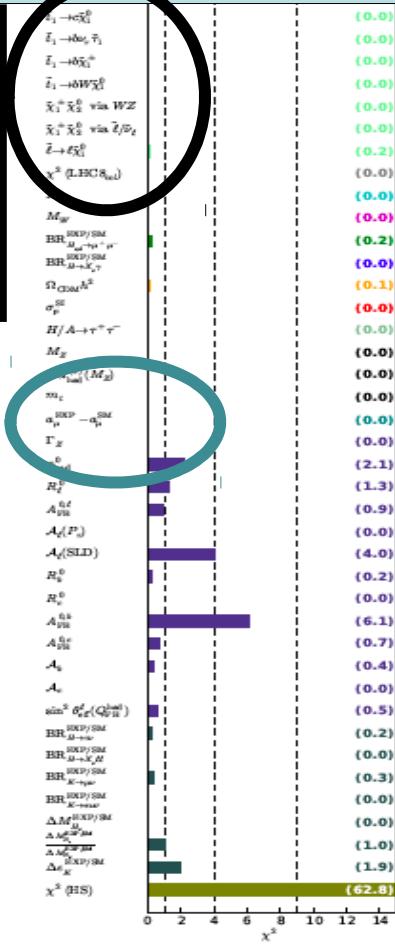
$\tau_{\text{stau}} > 10^3$ s gives problems with nucleosynthesis

$\tau_{\text{stau}} > 10^{-7}$ s gives separated vertex signature **for τ -like decays**

Phenomenological MSSM (pMSSM10)

LHC
MET
searches

$g_\mu - 2$



3 gaugino masses : $M_{1,2,3}$,
2 squark masses : $m_{\tilde{q}_1} = m_{\tilde{q}_2} \neq m_{\tilde{q}_3}$,
1 slepton mass : $m_{\tilde{\ell}}$,
1 trilinear coupling : A ,
Higgs mixing parameter : μ ,
Pseudoscalar Higgs mass : M_A ,
Ratio of vevs : $\tan \beta$.

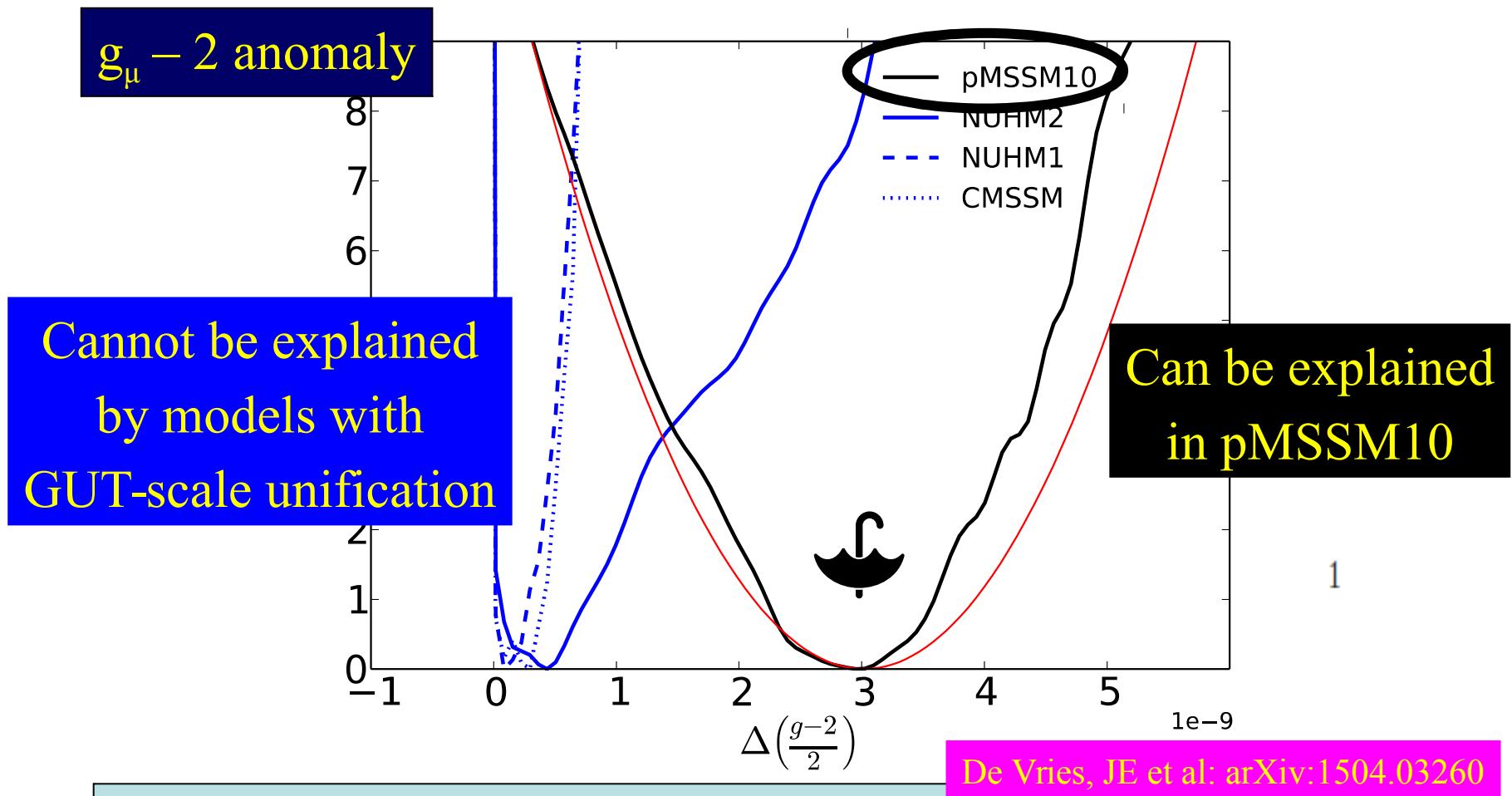
De Vries, JE et al; arXiv:1504.03260

Contributions
to global χ^2
from
different
observables

Observable	Contribution Type
χ^2 (LHC8 _{ewk}) + χ^2 (LHC8 _{stop})	BR($B_{s,d} \rightarrow \mu^+ \mu^-$)
χ^2 (LHC8 _{col})	BR($B \rightarrow X_s \gamma$)
M_h	$\Omega_{\text{CDM}} h^2$
M_W	σ_p^{SI}
	Other Flavour obs.
	LEP sparticle mass
	χ^2 (HS)
	nuisance
	$(g-2)_\mu$
	Z -pole

Anomalous Magnetic Moment of Muon

2012 ATLAS + CMS with 20/fb of LHC Data

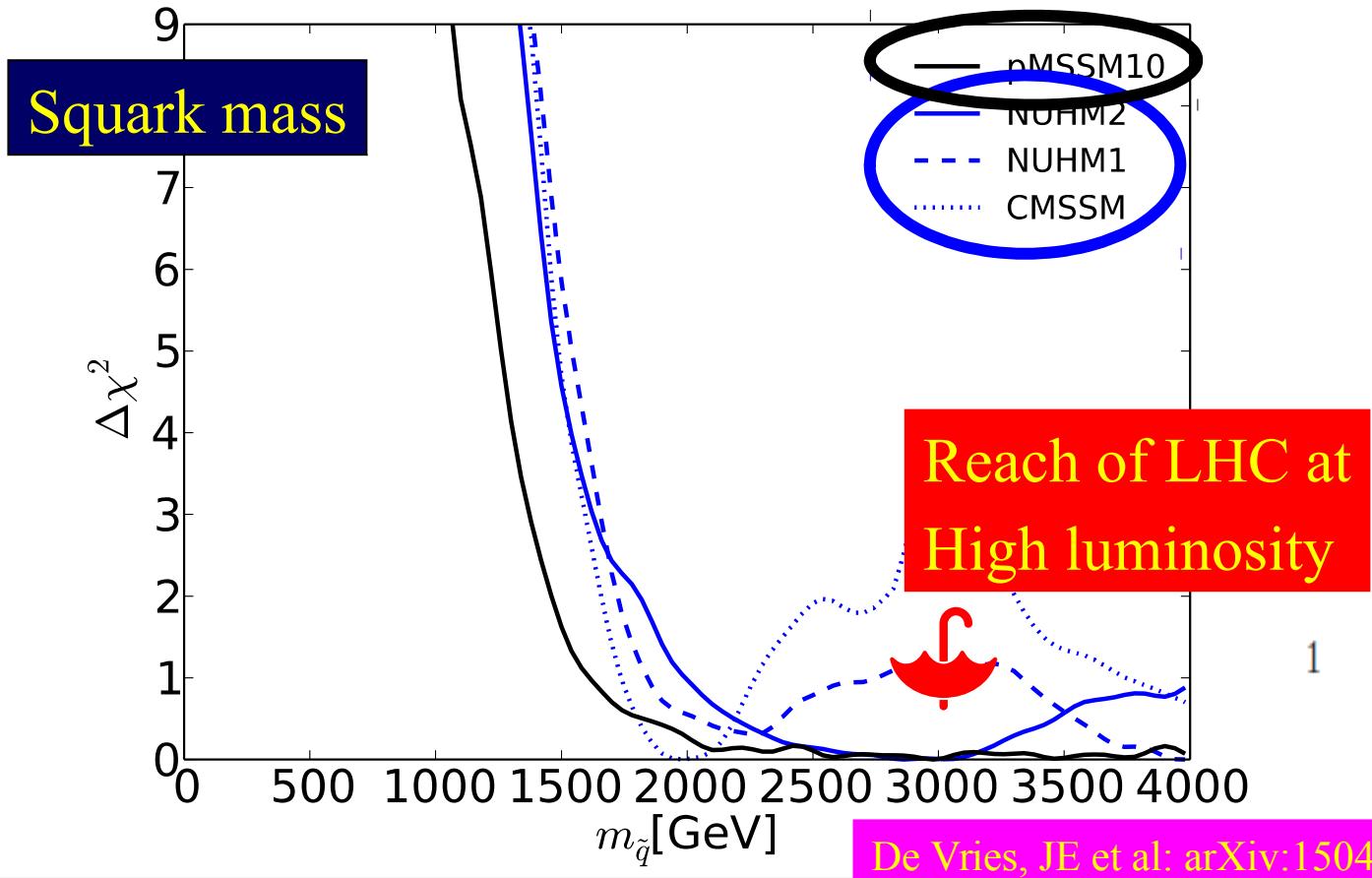


pMSSM10 can explain experimental measurements of $g_\mu - 2$

Fits to Supersymmetric Models



2012 ATLAS + CMS with 20/fb of LHC Data

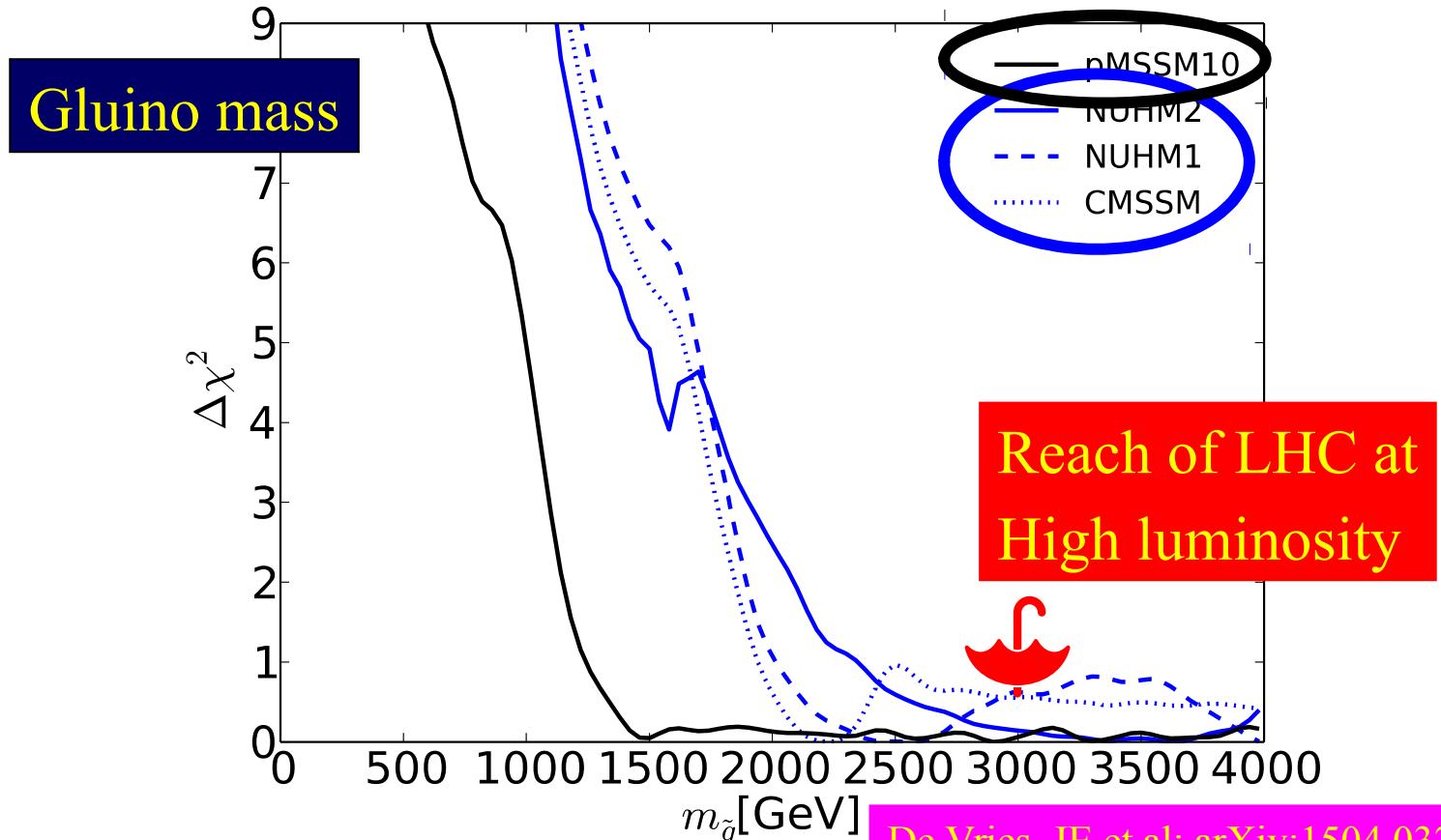


Favoured values of squark mass significantly above pre-LHC, ~ 1.5 TeV or more

Fits to Supersymmetric Models



2012 ATLAS + CMS with 20/fb of LHC Data

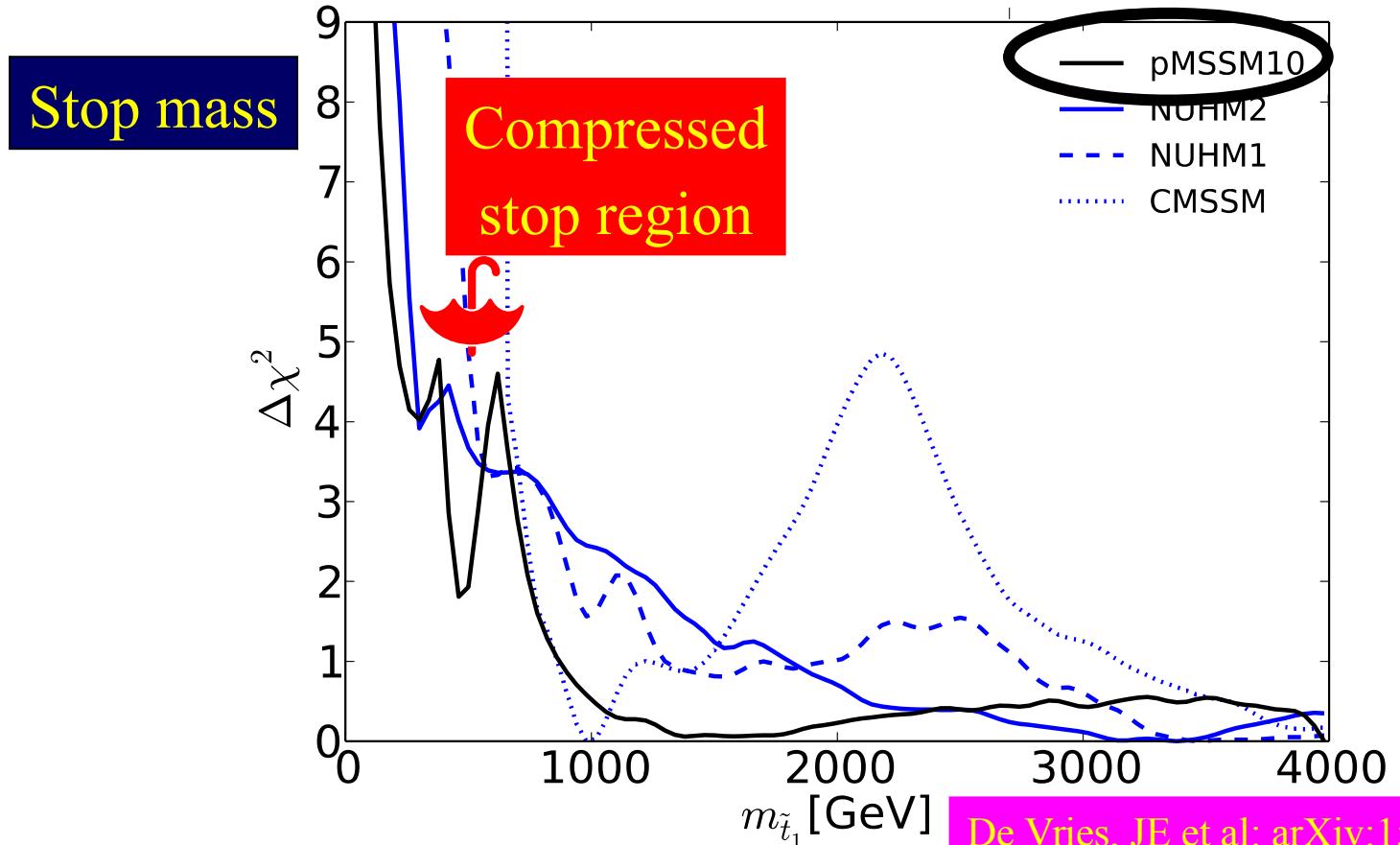


Favoured values of gluino mass also significantly above pre-LHC, > 1.2 TeV

Fits to Supersymmetric Models

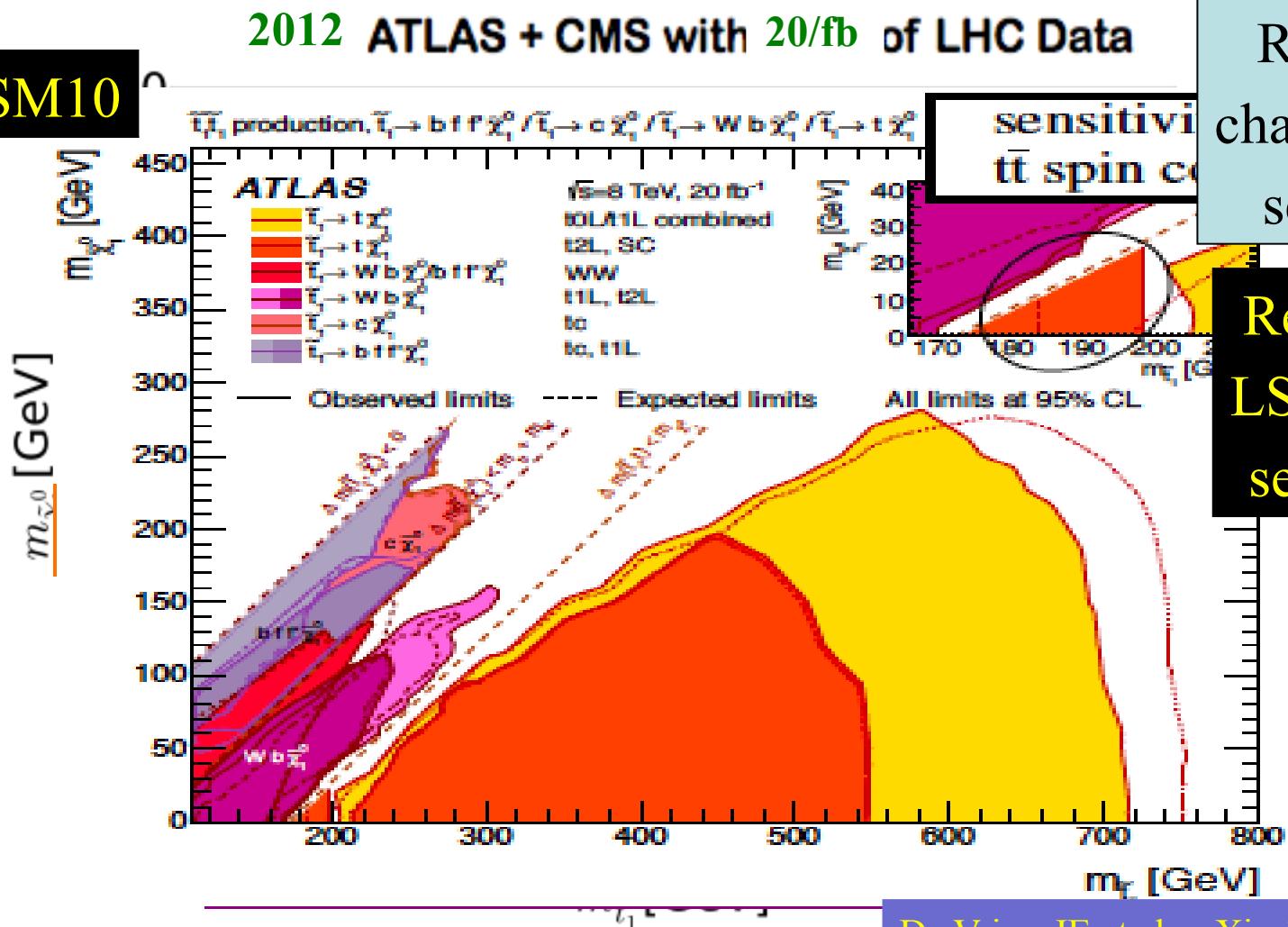


2012 ATLAS + CMS with 20/fb of LHC Data



Remaining possibility of a light “natural” stop weighing ~ 400 GeV

Exploring Light Stops @ Run 2



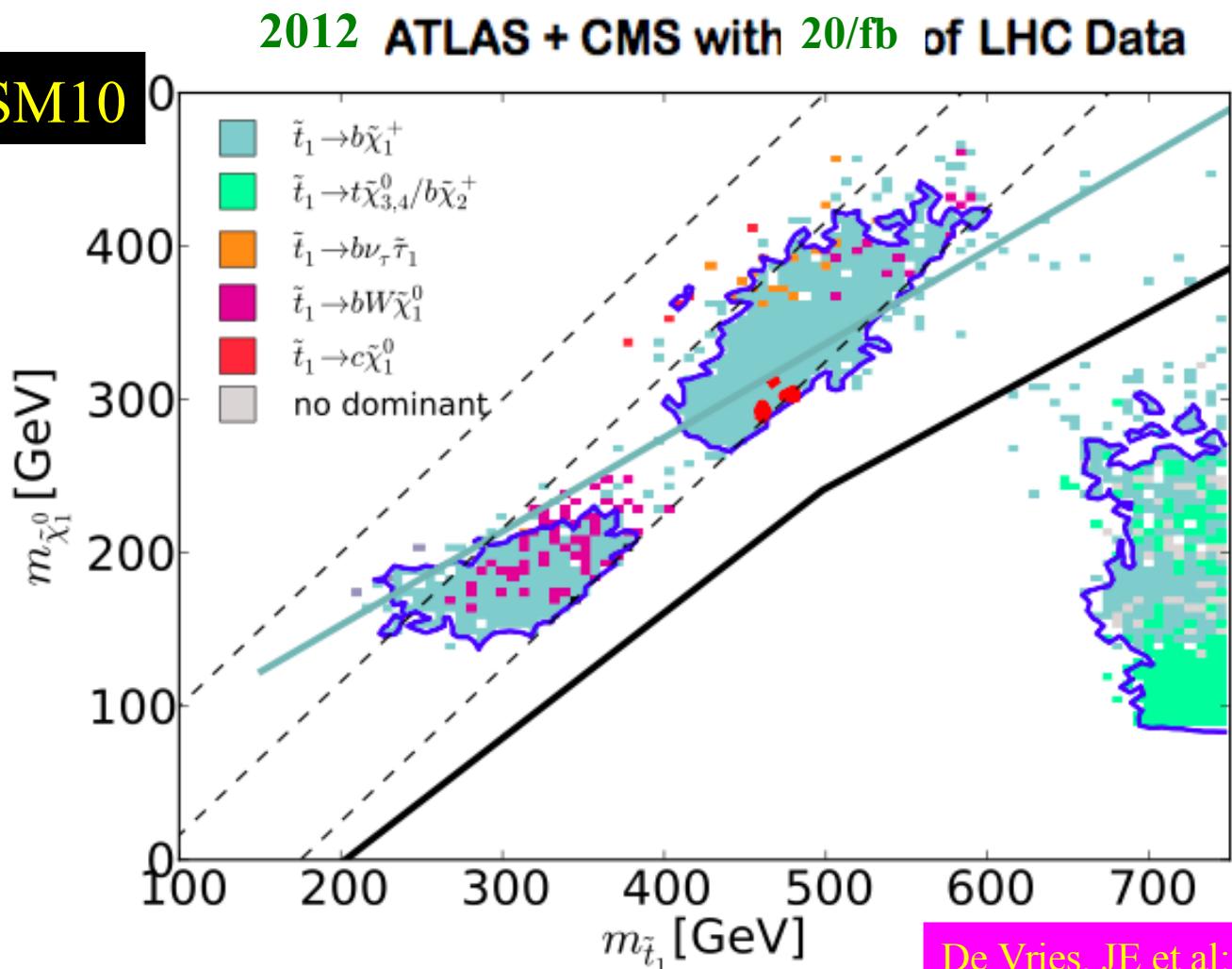
Reach of chargino + b searches

Reach of LSP + top searches

De Vries, JE et al: arXiv:1504.03260

Part of region of light “natural” stop weighing
~ 400 GeV can be covered

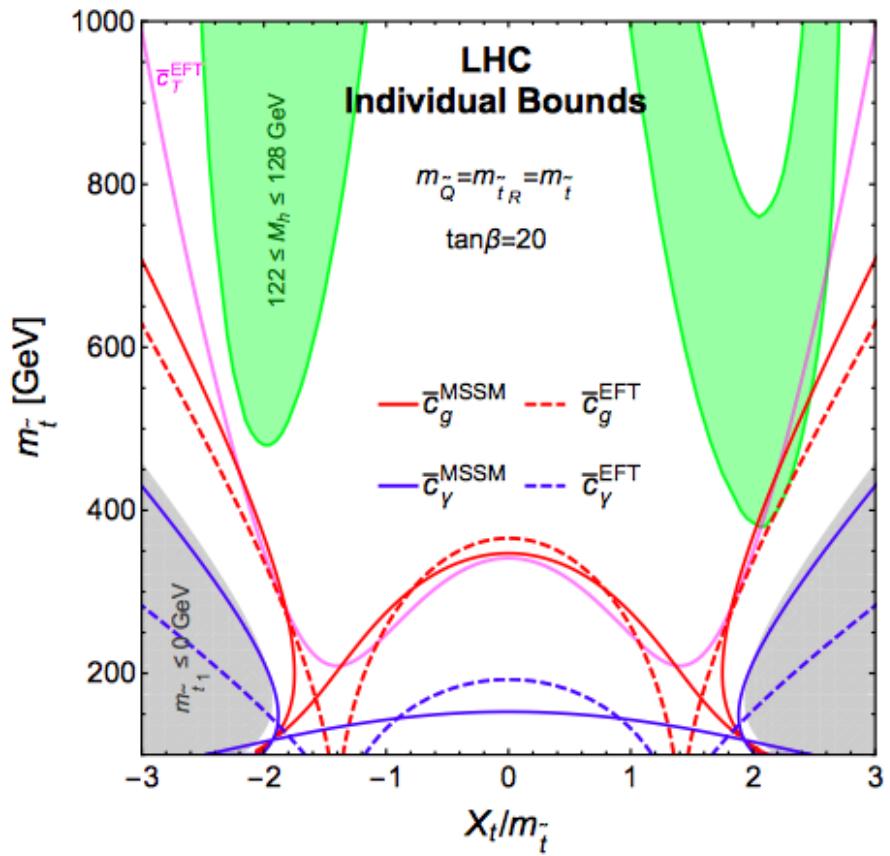
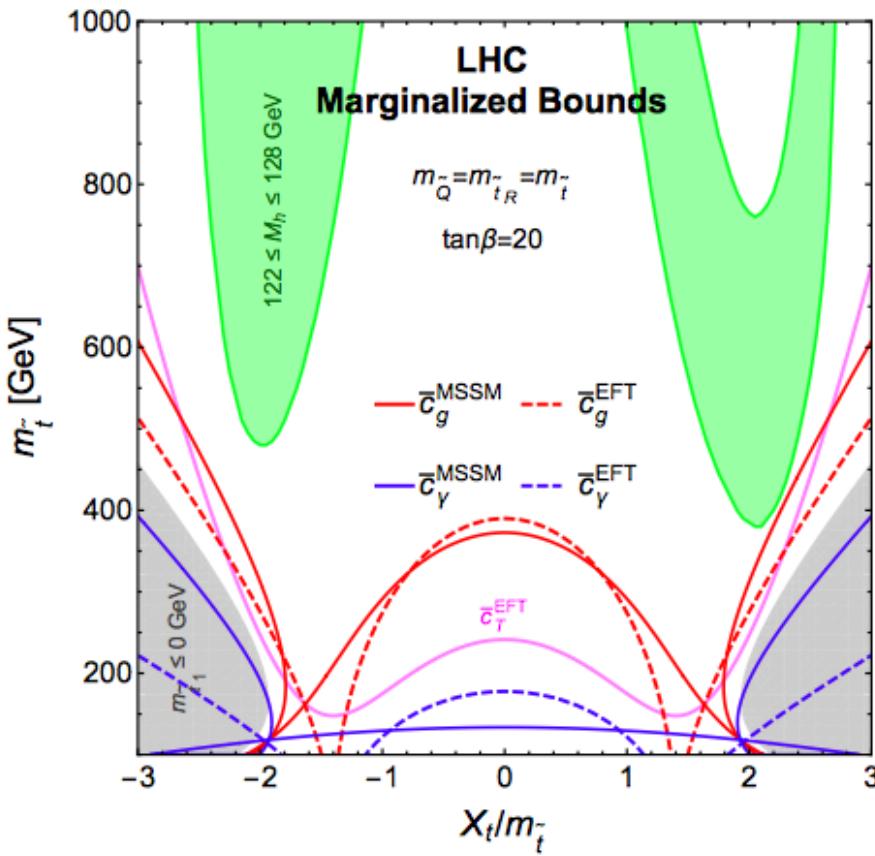
Exploring Light Stops @ Run 2



Part of region of light “natural” stop weighing
 ~ 400 GeV can be covered

Indirect Stop Limits from Precision EW Data

- Solid lines = full calculation, dashed lines = EFT



Universal One-Loop Effective Action

$$S_{\text{1-loop}}^{\text{eff}} = i c_s \int d^4x \int \frac{d^4q}{(2\pi)^4} \text{tr} \ln(-(P_\mu - q_\mu)^2 + M^2 + U)$$

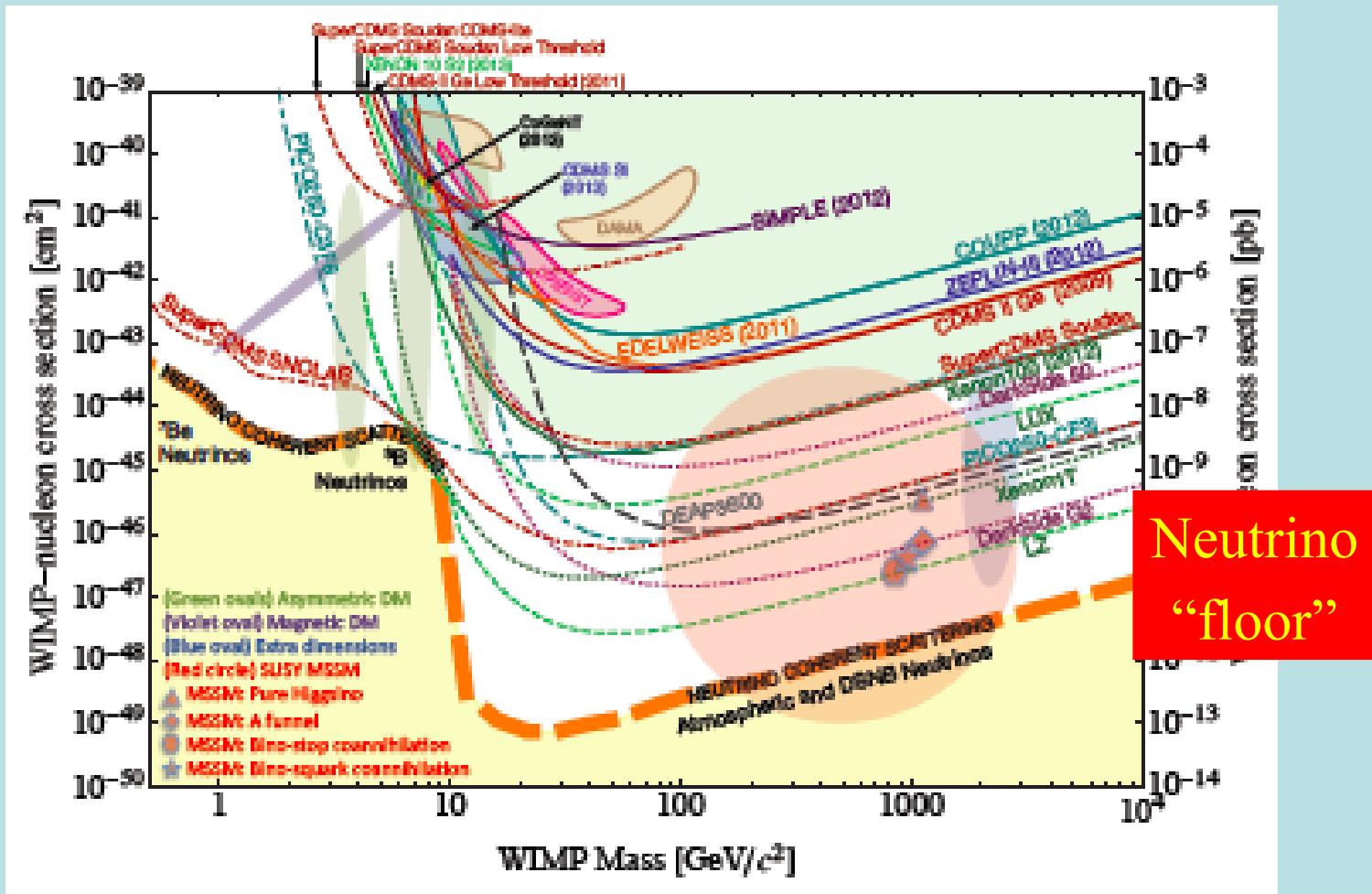
- Can be evaluated to any desired dimension, e.g., 6:

$$\begin{aligned} \mathcal{L}_{\text{1-loop}}^{\text{eff}}[\phi] \supset & -i c_s \left\{ f_1^i + f_2^i U_{ii} + f_3^i G'_{\mu\nu,ij}^2 + f_4^{ij} U_{ij}^2 \right. \\ & + f_5^{ij} (P_\mu G'_{\mu\nu,ij})^2 + f_6^{ij} (G'_{\mu\nu,ij})(G'_{\nu\sigma,jk})(G'_{\sigma\mu,ki}) + f_7^{ij} [P_\mu, U_{ij}]^2 + f_8^{ijk} (U_{ij} U_{jk} U_{ki}) \\ & + f_9^{ij} (U_{ij} G'_{\mu\nu,jk} G'_{\mu\nu,ki}) \\ & + f_{10}^{ijkl} (U_{ij} U_{jk} U_{kl} U_{li}) + f_{11}^{ijk} U_{ij} [P_\mu, U_{jk}] [P_\mu, U_{ki}] \\ & + f_{12,a}^{ij} [P_\mu, [P_\nu, U_{ij}]] [P_\mu, [P_\nu, U_{ji}]] + f_{12,b}^{ij} [P_\mu, [P_\nu, U_{ij}]] [P_\nu, [P_\mu, U_{ji}]] \\ & + f_{12,c}^{ij} [P_\mu, [P_\mu, U_{ij}]] [P_\nu, [P_\nu, U_{ji}]] \\ & + f_{13}^{ijk} U_{ij} U_{jk} G'_{\mu\nu,kl} G'_{\mu\nu,li} + f_{14}^{ijk} [P_\mu, U_{ij}] [P_\nu, U_{jk}] G'_{\nu\mu,ki} \\ & + \left(f_{15a}^{ijk} U_{i,j} [P_\mu, U_{j,k}] - f_{15b}^{ijk} [P_\mu, U_{i,j}] U_{j,k} \right) [P_\nu, G'_{\nu\mu,ki}] \\ & + f_{16}^{ijklm} (U_{ij} U_{jk} U_{kl} U_{lm} U_{mi}) + f_{17}^{ijkl} U_{ij} U_{jk} [P_\mu, U_{kl}] [P_\mu, U_{li}] + f_{18}^{ijkl} U_{ij} [P_\mu, U_{jk}] U_{kl} [P_\mu, U_{li}] \\ & \left. + f_{19}^{ijklmn} (U_{ij} U_{jk} U_{kl} U_{lm} U_{mn} U_{ni}) \right\}. \end{aligned}$$

Drozdz, JE, Quevillon & You: jutro

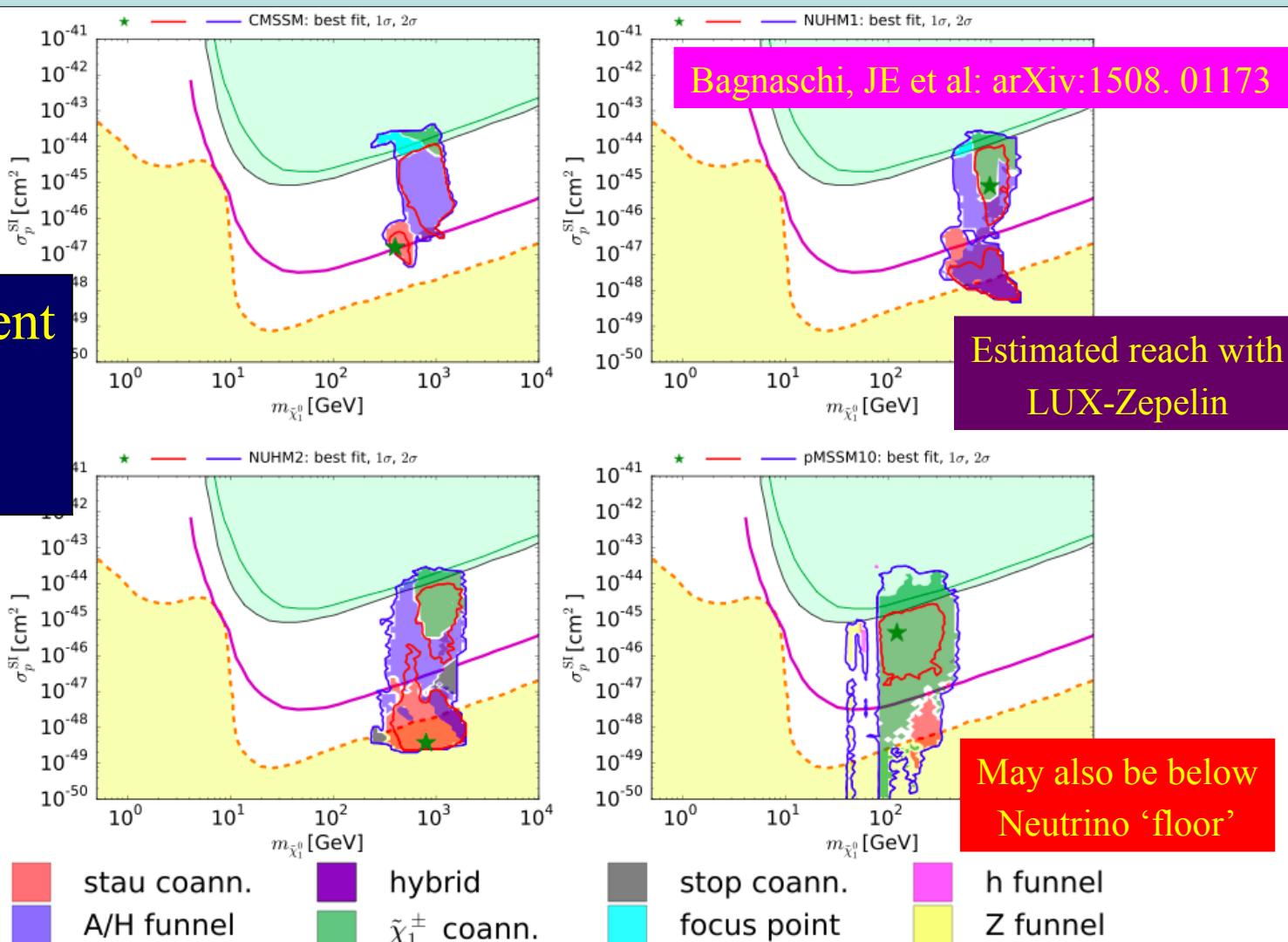
Direct Dark Matter Searches

- Compilation of present and future sensitivities



Direct Dark Matter Search: pMSSM10

Spin-independent
dark matter
scattering



Direct scattering cross-section may be very close to LUX upper limit, accessible to LZ experiment

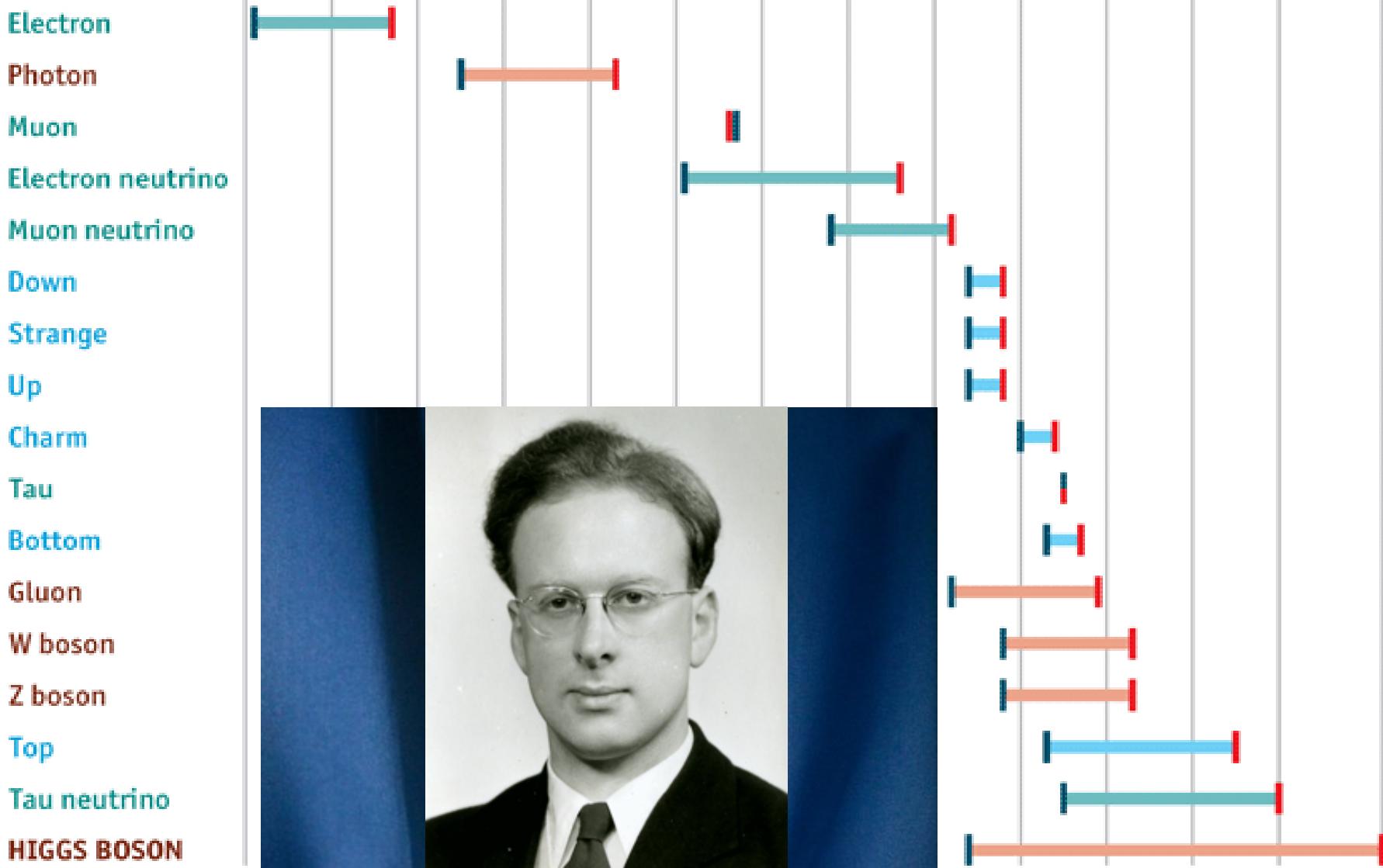
Prospects for SUSY Searches

- Different models, various dark matter mechanisms

DM mechanism	Exp't	Models			
		CMSSM	NUHM1	NUHM2	pMSSM10
$\tilde{\tau}_1$ coann.	LHC	✓ \cancel{E}_T , ✓ LL (✓)	(✓ \cancel{E}_T , ✓ LL) (✓)	(✓ \cancel{E}_T , ✓ LL) ✗	(✓ \cancel{E}_T), ✗ LL ✗
	DM	–	✗	✗	(✓ \cancel{E}_T) (✓)
$\tilde{\chi}_1^\pm$ coann.	LHC	–	✗	✗	(✓ \cancel{E}_T) (✓)
	DM	–	✓	✓	–
\tilde{t}_1 coann.	LHC	–	–	✓ \cancel{E}_T	–
	DM	–	–	✗	–
A/H funnel	LHC	✓ A/H	(✓ A/H)	(✓ A/H)	–
	DM	✓	✓	(✓)	–
Focus point	LHC	(✓ \cancel{E}_T)	–	–	–
	DM	✓	–	–	–
h, Z funnels	LHC	–	–	–	(✓ \cancel{E}_T) (✓)
	DM	–	–	–	–

- No guarantees, but good prospects

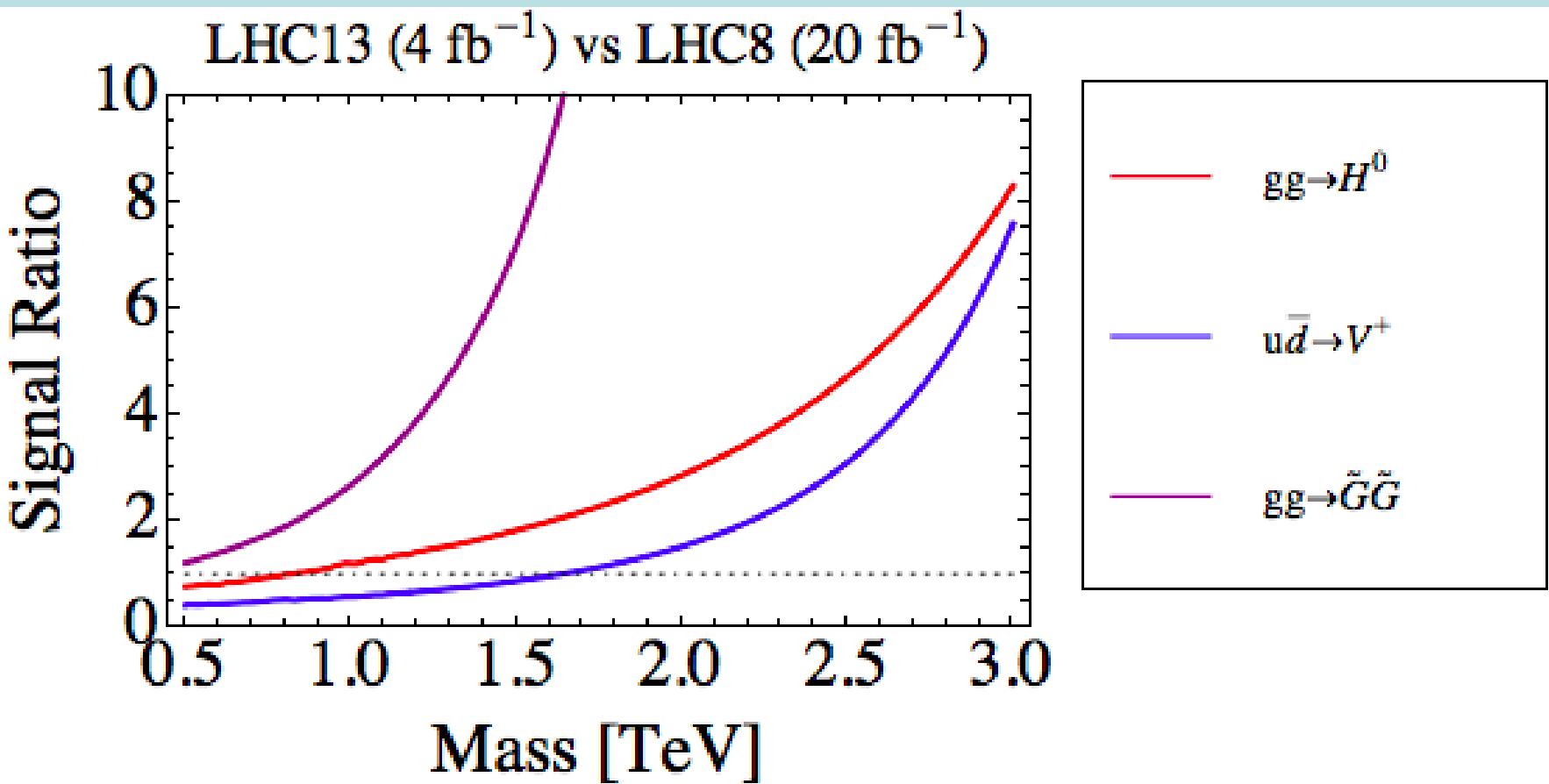
Standard Model Particles: Years from Proposal to Discovery



Source: *The Economist*

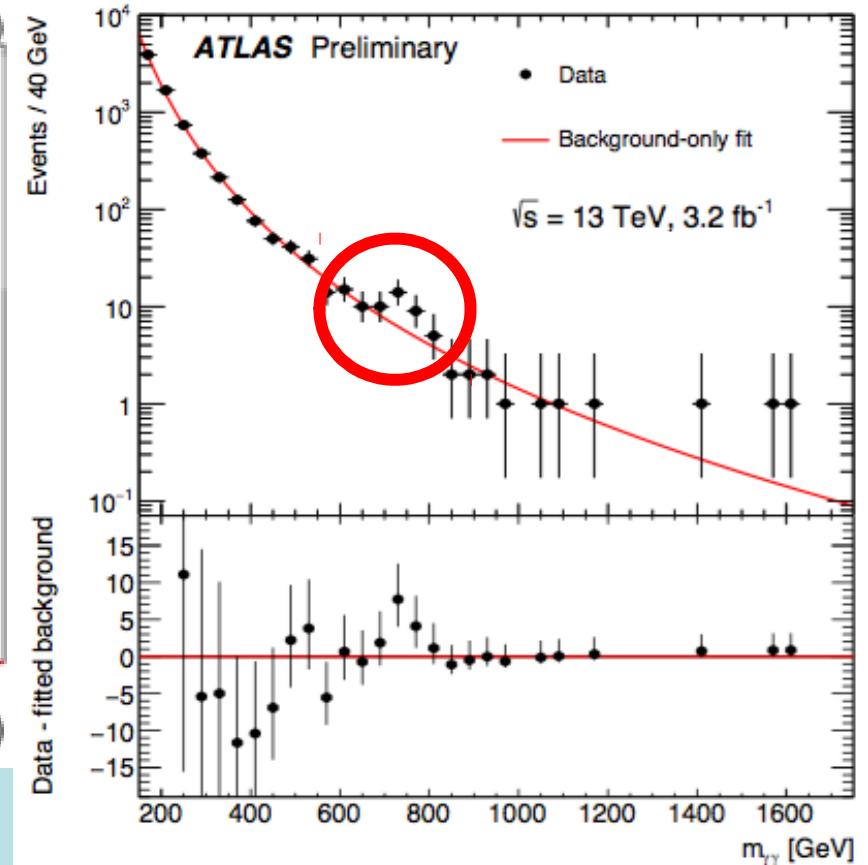
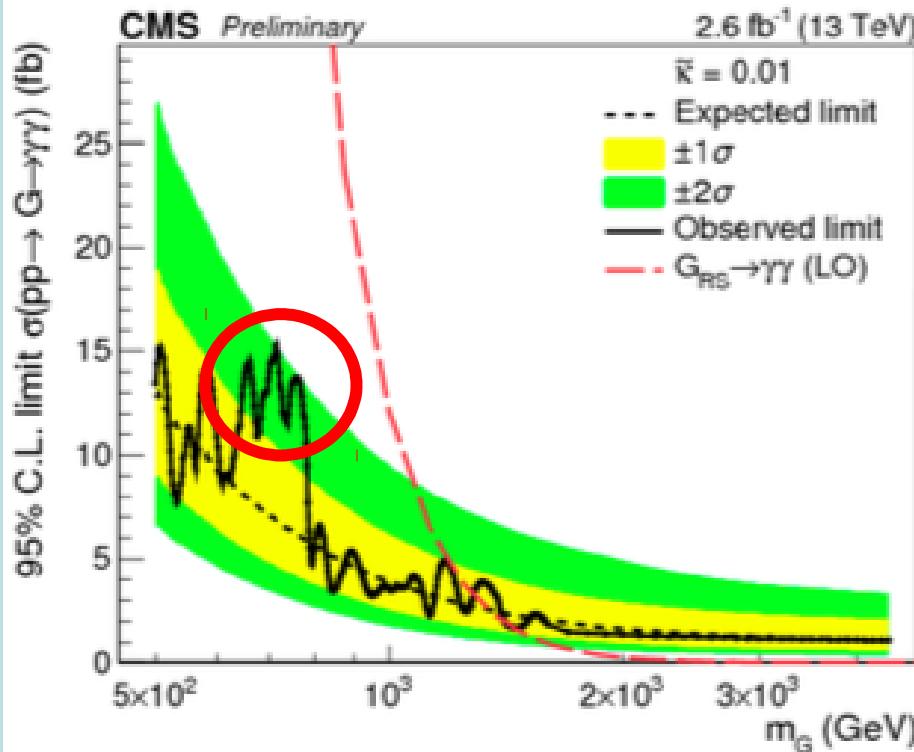
Why we are so excited by Run 2

- Expected 2015 Luminosity explores new physics



Reported on Tuesday, Dec. 15

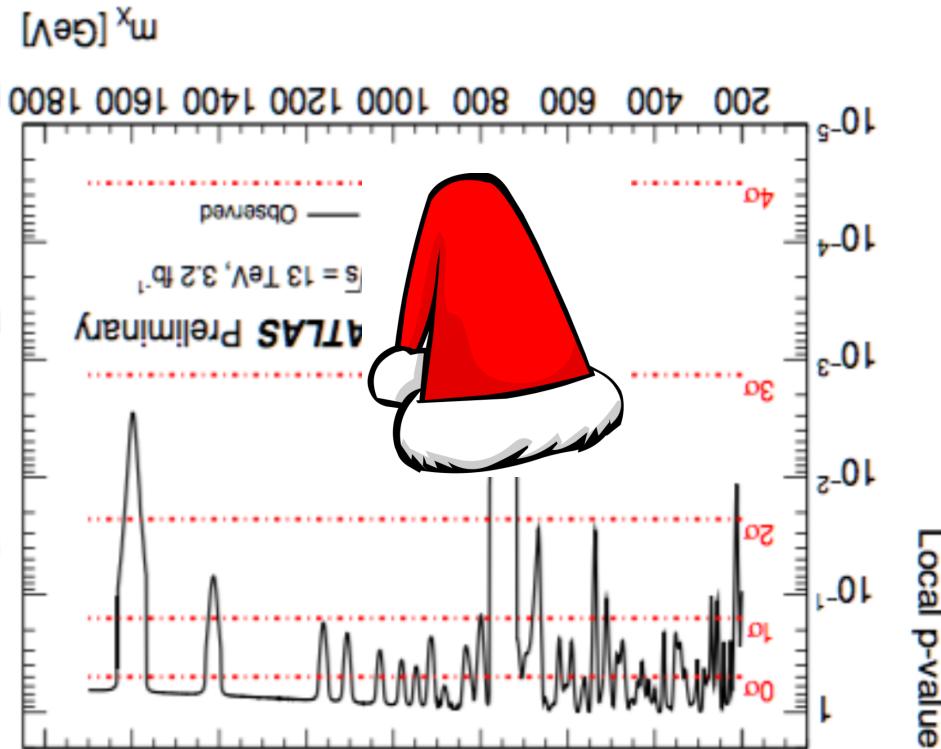
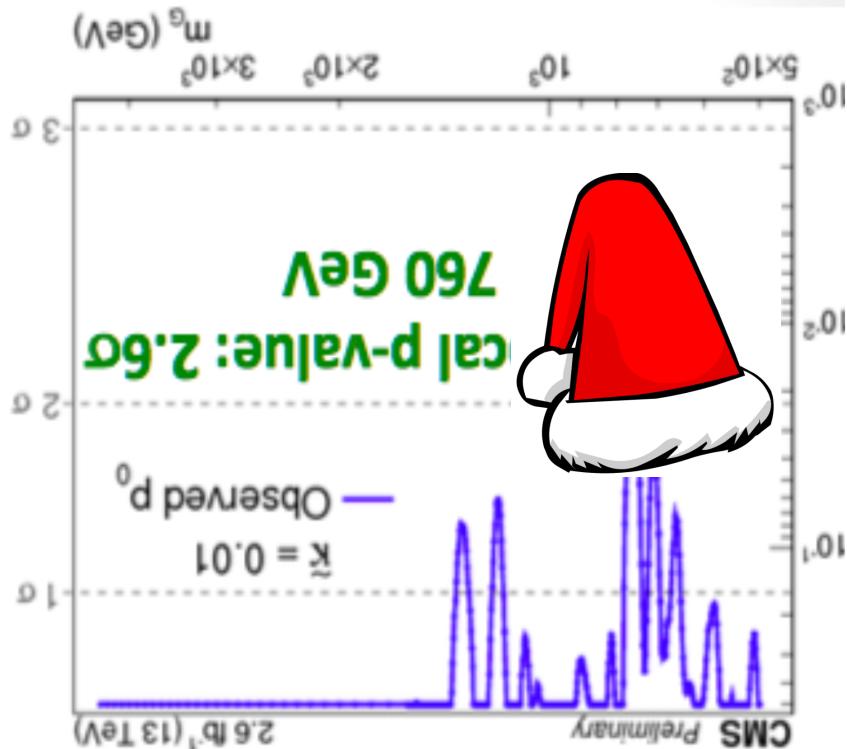
- Peaks in $\gamma\gamma$ invariant mass distributions



- Possible new particle X with mass ~ 750 GeV decaying into 2 photons

Reported on Tuesday, Dec. 15

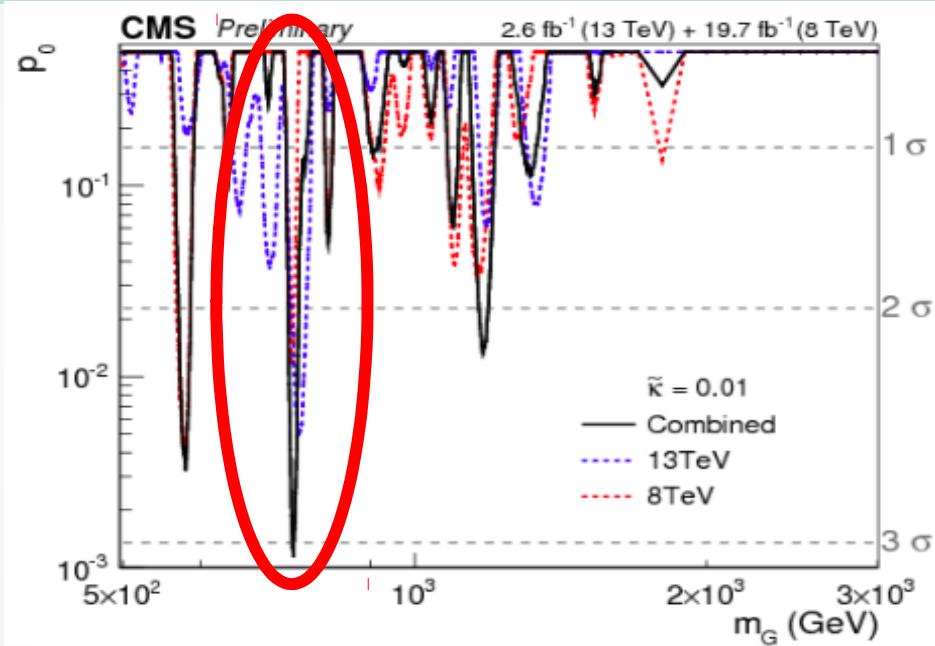
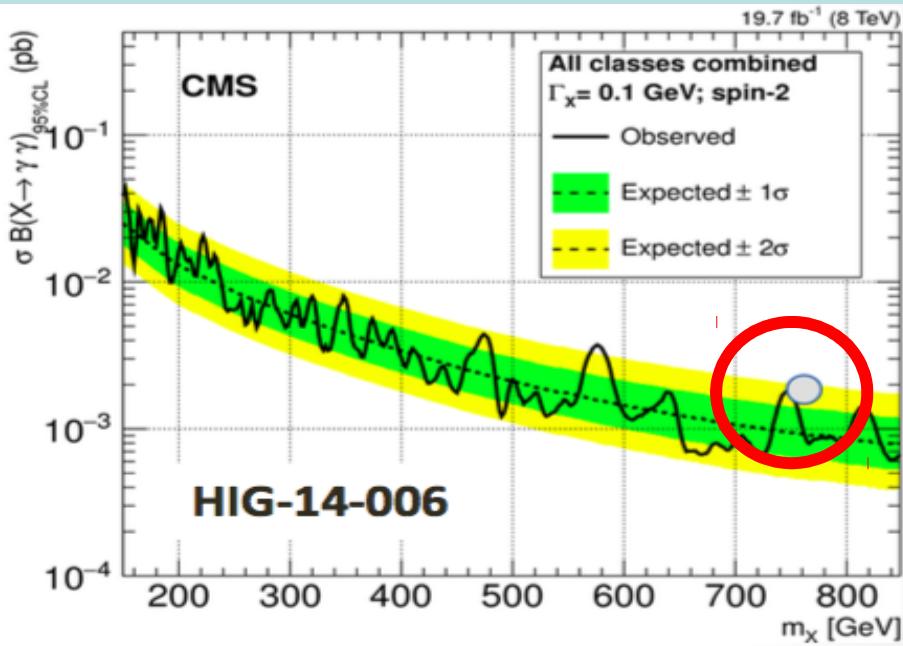
- Significances of local fluctuations



- CMS: 2.6σ , ATLAS: 3.6σ

Overall Significance of ‘Signal’?

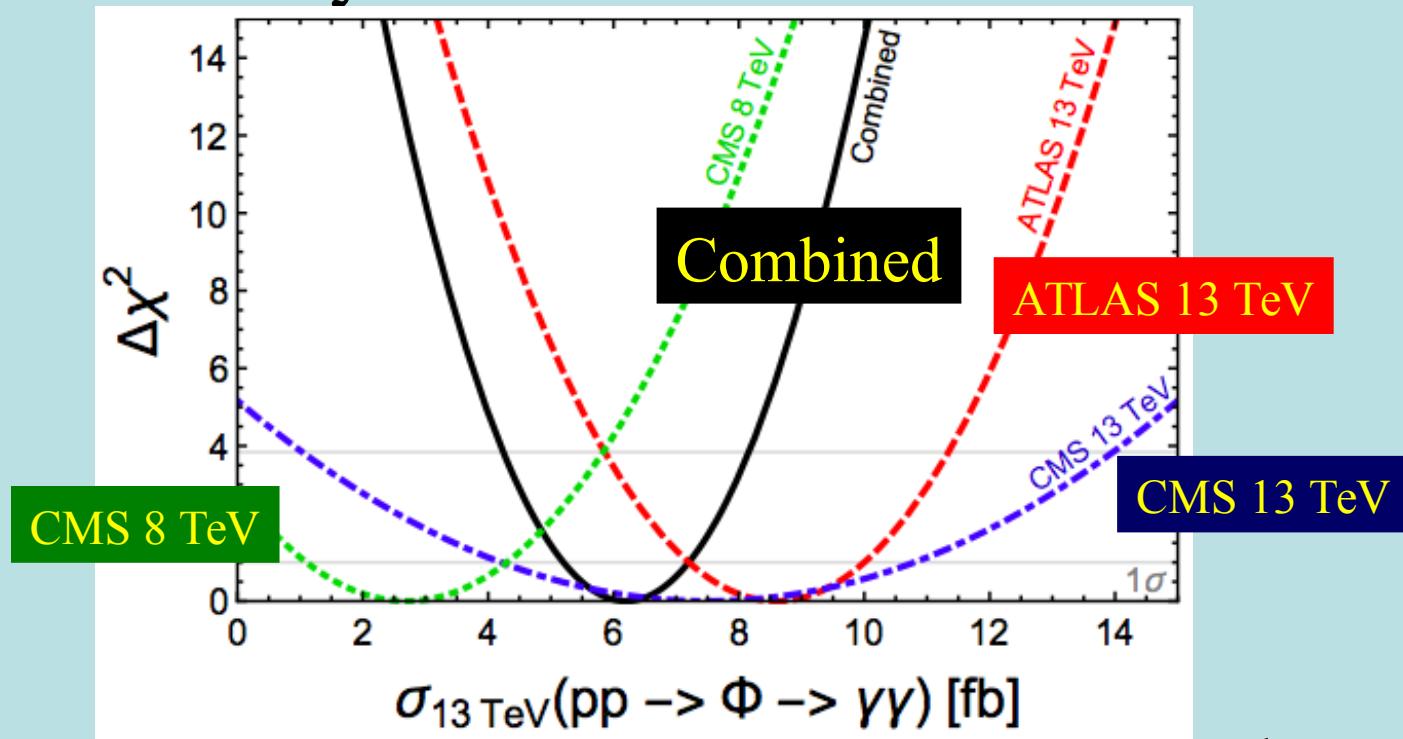
- CMS also saw hint in Run 1 data



- Combined significance $\sim 3 \sigma$
- Naïve combination with ATLAS $\sim 4.6 \sigma$
- ‘Look elsewhere effect’ (many bins) reduces to 3σ

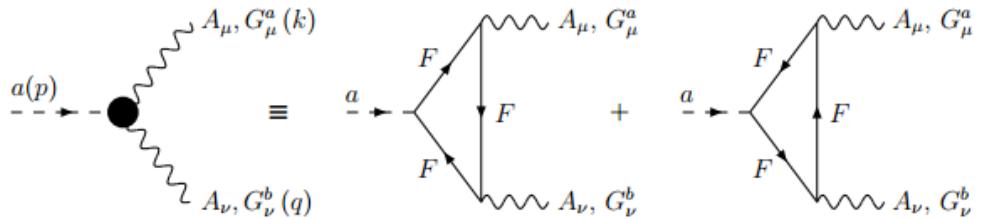
Global Analysis of X Signal

- Assume scalar or pseudoscalar
- Combined analysis of CMS and ATLAS data



- Some tension between data from Run 1 and Run 2?

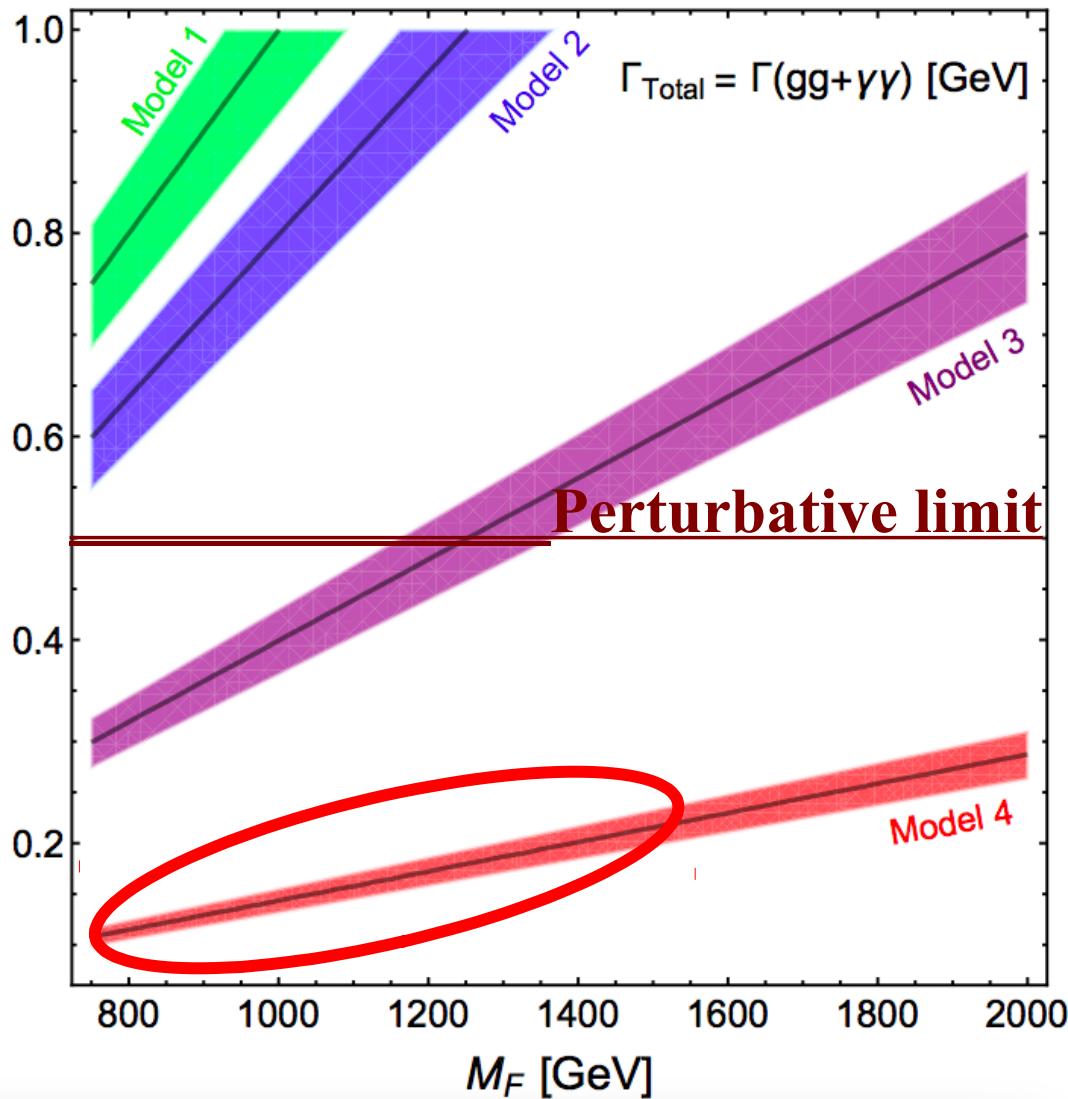
X Decays?



- Decay to $\gamma\gamma$ via anomalous triangle diagrams
- Probably also production via gluon fusion
- **Loops need heavy particles, $m > 350$ GeV**
- **Can't be 4th generation/minimal supersymmetry**
- Single vector-like quark enough, could be more
 - 1: Single VL quark, cf, t_R
 - 2: Doublet of VL quarks, cf, q_L
 - 3: Doublet + 2 singlets, cf, q_L, t_R, b_R
 - 4: Complete VL generation, including leptons
- **New world out there?** JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327

Scalar/Pseudoscalar Models for X

- Required X couplings λ to heavy fermions in different models
- Black line = best fit $\lambda/4\pi$
- **Band = 1 σ**
- **Perturbative limit**
- **Neutral fermion could be dark matter**



How to Probe Possible Models?

- Other possible decay modes

Model	$Tr[Y^2]$	$Tr[D(r)^2]$	$\frac{BR(X \rightarrow gg)}{BR(X \rightarrow \gamma\gamma)}$	$\frac{BR(X \rightarrow Z\gamma)}{BR(X \rightarrow \gamma\gamma)}$	$\frac{BR(X \rightarrow ZZ)}{BR(X \rightarrow \gamma\gamma)}$	$\frac{BR(X \rightarrow W^\pm W^\mp)}{BR(X \rightarrow \gamma\gamma)}$
1	8/3	0	180	1.2	0.090	0
2	1/3	3	460	10	9.1	61
3	11/3	3	460	1.1	2.8	15
4	20/3	4	180	0.46	2.1	11
Current limit			$\sim 2 \times 10^4$	7	13	46

- Predictions \leq experimental limits
- Potentially accessible to experiment
- Also look for heavy fermions!
- **Work for a generation – if X particle exists!**
- **Will know in 2016**

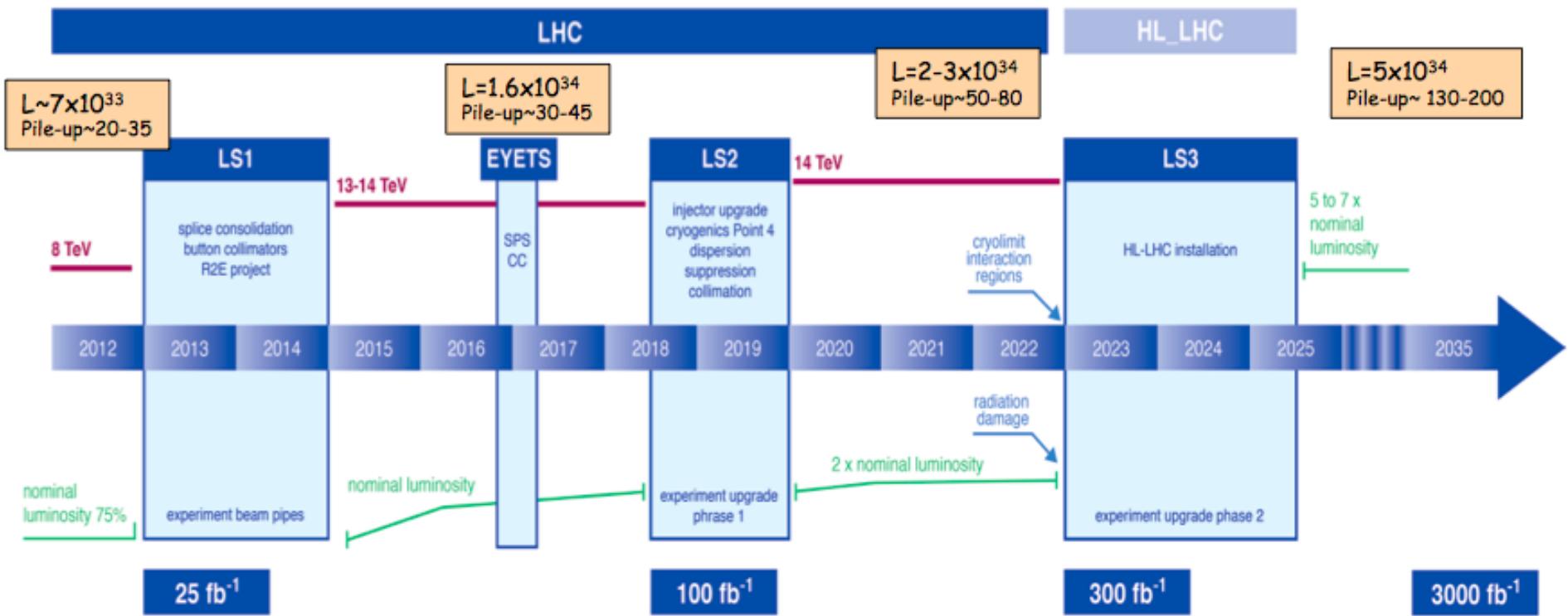
*“Plus un fait est extraordinaire,
plus il a besoin d'être appuyé de
fortes preuves”*

Laplace,
1812

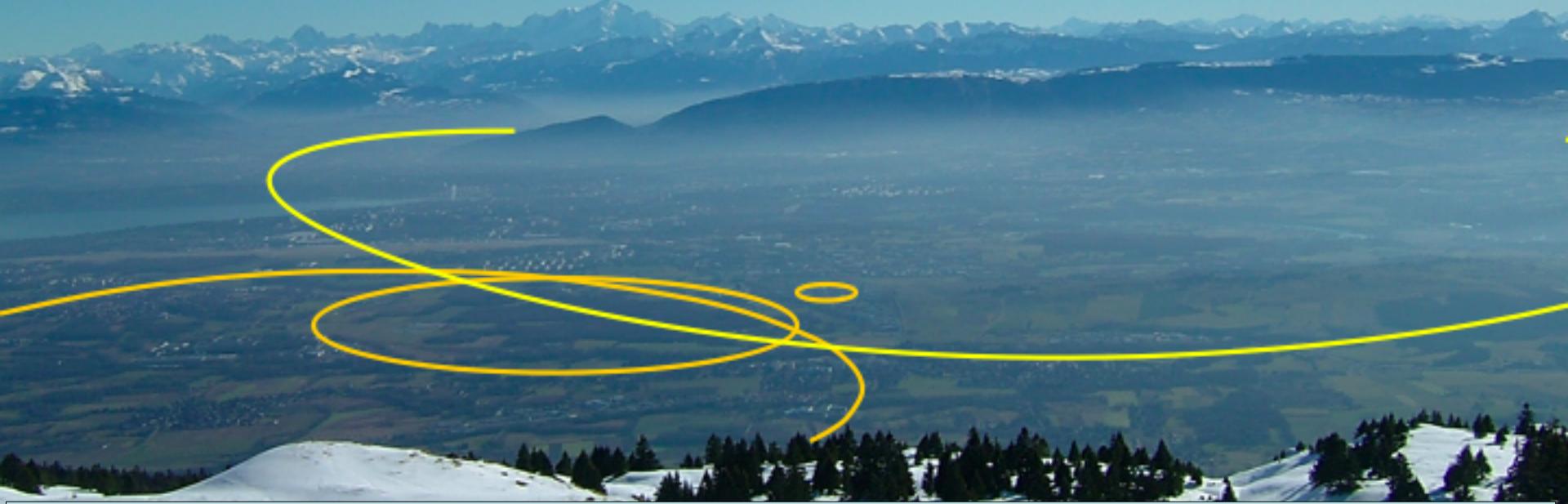
*“The more extraordinary a claim, the
stronger the proof required to support it.”*

The LHC timeline

Plans for future runs of the LHC



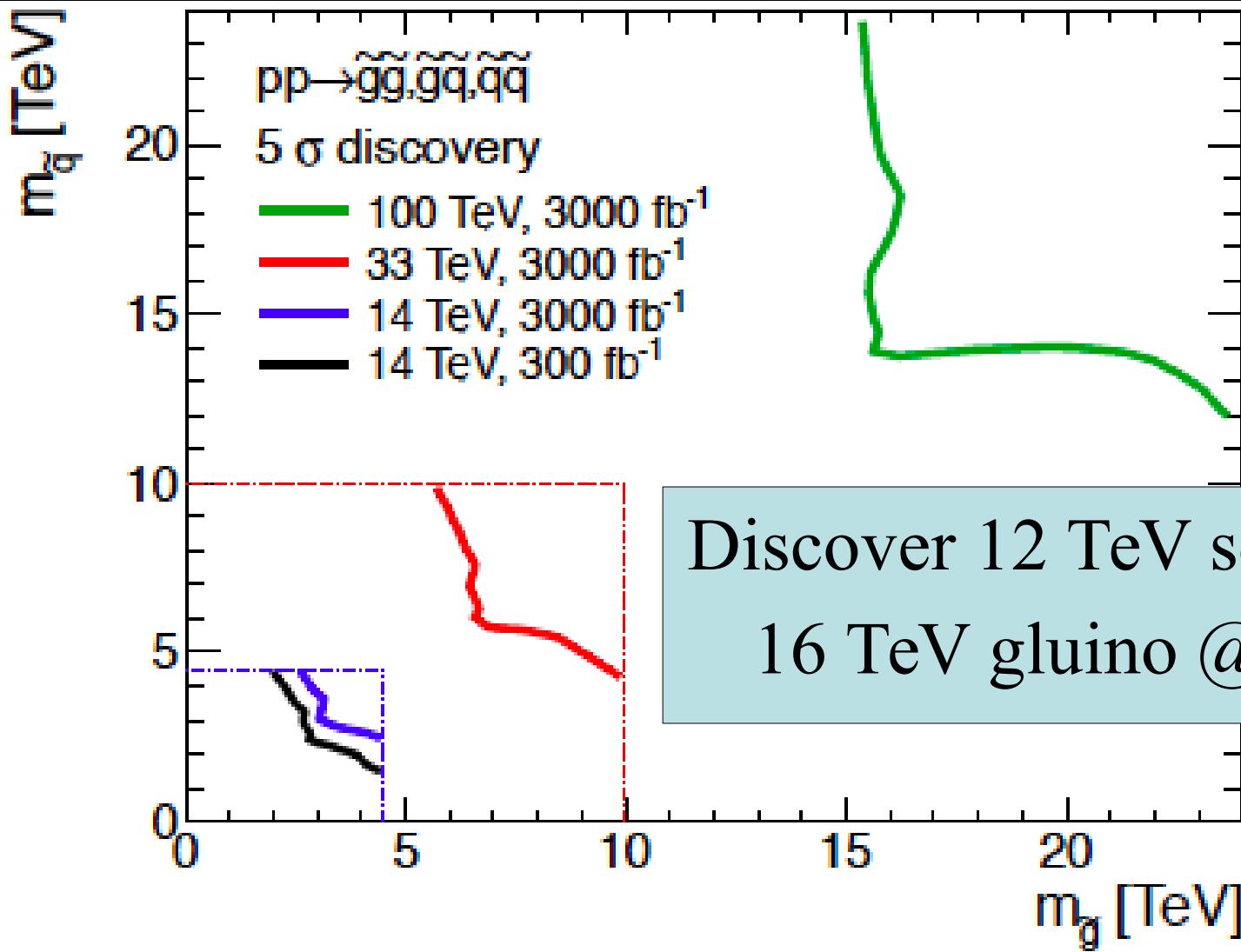
Future Circular Colliders



The vision:
explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

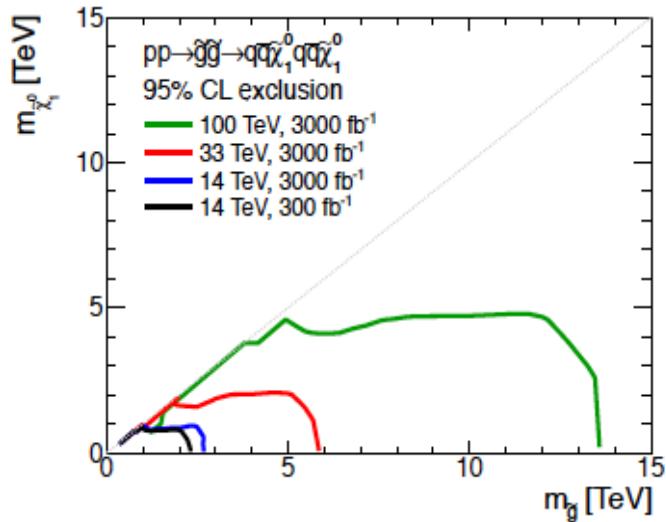
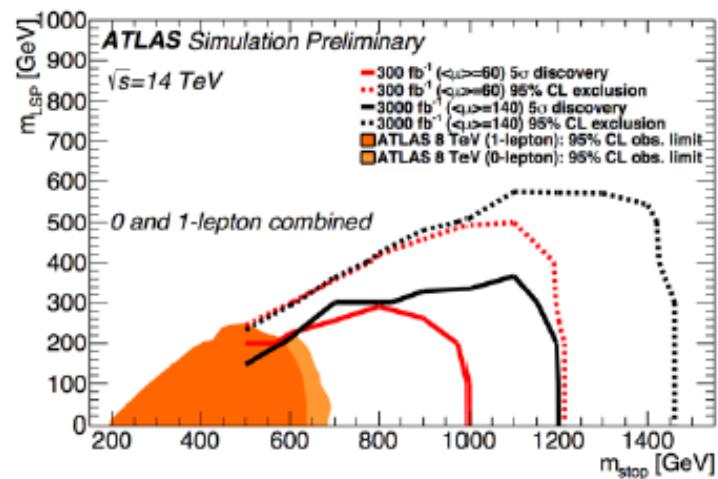
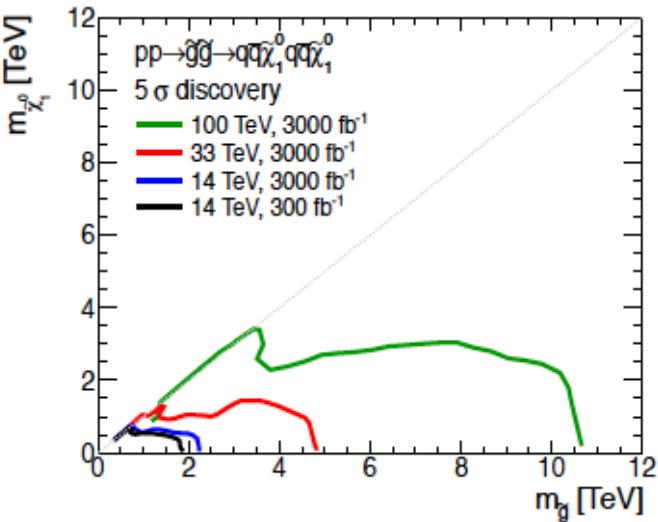
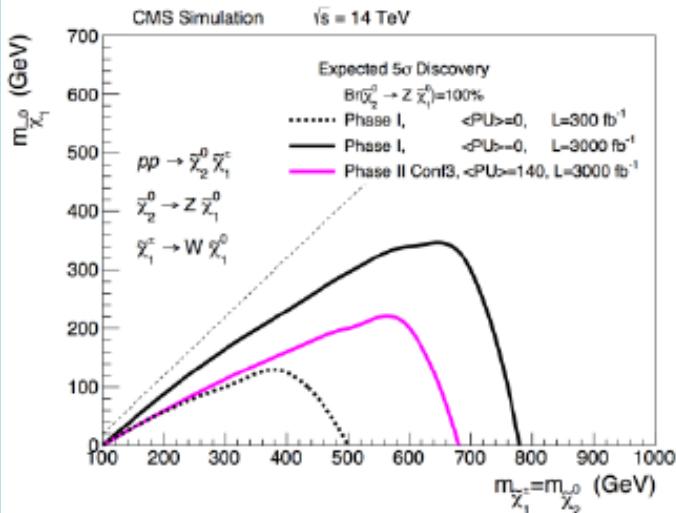


Squark-Gluino Plane



Prospects for Sparticles

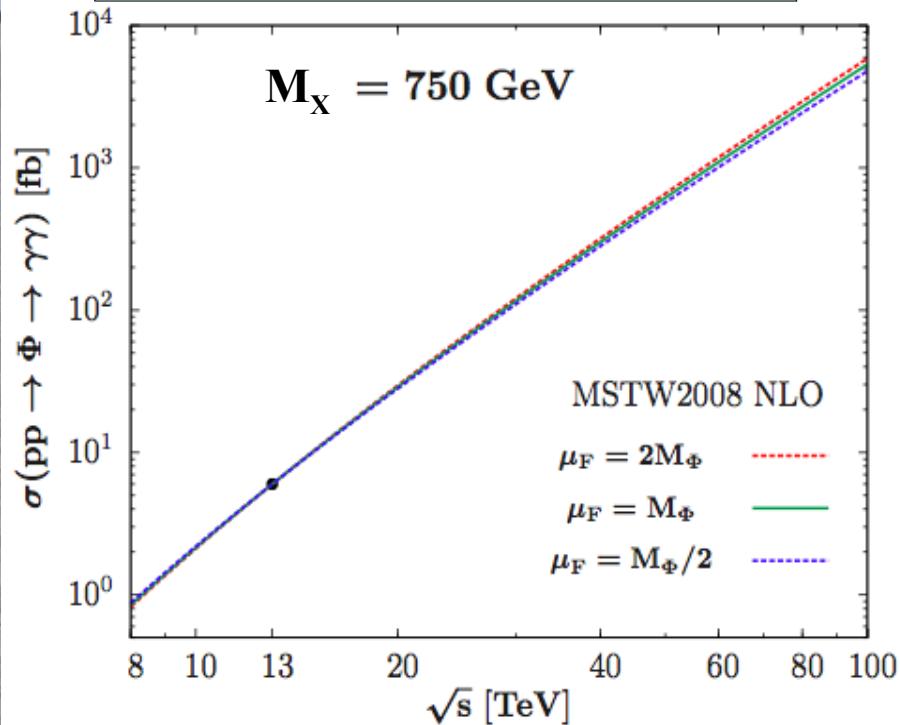
- @ LHC



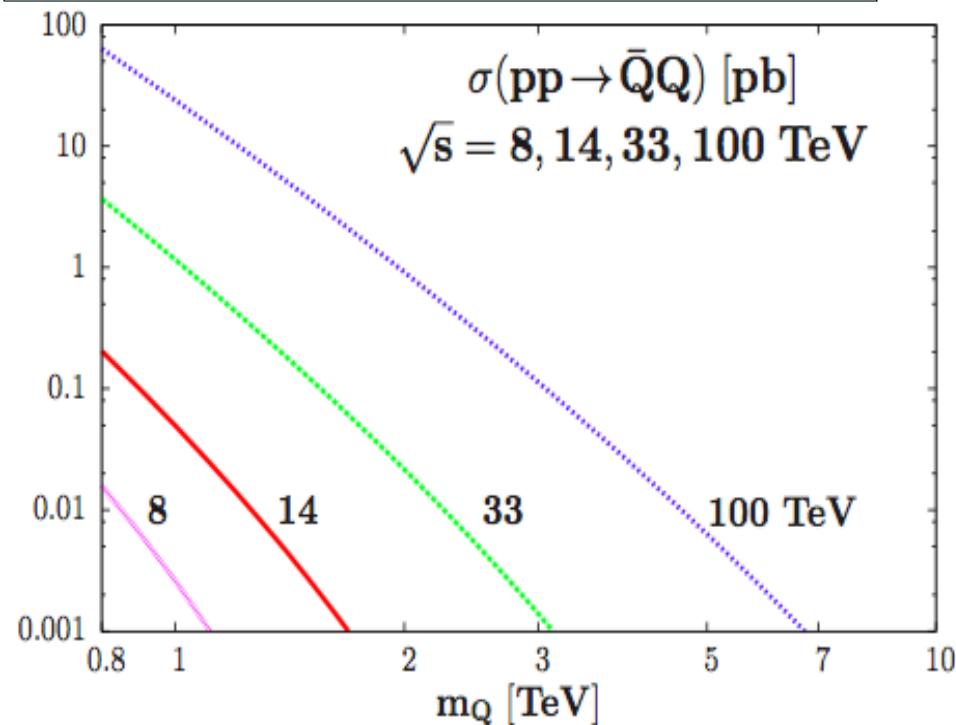
- @ HE-, VHE-LHC

What if the X Signal is Real?

Growth of X signal



Growth of QQbar signal



A cornucopia of possible new physics

Summary

- Rumours of the death of SUSY are exaggerated
 - Still the best framework for TeV-scale physics
- Still the best candidate for cold dark matter
- Simple models (CMSSM, etc.) under pressure
 - More general models quite healthy
- Good prospects for LHC Run 2 and for direct dark matter detection – no guarantees!
- **Whole new world if X(750) is real!**
- Maybe will need a higher-energy collider?