Perspectives for Particle Physics beyond the Standard Model

What is the Higgs boson trying to tell us?

Is supersymmetry waiting?

Can LHC Run 2 find it?

What if X(750) exists?

John Ellis

KING'S College LONDON

Higgs Champagne Bottle

July 4th 2012

The discovery of a new particle

Higgsdependence Day!

The Particle Higgsaw Puzzle

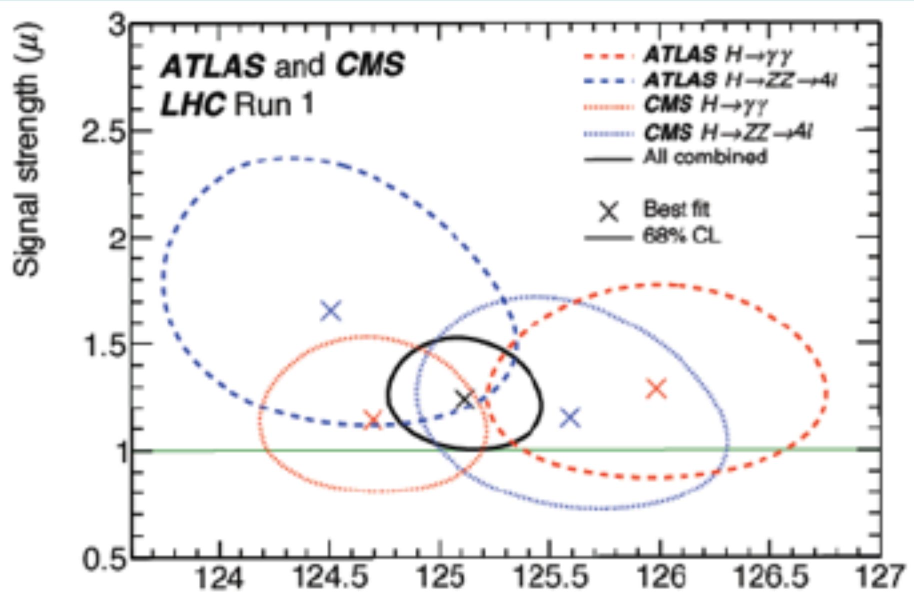
Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

Higgs Mass Measurements

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



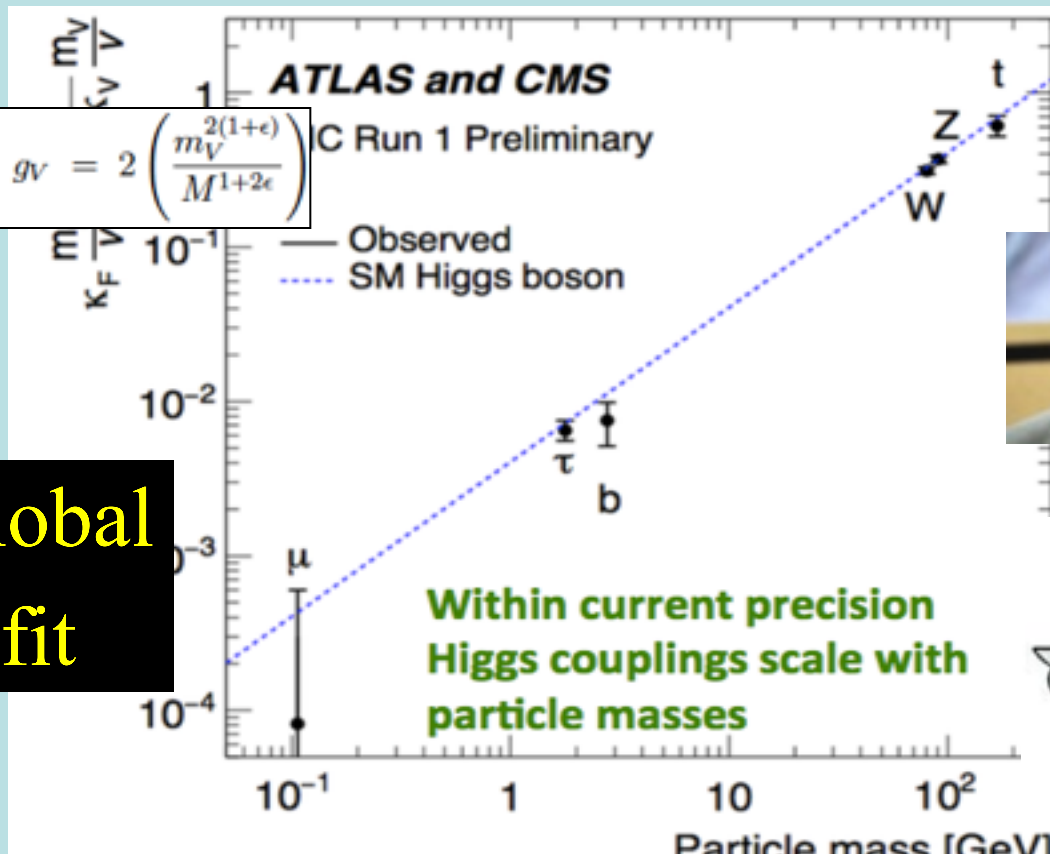
$$125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{syst})$$

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

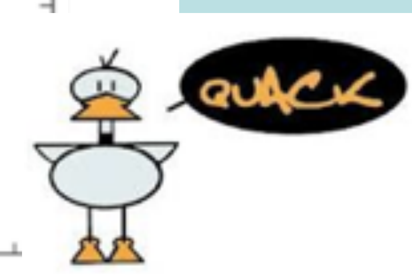
It Walks and Quacks like a Higgs

- 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



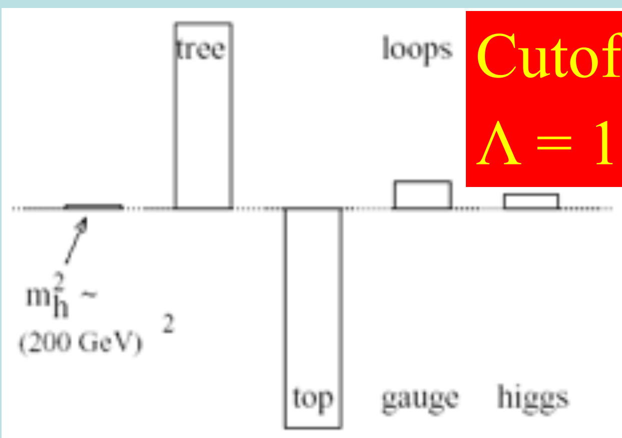
- •**Blue** dashed line = Standard Model

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- 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?
- Little Higgs, …
- Re-awakened by X(750)?

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:

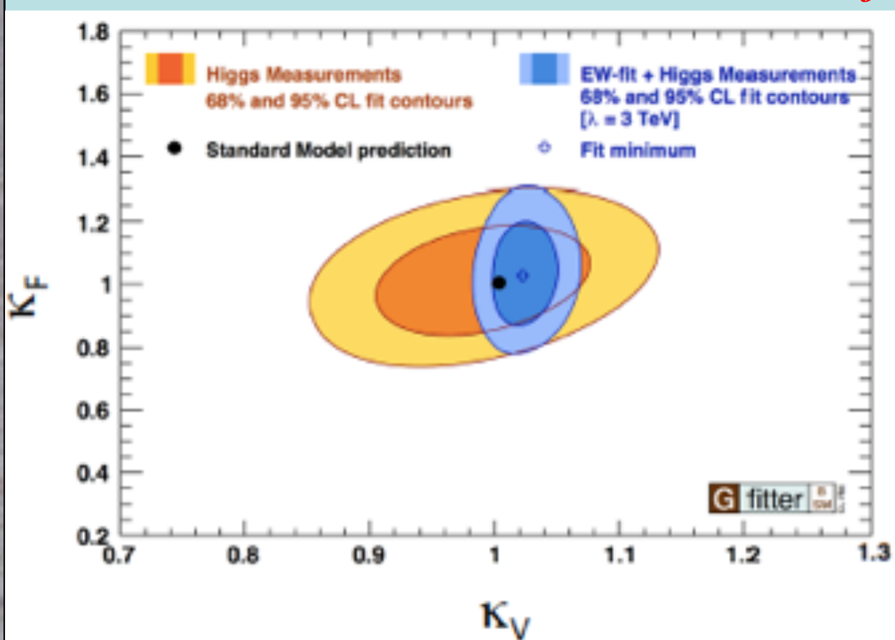
$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right) - m_i\bar{\psi}_L^i\Sigma\left(1 + c\frac{h}{v} + \ldots\right)\psi_R^i + \mathrm{h.c.}$$
$$+ \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3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

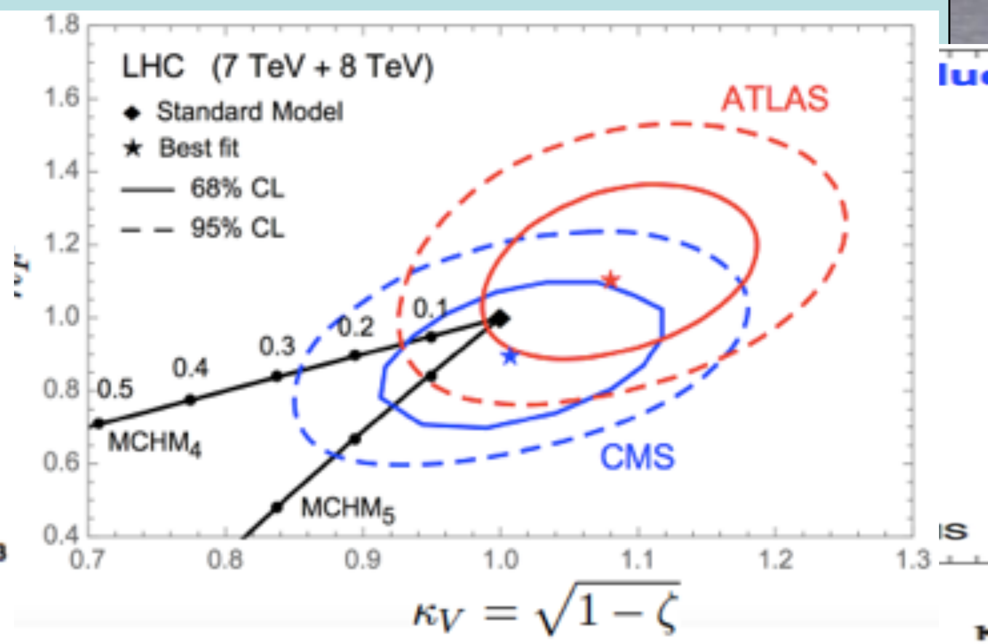
$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \quad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

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

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by 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**

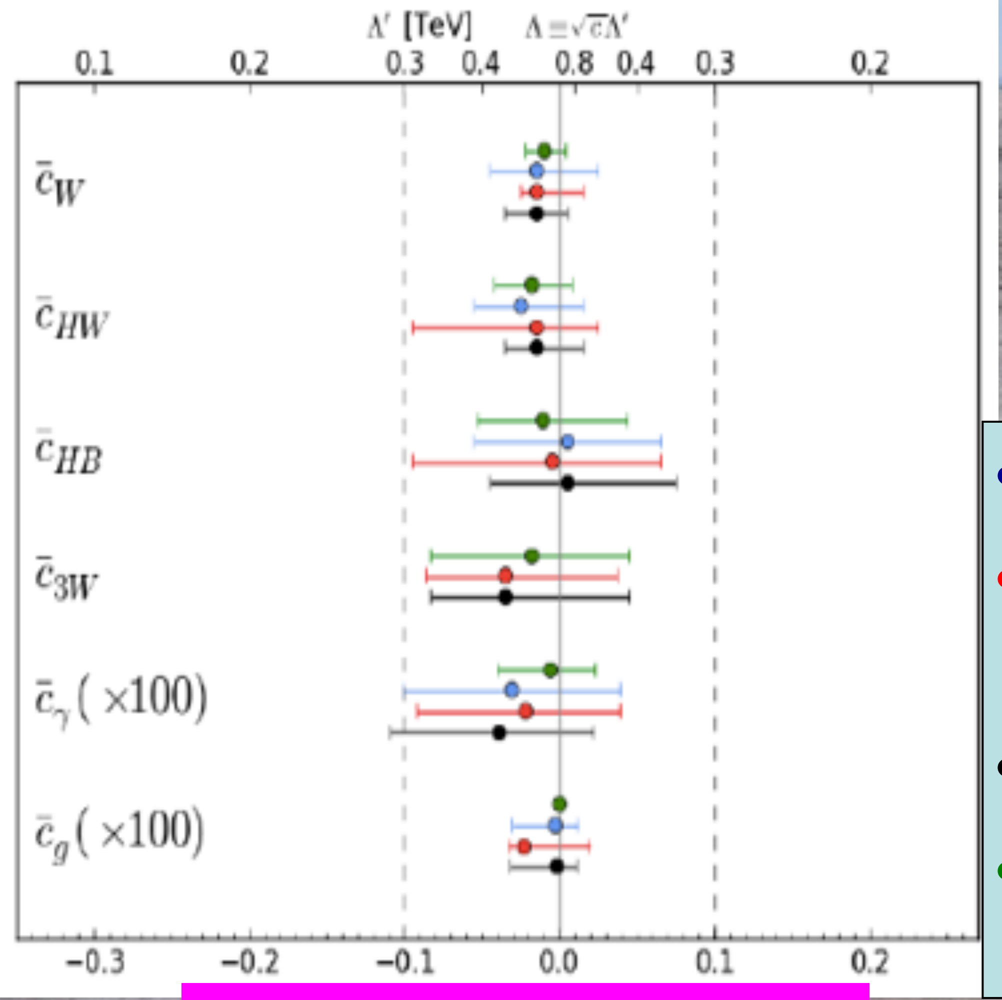
Why is there Nothing rather than Something?

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6: $\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$
- Operators constrained by SU(2) × U(1) symmetry:

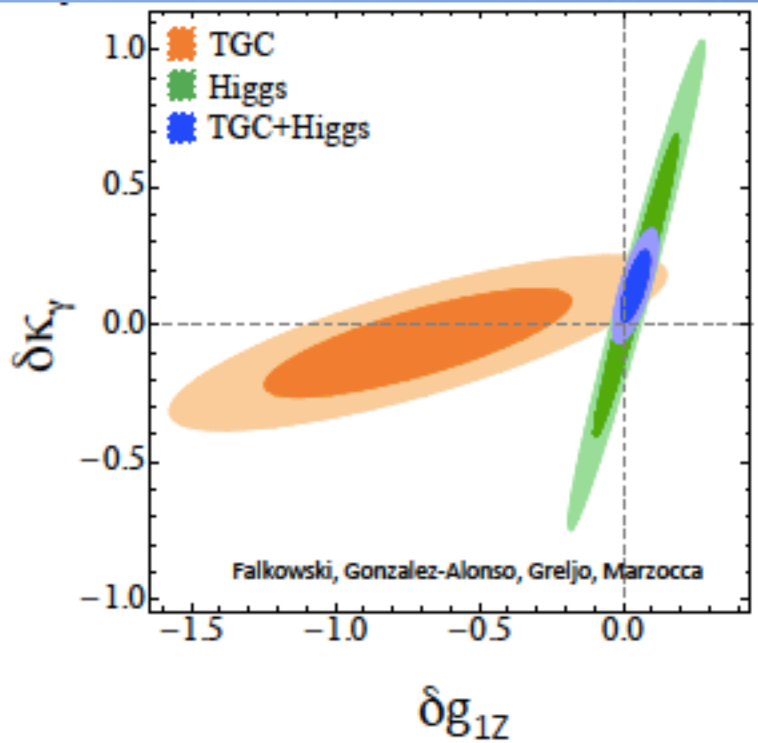
$$\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2} \partial^\mu \left[\Phi^\dagger \Phi\right] \partial_\mu \left[\Phi^\dagger \Phi\right] + \frac{g'^2\ \bar{c}_\gamma}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2} \Phi^\dagger \Phi G^a_{\mu\nu} G_a^{\mu\nu}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

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

Global Fits including LHC TGCs

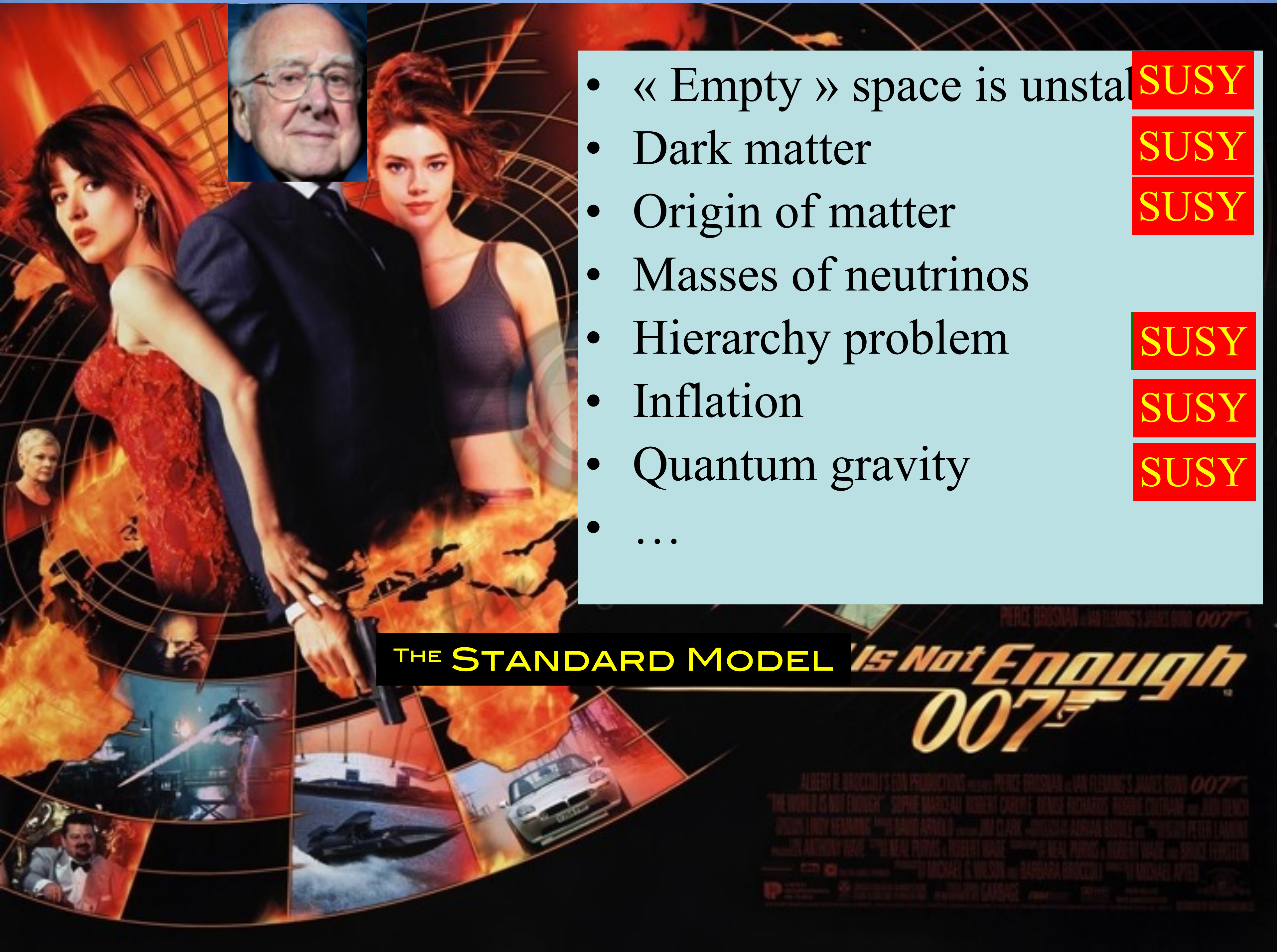


JE, Sanz & Tevong You, arXiv:1410.7703



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

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



What lies beyond the Standard Model?

Supersymmetry

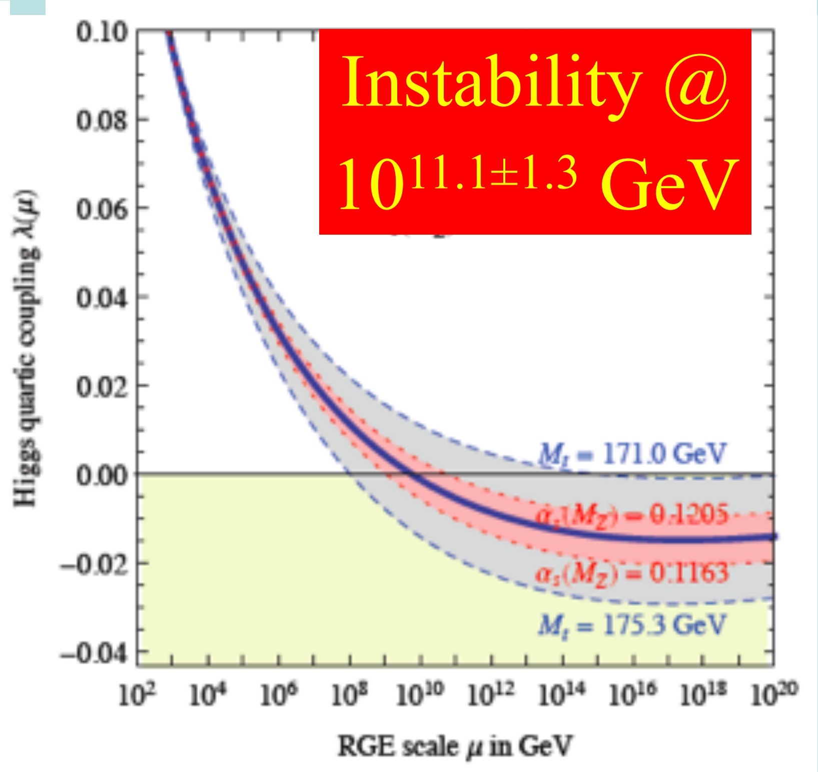
New motivations From LHC Run 1

- **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**

Theoretical Constraints on Higgs Mass

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

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

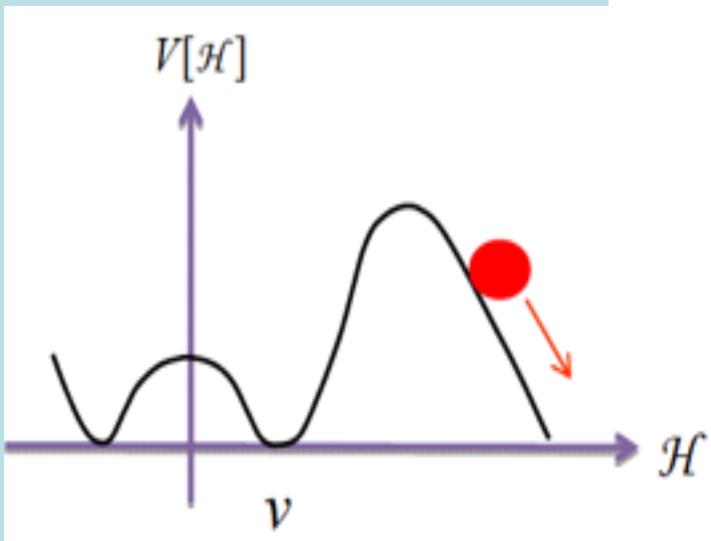


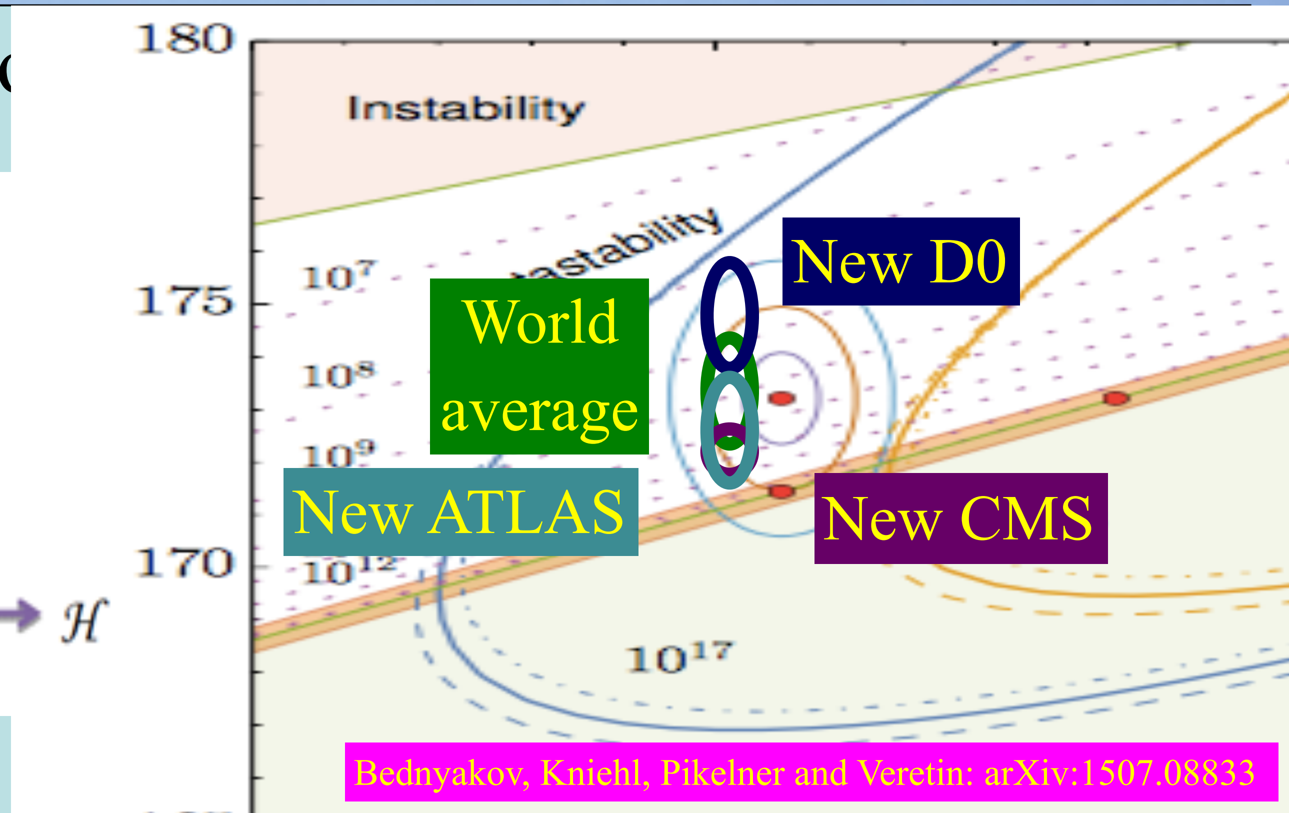
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

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

Vacuum Instability in the Standard Model

- Very sensitive t





Bednyakov, Kniehl, Pikelner and Veretin: arXiv:1507.08833

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

- Instability scale

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

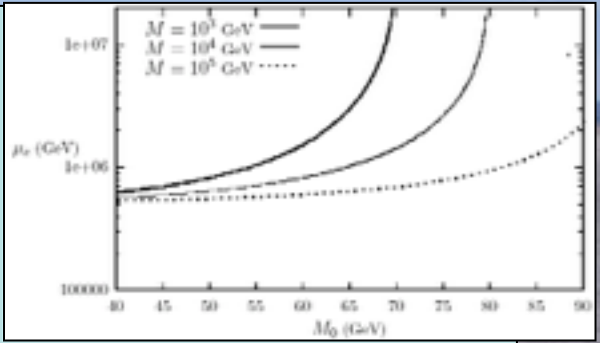
$m_t = 173.3 \pm 1.0$ GeV → $\log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3$

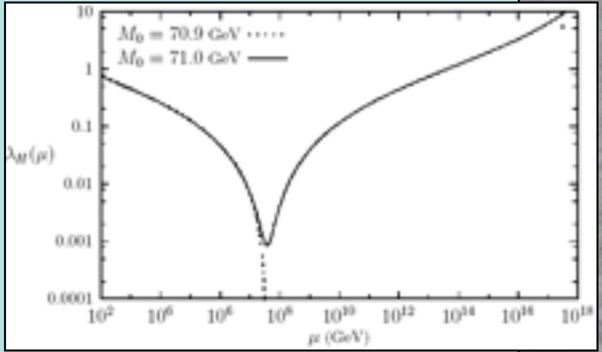
How to Stabilize a Light Higgs Boson?

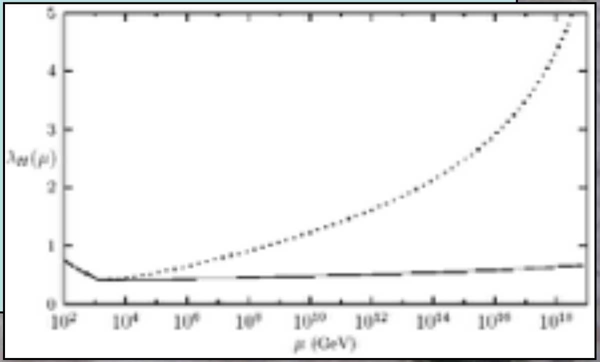
- Top quark destabilizes potential: introduce stop-like scalar:

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

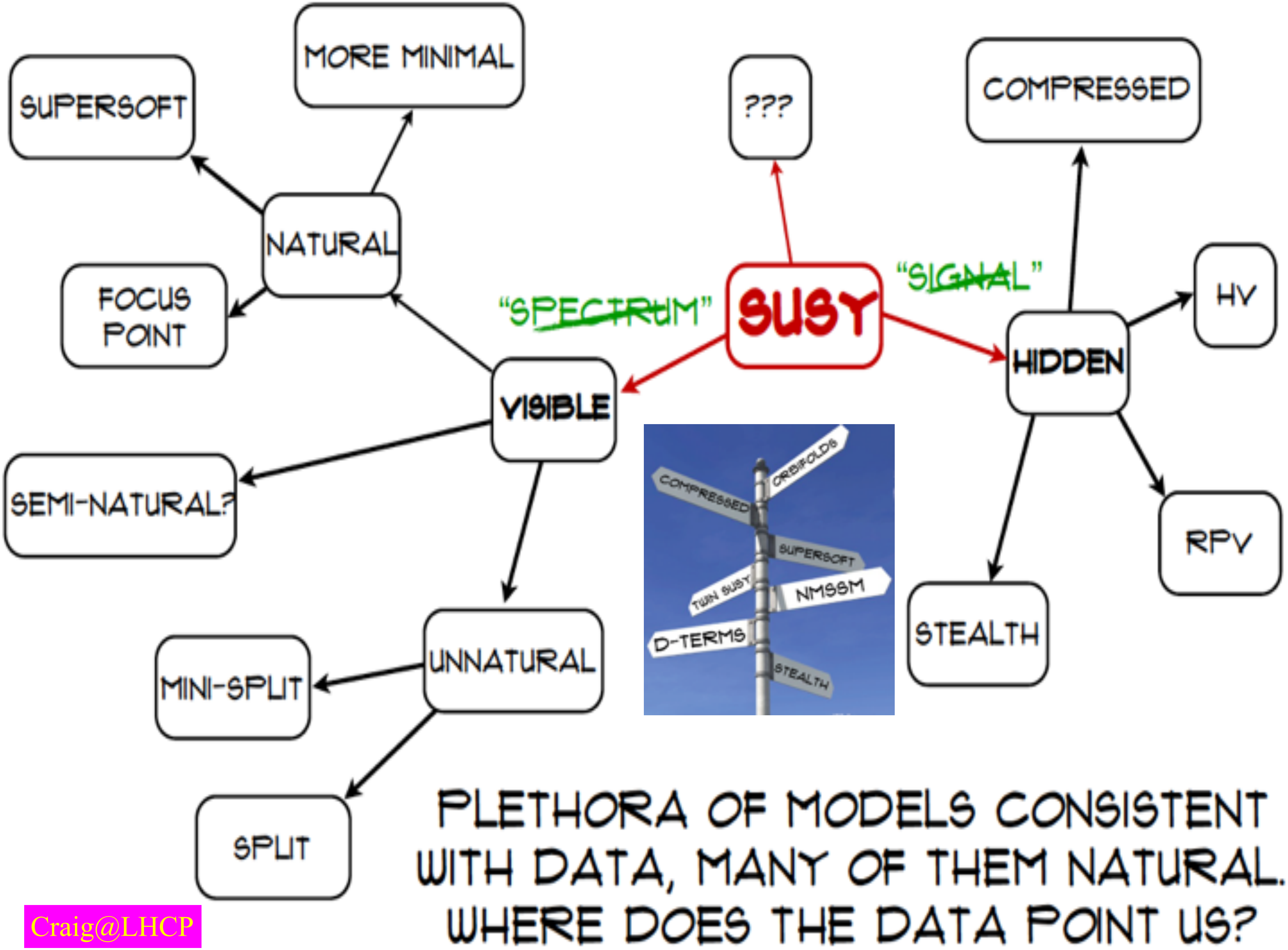
- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  – just like Higgsinos
- Very like **Supersymmetry!**





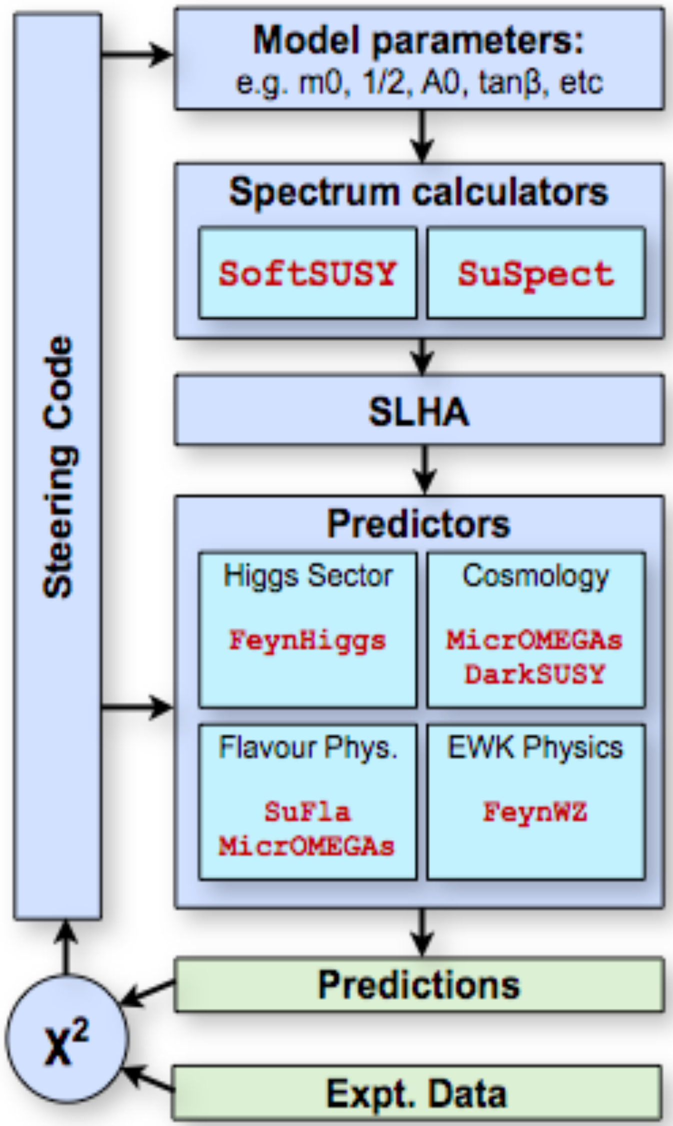


JE + D. Ross


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

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

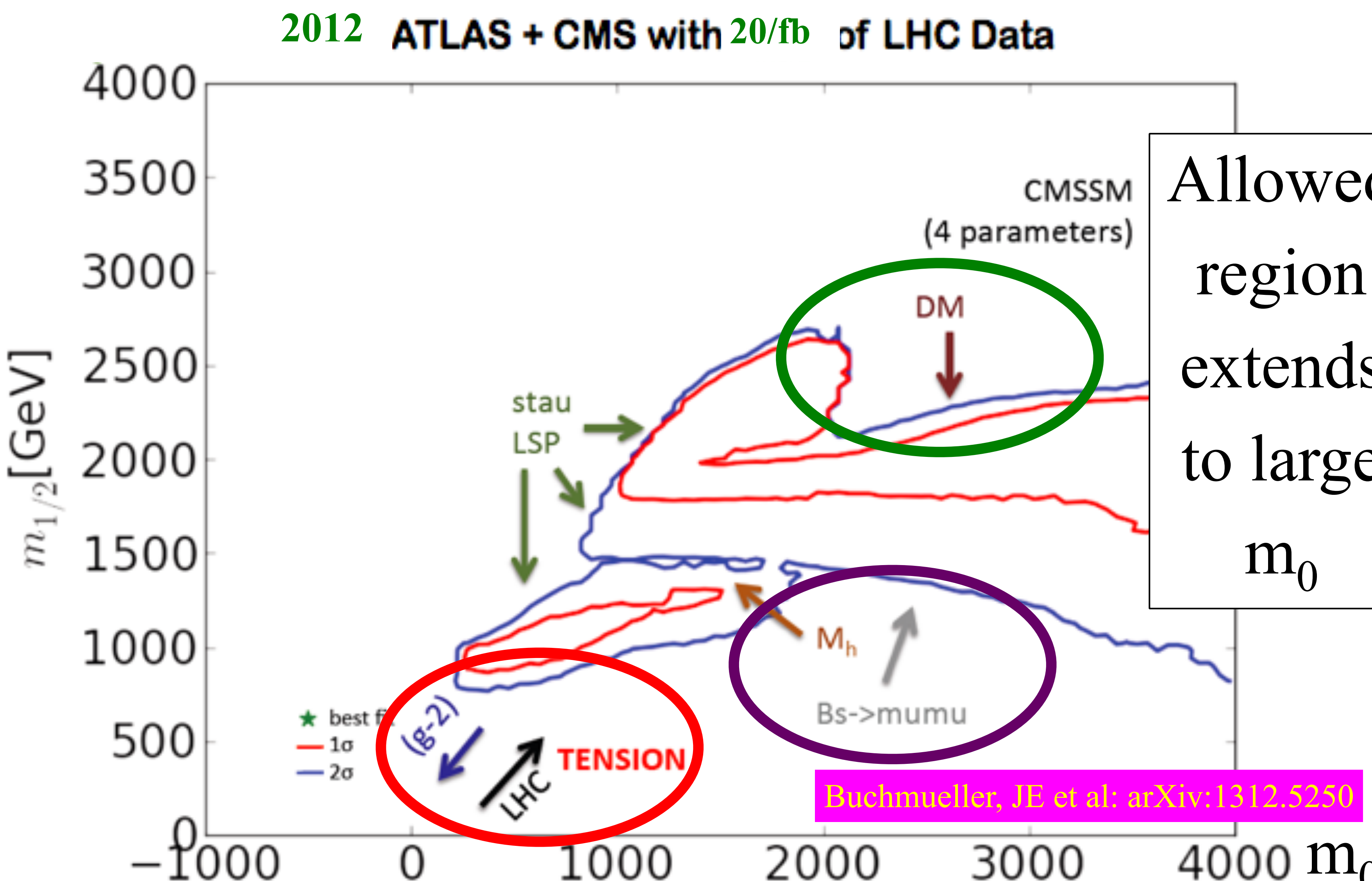


E. Bagnaschi, O. Buchmüller, R. Cavanaugh, M. Citron, A. De Roeck, M.J. Dolan, J.E., H. Flächer, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, K. Sakurai, G. Weiglein

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 ~ 0.1)**
- Treat soft supersymmetry-breaking masses as phenomenological inputs at EW scale
  - pMSSMn (n parameters)
  - With universality motivated by upper limits on flavour-changing neutral interactions: pMSSM10
- **Less strongly constrained by LHC (p ~ 0.3)**

Fit to Constrained MSSM (CMSSM)



Allowed region extends to large m_0

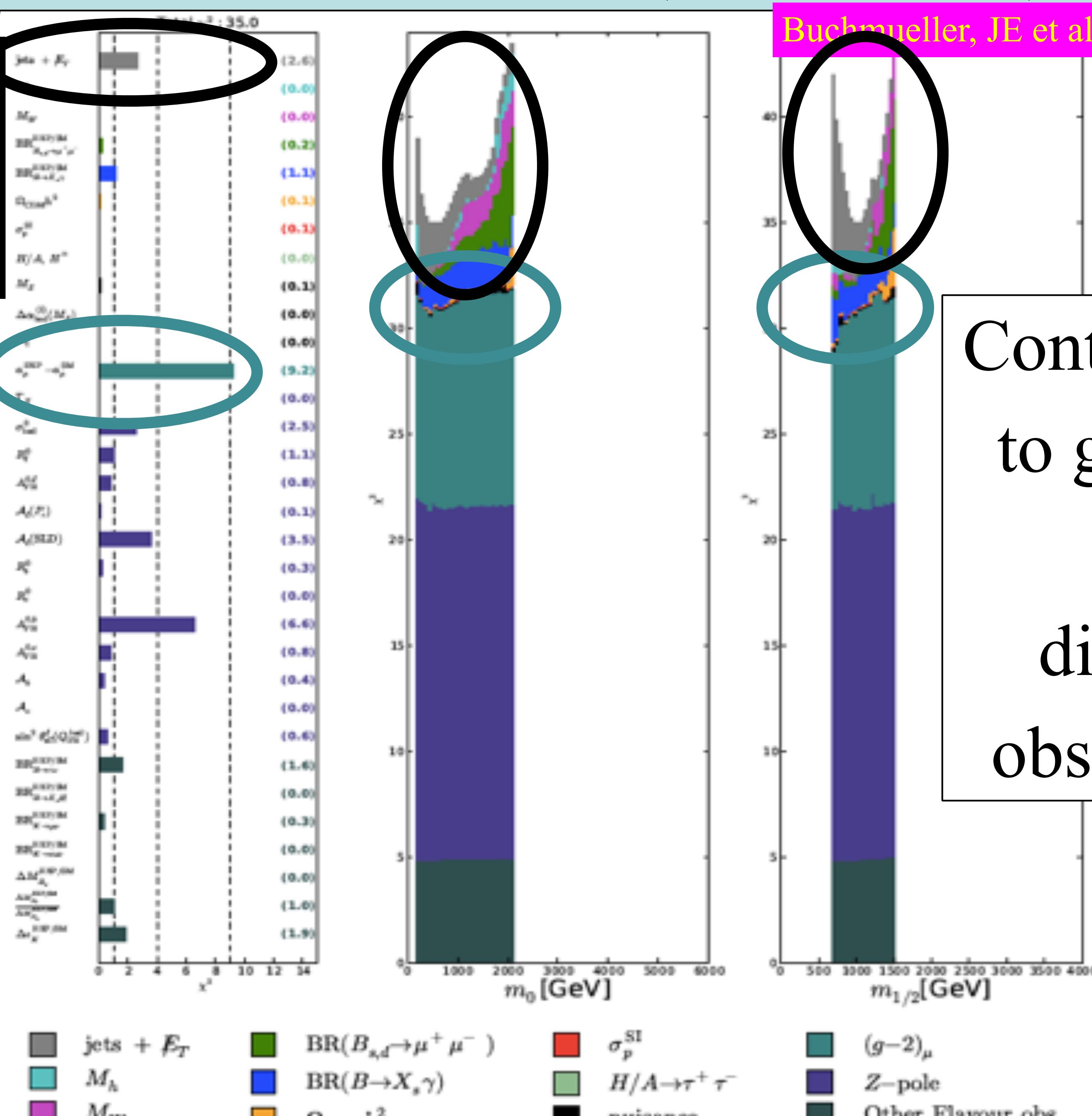
p-value of simple models ~ 10% (also SM)

Constrained MSSM (CMSSM)

Buchmueller, JE et al: arXiv:1312.5250

LHC
MET
searches

g_μ - 2



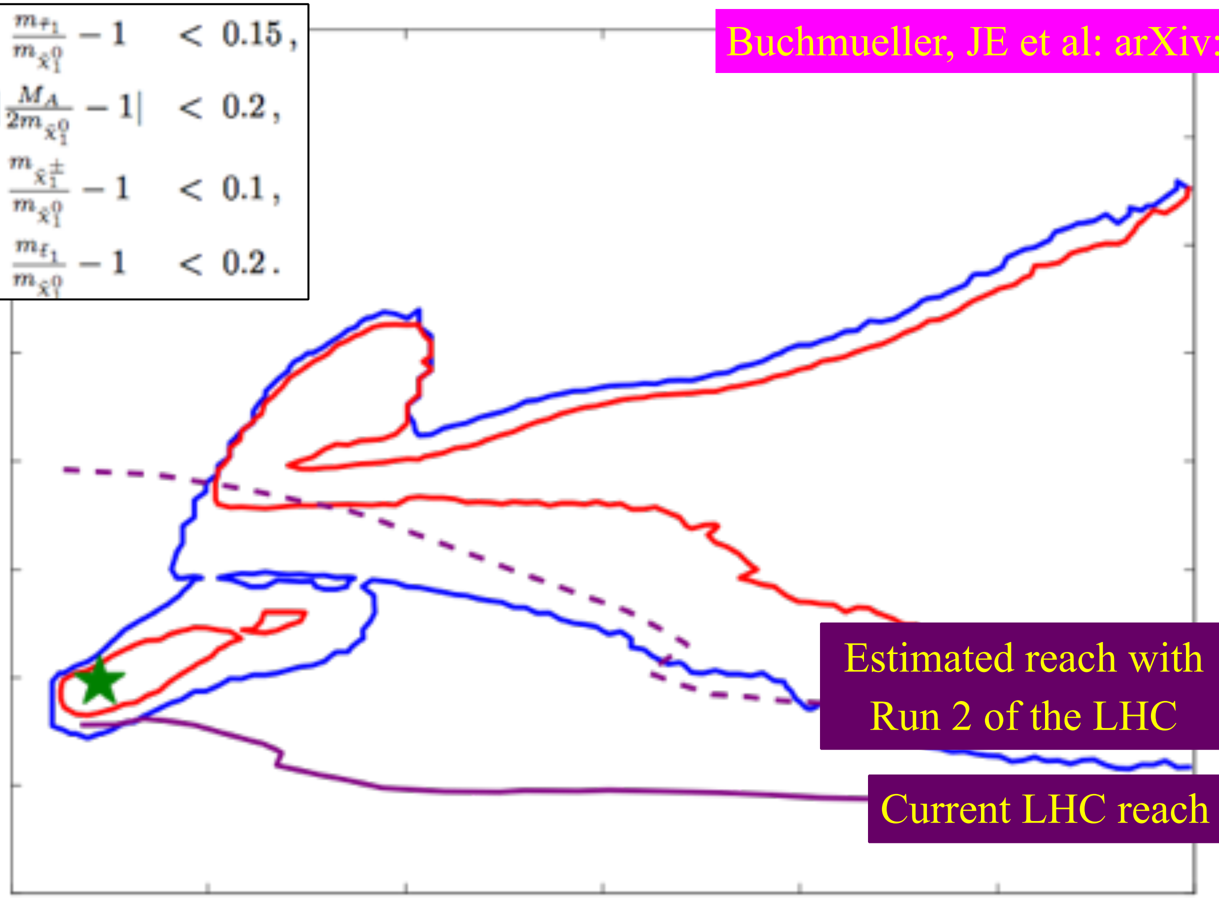
Contributions
to global χ^2
from
different
observables

Dark Matter Density Mechanisms

masterCODE

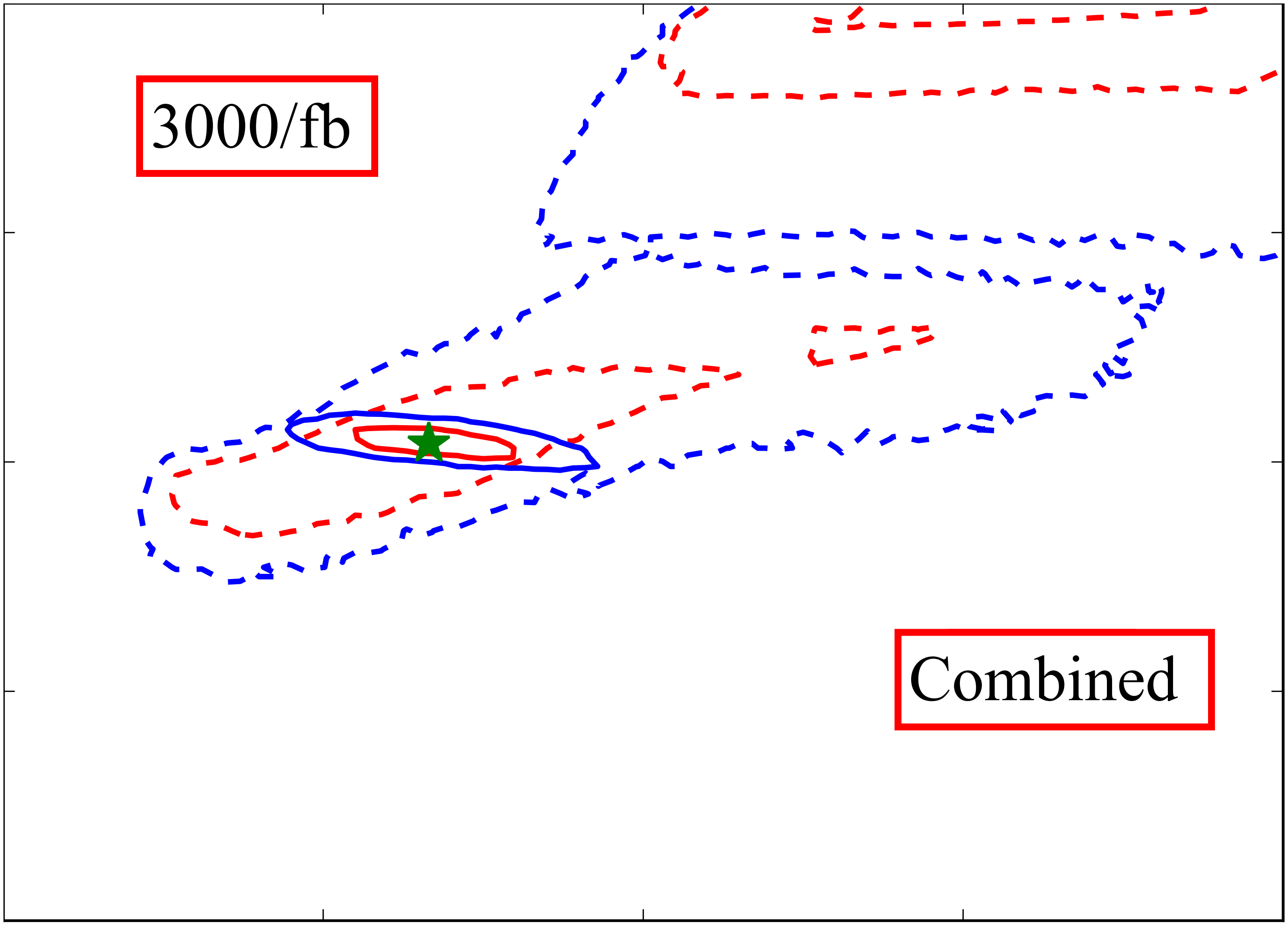
2012 ATLAS + CMS with 20/fb of LHC Data

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



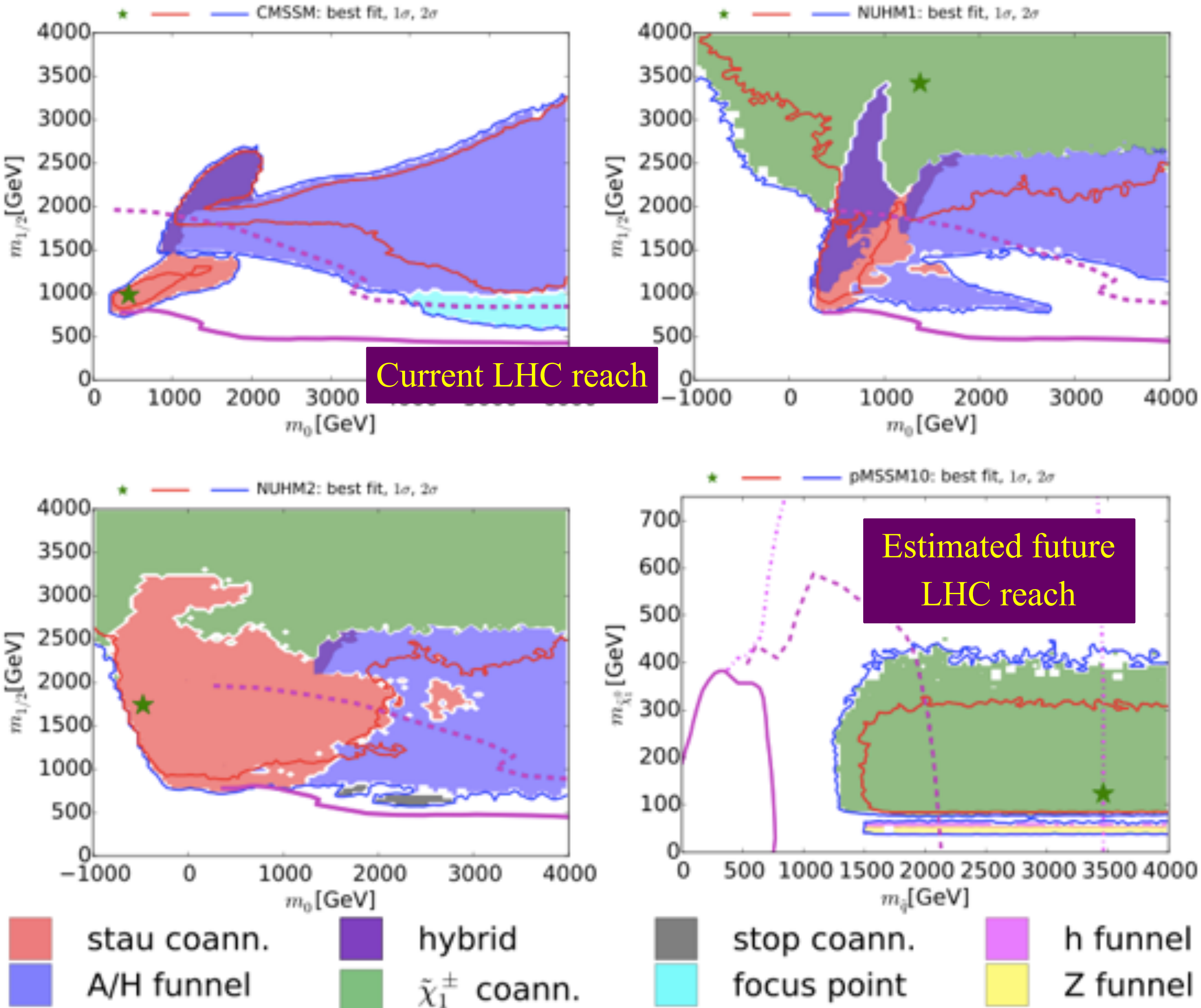
stau coann. A/H-funnel hybrid $\tilde{\chi}^{\pm}_1$ coann. focus point

Measuring the CMSSM with the LHC



Buchmueller, JE et al: arXiv:1505.04702

Dark Matter in CMSSM, NUHM1/2, pMSSM10



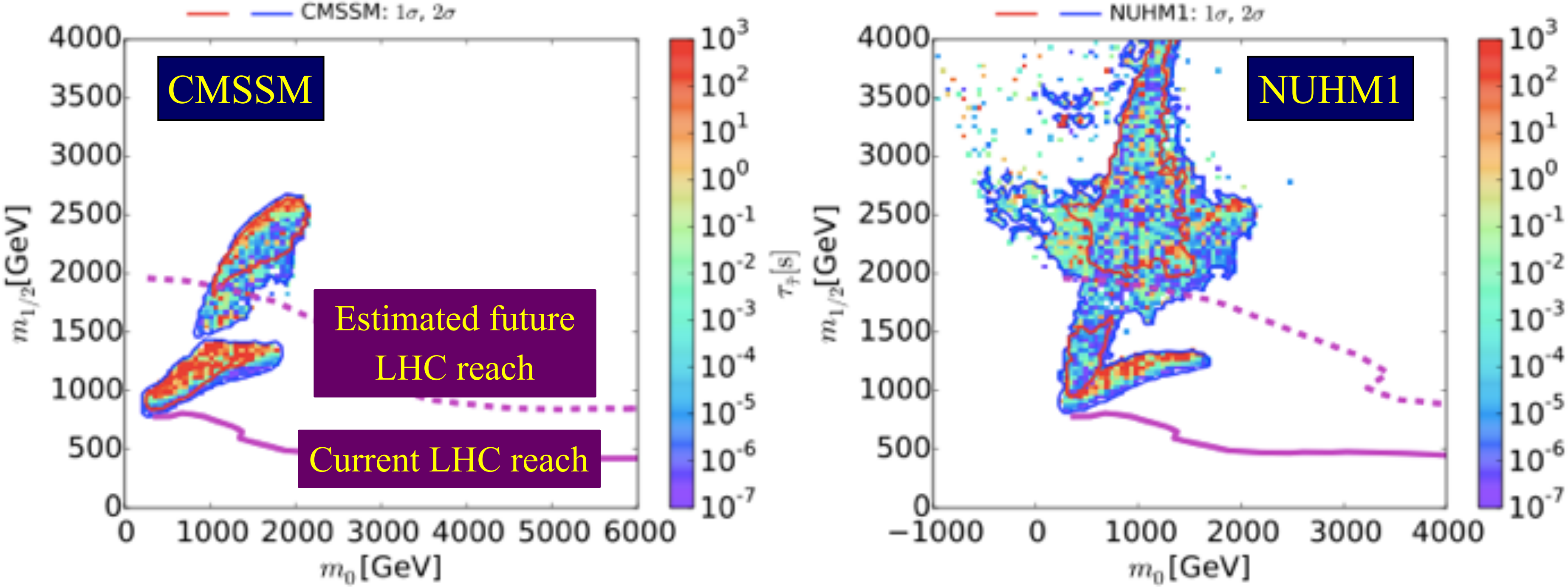
Bagnaschi, JE et al: arXiv:1508.01173

Long-Lived Stau in CMSSM, NUHM?

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

Generic possibility in CMSSM, NUHM

(stau coannihilation region)



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

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

Bagnaschi, JE et al: arXiv:1508. 01173

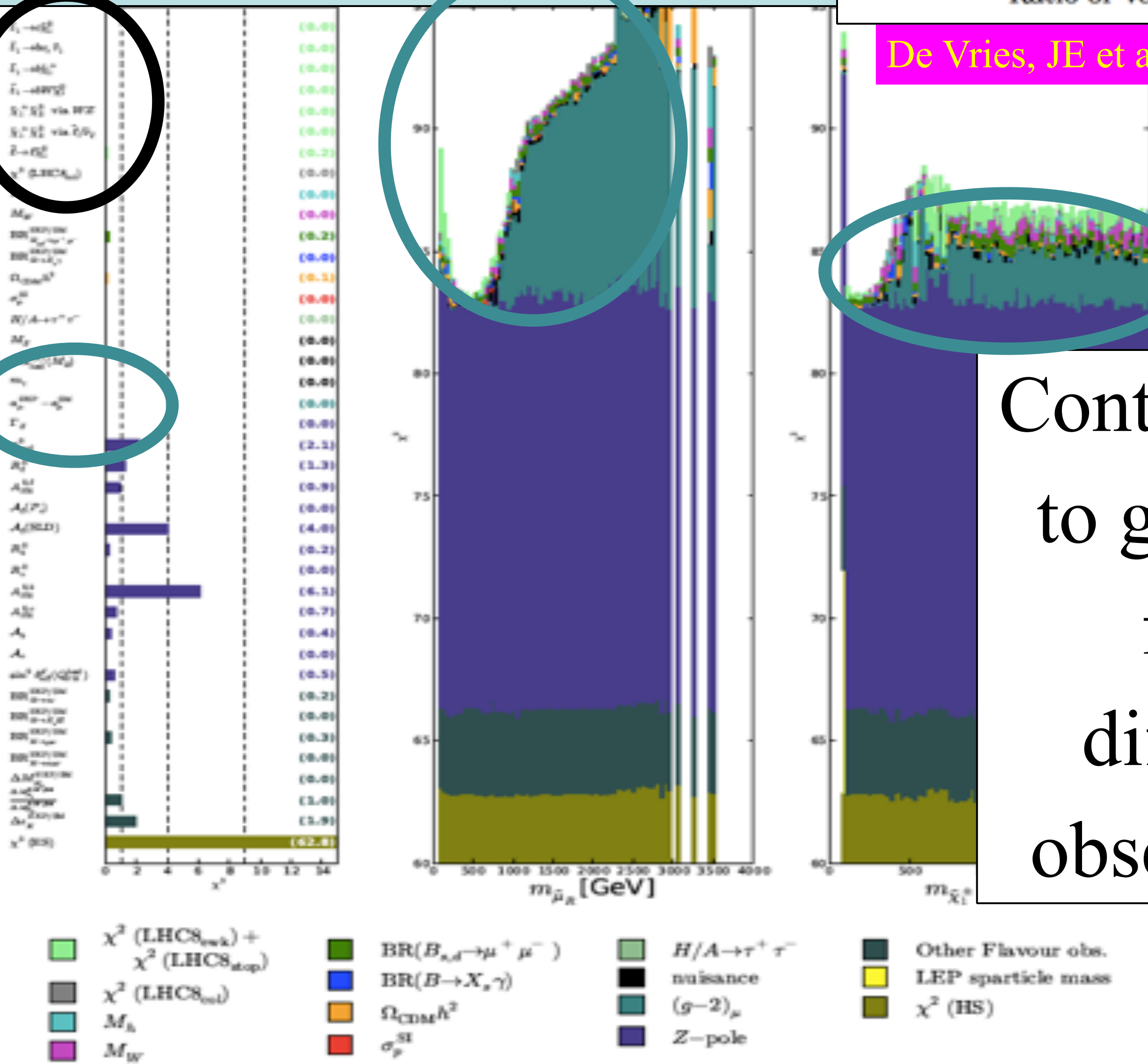
Phenomenological MSSM (pMSSM10)

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 : $m_{\tilde{l}}$,
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

LHC MET searches

g_μ - 2

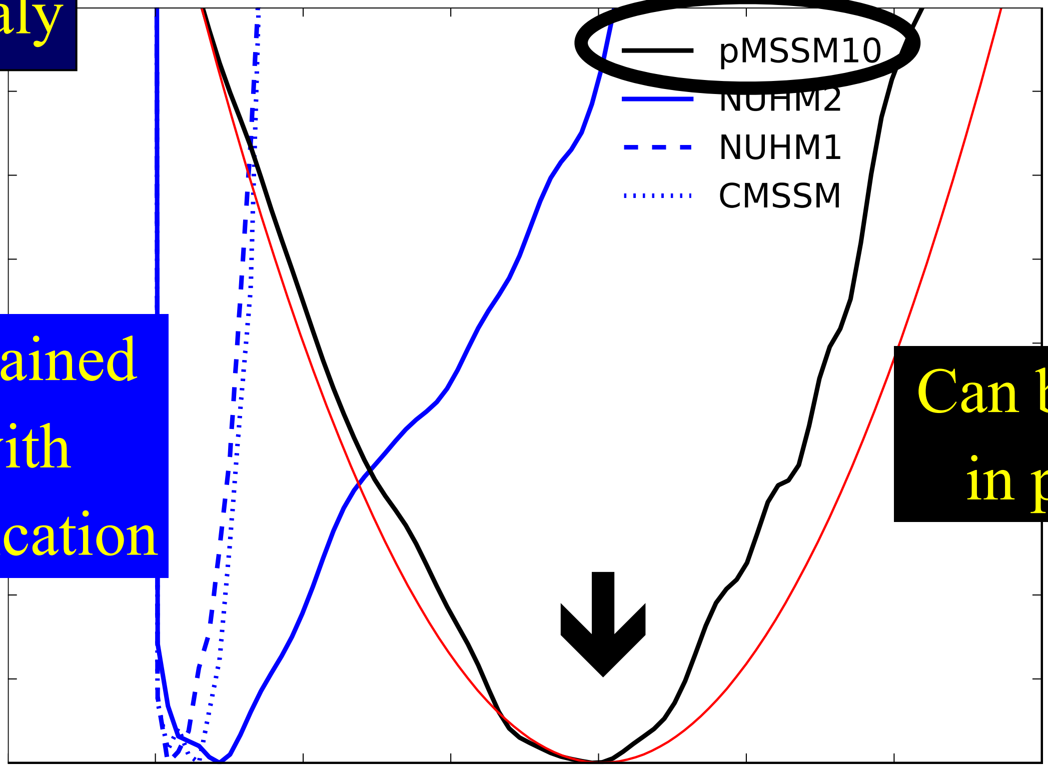


Contributions to global χ^2 from different observables

Anomalous Magnetic Moment of Muon

2012 ATLAS + CMS with 20/fb of LHC Data

$g_\mu - 2$ anomaly



Cannot be explained by models with GUT-scale unification

Can be explained in pMSSM10

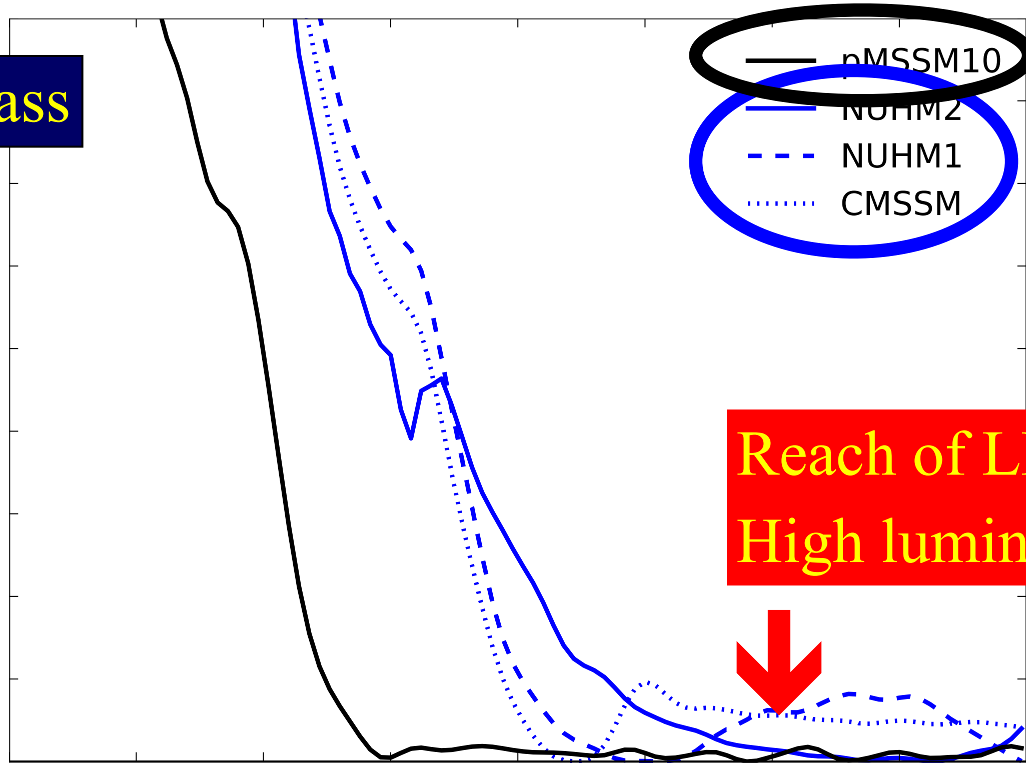
De Vries, JE et al: arXiv:1504.03260

pMSSM10 can explain experimental measurements of g_μ - 2

Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data

Gluino mass



Reach of LHC at High luminosity

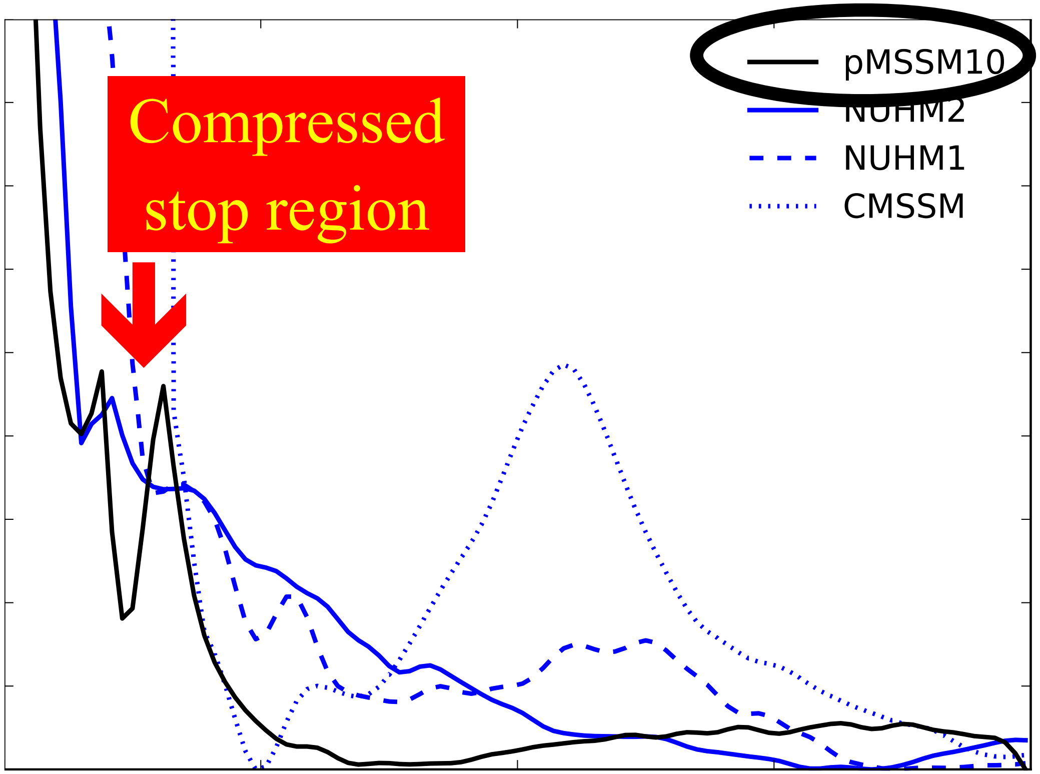
De Vries, JE et al: arXiv:1504.03260

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

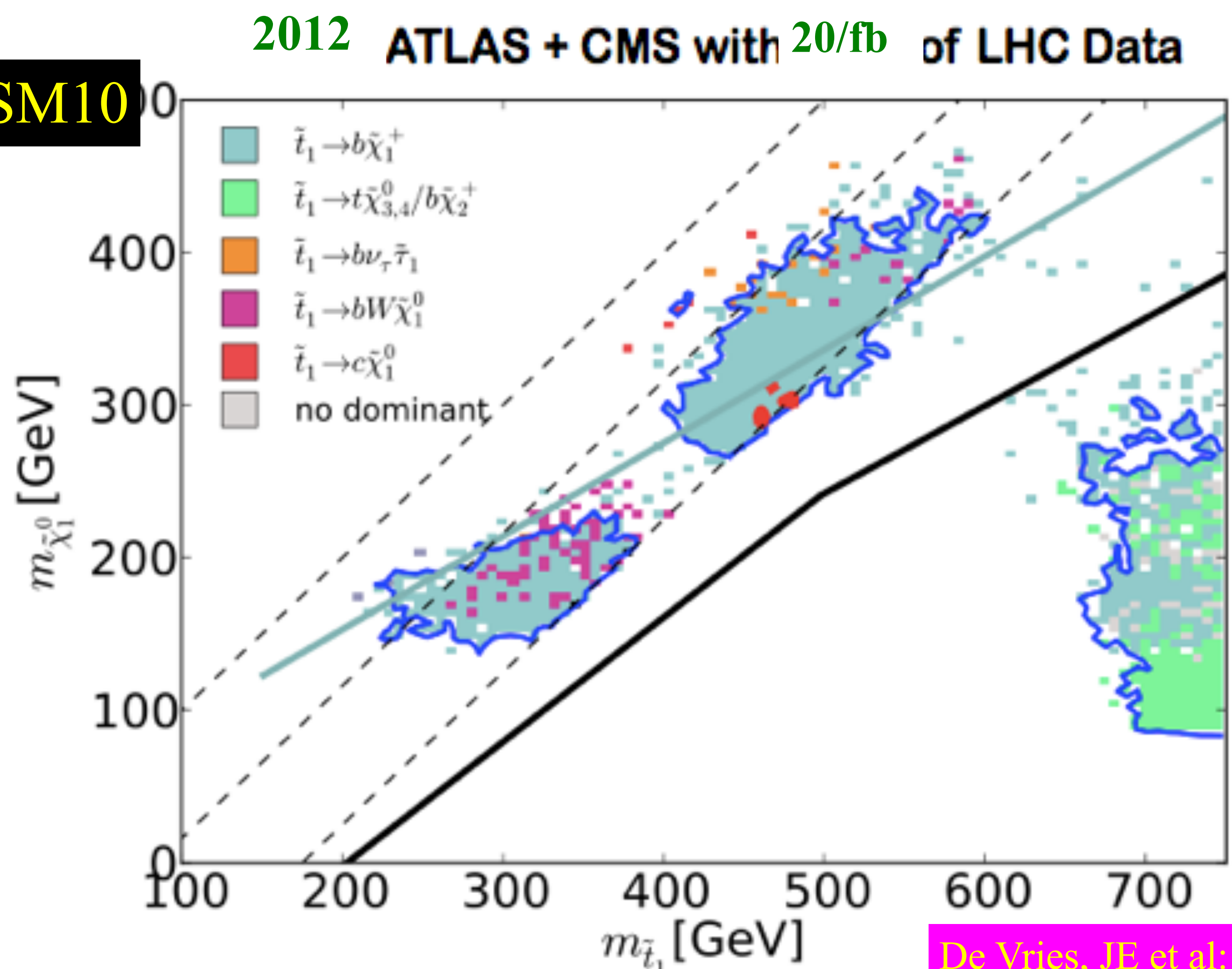
Stop mass



De Vries, JE et al: arXiv:1504.03260

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

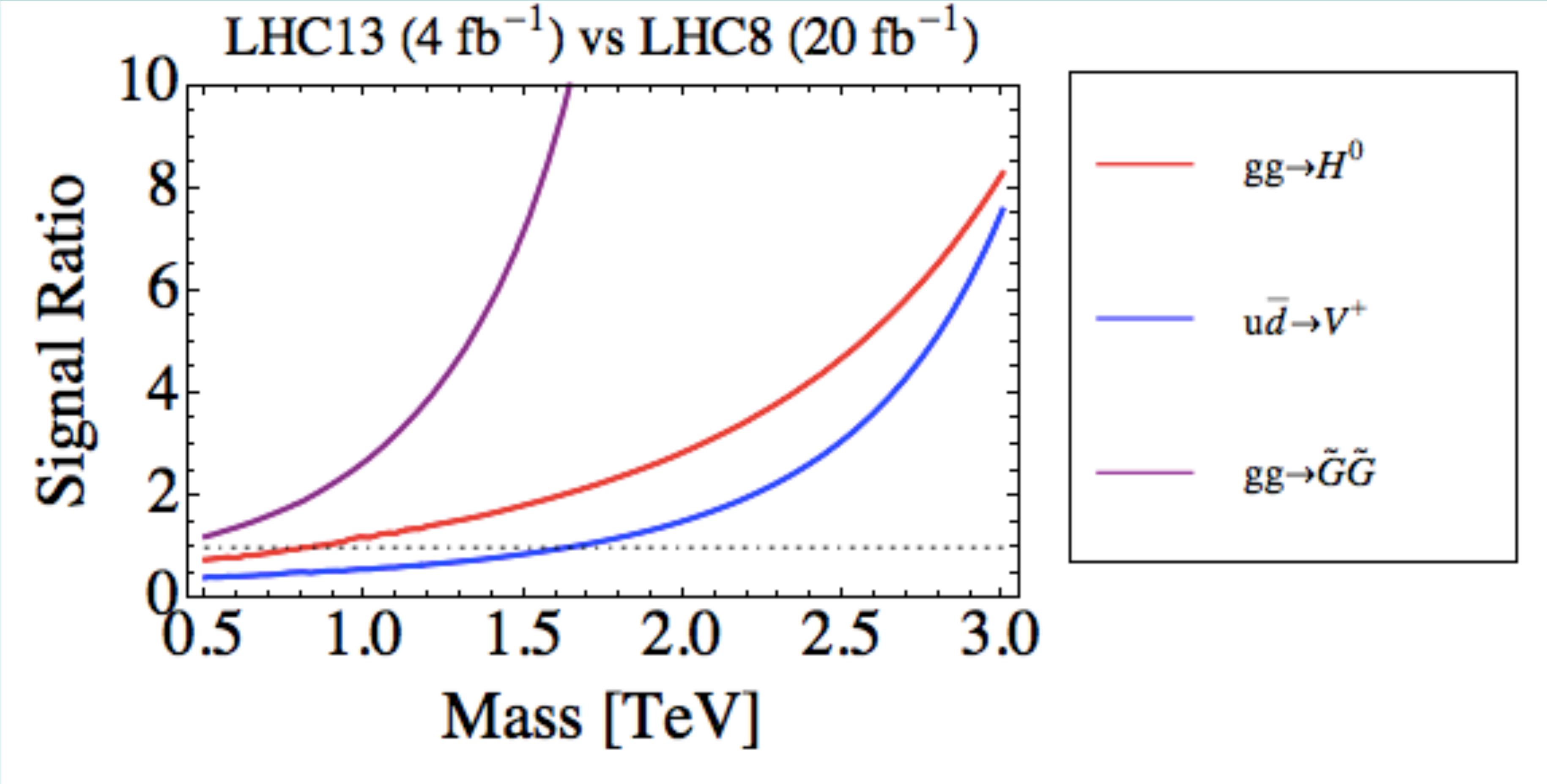
1

De Vries, JE et al: arXiv:1504.03260

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

Why we are so excited by Run 2

- 2015 luminosity already explores new physics



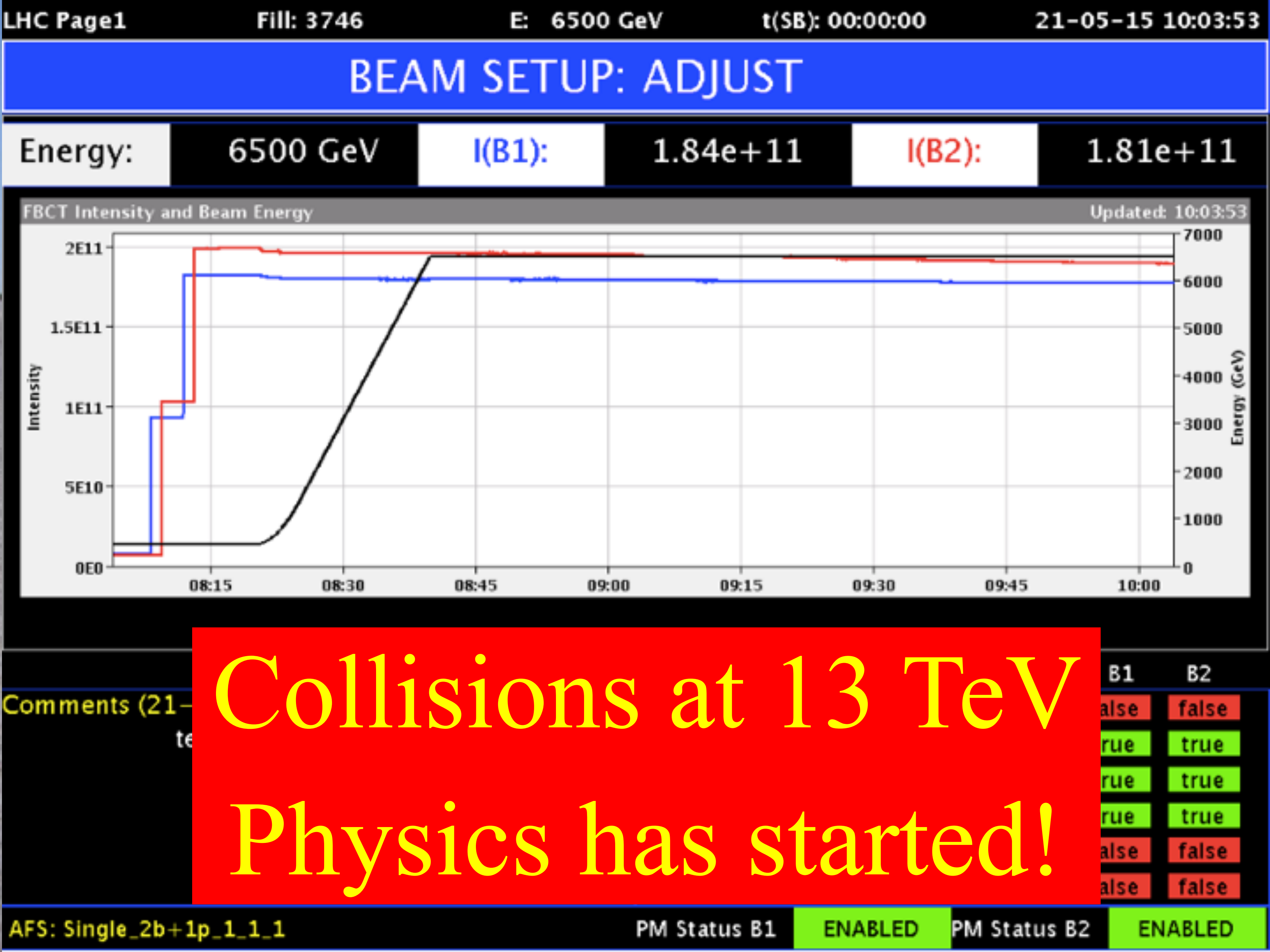
Prospects for SUSY Searches

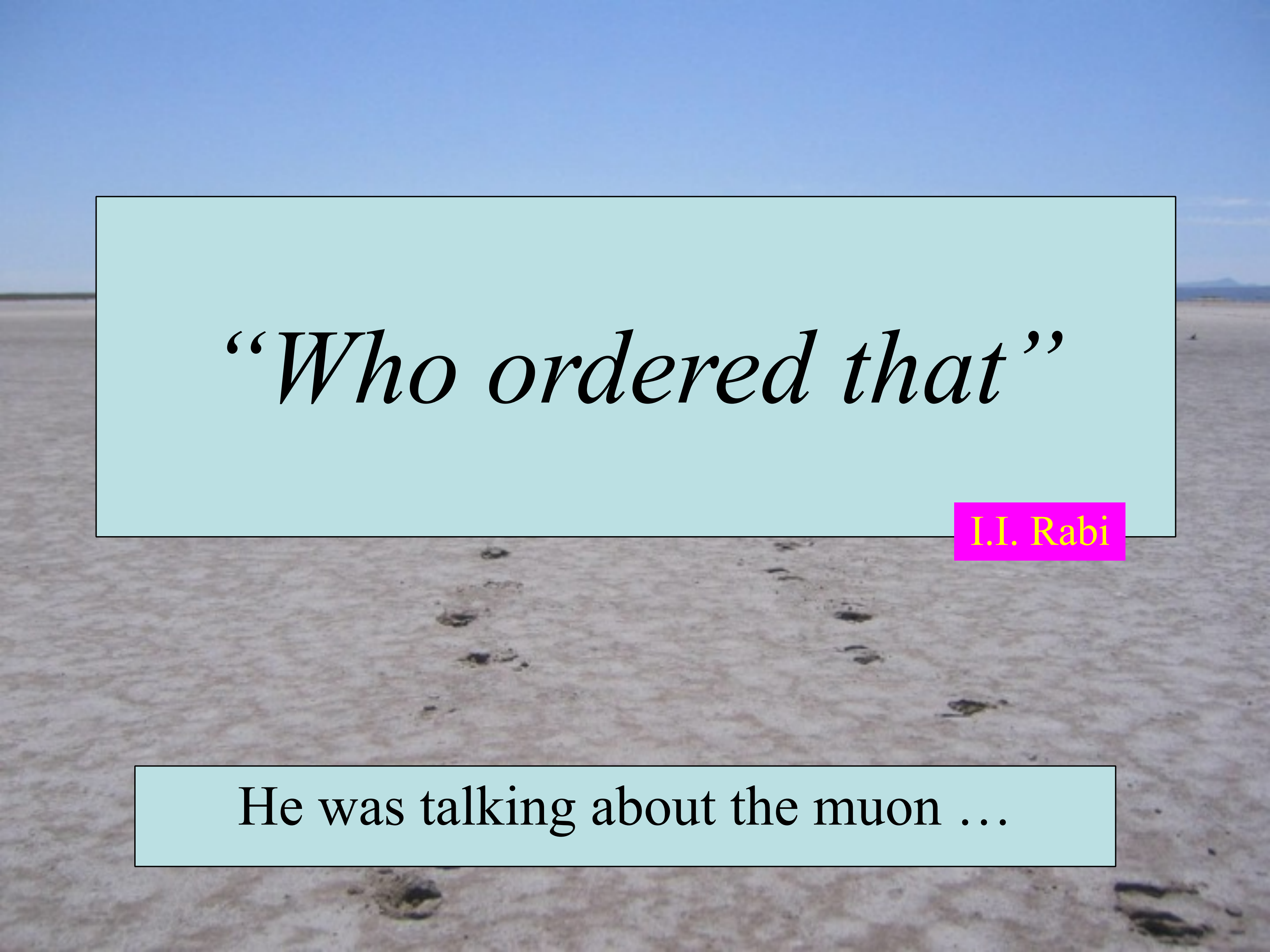
- Different models, various dark matter mechanisms

DM mechanism	Exp't	Models: CMSSM	NUHM1	NUHM2	pMSSM10
$\tilde{\tau}_1$ coann.	LHC	$\checkmark \not\!\!E_T$, $\checkmark$ LL	($\checkmark \not\!\!E_T$, $\checkmark$ LL)	($\checkmark \not\!\!E_T$, $\checkmark$ LL)	($\checkmark \not\!\!E_T$), $\times$ LL
	DM	($\checkmark$)	($\checkmark$)	$\times$	$\times$
$\tilde{\chi}_1^\pm$ coann.	LHC	–	$\times$	$\times$	($\checkmark \not\!\!E_T$)
	DM	–	$\checkmark$	$\checkmark$	($\checkmark$)
$\tilde{t}_1$ coann.	LHC	–	–	$\checkmark \not\!\!E_T$	–
	DM	–	–	$\times$	–
A/H funnel	LHC	$\checkmark$ A/H	($\checkmark$ A/H)	($\checkmark$ A/H)	–
	DM	$\checkmark$	$\checkmark$	($\checkmark$)	–
Focus point	LHC	($\checkmark \not\!\!E_T$)	–	–	–
	DM	$\checkmark$	–	–	–
h, Z funnels	LHC	–	–	–	($\checkmark \not\!\!E_T$)
	DM	–	–	–	($\checkmark$)

- No guarantees, but good prospects

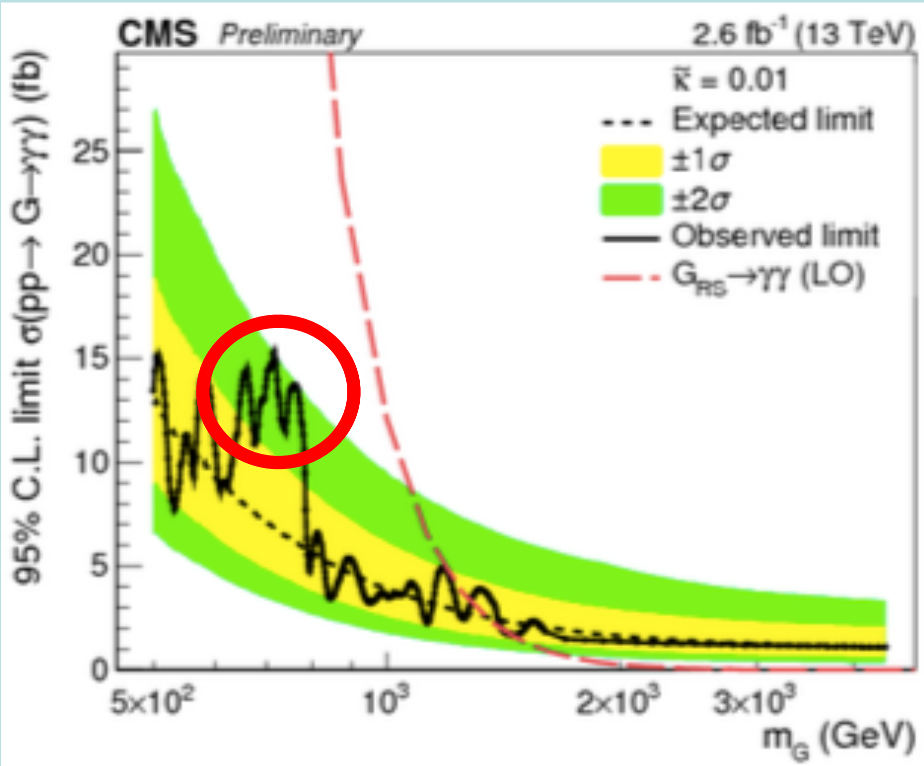
Bagnaschi, JE et al: arXiv:1508. 01173

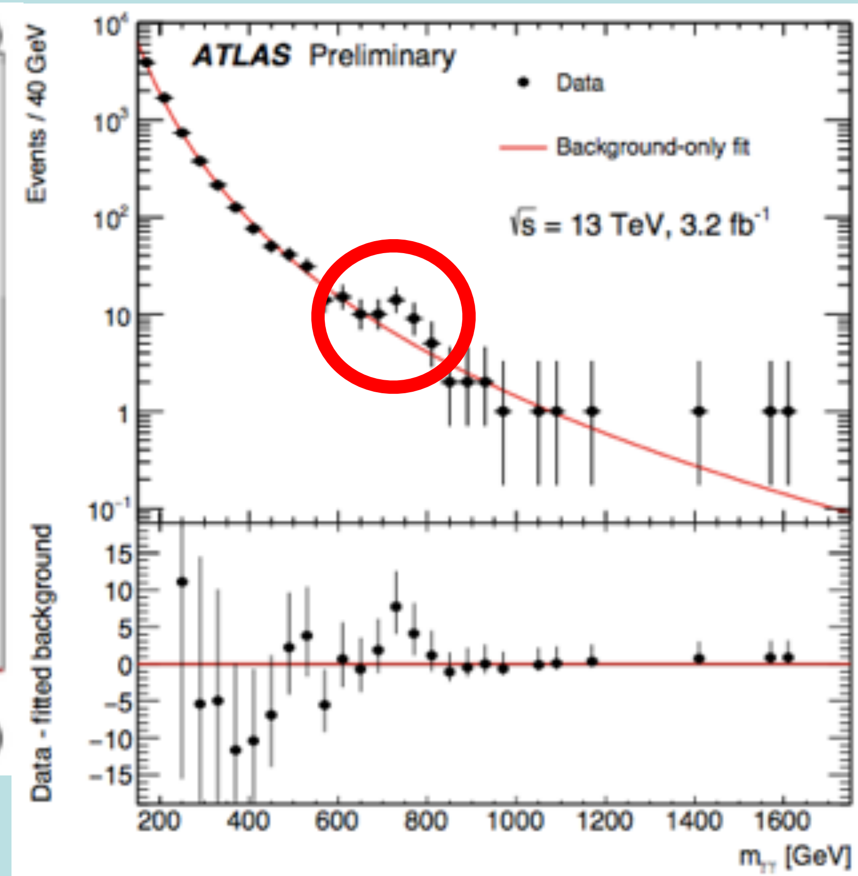

LHC Page1
Fill: 3746
E: 6500 GeV
t(SB): 00:00:00
21-05-15 10:03:53
BEAM SETUP: ADJUST
Energy:
6500 GeV
I(B1):
1.84e+11
I(B2):
1.81e+11
FBCT Intensity and Beam Energy
Updated: 10:03:53
Intensity
2E11
1.5E11
1E11
5E10
0E0
7000
6000
5000
4000
3000
2000
1000
0
Energy (GeV)
08:15
08:30
08:45
09:00
09:15
09:30
09:45
10:00
Collisions at 13 TeV
Physics has started!
B1
B2
false
true
true
true
false
false
AFS: Single_2b+1p_1_1_1
PM Status B1
ENABLED
PM Status B2
ENABLED


"Who ordered that"
I.I. Rabi
He was talking about the muon …

Reported on Tuesday, Dec. 15

- **Peaks in γγ invariant mass distributions**

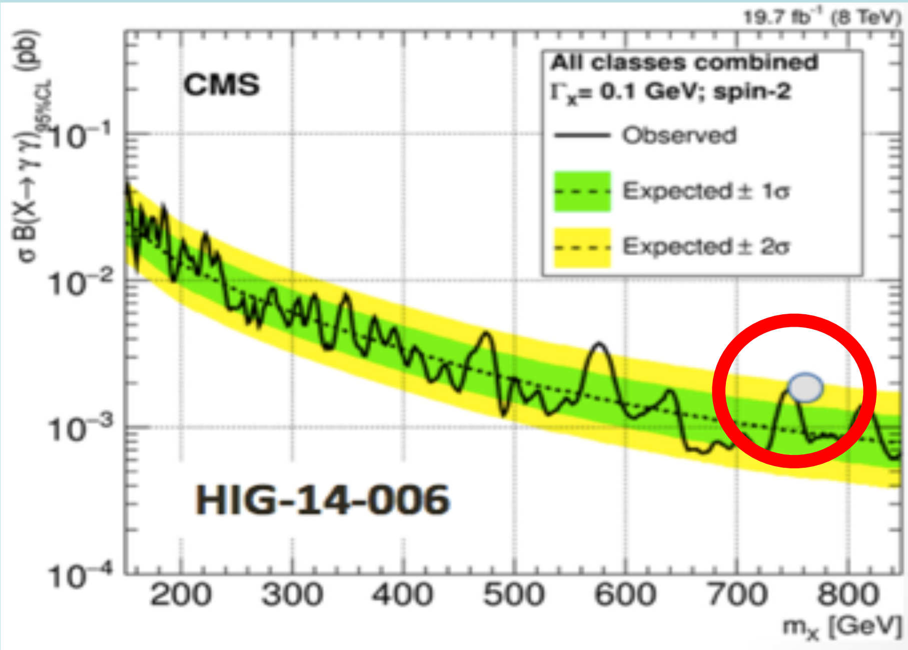


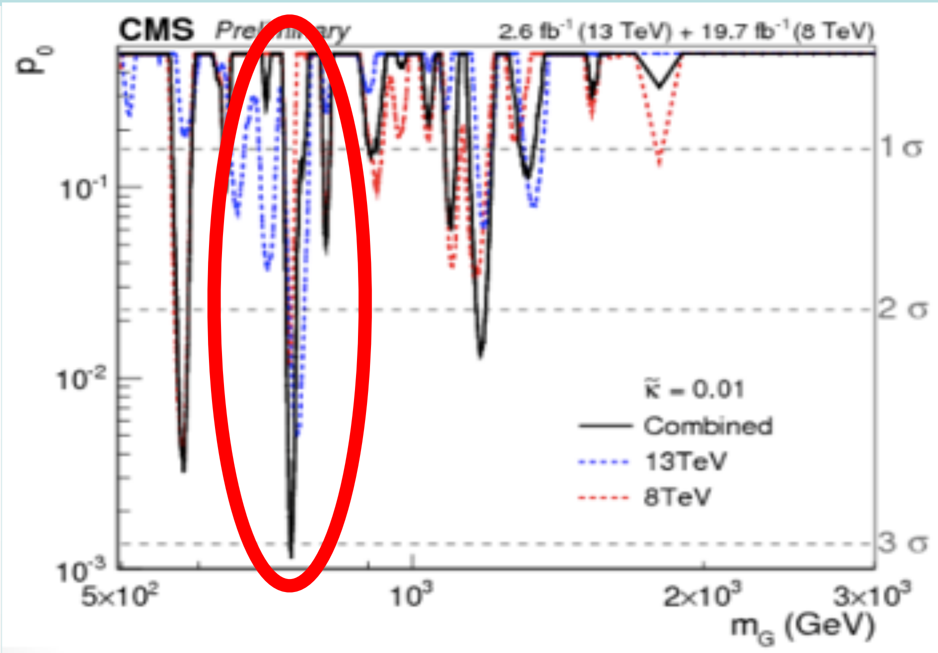


- Possible new particle X with mass ~ 750 GeV decaying into 2 photons

Overall Significance of 'Signal'?

- CMS also saw hint in Run 1 data

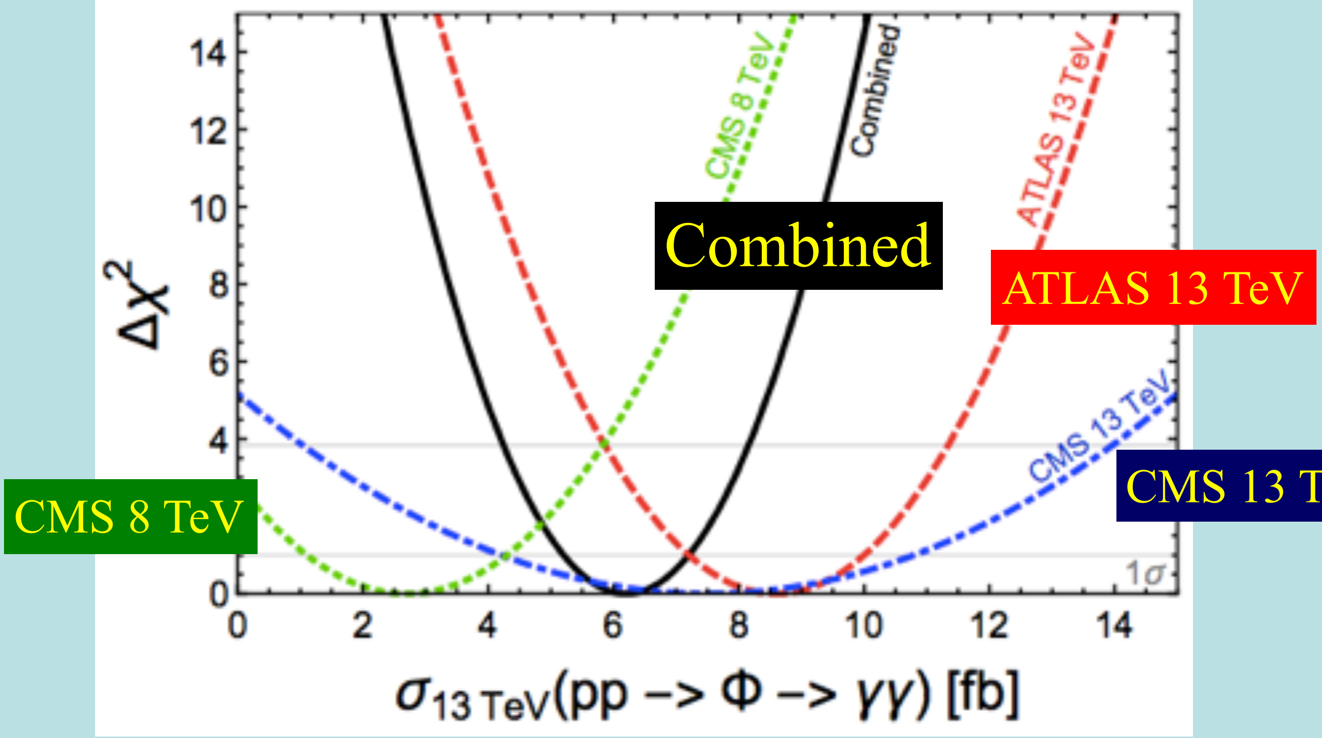




- Combined significance ~ 3 σ
- Naïve combination with ATLAS ~ 4.6 σ
- 'Look elsewhere effect' (many bins) reduces to 3 σ

Global Analysis of X Signal

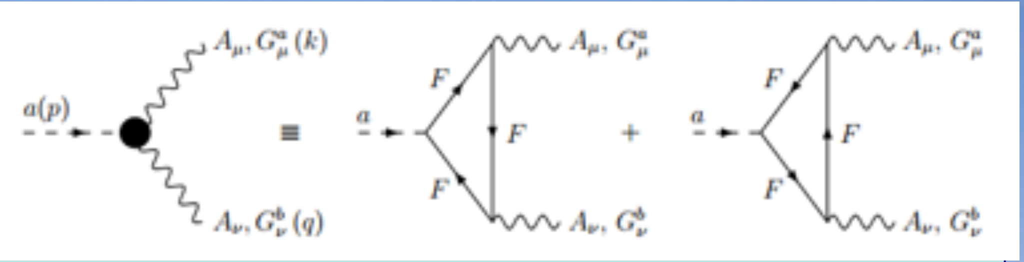
- Assume scalar/pseudoscalar (angular distribution?)
- Combined analysis of CMS and ATLAS data



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

JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327

X Decays?

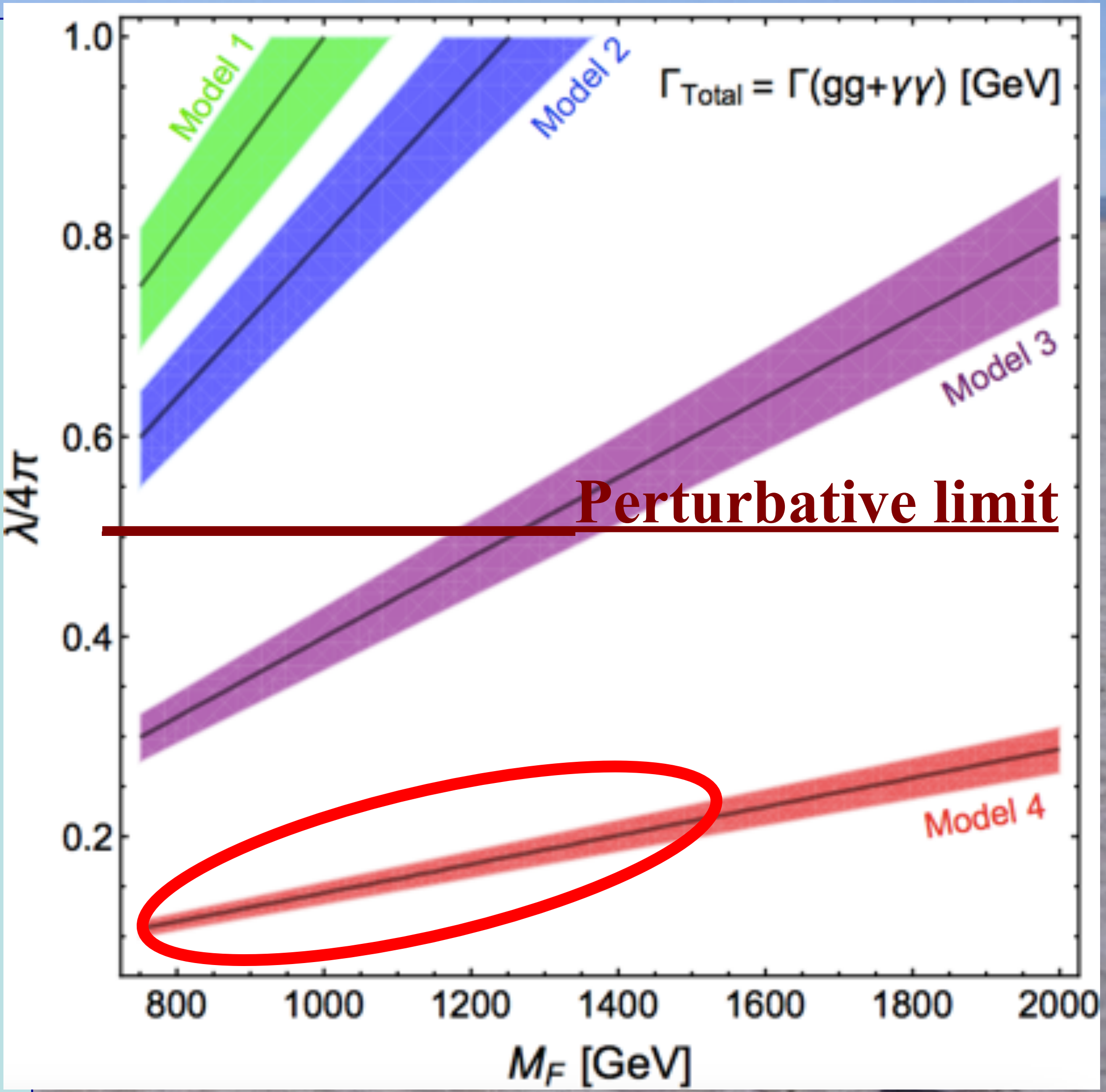


- Decay to γγ via anomalous triangle diagrams
- Probably also production via gluon fusion
- **Loops need heavy particles, m > 350 GeV**
- **Can't be 4th generation/minimal supersymmetry**
- Single vector-like quark enough, could be more
  - 1: Single VL quark, cf, t_R
  - 2: Doublet of VL quarks, cf, q_L
  - 3: Doublet + 2 singlets, cf, q_L, t_R, b_R
  - 4: Complete VL generation, including leptons
- **Assume *gg* decays dominant**

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
- **Band = 1 σ**
- **Perturbative limit**
- **Neutral fermion could be dark matter**



JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327

How to Probe Possible Models?

- Other possible decay modes

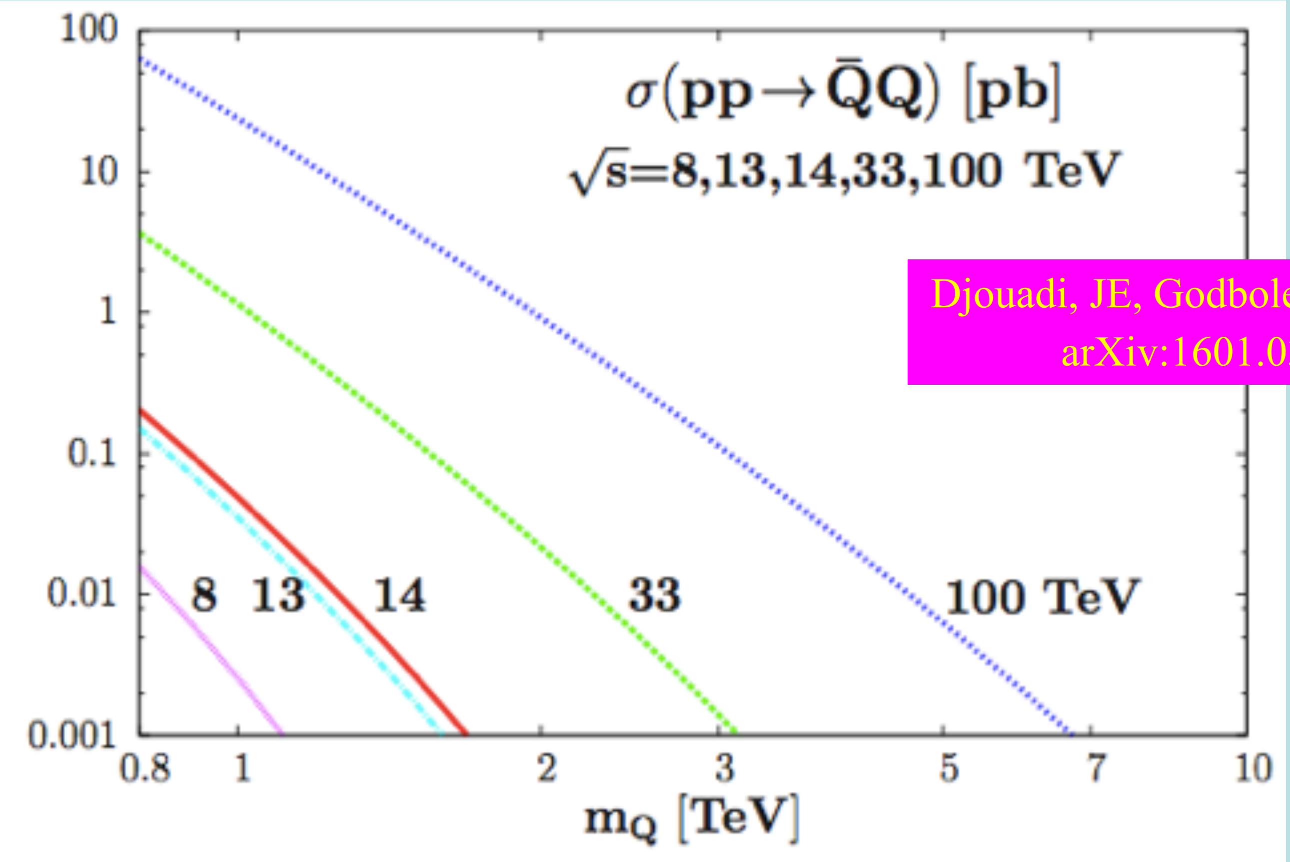
Model	$Tr[Y^2]$	$Tr[D(r)^2]$	$\frac{BR(X\to gg)}{BR(X\to\gamma\gamma)}$	$\frac{BR(X\to Z\gamma)}{BR(X\to\gamma\gamma)}$	$\frac{BR(X\to ZZ)}{BR(X\to\gamma\gamma)}$	$\frac{BR(X\to W^\pm W^\mp)}{BR(X\to\gamma\gamma)}$
1	8/3	0	180	1.2	0.090	0
2	1/3	3	460	10	9.1	61
3	11/3	3	460	1.1	2.8	15
4	20/3	4	180	0.46	2.1	11
Current limit			$\sim 2\times10^4$	7	13	46

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

JE, S.Ellis, Quevillon, Sanz & You, arXiv:1512.05327

Cross Sections for Vector-Like Q

- Pair-production at LHC, future circular colliders



Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

- Present lower mass limit ~ 800 GeV

Sensitivity to Vector-Like Q, L

model	Vector-like quark mass sensitivity				Vector-like lepton mass sensitivity			
	100fb^{-1} 13 TeV	300fb^{-1} 14 TeV	300fb^{-1} 33 TeV	20ab^{-1} 100 TeV	100fb^{-1} 13 TeV	300fb^{-1} 14 TeV	300fb^{-1} 33 TeV	20ab^{-1} 100 TeV
1	1.4	1.7	3.1	11.7	-			
2	1.5	1.8	3.4	12.7	-			
3	1.6	2.0	3.7	13.7	-			
4	1.6	2.0	3.7	13.7	0.56	0.73	1.7	5.3

Djouadi, JE, Godbole, Quevillon,
arXiv:1601.03696

- Model 1: Single VL quark, cf, t_R
  - Non-perturbative coupling required
- Model 2: Doublet of VL quarks, cf, q_L
  - Non-perturbative coupling favoured
- Model 3: Doublet + 2 singlets, cf, q_L, t_R, b_R
  - Perturbative range covered by LHC
- Model 4: Complete VL generation, including leptons
  - Covering perturbative range needs higher energy

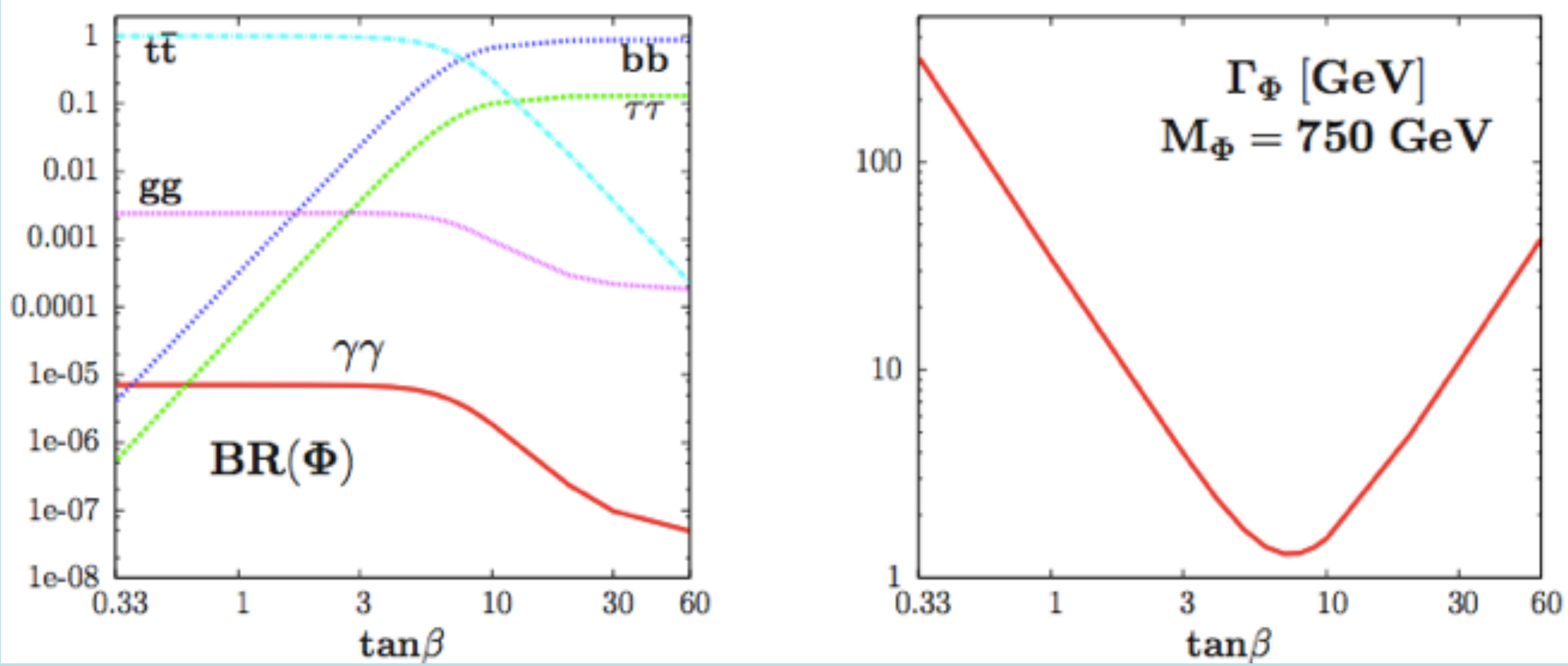
Alternative Higgs Doublet Scenario

- After singlet, doublet?
- Heavy Higgses in 2 Higgs doublet model: Φ = H, A
- Nearly degenerate in many versions, e.g., SUSY
- Expect t tbar decays to dominate
- Can accommodate $\Gamma_\Phi \sim 45$ GeV (ATLAS)
- Need larger enhancement of loops compared to singlet model
- **Rich bosonic phenomenology**

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Φ = H, A Decays in Doublet Model

- Dependences on tan β of branching ratios, Γ_Φ

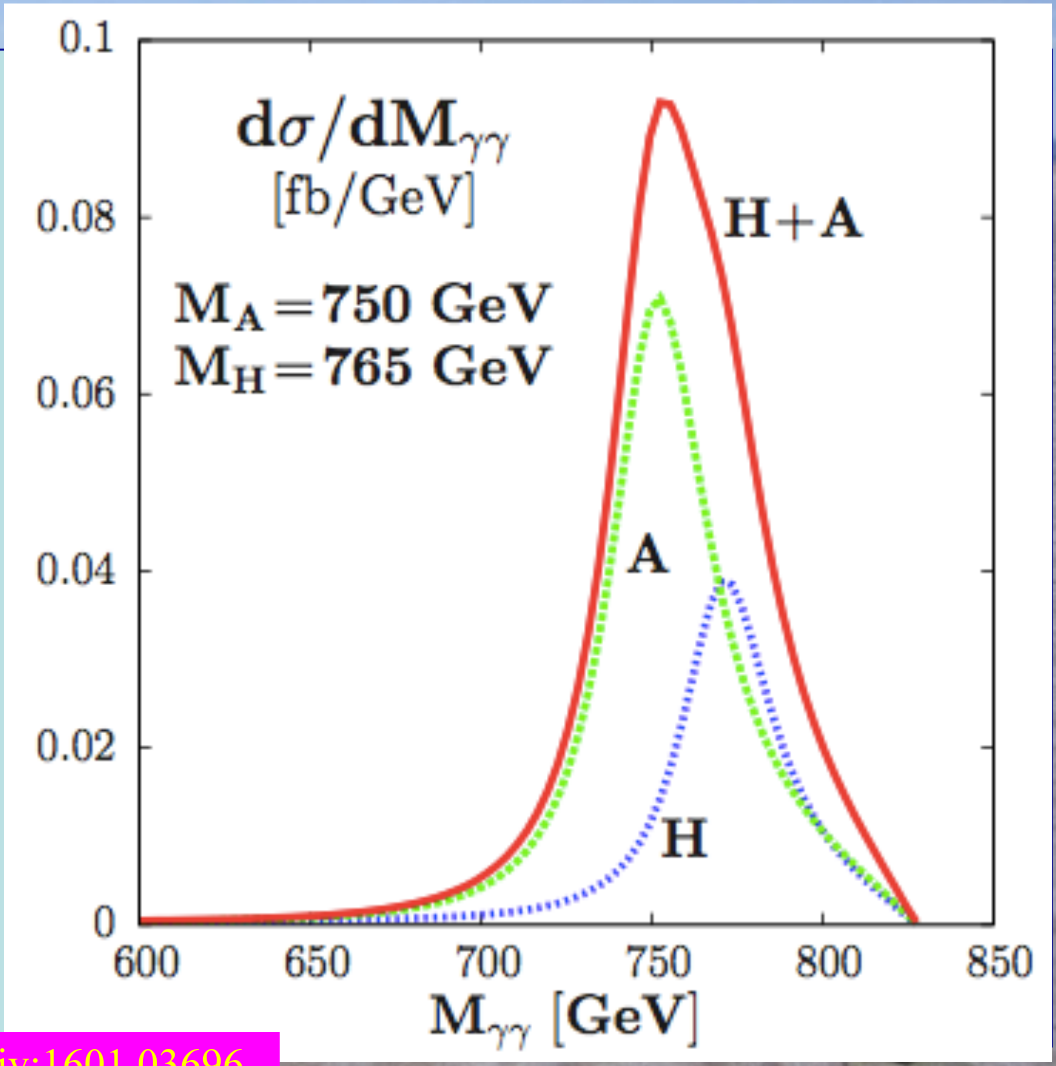


- Prefer tan β ~ 1
- Dominant Φ decays to t tbar

Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Lineshape in *pp* Collisions

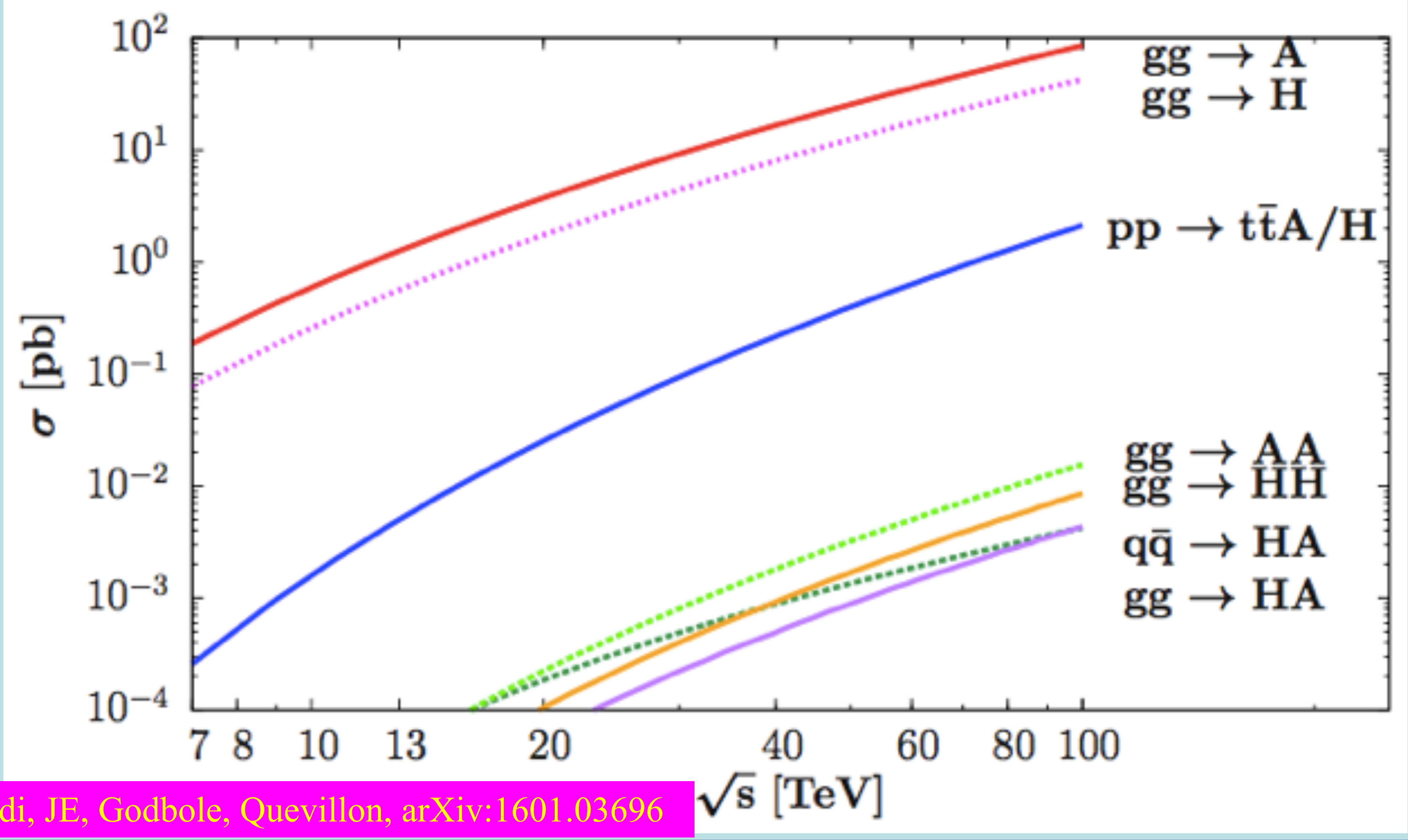
- +MSSM: $\tan\beta = 1$
- $M_H - M_A \sim 15$ GeV
- $\Gamma_H, \Gamma_A \sim 32, 35$ GeV
- $\sigma B(A \rightarrow \gamma\gamma) =$
  $2 \times \sigma B(H \rightarrow \gamma\gamma)$
- Asymmetric
  'Breit-Wigner'
- **Resolvable?**



Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

Possible Φ = H,A Signals

- Normalized to σB(γγ) = 6 fb @ 13 TeV



Djouadi, JE, Godbole, Quevillon, arXiv:1601.03696

July 4th 2016

The discovery of a new particle?

“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.”

Summary

- Is the Higgs boson as in the Standard Model?
- 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!**