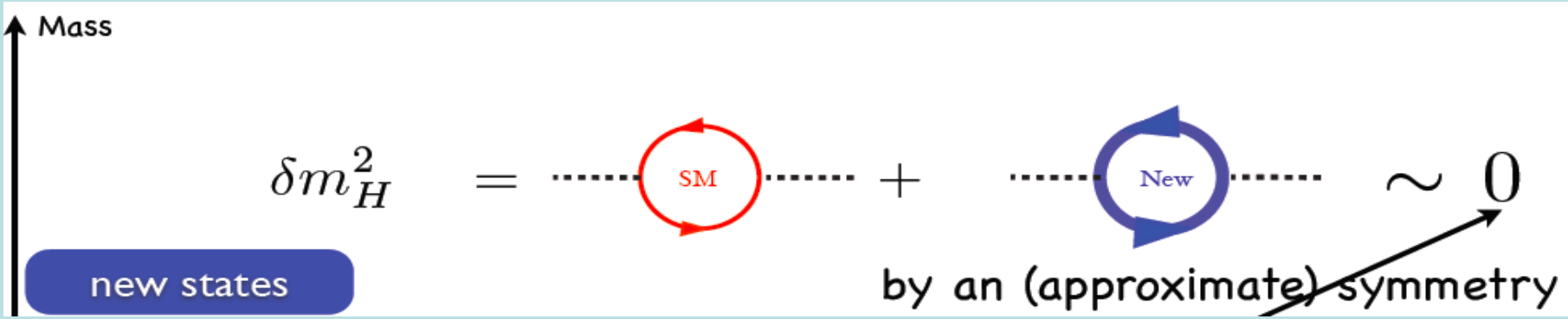
Outlook for Supersymmetry

- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for Higgs couplings
  - Should be within few % of SM values
- Could explain the dark matter
- Naturalness, GUTs, string, … (???)


•July 4th 2012
•The discovery of a new particle
International Herald Tribune
Discovery upends world of physics
The New York Times
Oil Backed Up, Iranians Put It On Idled Ships
ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX
Physicists Find Elusive Particle Seen as Key to Universe
The Economist
A giant leap for science
Finding the Higgs boson
ヒッグス粒子 発見か
新素粒子検出 年内に結論
日米欧2チーム
Le Monde
Science : la matière dévoilée
The Gazette
EL PAIS
Milhares de moradores de bairros sociais em risco de perderem RSI
В ТЕАТРЫ БУДУТ ПУСКАТЬ ПО МОБИЛЬНЫМ ТЕЛЕФОНАМ
МК
ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ
«КРЕМЛЕВСКИЕ» САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕПРАВЕ
МЕТРО СПУСТЯТ НА ВОДУ
AD
ALGEMEEN DAGBLAD
EINDELIJK GELIJK NA 48 JAAR
Frankfurter Allgemeine
ZEITUNG FÜR DEUTSCHLAND
CHINA DAILY
THE TIMES OF INDIA
Big bang moment: Scientists may have found 'God particle'
Adarsh scam: Finally, CBI charges sheets 13
THE HINDU
Elusive particle found, looks like Higgs boson
CERN physicists hail evidence of game-changing discovery of subatomic particle
CORRIERE DELLA SERA
Nomine Rai bloccate Scontro Fini-Schifani
La particella che può svelare i segreti dell'universo
gazeta WYBORCZA.PL
Cząstkę Higgsa fizycy najpierw wymyślili, potem szukali 40 lat
BOSKA MASA
আনন্দবাজার পত্রিকা
বিজ্ঞানের 'ঈশ্বর' দর্শন
'পেয়েছি, যা খুঁজছিলাম'

That's great, but …

- The LHC paradox:
  - Light Higgs + nothing else?
- If something light, why no indirect evidence?
- If nothing light, is light Higgs unnatural?



- Electroweak and Higgs coupling measurements complement searches for New Physics

Theoretical Confusion

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

Some Theoretical Views

Kane

Ibanez

Hall

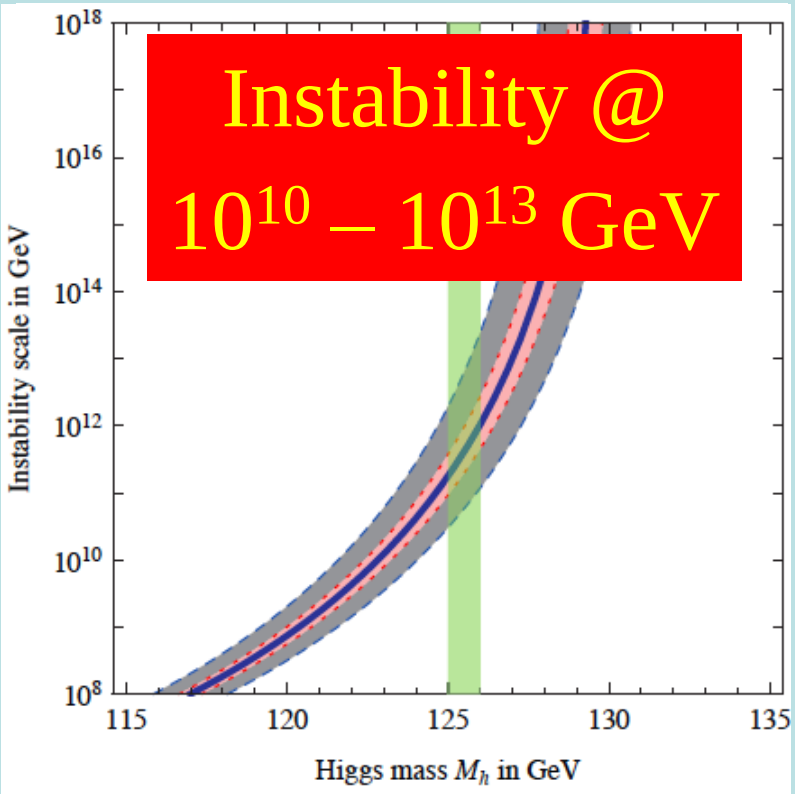
Isidori

Theoretical Constraints on Higgs Mass

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

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

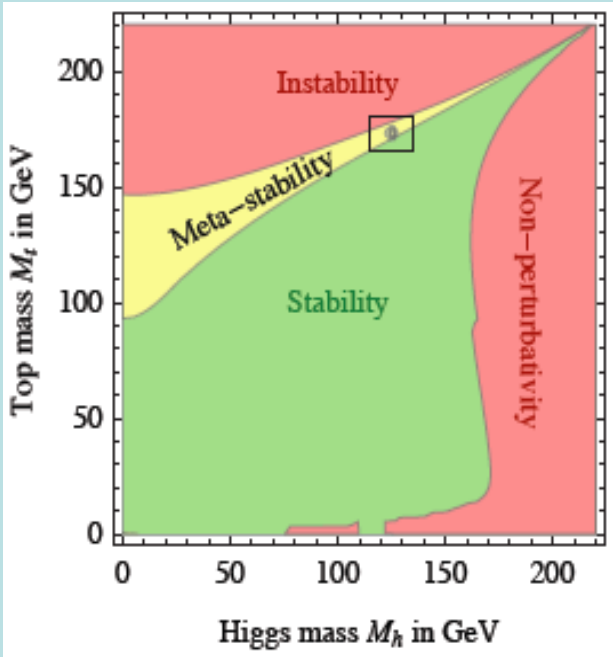
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

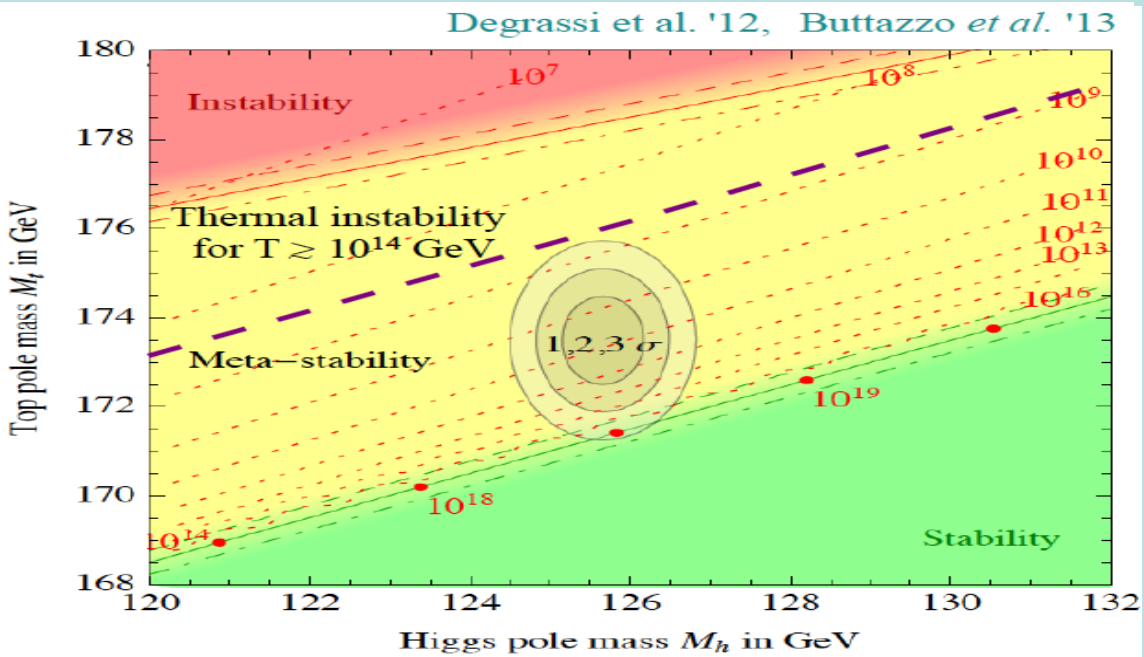


Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H





- Present vacuum probably metastable with lifetime >> age of the Universe

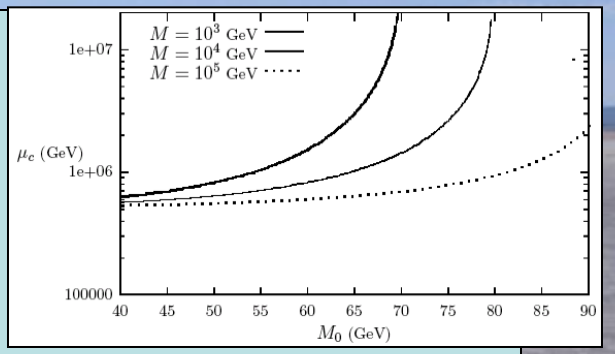
Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

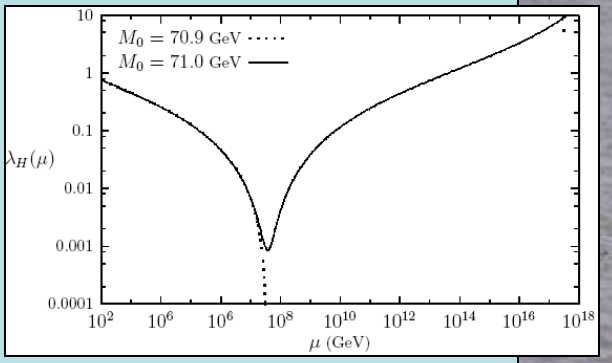
How to Stabilize a Light Higgs Boson?

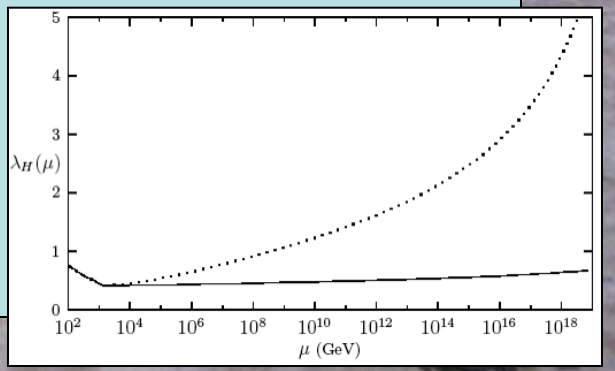
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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!**







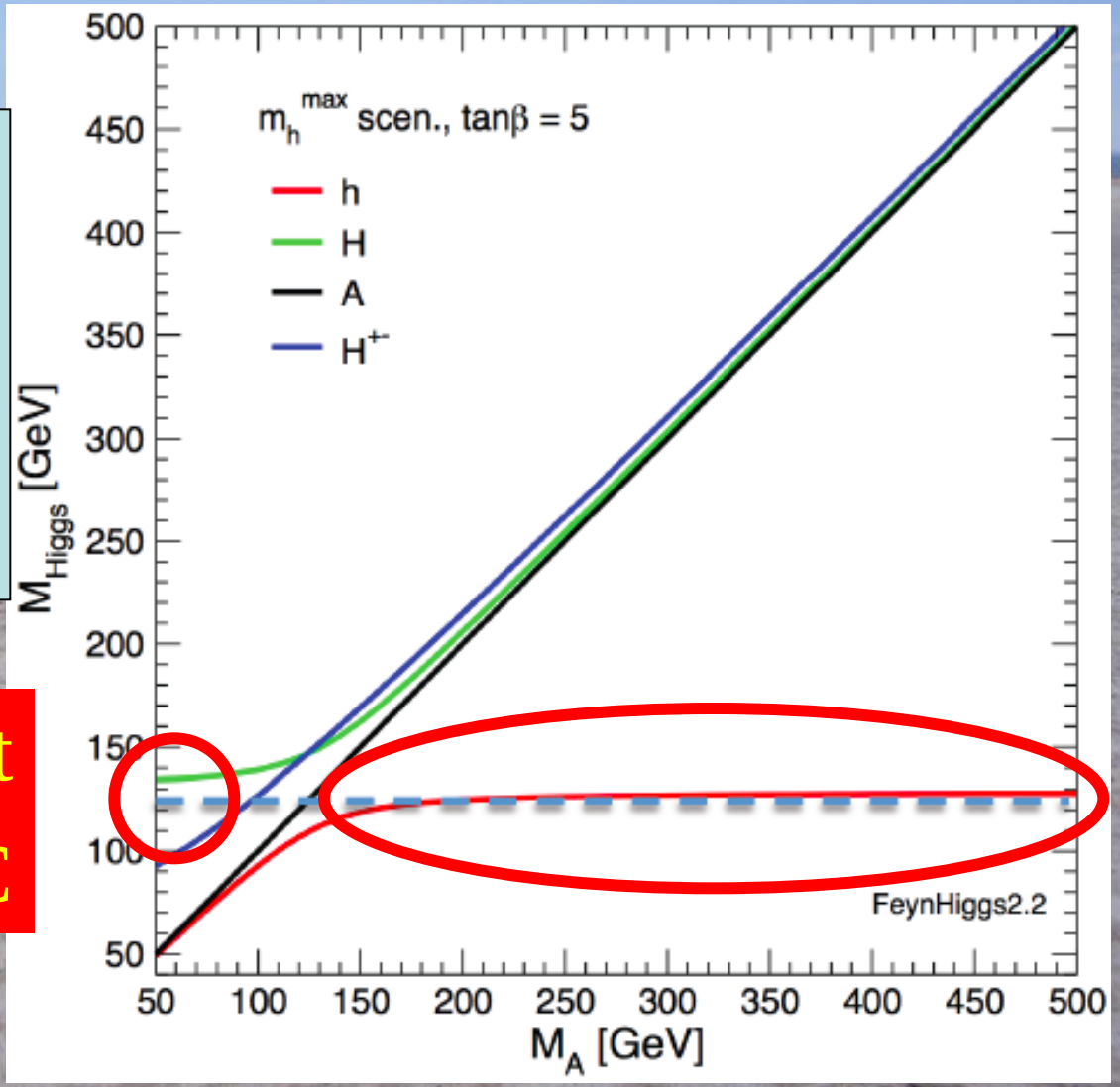
JE + D. Ross: hep-ph/0012067

MSSM Higgs Masses & Couplings

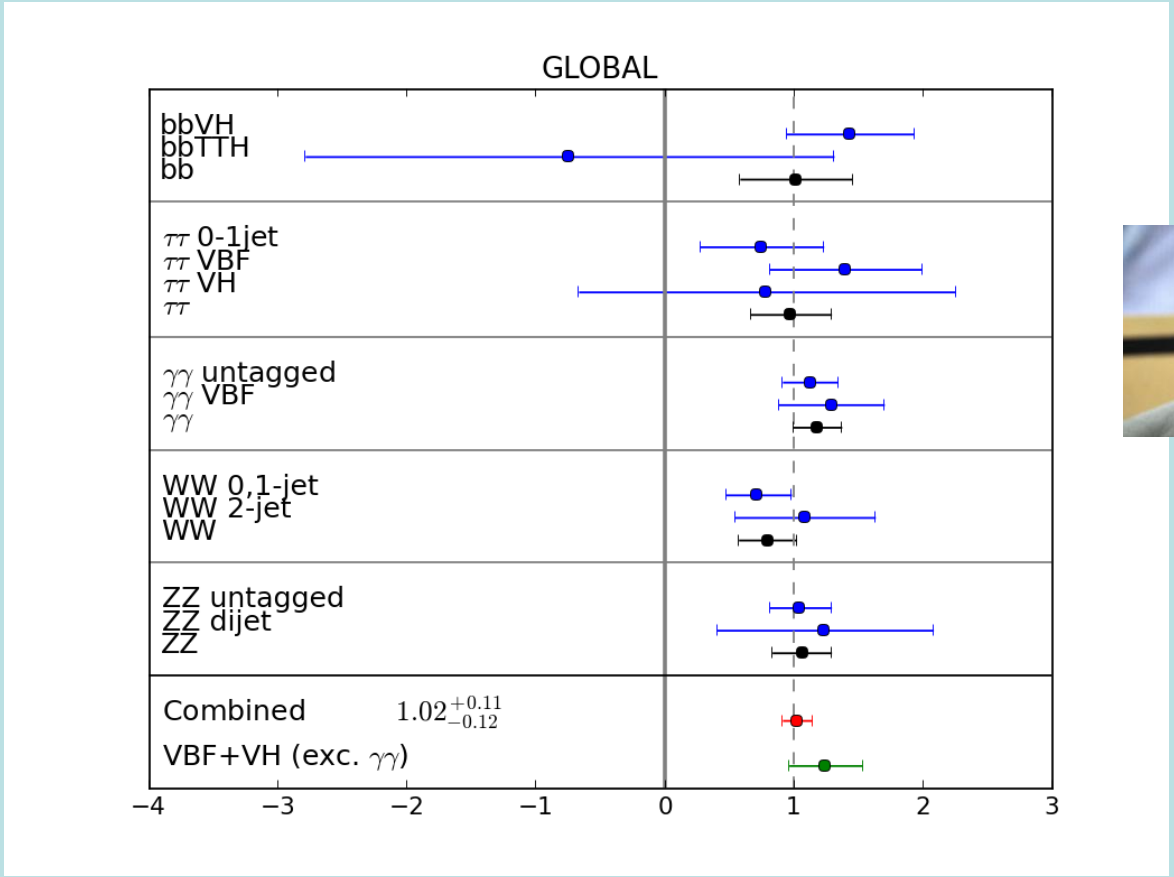
Lightest Higgs mass up to ~ 130 GeV

Heavy Higgs masses quite close

Consistent With LHC



Couples like Higgs of Standard Model



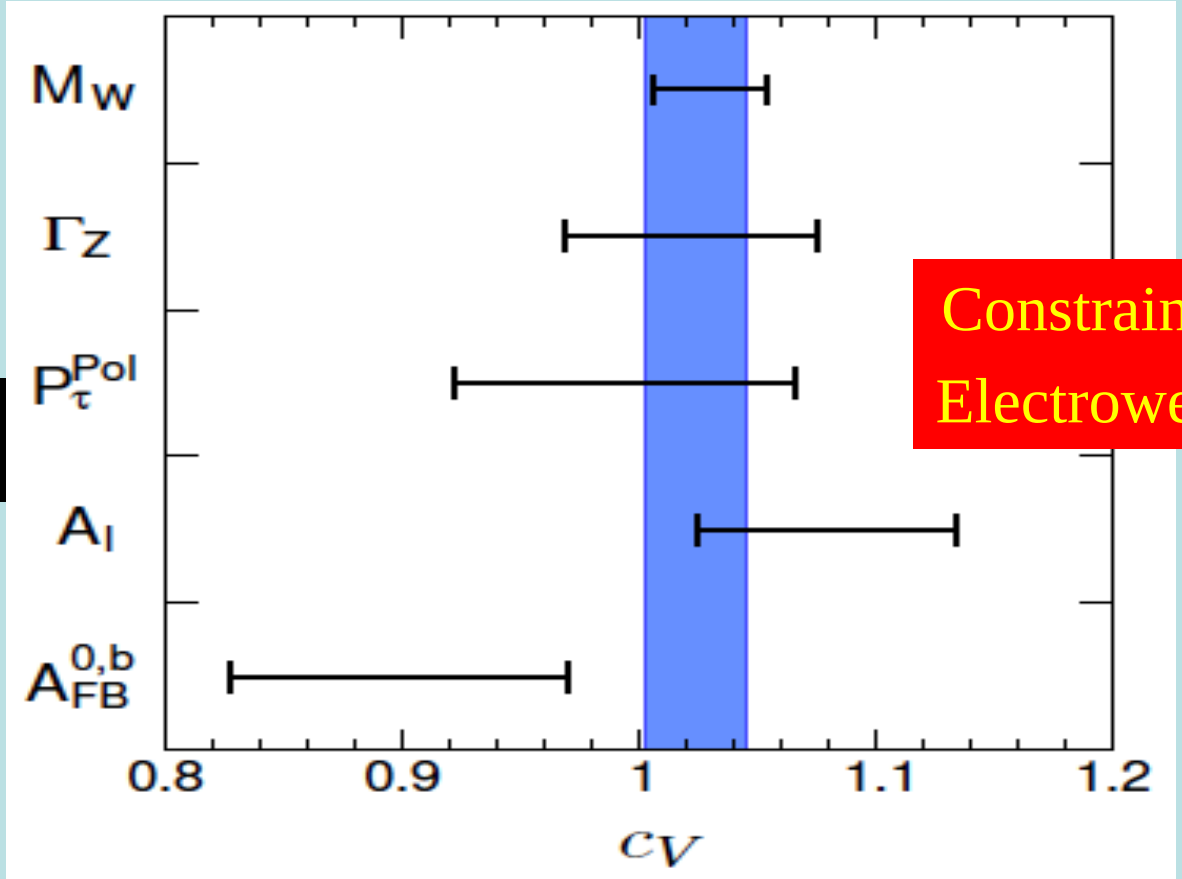
- No indication of any significant deviation from the Standard Model predictions

JE & Tevong You, arXiv:1303.3879

Global Analysis of Higgs-like Models

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

Global



Constraints from Electroweak data

Contino

- Standard Model: $a = c = 1$

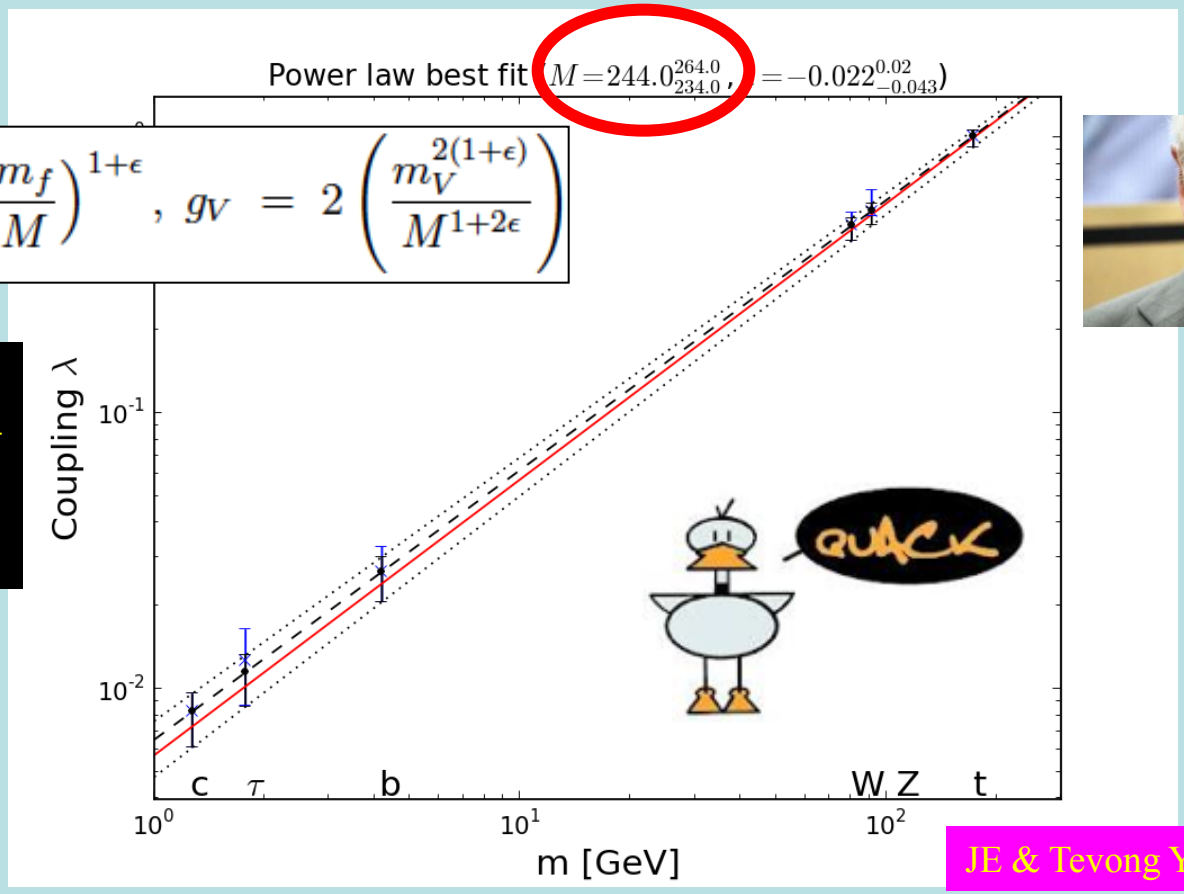
JE & Tevong You, arXiv:1303.3879

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

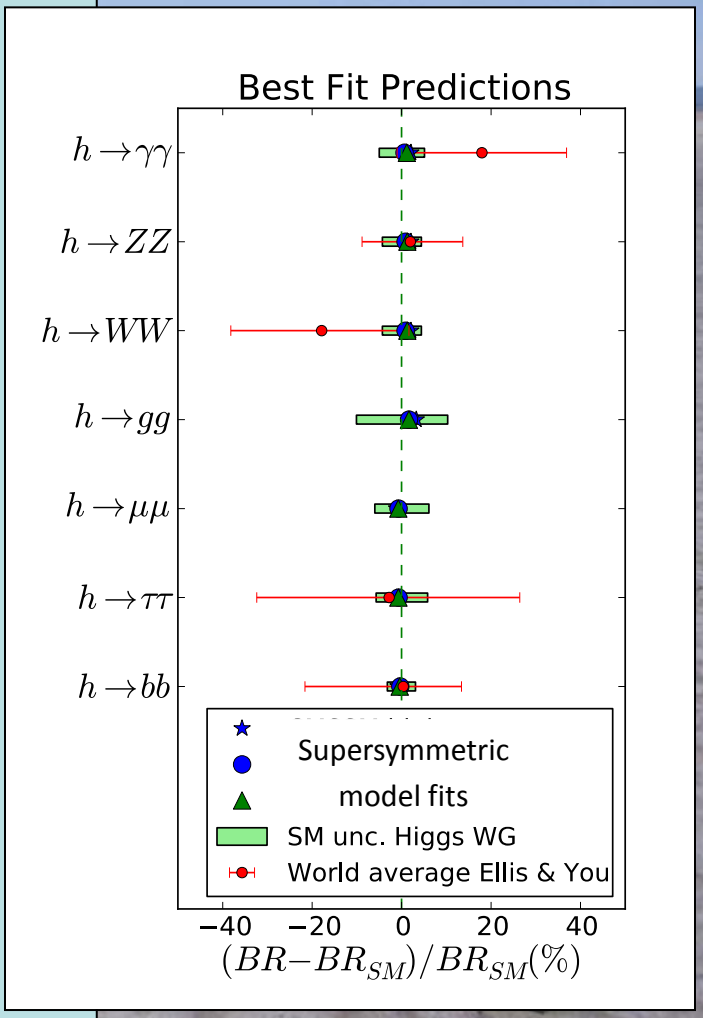
- **Red line = SM**, dashed line = best fit

Supersymmetric Models

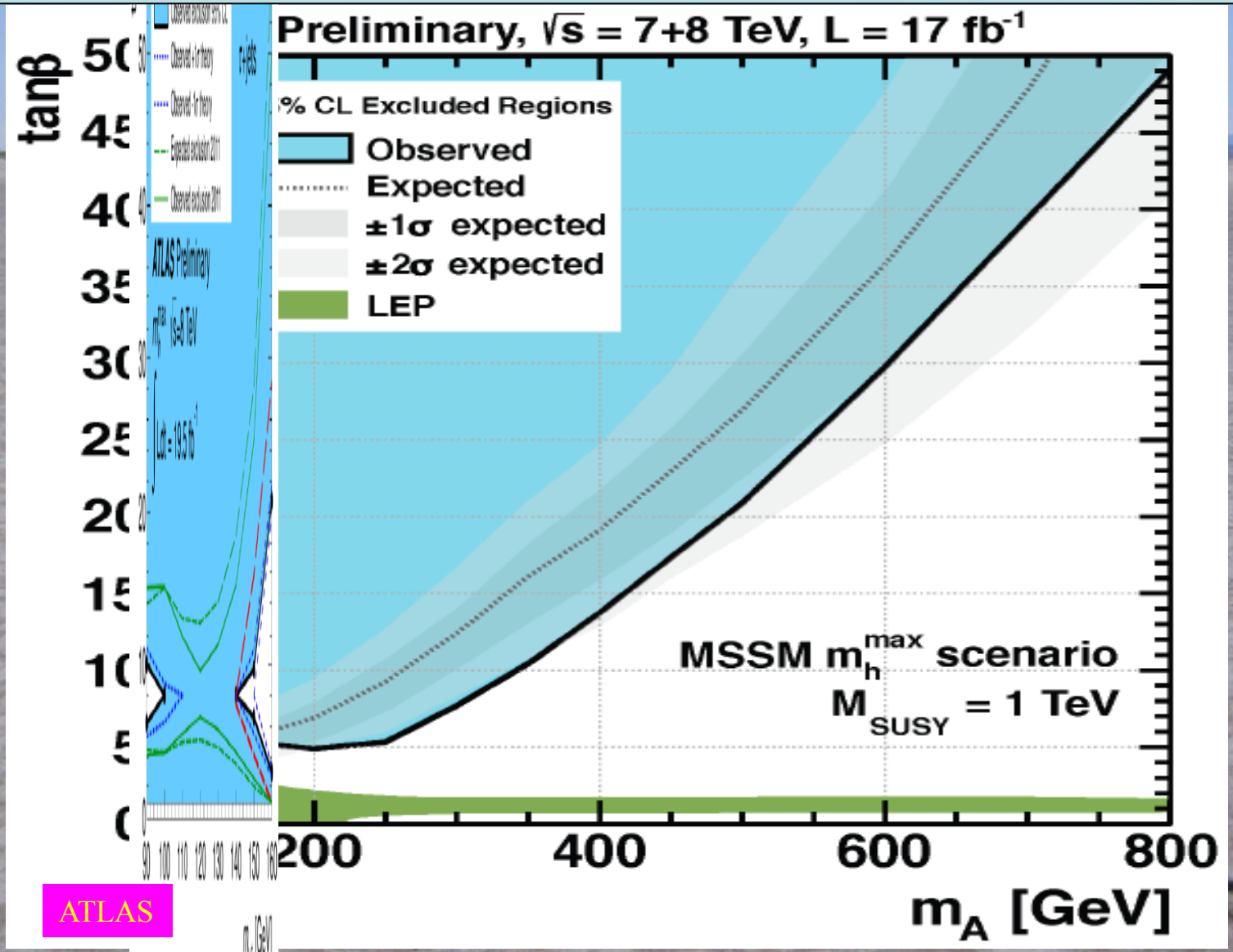
- Global fits within simplified models

  (universal soft supersymmetry-breaking masses, CMSSM NUHM1)

  suggest ~ SM couplings
- How to probe?
  - HL-LHC, Higgs factory ?



Limits on Heavy MSSM Higgses

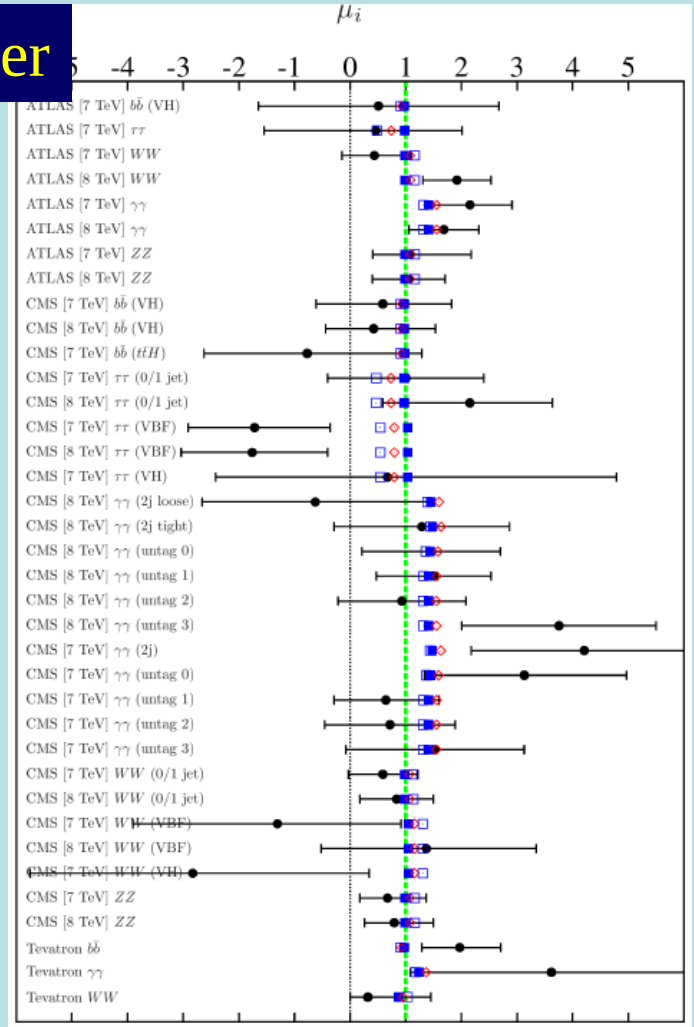


Bechtle et al., arXiv:1211.1955

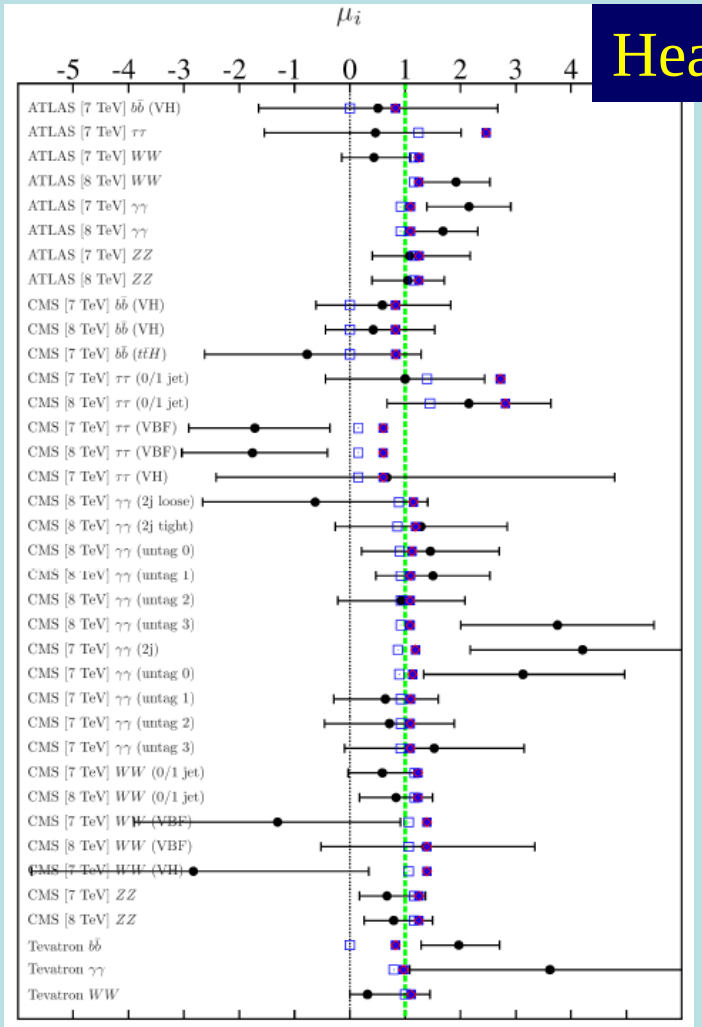
Maybe it is a Supersymmetric Duck?

- Fits with lighter/heavier scalar Higgs at 125 GeV

Lighter



Heavier



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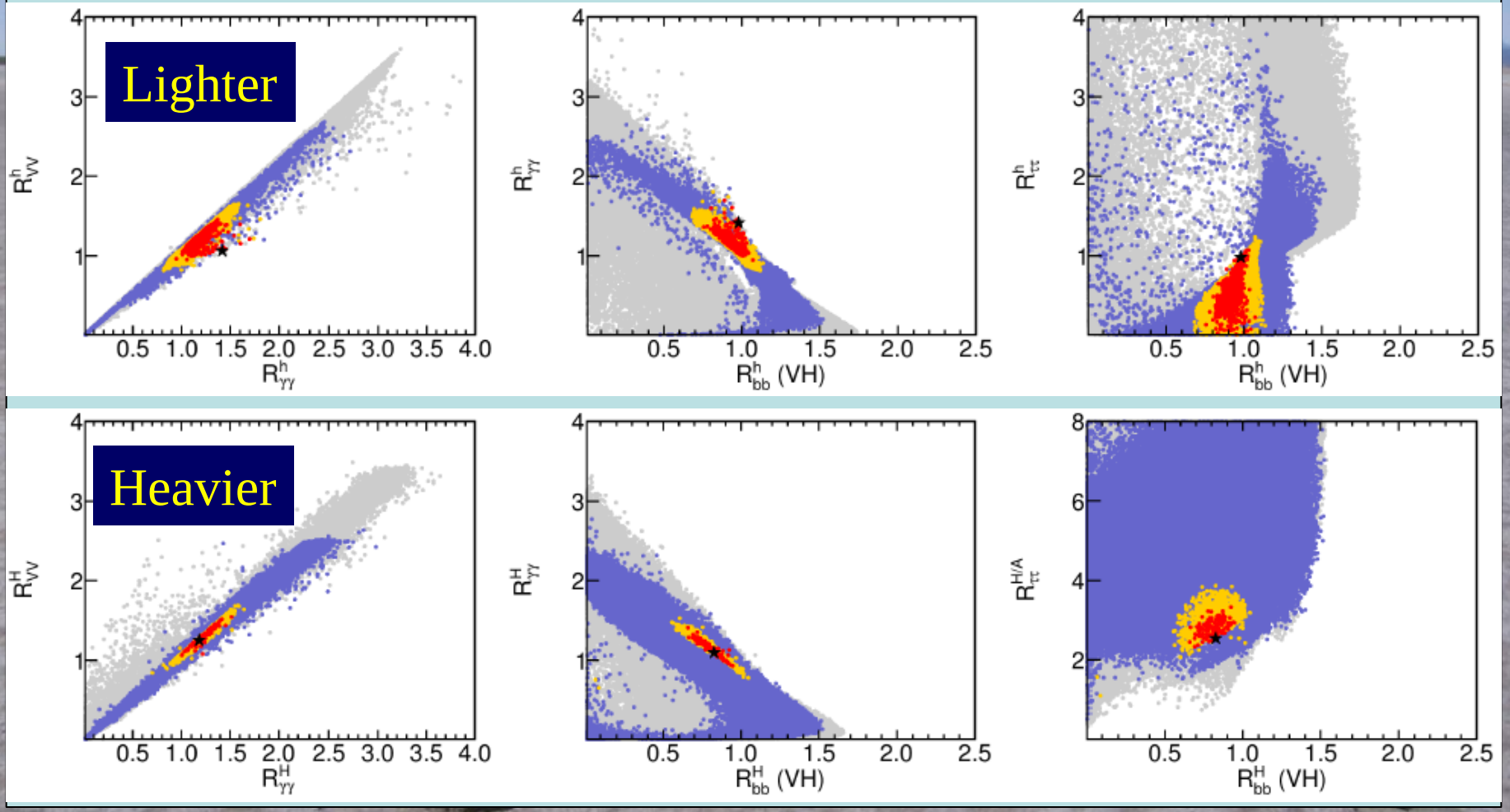
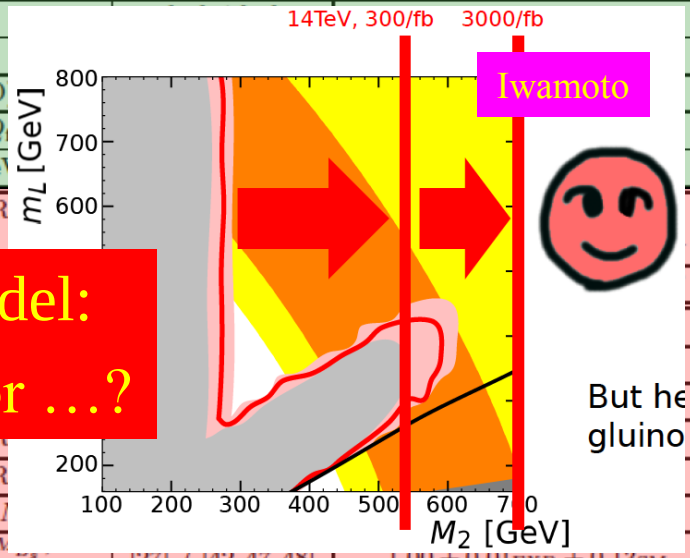


Data

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

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

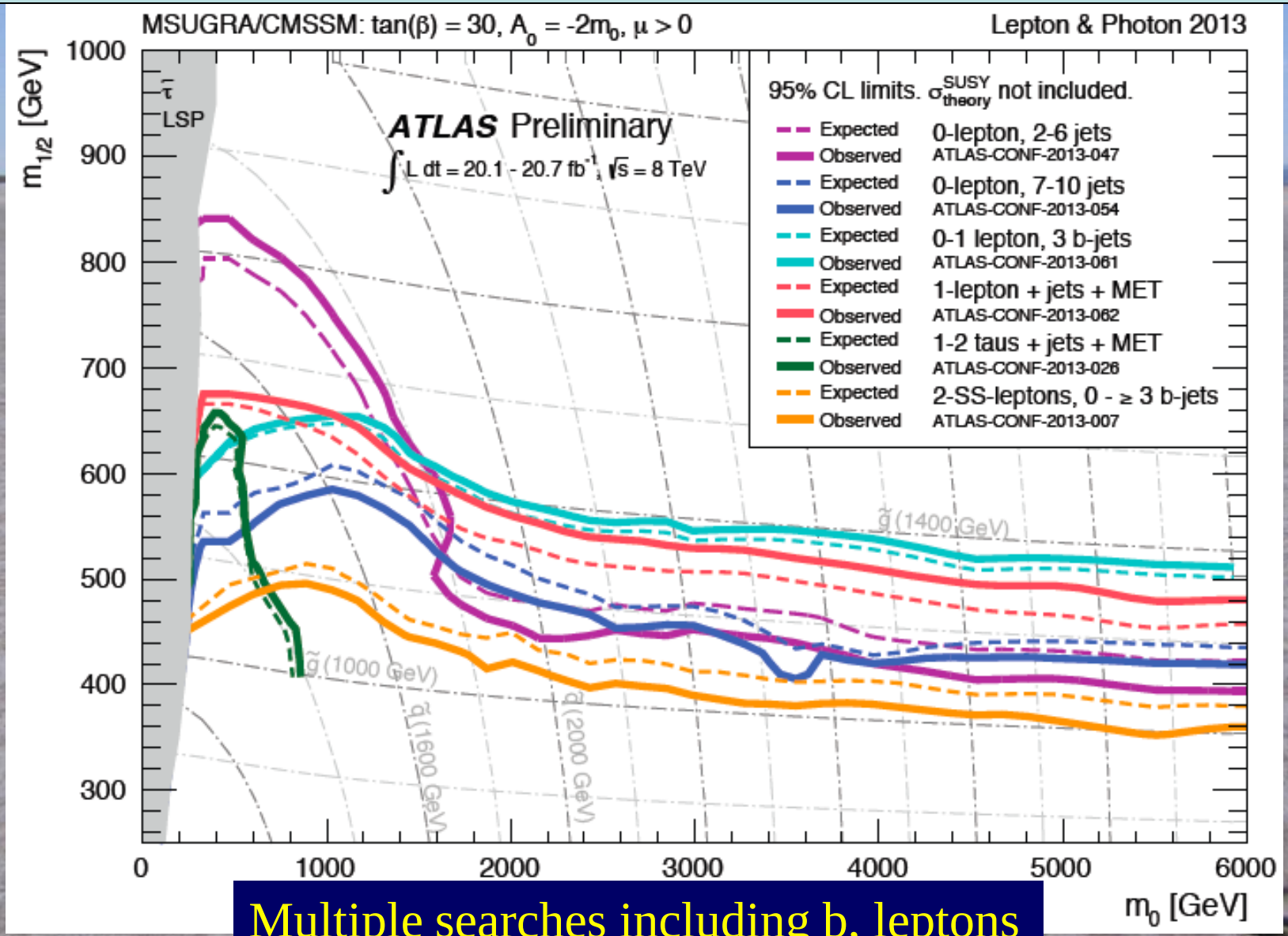
Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[24] / [40]	41.540 ± 0.037
R_l	[24] / [40]	20.767 ± 0.025
$A_{\rm fb}(\ell)$	[24] / [40]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[24] / [40]	0.1465 ± 0.0032
$R_{\rm b}$	[24] / [40]	0.21629 ± 0.00066
$R_{\rm c}$	[24] / [40]	0.1721 ± 0.0030
$A_{\rm fb}(b)$	[24] / [40]	0.0992 ± 0.0016
$A_{\rm fb}(c)$	[24] / [40]	0.0707 ± 0.0035
A_b		
A_c		
A_ℓ(SLD		
$\sin^2\theta^\ell_{\rm w}(Q$		
M_W [GeV		
$\mathrm{BR}^{\rm EXP}_{b\to s\gamma}/\mathrm{BR}$		
$\mathrm{BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/\mathrm{BR}$		
$\Delta M^{\rm EXP}_{B_s}/\Delta$		
$\frac{(\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s})}{(\Delta M^{\rm EXP}_{B_d}/\Delta M^{\rm SM}_{B_d})}$	[27] / [42, 47, 48]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon^{\rm EXP}_K/\Delta\epsilon^{\rm SM}_K$	[45] / [47, 48]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{\rm EXP}_\mu - a^{\rm SM}_\mu$	[49] / [38, 50]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
M_H		$\pm 1.5_{\rm SUSY}$
		56 ± 0.01^2 SUSY
σ_p	[23]	($m_{\tilde\chi^0_1}$, $\sigma^{\rm SI}_p$) plane
jets $+\not{E}_T$	[16, 18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan\beta)$ plane



$M_H = 125.6 \pm 0.3 \pm 1.5$ GeV

MasterCode: O.Buchmueller, JE et al.

Searches with 8 TeV Data

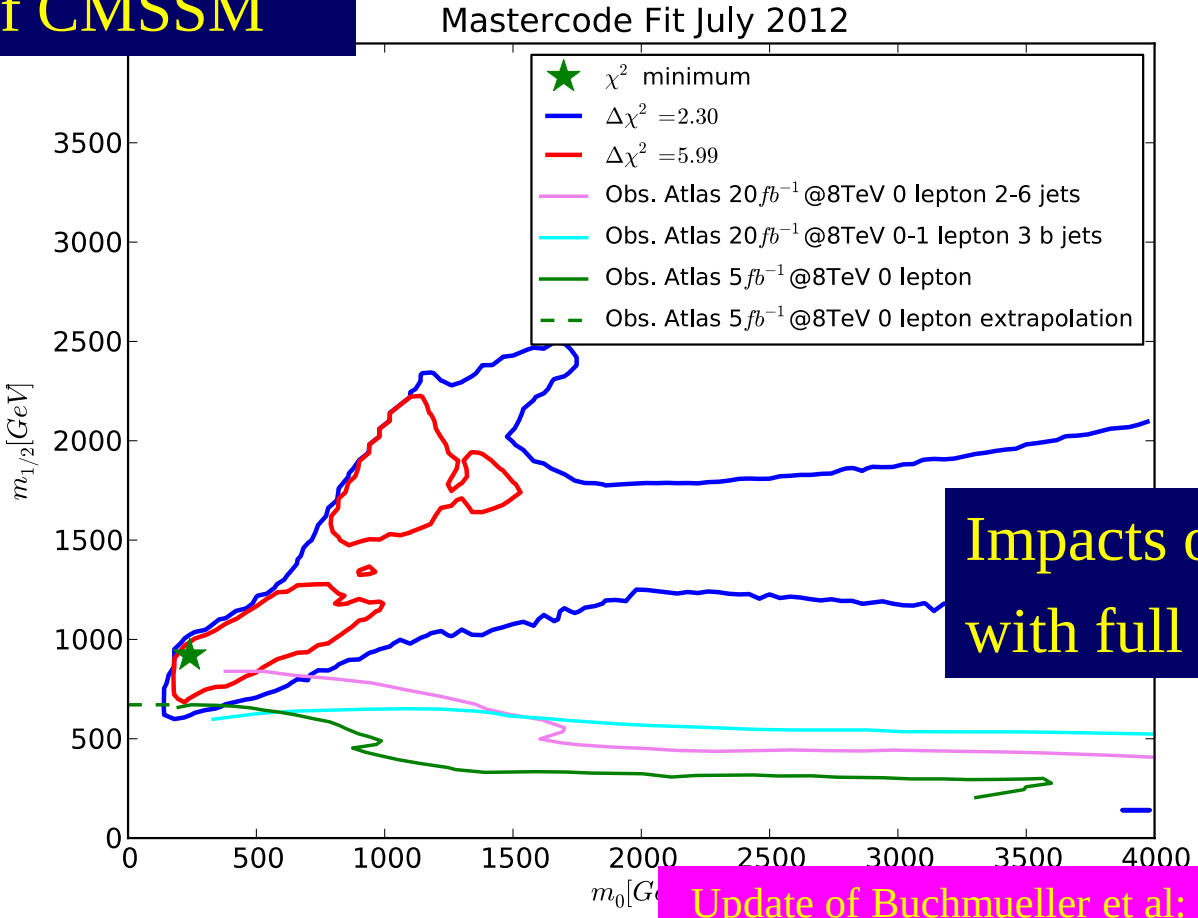


Multiple searches including b, leptons

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 5 fb^{-1} of LHC Data

Scan of CMSSM



Impacts of searches with full 2012 data

Update of Buchmueller et al: arXiv:1207.3715

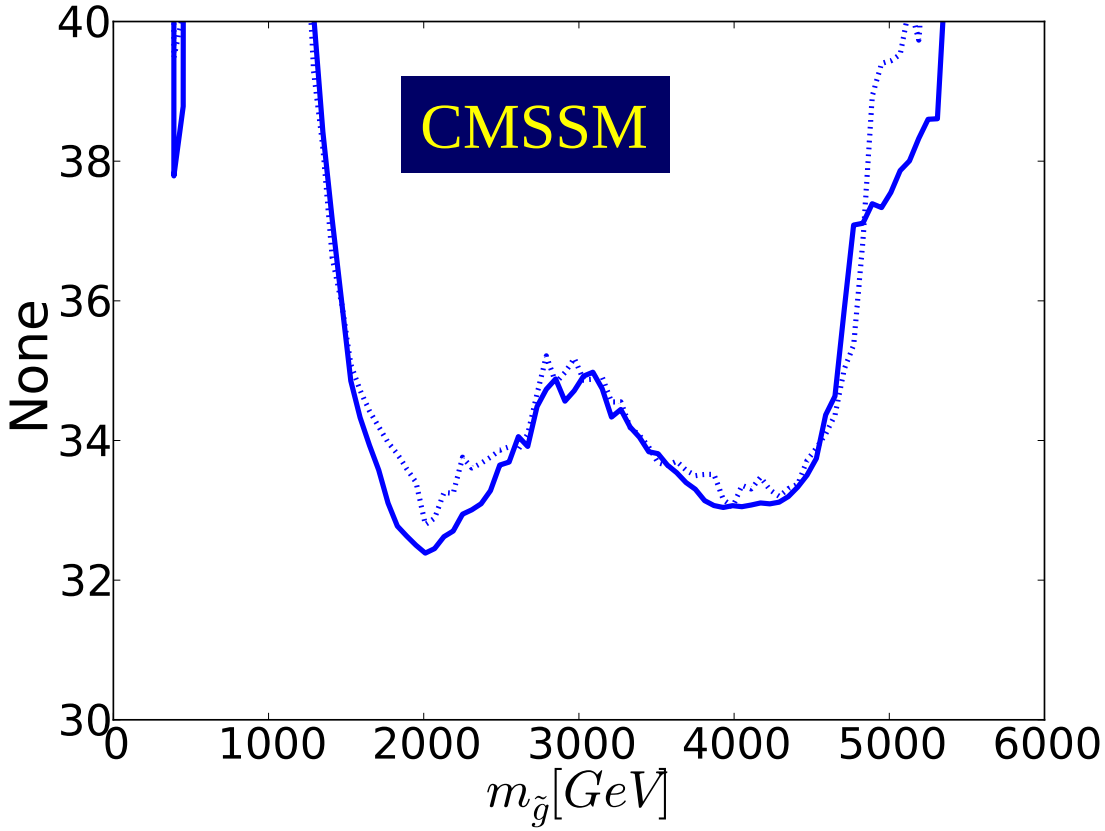
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ★

p-value of simple models < 10%

Post-LHC, Post-XENON100

201 1ATLAS + CMS with 5 fb^{-1} of LHC Data

Gluino mass



Update of Buchmueller, JE et al: arXiv:1207.3715

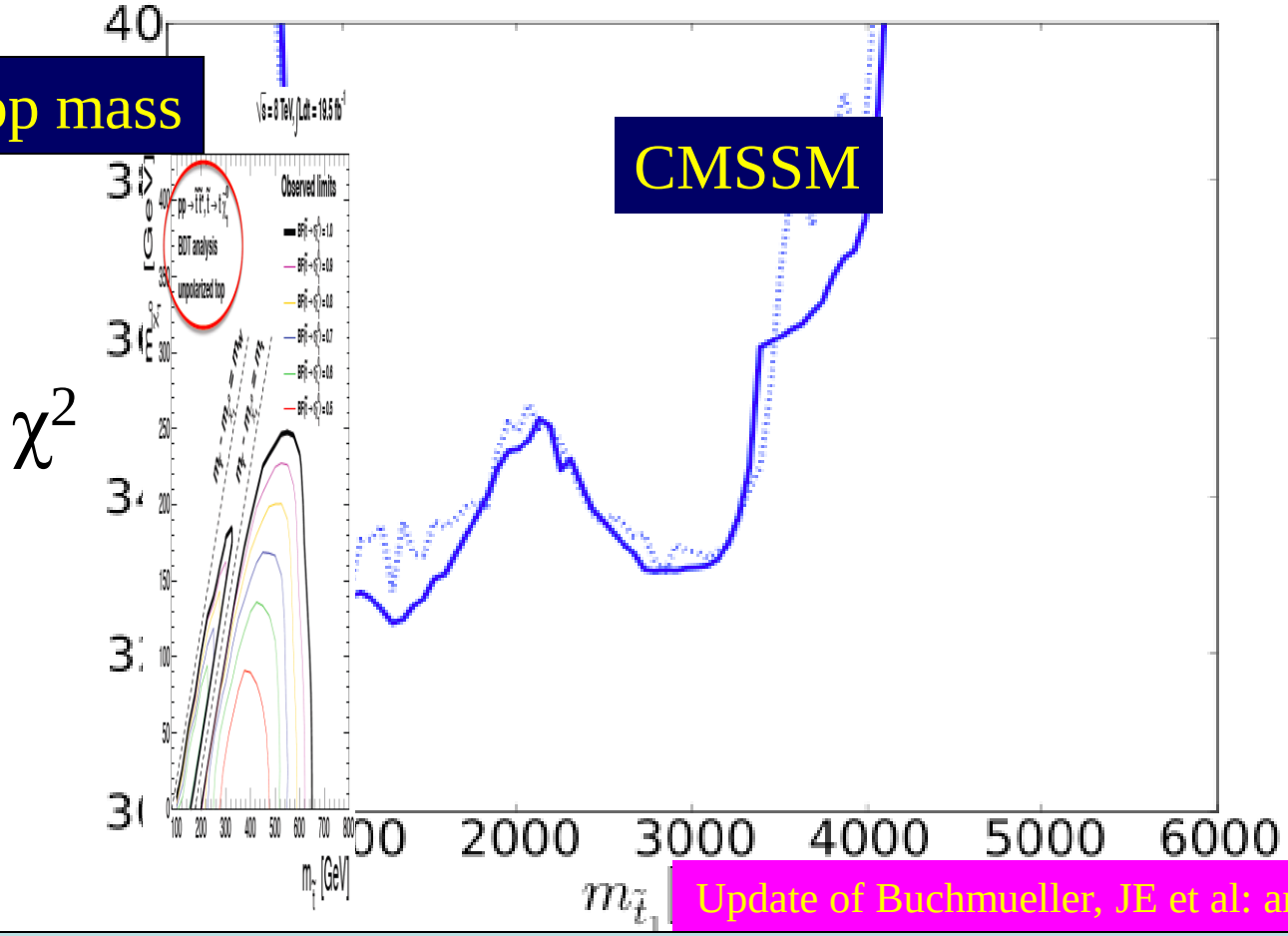
Favoured values of gluino mass significantly above pre-LHC, > 1.5 TeV

Post-LHC, Post-XENON100

201 1ATLAS + CMS with 5 fb^{-1} of LHC Data

Stop mass

CMSSM



1

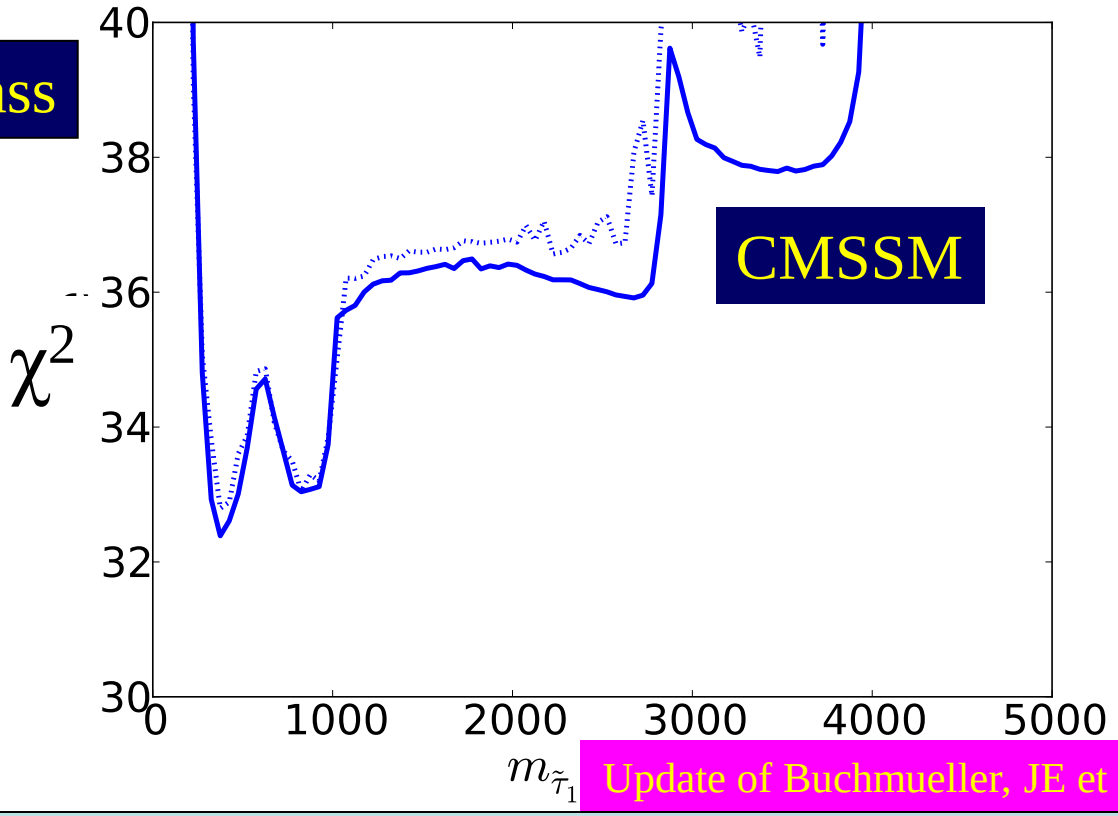
Update of Buchmueller, JE et al: arXiv:1207.3715

Favoured values of stop mass significantly below gluino, other squarks

Post-LHC, Post-XENON100

201 1ATLAS + CMS with 5 fb^{-1} of LHC Data

Stau mass



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Update of Buchmueller, JE et al: arXiv:1207.3715

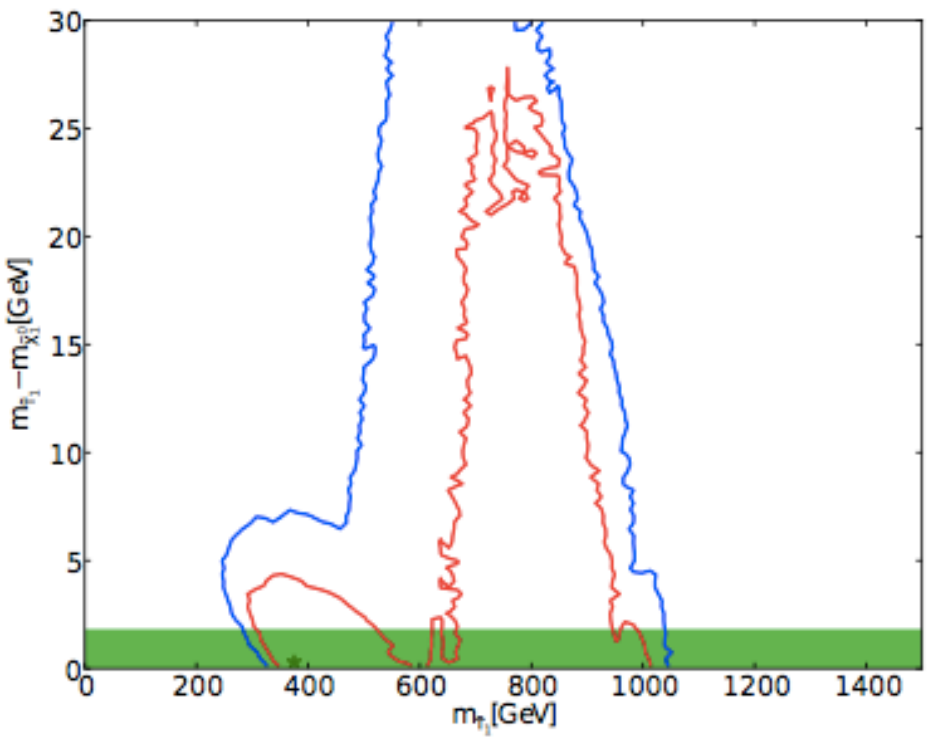
Favoured values of stau mass:

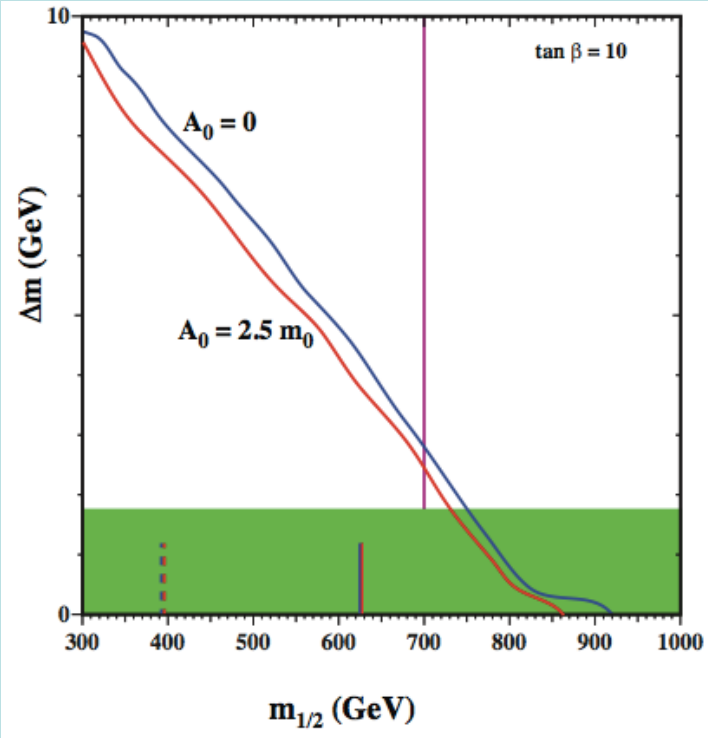
Several hundred GeV

What remains for the CMSSM?

Citron, JE, Luo, Marrouche, Olive, de Vries: arXiv:1212.2886

- Favoured regions of parameter space

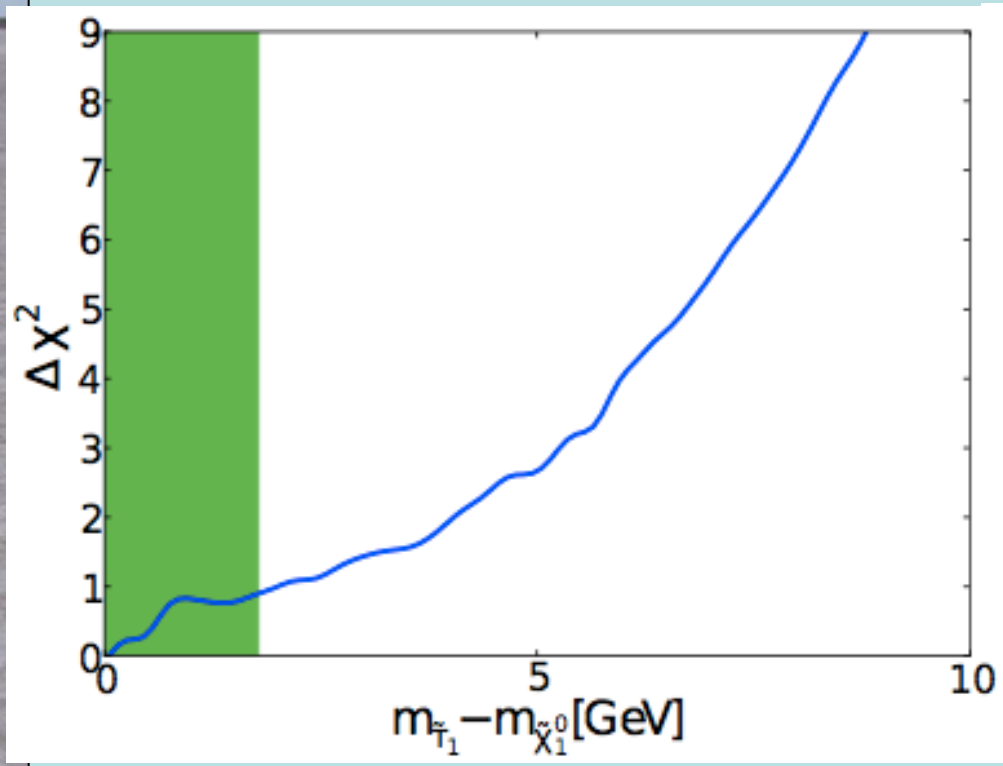


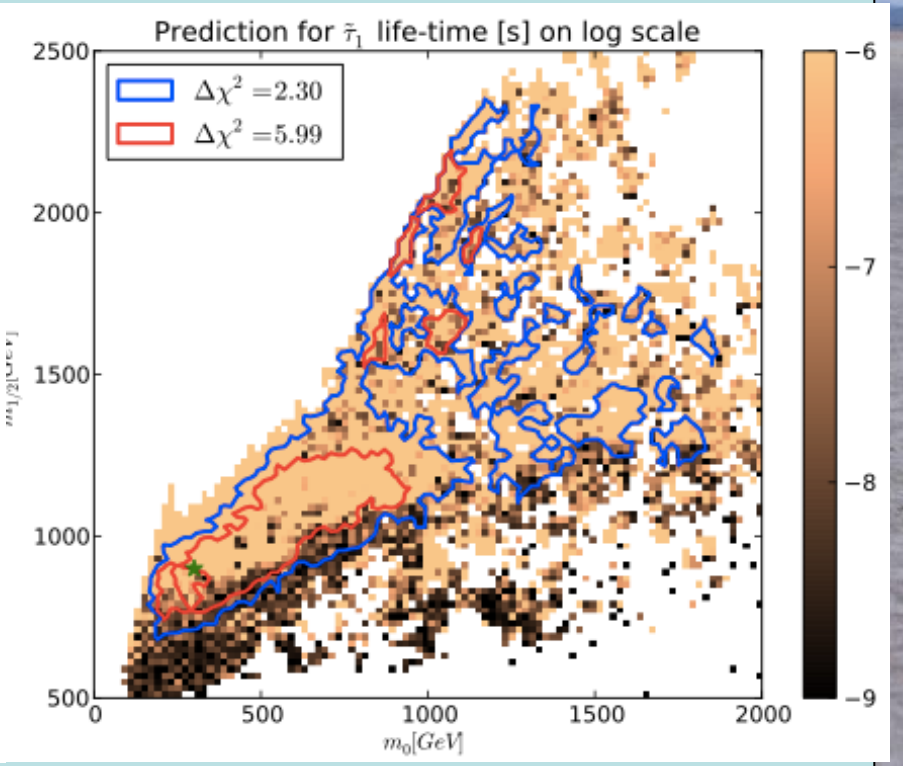


- Focus on the coannihilation strip
- Small mass difference – long-lived stau?

Search for long-lived Staus?

- Small Δm favoured in χ^2 analysis

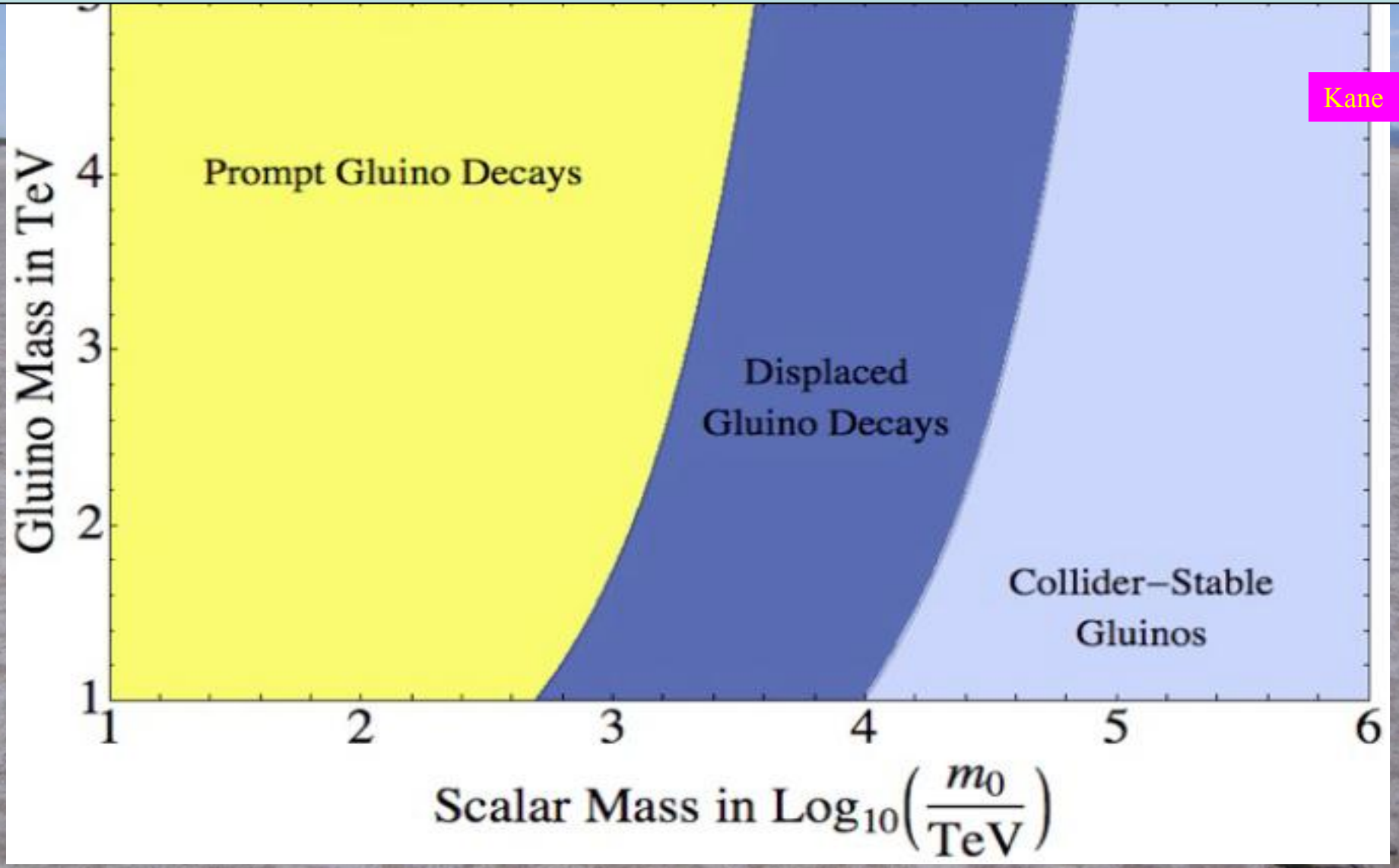




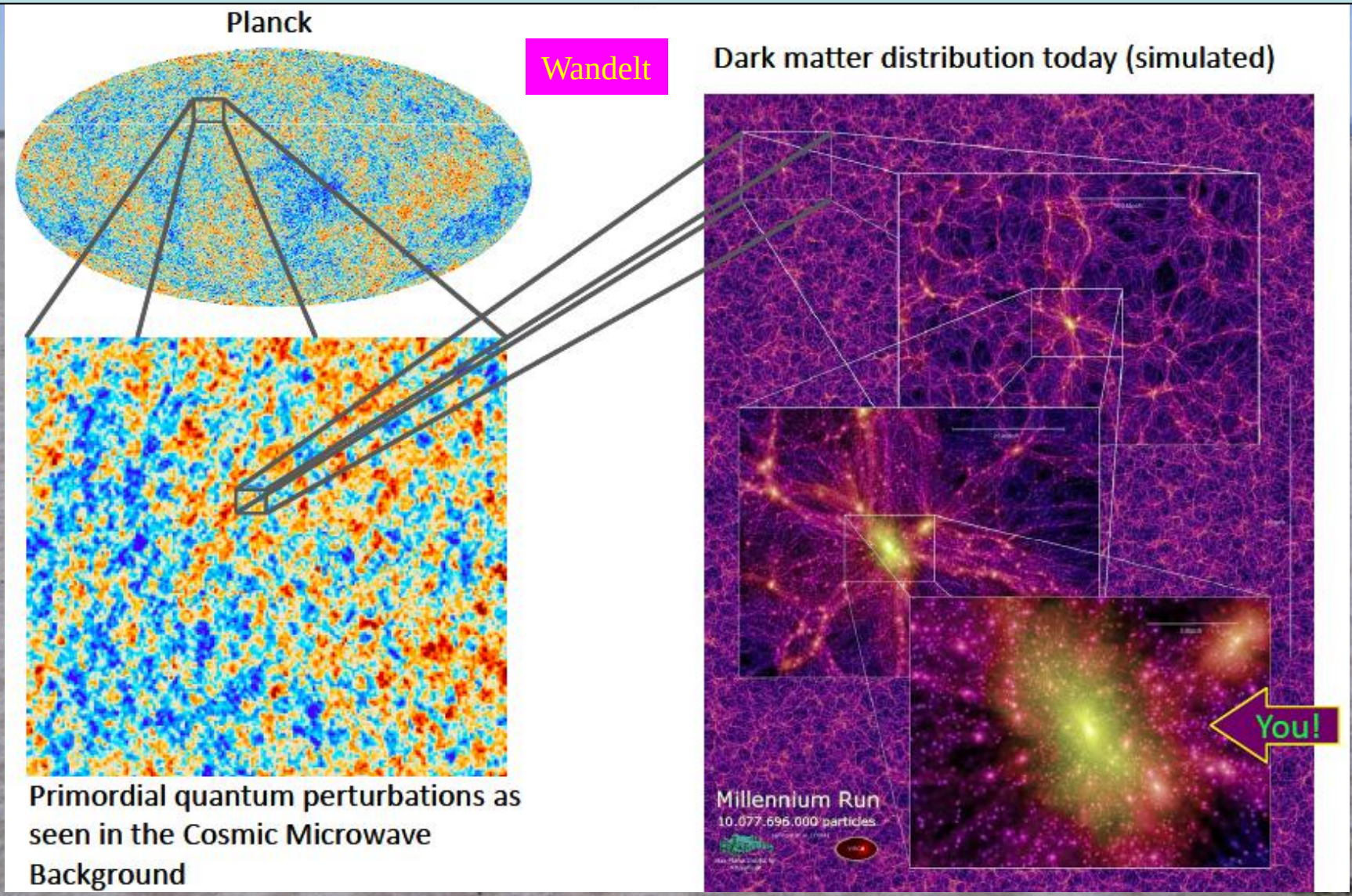
- May decay inside or outside the detector

Citron, JE, Luo, Marrouche, Olive, de Vries: arXiv:1212.2886

Long-lived Gluinos in Split SUSY?



SUSY in the Sky: Inflation, Dark Matter?

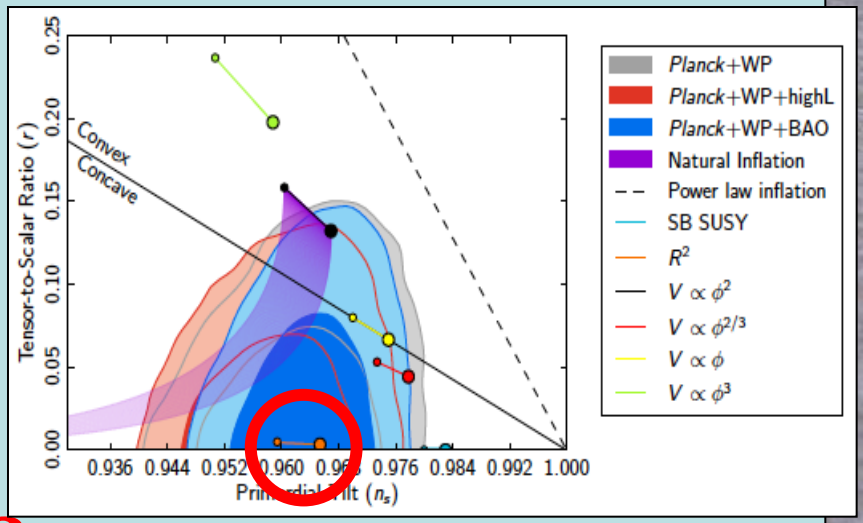


Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation
- Tilted scalar perturbation spectrum:

$$n_s = 0.9585 \pm 0.070$$

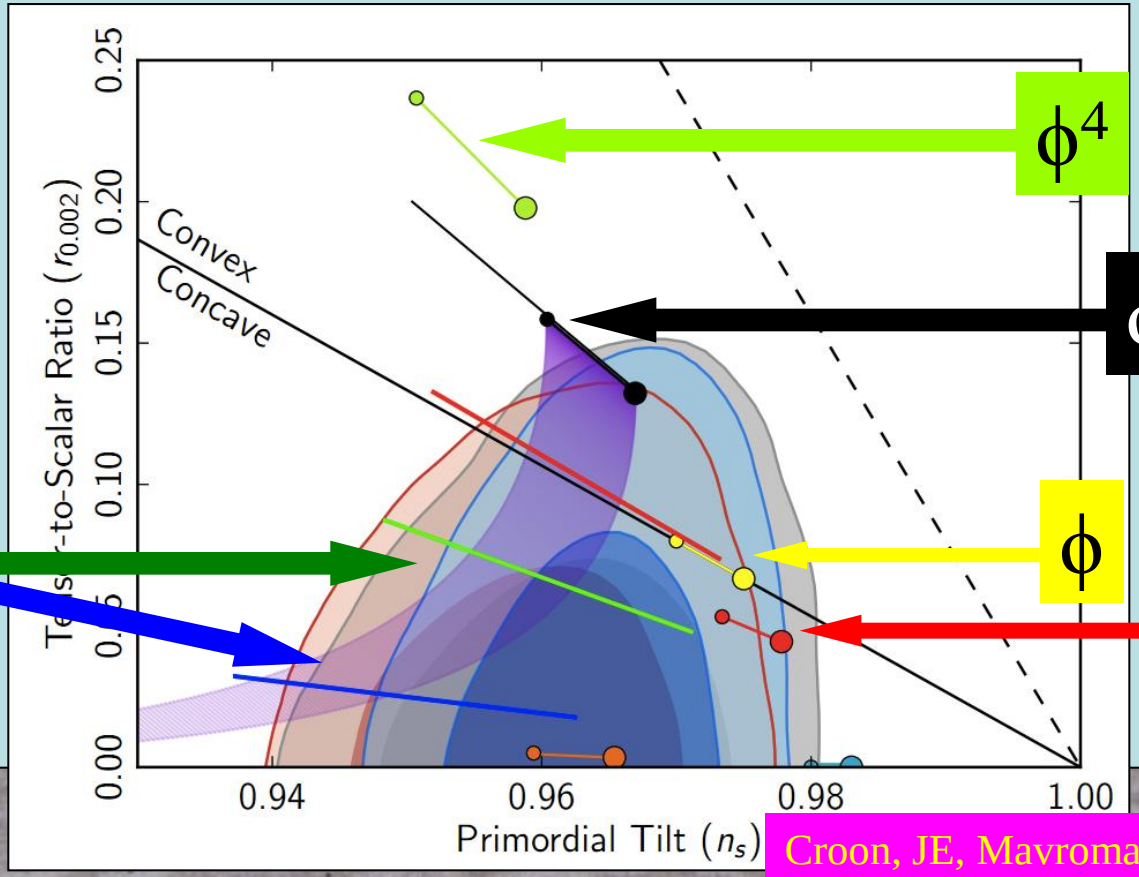
- **BUT** strengthen upper limit on tensor perturbations: $r < 0.10$
- Challenge for simple inflationary models
- **Starobinsky R^2 to rescue?**
- **Supersymmetry to rescue?**



Croon, JE & Mavromatos: arXiv:1303.6253

Supersymmetric Inflation in Light of Planck

- Supersymmetric Wess-Zumino (WZ) model consistent with Planck data



WZ

ϕ^4

ϕ^2

ϕ

$\phi^{2/3}$

Croon, JE, Mavromatos: arXiv:1303.6253

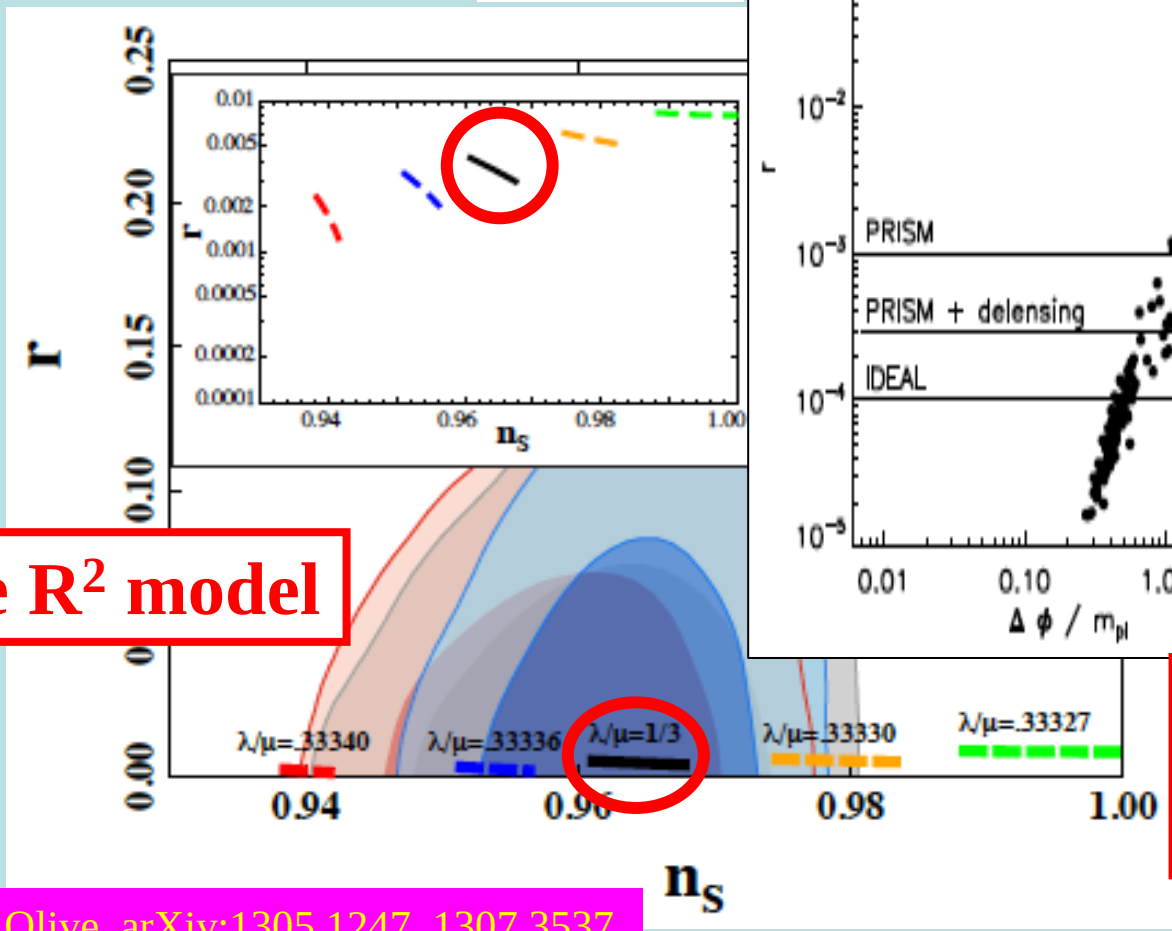
No-Scale Supergravity Inflation

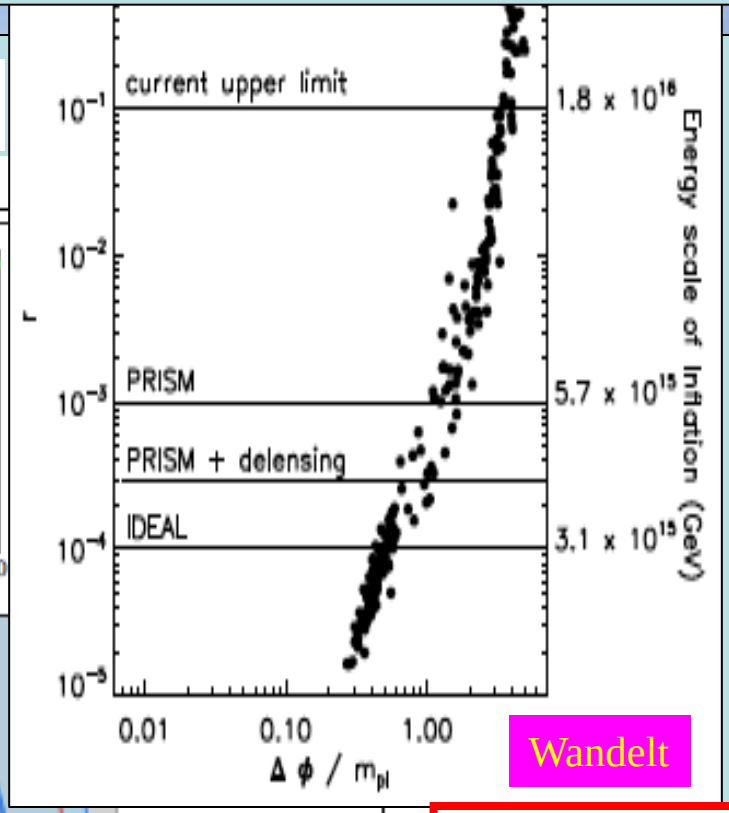
- The only good symmetry is a local symmetry
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = Supergravity**
- **BUT**: potentials in generic supergravity models have potential 'holes' with depths ~ $-M_P^4$
- Exception: **no-scale supergravity**
- Appears in compactifications of string
- Flat directions, scalar potential ~ global model + controlled corrections

JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537

No-Scale Supergravity Inflation

- Good inflation for $\lambda \simeq \mu/3$





Wandelt

Looks like R^2 model

Accessible to PRISM

JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537

Strategies for Detecting Supersymmetric Dark Matter

- Scattering on nucleus in laboratory

  $\chi + A \rightarrow \chi + A$

- Annihilation in core of Sun or Earth

  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

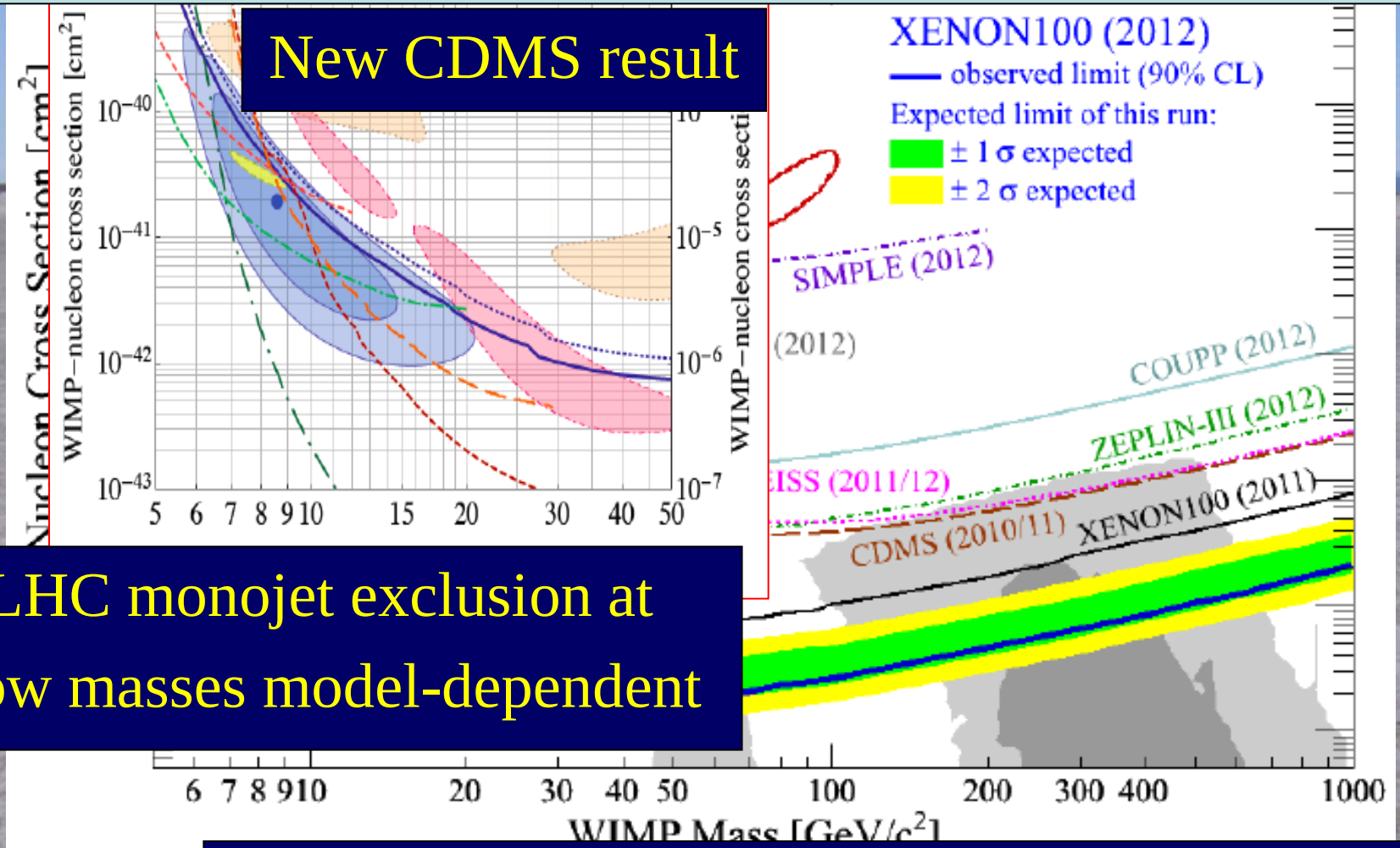
- Annihilation in galactic centre, dwarf galaxies

  $\chi - \chi \rightarrow \gamma + \ldots ?$

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ positrons, antiprotons, …?

Direct Searches for Dark Matter

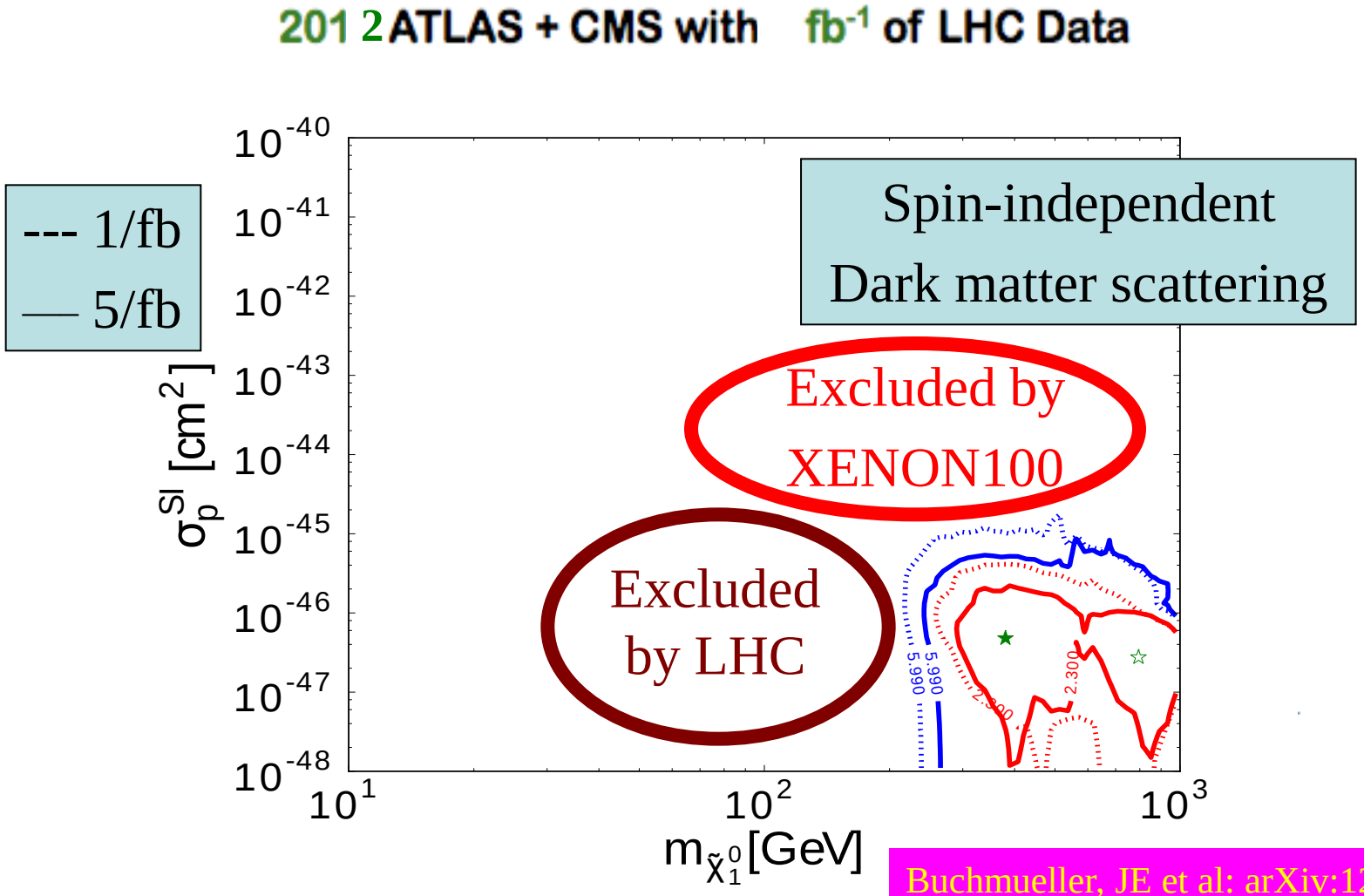


LHC monojet exclusion at
Low masses model-dependent

Best limit: XENON100 with 225 days of data
Confusion at low WIMP masses?

Aprile et al.

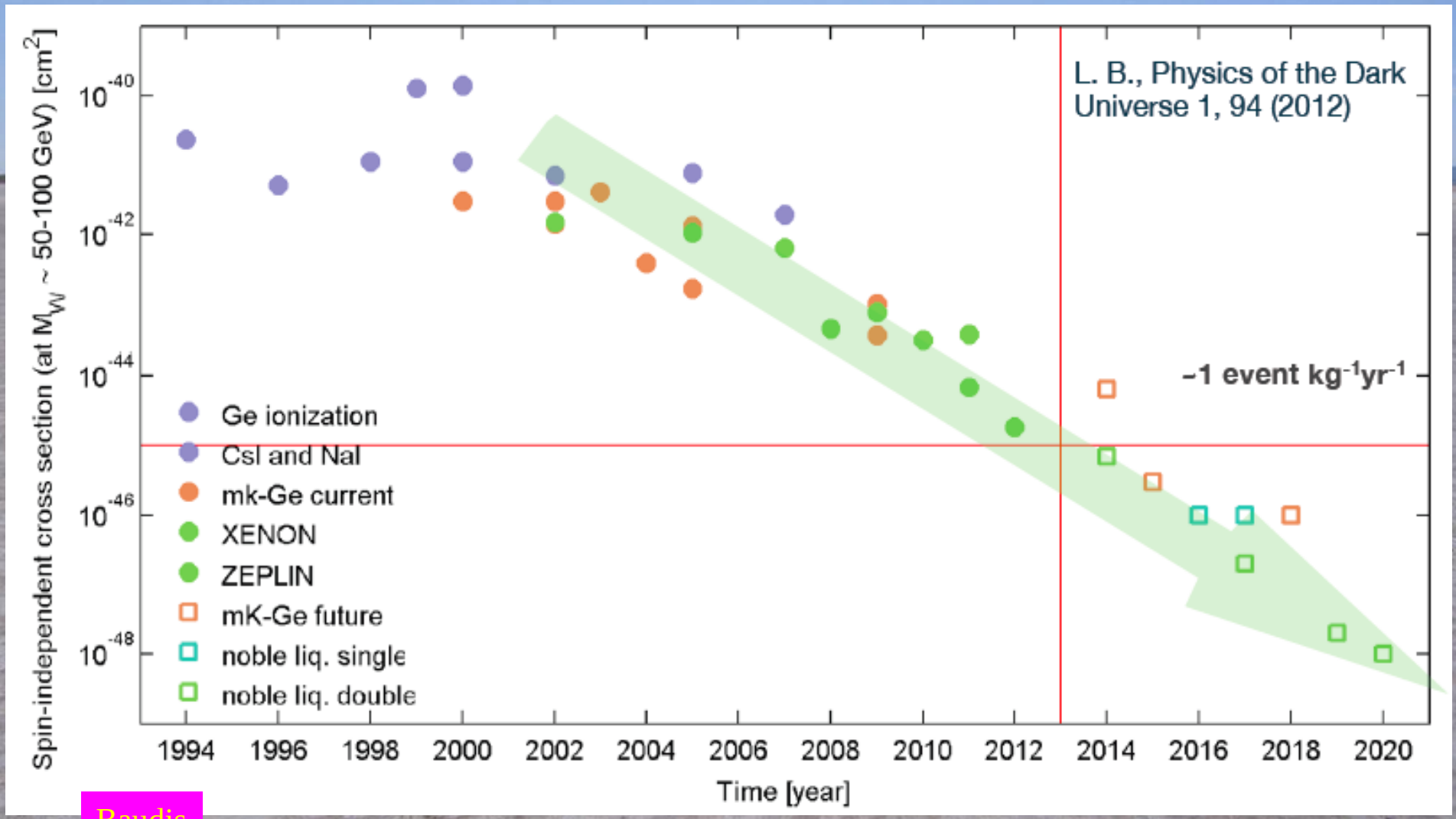
Global Fit to Supersymmetric Model



Buchmueller, JE et al: arXiv:1207.3715

Favoured values of dark matter scattering cross section significantly below XENON100

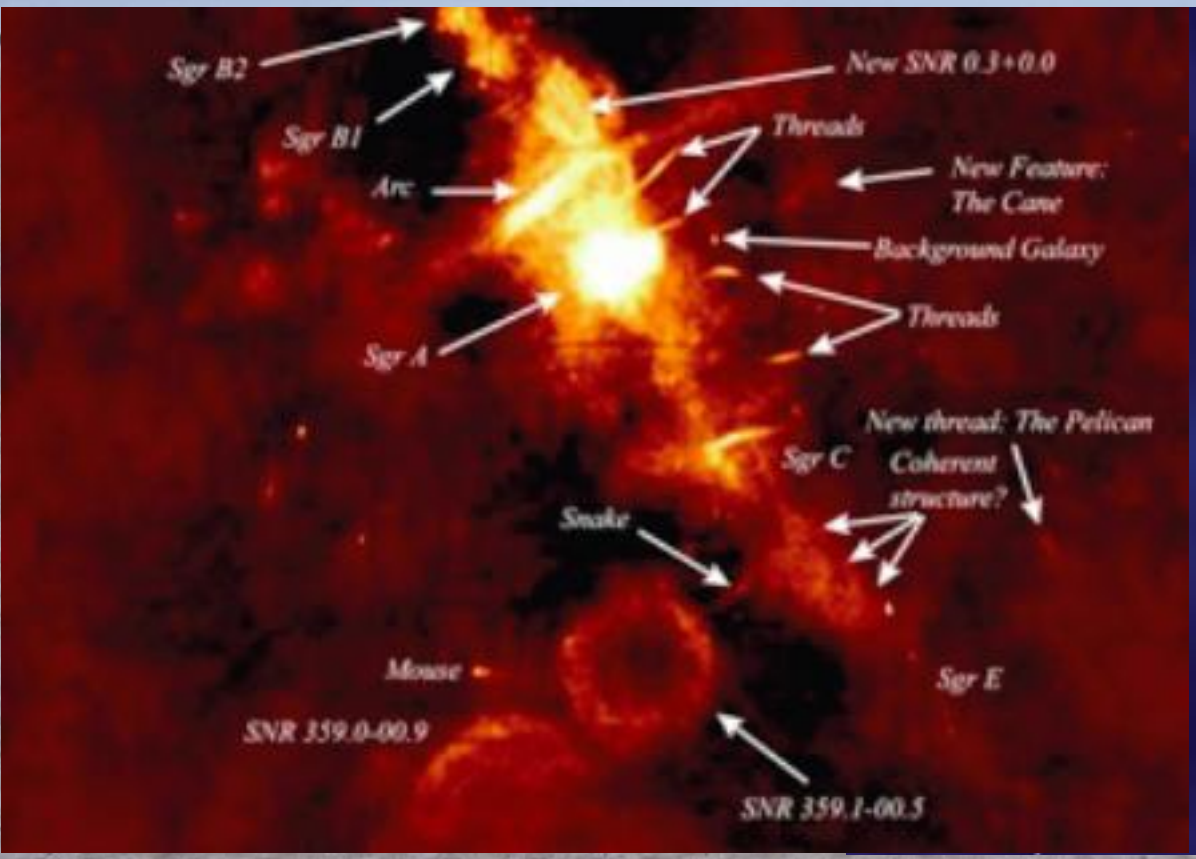
Prospective Future Sensitivity

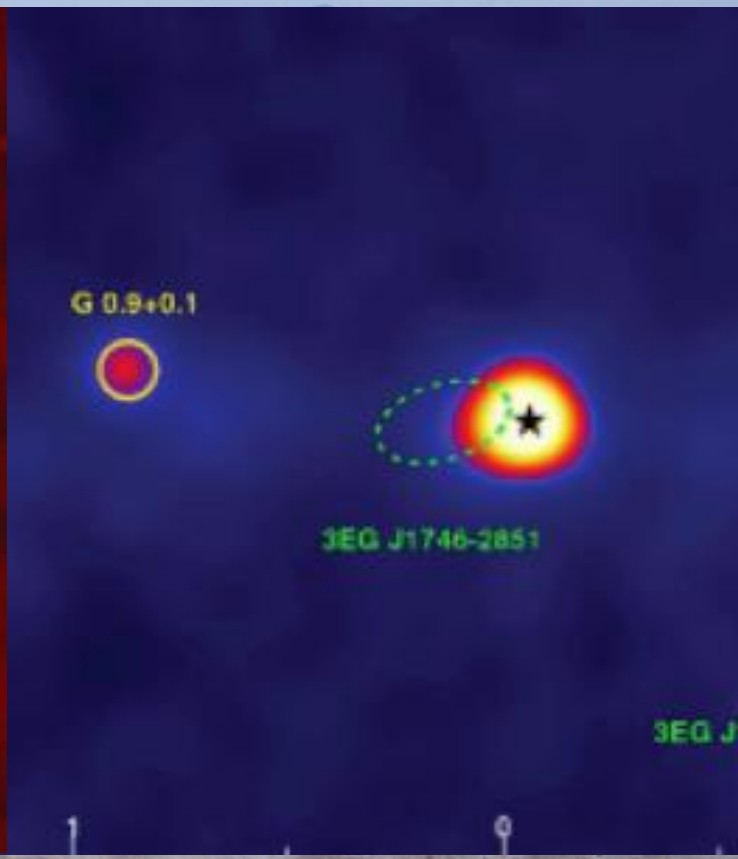


Baudis

Gamma Rays from Galactic Centre?

Galactic centre is a complicated place



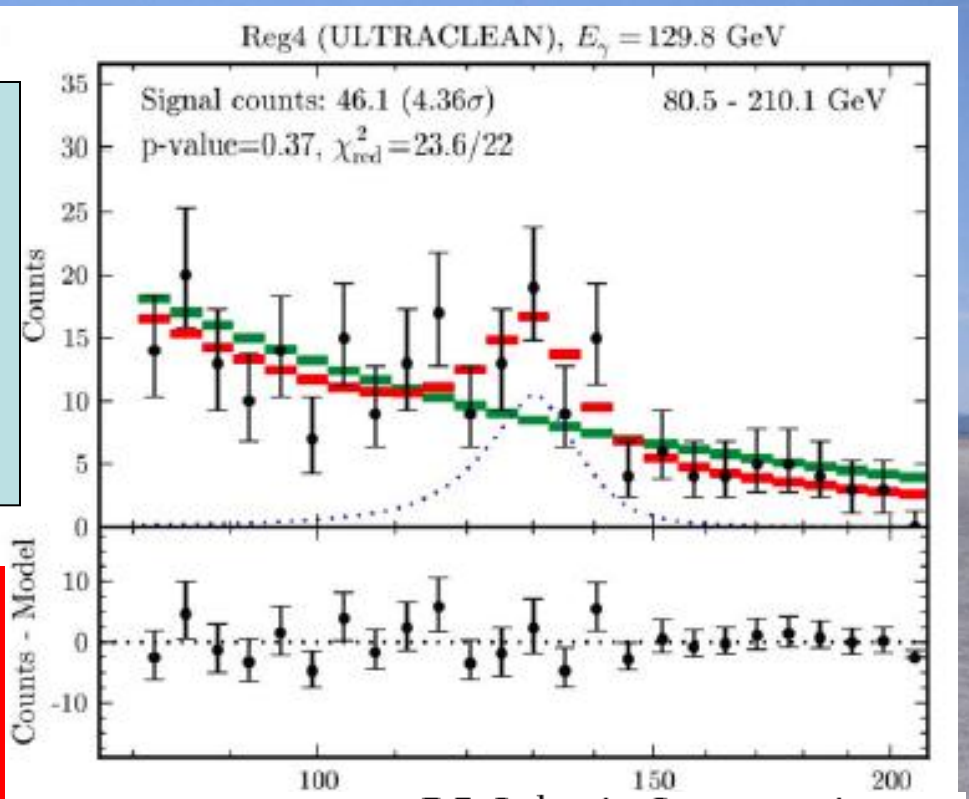


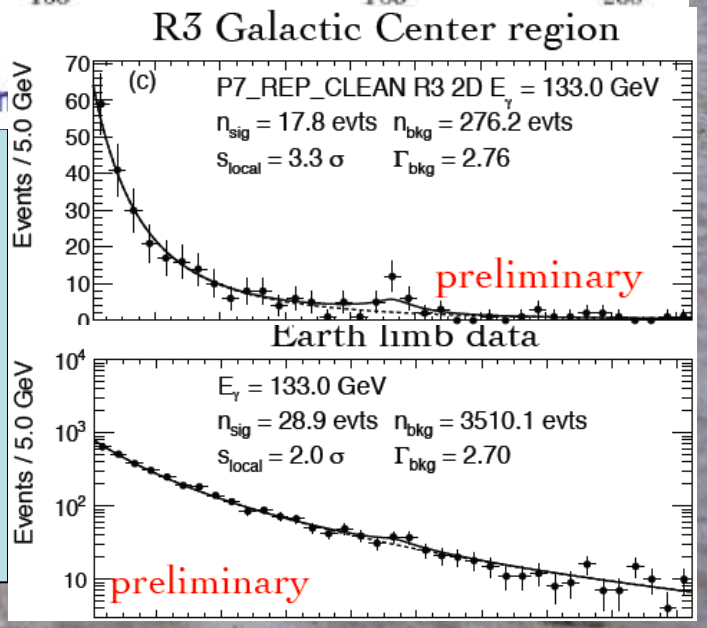
Profumo

Time variation in black hole Sgr A*?

Fermi γ line @ 130 GeV?

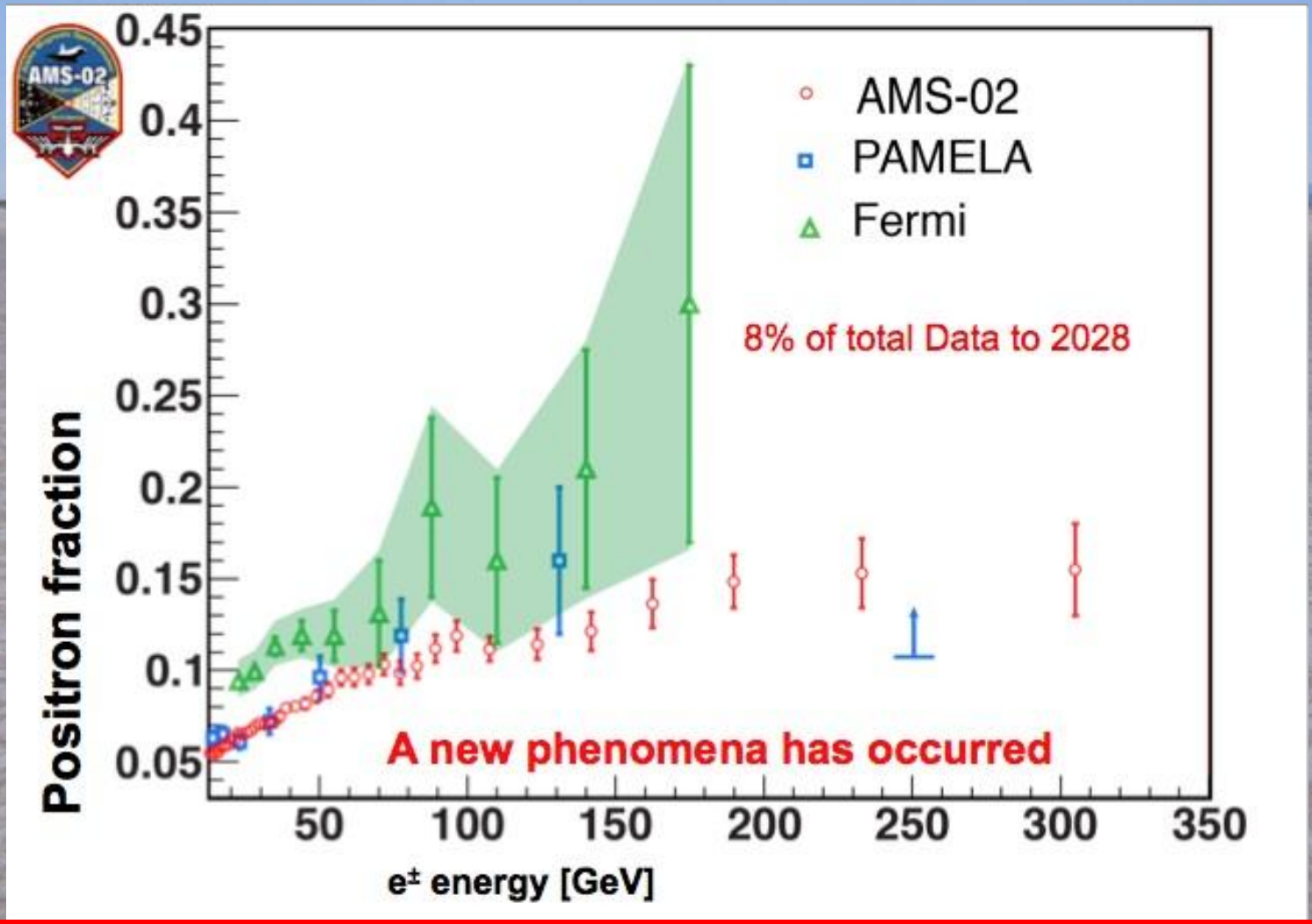
Weniger analysis claimed "4 σ"
(3 σ with look-elsewhere effect)





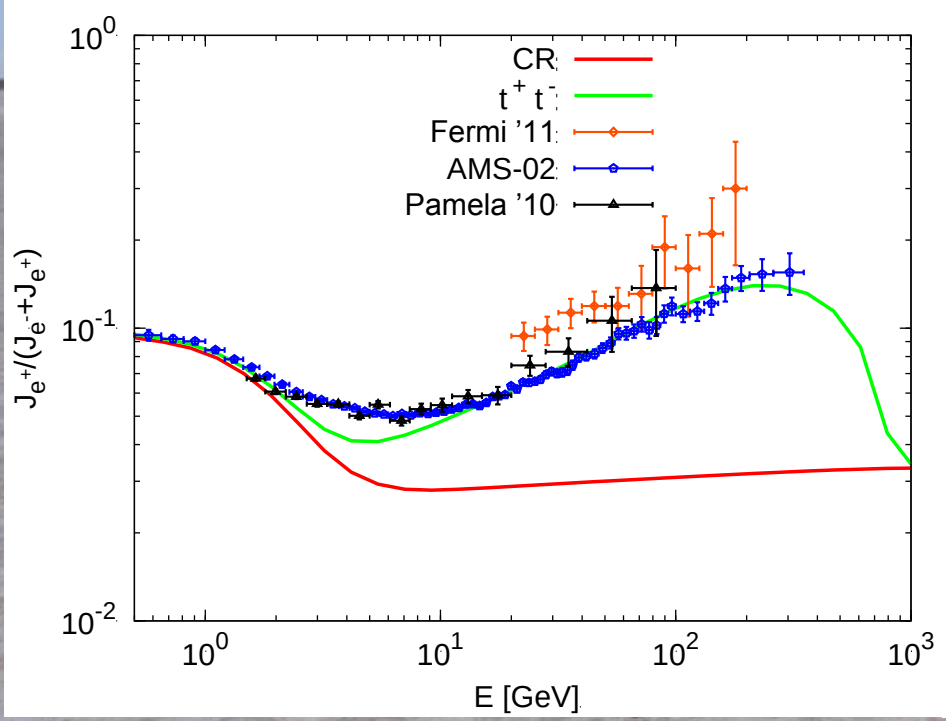
- **BUT:** Fermi Collaboration also sees bump in control sample of γ's from Earth's limb
- Presumably a systematic effect

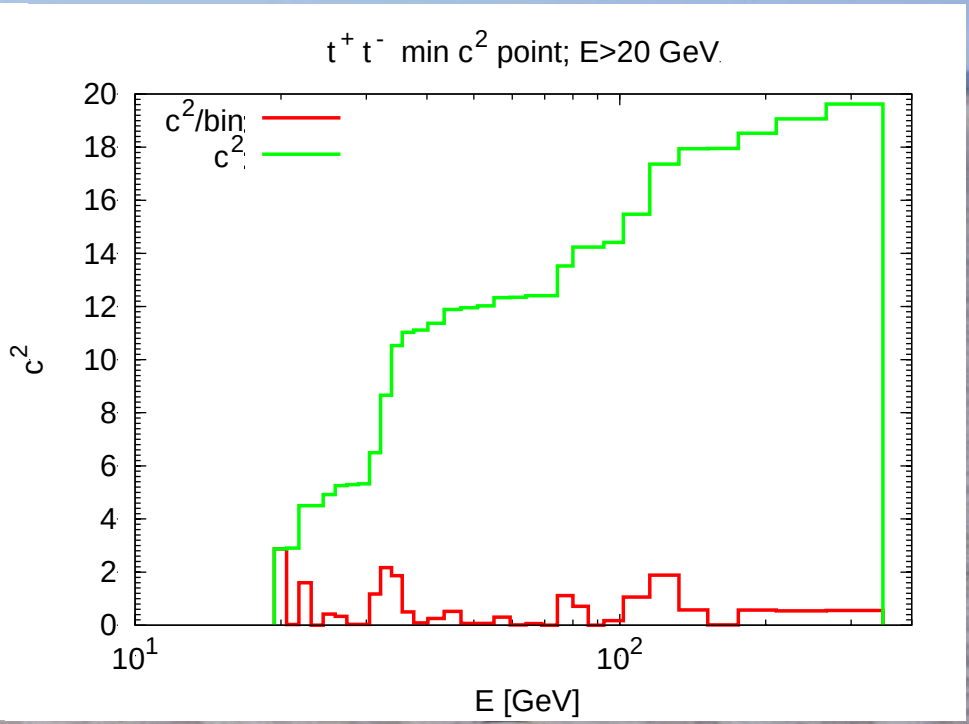
Positron Fraction Rising with E



Dark Matter? Galactic cosmic rays? Local sources?

Dark Matter Fit to AMS Positron Data

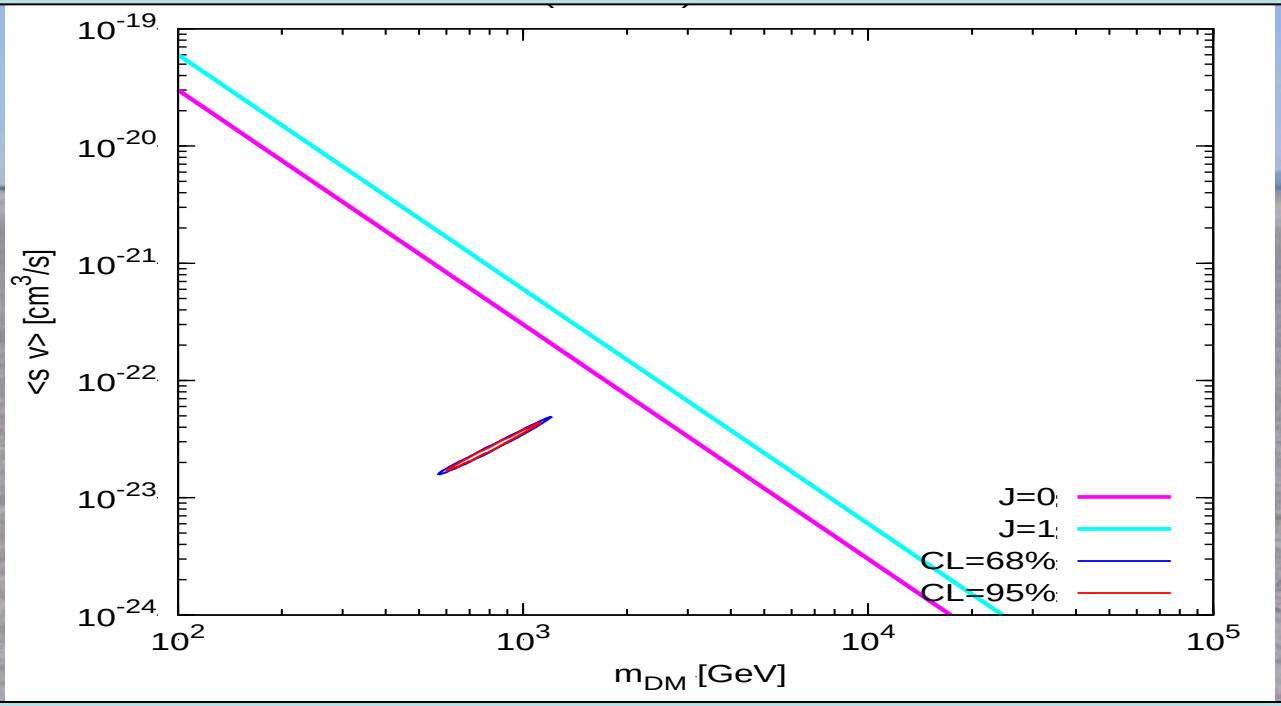




Can find good fit: $\chi^2 \sim 18$ with annihilation to $\tau^+\tau^-$ by modifying cosmic ray parameters

JE, Olive & Spanos, in preparation

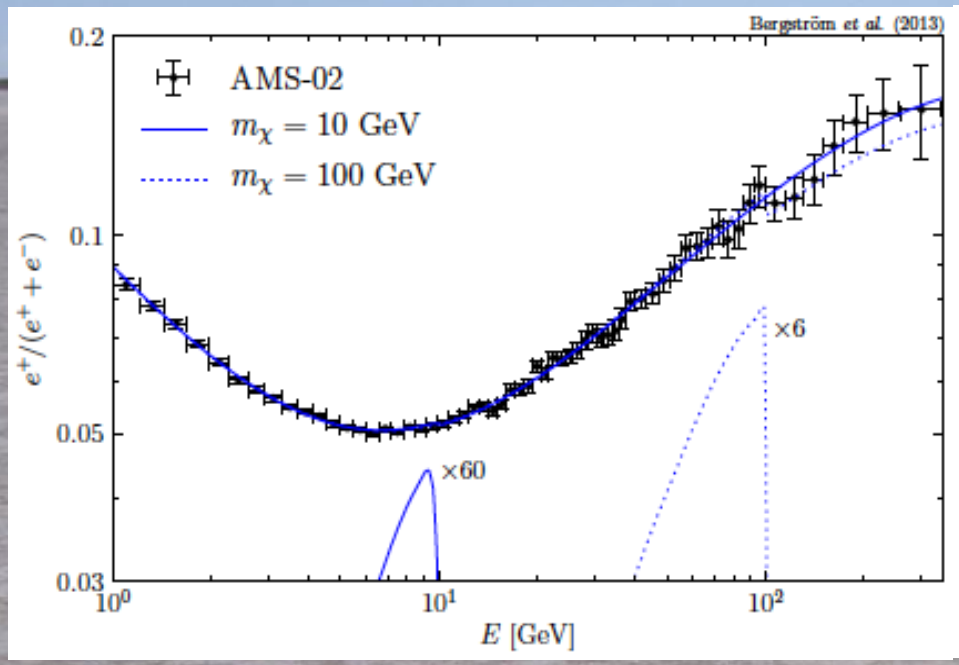
Dark Matter Fit to AMS Positron Data

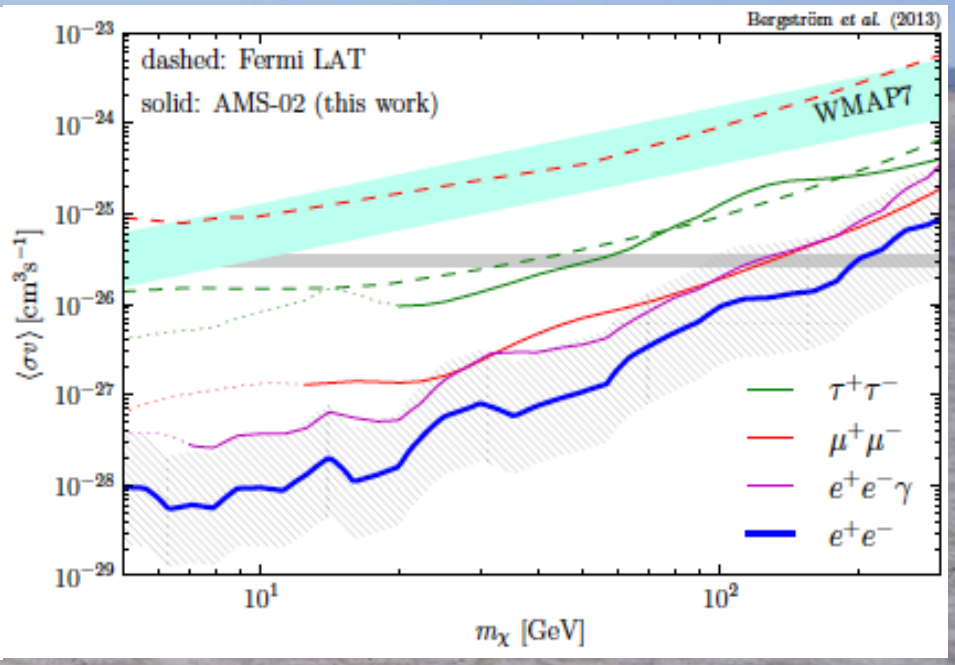


- **BUT:** very large annihilation cross section
  $\sim 3 \times 10^{-23}\,\mathrm{cm}^2$ >> required for relic density
- **OR:** very large boost from halo density fluctuation(s)

JE, Olive & Spanos, in preparation

Assume Local Source: Constrain any extra Dark Matter Contribution





Dark Matter annihilation could give feature above otherwise smooth distribution

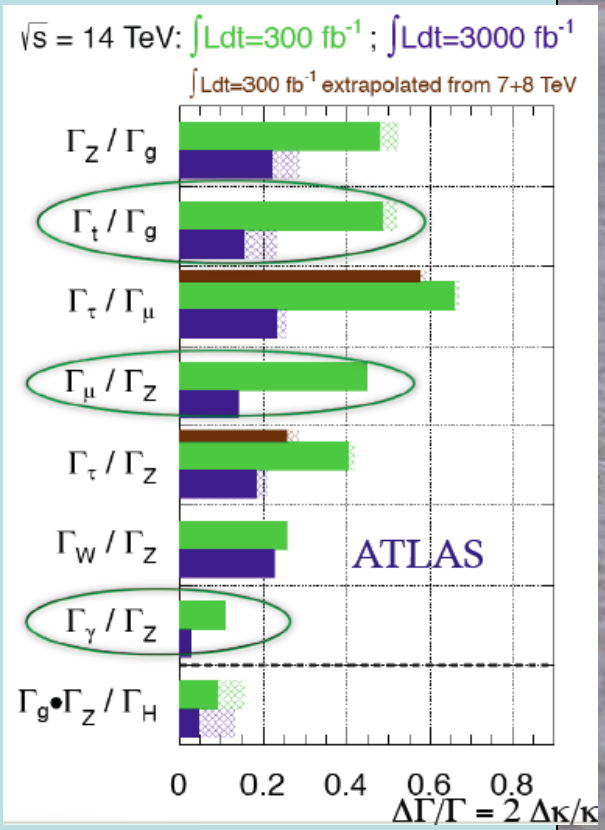
Bergstrom et al, arXiv::1306.3983

What Next: A Higgs Factory?

To study the 'Higgs' in detail:

- The LHC
  - Rethink LHC upgrades in this perspective?
- A linear collider?
  - ILC up to 500 GeV
  - CLIC up to 3 TeV

    (Larger cross section at higher energies)
- A circular e^+e^- collider: LEP3, TLEP
  - A photon-photon collider: SAPPHiRE
- A muon collider



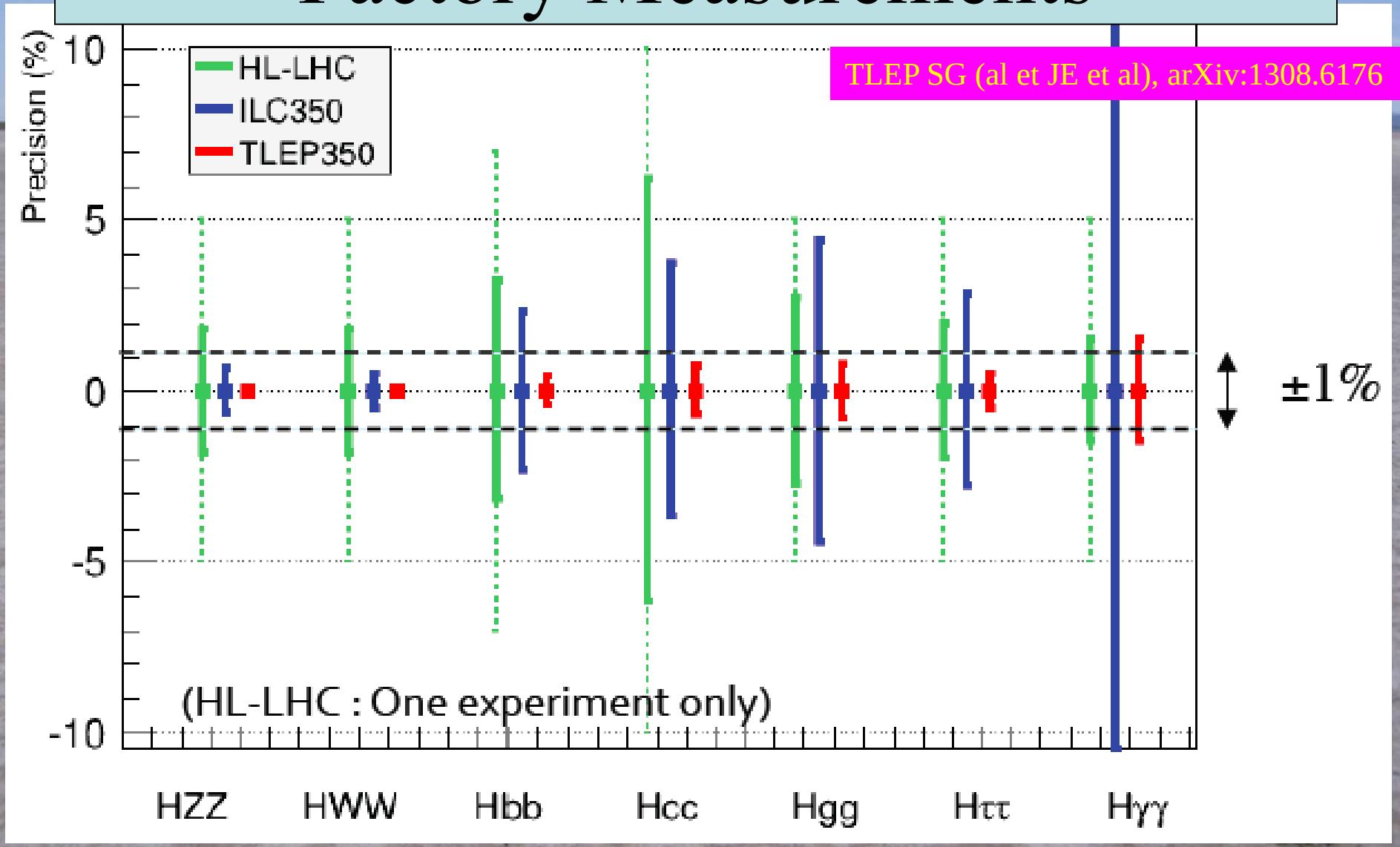
Higgs Factory Summary

Best precision

Accelerator →Physical quantity ↓	LHC 300fb^{-1} /exp	HL-LHC 3000fb^{-1} /exp	ILC (250) 250 fb^{-1}	ILC (250+350+1000)	LEP3 240 4 IP	TLEP 240 +350 4 IP
Approx. date	2021	2030	2035	2045	2035	2035
N_H	1.7 x 10^7	1.7 x 10^8	5 10^4 ZH	(10^5 ZH) (1.4 10^5 Hvv)	4 10^5ZH	2 10^6 ZH
m_H (MeV)	100	50	35	35	26	7
$\Delta\Gamma_H/\Gamma_H$	--	--	10%	3%	4%	1.3%
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	0.35%	0.15%
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	3.4%	1.4%
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	2.2%	0.7%
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1.5%	0.25%
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	0.65%	0.2%
$\Delta g_{HHH}/g_{HHH}$	--	< 30% (2 exp.)	--	~30%	--	--
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30	<10	--	--	14%	7%

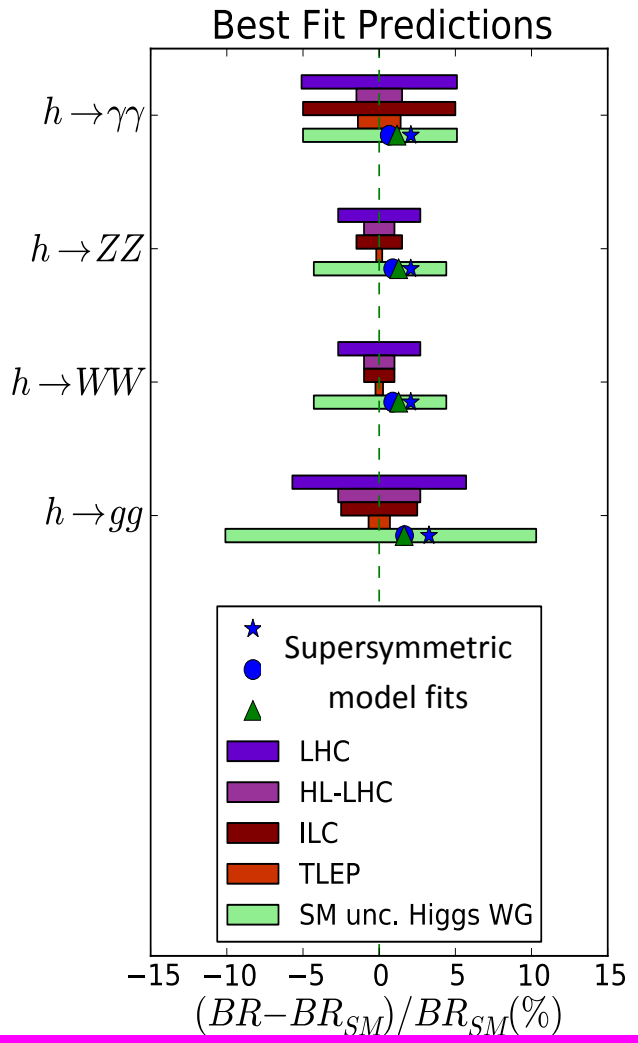
Possible TLEP Locations around Geneva

Comparison of Possible Higgs Factory Measurements



Impact of Higgs Factory?

- Predictions of current best fits in simple SUSY models
- Current uncertainties in SM calculations [LHC Higgs WG]
- Comparisons with
  - **LHC**
  - **HL-LHC**
  - **ILC**
  - **TLEP**
- **Don't decide before LHC 13/4**



TLEP SG (al et JE et al), arXiv:1308.6176

Part of a Vision for the Future

- A large circular tunnel
  - Circumference ~ 80 to 100 km
- Could accommodate TLEP and VHE-LHC
  - E_{CM} up to 100 TeV with 15 Tesla magnets
- Could be sited around Geneva
  - Interest in China, …
- TLEP study under way: TLEP SG (al et JE et al), arXiv:1308.6176

  http://tlep.web.cern.ch/
- VHE-LHC study now starting

Let us be patient …

- If you have a problem, postulate a new particle:
  - QM and Special Relativity: Antimatter
  - Nuclear spectra: Neutron
  - Continuous spectrum in β decay: Neutrino
  - Nucleon-nucleon interactions: Pion
  - Absence of lepton number violation: Second neutrino
  - Flavour SU(3): Ω^-
  - Flavour SU(3): Quarks
  - FCNC: Charm
  - CP violation: Third generation
  - Strong dynamics: Gluons
  - Weak interactions: $W^{\pm}$, Z^0
  - Renormalizability: H (48 years)
  - **Naturalness:** **Supersymmetry?** **(40 years)**