Prospects for Discovering Supersymmetry during Run 2 of the LHC

What next?

John Ellis

What lies beyond the Standard Model?

Supersymmetry

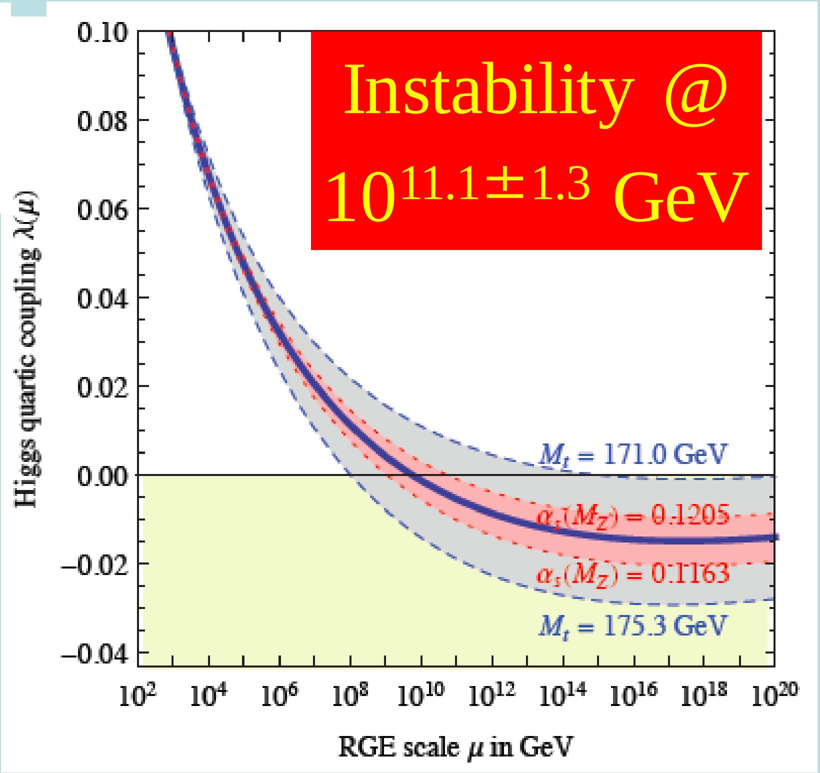
New motivations
From LHC Run 1

- **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

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

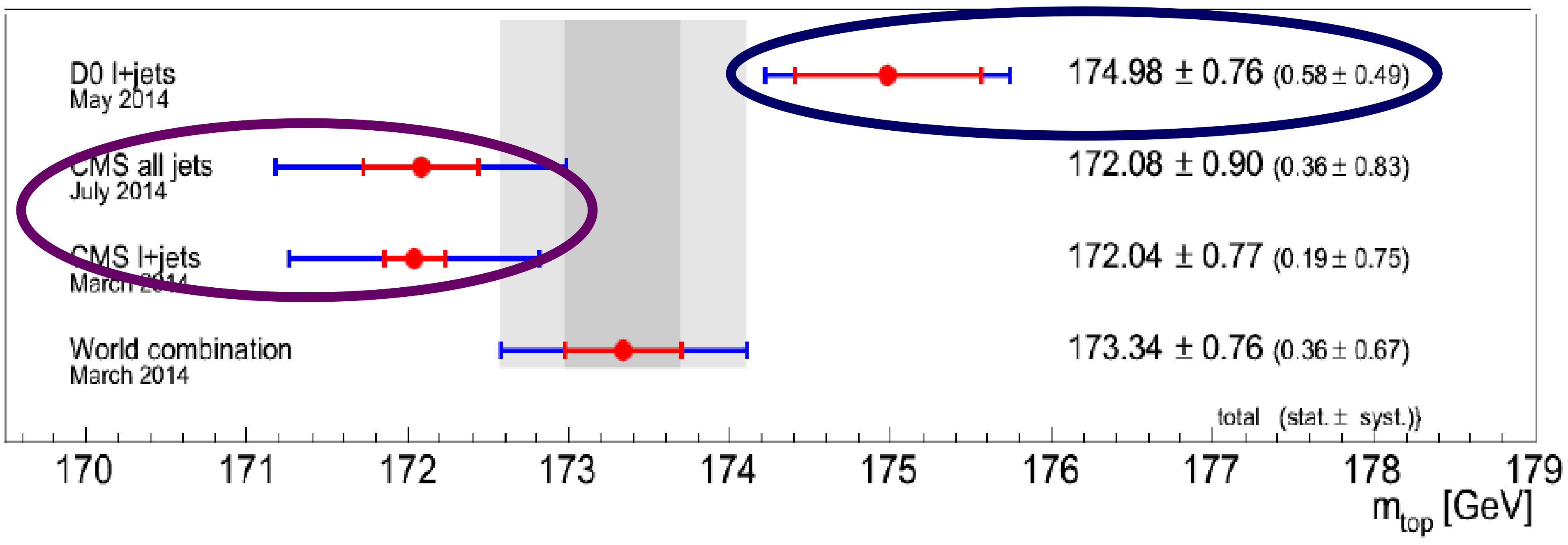


- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

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

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H



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

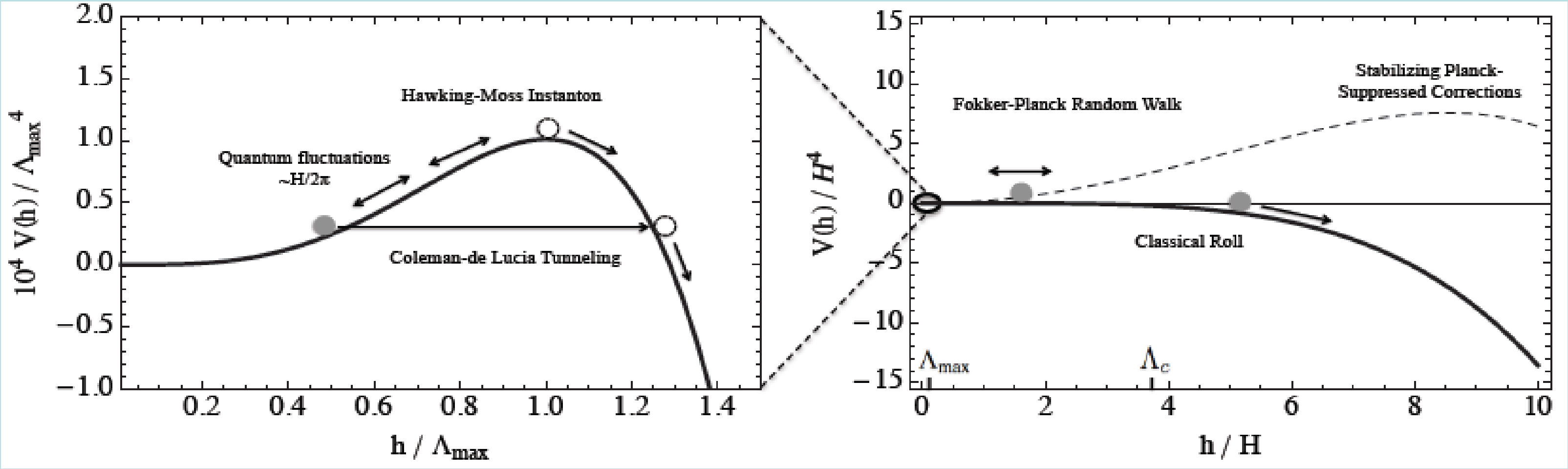
$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

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

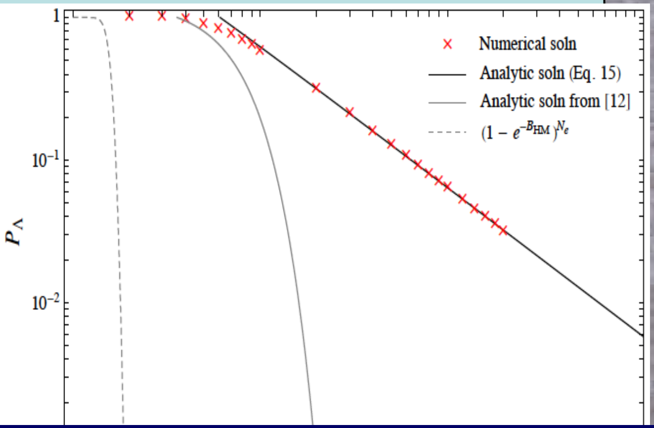
Instability during Inflation?

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



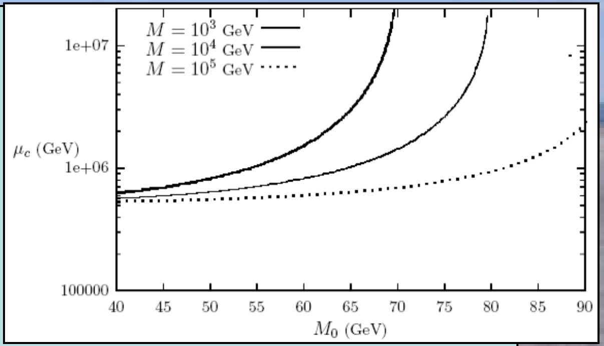
OK if dim-6 operator? Non-minimal gravity coupling?

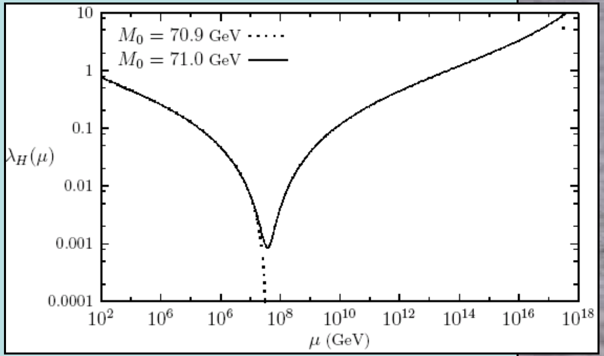
How to Stabilize a Light Higgs Boson?

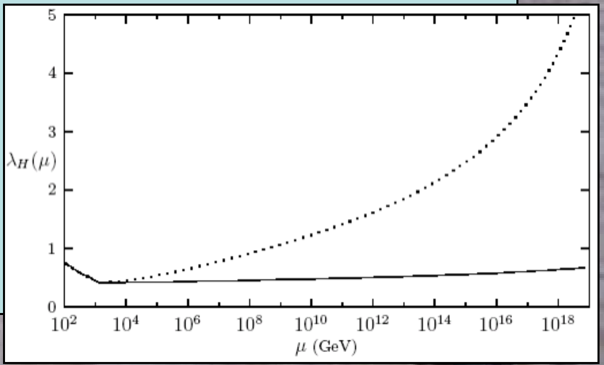
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Double up the known particles:

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

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

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

Nuclear Physics B238 (1984) 453–476

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

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Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

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 → lighter sparticles

- **Lightest supersymmetric particle (LSP) stable**

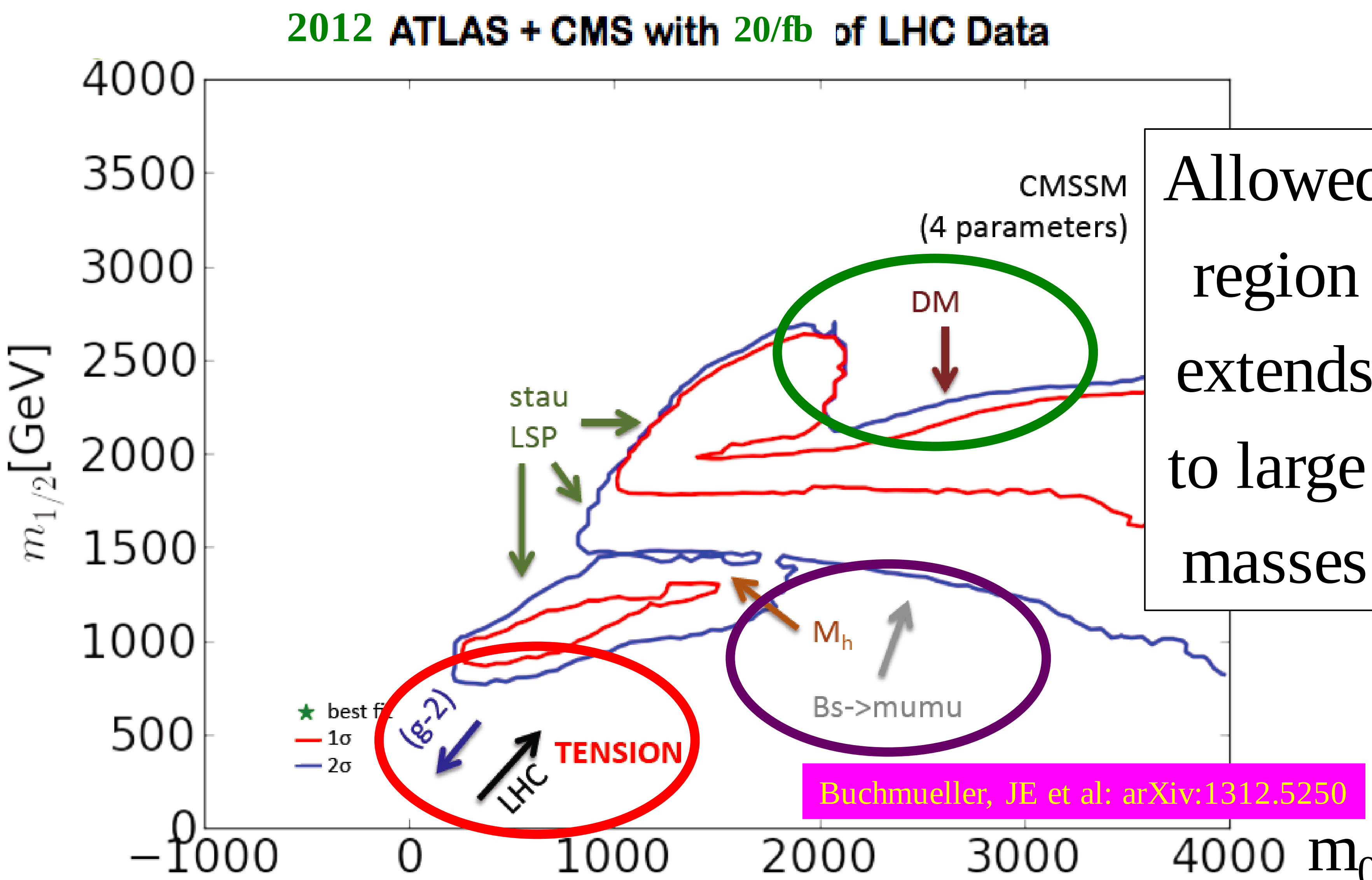
LSP as Dark Matter?

- 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)

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 masses

Buchmueller, JE et al: arXiv:1312.5250

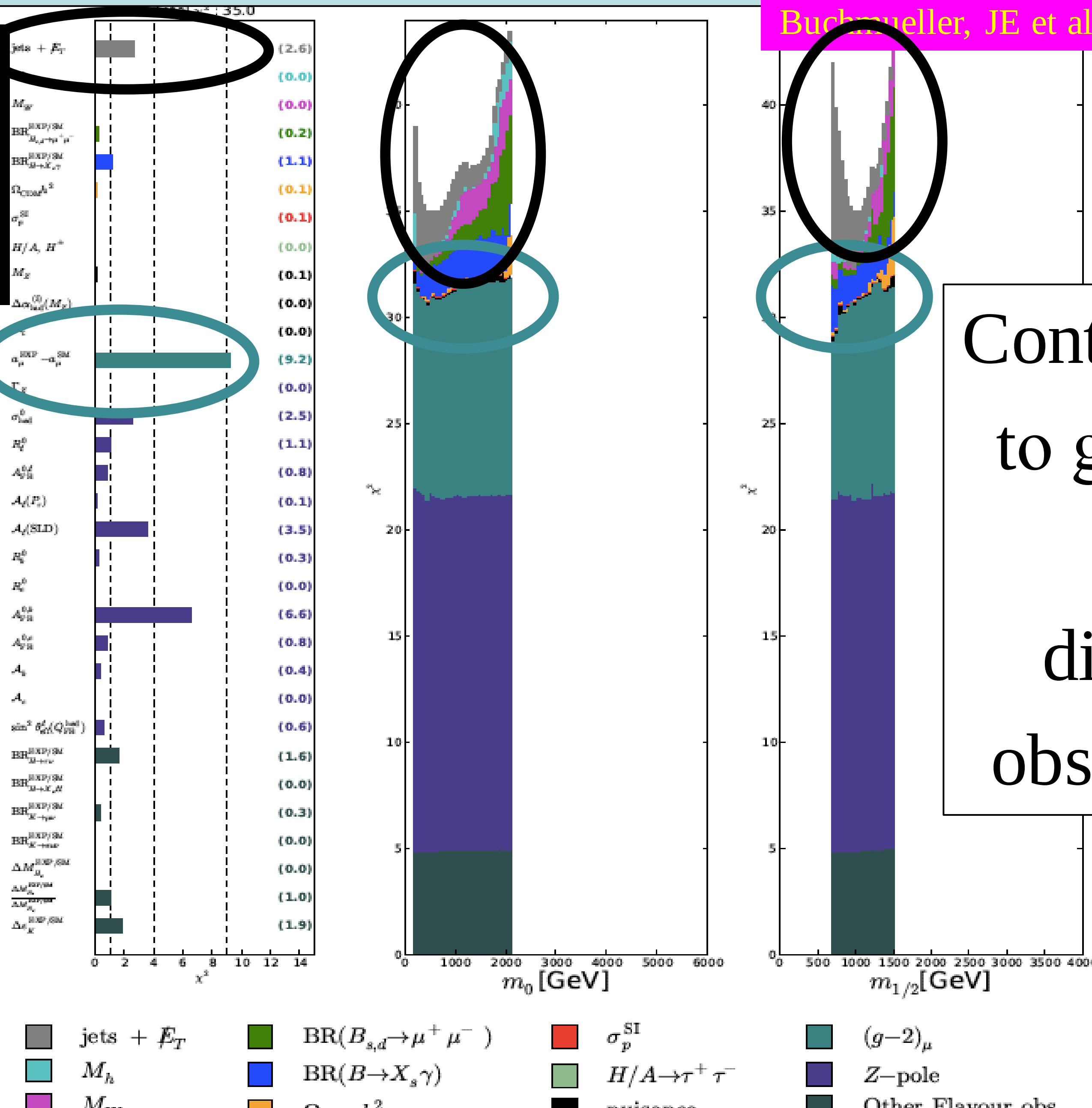
p-value of simple models ~ 10% (also SM)

Constrained MSSM (CMSSM)

Buchmueller, JE et al: arXiv:1312.5250

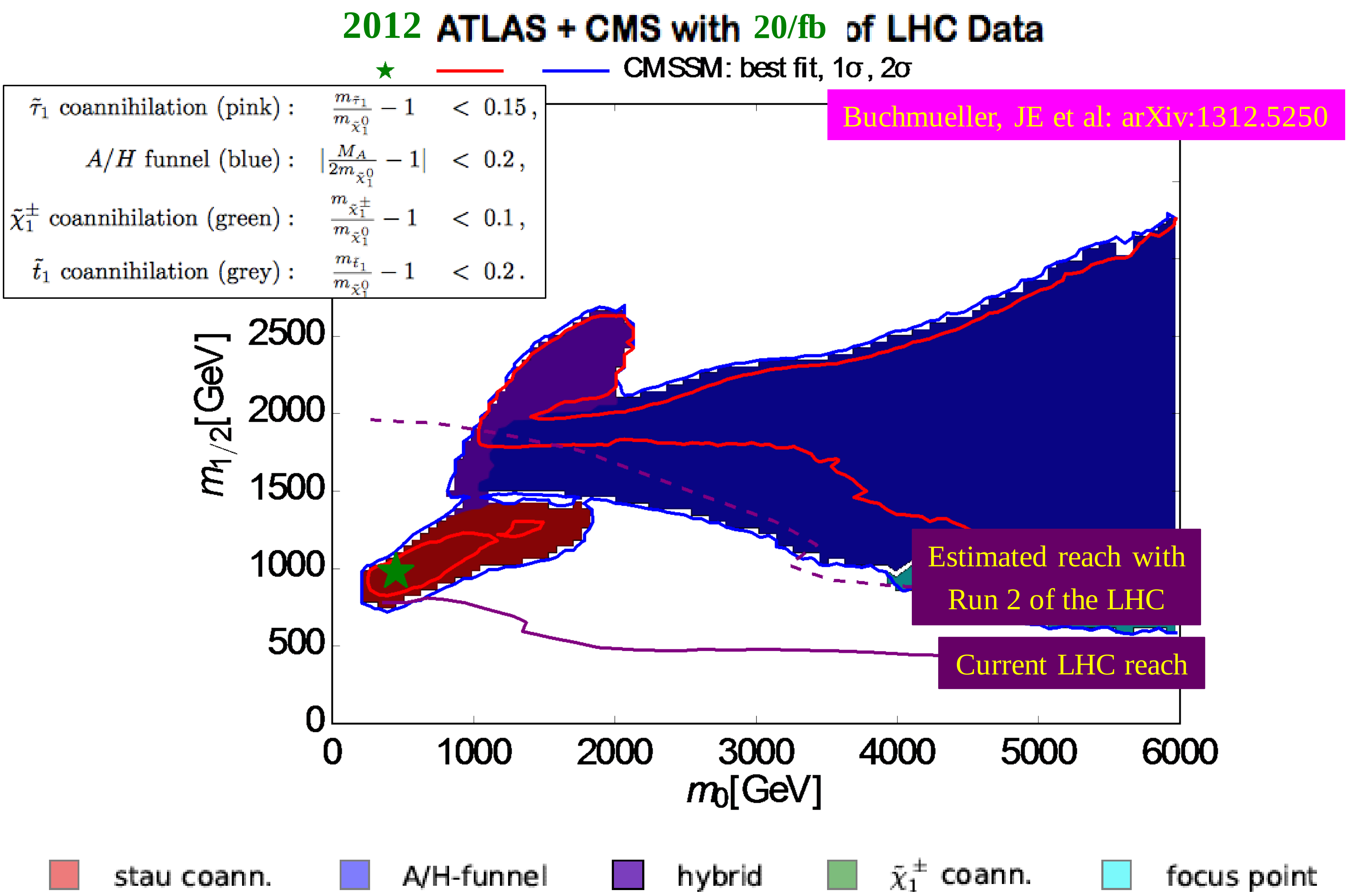
LHC MET searches

g_μ - 2



Contributions to global χ^2 from different observables

Dark Matter Density Mechanisms

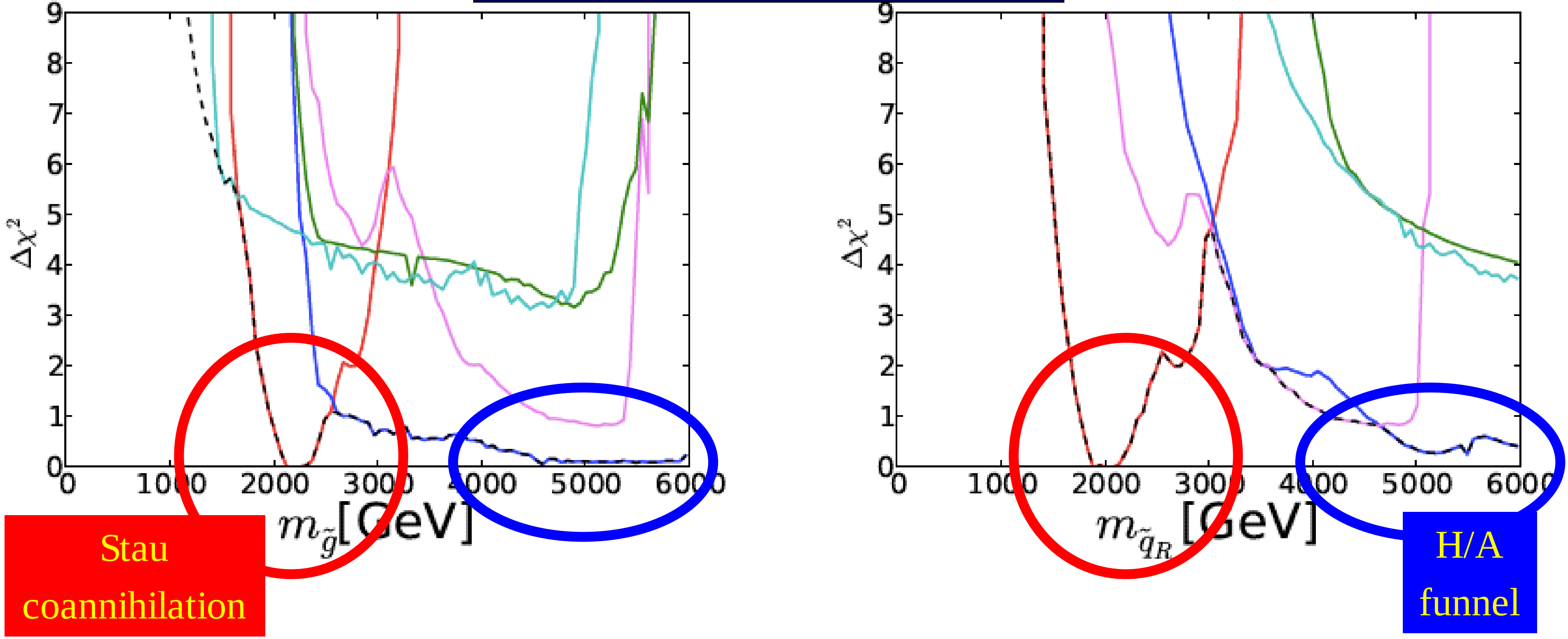


Fits to Supersymmetric Models

2012 ATLAS + CMS with **20/fb** of LHC Data

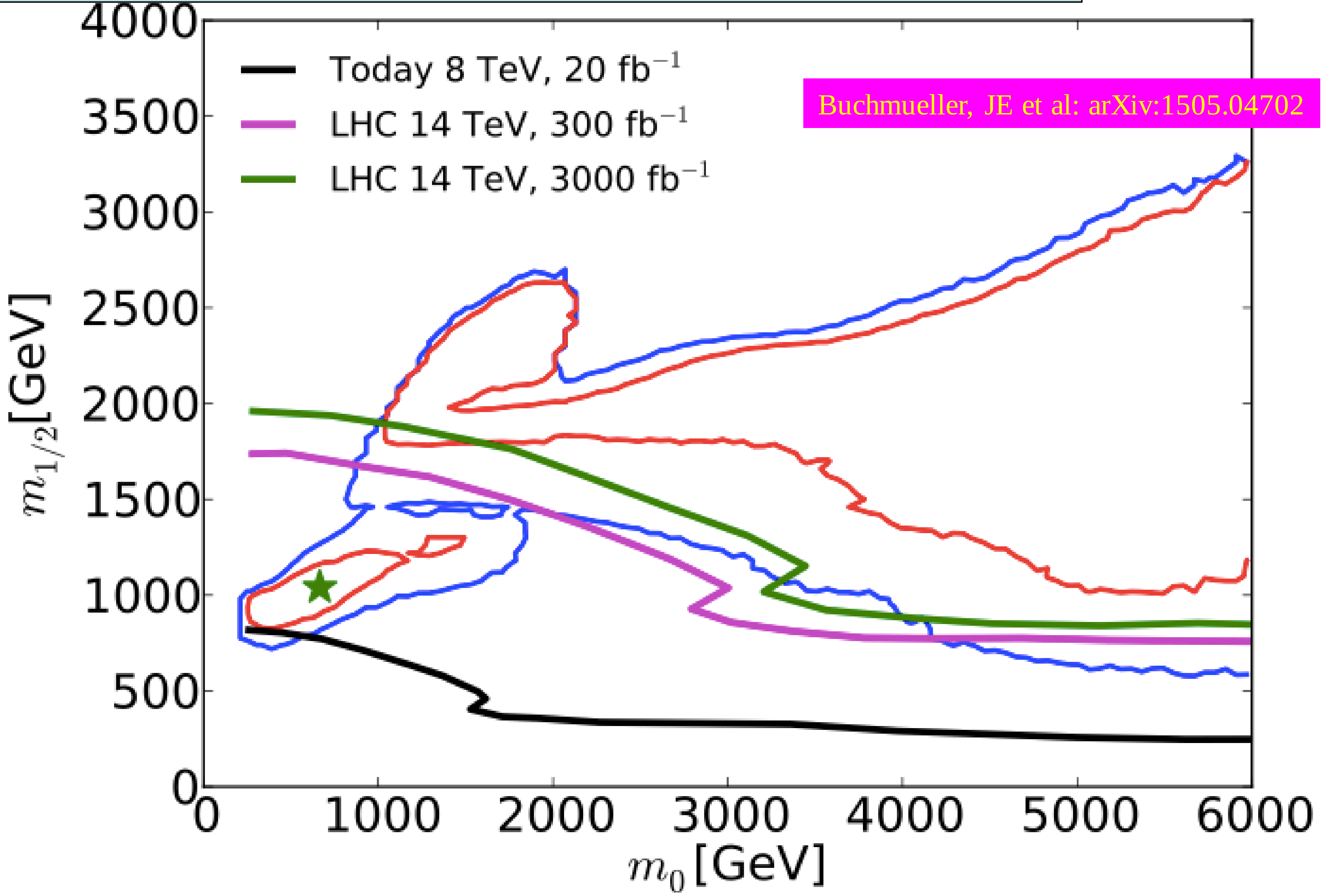
Buchmueller, JE et al: arXiv:1312.5250

Gluino and squark masses

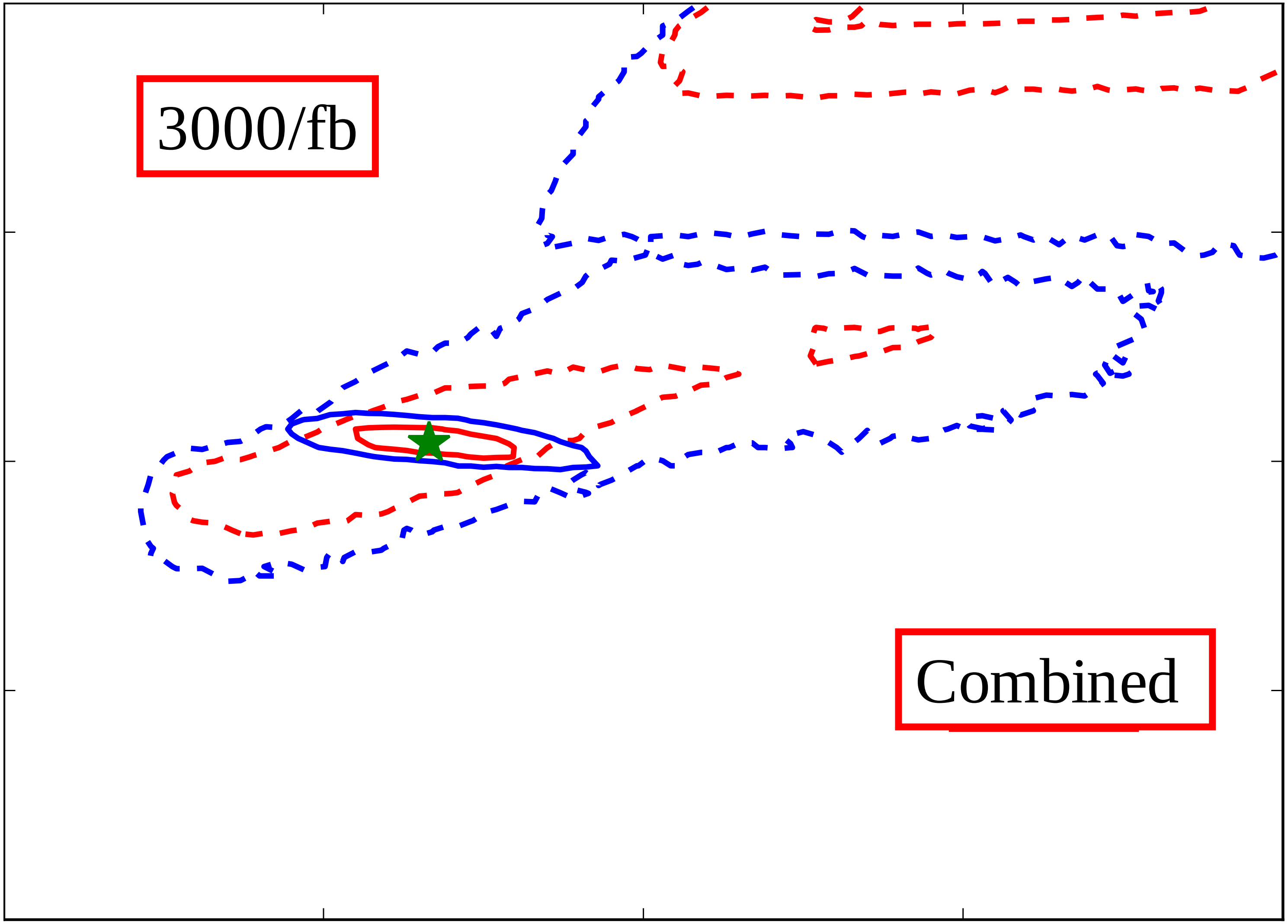


Favoured values of gluino and squark masses significantly above pre-LHC, ~ 2 TeV or more

Probing the CMSSM with the LHC

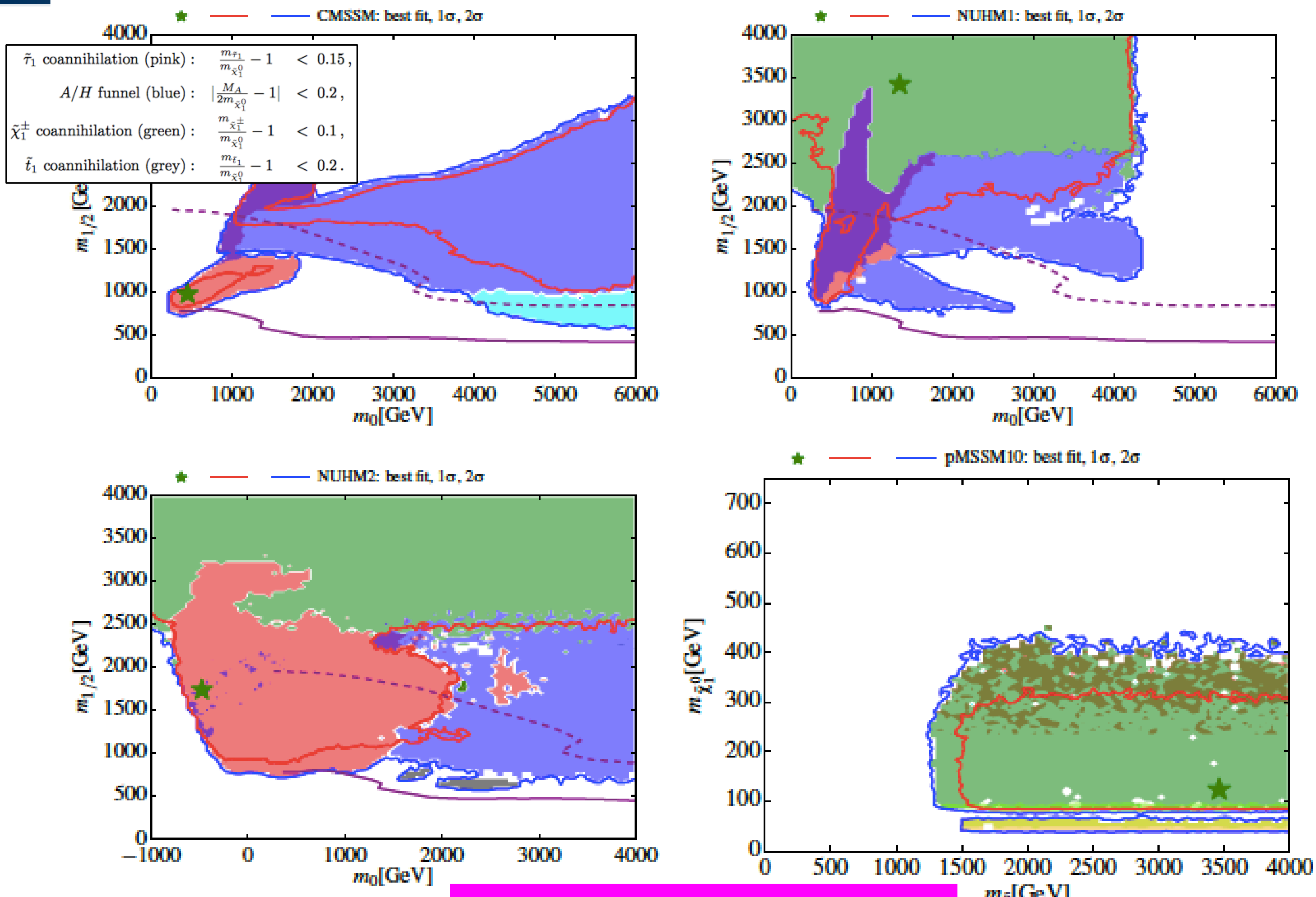


Measuring the CMSSM with the LHC



Buchmueller, JE et al: arXiv:1505.04702

Mechanisms in CMSSM, pMSSM10, NUHM1/2,



Bagnaschi, JE et al: arXiv:1507.xxxxx

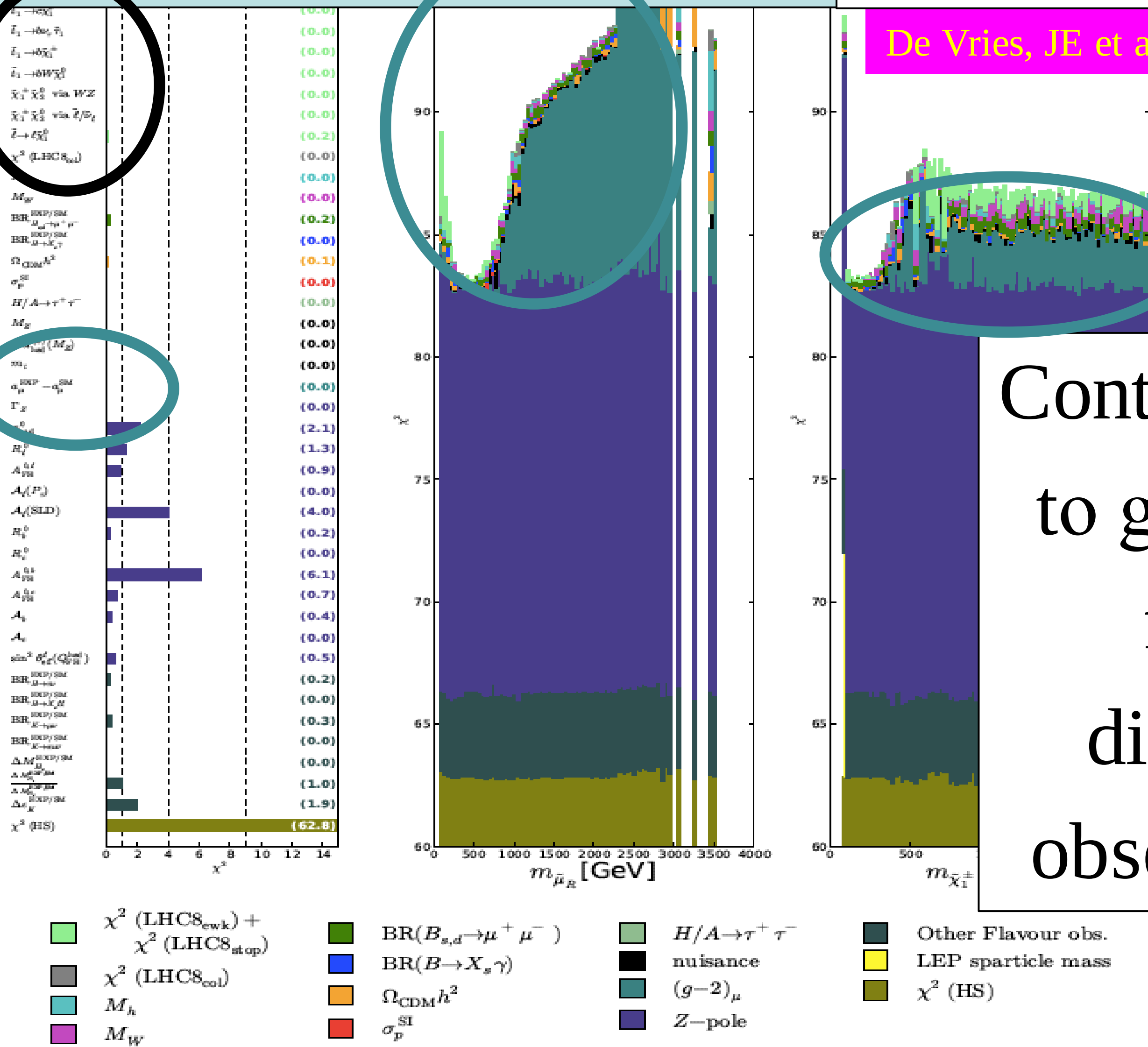
Phenomenological MSSM (pMSSM10)

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

LHC MET searches

$g_\mu - 2$

De Vries, JE et al: arXiv:1504.03260

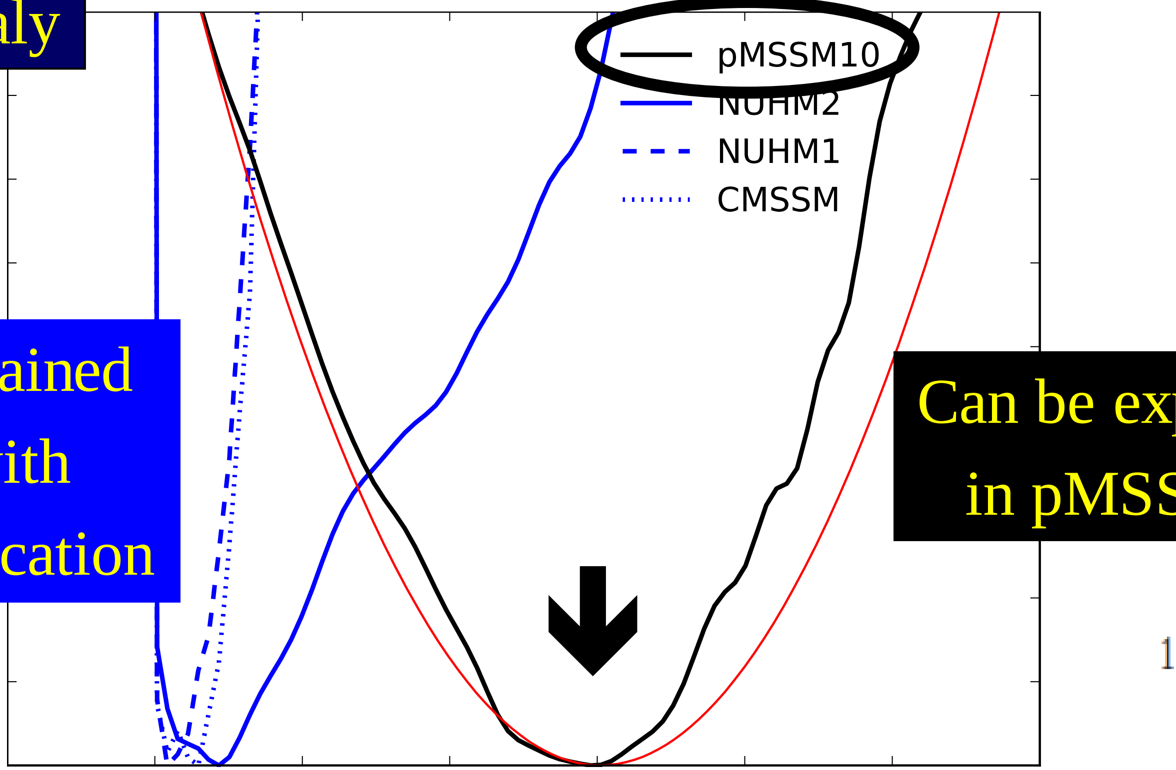


Contributions to global χ^2 from different observables

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

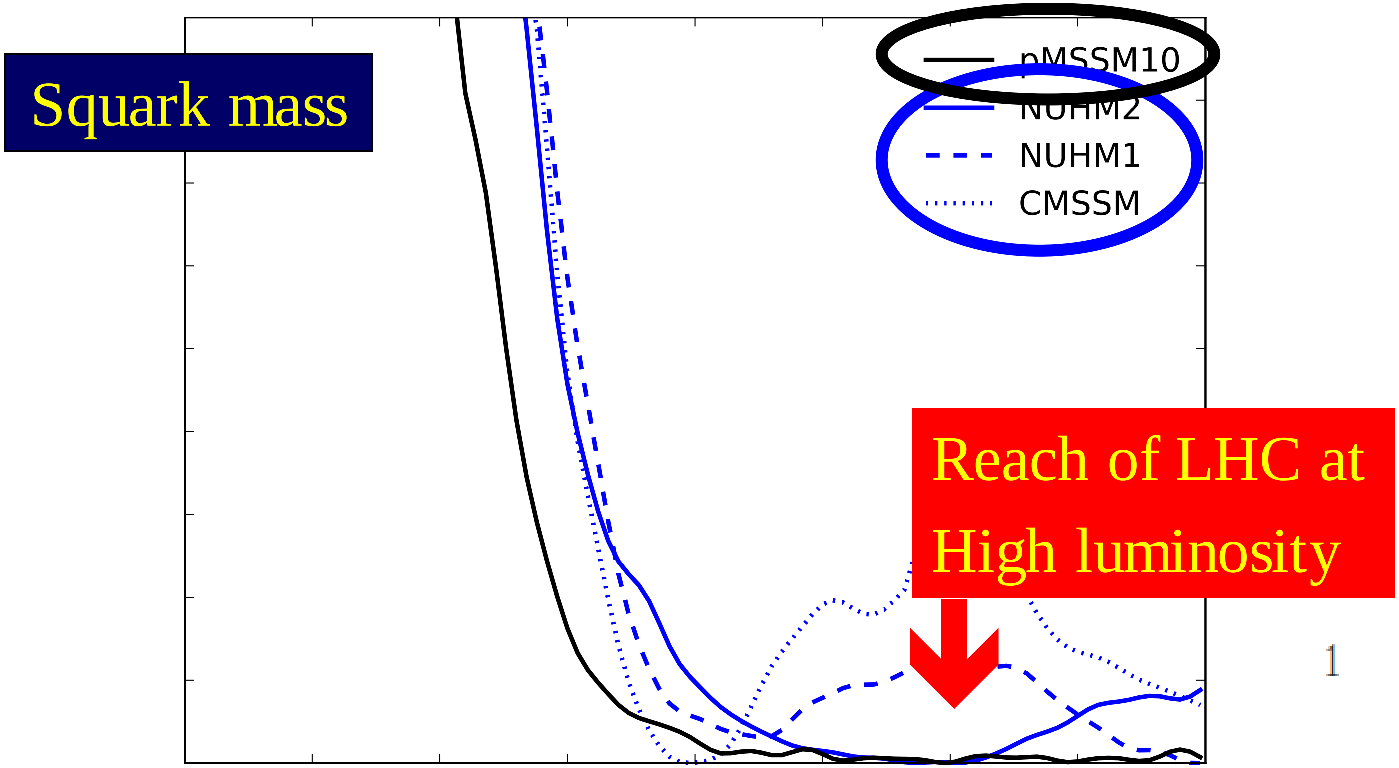
Can be explained in pMSSM10

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

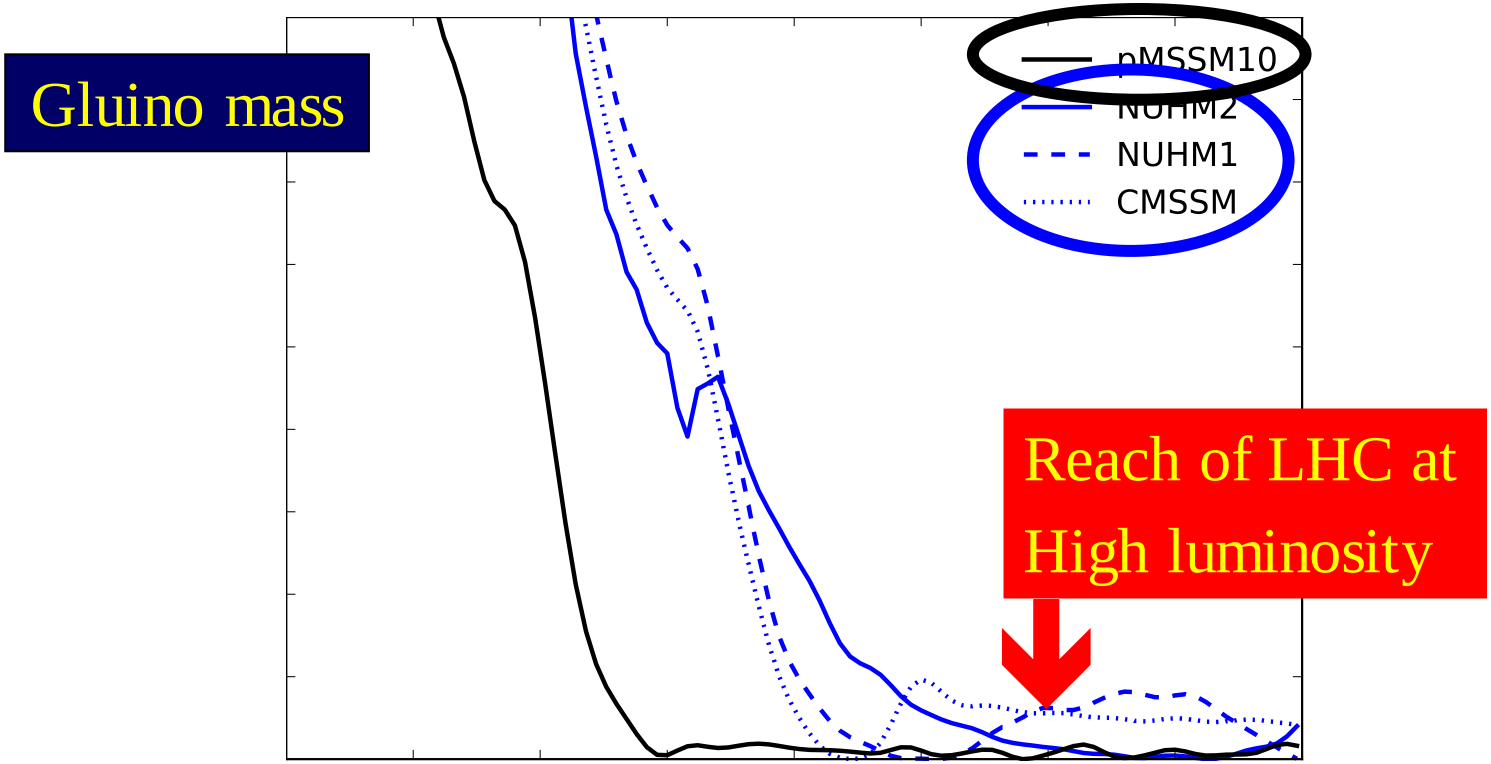


De Vries, JE et al: arXiv:1504.03260

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

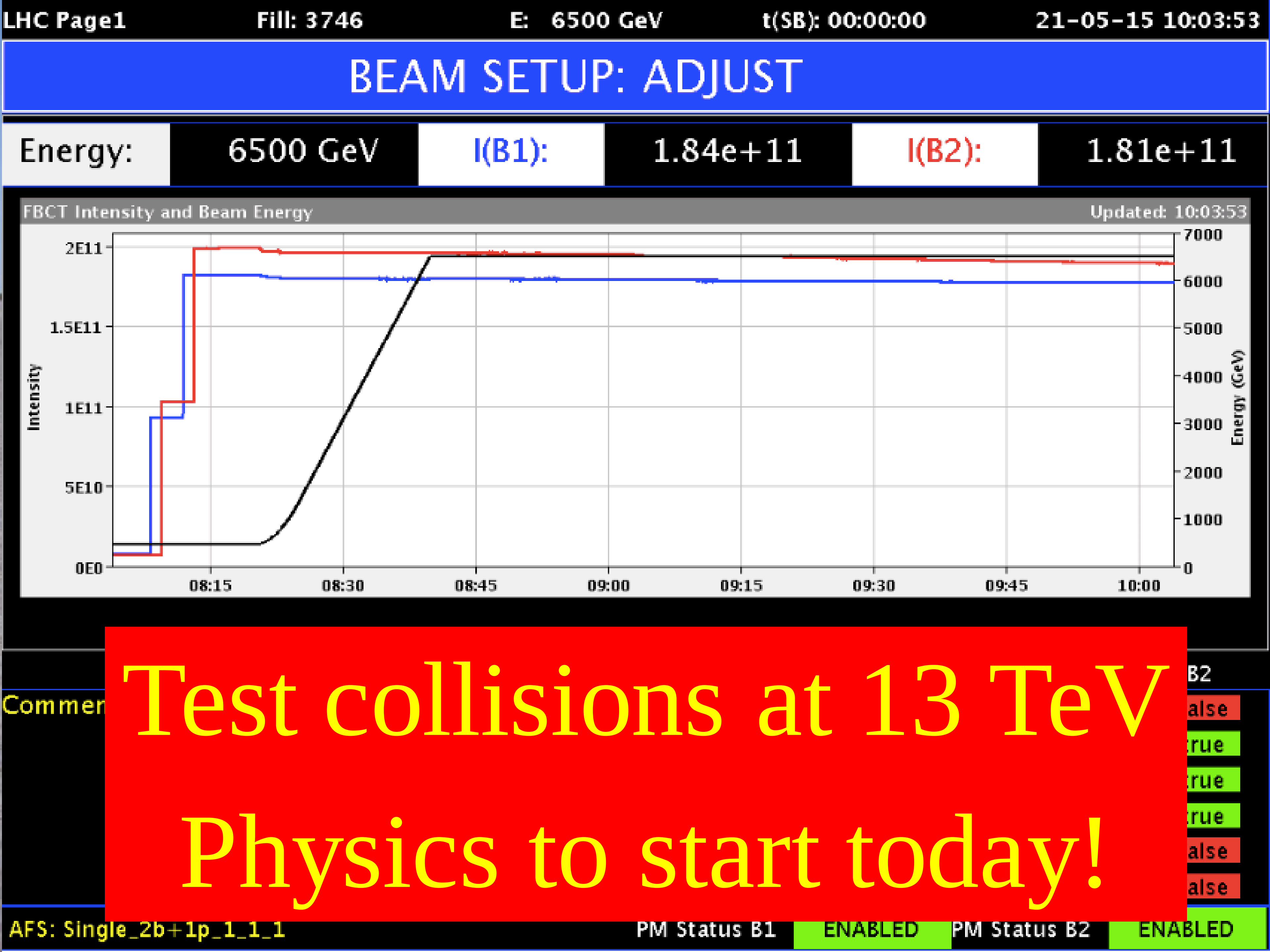
Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data



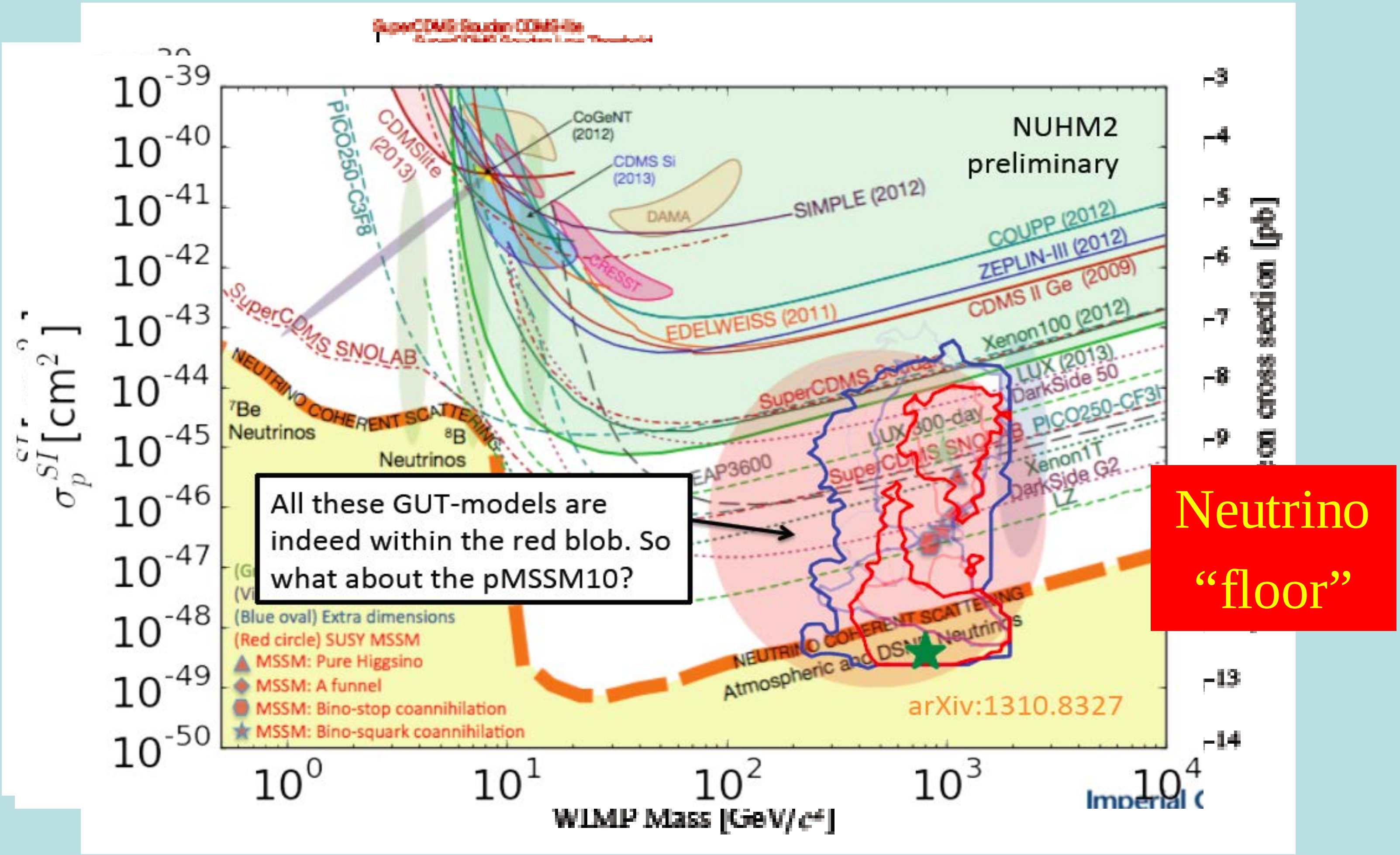
De Vries, JE et al: arXiv:1504.03260

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


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
Energy (GeV)
7000
6000
5000
4000
3000
2000
1000
0
08:15
08:30
08:45
09:00
09:15
09:30
09:45
10:00
Test collisions at 13 TeV
Physics to start today!
AFS: Single_2b+1p_1_1_1
PM Status B1
ENABLED
PM Status B2
ENABLED

Direct Dark Matter Searches

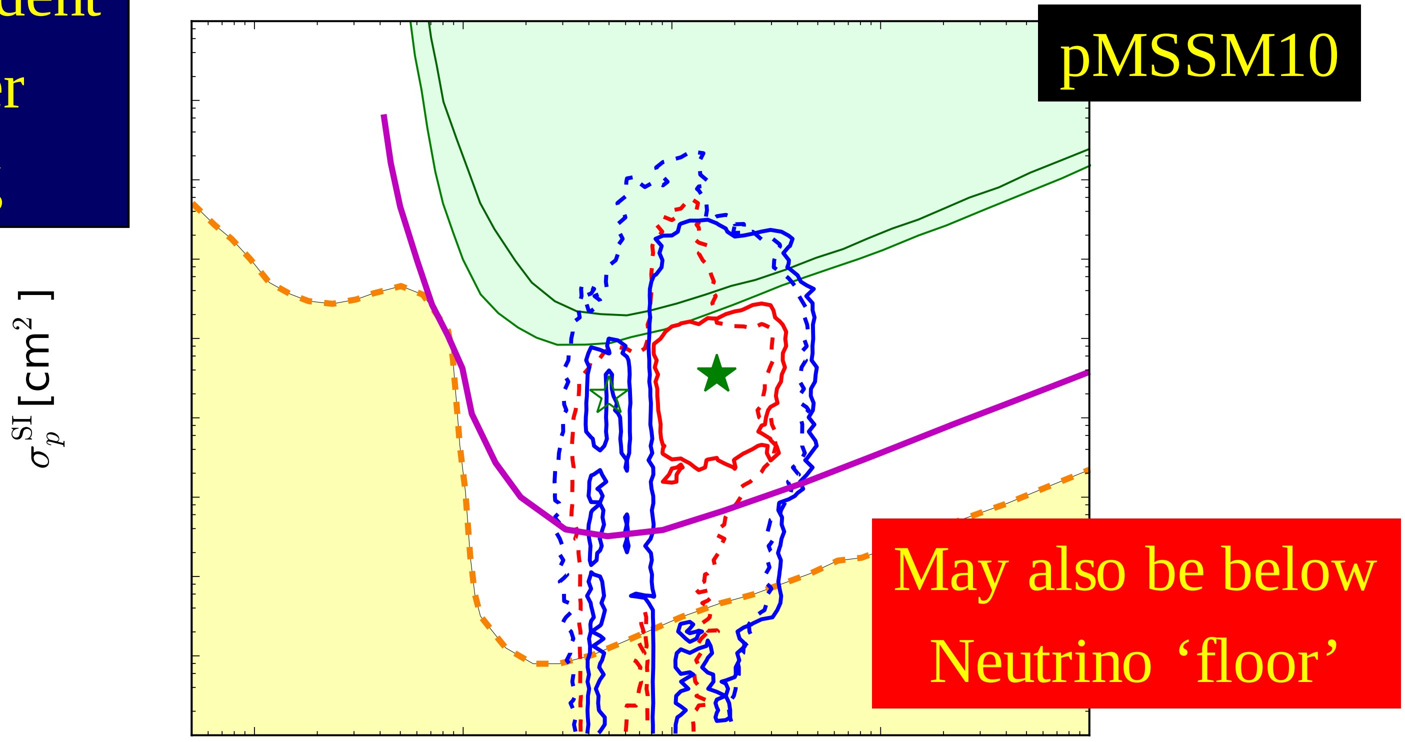
- Compilation of present and future sensitivities



Direct Dark Matter Search: pMSSM10

2012 ATLAS + CMS with 20/fb of LHC Data

Spin-independent dark matter scattering

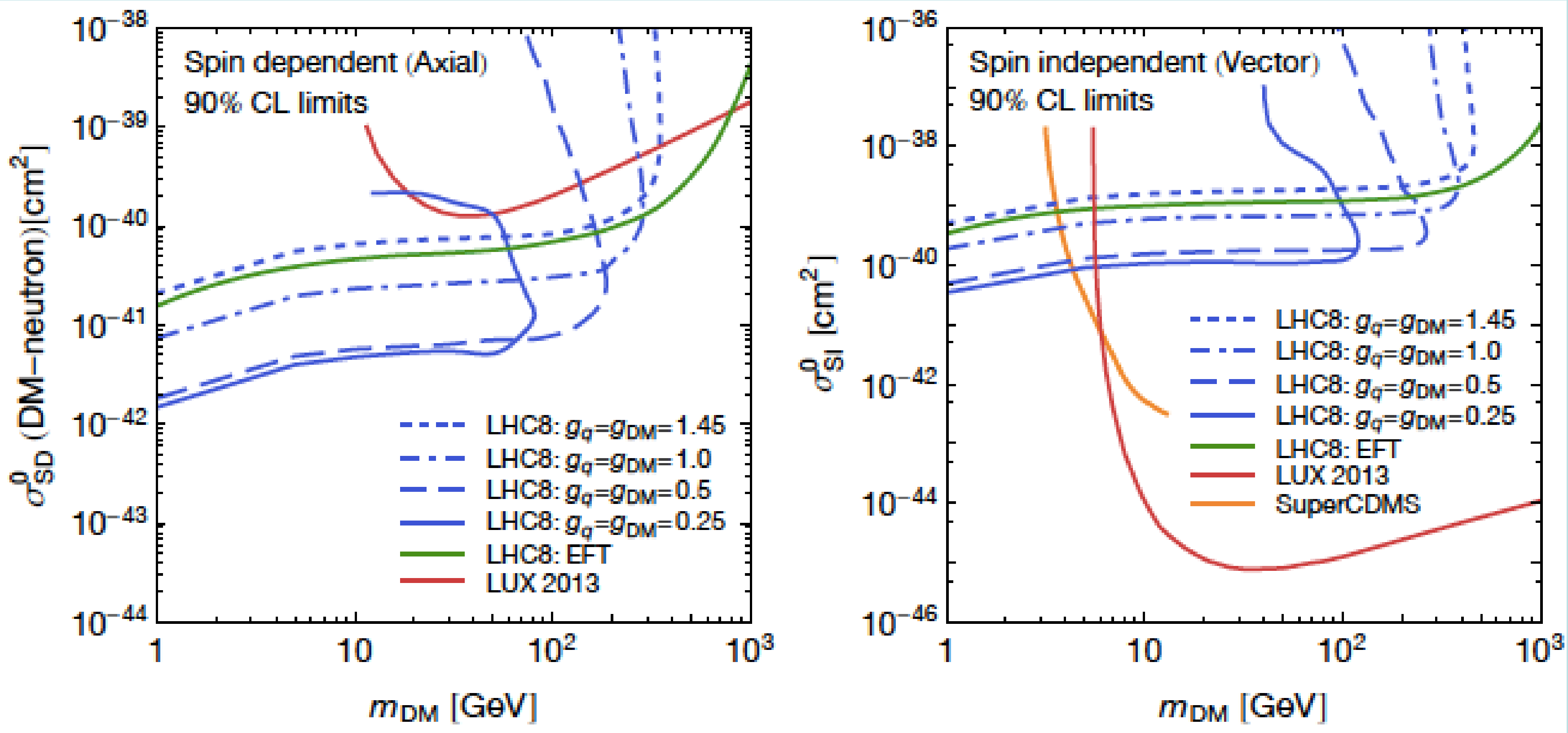


De Vries, JE et al: arXiv:1504.03260

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

LHC vs Dark Matter Searches

- Compilation of present "mono-jet" sensitivities



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

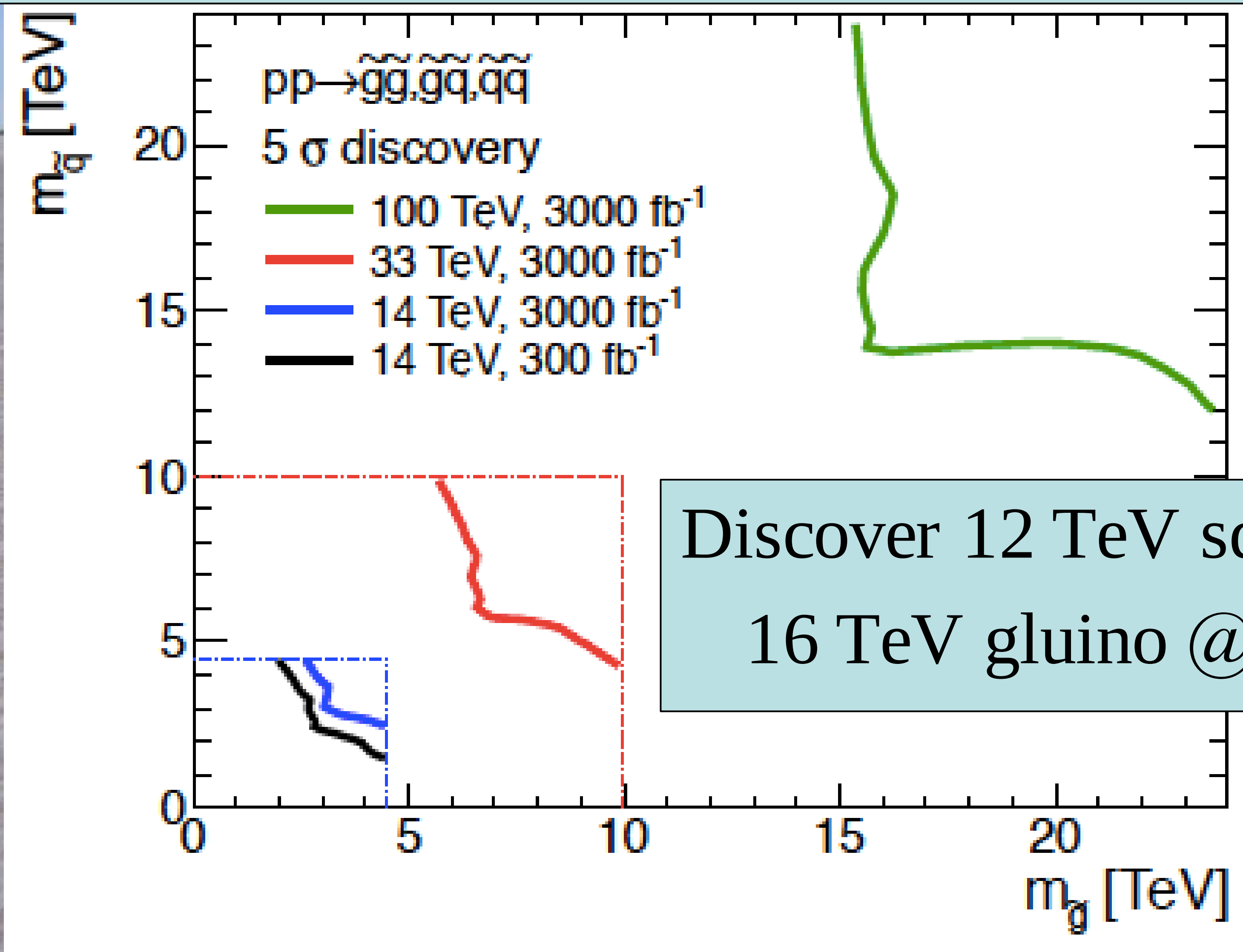
Buchmueller, Dolan, Malik & McCabe: arXiv:1407.8257; Malik, McCabe, …, JE et al: arXiv:1409.4075

Future Circular Colliders

The vision:

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

Squark-Gluino Plane

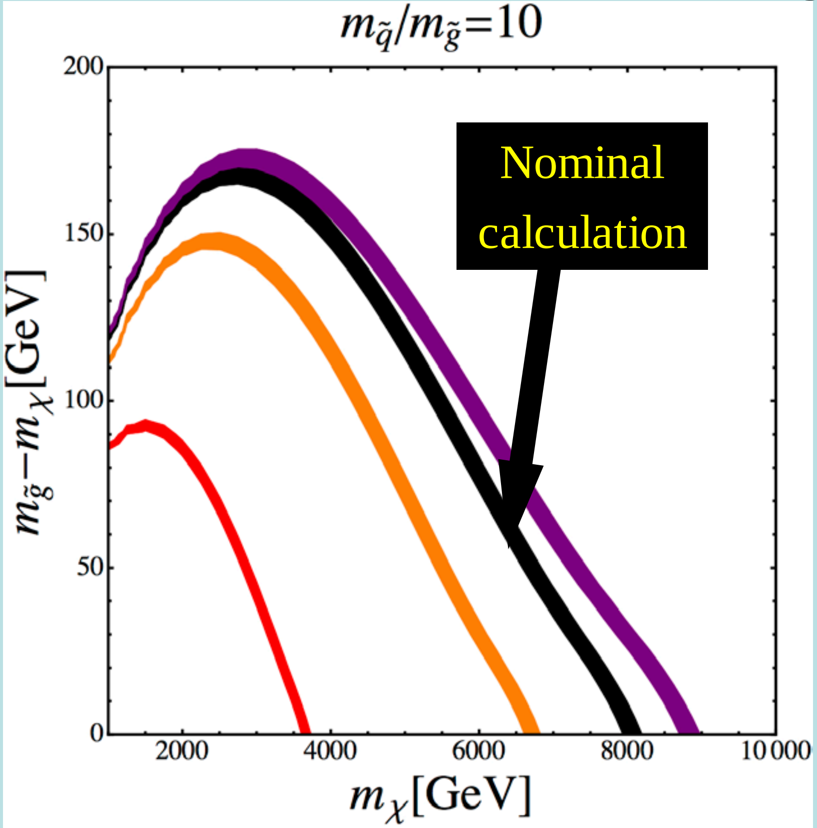


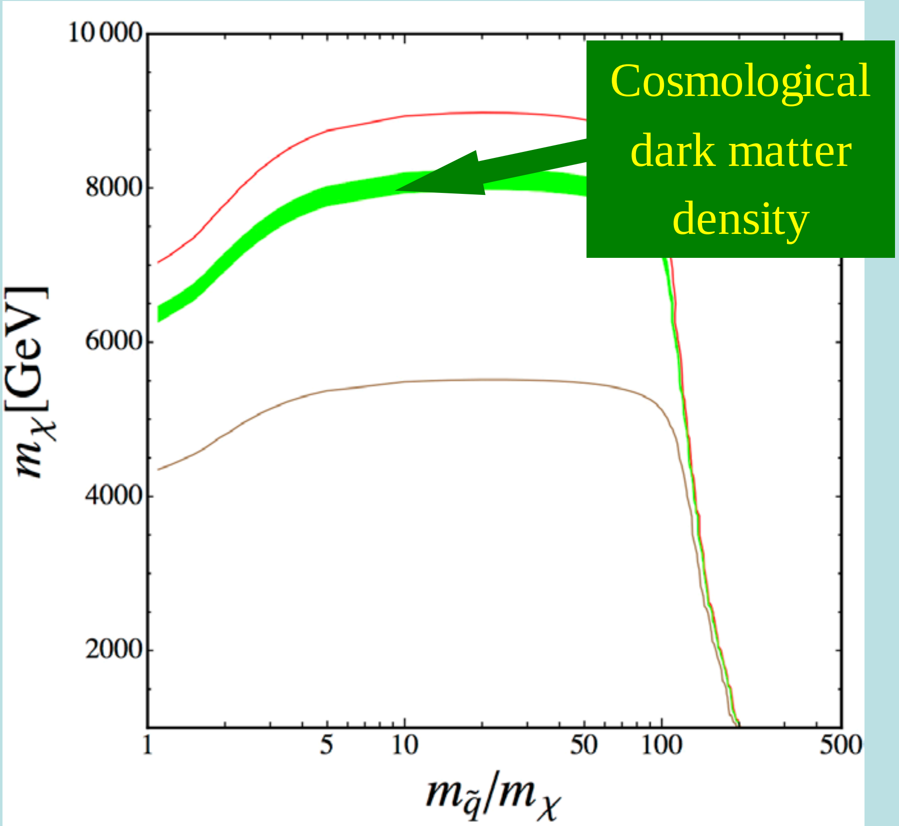
Discover 12 TeV squark,

16 TeV gluino @ 5σ

How Heavy could Dark Matter be in pMSSM?

- Largest possible mass in pMSSM is along gluino coannihilation strip: $m_{gluino} \sim m_{neutralino}$





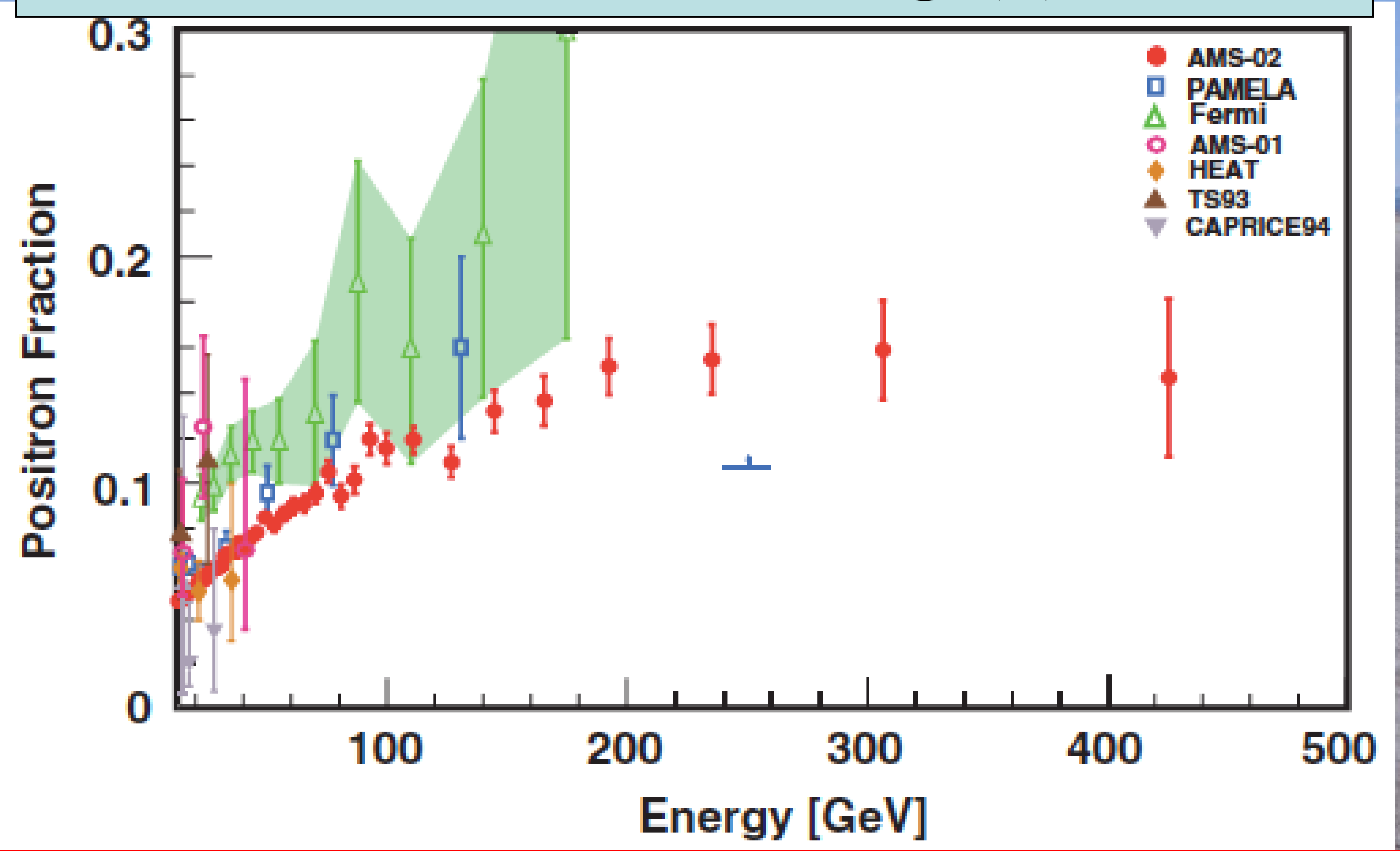
- **Extends to $m_{\chi} = m_{gluino} \sim$ 8 TeV**

JE, Luo & Olive: arXiv: 1503.07142

Summary

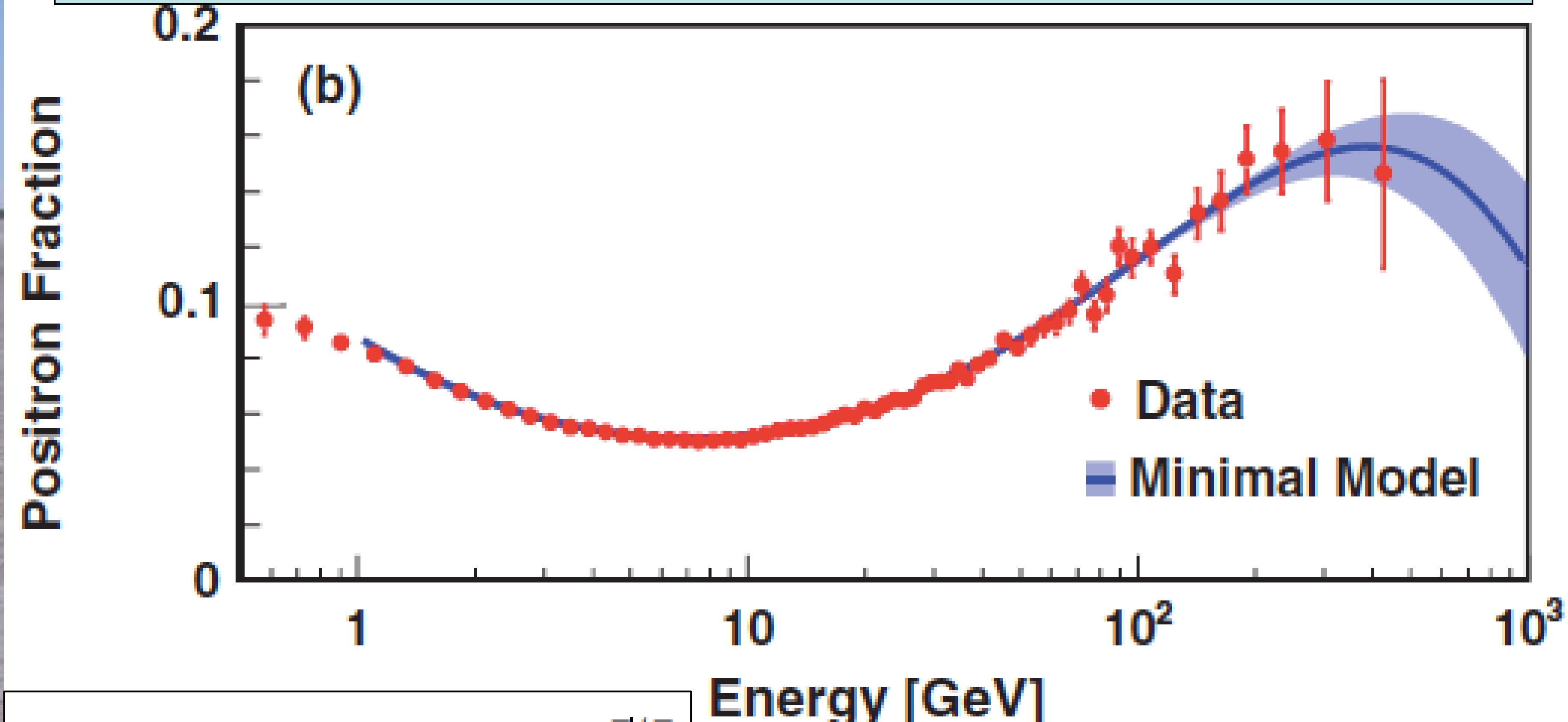
- Rumours of the death of SUSY are exaggerated
  - Still the best framework for TeV-scale physics
- Still the best candidate for cold dark matter
- Simple models (CMSSM, etc.) under pressure
  - More general models quite healthy
- Good prospects for LHC Run 2 and for direct dark matter detection
  -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

Positron Fraction Rising (?) with E



Dark Matter? Galactic cosmic rays? Local sources?

AMS Fit with 2-Component Model



$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

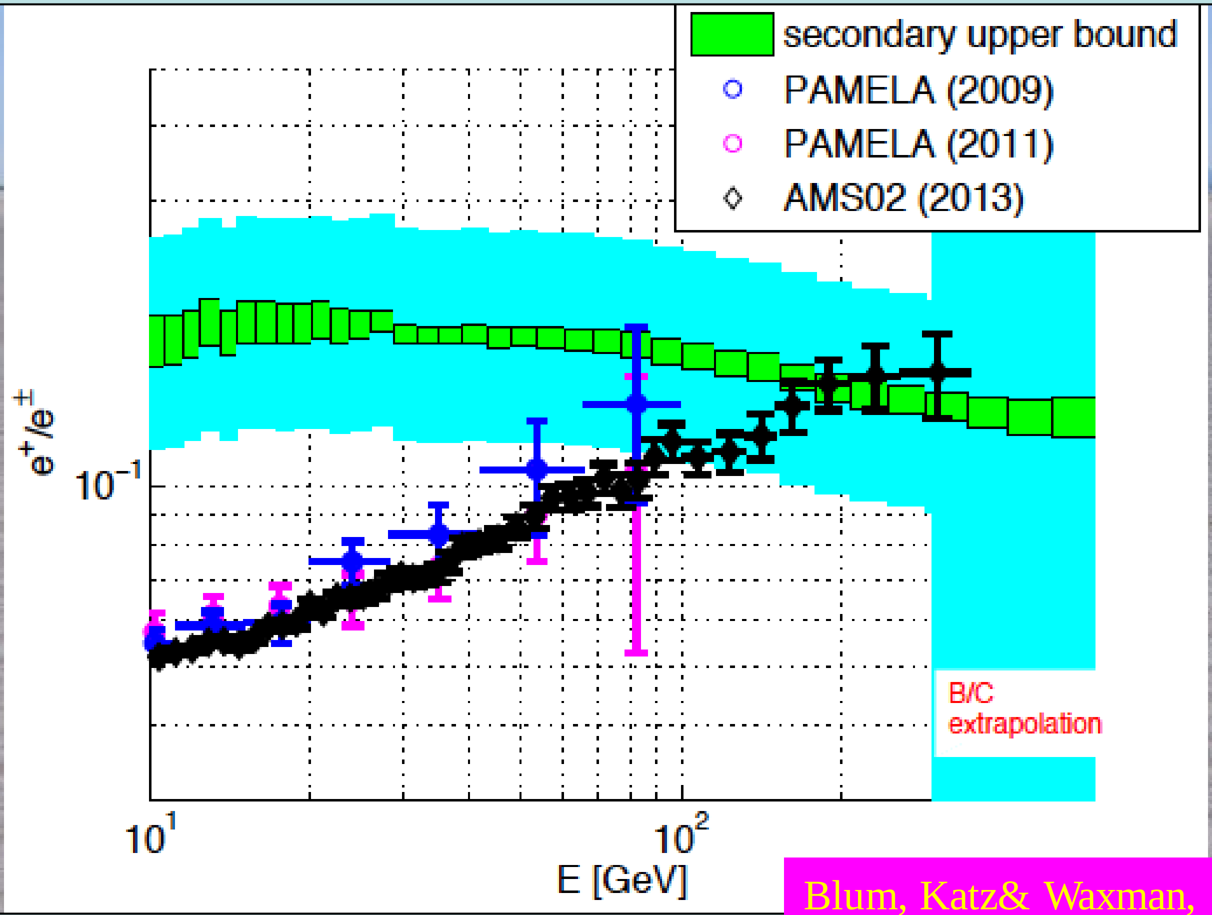
$1/E_s = 1.84 \pm 0.58\ \text{TeV}^{-1}$

$C_{e^+}/C_{e^-} = 0.091 \pm 0.001,\quad C_s/C_{e^-} = 0.0061 \pm 0.0009$

$\gamma_{e^-} - \gamma_{e^+} = -0.56 \pm 0.03,$ and $\gamma_{e^-} - \gamma_s = 0.72 \pm 0.04$

Could be galactic cosmic rays + local sources?

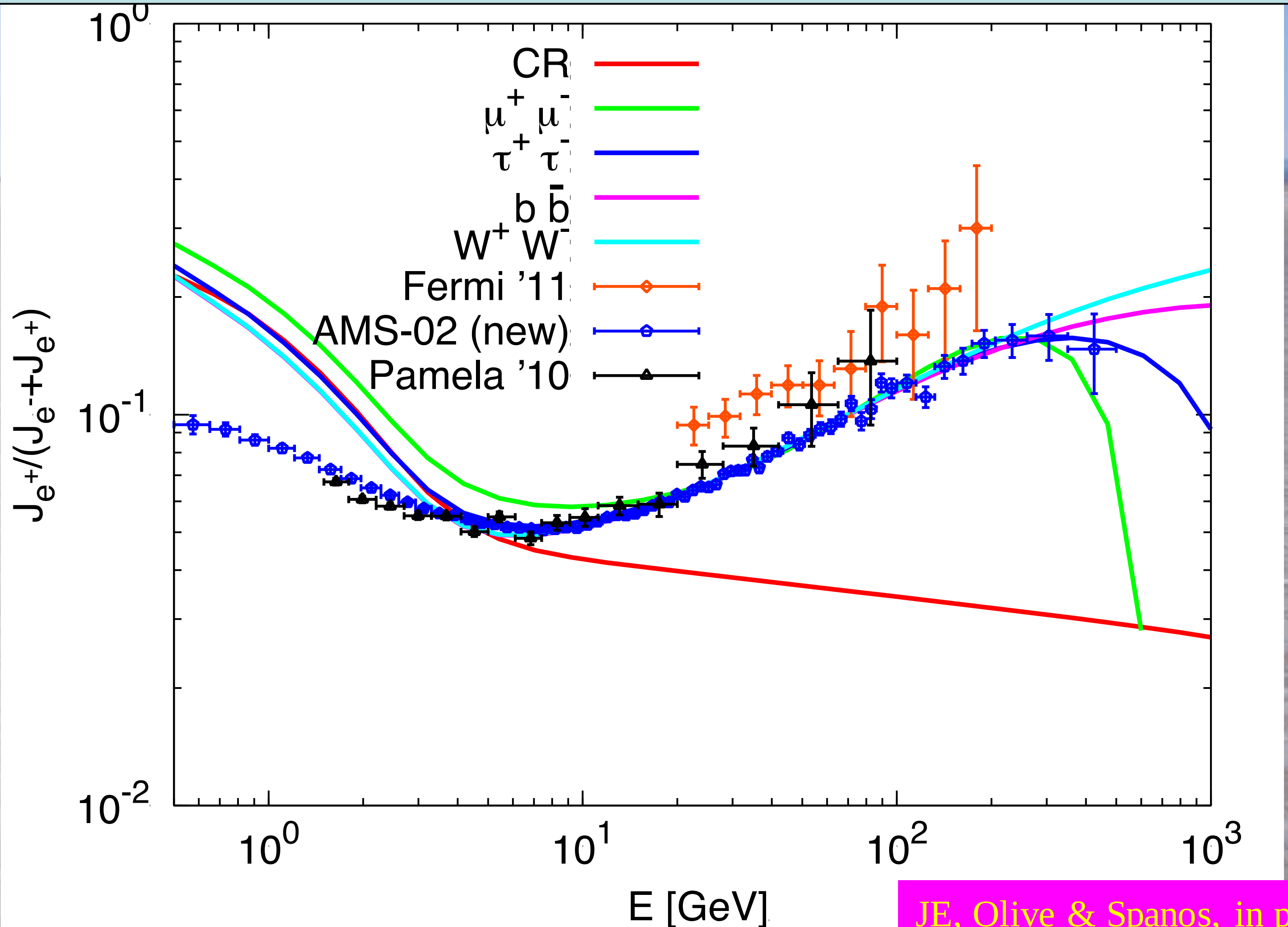
Galactic Cosmic Rays Alone?



Blum, Katz& Waxman, arXiv:1305.1324

Rising positron fraction compatible with model-independent bound on secondary e^+

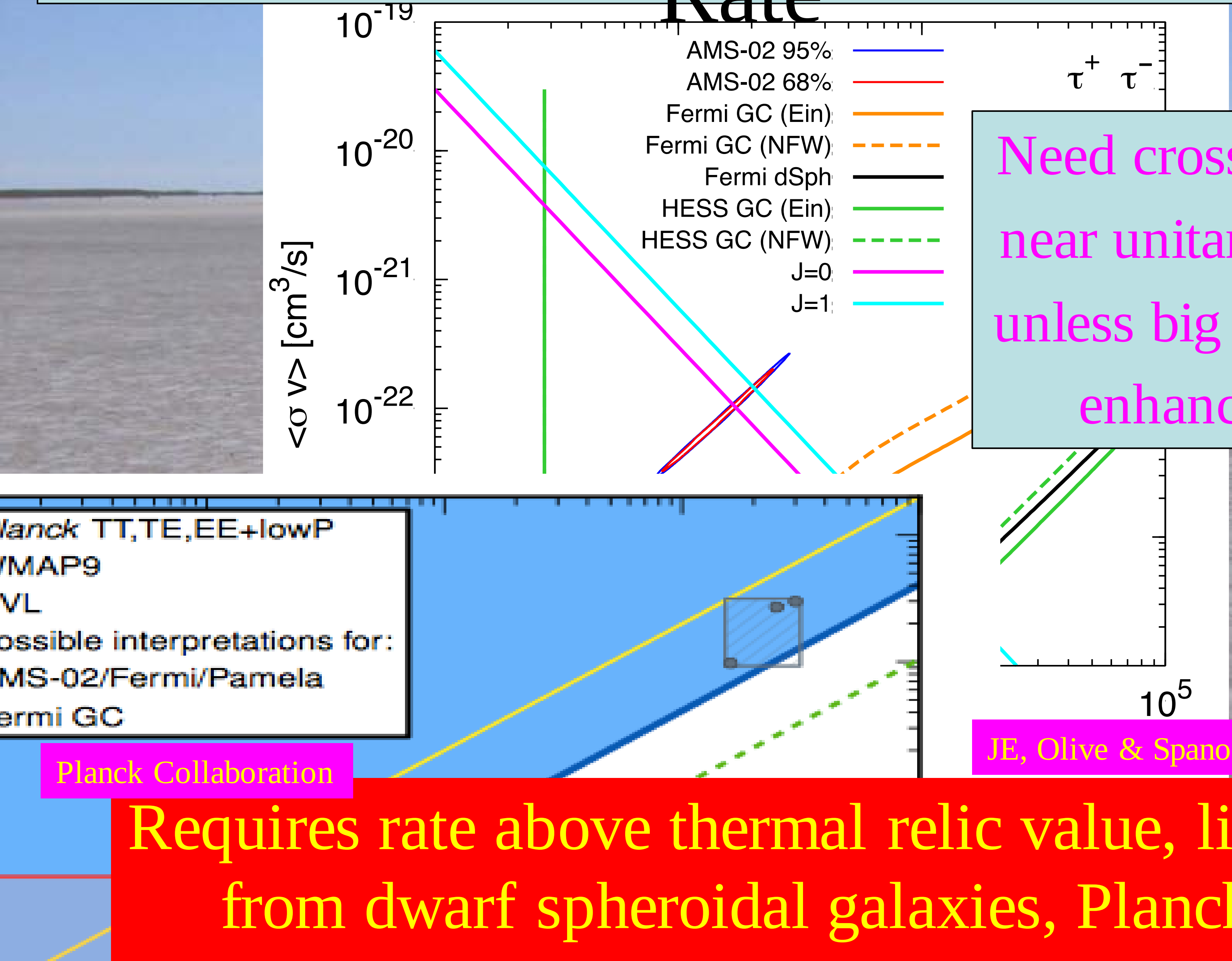
Dark Matter Fits to AMS Positron Data



JE, Olive & Spanos, in preparation

Fit with modified GALPROP parameters

$\tau^+\tau^-$ Fit needs Large Annihilation Rate



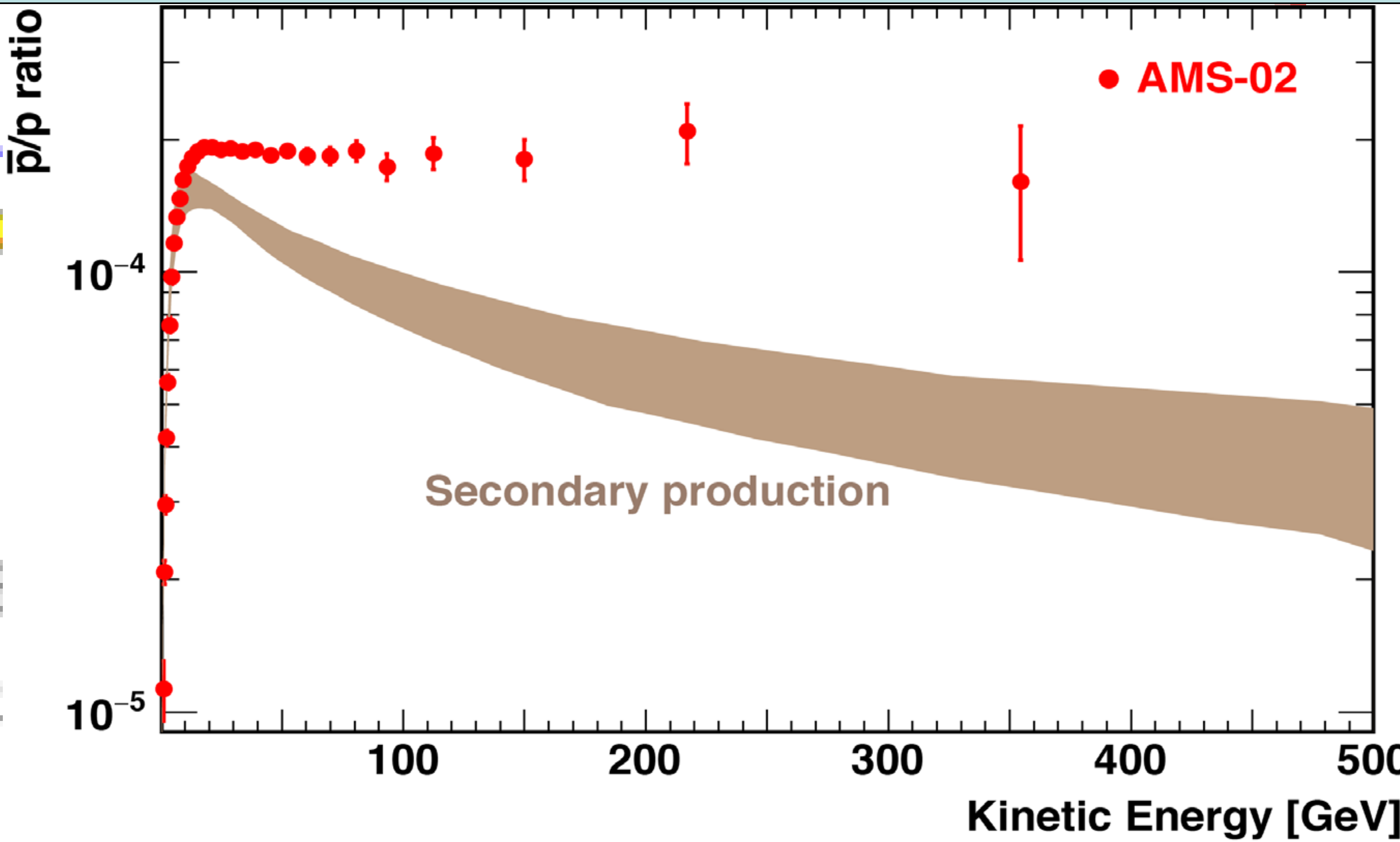
Need cross-section near unitarity limit unless big clumping enhancement

Planck Collaboration

JE, Olive & Spanos, in preparation

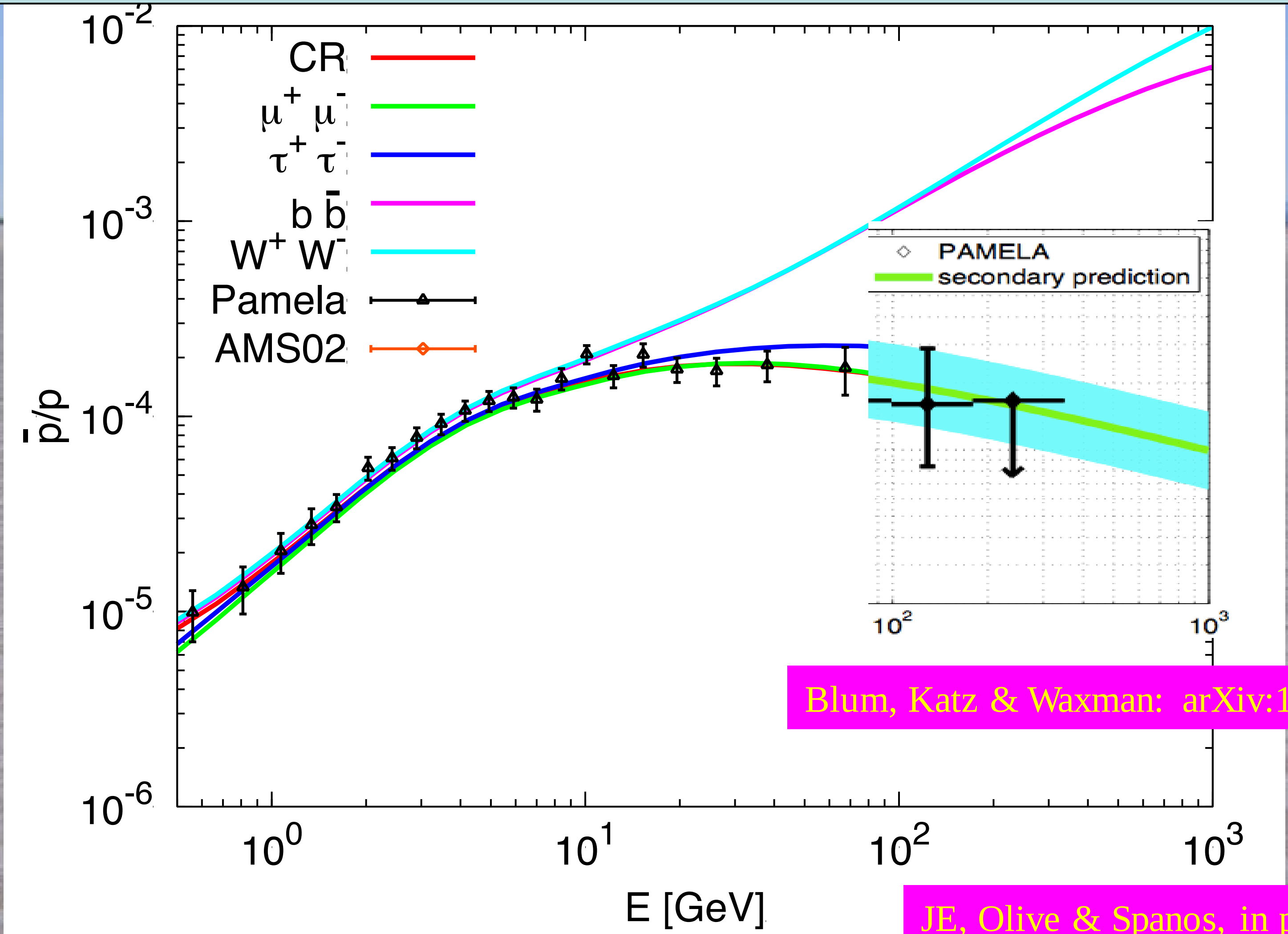
Requires rate above thermal relic value, limits from dwarf spheroidal galaxies, Planck

New Antiproton/Proton Ratio



Above previous estimate of secondary production

Antiproton/Proton Ratio

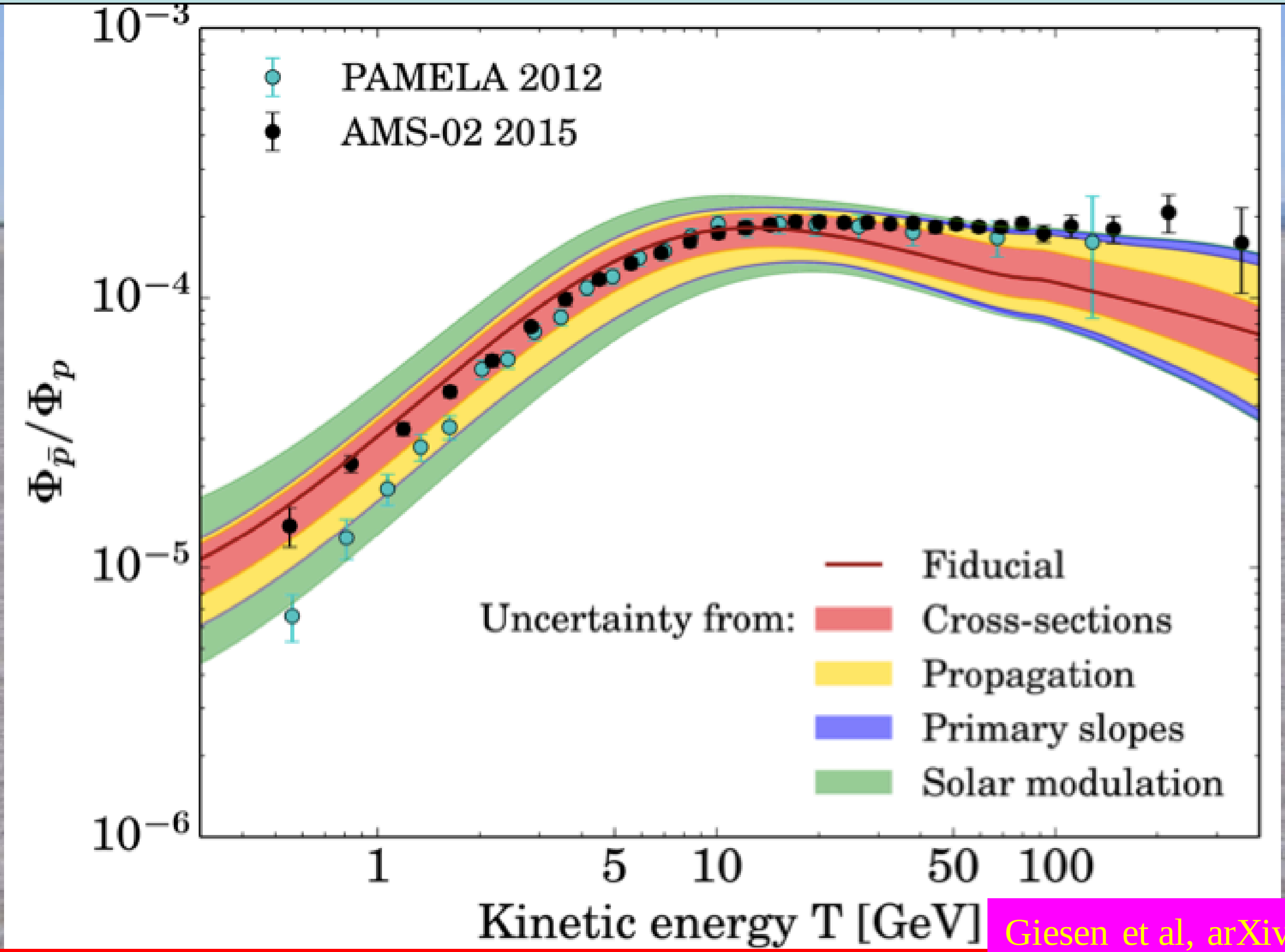


Blum, Katz & Waxman: arXiv:1305.1324

JE, Olive & Spanos, in preparation

GALPROP can give ~ constant ratio > 150 GeV

Antiproton/Proton Ratio



Giesen et al, arXiv:1504.04274

Secondary production compatible with AMS-02

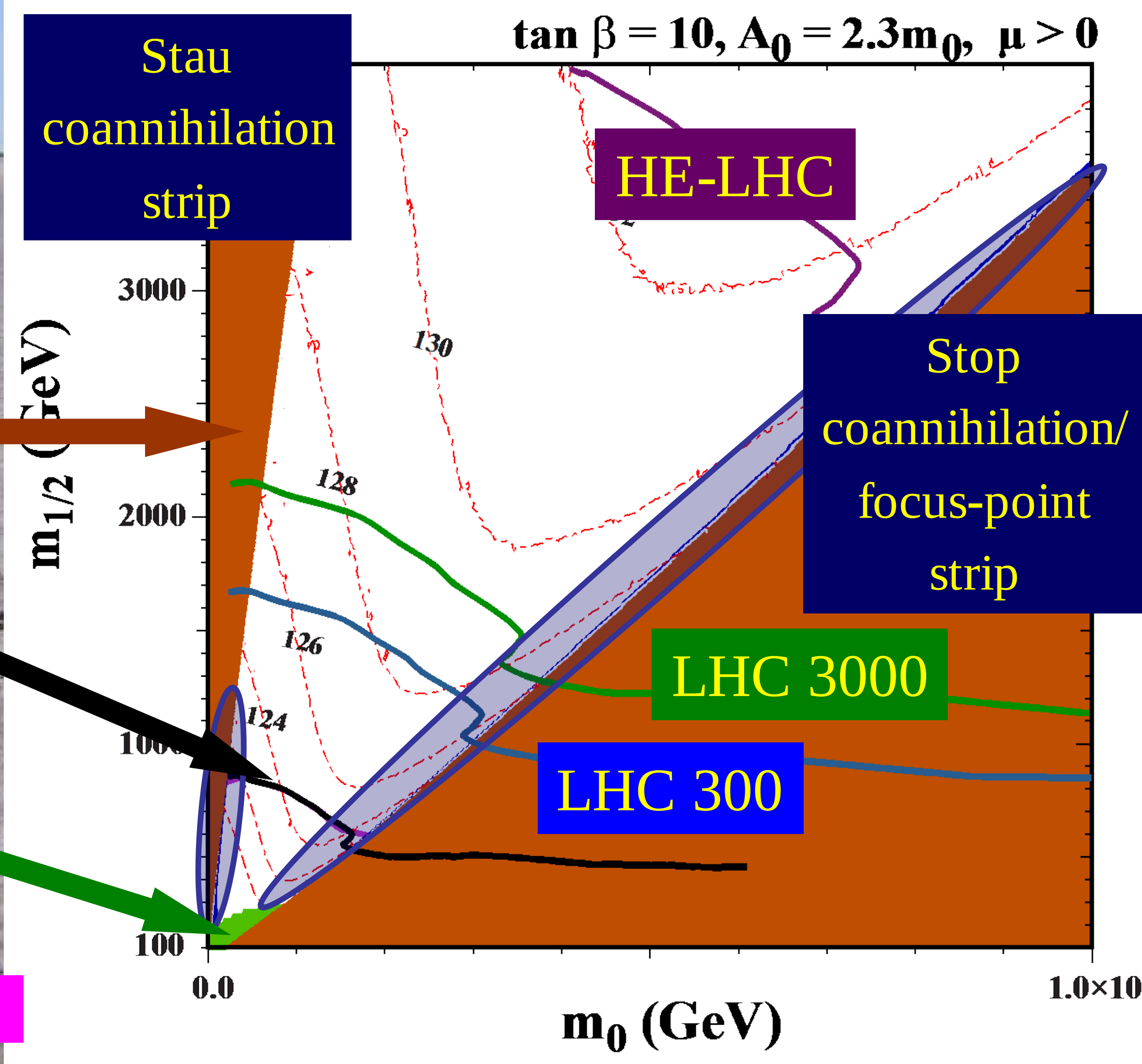
Where May CMSSM be Hiding?

Relic density constraint, assuming neutralino LSP

Excluded because stau or stop LSP

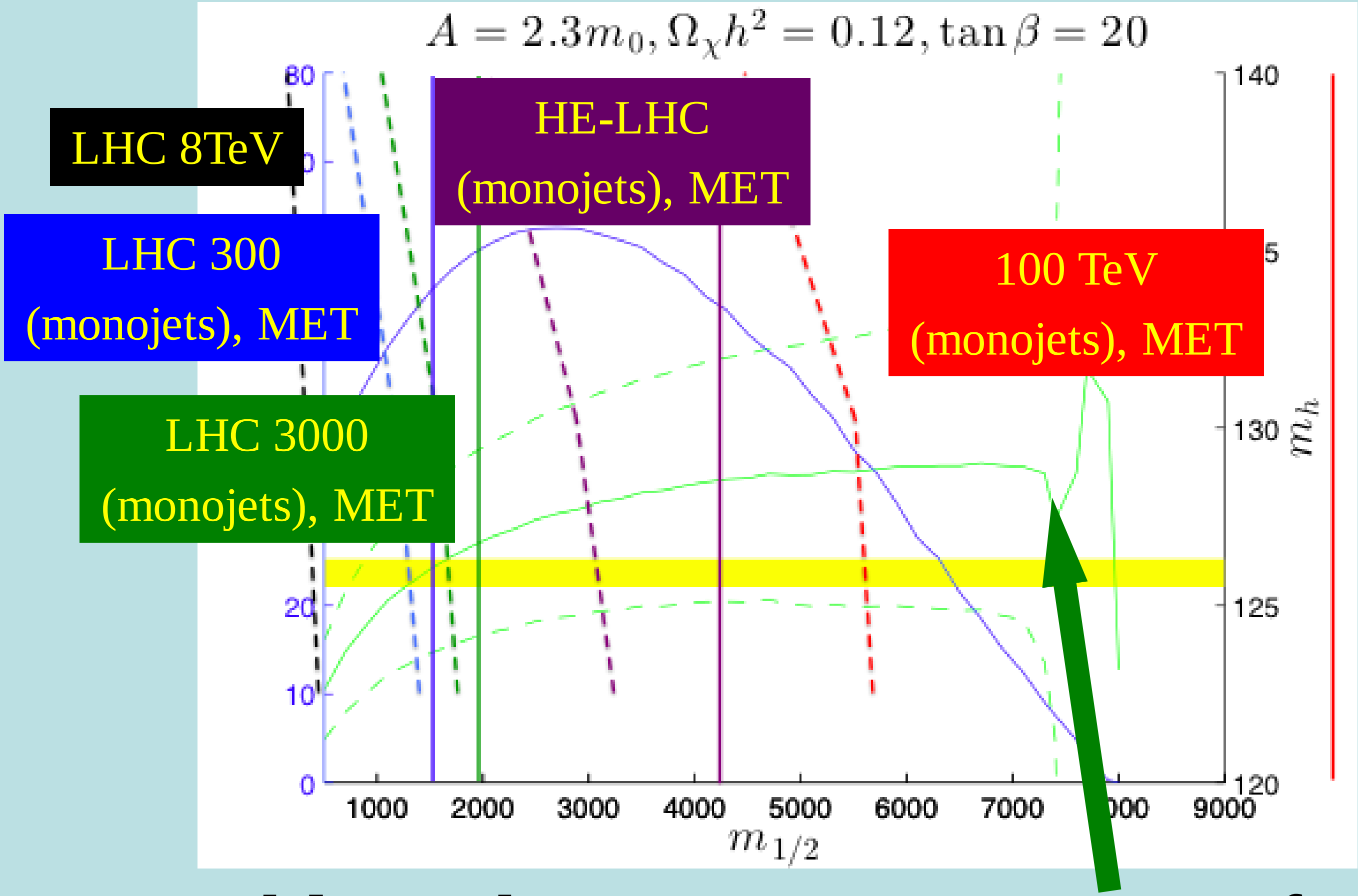
Excluded by ATLAS Jest + MET search

Excluded by $b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$



JE, Olive & Zheng: arXiv:1404.5571

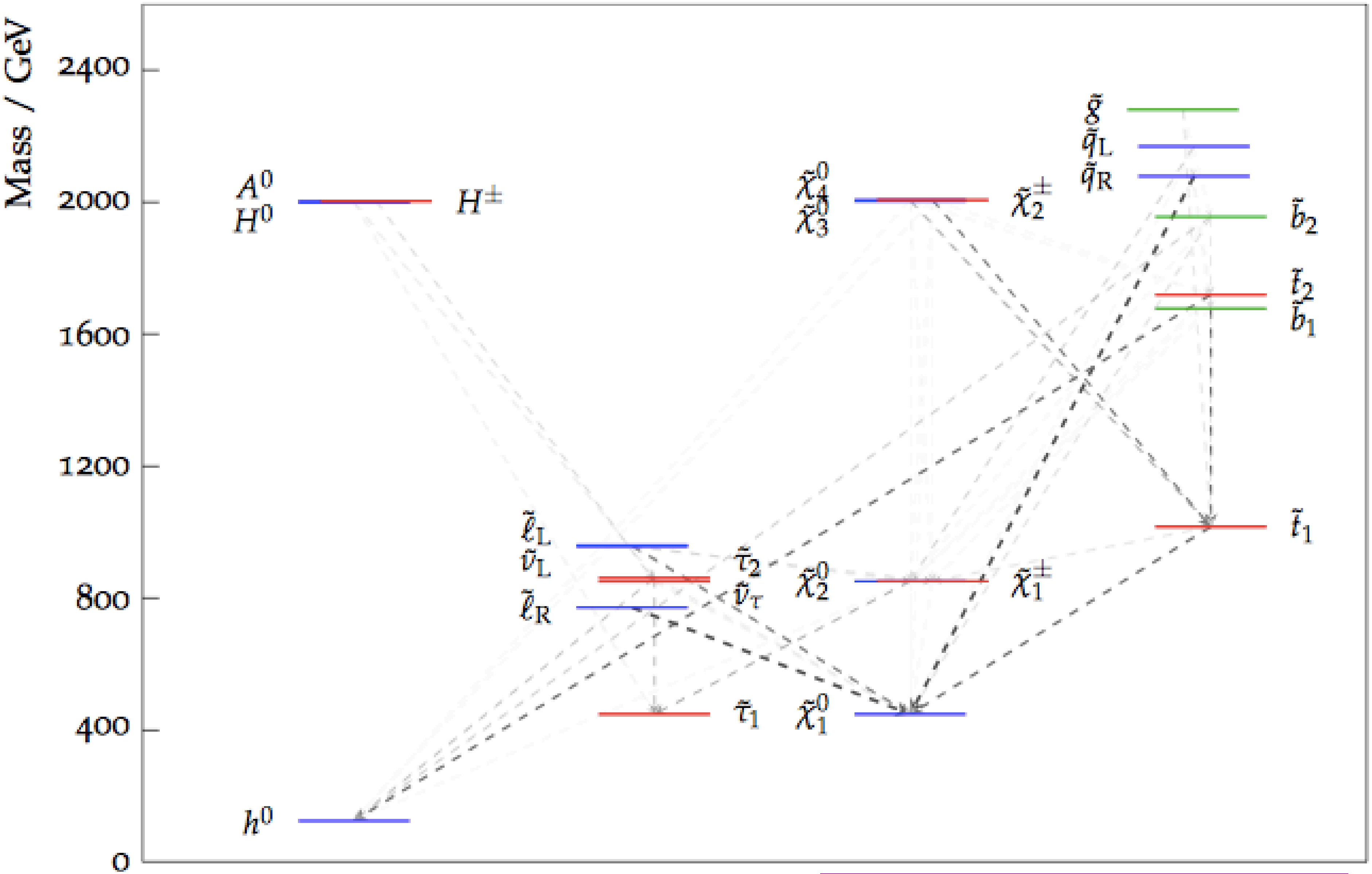
Exploring the **Stop Coannihilation Strip**



- Compatible with LHC measurement of m_h
- May extend to $m_\chi = m_{stop} \sim 6500$ GeV

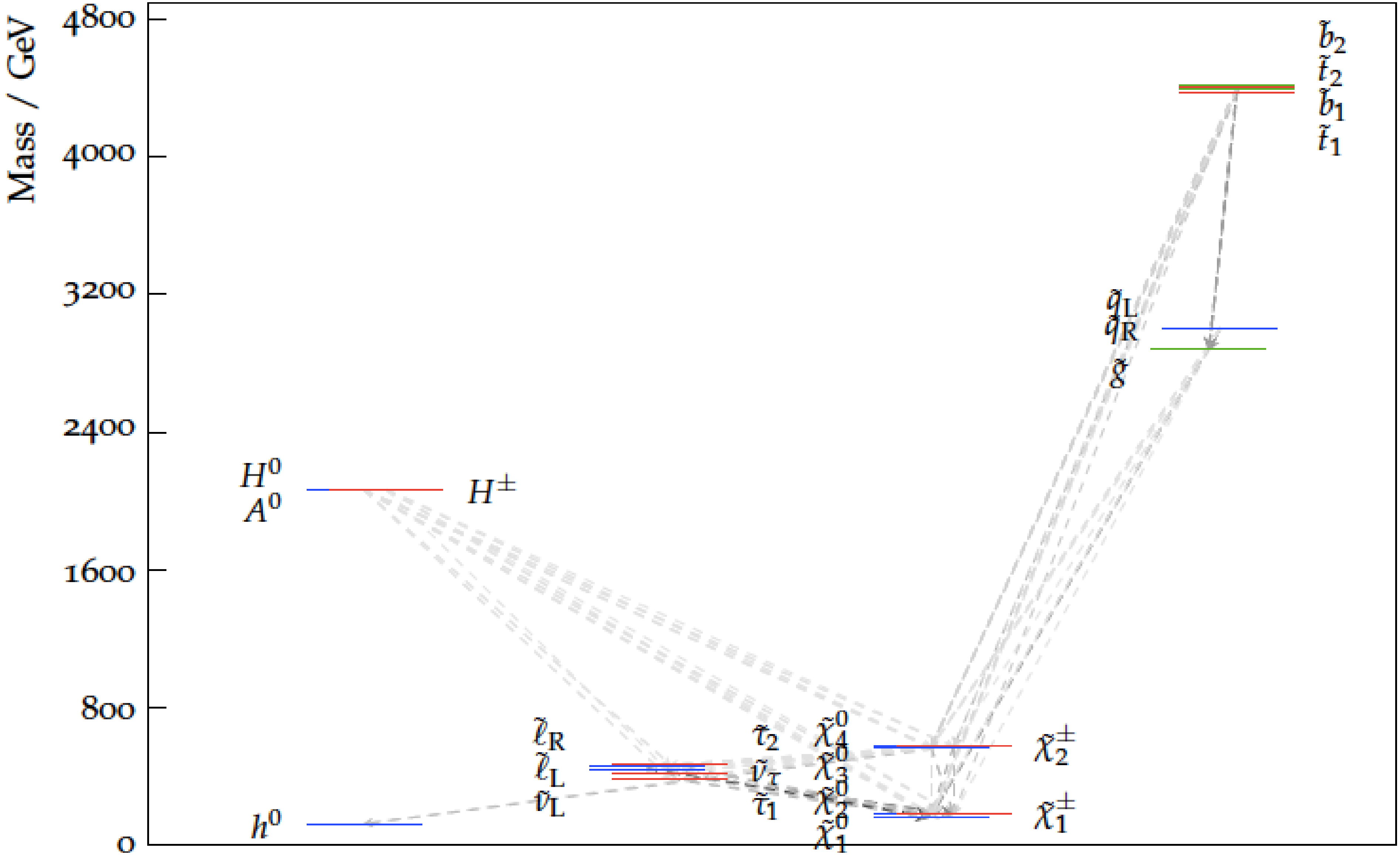
JE, Olive & Zheng: arXiv:1404.5571

Best-Fit Spectrum in CMSSM



Buchmueller, JE et al: arXiv:1312.5250

Best-Fit Spectrum in pMSSM10



Note near-degeneracy of $\chi^0_{1,2}$, $\chi^\pm$

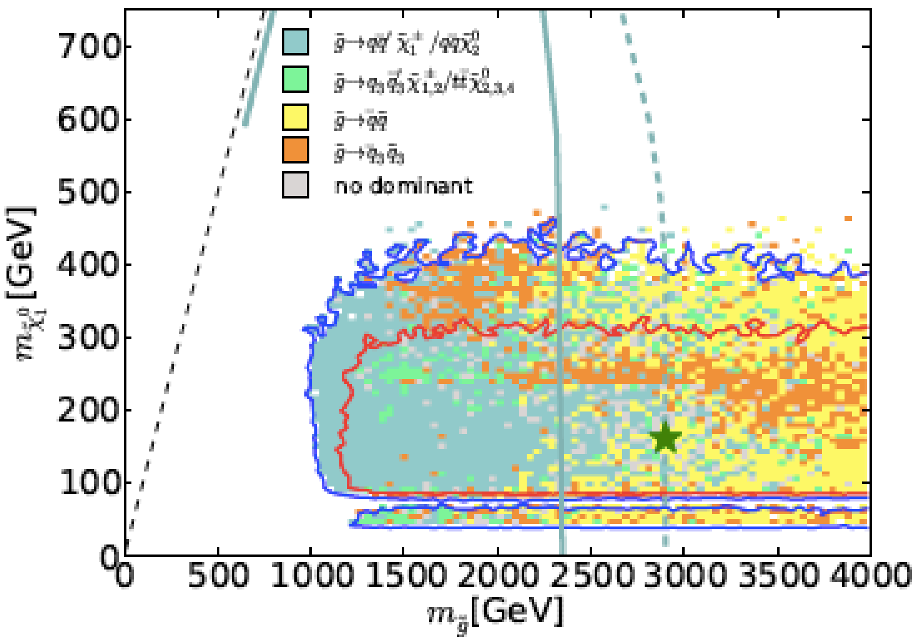
De Vries, JE et al: arXiv:1504.03260

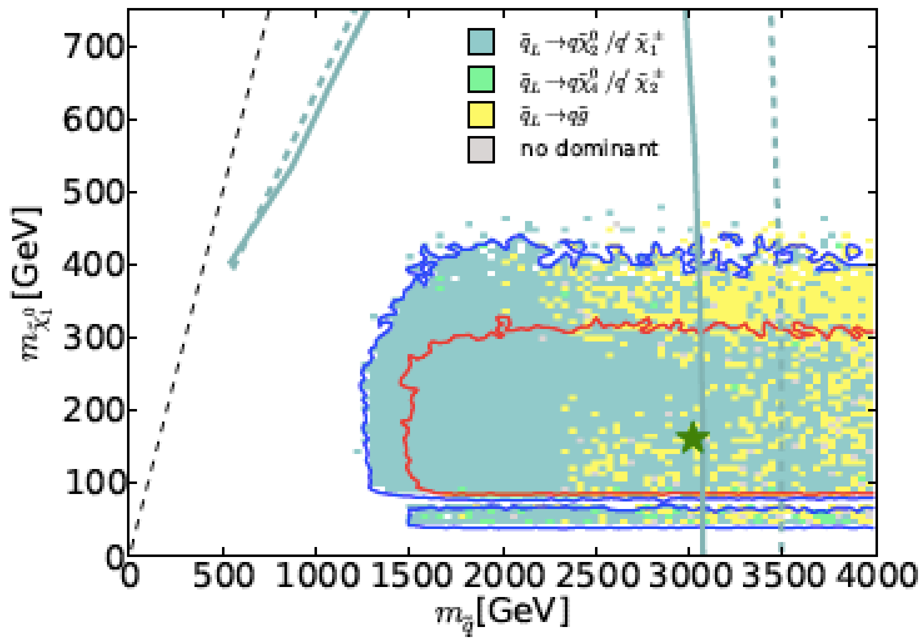
Exploring gluinos, squarks @ LHC

2012 ATLAS + CMS with 20/fb of LHC Data

pMSSM10

Reach of missing-energy searches





De Vries, JE et al: arXiv:1504.03260

Can reach gluino mass < 2500 (3000) GeV,

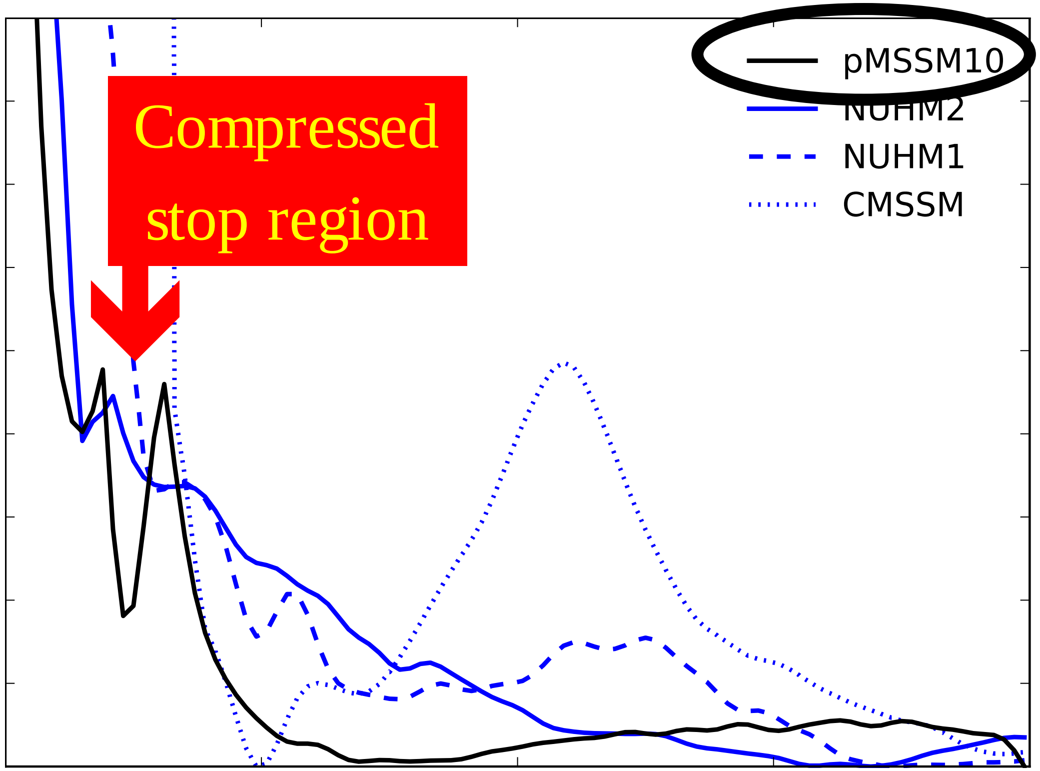
squark mass < 3000 (3500) GeV

With 300 (3000)/fb of LHC data

Fits to Supersymmetric Models

2012 ATLAS + CMS with 20/fb of LHC Data

Stop mass



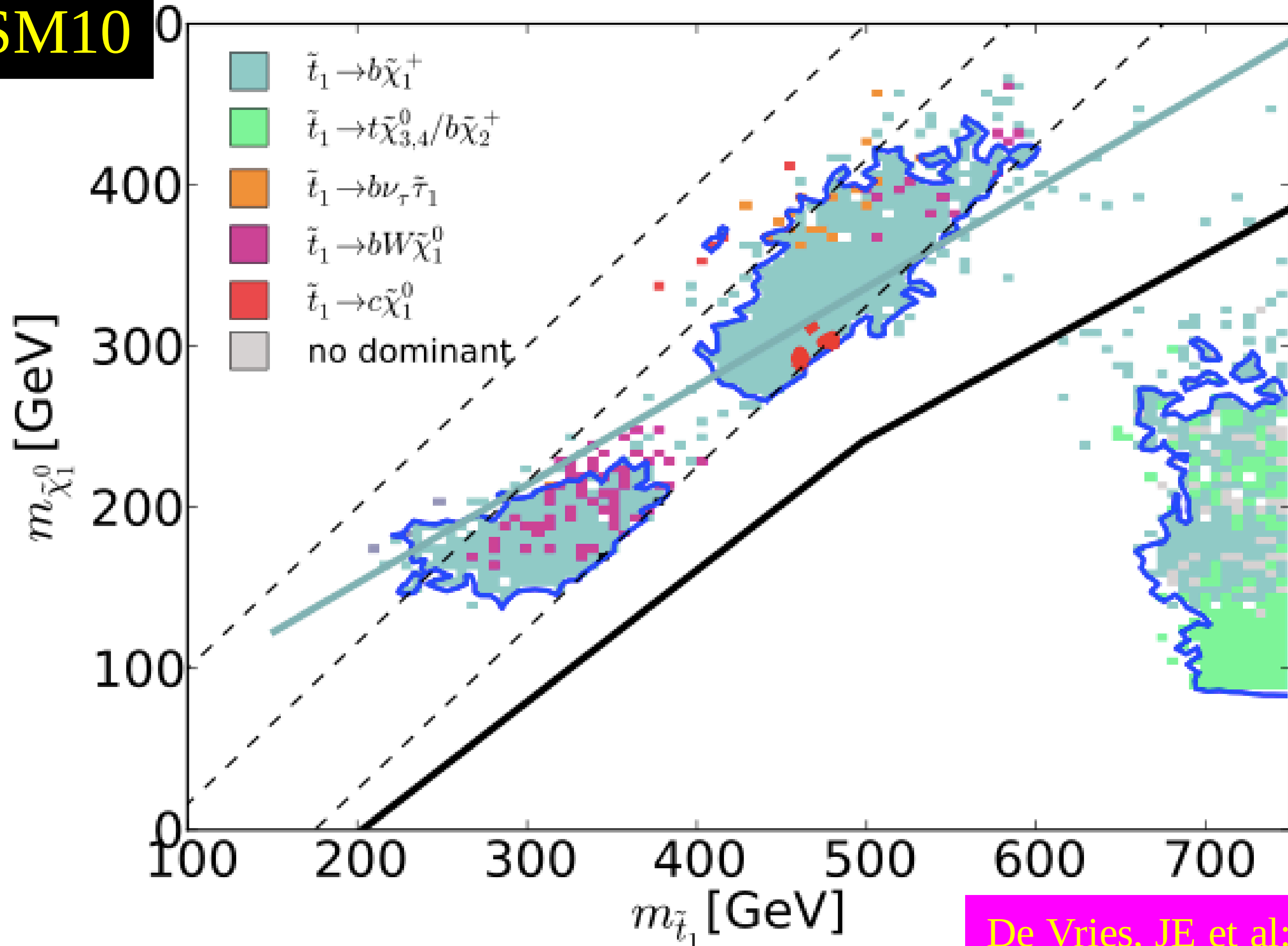
De Vries, JE et al: arXiv:1504.03260

Remaining possibility of a light "natural" stop weighing ~ 400 GeV

Exploring Light Stops @ Run 2

2012 ATLAS + CMS with 20/fb of LHC Data

pMSSM10



Reach of chargino + b searches

Reach of LSP + top searches

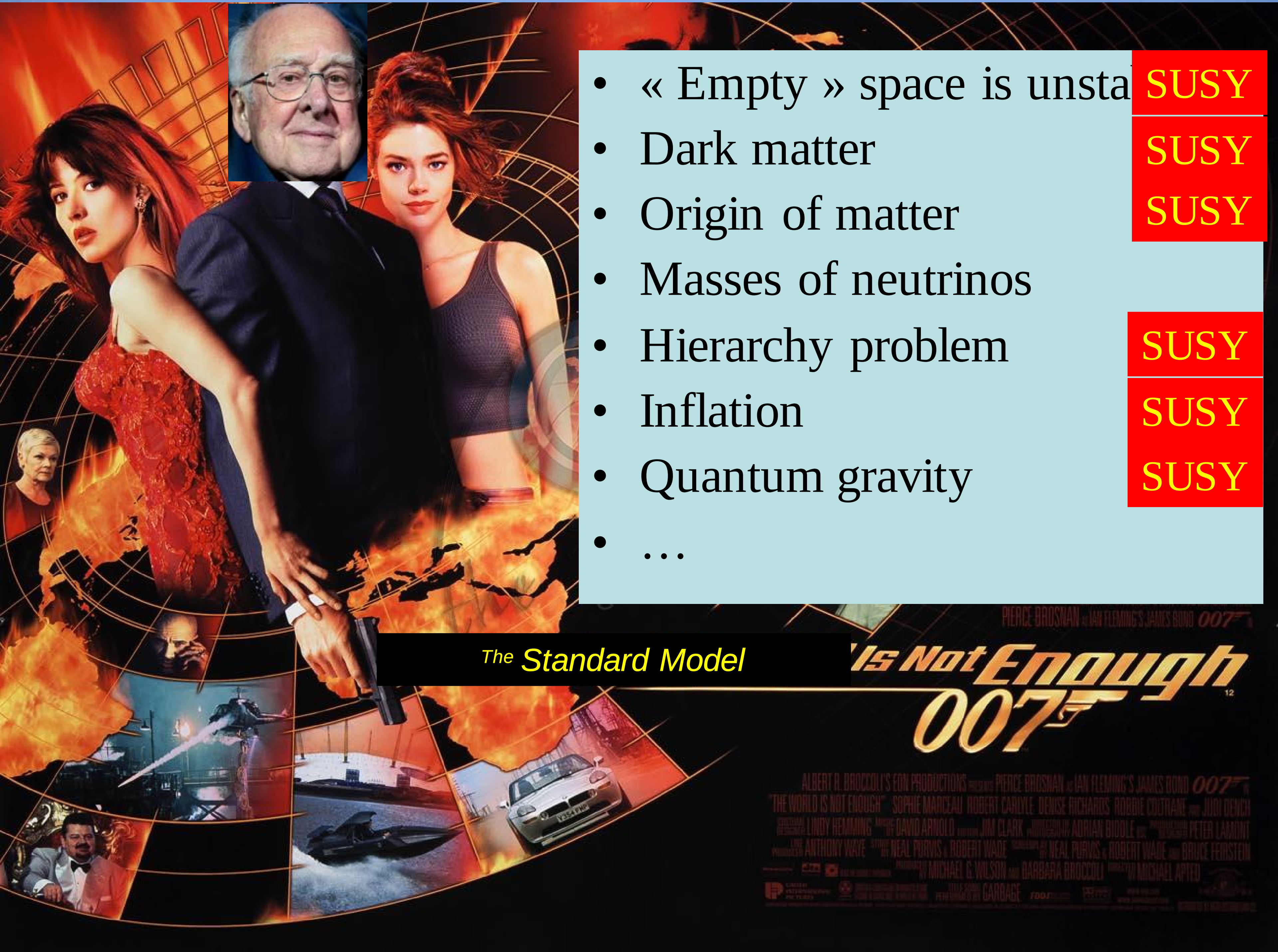
1

De Vries, JE et al: arXiv:1504.03260

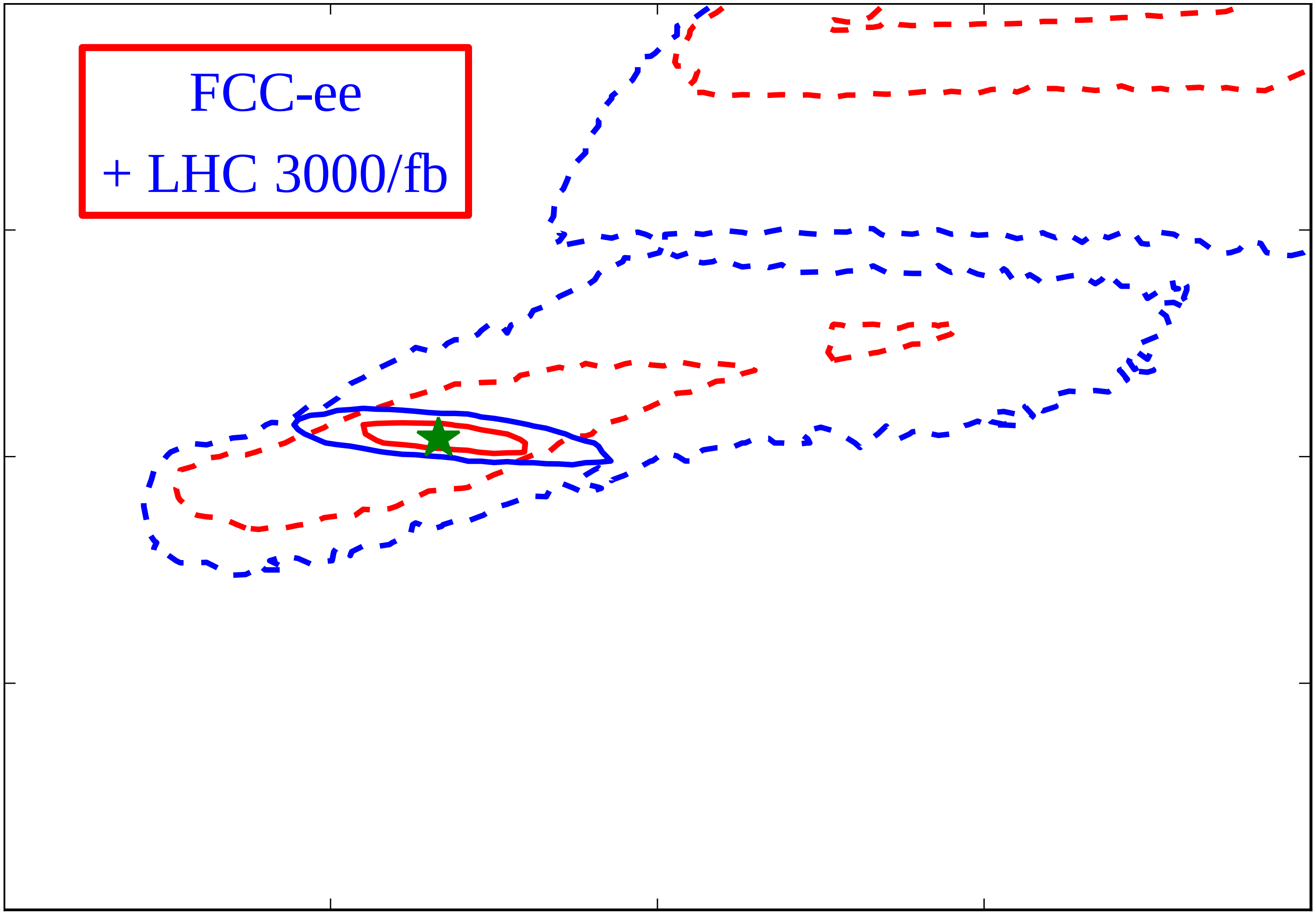
Part of region of light "natural" stop weighing ~ 400 GeV can be covered

Looking forward to the next 100 years

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



Measuring CMSSM with FCC-ee



Buchmueller, JE et al: arXiv:1505.04702

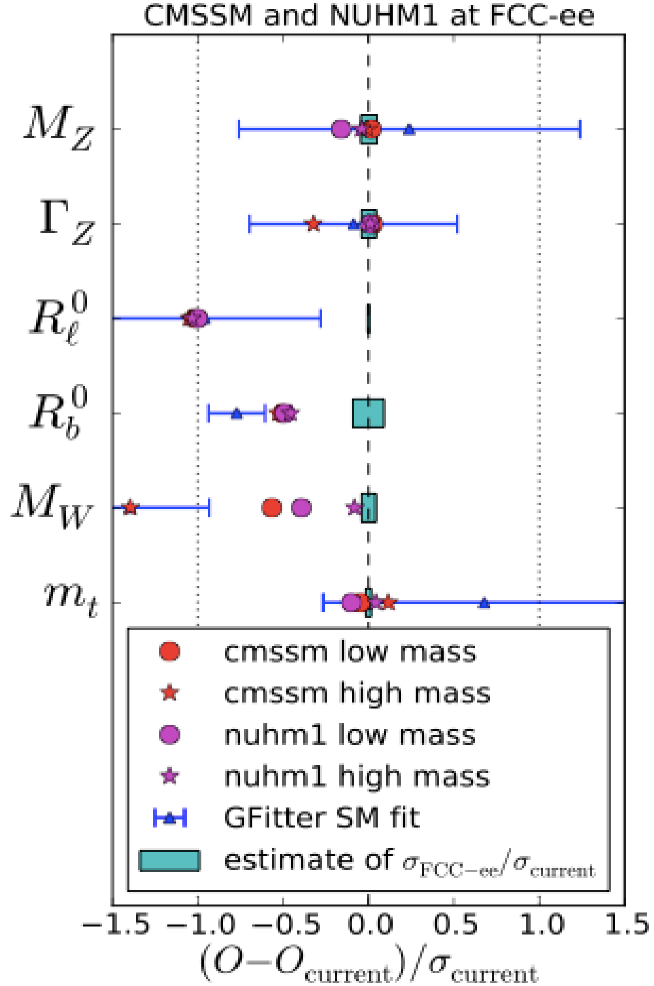
Possible FCC-ee Precision Measurements

- Conservatively based on LEP experience so far – it is just a start. Much work ahead.

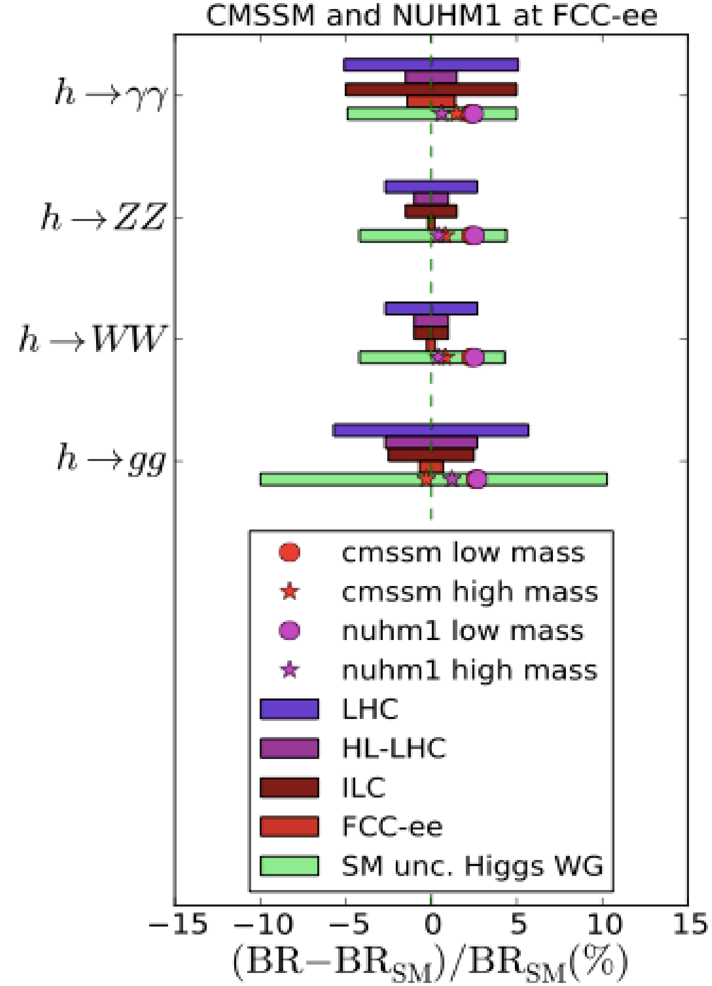
Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \rightarrow \gamma Z$, $Z \rightarrow \nu\nu$, ll	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

Precision FCC-ee Measurements

Precision Electroweak

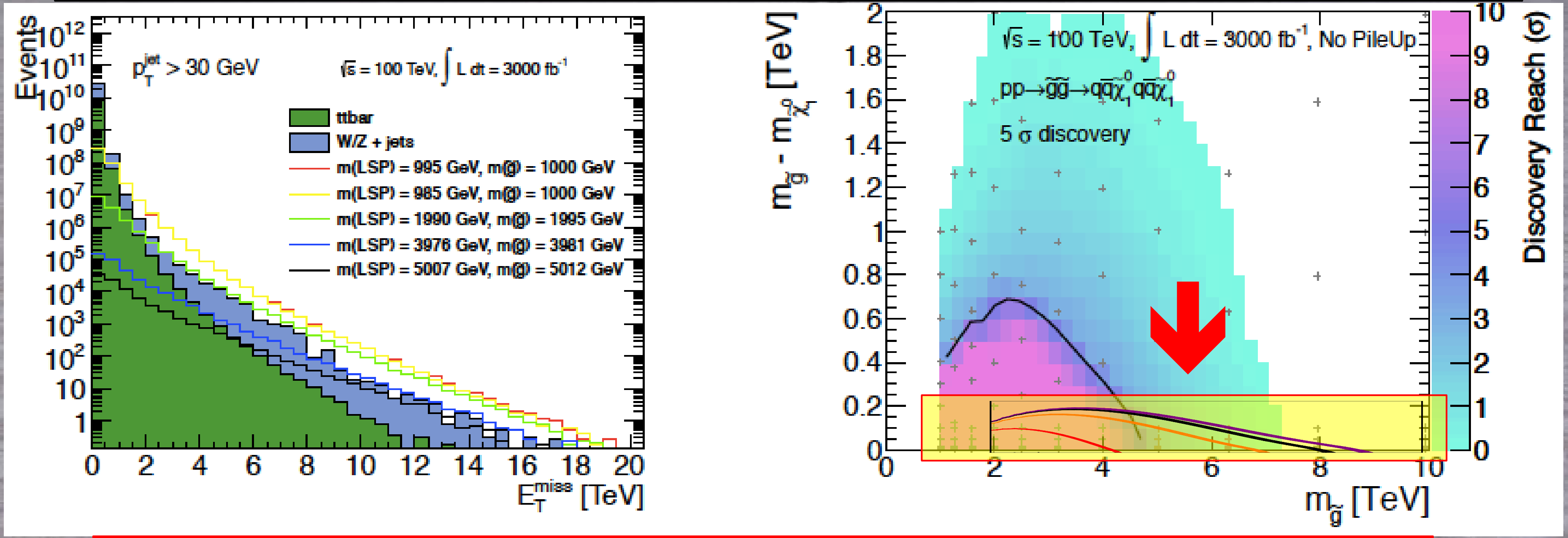


Precision Higgs



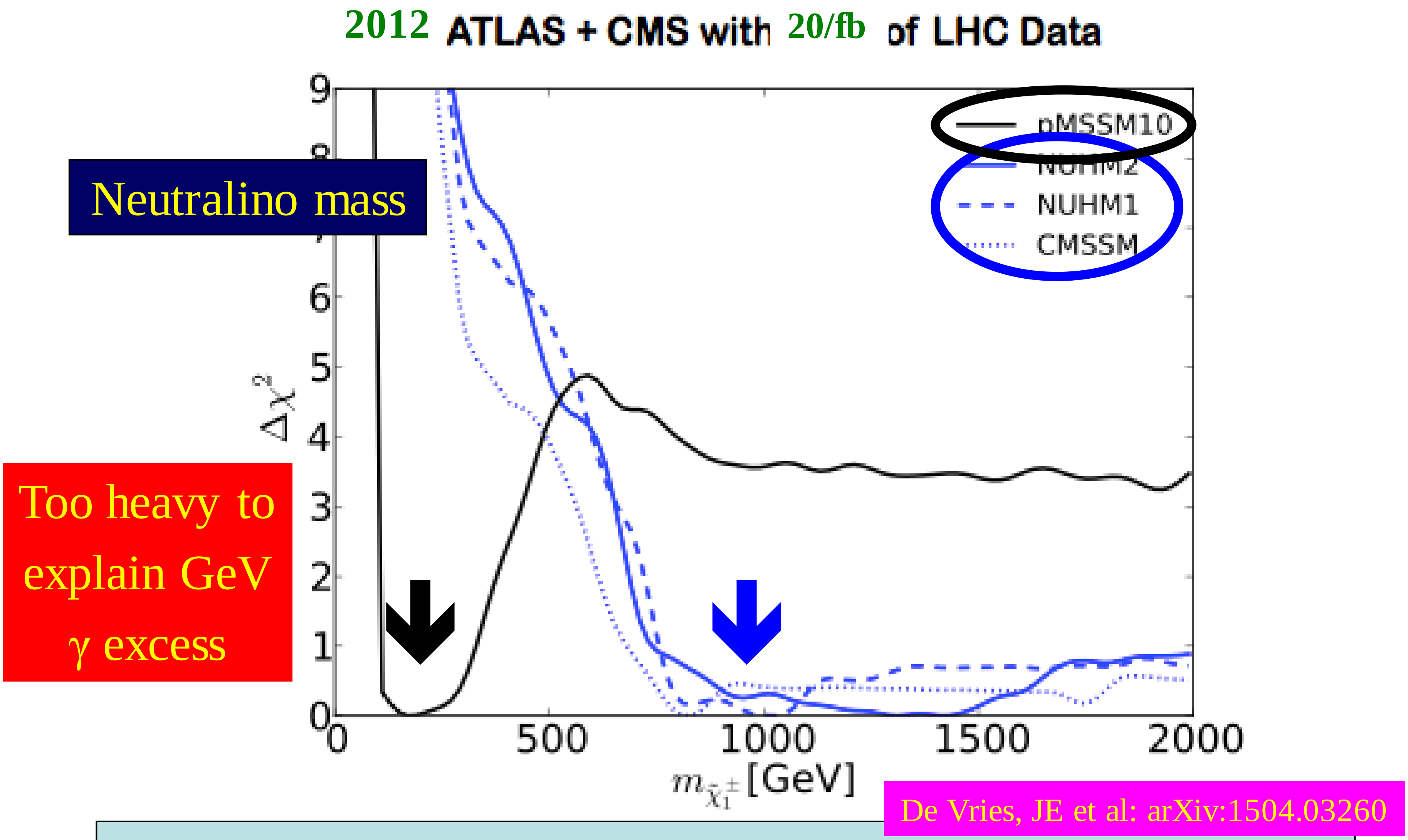
Reaches for Sparticles

Model with compressed spectrum: small gluino-neutralino mass difference



Large mass possible in gluino coannihilation scenario for dark matter

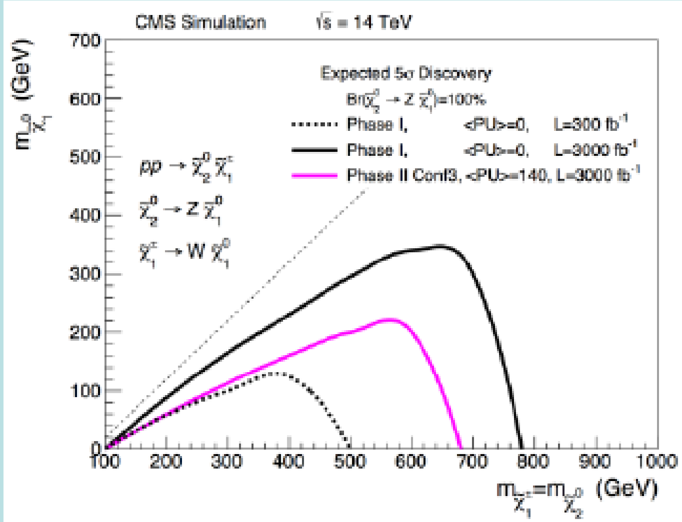
Possible Dark Matter Particle Mass

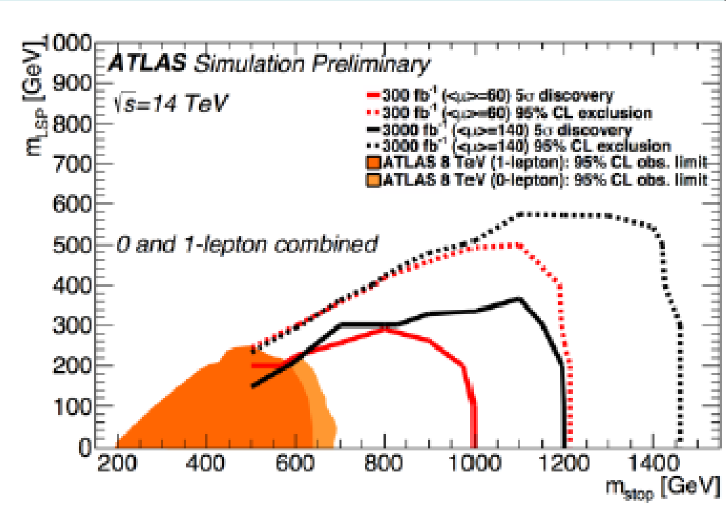


pMSSM10 favours smaller masses than in models with GUT-scale unification

Reaches for Sparticles

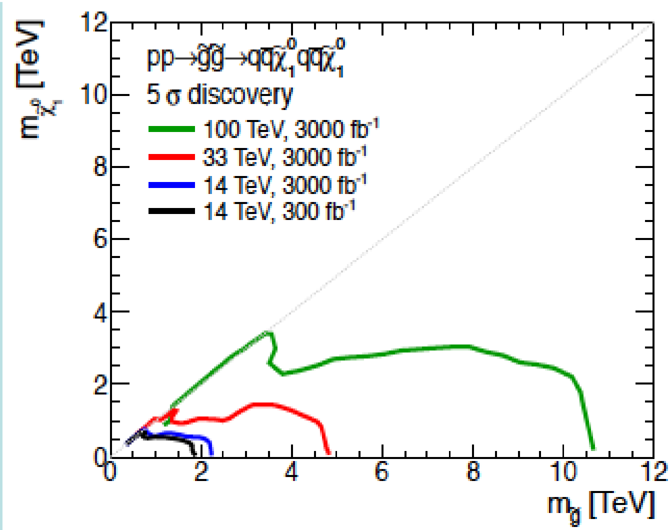
LHC:

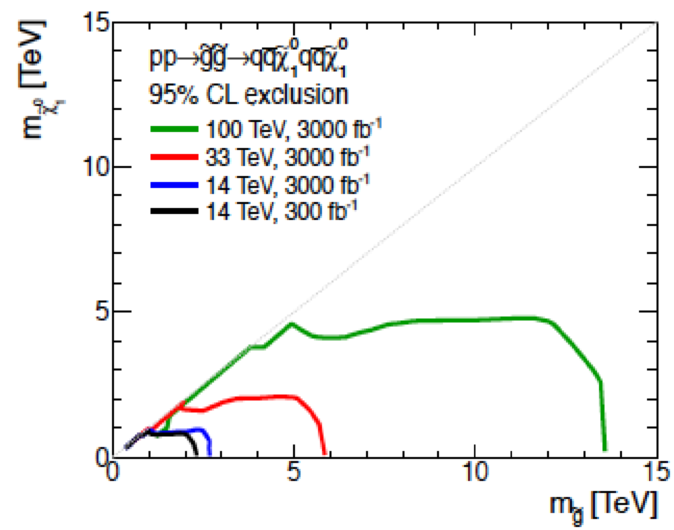




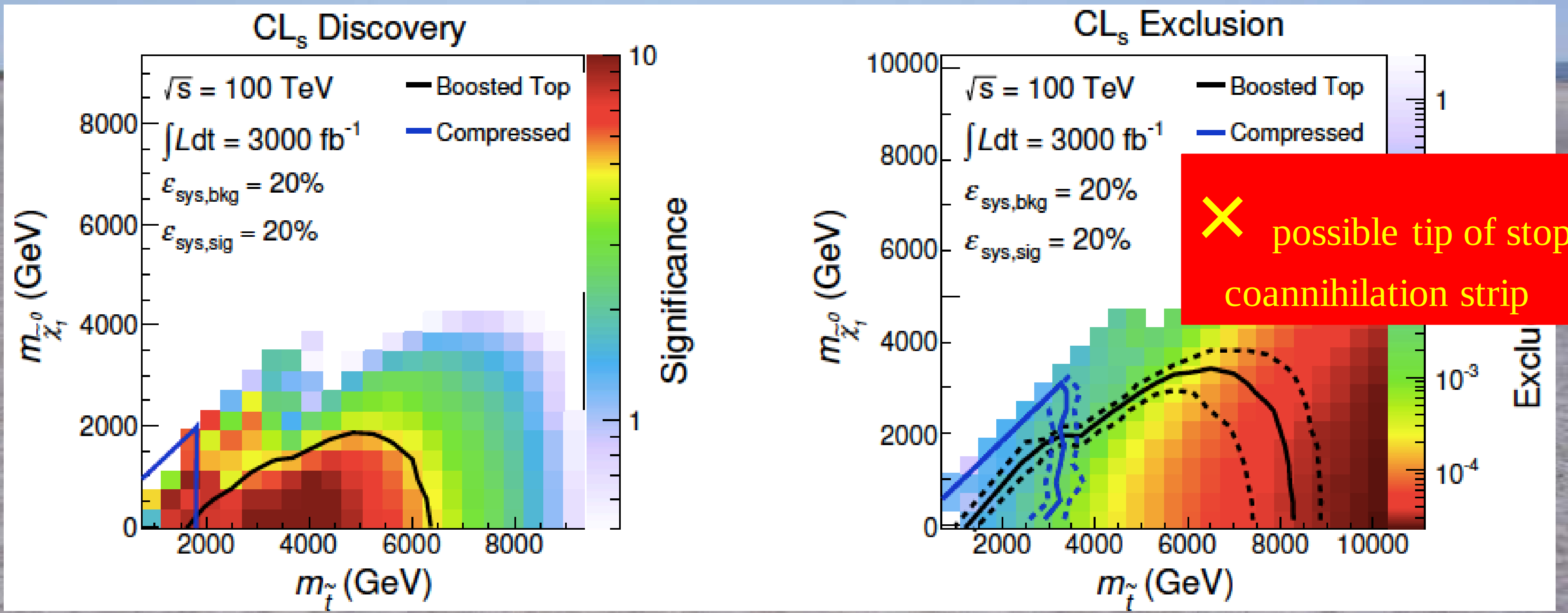
HE-LHC,

FCC-hh





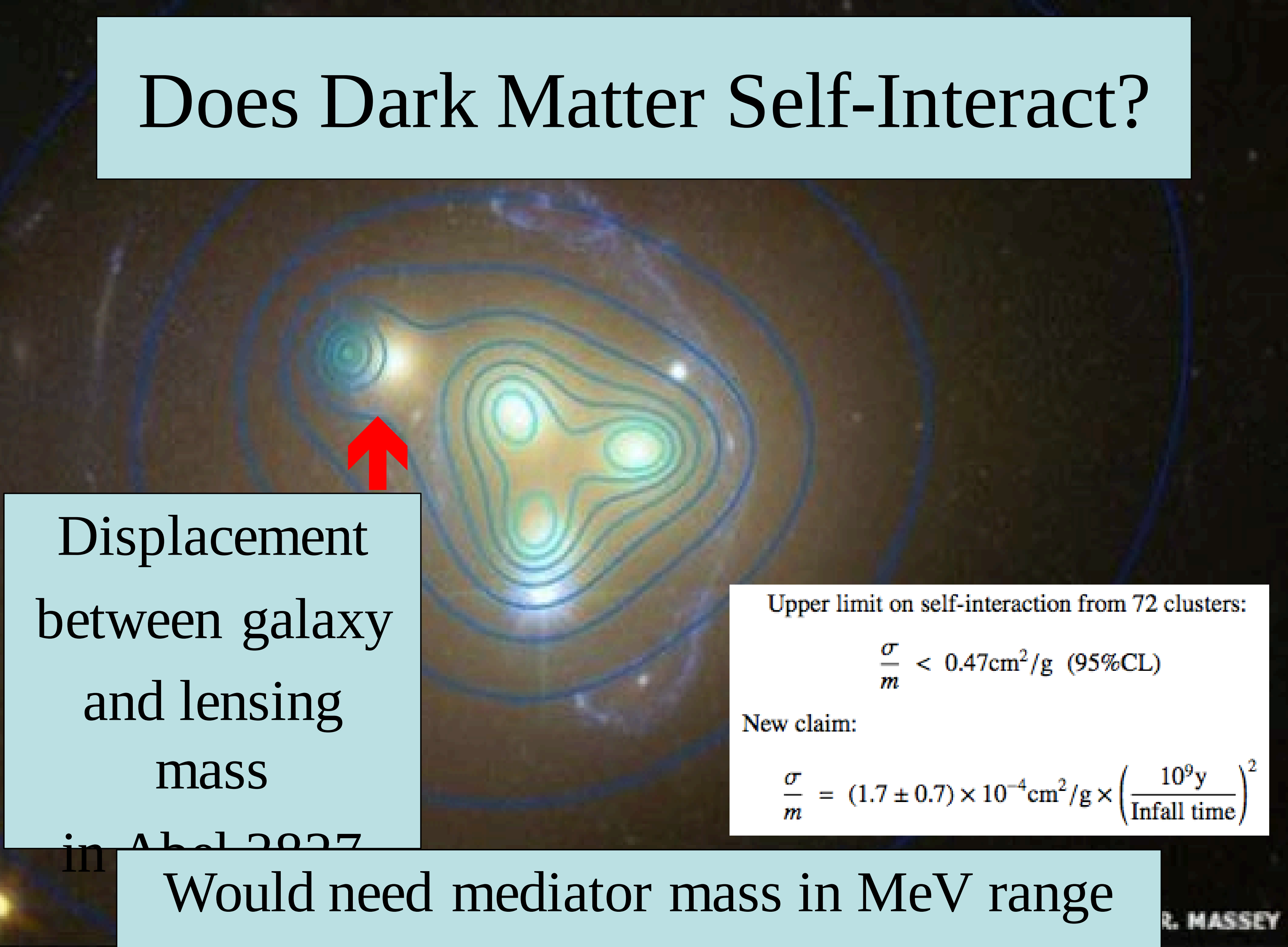
Reach for the Stop



Discover 6.5 TeV stop @ 5σ, exclude 8 TeV @ 95%

Stop mass up to 6.5 TeV possible along coannihilation strip

Does Dark Matter Self-Interact?



Displacement between galaxy and lensing mass in Abel 3827

Upper limit on self-interaction from 72 clusters:

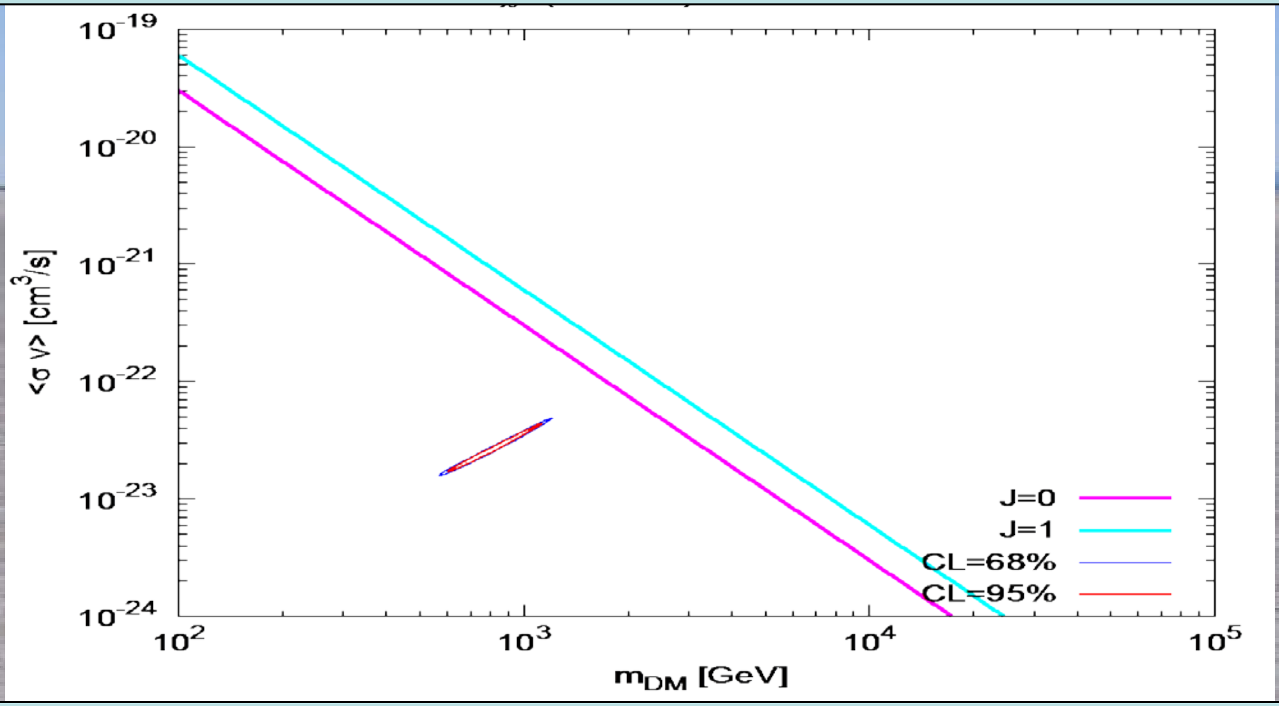
$$\frac{\sigma}{m} < 0.47\text{cm}^2/\text{g} \quad (95\%\text{CL})$$

New claim:

$$\frac{\sigma}{m} = (1.7 \pm 0.7) \times 10^{-4}\text{cm}^2/\text{g} \times \left(\frac{10^9\text{y}}{\text{Infall time}}\right)^2$$

Would need mediator mass in MeV range

Dark Matter Fit to AMS Positron Data

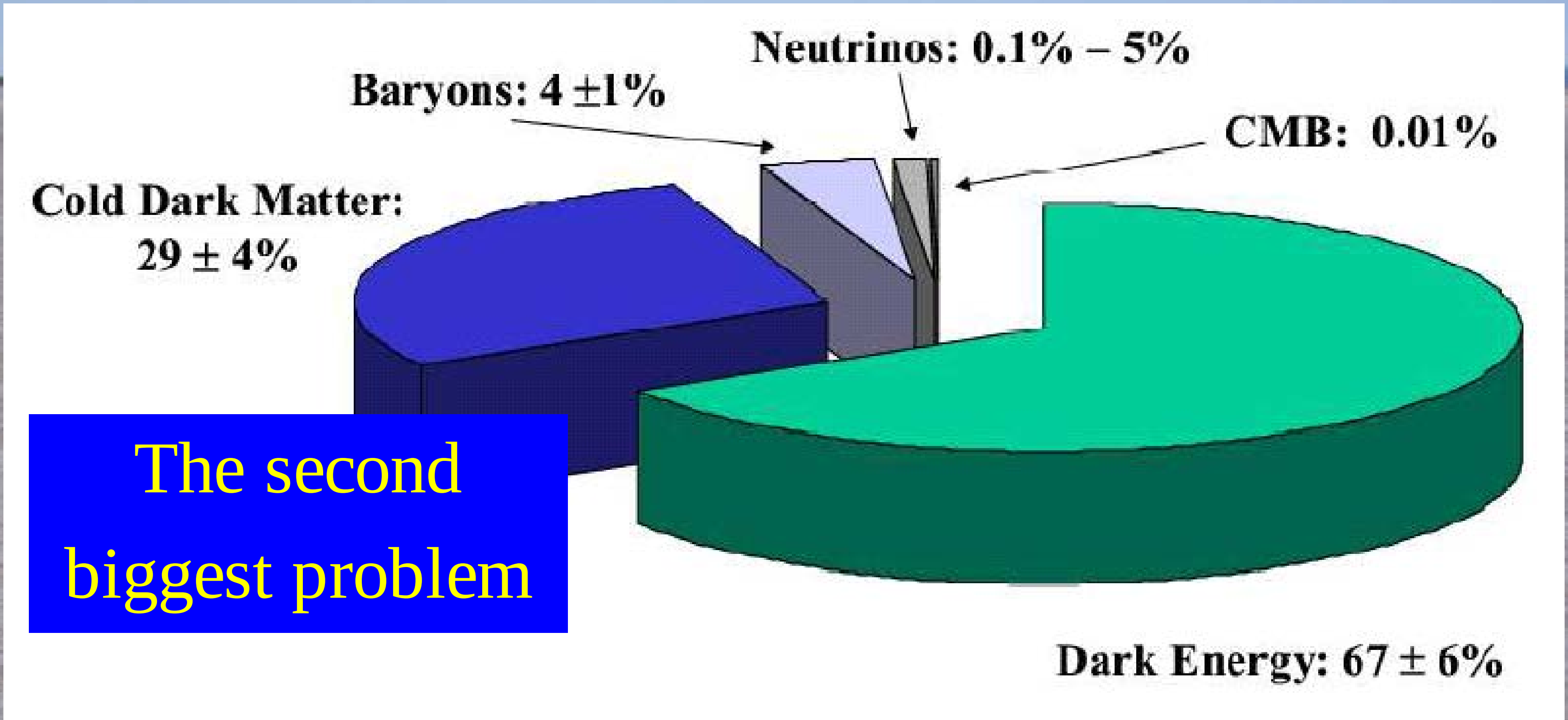


- **BUT:** very large annihilation cross section

  ~ 3 $\times$ 10^{-23} cm^2 >> required for relic density
- **OR:** very large boost from halo density fluctuation(s)

JE, Olive & Spanos, in preparation

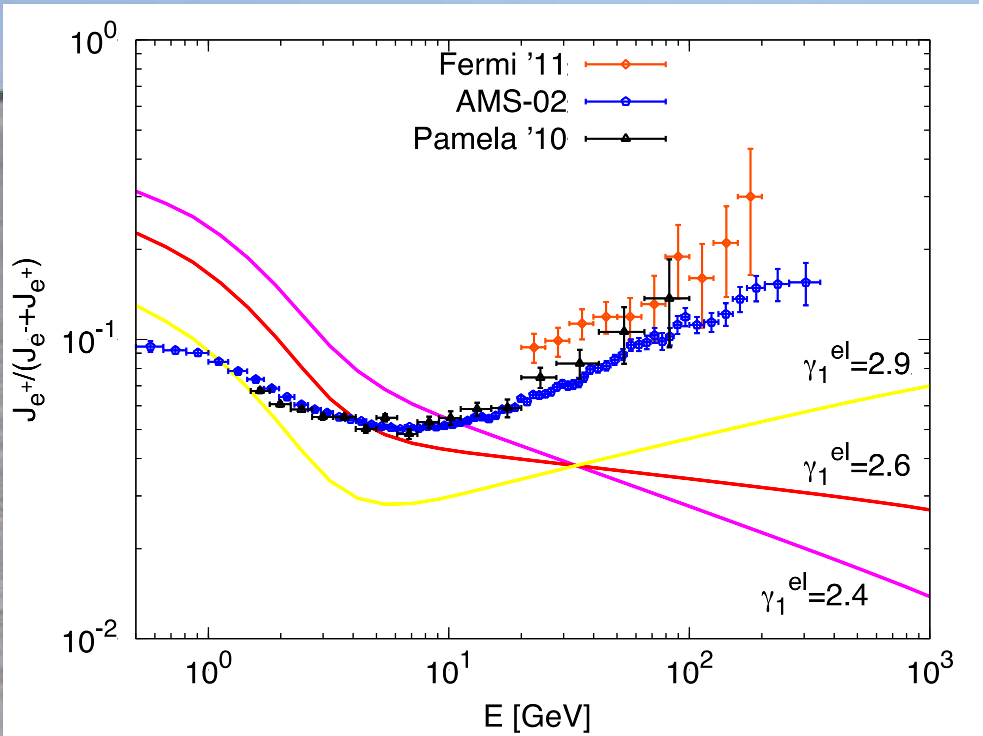
Strange Recipe for a Universe

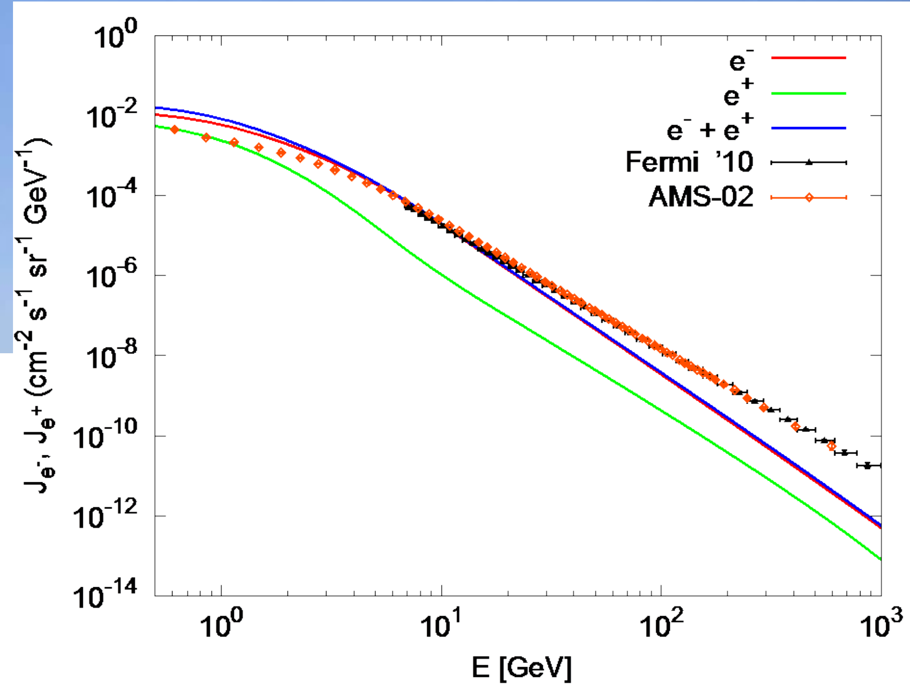


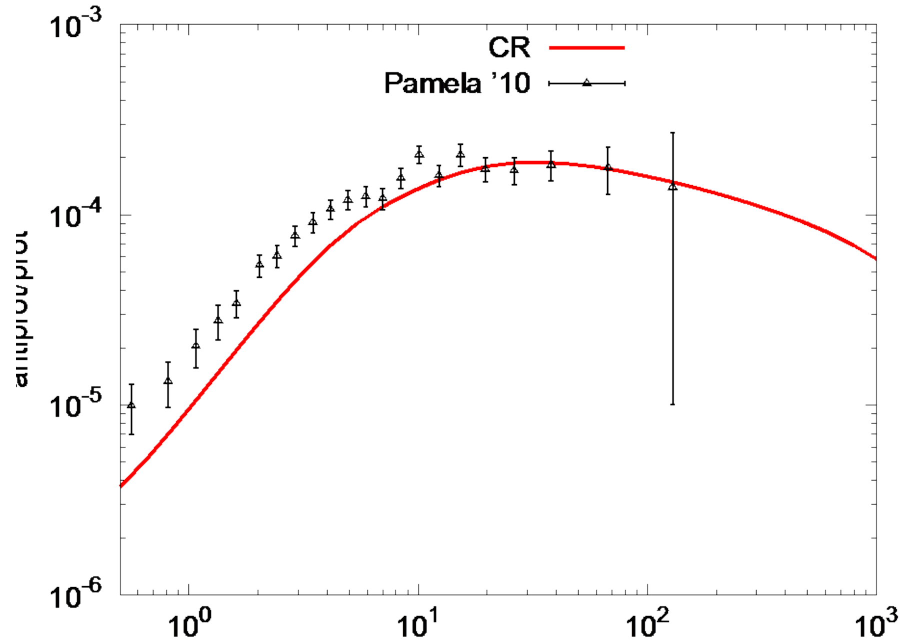
The second biggest problem

The 'Standard Model' of the Universe indicated by astrophysics and cosmology

Galactic Cosmic Rays Alone?





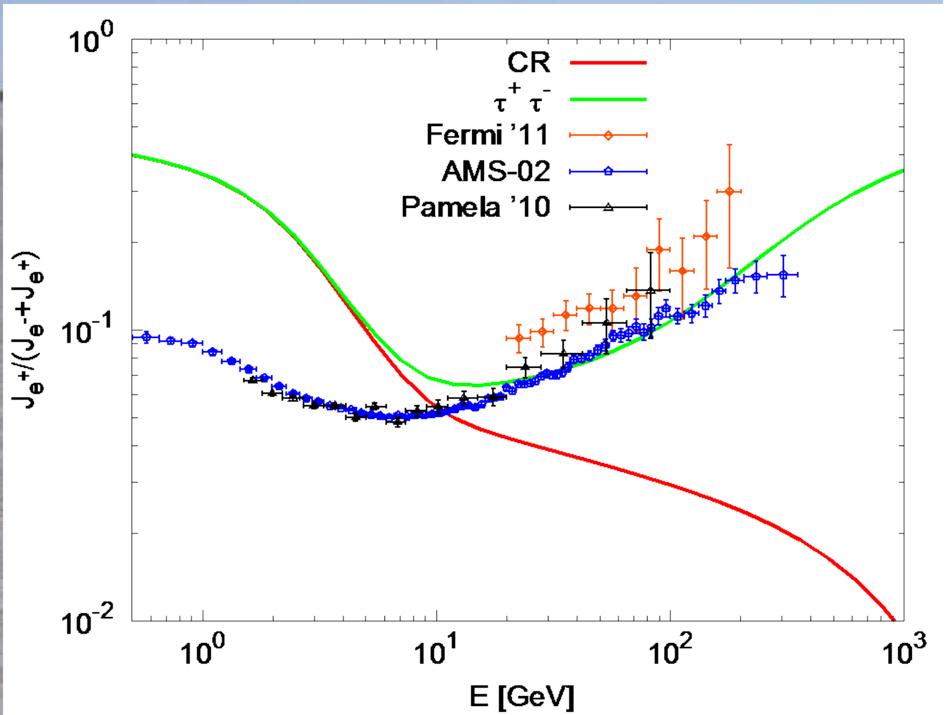


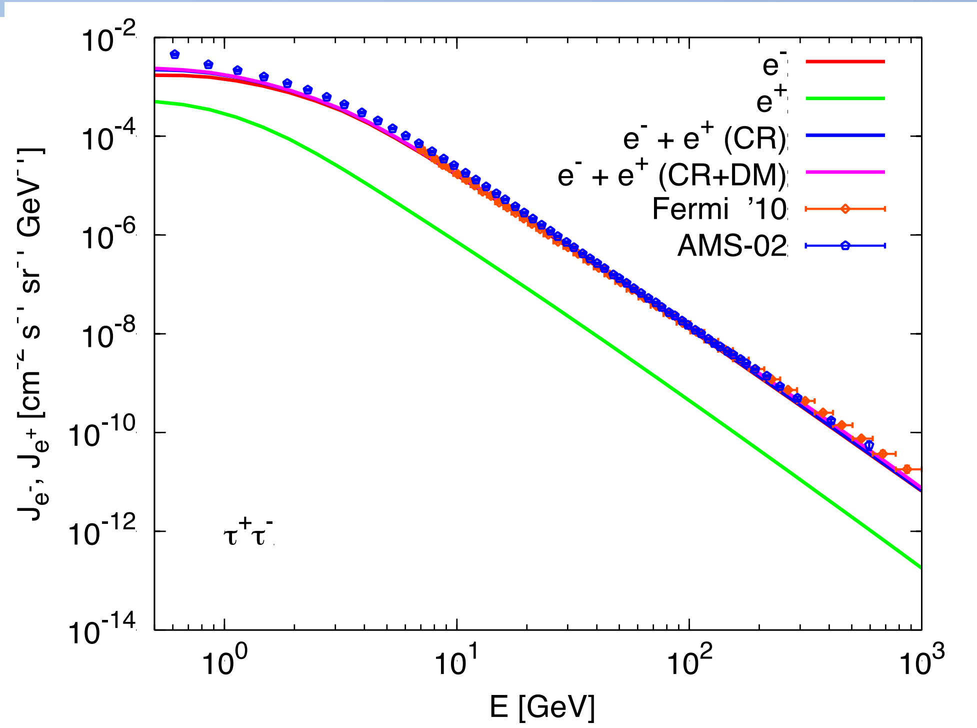
Can fit positrons > 10 GeV wit
modified GALPROP model

BUT: problems with e^-, low-E

JE, Olive & Spanos, in preparation

Dark Matter Fit to AMS Positron Data



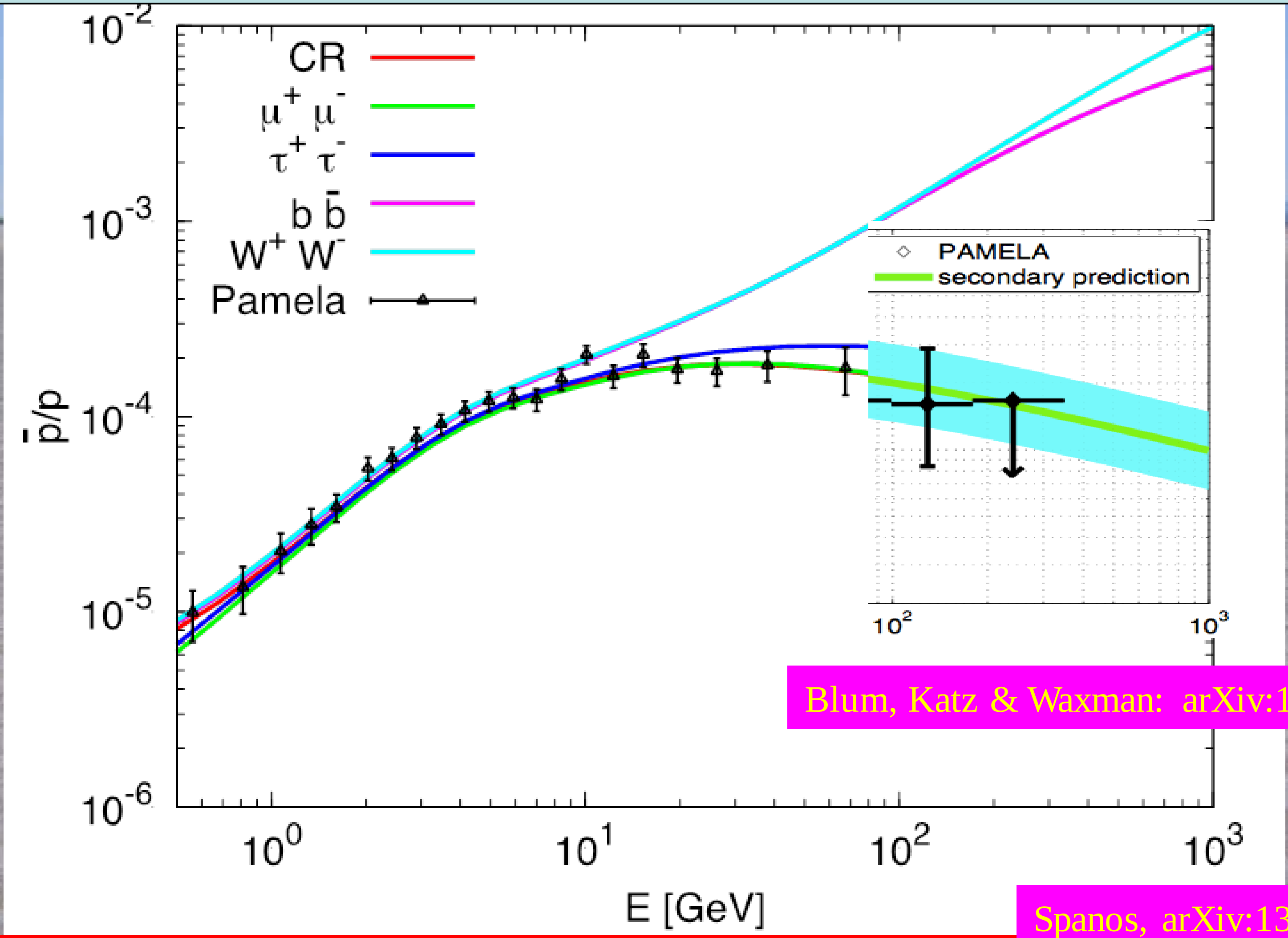


Fit with dark matter annihilation to

$\tau^+\tau^-$ and conventional GALPROP parameters

JE, Olive & Spanos, in preparation

Antiproton/Proton Ratio

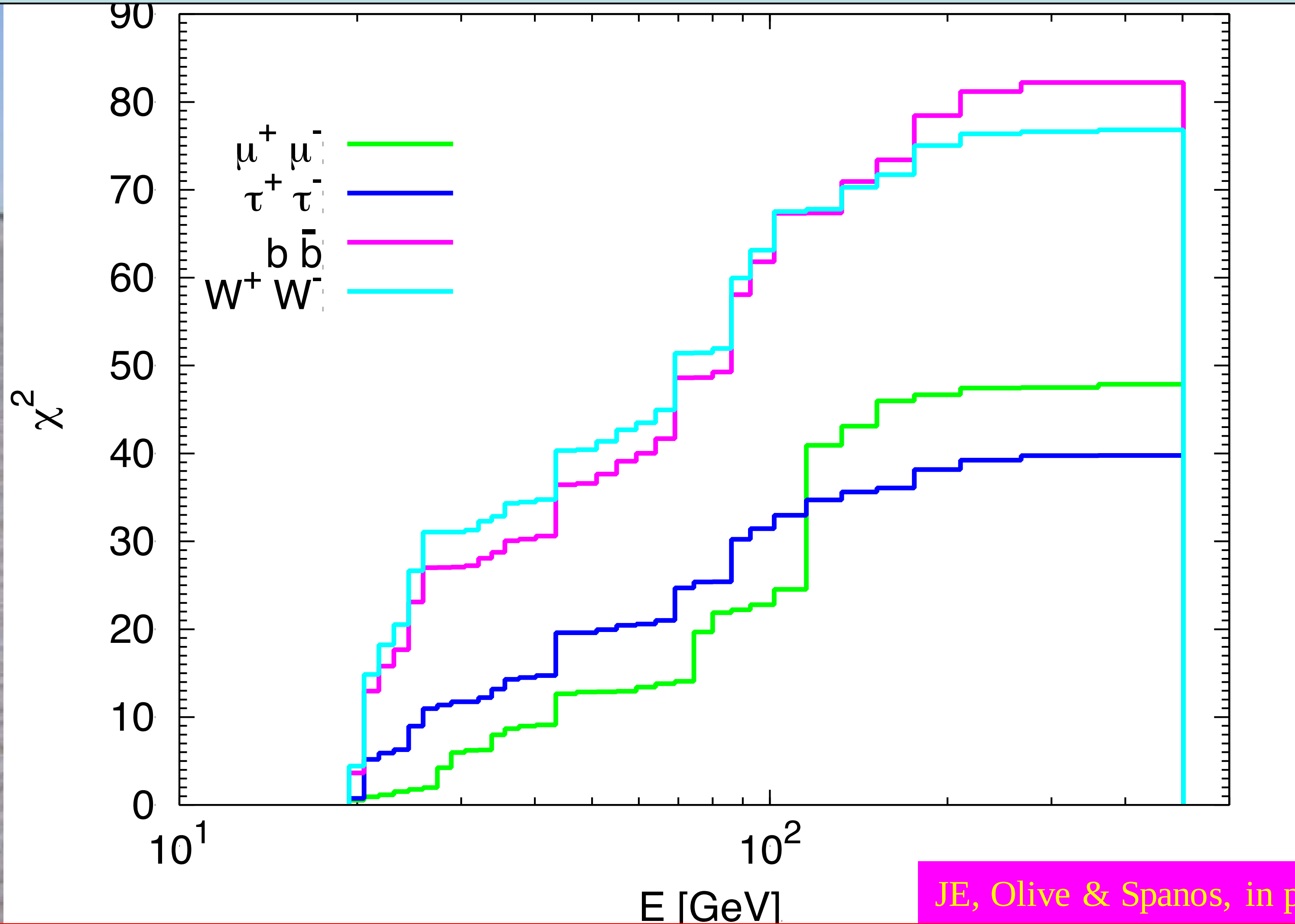


Blum, Katz & Waxman: arXiv:1305.1324

Spanos, arXiv:1312.7841

GALPROP can give ~ constant ratio > 150 GeV

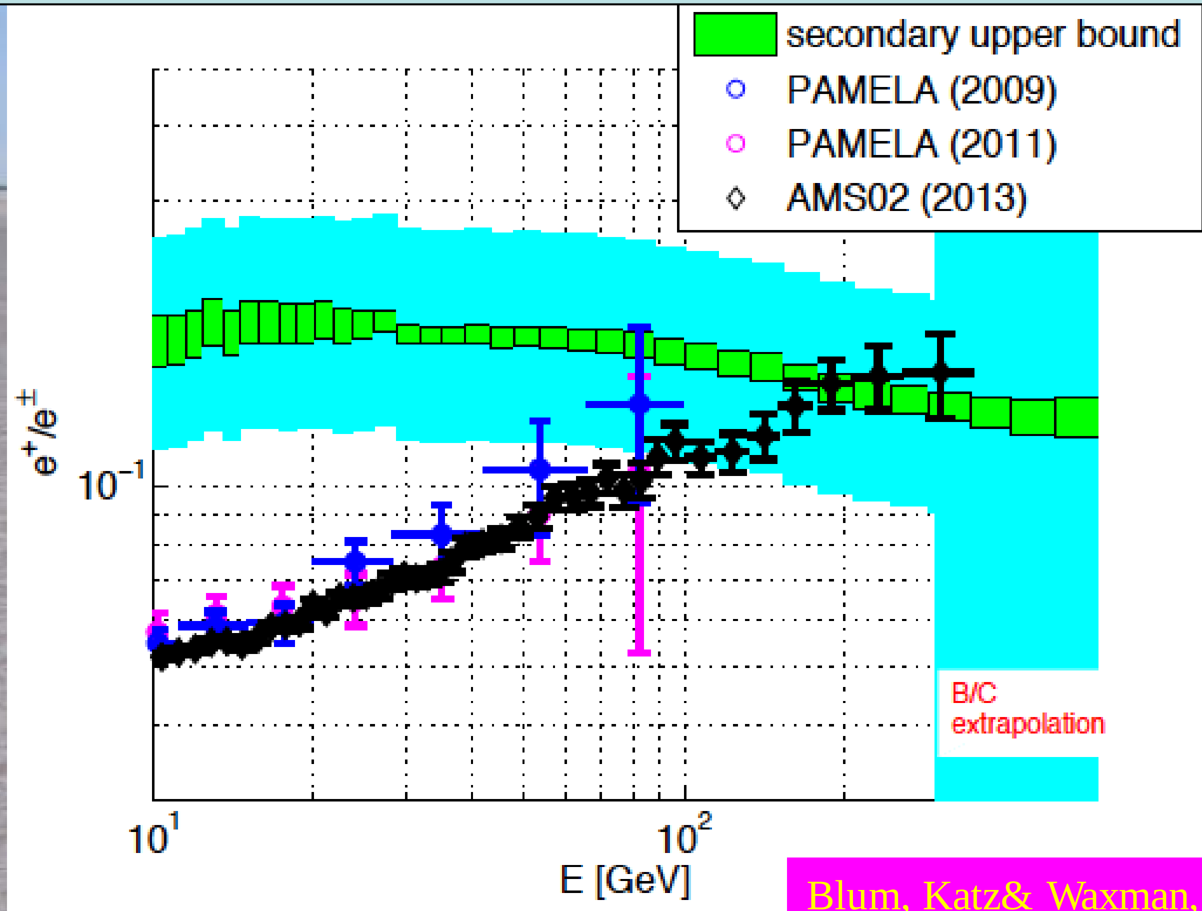
Fits with Different Final States



JE, Olive & Spanos, in preparation

Best fit with $\tau^+\tau^-$: $\mu^+\mu^-$ next best

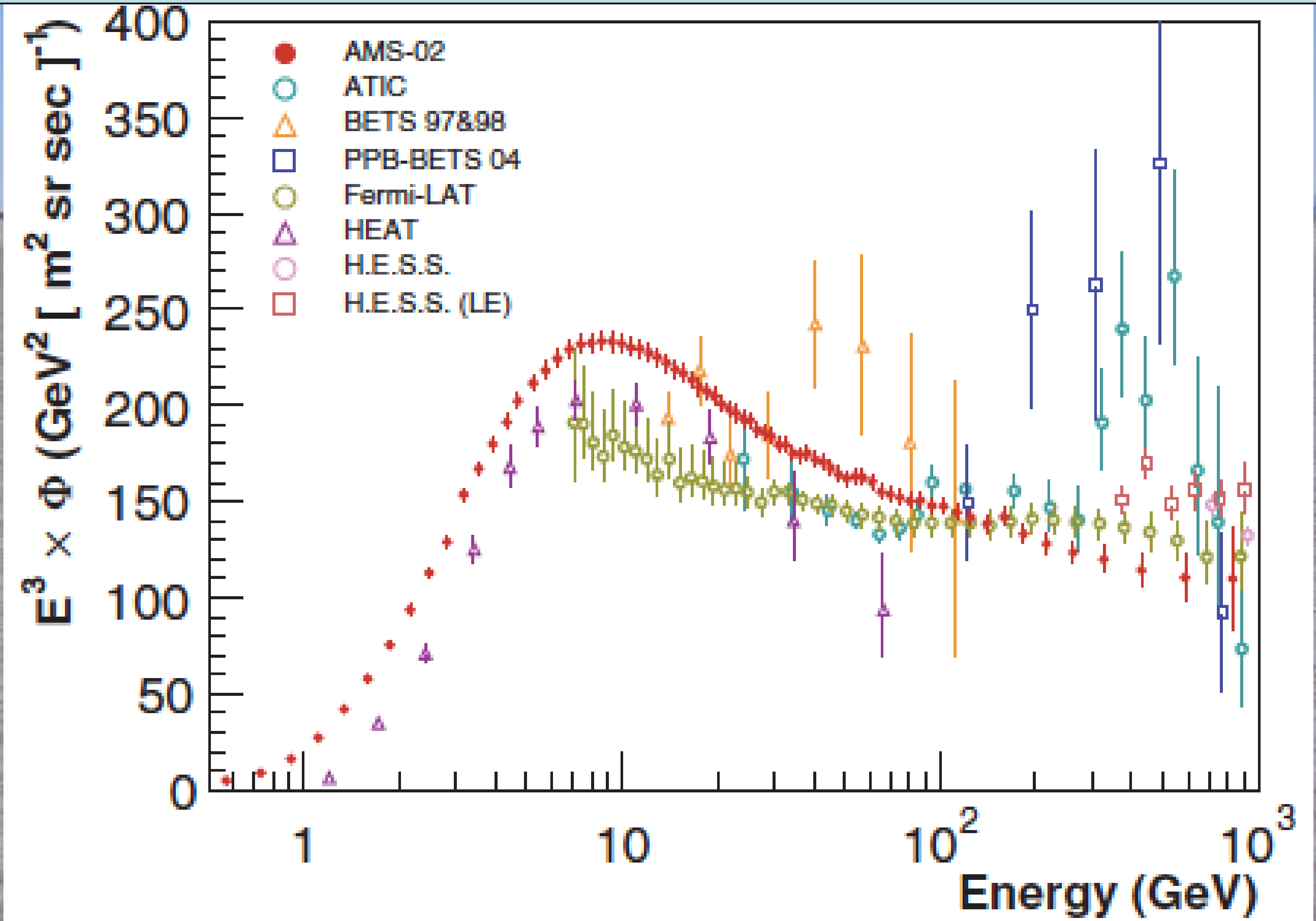
Galactic Cosmic Rays Alone?



Blum, Katz& Waxman, arXiv:1305.1324

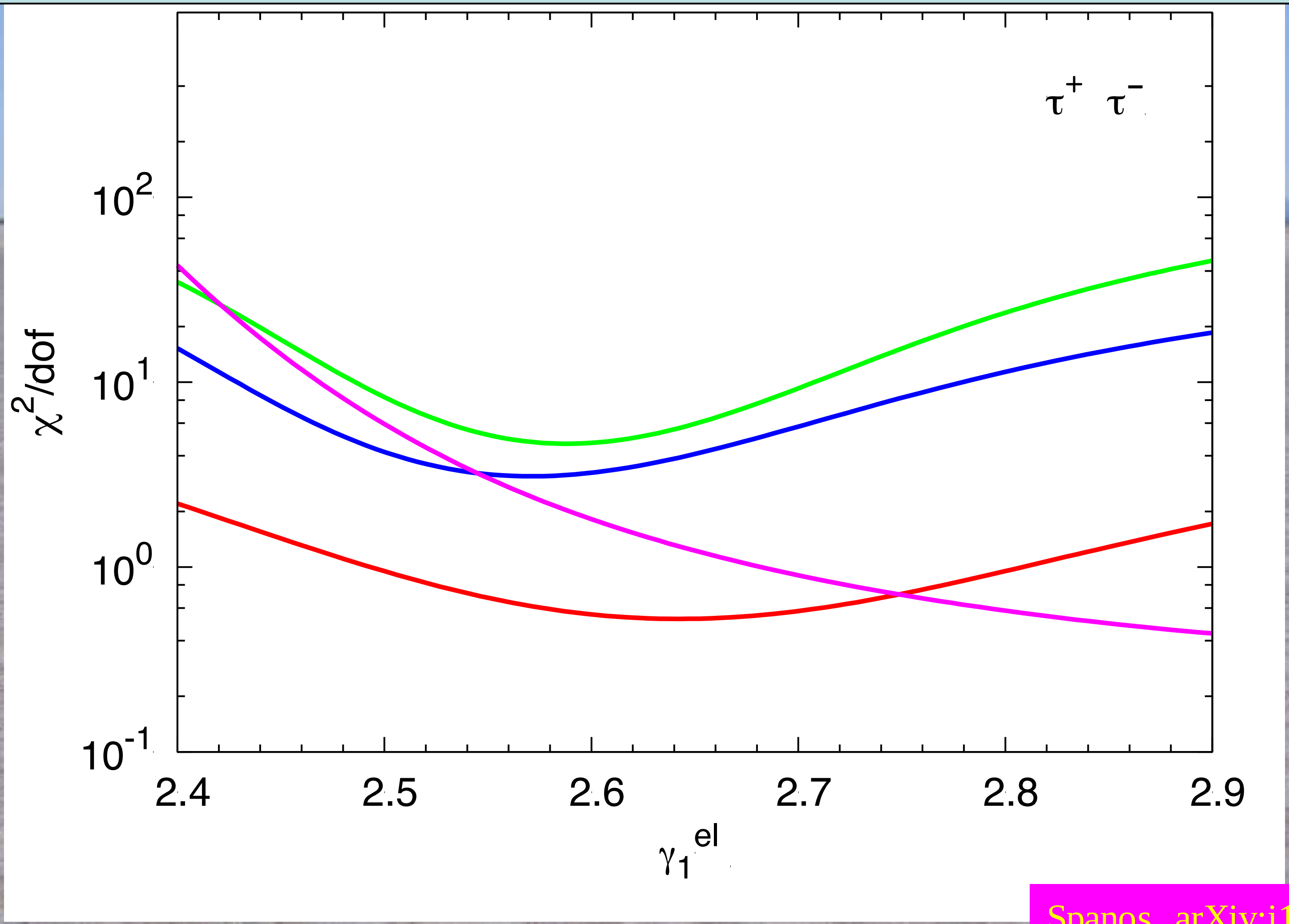
Rising positron fraction compatible with model-independent bound on secondary e^+

Sum of Electron + Positron Spectra



Dark Matter? Galactic cosmic rays? Local sources?

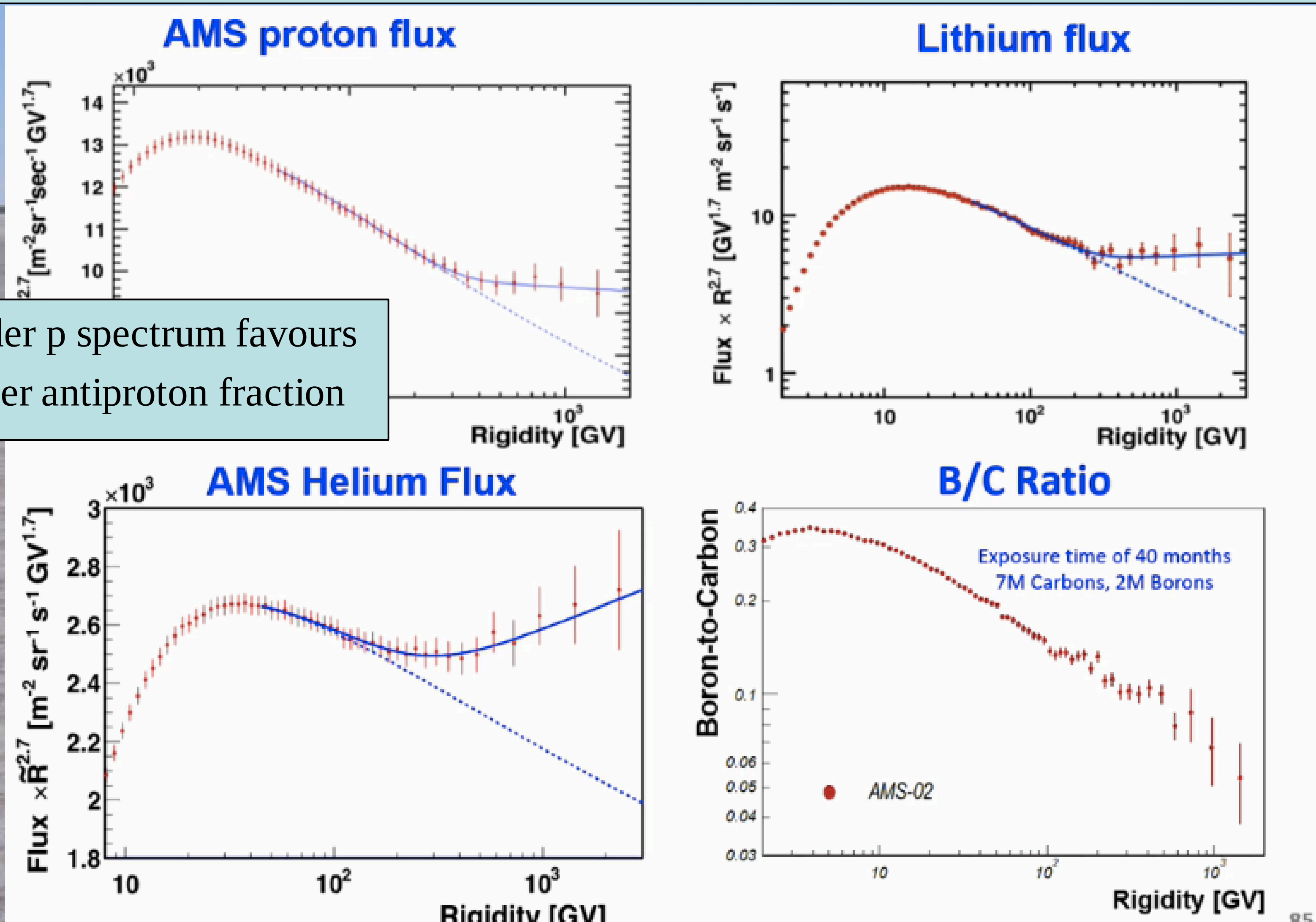
Quality of Fit with $\tau^+\tau^-$



Spanos, arXiv:i1312.7841

Good fit with modified GALPROP parameters

Potential impact of new AMS Data



Harder p spectrum favours flatter antiproton fraction

Will revolutionize calculations of cosmic-ray backgrounds

Searching for Supersymmetry

Bruno Zumino Memorial Meeting, CERN

April 27 – 28, 2015

John Ellis

King’s College London

& CERN

Papers with Bruno

1. **A Grand Unified Theory Obtained from Broken Supergravity**

(221) John R. Ellis (CERN), Mary K. Gaillard (Annecy, LAPP), Bruno Zumino (CERN). Apr 1980. 10 pp.
Published in **Phys.Lett. B94 (1980) 343**
CERN-TH-2842, LAPP-TH-16
DOI: 10.1016/0370-2693(80)90893-X

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service

Detailed record - Cited by 221 records 100+

2. **Superunification**

(34) John R. Ellis (CERN), Mary K. Gaillard (Annecy, LAPP), Bruno Zumino (CERN). Sep 1981. 36 pp.
Published in **Acta Phys.Polon. B13 (1982) 253-283**
LAPP-TH-44, CERN-TH-3152, C81-05-22-1

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; CERN Library Record

Detailed record - Cited by 34 records

3. **Supersymmetry and Noncompact Groups in Supergravity**

(31) John R. Ellis (SLAC), M.K. Gaillard (UC, Berkeley & LBL, Berkeley), Murat Gunaydin (Ecole Normale Superieure), B. Zumino (UC, Berkeley & LBL, Berkeley). Feb 1983. 40 pp.
Published in **Nucl.Phys. B224 (1983) 427-450**
SLAC-PUB-3065, LBL-15812, UCB-PTH-83-3
DOI: 10.1016/0550-3213(83)90384-X

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
SLAC Document Server; Link to Fulltext

Detailed record - Cited by 31 records

4. **The dimension of scale symmetry breaking**

(29) John R. Ellis, P.H. Weisz, B. Zumino (CERN). 1971.
Published in **Phys.Lett. B34 (1971) 91-94**
CERN-TH-1253
DOI: 10.1016/0370-2693(71)90516-8

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Detailed record - Cited by 29 records

5. **Attempts At Superunification**

(1) John R. Ellis (CERN), Mary K. Gaillard (Annecy, LAPP), Luciano Maiani (CERN & Rome U.), Bruno Zumino (CERN). Apr 1980. 20 pp.
LAPP-TH-15, CERN-TH-2841, C80-03-17-1
Presented at Conference: C80-03-17.1 (Erice EPS: Unification 1980:69)

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document

Detailed record - Cited by 1 record

Some Personal Memories

- First meeting Cambridge UK 1970
  (phenomenological Lagrangians)
- Brandeis school, summer 1970
  (scale and chiral invariance)
- Scale symmetry breaking 1971 (+ Weisz, **Bruno**)
- Scale anomaly 1972 (+ Chanowitz)
  (Anomalous Ward identities)
- Attempts at superunification 1980/3
  (+ Mary K, **Bruno,** Maiani, Murat G)

Most-Cited Paper with Bruno

A GRAND UNIFIED THEORY OBTAINED FROM BROKEN SUPERGRAVITY

John ELLIS
CERN, Geneva, Switzerland

Mary K. GAILLARD
LAPP, Annecy-le-Vieux, France

and

Bruno ZUMINO
CERN, Geneva, Switzerland

Received 12 May 1980

To our friend Jacques Prentki on the occasion of his 60th birthday

We examine the possibility that the "fundamental" particles appearing in grand unified theories are a subset of the SU(8) bound states of preons belonging to the SO(8) extended supergravity, selected by the requirement that they form a renormalizable gauge theory. Analysis of the SU(8) Higgs potential given by supersymmetry suggests that the maximal grand unification symmetry is SU(5). A maximal subset of fermions free of SU(5) anomalies, and hence renormalizable, contains three generations of $\bar{\mathbf{5}} + \mathbf{10}$ left-handed helicity states. The unbroken SU(5) theory may also contain **5** and **24** Higgs fields which are massless at the tree level.

Nuclear Physics B76 (1974) 310–332. North-Holland Publishing Company

No-Renormalization Theorems

BROKEN SUPERGAUGE SYMMETRY AND RENORMALIZATION

J. ILIOPOULOS *

Laboratoire de Physique Théorique, Orsay

B. ZUMINO

CERN, Geneva

Received 20 March 1974

Abstract: A field theory model invariant under supergauge transformations is shown to be renormalizable to all orders in perturbation theory. Renormalization is shown to be consistent with supergauge invariance. It is further shown that only one renormalization constant is needed, a common wave function renormalization for all fields. A symmetry breaking term is introduced which breaks the symmetry explicitly but so smoothly that the renormalization procedure of the symmetric case can still be applied. Relations among masses and coupling constants emerge. Among other topics discussed, the possibility that the supergauge symmetry is spontaneously broken and that a Goldstone spinor appears is examined.

Nuclear Physics B238 (1984) 453–476

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPOULOS, K. OLIVE†, and M. SREDNICKI‡

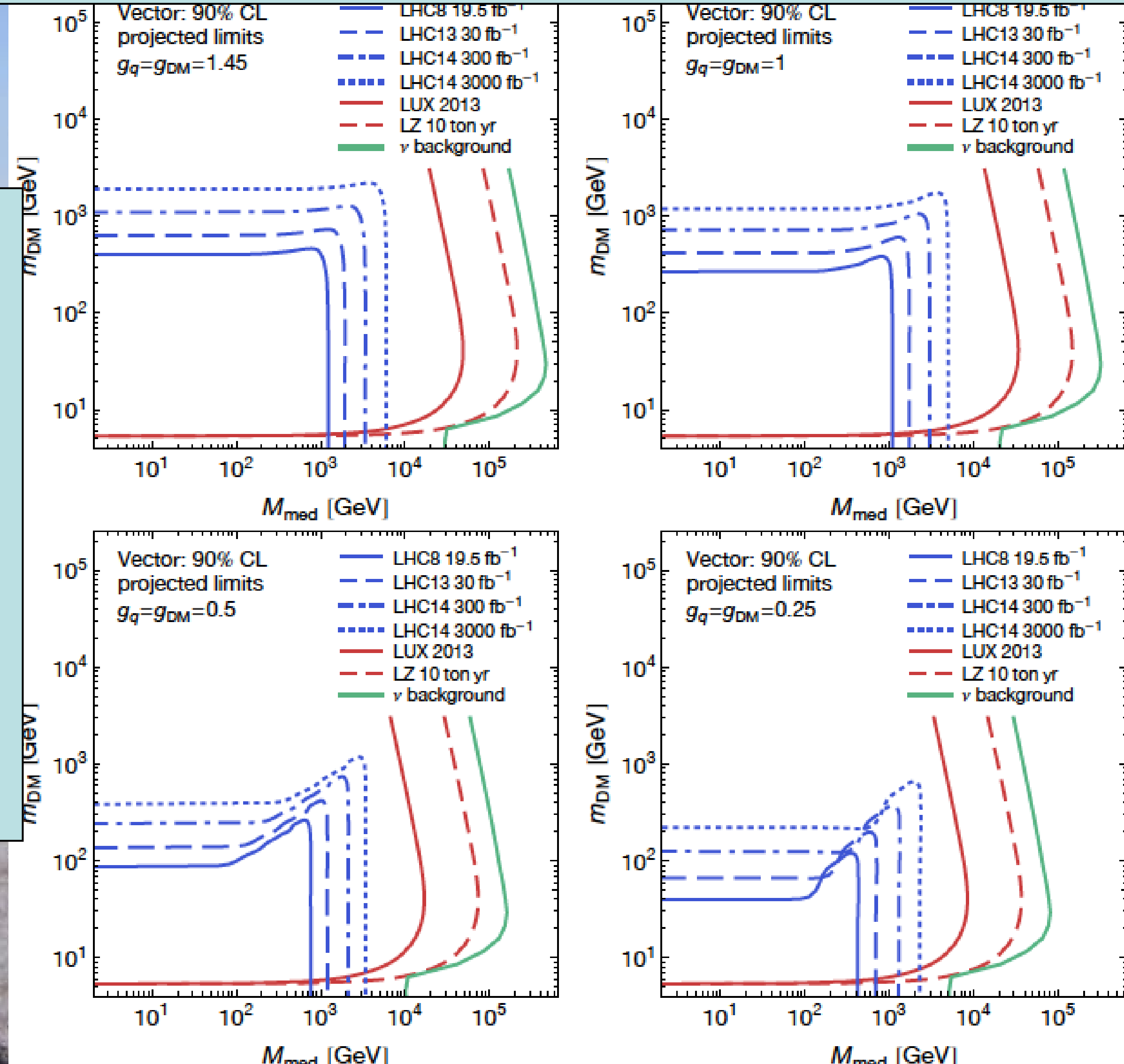
CERN, CH-1211 Geneva 23, Switzerland

Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

Projections for Future

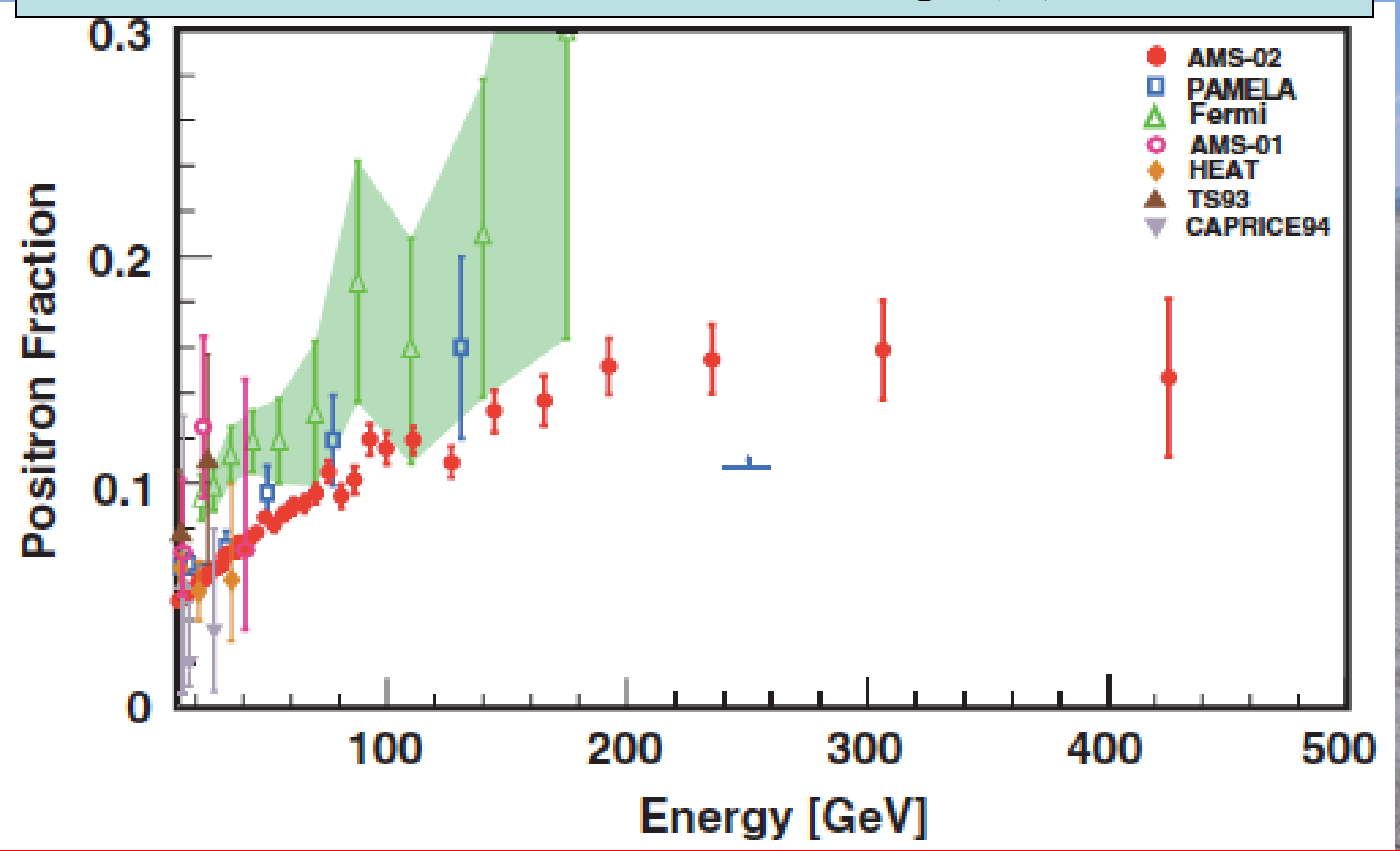
- Via searches for “mono-jets”
- Vector interaction
- Sensitive to mediator mass



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

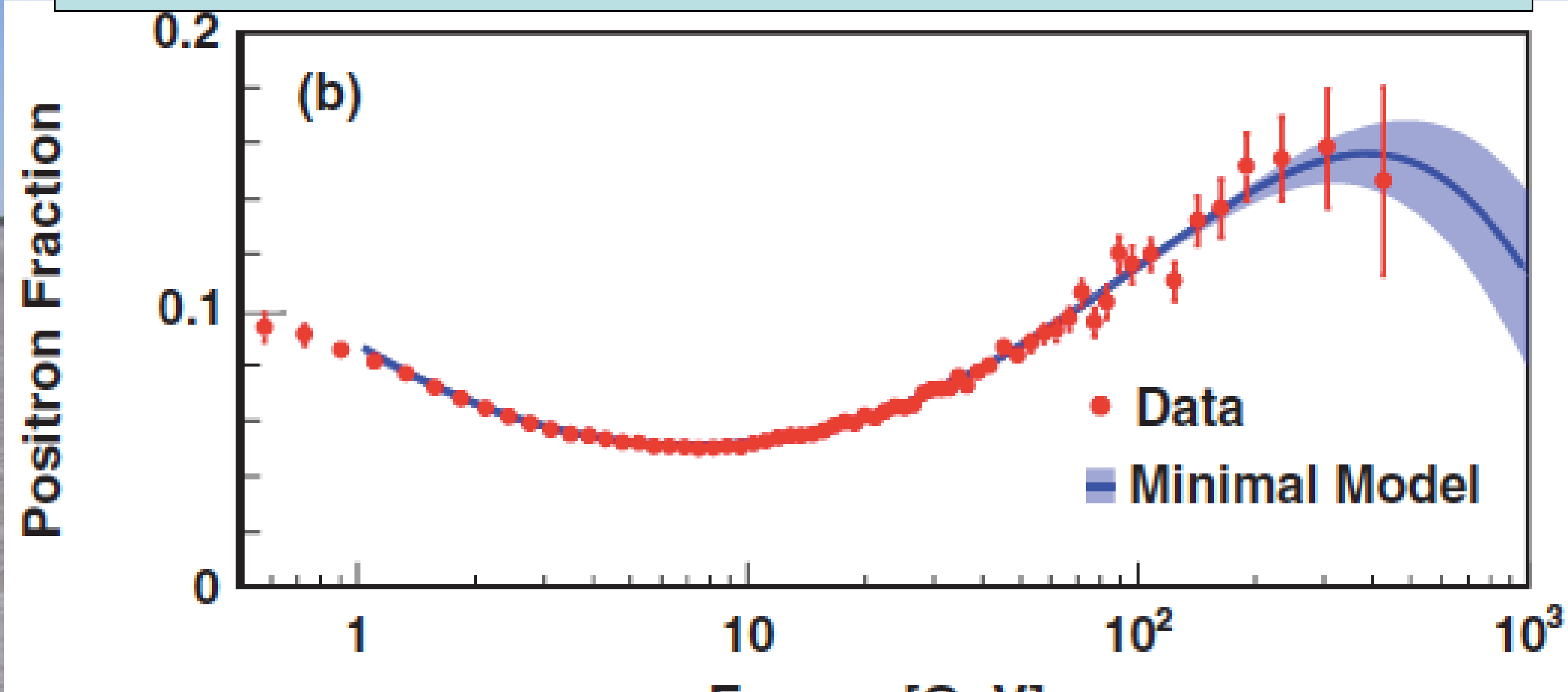

Supersymmetry
in the sky?

Positron Fraction Rising (?) with E



Dark Matter? Galactic cosmic rays? Local sources?

AMS Fit with 2-Component Model



$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

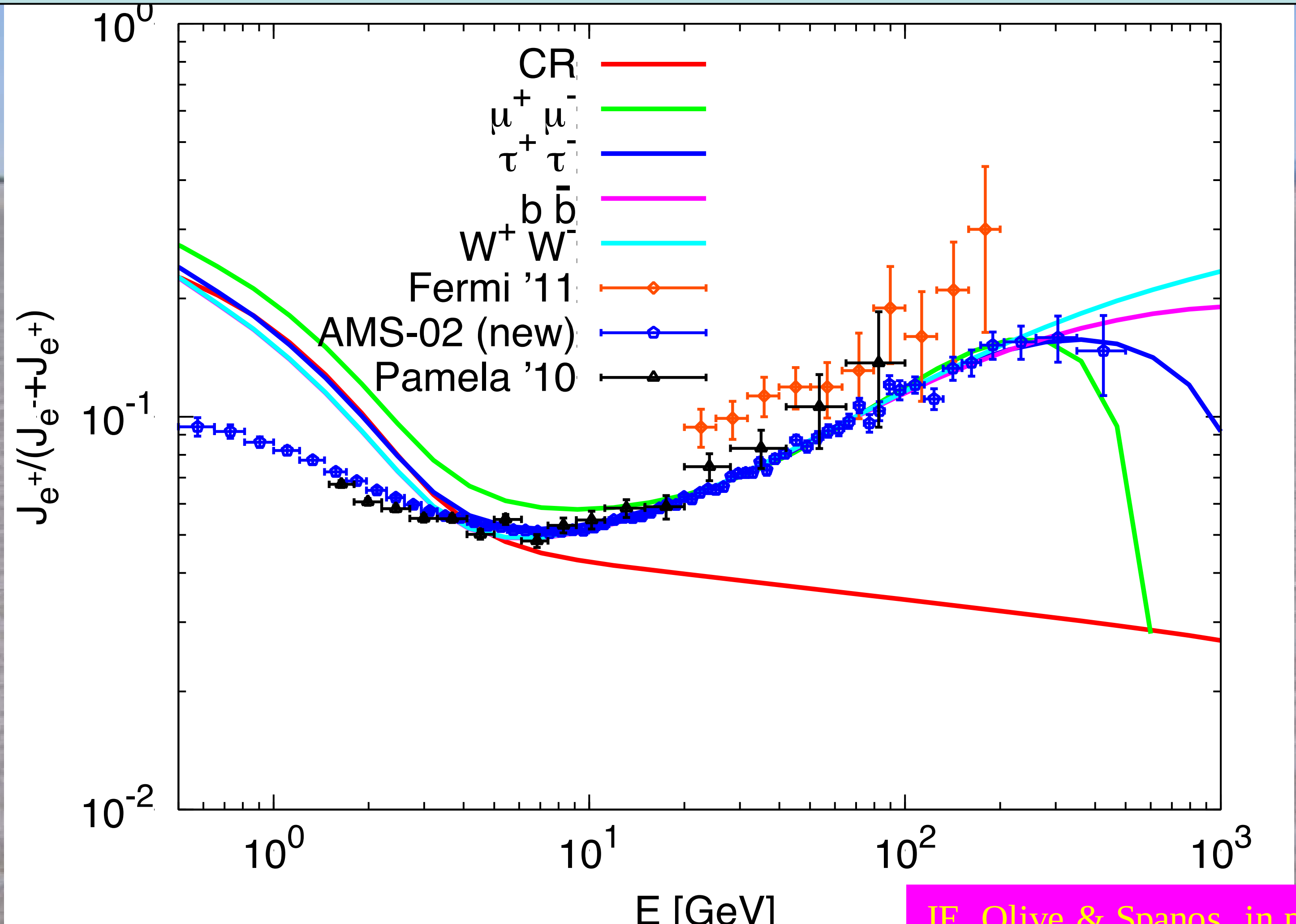
$1/E_s = 1.84 \pm 0.58\ \mathrm{TeV}^{-1}$

$C_{e^+}/C_{e^-} = 0.091 \pm 0.001$, $C_s/C_{e^-} = 0.0061 \pm 0.0009$

$\gamma_{e^-} - \gamma_{e^+} = -0.56 \pm 0.03$, and $\gamma_{e^-} - \gamma_s = 0.72 \pm 0.04$

Could be galactic cosmic rays + local sources?

Dark Matter Fits to AMS Positron Data



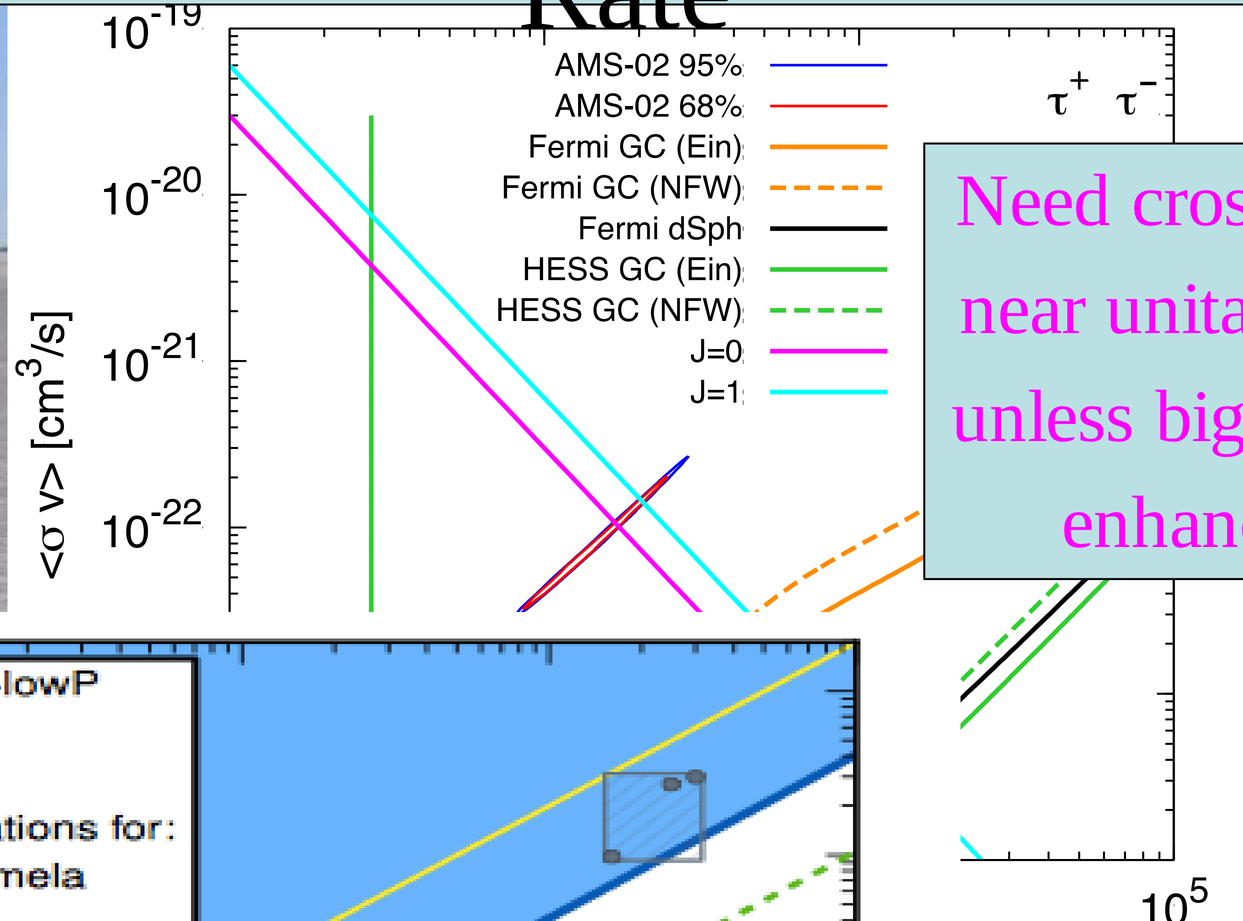
JE, Olive & Spanos, in preparation

Fit with modified GALPROP parameters

BUT

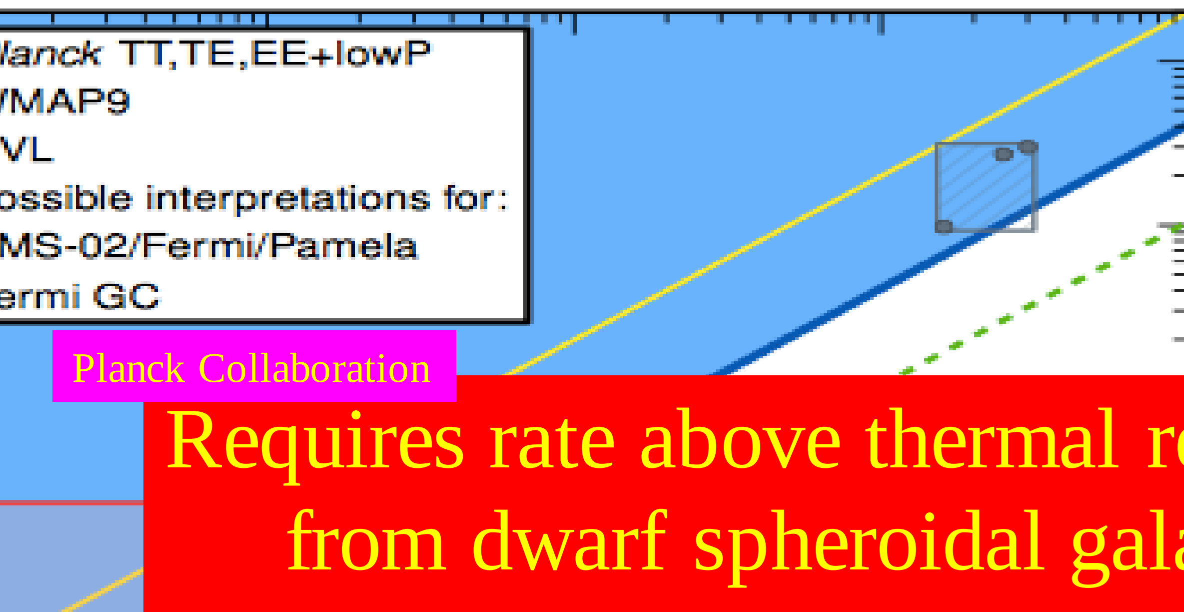
The required annihilation cross-section is VERY large

$\tau^+\tau^-$ Fit needs Large Annihilation Rate



Need cross-section near unitarity limit unless big clumping enhancement

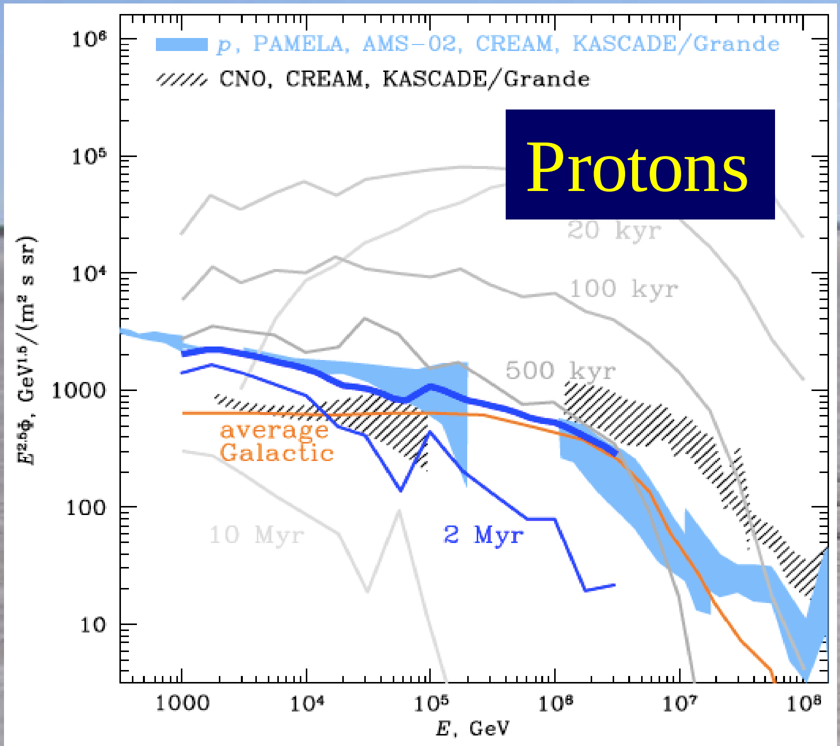
JE, Olive & Spanos, in preparation

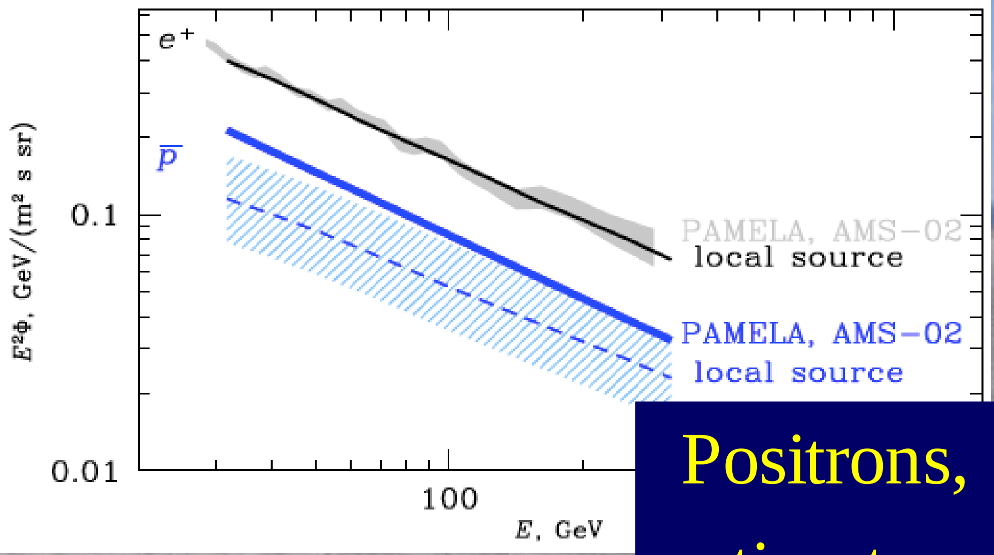


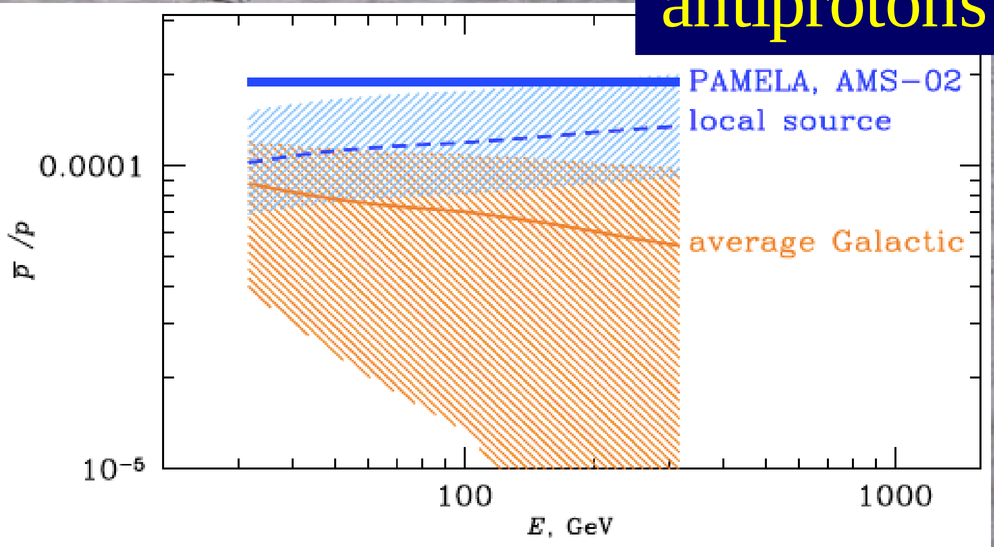
Planck Collaboration

Requires rate above thermal relic value, limits from dwarf spheroidal galaxies, Planck

Local Source of Cosmic Rays?







Positrons, antiprotons

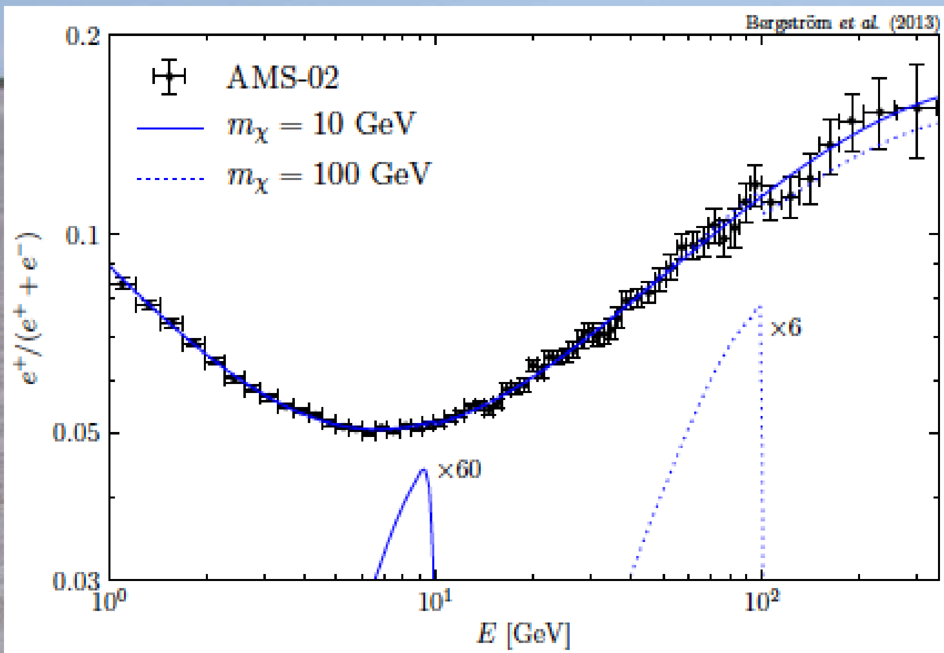
Nearby supernova

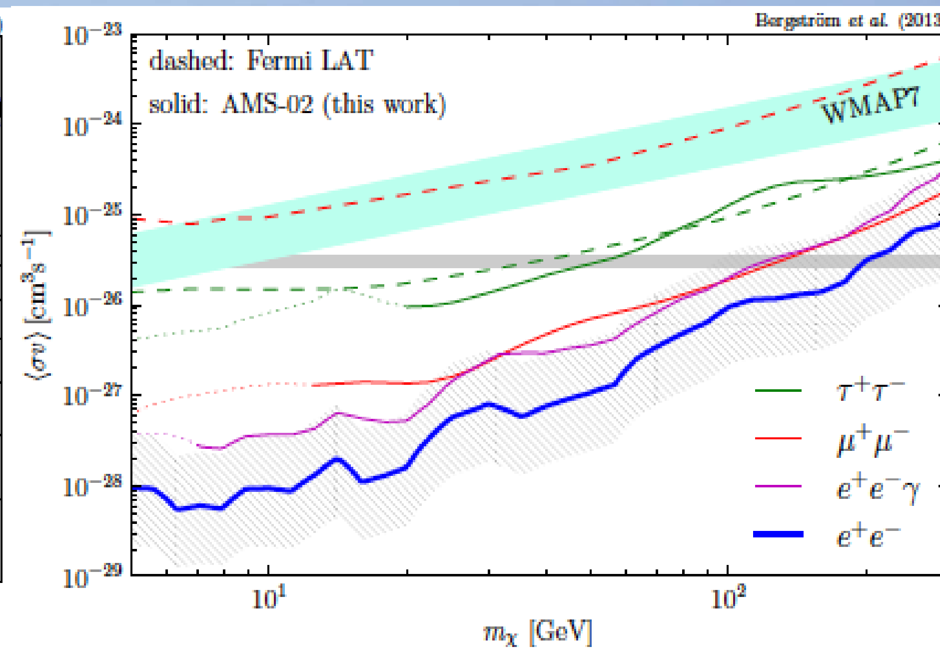
~ 2 million years ago?

Evidence from ^{60}Fe on ocean floor

Kachelriess, Neronov & Semikoz, arXiv:1504.06472

Assume Local Source: Constrain any extra Dark Matter Contribution

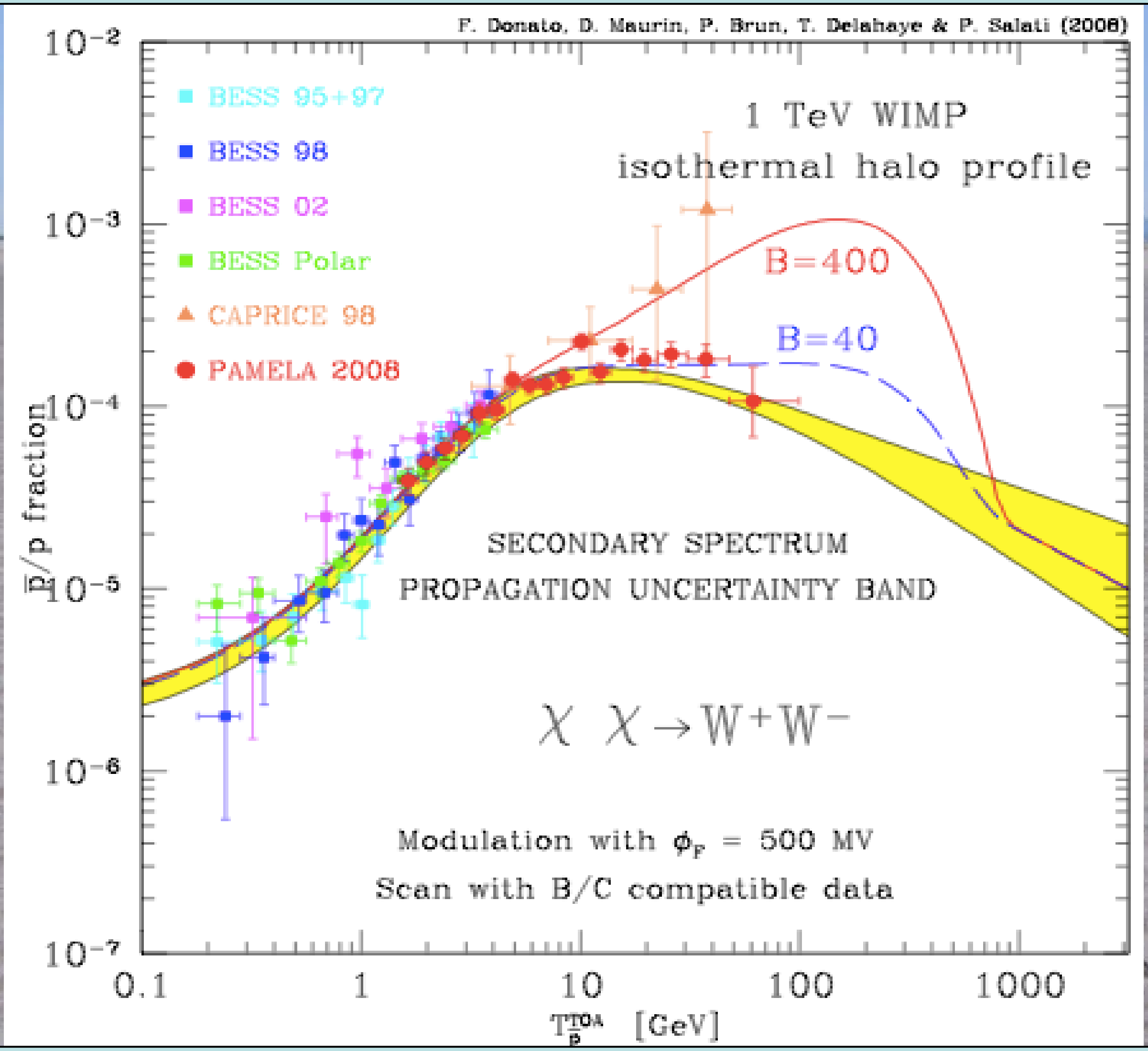




Dark Matter annihilation could give feature above otherwise smooth distribution

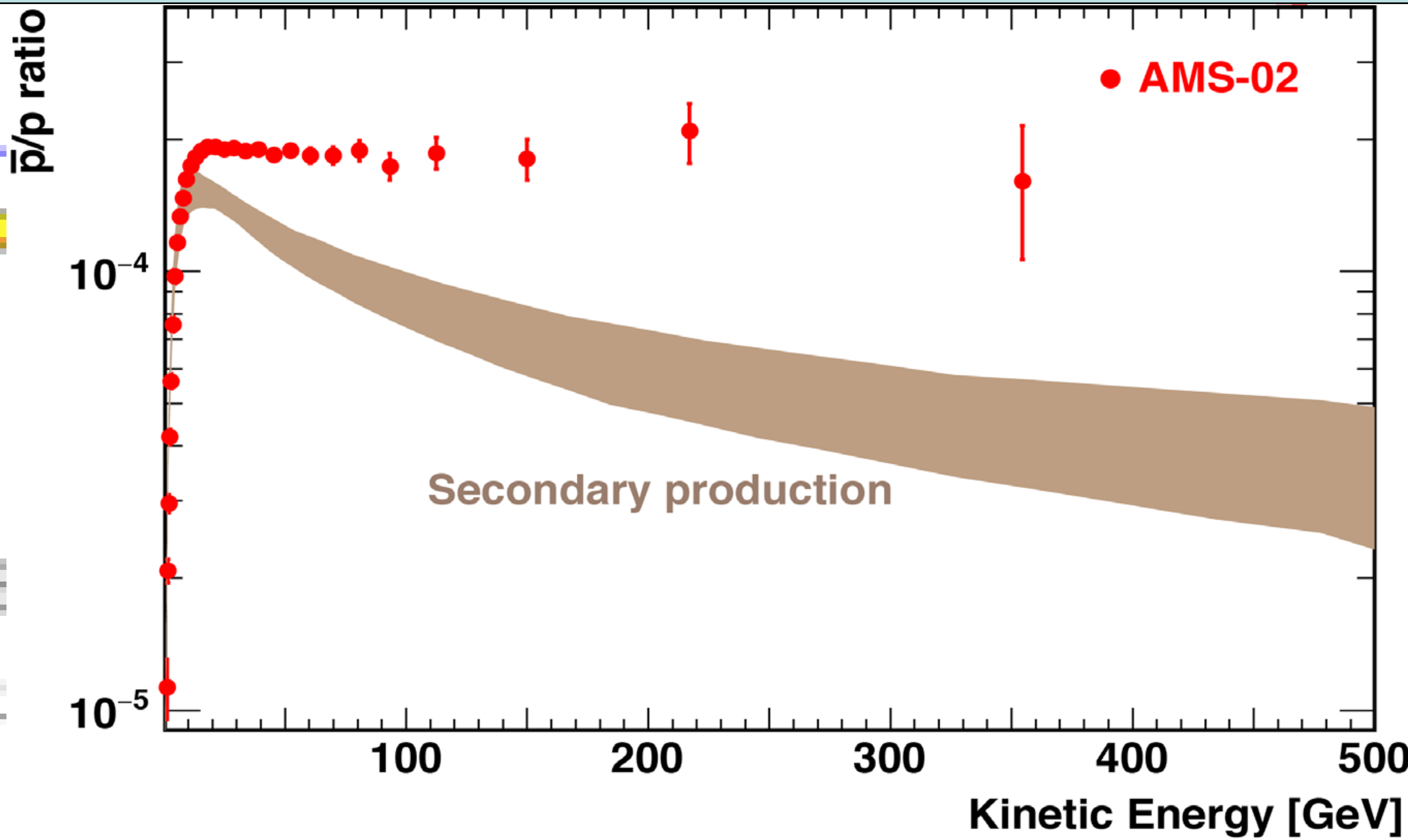
Bergstrom et al, arXiv::1306.3983

Previous Antiproton/Proton Ratio



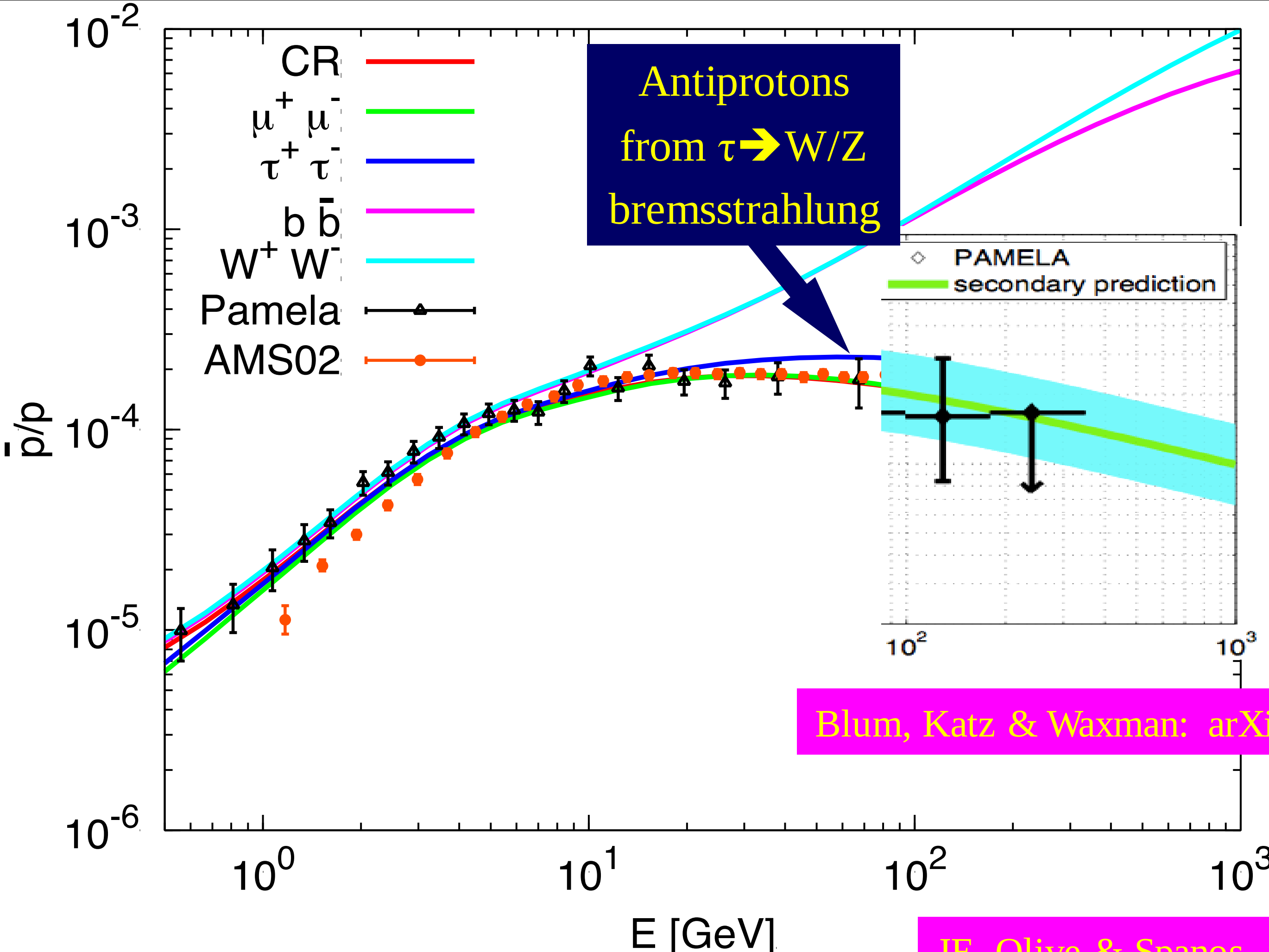
With previous estimate of secondary production

New Antiproton/Proton Ratio



Above previous estimate of secondary production

Antiproton/Proton Ratio

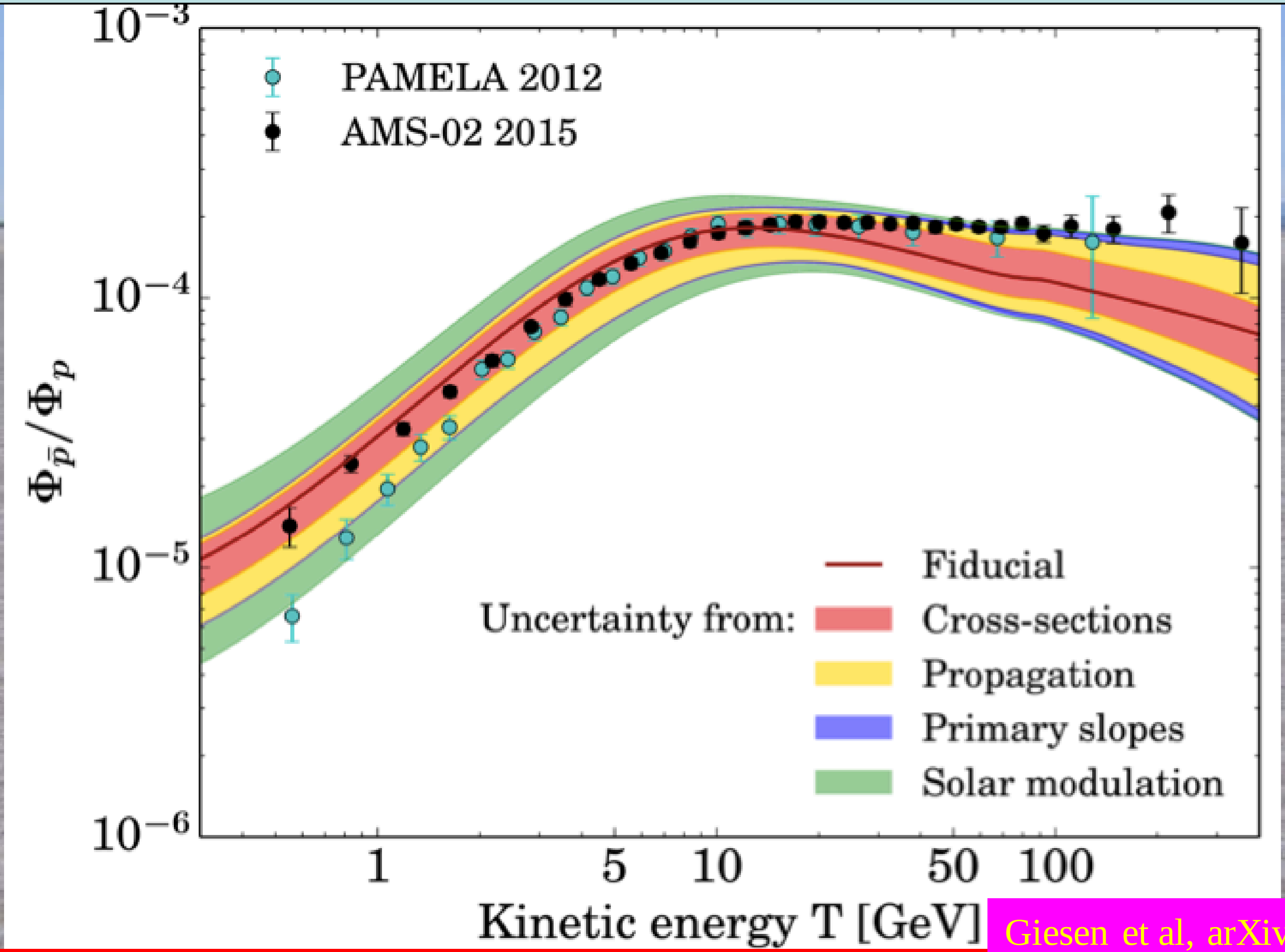


Blum, Katz & Waxman: arXiv:1305.1324

JE, Olive & Spanos, in preparation

GALPROP can give ~ constant ratio > 150 GeV

Antiproton/Proton Ratio



Giesen et al, arXiv:1504.04274

Secondary production compatible with AMS-02