SUSY Overview

Why still love SUSY?

SUSY after $g_\mu - 2$ and Run 2

pMSSM vs GUT-inspired models

Flipped SU(5)

Prospects for discovery in Runs ≥ 3

John Ellis

KING'S College LONDON

What lies beyond the Standard Model?

Supersymmetry

New motivations from LHC

- **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, inflation, **dark matter**, ..

Everything about Higgs is Puzzling

$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0$$

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**

SUSY

- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**

SUSY

- Cosmological constant term V_0:
  - **Dark energy**

SUSY

Supersymmetry & $g_\mu - 2$ go back a long way

- One-loop contribution from smuon/neutralino loop

$$\Delta(g-2)_\mu = -ab(\cos\alpha \sin\alpha/4\pi^2)(m_\mu/m_{\tilde{G}})$$
$$\times \{1/(1-\eta_1) + 2\eta_1/(1-\eta_1)^2$$
$$+ [2\eta_1/(1-\eta_1)^3] \log \eta_1 - (\eta_1 \leftrightarrow \eta_2)\},$$

- where $\eta_i \equiv (m^2_{s\mu_i}/m^2_{\tilde{G}})$

- and $\mathcal{L} = a\sqrt{2}\, s_\mu \bar{\mu}_L \tilde{G} + b\sqrt{2}\, t_\mu \bar{\mu}_R \tilde{G}$

Volume 116B, number 4 PHYSICS LETTERS (1982)

SPIN-ZERO LEPTONS AND THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

John ELLIS, John HAGELIN and D.V. NANOPOULOS
CERN, Geneva, Switzerland

Received 14 June 1982

The anomalous magnetic moment of the muon $(g-2)_\mu$ imposes constraints on the masses and mixing of spin-zero leptons (sleptons). We develop the predictions of models of spontaneous supersymmetry breaking for the slepton mass matrix, and show that they are comfortably consistent with the $(g-2)_\mu$ constraints.

During the present resurgence of interest in supersymmetry broken at low energies [1] new significance is attached to the classical phenomenological playgrounds of gauge theories such as the anomalous magnetic moments of the electron and muon [2], flavour-changing neutral interactions [3–5] parity [6] and *CP* violation [7,8] in the strong interactions. The three latter phenomena make life rather difficult [3,7] for the most general form of soft supersymmetry breaking, whereas simple models [9–11] of spontaneously broken supersymmetry naturally [3,4 7] respect the $\Delta F \neq 0$, *P* and *CP* violation constraints. As for the anomalous magnetic moments of the leptons, it has long been known that they vanish in an exactly supersymmetric theory [12], and Fayet [2] showed that in his model of supersymmetry breaking $(g-2)_\mu$ would be compatible with experiment if the spin-zero muon (smuon) masses were heavier than 15 GeV. Direct experimental searches [13] now exclude the existence of lighter smuons. Fayet's analysis [2] was in the context of a model with a very light photino $\tilde{\gamma}$ (see fig. 1a), and Grifols and Méndez [14] have recently made the interesting observation that his analysis is significantly altered for massive gauginos (see figs. 1b, 1c). They show that there are potentially nontrivial constraints on the smuon masses in models of broken supersymmetry.

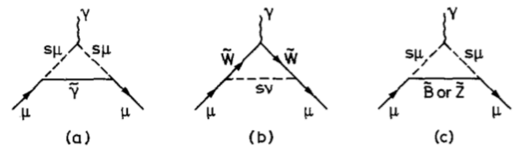


Fig. 1. One-loop diagrams contributing to $(g-2)_\mu$: (a) essentially massless photino $(\tilde{\gamma})$ exchange, (b) $\tilde{W}$ and sneutrino $(s\nu)$ exchange, and (c) $\tilde{B}$ or $\tilde{Z}$ exchange.

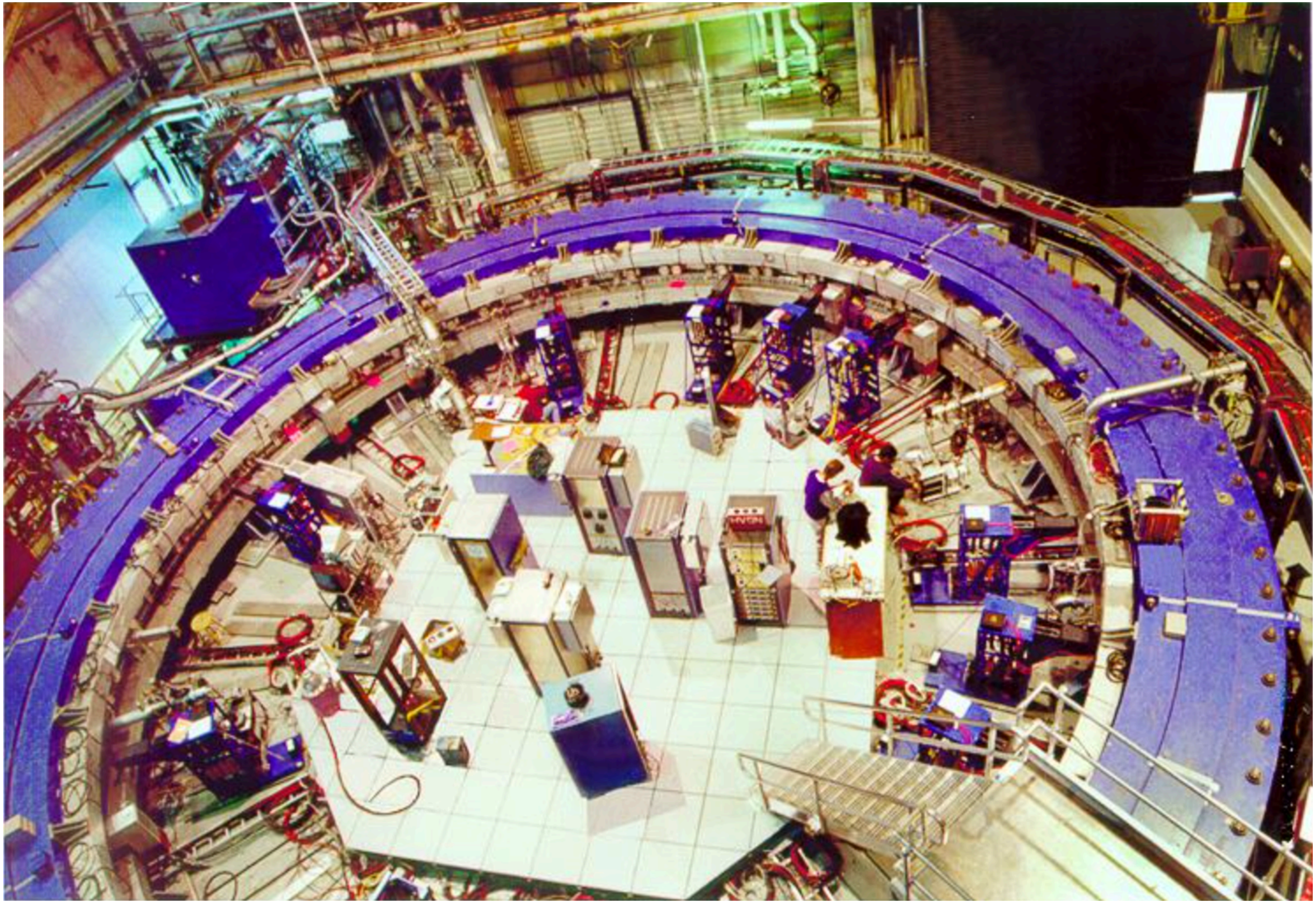
right transition operator there is a GIM [15]-like cancellation between the smuon mass eigenstates in fig. 1c which provides a potential suppression mechanism. We analyze recent models [10,11] of spontaneous supersymmetry breaking originating in the *D* and *F* sectors, respectively. We show that in the former case $(g-2)_\mu$ is suppressed by near degeneracy between the smuon mass eigenstates, while in the latter case $(g-2)_\mu$ is suppressed by small mixing angles between the left- and right-handed smuons. We close with some remarks about $(g-2)_e$ and about parity violation in the strong interactions.

When they examined figs. 1a, 1b and 1c, Grifols and Méndez [14] realized that there was a fundamental difference between the (almost ?) massless $\tilde{\gamma}$ diagram of fig. 1a and the $\tilde{W}$ diagram of fig. 1b as compared to the massive $\tilde{B}$ or $\tilde{Z}$ diagram of fig. 1c. The

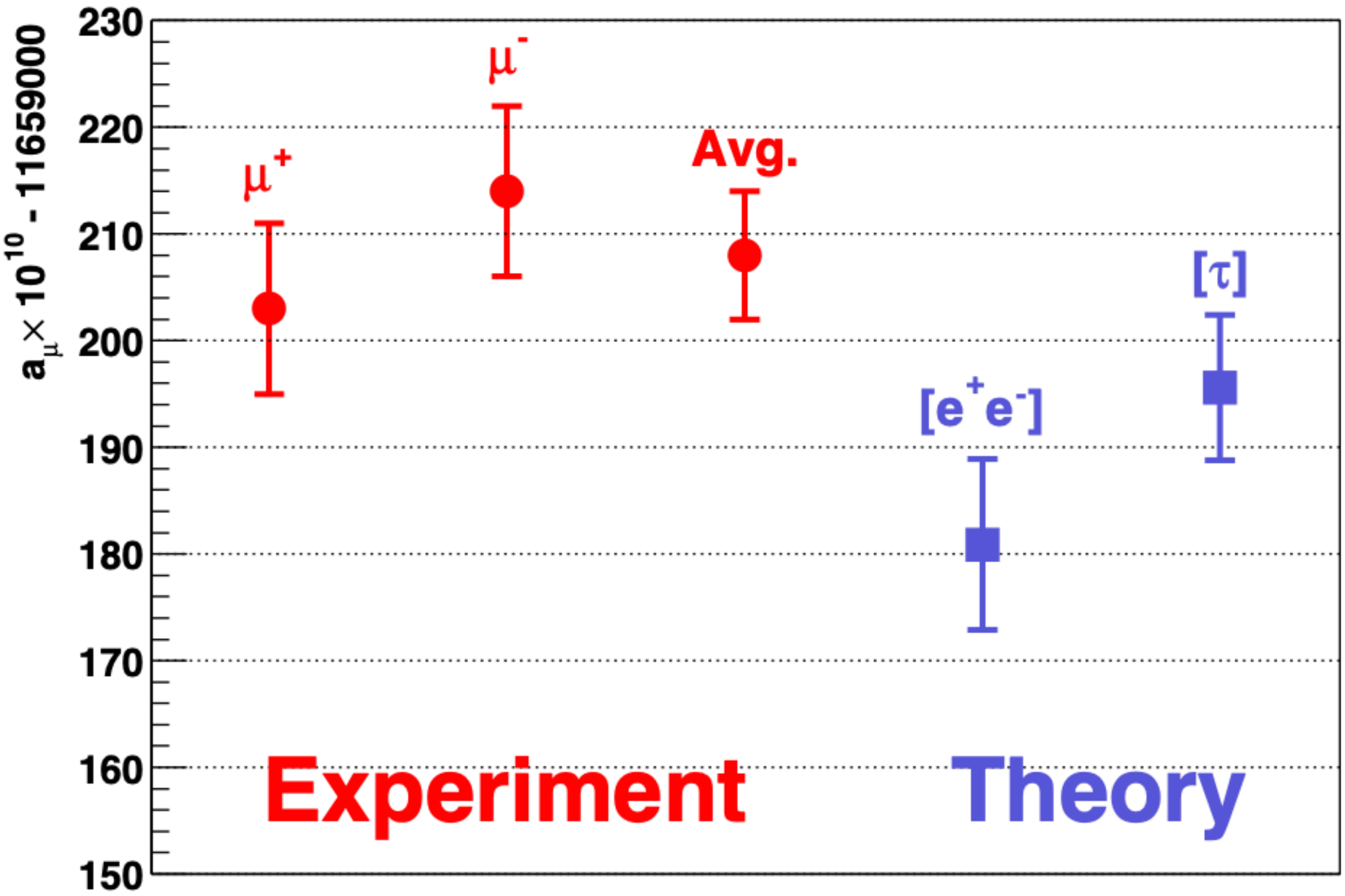
Before idea of supersymmetric dark matter

Even before BNL Experiment

(1984 - 2003)



Did BNL Discover Supersymmetry?



$$\delta a_\mu = \pm 0.47 \text{ ppm}$$

BNL E821 experiment, 2001 - 2006

$g_\mu - 2$ & DM in Supersymmetry v2: the CMSSM

N·H
ELSEVIER

24 May 2001

Physics Letters B 508 (2001) 65–73

PHYSICS LETTERS B

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Combining the muon anomalous magnetic moment with other constraints on the CMSSM

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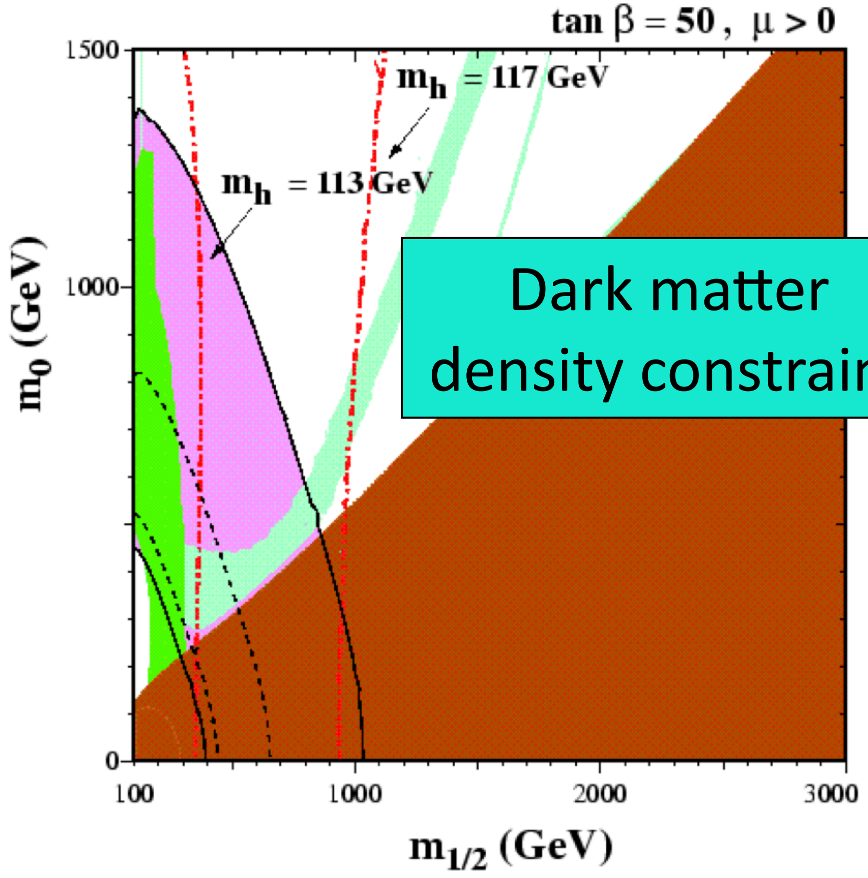
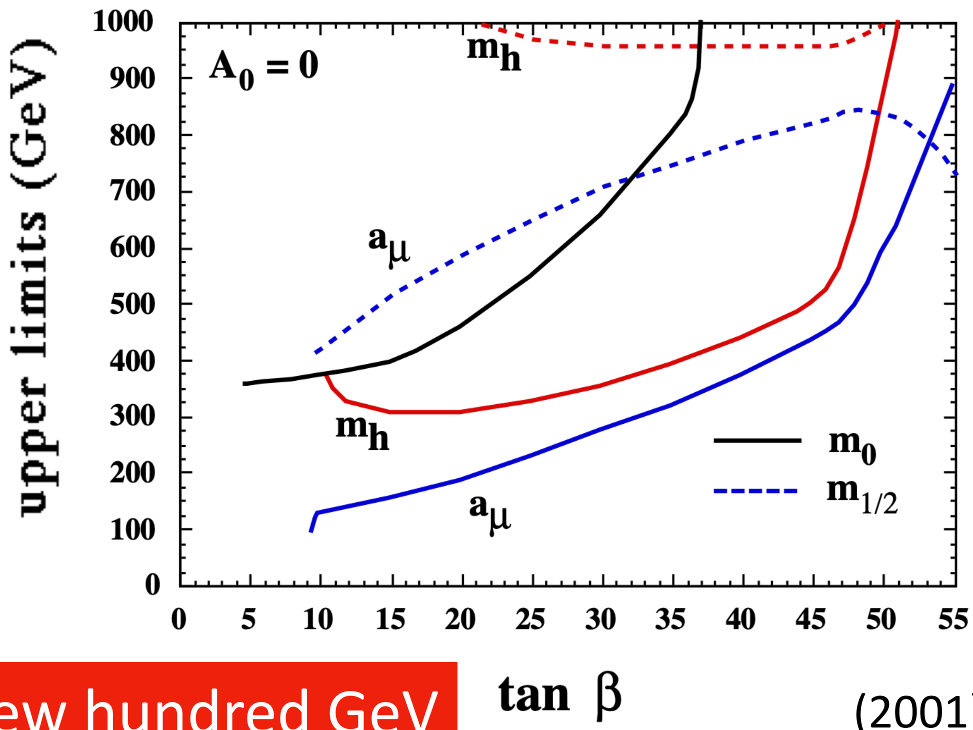
Received 16 March 2001; accepted 10 April 2001
Editor: R. Gatto

Abstract

We combine the constraint suggested by the recent BNL E821 measurement of the anomalous magnetic moment of the muon on the parameter space of the constrained MSSM (CMSSM) with those provided previously by LEP, the measured rate of $b \to s\gamma$ decay and the cosmological relic density $\Omega_\chi h^2$. Our treatment of $\Omega_\chi h^2$ includes carefully the direct-channel Higgs poles in annihilation of pairs of neutralinos χ and a complete analysis of $\chi - \tilde{\ell}$ coannihilation. We find excellent consistency between all the constraints for $\tan\beta \gtrsim 10$ and $\mu > 0$, for restricted ranges of the CMSSM parameters m_0 and $m_{1/2}$. All the preferred CMSSM parameter space is within reach of the LHC, but may not be accessible to the Tevatron collider, or to a first-generation e^+e^- linear collider with centre-of-mass energy below 1.2 TeV. © 2001 Published by Elsevier Science B.V.



Dark matter density constraint



Sparticle masses a few hundred GeV

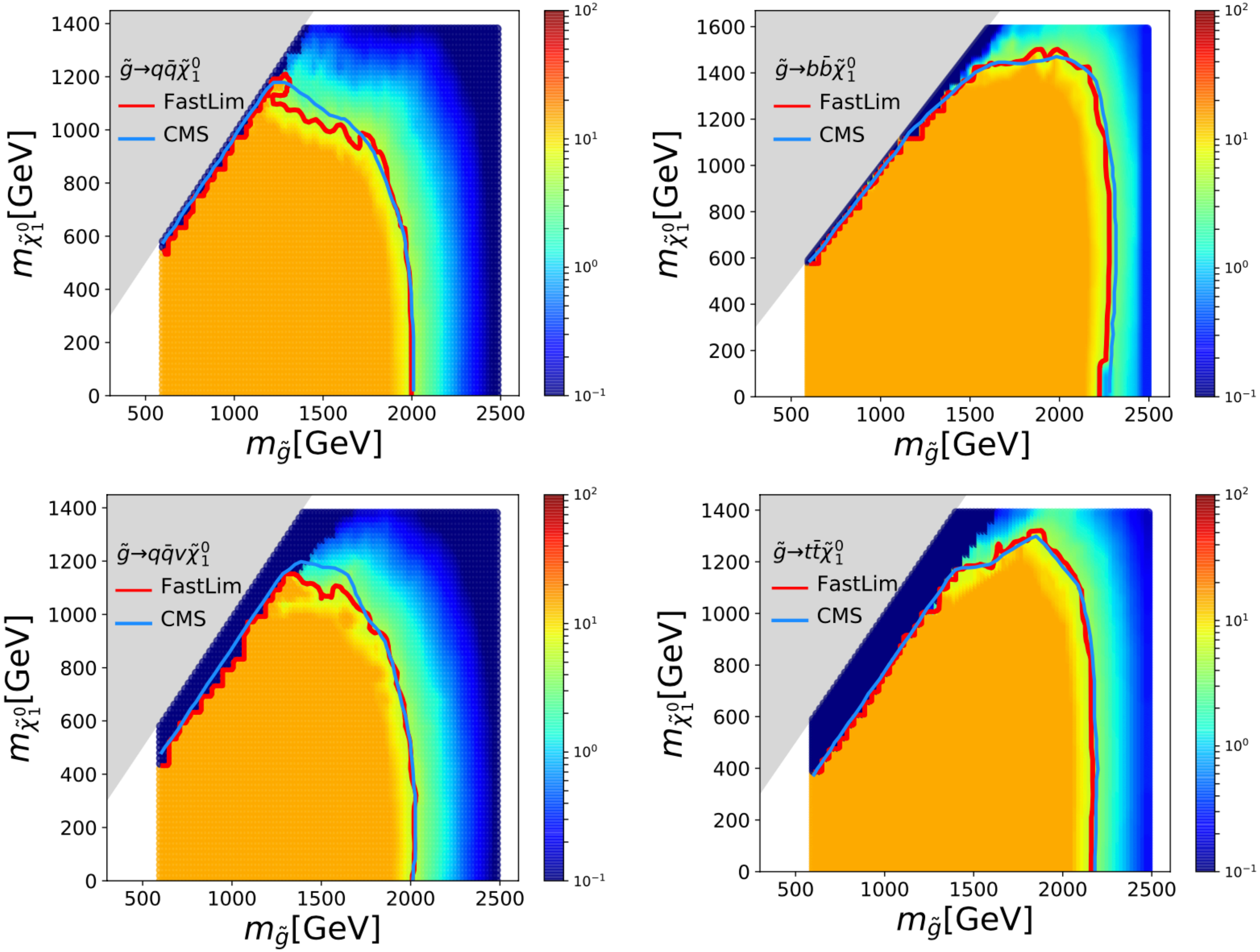
(2001)

Impact of LHC

Modelling LHC Constraints

Gluino decays:

Reproduce LHC constraints using FastLim (does what it says on the tin)



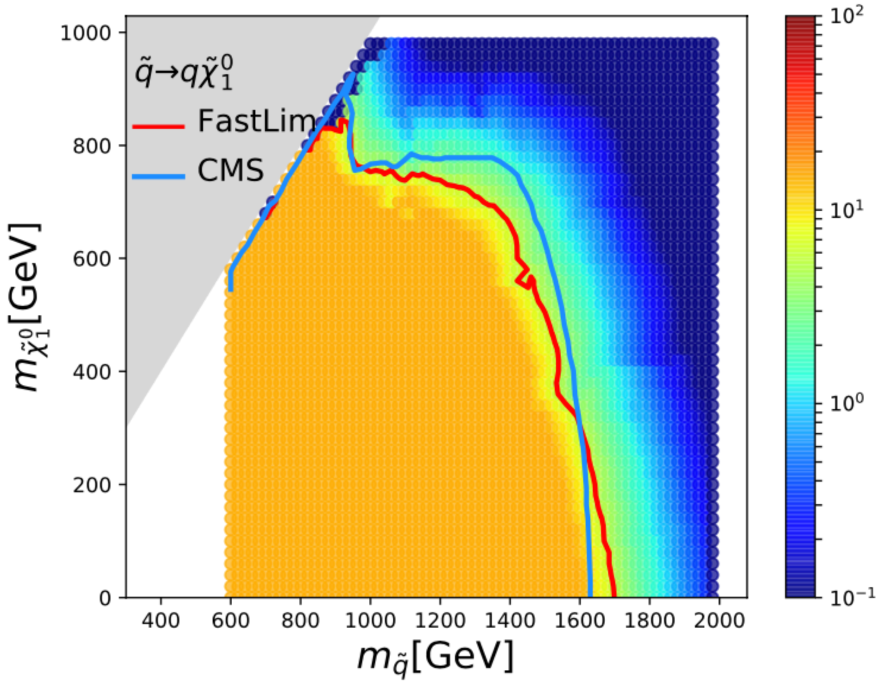
MasterCode, E. Bagnaschi, …, JE et al, arXiv:2111.xxxxx

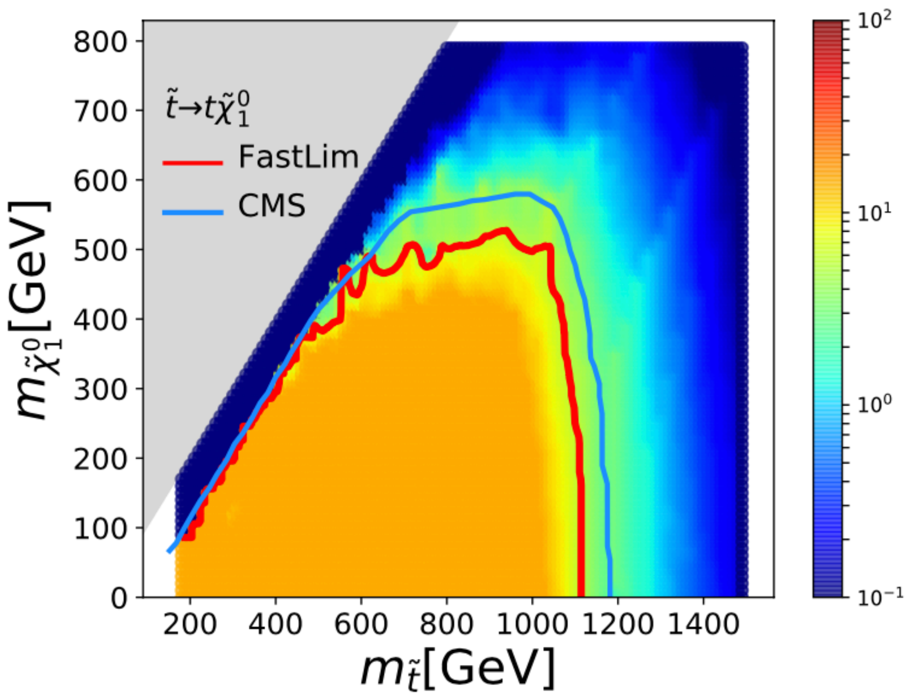
Impact of LHC

Modelling LHC Constraints

Squark and stop decays:

Reproduce LHC constraints using FastLim (does what it says on the tin)

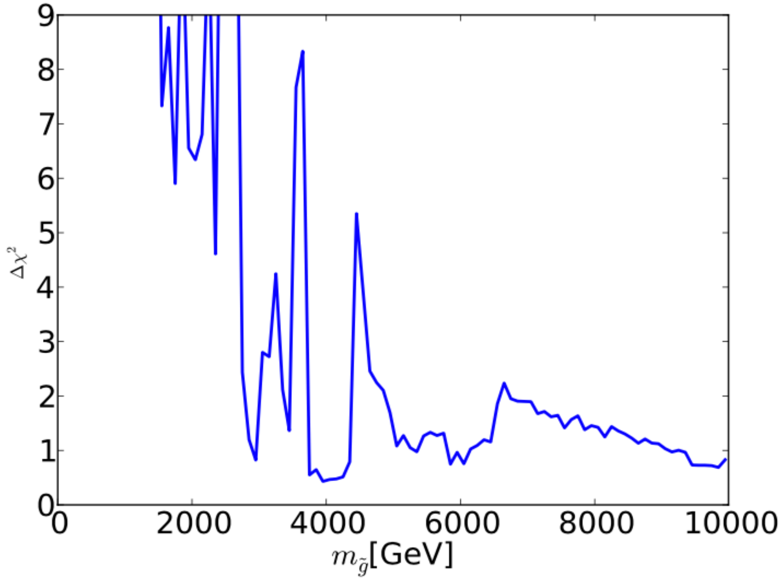


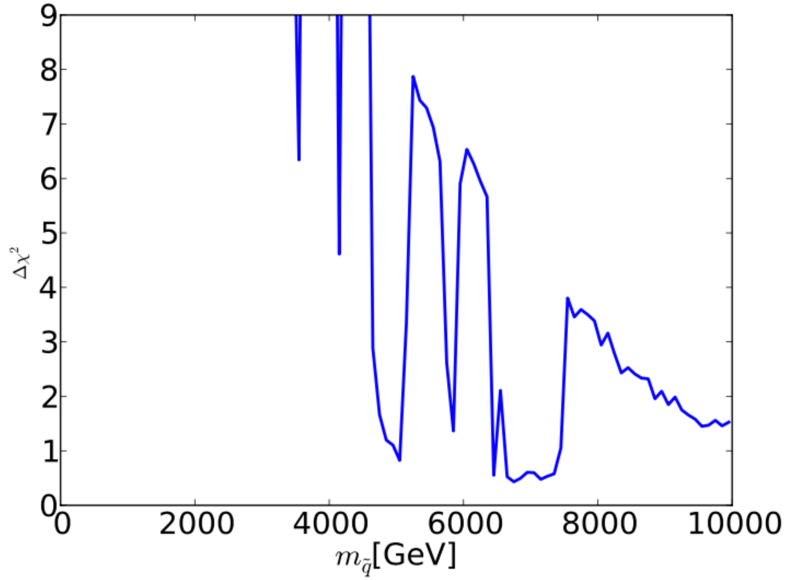


MasterCode, E. Bagnaschi, …, JE et al, arXiv:2111.xxxxx

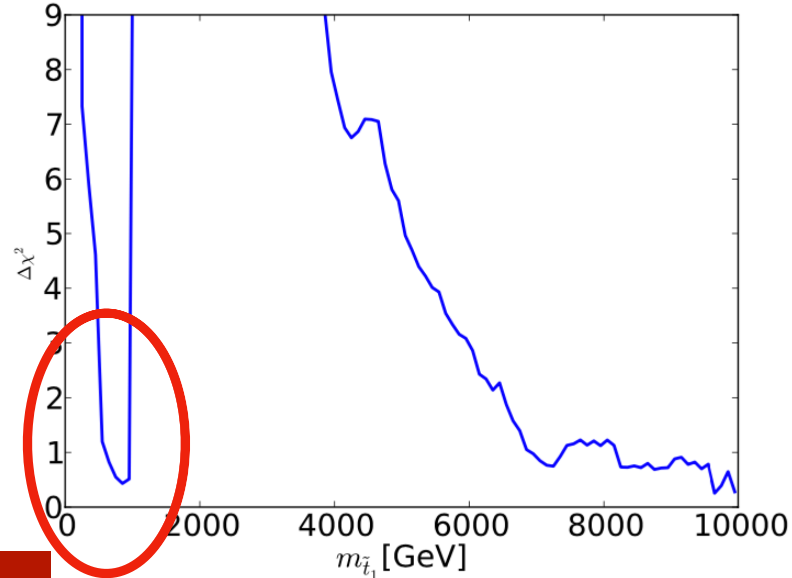
Impact of LHC

1D Profiled Likelihoods in CMSSM





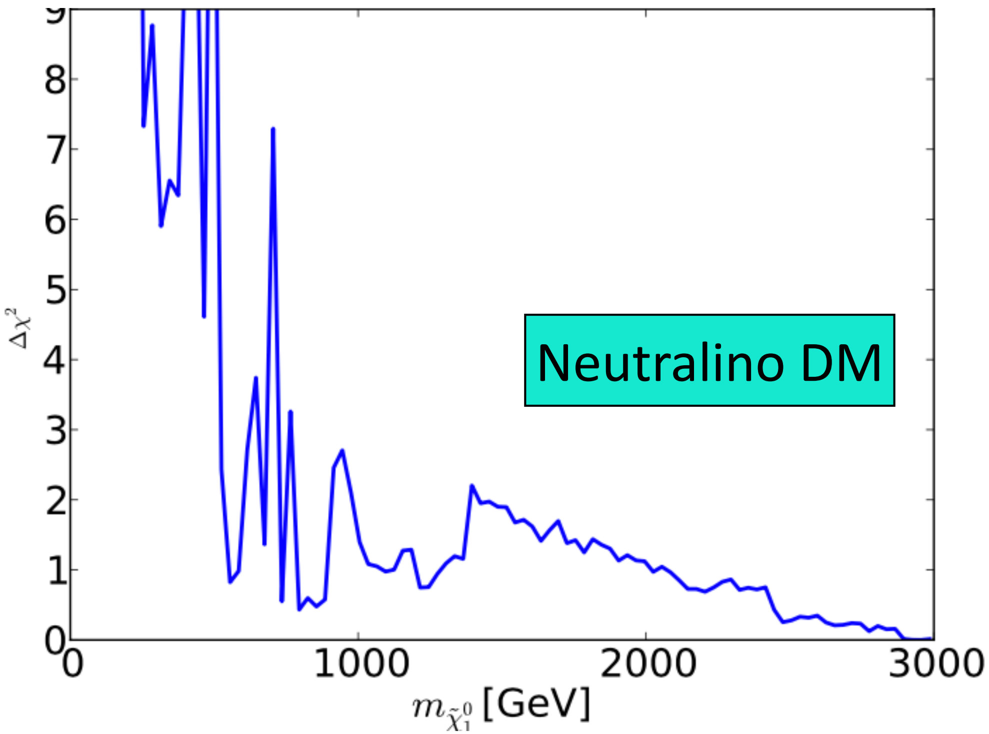
- Heavy squarks
- Very heavy gluon
- **Possibility of stop < 1 TeV**

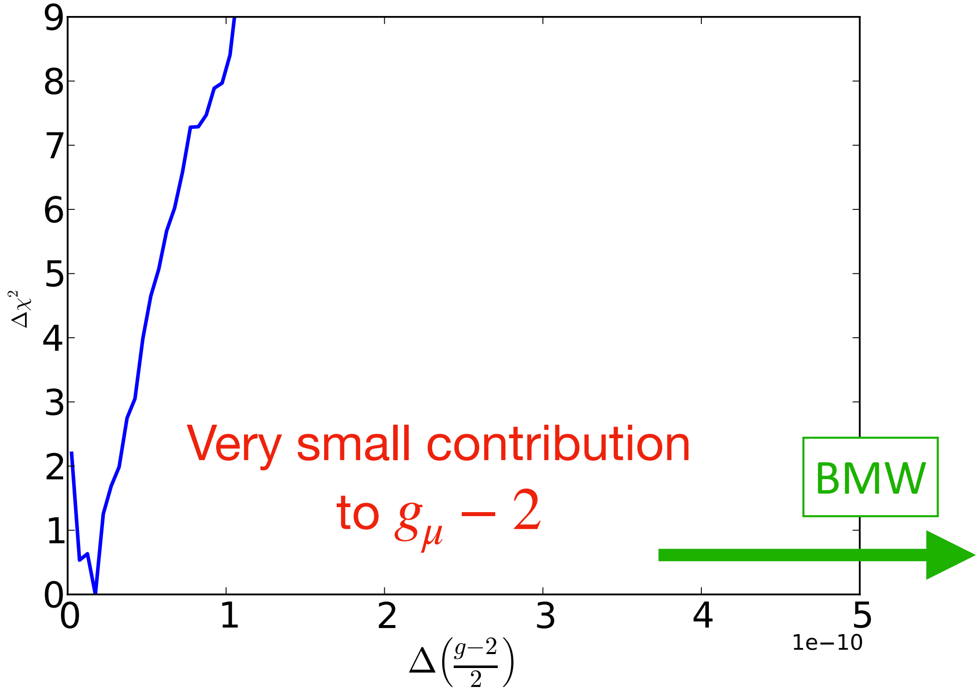


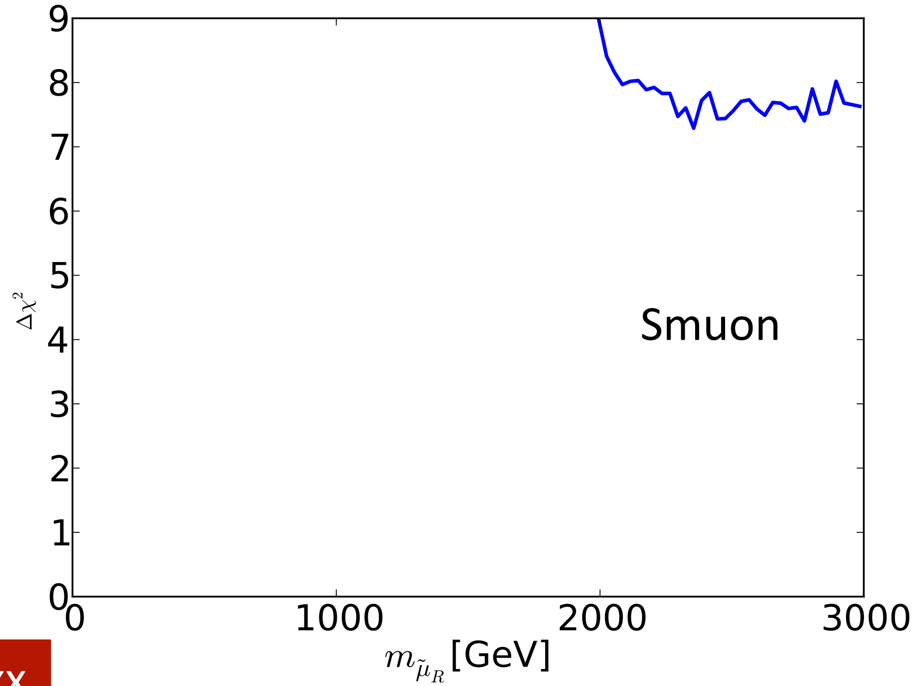
MasterCode, E. Bagnaschi, …, JE et al, arXiv:2111.xxxxx

Impact of LHC

$g_\mu - 2$ in CMSSM



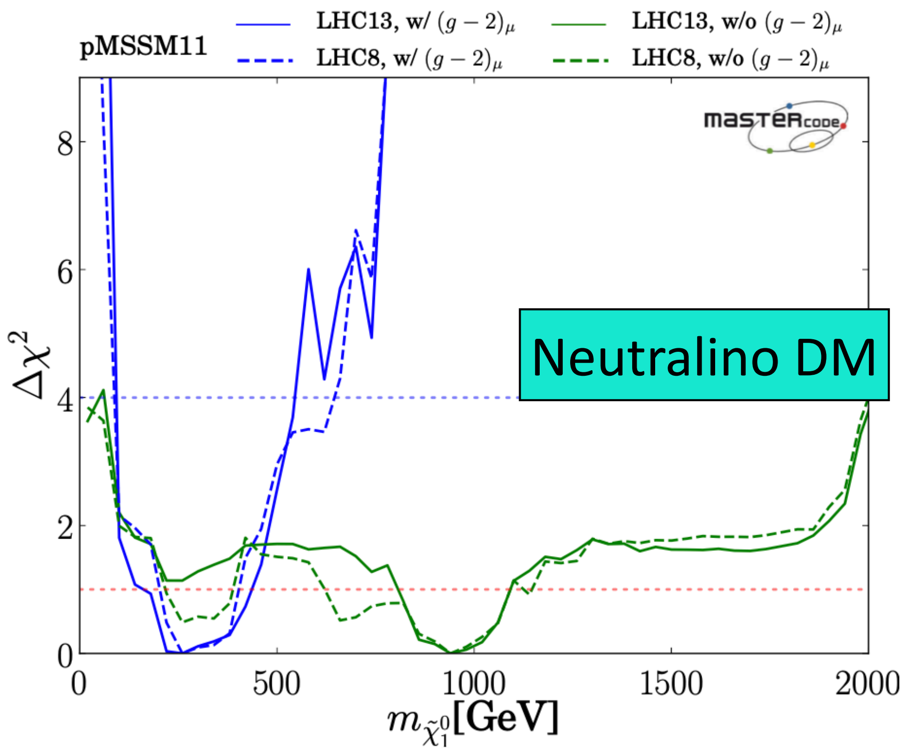




Scenario relates squark & gluino masses
to sleptons and neutralino
Cannot accommodate BNL/FNAL result
Smuon masses $\gtrsim 4$ TeV

MasterCode, E. Bagnaschi, …, JE et al, arXiv:2111.xxxxx

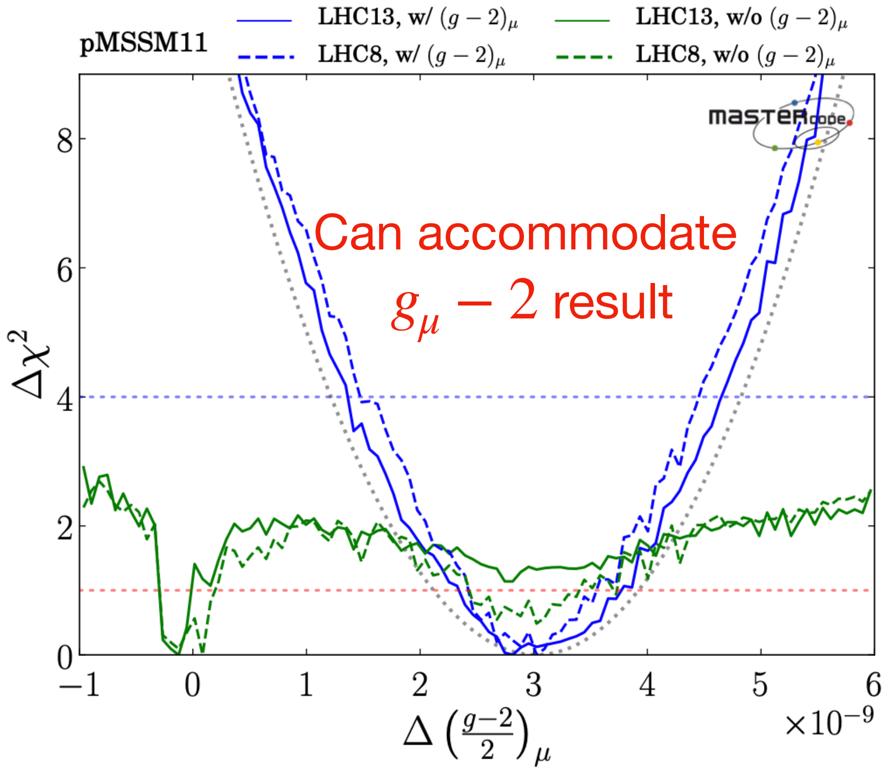
$g_\mu - 2$ in Phenomenological Supersymmetry
(pMSSM11)

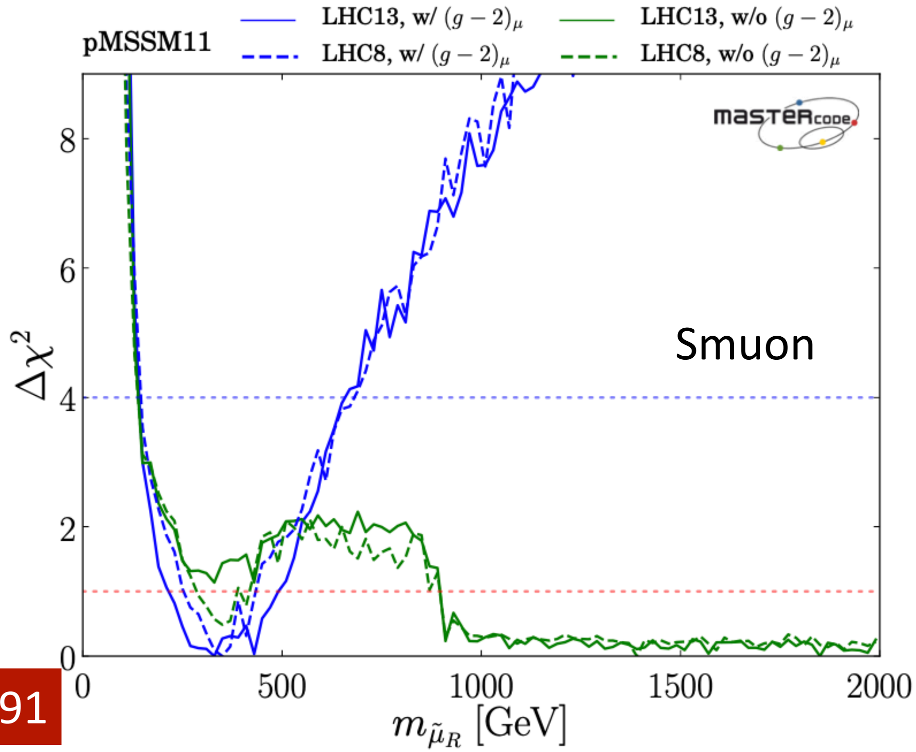


No relation between squark & gluino masses and sleptons and neutralino

No problem accommodating BNL/FNAL result

Neutralino DM, smuon masses $\sim 300/400$ GeV

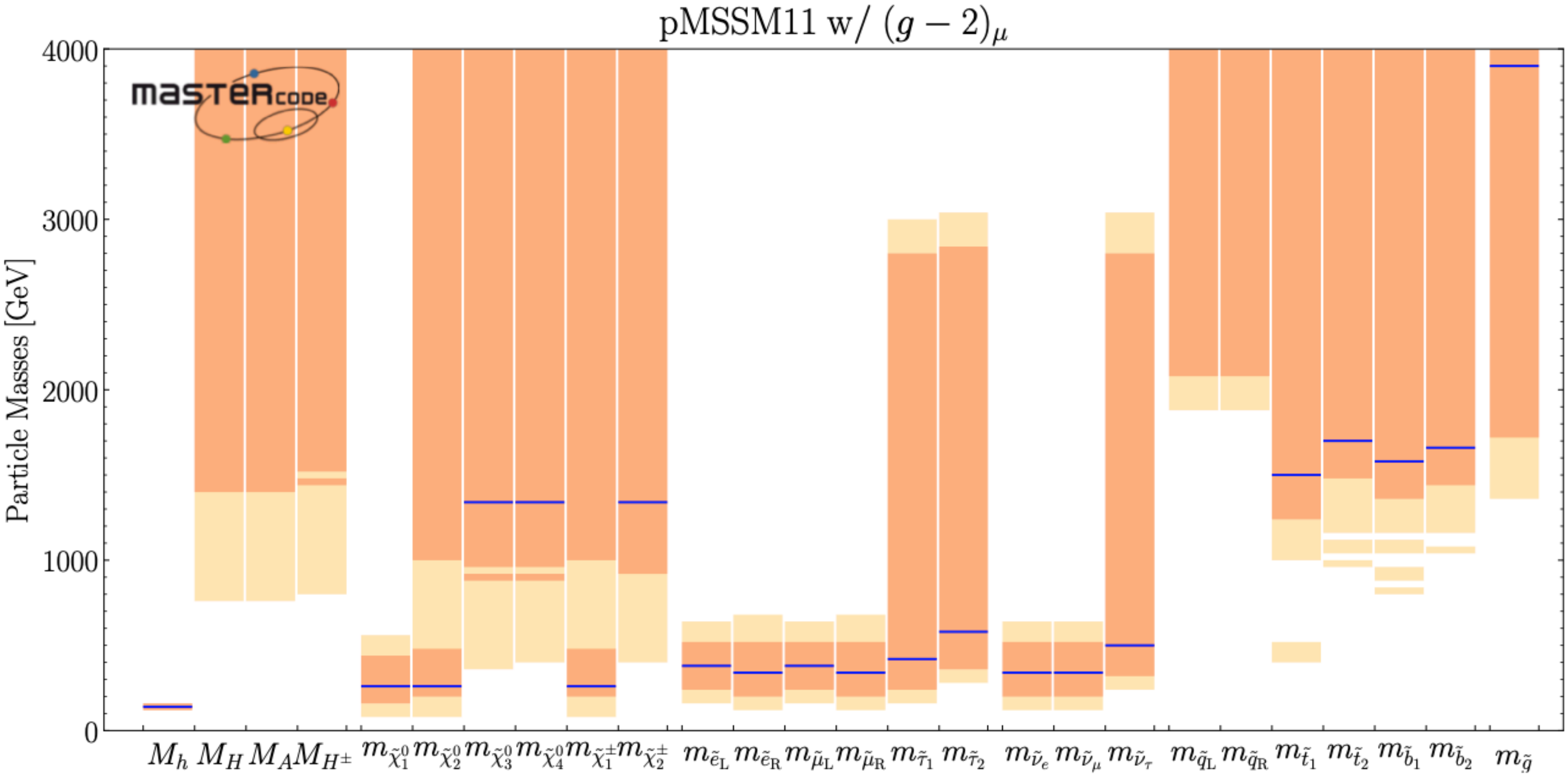




MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Phenomenological MSSM (pMSSM11)

Particle Spectrum with $g_\mu - 2$ Constraint

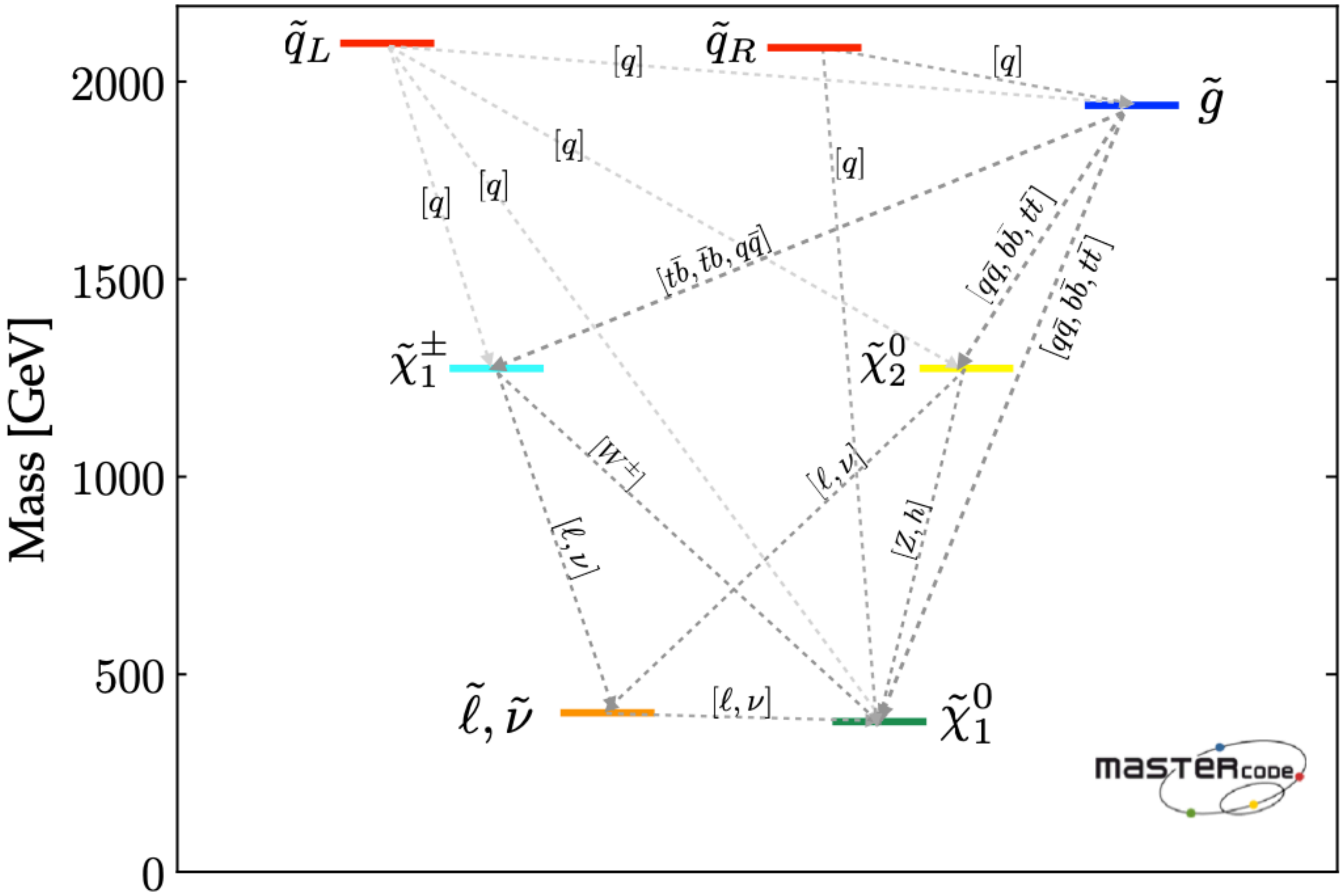


- **Possibilities for the LHC?**

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Phenomenological MSSM (pMSSM11)

Particle Decays with $g_\mu - 2$ Constraint



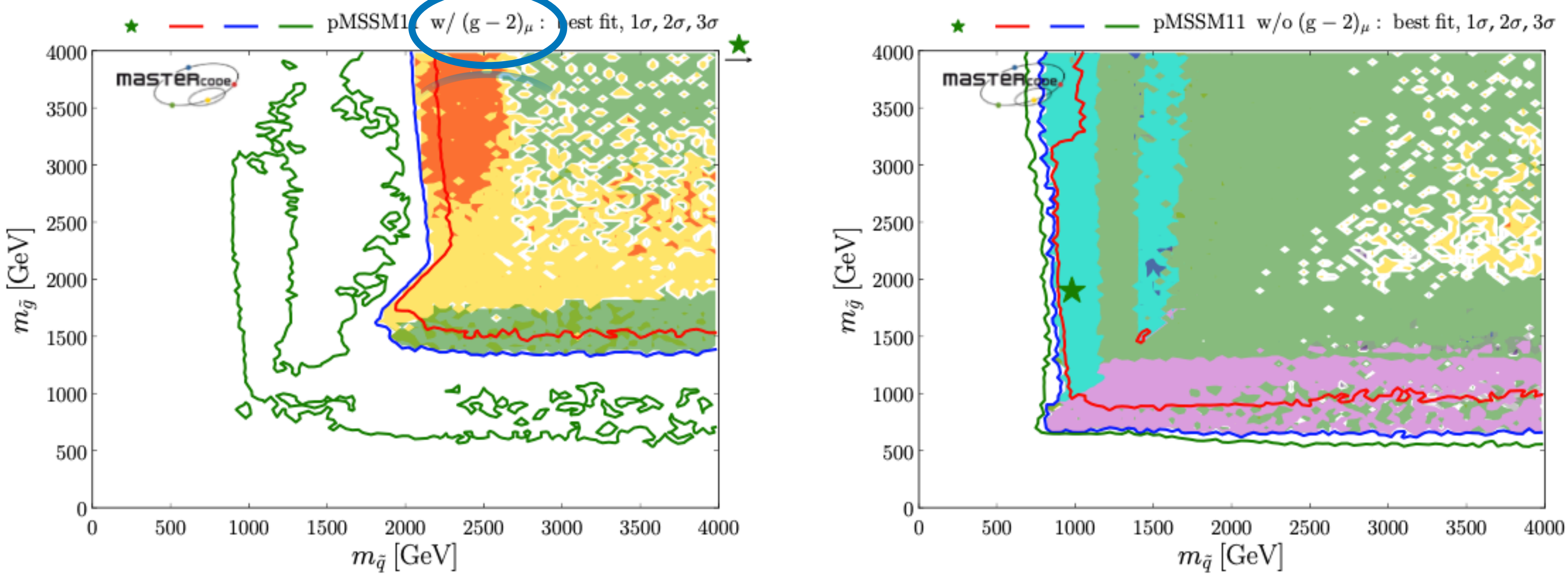
- **Possibilities for the LHC?**

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Phenomenological MSSM (pMSSM11)

LHC Constraints on Squarks & Gluinos

- Squarks and gluinos **with** and without $g_\mu - 2$ constraint



- Colour coded for dominant dark matter mechanism

$\tilde{\chi}_1^\pm$ coann. | slep coann. | gluino coann. | stop coann.
A/H funnel | stau coann. | squark coann. | sbot coann.

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MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

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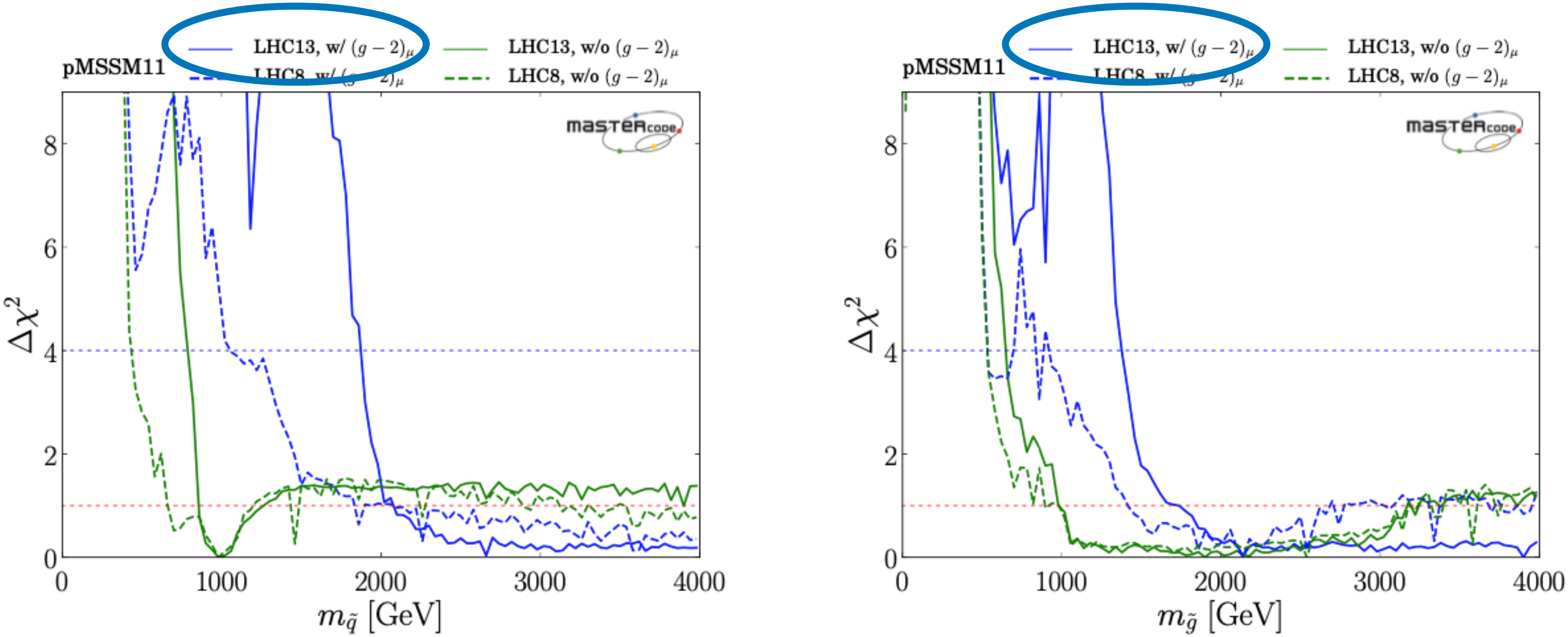


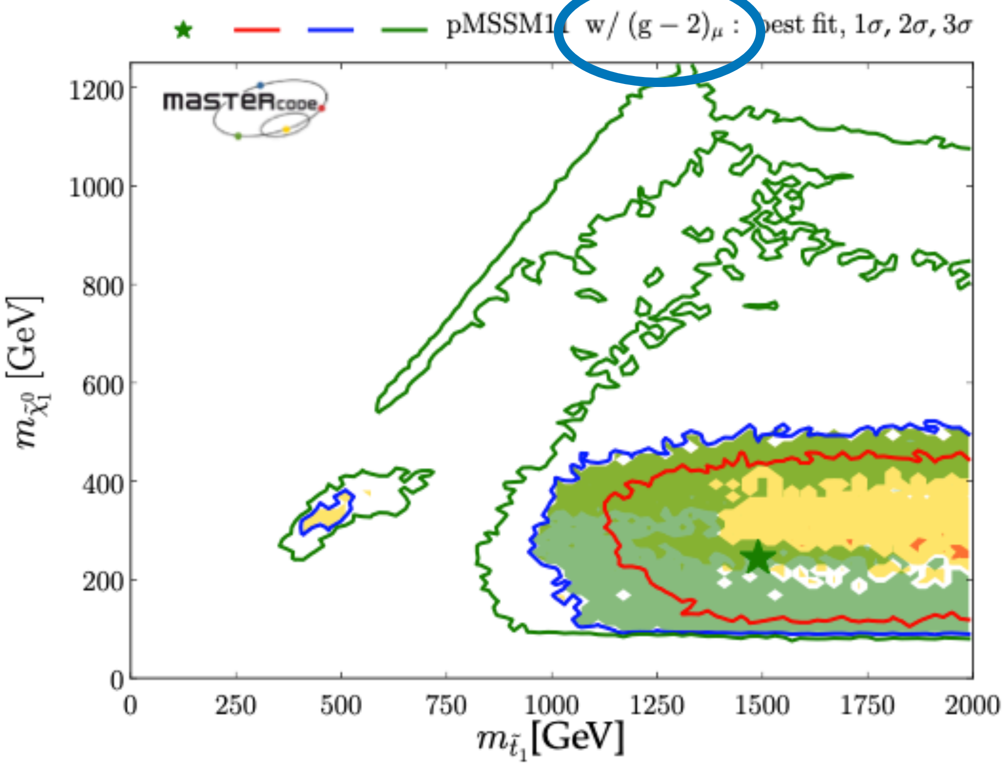
- **Possibilities for the LHC?**

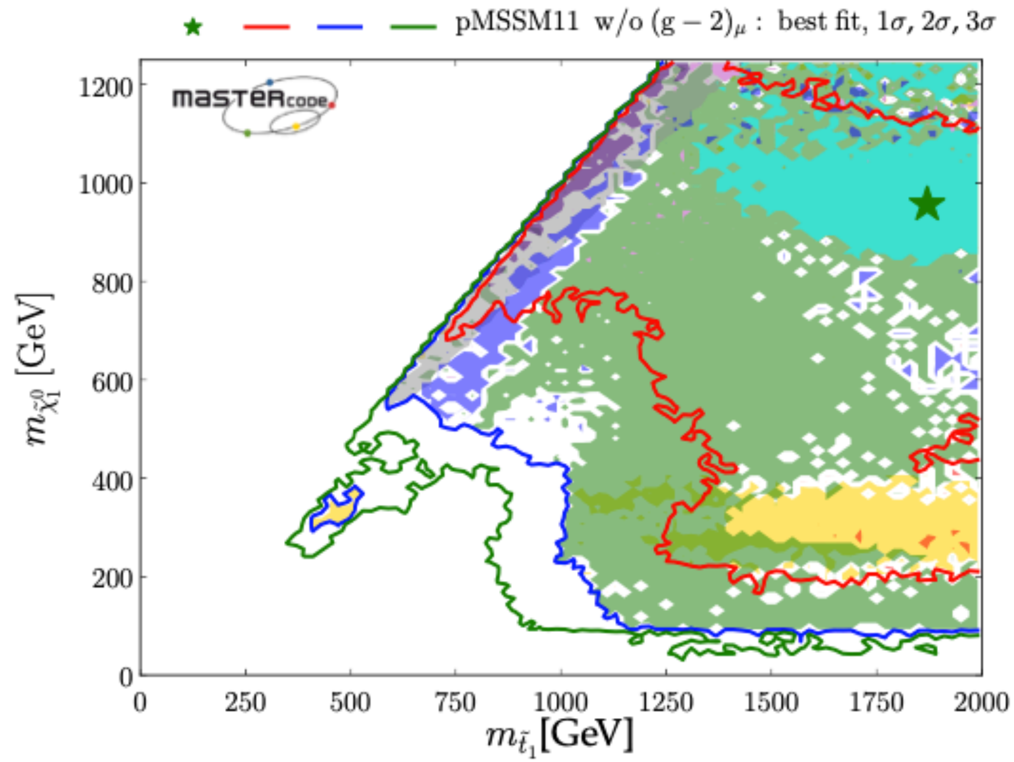
MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Phenomenological MSSM (pMSSM11)

LHC Constraints on Stop & Neutralino

- Stop and neutrino **with** and without $g_\mu - 2$ constraint





- Colour coded for dominant dark matter mechanism

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- slep coann.
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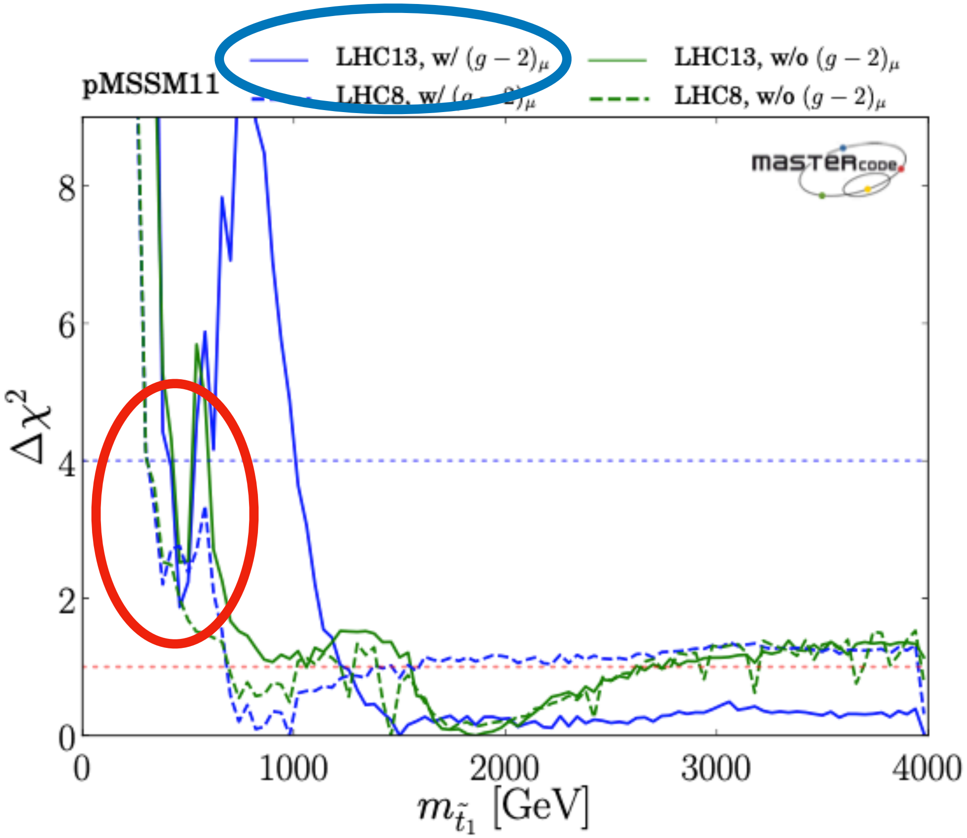
- stau coann.
- squark coann.
- sbot coann.

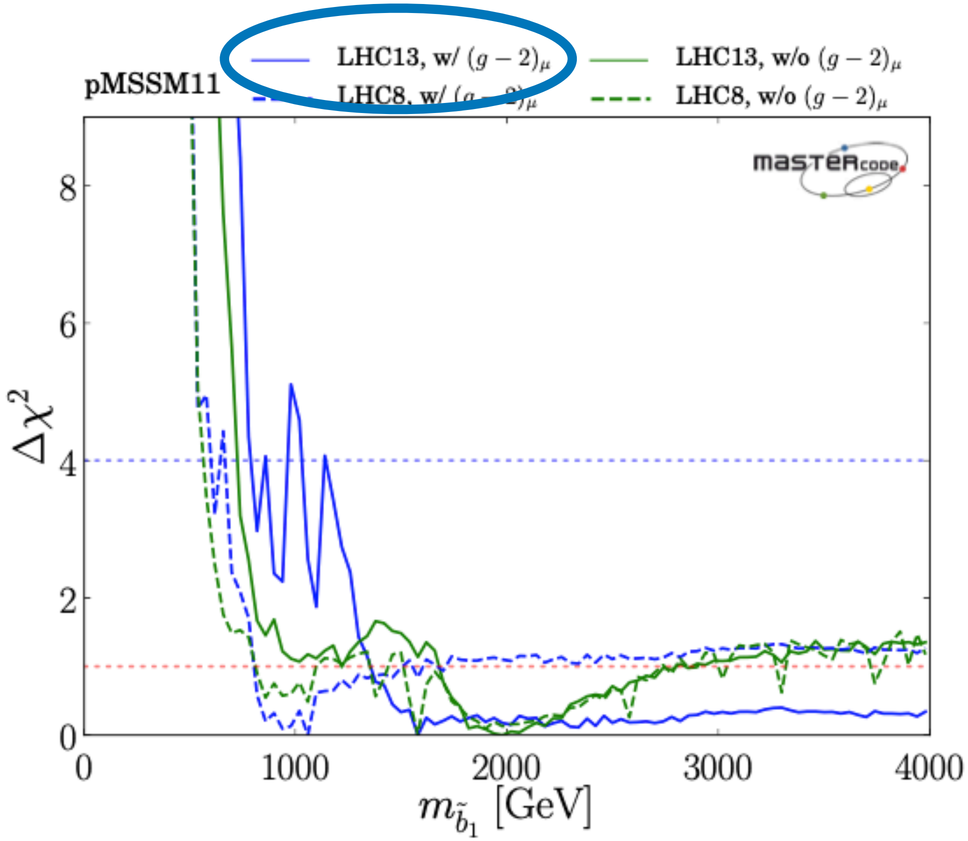
- **Possibilities for the LHC?**

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

LHC Constraints on Stop & Bottom

- Stop and bottom **with** and without $g_\mu - 2$ constraint





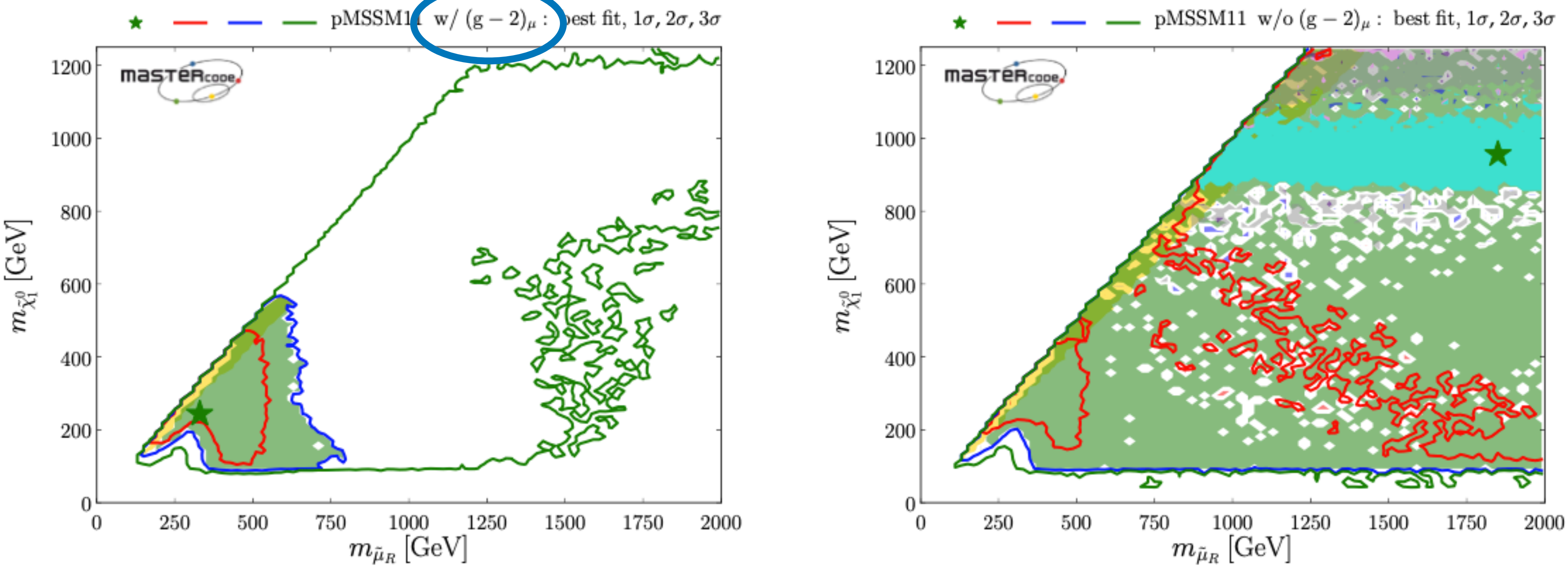
- **Possibilities for the LHC?**

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Phenomenological MSSM (pMSSM11)

LHC Constraints on Smuon & Neutralino

- Smuon and neutralino **with** and without $g_\mu - 2$ constraint



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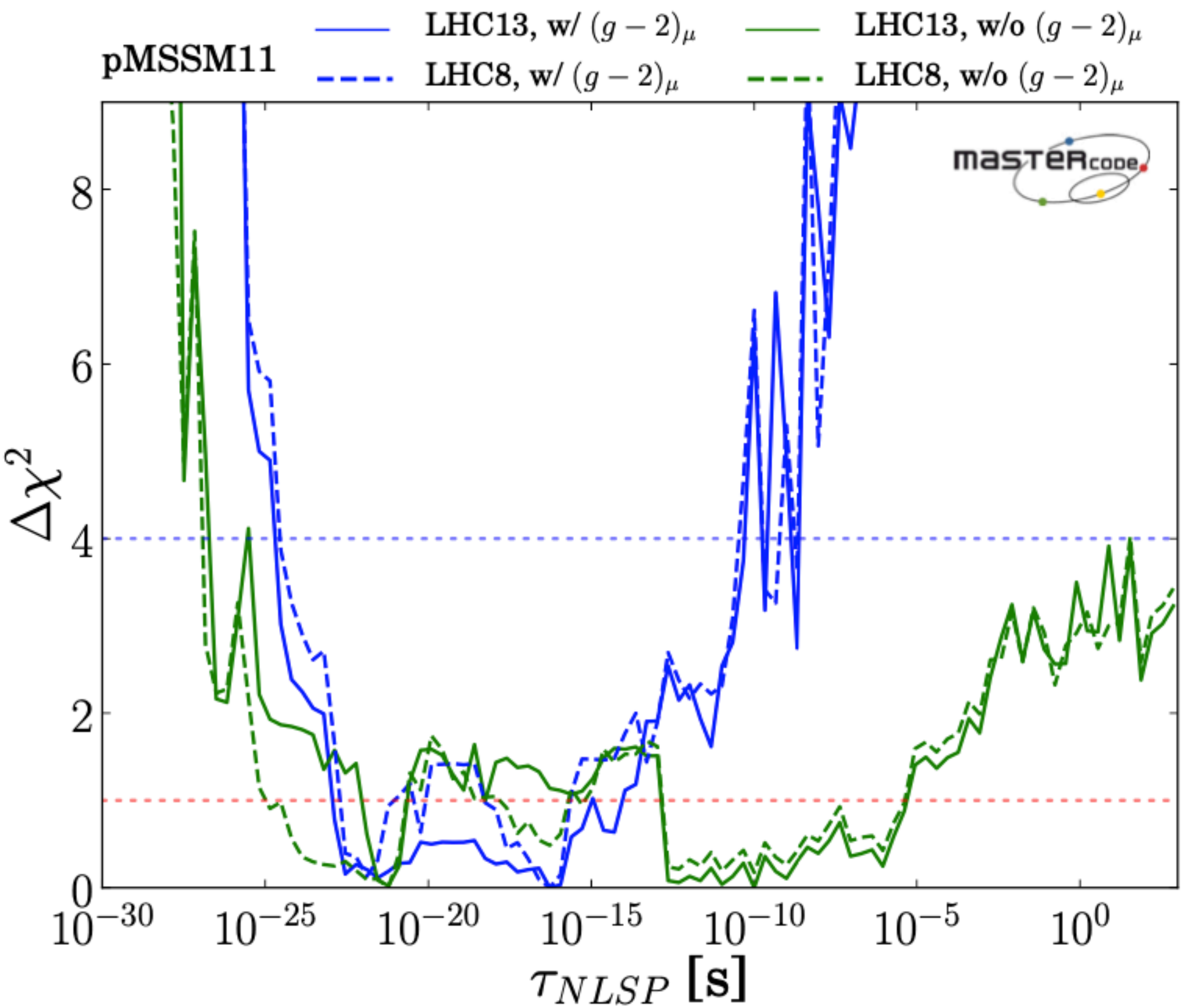
A/H funnel	stau coann.	squark coann.	sbot coann.

- **Slepton detection at the LHC?**

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Phenomenological MSSM (pMSSM11)

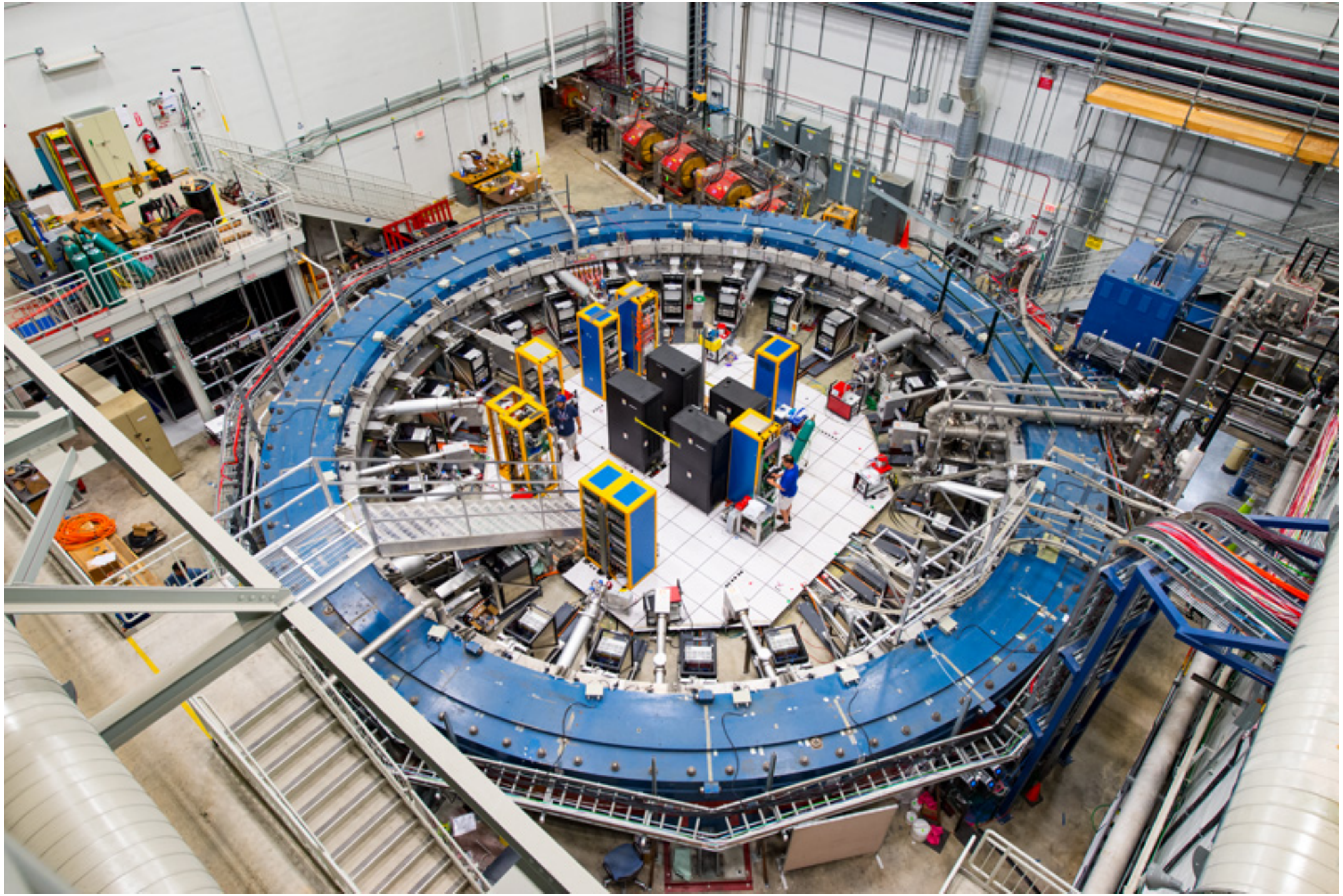
Long-Lived NLSP?



- **Possibilities for the LHC?**

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

Fermilab Experiment



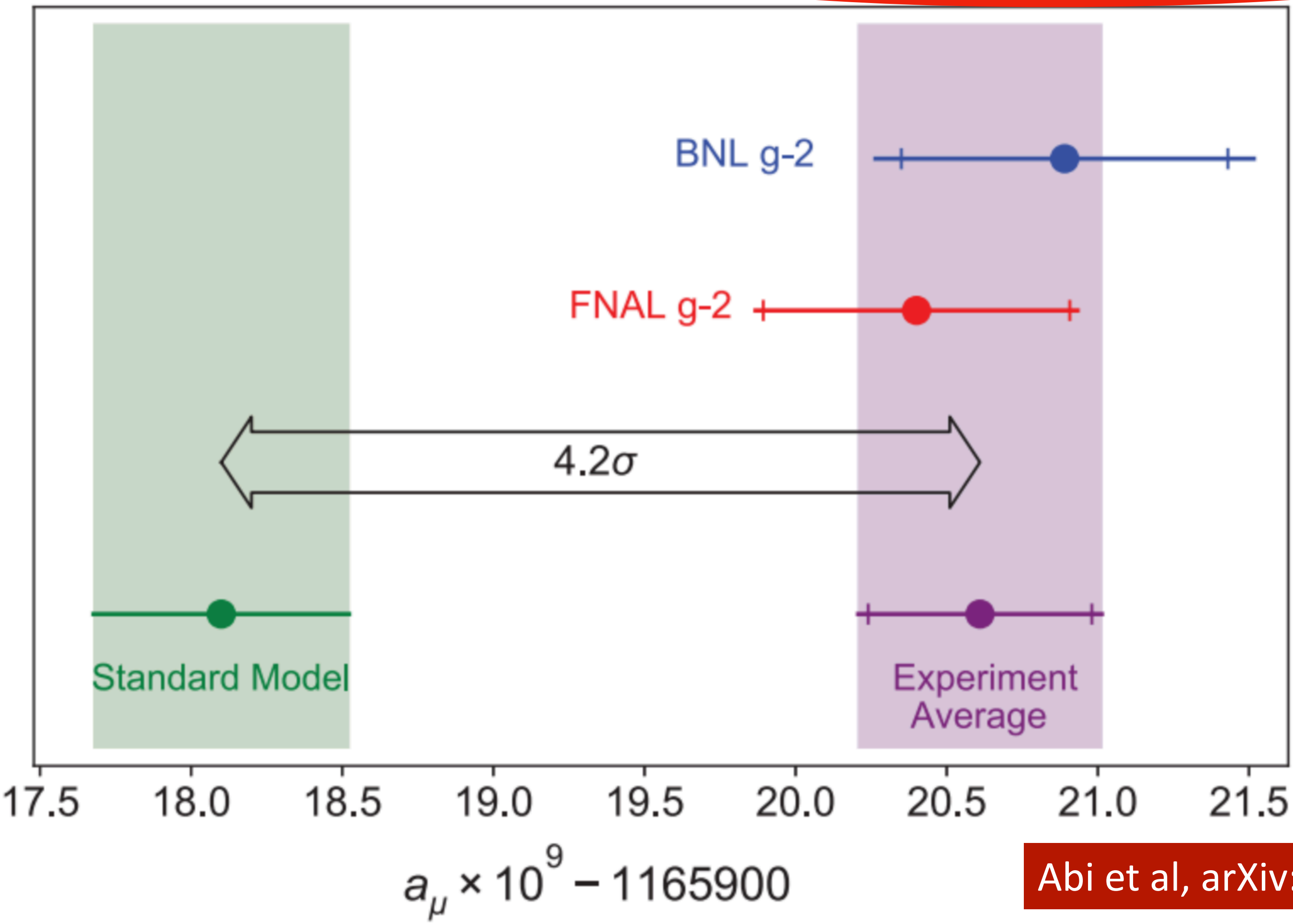
Does the magnet look familiar?

Fermilab Measurement

FNAL result: $a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm})$

Combined result: $a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm})$

Difference from Standard Model: $a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$



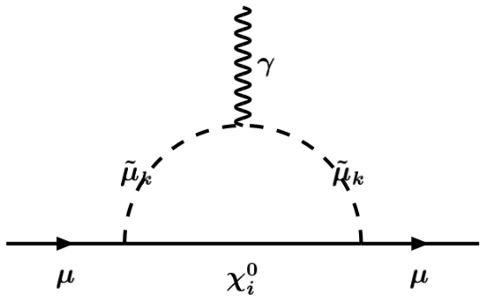
Abi et al, arXiv:2104.03281

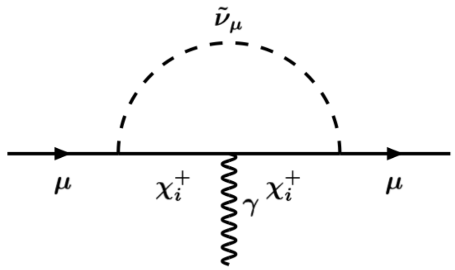
Interpretation Papers

2104.05685	Vector LQ	B	Du	
5656	L_\mu - L_\tau	DM	Borah	
5006	B_q - L_\mu	B	Cen	Leptoquarks
4494	LFV	LFV	Li	
4503	Pseudoscalar	DM, H decays	Lu	Extra U(1)
4456	2HDM	DM	Arcadi	
3542	B-LSSM	H decays	Yang	Extra Higgs
3701	Leptophilic spin 0	H factory	Chun	
3839	SUSY	HL-LHC	Aboubrahim	Supersymmetry
3691	Survey	DM, LHC	Athron	
3705	Seesaw	g_e	Escribano	Axion
3699	Gauged 2HDM	B	Chen	
3239	SUSY	Gravitino DM	Gu	
3284	NMSSM	DM	Cao	
3262	GUT-constrained SUSY	DM, LHC	Wang	
3292	MSSM	CPV	Han	
3296	lepton mass matrix	Flavour	Calibbi	
3280	Z_d	Cs weak charge	Cadeddu	
3334	E_6 3-3-1	H stability	Li	
3242	\mu-\tau-philic H	\tau decays, LHC	Wang	
3259	Anomaly mediation	DM	Yin	
3245	pMSSM	DM, fine-tuning	Van Beekveld	
3274	NMSSM	DM, AMS-02 pbar	Abdughani	
3290	MSSM	DM	Cox	
3367	2HDM	V-like leptons	Ferreira	
3267	Axion	Low-scale	Buen-Abad	
3340	L_\mu - L_tau	AMS-02 positrons	Zu	
3282	ALP	V-like fermions	Brdar	
3301	Lepton portal	DM	Bai	
3276	Dark axion portal	Dark photon	Ge	
3491	GmSUGRA	LHC	Ahmed	
3227	2HDM	LHC	Han	
3302	SUSY	small \mu	Baum	
3238	Scalar	DM, p radius	Zhu	
3489	\mu \nu SSM	B, H decays	Zhang	
3287	pMSSM	ILC	Chakraborti	
3228	DM	B, H decays	Arcadi	

890	Radiative seesaw		Chiang
2103.13991	Scalar LQ	B, H decays	Greljo
2012.11766	DM		D'Agnolo
2012.07894	Axions		Darmé
1812.06851	Charmphilic LQ		Kowalska
2104.04458	GUT-constrained SUSY	DM	Chakraborti
5730	LQ + charged singlet	B, Cabibbo	Marzocca
6320	L-R symmetry		Boyarkin
6858	L_\mu - L_\tau	\nu masses	Zhou
6854	D-brane	U(1), Regge	Anchordoqui
6656	vector LQ	B	Ban
7597	SUSY	LHC, landscape	Baer
7047	3HDM	Fermion masses	Carcamo
7680	Leptophilic Z'	Global analysis	Buras
8289	Custodial symmetry	Light scalar + pseudoscalar	Balkin
9205	U(1)D	Neutrino mass	Dasgupta
8819	Lepton non-universality	Naturalness	Cacciapaglia
8640	2x2x1	Higgses, heavy nus	Boyarkina
8293	Multi-TeV sleptons in FSSM	Extended H, tau decays	Altmannshofer
10114	SO(10)	Yukawa unification	Aboubrahim
7681	U(1)B-L	DUNE	Dev
10324	Gauged lepton number	Dark matter	Ma
10175	2HDM	Lighter Higgs?	Jueid
11229	LQ	Matter unification	Fileviez
15136	U(1)	HE neutrinos, H tension	Alonso
2105.00903	Anomalous 3-boson vertex	W mass	Arbuzov
7655	U(1)T3R	RK(*)	Dutta
8670	Leptoquark	nu mass, LFV	Zhang

$g_\mu - 2$ in Supersymmetry





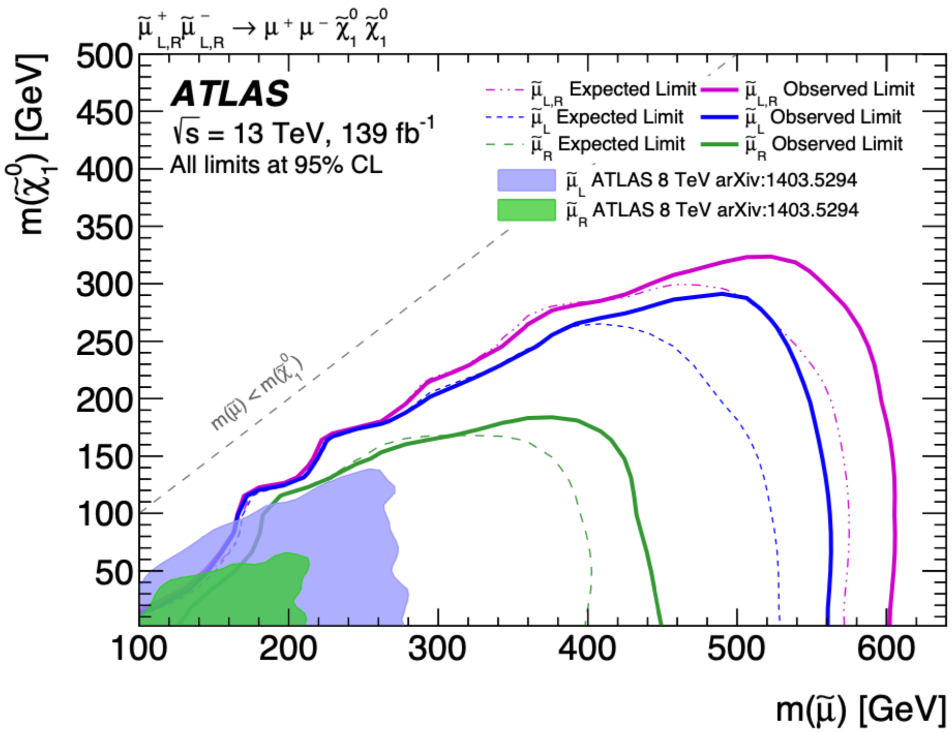
- Muon ψ_f, 4 neutralinos ψ_i, 2 smuons ϕ_k ($\tilde{\mu}_{L,R}$)

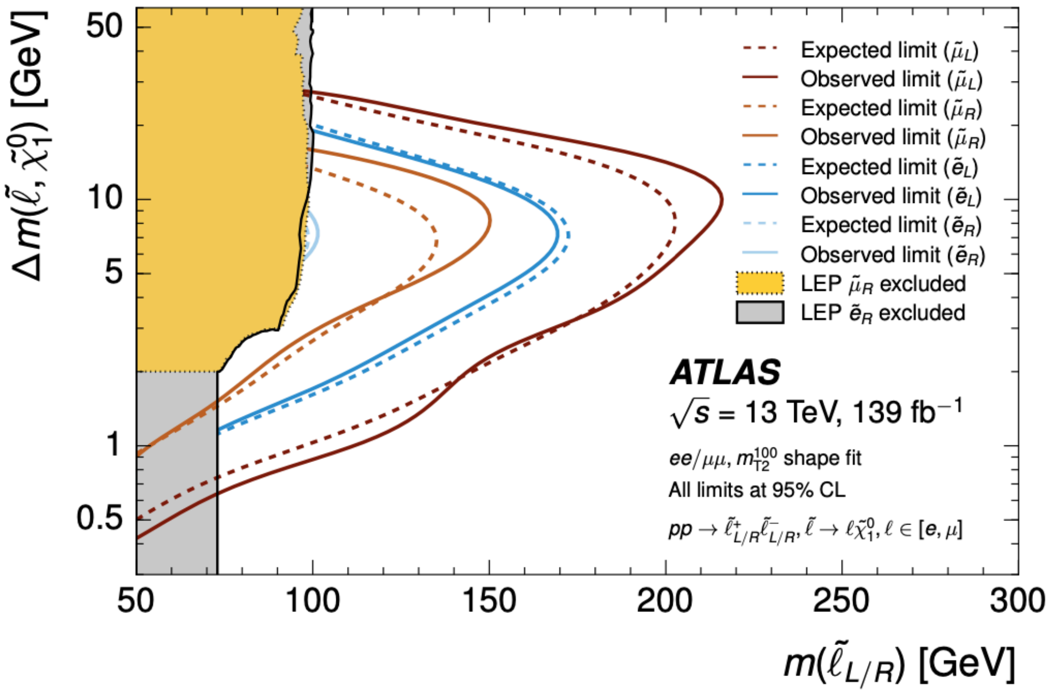
$$-\mathcal{L}_{int} = \sum_{ik} \bar{\psi}_f (K_{ik} \frac{1-\gamma_5}{2} + L_{ik} \frac{1+\gamma_5}{2}) \psi_i \phi_k + H.c.$$

- One-loop contributions from smuon/neutralino loops:
  - Left-right mixing: $a_f^{11} = \sum_{ik} \frac{m_f}{8\pi^2 m_i} Re(K_{ik} L_{ik}^*) I_1(\frac{m_f^2}{m_i^2}, \frac{m_k^2}{m_i^2})$
  - Unmixed: $a_f^{12} = \sum_{ik} \frac{m_f^2}{16\pi^2 m_i^2} (|K_{ik}|^2 + |L_{ik}|^2) I_2(\frac{m_f^2}{m_i^2}, \frac{m_k^2}{m_i^2})$

LHC vs Sleptons

- LHC does not exclude (relatively) light electroweakly-interacting particles, e.g., sleptons

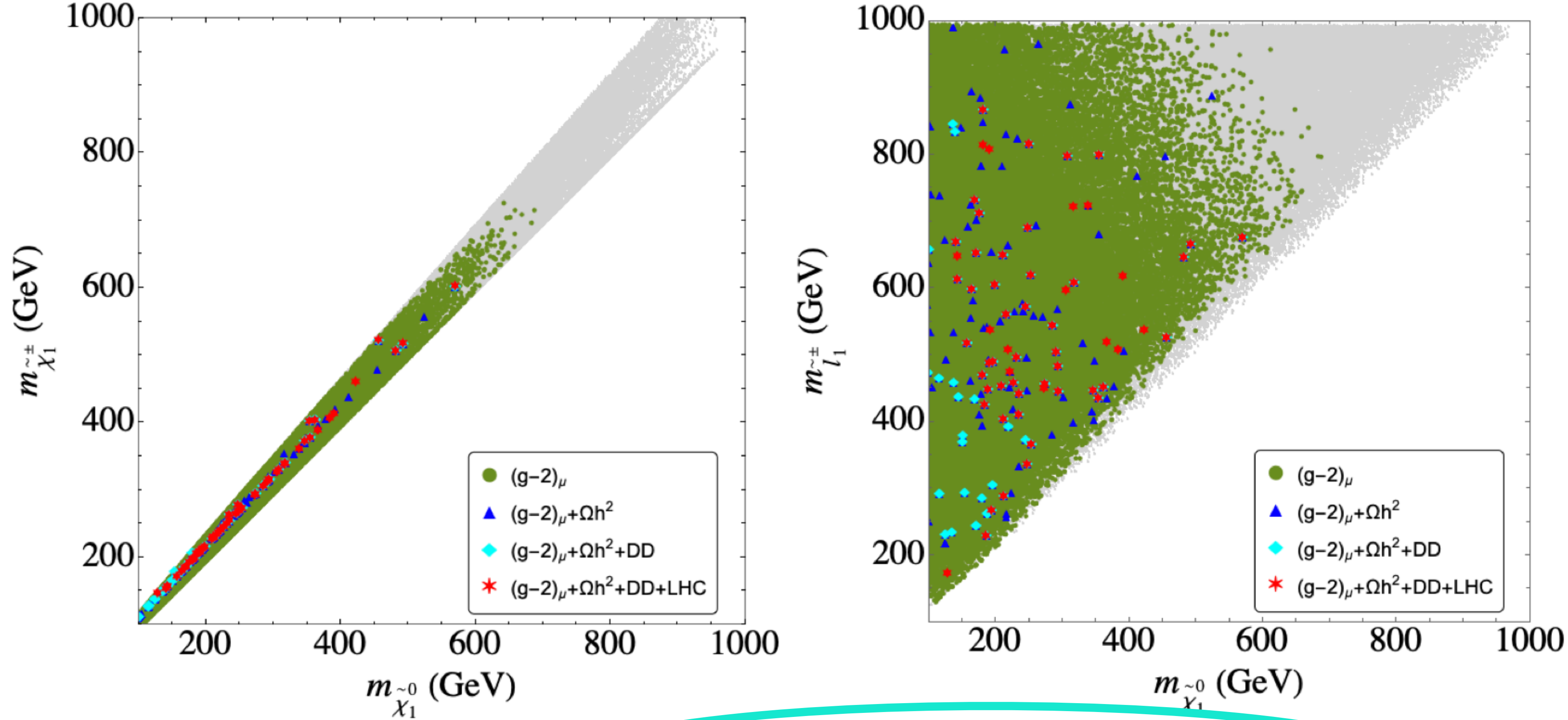




- LHC favours squarks & gluinos > 2 TeV (but loopholes)

Light Supersymmetry & $g_\mu - 2$

- $g_\mu - 2$-friendly scenario with light neutralino, chargino & slepton



- Red star points include all dark matter density, direct scattering & LHC constraints

- Prospects for the LHC?

Chakraborti, Heinemeyer & Saha, arXiv:2104.03287

$g_\mu - 2$ in Flipped SU(5) GUT

- Extend GUT SU(5) with additional U(1)

Antoniadis, JE, Hagelin, Nanopoulos, 1980s

- "Flipped" fermion assignments to representations:

$$\bar{f}_i(\bar{\mathbf{5}}, -3) = \{U_i^c, L_i\} \ , \quad F_i(\mathbf{10}, 1) = \{Q_i, D_i^c, N_i^c\} \ , \quad l_i(\mathbf{1}, 5) = E_i^c \ , \quad i = 1, 2, 3$$

- Break GUT symmetry with 10-dimensional Higgses, electroweak symmetry with 5-dimensional Higgses:

$$H(\mathbf{10}, 1) = \{Q_H, D_H^c, N_H^c\} \ , \qquad \bar{H}(\bar{\mathbf{10}}, -1) = \{\bar{Q}_H, \bar{D}_H^c, \bar{N}_H^c\}$$

$$h(\mathbf{5}, -2) = \{T_{H_c}, H_d\} \ , \qquad \bar{h}(\bar{\mathbf{5}}, 2) = \{\bar{T}_{\bar{H}_c}, H_u\}$$

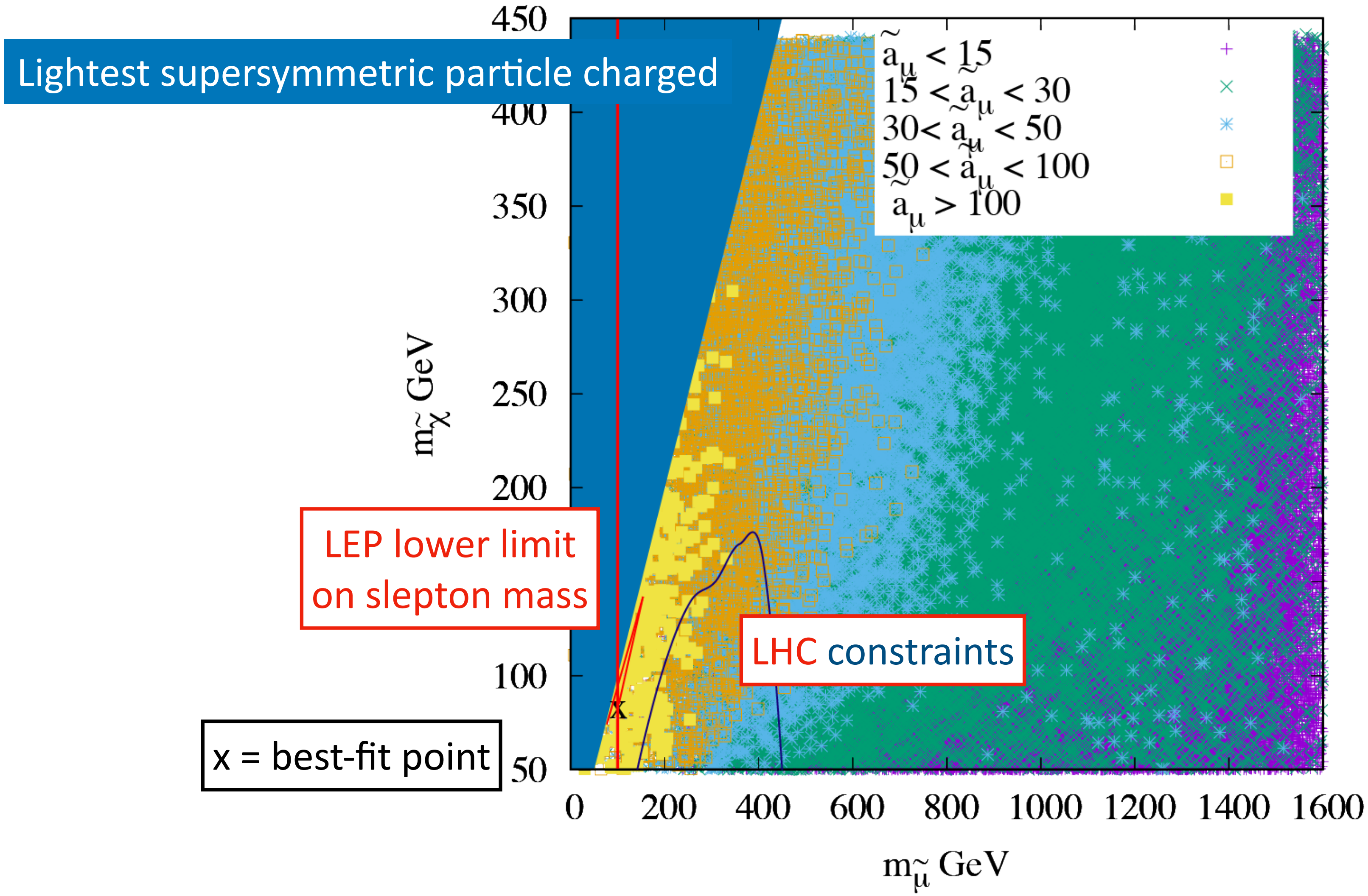
- Superpotential:

$$W = \lambda_1^{ij} F_i F_j h + \lambda_2^{ij} F_i \bar{f}_j \bar{h} + \lambda_3^{ij} \bar{f}_i \ell_j^c h + \lambda_4 H H h + \lambda_5 \bar{H} \bar{H} \bar{h}$$
$$+ \lambda_6^{ia} F_i \bar{H} \phi_a + \lambda_7^a h \bar{h} \phi_a + \lambda_8^{abc} \phi_a \phi_b \phi_c + \mu_\phi^{ab} \phi_a \phi_b \ ,$$

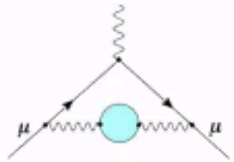
- Scan free parameters of model:

$$M_5, \ M_{X1}, \ m_{10}, \ m_5, \ m_1, \ \mu, \ M_A, \ A_0, \ \tan\beta$$

$g_\mu - 2$ in Flipped SU(5)

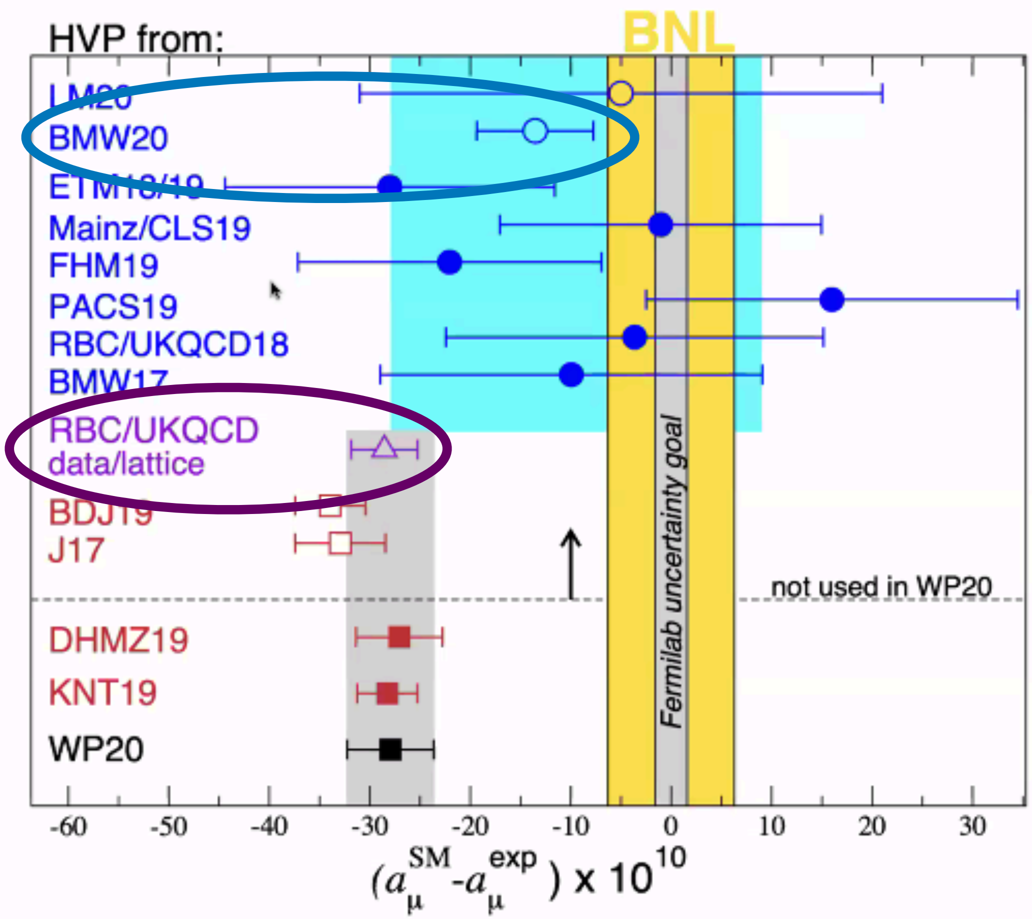


JE, Evans, Nagata, Nanopoulos & Olive, arXiv:2107.03025



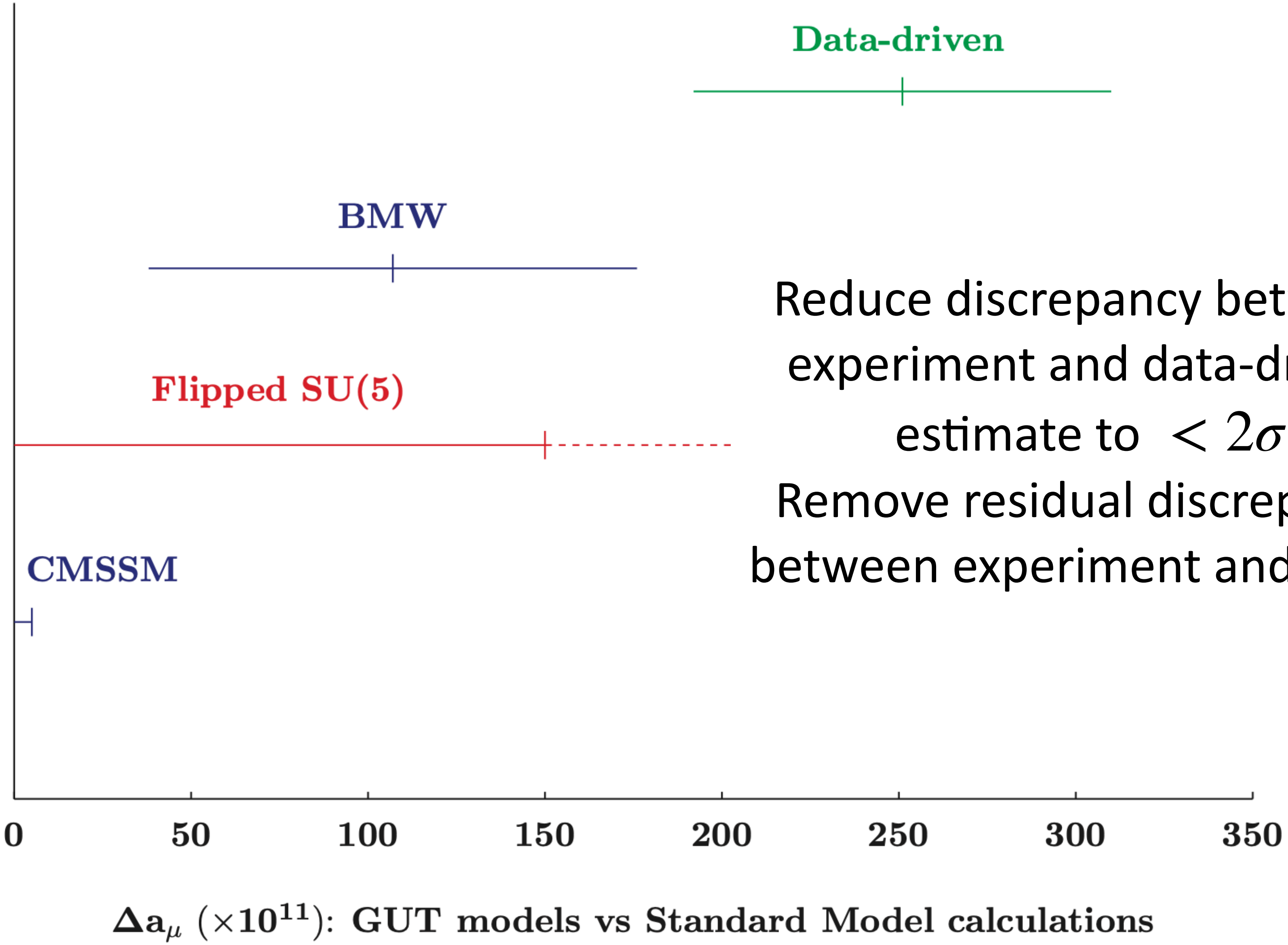
Comparison of Calculations of Hadronic Vacuum Polarization

$$a_\mu^{\mathrm{HVP}} + [a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Weak}} + a_\mu^{\mathrm{HLbL}}] \;\rangle\; a_\mu^{\mathrm{SM}}$$



Aoyama et al, arXiv:2006.04822

$g_\mu - 2$ in CMSSM & Flipped SU(5) vs Lattice, Data-Driven Calculation



Reduce discrepancy between experiment and data-driven estimate to $< 2\sigma$

Remove residual discrepancy between experiment and BMW

JE, Evans, Nagata, Nanopoulos & Olive, arXiv:2107.03025

$g_\mu - 2$ in Flipped SU(5)

Parameters & predictions at best-fit point

Input GUT parameters (masses in units of 10^{16} GeV)		
$M_{GUT} = 1.00$	$M_X = 0.79$	$V = 1.13$
$\lambda_4 = 0.1$	$\lambda_5 = 0.3$	$\lambda_6 = 0.001$
$g_5 = 0.70$	$g_X = 0.70$	$m_{\nu_3} = 0.05$ eV
Input supersymmetry parameters (masses in GeV units)		
$M_5 = 2460$	$M_1 = 240$	$\mu = 4770$
$m_{10} = 930$	$m_{\bar{5}} = 450$	$m_1 = 0$
$M_A = 2100$	$A_0/M_5 = 0.67$	$\tan\beta = 35$
MSSM particle masses (in GeV units)		
$m_\chi = 84$	$m_{\tilde{t}_1} = 4030$	$m_{\tilde{g}} = 5090$
$m_{\chi_2} = 2160$	$m_{\chi_3} = 5080$	[illegible]
$m_{\tilde{\mu}_R} = 101$	$m_{\tilde{\mu}_L} = 1600$	[illegible]
$m_{\tilde{q}_L} = 4470$	$m_{\tilde{d}_R} = 4250$	[illegible]
$m_{\tilde{t}_2} = 4410$	$m_{\tilde{b}_1} = 4170$	$m_{\tilde{b}_2} =$ [illegible]
$m_{\chi^\pm} = 2160$	$m_{H,A} = 2100$	$m_{H^\pm} = 2100$
Other observables		
$\Delta a_\mu = 150 \times 10^{-11}$	$\Omega_\chi h^2 = 0.13$	$m_h = 122$ [illegible]
Normal-ordered ν masses: $\tau_{p\to e^+\pi^0}\|_{NO} = 1.1 \times 10^{36}$ yrs	$\tau_{p\to\mu^+\pi^0}\|_{NO} = 1.1$ [illegible]	
Inverse-ordered ν masses: $\tau_{p\to e^+\pi^0}\|_{IO} = 3.2 \times 10^{37}$ yrs	$\tau_{p\to\mu^+\pi^0}\|_{IO} = 2.3 \times 10^{36}$ yrs	

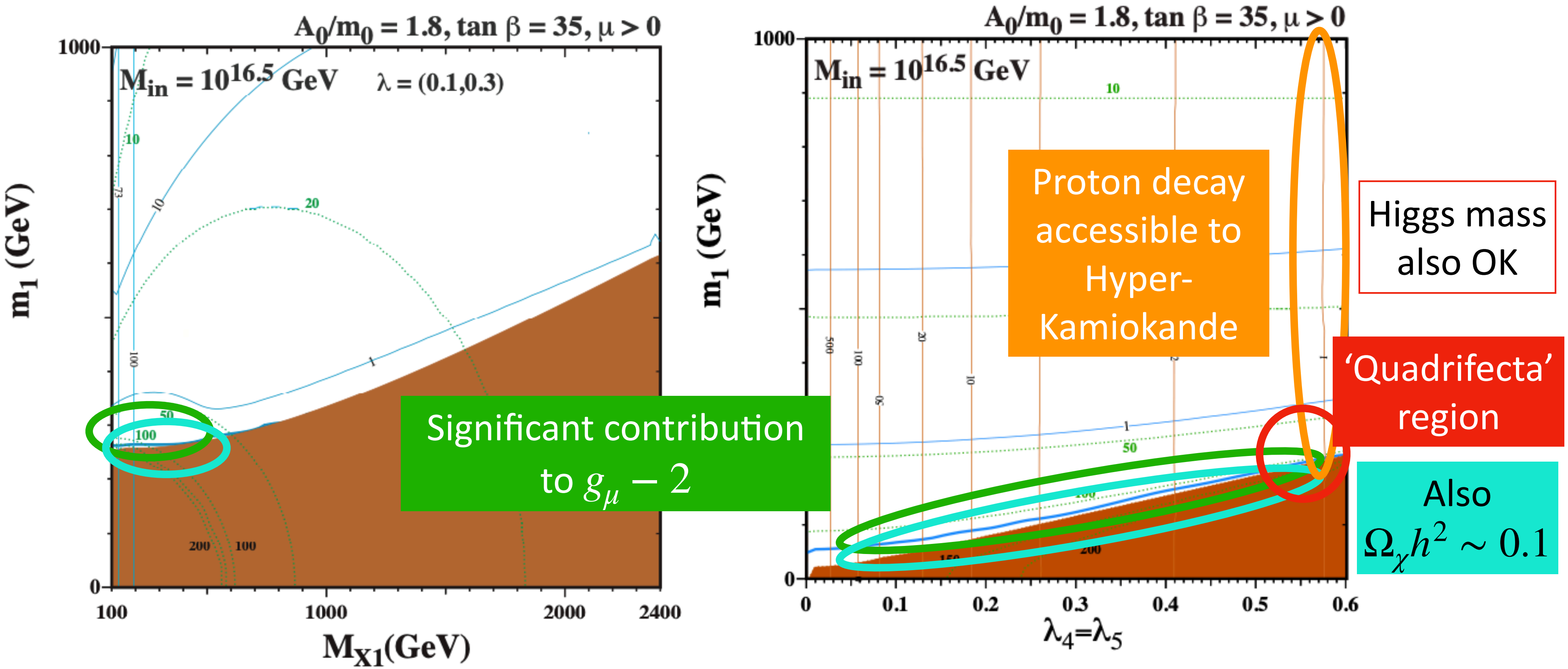
Opportunities to search for light smuon, neutralino at LHC
Other sparticles too heavy?

Get good CDM density without even trying!

JE, Evans, Nagata, Nanopoulos & Olive, arXiv:2107.03025

Flipped Supersymmetry, $g_\mu - 2$ & Dark Matter

- Exploration of $g_\mu - 2$, dark matter and proton decay possibilities



Soft supersymmetry-breaking parameters specific to flipped SU(5)

Sensitivity to superpotential parameters of flipped SU(5): effect on $p \to e^+\pi^0$ decay rate

JE, Evans, Nagata, Nanopoulos & Olive, arXiv:2110.06833

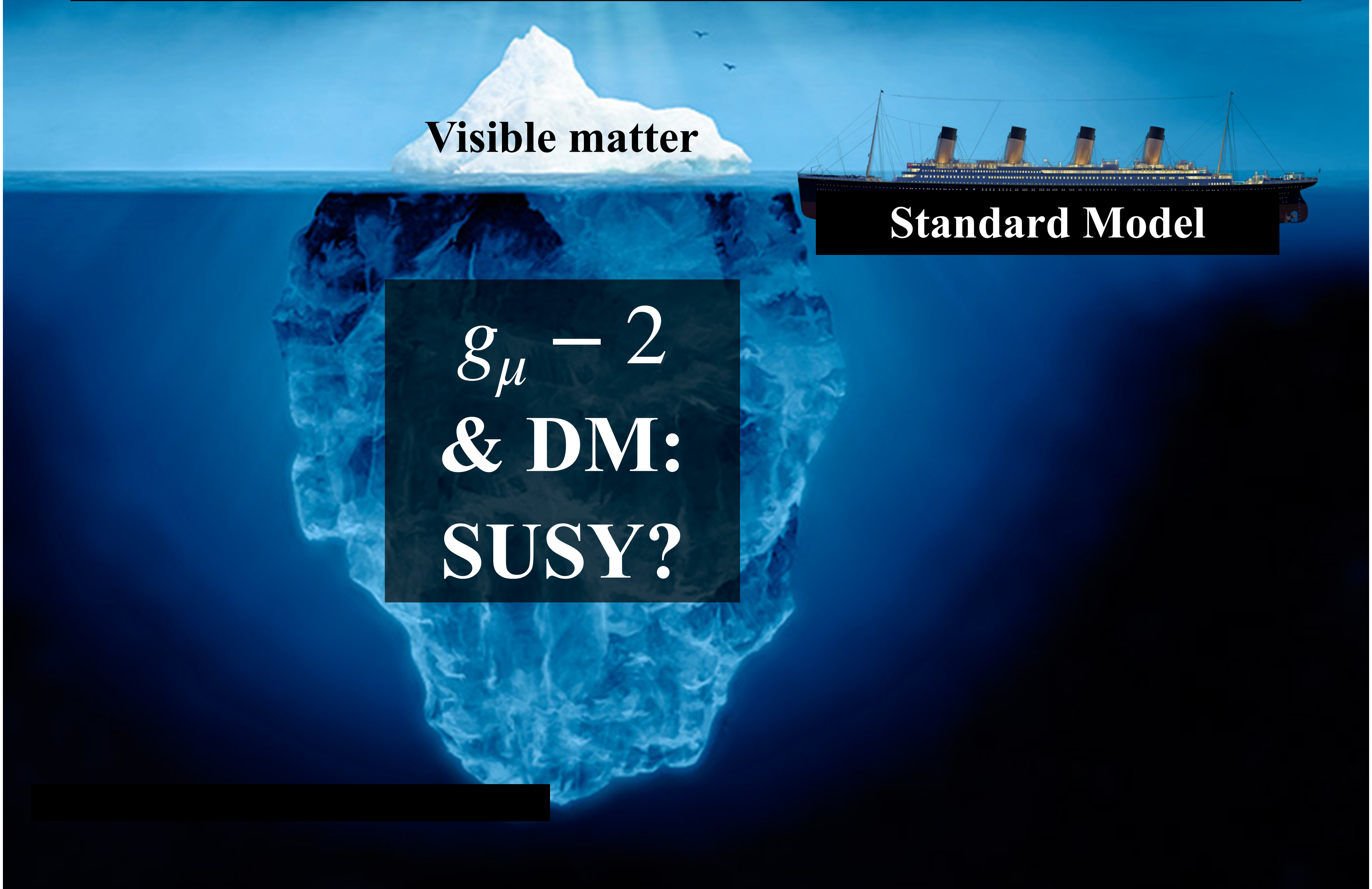
Supersymmetry: Nil carborundum

“Don’t let the bastards grind you down”

- Supersymmetry is (for me) still the best-motivated BSM scenario
- The BNL/FNAL measurements of $g_\mu - 2$ may have taken us (finally) beyond the Standard Model
- Supersymmetry could resolve the tension between experiment and the data-driven SM theory estimate of $g_\mu - 2$
- And simultaneously provide the cold dark matter
- Interesting possible LHC signatures (light sleptons, …)


We still believe in supersymmetry
You must be joking!

Summary



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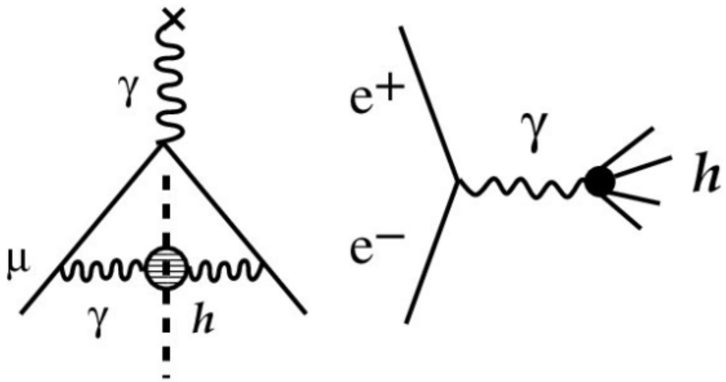
Theory Initiative

- Comprehensive review of calculations of the Standard Model contributions to $g_\mu - 2$
- Including discussion of the uncertainties
- Particularly in calculation of leading-order vacuum polarisation



Aoyama et al, arXiv:2006.04822

Physics Reports 887 (2020) 1–166

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The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

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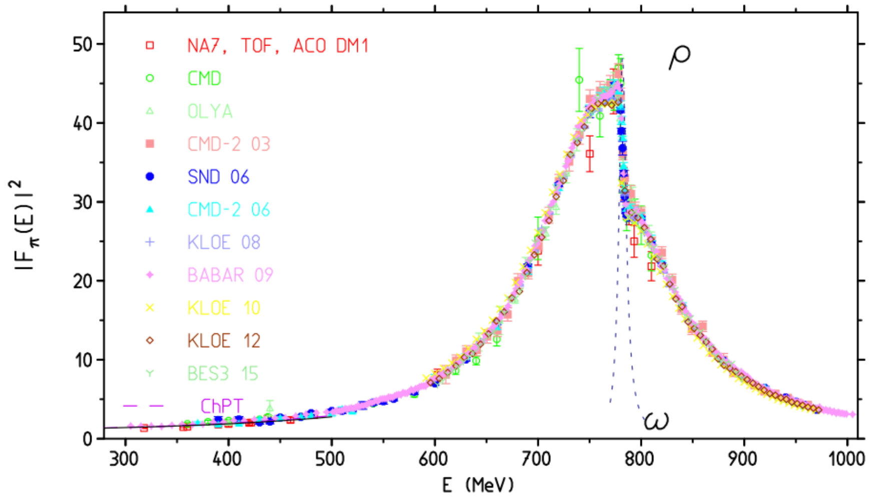
E-mail address: MUON-GM2-THEORY-SC@fnal.gov (G. Colangelo, M. Davier, S.I. Eidelman, A.X. El-Khadra, M. Hoferichter, C. Lehner, T. Mibe, A. Nyffeler, B.L. Roberts, T. Teubner).

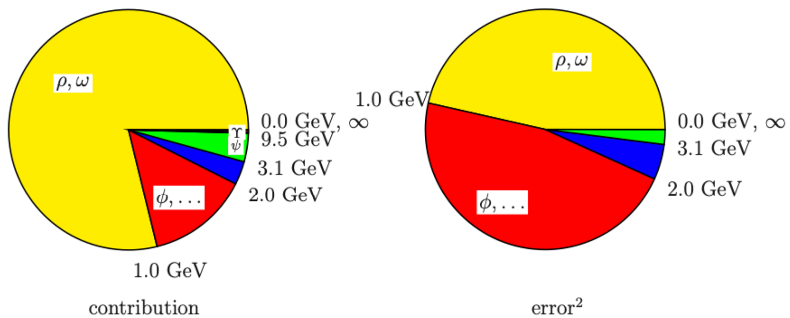
https://doi.org/10.1016/j.physrep.2020.07.006

Hadronic Vacuum Polarization

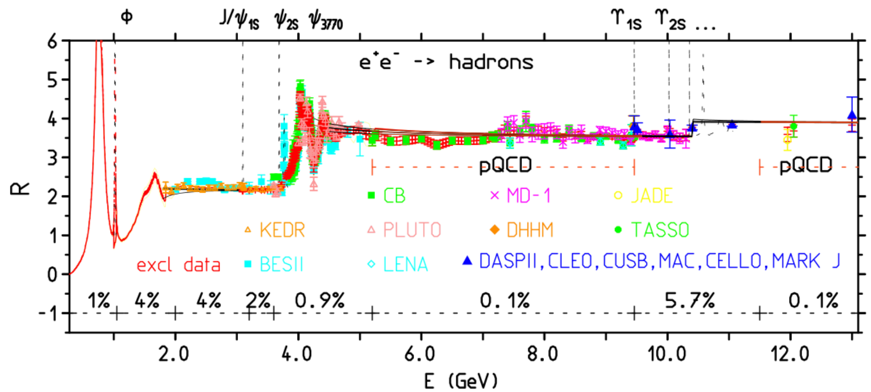
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects



- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)



- High energies under good control from perturbative QCD



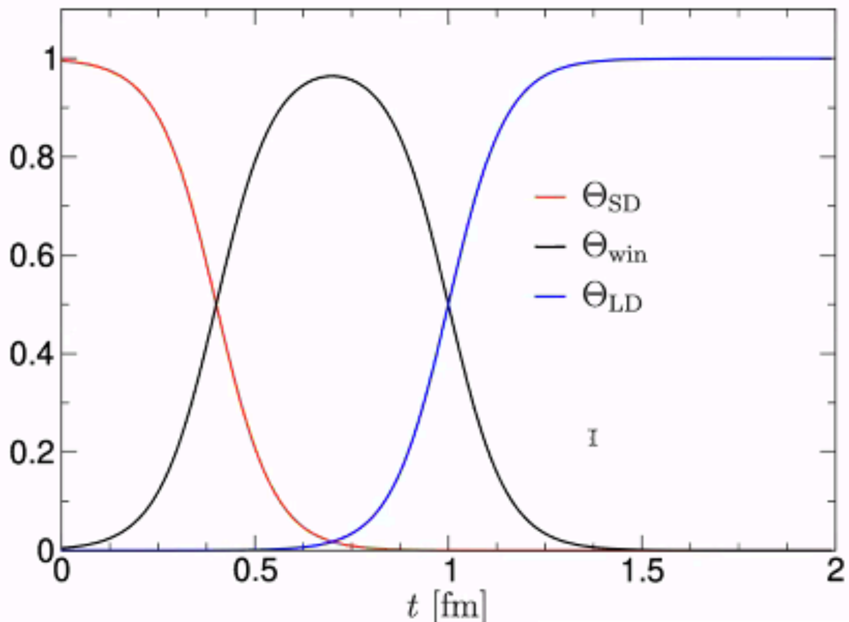
$$a_\mu^{\text{HVP, LO}} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{sys}}(0.7)_{\text{DV+QCD}} \times 10^{-10}$$
$$= 693.1(4.0) \times 10^{-10}\,.$$

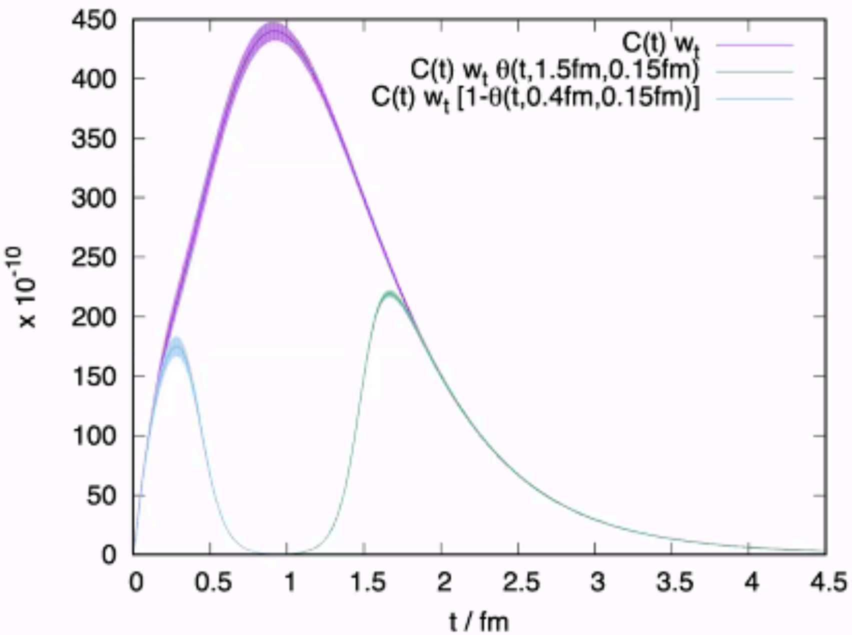
Aoyama et al, arXiv:2006.04822

RBC/UKQCD Hybrid Method

Replace lattice data at very short and long distances
by experimental e+e- scattering data

- Convert R-ratio data to Euclidean correlation function (via the dispersive integral) and compare with lattice results for windows in Euclidean time
- intermediate window:
  expect reduced FV effects and discretization errors



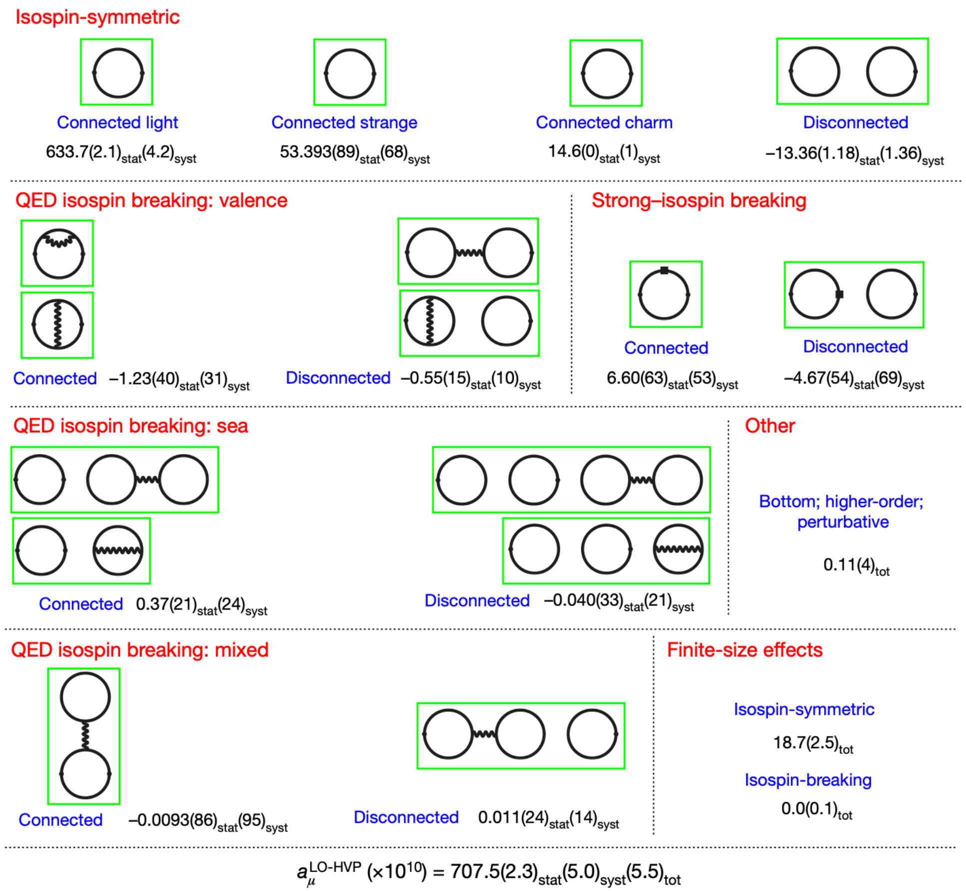


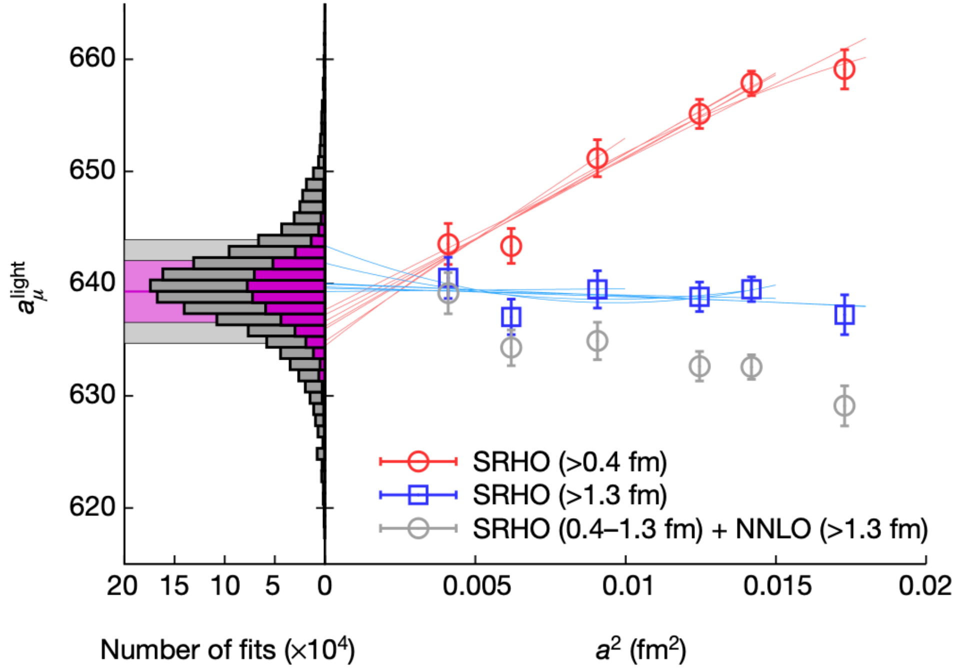
Blum et al, arXiv:1801.07224

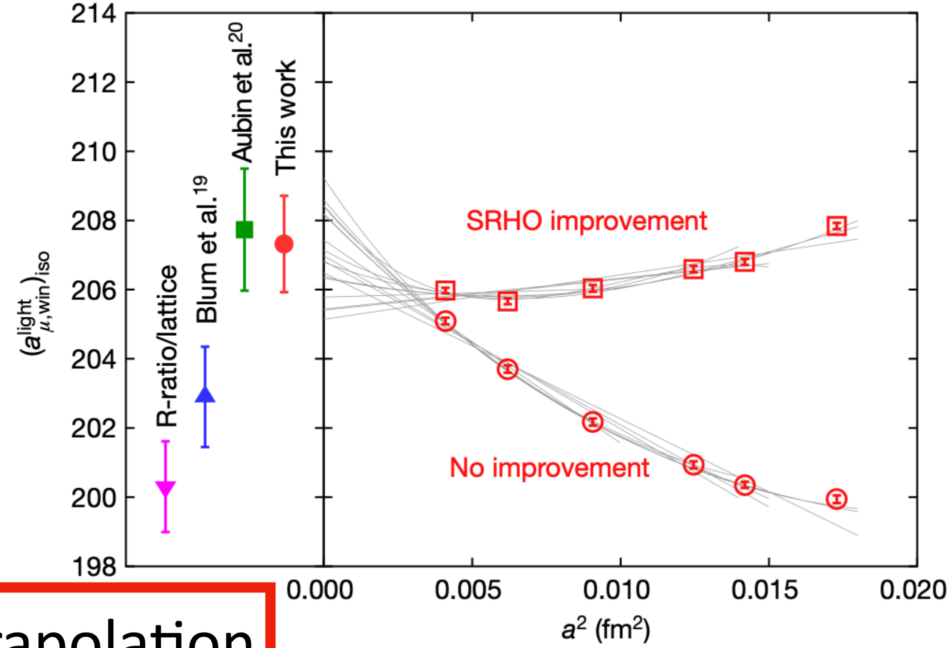
BUT

BMW Lattice Calculation

BMW Collaboration, Borsanyi et al, arXiv:2002.12347



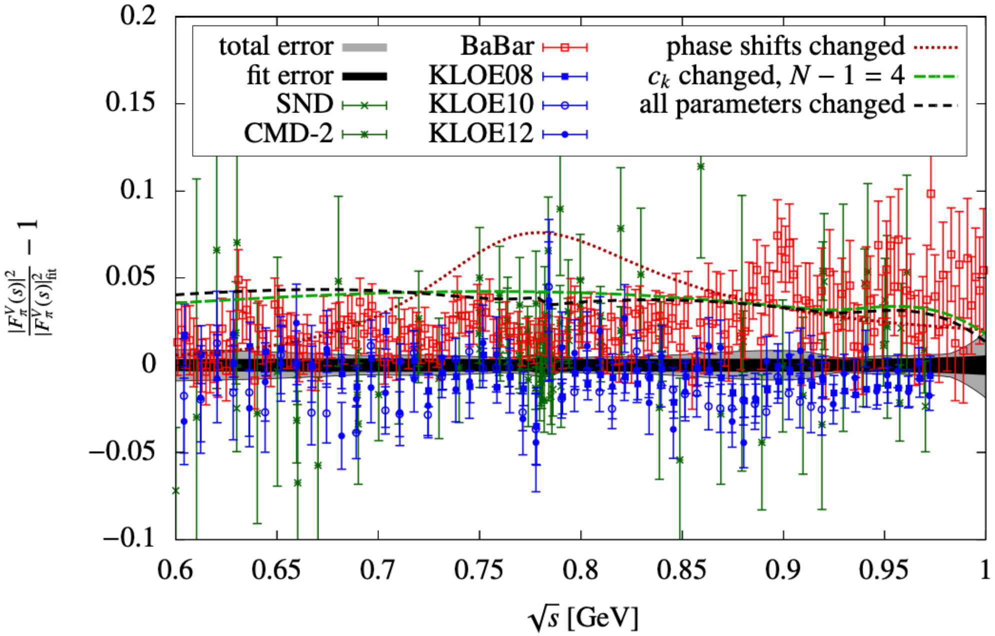


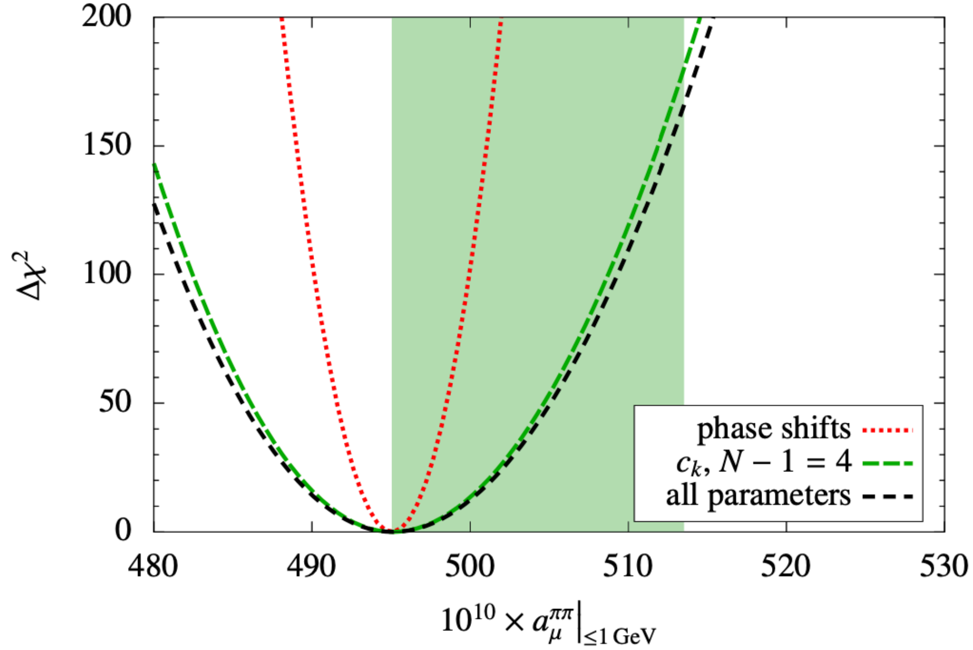


High statistics, accurate continuum extrapolation

$$a_\mu^{\rm EXP} - a_\mu^{\rm BMW} = 107(70)\times 10^{-11}$$

How to Accommodate BMW?





- Analyticity and unitarity constrain increase in $\pi^+\pi^-$ cross section < 1 GeV
- Maximum allowed conflicts with data, does not change greatly prediction for a_μ
- Increase in cross section at higher energies affects electroweak observables

Colangelo, Hoferichter & Stoffer, arXiv:2010.07943