Muon g-2 (and related pheno) in vector-like extensions of the MSSM

Enrico Maria Sessolo
Fakultät für Physik, TU Dortmund, Germany
National Centre for Nuclear Research, Warsaw, Poland

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A.Choudhury, L.Darmé, L.Roszkowski, EMS, S.Trojanowski

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Low-scale vector-like matter

SAFE

- **No gauge anomalies**
- **No problems with EWPO**

INTERESTING PHENOMENOLOGY

- **Extra contributions to MSSM Higgs mass**
  (Martin 0910.2732; Graham *et al.* 0910.3020; Faroughy, Grizzard 1405.4116; Lalak *et al.* 1502.05702, Nickel, Staub 1505.06077)

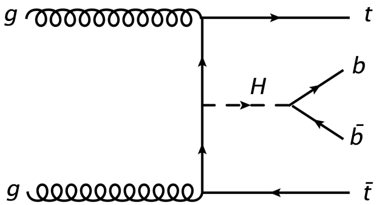
- **Lower MSSM fine tuning (in specific cases)**
  (Dermisek, 1606.09031)

- **Open additional channels for WIMP annihilation**
  (Abdullah, Feng 1510.06089)

- **Can resolve the muon g-2 with new leptons in the loops**
  (Endo *et al.* 1108.3071,1112.5653; Dermisek, Raval 1305.3522, Nishida Yoshioka 1605.06675...)

$$\delta\left(g-2\right)_{\mu}=(27.4\pm7.6)\times10^{-10}$$

- **Can provide fits to ttH anomaly with new quark Yukawas *O*(1)**
  (Angelescu, Djouadi, Moreau, 1510.07527)



Low-scale vector-like matter

SAFE

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HOW MUCH OF THIS CAN FIT IN A SIMPLE, FEW PARAMETER FRAMEWORK?

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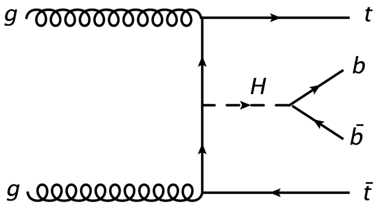

The models

SUGRA/CMSSM + 1 VL pair multiplets of SU(5)

1. The **LD** model $(1 \text{ extra } \mathbf{5} + \bar{\mathbf{5}})$

Low scale:

$$D = (\bar{\mathbf{3}}, \mathbf{1}, 1/3) \qquad D' = (\mathbf{3}, \mathbf{1}, -1/3)$$

$$L = (\mathbf{1}, \mathbf{2}, -1/2) \qquad L' = (\mathbf{1}, \mathbf{2}, 1/2)\,.$$

1 down-type quark, 1 charged lepton, 2 heavy neutrinos
(+ 2 squarks, 2 sleptons, 2 sneutrinos)

---

2. The **QUE** model $(1 \text{ extra } \mathbf{10} + \overline{\mathbf{10}})$

Low scale:

$$Q = (\mathbf{3}, \mathbf{2}, 1/6) \qquad Q' = (\bar{\mathbf{3}}, \mathbf{2}, -1/6)$$

$$U = (\bar{\mathbf{3}}, \mathbf{1}, -2/3) \qquad U' = (\mathbf{3}, \mathbf{1}, 2/3)$$

$$E = (\mathbf{1}, \mathbf{1}, 1) \qquad E' = (\mathbf{1}, \mathbf{1}, -1)\,.$$

2 up-type quarks, 1 down-type quark, 1 charged lepton
(+ 6 squarks, 2 sleptons)

The models

No symmetries imposed beyond SU(3) X SU(2) X U(1) and R-parity:

MSSM superpotential:

$$W = \mu\, H_u H_d - Y_d\, q H_d d - Y_e\, l H_d e + Y_u\, q H_u u$$

1. **LD** model terms:

$$W \supset -\lambda_D\, q H_d D - \lambda_L\, L H_d e + M_D D D' + M_L L L' + \widetilde{M}_L\, l L' + \widetilde{M}_D\, d D'$$

2. **QUE** model terms:

$$W \supset \lambda_{Qu}\, Q H_u u - \lambda_{Qd}\, Q H_d d + \lambda_U\, q H_u U - \lambda_E\, l H_d E + Y_{10}\, Q H_u U - Y'_{10}\, Q' H_d U'$$
$$+ M_Q Q Q' + M_U U U' + M_E E E' + \widetilde{M}_Q\, q Q' + \widetilde{M}_U\, u U' + \widetilde{M}_E\, e E',$$

The models

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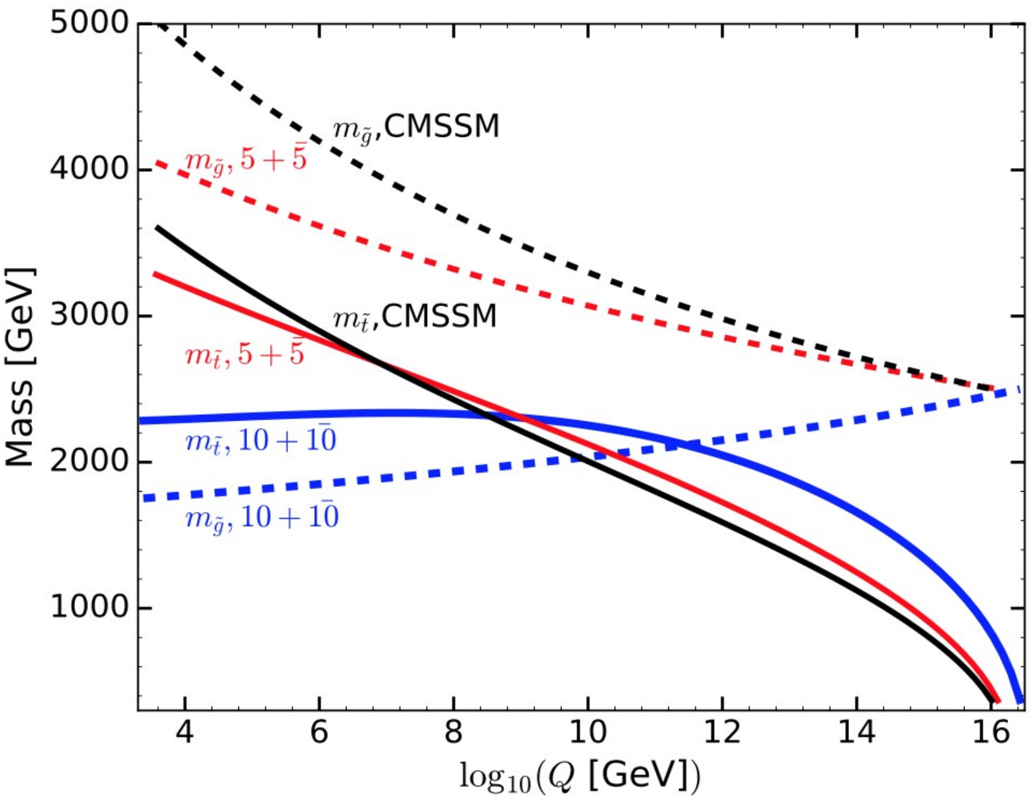
$$+ M_Q Q Q' + M_U U U' + M_E E E' + \underline{\widetilde{M}_Q\, q Q' + \widetilde{M}_U\, u U' + \widetilde{M}_E\, e E'},$$

Could in principle rotate these away

The models

General features of the models / Comparison with the MSSM



- Gluino RGE less steep with more matter:

$$\beta_{M_3}^{\rm MSSM} = -6g_3^2 M_3$$

$$\beta_{M_3}^{\rm LD} = -4g_3^2 M_3$$

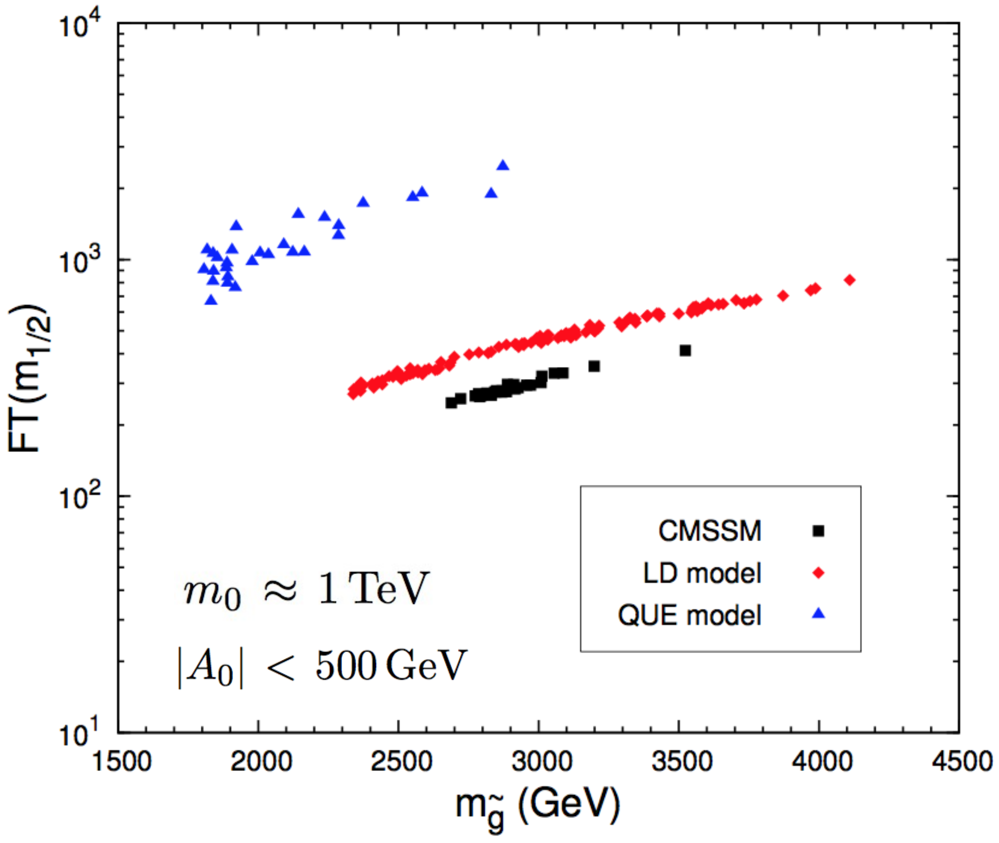
$$\beta_{M_3}^{\rm QUE} = 0$$

– Consequence:

LHC gluino bound $m_{\tilde{g}} \gtrsim 1.8 - 2\,\mathrm{TeV}$ **implies heavier squarks**

The models

General features of the models / Comparison with the MSSM



$$FT(m_{1/2}) = \left| \frac{\partial \log M_Z^2}{\partial \log m_{1/2}} \right|$$

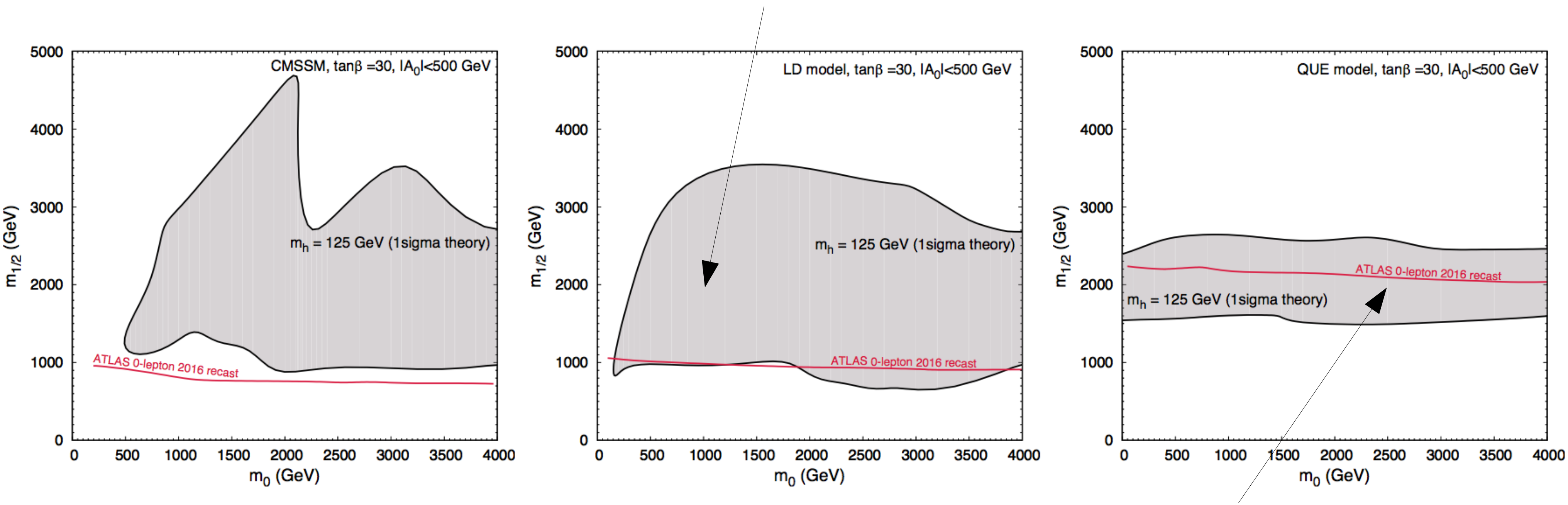
For equivalent gluino mass larger EW fine tuning with more matter

Additional VL matter *<u>does not</u>* make SUSY more natural (in GUT scenarios)

The models

General features of the models / Comparison with the MSSM

LD model: 125 GeV Higgs
leads to p.s. like CMSSM



QUE model: 125 GeV Higgs
for <2 TeV gluinos → LHC strong bounds already

Perturbativity Yukawa couplings + EWPO

Yukawas perturbative up to GUT scale imply...

In the LD model:

$$W \supset -\lambda_D\, qH_dD - \lambda_L\, LH_de$$

$$\beta_{y_b} \sim y_b\left(3|\lambda_D|^2 + |\lambda_L|^2\right)$$ implies

$$\lambda_D \lesssim \begin{cases} 1 & (\tan\beta = 5) \\ 0.7 & (\tan\beta = 60) \end{cases}$$

In the QUE model:

$$W \supset \lambda_{Qu}\, QH_uu - \lambda_{Qd}\, QH_dd + \lambda_U\, qH_uU - \lambda_E\, lH_dE + Y_{10}\, QH_uU - Y'_{10}\, Q'H_dU'$$

$$\beta_{y_t} \sim -6y_t\left(|\lambda_{U,2}|^2 + 2|\lambda_{U,3}|^2\right) + 3Y_{10}\left(|\lambda_{U,3}|^2 + Y_{10}y_t\right)$$ implies

$$\lambda_{U,2} \lesssim \begin{cases} 0.65 & (Y_{10} = 0.2) \\ 0.45 & (Y_{10} = 0.6) \end{cases}$$

$$\lambda_{U,3} \lesssim 0.45 \text{ with } Y_{10} = 0 \text{ and } \widetilde{M} = 0$$

No good fit to ttH!

(cf. Angelescu *et al.* 1510.07527)

Flavor structure and muon g-2

Assume underlying Froggatt-Nielsen type (non-specified)

Flavor structure for the LD model:

(~ very small)

$$\lambda_L = \lambda_D = \begin{pmatrix} 0 \\ \lambda_5 \\ \epsilon\lambda_5 \end{pmatrix} \qquad \widetilde{m}_L^2 = \widetilde{m}_D^2 = \begin{pmatrix} 0 \\ \widetilde{m}^2 \\ \alpha\widetilde{m}^2 \end{pmatrix}$$

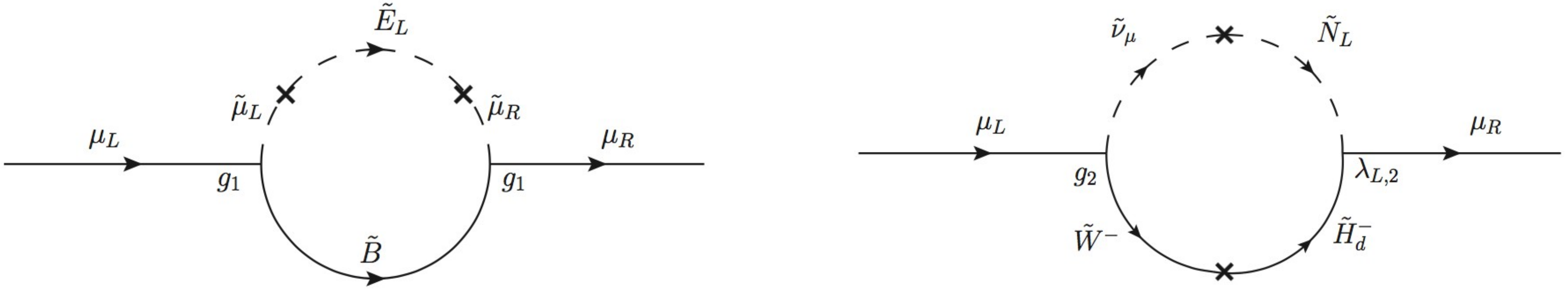
$$0 < \epsilon, \alpha < 1$$

And similar for the QUE model...

Flavor structure and muon g-2

Dominant mixing to 2nd generation gives extra contrib. to g-2

Example, **LD** model:

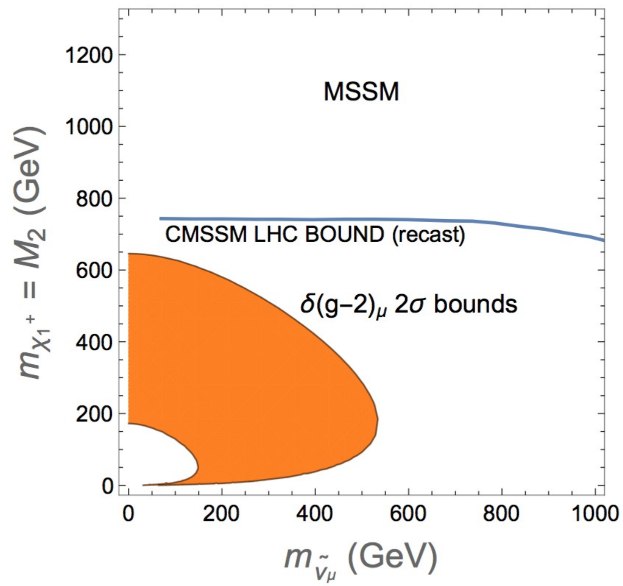


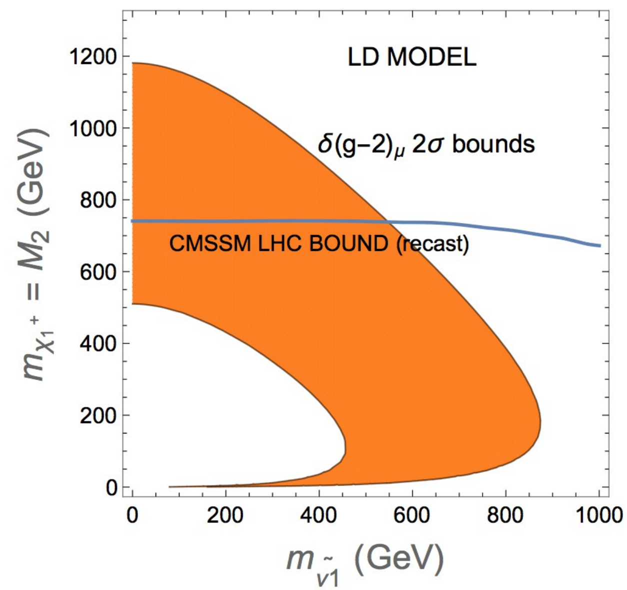
$$\Delta a_{\mu,\mathrm{VL}}^{\chi^\pm} \approx \frac{g_2\, m_\mu M_W}{12\sqrt{2}\,\pi^2}\,\frac{\mu\, M_2 \sin\beta}{m^2_{\chi_2^\pm} - m^2_{\chi_1^\pm}}\,\frac{\lambda_L(M_L \widetilde{M}_L + \widetilde{m}_L^2)}{m^2_{\tilde{\nu}_{\mu,2}} - m^2_{\tilde{\nu}_{\mu,1}}} \times \left[\frac{\mathcal{F}_C(z_{21}) - \mathcal{F}_C(z_{22})}{m^2_{\tilde{\nu}_{\mu,2}}} - \frac{\mathcal{F}_C(z_{11}) - \mathcal{F}_C(z_{12})}{m^2_{\tilde{\nu}_{\mu,1}}}\right]$$

Extra sources of slepton splitting enhance chirality flip!

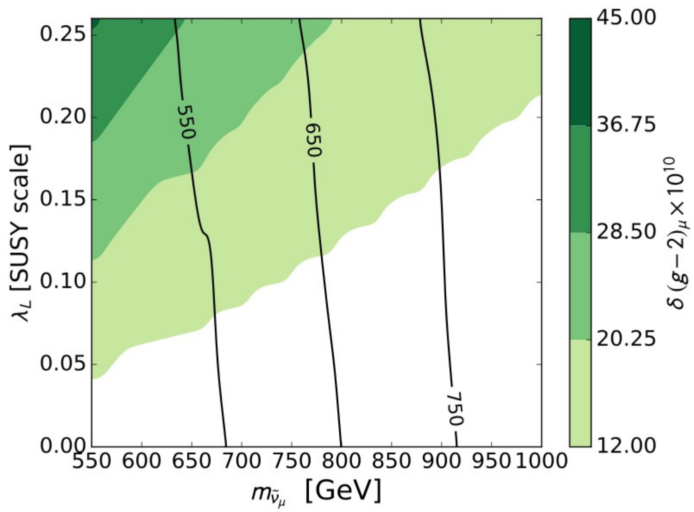
Flavor structure and muon g-2

Comparison with CMSSM:

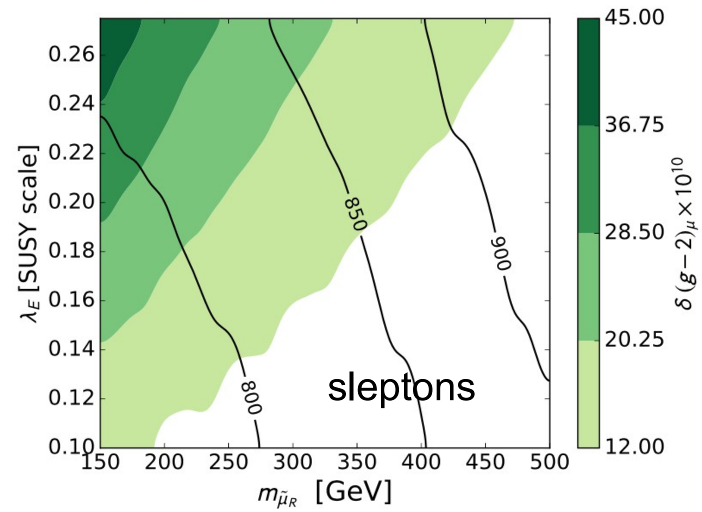




LD model parameter space



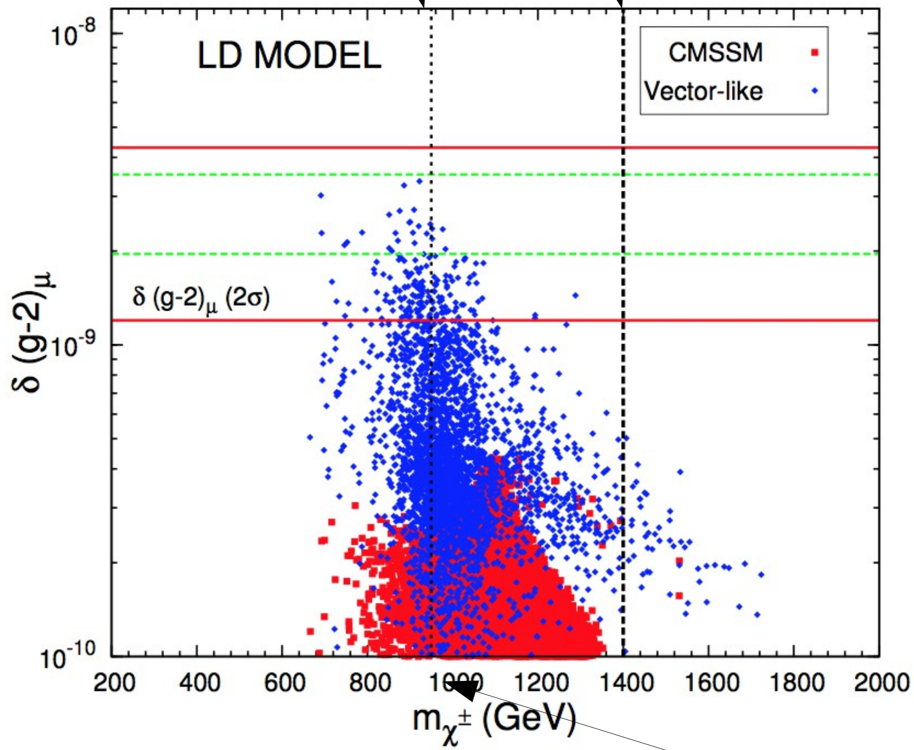
QUE model parameter space



LHC signatures VL SUSY models

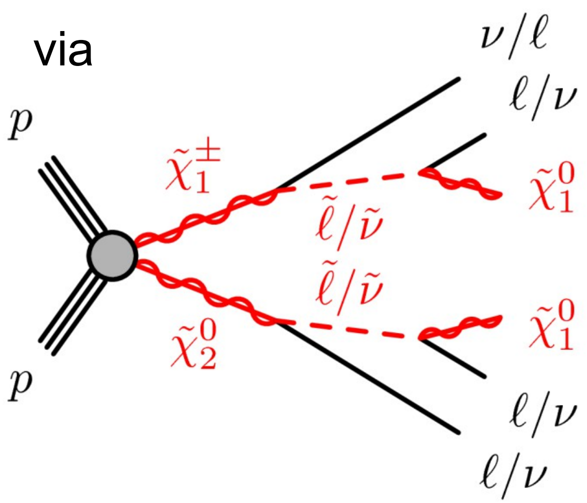
LHC 13 TeV,
~14/fb (ICHEP16)

Projected 300/fb (1503.08219)



Parameter space in reach of multilepton searches < 300/fb

via



However, simplified model interpretation (shown here) does not apply / <u>numerical simulation is required!</u>

DM signatures VL SUSY models

Neutralino dark matter, trivially not a problem

Region	SC	SC + bino ann.	AF
Model	<u>LD</u> / QUE	QUE	<u>LD</u> / QUE
m_χ	469.6 GeV	367.8 GeV	541.4 GeV
$m_{\tilde{\chi}^0_2} \simeq m_{\chi^\pm_1}$	886 GeV	670 GeV	1013.7 GeV
$m^2_{\tilde{L}_1}$	479.6 GeV	455.8 GeV	992.4 GeV
$m_{\tilde{\nu}_1}$	470.0 GeV	1163.7 GeV	988.0 GeV
m_A	1334.3 GeV	1543.1 GeV	1082.0 GeV
$\Omega_\chi h^2$	0.123	0.156	0.128
σ_p^{SI} [cm^2]	1.5×10^{-47}	3.1×10^{-47}	1.6×10^{-47}
$\delta(g-2)_\mu$	2.1×10^{-9}	1.6×10^{-9}	1.2×10^{-9}
m_h	123.9 GeV	123.8 GeV	123.1 GeV

Summary

- **Two MSSM-based GUT unified scenarios with minimal VL matter**

$$\mathbf{5}+\bar{\mathbf{5}},\ \mathbf{10}+\overline{\mathbf{10}}$$

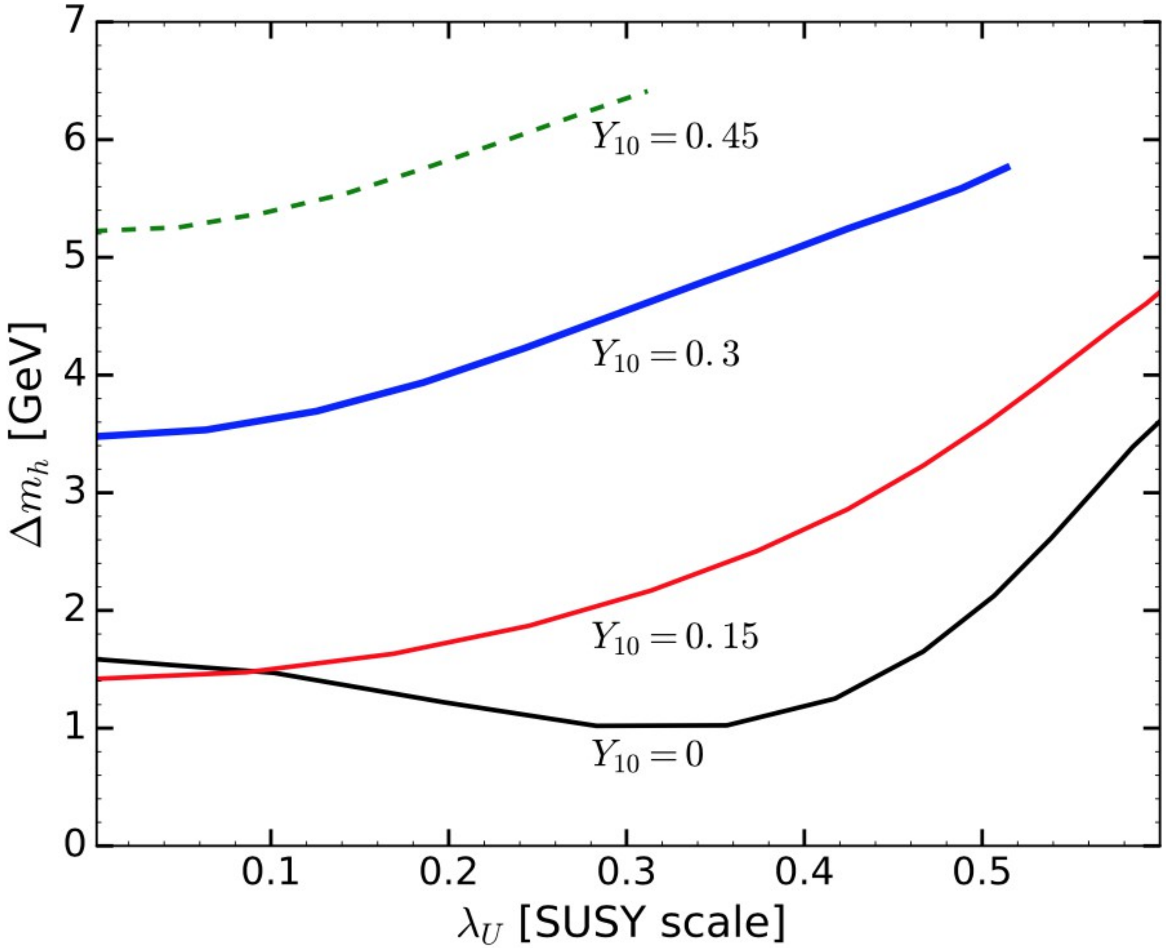
- **Much more restrictive than phenomenological parameterizations, but parameter space in agreement with wide array of constraints**

- **Do present some advantages with respect to CMSSM / NUHM → Mu g-2 OK, greater p.s. to bino dark matter**

- **Clear LHC signatures in multilepton searches**

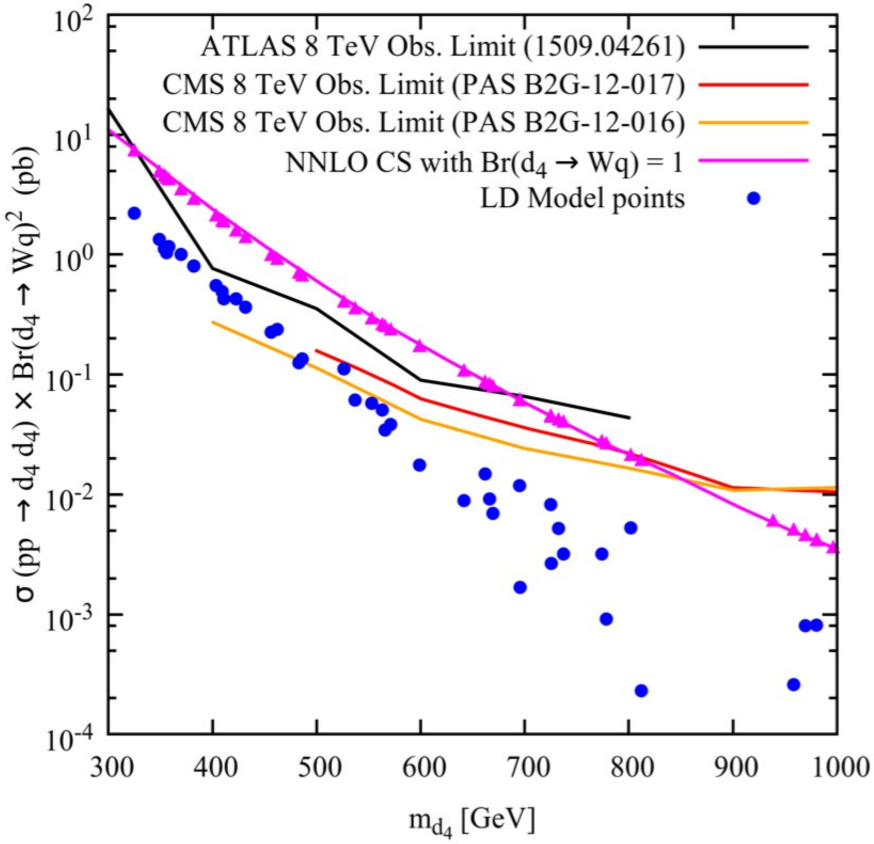
Backup

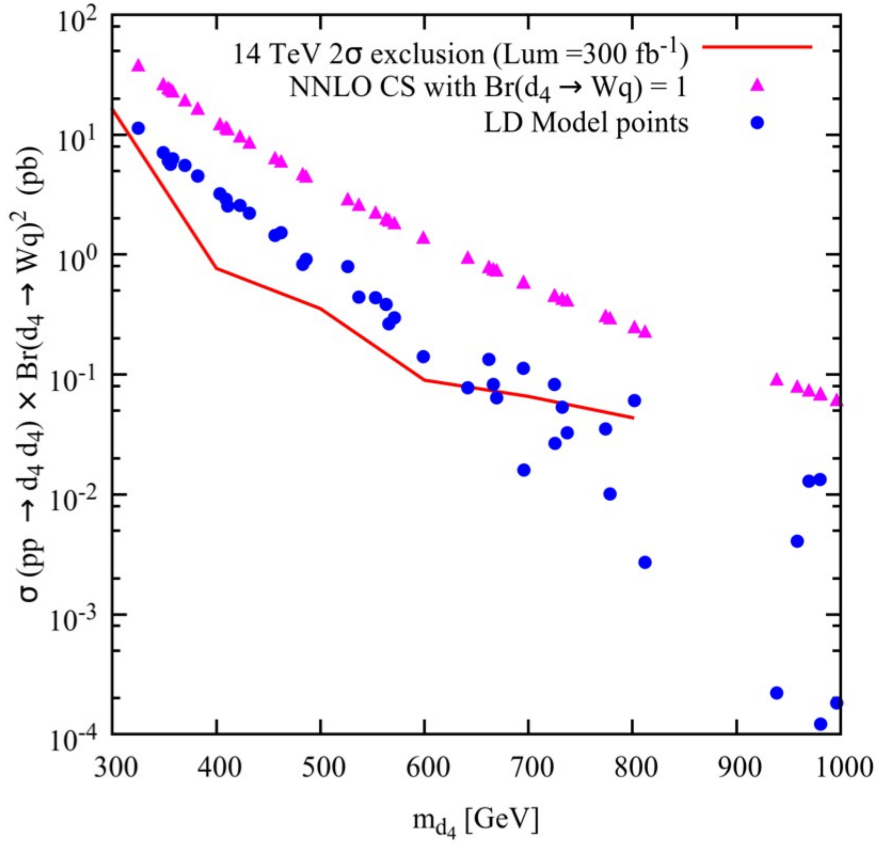
QUE model: Higgs mass enhancement



	Parameter	**LD**	**QUE**
GUT inputs	m_0	600	565
	$m_{1/2}$	1550	2500
	A_0	100	2500
	M_V	1000	250
	B_0	-250	0
	λ_5, λ_{10}	0.2	0.225
	Y_{10}	–	0
	$\widetilde{m}^2$	-1.2×10^6	-6×10^5
	$\widetilde{M}$	2	0
SUSY scale	$\tan\beta$	40	7.5
	$\lambda_{D,2}$, $\lambda_{U,2}$	0.47	0.59
	$\lambda_{Qu,2}$ / $\lambda_{Qd,2}$	–	0.56 / 0.76
	$\lambda_{L,2}$, $\lambda_{E,2}$	0.24	0.31
	μ	1680	3100
	B_μ	5.5×10^4	1×10^6
	M_1	546	377
	M_2	984	633
	M_3	2561	1757
	M_D, M_U	2125	810
	M_L, M_E	1352	298
	$\widetilde{M}_{D,2}$, $\widetilde{M}_{U,3}$	3.5	3.2
Pole Masses	m_h	124.4	126.2
	$m_{A,H}$	1084	2570
	$m_{\chi_1^0}$	539	372
	$m_{\chi_1^\pm}$	1013	675
	$m_{\tilde{g}}$	2700	1990
	$m_{\tilde{e}_1}$	651	374
	$m_{\tilde{e}_2}$	704	930
	$m_{\tilde{\nu}_1}$	710	1290
	$m_{\tilde{t}_R}$	2130	2210
	m_E	1370	302
	m_B	2260	1210
Low Energy	$\delta\,(g-2)_\mu$	2.2×10^{-9}	1.8×10^{-9}
	$\mathrm{BR}\,(B_u \to \tau\nu)$	1.28×10^{-4}	1.24×10^{-4}
	$\Omega_\chi h^2$	0.119	0.113

LHC vector-like bounds and 300/fb projections:





LD Model: constraints from Br(tau → mu gamma)