Exploring $(g-2)_\mu$ in the light of a Pati-Salam model with $A_4 \times Z_5$ family symmetry

(work in progress together with A. Belyaev, S. King, D. Miller, A. De Morais, J. Camargo-Molina)

Outline

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The Model

The anomalous magnetic moment of the muon $(g-2)_\mu$

Constraints

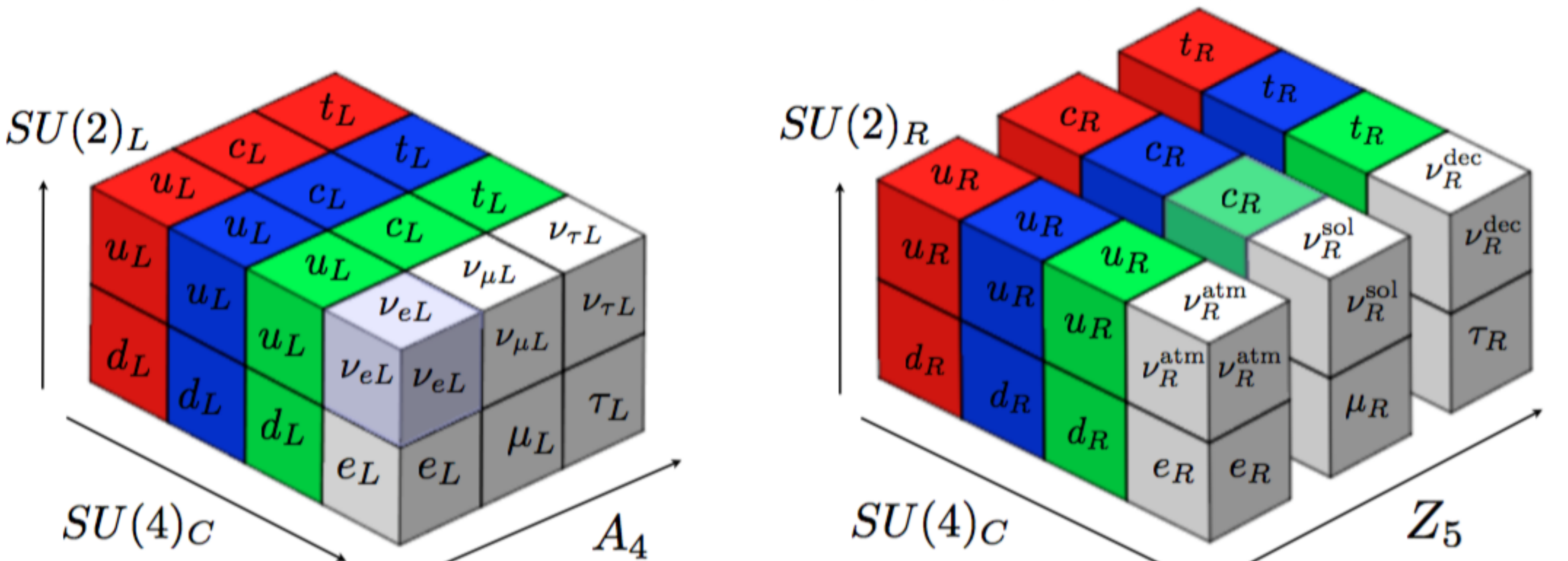
Results

LHC phenomenology

Conclusion and Outlook

The Model

$$SU(4)_C \times SU(2)_L \times SU(2)_R \times A_4 \times Z_5$$



[S. F. King JHEP 08 (2014) 130]

The Model

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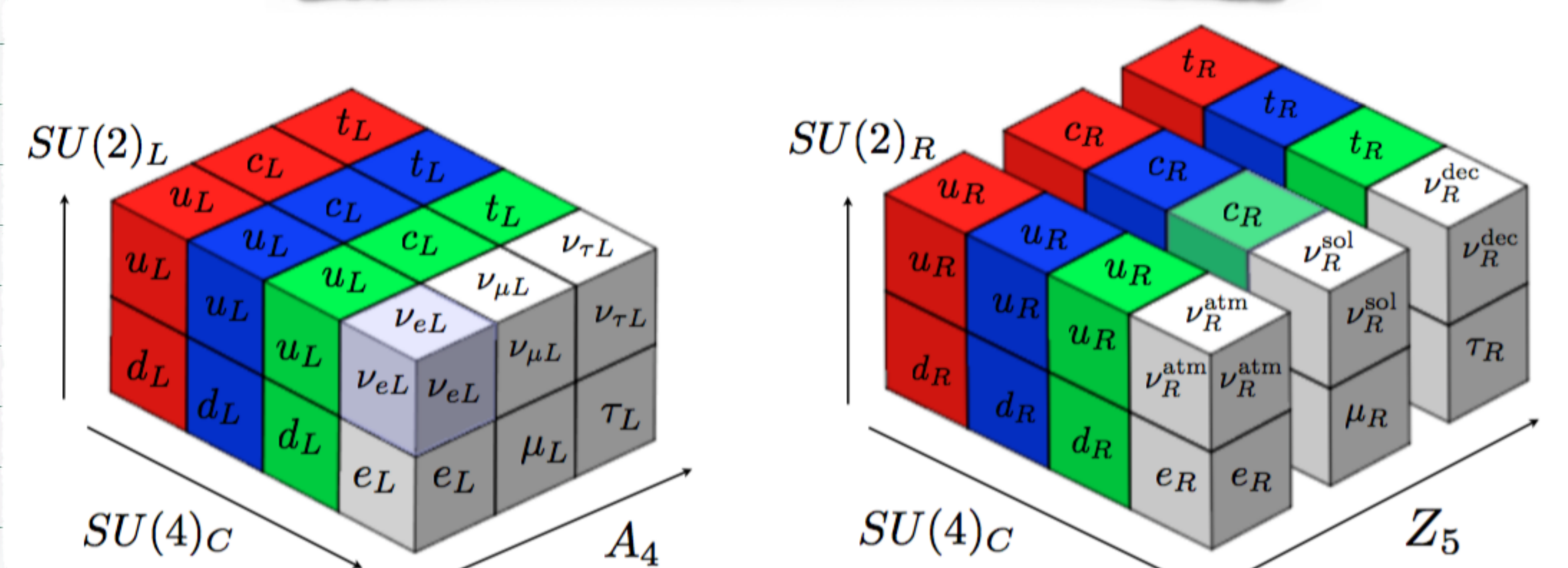

[S. F. King JHEP 08 (2014) 130]

very good at neutrino physics, but we're focussing on SUSY now

The Model

Quarks and leptons

$$F = (4,2,1)_i = \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_i \to (Q_i, L_i),$$

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The Model

Quarks and leptons

triplet under A_4, GUT scale mass m_0

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singlets under A_4, distinguished by Z_5 charges α, α^3, 1,
GUT scale masses m_1, m_2, m_3

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GUT scale masses m_1, m_2, m_3

→ novel boundary conditions at GUT scale
(more than MSSM, less than cMSSM)

The Model

PS breaks at GUT scale to SM by PS Higgs

$$H^c = (\bar{4}, 1, 2) = (u^c_H, d^c_H, \nu^c_H, e^c_H),$$
$$\overline{H^c} = (4, 1, 2) = (\bar{u}^c_H, \bar{d}^c_H, \bar{\nu}^c_H, \bar{e}^c_H)$$

VEVs close to GUT scale to keep gauge coupling unification

$$\langle H^c \rangle = \langle \nu^c_H \rangle = \langle \overline{H^c} \rangle = \langle \bar{\nu}^c_H \rangle \sim 2 \times 10^{16}\ \mathrm{GeV}$$

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→ model reduces to MSSM below GUT scale

The Model

Two types of Higgs bi-doublets

h_u: up-type quark and neutrino Yukawa couplings

h_d: down-type quark and charged-ℓ Yukawa couplings

h_3: A_4 triplet for third family Yukawa couplings

The Model

Two types of Higgs bi-doublets

h_u: up-type quark and neutrino Yukawa couplings

h_d: down-type quark and charged-ℓ Yukawa couplings

h_3: A_4 triplet for third family Yukawa couplings

after breaking, only light doublets survive

$$h_u, h_3 \to H_u, \qquad h_d, h_3 \to H_d$$

The Model

Model parameters

- m_0
- $m_i \, (i = 1, 2, 3)$
- $M_j \, (j = 1, 2, 3)$
- $m_{H_k} \, (k = u, d)$
- A_{tri}
- $\tan\beta$
- $\text{sgn}(\mu)$

left-handed quark and lepton masses
for all three generations

right-handed quark and lepton masses
for each generation i

Higgsino, Bino and Wino mass parameters

light Higgs doublet masses

$(g\text{-}2)_\mu$

Dirac equation predicts

$$\vec{M} = g_\mu \frac{e}{2\,m_\mu} \vec{S}$$

gyromagnetic ratio

classically, $g_\mu=2$

Quantum corrections change g_μ

$(g-2)_\mu$

Dirac equation predicts

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classically, $g_\mu=2$

gyromagnetic ratio

Quantum corrections change g_μ

→ parametrise change by

$$a_\mu = \frac{g_\mu - 2}{2}$$

anomalous magnetic moment

$(g-2)_\mu$

exp. value: $a_\mu = (11{,}659{,}209.1 \pm 6.4)\ 10^{-10}$

theo. SM value: $a_\mu = (11{,}659{,}1803.3 \pm 4.9)\ 10^{-10}$

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➡ 3-4σ difference, denoted by Δa_μ

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (28.8 \pm 8.0) \times 10^{-10}$$

$(g\text{-}2)_\mu$

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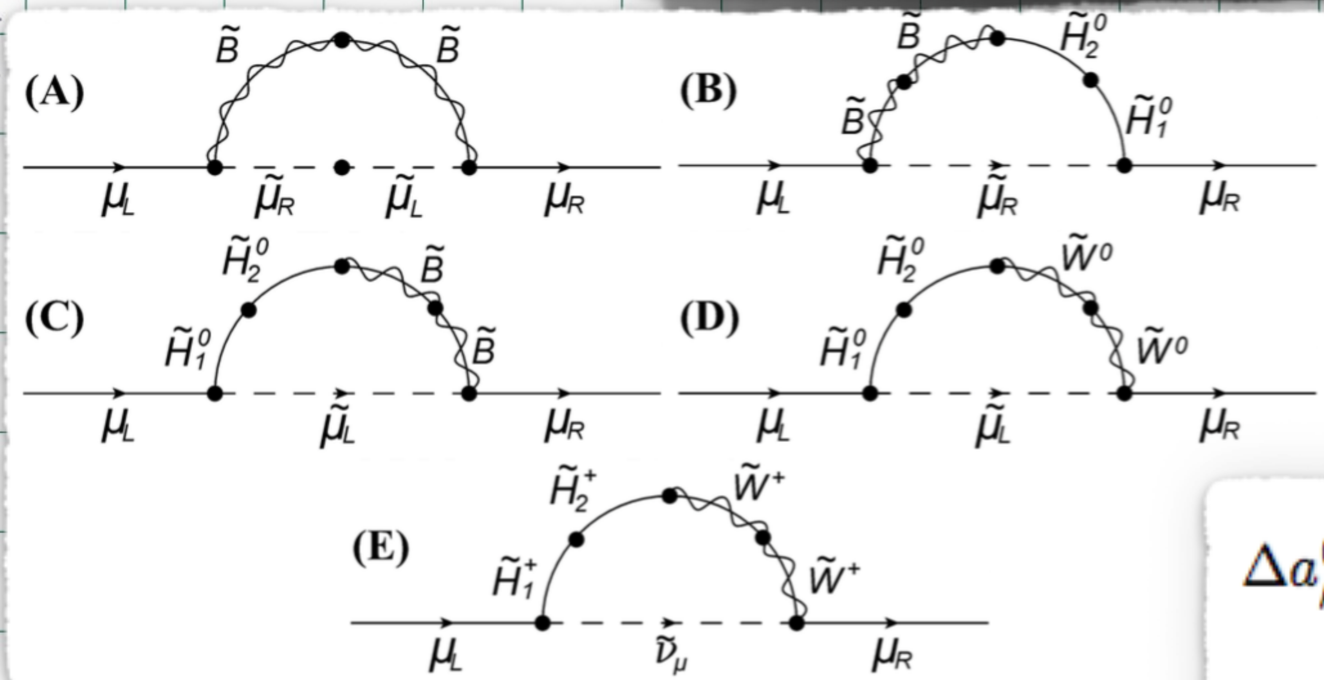
3-4σ difference, denoted by Δa_μ

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (28.8 \pm 8.0) \times 10^{-10}$$

SUSY could (partially) resolve this

$(g\text{-}2)_\mu$

One-loop MSSM contributions



[M. Endo et al. JHEP 01 (2014) 123]

$$0 \le f(x) \le 1$$

$$\Delta a_\mu^{(A)} = \left(\frac{M_1\mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2}\right)\frac{\alpha_1}{4\pi}m_\mu^2\tan\beta\cdot f_{\text{neutral}}\left(\frac{m_{\tilde{\mu}_L}^2}{M_1^2},\frac{m_{\tilde{\mu}_R}^2}{M_1^2}\right),$$

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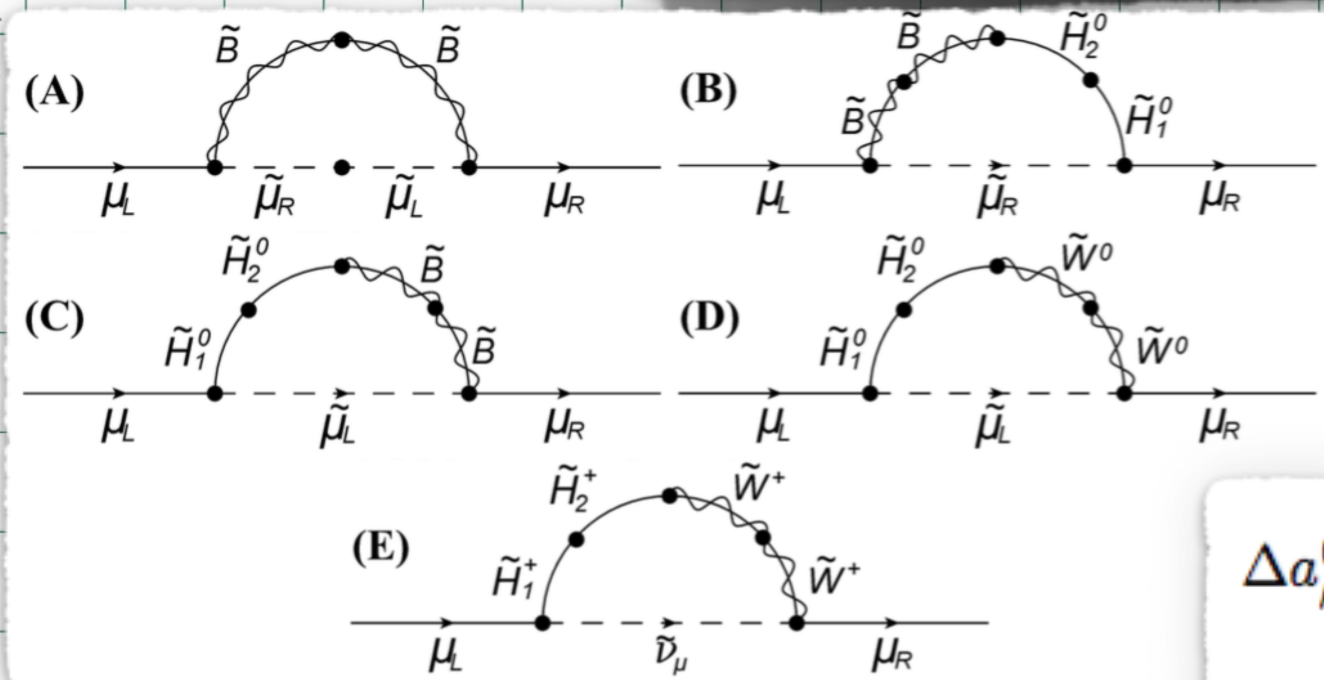
$$\Delta a_\mu^{(E)} = \left(\frac{1}{M_2\mu}\right)\frac{\alpha_2}{4\pi}m_\mu^2\tan\beta\cdot f_{\text{charged}}\left(\frac{M_2^2}{m_{\tilde{\nu}_\mu}^2},\frac{\mu^2}{m_{\tilde{\nu}_\mu}^2}\right),$$

[D. Stöckinger, hep-ph/0609168v1]

$(g\text{-}2)_\mu$

One-loop MSSM contributions



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only term linear in μ

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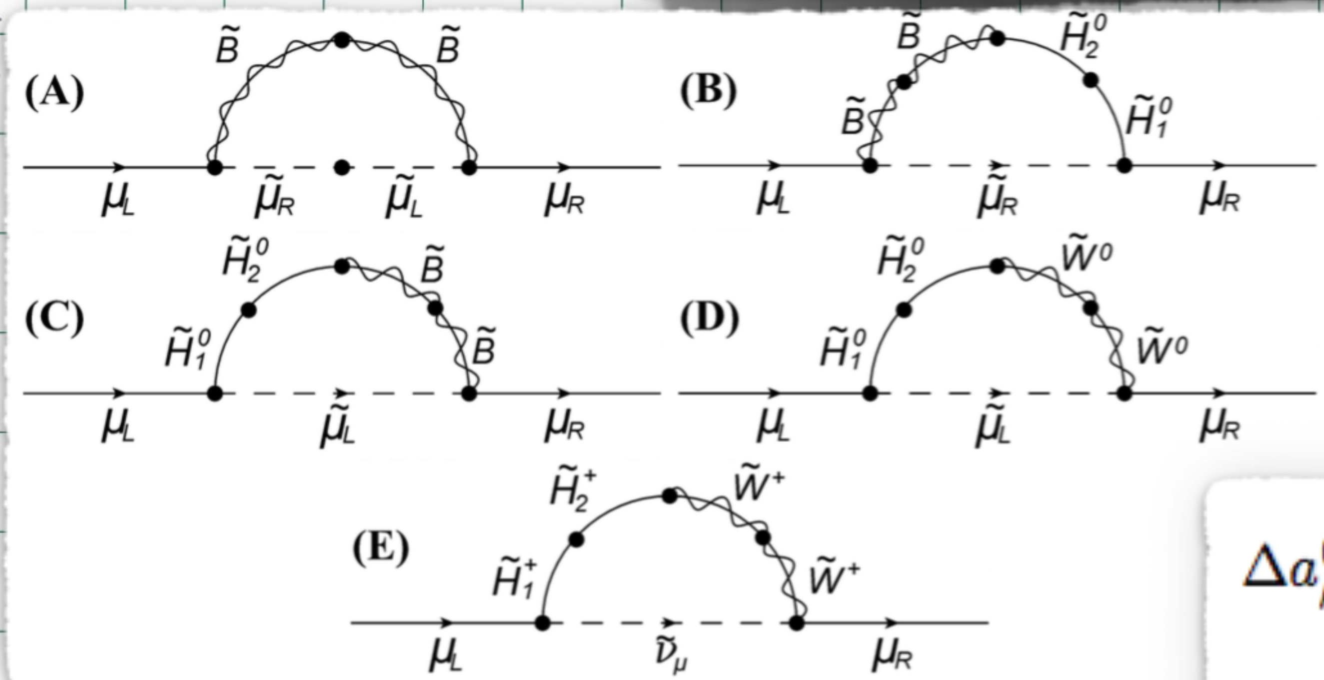

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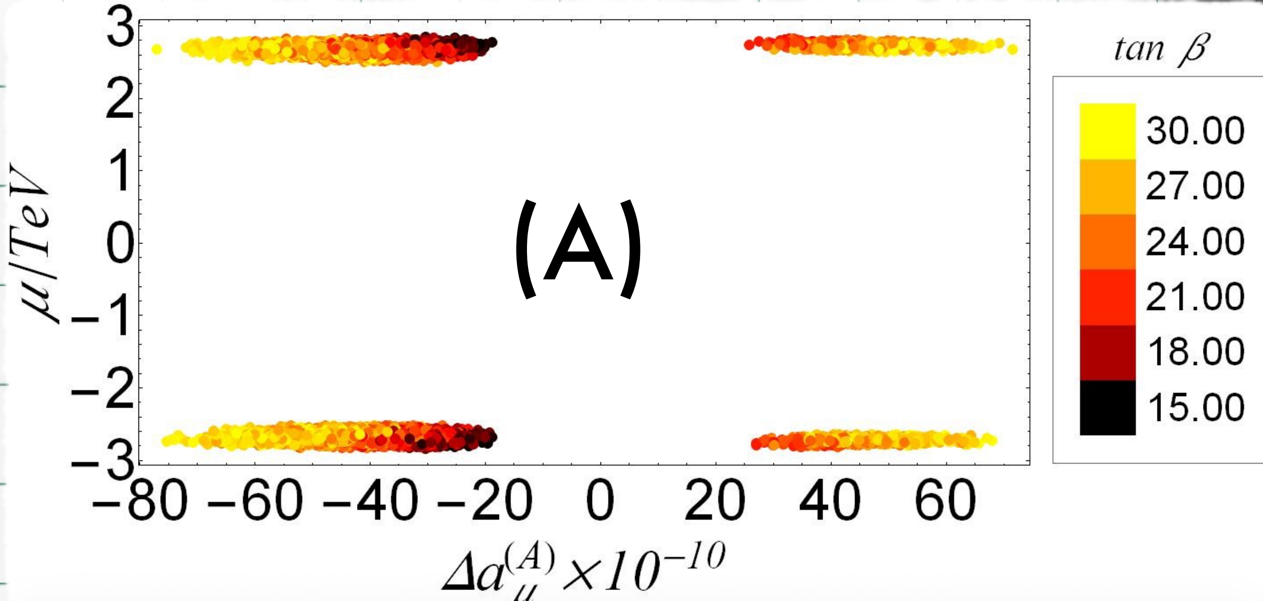
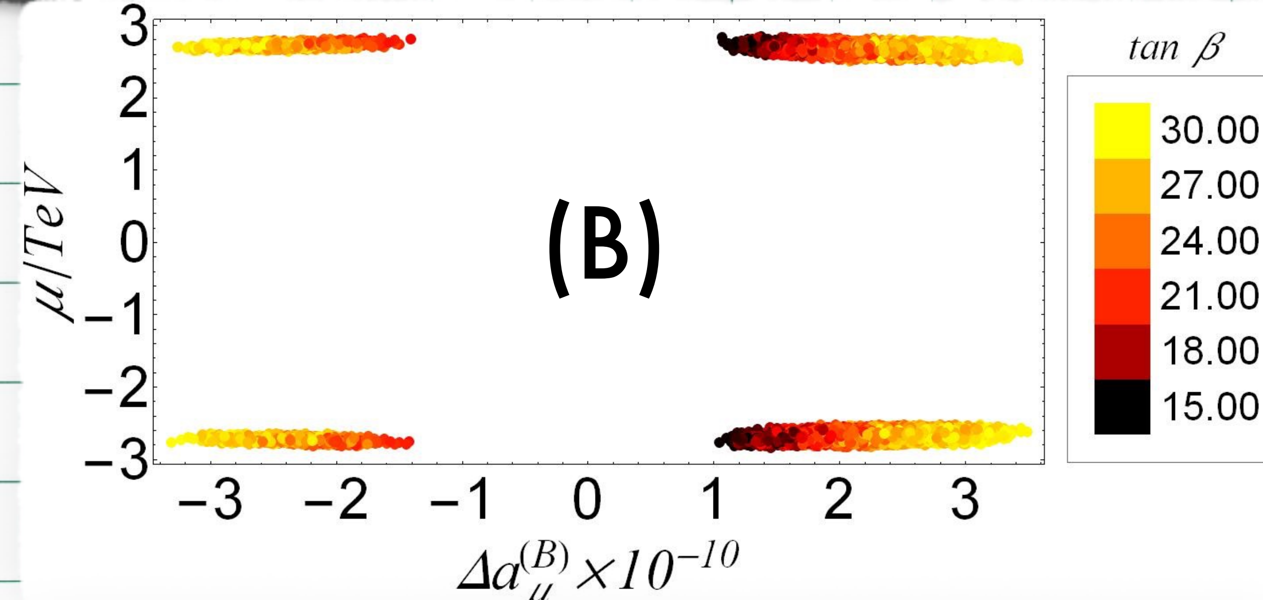
[D. Stöckinger, hep-ph/0609168v1]

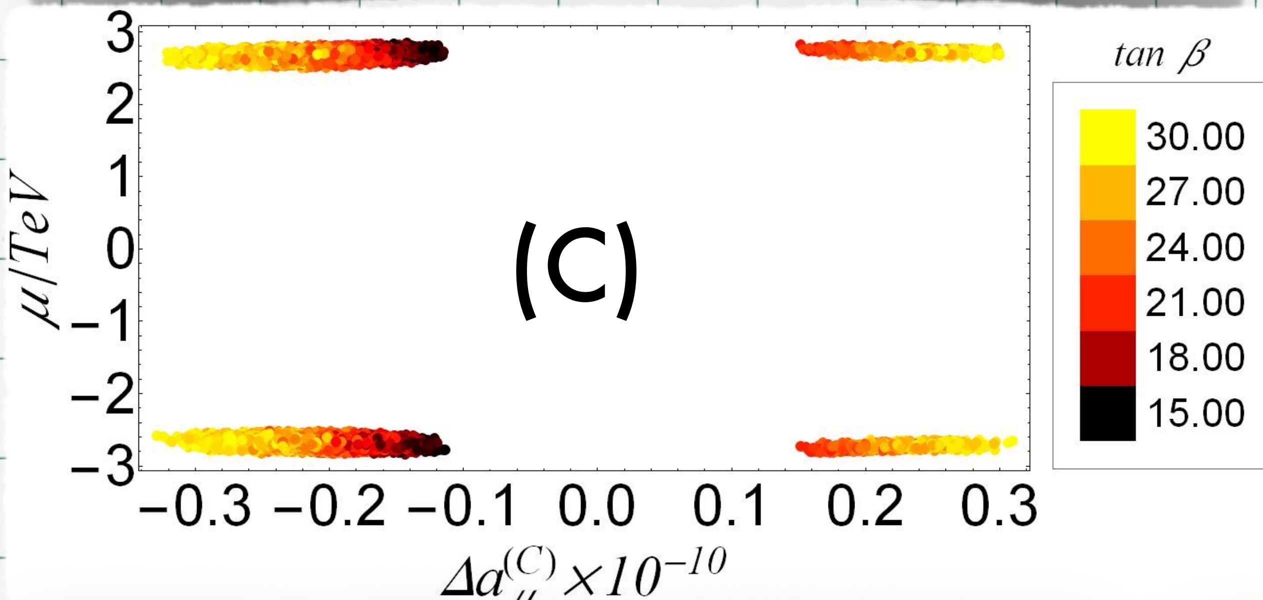
$\Delta a_\mu(A)$ benefits from:

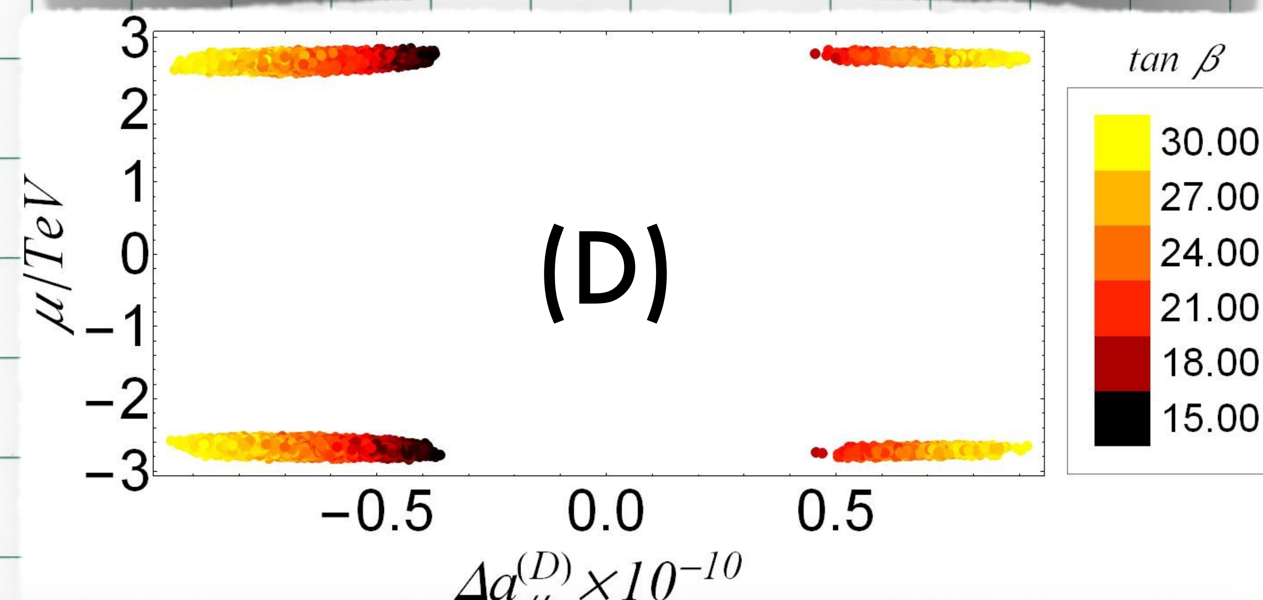
- small smuon masses
- large μ

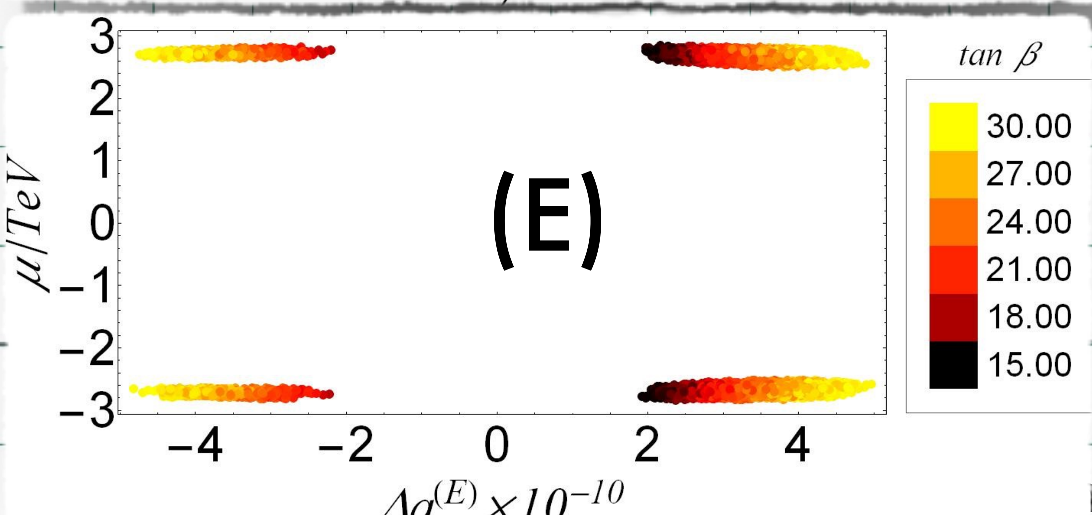
$(g-2)_\mu$











Parameter	range	Parameter	range
$\lvert A_{tri}\rvert$	1 – 1200	$\lvert M_1\rvert$	300 – 400
m_0	450 – 550	$\lvert M_2\rvert$	500 – 600
$m_1,\, m_2$	50 – 150	$\lvert M_3\rvert$	1900 – 2200
m_3	2000 – 2400	$\tan\beta$	15 – 30
m_{H_1}	500 – 600	$sign\,(\mu)$	± 1
m_{H_2}	350 – 450		

Constraints

Model should successfully describe

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Dark Matter

relic density Ωh^2, DM direct detection cross sections

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Collider constraints

Higgs mass, $b > s\gamma$, $B_S > \mu^+\mu^-$, $\Delta\rho$

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Δa_μ

Constraints

Additional requirements

heavy coloured sparticles $\xrightarrow{\text{controlled by}}$ m_3, M_3

→ keep m_H via low-scale stop loop contributions

light sleptons, esp. smuons → m_i $(i=0,1,\underline{2},3)$

→ increase $\Delta a_\mu(A)$

Constraints

Additional requirements

controlled by

bino-like LSP

for correct Dark Matter

$m_{\mathrm{LSP}} - m_{\tilde{\mu}}$ large

avoid soft leptons at LHC

Results

Schematic Workflow

Choose input parameters

SoftSUSY generates spectra

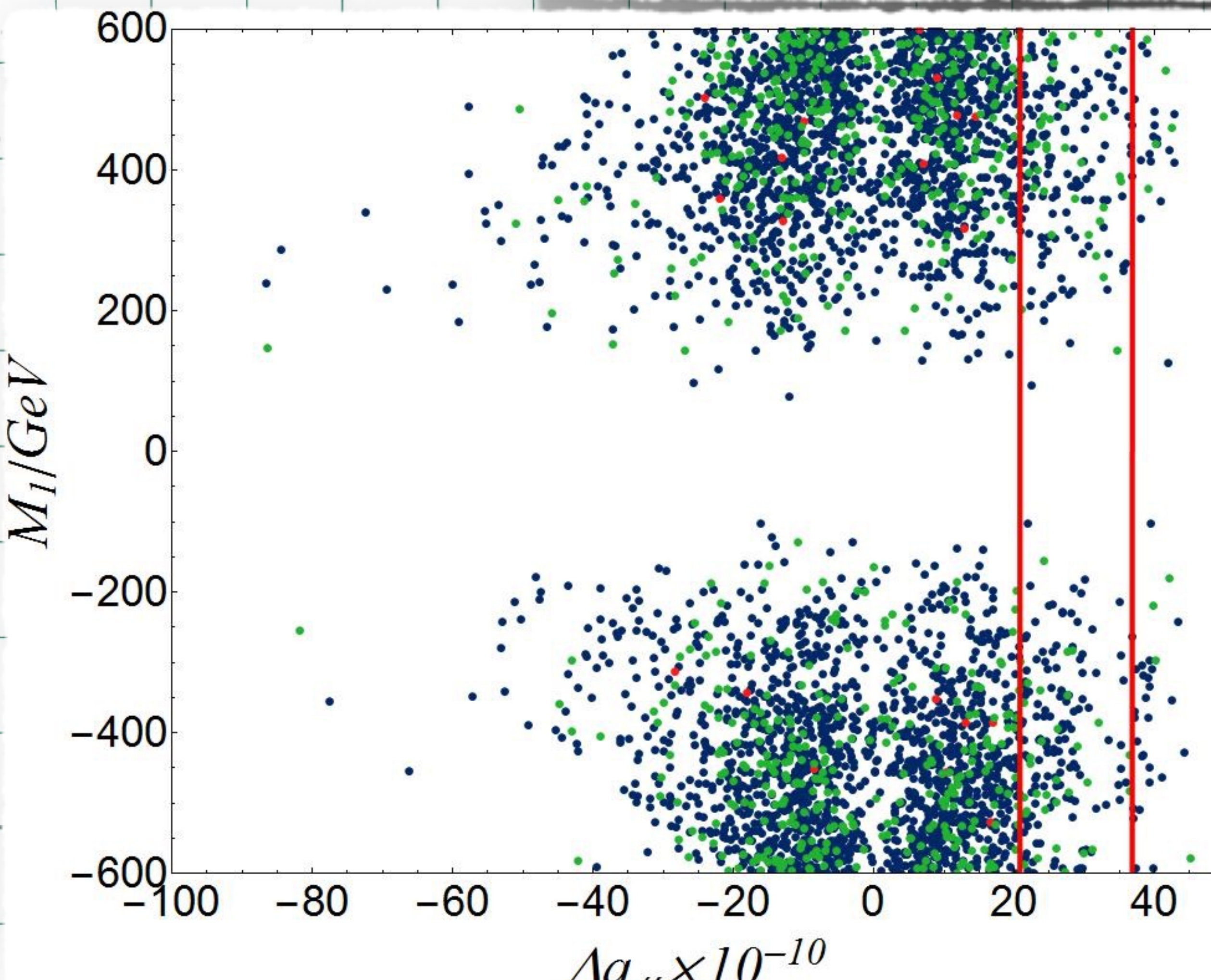
micrOMEGAs checks spectra on constraints

redo, if necessary

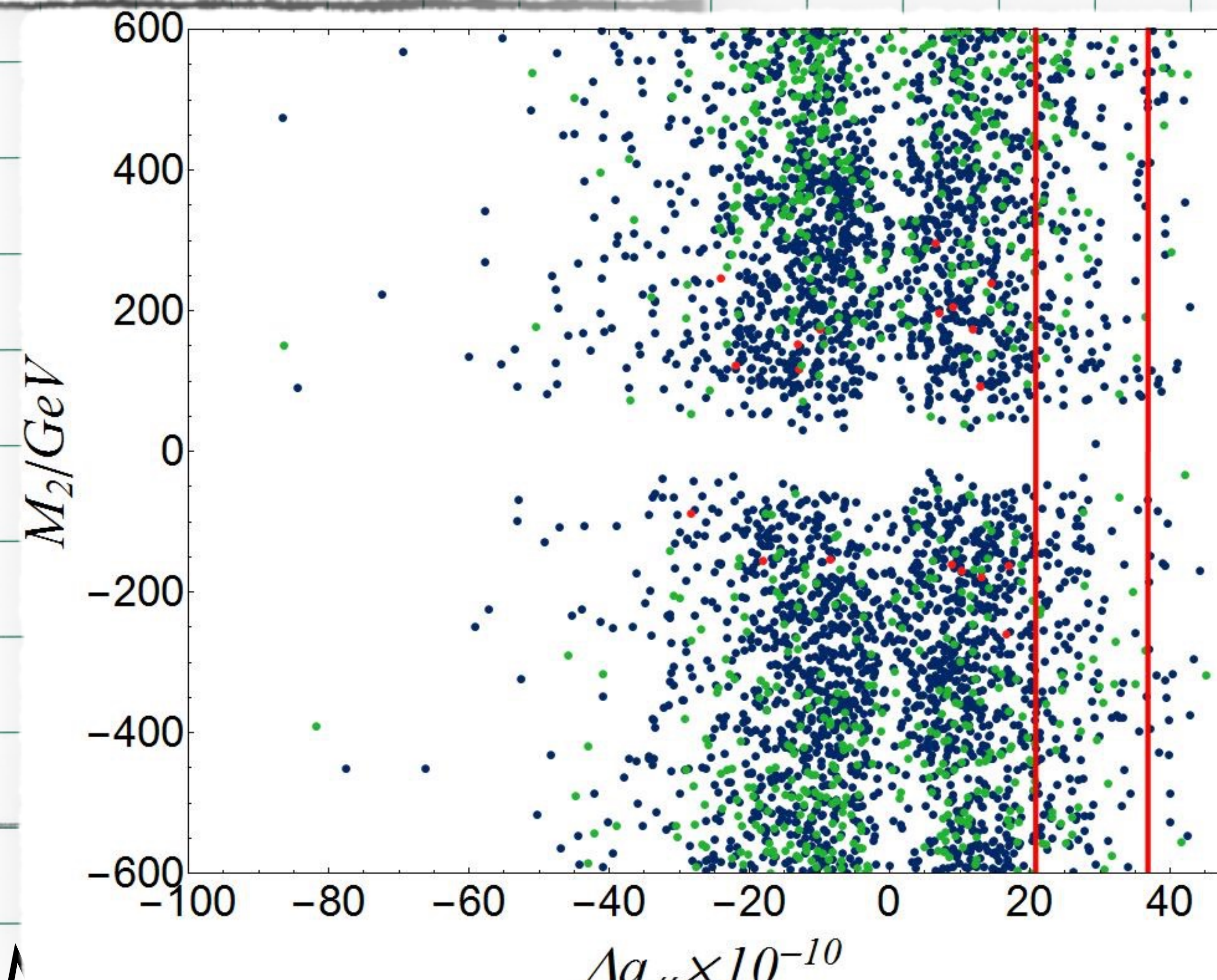
Results

A first inclusive scan

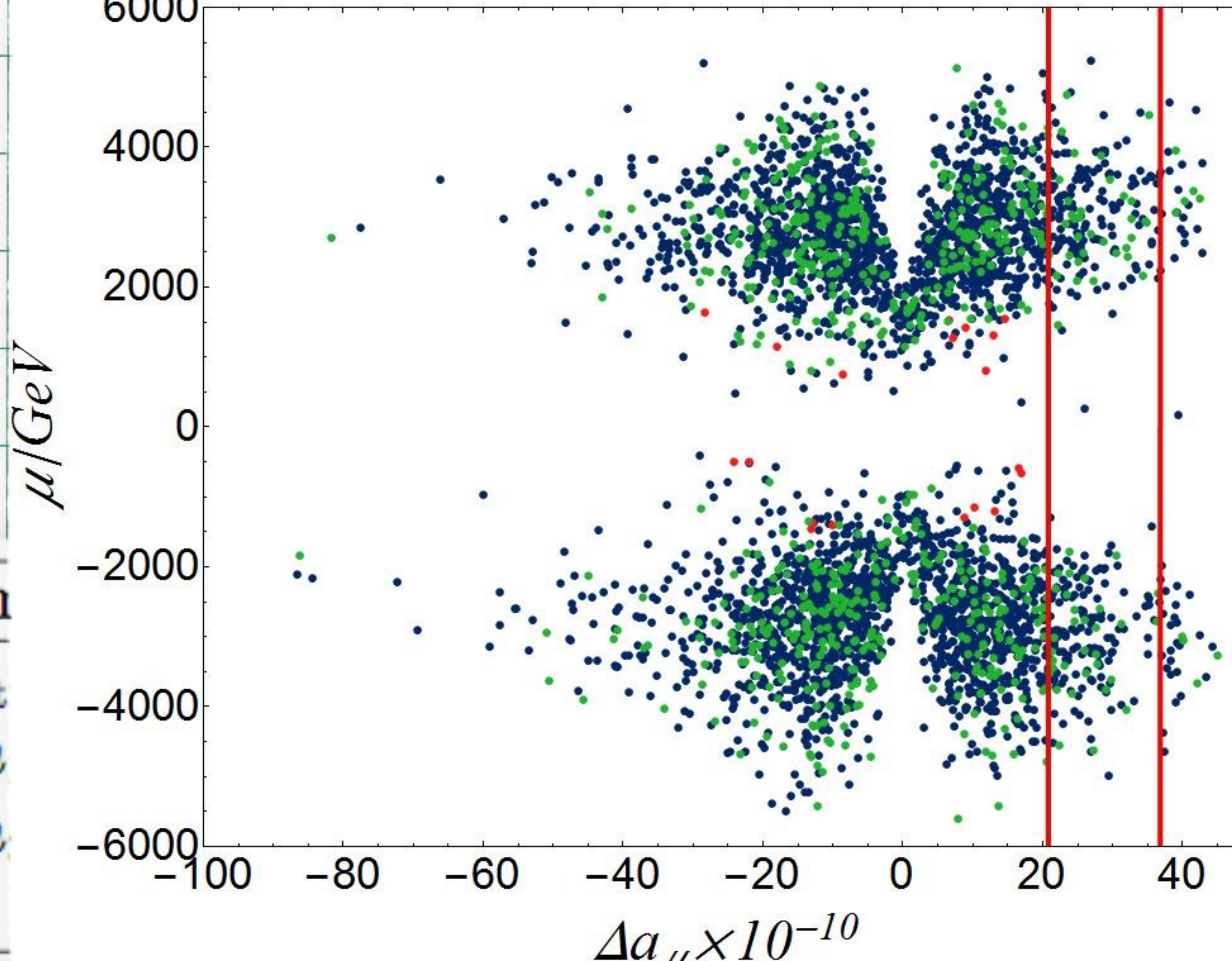
Parameter	range	Parameter	range
$\lvert A_{\rm tri}\rvert$	1 – 3000	$\lvert M_1\rvert,\ \lvert M_2\rvert$	1 – 600
$m_0,\ m_1,\ m_2$	1 – 500	$\lvert M_3\rvert$	1 – 6000
m_3	1 – 3000	$\tan\beta$	5 – 50
$m_{H_1},\ m_{H_2}$	1 – 3000	$\mathrm{sgn}\,(\mu)$	± 1

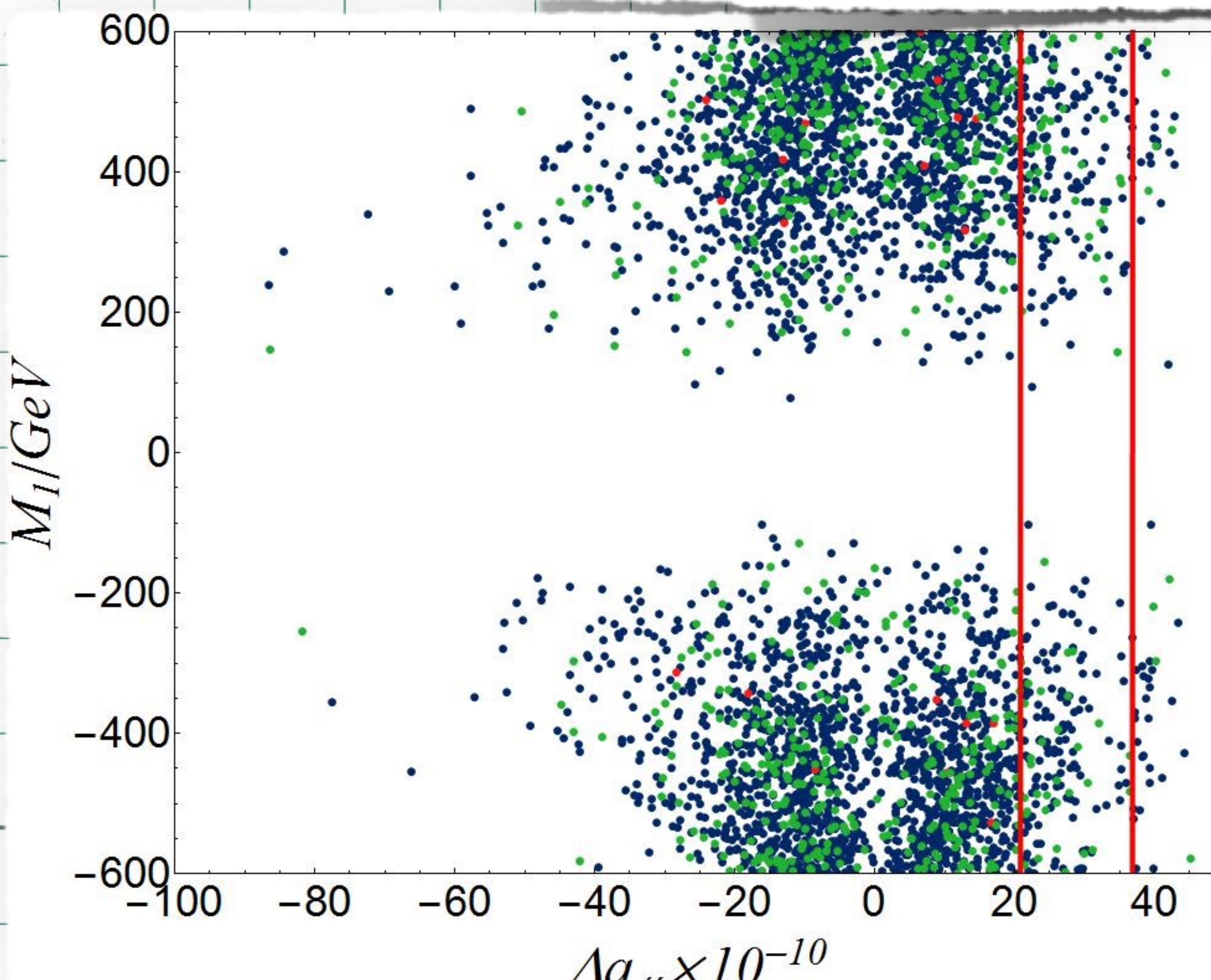


From

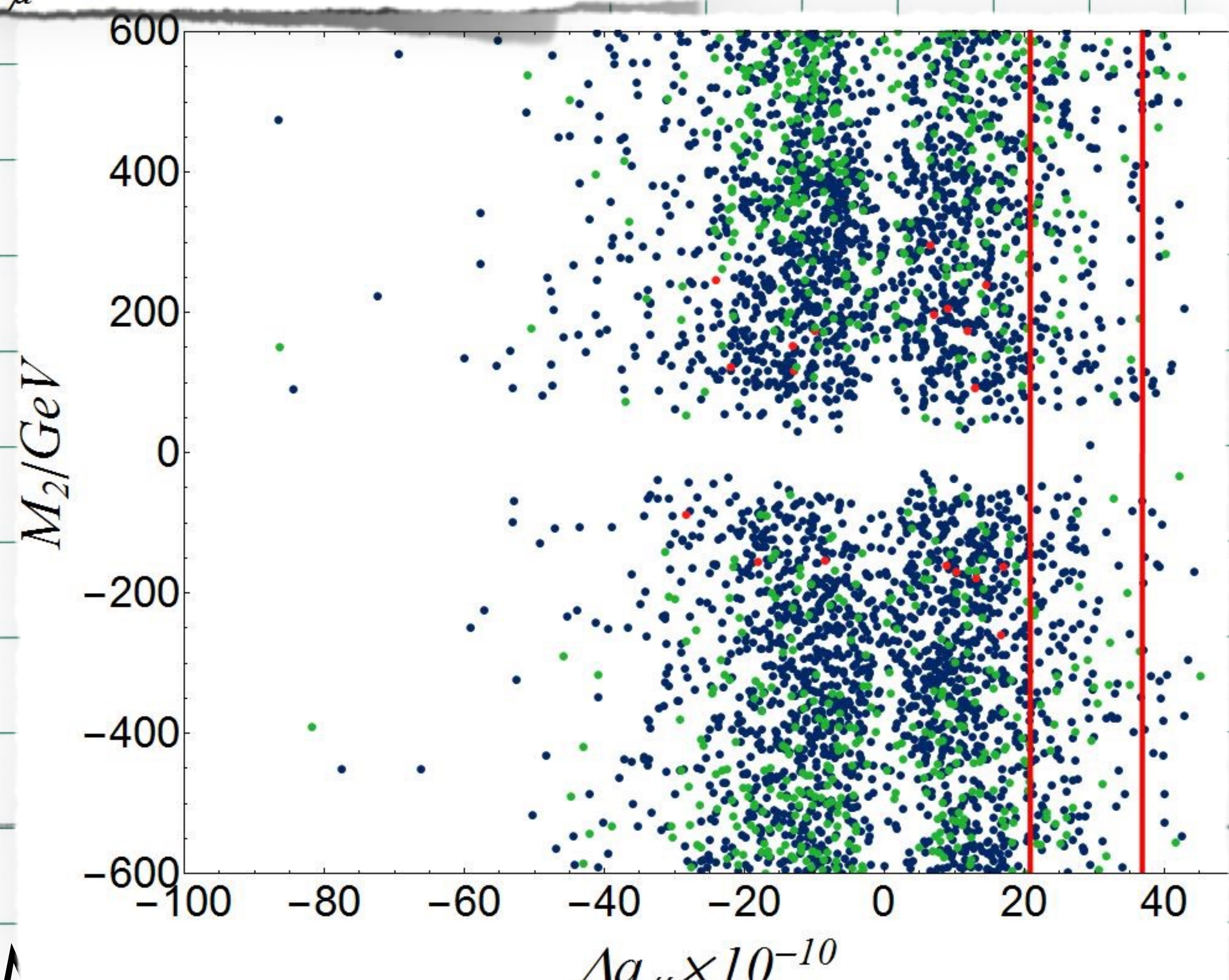


Paran |
$|A_t$ | 00
m_0, m | 000
m | 0
m_{H_1},





From M



Results

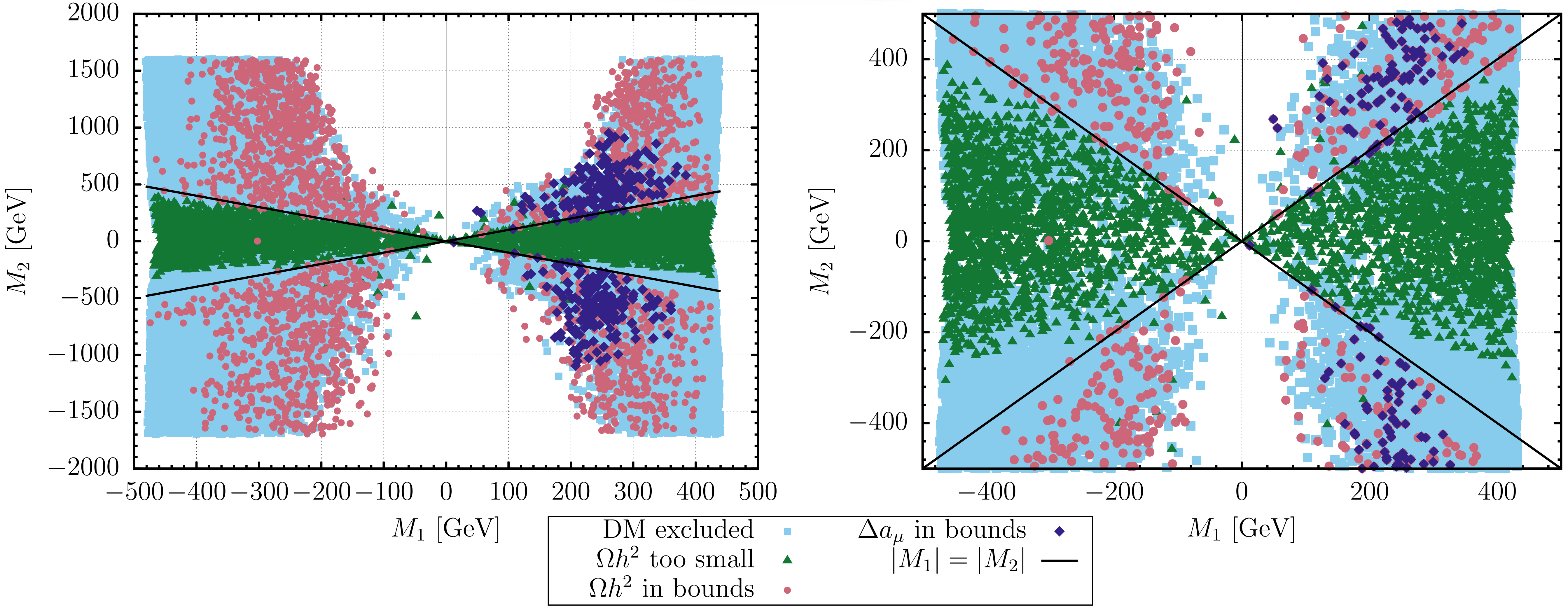
Final scan range

Parameter	range	Parameter	range
A_{tri}	-3000 – 0	M_1	-1000 – 1000
m_0	100 – 300	M_2	-2000 – 2000
m_1	500 – 1500	M_3	2000 – 3000
m_2	100 – 400	$\tan\beta$	5 – 50
m_3	1000 – 2000	$\text{sgn}(\mu)$	± 1
m_{H_1}, m_{H_2}	100 – 3000		

- small m_0, m_2 keep smuons light
- high m_3, M_3 keep squarks and gluino heavy
- negative A_{tri} consequence of prev. scans

Results

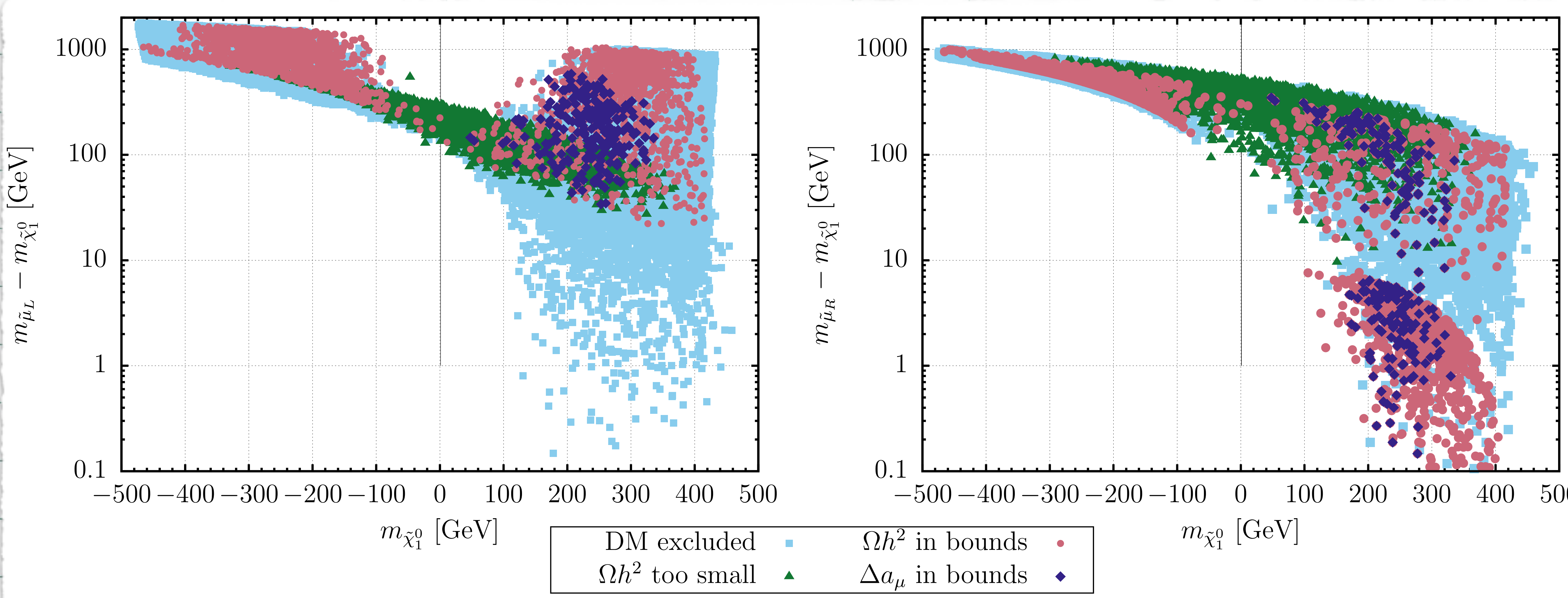
M_1 vs. M_2



→ all dark-blue diamonds bino-like

Results

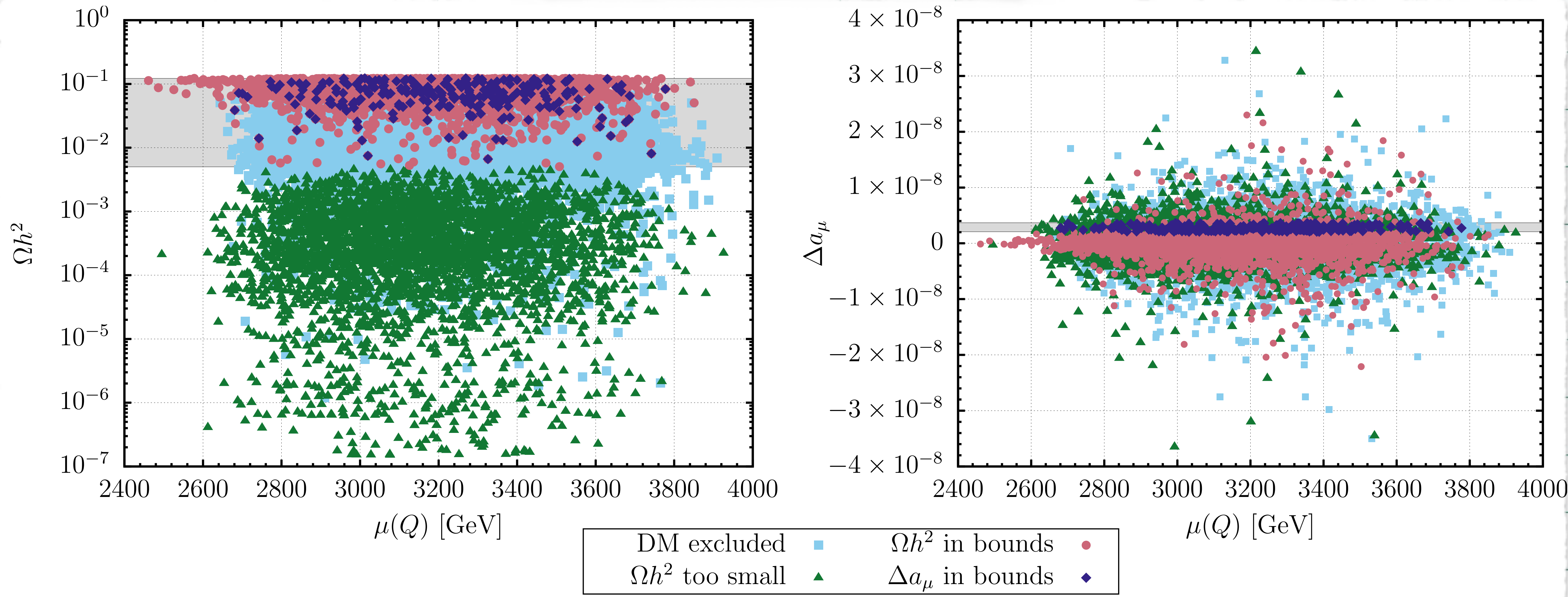
$m_{\tilde{\mu}_{L/R}} - m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{\chi}_1^0}$



→ high mass gaps between smuons and LSP ($\chi^0{}_1$) possible

Results

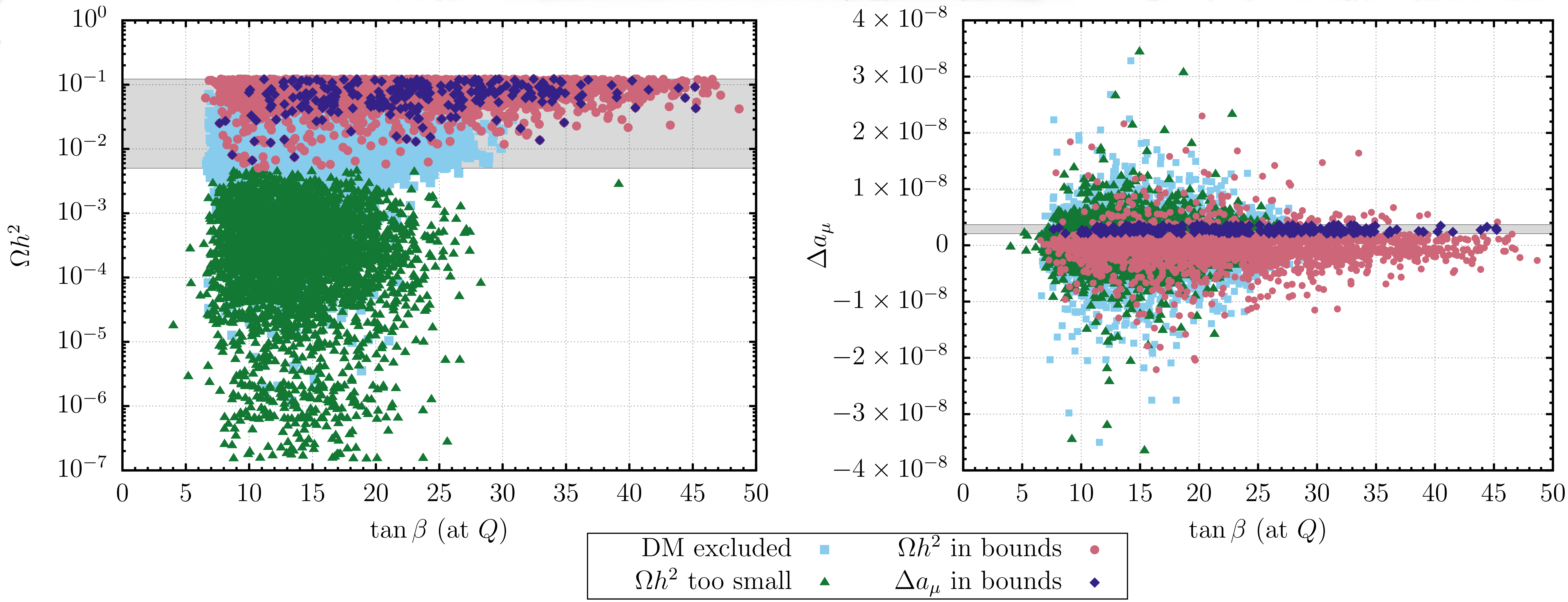
Ωh^2 and Δa_μ vs. $\mu(Q)$



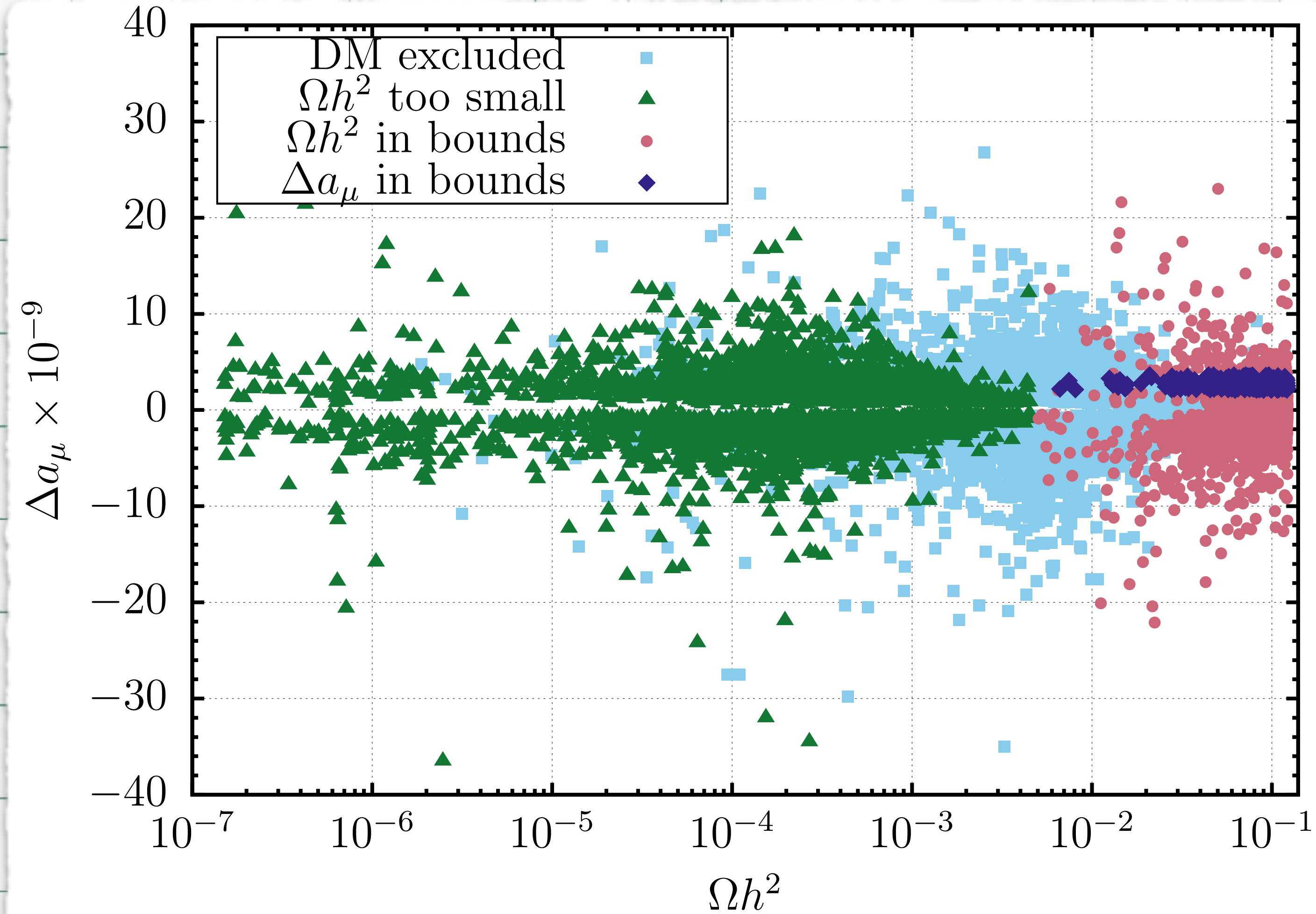
→ plenty of good points at high μ

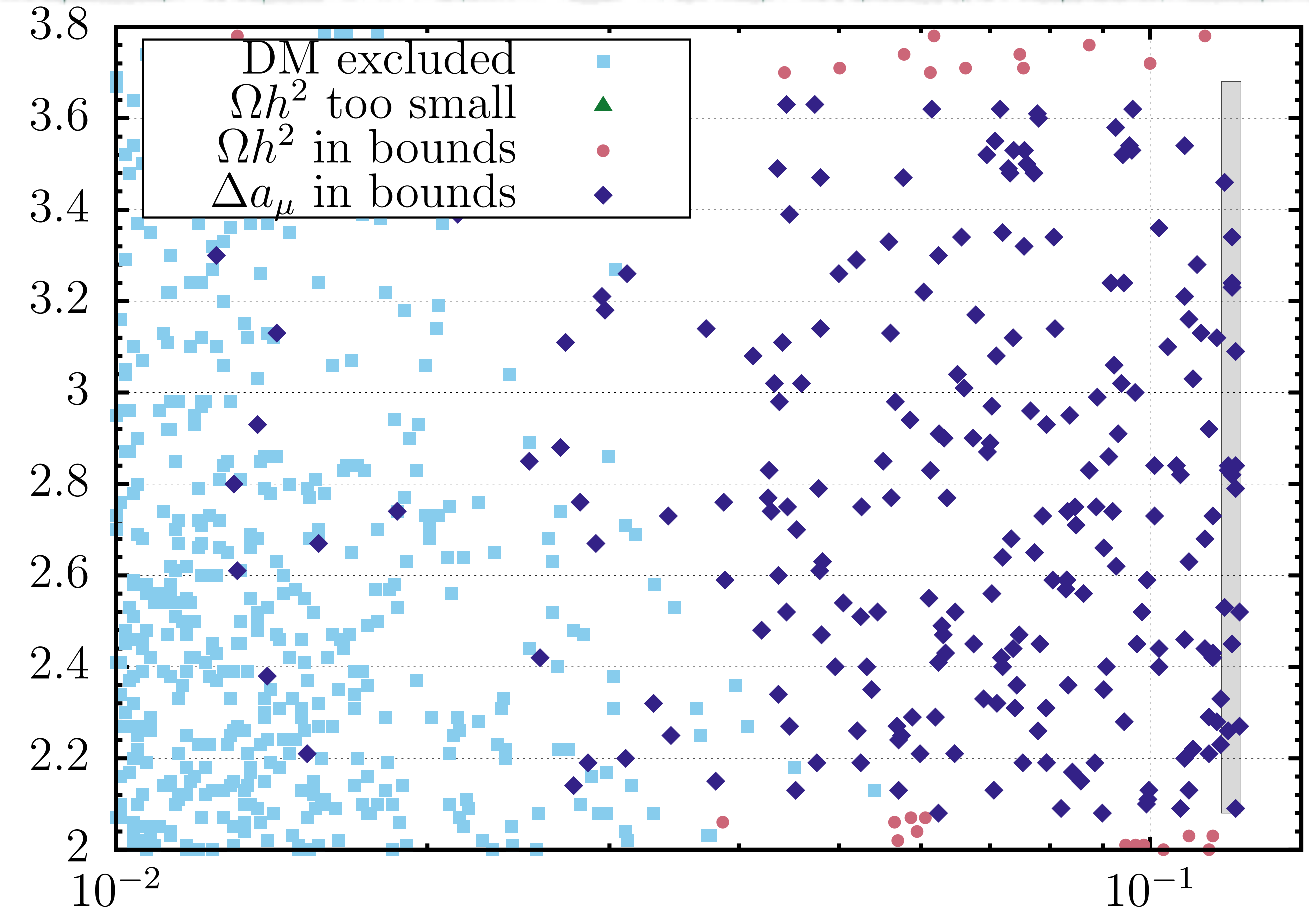
Results

Ωh^2 and Δa_μ vs. tan(β)

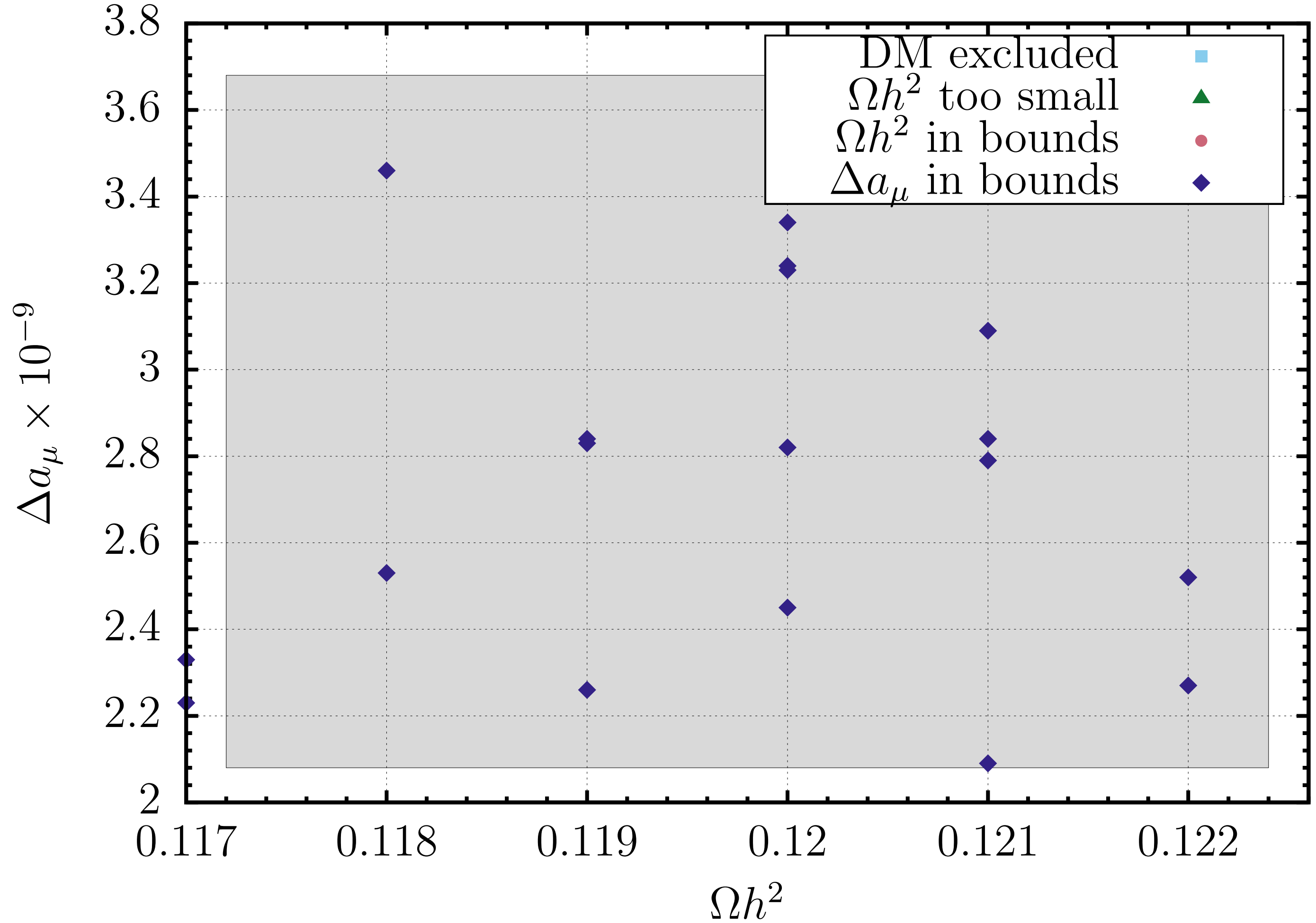


Ωh^2 and Δa_μ mainly independent of tan(β)





several points fulfil Ωh^2 and Δa_μ perfectly (both in exp. bounds)



Results

Keep best points as benchmark points

	Scanpoints:	25804	37470	38793	39936	40125	43253	
Input at GUT scale	$\tan\beta$	13.46	13.41	23.11	21.23	16.86	16.06	
	$\mathrm{sgn}(\mu)$	+	+	+	+	+	+	
	m_0	265.11	218.69	231.64	234.81	174.97	247.95	[GeV]
	m_1	1286.94	929.91	831.21	827.94	555.14	775.83	
	m_2	203.78	345.51	367.07	295.69	243.26	309.78	
	m_3	1286.94	1936.06	1507.70	1299.67	1184.39	1330.39	
	M_1	644.47	422.67	555.63	340.59	537.13	386.74	
	M_2	-314.40	376.66	504.74	-303.61	452.07	-275.54	
	M_3	2926.15	2986.71	2024.11	2127.89	2826.53	2374.10	
	$M_{h_1}^2$	1419.23	529.49	828.93	1925.57	2638.13	295.61	
	$M_{h_2}^2$	870.33	258.61	2288.91	314.16	966.01	2529.62	
	A_{tri}	-622.31	-432.63	-2396.39	-2453.70	-427.72	-2919.38	

Results

Keep best points as benchmark points

	Scanpoints:	12144	19223	24289	27146	32375	
	$\tan\beta$	28.95	14.17	38.03	11.77	30.62	
	$\mathrm{sgn}(\mu)$	+	+	+	+	+	
Input at GUT scale	m_0	298.31	156.76	175.11	269.49	120.90	[GeV]
	m_1	1237.47	1130.46	1028.91	650.60	1251.34	
	m_2	235.37	122.78	272.25	115.04	133.48	
	m_3	1378.14	1323.65	1971.72	1413.28	1440.07	
	M_1	668.87	582.54	472.27	604.02	678.72	
	M_2	537.19	-538.15	-759.35	-313.94	903.51	
	M_3	2316.28	2899.29	2431.36	2813.85	2990.78	
	$M^2_{h_1}$	908.83	604.90	484.49	1328.00	2131.77	
	$M^2_{h_2}$	1389.90	370.81	2857.00	573.23	739.13	
	A_{tri}	-1898.98	-1885.31	-2934.84	-2265.06	-1601.80	

Results

So far, model explains all desired quantities

Results

So far, model explains all desired quantities

However, two questions remain:

Can the predicted particles (mainly smuons) be discovered at the LHC?

Is the model able to explain di-lepton excesses found at CMS and ATLAS?

LHC phenomenology

Schematic Workflow

Choose input parameters

SoftSUSY generates spectra

micrOMEGAs checks spectra on constraints

MadGraph generates event files

CheckMATE checks event files on collider studies (8 TeV)

redo, if necessary

LHC phenomenology

Schematic Workflow

these worked (see plots)

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these worked (see plots)

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redo, if necessary

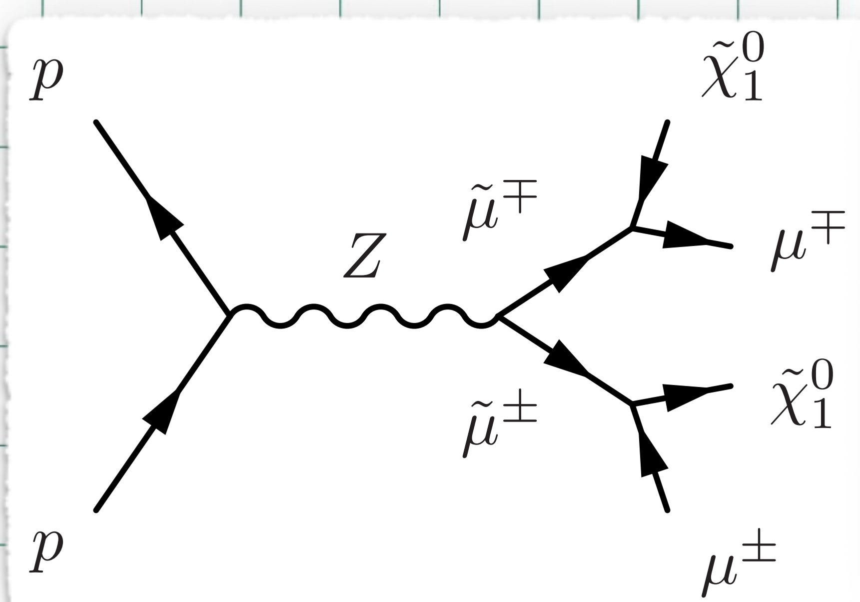
this comes now

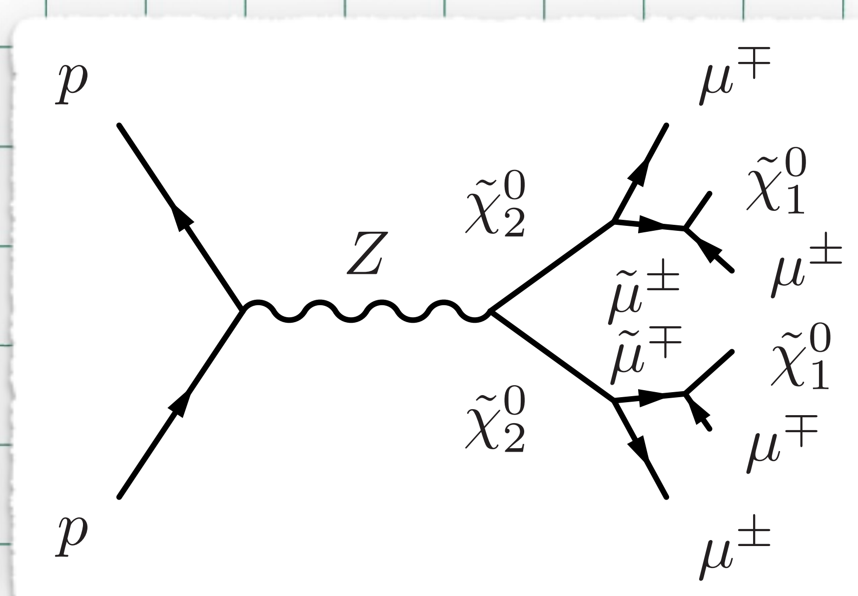
LHC phenomenology

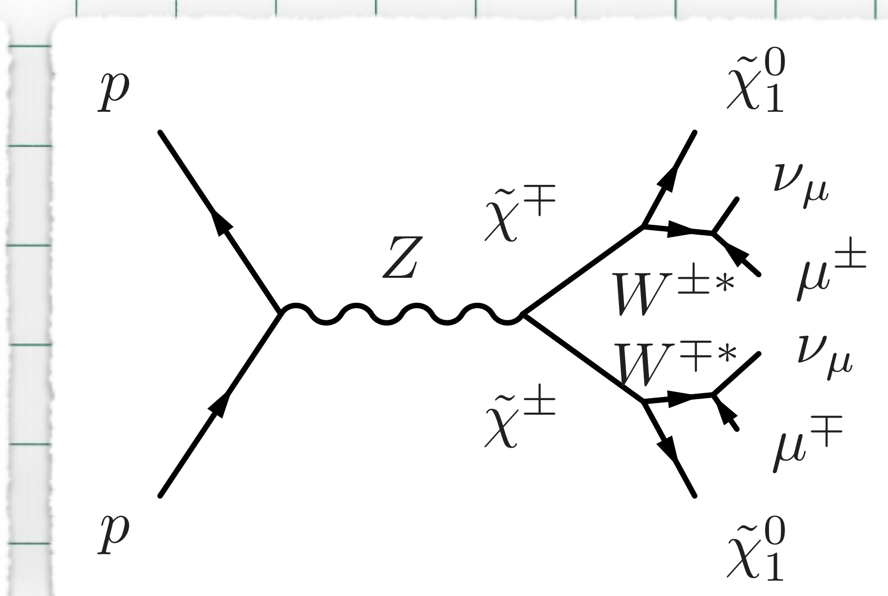
CheckMATE excludes a point, if r ≥ 1

$$r \equiv \frac{S - 1.96\Delta S}{S^{95}_{\rm exp}} = \frac{\text{95\% lower limit on the number of signal events, determined by Checkmate}}{\text{Experimentally measured 95\% confidence limit on signal events}}$$

First check on easy channels (smuon, χ^0_2, $\chi^\pm$ pair prod.)







LHC phenomenology

Benchmark point	$r_{\tilde{\mu}}$	$r_{\tilde{\chi}_2^0}$	$r_{\tilde{\chi}^\pm}$	Best $\tilde{\mu}$ signal region
22647	0.45	$0.5 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$	SR_mT2_90_mumu
25804	0.34	$1.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$	SR_mT2_90_mumu
32128	0.16	$0.5 \cdot 10^{-4}$	$0.8 \cdot 10^{-4}$	SR_mT2_90_mumu
37470	0.66	$1.0 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$	SR_mT2_90_mumu
38793	0.09	$0.0 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$	SR_mT2_90_mumu
39936	1.25	$0.7 \cdot 10^{-4}$	$0.1 \cdot 10^{-4}$	SR_mT2_110_mumu
40125	0.45	$2.1 \cdot 10^{-4}$	0.18	SR_mT2_90_mumu
43253	0.41	$0.4 \cdot 10^{-4}$	0.02	SR_mT2_90_mumu
12144	0.11	$0.0 \cdot 10^{-4}$	$2.4 \cdot 10^{-4}$	SR_mT2_110_mumu
19223	0.27	$2.3 \cdot 10^{-4}$	0.61	SR_mT2_110_mumu
24289	0.28	$1.2 \cdot 10^{-4}$	0.07	SR_mT2_110_mumu
27146	0.05	$1.4 \cdot 10^{-4}$	0.02	SR_mT2_90_mumu
32375	0.05	$0.6 \cdot 10^{-4}$	0.10	SR_mT2_110_mumu

smuon pp. mostly favoured

LHC phenomenology

Signal regions defined in
[ATLAS-CONF-2013-049]
2 OS ℓ, no jets, MET @ LHC8, 20 fb^{-1}

Benchmark point	$r_{\tilde\mu}$	$r_{\tilde\chi_2^0}$	$r_{\tilde\chi^\pm}$	Best $\tilde\mu$ signal region
			10^{-4}	SR_mT2_90_mumu
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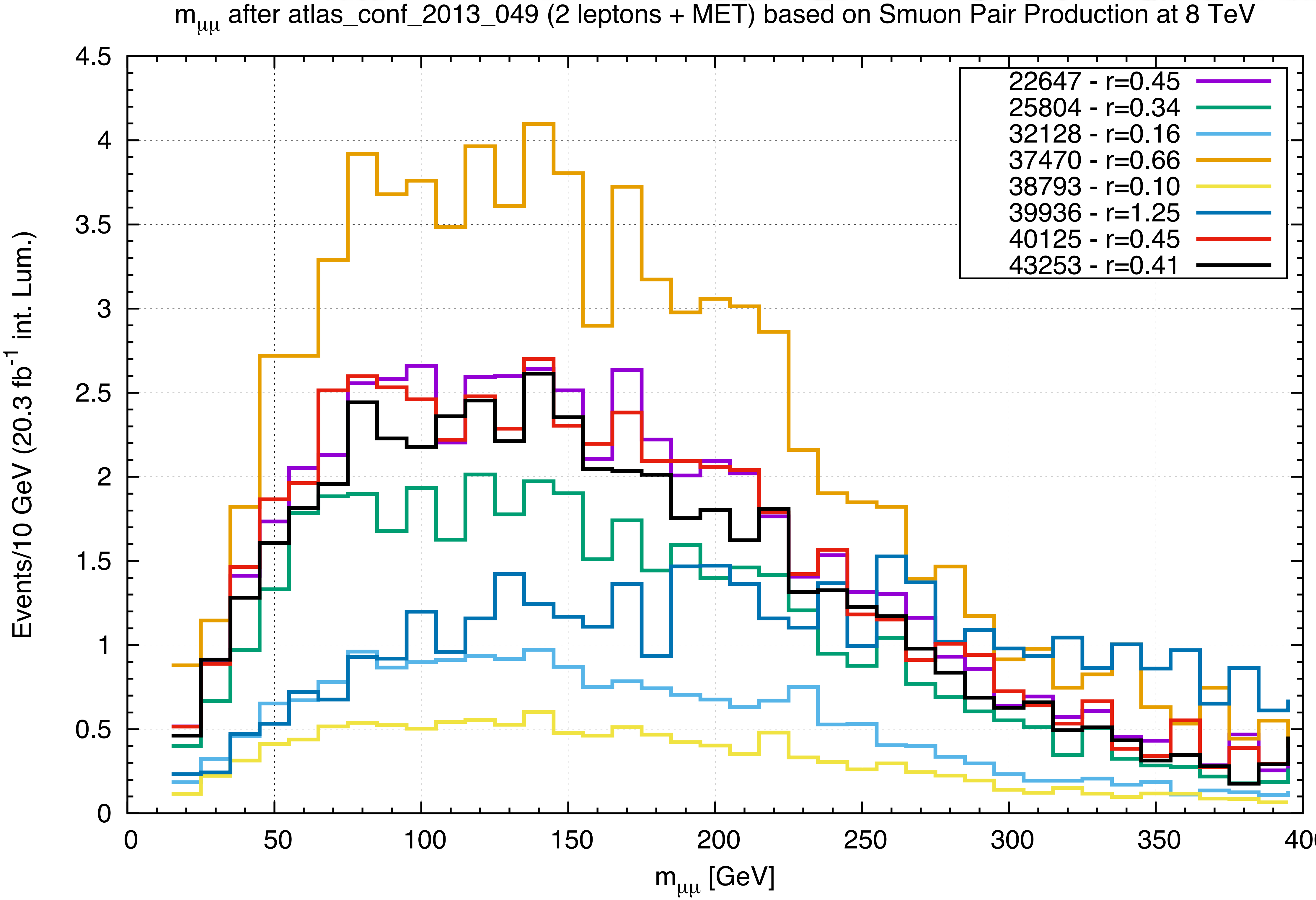
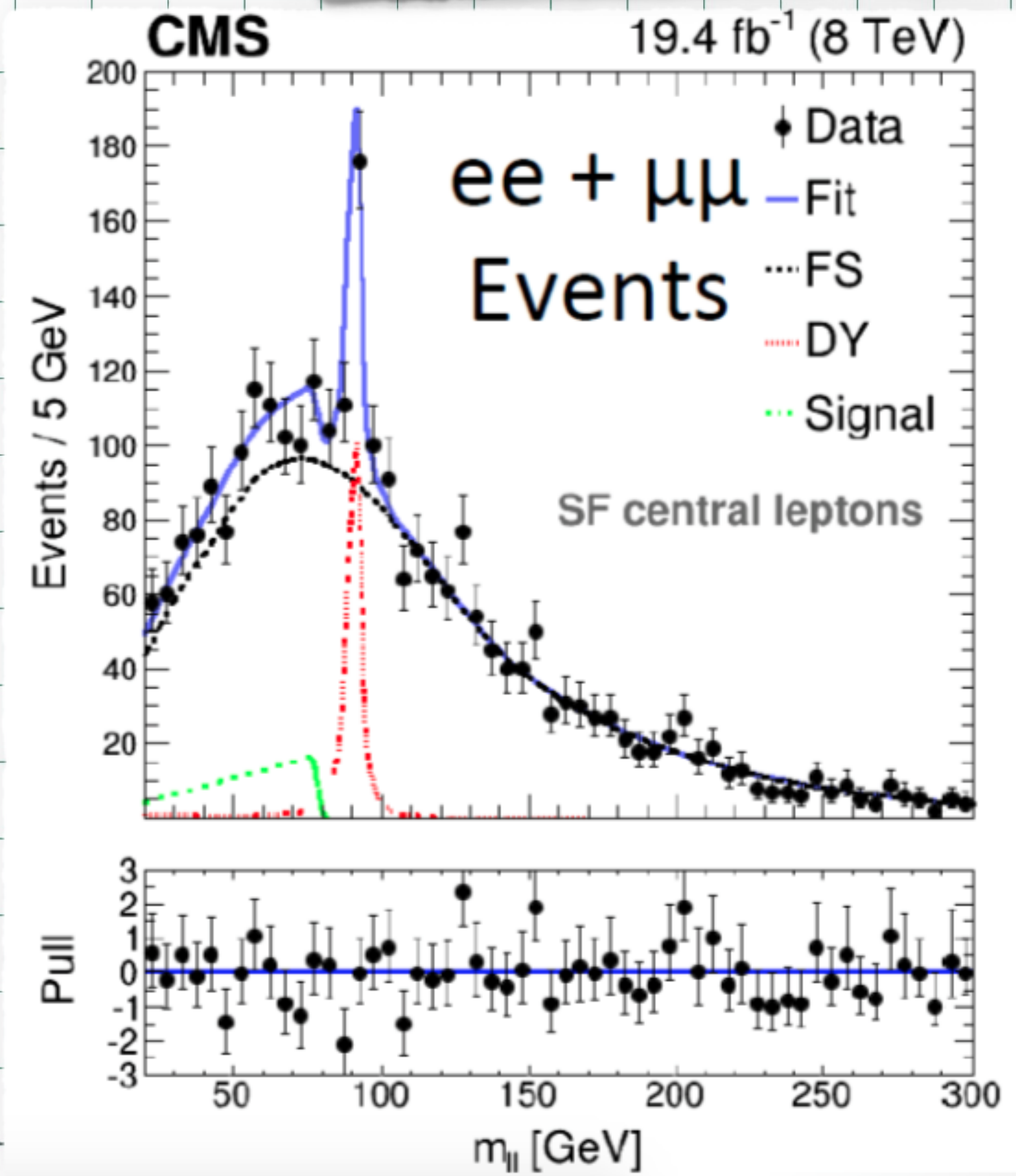
LHC phenomenology



LHC phenomenology

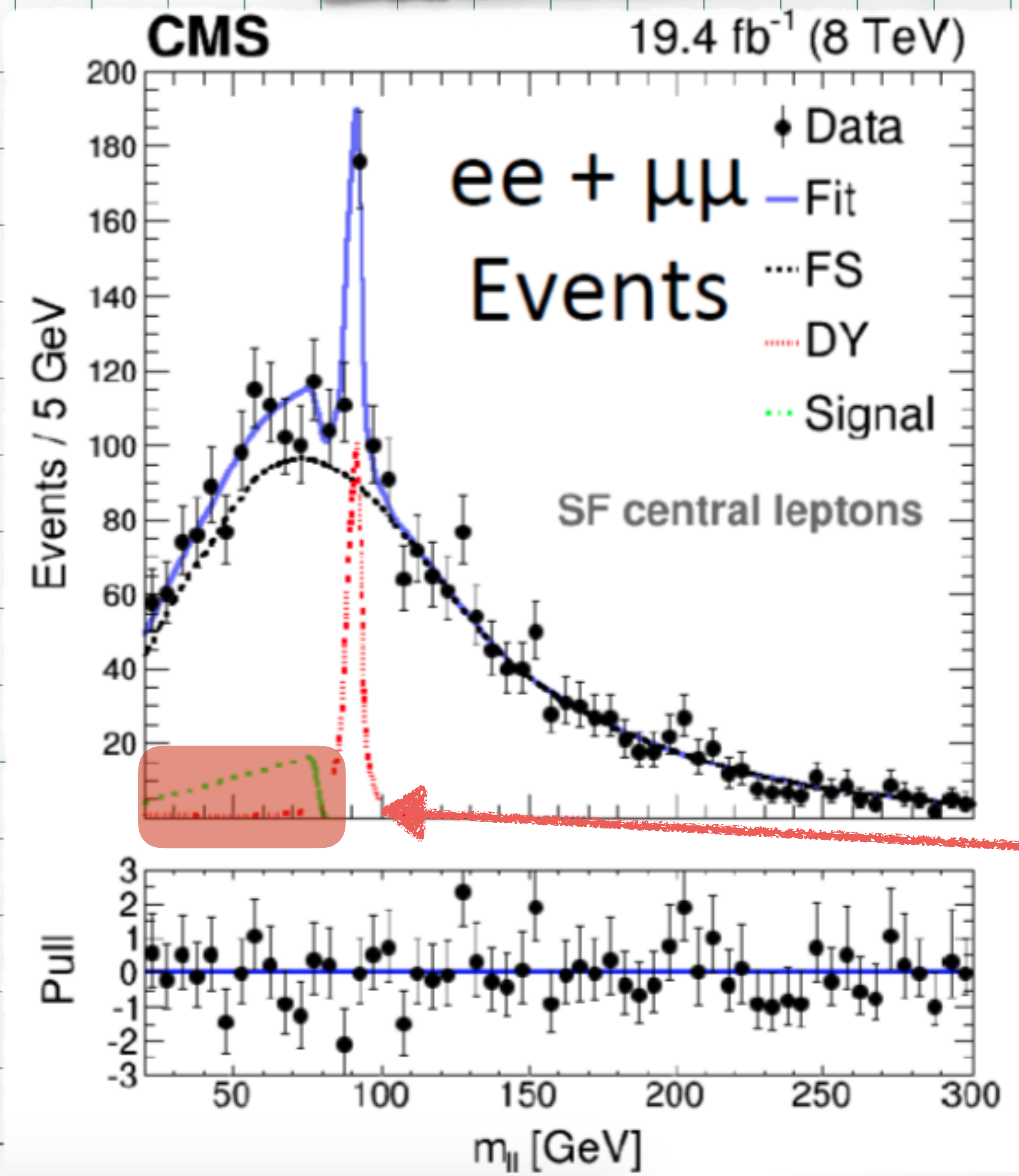


CMS search for 2 OSSF leptons, jets and MET @ LHC8 (19.4 fb^{-1})

[CMS PAS SUS-12-019]

ATLAS observed nothing off-peak

LHC phenomenology



CMS search for 2 OSSF leptons, jets and MET @ LHC8 (19.4 fb^{-1})

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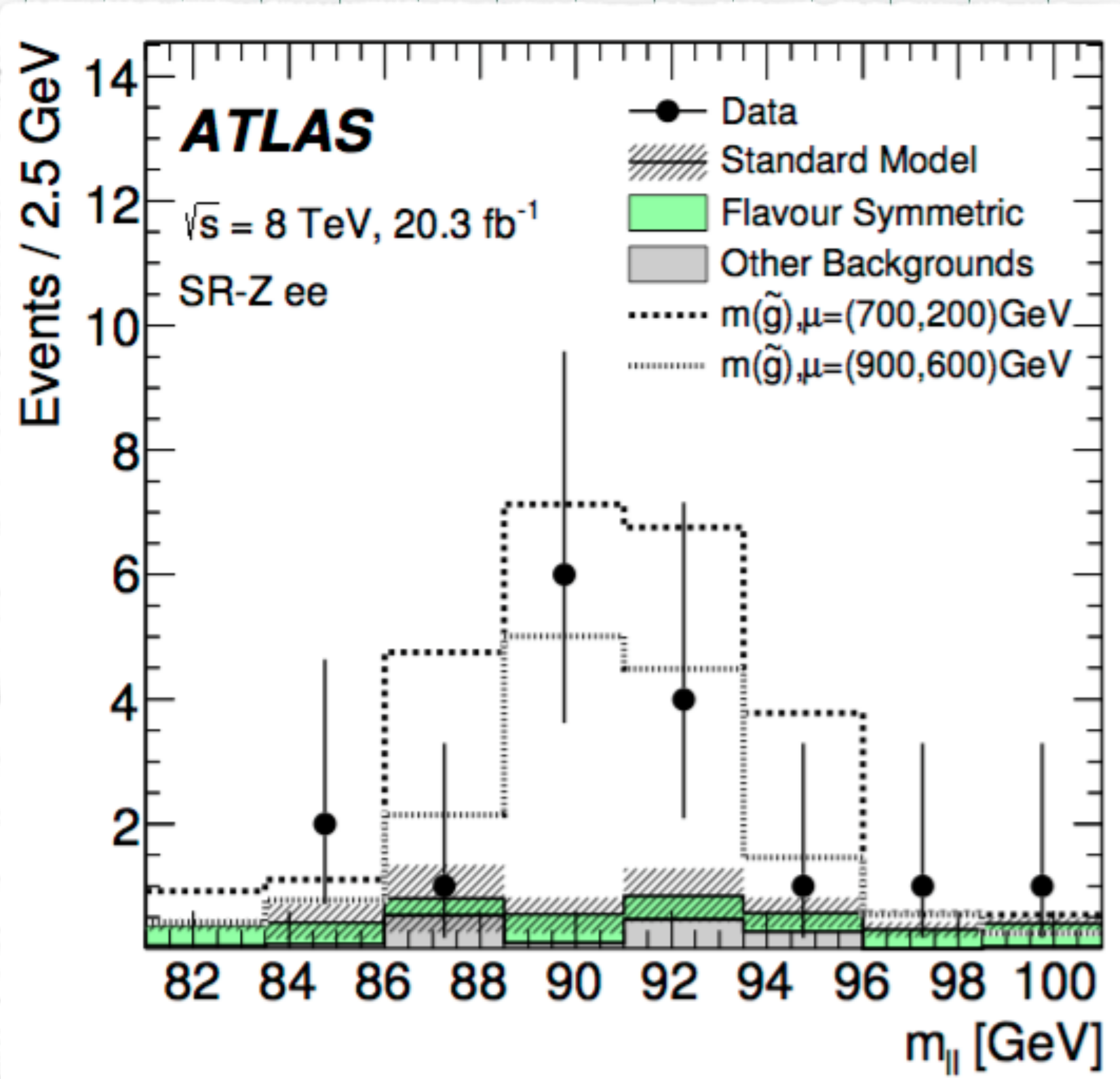
di-lepton edge

LHC phenomenology

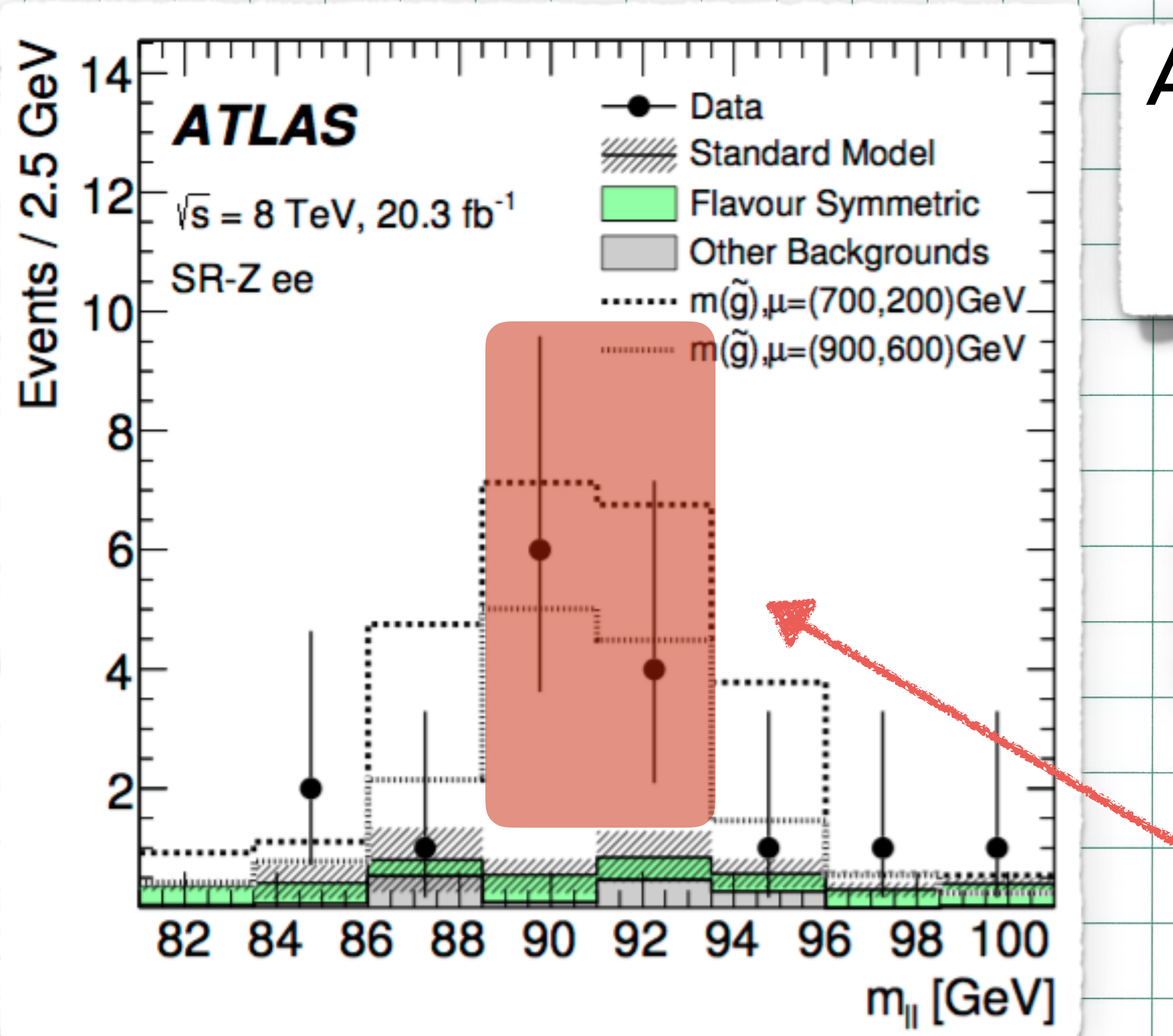


ATLAS search for 2 OSSF leptons, jets and MET @ LHC8 (20.3 fb^{-1})

[1503.03290v3]

CMS observed nothing on-peak

LHC phenomenology



ATLAS search for 2 OSSF leptons, jets and MET @ LHC8 (20.3 fb^{-1})

[1503.03290v3]

CMS observed nothing on-peak

Conclusion and Outlook

Model is able to explain relic density, Δa_μ as well as "the usual" collider constraints (Higgs mass, $b > s\gamma$, $B_S > \mu^+\mu^-$, $\Delta\rho$)

Simple SUSY pair production processes favour smuon pp.

Smuon pp. benchmarks close to detection/exclusion

$\chi^0_2, \chi^\pm$ pp. benchmarks out of detection limit

Outlook

ATLAS/CMS Excess studies not fully implemented/checked yet

Reconsider model for new 13 TeV LHC studies

Try pushing simple pp. limits closer to detection/exclusion (heavy neutralinos?)

Thank you!