

SO(10) Yukawa unification : gluinos at the LHC

Stuart Raby

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Fermi Lab

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DEPARTMENT OF
PHYSICS

Outline

- Predictability in SUSY theories
- SO(10) Yukawa unification
 - w/ Universal gaugino masses
- Third family analysis - predictions
- LHC bounds
- Three family analysis - more predictions
- Conclusions

Minimal SUSY spectrum

$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\frac{\bar{\nu}_i}{e_i}$	$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\frac{\bar{u}_i}{\bar{d}_i}$	$\begin{pmatrix} \nu \\ \tilde{e} \end{pmatrix}_i$	$\frac{\bar{\nu}_i}{\bar{e}_i}$	$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\frac{\bar{u}_i}{\bar{d}_i}$
$i = 1, 2, 3$				$i = 1, 2, 3$			
g	W^\pm	Z	γ			g	$\chi_{i=1,2}^\pm$
h	H	A	H^\pm				$\chi_{i=1,2,3,4}^0$

Predictability

- **SMA - Quark & lepton masses**

Eg. m_u, m_d Two 3×3 complex matrices $\Rightarrow 10$ obs.
36 arbitrary paras.

Suggests - Family symmetries to
reduce no. arbitrary paras.

Eg. $SU(2) \times U(1)$ 3rd family & Higgs special

- **MSSM - R parity conservation**
reduce no. arbitrary couplings

Predictability & ~~SUSY~~

$$m_a^2 |s_a|^2, \quad s_a = \{ q_i, \overline{u}_i, \overline{d}_i, \ell_i, \overline{\nu}_i, \overline{e}_i \}, \quad i = 1, 2, 3$$

$$(A_u)_{ij} (\lambda_u)_{ij} q_i H_u \overline{u}_j + (A_d)_{ij} \dots + (A_e)_{ij} \dots$$

$$M_i (\lambda_i \lambda_i), \quad i = 1, 2, 3$$

$$\mu, \tan\beta$$

Too many arbitrary parameters !
FCNCs !!

$SO(10)$ Grand Unification

1 {
10 {
-5 {

State	Y $= \frac{2}{3}\Sigma(C) - \Sigma(W)$	Color C spins	Weak W spins
$\bar{\nu}$	0	---	--
\bar{e}	2	---	++
u_r		+ --	- +
d_r		+ --	+ -
u_b	$\frac{1}{3}$	- + -	- +
d_b		- + -	+ -
u_y		- - +	- +
d_y		- - +	+ -
\bar{u}_r		- + +	--
\bar{u}_b	$-\frac{4}{3}$	+ - +	--
\bar{u}_y		+ + -	--
\bar{d}_r		- + +	++
\bar{d}_b	$\frac{2}{3}$	+ - +	++
\bar{d}_y		+ + -	++
ν	-1	+++	- +
e		+++	+ -

Georgi
Fritzsch & Minkowski

spinor repsn.
of $SO(10)$

tensor product
of 5 spin $1/2$
w/ even no. + signs

Georgi & Glashow

SU(5)

SUSY GUT + family symmetry

$$m_{16_i}^2 |16_i|^2, \quad 16_i = \{ q_i, \overline{u}_i, \overline{d}_i, \ell_i, \overline{\nu}_i, \overline{e}_i \}, \quad i = 1, 2, 3$$

m_{16}^2 "SU(2) family symmetry" + simplicity

3rd family Yukawa dominates

$$\lambda 16_3 10 16_3 \Rightarrow (A_0) \lambda 16_3 10 16_3$$

$$M_{1/2} (\lambda_i \lambda_i), \quad i = 1, 2, 3$$

$\mu, \tan\beta$

$$m_{16}, m_{10}, A_0, M_{1/2}, \mu, \tan\beta$$

Yukawa Unification & Soft SUSY breaking

Blazek, Dermisek & Raby PRL 88, 111804 (2002)

PRD 65, 115004 (2002)

Baer & Ferrandis, PRL 87, 211803 (2001)

Auto, Baer, Balazs, Belyaev, Ferrandis & Tata
JHEP 0306:023 (2003)

Tobe & Wells NPB 663, 123 (2003)

Baer, Kraml, Sekmen & Summy
JHEP 0909:005 (2009)

Badziak, Olechowski & Pokorski
JHEP 1108:147 (2011)

Gogoladze, Shafi & Saleh Un JHEP 1208:028 (2012)

Anandakrishnan, Raby & Wingerter arXiv:1212.0542

Anandakrishnan & Raby arXiv:1303.5125

$\lambda \quad 16_3 \quad 10 \quad 16_3$

$$\lambda_t = \lambda_b = \lambda_\tau = \lambda_{\nu_\tau} \equiv \lambda$$

Note, CANNOT predict top mass due to
large SUSY threshold corrections to
bottom and tau mass

Hall, Rattazzi & Sarid

Carena, Olechowski, Pokorski & Wagner

So instead use Yukawa unification to predict
soft SUSY breaking masses !!

Bottom mass corrections

$$\frac{\delta m_b}{m_b} \propto \frac{\alpha_3 \mu M_g \tan \beta}{m_{\tilde{b}}^2} + \frac{\lambda_t^2 \mu A_t \tan \beta}{m_{\tilde{t}}^2} + \log corr.$$

$$\frac{\delta m_b}{m_b} \leq -2\%$$

Needed to fit data

$$\mu M_g > 0 \Rightarrow \mu A_t < 0$$

Anandakrishnan, Raby & Wingerter

arXiv:1212.0542

PR D87 (2013) 055005

Anandakrishnan, Bryant, Raby & Wingerter

arXiv:1307.7723

PR D88 (2013) 075002

Global χ^2 analysis

Free parameters - w/ Universal gaugino masses

Sector	Third Family Analysis	#
gauge	$\alpha_G, M_G, \epsilon_3$	3
SUSY (GUT scale)	$m_{16}, M_{1/2}, A_0, m_{H_u}, m_{H_d}$	5
textures	λ	1
neutrino		0
SUSY (EW scale)	$\tan \beta, \mu$	2
Total #		11

Radiative EWSB requires

$$\Delta m_H^2 \equiv \frac{\left(m_{H_d}^2 - m_{H_u}^2\right)}{2m_{10}^2} \approx 13\%$$

Roughly $\frac{1}{2}$ comes
From RG running from

$$M_G \rightarrow m_{\nu_\tau}$$

Blazek, Dermisek & Raby

“Just so” = “NUHM”

Low energy observables

Observable	Exp. Value	Ref.	Program	Th. Error
$\alpha_3(M_Z)$	0.1184 ± 0.0007	[23]	maton	0.5%
α_{em}	$1/137.035999074(44)$	[23]	maton	0.5%
G_μ	$1.16637876(7) \times 10^{-5} \text{ GeV}^{-2}$	[23]	maton	1%
M_W	$80.385 \pm 0.015 \text{ GeV}$	[23]	maton	0.5%
M_Z	91.1876 ± 0.0021	[23]	Input	0.0%
M_t	$173.5 \pm 1.0 \text{ GeV}$	[23]	maton	0.5%
$m_b(m_b)$	$4.18 \pm 0.03 \text{ GeV}$	[23]	maton	0.5%
M_τ	$1776.82 \pm 0.16 \text{ MeV}$	[23]	maton	0.5%
M_h	$125.3 \pm 0.4 \pm 0.5 \text{ GeV}$	[24]	Ref. [25]	3 GeV
$\text{BR}(b \rightarrow s\gamma)$	$(343 \pm 21 \pm 7) \times 10^{-6}$	[26]	SuperIso	$(181 - 505) \times 10^{-6}$
$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$	3.2×10^{-9}	[27]	susy_flavor	1.5×10^{-9}

Yukawa Unification

$$\lambda \ 16_3 \ 10 \ 16_3$$

Universal Gaugino Masses

Fit t,b,tau requires

$$A_0 \approx -2m_{16} \quad m_{10} \approx \sqrt{2}m_{16}$$

$$m_{16} > \text{few TeV} \quad \mu, M_{1/2} \ll m_{16}$$

$$\tan \beta \approx 50$$

Inverted scalar mass hierarchy

Bagger, Feng, Polonsky & Zhang
PLB473, 264 (2000)

Third family scalars lighter than first two !
Suppresses flavor & CP violation

$$A_0 \approx -2m_{16} \quad m_{10} \approx \sqrt{2}m_{16}$$

$$m_{16} > \text{few TeV} \quad \mu, M_{1/2} \ll m_{16}$$

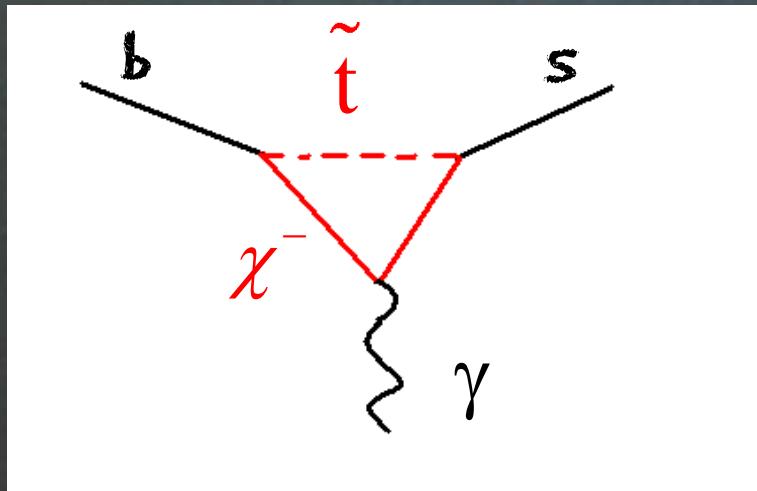
$$\tan \beta \approx 50$$

Heavy scalars

Need Heavy scalars !

$$BR(B \rightarrow X_s \gamma) = (3.55 \pm 0.26) \times 10^{-4} \quad \text{Exp.}$$

$$BR(B \rightarrow X_s \gamma)_{SM} = (3.15 \pm 0.23) \times 10^{-4} \quad \text{NNLO Th.}$$



$$C_7^{eff} = C_7^{SM} + C_7^{SUSY}$$

$$C_7^{eff} \approx \mp C_7^{SM}$$

$$C_7^{\chi^+} \propto \frac{\mu A_t}{m^2} \tan \beta \times \text{sign}(C_7^{SM}) \approx \begin{cases} -2C_7^{SM} \\ 0 \end{cases}$$

$$\mu M_g > 0 \Rightarrow \mu A_t < 0$$

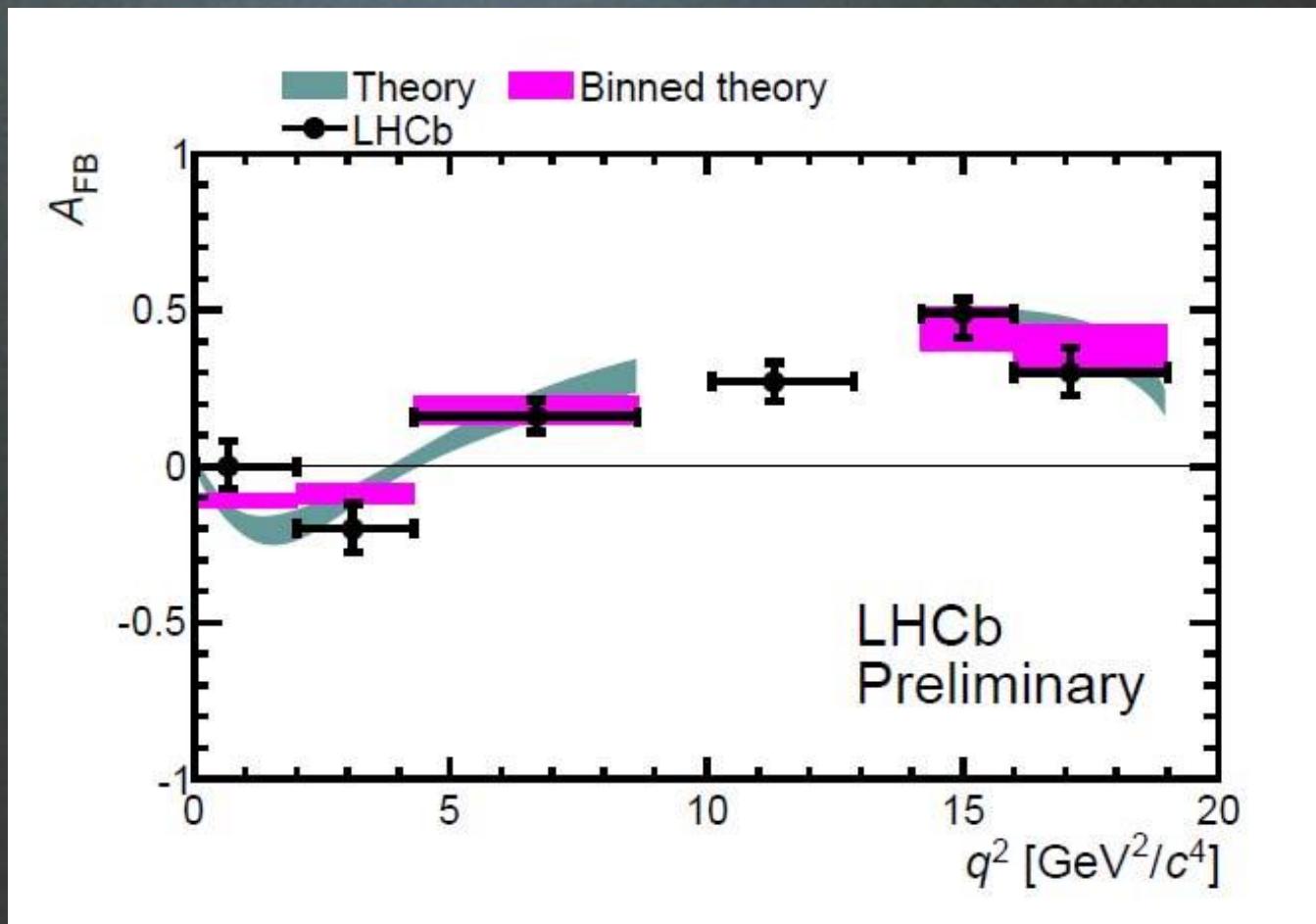
$$m_{16} \sim 4 - 5 \text{ TeV}$$

light squarks and sleptons !!

$$C_7^{\chi^+} \approx -2C_7^{\text{SM}} \quad \text{or}$$

$$C_7 = C_7^{\text{SM}} + C_7^{\chi^+} \approx -C_7^{\text{SM}}$$

LHCb $\text{BR}(\text{B} \rightarrow \text{K}^* \mu^+ \mu^-)$ favors $C_7 \approx +C_7^{\text{SM}}$



tension between $b \rightarrow s \gamma$ & $b \rightarrow s l^+ l^-$

Albrecht, Altmannshofer, Buras, Guadagnoli, & Straub

JHEP 0710:055 (2007)

$$C_7^{\chi^+} \approx 0 \quad \text{or}$$

$$C_7 = C_7^{\text{SM}} + C_7^{\chi^+} \approx +C_7^{\text{SM}}$$



$$m_{16} \geq 8 \text{ TeV}$$

Light Higgs
SMA-like

Light Higgs mass

$$m_h^2 \approx M_Z^2 \cos^2 2\beta$$

$$+ \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \left(\frac{M_{SUSY}^2}{m_t^2} \right) + \frac{X_t^2}{M_{SUSY}^2} \left(1 - \frac{X_t^2}{12M_{SUSY}^2} \right) \right]$$

$$X_t = A_t - \frac{\mu}{\tan \beta} \quad \frac{X_t}{M_{SUSY}} \sim -\sqrt{6} \quad \text{Max mixing}$$

Large A_t & $M_{SUSY} \Rightarrow m_h \simeq 125 \text{ GeV}$ Easy

$\text{Br}(B_s \rightarrow \mu^+ \mu^-) :$
Light Higgs SM-like

SM : 3×10^{-9} MSSM : $\sim (\tan \beta)^6 / m_A^4$

CDF $1.8^{+1.8}_{-0.9} \times 10^{-8}$ (95% CL) w/ 7 fb^{-1}

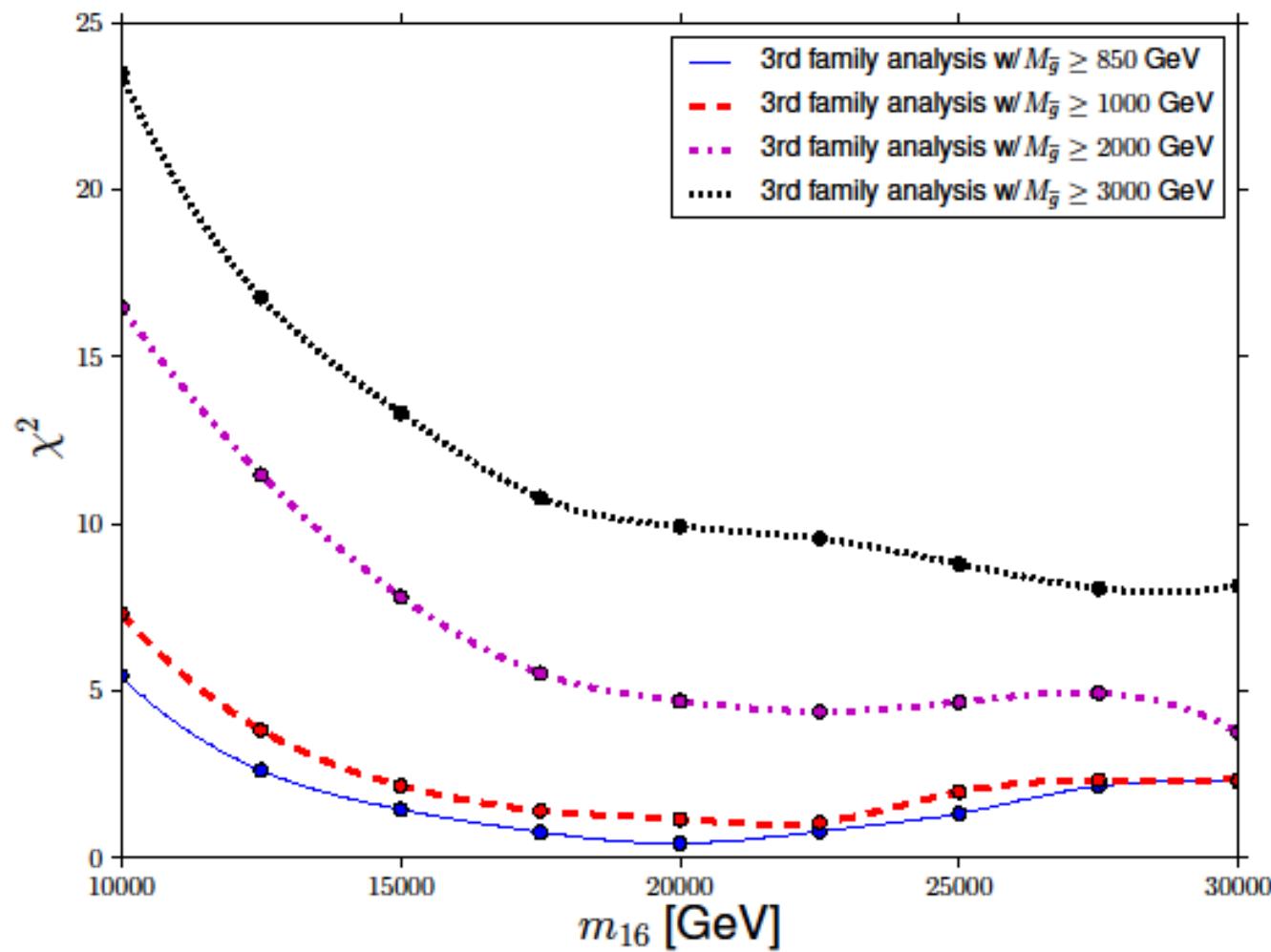
LHCb $(2.9^{+1.1}_{-1.0}) \times 10^{-9}$
w/ 1 fb^{-1} (7TeV) + 2 fb^{-1} (8TeV)

$$m_A \geq 1 \text{ TeV}$$

$m_A \sim m_H \sim m_{H^\pm} \Rightarrow h \text{ SM-like}$

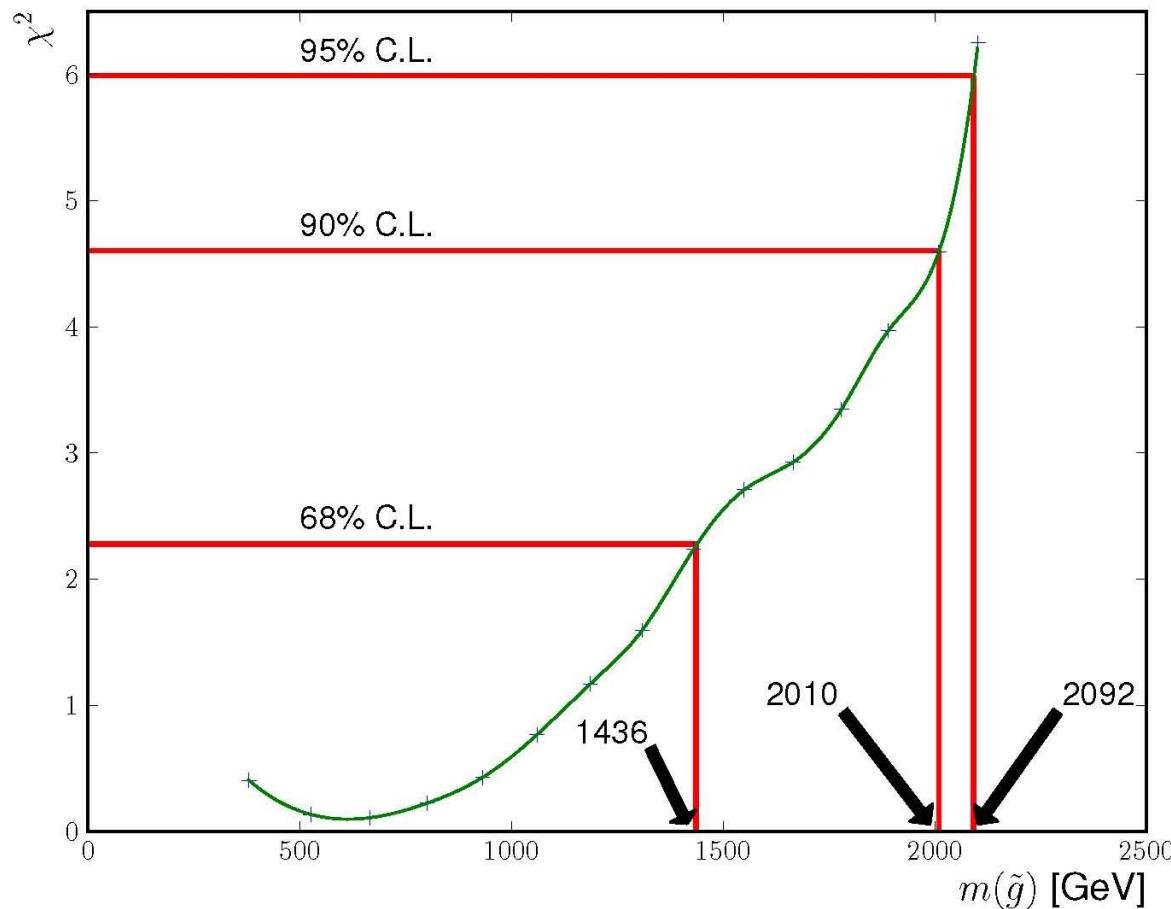
Gluino mass ≤ 2 TeV

Gluino mass bound



Gluino mass bound

$m_{16} = 20 \text{ TeV}$, $M_{1/2}$ varied \rightarrow 2 d.o.f.



Benchmark point

$\alpha_G^{-1}, M_G, \varepsilon_3 : 25.9, 2.9 \times 10^{16} \text{ GeV}, -0.01$

$\lambda, \tan\beta, M_{1/2}, m_{16} : 0.6, 49.7, 150 \text{ GeV}, 20 \text{ TeV}$

$m_{H_d}, m_{H_u}, A_0 : 1.9 m_{16}, 1.6 m_{16}, -41 \text{ TeV}$

g	801			
χ^\pm	264	877		
χ^0	129 (bino)	264	876	873
U	2×10^4	4.7×10^3	3775	
D	2×10^4	4.6×10^3	4962	
E	2×10^4	1.2×10^4	7.8×10^3	
N	2×10^4	1.2×10^4		

LHC - Gluino decay modes using SDecay

$\tilde{g} \rightarrow t\bar{t} \tilde{\chi}_{1,2}^0$ 26%

$t\bar{b} \tilde{\chi}_1^-$ 26%

$b\bar{t} \tilde{\chi}_1^+$ 26%

$g \tilde{\chi}_{1,2}^0$ 20%

NOT
Simplified
Model

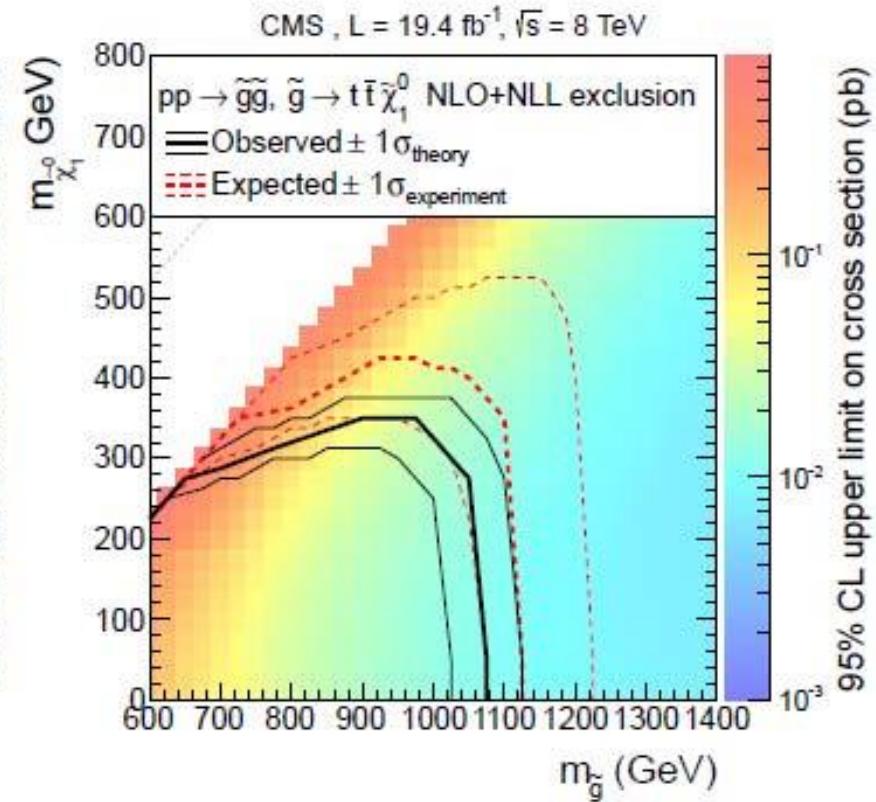
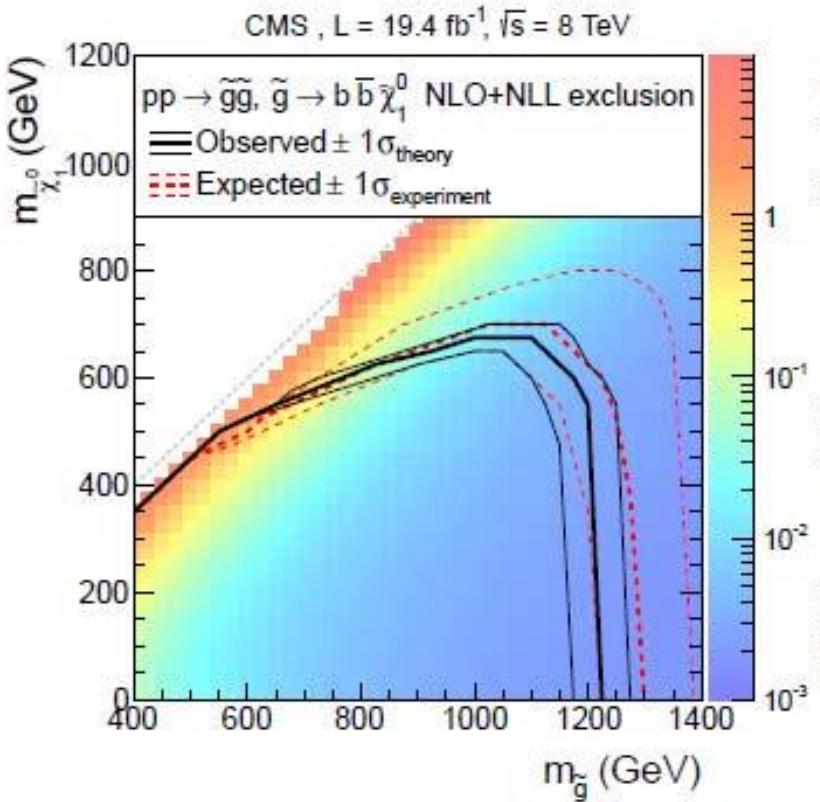


Analysis	Luminosity	Signal Region	Reference
SS dilepton	10.5	$N_{\text{jet}} \geq 4, N_{\text{b-jet}} \geq 2,$ $E_T^{\text{miss}} > 120, H_T > 200$	[1]
α_T analysis (for Simplified models) (for the benchmark models)	11.7	$N_{\text{jet}} \geq 4, N_{\text{b-jet}} = 2, 775 < H_T < 875$ $N_{\text{jet}} \geq 4, N_{\text{b-jet}} \geq 2, 775 < H_T < 875$	[2]
$\Delta\phi$ analysis	19.4	$N_{\text{b-jet}} \geq 3, E_T^{\text{miss}} > 350, H_T > 1000$	[3]

Table 1: The most constraining signal region for each of the analyses studied in this work. All energies are in units of GeV and luminosity in fb^{-1} .

References

- [1] CMS Collaboration Collaboration, S. Chatrchyan *et al.*, “Search for new physics in events with same-sign dileptons and b jets in pp collisions at $\sqrt{s} = 8$ TeV,” *JHEP* **1303** (2013) 037, [1212.6194](#).
- [2] CMS Collaboration Collaboration, S. Chatrchyan *et al.*, “Search for supersymmetry in hadronic final states with missing transverse energy using the variables α_T and b -quark multiplicity in pp collisions at $\sqrt{s} = 8$ TeV,” [1303.2985](#).
- [3] CMS Collaboration Collaboration, S. Chatrchyan *et al.*, “Search for gluino mediated bottom- and top-squark production in multijet final states in pp collisions at 8 TeV,” [1305.2390](#).



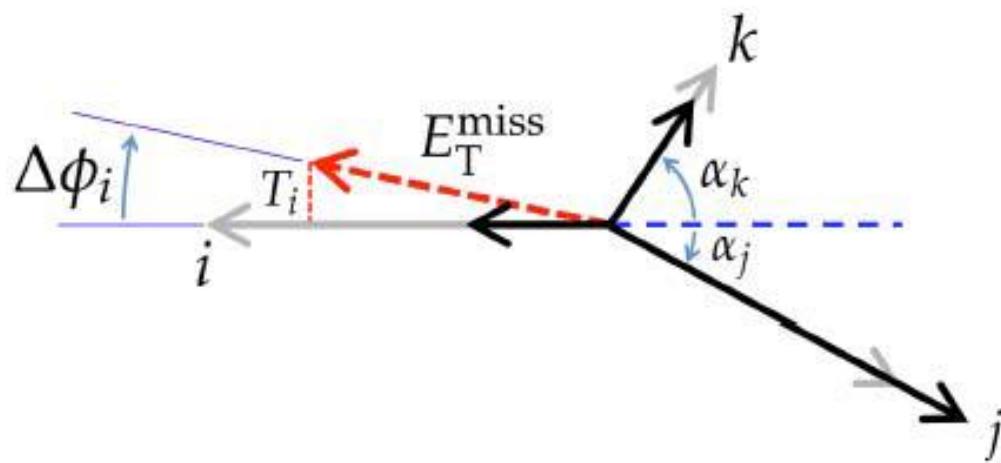
$m_g \geq 1200$ GeV

$m_g \geq 1100$ GeV

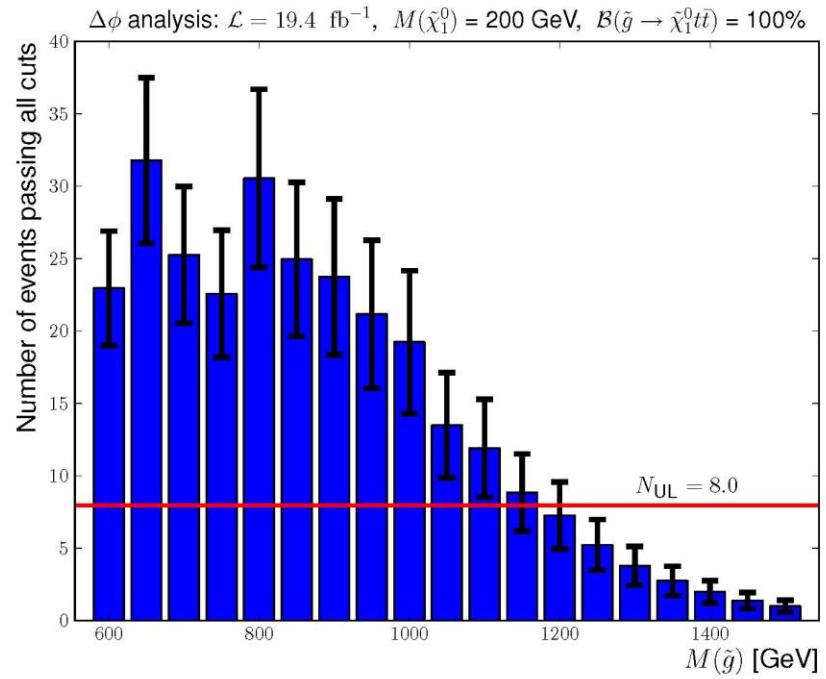
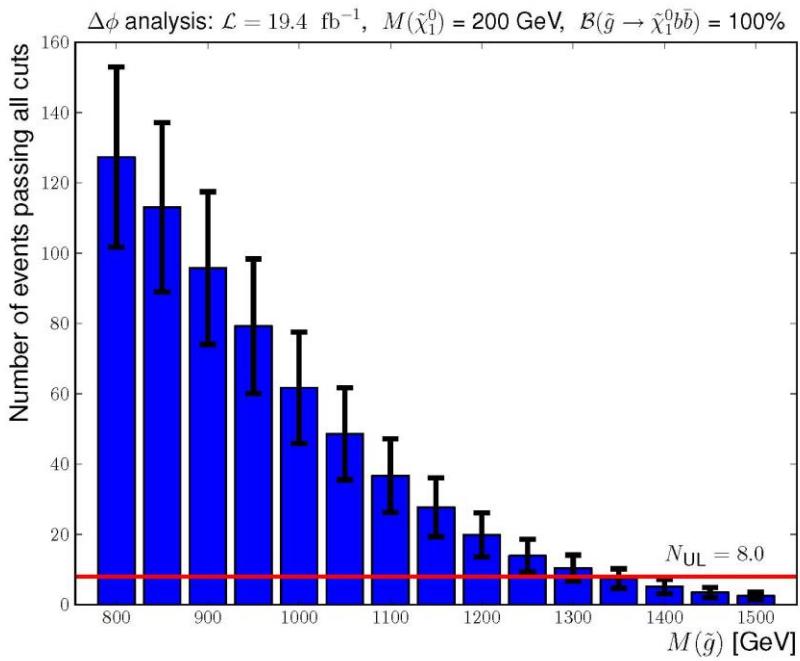
$\Delta\phi$ hadronic analysis

- At least 3 jets (and at least 1 b-tagged jet) with $p_T > 50$ GeV and $|\eta| < 2.4$.
- $H_T > 400$ GeV and $E_T^{\text{miss}} > 125$ GeV.
- no identified, isolated electrons or muons with $p_T > 10$ GeV; or charged tracks with $p_T > 15$ GeV
- $\Delta\hat{\phi}_{\min} > 4.0$, where

$$\Delta\hat{\phi}_{\min} = \min (\Delta\phi_i / \sigma_{\Delta\phi_i})$$



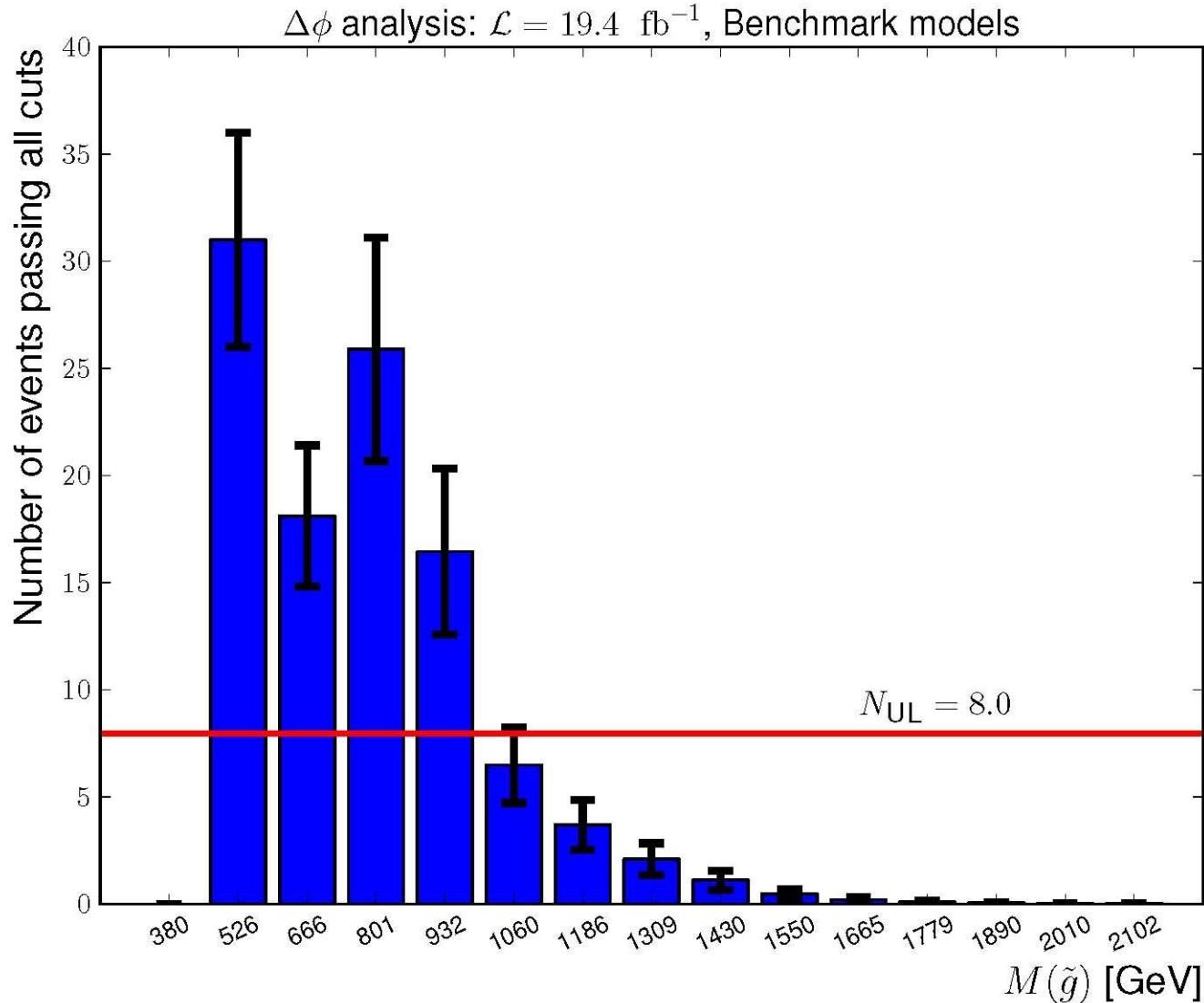
Validation



$m_g \geq 1300 \text{ GeV}$

$m_g \geq 1175 \text{ GeV}$

$\Delta\phi$ hadronic analysis



$$m_g \geq 1000 \text{ GeV}$$



Analysis	Luminosity	Signal Region	Reference
SS dilepton	10.5	$N_{\text{jet}} \geq 4, N_{\text{b-jet}} \geq 2,$ $E_T^{\text{miss}} > 120, H_T > 200$	[1]
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Table 1: The most constraining signal region for each of the analyses studied in this work. All energies are in units of GeV and luminosity in fb^{-1} .

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- [2] CMS Collaboration Collaboration, S. Chatrchyan *et al.*, “Search for supersymmetry in hadronic final states with missing transverse energy using the variables α_T and b -quark multiplicity in pp collisions at $\sqrt{s} = 8$ TeV,” [1303.2985](#).
- [3] CMS Collaboration Collaboration, S. Chatrchyan *et al.*, “Search for gluino mediated bottom- and top-squark production in multijet final states in pp collisions at 8 TeV,” [1305.2390](#).

CMS - same sign di-leptons

Table 2: A summary of the combination of results for this search. For each signal region (SR), we show its most distinguishing kinematic requirements, the prediction for the three background (BG) components as well as the total, and the observed number of events. Note that the count of the number of jets on the first line of the table includes both tagged and untagged jets.

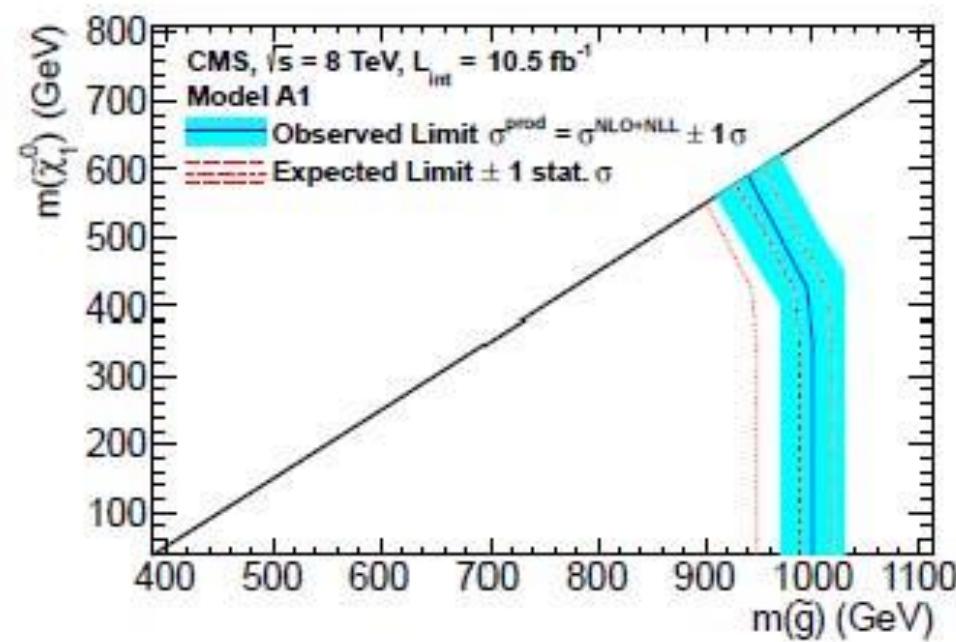
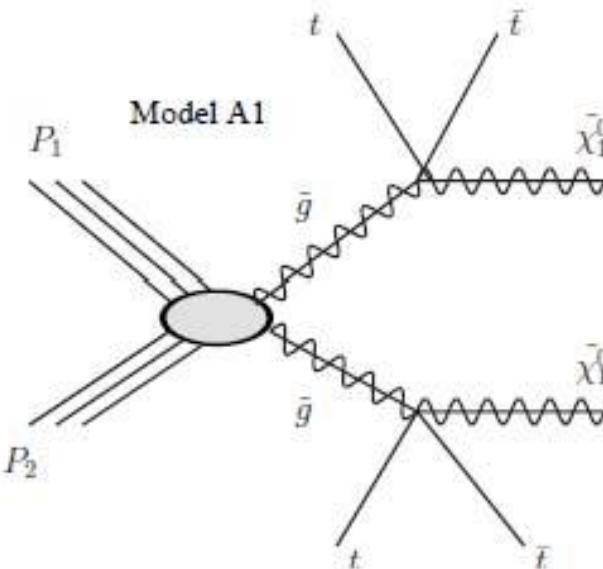
SR3

No. of jets	≥ 2	≥ 2	≥ 2	≥ 4	≥ 4	≥ 4	≥ 4	≥ 3	≥ 4
No. of btags	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
Lepton charges	$+ + / - -$	$+ + / - -$	$+ +$	$+ + / - -$	$+ + / - -$	$+ + / - -$	$+ + / - -$	$+ + / - -$	$+ + / - -$
E_T^{miss}	$> 0 \text{ GeV}$	$> 30 \text{ GeV}$	$> 30 \text{ GeV}$	$> 120 \text{ GeV}$	$> 50 \text{ GeV}$	$> 50 \text{ GeV}$	$> 120 \text{ GeV}$	$> 50 \text{ GeV}$	$> 0 \text{ GeV}$
H_T	$> 80 \text{ GeV}$	$> 80 \text{ GeV}$	$> 80 \text{ GeV}$	$> 200 \text{ GeV}$	$> 200 \text{ GeV}$	$> 320 \text{ GeV}$	$> 320 \text{ GeV}$	$> 200 \text{ GeV}$	$> 320 \text{ GeV}$
Charge-flip BG	3.35 ± 0.67	2.70 ± 0.54	1.35 ± 0.27	0.04 ± 0.01	0.21 ± 0.05	0.14 ± 0.03	0.04 ± 0.01	0.03 ± 0.01	0.21 ± 0.05
Fake BG	24.77 ± 12.62	19.18 ± 9.83	9.59 ± 5.02	0.99 ± 0.69	4.51 ± 2.85	2.88 ± 1.69	0.67 ± 0.48	0.71 ± 0.47	4.39 ± 2.64
Rare SM BG	11.75 ± 5.89	10.46 ± 5.25	6.73 ± 3.39	1.18 ± 0.67	3.35 ± 1.84	2.66 ± 1.47	1.02 ± 0.60	0.44 ± 0.39	3.50 ± 1.92
Total BG	39.87 ± 13.94	32.34 ± 11.16	17.67 ± 6.06	2.22 ± 0.96	8.07 ± 3.39	5.67 ± 2.24	1.73 ± 0.77	1.18 ± 0.61	8.11 ± 3.26
Event yield	43	38	14	1	10	7	1	1	9
N_{UL} (13% unc.)	27.2	26.0	9.9	3.6	10.8	8.6	3.6	3.7	9.6
N_{UL} (20% unc.)	28.2	27.2	10.2	3.6	11.2	8.9	3.7	3.8	9.9
N_{UL} (30% unc.)	30.4	29.6	10.7	3.8	12.0	9.6	3.9	4.0	10.5

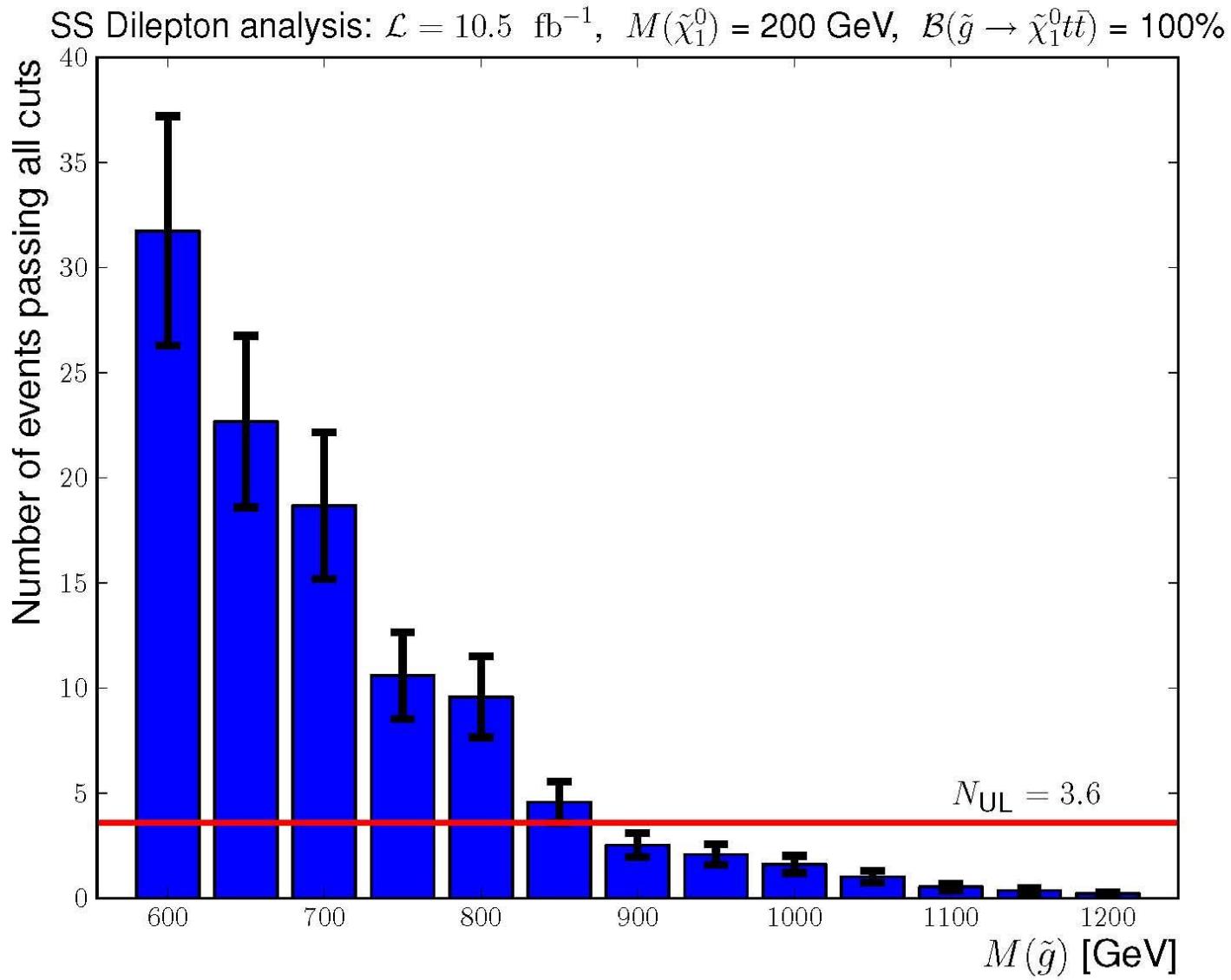
Simplified model bound

CMS - same sign di-leptons

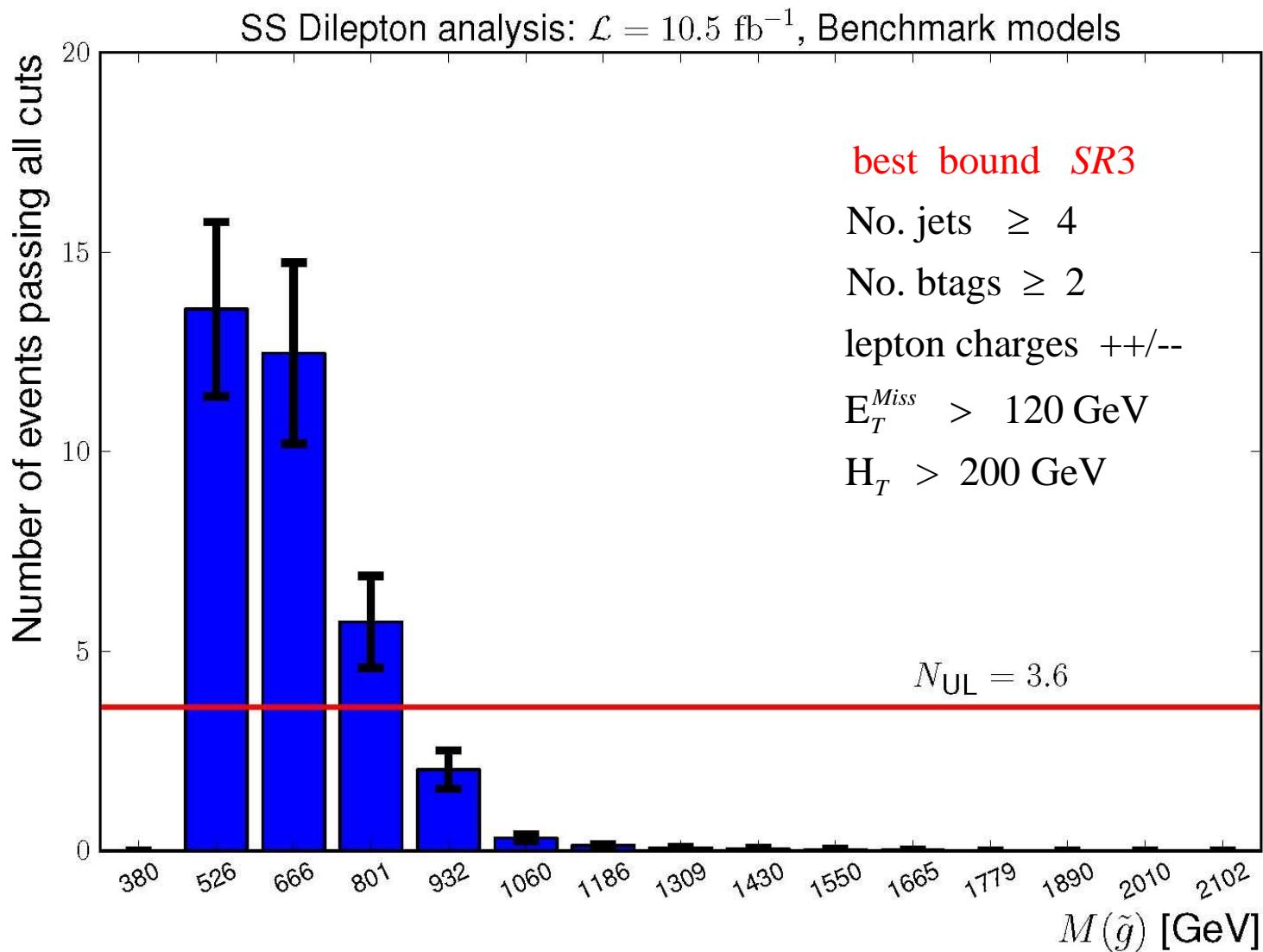
$$m_g \geq 1000 \text{ GeV}$$



Validation SR3



$m_g \geq 875 \text{ GeV}$



$$m_g \geq 865 \text{ GeV}$$

Simplified model bounds vs. Benchmark models

- Purely hadronic bounds 10 - 20% less significant \leftrightarrow fewer b -jets
- SS di-lepton bounds most significant

$$m_g \geq 1000 \text{ GeV}$$

Dark Matter ?

LSP bino - over-closes the universe
Axion, axino DM ???
Or non-thermal DM !

Anandakrishnan & Sinha

arXiv:1310.7579

Non-universal gaugino masses - “mirage mediation”
Thermal DM !

Well tempered $B / H / W$

Three family model
gives good fits
to low energy data

3 Family $SO(10)$ + family symmetry

Dermisek & Raby

PLB 622:327 (2005).

Dermisek, Harada & Raby PRD74, 035011 (2006)

Albrecht, Altmannshofer, Buras, Guadagnoli & Straub
JHEP 0710:055 (2007)

AnandaKrishnan, Raby & Wingerter

arXiv:1212.0542

3 family SO_{10} SUSY Model

- $D_3 \times U(1)$ Family Symmetry
- Superpotential
- Yukawa couplings
- χ^2 analysis
- Charged fermion masses & mixing
- Neutrino masses & mixing

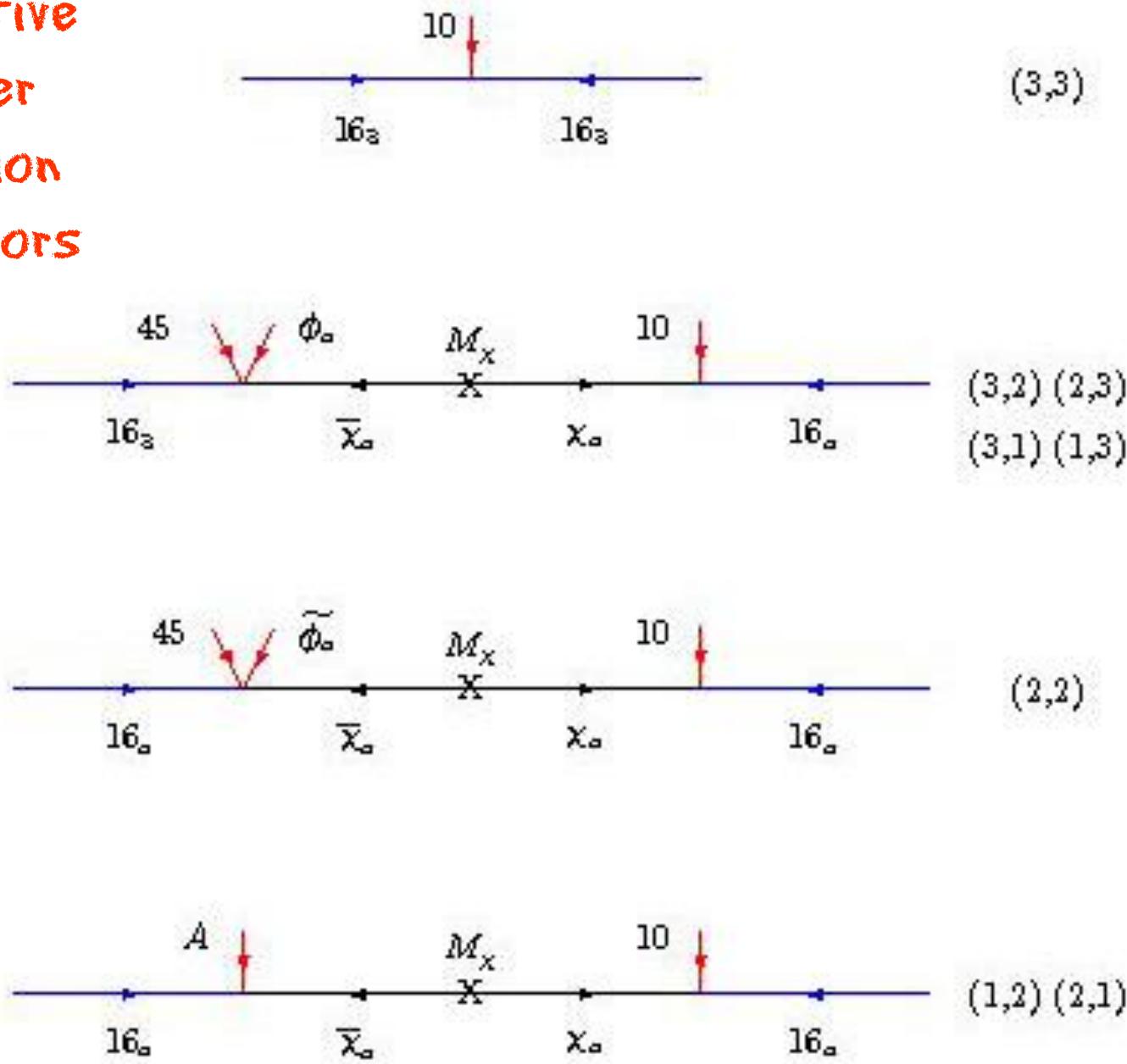
Superpotential for charged fermion Yukawa couplings

$$W_{ch, \text{fermions}} = 16_3 10 16_3 + 16_a 10 \chi_a \\ + \overline{\chi}_a \left(M_\chi \chi_a + 45 \frac{\phi_a}{M} 16_3 + 45 \frac{\phi_a}{M} 16_a + A 16_a \right)$$

$$\langle \phi \rangle = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \quad \langle \phi \rangle = \begin{pmatrix} 0 \\ \phi_2 \end{pmatrix} \quad \langle 45 \rangle = (B - L) M_G$$

Familon VEVs assumed

Effective higher dimension operators



$SO(10) \times (D_3 \times U(1))$ family sym. Yukawa Unification for 3rd Family

7 real para's
+ 4 phases

+ 3 real Majorana
Neutrino masses

Dermisek & Raby
PLB 622:327 (2005)

$$Y_u = \begin{pmatrix} 0 & \epsilon' \rho & -\epsilon \xi \\ -\epsilon' \rho & \tilde{\epsilon} \rho & -\epsilon \\ \epsilon \xi & \epsilon & 1 \end{pmatrix} \lambda$$

$$Y_d = \begin{pmatrix} 0 & \epsilon' & -\epsilon \xi \sigma \\ -\epsilon' & \tilde{\epsilon} & -\epsilon \sigma \\ \epsilon \xi & \epsilon & 1 \end{pmatrix} \lambda$$

$$Y_e = \begin{pmatrix} 0 & -\epsilon' & 3 \epsilon \xi \\ \epsilon' & 3 \tilde{\epsilon} & 3 \epsilon \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda$$

$$Y_\nu = \begin{pmatrix} 0 & -\epsilon' \omega & \frac{3}{2} \epsilon \xi \omega \\ \epsilon' \omega & 3 \tilde{\epsilon} \omega & \frac{3}{2} \epsilon \omega \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda$$

Extend to neutrino sector

$$W_{neutrino} = \overline{16}(\lambda_2 N_a 16_a + \lambda_3 N_3 16_3) + \frac{1}{2}(S_a N_a N_a + S_3 N_3 N_3)$$

$$\langle S_a \rangle = M_a \quad \langle S_3 \rangle = M_3 \quad \langle \overline{16} \rangle = v_{16}$$



Assume 3 new real para's

$$W_{neutrino} = \nu m_\nu \bar{\nu} + \bar{\nu} V N + \not{\! \! \! /}_2 N M_N N$$

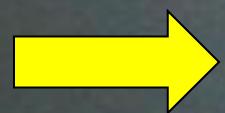
$$m_\nu=Y_\nu\,\frac{\nu}{\sqrt{2}}\sin\beta$$

$$M_R=V\,M_N^{-1}\,V^T\equiv {\rm diag}(M_{R_1},M_{R_2},M_{R_3})$$

$$M_{R_1}=(\lambda_2~\nu_{16})^2/M_2,$$

$$M_{R_2}=(\lambda_2~\nu_{16})^2/M_1,$$

$$M_{R_3}=(\lambda_3~\nu_{16})^2/M_3$$

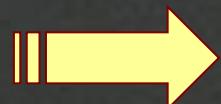


$$M_\nu = U_e^T \left(m_\nu M_R^{-1} m_\nu^T \right) U_e$$

Using χ^2 analysis, fit

15 charged fermion & 5 neutrino
low energy observables with

II arbitrary Yukawa & 3 Majorana mass
parameters



4 & 2 d.o.f. or 6 predictions

Global χ^2 analysis

Sector	#	Parameters
gauge	3	$\alpha_G, M_G, \epsilon_3,$
SUSY (GUT scale)	5	$m_{16}, M_{1/2}, A_0, m_{H_u}, m_{H_d},$
textures	11	$\epsilon, \epsilon', \lambda, \rho, \sigma, \tilde{\epsilon}, \xi,$
neutrino	3	$M_{R_1}, M_{R_2}, M_{R_3},$
SUSY (EW scale)	2	$\tan \beta, \mu$

24 parameters at GUT scale

compared to SM - 27 parameters

CMSM - 32 parameters

Table 1: Initial parameters for benchmark point with $m_{16} = 20$ TeV:
 $(1/\alpha_G, M_G, \epsilon_3) = (25.90, 3.13 \times 10^{16}$ GeV, -1.45%),
 $(\lambda, \lambda\epsilon, \sigma, \lambda\tilde{\epsilon}, \rho, \lambda\epsilon', \lambda\epsilon\xi) = (0.60, 0.031, 1.14, 0.0049, 0.070, -0.0019, 0.0038)$,
 $(\Phi_\sigma, \Phi_{\tilde{\epsilon}}, \Phi_\rho, \Phi_\xi) = (0.533, 0.548, 3.936, 3.508)$ rad,
 $(m_{16}, M_{1/2}, A_0, \mu(M_Z)) = (20000, 168, -41087, 1163.25)$ GeV,
 $((m_{H_d}/m_{16})^2, (m_{H_u}/m_{16})^2, \tan\beta) = (1.85, 1.61, 49.82)$
 $(M_{R_3}, M_{R_2}, M_{R_1}) = (3.2 \times 10^{13}$ GeV, 6.1×10^{11} GeV, 0.9×10^{10} GeV)

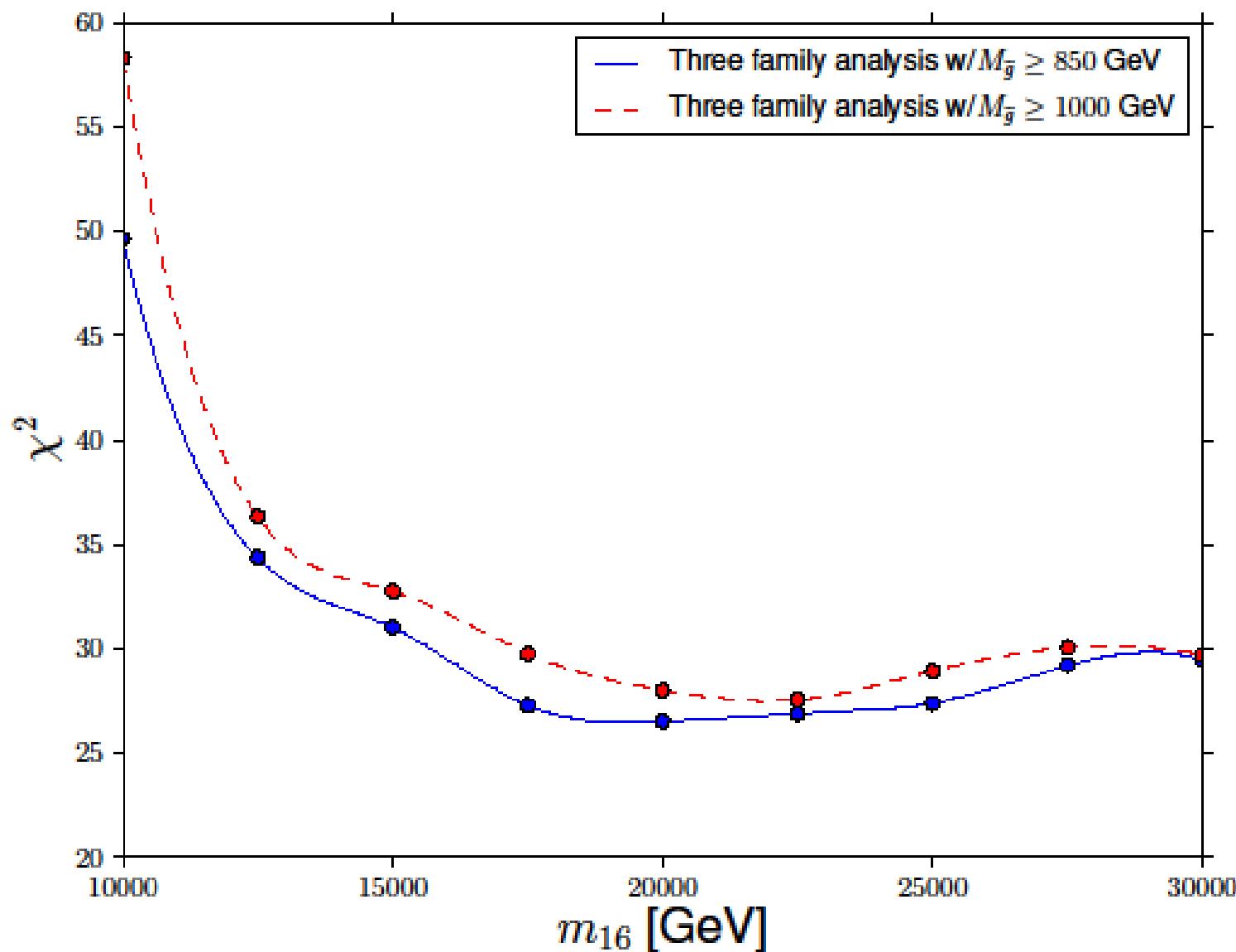
Observable	Fit value	Exp value	Pull	Sigma
M_Z	91.1876	91.1876	0.0000	0.4559
M_W	80.5452	80.3850	0.3982	0.4022
$1/\alpha_{em}$	137.0725	137.0360	0.0533	0.6852
$G_\mu \times 10^5$	1.1713	1.1664	0.4250	0.0117
α_3	0.1184	0.1184	0.0467	0.0009
M_t	174.0184	173.5000	0.3916	1.3238
$m_b(m_b)$	4.1849	4.1800	0.1334	0.0366
M_τ	1.7755	1.7768	0.1462	0.0089
$m_c(m_c)$	1.2547	1.2750	0.7876	0.0258
m_s	0.0964	0.0950	0.2807	0.0050
m_d/m_s	0.0692	0.0526	2.9891	0.0055
$1/Q^2$	0.0018	0.0019	0.4749	0.0001
M_μ	0.1056	0.1057	0.1049	0.0005
$M_e \times 10^4$	5.1122	5.1100	0.0862	0.0255
Total χ^2			26.5812	

$\chi^2/\text{dof} = 2$

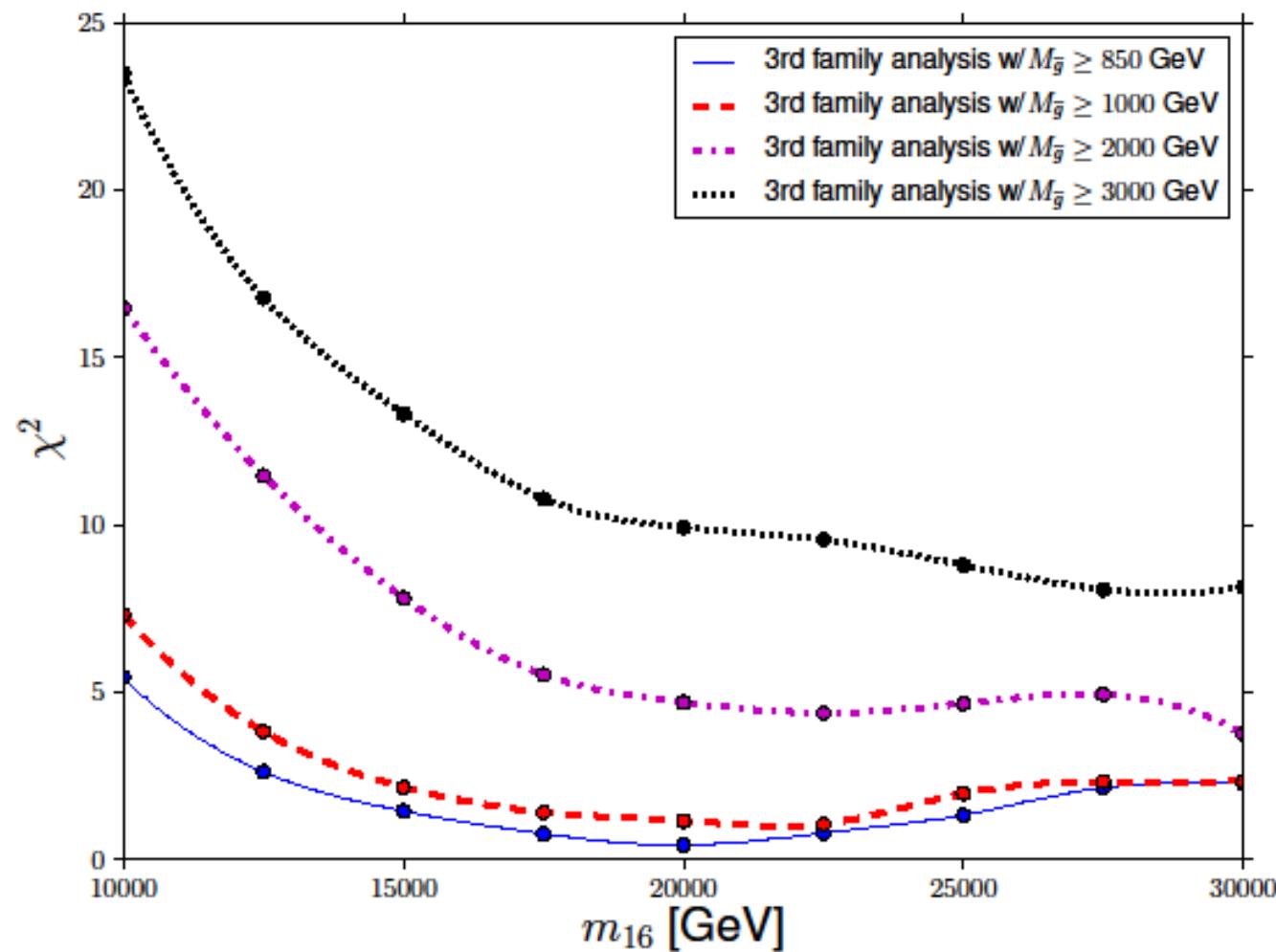
Table 1: Initial parameters for benchmark point with $m_{16} = 20$ TeV:

Observable	Fit value	Exp value	Pull	Sigma
$ V_{us} $	0.2243	0.2252	0.5964	0.0014
$ V_{cb} $	0.0415	0.0406	0.4511	0.0020
$ V_{ub} \times 10^3$	3.2023	3.7700	0.6678	0.8502
$ V_{td} \times 10^3$	8.9819	8.4000	0.9675	0.6015
$ V_{ts} $	0.0407	0.0429	0.8518	0.0026
$\sin 2\beta$	0.6304	0.6790	2.3959	0.0203
ϵ_K	0.0023	0.0022	0.3823	0.0002
$\Delta M_{Bs}/\Delta M_{Bd}$	39.4933	35.0600	0.6311	7.0246
$\Delta M_{Bd} \times 10^{13}$	3.9432	3.3370	0.9072	0.6682
$m_{21}^2 \times 10^5$	7.5126	7.5450	0.0593	0.5463
$m_{31}^2 \times 10^3$	2.4828	2.4800	0.0135	0.2104
$\sin^2 \theta_{12}$	0.2949	0.3050	0.2880	0.0350
$\sin^2 \theta_{23}$	0.5156	0.5050	0.0640	0.1650
$\sin^2 \theta_{13}$	0.0131	0.0230	1.4134	0.0070
M_h	124.07	125.30	0.4010	3.0676
$BR(B \rightarrow X_s \gamma) \times 10^4$	3.4444	3.4300	0.0088	1.6374
$BR(B_s \rightarrow \mu^+ \mu^-) \times 10^9$	1.6210	3.2000	0.9682	1.6308
$BR(B_d \rightarrow \mu^+ \mu^-) \times 10^{10}$	1.0231	8.1000	0.0000	5.2559
$BR(B \rightarrow \tau \nu) \times 10^5$	6.3855	16.6000	1.1436	8.9320
$BR(B \rightarrow K^* \mu^+ \mu^-) (\text{low}) \times 10^8$	5.1468	19.7000	1.2123	12.0051
$BR(B \rightarrow K^* \mu^+ \mu^-) (\text{high}) \times 10^8$	7.7469	12.0000	0.5839	7.2835
$q_0^2(B \rightarrow K^* \mu^+ \mu^-)$	4.5168	4.9000	0.2945	1.3009
Total χ^2		26.5812		

Gluino mass bound - 3 fam.



Gluino mass bound - 3rd fam. only



	10 TeV	15 TeV	20 TeV	25 TeV	30 TeV
m_{16}					
χ^2	49.65	31.02	26.58	27.93	29.48
M_A	2333	3662	1651	2029	2036
$m_{\tilde{t}_1}$	1681	2529	3975	4892	5914
$m_{\tilde{b}_1}$	2046	2972	5194	6353	7660
$m_{\tilde{\tau}_1}$	3851	5576	7994	9769	11620
$m_{\tilde{\chi}_1^0}$	133	134	137	149	167
$m_{\tilde{\chi}_1^+}$	260	263	279	309	351
$M_{\tilde{g}}$	853	850	851	910	1004

	Current Limit	10 TeV	15 TeV	20 TeV	25 TeV	30 TeV
e EDM $\times 10^{28}$	$< 10.5 \text{ e cm}$	-0.224	-0.0408	-0.0173	-0.0113	-0.0084
μ EDM $\times 10^{28}$	$(-0.1 \pm 0.9) \times 10^9 \text{ e cm}$	34.6	6.23	3.04	1.77	1.20
τ EDM $\times 10^{28}$	$-0.220 - 0.45 \times 10^{12} \text{ e cm}$	-2.09	-0.394	-0.185	-0.109	-0.0732
BR($\mu \rightarrow e\gamma$) $\times 10^{12}$	< 2.4	5.09	1.23	0.211	0.0937	0.0447
BR($\tau \rightarrow e\gamma$) $\times 10^{12}$	$< 3.3 \times 10^4$	58.8	13.9	2.40	1.04	0.502
BR($\tau \rightarrow \mu\gamma$) $\times 10^8$	< 4.4	1.75	0.498	0.0837	0.0385	0.0182
$\sin \delta$		-0.60	-0.87	-0.27	-0.42	-0.53

Conclusions

- SO(10) Yukawa unification
- Boundary conditions at M_{GUT}
 - Universal gaugino masses
- Light Higgs - SM-like
- simplified models NOT
 - (in general) applicable gluino w/ multi-leptons
 - LSP - bino
- $2 \text{ TeV} \geq m_g \geq 1 \text{ TeV}$