Leptogenesis after Inflation in a Pati-Salam Model

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Planck 2017
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THE OHIO STATE UNIVERSITY
DEPARTMENT OF PHYSICS

Subcritical Hybrid Inflation in a Pati-Salam Model

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Outline

- Subcritical hybrid F-term inflation
- Re-heating
- Pati-Salam 3 family model
  with D_4 family symmetry & $\mathbb{Z}_4^R$ symmetry
- Yukawa Unification - 3rd family only
- Global χ^2 fits & predictions
- Conclusions

Subcritical hybrid F-term inflation

B. Charles Bryant & S. Raby arXiv:1601.03749

Following work on subcritical hybrid D-term inflation by

Buchmuller, Domcke & Schmitz
J. Cosmol.Astropart. Phys. 11, 006 (2014)

Buchmuller & Ishiwata PRD91, 081302 (2015)

$$W_I = \Phi(\kappa \overline{S^c} S^c + mY + \alpha H H) + \lambda X \left(\overline{S^c} S^c - \frac{v_{PS}^2}{2} \right)$$

$$+ S^c \Sigma S^c + \overline{S^c} \Sigma \overline{S^c}$$

$$\mathrm{K} = \frac{1}{2}\left(\Phi + \Phi^\dagger\right)^2 + \left(S^c\right)^\dagger S^c + Y^\dagger Y + X^\dagger X \left[1 - c_X \frac{X^\dagger X}{M_{Pl}^2} + \alpha_X \left(\frac{X^\dagger X}{M_{Pl}^2} \right)^2 \right]$$

$$SU(4)_C \times SU(2)_L \times SU(2)_R \times \mathbb{Z}_4^R$$

$$\Phi, X = (1,1,1,2),\ S^c = (\bar{4},1,\bar{2},0),\ \overline{S}^c = \left(4,1,2,0\right)$$

$$\Sigma = (6,1,1,2),\ Y = (1,1,1,0),\ H = (1,2,\bar{2},0)$$

$$S^c = \exp(i\,T_{SU(4)_C/SU(3)}\ \phi_u^c)\ \exp(i\,T_{SU(2)_R/U(1)_R}\ \phi_e^c) \begin{pmatrix} 0 & \frac{1}{\sqrt{2}}\exp(i\,T)\ V^c \\ d_S^c & 0 \end{pmatrix}$$

$$\bar{S}^c = \exp(-i\,T^T_{SU(4)_C/SU(3)}\ \bar{\phi}_u^c)\ \exp(-i\,T^T_{SU(2)_R/U(1)_R}\ \bar{\phi}_e^c) \begin{pmatrix} 0 & \frac{1}{\sqrt{2}}\exp(-i\,T)\ V^c \\ \bar{d}_{\bar{S}}^c & 0 \end{pmatrix}$$

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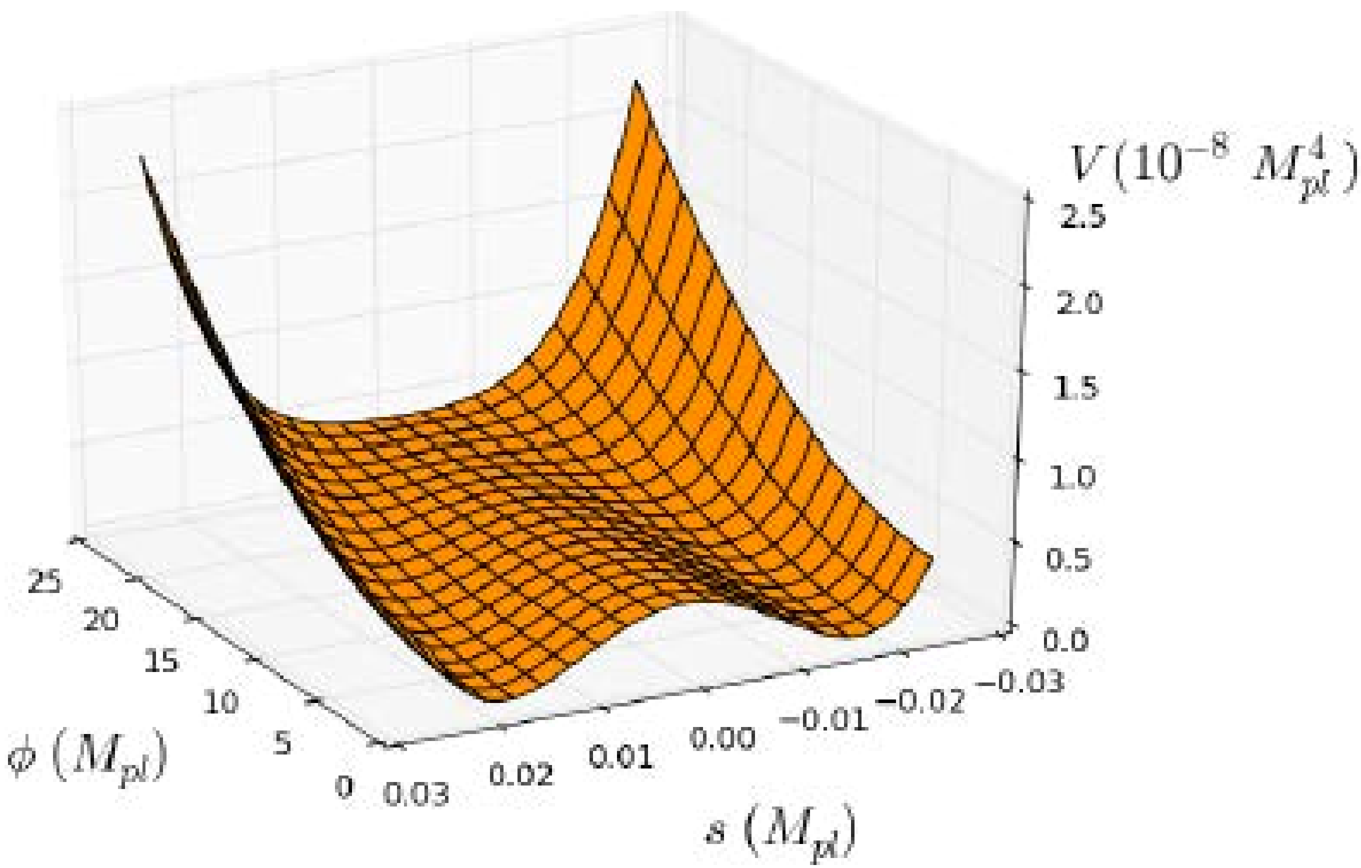
$$\Phi \supset \frac{a + i\phi}{\sqrt{2}}, \quad V^c \supset \frac{s + i\tau}{\sqrt{2}}, \quad Y \supset \frac{y + iu}{\sqrt{2}}$$

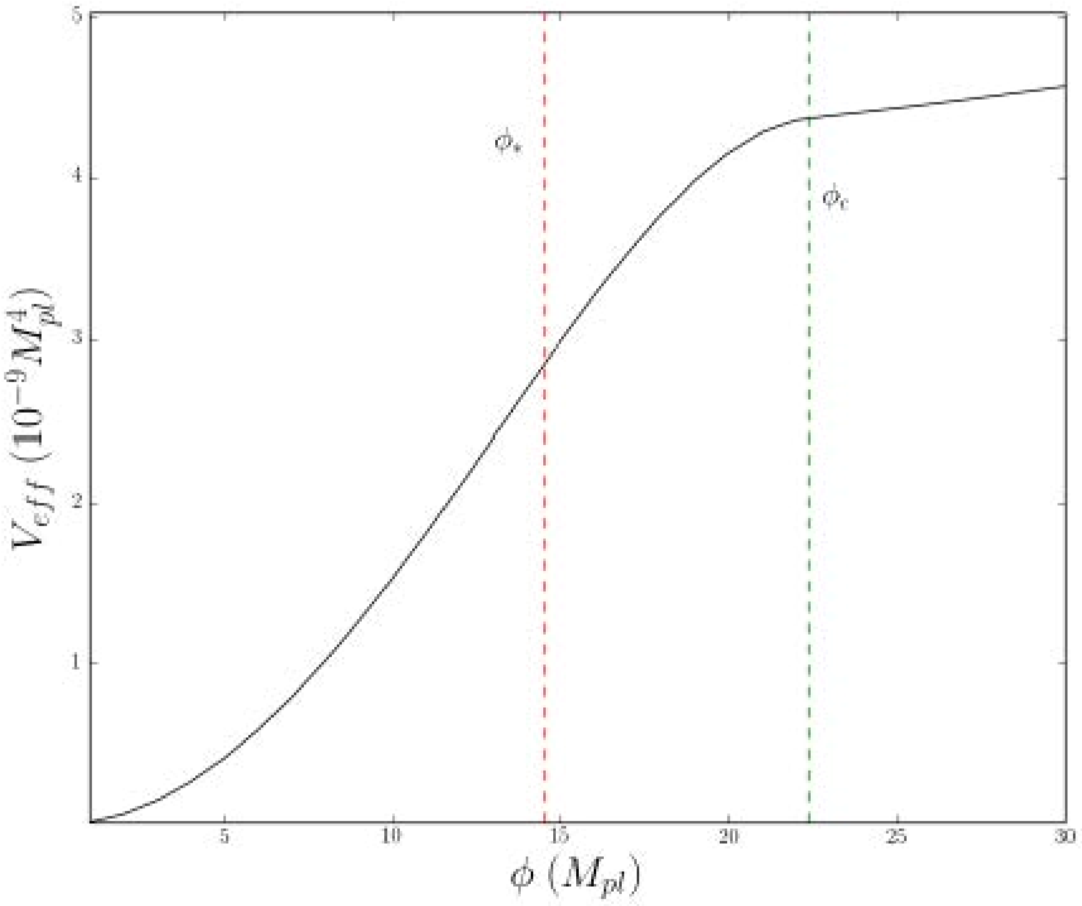
$$s = \sigma + \sqrt{2} v_{PS} \text{ and } y = h - \kappa v_{PS}^2/\sqrt{2} m$$

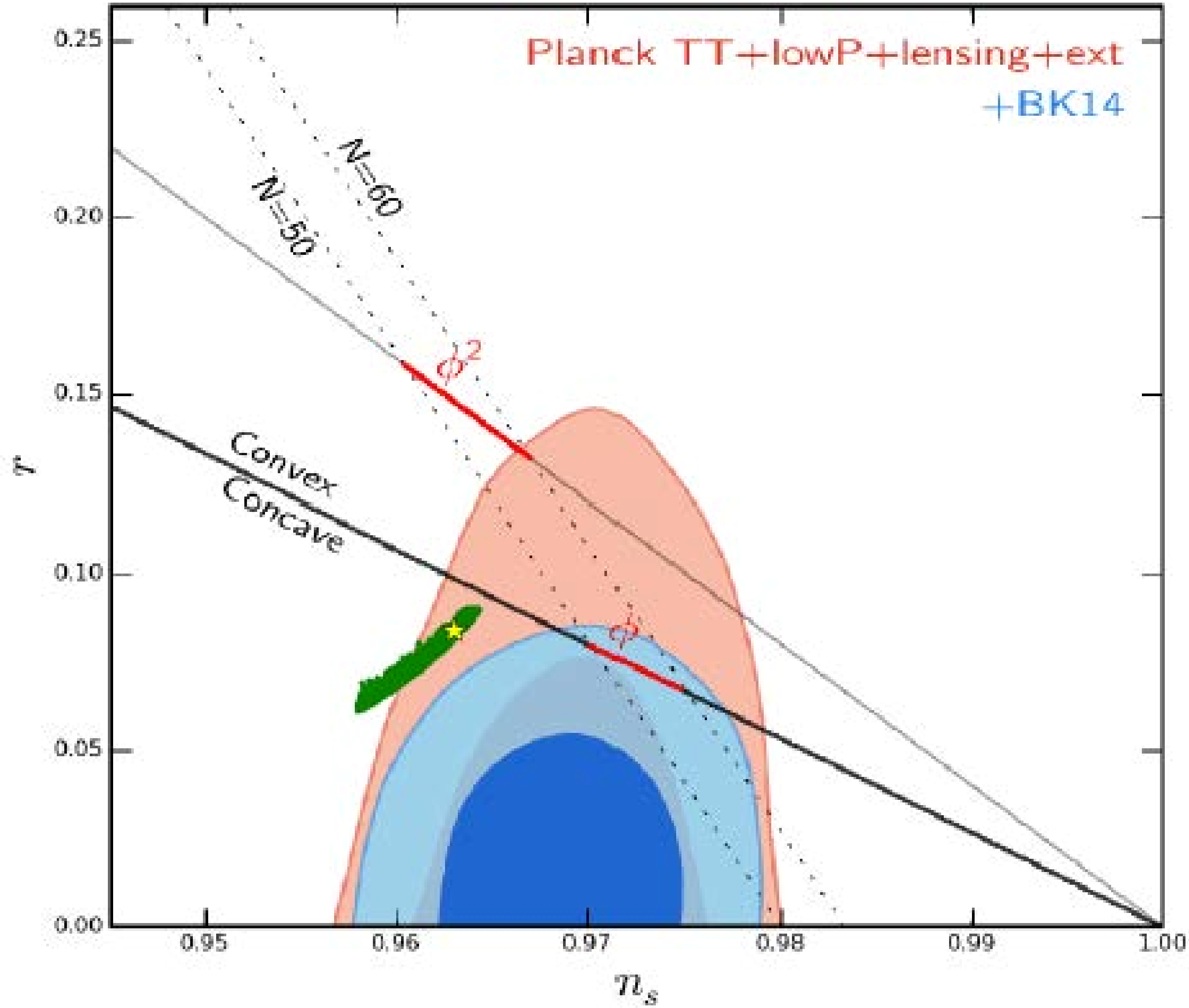
$$V(\phi, s, 0) \simeq \frac{\lambda^2 v_{PS}^4}{4} + \frac{1}{4}\left(\kappa^2\phi^2 - \lambda^2 v_{PS}^2\right) s^2 + \frac{\lambda^2}{16} s^4 + \frac{1}{2} m^2 \phi^2$$

$$\phi_c \equiv \frac{\lambda v_{PS}}{\kappa} \qquad \kappa \ll \lambda \qquad s_{\min}^2(\phi) = 2 v_{PS}^2 \left(1 - \frac{\phi^2}{\phi_c^2}\right)$$



$$V_{eff}(\phi) = \frac{\lambda^2 v_{PS}^4}{2}\frac{\phi^2}{\phi_c^2}\left[\left(1+\frac{m^2}{\kappa^2 v_{PS}^2}\right) - \frac{\phi^2}{2\phi_c^2}\right] \simeq \frac{\lambda^2 v_{PS}^4}{2}\frac{\phi^2}{\phi_c^2}\left[1 - \frac{\phi^2}{2\phi_c^2}\right]$$




Planck TT+lowP+lensing+ext
+BK14
N=60
N=50
ϕ^2
ϕ
Convex
Concave
0.25
0.20
0.15
0.10
0.05
0.00
0.95
0.96
0.97
0.98
0.99
1.00
r
n_s

At the end of inflation

$$\rho_\phi^0 \approx 5 \times 10^{-11}\, M_{pl}^4 \quad , \quad \rho_\sigma^0 \approx 7 \times 10^{-14}\, M_{pl}^4$$

$$\mathcal{W}_\Phi = \alpha \Phi \mathcal{H} \mathcal{H}$$

$$\Gamma_{\phi \to \tilde{h}_u^0 \tilde{h}_d^0 + \tilde{h}_u^+ \tilde{h}_d^-} \approx \frac{\alpha^2}{8\pi}\, m$$

Reheat temperature

$$T_R^\phi = \left(\frac{90}{\pi^2 g_*} \Gamma_\phi^2 M_{pl}^2 \right)^{1/4} \Rightarrow \quad T_R^\phi \simeq 2 \times 10^{10} \left(\frac{\alpha}{10^{-4}} \right) \left(\frac{m}{10^{-6} M_{Pl}} \right)^{1/2} \text{GeV}$$

At the end of inflation $\mathcal{W}_\Phi = \alpha\Phi\mathcal{H}\mathcal{H}$

A word about leptogenesis

Instant preheating can non-perturbatively create Higgses every time inflaton VEV vanishes

Then when inflaton VEV reaches a maximum the Higgs gets heavy and can decay into right-handed neutrinos and radiation. Right-handed neutrinos decay and produce non-zero lepton asymmetry.
$\varepsilon_3 < 0$ good , $\varepsilon_{1,2} > 0$ bad

Problem : reheat temperature is too high and Lepton asymmetry is washed out !!

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SO(10) Grand Unification

	State	$Y = \frac{2}{3}\Sigma(C) - \Sigma(W)$	Color C spins	Weak W spins
1	$\bar{\nu}$	0	$- - -$	$- -$
10	$\bar{e}$	2	$- - -$	$+ +$
	u_r	$\frac{1}{3}$	$+ - -$	$- +$
	d_r		$+ - -$	$+ -$
	u_b		$- + -$	$- +$
	d_b		$- + -$	$+ -$
	u_y		$- - +$	$- +$
	d_y		$- - +$	$+ -$
	$\bar{u}_r$	$-\frac{4}{3}$	$- + +$	$- -$
	$\bar{u}_b$		$+ - +$	$- -$
	$\bar{u}_y$		$+ + -$	$- -$
$\bar{5}$	$\bar{d}_r$	$\frac{2}{3}$	$- + +$	$+ +$
	$\bar{d}_b$		$+ - +$	$+ +$
	$\bar{d}_y$		$+ + -$	$+ +$
	ν	-1	$+ + +$	$- +$
	e		$+ + +$	$+ -$

Georgi
Fritzsch & Minkowski

spinor repsn. of SO(10) – 16

tensor product of 5 spin ½ w/ even no. + signs

$$\mathrm{SO}(10) \to \mathrm{SU}(5) \otimes \mathrm{U}(1)$$

$$\to \mathrm{SO}(6) \otimes \mathrm{SO}(4) \approx \mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$$

$$Q = \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix} \qquad \overline{Q} = \begin{pmatrix} \overline{u} & \overline{u} & \overline{u} & \overline{\nu} \\ \overline{d} & \overline{d} & \overline{d} & \overline{e} \end{pmatrix}$$

$$Q = (4,\ 2,\ 1) \qquad \overline{Q} = (\overline{4},\ 1,\ \overline{2})$$

Lepton number is the 4th Color !!

Pati-Salam $SU(4)_C \times SU(2)_L \times SU(2)_R$

$$Q_{EM} = \tfrac{1}{2}\left(B - L\right) + T_L^3 + T_R^3$$

Unique $\mathbb{Z}_4^R$ symmetry for the MSSM

Lee, Raby, Ratz, Ross, Shieren, Schmidt-Hoberg & Vaudrevange
Phys.Lett. B694, 491-495 (2011)
Nucl.Phys. B850, 1-30 (2011)

Kappl, Peterson, Raby, Ratz, Schieren & Vaudrevange
Nucl.Phys. B847, 2325-349 (2011)

$\mathbb{Z}_4^R$ symmetry - anomaly cancelled by Green-Schwartz

$$A_{SU(4)_C - SU(4)_C - \mathbb{Z}_4^R} = A_{SU(2)_L - SU(2)_L - \mathbb{Z}_4^R} = A_{SU(2)_R - SU(2)_R - \mathbb{Z}_4^R} = 1(\mathrm{mod}(2))$$

Forbids $Q\,Q\,Q\,Q,\ Q^c Q^c\, Q^c Q^c,\ Q\,Q\,Q^c Q^c,\ H\,H$

$S^c\,Q^c\,Q^c\,Q^c \quad + \quad \cdots$

$$\text{under } \mathbb{Z}_4^R:\ \ S \to S + \frac{i}{2}\Delta_{GS}$$

$$\langle W \rangle_{np} \sim \exp(-\langle S \rangle) \sim m_{3/2}\ M_{Pl}^2$$

$$\Rightarrow \quad \frac{m_{3/2}}{M_{Pl}^2}\, Q\,Q\,Q\,Q,\ \ m_{3/2}\ H\,H$$

Suppresses μ and Dimension 5 proton decay ops.

Preserves R parity !!

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Soft SUSY breaking terms

m_{16}^2 Universal scalar masses

$m_{10}^2 \pm \Delta m_H^2 \rightarrow NUHM\,2$

A_0 Universal A parameter, μ, $\tan\beta$

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

$M_i = M_{1/2}$

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

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)
Dermisek & Raby Phys. Lett. B 622, 327 (2005)
Baer, Kraml, Sekmen & Summy JHEP 0909 :005 (2009)
Anandakrishnan, Raby & Wingerter arXiv:1212.0542
Anandakrishnan & Raby arXiv:1303.5125
Anandakrishnan, Bryant & Raby arXiv:1404.5628
Poh & Raby arXiv:1505.00264

$$\lambda \ \overline{Q}_3 \, H \ Q_3$$

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

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

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

$$\delta m_b / m_b \leq -2\%$$

Needed to fit data

$$\mu M_{\tilde{g}} > 0 \quad \Rightarrow \quad \mu A_t < 0$$

AnandaKrishnan, Raby & Wingerter

arXiv:1212.0542

AnandaKrishnan, Bryant & Raby

arXiv:1404.5628

Global χ^2 analysis

3rd family only

Yukawa Unification

$$\lambda \; 16_3 \, 10 \, 16_3$$

~ Universal Gaugino Masses

Fit t,b,tau requires

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

$$m_{16} > \textit{few} \;\text{TeV} \qquad \mu, M_{1/2} << \; m_{16}$$

$$\tan\beta \approx 50$$

Inverted scalar mass hierarchy

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

Third family scalars lighter than first two !

Suppresses flavor & CP violation

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

$$m_{16} > \textit{few}\ \text{TeV} \qquad \mu, M_{1/2} << m_{16}$$

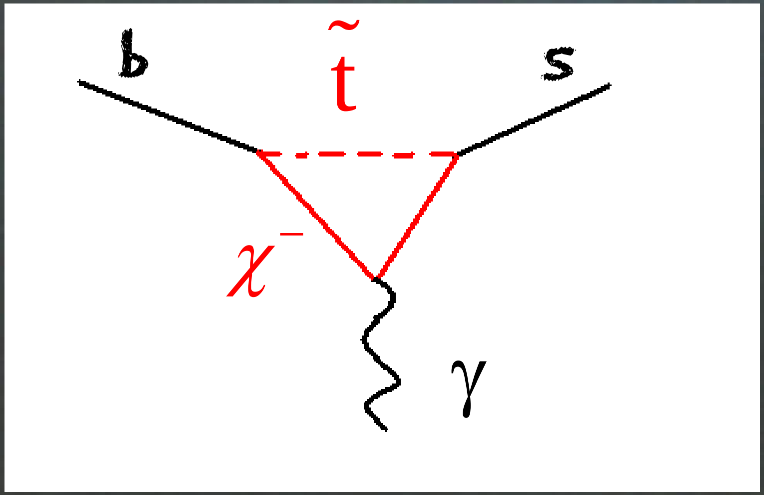
$$\tan\beta \approx 50$$

Heavy scalars

Need Heavy scalars !

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

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



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

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

$$C_7^{\chi^+} \propto \frac{\mu A_t}{\tilde{m}^2} \tan\beta \times \mathrm{sign}\left(C_7^{SM}\right) \approx \begin{Bmatrix} -2C_7^{SM} \\ 0 \end{Bmatrix}$$

$$\mu M_{\tilde{g}} > 0 \Rightarrow \mu A_t < 0$$

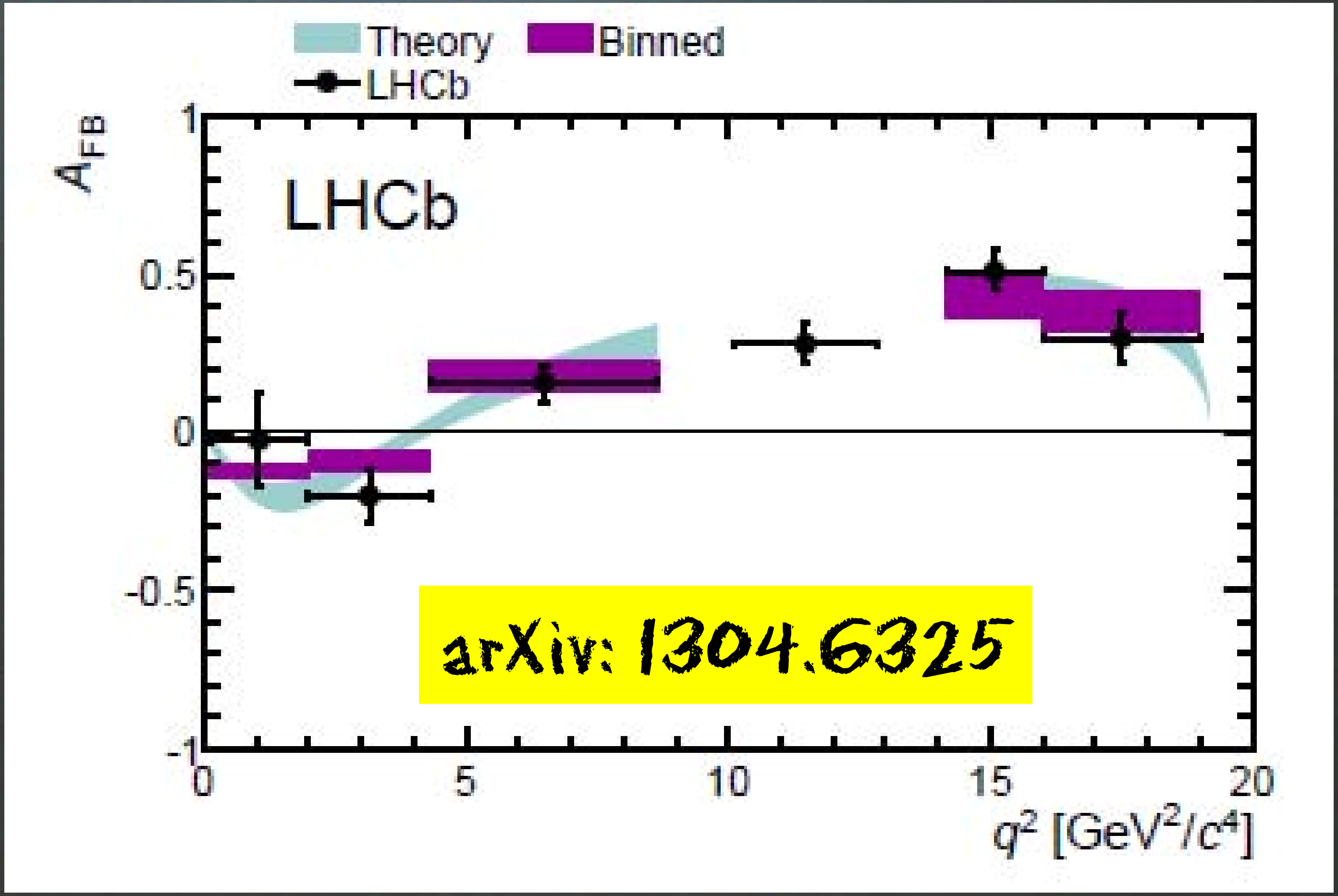
$$m_{16} \sim 4-5 \ \text{TeV}$$

light squarks and sleptons !!

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

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

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



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

Albrecht, Altmannshofer, Buras, Guadagnoli, & Straub

JHEP 0710:055 (2007)

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

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

$$\Rightarrow \quad m_{16} \geq 8\ \mathrm{TeV}$$

Albrecht, Altmannshofer, Buras, Guadagnoli, & Straub

JHEP 0710:055 (2007)

m_{16}	10000
μ	1200
$\mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^8$	2.1
$\hat{s}_0$	0.14
$\mathrm{BR}(\mu \to e\gamma) \times 10^{13}$	0.0026
$\delta a_\mu^{\mathrm{SUSY}} \times 10^{10}$	+0.52
M_{h_0}	129
M_A	842
$m_{\tilde{t}_1}$	1903
$m_{\tilde{b}_1}$	2366
$m_{\tilde{\tau}_1}$	3933
$m_{\tilde{\chi}_1^0}$	60
$m_{\tilde{\chi}_1^+}$	120
$m_{\tilde{g}}$	506

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Light Higgs
SM-like

Br($B_s \to \mu^+ \mu^-$):
Light Higgs SM-like

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

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

$$LHCb \quad \left(2.9\,{}^{+1.1}_{-1.0}\right) \times 10^{-9}$$

$$\text{w/ } 1\ \text{fb}^{-1}\ (7\text{TeV}) + 2\,\text{fb}^{-1}\ (8\text{TeV})$$

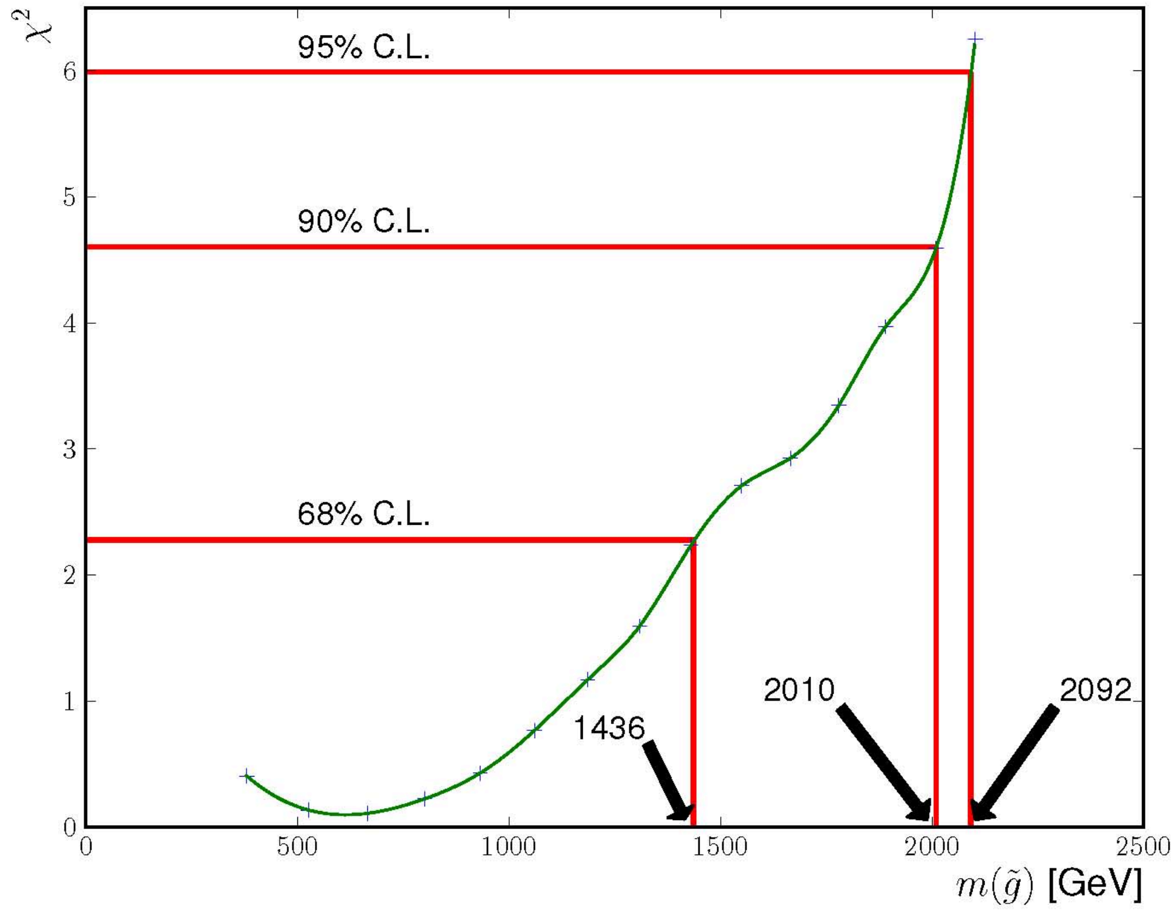
$$m_A \geq 1\,\text{TeV}$$

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

Gluino mass bound - Third family only

Anandakrishnan, Raby & Wingerter

m_{16} = 20 TeV, $M_{1/2}$ varied -> 2 d.o.f.



Summary
First order results
Third family only

- Universal scalar masses ~ 25 TeV
- Third family scalars much lighter
- Light Higgs is SM-like
- Gluinos want to be light,
  But constrained by data !

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Three family model gives good fits to low energy data

In this talk we introduce a new YuKawa sector with two new real parameters

First before - then after adding New parameters

$$
\begin{aligned}
W_{\rm PS} = &\lambda Q_3\, \mathcal{H}\, Q_3^c + Q_a\, \mathcal{H}\, F_a^c + F_a\, \mathcal{H}\, Q_a^c \\
&+ \bar{F}_a^c \left(M_F\, F_a^c + \mathbf{15}\, \frac{\phi_a}{\hat{M}}\, Q_3^c + \mathbf{15}\, \frac{\tilde{\phi}_a}{\hat{M}}\, Q_a^c + \mathbf{A}\, Q_a^c \right) \\
&+ \bar{F}_a \left(M_F\, F_a + \mathbf{15}\, \frac{\phi_a}{\hat{M}}\, Q_3 + \mathbf{15}\, \frac{\tilde{\phi}_a}{\hat{M}}\, Q_a + \mathbf{A}\, Q_a \right)
\end{aligned}
$$

$$\{Q_3,\, Q_a,\, F_a\} = (4,2,1,1), \quad \{Q_3^c,\, Q_a^c,\, F_a^c\} = (\bar{4},\bar{2},1,1)$$

$\phi_a,\ \theta_a,\ B_2,\ A$ flavon fields

$a = 1,2$ D_4 family index

$$M_F \propto 1 + \alpha\, X + \beta\, Y, \quad \langle 15 \rangle \propto B - L$$

Global χ^2 analysis

Sector	#	Parameters
gauge	3	α_G, M_G, ϵ_3,
SUSY (GUT scale)	5	m_{16}, $M_{1/2}$, A_0, m_{H_u}, m_{H_d},
textures	11	ϵ, ϵ', λ, ρ, σ, $\tilde{\epsilon}$, ξ,
neutrino	3	M_{R_1}, M_{R_2}, M_{R_3},
SUSY (EW scale)	2	$\tan\beta$, μ

Poh & Raby arXiv:1505.00264

24 parameters at GUT scale

45 Low energy observables

Before $m_{16} = 25$ TeV

Observable	Fit	Exp.	Pull	σ
M_Z	91.1876	91.1876	0.0000	0.4535
M_W	80.4507	80.3850	0.1633	0.4025
$1/\alpha_{em}$	137.7125	0.0073	0.9825	0.6886
$G_\mu \times 10^5$	1.1732	1.1664	0.5798	0.0117
$\alpha_3(M_Z)$	0.1188	0.1185	0.4140	0.0008
M_t	174.1882	173.2100	0.7927	1.2340
$m_b(m_b)$	4.1954	4.1800	0.4220	0.0366
m_τ	1.7781	1.7768	0.1417	0.0089
$M_b - M_c$	3.1568	3.4500	0.9175	0.3196
$m_c(m_c)$	1.2595	1.2750	0.5993	0.0258
$m_s(2\text{GeV})$	0.0939	0.0950	0.2147	0.0050
$m_d / m_s(2\text{GeV})$	0.0701	0.0513	2.8052	0.0067
$1/Q^2$	0.0018	0.0019	0.5139	0.0001
M_μ	0.1056	0.1057	0.1818	0.0005
$M_e \times 10^4$	5.1145	5.1100	0.1749	0.0256
$\lvert V_{us}\rvert$	0.2244	0.2253	0.6763	0.0014
$\lvert V_{cb}\rvert$	0.0404	0.0408	0.1729	0.0021
$\lvert V_{ub}\rvert \times 10^3$	3.1033	3.8500	0.8681	0.8601
$\lvert V_{td}\rvert \times 10^3$	8.8101	8.4000	0.6817	0.6016
$\lvert V_{ts}\rvert$	0.0396	0.0400	0.1531	0.0027
$\sin 2\beta$	0.6270	0.6820	2.8562	0.0193
ϵ_K	0.0022	0.0022	0.2052	0.0002
$\Delta M_{B_s}/\Delta M_{B_d}$	35.3739	35.0345	0.0479	7.0854
$\Delta M_{B_d} \times 10^{13}$	3.9433	3.3370	0.7681	0.7894

Observable	Fit	Exp.	Pull	σ
$m_{21}^2 \times 10^5$	7.6562	7.5550	0.1886	0.5364
$m_{31}^2 \times 10^3$	2.4631	2.4620	0.0077	0.1455
$\sin^2\theta_{12}$	0.3170	0.3070	0.2689	0.0370
$\sin^2\theta_{23}$	0.6264	0.5125	0.8722	0.1305
$\sin^2\theta_{13}$ $\theta_{13} \approx 7^o$	0.0149	0.0218	2.1658	0.0032
M_h	124.5054	125.7000	0.3947	3.0265
$BR(B \to s\gamma) \times 10^4$	2.6840	3.4300	0.5789	1.2887
$BR(B_s \to \mu^+\mu^-) \times 10^9$	3.0247	2.8000	0.2429	0.9252
$BR(B_d \to \mu^+\mu^-) \times 10^{10}$	1.1022	3.9000	1.7323	1.6151
$BR(B \to \tau\nu) \times 10^5$	6.1884	11.4000	1.3727	3.7966
$BR(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2} \times 10^8$	4.7640	3.4000	0.2707	5.0381
$BR(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2} \times 10^8$	7.5110	5.6000	0.1336	14.3059
$q_0^2(A_{\mathrm{FB}}(B \to K^*\mu^+\mu^-))$	3.6690	4.9000	0.9579	1.2850
$F_L(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.7225	0.6500	0.2149	0.3374
$F_L(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	0.3108	0.3300	0.0726	0.2644
$P_2(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.0228	0.3300	2.5196	0.1219
$P_2(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	-0.4336	-0.5000	0.3364	0.1974
$P_4'(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.5820	0.5800	0.0050	0.4001
$P_4'(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	1.2190	-0.1800	1.7066	0.8198
$P_5'(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	-0.4455	0.2100	2.2578	0.2903
$P_5'(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	-0.7116	-0.7900	0.1552	0.5052
Total χ^2			48.8413	

New Yukawa sector with two new real parameters

Now after adding
New parameters

$$W_{\rm PS} = \lambda \mathcal{Q}_3\ \mathcal{H}\ \mathcal{Q}_3^c + \mathcal{Q}_a\ \mathcal{H}\ F_a^c + F_a\ \mathcal{H}\ \mathcal{Q}_a^c$$
$$+ \bar{F}_a^c \left(M_F\ F_a^c + \mathbf{15}\ \frac{\phi_a}{\hat{M}}\ \mathcal{Q}_3^c + \mathbf{15}\ \frac{\tilde{\phi}_a}{\hat{M}}\ \mathcal{Q}_a^c + \mathbf{A}\ \mathcal{Q}_a^c + \Theta'\ \mathcal{Q}_a^c + \frac{\tilde{\Theta}_a}{\hat{M}}\ \mathcal{Q}_a^c \right)$$
$$+ \bar{F}_a \left(M_F\ F_a + \mathbf{15}\ \frac{\phi_a}{\hat{M}}\ \mathcal{Q}_3 + \mathbf{15}\ \frac{\tilde{\phi}_a}{\hat{M}}\ \mathcal{Q}_a + \mathbf{A}\ \mathcal{Q}_a + \Theta'\ \mathcal{Q}_a - \frac{\tilde{\Theta}_a}{\hat{M}}\ \mathcal{Q}_a \right)$$

$$\{Q_3,\ Q_a,\ F_a\} = (4,2,1,1),\ \ \{Q_3^c,\ Q_a^c,\ F_a^c\} = (\bar{4},\bar{2},1,1)$$

$$\phi_a,\ \ \theta_a,\ B_2,\ A,\ \left\{\tilde{\theta}_a,\ \theta'\right\}\quad \text{flavon fields}$$

$$a = 1,2 \quad D_4 \ \text{ family index}$$

$$M_F \propto 1 + \alpha X + \beta Y,\ \ \langle 15 \rangle \propto B - L$$

$\tilde{\theta}_a,\ \theta'$ terms added (real), $\alpha,\ \beta$ now complex

$$
\begin{aligned}
\mathcal{W}_{neutrino} &= \bar{S}^c\,(\lambda_2\, N_a\, Q^c_a \;+\; \lambda_3\, N_3\, Q^c_3) \\
&\quad -\frac{1}{2}\,(\lambda'_2 Y\; N_a\; N_a \;+\; \frac{\tilde{\theta}_a\,\tilde{\theta}_b}{\hat{M}}\; N_a\, N_b \;+\; \lambda'_3 Y\; N_3\; N_3) \\
&= \frac{\lambda_2^2}{2\, M_1}(\bar{S}^c\; Q^c_1)^2 \;+\; \frac{\lambda_2^2}{2\, M_2}(\bar{S}^c\; Q^c_2)^2 \;+\; \frac{\lambda_3^2}{2\, M_3}(\bar{S}^c\; Q^c_3)^2,
\end{aligned}
$$

$$
M_1 = \lambda'_2 Y,\;\; M_2 = \lambda'_2 Y + \frac{\tilde{\theta}_2^2}{\hat{M}},\;\; M_3 = \lambda'_3 Y
$$

$$
\Rightarrow \qquad \frac{1}{2} M_{R_1}\, \overline{\nu_1}\; \overline{\nu_1} + \frac{1}{2} M_{R_2}\, \overline{\nu_2}\; \overline{\nu_2} + \frac{1}{2} M_{R_3}\, \overline{\nu_3}\; \overline{\nu_3}
$$

$$Y_u = \begin{pmatrix} -\tilde{\theta} G^-_{1,-\frac{4}{3};1,\frac{1}{3}} & \epsilon' G^-_{1,-\frac{4}{3};1,\frac{1}{3}} + \theta' G^+_{1,-\frac{4}{3};1,\frac{1}{3}} & -\epsilon\xi G_{1,-\frac{4}{3}} \\ -\epsilon' G^-_{1,-\frac{4}{3};1,\frac{1}{3}} + \theta' G^+_{1,-\frac{4}{3};1,\frac{1}{3}} & \tilde{\epsilon} G^-_{1,-\frac{4}{3};1,\frac{1}{3}} & -\epsilon G_{1,-\frac{4}{3}} \\ \epsilon\xi G_{1,\frac{1}{3}} & \epsilon G_{1,\frac{1}{3}} & \lambda \end{pmatrix},$$

$$Y_d = \begin{pmatrix} -\tilde{\theta} G^-_{-3,\frac{2}{3};1,\frac{1}{3}} & \epsilon' G^-_{-3,\frac{2}{3};1,\frac{1}{3}} + \theta' G^+_{-3,\frac{2}{3};1,\frac{1}{3}} & -\epsilon\xi G_{-3,\frac{2}{3}} \\ -\epsilon' G^-_{-3,\frac{2}{3};1,\frac{1}{3}} + \theta' G^+_{-3,\frac{2}{3};1,\frac{1}{3}} & \tilde{\epsilon} G^-_{-3,\frac{2}{3};1,\frac{1}{3}} & -\epsilon G_{-3,\frac{2}{3}} \\ \epsilon\xi G_{1,\frac{1}{3}} & \epsilon G_{1,\frac{1}{3}} & \lambda \end{pmatrix},$$

$$Y_e = \begin{pmatrix} \tilde{\theta} G^-_{-3,-1;1,2} & -\epsilon' G^-_{-3,-1;1,2} + \theta' G^+_{-3,-1;1,2} & 3\epsilon\xi G_{1,2} \\ \epsilon' G^-_{-3,-1;1,2} + \theta' G^+_{-3,-1;1,2} & 3\tilde{\epsilon} G^-_{-3,-1;1,2} & 3\epsilon G_{1,2} \\ -3\epsilon\xi G_{-3,-1} & -3\epsilon G_{-3,-1} & \lambda \end{pmatrix},$$

$$Y_\nu = \begin{pmatrix} \tilde{\theta} G^-_{-3,-1;5,0} & -\epsilon' G^-_{-3,-1;5,0} + \theta' G^+_{-3,-1;5,0} & 3\epsilon\xi G_{5,0} \\ \epsilon' G^-_{-3,-1;5,0} + \theta' G^+_{-3,-1;5,0} & 3\tilde{\epsilon} G^-_{-3,-1;5,0} & 3\epsilon G_{5,0} \\ -3\epsilon\xi G_{-3,-1} & -3\epsilon G_{-3,-1} & \lambda \end{pmatrix},$$

$$G_{x,y} = \frac{M_0}{M_\chi} = \frac{1}{1+\alpha x+\beta y} \qquad G^\pm_{x_1,y_1;x_2,y_2} = G_{x_1,y_1} \pm G_{x_2,y_2}$$

New Global χ^2 analysis

Sector	Input Parameters	No.
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
Yukawa Textures	$\lambda, \epsilon, \tilde{\epsilon}, \epsilon', \xi, \alpha, \beta, \theta', \tilde{\theta}, \phi_{\epsilon'}, \phi_\xi, \phi_\alpha, \phi_\beta$	13
Neutrino	$M_{R_1},\ M_{R_2},\ M_{R_3}$	3
SUSY (EW Scale)	$\tan\beta,\ \mu$	2
Total		26

Poh, Raby and Wang arXiv:1703.09309

Vary 24 parameters at GUT/EW scale –

m_{16}, $M_{1/2}$ fixed

51 Observables in χ^2 function

m_{16}/TeV	20	25
$M_{\tilde{g}}$/TeV	1.90	1.90
$g\tilde{\chi}_1^0$	0.000	0.000
$g\tilde{\chi}_2^0$	0.002	0.001
$g\tilde{\chi}_3^0$	0.005	0.007
$g\tilde{\chi}_4^0$	0.002	0.004
$tb\tilde{\chi}_1^+$	0.234	0.186
$tb\tilde{\chi}_2^+$	0.274	0.322
$t\bar{t}\tilde{\chi}_1^0$	0.019	0.023
$t\bar{t}\tilde{\chi}_2^0$	0.054	0.039
$t\bar{t}\tilde{\chi}_3^0$	0.113	0.105
$t\bar{t}\tilde{\chi}_4^0$	0.097	0.106
$b\bar{b}\tilde{\chi}_1^0$	0.010	0.011
$b\bar{b}\tilde{\chi}_2^0$	0.064	0.054
$b\bar{b}\tilde{\chi}_3^0$	0.082	0.082
$b\bar{b}\tilde{\chi}_4^0$	0.044	0.059

Bound on gluino mass ??

NOT simplified model

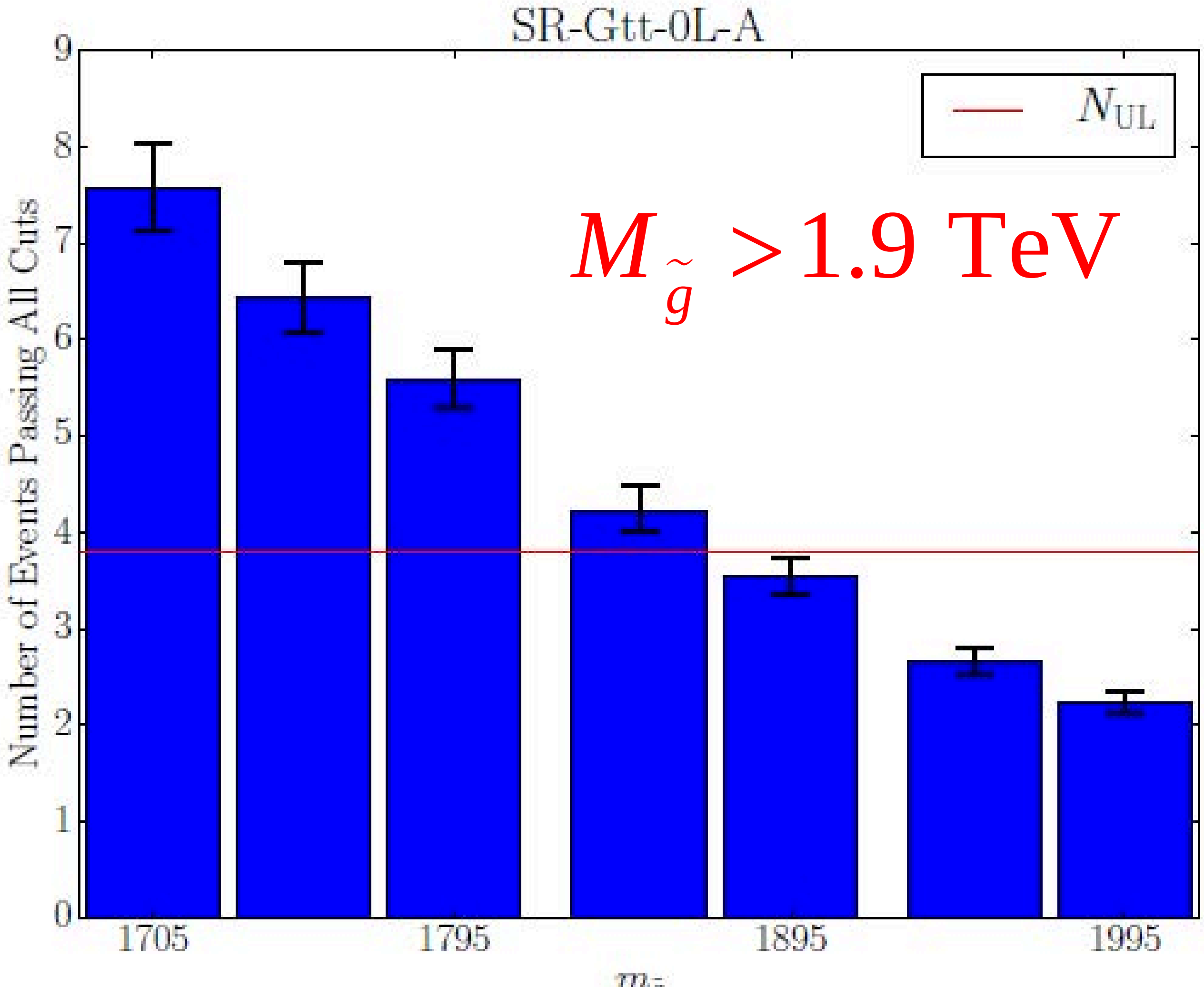
Compare to ATLAS & CMS data

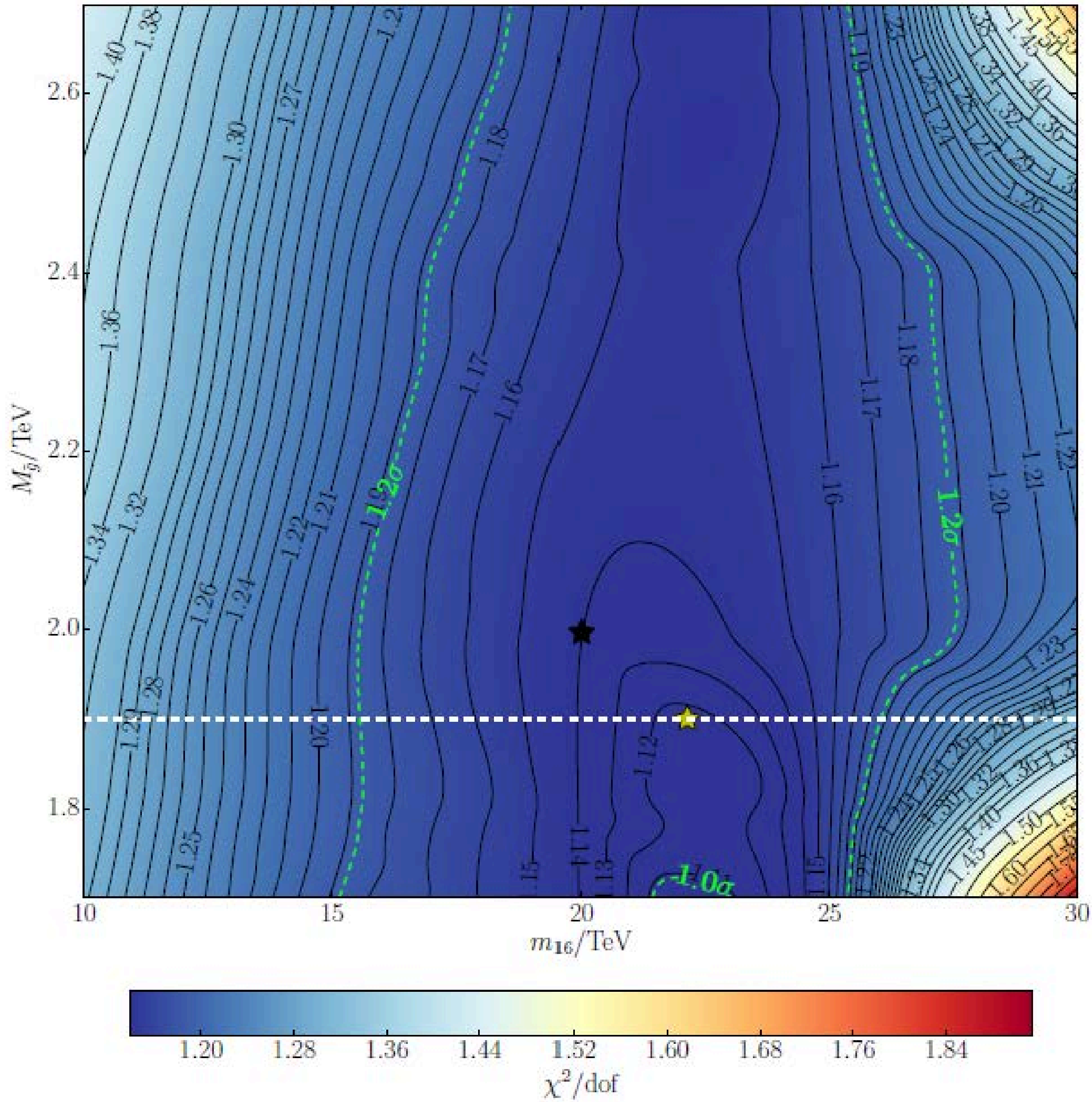
ATLAS - CONF - 2016 - 52

Our model

$$N^{Signal\ Leptons} = 0,\ N^{Jet} \geq 8,\ N_{b-jet} \geq 3,\ p_T^{jet} > 30\,\mathrm{GeV},\ E_T^{miss} > 400\,\mathrm{GeV},$$

$$\Delta\phi_{\min}^{4j} > 0.4\,rad,\ m_{T,\min}^{b-jets} > 80\,\mathrm{GeV},\ \mathrm{m}_{eff}^{incl} > 2000\ \mathrm{GeV},\ \mathrm{M}_J^{\Sigma} > 200\ \mathrm{GeV}$$




$M_{\tilde{g}}$/TeV
$m_{\mathbf{16}}$/TeV
χ^2/dof
1.20 1.28 1.36 1.44 1.52 1.60 1.68 1.76 1.84
1.2σ
1.0σ

Benchmark point with $m_{16} = 20.0\,\text{TeV}, M_{\tilde{g}} = 2.00\,\text{TeV}$

Sector	Input Param.	Best Fit
Gauge	$1/\alpha_G$	26.0
	$M_G/10^{16}$ GeV	2.25
	$\epsilon_3/\%$	-1.68
SUSY (GUT scale)	m_{16}/TeV	20.0
	$m_{1/2}$/GeV	660
	A_0/TeV	-40.6
	$(m_{H_d}/m_{16})^2$	1.98
	$(m_{H_u}/m_{16})^2$	1.61
Neutrino	$M_{R_1}/10^9$ GeV	4.62
	$M_{R_2}/10^{11}$ GeV	8.32
	$M_{R_3}/10^{13}$ GeV	4.71
SUSY (EW Scale)	$\tan\beta$	50.4
	μ/GeV	630

Sector	Input Param.	Best Fit
Yukawa Textures	λ	0.617
	$\lambda\epsilon$	0.0326
	$\lambda\tilde{\epsilon}$	0.0100
	$\lambda\epsilon'$	-0.00300
	$\lambda\xi$	0.00201
	α	0.138
	β	0.0277
	$\theta'/10^{-5}$	5.03
	$\tilde{\theta}/10^{-5}$	2.92
	$\phi_{\epsilon'}$/rad	-0.277
	ϕ_ξ/rad	3.41
	ϕ_α/rad	0.963
	ϕ_β/rad	-1.26

Benchmark point with $m_{16} = 20.0\,\text{TeV}$, $M_{\tilde{g}} = 2.00\,\text{TeV}$

Observable	Fit	Exp.	Pull	σ
M_Z/GeV	91.1876	91.1876	0.0000	0.4514
M_W/GeV	80.4734	80.3850	0.2238	0.3949
$1/\alpha_{em}$	137.3435	137.0360	0.4478	0.6867
$G_\mu/10^{-5}\,\text{GeV}^{-2}$	1.1761	1.1664	0.8264	0.0118
$\alpha_3(M_Z)$	0.1177	0.1181	0.4791	0.0008
M_t/GeV	174.0978	173.2100	0.4161	2.1338
$m_b(m_b)/\text{GeV}$	4.3264	4.1850	1.0388	0.1362
m_τ/Mev	1776.0100	1776.8600	0.0428	19.8568
$(M_b - M_c)/\text{GeV}$	3.3028	3.4500	0.4098	0.3592
$m_c(m_c)/\text{GeV}$	1.2685	1.2700	0.0442	0.0332
$m_s(2\,\text{GeV})/\text{Mev}$	97.7602	98.0000	0.0393	6.0987
$m_s/m_d(2\,\text{GeV})$	18.5692	19.5000	0.3843	2.0519
Q	21.5785	23.0000	0.6256	2.2725
$m_u(2\,\text{GeV})/\text{MeV}$	2.6880	2.3000	0.7758	0.5002
$m_d(2\,\text{GeV})/\text{MeV}$	5.2646	4.7500	1.1417	0.4508
M_μ/MeV	105.2131	105.6584	0.2053	2.1690
M_e/MeV	0.5108	0.5110	0.0278	0.0057
$\lvert V_{ud}\rvert$	0.9745	0.9742	0.0622	0.0049
$\lvert V_{us}\rvert$	0.2245	0.2248	0.2615	0.0013
$\lvert V_{ub}\rvert/10^{-3}$	3.9904	4.1300	0.2305	0.6056
$\lvert V_{cd}\rvert$	0.2244	0.2200	0.8509	0.0051
$\lvert V_{cs}\rvert$	0.9735	0.9950	1.2853	0.0167
$\lvert V_{cb}\rvert/10^{-3}$	44.1574	40.7500	1.4038	2.4272
$\lvert V_{td}\rvert/10^{-3}$	7.9898	8.2000	0.3378	0.6222
$\lvert V_{ts}\rvert/10^{-3}$	43.6115	40.0000	1.2691	2.8458
$\lvert V_{tb}\rvert$	0.9990	1.0090	0.3179	0.0314
$\sin 2\beta$	0.6922	0.6910	0.0672	0.0173
$\epsilon_K/10^{-3}$	2.0225	2.2330	1.0379	0.2028

$\Delta M_{B_s}/\Delta M_{B_d}$	43.7269	34.8479	1.0037	8.8463
$\Delta M_{B_d}/10^{-10}$ MeV	2.9005	3.3540	0.7802	0.5812
$m^2_{21}/10^{-5}$ eV^2	7.3484	7.3750	0.0658	0.4044
$m^2_{31}/10^{-3}$ eV^2	2.5096	2.5000	0.0726	0.1323
$\sin^2\theta_{12}$	0.2960	0.2975	0.0915	0.0166
$\sin^2\theta_{23}$	0.4419	0.4435	0.0599	0.0266
$\sin^2\theta_{13}$	0.0217	0.0215	0.1493	0.0010
M_h/GeV	122.7975	125.0900	0.4854	4.7225
$BR(b \to s\gamma)/10^{-6}$	299.9500	332.0000	0.2243	142.9017
$BR(B_s \to \mu^+\mu^-)/10^{-9}$	5.1836	2.9500	1.6808	1.3289
$BR(B_d \to \mu^+\mu^-)/10^{-9}$	0.1223	0.4000	1.8234	0.1523
$BR(B \to \tau\nu)/10^{-6}$	96.4950	106.0000	0.1822	52.1761
$BR(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\,\mathrm{GeV}^2}/10^{-7}$	0.5456	0.3400	0.3567	0.5765
$BR(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\,\mathrm{GeV}^2}/10^{-7}$	0.7904	0.5600	0.1531	1.5055
$q_0^2(A_{\mathrm{FB}}(B \to K^*\mu^+\mu^-))/\mathrm{GeV}^2$	3.8492	4.9000	0.7921	1.3265
$F_L(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\,\mathrm{GeV}^2}$	0.7522	0.6500	0.2917	0.3503
$F_L(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\,\mathrm{GeV}^2}$	0.3514	0.3300	0.0725	0.2952
$P_2(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\,\mathrm{GeV}^2}$	0.0679	0.3300	1.4536	0.1803
$P_2(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\,\mathrm{GeV}^2}$	-0.4333	-0.5000	0.3381	0.1973
$P'_4(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\,\mathrm{GeV}^2}$	0.5788	0.5800	0.0029	0.4007
$P'_4(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\,\mathrm{GeV}^2}$	1.2177	-0.1800	1.7055	0.8195
$P'_5(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\,\mathrm{GeV}^2}$	-0.3221	0.2100	2.0721	0.2568
$P'_5(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\,\mathrm{GeV}^2}$	-0.7119	-0.7900	0.1545	0.5053
Total χ^2			30.9061	

m_{16}/TeV	20	25	20	25
$M_{\tilde{g}}$/TeV	2.00	2.00	2.60	2.60
χ^2/dof	1.14	1.16	1.18	1.17
$m_{\tilde{t}_1}$/TeV	3.68	4.70	3.70	4.65
$m_{\tilde{t}_2}$/TeV	4.38	5.52	4.43	5.49
$m_{\tilde{b}_1}$/TeV	4.17	5.32	4.17	5.23
$m_{\tilde{b}_2}$/TeV	4.32	5.47	4.36	5.43
$m_{\tilde{\tau}_1}$/TeV	7.47	9.30	7.52	9.27
$m_{\tilde{\tau}_2}$/TeV	12.2	15.2	12.2	15.2
$m_{\tilde{\chi}_1^0}$/GeV	352	352	474	474
$m_{\tilde{\chi}_2^0}$/GeV	586	636	650	665
$m_{\tilde{\chi}_1^+}$/GeV	585	636	646	661
$m_{\tilde{\chi}_2^+}$/GeV	710	751	911	914
$(M_A \approx M_{H^0} \approx M_{H^\pm})$/TeV	5.18	6.39	5.39	6.67
$\mathrm{edm}_e/10^{-32}$ e cm	-3.46	-1.77	-4.47	-2.28
$\mathrm{BR}(\mu \to e\gamma)/10^{-17}$	2.08	0.922	1.84	0.869
$\sin\delta$	0.759	0.935	0.644	0.993

Conclusions

Pati-Salam x $\mathbb{Z}_4^R$ yields Sub-Critical Hybrid Inflation consistent with Bicep2-Keck-Planck data with inflation at "GUT" scale and MSSM at low energy

- SO(10)/PS Yukawa unification
- Inverted scalar mass hierarchy
- Light Higgs - SM-like
- Three family model fits low energy data !!
- $2.7 \geq m_{\tilde{g}} \geq 1.9\ \text{TeV}$
- Third family scalars significantly lighter than first two $\Rightarrow$

  $\tilde{g} \to t\bar{b}\,\chi^-, \bar{t}b\,\chi^+, t\bar{t}\,\chi_i^0, b\bar{b}\,\chi_i^0$
- Not simplified model !