E_6 inspired $U(1)'$ Extended MSSM: From Dark Matter to LHC.

Jack Y. Araz, Gennaro Corcella, Mariana Frank, Benjamin Fuks

based on PhysRevD96.015017 & JHEP02(2018)092

Concordia University — INFN — UPMC — LPTHE

INFN Frascati, Italy
March 6th, 2018

Outline

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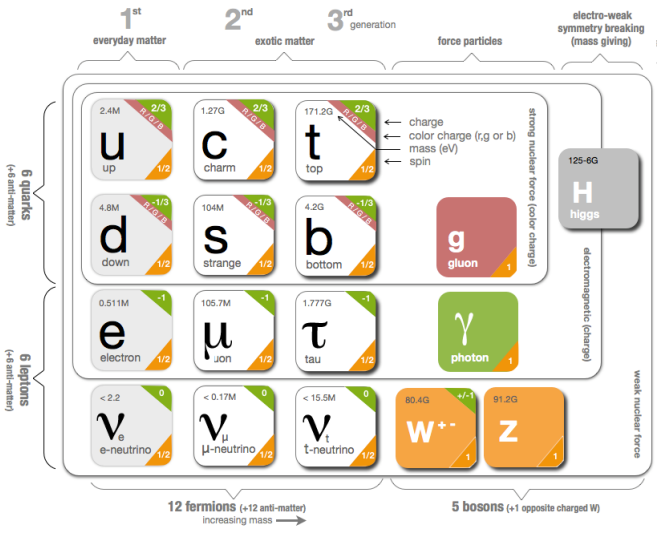
The Standard Model of Particle Physics.



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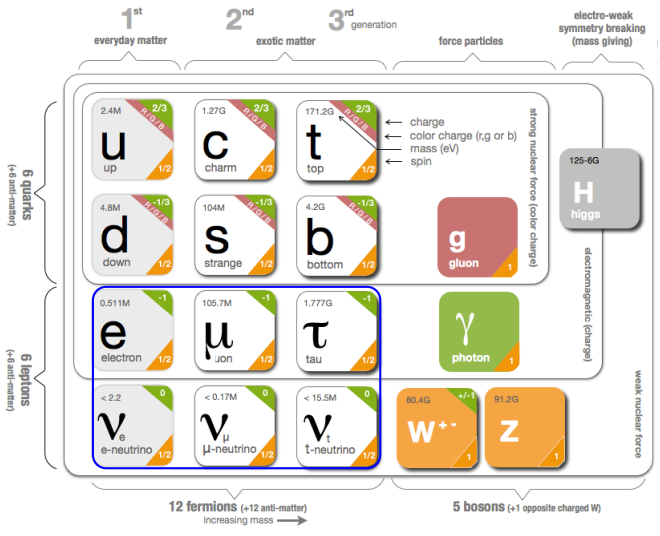

$$\mathcal{G}_{321} \equiv SU(2)_L \otimes U(1)_Y$$

	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$	I_3	Q_I [e]
$L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, -1)$	$\frac{1}{2}$	0
		$-\frac{1}{2}$	-1
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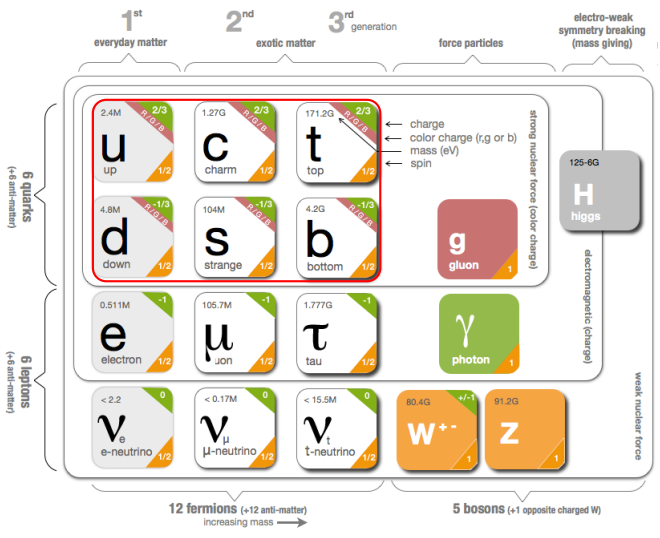

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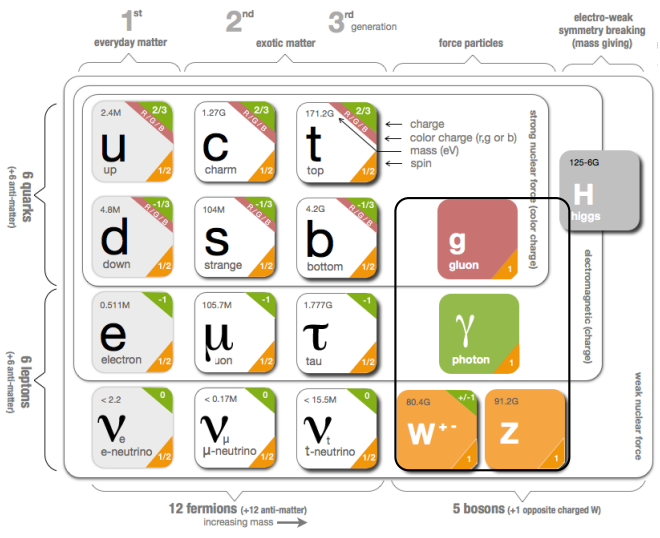

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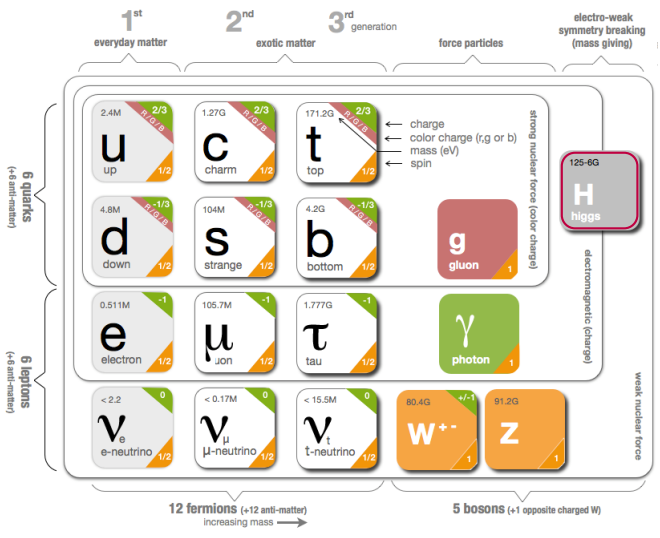

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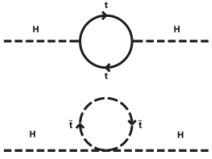
d_R	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$	0	$-\frac{1}{3}$
$\Phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, 1)$	$-\frac{1}{2}$	0

$$\mathcal{L} \equiv \frac{g_f}{\sqrt{2}} \bar{\Psi}_L v \Psi_R + \text{h.c.}$$

The SM is not the choosen one!

Gauge Hierarchy Problem!



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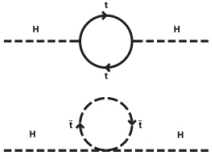

Neutrino Mass & Oscillations!

via nobelprize.org

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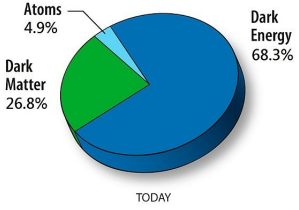
Dark Matter?



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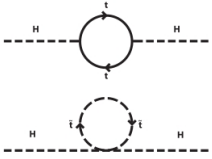

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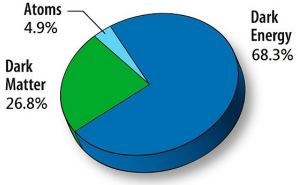

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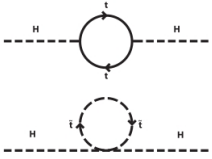

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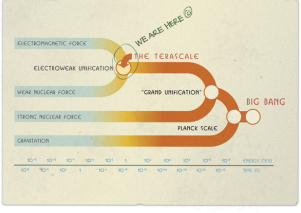

Grand Unification!

- Supersymmetry has reasonable solutions to all of these problems.

Minimal Supersymmetric Extention of the Standard Model.

	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$	I_3	Q_f [e]
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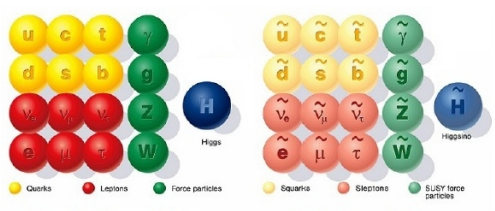

Standard particles **SUSY particles**

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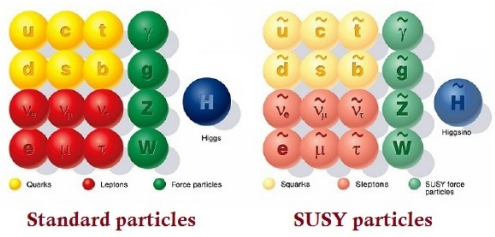

$$W = \mathbf{Y}_u \hat{u} \hat{Q} \hat{H}_u - \mathbf{Y}_d \hat{d} \hat{Q} \hat{H}_d - \mathbf{Y}_e \hat{e} \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$

Solutions to the SM problems:

- Dark Matter candidate!
- Cancellation terms to Higgs mass loop corrections.
- Force Unification.

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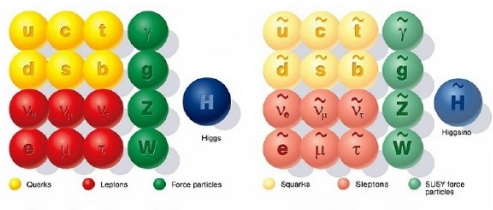

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What's wrong?:

- Neutrino mass?
- μ problem.
- Proton decay!

Outline

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What are the options?

> Needs to be rank 4 or more.
> Needs to satisfy the SM quantum numbers.
> Needs to decompose to the SM group $\mathcal{G}_{321}$.

- $SU(n)$ $(n \geq 5)$, $SO(4k+2)$ $(k \geq 2)$ or E_6

- Slansky, R. (1981). Group theory for unified model building. Physics Reports, 79(1).
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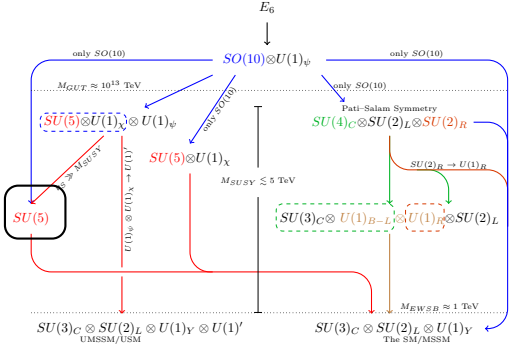

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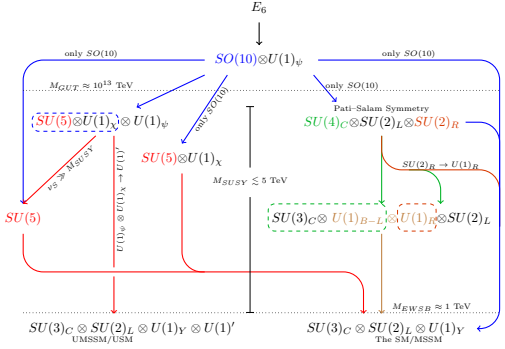

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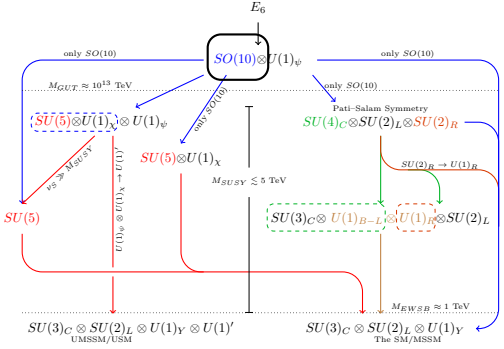

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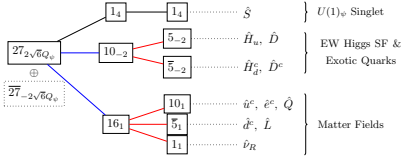

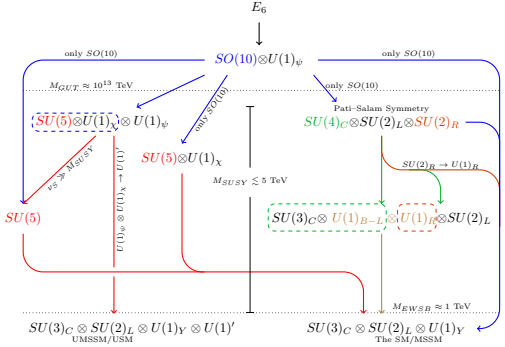

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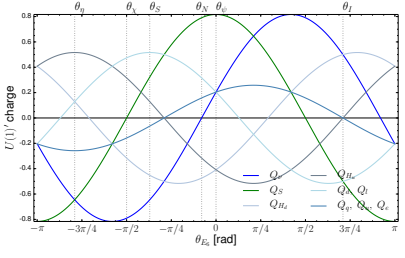
GUT-inspired $U(1)'$ extended MSSM
symmetry breaking scheme

$$
\begin{aligned}
E_6 &\longrightarrow SO(10) \otimes U(1)'_\psi \\
&\longrightarrow \left(SU(5) \otimes U(1)'_\chi\right) \otimes U(1)'_\psi
\end{aligned}
$$

$$Q'(\theta_{E_6}) = Q'_\psi \cos\theta_{E_6} - Q'_\chi \sin\theta_{E_6}$$

MSSM $\otimes$ $U(1)'$ Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	$U(1) \otimes \mathrm{SU}(2) \otimes \mathrm{SU}(3) \otimes U(1)'$
$\hat{q}$	$\tilde{q}$	q	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, Q_q)$
$\hat{l}$	$\tilde{l}$	l	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, Q_l)$
$\hat{H}_d$	H_d	$\tilde{H}_d$	$(-\frac{1}{2}, \mathbf{2}, 1, Q_{H_d})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, Q_{H_u})$
$\hat{d}$	$\tilde{d}^*_R$	d^*_R	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, Q_d)$
$\hat{u}$	$\tilde{u}^*_R$	u^*_R	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, Q_u)$
$\hat{e}$	$\tilde{e}^*_R$	e^*_R	$(1, \mathbf{1}, \mathbf{1}, Q_e)$
$\hat{\nu}_R$	$\tilde{\nu}^*_R$	ν^*_R	$(0, \mathbf{1}, \mathbf{1}, Q_\nu)$
$\hat{s}$	S	$\tilde{S}$	$(0, \mathbf{1}, \mathbf{1}, Q_s)$



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$$Q'(\theta_{E_6}) = Q'_\psi \cos\theta_{E_6} - Q'_\chi \sin\theta_{E_6}$$

$$W = \mathbf{Y}_u \hat{u}\hat{q}\hat{H}_u - \mathbf{Y}_d \hat{d}\hat{q}\hat{H}_d - \mathbf{Y}_e \hat{e}\hat{l}\hat{H}_d + \mu \hat{H}_u \hat{H}_d$$

$$W_{\text{UMSSM}} = W_{\mu\to\mu_{\text{eff}}} + \mathbf{Y}_\nu \hat{l}\hat{H}_u\hat{\nu}_R$$

$$\mu_{\text{eff}} = \frac{\lambda v_S}{\sqrt{2}} \quad , \quad \mu\hat{H}_u\hat{H}_d \to \lambda \hat{H}_u\hat{H}_d\hat{s}$$

$$M_{Z'}^2 = 2g'^2(Q_{H_u}^2\langle H_u\rangle^2 + Q_{H_d}^2\langle H_d\rangle^2 + Q_S^2\langle S\rangle^2)$$

- μ-problem
- Additional DM candidate
- Muon anomalous magnetic moment

MSSM $\otimes$ $U(1)'$ Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	$U(1)\otimes \mathrm{SU}(2)\otimes \mathrm{SU}(3)\otimes U(1)'$
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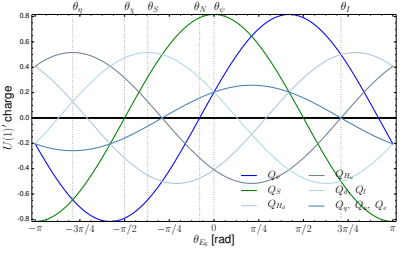
$\hat{H}_d$	H_d	$\tilde{H}_d$	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, Q_{H_d})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, Q_{H_u})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, Q_d)$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, Q_u)$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	$(1, \mathbf{1}, \mathbf{1}, Q_e)$
$\hat{\nu}_R$	$\tilde{\nu}_R^*$	ν_R^*	$(0, \mathbf{1}, \mathbf{1}, Q_\nu)$
$\hat{s}$	S	$\tilde{S}$	$(0, \mathbf{1}, \mathbf{1}, Q_s)$



Parameter Space & Constraints.

Universality Conditions[1]

GUT Scale

- $M_{1,2,3,4} = M_{1/2}$
- $m^2_{\tilde{q},\tilde{u},\tilde{d}} = diag[M_0^2]$
- $g_1 = g_2 = g'\sqrt{3/5} \approx g_3$

SUSY Scale

- Setting v_S, λ & A_λ
- $m^2_{\tilde{L},\tilde{e},\tilde{\nu}}$; split family
- $M_{SUSY} \leq 5$ TeV

[1] Scalar soft-breaking terms, $m^2_{H_{u,d}}$ & m^2_S, are derived from tadpole equations.

Parameter Space & Constraints.

Universality Conditions[1]

GUT Scale

- $M_{1,2,3,4} = M_{1/2}$
- $m^2_{\tilde{q},\tilde{u},\tilde{d}} = diag[M_0^2]$
- $g_1 = g_2 = g'\sqrt{3/5} \approx g_3$

SUSY Scale

- Setting v_S, λ & A_λ
- $m^2_{\tilde{L},\tilde{e},\tilde{\nu}}$; split family
- $M_{SUSY} \leq 5$ TeV

Scanned range of the free parameters in the model.

Parameter	Scanned range	Parameter	Scanned range
M_0	$[0,3]$ TeV	μ	$[-2,2]$ TeV
$M_{1/2}$	$[0,5]$ TeV	A_λ	$[-7,7]$ TeV
A_0	$[-3,3]$ TeV	$M_{Z'}$	$[1.98,5.2]$ TeV
$\tan\beta$	$[0,60]$	$m^2_{\tilde{\nu}}$	$[-6.8,9]$ TeV^2
θ_{E_6}	$[-\pi,\pi]$	$m^2_{\tilde{e},\tilde{l}}$	$[0,1]$ TeV^2

$$Y_\nu = diag[10^{-11}]$$

Experimental constraints imposed within our scanning procedure in order to determine the parameter space regions of interest.

Observable	Constraints	Observable	Constraints
M_h	125.09 ± 3 GeV	$\chi^2(\hat{\mu})$	≤ 70
$\lvert\alpha_{ZZ'}\rvert$	$O(10^{-3})$	$M_{\tilde{g}}$	> 1.75 TeV
$M_{\chi^0_2}$	> 62.4 GeV	$M_{\chi^0_3}$	> 99.9 GeV
$M_{\chi^0_4}$	> 116 GeV	$M_{\chi^\pm_1}$	> 103.5 GeV
$M_{\tilde{\tau}}$	> 81 GeV	$M_{\tilde{e}}$	> 107 GeV
$M_{\tilde{\mu}}$	> 94 GeV	$M_{\tilde{t}}$	> 900 GeV
$\mathrm{BR}(B_s^0 \to \mu^+\mu^-)$	$[1.1\times10^{-9}, 6.4\times10^{-9}]$	$\frac{\mathrm{BR}(B\to\tau\nu_\tau)}{\mathrm{BR}_{SM}(B\to\tau\nu_\tau)}$	$[0.15, 2.41]$
$\mathrm{BR}(B^0 \to X_s\gamma)$	$[2.99, 3.87]\times10^{-4}$		

[1] Scalar soft-breaking terms, $m^2_{H_{u,d}}$ & m^2_S, are derived from tadpole equations.

Outline.

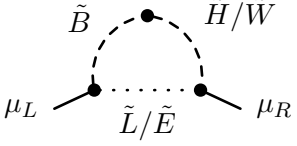
INFN

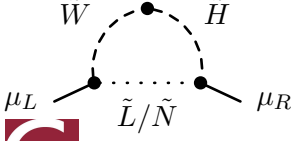
Muon Anomalous Magnetic Moment

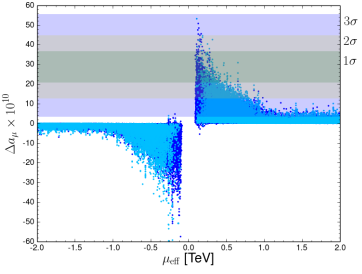
$$a_\mu = \frac{g_\mu - 2}{2}$$

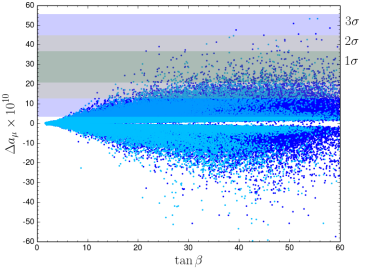
$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm Had}$$

$$(3.4 < \Delta a_\mu < 55.6) \times 10^{-10} : 3\sigma$$









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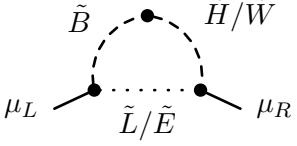

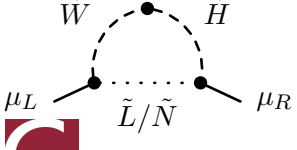

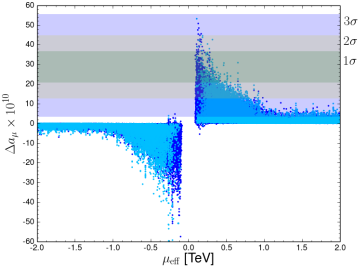

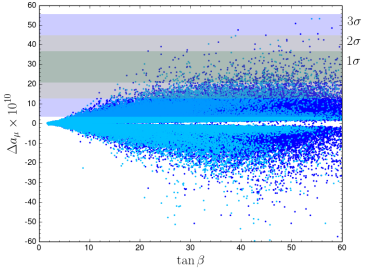

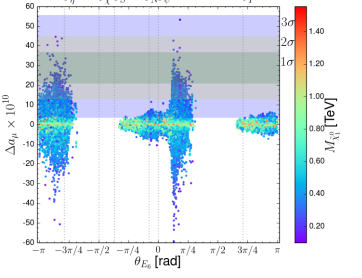

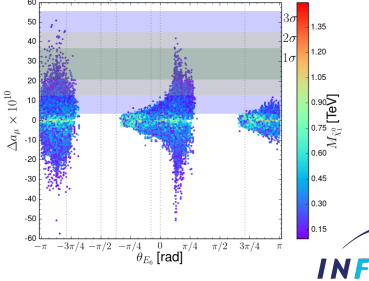

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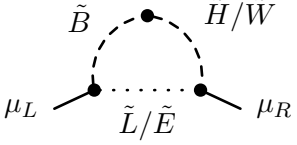
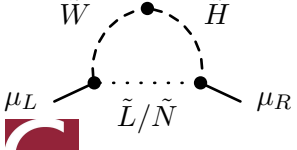
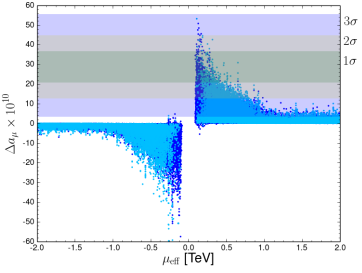
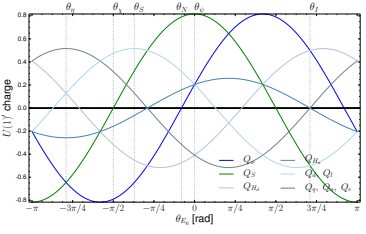
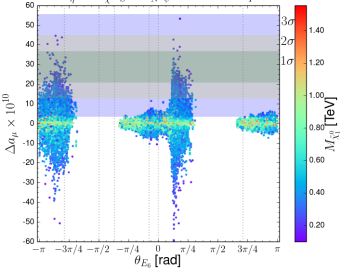
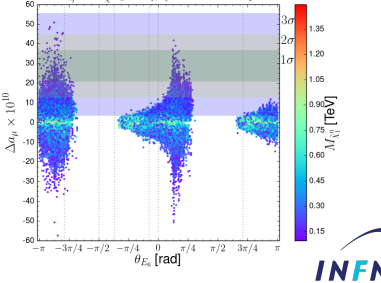






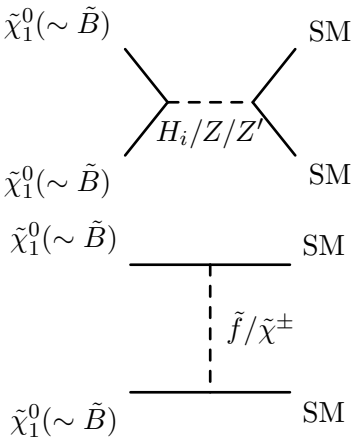


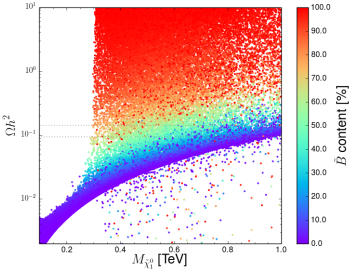


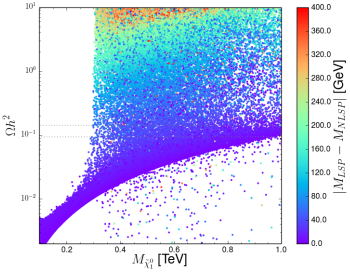


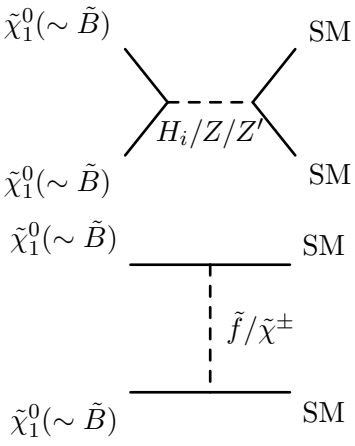
Outline

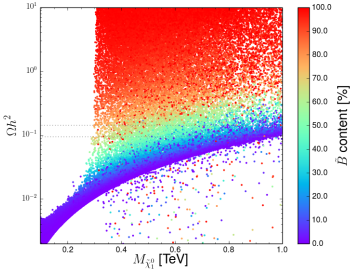
INFN

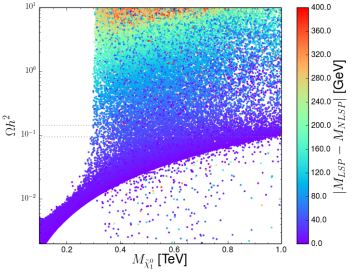

$\tilde{\chi}_1^0(\sim \tilde{B})$
SM
$H_i/Z/Z'$
$\tilde{\chi}_1^0(\sim \tilde{B})$
SM
$\tilde{\chi}_1^0(\sim \tilde{B})$
SM
$\tilde{f}/\tilde{\chi}^{\pm}$
$\tilde{\chi}_1^0(\sim \tilde{B})$
SM

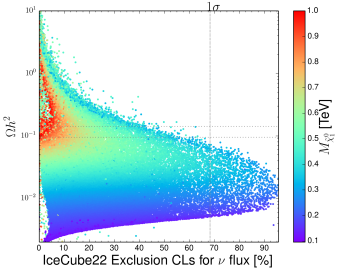

Ωh^2
$M_{\tilde{\chi}_1^0}$ [TeV]
$\tilde{B}$ content [%]

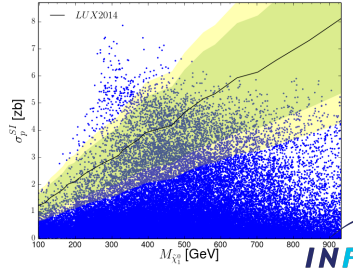

Ωh^2
$M_{\tilde{\chi}_1^0}$ [TeV]
$|M_{LSP} - M_{NLSP}|$ [GeV]


$\tilde{\chi}_1^0(\sim \tilde{B})$
SM
$H_i/Z/Z'$
$\tilde{\chi}_1^0(\sim \tilde{B})$
SM
$\tilde{\chi}_1^0(\sim \tilde{B})$
SM
$\tilde{f}/\tilde{\chi}^{\pm}$
$\tilde{\chi}_1^0(\sim \tilde{B})$
SM


Ωh^2
$M_{\tilde{\chi}_1^0}$ [TeV]
$\tilde{B}$ content [%]


Ωh^2
$M_{\tilde{\chi}_1^0}$ [TeV]
$|M_{LSP} - M_{NLSP}|$ [GeV]

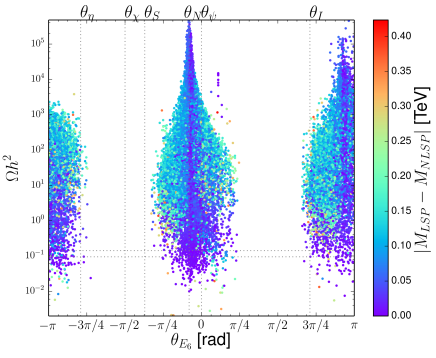

1σ
Ωh^2
$M_{\tilde{\chi}_1^0}$ [TeV]
IceCube22 Exclusion CLs for ν flux [%]


LUX2014
σ_{SI} [zb]
$M_{\tilde{\chi}_1^0}$ [GeV]

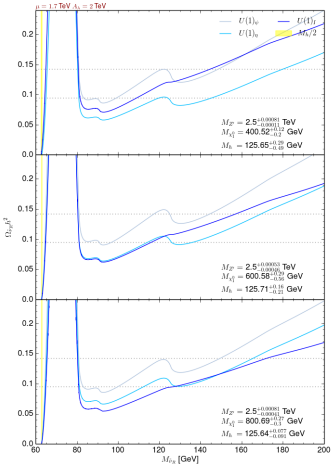
Model based, mass scan for certain bench marks

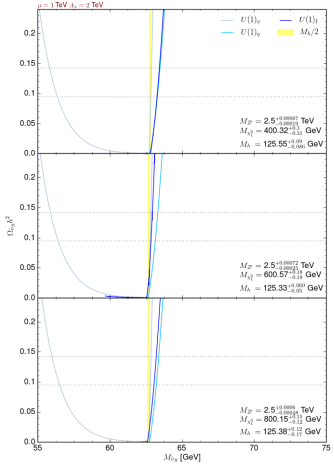
- $\mu_{\text{eff}} = 1 - 1.7$ TeV
- $A_\lambda = 1 - 2$ TeV
- $M_{Z'} = 2 - 2.5$ TeV
- $M_{\tilde{\chi}_1^0} = 400 - 600 - 800$ GeV
- Fix slepton masses depending on θ_{E_6}

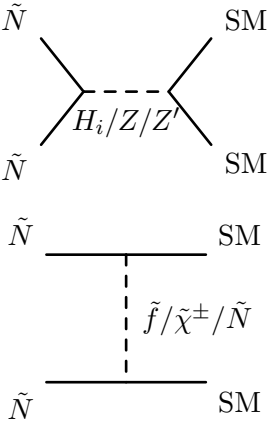
$U(1)'_N$ excluded due to unpredictible relic density.



RH Scalar Neutrino Dark Matter







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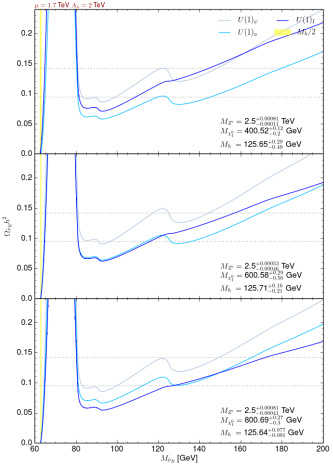

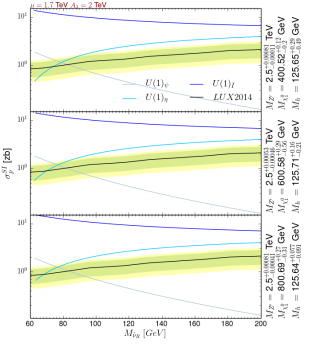

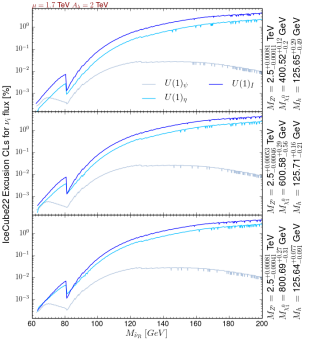

Outline.

INFN

Heavy Z Bosons & Where to Find Them.

Model	θ_{E_6} [rad]	Lower limits on $M_{Z'}$ [TeV]				
		ee		$\mu\mu$		$\ell\ell$
		Obs	Exp	Obs	Exp	Obs
Z'_{SSM}	-	4.3	4.3	4.0	3.9	4.5
Z'_{χ}	0.50 π	3.9	3.9	3.6	3.6	4.1
Z'_{S}	0.63 π	3.9	3.8	3.6	3.5	4.0
Z'_{I}	0.71 π	3.8	3.8	3.5	3.4	4.0
Z'_{η}	0.21 π	3.7	3.7	3.4	3.3	3.9
Z'_{N}	-0.08 π	3.6	3.6	3.4	3.3	3.8
Z'_{ψ}	0 π	3.6	3.6	3.3	3.2	3.8

Retrieved from JHEP 10 (2017) 182

$$\mathcal{L}_{\mathrm{int}} = -\bar{\psi}_i \gamma^\mu (g_1 Y_i \hat{B}_\mu + g' Q'_i \hat{Z}'_\mu) \psi_i$$

$$\mathcal{L}_{\mathrm{kin}} = -\frac{1}{4} \hat{B}^{\mu\nu} \hat{B}_{\mu\nu} - \frac{1}{4} \hat{Z}'^{\mu\nu} \hat{Z}'_{\mu\nu}$$

Heavy Z Bosons & Where to Find Them.

$$g'(M_{\mathrm{GUT}})/g_1 = \sqrt{5/3}$$

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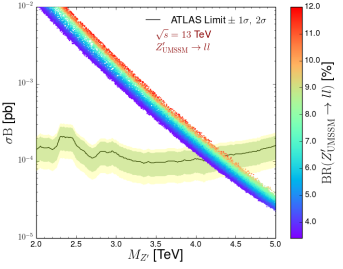
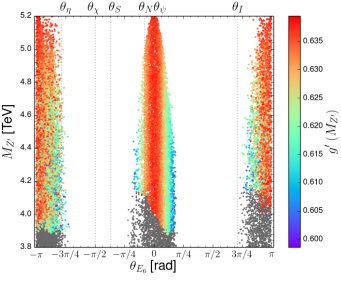
Retrieved from JHEP 10 (2017) 182





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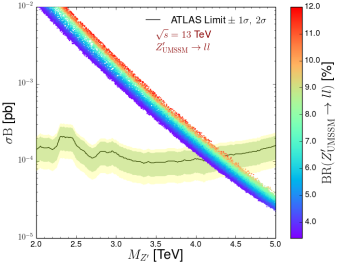
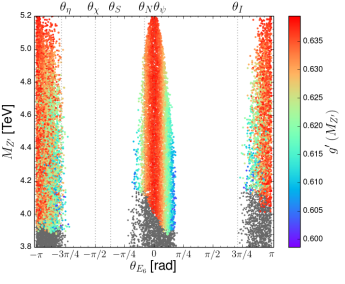
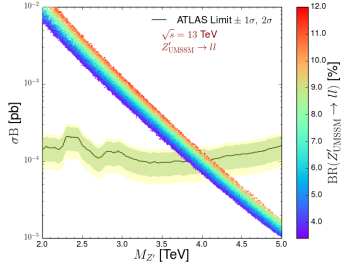
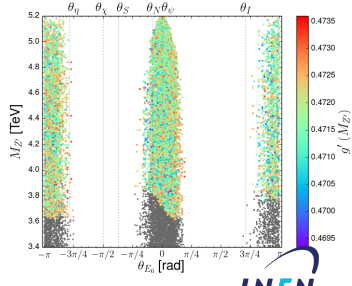




$g'(M_{Z'})/g_1 = \sqrt{5/3}$





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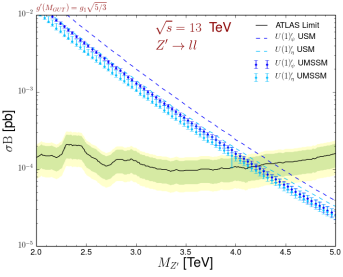
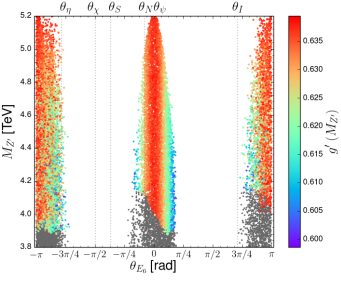
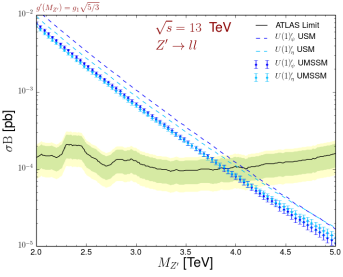
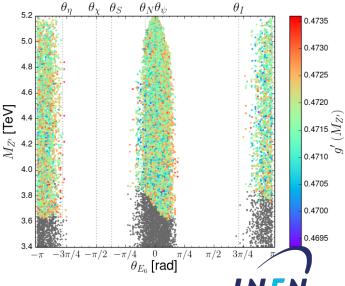
$g'(M_{\rm GUT})/g_1 = \sqrt{5/3}$



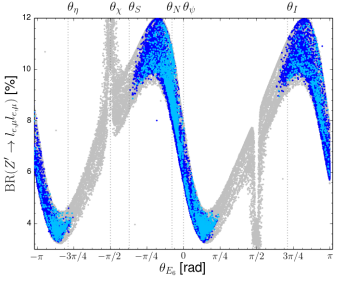


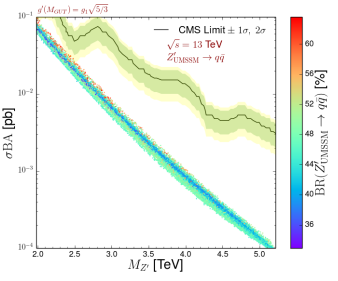
$g'(M_{Z'})/g_1 = \sqrt{5/3}$

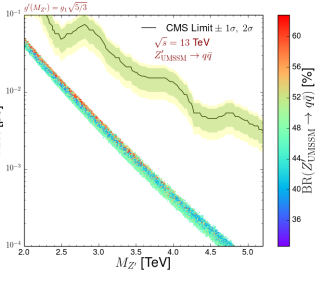




Heavy Z Bosons & Where to Find Them.







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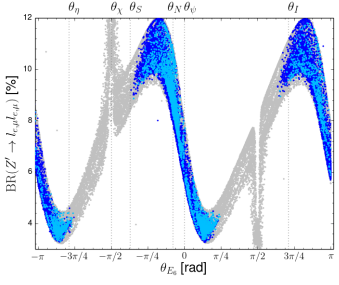

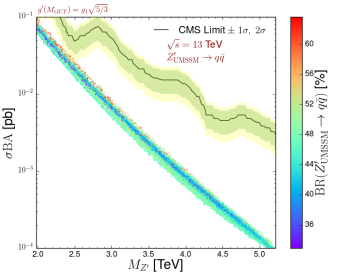

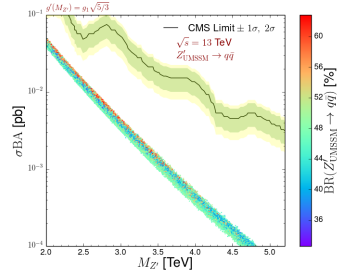

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$$\begin{pmatrix}\hat{B}_\mu \\ \hat{Z}'_\mu\end{pmatrix} = \begin{pmatrix}1 & -\tan\chi \\ 0 & \sec\chi\end{pmatrix}\begin{pmatrix}B_\mu \\ Z'_\mu\end{pmatrix}$$

$$\mathcal{L}_{\mathrm{int}} = -\bar{\psi}_i\gamma^\mu(g_1 Y_i B_\mu + g'\bar{Q}_i Z'_\mu)\psi$$

$$\bar{Q}_i = Q'_i\sec\chi - \frac{g_1}{g'}Y_i\tan\chi$$

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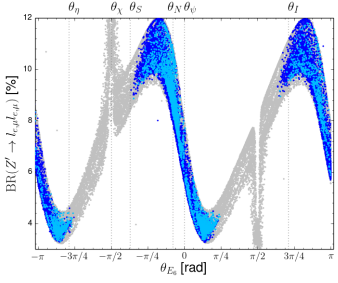
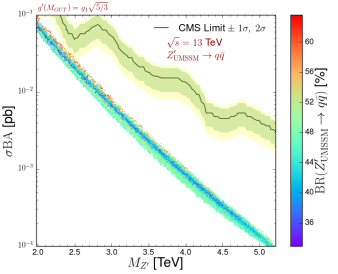
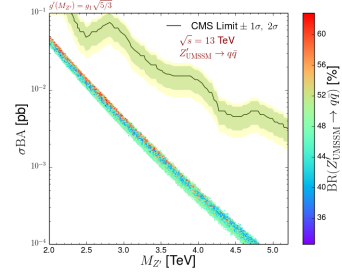
Heavy Z Bosons & Where to Find Them.







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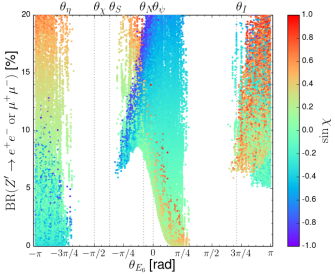

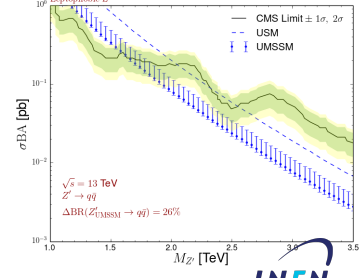

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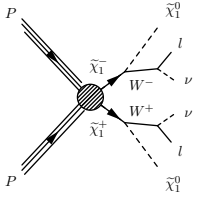
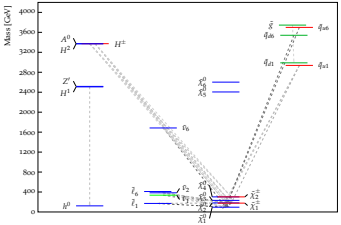
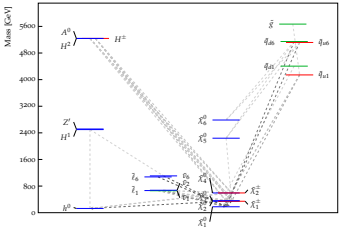




BM I



BM II

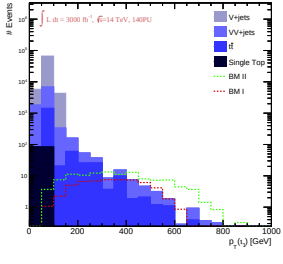
- Background: Dibosons+Jets, Bosons+Jets, Top pair production, Single top production.
- Simulated with FastJet+Delphes using anti-k$_T$ alrorithm with 60% tagging efficiency.

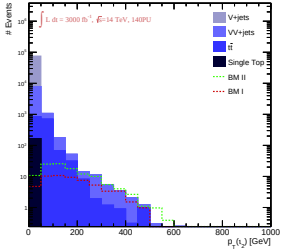
Parameter	BM I
θ_{E_6}	-0.8π
$\tan\beta$	9.11
$\sin\chi$	-0.35
μ [GeV]	218.87
g'	0.47
$\Gamma_{Z'}$	40.29
BR$(Z' \to jj)$ [%]	54.9
BR$(Z' \to \nu\nu)$ [%]	23.4
BR$(Z' \to \chi_1^\pm \chi_1^\mp)$ [%]	1.7
$\sigma_{NLO}^{\sqrt{s}=14\text{TeV}}(pp \to Z')$ [pb]	0.12

Parameter	BM II
θ_{E_6}	0.2π
$\tan\beta$	16.09
$\sin\chi$	0.33
μ [GeV]	345.35
g'	0.47
$\Gamma_{Z'}$	38.48
BR$(Z' \to jj)$ [%]	53.7
BR$(Z' \to \nu\nu)$ [%]	22.8
BR$(Z' \to \chi_1^\pm \chi_1^\mp)$ [%]	6.3
$\sigma_{NLO}^{\sqrt{s}=14\text{TeV}}(pp \to Z')$ [pb]	0.12

Heavy Z Bosons & Where to Find Them.

Step	Requirements	Background	**BM I**	**BM II**
0	Initial	1.7×10^{11}	8.8×10^{3}	1.9×10^{4}
1	$N^l = 2$	6.1×10^{8}	401	860
2	Electron veto	2.9×10^{8}	100	230
3	$\lvert\eta^l\rvert < 1.5$	1.7×10^{8}	76	170
4	$I^{\mu}_{\text{rel}} < 0.15$	7.9×10^{5}	63	130
5	$\Delta R(l_1, l_2) > 2.5$	7.9×10^{5}	62	130
6	Jet veto	7.7×10^{4}	57	120





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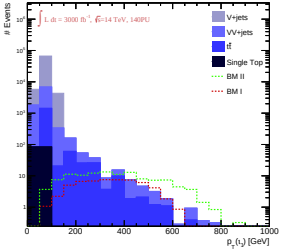
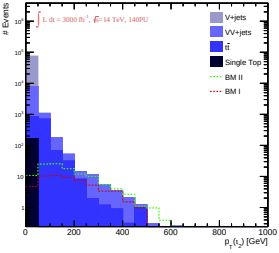
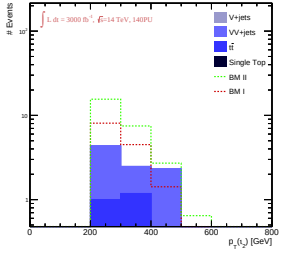
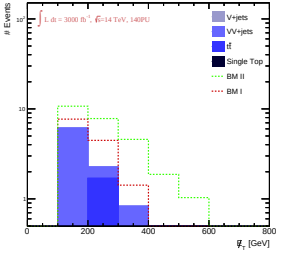
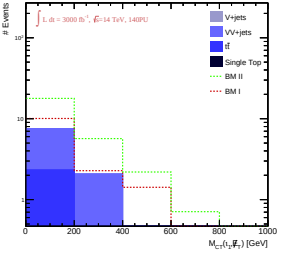
6	Jet veto	7.7×10^{4}	57	120
7	$p_T(l_1) > 300$ GeV	44	36	71
8	$p_T(l_2) > 200$ GeV	20	19	32
9	$\not{E}_T > 100$ GeV	10	14	27
	s		3.77σ	7.14σ
	Z_A		3.03σ	5.05σ











Outline.

INFN

Conclusion.

Pro's

- Up to 1σ accuracy with $(g-2)_\mu$ experimental results
- Two successive dark matter candidate
- Up to 7σ observability in HL-LHC

Con's

- No experimental evidence for RH neutrinos
- Naturalness problem
- Heavy higgs sector

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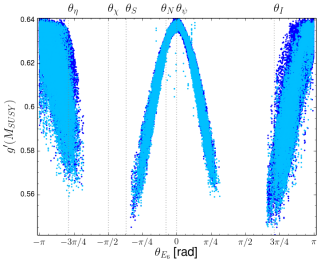
Gratitude, for your kind attention...

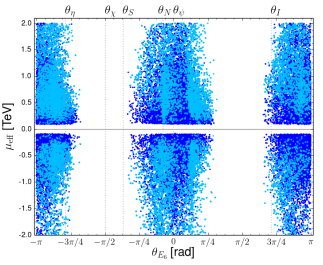
Special thanks to both LPTHE & INFN for the hospitality.

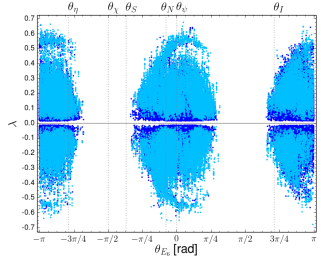
BACKUP

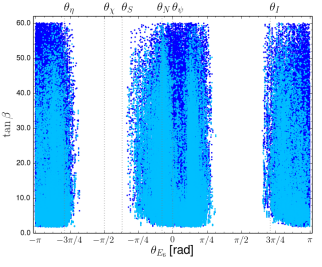
INFN

Parameter Space









Significance Calculation.

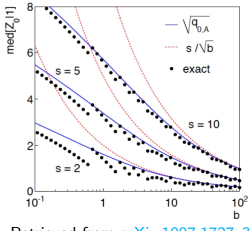
> Standard Significance

$$s = \frac{S}{\sqrt{b + \sigma_b^2}}$$

- S: Expected number of events from signal
- b: Expected number of background events
- σ: Variance, uncertainty of background

> Asimov Significance

$$Z_A = \left[2 \left((s+b) ln \left[\frac{(s+b)(b+\sigma_b^2)}{b^2 + (s+b)\sigma_b^2} \right] \right. \right.$$
$$\left. \left. \cdots - \frac{b^2}{\sigma_b^2} ln \left[1 + \frac{\sigma_b^2 s}{b(b+\sigma_b^2)} \right] \right) \right]^{\frac{1}{2}}$$



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