

# $U(1)_R$ GAUGE SYMMETRY IN THE LHC ERA

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Based on 1707.07858

Gauge bosons									
SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	19.3	$Z'$ mass		<b>4.05 TeV</b>		ATLAS-CONF-2016-045
SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	19.5	$Z'$ mass		<b>2.02 TeV</b>		1502.07177
Lepto-phobic $Z' \rightarrow bb$	-	$2 b$	-	3.2	$Z'$ mass		<b>1.5 TeV</b>		1603.08791
SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	13.3	$W'$ mass		<b>4.74 TeV</b>		ATLAS-CONF-2016-061
HVT $W' \rightarrow WZ \rightarrow qqqq$ model A	$0 e, \mu$	1 J	Yes	13.2	$W'$ mass		<b>2.4 TeV</b>		ATLAS-CONF-2016-062
HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	-	2 J	-	15.5	$W'$ mass		<b>3.0 TeV</b>		ATLAS-CONF-2016-055
HVT $V' \rightarrow WH/ZH$ model B	multi-channel			3.2	$V'$ mass		<b>2.31 TeV</b>		1607.05821
LRSM $W'_R \rightarrow tb$	$1 e, \mu$	$2 b, 0-1 j$	Yes	20.3	$W'$ mass		<b>1.92 TeV</b>		1410.4103
LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	-	20.3	$W'$ mass		<b>1.76 TeV</b>		1408.0886

# Outline

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- Basic set up of  $U(1)_R$
- Vacuum stability
- $Z-Z'$  Mixing
- LEP constraints
- Neutrino masses
- Dark matter
- Signatures at the LHC
- Conclusion

# Minimal SM is not enough!

	mass →	$\approx 2.3 \text{ MeV}/c^2$	charge →	$2/3$	spin →	$1/2$	
QUARKS	mass →	$\approx 2.3 \text{ MeV}/c^2$	charge →	$2/3$	spin →	$1/2$	u
	charge →	$2/3$	spin →	$1/2$	up		c
	spin →	$1/2$					t
LEPTONS	mass →	$\approx 1.275 \text{ GeV}/c^2$	charge →	$2/3$	spin →	$1/2$	g
	charge →	$2/3$	spin →	$1/2$			H
	spin →	$1/2$					Higgs boson
mass →	$\approx 4.8 \text{ MeV}/c^2$	charge →	$-1/3$	spin →	$1/2$	d	...
charge →	$-1/3$	spin →	$1/2$			s	Baryon asymmetry
spin →	$1/2$					b	...
mass →	$\approx 95 \text{ MeV}/c^2$	charge →	$-1/3$	spin →	$1/2$	down	...
charge →	$-1/3$	spin →	$1/2$			strange	...
spin →	$1/2$					bottom	...
mass →	$0.511 \text{ MeV}/c^2$	charge →	-1	spin →	$1/2$	e	...
charge →	-1	spin →	$1/2$			$\mu$	...
spin →	$1/2$					$\tau$	...
mass →	$105.7 \text{ MeV}/c^2$	charge →	-1	spin →	$1/2$	electron	...
charge →	-1	spin →	$1/2$			muon	...
spin →	$1/2$					tau	...
mass →	$1.777 \text{ GeV}/c^2$	charge →	-1	spin →	$1/2$	$\nu_e$	...
charge →	-1	spin →	$1/2$			$\nu_\mu$	...
spin →	$1/2$					$\nu_\tau$	...
mass →	$91.2 \text{ GeV}/c^2$	charge →	0	spin →	$1/2$	electron neutrino	...
charge →	0	spin →	$1/2$			muon neutrino	...
spin →	$1/2$					tau neutrino	...
mass →	$<2.2 \text{ eV}/c^2$	charge →	0	spin →	$1/2$	$Z$	...
charge →	0	spin →	$1/2$			Z boson	...
spin →	$1/2$					W	...
mass →	$<0.17 \text{ MeV}/c^2$	charge →	0	spin →	$1/2$	$\nu_e$	...
charge →	0	spin →	$1/2$			$\nu_\mu$	...
spin →	$1/2$					$\nu_\tau$	...
mass →	$<15.5 \text{ MeV}/c^2$	charge →	0	spin →	$1/2$	W boson	...
charge →	0	spin →	$1/2$				...
spin →	$1/2$						...

## Problems:

- ◆ Neutrino mass
- ◆ Dark matter
- ◆ Baryon asymmetry
- ◆ ...



## New physics beyond SM

New symmetries

New particles

New interactions



# U(1) extensions of the SM

U(1) gauge symmetries	New ingredients
$L_i - L_j$	No
$B - L$	Right-handed neutrinos
$R$	Right-handed neutrinos
$L$	Vector-like fermions
$B$	Vector-like fermions
$B + L$	Vector-like fermions
$PQ\dots$	

$U(1)_{B-L}$  share many similarities with  $U(1)_R$

- \* The same particle contents
- \* Both may come from left-right or SO(10) GUT

# Basic setup of the $U(1)_R$

## Particles and quantum numbers

Fields	$I_L$	$E_R$	$N_R$	$Q_L$	$U_R$	$D_R$	$H$	$S$
$U(1)_R$	0	-1	+1	0	+1	-1	1	-2
$Z_2$	+	+	-	+	+	+	+	+

Anomalies cancellations

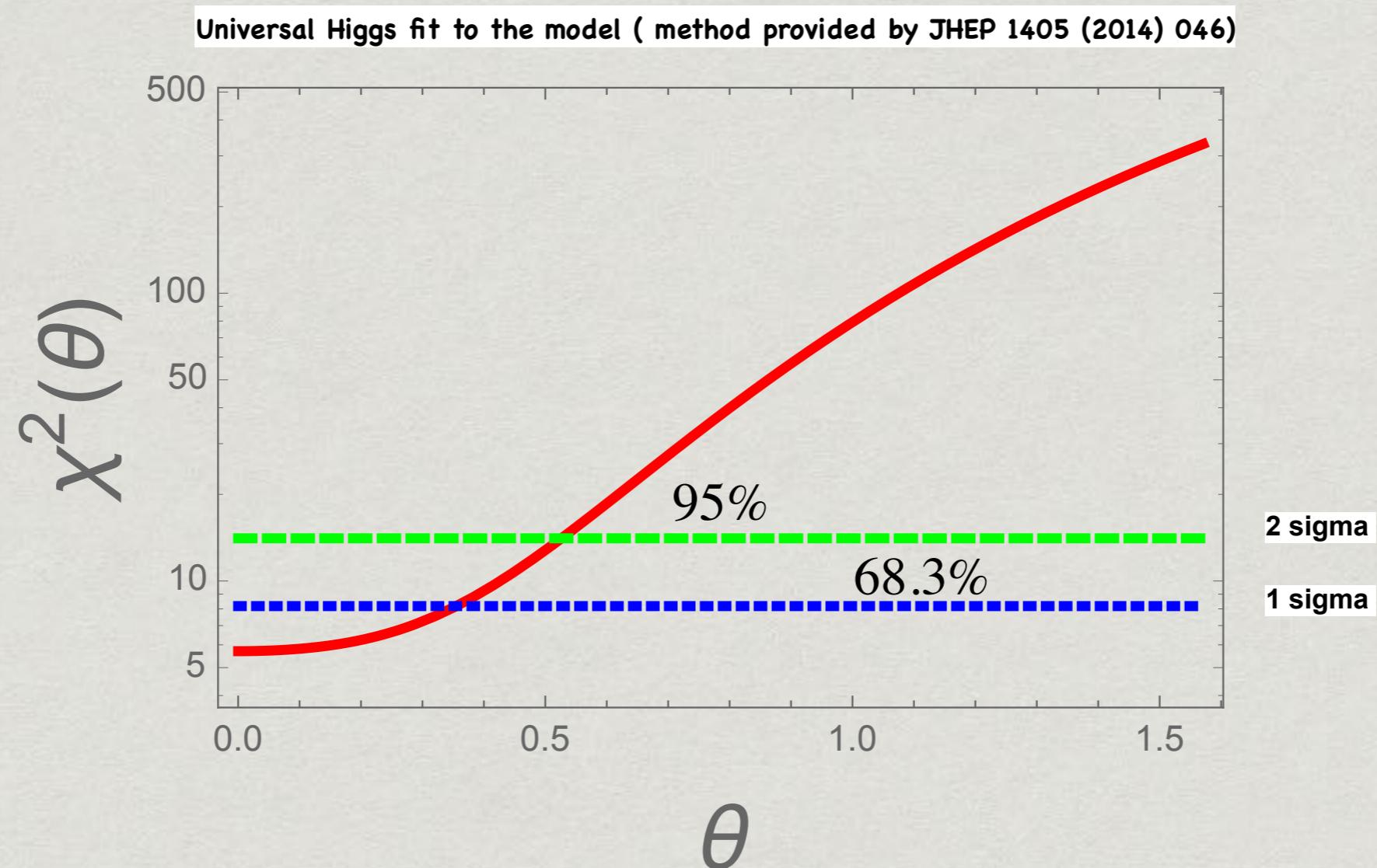
Scalar sector:

anomalies	anomaly free conditions
$SU(3)_C^2 U(1)_R$ :	$-2(\beta) - 2(-\beta) = 0$
$U(1)_Y^2 U(1)_R$ :	$- \left[ 3 \left(\frac{2}{3}\right)^2 \beta + 3 \left(\frac{1}{3}\right)^2 (-\beta) + (-1)^2 (-\beta) \right] = 0$
$U(1)_R^2 U(1)_Y$ :	$-\beta^2 [3 \times \frac{2}{3} - 3 \times \frac{1}{3} - 1] = 0$
$U(1)_R$ :	$-\beta + (-\beta) - 3[\beta + (-\beta)] = 0$
$U(1)_R^3$ :	$-\beta^3 + (-\beta)^3 - 3[\beta^3 + (-\beta)^3] = 0$

$$m_{h,\phi}^2 = (v^2 \lambda + v_\Phi^2 \lambda_1) \mp \sqrt{(v^2 \lambda - v_\Phi^2 \lambda_1)^2 + v^2 v_\Phi^2 \lambda_2^2}$$

$$\theta = \frac{1}{2} \arctan \left[ \frac{v v_\Phi \lambda_2}{v^2 \lambda - v_\Phi^2 \lambda_1} \right]$$

# Constraints on the scalar sector

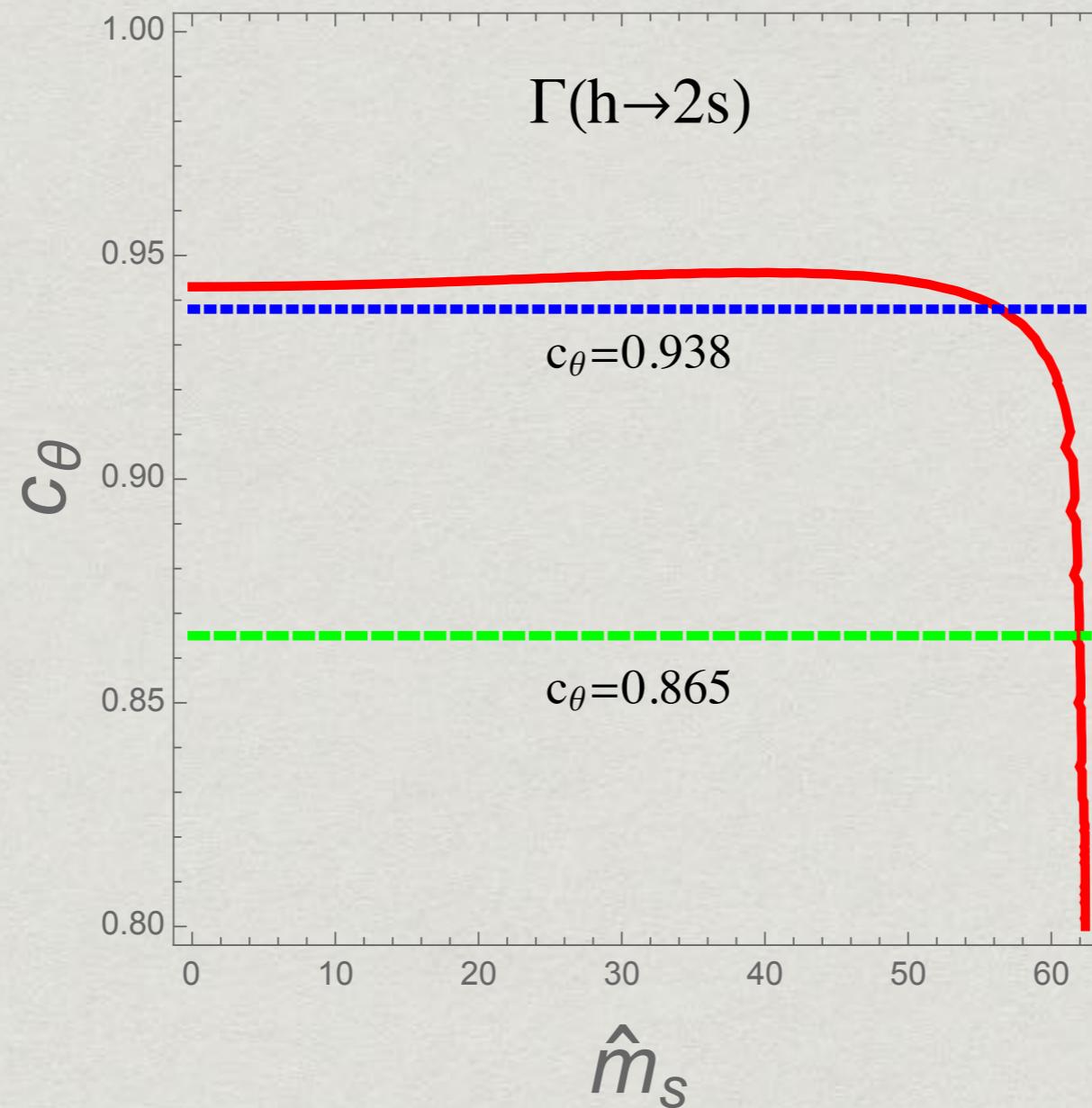


$$\cos \theta > 0.938(1\sigma), 0.865(2\sigma)$$

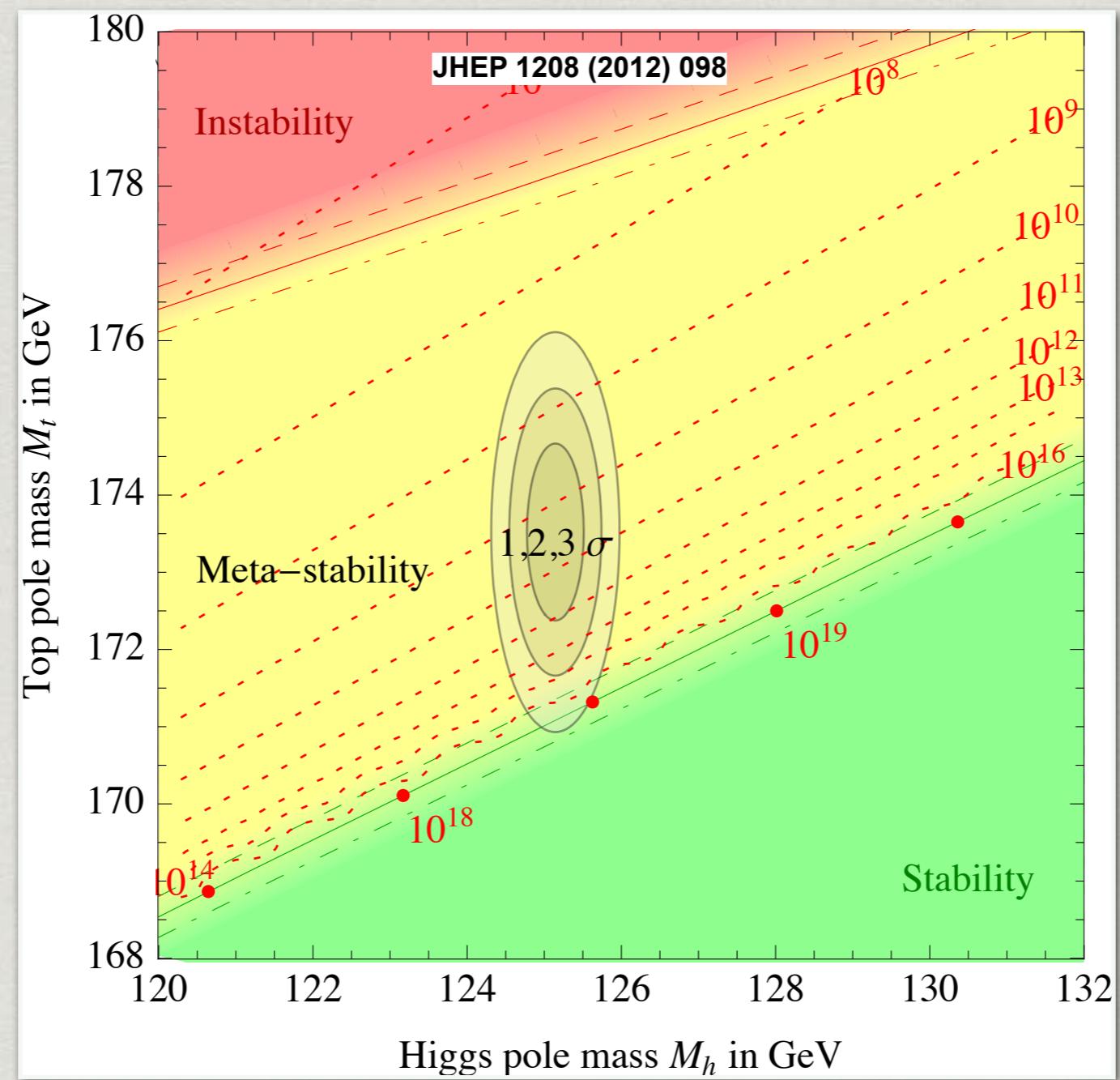
# Constraints on the scalar sector

ATLAS, EPJC76(2016)6:

$$BR(h \rightarrow 2s) < 49\%$$



# Vacuum stability



天道有缺！ -老子

New physics!

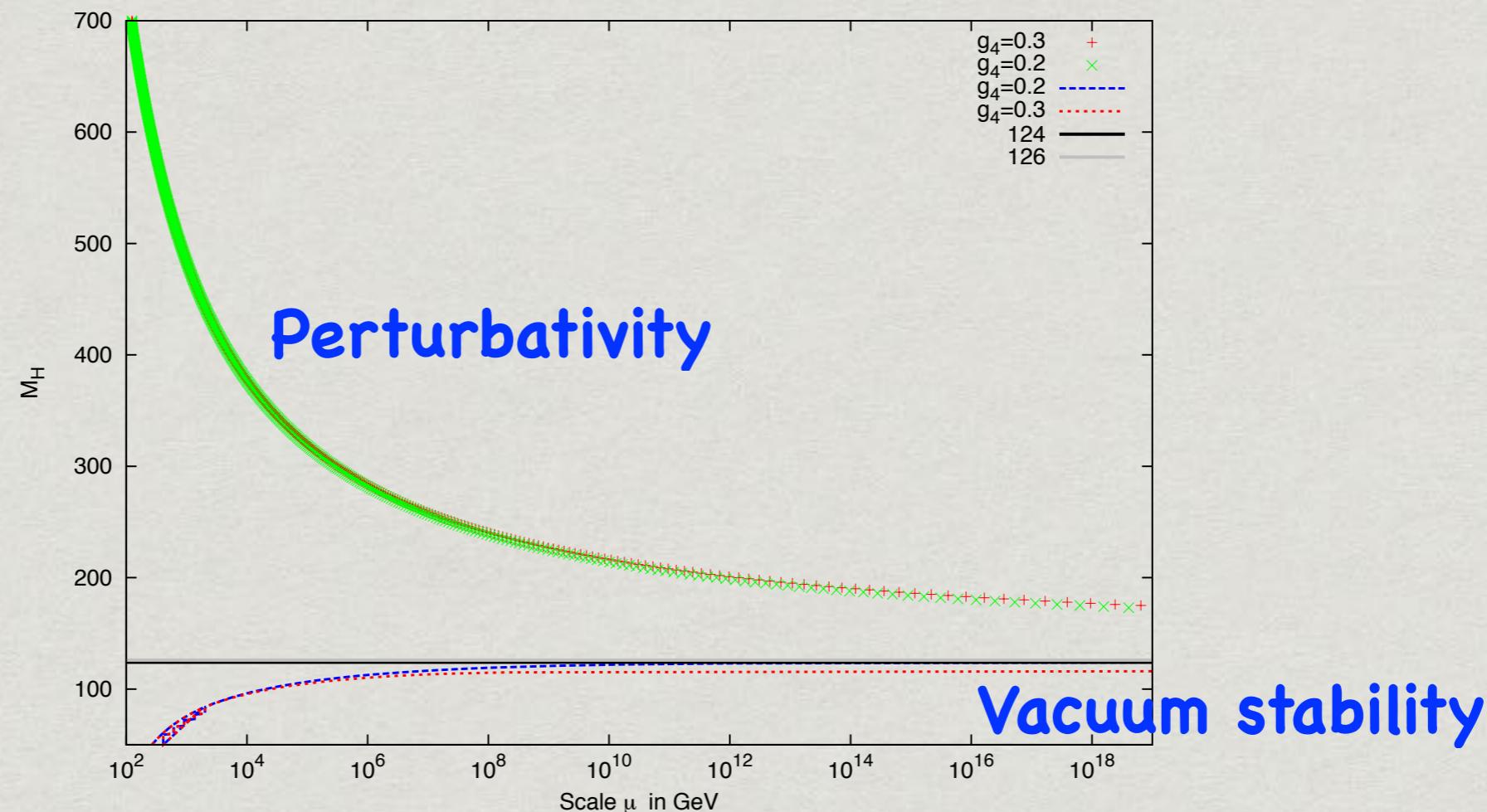
# Vacuum stability

New gauge interaction

$$16\pi^2 \beta_\lambda^{(1)} = 16\pi^2 (\beta_\lambda^{(1)})_{\text{SM}} + \frac{3}{4} \left( 16g_4^4 + \frac{24}{5} g_1^2 g_4^2 + 8g_2^2 g_4^2 \right) - 12g_4^2 \lambda$$

Beta function of Higgs self coupling

Effect of  $s$  is neglected!



# Z-Z' mixing

Mass matrix of neutral gauge bosons:

$$M^2 = \frac{v^2}{4} \begin{pmatrix} g'^2 & -g'g & 2g'g_R \\ -g'g & g^2 & -2gg_R \\ 2g'g_R & -2gg_R & 4g_R^2(1+\Delta) \end{pmatrix}$$

Mixing matrix:

$$\mathcal{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & c_{13} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ -c_{12}c_{23}s_{13} + s_{12}s_{23} & -c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$

No kinematic mixing term

Loop corrections are neglected

$$M_{Z_R(Z)}^2 = \frac{v^2}{8} \left\{ g^2 + g'^2 + 4g_R^2(1+\delta) \pm \sqrt{-16\delta(g^2 + g'^2)g_R^2 + [g^2 + g'^2 + 4g_R^2(1+\delta)]^2} \right\}$$

Mass eigenvalues

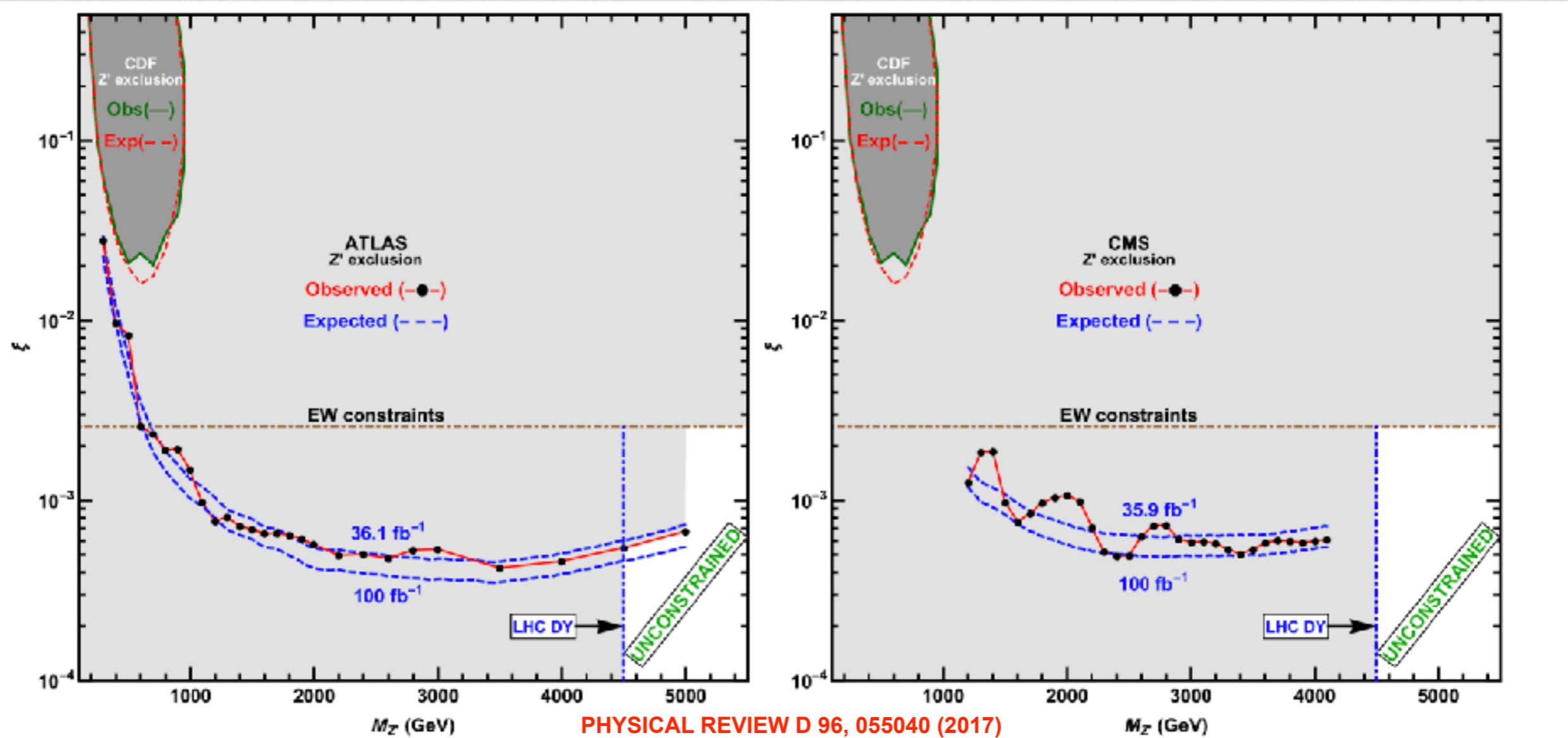
$$\tan \theta_{23} = -\frac{g}{2g_R} \left( 1 - \frac{g_R^2 v^2 \delta}{M_{Z_R}^2} \right)$$

$$\sin \theta_{13} = \frac{g'(M_{Z_R}^2 - g_R^2 v^2 \delta)}{[(g^2 + g'^2)(M_{Z_R}^2 - g_R^2 v^2 \delta)^2 + 4g_R^2 M_{Z_R}^4]^{1/2}}$$

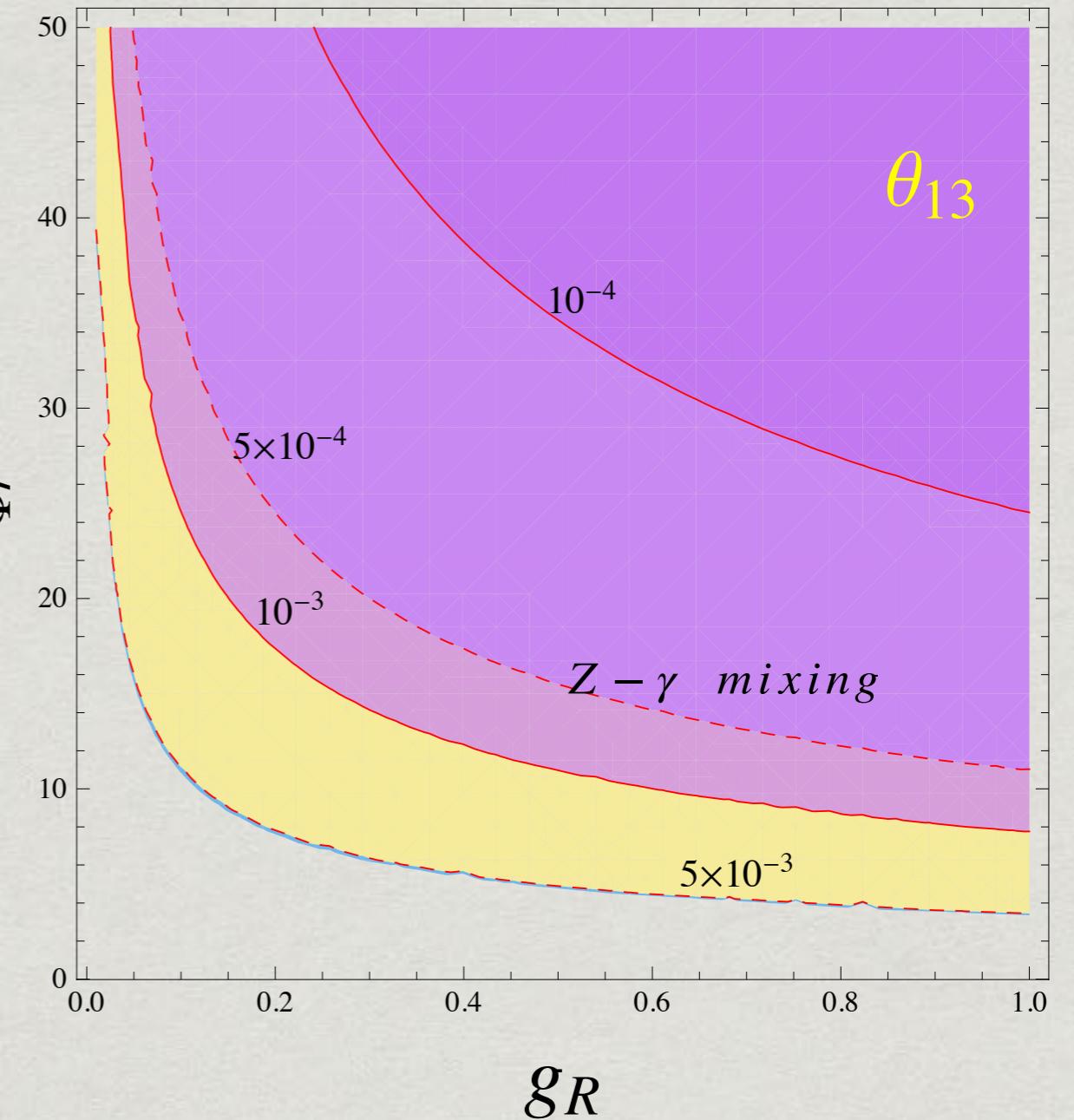
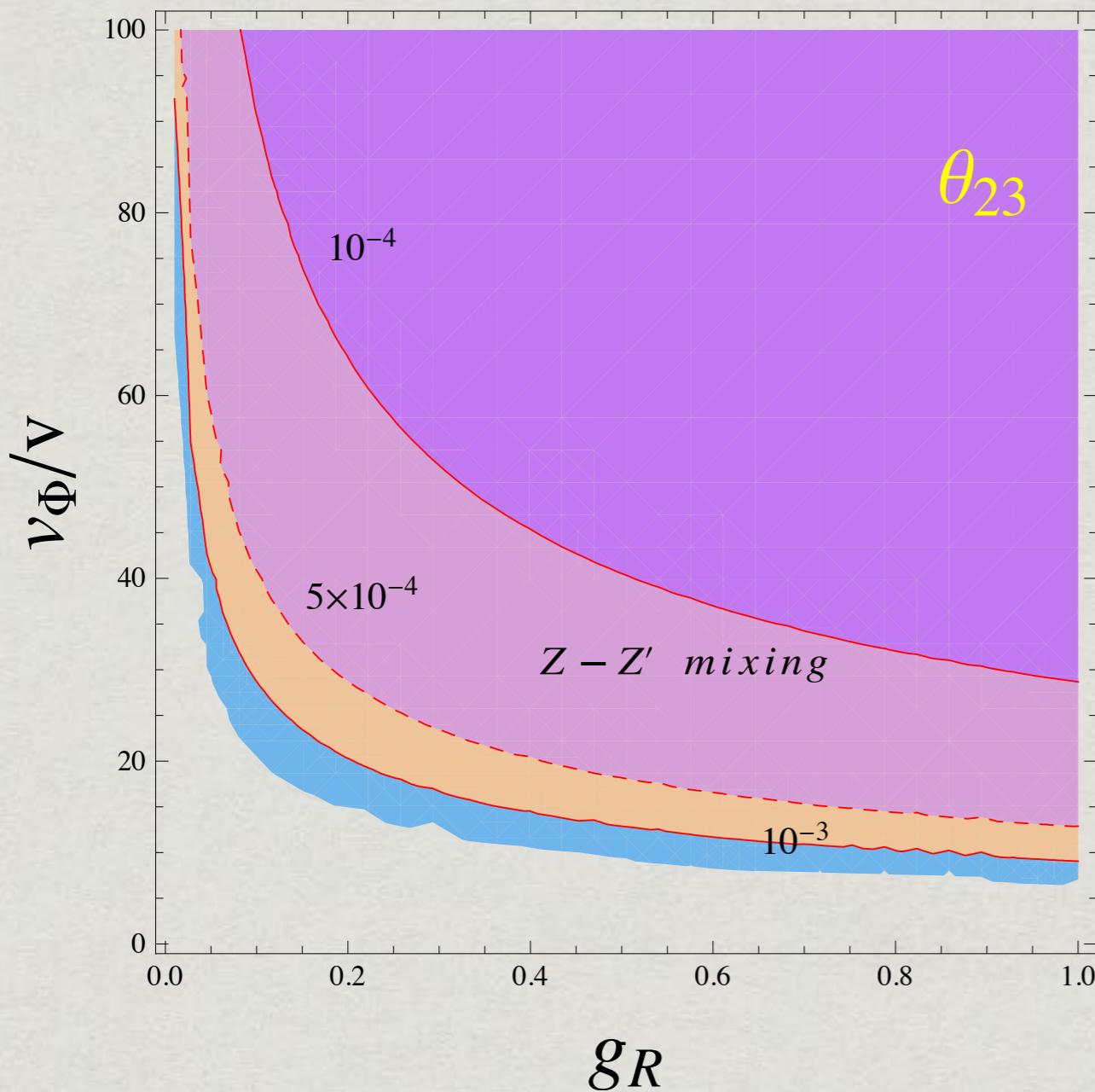
$$\tan \theta_{12} = \frac{g'(M_Z^2 - g_R^2 v^2 \delta) \sqrt{g^2 + g'^2}}{g [(g^2 + g'^2)(M_Z^2 - g_R^2 v^2 \delta)^2 + 4g_R^2 M_Z^4]^{1/2}}$$

Mixing angles:

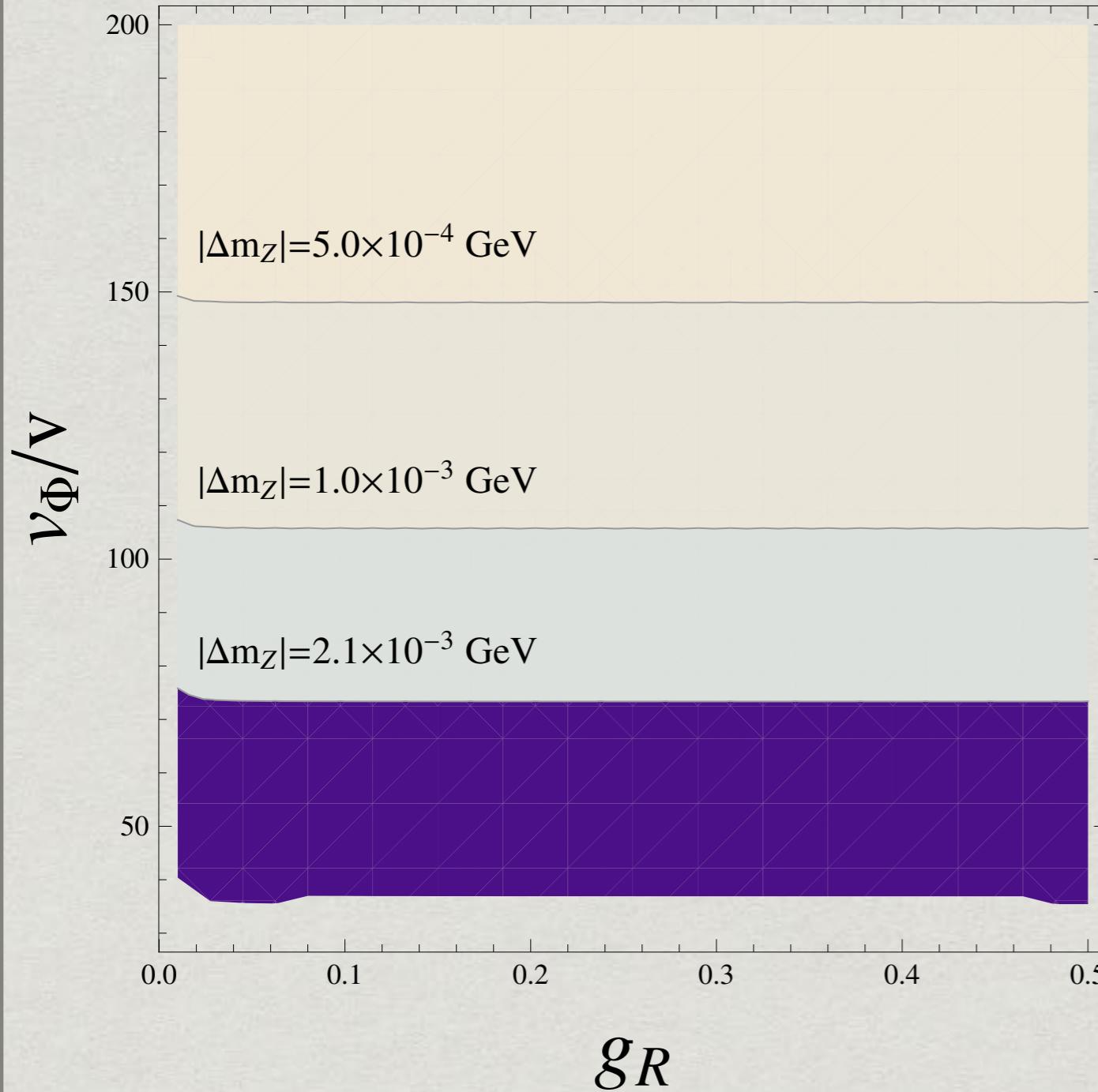
# $Z$ - $Z'$ mixing



# $Z$ - $Z'$ mixing



# Z-boson mass



VALUE (GeV)	EVTS	DOCUMENT ID	TECN	COMMENT
<b>91.1876±0.0021 OUR FIT</b>				
91.1852±0.0030	4.57M	<sup>1</sup> ABBIENDI	014	OPAL $E_{cm}^{ee} = 88-94 \text{ GeV}$
91.1863±0.0028	4.08M	<sup>2</sup> ABREU	00F	DLPH $E_{cm}^{ee} = 88-94 \text{ GeV}$
91.1890±0.0031	3.96M	<sup>3</sup> ACCIARRI	00C	L3 $E_{cm}^{ee} = 88-94 \text{ GeV}$
91.1885±0.0031	4.57M	<sup>4</sup> BARATE	00C	ALEP $E_{cm}^{ee} = 88-94 \text{ GeV}$

Inputs

$$\alpha(M_Z)^{-1} = 127.918$$

$$\sin^2 \theta_W(M_Z) = 0.23122$$

$$M_Z = 91.1876 \text{ GeV}$$

Conclusion:  $v_\Phi/v > 73.32$

$$v_\Phi > 18 \text{ TeV}$$

# LEP Constraint

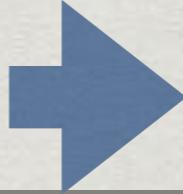
Effective Lagrangian for  $Z'$  mediated interactions

$$\mathcal{L}_{\text{eff}} = \frac{4\pi}{(1+\delta)\Lambda^2} \overline{e_R} \gamma_\mu e_R \overline{f_R} \gamma^\mu f_R$$

Model	$e^+e^- \rightarrow \ell^+\ell^-$				LEP, Phys.Rept. 352(2013)119			
	$\Lambda_{ee}^-$ (TeV)	$\Lambda_{ee}^+$	$\Lambda_{\mu\mu}^-$ (TeV)	$\Lambda_{\mu\mu}^+$	$\Lambda_{\tau\tau}^-$ (TeV)	$\Lambda_{\tau\tau}^+$	$\Lambda_{\ell^+\ell^-}^-$ (TeV)	$\Lambda_{\ell^+\ell^-}^+$
LL	8.0	8.7	9.8	12.2	9.1	9.1	11.8	13.8
RR	7.9	8.6	9.3	11.6	8.7	8.7	11.3	13.2
VV	15.3	20.6	16.3	18.9	13.8	15.8	20.0	24.6
AA	14.0	10.1	13.4	16.7	14.1	11.4	18.1	17.8
LR	8.5	11.9	2.2	9.1	2.2	7.7	10.0	13.5
RL	8.5	11.9	2.2	9.1	2.2	7.7	10.0	13.5
V0	11.2	12.4	13.5	16.9	12.6	12.5	16.2	19.3
A0	11.8	17.0	12.1	12.6	8.9	12.1	14.5	19.0
A1	4.0	3.9	4.5	5.8	3.9	4.7	5.2	6.3

Conclusion:

$$\frac{M_{Z'}}{g_R} > 3.71 \text{ TeV}$$



$$v_\Phi > 1.8 \text{ TeV}$$

# Neutrino masses

Problems relevant to neutrino physics



## Neutrino mass generation in the $U(1)_R$ model

$$-\mathcal{L}_\Delta = M_\Delta^2 \Delta^\dagger \Delta + \left( \tilde{\lambda} H^T i\sigma_2 \Delta H \Phi + \text{h.c.} \right) + (\overline{\ell}_L Y_\Delta \Delta \ell_L + \text{h.c.}) + \dots$$



Small according to the naturalness criteria of t'Hooft

Active neutrino masses:

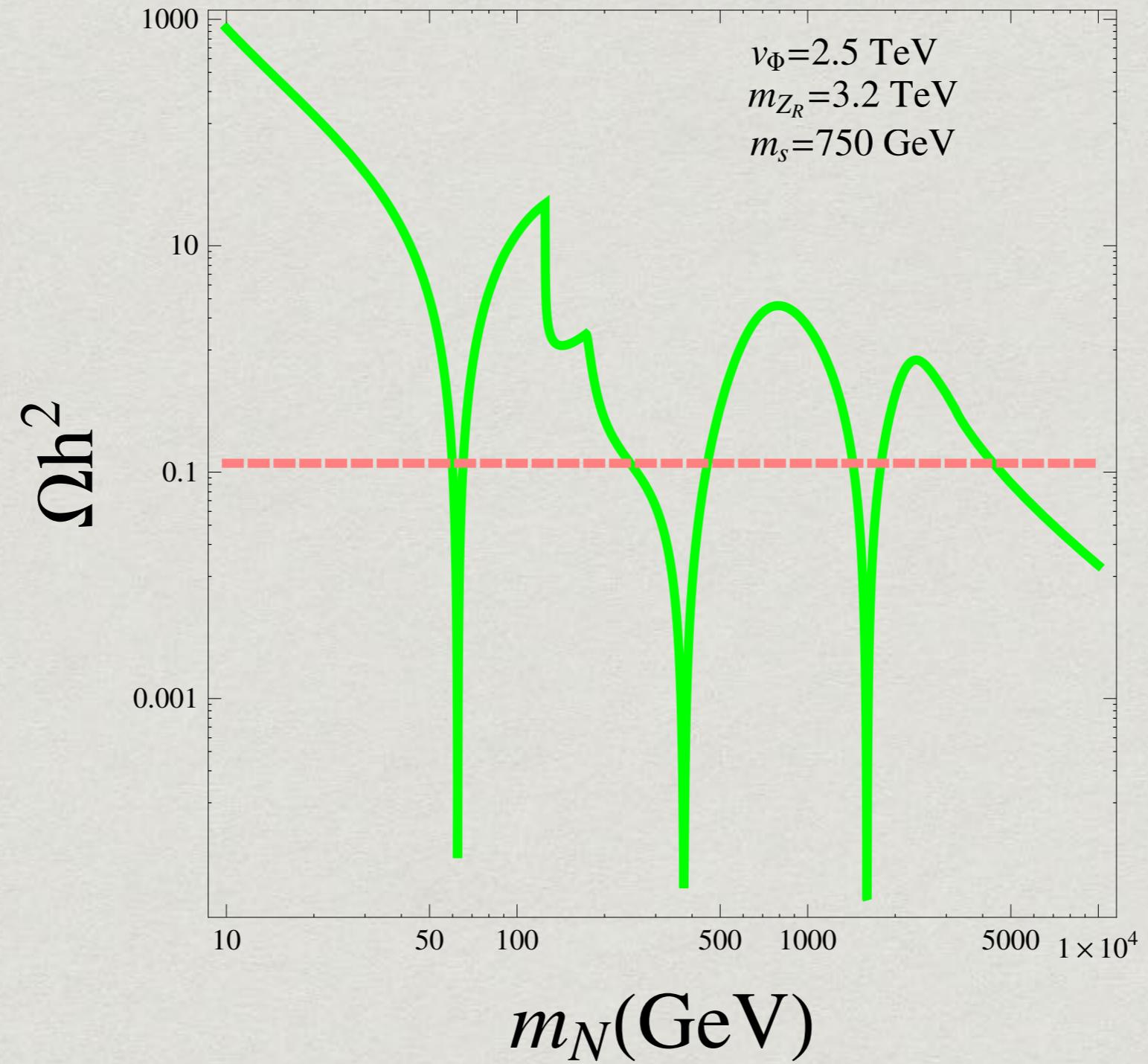
$$M_\nu = Y_\Delta v_\Delta \approx Y_\Delta \tilde{\lambda} \frac{v^2 v_\Phi}{M_\Delta^2}$$

# Dark matter

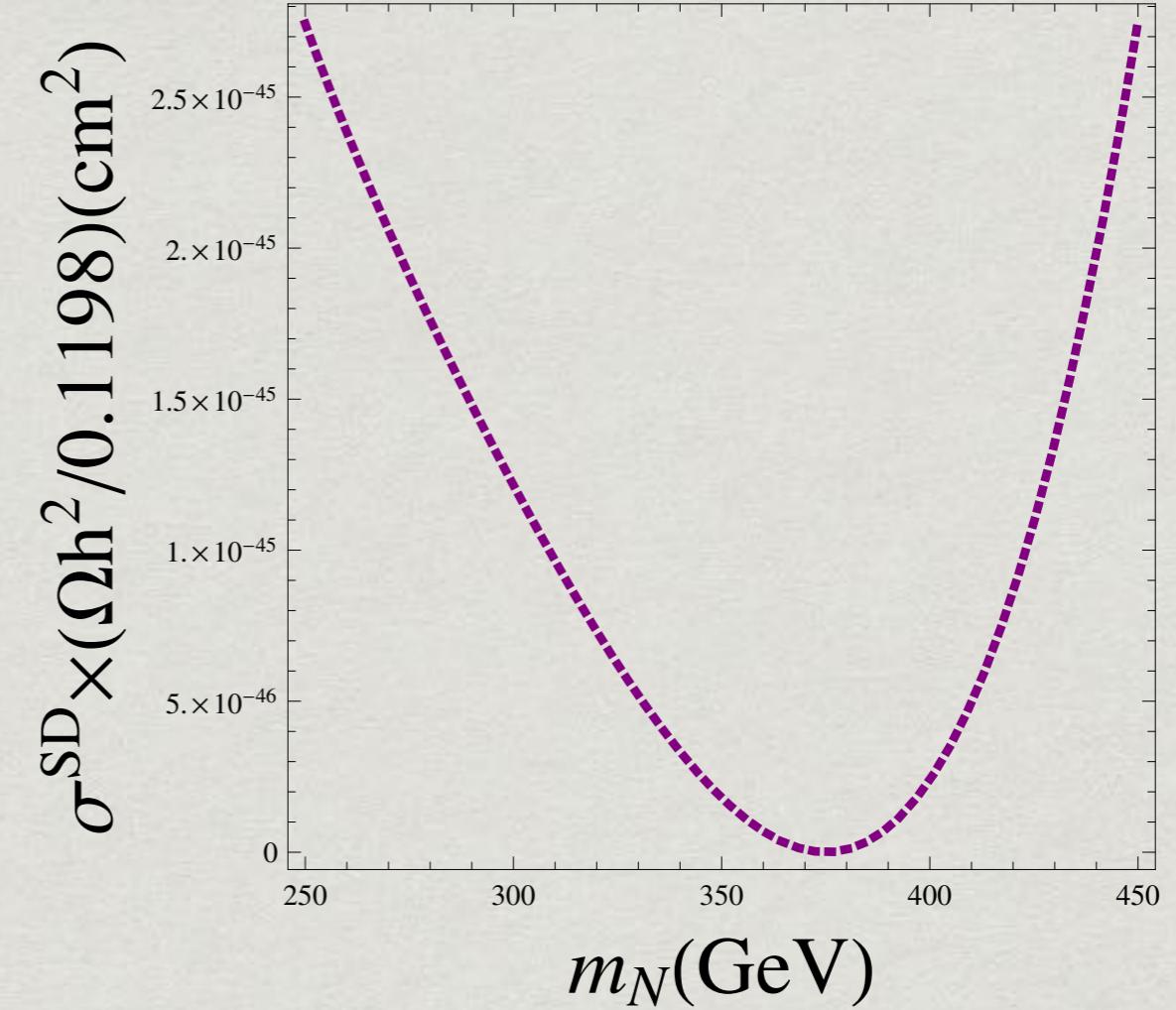
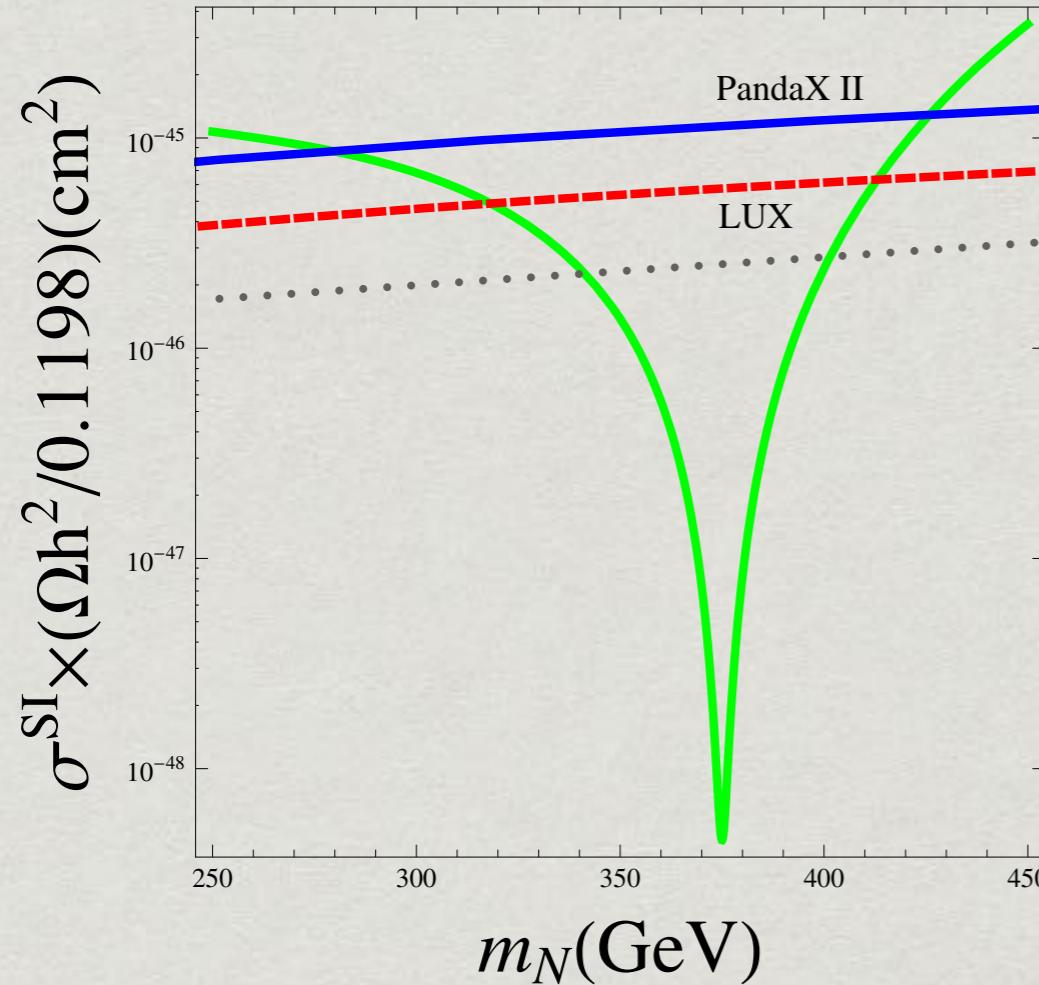
## Basic inputs

◆ Interactions	$-\mathcal{L} \sim \frac{1}{2} \bar{\mathbf{N}} i g_{\mathbf{R}} \gamma_\mu \gamma_5 Z_{\mathbf{R}}^\mu \mathbf{N} + \frac{1}{2} \frac{m_{\mathbf{N}}}{v_\Phi} \bar{\mathbf{N}} (c_\alpha \hat{s} - s_\alpha \hat{h}) \mathbf{N}$
◆ Relic Density	$\Omega_{\text{DM}} h^2 = \frac{1.07 \times 10^9}{M_{pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{a + 3b/x_F}$
◆ SI Direct Det.	$\sigma_{\text{SI}} = \frac{\mu^2 s_{2\alpha}^2 m_N^2}{4\pi v^2 v_\Phi^2} \left( \frac{1}{m_h^2} - \frac{1}{m_s^2} \right)^2 [Z f_p + (A - Z) f_n]^2$
◆ SD Direct Det	$\sigma^{\text{SD}} = \frac{g_{\mathbf{R}}^2 \mu^2}{\pi M_{Z_{\mathbf{R}}}^4} \left( \sum_{q=u,d,s} \lambda_q \right)^2 J_N (J_N + 1)$

# Dark matter



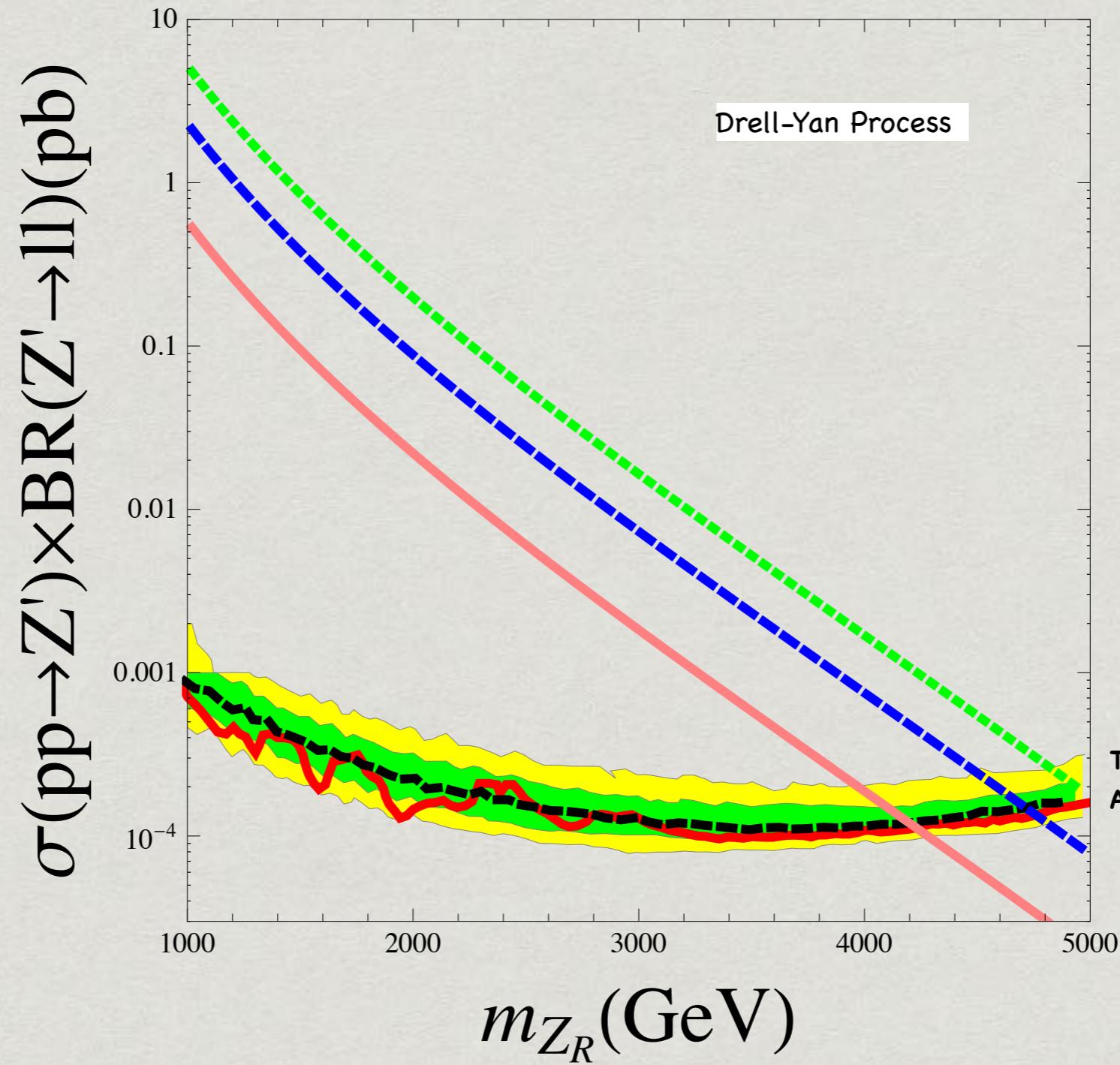
# Dark matter



The smallest excluded cross section  
(PRL118.071301) at m=45 GeV:

$$\langle \sigma v \rangle = 4.3 \times 10^{-41} \text{ cm}^2$$

# Collider signature



# Conclusions

- A new U(1) gauge symmetry is investigated;
- Constraints from Z-Z' mixing, Z-boson mass and collider was studied;
- Neutrino mass can be generated via the seesaw mechanism;
- Dark matter is available at the resonant regime or super heavy region;
- Collider constraints is stronger than that of Z-boson mass for  $g_R < 0.121$ .

**Thank you for attention**