Augury of Darkness

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Based on:

A. Alves, G.A., P.V. Dong, L. Duarte, F. Queiroz, J. Valle, arXiv:1612.04383

A. Alves, G.A., Y. Mambrini, S. Profumo, F. Queiroz, arXiv:1612.07282

G.A., M. Lindner, Y. Mambrini, M. Pierre, F. Queiroz, arXiv:1704.02328

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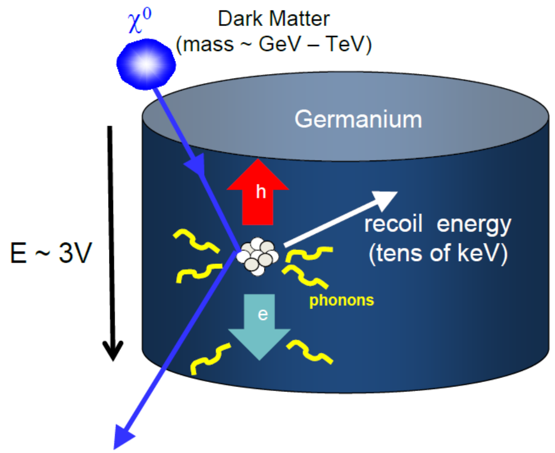
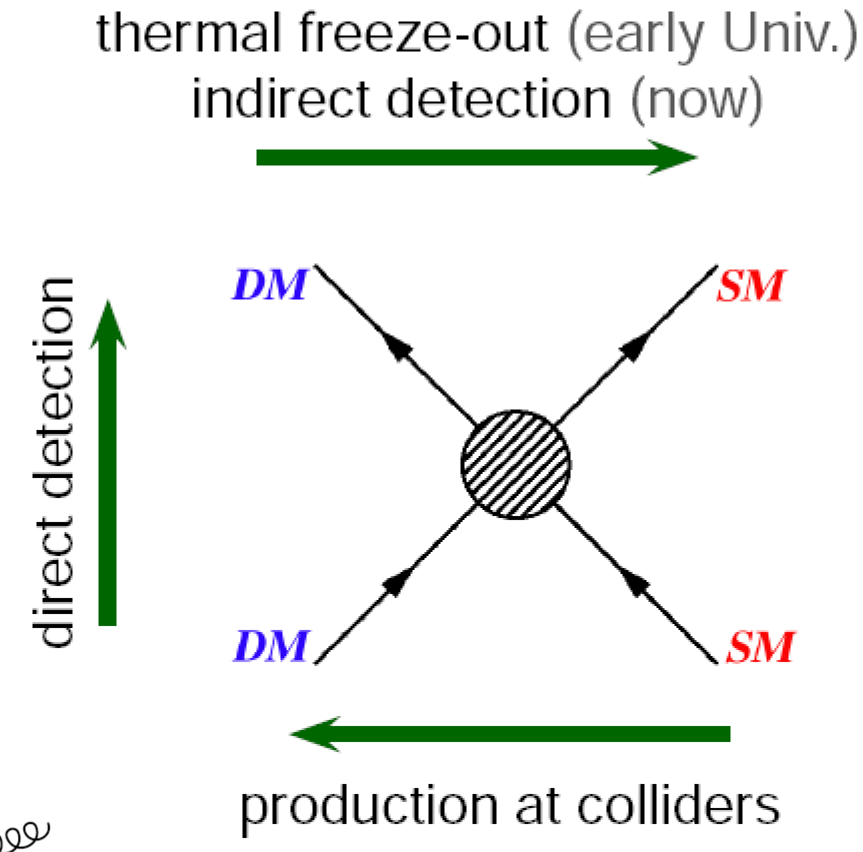
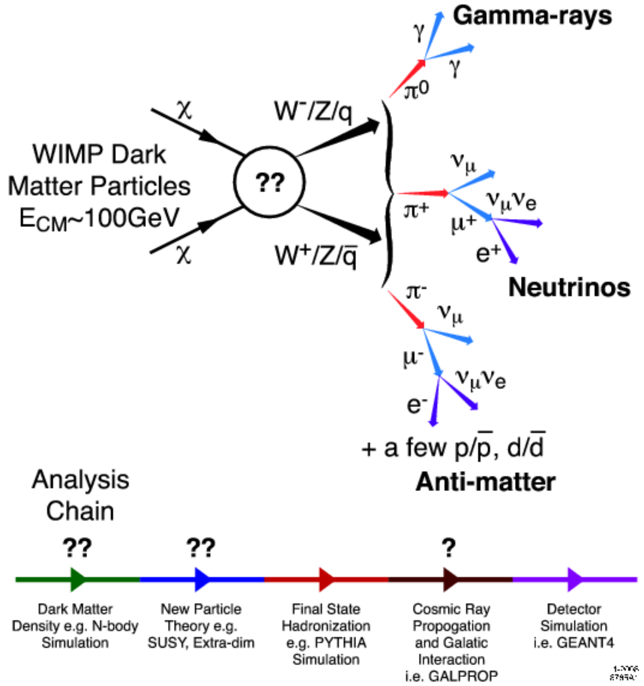
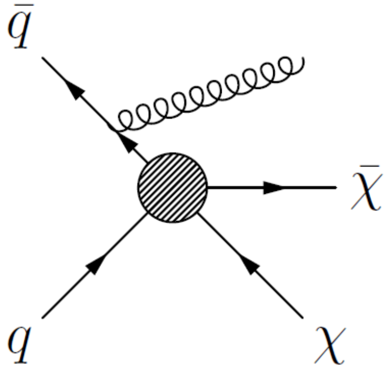
WIMP scenarios feature a strong complementarity between Dark Matter searches.



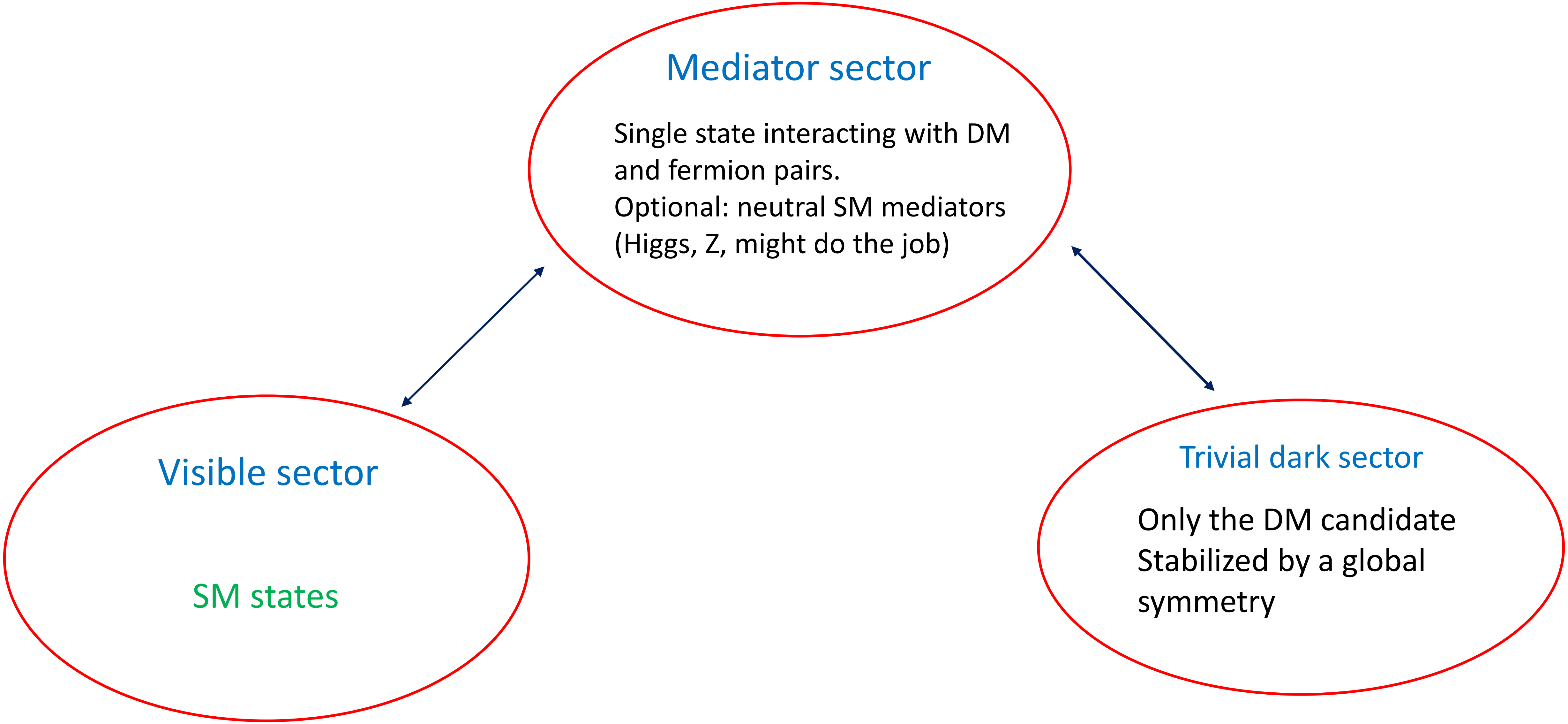






$$\Omega h^2 \simeq 0.12 \longrightarrow \langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Simplified models: “Dark portals“



Case of study: fermionic DM interacting with spin-1 (Z') mediator

High invisible branching fraction:

monojet searches

Correlation

Low Invisible branching fraction

Resonance searches

$$\sigma^{\rm SI}_{\rm DM,p} \propto \frac{\mu^2_{\rm DM,p}}{\pi m^4_{Z'}} \frac{\left[Z f_p + (A-Z) f_n\right]^2}{A^2}$$

$$f_p = 2V_u^{Z'} + V_d^{Z'} \qquad f_n = V_u^{Z'} + 2V_d^{Z'}$$

$$\sigma^{\rm SD}_{\rm DM,p} \propto \frac{3\mu^2_\chi}{m^4_{Z'}} \left[A_u^{Z'} \Delta_u^p + A_d^{Z'} (\Delta_d^p + \Delta_s^p)\right]^2$$

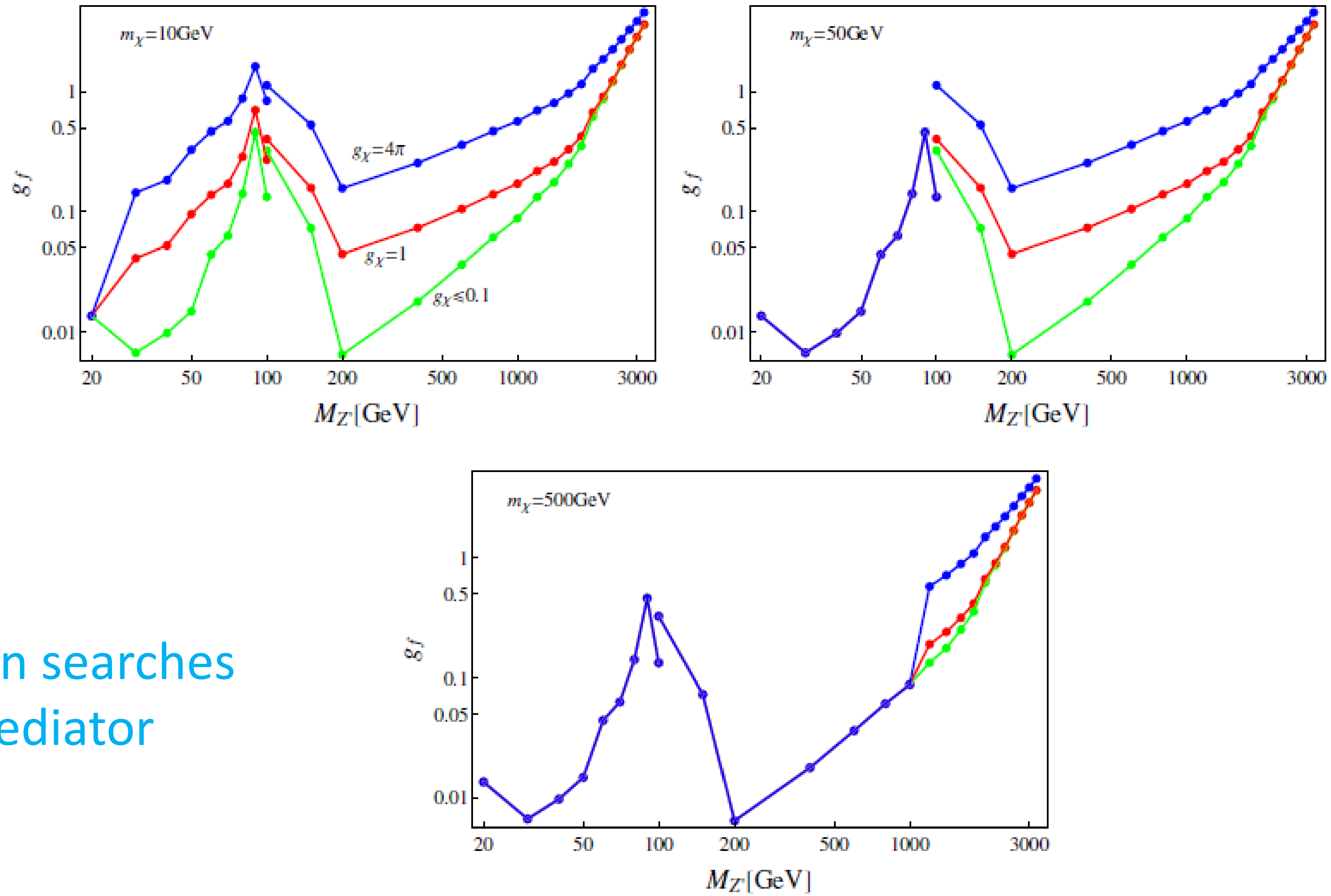
$$\langle \sigma v \rangle = \frac{m_\chi^2}{\pi m^4_{Z'}} |V_\chi|^2 \left[(a_V + b_V v^2) + \alpha^2 (a_A + b_A v^2)\right]$$

$$\langle \sigma v \rangle = f_1 \sigma^{\rm SI}_{\chi N} + f_2 \sigma^{\rm SD}_{\chi N} \qquad \alpha = \frac{A_\chi}{V_\chi}$$

Light Z‘

$$\mathcal{L} \supset \left[\bar{\chi}\gamma^{\mu}(g_{\chi v} + g_{\chi a}\gamma^5)\chi + g_f \bar{f}\gamma^{\mu}\gamma^5 f\right] Z'_{\mu}$$

→ Universal couplings with the fermions



Limits from dilepton searches extended at low mediator masses.

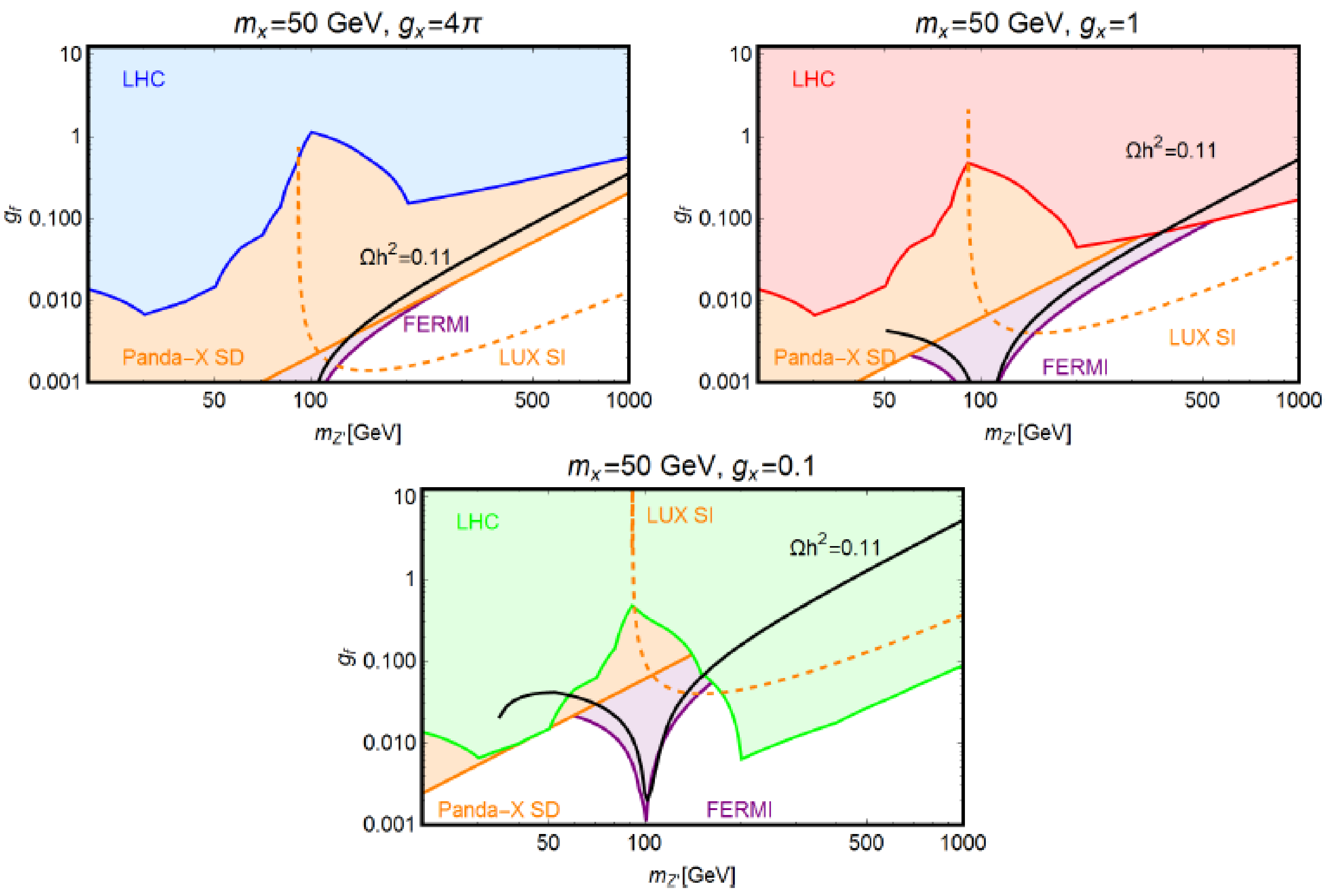
RGE Corrections

$$\mathcal{L} \supset \left[\bar{\chi}\gamma^\mu(g_{\chi v} + g_{\chi a}\gamma^5)\chi + g_f \bar{f}\gamma^\mu\gamma^5 f\right] Z'_\mu$$

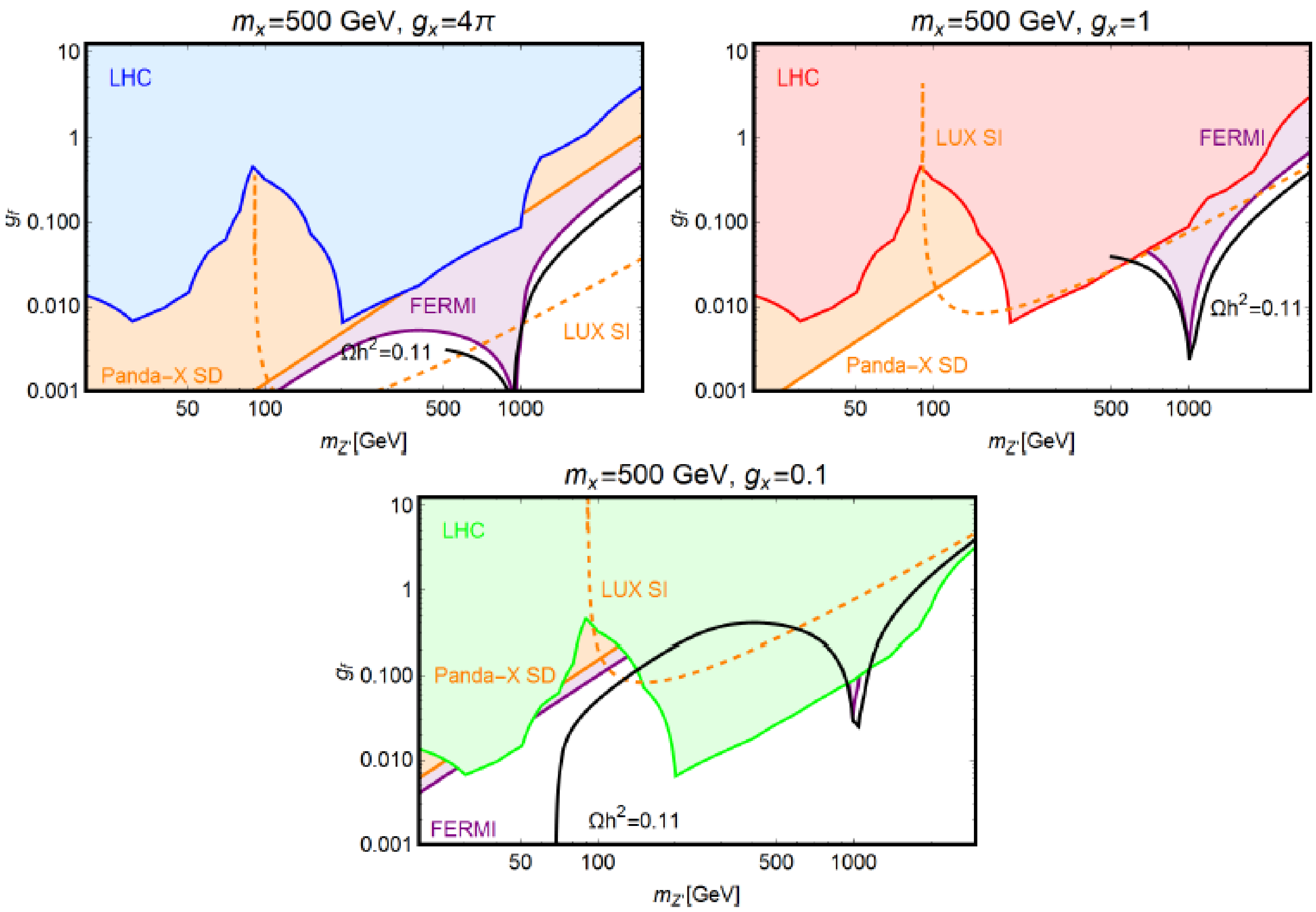
$$\tilde{V}_u^{Z'} = \frac{\alpha_t}{2\pi}(3 - 8s_W^2)A_u^{Z'} \log\left(\frac{m_{Z'}}{m_Z}\right) - (3 - 8s_W^2)\left[\frac{\alpha_b}{2\pi}A_d^{Z'} + \frac{\alpha_\tau}{6\pi}A_e^{Z'}\right] \log\left(\frac{m_{Z'}}{\mu_N}\right)$$

$$\tilde{V}_d^{Z'} = -\frac{\alpha_t}{2\pi}(3 - 4s_W^2)A_u^{Z'} \log\left(\frac{m_{Z'}}{m_Z}\right) + (3 - 4s_W^2)\left[\frac{\alpha_b}{2\pi}A_d^{Z'} + \frac{\alpha_\tau}{6\pi}A_e^{Z'}\right] \log\left(\frac{m_{Z'}}{\mu_N}\right)$$

F. d’Eramo, B. J. Kavanagh, P. Panci 1605.04917



A. Alves, G.A., Y. Mambrini, S. Profumo, F. Queiroz, 1612.07282



m_x=500 GeV, g_x=4π
LHC
FERMI
Ωh²=0.11
LUX SI
Panda-X SD
g_f
10
1
0.100
0.010
0.001
50
100
500
1000
$m_{Z'}$[GeV]
m_x=500 GeV, g_x=1
LHC
LUX SI
FERMI
Ωh²=0.11
Panda-X SD
m_x=500 GeV, g_x=0.1
LHC
LUX SI
Panda-X SD
FERMI
Ωh²=0.11

Spin-1 mediator as new gauge bosons

Spin-1 BSM mediators can be interpreted as gauge bosons of extra symmetry groups

$E_6 \to SO(10) \times U(1)_\psi$ → Extra U(1) from Grand Unified theories

$SO(10) \to SU(5) \times U(1)_\chi$

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2) \times U(1)_Y \times U(1)_{LR}$

General implementation:

$$\mathcal{L} = \sum_f g_f^{'} \bar{f} \gamma^\mu \left(\epsilon_L^f P_L + \epsilon_R^f P_R \right) f Z_\mu^{'} + g_\chi^{'} \bar{\chi} \gamma^\mu \left(\epsilon_L^\chi P_L + \epsilon_R^\chi P_R \right) \chi Z_\mu^{'}$$

$$\epsilon_{L,R}^f = \hat{\epsilon}_{L,R}^f / D$$

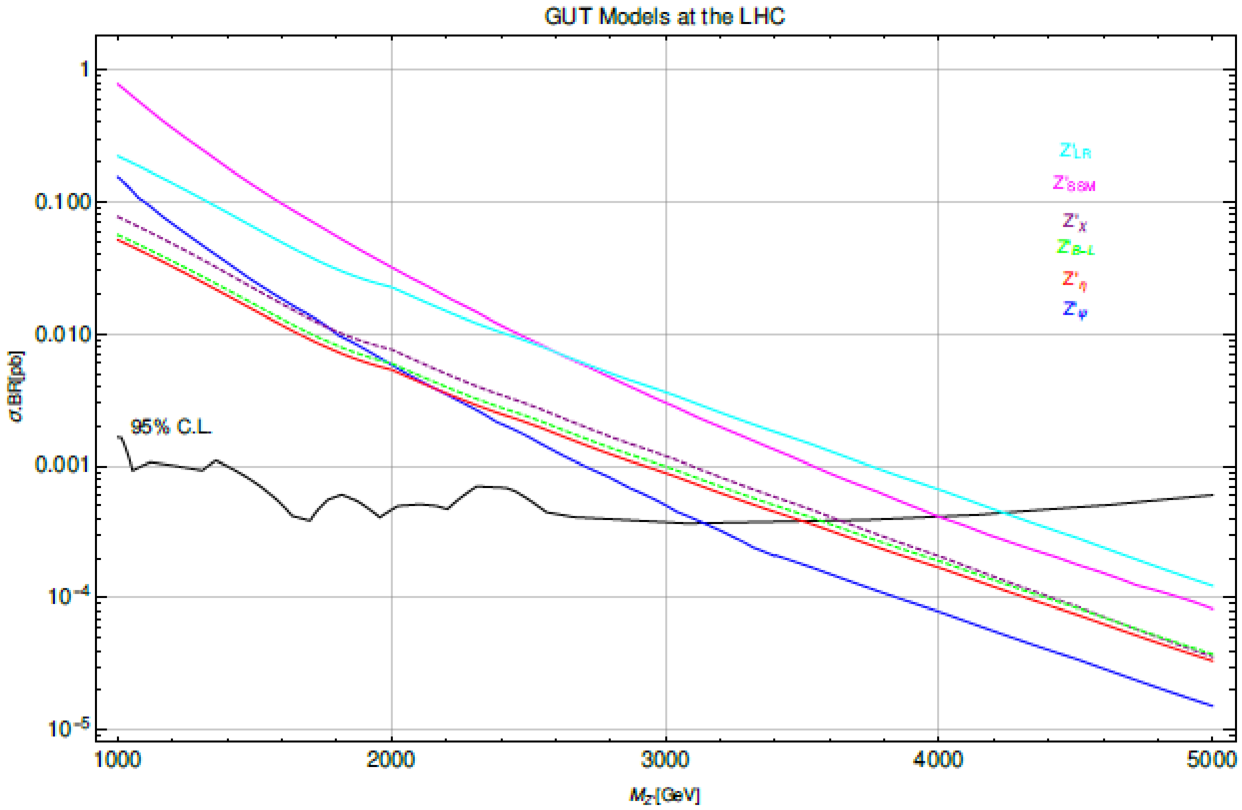
	χ	ψ	η	LR	B-L	SSM
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1
$\hat{\epsilon}_L^u$	-1	1	-2	-0.109	1/6	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}_L^d$	-1	1	-2	-0.109	1/6	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}_R^u$	1	-1	2	0.656	1/6	$-\frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}_R^d$	-3	-1	-1	-0.874	1/6	$\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}_L^\nu$	3	1	1	0.327	-1/2	$\frac{1}{2}$
$\hat{\epsilon}_L^l$	3	1	1	0.327	-1/2	$-\frac{1}{2} + \sin^2\theta_W$
$\hat{\epsilon}_R^e$	1	-1	2	-0.438	-1/2	$\sin^2\theta_W$

Han et al. 1308.2738

Vectorial and axial couplings are actually combinations of left-handed and right-handed currents

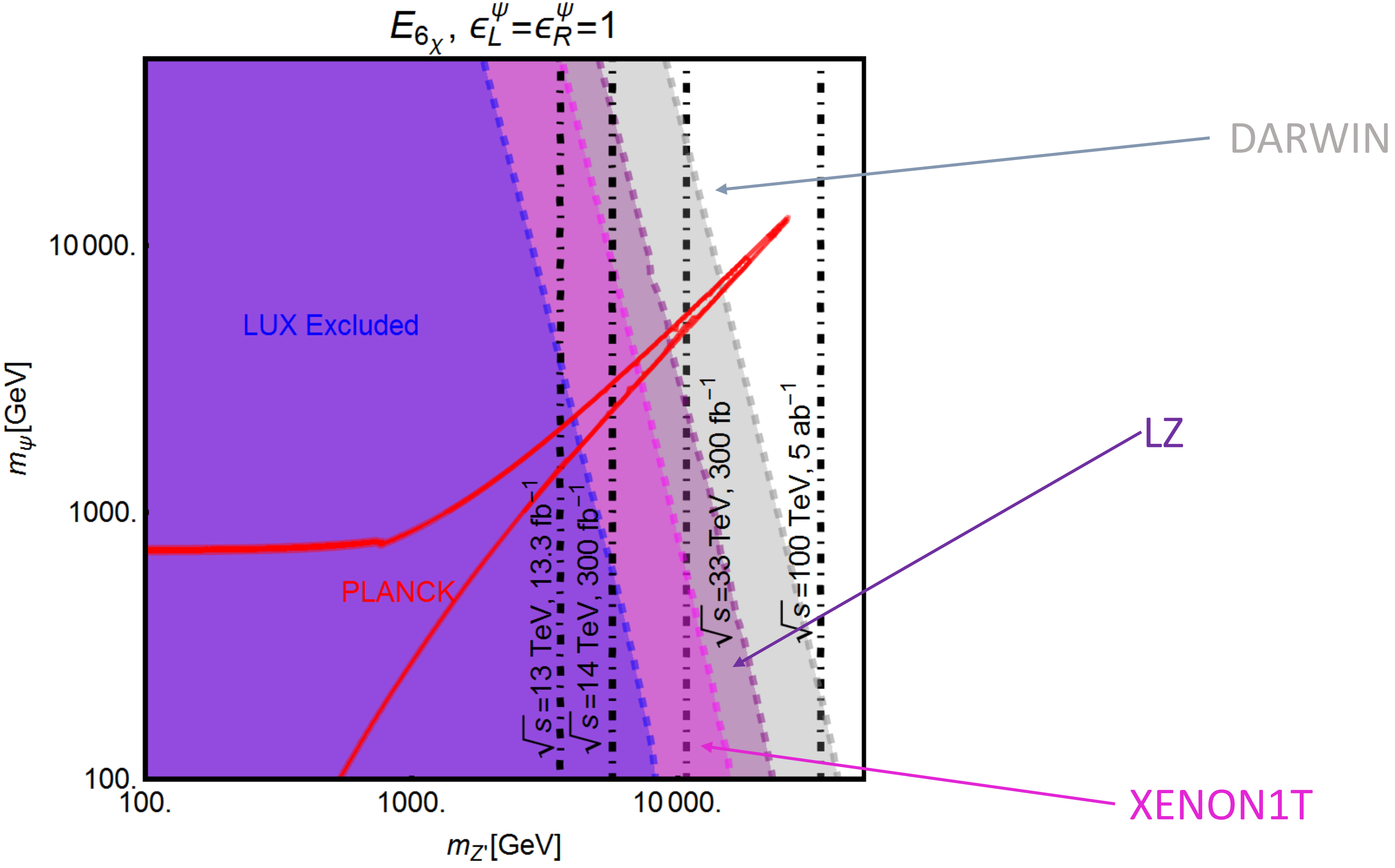
$$g^{'} V_f = \frac{g_f^{'}}{2} \left(\epsilon_L^f + \epsilon_R^f \right) \qquad g^{'} A_f = \frac{g_f^{'}}{2} \left(\epsilon_L^f - \epsilon_R^f \right)$$

$$g^{'} V_\chi = \frac{g_\chi^{'}}{2} \left(\epsilon_L^\chi + \epsilon_R^\chi \right) \qquad g^{'} A_\chi = \frac{g_\chi^{'}}{2} \left(\epsilon_L^\chi - \epsilon_R^\chi \right)$$



G.A., M. Lindner, Y. Mambrini, M. Pierre, F. Queiroz, 1704.023028

Model	13 TeV,13.3 fb^{-1}	13 TeV,37 fb^{-1}	14 TeV,100 fb^{-1}	14 TeV,300 fb^{-1}	33 TeV,100 fb^{-1}	33 TeV,300 fb^{-1}	100 TeV,5 ab^{-1}
Z'_{ψ}	3.13 TeV	3.68 TeV	4.46 TeV	5.13 TeV	7.98 TeV	9.47 TeV	30.54 TeV
Z'_{η}	3.47 TeV	4.04 TeV	4.85 TeV	5.51 TeV	8.85 TeV	10.38 TeV	33.25 TeV
Z'_{B-L}	3.55 TeV	4.11 TeV	5.55 TeV	5.59 TeV	9.03 TeV	10.56 TeV	33.8 TeV
Z'_{χ}	3.63 TeV	4.19 TeV	5.55 TeV	5.68 TeV	9.23 TeV	10.76 TeV	34.41 TeV
Z'_{SSM}	4.02 TeV	4.59 TeV	6.05 TeV	6.09 TeV	10.21 TeV	11.75 TeV	37.36 TeV
Z'_{LR}	4.23 TeV	4.8 TeV	6.27 TeV	6.31 TeV	10.73 TeV	12.28 TeV	38.92 TeV



G.A., M. Lindner, Y. Mambrini, M. Pierre, F. Queiroz, 1704.023028

Z' from $SU(3)_c \otimes SU(3)_L \otimes U(1)_X \otimes U(1)_N$

$$Q = T_3 - \frac{1}{\sqrt{3}}T_8 + X, \qquad B - L = -\frac{2}{\sqrt{3}}T_8 + N$$

Leptons	1-2nd Generations	3th Generation
$l_{aL} = \begin{pmatrix} \nu_a \\ e_a \\ N_a \end{pmatrix}_L$	$q_{\alpha L} = \begin{pmatrix} d_\alpha \\ -u_\alpha \\ D_\alpha \end{pmatrix}_L$	$q_{3L} = \begin{pmatrix} u_3 \\ d_3 \\ U \end{pmatrix}_L$
ν_{aR}, e_{aR}, N_{aR}	$u_{\alpha R}, d_{\alpha R}, D_{\alpha R}$	u_{3R}, d_{3R}, U_R

Scalars

$$\eta = \begin{pmatrix} \eta_1^0 \\ \eta_2^- \\ \eta_3^0 \end{pmatrix} \qquad \rho = \begin{pmatrix} \rho_1^+ \\ \rho_2^0 \\ \rho_3^+ \end{pmatrix} \qquad \chi = \begin{pmatrix} \chi_1^0 \\ \chi_2^- \\ \chi_3^0 \end{pmatrix}, \qquad \phi$$

Multiplet	l_{aL}	ν_{aR}	e_{aR}	N_{aR}	$q_{\alpha L}$	q_{3L}	u_{aR}	d_{aR}	U_R	$D_{\alpha R}$	η	ρ	χ	ϕ
X	$-1/3$	0	-1	0	0	1/3	2/3	$-1/3$	2/3	$-1/3$	$-1/3$	2/3	$-1/3$	0
N	$-2/3$	-1	-1	0	0	2/3	1/3	1/3	4/3	$-2/3$	1/3	1/3	$-2/3$	2

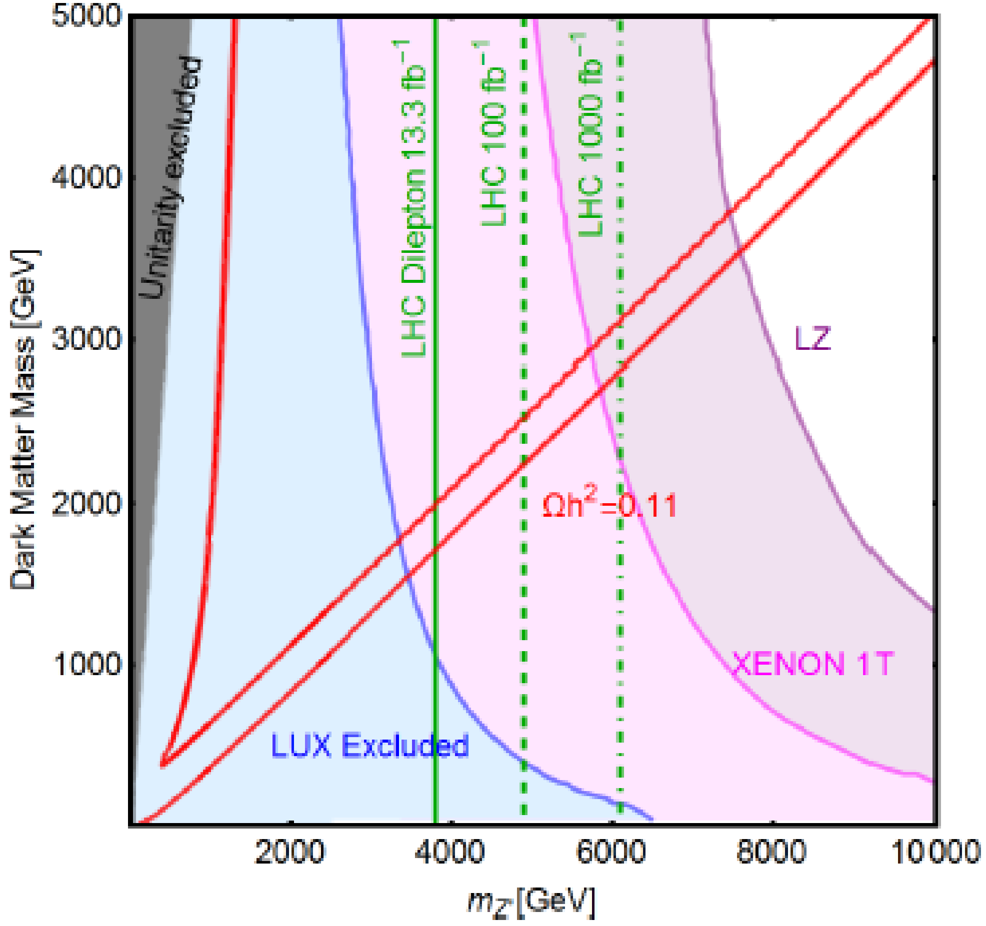
f	g_V^f	g_A^f
ν_a	$\frac{c_{2W}}{2\sqrt{3-4s_W^2}}$	$\frac{c_{2W}}{2\sqrt{3-4s_W^2}}$
e_a	$\frac{1-4s_W^2}{2\sqrt{3-4s_W^2}}$	$\frac{1}{2\sqrt{3-4s_W^2}}$
N_a	$-\frac{c_W^2}{\sqrt{3-4s_W^2}}$	$-\frac{c_W^2}{\sqrt{3-4s_W^2}}$
u_α	$-\frac{3-8s_W^2}{6\sqrt{3-4s_W^2}}$	$-\frac{1}{2\sqrt{3-4s_W^2}}$
u_3	$\frac{3+2s_W^2}{6\sqrt{3-4s_W^2}}$	$\frac{c_{2W}}{2\sqrt{3-4s_W^2}}$
d_α	$-\frac{(3-2s_W^2)}{6\sqrt{3-4s_W^2}}$	$-\frac{c_{2W}}{2\sqrt{3-4s_W^2}}$
d_3	$\frac{\sqrt{3-4s_W^2}}{6}$	$\frac{1}{2\sqrt{3-4s_W^2}}$

DM stabilized by a R-parity

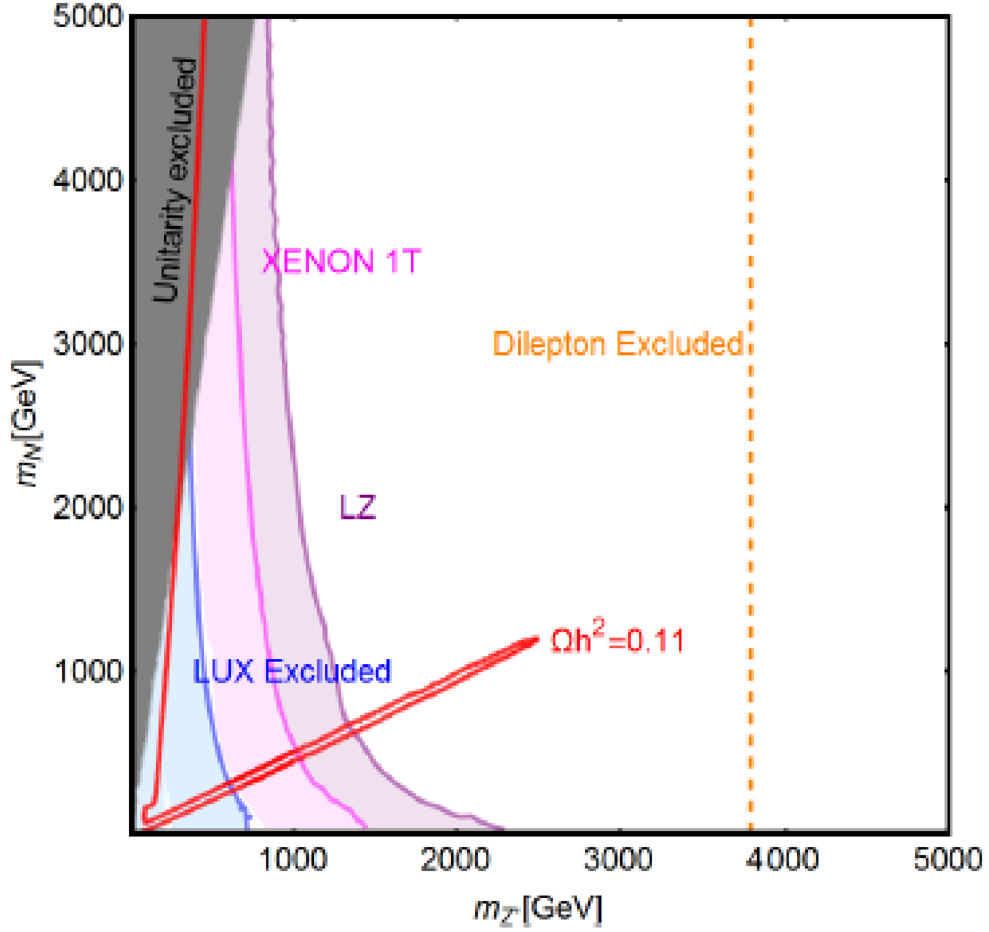
$$R_P = (-1)^{3(B-L)+2s}$$

remnant of the spontaneous breaking of the gauge symmetry

Dirac Dark Matter



Majorana Dark Matter



Conclusions

There is a potential strong correlation between Dark Matter phenomenology and collider searches of new physics.

We have discussed some examples in an interesting and theoretically motivated framework.

Next generation experiments have the potential capability of fully testing the WIMP paradigm.

Back up

Low mass Z‘ analysis

We have determined exclusion bounds on low mass (less than 500 GeV) Z’ through a CLs method

Low mass region $15 < M_{\ell\ell} < 100 \text{ GeV}$

$$p_T(\mu_1) > 14 \text{ GeV} \ , \ p_T(\mu_2) > 9 \text{ GeV} \ , \ |\eta_\mu| < 2.4$$

High mass region $M_{\ell\ell} > 100 \text{ GeV}$

$$p_T(\mu_1) > 25 \text{ GeV} \ , \ p_T(\mu_2) > 25 \text{ GeV} \ , \ |\eta_\mu| < 2.47$$

Observed events per bin

Signal

Background

$$\chi^2(\mu_s) = \min_{\{\mu_b\}} \sum_i \frac{(d_i - \mu_s s_i - \mu_b b_i)^2}{\mu_s s_i + \mu_b b_i}$$

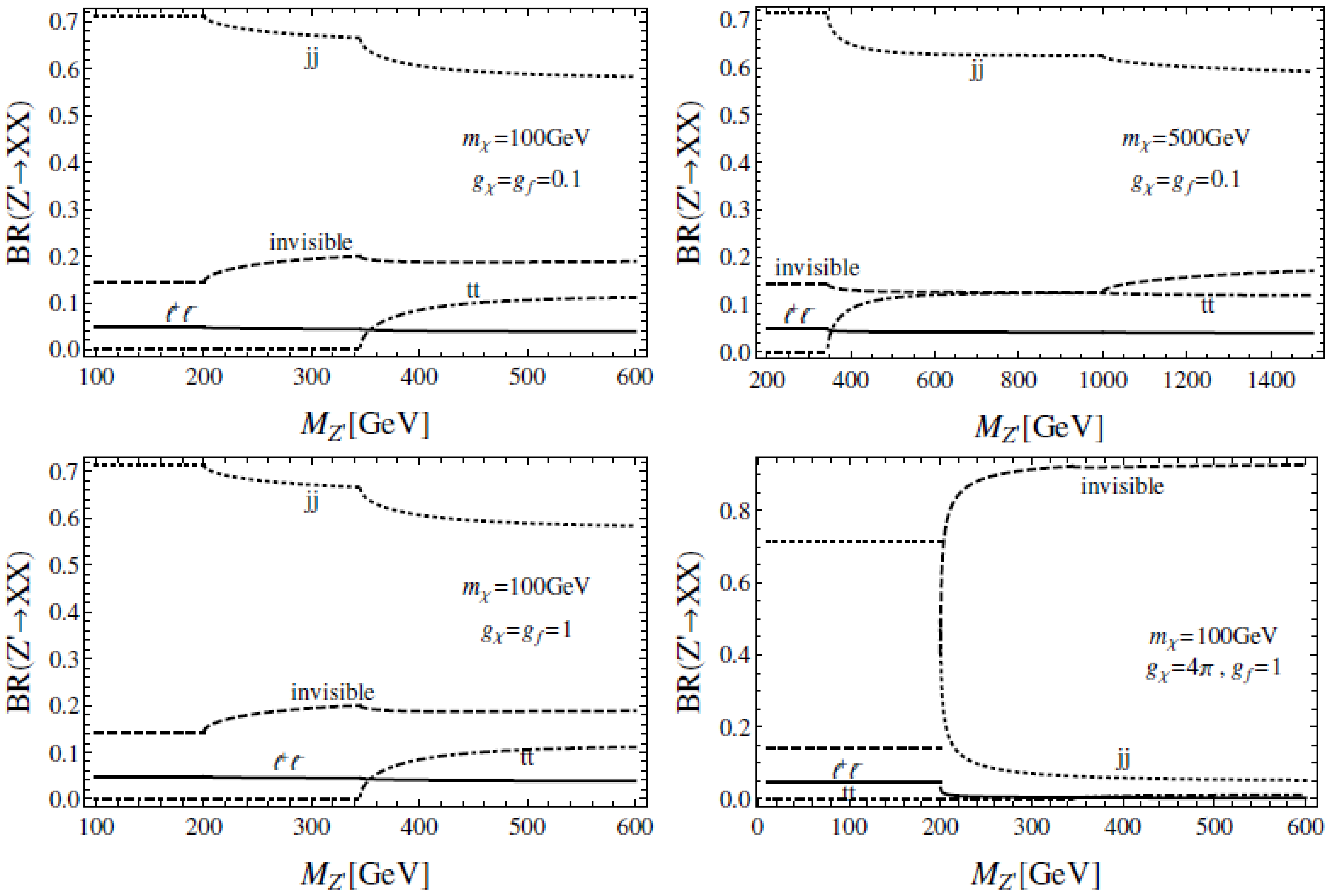
Best fit

$$q(\mu_s) = \chi^2(\mu_s) - \chi^2(\hat{\mu}_s)$$

$$\mathrm{CL_S} = \frac{1 - \Phi(\sqrt{q(\mu_s)})}{1 - \Phi(\sqrt{q(\mu_s)}) - \Phi(\sqrt{q_A(\mu_s)})} = 0.05$$

Cumulative probability of the standard Normal distribution

q-statistic in the background only hyphothesis


BR(Z'→XX)
$M_{Z'}$[GeV]
jj
invisible
tt
$\ell^+\ell^-$
m_χ=100GeV
g_χ=g_f=0.1
m_χ=500GeV
g_χ=g_f=0.1
m_χ=100GeV
g_χ=g_f=1
m_χ=100GeV
g_χ=4π , g_f=1

Search of heavy dilepton resonances

- $E_T(e_1) > 30\,\text{GeV}, E_T(e_2) > 30\,\text{GeV}, |\eta_e| < 2.5,$
- $p_T(\mu_1) > 30\,\text{GeV}, p_T(\mu_2) > 30\,\text{GeV}, |\eta_\mu| < 2.5,$
- $80\,\text{GeV} < M_{ll} < 6000\,\text{GeV},$

$$\frac{N_{\text{signal events}}(M^2_{\text{new}}, E_{\text{new}}, \mathcal{L}_{\text{new}})}{N_{\text{signal events}}(M^2, 13\text{ TeV}, 13.3 fb^{-1})} = 1,$$

Projected bounds obtained through COLLIDER REACH CODE