Cosmological constraints, and LHC signatures of a Z' mediator between dark matter and the SU(3) sector

Lucien Heurtier

Bruxelles, November 2015

Based on :

- E. Dudas, L.H., Y. Mambrini and B. Zaldivar, *"Extra U(1), effective operators, anomalies and dark matter"*, **Arxiv : 1307.0005**
- O. Ducu, L.H., J. Maurer, *"LHC signatures of a Z' mediator between dark matter and the SU(3) sector"* **ArXiv : 1509.05615**

Outline

- Why a $U(1)'$ symmetry?
- Introduction to an effective Z' model
- State of the art in the electroweak sector
- What about colour?
- Dark matter constraints
- LHC constraints
- New possible signatures at LHC?

Why a $U(1)'$ symmetry?

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Need to parametize our lack of knowledge!

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- Motivate additional effective operators
- Try to understand a smart toy-model!

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  $\longrightarrow$ FCNC constraints
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- **Uncharged SM fermions**
  $\longrightarrow$ Motivations from string theory (D-brane models)
  $\longrightarrow$ Heavy States $\rightsquigarrow$ effective higher-dimensional operators

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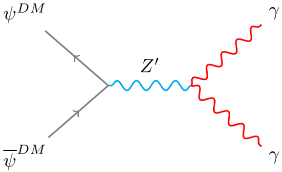
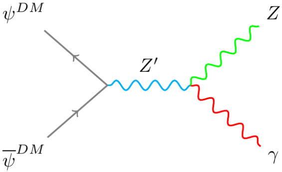
	ψ_{DM}	Ψ_M	ψ_{SM}
$U(1)'$	•	•	
$SU(3)_c \times SU(2)_L \times U(1)_Y$		•	•

The little story of a little rayline

Annihilation into photons :

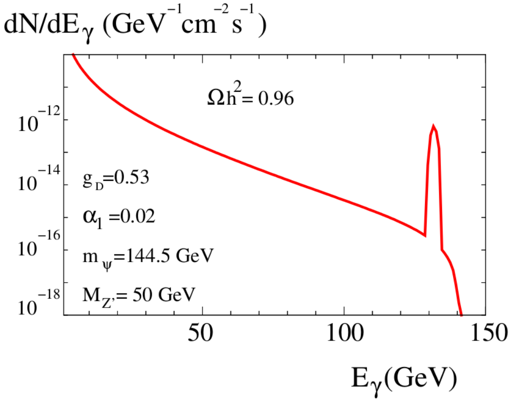




$$E_\gamma = m_{DM}\left(1 - \frac{m_Z^2}{4m_{DM}^2}\right) \quad (1.1)$$

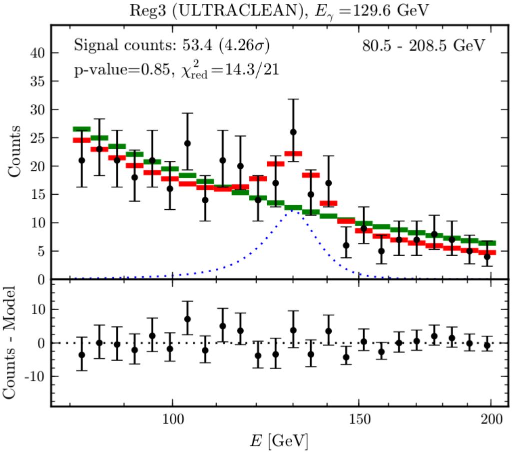
The little story of a little light ray

[Dudas et al., 2012]



The little story of a little light ray

[Weniger, 2012]



End of the story?...

$\hookrightarrow$ detected in other regions of the sky

$\hookrightarrow$ detector effects suspected...

◇ Look at other possible interactions : What about SU(3) channels?

Reminder Box

	ψ_{DM}	Ψ_M	ψ_{SM}
$U(1)'$	•	•	
$SU(3)_c \times SU(2)_L \times U(1)_Y$		•	•

Introduction : The model

◇ **Heavy intermediate states : heavy SM fermions**

Heavy mass scale : breaking of the heavy $U(1)'$ higgs sector

Stueckelberg realization

$$\Phi = \frac{V+\phi}{\sqrt{2}} exp(ia_X/V) \longrightarrow \Phi = \frac{V}{\sqrt{2}} exp(ia_X/V)$$

$U(1)'$ transformations

$$\delta Z'_\mu = \partial_\mu \alpha \quad , \quad \delta\theta_X = \frac{g_X}{2}\alpha \quad \text{where} \quad \theta_X \equiv \frac{a_X}{V}$$

Initial lagrangian

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu a_X - M_{Z'} Z'_\mu)^2 - \frac{1}{4} F^X_{\mu\nu} F^{X\,\mu\nu} \\
&+ \bar{\Psi}^i_L \left(i\gamma^\mu D_\mu + \frac{g_X}{2} X^i_L \gamma^\mu Z'_\mu \right) \Psi^i_L \\
&+ \bar{\Psi}^i_R \left(i\gamma^\mu D_\mu + \frac{g_X}{2} X^i_R \gamma^\mu Z'_\mu \right) \Psi^i_R \\
&- \left(\bar{\Psi}^i_L M_{ij} e^{\frac{i a_X (X^i_L - X^j_R)}{V}} \Psi^j_R + \text{h.c.} \right)
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$$

where $$M_{Z'} \equiv g_X \frac{V}{2}\,.$$

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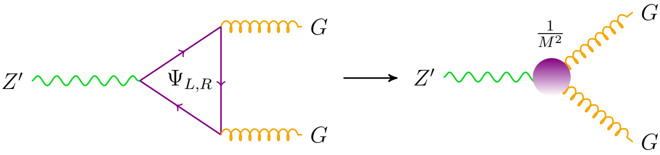
↪ Invariant under $U(1)'$ transformations

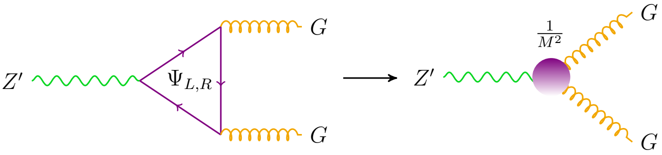
↪ $\mathcal{L}$ anomaly-free & $\mathcal{L}_{SM}$ neutral under $U(1)' \Rightarrow \Psi_M$ set anomaly-free

↪ Kinetic mixing term $\frac{\delta}{2}\, F^{\mu\nu}_X\, F^Y_{\mu\nu}$ is neglected Why ?...

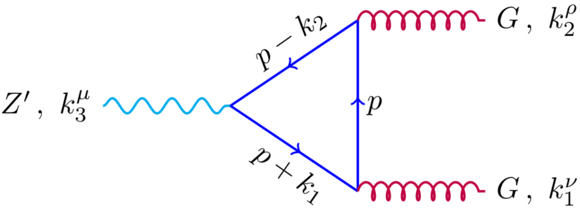
Effective couplings

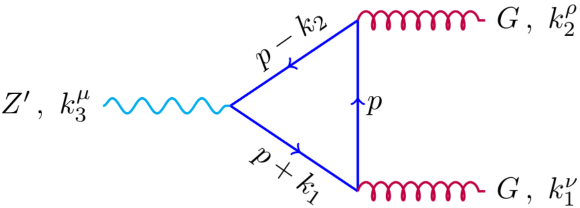


Effective couplings



$$
\begin{aligned}
\mathcal{L}^{(6)}_{\text{CP even}} &= \frac{1}{M^2}\Big\{ d_g \partial^\mu D_\mu \theta_X \mathcal{T}r(G\tilde{G}) + d'_g \partial^\mu D^\nu \theta_X \mathrm{Tr}(G_{\mu\rho}\tilde{G}^\rho_\nu) \\
&+ e_g D^\mu \theta_X \mathrm{Tr}(G_{\nu\rho}\mathcal{D}_\mu \tilde{G}^{\rho\nu}) + e'_g D_\mu \theta_X \mathrm{Tr}(G_{\alpha\nu}\mathcal{D}^\nu \tilde{G}^{\mu\alpha}) \Big\} \\
&+ \frac{1}{M^2}\Big\{ D^\mu \theta_X \left[i(D^\nu H)^\dagger (c_1 \tilde{F}^Y_{\mu\nu} + 2c_2 \tilde{F}^W_{\mu\nu}) H + h.c. \right] \\
&+ \partial^m D_m \theta_X (d_1 \mathcal{T}r(F^Y \tilde{F}^Y) + 2 d_2 \mathcal{T}r(F^W \tilde{F}^W)) \\
&+ d'_{ew} \partial^\mu D^\nu \theta_X \mathrm{Tr}(F_{\mu\rho}\tilde{F}^\rho_\nu) \\
&+ e_{ew} D^\mu \theta_X \mathrm{Tr}(F_{\nu\rho}\mathcal{D}_\mu \tilde{F}^{\rho\nu}) + e'_{ew} D_\mu \theta_X \mathrm{Tr}(F_{\alpha\nu}\mathcal{D}^\nu \tilde{F}^{\mu\alpha}) \Big\} \quad (1.2)
\end{aligned}
$$


Z' , k_3^μ
$p - k_2$
p
$p + k_1$
G , k_2^ρ
G , k_1^ν



$$\mathcal{O} = \frac{g_3^2}{24\pi^2}\sum_i \mathrm{Tr}\left(\frac{(X_L - X_R)T_a T_a}{M^2}\right)_i$$

$$\times \left[\partial^\mu D_\mu \theta_X \mathcal{T}r(G\tilde{G}) - 2D_\mu\theta_X \mathrm{Tr}(G_{\alpha\nu}\mathcal{D}^\nu \tilde{G}^{\mu\alpha})\right]$$

couplings

$$\mathcal{L}_{\text{CP even}} = \frac{1}{M^2}\Big\{ d_g \partial^\mu D_\mu \theta_X Tr(G\tilde{G}) + d'_g \partial^\mu D^\nu \theta_X \mathrm{Tr}(G_{\mu\rho}\tilde{G}^\rho_\nu) + e_g D^\mu \theta_X \mathrm{Tr}(G_{\nu\rho}\mathcal{D}_\mu \tilde{G}^{\rho\nu}) + e'_g D_\mu \theta_X \mathrm{Tr}(G_{\alpha\nu}\mathcal{D}^\nu \tilde{G}^{\mu\alpha}) \Big\}$$

$$\mathcal{L}_{DM} = \bar{\psi}_L^{DM} \frac{1}{2} g_X X_L^{DM} \gamma^\mu Z'_\mu \psi_L^{DM} + \bar{\psi}_R^{DM} \frac{1}{2} g_X X_R^{DM} \gamma^\mu Z'_\mu \psi_R^{DM}$$

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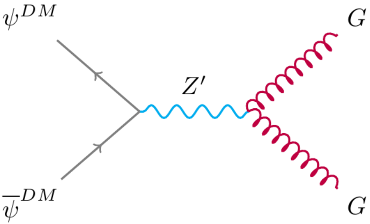

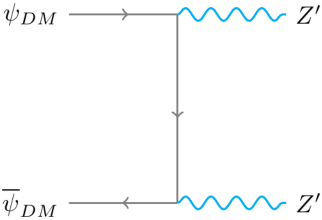

DM annihilation into Gluons

$\hookrightarrow$Non-chiral dark matter : no contribution

DM annihilation into Gluons

↪Non-chiral dark matter : no contribution

↪Chiral dark matter :

$$\langle \sigma v \rangle_{s-ch.} \simeq \frac{d_g^2}{M^4} \frac{g_X^4 m_\psi^6 (X_L - X_R)^2}{\pi M_{Z'}^4} \left\{ \frac{2\left(M_{Z'}^2 - 4m_\psi^2\right)^2}{\left(M_{Z'}^2 \Gamma^2(Z') + \left(M_{Z'}^2 - 4m_\psi^2\right)^2\right)} \right\}$$

$$\langle \sigma v \rangle_{t-ch.} \simeq \frac{g_X^4 \sqrt{m_\psi^2 - M_{Z'}^2}}{128\pi^2 m_\psi M_{Z'}^2 \left(2m_\psi^2 - M_{Z'}^2\right)^2} P_4\left(m_\psi^2, M_{Z'}^2, X_R^2, X_L^2\right)$$

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Main features :

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$\hookrightarrow$T-channel opening at $m_\psi = M_{Z'}$

$\hookrightarrow$T-channel mostly sensible to g_X

Experimental constraints

A few parameters in this model : $M_{Z'}$, m_ψ, g_X, $\frac{d_g}{M^2}$, X_L, X_R.

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Experimental constraints :

- Relic abundance
- Indirect detection
- LHC mono-jets events

What about direct detection?

Direct detection?

- Integrating out Z' :

$$\frac{d_g}{M^2 M_{Z'}^2} \bar{\psi}^{DM}\gamma^\mu\left(\frac{X_R+X_L}{2}+\frac{X_R-X_L}{2}\gamma_5\right)\psi^{DM}\mathcal{T}r\ \partial_\mu(G\tilde{G})$$

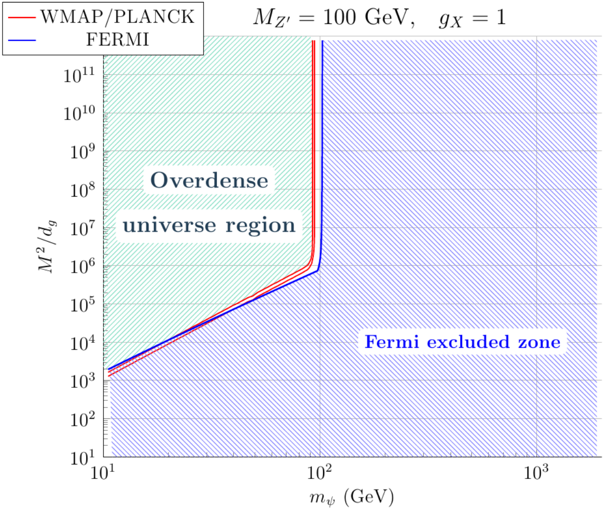
- Imposing CP invariance for strong interactions :

$\langle N(p)|\mathrm{Tr}\ G_\mu^\nu \tilde{G}_\nu^\lambda|N(p')\rangle = A\epsilon_\mu^{\lambda\alpha\beta}p_\alpha p'_\beta$ where A invariant.

$$\Rightarrow \quad \langle N(p)|\mathcal{T}r\ \partial_\mu(G\tilde{G})|N(p')\rangle = 0$$

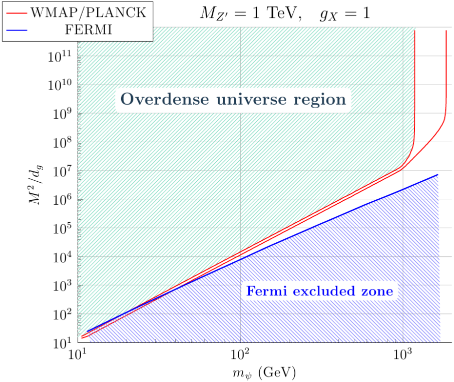
No constraint from direct detection.

Relic abundance and indirect detection



Other curves

Relic abundance and indirect detection



Other curves

LHC constraints

Possible mono-jets final states

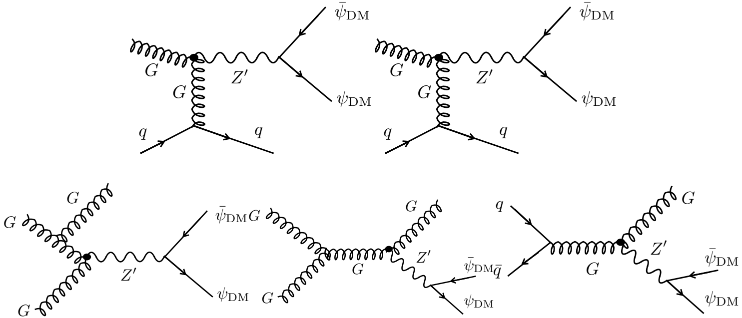


Figure : Dark matter production processes at the LHC (at partonic level), in association with 1 jet: $p\ p \rightarrow j\bar{\psi}_{\rm DM}\psi_{\rm DM}$.

LHC constraints

Using CMS data [[CMS Collaboration], CMS-PAS-EXO-12-048],
$E_{CM} = 8$ TeV:

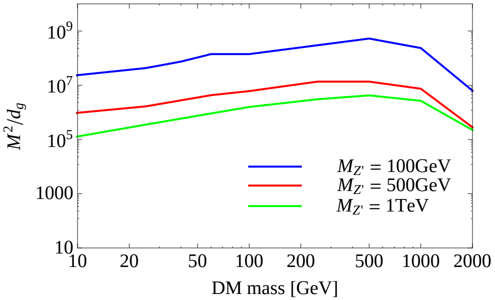
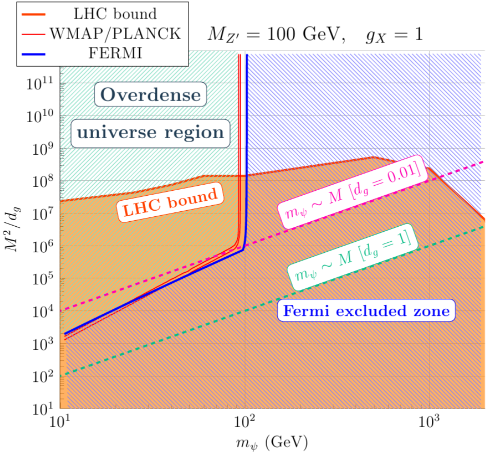


Figure : 90% CL lower bounds on the quantity M^2/d_g as a function of the dark matter mass, for $M_{Z'} = 100$ GeV (blue), 500 GeV (red) and 1 TeV (green). Based on the CMS analysis with collected data using a center-of-mass energy of 8 TeV and a luminosity of 19.5/fb.

Synthesis



Other curves

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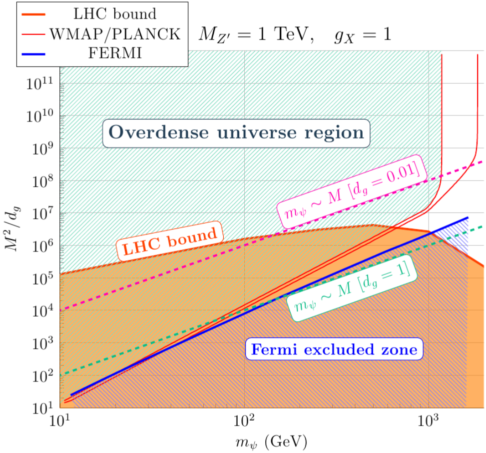
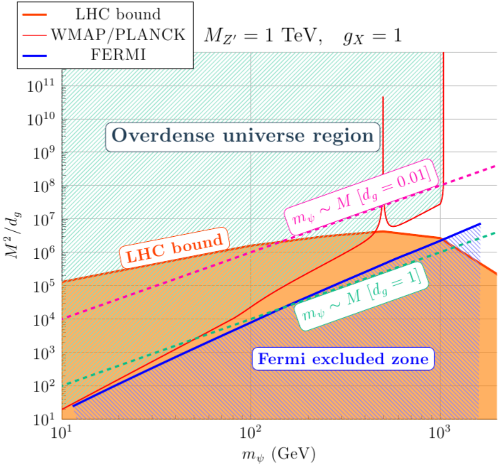


Other curves

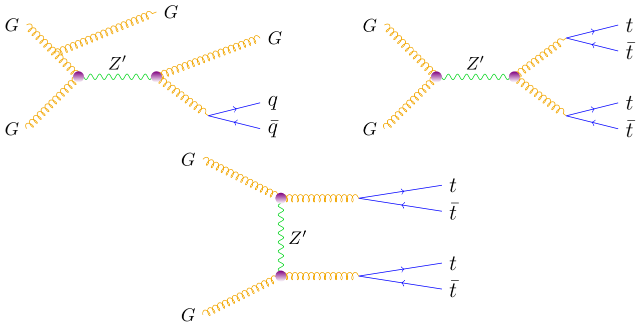
Comparison with EW sector



Other curves

Any signature? ...

Interesting channels : multi-tops production



- $Z' \to GG$ forbidden by Landau-Yang
- Need (e.g.) ISR to feel the resonance
- Off-shell contributions in the $t\bar{t}t\bar{t}$ channel

Interesting channels : multi-tops production

1/ Tri-jets invariant mass :

- ISR+$Z' \rightarrow q\bar{q}G$ (Br $\sim$ 100 %)
- Studies of resonances : mainly di-jets or pair production
- Yet, at 7TeV : $\frac{d\sigma}{d\Omega}(m_{jjj})$:
  [*Khachatryan et al.* (CMS) arXiv:1412.1633]

$\hookrightarrow$ Upper limit on $\frac{d_g}{M^2}$

Tri-jets invariant mass

- Reproduce CMS cuts : $p_T > 100\text{GeV}$, $|y| < 3.0$
- Dissociate $|y|_{max} < 1$ and $1 \leqslant |y|_{max} \leqslant 2$
- Using Madgraph, CTEQ6L1, Pythia to MC, pdf and hadronisation

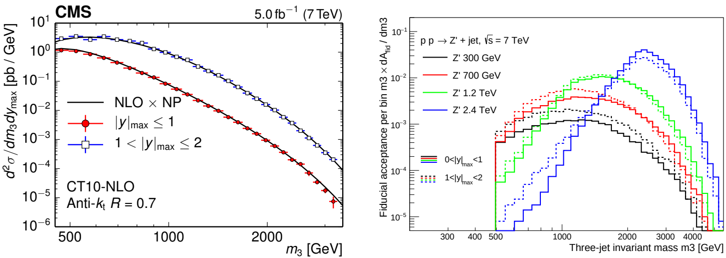
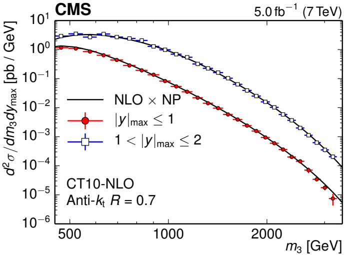
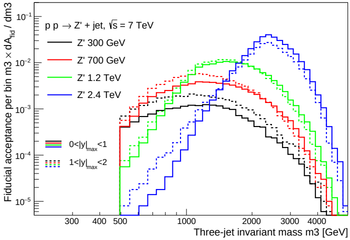


Figure : Three-jet invariant mass spectrum for QCD (left) and Z' signal models of various masses (right).

Tri-jets invariant mass





- Light Z' : peak smeared $\rightarrow$ ISR selected in the tri-jets ...
- $+$: Populates high energetic bins
- $+$: QCD background is lower there
- - : Interpretation of the signal rendered less trivial..
- Exclusion limits on Z' at 7 TeV $\rightarrow$ upper limits on d_g/M^2

$t\bar{t}t\bar{t}$ production

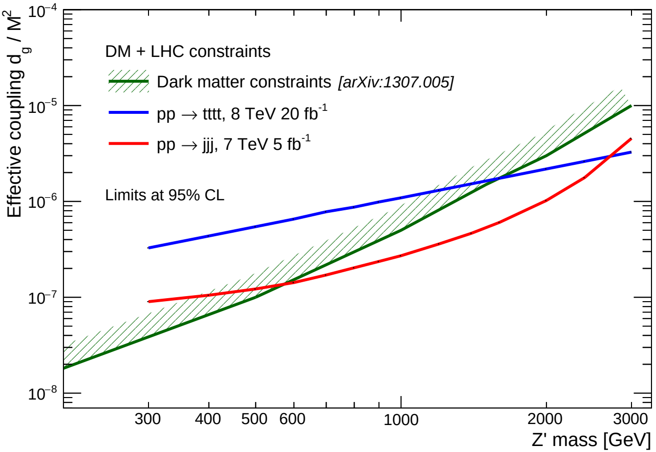
- A promising channel : $t\bar{t}t\bar{t}$

	SM	Z' 300GeV	500GeV	800GeV	1.6TeV	3TeV
8TeV	$\sim$ 1.3 fb	2.8 pb	0.36 pb	55 fb	5.9 fb	0.28 fb
13TeV	9.2 fb	0.57 μb	74 pb	11 pb	1.2 pb	57 fb

- Very small coupling in the SM
- Landau-Yang suppression $\rightarrow$ off-shell contributions
  $\hookrightarrow$ no dependance on the Z' width
- Interferences SM-Z' negligible (<5%)
- CMS bound : $\sigma(t\bar{t}t\bar{t}) < 32\text{fb}$ at 8TeV

[Khachatryan et al.[CMS Collaboration] arXiv:1409.7339]

Constraints of LHC, run 1

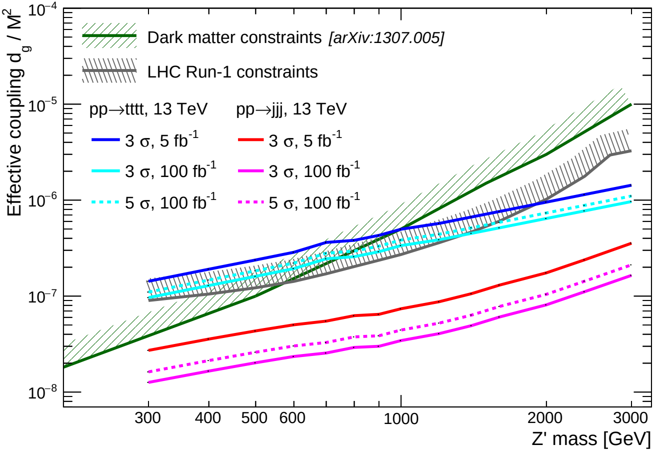


From exclusion limits to projections

- LHC run 2 : up to $100fb^{-1}$ at 13 TeV
- Potential of discovery for this model?
- **Tri jets :** MC simulation of the background for $pp \to jjj$ up to $m_{Z'} = 5\mathrm{TeV}$
  $\hookrightarrow$ Overestimation of the background compared to CMS at high E : more conservative in our case
- **Four-tops :** at 13 TeV :

$$\sigma_{SM}(t\bar{t}t\bar{t}) \to \times 7$$
$$\sigma_{Z'}(t\bar{t}t\bar{t}) \to \times 200 \text{ !}$$

Results


Effective coupling d_g / M^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Dark matter constraints *[arXiv:1307.005]*
LHC Run-1 constraints
pp→tttt, 13 TeV
3 σ, 5 fb^{-1}
3 σ, 100 fb^{-1}
5 σ, 100 fb^{-1}
pp→jjj, 13 TeV
3 σ, 5 fb^{-1}
3 σ, 100 fb^{-1}
5 σ, 100 fb^{-1}
300
400
500
600
1000
2000
3000
Z' mass [GeV]

Conclusions and outlooks

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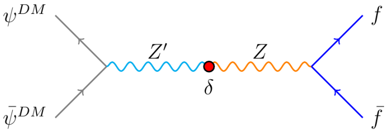
- Possible predictions for the next runs of the LHC...

The End

Thank you!

Constraints on kinetic mixing

If not neglected $\longrightarrow$ new diagrams



$$\langle \sigma v \rangle_{GG} \simeq \frac{d_g^2}{M^4} \frac{2 g_X^4}{\pi} \frac{m_\psi^6}{M_{Z'}^4} \ . \qquad (5.1)$$

$\rightarrow$[X. Chu, Y. Mambrini, J. Quevillon and B. Zaldivar, arXiv:1306.4677 [hep-ph]]

$$\langle \sigma v \rangle_\delta \simeq \frac{16}{\pi} g_X^2 g^2 \delta^2 \frac{m_\psi^2}{M_{Z'}^4} \quad , \quad m_\psi < M_Z$$

$$\langle \sigma v \rangle_\delta \simeq \frac{g_X^2 g^2 \delta^2 M_Z^4}{\pi m_\psi^2 M_{Z'}^4} \quad , \quad m_\psi > M_Z . \qquad (5.2)$$

Constraints on kinetic mixing

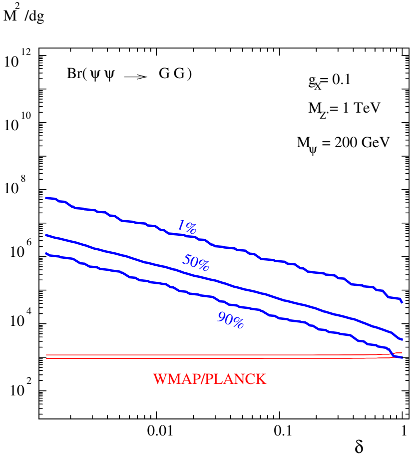
Kinetic mixing competes with other effective operators if

$$\delta \gtrsim \frac{d_g}{M^2} \frac{g x}{2\sqrt{2} g} m_\psi^2 \quad , \quad m_\psi < M_Z$$

$$\delta \gtrsim \frac{d_g}{M^2} \frac{\sqrt{2} g x}{g} \frac{m_\psi^4}{M_Z^2} \quad , \quad m_\psi > M_Z \tag{5.3}$$

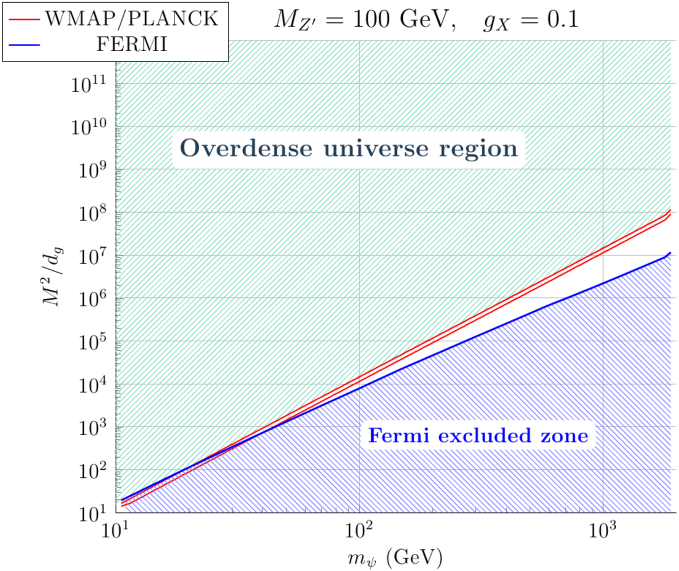
$\hookrightarrow$ For $m_\psi = 200$ GeV : $\frac{d_g}{M^2} \lesssim 10^{-4} \times \delta \;\; GeV^{-2}$

Constraints on kinetic mixing

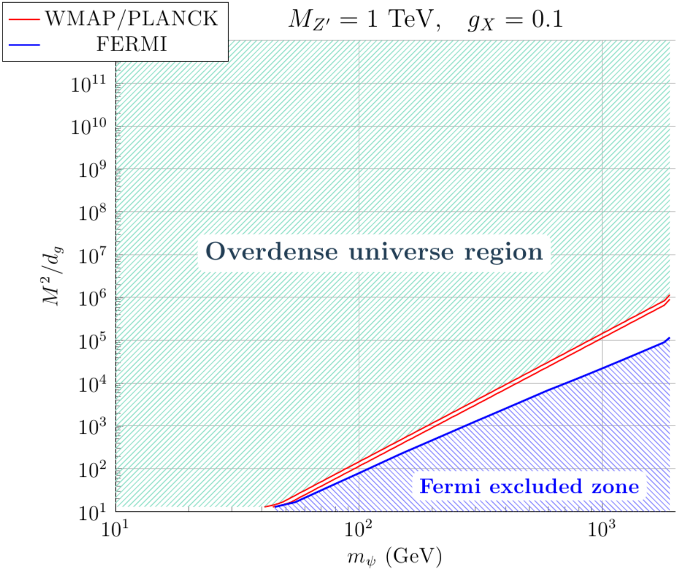


$\hookrightarrow$ $\delta \gtrsim 0.8$ excluded by LEP experiments...

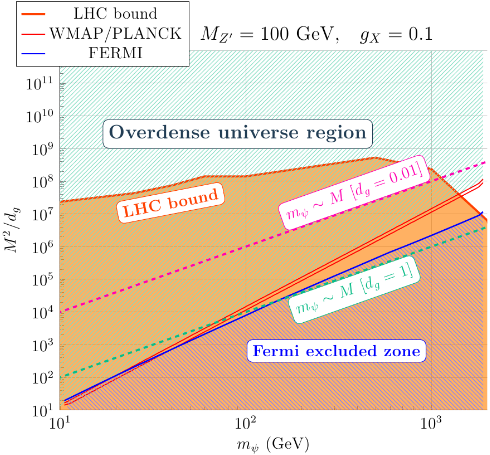
Relic abundance and indirect detection



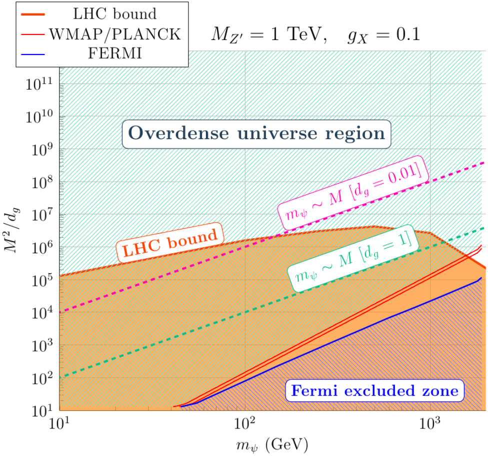
Relic abundance and indirect detection



Synthesis


LHC bound
WMAP/PLANCK
FERMI
$M_{Z'} = 100$ GeV, $g_X = 0.1$
Overdense universe region
LHC bound
$m_\psi \sim M$ [$d_g = 0.01$]
$m_\psi \sim M$ [$d_g = 1$]
Fermi excluded zone
M^2/d_g
m_ψ (GeV)
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^1
10^2
10^3

Synthesis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10^1
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10^{10}
10^{11}