Effective Theory for Electroweak Doublet Dark Matter

Dimitrios Karamitros

University of Ioannina,
Greece

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In collaboration with

Athanasios Dedes and Vassilis Spanos

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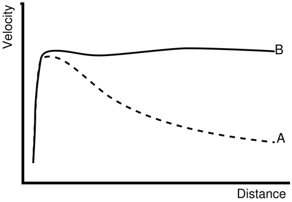
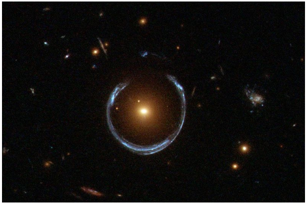
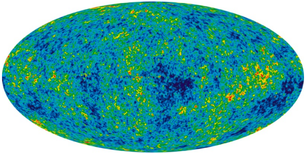
Why dark matter







There is extra matter in the universe! Relic abundance[1] $\Omega h^2 \sim 0.12$.

[1] P. Ade et al. Astron. Astrophys. **571**, A16 (2014) [arXiv:1303.5076].

WIMPs

WIMP=Weakly Interacting Massive Particle.

- Lifetime much larger than the age of the universe.
- Electrically neutral (because it's dark).
- Interacts weakly.
- Massive (cold dark matter).

Freeze-out of WIMPs

Three stages:

- Everything is in equilibrium. $T \gtrsim M_{DM}$.
- WIMP production stops. $T \lesssim M_{DM}$.
- WIMP annihilation stops (becomes much smaller than the expansion rate of the universe). $T = T_{FO} \sim \dfrac{M_{DM}}{20}$.

EFT Content

- A pair of Weyl fermion $SU(2)_L$ doublets with opposite hypercharges (anomaly free).
- Z_2 parity (stable lightest particle).
- Non-renormalizable dim=5 operators in the Lagrangian $\Rightarrow$ Yukawa interactions, mass splitting and dipole operators.
- A symmetry which limits the number of free parameters.

Motivation

- Dark Matter around the Electroweak scale $\Rightarrow$ possible detection at LHC.
- Non-zero dipole moments $\Rightarrow$ indirect detection via gamma-ray lines.
- Custodial symmetry in the Yukawa sector helps avoiding direct detection without fine tuning (small number of relevant parameters).
- Since it is an Effective Theory, it shows that there is a family of models with similar features.
- Fermionic bi-doublets in many models like MSSM, doublet-singlet, doublet-triplet, $SO(10)$ GUTs and subgroups (left-right symmetric model).

Yukawa interactions

$$- \mathcal{L}_{\text{mass+Yukawa}} \supset \frac{y_1}{2\,\Lambda_{UV}} (H^T \epsilon D_1)\,(H^T \epsilon D_1) + \frac{y_2}{2\Lambda_{UV}} (H^\dagger D_2)\,(H^\dagger D_2)$$

$$+ \frac{y_{12}}{\Lambda_{UV}} (H^T \epsilon D_1)\,(H^\dagger D_2) + \frac{\xi_{12}}{\Lambda_{UV}} (D_1^T \epsilon D_2)(H^\dagger H) + M_D\, D_1^T \epsilon D_2$$

$$+ \text{H.c.}$$

The Yukawa parameters are assumed to be real numbers. M_D can be redefined (through redefinition of the doublets) to be a real positive number.

Symmetries I: Custodial Symmetry

Representing H and $D_{1,2}$ as[2]

$$\mathcal{H} = \begin{pmatrix} -H^{0*} & H^{+} \\ H^{-} & H^{0} \end{pmatrix}$$

and

$$\mathcal{D} = \begin{pmatrix} D_1^0 & D_2^+ \\ D_1^- & D_2^0 \end{pmatrix}$$

The Yukawa sector is invariant under and $SU(2)_R$ (custodial) with

$$\mathcal{H} \to U_L \mathcal{H} U_R$$

$$\mathcal{D} \to U_L \mathcal{D} U_R$$

for $\mathbf{y_1} = \mathbf{y_2} = \mathbf{y}$, $\mathbf{y_{12}} = \pm\mathbf{y}$

$$-\mathcal{L}_{\mathrm{y_1,y_2,y_{12}}} \supset \frac{y}{\Lambda_{UV}} \left[Tr(\mathcal{H}^{\dagger}\mathcal{D}) \right]^2 + H.c.$$

[2] Similar to P. Sikivie, L. Susskind, M. B. Voloshin, and V. I. Zakharov, Isospin Breaking in Technicolor Models, Nucl.Phys. B173 (1980) 189.

Dipole operators

$$\mathcal{L}_{\rm dipoles} \supset \frac{d_\gamma}{\Lambda_{UV}} D_1^T \sigma^{\mu\nu} \epsilon D_2 B_{\mu\nu} + \frac{d_W}{\Lambda_{UV}} \left(D_1^T \sigma^{\mu\nu} \epsilon \vec{\tau} D_2\right) \cdot \vec{W}_{\mu\nu} +$$

$$\frac{i\, e_\gamma}{\Lambda_{UV}} D_1^T \sigma^{\mu\nu} \epsilon D_2 \widetilde{B}_{\mu\nu} + \frac{i\, e_W}{\Lambda_{UV}} \left(D_1^T \sigma^{\mu\nu} \epsilon \vec{\tau} D_2\right) \cdot \widetilde{\vec{W}}^A_{\mu\nu} +$$

$$\text{H.c.}\ ,$$

where d_γ and d_W are real numbers and, since we are not concerned about CP violation, $e_\gamma = e_W = 0$.

Symmetries II: Charge Conjugation

For $\mathbf{y_1} = \mathbf{y_2} = \mathbf{y}$, the dark sector is invariant under a Charge Conjugation, which exchanges D_1 and D_2.

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Benchmark points:

$$y_{12} = -y, 0.$$

Finally, the free parameters are:

$$\Lambda_{UV}, \; M_D, \; y, \; \xi_{12}, \; d_W, \; d_\gamma$$

Physical states: particles and masses

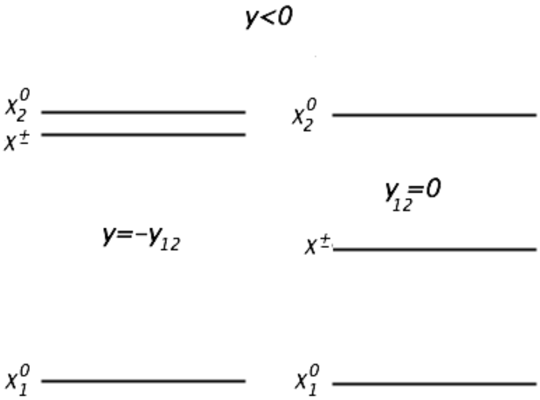
After diagonalization of the mass matrix:

$$\chi_1^0 = \frac{1}{\sqrt{2}} \left(D_1^0 + D_2^0 \right) , \quad \chi_2^0 = -\frac{i}{\sqrt{2}} \left(D_1^0 - D_2^0 \right) ,$$

$$\chi^+ = i\, D_2^+ , \qquad \chi^- = i\, D_1^- .$$

$$\begin{aligned} m_{\chi^\pm} &= M_D + \xi_{12}\,\omega , \\ m_{\chi_1^0} &= m_{\chi^\pm} + \omega\,(y - y_{12}) , \qquad \omega \equiv \frac{v^2}{\Lambda_{UV}} , \\ m_{\chi_2^0} &= m_{\chi^\pm} - \omega\,(y + y_{12}) . \end{aligned}$$

Spectrum



Physical states: fermion fermion Higgs interaction

$$\mathcal{L}^{\rm dim=5}_{\chi\,\chi\,\rm h} = - \, Y^{h\chi^-\chi^+} \, h \, \chi^- \, \chi^+ \; - \; \frac{1}{2} \, Y^{h\chi_i^0\chi_j^0} \, h \, \chi_i^0 \, \chi_j^0 \; ,$$

$$Y^{h\chi^-\chi^+} = \sqrt{2}\,\xi_{12}\,\frac{\omega}{v},$$

$$Y^{h\chi_1^0\chi_1^0} = \frac{\sqrt{2}\,\omega}{v}\,(\xi_{12} + y - y_{12}),$$

$$Y^{h\chi_2^0\chi_2^0} = \frac{\sqrt{2}\,\omega}{v}\,(\xi_{12} - y - y_{12}),$$

$$Y^{h\chi_1^0\chi_2^0} = 0.$$

Notice that the custodial fixes $Y^{h\chi_1^0\chi_1^0} \sim \xi_{12} + y - y_{12}$, so current Direct Detection can be avoided easily. There is at least one model[3] where, under the same custodial, $Y^{h\chi_1^0\chi_1^0} = 0$ (at tree level).

[3] Doublet-Triplet Fermionic Dark Matter. A.Dedes and D.Karamitros PhysRevD.89.115002 [arXiv:1403.7744].

Physical states: neutral Gauge boson interactions

$$\mathcal{L}^{\rm dim=4}_{\rm neutral\ 3-point} = -(+e)\,(\chi^+)^\dagger \bar\sigma^\mu \chi^+ \, A_\mu - (-e)\,(\chi^-)^\dagger \bar\sigma^\mu \chi^- \, A_\mu + \frac{g}{c_W} O'^{\,L}\,(\chi^+)^\dagger\,\bar\sigma^\mu\,\chi^+\,Z_\mu - \frac{g}{c_W} O'^{\,R}\,(\chi^-)^\dagger\,\bar\sigma^\mu\,\chi^-\,Z_\mu + \frac{g}{c_W} O''^{\,L}_{ij}\,(\chi^0_i)^\dagger\,\bar\sigma^\mu\,\chi^0_j\,Z_\mu,$$

$$\mathcal{L}^{\rm dim=5}_{\rm neutral\ 3-point} = -\frac{\omega}{v^2}\,(d_\gamma\, s_W + d_W\, c_W)\,O''^{L}_{ij}\,\chi^0_i\,\sigma_{\mu\nu}\,\chi^0_j\,F^{\mu\nu}_Z - \frac{\omega}{v^2}\,(d_\gamma\, s_W - d_W\, c_W)\,\chi^-\,\sigma_{\mu\nu}\,\chi^+\,F^{\mu\nu}_Z + \frac{\omega}{v^2}\,(d_\gamma\, c_W - d_W\, s_W)\,O''^{L}_{ij}\,\chi^0_i\,\sigma_{\mu\nu}\,\chi^0_j\,F^{\mu\nu}_\gamma + \frac{\omega}{v^2}\,(d_\gamma\, c_W + d_W\, s_W)\,\chi^-\,\sigma_{\mu\nu}\,\chi^+\,F^{\mu\nu}_\gamma + \text{H.c.}$$

$$O'^{\,L} = O'^{\,R} = -\frac{1}{2}(1-2s_W^2) \text{ and } O''^{\,L} = -\frac{i}{2}\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Physical states: charged Gauge boson interactions

$$\mathcal{L}^{\mathrm{dim}=4}_{\mathrm{charged\ 3-point}} = g\ O_i^L\,(\chi_i^0)^\dagger\,\bar{\sigma}^\mu\,\chi^+\,W_\mu^- - g\ O_i^R\,(\chi^-)^\dagger\,\bar{\sigma}^\mu\,\chi_i^0\,W_\mu^- + g\ O_i^{L*}\,(\chi^+)^\dagger\,\bar{\sigma}^\mu\,\chi_i^0\,W_\mu^+ - g\ O_i^{R*}\,(\chi_i^0)^\dagger\,\bar{\sigma}^\mu\,\chi^-\,W_\mu^+,$$

$$\mathcal{L}^{\mathrm{dim}=5}_{\mathrm{charged\ 3-point}} = -\,2\frac{\omega}{v^2}\,d_W\ O_i^{R\,*}\,\chi^-\,\sigma_{\mu\nu}\,\chi_i^0\,F^{\mu\nu}_{W^+} + 2\frac{\omega}{v^2}\,d_W\ O_i^L\,\chi^+\,\sigma_{\mu\nu}\,\chi_i^0\,F^{\mu\nu}_{W^-}\ +\ \mathrm{H.c.}$$

$$O_i^L = \frac{1}{2}\begin{pmatrix} i \\ -1 \end{pmatrix},\ O_i^R = \frac{1}{2}\begin{pmatrix} i \\ -1 \end{pmatrix}.$$

"Earth" Constraints

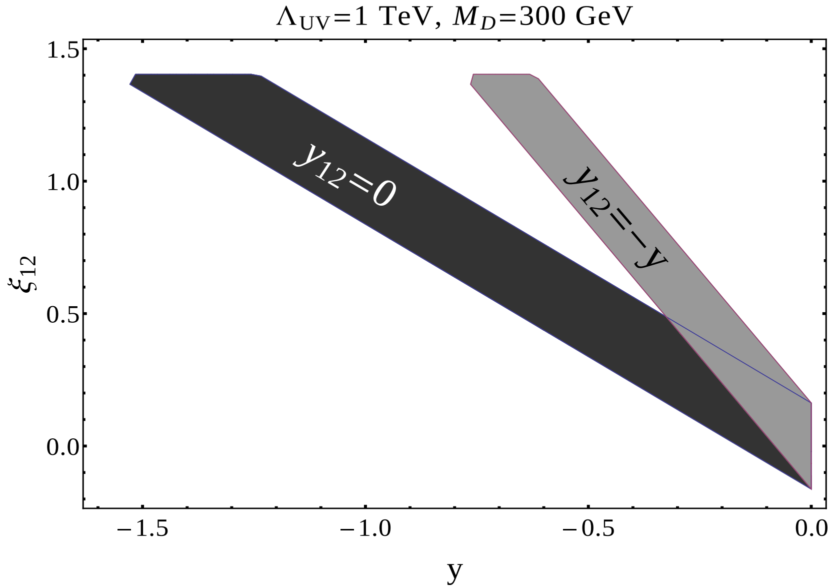
- *Direct Detection experiments (LUX*[4]*) limit* $\xi_{12} + y - y_{12}$.
- *LEP*[5] $\Rightarrow m_{\chi^\pm} = \xi_{12}\dfrac{v^2}{\Lambda_{UV}} + M_D \gtrsim 100\ GeV$.
- *CMS and ATLAS*[6] $h \to \gamma\gamma$ *limits* $\dfrac{\xi_{12} v^2}{m_{\chi^\pm}\Lambda_{UV}}$.

Result:

- $M_D \gtrsim 90 GeV$ (mainly from LEP).
- $\xi_{12} \approx -(2)y \pm 0.16$ (from LUX).
- small values of ξ_{12} (from LHC: $BR_{h\to\gamma\gamma}$).

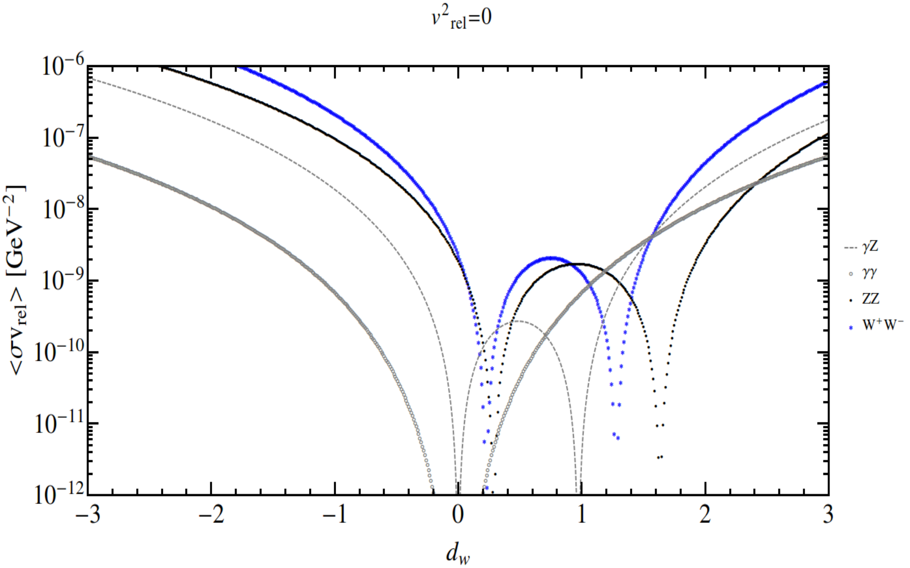
[4] D. S. Akerib et al. Phys. Rev. Lett. **116** (2016) no.16, 161301 [arXiv:1512.03506].
[5] P. Achard et al. Phys. Lett. B **517**, 75 (2001) [hep-ex/0107015].
[6] G. Aad et al. Phys. Rev. Lett. **114** (2015) 191803 [arXiv:1503.07589].

"Earth" Constraints

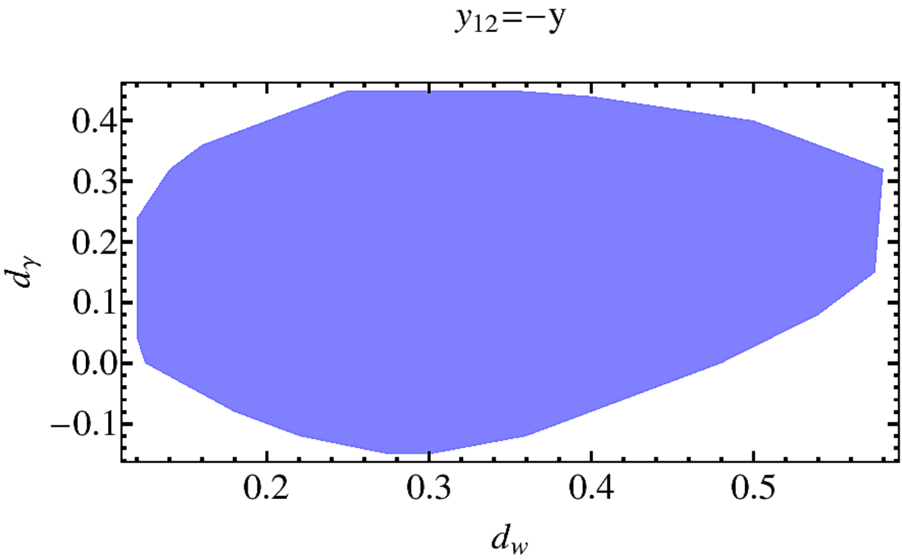


The role of dipoles

The dipoles minimize the total annihilation cross section.



"Astrophysical" Constraints (Relic Density)



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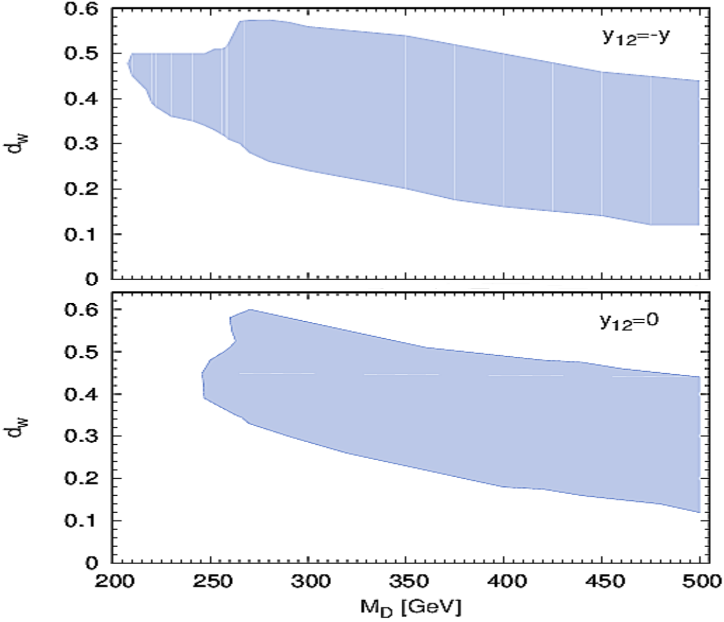

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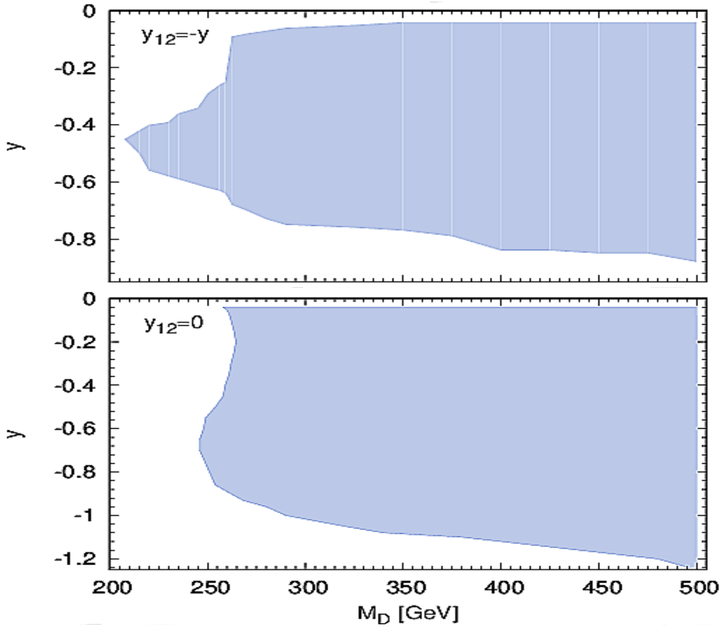
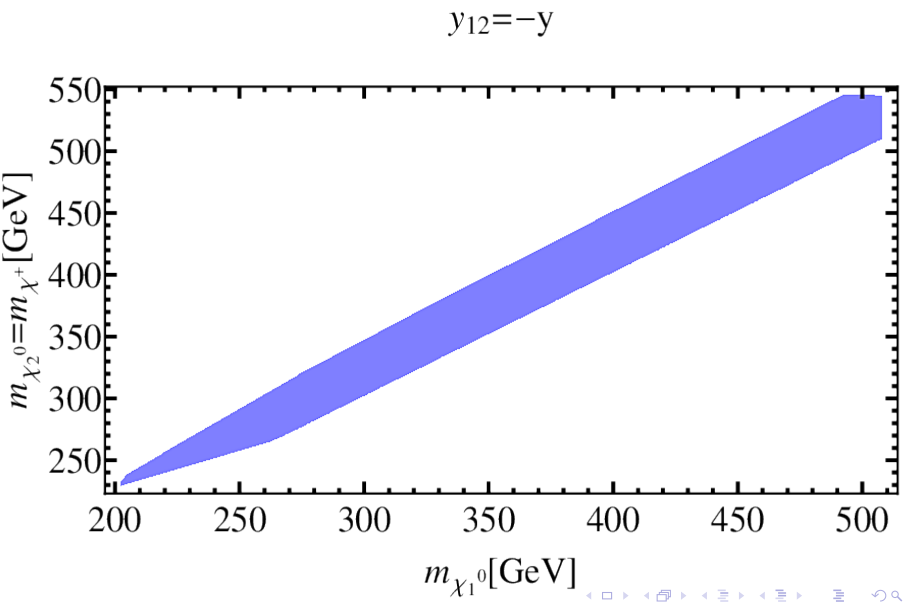
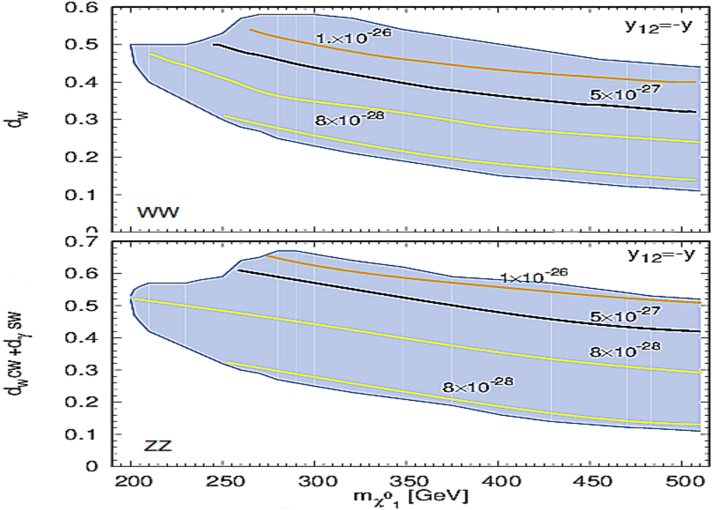




y12=−y
550
500
450
400
350
300
250
200
250
300
350
400
450
500
$m_{\chi_2^0}=m_{\chi^+}$[GeV]
$m_{\chi_1^0}$[GeV]

"Astrophysical" Constraints (Continuous Gamma-rays)

Fermi-LAT[7] bound from *dwarf Spheroidal galaxies:* $< \sigma_{DMDM \to WW,\, ZZ} v > \lesssim 5 \times 10^{-26}\ cm^3 s^{-1}$ *(for Dark Matter mass above* $\sim 200\ GeV$*, assuming* $BR = 100\%$*)*



[7] M. Ackermann et al. Phys. Rev. Lett. **115** (2015) no.23, 231301 [arXiv:1503.02641].

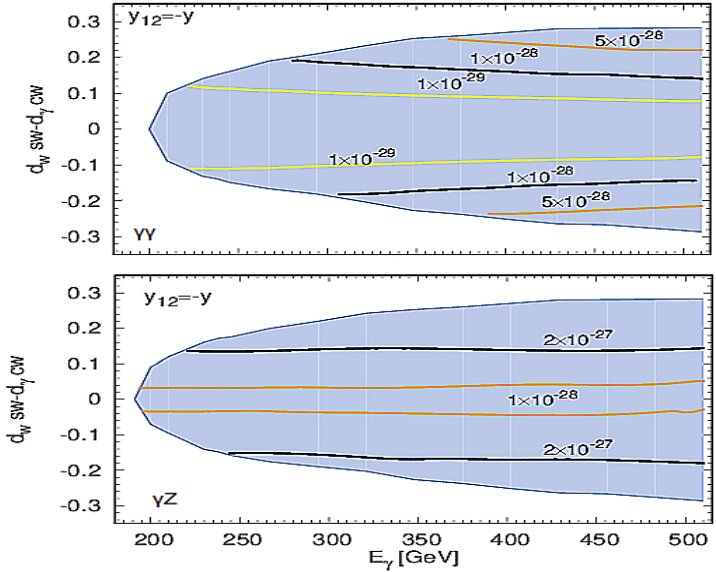
"Astrophysical" Constraints (Gamma-ray lines)

Fermi-LAT[8] bounds on the annihilation of Dark Matter particles to monochromatic gamma rays at the center of our galaxy. There are two relevant channels in this model, since the coupling to the Higgs is suppressed from Direct Detection.

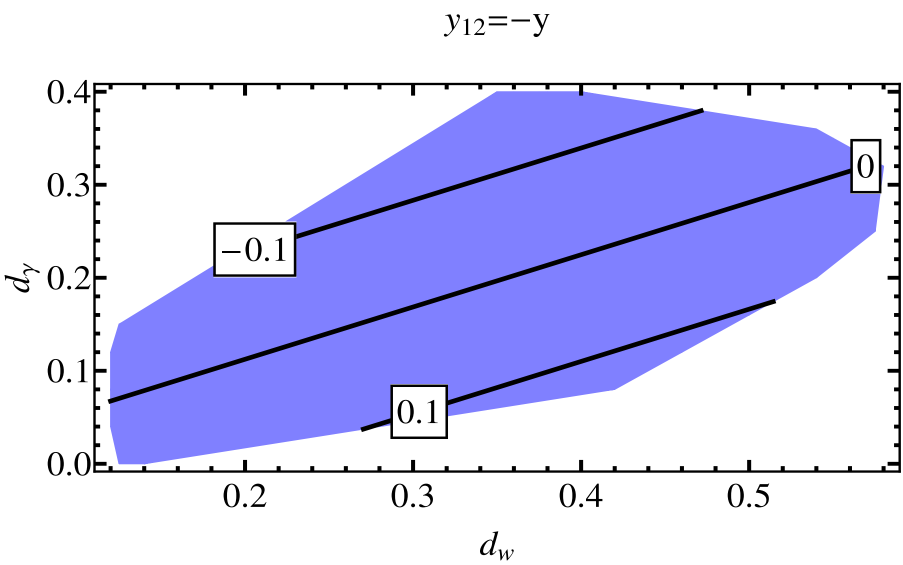
- $\chi_1^0\,\chi_1^0 \to \gamma\,\gamma$, with energy $E_\gamma = m_{\chi_1^0}$.
  Cross section$\lesssim 10^{-28} - 3 \times 10^{-28}\ cm^3 s^{-1}$ for photon energies $\sim 200 - 500\ GeV$.
- $\chi_1^0\,\chi_1^0 \to \gamma\,Z$, with energy $E_\gamma = m_{\chi_1^0}\left(1 - \frac{m_Z^2}{4m_{\chi_1^0}^2}\right)$
  Cross section$\lesssim 2 \times 10^{-28} - 6 \times 10^{-28}\ cm^3 s^{-1}$ for photon energies $\sim 200 - 500\ GeV$.

[8] M. Ackermann et al. Phys. Rev. D **91** (2015) no.12, 122002 [arXiv:1506.00013].

"Astrophysical" Constraints (Gamma-ray lines)



The parameter space after the gamma-ray constraints

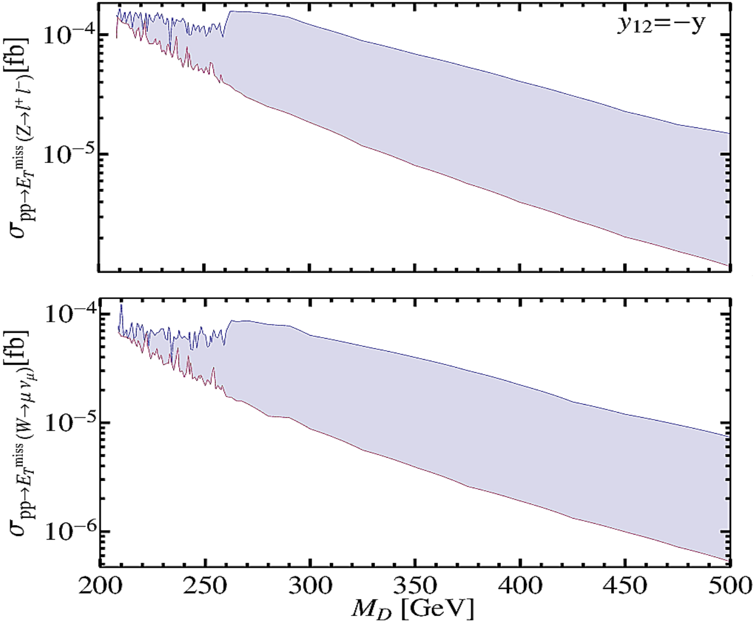


LHC Run I at $\sqrt{s} = 8\ TeV$ and $\int Ldt \approx 20 fb^{-1}$
Missing energy channels[9]:

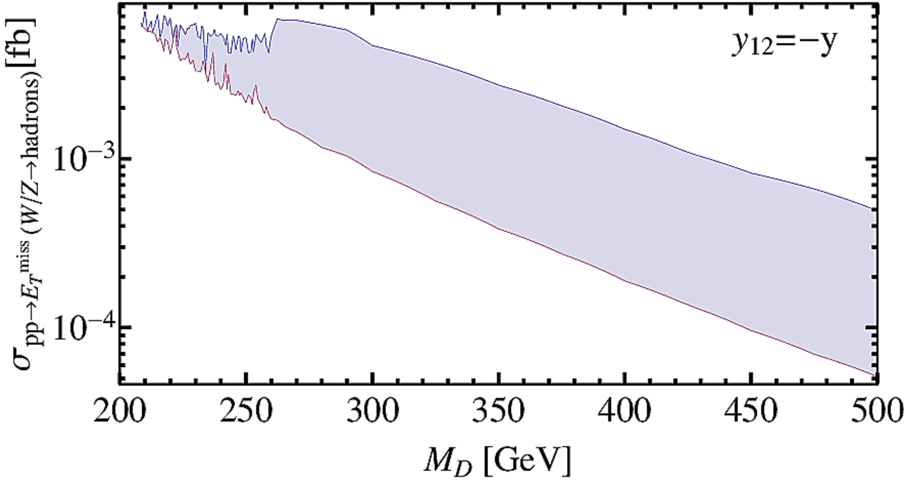
- $pp \to \chi_1^0 \chi_1^0 + \gamma$. Cross section $\lesssim 0.22\ fb$.
  Extremely suppressed in our case due to Fermi-LAT (cross section below $10^{-5} fb$).
- $pp \to \chi_1^0 \chi_1^0 + (Z \to l^+ l^-)$, $l = e, \mu$. Cross section $\lesssim 0.27\ fb$
- $pp \to \chi_1^0 \chi_1^0 + (W \to \mu \nu_\mu)$. Cross section $\lesssim 0.54\ fb$
- $pp \to \chi_1^0 \chi_1^0 + (W/Z \to hadrons)$. Cross section $\lesssim 2.2\ fb$
- $pp \to \chi_1^0 \chi_1^0 + 2\, jets$. Cross section $\lesssim 4.8\ fb$
- $pp \to \chi_1^0 \chi_1^0 + \nu \bar{\nu} + jet$. Cross section $\lesssim 6.1\ fb$

[9] These channels are studied (for $dim = 7$ operators) in A. Crivellin, U. Haisch and A. Hibbs, Phys. Rev. D **91** (2015) 074028 [arXiv:1501.00907].

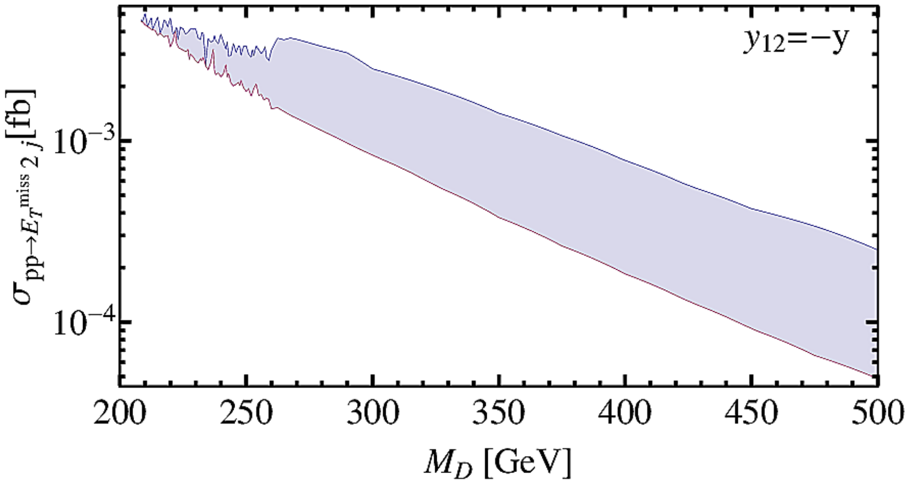
Mono-Z/W at 8 *TeV*



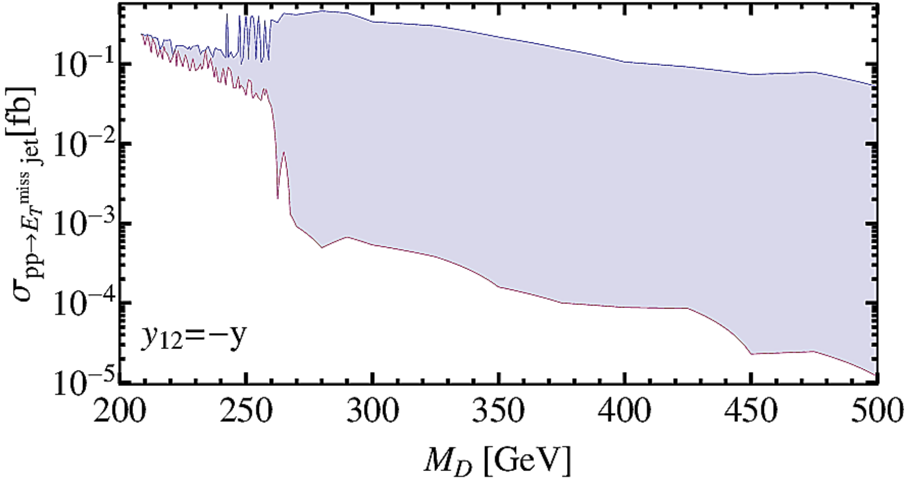
Hadronically decaying W/Z at 8 TeV



Dijet at 8 *TeV*



Monojet at 8 *TeV*

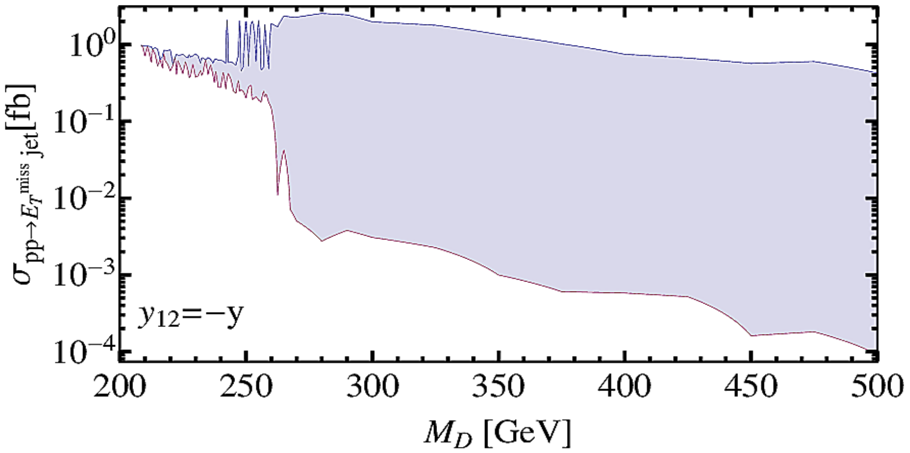


Future LHC

LHC at $\sqrt{s} = 13\ TeV$ and $\int Ldt \approx 100 - 300 fb^{-1}$

The most promising for our case is the mono-jet signal $pp \to \not{E}_T + jet$

Monojet at 13 *TeV*



Summing up...

- Dark Matter with mass around the Electroweak scale, while avoids current bounds from different experiments.
- Possible indirect detection in the future (gamma-ray lines).
- Can produce some events at the next runs of LHC ($\not{E}_T$ signal).
- Possible direct detection detection in the future direct detection experiments.

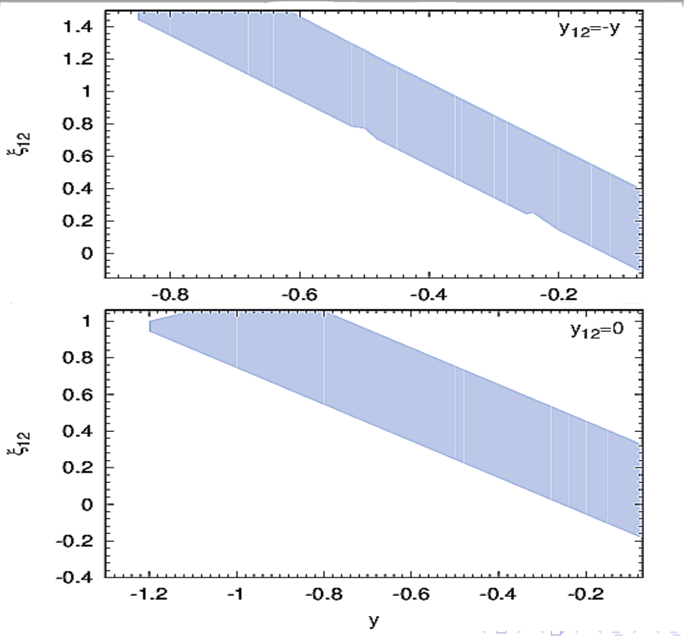
Open questions...

- Classification of *UV* complete models?
- Other possible detection channels for LHC?

Thank You!

More figures!

"Astrophysical" Constraints (Relic Density)



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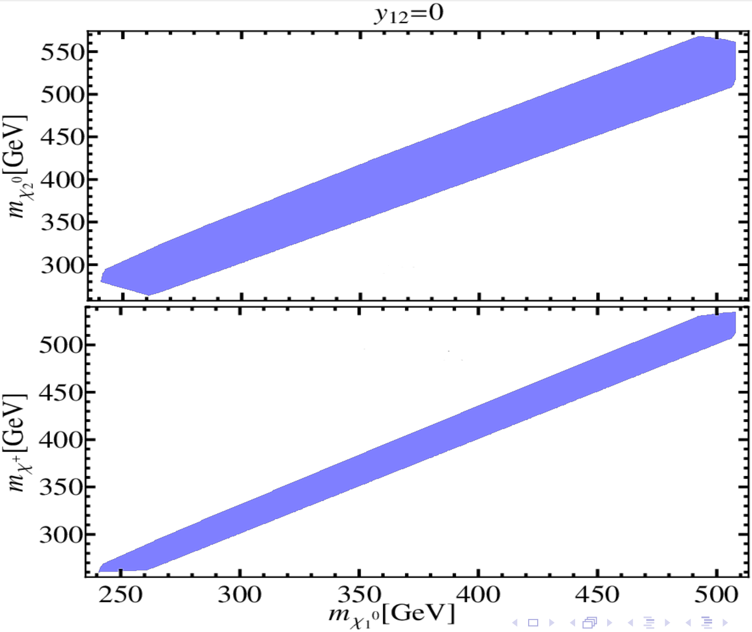

"Astrophysical" Constraints (Continuous Gamma-rays)

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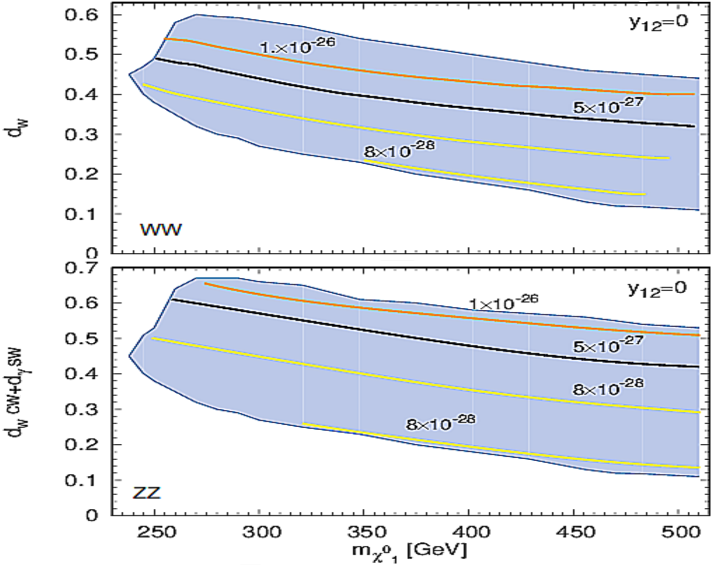
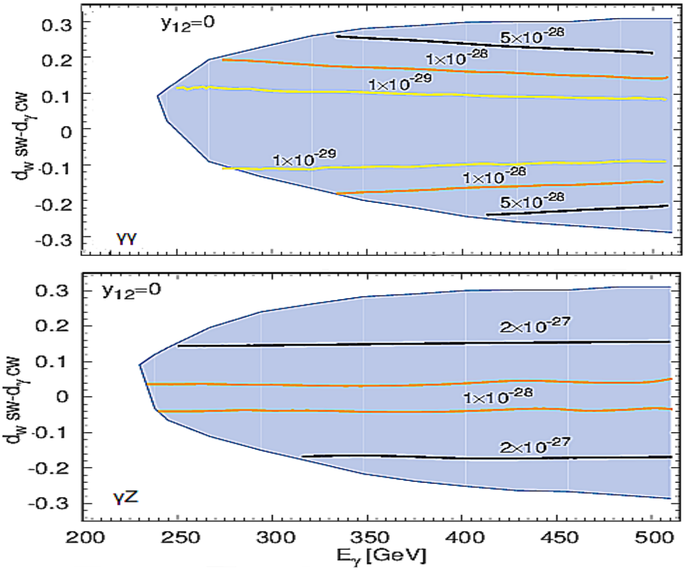
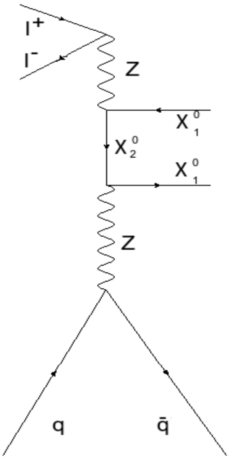


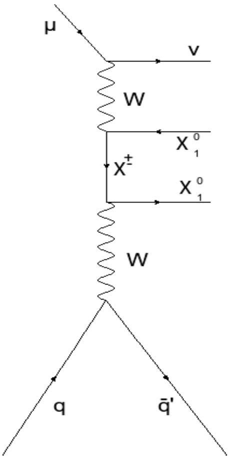
"Astrophysical" Constraints (Gamma-ray lines)



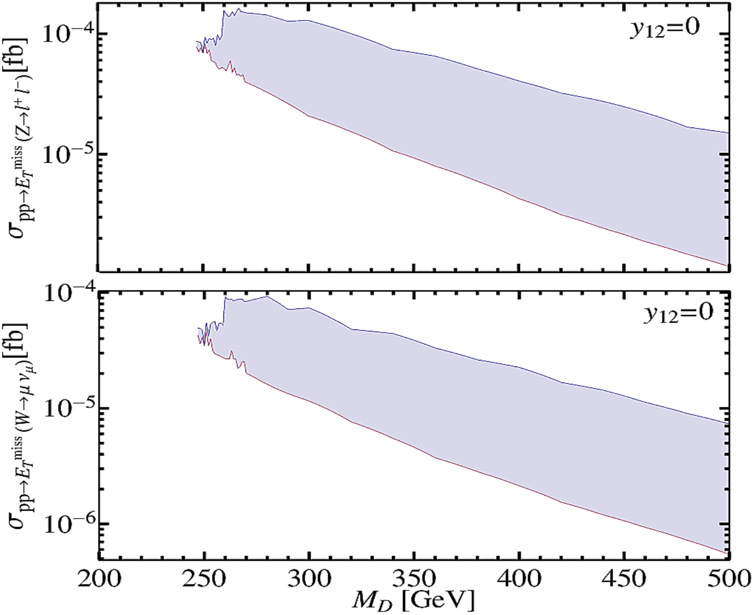
Feynman Diagrams for LHC: Mono-Z



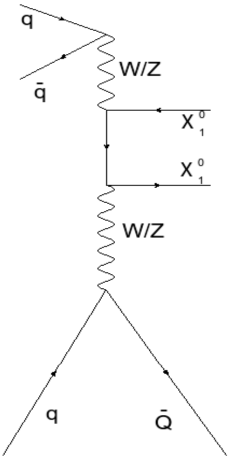
Feynman Diagrams for LHC: Mono-W



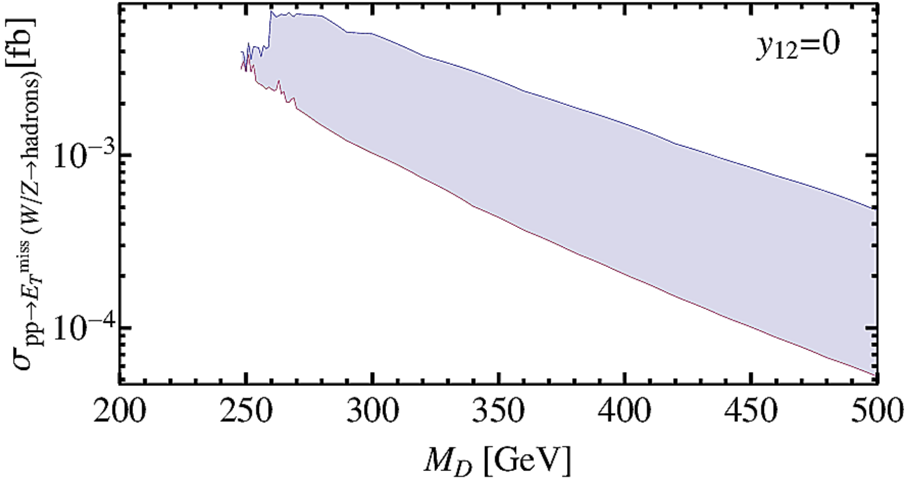
Mono-Z/W at 8 TeV



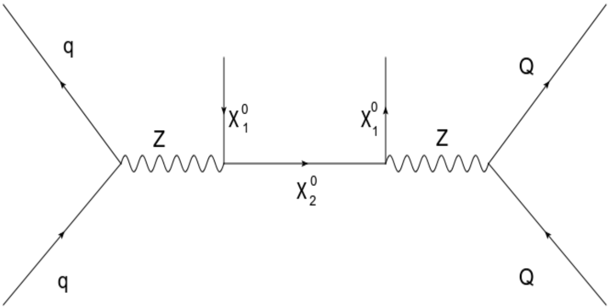
Feynman Diagrams for LHC: Hadronically decaying W/Z



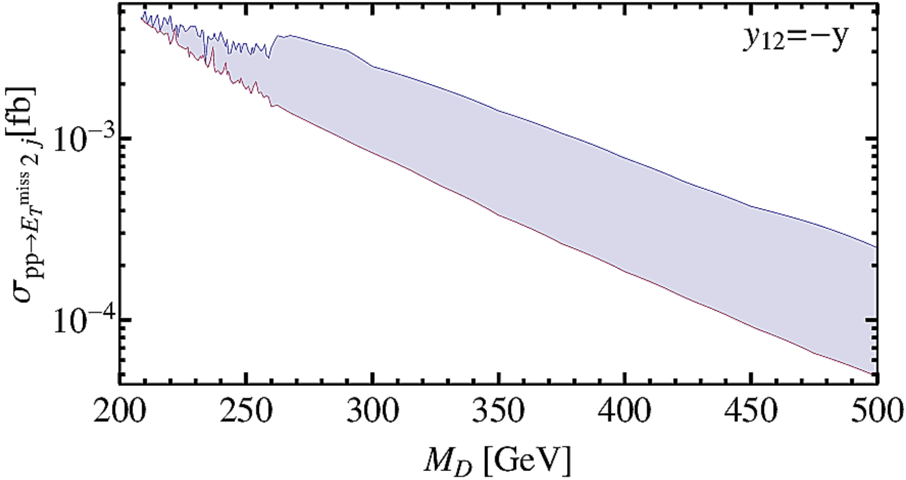
Hadronically decaying W/Z at 8 TeV

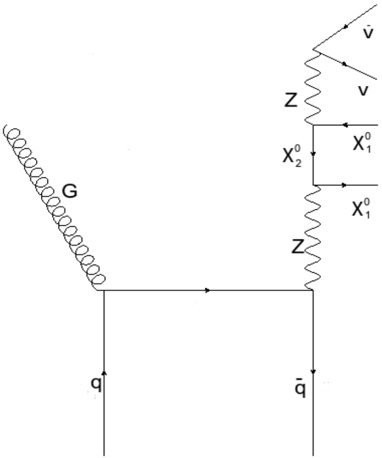


Feynman Diagrams for LHC: Dijet



Dijet at 8 *TeV*




v̄
v
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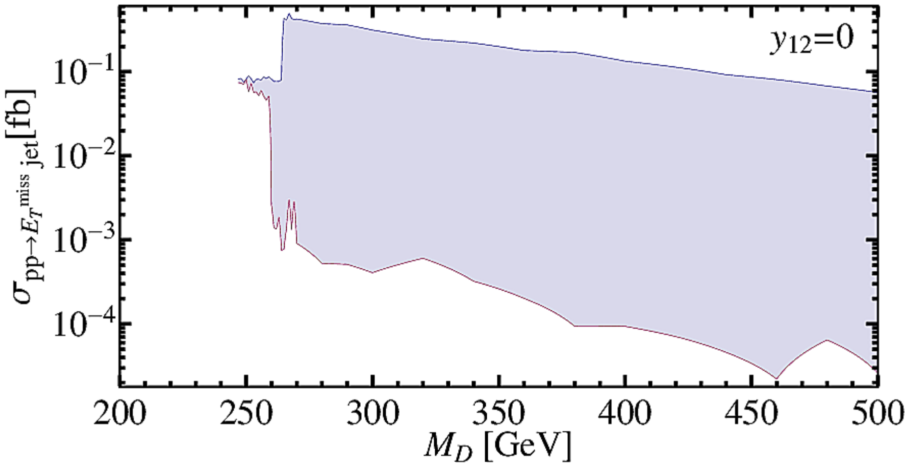
X$_1^0$
X$_2^0$
G
X$_1^0$
Z
q
q̄

Monojet at 8 *TeV*



Monojet $\frac{d\sigma}{dM_{inv}}$