Review on dark portals

Giorgio Arcadi
LPT Orsay

ERC Higgs@LHC

cnrs dépasser les frontières

université PARIS-SACLAY
DÉPARTEMENT Sciences de la Planète et de l'Univers

LPT Orsay

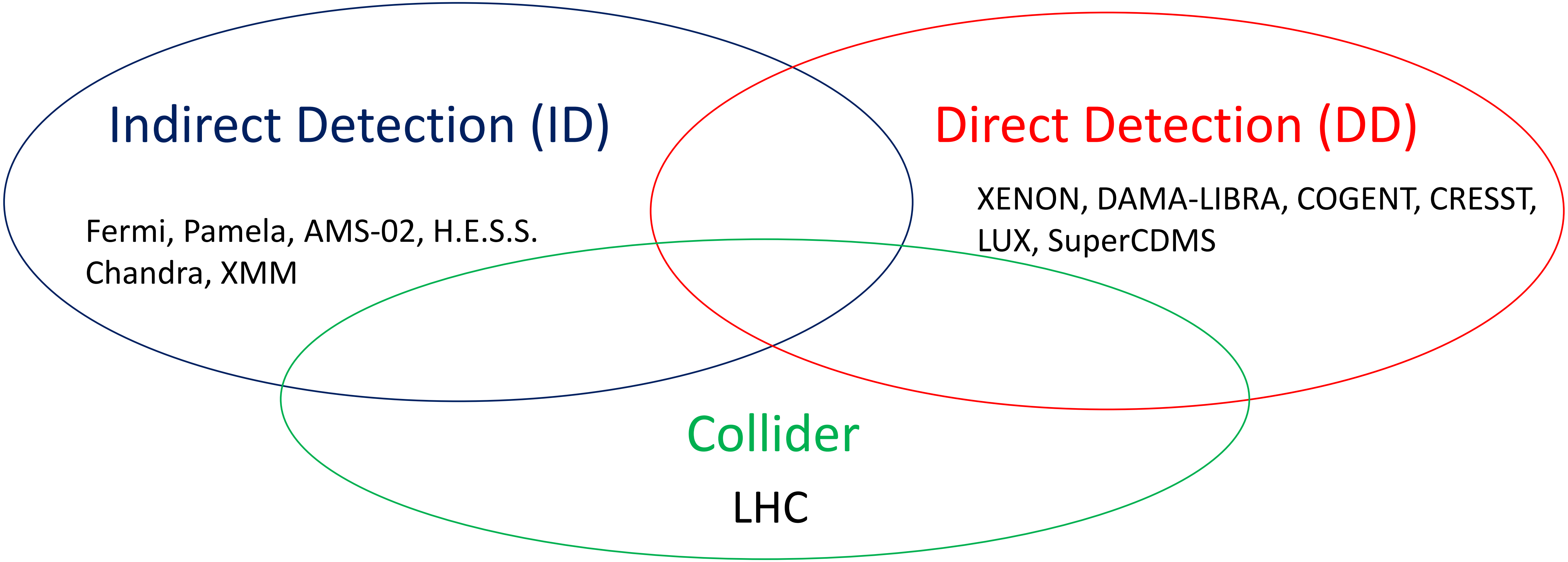
PARTICLE DM

Dark Matter is one of the building blocks of the Standard Cosmological model.
Contributes to around 27% of the energy budget of the Universe.
Evidences from astrophysics and cosmology.

Stable on cosmological scales.
Weakly or SuperWeakly interacting with ordinary matter, photons.
Cold (up to warm) as opposed to hot.

No (confirmed) detection so far.

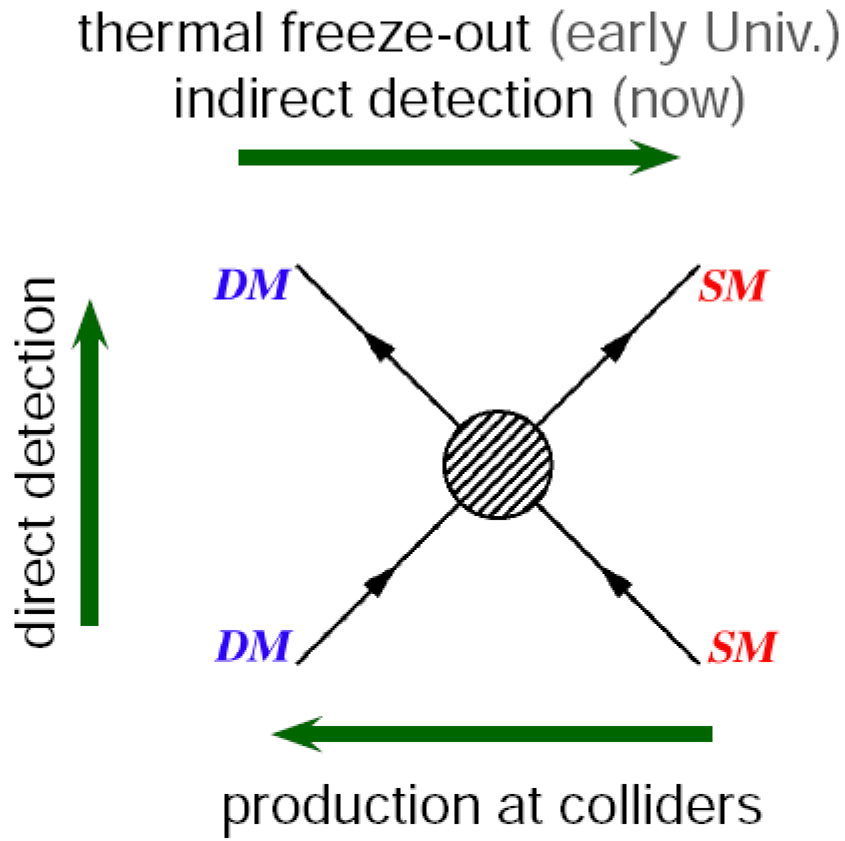
Three, possibly complementary, kinds of DM searches:



Complementary information from DM relic density. Case of study WIMP mechanism:

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

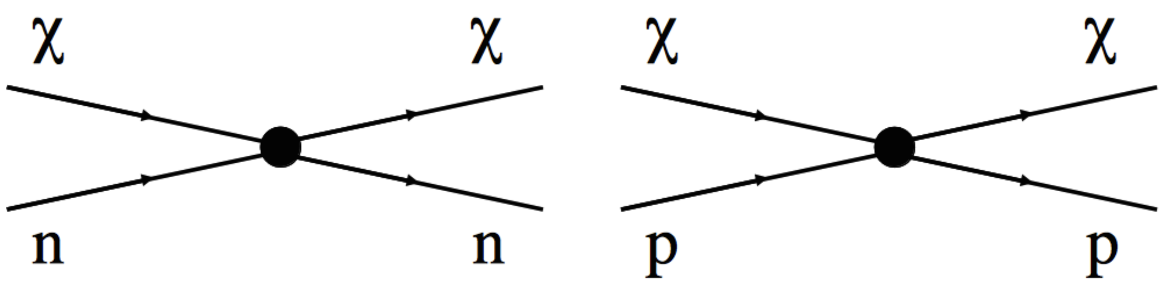
WIMP scenarios feature a strong complementarity between Dark Matter searches.

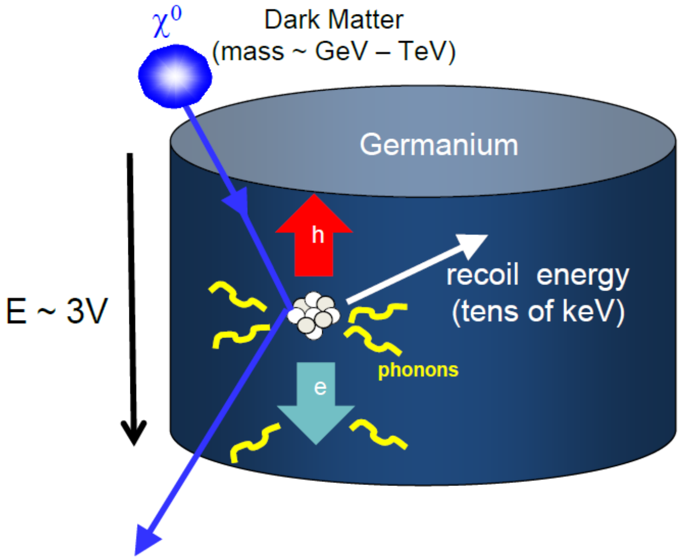


DM Direct Detection

Microscopic description through interactions of DM with quarks (or gluons)

Translated as effective interaction with nucleons.



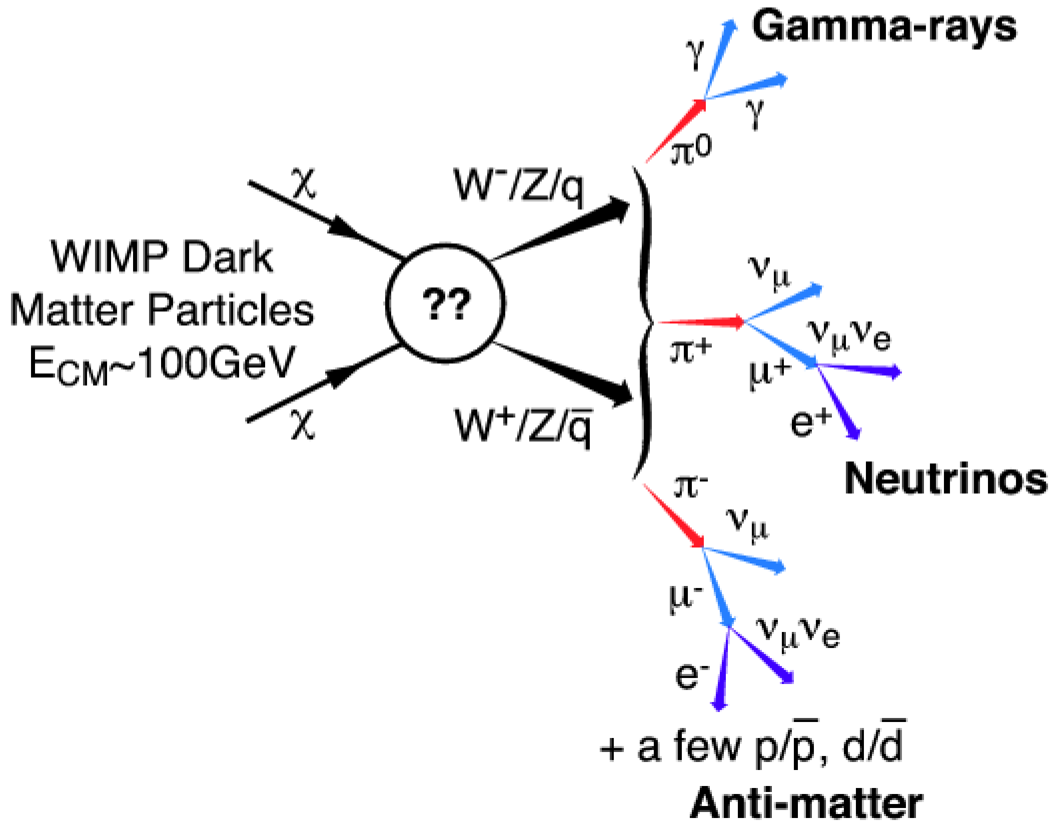


Two kinds of interactions customarily distinguished

Spin Indipendent (SI) interactions: Sum coherently among nucleons of the target

Spin Dependent (SD) interactions: Sensitive to the contributions from protons and nucleons to the nuclear spin.

Dark Matter Indirect Detection



Dark Matter Indirect Searches rely on the detection
Of the products of DM annihilations and decay.

Typically studied:
Antiprotons (AMS-02, PAMELA)
Electron/Positrons (PAMELA)
Photons (FERMI, XMM, CHANDRA, SUZAKU, HESS)

DM at colliders

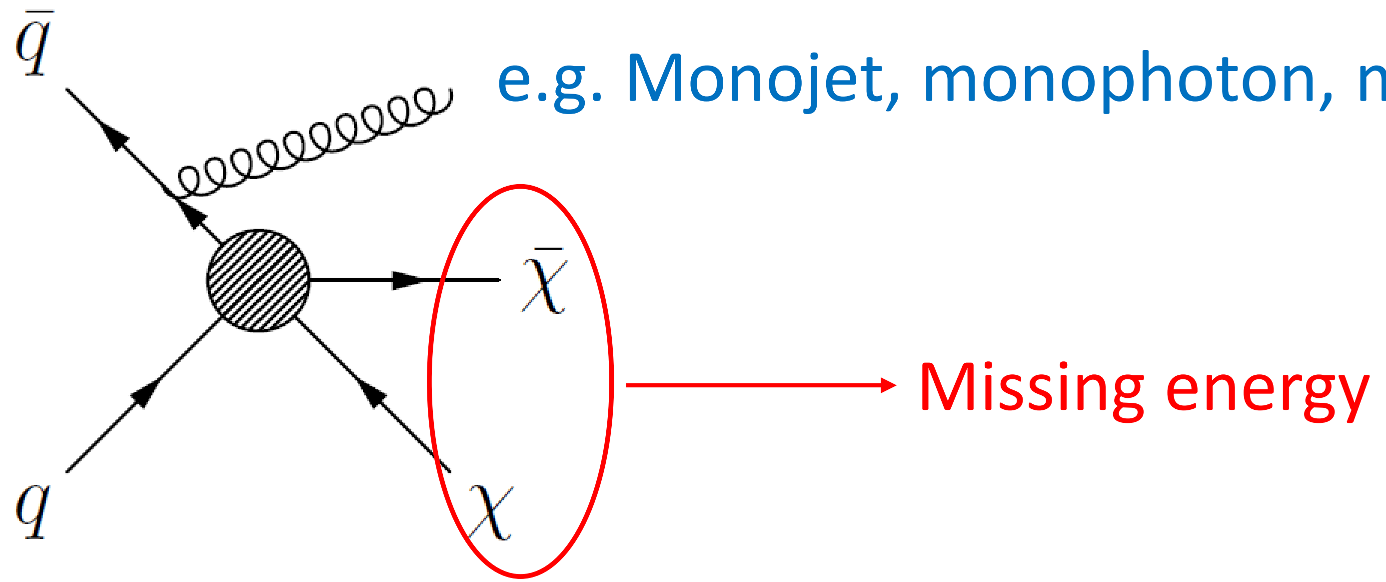
Increasing interest on recent times on the possibility of DM production at colliders (LHC)

Two possibilities

Production from decay of exotic particles.
Example: end of decay chains of supersymmetric particles.

Direct production at collider

Pair production of DM can be detected in events with missing energy and initial state radiation (ISR)



In any case the DM miss direct detection at collider detectors. Complementary information from other searches is required.

Relic density vs Indirect signal

Away from thresolds and resonances the annihilation cross-section can be velocity expanded

$$\langle \sigma v \rangle = a + b v^2$$

s-wave contribution.
Constant between freeze-out and present times

p-wave contribution.
Sizable at freeze-out negligible at present times.

Indirect signal possible only in presence of sizable s-wave component.

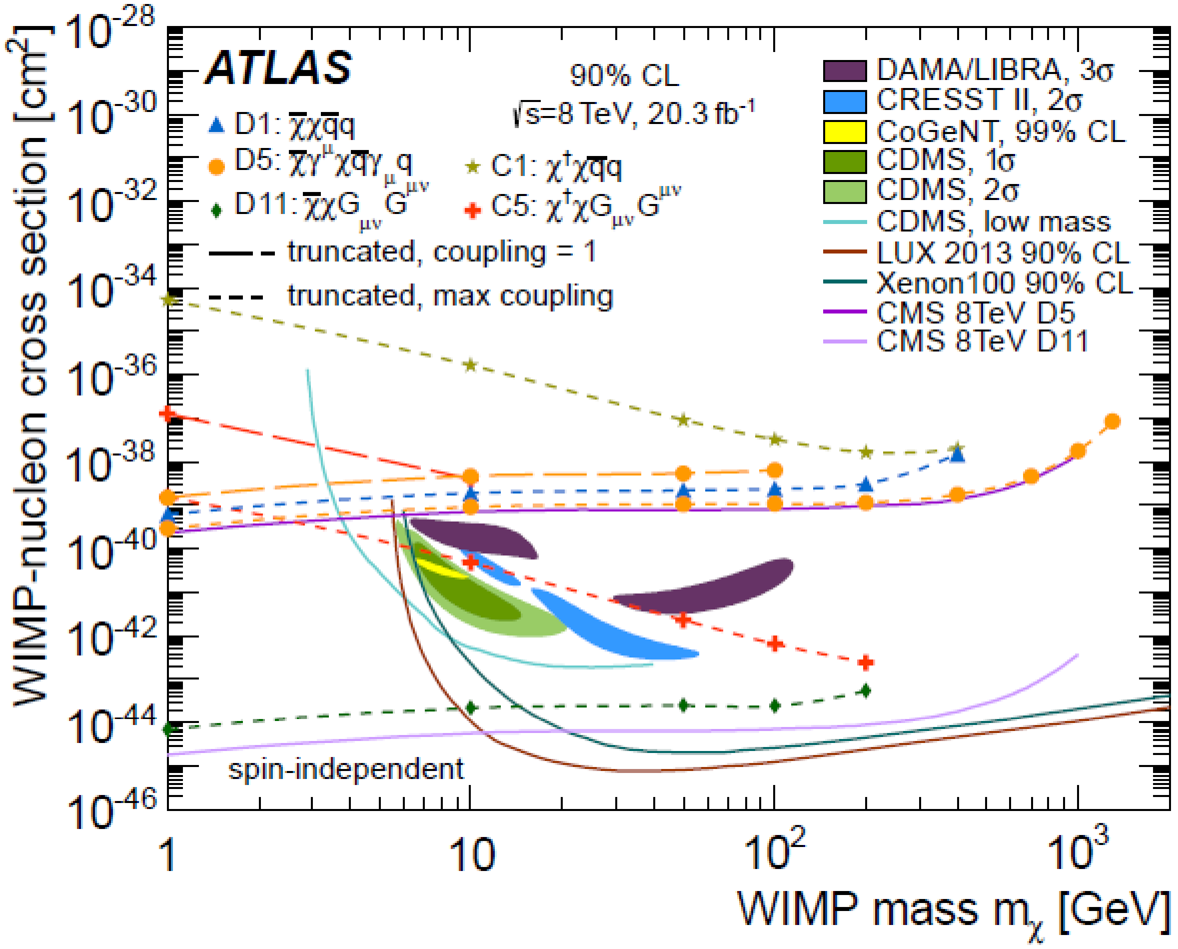
DM bilinear	*SM fermion bilinear*			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2$, $\sigma_{\rm SD} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\sigma v \sim 1$, $\sigma_{\rm SI} \sim q^2$	$\sigma v \sim 1$, $\sigma_{\rm SD} \sim q^4$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1$, $\sigma_{\rm SI} \sim 1$	$\sigma v \sim 1$, $\sigma_{\rm SD} \sim v_\perp^2$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim v_\perp^2$	$\sigma v \sim 1$, $\sigma_{\rm SD} \sim 1$

(Berlin et al. 1404.0022)

Analysis in Effective Field Theory (EFT)

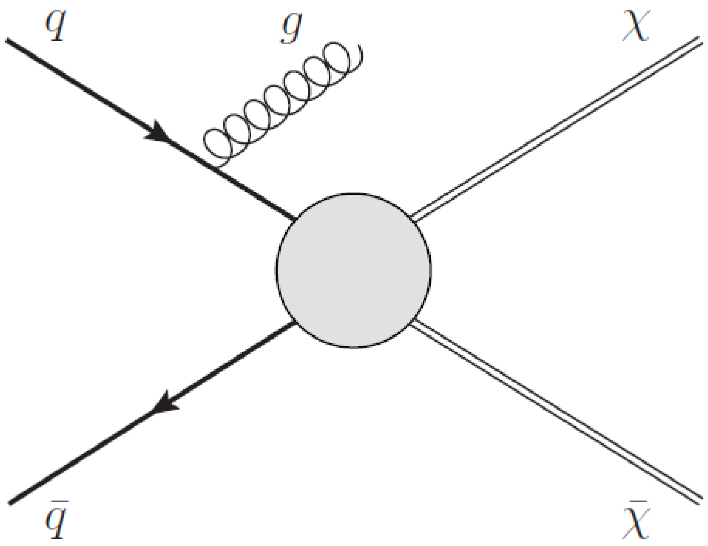
Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

(Goodman et al. 1008.1783)



The simplest way to enforce complementarity between DM searches is through effective field theory.

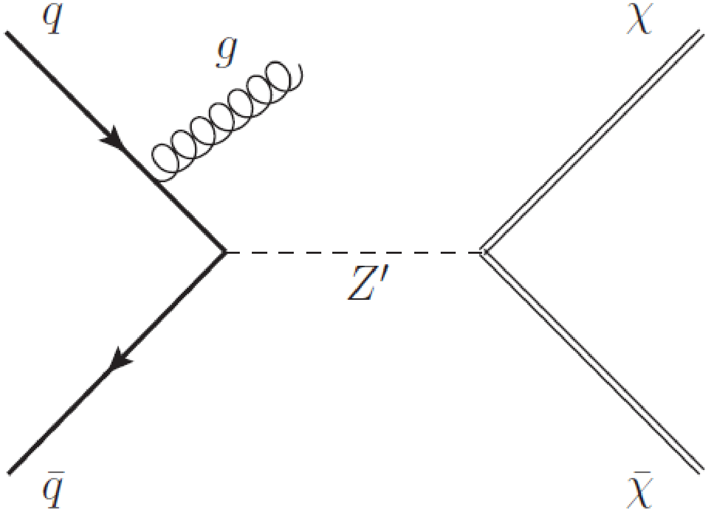
From EFT to simplified models



EFT provide a very simple way to express experimental limits (only one parameter)

The validity of EFT approach is controversial.

Some interesting scenarios are not described by EFT.



EFT analysis should be complemented by the use of simplified models.

Increased number of parameters.

It is still possible to profit of complementarity with DM searches.

Simplified models (Dark portals)

Dark portals are simple extensions of the SM with a DM candidate and a mediator interacting with the DM and SM fermions.

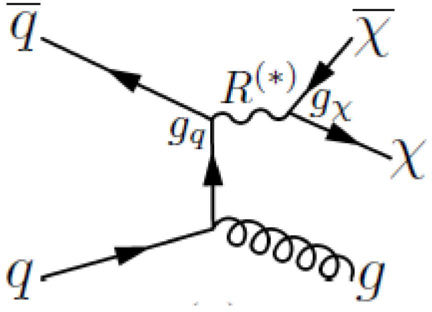
Scalar/pseudoscalar portal

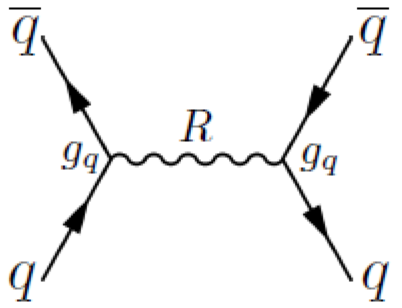
$$\mathcal{L} = s\left[\lambda_s^\chi \bar{\chi}\chi + \lambda_s^f \bar{f} f\right] + a\left[i\lambda_a^\chi \bar{\chi}\gamma_5\chi + i\lambda_a^f \bar{f}\gamma_5 f\right]$$

Vector/Axial portal

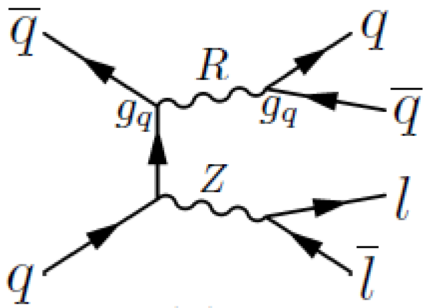
$$\mathcal{L} = g_D \bar{\chi}\gamma^\mu \left(V_\chi - A_\chi \gamma_5\right)\chi R_\mu + g_f \sum_f \bar{f}\gamma^\mu \left(V_f - A_f\gamma_5\right) f R_\mu$$

Complementarity in simplified models

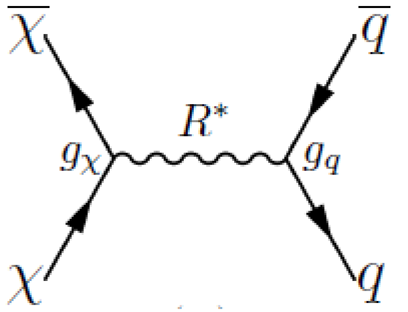




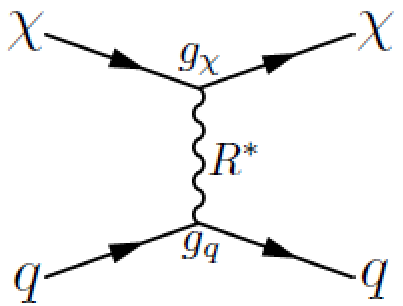
Chala et al. 1503.05916



Light mediators can be produced on shell. Additional signals (resonances) also from decays into SM particles.



Relic density / ID



Direct Detection

Concrete examples: vector portals

SM particle spectrum is enhanced with a (dirac) fermionic dark matter and a spin one mediator.

- Both two typical components of dark Matter direct detection, Spin Independent (SI) and Spin Dependent (SD), unsuppressed.
- Easily motivated in U(1) extensions (GUT) of the SM gauge group (DM stability can also originate from the symmetry pattern of the theory (Mambrini et al: 1502.06929))
- Refinements of these scenarios can account for some recent collider anomalies.

$$E_6 \to SO(10) \times U(1)_\psi$$

→ Extra U(1) from Grand Unified theories

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

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

Definite theoretical frameworks provide predictions of the relevant couplings.

Comparison with current constraints.

Prediction of future signals

Dark Z´ models

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

DM phenomenology relies on vectorial and axial combinations.

$$g_2 V_f = \frac{g_f}{2}\left(\epsilon_L^f + \epsilon_R^f\right) \qquad g_2 A_f = \frac{g_f}{2}\left(\epsilon_L^f - \epsilon_R^f\right)$$

$$g_2 V_\chi = \frac{g_\chi}{2}\left(\epsilon_L^\chi + \epsilon_R^\chi\right) \qquad g_2 A_\chi = \frac{g_\chi}{2}\left(\epsilon_L^\chi - \epsilon_R^\chi\right)$$

Correlation of DM searches

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

$$\alpha = \frac{A_\chi}{V_\chi}$$

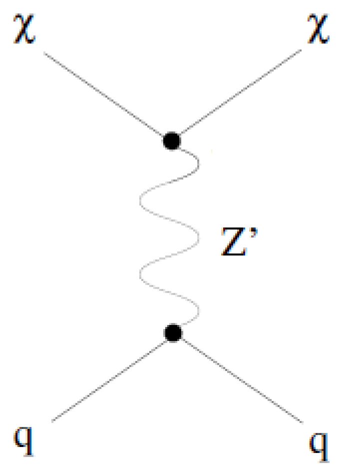
$$\langle \sigma v \rangle = f_1 \sigma_{\chi N}^{\rm SI} + f_2 \sigma_{\chi N}^{\rm SD}$$

DD constraints the relic abundance of DM.

Possible constraints from ID

Prediction of the value of the scattering cross-section from the requirement the DM is thermal.

DD for Z/Z′



$\sigma_{\chi q}$

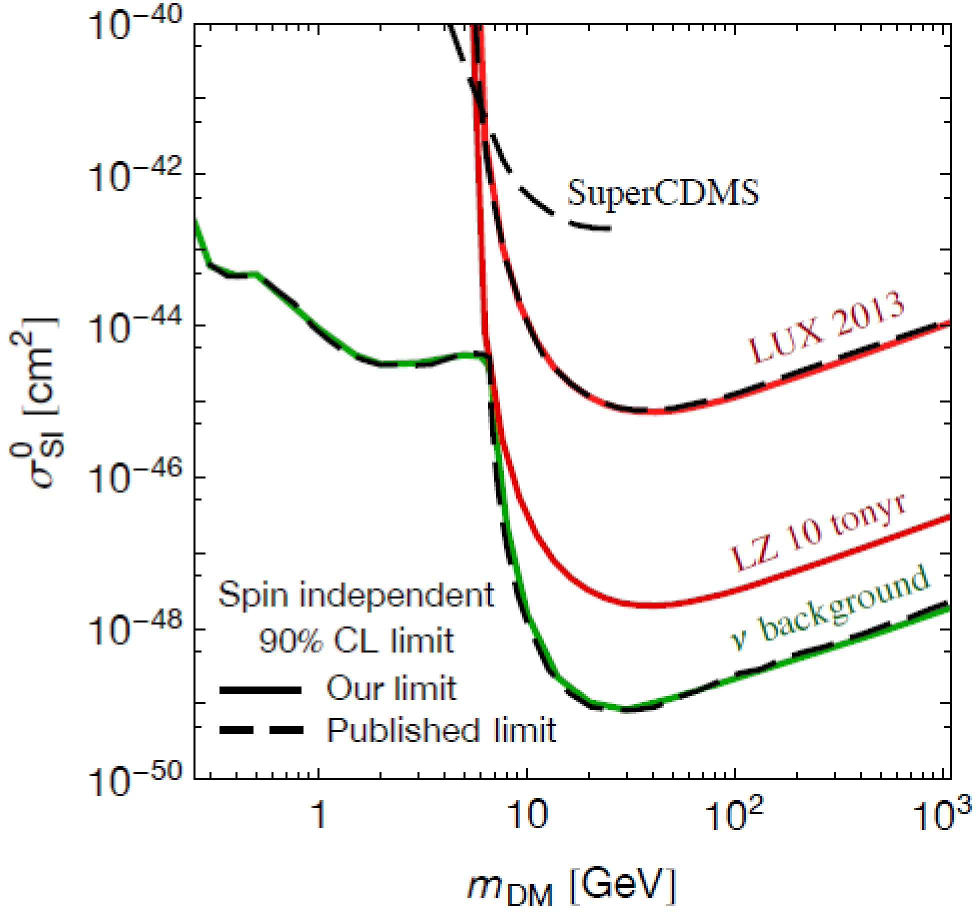
$$\sigma_{\chi p}^{\rm SI}=\frac{g_2^4\mu_\chi^2}{\pi m_{Z'}^4}|V_\chi|^2\alpha_{\rm SI}$$

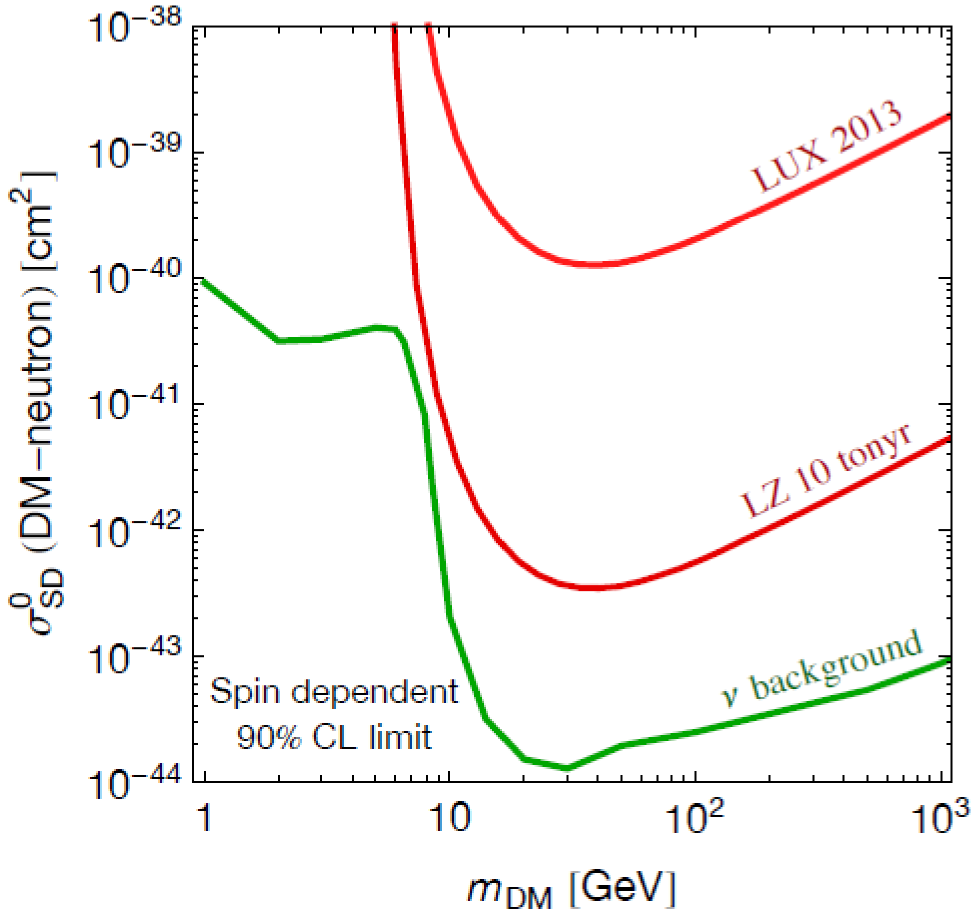
$$\sigma_{\chi p}^{\rm SD}=\frac{3g_2^4\mu_\chi^2}{\pi m_{Z'}^4}\alpha^2|V_\chi|^2\alpha_{\rm SD}$$

$$\alpha_{SI}=\frac{\sum_A \eta_A A^2\left[V_u^{'}\left(1+\frac{Z}{A}\right)+V_d^{'}\left(2-\frac{Z}{A}\right)\right]^2}{\sum_A \eta_A A^2}$$

Factor accounting for isospin violation

$$\alpha_{SD}=\frac{\sum_A \eta_A\left[A_u^{'}(\Delta_u^p S_p^A+\Delta_d^p S_n^A)+A_d^{'}\left((\Delta_d^p+\Delta_s^p)S_p^A+(\Delta_u^p+\Delta_s^p)S_n^A\right)\right]^2}{\sum_A \eta_A (S_p^A+S_n^A)^2}$$





Buchmuller et al., 1407.8257

Z-portal

$$\mathcal{L} = \frac{g}{4\cos\theta_W}\left(\overline{\chi}\gamma^\mu\left(V_\chi - A_\chi\gamma^5\right)\chi Z_\mu + \overline{f}\gamma^\mu\left(V_f - A_f\gamma^5\right) f Z_\mu\right)$$

General scenario. Need completion at high scales

Concrete examples

Effective operators

$$\mathcal{L} = \frac{ig}{\Lambda^2} H^\dagger D_\mu H\left[\overline{\chi}\gamma^\mu\left(v_\chi - a_\chi\gamma_5\right)\chi\right]$$

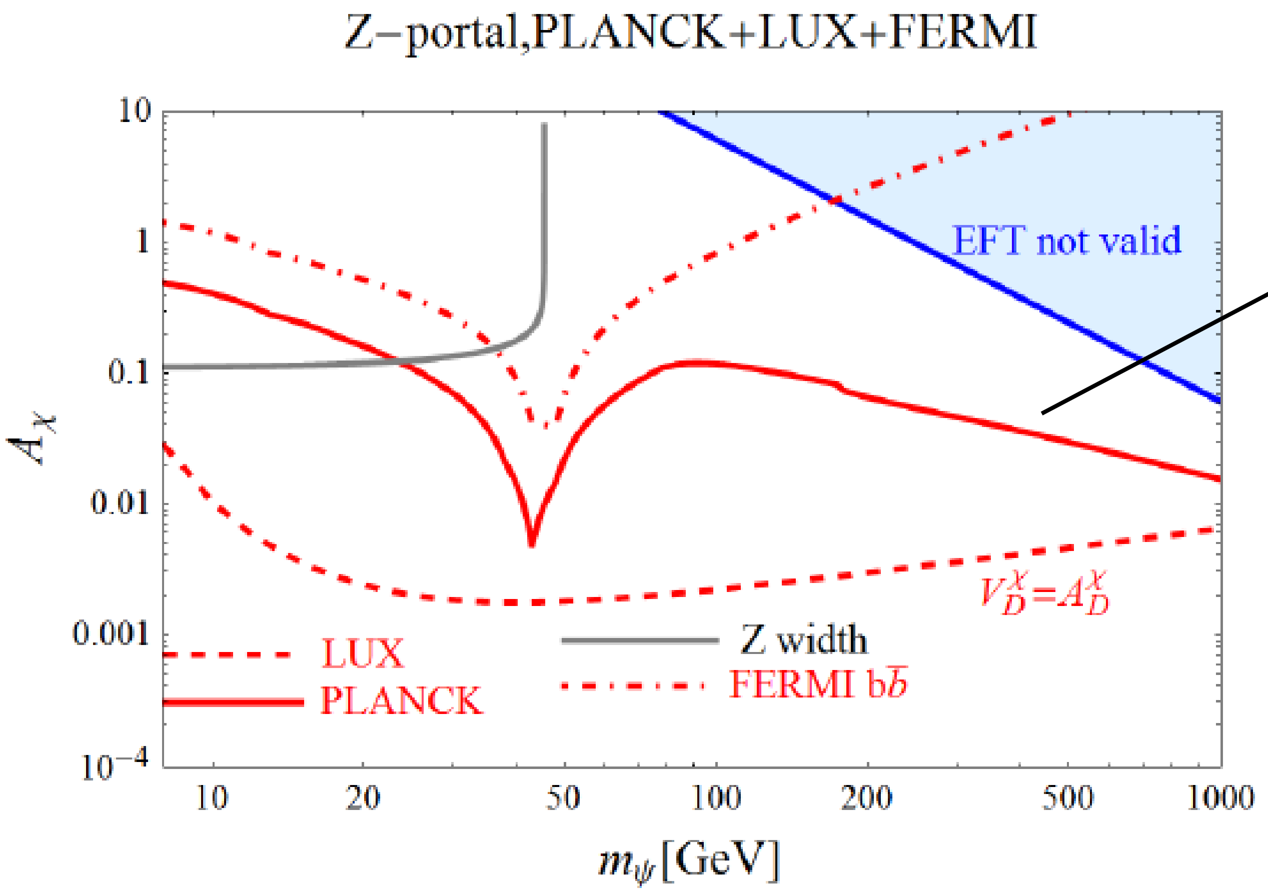
$$H^\dagger D_\mu H \to \frac{v_h^2}{4\cos\theta_W} Z_\mu \longrightarrow V_\chi = \frac{v_h^2}{\Lambda^2}\, v_\chi$$

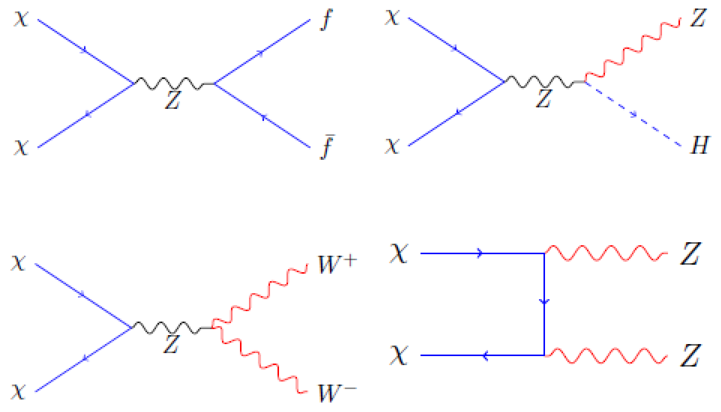
De Simone et al. JHEP1406 (2014) 081

Kinetic mixing

$$\delta B_{\mu\nu} B'^{\mu\nu} \qquad m_{Z'} \gg m_Z$$

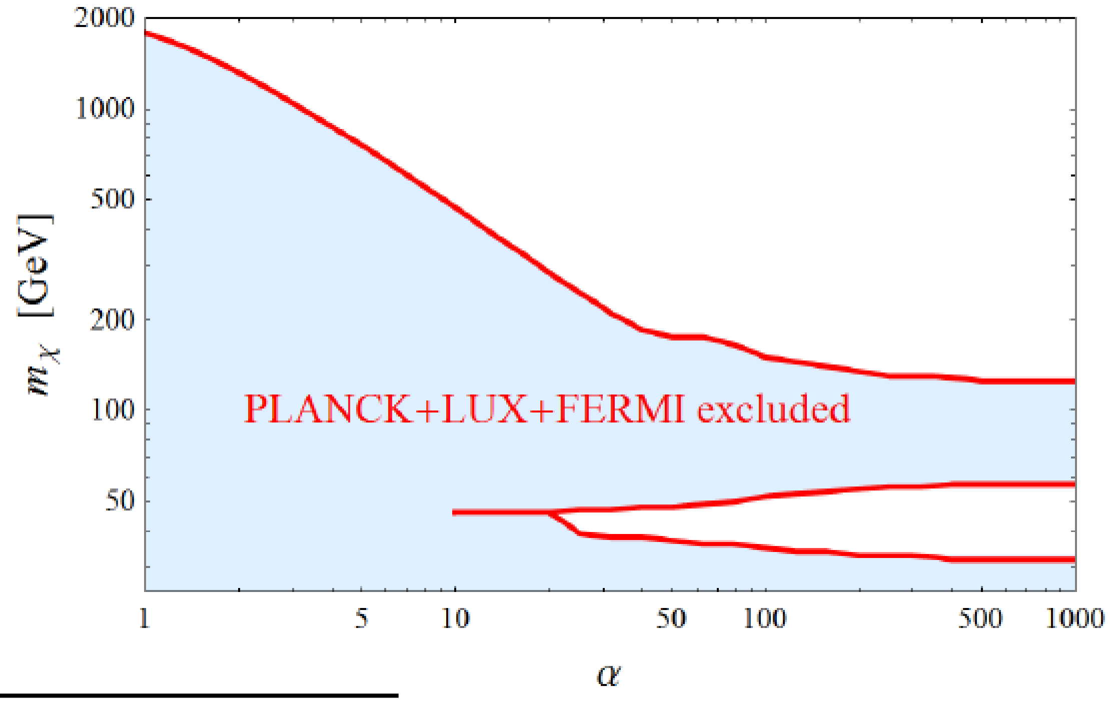
$$V_\chi = q_D \frac{g_D}{g}\tan\theta_W \delta \frac{m_Z}{m_{Z'}}$$





Additional annihilation channels

The case of comparable axial and vector couplings is excluded by limits from LUX (SI) and Z-width.

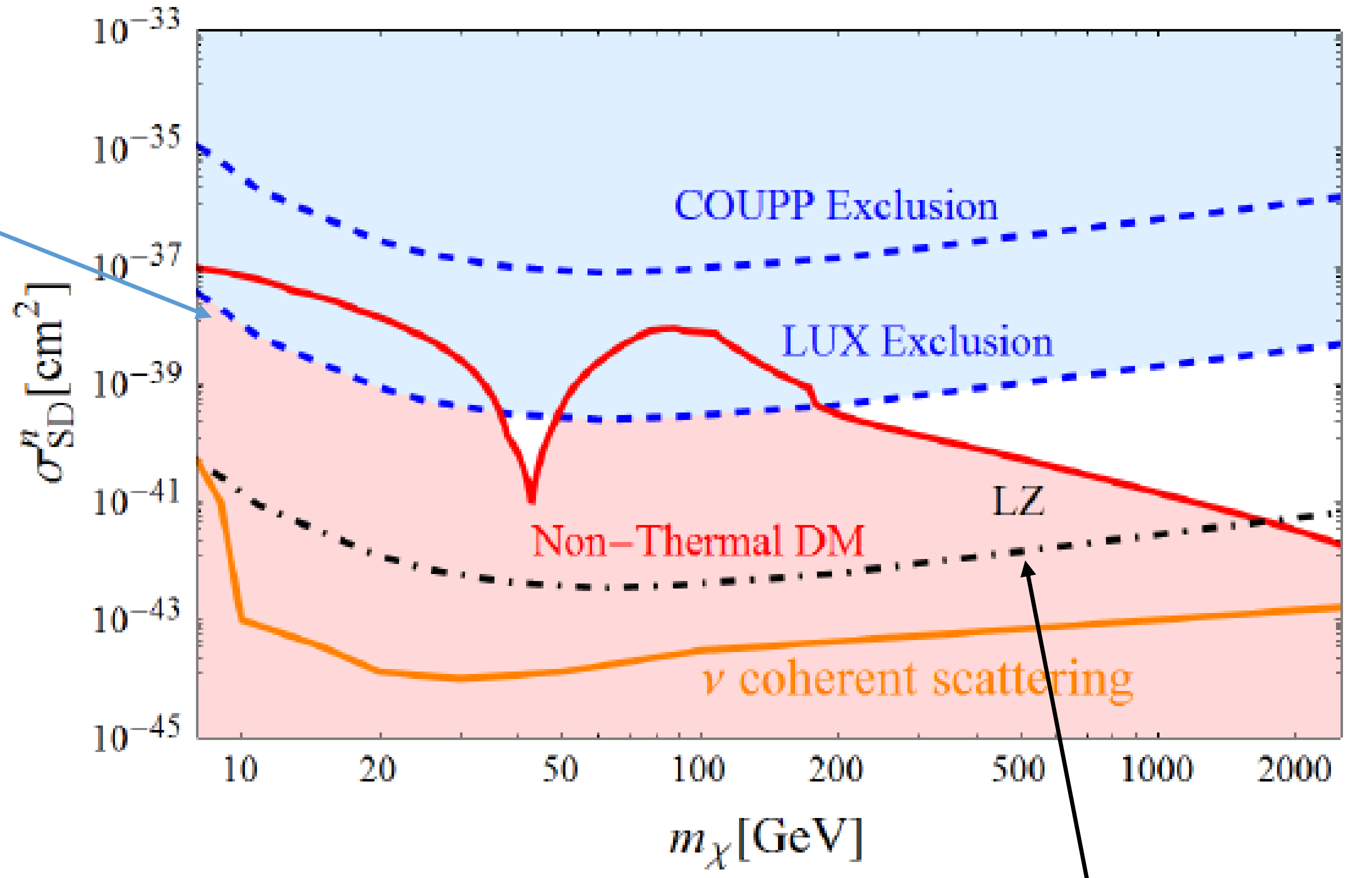


$$\alpha = \frac{A_\chi}{V_\chi}$$

Z-portal viable for almost pure axial couplings except for Z-pole and multi TeV regions.

Correct relic density (dominant axial interaction) ⟷ Lower bound on SD cross-section

Interaction of DM with neutrons



Next future experiments can completely probe Z portal scenario

$$\sigma_{\chi p}^{\rm SI} = \frac{g_2^4 \mu_\chi^2}{\pi m_{Z'}^4} |V_\chi|^2 \alpha_{\rm SI}$$

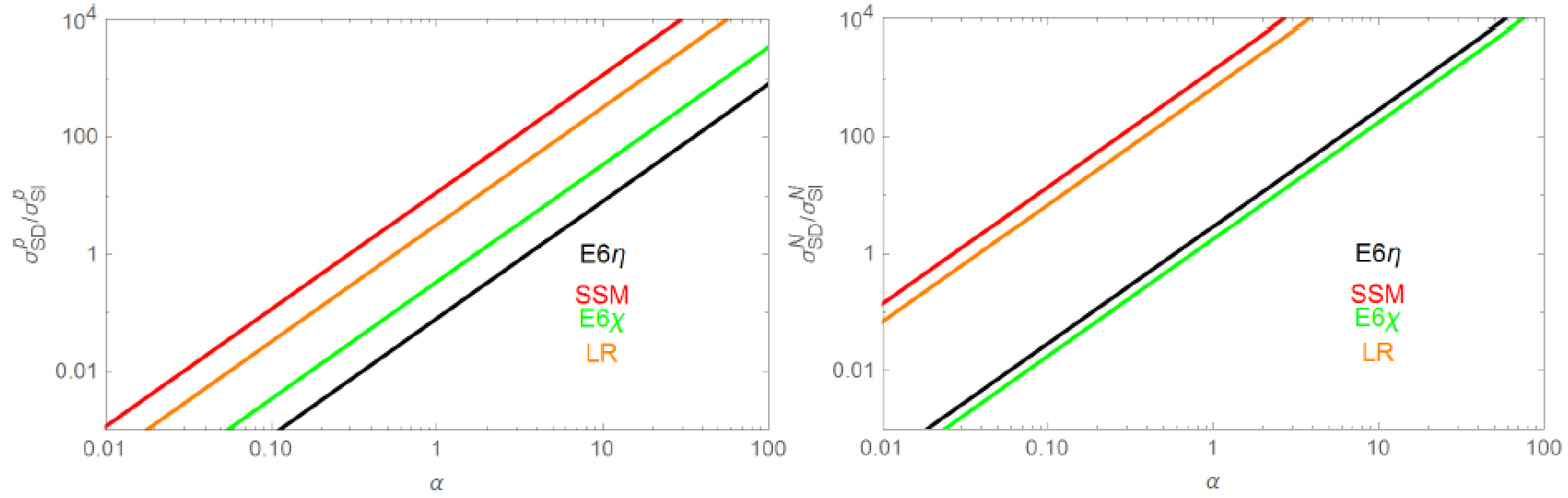
$$\sigma_{\chi p}^{\rm SD} = \frac{3 g_2^4 \mu_\chi^2}{\pi m_{Z'}^4} \alpha^2 |V_\chi|^2 \alpha_{\rm SD}$$

Factors depending on the couplings with the fermions and the detector material

$$\frac{\sigma_{SD}^p}{\sigma_{SI}^p} = 3\alpha^2 \frac{\alpha_{SD}}{\alpha_{SI}}$$

$$\alpha = \frac{A_\chi}{V_\chi}$$

Different Z` realizations might be distinguished by measuring both components of the DM scattering cross-section.



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

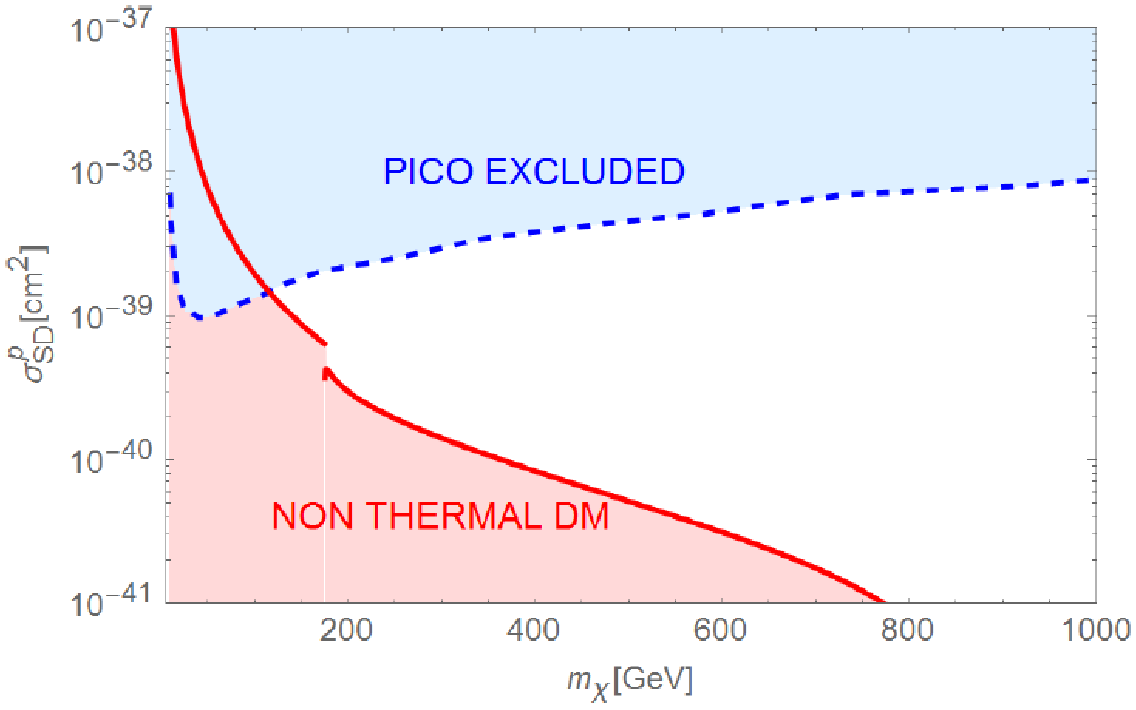
Very severe limits from direct detection (LUX) imply: $|V_\chi| \ll 1$

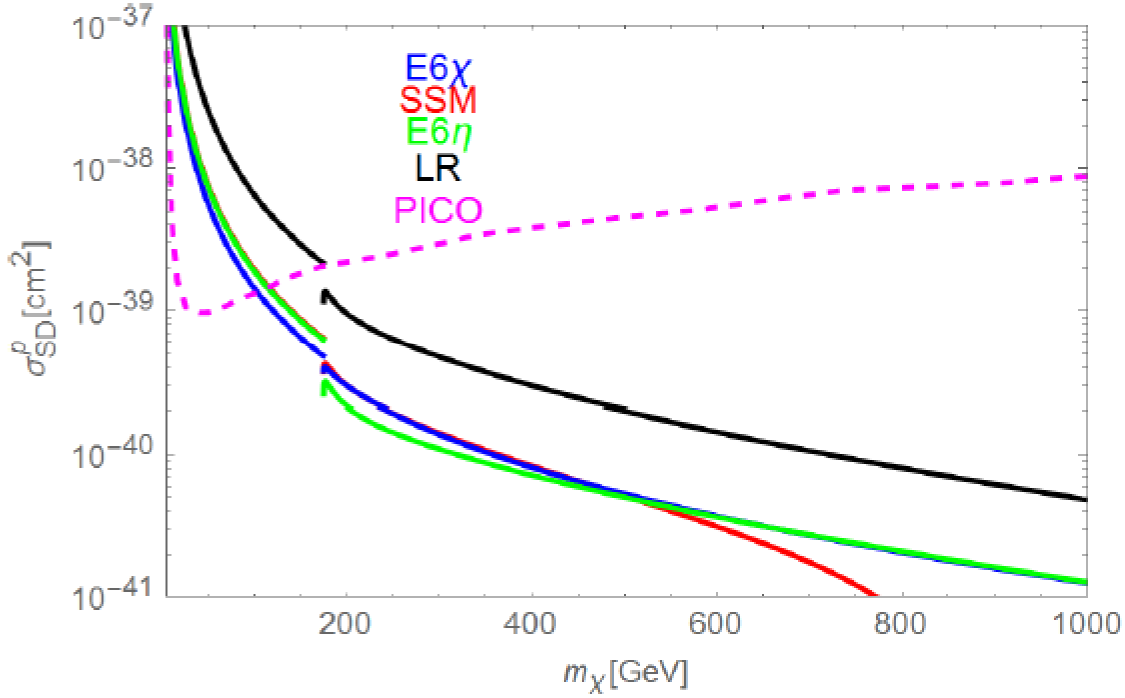
Correct relic density requires: $\alpha \gg 1$

$$\alpha \approx 1.1 \times 10^3 \sqrt{\frac{\alpha_{\rm SI}}{\sum_f n_c^f |V_f|^2 + |A_f|^2}} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\,{\rm cm^3 s^{-1}}} \right)^{1/2} \left(\frac{\sigma_{N\chi}^{\rm SI}}{10^{-44}\,{\rm cm}^2} \right)^{-1/2} \left(\frac{m_\chi}{100\,{\rm GeV}} \right)^{-1}$$

Prediction for the SD cross-section:

$$\sigma_{N\chi}^{\rm SD} \approx 1.6 \times 10^{-37}\,{\rm cm}^2 \frac{\alpha_{\rm SD}}{n_c^f \sum_f |V_f|^2 + |A_f^2|} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\,{\rm cm^3 s^{-1}}} \right) \left(\frac{m_\chi}{100\,{\rm GeV}} \right)^{-2}$$





Limit on SD cross-section can probe thermal Dark matter up to O(150-200) GeV.

Annihilation into SM fermions final states can be expressed in terms of SI and SD cross-sections.

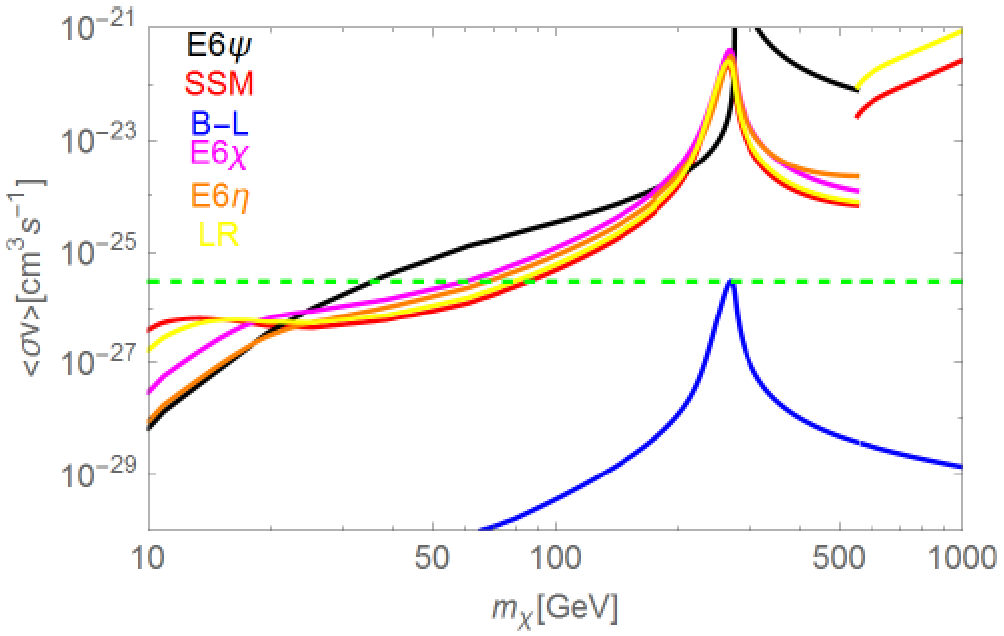
Mass and velocity suppressed

$$\langle \sigma v \rangle_{f\bar{f}} \simeq \frac{g_2^4 m_\chi^2}{2\pi m_{Z'}^4} \sum_f n_c^f \left(|V_f|^2 + |A_f|^2\right) \left(1 - \frac{4m_\chi^2}{m_{Z'}^2}\right)^{-2} \left[2|V_\chi|^2 + |A_\chi|^2 \left(\frac{m_b^2}{m_\chi^2} \frac{|A_b|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{m_t^2}{m_\chi^2} \frac{|A_t|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{v^2}{6}\right)\right]$$

If final state kinematically allowed

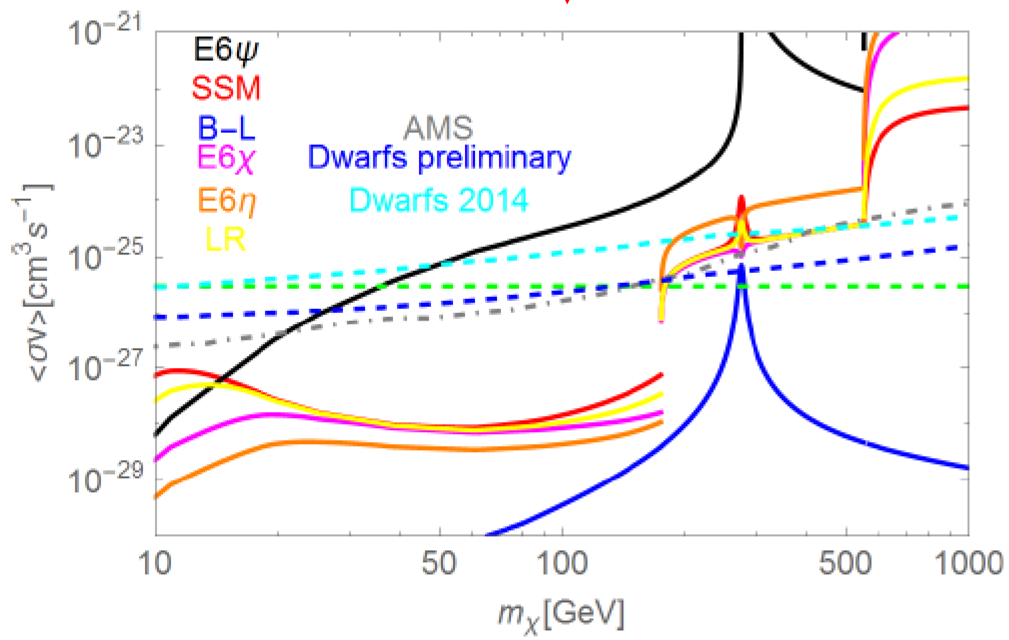
$$= \frac{2m_\chi^2}{\mu_{\chi p}^2} \sum_f n_c^f \left(|V_f|^2 + |A_f|^2\right) \left(1 - \frac{4m_\chi^2}{m_{Z'}^2}\right)^{-2} \left[2\frac{\sigma_{\chi p}^{\rm SI}}{\alpha_{\rm SI}} + \frac{\sigma_{\chi p}^{\rm SD}}{3\alpha_{\rm SD}} \left(\frac{m_b^2}{m_\chi^2} \frac{|A_b|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{m_t^2}{m_\chi^2} \frac{|A_t|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{v^2}{6}\right)\right]$$

Relic density deeply tight to SI cross-section



Decoupling time

Present time



s-wave component of the annihilation cross-section is proportional to the vectorial coupling suppressed by LUX.
Indirect signals suppressed.

Complementarity with collider searches

$$\sigma_{Z'll} \rightarrow \left(\frac{g_2}{g}\right)^2 \times (1 - Br_\chi) \times \sigma_{Z'll}$$

Dilepton-Dijet production cross-section influenced by invisible branching fraction.

$$Br_\chi = \frac{\Gamma^\chi_{Z'}}{\Gamma^\chi_{Z'} + \sum_f \Gamma^f_{Z'}} = \left[1 + \left(\frac{2 g_2^2 \mu_{\chi N}}{M^2_{Z'}\sqrt{\pi}}\right)^2 \frac{\sum_f c_f [|V'_f|^2 + |A'_f|^2]}{\sigma^{\mathrm{SI}}_{\chi N}/\alpha^{\mathrm{SI}}_{Z,A} + 1/3\sigma^{\mathrm{SD}}_{\chi N}/\alpha^{\mathrm{SD}}_{Z,A}}\right]^{-1}$$

Determined by DM relic density or from experimental limits

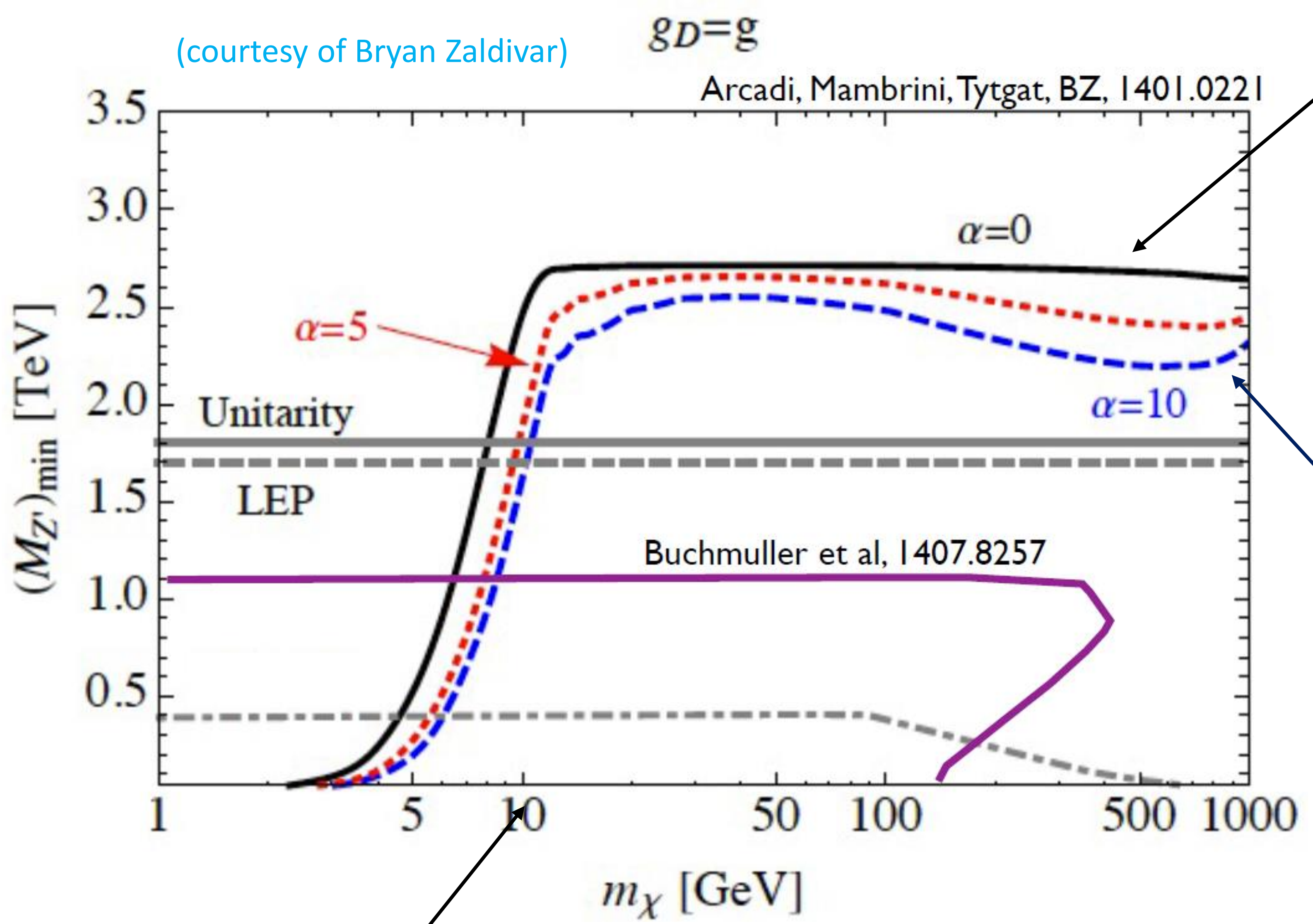
High invisible branching fraction:

monojet searches

Amount of invisible branching fraction depends on DM phenomenology.

Low Invisible branching fraction

Resonance searches



High DM masses. LUX limit implies
low invisible branching fraction.
LHC Dilepton limit
applies (indipendent from DM mass)

Weaker limits in presence of
axial couplings

Low DM masses. Sensitive invisible branching fraction allowed. LHC limits should be modified.

Unitarity bound

$$m_\chi \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_2 |A_\chi|}$$

In a not gauge invariant setup axial couplings lead to cross-sections which violate perturbative unitarity (Kahlhoefer et al: 1510.02110)

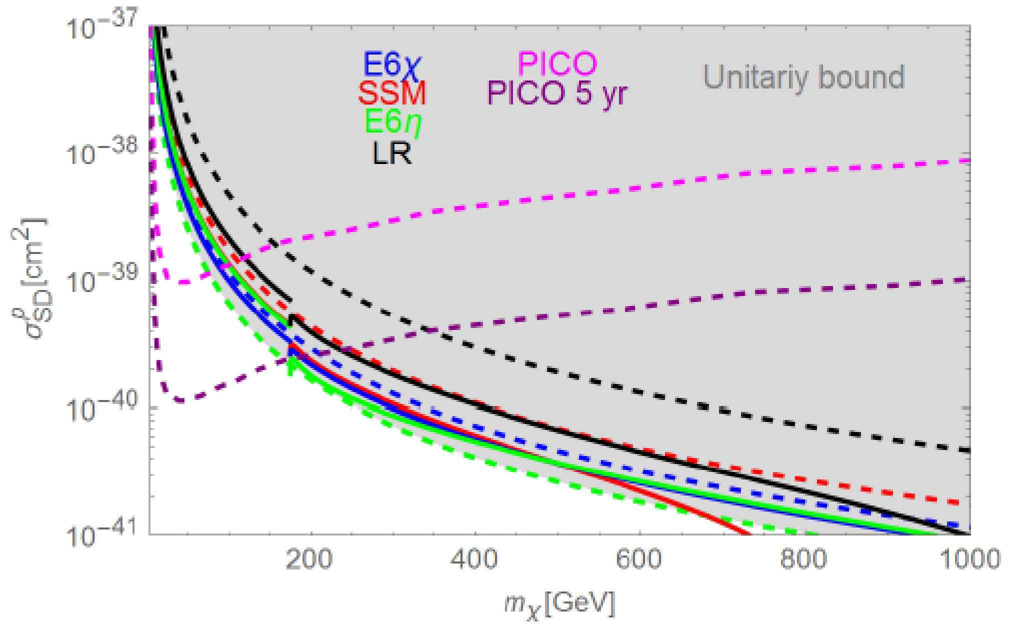
The bound is evaded by considering a theory with only vectorial couplings (e.g. kinetic mixing) or by explicitly introducing a higgs mechanism in the new U(1) sector.

$$m_s < \frac{\pi m_{Z'}^2}{g_2^2 |A_\chi|^2 m_\chi}$$

Possibly different phenomenology associated to a second scalar mediator

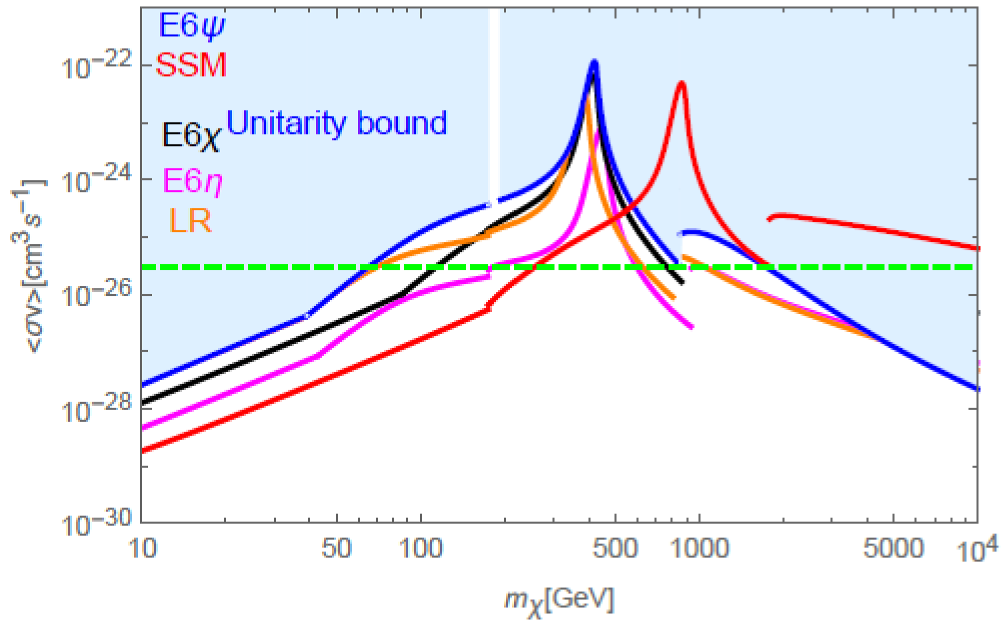
$$\delta m^2 = -\frac{1}{4} \frac{e\, g'\, q_H}{s_W\, c_W} v^2$$

In presence of axial couplings, gauge invariance implies that the SM higgs is charged under
the new U(1) and generates a Z/Z‘ mixing thus implying couplings with the gauge bosons.



Perturbative unitarity combined with collider limits strongly limits the range of viable DM masses.

$$\sigma^{\rm SD}_{\chi p,\rm uni} \approx 5.8 \times 10^{-38} {\rm cm}^2 \alpha_{\rm SD} \left(\frac{m_\chi}{100\,{\rm GeV}}\right)^{-2} \left(\frac{m_{Z'}}{1\,{\rm TeV}}\right)^{-2}$$



Conclusion

Simplified dark portals are optimal benchmarks for the study of new particles and interactions.

Combination of different DM search strategies is a powerfull tool.

Correlation with other searches of New Physics can be enforced as well.

Progress in model building is similarly relevant.

BACK UP

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

$$\frac{\langle \sigma v \rangle}{\sigma_\chi^{\rm SI}} = \frac{m_\chi^2}{\mu_{\chi N}^2 \alpha_{\rm SI}} \left[\left(a_V + b_V v^2 \right) + \alpha^2 \left(a_A + b_A v^2 \right) \right]$$

For light DM

$$\frac{\langle \sigma v \rangle}{\sigma_{N\chi}^{\rm SI}} \simeq \frac{m_\chi^2}{\mu_{\chi N}^2 \alpha_{\rm SI}} \left[1 + \frac{\alpha^2}{2} \left[\frac{m_b^2}{m_\chi^2} \frac{|A_b|^2}{\sum_f |V_f|^2 + |A_f|^2} + \frac{v^2}{6} \right] \right] n_c^f \sum_f |V_f|^2 + |A_f|^2$$

$$\simeq \frac{m_\chi^2}{\mu_{\chi N}^2 \alpha_{\rm SI}} \left[1 + \frac{\alpha^2}{12} \right] n_c^f \sum_f |V_f|^2 + |A_f|^2$$

DM bilinear	*SM fermion bilinear*			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\rm SD} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim q^2$	$\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^4$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\sigma v \sim 1,\ \sigma_{\rm SD} \sim v_\perp^2$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim v_\perp^2$	$\sigma v \sim 1,\ \sigma_{\rm SD} \sim 1$

(Berlin et al. 1404.0022)