Dark Matter Searches with the ATLAS detector

Mono-ANYTHING ?

ENIGMASS – 11.10.2012

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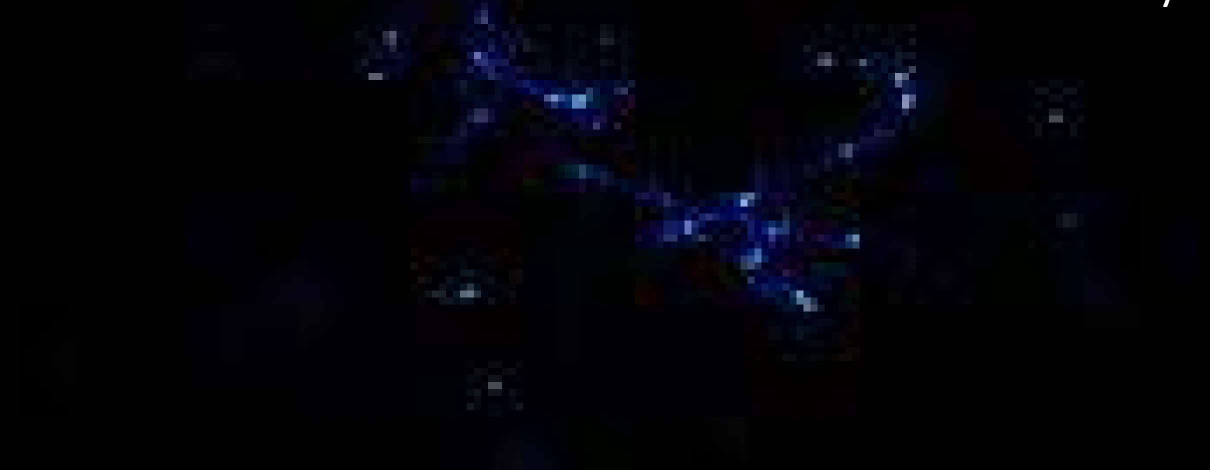
While astrophysical observations provide convincing proof
for the existence of a **non-baryonic dark component** to the Universe
and precise measurements concerning its abundance,
they offer no clue as to the **mass of dark matter** (DM) particles,
how they **fit into the SM**
or even whether or not the dark matter has interactions beyond gravitational



The most persuasive vision of dark matter is
a weakly interacting massive particle (WIMP)
which offers the possibility to understand
the relic abundance of dark matter
as a natural consequence of the thermal history of the Universe

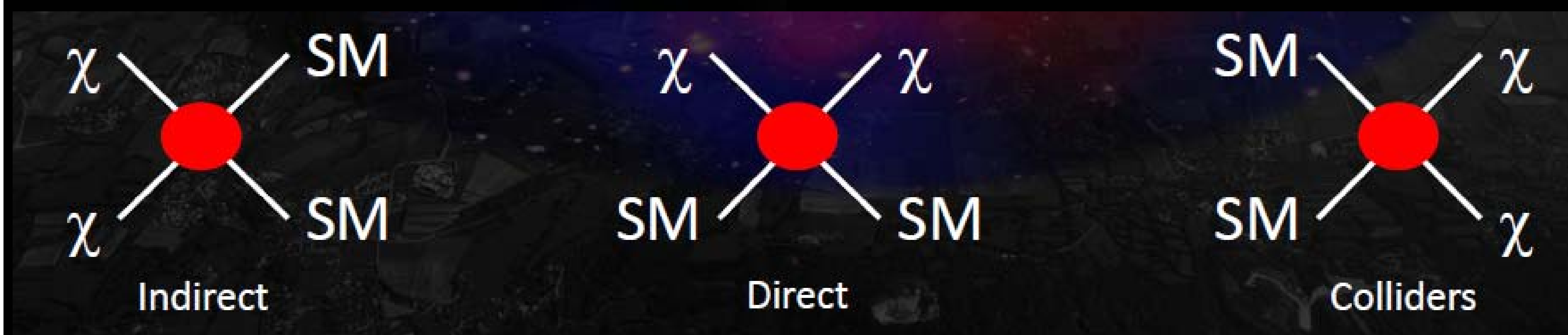
The large interactions of WIMPs with SM particles may imply

1. Detectable rates of WIMP annihilations into SM final states
–Indirect searches –

2. Scattering of WIMPs with heavy nuclei
– Direct searches –

and

3. Production of WIMPs
– colliders –



Low mass particles are particularly accessible to searches at colliders
since cross sections at the LHC fall dramatically with the mass of produced states.
Light states can thus be produced with very large rates

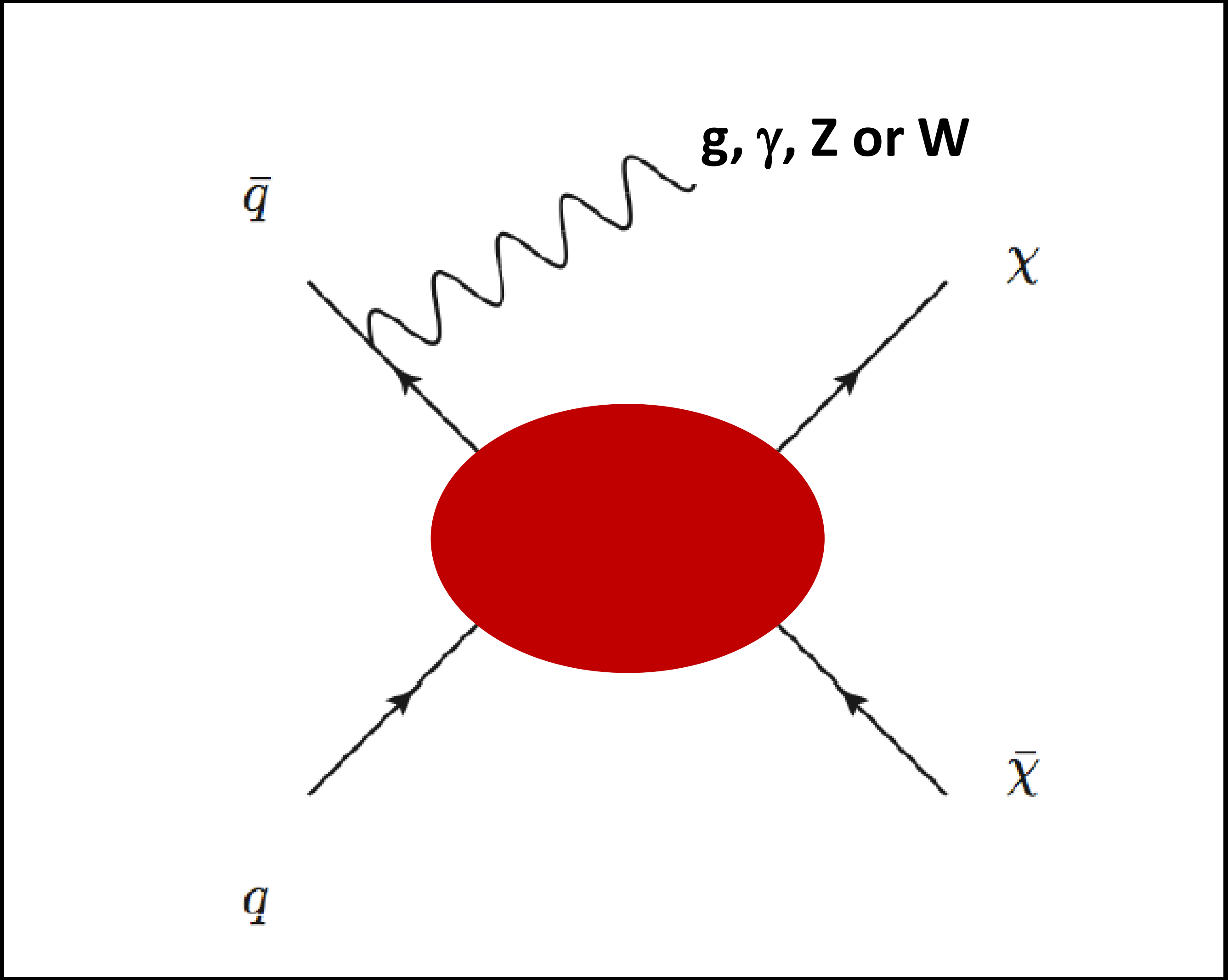
In the case of a WIMP,
stability on the order of the lifetime of the Universe implies (arXiv:1008.1783v2)
that **pair production must highly dominate** over single production
and **prevents the WIMP from decaying within the detector volume**

WIMPs therefore appear as missing energy in our detectors

In order to make the search possible
one relies on the presence of a (single) identifiable object in the event
e.g. from ISR

Mono : photon, Z, W, jet

WIMP pair production (+ ISR) at the LHC : mono-something !



Assumptions about red bubble needed to interpret measurements in terms of χ
and to relate measurements to other fields of DM searches

What exactly do we search for in our detector ?

Mono photon

or

Mono jet

or

Mono W

or

Mono Z

(tag)

+

MET

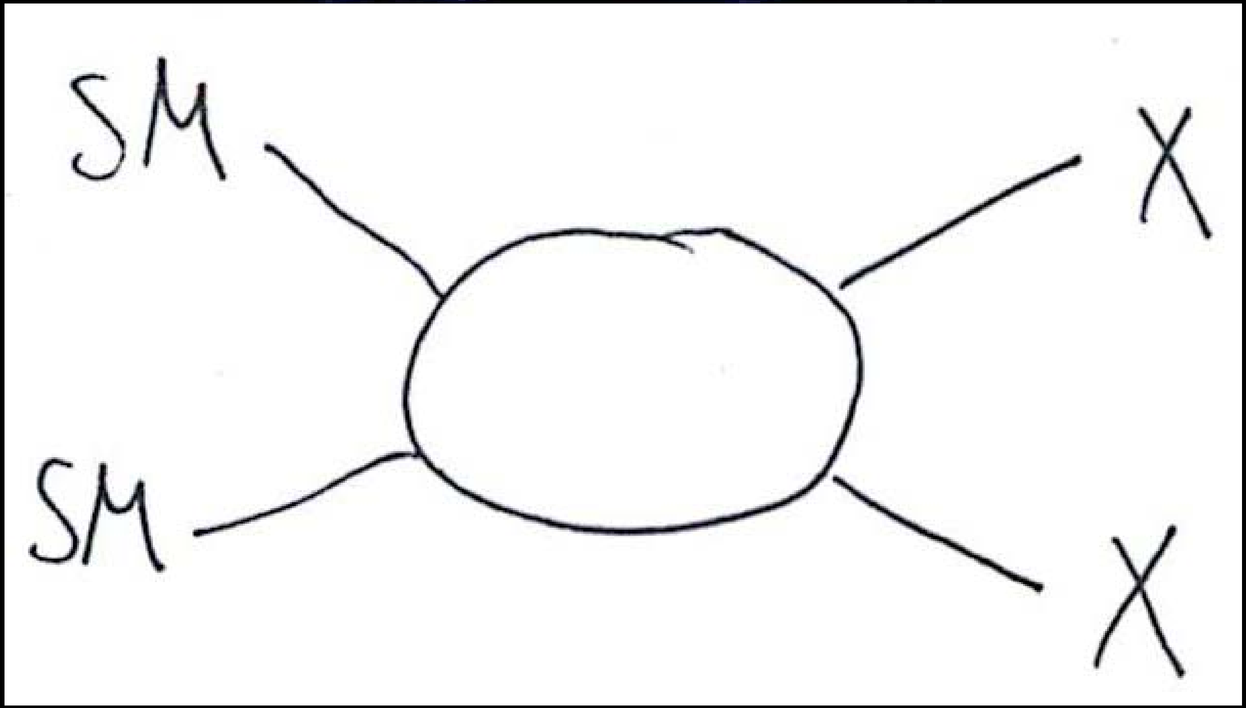
→ Non-resonance excess in large MET region

Considering the situation where the WIMP is the only new particle in the energy ranges relevant for current experiments

the WIMP will couple to the SM particles through higher dimensional operators

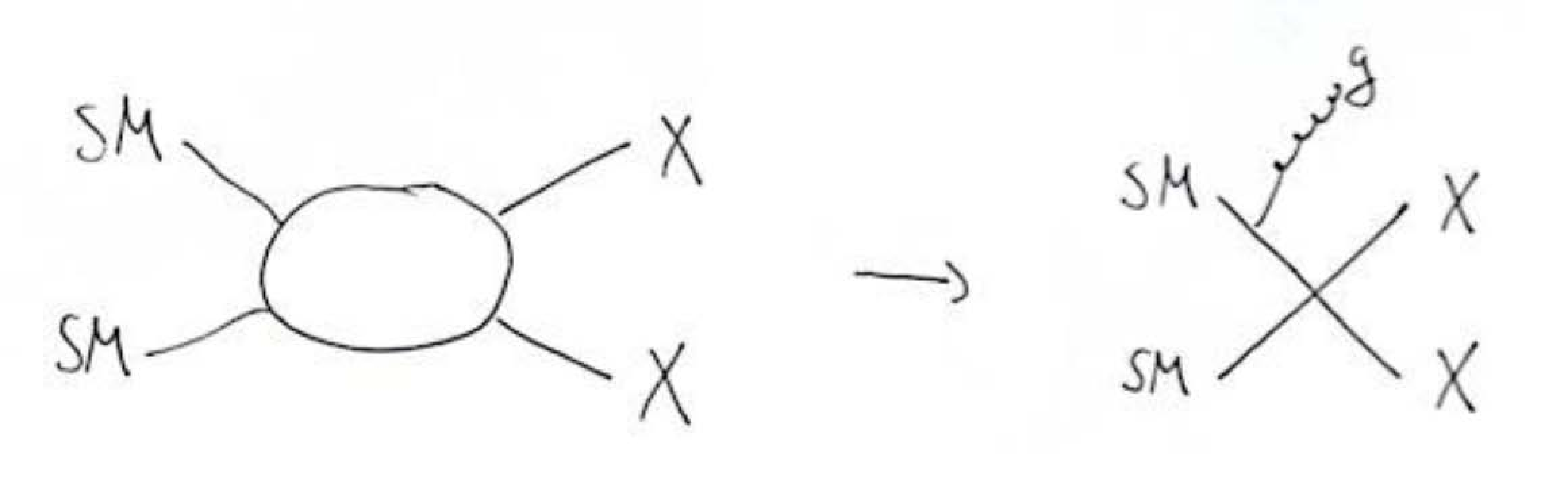
presumably mediated by particles of the dark sector which are somewhat heavier than the WIMP itself

One can have a contact operator approach to WIMP pair production



One can have a contact operator approach to WIMP pair production

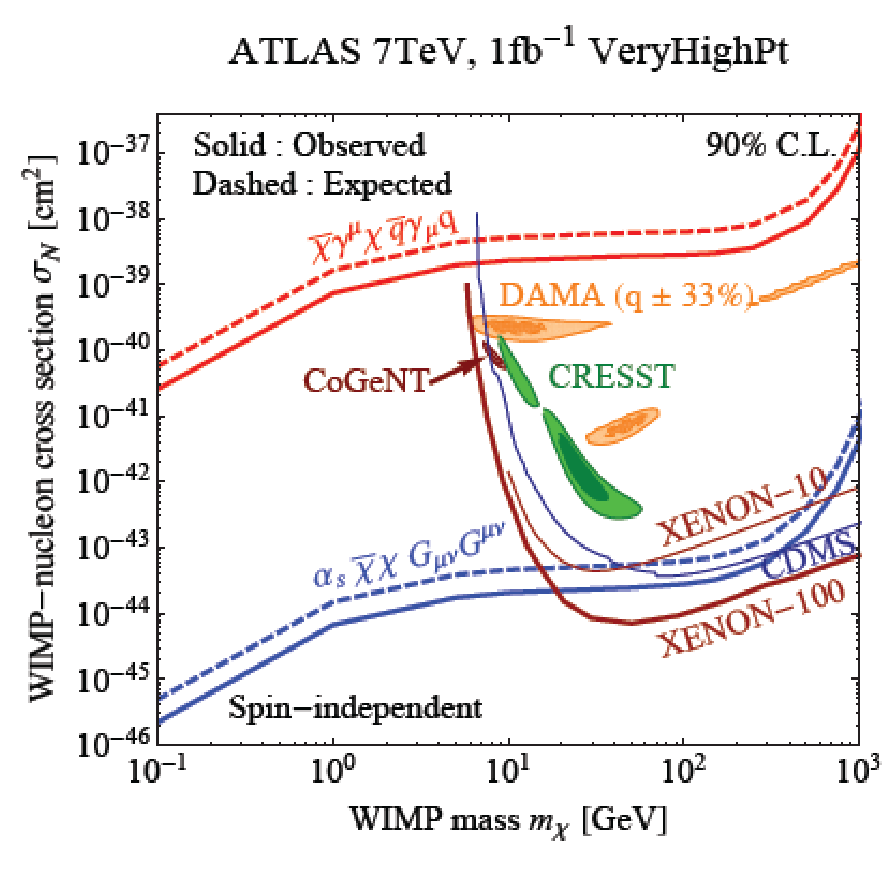
- Effective field theory approach
- χ–SM coupling set by m_χ and Λ (cutoff scale)
- χ is a Dirac fermion



LHC limit on cutoff scale can be translated to direct or indirect detection plane
Convert LHC limits to WIMP-nucleon cross sections

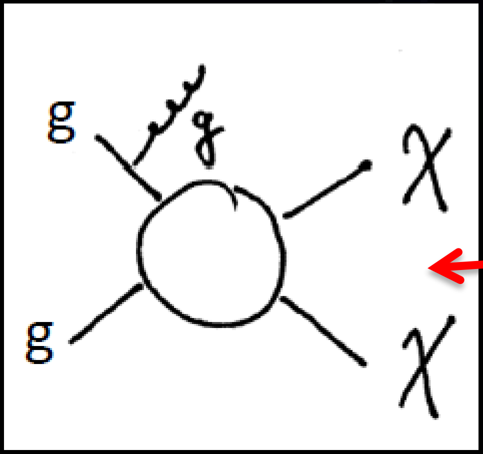
Limits on spin-independent Nucleon-WIMP scattering cross-section

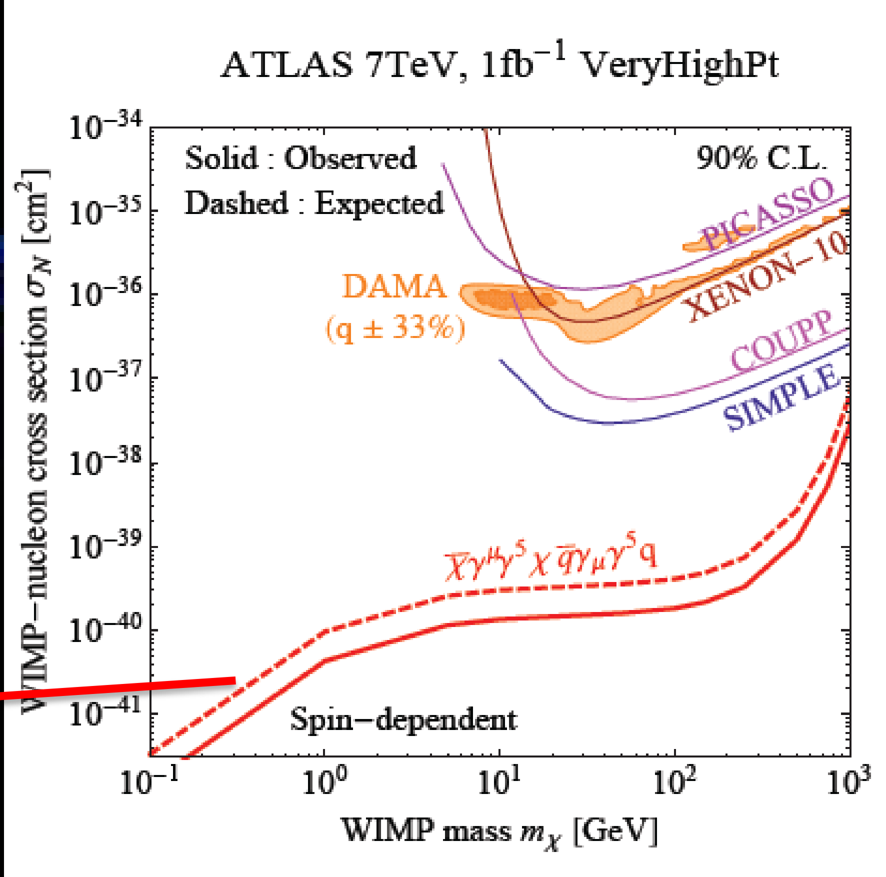
- LHC measurement translates into one line per operator
- Low-mass LHC reach complementary to direct detection experiments
- LHC limits don't suffer from astrophysical uncertainties



Limits on spin-dependent Nucleon-WIMP scattering cross-section

- LHC reach complementary to direct detection experiments ove the full mass range





Why search for WIMPs at the LHC?

Experimental limits will push theory forward
(and vice versa)

Plots of WIMP-nucleon (or annihilation cross section limits)
will be referenced by direct and indirect detection experiments
(and theory papers)

Interpretation provides a language to probe DM parameters
and
compare to other DM fields

What else can we wring out of a mono-something signal?

Interpretation in the context of

Compressed SUSY scenarios

e.g. arXiv:1205.1463v1

Geneviève Bélanger (LAPTH), Matti Heikinheimo and Verónica Sanz

Particles too soft to be reconstructed

produced in the decay chain of a new particle

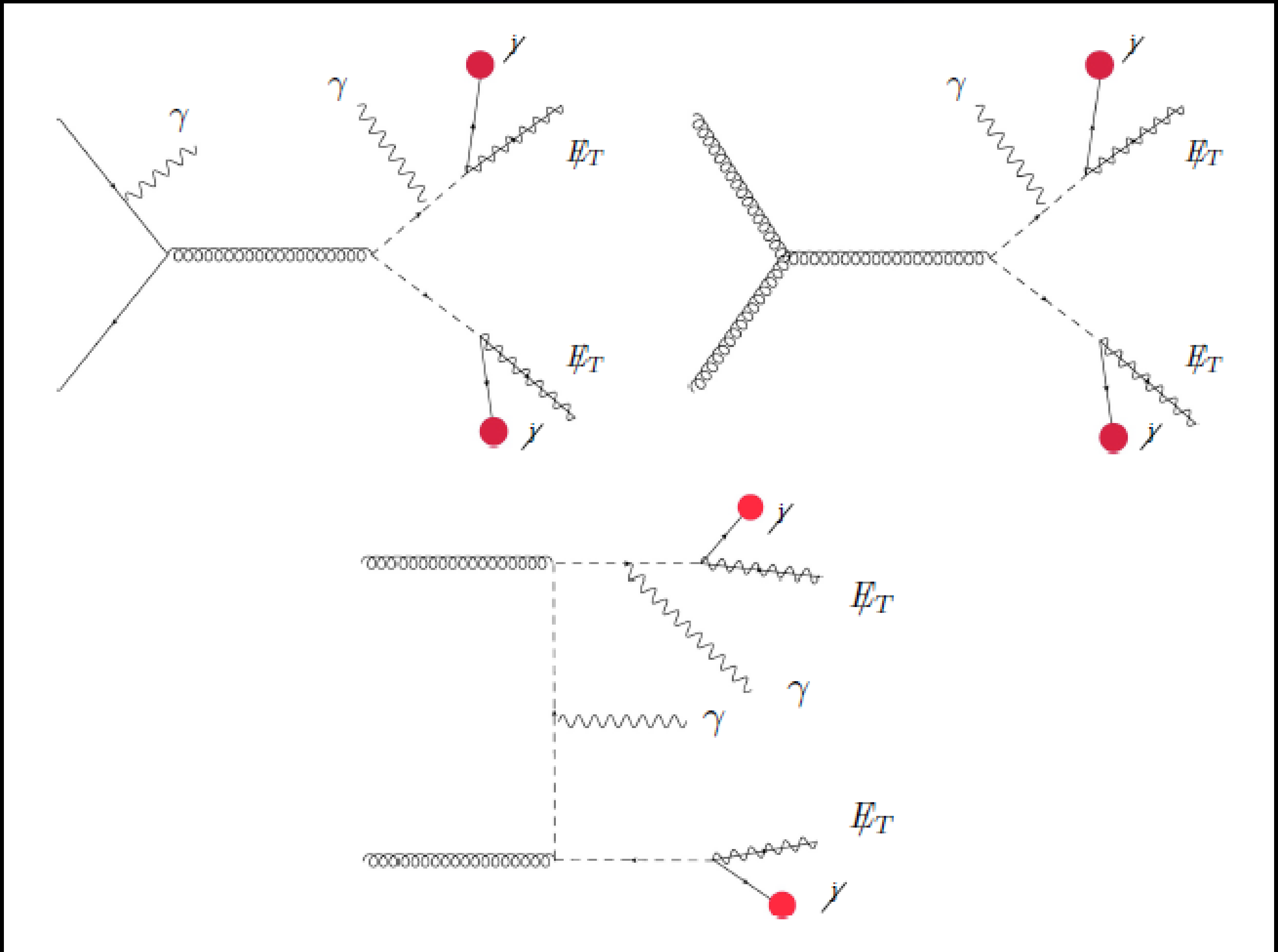
ADD extra dimensional model

KK graviton escapes into the bulk and a SM particle (photon or jet) is emitted

Compressed SUSY scenarios

arXiv:1205.1463v1

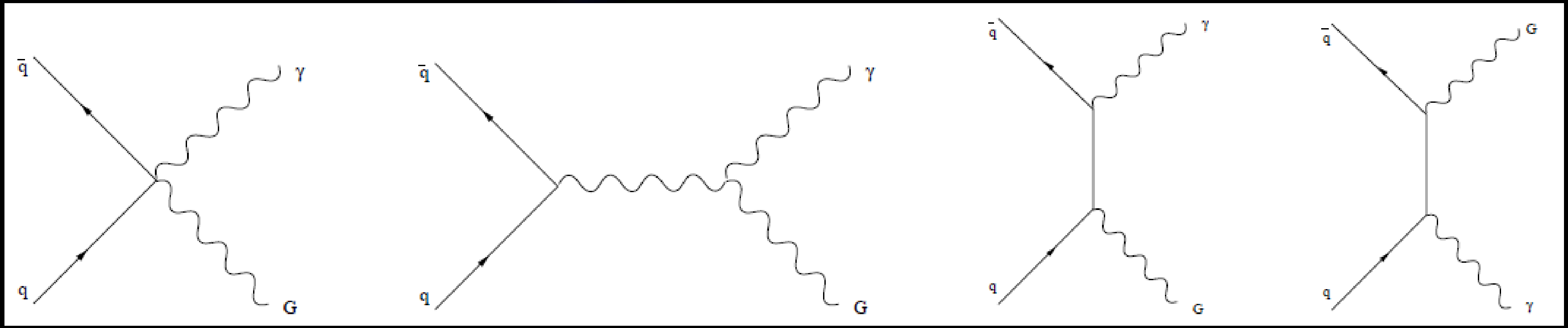
Geneviève Bélanger, Matti Heikinheimo and Verónica Sanz



Arkani-Hamed–Dvali–Dimopoulos extra dimensional model

Non interacting-graviton escaping the detector accompanied by a photon or a jet

$gg \rightarrow qG$
$q\bar{q} \rightarrow gG$ (qqbar → gG)
$qg \rightarrow qG$
$qq \rightarrow \gamma G$



So, why an ENIGMASS postdoctoral fellow ?

DM is an important enigma in particle physics
Direct, indirect and collider searches are complementary in the understanding of it

Coherent with LAPP and LPSC projects (ENIGMASS + ANR)

ATLAS Exotics mono-photon/W/Z/jet effort is underwomanned/undermanned
Presently ~ 4 people
Calling for contributors

LPSC is deeply involved in the ATLAS-Exotics group
and in particular in analyses with photon final states

Marie-Hélène has been greatly involved in SUSY (ex-Etmiss convenor) and DM searches
and would be interested in looking into the compressed SUSY interpretation
as discussed by Bélanger etal from LAPTH

My (HP) ongoing work is with the ATLAS SUSY and Exotics groups
1 or 2 photon final states + MET
Involved in extra dimensions (Randall Sundrum + UED) since 2003

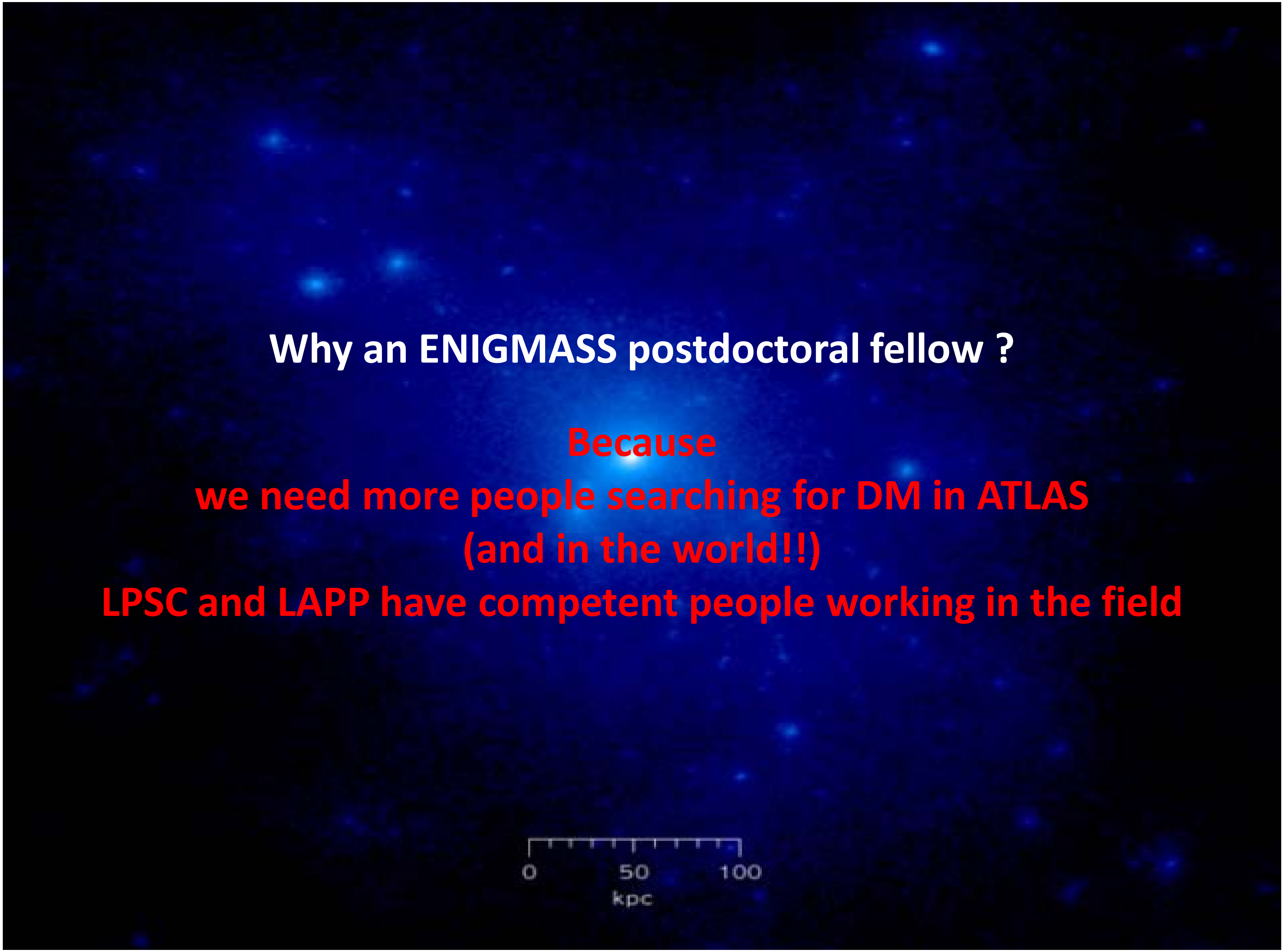
Why an ENIGMASS postdoctoral fellow ?

Because

we need more people searching for DM in ATLAS

(and in the world!!)

LPSC and LAPP have competent people working in the field



Backup slides

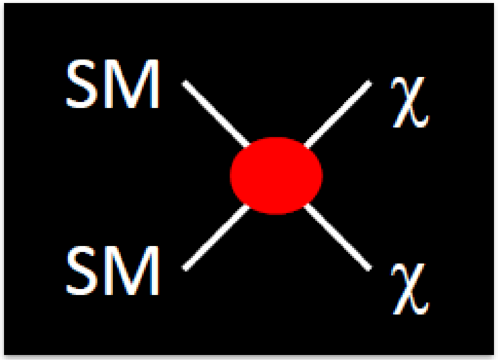
Operators currently used in ATLAS

WIMP as Dirac fermion

Cutoff scale now called M*

$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$	(D1)	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	(D8)
$\frac{m_q}{M_*^3}\bar{\chi}\gamma^5\chi\bar{q}q$	(D2)	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	(D9)
$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	(D3)	$\frac{1}{M_*^2}\epsilon^{\mu\nu\alpha\beta}\bar{\chi}\sigma_{\mu\nu}\chi\bar{q}\sigma_{\alpha\beta}q$	(D10)
$\frac{m_q}{M_*^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	(D4)	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s\left(G_{\mu\nu}^a\right)^2$	(D11)
$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	(D5)	$\frac{1}{4M_*^3}\bar{\chi}\gamma^5\chi\alpha_s\left(G_{\mu\nu}^a\right)^2$	(D12)
$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	(D6)	$\frac{1}{4M_*^3}\bar{\chi}\chi G_{\mu\nu}^a\tilde{G}^{a,\mu\nu}$	(D13)
$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_m u\gamma^5 q$	(D7)	$\frac{1}{4M_*^3}\bar{\chi}\gamma^5\chi G_{\mu\nu}^a\tilde{G}^{a,\mu\nu}$	(D14)

Representative set of operators chosen, monojet analysis in review stage (Exotics approval on Friday)



Convert LHC to WIMP-nucleon cross sections

http://arxiv.org/abs/1008.1783

$$\sigma_0^{D1} = 1.60 \times 10^{-37}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{20\mathrm{GeV}}{M_*}\right)^6, \quad (3)$$

$$\sigma_0^{D5,C3} = 1.38 \times 10^{-37}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{300\mathrm{GeV}}{M_*}\right)^4, \quad (4)$$

$$\sigma_0^{D8,D9} = 9.18 \times 10^{-40}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{300\mathrm{GeV}}{M_*}\right)^4, \quad (5)$$

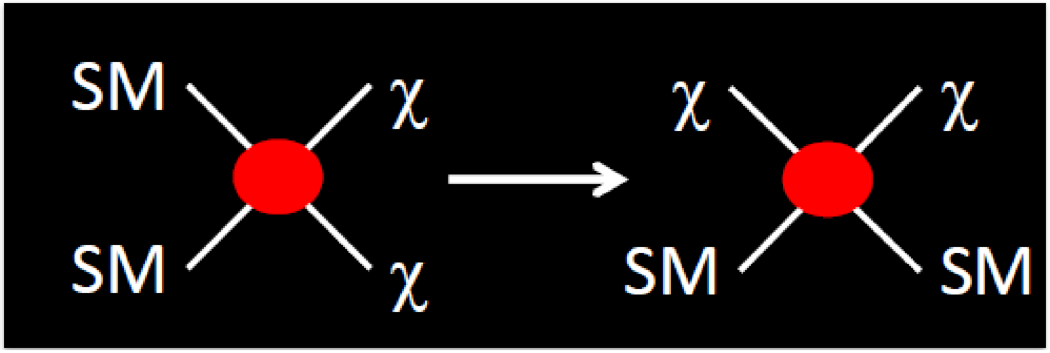
$$\sigma_0^{D11} = 3.83 \times 10^{-41}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{100\mathrm{GeV}}{M_*}\right)^6, \quad (6)$$

$$\sigma_0^{C1,R1} = 2.56 \times 10^{-36}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{10\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{10\mathrm{GeV}}{M_*}\right)^4, \quad (7)$$

$$\sigma_0^{C5,R3} = 7.40 \times 10^{-39}\mathrm{cm}^2 \left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2 \left(\frac{10\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{60\mathrm{GeV}}{M_*}\right)^4. \quad (8)$$

LHC cross section -> M* for a given m_χ -> $\sigma_{\text{WIMP-nucleon}}$

Cross process to transfer LHC measurment:



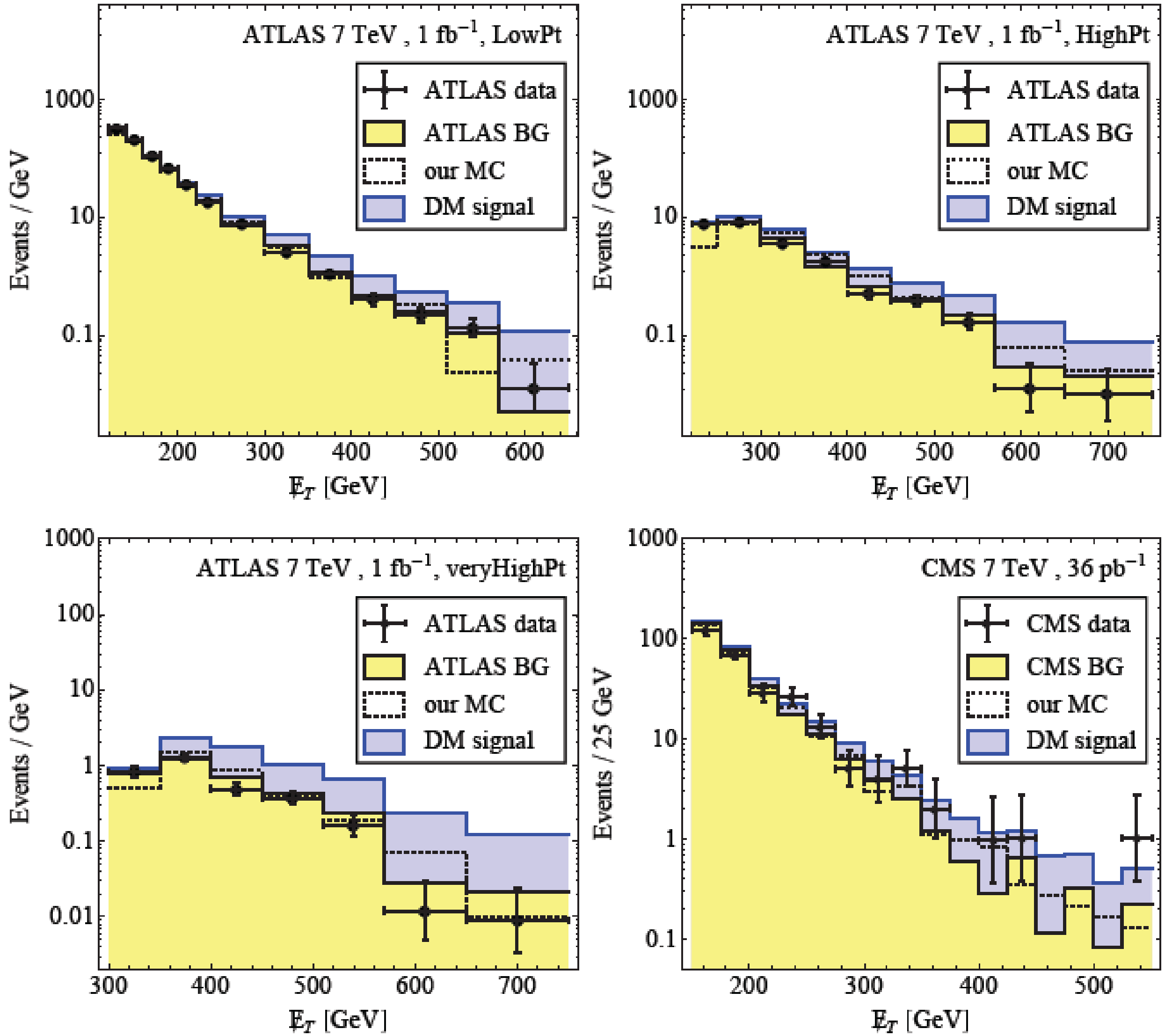


Figure 2: Measured missing energy spectra of $j + \not{E}_T$ for the three ATLAS analyses and the CMS analysis discussed in the text (black data points with error bars) compared to the collaborations' background predictions (yellow shaded histograms) and to our Monte Carlo prediction with (blue histograms) and without (black dotted lines) a dark matter signal. In all cases the DM signal comes from the vector operator, $\mathcal{O}_V$, and $m_\chi = 10\,\text{GeV}$, $\Lambda = 400\,\text{GeV}$. Our simulations are rescaled to match the overall normalization of the collaborations' background predictions.

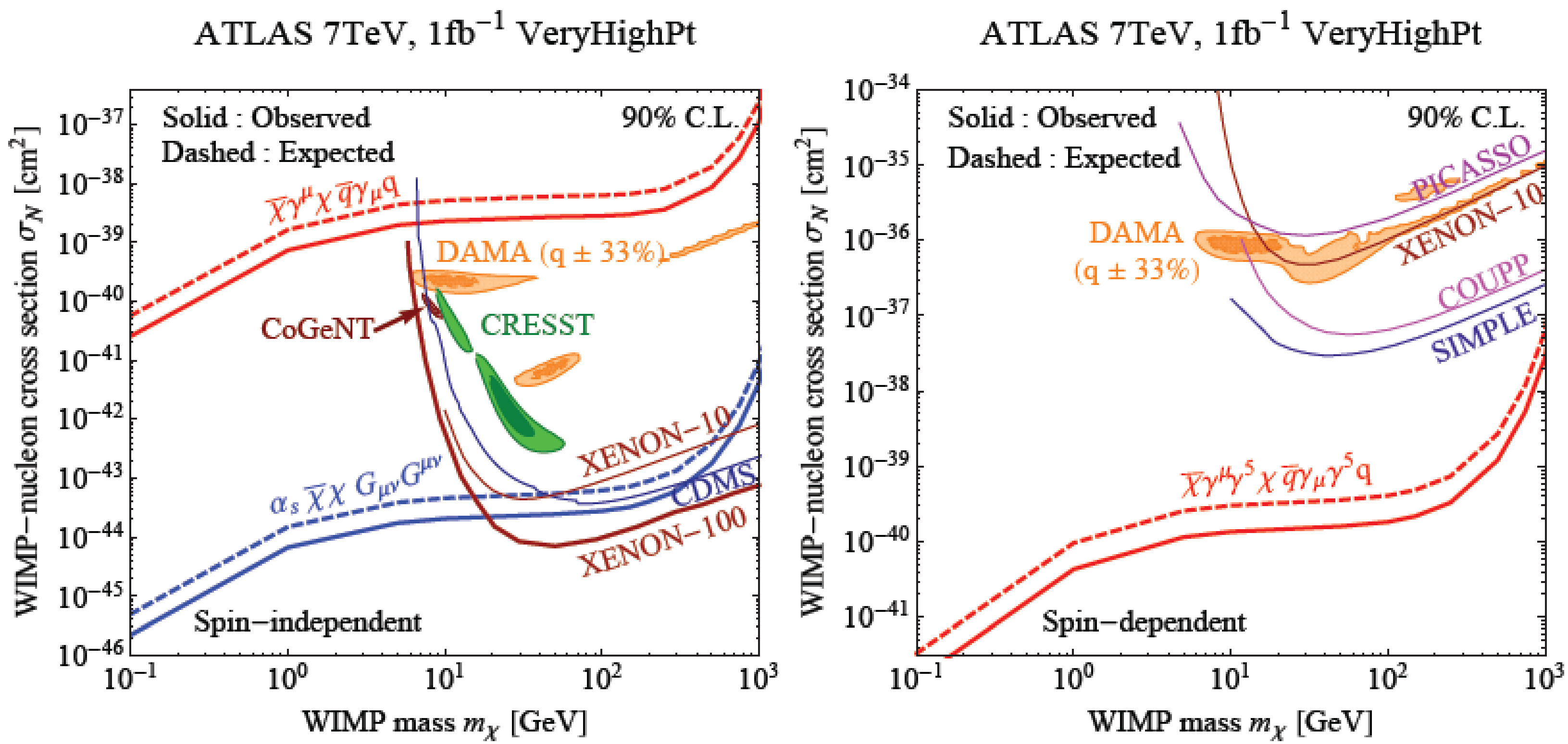


Figure 5: ATLAS limits on (a) spin-independent and (b) spin-dependent dark matter–nucleon scattering, compared to limits from the direct detection experiments. In particular, we show constraints on spin-independent scattering from CDMS [42], XENON-10 [43], XENON-100 [44], DAMA [45], CoGeNT [46, 47] and CRESST [48], and constraints on spin-dependent scattering from DAMA [45], PICASSO [49], XENON-10 [50], COUPP [51] and SIMPLE [52]. DAMA and CoGeNT allowed regions are based on our own fits [11, 47, 53] to the experimental data. Following [54], we have conservatively assumed large systematic uncertainties on the DAMA quenching factors: $q_{\mathrm{Na}} = 0.3 \pm 0.1$ for sodium and $q_{\mathrm{I}} = 0.09 \pm 0.03$ for iodine, which leads to an enlargement of the DAMA allowed regions. All limits are shown at 90% confidence level, whereas for DAMA and CoGeNT we show 90% and 3σ contours. For CRESST, the contours are 1σ and 2σ as in [48].

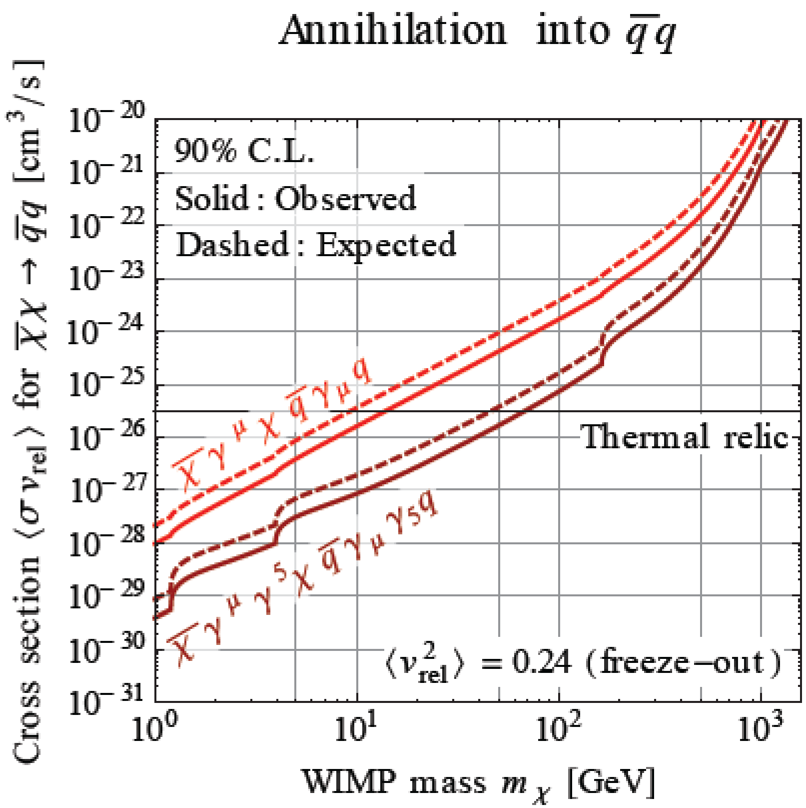
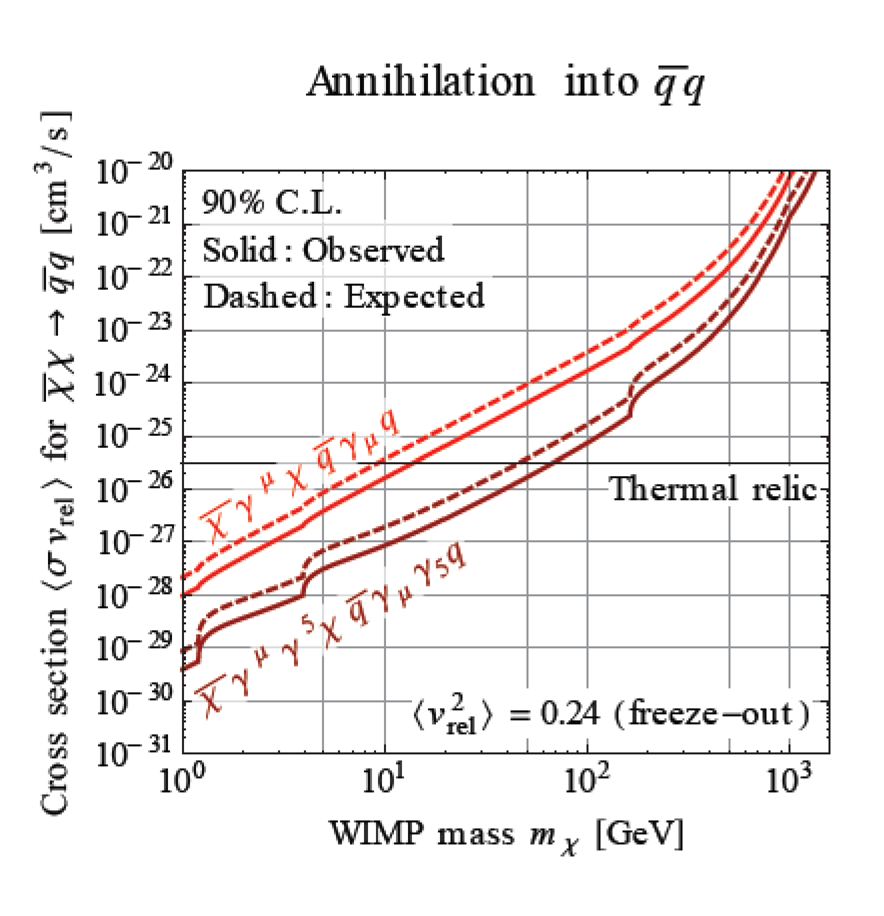


Figure 6: ATLAS constraints on dark matter annihilation for flavor-universal vector or axial vector couplings of dark matter to quarks. (If dark matter can annihilate also to leptons, the bounds are weakened by a factor $1/\mathrm{BR}(\bar{\chi}\chi \to \bar{q}q)$.) We consider an environment with $\langle v_{\rm rel}^2\rangle = 0.24$, corresponding to the epoch at which thermal relic dark matter freezes out in the early universe. $\langle v_{\rm rel}^2\rangle$ is much smaller in present-day environments such as galaxies, which leads to improved collider bounds on the annihilation rate in those systems. The value of $\langle \sigma v_{\rm rel}\rangle$ required for dark matter to be a thermal relic is indicated by the horizontal black line.

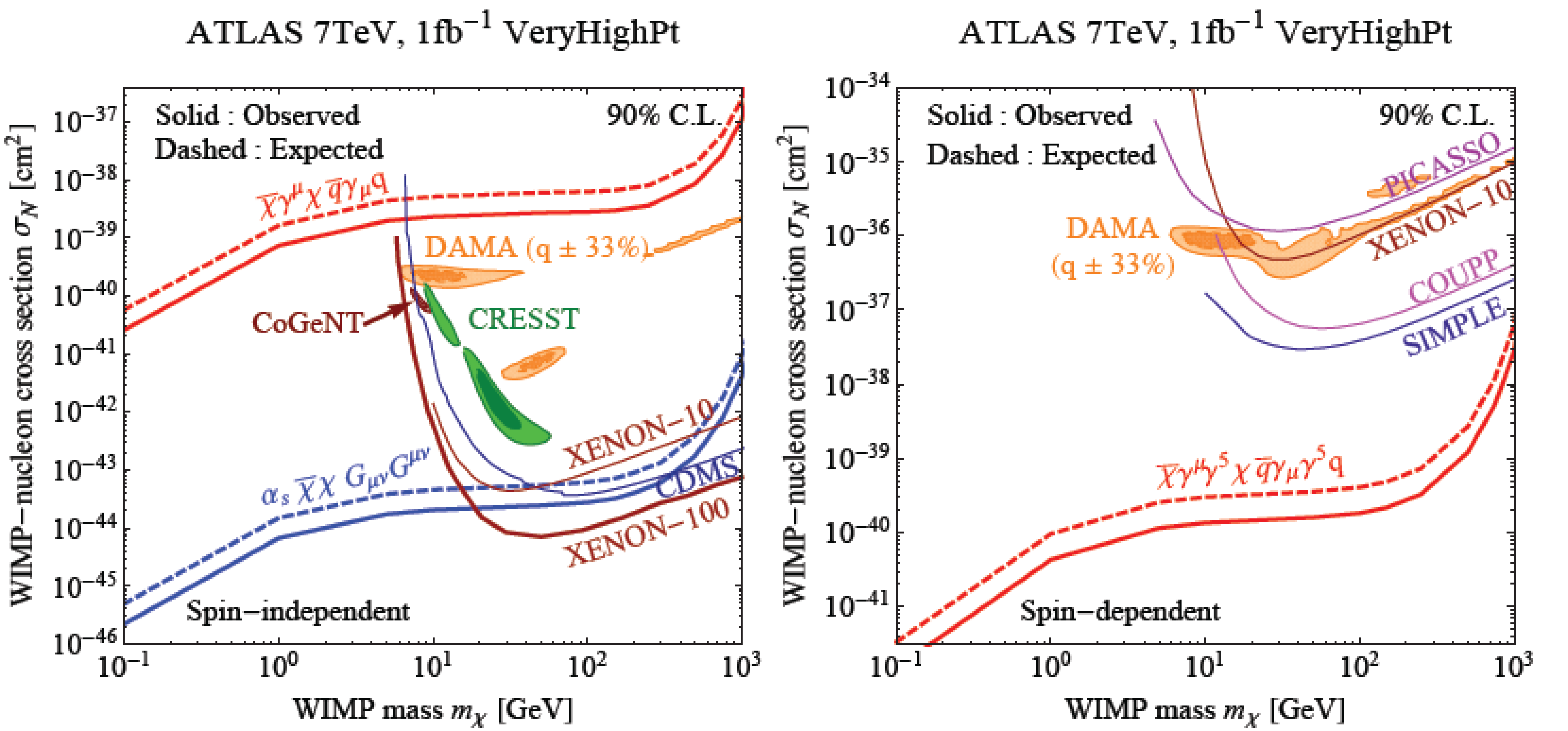
Limits on annihilation cross section

- DM annihilation at freeze-out temperatures
- Assume DM couples to quarks only (otherwise weaker bounds)
- Assume effective field theory approach is viable

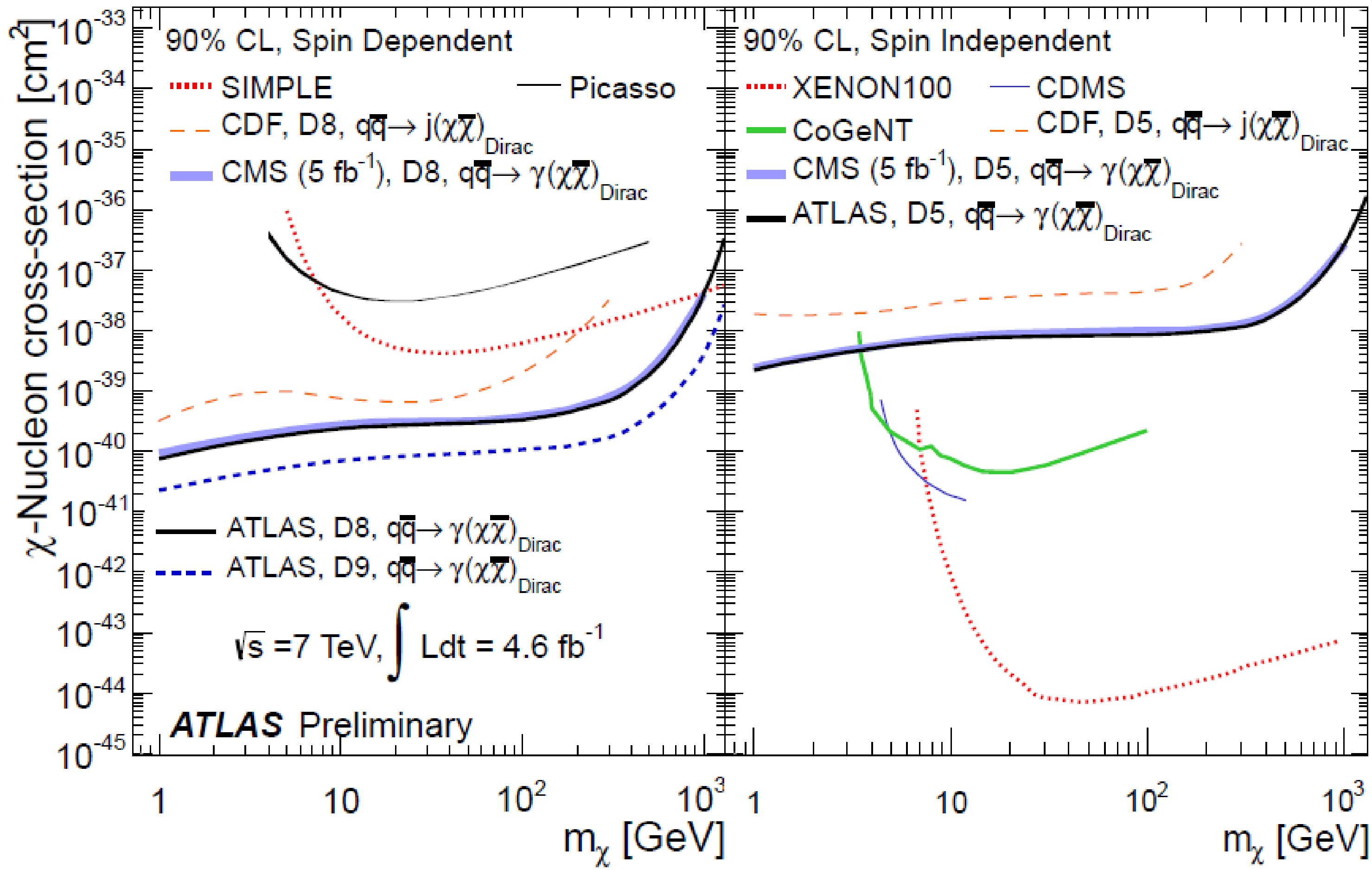


ATLAS limits on (a) spin-independent (red:D5; blue: D11) and (b) spin-dependent (D8) dark matter–nucleon scattering compared to limits from the direct detection experiments.

All limits are shown at 90% confidence level, except for DAMA and CoGeNT are shown 90% and 3σ contours. For CRESST, the contours are 1σ and 2σ



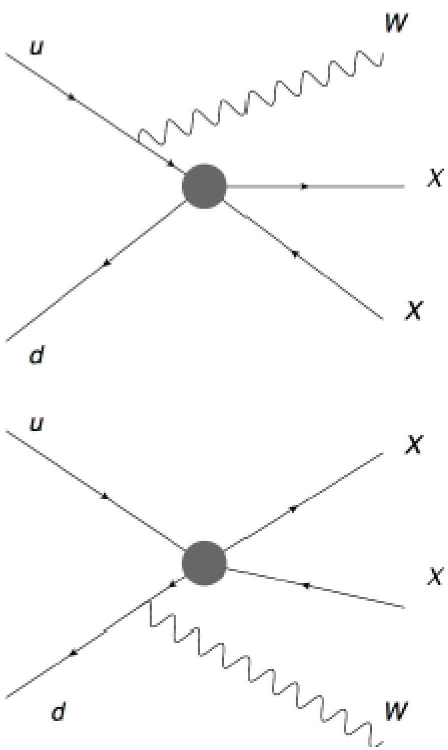
ATLAS-CONF-2012-085



Here we have assumed that DM is a Dirac fermion,
the case of a Majorana fermion would not greatly alter our results,
except in the case of the vector operator O_V (vector, s-channel),
which vanishes if χ is a Majorana fermion.

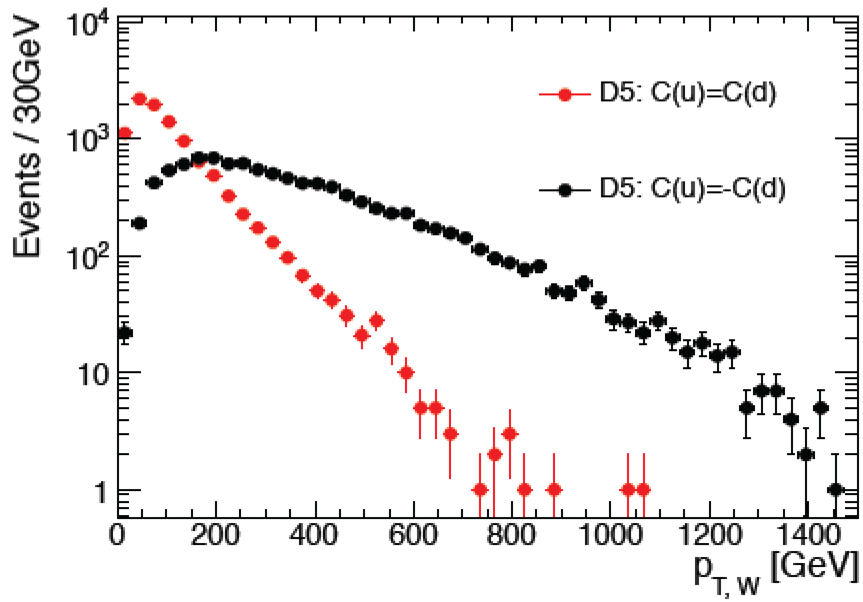
Mono-W

- Unique feature of mono-W diagrams in D5 mode
  - Constructive interference: C(u) = - C(d), 200 fb (M*=1TeV)
    - Enhance production rate and W boosting
  - Destructive interference: C(u) = C(d), 26 fb
- Preliminary studies from 7TeV data show that for the constructive mode, mono-W is expected to be even more sensitive than mono-jet



arXiv:1208.4361

$$\frac{1}{M^{*2}}\bar{\chi}\gamma^{\mu}\chi\left(\bar{u}\gamma_{\mu}u+\xi\cdot\bar{d}\gamma_{\mu}d\right)$$



Constraints on Dark Matter from Colliders
arXiv:1008.1783v2

Our results are qualitatively similar to our previous paper. In general collider constraints are very strong for lighter dark matter and fall off when the dark matter mass exceeds the typical energy reach of the collider. The constraints also depend on the coupling of the dark matter; if the dark matter primarily couples to gluons, the constraints from colliders become especially strong.

One of the most interesting results is that collider constraints on spin dependent interactions are stronger than direct searches over a significant portion of parameter space.

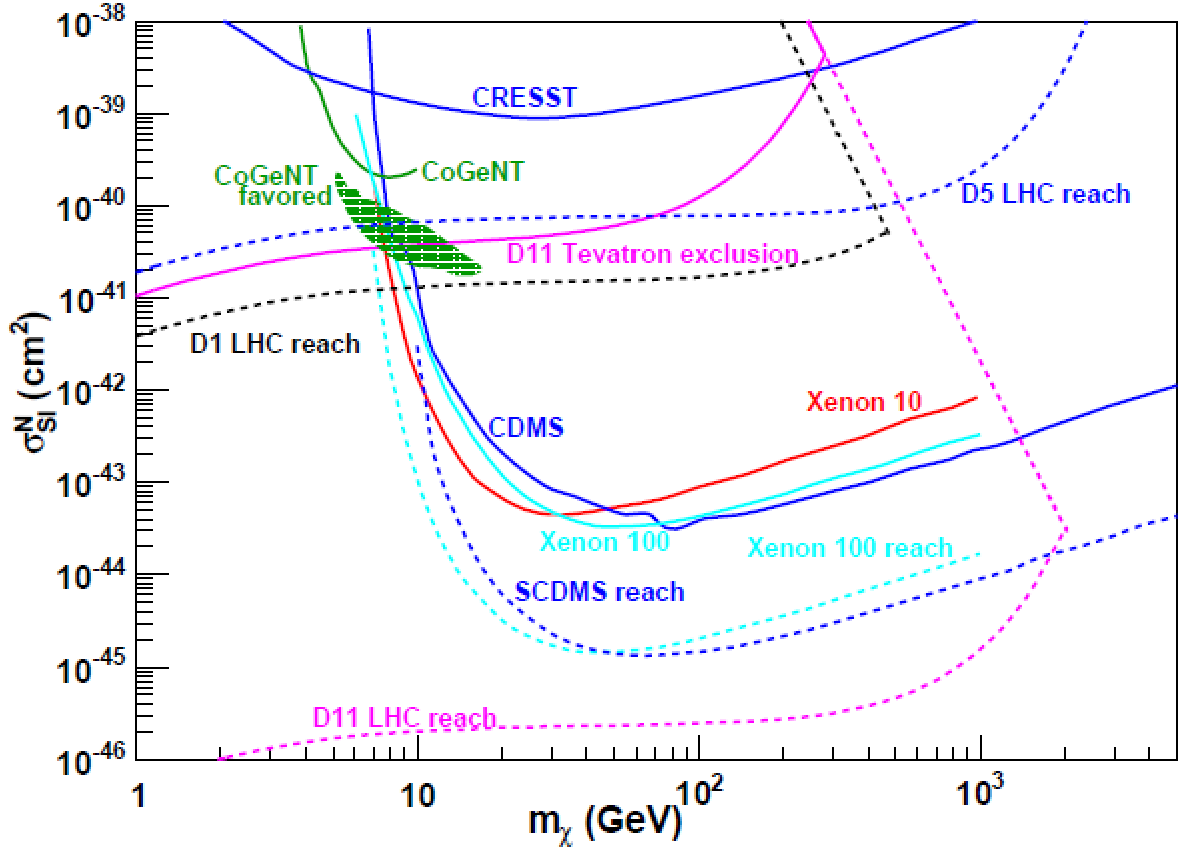


FIG. 1: Current experimental limits on spin-independent WIMP direct detection from CRESST [52], CDMS [53], Xenon 10 [54], CoGeNT [13], and Xenon 100 [15], (solid lines as labeled), as well as the CoGeNT favored region [13] and future reach estimates for SCDMS [55] and Xenon 100 [56], where we have chosen the line using a threshold of 3PE and the conservative extrapolation of $\mathcal{L}_{eff}$ (dashed lines as labeled). Also shown are the current Tevatron exclusion for the operator D11 (solid magenta line) as well as LHC discovery reaches (dashed lines as labeled) for relevant operators.

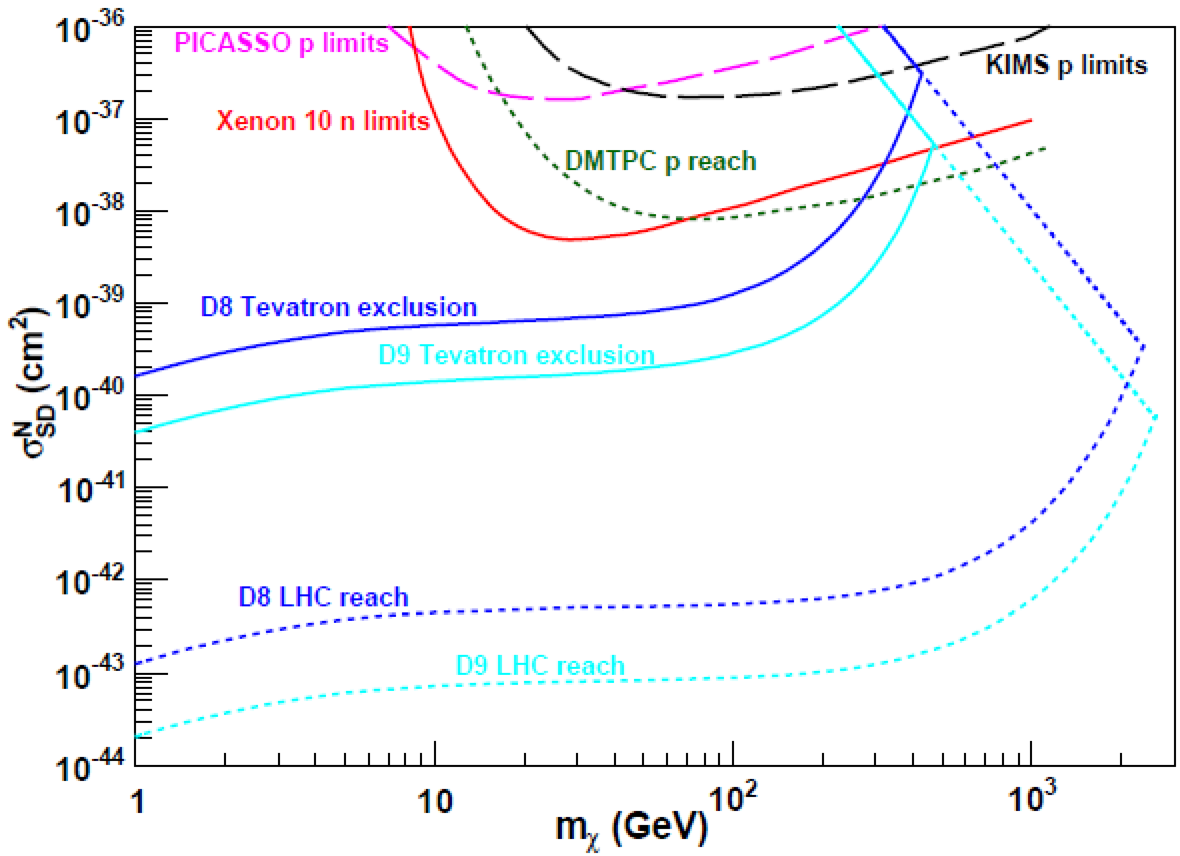


FIG. 2: Current experimental limits on spin-dependent WIMP direct detection from Picasso [57], KIMS [58], and Xenon 10 [54], as well as the future reach of DMTPC [59]. Also shown are the current Tevatron exclusions (solid lines as labeled) and LHC discovery reaches (dashed lines as labeled) for relevant operators.

Compressed SUSY spectrum

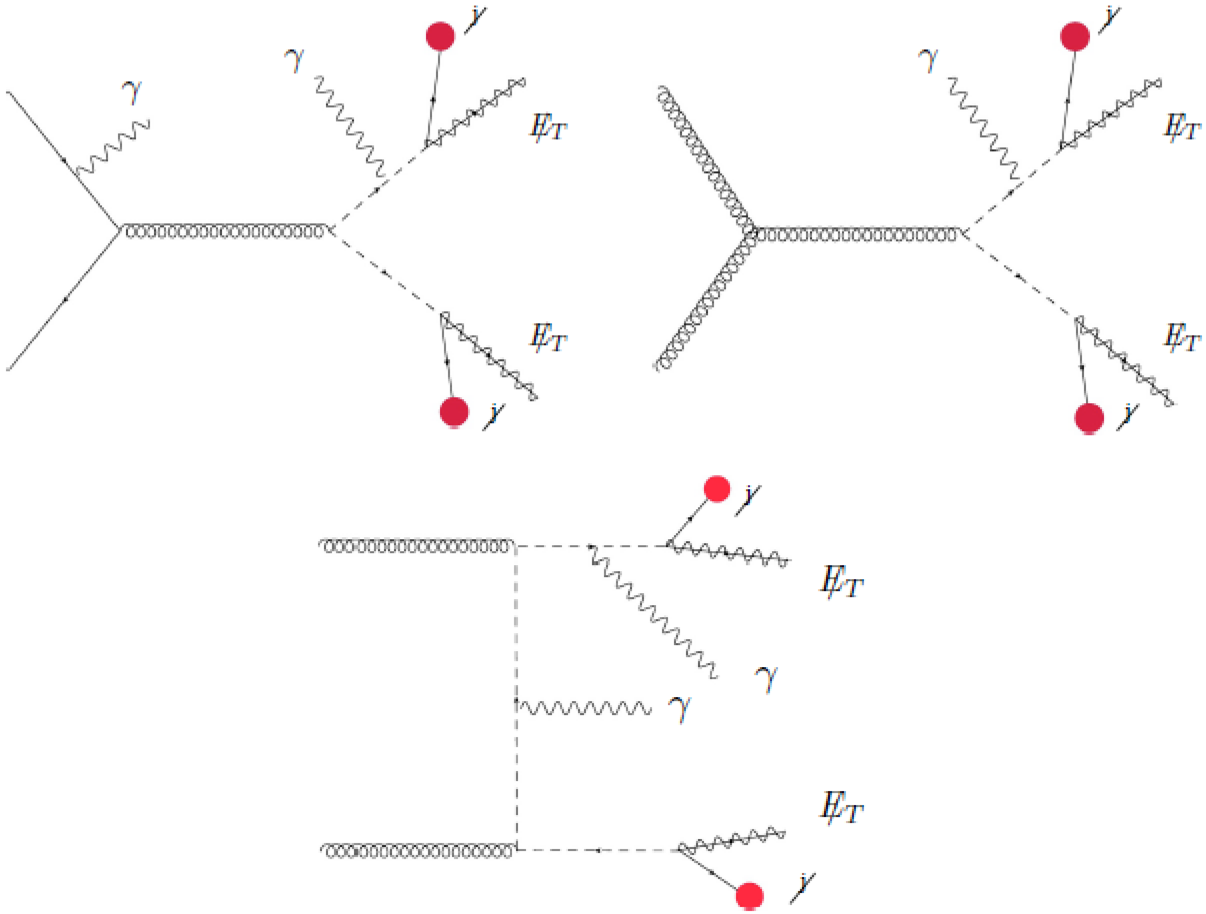


FIG. 1: Squark production and decay diagrams.

References

• Consider WIMP pair production at colliders, idea goes back to:
– Birkedal et al (hep-ph/0403004)
– Beltran et al: Maverick Dark Matter (hep-ph/1002.4137)
• Latest papers based on LHC results:
– Fox et al, arxiv:1109.4398, arXiv:1202.1662, arXiv:1203.1662 (FNAL crew, monojets and razor)
– Rajamaran et al, arxiv:1108.1196 (UCI crew, monojets)
– etc.

–Constraints on Dark Matter from Colliders : arXiv:1008.1783v2
– Model-Independent Bounds on Squarks from Monophoton Searches : arXiv:1205.1463v1 (Bélanger etal)
– Missing Energy Signatures of Dark Matter at the LHC : arXiv:1109.4398v1
– Search for dark matter candidates and large extra dimensions in events with a photon and missing transverse momentum in pp collision data at √s =7 TeV with the ATLAS detector : ATLAS-CONF-2012-085