Current Collider Bounds on Dark Matter

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In collaboration with Patrick Fox, Roni Harnik, and Joachim Kopp

Cornell Theory Seminar, 19 Oct 2011

Cornell University

Fermilab

The talk is based on the following works

Missing Energy Signatures of Dark Matter at the LHC
arXiv:1109.4398

LEP Shines Light on Dark Matter
Phys. Rev. **D84**, 014028 (2011).

See also

J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd,
T. M. P. Tait, A. M. Wijangco, and H. -B. Yu

LHC Bounds on Interactions of Dark Matter
arXiv:1108.1196

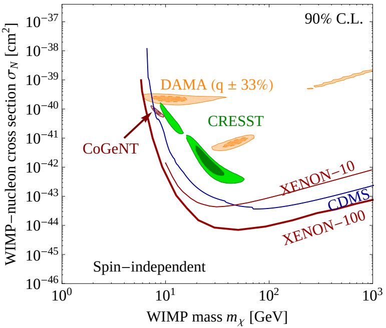
Constraints on Dark Matter from Colliders
Phys. Rev. **D82**, 116010 (2010)

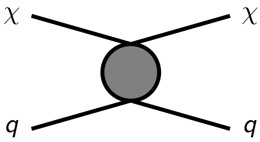
Constraints on Light Majorana dark Matter from Colliders
Phys. Lett. **B695**, 185-188 (2011)

Main question

How can colliders help to solve the (in-)direct detection anomalies?

The Direct Detection bound





Ahmed et al. (10), Angle et al. (08), Kopp et al. (10)

Naively...

- It's a nice plot!
- It contains the information we need.
- Let's start to build a model!

Well...wait a sec...

There's something I haven't told you...

$$\frac{d\,R}{d\,E_R} = N_T\,\frac{\rho_0}{m_\chi}\int_{v_{\min}}^{v_{esc}} d^3v\,\frac{d\,\sigma}{d\,E_R}\,v\,f(v)$$

There is a lot of uncertainties hidden in this equation.

- DM density $\rho_0 \sim 0.3\,\mathrm{GeV\,cm^{-3}}$
- Recoil energy $E_{\mathrm{R}} = E_{\mathrm{obv}}\,/\,quenching\ q_{\mathrm{Na}} = 0.3 \pm 0.1,\ q_{\mathrm{I}} = 0.09 \pm 0.03$
- Velocity distribution $f(v)$ Maxwell-Boltzman
- Escape velocity $v_{\mathrm{esc}} \sim 650\,\mathrm{km\,s^{-1}}$
- v_{min}, (in-)elastic scattering?
- Spin Independent σ, Spin Dependent $\sigma(v)$.
- XXXX

Well...wait a sec...

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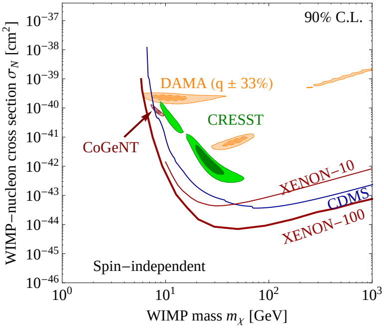


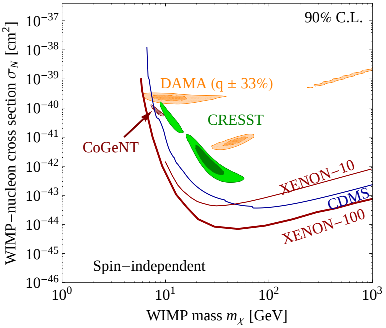
$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{v_{esc}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f(v)$$

Recoil Energy $E_R = E_{obv} / q$

Channeling may enhance q.

Well...wait a sec...

There's something I haven't told you...



$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{v_{esc}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f(v)$$

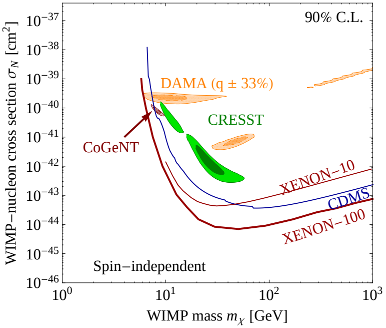
Local DM density ρ_0

Velocity Distribution $f(v)$

Depend on the Halo Structure

Well...wait a sec...

There's something I haven't told you...



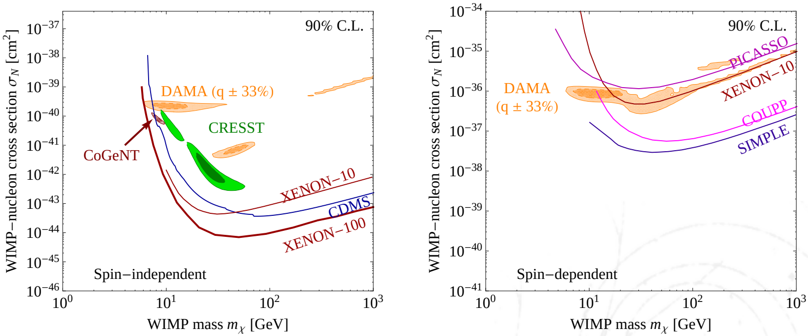
$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{v_{esc}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f(v)$$

Minimum velocity $v_{\min}$

Depend on if the scattering is (in-)elastic.

More problems...

- Light DM is interesting, but hard to measure. (E_R threshold)
- The Spin Dependent bounds are bad. (velocity suppression)



Bernabei et al. (08), Angle et sl. (08), overlinenabe-Heider et al. (05), Behnke et al. (10), Girard et al. (11)

Want to have a measurement...

- independent of astrophical and experimental assumptions.
- good bounds on light DM.
- good bounds on spin dependent case.

Does this measurement exist?

Want to have a measurement...

- independent of astrophical and experimental assumptions.
- good bounds on light DM.
- good bounds on spin dependent case.

Does this measurement exist?

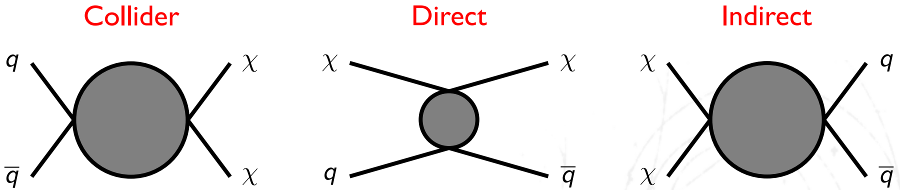
YES

Collider Expermients

'Collider bounds' in this talk

Collider Bounds

The $\sigma - m_\chi$ bounds given by constraining the effective couplings between DM/SM using colliders.

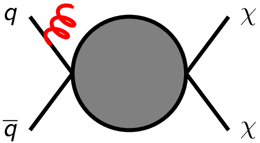


MonoJet @ Tevatron

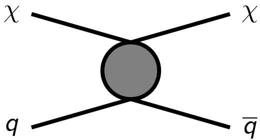
Y. Bai, P. J. Fox, and R. Harnik, **JHEP 12**, 048 (2010)
J. Goodman et al., Phys. Rev. **D82**, 116010 (2010)
J. Goodman et al., Phys. Lett. **B695**, 185 (2011)

DM in Monojet Searches

Tevatron



Direct Detection



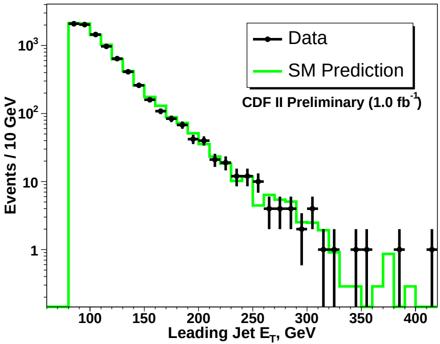
- Assume fermionic DM.
- 4-fermi interactions:

$$\mathcal{O}_V = \frac{(\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)}{\Lambda^2} \qquad \mathcal{O}_S = \frac{(\overline{\chi}\chi)(\overline{q}q)}{\Lambda^2}$$

$$\mathcal{O}_A = \frac{(\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)}{\Lambda^2} \qquad \mathcal{O}_t = \frac{(\overline{\chi}q)(\overline{q}\chi)}{\Lambda^2}$$

Monojet @ Tevatron

- In search of Large Extra Dimension (ADD)
- New physics channels: $q\,\overline{q} \rightarrow g\,G$, $q\,g \rightarrow g\,G$, $g\,g \rightarrow g\,G$.
- Main Cuts: Jet Et and $\not{E}$t $>$ 80 GeV.
- Background: Jet $+$ ($Z \rightarrow \nu\,\overline{\nu}$, $W \rightarrow \nu\,l$), QCD...

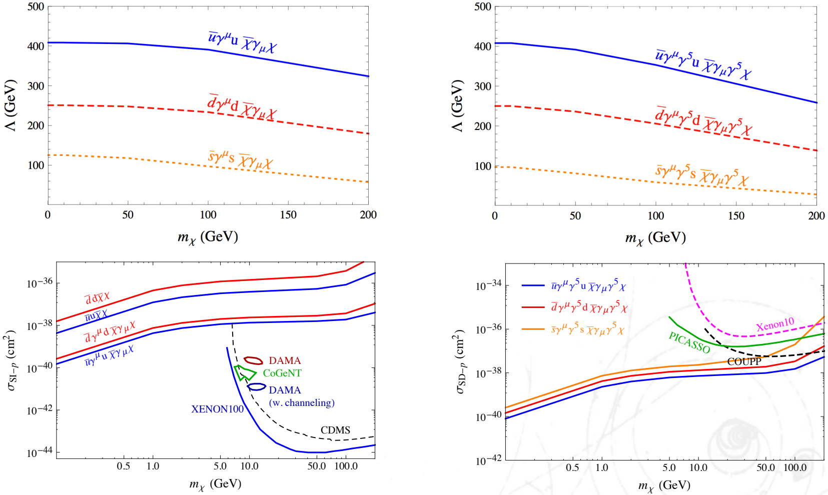


Luminosity: $1\,\mathrm{fb}^{-1}$

SM BG Events: 8663 ± 332

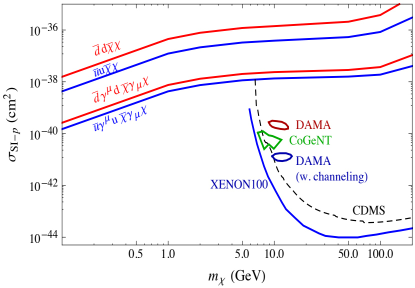
Observed Events: 8449

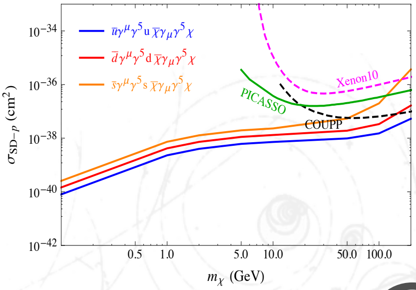
Bounds from $q\,\bar{q} \to$ Jet $+\ \chi\,\chi$



This is what we want!

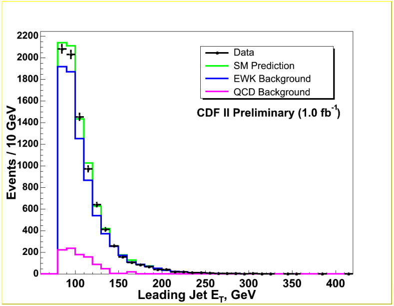
- Independent of astrophical and experimental assumptions.
- Good bounds on Light DM.
- Good bounds on spin dependent couplings.





Can we do better?

- The MonoJet bound @ Tevatron is limited by the theoretical uncertainty of the QCD background.



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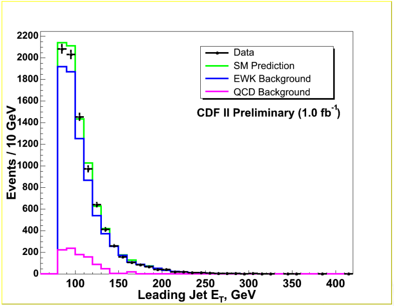

- Different process? MonoPhoton Search at LEP

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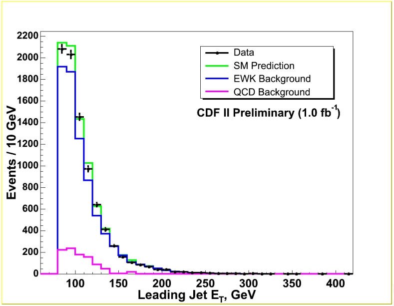
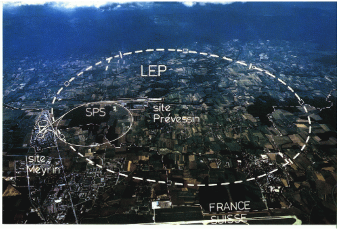


- Different process? MonoPhoton Search at LEP
- Higher jet P_T? The searches at LHC

MonoPhoton @ LEP



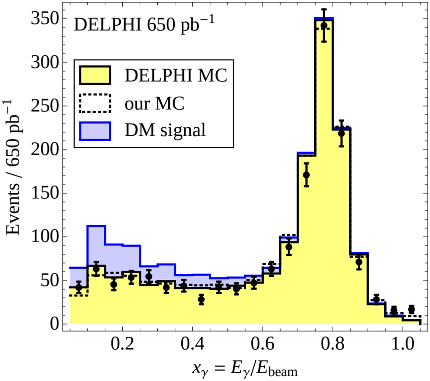
P. J. Fox, R. Harnik, J. Kopp, and YT, 1103.0240

With ILC

A. Birkedal, K. Matchev, and M. Perelstein, hep-ph/0403004

Jet → Photon Tevatron → LEP

- In search of Large Extra Dimension (ADD)
- New physics channels: $e\,\bar{e} \to \gamma\, G$

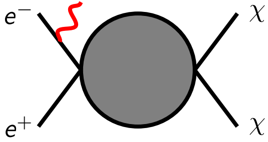


- Experiment: DELPHI
- $E_{\rm beam}$: 90 – 105 GeV
- Use the cuts in [1], ($E_\gamma \gtrsim 10$GeV).
- Background: $e^+e^- \to \gamma\nu\bar{\nu}$
- We use CompHEP.

[1] DELPHI Collaboration, hep-ex/0406019.

Direct Detection Bound

- Assume DM particle is a Dirac fermion.
- Use shape analysis (χ^2) to contraint the size the coupling

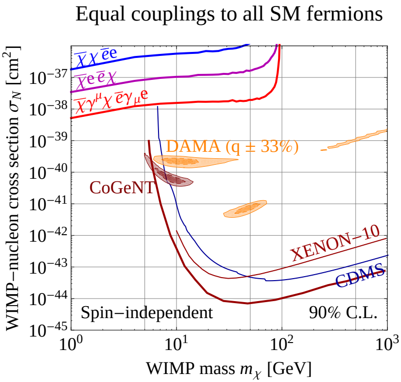


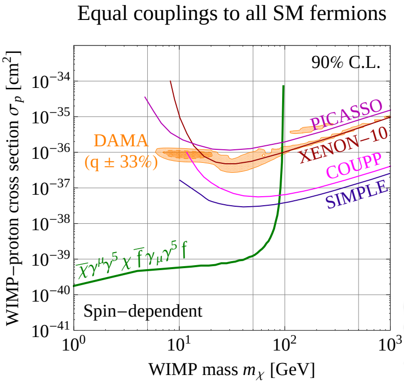
Need the coupling to quarks!

Consider Two Possibilities:

- Equal Coupling: to quarks and leptons.
- Leptophilic: coupling to leptons only.

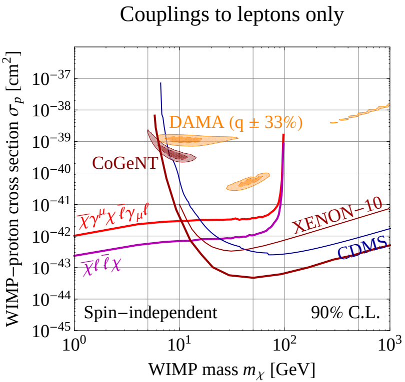
Equal couplings

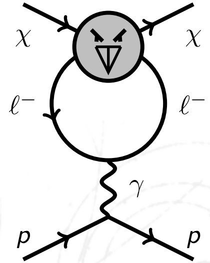




Leptophilic: no direct coupling to q's

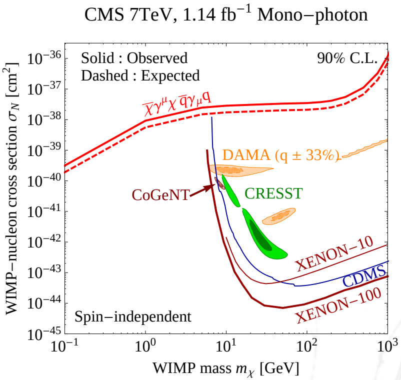
- Get loop suppression. $\mathcal{O}_A$, $\mathcal{O}_S$ vanish at one loop.
- Leptophilic model proposed to explain DAMA or CoGeNt is ruled out.



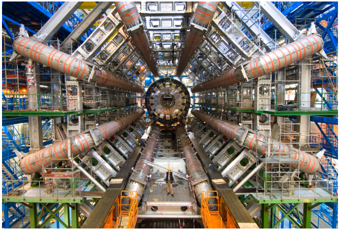


MonoPhoton from LHC

The CMS MonoPhoton search



MonoJet @ LHC



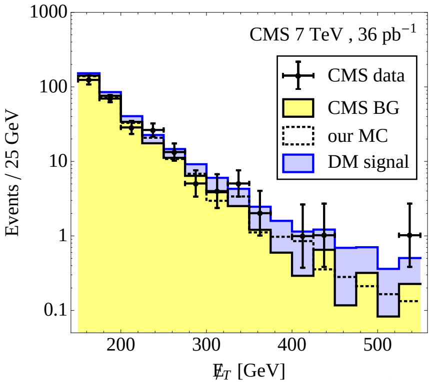
P. J. Fox, R. Harnik, J. Kopp, and YT, 1109.4398

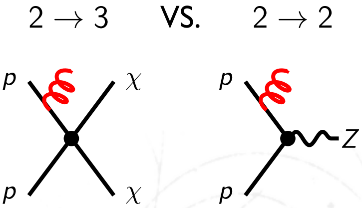
A. Rajaraman, W. Shepherd, T.M.P. Tait, A.M. Wijangco ,
1108.1196

How to improve the bounds?

There are two ways we can go

- Getting more data.
- Looking at the higher p_T region.





The shapes are different!

How to improve the bounds?

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- Looking at the higher p_T region.

At the current stage

Optimizing the higher p_T search is more important!

We can get some idea from the following Mono-Jet searches:

- CMS $36\,\mathrm{pb}^{-1}$
- ATLAS $1\,\mathrm{fb}^{-1}$: LowPt, HighPt and veryHighPt.

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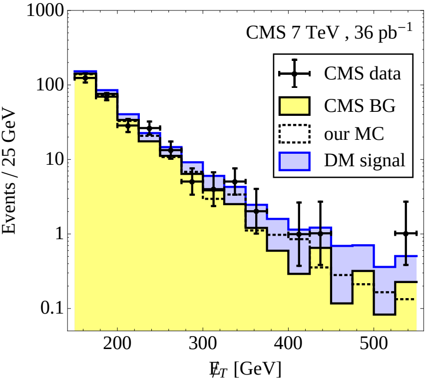
Mono-Jet search at CMS

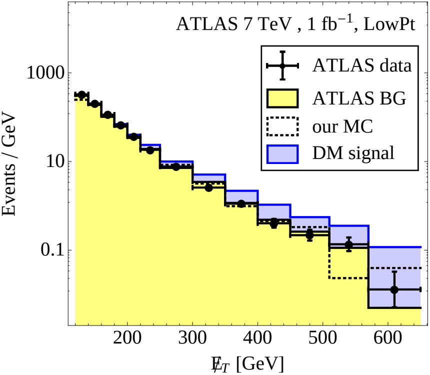
arXiv:1106.4775



- 7 TeV, 36 pb^{-1}
- Search: Mono-Jet $+ \not{E}_T$.
- Background:
  Jet $+ (Z \to \nu\nu,\ W \to \nu\ell)$.
- Main cuts:
  $\not{E}_T > 150$ GeV, $p_{T,j_1} > 110$ GeV.
- Result: 275 (297 $\pm$ 45 for the BG).

Mono-Jet search at ATLAS (LowPt)

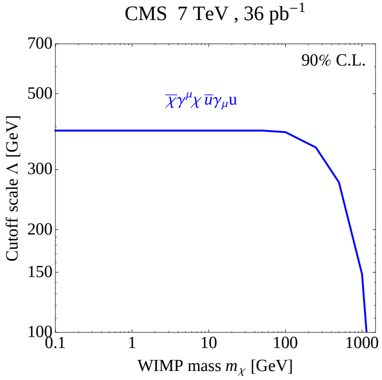
ATLAS-CONF-2011-096

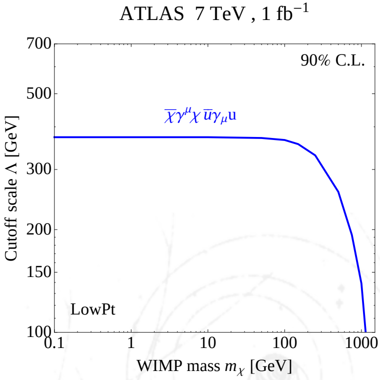


- 7 TeV, 1 fb^{-1}
- Search: Mono-Jet + $\not\!\!E_T$.
- Background:
  Jet + ($Z \to \nu\nu$, $W \to \nu\ell$).
- Main cuts:
  $\not\!\!E_T >$ 120 GeV, $p_{T,j_1} >$ 120 GeV.
- Result: 15740 ($15100 \pm 170 \pm 680$).

Lower bound on the cutoffs

- Bound for vector operator $\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{u}\gamma_{\mu}u)}{\Lambda^2}$ from counting.





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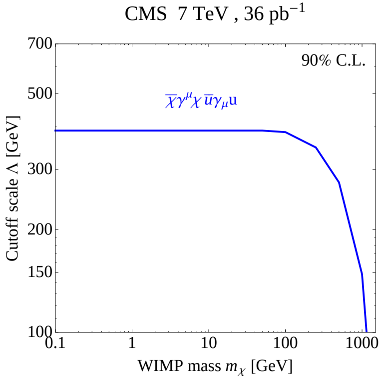
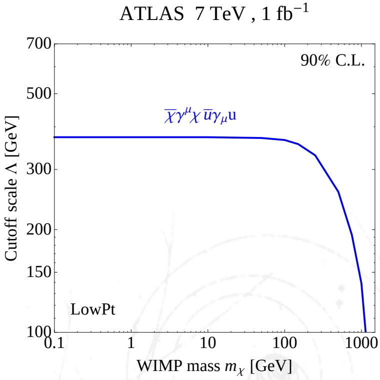
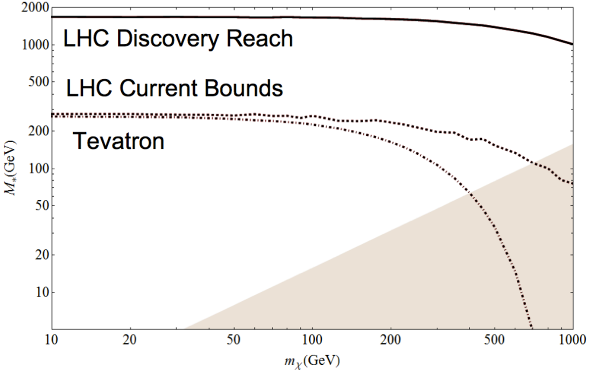




36 pb^{-1} → 1 fb^{-1} doesn't buy us much!

ATLAS LowPt VS. CDF 1 fb^{-1}

A. Rajaraman, W. Shepherd, T. Tait, A. Wijangcoar (1106.4775)

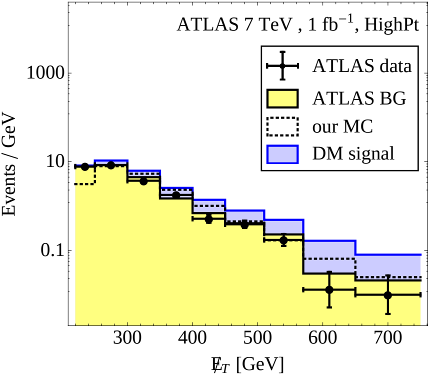


- $\frac{(\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{u}\gamma_\mu u)}{2M_*^2}$
- Majorana DM
- 2σ for Current Bounds.
- 5σ assuming 100 fb^{-1} for Discovery Reach.

Mono-Jet search at ATLAS (HighPt)

Go to the higher p_T region!

ATLAS-CONF-2011-096

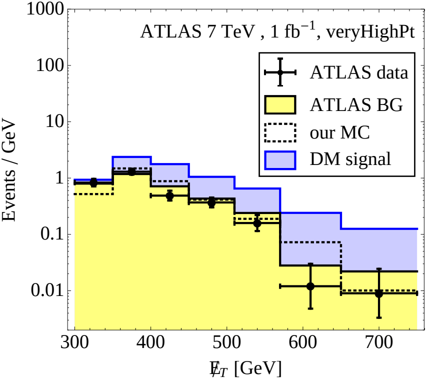


- 7 TeV, 1 fb^{-1}
- Search: Mono-Jet + $\not{E}_T$.
- Background:
  Jet + $(Z \to \nu\nu,\ W \to \nu\ell)$.
- Main cuts:
  $\not{E}_T >$ 220 GeV, $p_{T,j_1} >$ 250 GeV.
- Result: 965 ($1010 \pm 37 \pm 65$).

Mono-Jet search at ATLAS (veryHighPt)

Go to the higher p_T region!

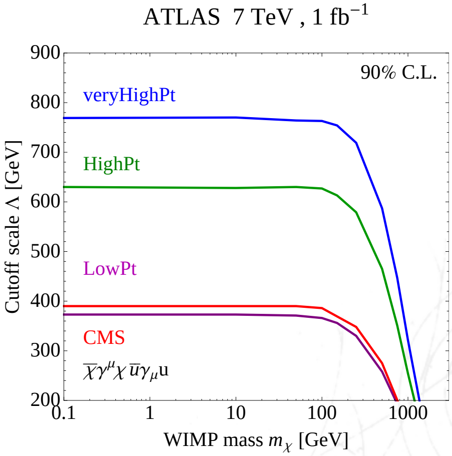
ATLAS-CONF-2011-096



- 7 TeV, 1 fb^{-1}
- Search: Mono-Jet + $\not{E}_T$.
- Background:
  Jet + $(Z \to \nu\nu,\ W \to \nu\ell)$.
- Main cuts:
  $\not{E}_T >$ 350 GeV, $p_{T,j_1} >$ 300 GeV.
- Result: 167 $(193 \pm 15 \pm 20)$.

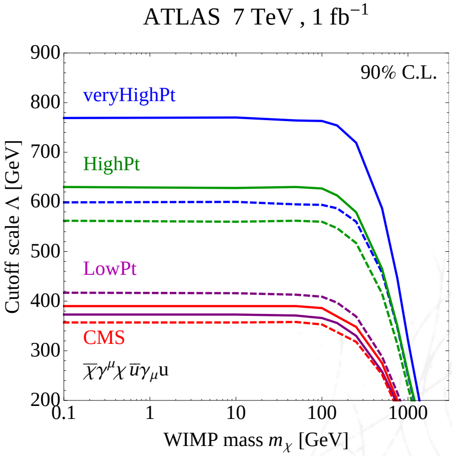
Higher p_T rocks!

- Current bounds: vector operator $\frac{(\bar{\chi}\gamma^\mu\chi)(\bar{u}\gamma_\mu u)}{\Lambda^2}$ from counting.



Higher p_T rocks!

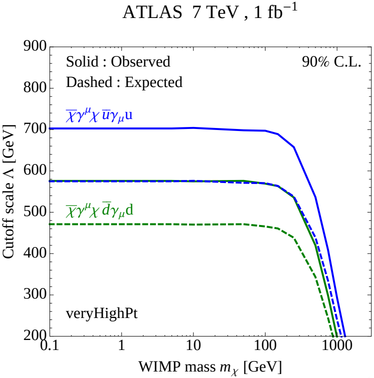
- Expected bounds: vector operator $\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{u}\gamma_{\mu}u)}{\Lambda^2}$ from counting.

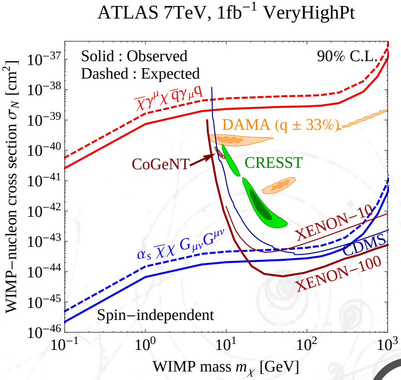


Bounds from higher p_T searches

Spin-independent case

- Using ATLAS 1 fb^{-1} veryHighPt.
- Direct detection bound for universal coupling $q \in (u, d)$.





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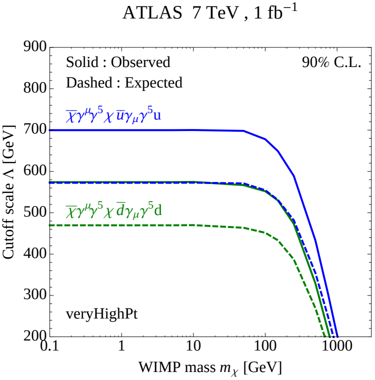
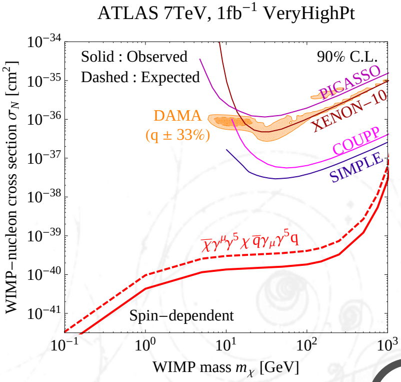
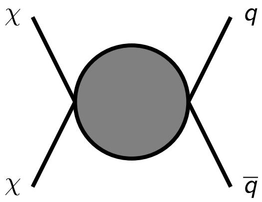




Bounds for Indirect Detections

Bounds for Indirect Detections

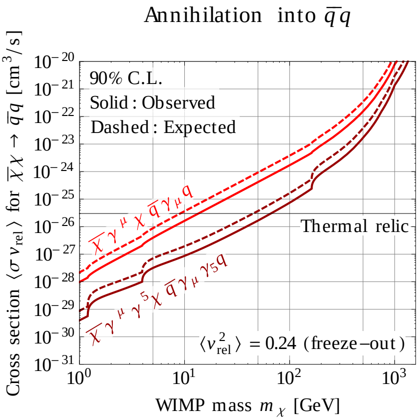


Two things to compare:

- Thermal-relic bound
- Fermi observation bounds.

Comparing to the thermal relic bound

How to read the plot?



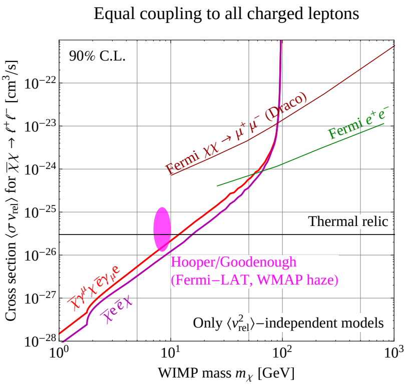
IF

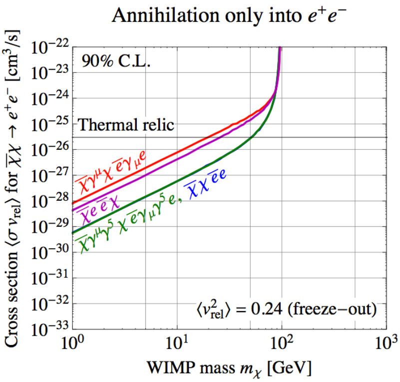
- DM is a thermal relic.
- DM mainly annihilate into quarks.

THEN

- m_χ with σv smaller than Thermal relic case is excluded!

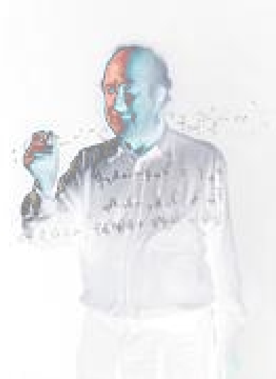
Bounds from LEP





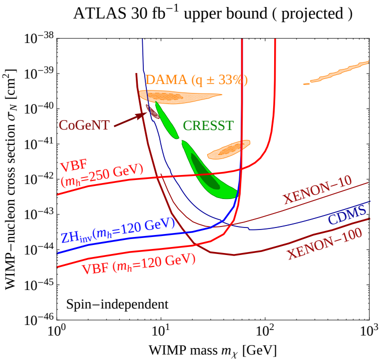
Future Bound:

Invisible Higgs Search



Invisible-higgs search at LHC

When DM couples through higgs portal



Conclusion

Collider bounds are awesome!

- Can do what direct detections cannot do.
- Mono-γ at LEP gives competitive bounds.
- MonoJet at LHC gives the best current bounds.
- Stringent bounds on DM annihilation.
- Many other interesting possibilities: DM coupling to Higgs, Light mediator,...

Conclusion

Collider bounds are awesome.

- less dependence on astrophysical and experiemntal issues
- good Light DM and spin-dependent bound

Mono-γ at LEP gives competitive bounds.

- rule out Leptophilic model explaining DAMA/CoGeNT.

MonoJet at LHC gives the best current bounds.

- Motivation for the high p_T search.
- Important constraints for the gluon and spin dependent couplings.

Colliders put stringent bounds on DM annihilation

- Strong constraints for thermal relic DM.
- Better bounds than Fermi for light DM.

Many other interesting bounds.

- Invisible Higgs search, light mediator,...

Backup Slides

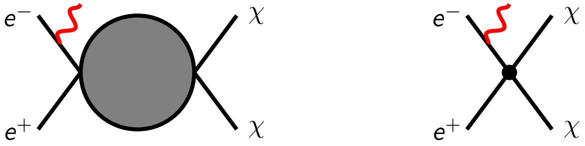
Annihilation cross sections

σ_S and σ_A are velocity suppressed:

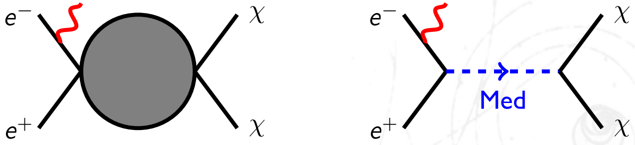
$$
\begin{aligned}
\sigma_S v_{rel} &= \beta\,(m_\chi^2 - m_\ell^2)\, v_{rel}^2 \,, \\
\sigma_V v_{rel} &= \frac{1}{6}\,\beta \left(24(2m_\chi^2 + m_\ell^2) + \frac{8m_\chi^4 - 4m_\chi^2 m_\ell^2 + 5m_\ell^4}{m_\chi^2 - m_\ell^2}\, v_{rel}^2 \right) \,, \\
\sigma_A v_{rel} &= \frac{1}{6}\,\beta \left(24 m_\ell^2 + \frac{8m_\chi^4 - 22m_\chi^2 m_\ell^2 + 17m_\ell^4}{m_\chi^2 - m_\ell^2}\, v_{rel}^2 \right) \,, \\
\sigma_t v_{rel} &= \frac{1}{24}\,\beta \left(24(m_\chi + m_\ell)^2 + \frac{(m_\chi + m_\ell)^2 (8m_\chi^2 - 16 m_\chi m_\ell + 11 m_\ell^2)}{m_\chi^2 - m_\ell^2}\, v_{rel}^2 \right) \,, \\
\beta &= \frac{1}{8\,\pi\,\Lambda^4} \sqrt{1 - \frac{m_\ell^2}{m_\chi^2}} \,.
\end{aligned}
$$

What happens if the mediator is light?

- When it is heavy, we consider contact operators only:
  $m_{\text{Med}} \gg 2\,E_{\text{beam}}$

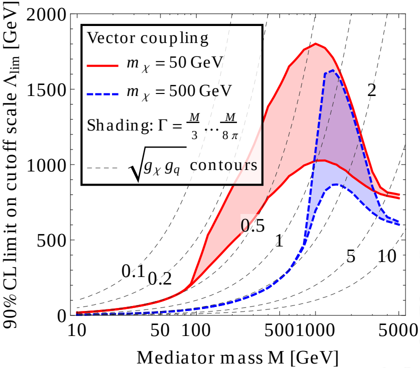


- When it can be on-shell, the kinematics is important:
  $m_{\text{Med}} \ll 2\,E_{\text{beam}}$



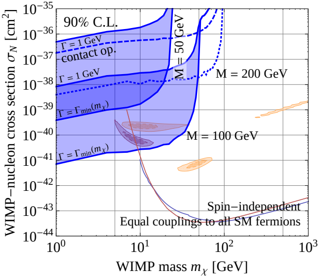
Light DM @ LHC

Cutoff bounds from ATLAS MonoJet veryHighPT

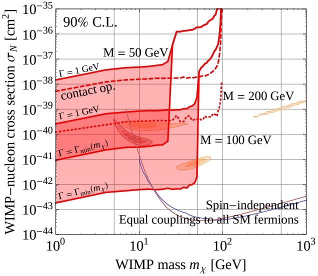


Direct Detection w/ light mediator

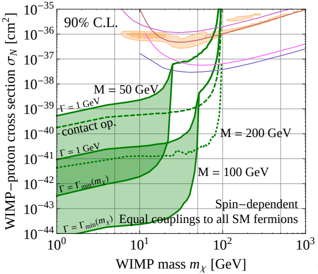
$\overline{\chi}\chi\,\overline{f}f$



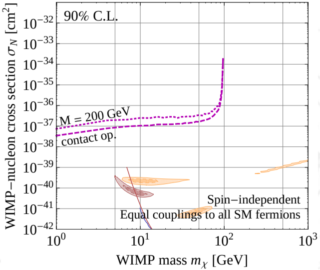
$\overline{\chi}\gamma^\mu\chi\,\overline{f}\gamma_\mu f$



$\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{f}\gamma_\mu\gamma^5 f$

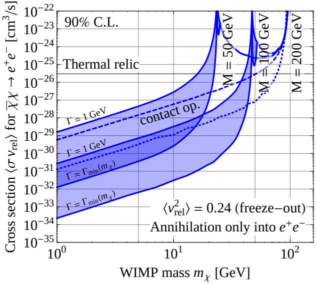


$\overline{\chi}f\,\overline{f}\chi$

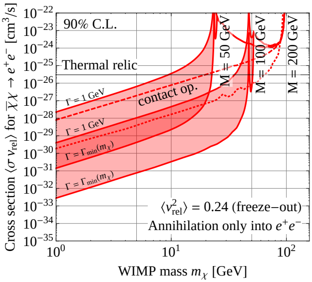


Indirect Detection w/ Light Mediators

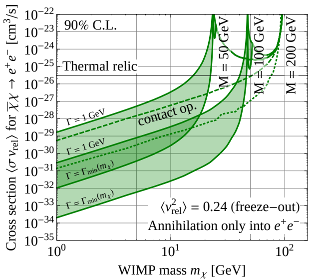
$\overline{\chi}\chi\,\overline{e}e$



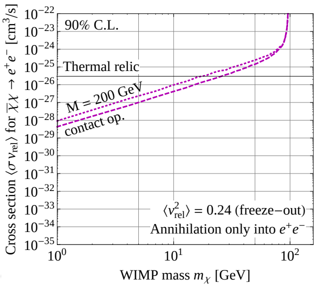
$\overline{\chi}\gamma^{\mu}\chi\,\overline{e}\gamma_{\mu}e$



$\overline{\chi}\gamma^{\mu}\gamma^{5}\chi\,\overline{e}\gamma_{\mu}\gamma^{5}e$



$\overline{\chi}e\,\overline{e}\chi$



Few remarks about the loop calculation

(show this if people stay awake)

The loop-suppressed cross section is

$$\sigma_{1-\text{loop}} \simeq \frac{4\alpha^2\mu_p^2}{18^2\pi^3\Lambda^4}\cdot\left[\sum_{\ell=e,\mu,\tau} f(q^2, m_\ell)\right]^2$$

where $f(q^2, m_\ell) =$

$$\frac{1}{q^2}\left[5q^2+12m_\ell^2+6(q^2+2m_\ell^2)\sqrt{1-\frac{4m_\ell^2}{q^2}}\coth^{-1}\left(\sqrt{1-\frac{4m_\ell^2}{q^2}}\right)-3q^2\ln\left(\frac{m_\ell^2}{{\Lambda_{\text{ren}}}^2}\right)\right]$$

- Take the most conservative case (the largest σ):
  $v_\chi = v_{\text{esc}} = 500$ km/sec, scattering angle 180°.
- This gives $q^2 = -4\mu_p^2 v_\chi^2$.
- Take the cutoff Λ_{ren} from the loop integral the same as the operator cutoff Λ.