Collider searches for dark matter

Joachim Kopp

Moriond Electroweak Session, March 18th, 2011

Fermilab

Outline

Outline

Search strategies for dark matter (DM)

Direct searches

Look for DM–nucleus scattering.

Uncertainties:

- Local DM density
- Backgrounds
- Calibration

Indirect searches

Look for astrophysical signatures of DM annihilation or decay.

Uncertainties:

- Profile of Milky Way's DM halo
- Cosmic ray propagation

Collider searches

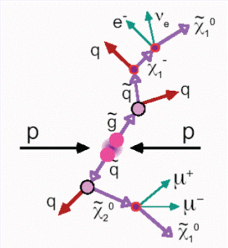
Look for missing energy signatures.

Problem:

- Can only find DM *candidate* (no proof that it is DM)

Model-dependent strategy: Cascade decays with $\not{E}_T$

Model-independent strategies: THIS TALK



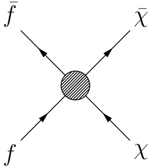
Mono-jet and mono-photon signatures of dark matter

Assumption:
DM (χ) interactions described by effective field theory

Sample operators: (Λ = suppression scale)

$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{f}f)}{\Lambda^2} \qquad \text{(scalar, } s\text{-channel)}$$

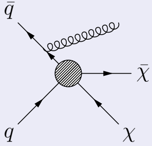
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu\gamma_5 f)}{\Lambda^2} \qquad \text{(axial vector, } s\text{-channel)}$$



Tevatron/LHC: Mono-jets

χ–q coupling probed in jet(s) + $\not{E}_T$

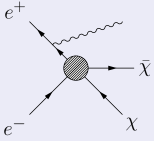
CDF (1.1 fb^{-1}): PRL 101 (2008) 181602
Goodman *et al.*, arXiv:1005.1286, arXiv:1008.1783
Fox Harnik Bai, arXiv:1005.3797



LEP: Mono-photons

χ–e coupling probed in photon + $\not{E}$

DELPHI (650 pb^{-1}): hep-ex/0406019, arXiv:0901.4486
Fox Harnik JK Tsai, arXiv:1103.0240



Outline

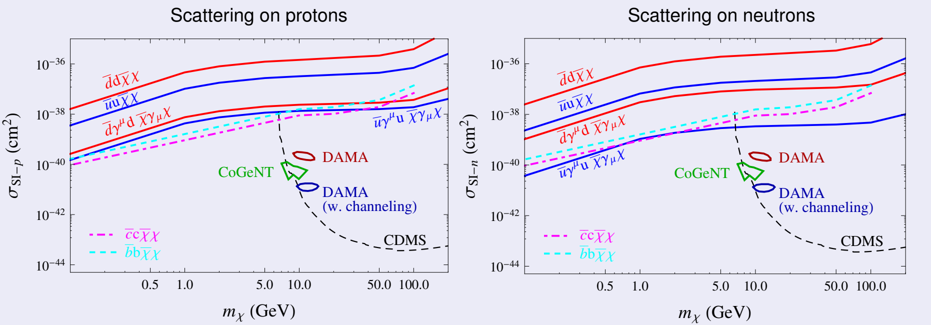
The Tevatron at the frontier of direct DM detection

Method:

- Compute expected number of mono-jet events from DM production + SM
- Compare to observed number of mono-jet events at CDF and compute limit on suppression scale Λ.
- Convert limit on Λ to limit on DM–nucleon scattering cross section

Spin-independent DM–nucleon scattering

Fox Harnik Bai, arXiv:1005.3797



The Tevatron at the frontier of direct DM detection

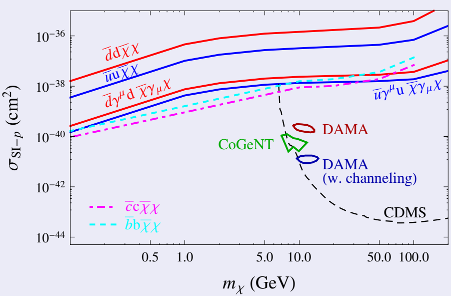
Method:

- Compute expected number of mono-jet events from DM production + SM
- Compare to observed number of mono-jet events at CDF and compute limit on suppression scale Λ.
- Convert limit on Λ to limit on DM–nucleon scattering cross section

Spin-independent DM–nucleon scattering

Fox Harnik Bai, arXiv:1005.3797

Scattering on protons



- The *only* limits at $m_\chi \lesssim 5$ GeV
- Not yet competitive at larger m_χ
- Currently limited by systematic uncertainties.
- Future improvements:
  - Include mono-jet spectrum
  - Perform inclusive search

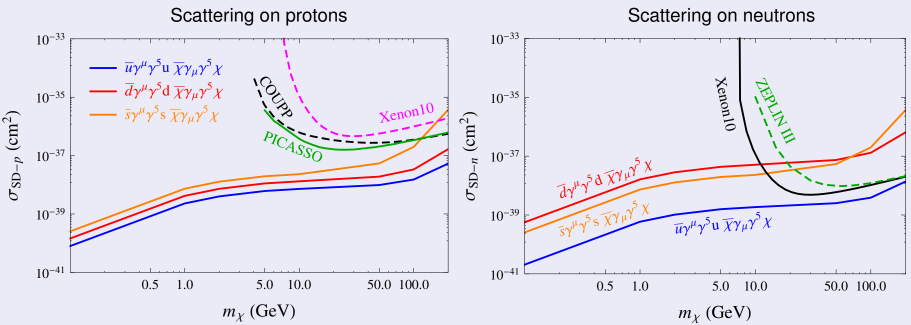
The Tevatron at the frontier of direct DM detection

Method:

- Compute expected number of mono-jet events from DM production + SM
- Compare to observed number of mono-jet events at CDF and compute limit on suppression scale Λ.
- Convert limit on Λ to limit on DM–nucleon scattering cross section

Spin-dependent DM–nucleon scattering

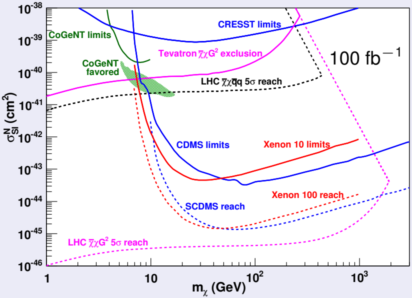
Fox Harnik Bai, arXiv:1005.3797



Projected LHC limits on dark matter scattering

Spin-independent DM–nucleon scattering

Goodman *et al.*, arXiv:1005.1286



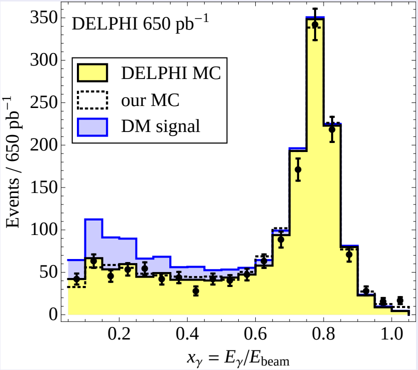
- Improvement by several orders of magnitude
- …especially for DM coupling to gluons: $\bar{\chi}\chi G_{\mu\nu} G^{\mu\nu}$ etc.
- But: Systematic uncertainties at LHC not yet known

Outline

Mono-photons + $\not{E}$ at DELPHI

The mono-photon spectrum

Fox Harnik JK Bai, arXiv:1103.0240

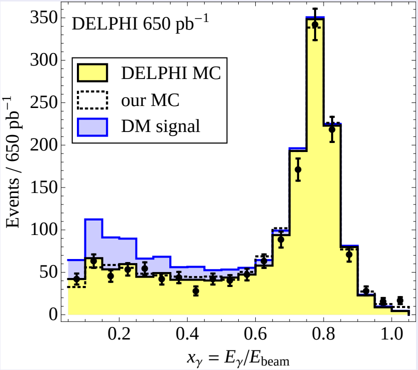


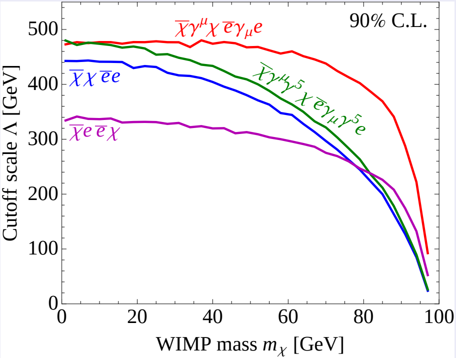
- SM background: $e^+e^- \to \gamma + (Z \to \bar{\nu}\nu)$ (well understood)
- Signal has different spectral shape
- Search is limited by statistics
- Again, we first derive limits on the suppression scale Λ

Mono-photons + $\not{E}$ at DELPHI

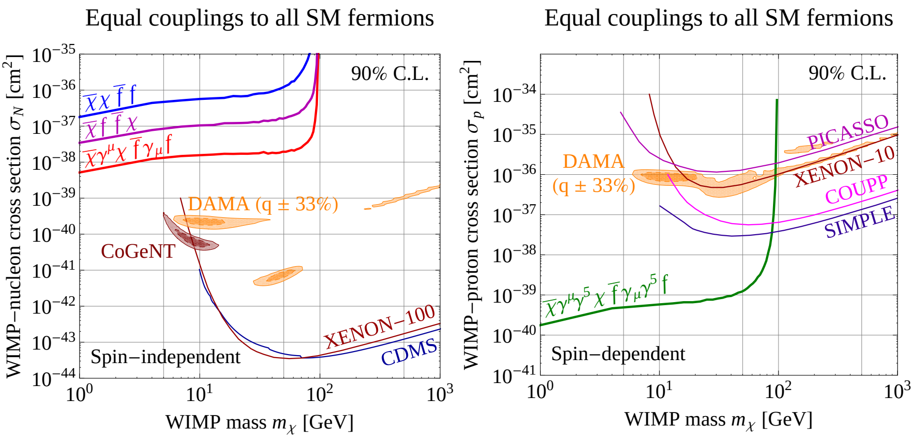
The mono-photon spectrum

Fox Harnik JK Bai, arXiv:1103.0240





LEP limits on the DM–nucleon scattering cross section



Fox Harnik JK Bai, arXiv:1103.0240

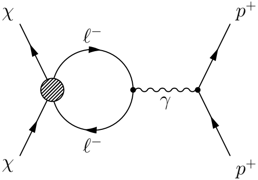
- LEP only constrains DM–electron coupling
- Additional assumptions needed to set limit on DM–nucleon scattering
- Here: Equal coupling to all SM fermions assumed
- Limits comparable to those from the Tevatron, but slightly more model-dependent

LEP constraints on leptophilic dark matter

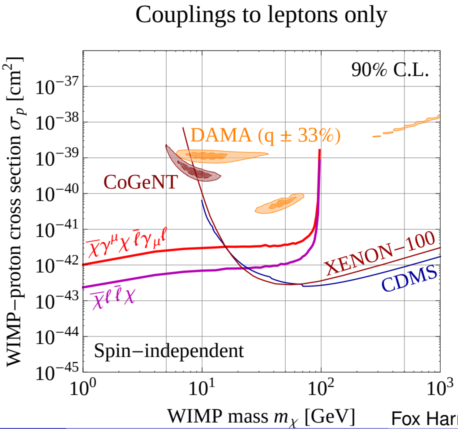
What if dark matter couples *only* to electrons at tree level?

→ There can still be *loop-level* couplings to quarks

JK Niro Schwetz Zupan arXiv:0907.3159



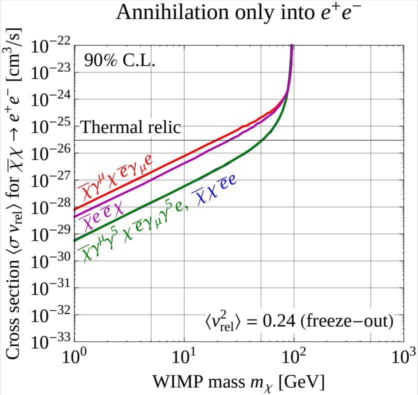
Result: Great advantage for LEP



Fox Harnik JK Bai, arXiv:1103.0240

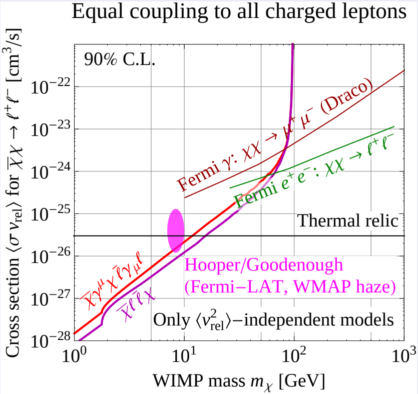
Comparison to indirect dark matter detection

$\bar{\chi}\chi \to e^+e^-$



- Light thermal relic annihilating only to e^+e^- ruled out
- Constraint weakens if DM has also other annihilation channels

$\bar{\chi}\chi \to \ell^+\ell^-$

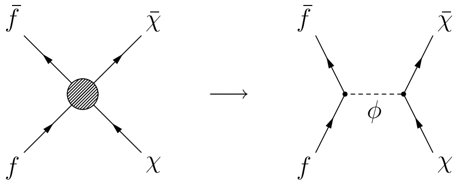


- For light dark matter LEP limits superior to astrophysical constraints

Fox Harnik JK Bai, arXiv:1103.0240

Beyond effective field theory

Assume DM interactions mediated by light particle
$\rightarrow$ effective field theory breaks down, have to include mediator explicitly



Collider cross section

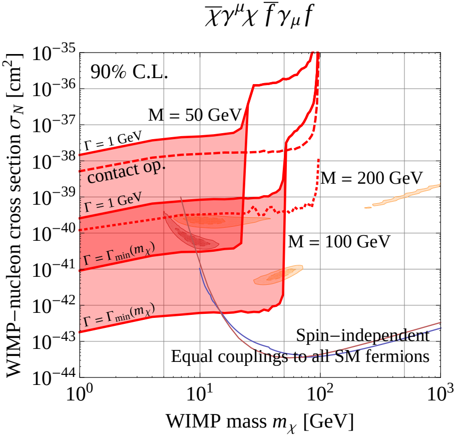
$$\sigma_{\text{coll}} \sim \frac{1}{(s - M_{\text{med}}^2)^2 + \Gamma_{\text{med}}^2/4}\, s$$

Direct detection cross section

$$\sigma_{\text{scatter}} \sim \frac{1}{M_{\text{med}}^4} \frac{m_N^2 m_\chi^2}{(m_N + m_\chi)^2}$$

- For light dark matter, direct detection has relative advantage
- ...unless a narrow mediator can be produced on-shell and decays to DM

Constraints on DM–nucleon scattering for light mediators



- $m_\chi > M_{\text{med}}/2$: Limit is weaker than for the effective field theory (contact operator) case
- $m_\chi < M_{\text{med}}/2$: Mediator produced on-shell
  - Limit improves again
  - ...but depends on the partial width for Mediator $\to \bar{\chi}\chi$
  - Note: If Mediator $\to$ SM SM is possible, other constraints may apply.

Outline

Conclusions

- Mono-jet and Mono-photon signatures provide largely model-independent constraints on dark matter properties in an effective field theory formalism
- Superior to direct searches if dark matter is very light ($\lesssim \mathcal{O}(5\text{ GeV})$) or if interactions are spin-dependent or leptophilic
- Superior to indirect searches if dark matter is light ($\lesssim \mathcal{O}(100\text{ GeV})$)
- ... and always independent of astrophysical uncertainties
- Limits can weaken if mediator is light
- Dedicated searches by the experimental collaborations?
  (CDF monojet analysis underway)

Thank you!