# Collider searches for dark matter

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SLAC, October 5, 2011

Fermilab

based on work done in collaboration with
Patrick Fox, Roni Harnik, Yuhsin Tsai

# Outline

1. Mono-jet and mono-photon signals of dark matter
2. Collider limits on direct detection cross sections
3. Collider limits on annihilation cross sections
4. Beyond effective field theory
5. Invisible Higgs decays to dark matter
6. Summary & Conclusions

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# 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

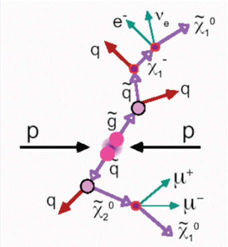
Look for missing energy signatures.

Problem:

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

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

Less model-dependent strategies: THIS TALK



# Dark matter in an effective theory approach

Assumption: DM interactions described by effective field theory

Sample operators: ($\chi$ = dark matter, $f$ = SM fermion, $\Lambda$ = suppression scale)

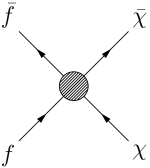
$$\mathcal{O}_V = \frac{(\bar\chi\gamma_\mu\chi)(\bar f\gamma^\mu f)}{\Lambda^2}\,,$$ (vector, $s$-channel)

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

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

$$\mathcal{O}_t = \frac{(\bar\chi P_L f)(\bar f P_R\chi)}{\Lambda^2} + (L \leftrightarrow R)\,,$$ (scalar, $t$-channel)
can be Fierz'ed into $s$-channel operators

$$\mathcal{O}_g = \frac{\alpha_s(\bar\chi\chi)(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^2}$$ (scalar , $s$-channel)



In a full, UV complete theory:

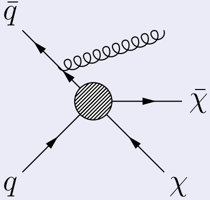
$$\Lambda = M/\sqrt{g_f g_\chi}$$

# Mono-jet and mono-photon signatures of dark matter

Idea: Pair production of DM + some visible particles

## Tevatron, LHC: Mono-jets

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

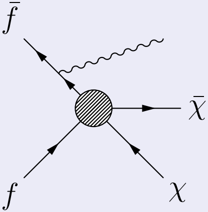


CDF (1.1 fb$^{-1}$): 0807.3132,
ATLAS (1 fb$^{-1}$): ATLAS-CONF-2011-096,
CMS (1.1 fb$^{-1}$) : CMS-PAS-EXO-11-059

Goodman Ibe Rajaraman Shepherd Tait Yu
1005.1286, 1008.1783
Rajaram Shepherd Tait Wijangco 1108.1196
Bai Fox Harnik, 1005.3797
Fox Harnik JK Tsai 1109.4398

## LEP, Tevatron, LHC: Mono-$\gamma$

$\chi$–$f$ coupling probed in photon + $\not{E}$



DELPHI (650 pb$^{-1}$): hep-ex/0406019, 0901.4486
CDF (2 fb$^{-1}$): 0807.3132
DØ(1 fb$^{-1}$): 0803.2137
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Fox Harnik JK Tsai 1103.0240, 1109.4398

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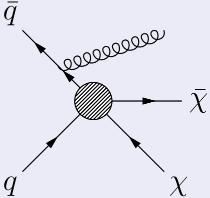

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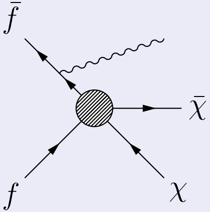

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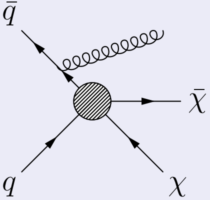

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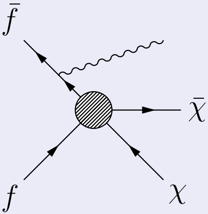

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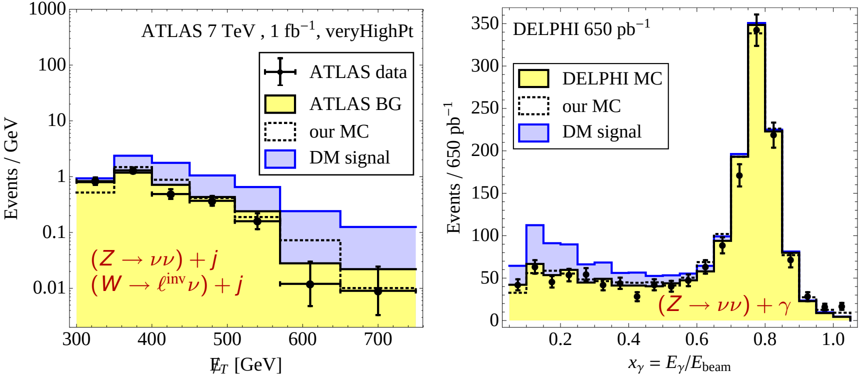
# Limit setting procedure

1. Simulate signal process $pp/p\bar{p} \to j + \bar{\chi}\chi$ or $pp/p\bar{p}/e^+e^- \to \gamma + \bar{\chi}\chi$ in MadGraph, Pythia, Delphes/PGS
   (Simulate also SM backgrounds for verification)



- Our simulations in excellent agreement with the collaborations' (after correcting normalization by 10–30%)
- Signal and background have different spectral shape

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   (Simulate also SM backgrounds for verification)
2. Compare signal + BG prediction to data:
   (require $\chi^2 = 2.71$ to derive 90% C.L. limit on $\Lambda$)

$$\text{LHC:} \quad \chi^2 \equiv \frac{[N_{\rm obs} - N_{\rm SM} - N_{\rm DM}(m_\chi, \Lambda)]^2}{N_{\rm DM}(m_\chi, \Lambda) + N_{\rm SM} + \sigma_{\rm SM}^2}$$

$$\text{LEP:} \quad \chi^2 \equiv 2 \sum_{j=\rm bins} \left[ N^j_{\rm SM} + N^j_{\rm DM}(m_\chi, \Lambda) - N^j_{\rm obs} + N^j_{\rm obs} \log \frac{N^j_{\rm obs}}{N^j_{\rm SM} + N^j_{\rm DM}(m_\chi, \Lambda)} \right]$$

- Only total rate analysis for LHC mono-jet
  (cannot model systematic uncertainties in background shape)
- LEP mono-photon analysis is statistics dominated
  → can use spectral information

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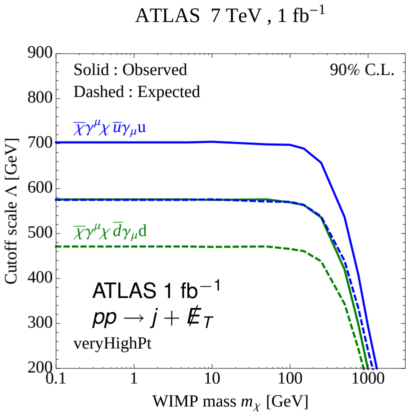

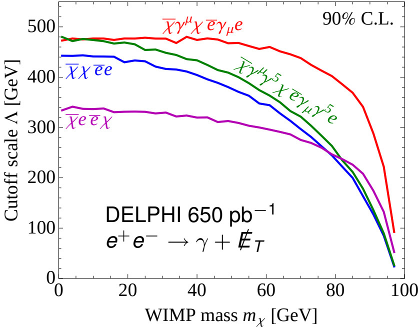

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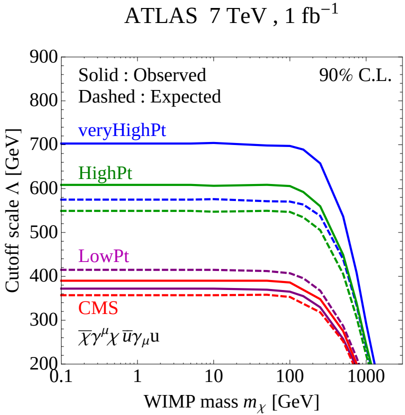

- High jet $p_T$ and $\not{E}_T$ cuts are *very* beneficial

# Limit setting procedure

1. Simulate signal process $pp/p\bar{p} \rightarrow j + \bar{\chi}\chi$ or $pp/p\bar{p}/e^+e^- \rightarrow \gamma + \bar{\chi}\chi$ in MadGraph, Pythia, Delphes/PGS
   (Simulate also SM backgrounds for verification)
2. Compare signal + BG prediction to data:
3. Convert limits on $\Lambda$ into limits on DM–nucleus scattering cross section or DM annihilation cross section

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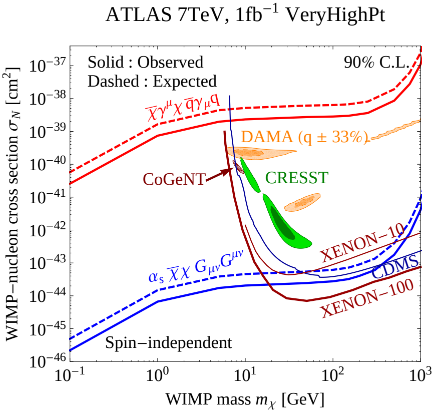
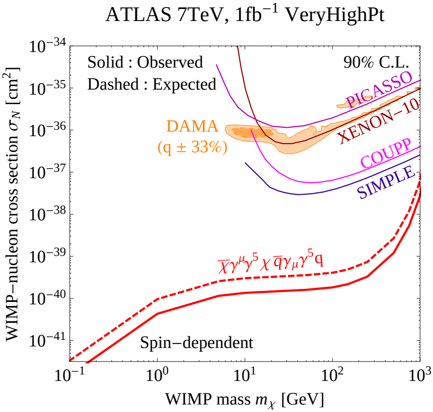
# LHC limits on the DM–nucleon scattering cross section

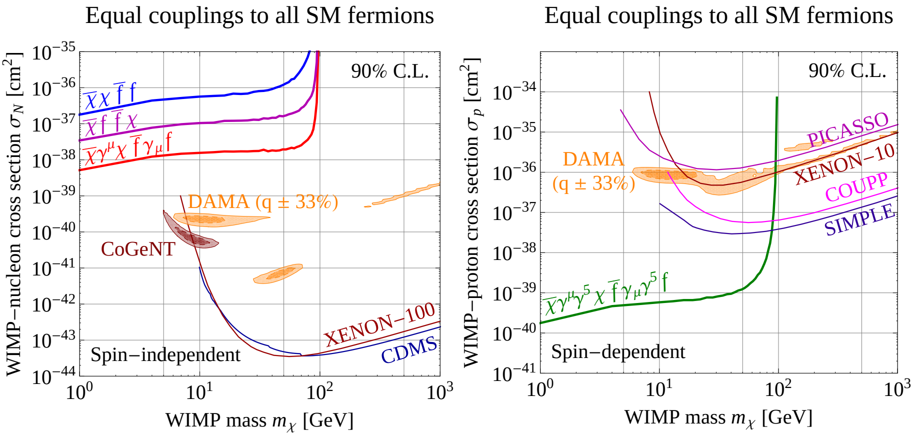




See also work by
Rajaraman et al. 1108.1196

- Assumption here: Equal coupling to all quark flavors
- Extremely competitive limits for
  - Light dark matter (below direct detection threshold)
  - DM coupled to gluons (high gluon luminosity at the LHC)
  - Spin-dependent DM interactions (DD suffers from loss of coherence)
- $\gamma + \not{E}_T$ final state slightly less sensitive, but could provide confirmation or discriminate between models if signal is observed in $j + \not{E}_T$

# LEP limits on the DM–nucleon scattering cross section

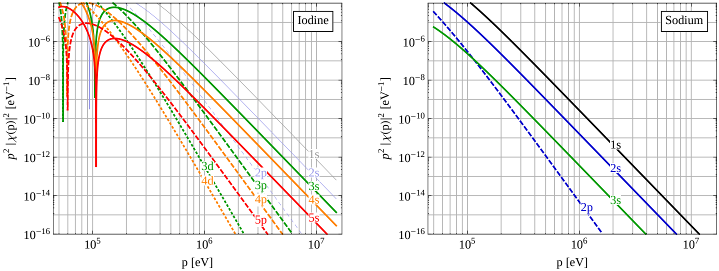


- LEP only constrains DM–electron coupling
- Additional assumptions needed to set limit on DM–nucleon scattering
- Here: Equal coupling to all SM fermions assumed
- Limits only slightly weaker than those from the LHC, but slightly more model-dependent

# Direct detection phenomenology of leptophilic DM

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

- Scattering on an electron
  - Outer-shell electrons can be kicked out (WIMP-electron scattering)
  - Inner-shell electrons will remain bound (elastic WIMP-atom scattering) $\longrightarrow$ recoil transferred to nucleus
  - Electrons can be excited to an outer shell, but remain bound (inelastic WIMP-atom scattering) $\longrightarrow$ recoil partly transferred to nucleus
  - Problem: Typically very small recoil energies ($m_\chi \gg m_e$)
  - Visible events probe high-momentum tail of $e^-$ wave functions

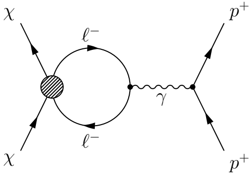


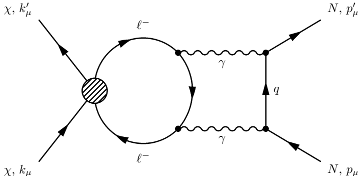
JK Niro Schwetz Zupan arXiv:0907.3159

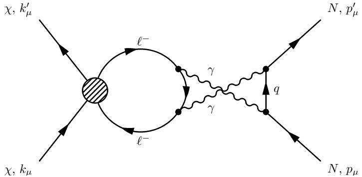
# Direct detection phenomenology of leptophilic DM

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

- Scattering on an electron
  - Strongly suppressed
- Loop-induced scattering on the nucleus
  - Dominant if allowed
  - Forbidden e.g. for axial vector operator $(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu\gamma_5 f)$
  - Suppressed by loop factor



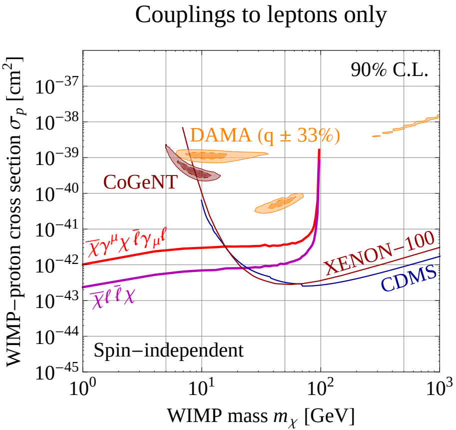


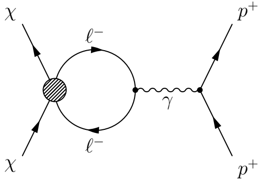


JK Niro Schwetz Zupan arXiv:0907.3159

# LEP constraints on leptophilic dark matter

- Scattering on an electron (Loop forbidden), e.g. $(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{e}\gamma^\mu\gamma_5 e)$: LEP provides the only meaningful limit on DM–SM scattering
- Loop-suppressed scattering on the nucleus, e.g. $(\bar{\chi}\gamma_\mu\chi)(\bar{e}\gamma^\mu e)$: LEP still has a great advantage:





Fox Harnik JK Tsai, arXiv:1103.0240

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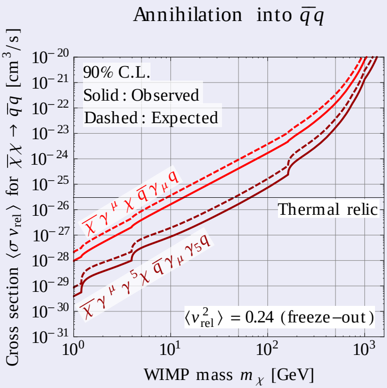
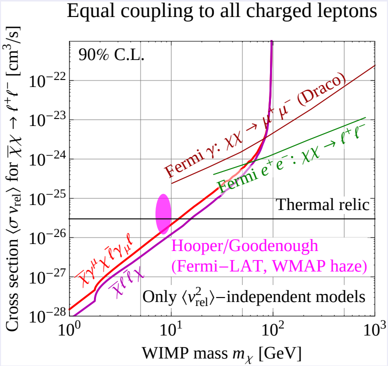
# Collider limits on DM annihilation

### $\bar{\chi}\chi \to \bar{q}q$ (LHC limits)



### $\bar{\chi}\chi \to \ell^+\ell^-$ (LEP limits)



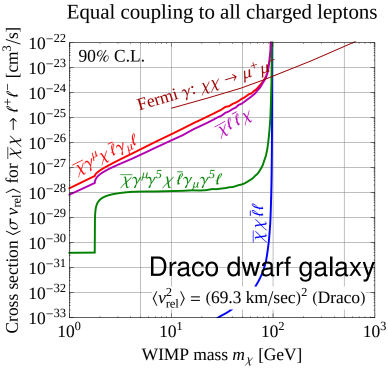
- Light thermal relic ruled out
- Constraints weakens by $1/BR(\bar{\chi}\chi \to \bar{q}q)$ resp. $1/BR(\bar{\chi}\chi \to \bar{\ell}\ell)$ if DM has also other annihilation channels

# Velocity-dependent annihilation cross sections

$$\sigma_S v_{\rm rel} = \frac{1}{8\pi\Lambda^4}\sqrt{1-\frac{m_f^2}{m_\chi^2}}\,(m_\chi^2 - m_f^2)\, v_{\rm rel}^2 \qquad \text{scalar}$$

$$\sigma_A v_{\rm rel} = \frac{1}{48\pi\Lambda^4}\sqrt{1-\frac{m_f^2}{m_\chi^2}}\left(24 m_f^2 + \frac{8m_\chi^4 - 22 m_\chi^2 m_f^2 + 17 m_f^4}{m_\chi^2 - m_f^2}\, v_{\rm rel}^2\right) \qquad \text{axial vector}$$

For some operators, $\sigma v_{\rm rel}$ is suppressed by $v_{\rm rel}^2$ or $m_f^2/m_\chi^2$.
→ advantage for colliders compared to astrophysical searches



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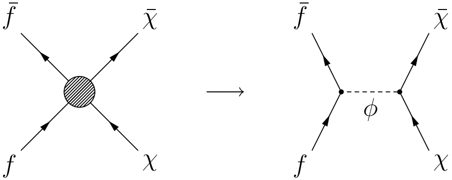
# Beyond effective field theory

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



## Collider cross section

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

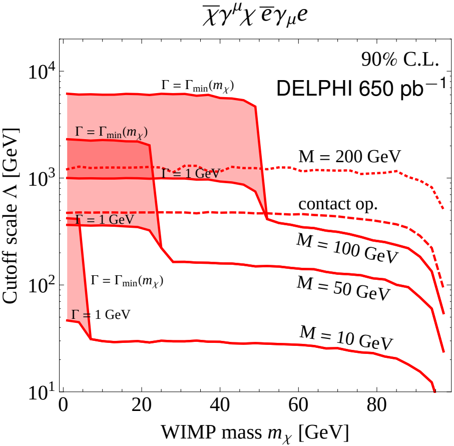
## Direct detection cross section

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

- For light mediators, colliders have a relative disadvantage
- …unless a narrow mediator can be produced on-shell and decays to DM

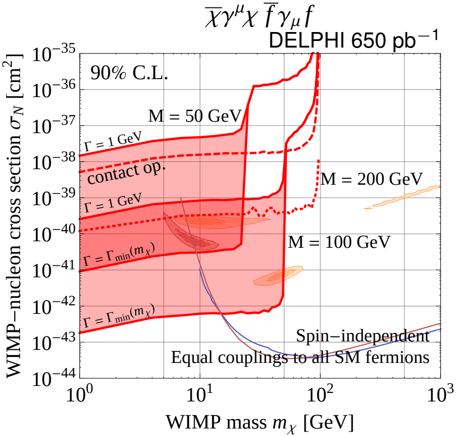
# Constraints on suppression scale Λ for light mediators

Continue to use $\Lambda \equiv M_{\rm med}/\sqrt{g_\chi g_f}$ as measure for DM interaction strength



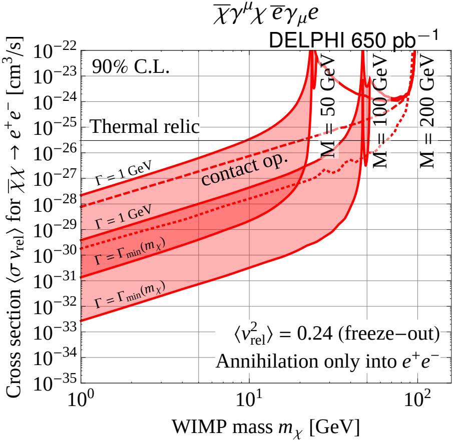
- $m_\chi > M_{\rm med}/2$: Limit is weaker than for the effective field theory (contact operator) case
- $m_\chi < M_{\rm med}/2$: Mediator produced on-shell
    - Limit improves again
    - …but depends on the partial width for Mediator $\rightarrow \bar{\chi}\chi$
    - Note: If Mediator → SM SM is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

# DM–nucleon scattering with light mediators



- $m_\chi > M_{\mathrm{med}}/2$: Limit weaker
- $m_\chi < M_{\mathrm{med}}/2$: Limit stronger or weaker, depending on width

# DM annihilation with light mediators



- $m_\chi > M_{\rm med}/2$: Limit weaker
- $m_\chi < M_{\rm med}/2$: Limit stronger or weaker, depending on width
- "Spikes" due to resonant annihilation

# Are our bounds within the regime of validity of EFT?

Question: Are there UV-complete models that saturate our limits
and can still be described by effective operators?

- For LEP: No problem — $\sqrt{s} \simeq 200$ GeV, $\Lambda_{\text{lim}} \sim \mathcal{O}(300\text{–}500)$ GeV.
  → models with $M_{\text{med}} \sim 500$ GeV and $g_\chi, g_f \sim 1$ are OK

# Are our bounds within the regime of validity of EFT?

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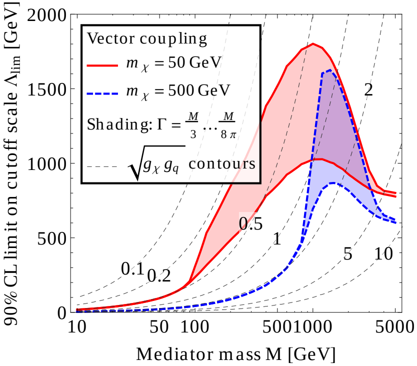
- For LEP: No problem
- For LHC:
  - Models with $M_{\text{med}} \gtrsim 5$ TeV and $g_\chi, g_f \gtrsim 5$ required
  - For smaller (but not too small) $M_{\text{med}}, g_\chi, g_f$, limits derived in EFT are overly conservative



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- For LHC: No problem
- EFT might work even better for more sophisticated UV completions

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and can still be described by effective operators?

- For LEP: No problem
- For LHC: No problem
- EFT might work even better for more sophisticated UV completions
- Note: EFT may be problematic for scalar operators
  ($SU(2)$ invariance requires Higgs insertions)

Fox Harnik JK Tsai 1109.4398

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# Invisible Higgs decays to dark matter

A special case of a “light mediator” is the SM Higgs boson.

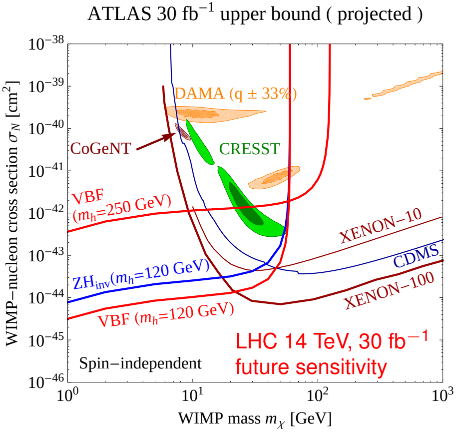
- Best limits come not from the $j + \not{E}_T$ or $\gamma + \not{E}_T$ channels, but from invisible Higgs searches
  - Vector boson fusion: forward jets + $\not{E}_T$
  - Associated production with a $Z$: $Z + \not{E}_T$
- Limits on $\mathrm{BR}(h \to \mathrm{inv})$ can be translated into Higgs–DM coupling $y_\chi$

$$\mathrm{BR}(h \to \bar{\chi}\chi) = \frac{\Gamma(h \to \bar{\chi}\chi)}{\Gamma(h \to \bar{\chi}\chi) + \Gamma(\mathrm{SM})},$$

$$\Gamma(h \to \bar{\chi}\chi) = \frac{y_\chi^2}{8\pi}\, m_h \left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{3/2},$$

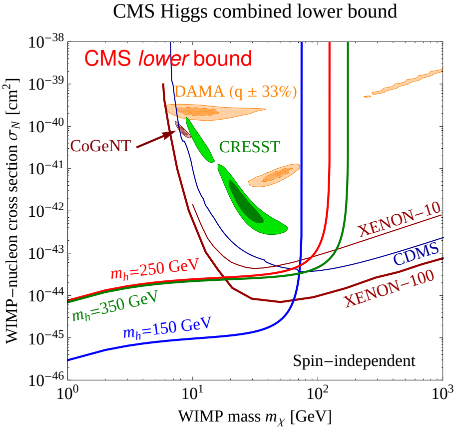
# Projected limits from invisible Higgs decay

No invisible Higgs search yet → compute future sensitivity
(based on projected BR($h \to$ inv) sensitivity from Gagnon et al. ATLAS CSC NOTE 10)



# A lower limit on DM–nucleon scattering

- Assume DM interacts through Higgs exchange
- Assume specific value for $m_h$
- Non-observation of Higgs at $m_h$ can be interpreted as a lower limit on BR($h \to$ inv)



# Outline

1. Mono-jet and mono-photon signals of dark matter
2. Collider limits on direct detection cross sections
3. Collider limits on annihilation cross sections
4. Beyond effective field theory
5. Invisible Higgs decays to dark matter
6. Summary & Conclusions

# Summary & Conclusions

- Mono-jet and Mono-photon searches at LEP and LHC provide strong constraints on dark matter properties in an effective field theory formalism
- Colliders are superior to direct searches if dark matter is very light ($\lesssim \mathcal{O}(5\text{ GeV})$) or if interactions are spin-dependent or leptophilic
- Colliders are superior to indirect searches if dark matter is light ($\lesssim$ few $\times$ 10 GeV)
- …and always independent of astrophysical uncertainties
- Limits can become stronger or weaker if mediator is light
- Special case: DM interacting through the Higgs
  → Invisible Higgs searches will be very sensitive

Thank you!

# Simulation of the DELPHI detector

- CompHEP: Event generation
- Hacked MadAnalysis: Detector response

DELPHI, hep-ex/0406019, arXiv:0901.4486

# Simulation of the DELPHI detector

- CompHEP: Event generation
- Hacked MadAnalysis: Detector response

Three EM calorimeters:

- High Density Projection Chamber (HPC)
  - $45^\circ < \theta < 135^\circ$
  - $x_\gamma = E_\gamma / E_{\text{beam}} > 0.06$
  - Trigger efficiency: 52% @ $E_\gamma = 6$ GeV, 77% @ 30 GeV, 84% @ 100 GeV
  - Cut efficiency: 41% @ 6 GeV, 78% @ 80 GeV
  - Resolution: $0.043 \oplus 0.32/\sqrt{E}$

DELPHI, hep-ex/0406019, arXiv:0901.4486

# Simulation of the DELPHI detector

- CompHEP: Event generation
- Hacked MadAnalysis: Detector response

Three EM calorimeters:

- High Density Projection Chamber (HPC)
- Forward EM calorimeter (FEMC)
  - $12^\circ < \theta < 32^\circ$
  - $x_\gamma = E_\gamma / E_{\rm beam} > 0.1$
  - Trigger eff.: 93% @ 10 GeV, 100% @ 15 GeV
  - Cut efficiency: 57% @ 10 GeV, 75% @ 100 GeV
  - Noise/machine bg: 11% loss
  - Resolution: $0.03 \oplus 0.12/\sqrt{E} \oplus 0.11/E$)

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# Simulation of the DELPHI detector

- CompHEP: Event generation
- Hacked MadAnalysis: Detector response

Three EM calorimeters:

- High Density Projection Chamber (HPC)
- Forward EM calorimeter (FEMC)
- Small Angle Tile Calorimeter (STIC)
  - $3.8^\circ < \theta < 8^\circ$
  - $x_\gamma = E_\gamma / E_{\text{beam}} > 0.3$
  - Efficiency: 48%
  - Resolution: $0.0152 \oplus 0.135/\sqrt{E}$

DELPHI, hep-ex/0406019, arXiv:0901.4486

# Simulation of the DELPHI detector

- CompHEP: Event generation
- Hacked MadAnalysis: Detector response

Three EM calorimeters:

- High Density Projection Chamber (HPC)
- Forward EM calorimeter (FEMC)
- Small Angle Tile Calorimeter (STIC)

In addition (fudge factors):

- 90% efficiency fudge factor
- Lorentzian energy smearing, width 0.052 $E$

DELPHI, hep-ex/0406019, arXiv:0901.4486

# LHC mono-photon limits