Dark mattter searches at the LHC

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Based in part on work done in collaboration with
Patrick Fox, Roni Harnik, Ethan Neil,
Reinard Primulando, Jure Zupan
(arXiv:1109.4398 and arXiv:1301.1683)

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Outline

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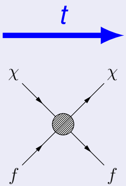
1. Mono-X signatures at the LHC
2. Dark matter and the Higgs
3. Dark matter searches in specific models
4. Conclusions

Dark matter detection strategies

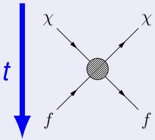
Direct searches

Look for DM scattering on SM fermions



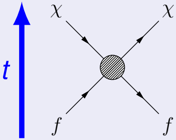
Indirect searches

Look for annihilation products of DM in space



Collider searches

Direct production of DM in high-*E* collisions



Problem:
Need visible particle(s) to trigger on.

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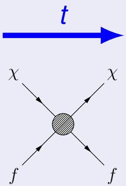

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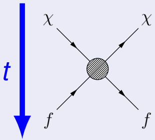

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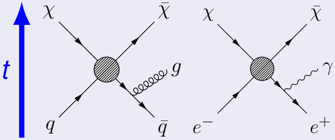


Problem:
Need visible particle(s) to trigger on.

Most generic signatures:
Mono-jet or mono-photon

→ David Berge's talk

Bai Goodman Fox Harnik Ibe JK
Rajaraman Shepherd Tait Tsai Wijangco Yu . . .

Dark matter in EFT (contact operator approach)

Assumption: DM interactions described by effective field theory

Sample operators: (χ = dark matter, f = SM fermion, Λ = suppression scale)

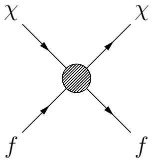
$$\mathcal{O}_V = \frac{(\bar\chi\gamma_\mu\chi)(\bar f\gamma^\mu f)}{\Lambda^2}\,,$$ (vector, s-channel)

$$\mathcal{O}_S = \frac{(\bar\chi\chi)(\bar f f)}{\Lambda^2}$$ (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

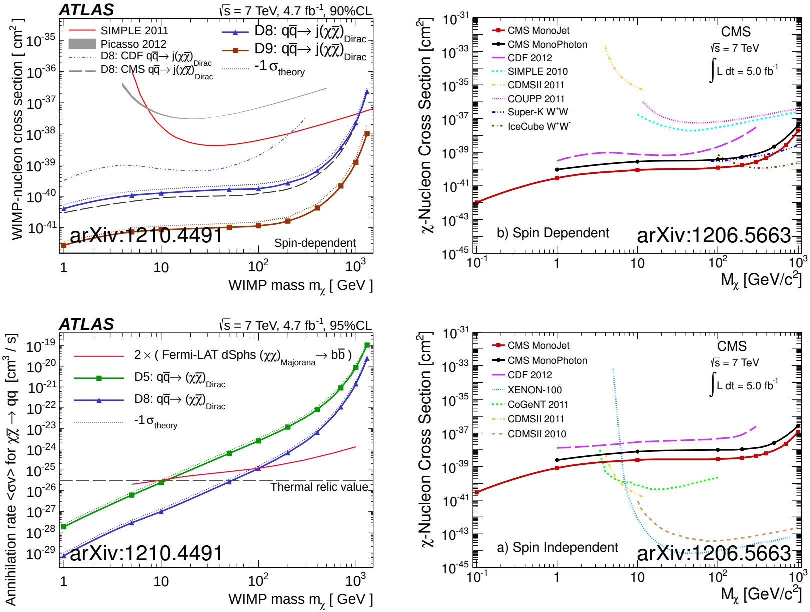
$$\mathcal{O}_g = \frac{\alpha_s(\bar\chi\chi)(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^2}$$ (scalar , s-channel)



In a full, UV complete theory:

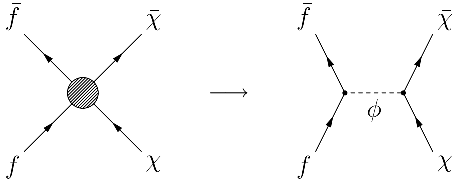
$$\Lambda = M/\sqrt{g_f g_\chi}$$

ATLAS and CMS limits from mono-jet events



Generalizing mono-X searches: Light mediators

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



Collider cross section

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

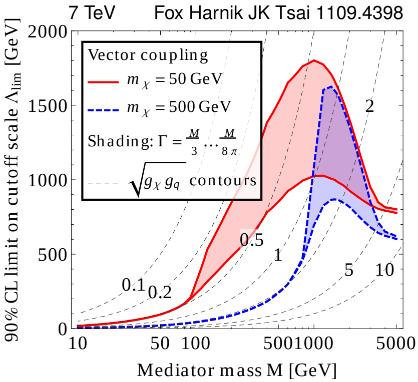
Direct detection cross section

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

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

Constraints on NP scale Λ for light mediators

Continue to use $\Lambda \equiv M_{\rm med}/\sqrt{g_\chi g_f}$ as measure for DM interaction strength.
(simplifies comparison to direct detection results)

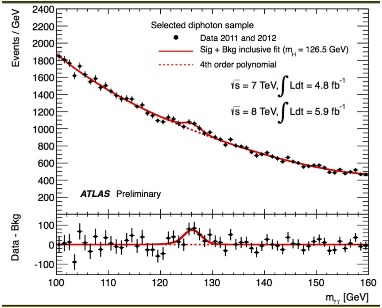


Three regimes

- $M_{\rm med} \gtrsim 5$ TeV
  - Contact operator approach valid
  - Models that saturate limits are close to non-perturbative
- $2M_\chi < M_{\rm med} \lesssim 5$ TeV
  - Mediator produced on-shell
  - Strong dependence on its width
- $M_{\rm med} < 2M_\chi$
  - Collider limits not competitive

Outline

A new particle!



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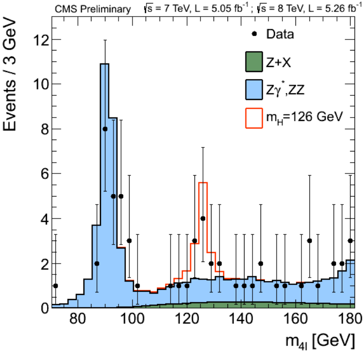

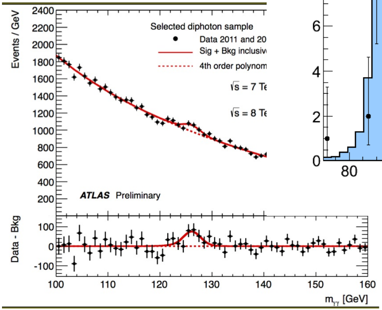

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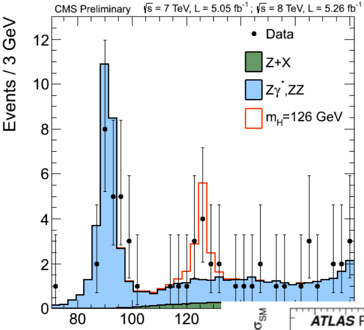

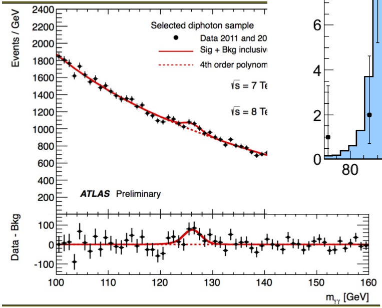

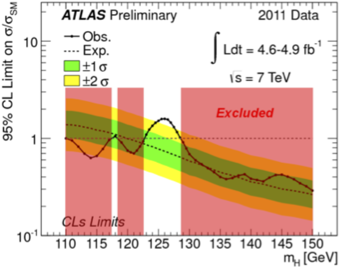

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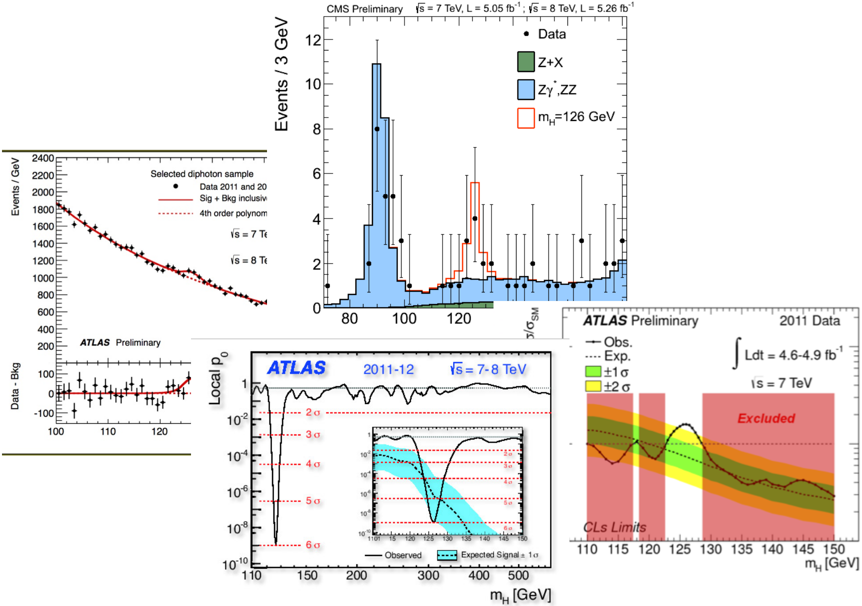

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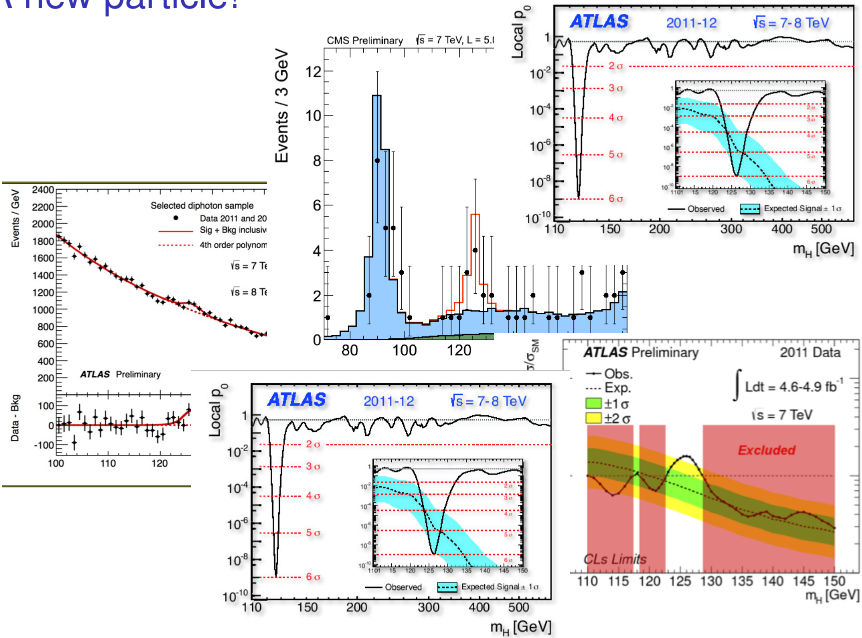

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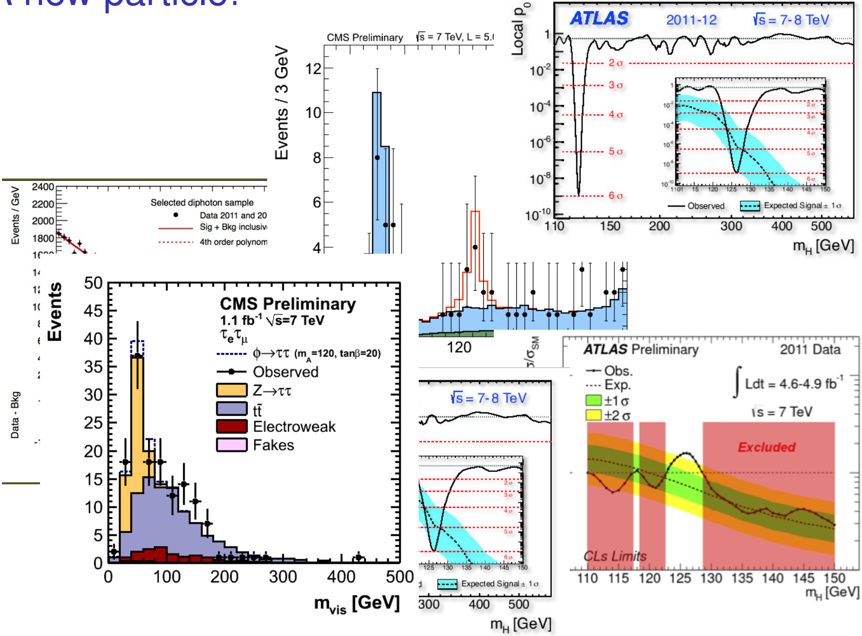

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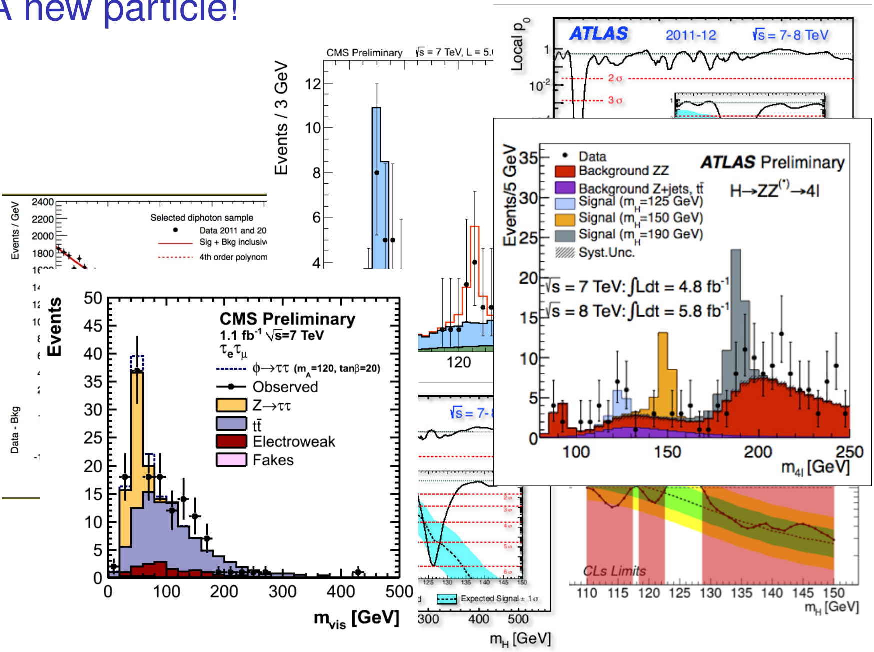

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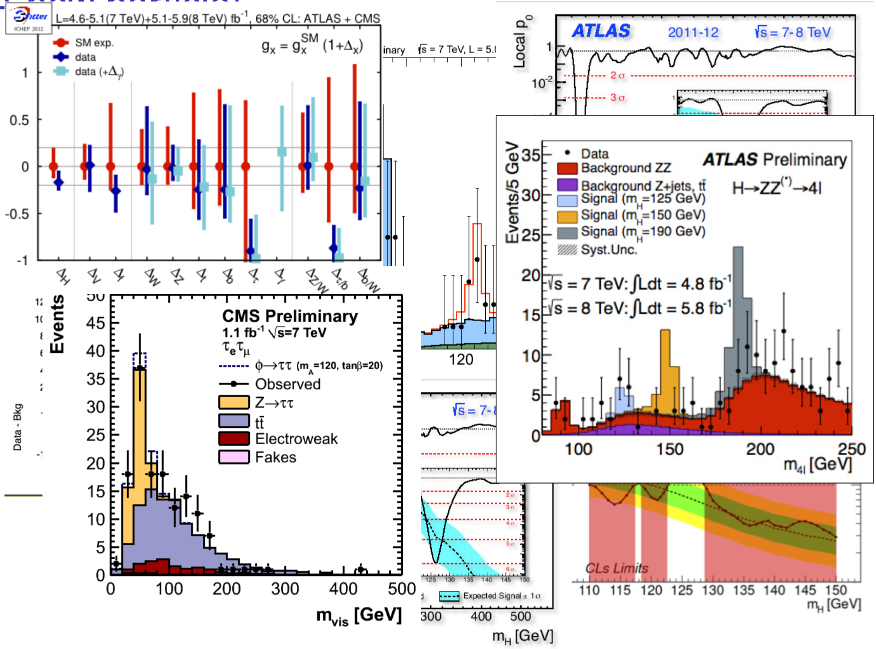

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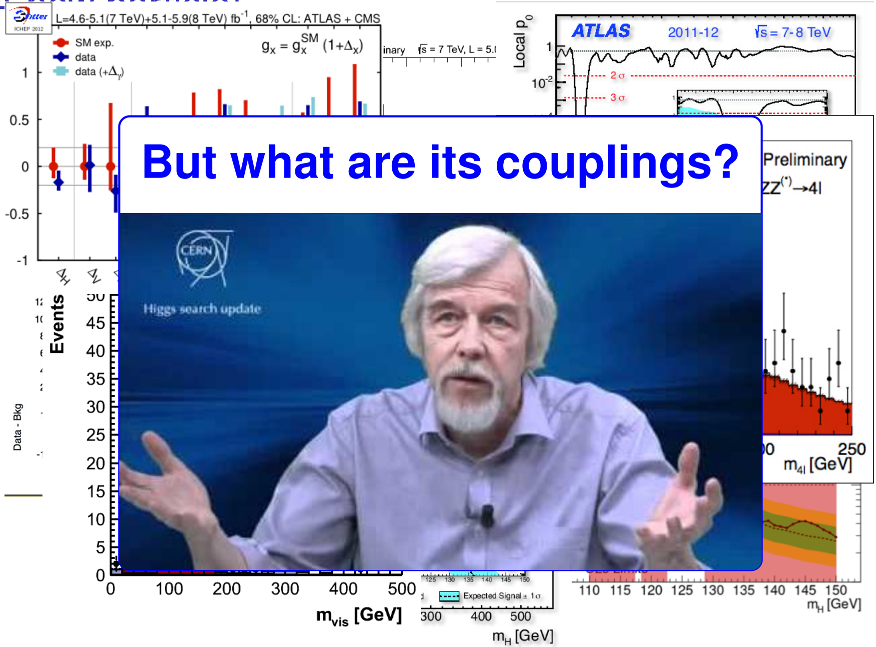
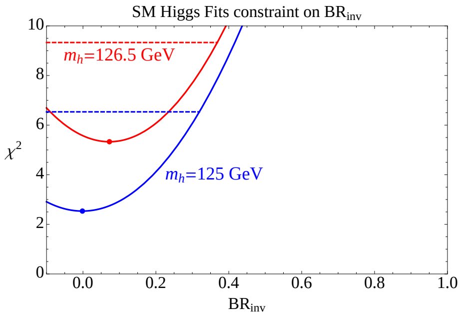


But what are its couplings?

Invisible Higgs decays

Interesting possibility: Higgs decays to dark matter.

Limits on invisible Higgs decays width from a global fit:



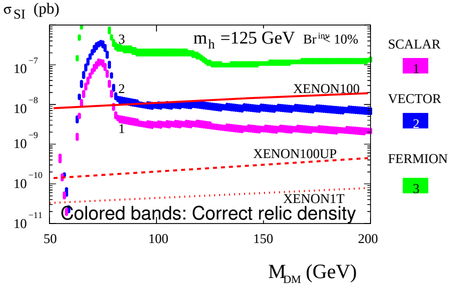
Espinosa Grojean Mühlleitner Trott, arXiv:1207.1717

Result

$BR_{inv} \lesssim 0.3$ still allowed! (at 95% CL)

Status of “Higgs portal” dark matter

Higgs portal operator: $\mathcal{L} \supset (H^\dagger H)(\chi^\dagger \chi)$ mediated, for instance, by new scalar S



Djouadi Lebedev Mambrini Quevillon 1112.3299

- Simplest models are in tension with Xe-100
- Cannot satisfy direct detection and relic denisty constraints simultaneously

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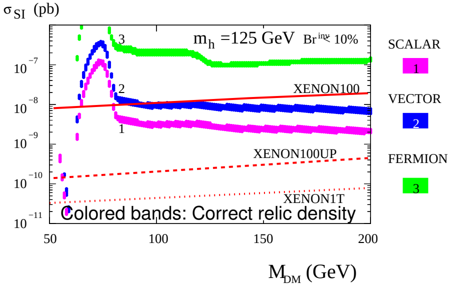

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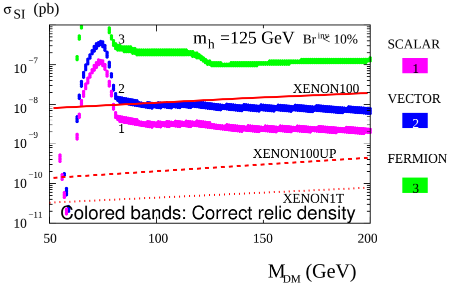

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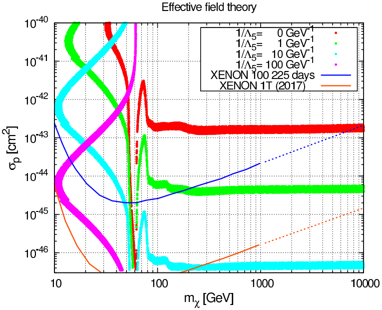

Lopez-Honorez Schwetz Zupan 1203.2064

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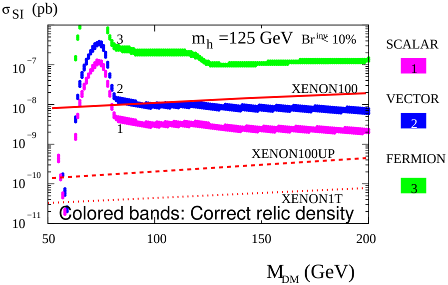

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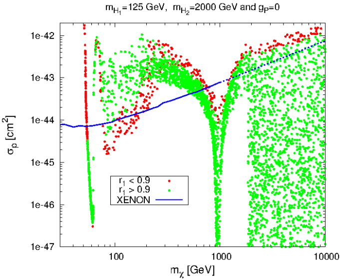
Ways out:

- Resonant annihilation: $m_{DM} \simeq m_h/2$
- Parity-violating couplings
- Indirect Higgs portal:
  New annihilation channel $\chi\chi \to SS$
  sets relic density



Lopez-Honorez Schwetz Zupan 1203.2064

Outline

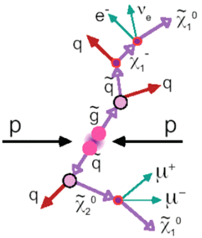
Searching for the mediators of DM interactions

- Mono-X + MET signatures are the most model-independent way of searching for DM production at the LHC
- But: DM couplings are tiny
  - Extremely challenging!
- Fortunately, DM usually doesn't come alone
- An alternative strategy:

> Search for the mediators of DM interactions

Supersymmetric dark matter

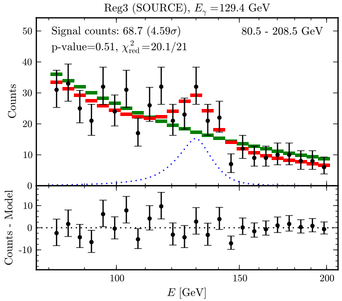
- SUSY models provide some of the best motivated DM candidates.
- Search strategy:
  - Look for cascade decays of strongly interacting SUSY particles
  - Generic signature: Lots of SM particles + missing energy
- Specific challenges:
  - SUSY particles too heavy?
  - Compressed spectra
    $\longrightarrow$ Cannot trigger on missing energy
  - *R*-parity violation
    $\longrightarrow$ LSP unstable



A non-SUSY example

Motivation:

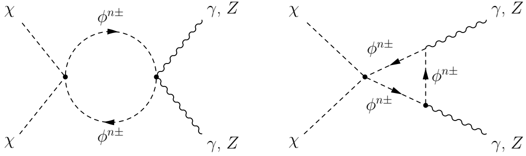
- Gamma ray observatories like Fermi-LAT and HESS are reaching unprecedented levels of sensitivity
- The "cleanest" DM signature would be a monochromatic line
- Interpretation: $\chi + \chi \to \gamma + \gamma/Z/h$
- Naively:
  - Such signals should be suppressed because they arise only at 1-loop level
- Reality:
  - Huge literature on models that feature strong gamma ray line signals
- Recently: A possible hint for a gamma ray line



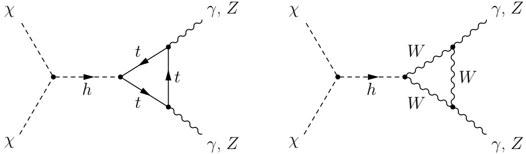
Bringmann Huang Ibarra Vogl Seniger arXiv:1203.1312
Weniger arXiv:1204.2797

A gamma ray line from a secluded DM model

- Introduce electroweak *N*-plet ϕ that mediates DM–SM interactions



- In addition: Higgs portal interactions



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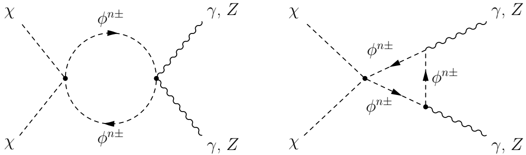


- In addition: Higgs portal interactions

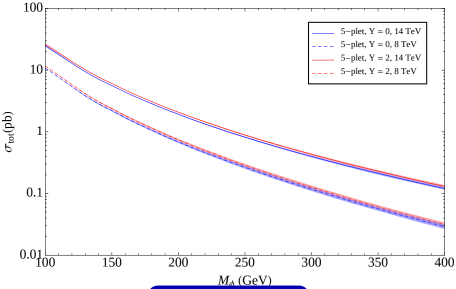
Indirect detection

- Strong gamma ray line through multiply charged components of ϕ
- Not constrained by gamma ray continuum (if Higgs portal weak)
- Correct relic density
- Fully perturbative

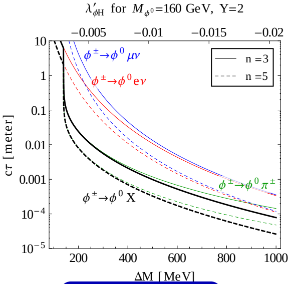
Direct detection

- DM–nucleus scattering through 2-loop diagrams or through Higgs portal
- Compatible with Xenon-100
- Challenging even for ton-scale experiments

Collider phenomenology



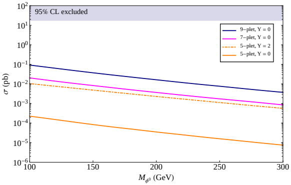
$\phi^{n\pm}$ production



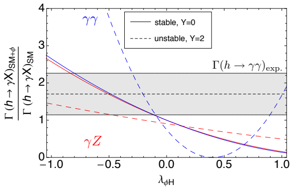
Charged tracks

Typically small mass splittings $\to$ decays too soft to be observable

$\phi^{n\pm} \to \phi^{(n-1)\pm}$ decays



Monophoton production



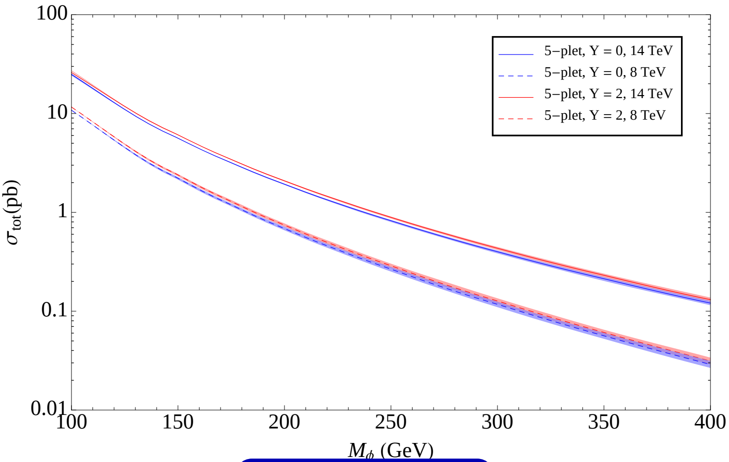
$h \to \gamma\gamma$ and $h \to \gamma Z$

Outline

Conclusions

- Mono-X signatures
  - Signature is quite model-independent
  - But interpretation may be model-dependent
  - When EFT is not valid, naive limits can be too optimistic or too conservative
- Dark matter and the Higgs
  - Invisible Higgs decays will become interesting with more luminosity
  - The “Higgs portal” is a very interesting type of DM coupling
  - Simplest models are in tension with the data
- Model-specific DM bounds from the LHC
  - Strategy: Look for charged dark sector particles
  - Signatures in some sample models include
    - Cascade decays
    - Charged tracks
    - Modified Higgs decays
    - . . .

Thank you!



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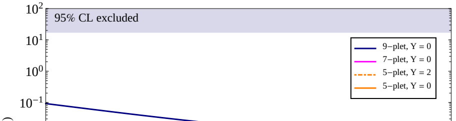

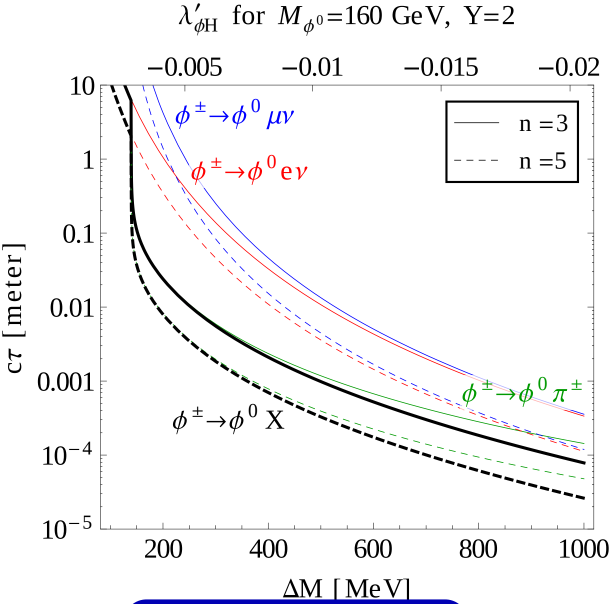

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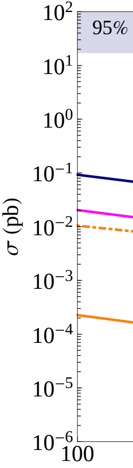

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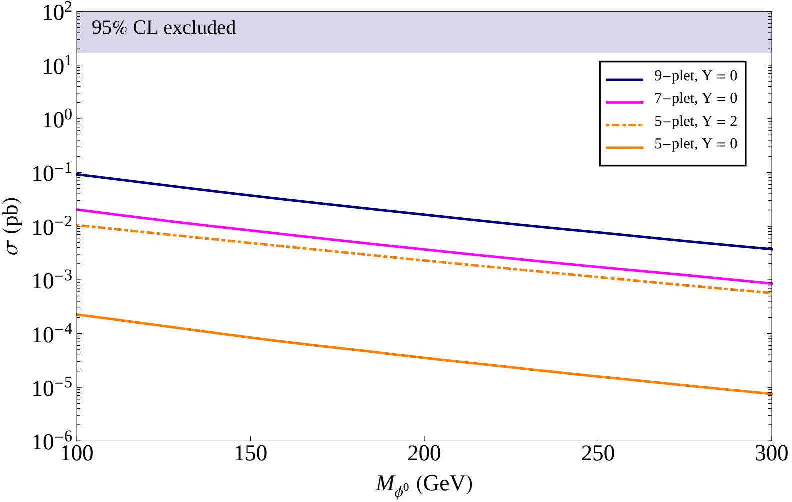

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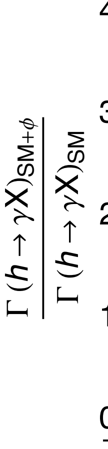

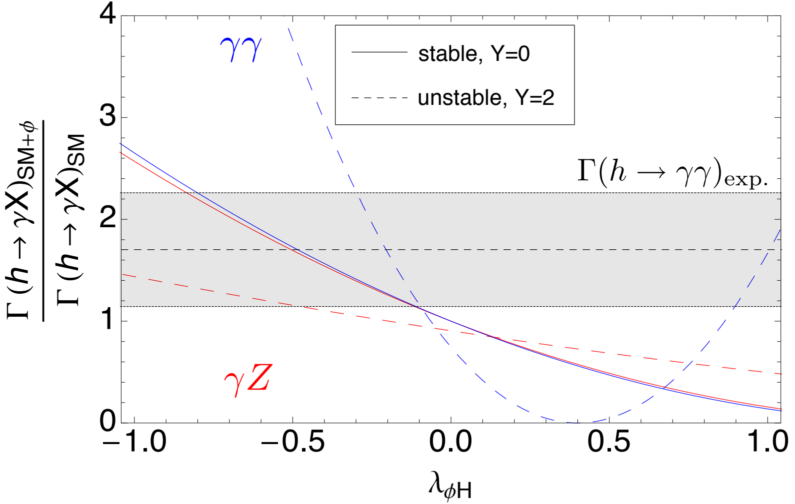

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