Dark matter at colliders

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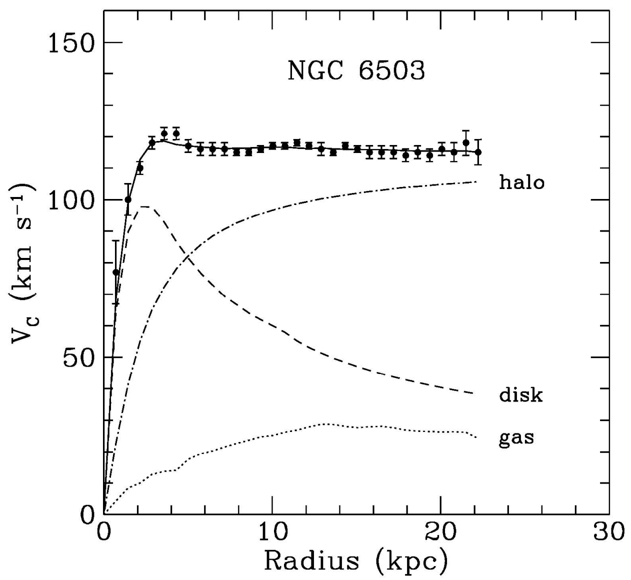
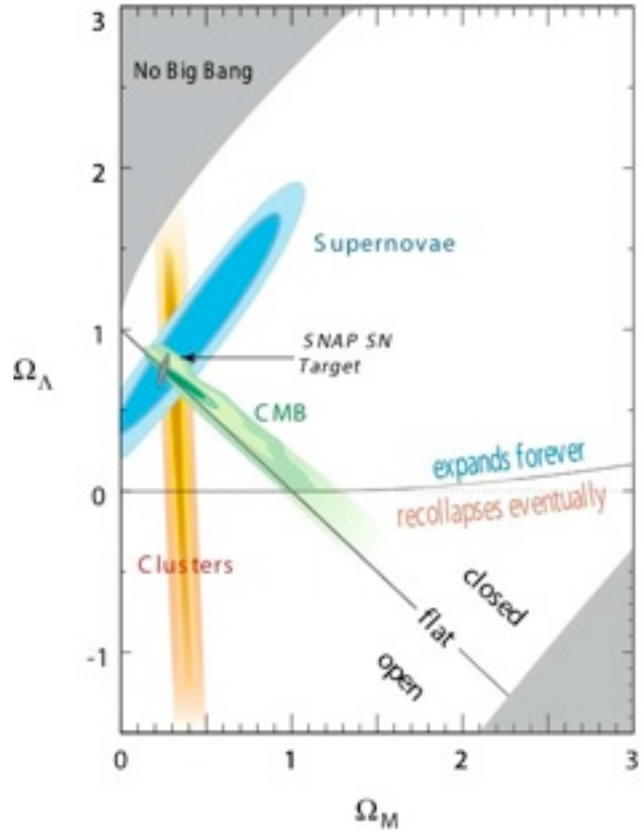
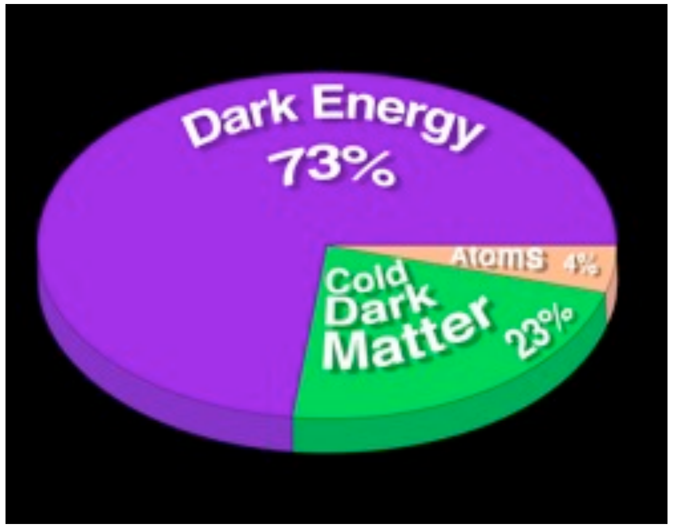
University of Chicago

Aspen winter 2013

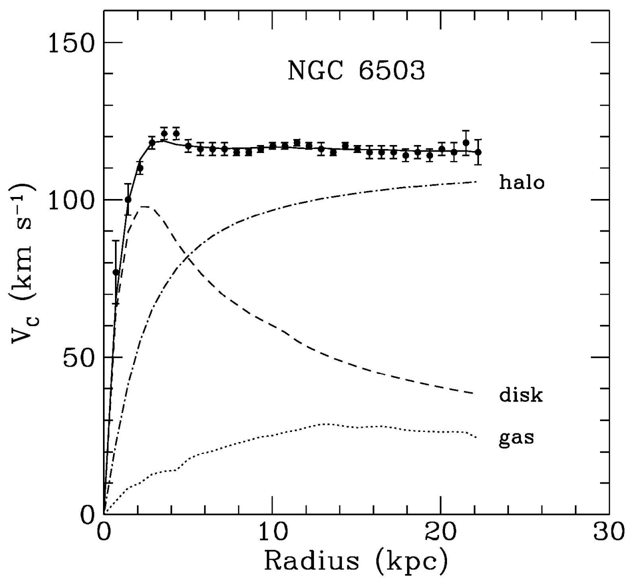
Only concrete evidence of new physics beyond the SM.

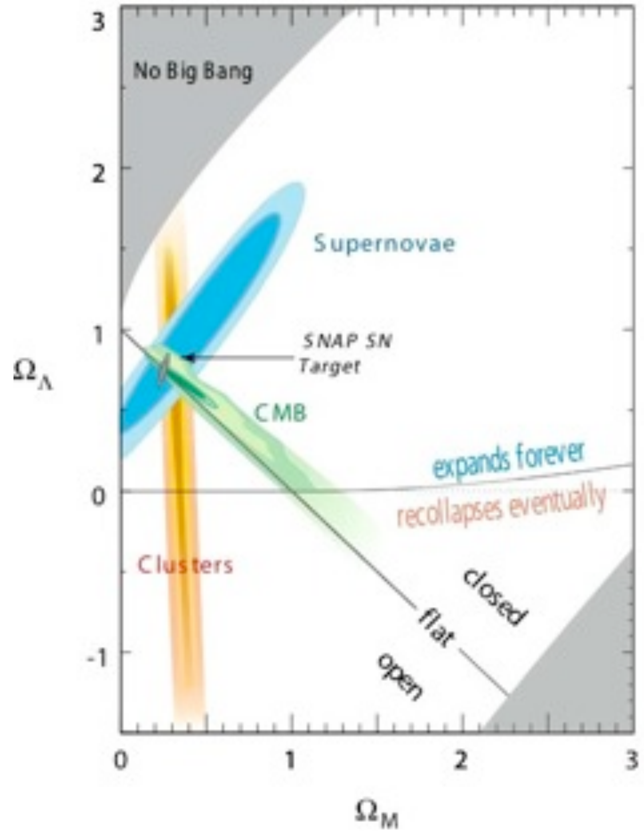




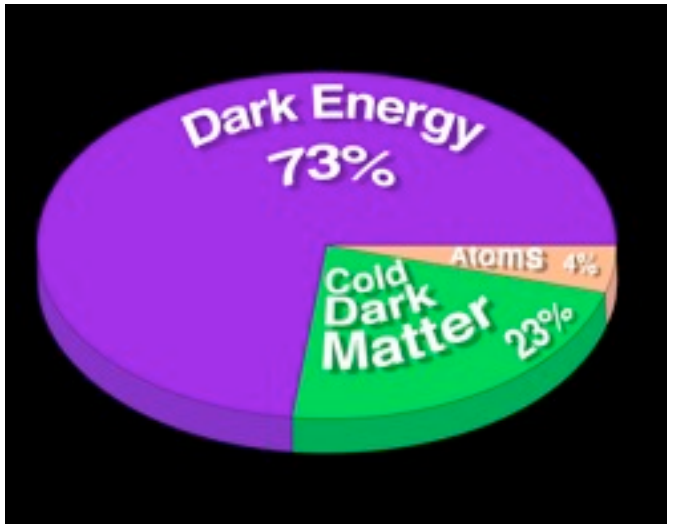


Only concrete evidence of new physics beyond the SM.

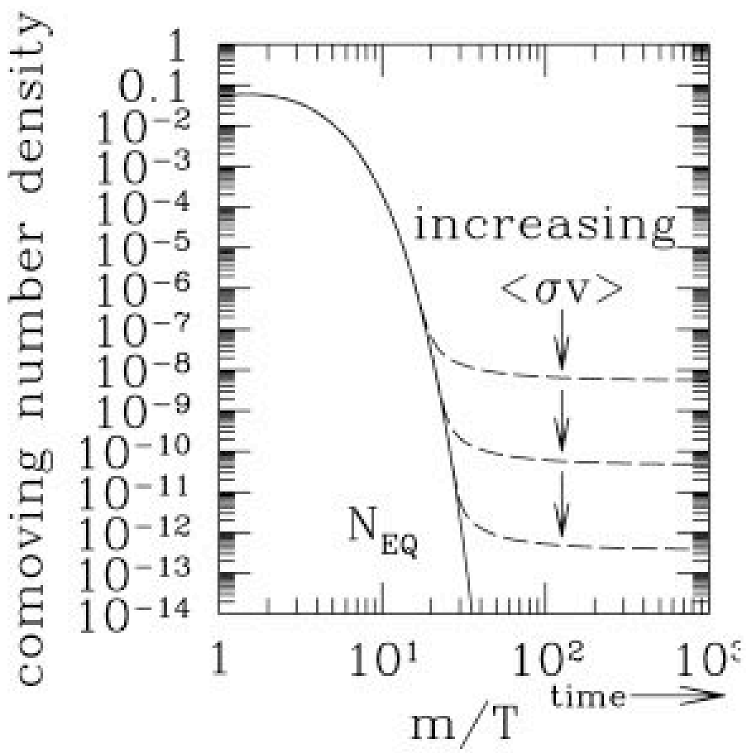


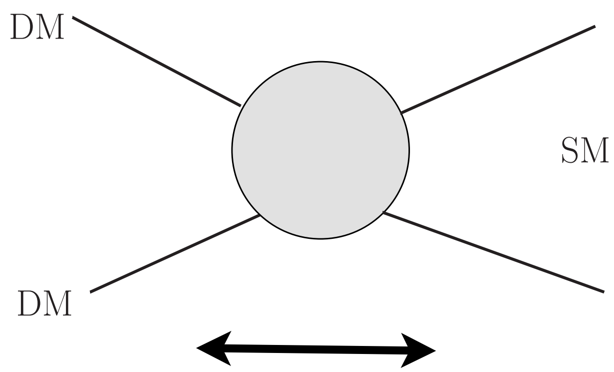


- Exists
- gravitates.
- is dark.



TeV dark matter: WIMP miracle.





Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$

Freeze out: dropping out of thermal eq.

Stronger coupling, lower abundance.

- If dark matter is
  - Weakly interacting: $g_D \sim 0.1$
  - Weakscale: $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- A major hint of TeV scale new physics.
  - We can produce and study them at the LHC!

WIMP DM plausible.

- Many NP scenarios have been considered for solving hierarchy problem between Planck scale and weak scale ≈ 10^2 GeV.

- M_{NP} not very different from M_{WIMP} (fac. of 10, give or take).

- Perhaps NP sets the mass scale of the dark matter as well.
  - Typical example: supersymmetry.

- Weak scale dark matter ⇒ major physics opportunity at the LHC.

Candidates, models, scenarios...

Different spin
different Z_2

SUSY LSP
Extra Dim. LKP
T-parity LTP
LZP
L...P
Z_3

Candidates, models, scenarios...

More model independent	Different spin different Z_2
Effective operator	SUSY LSP
	Extra Dim. LKP
	T-parity LTP
	LZP
	L...P
	Z_3

Candidates, models, scenarios...

More model independent	Different spin different Z_2	Extended Models
Effective operator	SUSY LSP	dark sectors
	Extra Dim. LKP	
	T-parity LTP	
	LZP	
	L...P	
	Z_3	

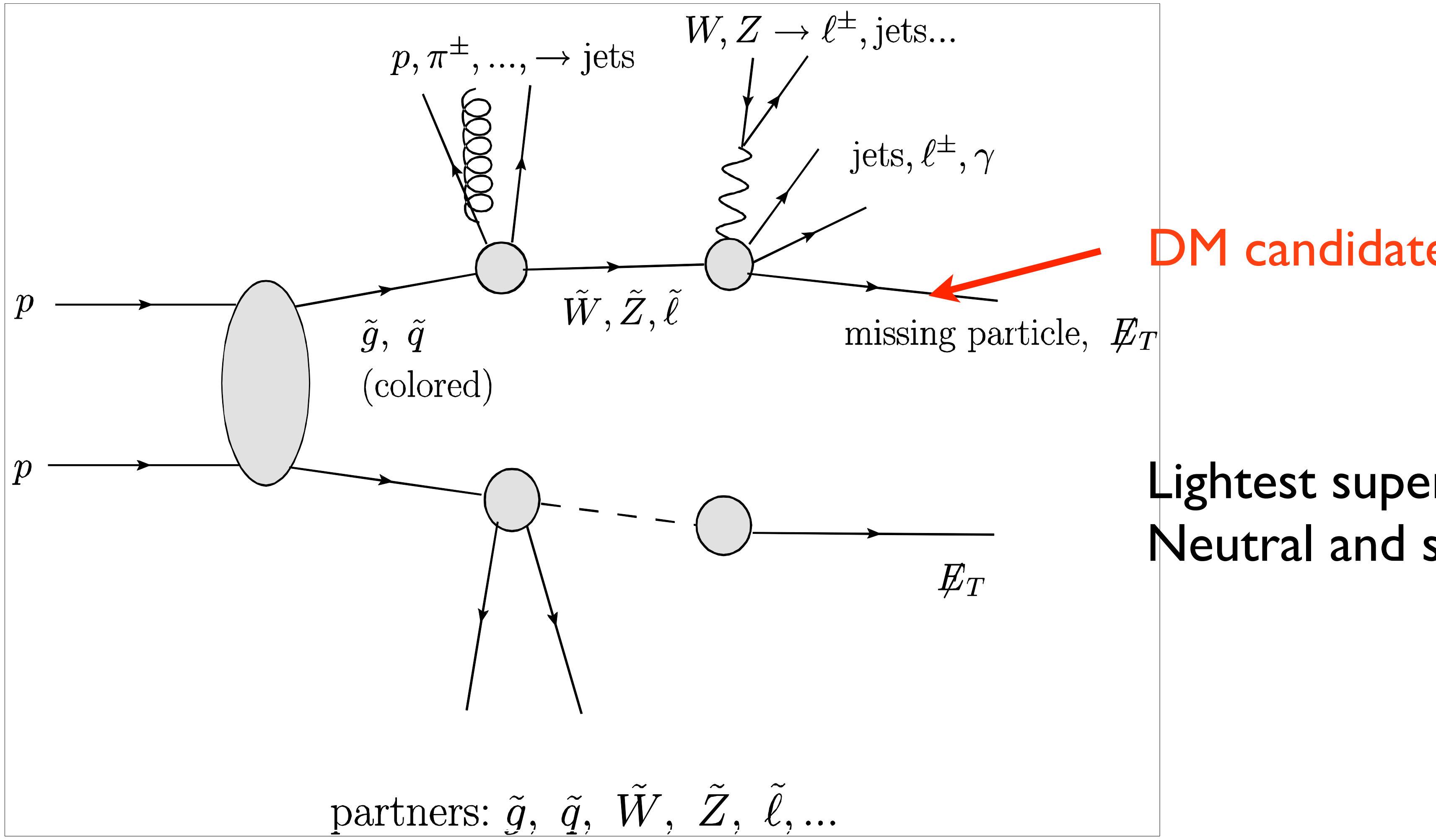
This talk, an over view of

- Brief overview of SUSY-like dark matter, and measure its properties. See also talks by Baer, Dutta
- Connection with direct detection, focusing on light dark matter. See also Tim Tait's talk
- Extended models. (Very brief.)

Search for SUSY
(or SUSY-like) dark matter

In SUSY like scenario

- DM candidate embedded in an extended TeV new physics scenario



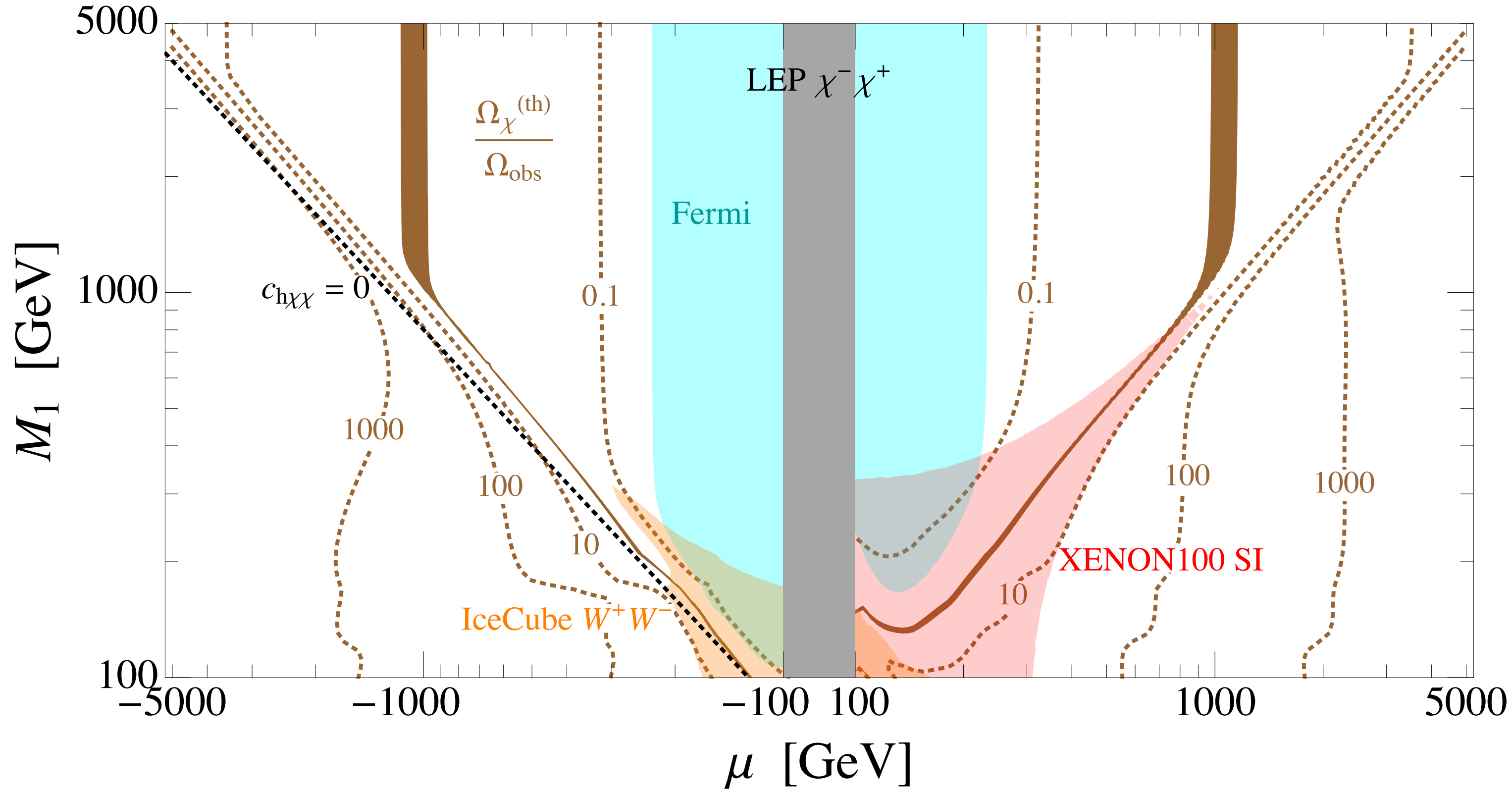
Lightest superpartner (LSP)
Neutral and stable.

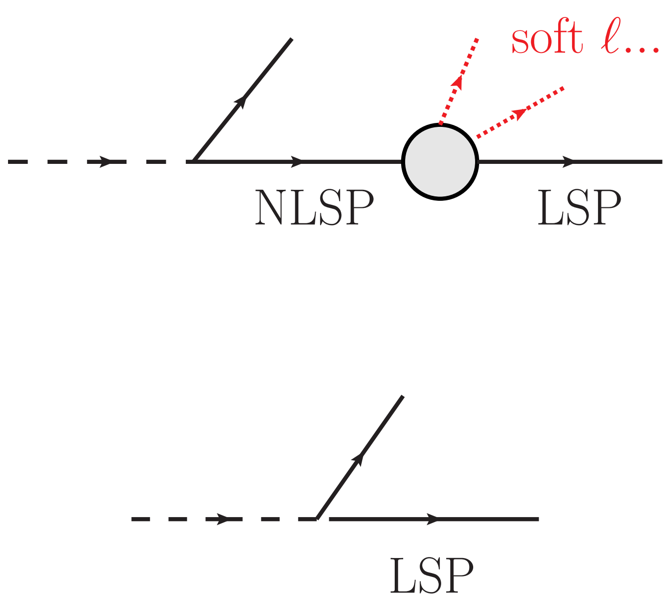
- Discovery could be ``straightforward".
- Measuring the properties (mass, spin ...) hard.

See also talks by Baer, Dutta.

SUSY example.

N. Arkani-Hamed, A. Delgado, G. Giudice, hep-ph/0601041





Cheung, Hall, Pinner, Ruderman, 1211.4873

$$m_{\rm NLSP} - m_{\rm LSP} \sim 10 - 20 \text{ GeV}$$

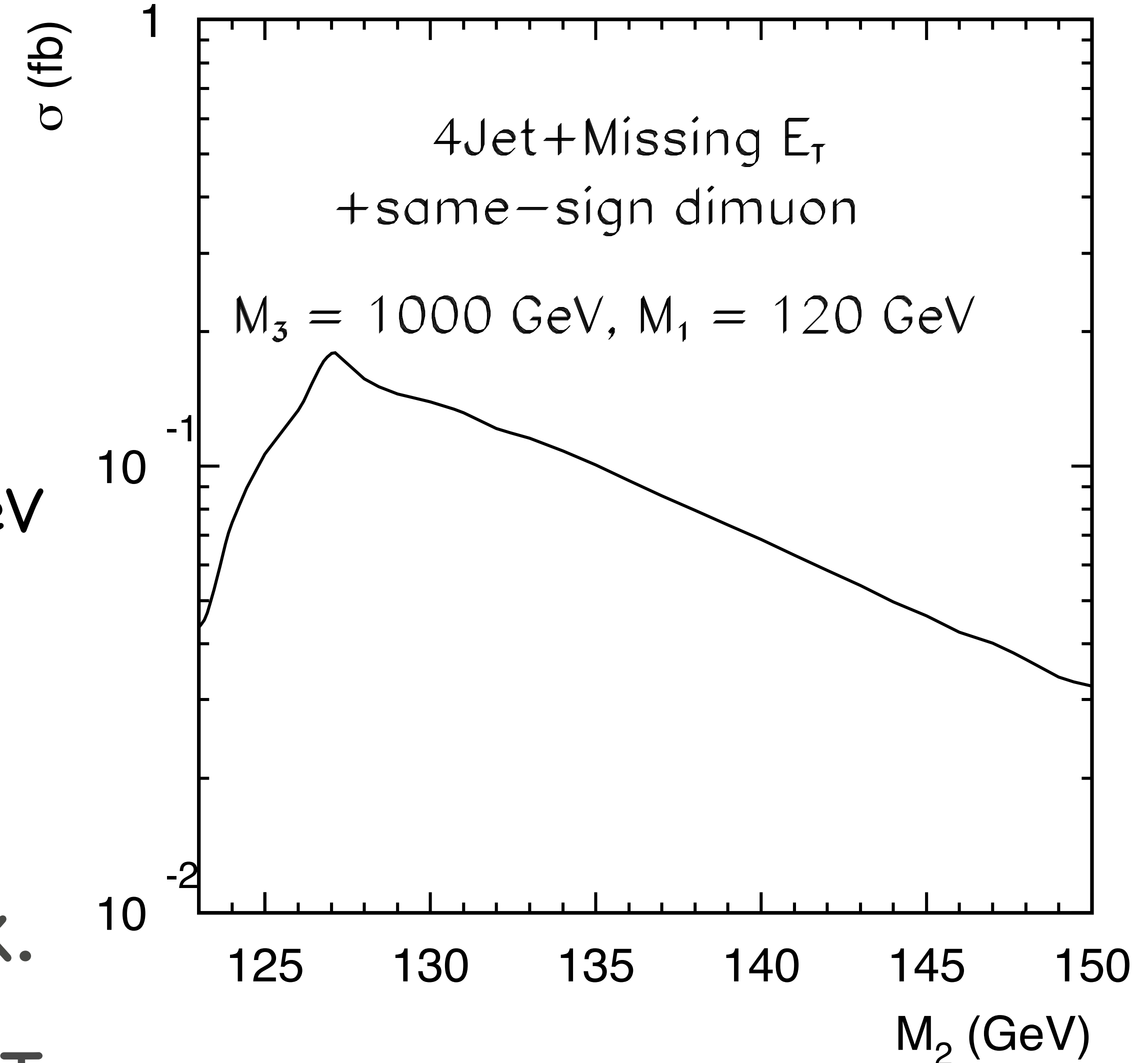
- For example: the "well tempered" scenario.

- Challenging at the LHC.

LHC prospect for well tempered DM

G. Giudice, T. Han, K. Wang and LTW, 1004.4902

LHC at 14 TeV.
Soft muon:
3 GeV < p_T < 10 GeV

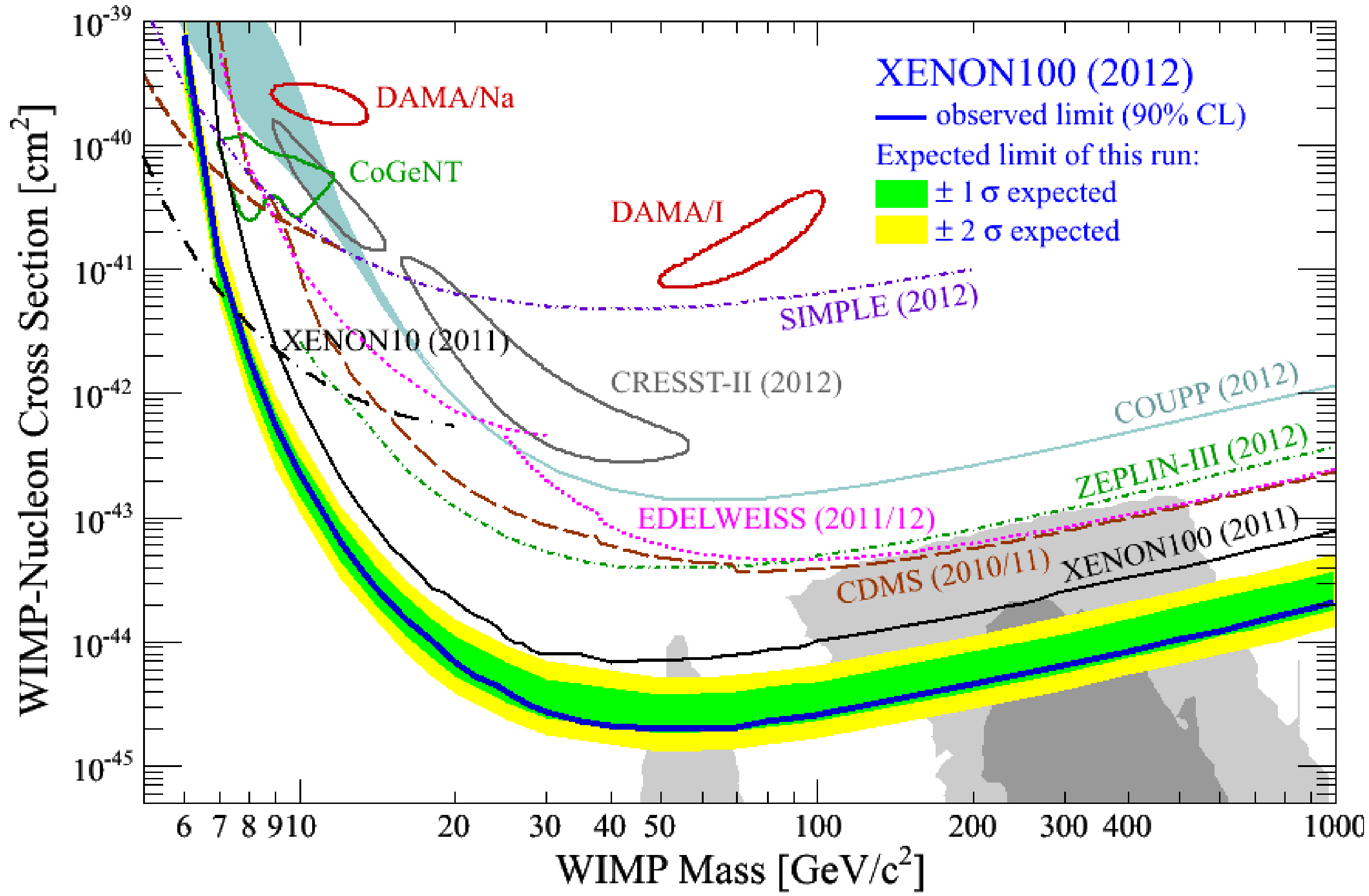


- Light-ish gluino or squark.
  - Discovery from jets+MET.
  - soft leptons ↔ well tempered, long term.
- No light gluino or squark, very hard.
  - VBF, Drell-Yan.

Probing light dark matter, collider searches in connection with direct detection

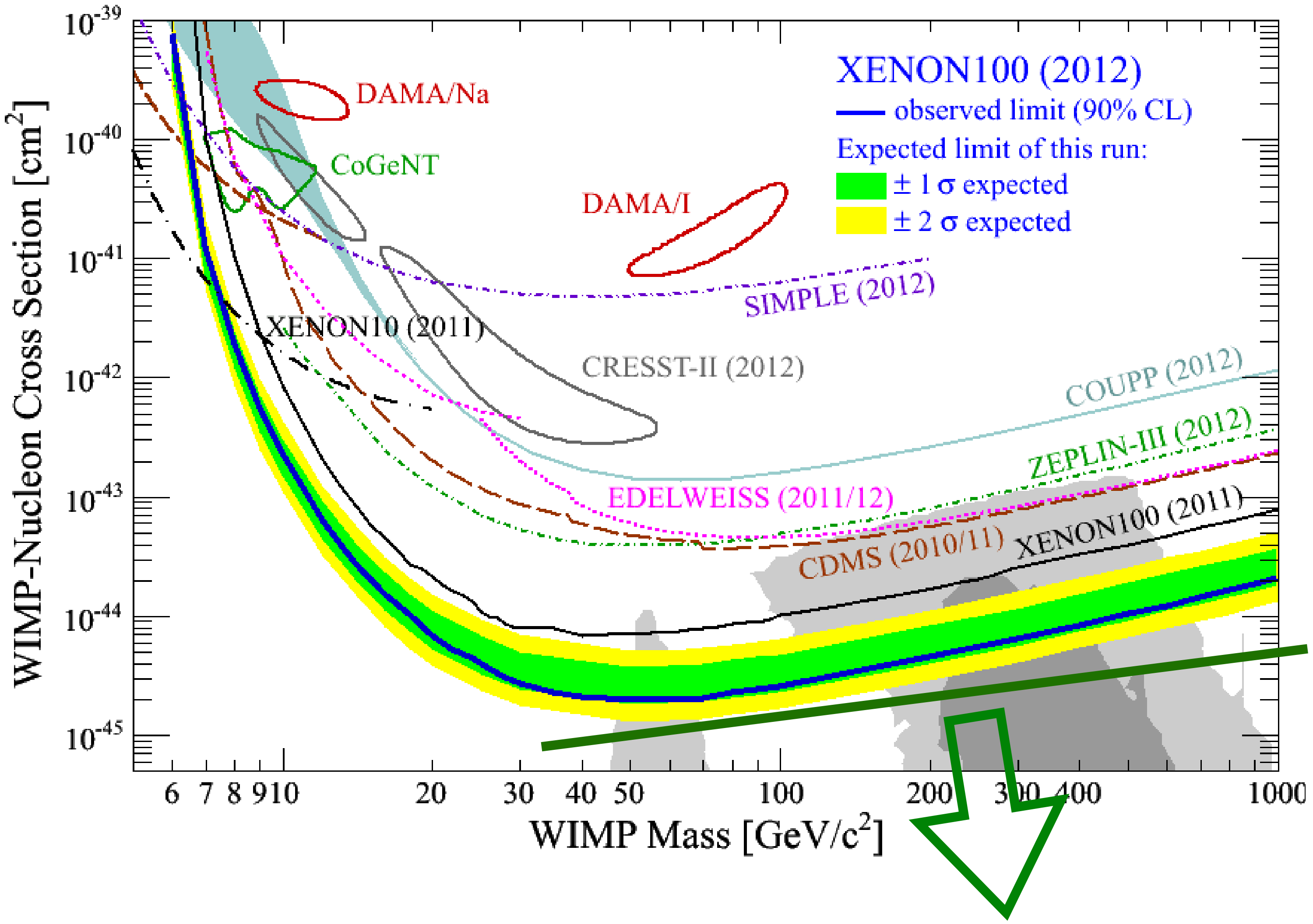
Probe NP with direct detection

XENON 100



Probe NP with direct detection

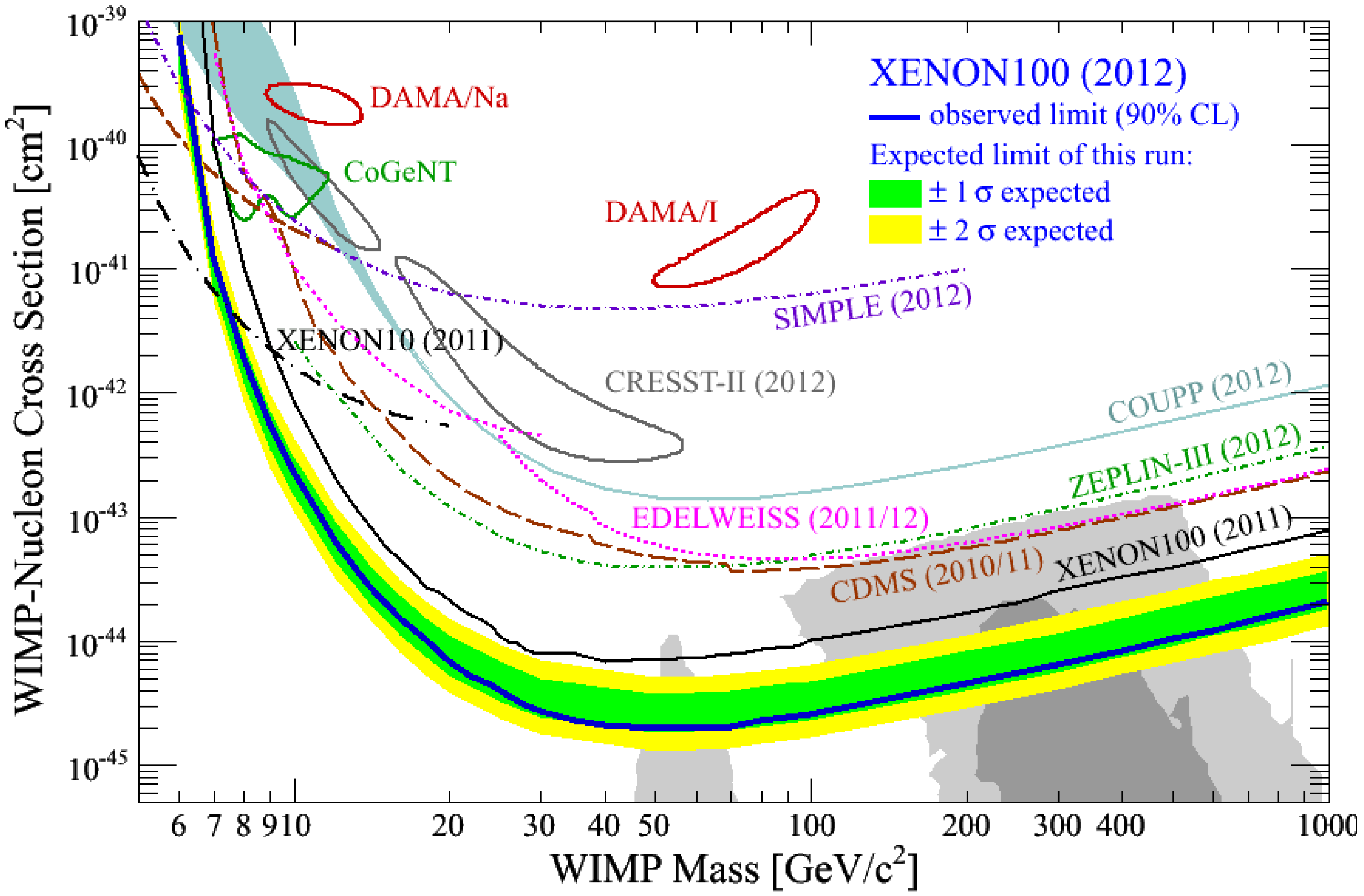
XENON 100



- $M_{WIMP} = O(10^2)$ GeV.
- DM of “Typical” scenarios: SUSY LSP, …

Probe NP with direct detection

XENON 100



Probe NP with direct detection

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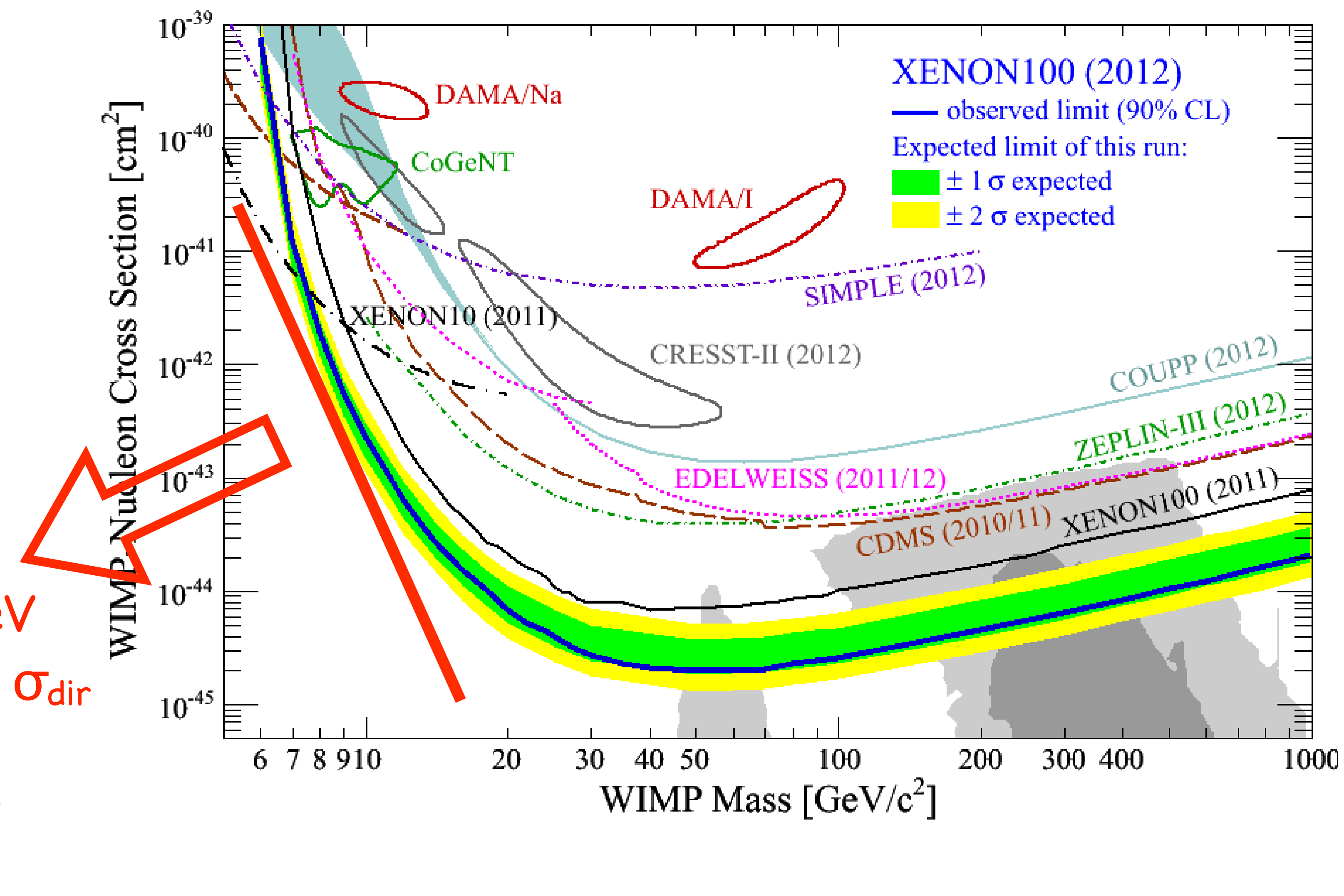


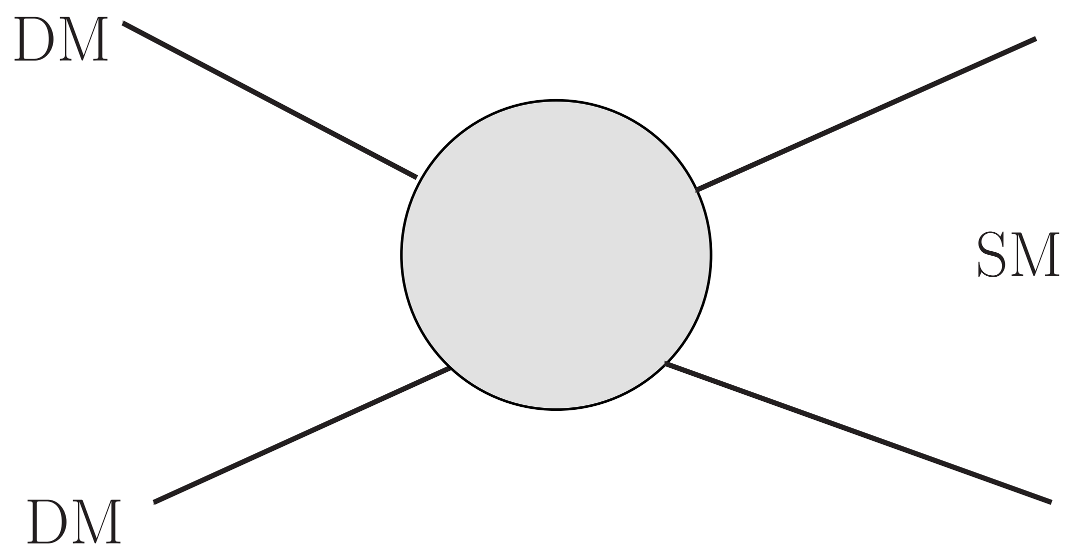
m_{WIMP}: O(1-10) GeV

Much larger σ_{dir}

- Collider searches provide stronger bounds/potential

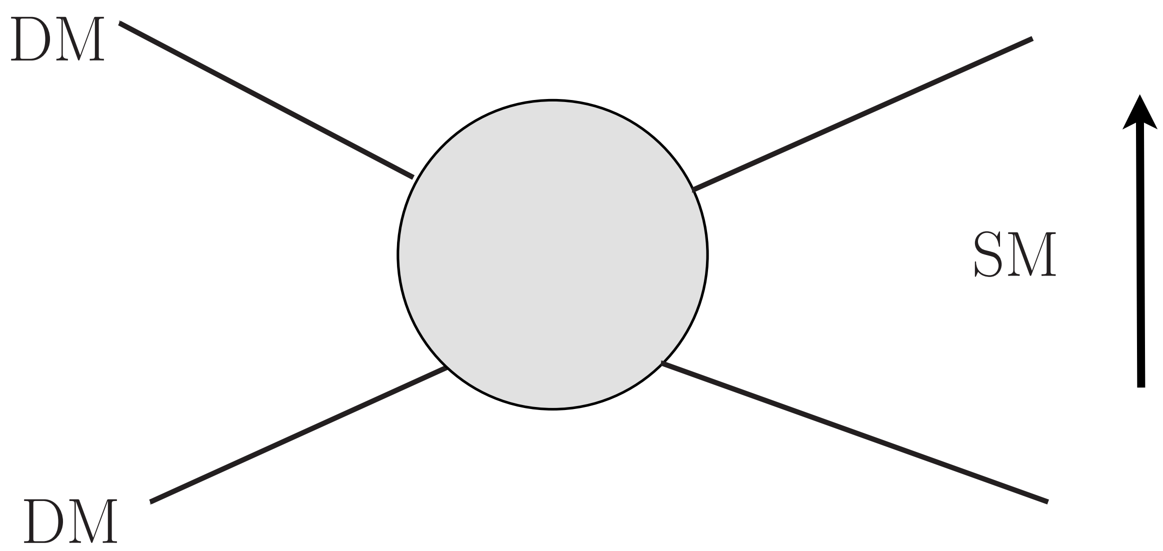
Effective operator approach

Tim Tait's talk



Effective operator approach

Tim Tait's talk

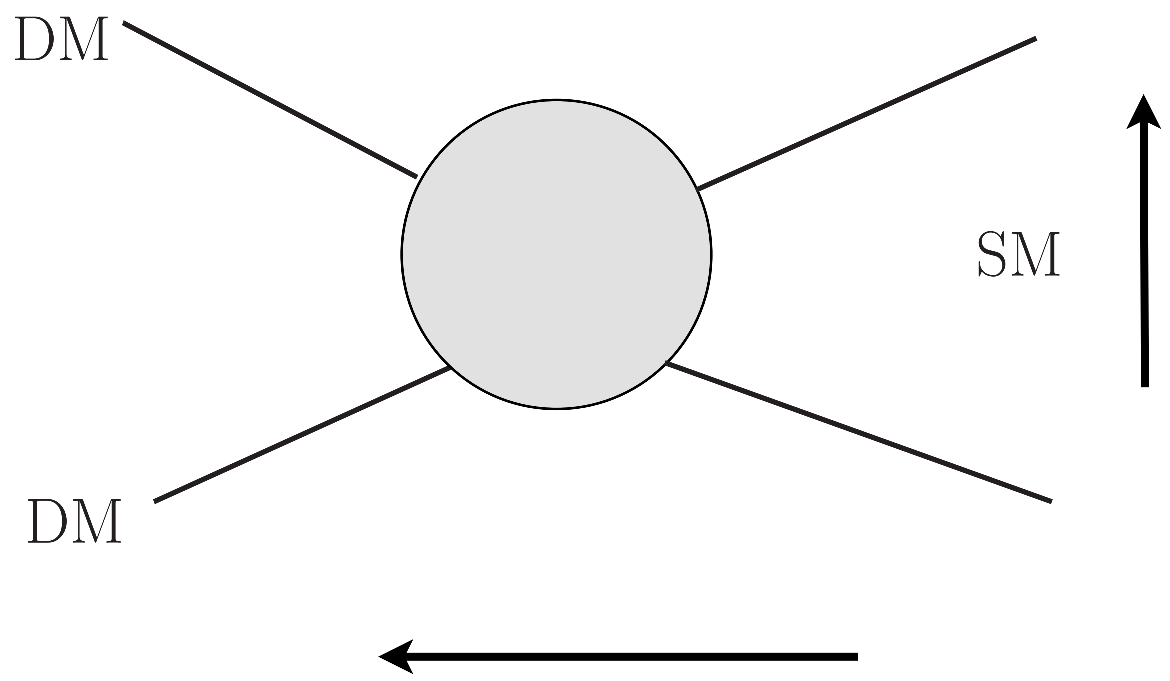


momentum exchange
q~100 MeV << m_Φ
effectively,

$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

Effective operator approach

Tim Tait's talk



momentum exchange
q~100 MeV << m_Φ
effectively,

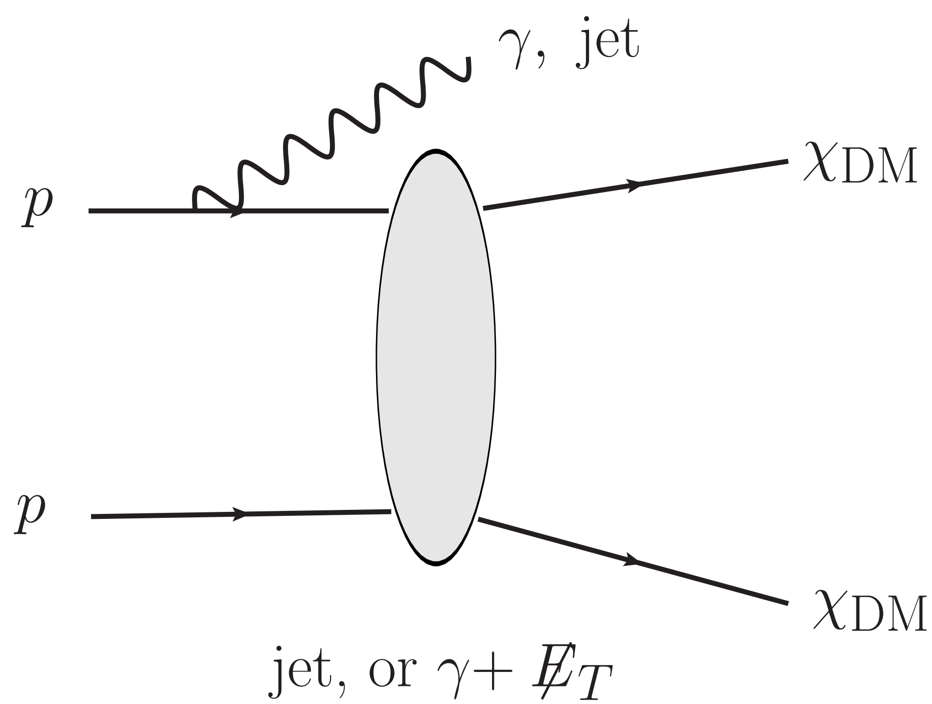
$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

Use colliders to constrain and probe the same operator

$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

Basic channel

- pair production + additional radiation.



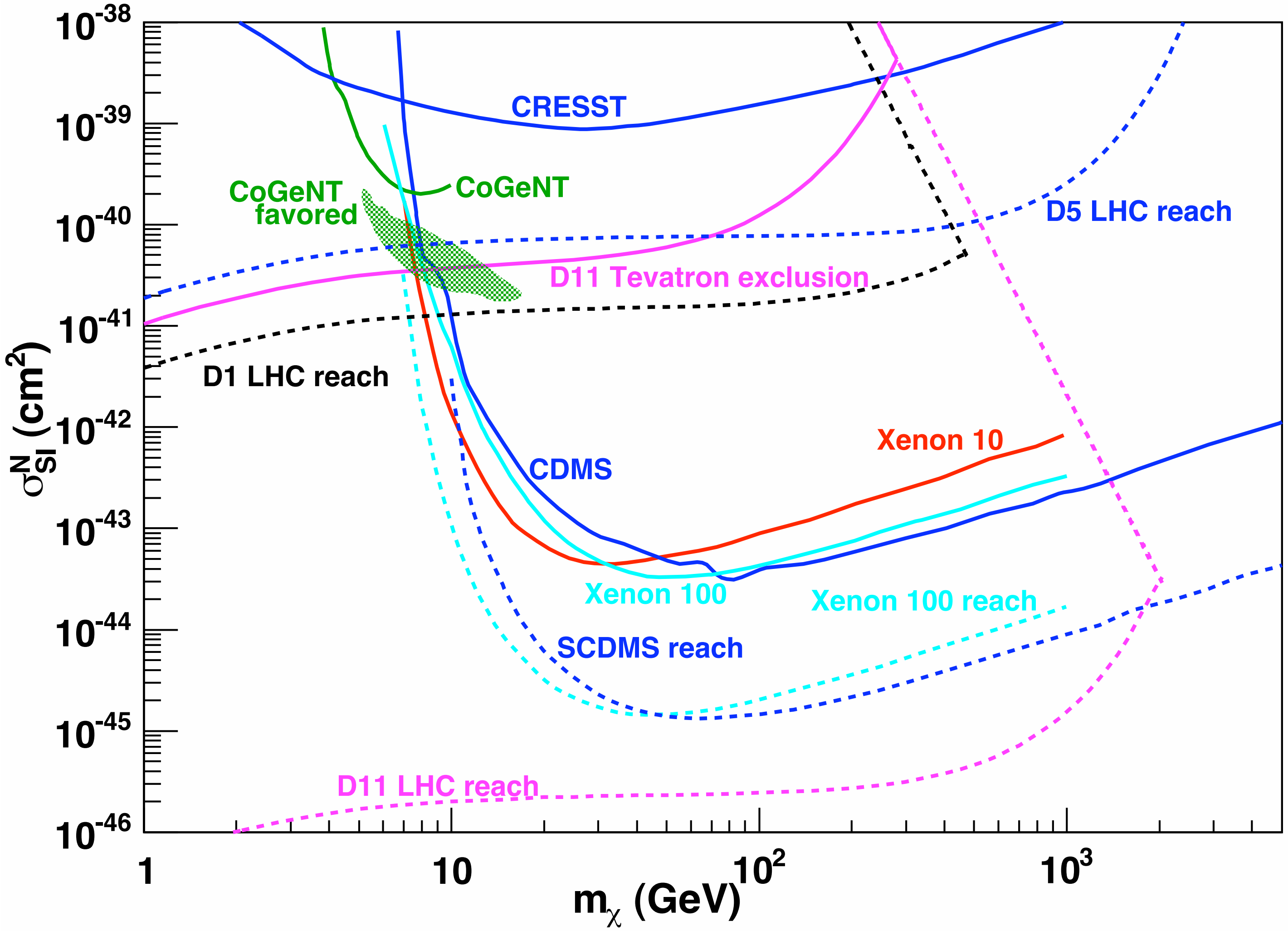
- Large Standard Model background, about 10 times the signal.

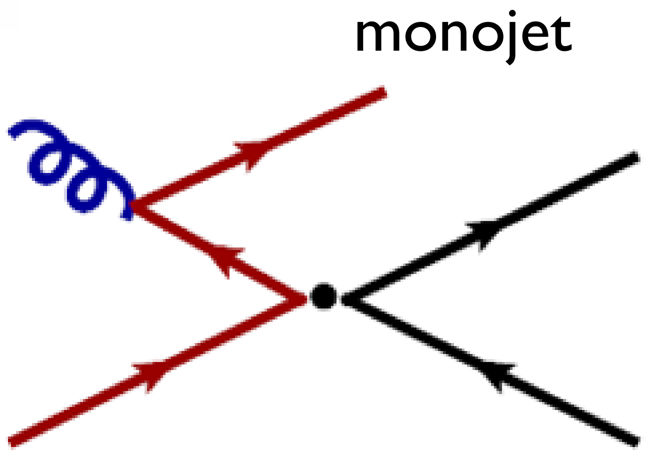
Recent studies.

1. Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
2. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
3. Bai, Fox, Harnik, 1005.3797
4. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783
5. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1009.0008
6. Fox, Harnik, Kopp, Tsai, 1103.0240
7. Fortin, Tait, 1103.3289
8. Cheung, Tseng, Yuan, 1104.5329
9. Shoemaker, Vecchi, 1112.5457
10. more...

For example, 1008.1783

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783





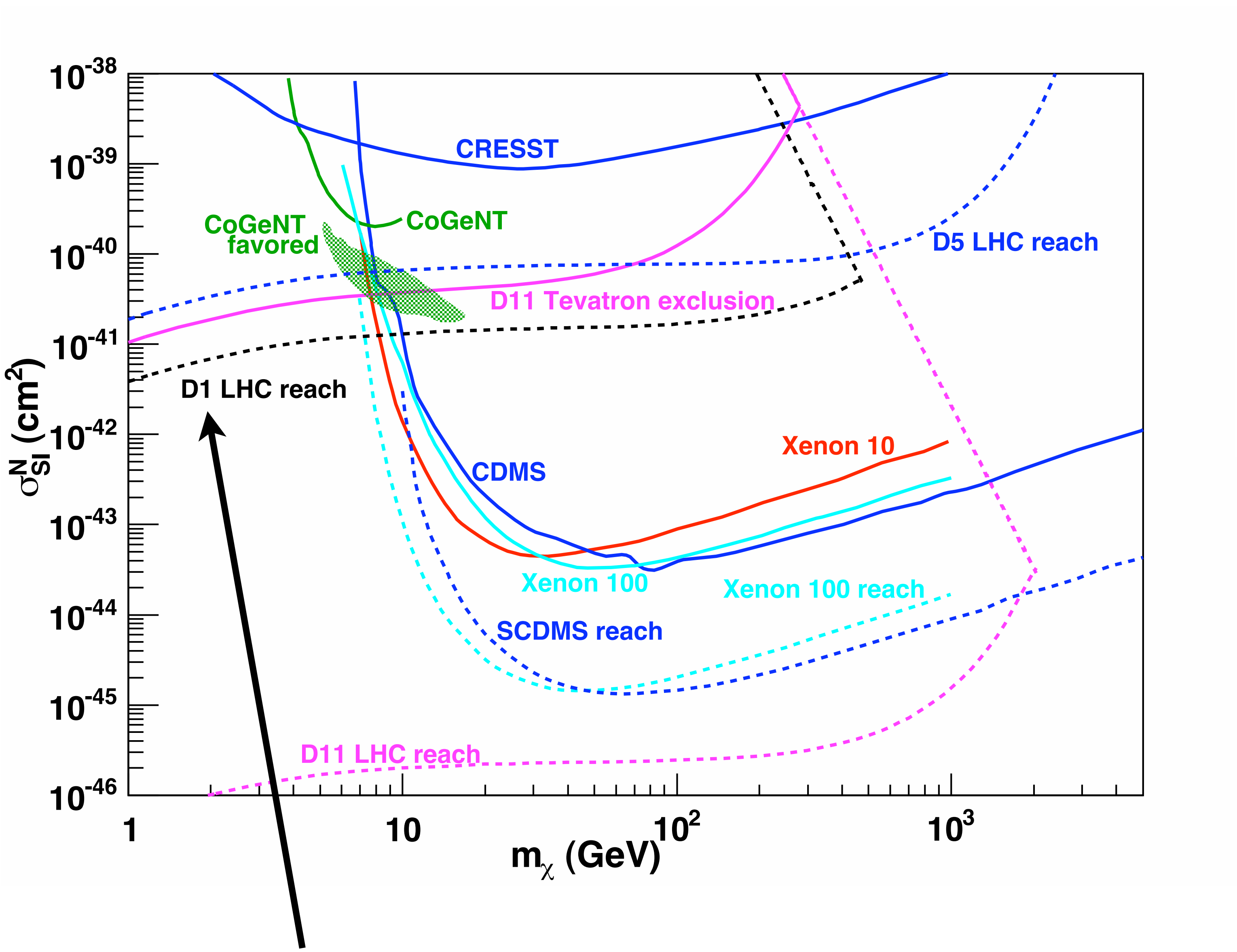
D1 $\bar{\chi}\chi\bar{q}q$

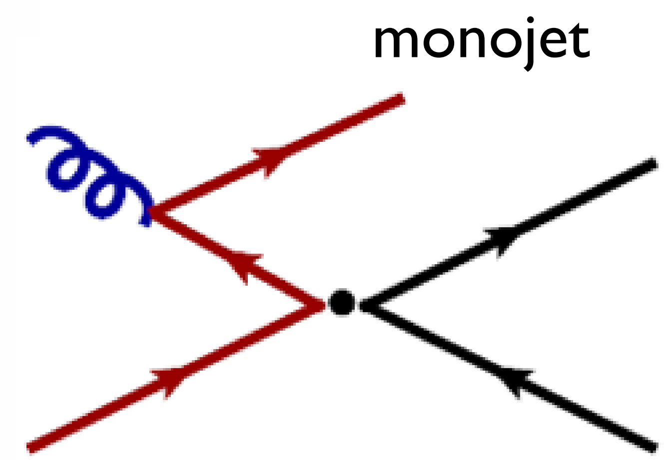
D5 $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$

D11 $\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

For example, 1008.1783

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783

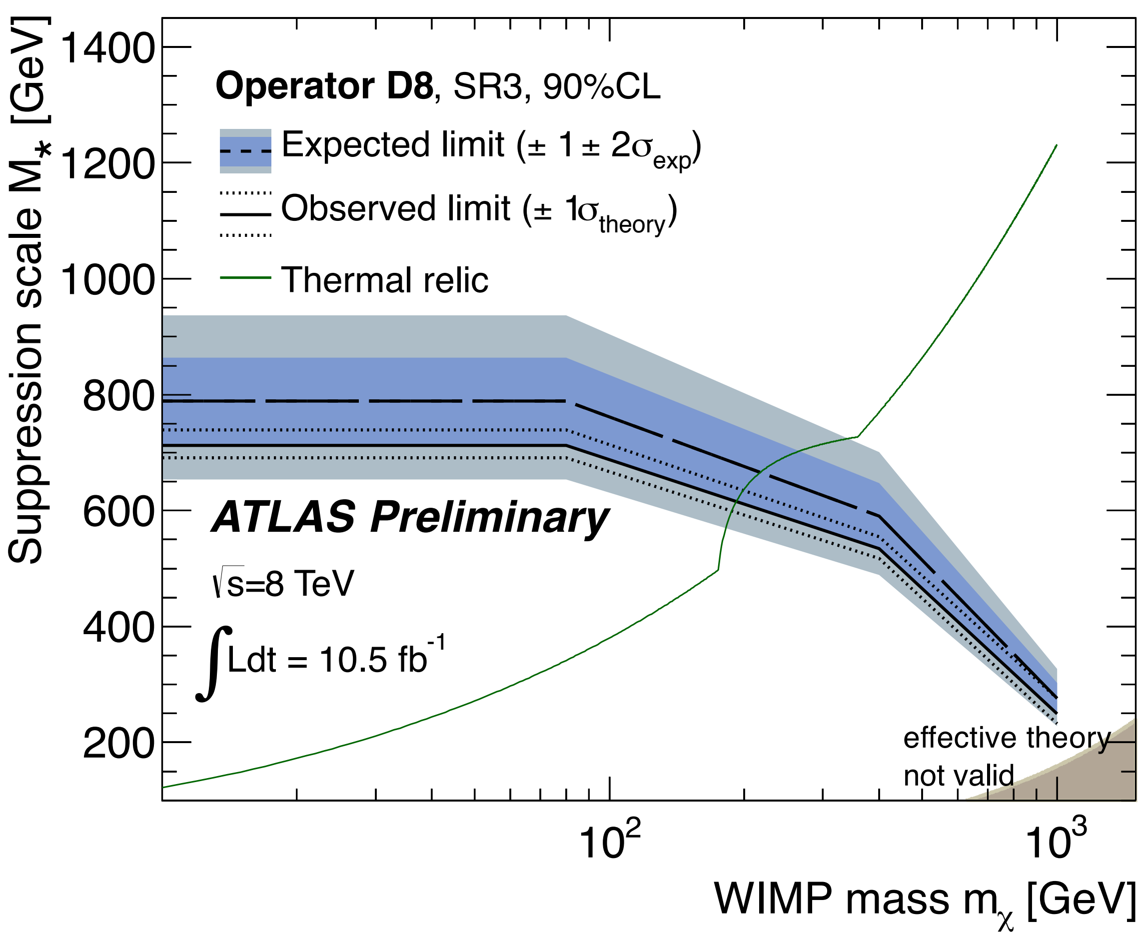


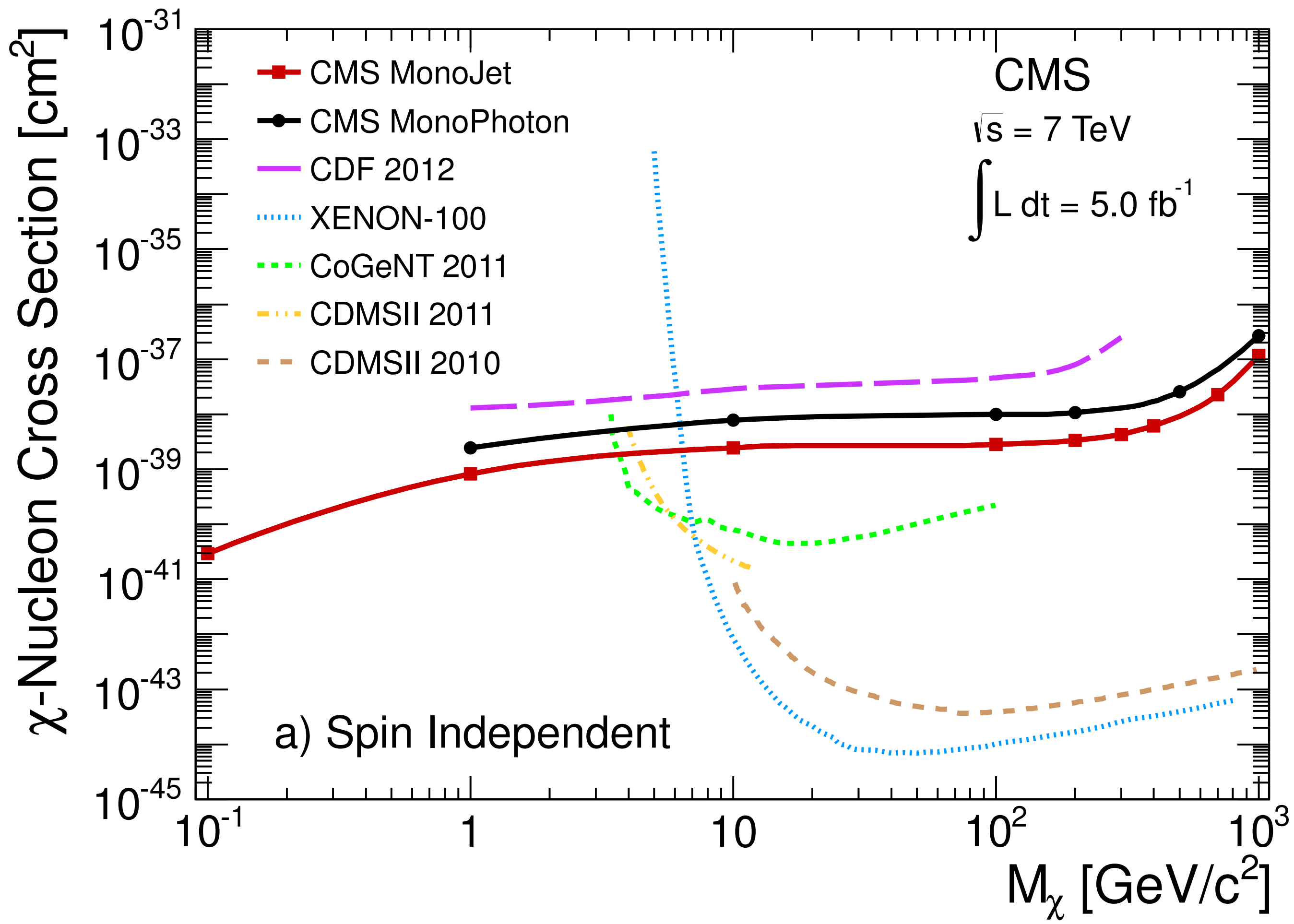


D1	$\bar{\chi}\chi\bar{q}q$
D5	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

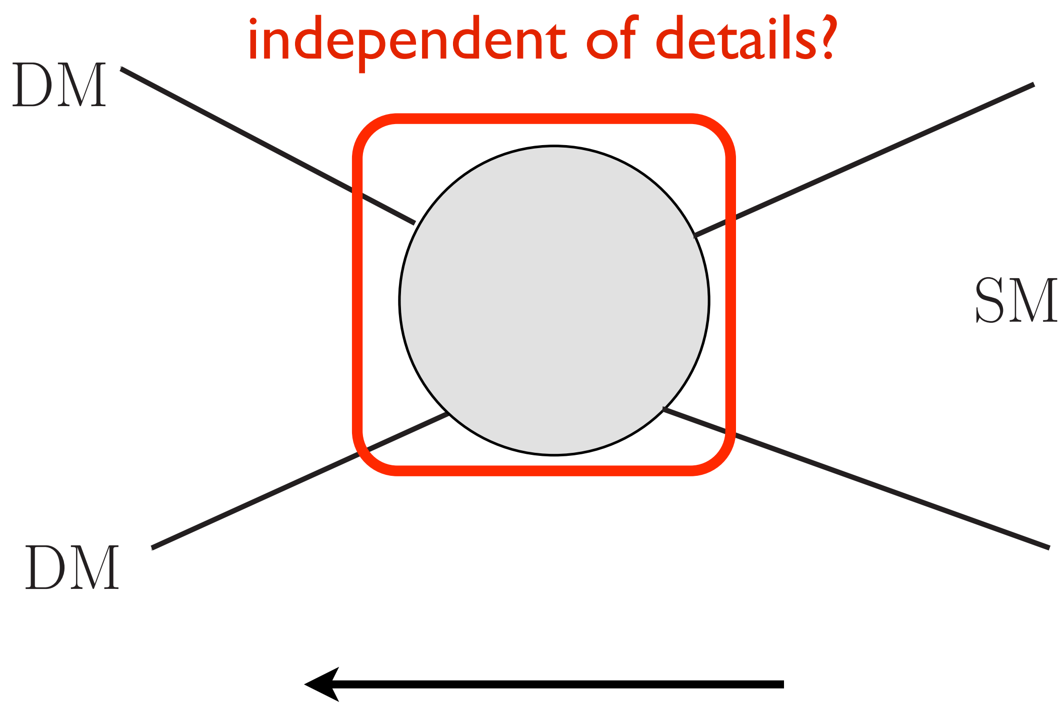
For small m_χ,
collider rates controlled by larger mass scales, i.e., p_T cut;
does not depend on m_χ.
Collider bounds flat and stronger.

Recent results





Effective operator effective?



Use colliders to constrain and probe the same operator

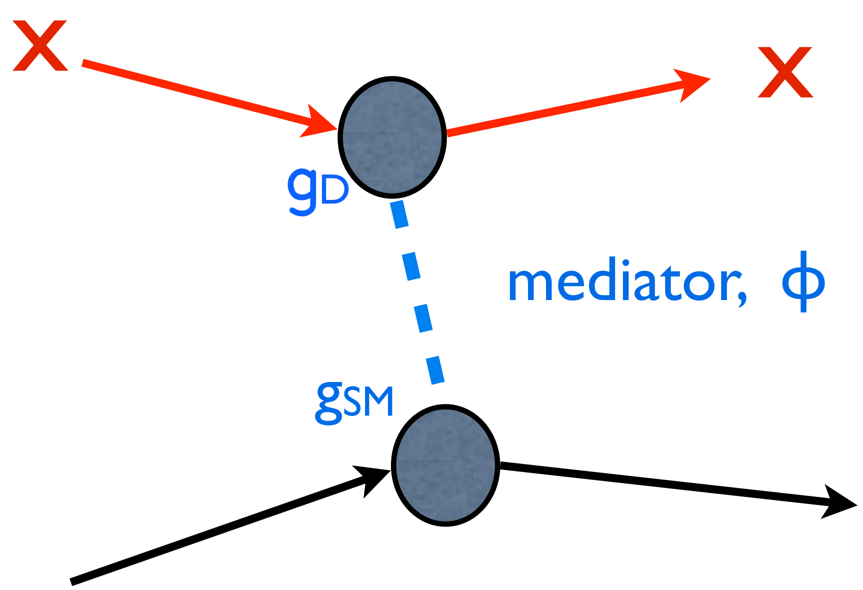
$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

However, E_{cm} = 100s GeV$\sim$ m_Φ (mediator mass), probing more structure of the s-matrix. Depending on more details of the mediator.

Moreover, the mediator itself should be within reach!

The dependence on the mass of the mediator has been explored in: 1105.3797, 1103.0240, 1111.2359

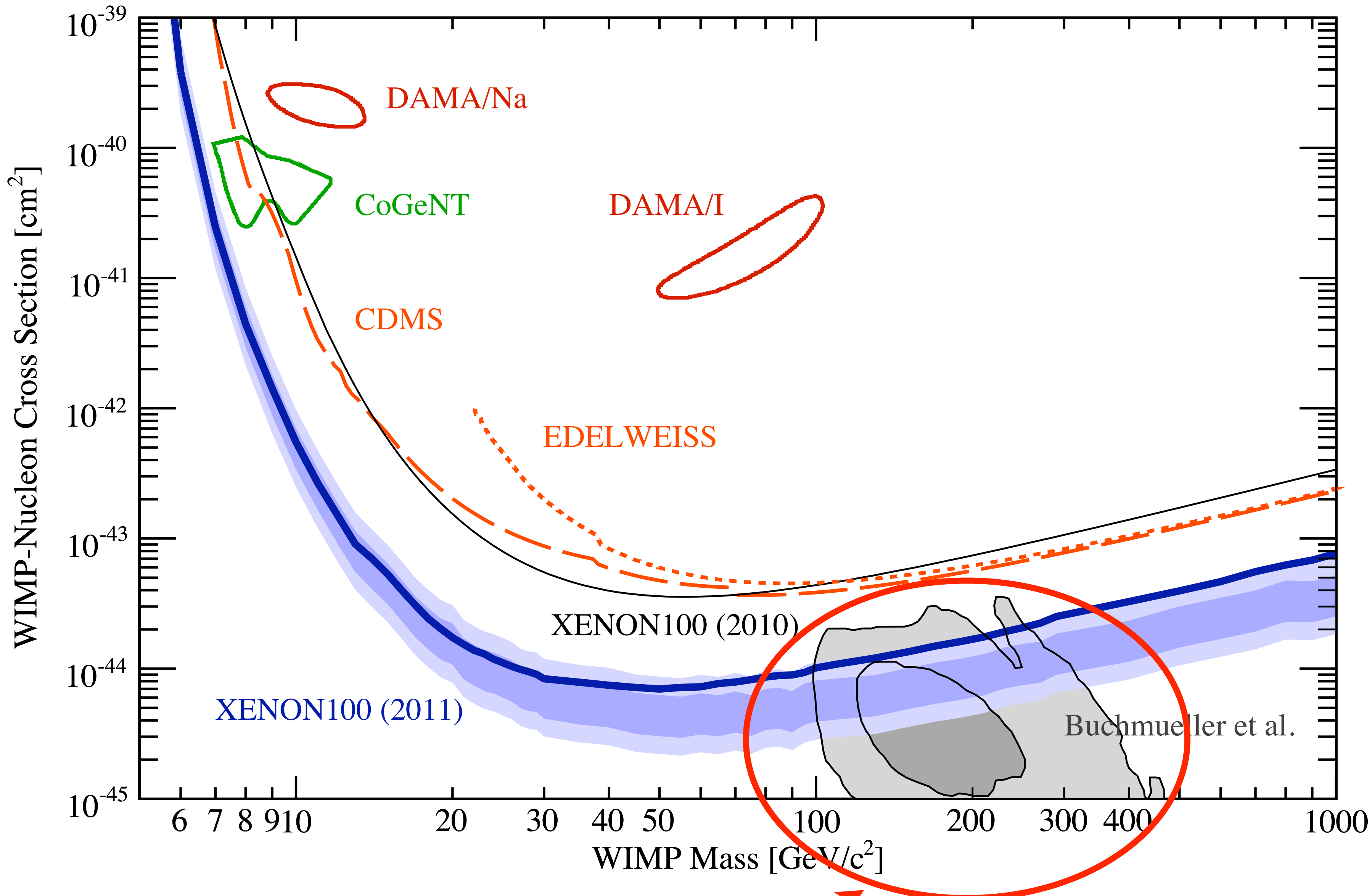
Mediator, two typical examples.



N= Ar, Ge, Xe, ...

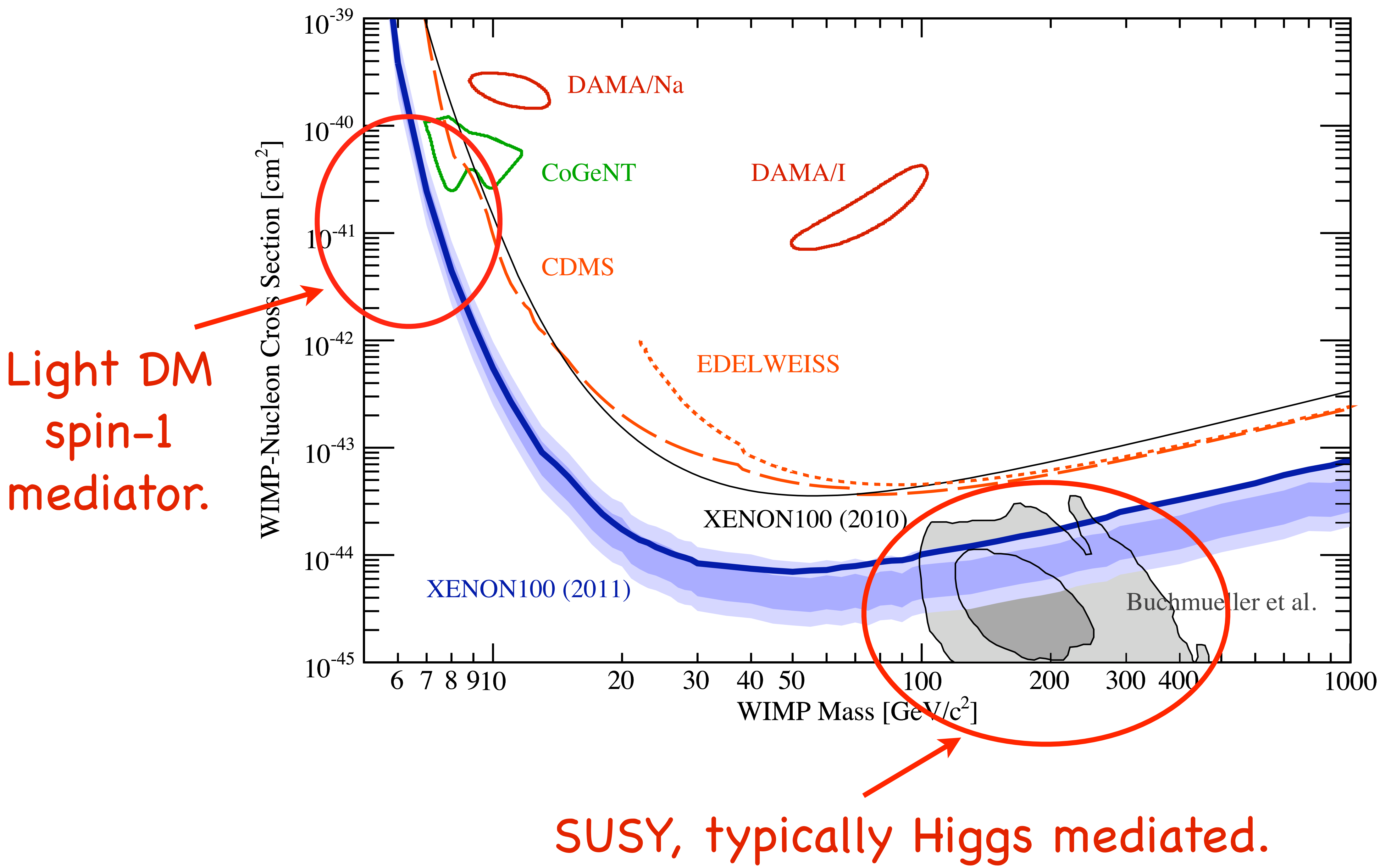
- ϕ=Higgs
  - g_{SM}≈(100 MeV)/(100 GeV)
  - $m_X \approx 100$ GeV
  - $\sigma_n \approx 10^{-43}$–$10^{-45}$ cm^{-2}
- Φ=100 GeV spin-1, D=dirac fermion
  - $\sigma_n \approx 10^{-36}$–$10^{-39}$ cm^{-2}

Probe NP with direct detection



SUSY, typically Higgs mediated.

Probe NP with direct detection

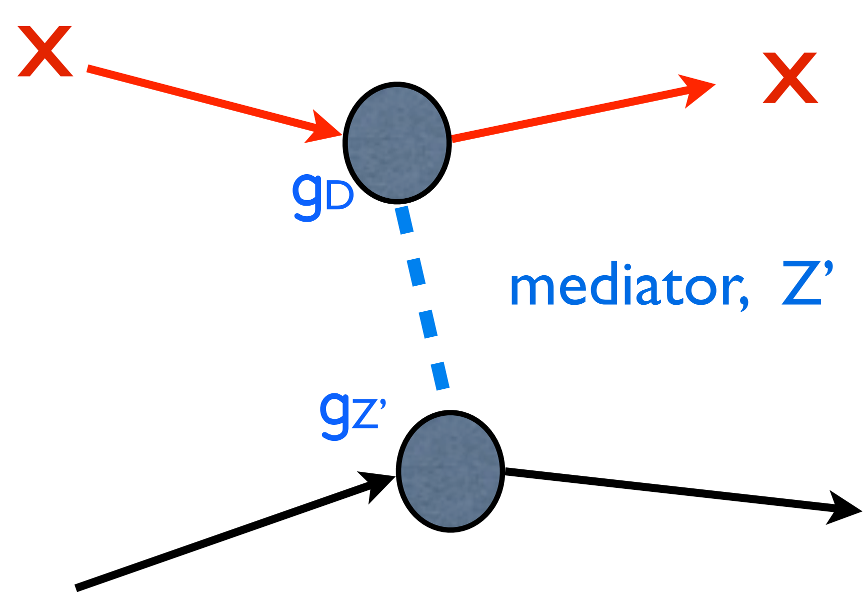


Case study: a spin-1 Z′

Xiang-Dong. Ji, Haipeng An, LTW 11xx.xxxx

$$\mathcal{L} = Z'_\mu[\bar{q}(g_{Z'}\gamma^\mu + g_{Z'5}\gamma^\mu\gamma_5)q + \bar{X}(g_D\gamma^\mu + g_{D5}\gamma^\mu\gamma_5)X]$$

Only couples to SM quarks and DM.

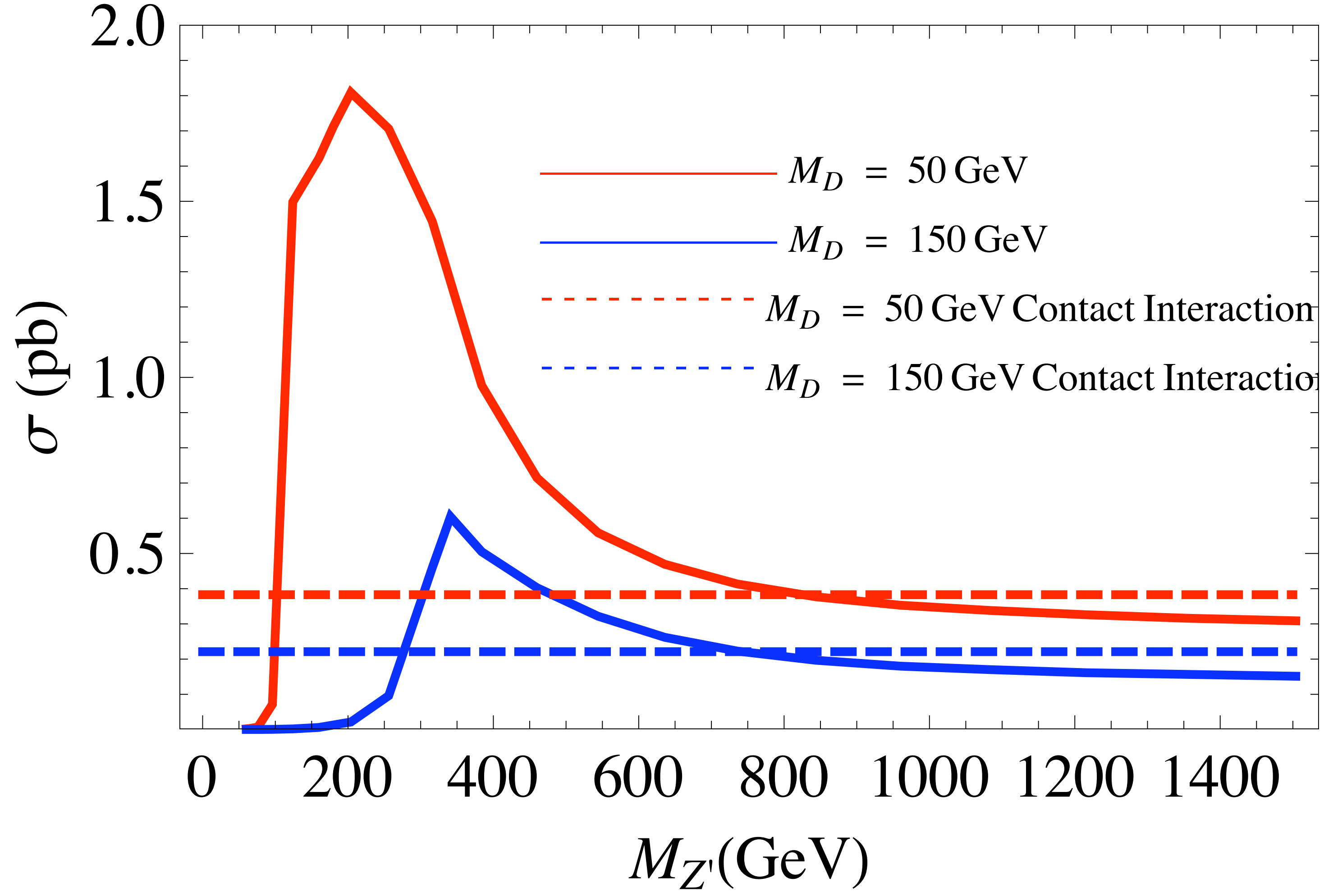


$$g_D \sim g'_Z \to \sigma_{\rm dir} \propto \frac{g'^4_Z}{m^4_{Z'}}$$

N= Ar, Ge, Xe, ...

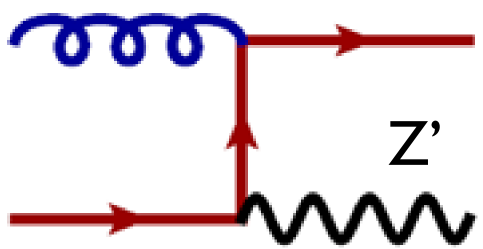
Connection with direct detection

Tevatron rate for
Monojet + (MET> 80 GeV)



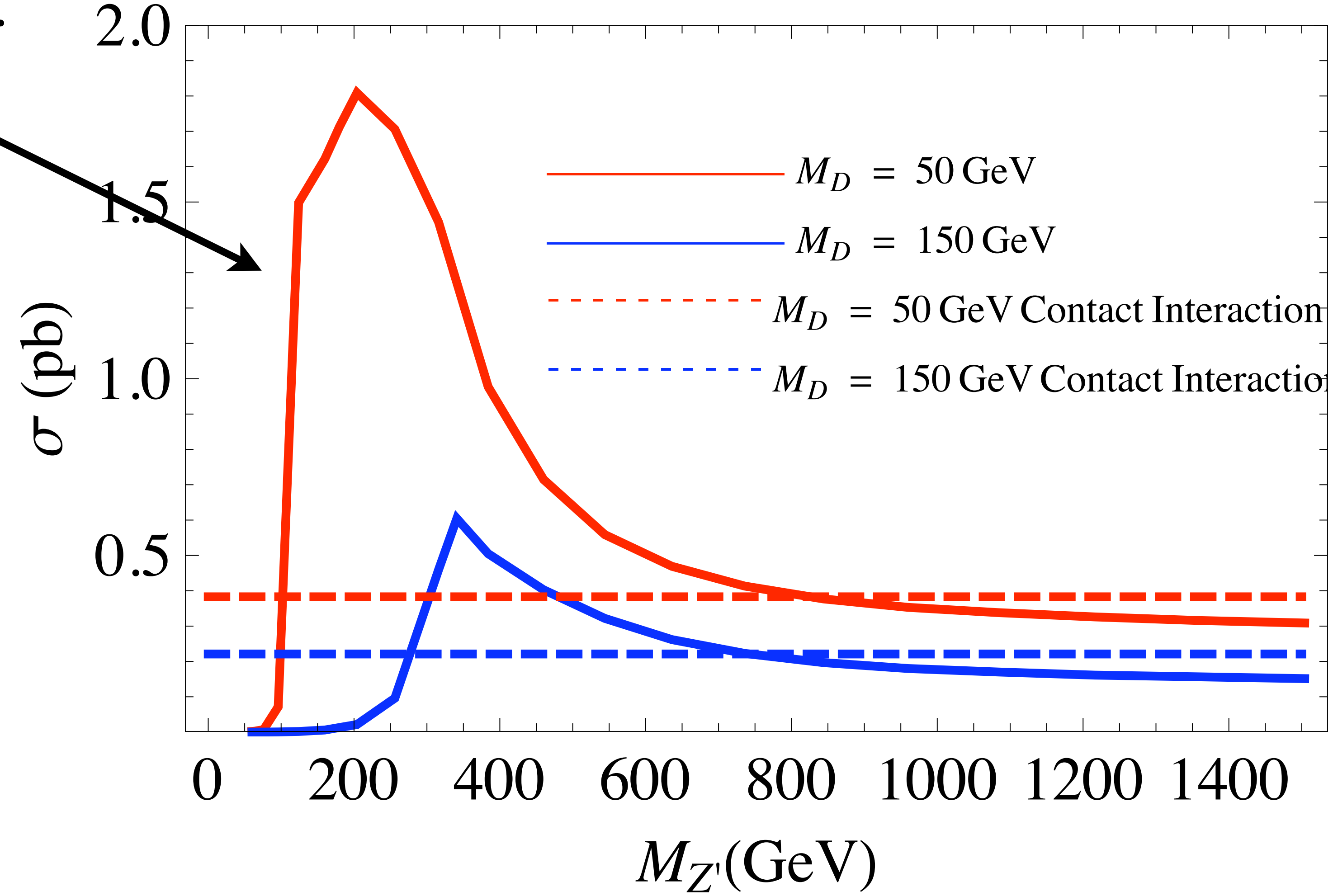
$g_D = g_{Z'}$, fixed σ_{dir}

Connection with direct detection



resonance prod.

Tevatron rate for
Monojet + (MET> 80 GeV)



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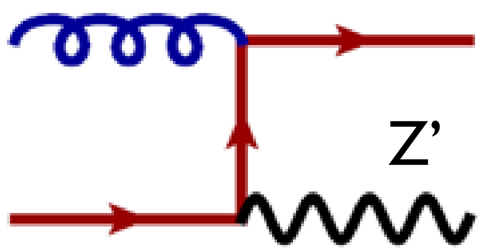

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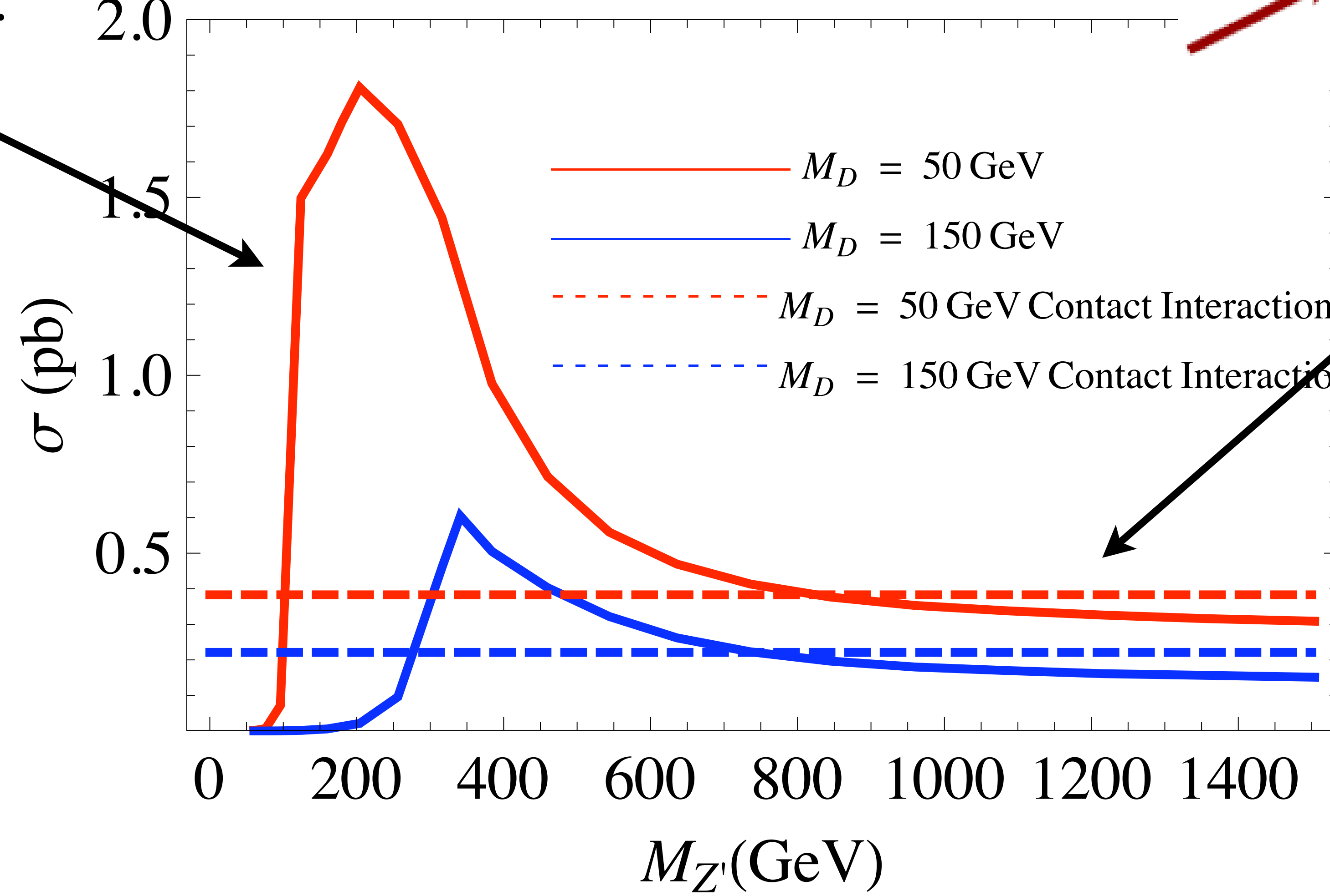
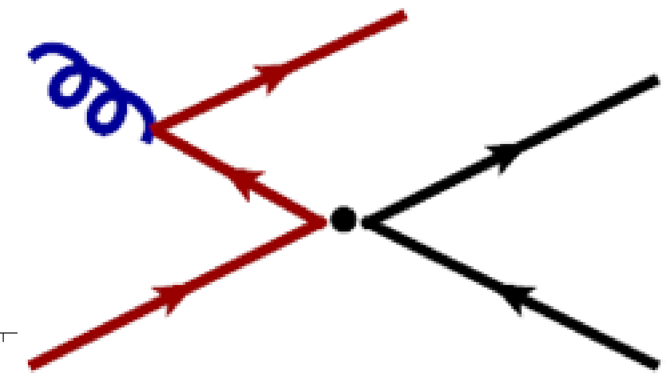


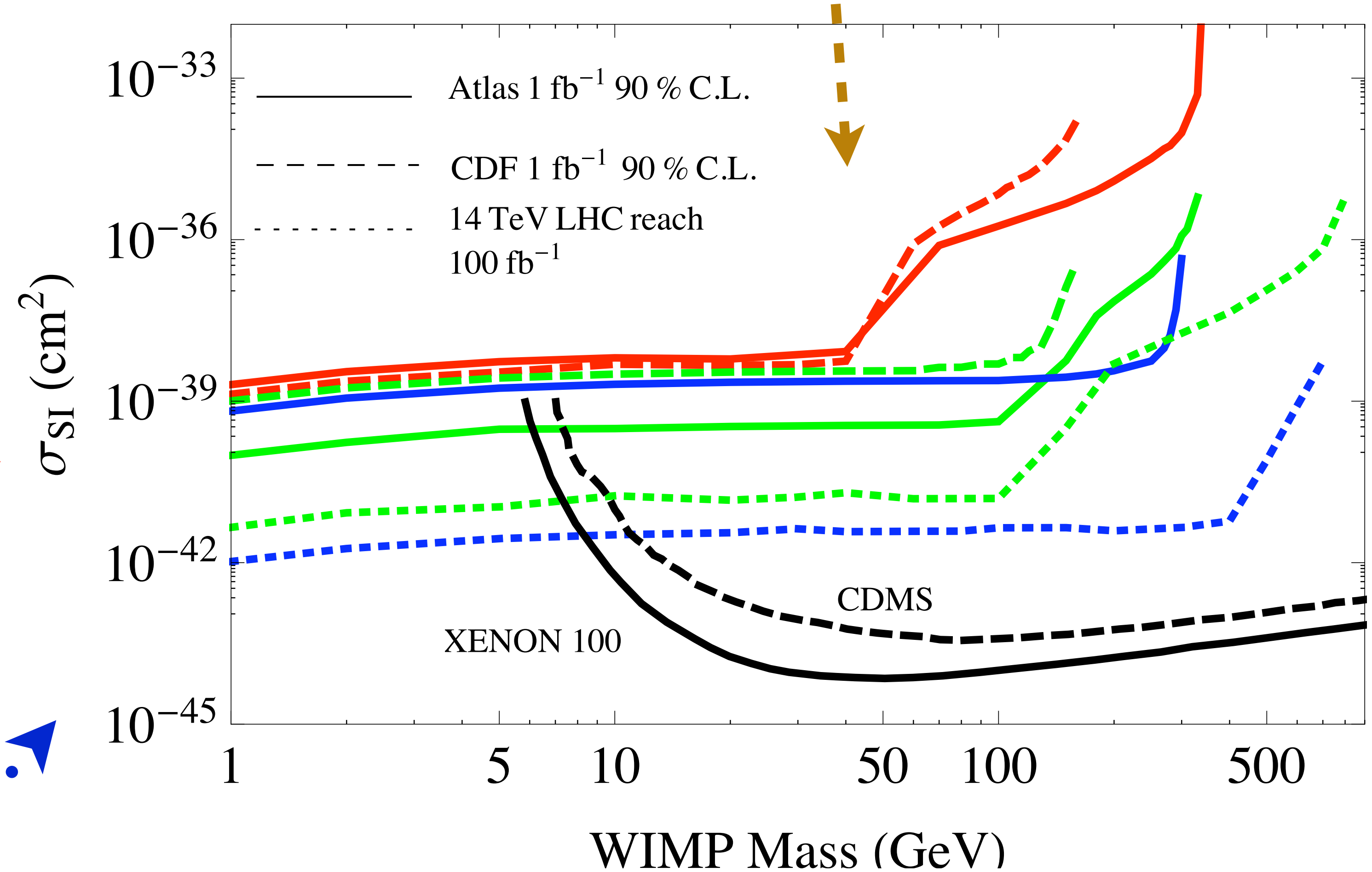


contact-like

$g_D = g_{Z'}$, fixed σ_{dir}

Limits and reaches: monojet+MET

Dashed: Tevatron 1 fb^{-1}, MET > 80 GeV, CDF, PRL 101, 2008



Solid:
LHC, 7 TeV 1 fb^{-1}
Very High PT

Dotted:
LHC 14 TeV, 100 fb^{-1}
MET > 500 GeV

$g_{Z'}=g_D$, $g_{Z'5}=g_{D5}=0$

$M_{Z'}$ = 100 GeV, 300 GeV, 1 TeV

Xiangdong Ji, Haipeng An, LTW, 1202.2894.

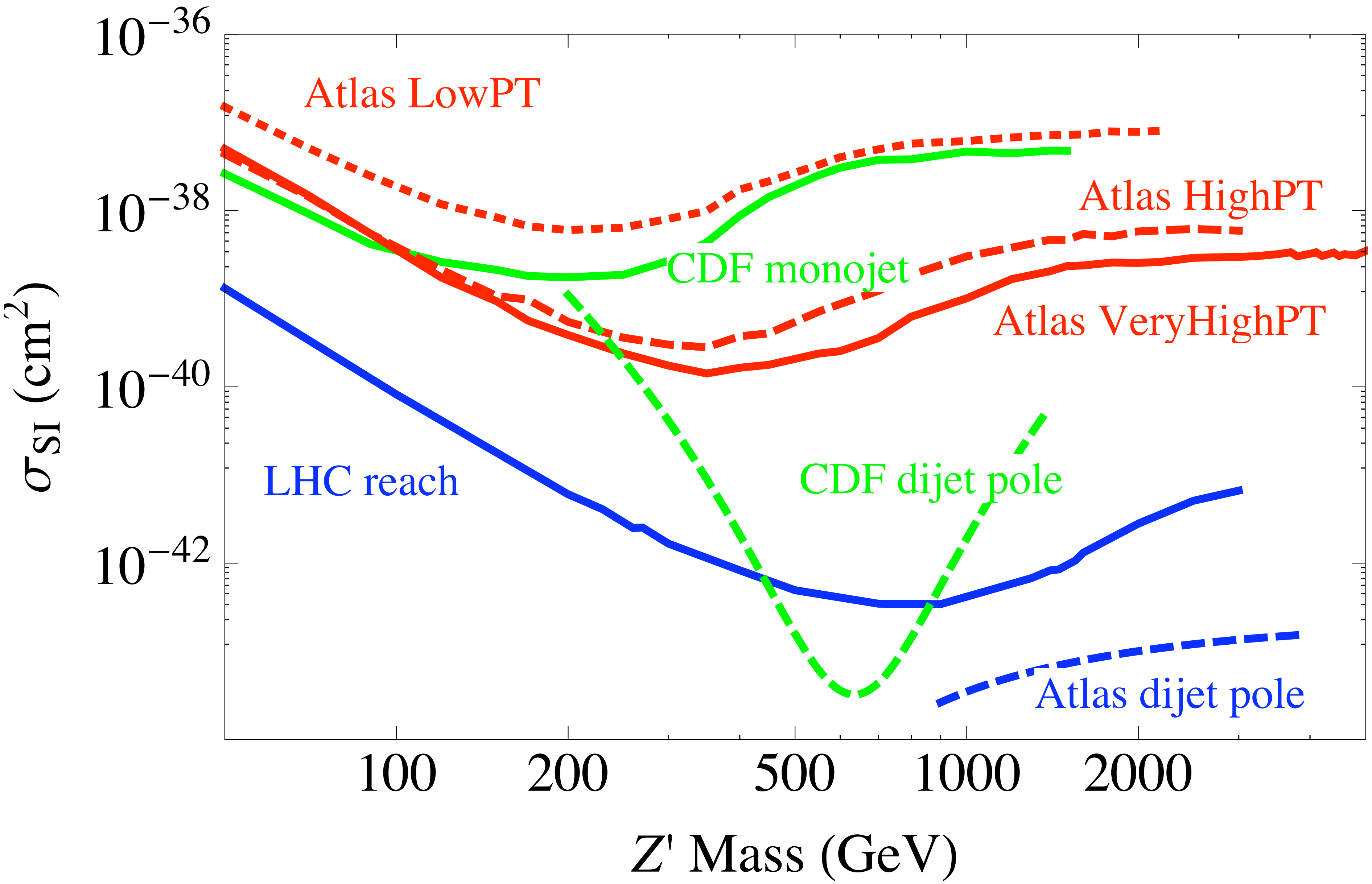
Di-jet resonance searches.

We could, and should, search for the mediator directly!

- Resonance searches.
  - ATLAS: 1 fb^{-1} 1108.6311
  - CMS: 1 fb^{-1} 1107.4771
  - CDF: Phys. Rev. D79 (2009).
- Compositeness.
  - CMS 36 pb^{-1}: Phys. Rev. Lett. 106 (2011)
  - Dzero: Phys. Rev. Lett. 103 (2009)

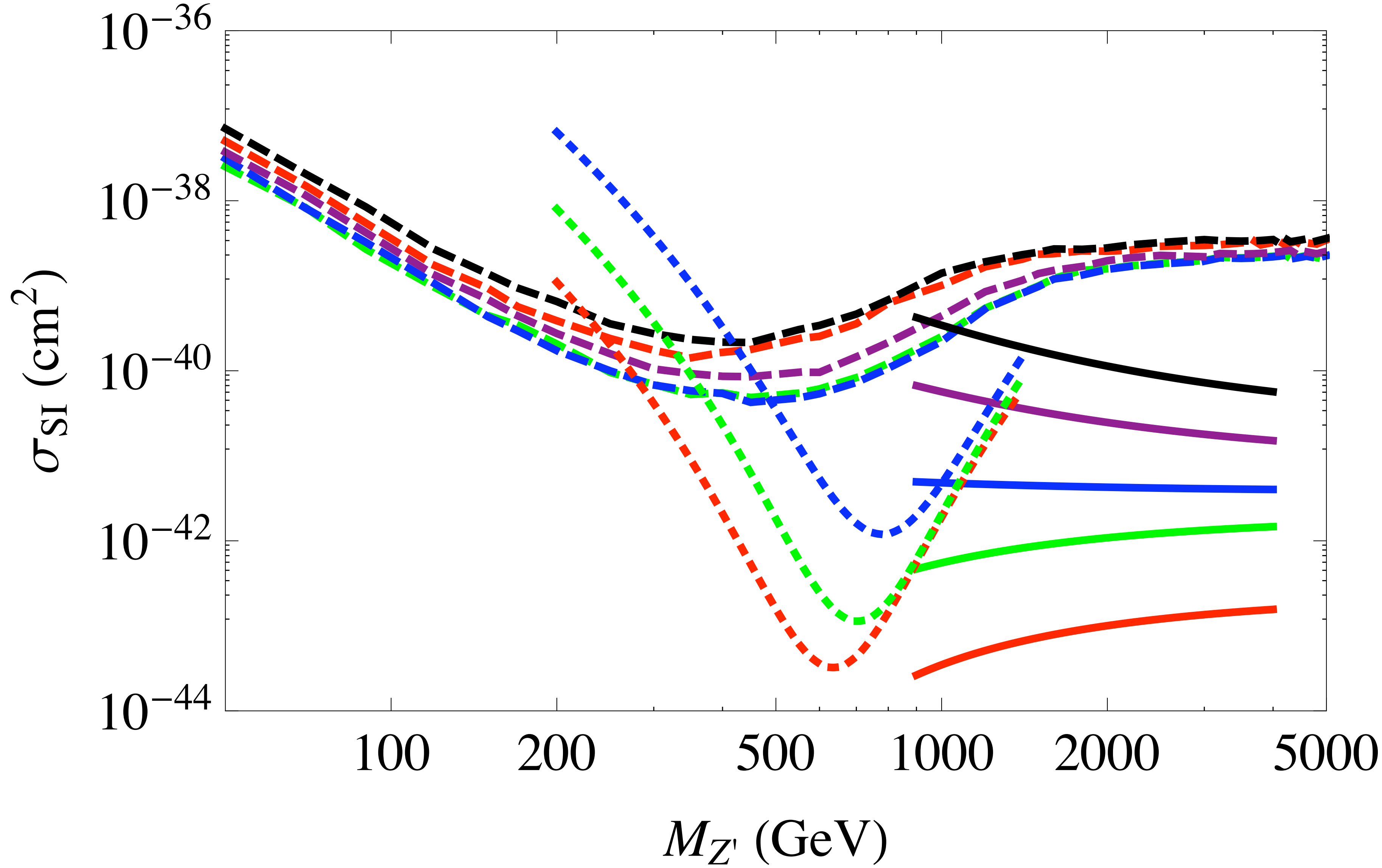
Combining di-jet with monojet

Assume $g_{Z'} = g_D$



Varying y=(gD/gZ′)

-

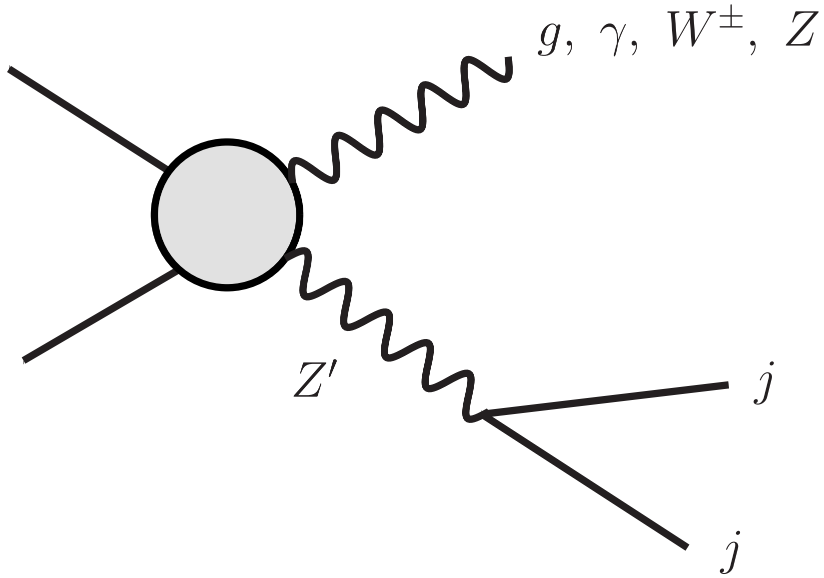


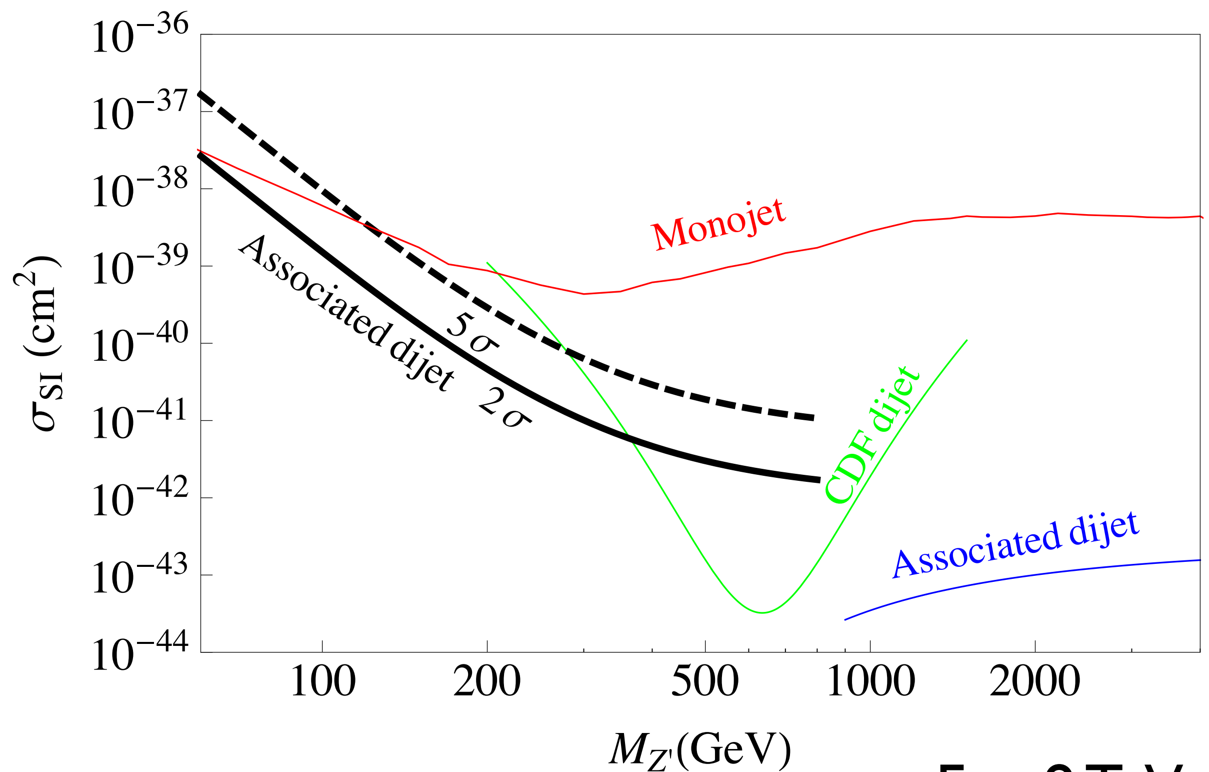
$\sigma_{\rm SI} \propto \frac{g_D^2 g_{Z'}^2}{m_{Z'}^4}$ $y = \frac{g_D}{g_{Z'}}$ 1, 3, 5, 10, 20

Searching for lighter hadronic Z′

- di-jet searches are sensitive to high mass Z′ due to pre-scaling.

- How about associated production?





For 8 TeV, 15 fb^{-1}

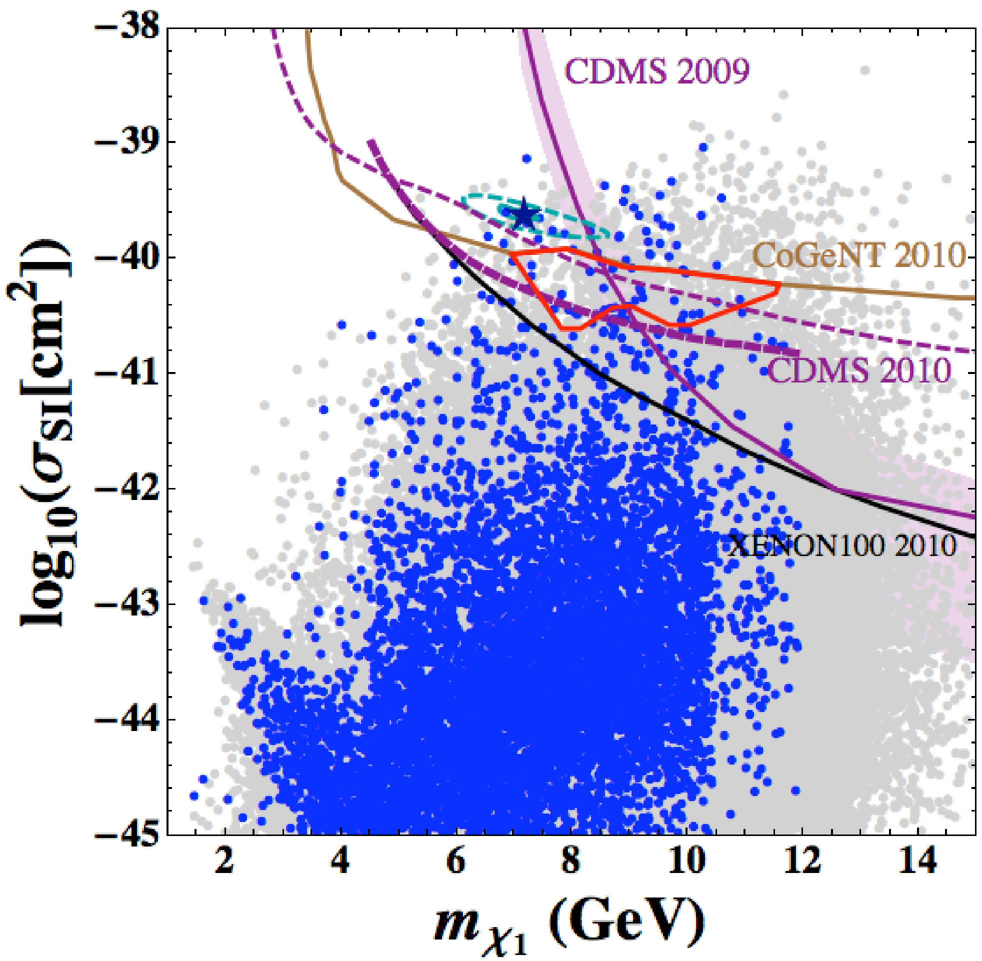
H. An, R. Huo, LTW, 1212.2221

Signals from new model extensions

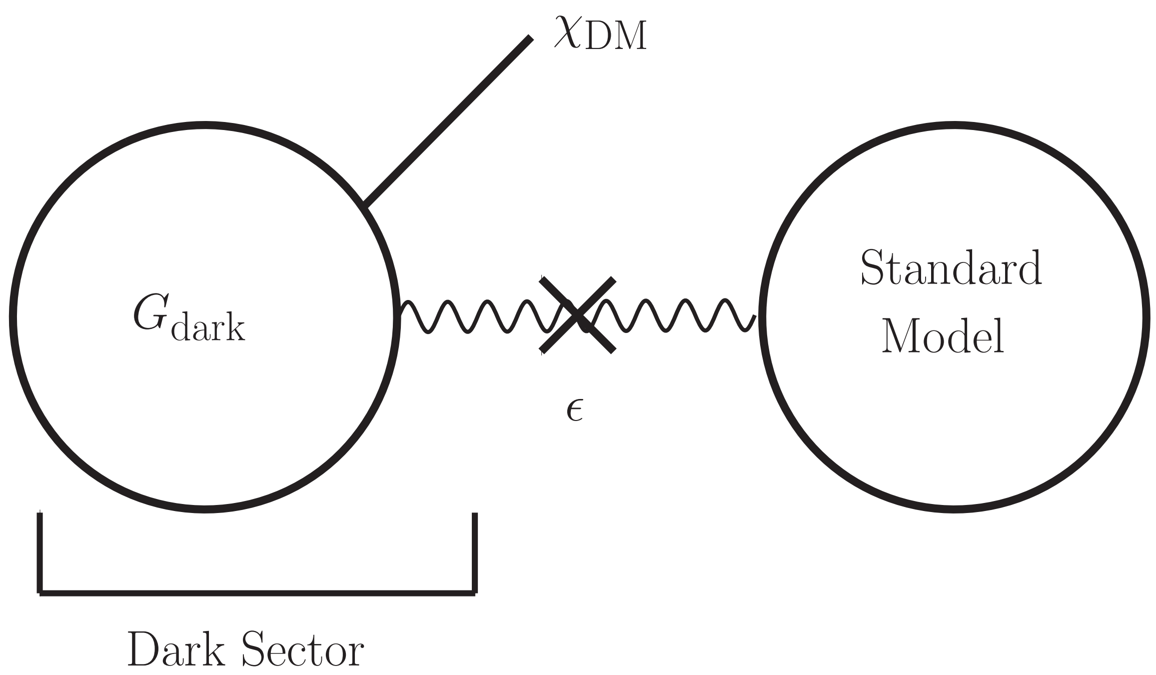
Dark light Higgs

Draper, Liu, Wagner, LTW, Zhang, 1009.3963

- NMSSM near PQ limit.
  - Very light GeV- 10 GeV scalars.
  - Singlino-like light dark matter. Large σ_{SI}.
  - LHC signal: higgs exotic decay, ...



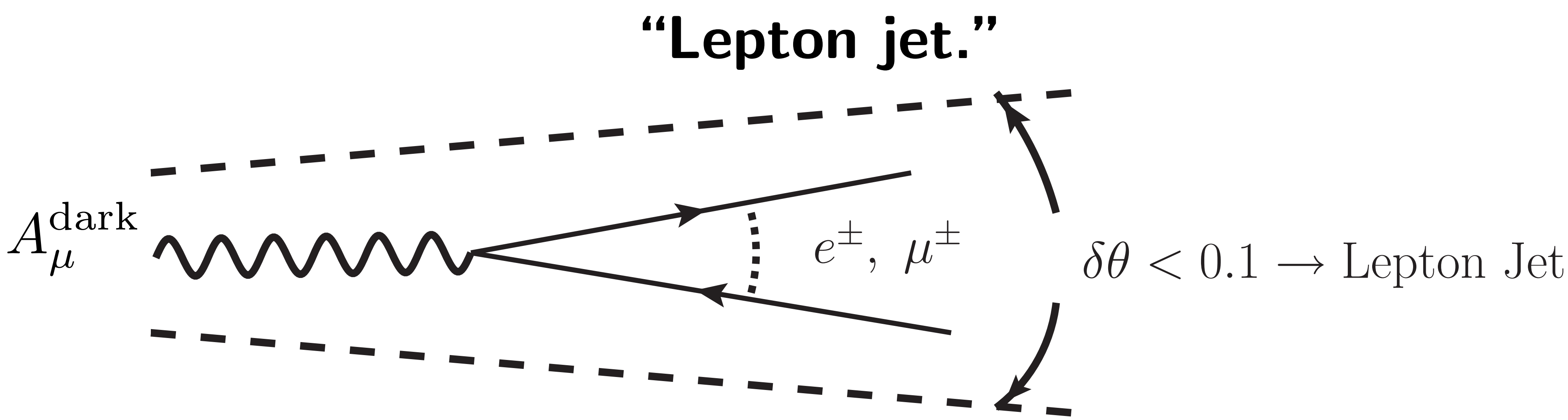
CDM embedded in a dark sector?



- Dark force, suppressed couplings to the SM.
- Force carriers part of the dark sector, expected to be light.
  - Direct detection rate could still be significant.

Very light Z' -> Lepton Jets

- Decay of the dark photon arising from a heavier particle (Z boson, MSSM LSP) leads to a highly



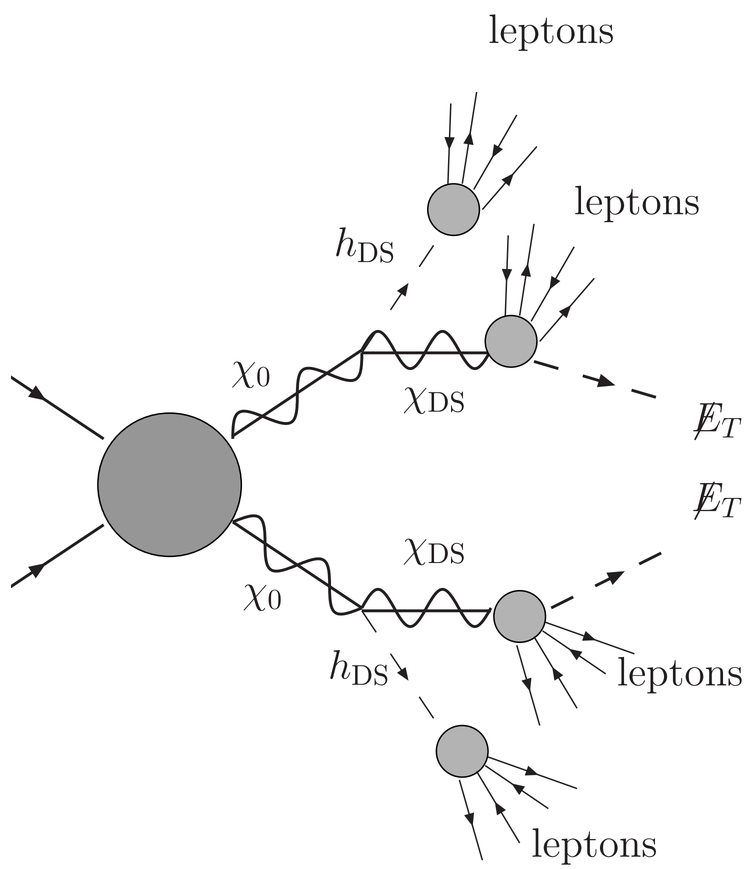
$$\left.\begin{array}{r}\text{Typical } E_{\gamma'} > 10 \text{ GeV} \\ m_{\gamma'} \sim \text{ GeV}\end{array}\right\} \rightarrow \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$$

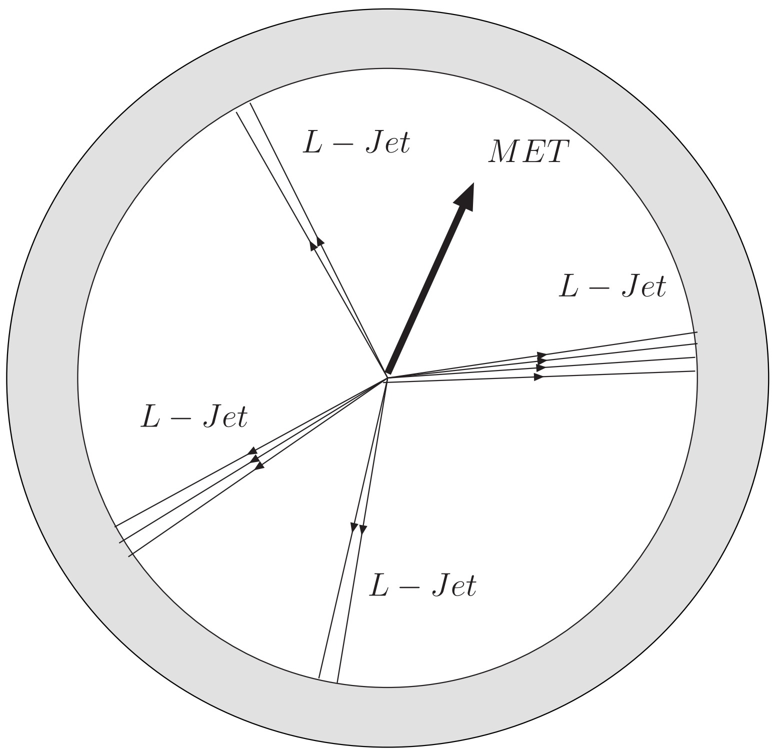
- Arkani-Hamed, Weiner 0810.0714;

- Baumgart, Cheung, Ruderman, LTW, Yavin 0901.0283; Cheung, Ruderman, LTW, Yavin 0909.0290

Supersymmetric dark force

- Most natural way of generating the GeV scale.
- Spectacular signal.





Conclusion.

- One of the most exciting opportunities: Discovering the WIMP dark matter and measuring its properties.

- LHC will play a crucial and complementary role in this pursuit.

- Multiple aspects and approaches.
    - Search for "conventional" CDM.
    - More model independent searches.
    - Alternative models with distinct signatures.