Probing Light Dark Matter at the LHC

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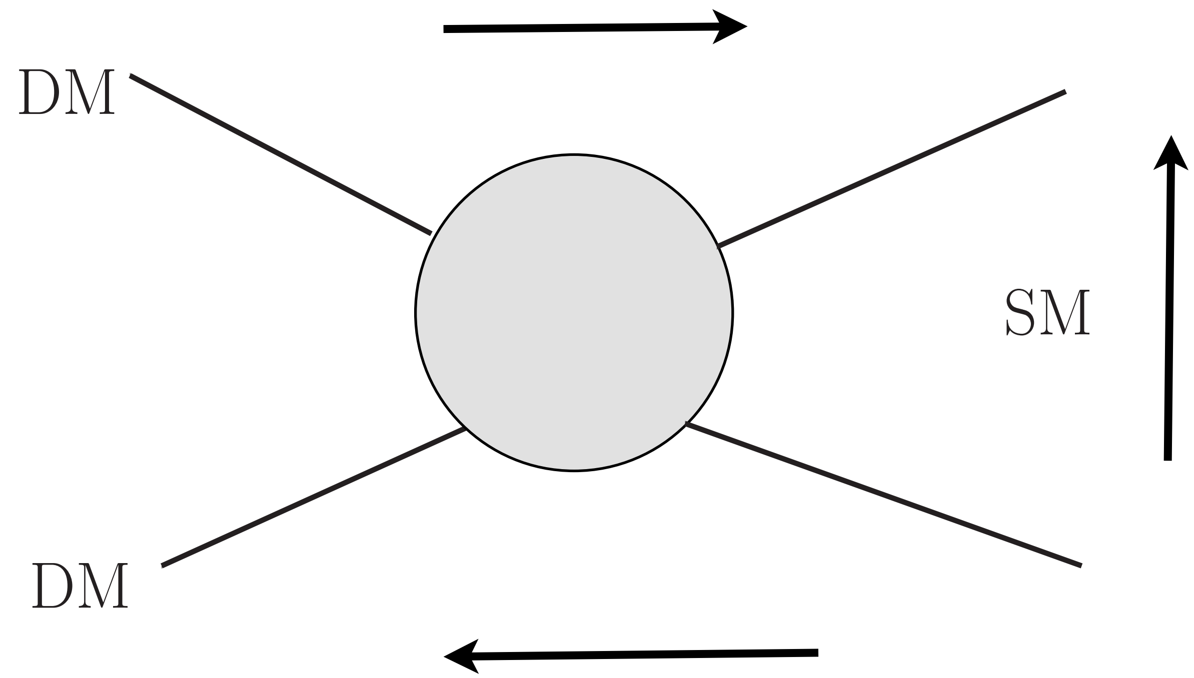
University of Chicago

Exploring Low-mass Dark Matter Candidates
PACC, UPITT
Nov. 14, 2011

Searching for WIMP dark matter

Indirect detection:
AMS2, PAMELA, Fermi-LAT
.....



Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON
.....

Collider searches:
LEP
LHC
Tevatron

Searching for WIMP dark matter

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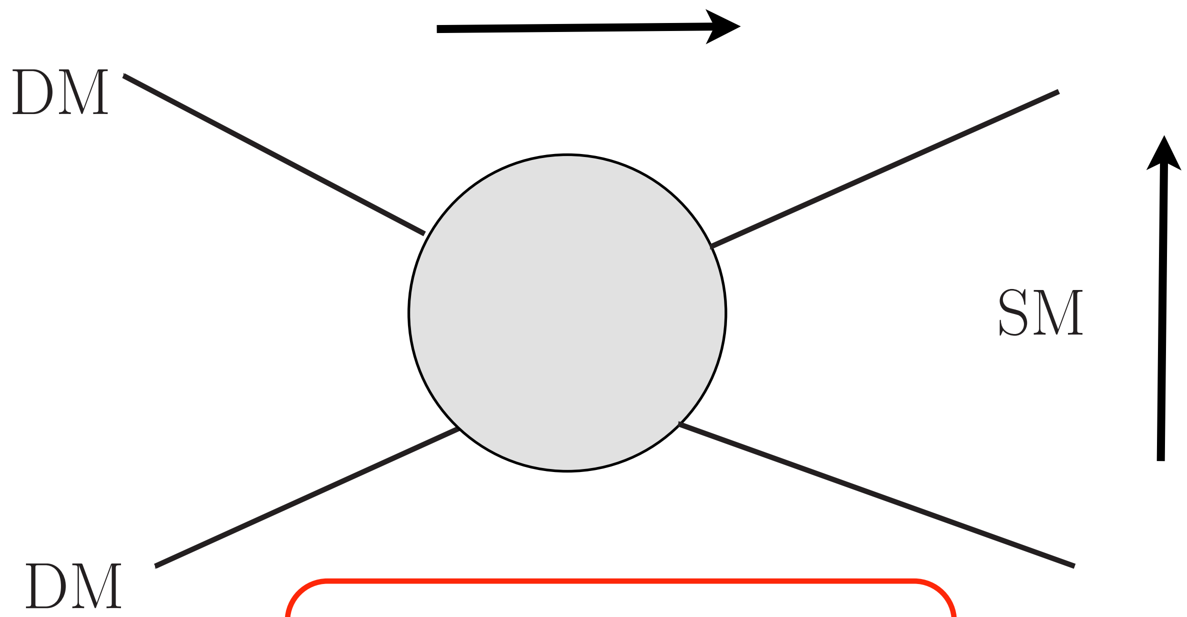

Direct detection:
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This talk.

Candidates, models, scenarios...

Different spin

different Z_2

LSNPs:

SUSY LSP

Extra Dim. LKP

T-parity LTP

LZP

L...P

Z_3

Candidates, models, scenarios...

"Model independent"

Effective operator

Different spin different Z_2

LSNPs:

SUSY LSP

Extra Dim. LKP

T-parity LTP

LZP

L...P

Z_3

Extended Models

dark sectors

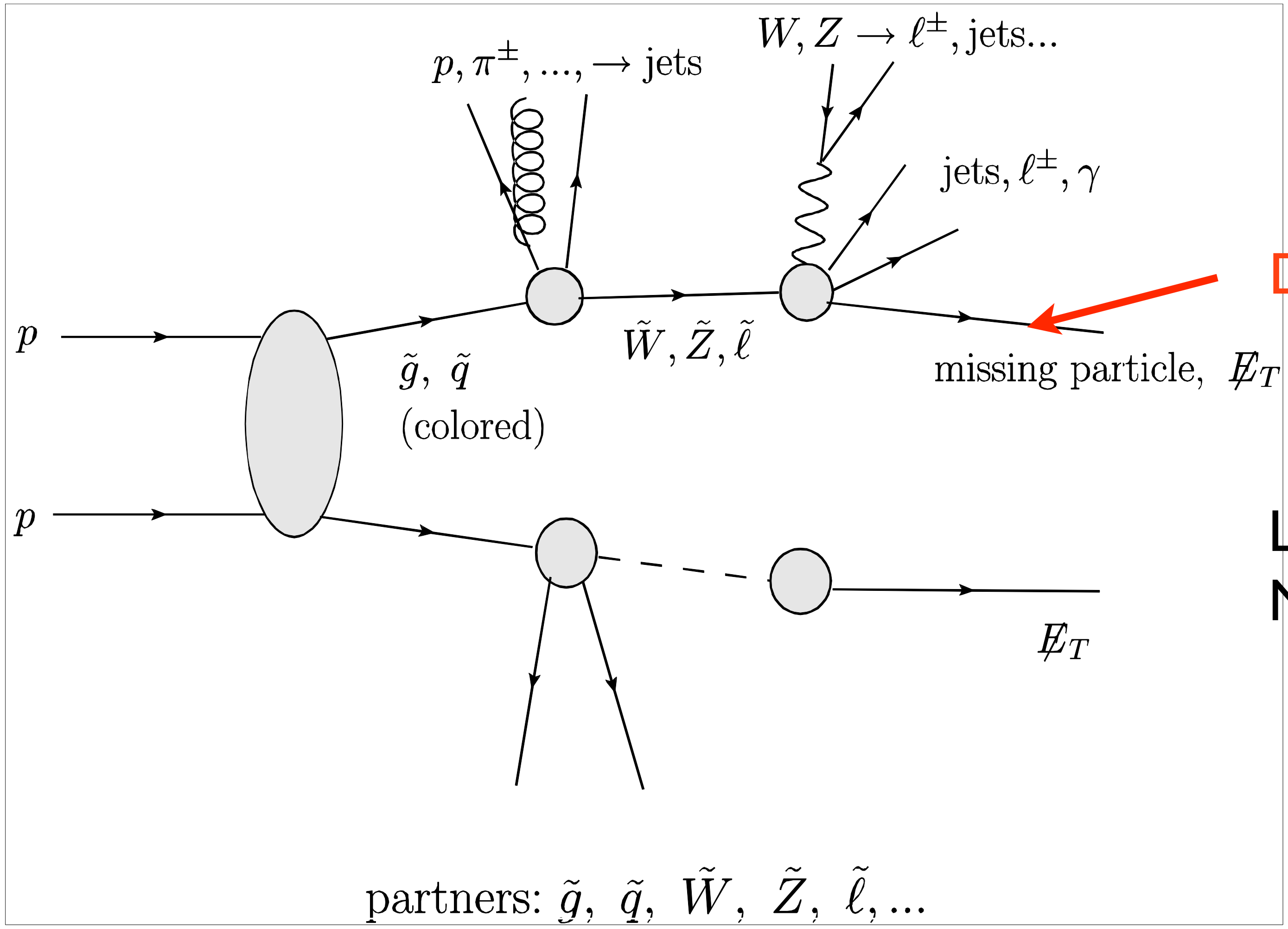
This talk

- Dark matter part of a rich TeV NP scenario.
  - Search for SUSY dark matter, and measure its properties (Highlight challenges).
- Connection between collider searches and direct detection, focusing on light dark matter.
  - Effective operator.
  - Searching for the mediator.
- Signals from new model extensions. (brief)

Search for SUSY dark matter

Discovering dark matter:

- DM candidate embedded in an extended TeV new physics scenario, such as SUSY.



DM candidate

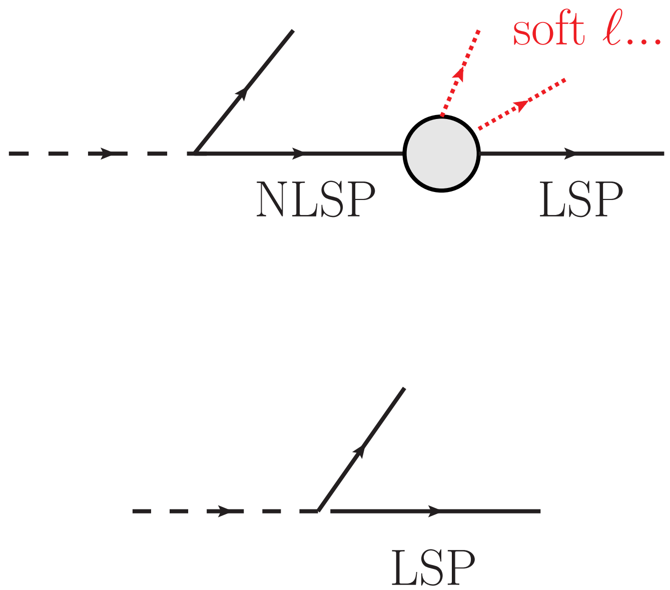
Lightest superpartner (LSP)
Neutral and stable.

- Other new physics scenarios (extra-dim, compositeness...) similar.

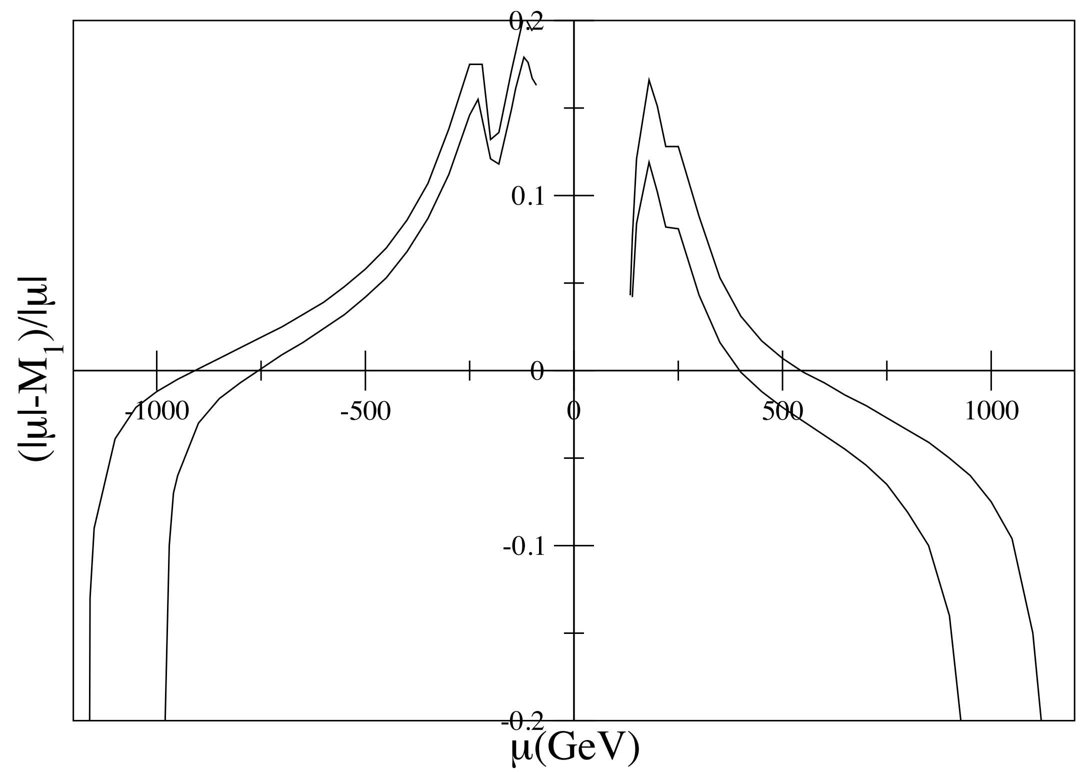
Could be challenging to identify.

- For example: the "well tempered" scenario. Nearly degenerate NLSP and LSP.

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



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

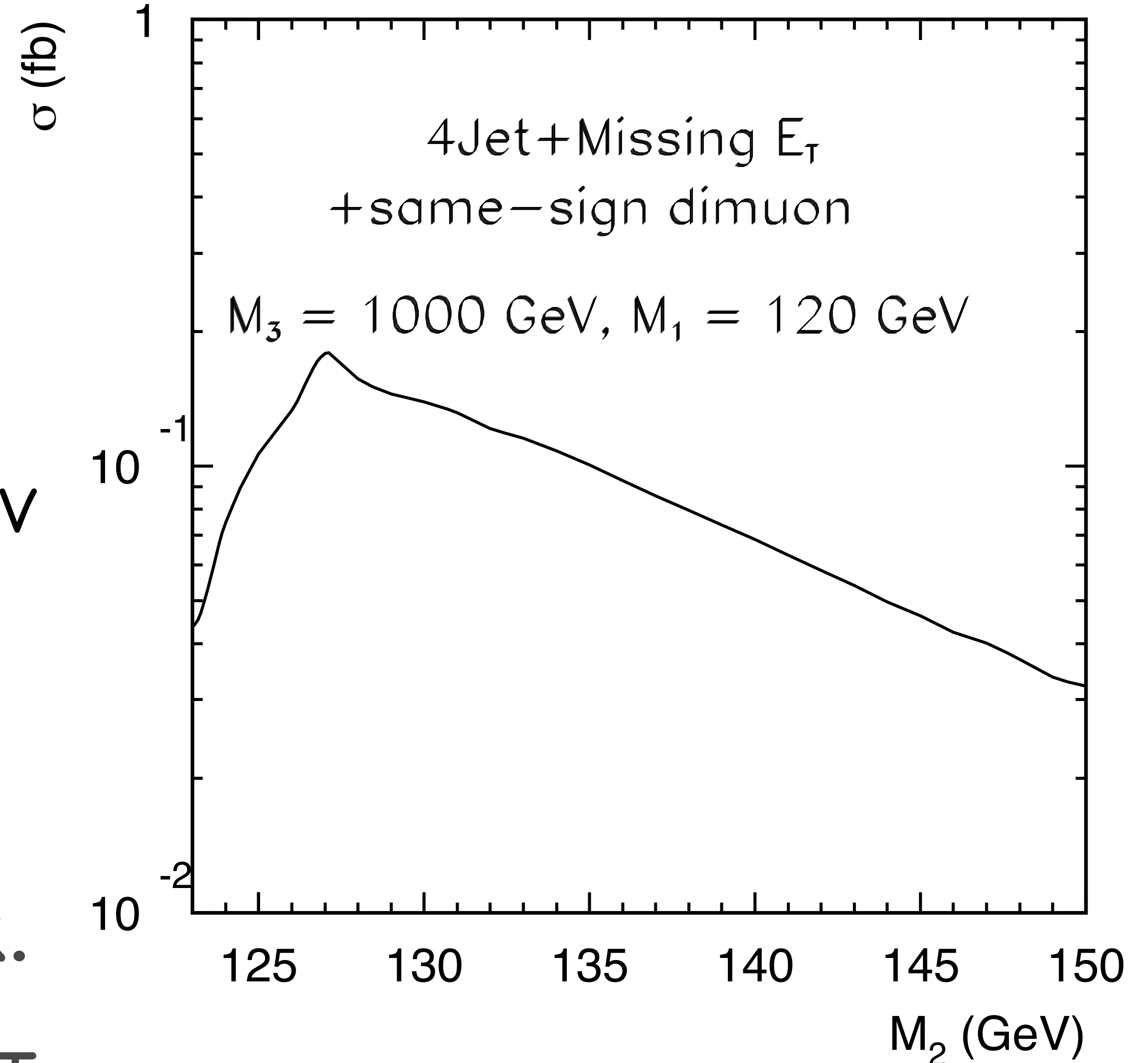


See also, S. Gori, P. Sechwaller, C. Wagner, 1103.4138

LHC prospect for well tempered DM

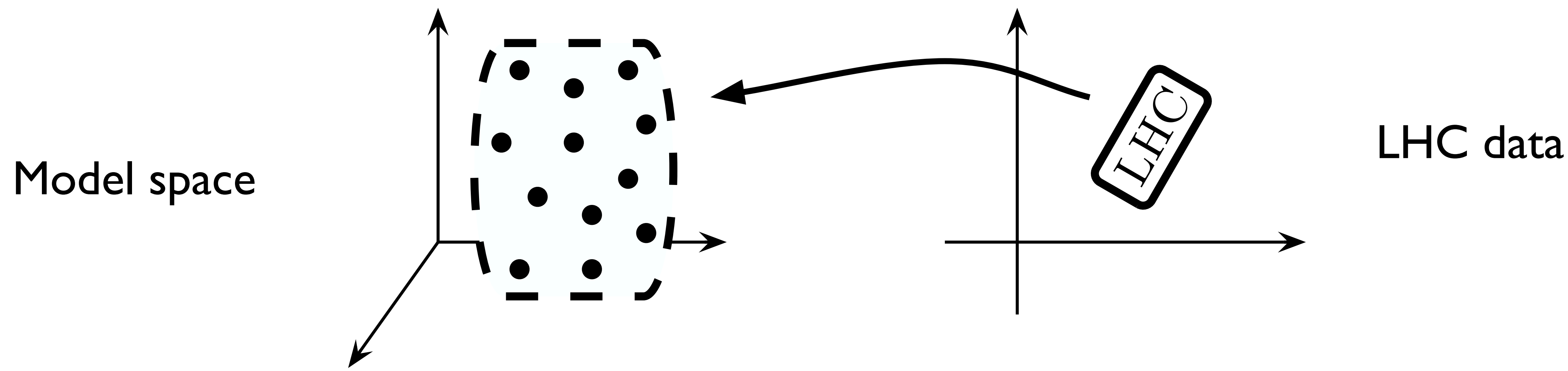
G. Giudice, T. Han, K. Wang and LTW, 1004.4902

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.

In general, hard to interpret.



- After the discovery, we can derive some basic properties, such as whether the new particles are colored or not, whether they decay to leptons, and so on.

- Many possible interpretations.

Degeneracies! Quantum number, mass, spin...

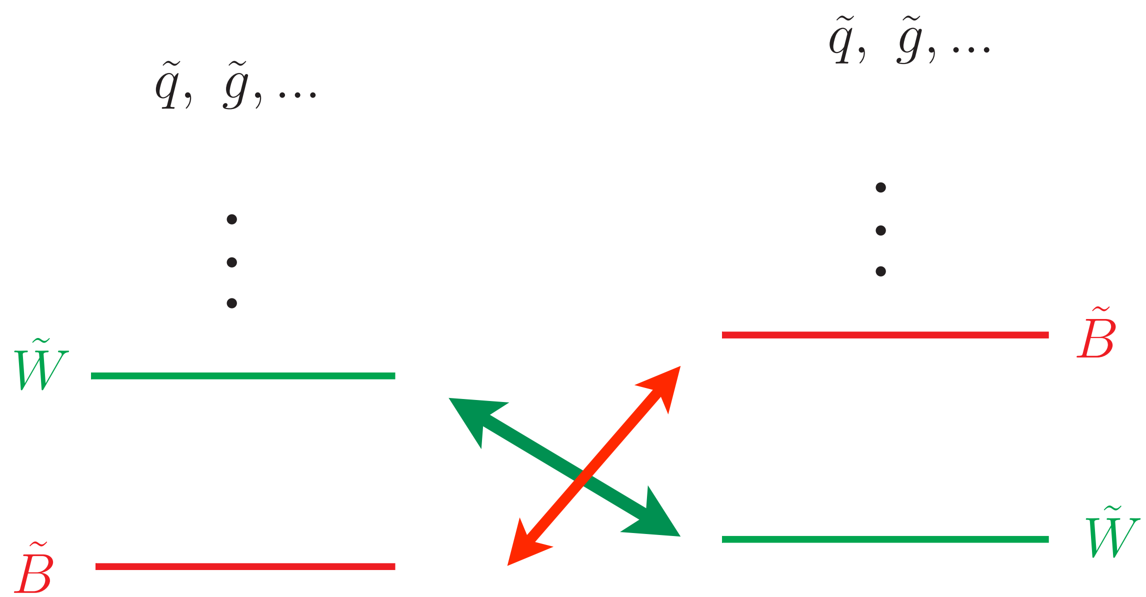
For example: in supersymmetry, bino vs wino, squark vs gluino...

Arkani-Hamed, Kane, Thaler, and Wang, JHEP 0608:070,2006.

Possible degeneracies in:

- The identity of new physics particles. For example:

Two different SUSY spectra.



Identity swap, hard to distinguish

- In addition
  - M_{LSP}.
  - Spin.
- Crucial to combine with direct/indirect detections

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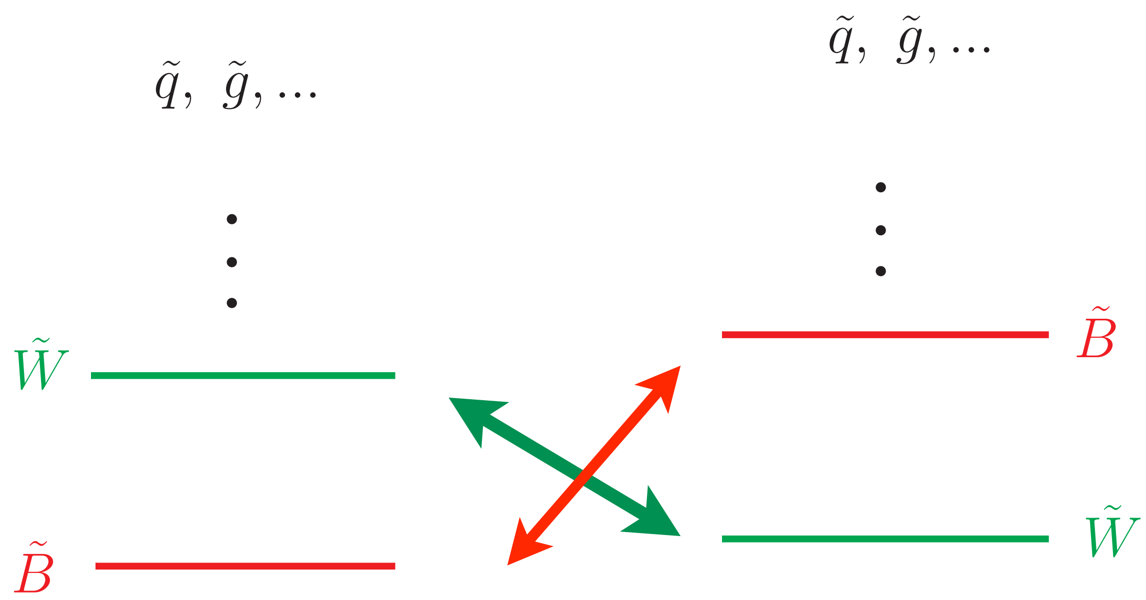


Identity swap, hard to distinguish

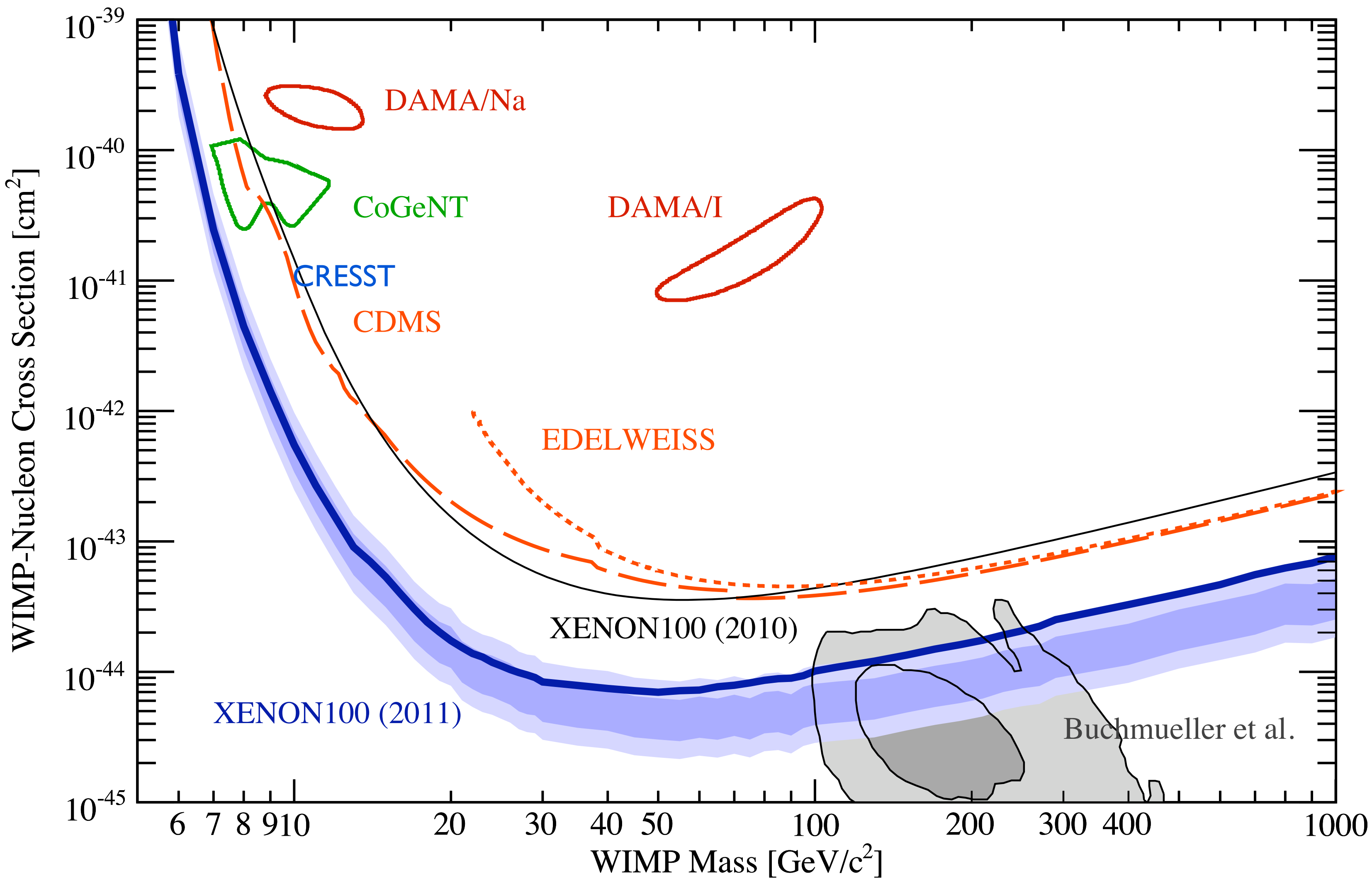
- In addition
  - M_{LSP}.
  - Spin.
- Crucial to combine with direct/indirect detections

Difficult task, but accomplishable.

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

Probe NP with direct detection

XENON 100, 1104.2549



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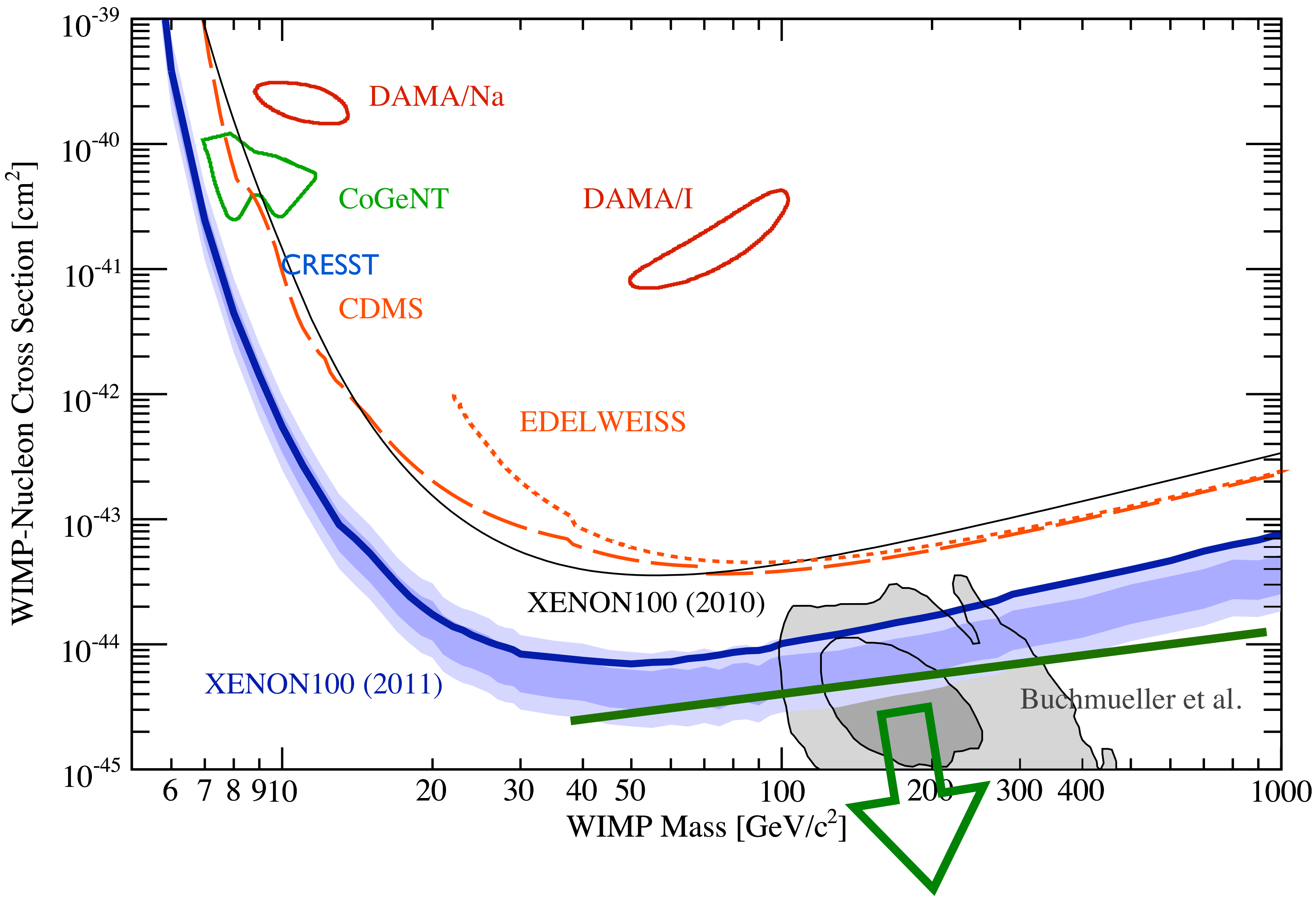
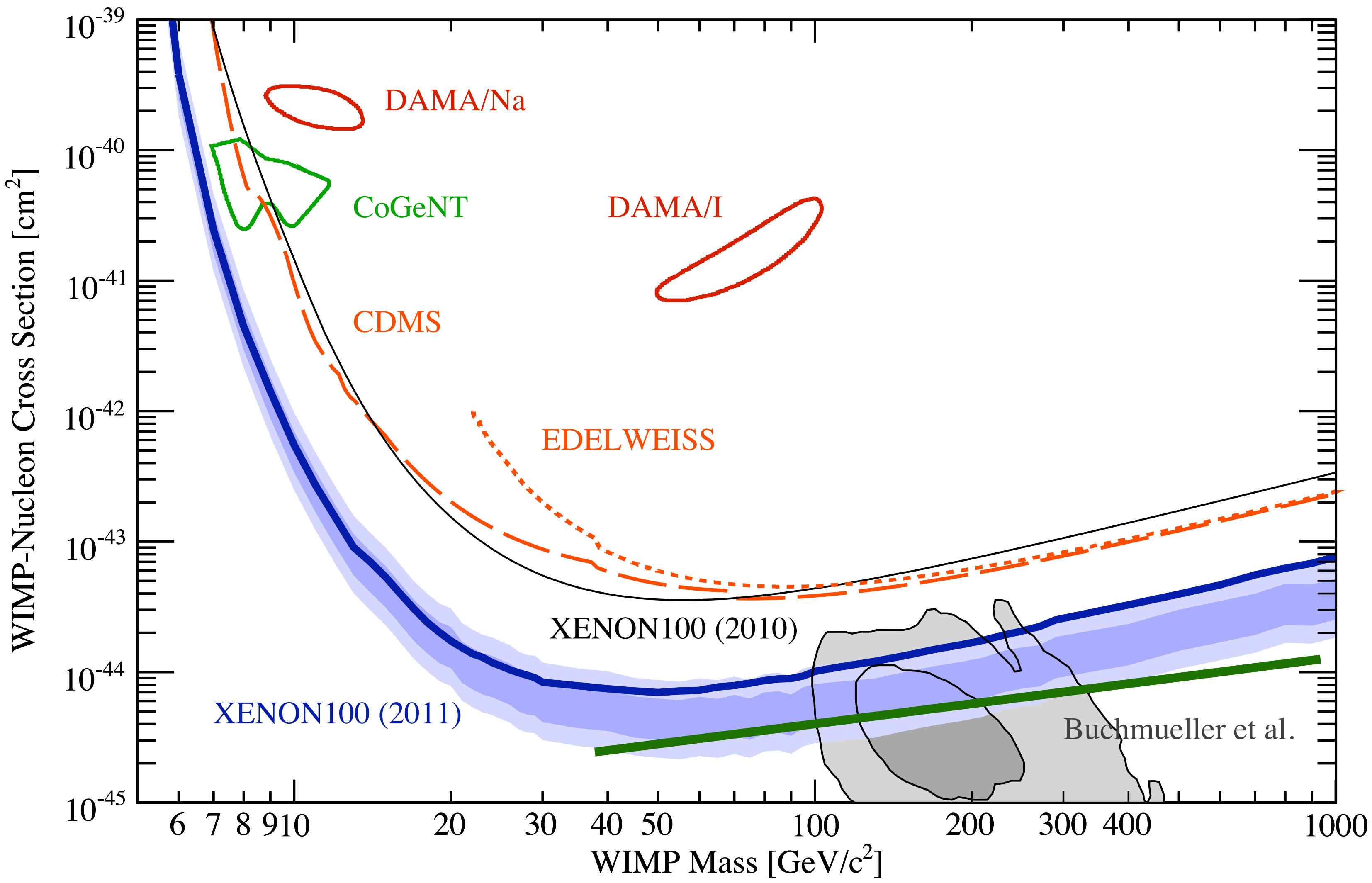


- $M_{WIMP} = O(10^2)$ GeV.
- DM of "Typical" scenarios: SUSY LSP, ...

Probe NP with direct detection

XENON 100, 1104.2549



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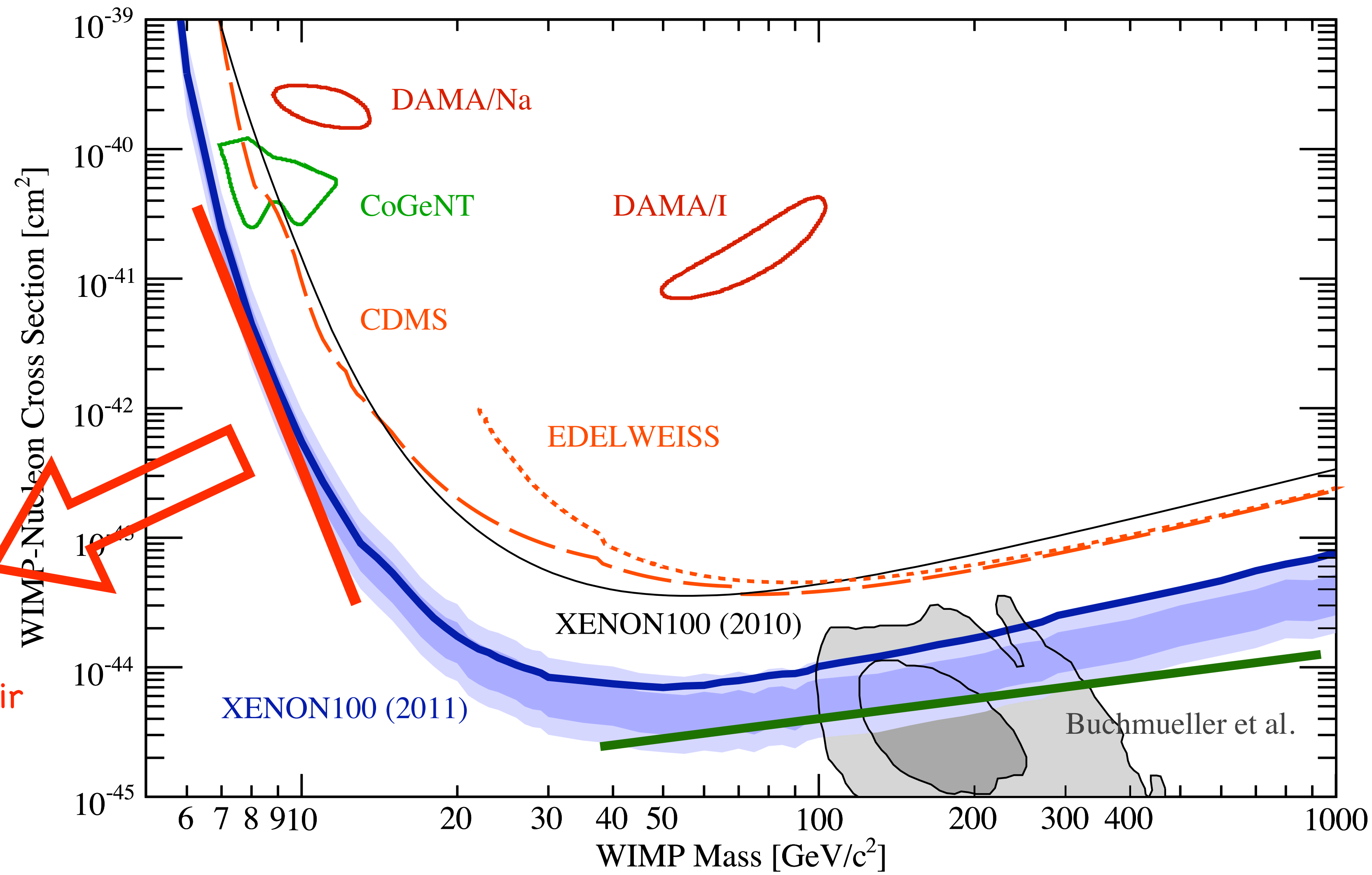
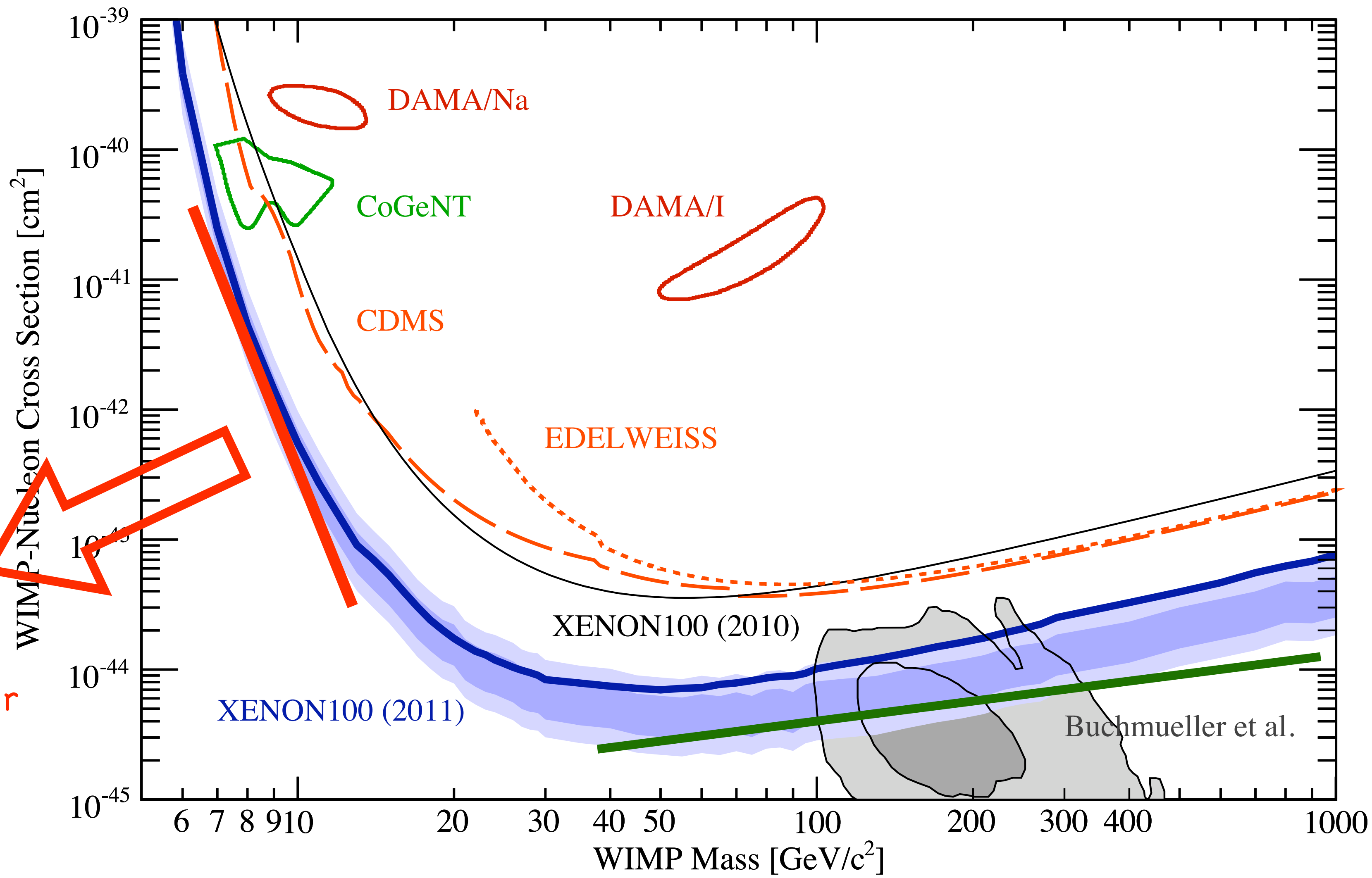


m_{WIMP}:
O(1-10) GeV
Much larger σ_{dir}

Probe NP with direct detection

XENON 100, 1104.2549



m_{WIMP}:

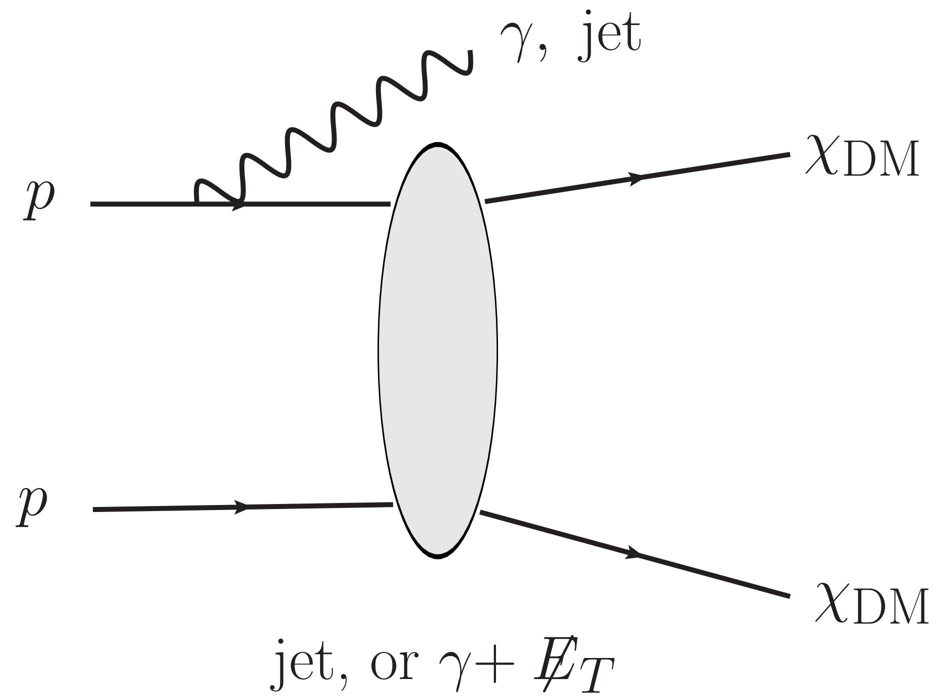
O(1-10) GeV

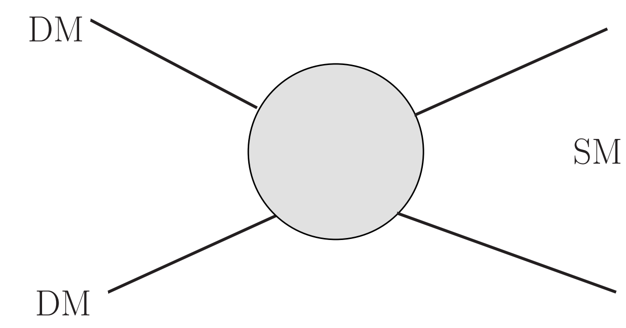
Much larger σ_{dir}

- Collider searches provide stronger bounds/potential

Basic channel

- Pair production + additional radiation.

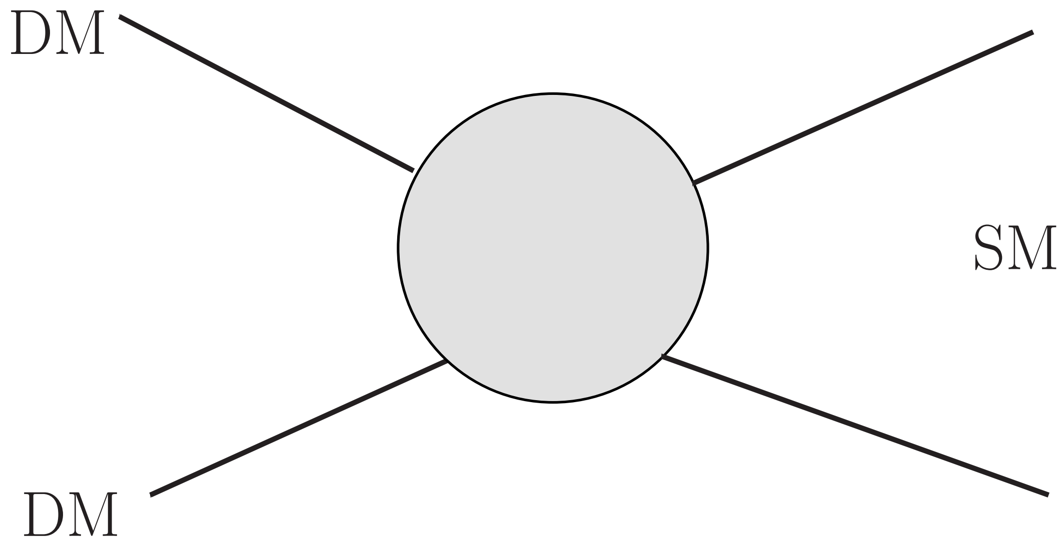




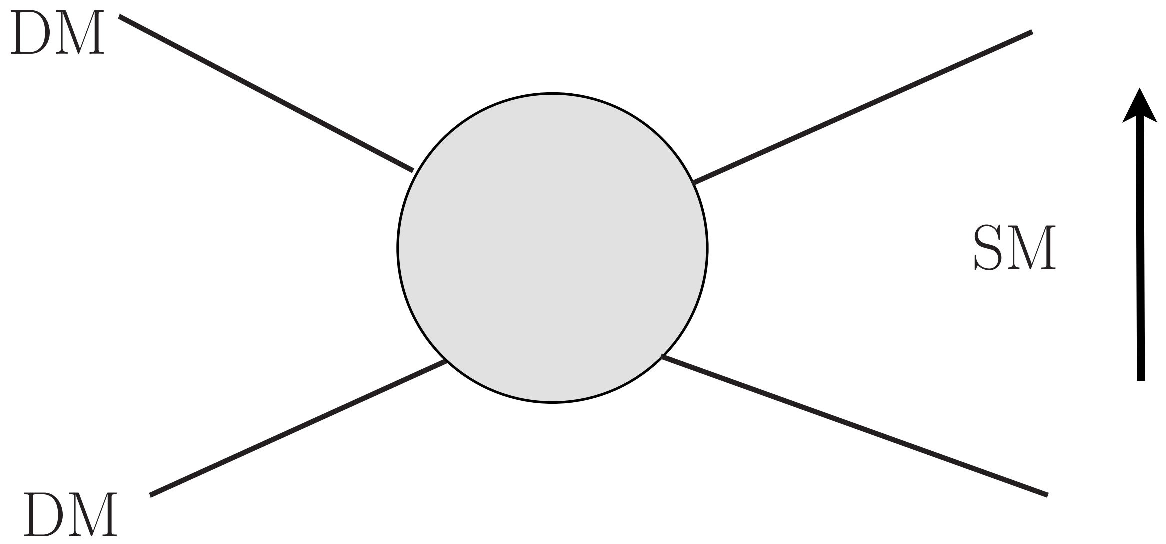
- Large Standard Model background, about 10 times the signal.

- Very challenging.

Effective operator approach



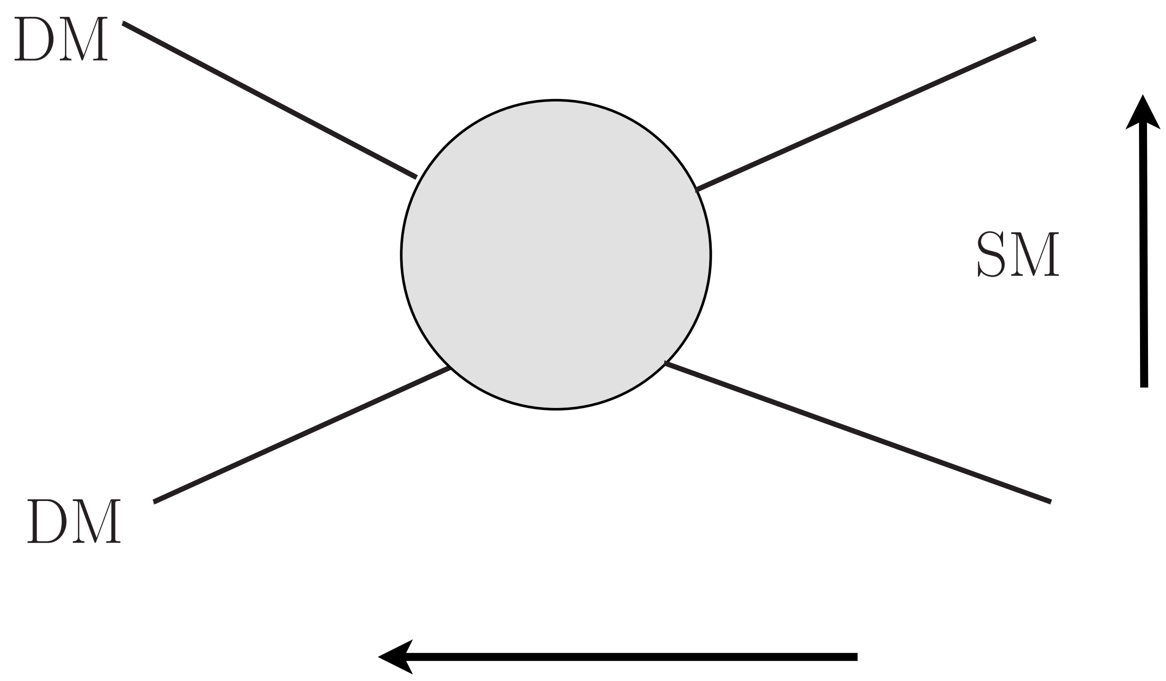
Effective operator approach



momentum exchange
q~100 MeV << m_Φ
effectively,

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

Effective operator approach



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Use colliders to constrain and probe the same operator

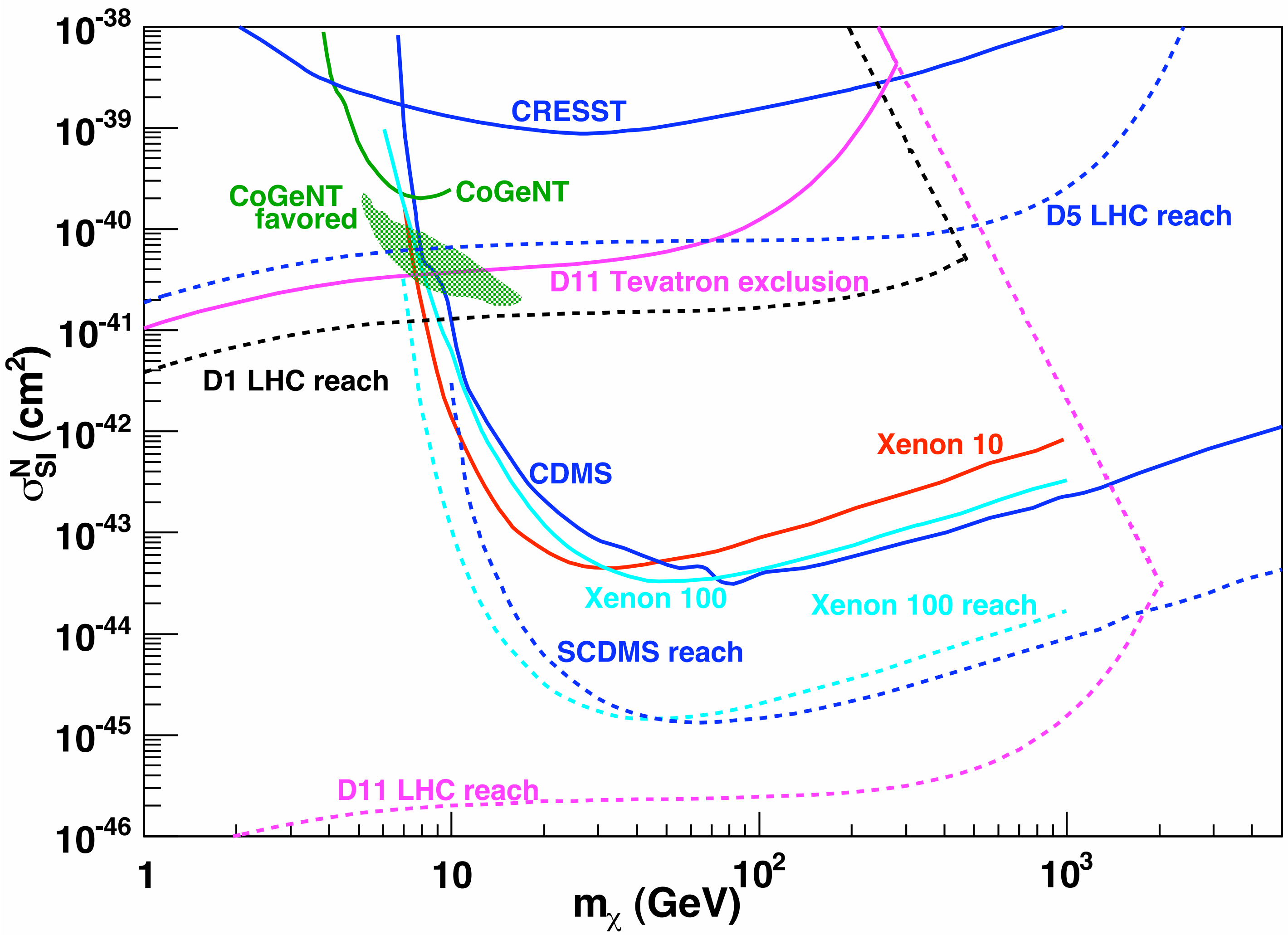
$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

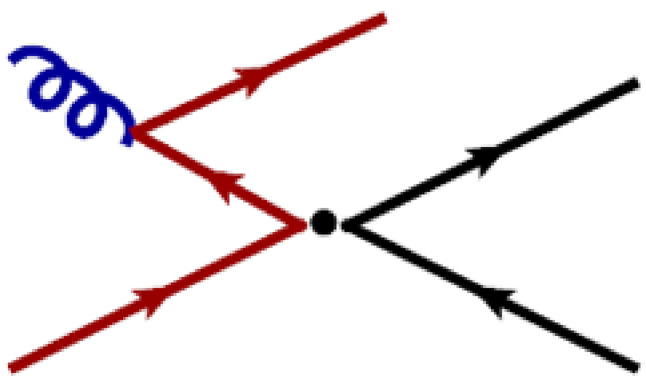
Recent studies.

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. Fox, Harnik, Kopp, Tsai, 1109.4398
10. Goodman, Shepherd, 1111.2359

For example, 1008.1783

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

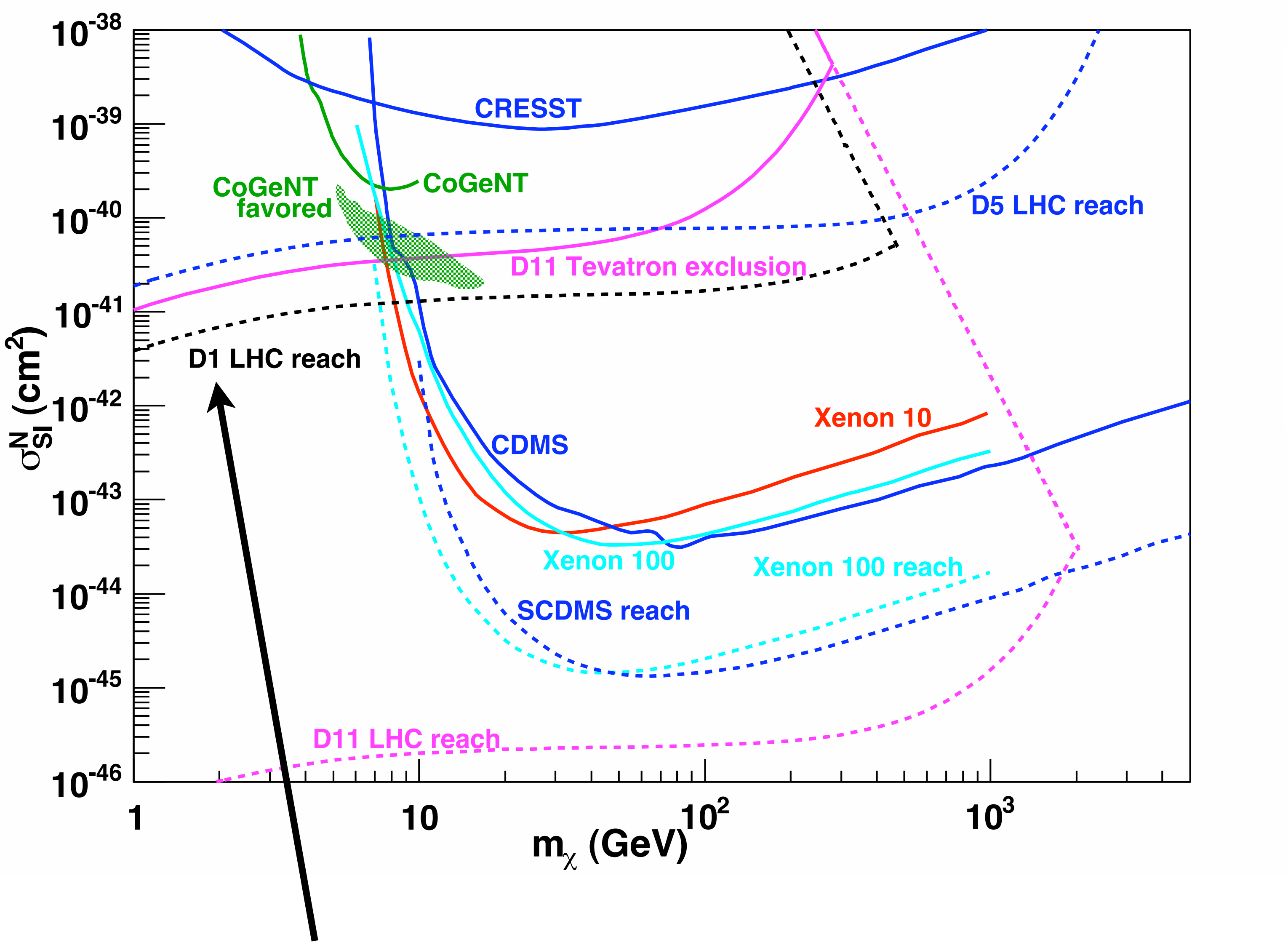


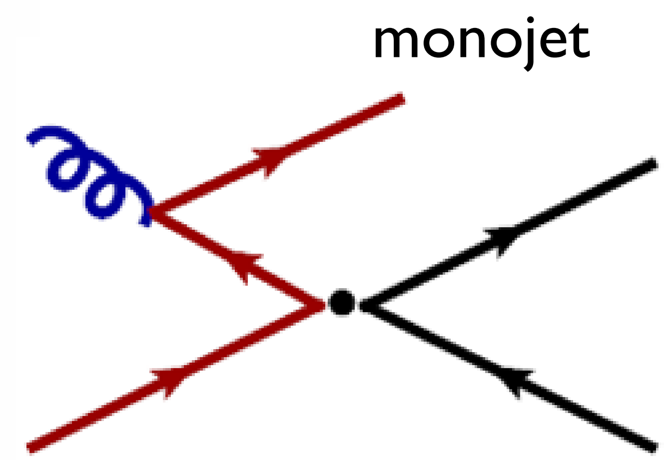


D1	$\bar{\chi}\chi\bar{q}q$
D5	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

For example, 1008.1783

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





D1	$\bar{\chi}\chi\bar{q}q$
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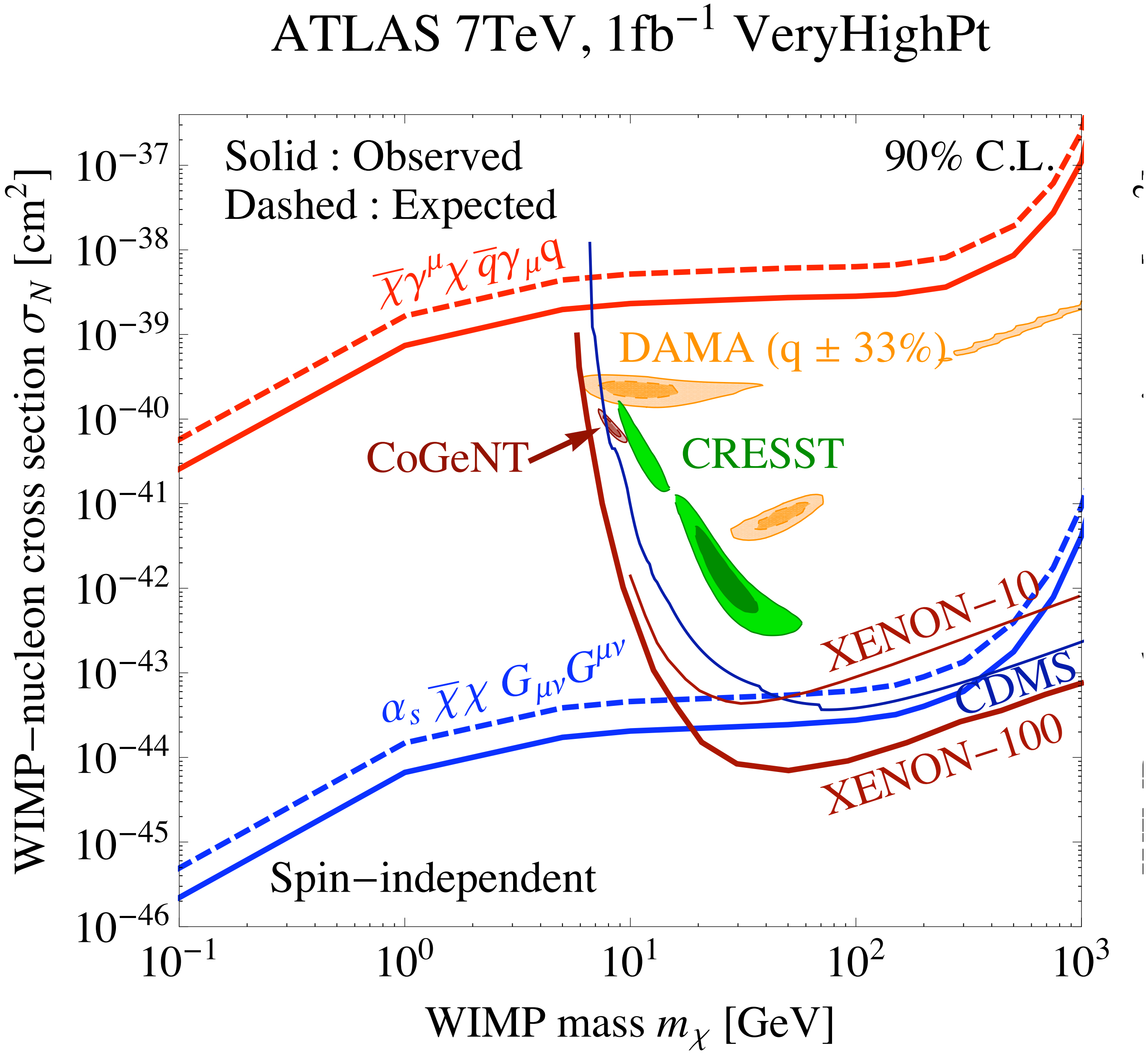
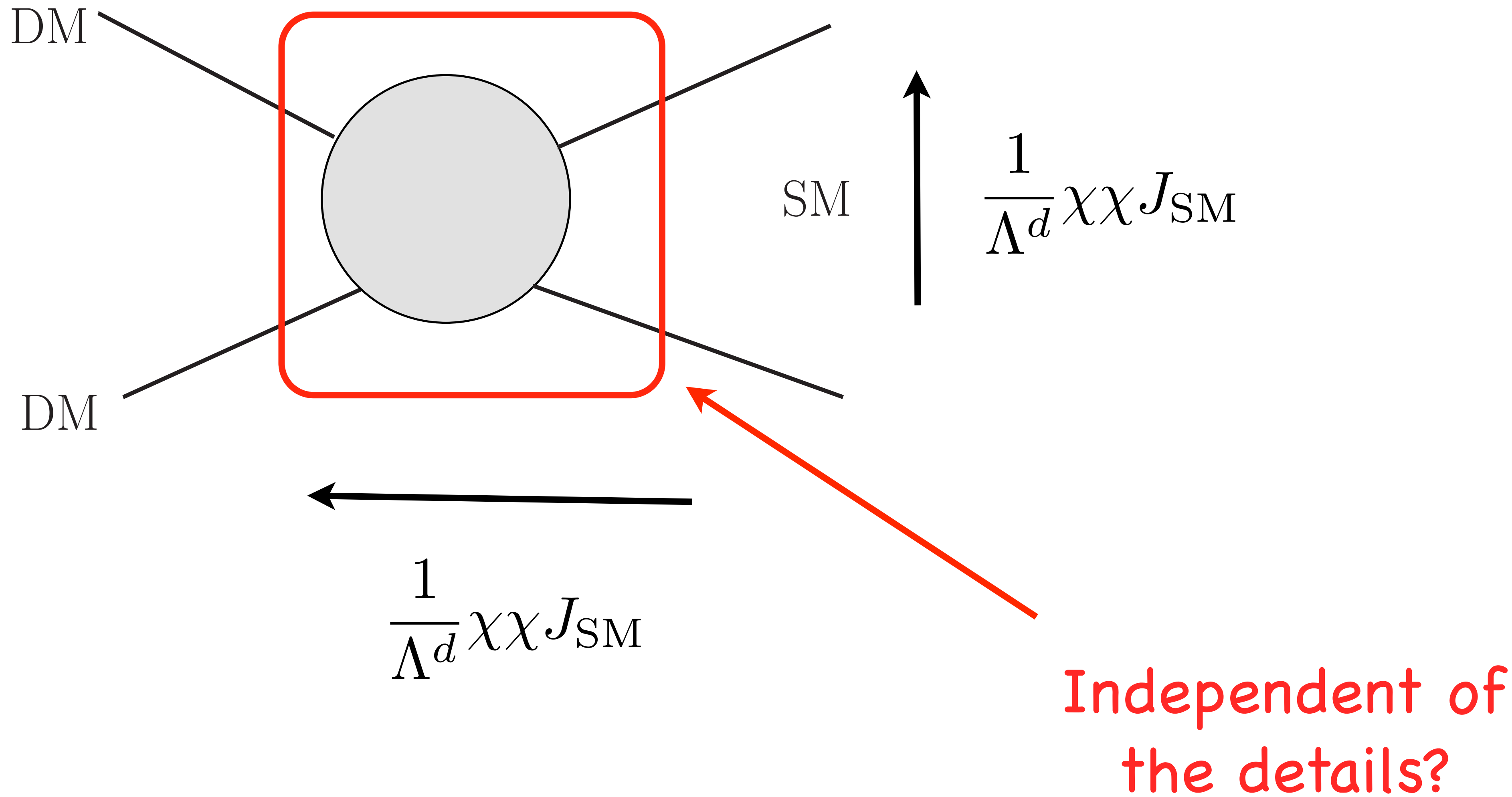
For small m_X,
collider rates controlled by larger mass scales, i.e., p_T cut;
does not depend on m_X.
Collider bounds flat and stronger.

More recently



Fox, Harnik, Kopp, and Tsai, 1109.4398

Effective operator effective?



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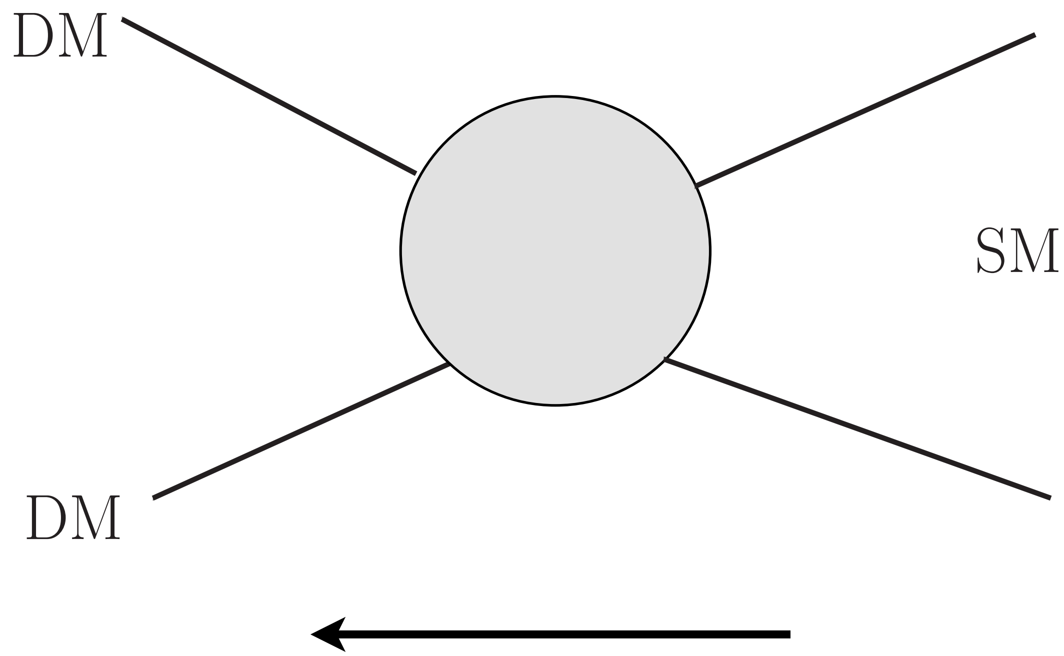


Use colliders to constrain and probe the same operator

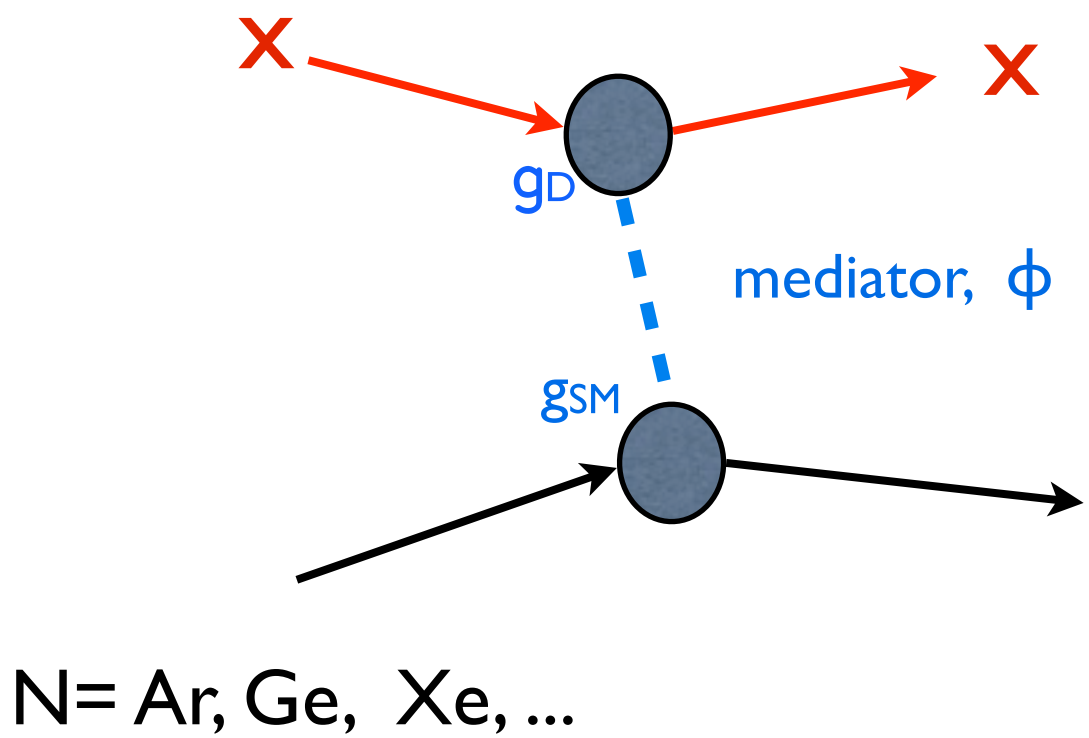
$$\frac{1}{\Lambda^d}\chi\chi J_{\mathrm{SM}}$$

However, E_{cm} = 100s GeV ~ 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!

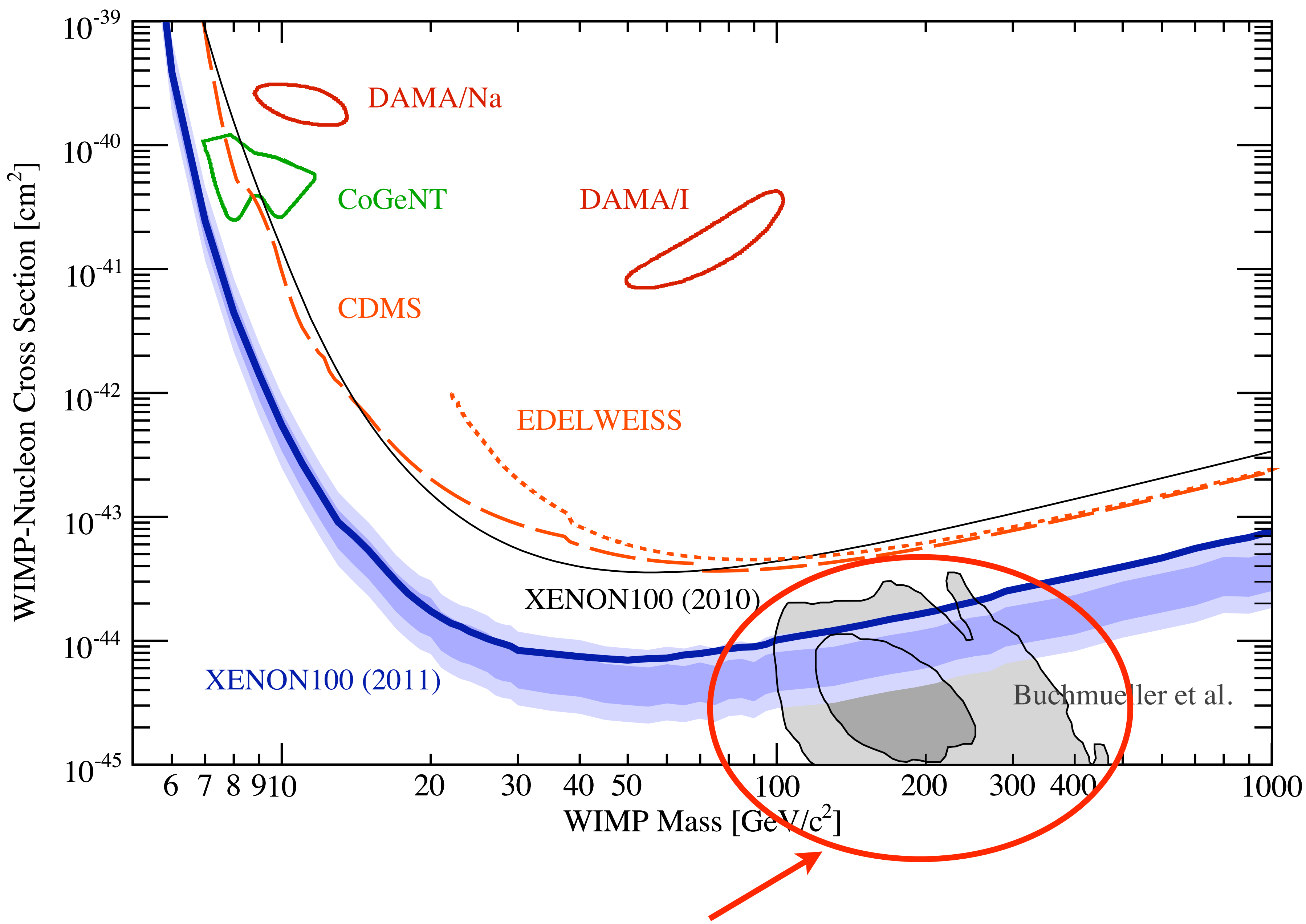
The dependence on the mass of the mediator has been explored in: 1105.3797, 1103.0240, 1111.2359

Mediator, two typical examples.



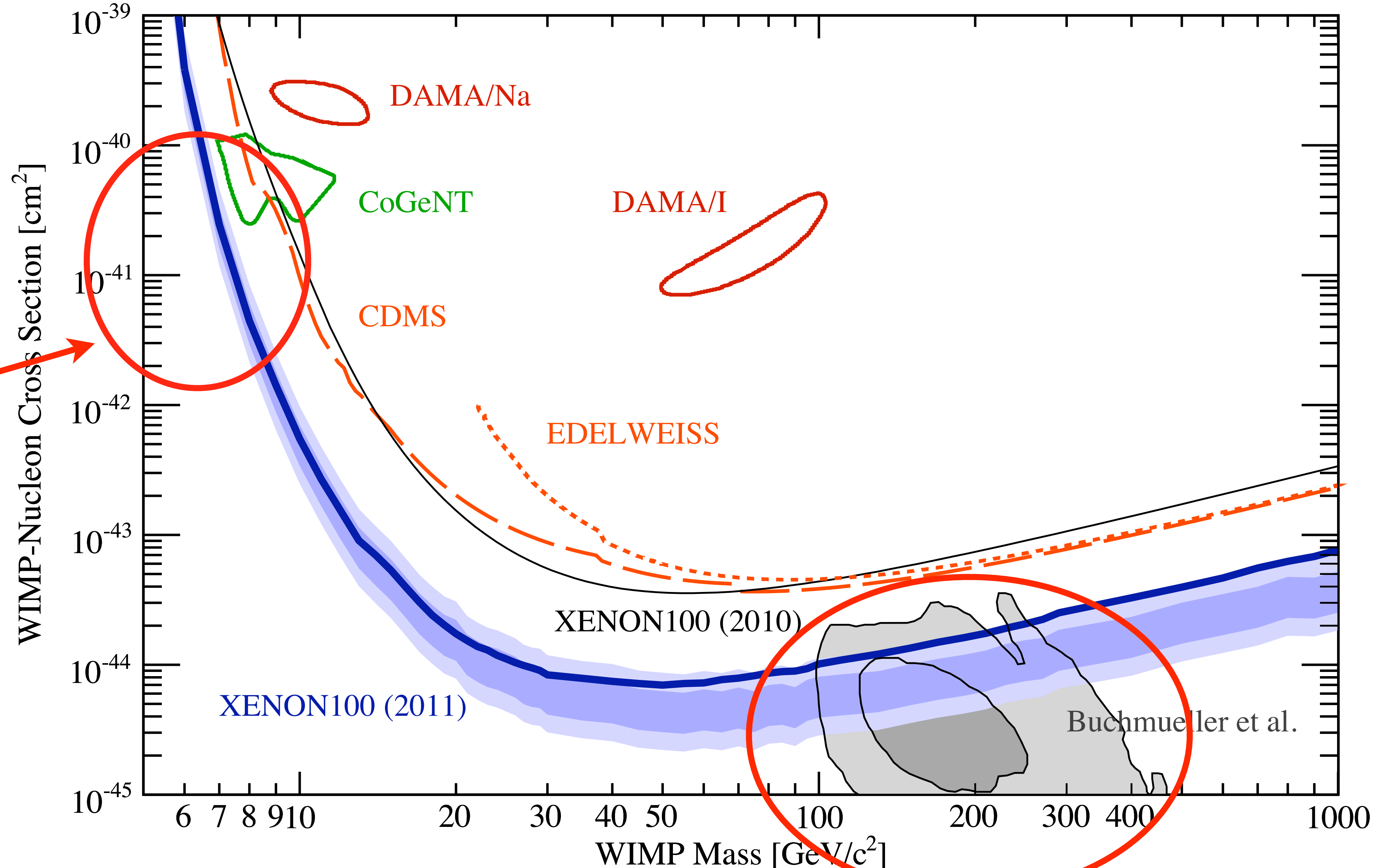
- ϕ=Higgs
  - $g_{SM} \approx (100\ \text{MeV})/(100\ \text{GeV})$
  - $m_X \approx 100$ GeV
  - $\sigma_n \approx 10^{-43}$–$10^{-45}$ cm^{-2}
- Φ=100 GeV spin-1, D=dirac fermion
  - $\sigma_n \approx 10^{-36}$–$10^{-39}$ cm^{-2}

Probe NP with direct detection



SUSY, typically Higgs mediated.

Probe NP with direct detection



Light DM spin-1 mediator.

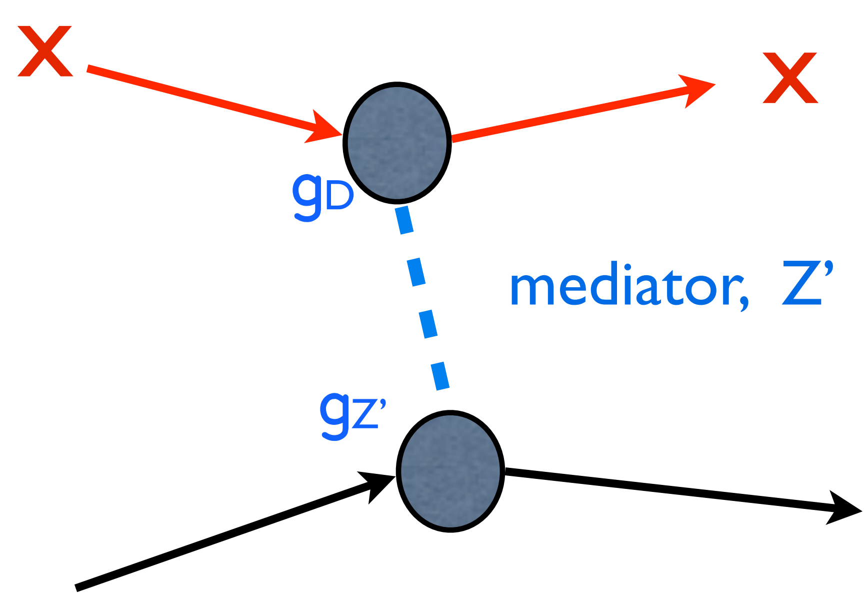
SUSY, typically Higgs mediated.

Case study: a spin-1 Z′

Xiang-Dong. Ji, Haipeng An, LTW in progress

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

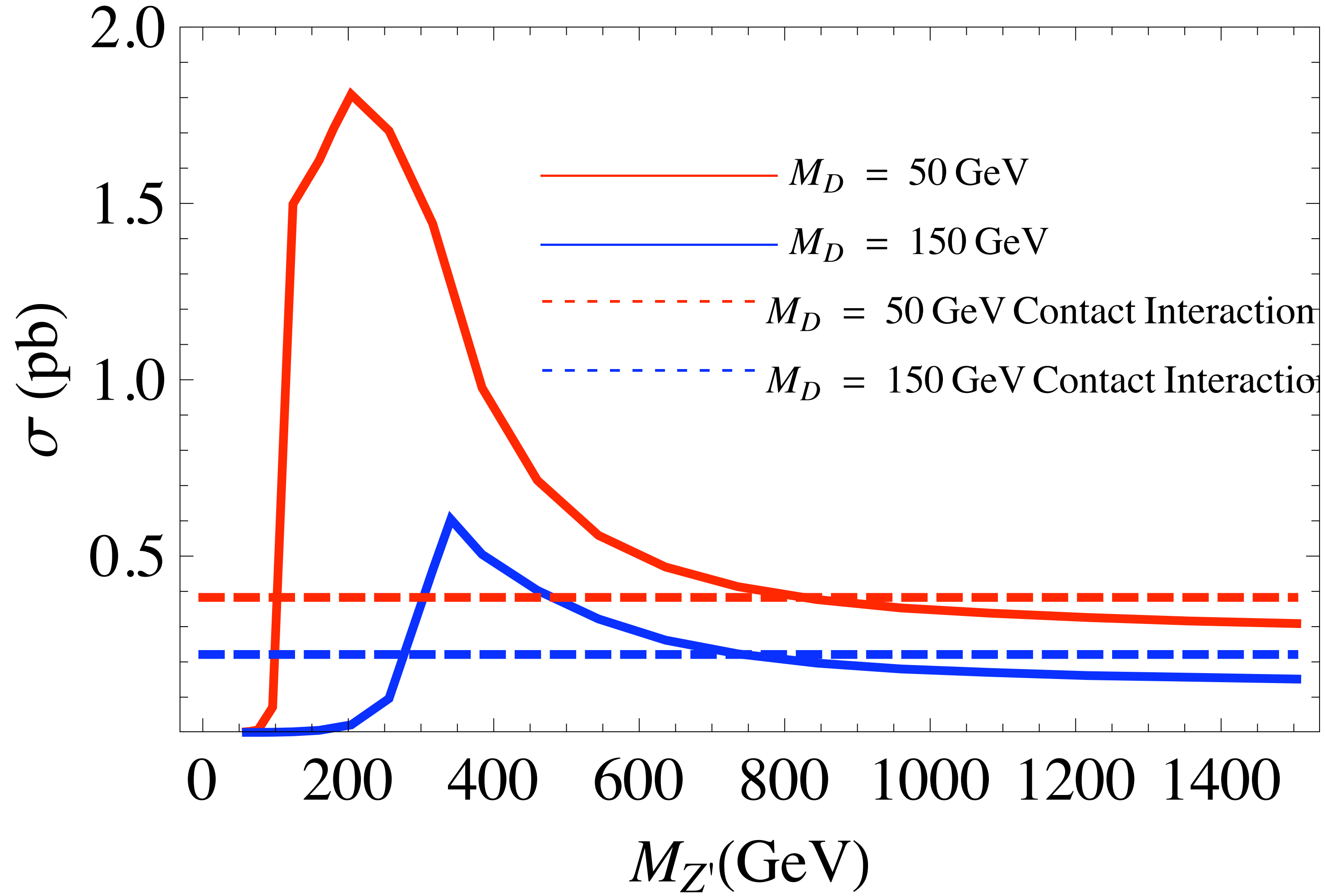
Only couples to SM quarks and DM.



N= Ar, Ge, Xe, ...

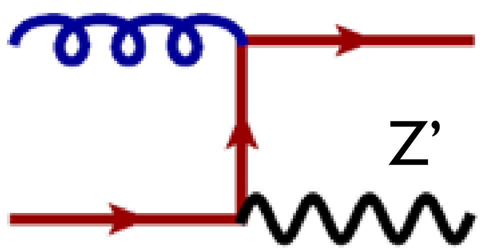
Connection with direct detection

Tevatron rate for
Monojet + (MET> 80 GeV)



$g_D = g_{Z'}$, fix $g_{Z'}/M_{Z'}$

Connection with direct detection



resonance prod.

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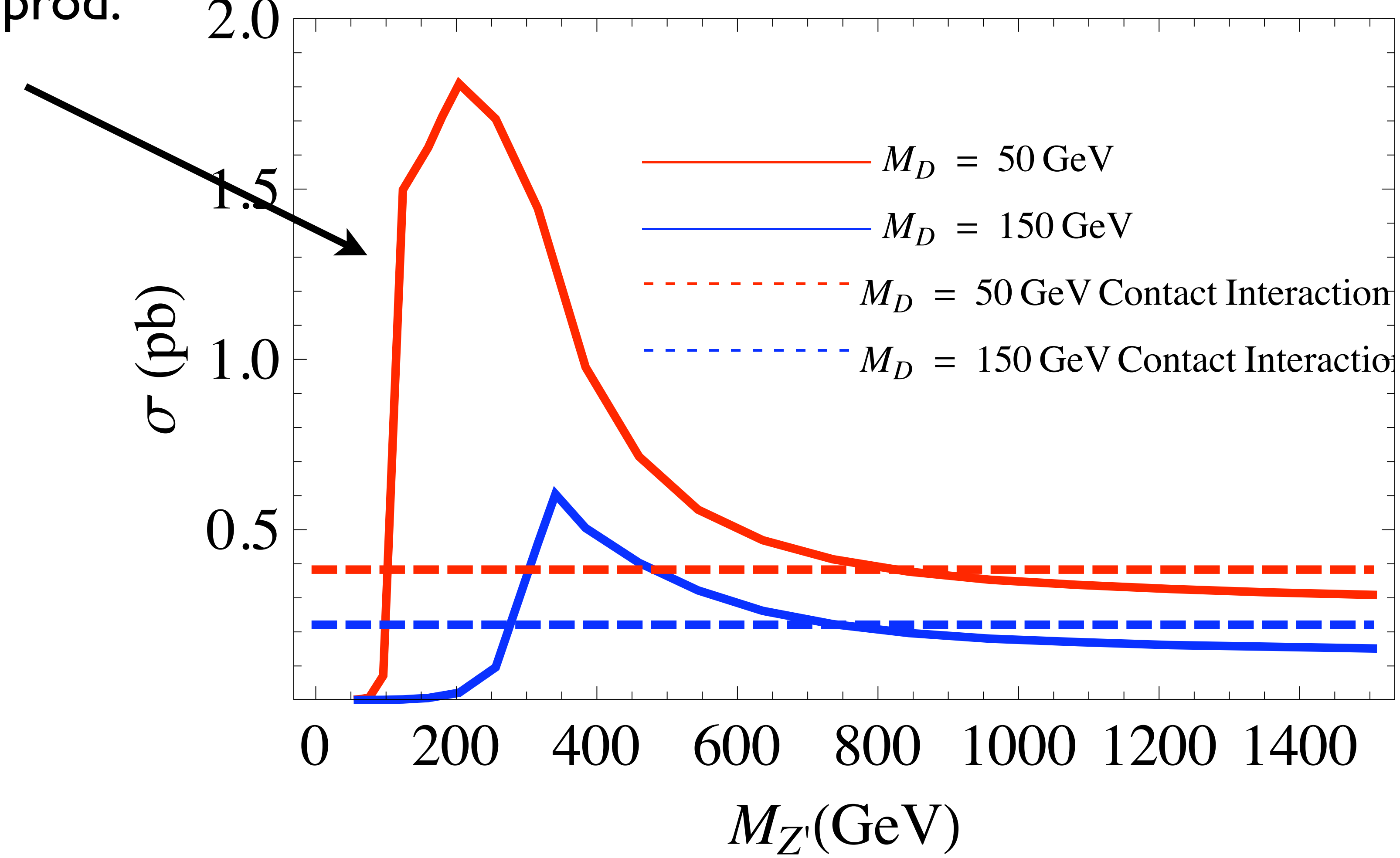

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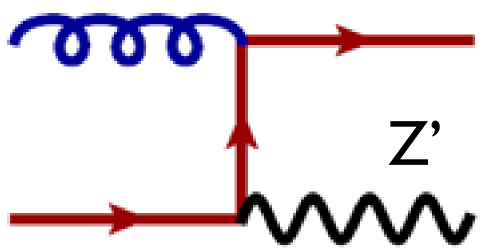

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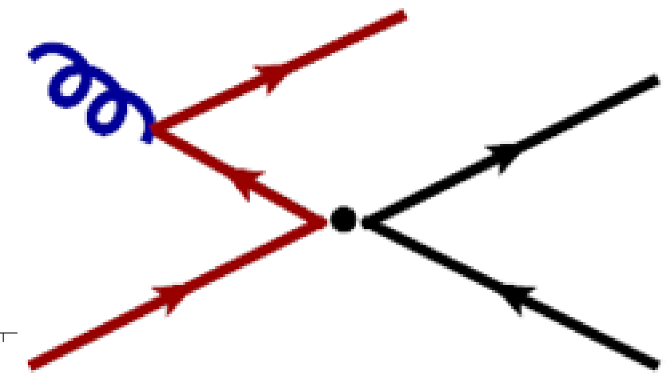
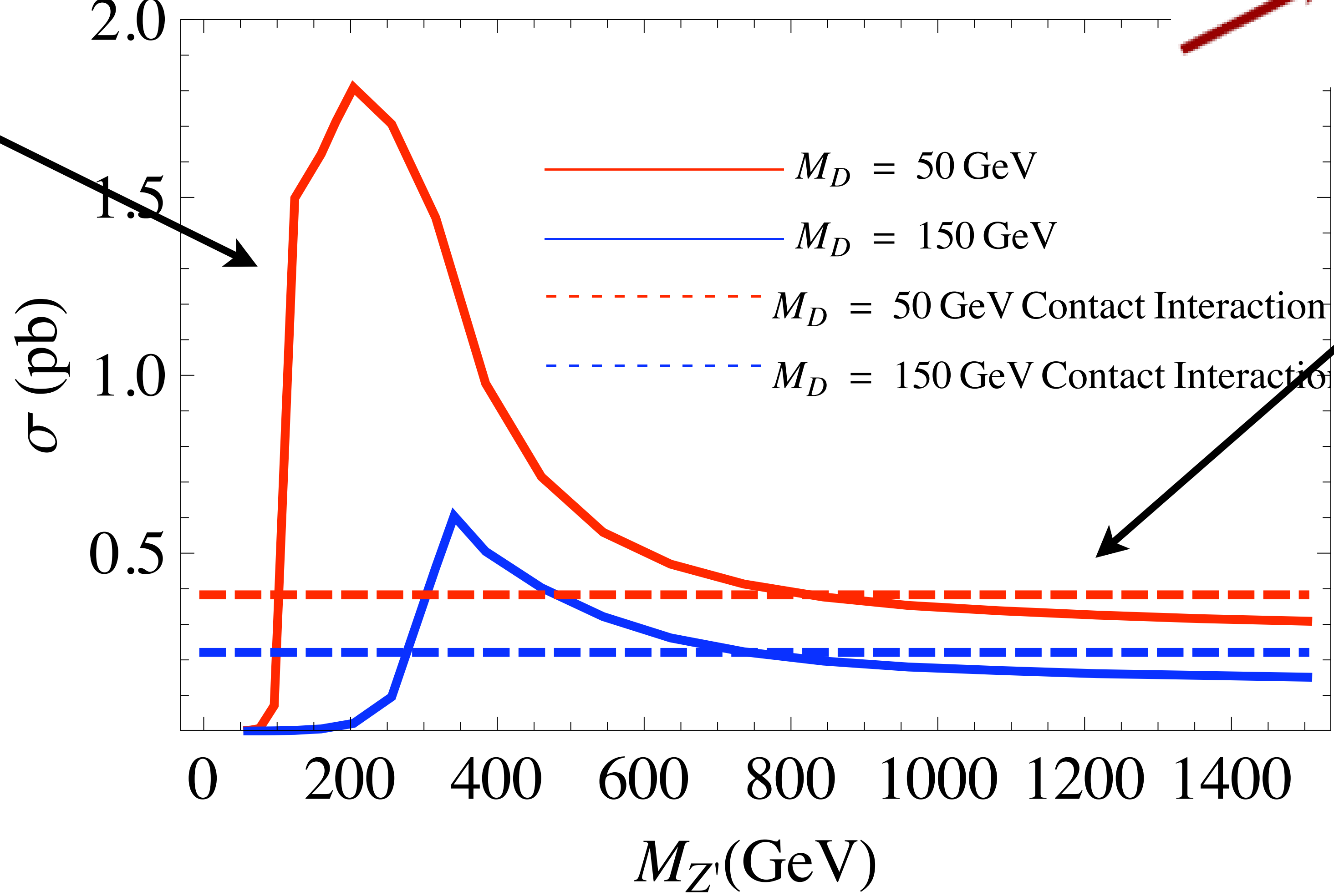


contact-like



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Connection with direct detection

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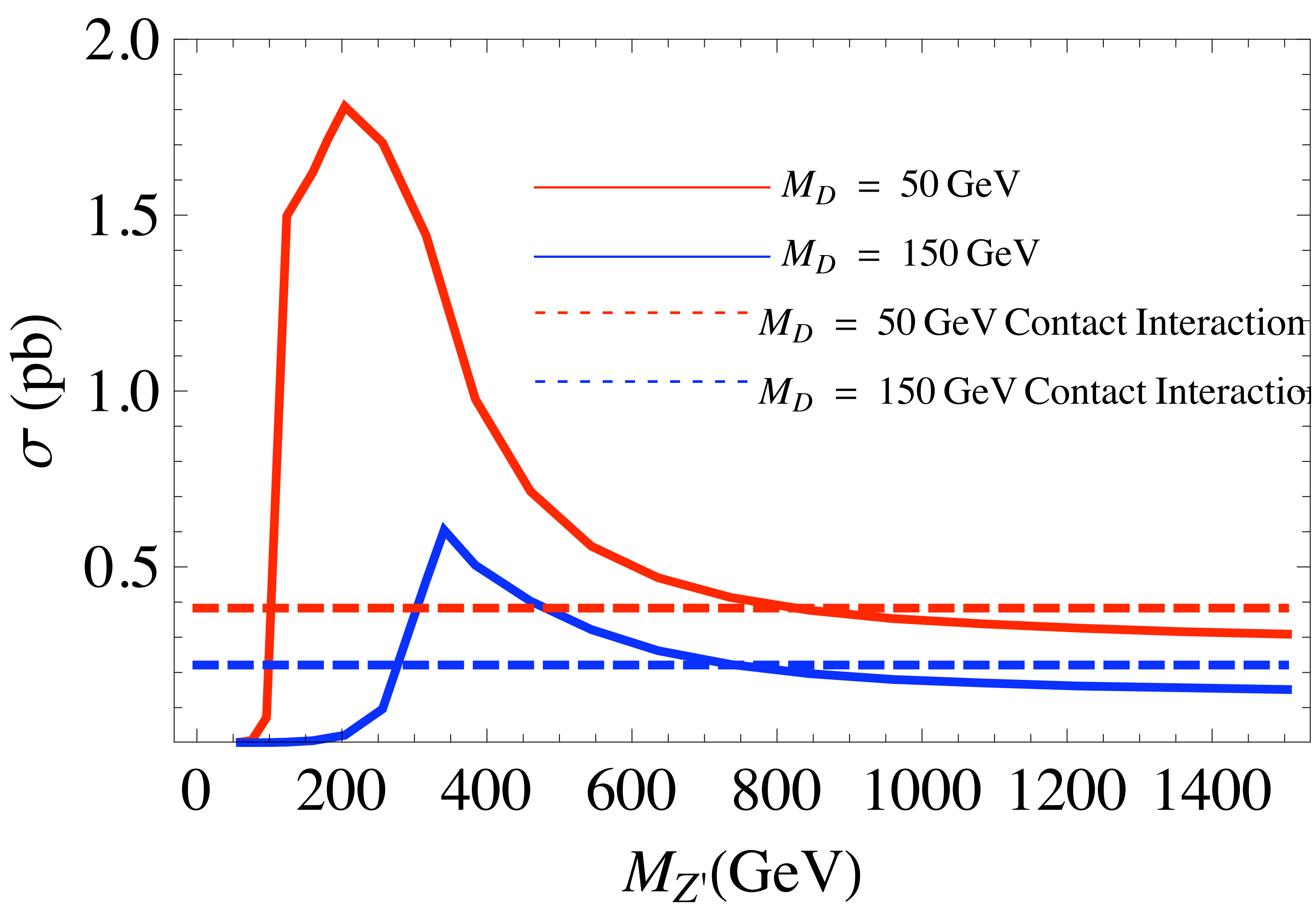
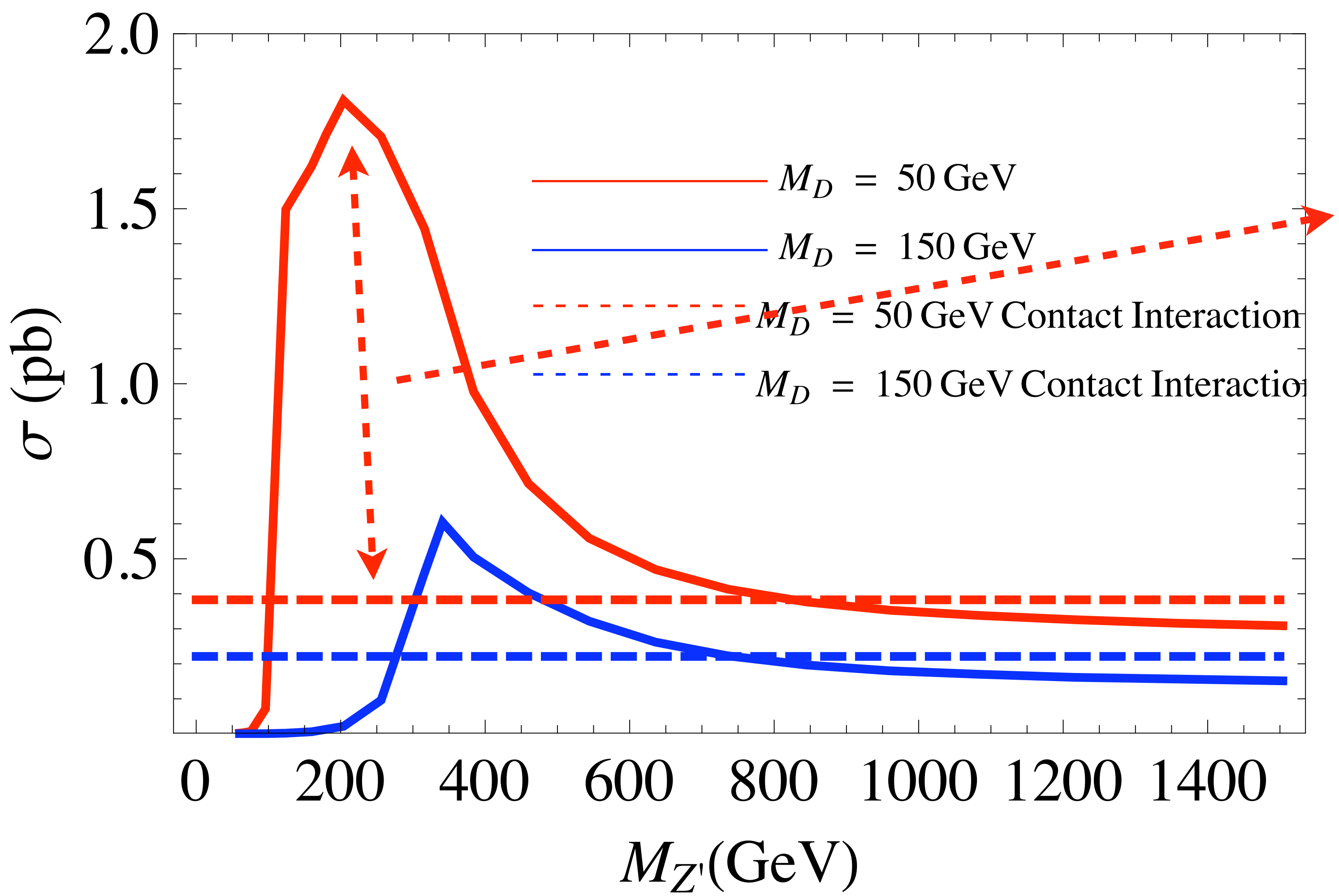


$g_D = g_{Z'}$, direct detection rate only depends on $g_{Z'}/M_{Z'}$

Connection with direct detection

Tevatron rate for
Monojet + (MET> 80 GeV)



A factor of 3 in $\sigma_{collider}$
→ a factor of 3 in $(g_{Z'})^2$
$\sigma_{dir} \propto (g_{Z'})^4$
→ a factor of 9

$g_D = g_{Z'}$, direct detection rate only depends on $g_{Z'}/M_{Z'}$

Operators for direct detection

	Operator	Structure	DM-nucleon Cross Section
O_1	$\bar{N}\gamma^\mu N\bar{\chi}\gamma_\mu\chi$	SI, MI	$\frac{9g_{Z'}^2 g_D^2 M_N^2 M_\chi^2}{\pi M_{Z'}^4 (M_N+M_\chi)^2}$
O_2	$\bar{N}\gamma^\mu N\bar{\chi}\gamma_\mu\gamma_5\chi$	SI, MD $\propto \Delta\vec{p}_N \cdot \Delta\vec{s}_\chi$, (σ_χ)	$\frac{g_{Z'}^2 g_{D5}^2 M_N^4 M_\chi^2 v^2}{\pi M_{Z'}^4 (M_N+M_\chi)^4}$
O_3	$\bar{N}\gamma^\mu\gamma_5 N\bar{\chi}\gamma_\mu\chi$	SD, MD $\propto \Delta\vec{s}_N \cdot \Delta\vec{p}_\chi$	$\frac{g_{Z'5}^2 g_D^2 M_N^2 M_\chi^2[(M_N+M_\chi)^2+2M_N^2]v^2}{2\pi M_{Z'}^4 (M_N+M_\chi)^4}$
O_4	$\bar{N}\gamma^\mu\gamma_5 N\bar{\chi}\gamma_\mu\gamma_5\chi$	SD, MI $\propto \Delta s_N \cdot \Delta s_\chi$	$\frac{3g_{Z'5}^2 g_{D5}^2 M_N^2 M_\chi^2}{\pi M_{Z'}^4 (M_N+M_\chi)^2}$

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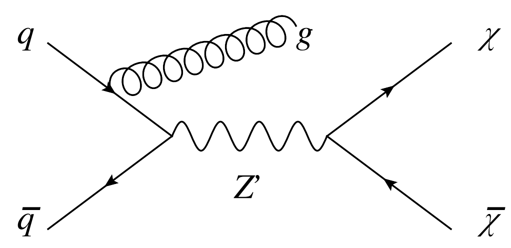
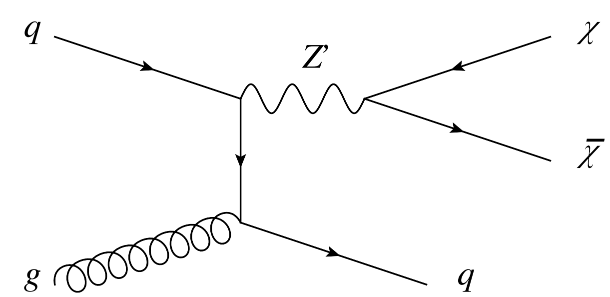
O_3	$\bar{N}\gamma^\mu\gamma_5 N\bar{\chi}\gamma_\mu\chi$	SD, MD $\propto \Delta\vec{s}_N \cdot \Delta\vec{p}_\chi$	$\frac{g_{Z'5}^2 g_D^2 M_N^2 M_\chi^2[(M_N+M_\chi)^2+2M_N^2]v^2}{2\pi M_{Z'}^4 (M_N+M_\chi)^4}$
O_4	$\bar{N}\gamma^\mu\gamma_5 N\bar{\chi}\gamma_\mu\gamma_5\chi$	SD, MI $\propto \Delta s_N \cdot \Delta s_\chi$	$\frac{3g_{Z'5}^2 g_{D5}^2 M_N^2 M_\chi^2}{\pi M_{Z'}^4 (M_N+M_\chi)^2}$

$$\sigma_{\rm SI} = \frac{9g_{Z'}^2 g_D^2 M_N^2 M_D^2}{\pi M_{Z'}^4 (M_N + M_D)^2} \simeq 3.9\times 10^{-39}{\rm cm}^2 \left(\frac{g_{Z'}}{0.3}\right)^2 \left(\frac{g_D}{0.3}\right)^2 \left(\frac{200\ {\rm GeV}}{M_{Z'}}\right)^4$$

Will also show results for O_4

Monojet search





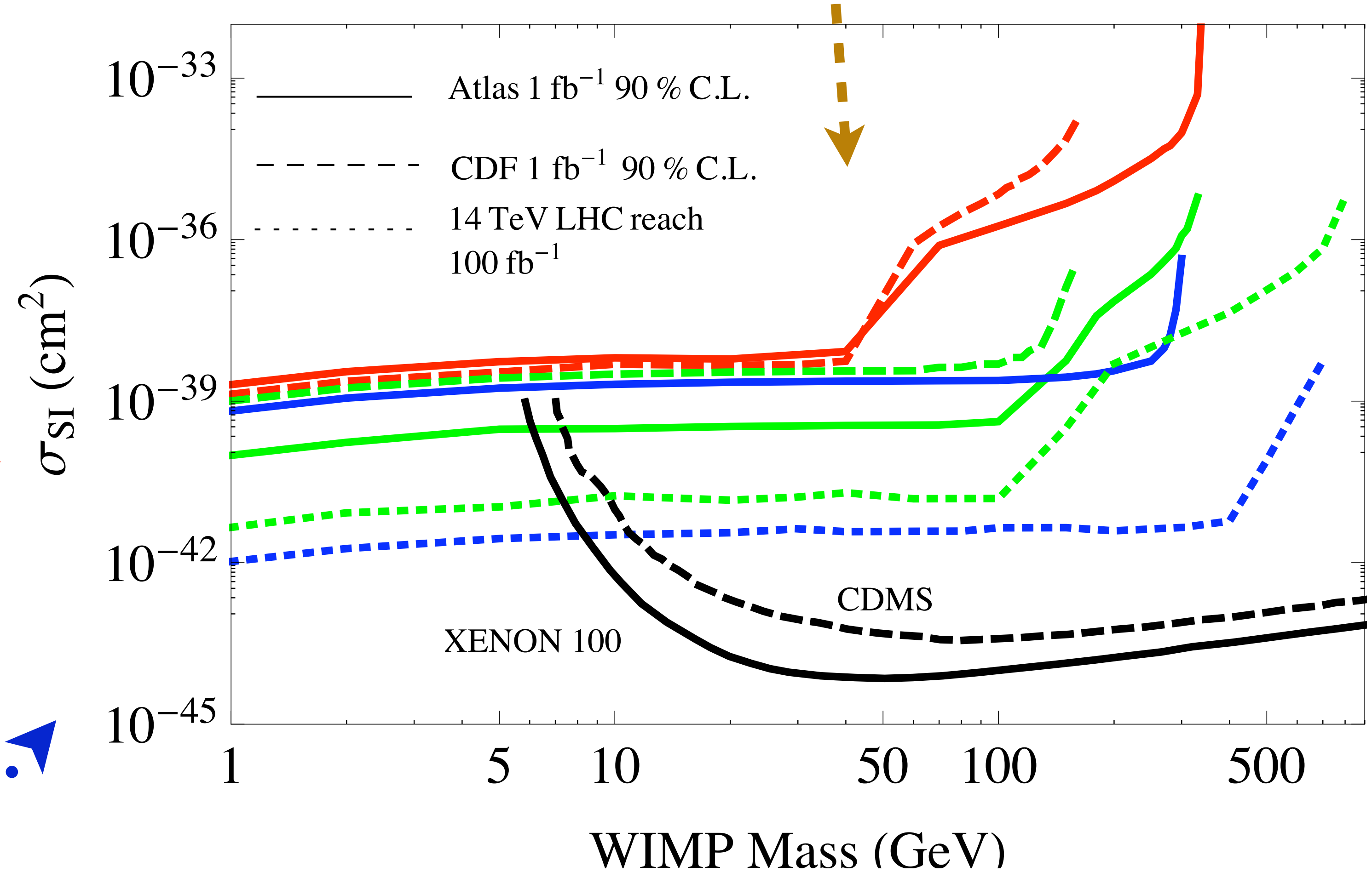
- Tevatron. CDF 1 fb^{-1}, MET>80 GeV.
- LHC. ATLAS 1 fb^{-1}

LowPT	Selection requires $\not{E}_T > 120$ GeV, one jet $p_T(j_1) > 120$ GeV, $\lvert\eta(j1)\rvert < 2$, events are vetoed if they contain a second jet with $p_T(j_2) > 30$ GeV and $\lvert\eta(j_2)\rvert < 4.5$.
HighPT	Selection requires $\not{E}_T > 220$ GeV, $p_T(j_1) > 250$ GeV, $\lvert\eta(j1)\rvert < 2$, events are vetoed if there is a second jet with $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \not{E}_T) < 0.5$ and $\lvert\eta(j_2)\rvert < 4.5$. Any further jets with $\lvert\eta(j_3)\rvert < 4.5$ must have $p_T(j_3) < 30$ GeV.
vertHighPT	Selection requires $\not{E}_T > 300$ GeV, one jet with $p_T(j_1) > 350$ GeV, $\lvert\eta(j_1)\rvert < 2$, and events are vetoed if there is a second jet with $\eta(j_2) < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta(j_2, \not{E}_T) < 0.5$. Any further jets with $\lvert\eta(j_3)\rvert < 4.5$ must have $p_T(j_3) < 30$ GeV.

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, appearing soon.

Spin dependent

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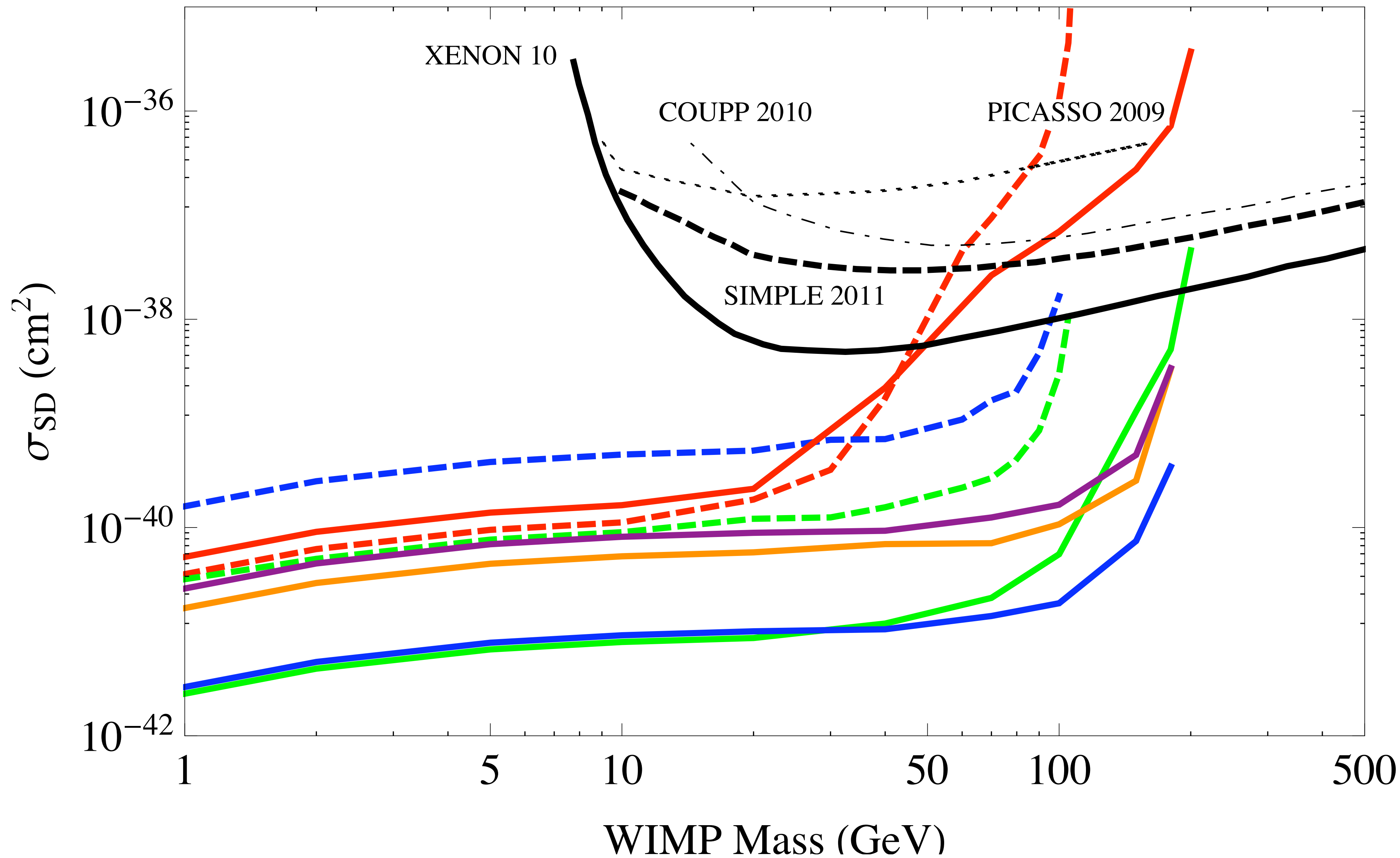
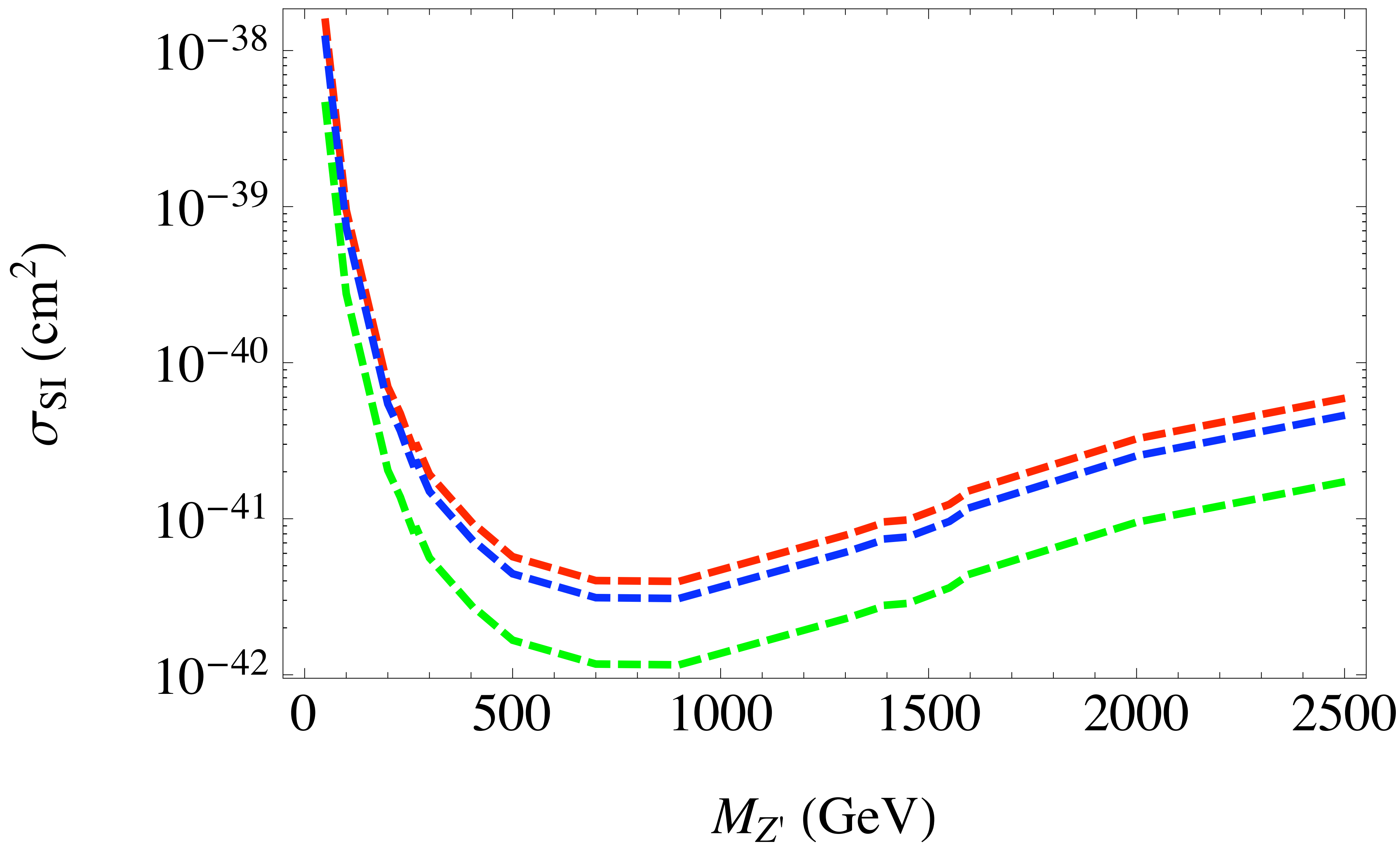
Solid: LHC, 7 TeV 1 fb^{-1} Very High PT



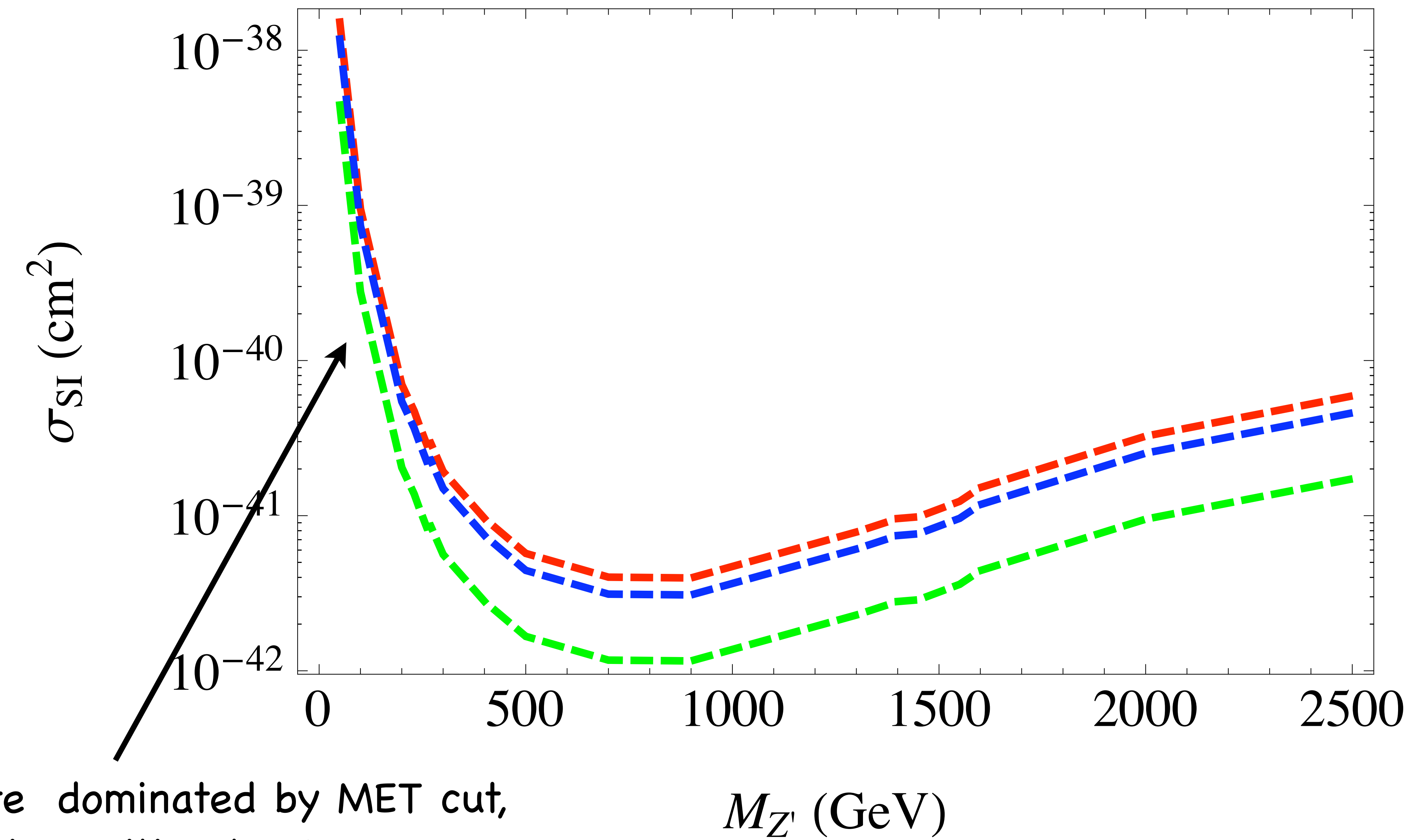
$M_{Z'}$ = 100 GeV, 300 GeV, 500 GeV, 1 TeV, 1.5 TeV

LHC reach in monojet+MET.



More scenarios are under study.
Xiangdong Ji, Haipeng An, LTW, appearing soon.

LHC reach in monojet+MET.



LHC rate dominated by MET cut, insensitive to $M_{Z'}$.

→ LHC bounds only on $g_{Z'}$

Bounds on $\sigma_{SI} \propto (M_{Z'})^{-4}$

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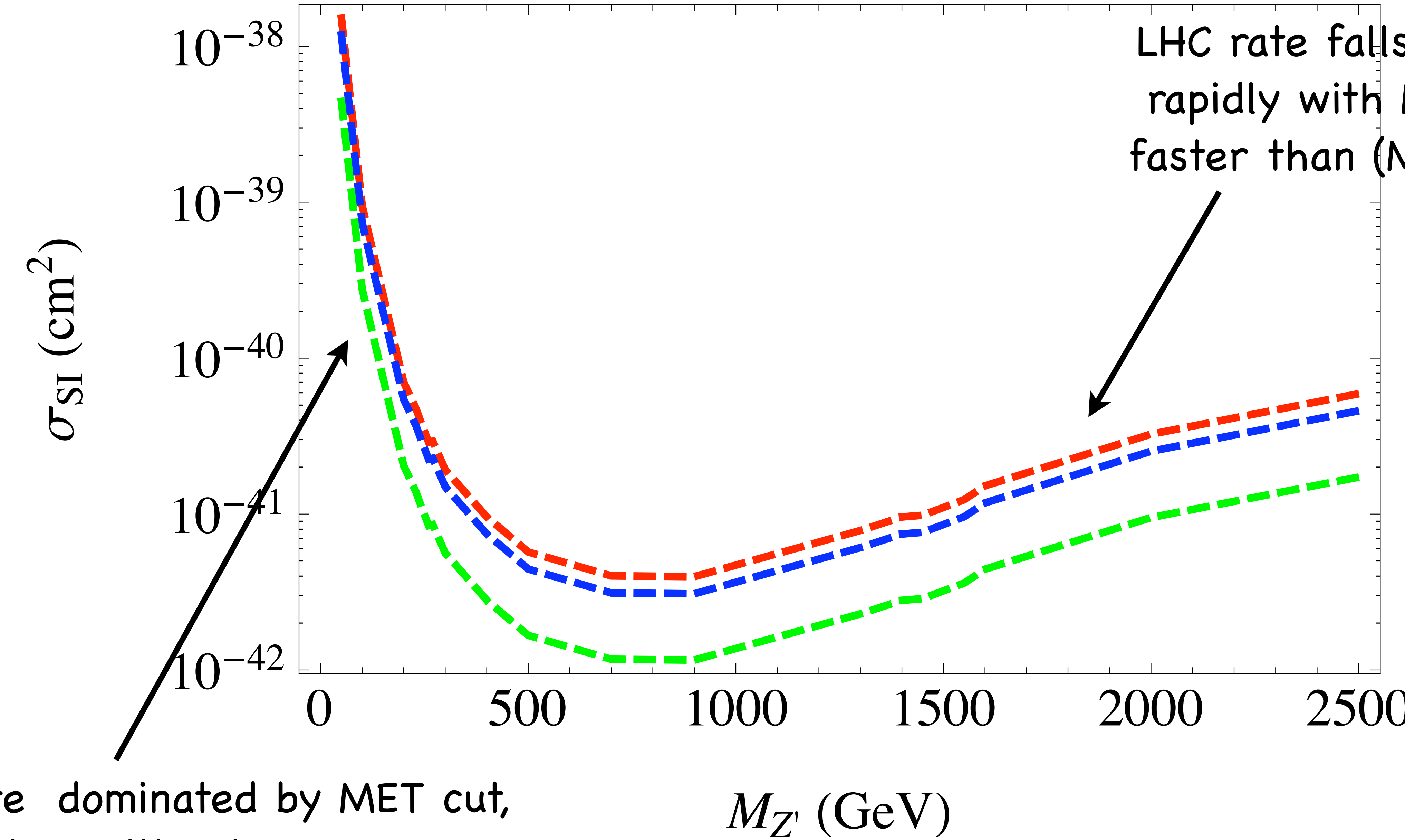
LHC reach in monojet+MET.



LHC rate falls off rapidly with $M_{Z'}$, faster than $(M_{Z'})^{-4}$

LHC rate dominated by MET cut, insensitive to $M_{Z'}$.

→ LHC bounds only on $g_{Z'}$

Bounds on $\sigma_{SI} \propto (M_{Z'})^{-4}$

More scenarios are under study.

Xiangdong Ji, Haipeng An, LTW, appearing soon.

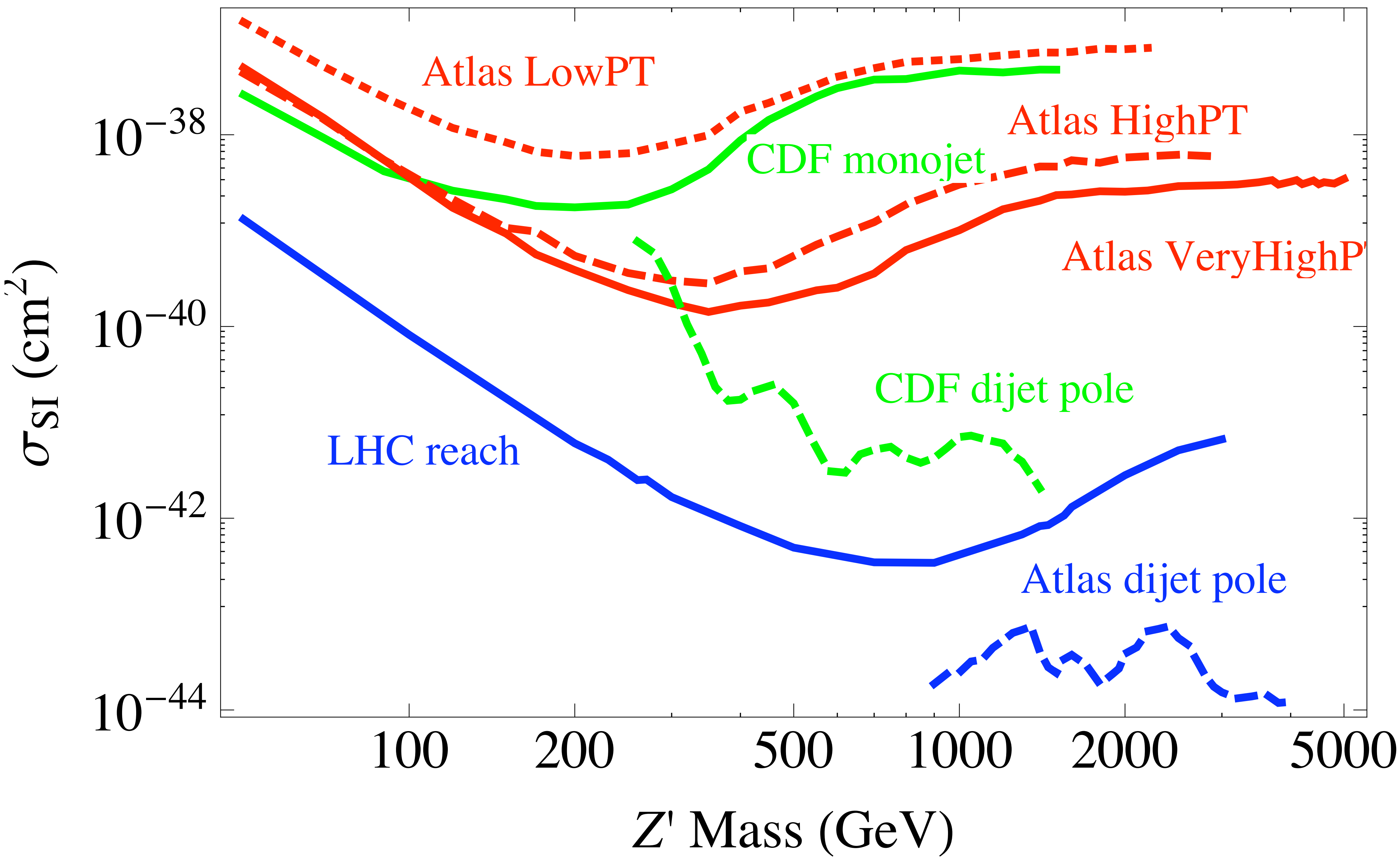
Di-jet resonance searches.

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

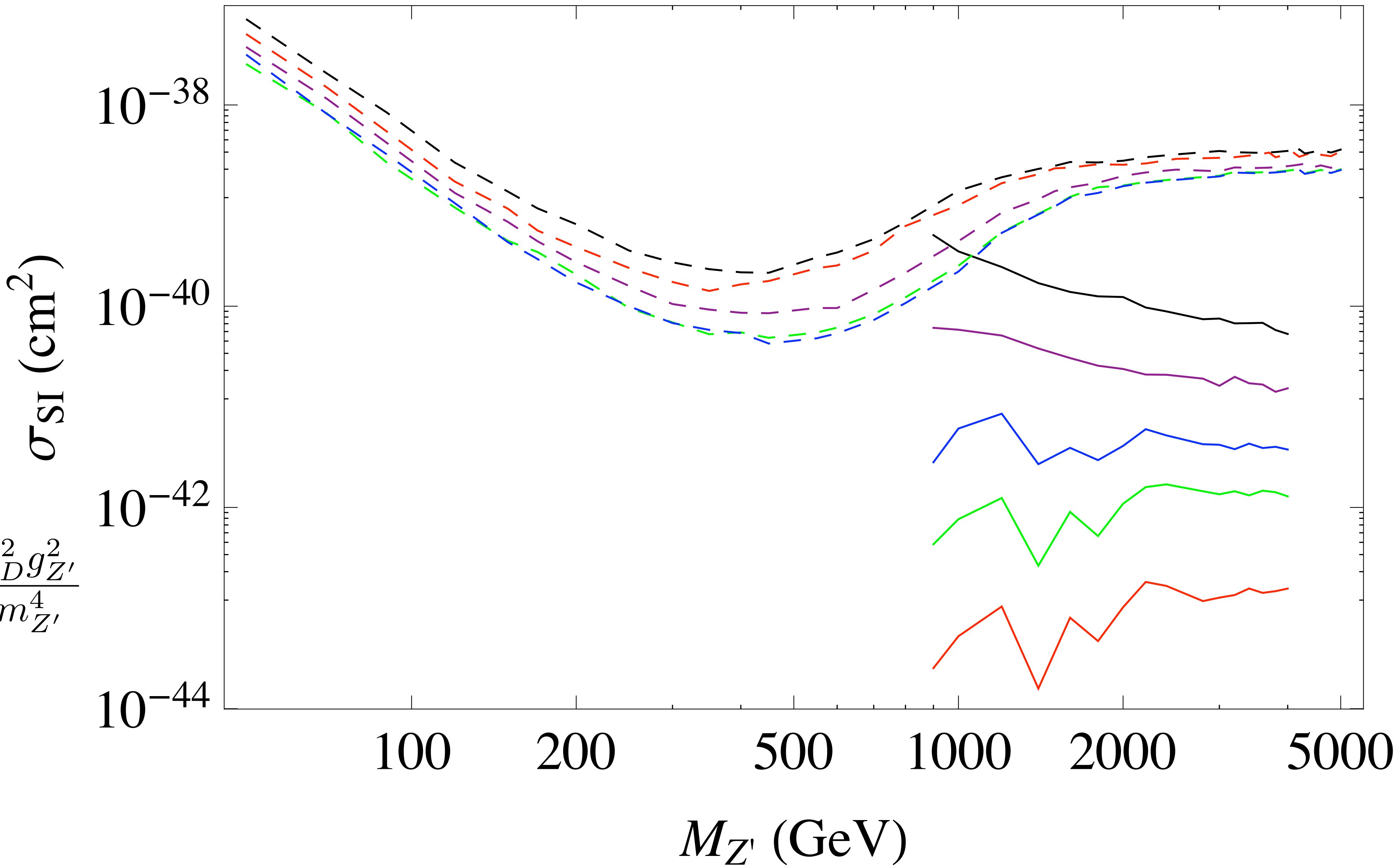
- Resonance searches.
  - ATLAS: 1 fb^{-1} 1108.6311
  - CMS: 1 fb^{-1} 1107.4771
  - CDF: Phys. Rev. D79 (2009).
- Compositeness.
  - CMS 36 pb^{-1}: Phys. Rev. Lett. 106 (2011)
  - Dzero: Phys. Rev. Lett. 103 (2009)

Combining di-jet with monojet

Assume $g_{Z'} = g_D$



Varying $y=(g_D/g_{Z'})$



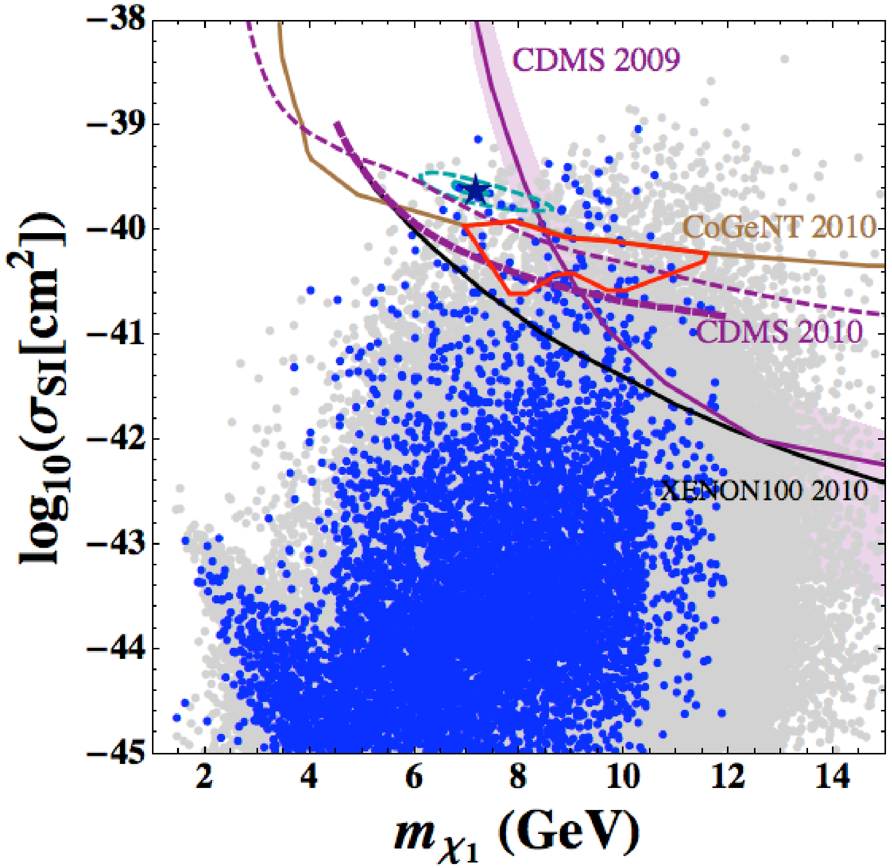
$$\sigma_{SI} \propto \frac{g_D^2 g_{Z'}^2}{m_{Z'}^4}$$

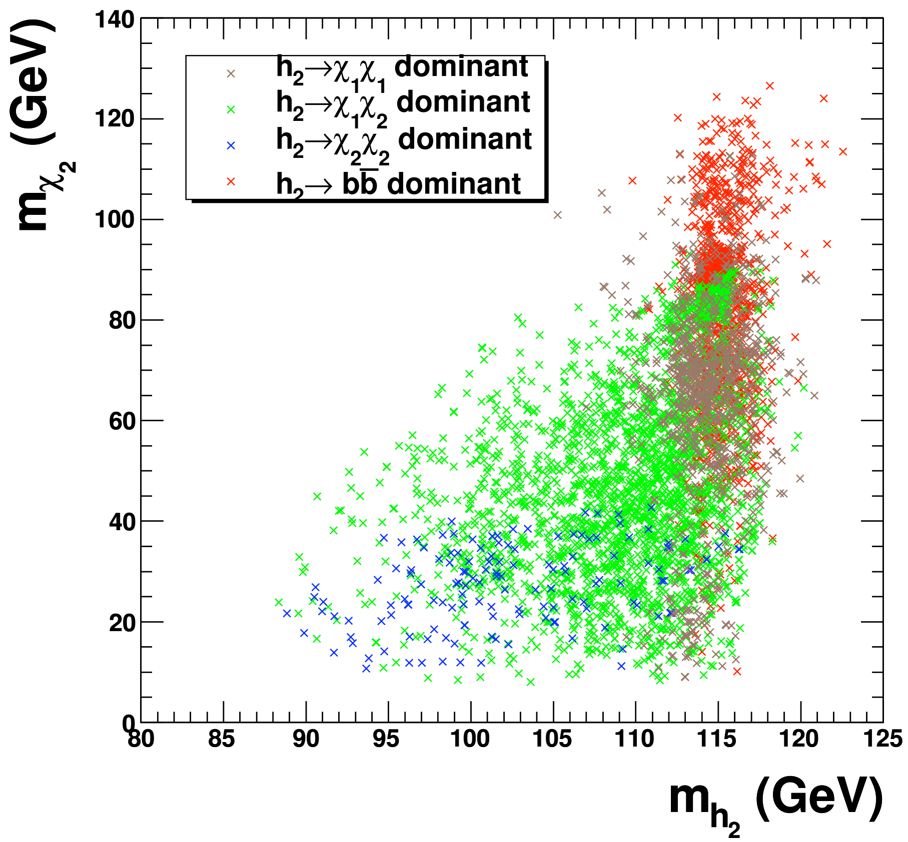
$$y = \frac{g_D}{g_{Z'}}$$ 1, 3, 5, 10, 20

Signals from new model extensions

Dark light Higgs

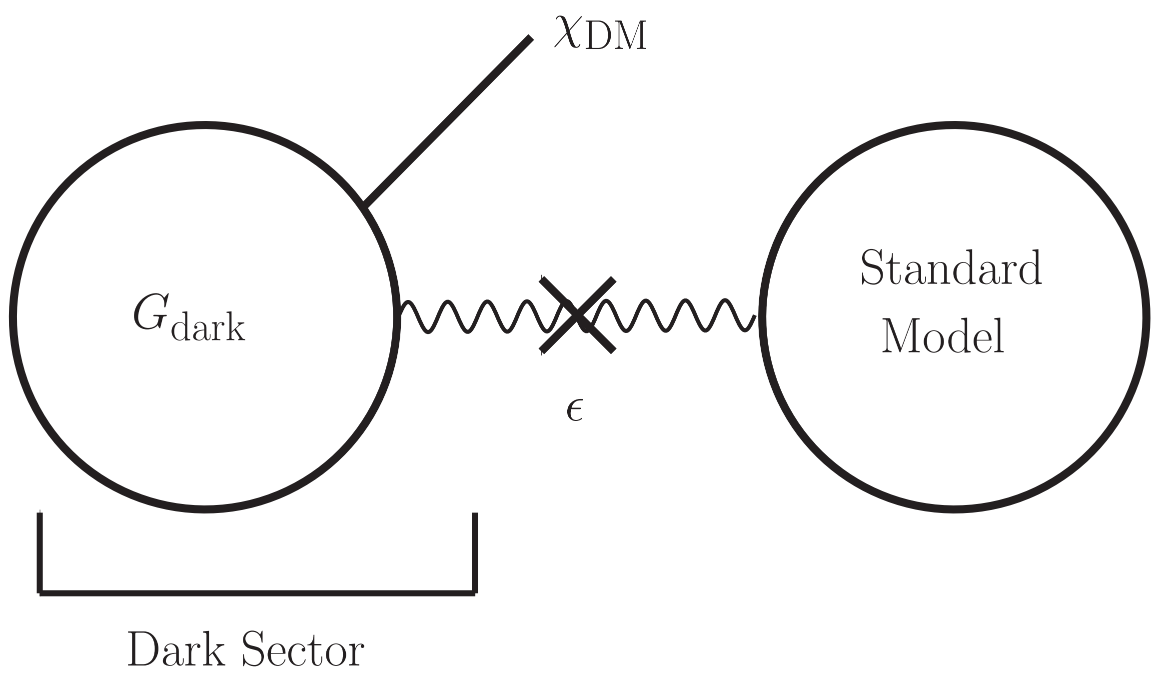
- NMSSM near PQ limit.
  - Very light GeV- 10 GeV scalars.
  - Singlino-like light dark matter. Large σ_{SI}.





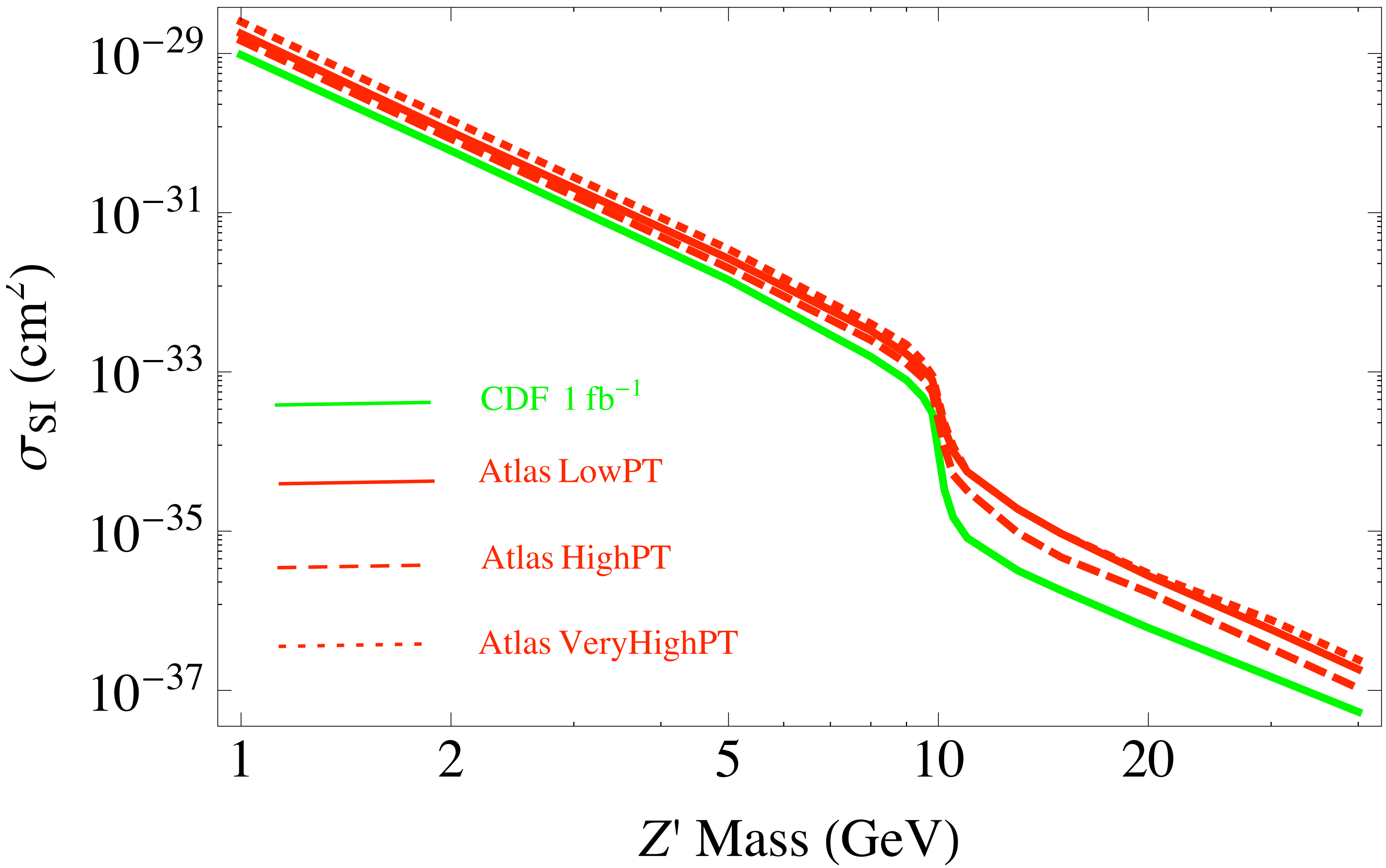
hiding Higgs?

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.

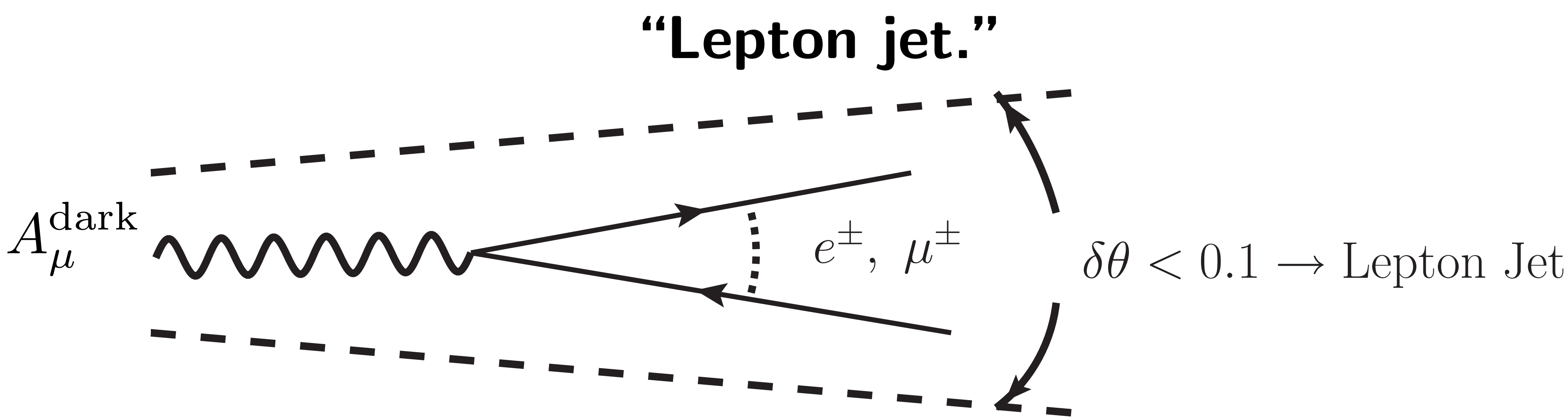
Small Z′ mass.



10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
σ_{SI} (cm^2)
CDF 1 fb^{-1}
Atlas LowPT
Atlas HighPT
Atlas VeryHighPT
1
2
5
10
20
Z' Mass (GeV)

Very light Z' -> Lepton Jets

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



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

- Arkani-Hamed, Weiner 0810.0714;

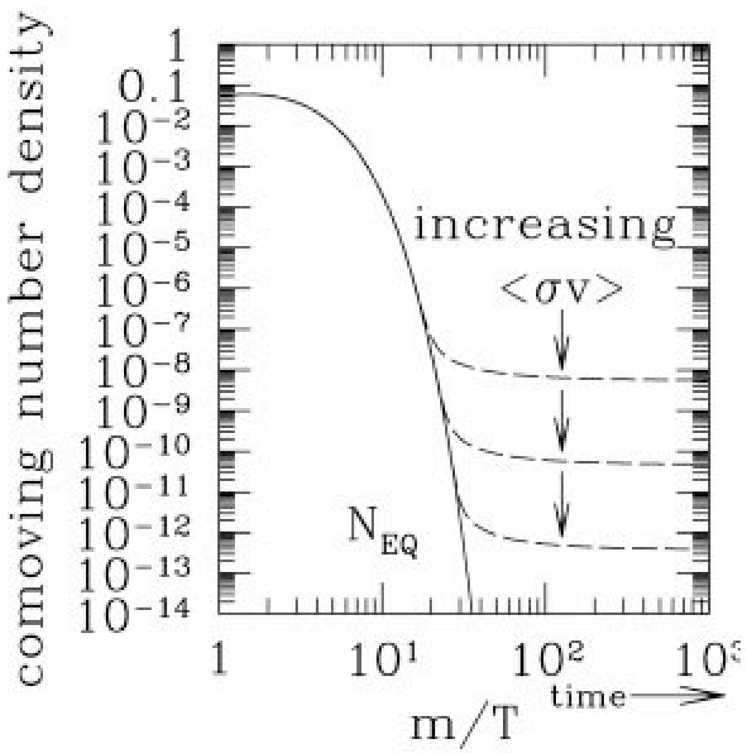
- Baumgart, Cheung, Ruderman, LTW, Yavin 0901.0283; Cheung, Ruderman, LTW, Yavin 0909.0290

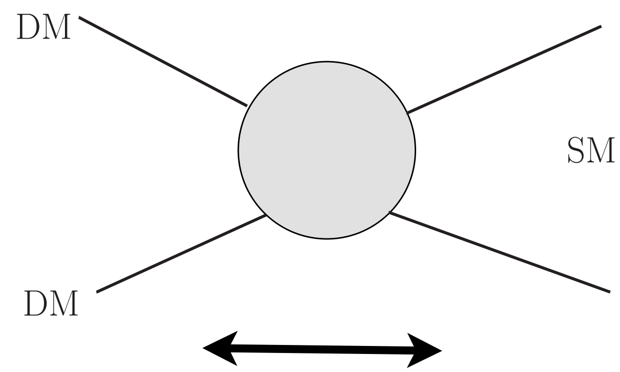
Conclusion.

- One of the most exciting opportunities: Discovering the WIMP dark matter and measuring its properties.
- LHC will play a crucial role in this pursuit.
- Multiple aspects and approaches.
  - Search for "conventional" CDM.
  - More "model independent" searches.
  - Alternative models with distinct signatures.

extra

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.

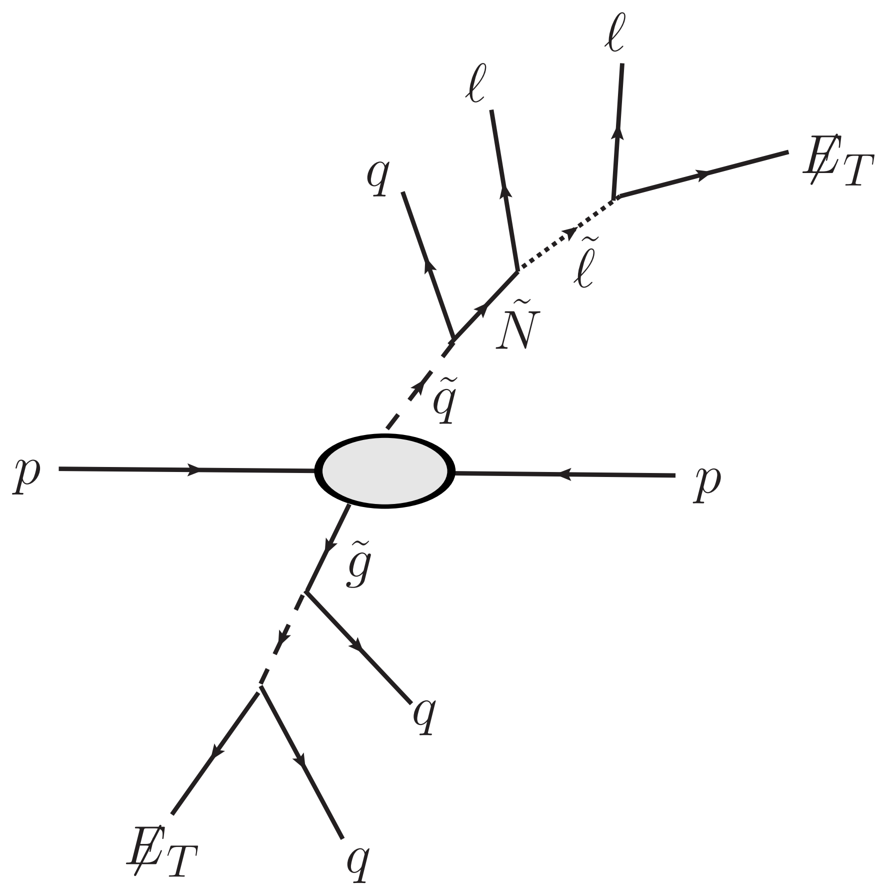
- If dark matter is
  - Weakly interacting: $g_D \sim 0.1$
  - Weakscale: $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- A major hint of TeV scale new physics.
  - We can produce and study them at the LHC!

Spin measurements. Supersymmetry?

Spin measurements. Supersymmetry?

Example: spin of $\tilde{N}$

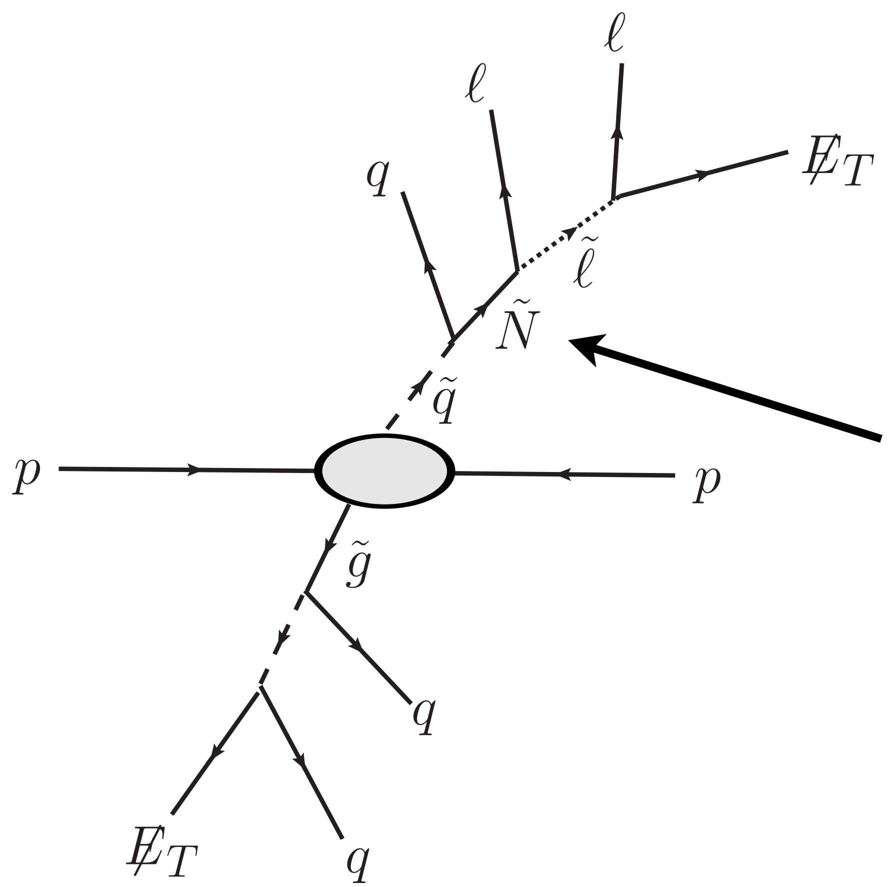
Spin measurements. Supersymmetry?



Example: spin of $\tilde{N}$

Clean exclusive sample

Spin measurements. Supersymmetry?

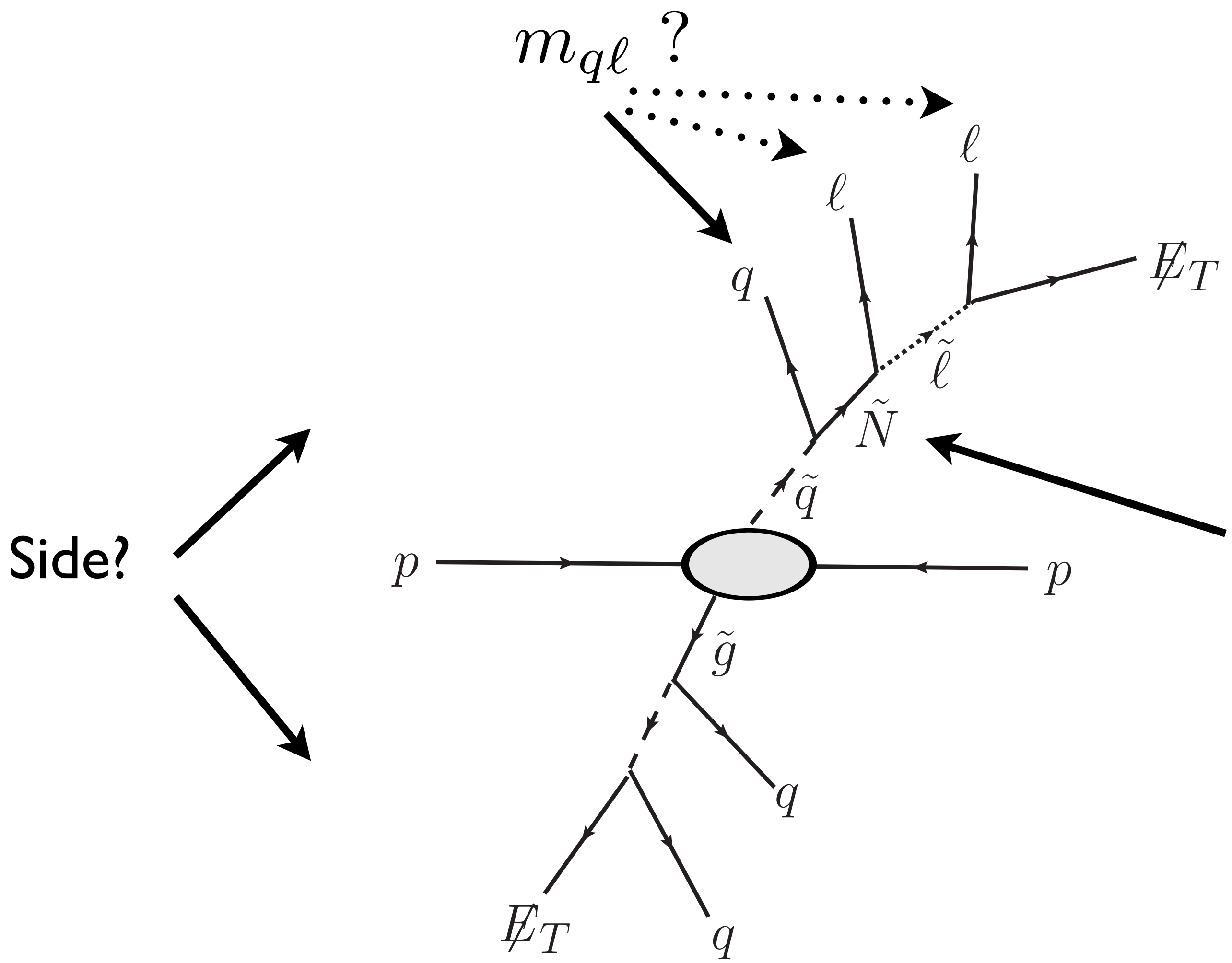


Example: spin of $\tilde{N}$

Clean exclusive sample

Boost (kinematics) vs matrix element (spin)
$\rightarrow$ Consider $m_{q\ell}$

Spin measurements. Supersymmetry?



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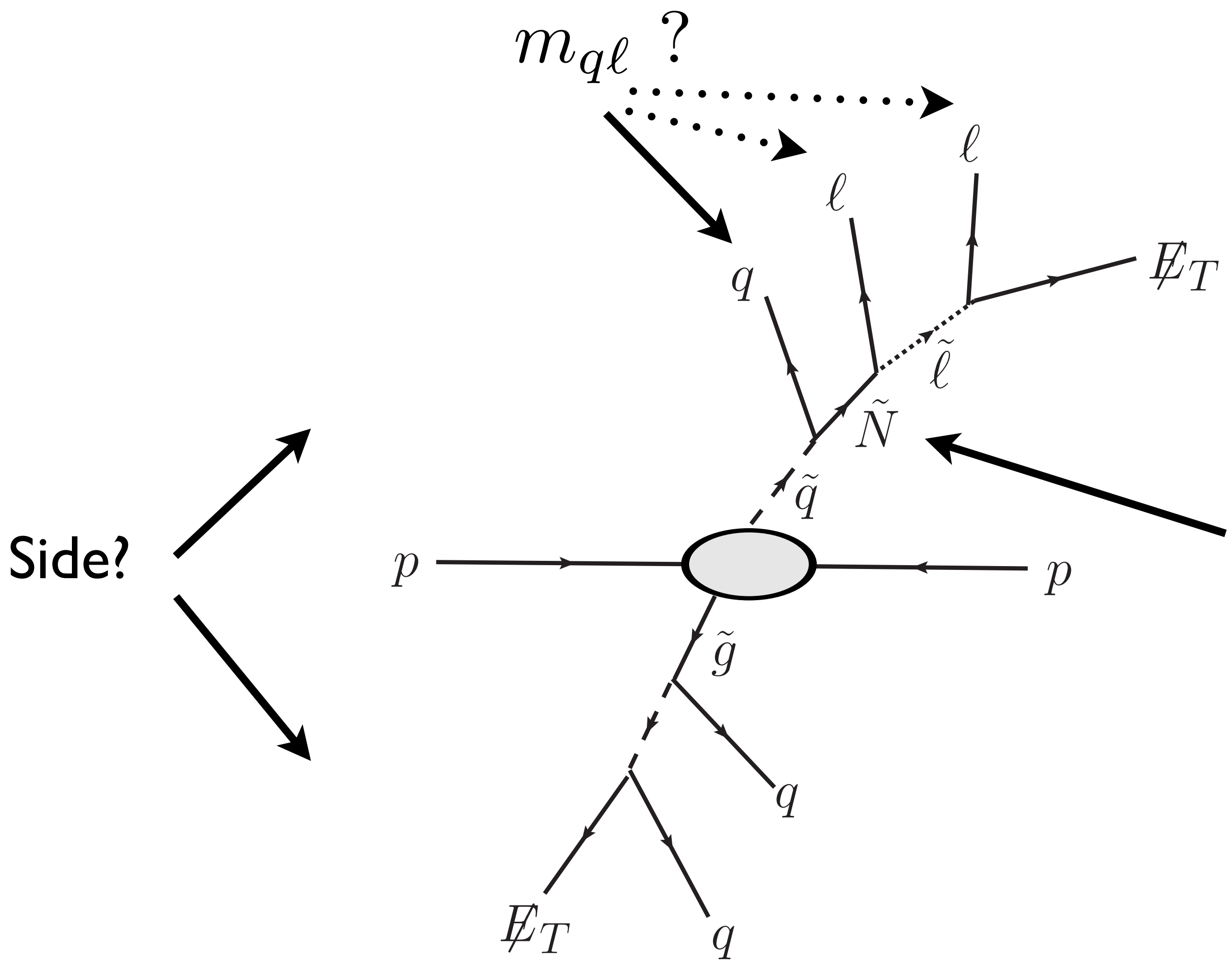
Combinatorics

Spin measurements. Supersymmetry?



Example: spin of $\tilde{N}$

Clean exclusive sample

Boost (kinematics) vs matrix element (spin)

$\rightarrow$ Consider $m_{q\ell}$

Combinatorics

- No universally applicable method. Different strategies will be used in different scenarios.

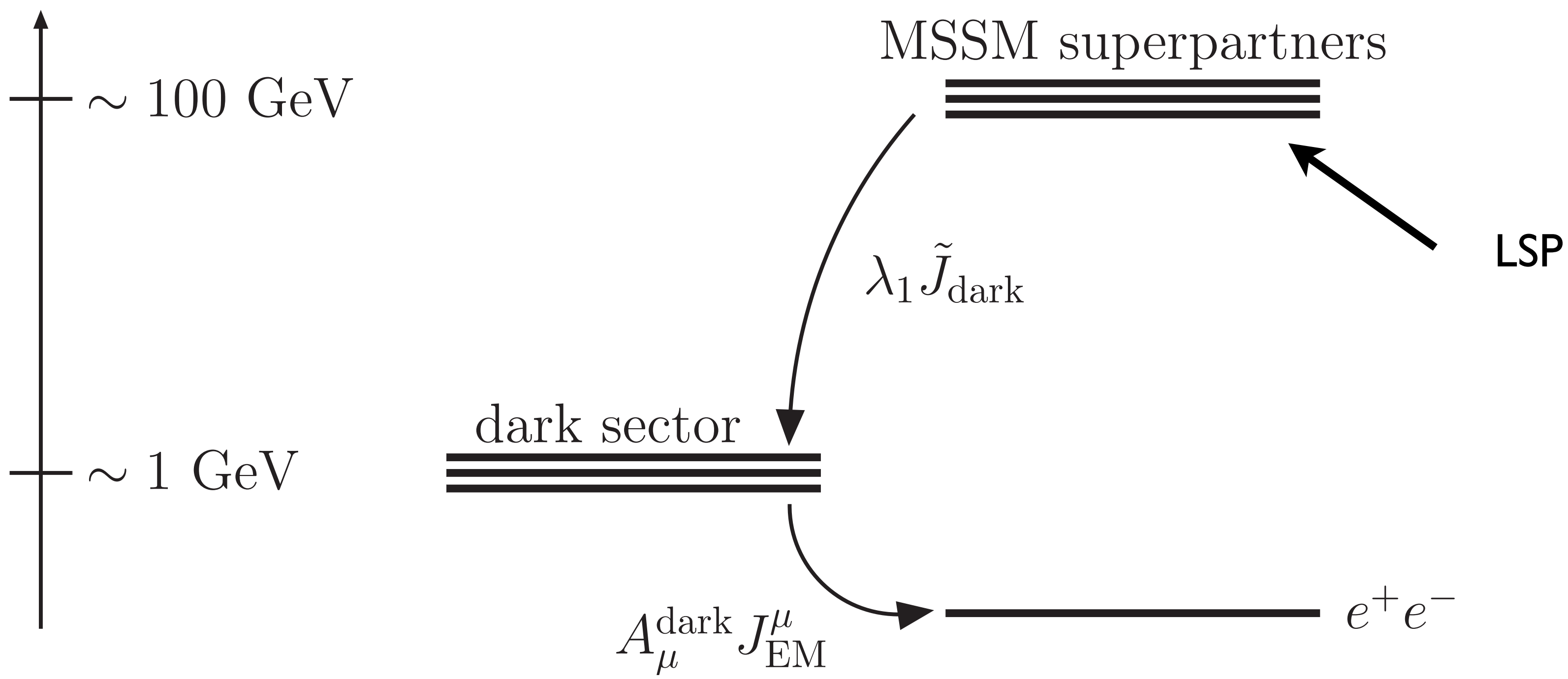
A review: LTW and Yavin, arXiv:0802.2726

- More information of the signal, masses and underlying processes, is crucial.

SUSY dark force.

- Dark matter self-interaction, mediated by

$$A_\mu^{\text{dark}}, \quad m_{A^{\text{dark}}} \sim \ (100\text{s MeV - GeV})$$



Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
Arkani-Hamed, Weiner 0810.0714
also see Pospelov, Ritz, Voloshin 0711.4866

Supersymmetric dark force

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