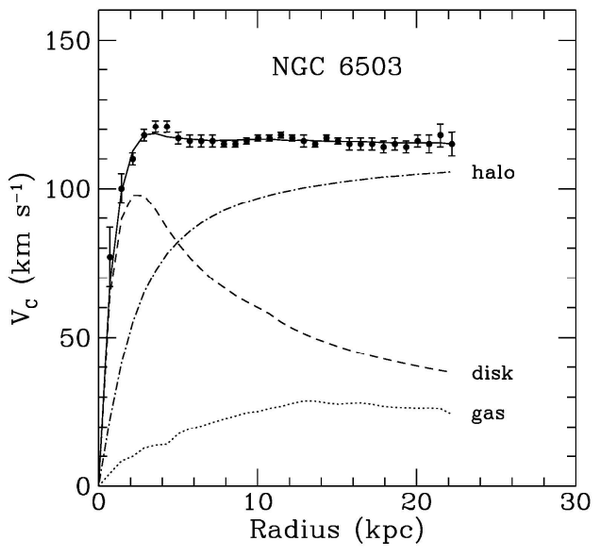
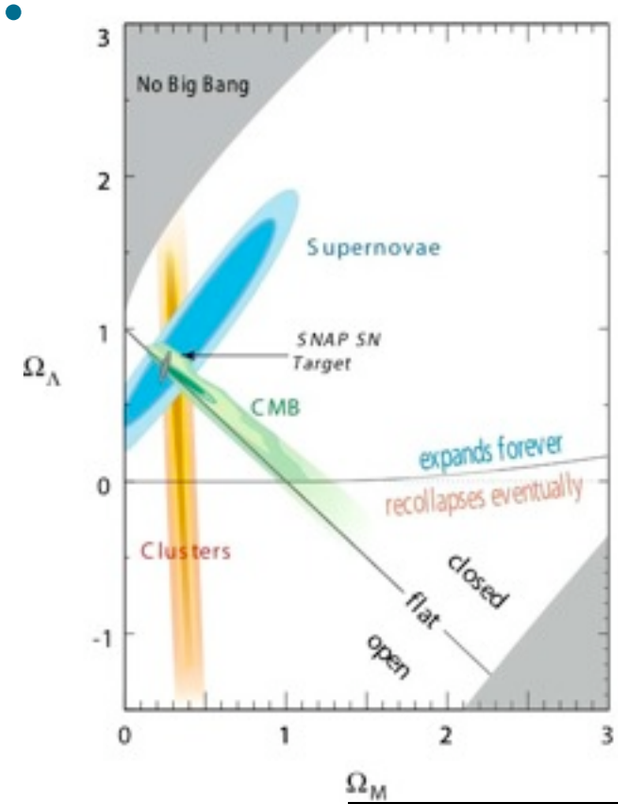
Dark matter at colliders

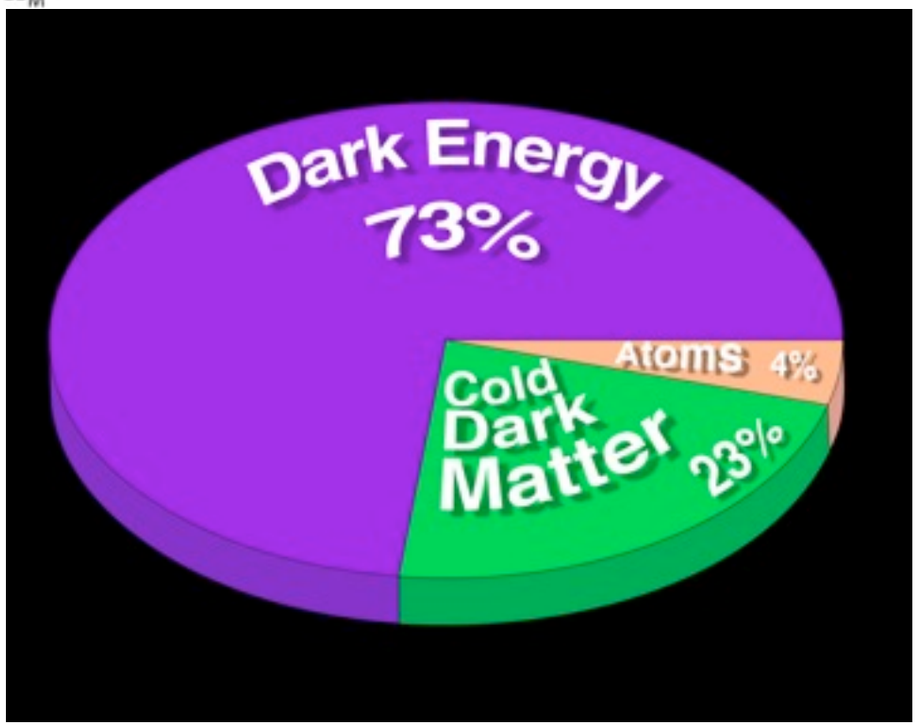
Lian-Tao Wang
University of Chicago

PPC 2011, CERN
June 15, 2011

We have solid evidence that dark matter:







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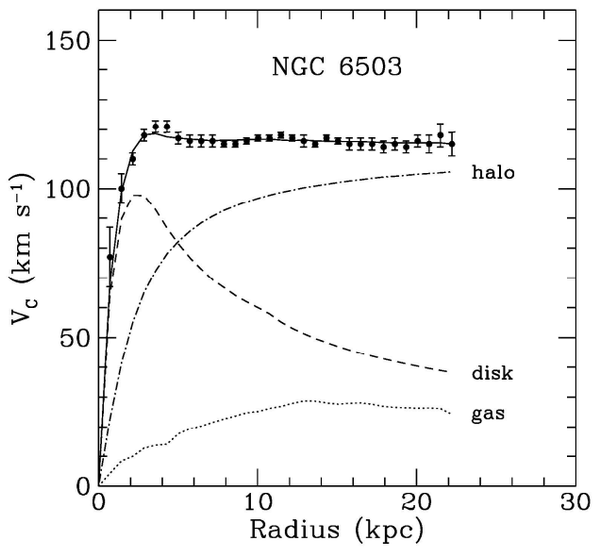
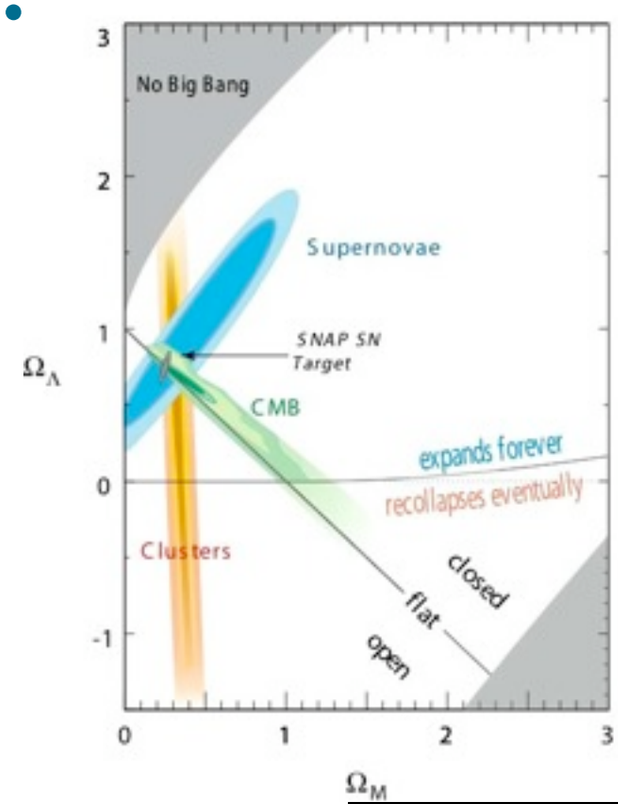
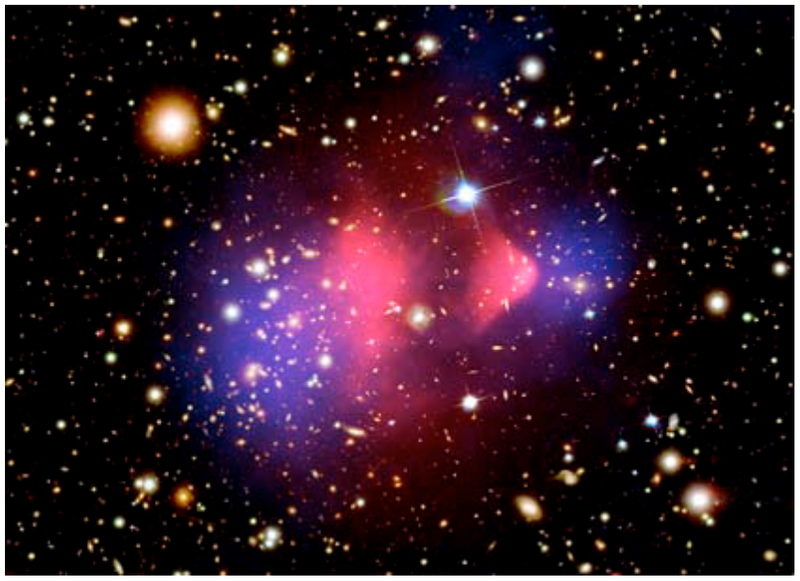
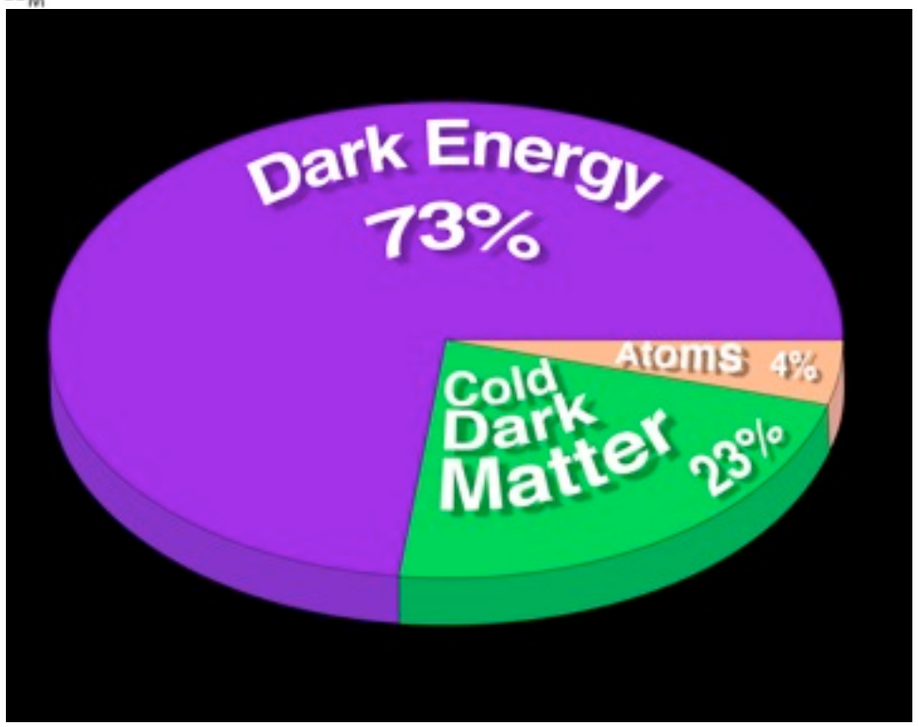






- gravitates.



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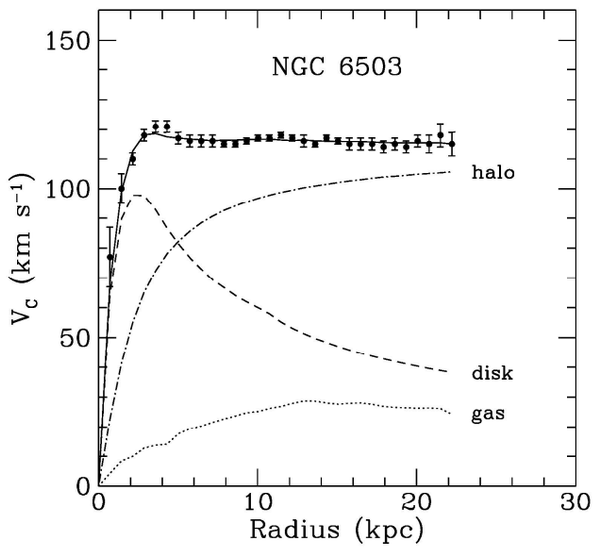
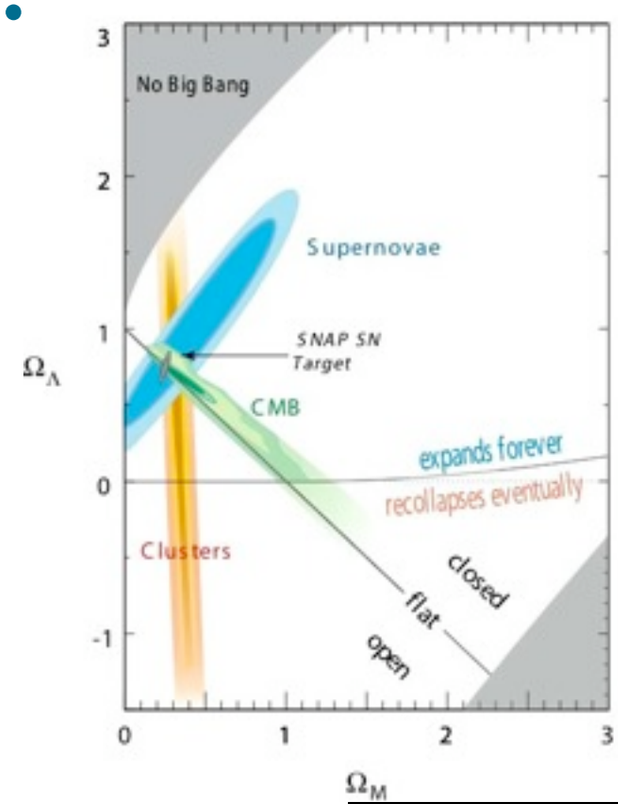
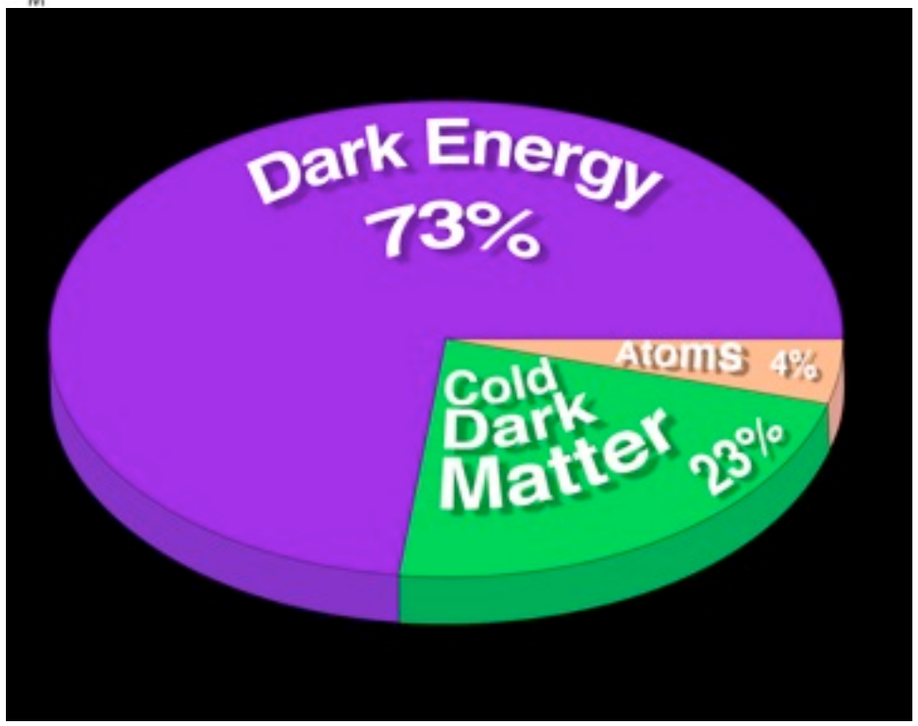




- gravitates.
- is dark.



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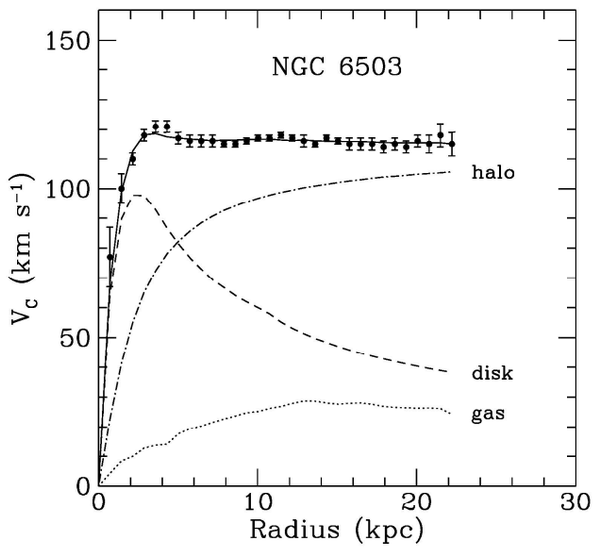
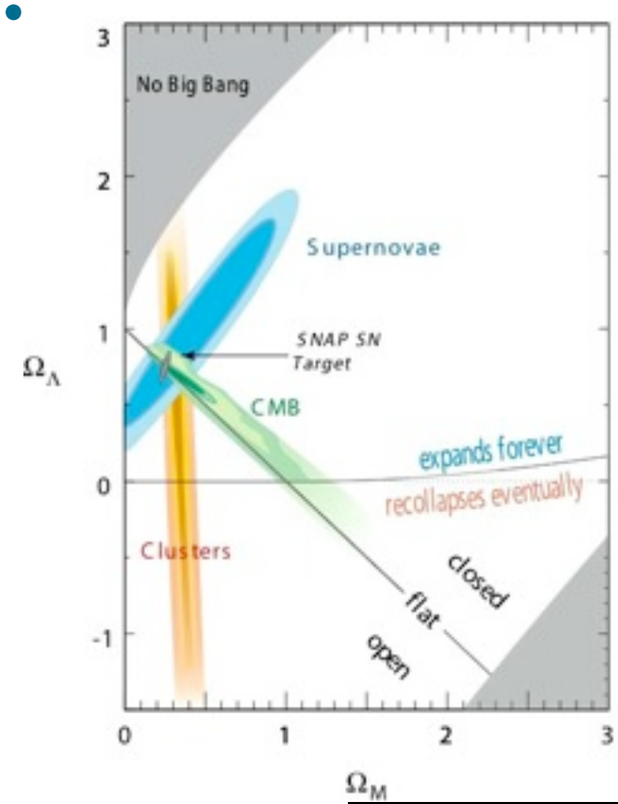
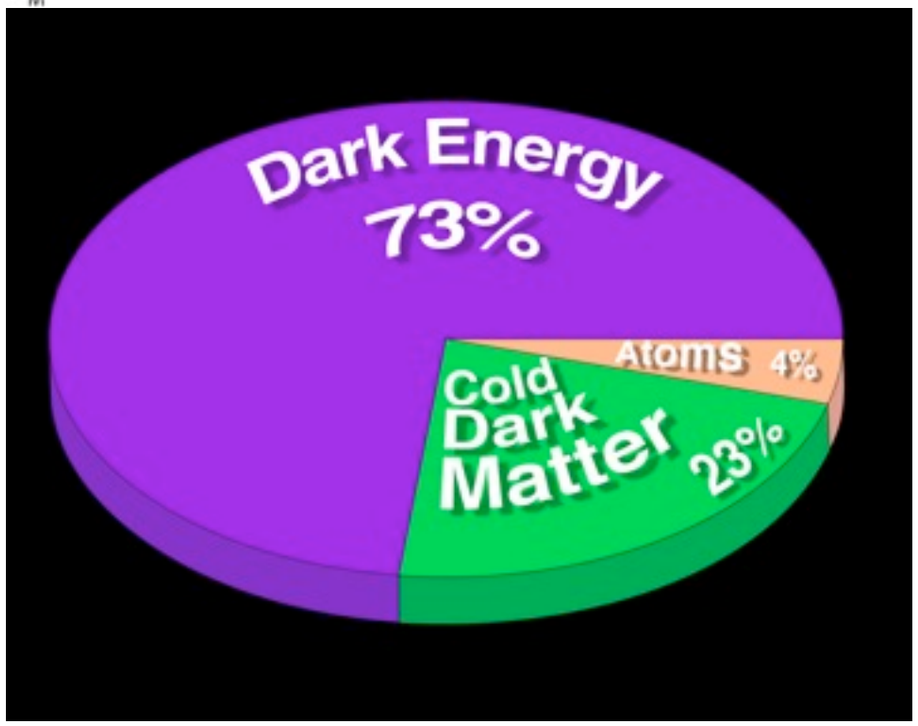
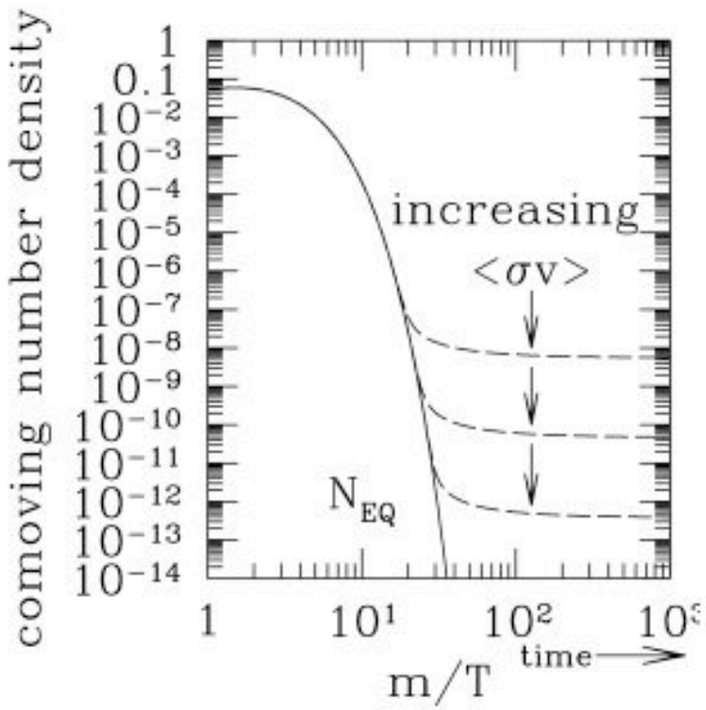


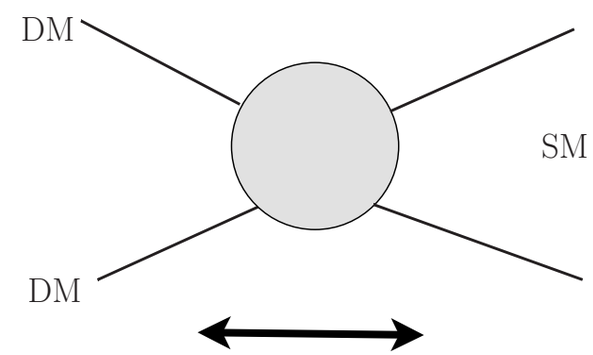


- gravitates.
- is dark.
- Only NP beyond SM discovered so far.



TeV dark matter: WIMP miracle.





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

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!

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

Different spin
different Z_2

Effective operator

LSNPs:
SUSY LSP
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Candidates, models, scenarios...

Model independent

Different spin different Z_2

Extended Models

Effective operator

LSNPs:
SUSY LSP
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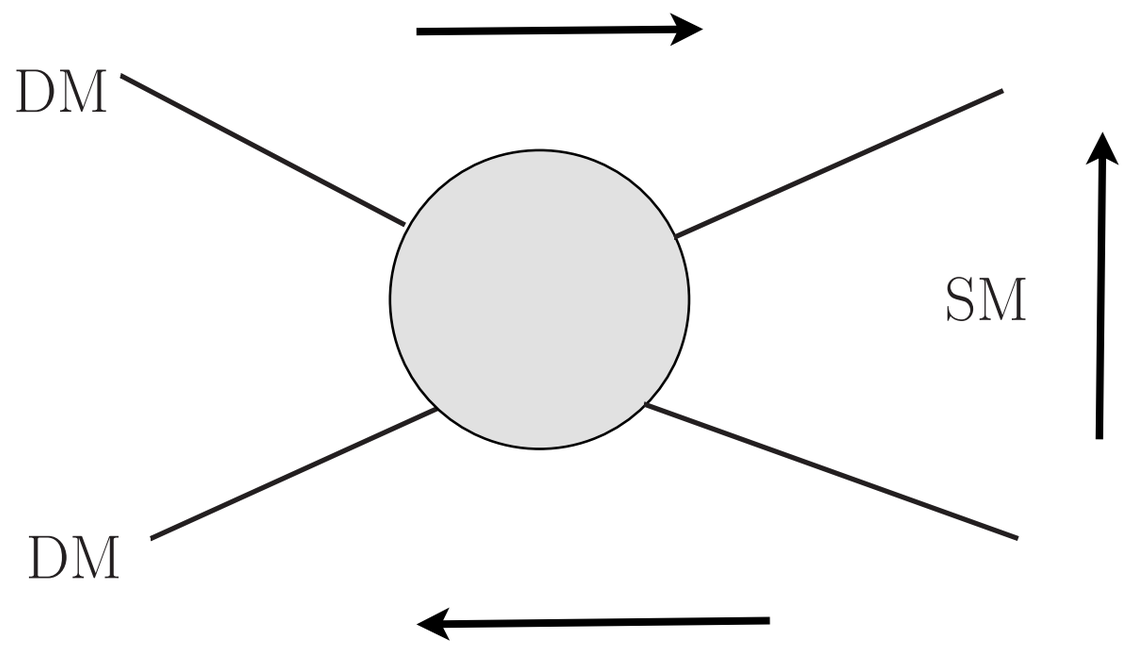
L...P
Z_3

dark sectors

Searching for WIMP dark matter

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



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

Collider searches:
LEP
LHC
Tevatron

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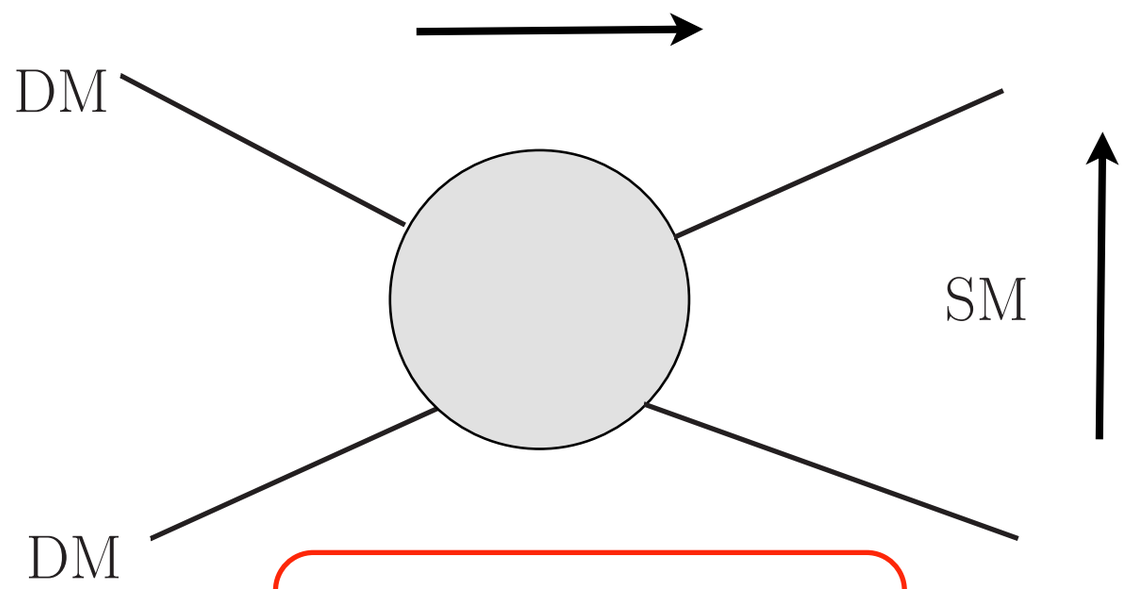

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This talk.

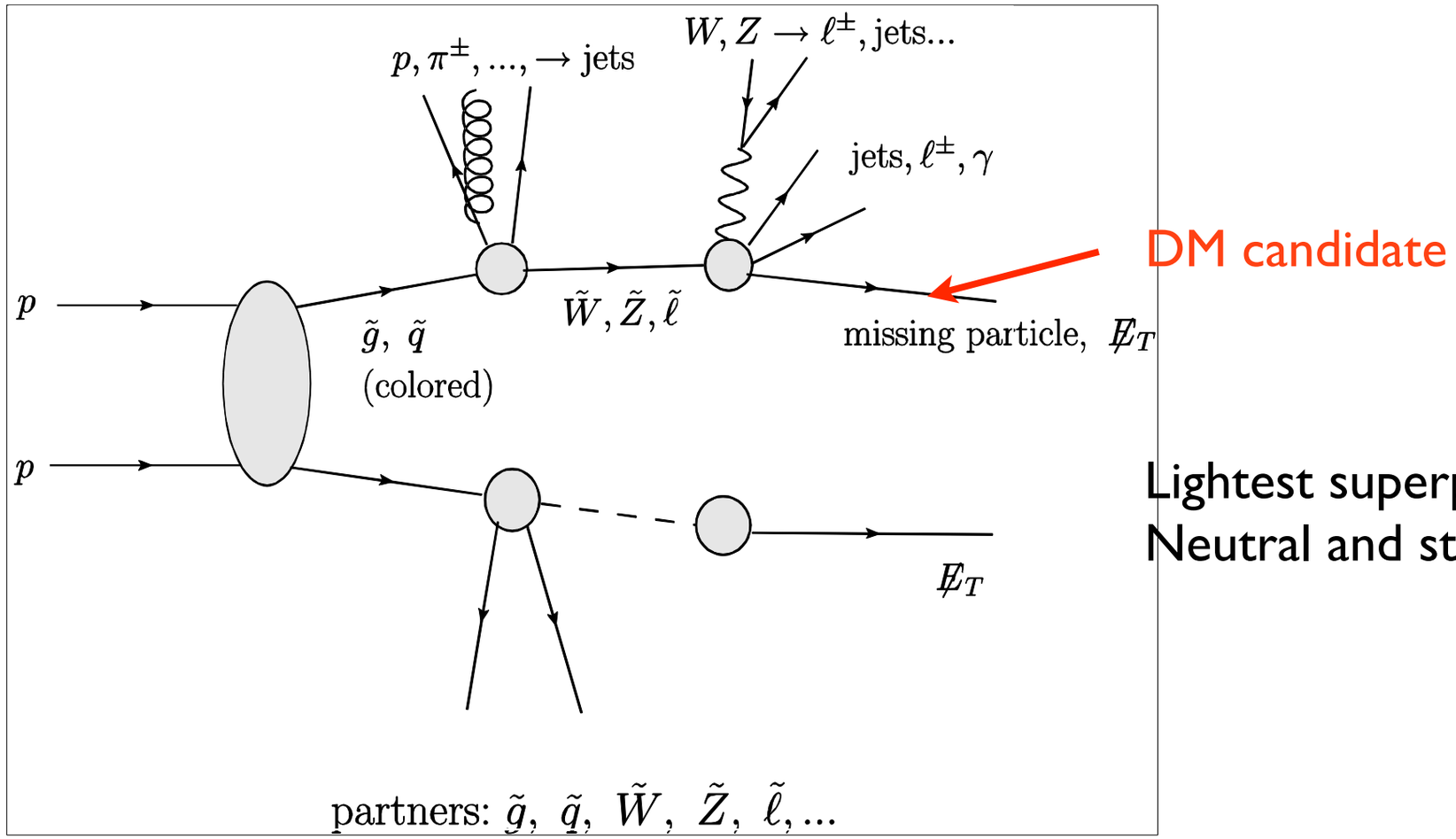
This talk, a brief overview of

- Search for SUSY dark matter, and measure its properties.
  - Highlight challenges.
- Connection between collider searches and direct detection.
- Dark sector.

Search for SUSY dark matter

Discovering dark matter:

- DM candidate embedded in an extended TeV new physics scenario



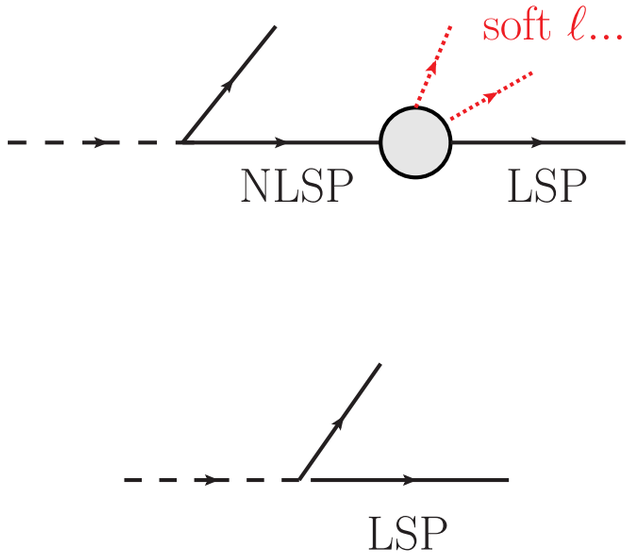
Lightest superpartner (LSP)
Neutral and stable.

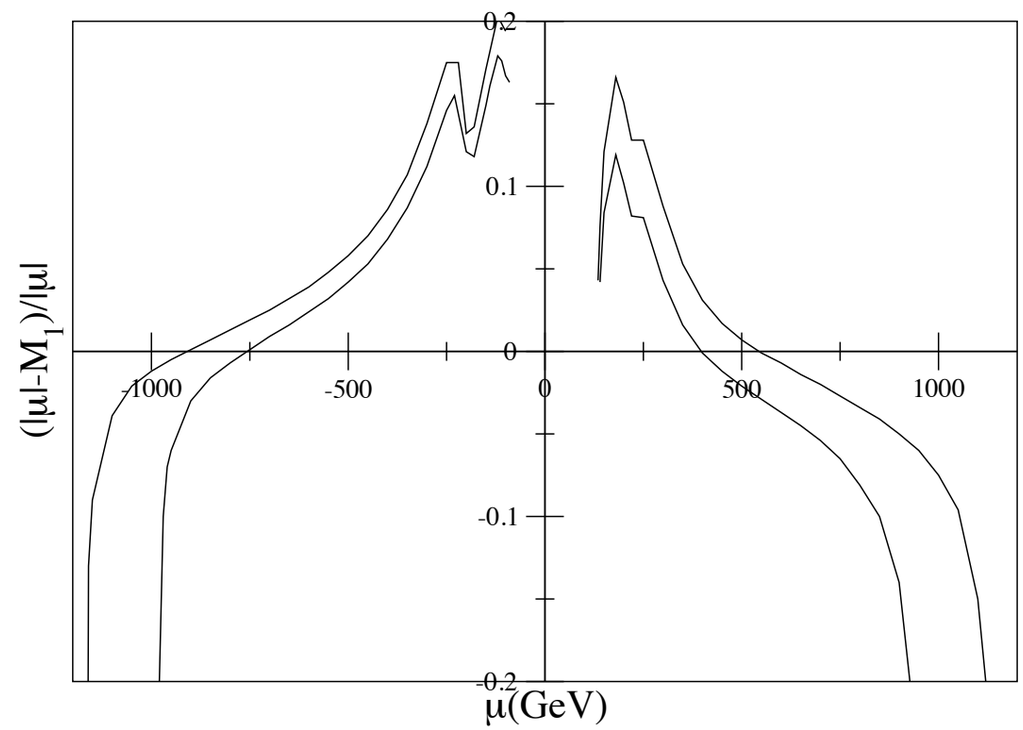
- Could be early discovery.

Could be harder to make sure.

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

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





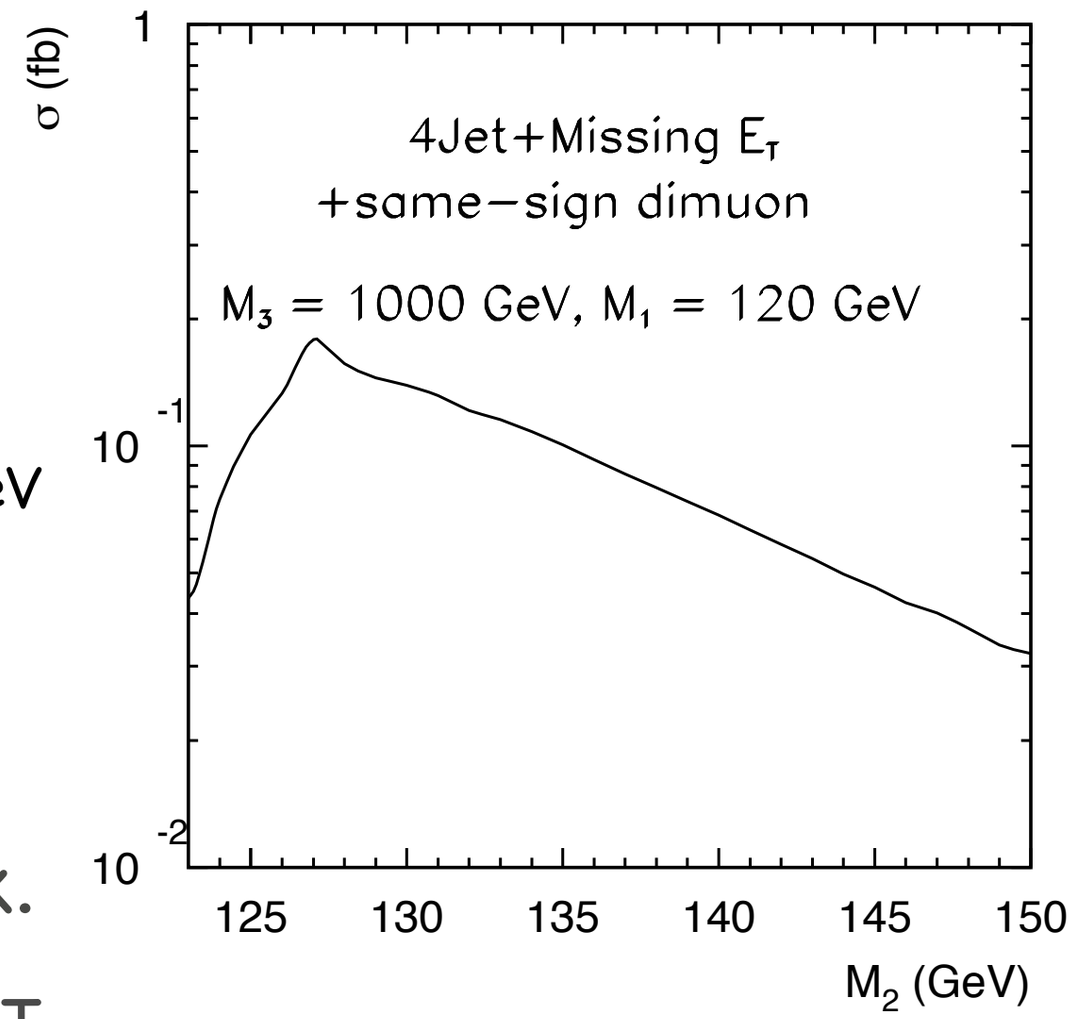
$$m_{\rm NLSP} - m_{\rm LSP} \sim 10 - 20 \text{ GeV}$$

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

LHC prospect for well tempered DM

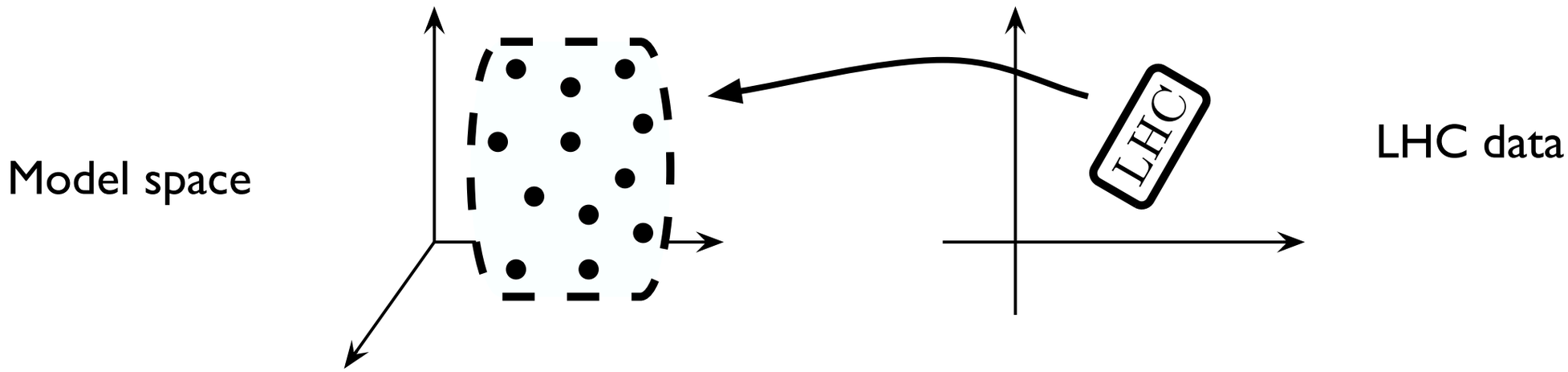
G. Giudice, T. Han, K. Wang and LTW, 1004.4902

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.

After discovery, 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...

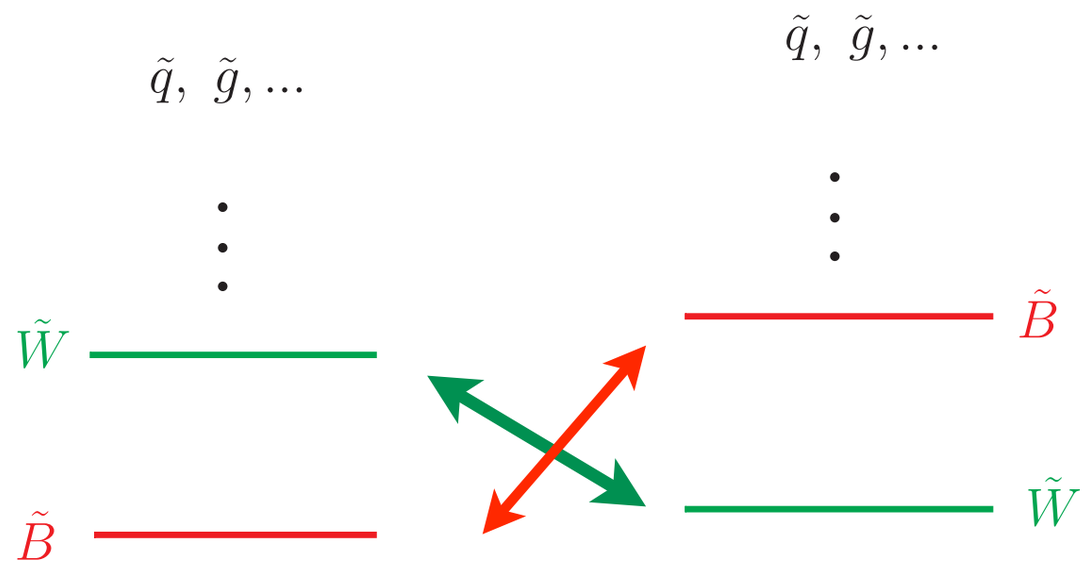
For example: in supersymmetry, bino vs wino, squark vs gluino...

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

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

- M_{LSP}.

- Spin.

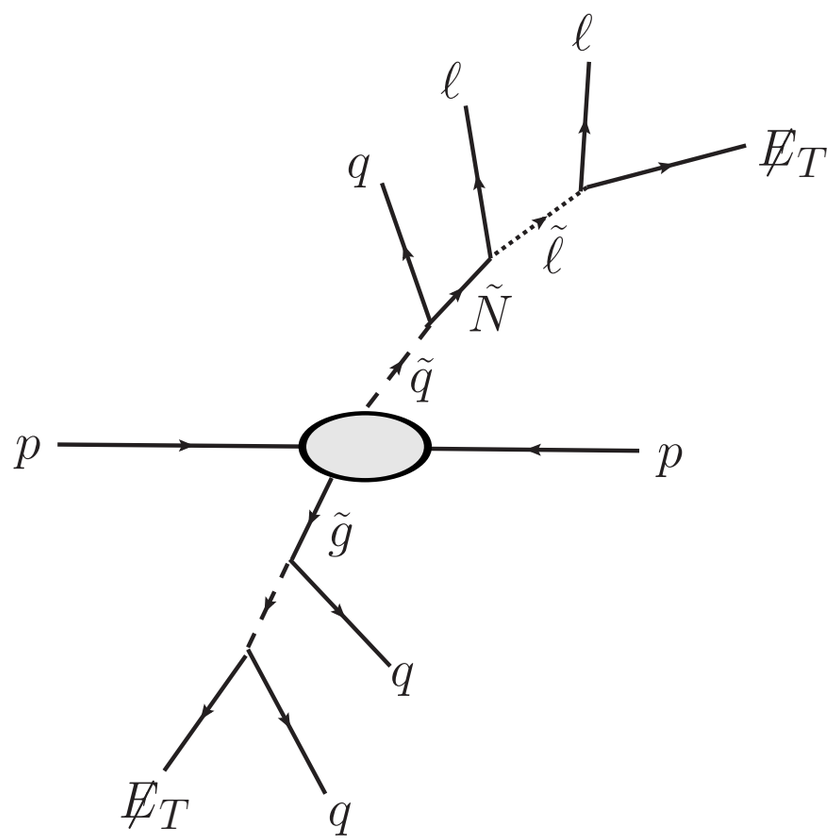
Many recent progresses.
For example, Dutta's talk in this workshop

Spin measurements. Supersymmetry?

Spin measurements. Supersymmetry?

Example: spin of $\tilde{N}$

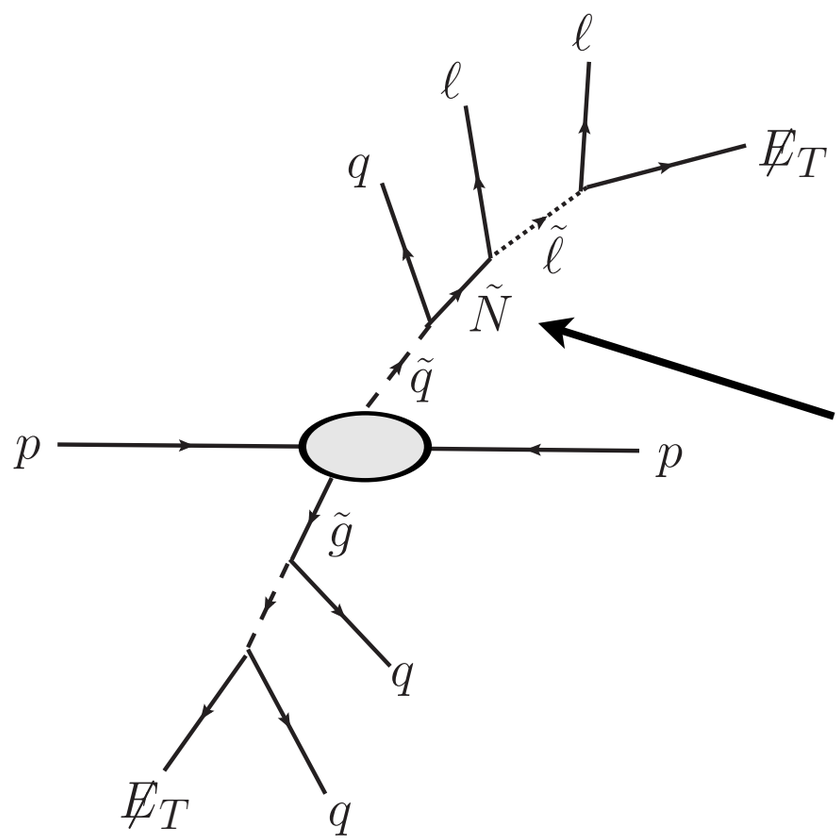
Spin measurements. Supersymmetry?



Example: spin of $\tilde{N}$

Clean exclusive sample

Spin measurements. Supersymmetry?



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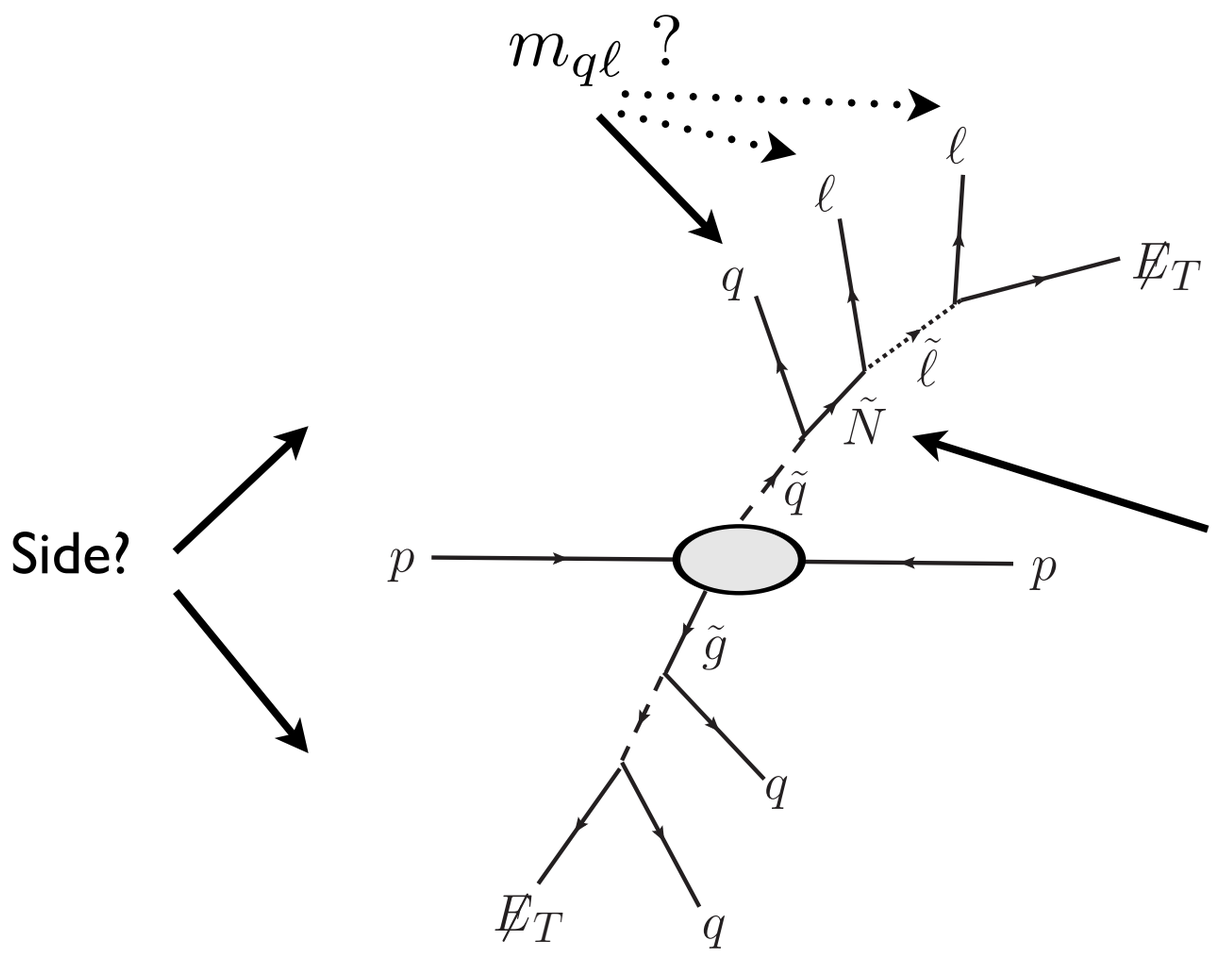
Clean exclusive sample

Boost (kinematics) vs matrix element (spin)

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

Spin measurements. Supersymmetry?



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Combinatorics

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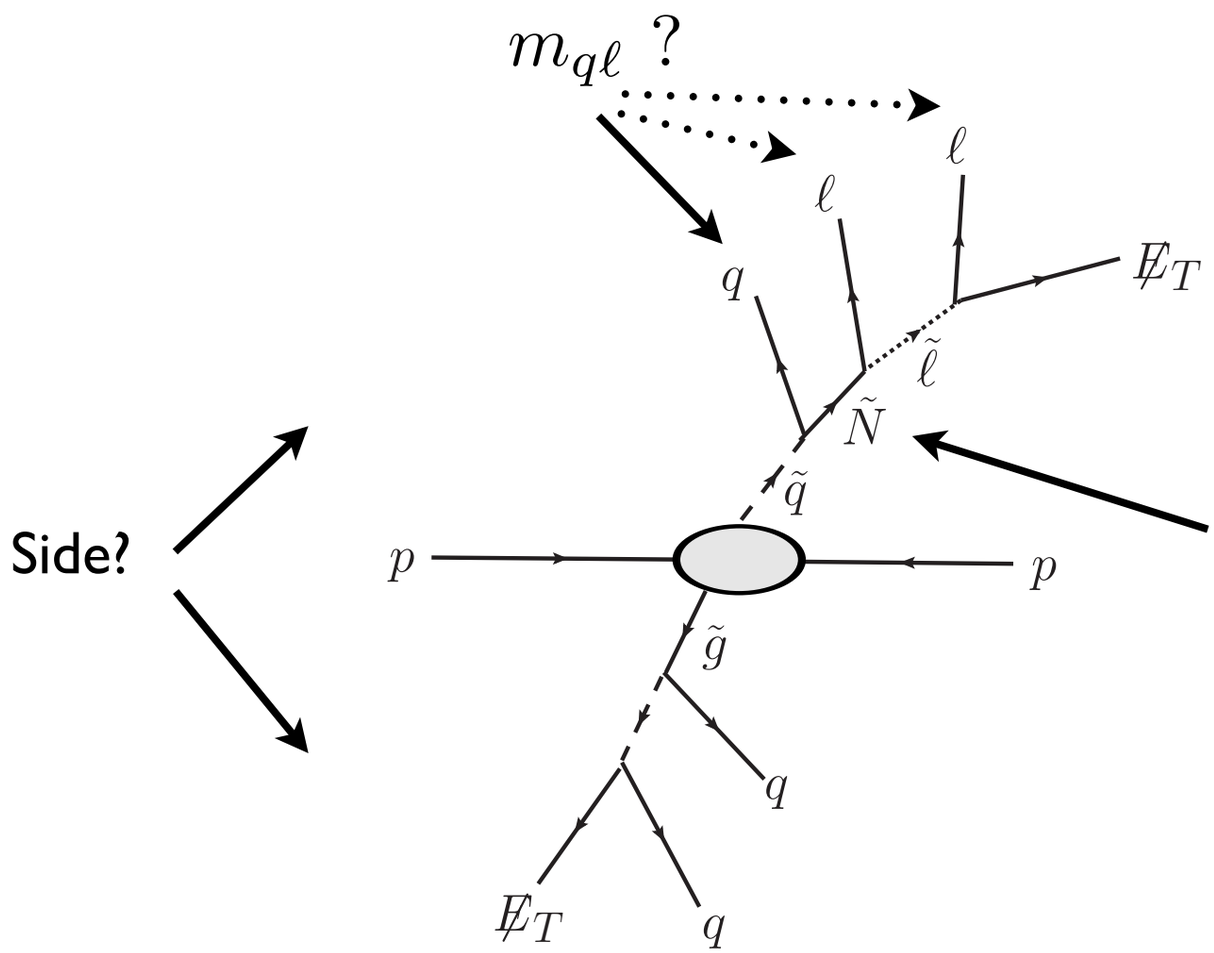


Example: spin of $\tilde{N}$

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.

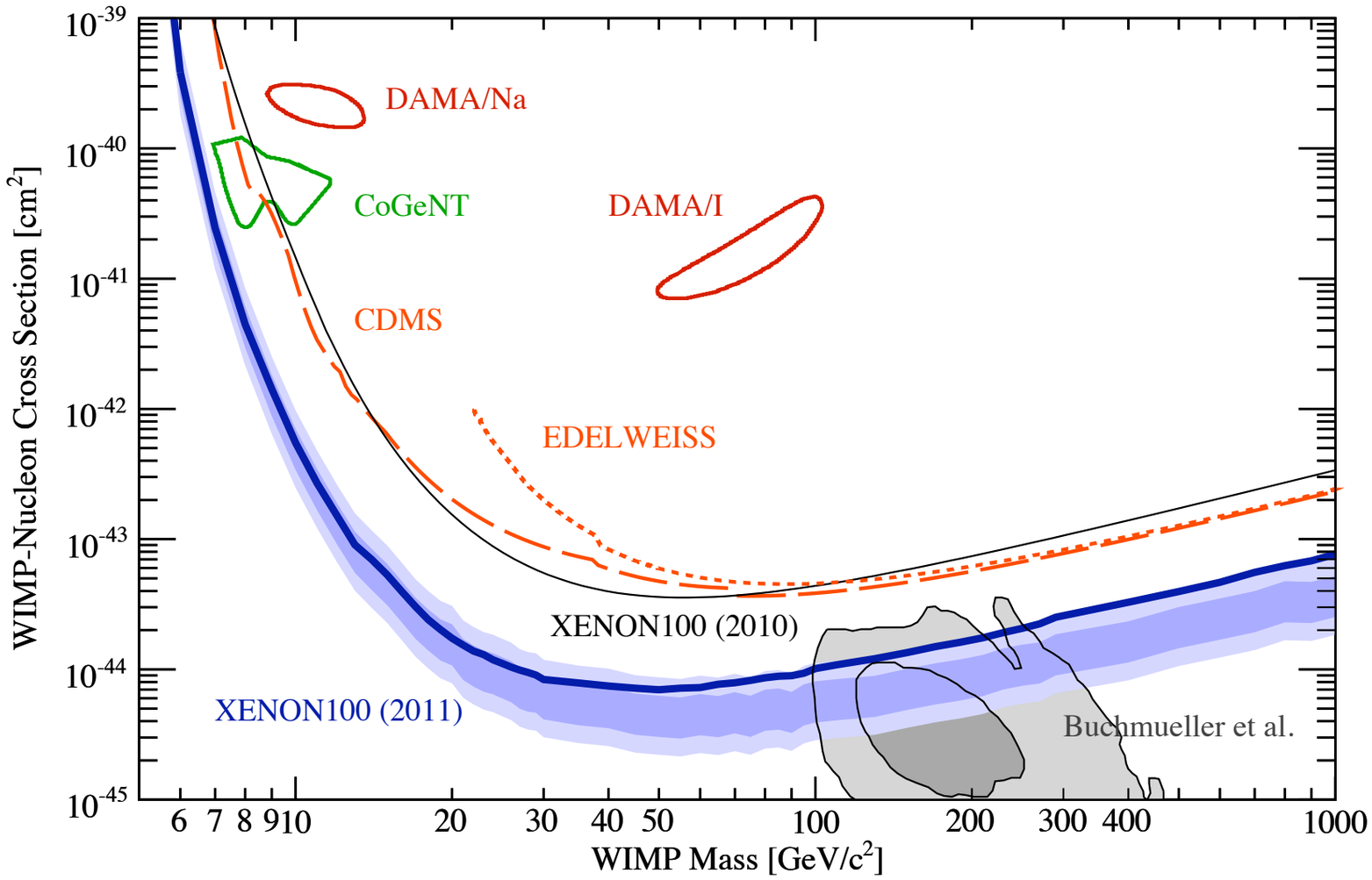
Possible path to measure mass and spin.

- With early data, O(fb^{-1})
  - Rough estimate of mass scale.
  - A guess of the spin. ⇦ Model dependent
- With high statistics, O(100 fb^{-1})
  - Precise mass measurement.
  - Spin measurement.
- Early estimates can help designing best strategies for precise study.

Connection with direct detection

Probe NP with direct detection

XENON 100, 1104.2549



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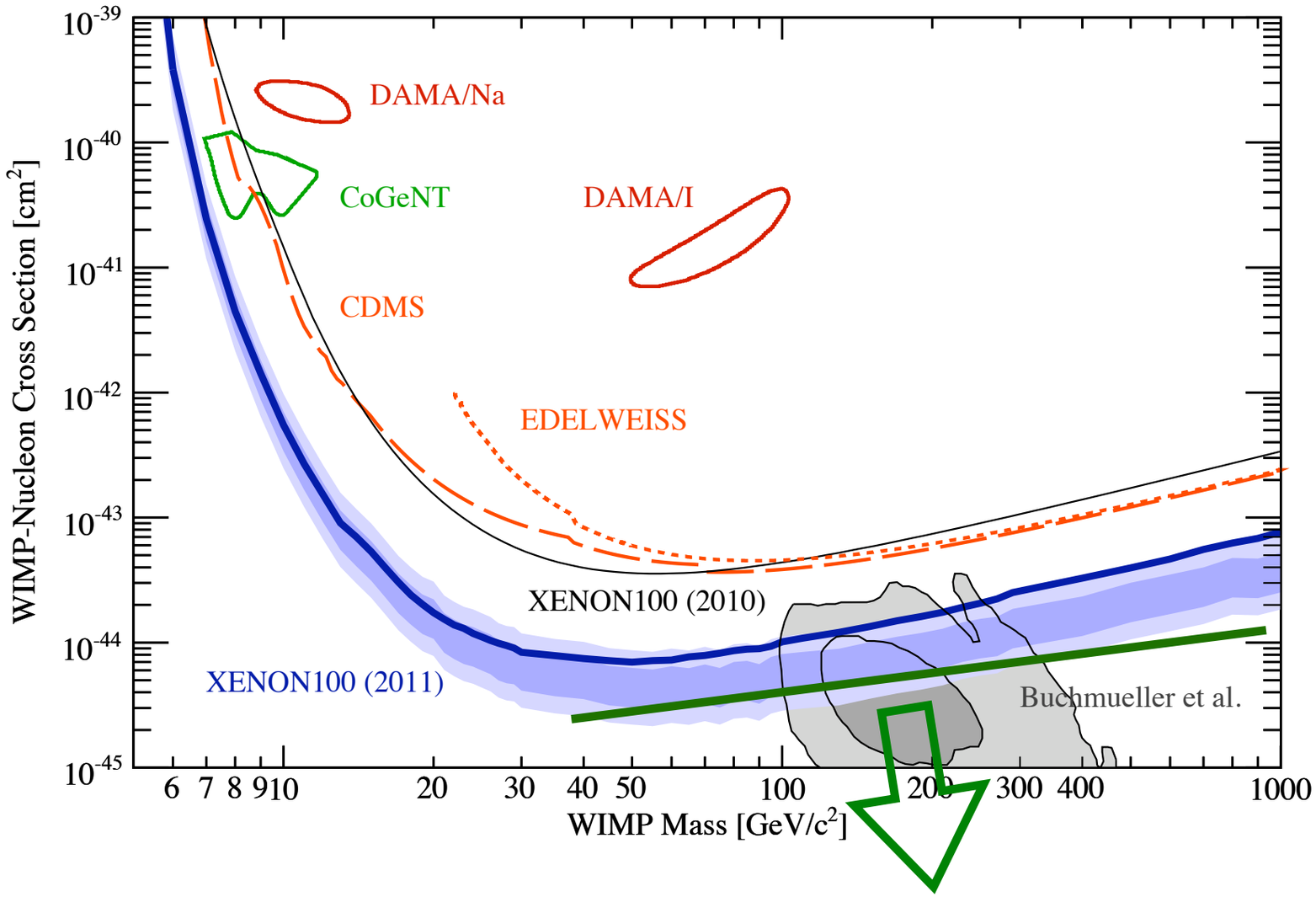

- $M_{WIMP} = O(10^2)$ GeV.
- DM of "Typical" scenarios: SUSY LSP, ...

Probe NP with direct detection

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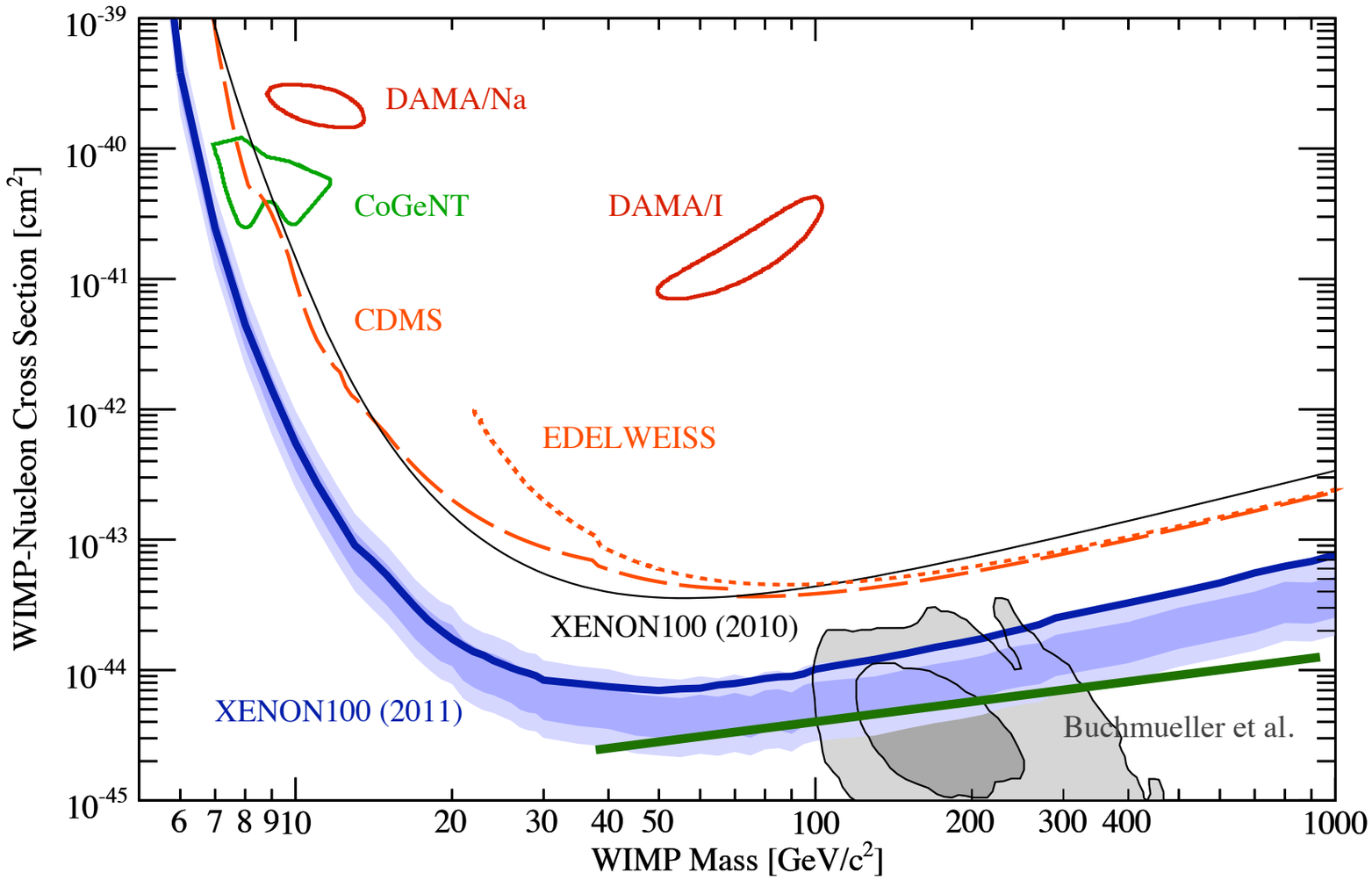

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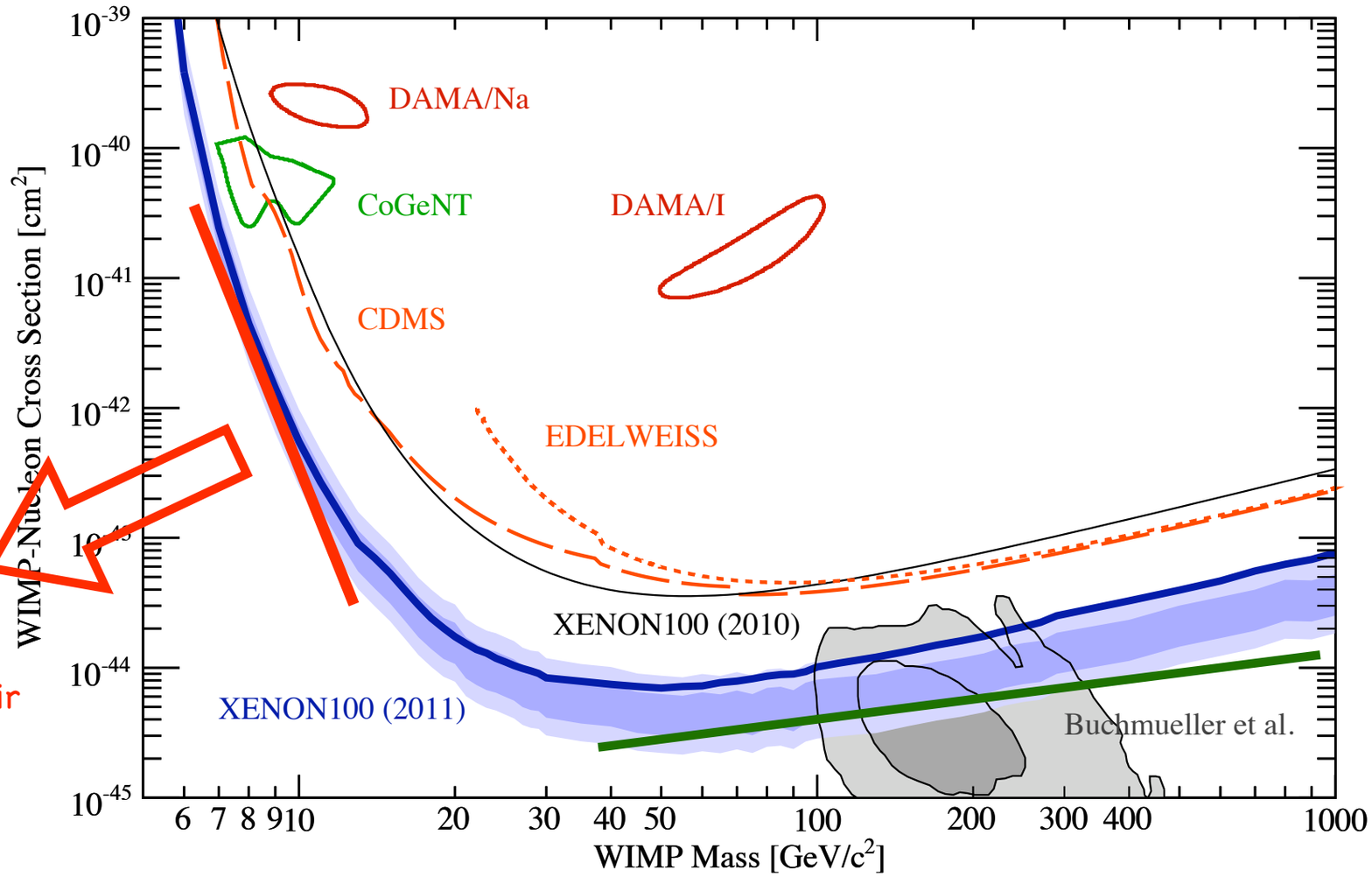

m_{WIMP}:
O(1-10) GeV
Much larger σ_{dir}

Probe NP with direct detection

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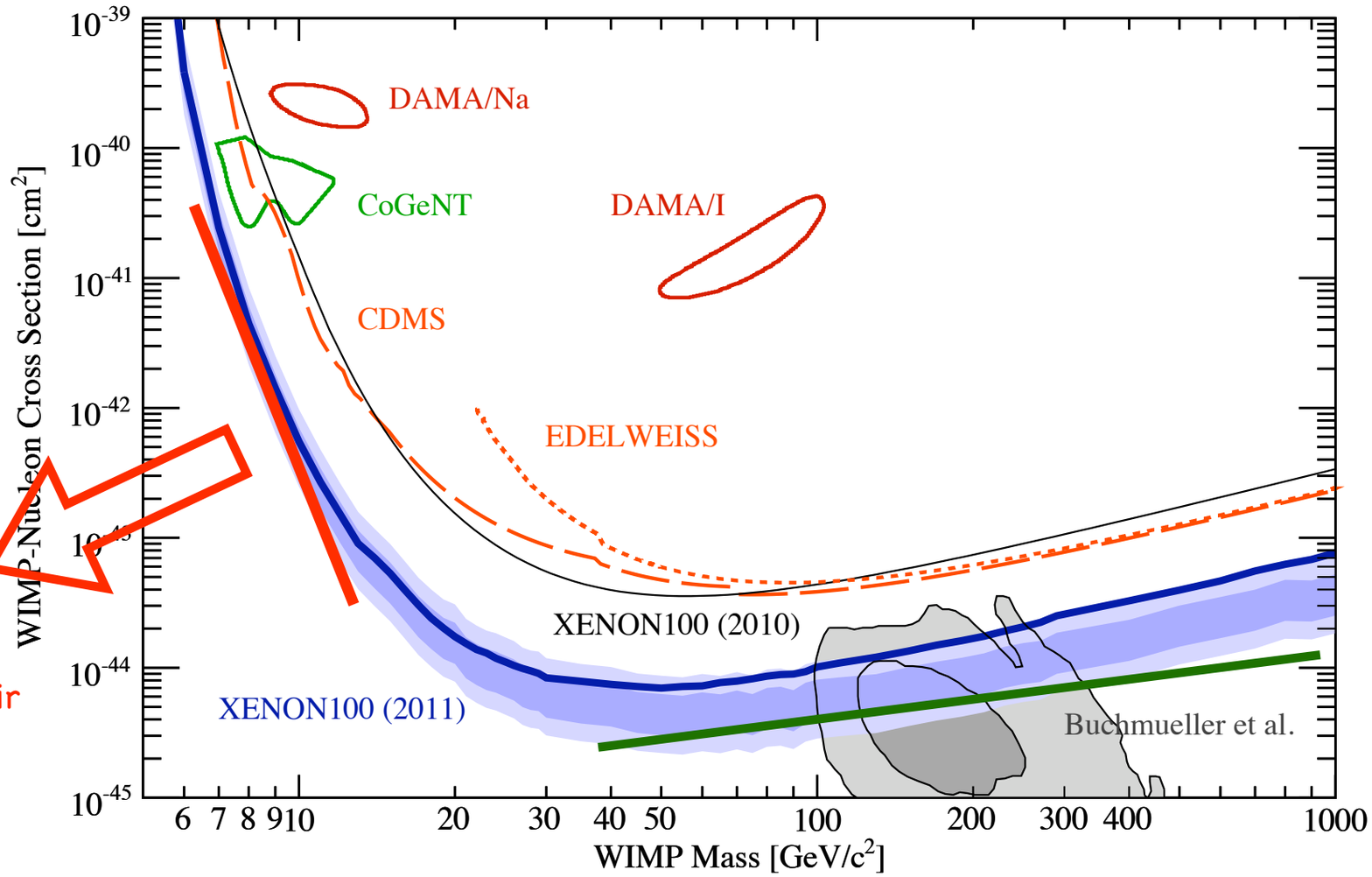
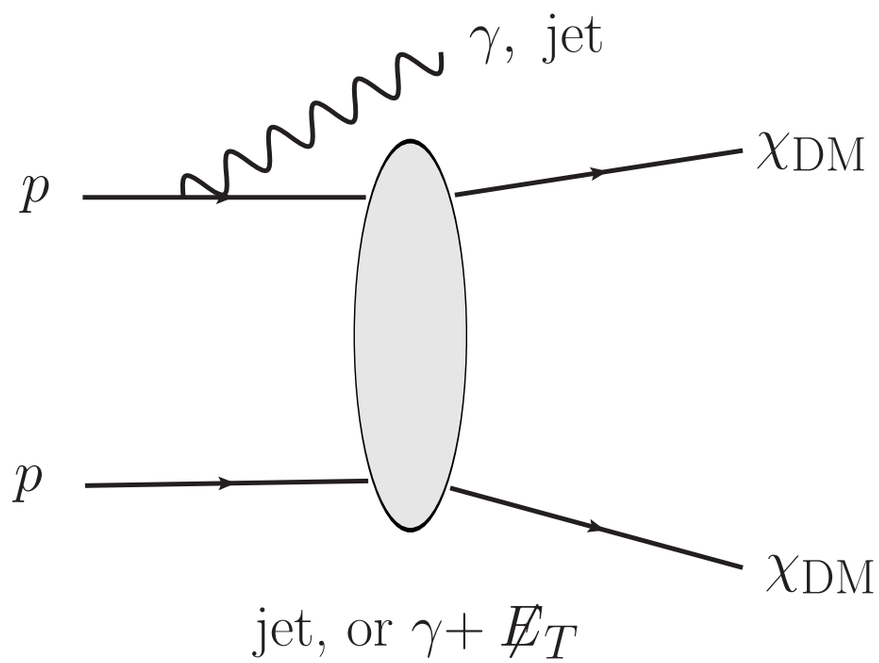


m_{WIMP}:
O(1-10) GeV
Much larger σ_{dir}

- Collider searches provide stronger bounds/potential

Basic channel

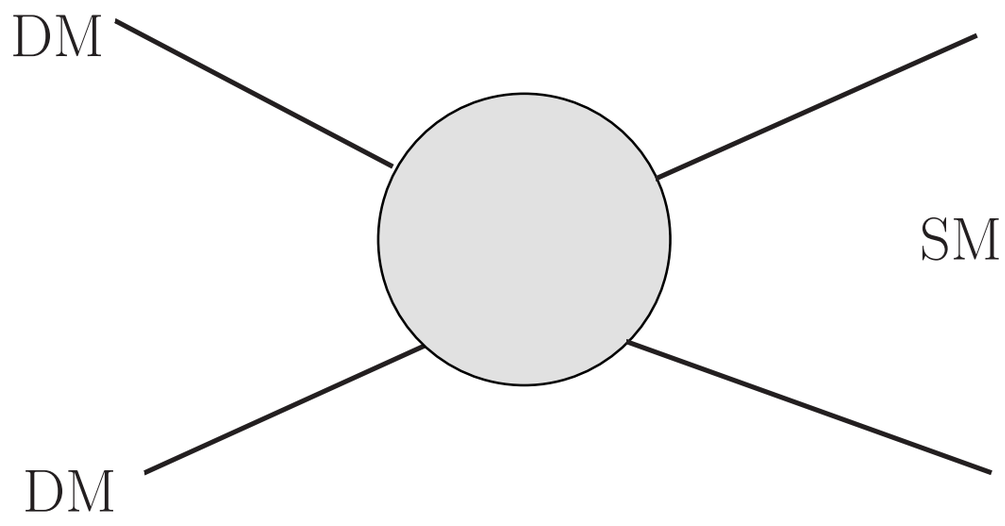
- Pair production + additional radiation.



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

- Very challenging.

Effective operator approach



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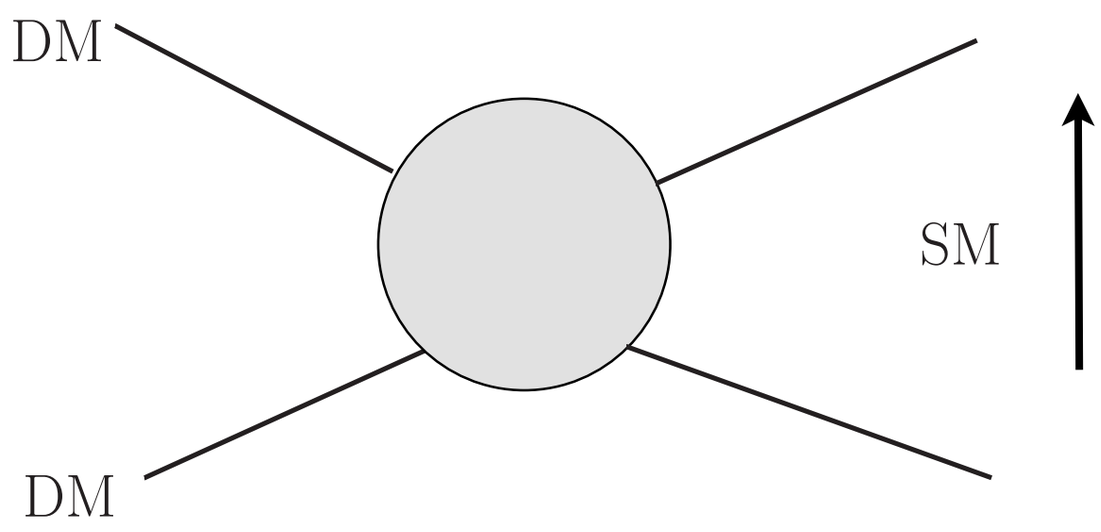
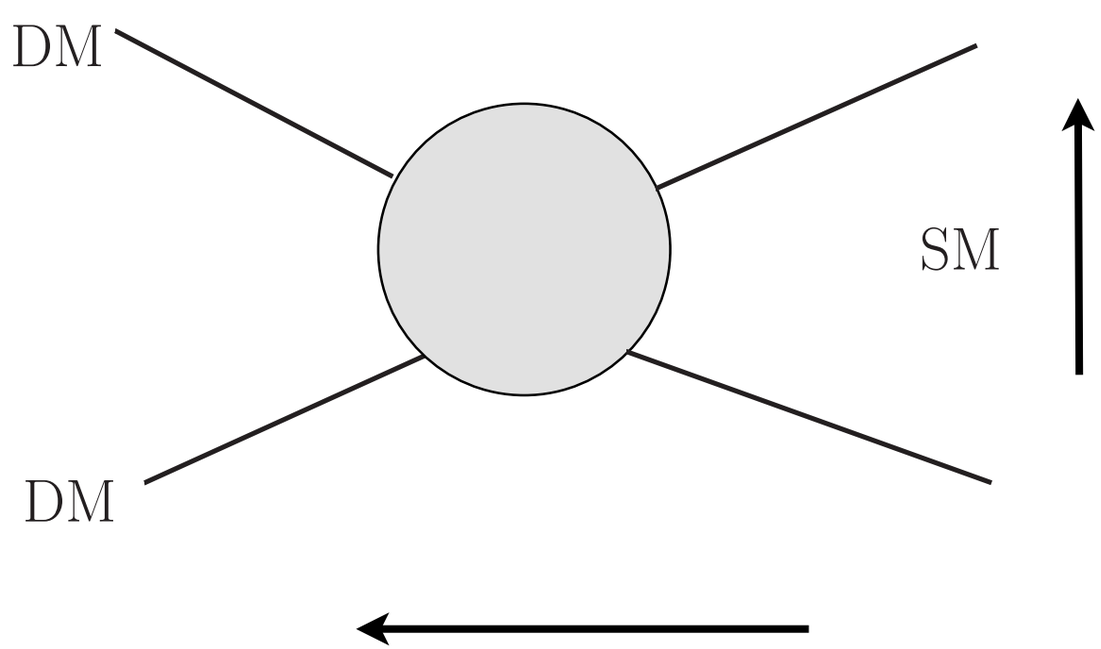


momentum exchange
q~100 MeV << m_Φ
effectively,

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

Effective operator approach



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effectively,

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Use colliders to constrain and probe
the same operator

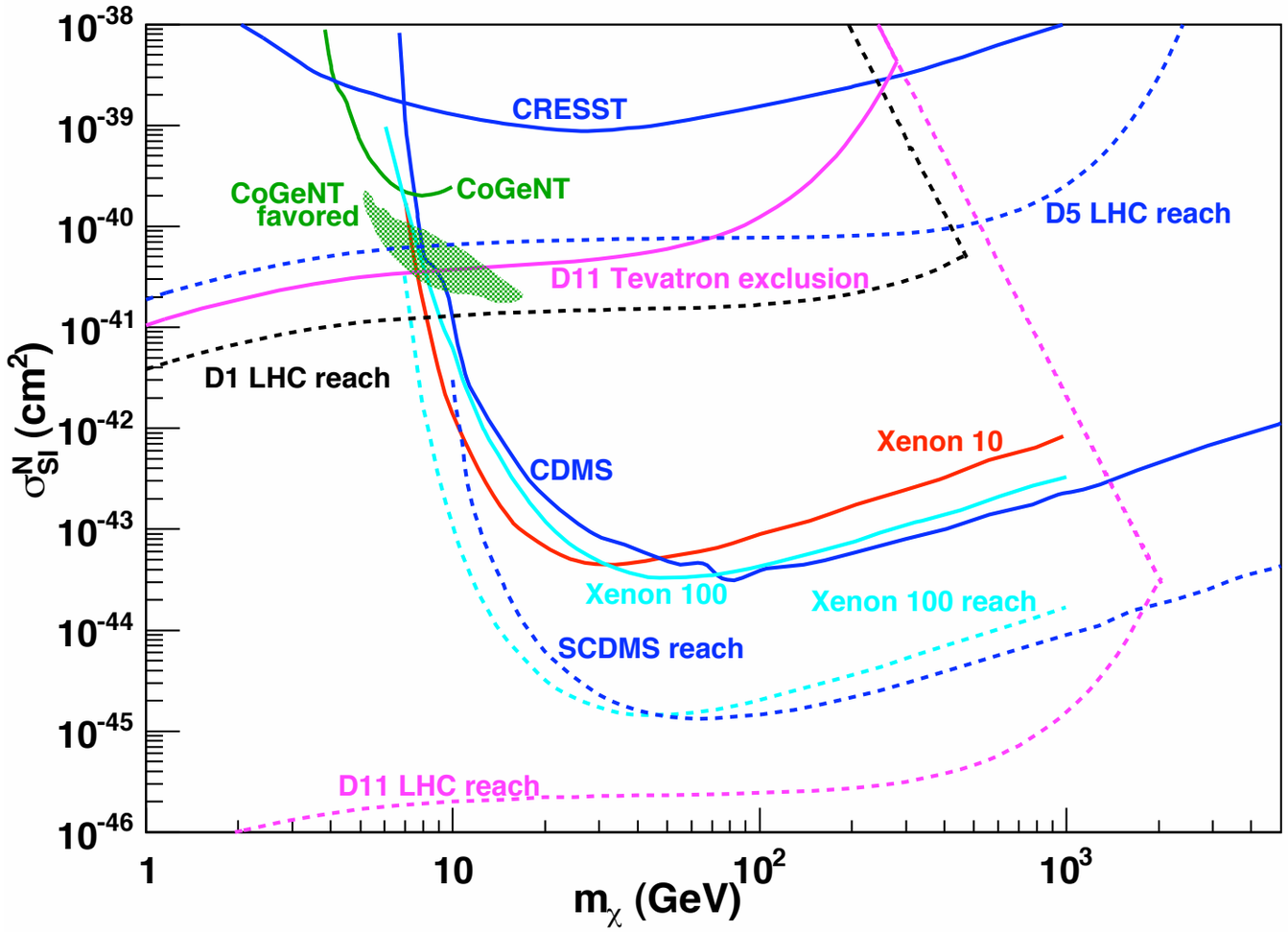
$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

Recent studies.

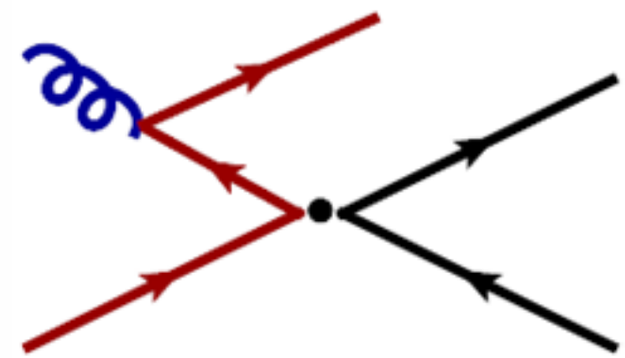
1. Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
2. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
3. Bai, Fox, Harnik, 1005.3797
4. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783
5. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1009.0008
6. Fox, Harnik, Kopp, Tsai, 1103.0240
7. Fortin,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

For example, 1008.1783

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



monojet



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

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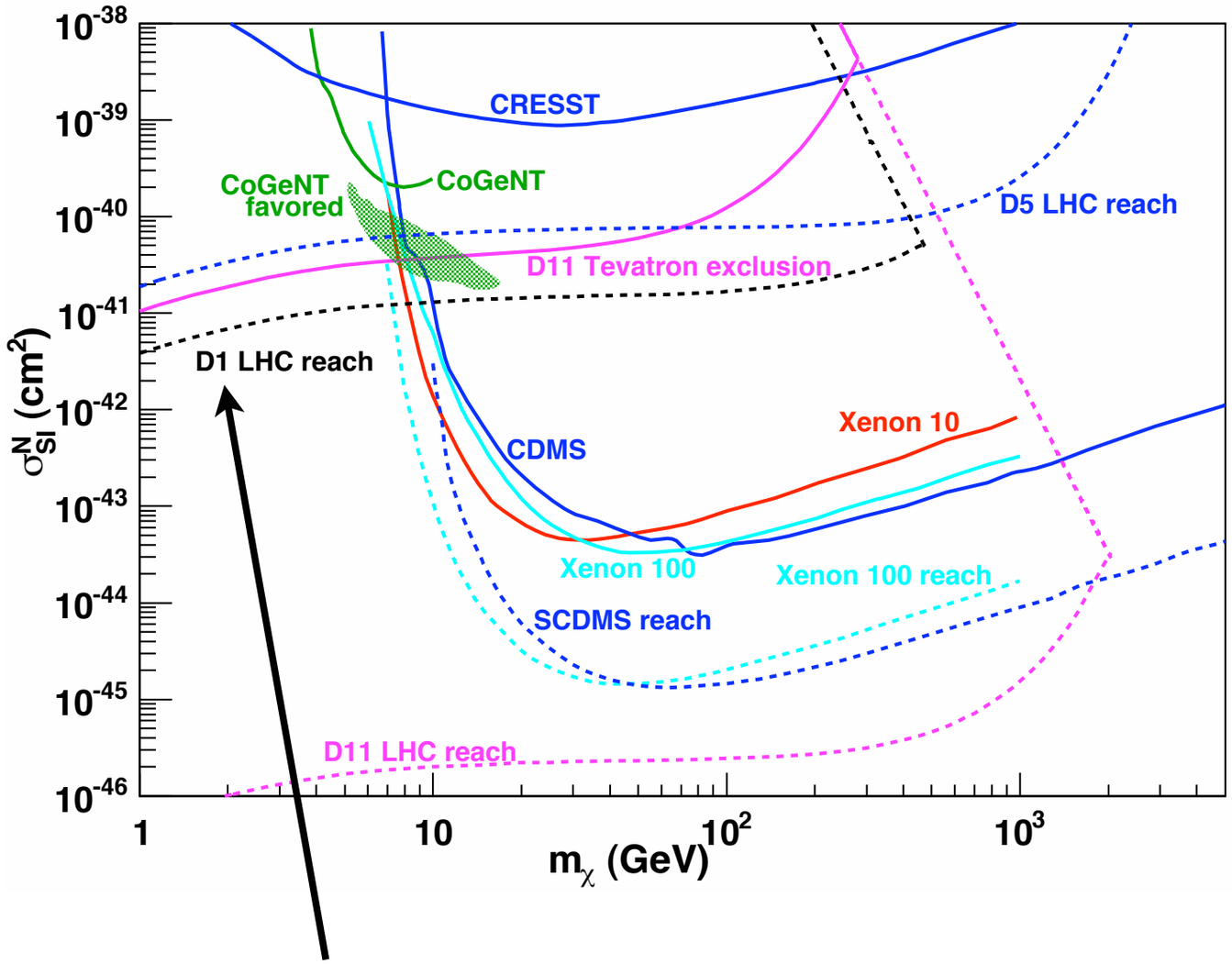

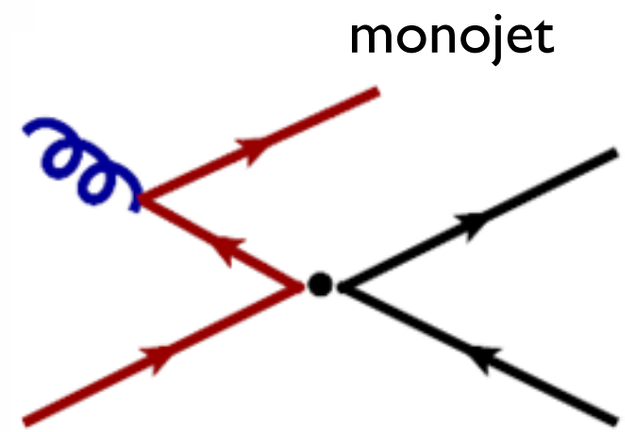

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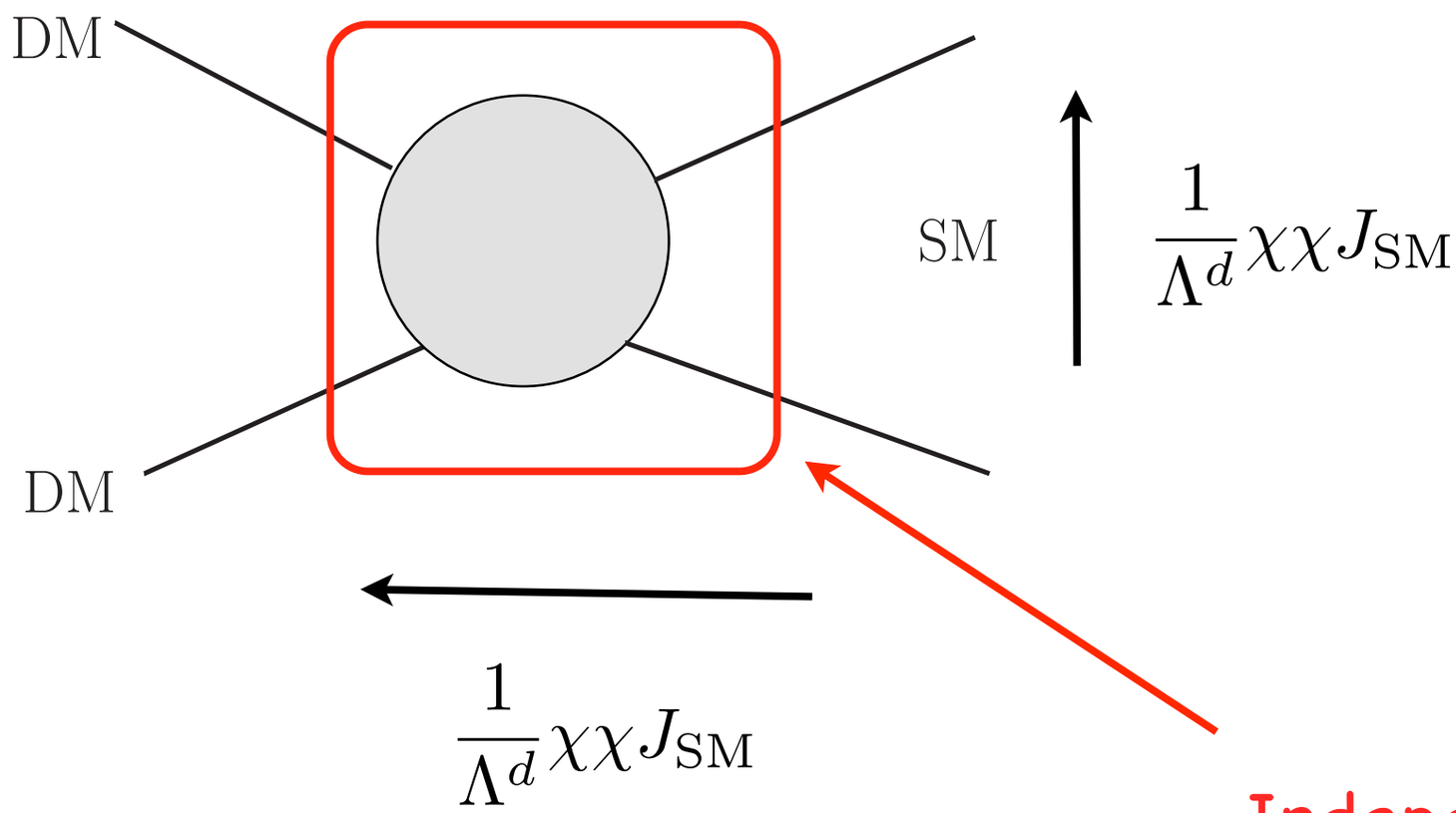
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

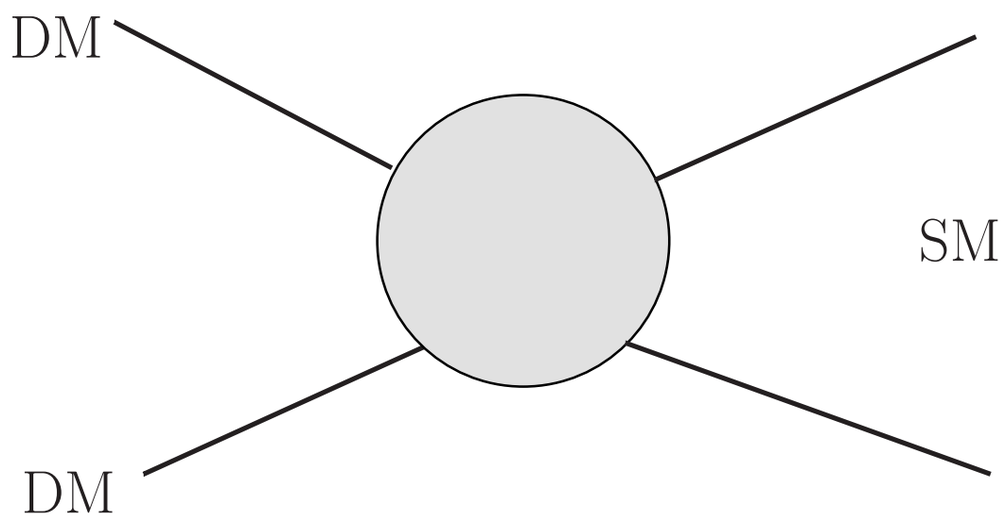
For small m_χ,
collider rates controlled by larger mass scales, i.e., p_T cut;
does not depend on m_χ.
Collider bounds flat and stronger.

Effective operator effective?



Independent of the details?

Effective operator effective?



Use colliders to constrain and probe the same operator

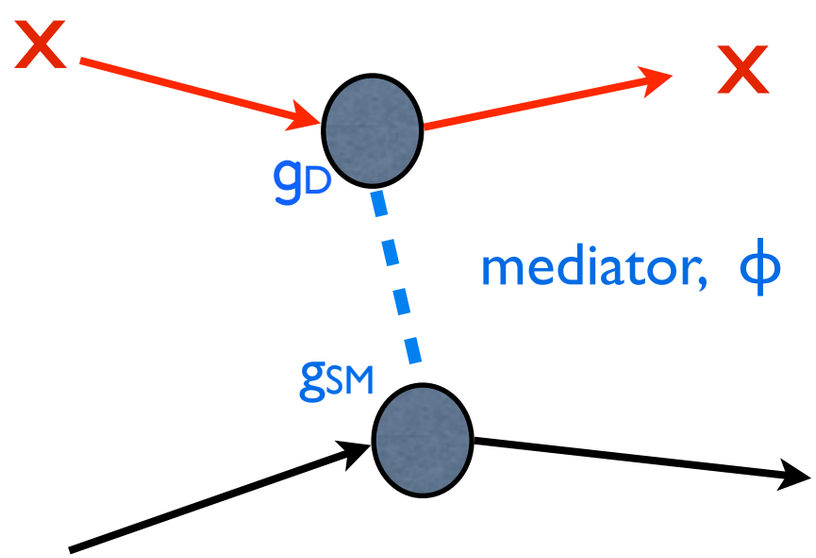
$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

However, E_{cm} = 100s GeV~ m_Φ, probing more structure of the s-matrix.

Depending on more details of the mediator.

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

Mediator, two typical examples.



N= Ar, Ge, Xe, ...

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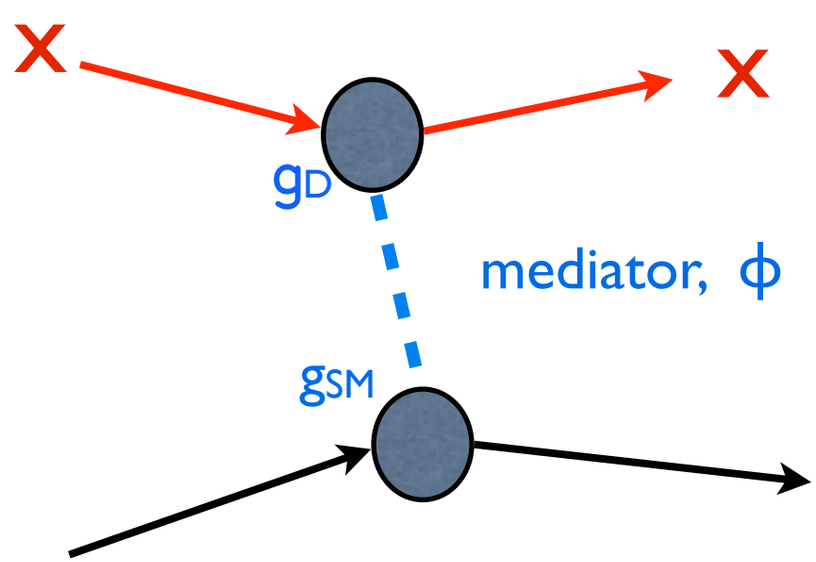
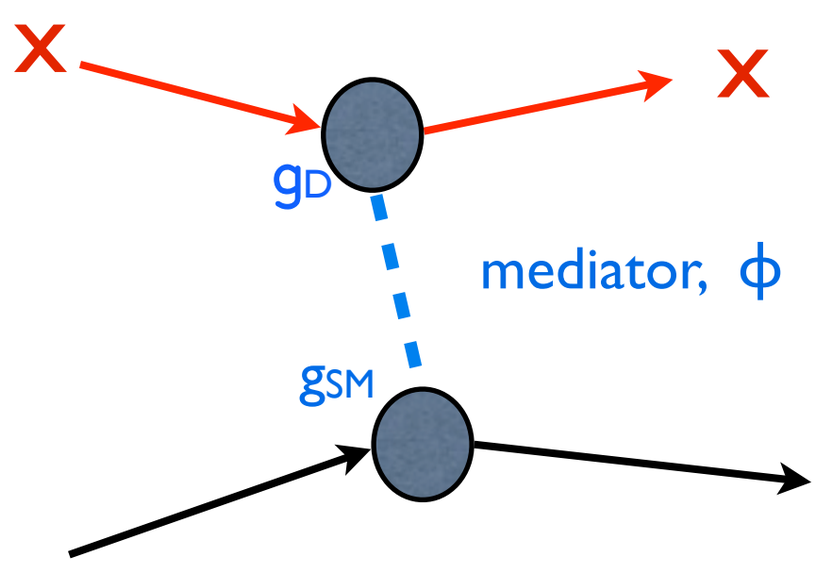


N= Ar, Ge, Xe, ...

- 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}

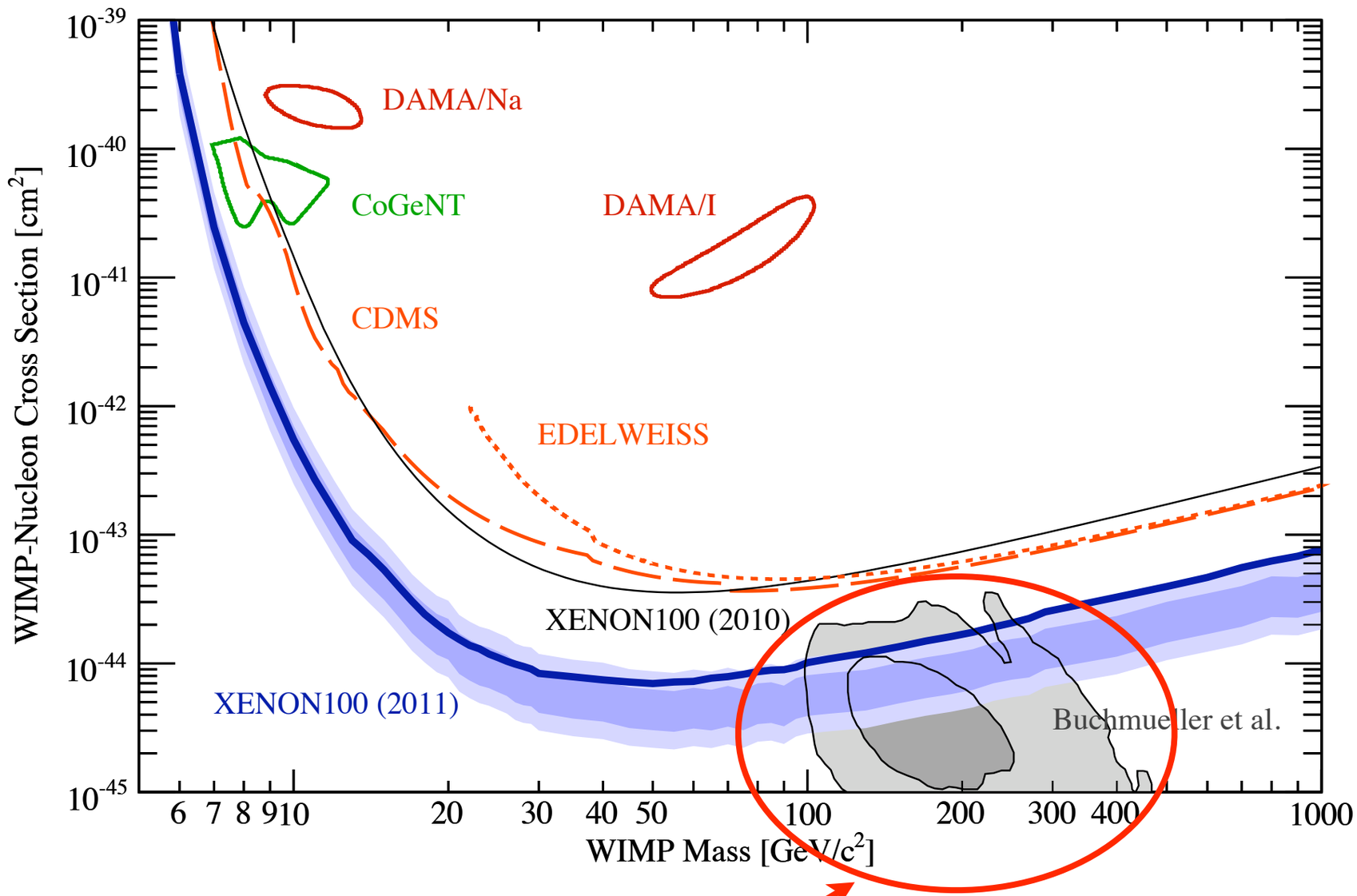
Mediator, two typical examples.



N= Ar, Ge, Xe, ...

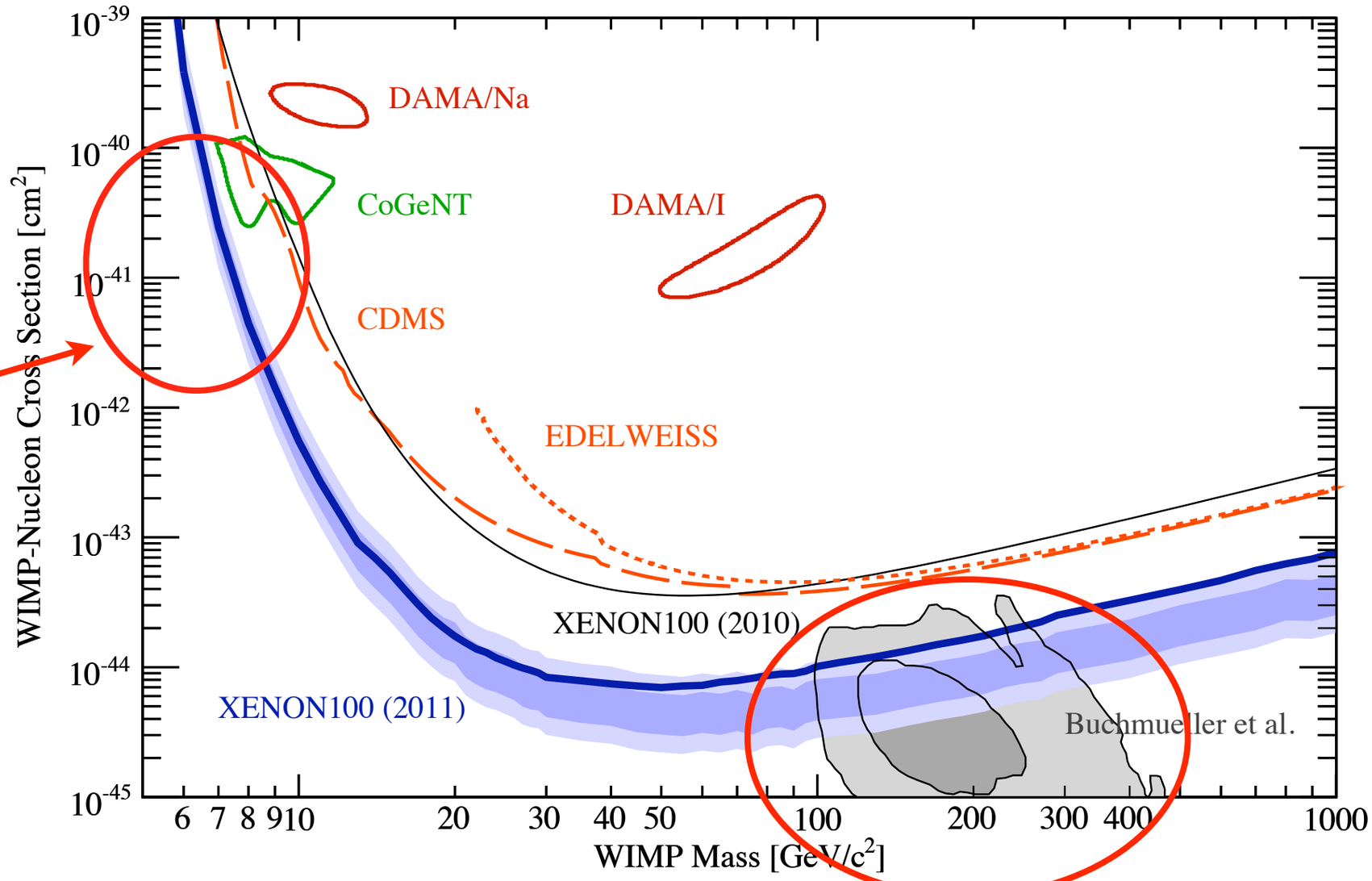
- ϕ=Higgs
  - $g_{SM} \approx$(100 MeV)/(100 GeV)
  - $m_x \approx$ 100 GeV
  - $\sigma_n \approx 10^{-43}$–$10^{-45}$ cm^{-2}
- Φ=100 GeV spin-1, D=dirac fermion
  - $\sigma_n \approx 10^{-36}$–$10^{-38}$ cm^{-2}

Probe NP with direct detection



SUSY, typically Higgs mediated.

Probe NP with direct detection



Light DM spin-1 mediator.

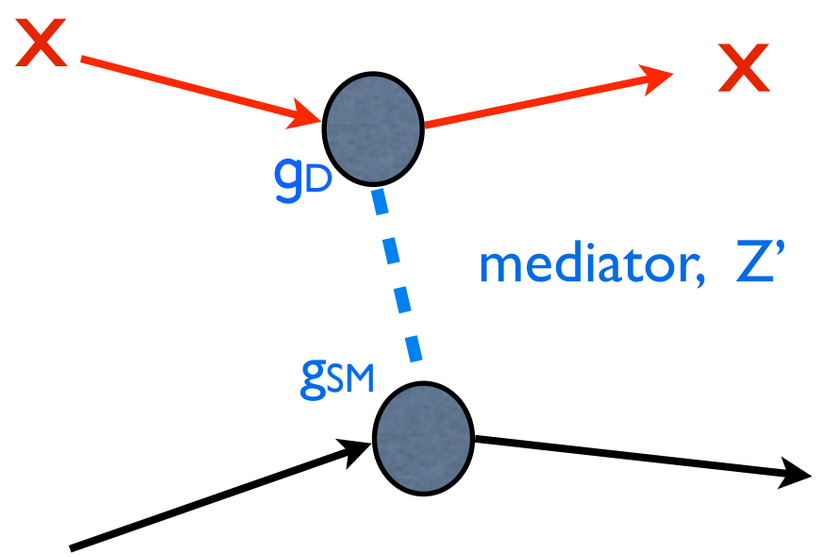
SUSY, typically Higgs mediated.

Case study: a spin-1 Z′

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

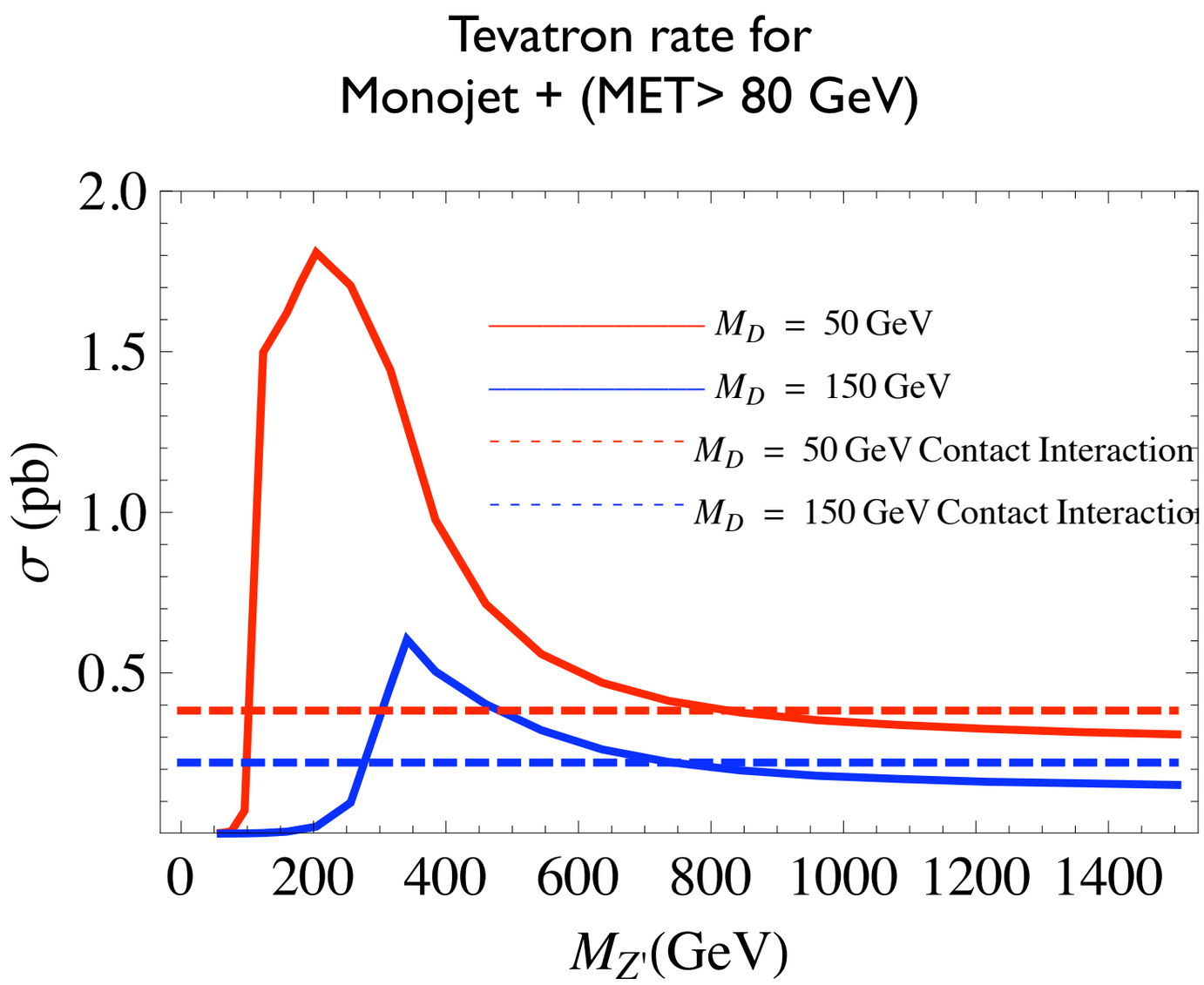
$$\mathcal{L} = Z'_\mu[\bar{q}(g_{Z'}\gamma^\mu + g_{Z'5}\gamma^\mu\gamma_5)q + \bar{X}(g_D\gamma^\mu + g_{D5}\gamma^\mu\gamma_5)X]$$

Only couples to SM quarks and DM.



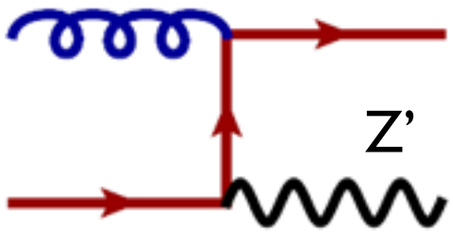
N= Ar, Ge, Xe, ...

Effectiveness of effective operator



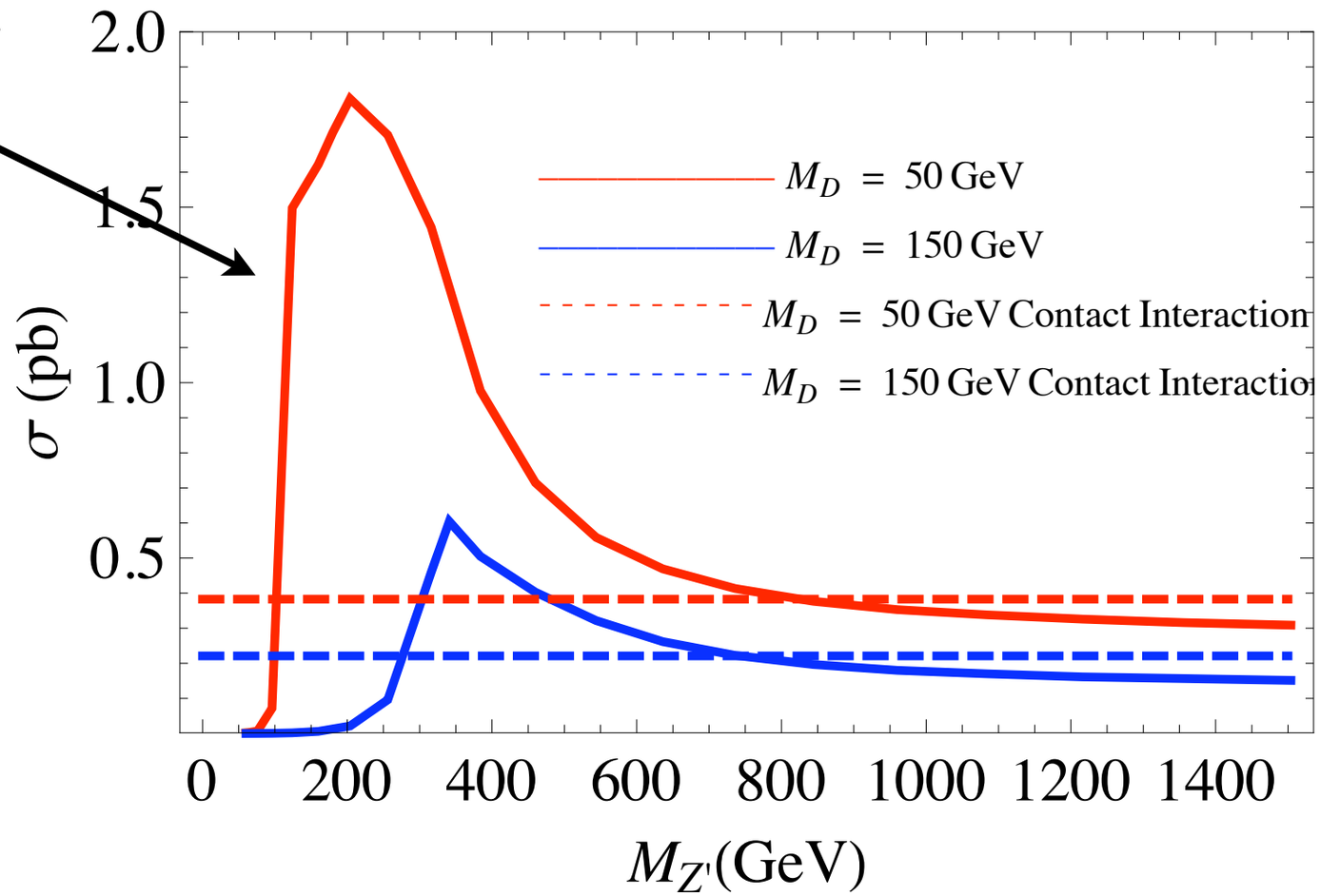
$g_D = g_{Z'}$, fix $g_{Z'}/M_{Z'}$

Effectiveness of effective operator



resonance prod.

Tevatron rate for
Monojet + (MET> 80 GeV)



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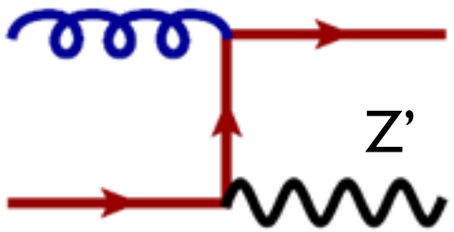

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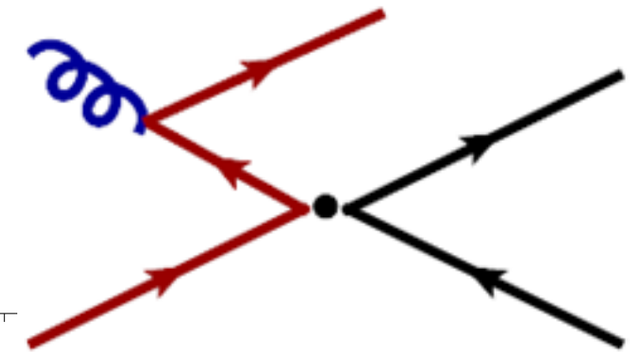
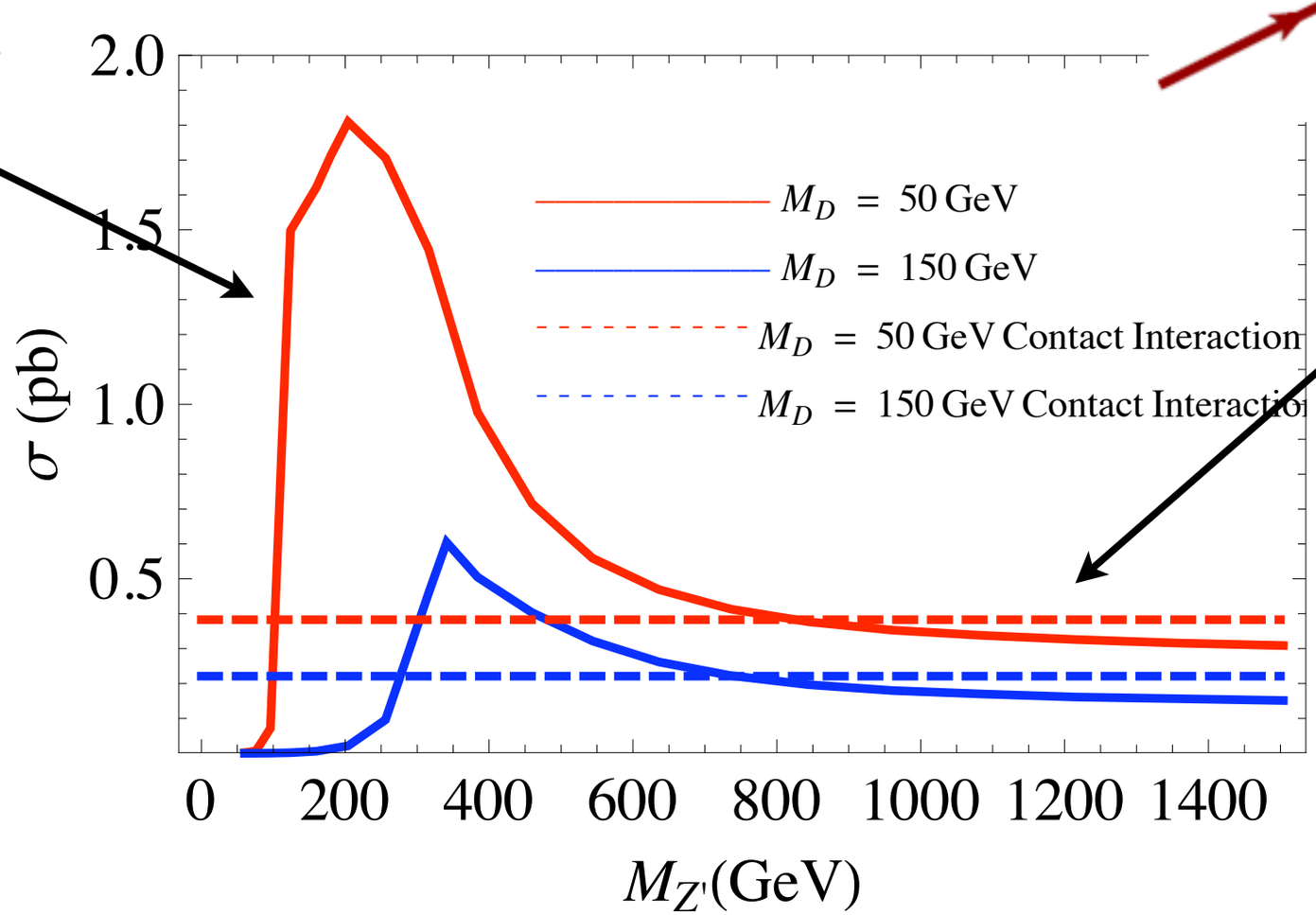


contact-like



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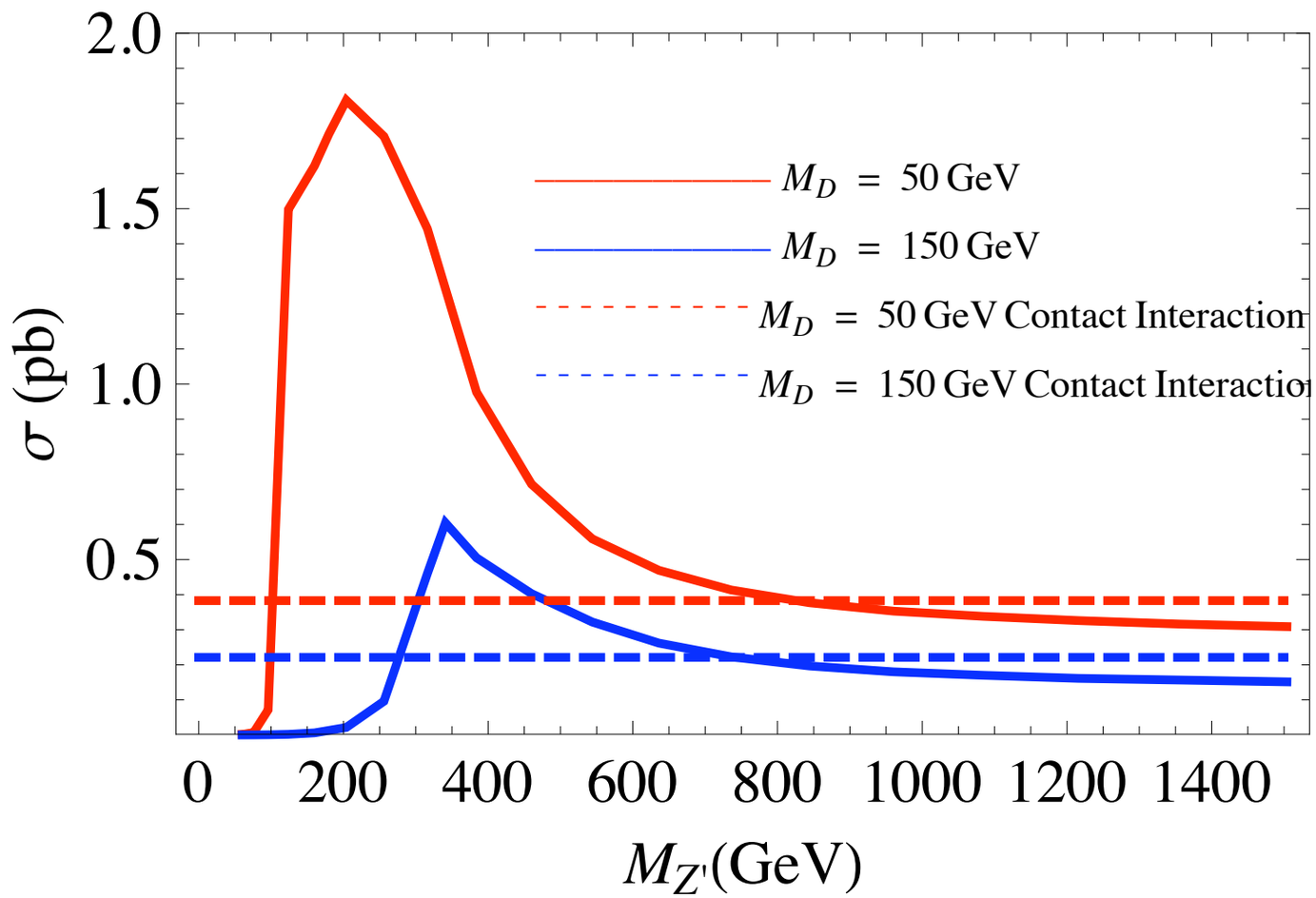

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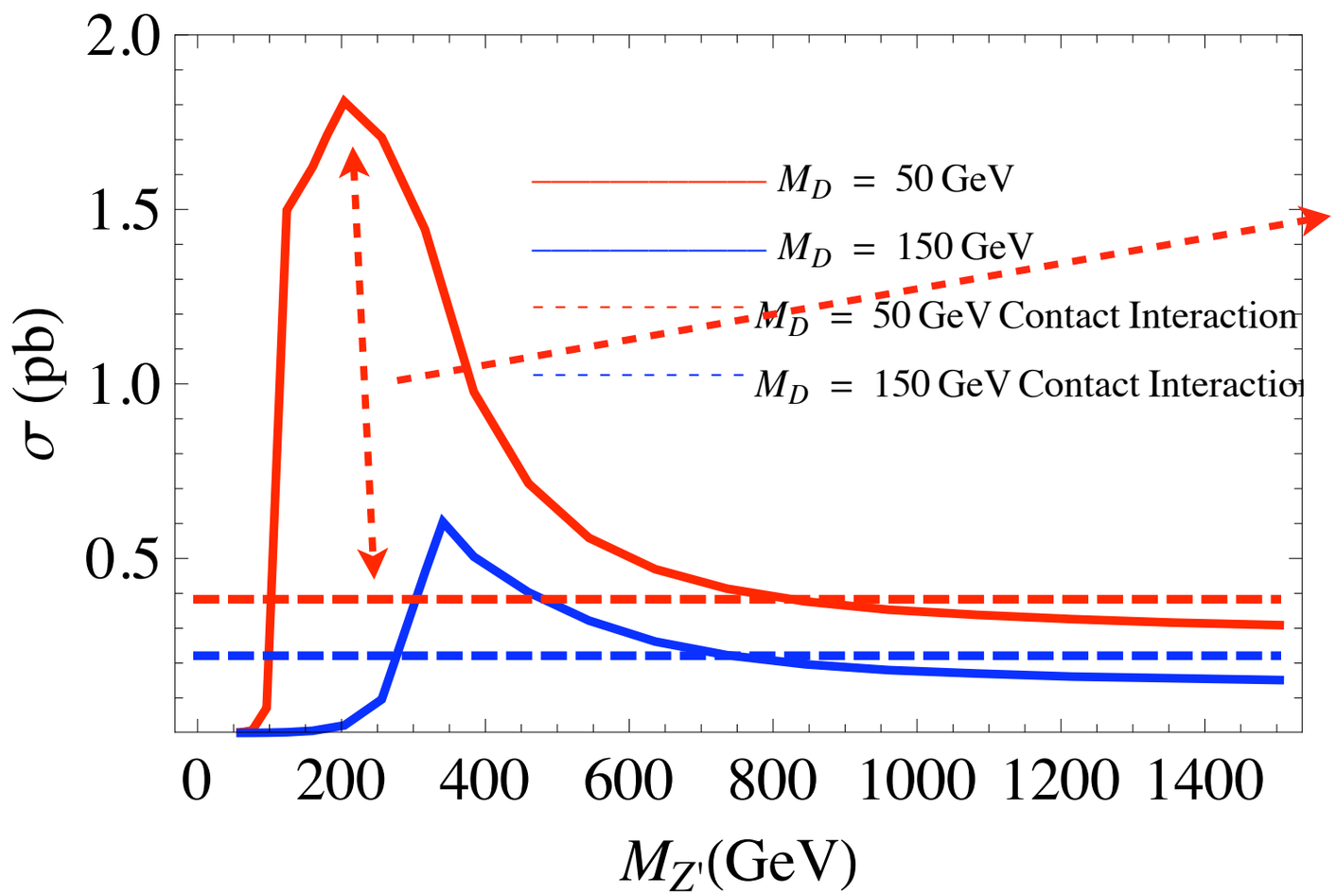
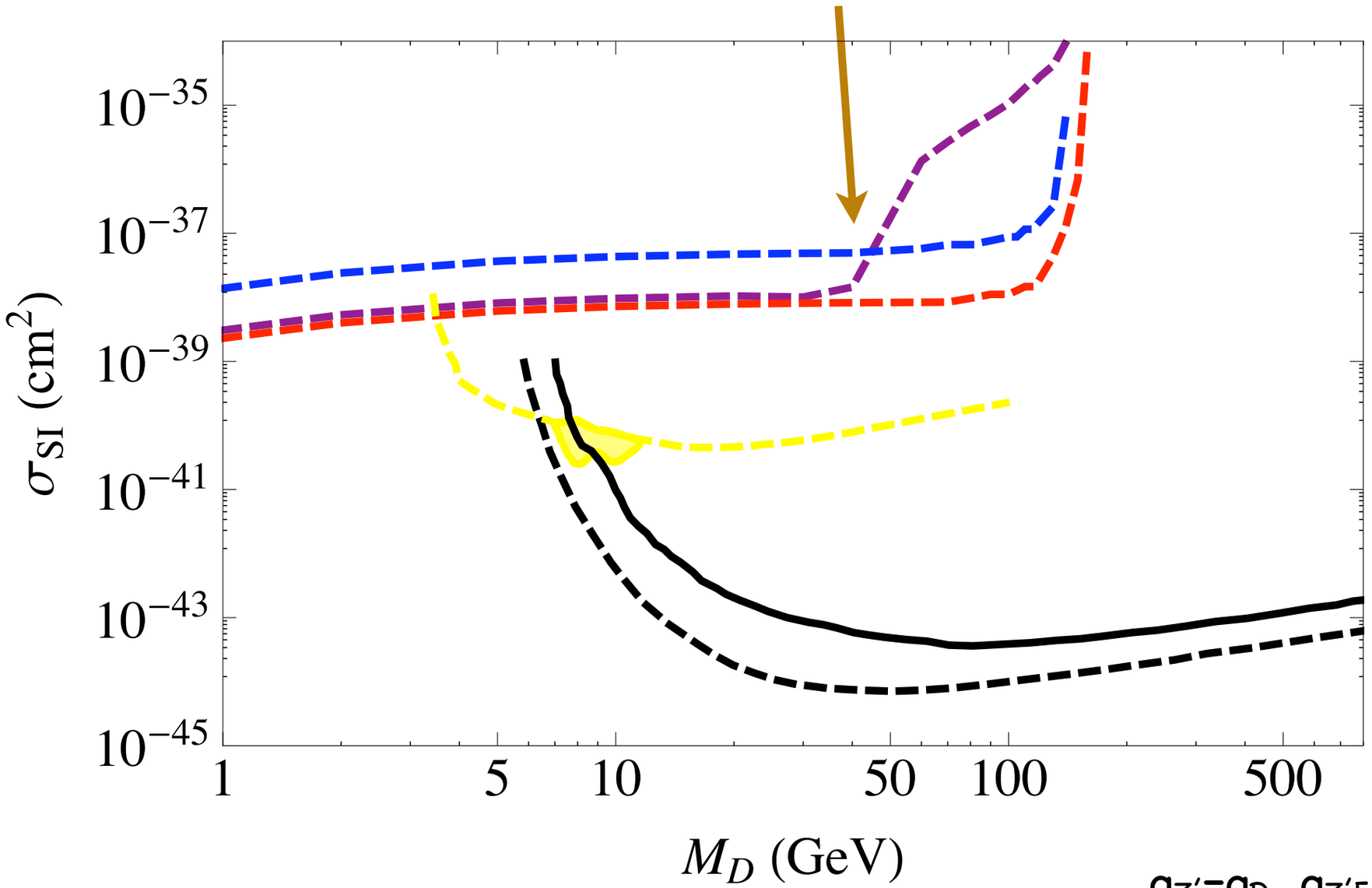


A factor of 3 in $\sigma_{collider}$
→ a factor of 3 in $(g_{Z'})^2$
$\sigma_{dir} \propto (g_{Z'})^4$
→ a factor of 9

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

Limits and reaches: monojet+MET

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



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

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

Xiangdong Ji, Haipeng An, LTW, appearing soon.

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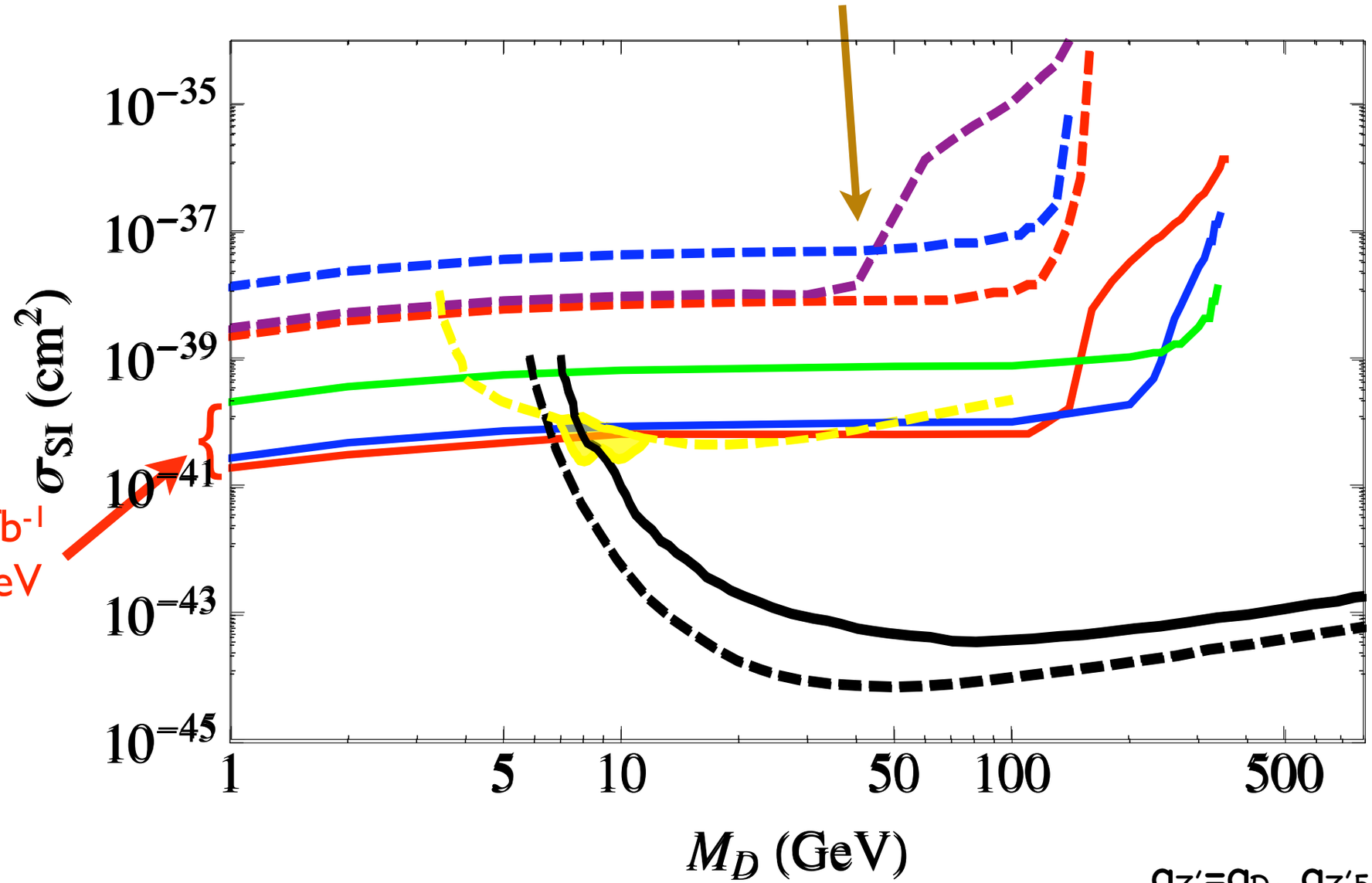

LHC, 7 TeV 5 fb^{-1}
MET > 200 GeV

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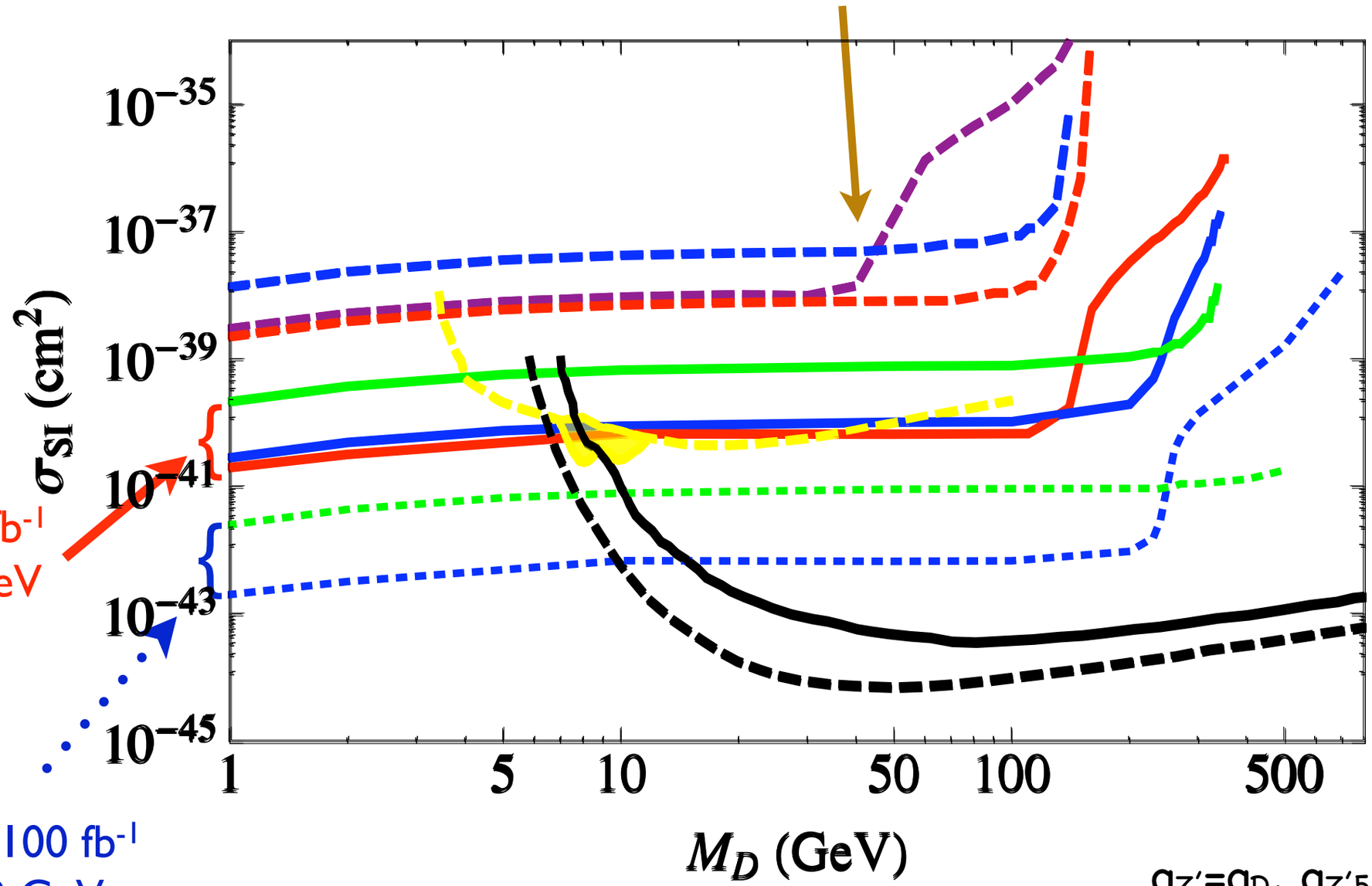

LHC, 7 TeV 5 fb^{-1}
MET > 200 GeV

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

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

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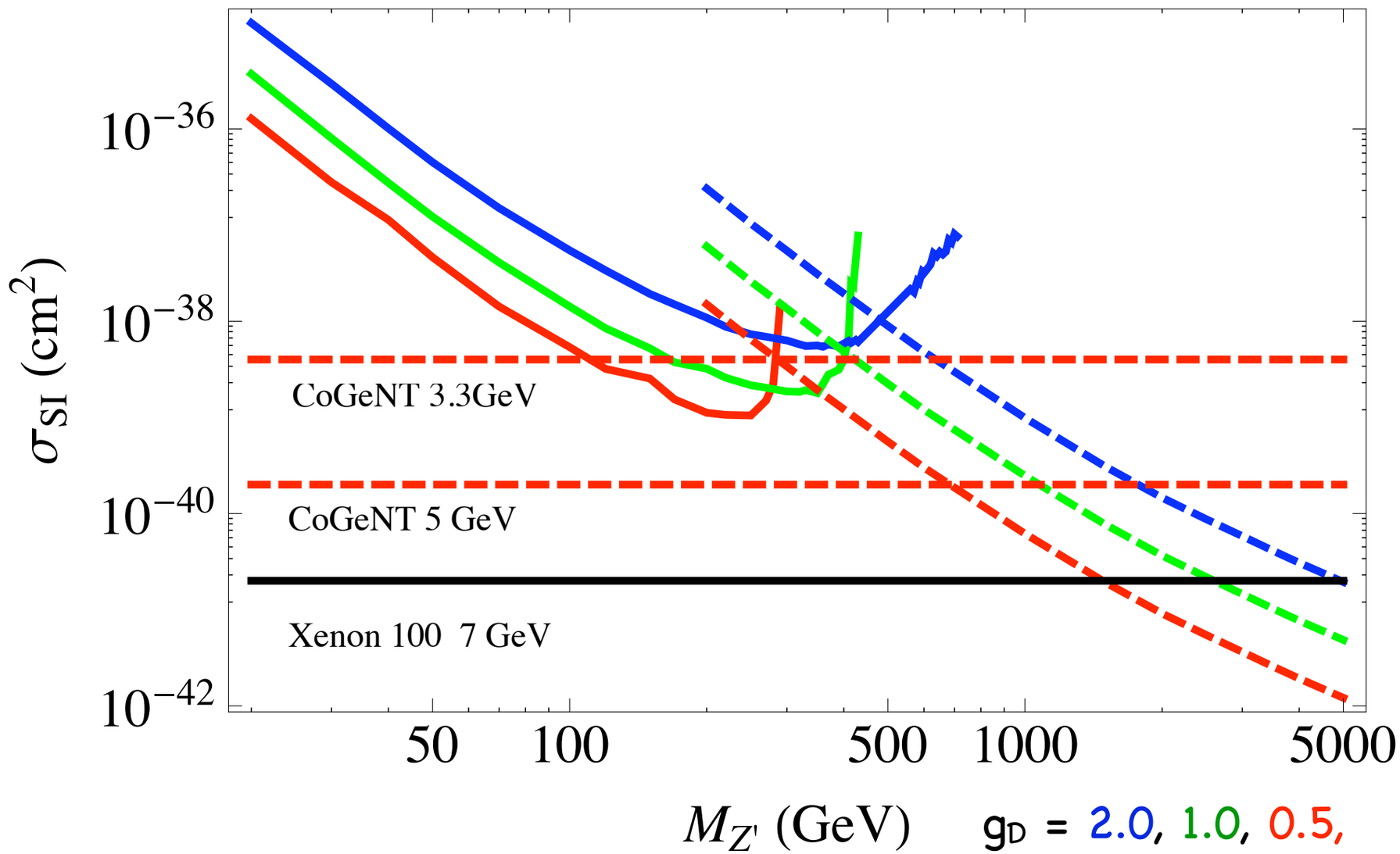
Combining with early LHC data



g_D = 2.0, 1.0, 0.5,

M_{WIMP} = 5 GeV

More scenarios are under study.

Xiangdong Ji, Haipeng An, LTW, appearing soon.

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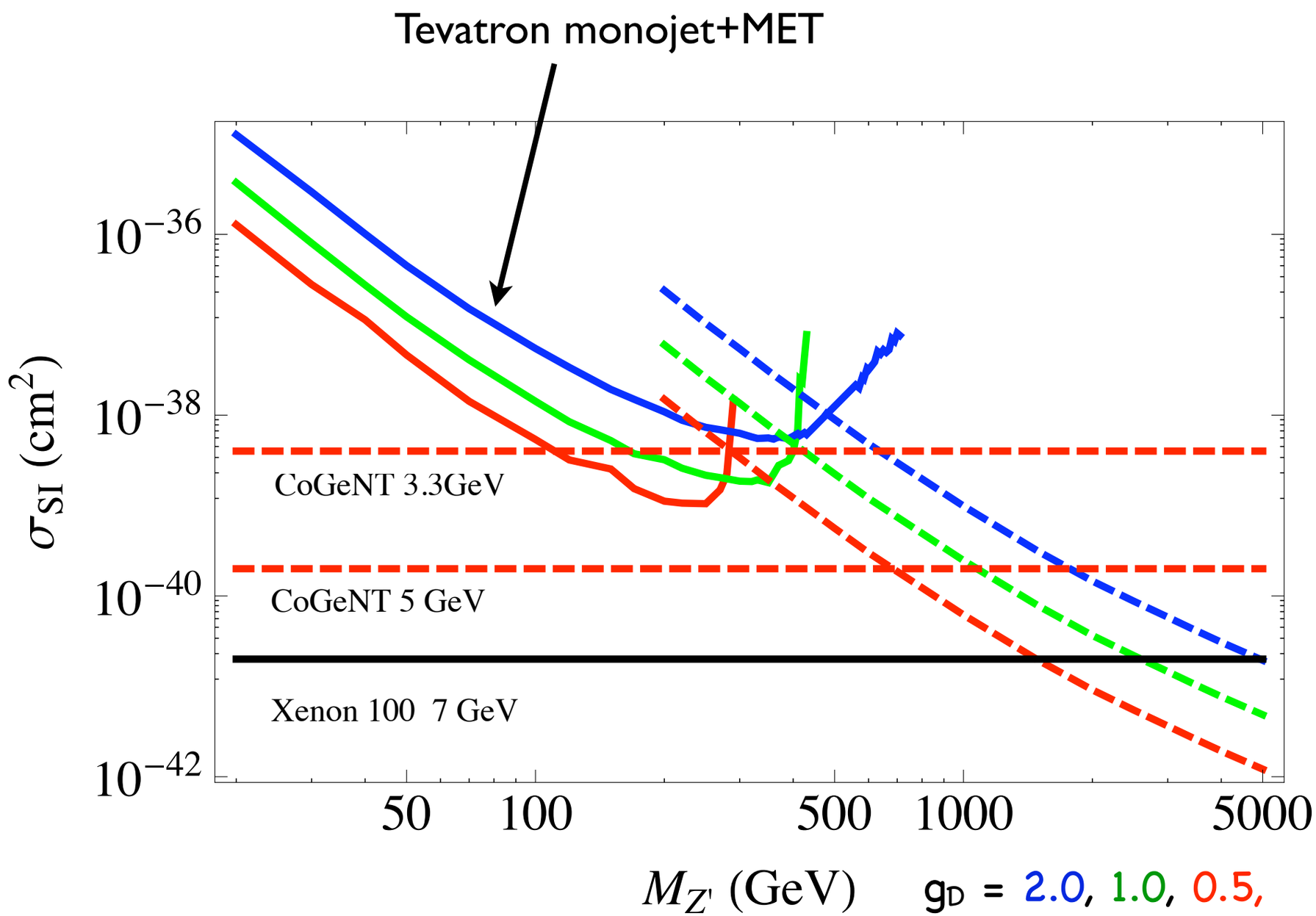

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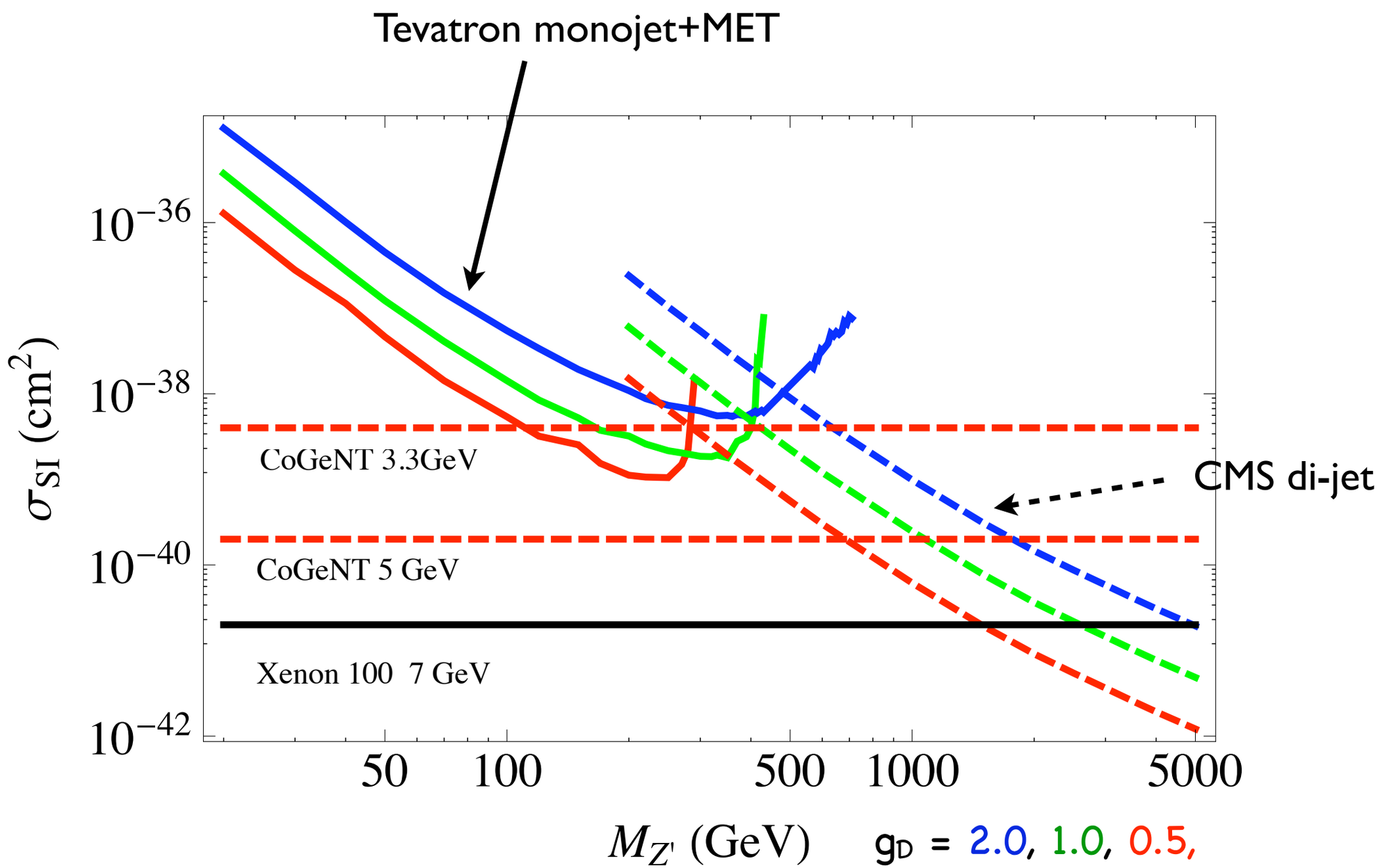

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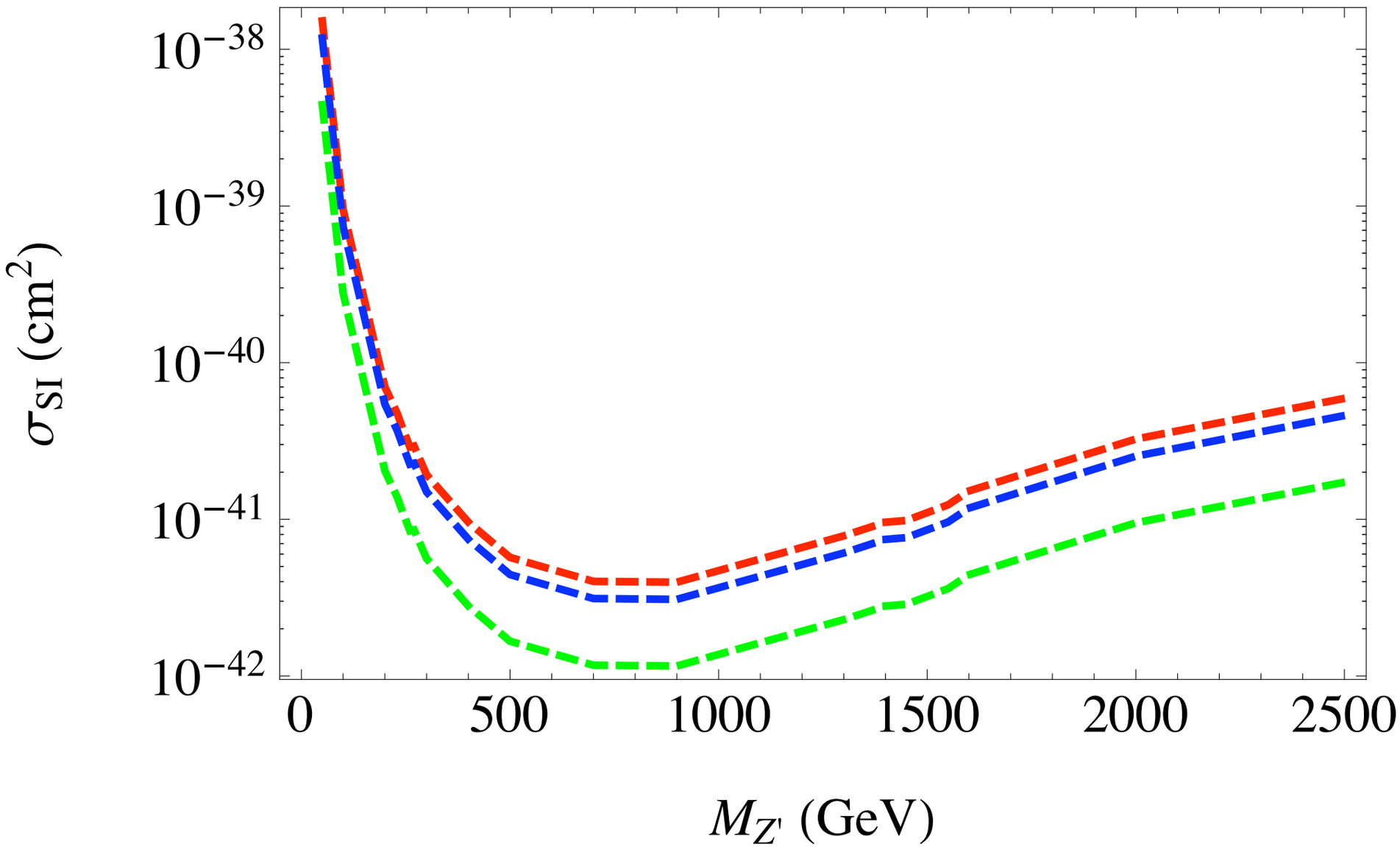

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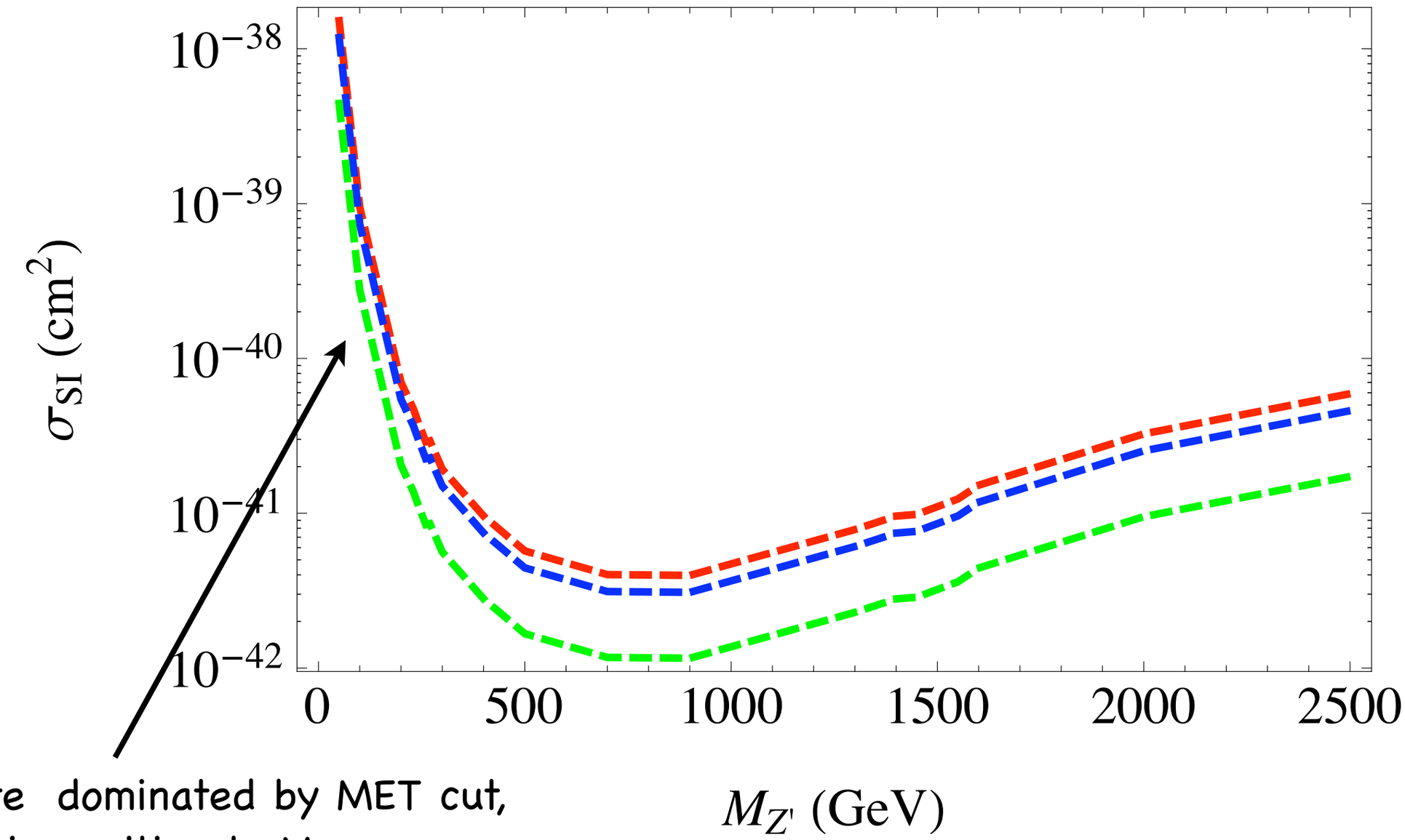

LHC rate dominated by MET cut, insensitive to $M_{Z'}$.

→ LHC bounds only on $g_{Z'}$

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

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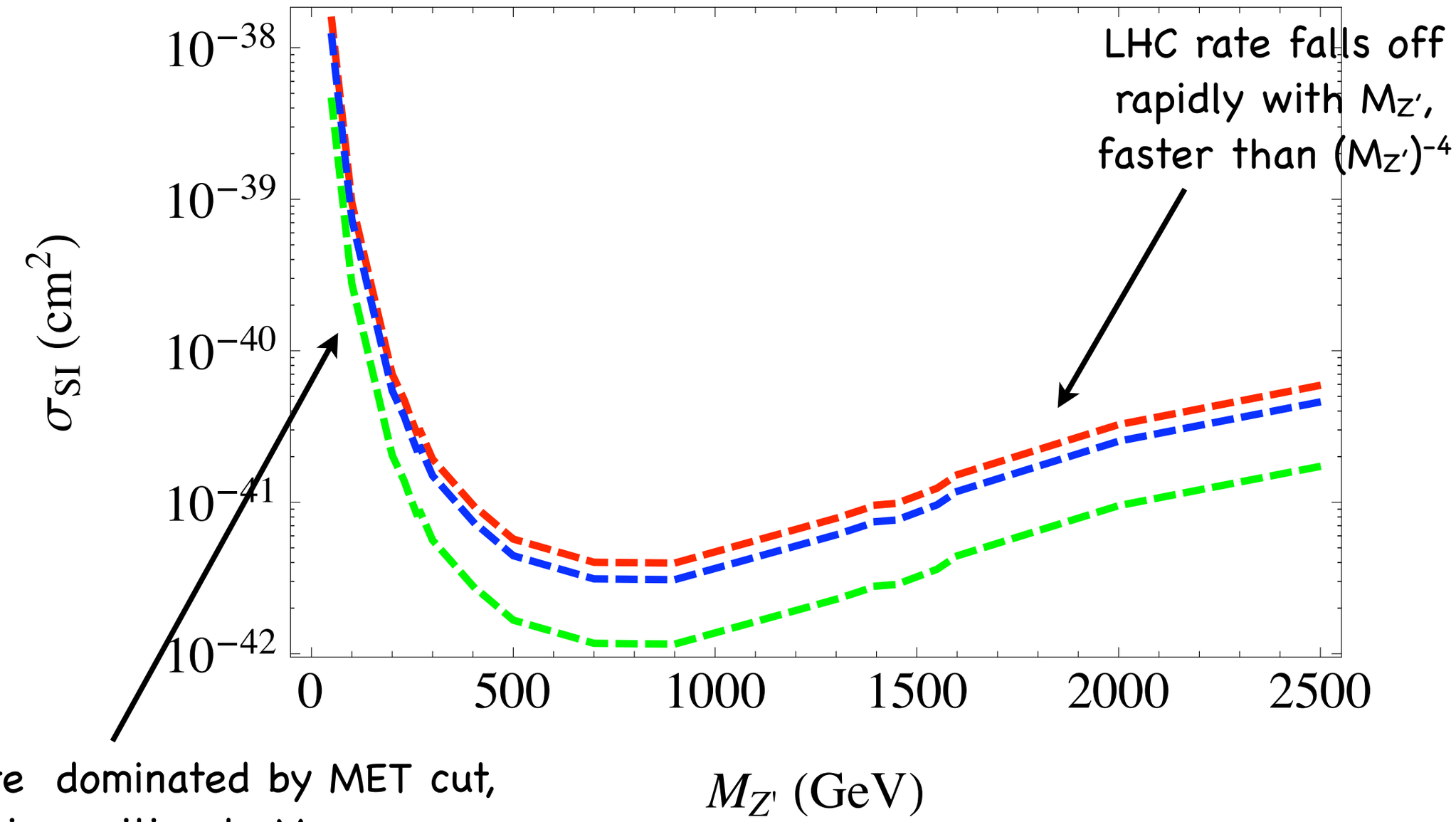
LHC reach in monojet+MET.



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Dark sector

Motivation of Light Dark Sector

- Dark Matter in the universe.
  - Cold, dark, and gravitationally coupled.
- Perhaps dark matter has self-interactions too.
  - Force carrier is an example of dark sector.
- Motivations from astrophysical observations.
  - Fermi, Pamela, ... $M_{\rm dark} \sim {\rm GeV}$

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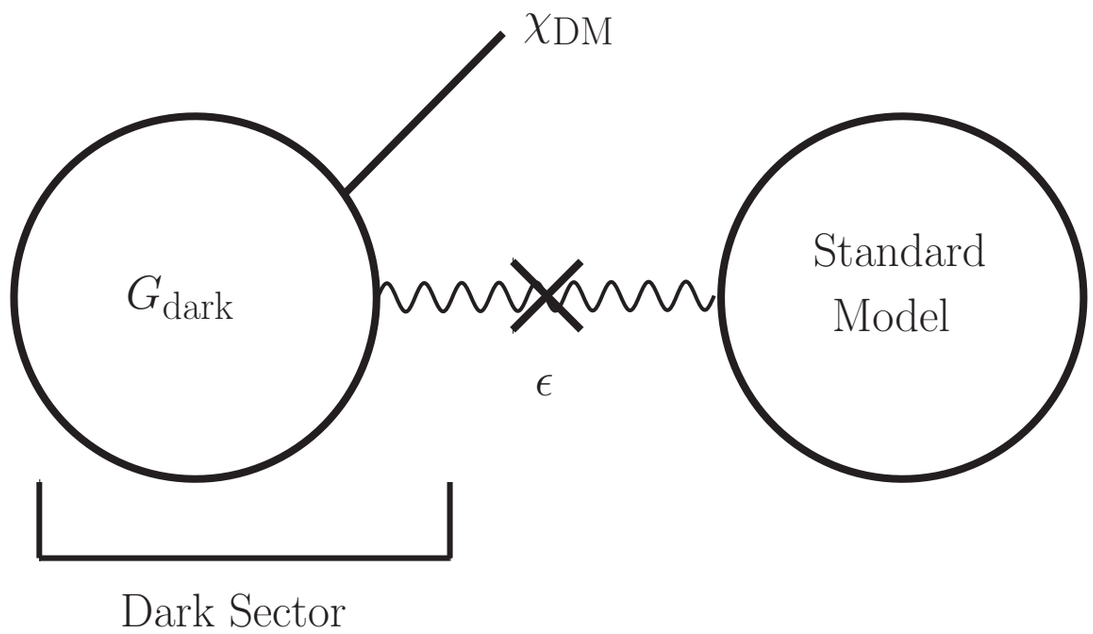
May or may not be the right motivation.

But this class of dark sector can be generic and interesting on its own.

A GeV dark sector.

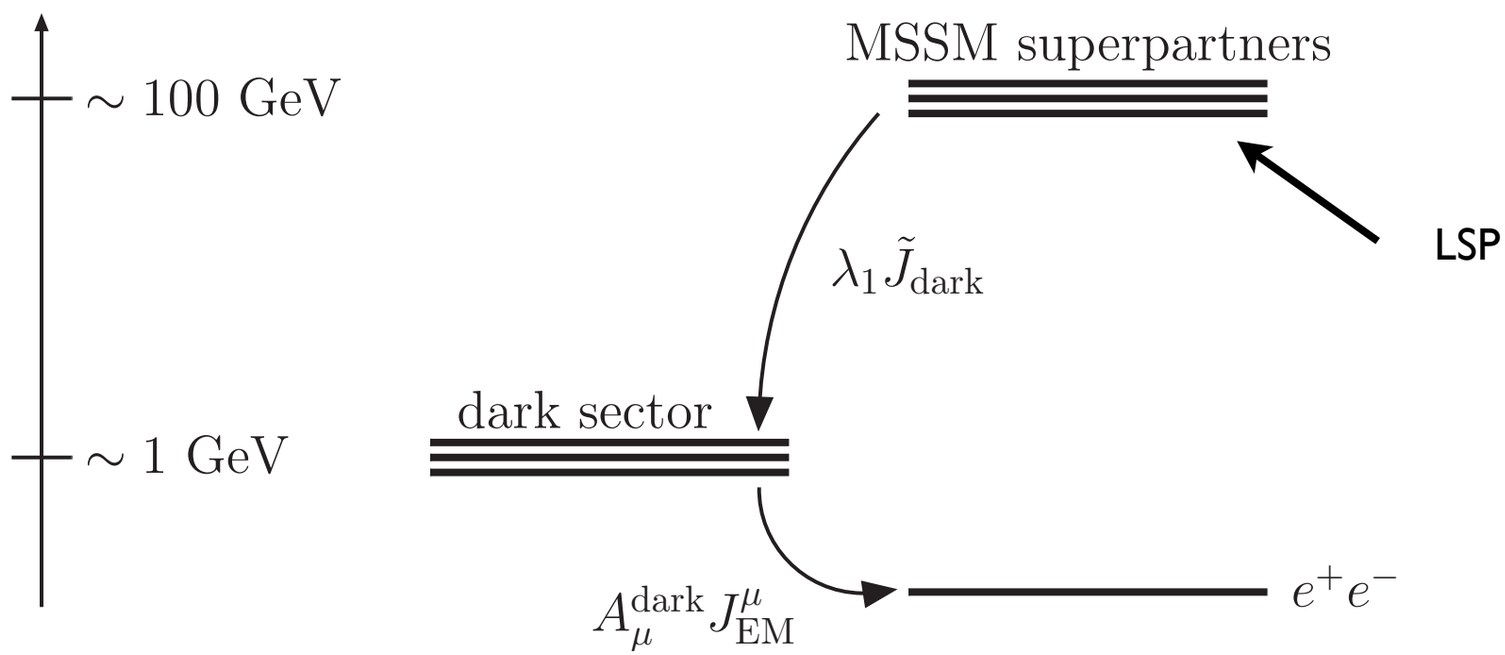


- Dark matter self-interaction, mediated by A_{dark}
  - $m_A \sim$ 100s MeV - GeV
- Dark sector couples to SM with tiny couplings, parameterized by $\epsilon \sim 10^{-3}$
- Nice SUSY implementations.

New class of signal: dark Force

- Dark matter self-interaction, mediated by

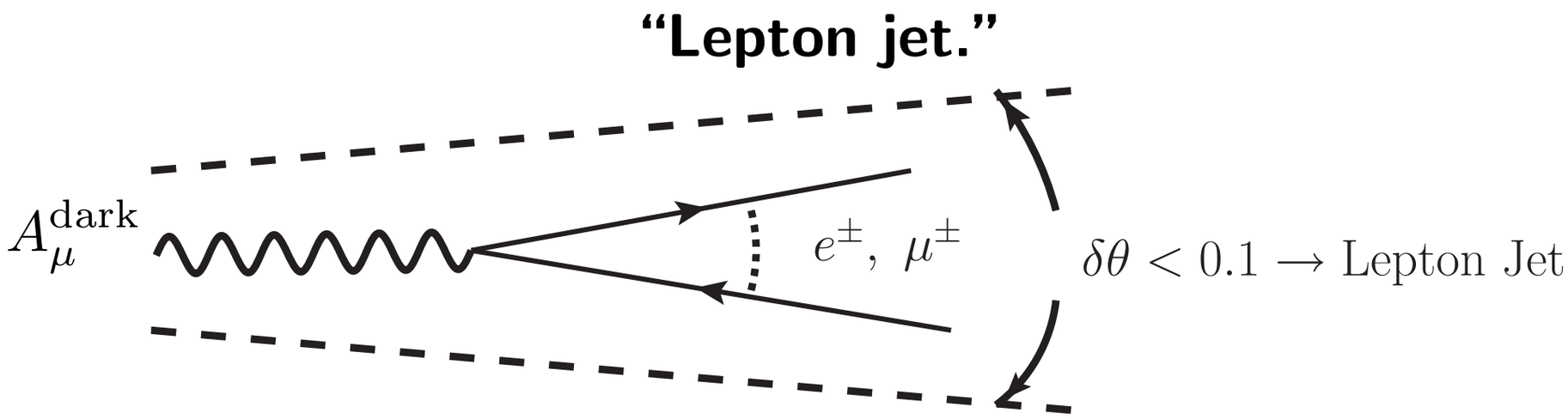
$$A_\mu^{\rm dark}, \quad m_{A^{\rm dark}} \sim \ (100{\rm s\ MeV\ -\ GeV})$$



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

Lepton Jets

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



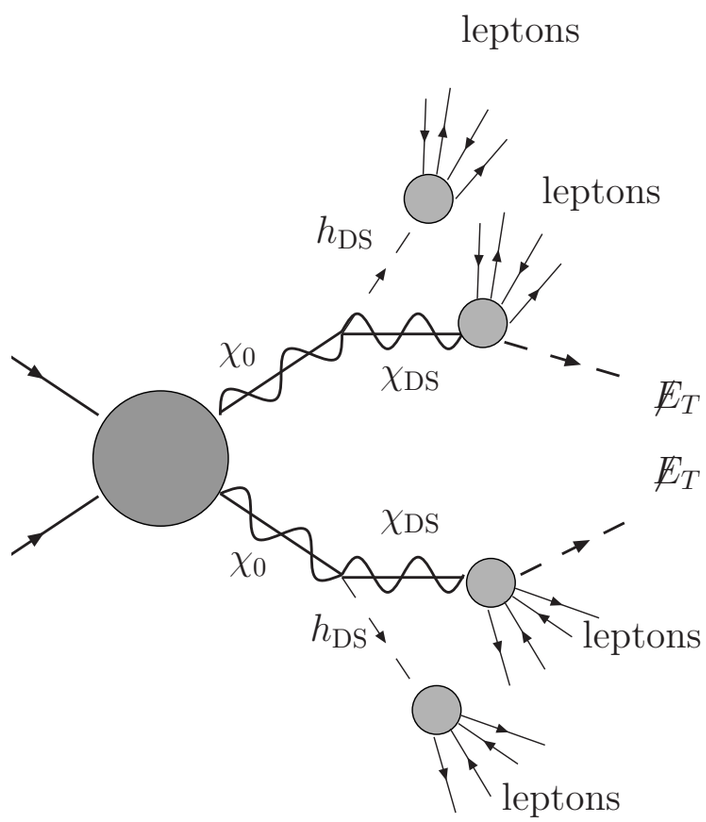
$$\begin{array}{r} \text{Typical } E_{\gamma'} > 10 \text{ GeV} \\ m_{\gamma'} \sim \text{ GeV} \end{array} \rightarrow \ \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$$

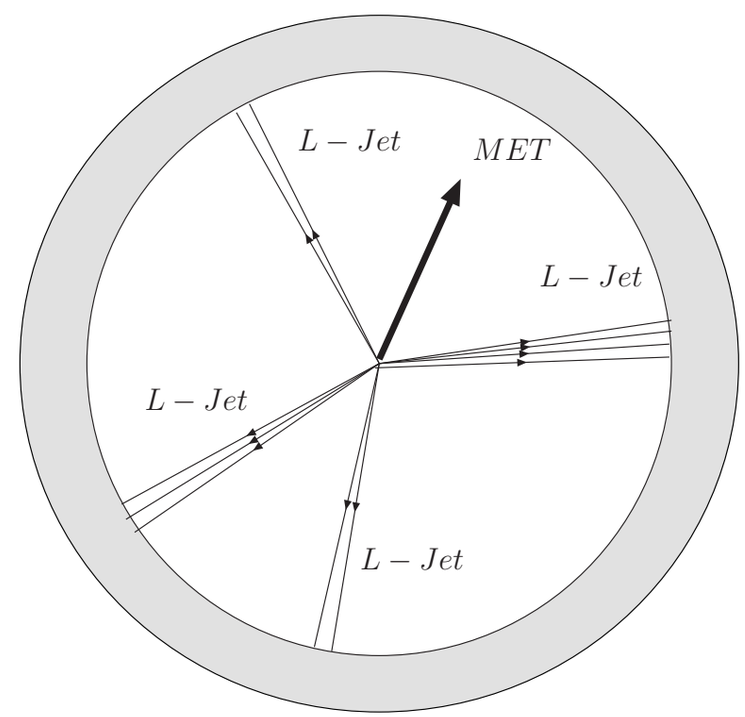
- Arkani-Hamed, Weiner 0810.0714;

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

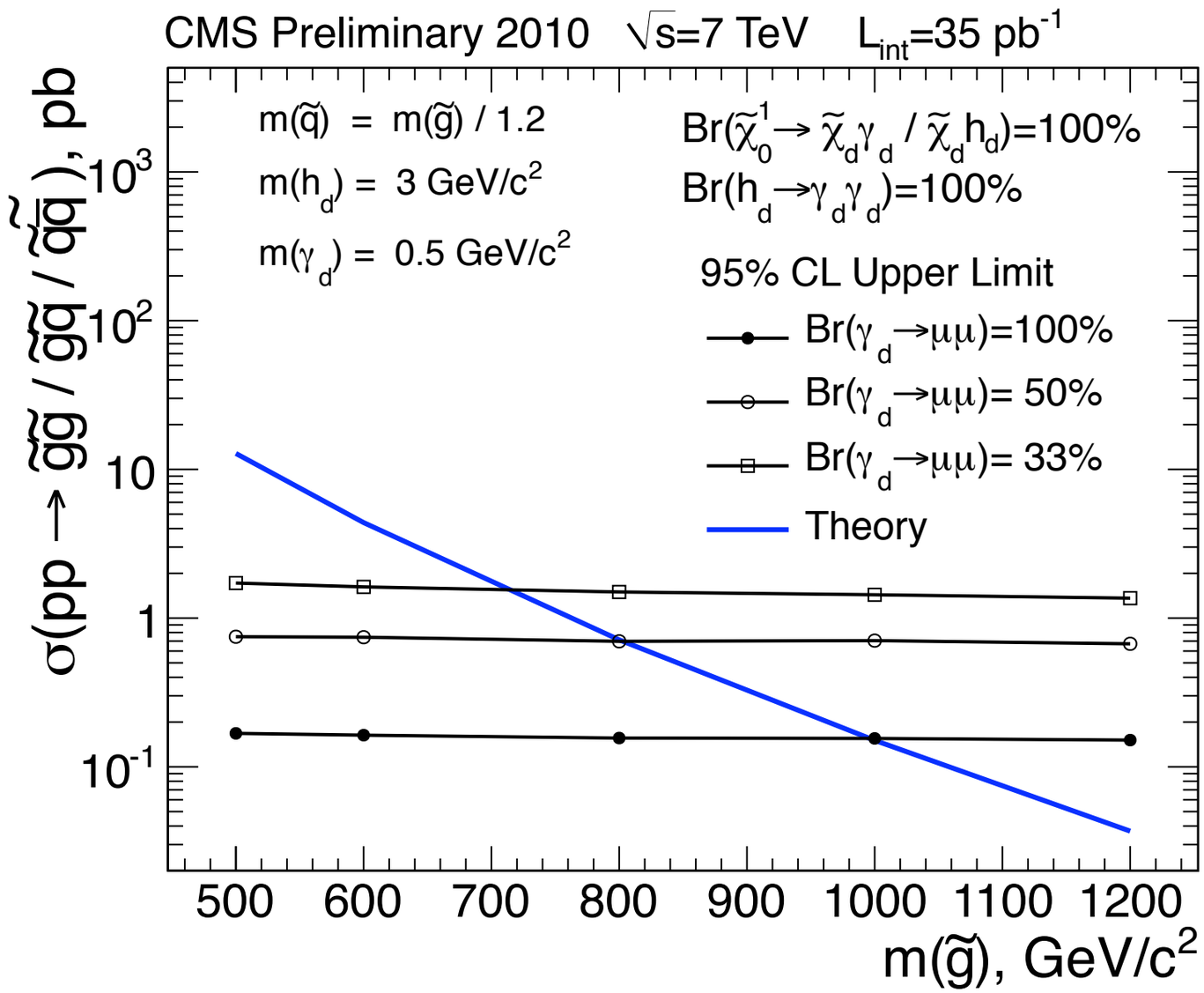
Supersymmetric dark force

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





With LHC early data



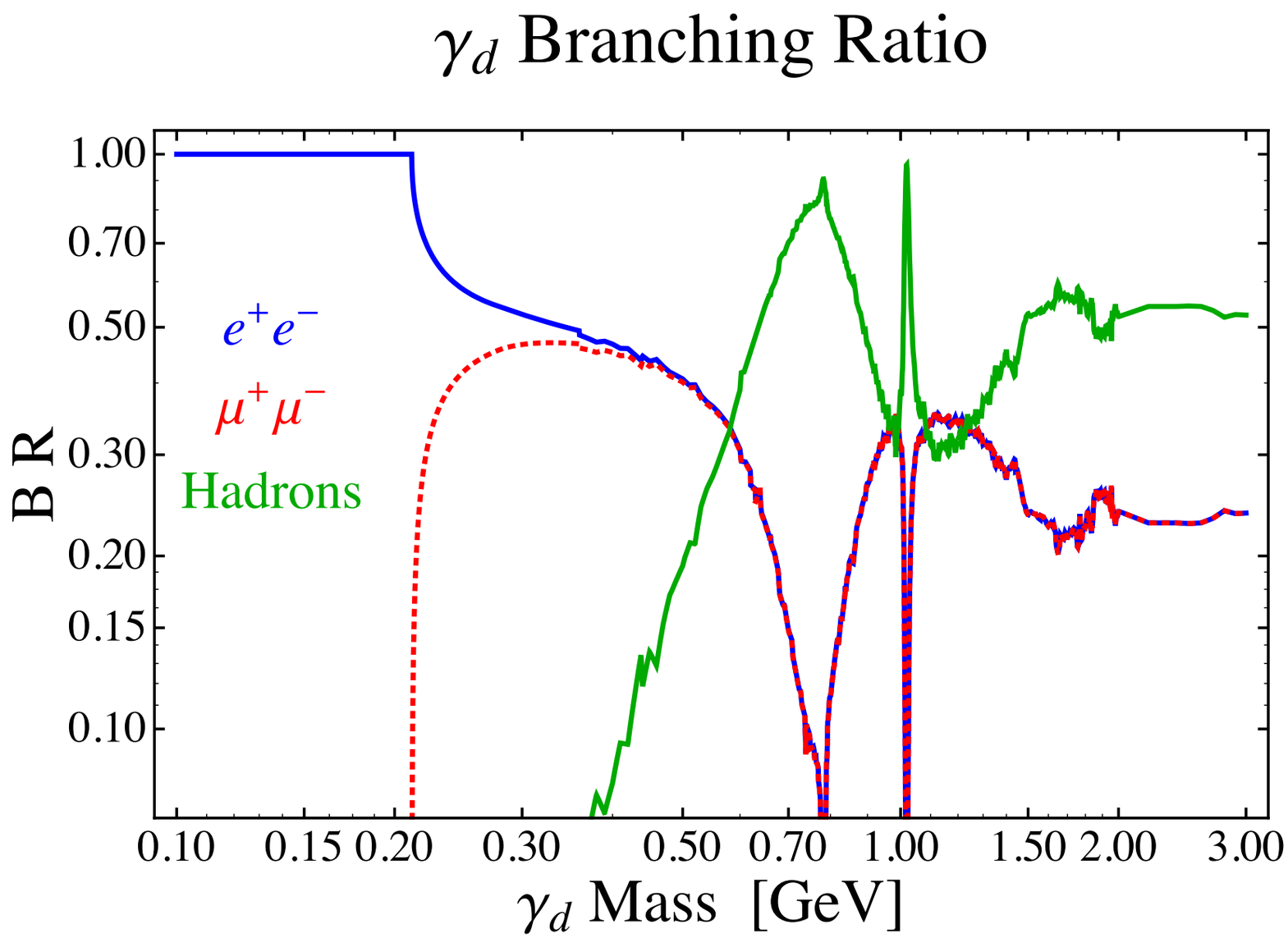
CMS, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11013

Conclusion.

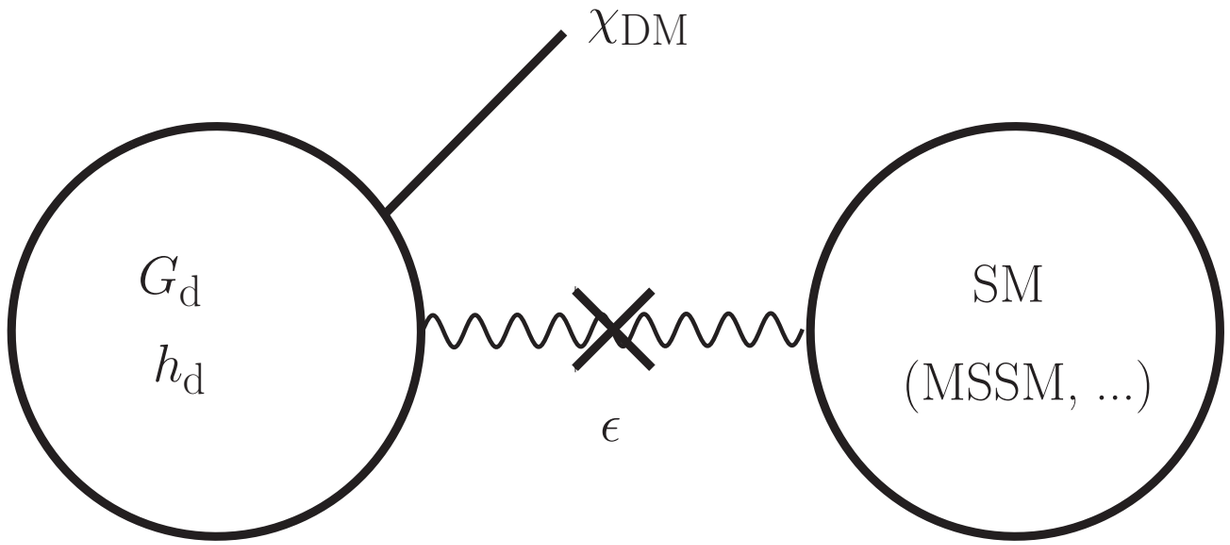
- One of the most exciting opportunities: Discovering the WIMP dark matter and measuring its properties.
- LHC will play a crucial role in this pursuit.
- Multiple aspects and approaches.
  - Search for "conventional" CDM.
  - More model independent searches.
  - Alternative models with distinct signatures.

extra

Dark photon decay.

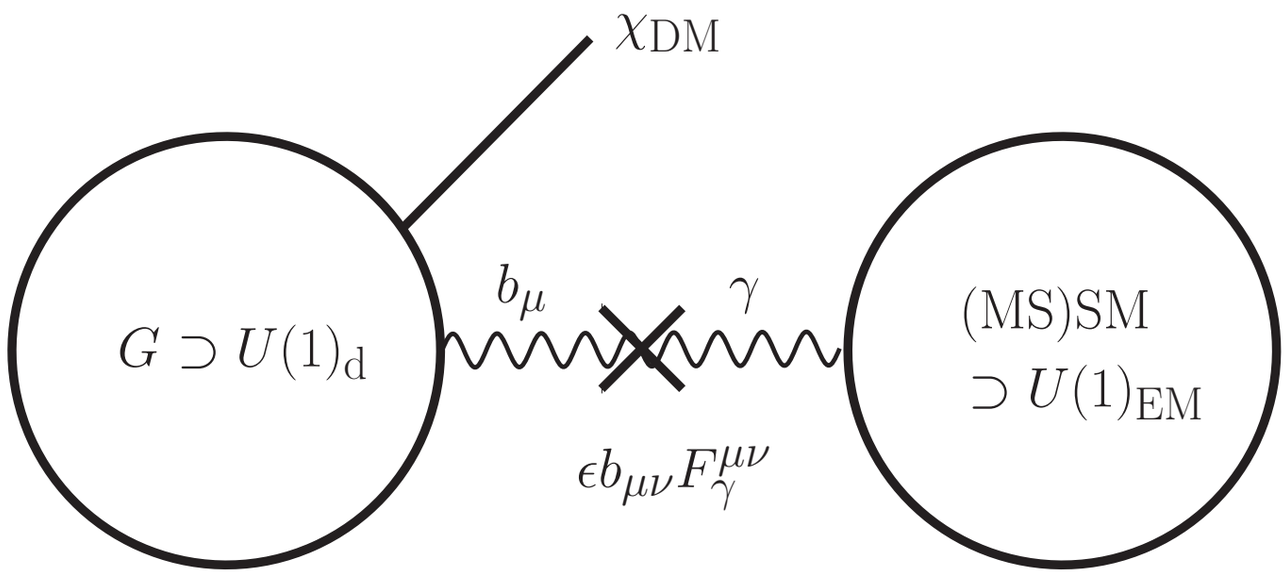


Basic dark sector model ingredients:



- Model choices:
  - Dark matter identity.
  - Self-interaction $G_{\rm d}$: gauge interaction...
  - GeV scale, dark higgs $h_{\rm d} : v_d = \langle h_d \rangle \sim {\rm GeV}$
  - Supersymmetric scenarios: natural generation of the GeV Scale.

Simplest choice: abelian dark sector



- Simplest self-interaction: $G_{\rm d} = U(1)_{\rm d}$
- Natural connection to the SM: kinetic mixing

$$\mathcal{L}_{\rm kin.mix} = -\frac{\epsilon}{2} b_{\mu\nu} F_\gamma^{\mu\nu}$$

- Supersymmetry can be an elegant way of generating the GeV scale.

For a very simple and predictive construction:
C. Cheung, J. Ruderman, LTW and I. Yavin, arXiv:0902.3246
See also: D. E. Morrissey, D. Poland and K. M. Zurek, arXiv:0904.2567

Benefits of Collider searches

- More information of the S-matrix.
  - Precision measurement of the properties of the WIMP dark matter.
- Direct detection can have additional suppressions.
  - Spin dependent.
  - Velocity of WIMP.
  - Collider searches are not suppressed in these cases.