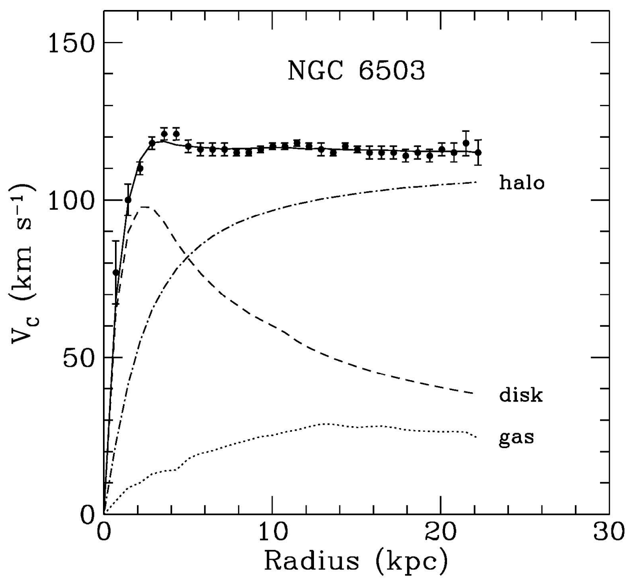
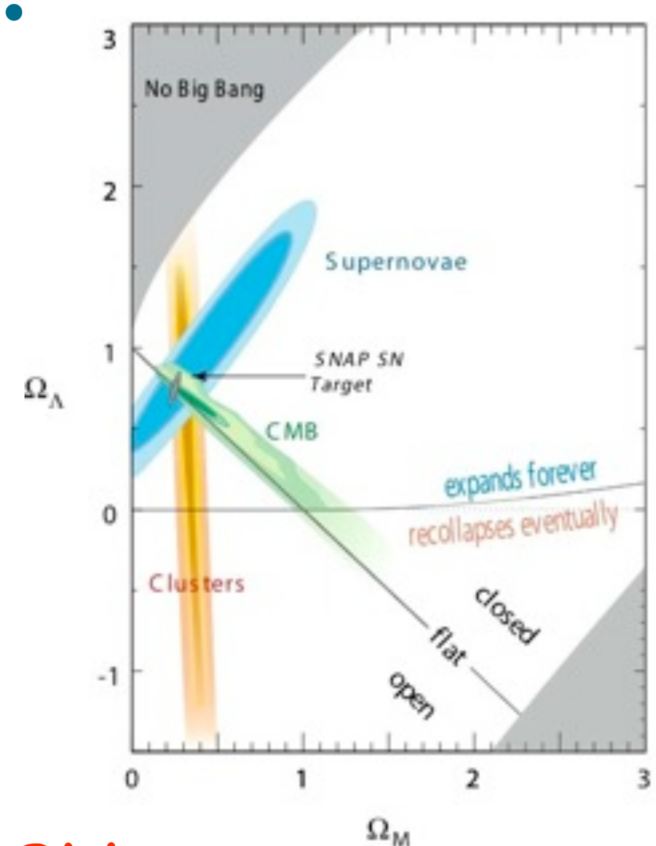
Dark matter at colliders

Lian-Tao Wang
University of Chicago

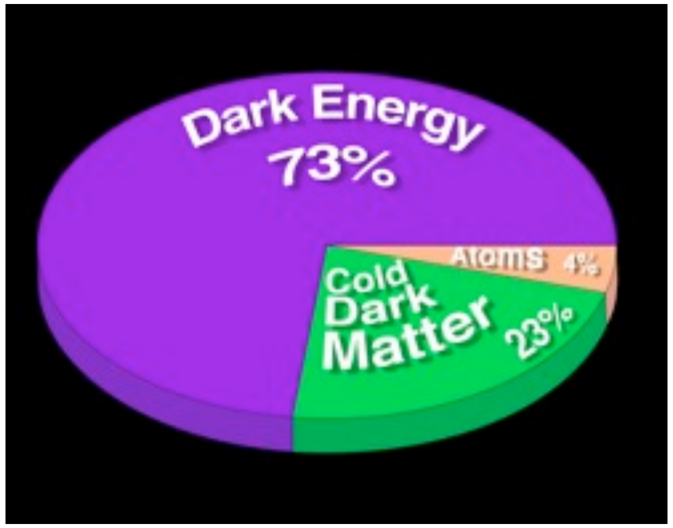
LPC seminar, March 27

We have solid evidence for dark matter:





Only NP beyond SM discovered so far.



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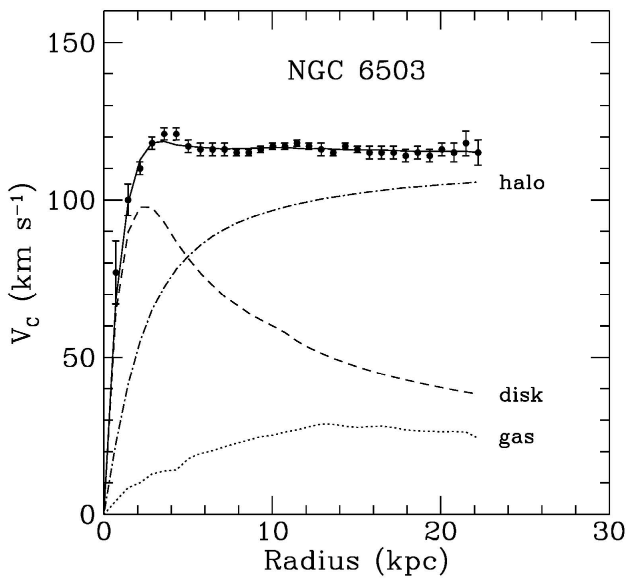
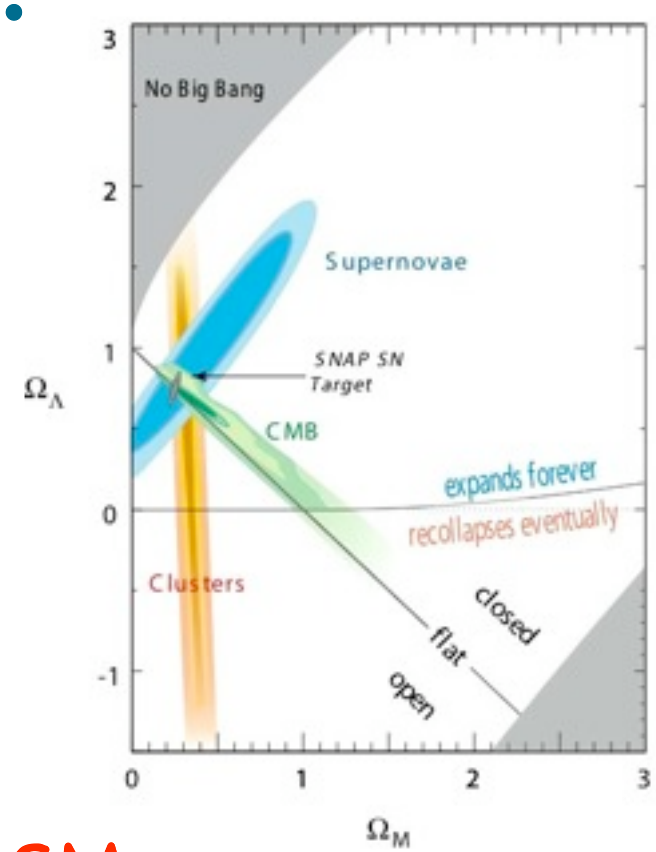
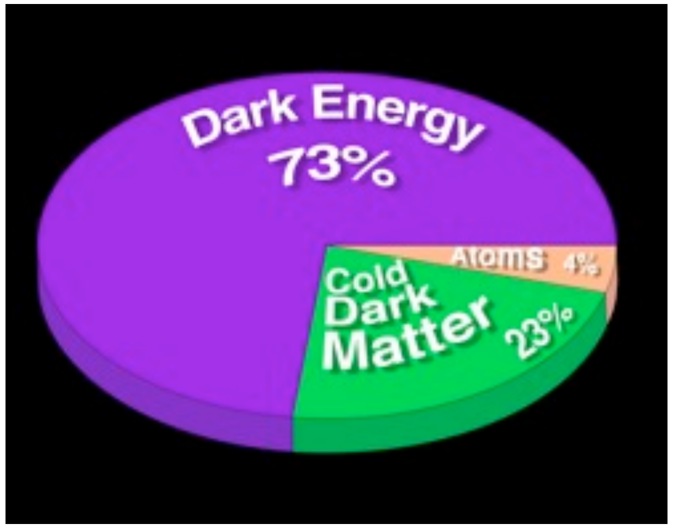




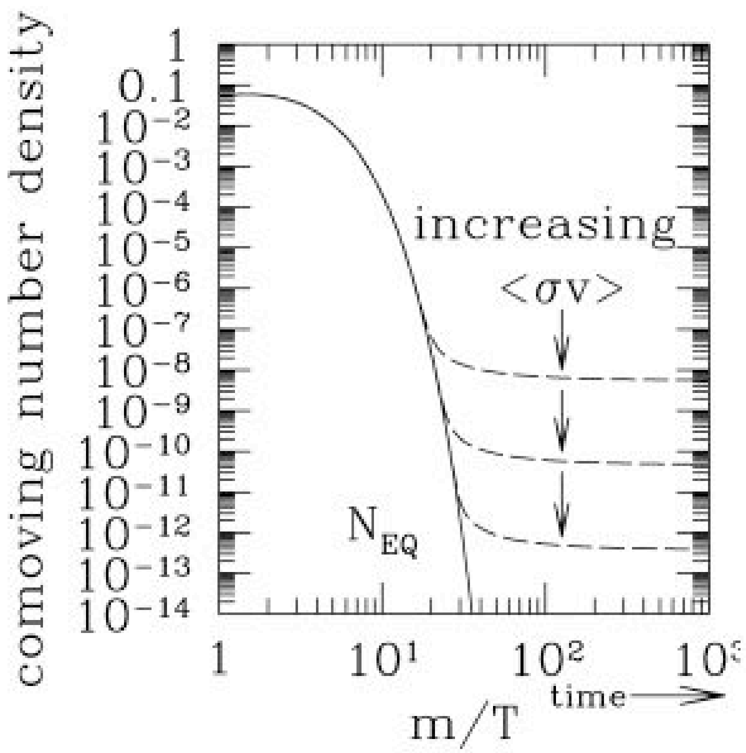
Only NP beyond SM discovered so far.

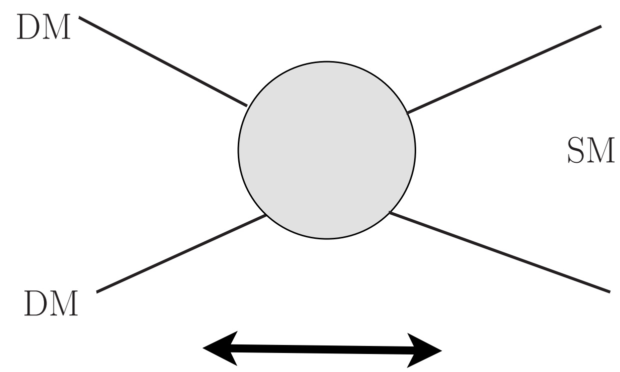
- Exists
- gravitates.
- is dark.



Tuesday, March 27, 2012

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!

Dark matter and new physics, EWSB

- 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} .

- Perhaps NP sets the mass scale of the dark matter as well.

- Typical example: supersymmetry.

NP wants to have WIMP dark matter

NP wants to have WIMP dark matter

- Little Hierarchy problem

$$\text{Naturalness of the weak scale} \quad : \quad \Lambda_{\rm NP}^2 \sim 16\pi^2 \Lambda_{\rm EW}^2$$

$$\frac{\mathcal{O}^{(5)}}{\Lambda_{\rm NP}},\ \frac{\mathcal{O}^{(6)}}{\Lambda_{\rm NP}^2} \to \text{EWPT, flavor, EDM...} \quad : \quad \Lambda_{\rm NP}^2 \sim (16\pi^2)^2 \Lambda_{\rm EW}^2$$

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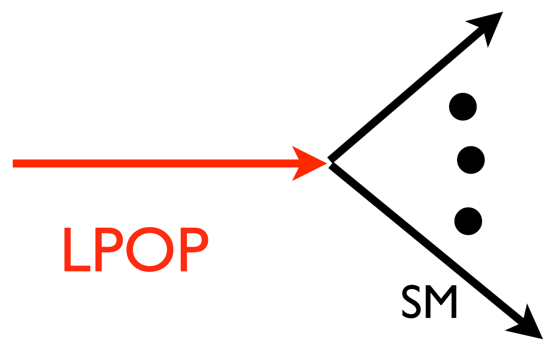
- Partial solution: a discrete symmetry, e.g. Z_2
  - NP odd under this Z_2 , SM even.
  - Additional $1/16\pi^2$ suppression on EWPT, flavor...

Lightest Partiy Odd Particle (NP) stable



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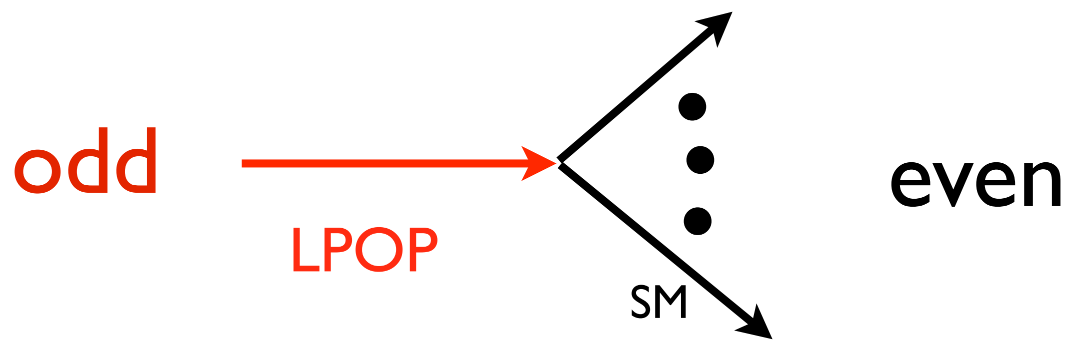

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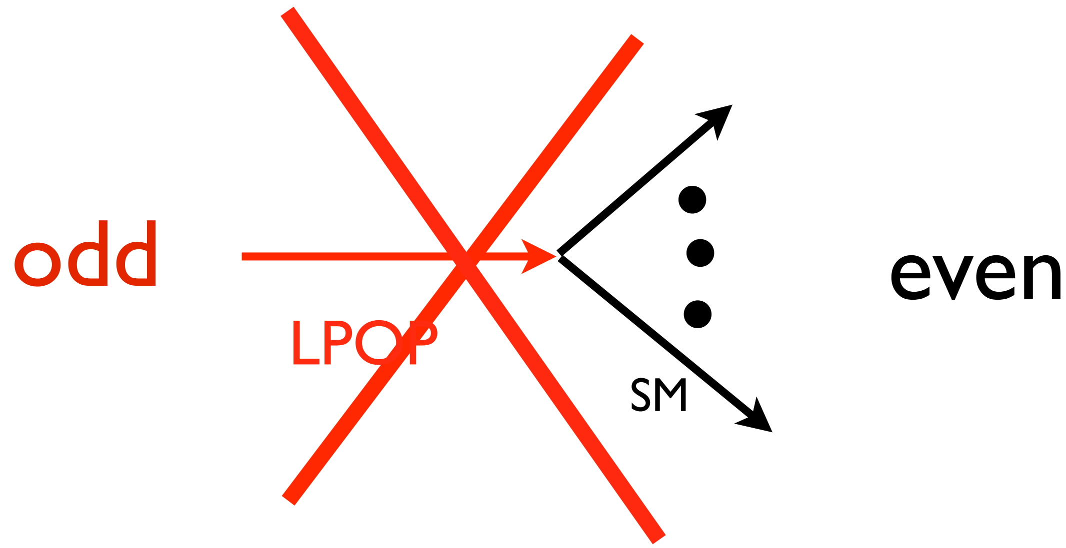

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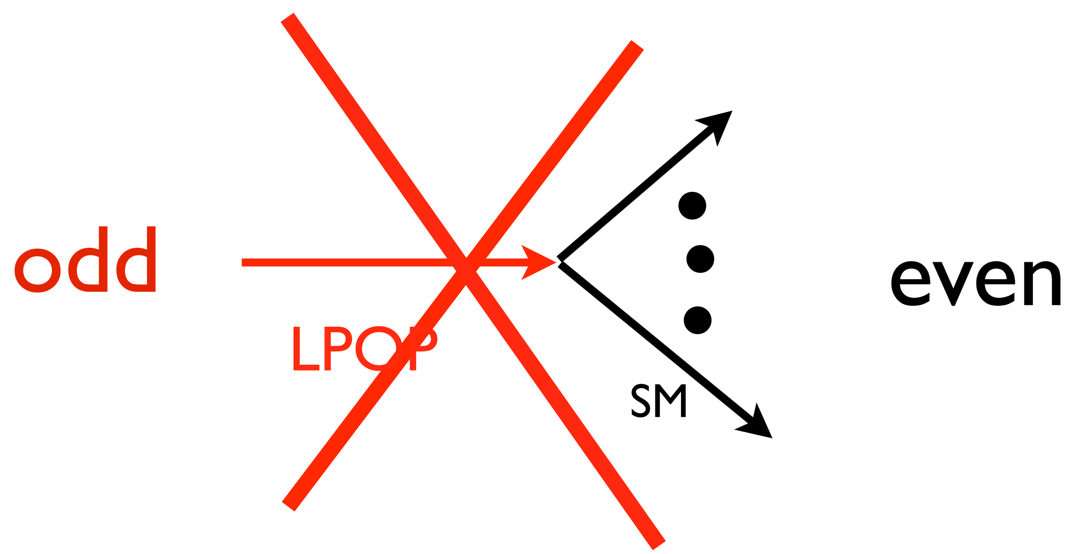


- Neutral LPOP a natural candidate for WIMP dark matter.
  - $O(\Lambda_{EW})$
  - Weakly coupled.
  - Typical example: R-parity odd LSP in SUSY.

Candidates, models, scenarios...

Different spin
different Z_2

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

Candidates, models, scenarios...

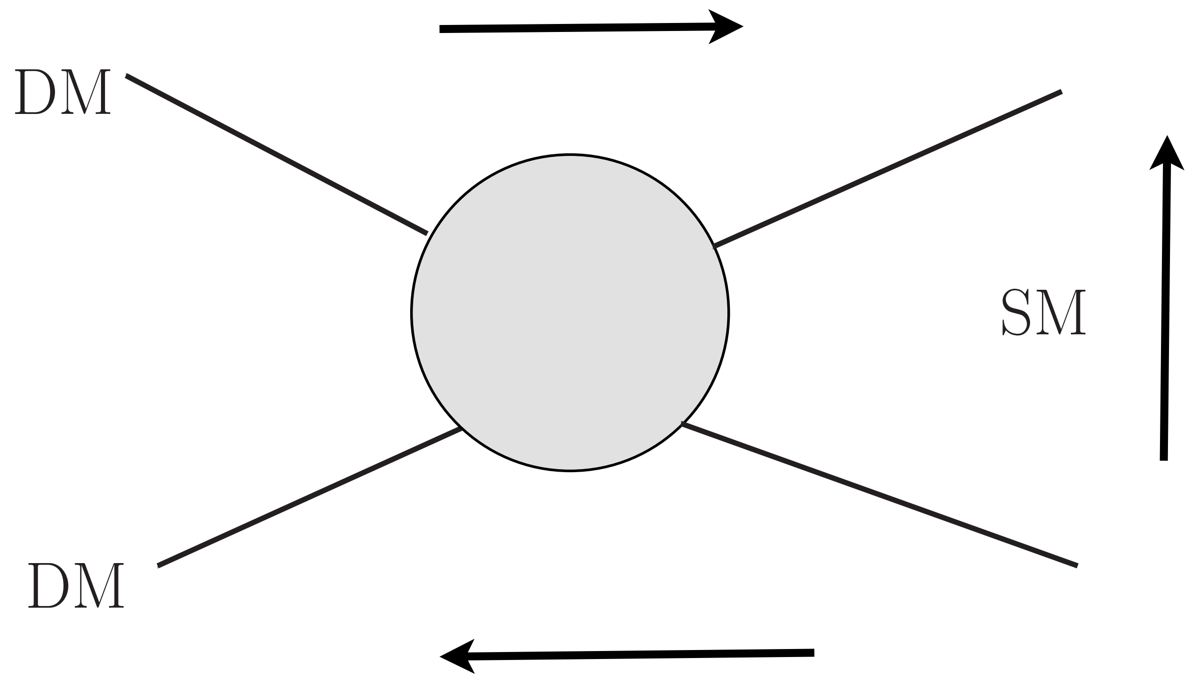
Model independent	Different spin different Z_2
Effective operator	SUSY LSP Extra Dim. LKP T-parity LTP LZP L...P Z_3

Candidates, models, scenarios...

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

Searching for WIMP dark matter

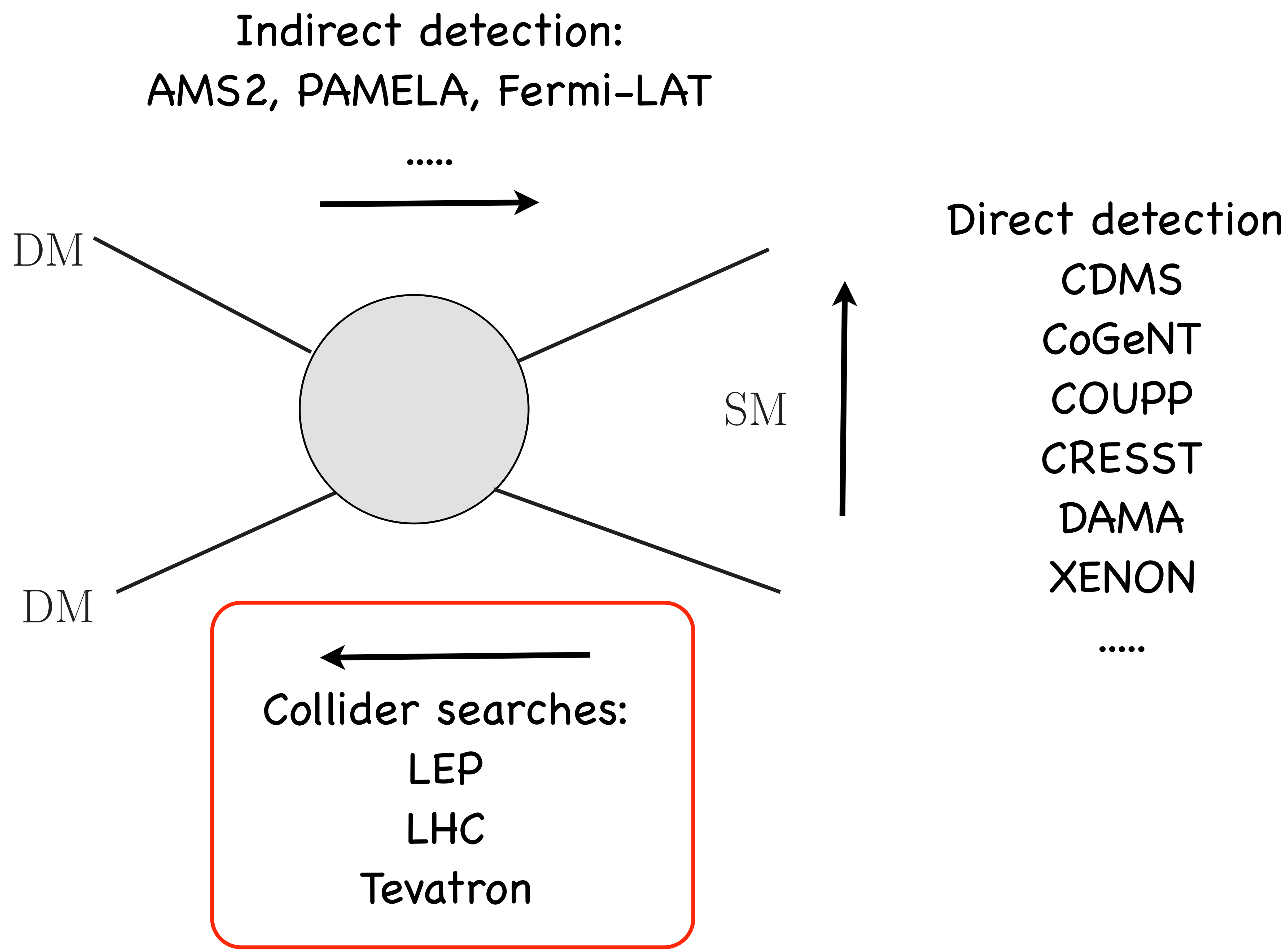
Indirect detection:
AMS2, PAMELA, Fermi-LAT
.....



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

Collider searches:
LEP
LHC
Tevatron

Searching for WIMP dark matter



This talk.

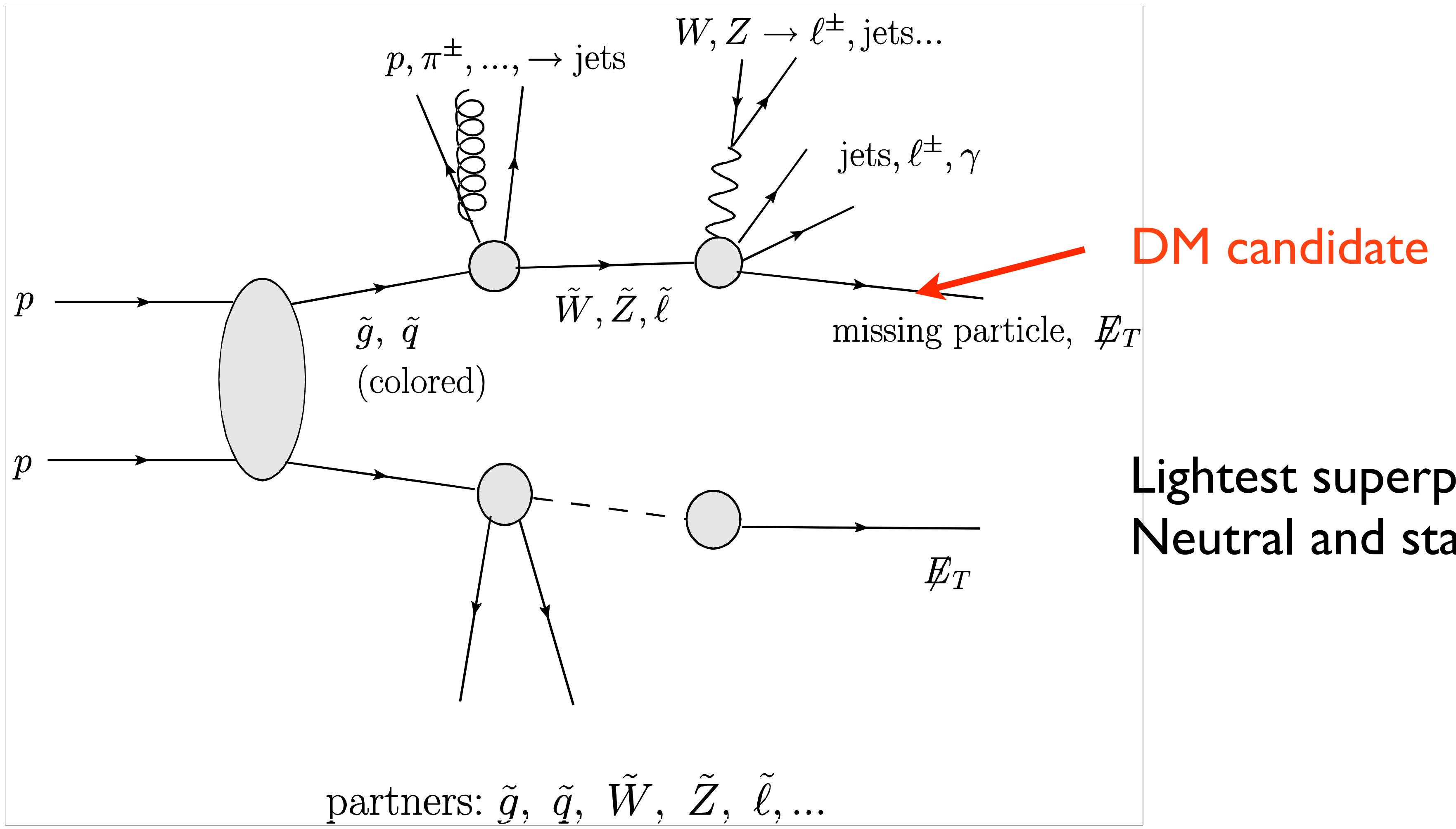
This talk, an over view of

- Search for SUSY dark matter, and measure its properties.
  - Highlight challenges.
- Connection with direct detection.
- Extended models (brief)

Search for SUSY dark matter

Discovering dark matter:

- DM candidate embedded in an extended TeV new physics scenario



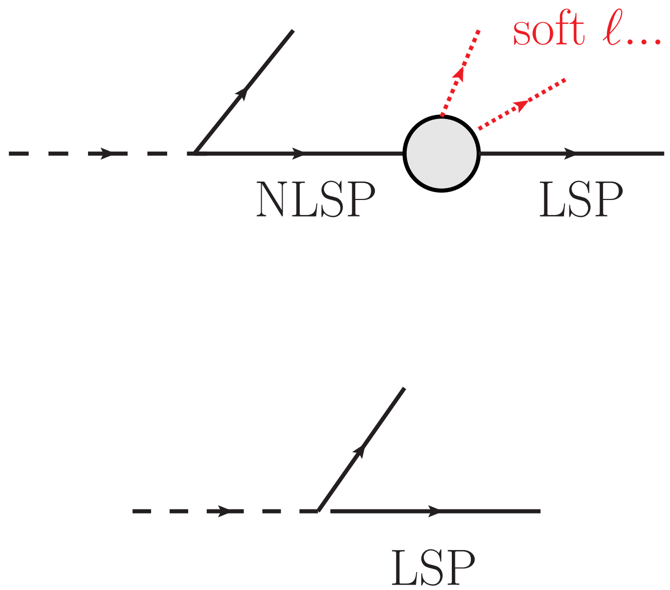
Lightest superpartner (LSP)
Neutral and stable.

- Could be early discovery.

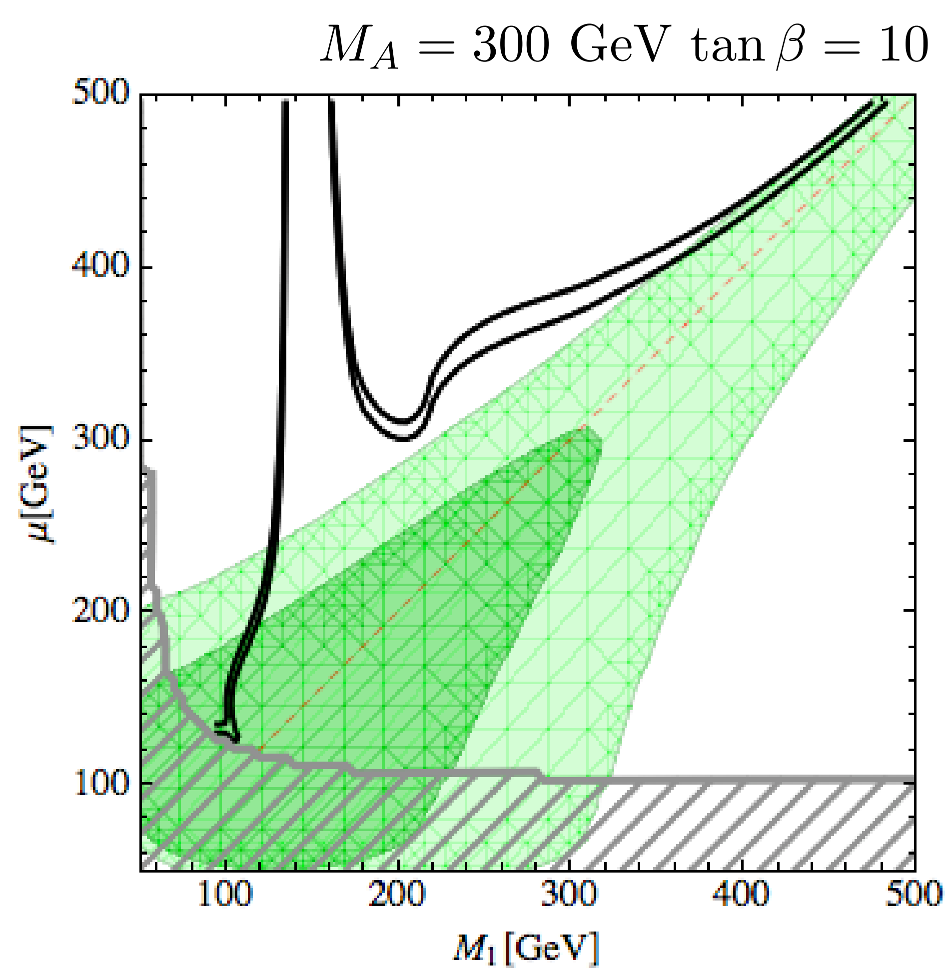
Could be harder make sure.

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

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



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

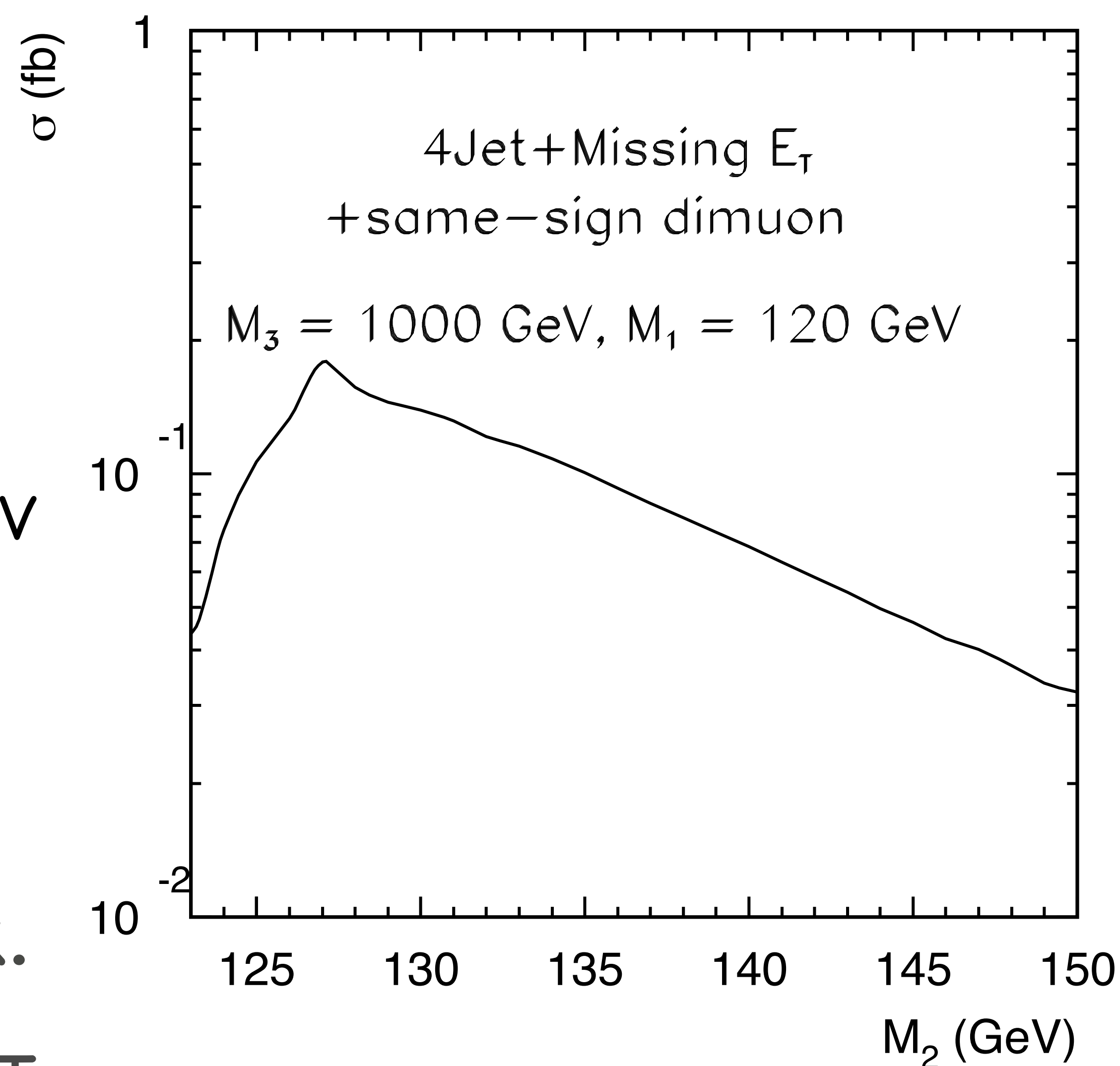


S. Gori, P. Sechwaller, C. Wagner, 1103.4138

LHC prospect for well tempered DM

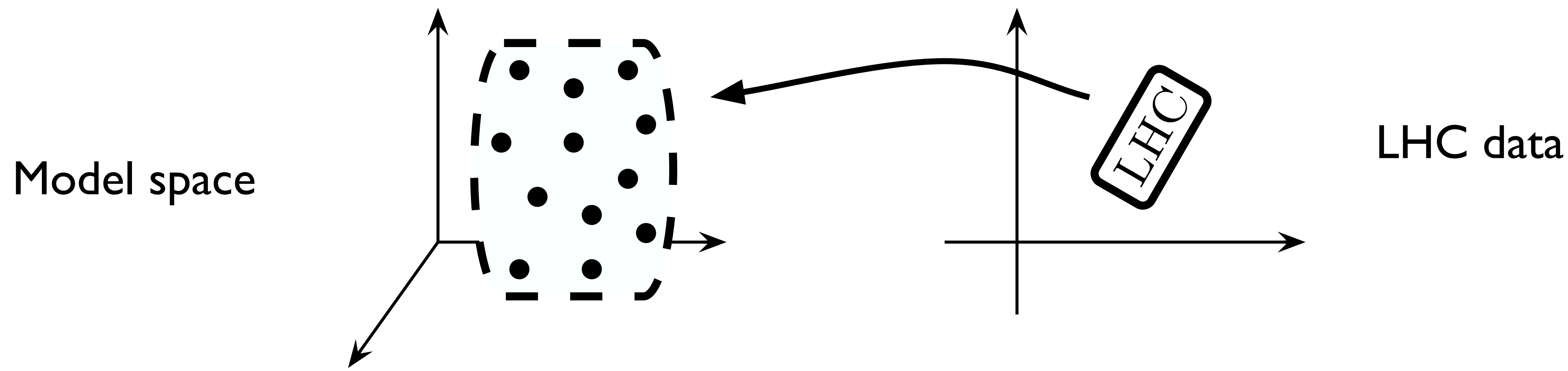
G. Giudice, T. Han, K. Wang and LTW, 1004.4902

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.

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...

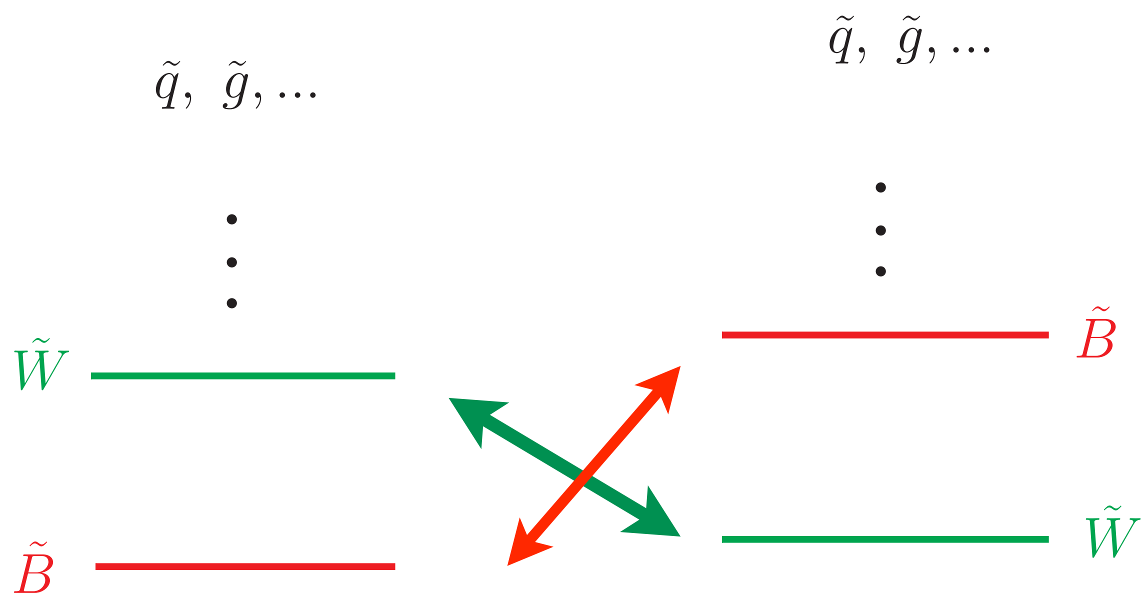
For example: in supersymmetry, bino vs wino, squark vs gluino...

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

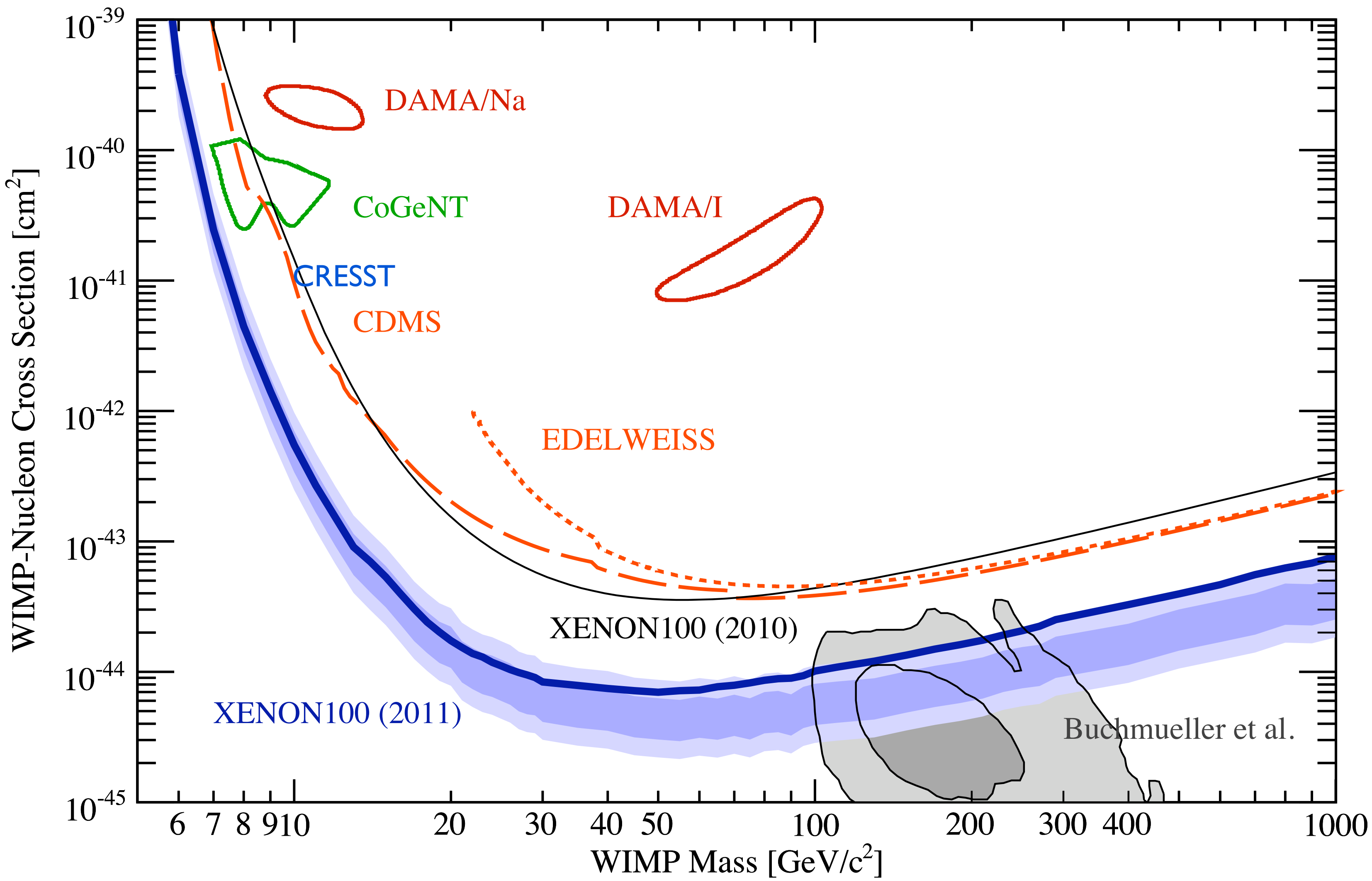
Arkani-Hamed, Kane, Thaler, and Wang, JHEP 0608:070,2006

- In addition: M_{LSP}, spin.

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

Probe NP with direct detection

XENON 100, 1104.2549



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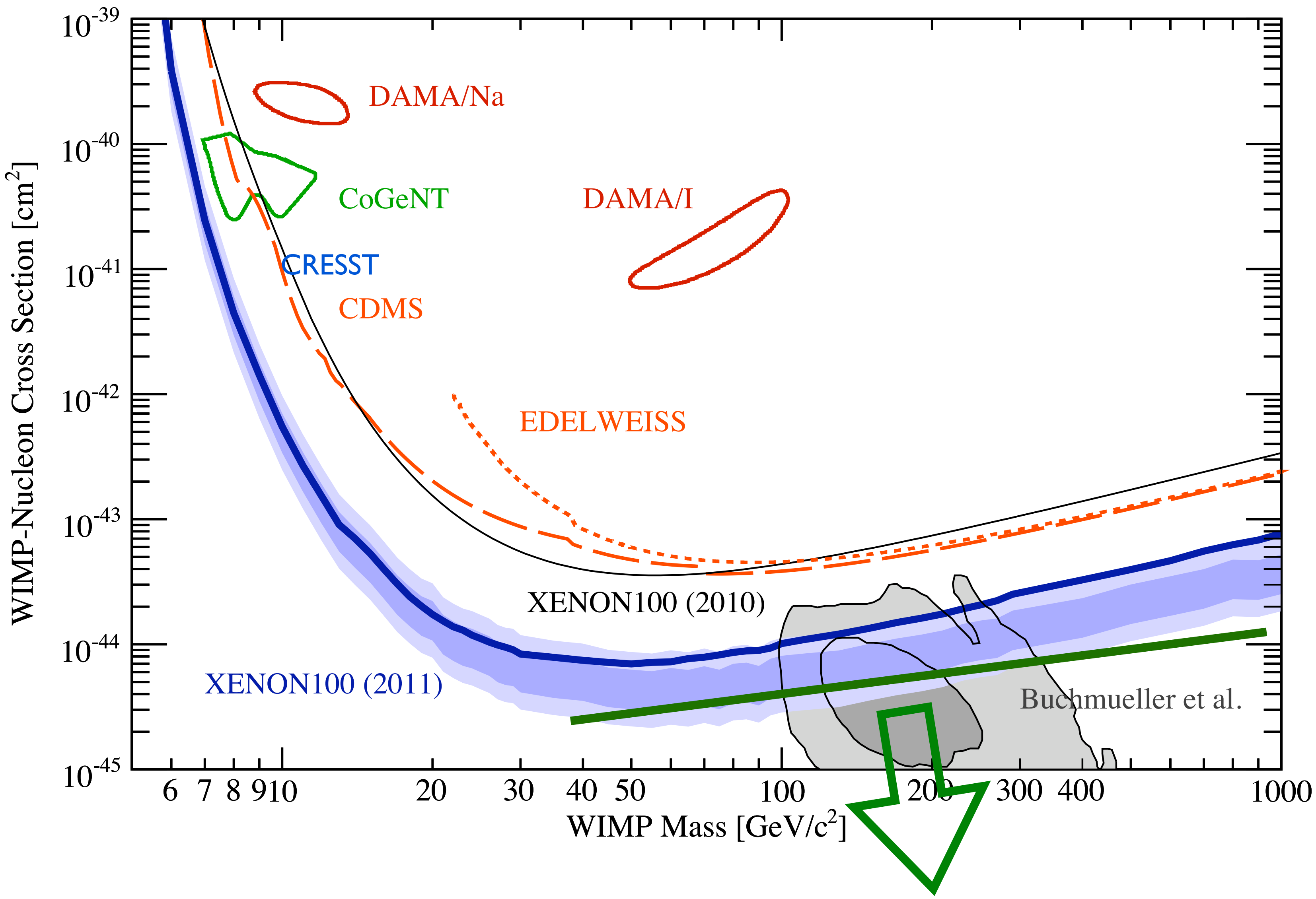
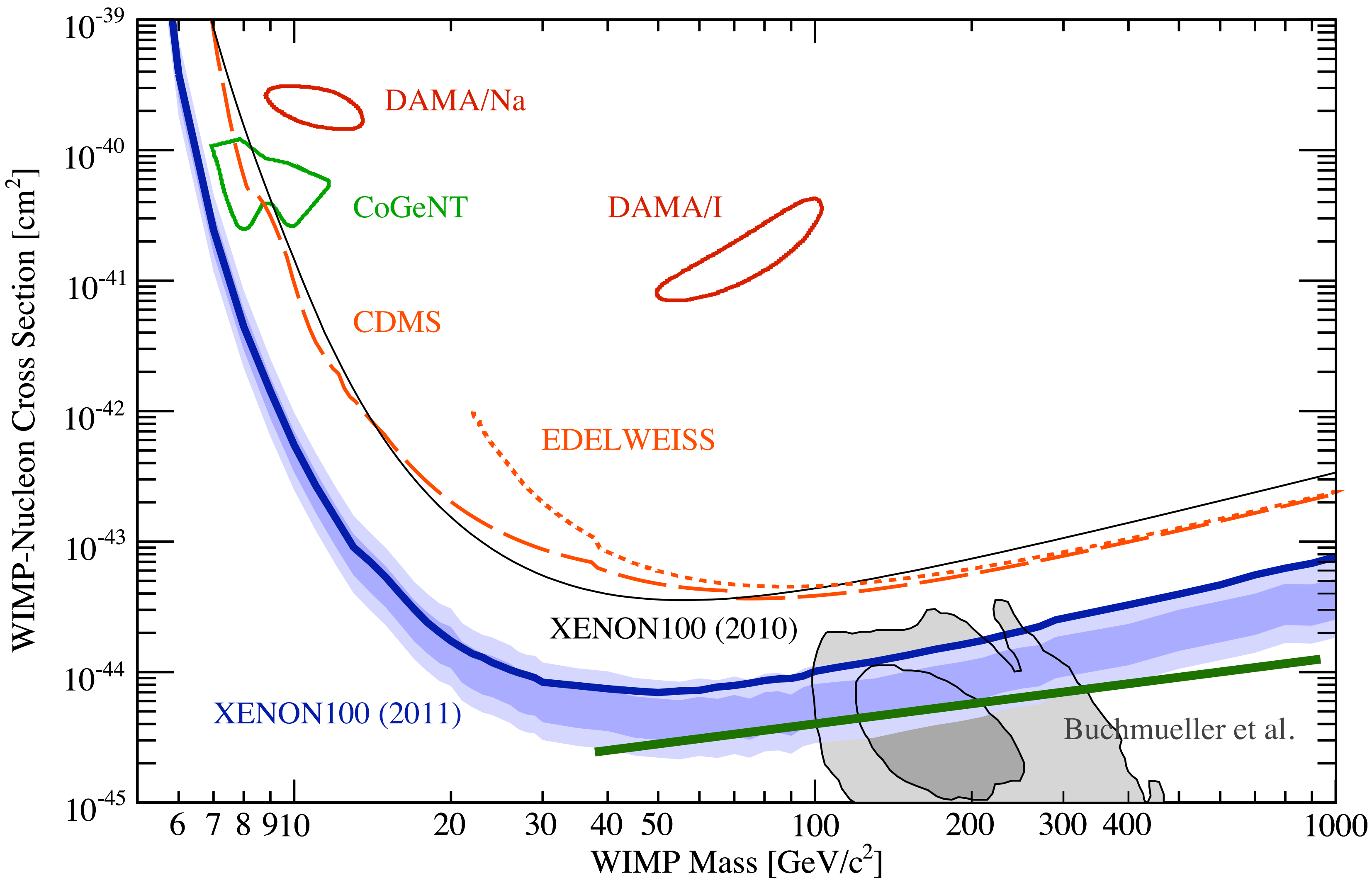


- $M_{WIMP} = O(10^2)$ GeV.
- DM of "Typical" scenarios: SUSY LSP, ...

Probe NP with direct detection

XENON 100, 1104.2549



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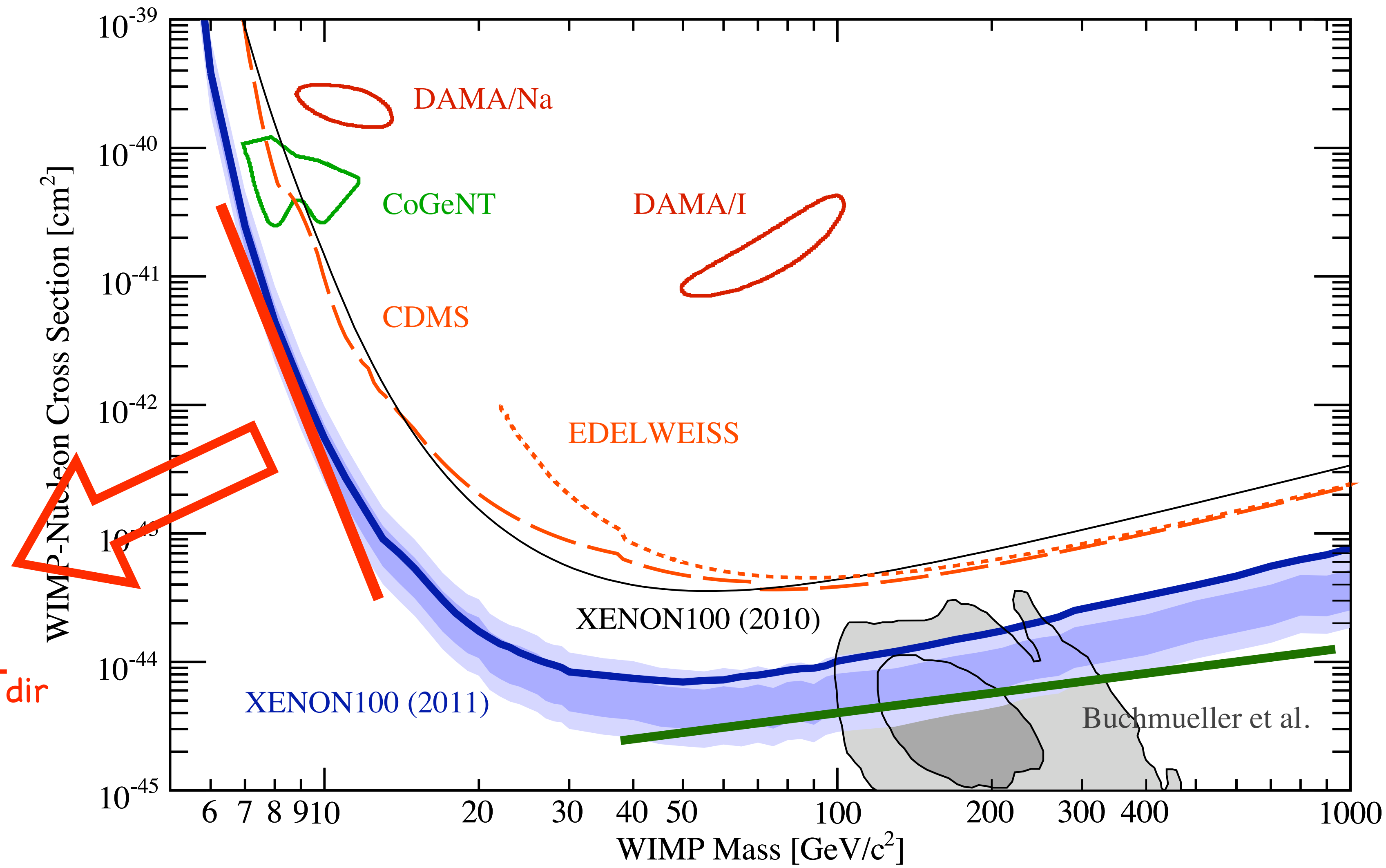
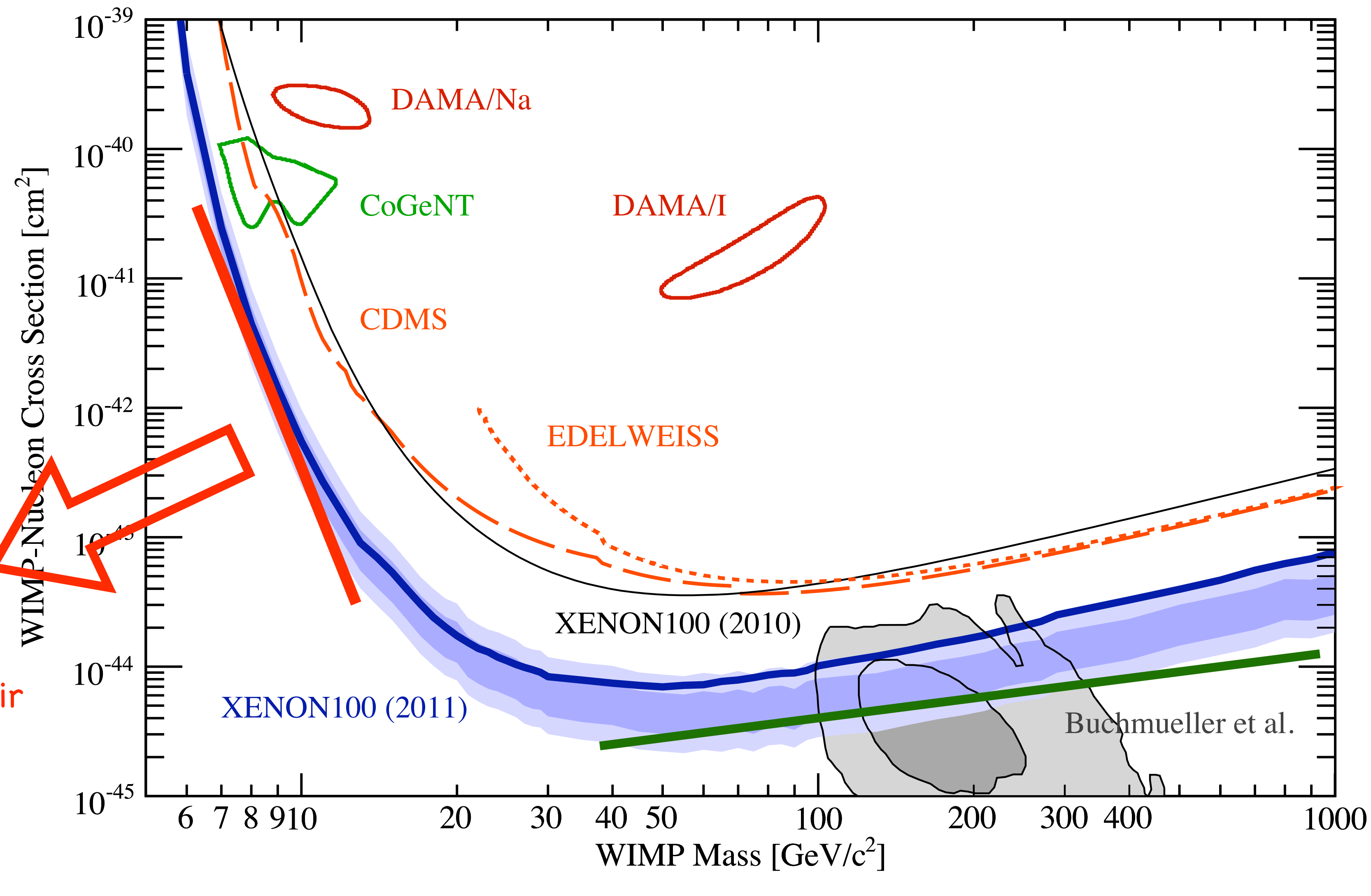


m_{WIMP}:
O(1-10) GeV
Much larger σ_{dir}

Probe NP with direct detection

XENON 100, 1104.2549

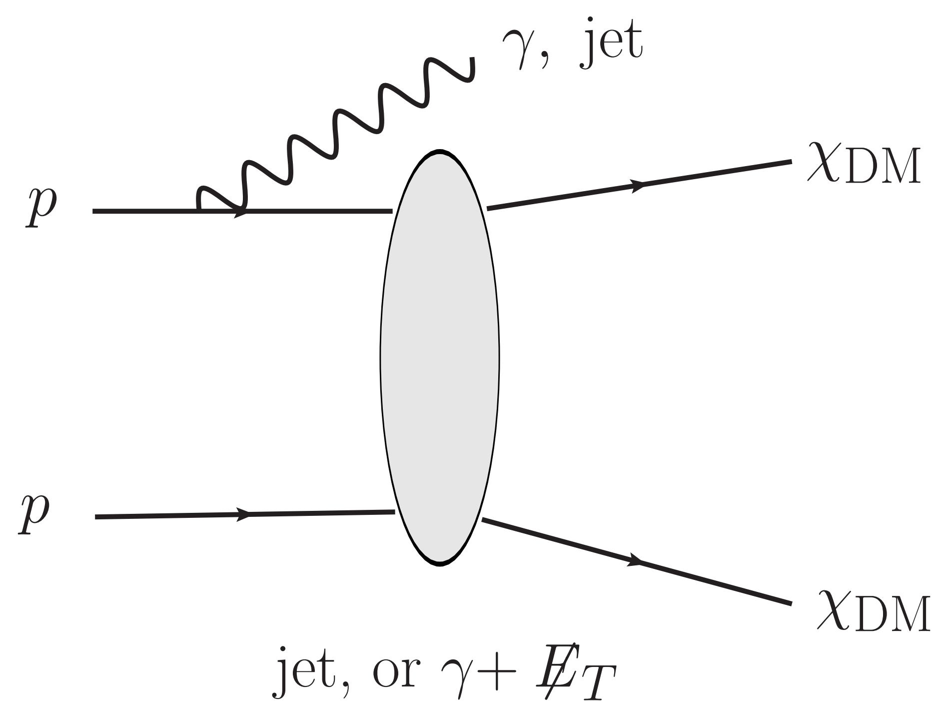


m_{WIMP}:
O(1-10) GeV
Much larger σ_{dir}

- Collider searches provide stronger bounds/potential

Collider Signals of dark matter.

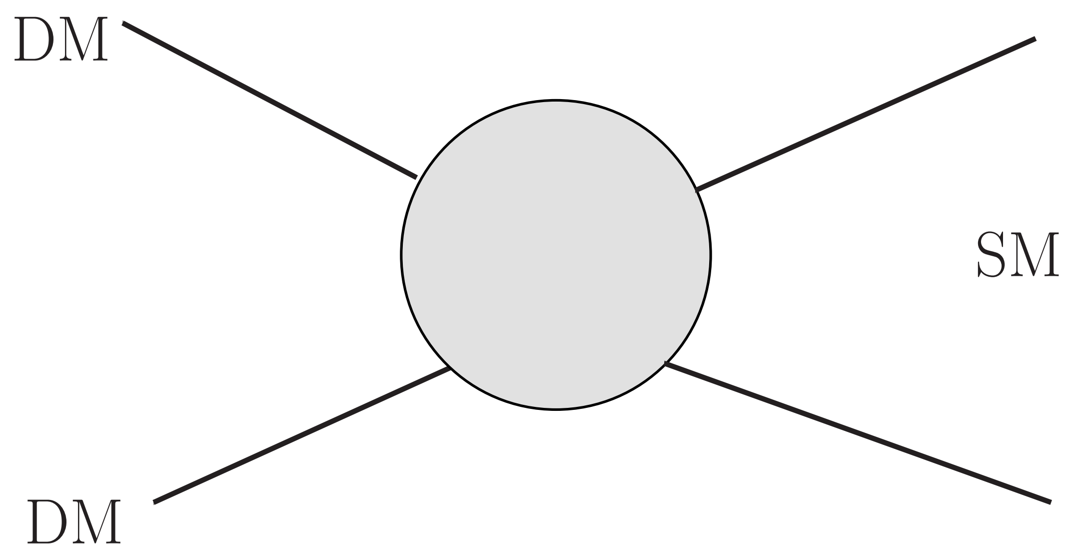
- Basic channel: pair production + additional radiation.



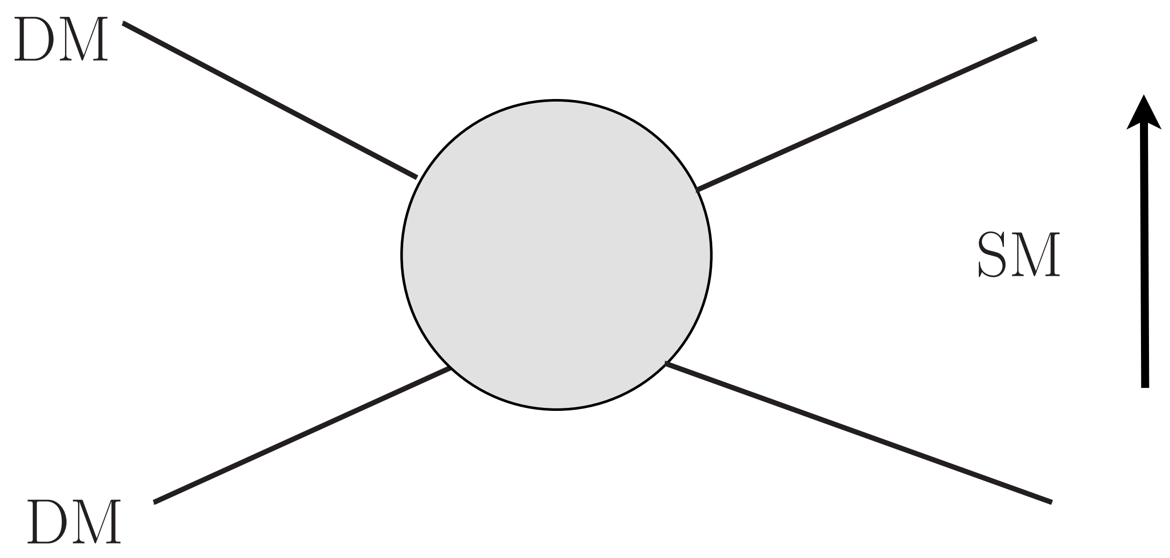
- Large Standard Model background, about 10 times the signal.

- Very challenging.

Effective operator approach



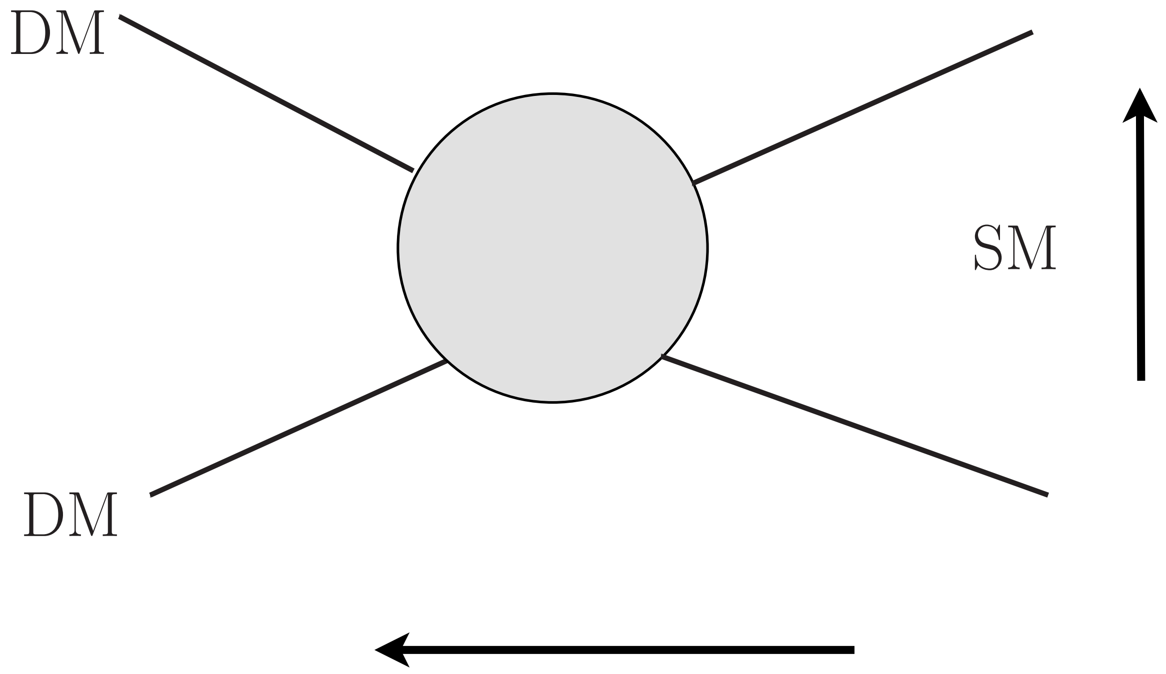
Effective operator approach



momentum exchange
q~100 MeV << m_Φ
effectively,

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

Effective operator approach



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

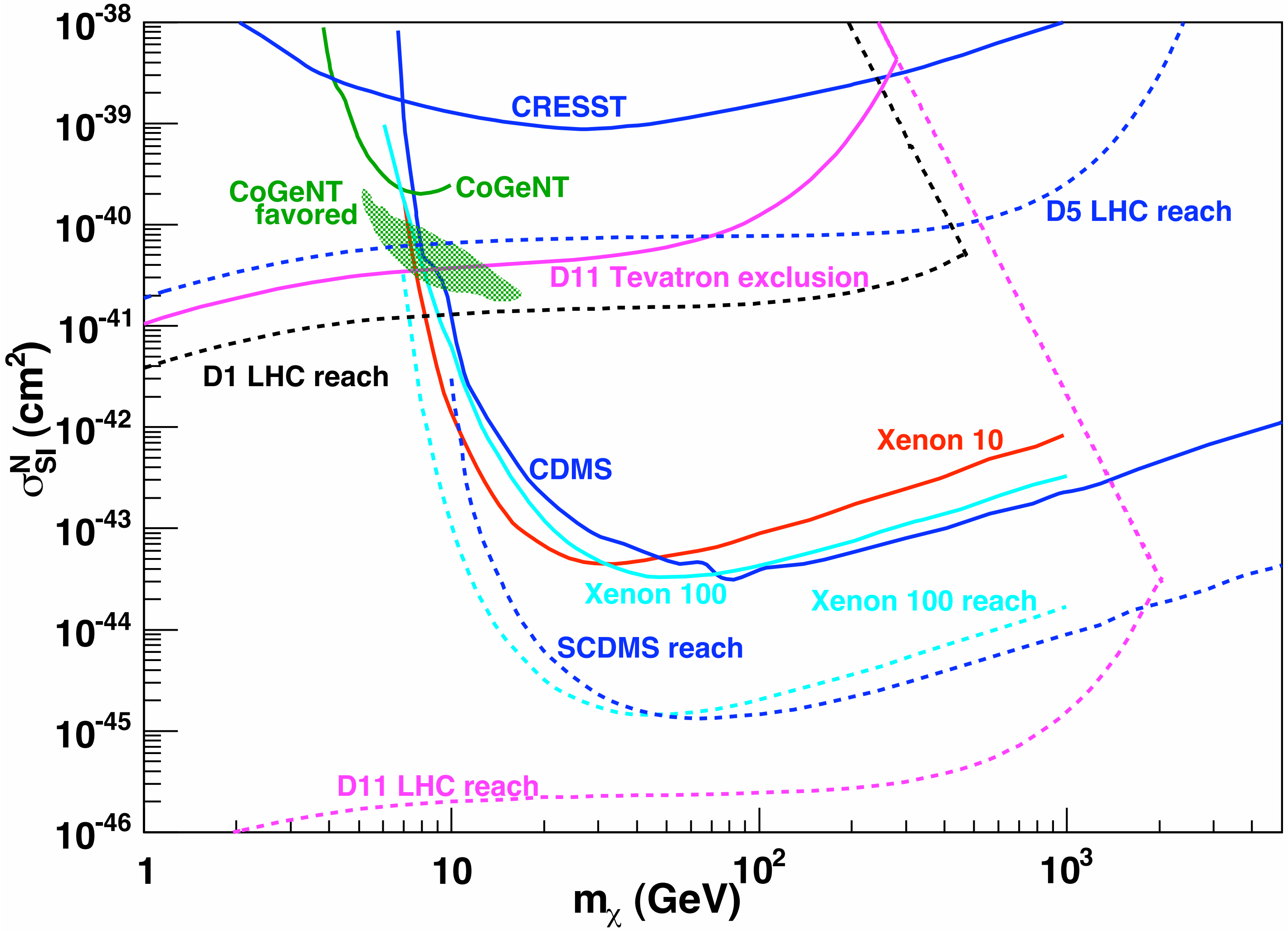
$$\frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

Recent studies.

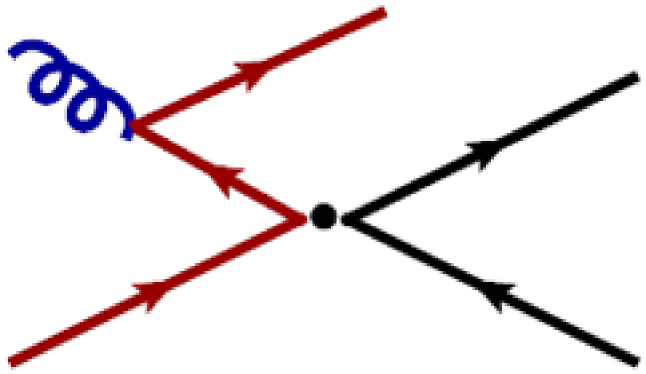
1. Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
2. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
3. Bai, Fox, Harnik, 1005.3797
4. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783
5. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1009.0008
6. Fox, Harnik, Kopp, Tsai, 1103.0240
7. Fortin,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



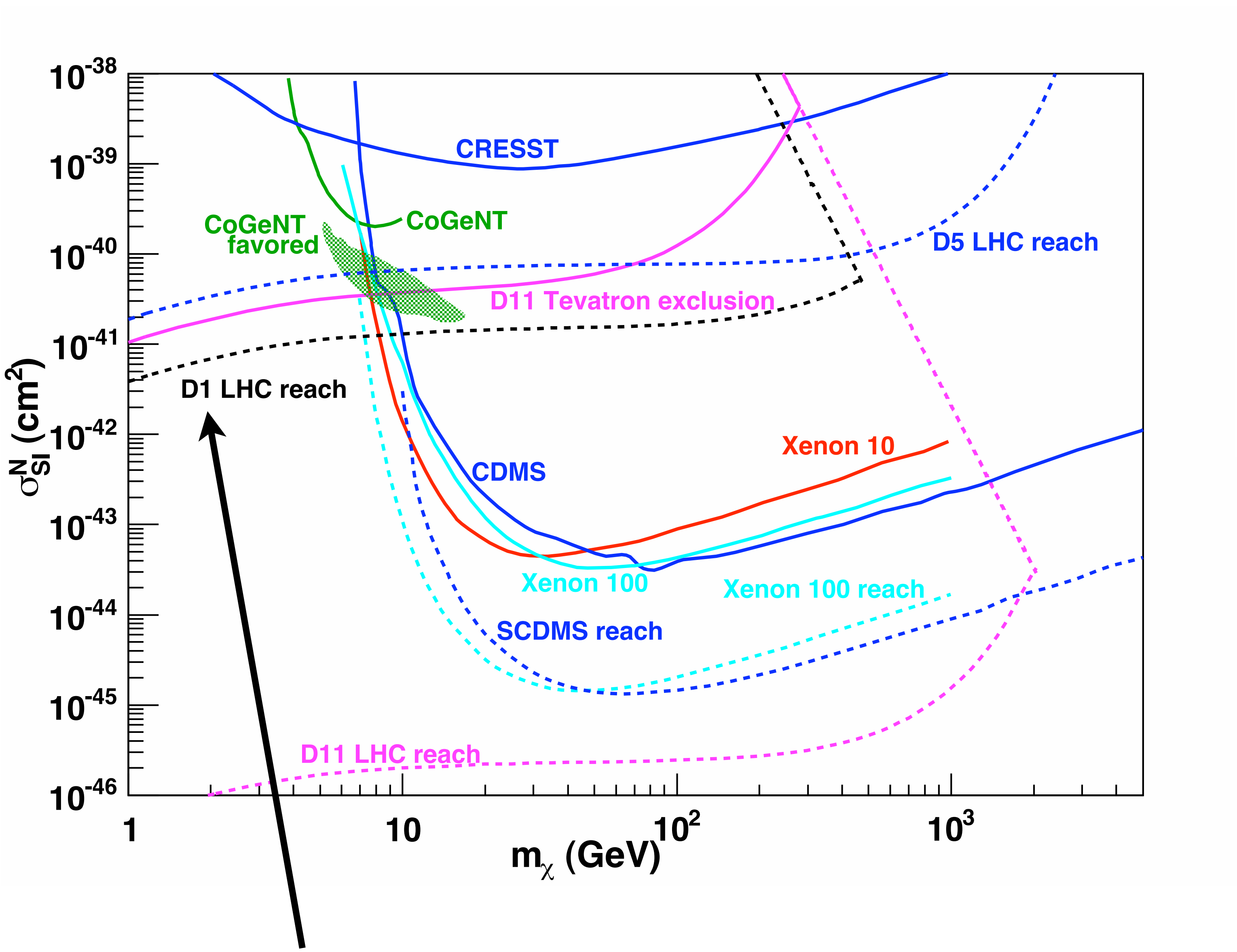
monojet

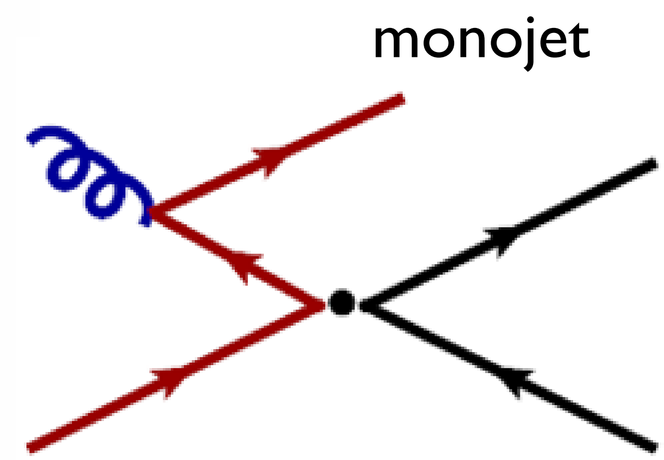


D1	$\bar{\chi}\chi\bar{q}q$
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

For example, 1008.1783

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





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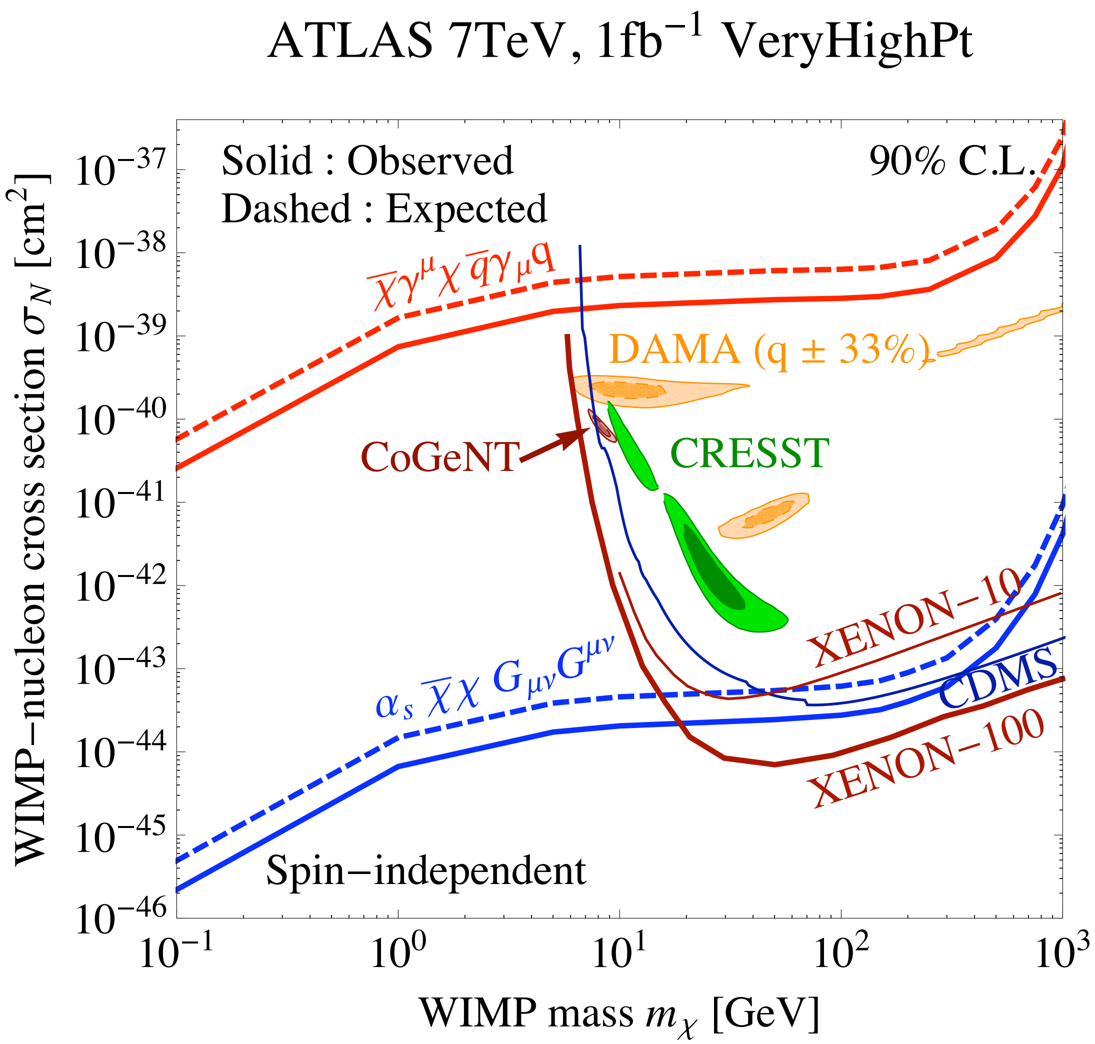
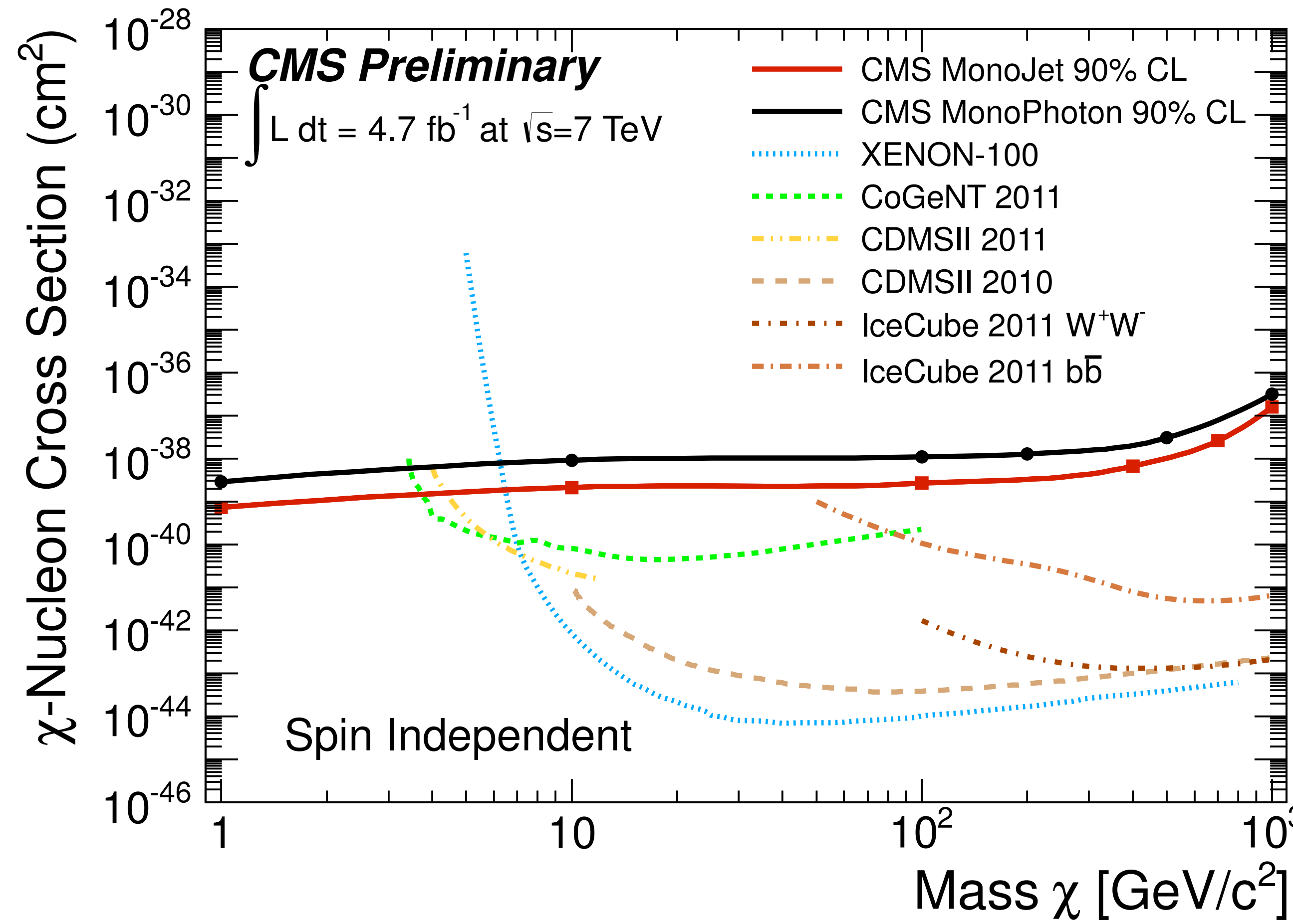
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

For small m$_\chi$,
collider rates controlled by larger mass scales, i.e., p$_T$ cut;
does not depend on m$_\chi$.
Collider bounds flat and stronger.

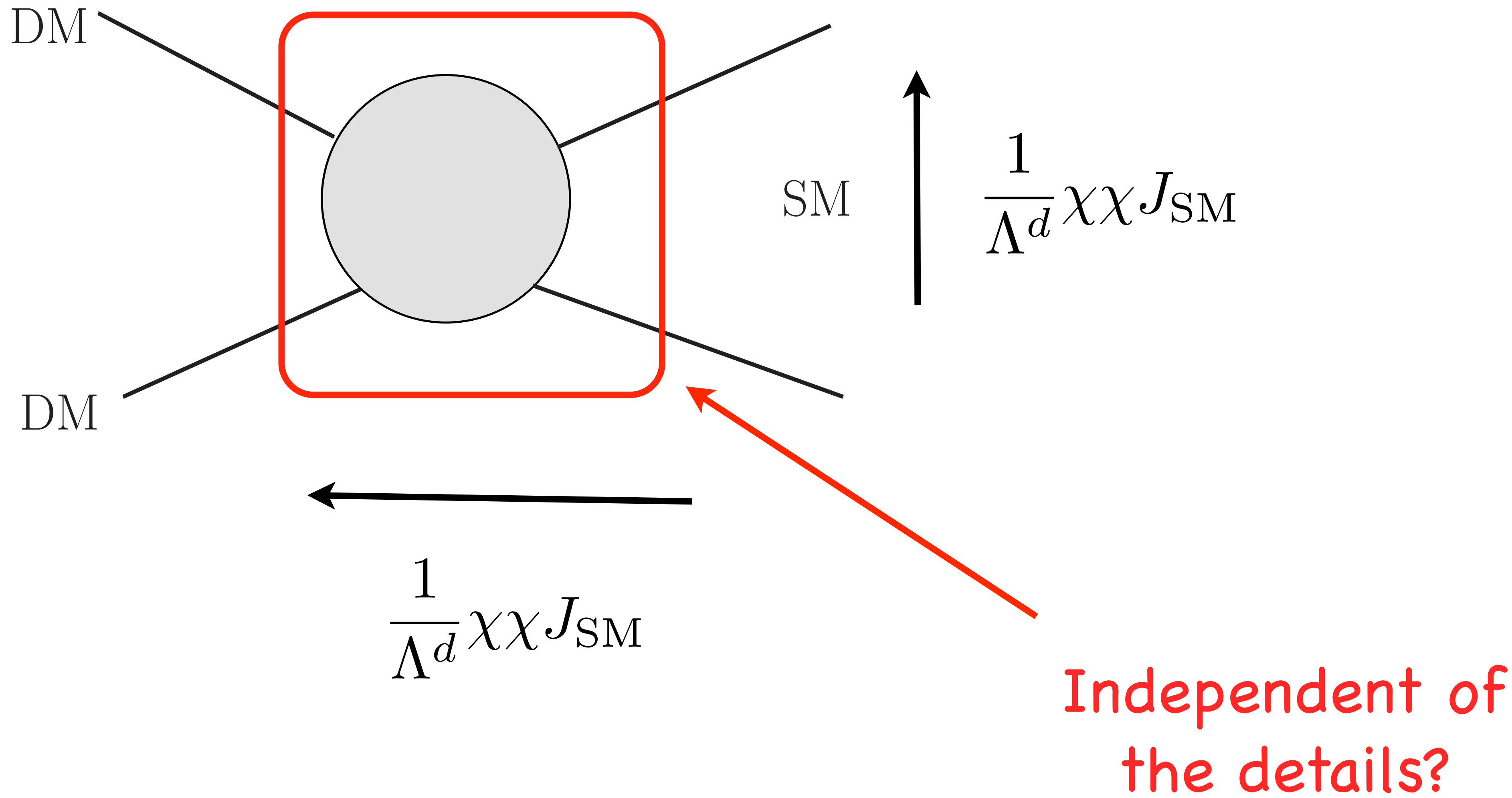
More recently





Fox, Harnik, Kopp, and Tsai, 1109.4398

Effective operator effective?



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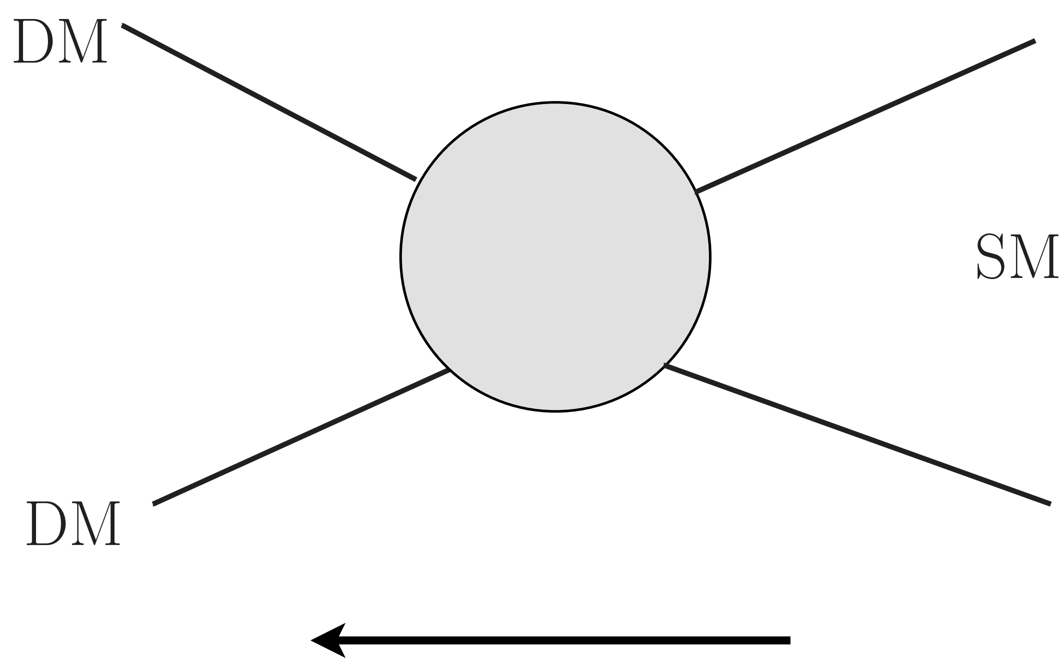


Use colliders to constrain and probe the same operator

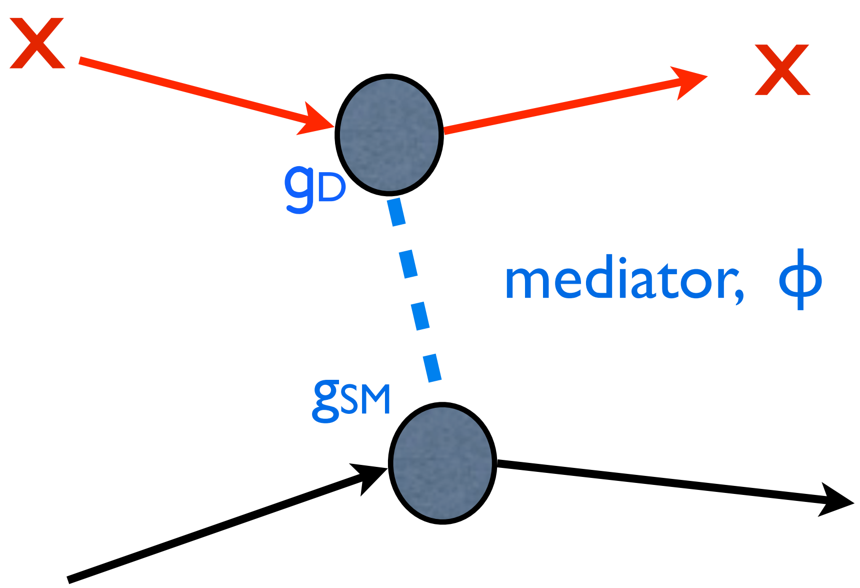
$$\frac{1}{\Lambda^d}\chi\chi J_{\mathrm{SM}}$$

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

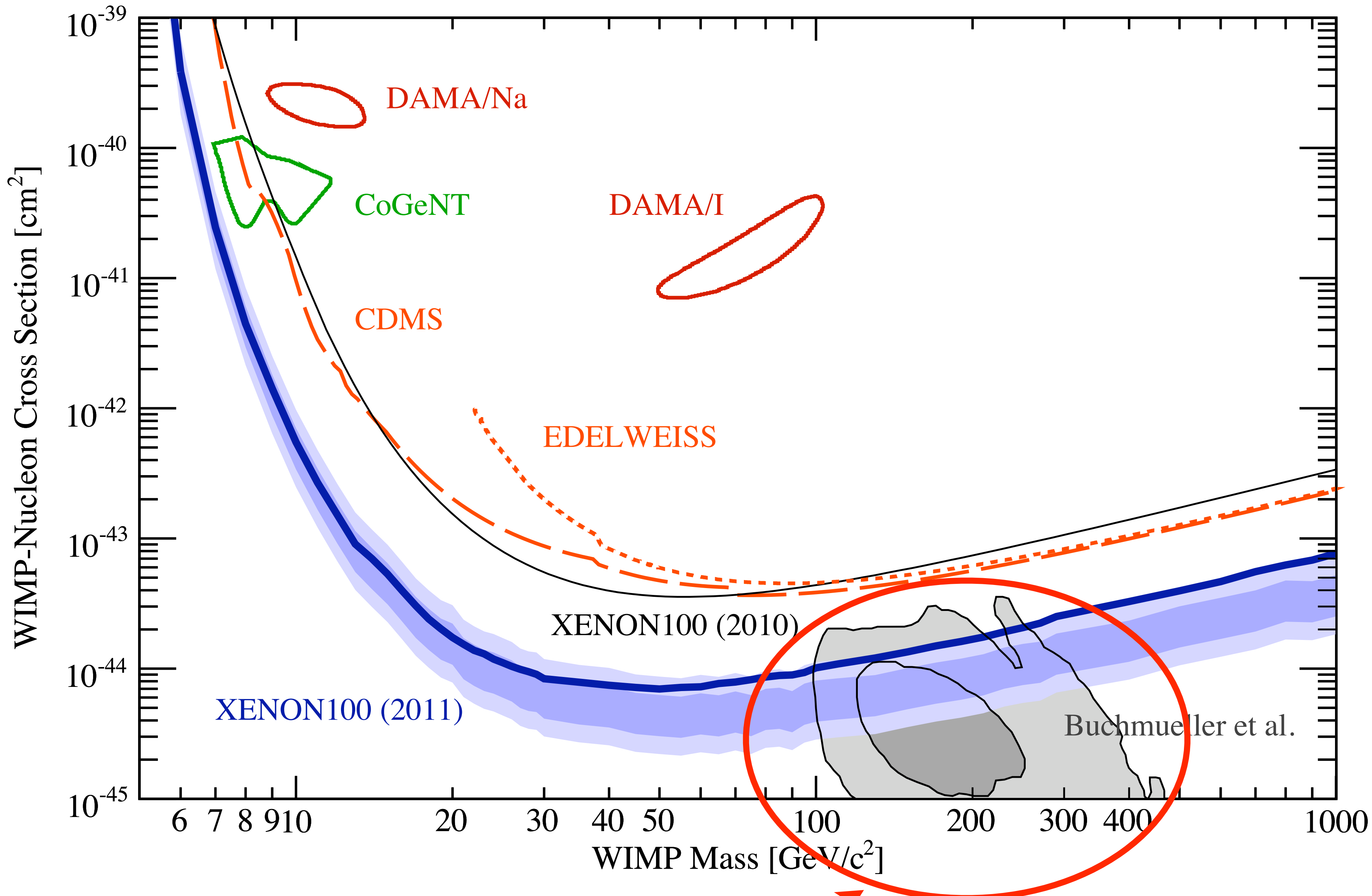
Mediator, two typical examples.



N= Ar, Ge, Xe, ...

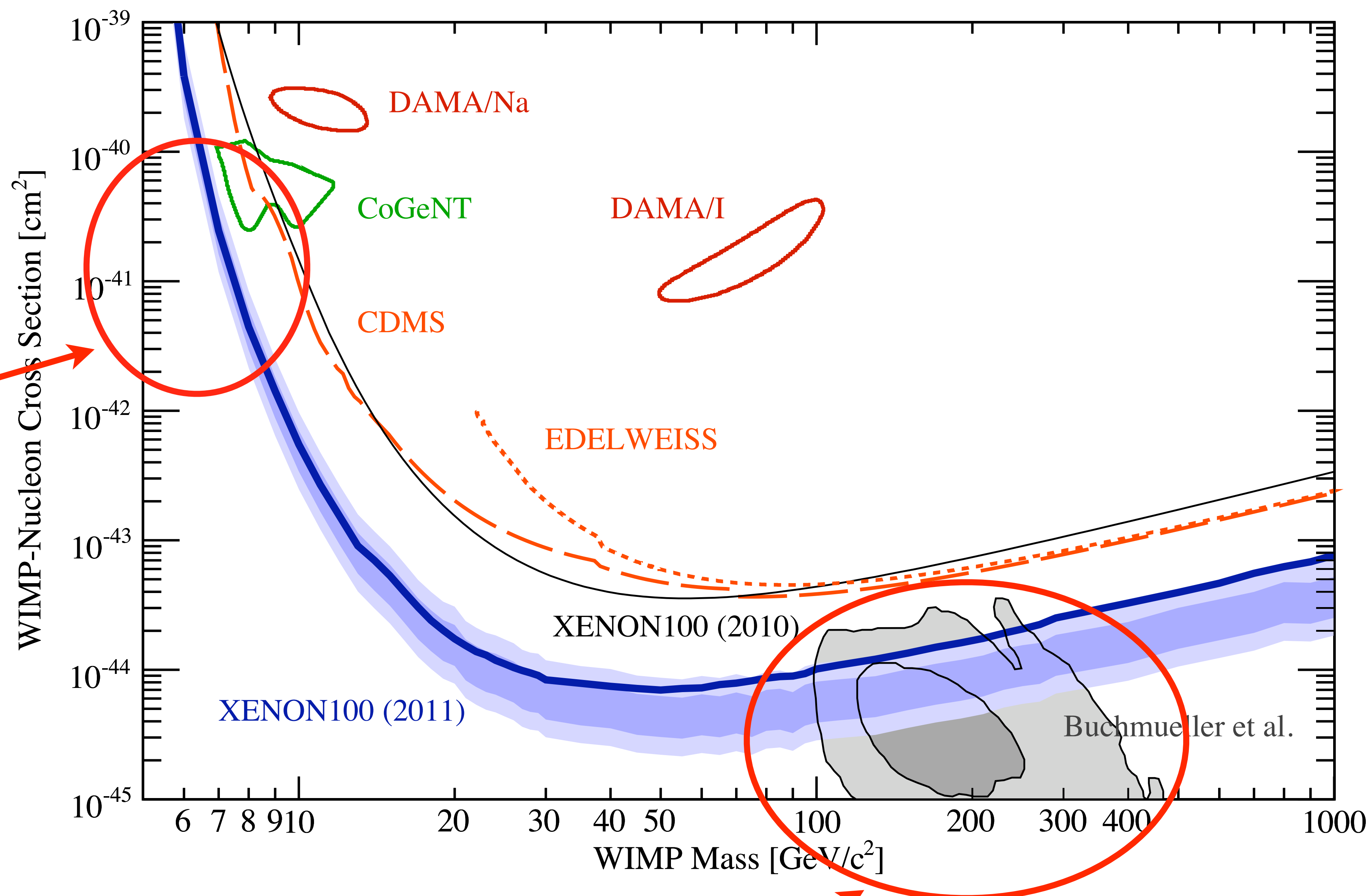
- ϕ=Higgs
  - $g_{SM} \approx (100\ \text{MeV})/(100\ \text{GeV})$
  - $m_X \approx 100$ GeV
  - $\sigma_n \approx 10^{-43}$–$10^{-45}$ cm^{-2}
- Φ=100 GeV spin-1, D=dirac fermion
  - $\sigma_n \approx 10^{-36}$–$10^{-39}$ cm^{-2}

Probe NP with direct detection



SUSY, typically Higgs mediated.

Probe NP with direct detection



Light DM spin-1 mediator.

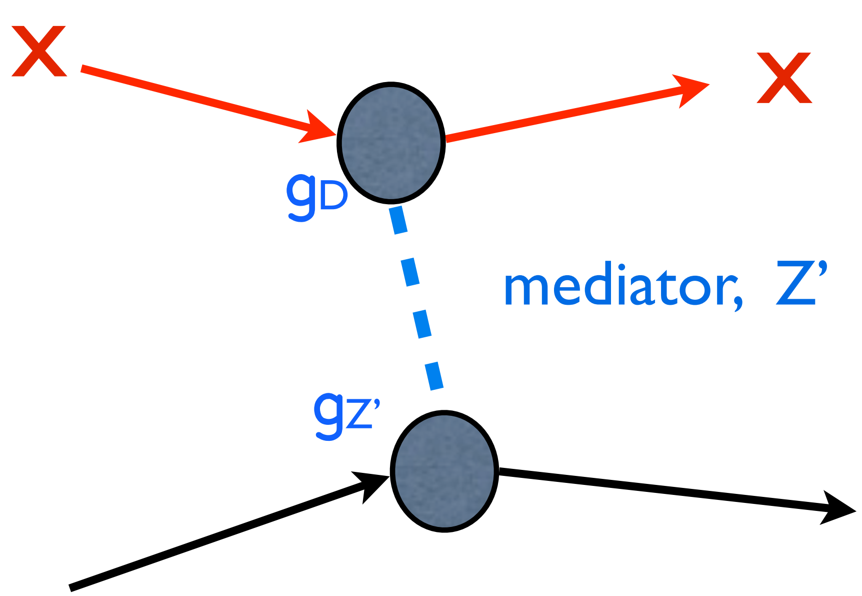
SUSY, typically Higgs mediated.

Case study: a spin-1 Z′

Xiang-Dong. Ji, Haipeng An, LTW 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.

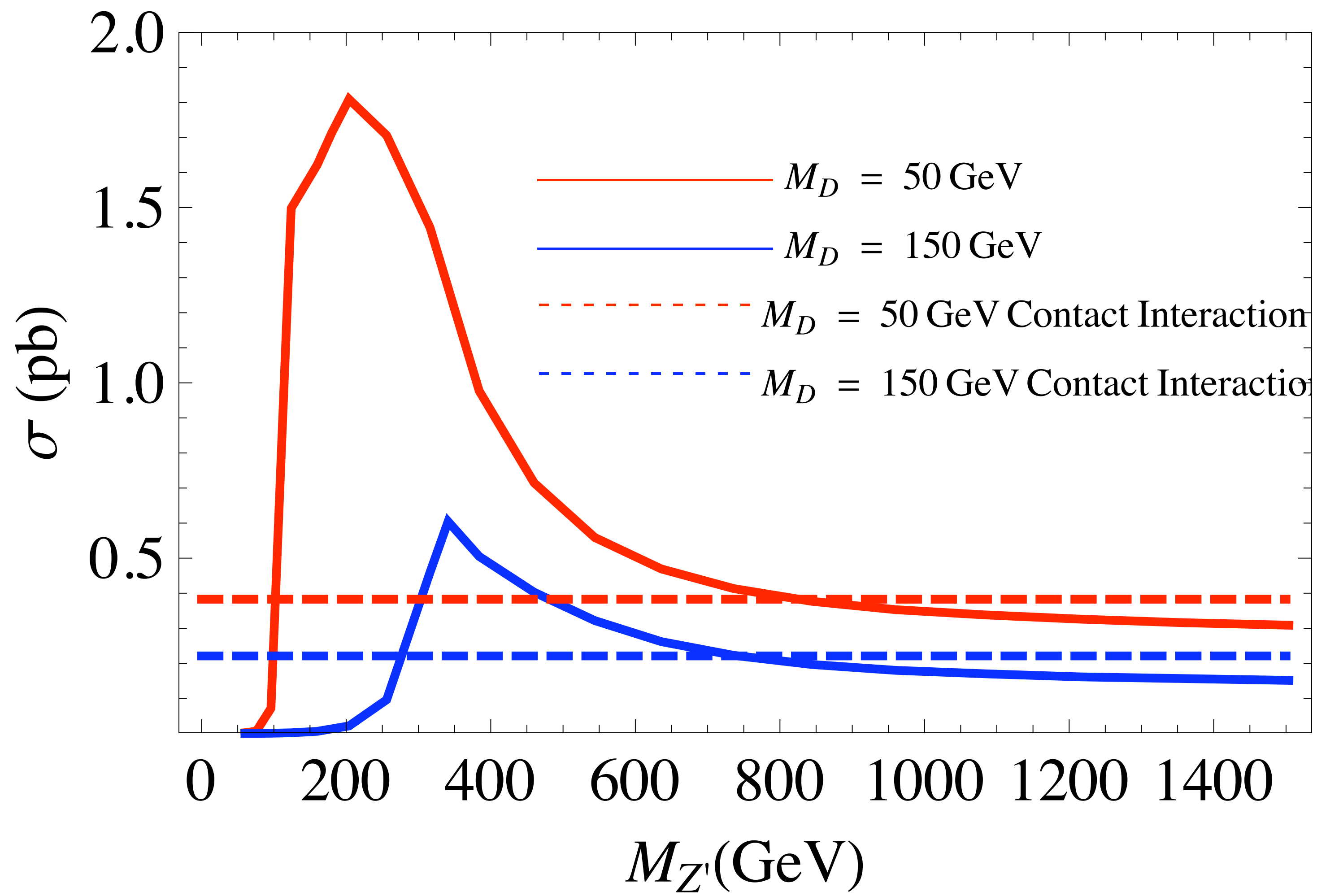


$$g_D \sim g'_Z \rightarrow \sigma_{\rm dir} \propto \frac{g'^4_Z}{m^4_{Z'}}$$

N= Ar, Ge, Xe, ...

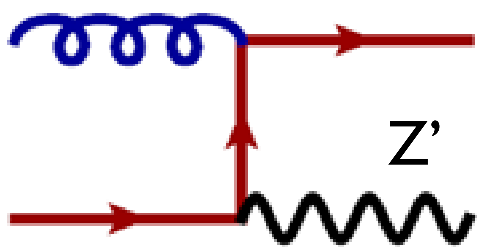
Connection with direct detection

Tevatron rate for
Monojet + (MET> 80 GeV)



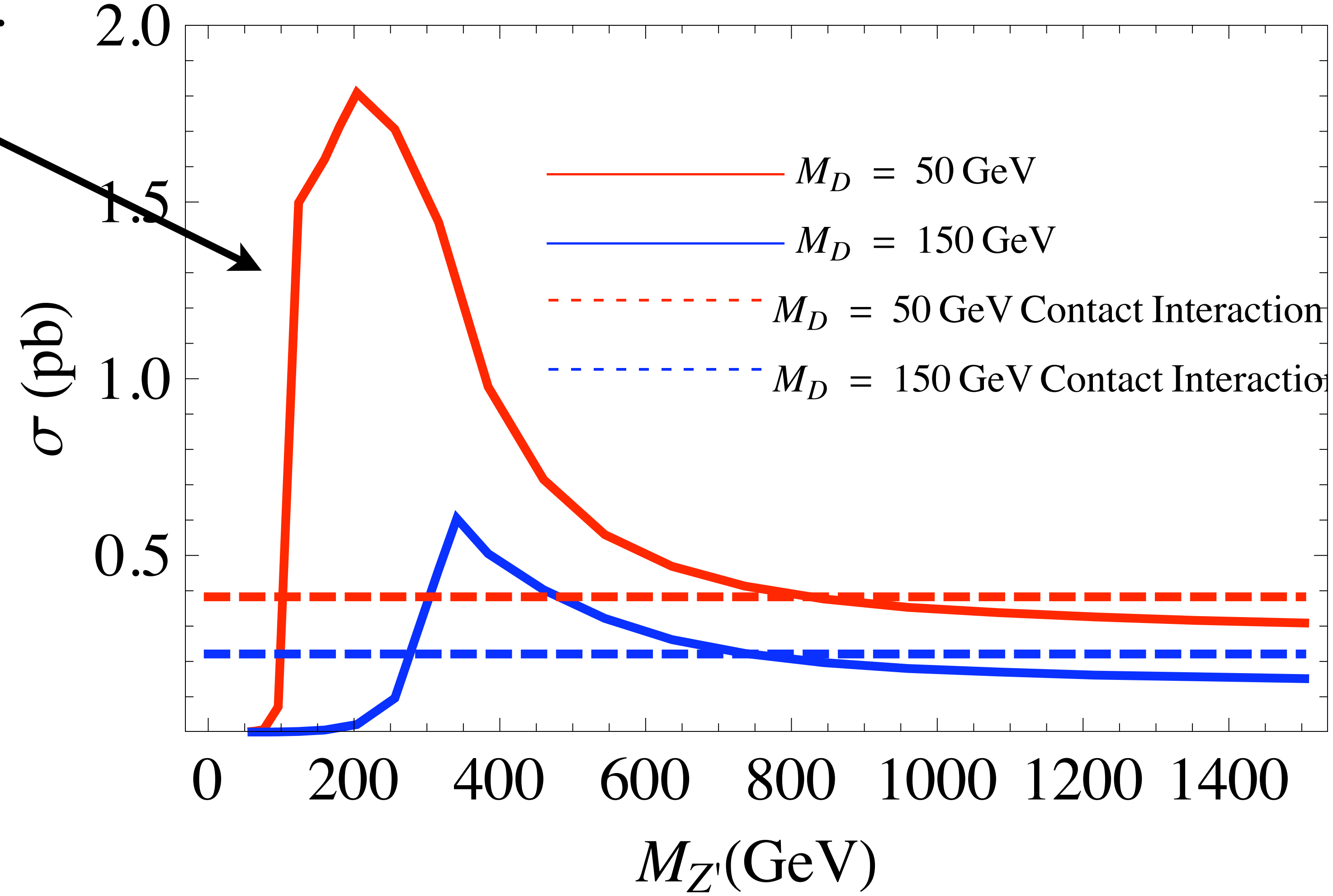
$g_D = g_{Z'}$, fix $g_{Z'}/M_{Z'}$ (σ_{dir})

Connection with direct detection



resonance prod.

Tevatron rate for
Monojet + (MET> 80 GeV)



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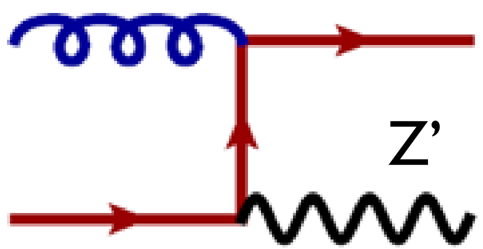
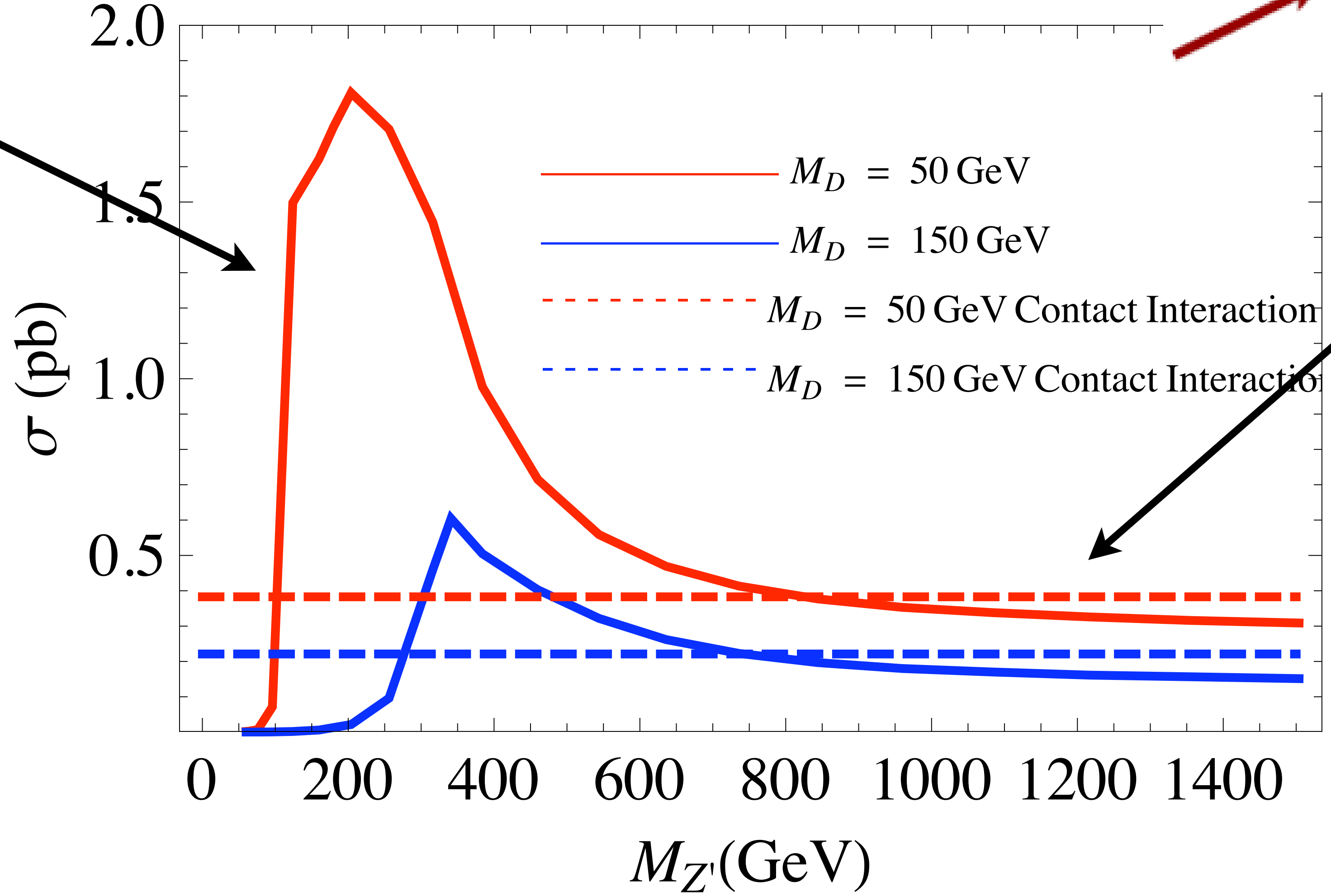
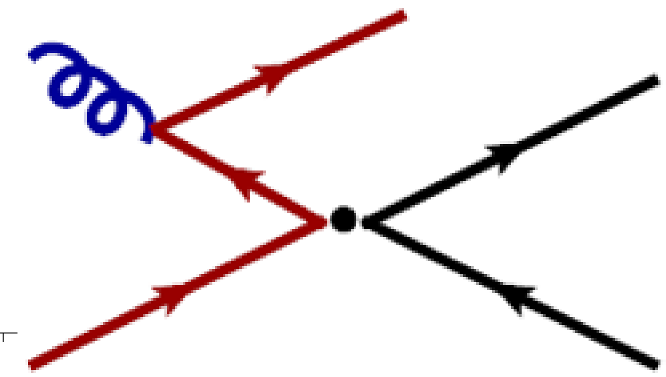


resonance prod.

Tevatron rate for
Monojet + (MET> 80 GeV)



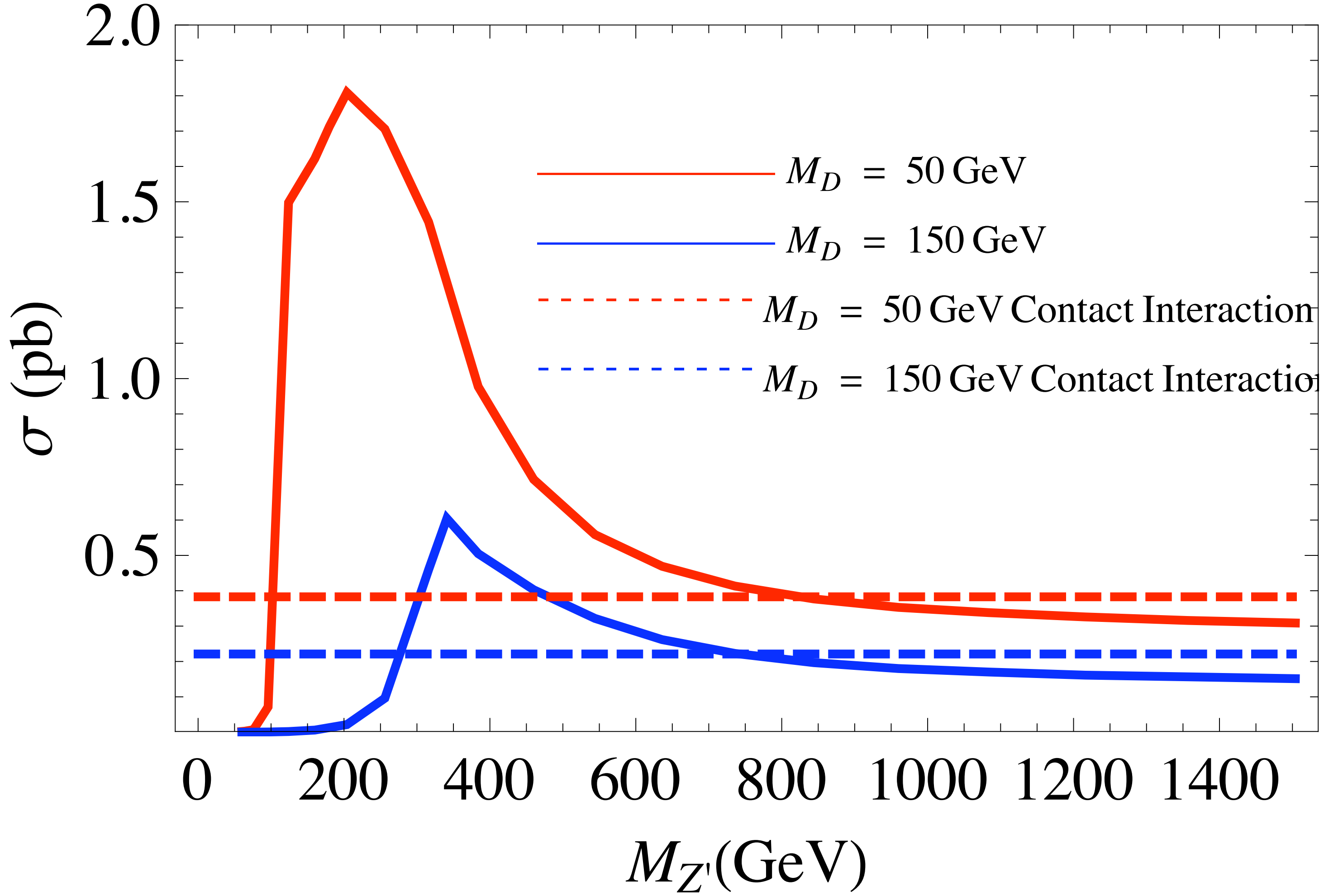


contact-like

$g_D = g_{Z'}$, fix $g_{Z'}/M_{Z'}$ (σ_{dir})

Connection with direct detection

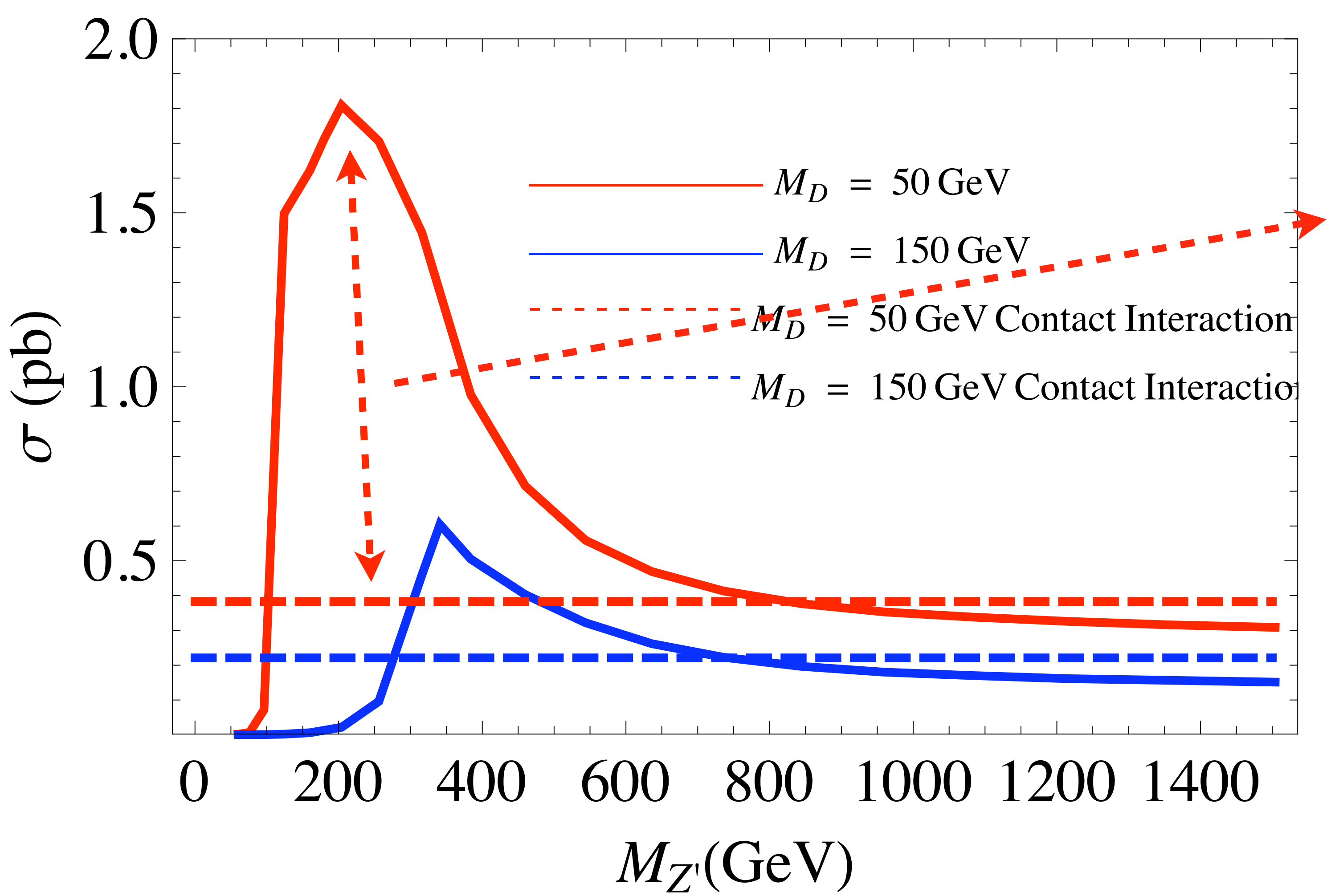
Tevatron rate for
Monojet + (MET> 80 GeV)



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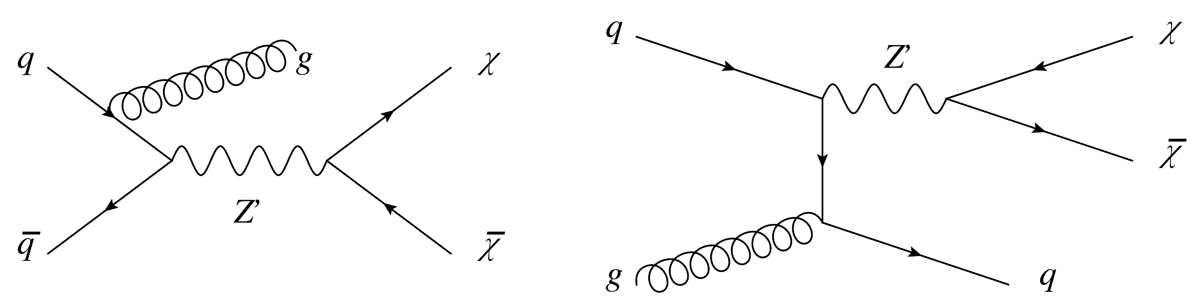
$$\sigma_{\rm SI} = \frac{9g_{Z'}^2 g_D^2 M_N^2 M_D^2}{\pi M_{Z'}^4 (M_N + M_D)^2} \simeq 3.9 \times 10^{-39} {\rm cm}^2 \left(\frac{g_{Z'}}{0.3}\right)^2 \left(\frac{g_D}{0.3}\right)^2 \left(\frac{200 \text{ GeV}}{M_{Z'}}\right)^4$$

Will also show results for O_4

Monojet search



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

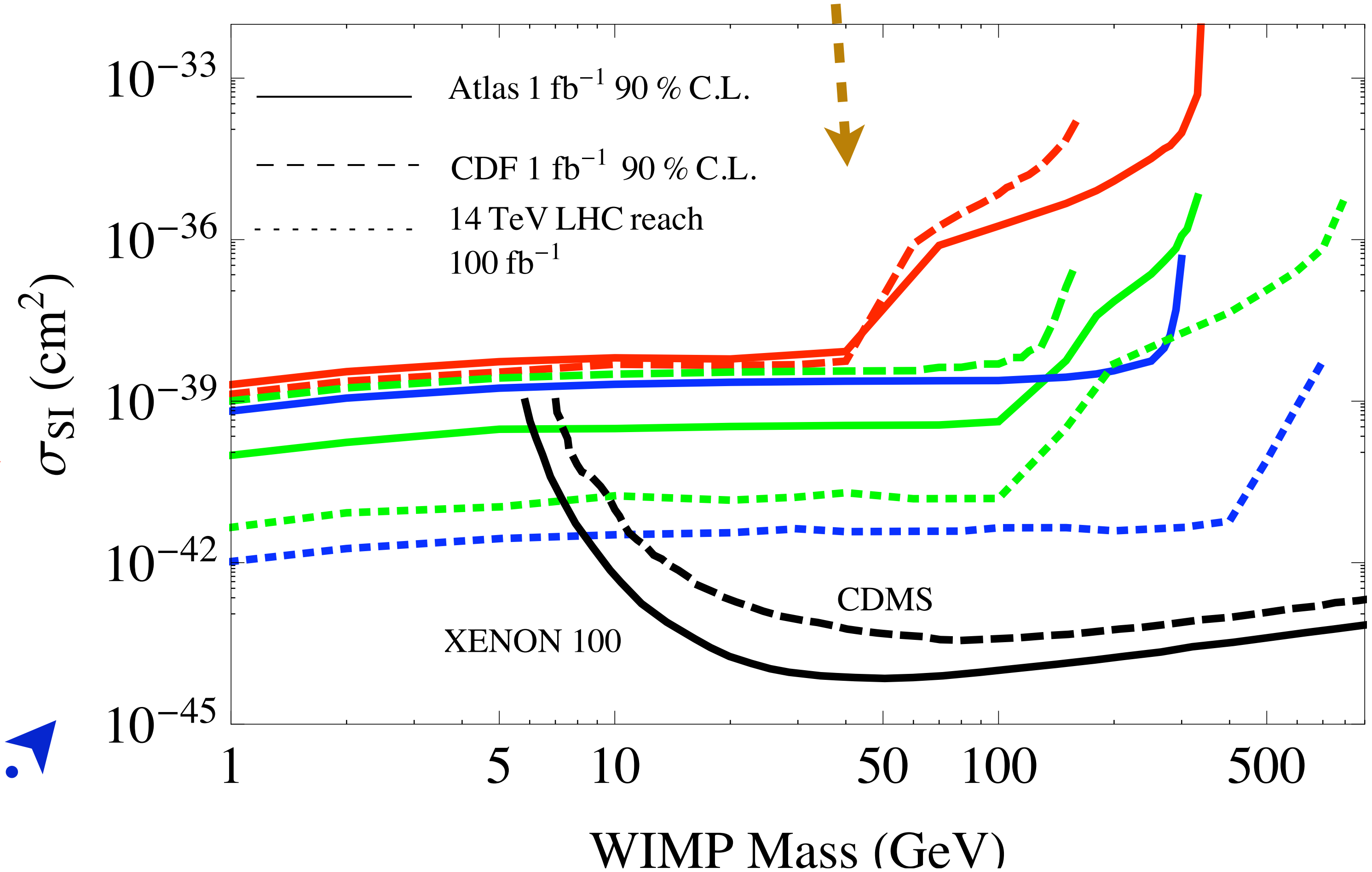
- LHC. ATLAS 1 fb^{-1}

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, 1202.2894.

Spin dependent

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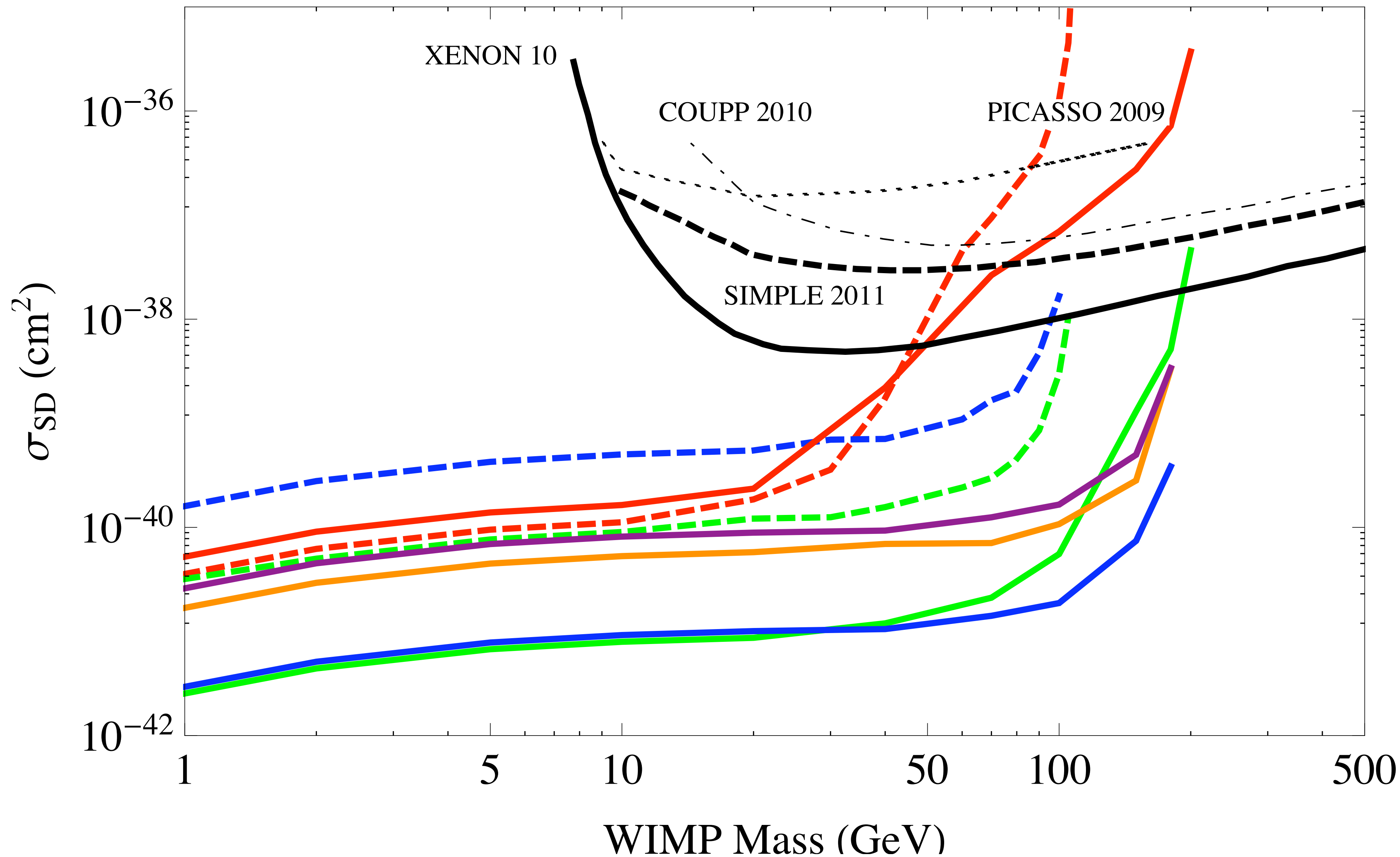
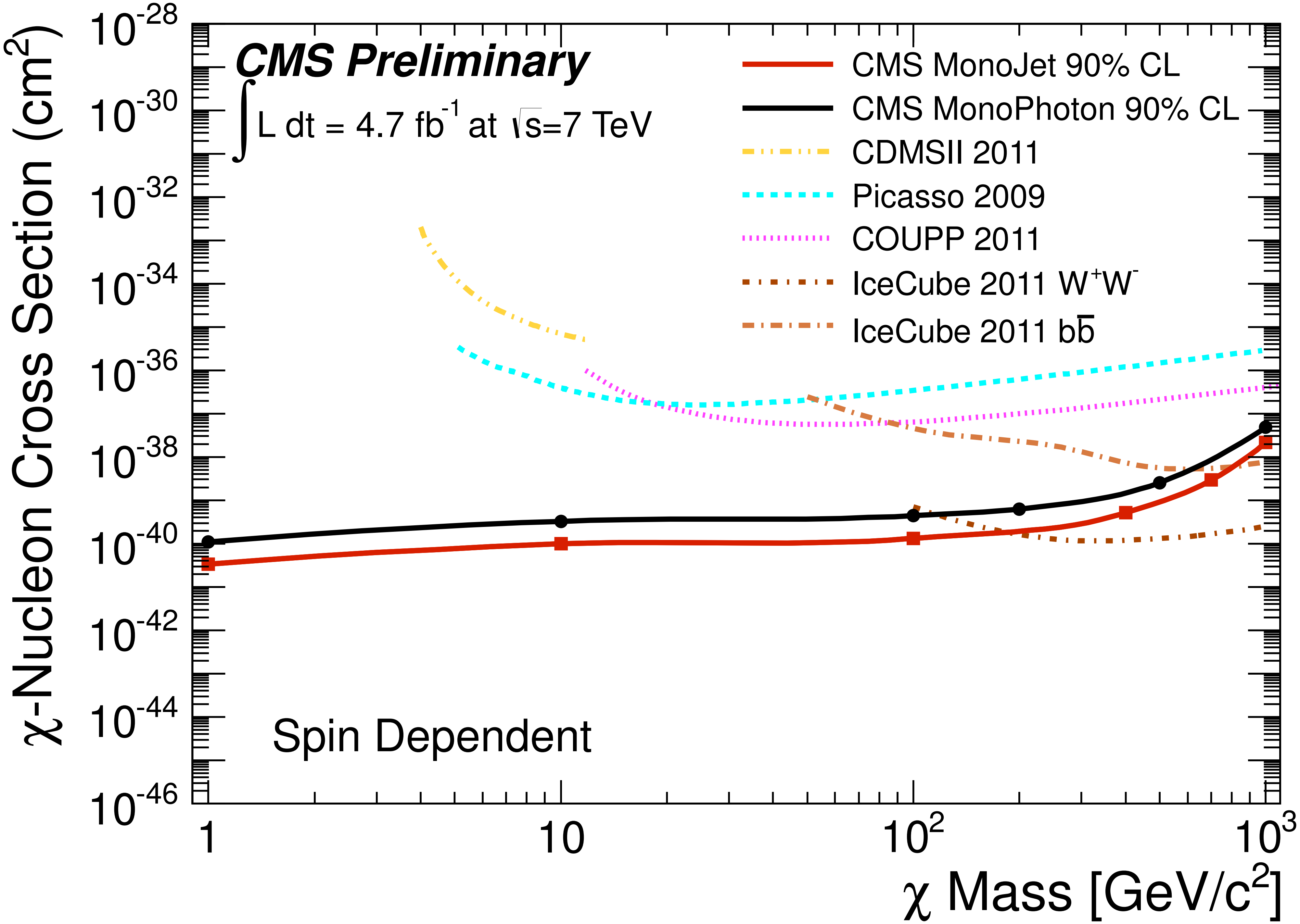
Solid: LHC, 7 TeV 1 fb^{-1} Very High PT

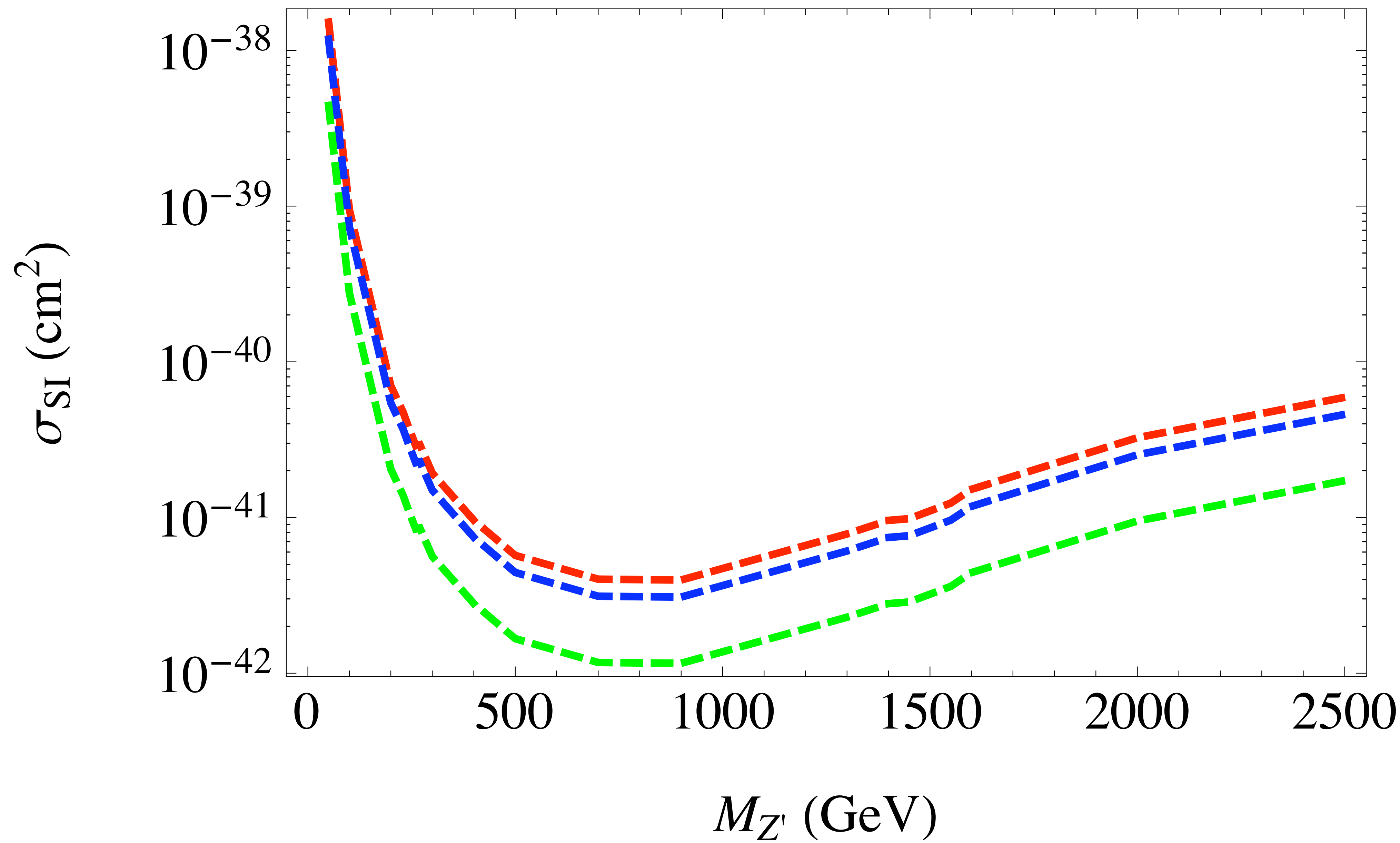


$M_{Z'}$ = 100 GeV, 300 GeV, 500 GeV, 1 TeV, 1.5 TeV

Recent CMS result

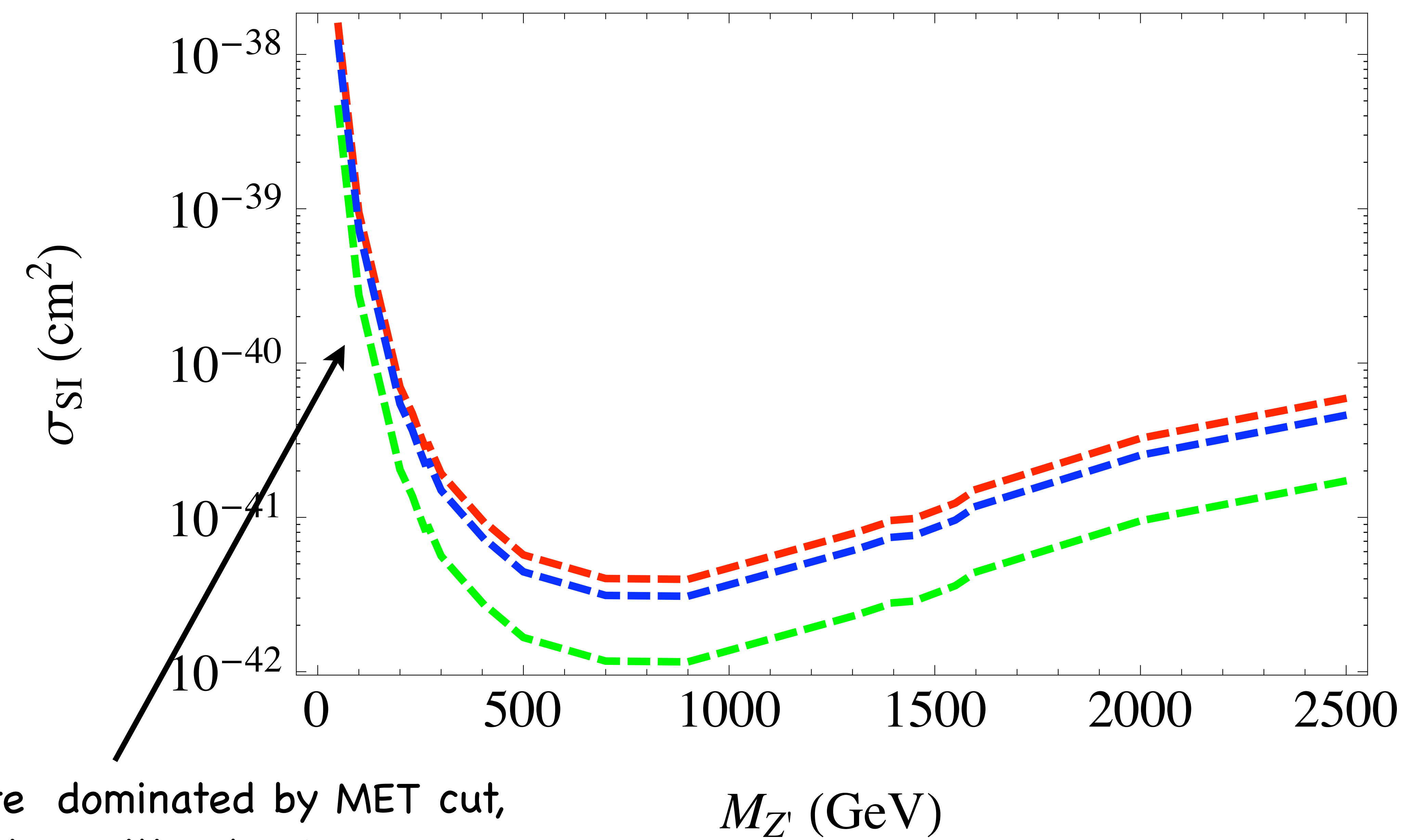


LHC reach in monojet+MET.



Xiangdong Ji, Haipeng An, LTW.

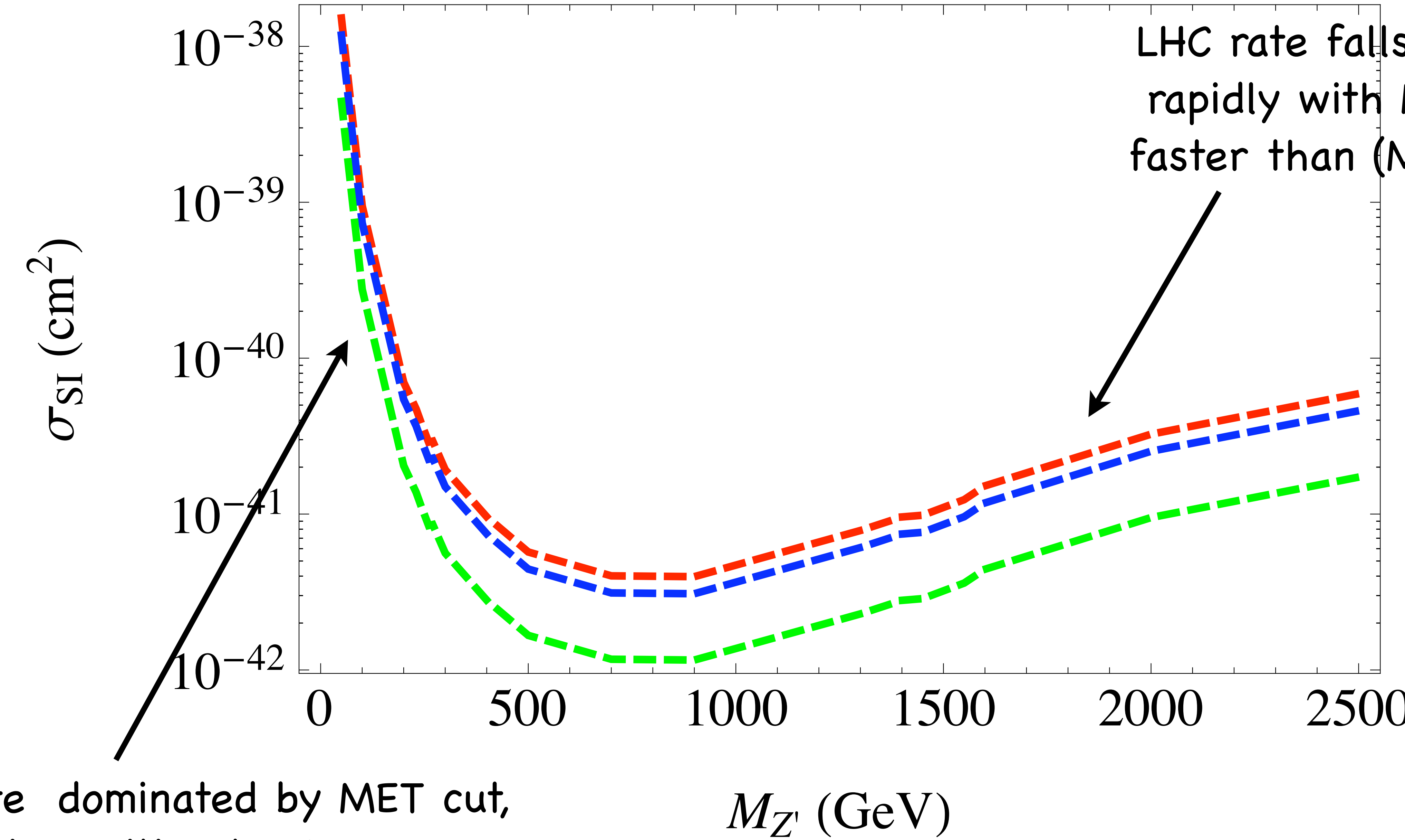
LHC reach in monojet+MET.



LHC rate dominated by MET cut, insensitive to $M_{Z'}$.
→ LHC bounds only on $g_{Z'}$
Bounds on $\sigma_{SI} \propto (M_{Z'})^{-4}$

Xiangdong Ji, Haipeng An, LTW.

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

Xiangdong Ji, Haipeng An, LTW.

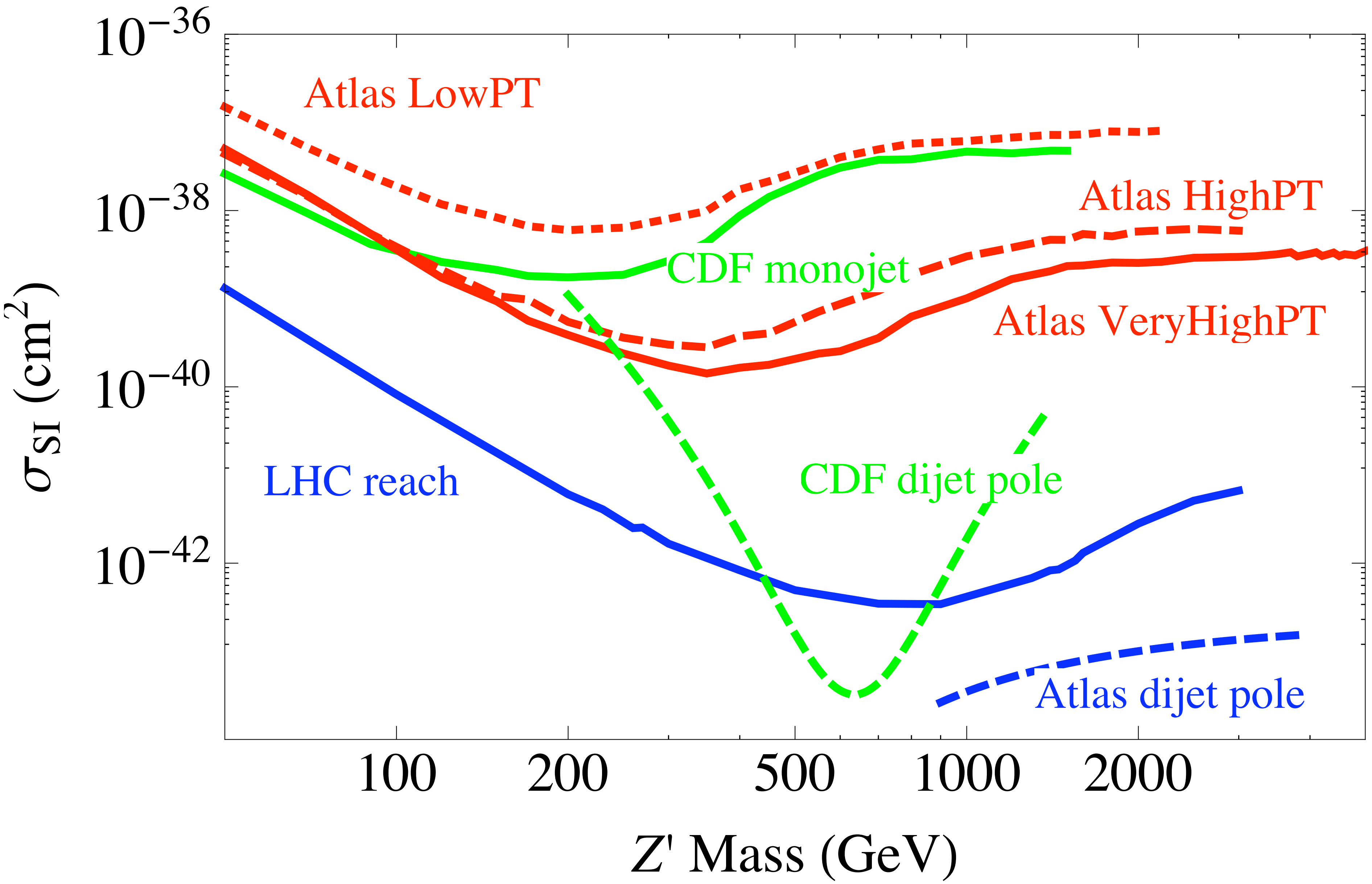
Di-jet resonance searches.

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)

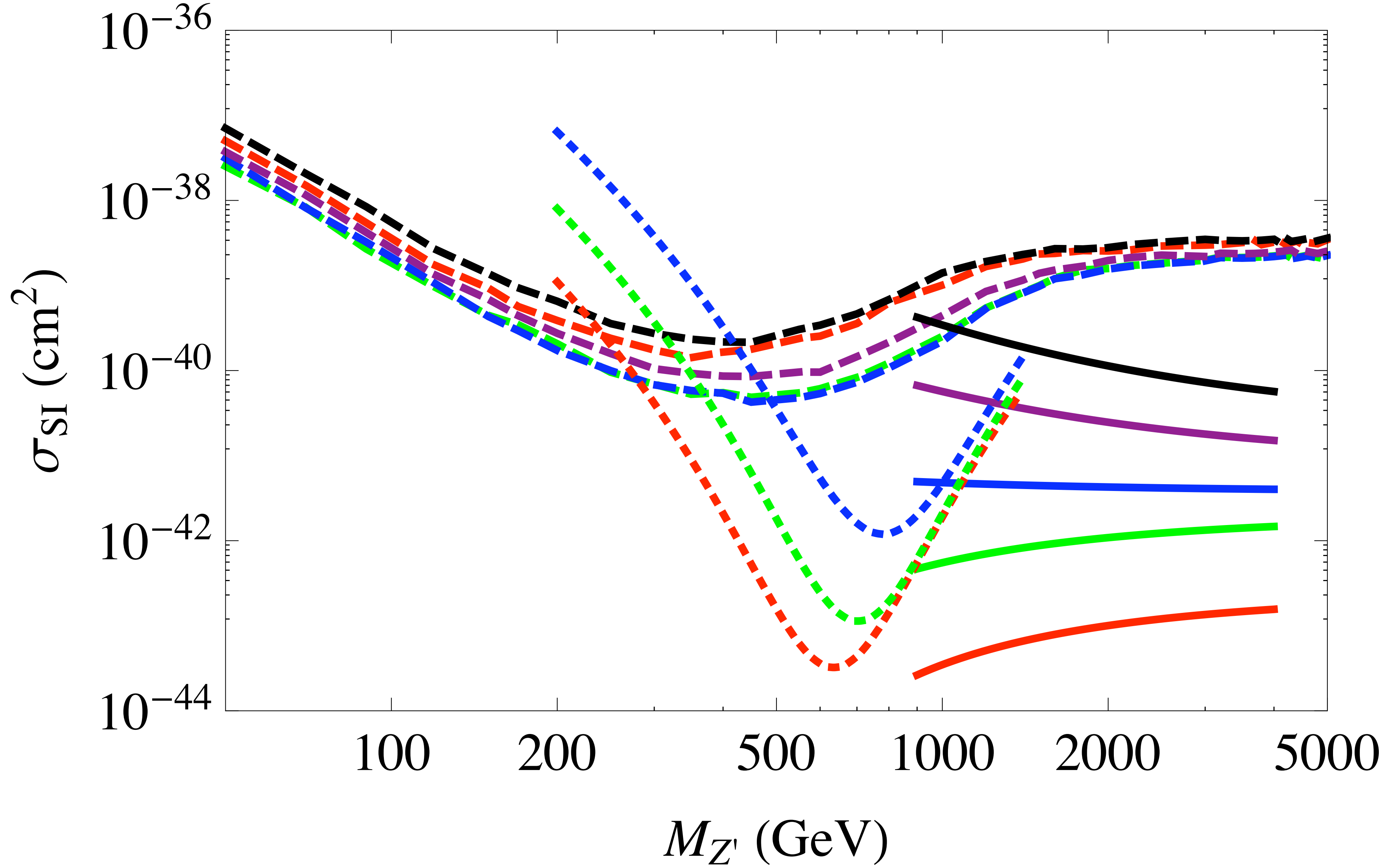
Combining di-jet with monojet

Assume $g_{Z'} = g_D$



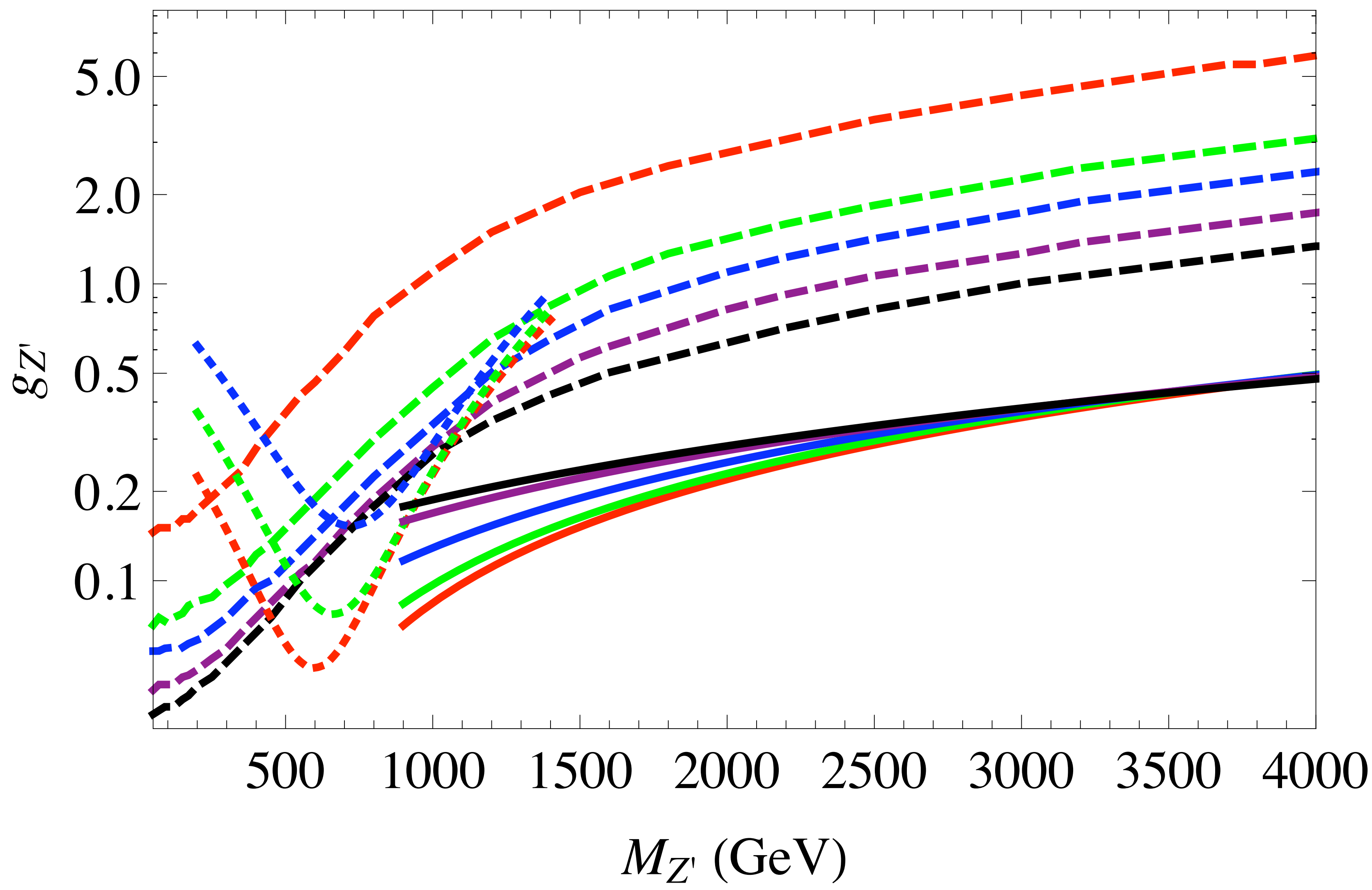
Varying y=(g_D/g_Z')

–



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

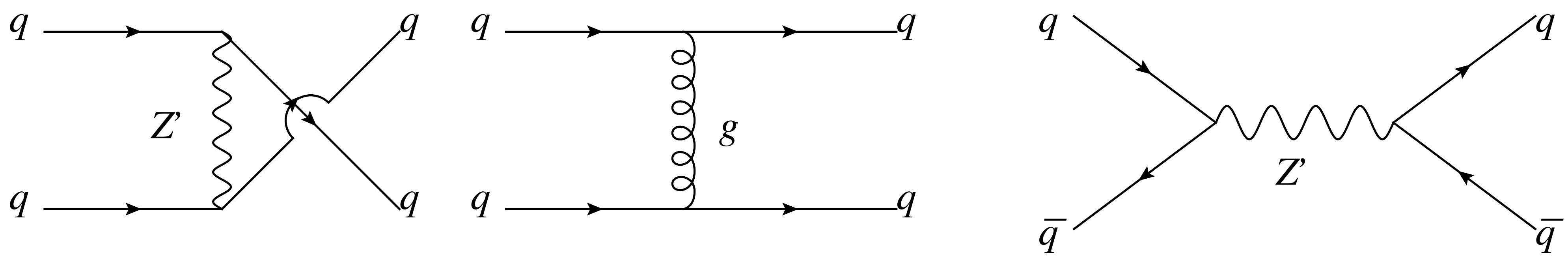
Constraints on Z′ coupling



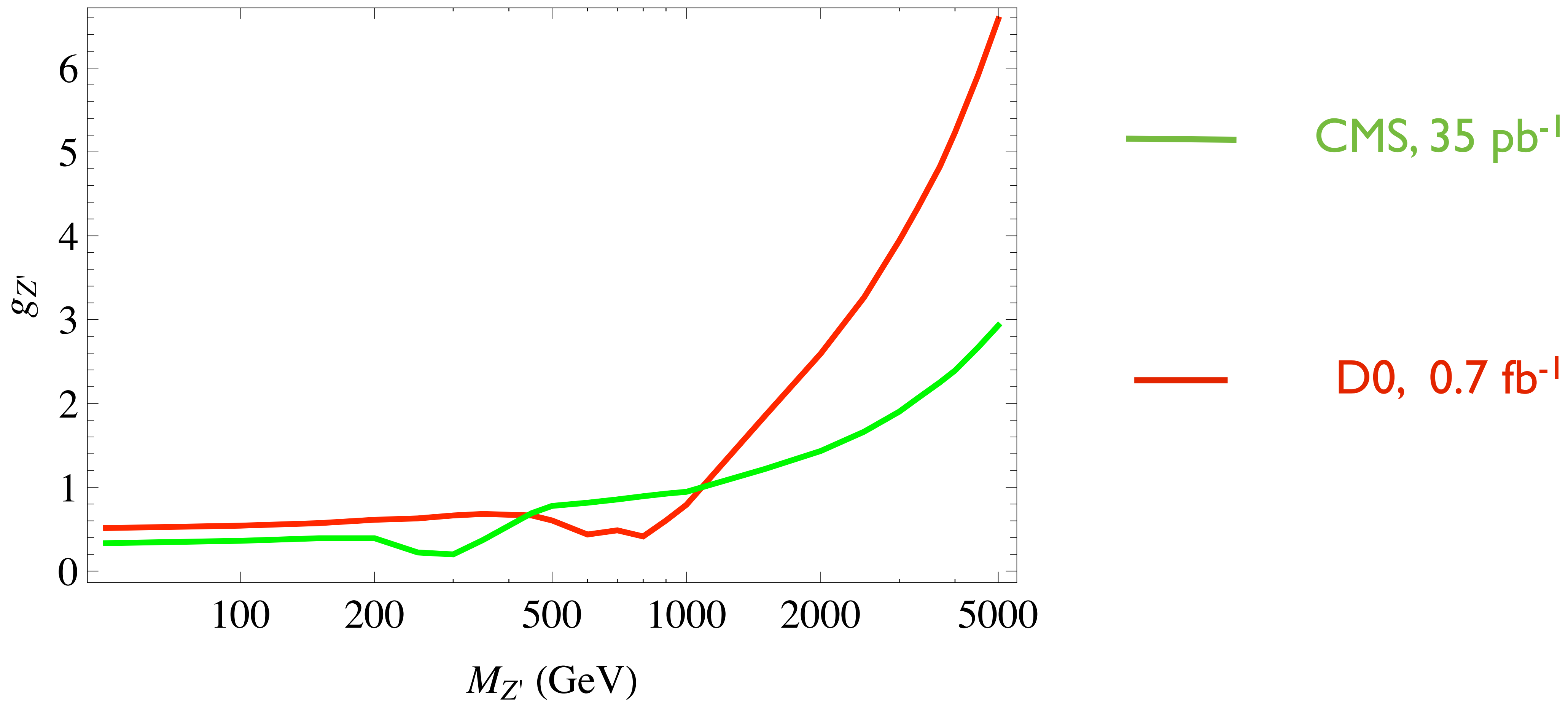
Di-jet Angular correlation

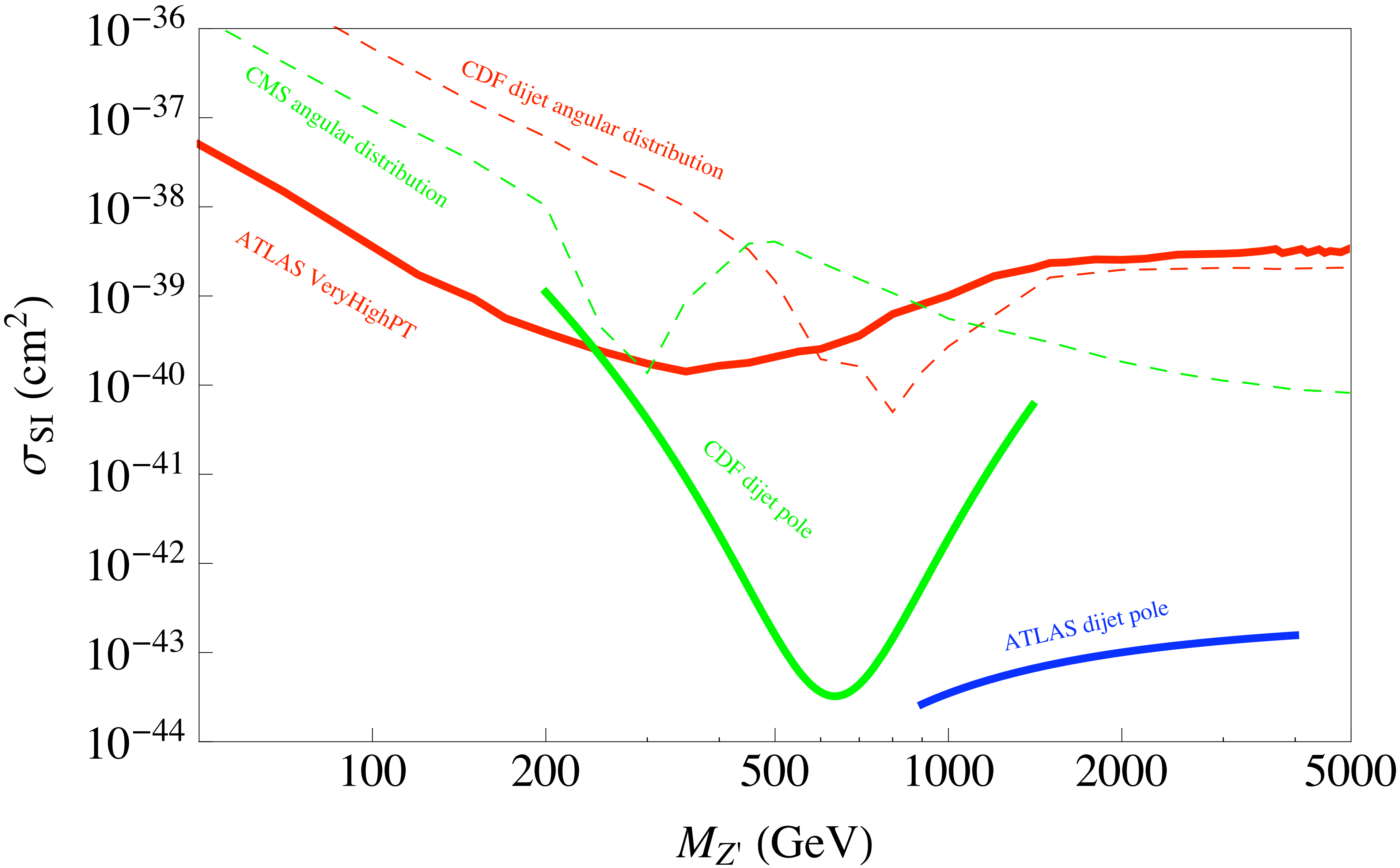
$$\frac{1}{\sigma_{\rm dijet}}\frac{d\sigma_{\rm dijet}}{d\chi_{\rm dijet}} \qquad \chi_{\rm dijet} = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

CDF, 9609011
D0, 0906.4819
ATLAS: 1103.3864
CMS:1102.2020



Constraint on the Zprime coupling



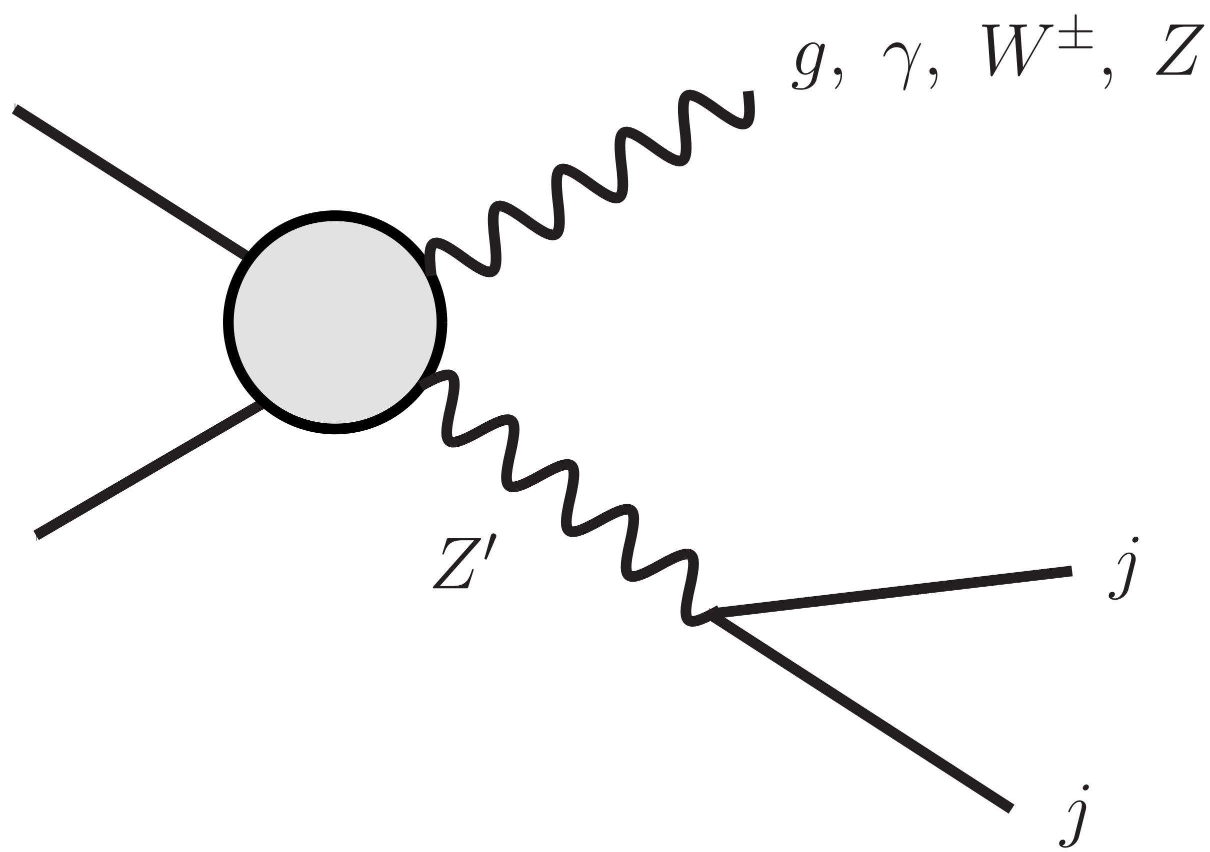


10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
σ_{SI} (cm^2)
CDF dijet angular distribution
CMS angular distribution
ATLAS VeryHighPT
CDF dijet pole
ATLAS dijet pole
100
200
500
1000
2000
5000
$M_{Z'}$ (GeV)

Searching for lighter hadronic Z′

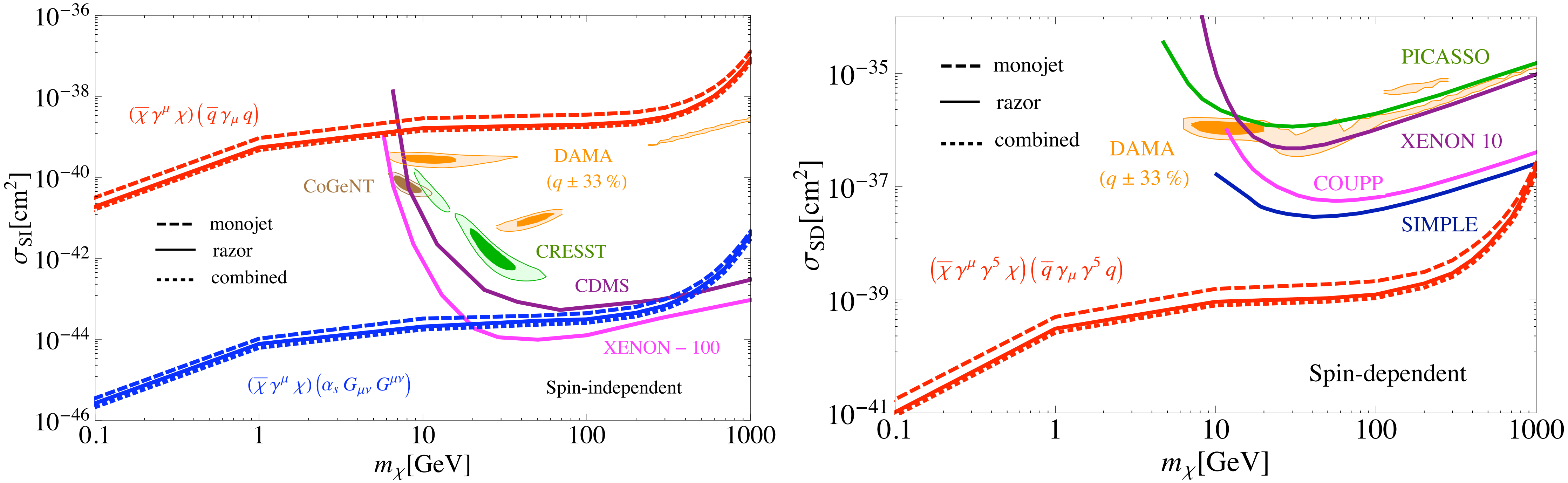
- di-jet searches are sensitive to high mass Z′ due to pre-scaling.

- How about associated production?



Mono-jet → multiple jets

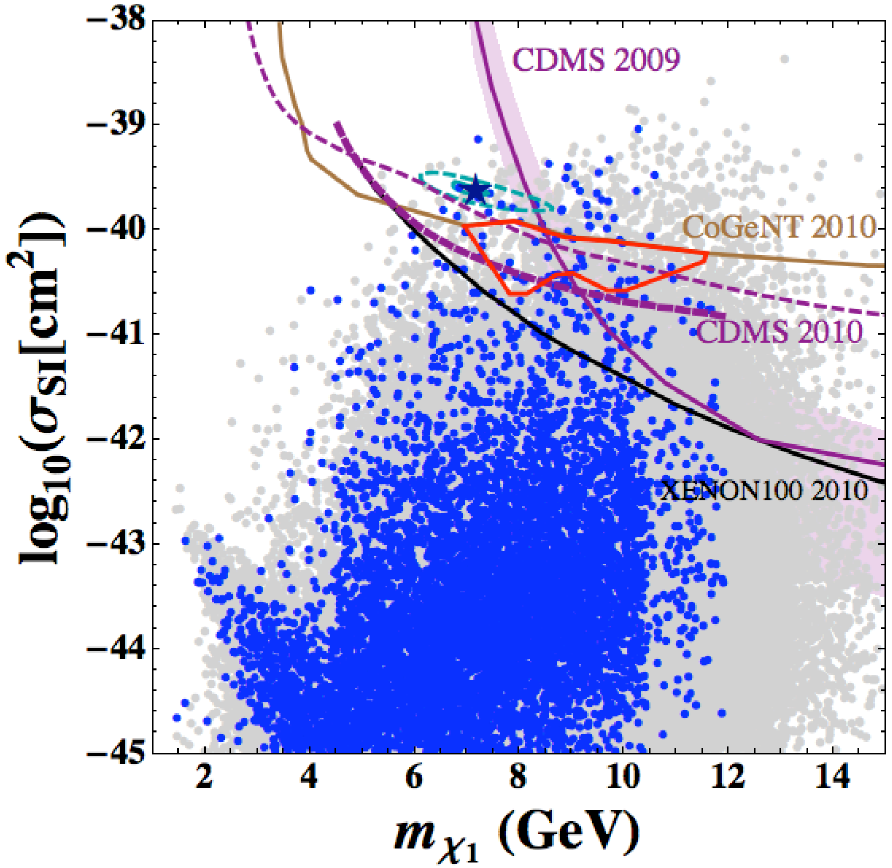
Fox, Harnik, Primulando, Yu, 1203.1662

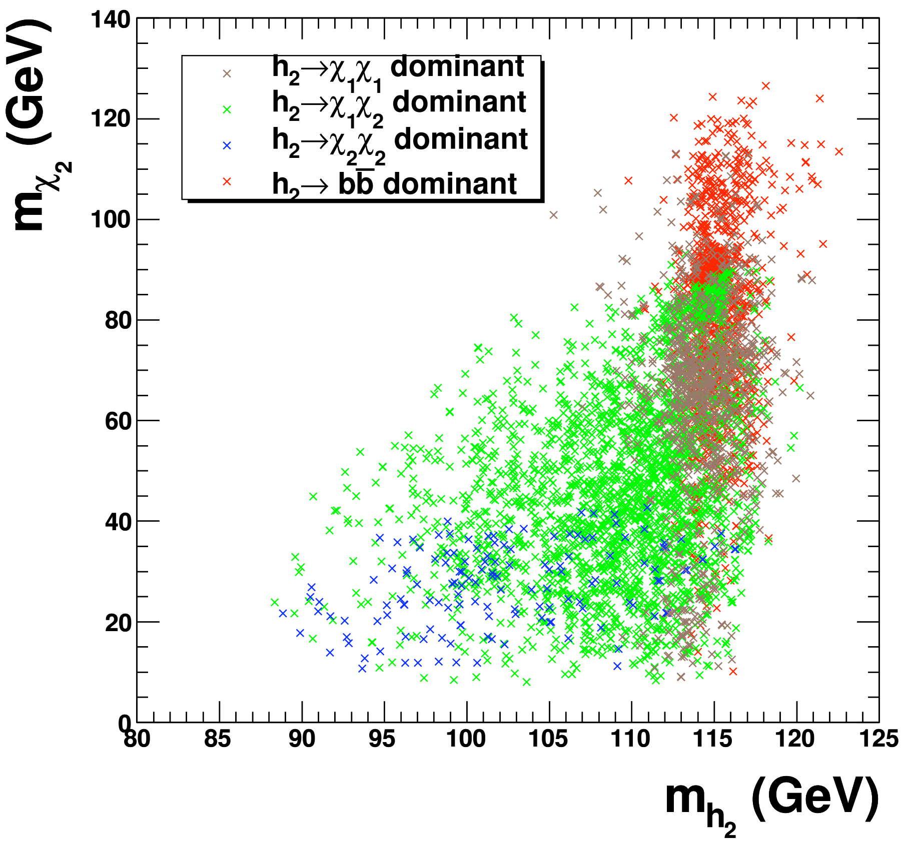


Signals from new model extensions

Dark light Higgs

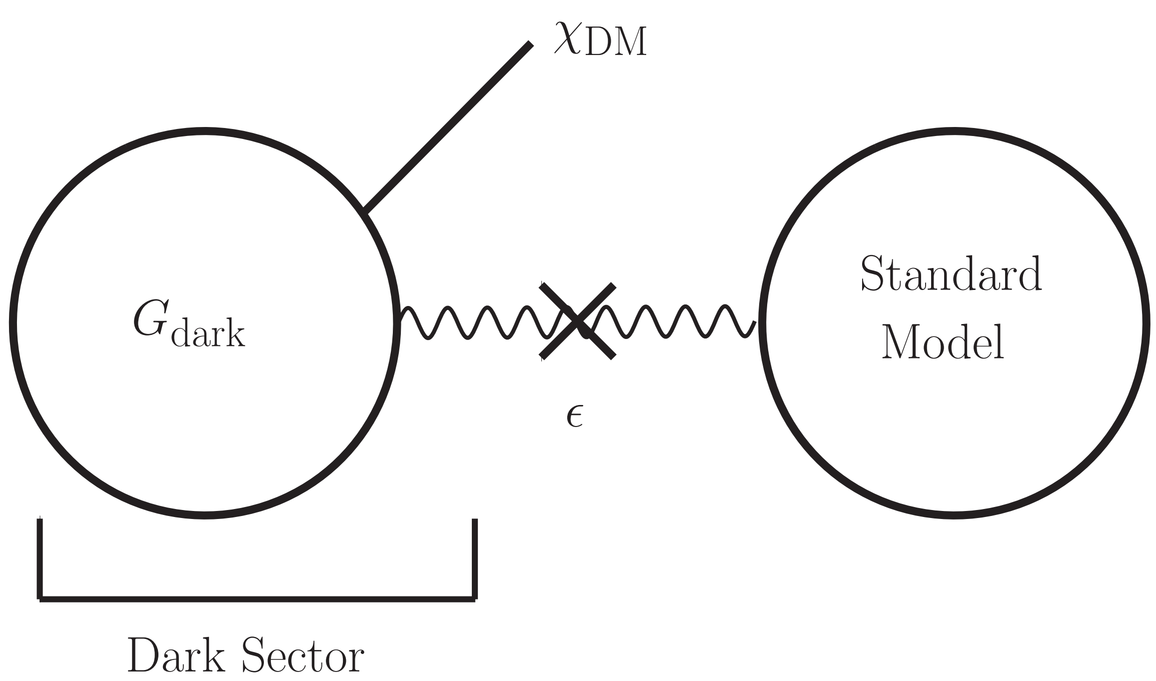
- NMSSM near PQ limit.
  - Very light GeV- 10 GeV scalars.
  - Singlino-like light dark matter. Large σ_{SI}.





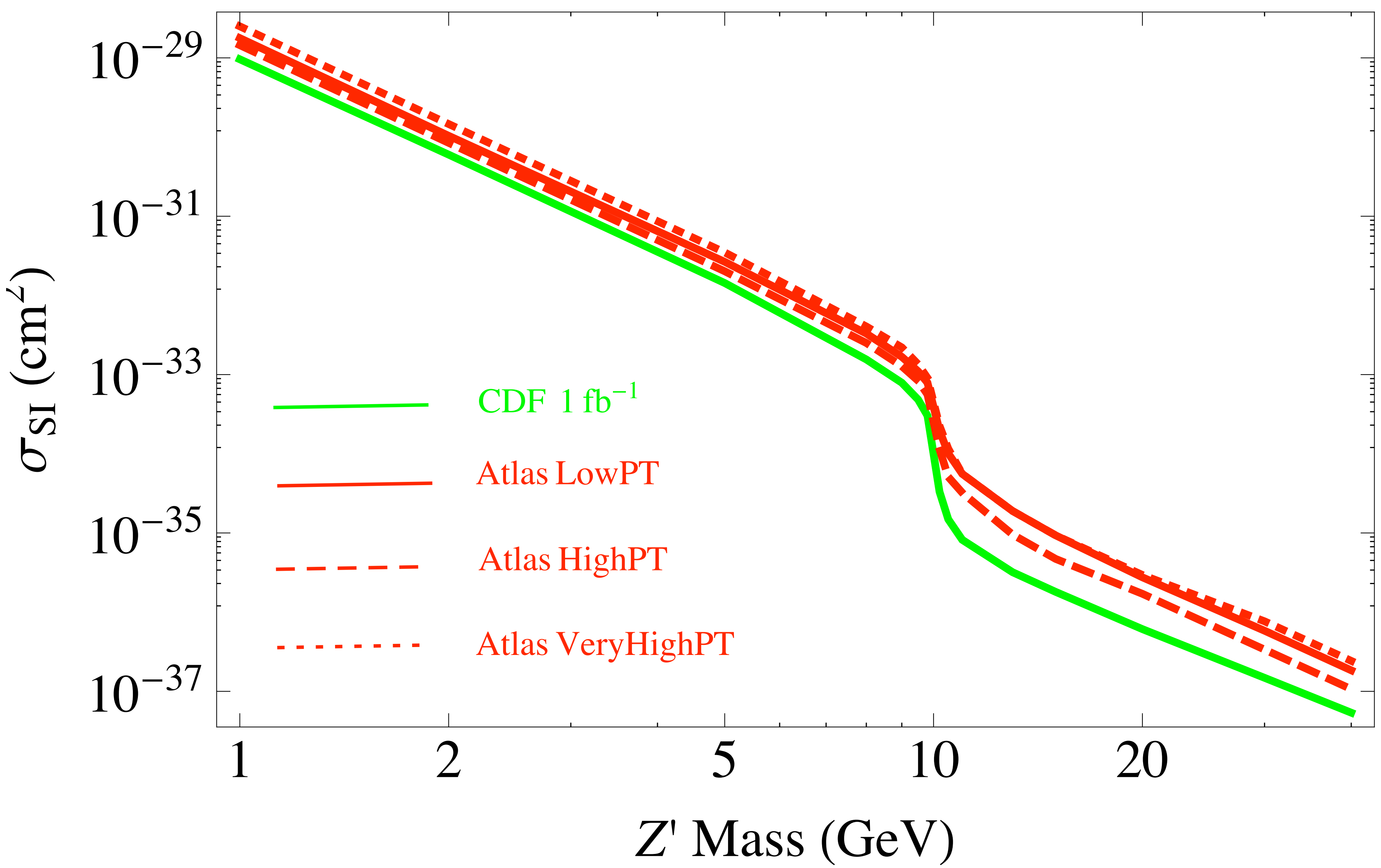
Change Higgs decay

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.

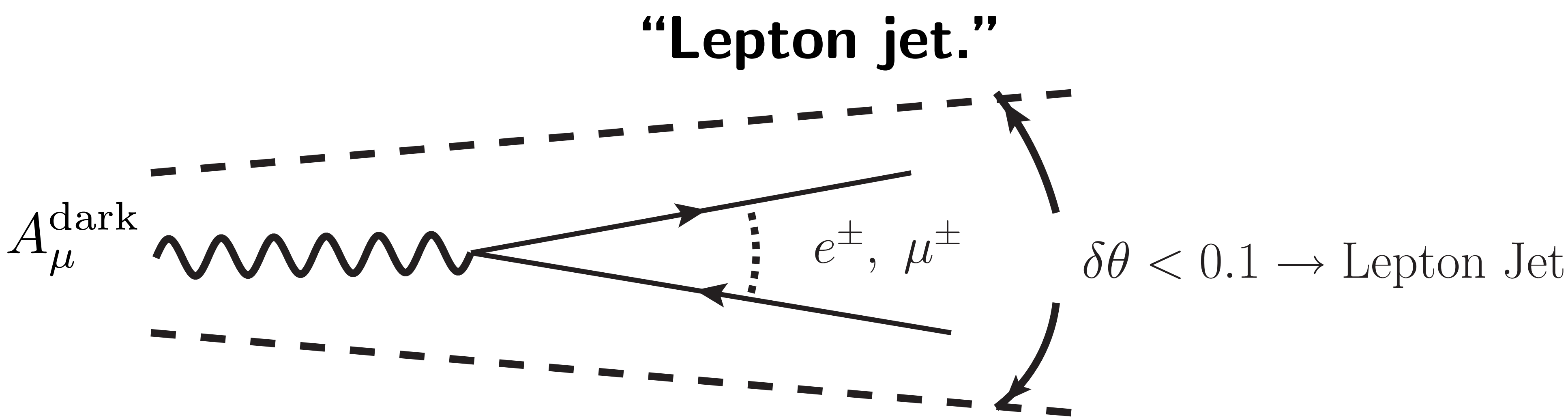
Small Z′ mass.



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.

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.

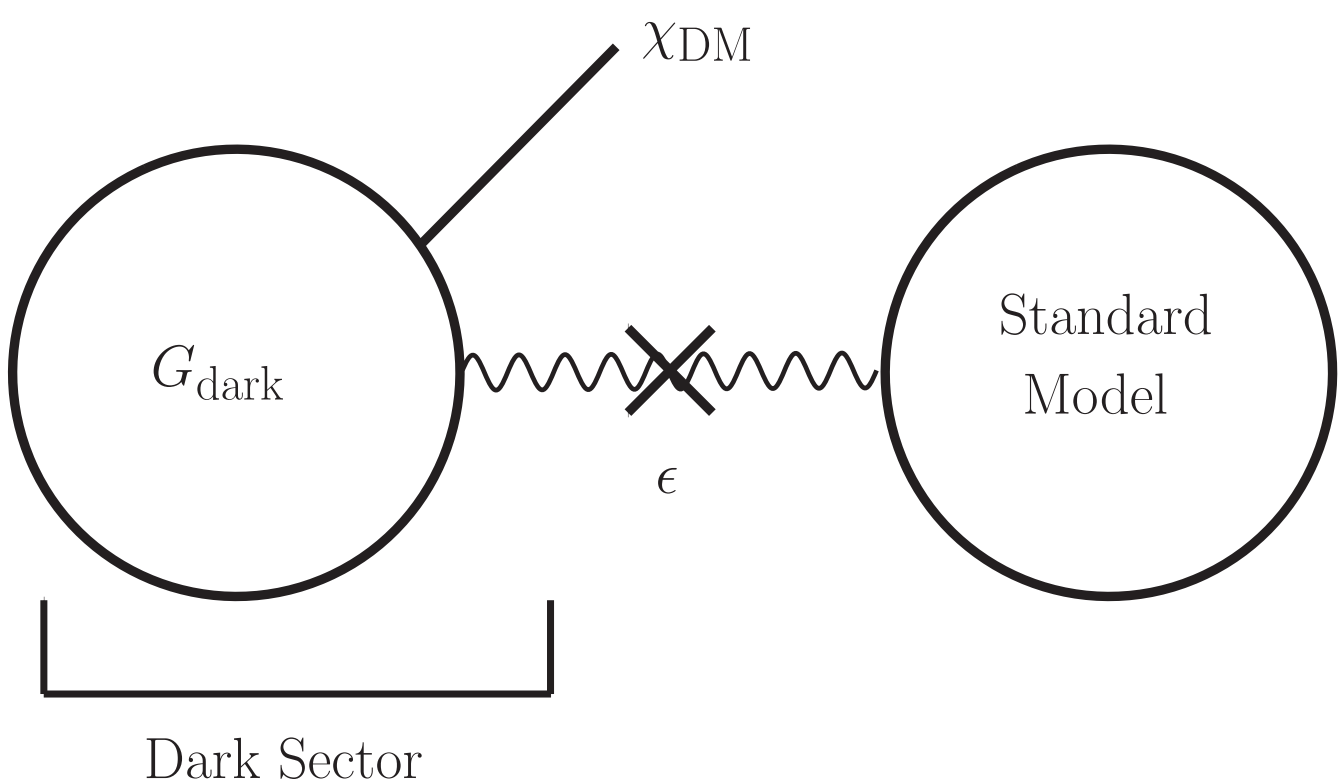
- Dark matter self-interaction, mediated by

$$b_{\rm dark} \subset \text{dark sector.}$$

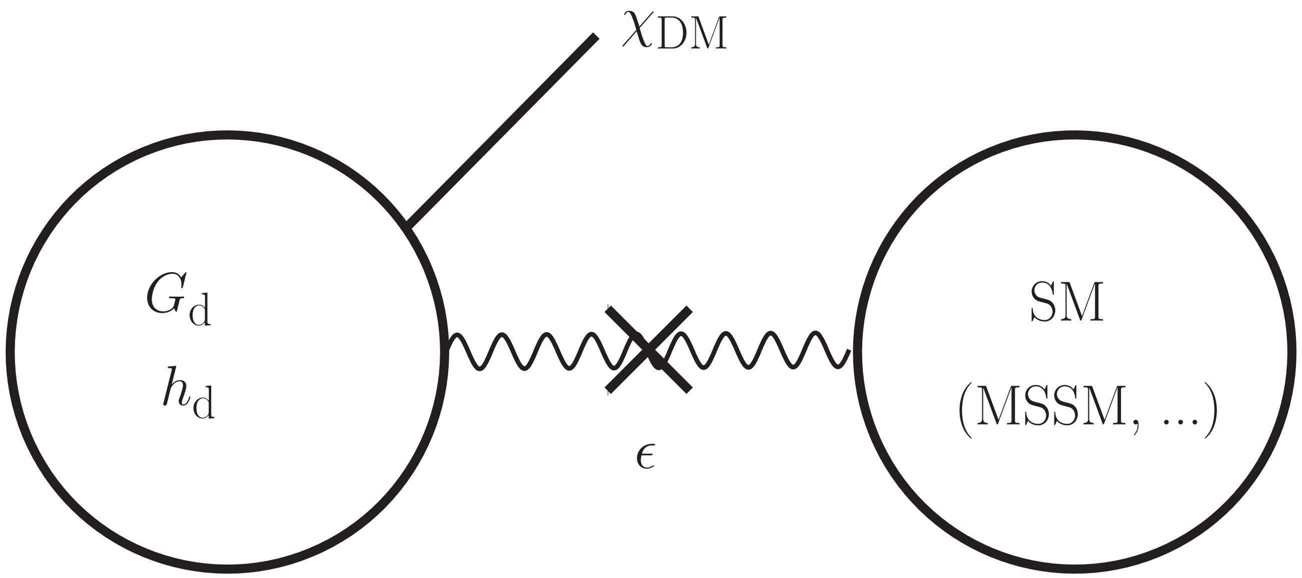
- Range of dark force $m_{b_{\rm dark}} \sim 100s\ \text{MeV} - \text{GeV}$

- Dark sector couples to SM with tiny couplings, parameterized by ϵ Typically: $\epsilon \leq 10^{-3}$

-

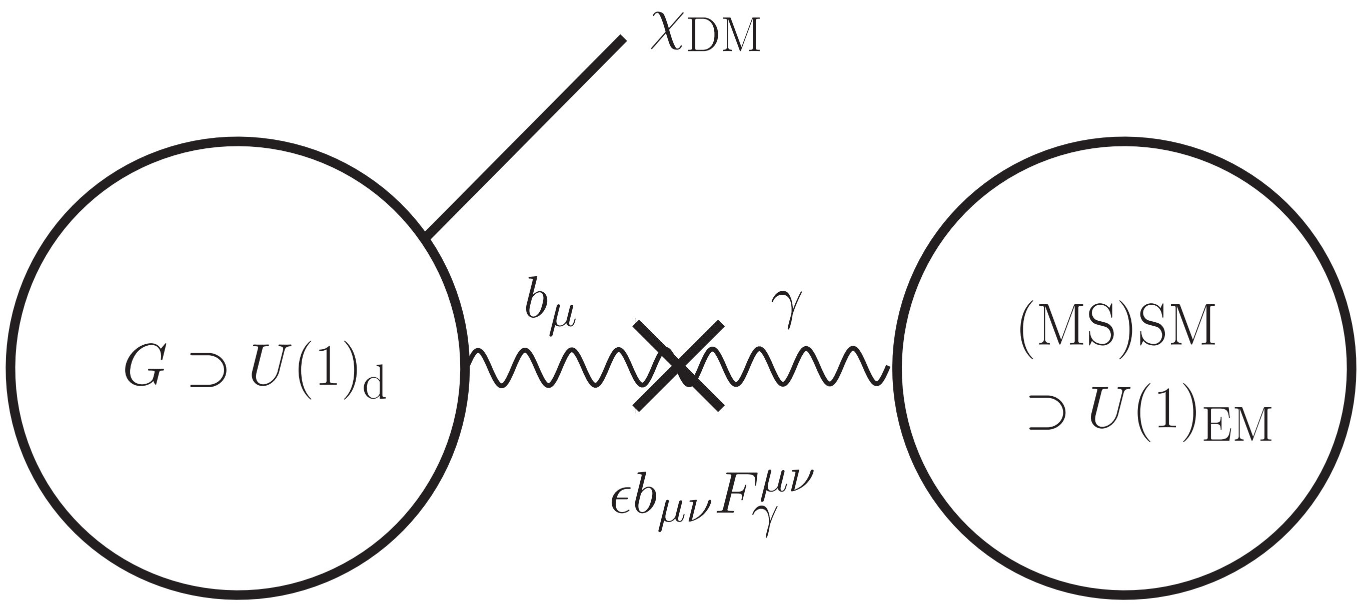


Basic dark sector model ingredients:



- Model choices:
  - Dark matter identity.
  - Self-interaction $G_{\rm d}$: gauge interaction...
  - GeV scale, dark higgs $h_{\rm d} : v_d = \langle h_d \rangle \sim \text{GeV}$
  - 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

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

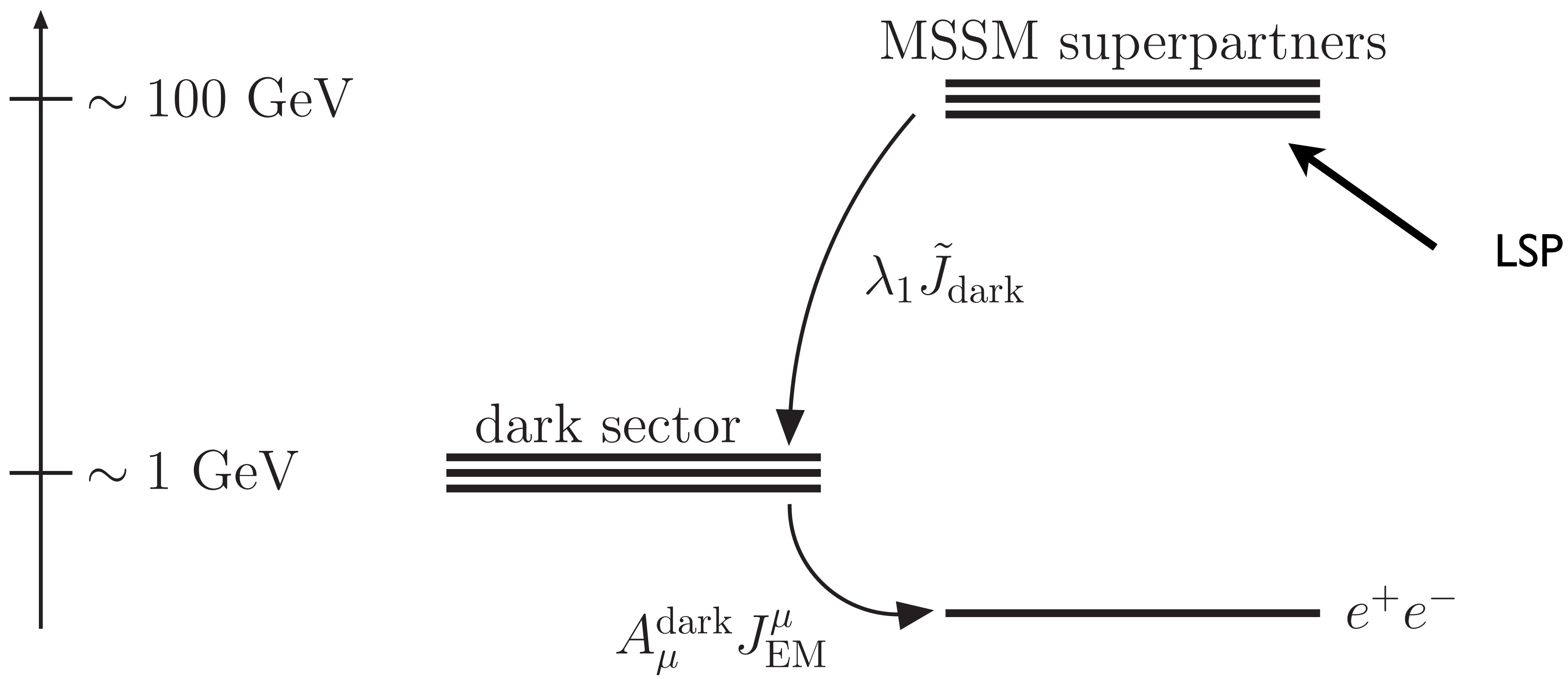
- Supersymmetry can be an elegant way of generating the GeV scale.

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

New class of signal: dark Force

- Dark matter self-interaction, mediated by

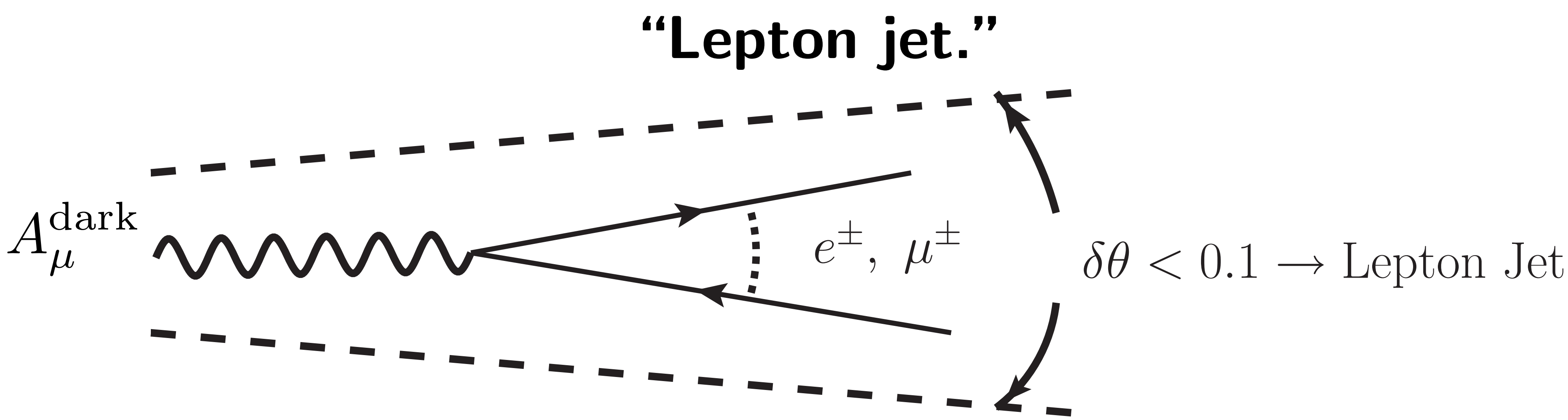
$$A_\mu^{\text{dark}}, \quad m_{A^{\text{dark}}} \sim \ (100\text{s MeV - GeV})$$



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

Lepton Jets

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



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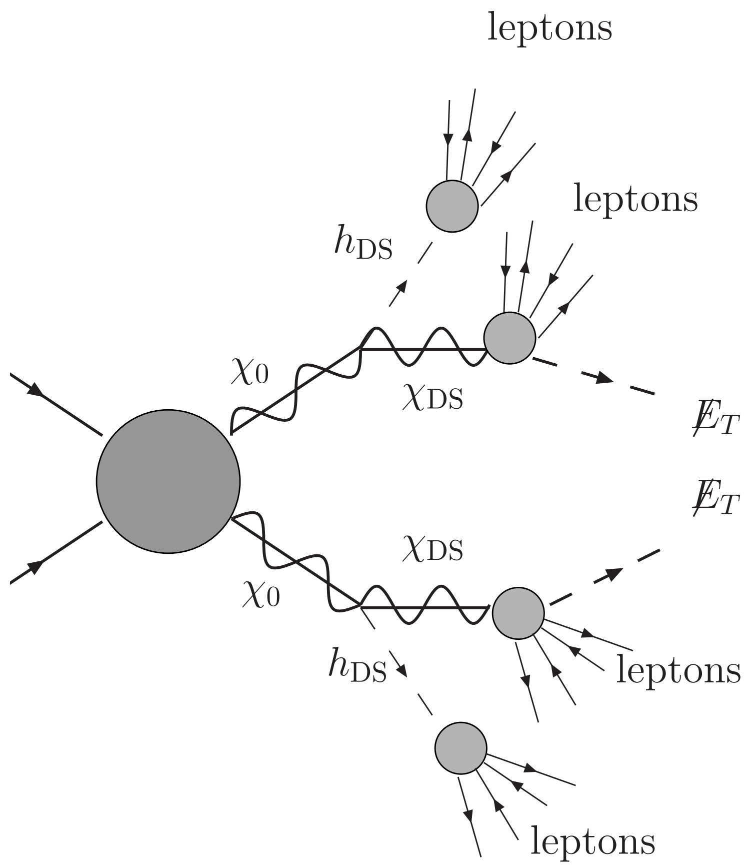
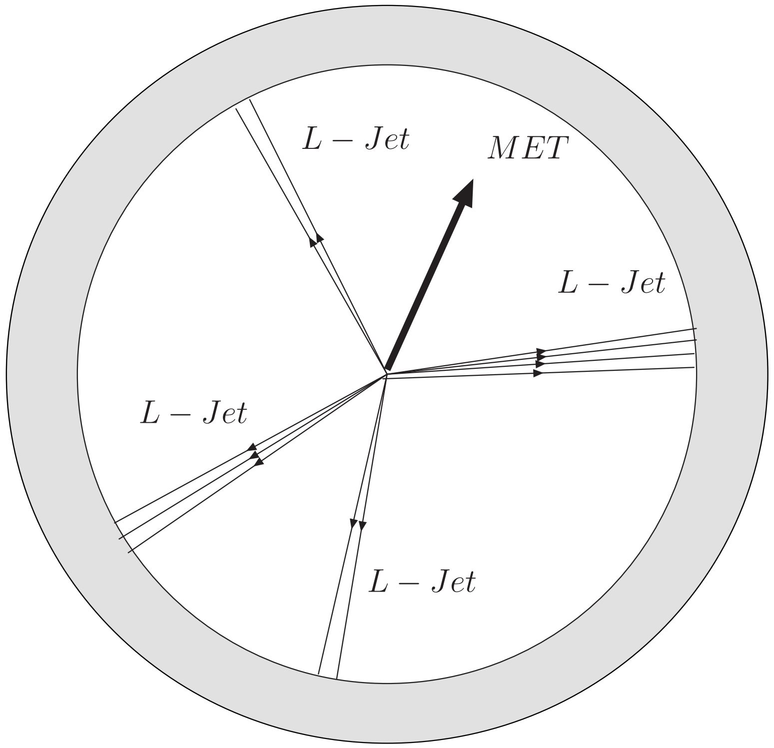
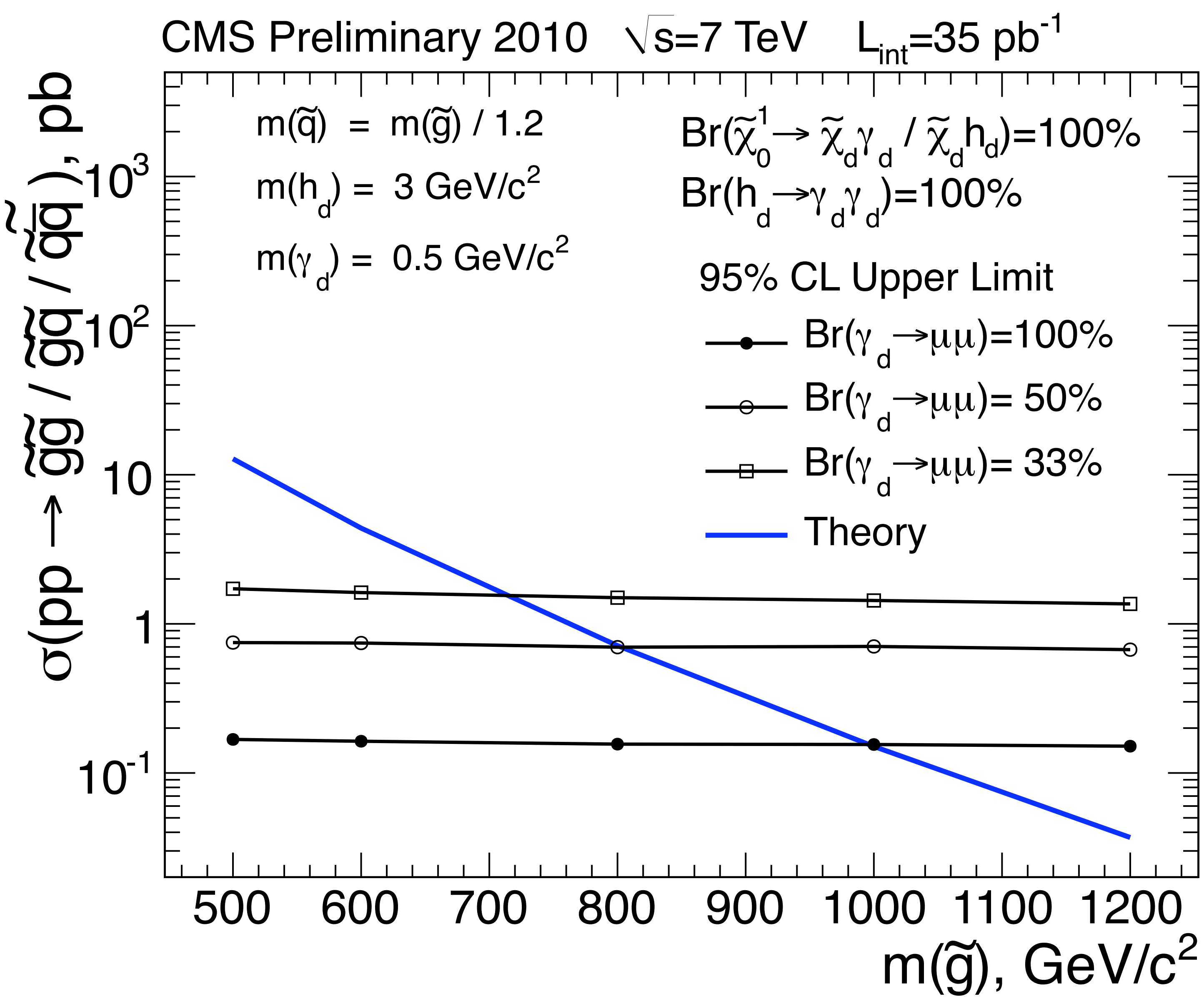
Supersymmetric dark force

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



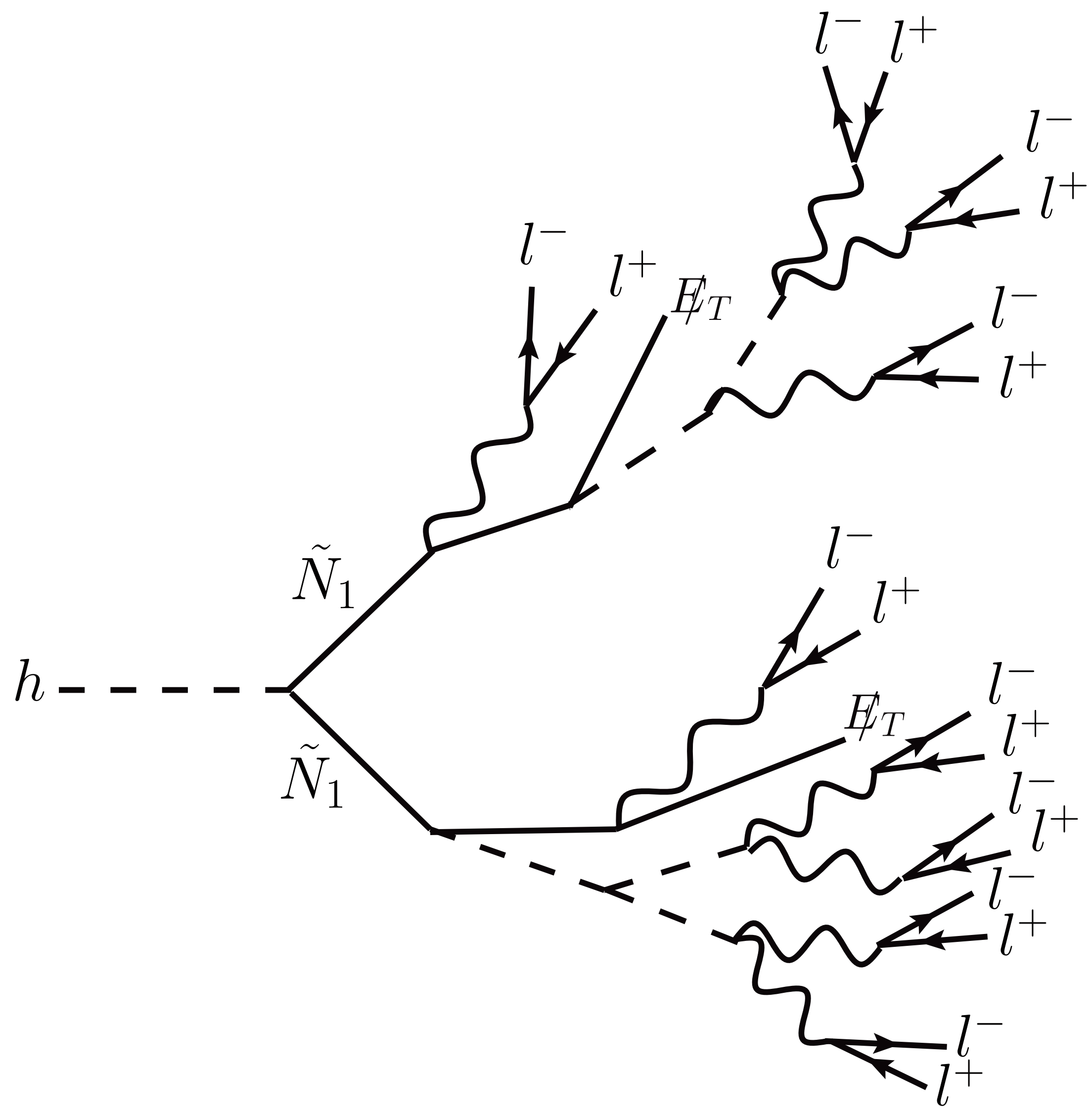


With LHC early data



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

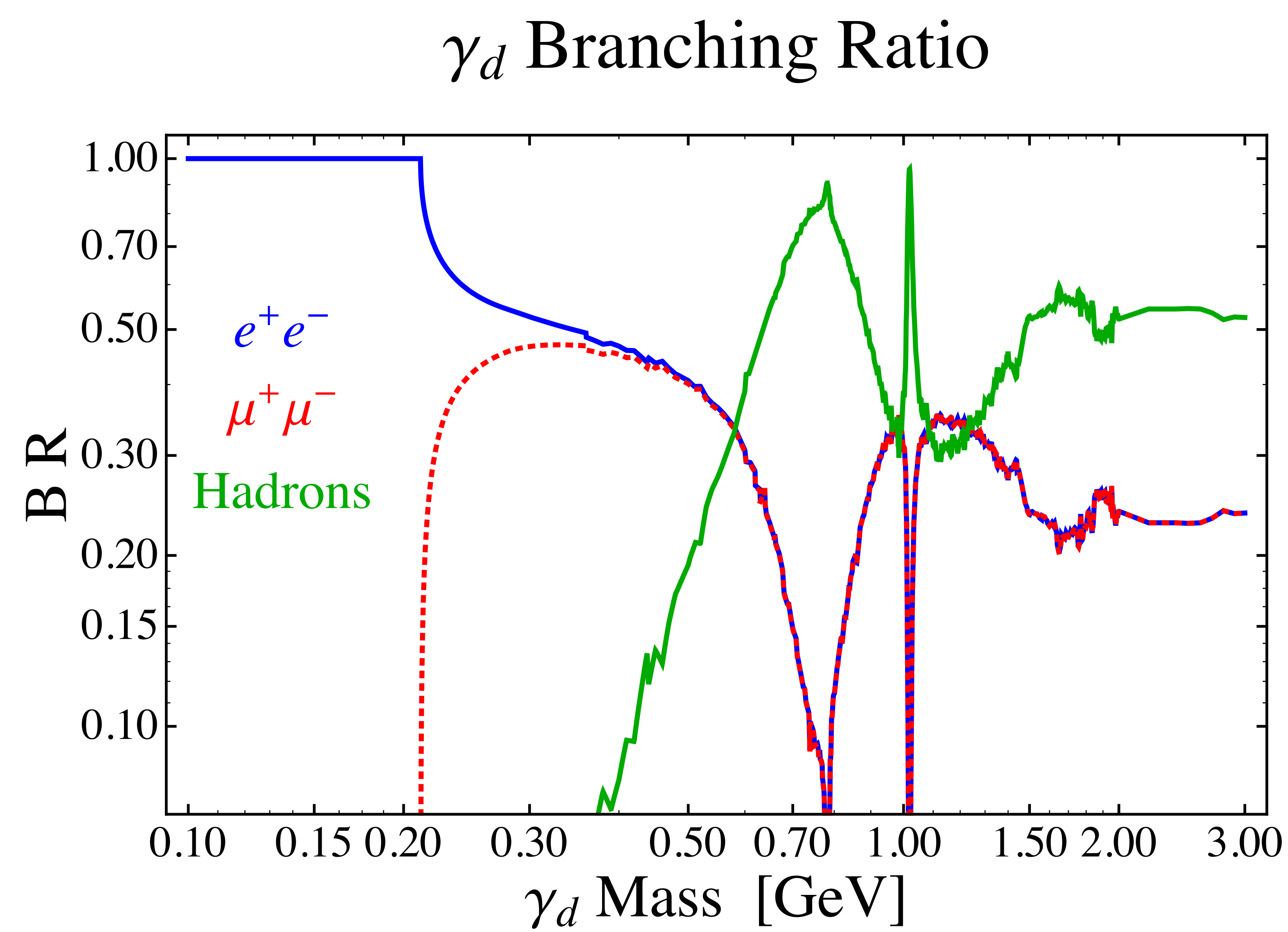
Hiding Higgs?



Current study at CDF:
Frisch, Krop, Wilbur

extra

Dark photon decay.



Dark matter search at colliders.

- DM particle can not be singly produced. Otherwise,

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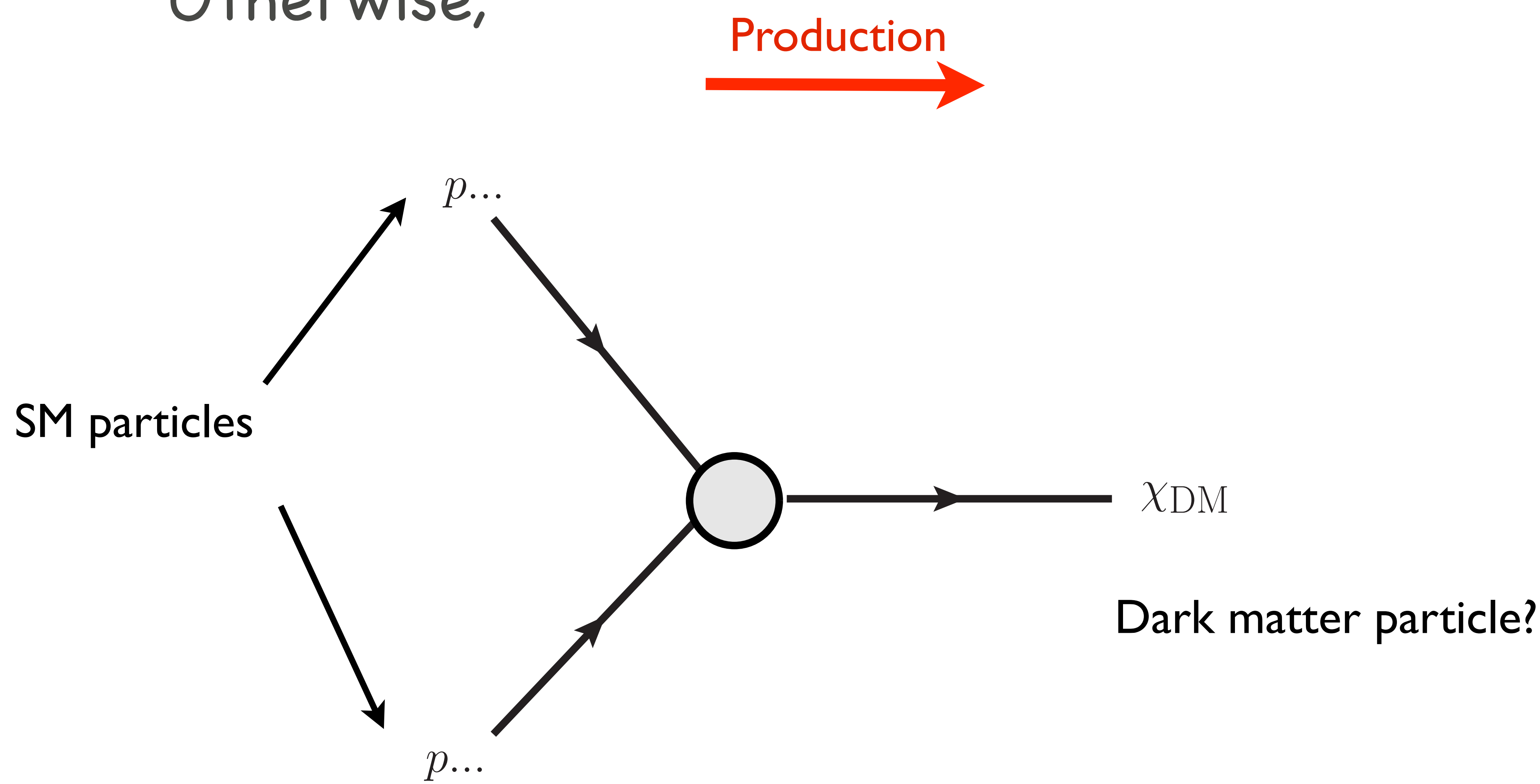

Dark matter search at colliders.

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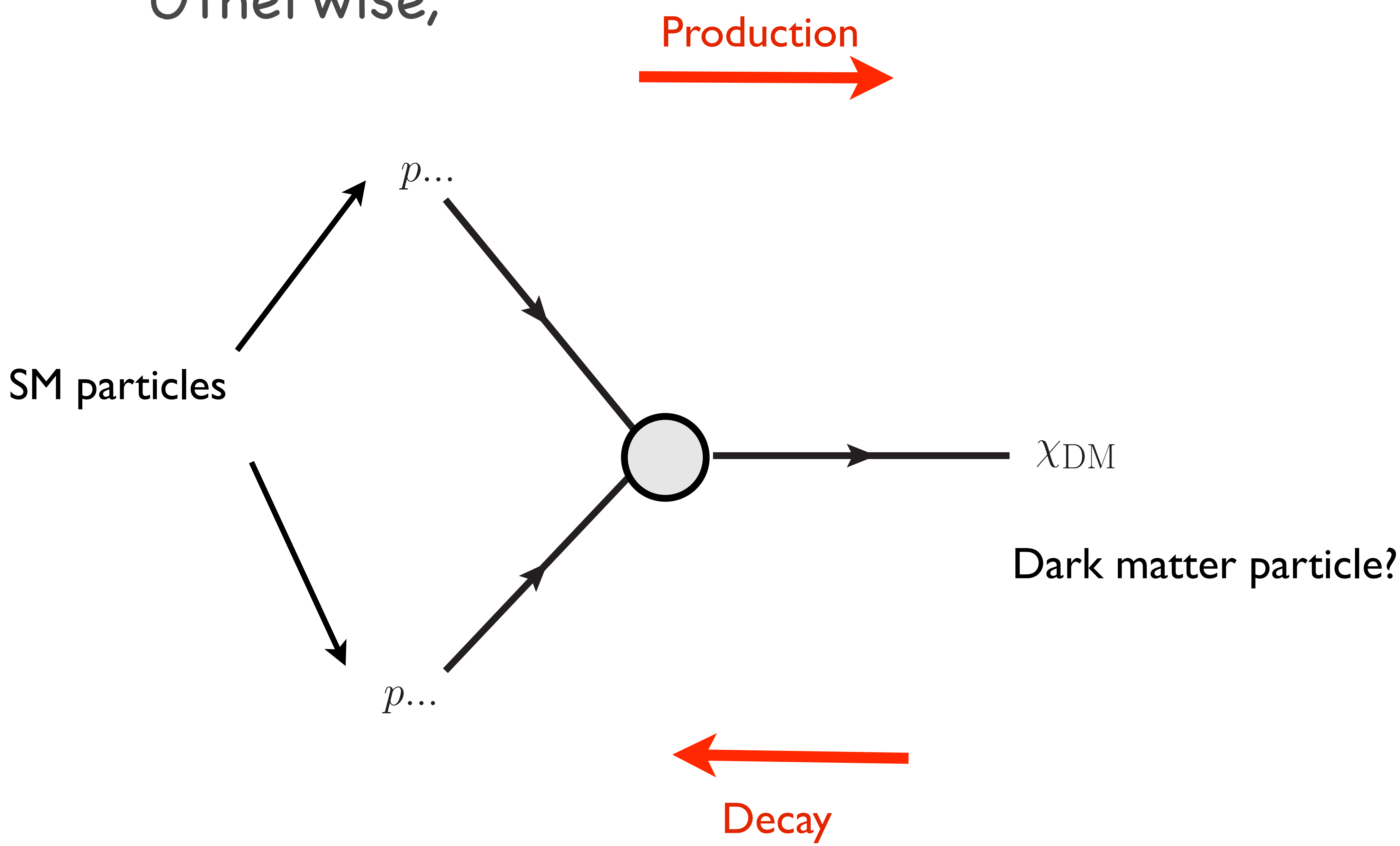
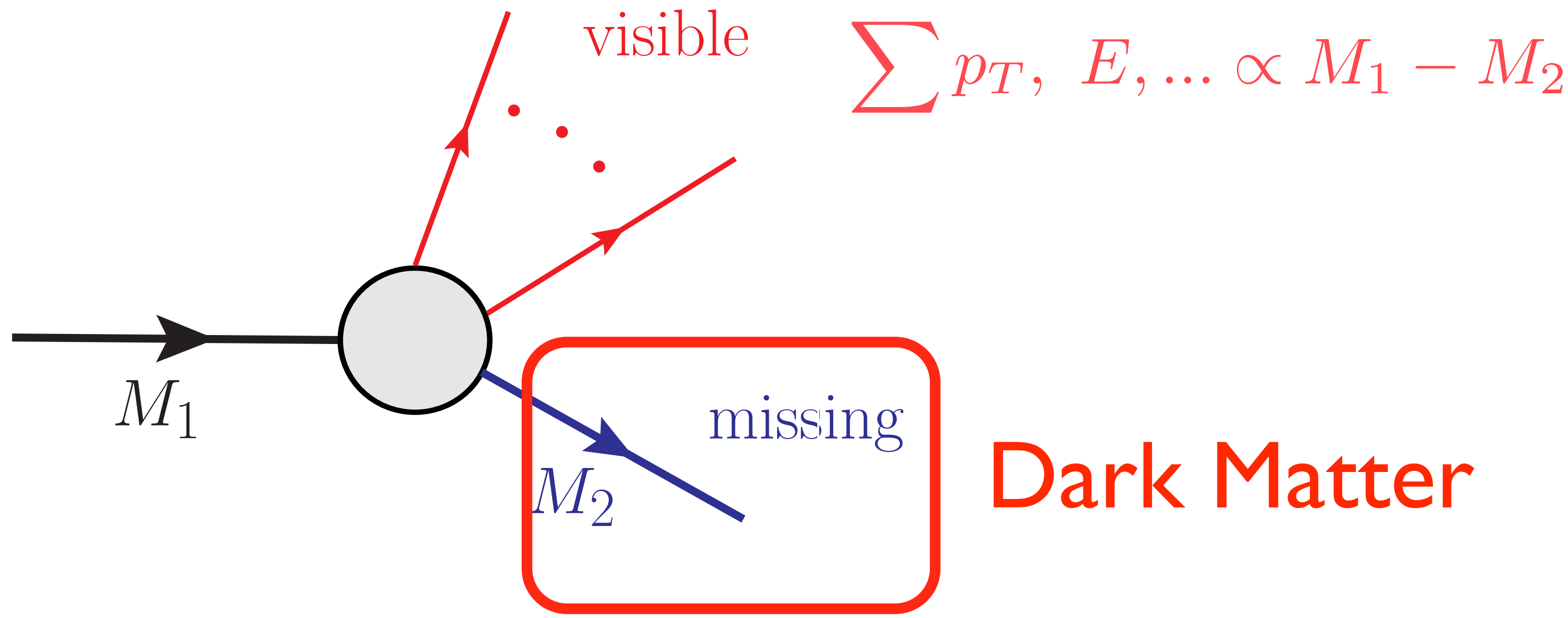


Not stable, cannot be dark matter!

Model independent mass Measurements.

- Likely, not enough information to fully reconstruct the kinematics of the event.

- Simple variables only measure mass differences.



- More detailed kinematical information, special kinematical configurations and subtle features.

$$M_{T2},\ \mathrm{MAOs},\ \hat{s}_{\min}, \ldots$$

Cheng et. al.; Choi et. al.; Barr et. al.; Han et. al.; Matchev et. al.

Spin measurements. Supersymmetry?

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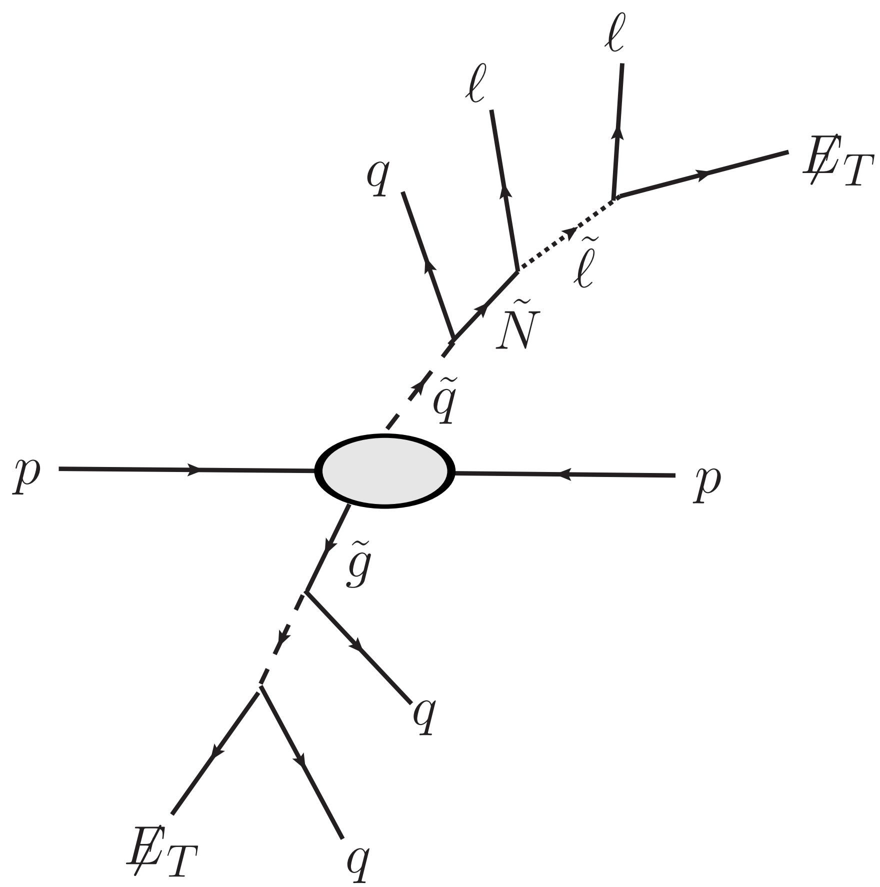
Example: spin of $\tilde{N}$

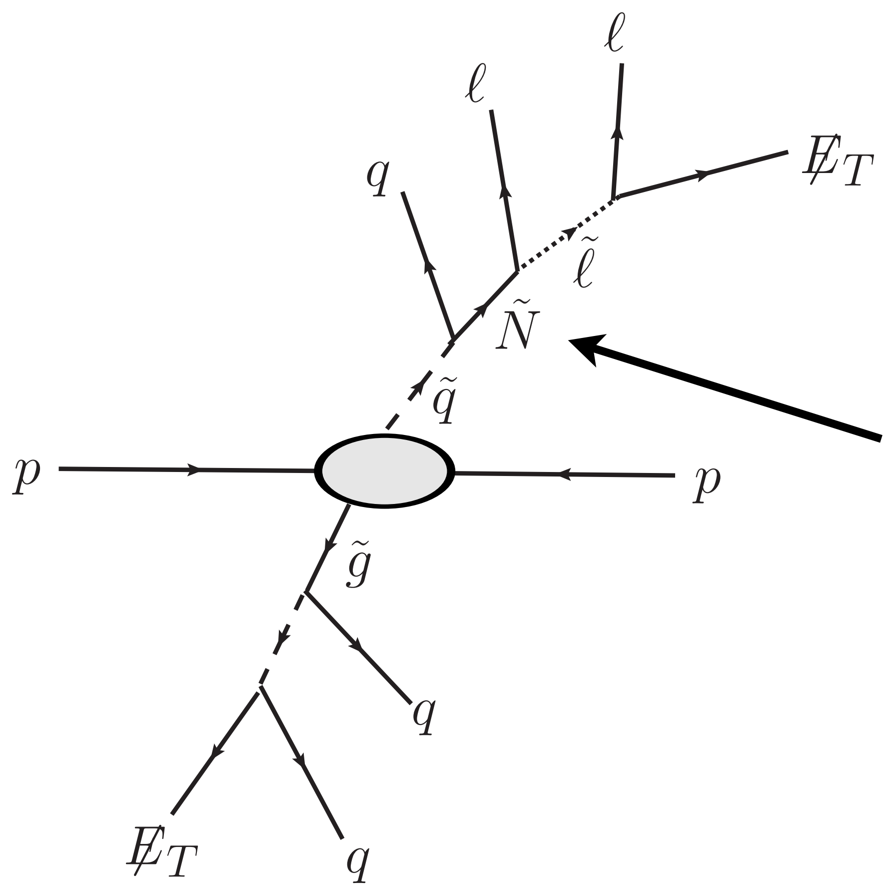
Spin measurements. Supersymmetry?



Example: spin of $\tilde{N}$

Clean exclusive sample

Spin measurements. Supersymmetry?



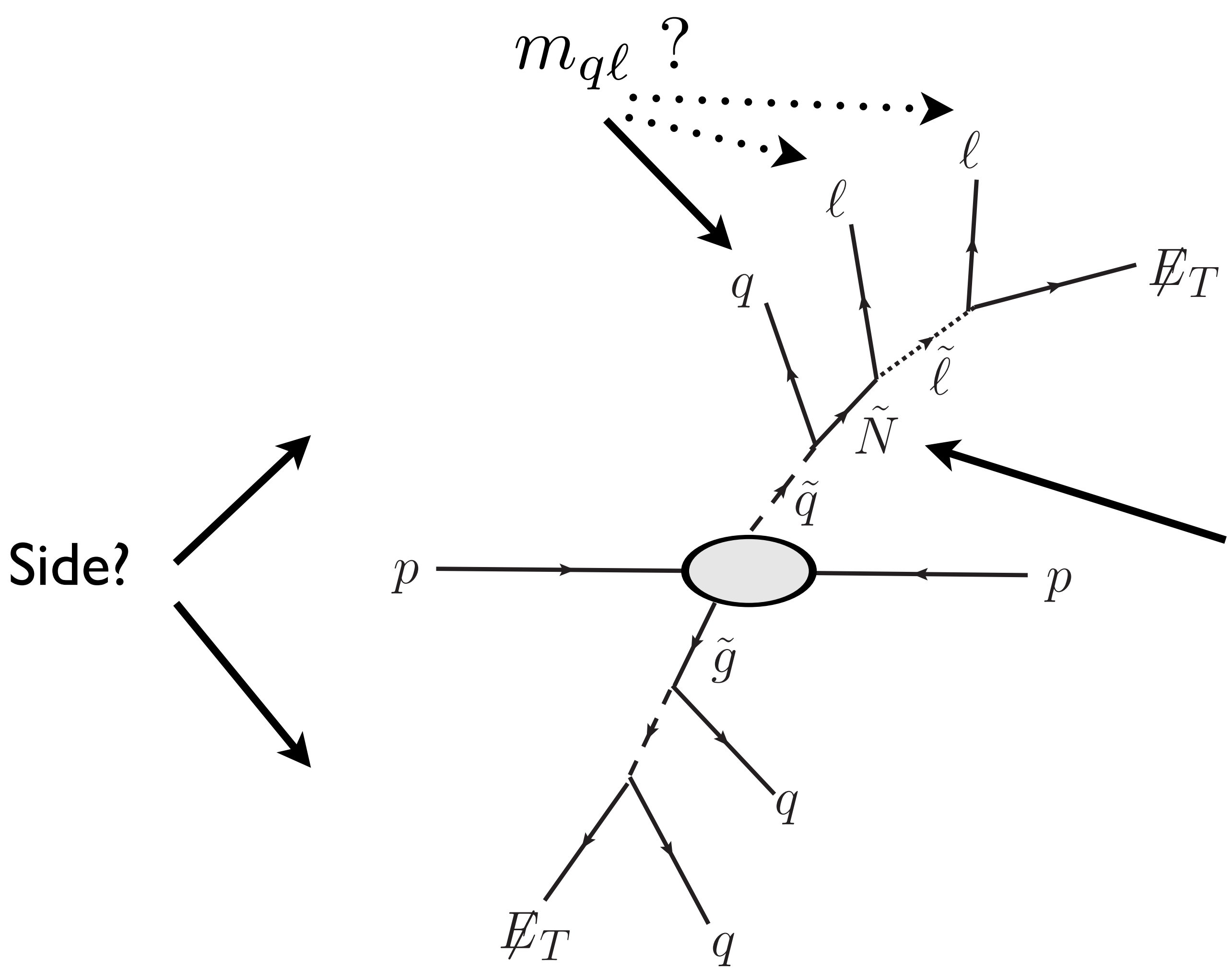
Example: spin of $\tilde{N}$

Clean exclusive sample

Boost (kinematics) vs matrix element (spin)

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

Spin measurements. Supersymmetry?



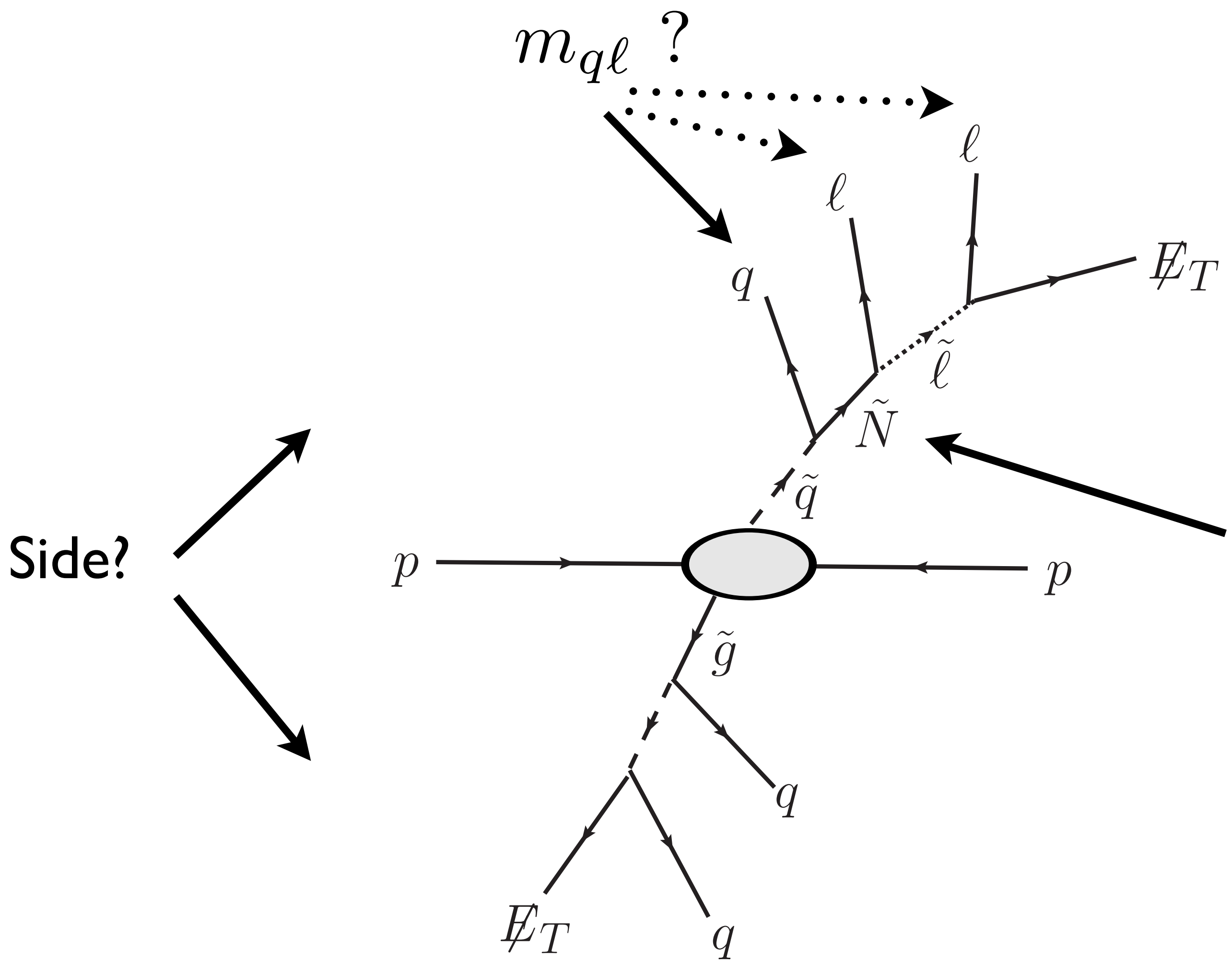
Example: spin of $\tilde{N}$

Clean exclusive sample

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

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.

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.