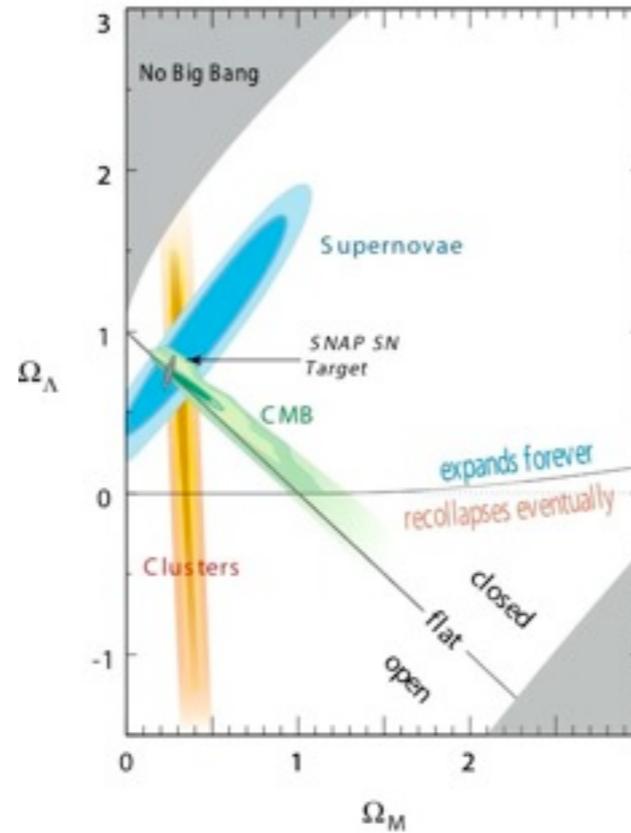
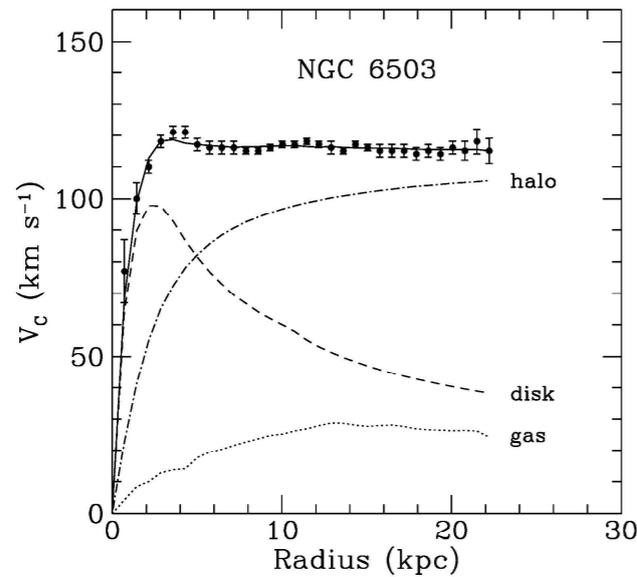


# Dark matter at Colliders

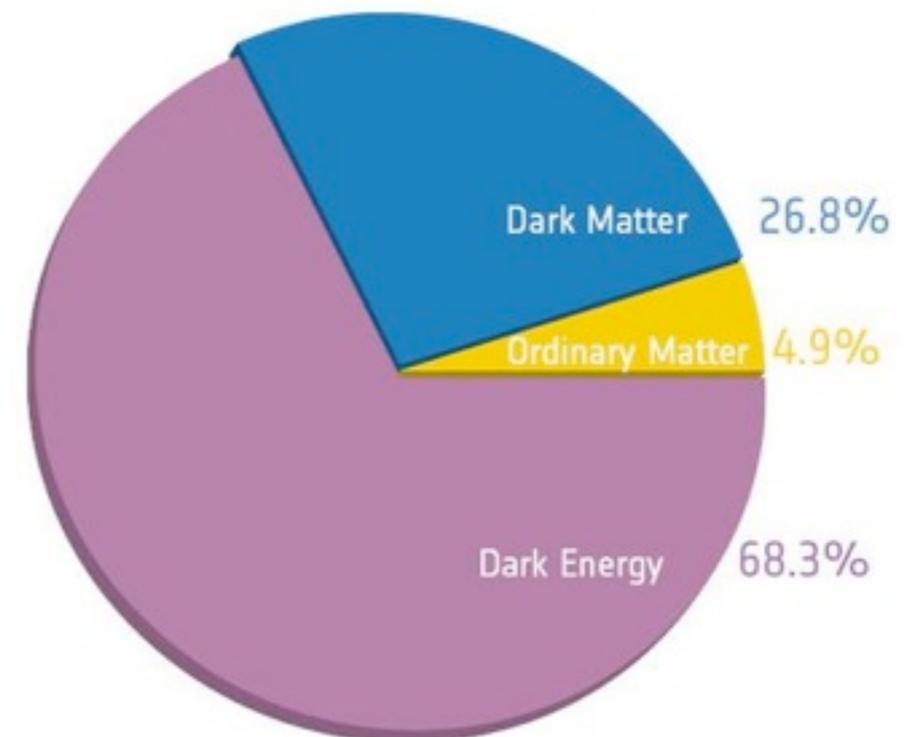
Lian-Tao Wang  
University of Chicago

Pheno 2014, May 6, 2014

# We have solid evidence for dark matter:



Only NP beyond SM discovered so far!



# Dark matter candidate?

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- We know very little. Vast range of possibilities
  - ▶ Can be  $10^{-31}$  GeV to  $10^{48}$  GeV.

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  - ▶ Not so different from the particles we know
    - Weak scale mass, couplings not too large or small
    - Measure the properties in the lab.
  - ▶ Not so dependent on the history of the early universe.
    - Because we don't know too much about it.
    - Idea: thermal equilibrium in early universe.

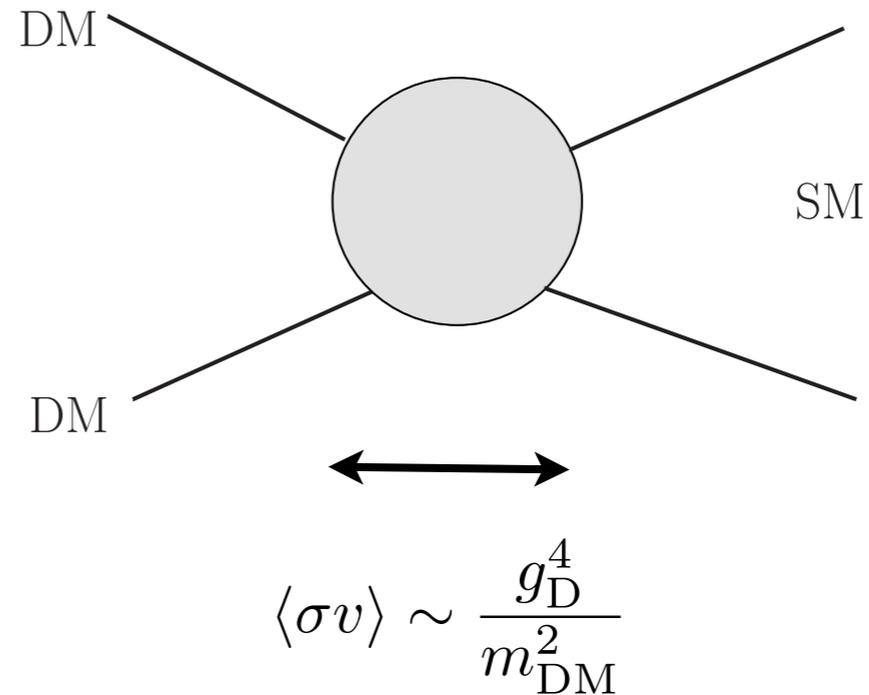
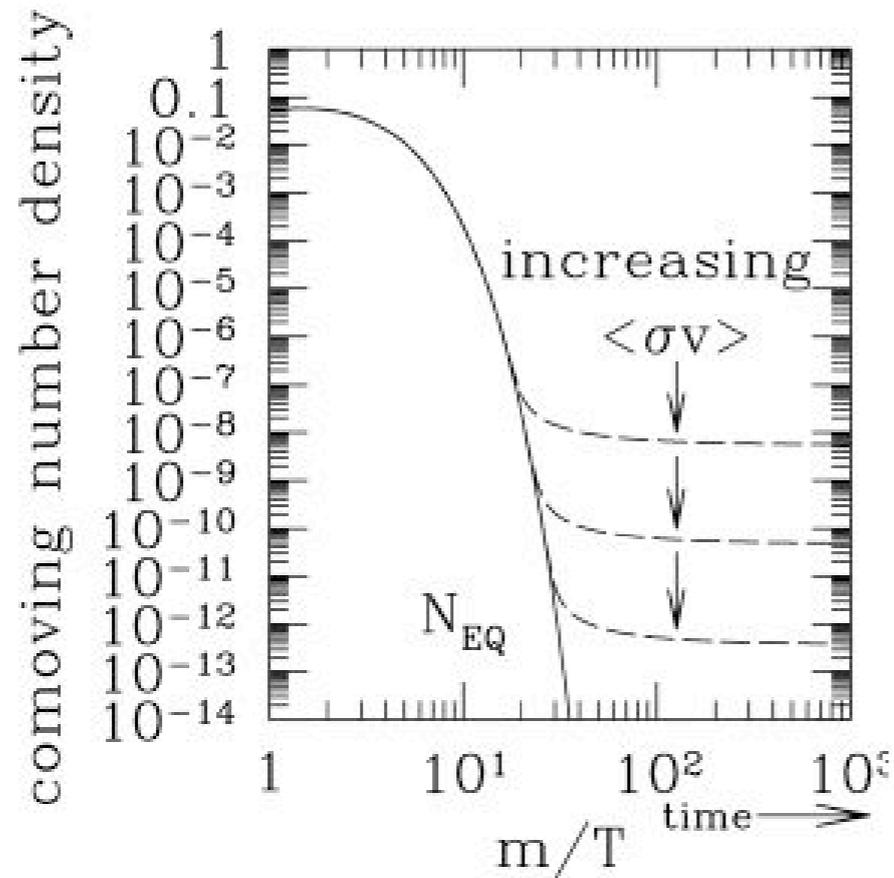
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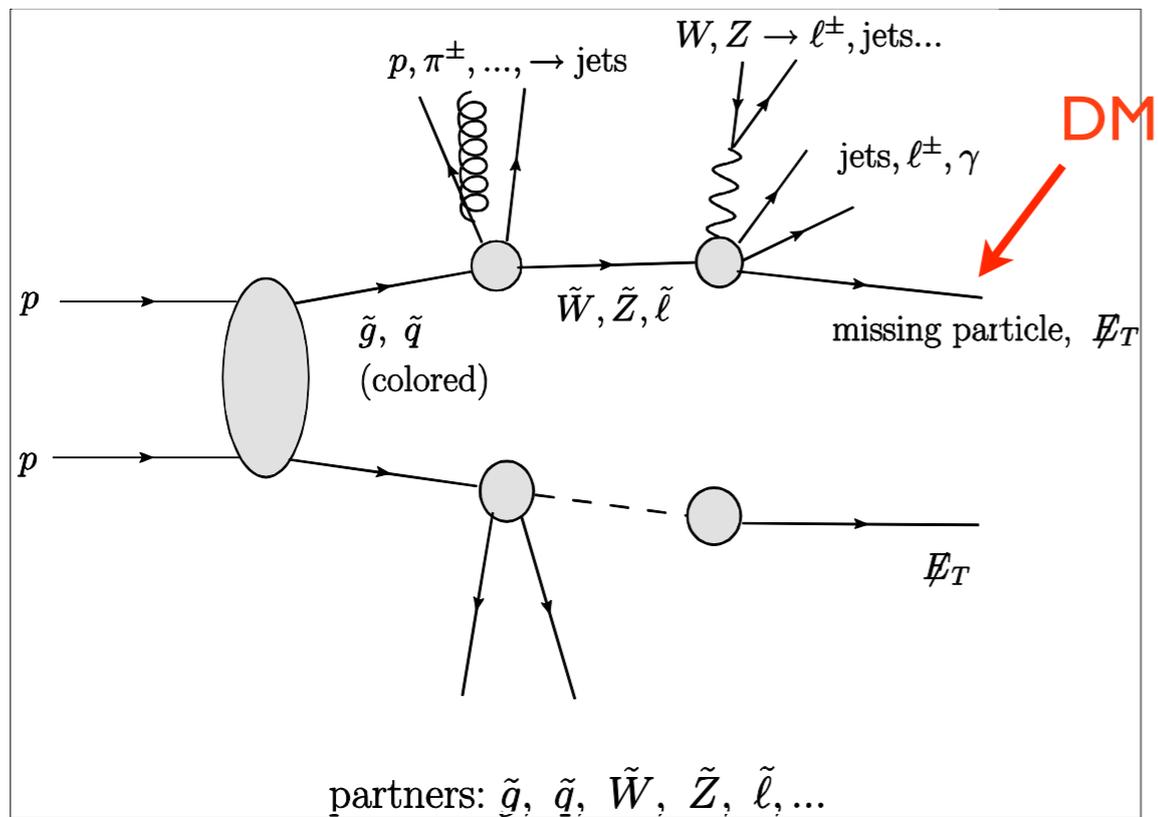
**WIMP**

# WIMP miracle



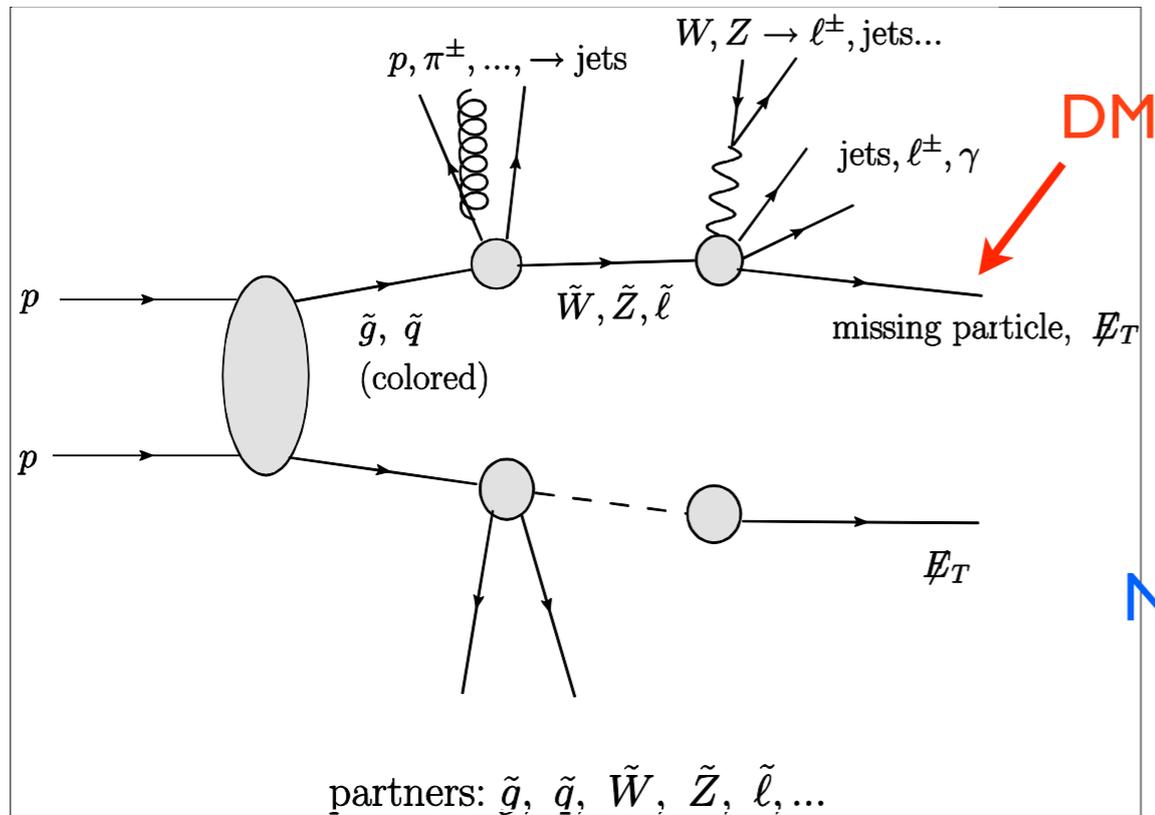
- If  $g_D \sim 0.1$   $M_D \sim 10$ s GeV - TeV
  - ▶ We get the right relic abundance of dark matter.
- Major hint for weak( $\pm$ ) scale new physics!

# "standard" story.

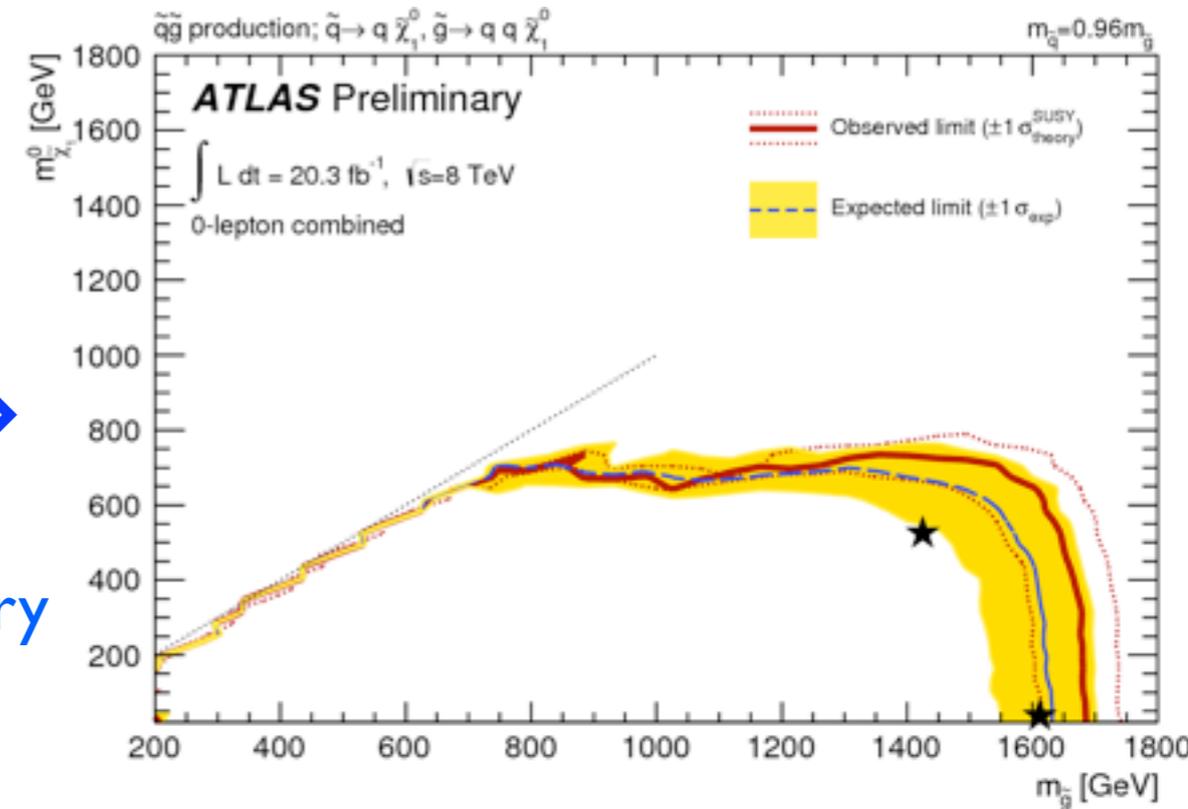


- WIMP is part of a complete model at weak scale.
- It's produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- The reach is correlated with the rest of the particle spectrum.

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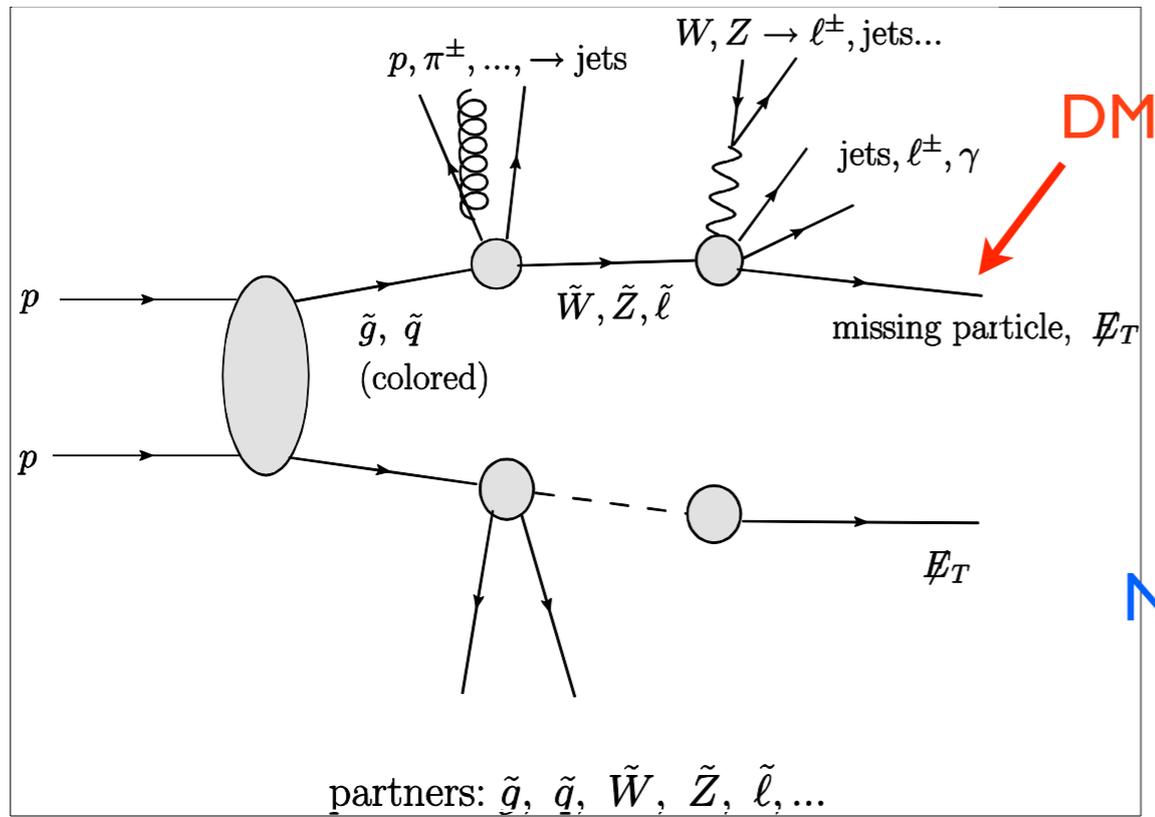


➡  
No discovery yet

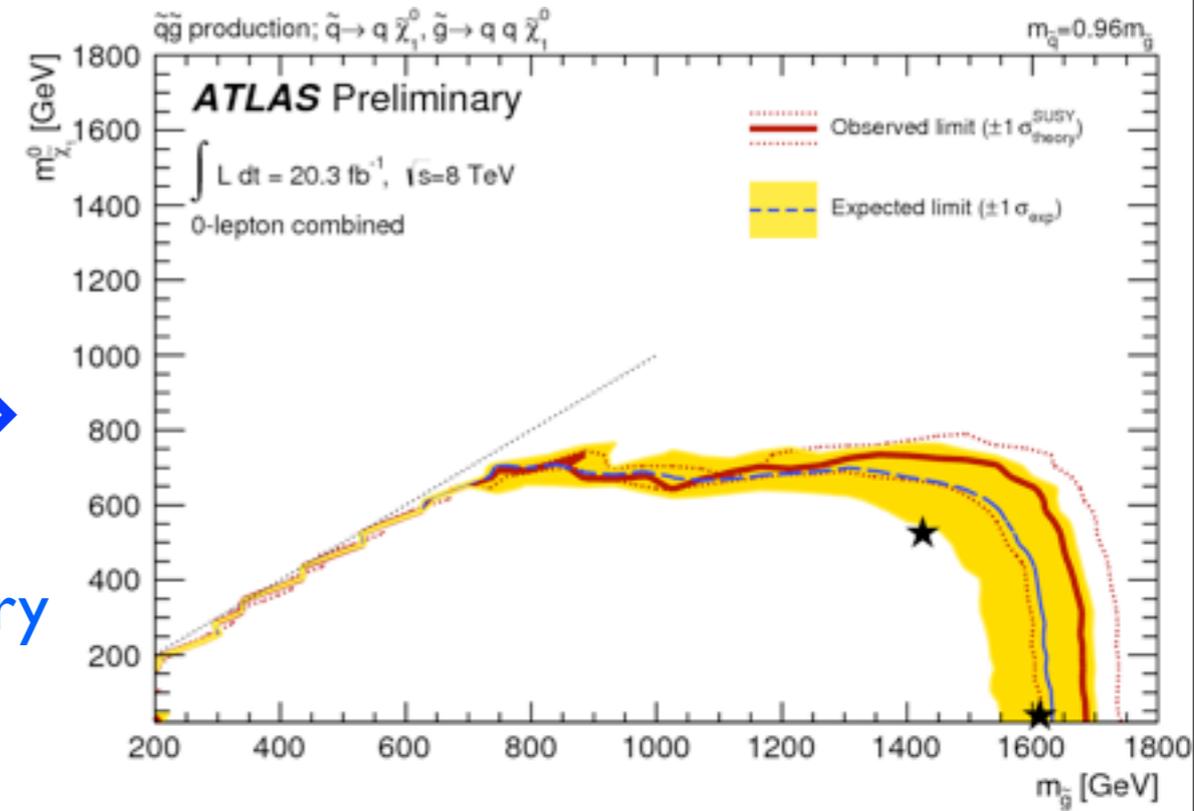


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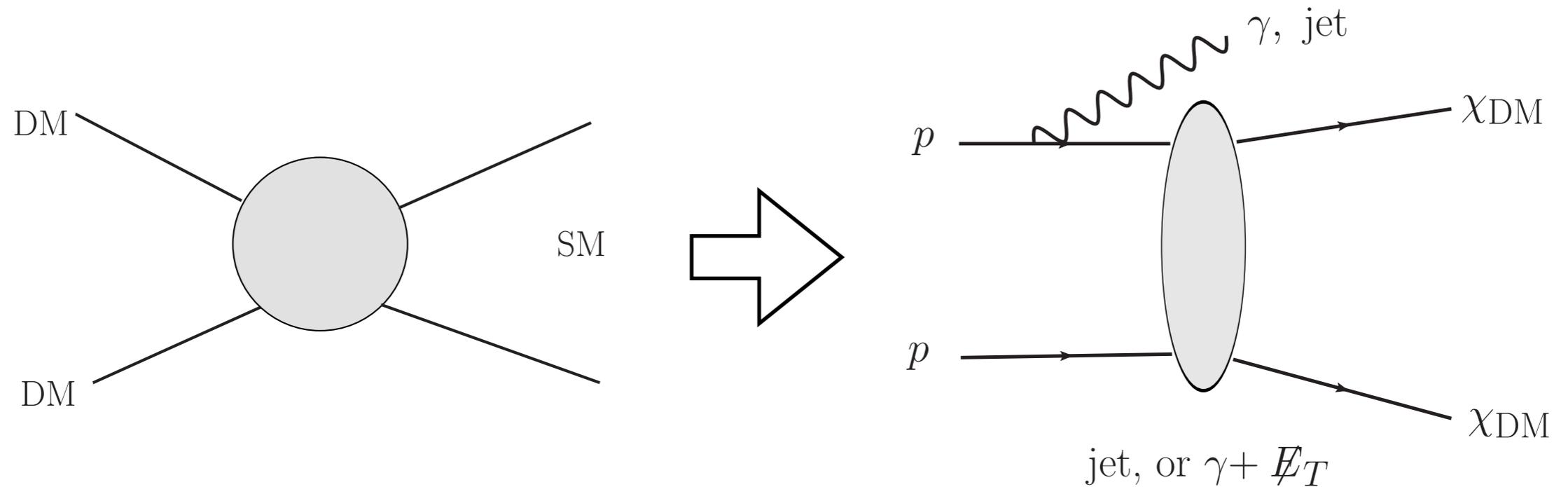
➡  
No discovery yet



Of course, still plausible at the LHC, will keep looking.  
 Higher energy  $\Rightarrow$  higher reach

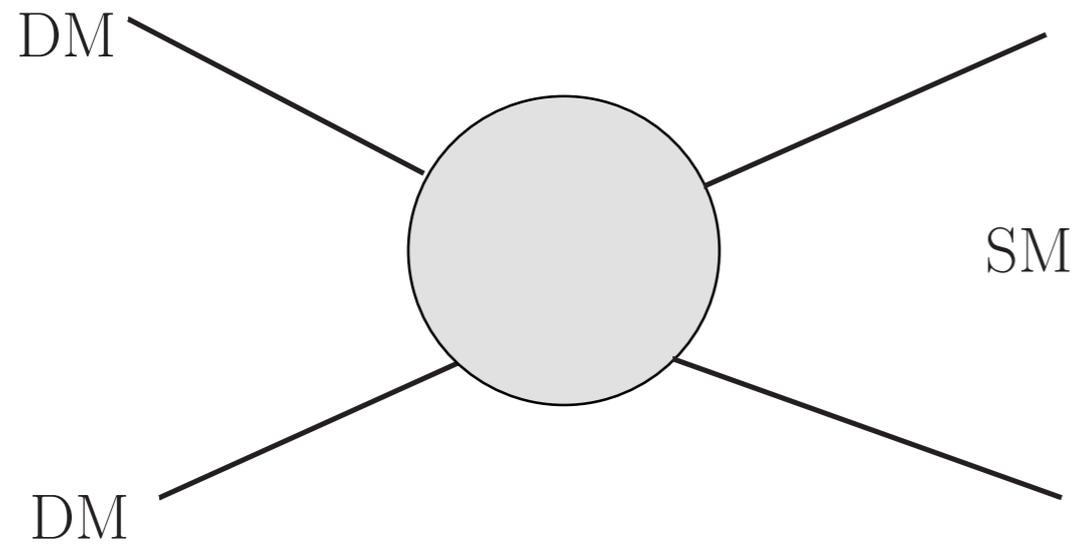
# Back to the basics

- pair production + additional radiation.



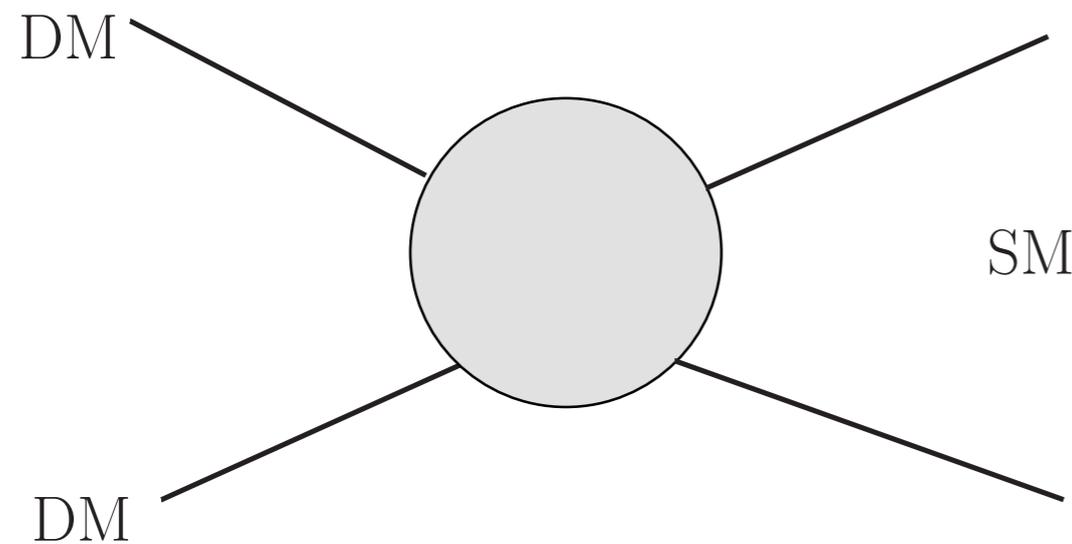
- Mono-jet, mono-photon, mono-...
- Have become "Standard" LHC searches.

# Effective operator approach



Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137  
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286  
Bai, Fox, Harnik, 1005.3797 .....

# Effective operator approach

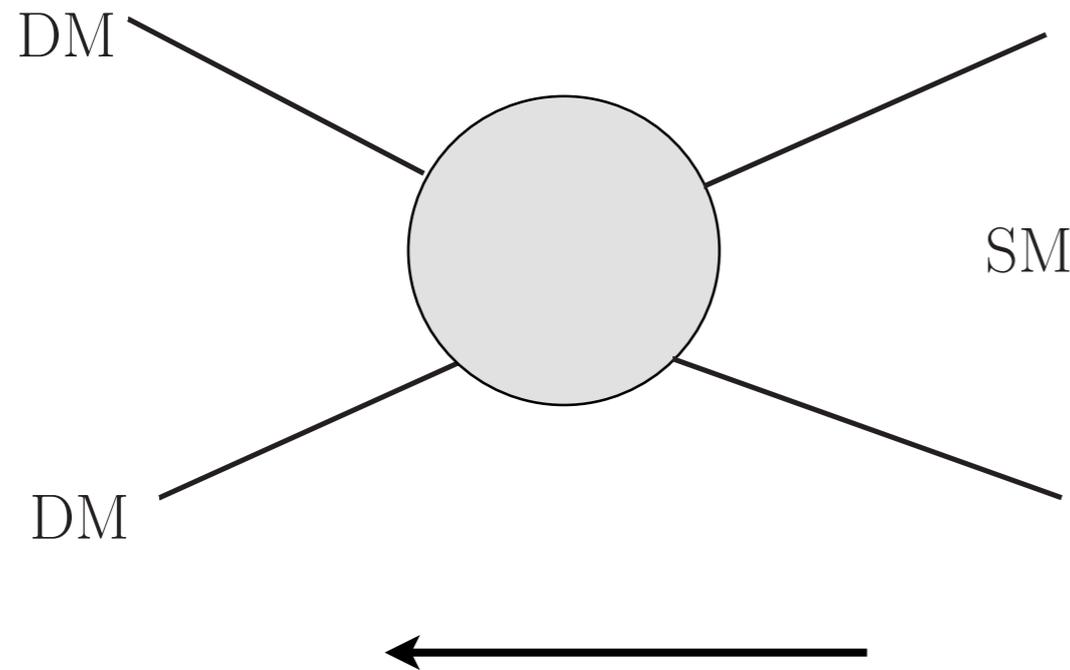


momentum exchange  
 $q \sim 100 \text{ MeV} \ll m_\phi$   
effectively,

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

Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137  
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286  
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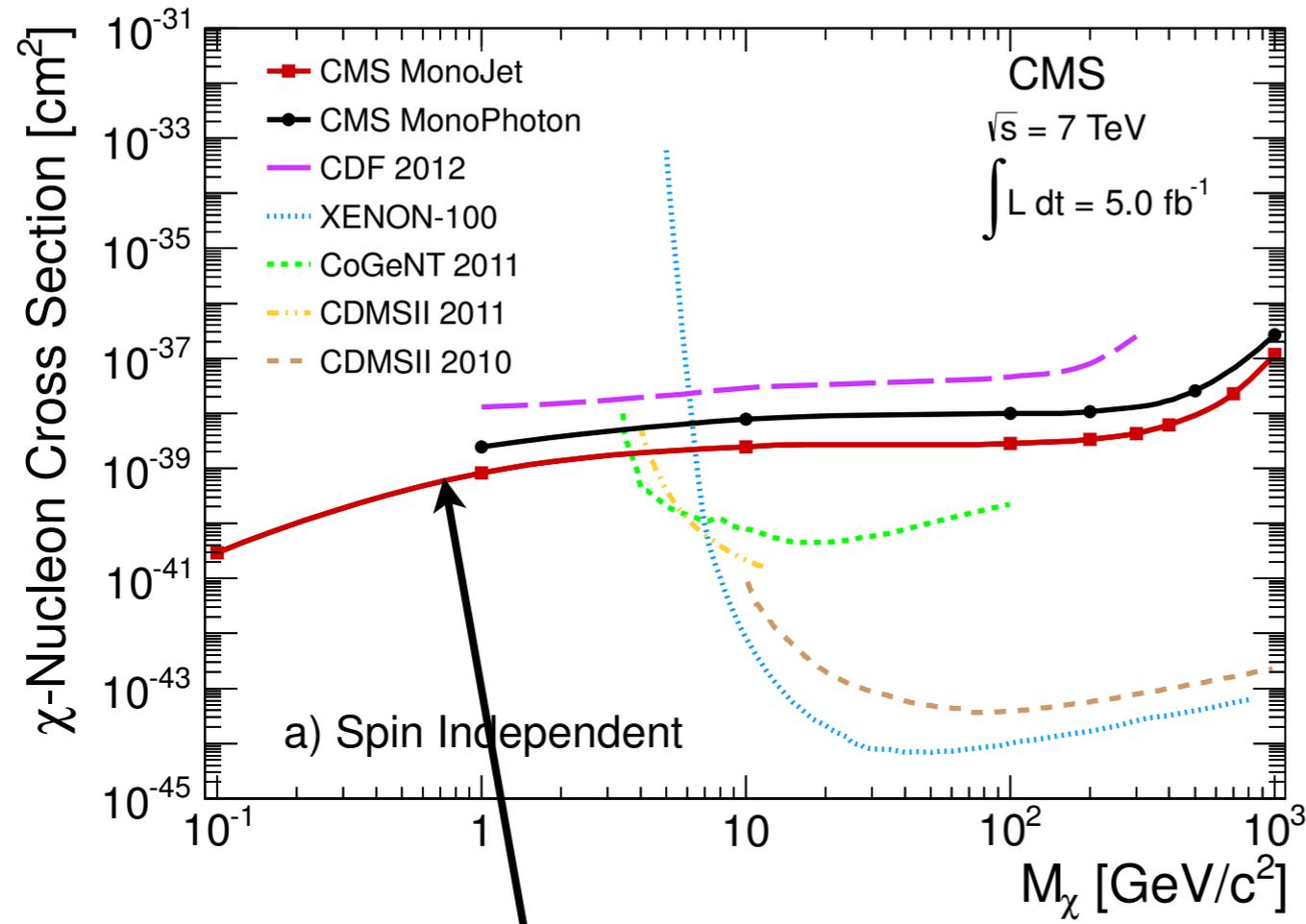
$$\frac{1}{\Lambda^d} \chi\chi J_{\text{SM}}$$

Use colliders to constrain and probe  
the same operator

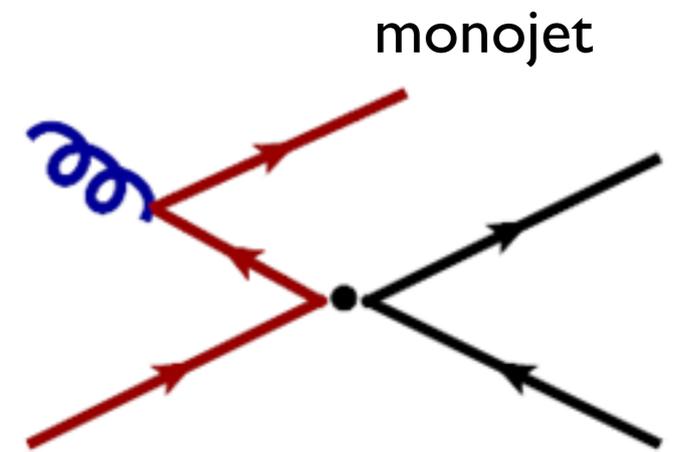
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# For example



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.



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

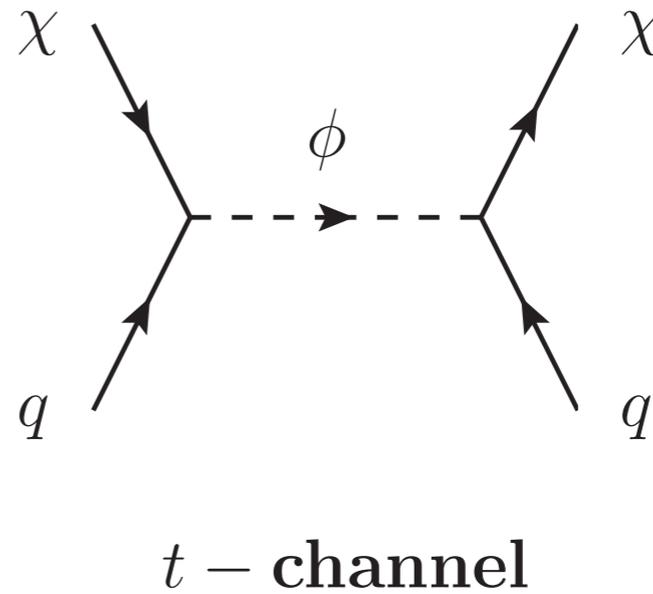
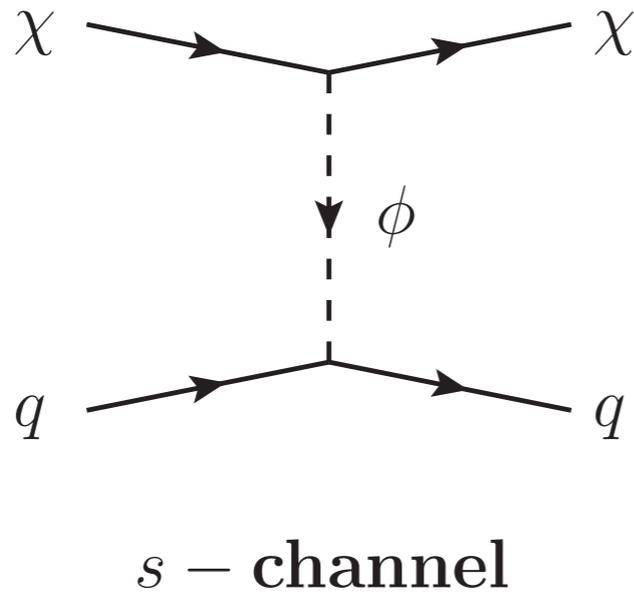
# Is this simple approach effective?

- Simple approach.
- Valid as field theory? Could be in some parameter region.
- Representative of possible UV completion? And, representative of possible signals?
  - ▶ Consider possible mediators.

# Simplified mediator models

direct detection  $\rightarrow$

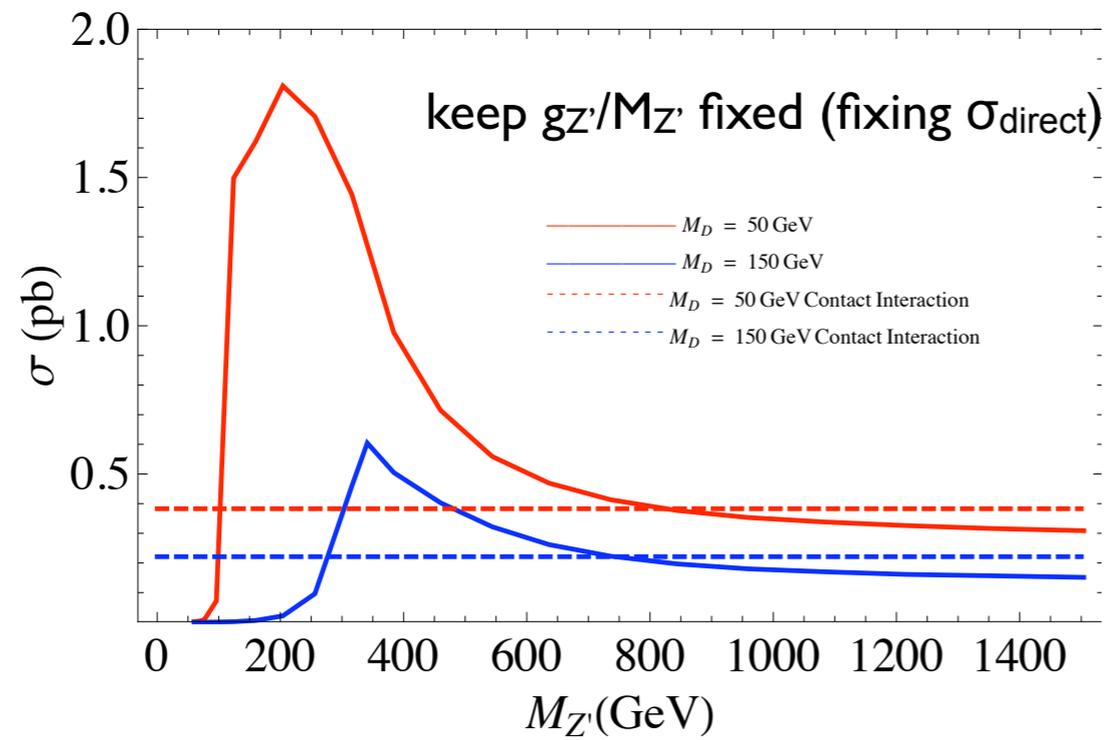
collider detection  $\uparrow$



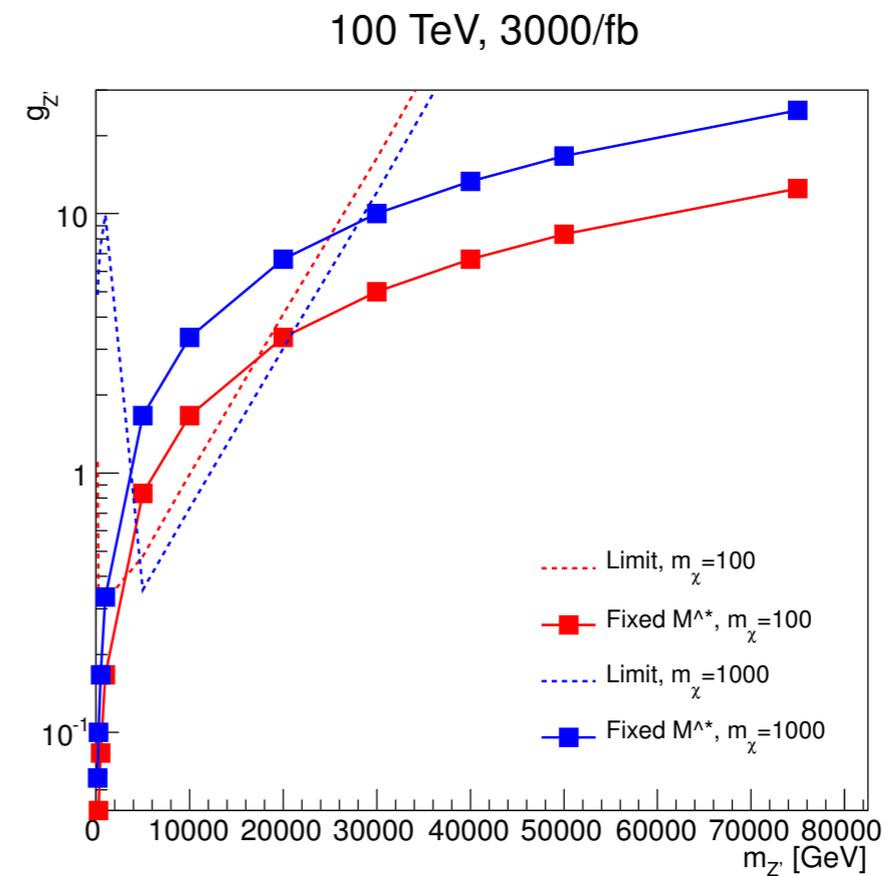
indirect detection  $\rightarrow$

can be scalar or  $Z'$

squark like



Tevatron rate,  $Z'$  vs effective operator  
An, Ji, LTW, I202.2894

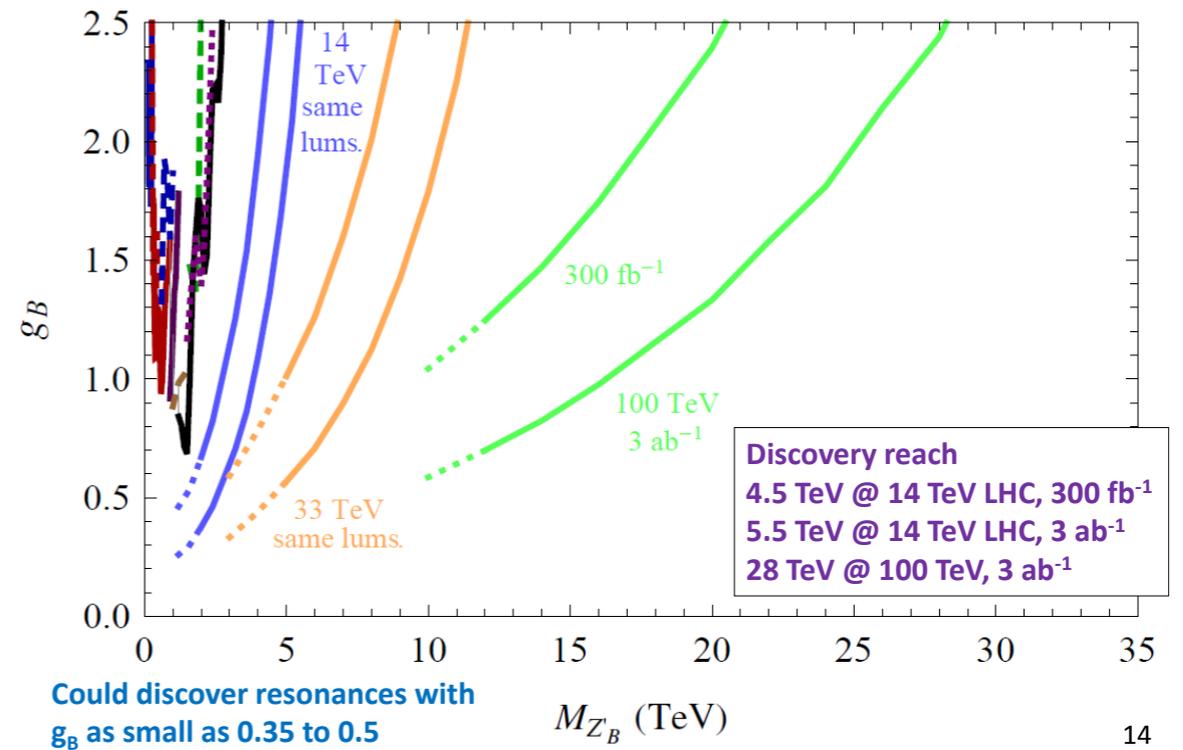
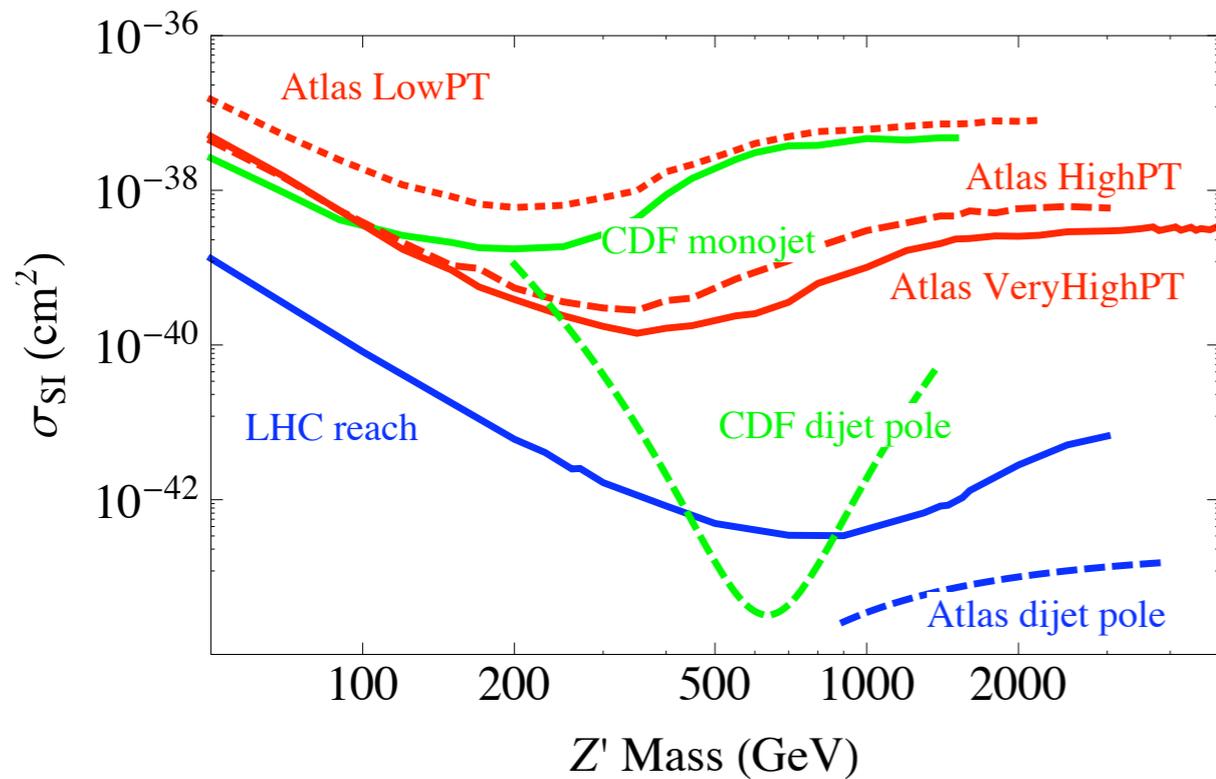


Zhou, Berge, LTW, Whiteson, Tait, I307.5327

## – $Z'$ like simplified models.

- ▶ Large deviations from the effective operator approach.
- ▶ Effective contact operator only recovered for large mediator mass and strong coupling.

# Possible to discover the mediator first!

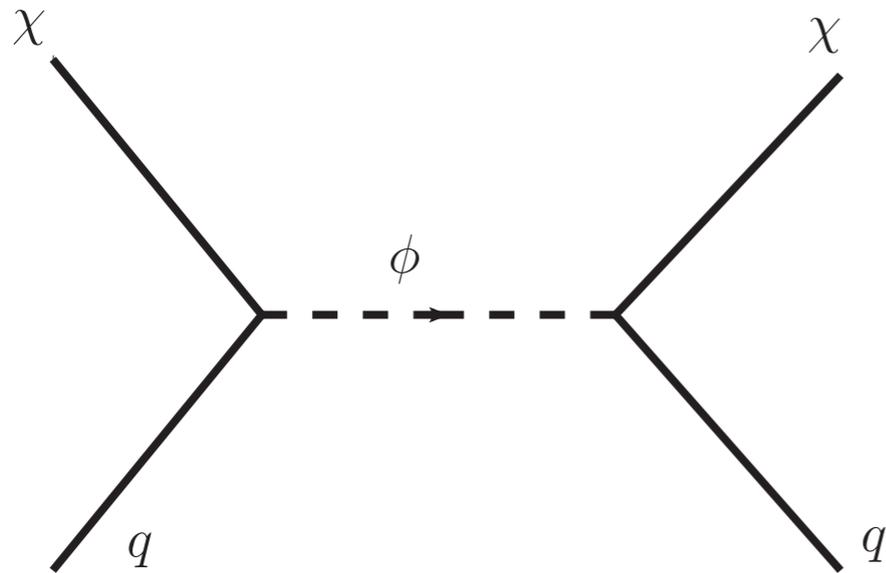


An, Ji, LTW, I202.2894 Assume  $g_{Z'} = g_D$

Felix Yu, 2013

# t-channel

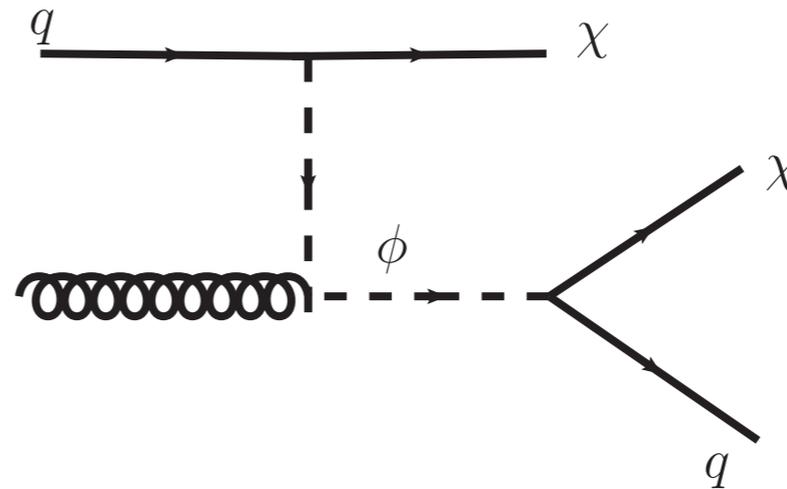
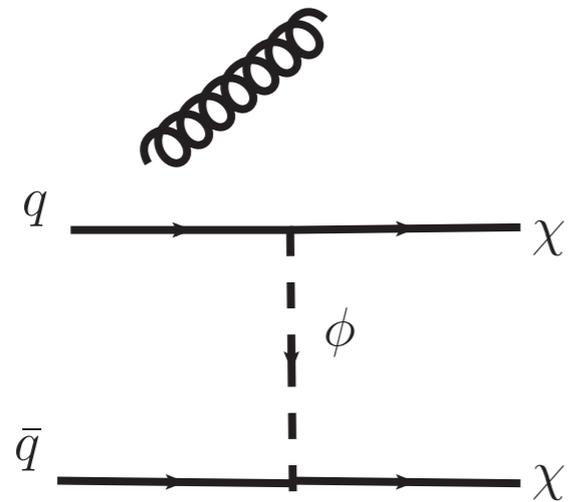
Chang, Edezhath, Hutchinson, Luty, I307.8120  
An, Zhang, LTW, I308.0592  
Bai, Berger, I308.0612  
DiFranzo, Nagao, Rajaraman, Tait, I308.2679  
Papucci, Vichi, Zurek, I402.2285



$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

- For fermionic (scalar) dark matter, the mediator could be scalar (fermion).
- FCNC constraints  $\Rightarrow \phi$  or  $\chi$  in flavor multiplet.
  - ▶ Consider the case where dark matter is singlet.
  - ▶  $\square \phi$  is 3 under  $SU(3)_R$ , has universal coupling to all quarks. (example: right-handed squarks with universal masses)

# Collider searches

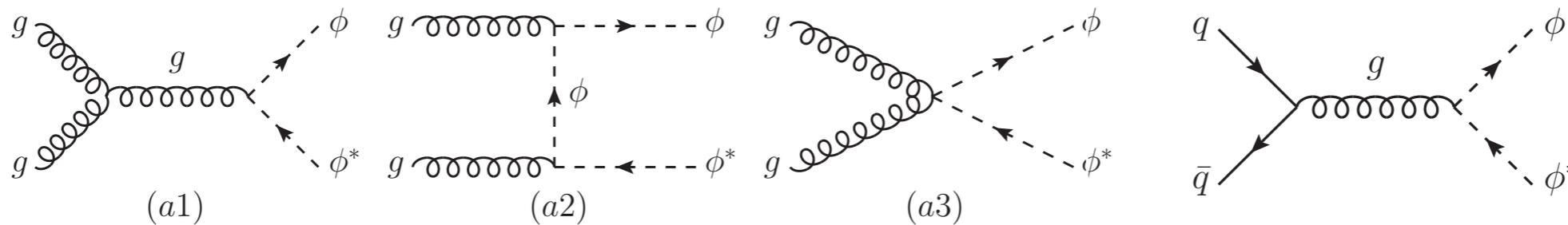


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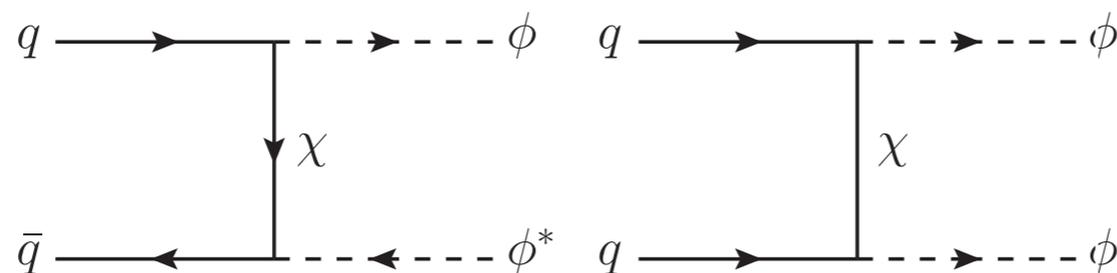
- 2 kinds of contributions for monojet.
- $pp \rightarrow \chi \phi$  gives harder (mono)jet!

# Direct mediator production

- $\phi$  is 3 under  $SU(3)_R$  (just like squarks with universal masses)
- $pp \rightarrow \phi\phi^{(*)}$  (di-jet + MET like searches)



“usual” squark searches

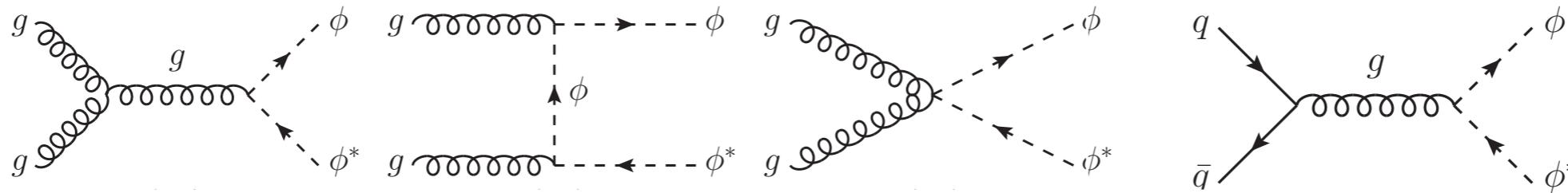


new channels, different kinematics  
Can start with valence qq if  $\chi$  is majorana

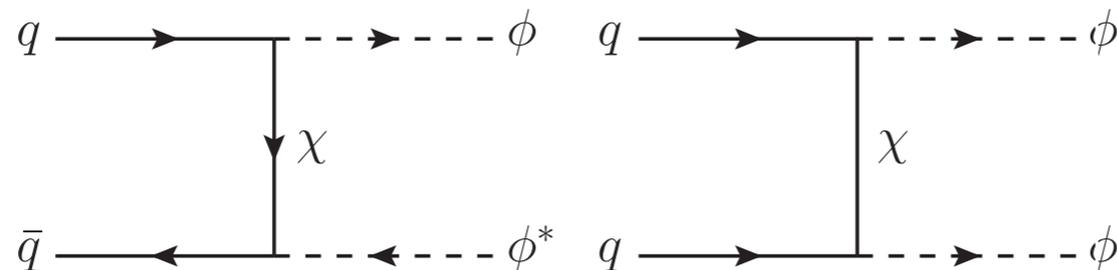
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Interestingly, CMS mono-jet search allows 2 hard jet  
Also sensitive to direct mediator pair production



$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

new channels, different kinematics  
Can start with valence qq if  $\chi$  is majorana

# 8 TeV limits

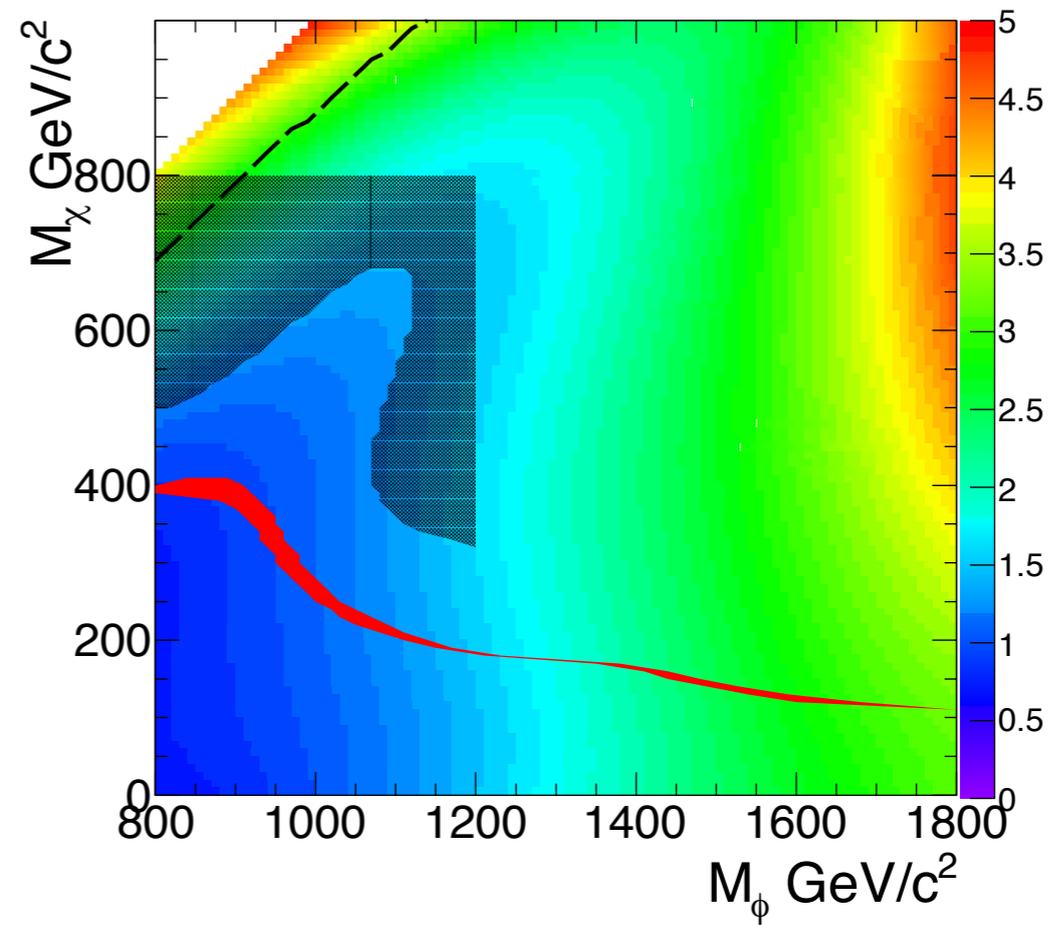
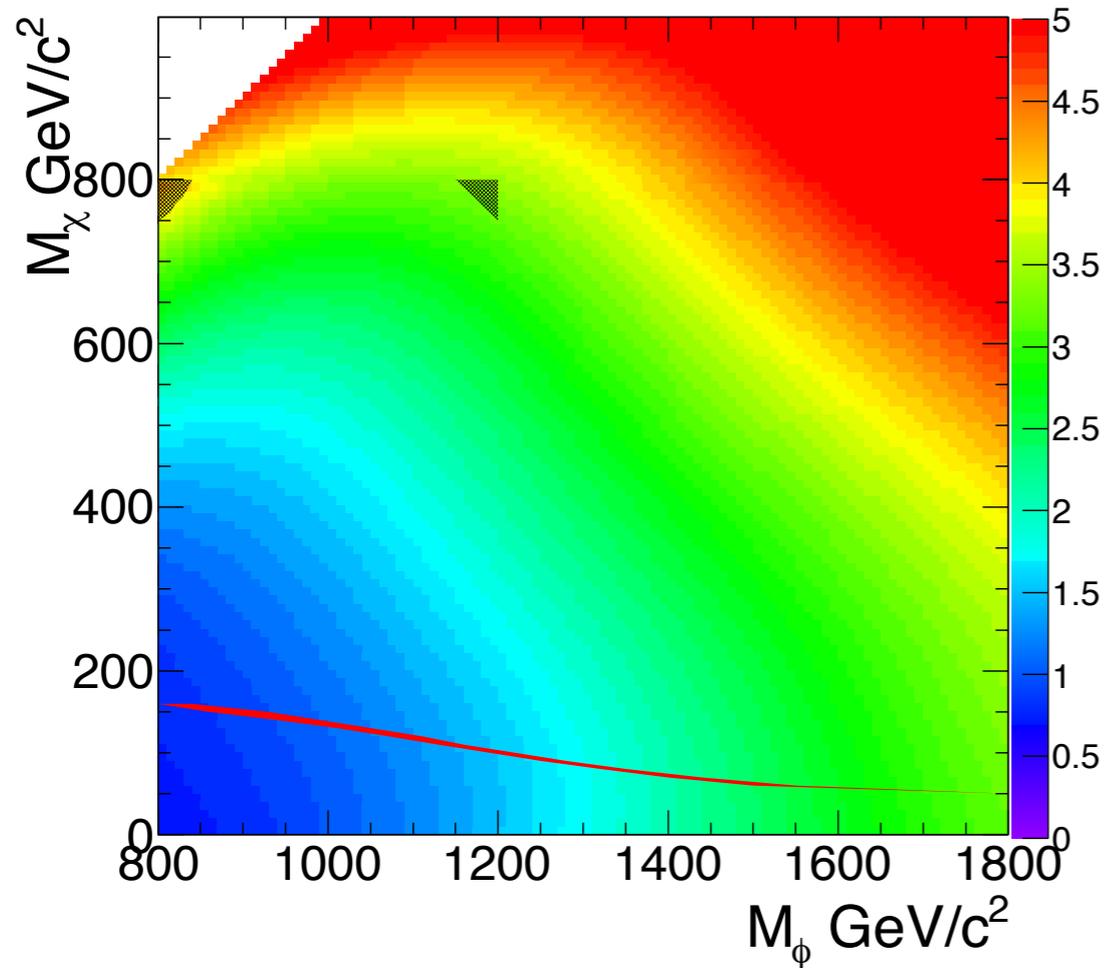
Monojet: CMS-PAS-EXO-12-048

squark: CMS-PAS-EXO-13-012

Dirac

Contours, limits on coupling  $\lambda_q$

Majorana



In general, the processes involving mediator direct production give strongest limit.

Stronger limit come from squark search (gray) or CMS-style monojet search.

Haipeng An, Hao Zhang, LTW, I308.0592

# Summary of simplified models

- Adding mediators can dramatically change the search strategy and reach.
- Processes with mediator direct production usually give stronger limits.
- These mediators are new physics particles themselves. Very simple DM+New forces!
- Simplify the other way
  - ▶ More involved DM + SM forces are mediator?

# Back to SUSY

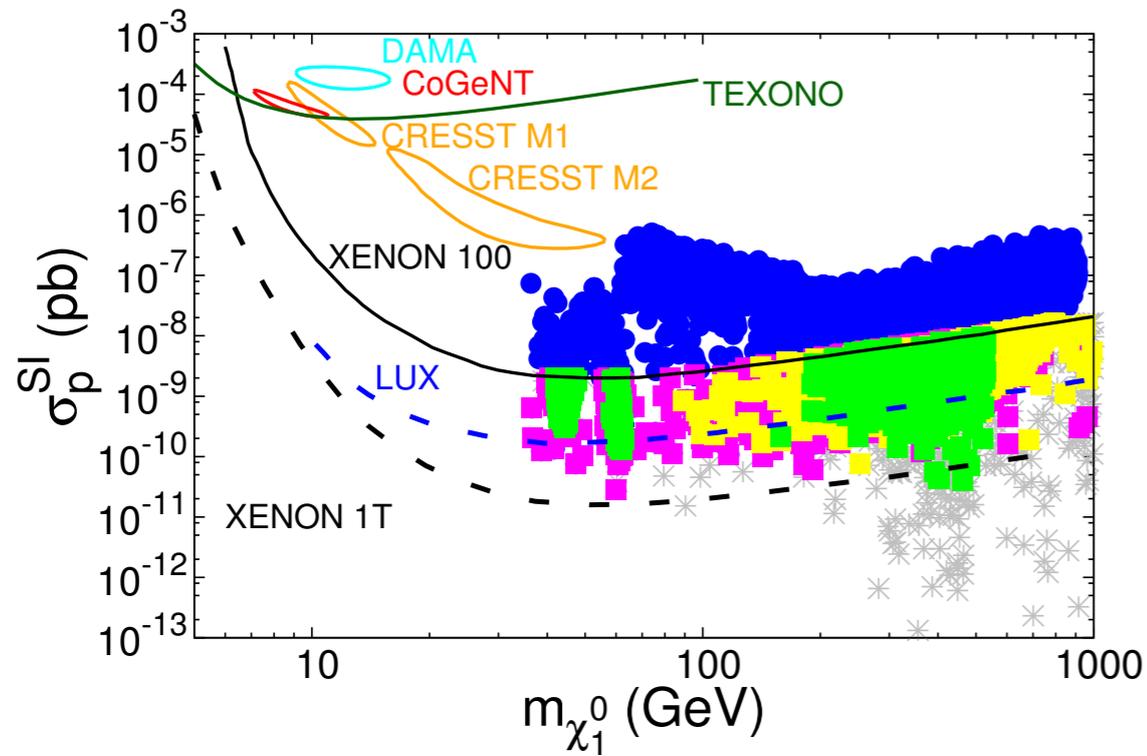
- Not just because we love SUSY.
- SUSY LSP  $\Rightarrow$  a set of good examples of more generic WIMP candidates.
  - ▶ Bino  $\Leftrightarrow$  singlet fermion dark matter
  - ▶ Higgsino  $\Leftrightarrow$  Doublet. Heavy exotic lepton.
  - ▶ Wino  $\Leftrightarrow$  EW Triplet DM
  - ▶ Can have co-annihilation regions

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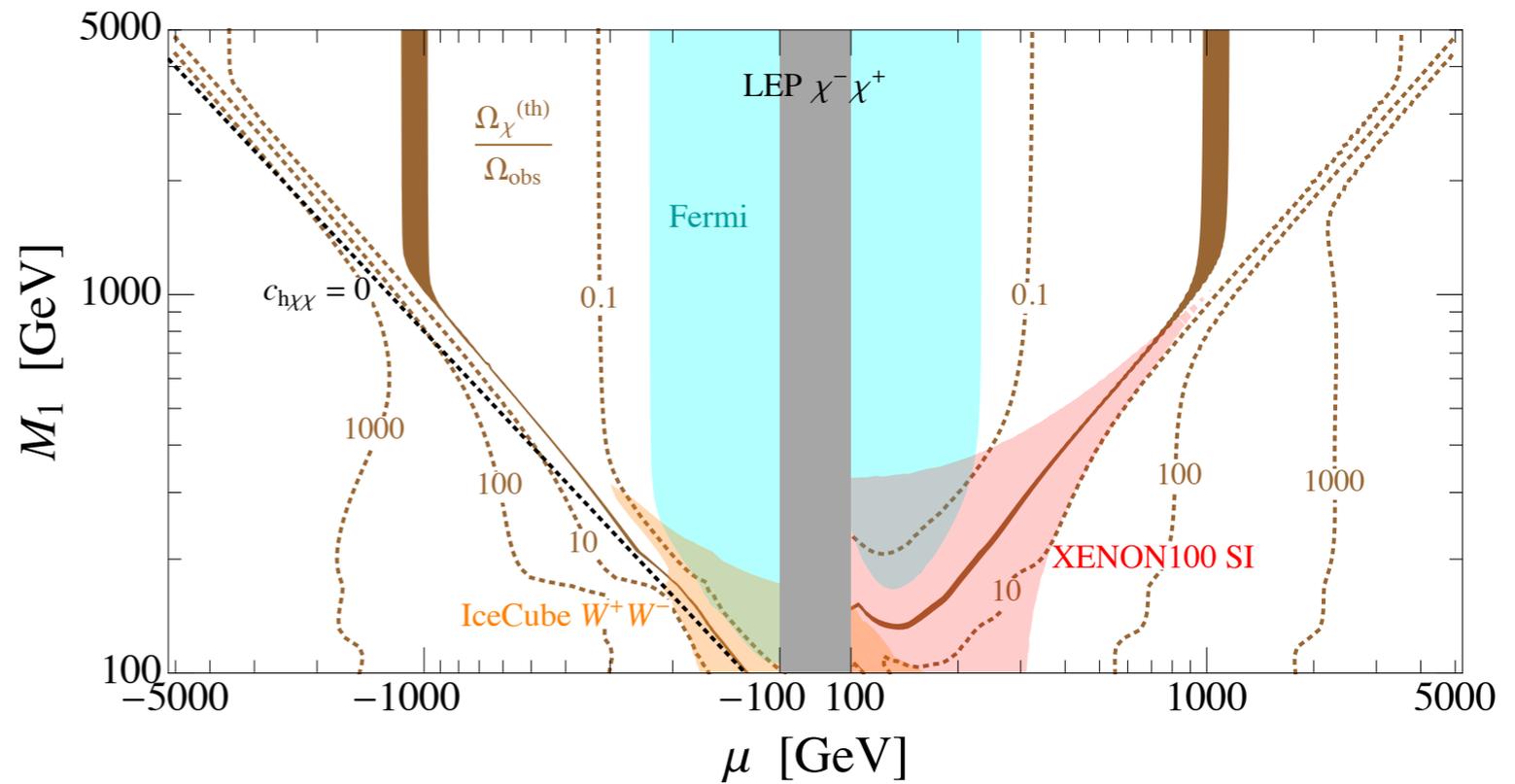
Good starting point to investigate more  
general WIMP candidates  
Mediators are SM gauge boson, Higgs.

# Narrowing parameter space.



Cheung, Hall, Pinner, Ruderman, 1211.4873

Han, Liu, Natarajan, 1303.3040



# Possible scenarios (not over-closing)

– Higgsino  $\lesssim$  TeV

– Wino  $\lesssim$  3 TeV

– Well temper:  $\tilde{h}, \tilde{W}$  \_\_\_\_\_  
 $\tilde{B}$  \_\_\_\_\_  $\Delta M \sim$  several %  $\times M_{\text{DM}}$

Arkani-Hamed, Delgado, Giudice, hep-ph/0601041

– Coannihilation:  $\tilde{\tau}, \tilde{q}, \tilde{t}, \dots$  \_\_\_\_\_  
 $\tilde{B}$  \_\_\_\_\_  $\Delta M \sim$  several %  $\times M_{\text{DM}}$

– Funnel:  $2 M_{\text{DM}} \approx M_X$   $X = A, H, \dots$

Cahill-Rowley, Hewett, Ismail, Peskin, Rizzo, I305.2419

Cohen, Wacker, I305.2914

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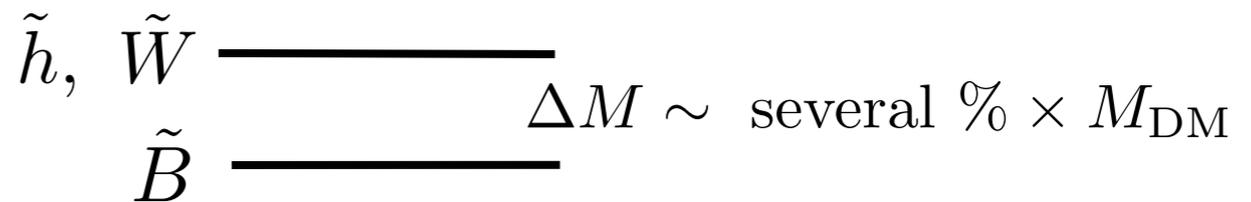
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– Wino  $\lesssim$  3 TeV

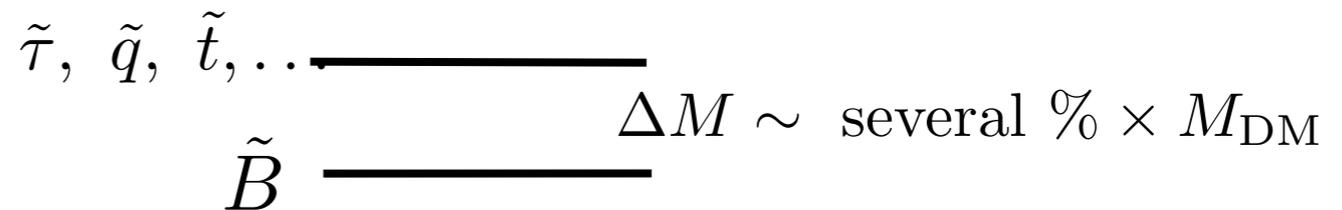
– Well temper:

– Coannihilation:

Common feature:  
very small mass splitting “compressed”



Arkani-Hamed, Delgado, Giudice, hep-ph/0601041



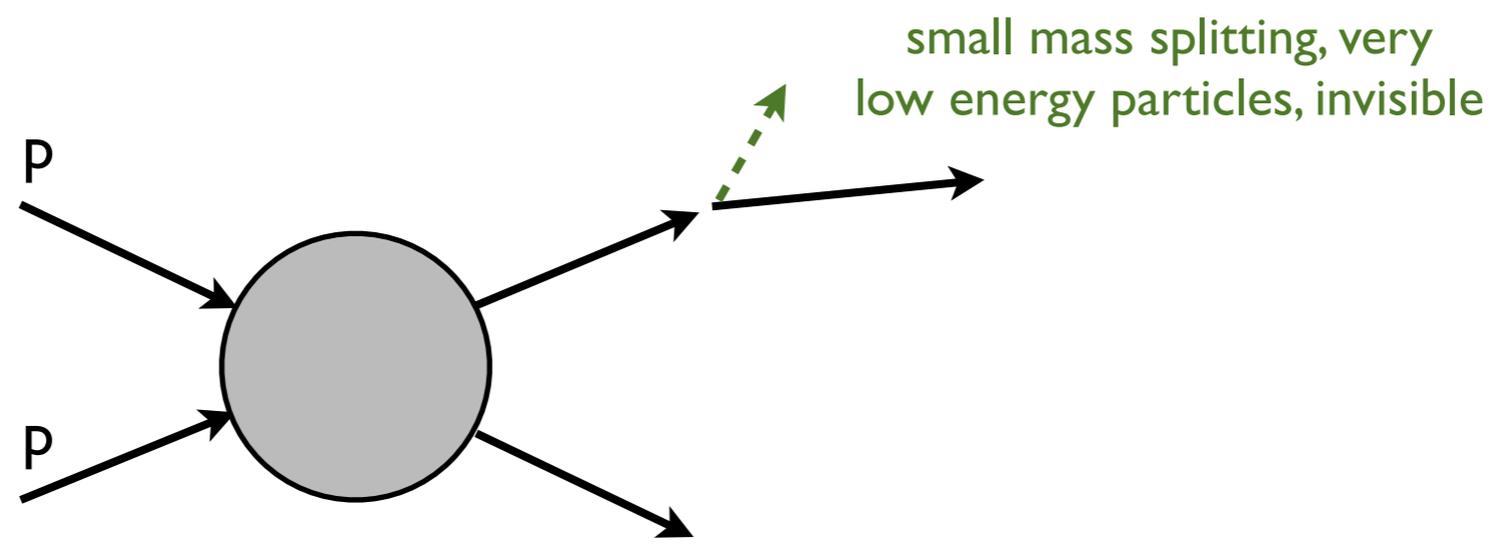
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Cahill-Rowley, Hewett, Ismail, Peskin, Rizzo, I305.2419

Cohen, Wacker, I305.2914

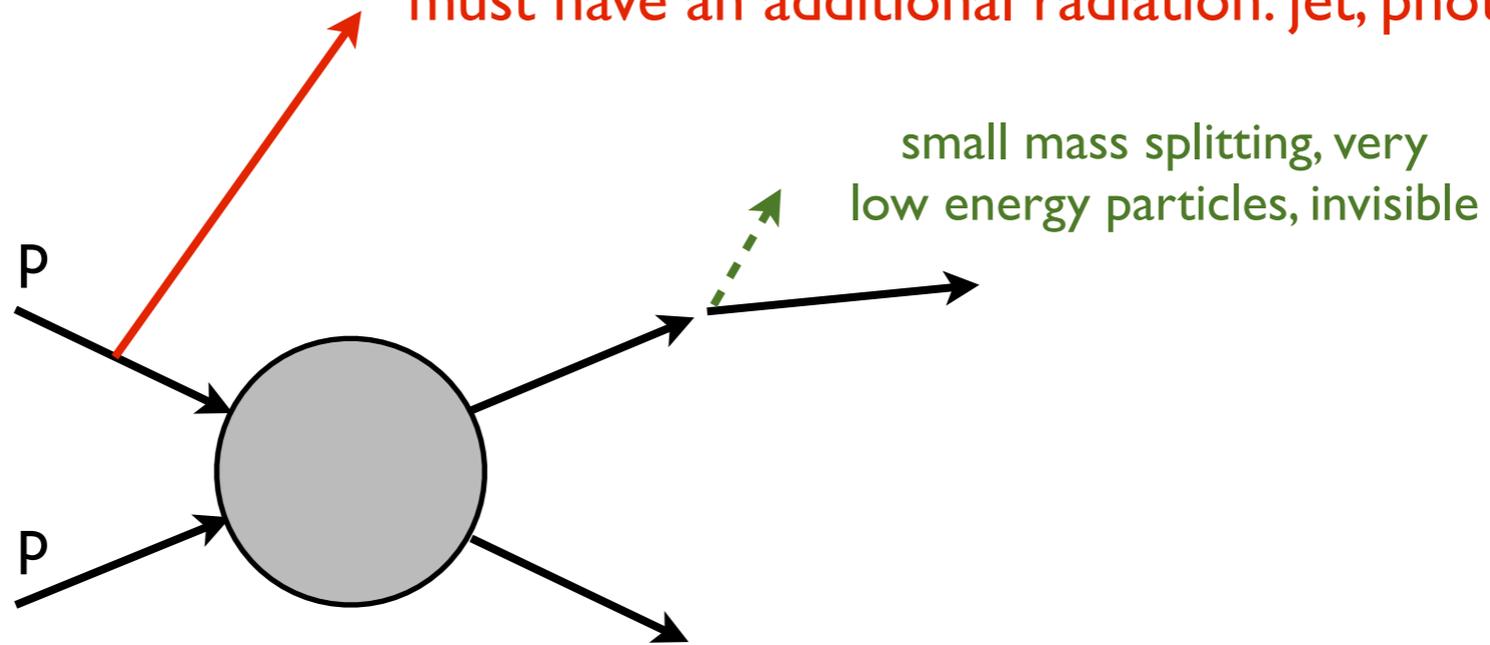


# SUSY DM signal in the compressed case

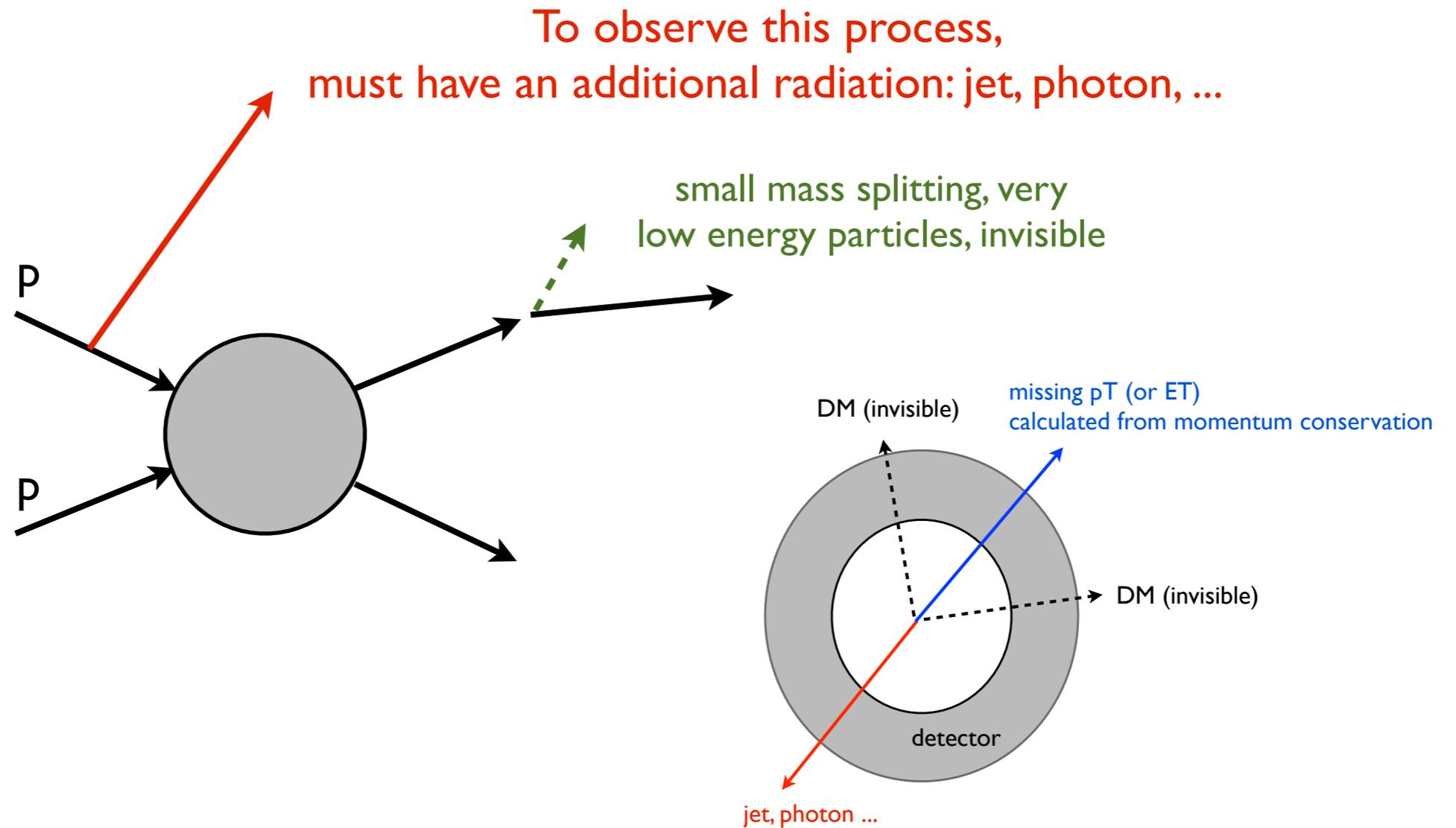


# SUSY DM signal in the compressed case

To observe this process,  
must have an additional radiation: jet, photon, ...

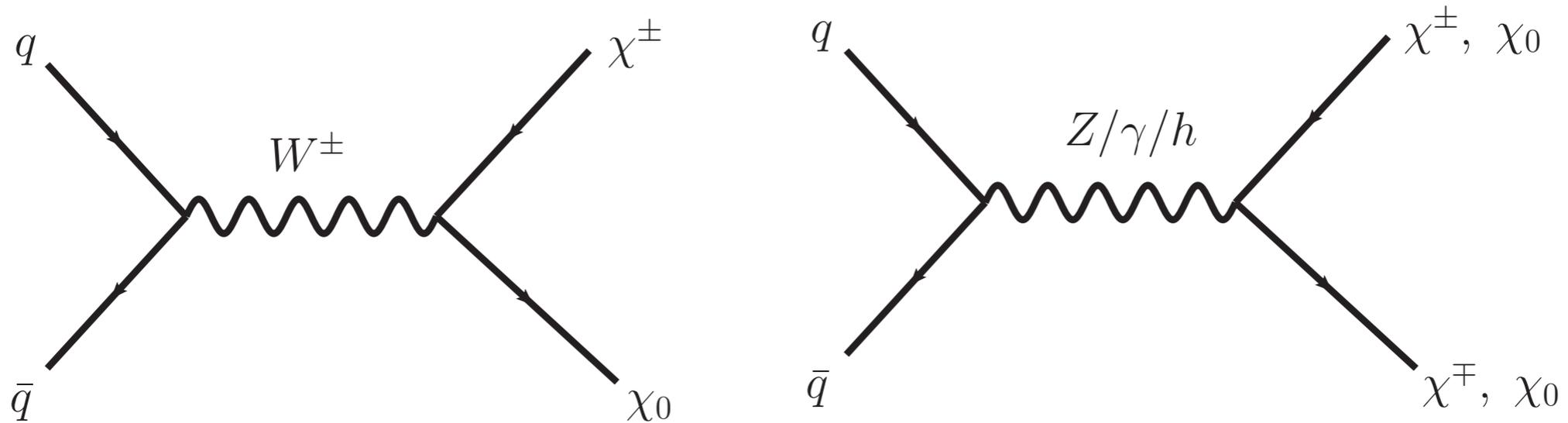


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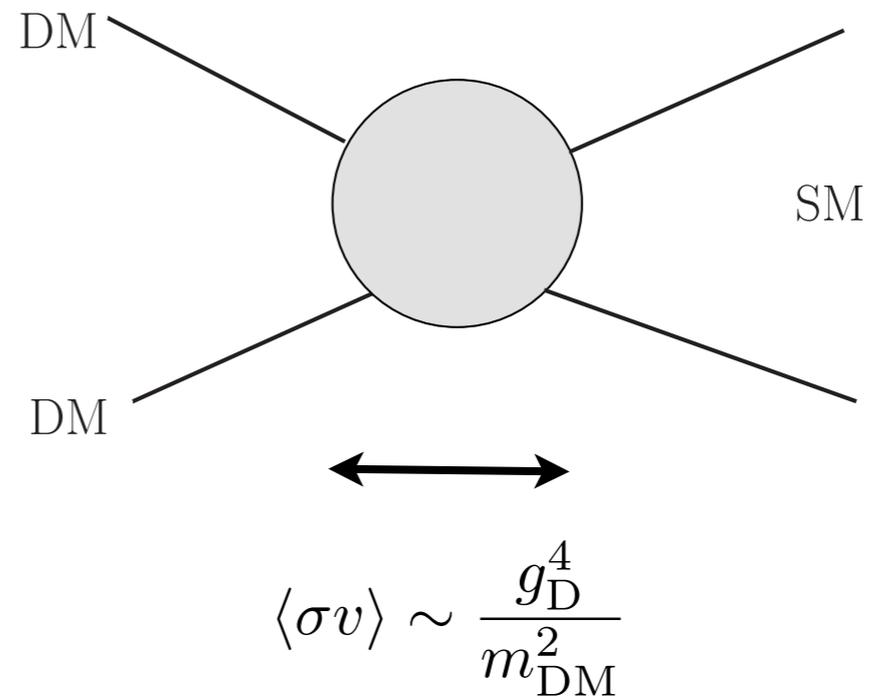
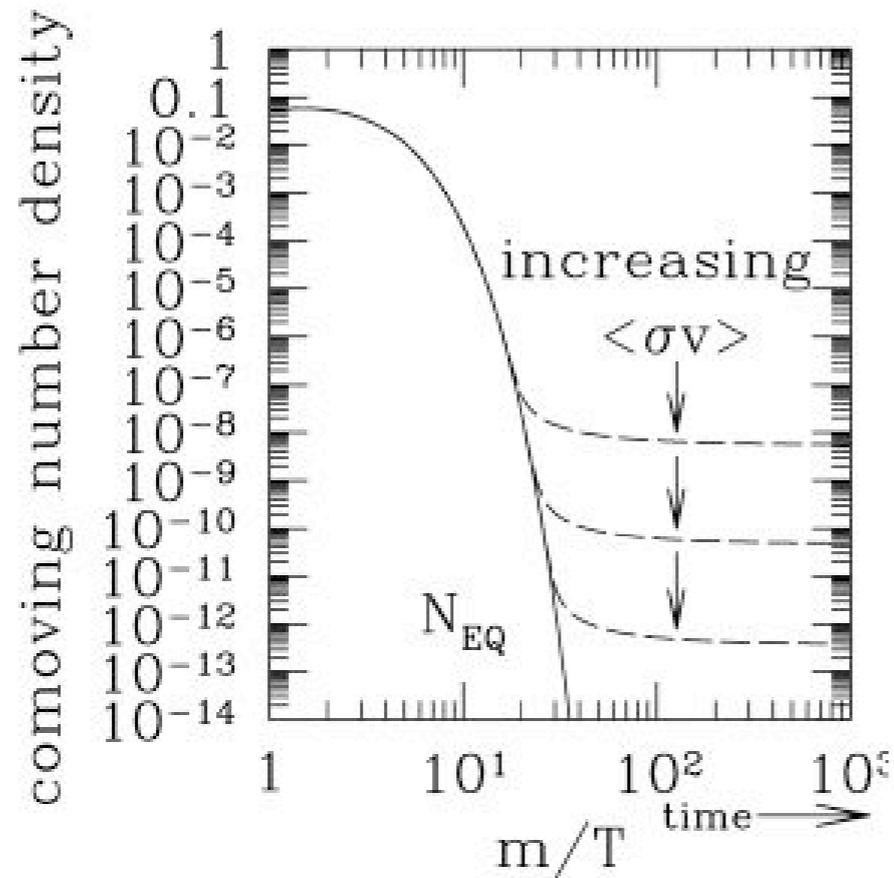
- Back to the basic mono-jet, mono-photon...

# No additional mediator



- In simple scenario of SUSY, there is no additional new mediator to search.
  - ▶ Mediated by  $W/Z/h$ .
- In principle, there are also gluino and squarks...
  - ▶ They can be heavy and play no role in dark matter physics.

# WIMP miracle

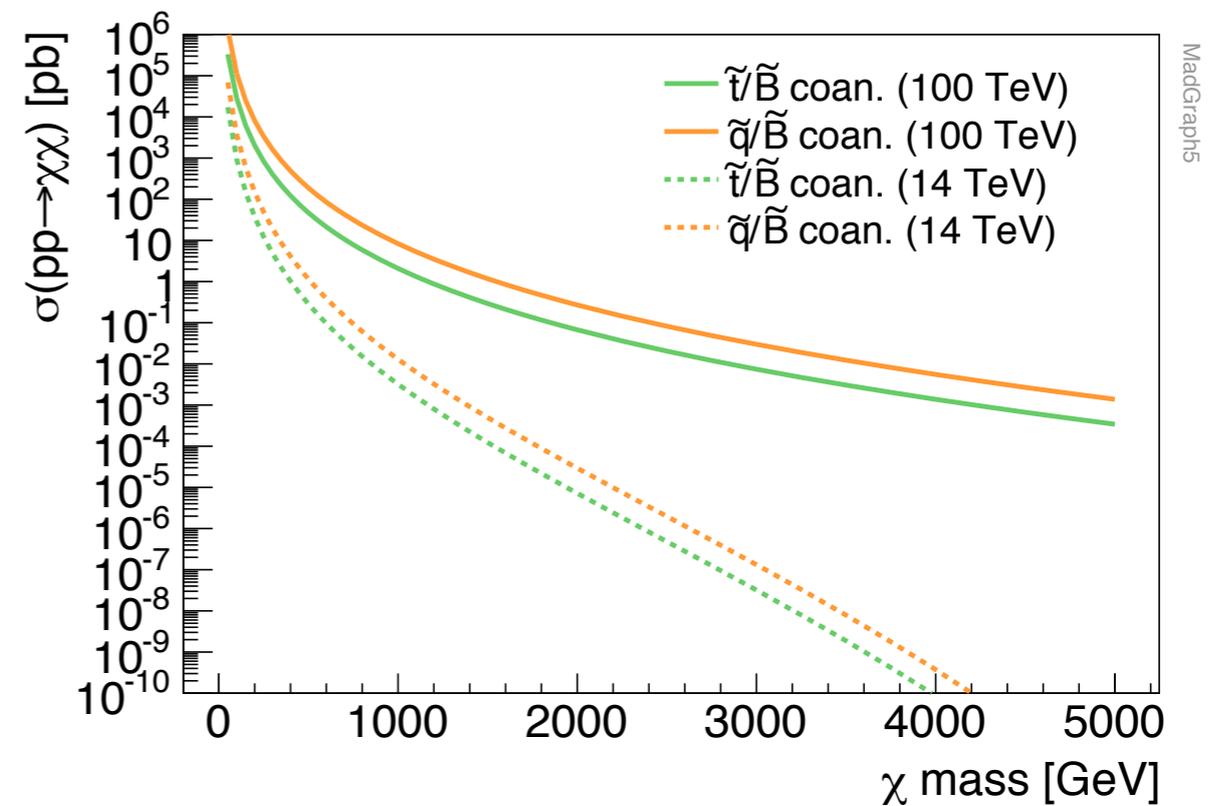
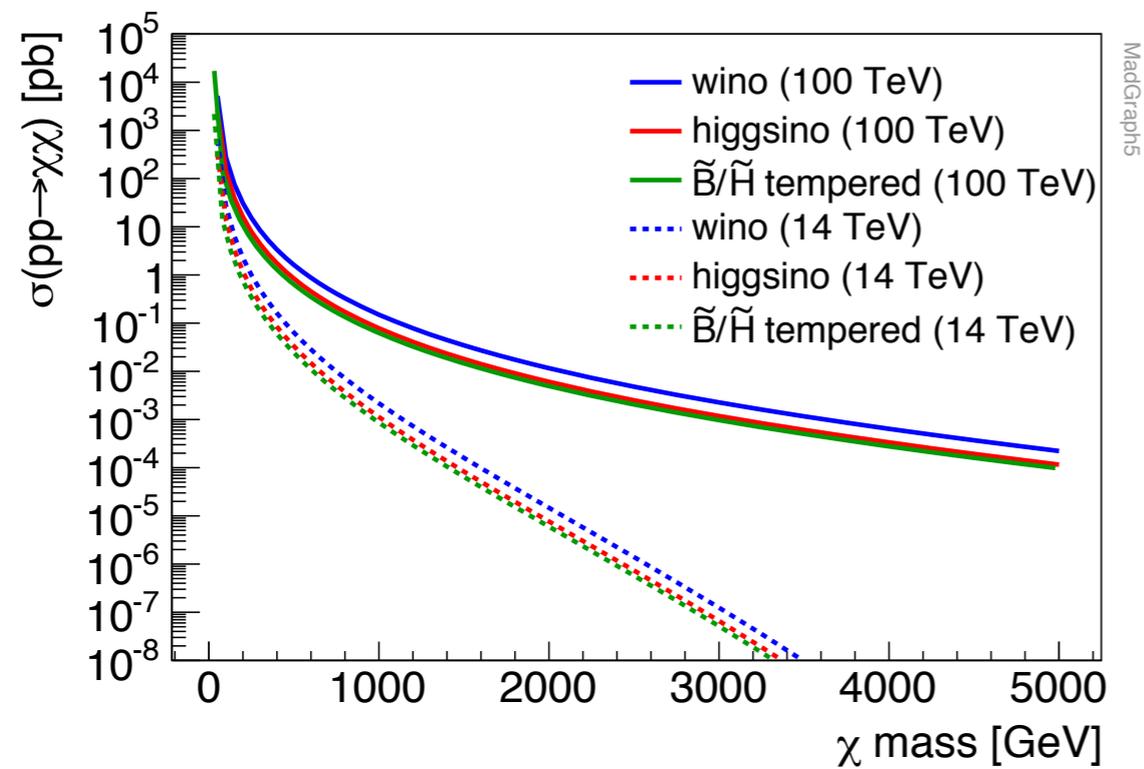


- More precisely, to get the correct relic abundance

$$M_{\text{WIMP}} \leq 1.8 \text{ TeV} \left( \frac{g^2}{0.3} \right)$$

- Much of the parameter space out of reach for the LHC.

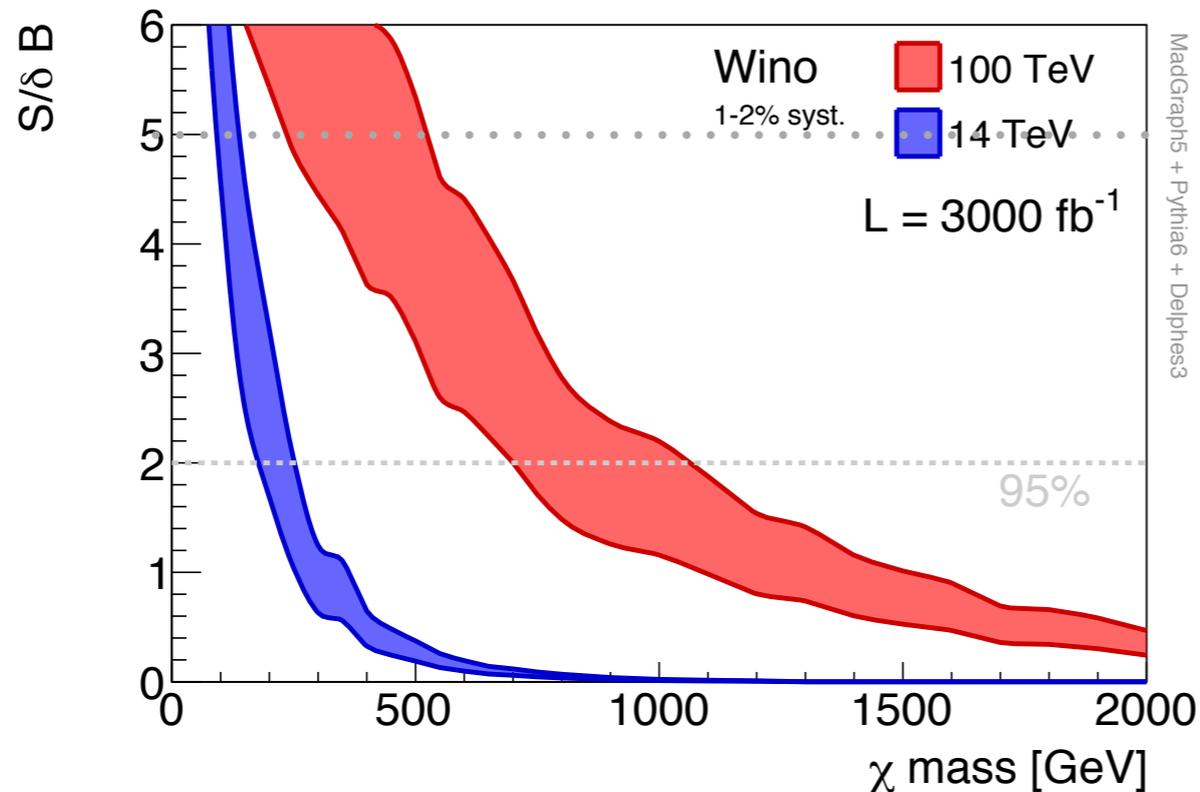
# Considering 14 and even higher



- Higher energy, higher rates
- Expecting large improvement from 14 to 100.

# Example: Wino. Monojet channel

Matthew Low, LTW, 2014



$p_T(\text{jet}) > 300$  (1200) GeV,  
for 14 (100) TeV  $E_{\text{cm}}$   
lepton veto ...

mono- $\gamma$  and mono- $W/Z$   
don't add that much.

significance: 
$$\frac{S}{\sqrt{B + \lambda^2 B^2 + \gamma^2 S^2}}, \quad \lambda = (1 - 2)\%, \quad \gamma = 10\%$$

Band: varying systematic error of background,  $\lambda$ , between 1-2%

— A factor of 4-5 enhancement from 14 to 100 TeV.

Recent works on mono-jet for electroweak-inos

Schwaller, Zurita, 1312.7350

Baer, Tata, 1401.1162

Han, Kribs, Martin, Menon, 1401.1235

# Disappearing track

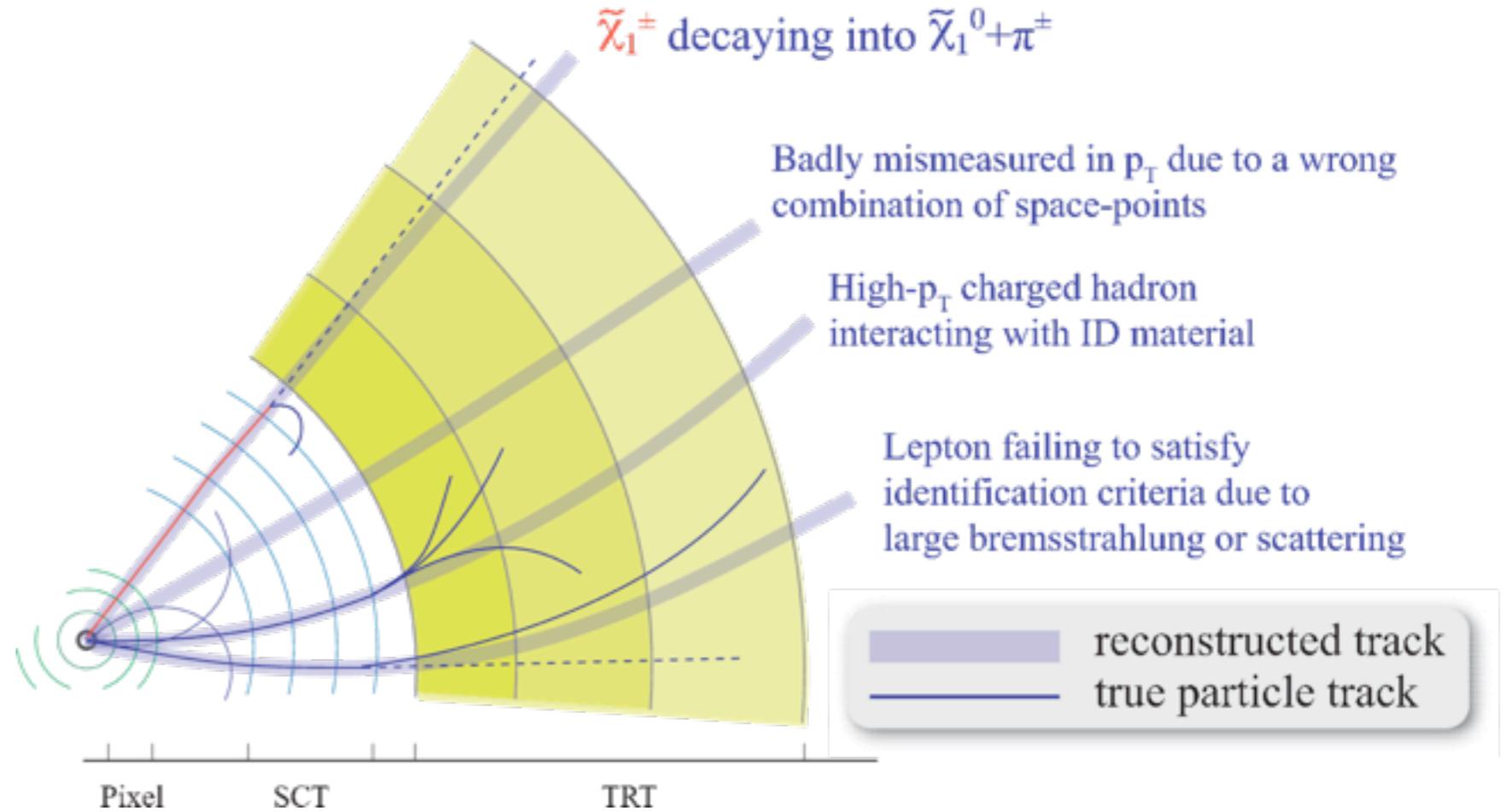
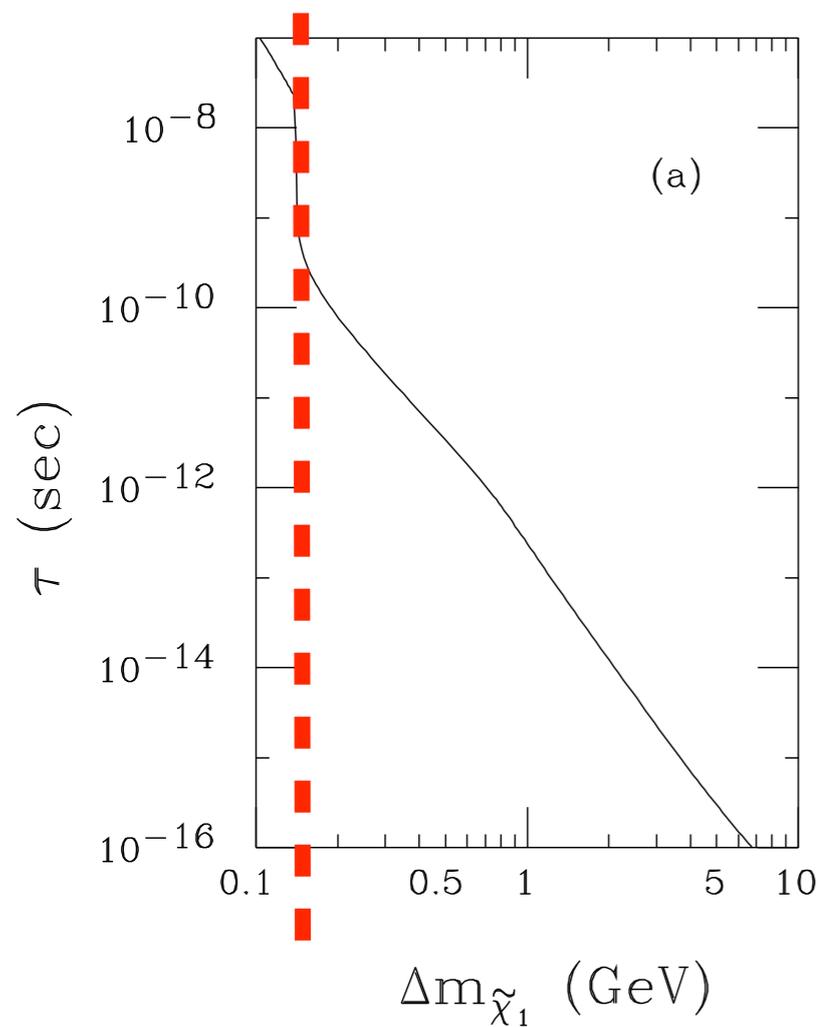
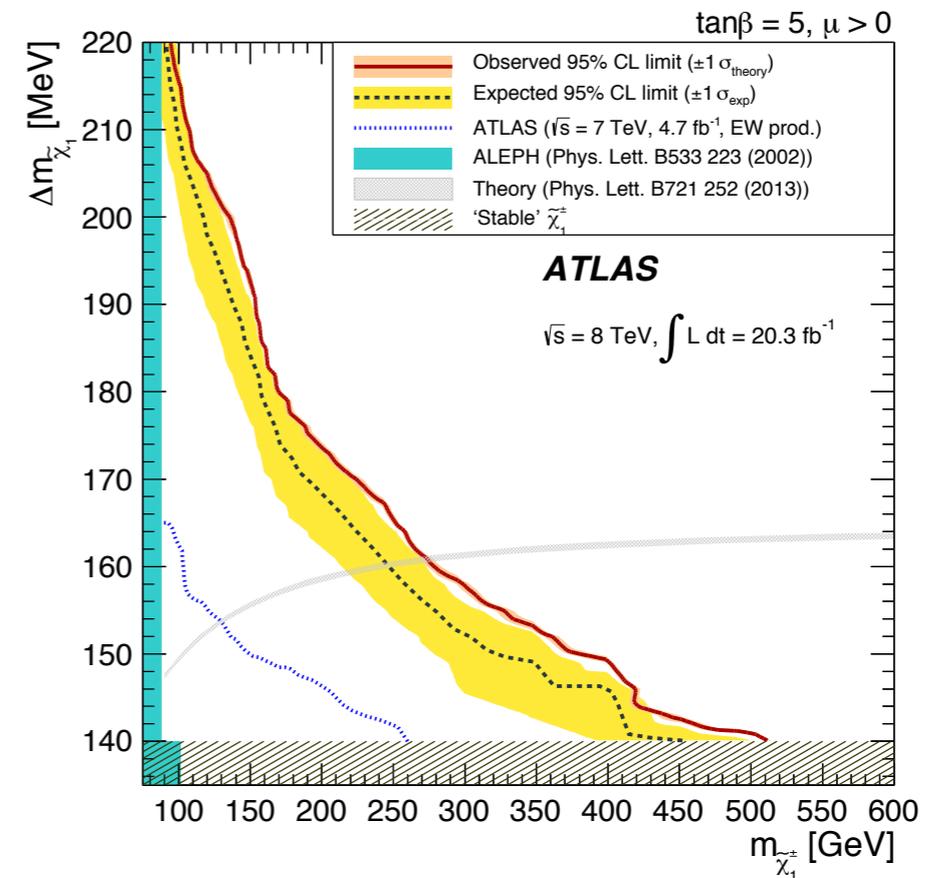
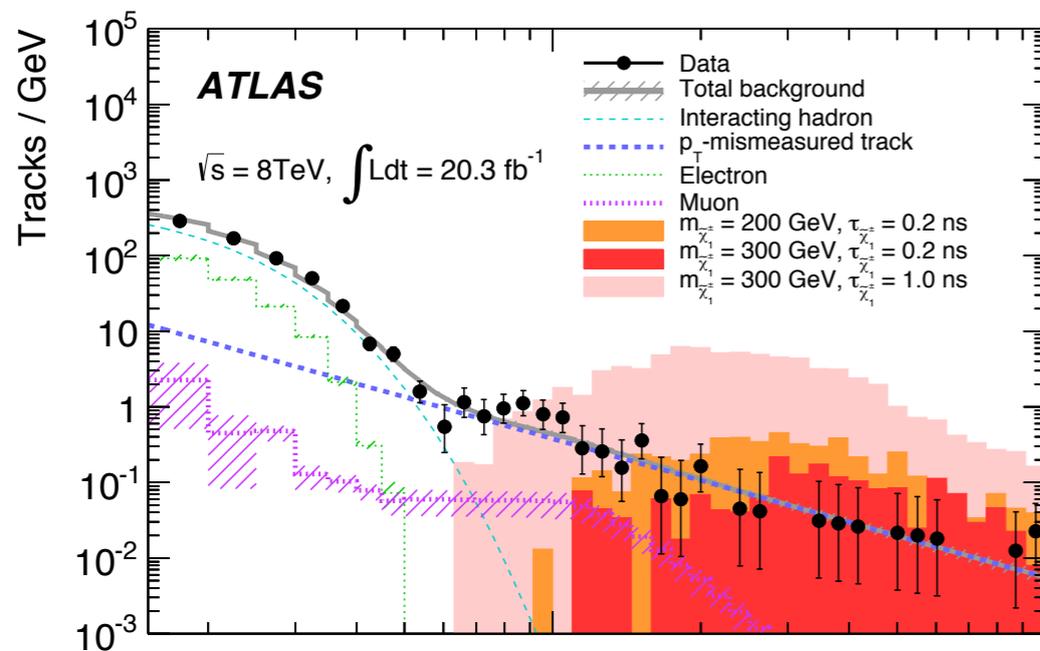


Figure from ATLAS disappearing track search twiki

- Main decay mode  $\chi^\pm \rightarrow \pi^\pm + \chi^0$
- Charge track  $\approx 10(s)$  cm

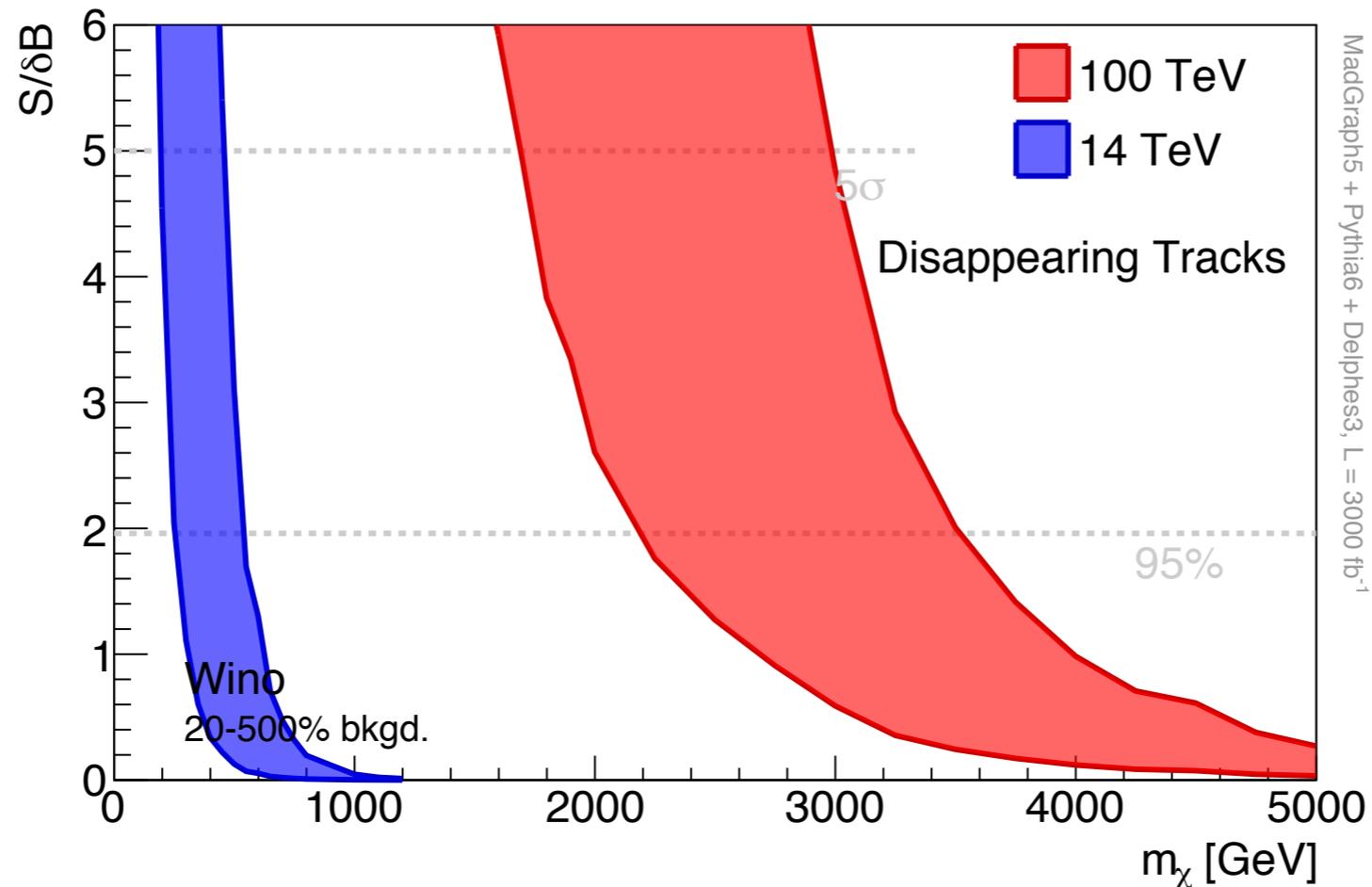
# ATLAS search

ATLAS, I310.3675



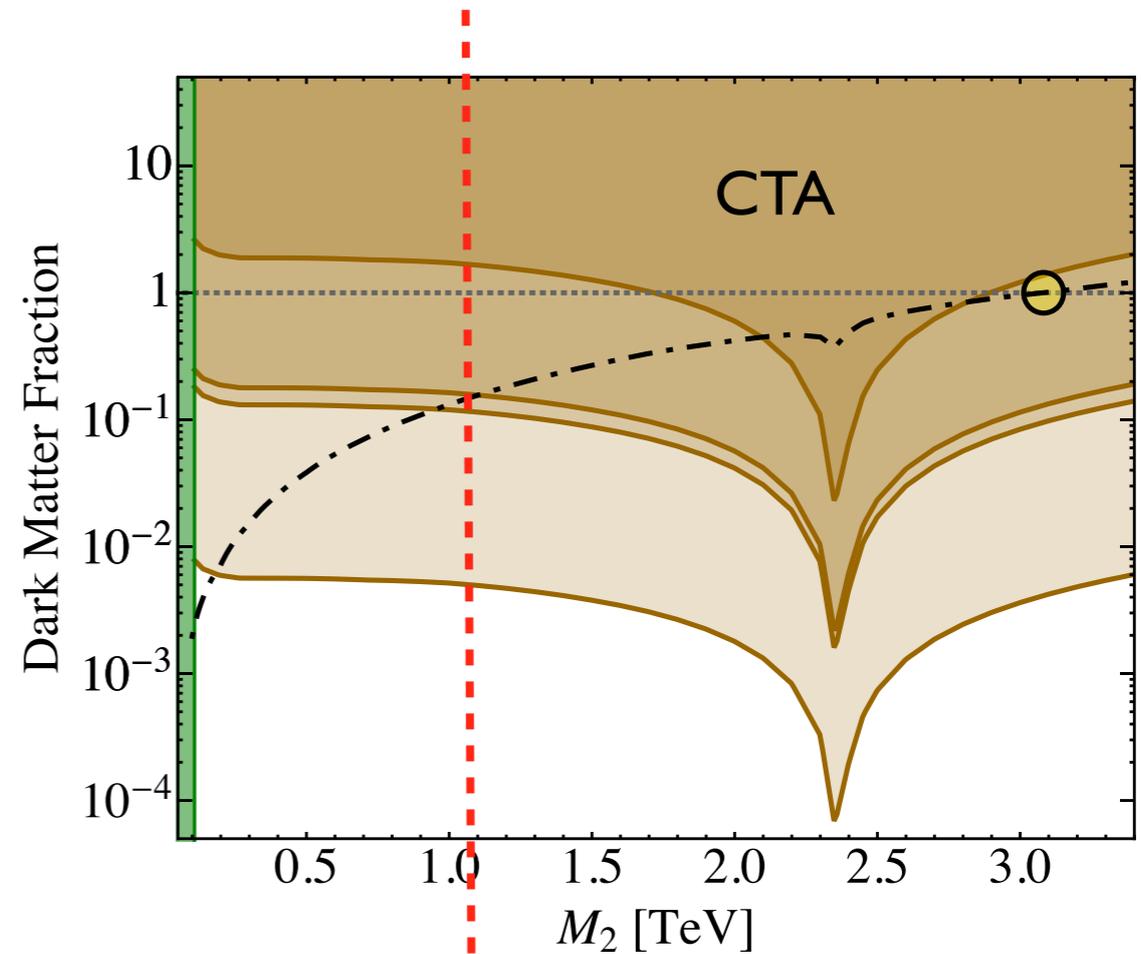
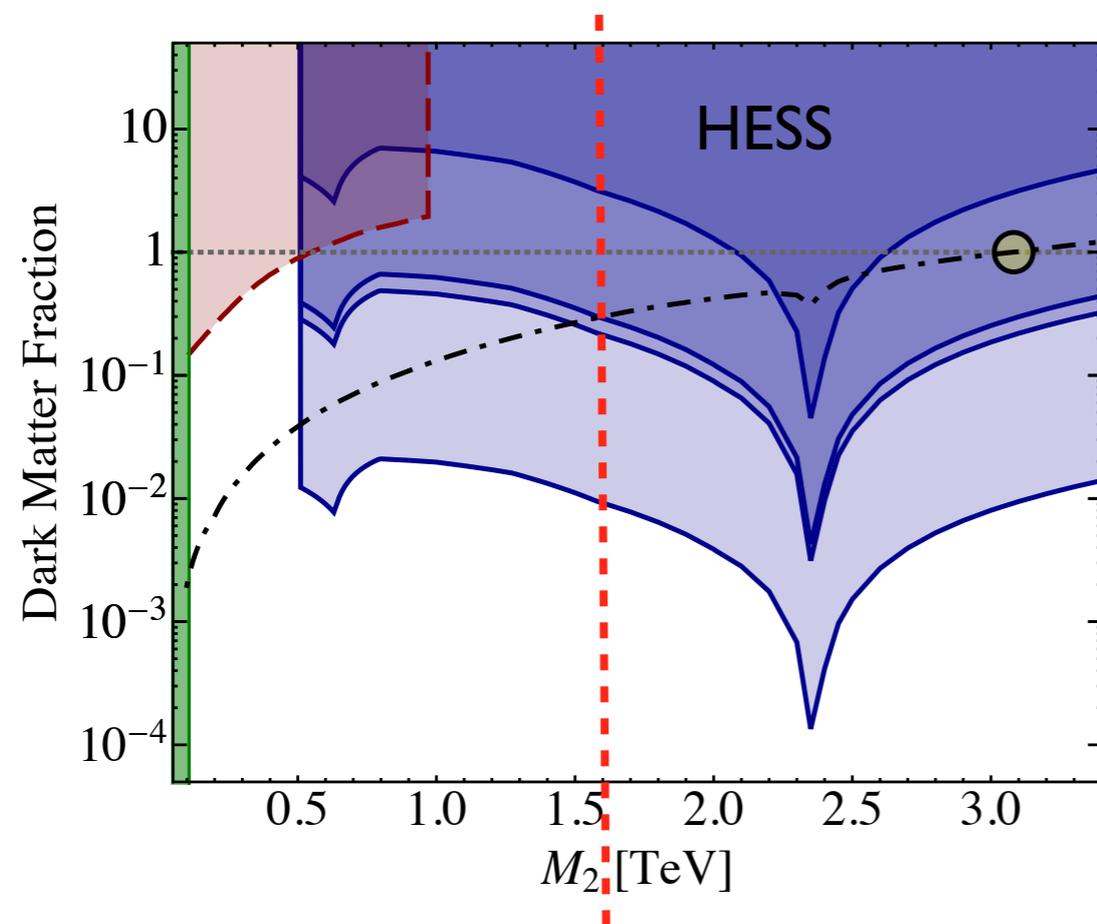
- Essentially free of physics background.
- Dominated by  $p_T$  mis-measured tracks.
- Very promising reach, much better than mono-jet

# (Rough) Extrapolation from ATLAS search



- Scale the ATLAS background rates according to hard jet + MET rates.
- Band: varying background estimate by 5 either way.

# Wino, interplay with indirect detection

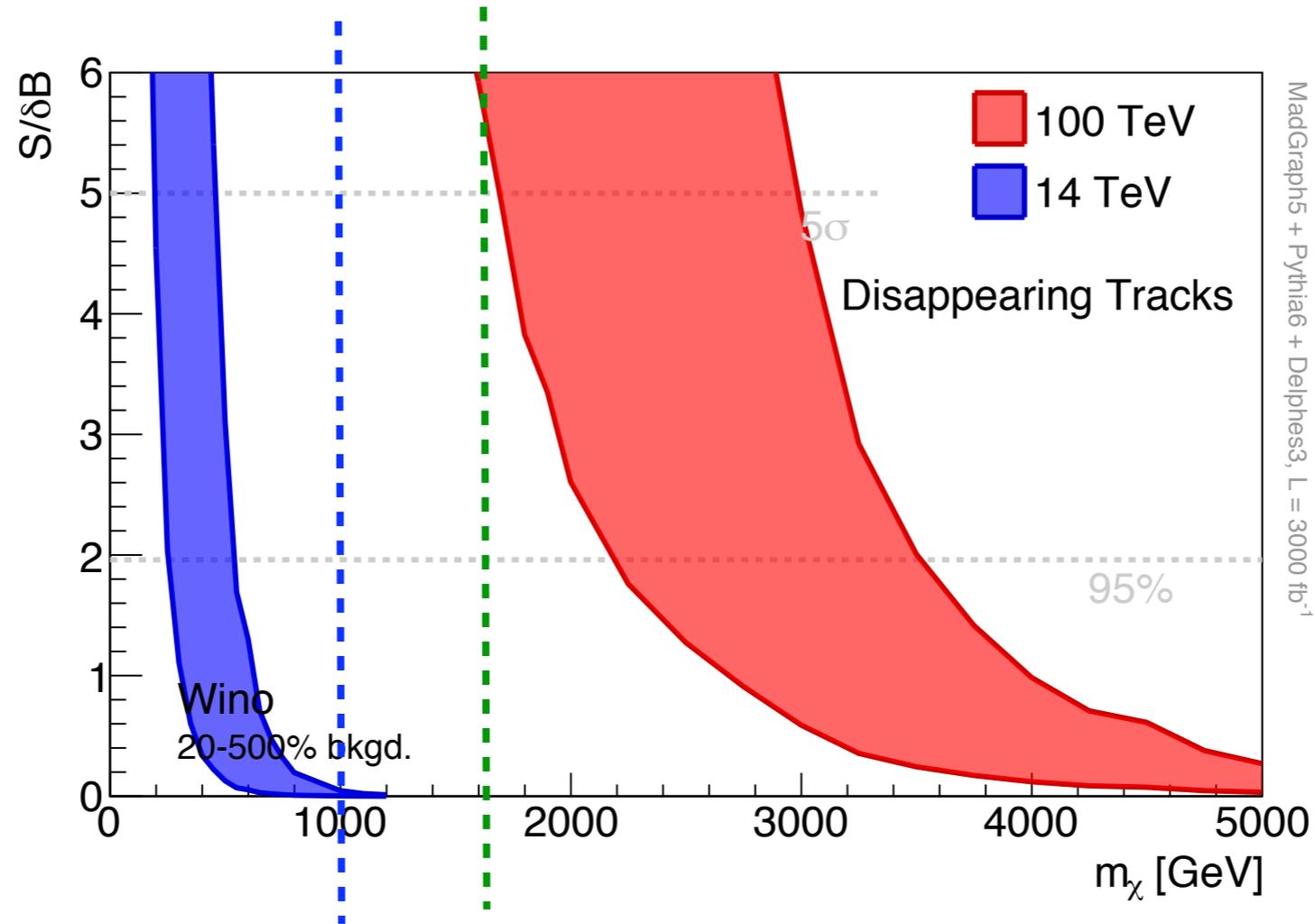


Cohen, Lisanti, Pierce, Slatyer, I307.4082

See also Fan, Reece, I307.4400

# Wino summary

CTA HESS



- There is hope to “completely cover” the wino parameter space.

# More broadly

LHC	VLHC 100 TeV	Lepton collider
$M_{\text{DM}} \sim 10^2 \text{s GeV}$	$M_{\text{DM}} \sim \text{TeV}$	$M_{\text{DM}} \sim 0.5 E_{\text{cm}}$ Spin, coupling Is it WIMP?

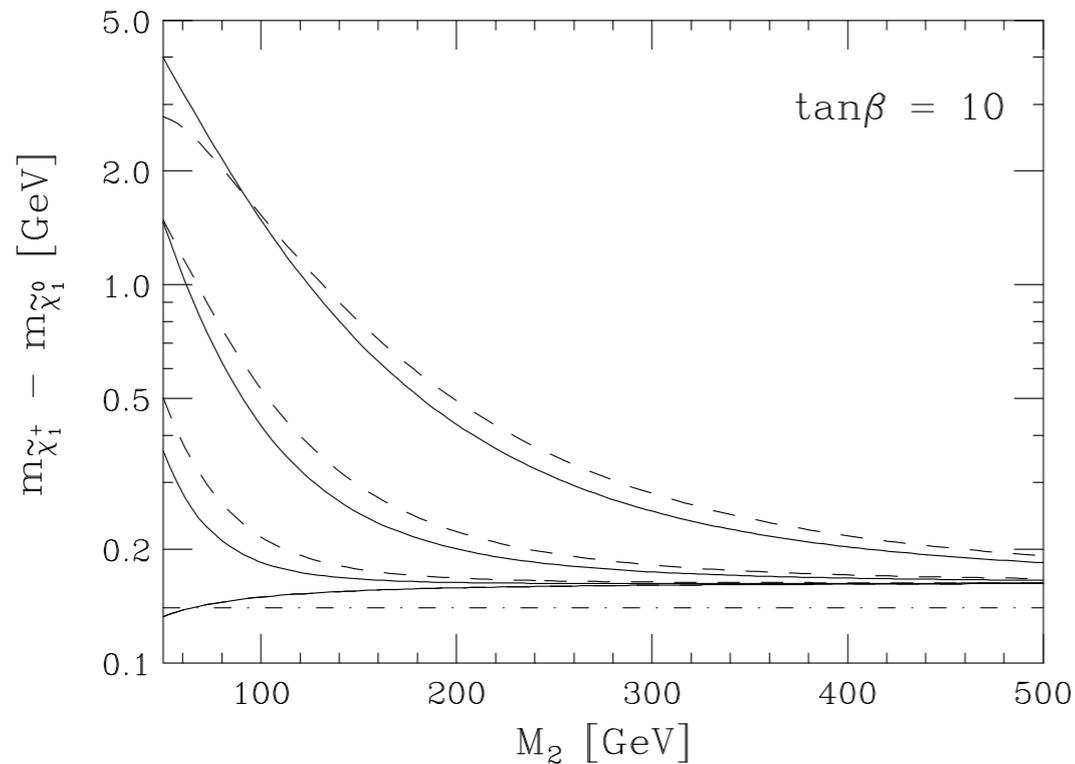
- Could also link to a possible dark sector.
- Strategy at collider searches strongly correlated with potential discovery at in direct/indirect detection.

# Conclusions

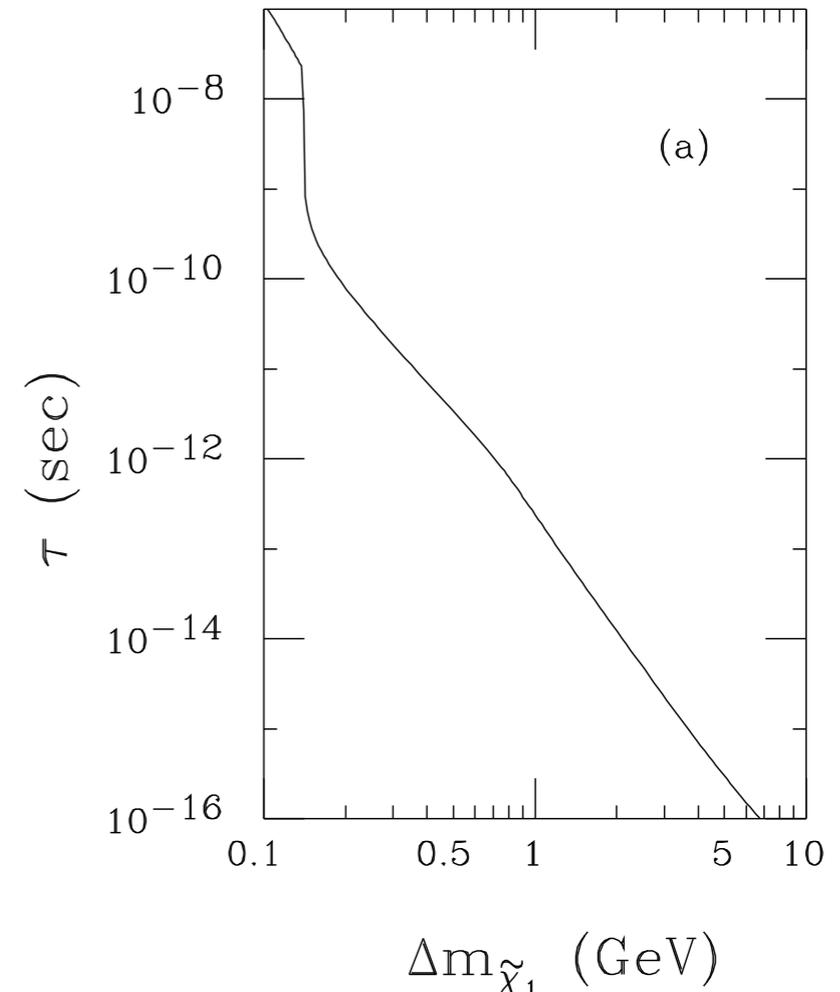
- Searching for dark matter is and will continue to be a main part of the physics program at colliders.
- Need to go beyond the simple contact operator approach.
- “Simplified models”, new mediator.
  - ▶ Direct search for the mediator usually more powerful.
- SUSY-like models. Challenging! Limited reach at the LHC
  - ▶ Need to think/work harder. Tracks...?
  - ▶ Going to the next generation of colliders can cover most of the parameter space.

extras

# Wino decay



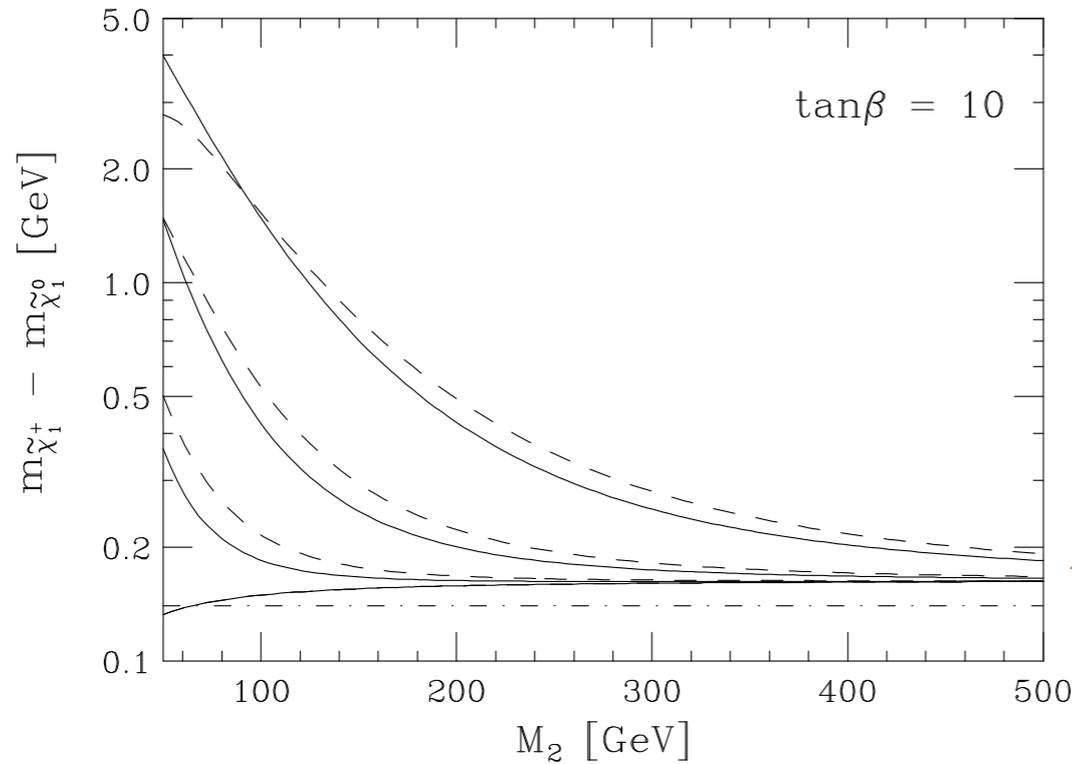
Gherghetta, Giudice and Wells, hep-ph/9904378



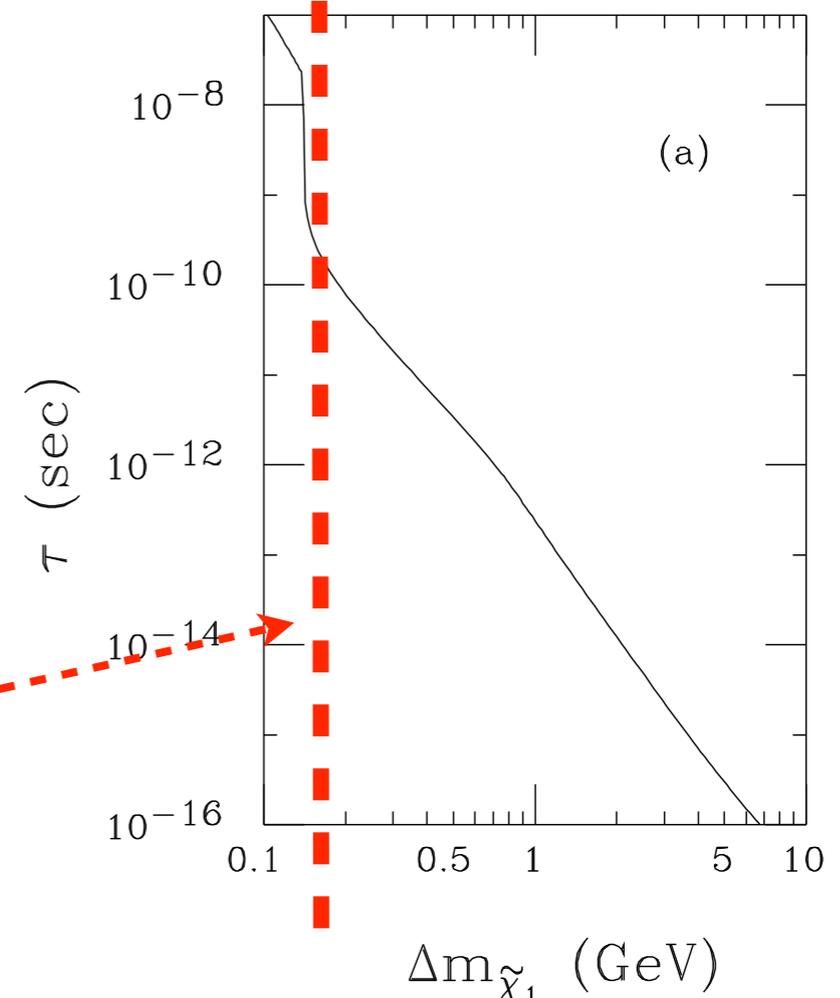
Chen, Drees and Gunion, hep-ph/9902309

- Main decay mode  $\chi^\pm \rightarrow \pi^\pm + \chi^0$
- Charge track  $\approx 10(\text{s}) \text{ cm}$

# Wino decay



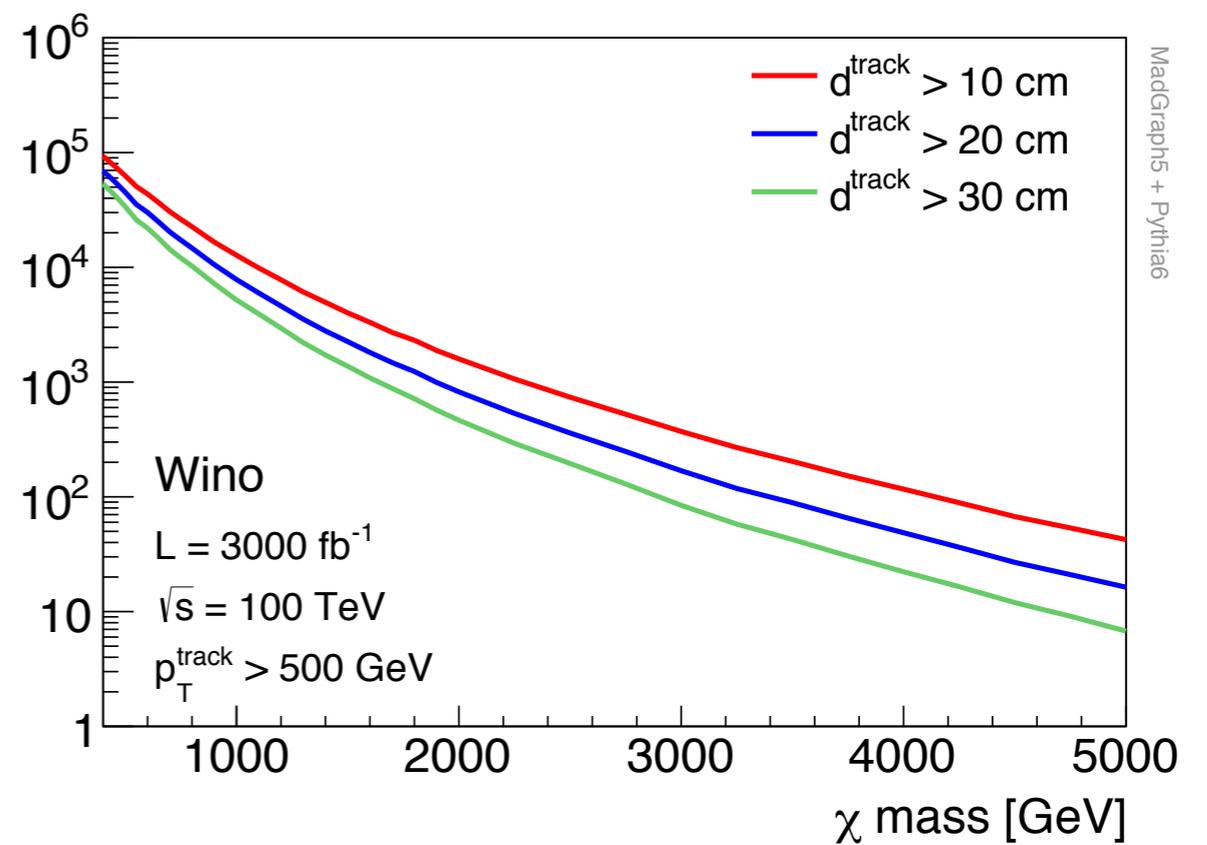
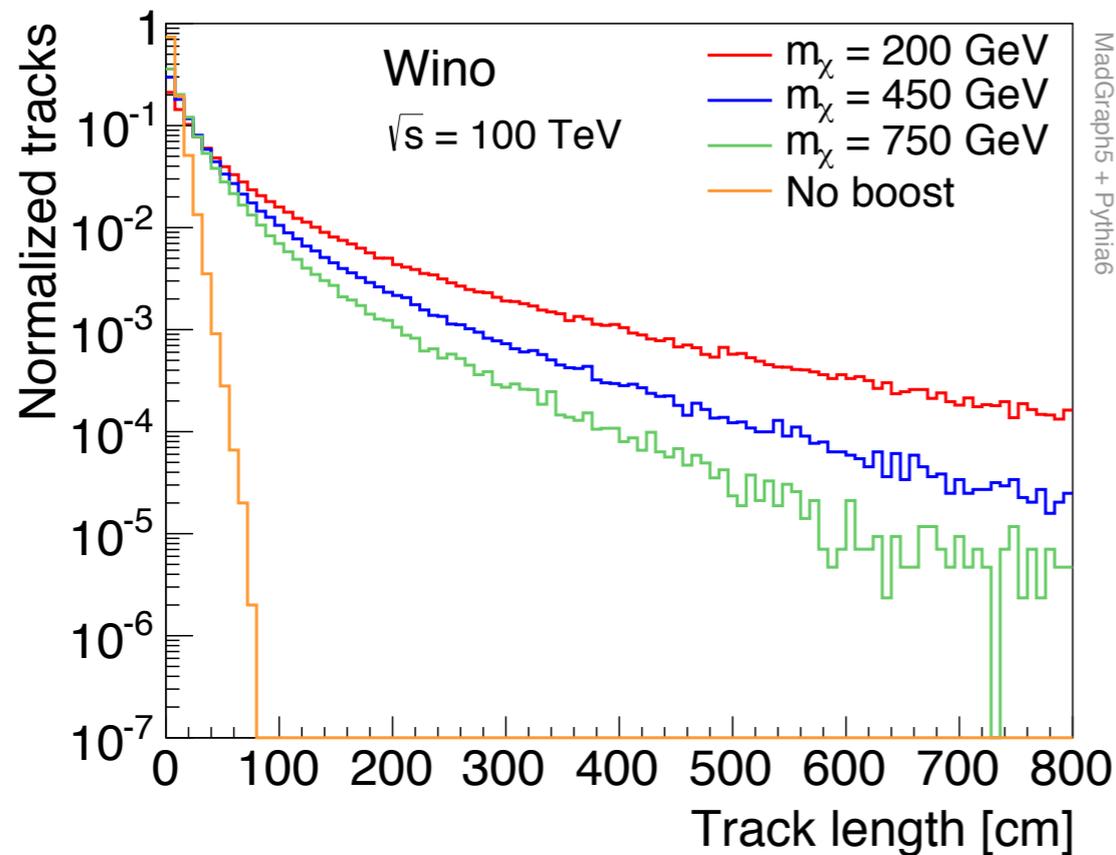
Gherghetta, Giudice and Wells, hep-ph/9904378



Chen, Drees and Gunion, hep-ph/9902309

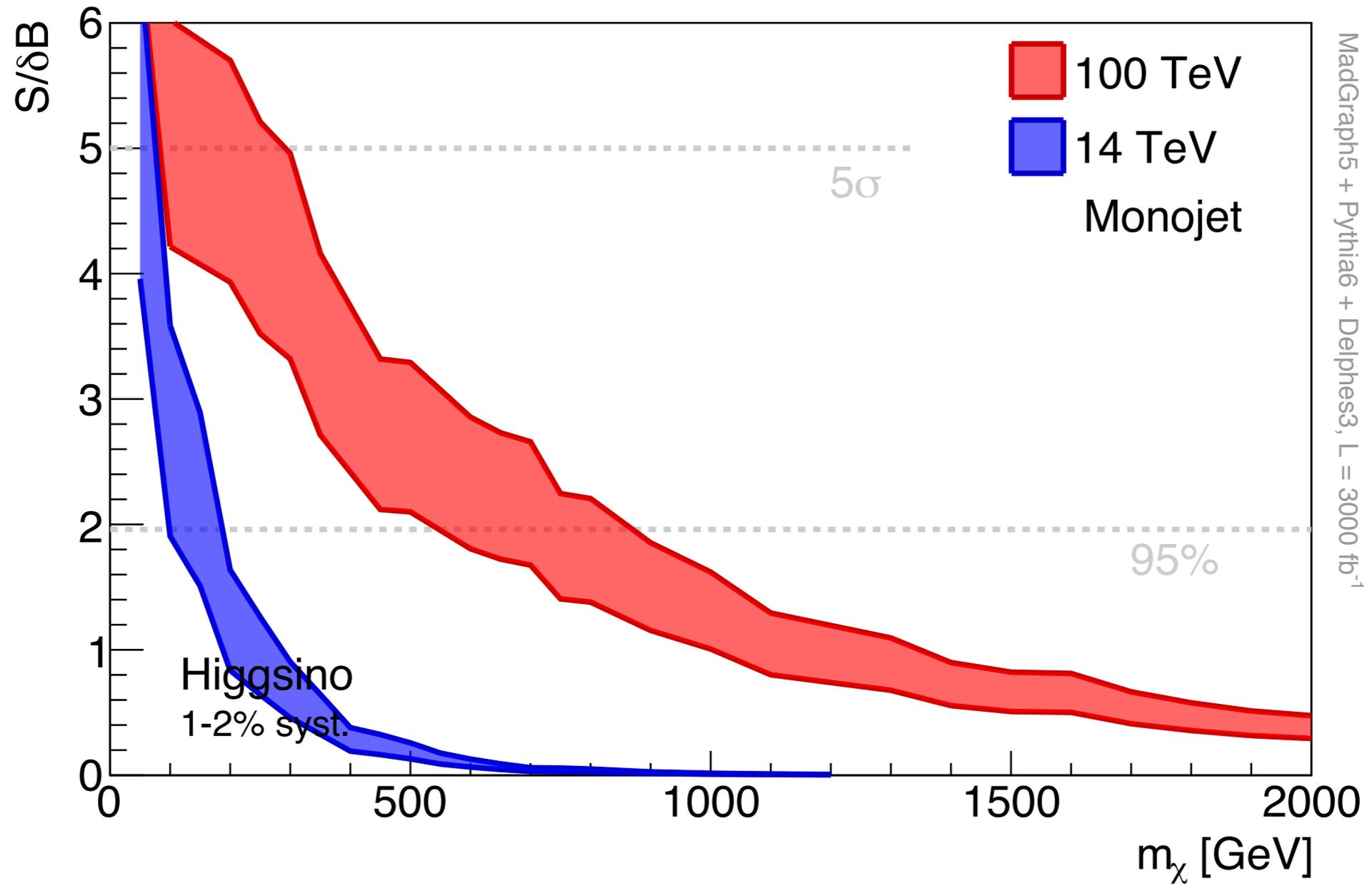
- Main decay mode  $\chi^\pm \rightarrow \pi^\pm + \chi^0$
- Charge track  $\approx 10(\text{s}) \text{ cm}$

# Rates (with long tracks)

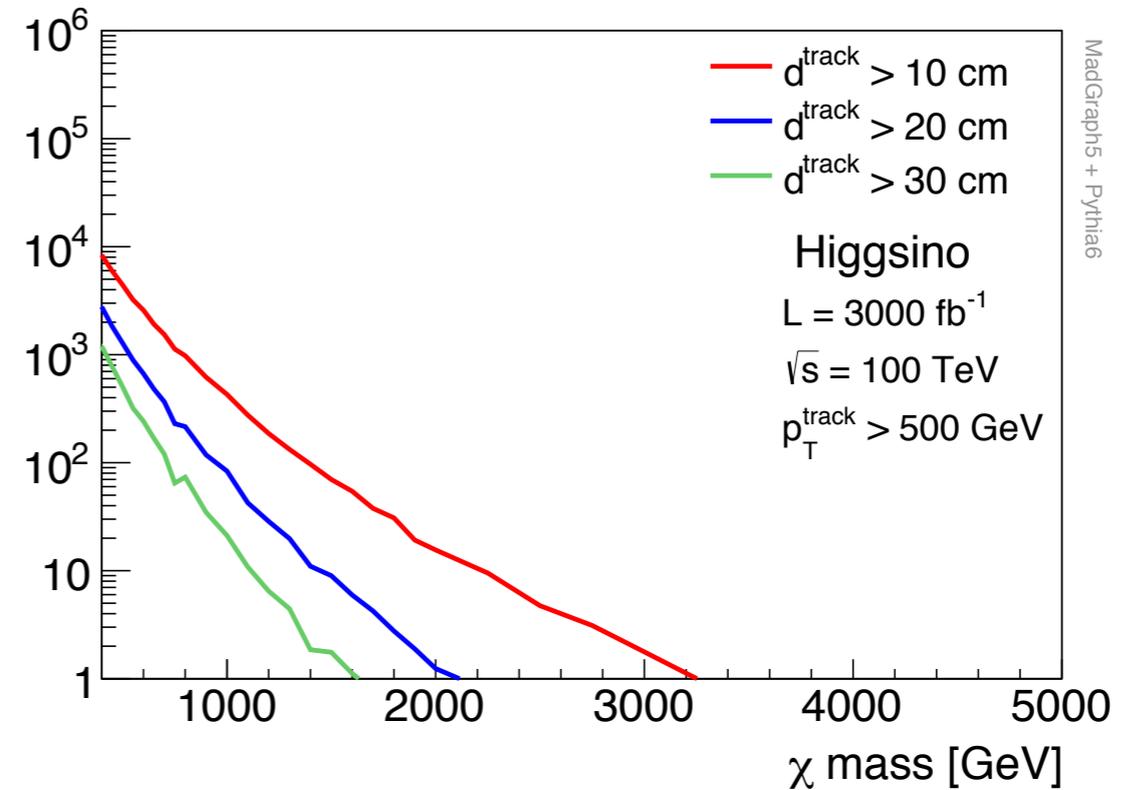
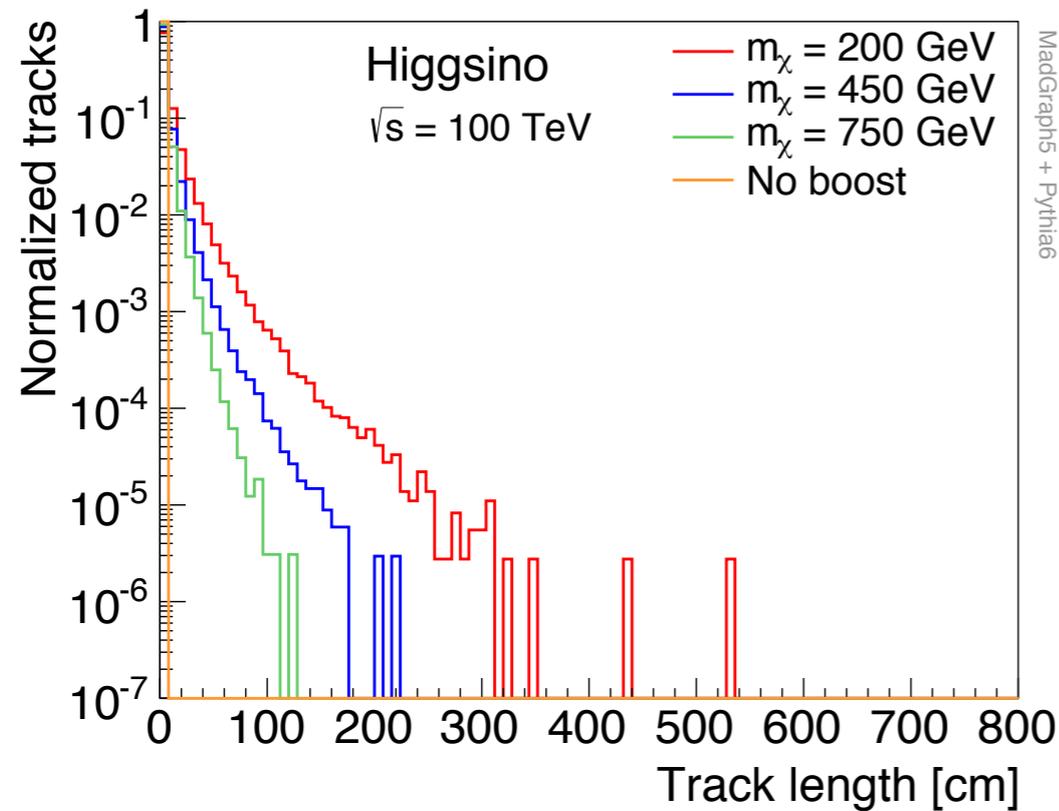


- Disappearing track, stub, kink...
- Could also be long lived

# Mono-jet

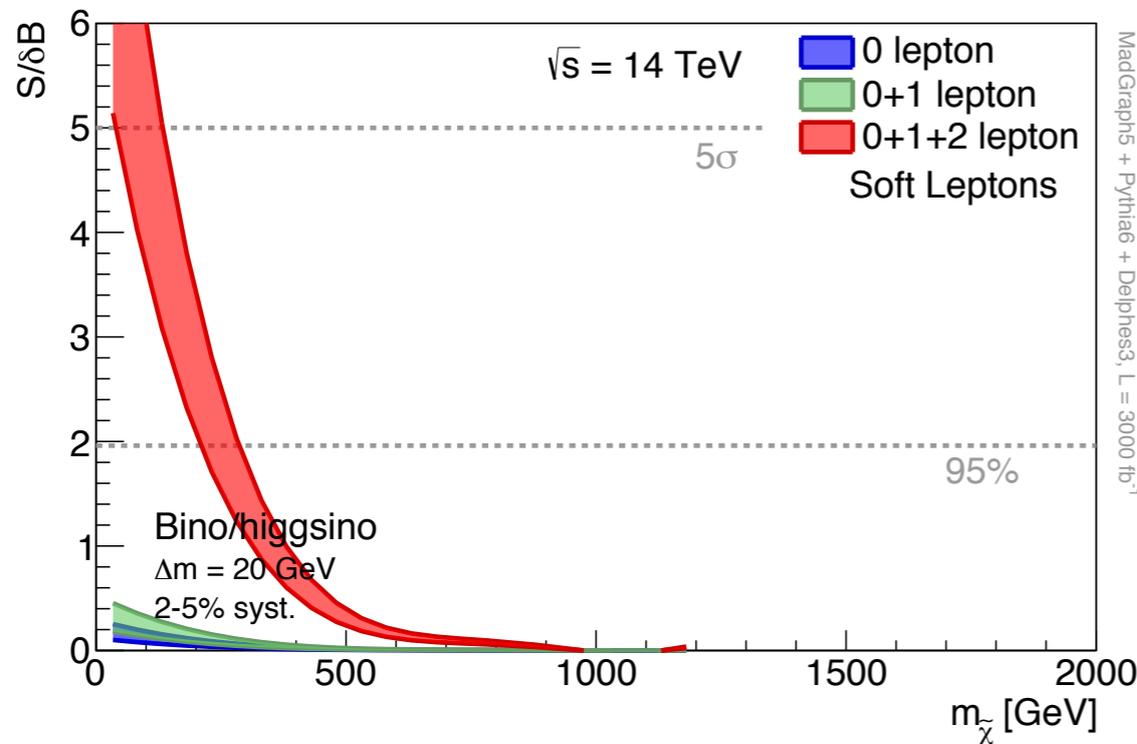


# Tracks?

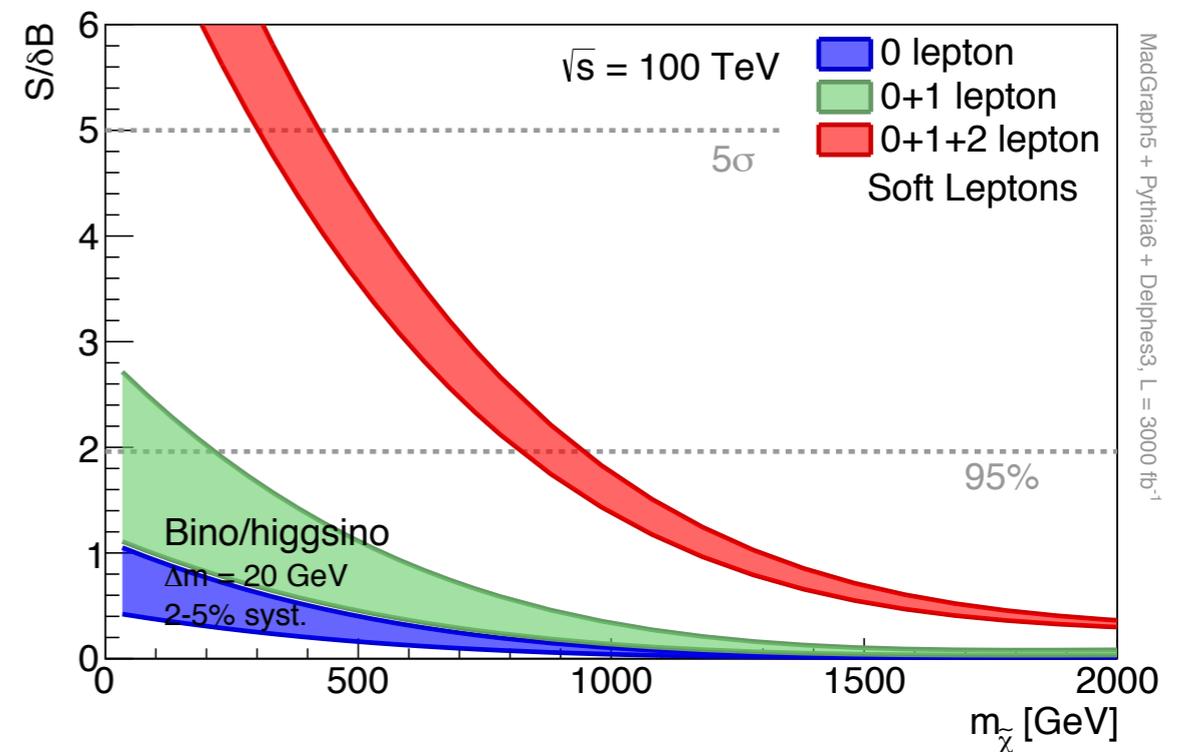


- Depends on detector design
  - ▶ How long the track needs to be?
  - ▶ Background discrimination?
- Can change mass splitting in extended models.

# Well-tempered, mono-jet + soft lepton



20 GeV < pT lepton < 40 GeV



10 GeV < pT lepton < 30 GeV

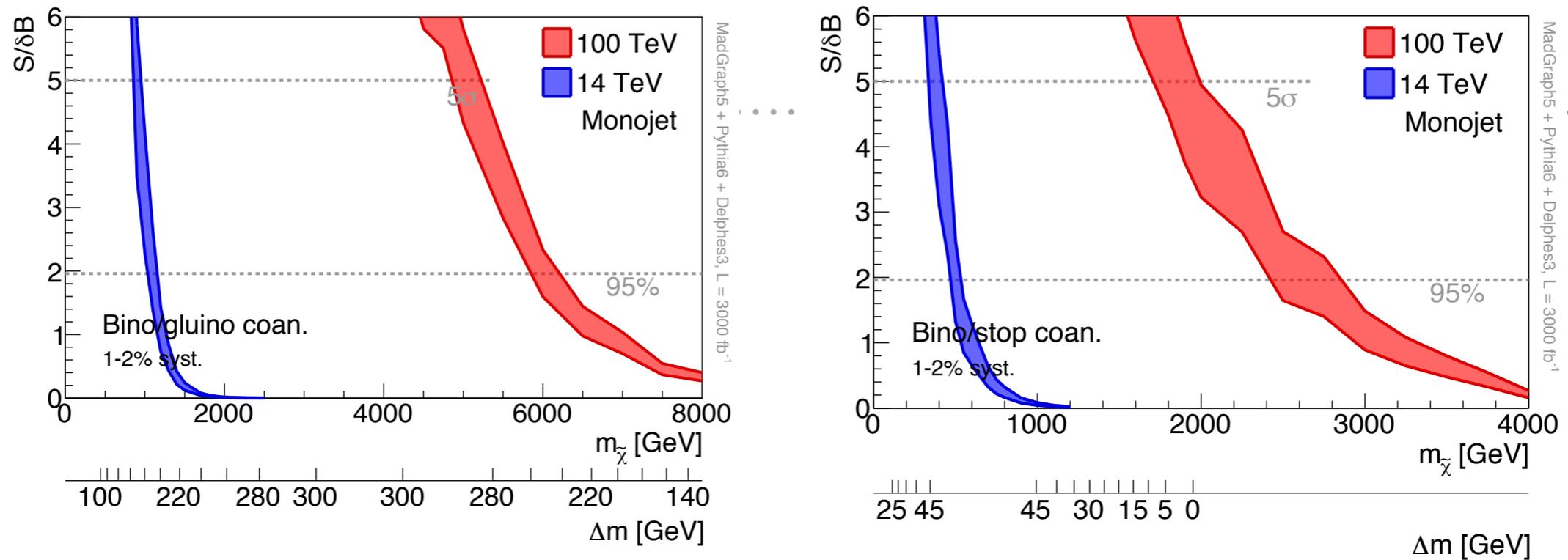
- Adding soft lepton. S/B is O(1).
- Mitigating factor: Higher lepton threshold (?) at 100 TeV.

Giudice, Han, Wang and LTW, 1004.4902

Schwaller, Zurita, 1312.7350

Han, Kribs, Martin, Menon, 1401.1235

# Co-annihilation, monojet



- Driven by stop/gluino production.
- Impressive reach from mono-jet.
- Could consider soft lepton in the stop case.

# Cuts, monojet

Cut	8 TeV	14 TeV	100 TeV
$p_T(j_1), \eta(j_1)$	110 GeV, 2.4	300 GeV, 2.4	1200 GeV, 2.4
$p_T(j_2), \eta(j_2)$	30 GeV, 4.5	30 – 120 GeV, 4.5	100 – 400 GeV, 4.5
$n_{\text{jet}}$	2	2	2
$\Delta\phi(j_1, j_2)$	2.5	2.5	2.5
$p_T(e), \eta(e)$	10 GeV, 2.5	20 GeV, 2.5	20 GeV, 2.5
$p_T(\mu), \eta(\mu)$	10 GeV, 2.1	20 GeV, 2.1	20 GeV, 2.1
$p_T(\tau), \eta(\tau)$	20 GeV, 2.3	30 GeV, 2.3	40 GeV, 2.3
$\cancel{E}_T$	250 – 550 GeV	350 – 1000 GeV	2 – 5 TeV

**Table 5:** Cuts used in monojet analysis. For  $p_T(j_2)$  and  $\cancel{E}_T$  the range represents the values scanned over, where the values used for each spectra are shown in Table 6.

$\sqrt{s}$	Cut	Wino	Higgsino	Gluino coan.	Stop coan.	Squark coan.	Stau coan.
14 TeV	$\cancel{E}_T$	650 GeV	650 GeV	750 GeV	650 GeV	650 GeV	650 GeV
	$p_T(j_2)$	30 GeV	30 GeV	120 GeV	120 GeV	120 GeV	120 GeV
100 TeV	$\cancel{E}_T$	3.5 TeV	3.5 TeV	4.0 TeV	3.5 TeV	3.5 TeV	3.5 TeV
	$p_T(j_2)$	300 GeV	250 GeV	400 GeV	400 GeV	400 GeV	400 GeV

**Table 6:**  $\cancel{E}_T$  and  $p_T(j_2)$  cuts used in the monojet analysis for each spectra. Table 5 shows the other cuts used.

# Cuts, soft lepton

Cut	100 TeV	14 TeV
$p_T(j_1), \eta(j_1)$	1200 GeV, 2.4	300 GeV, 2.4
$p_T(j_2), \eta(j_2)$	300 GeV, 4.5	30 GeV, 4.5
$n_{\text{jet}}$	2	2
$\Delta\phi(j_1, j_2)$	2.5	2.5
$p_T(e), \eta(e)$	$\in (10 \text{ GeV}, 30 \text{ GeV}), 2.5$	$\in (10 \text{ GeV}, 30 \text{ GeV}), 2.5$
$p_T(\mu), \eta(\mu)$	$\in (10 \text{ GeV}, 30 \text{ GeV}), 2.1$	$\in (10 \text{ GeV}, 30 \text{ GeV}), 2.1$
$\cancel{E}_T$	1250 GeV	350 GeV

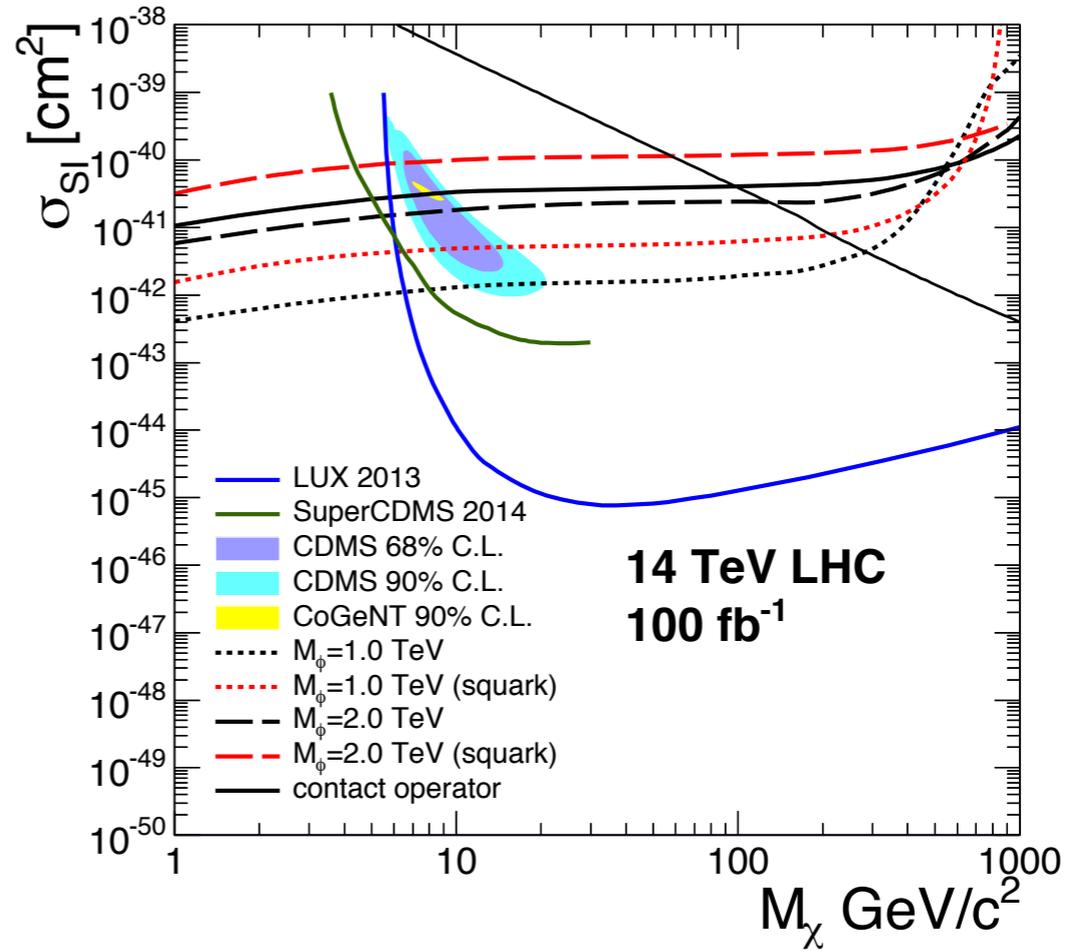
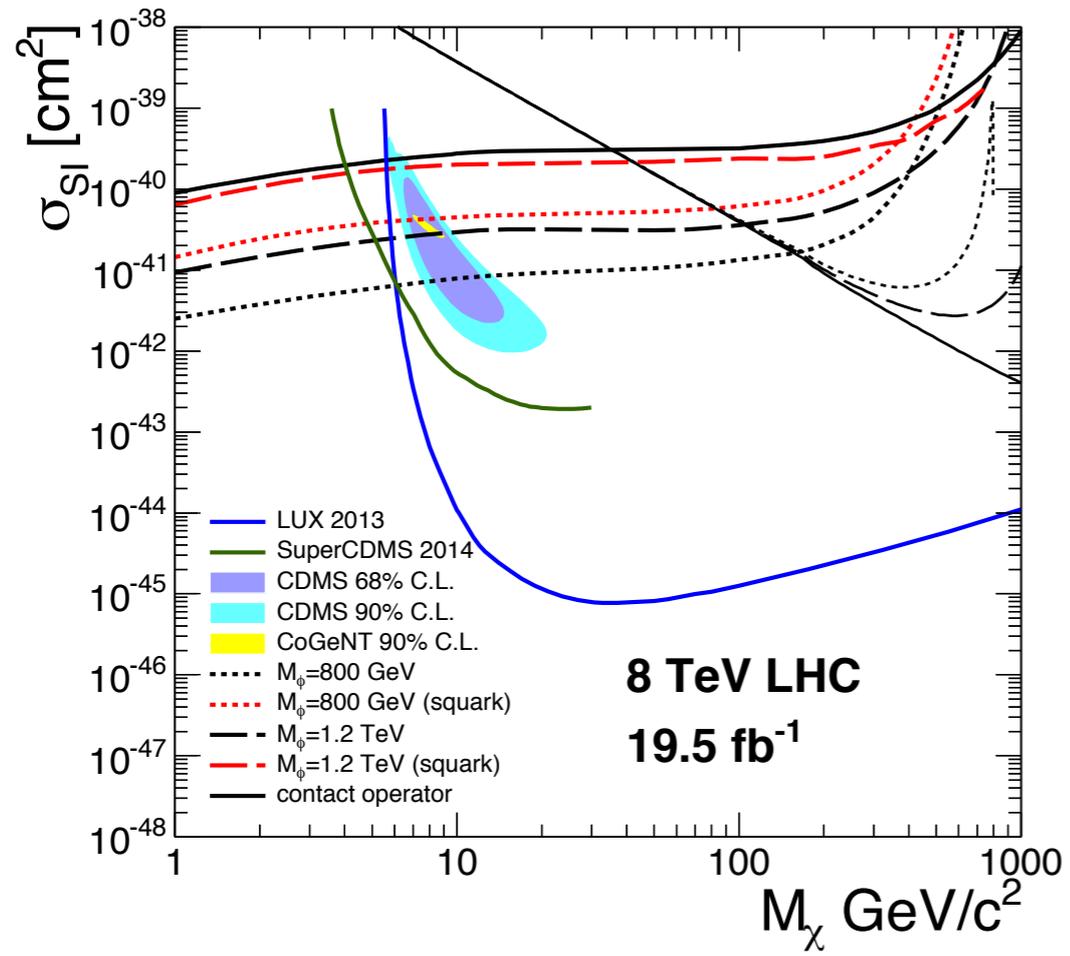
**Table 7:** Cuts used in soft lepton analysis.

# Cuts, disappearing track

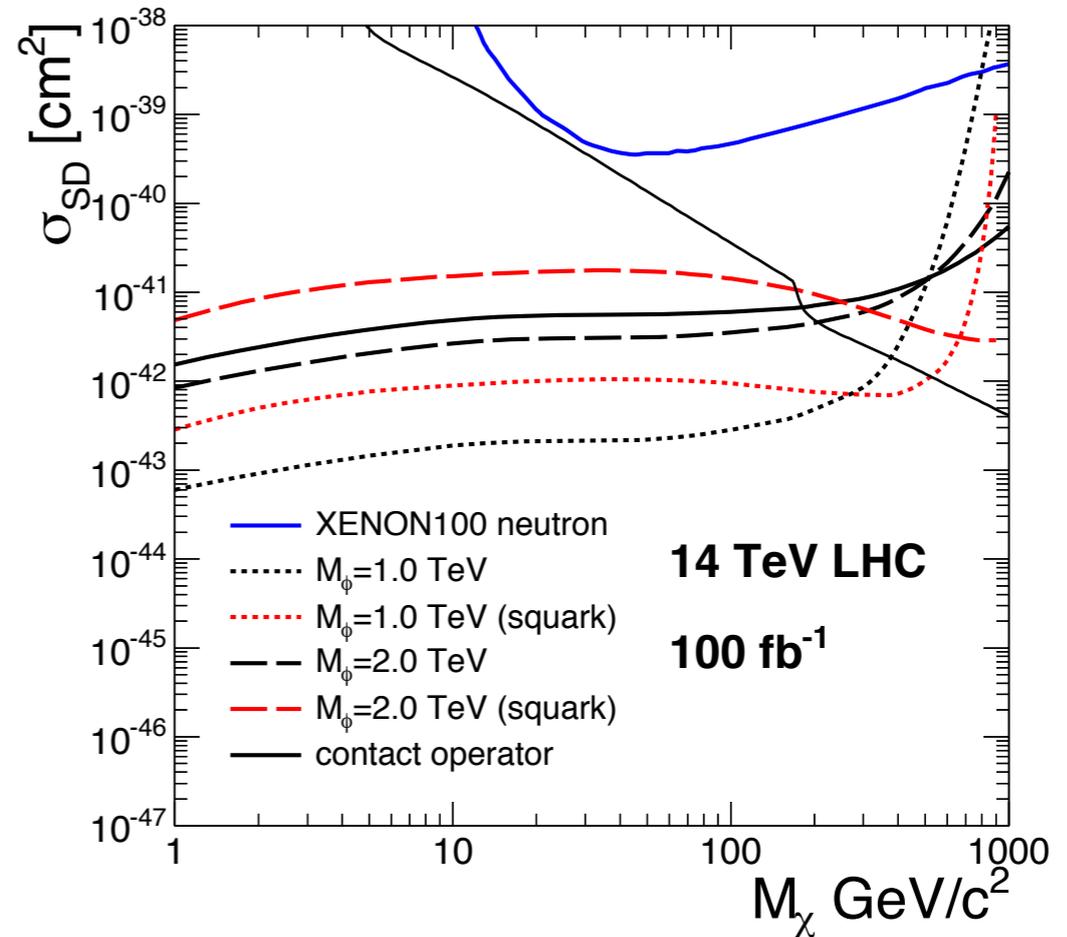
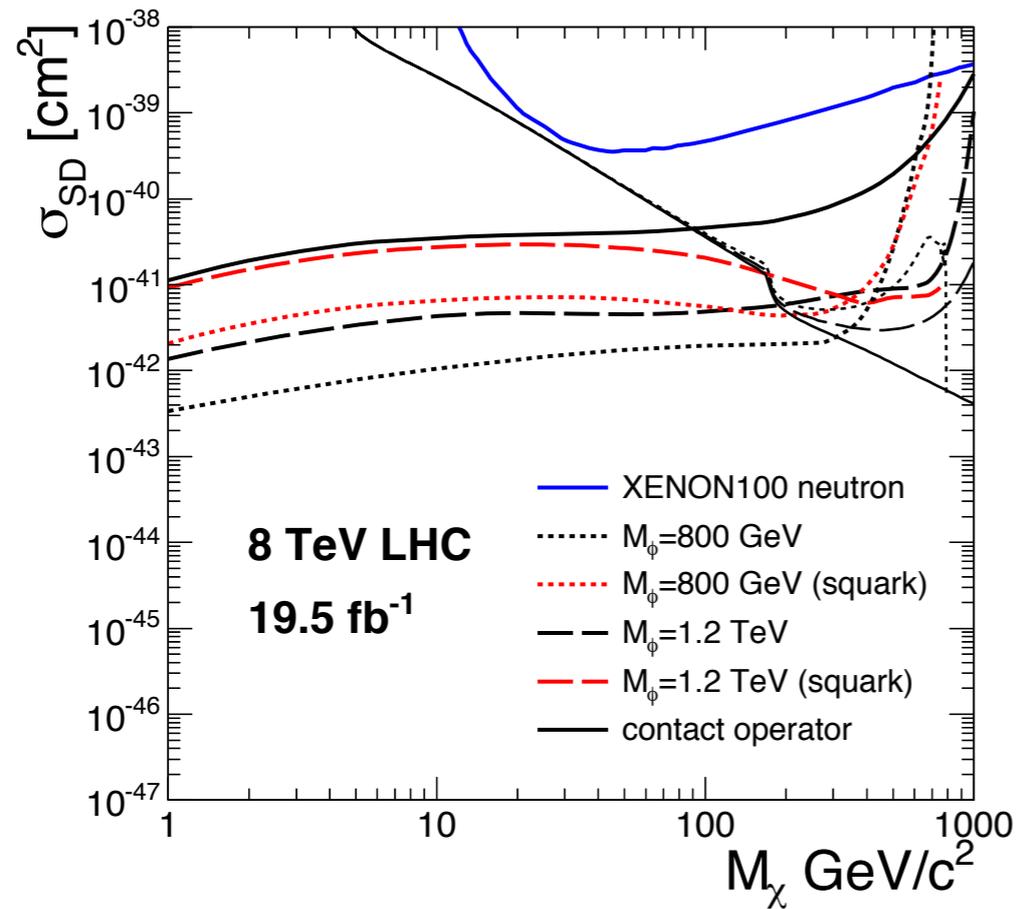
Cut	8 TeV	14 TeV	100 TeV
$\cancel{E}_T$	90 GeV	130 GeV	975 GeV
$p_T(j_1)$	90 GeV	130 GeV	975 GeV
$p_T(j_2)$	45 GeV	70 GeV	500 GeV
$\Delta\phi_{\min}(j, \cancel{E}_T)$	1.5	1.5	1.5
$\eta^{\text{track}}$	$\in (0.1, 1.9)$	$\in (0.1, 1.9)$	$\in (0.1, 1.9)$
$p_T^{\text{track}}$	75 – 200 GeV	250 GeV	1.5 TeV

**Table 8:** Cuts used in disappearing track analysis.

# Spin independent



# Spin dependent



- Leading direct detection channel for Majorana DM.