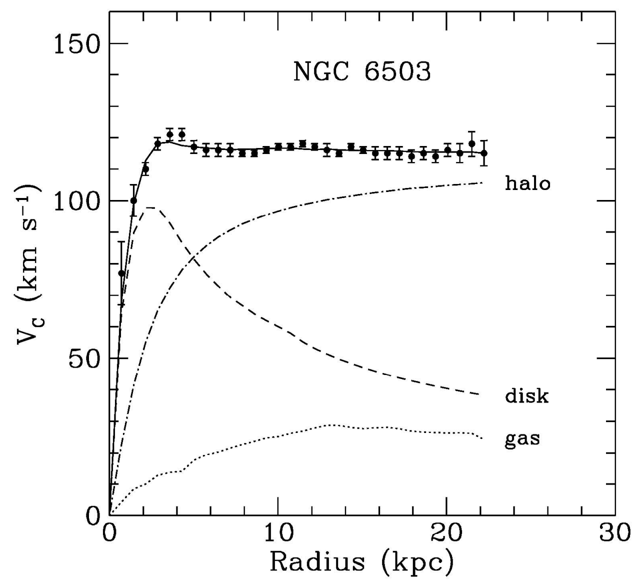
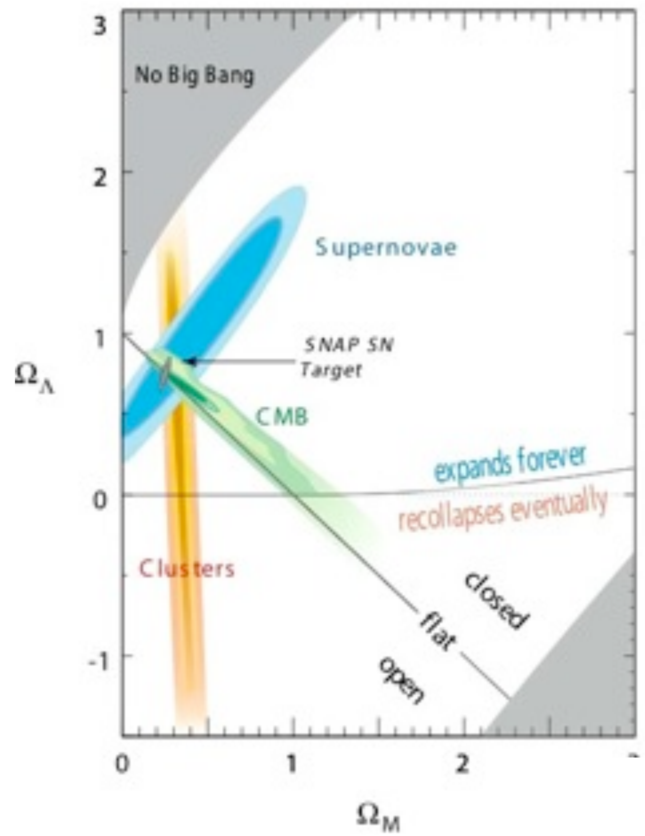
Dark matter at Future Colliders

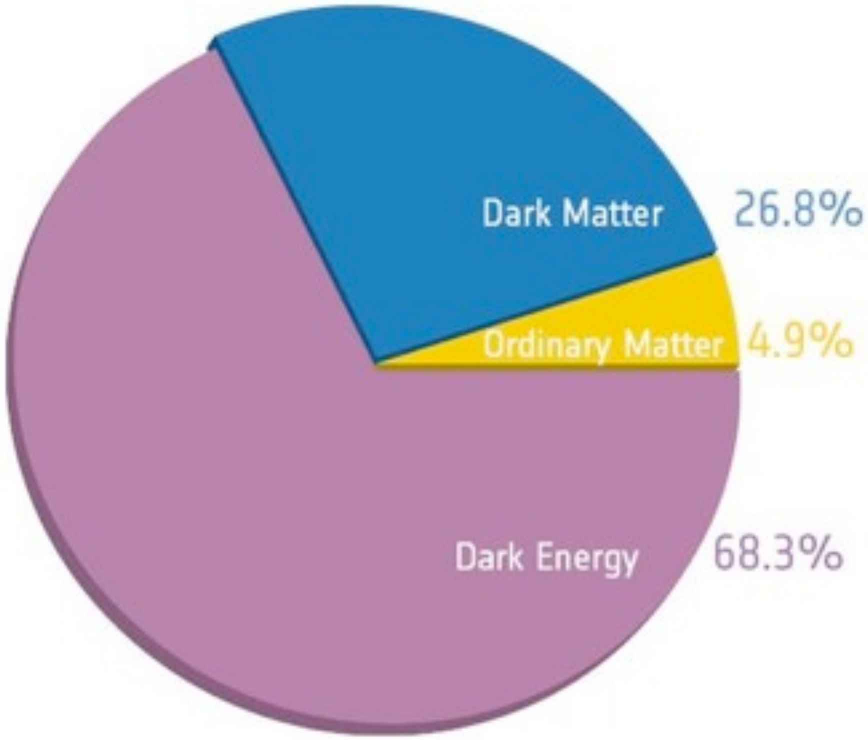
王连涛
University of Chicago

TeV 工作组学术研讨会, 广州，May 16, 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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- Looking for a compelling story.
  - 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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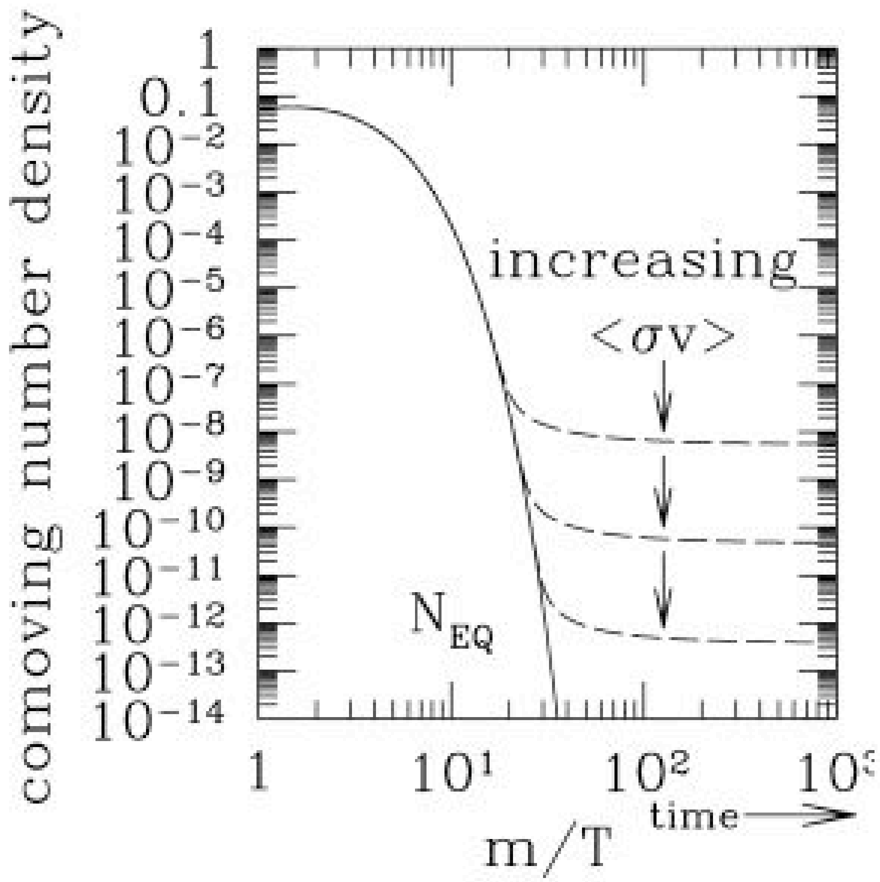
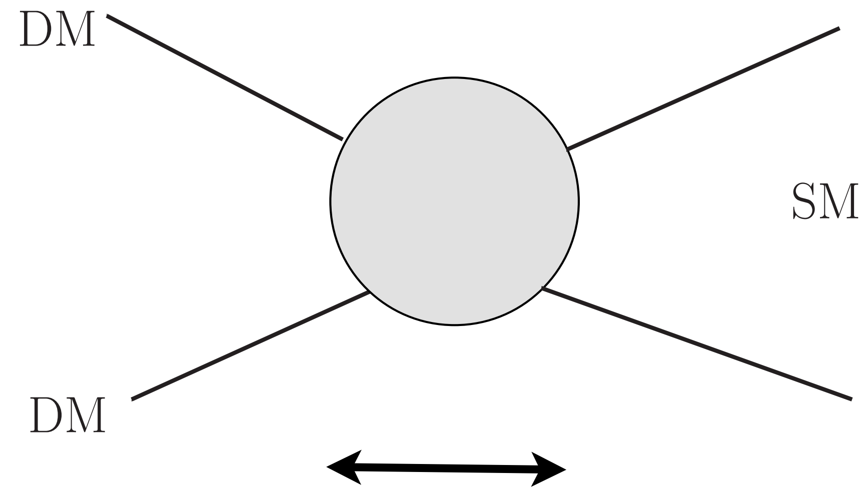
WIMP

WIMP miracle



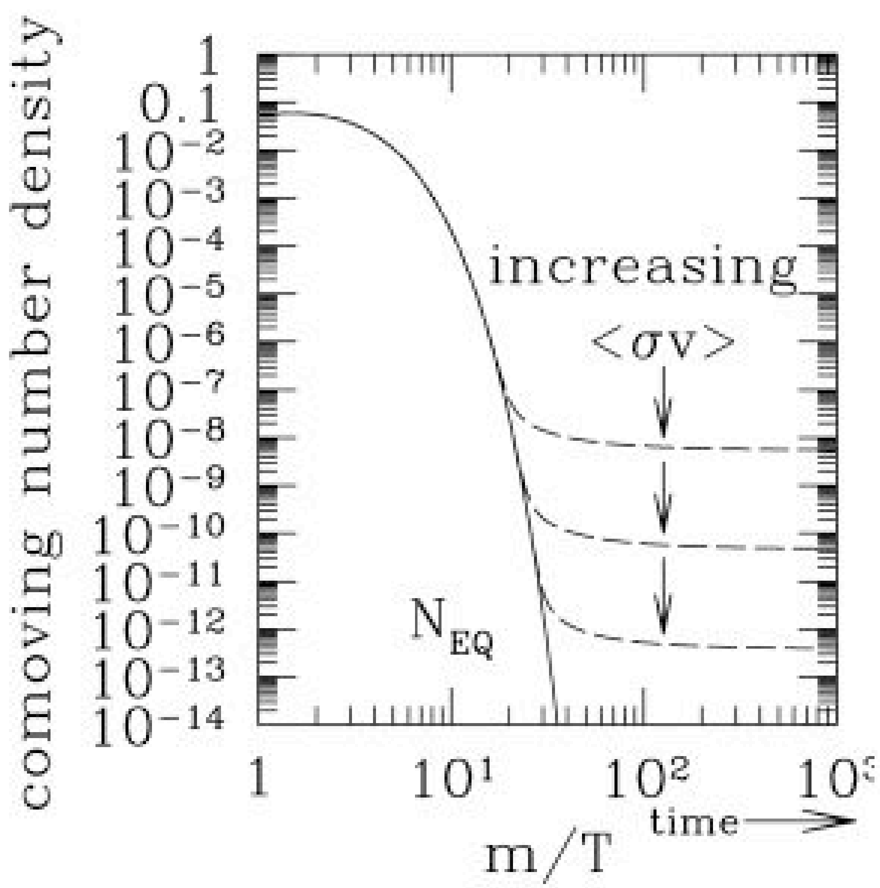


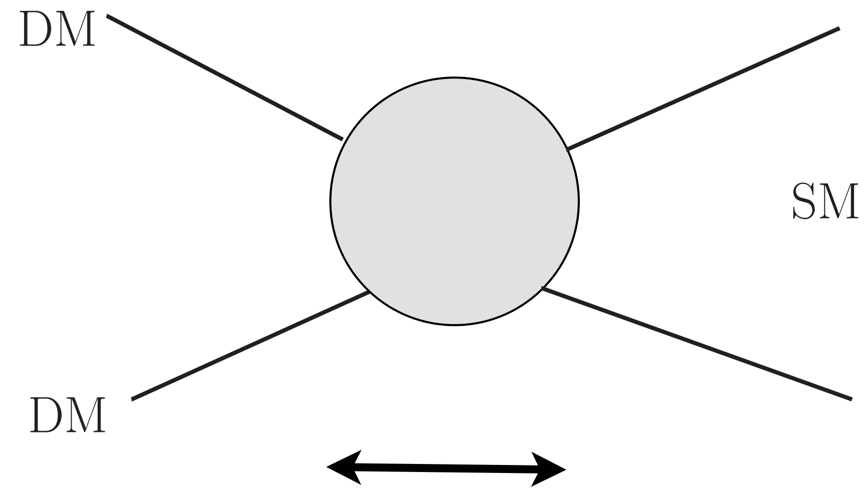
$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.

- Major hint for weak(±) scale new physics!

WIMP miracle



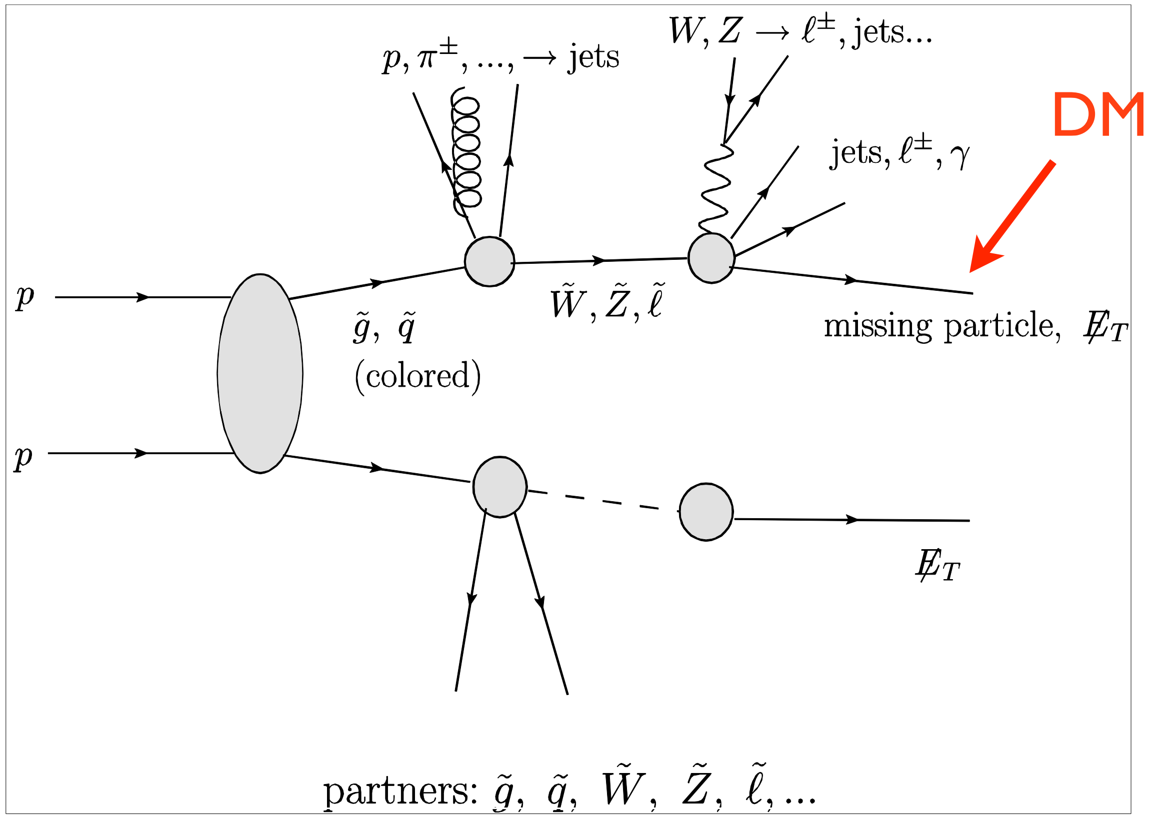


$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- More precisely, to get the correct relic abundance

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

"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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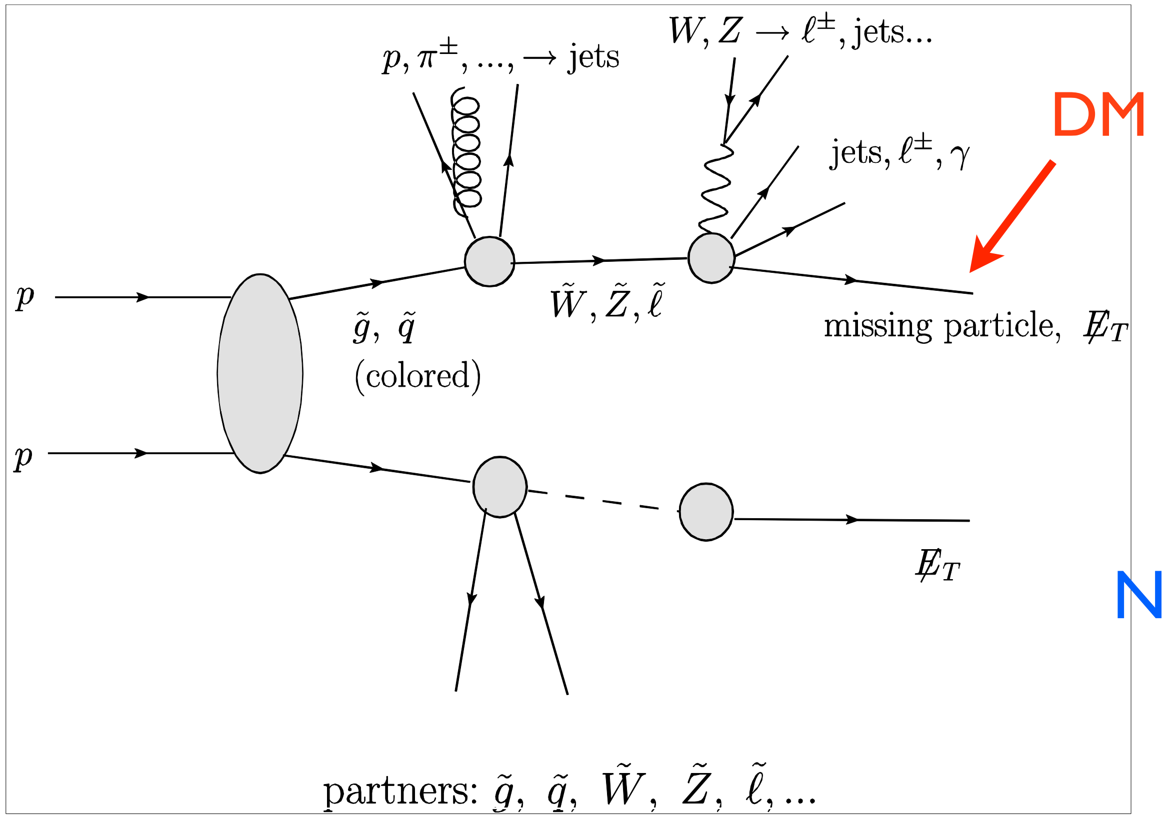
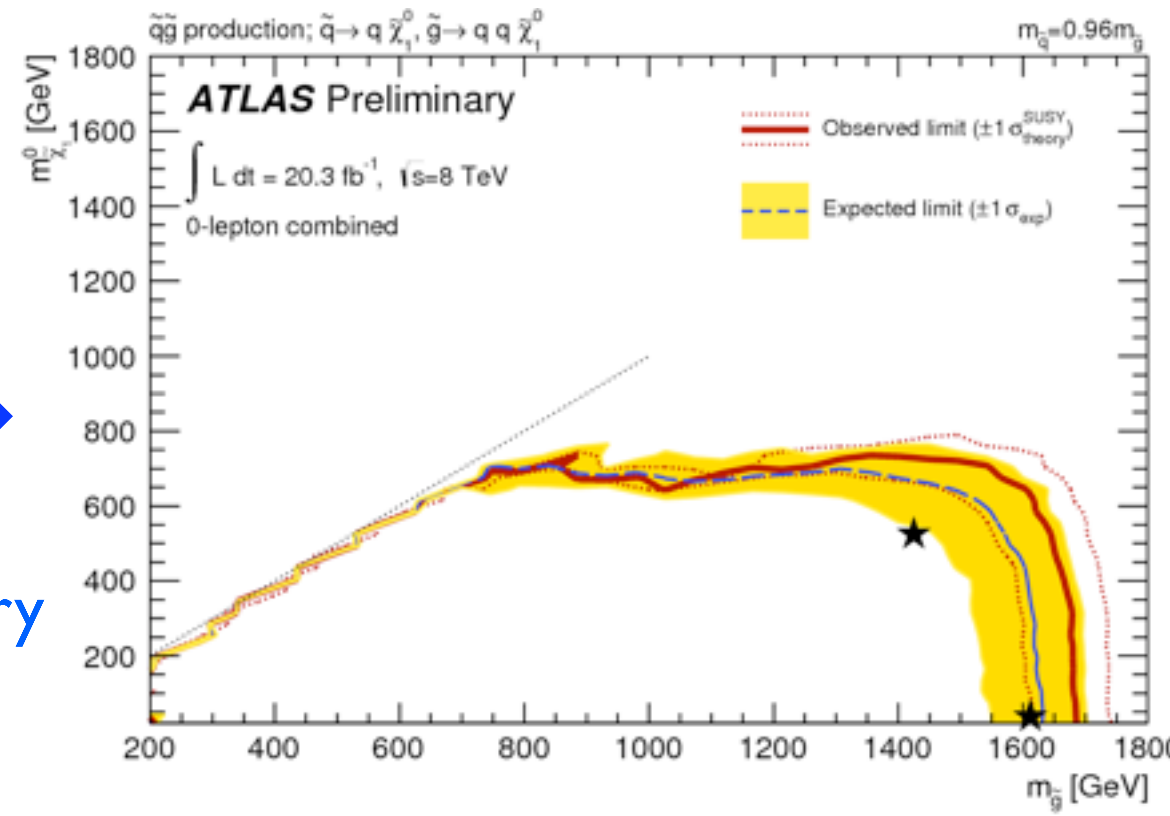


No discovery yet



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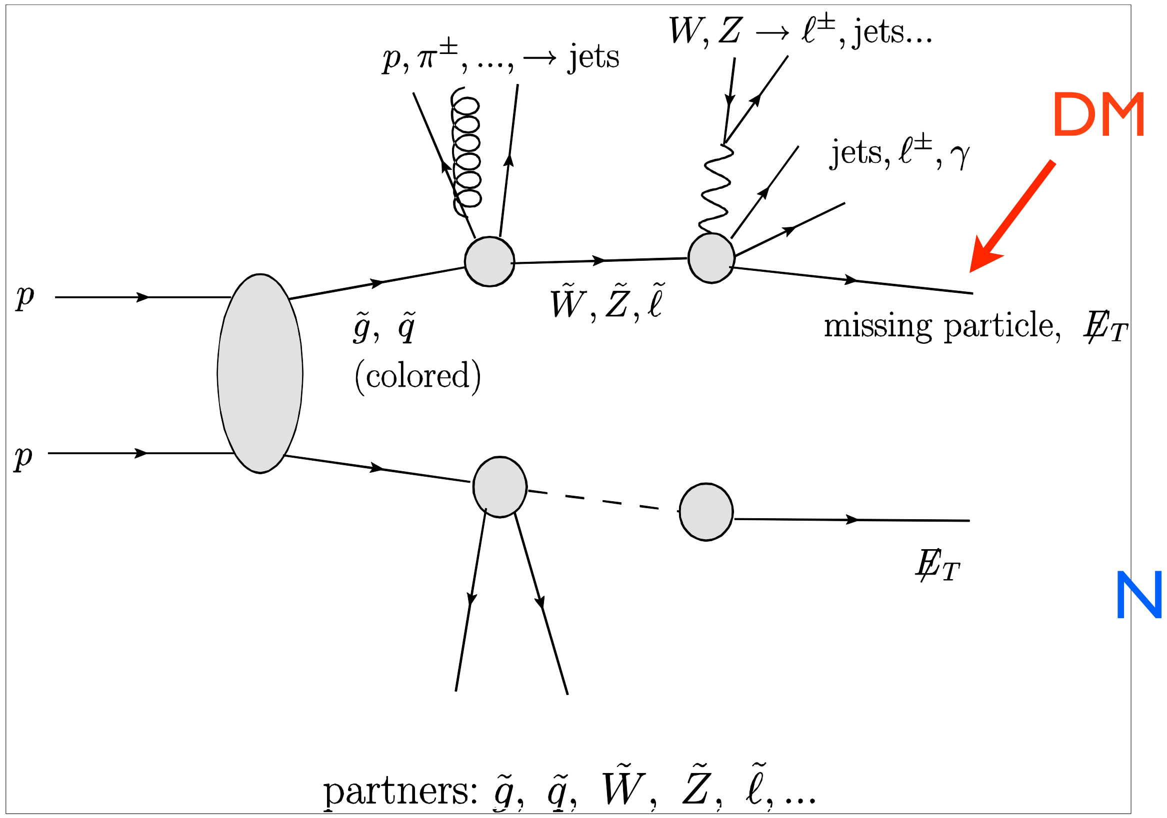

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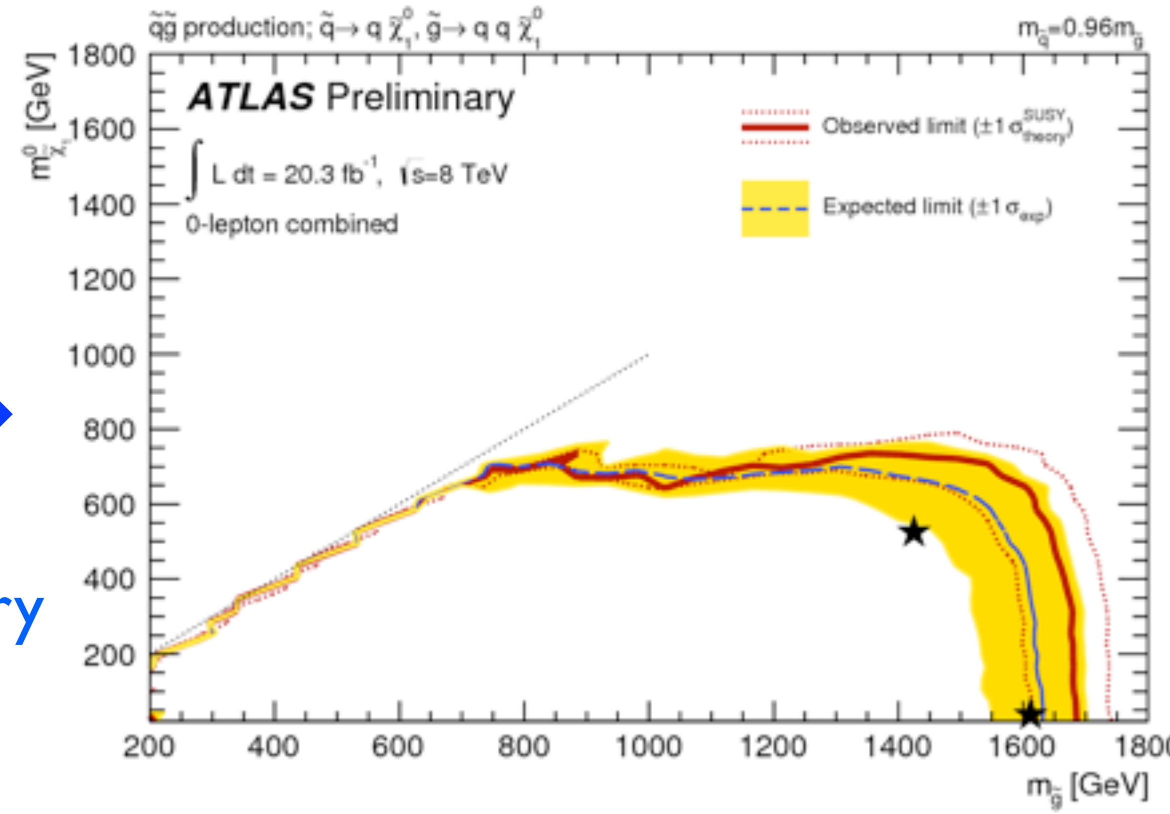
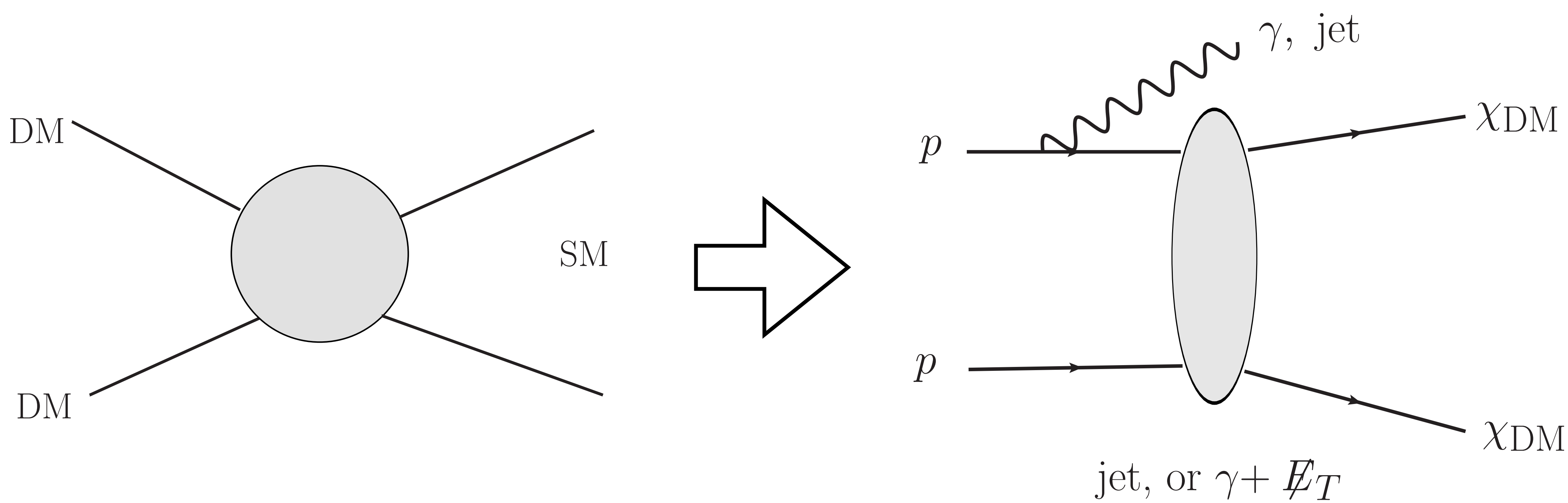


Of course, still plausible at the LHC, will keep looking.
Higher energy ⇒ higher reach

Back to the basics

- pair production + additional radiation.



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

SUSY-like simple models

- 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

Possible scenarios (not over-closing)

- Higgsino $\lesssim$ TeV
- Wino $\lesssim$ 3 TeV
- Well temper: $\tilde{h},\ \tilde{W}$ / $\tilde{B}$ — $\Delta M \sim$ several $\% \times M_{\rm DM}$

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

- Coannihilation: $\tilde{\tau},\ \tilde{q},\ \tilde{t},\ldots$ / $\tilde{B}$ — $\Delta M \sim$ several $\% \times M_{\rm DM}$
- Funnel: $2\ M_{DM} \approx M_X$ X= A, H...

Cahill-Rowley, Hewett, Ismail, Peskin, Rizzo, 1305.2419
Cohen, Wacker, 1305.2914

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

Common feature:
very small mass splitting "compressed"

$\tilde{h},\ \tilde{W}$

$\Delta M \sim$ several $\% \times M_{\rm DM}$

$\tilde{B}$

$\tilde{\tau},\ \tilde{q},\ \tilde{t}, \ldots$

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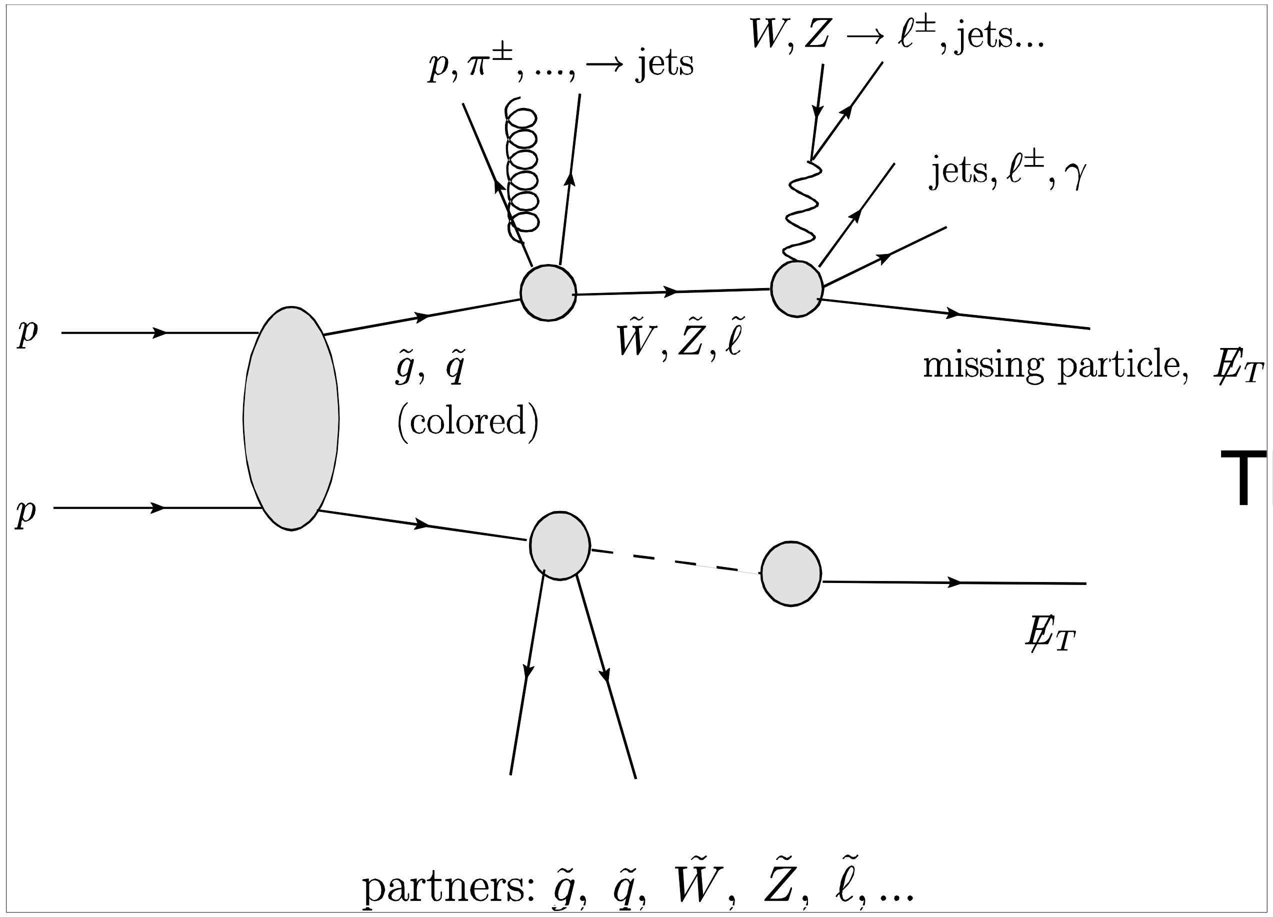
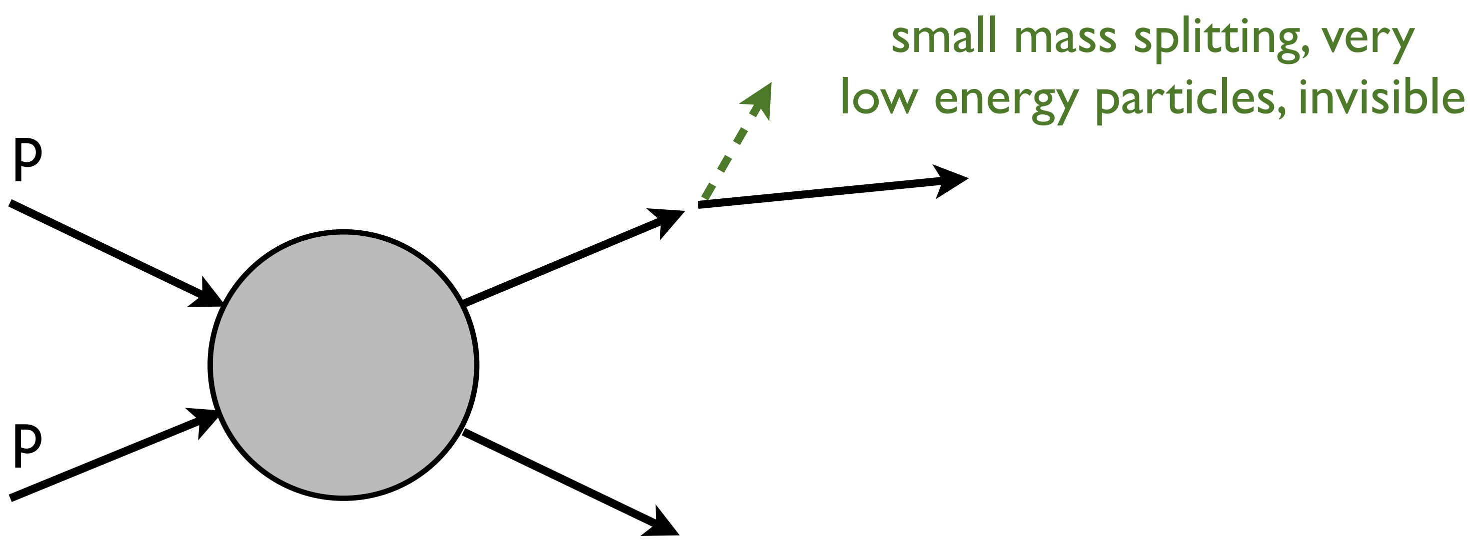
SUSY DM signal in the compressed case



The "usual" story

SUSY DM signal in the compressed case



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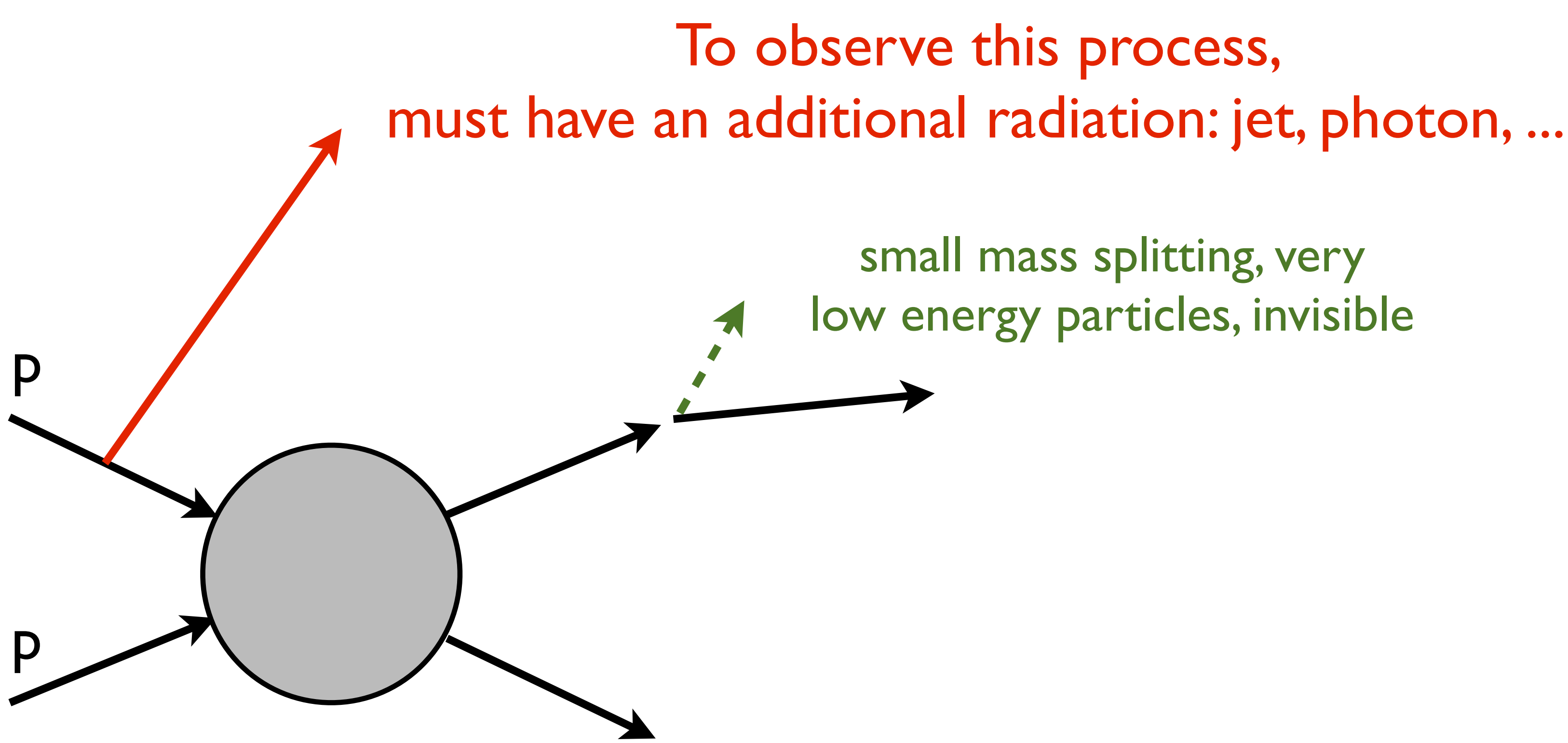

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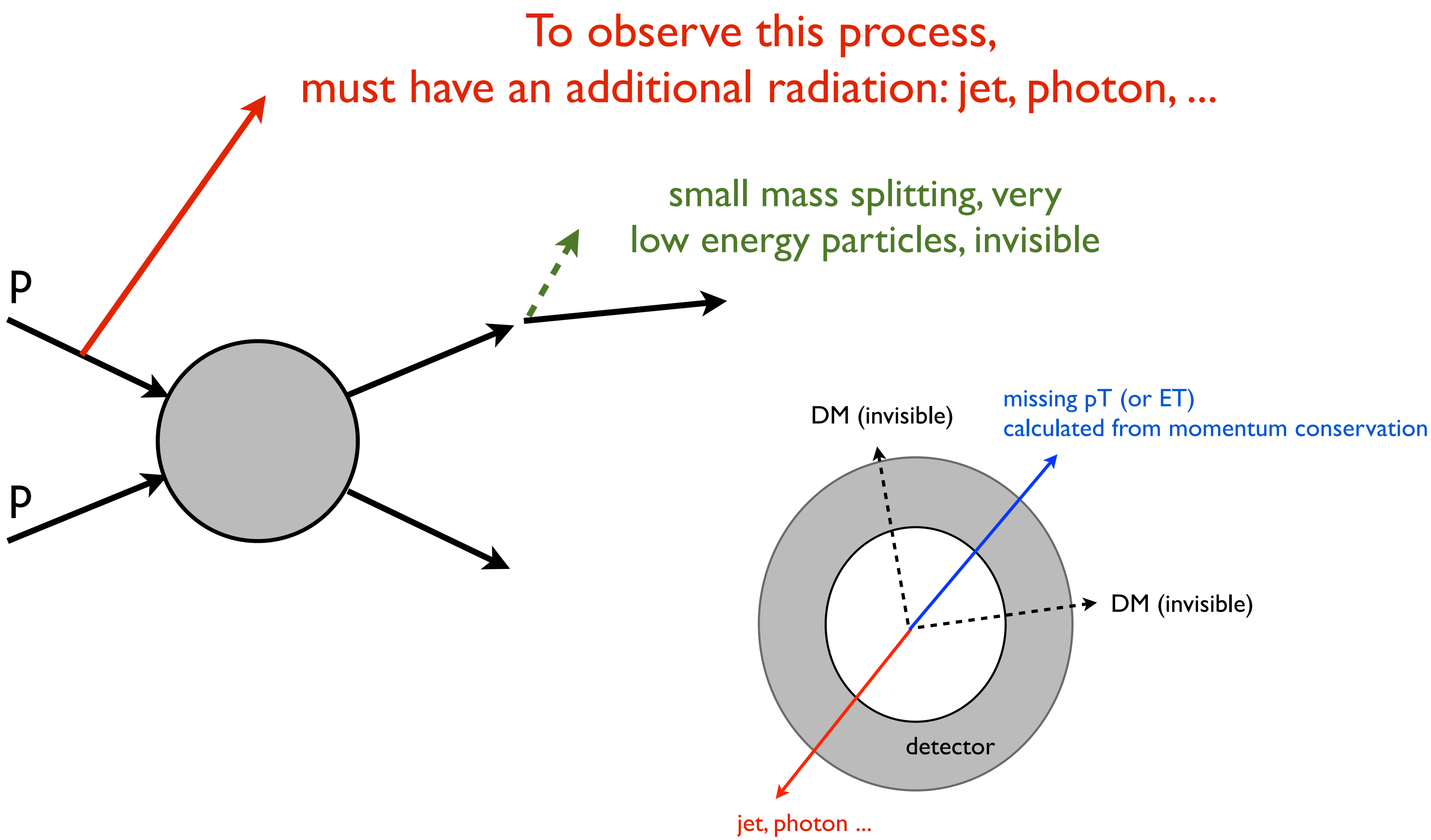
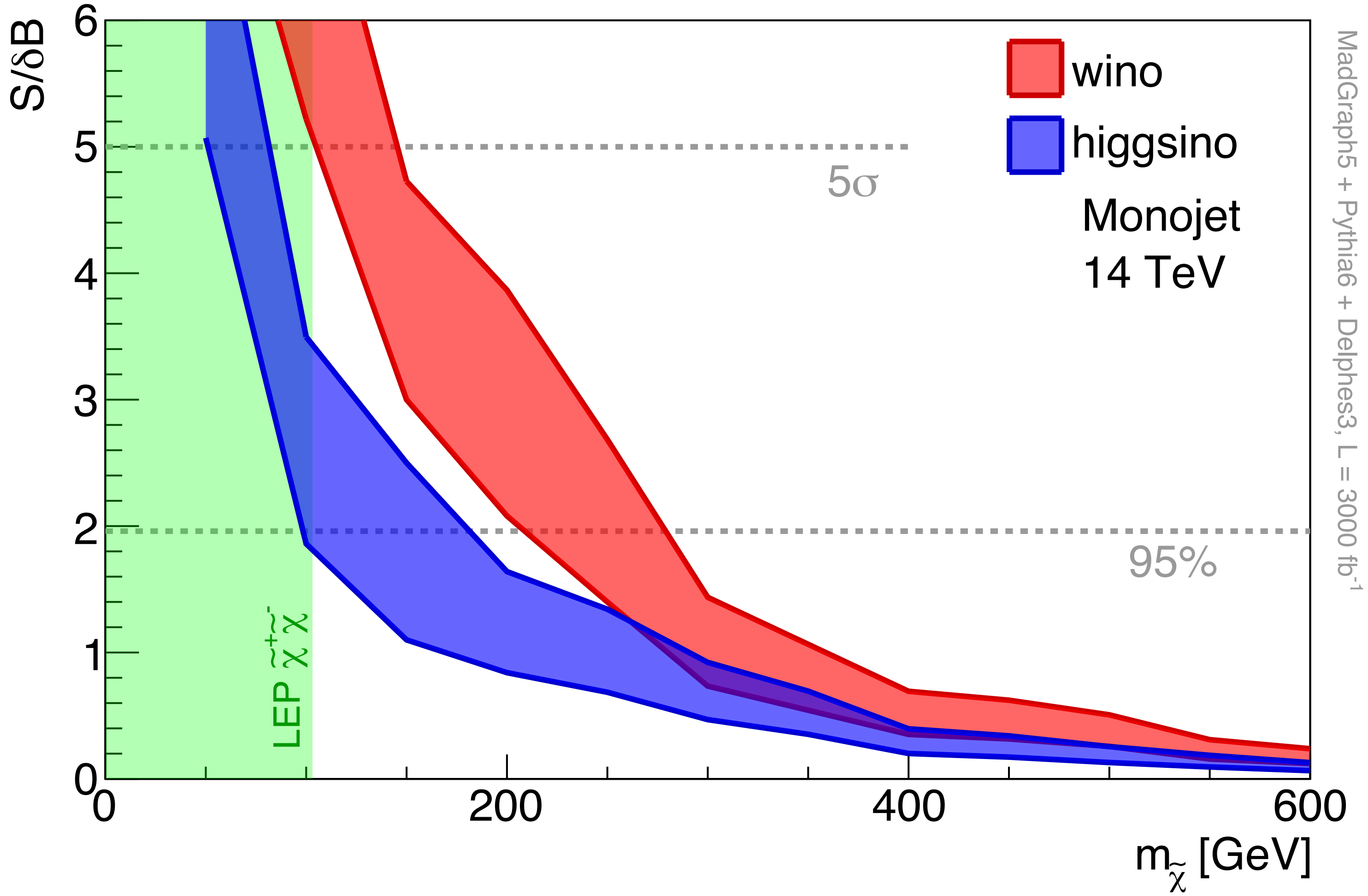


- Basic mono-jet, mono-photon... will be the main search channel.

LHC (14 TeV) is not enough



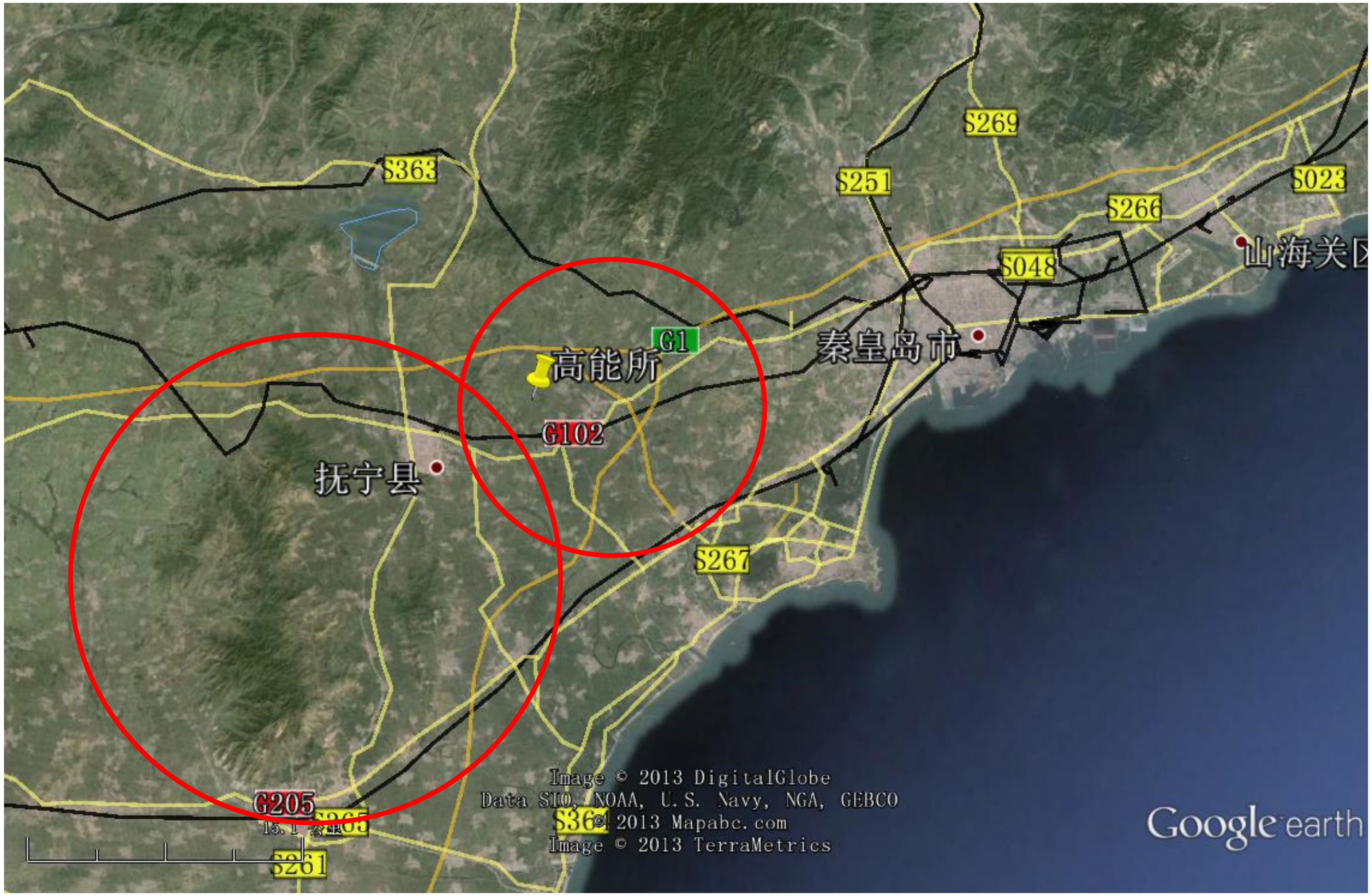
$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

- Much of the parameter region out of the reach at the LHC.

Two questions:

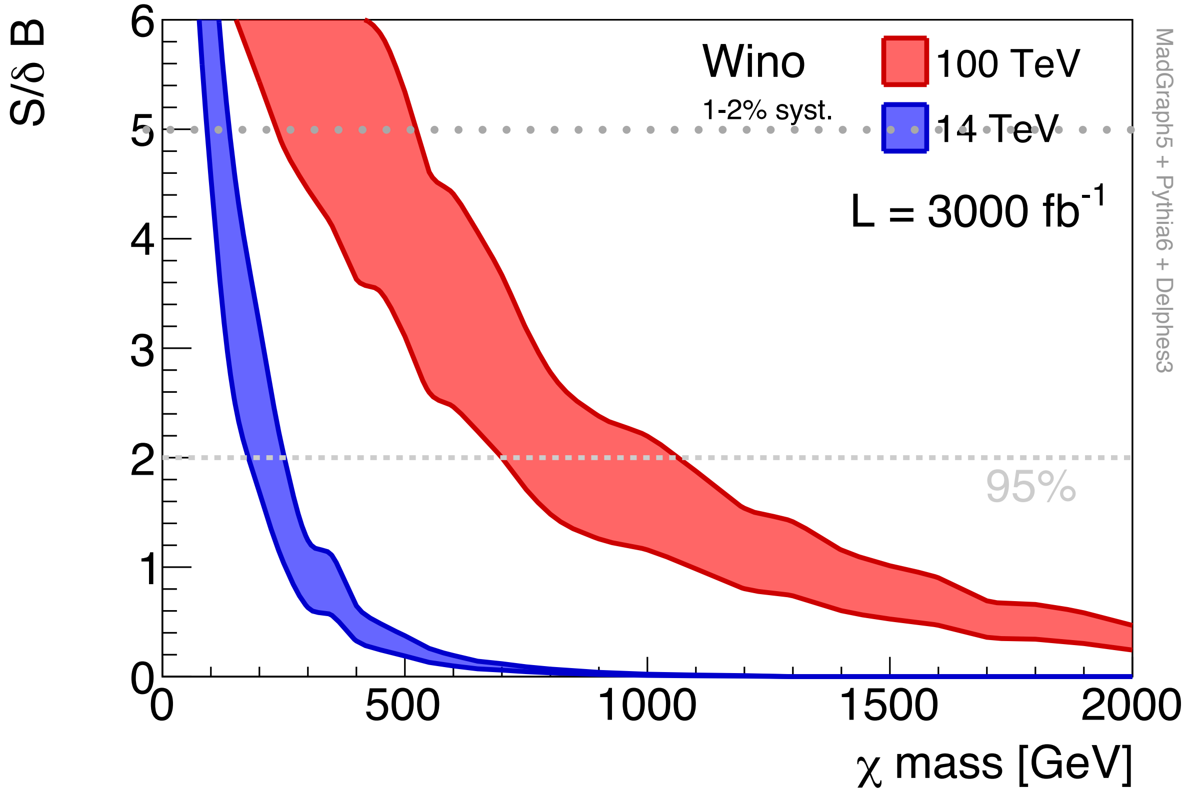
- What can higher energy collider do?
  - Using 100 TeV pp-collider as an example.
- Can the LHC (14) do more?
  - Going beyond simple SUSY-like models.
    - In SUSY , mediators between SM and DM: W/Z/h
    - Adding new mediators.

Going to higher energies.



Example: Wino. Monojet channel

Matthew Low, LTW, 2014



pT(jet) > 300 (1200) GeV, for 14 (100) TeV Ecm lepton veto ...

mono-γ and mono-W/Z don't add that much.

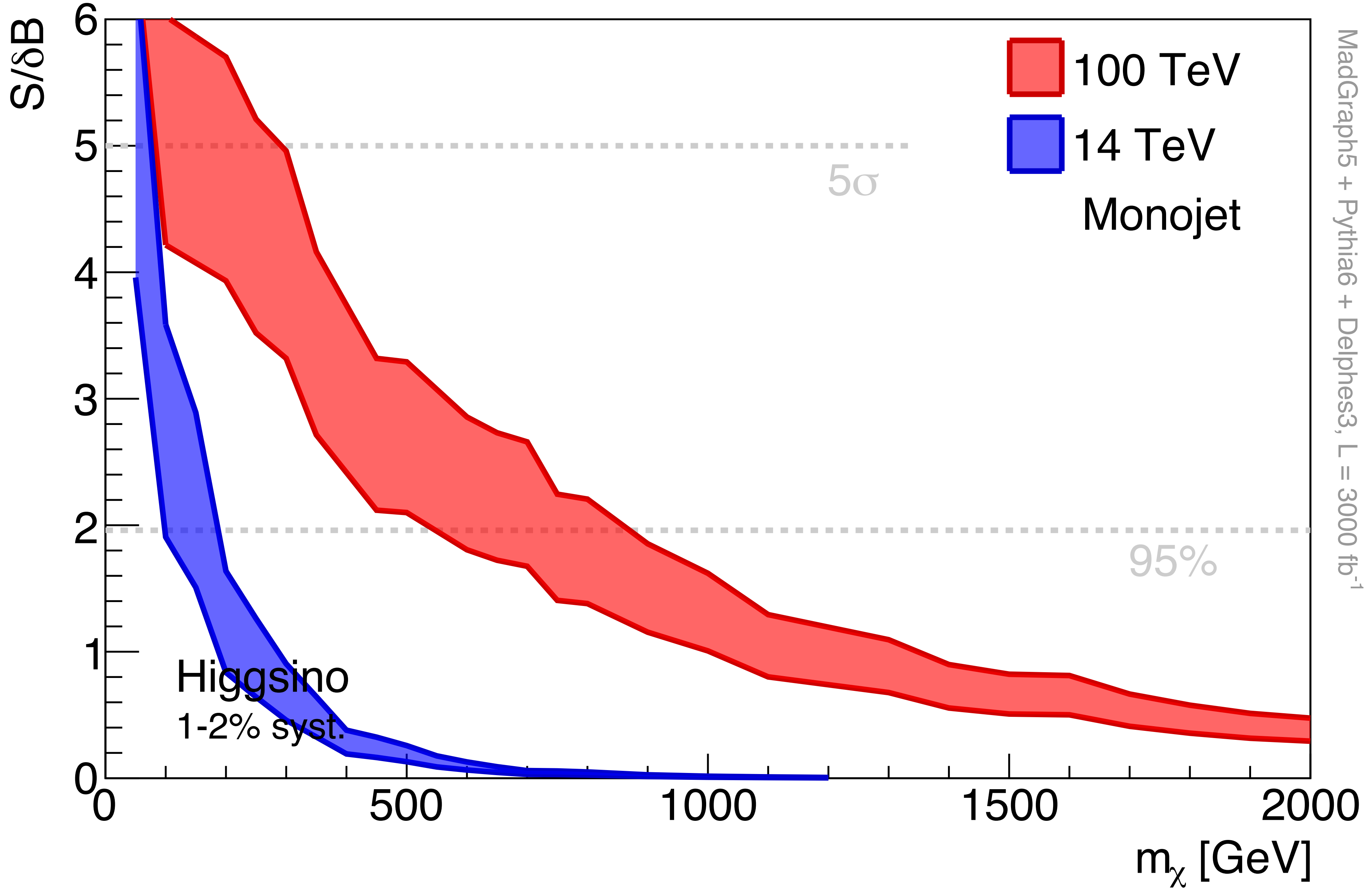
significance: $$\frac{S}{\sqrt{B + \lambda^2 B^2 + \gamma^2 S^2}}, \ \lambda = (1-2)\%, \gamma = 10\%$$

Band: varying systematic error of background, λ, between 1-2%

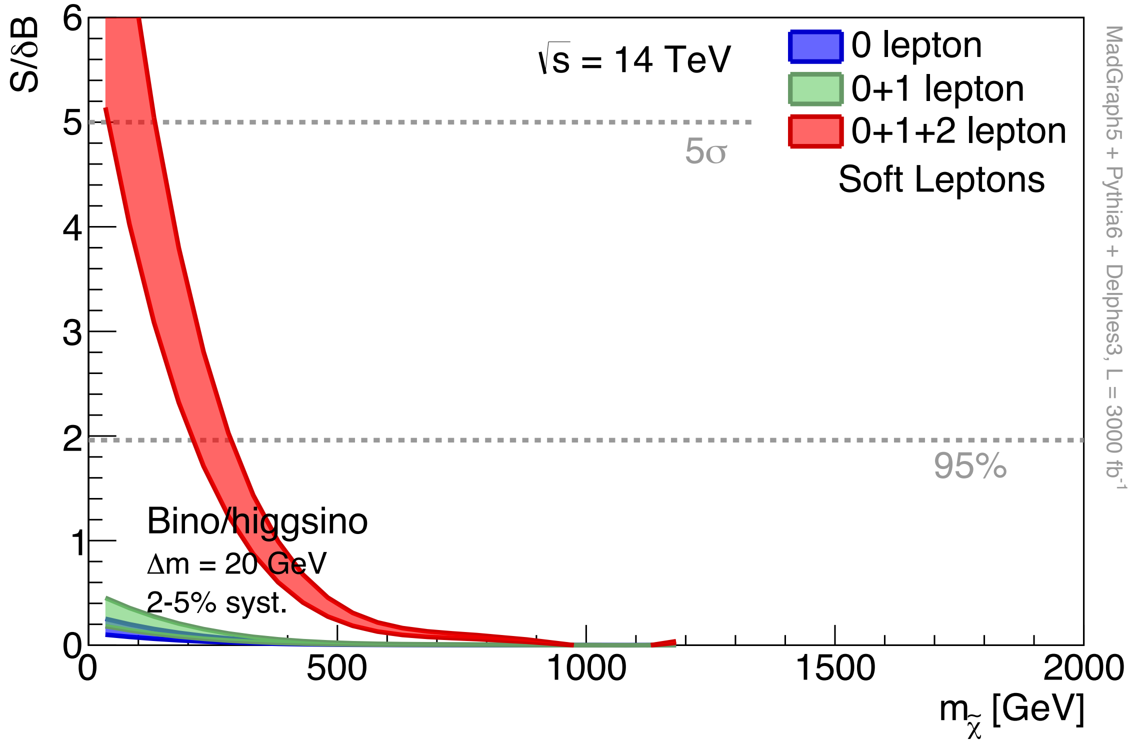
- A factor of 4-5 enhancement from 14 to 100 TeV.

Recent works on mono-jet for electroweak-inos
Schwaller, Zurita, 1312.7350
Baer, Tata, 1401.1162
Han, Kribs, Martin, Menon, 1401.1235

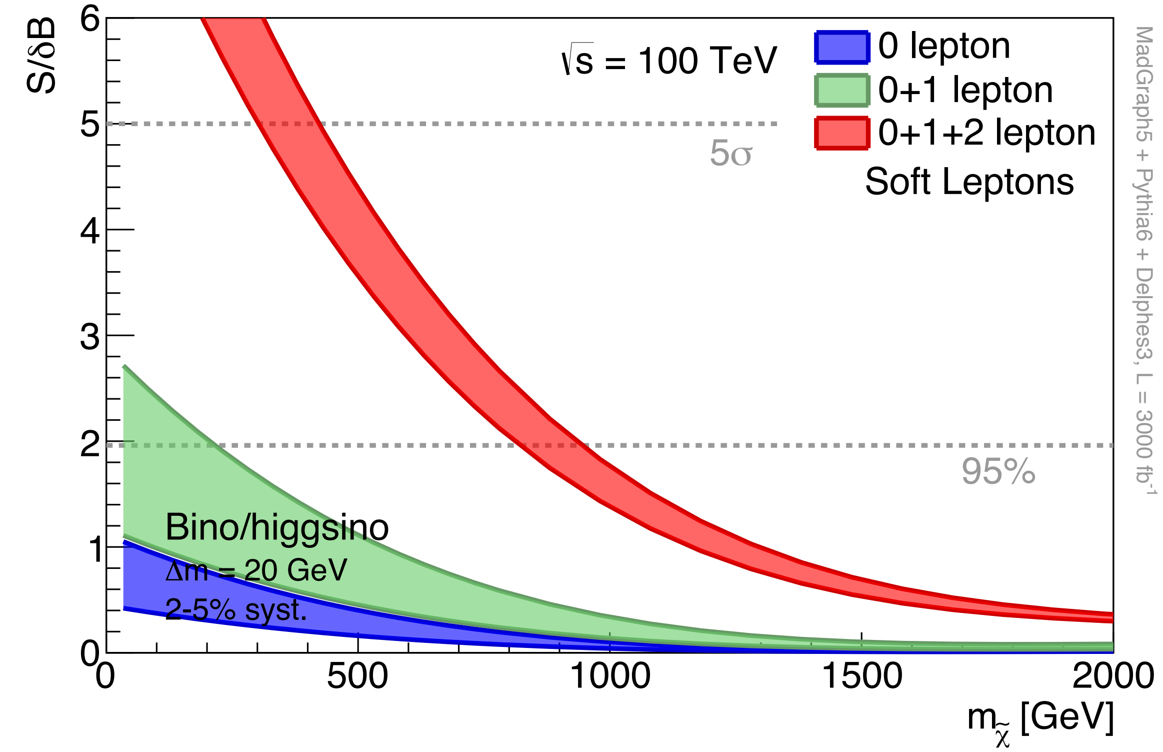
Mono-jet for Higgsino



Well-tempered, mono-jet + soft lepton



20 GeV < pT lepton < 40 GeV



10 GeV < pT lepton < 30 GeV

$\tilde{h},\ \tilde{W}$ ———

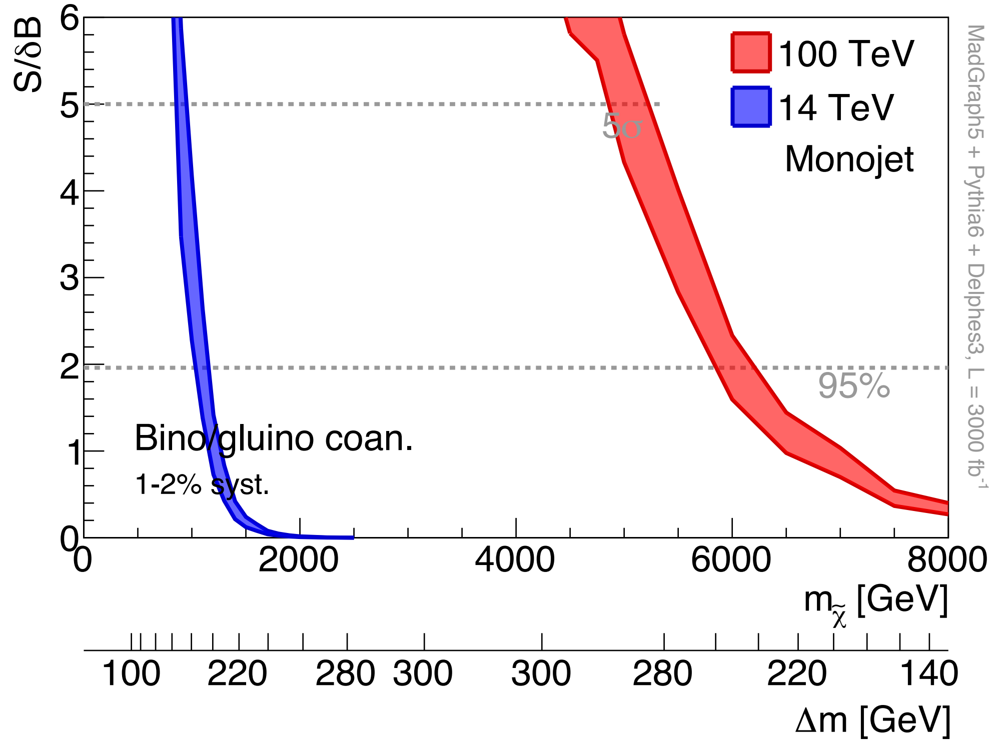
$\Delta M \sim$ several $\% \times M_{\rm DM}$

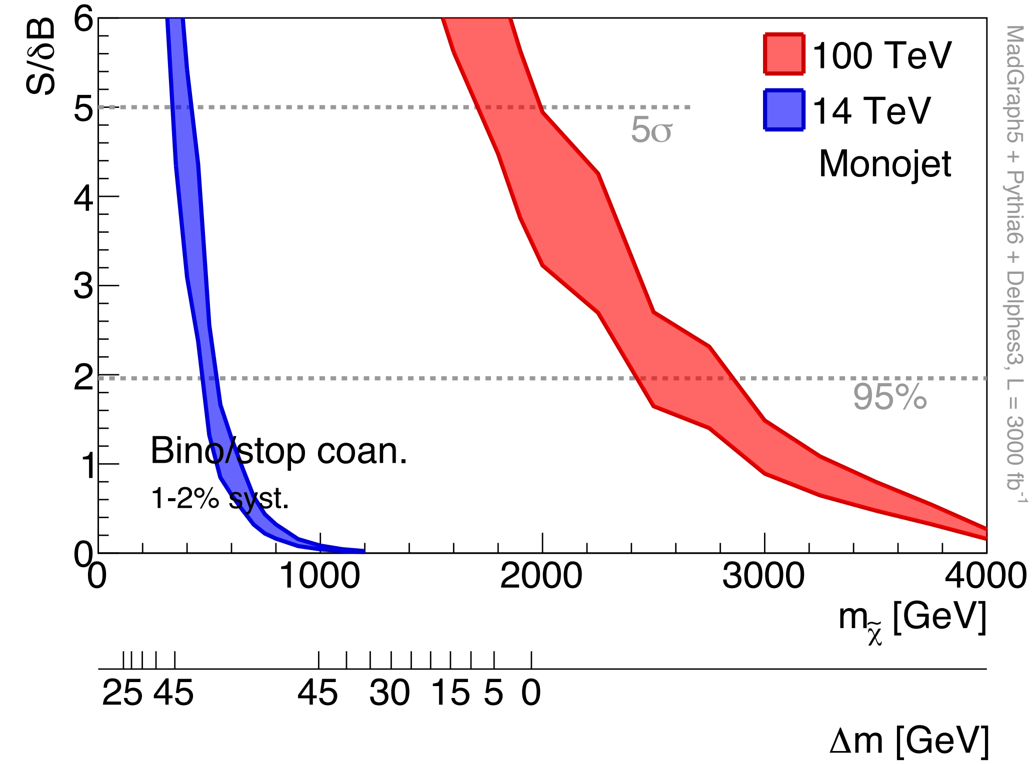
$\tilde{B}$ ———

- Important to add soft lepton. S/B is O(1).

Giudice, Han, Wang and LTW, 1004.4902
Schwaller, Zurita, 1312.7350
Han, Kribs, Martin, Menon, 1401.1235

Co-annihilation, monojet





$\tilde{\tau},\ \tilde{q},\ \tilde{t}, \ldots$

$\Delta M \sim$ several $\% \times M_{\rm DM}$

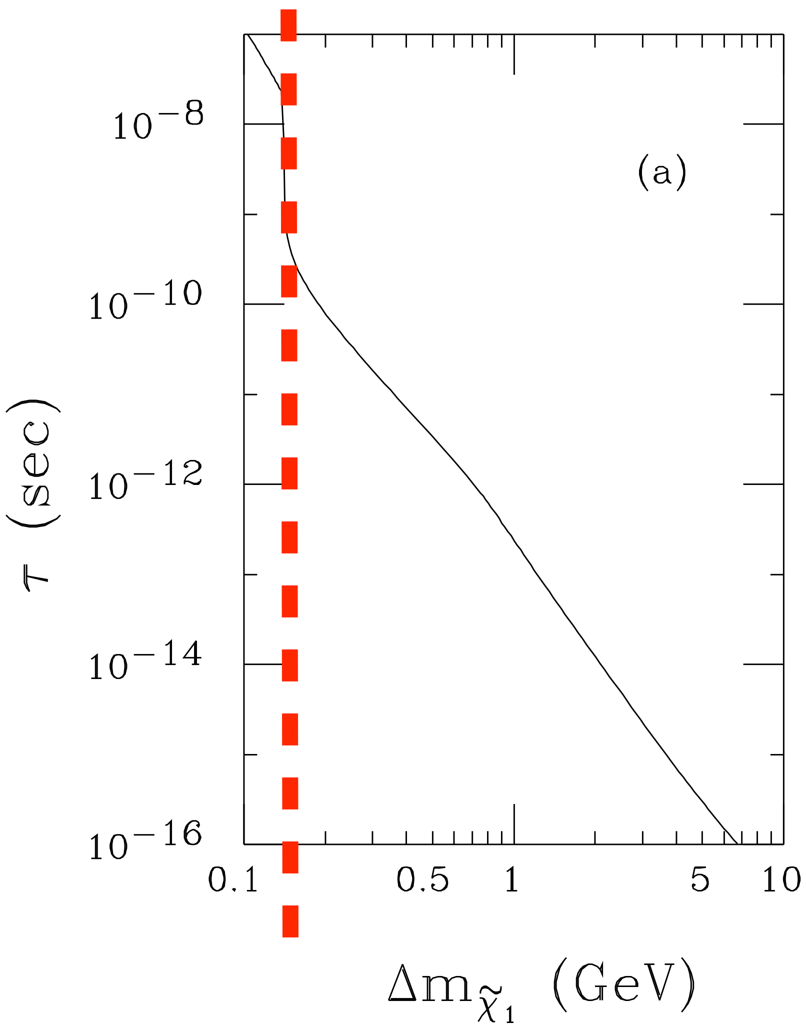
$\tilde{B}$

- Driven by stop/gluino production.
- Impressive reach from mono-jet.

Mono-jet at 100 TeV

- Impressive enhancement of reach, a factor of 5-7 in comparison with LHC 8 TeV.
- Still very challenging, systematic dominated.
- Can we do more?
  - Yes, in the wino case.
  - I am hopeful more progresses can be made in other cases.

Disappearing track



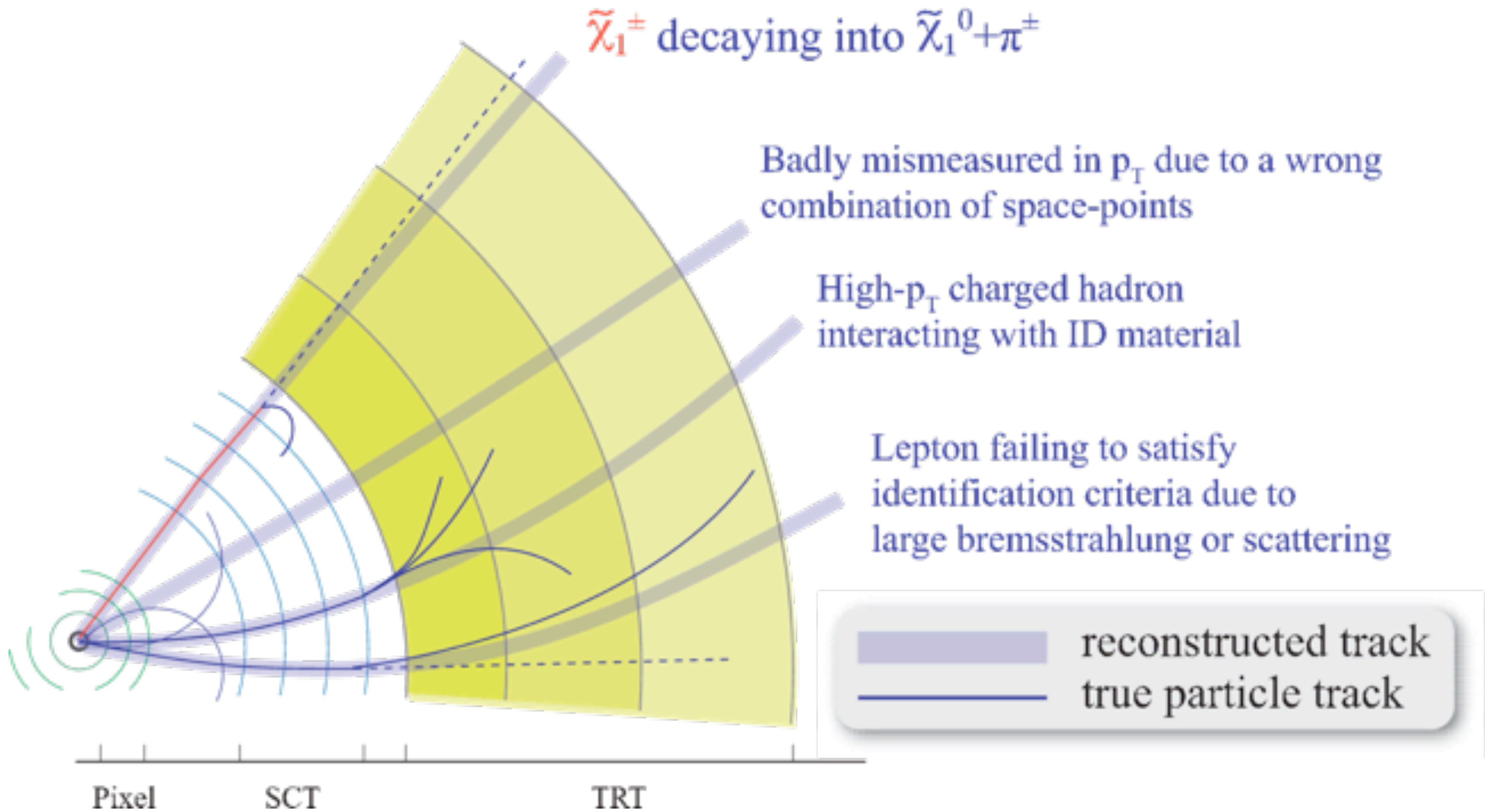
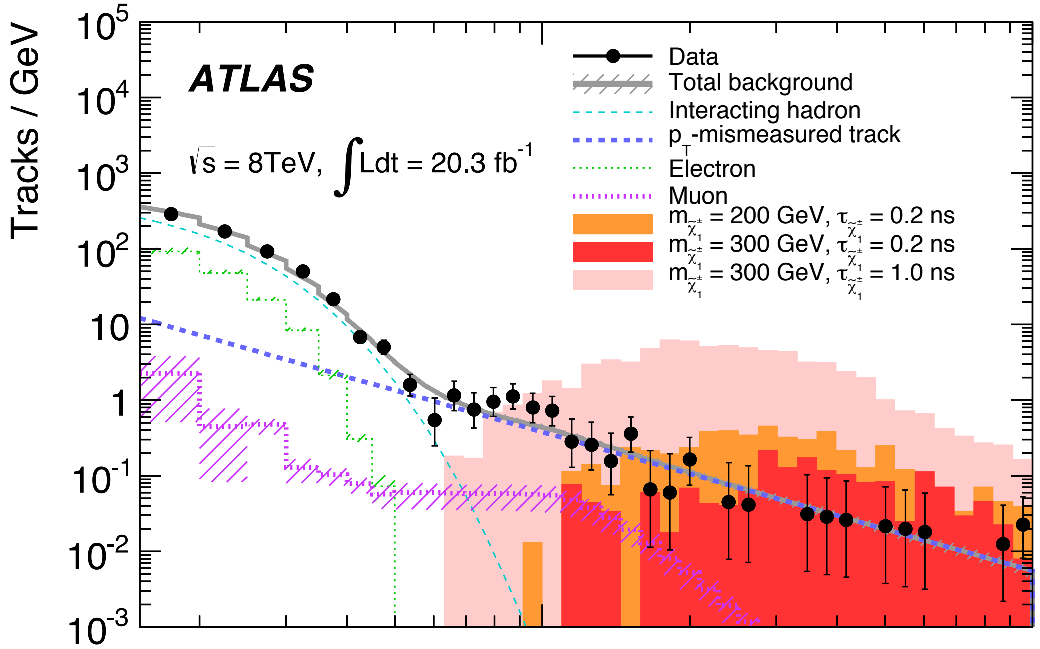


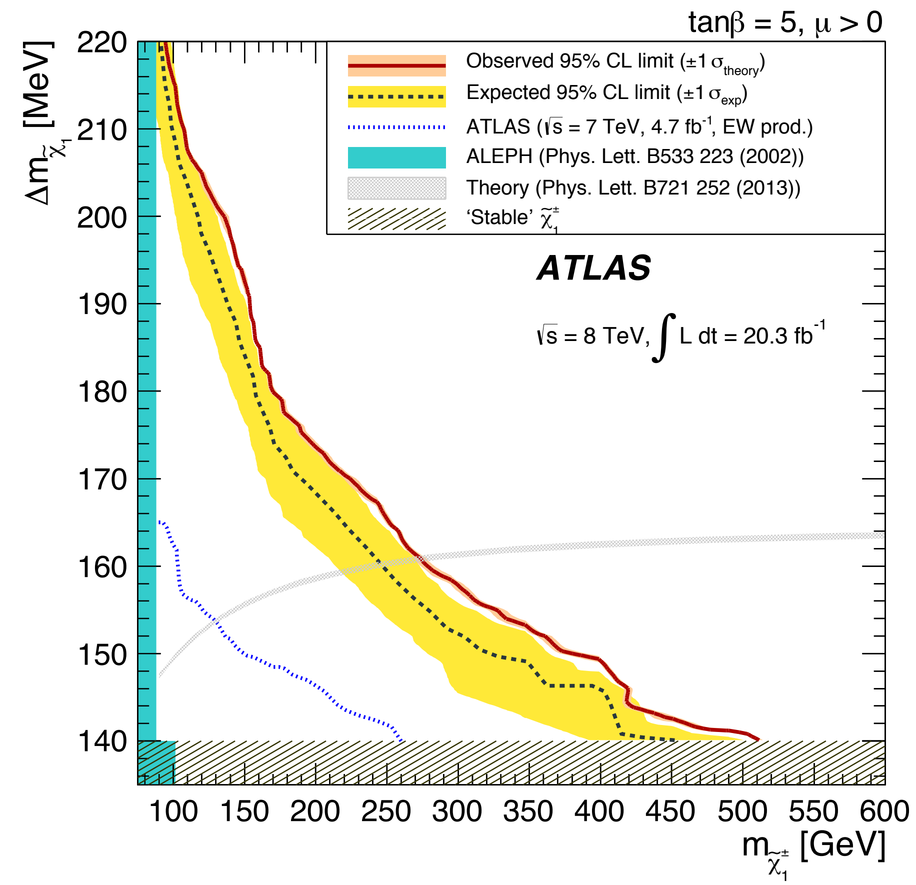
Figure from ATLAS disappearing track search twiki

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

ATLAS search

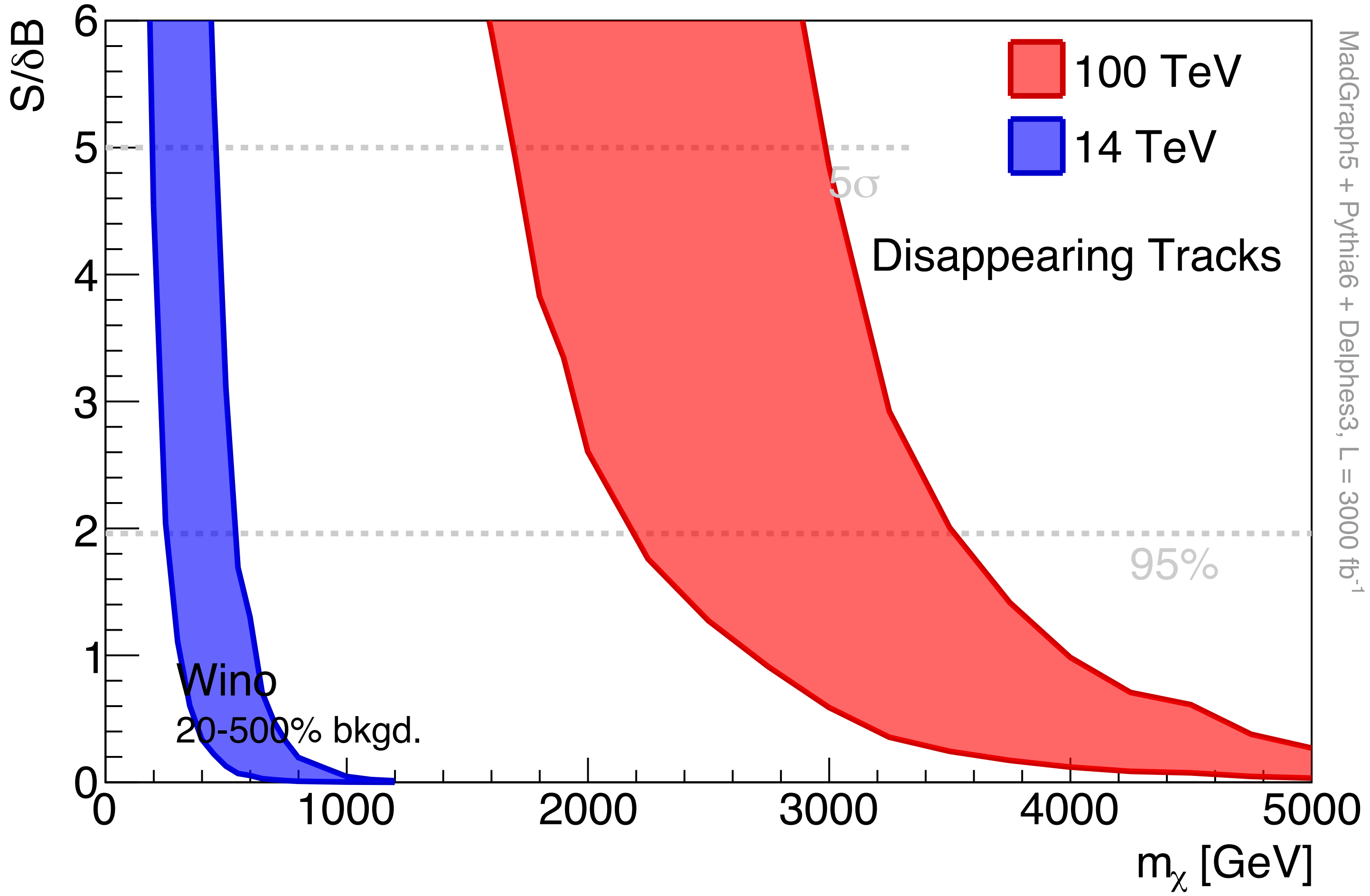
ATLAS, 1310.3675





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

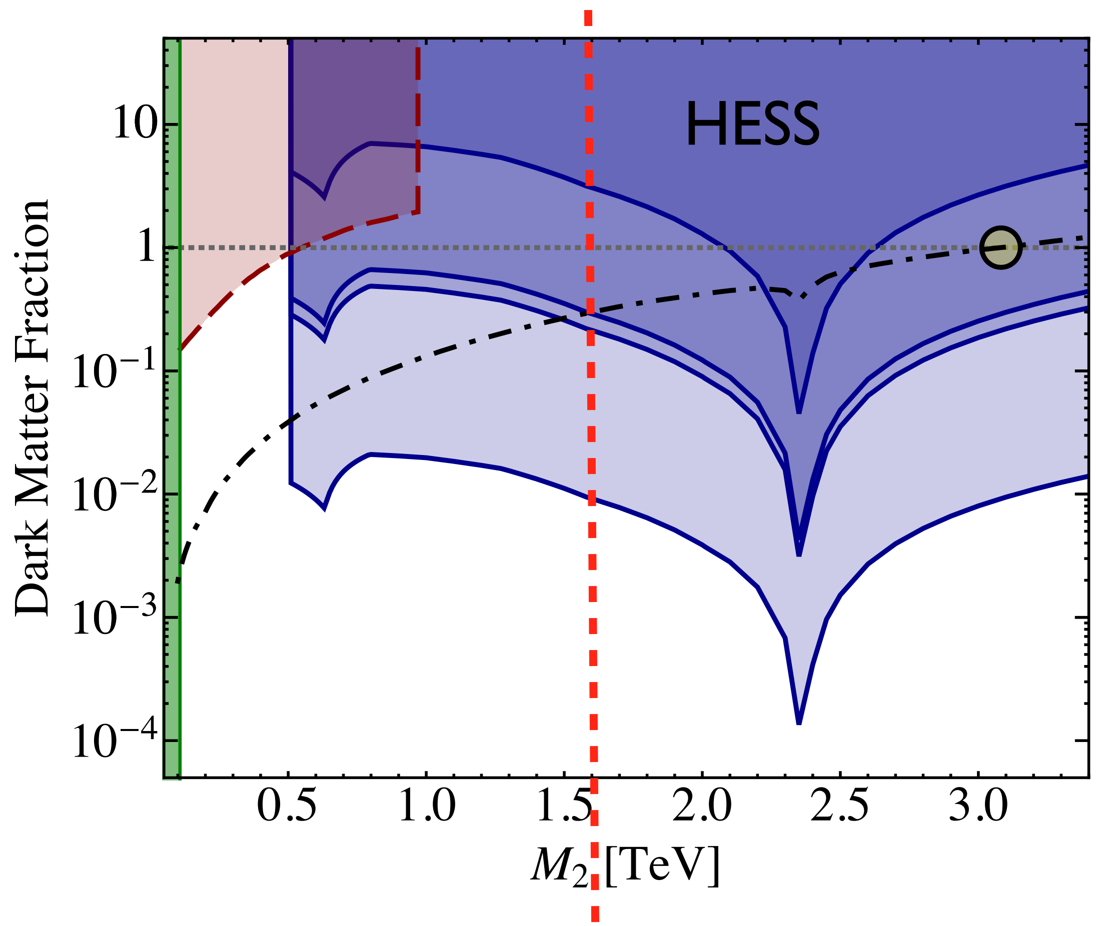
(Rough) Extrapolation from ATLAS search

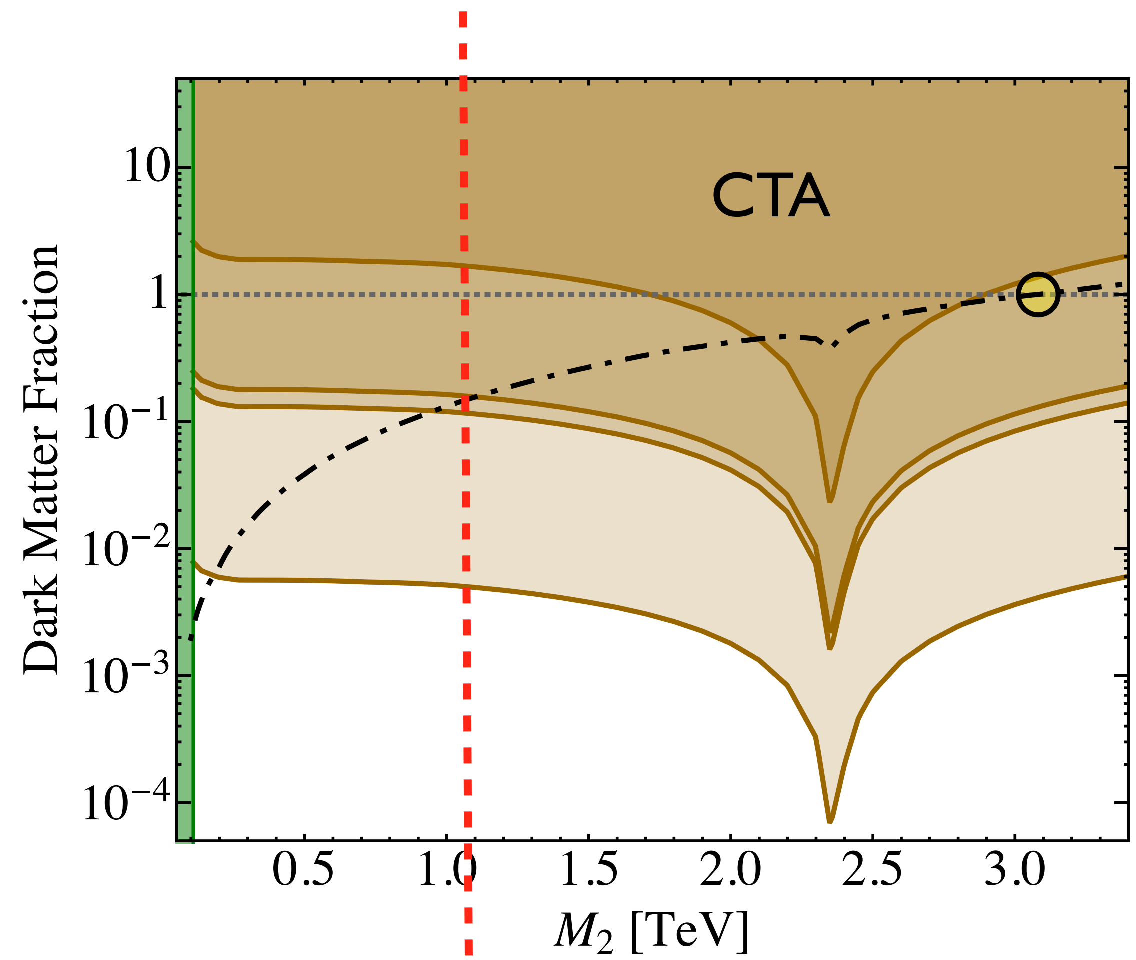


- Scale the ATLAS background rates according to hard jet + MET rates.

- Band: varying background estimate by 5 either way.

Wino, interplay with indirect detection

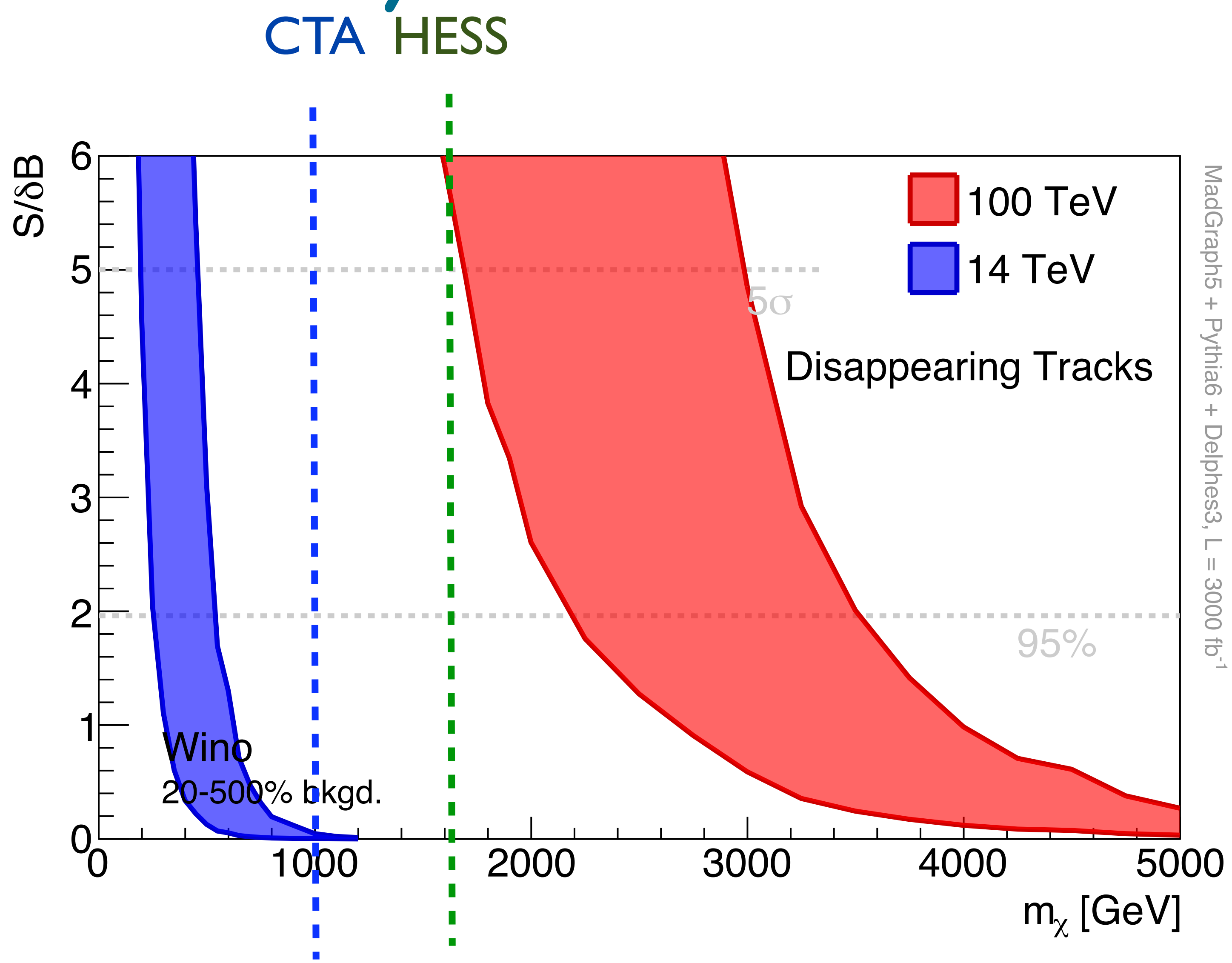




Cohen, Lisanti, Pierce, Slatyer, 1307.4082

See also Fan, Reece, 1307.4400

Wino summary



– There is hope to "completely cover" the wino parameter space.

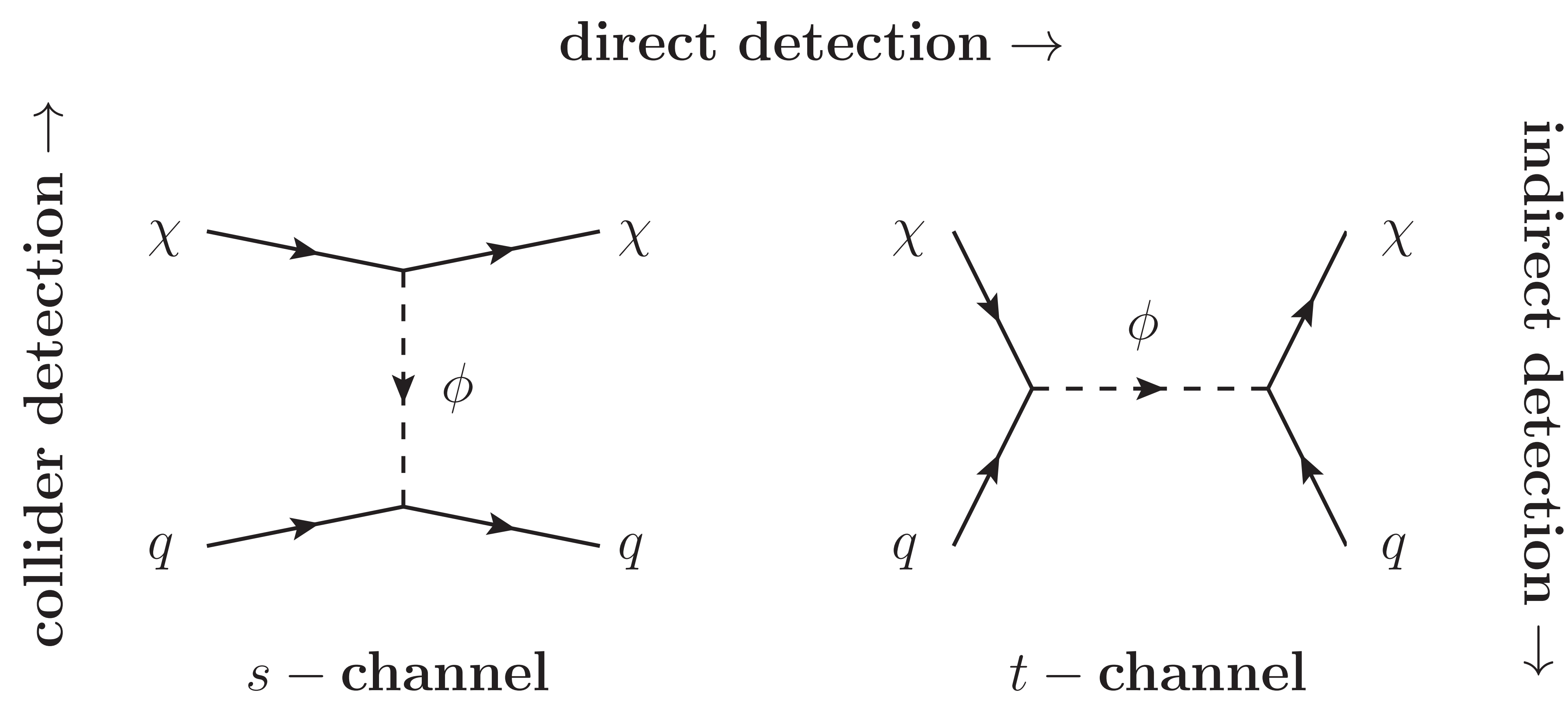
More broadly

LHC	VLHC 100 TeV	Lepton collider
M_{DM} ~10^2s GeV	M_{DM} ~TeV	M_{DM} ~ 0.5 E_{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.

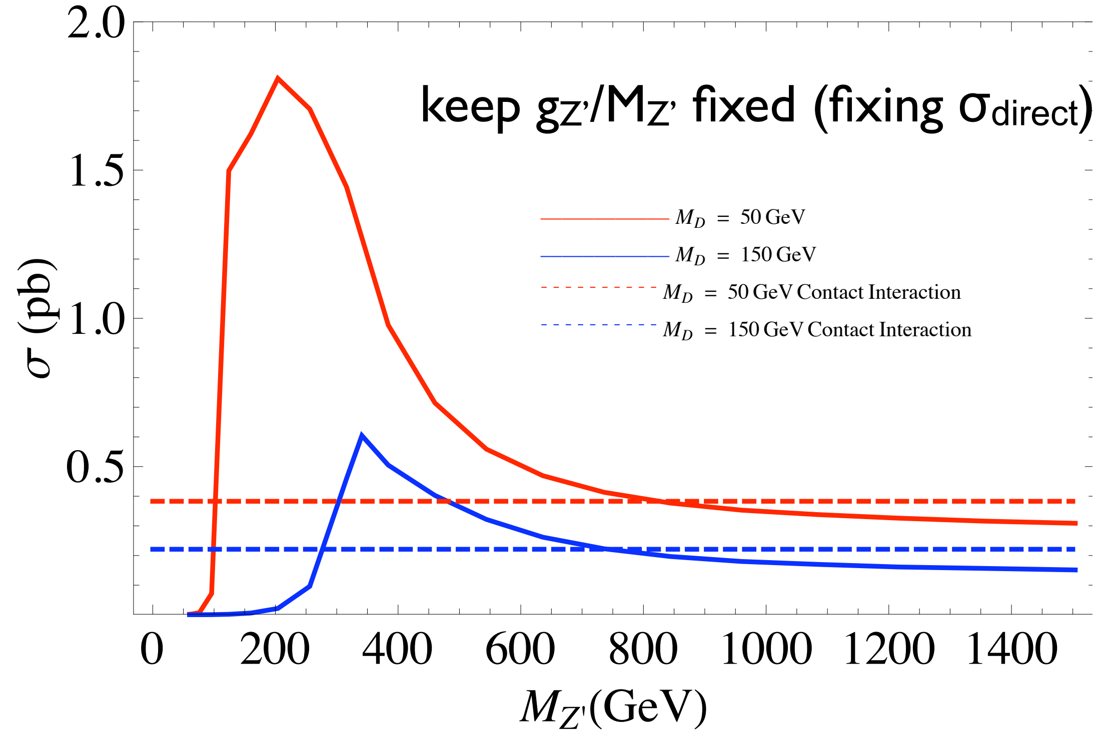
Adding mediators

Simplified mediator models



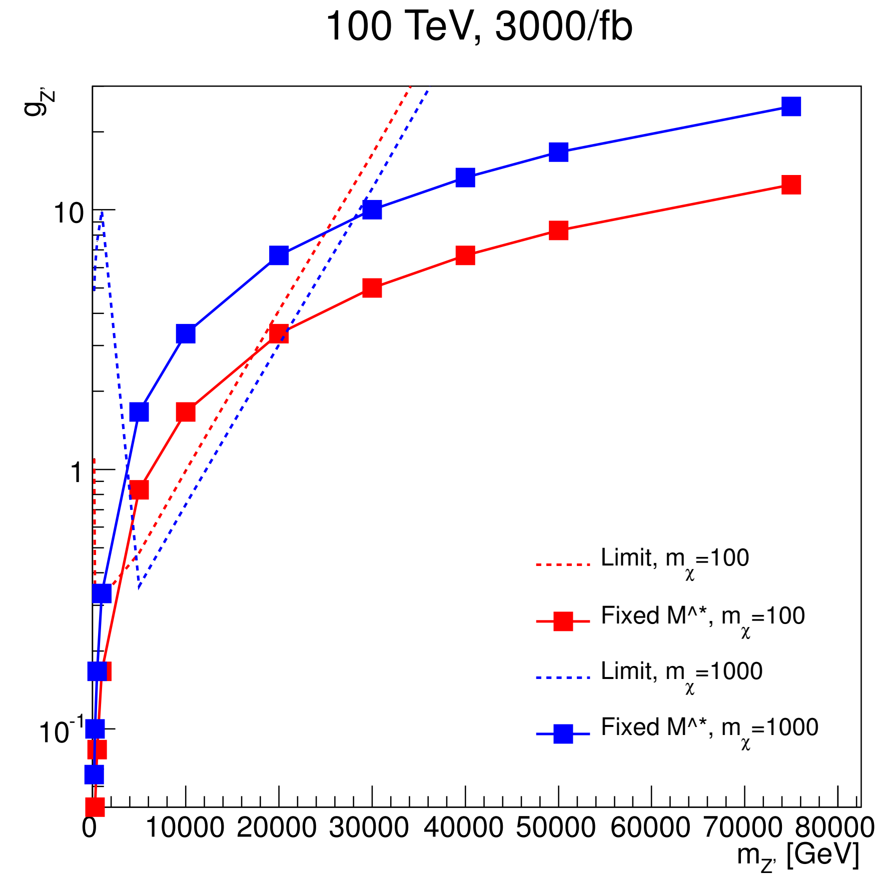
- □can be scalar or Z’
- □squark like

In contrast to SUSY, where mediators at W/Z/h



Tevatron rate, Z' vs effective operator

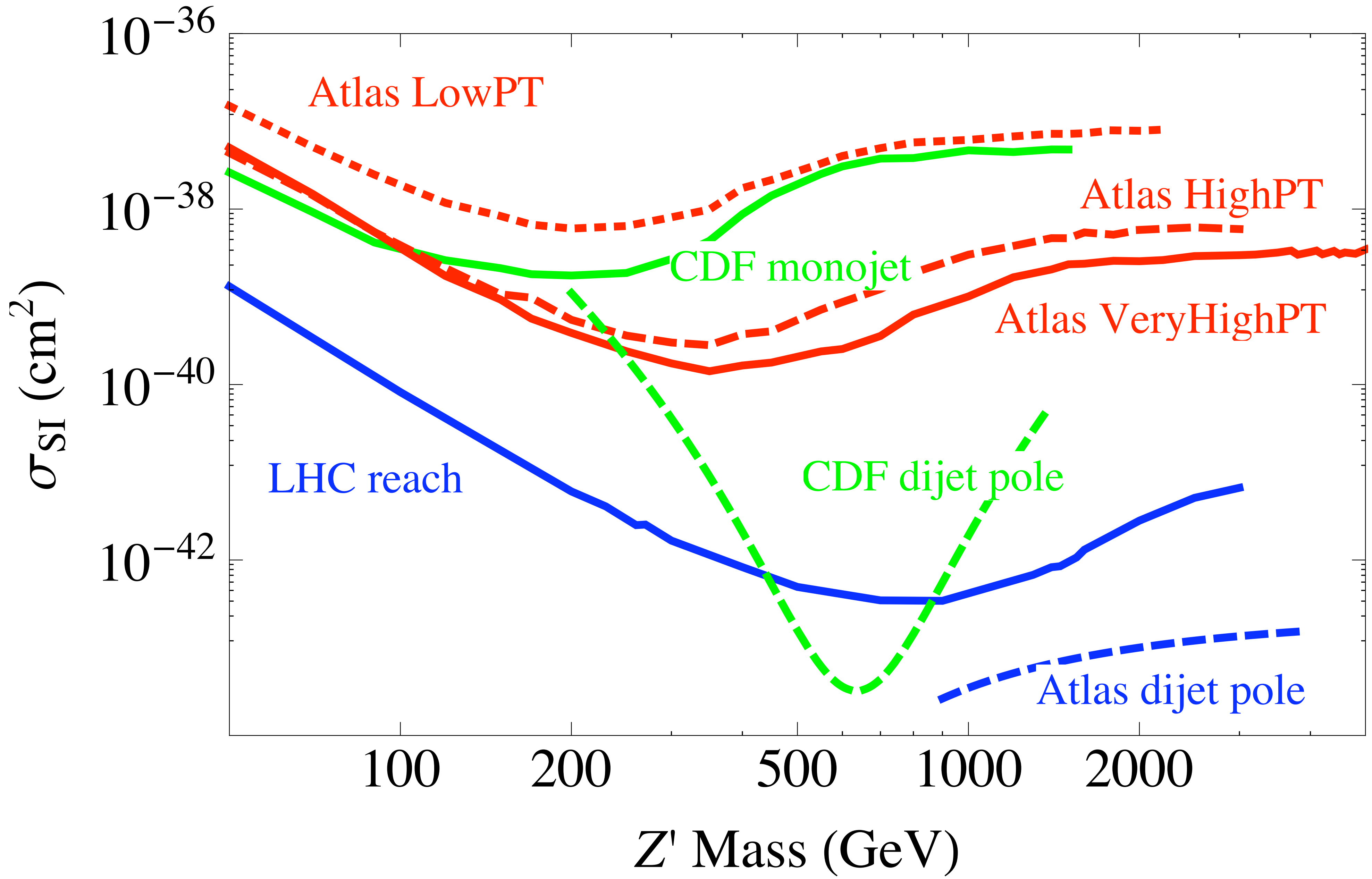
An, Ji, LTW, 1202.2894



Zhou, Berge, LTW, Whiteson, Tait, 1307.5327

- Z' like simplified models.
  - We see the significant resonance effect in the mono-jet process.

Easier to discover the mediator first!



An, Ji, LTW, 1202.2894 Assume $g_{Z'} = g_D$

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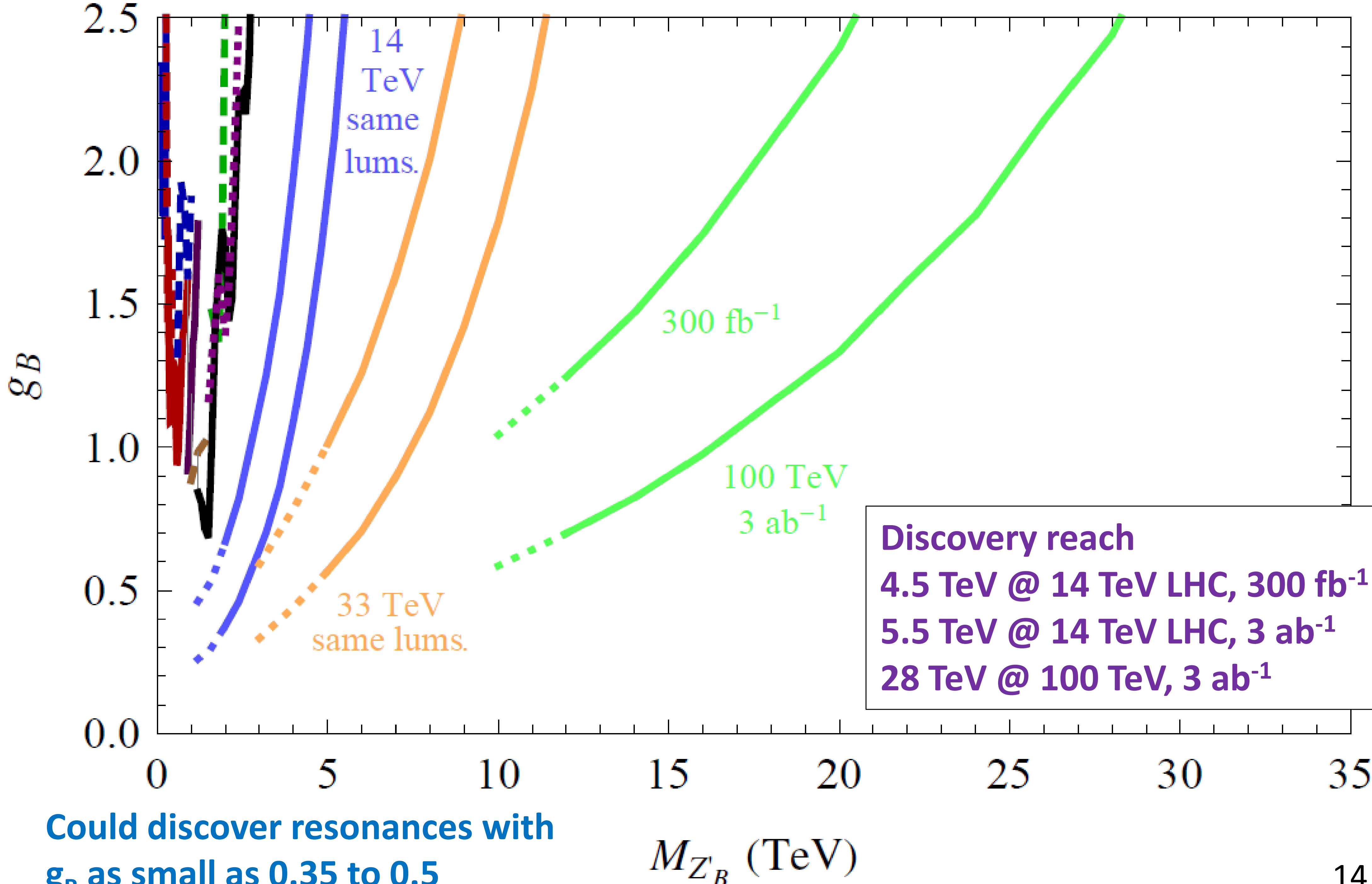


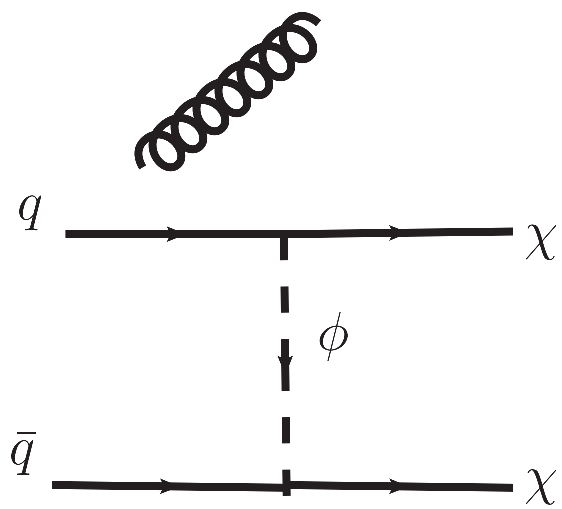
Discovery reach
4.5 TeV @ 14 TeV LHC, 300 fb^{-1}
5.5 TeV @ 14 TeV LHC, 3 ab^{-1}
28 TeV @ 100 TeV, 3 ab^{-1}

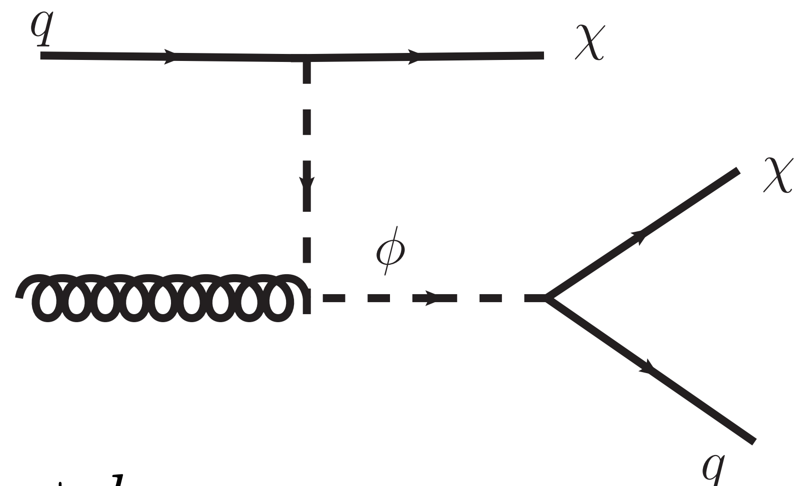
Could discover resonances with g_B as small as 0.35 to 0.5

Felix Yu, 2013

Collider searches

Chang, Edezhath, Hutchinson, Luty, 1307.8120
An, Zhang, LTW, 1308.0592
Bai, Berger, 1308.0612
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679
Papucci, Vichi, Zurek, 1402.2285



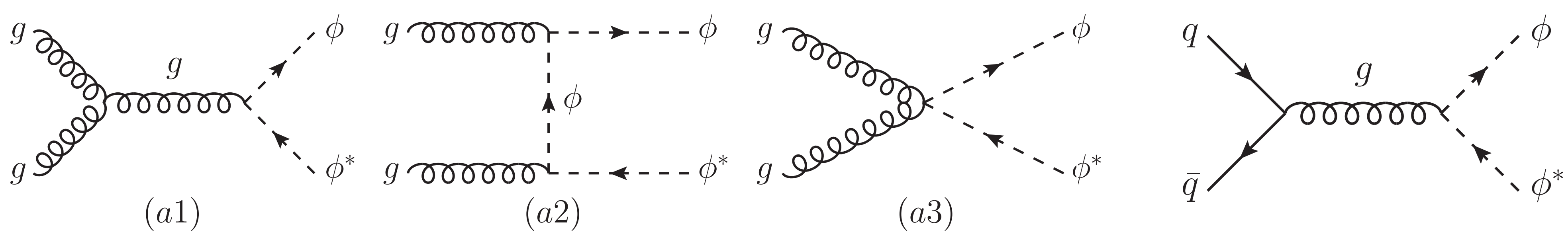


$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

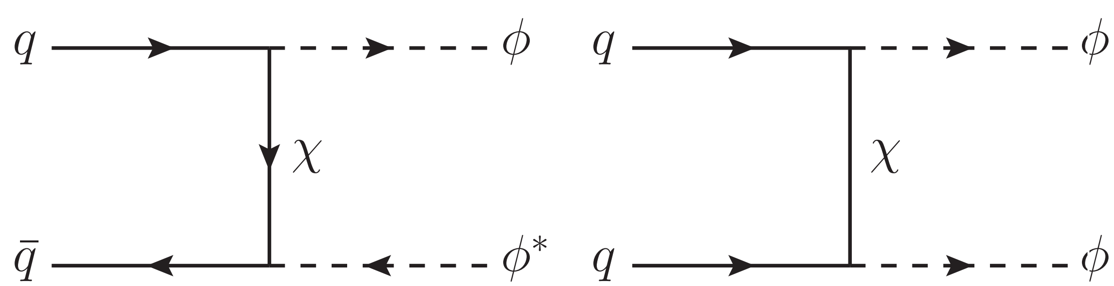
- 2 kinds of contributions for monojet.
- pp→$\chi\phi$ gives harder (mono)jet!

Direct mediator production

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



"usual" squark searches

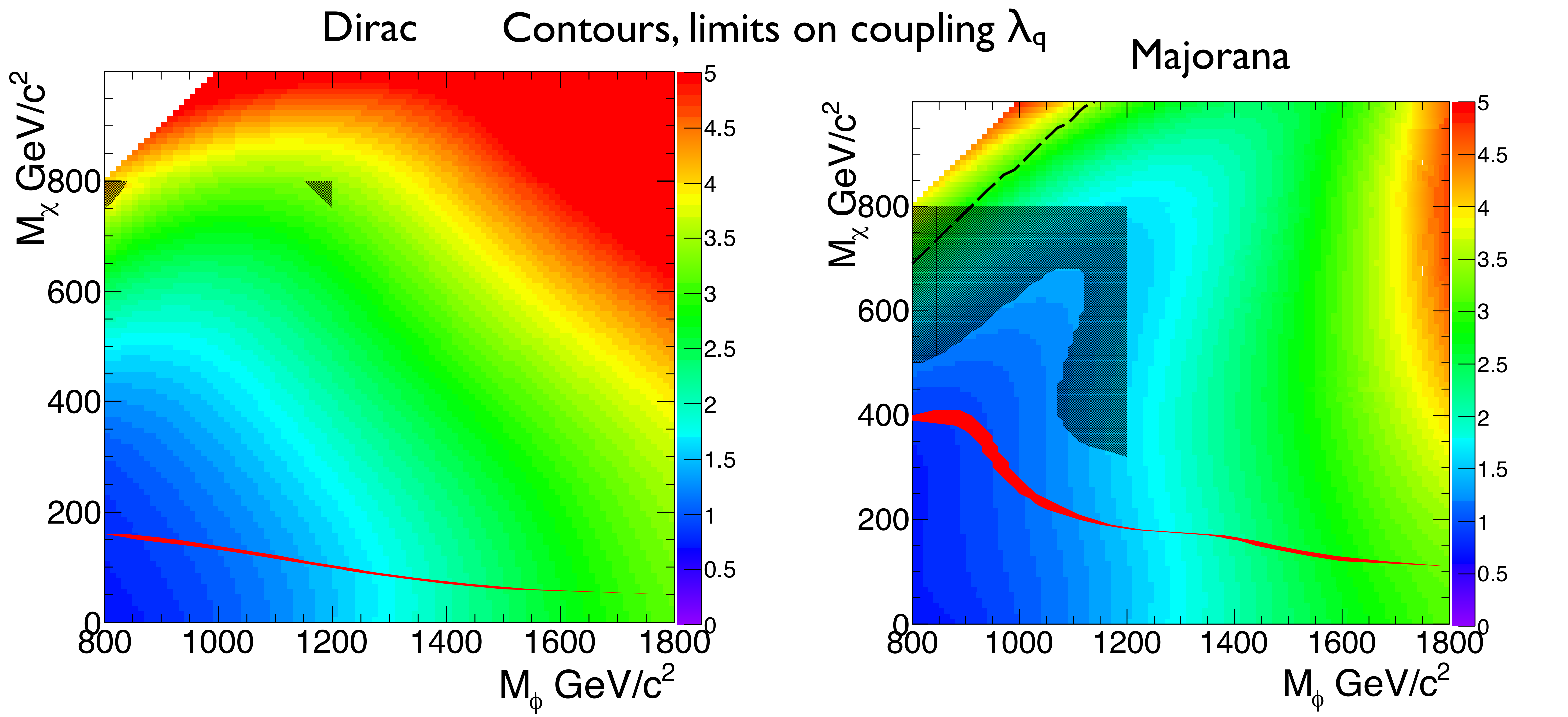


$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

new channels, different kinematics
Can start with valence qq if χ is majorana

8 TeV limits

Monojet: CMS-PAS-EXO-12-048
squark: CMS-PAS-EXO-13-012



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, 1308.0592

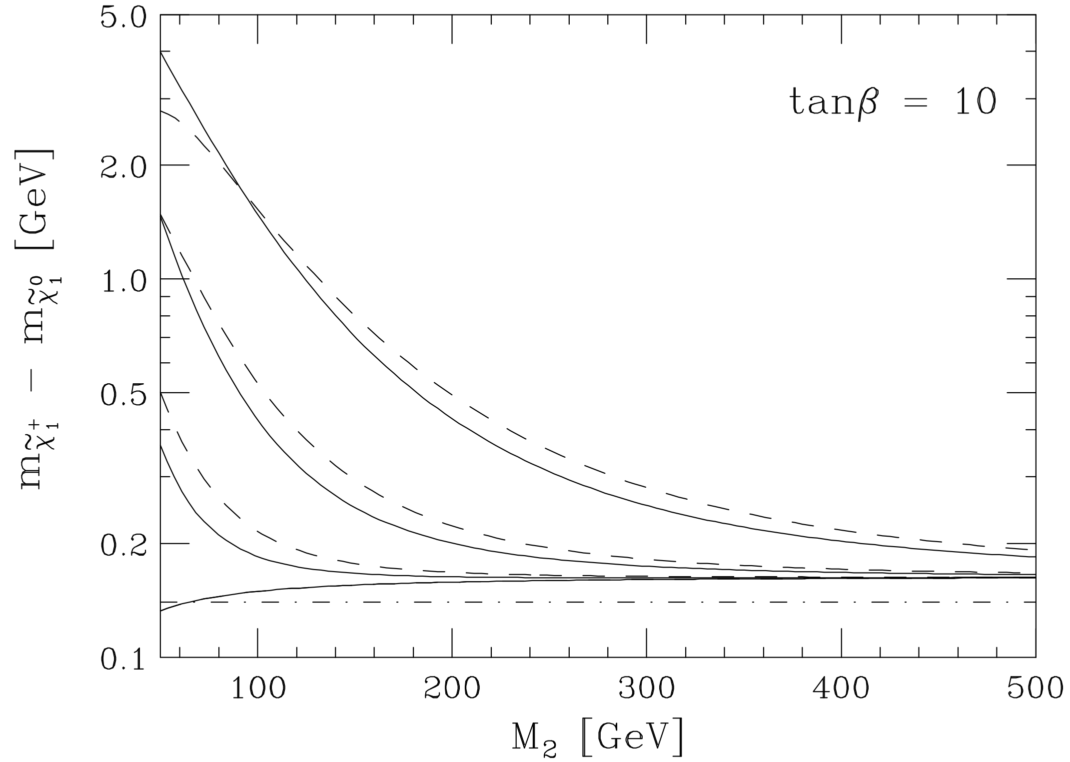
Conclusions

- Searching for dark matter is and will continue to be a main part of the physics program at colliders.
- SUSY-like models. General and representative.
  - 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.
- "Simplified models", new mediator.
  - Direct search for the mediator usually more powerful.
  - LHC will have interesting reach.

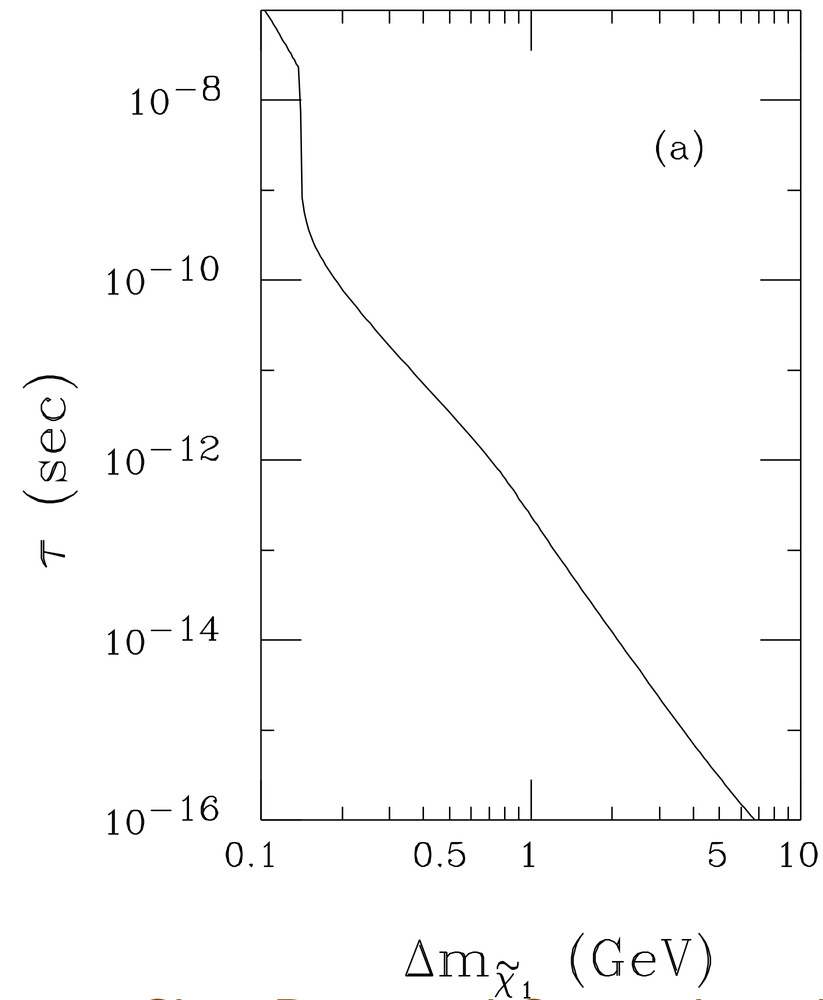
Go for the most exciting adventure!

extras

Wino decay



Gherghetta, Giudice and Wells, hep-ph/9904378



Chen, Drees and Gunion, hep-ph/9902309

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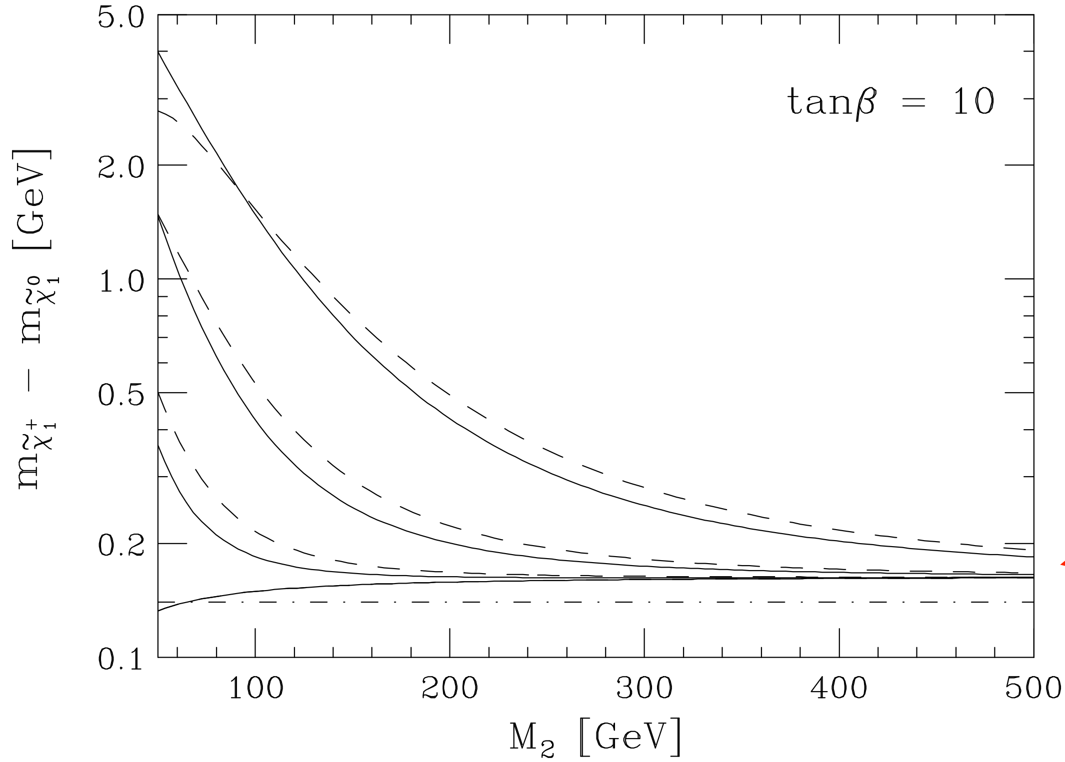
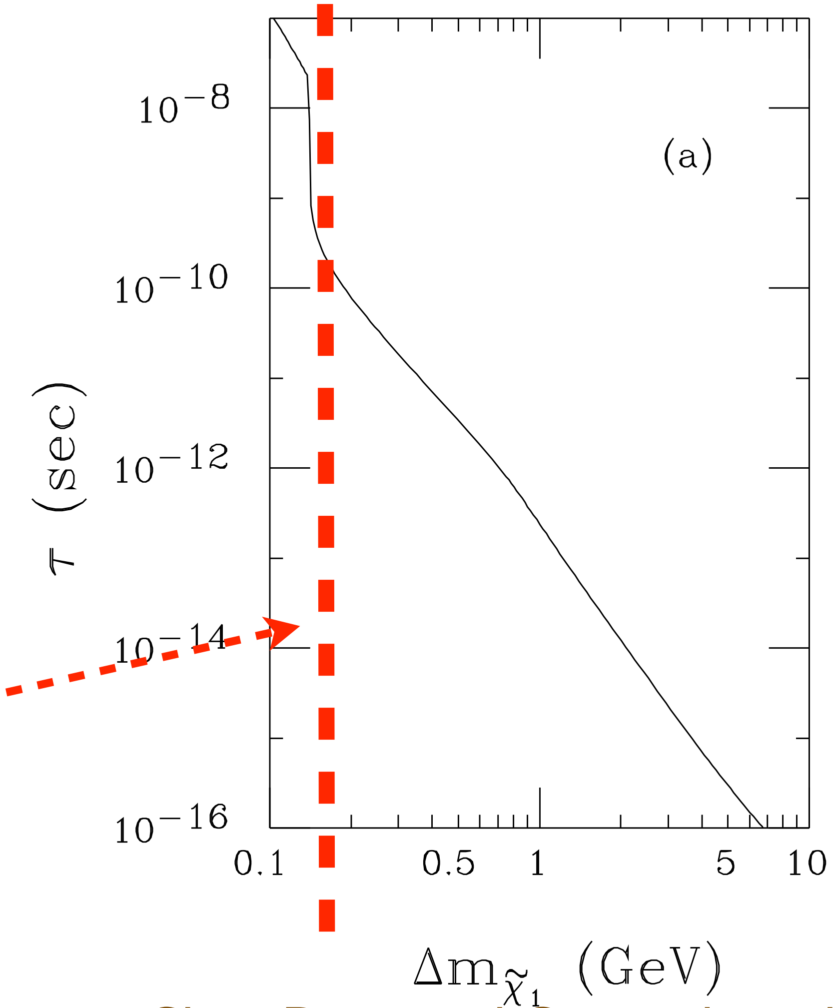
- Charge track ≈ 10(s) cm

Wino decay



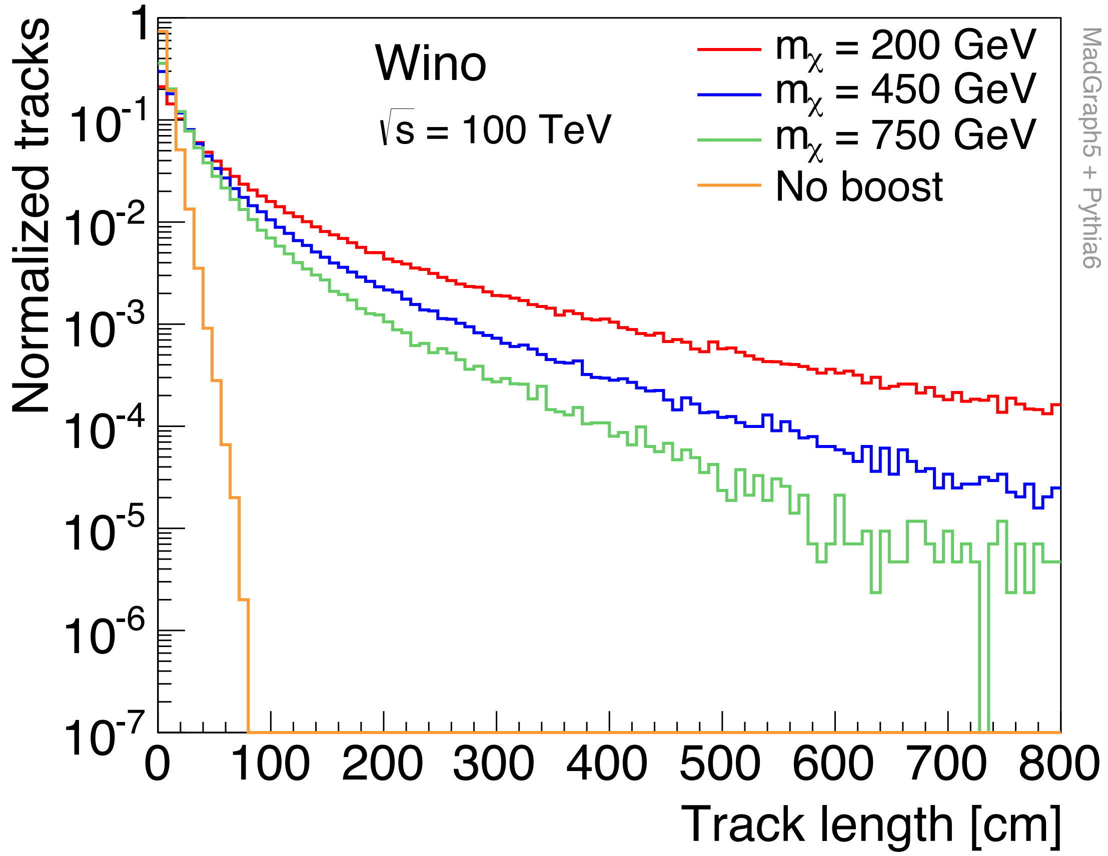
Gherghetta, Giudice and Wells, hep-ph/9904378

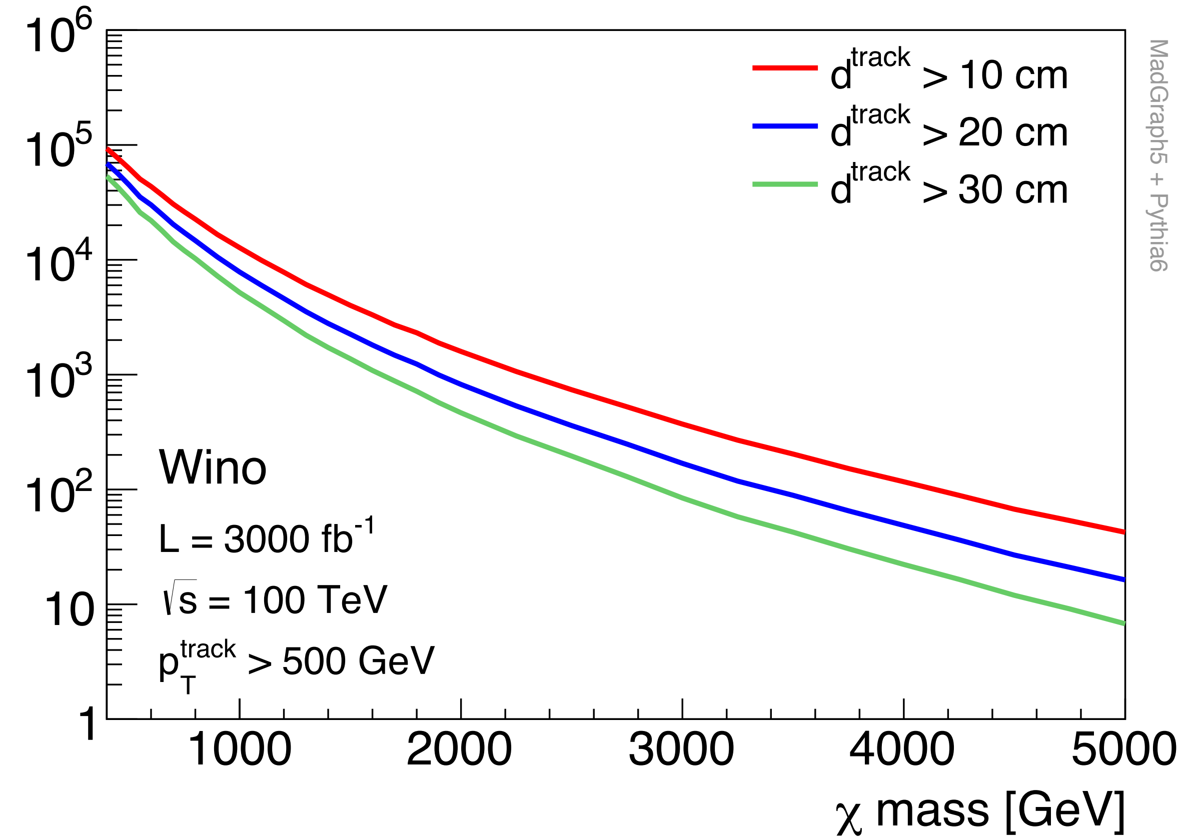


Chen, Drees and Gunion, hep-ph/9902309

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

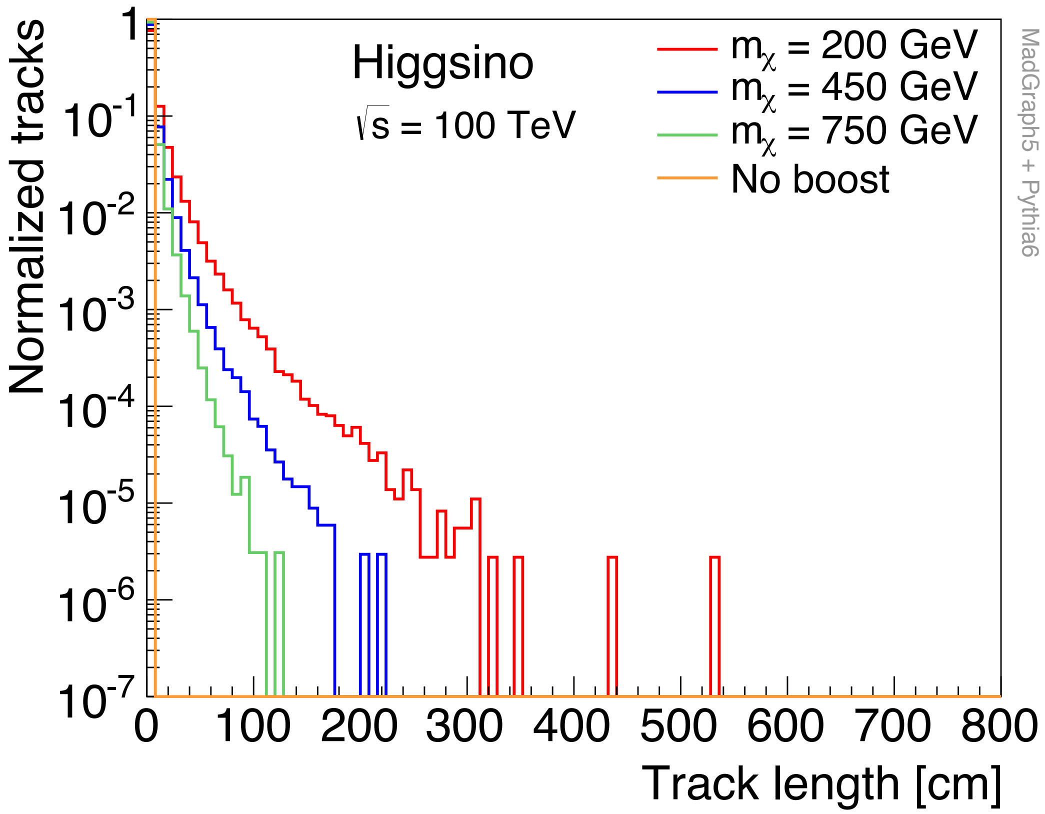
Rates (with long tracks)

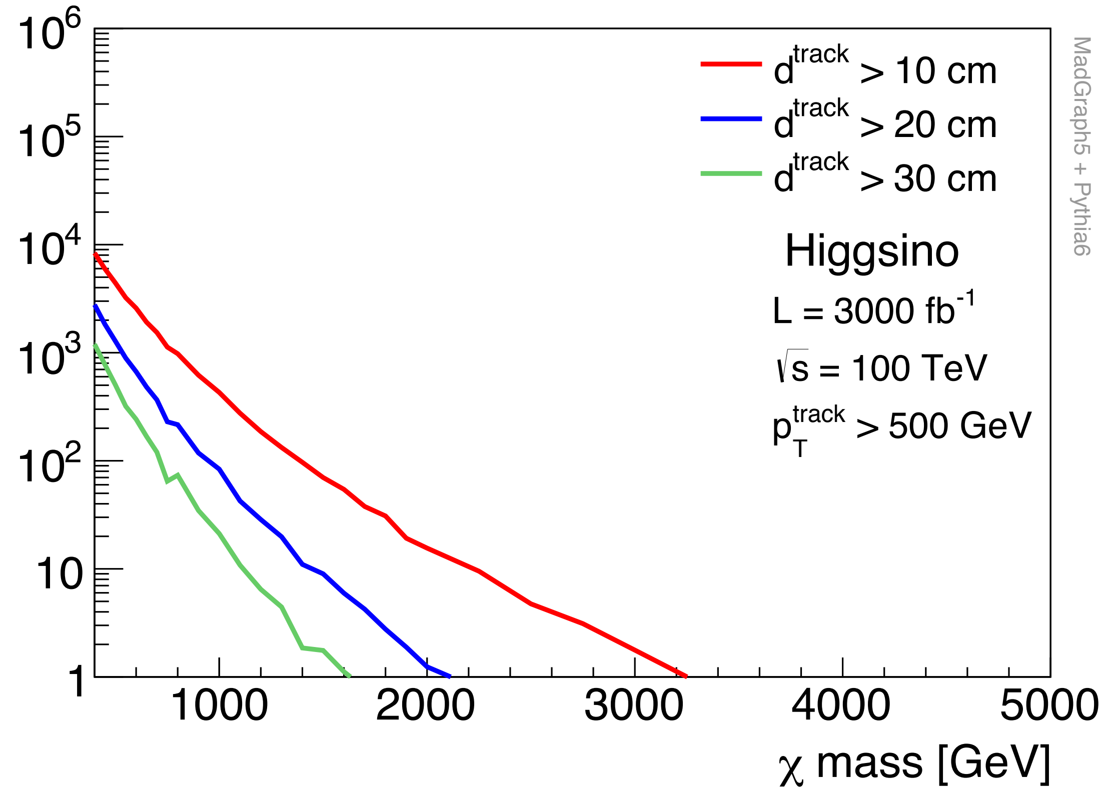




- Disappearing track, stub, kink...
- Could also be long lived

Tracks?





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

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_{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
$\not{E}_T$	250 – 550 GeV	350 – 1000 GeV	2 – 5 TeV

Table 5: Cuts used in monojet analysis. For $p_T(j_2)$ and $\not{E}_T$ 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	$\not{E}_T$	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	$\not{E}_T$	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: $\not{E}_T$ 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_{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
$\not{E}_T$	1250 GeV	350 GeV

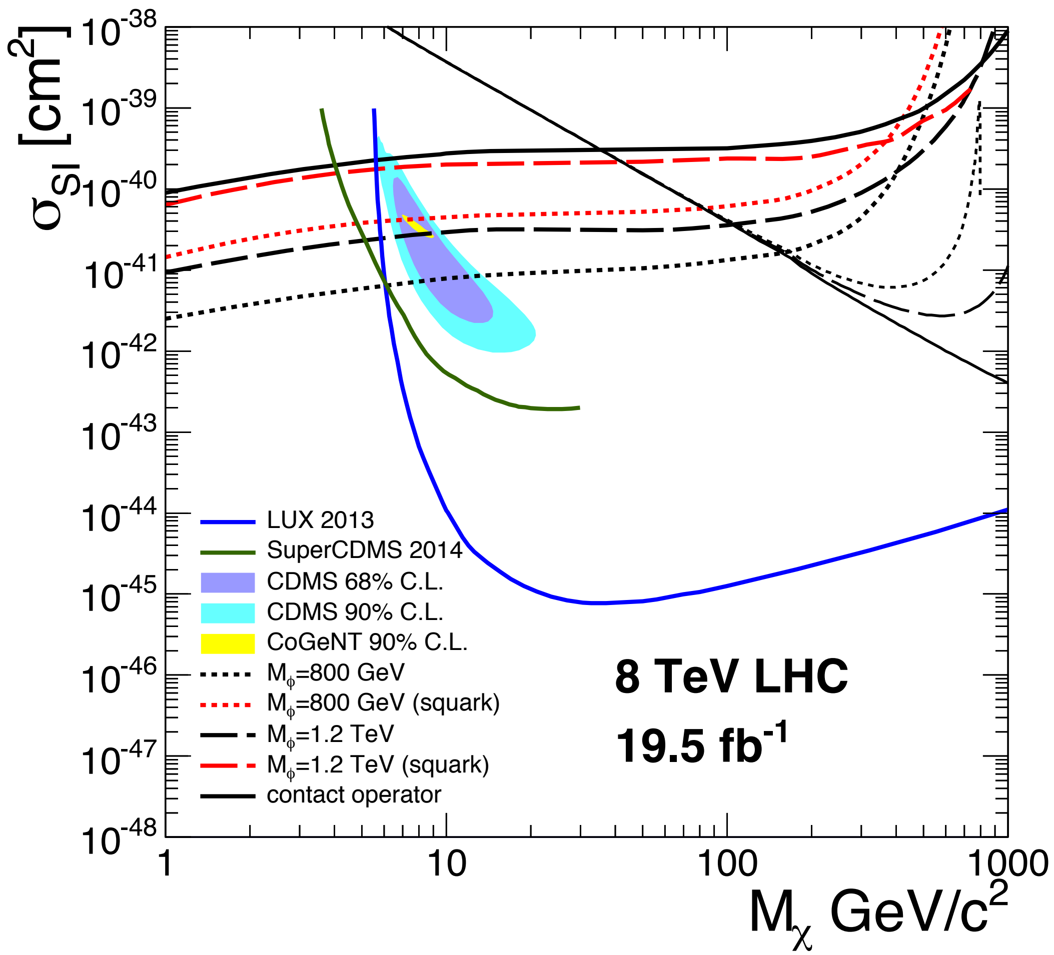
Table 7: Cuts used in soft lepton analysis.

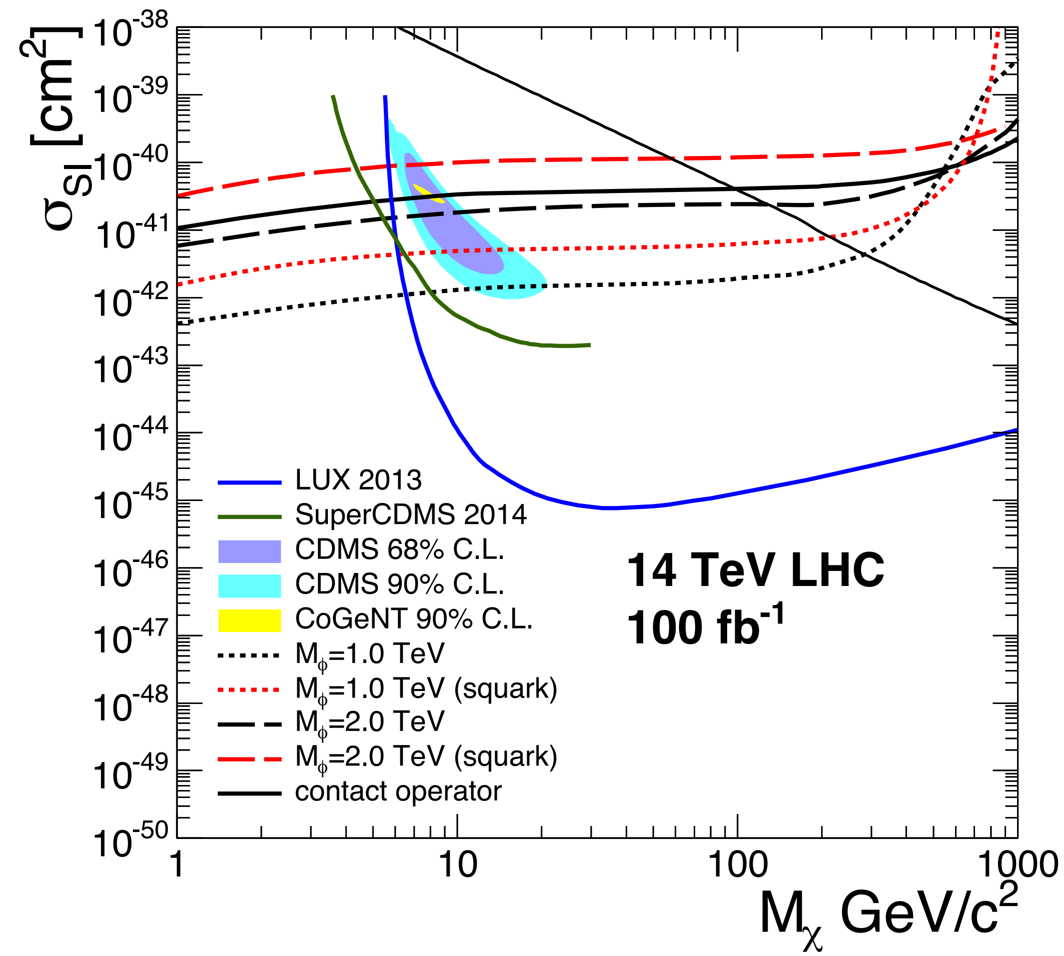
Cuts, disappearing track

Cut	8 TeV	14 TeV	100 TeV
$\not{E}_T$	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
$\Delta\phi_{\min}(j, \not{E}_T)$	1.5	1.5	1.5
η^{track}	$\in (0.1, 1.9)$	$\in (0.1, 1.9)$	$\in (0.1, 1.9)$
p_T^{track}	75 – 200 GeV	250 GeV	1.5 TeV

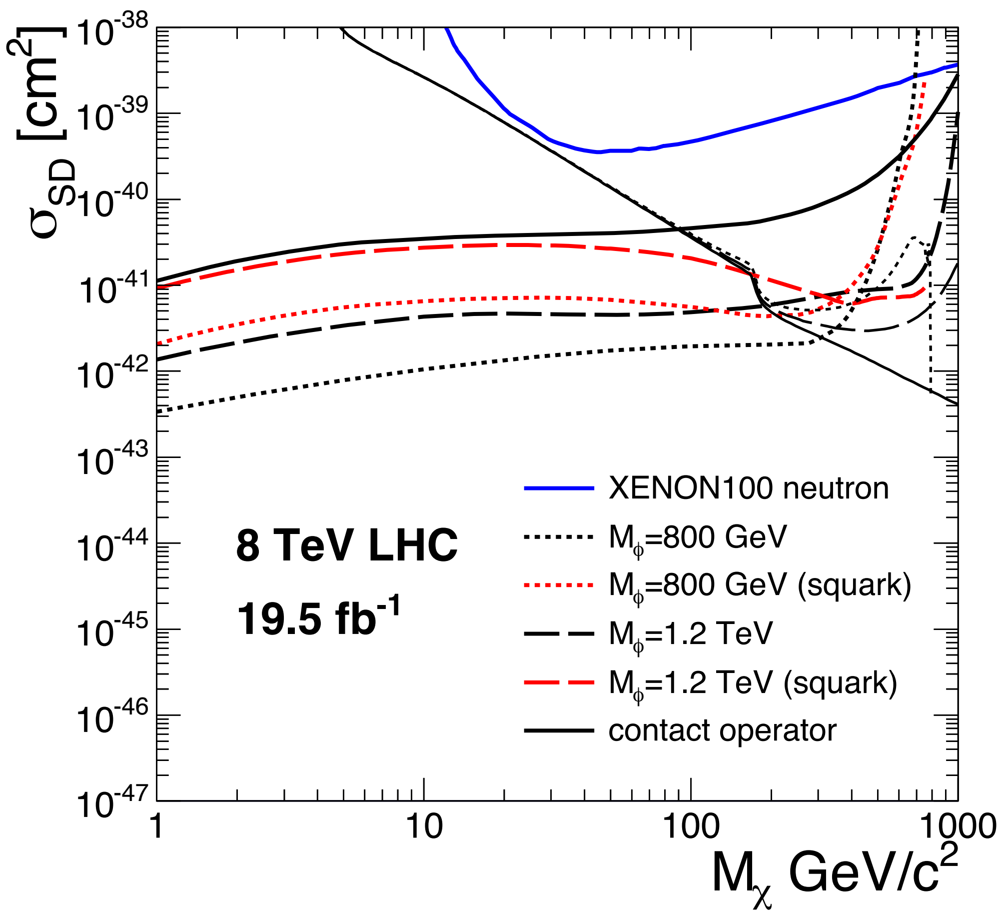
Table 8: Cuts used in disappearing track analysis.

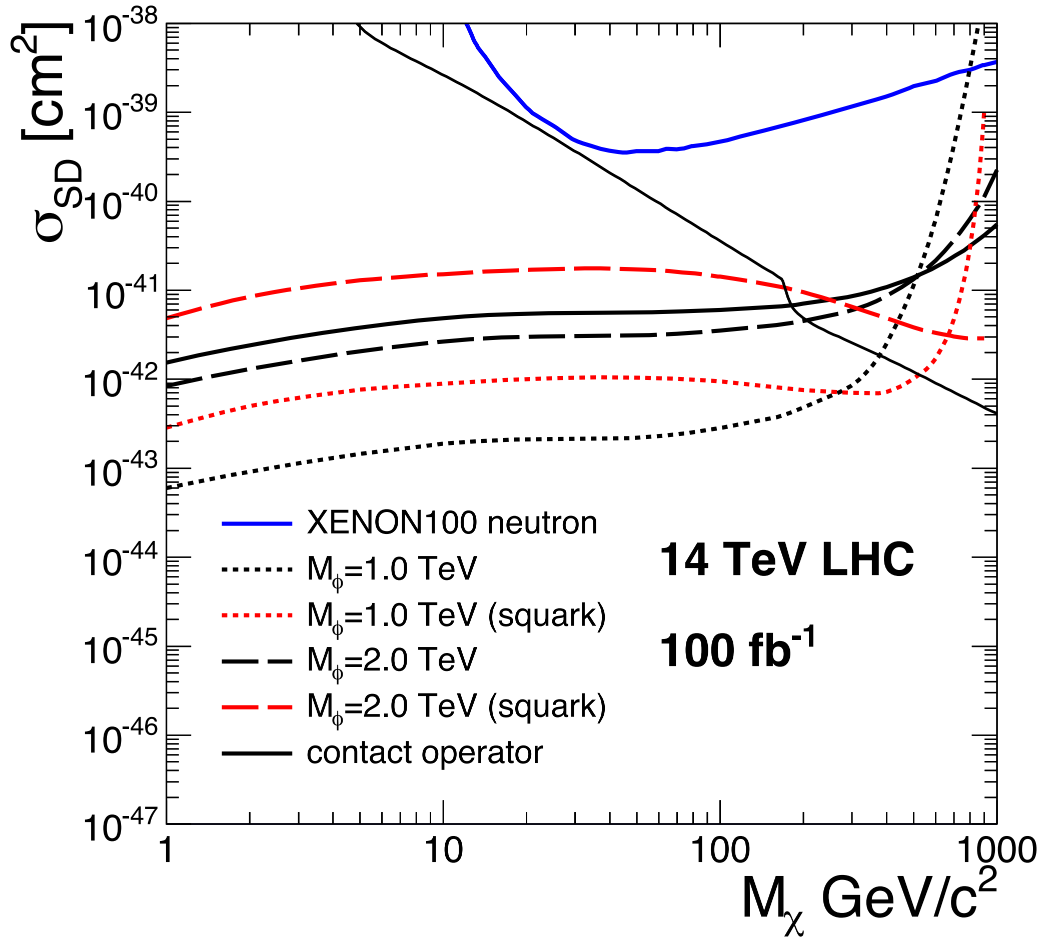
Spin independent





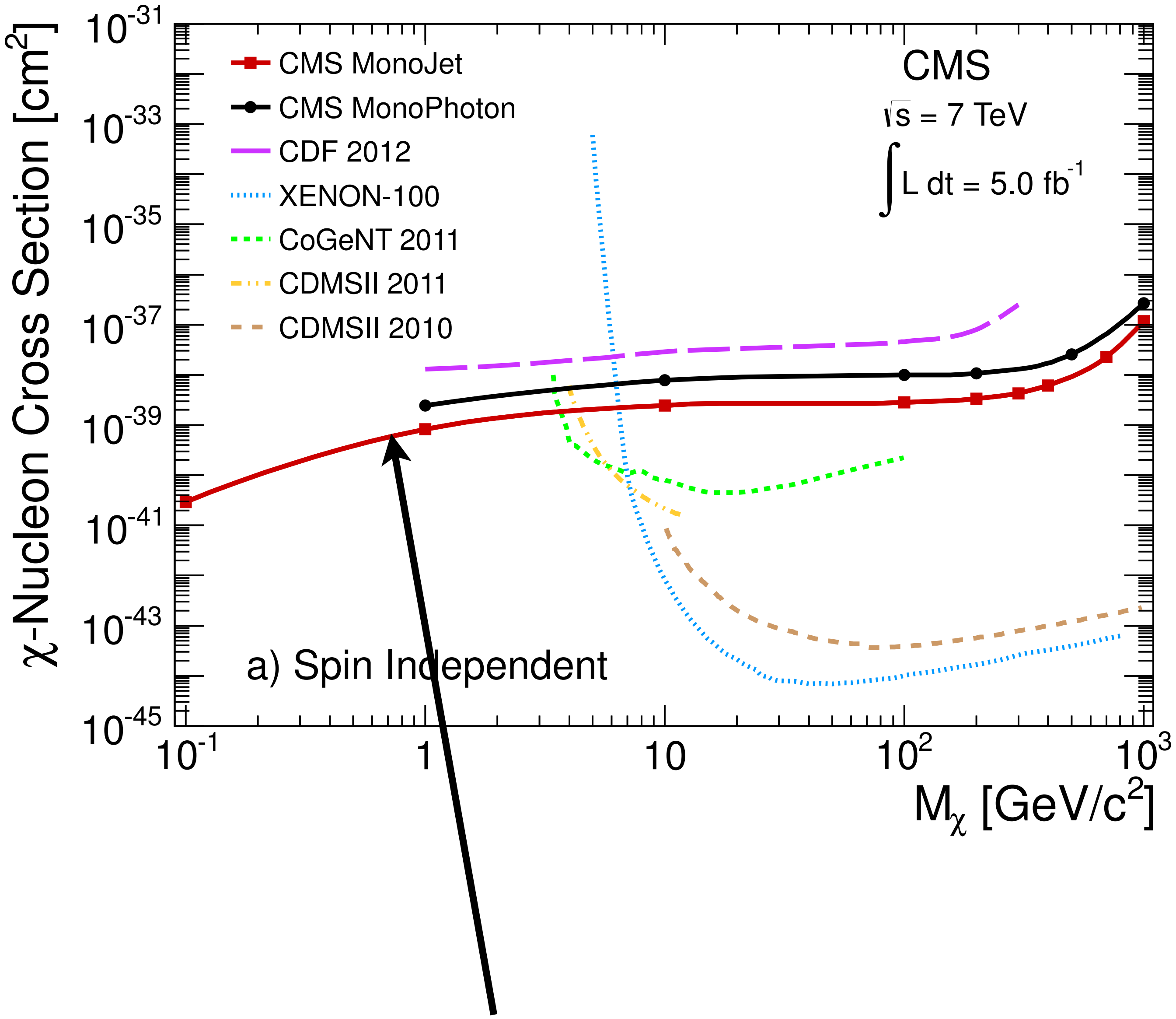
Spin dependent

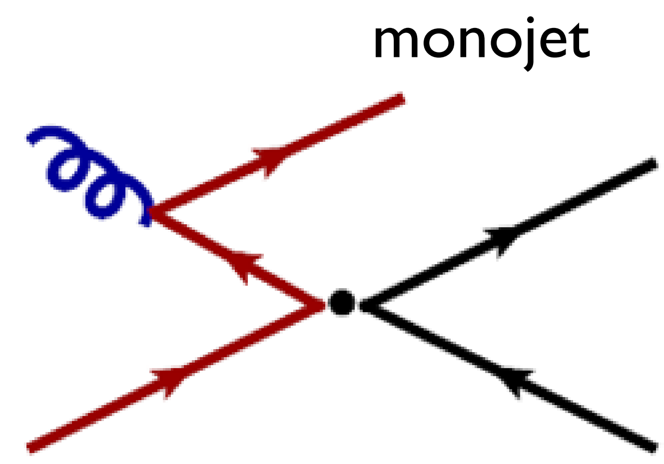




- Leading direct detection channel for Majorana DM.

For example

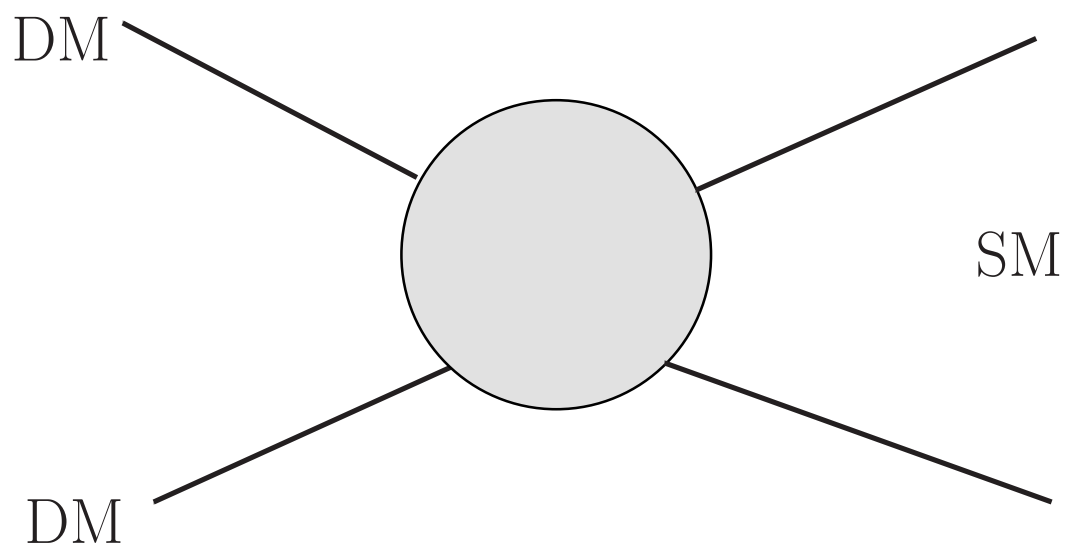




D1	$\bar{\chi}\chi\bar{q}q$
D5	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

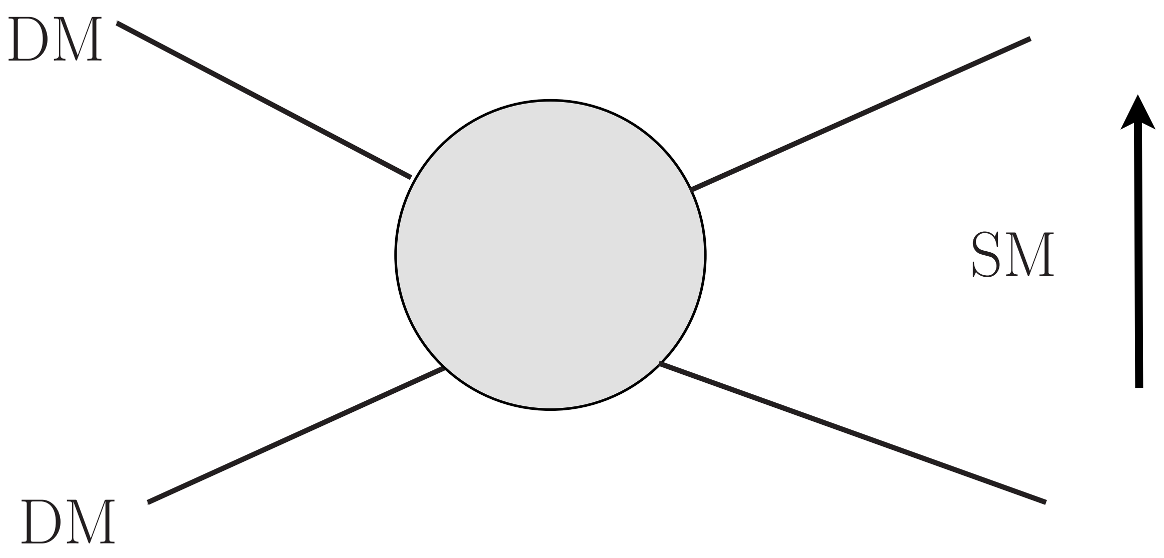
For small m_X,
collider rates controlled by larger mass scales, i.e., p_T cut;
does not depend on m_X.
Collider bounds flat and stronger.

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

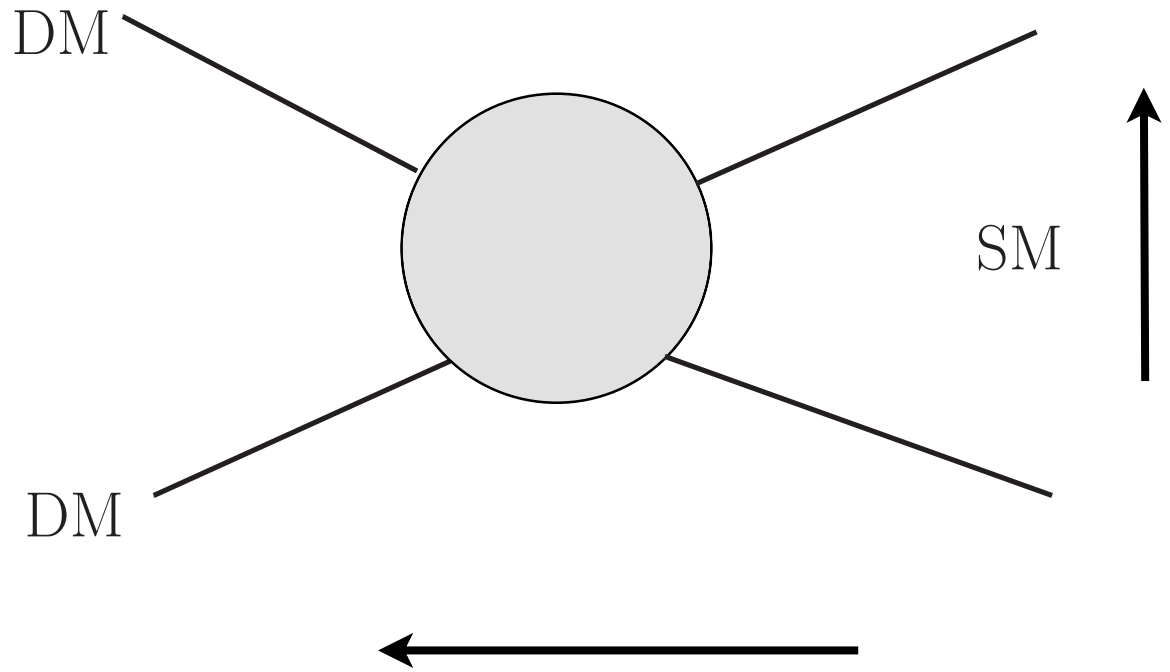


momentum exchange
q~100 MeV << m_Φ
effectively,

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

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~100 MeV << m_Φ
effectively,

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

Use colliders to constrain and probe the same operator

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

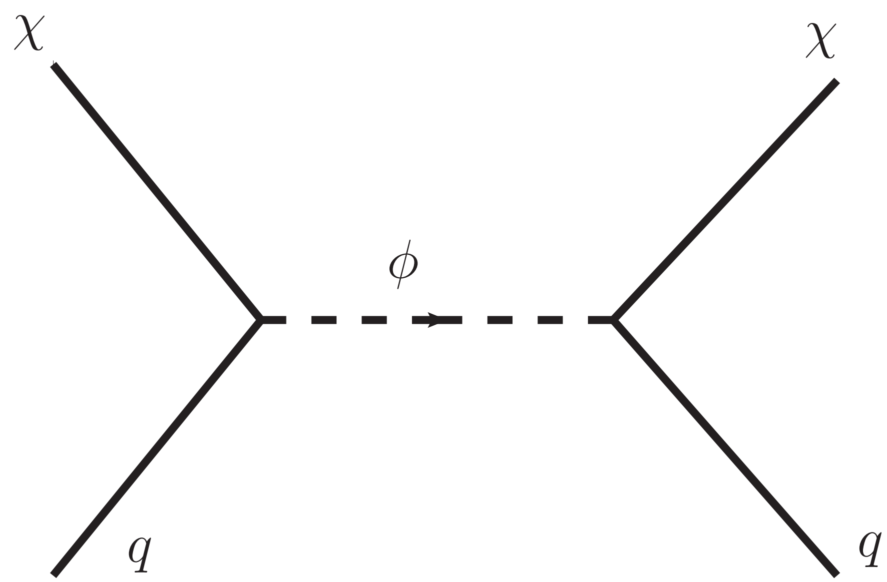
Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
Bai, Fox, Harnik, 1005.3797 .....

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.

t-channel

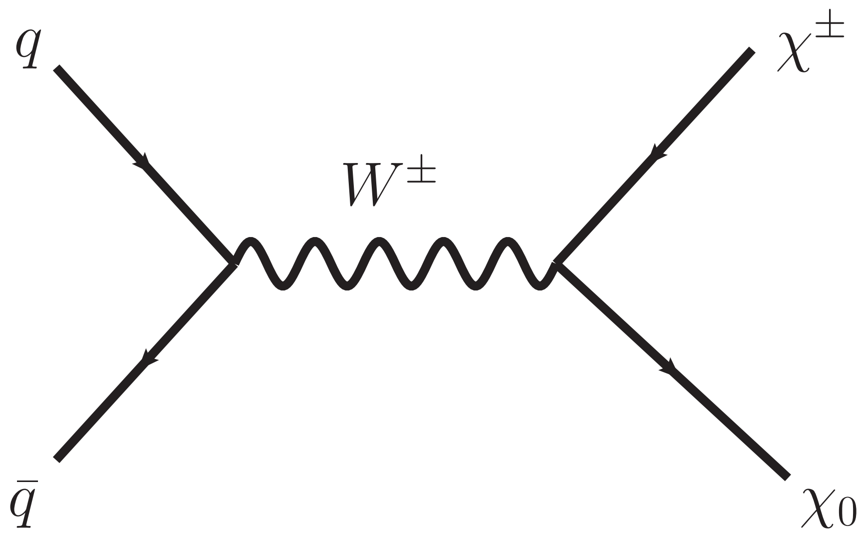
Chang, Edezhath, Hutchinson, Luty, 1307.8120
An, Zhang, LTW, 1308.0592
Bai, Berger, 1308.0612
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679
Papucci, Vichi, Zurek, 1402.2285

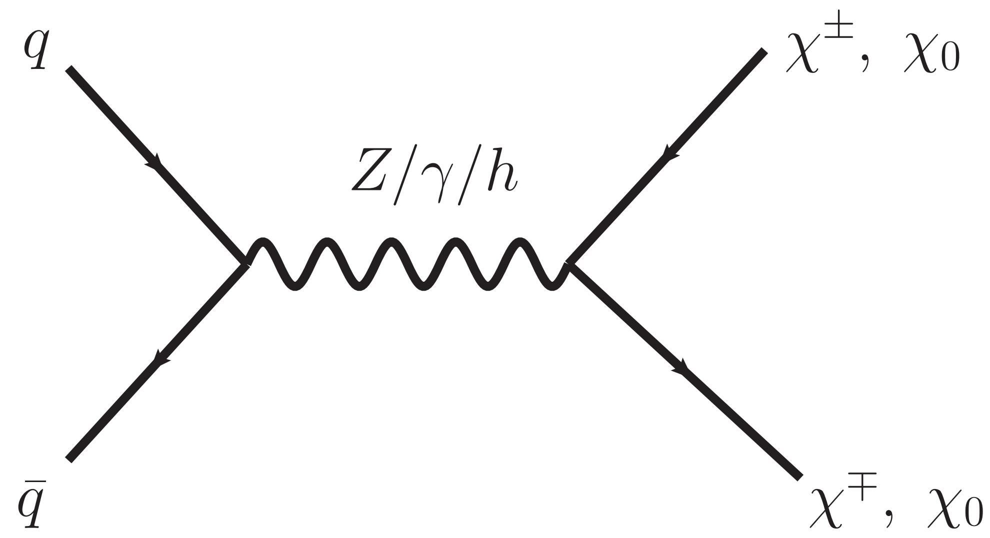


$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

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

No additional mediator

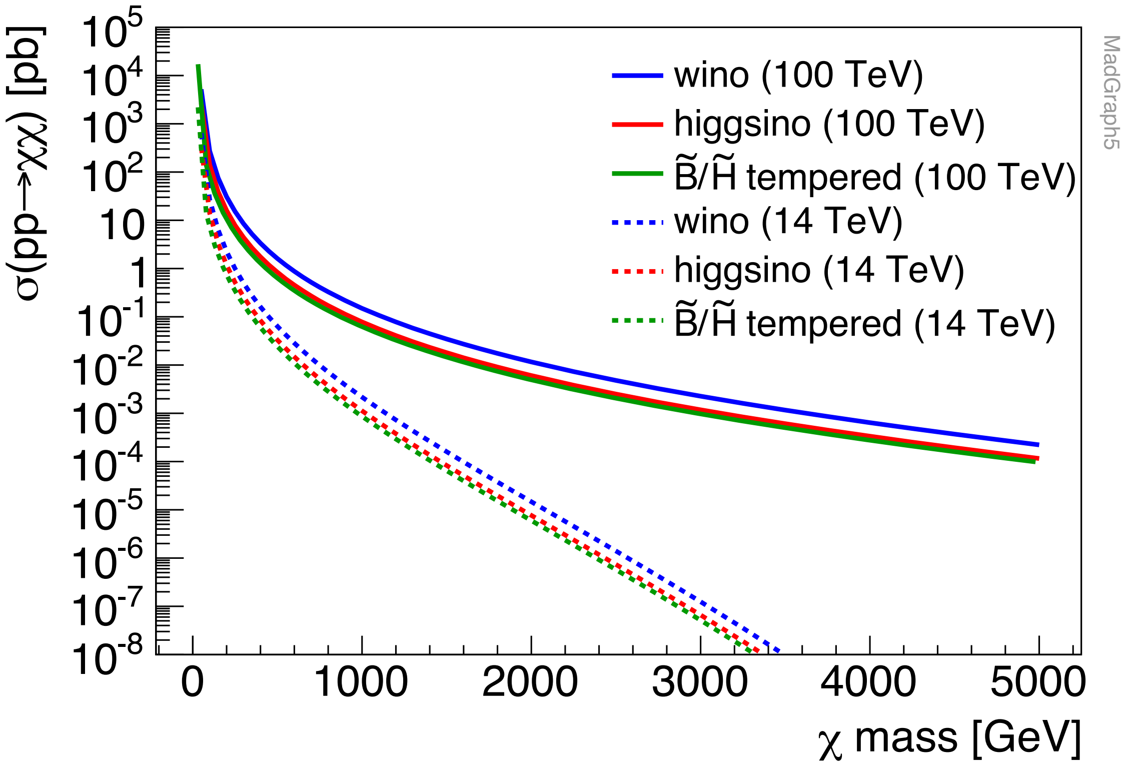


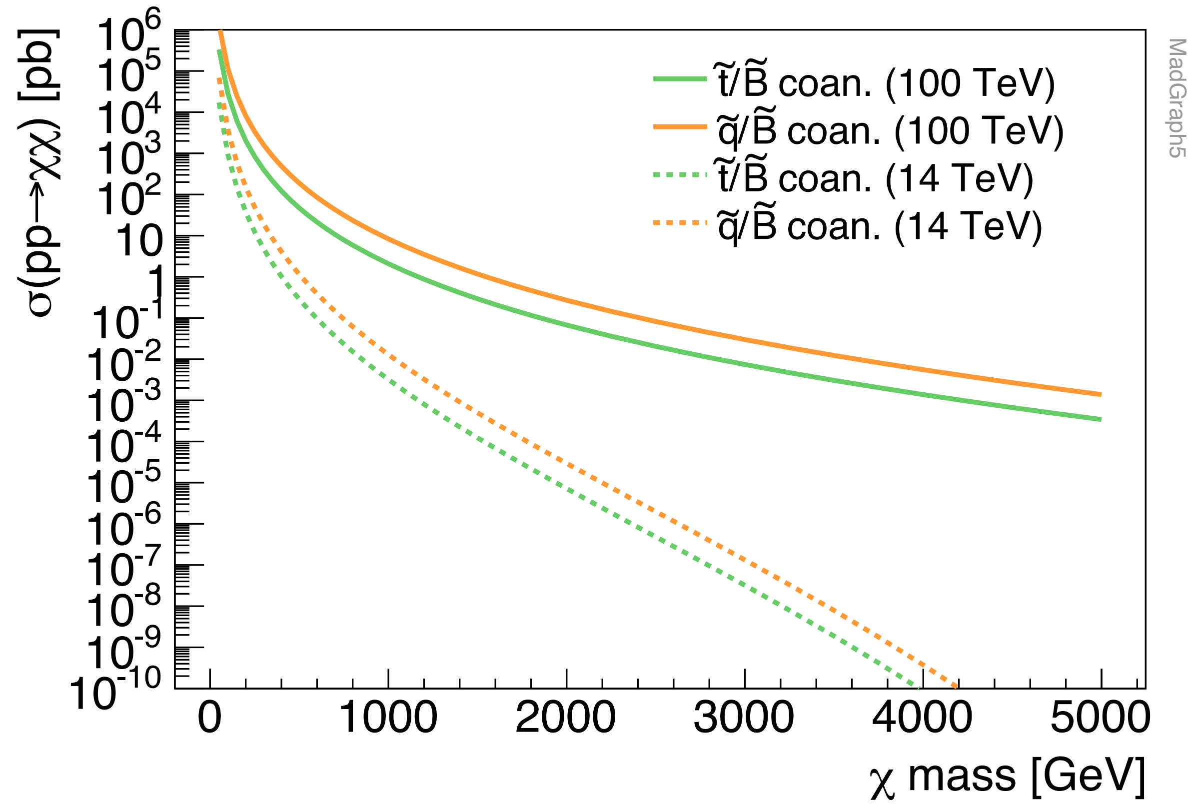


- In simple scenario of SUSY, there is no additional new mediator to search.
  - Mediated by W/Z/h.

- In principle, there are also gluino and squarks....
  - They can be heavy and play no role in dark matter physics.

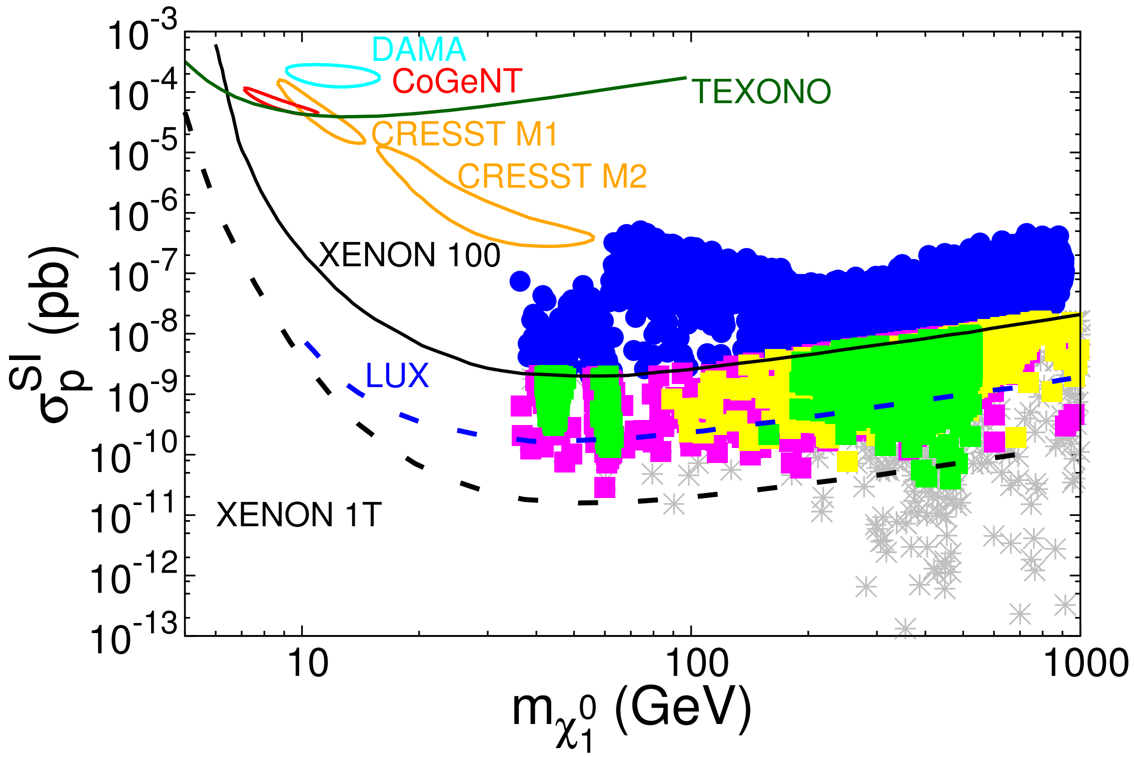
Considering 14 and even higher





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

Narrowing parameter space.



Han, Liu, Natarajan, 1303.3040

Cheung, Hall, Pinner, Ruderman, 1211.4873