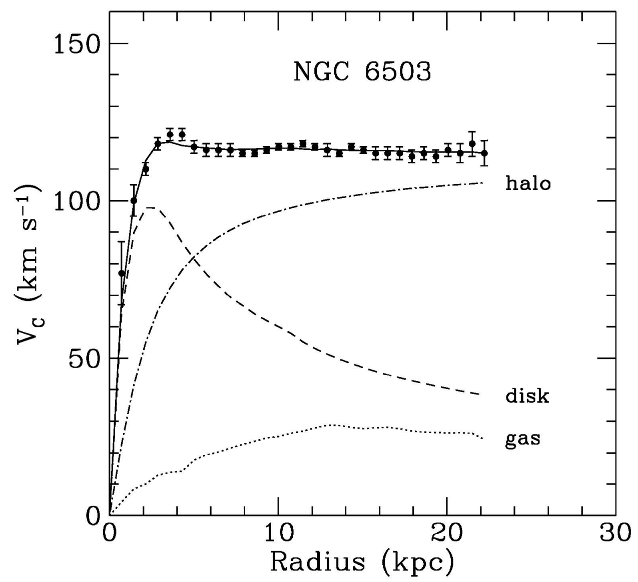
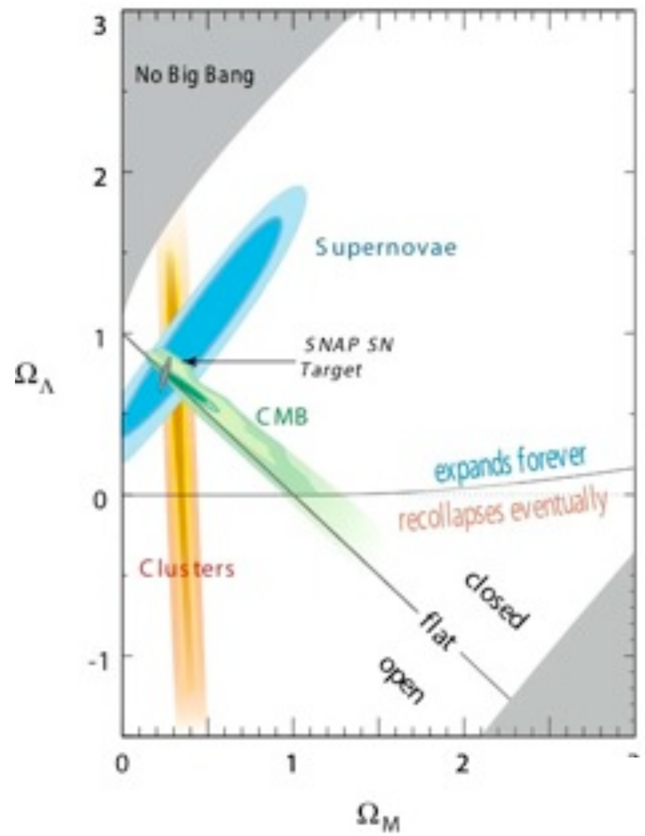
Dark matter at Colliders

Lian-Tao Wang
University of Chicago

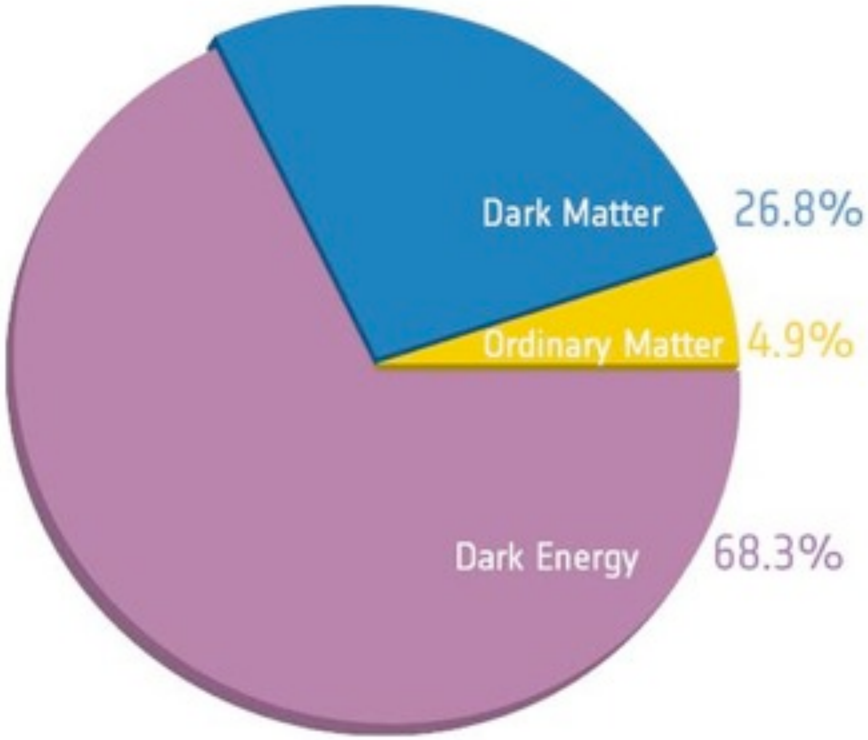
MITP, Mainz June 30, 2014

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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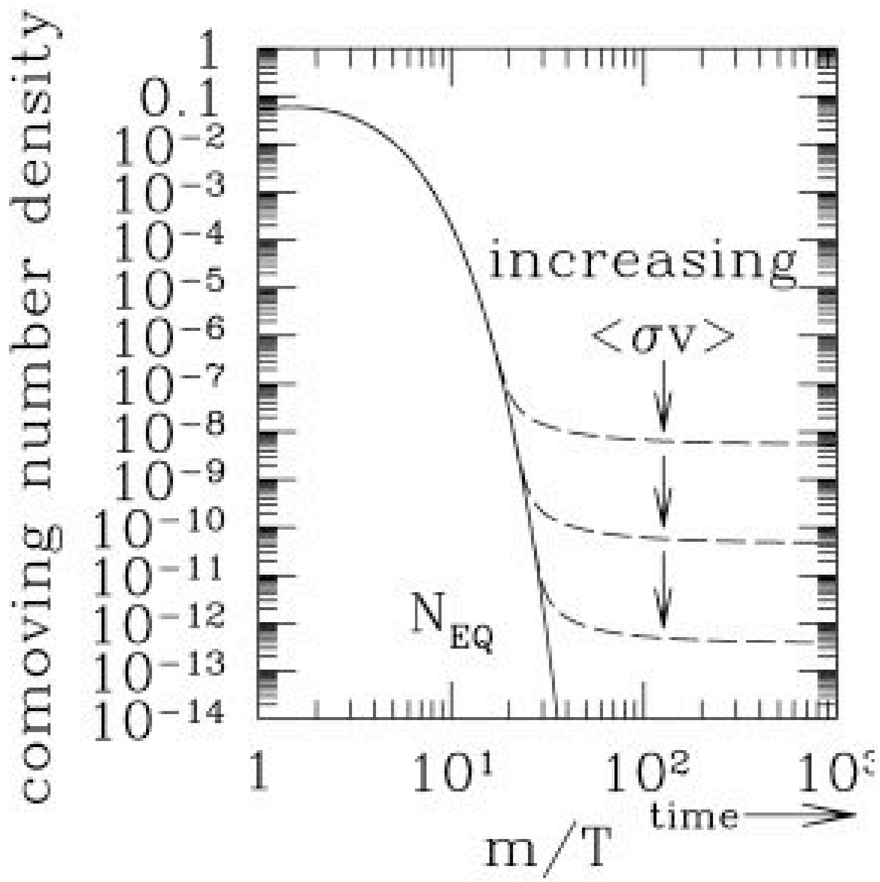
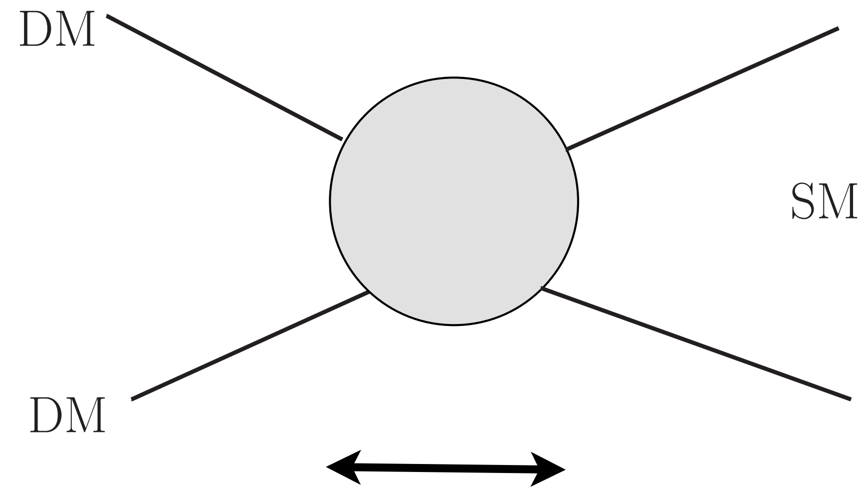
- We know very little. Vast range of possibilities
  - Can be 10^{-31} GeV to 10^{48} GeV.
- WIMP, a compelling story.
  - Not so different from the particles we know
    - Weak scale mass, couplings not too large or small
    - Measure the properties in the lab.
  - Not so dependent on the history of the early universe.
    - Because we don't know too much about it.
    - Idea: thermal equilibrium in early universe.

WIMP miracle



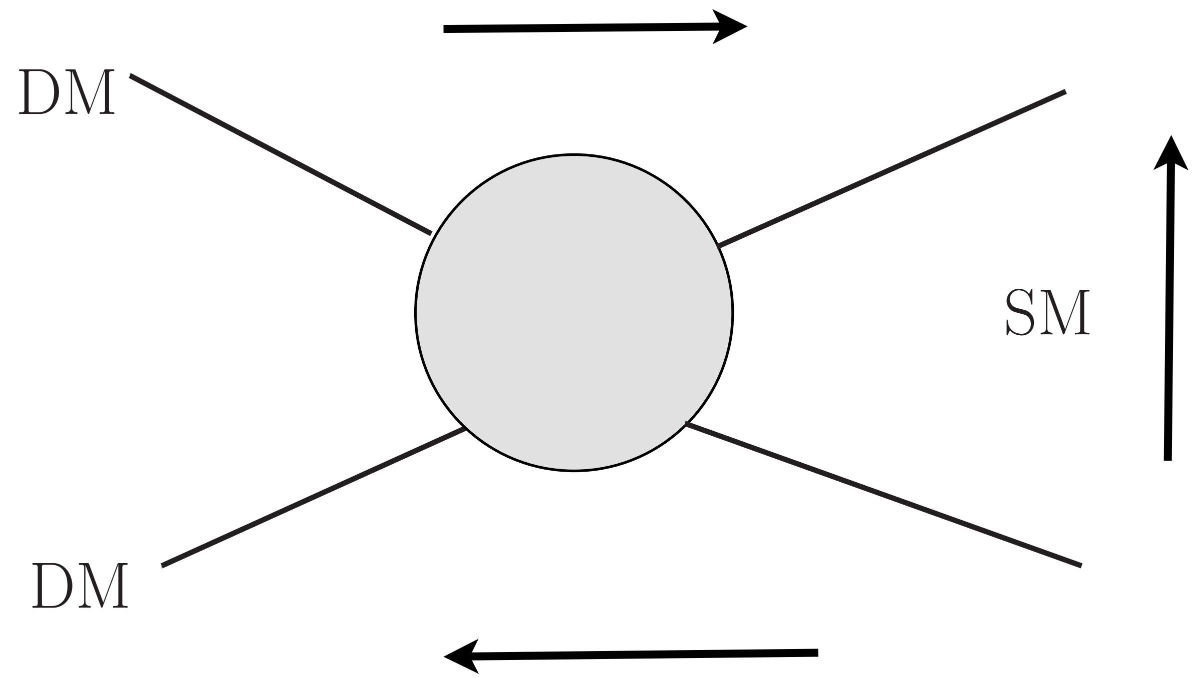


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- 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!

Searching for WIMP dark matter

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



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

Collider searches:
LEP
LHC
Tevatron

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"excesses"
come and go...

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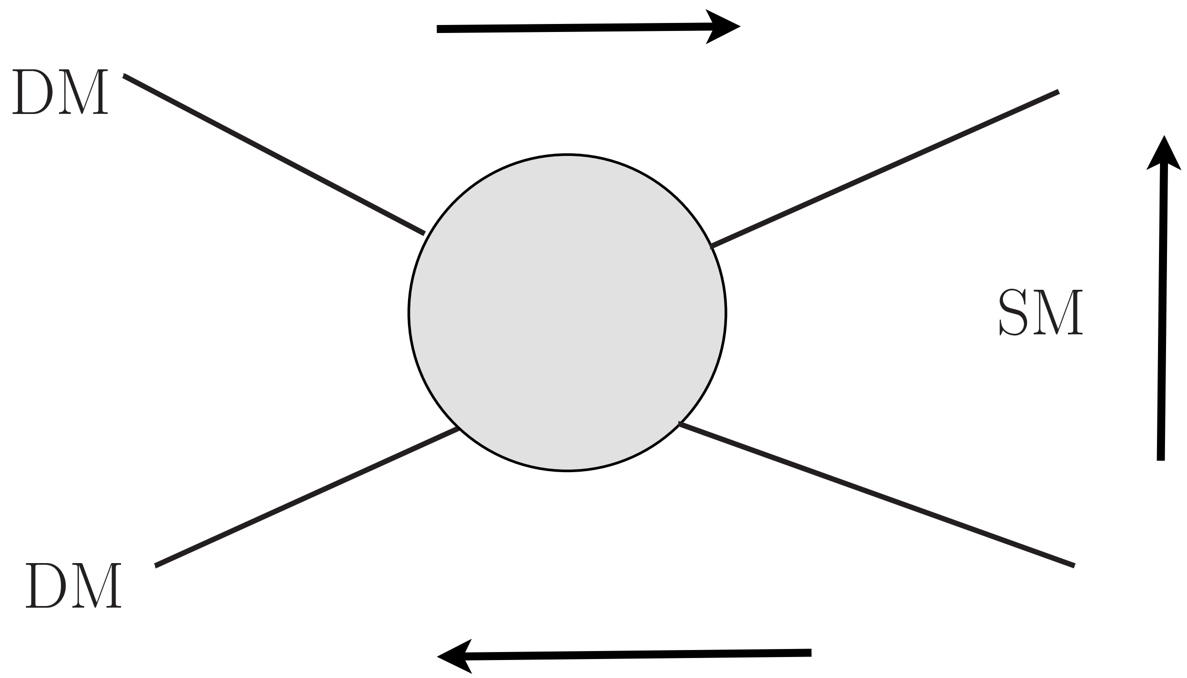

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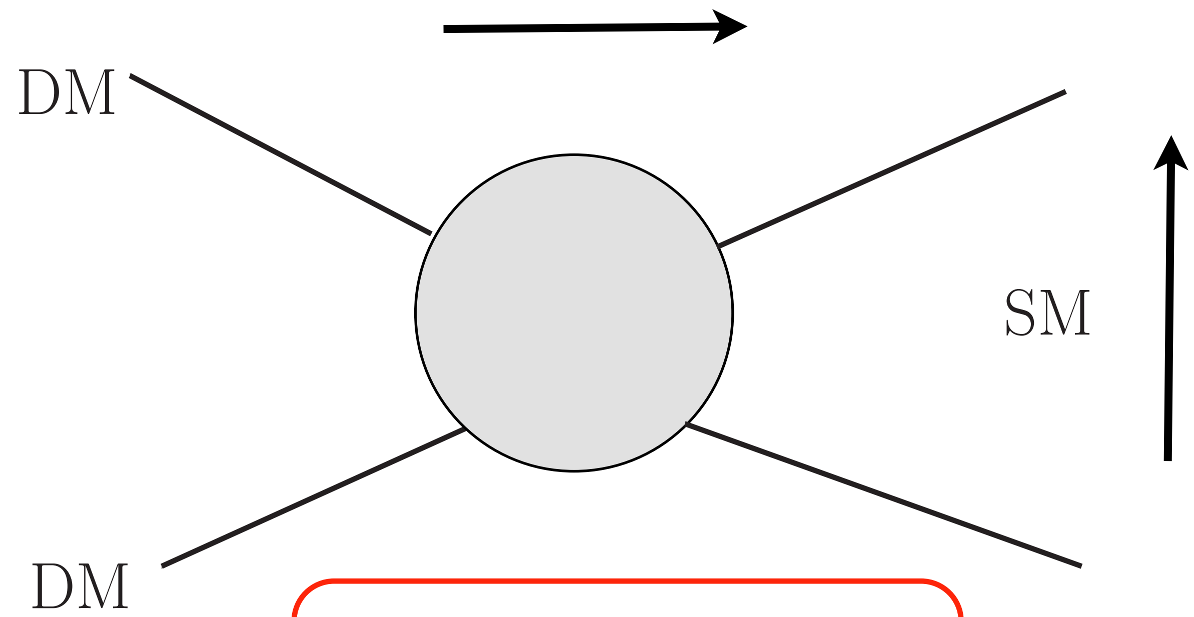

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CDMS
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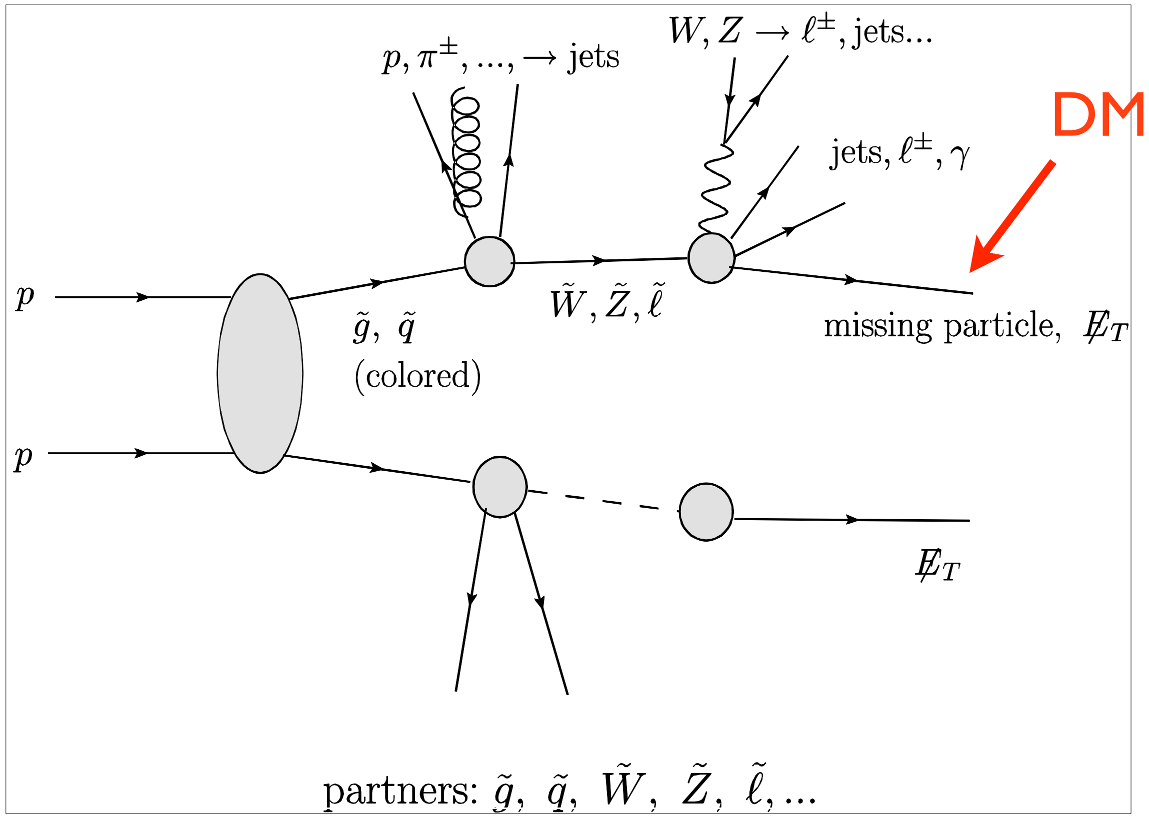
This talk.

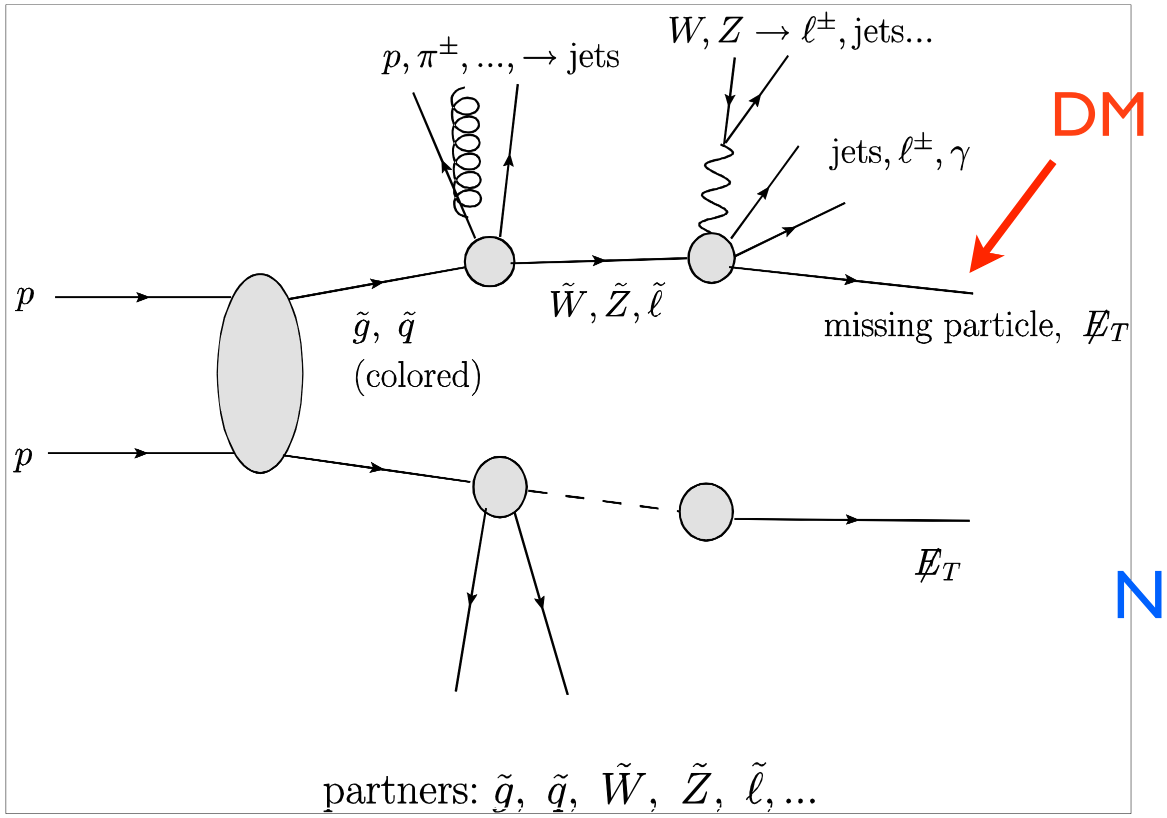
“standard” story.



SUSY, UED, etc.

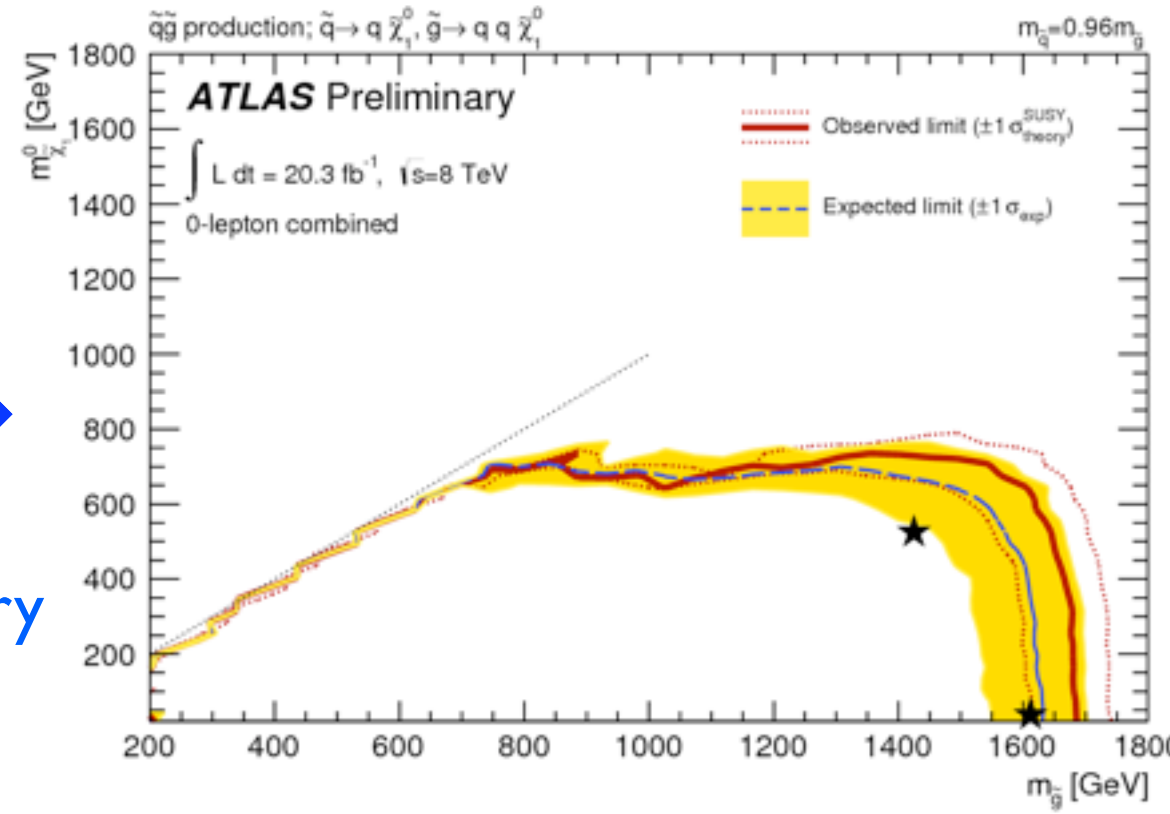
- WIMP is part of a complete model at weak scale.
- It's produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- The reach is correlated with the rest of the particle spectrum.

"standard" story.



SUSY, UED, etc.

No discovery yet



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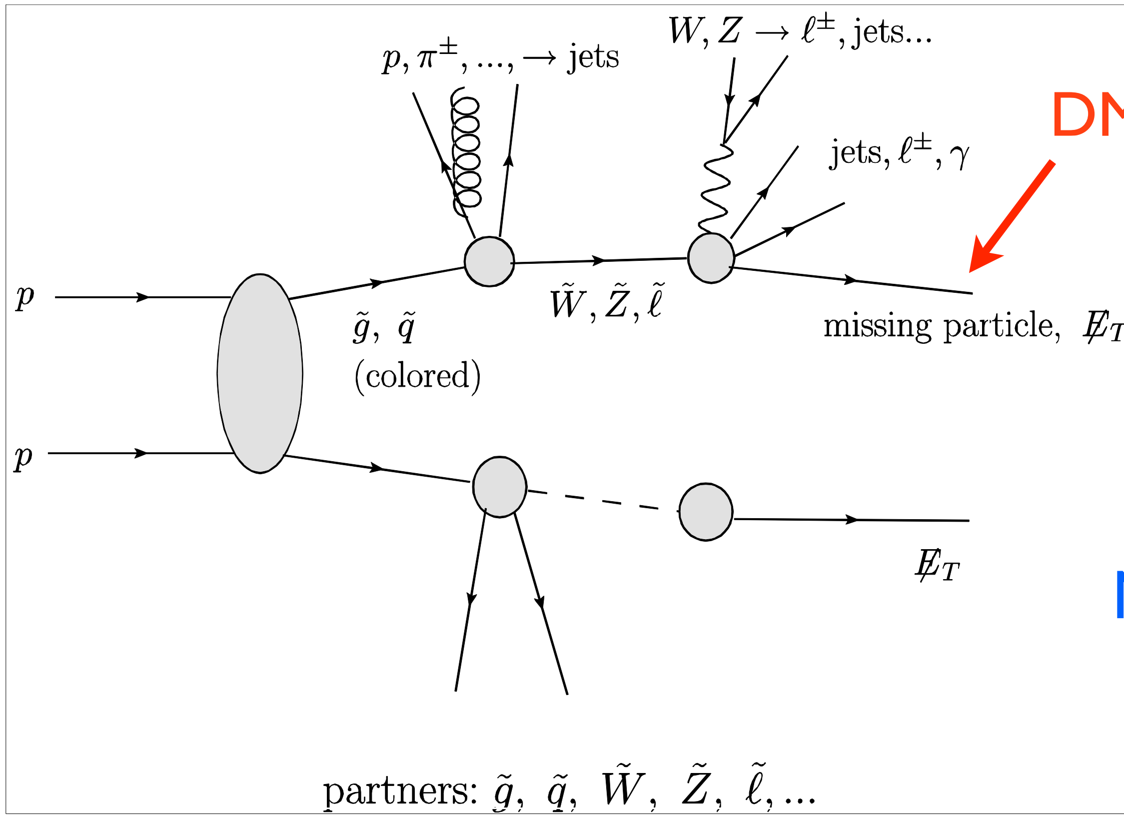
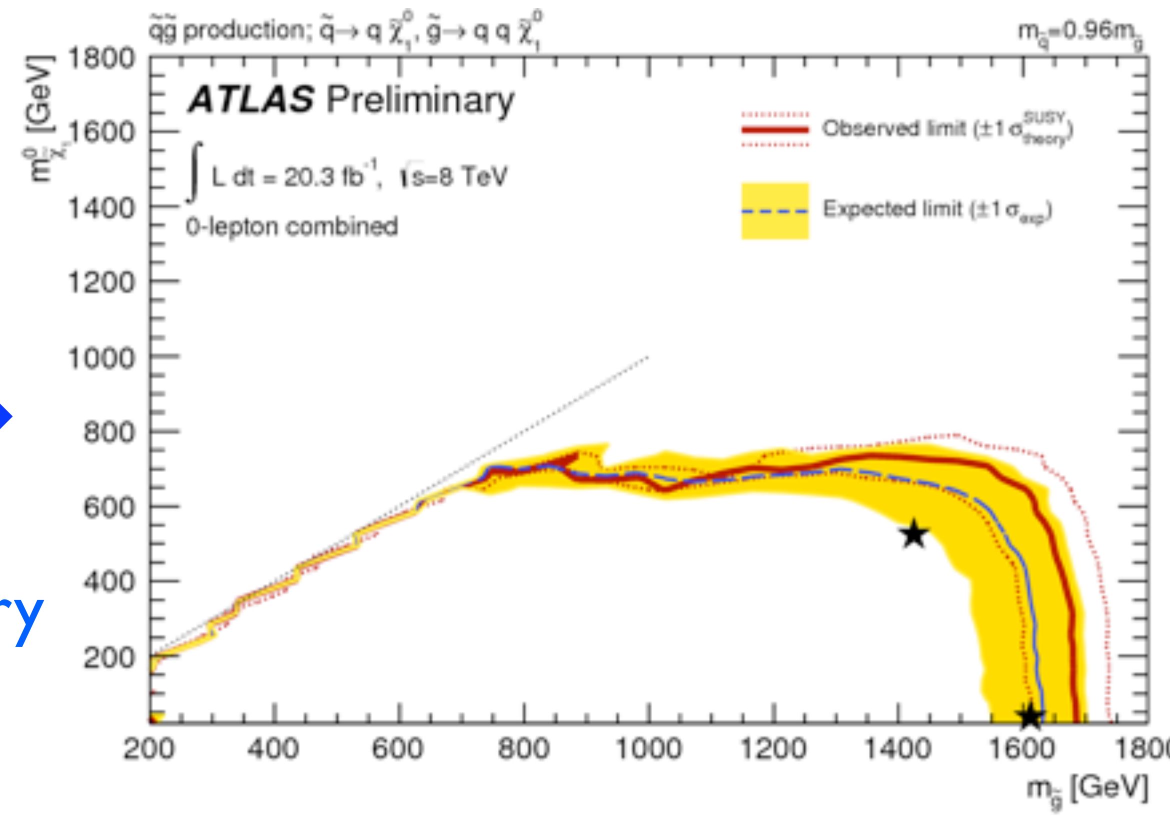


DM

SUSY, UED, etc.

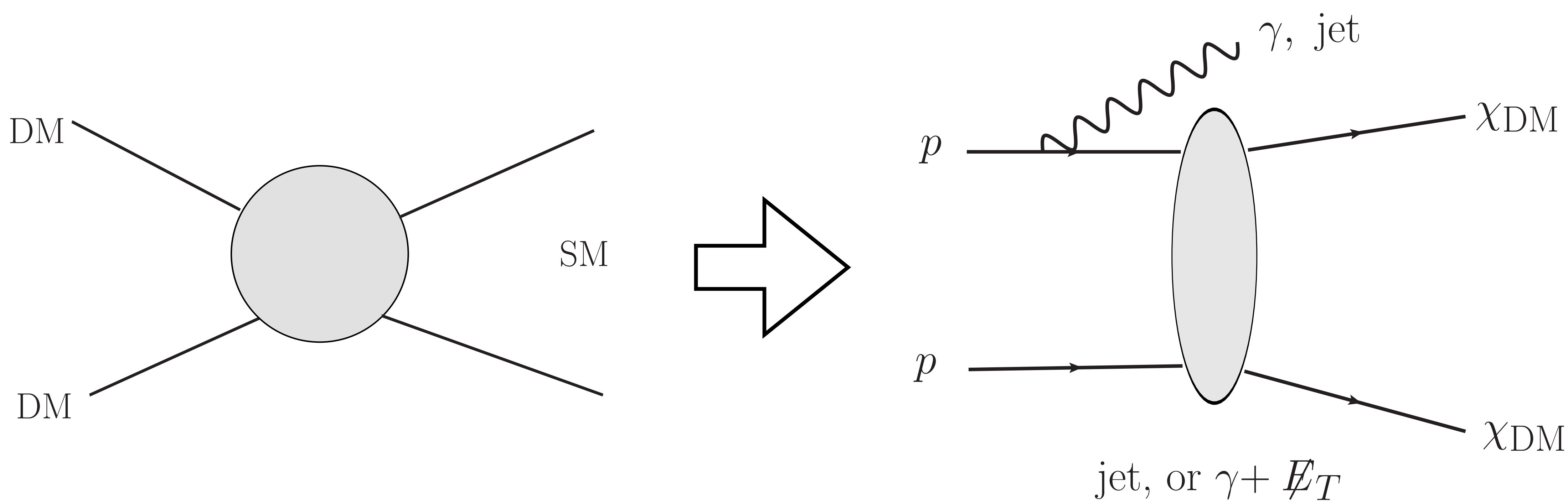
No discovery yet



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

Back to the basics

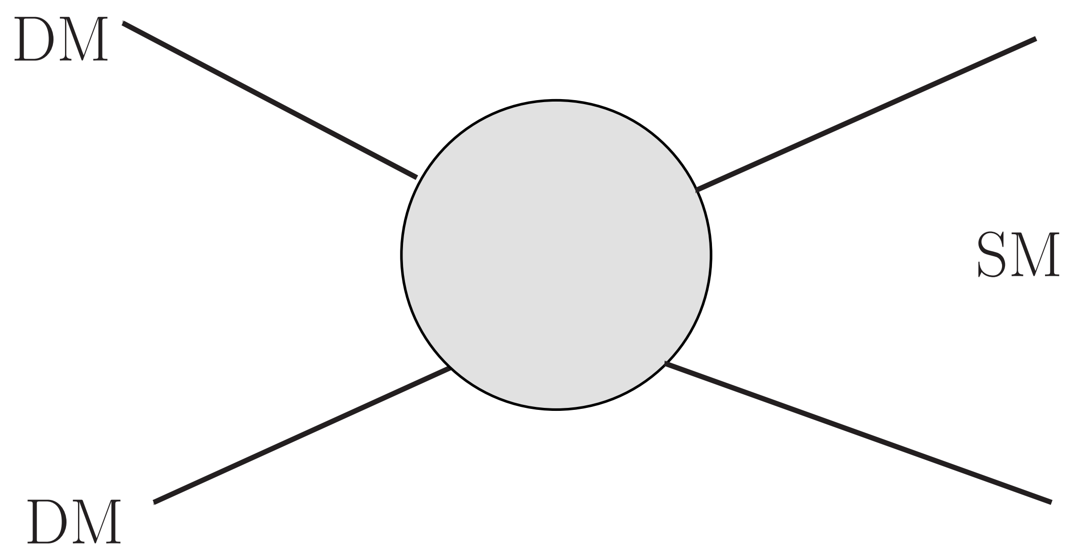
- pair production + additional radiation.



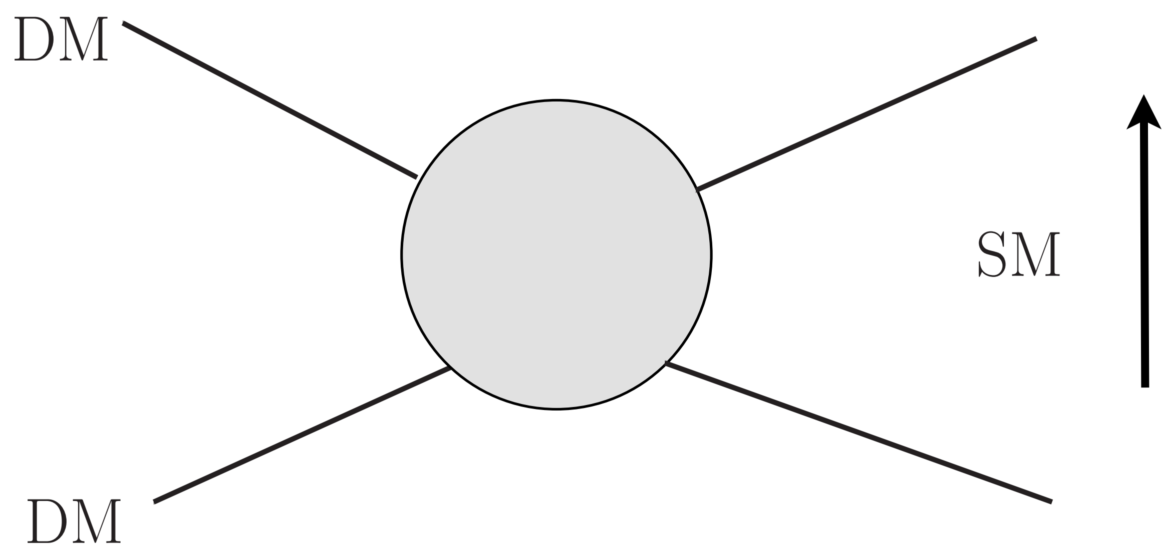
- Mono-jet, mono-photon, mono-...

- Have become "Standard" LHC searches.

Effective operator approach



Effective operator approach



momentum exchange
q~100 MeV << m_Φ
effectively,

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

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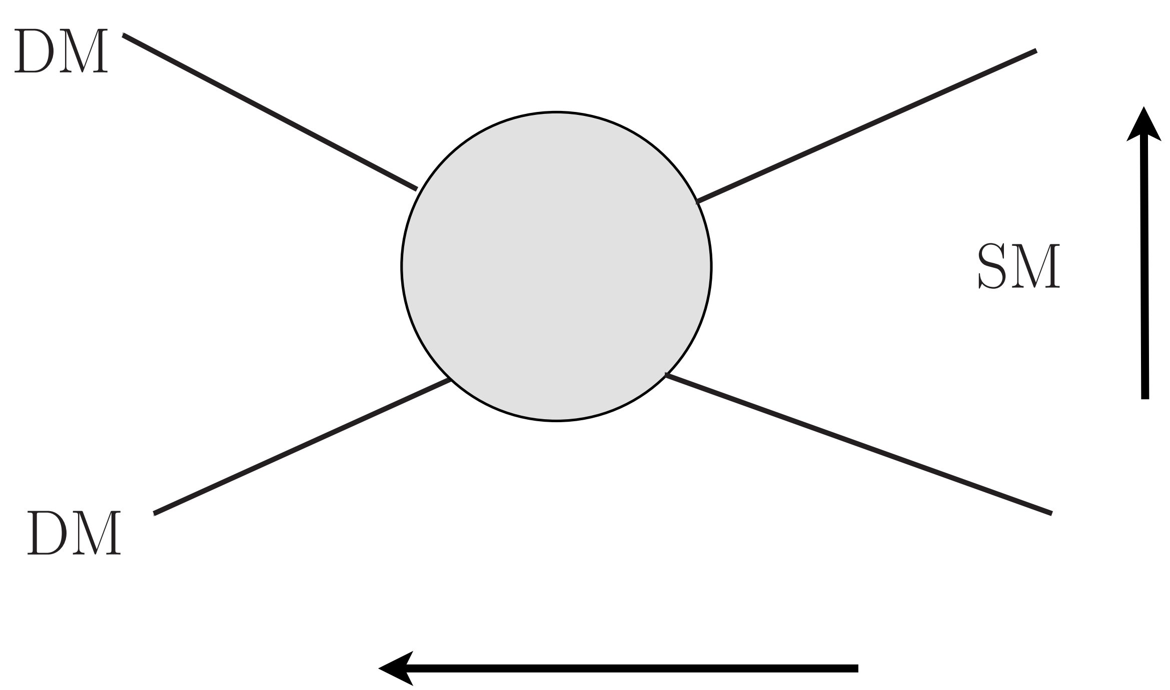

momentum exchange
q~100 MeV << m_Φ
effectively,

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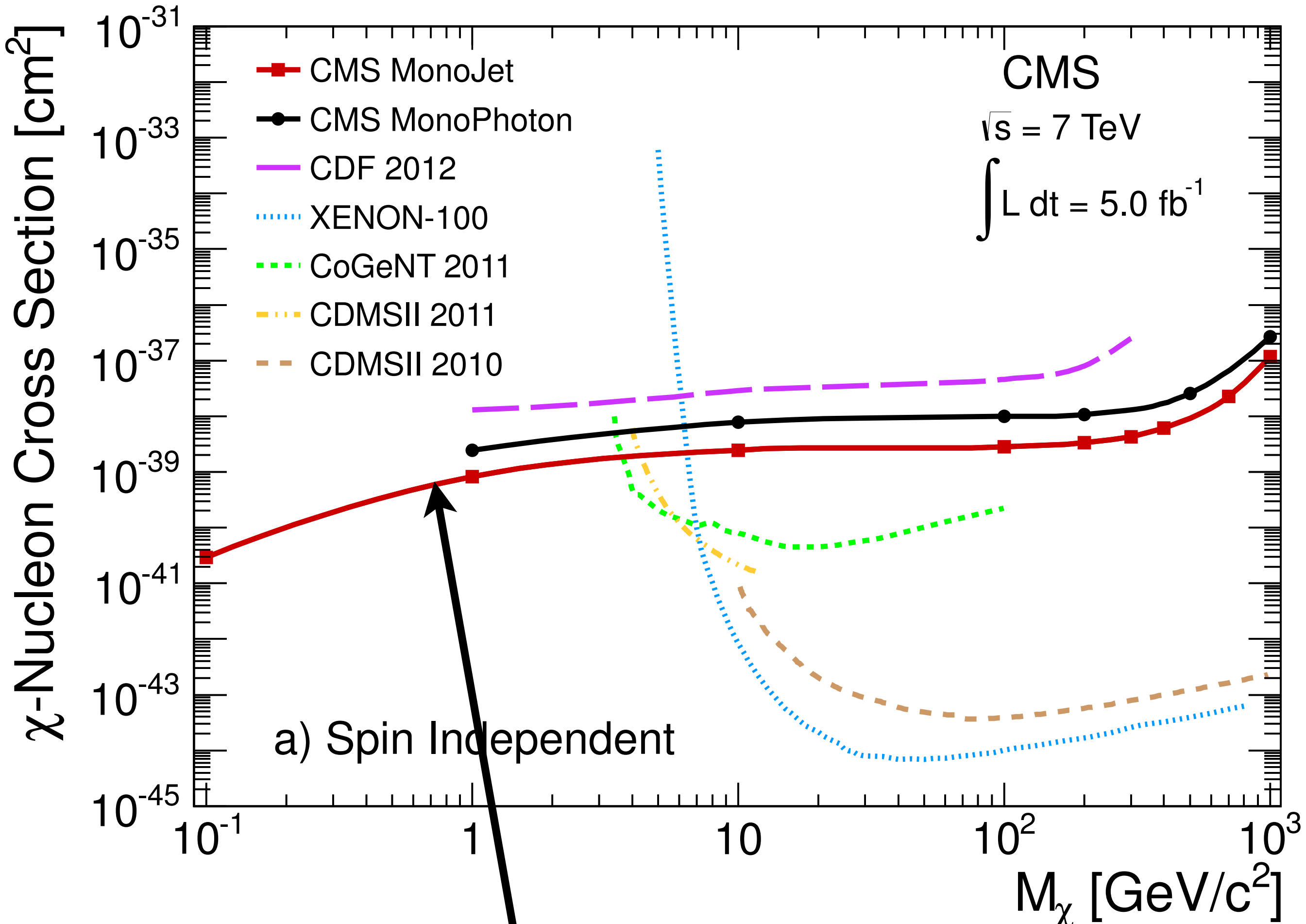
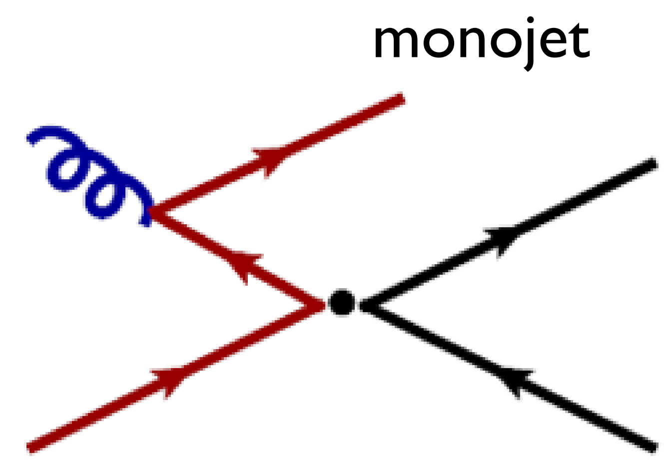
Use colliders to constrain and probe the same operator

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

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

For example

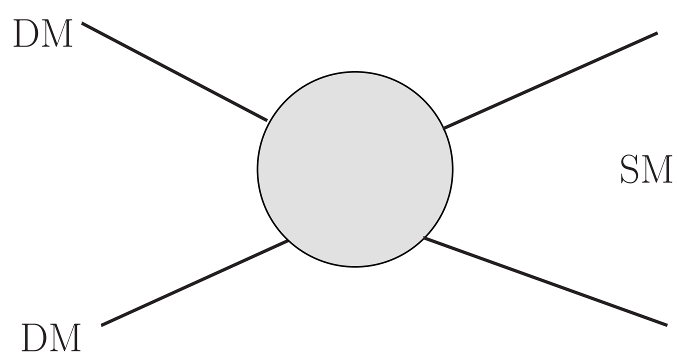




D1	$\bar{\chi}\chi\bar{q}q$
D5	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$

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

Is this simple approach effective?



=

- Valid as field theory?
  - Already questionable in run 1, will be quite problematic at for run 2.
- More over, is this representative of possible UV completion? And, representative of possible signals?
- For both reasons, need to consider simple models beyond effective operators. In particular for run 2.

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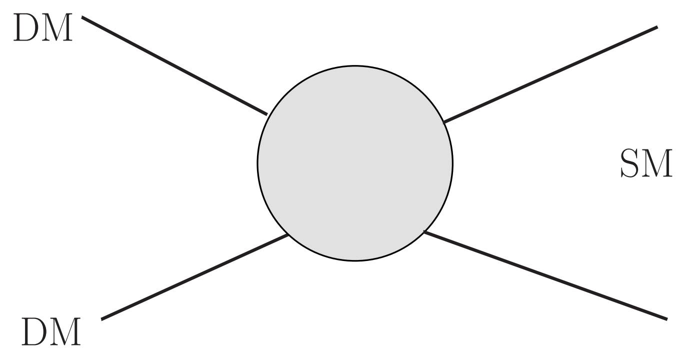

$$= \frac{1}{\Lambda^d}\chi\chi J_{\rm SM}$$

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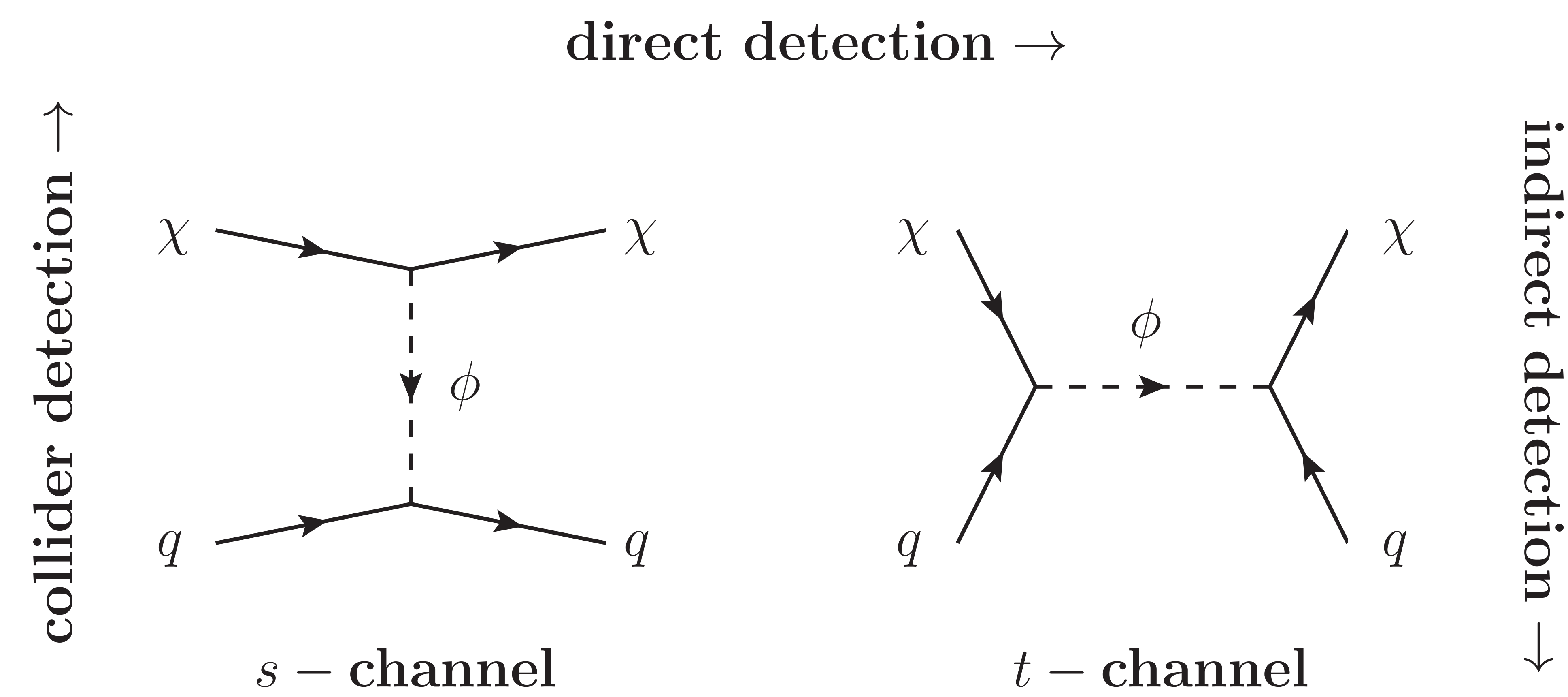
two simple ways of going beyond

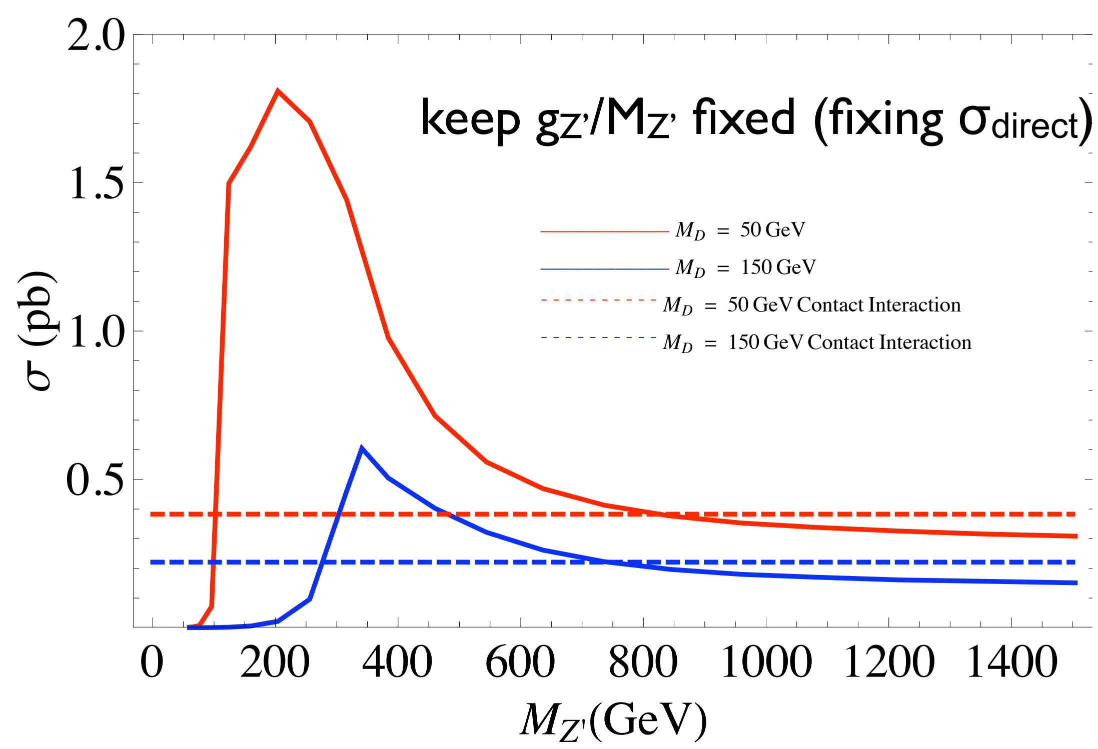
- Singlet dark matter + new mediators between DM and SM.

- Dark matter in a weak multiplet.
  - Mediators = W/Z/h

1. Simplified mediator models

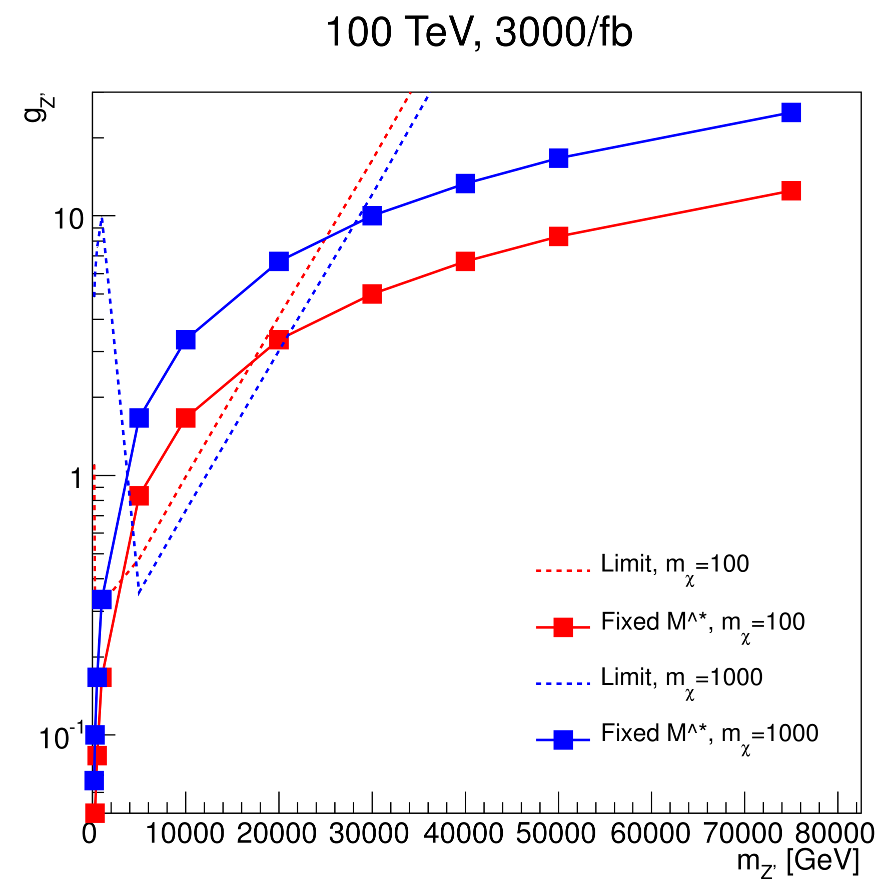


- can be scalar or Z'
- squark like



Tevatron rate, Z' vs effective operator

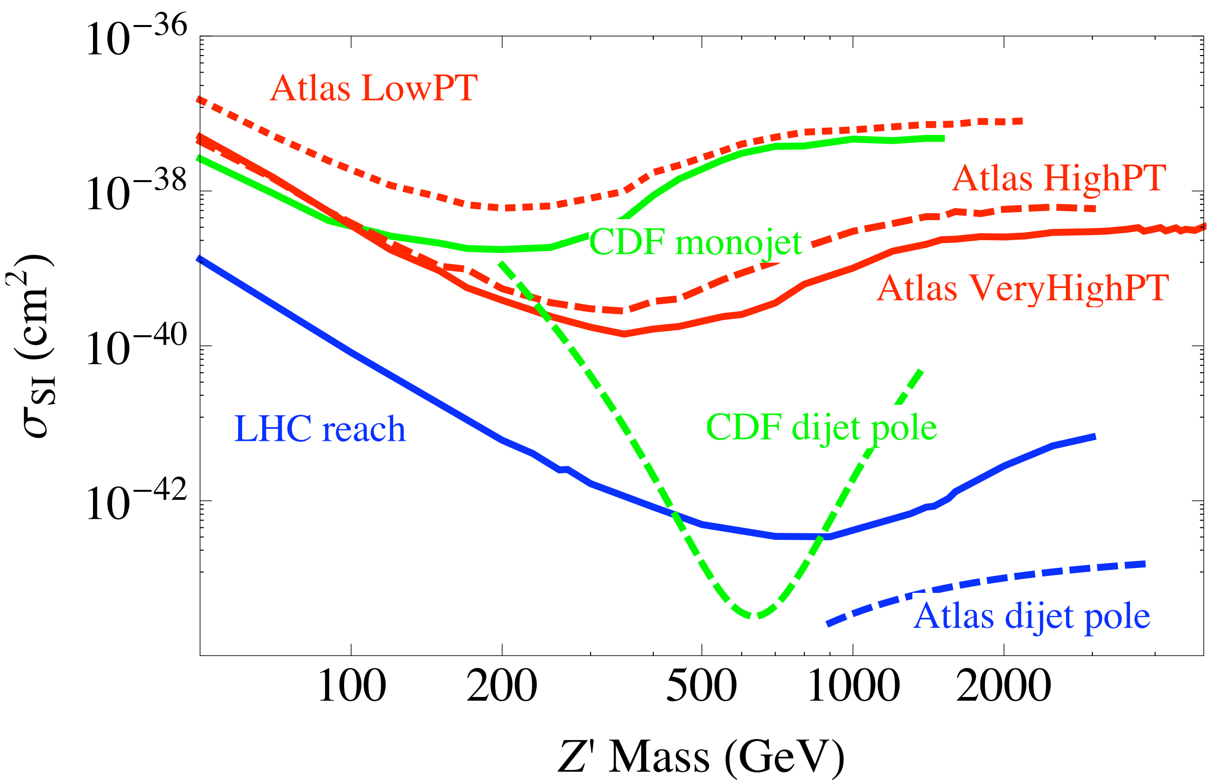
An, Ji, LTW, 1202.2894

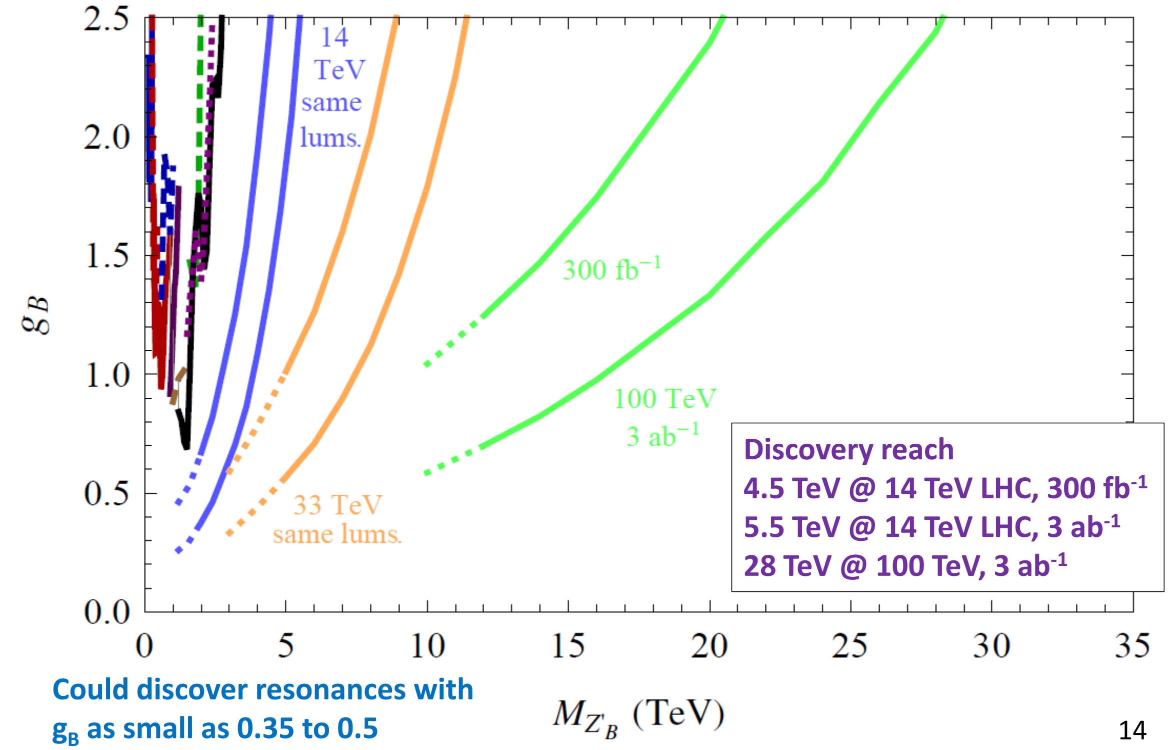


Zhou, Berge, LTW, Whiteson, Tait, 1307.5327

- 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!





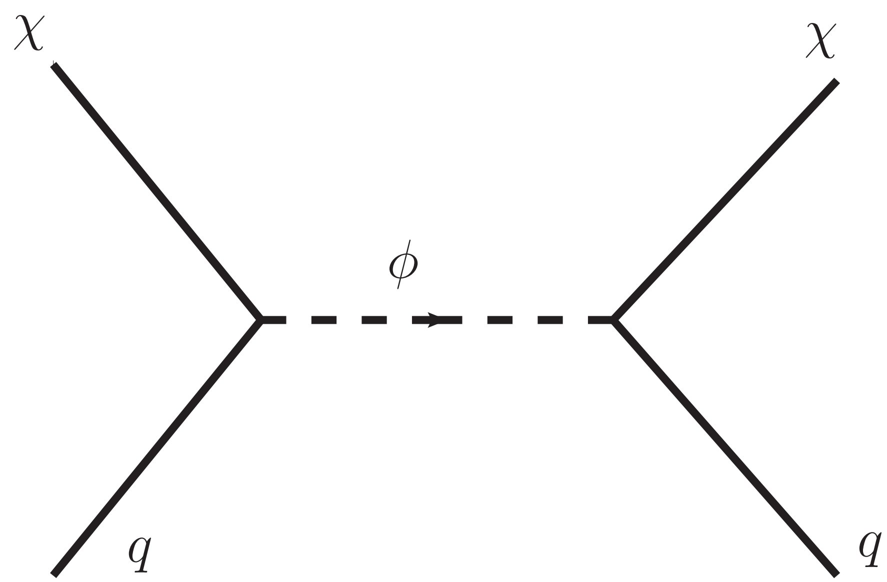
Could discover resonances with g_B as small as 0.35 to 0.5

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

Felix Yu, 2013

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

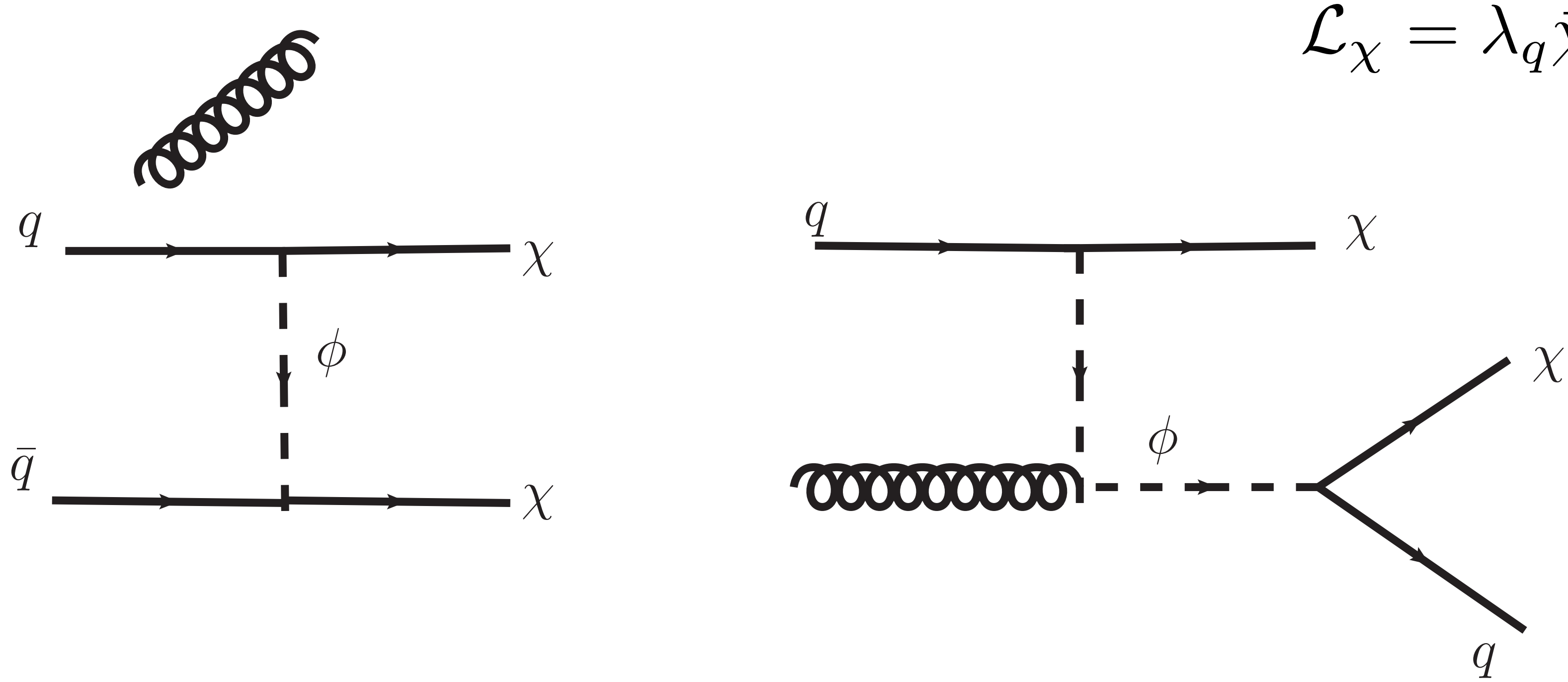


$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

- 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)

Collider searches

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

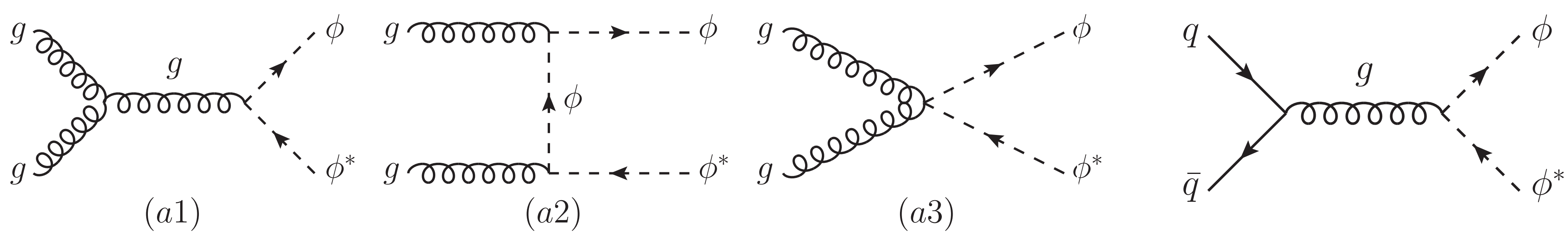


- 2 kinds of contributions for monojet.
- pp→χϕ gives harder (mono)jet!

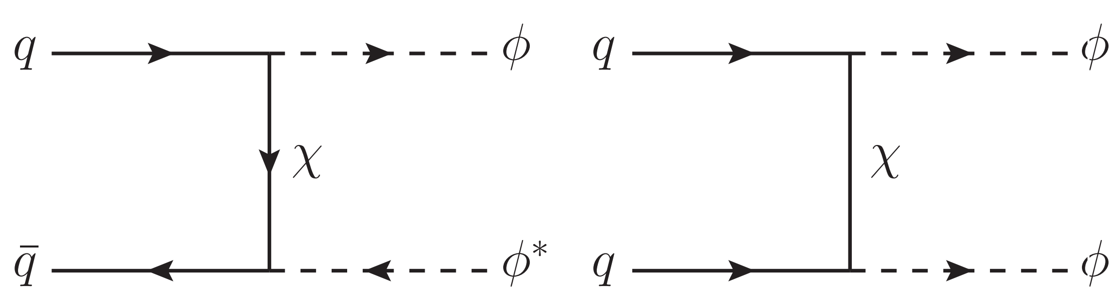
Direct mediator production

- 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

Direct mediator production

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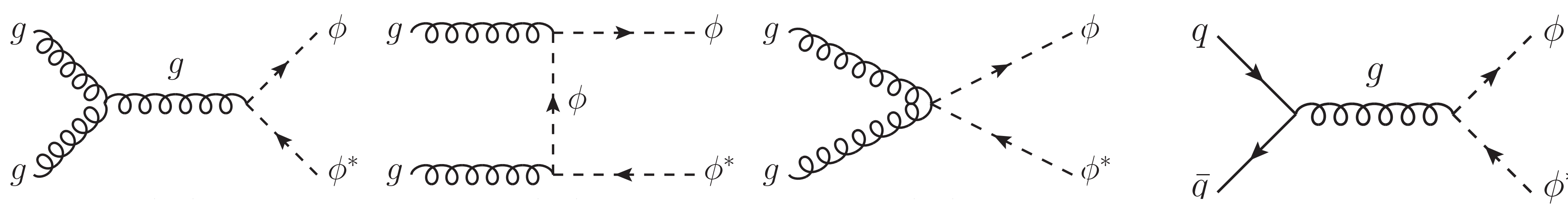
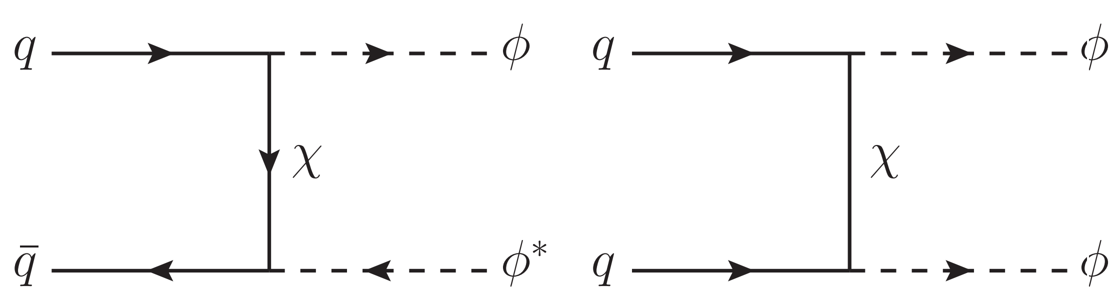
- $pp \to \phi\phi^{(*)}$ (di-jet + MET like searches)





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new channels, different kinematics

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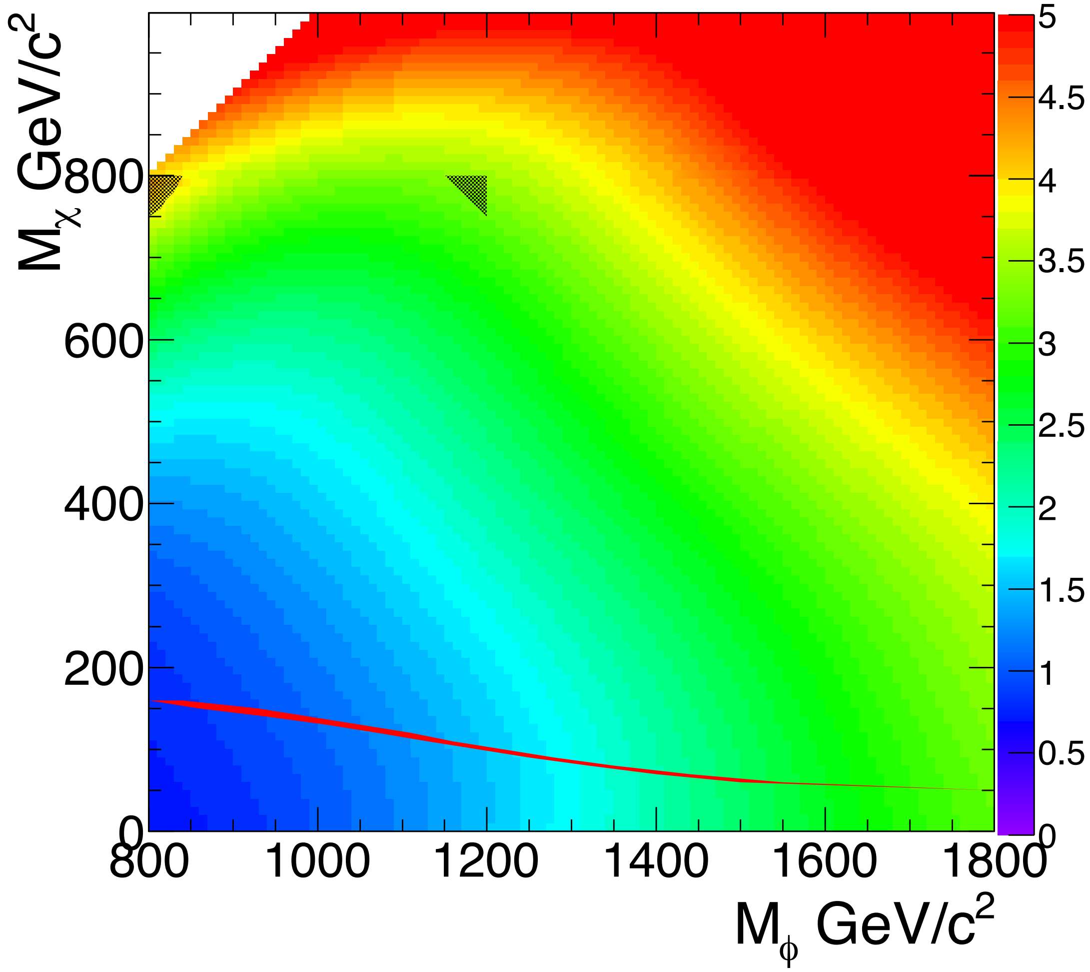
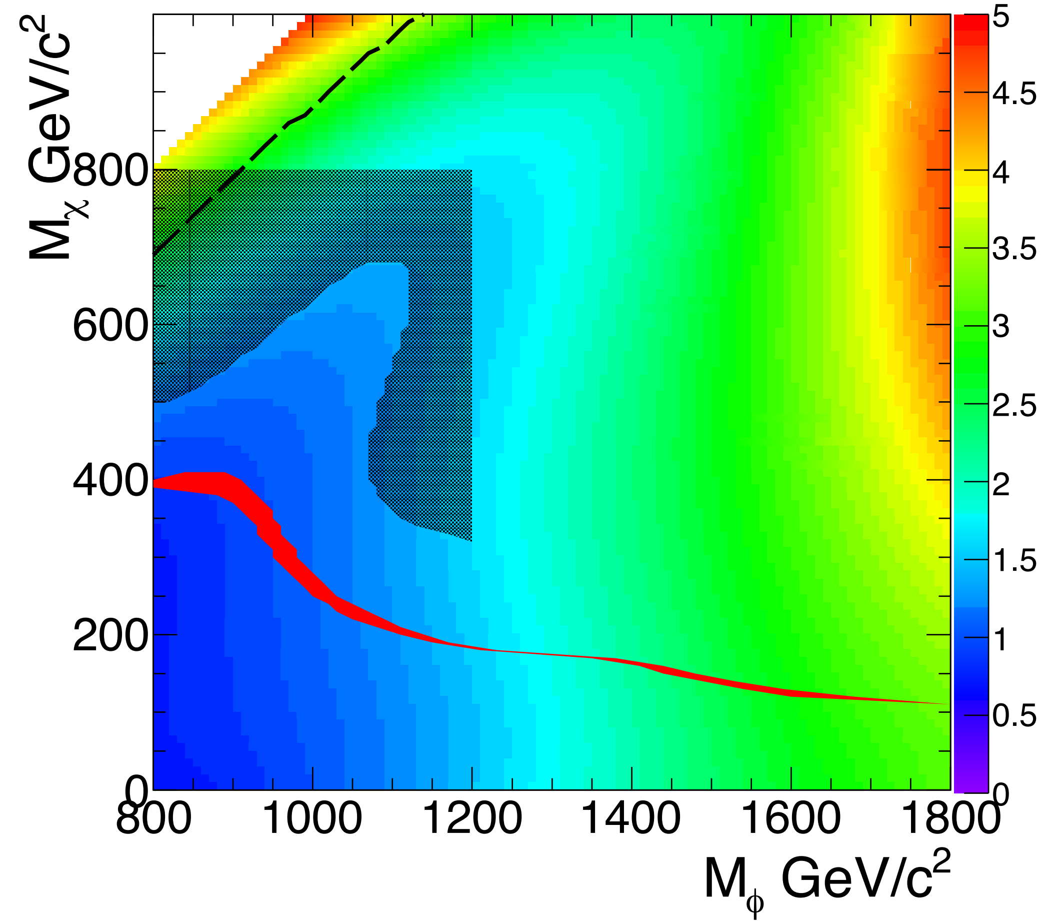
8 TeV limits

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

Dirac Contours, limits on coupling λ_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, 1308.0592

Summary of simplified mediator models

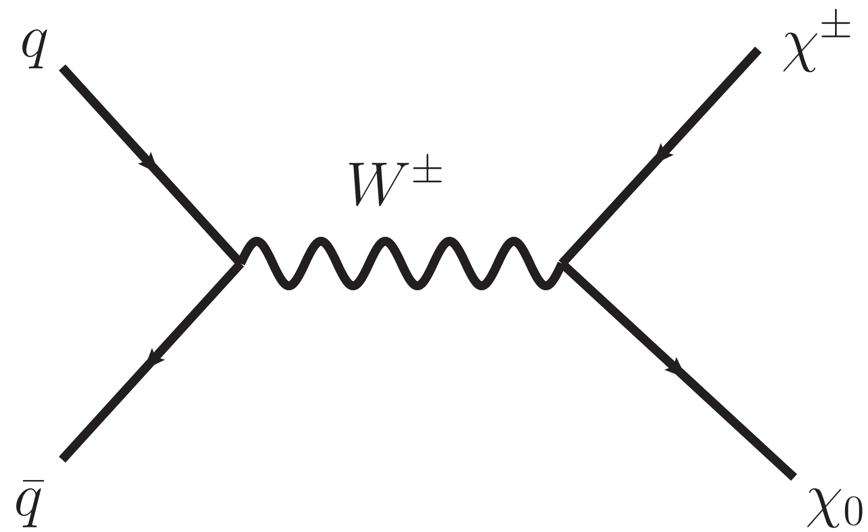
- Adding mediators can dramatically change the search strategy and reach.

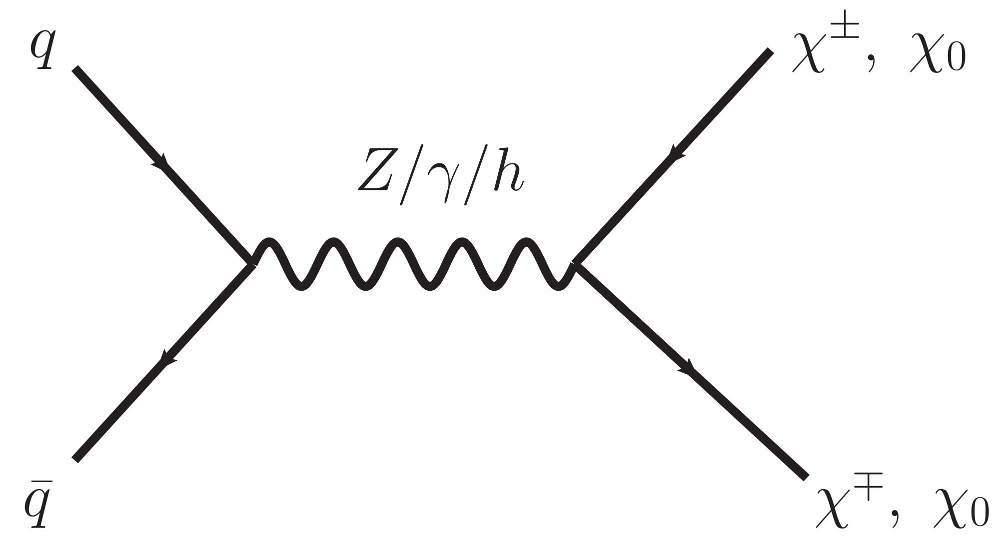
- Processes with mediator direct production usually give stronger limits.

- These mediators are new physics particles themselves. Very simple DM+New forces!

- Simplify the other way
  - More involved DM + SM forces are mediator?

2. No additional mediator



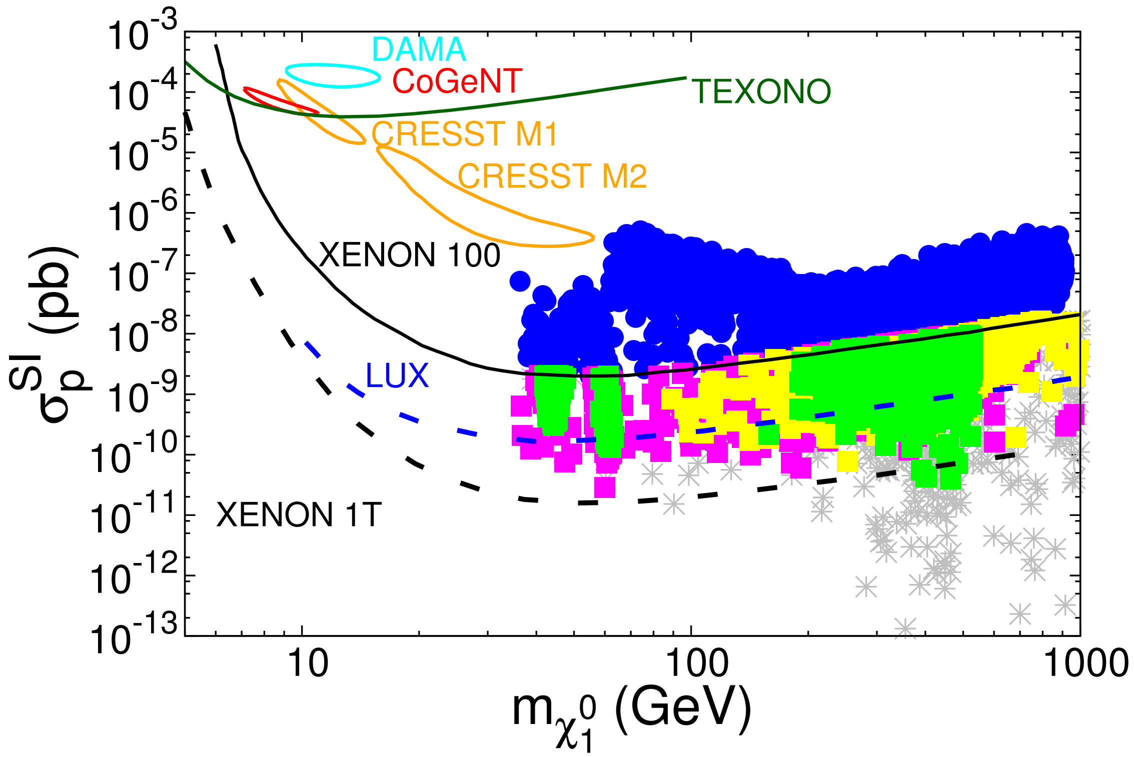


- Dark matter part of a weak multiplet.
  - Mediated by W/Z/h.

SUSY as an example

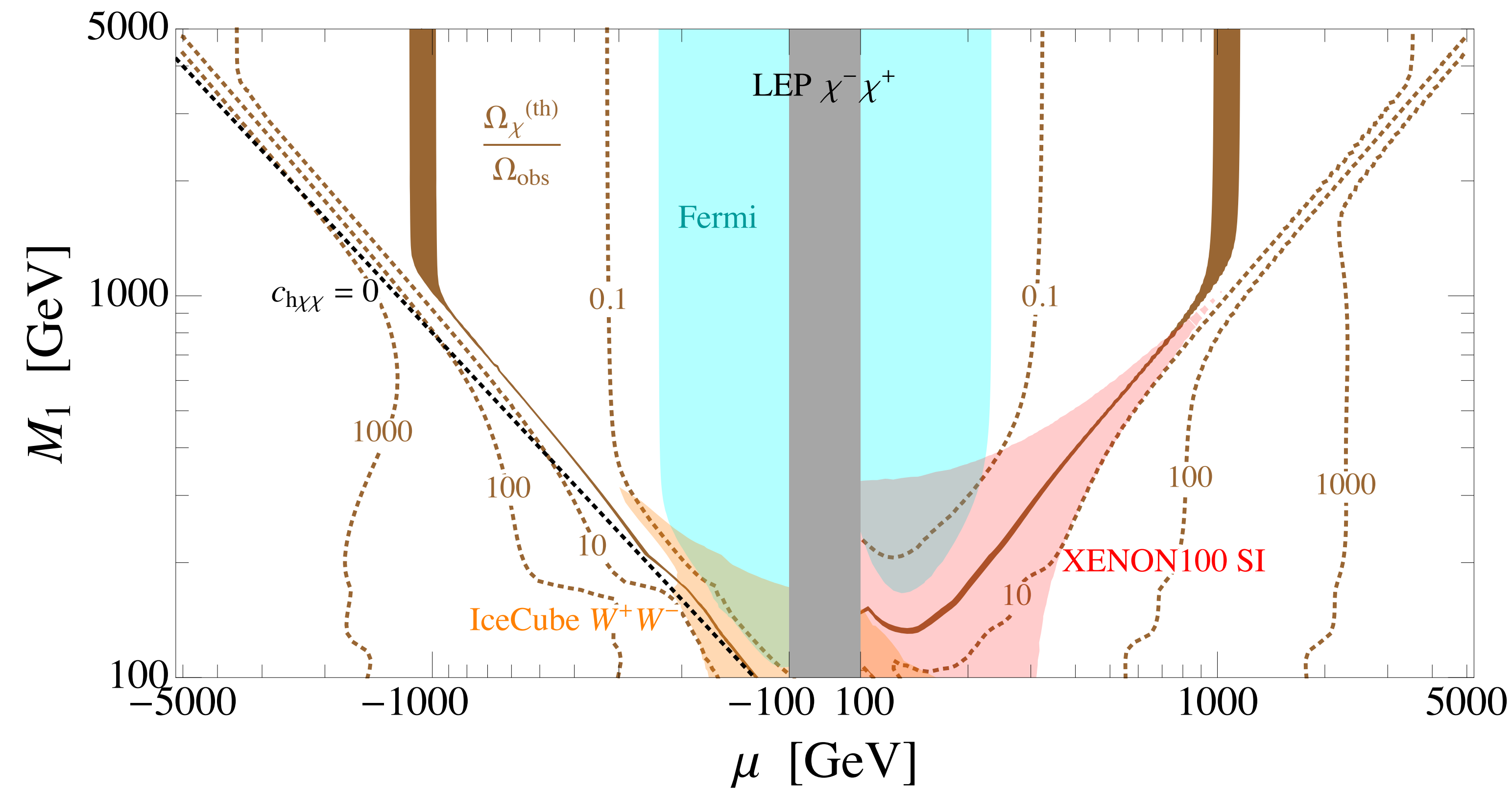
- Not just because we love SUSY.
- SUSY LSP $\Rightarrow$ a set of good examples of more generic WIMP candidates.
  - Bino $\Leftrightarrow$ singlet fermion dark matter
  - Higgsino $\Leftrightarrow$ Doublet. Heavy exotic lepton.
  - Wino $\Leftrightarrow$ EW Triplet DM
  - Can have co-annihilation regions

Narrowing parameter space.



Han, Liu, Natarajan, 1303.3040

Cheung, Hall, Pinner, Ruderman, 1211.4873



Possible scenarios (not over-closing)

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

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

- Coannihilation: $\tilde{\tau},\ \tilde{q},\ \tilde{t}, \ldots$ / $\tilde{B}$ $\quad \Delta M \sim$ 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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- Higgsino $\lesssim$ TeV
- Wino $\lesssim$ 3 TeV
- Well temper:

  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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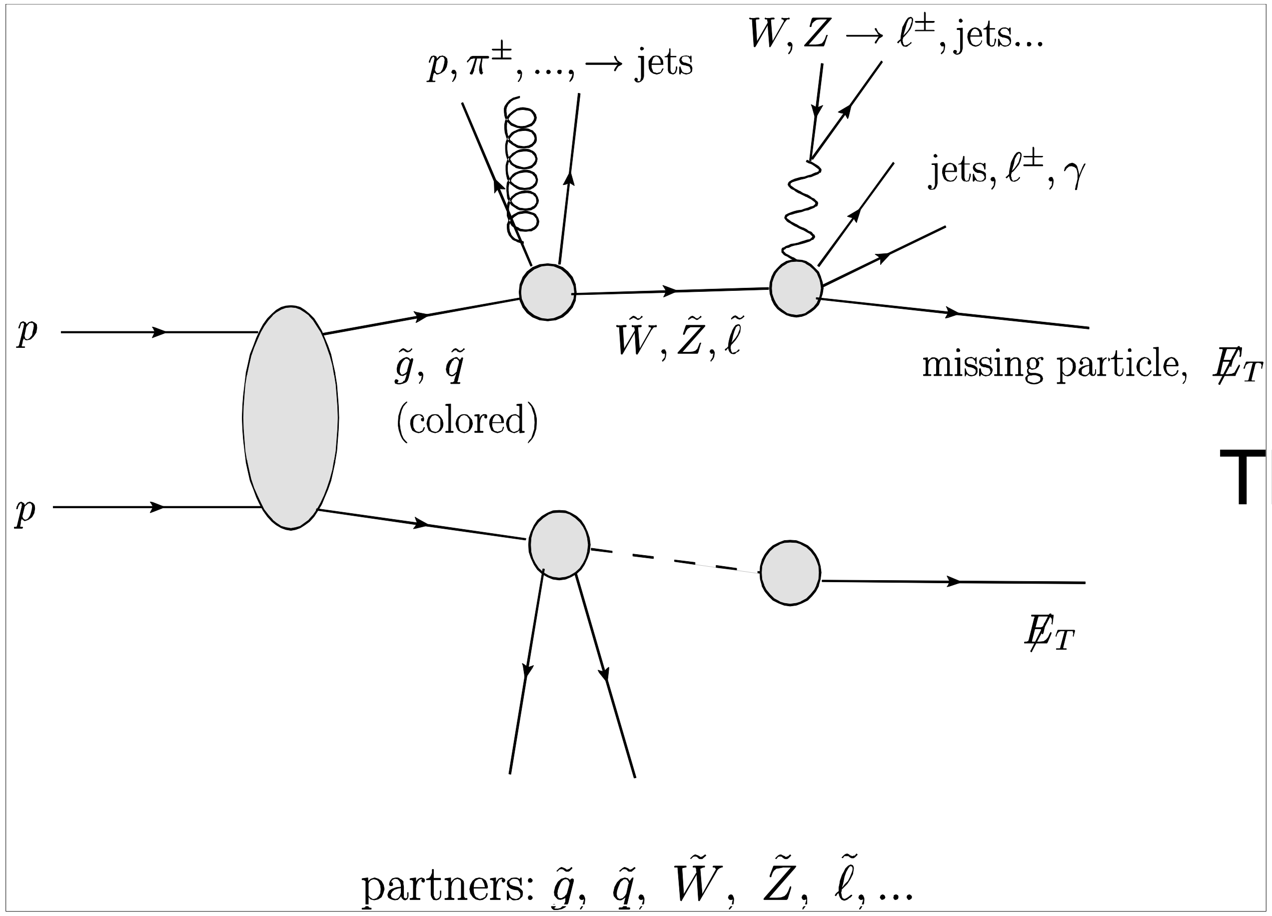
SUSY DM signal in the compressed case



The "usual" story

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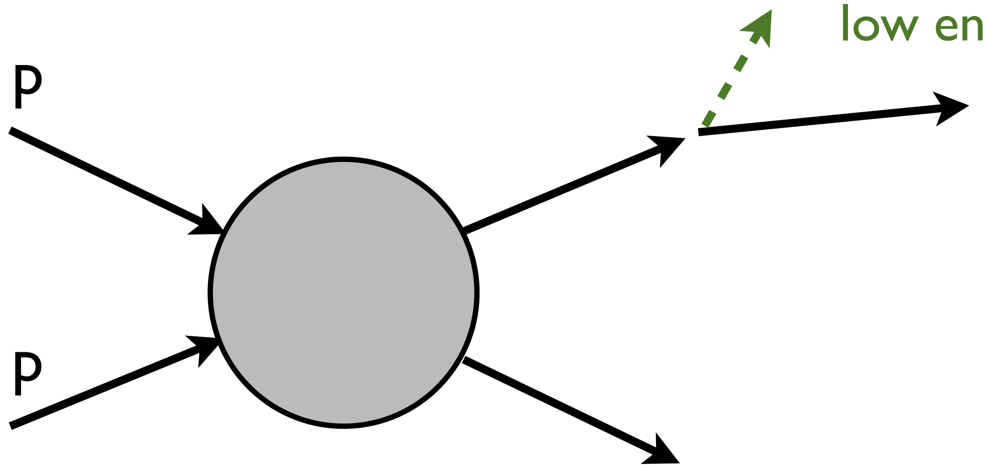

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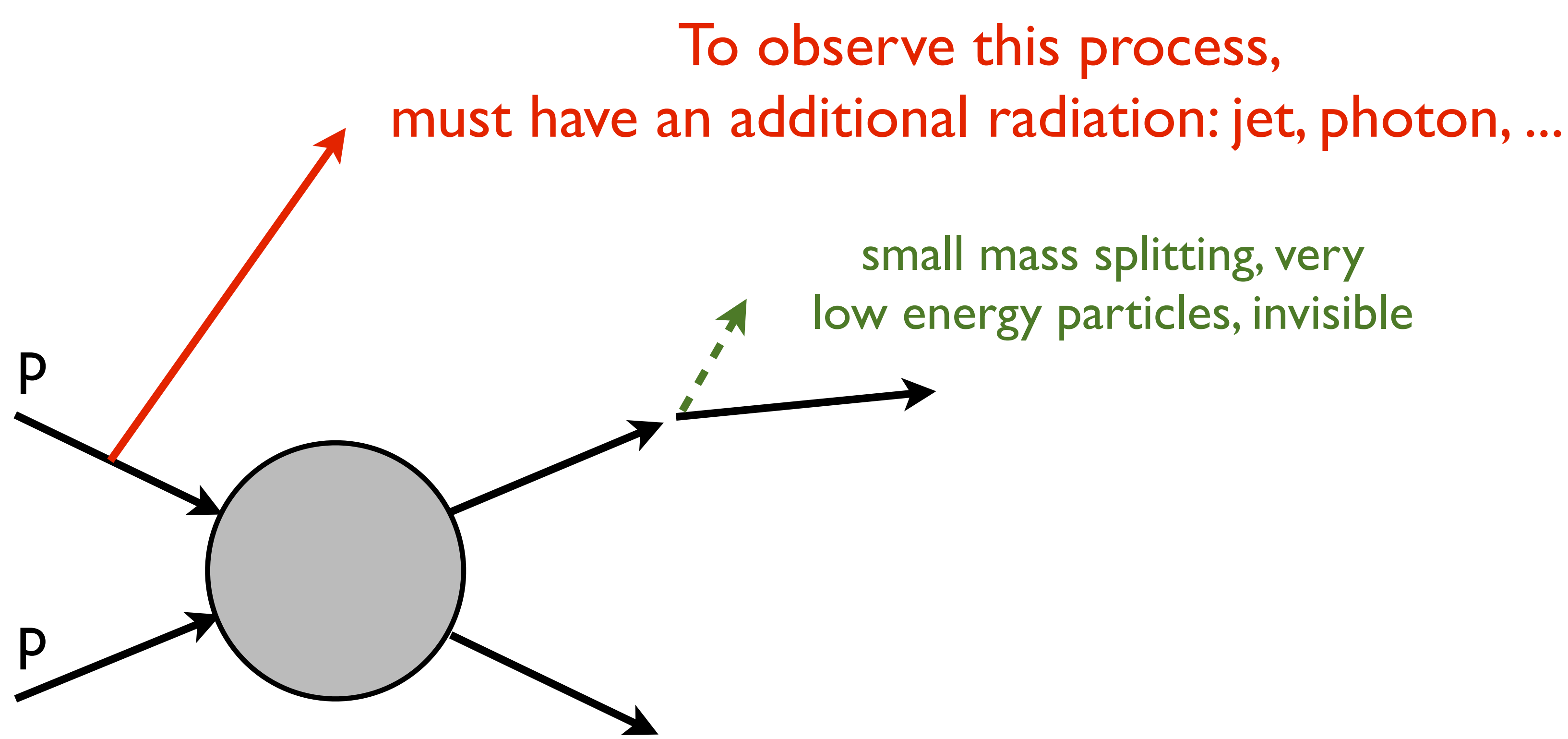

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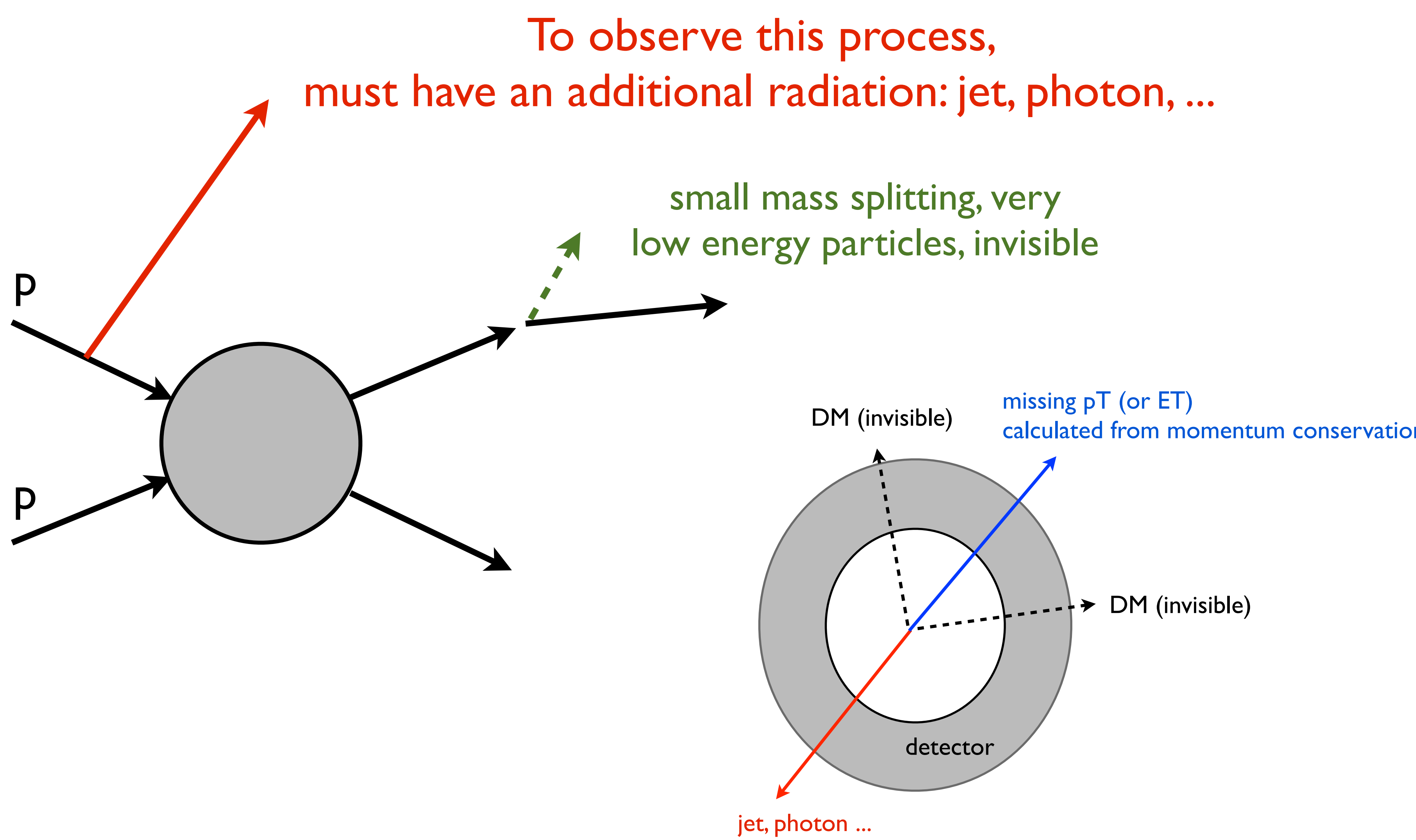
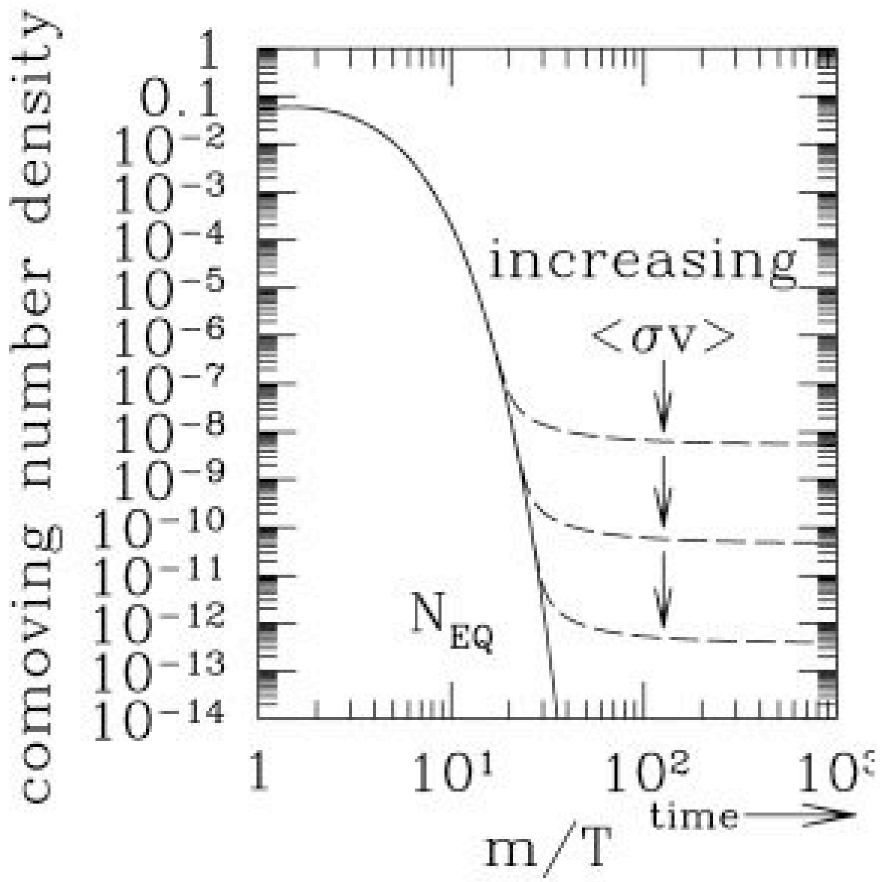
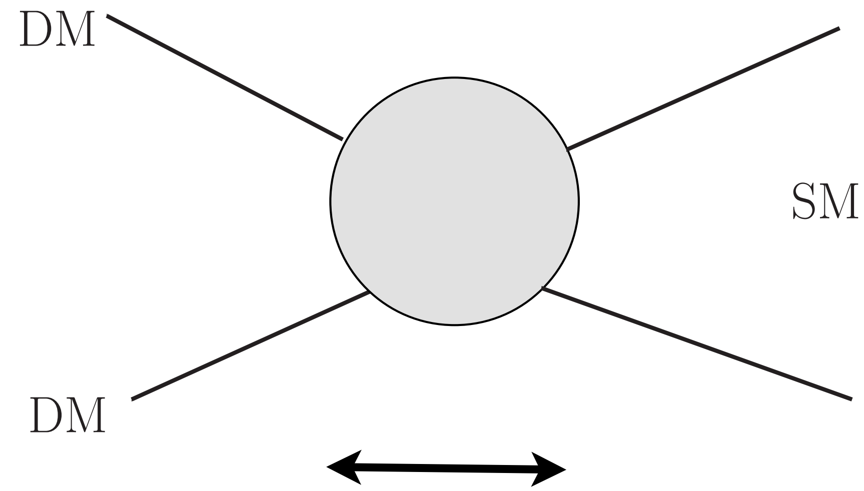


- Back to the basic mono-jet, mono-photon...

WIMP miracle





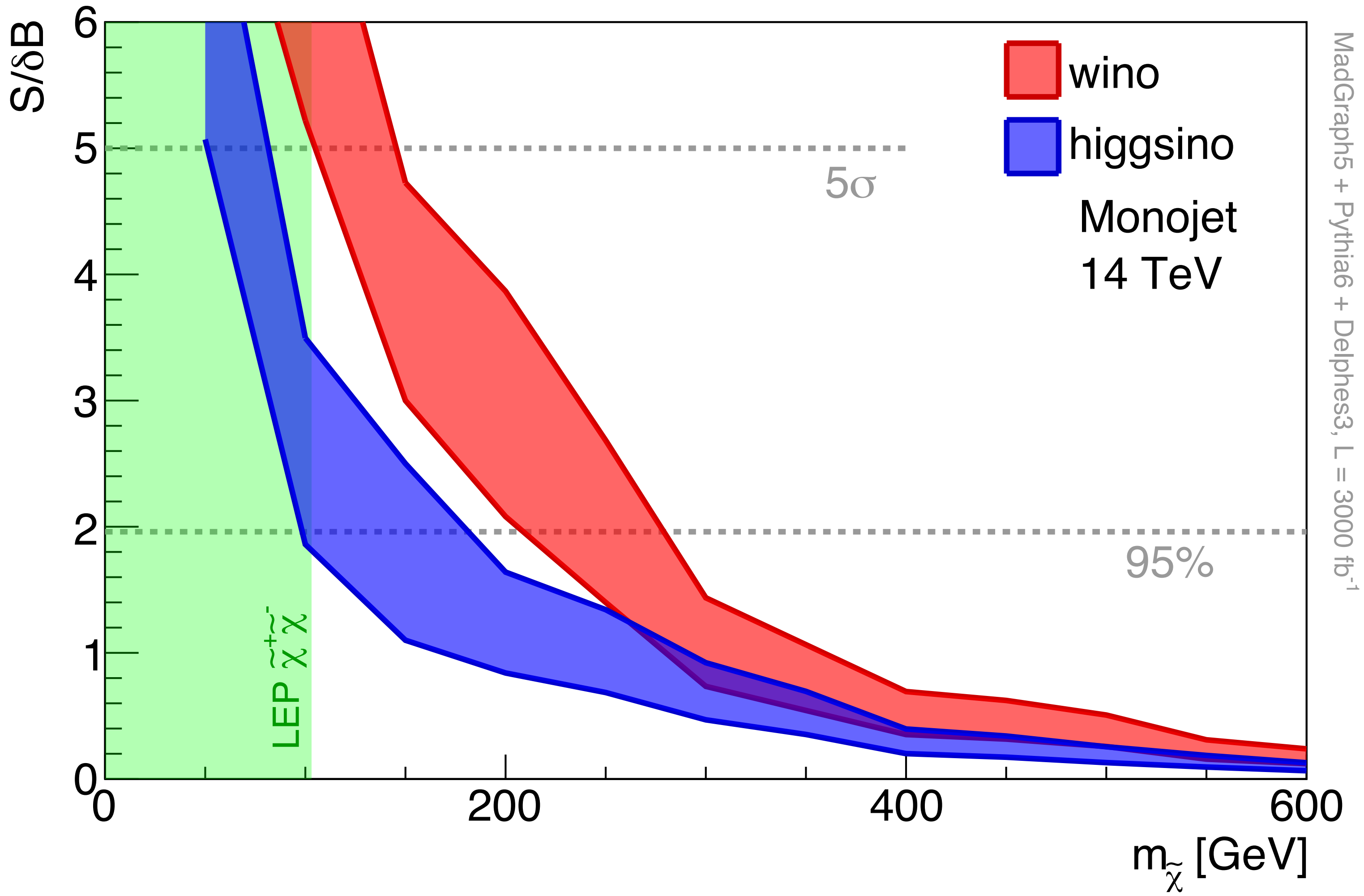
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- More precisely, to get the correct relic abundance

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

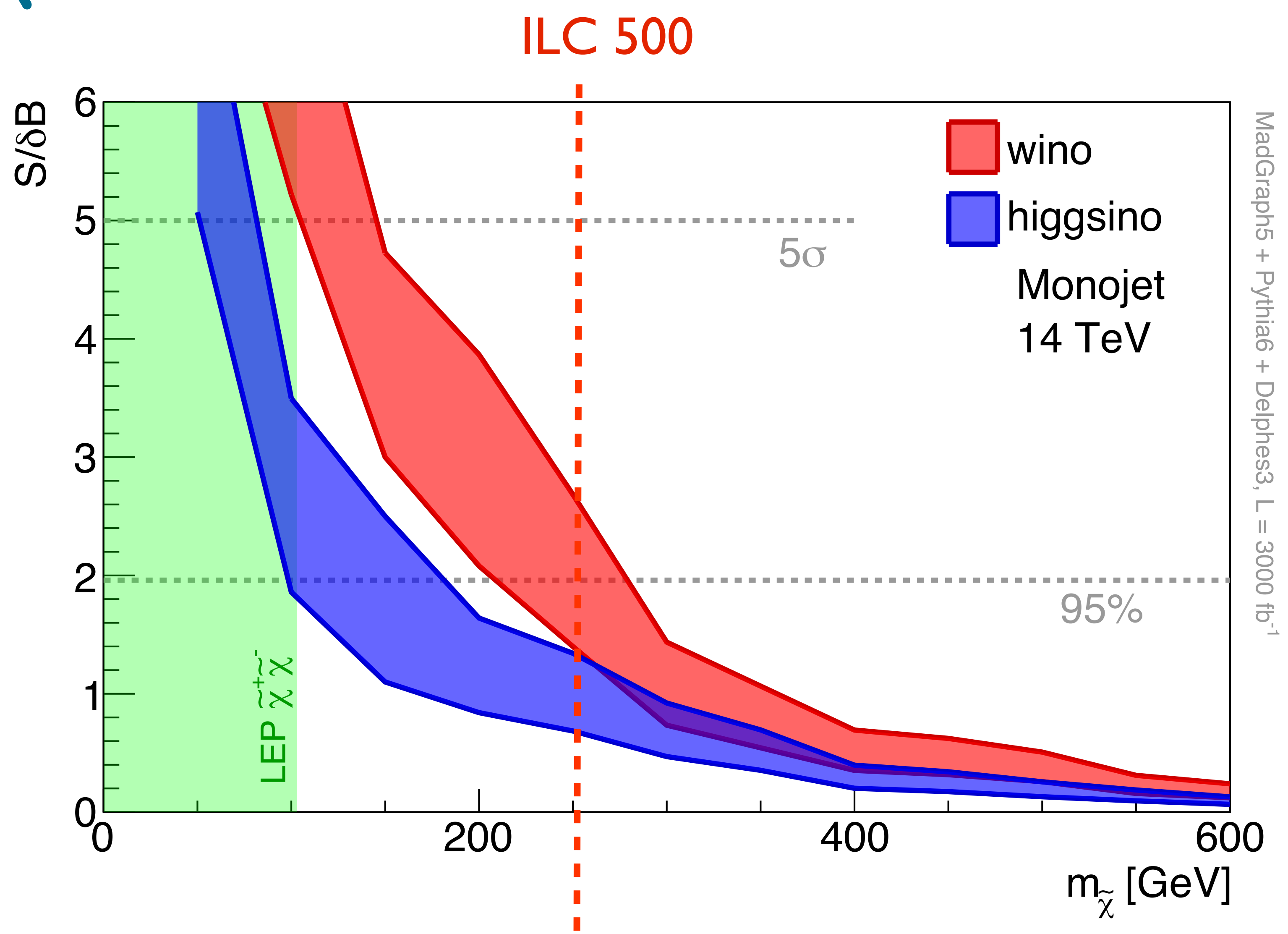
- Much of the parameter space out of reach for the LHC.

Mono-X



- Very challenging. Systematics dominated
  - No limit from the 8 TeV run.
  - Very weak discovery reach at 14 TeV, 3 ab^{-1} .
- Reach at lepton collider, about 1/2 E_{CM}.

Mono-X



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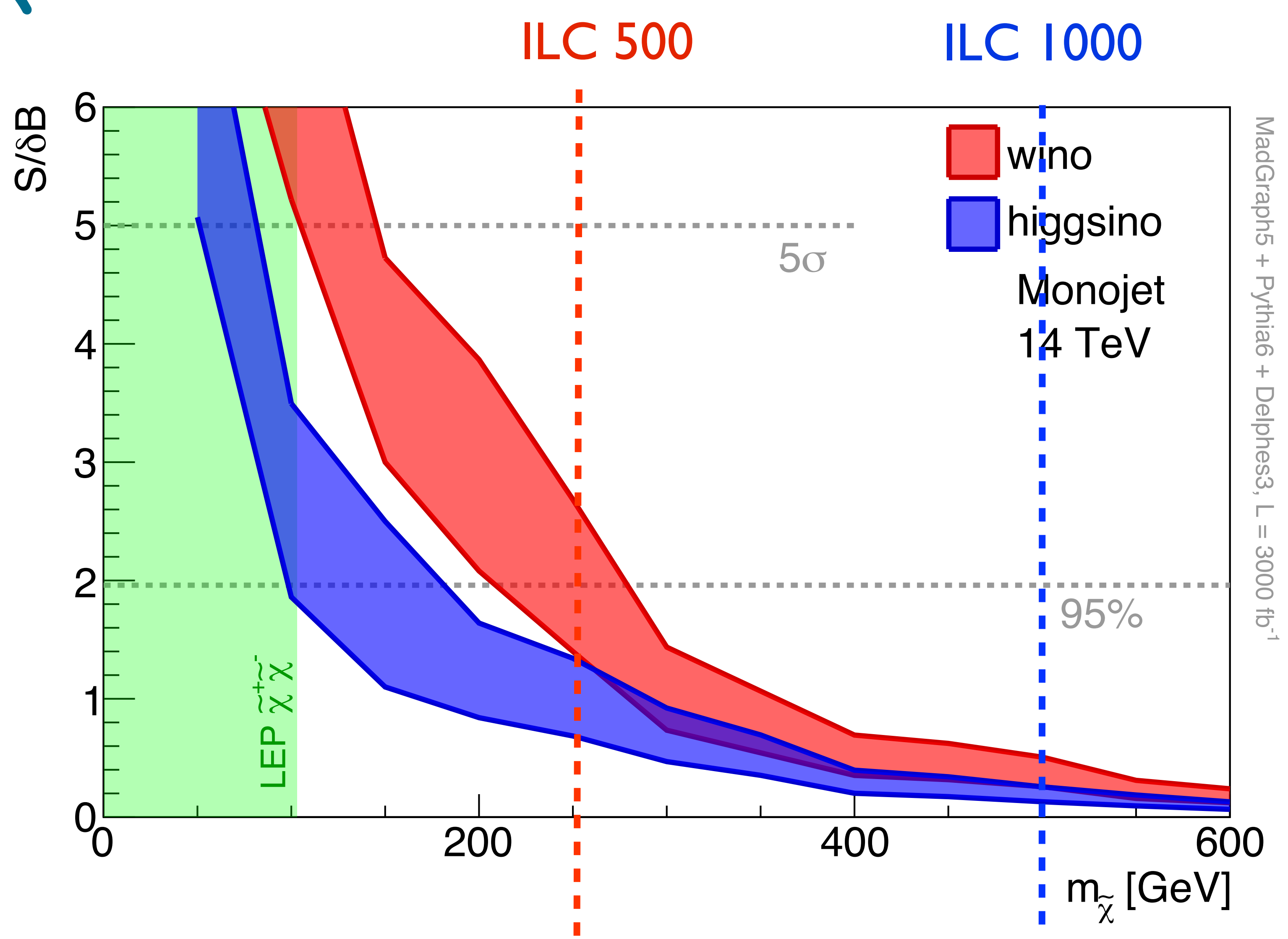

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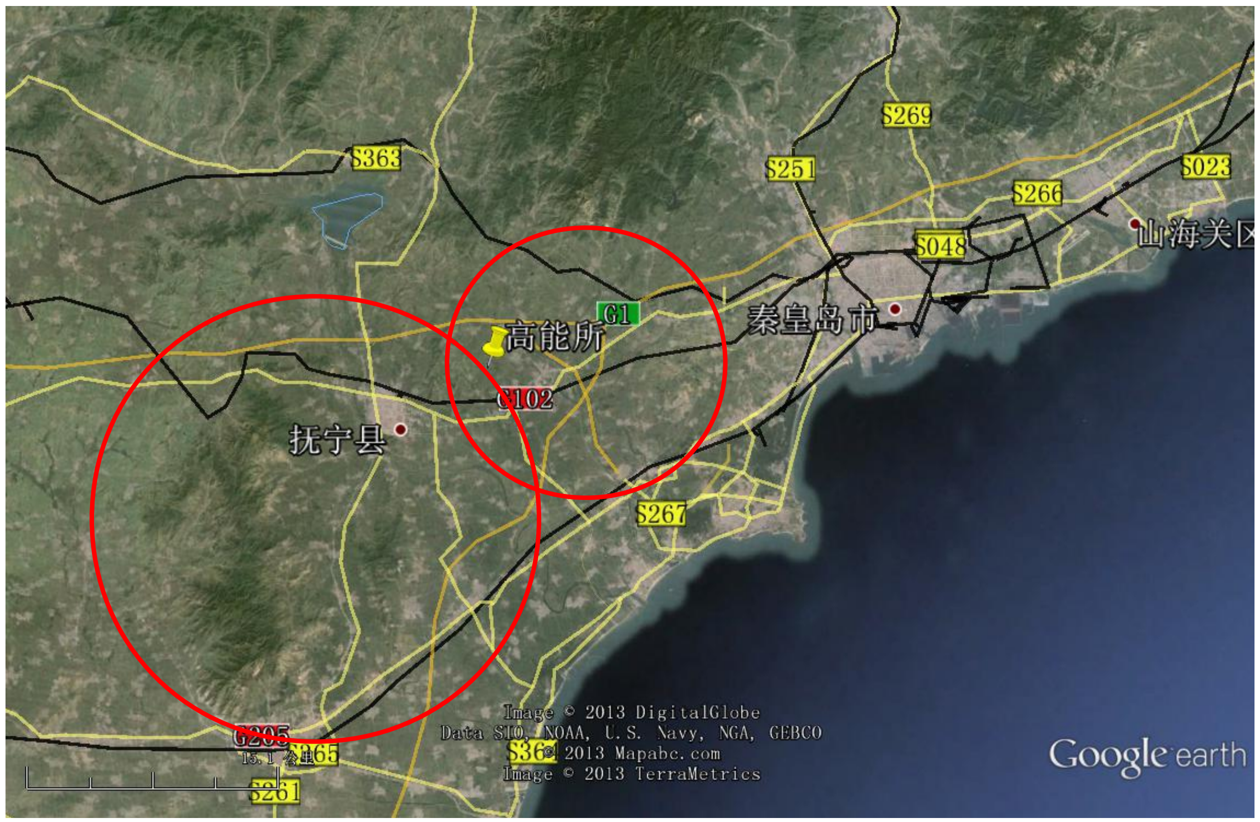
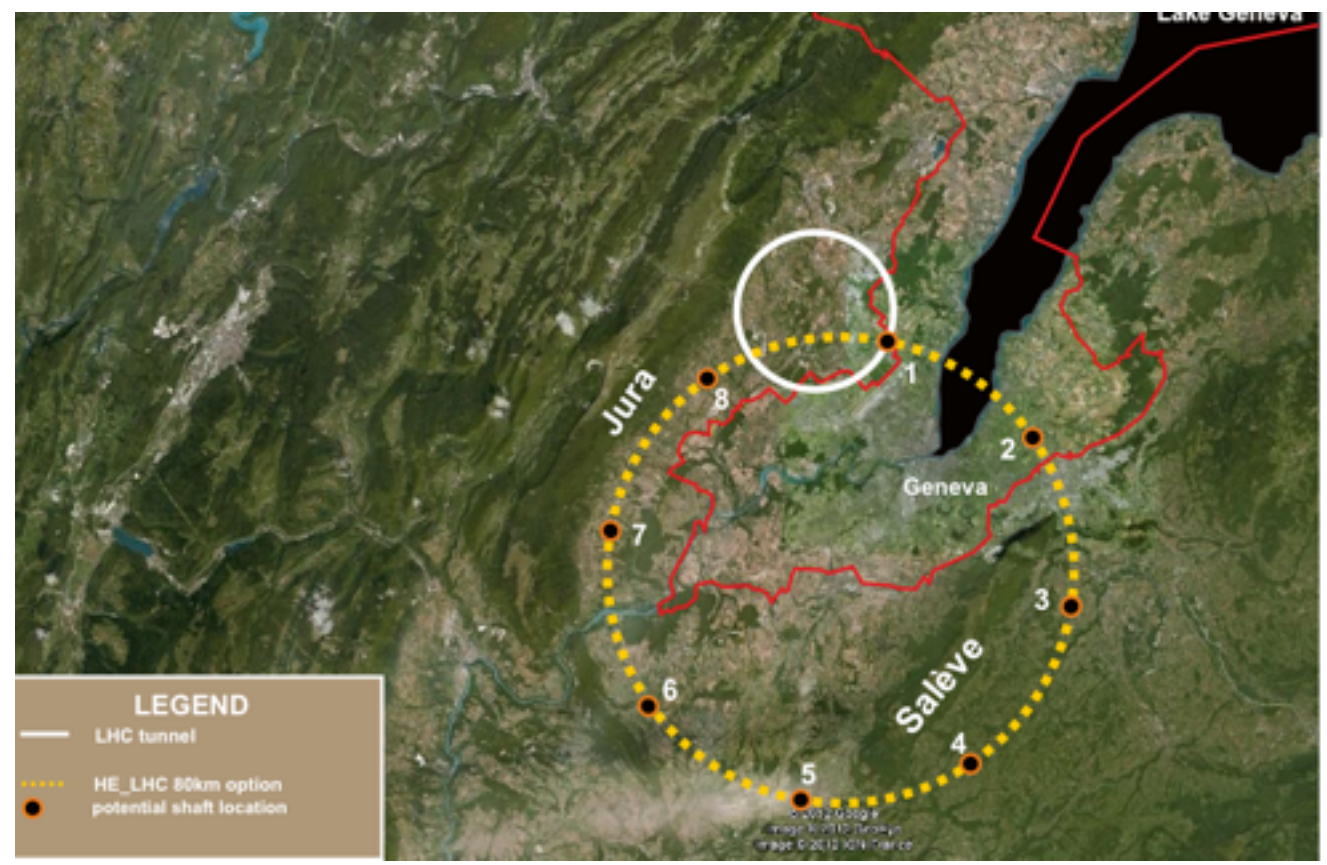
- Reach at lepton collider, about 1/2 E_{CM}.

People started to think about possible next generation large colliders already, such as a pp collider with E_{CM} about 100 TeV.

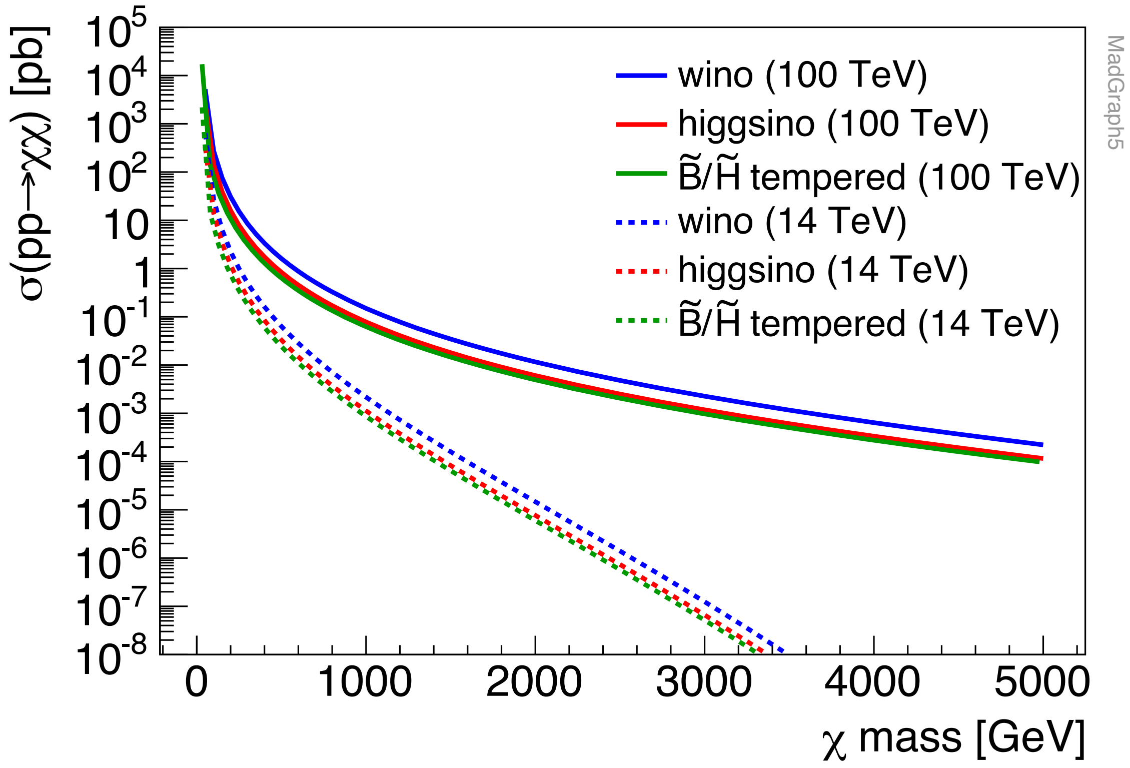


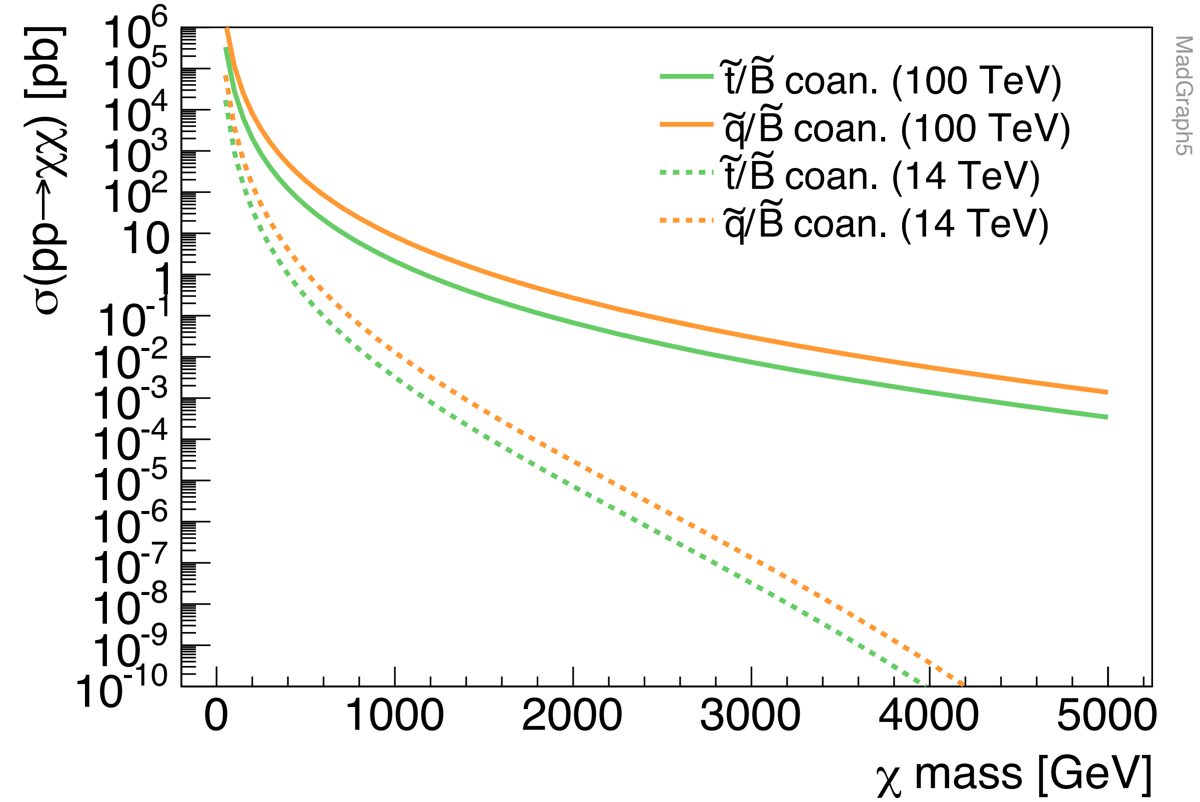
秦皇岛

CERN



higher energy pp collider

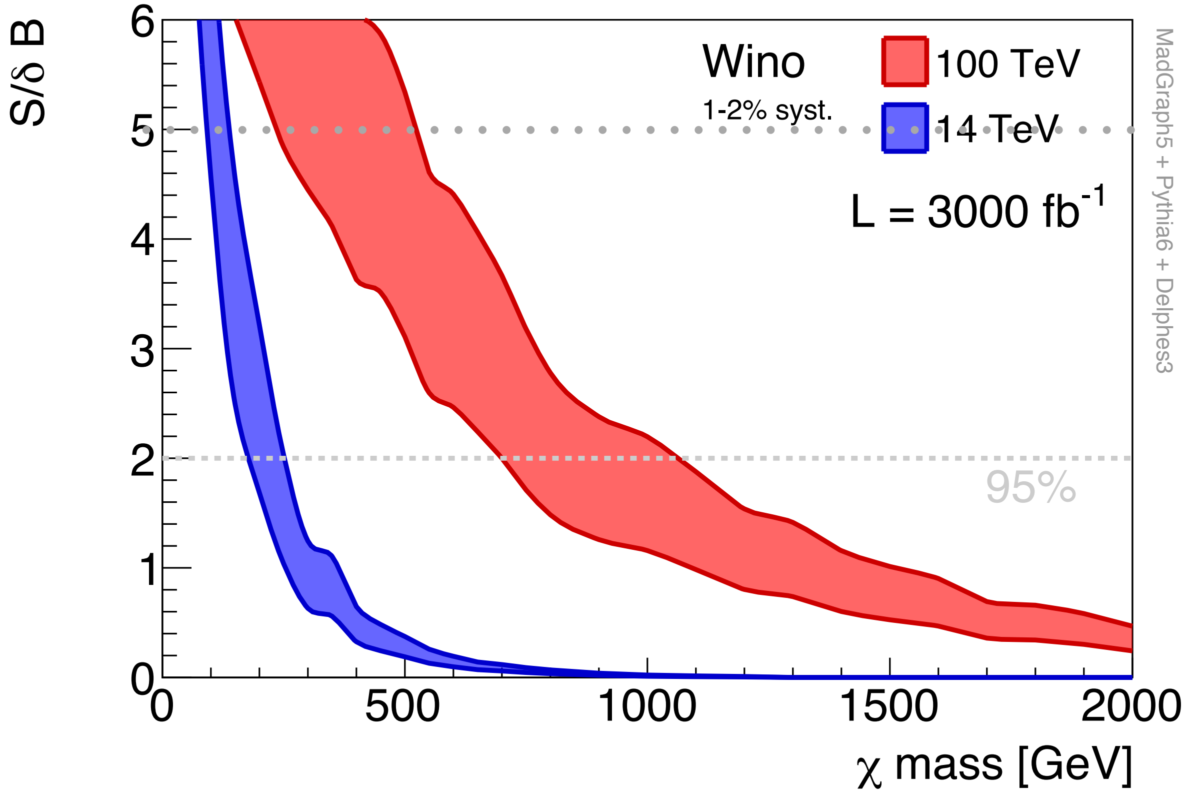




- Higher energy, higher rates
- Expecting large improvement from 14 to 100.

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.

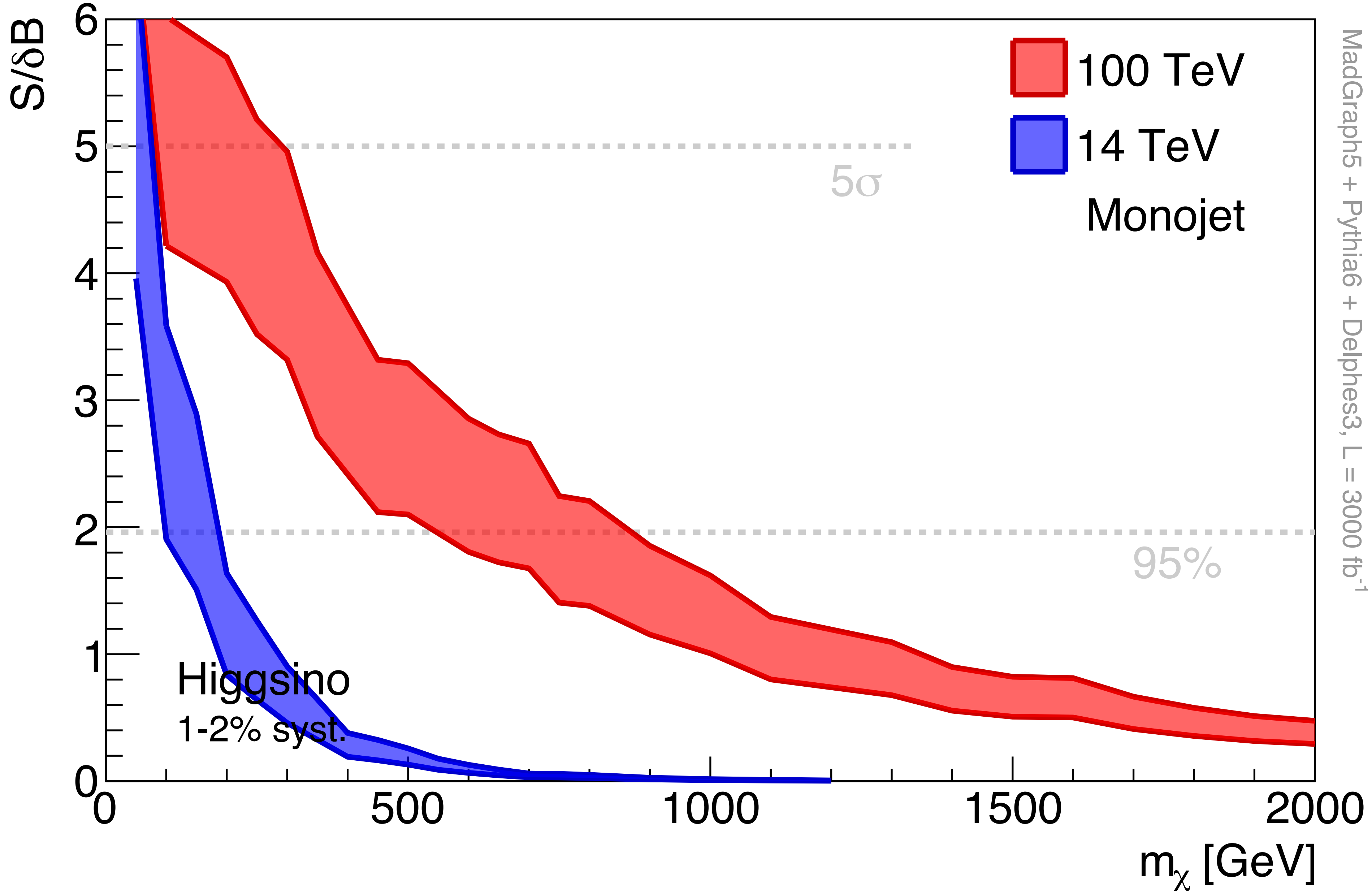
significance: $$\frac{S}{\sqrt{B+\lambda^2 B^2+\gamma^2 S^2}}, \quad \lambda=(1-2)\%, \gamma=10\%$$

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

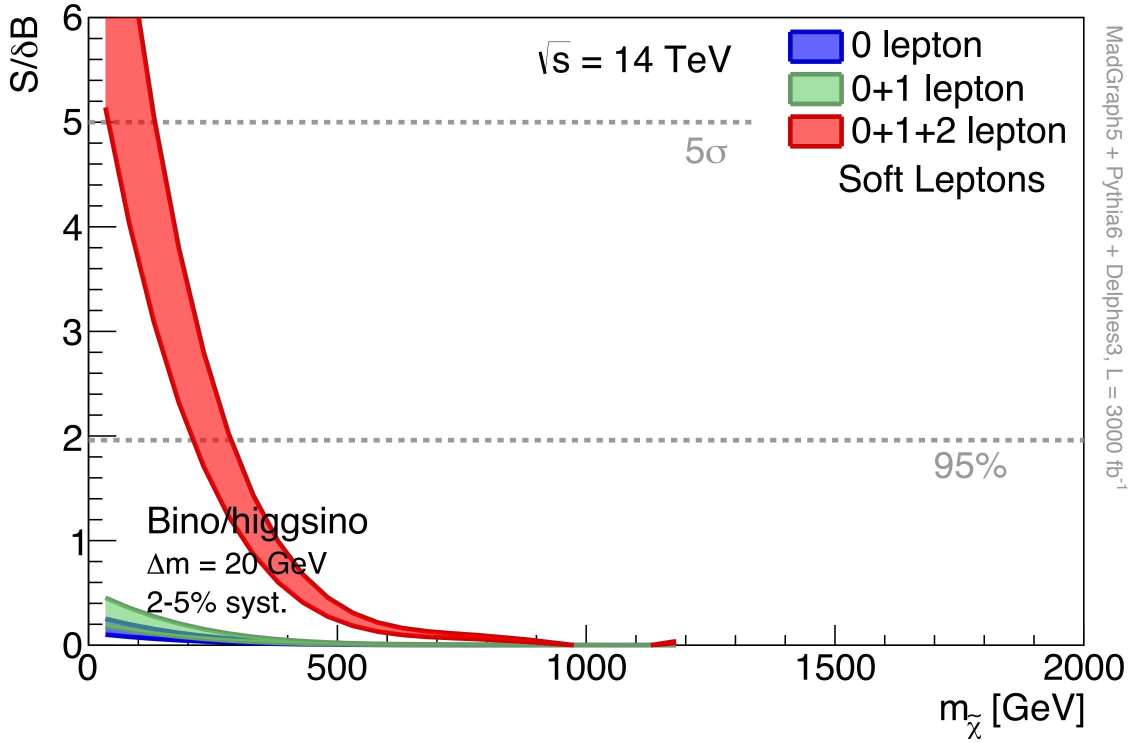
– A factor of 4-5 enhancement from 14 to 100 TeV.

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

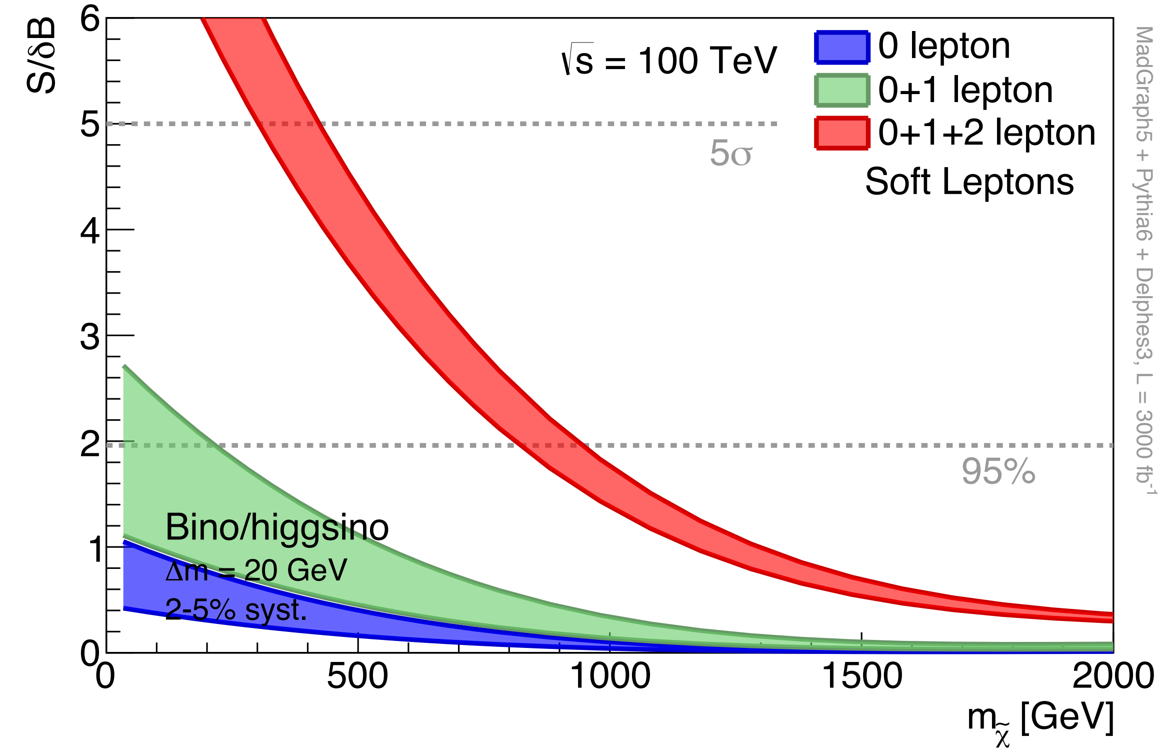
Mono-jet for Higgsino



Well-tempered, mono-jet + soft lepton



20 GeV < pT lepton < 40 GeV



10 GeV < pT lepton < 30 GeV

- Adding soft lepton. S/B is O(1).

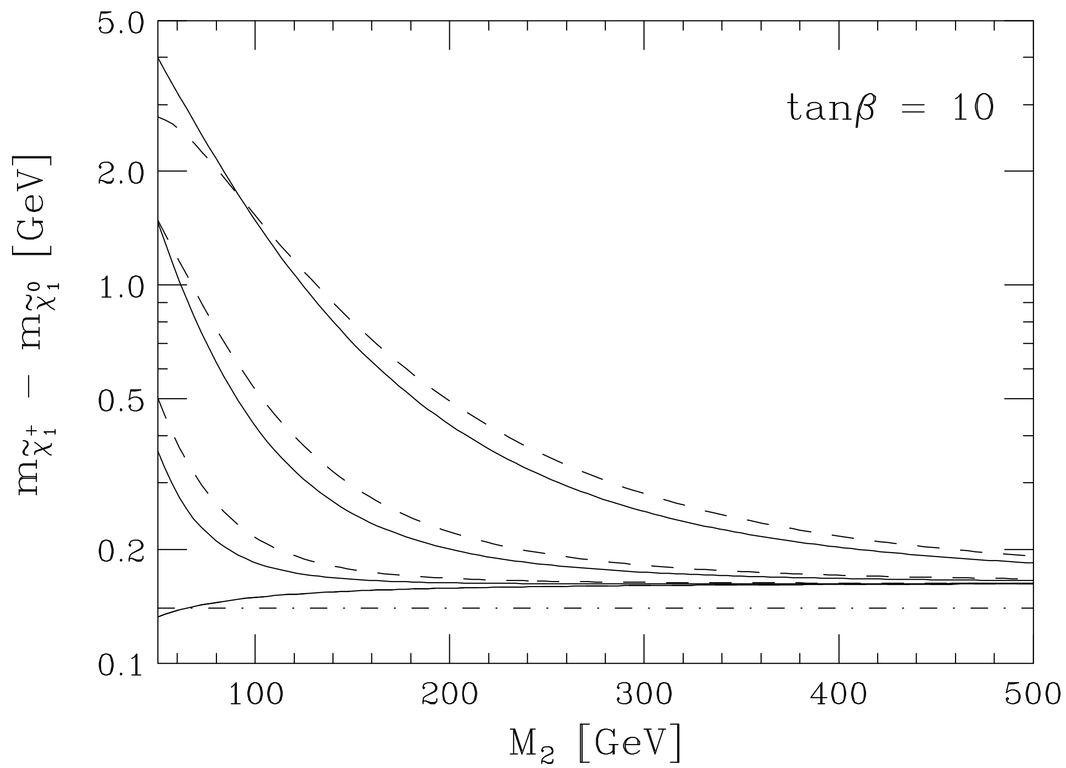
- Mitigating factor: Higher lepton threshold (?) at 100 TeV.

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

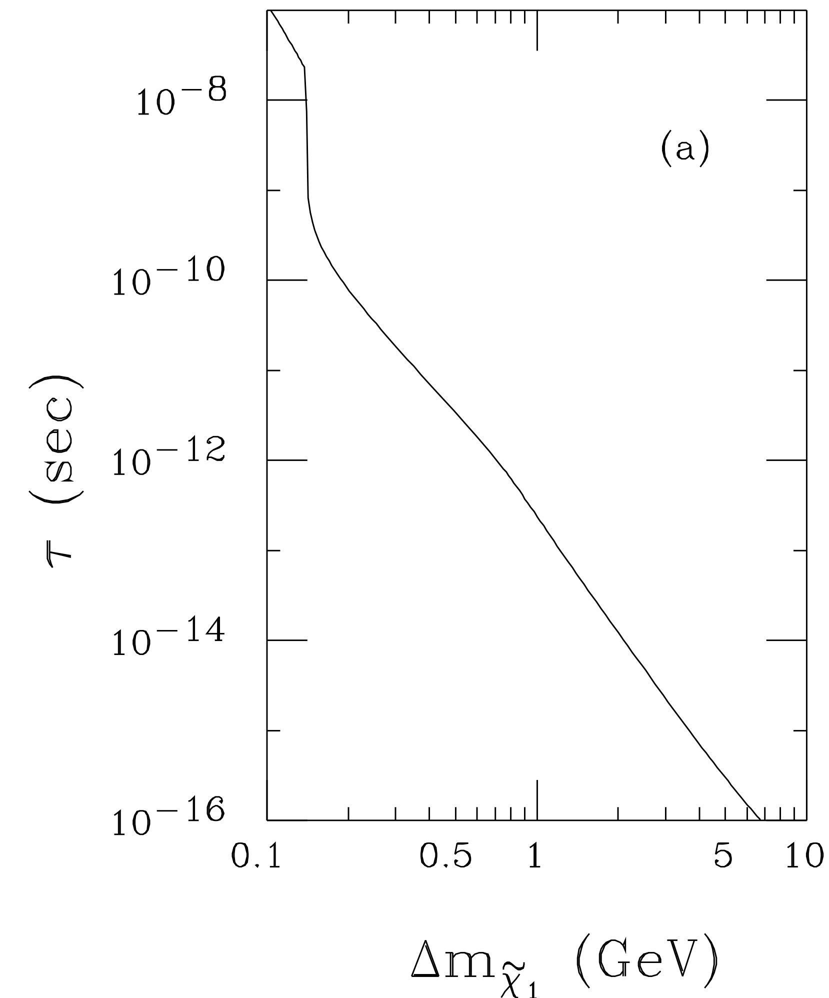
Doing more for the wino case

- AMSB
- AMSB + heavy scalars (Wells 2003, split...)

Doing more in the wino case



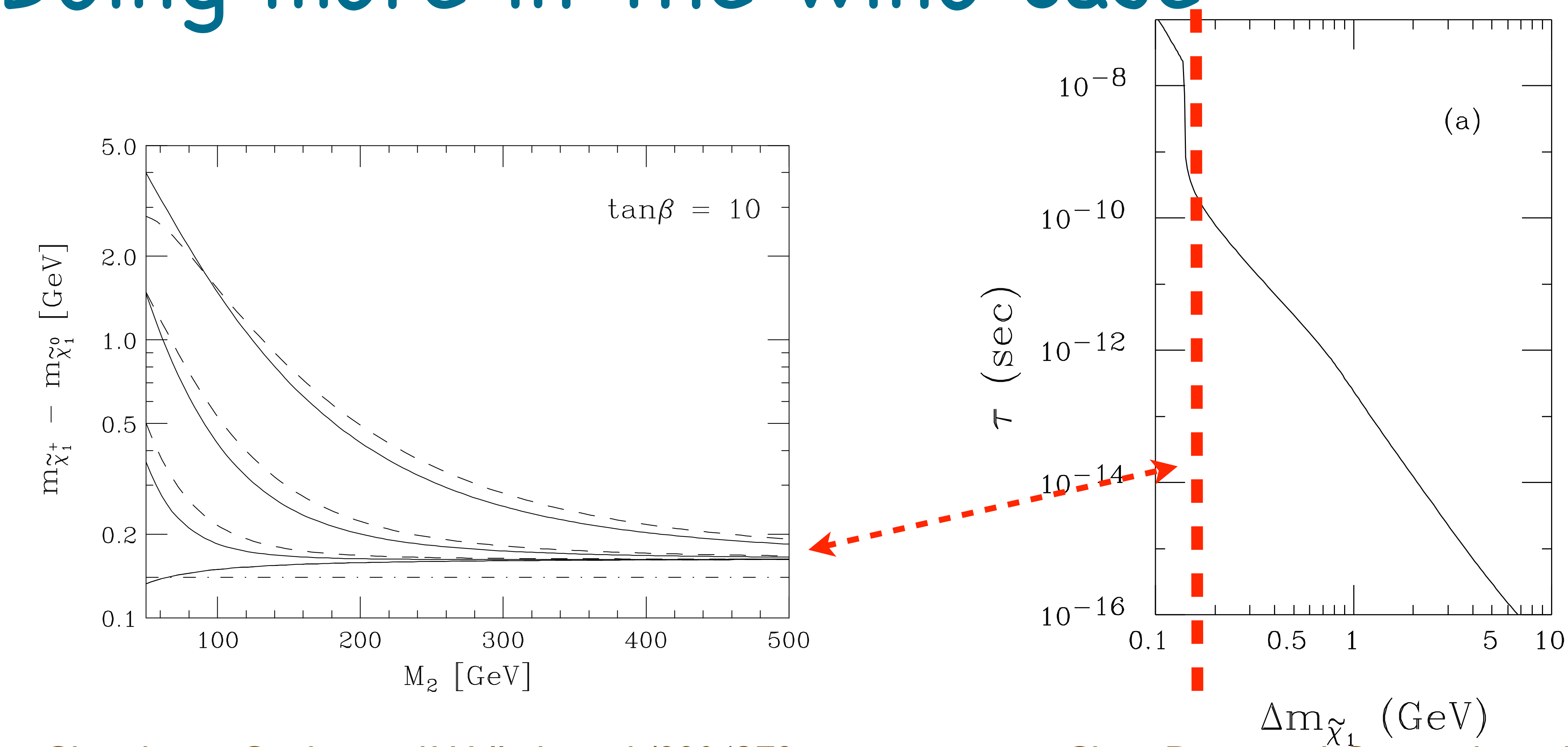
Gherghetta, Giudice and Wells, hep-ph/9904378



Chen, Drees and Gunion, hep-ph/9902309

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

Doing more in the wino case

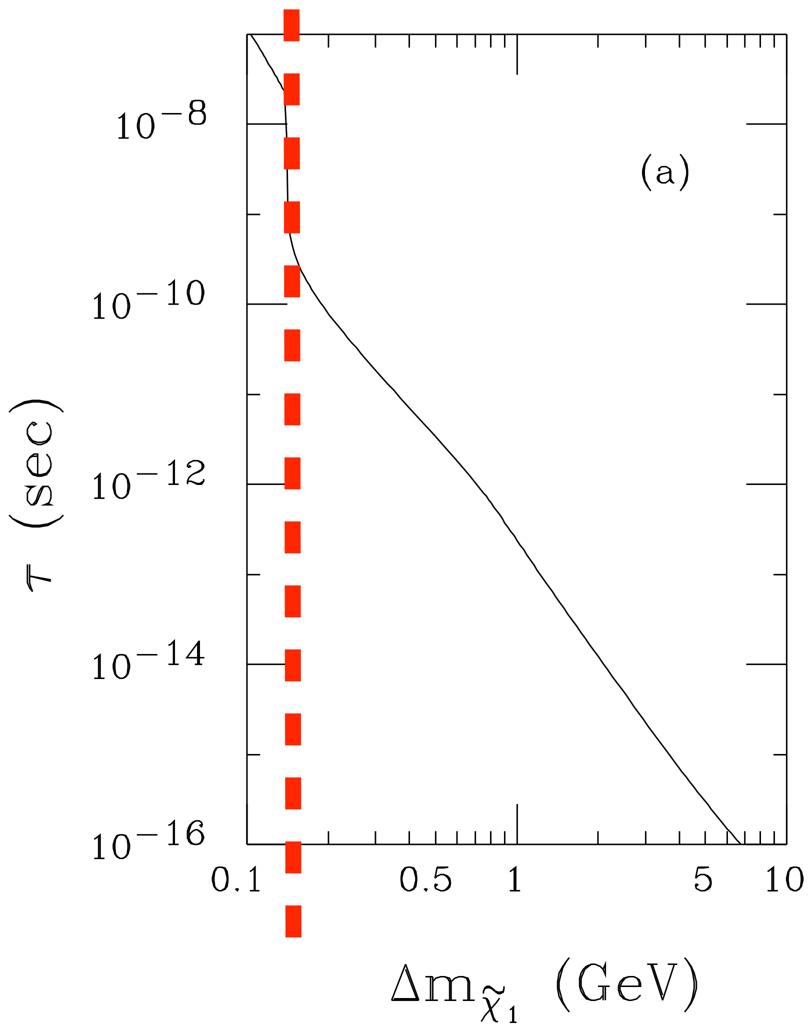


Gherghetta, Giudice and Wells, hep-ph/9904378

Chen, Drees and Gunion, hep-ph/9902309

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

Disappearing track



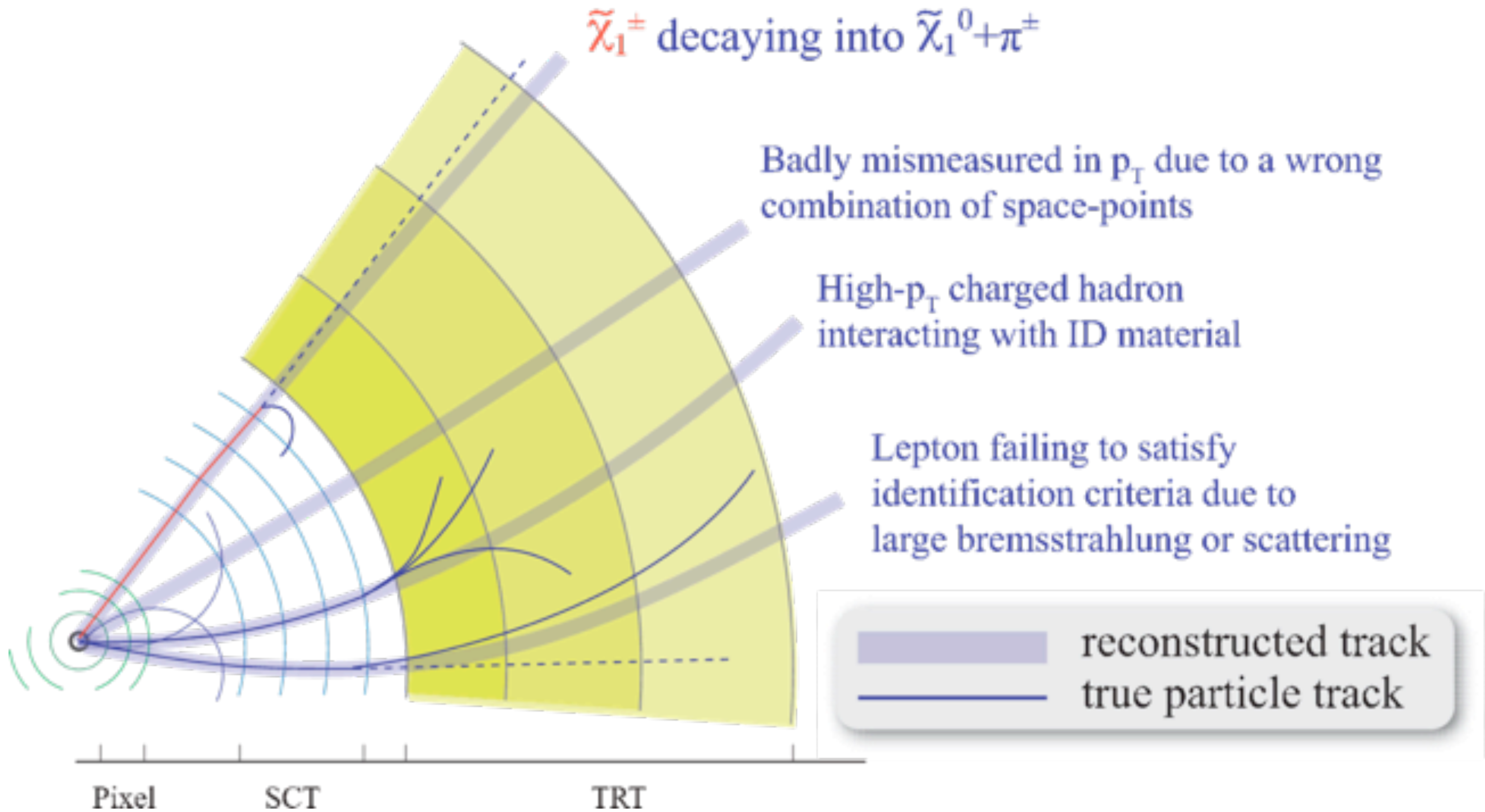


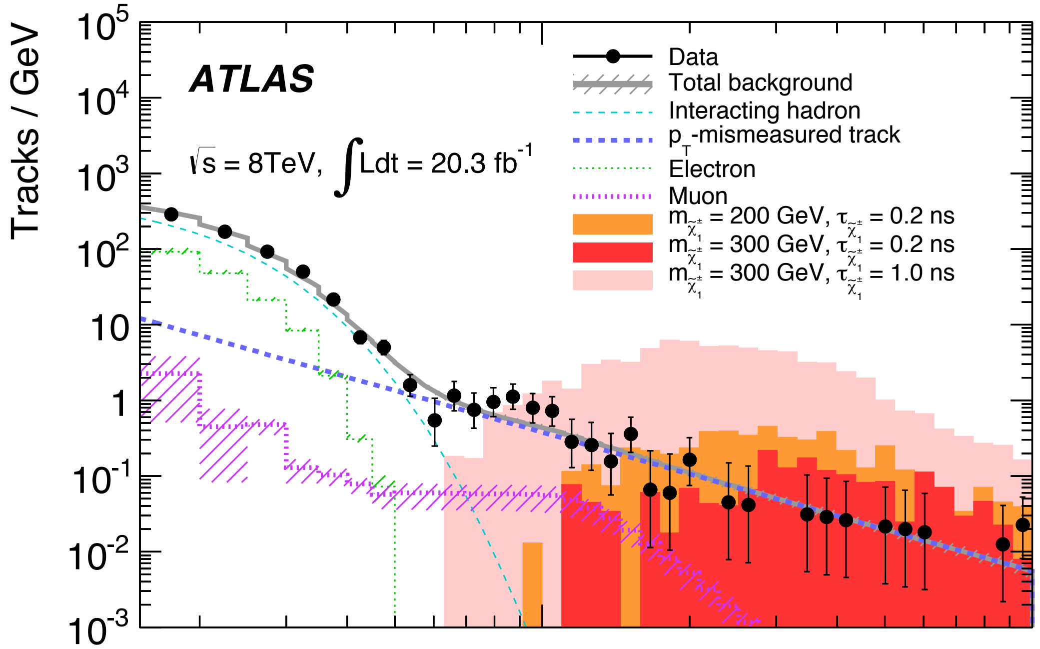
Figure from ATLAS disappearing track search twiki

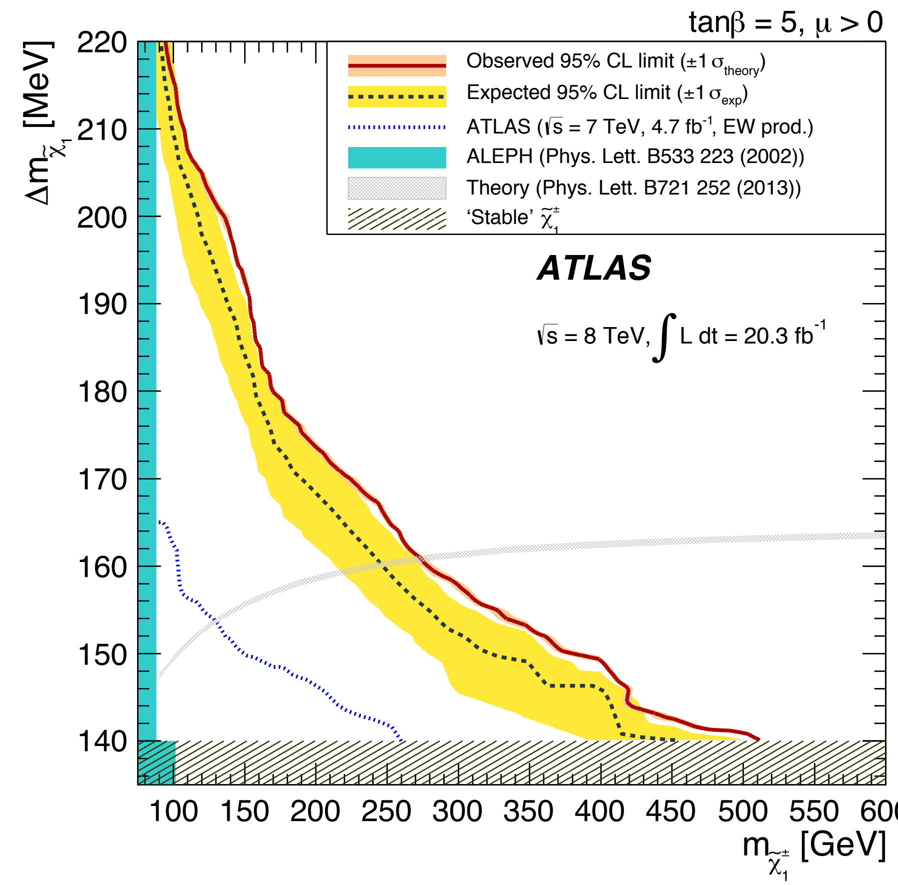
- Main decay mode $\chi^{\pm} \rightarrow \pi^{\pm} + \chi^{0}$

- Charge track ≈ 10(s) cm

ATLAS search

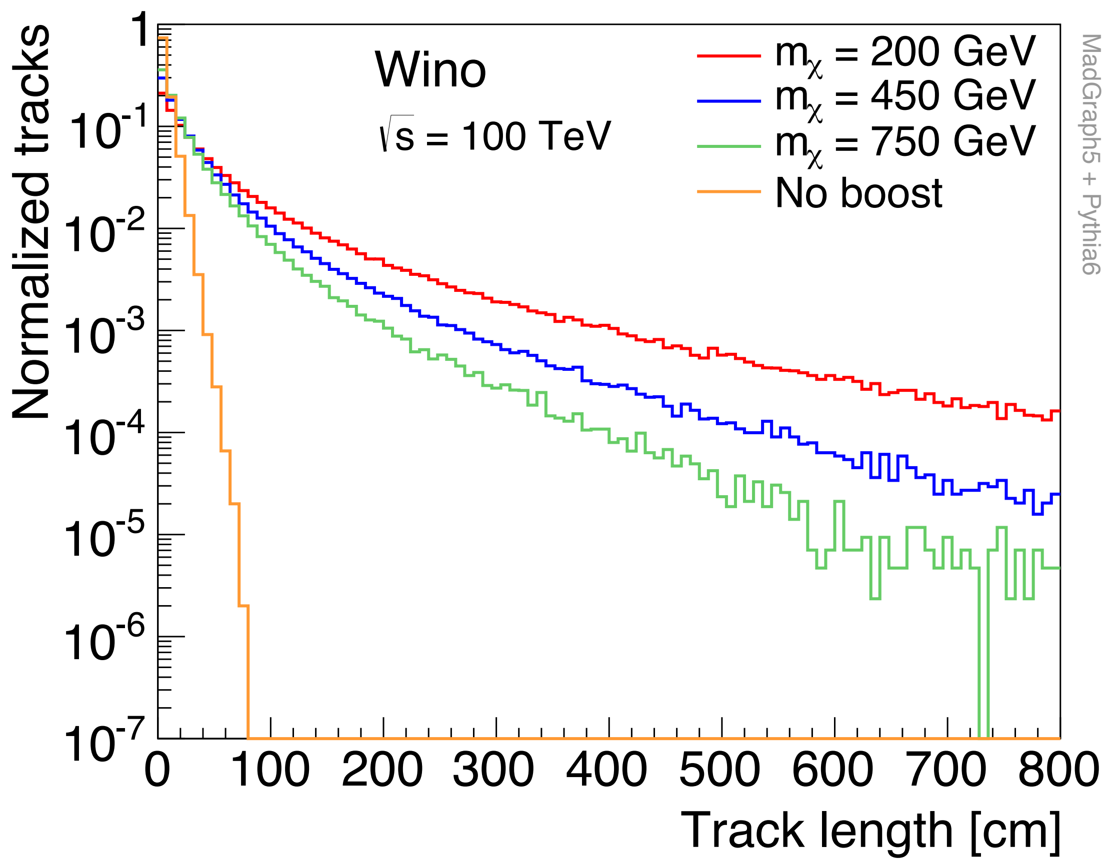
ATLAS, 1310.3675

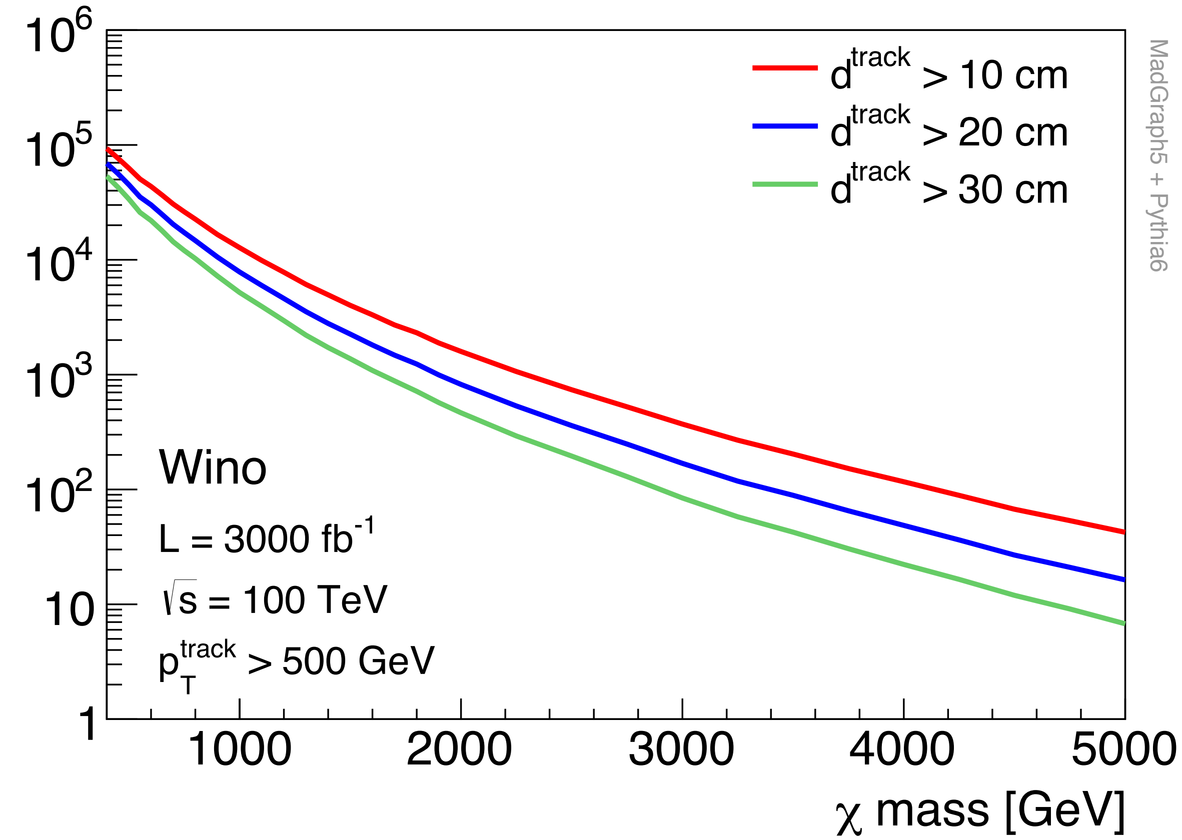




- Essentially free of physics background.
- Dominated by p_T mis-measured tracks.
- Very promising reach, much better than mono-jet

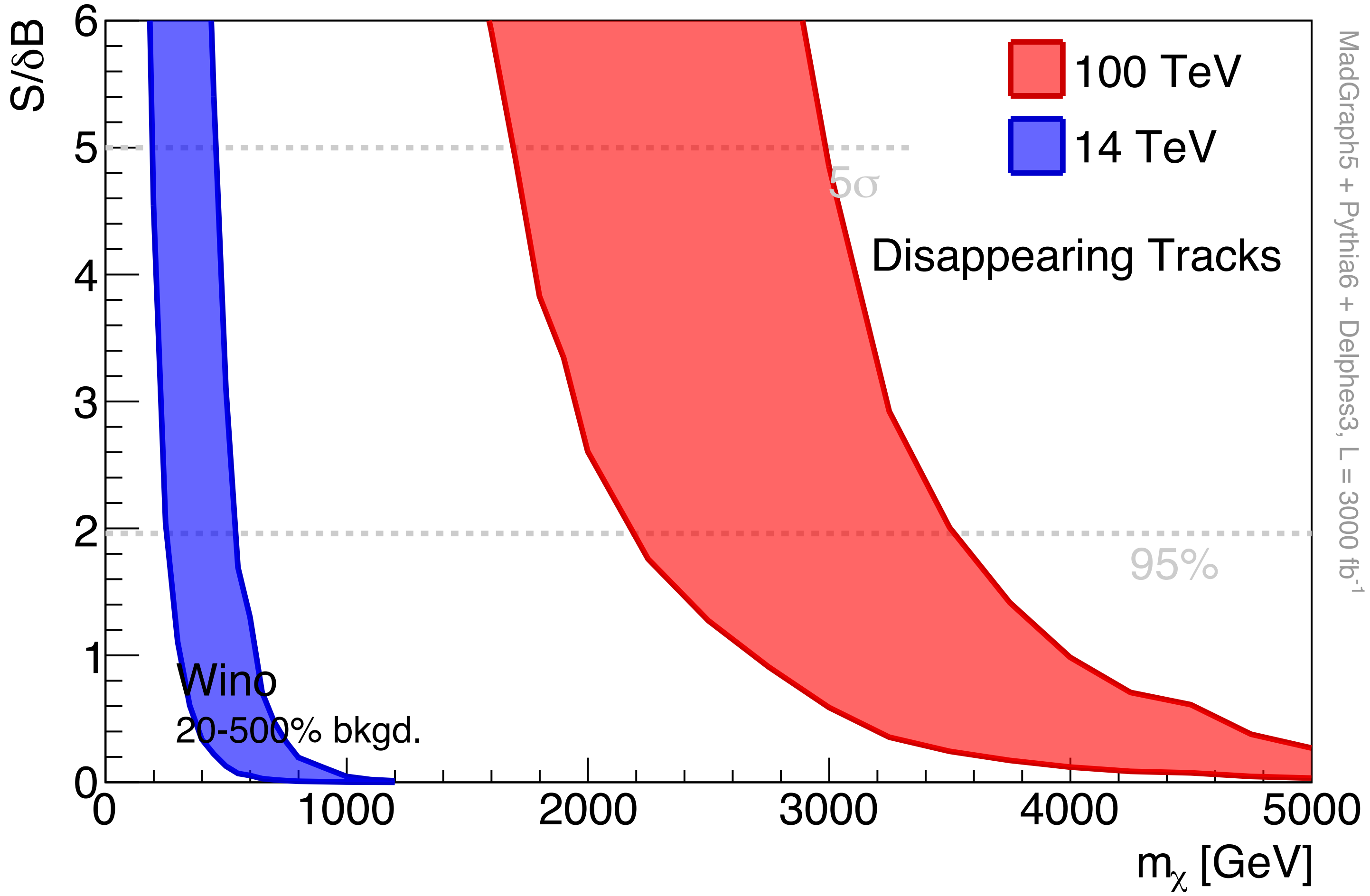
Rates (with long tracks)





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

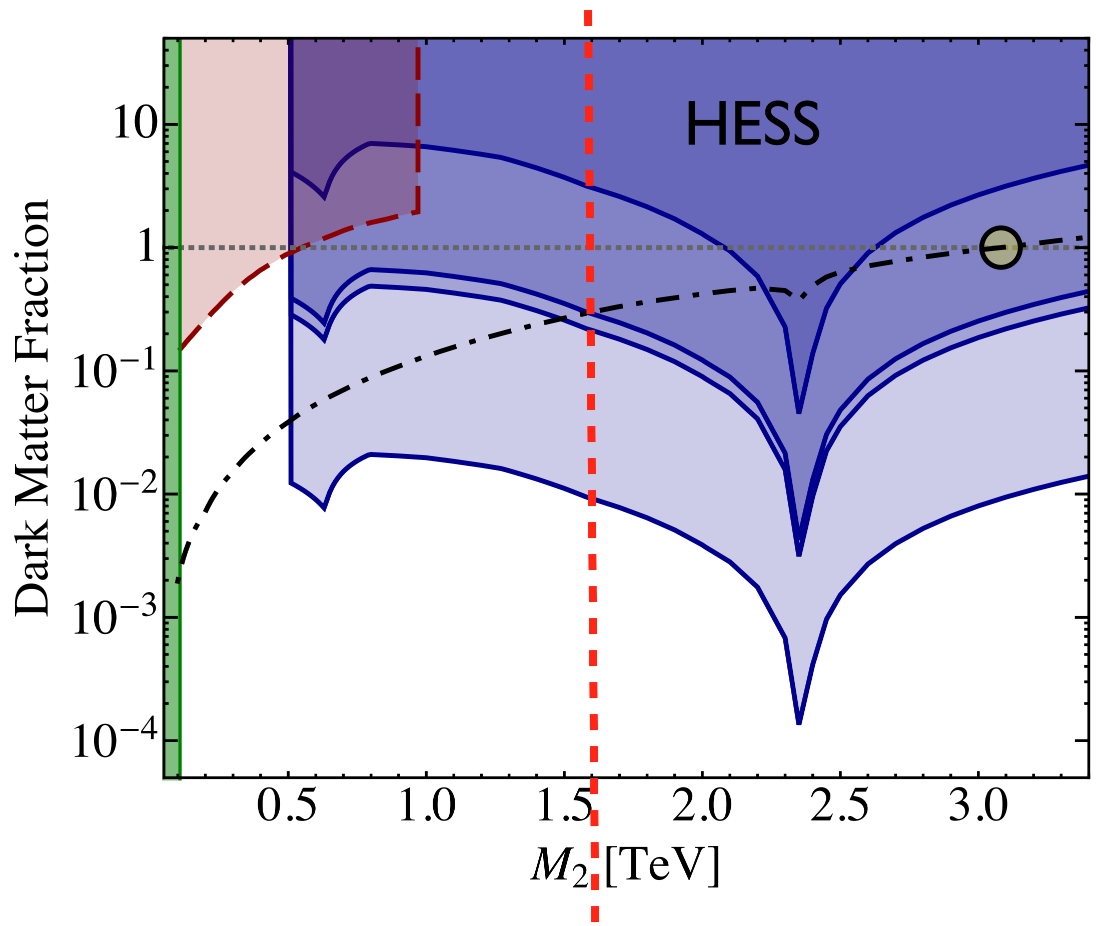
(Rough) Extrapolation from ATLAS search

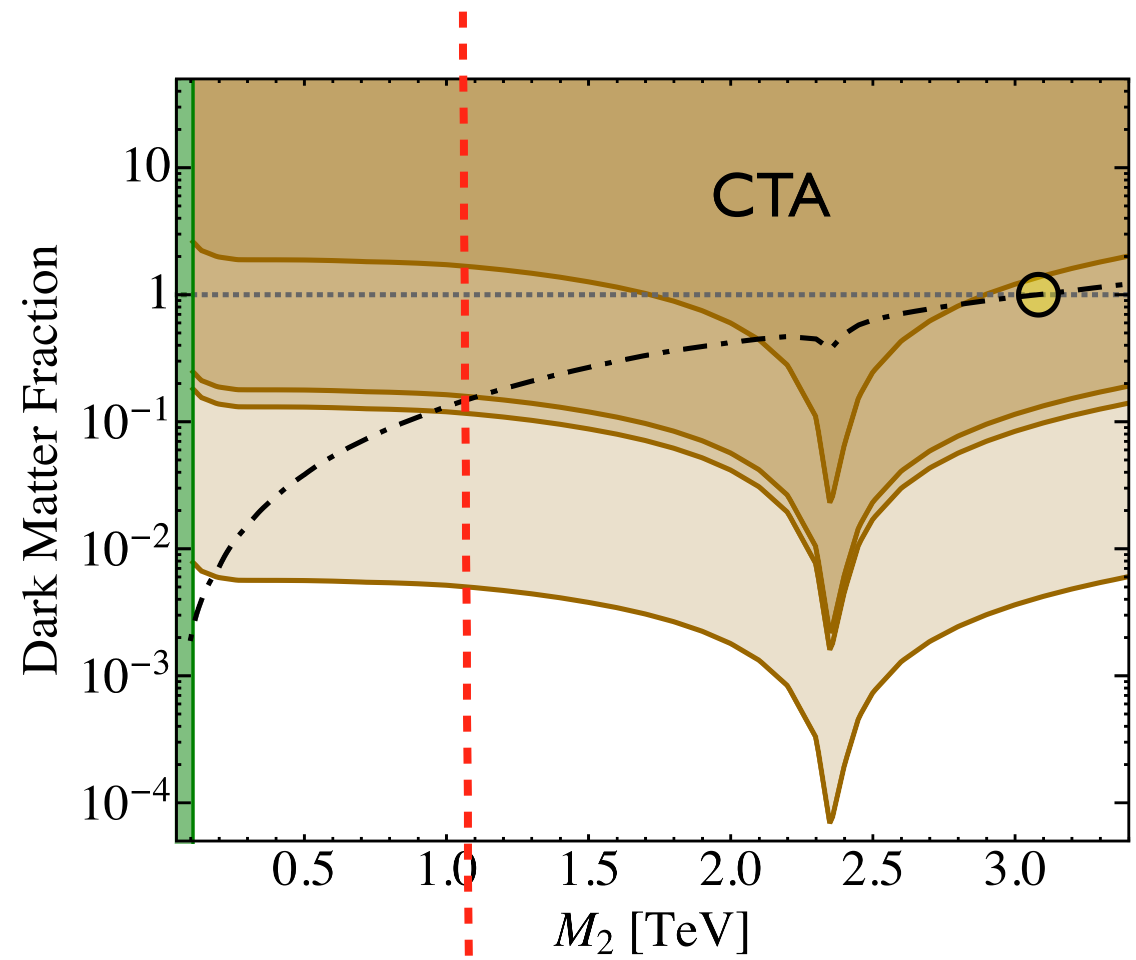


- Scale the ATLAS background rates according to hard jet + MET rates.

- Band: varying background estimate by 5 either way.

Wino, interplay with indirect detection

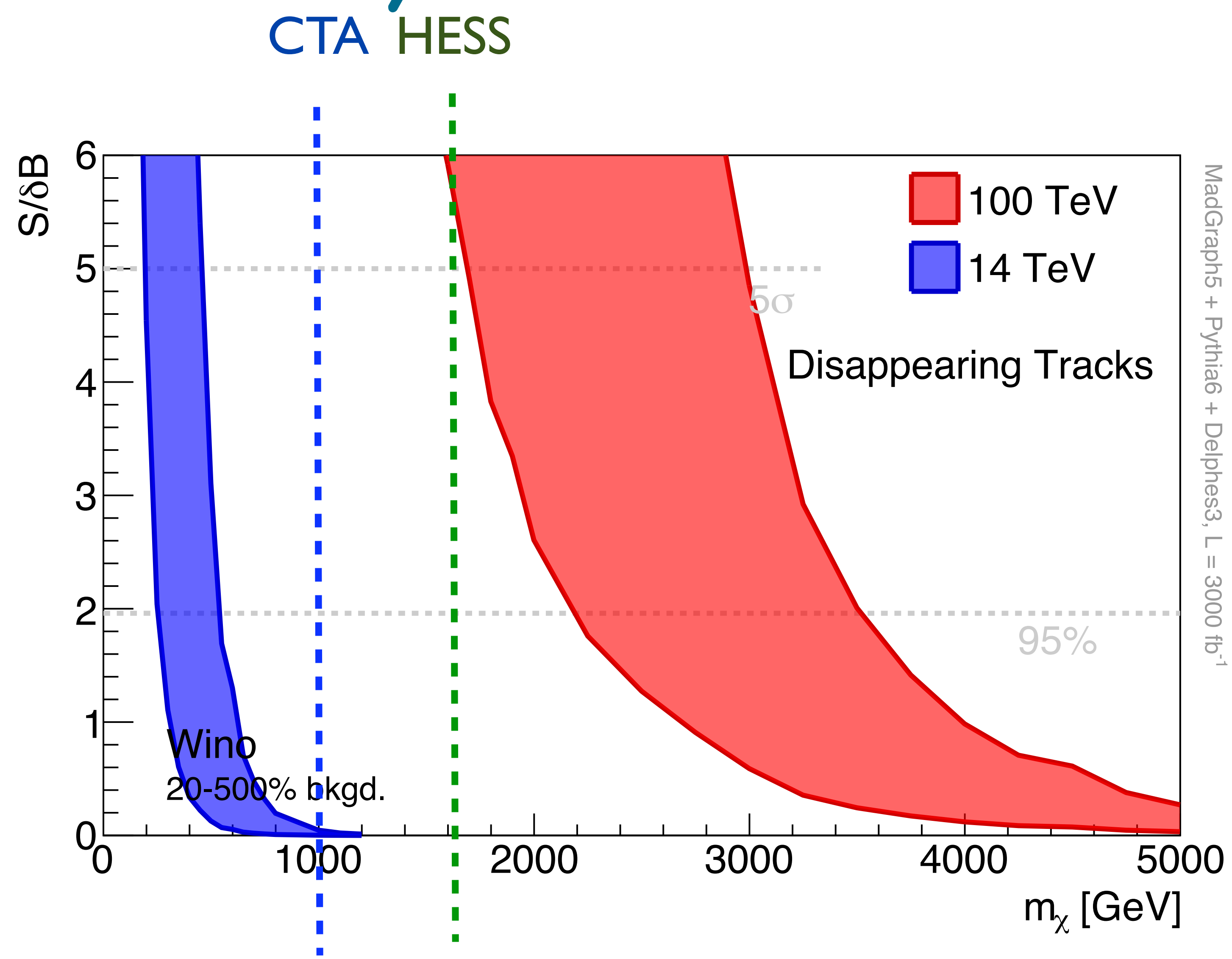




Cohen, Lisanti, Pierce, Slatyer, 1307.4082

See also Fan, Reece, 1307.4400

Wino summary

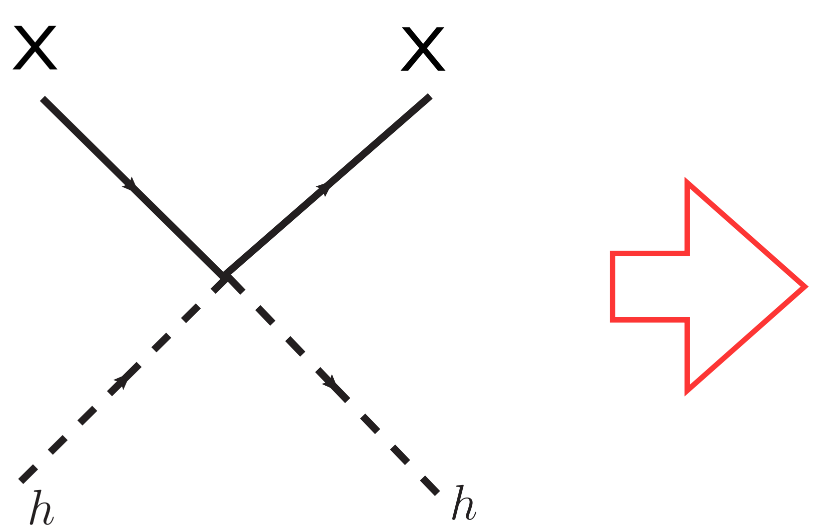


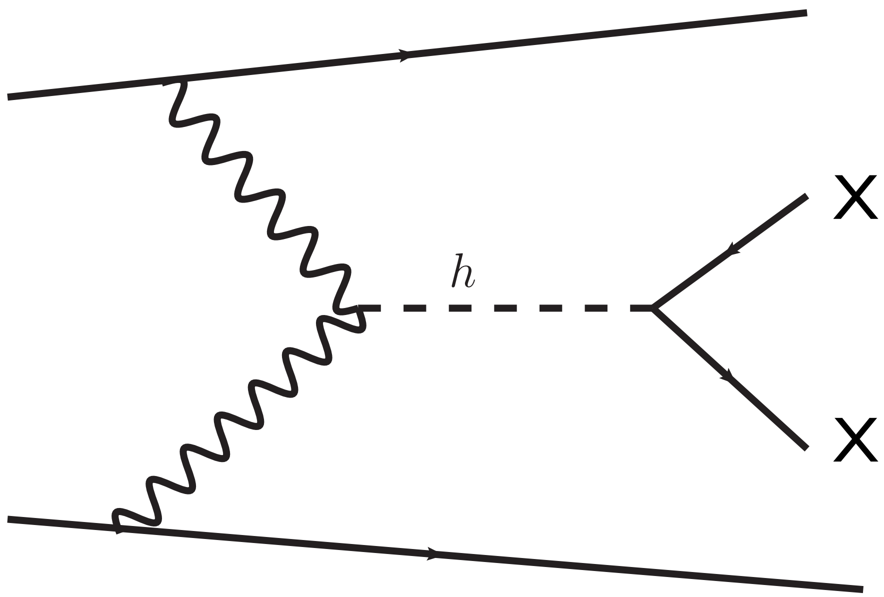
- There is hope to "completely cover" the wino parameter space.

“blind spots” for colliders

- Heavier WIMPs.
  - Coupling stronger than weak gauge coupling.
  - Higher energy collider.
- Heavy and only couples to leptons.
  - Higher energy lepton collider
- Higgs-like coupling. Lower production rate.
  - Third generation signatures (b + MET).
  - Higgs coupling measurements.

Higgs portal like coupling

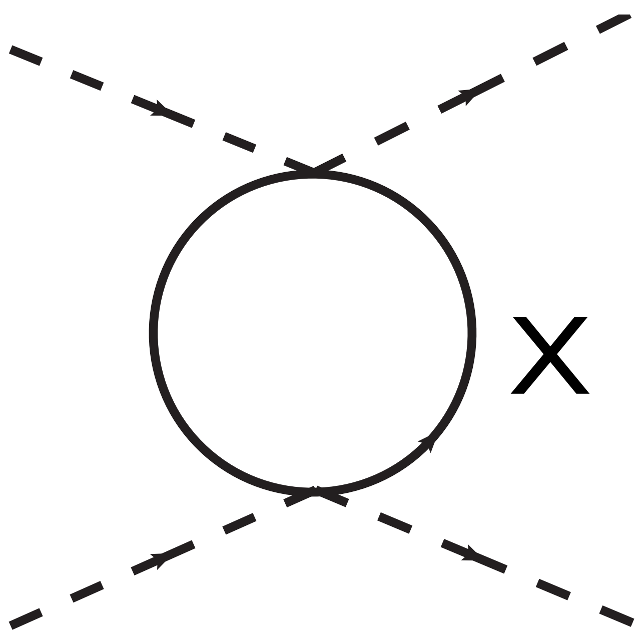




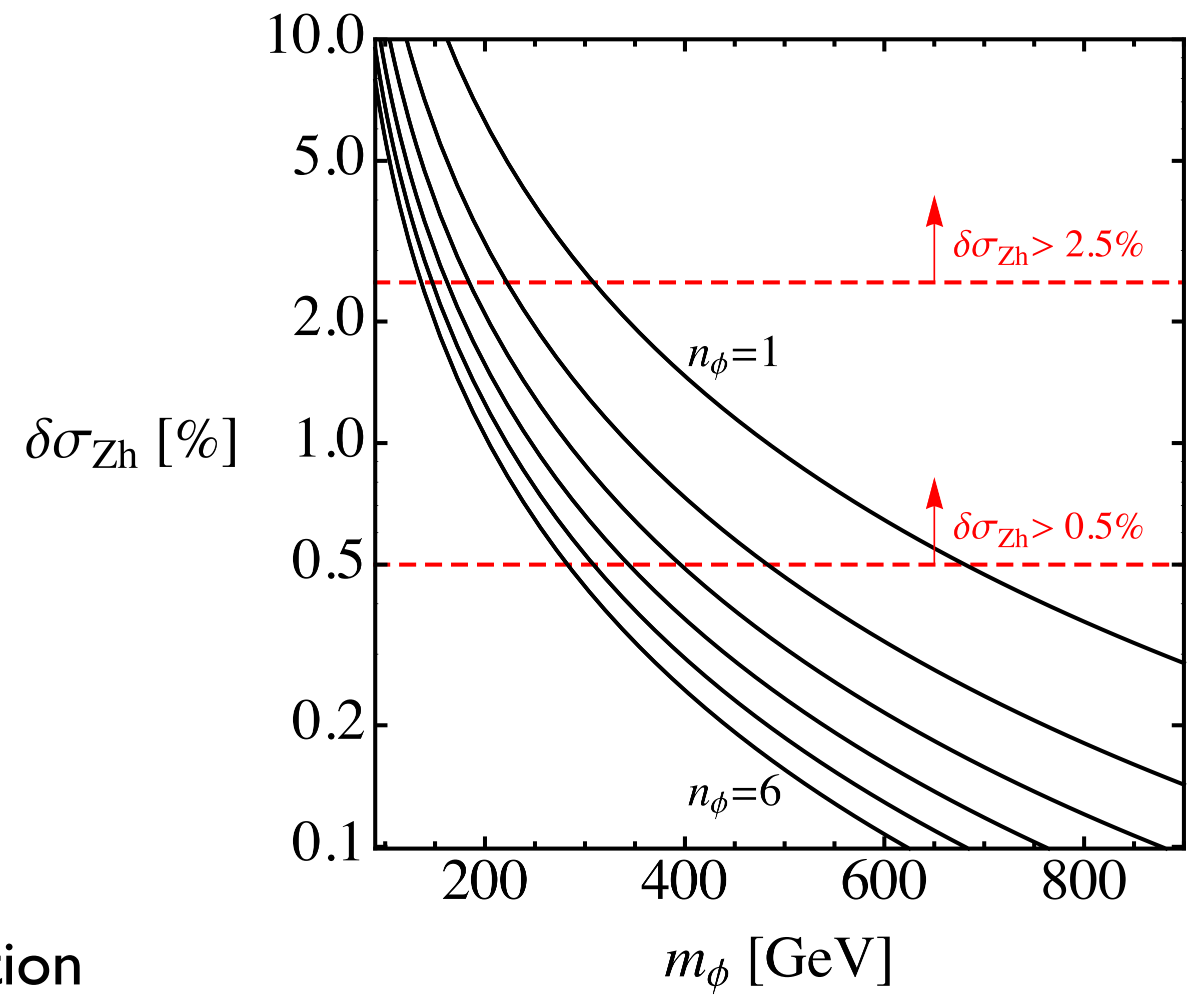
direct production at collider

- Study to be done!
  - Reach probably very limited, 100s GeV (my guess)

Anything else we can do?



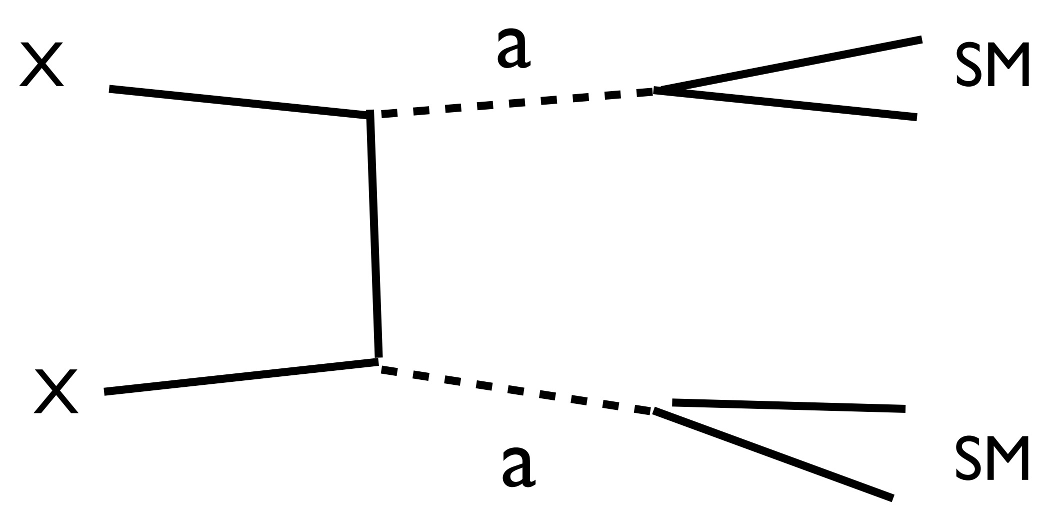
Wavefunction renormalization
Induce shift in Higgs coupling.



Craig, Englert, McCullough, 2013

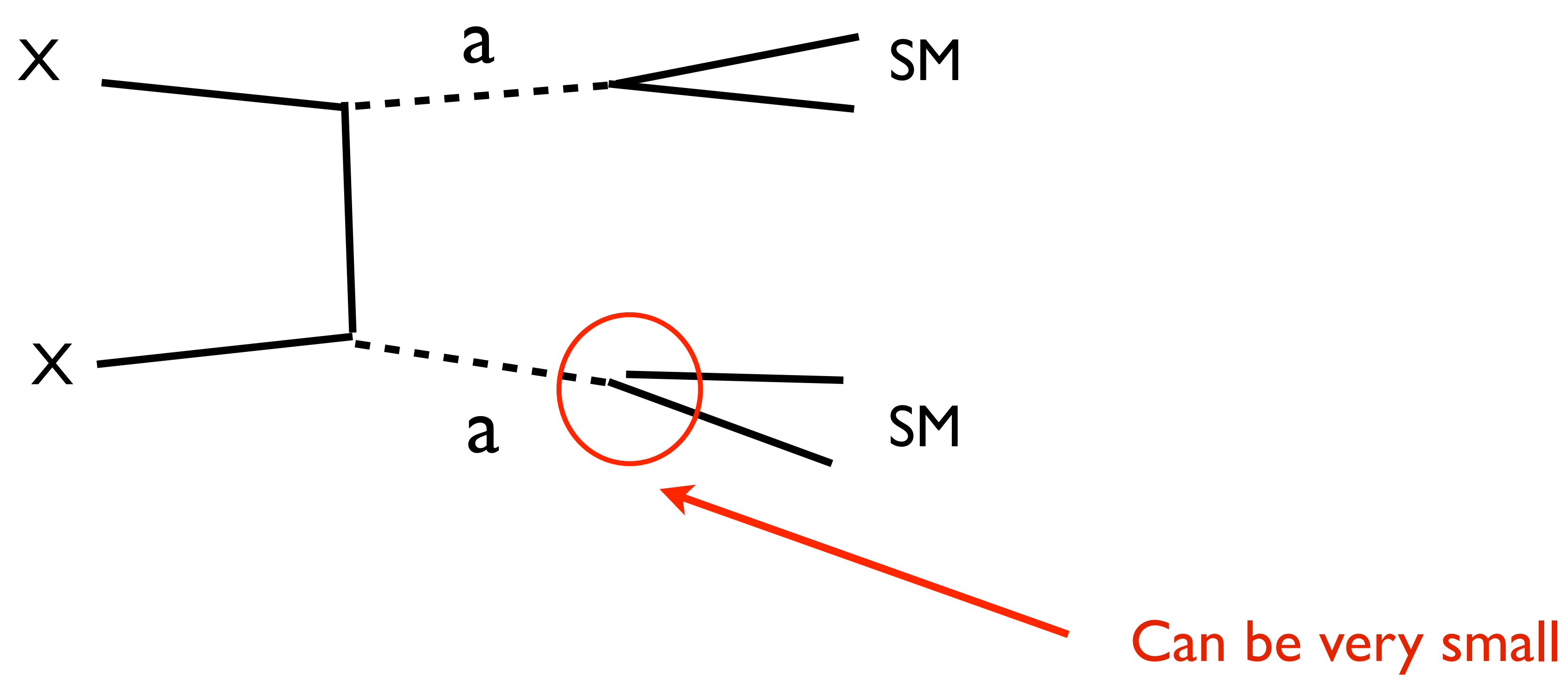
- Precision Higgs measurement is the best way to go.

Perhaps the most difficult case



- “a” can be dark photon, etc.
- Fixed target dark photon searches..

Perhaps the most difficult case



- "a" can be dark photon, etc.

- Fixed target dark photon searches..

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.

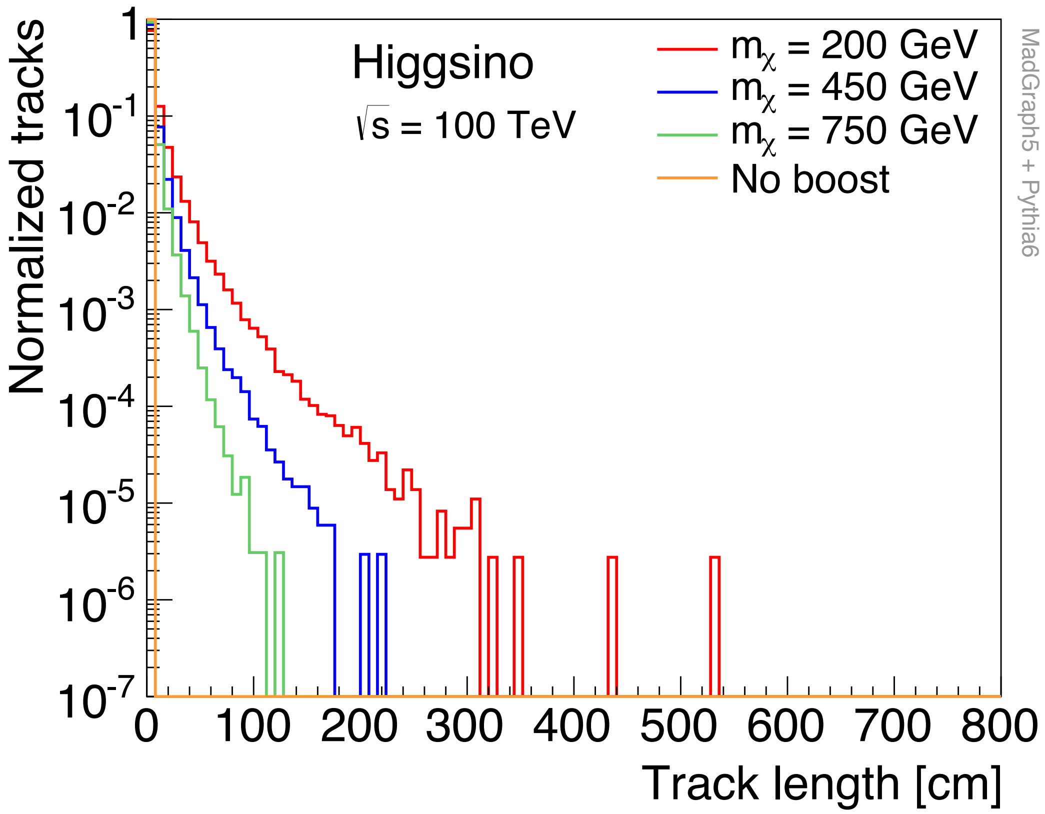
More broadly

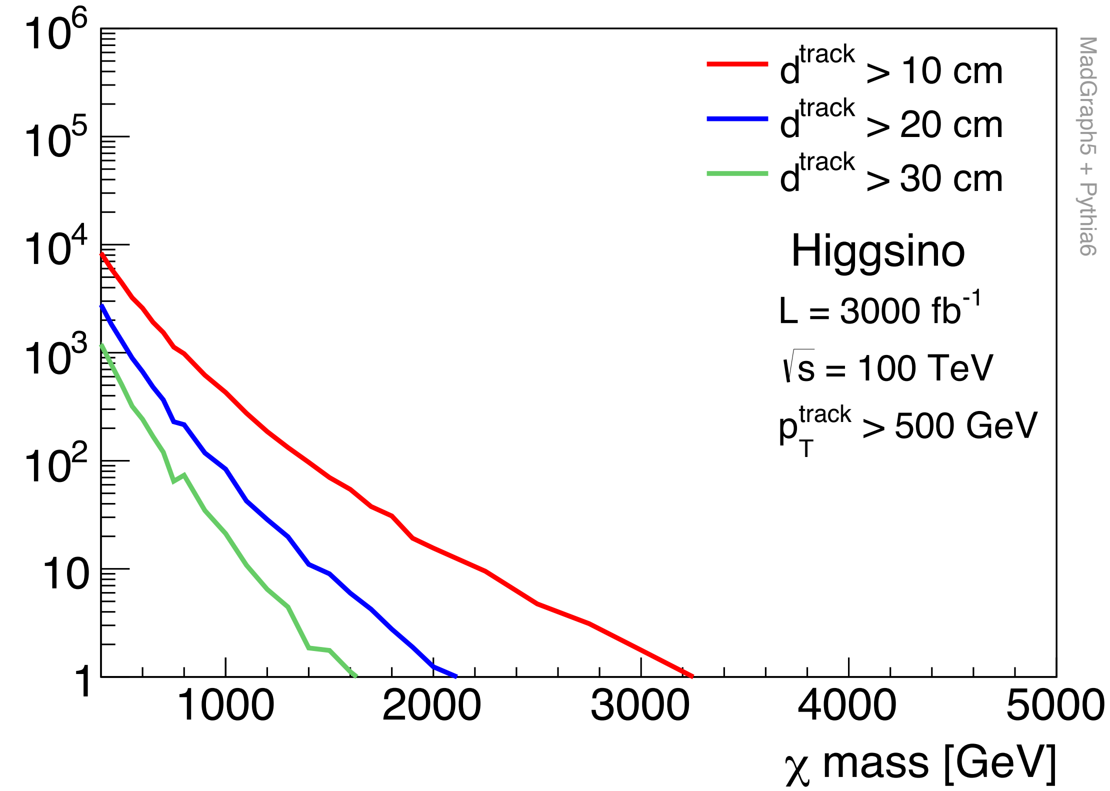
LHC	VLHC 100 TeV	Lepton collider
M_{DM} ~10^2s GeV	M_{DM} ~TeV	M_{DM} ~ 0.5 E_{cm} Spin, coupling Is it WIMP?

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

extras

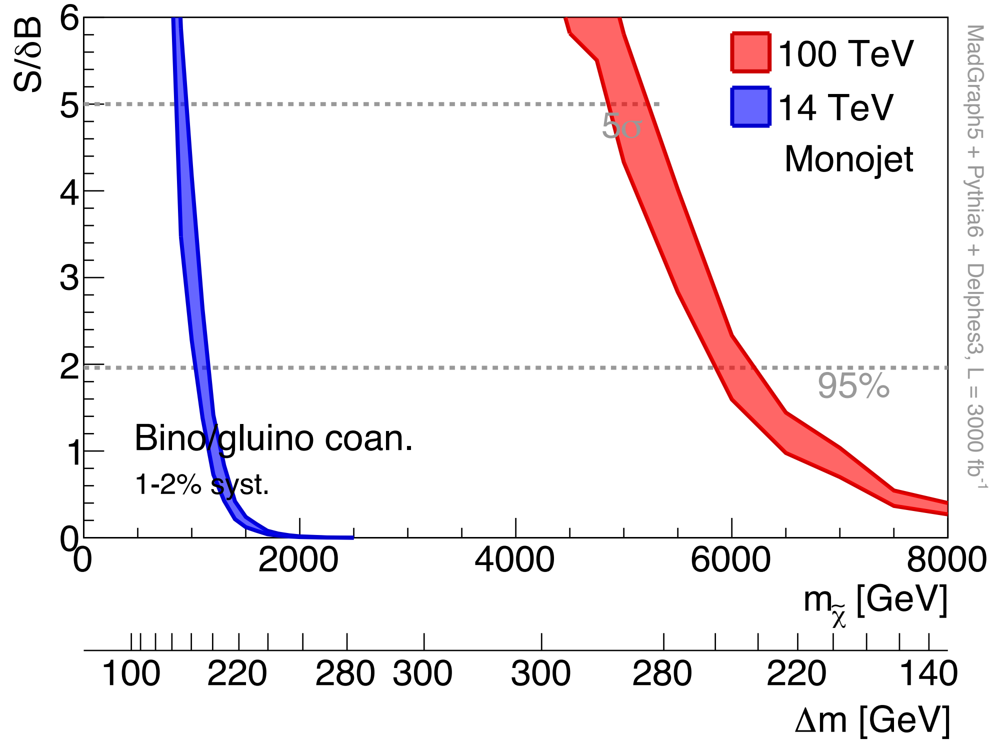
Tracks?

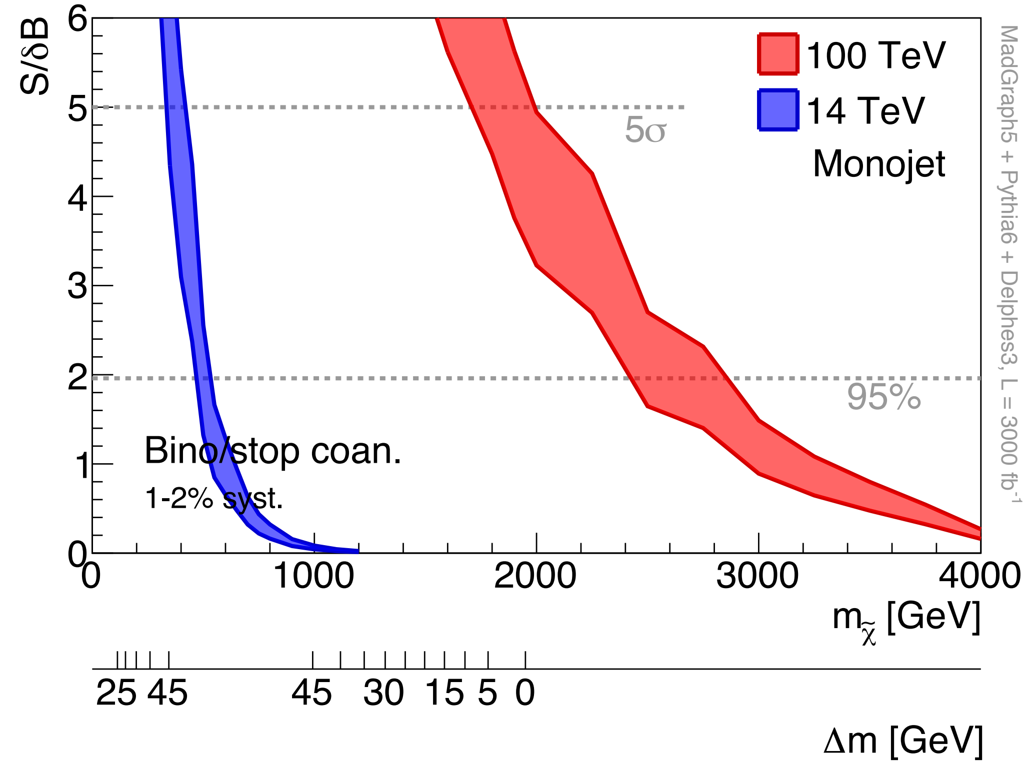




- Depends on detector design
  - How long the track needs to be?
  - Background discrimination?
- Can change mass splitting in extended models.

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_{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 GeV, 30 GeV), 2.5	$\in$ (10 GeV, 30 GeV), 2.5
$p_T(\mu)$, $\eta(\mu)$	$\in$ (10 GeV, 30 GeV), 2.1	$\in$ (10 GeV, 30 GeV), 2.1
$\not{E}_T$	1250 GeV	350 GeV

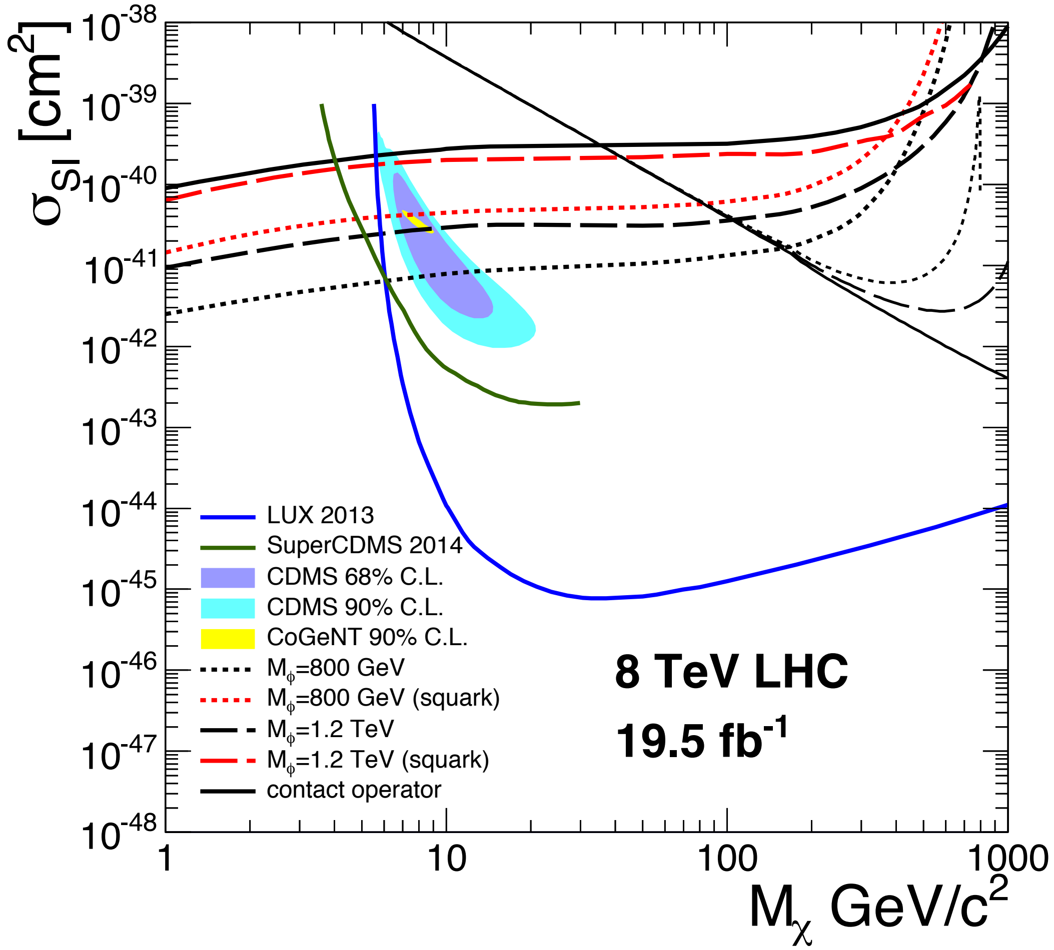
Table 7: Cuts used in soft lepton analysis.

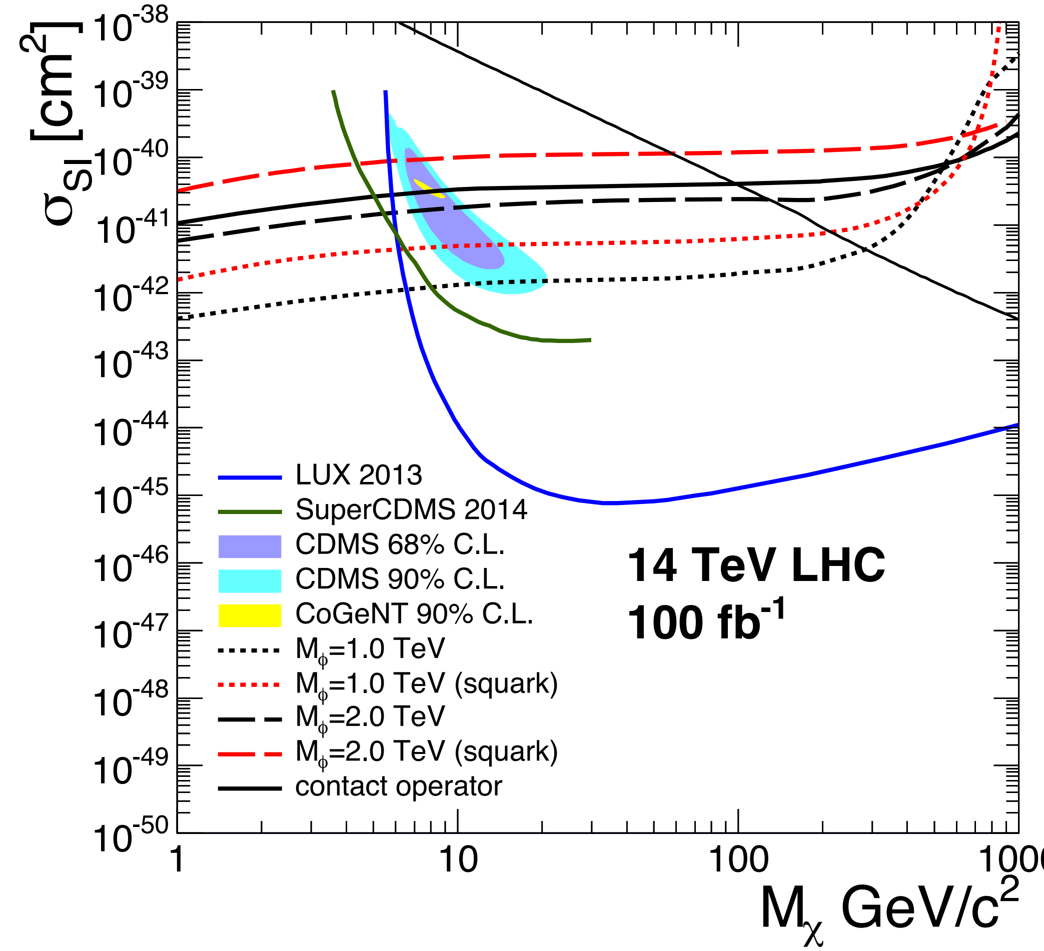
Cuts, disappearing track

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
$\Delta\phi_{\rm min}(j, \not{E}_T)$	1.5	1.5	1.5
$\eta^{\rm track}$	$\in (0.1, 1.9)$	$\in (0.1, 1.9)$	$\in (0.1, 1.9)$
$p_T^{\rm track}$	75 – 200 GeV	250 GeV	1.5 TeV

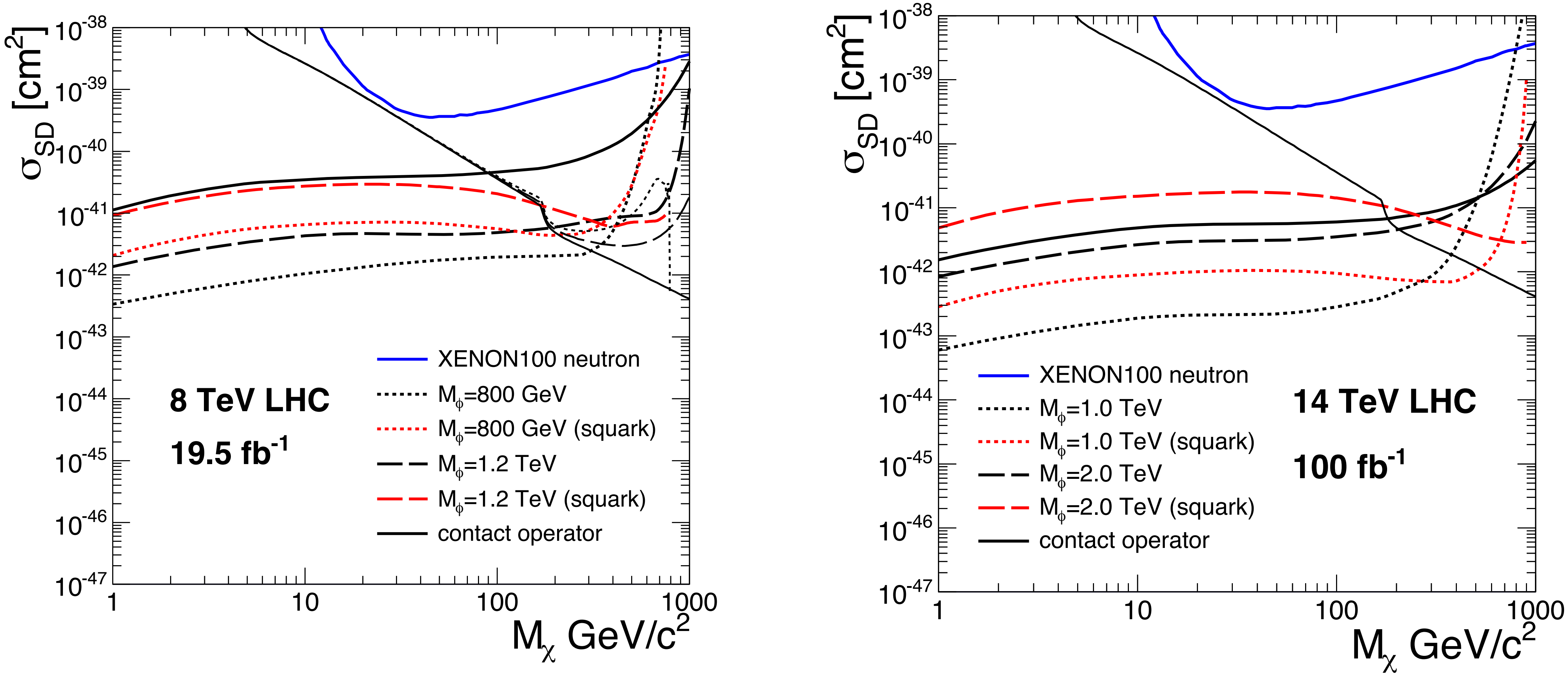
Table 8: Cuts used in disappearing track analysis.

Spin independent





Spin dependent



- Leading direct detection channel for Majorana DM.