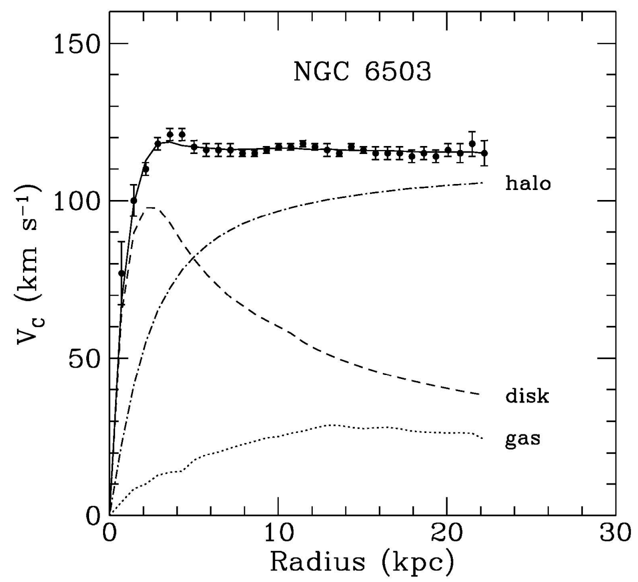
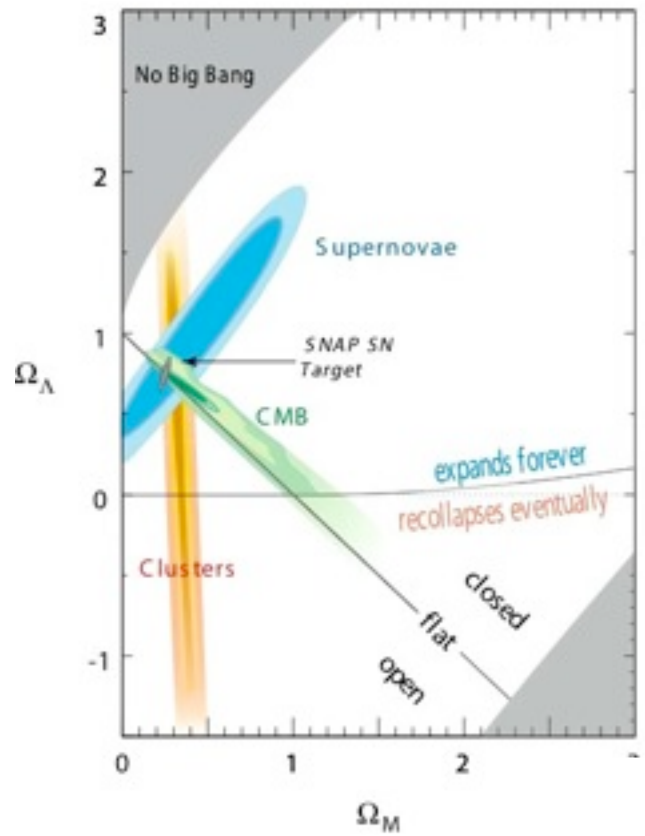
WIMP dark matter at 100 TeV

Lian-Tao Wang
University of Chicago

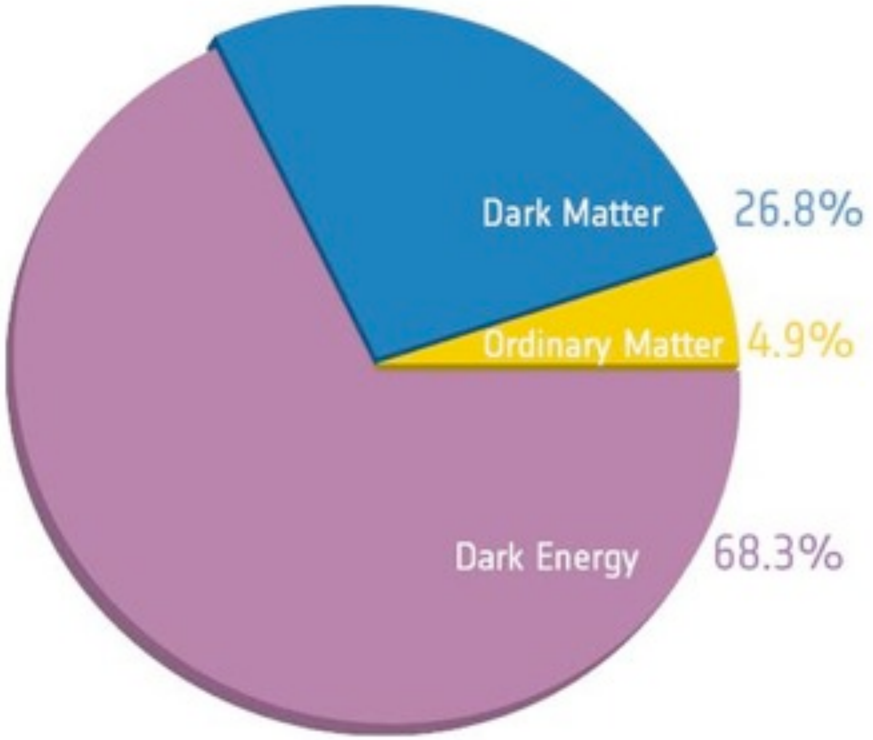
1st CFHEP Symposium on circular collider physics, Feb. 24, 2014

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^{50} GeV.

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- Looking for a compelling story.
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    - 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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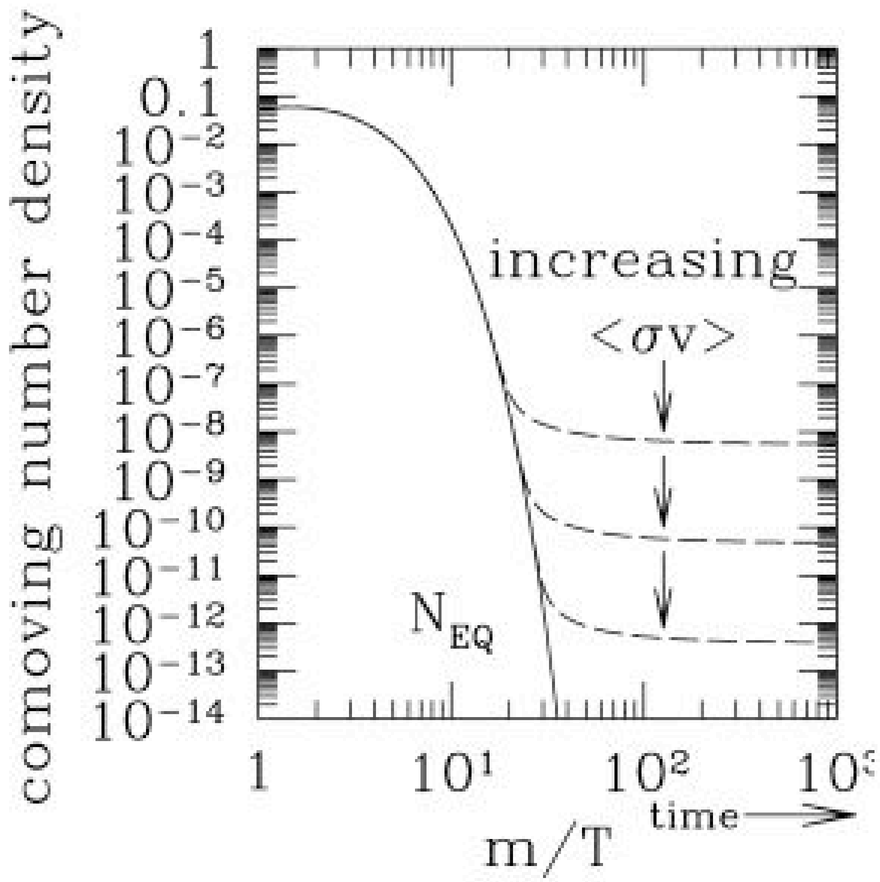
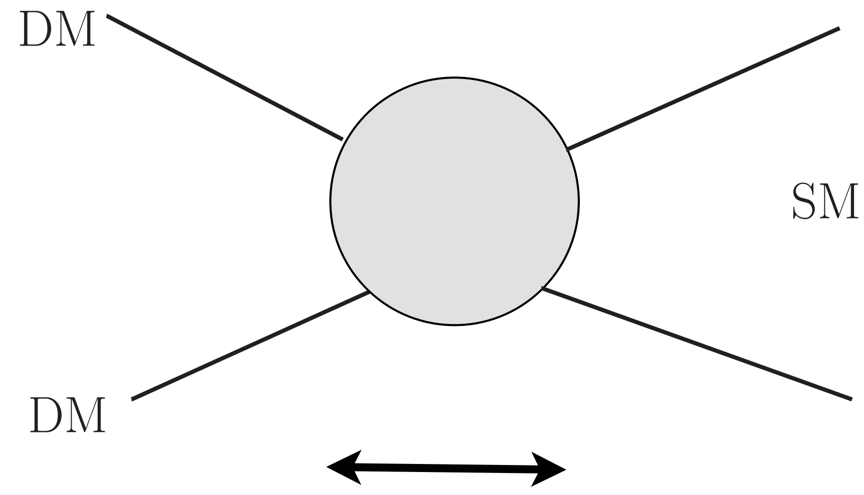
WIMP

WIMP miracle

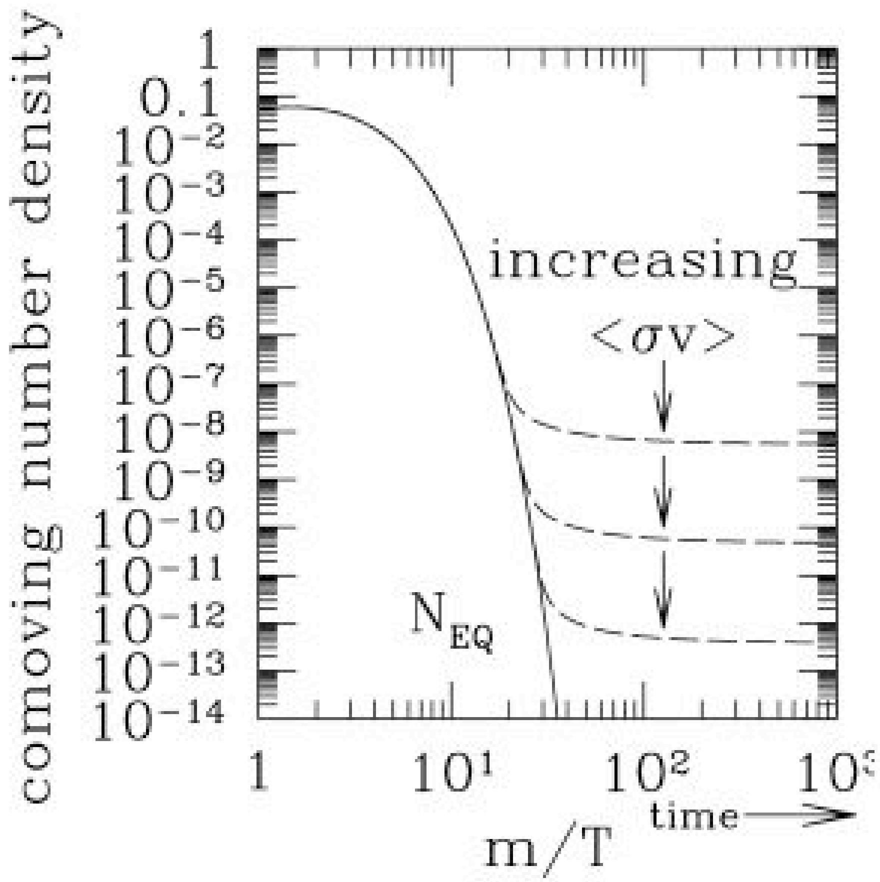


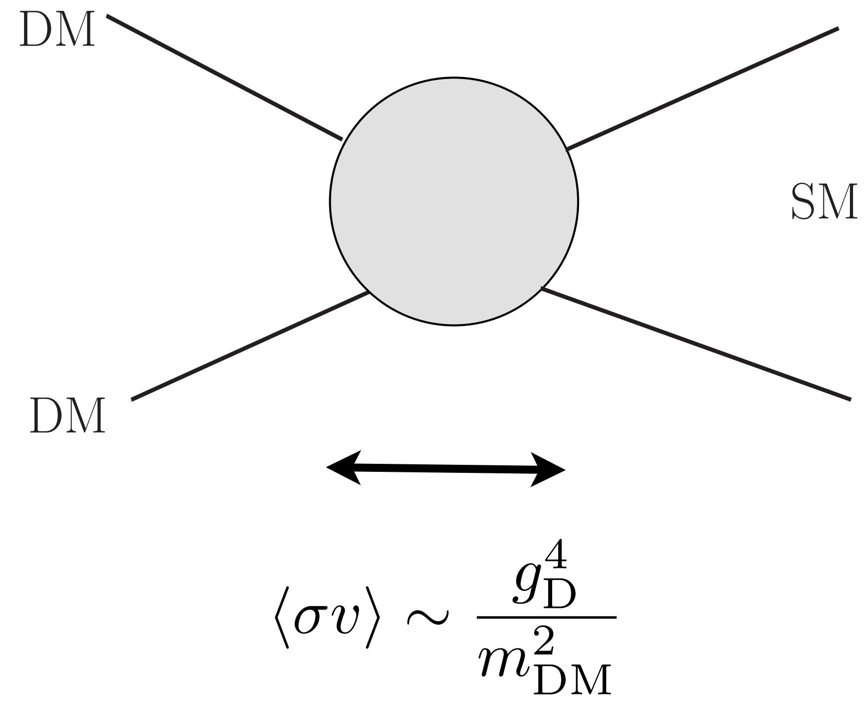


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- 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



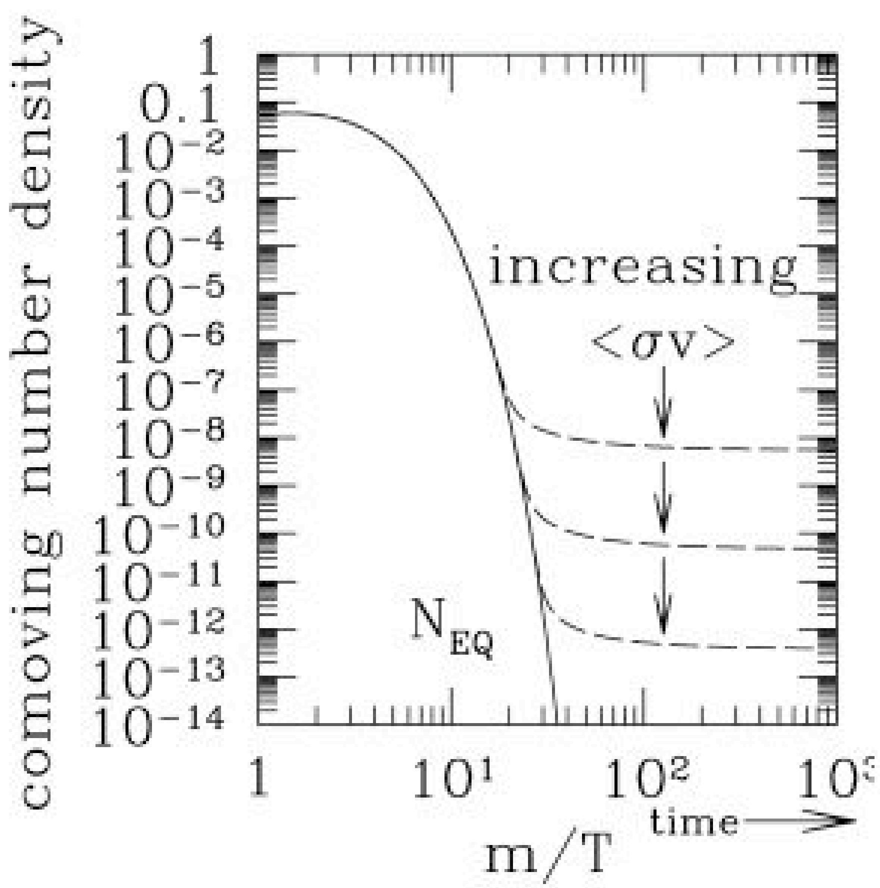


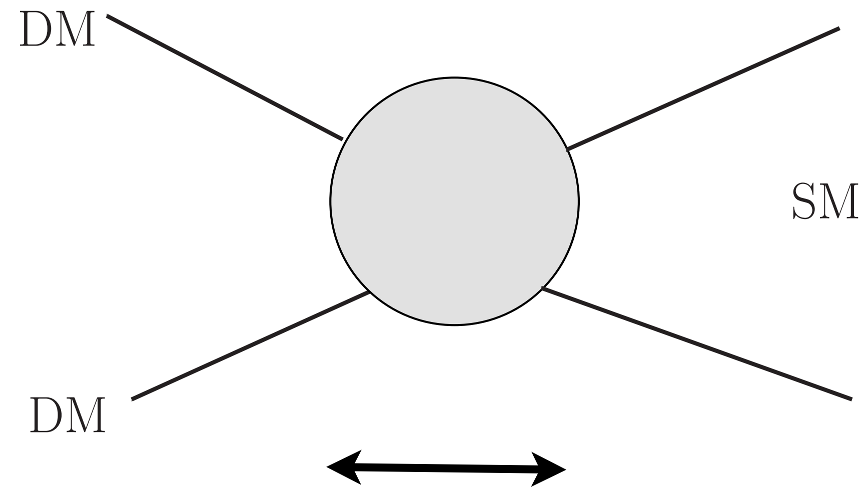
- More precisely, to get the correct relic abundance

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

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

WIMP miracle





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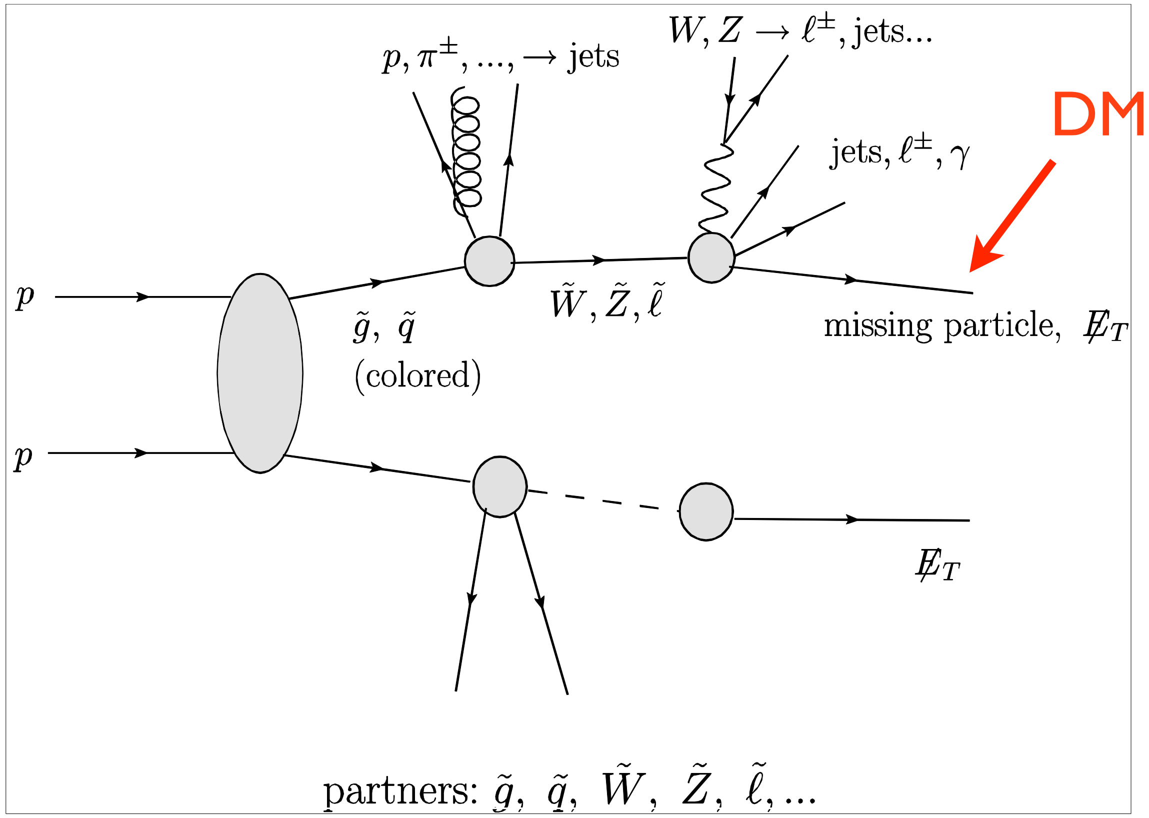
Will use 100 TeV for comparison here.

“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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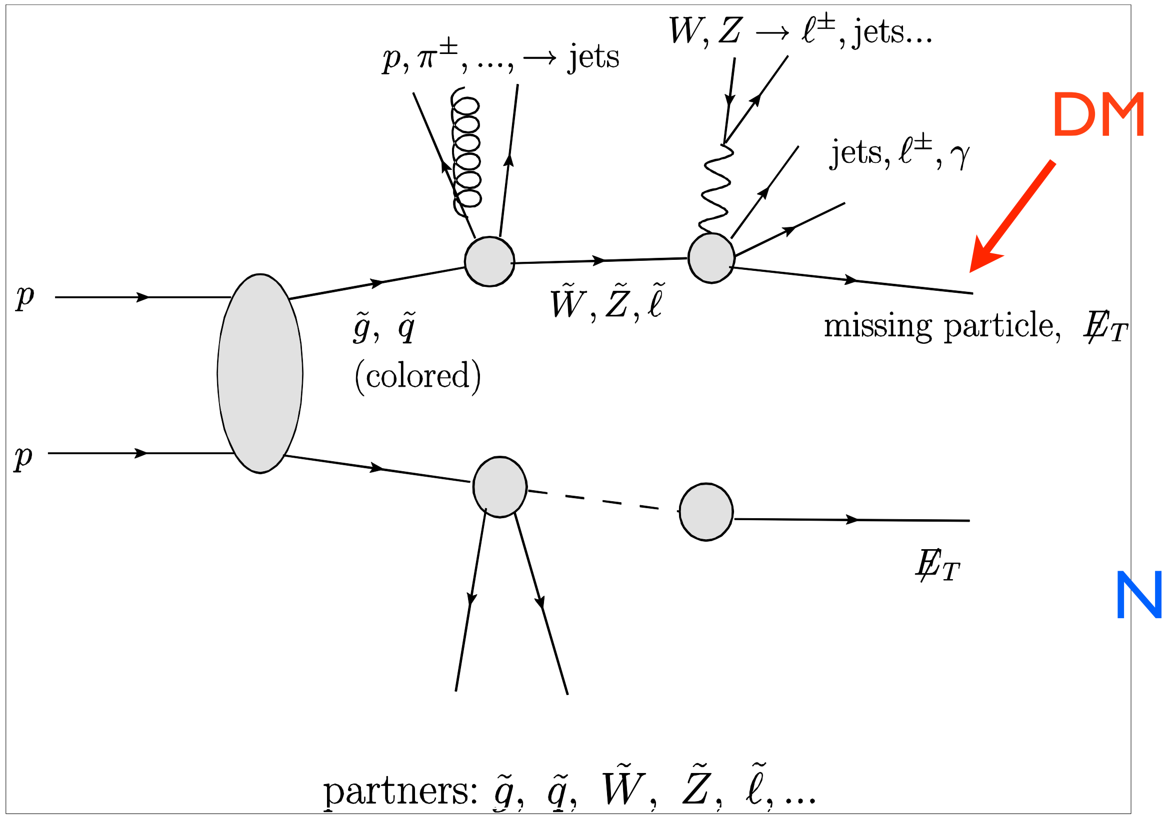
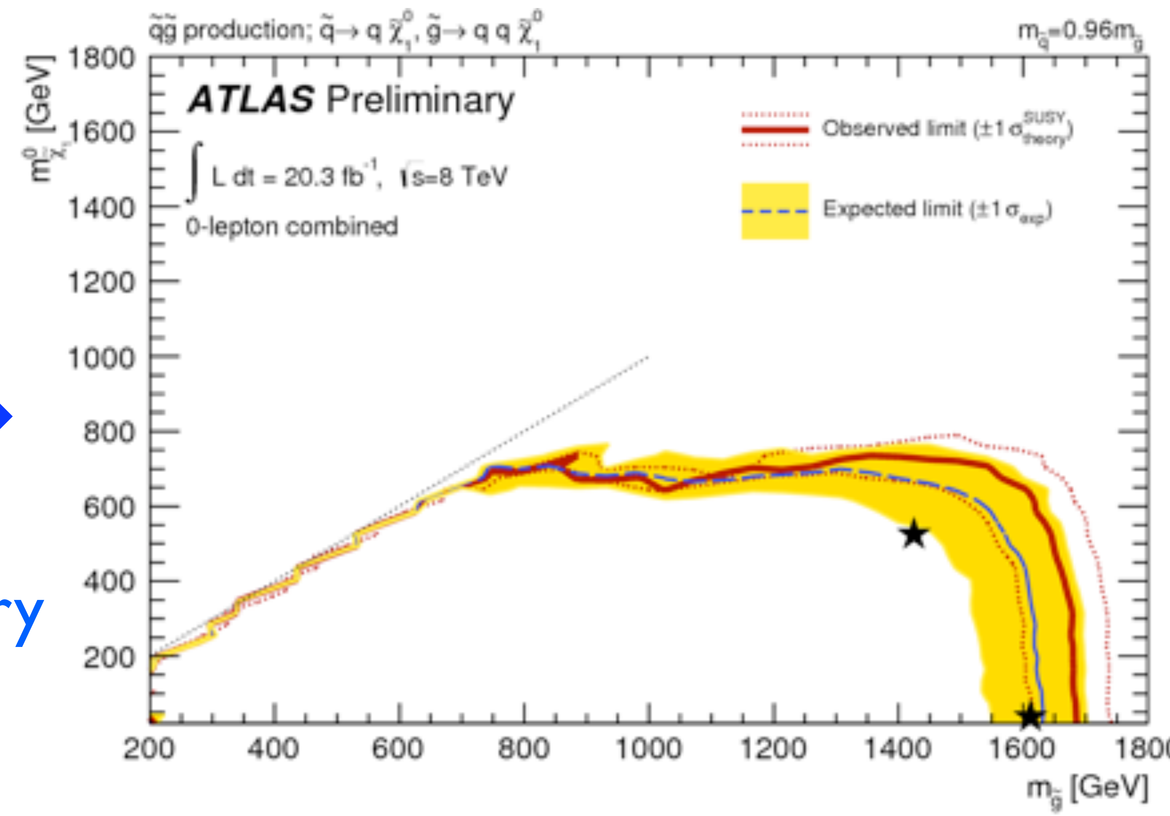


No discovery yet



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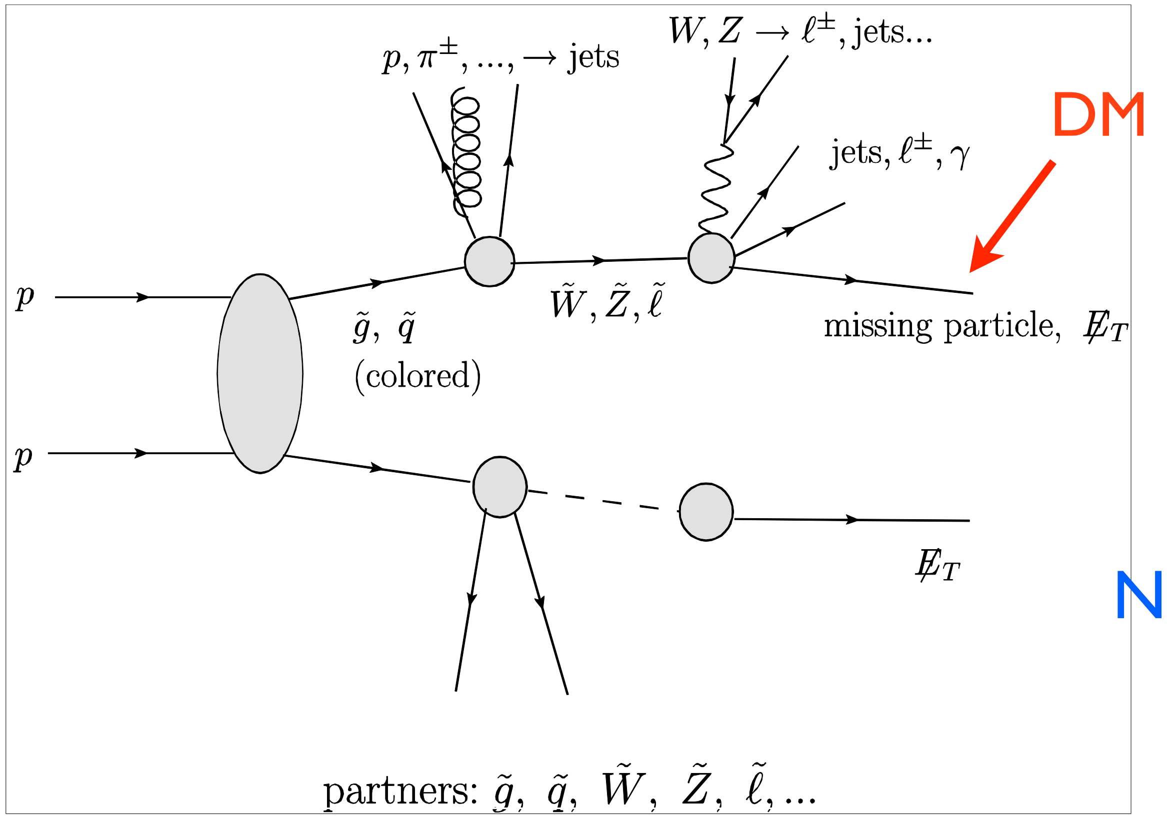

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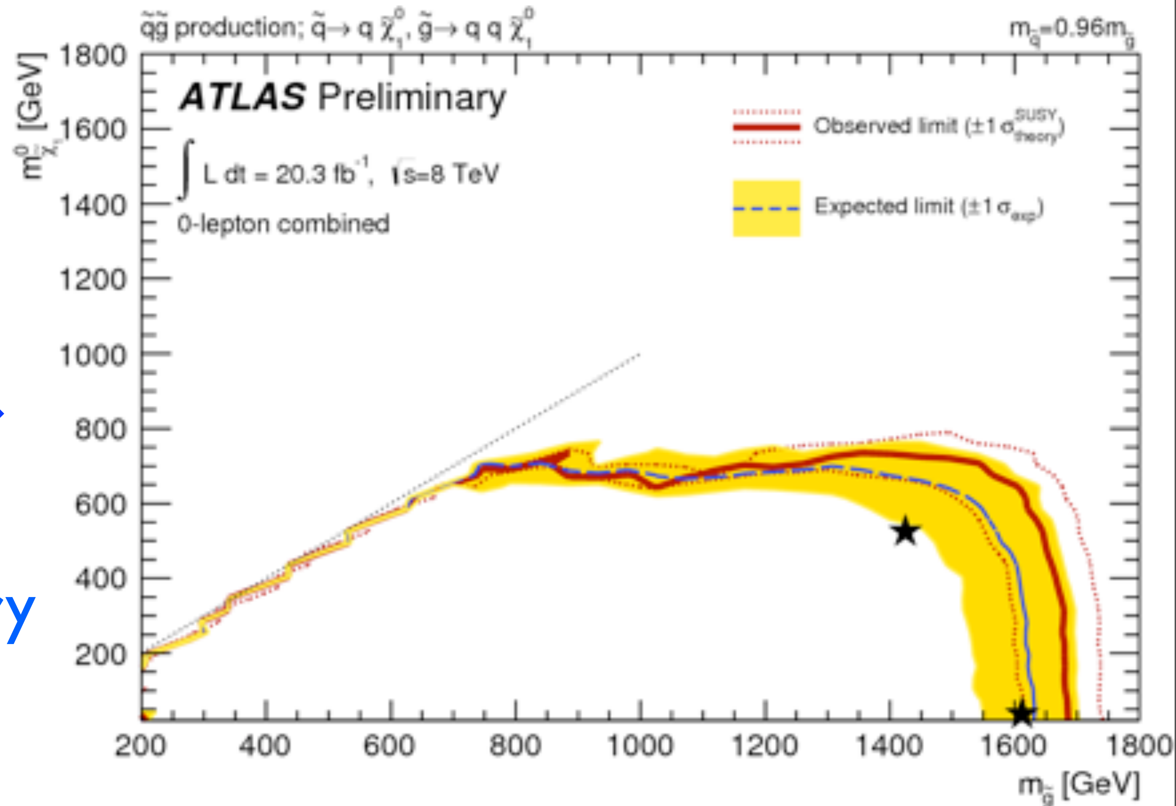
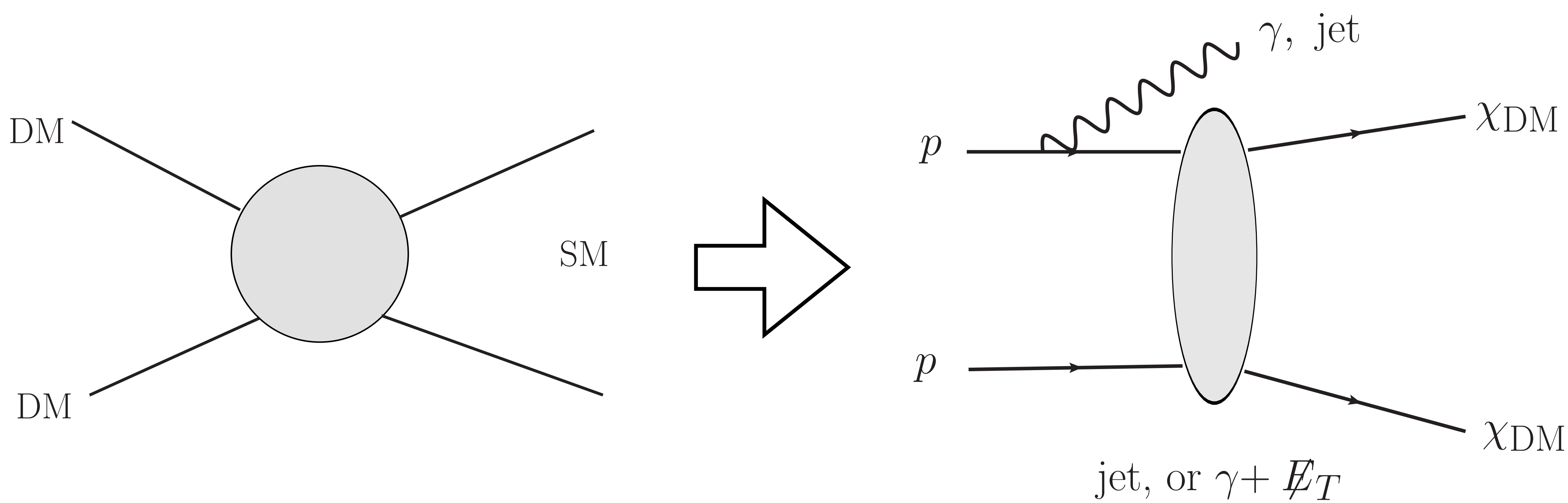


Of course, still plausible at the LHC, will keep looking.

Higher energy ⇒ higher reach

Back to the basics

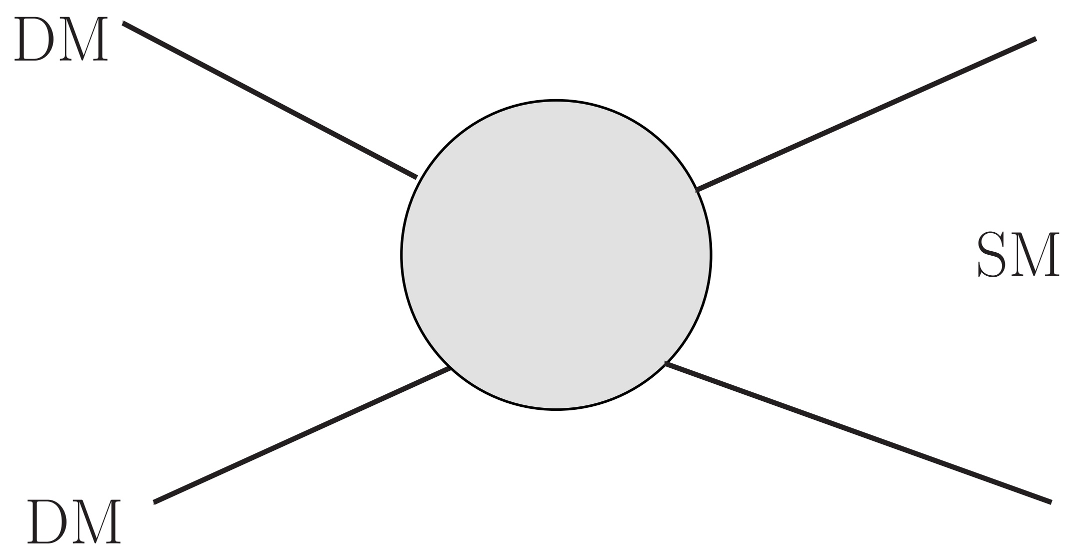
- pair production + additional radiation.



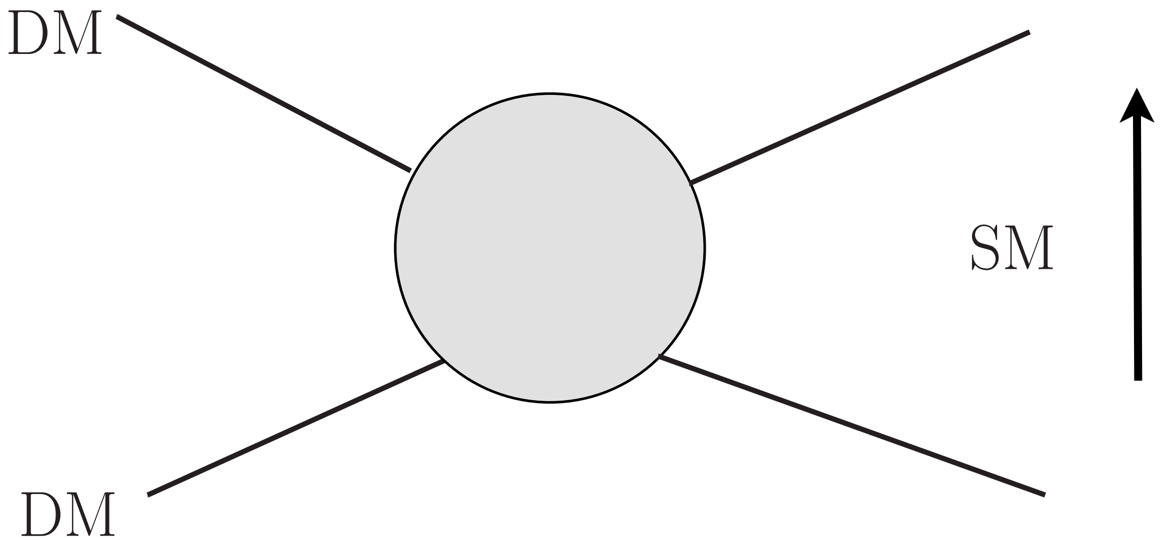
- Mono-jet, mono-photon, mono-...

- Have become "Standard" LHC searches.

Effective operator approach



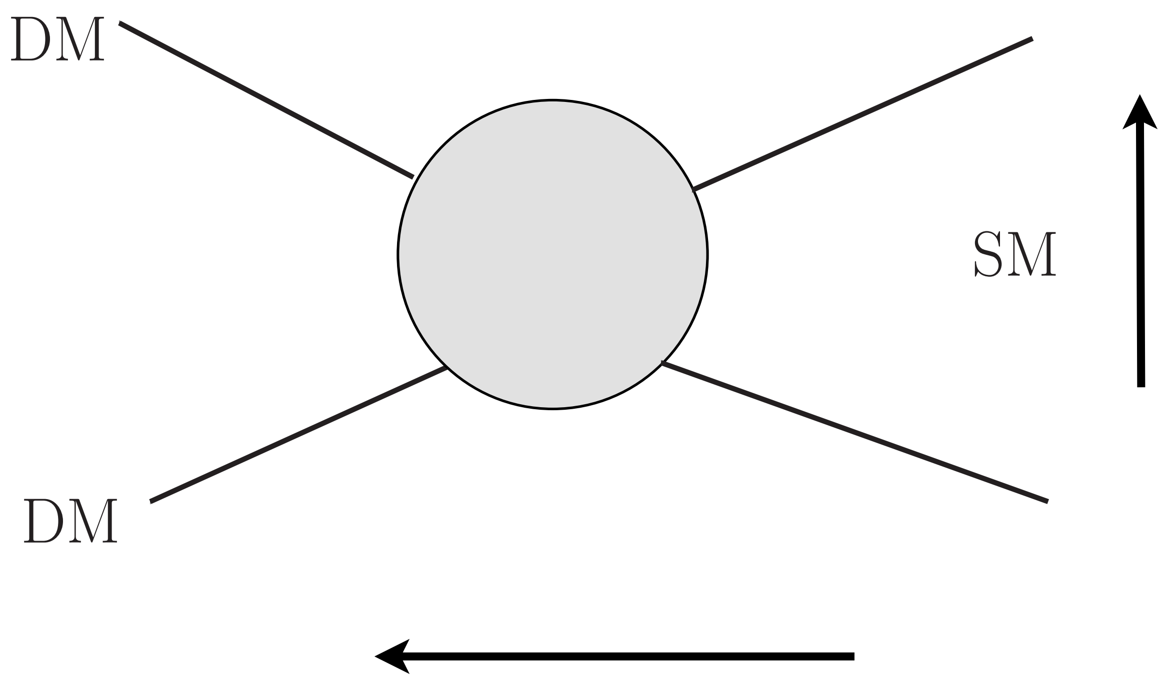
Effective operator approach



momentum exchange
q~100 MeV << m_Φ
effectively,

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

Effective operator approach



momentum exchange
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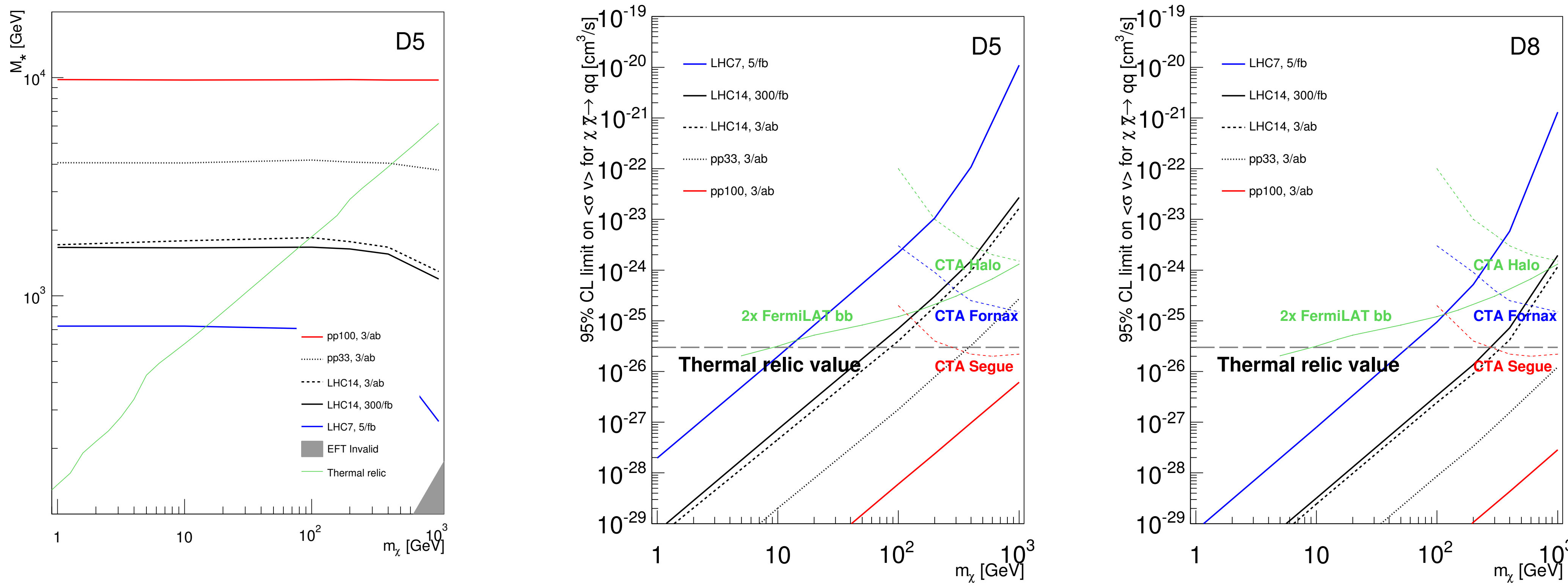
Use colliders to constrain and probe
the same operator

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

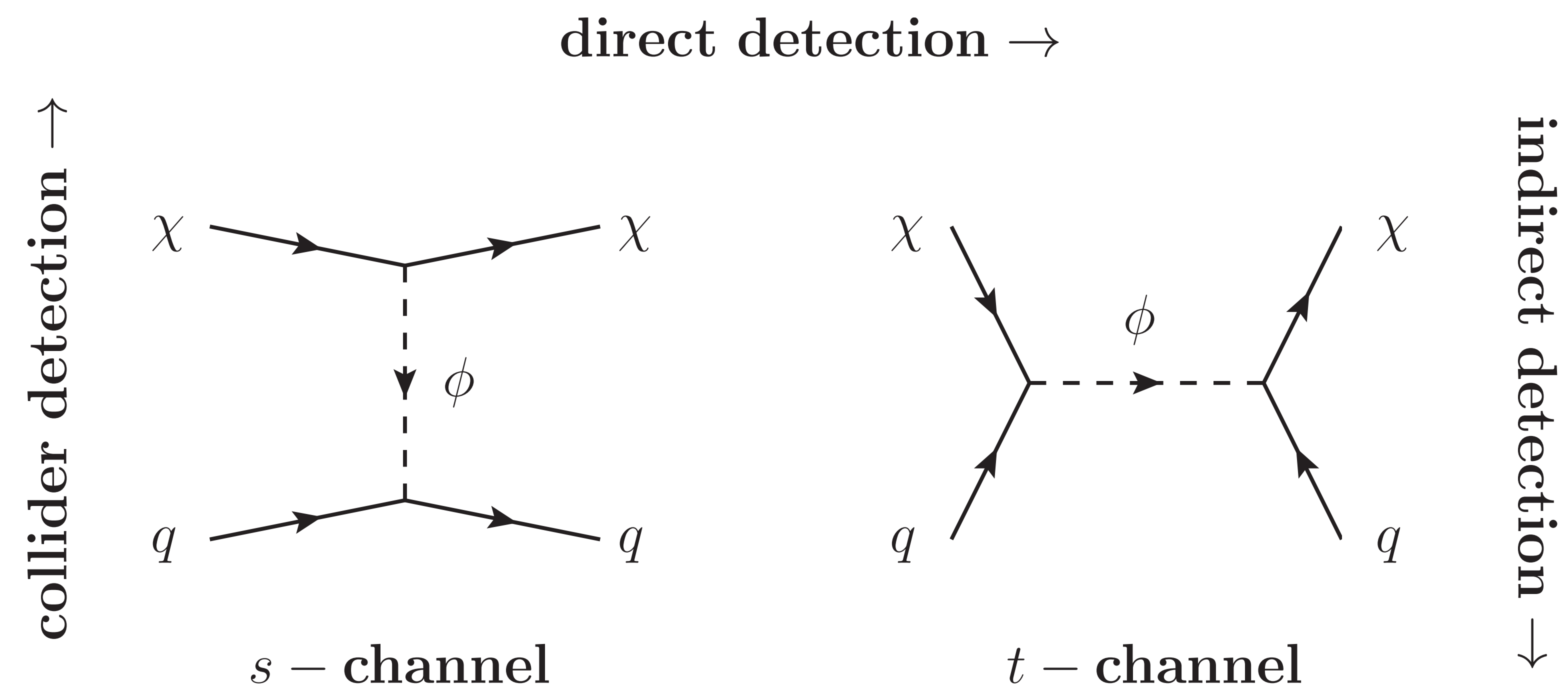
Effective operator approach



Zhou, Berge, LTW, Whiteson, Tait, 1307.5327

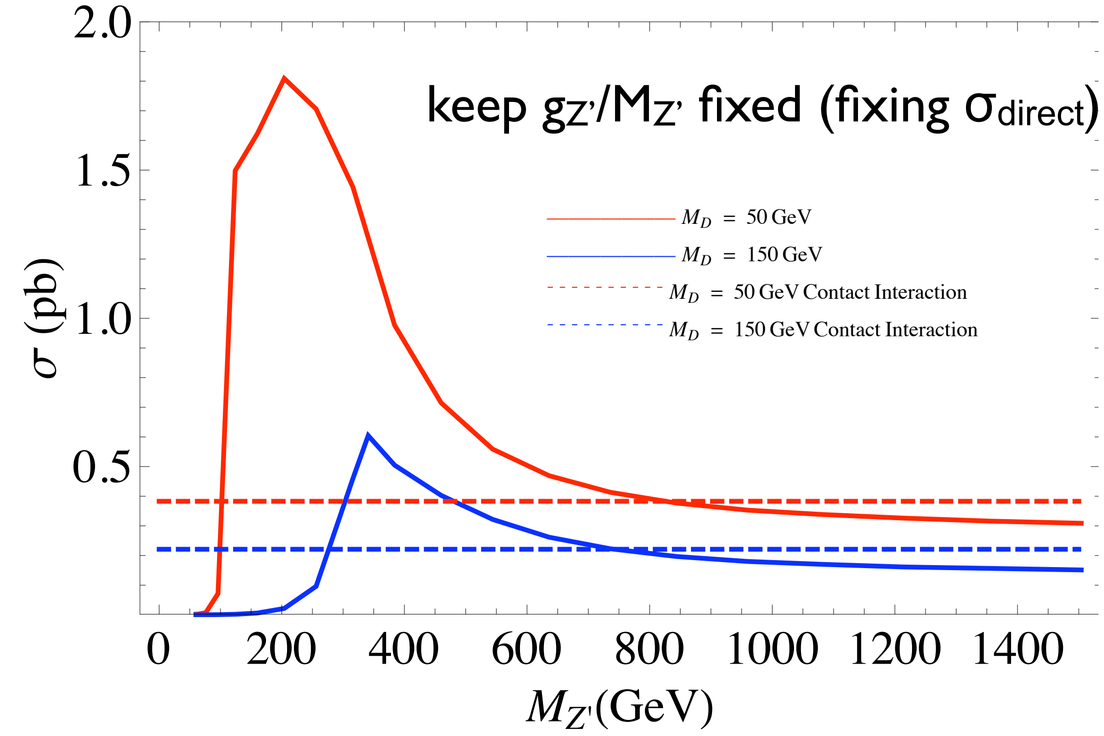
- Effective?
  - Valid? Could be in some parameter region.
  - Representative of possible UV completion? And, representative of possible signals?
    - Consider possible mediators.

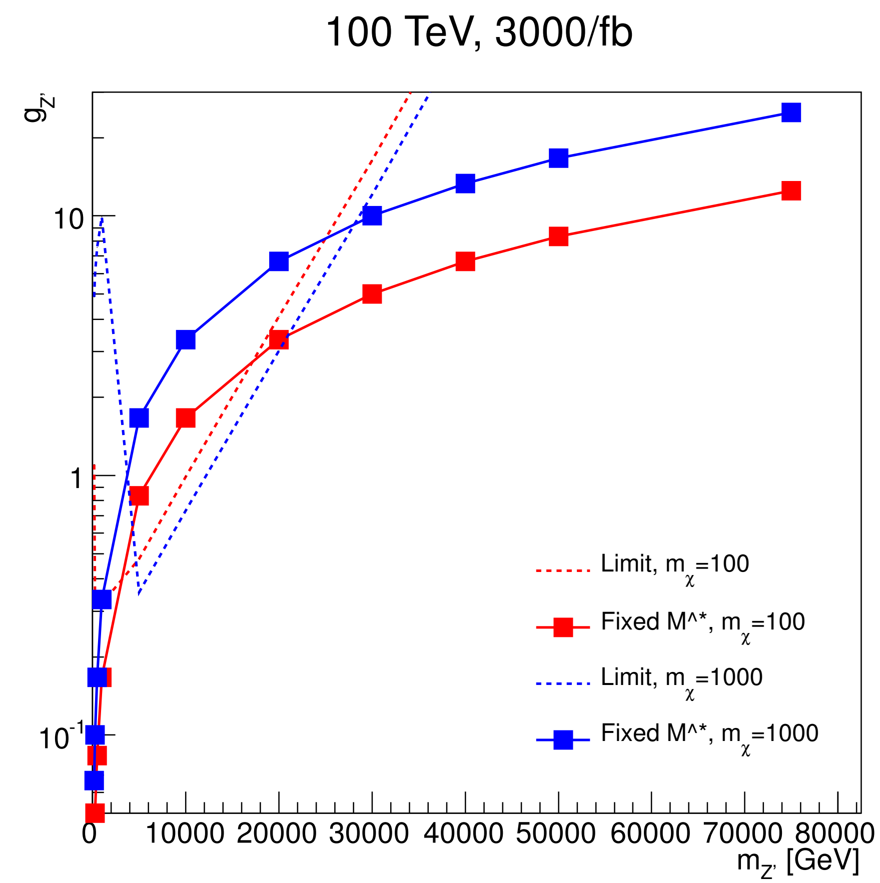
Simplified mediator models



ϕ can be scalar or Z'

ϕ squark like





Tevatron rate, Z' vs effective operator

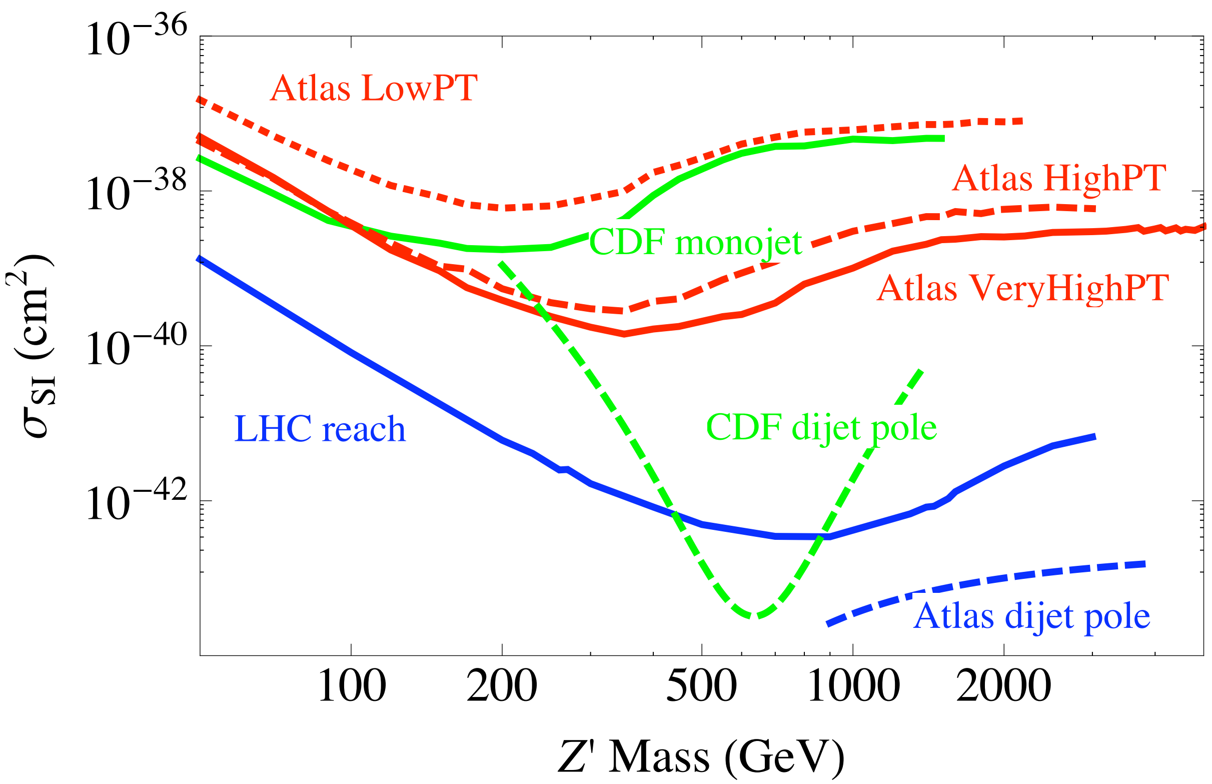
An, Ji, LTW, 1202.2894

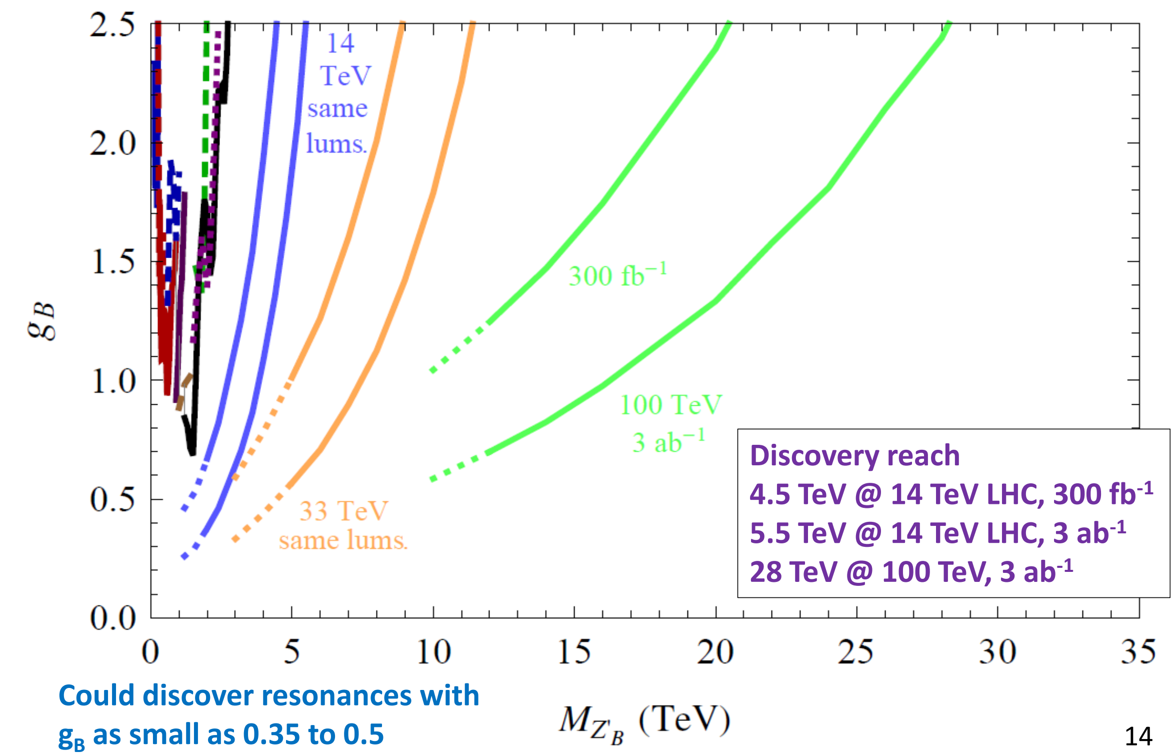
Zhou, Berge, LTW, Whiteson, Tait, 1307.5327

- Contact operator ~ heavier, more strongly coupled mediator.

- EFT also don't capture SUSY, $M_{med} \approx M_{DM}$

Possible to discover the mediator first!





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

Felix Yu, talk at LPC Jan. 31

For t-channel mediator, squark like searches

Back to SUSY

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

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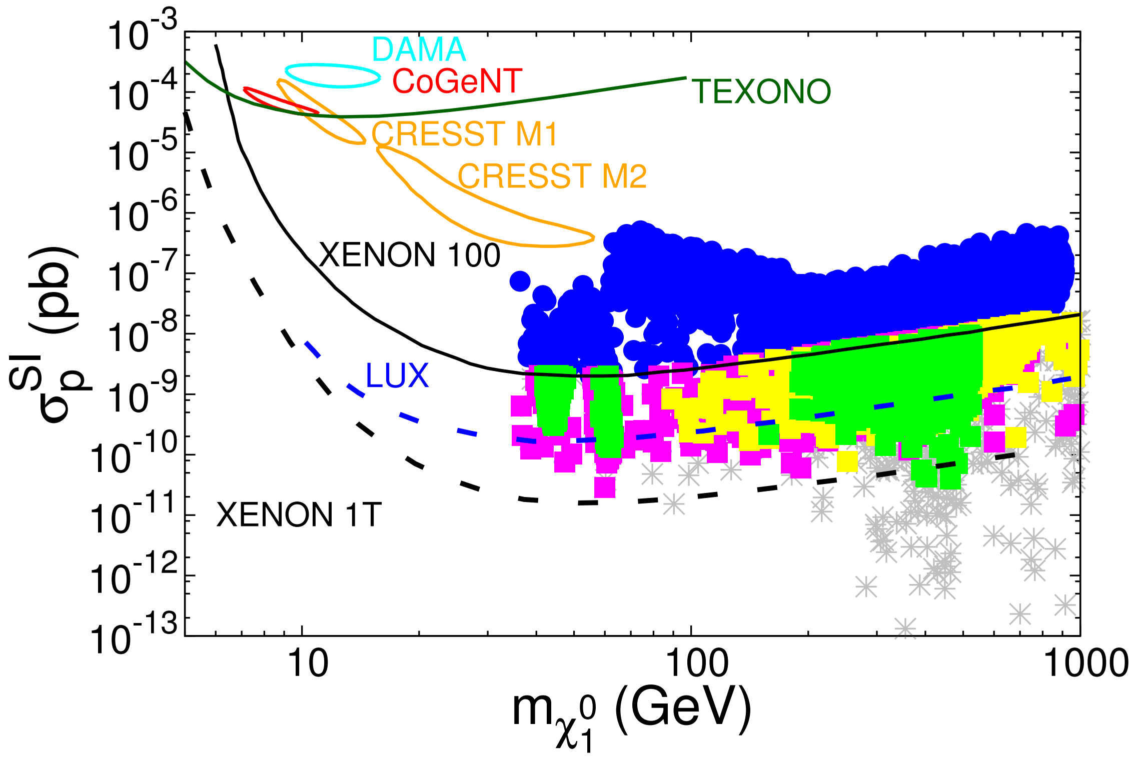
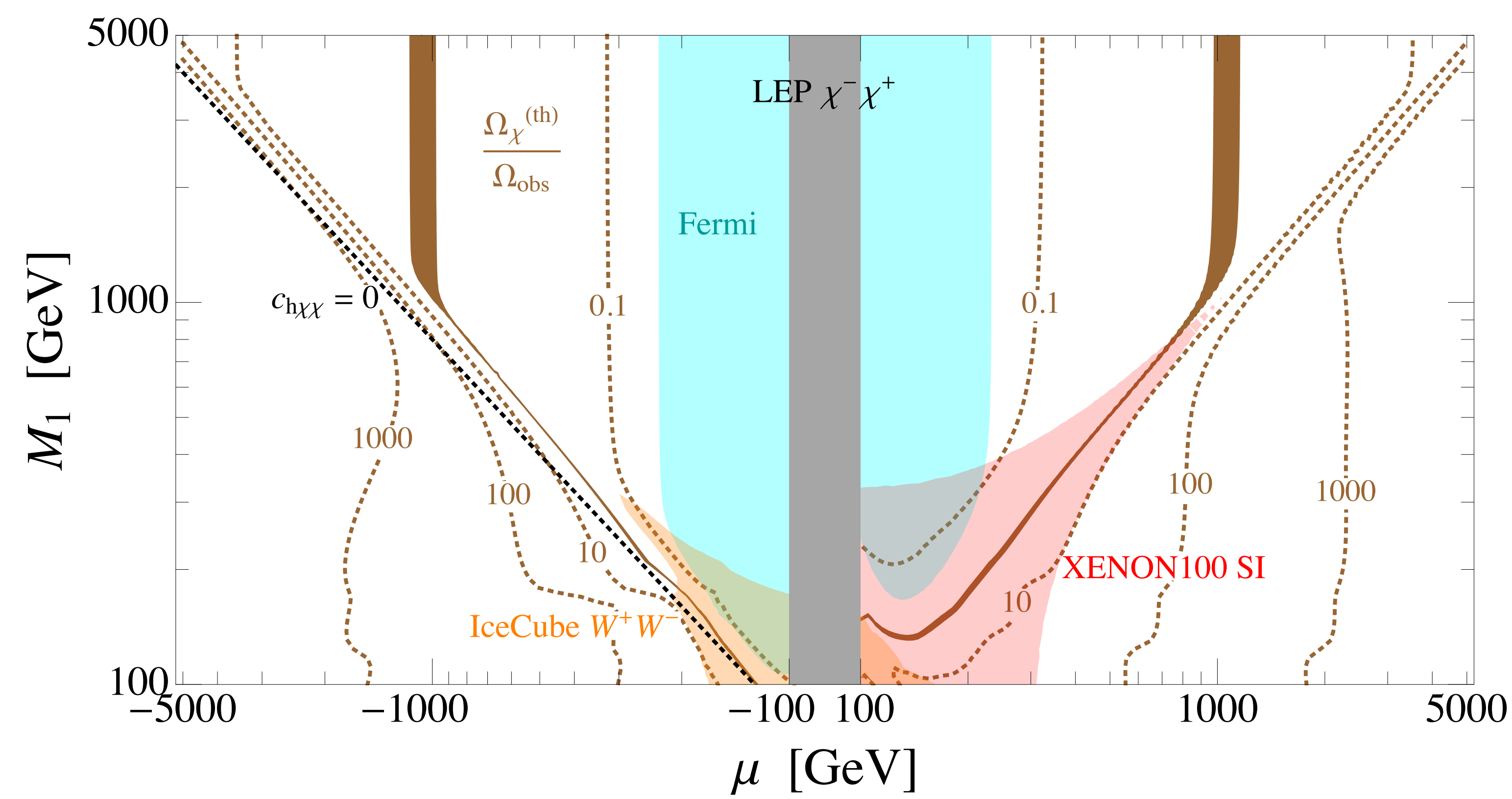
Good starting point to investigate more general WIMP candidates

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: $\tilde{h},\ \tilde{W}$ / $\tilde{B}$ — $\Delta M \sim$ 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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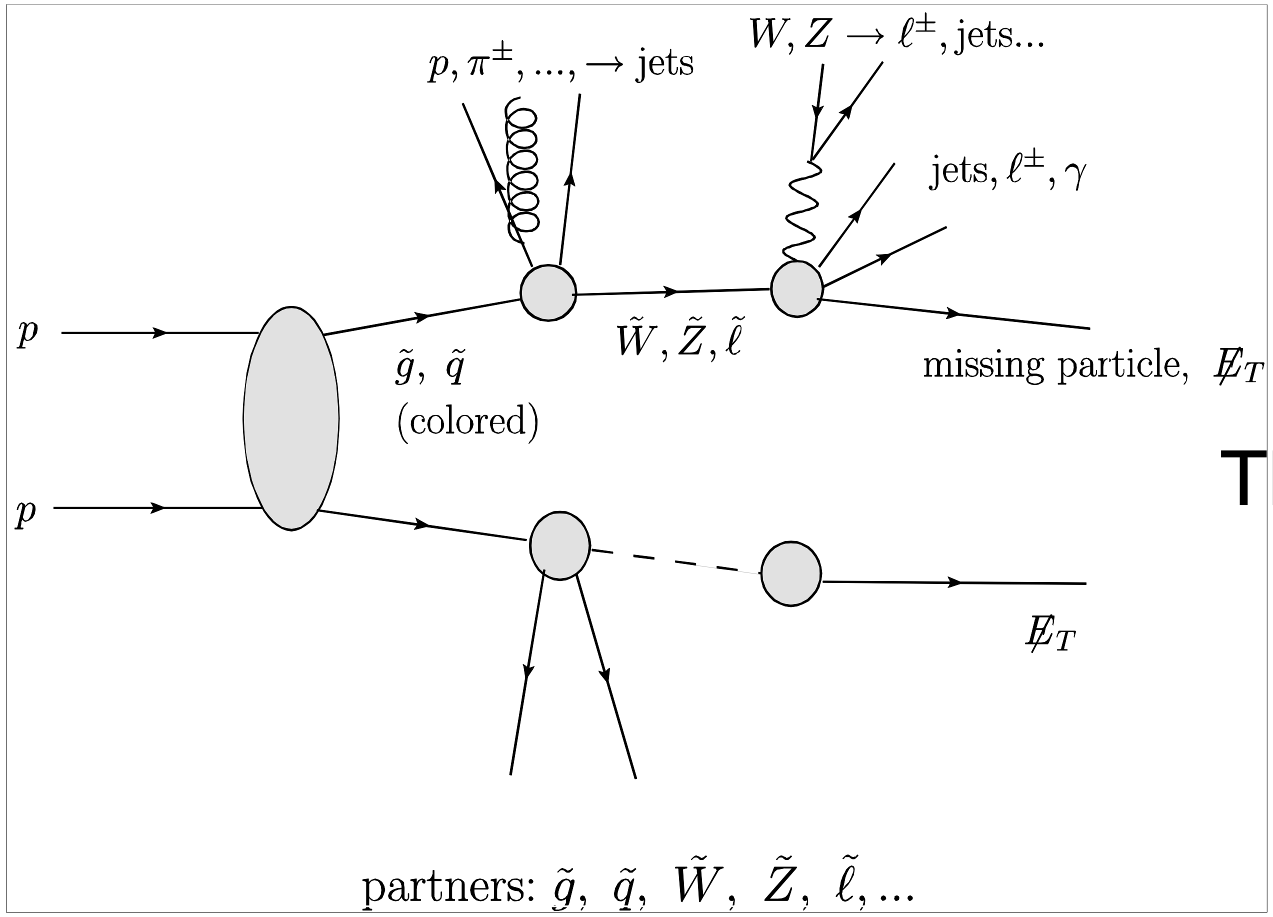
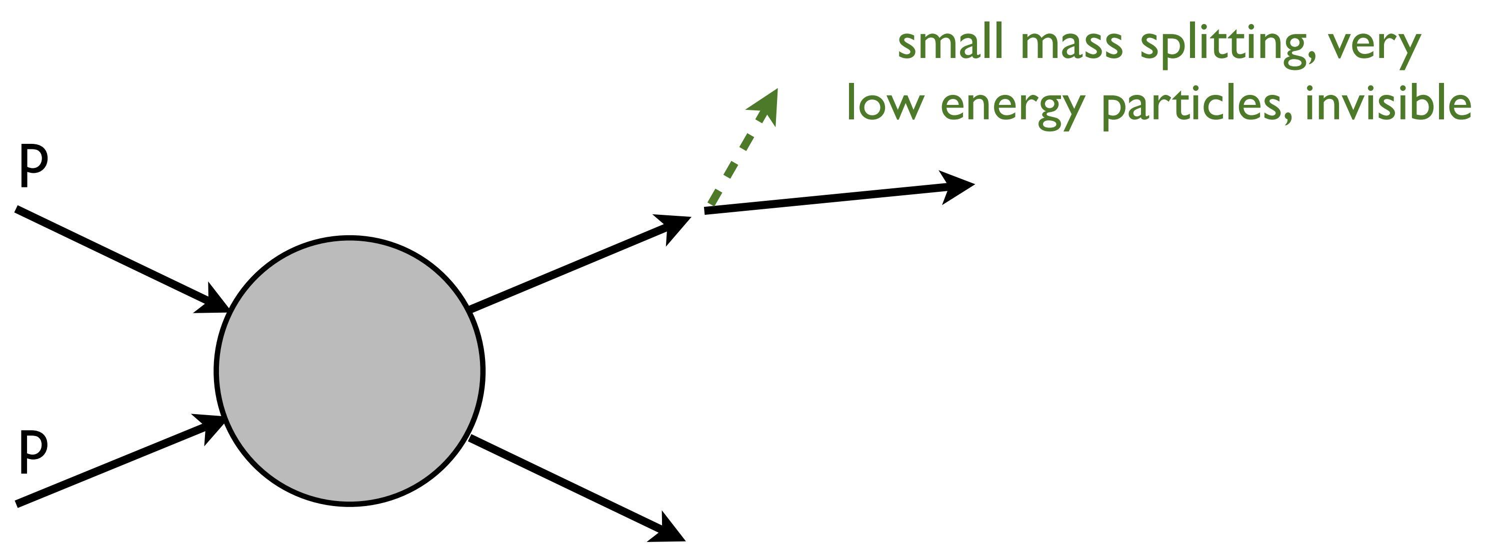
SUSY DM signal in the compressed case



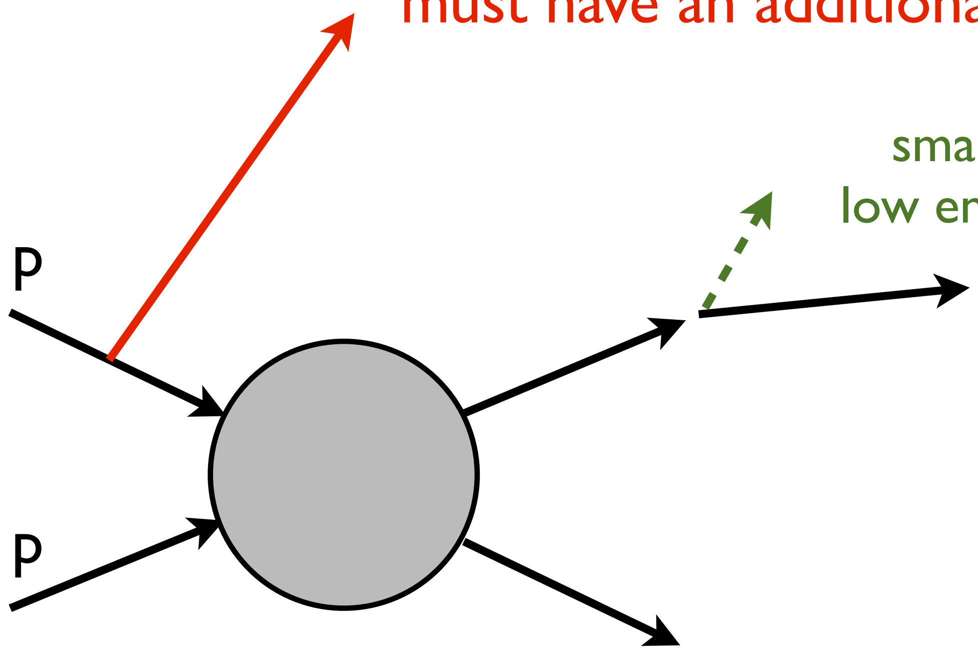
The "usual" story

SUSY DM signal in the compressed case



SUSY DM signal in the compressed case

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



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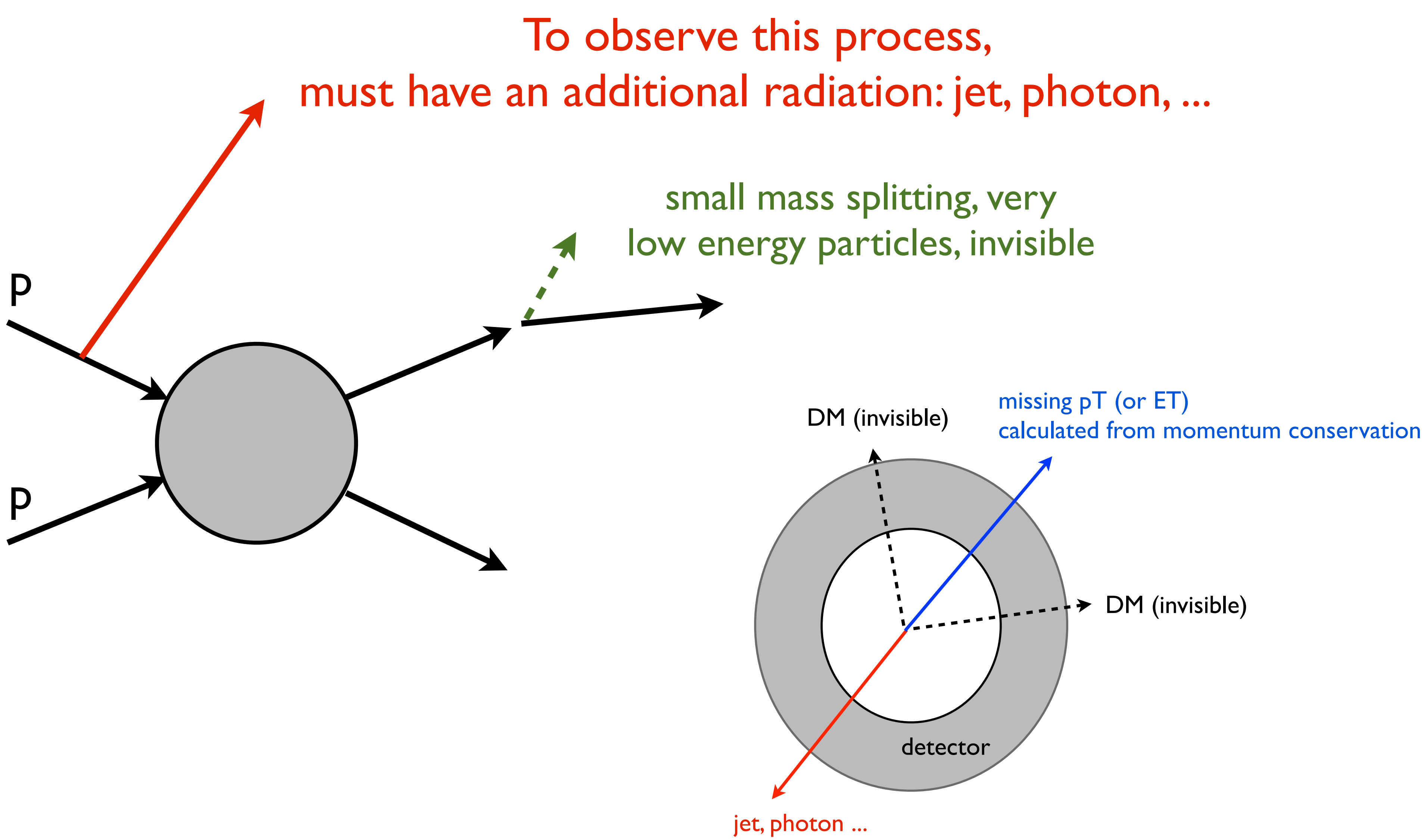
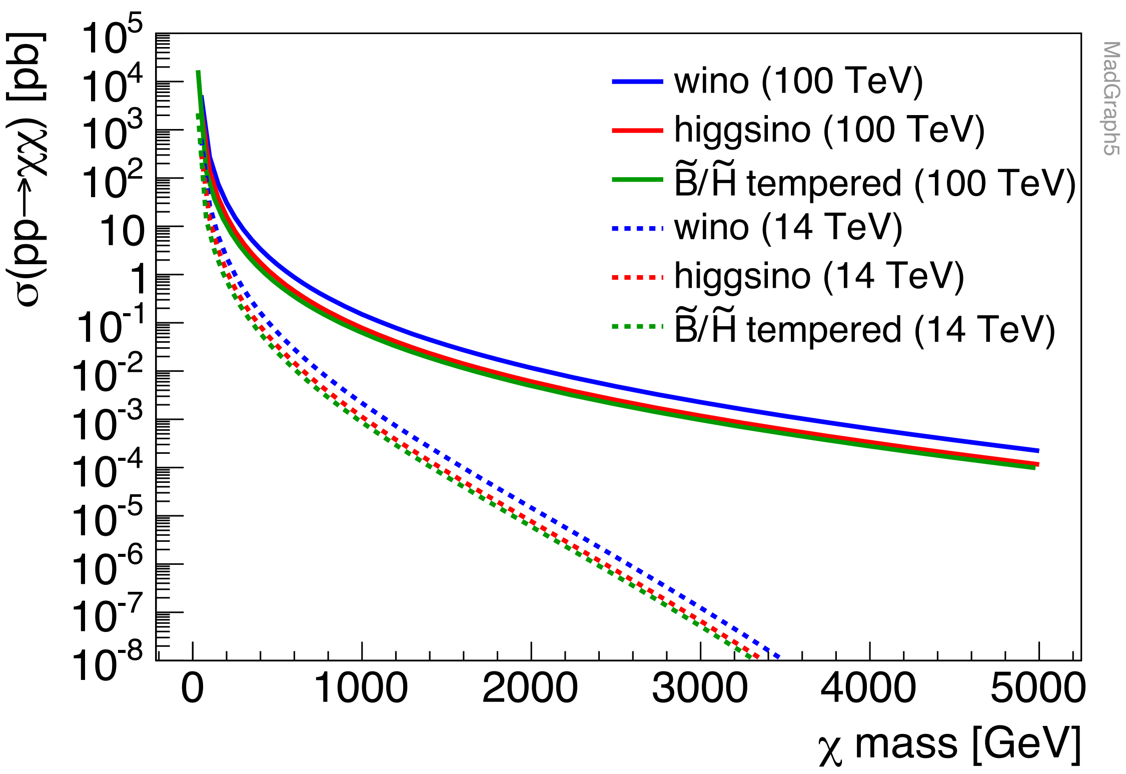
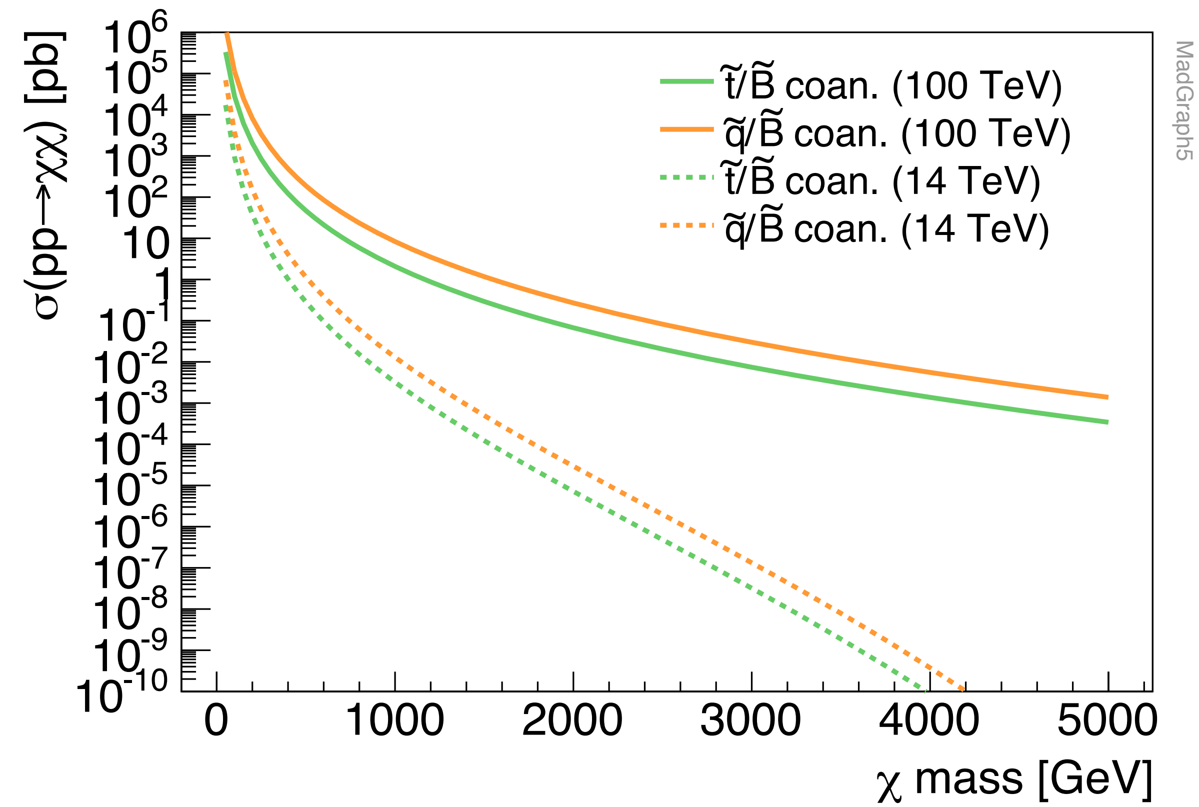


– Back to the basic mono-jet, mono-photon...

14 vs 100 TeV



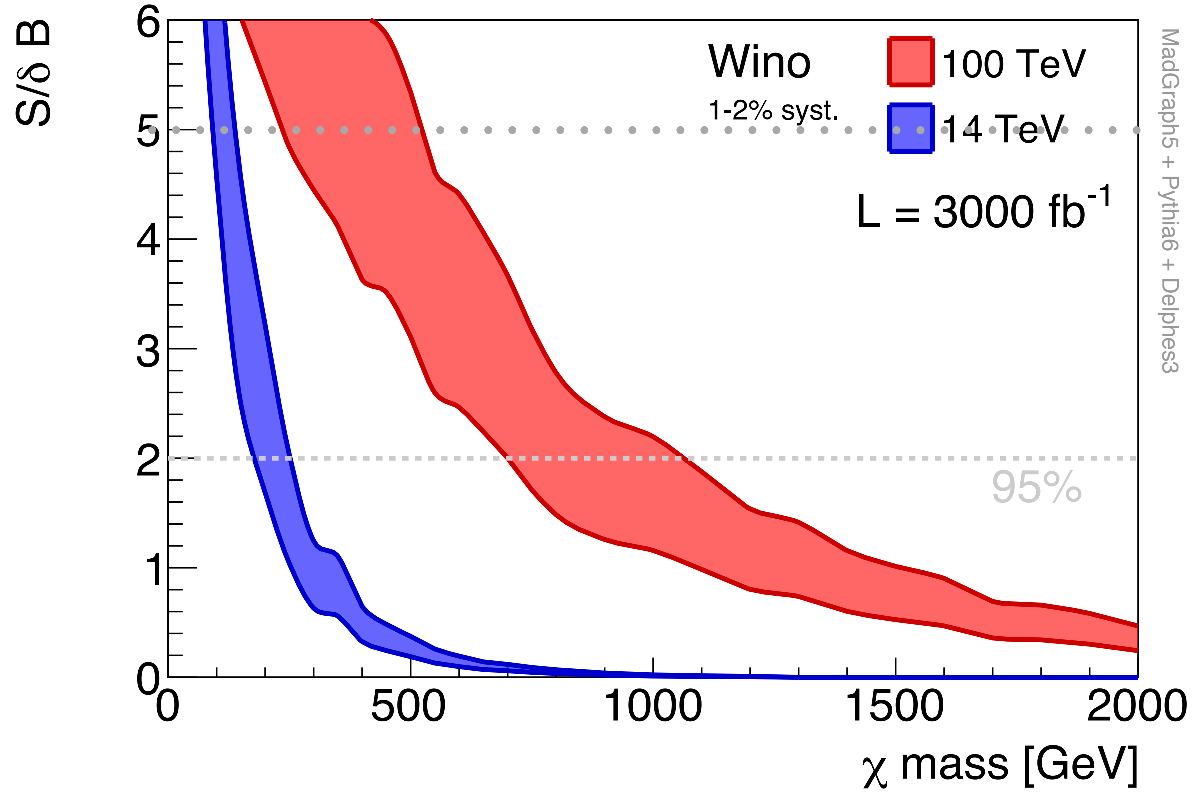


- Higher energy, higher rates
- Expecting large improvement from 14 to 100.

Wino LSP

Basic Monojet channel

Matthew Low, LTW, in prep



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

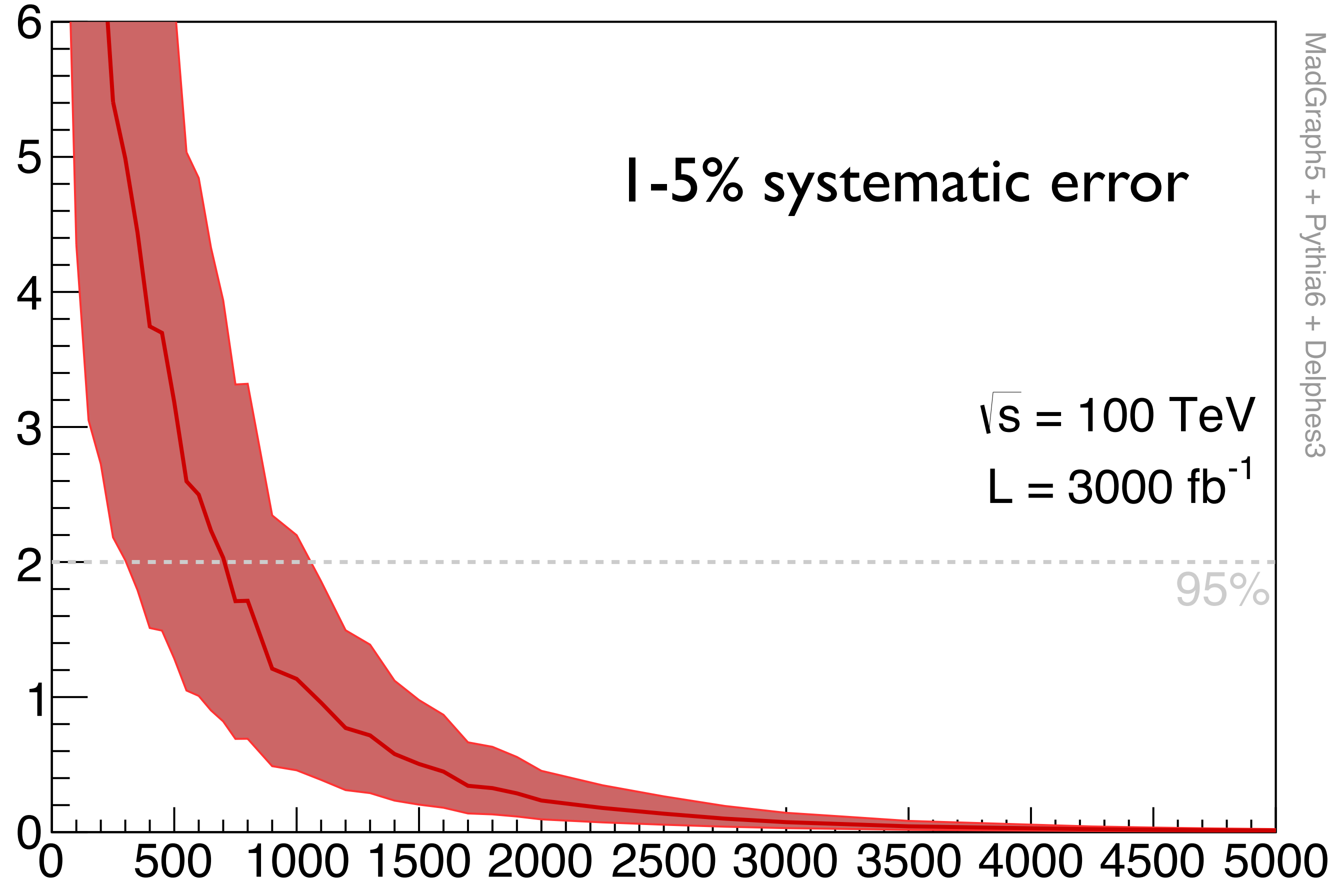
mono-γ and mono-W/Z don't add that much.

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%

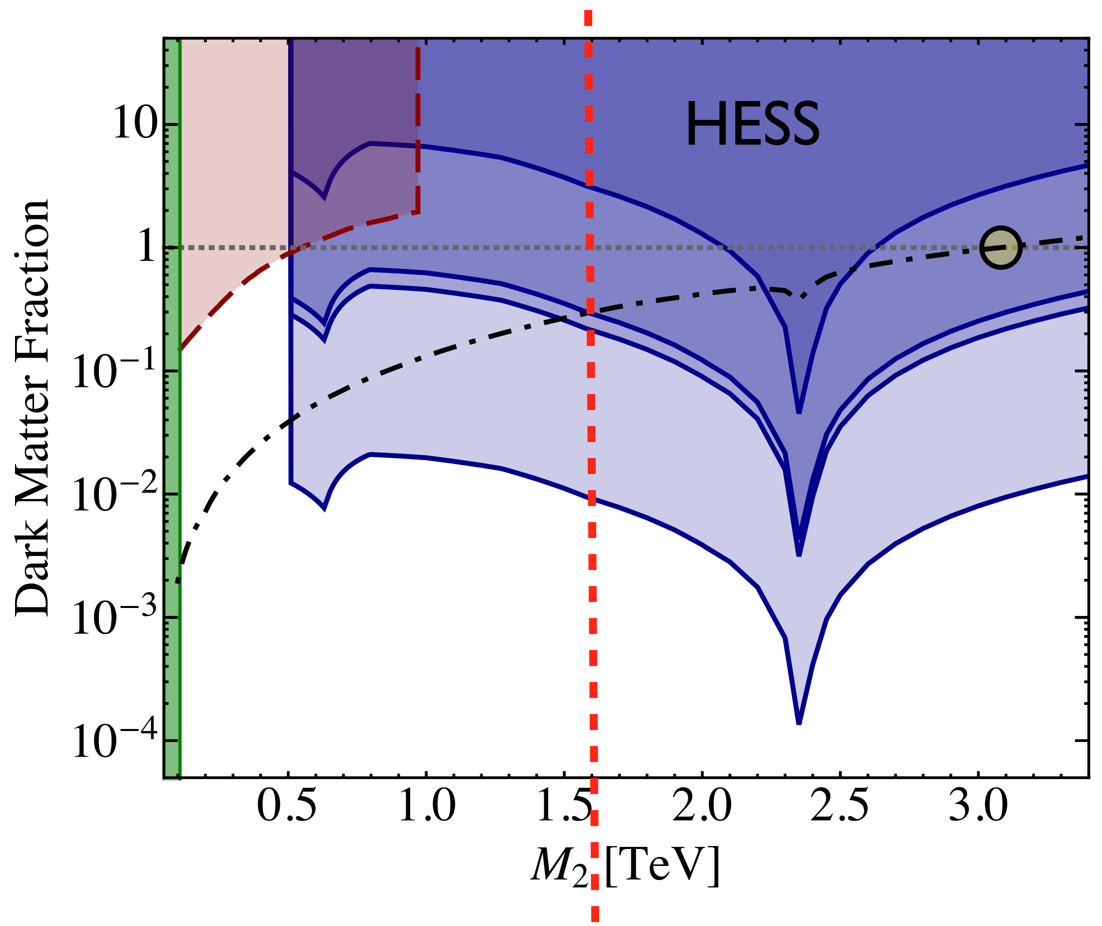
– A factor of 4-5 enhancement from 14 to 100 TeV.

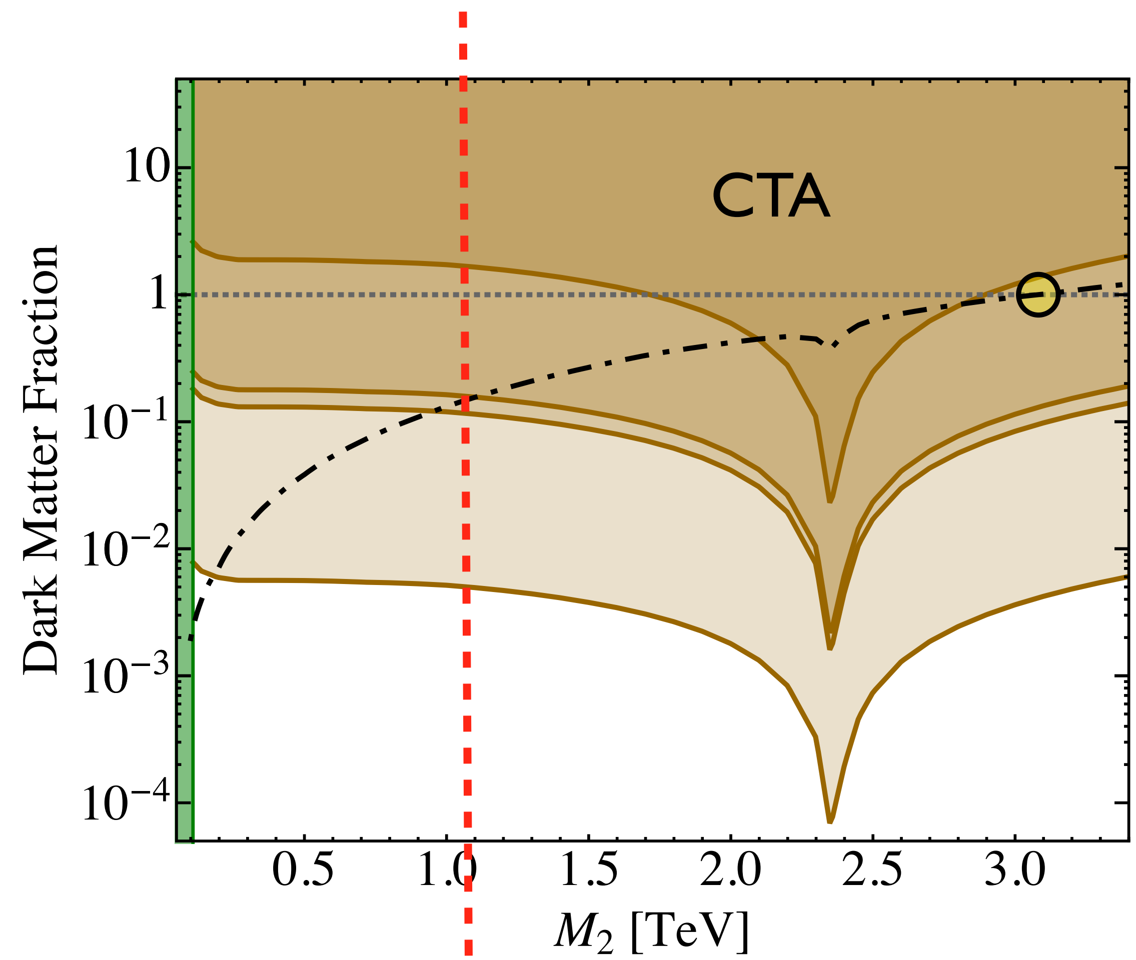
Recent works on mono-jet for electroweak-inos
Schwaller, Zurita, 1312.7350
Baer, Tata, 1401.1162
Han, Kribs, Martin, Menon, 1401.1235



- Dominated by systematical error of background.
- simple scaling with luminosity gives .5% (even remotely realistic?)
- Useful to keep in mind in designing detectors.

Wino, interplay with indirect detection

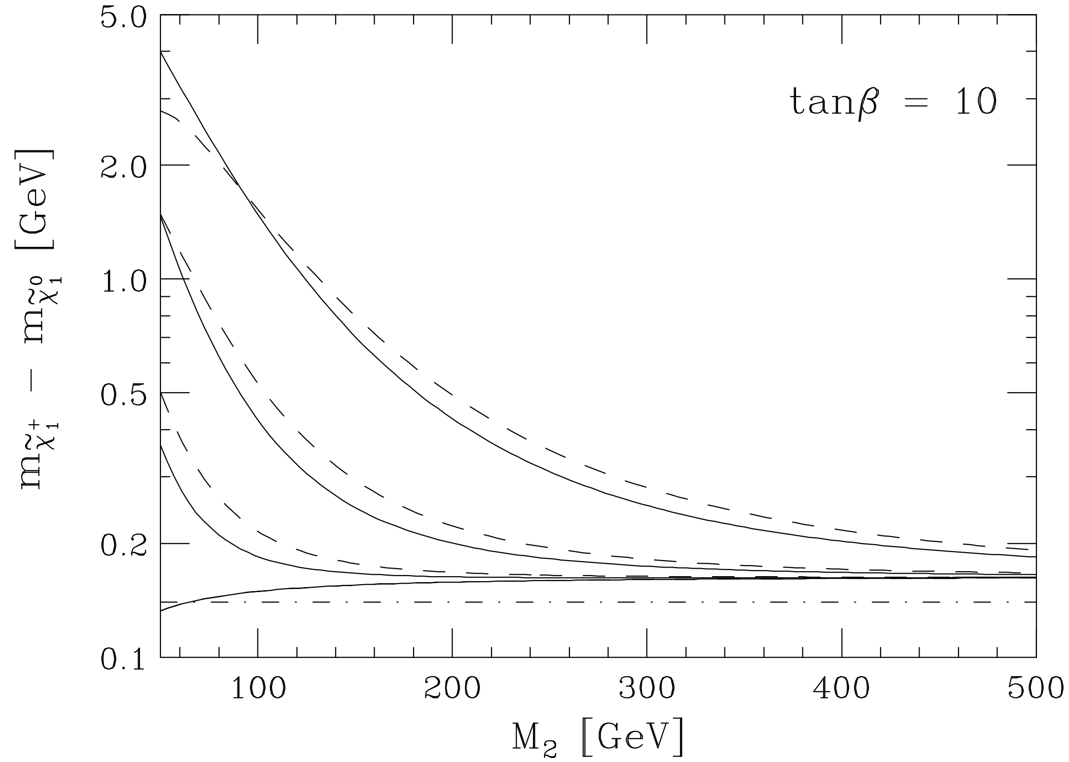




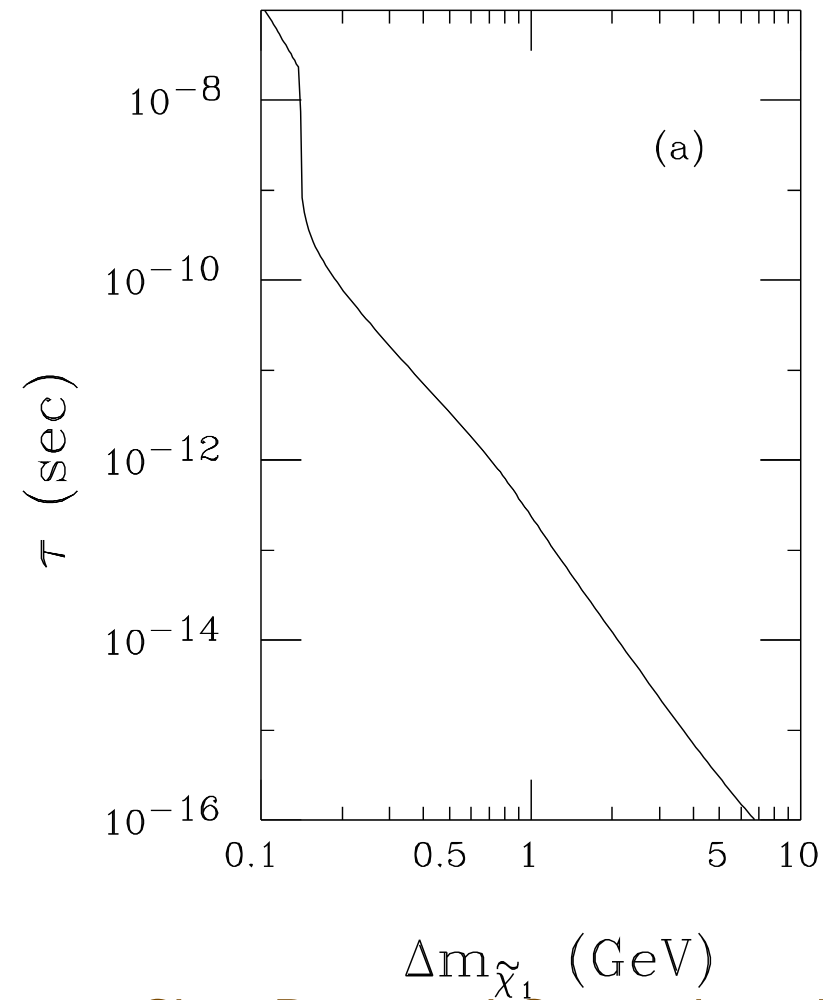
Cohen, Lisanti, Pierce, Slatyer, 1307.4082

See also Fan, Reece, 1307.4400

Wino decay



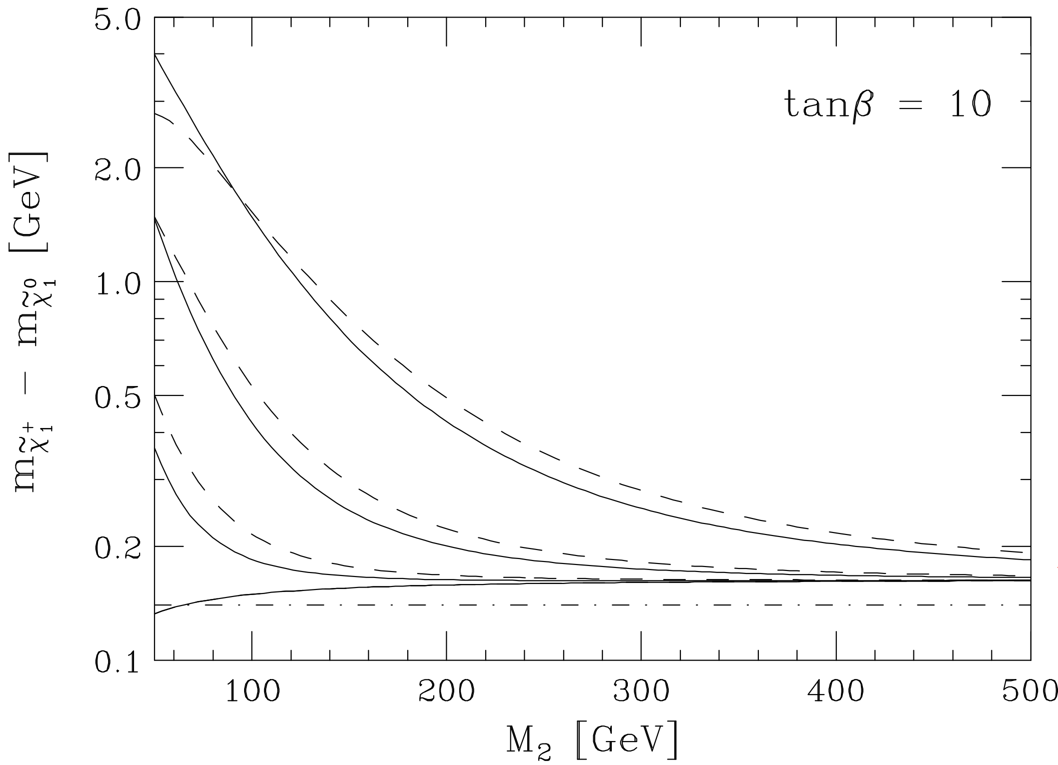
Gherghetta, Giudice and Wells, hep-ph/9904378



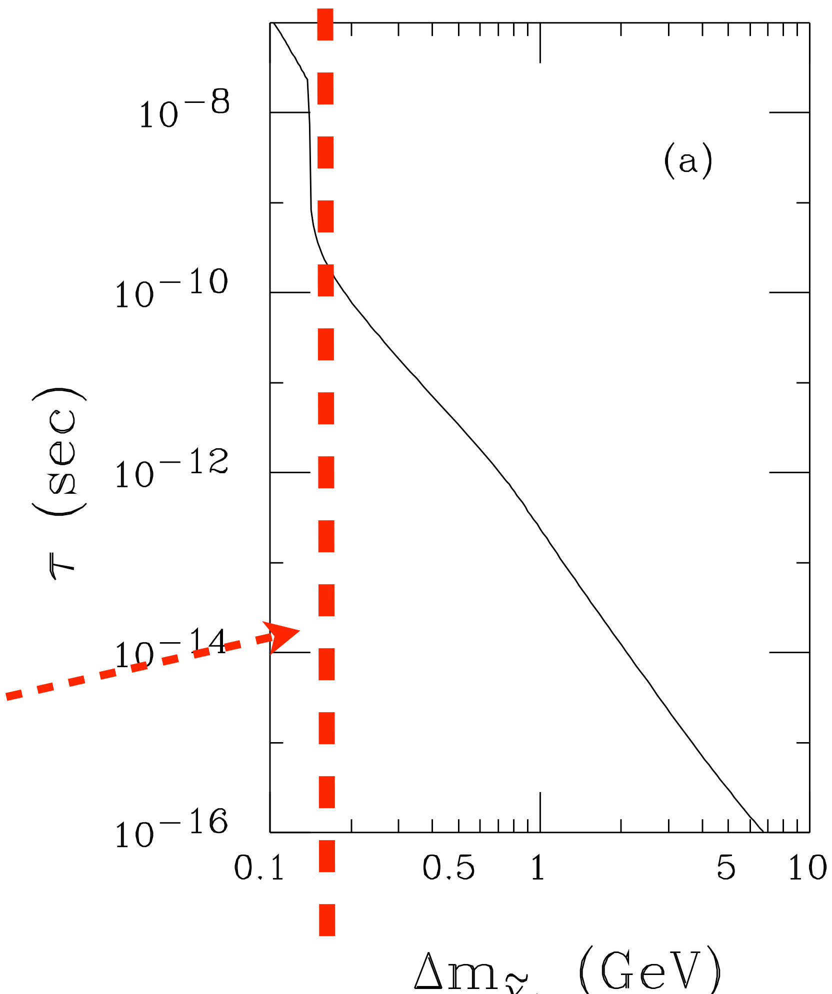
Chen, Drees and Gunion, hep-ph/9902309

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

Wino decay



Gherghetta, Giudice and Wells, hep-ph/9904378



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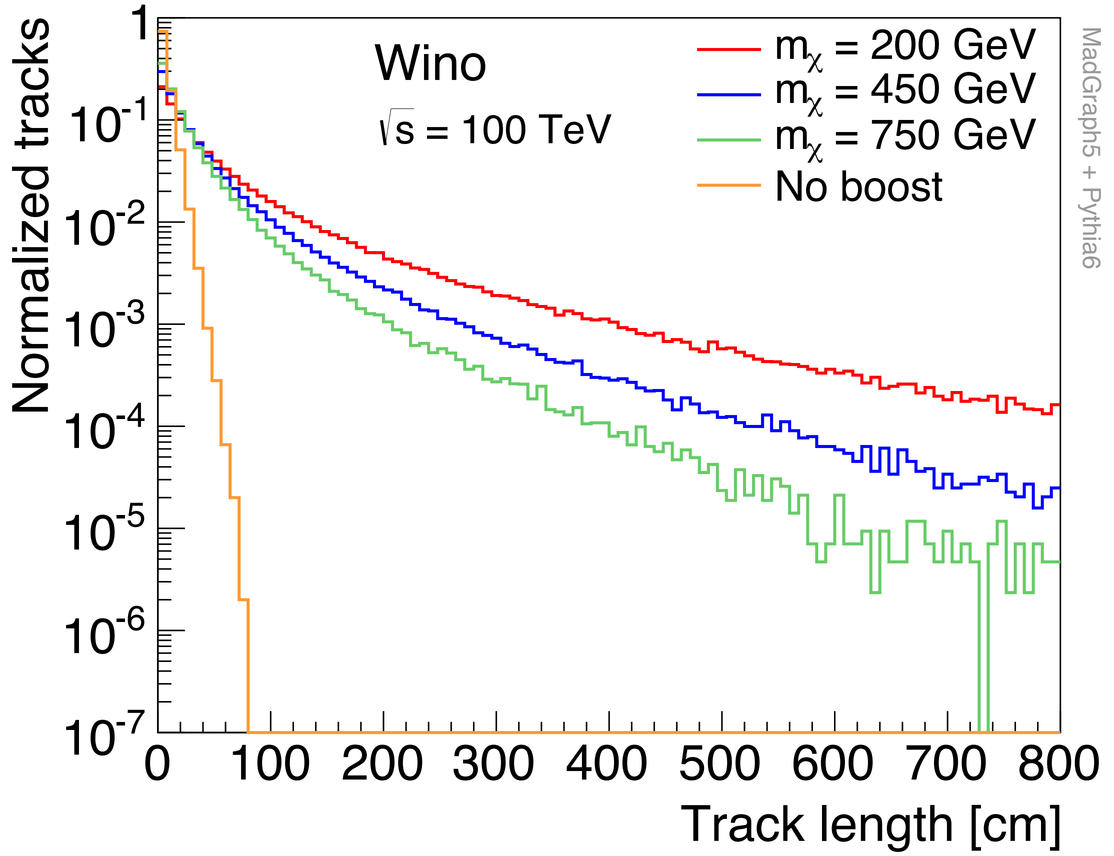
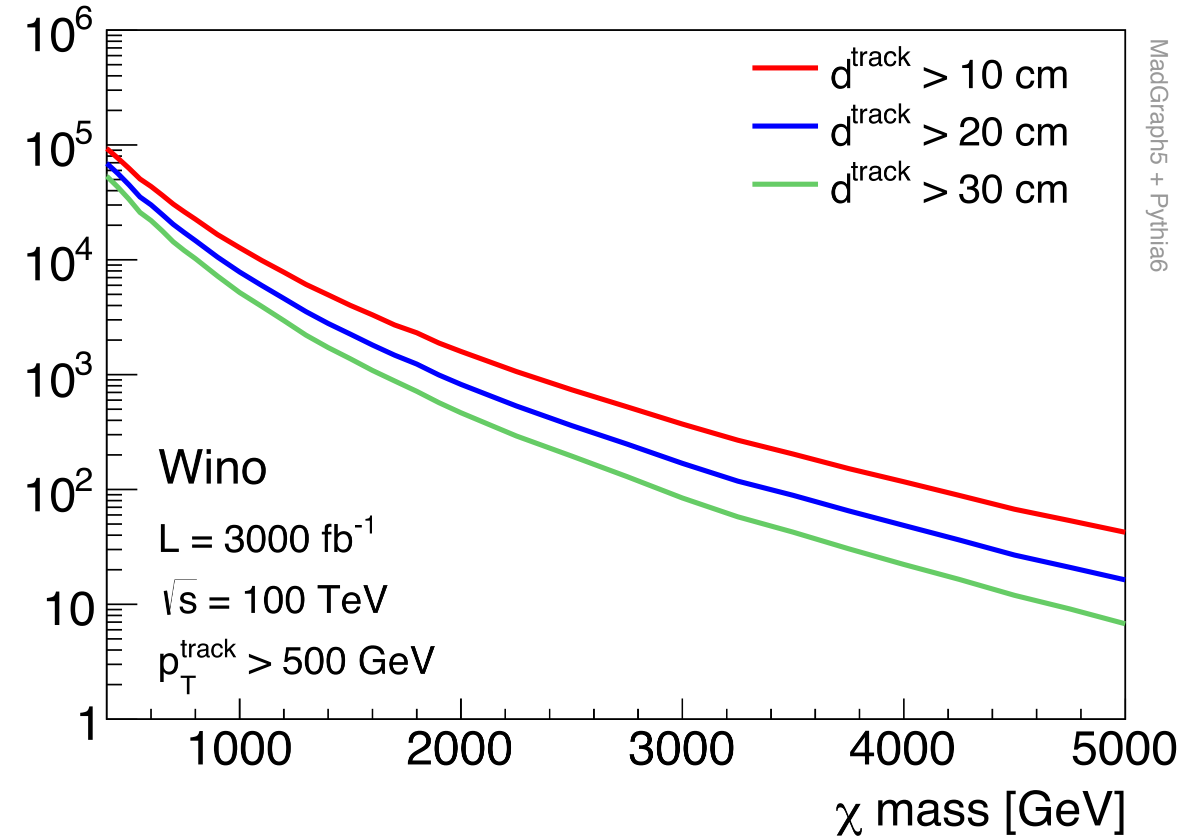
Rates (with long tracks)





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

Disappearing track + background

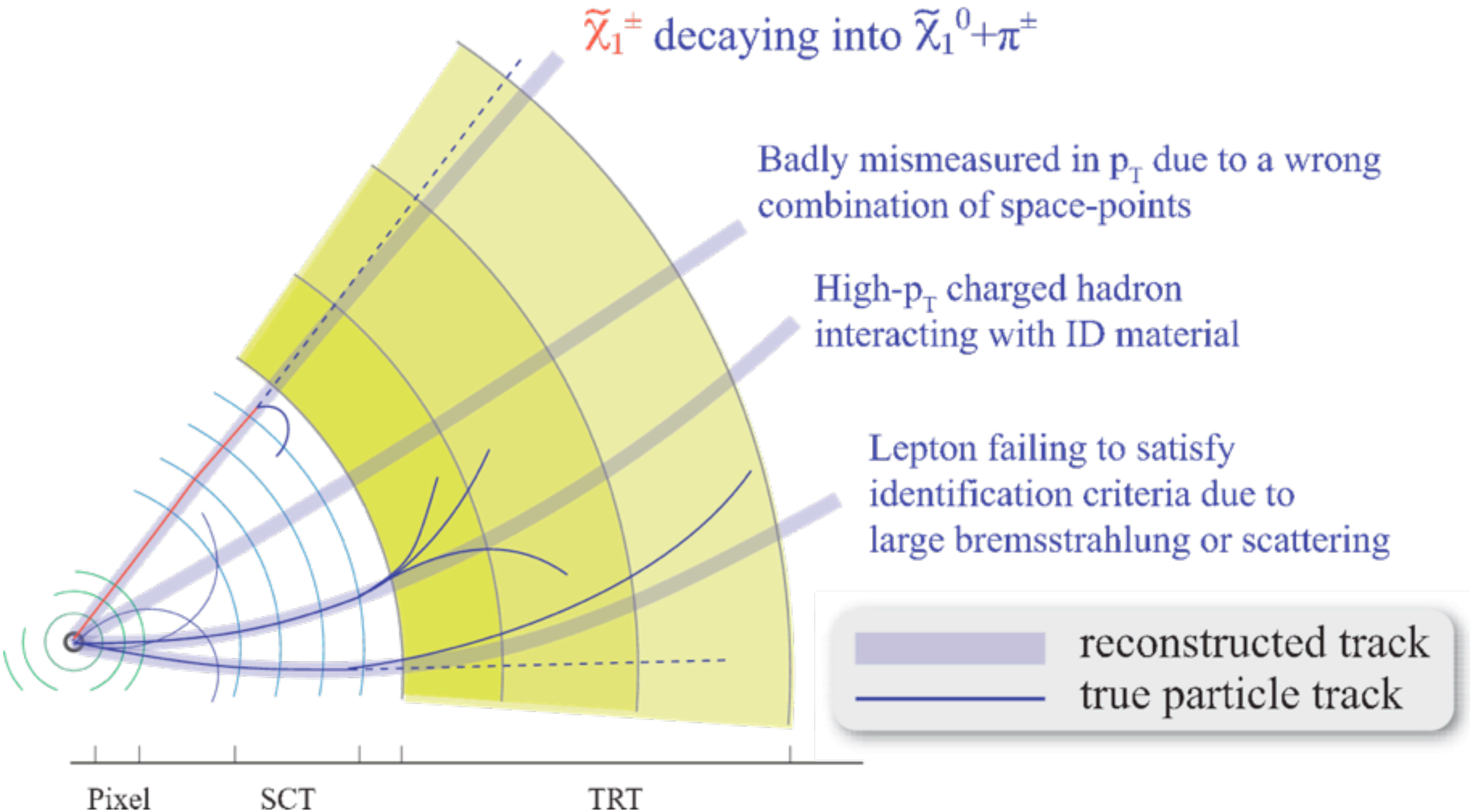
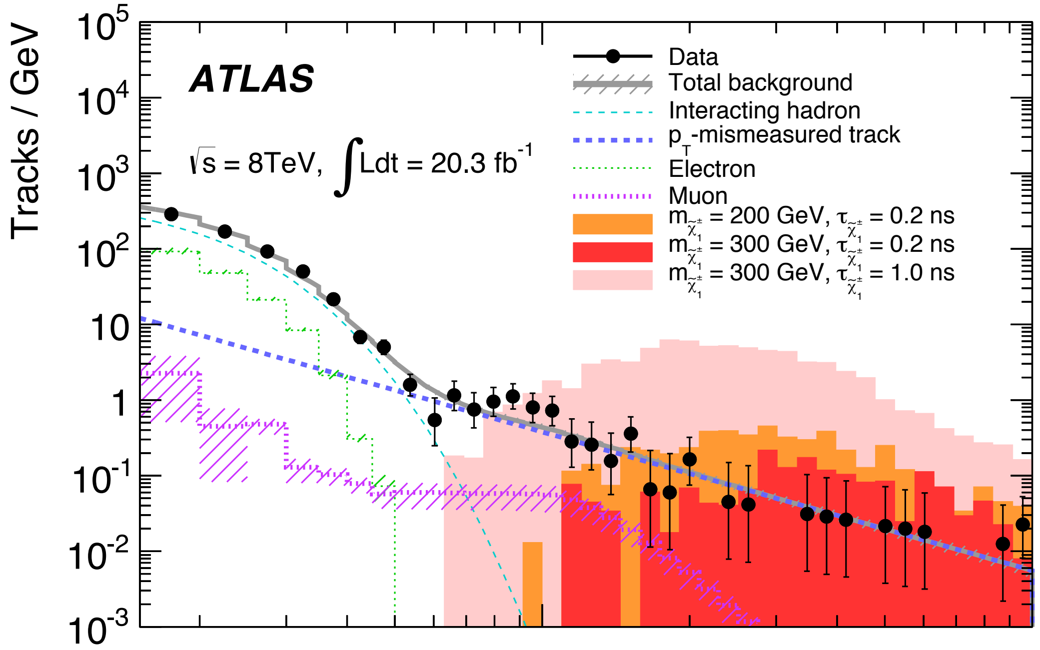
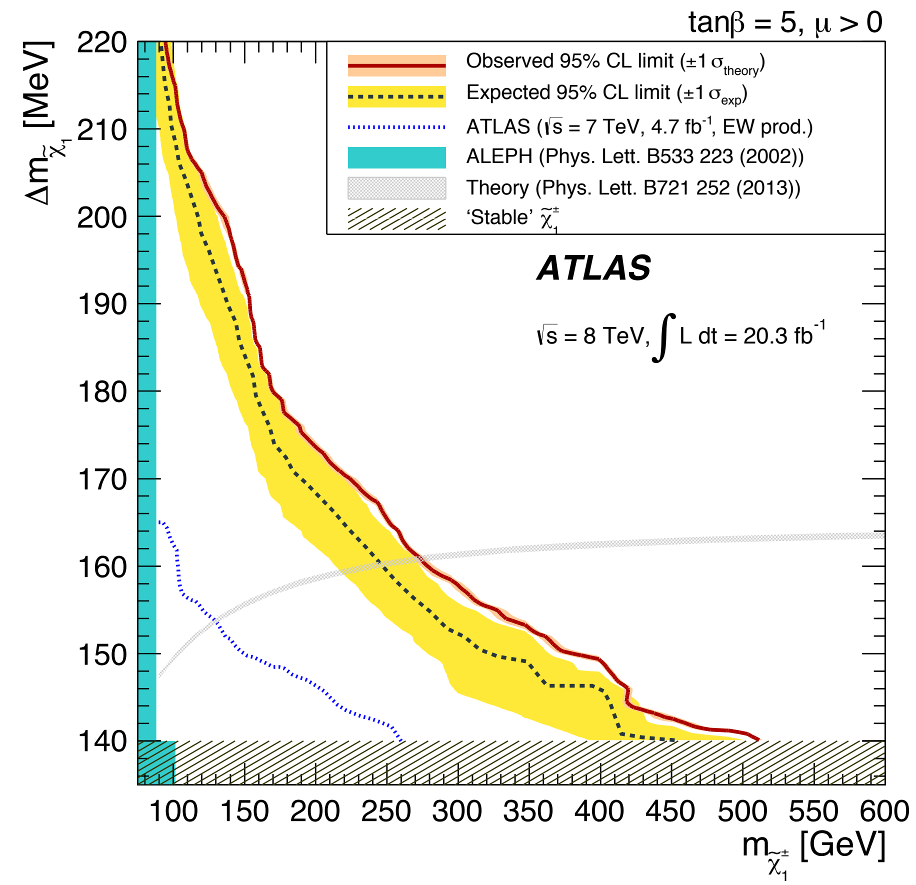


Figure from ATLAS disappearing track search twiki

ATLAS search

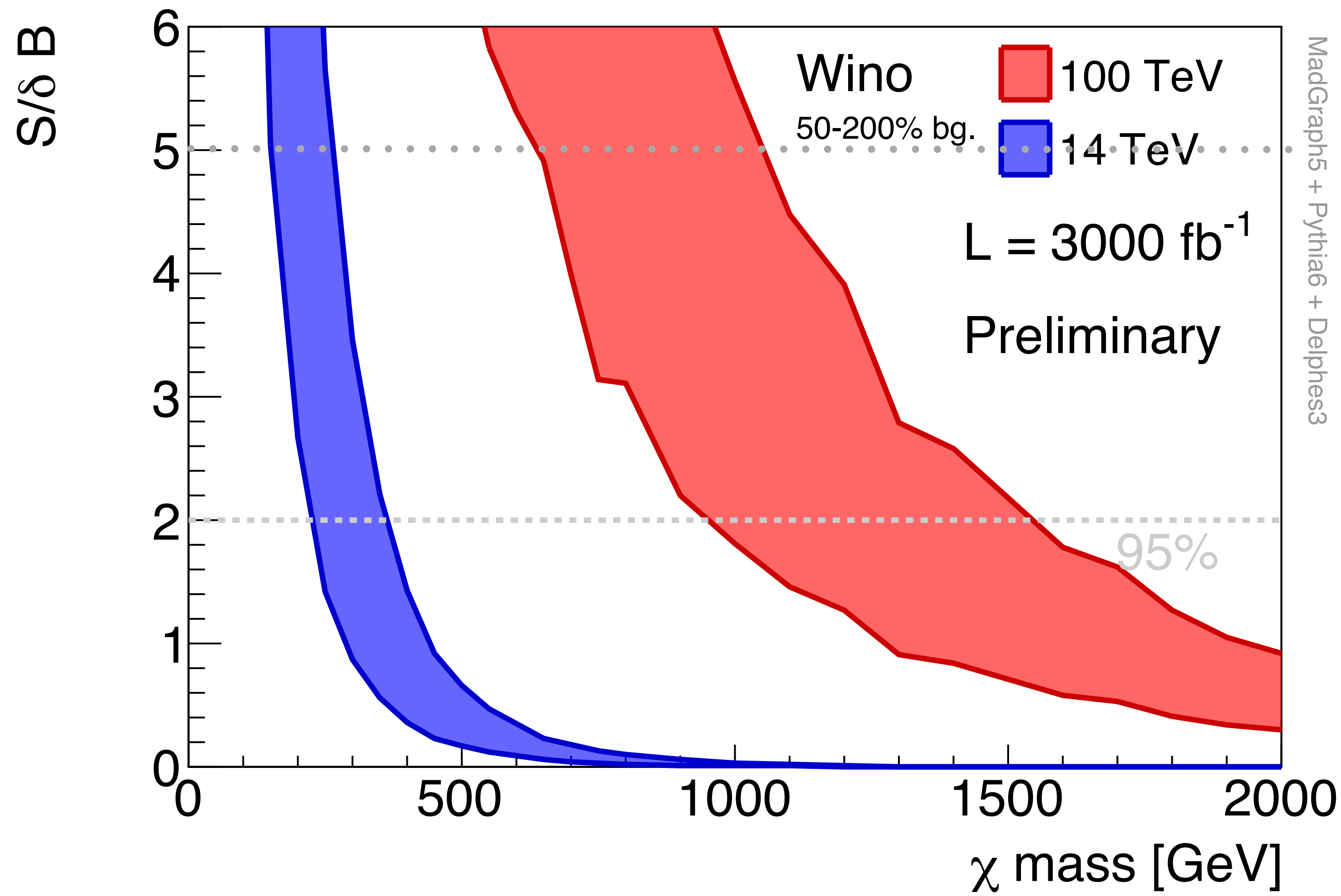
ATLAS, 1310.3675





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

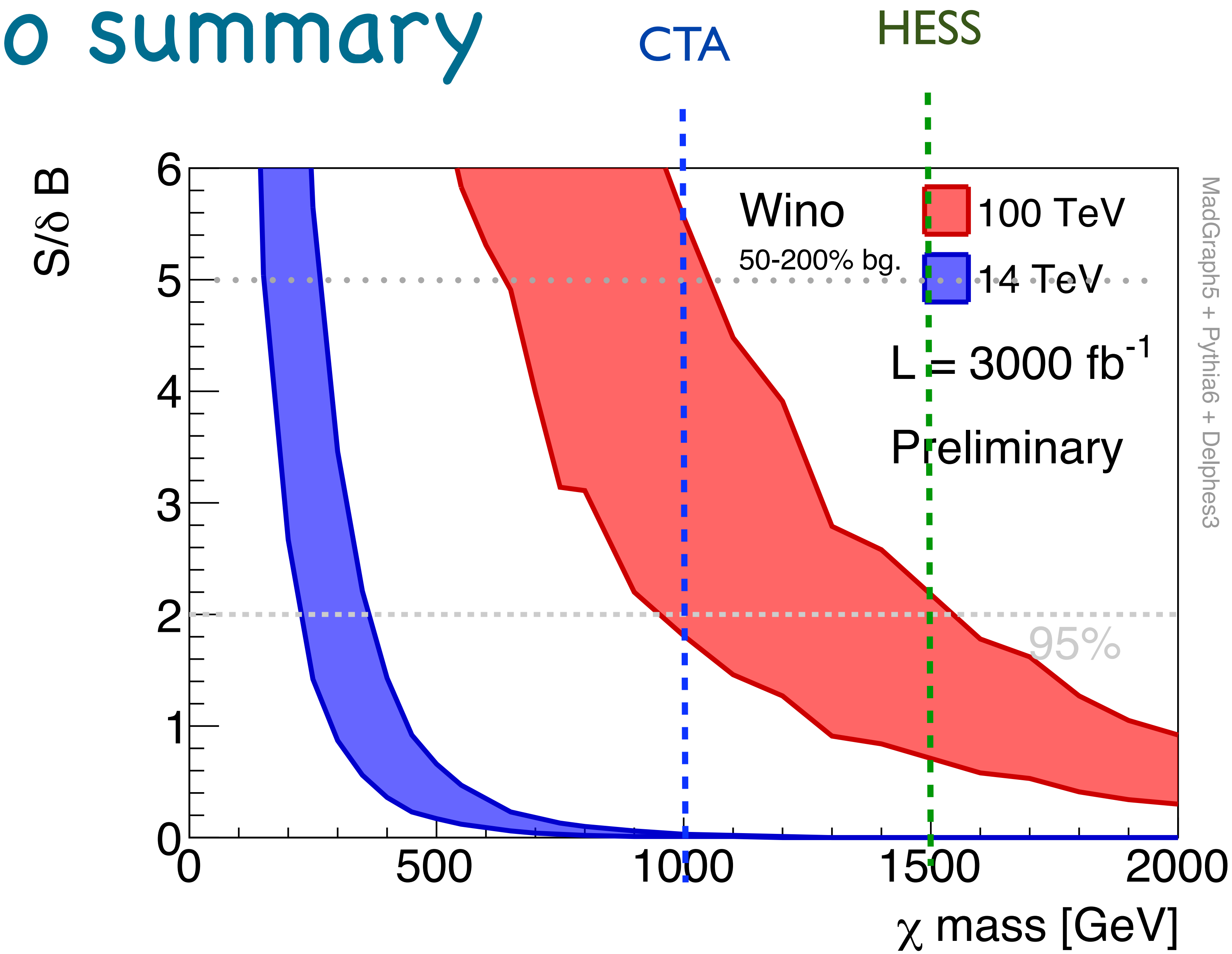
(Rough) Extrapolation from ATLAS search



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

- Band: varying background estimate by 2 either way.

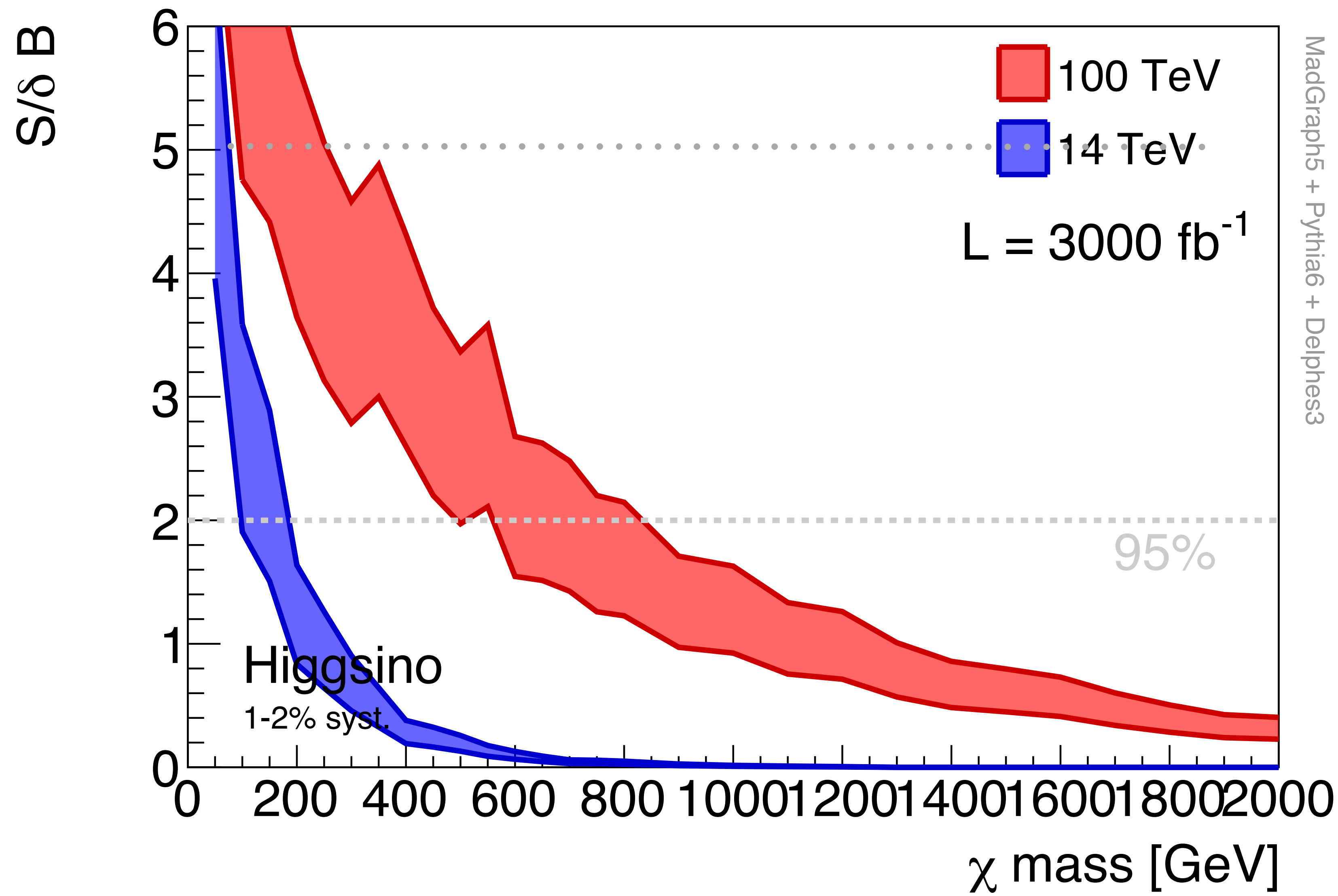
Wino summary



– In combination with indirect detection, there is hope to "completely cover" the wino parameter space.

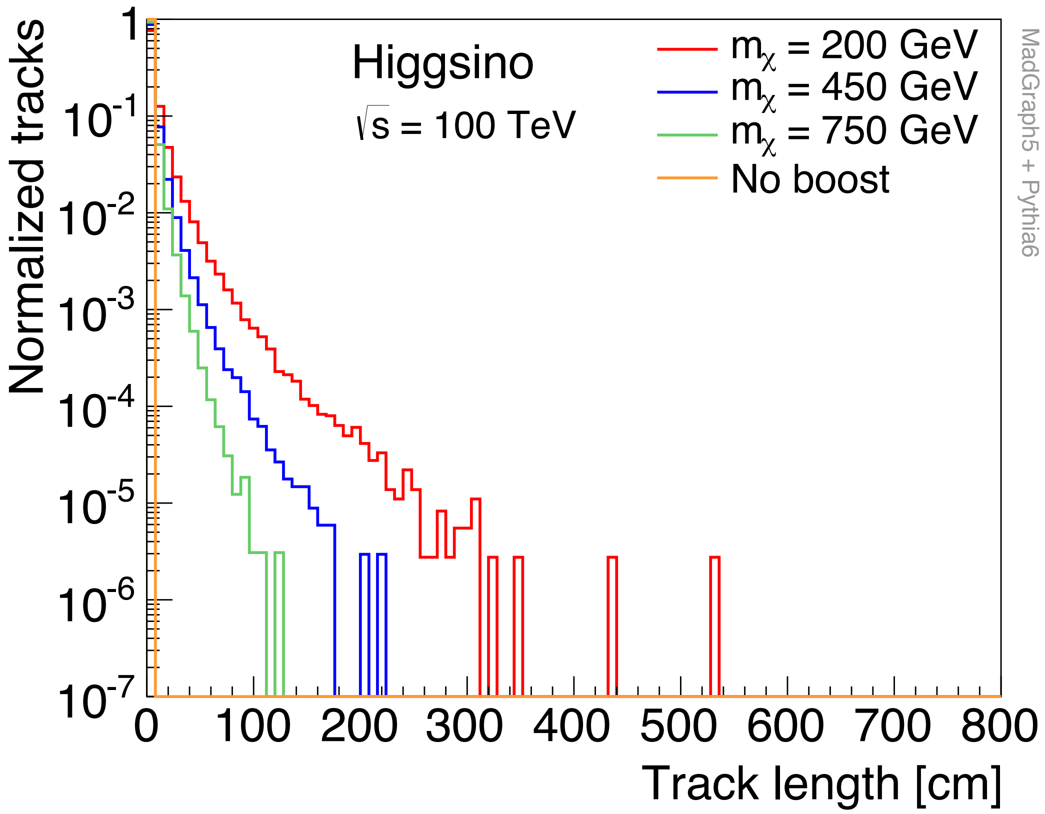
Higgsino

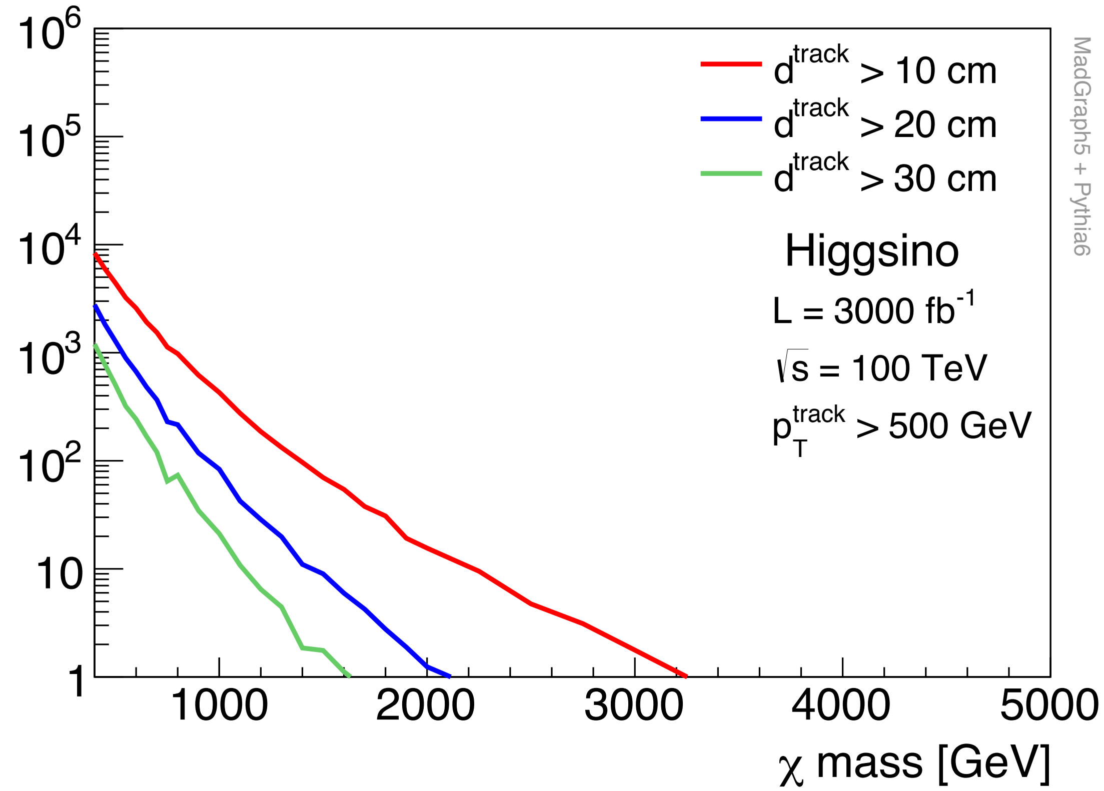
Mono-jet



S/δ B
100 TeV
14 TeV
L = 3000 fb-1
MadGraph5 + Pythia6 + Delphes3
95%
Higgsino
1-2% syst.
0 200 400 600 800 1000 1200 1400 1600 1800 2000
χ mass [GeV]
0 1 2 3 4 5 6

Tracks?

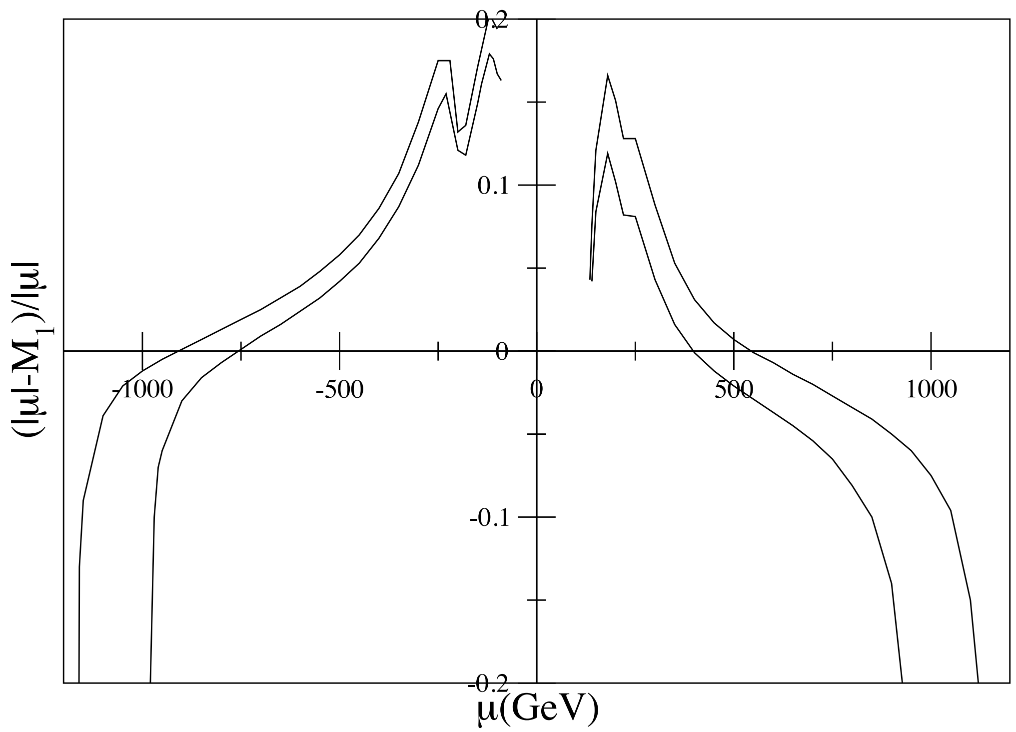


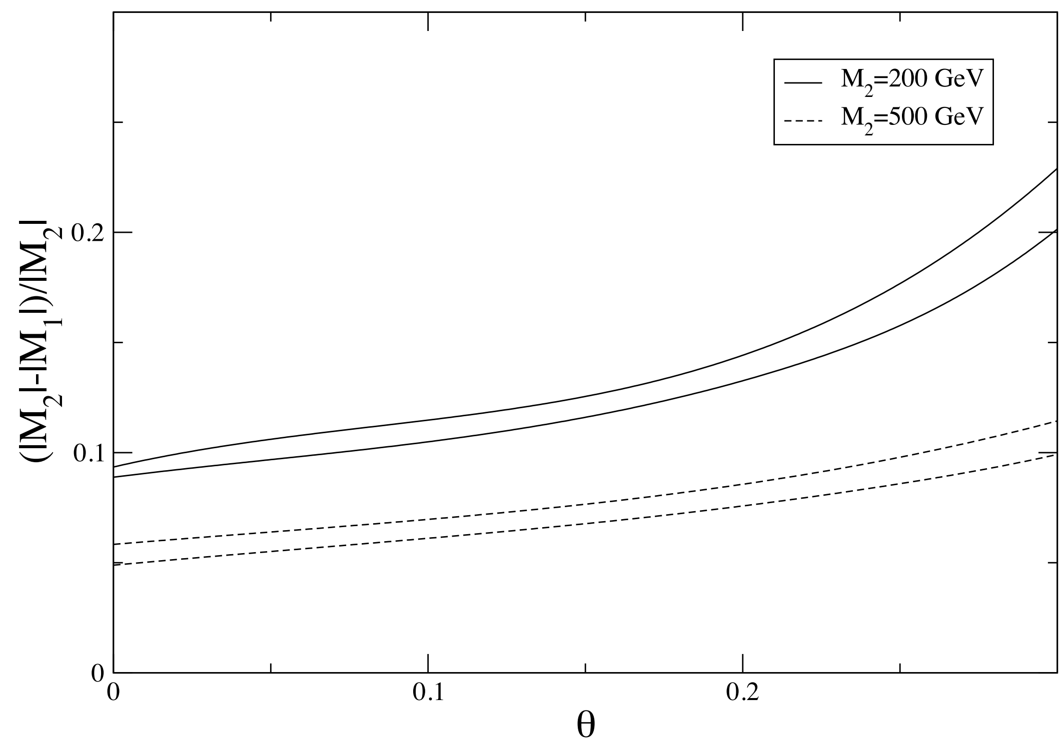


- Depends on detector design
  - How long the track needs to be?
  - Background discrimination?
- Can change mass splitting in extended models.

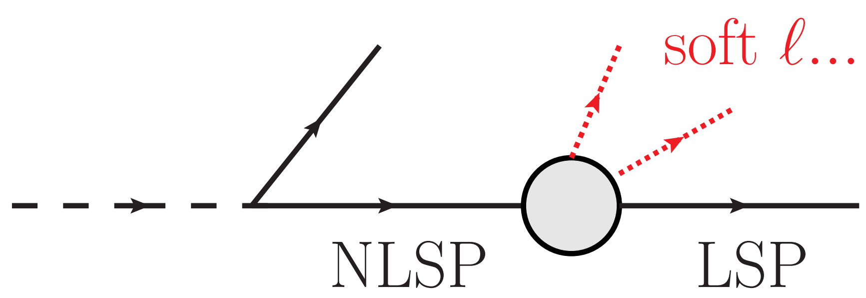
Well-tempered

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



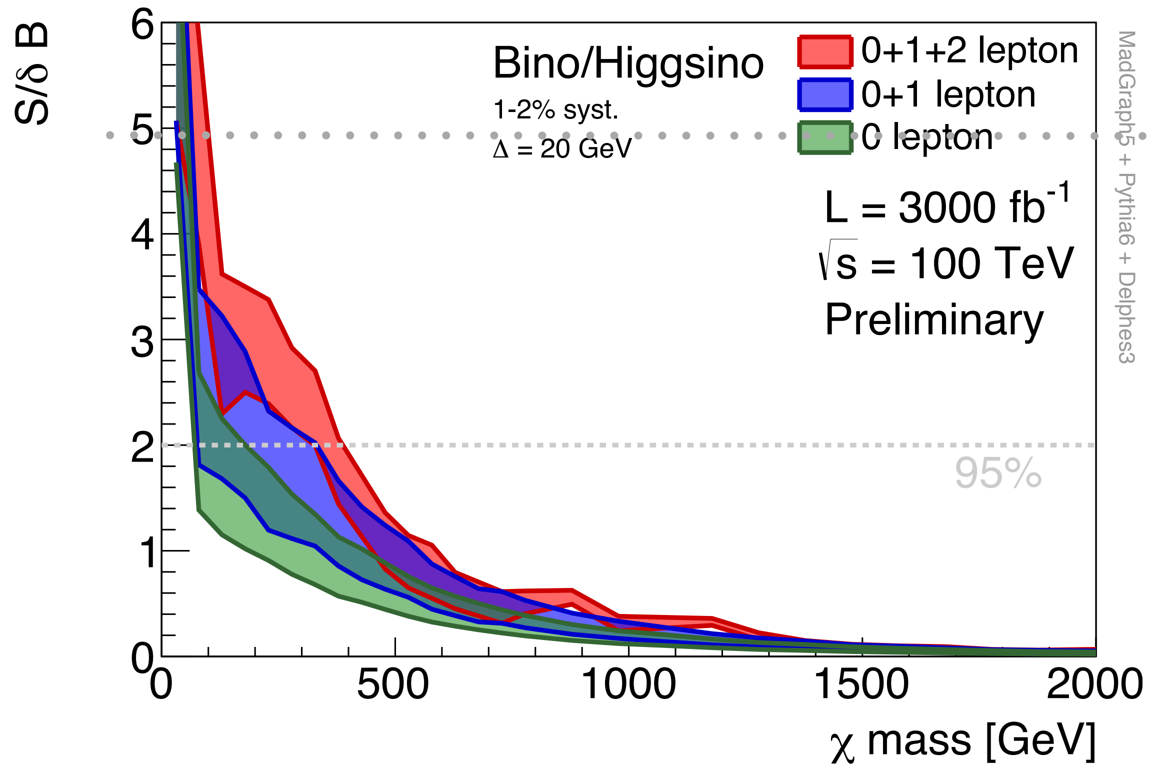


- Adding soft lepton

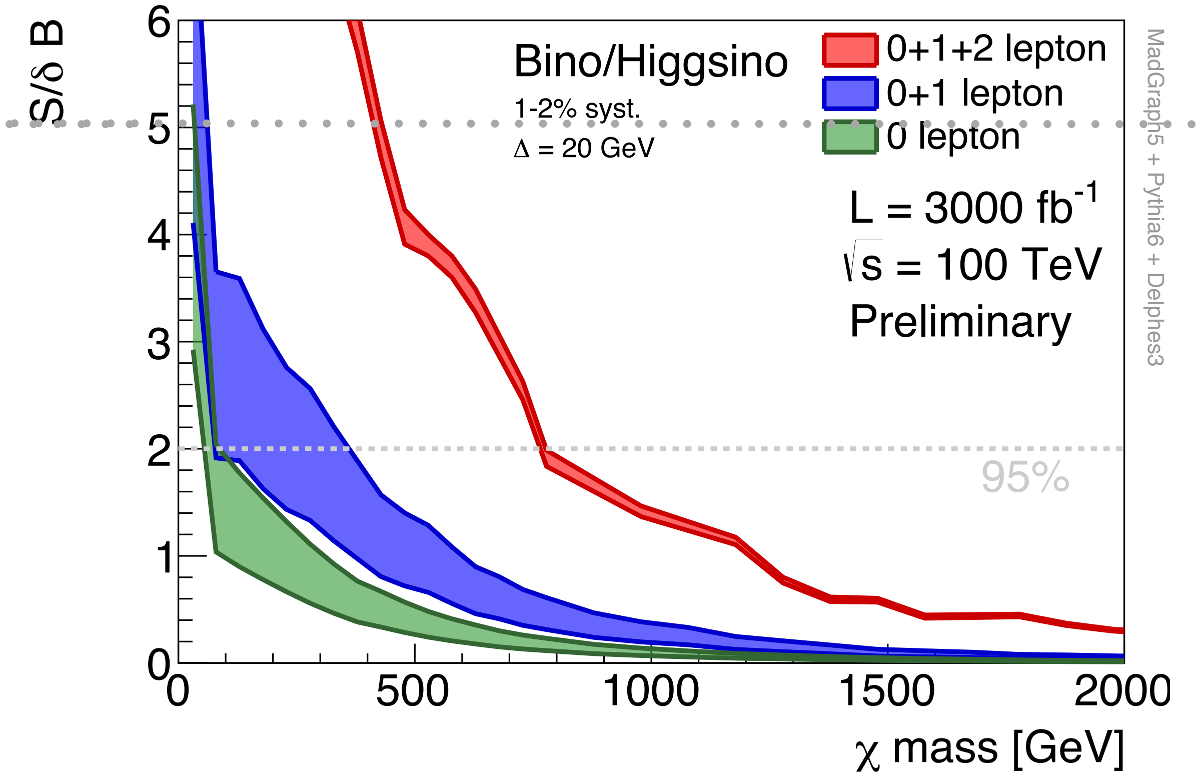


Giudice, Han, Wang and LTW, 1004.4902
Schwaller, Zurita, 1312.7350
Han, Kribs, Martin, Menon, 1401.1235

Well-tempered, mono-jet + soft lepton



20 GeV < pT lepton < 40 GeV

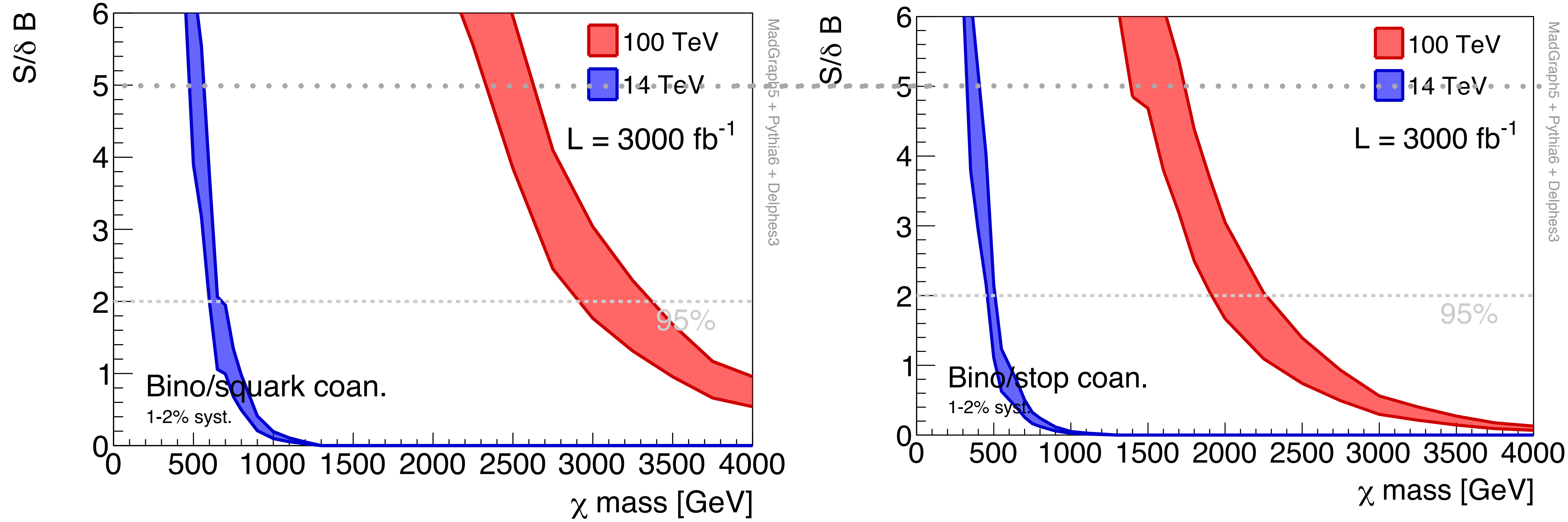


10 GeV < pT lepton < 30 GeV

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

Conclusion and outlook

- Significant enhancement in reach by going to 100 TeV.
  - A factor of 4-5 in mono-jet channel
- Wino can be "completely covered".
- Motivation for optimizing detector design
  - Systematics in mono-jet, track-pT measurement...
  - Discrimination against mis-measured tracks
  - How soft can lepton be?

Conclusions and outlook

- Further studies:
  - Careful detector simulation for disappearing tracks...
  - Do more with higgsino-like and well-temper (or nearly degenerate) case.
  - More general scenarios in addition to the bench marks considered here.
    - Electroweakino+higgsino?
  - Heavy flavor, VBF ...

extras

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?

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

Cuts, monojet

$\sqrt{s} = 8$ TeV (CMS analysis)

Jet cuts	Lepton vetoes		$\not{E}_T$ cuts
$p_T(1) > 110$ GeV	$p_T(e) > 10$ GeV and	$\vert\eta(e)\vert < 2.5$	$\not{E}_T > 250$ GeV
$\vert\eta(1)\vert < 2.4$	$p_T(\mu) > 10$ GeV and	$\vert\eta(\mu)\vert < 2.1$	$\not{E}_T > 300$ GeV
$p_T(2) > 30$ GeV	$p_T(\tau) > 20$ GeV and	$\vert\eta(\tau)\vert < 2.3$	$\not{E}_T > 350$ GeV
$\vert\eta(2)\vert < 4.5$			$\not{E}_T > 400$ GeV
$n_{\text{jet}} \leq 2$			$\not{E}_T > 450$ GeV
$\Delta\phi(1,2) < 2.5$			$\not{E}_T > 500$ GeV
			$\not{E}_T > 550$ GeV

$\sqrt{s} = 14$ TeV

Jet cuts	Lepton vetoes		$\not{E}_T$ cuts
$p_T(1) > 300$ GeV	$p_T(e) > 20$ GeV and	$\vert\eta(e)\vert < 2.5$	$\not{E}_T > 300$ GeV
$\vert\eta(1)\vert < 2.4$	$p_T(\mu) > 20$ GeV and	$\vert\eta(\mu)\vert < 2.1$	$\not{E}_T > 350$ GeV
$p_T(2) > 60$ GeV	$p_T(\tau) > 20$ GeV and	$\vert\eta(\tau)\vert < 2.3$	$\not{E}_T > 400$ GeV
$\vert\eta(2)\vert < 4.5$			$\not{E}_T > 450$ GeV
$n_{\text{jet}} \leq 2$			$\not{E}_T > 500$ GeV
$\Delta\phi(1,2) < 2.5$			$\not{E}_T > 550$ GeV
			$\not{E}_T > 600$ GeV
			$\not{E}_T > 650$ GeV
			$\not{E}_T > 700$ GeV
			$\not{E}_T > 750$ GeV
			$\not{E}_T > 1000$ GeV

Cuts, monojet

$\sqrt{s} = 100$ TeV

Jet cuts	Lepton vetoes		$\not{E}_T$ cuts
$p_T(1) > 1200$ GeV	$p_T(e) > 20$ GeV and	$\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 1000$ GeV
$\lvert\eta(1)\rvert < 2.4$	$p_T(\mu) > 20$ GeV and	$\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 1800$ GeV
$p_T(2) > 200$ GeV	$p_T(\tau) > 40$ GeV and	$\lvert\eta(\tau)\rvert < 2.3$	$\not{E}_T > 2000$ GeV
$\lvert\eta(2)\rvert < 4.5$			$\not{E}_T > 2200$ GeV
$n_{\text{jet}} \leq 2$			$\not{E}_T > 2400$ GeV
$\Delta\phi(1,2) < 2.5$			$\not{E}_T > 2600$ GeV
			$\not{E}_T > 2800$ GeV
			$\not{E}_T > 3000$ GeV
			$\not{E}_T > 3200$ GeV
			$\not{E}_T > 3400$ GeV
			$\not{E}_T > 5000$ GeV

Cuts, soft lepton

$\sqrt{s} = 8$ TeV

Jet cuts	Lepton bins	$\not{E}_T$ cuts
$p_T(1) > 110$ GeV	0-bin: $p_T(e) > 10$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 250$ GeV
$\lvert\eta(1)\rvert < 2.4$	$1,2$-bin: $50 > p_T(e) > 10$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 300$ GeV
$p_T(2) > 30$ GeV	0-bin: $p_T(\mu) > 10$ GeV and $\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 350$ GeV
$\lvert\eta(2)\rvert < 4.5$	$1,2$-bin: $50 > p_T(\mu) > 10$ GeV and $\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 400$ GeV
$n_{\rm jet} \leq 2$	0-bin: $p_T(\tau) > 20$ GeV and $\lvert\eta(\tau)\rvert < 2.3$	$\not{E}_T > 450$ GeV
$\Delta\phi(1,2) < 2.5$		$\not{E}_T > 500$ GeV
		$\not{E}_T > 550$ GeV

$\sqrt{s} = 14$ TeV

Jet cuts	Lepton bins	$\not{E}_T$ cuts
$p_T(1) > 300$ GeV	0-bin: $p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 300$ GeV
$\lvert\eta(1)\rvert < 2.4$	$1,2$-bin: $50 > p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 350$ GeV
$p_T(2) > 60$ GeV	0-bin: $p_T(\mu) > 20$ GeV and $\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 400$ GeV
$\lvert\eta(2)\rvert < 4.5$	$1,2$-bin: $50 > p_T(\mu) > 20$ GeV and $\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 450$ GeV
$n_{\rm jet} \leq 2$	0-bin: $p_T(\tau) > 30$ GeV and $\lvert\eta(\tau)\rvert < 2.3$	$\not{E}_T > 500$ GeV
$\Delta\phi(1,2) < 2.5$		$\not{E}_T > 550$ GeV
		$\not{E}_T > 600$ GeV
		$\not{E}_T > 650$ GeV
		$\not{E}_T > 700$ GeV
		$\not{E}_T > 750$ GeV
		$\not{E}_T > 1000$ GeV

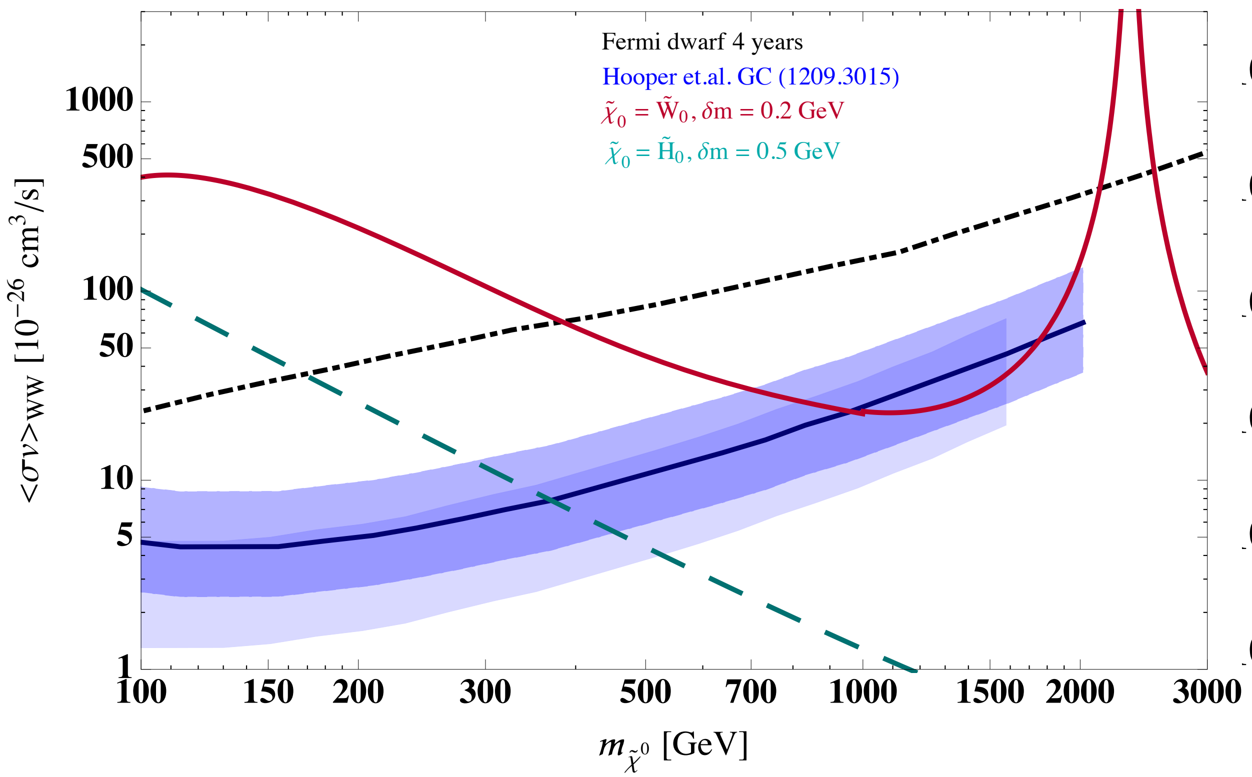
Cuts, soft lepton

$\sqrt{s} = 100$ TeV

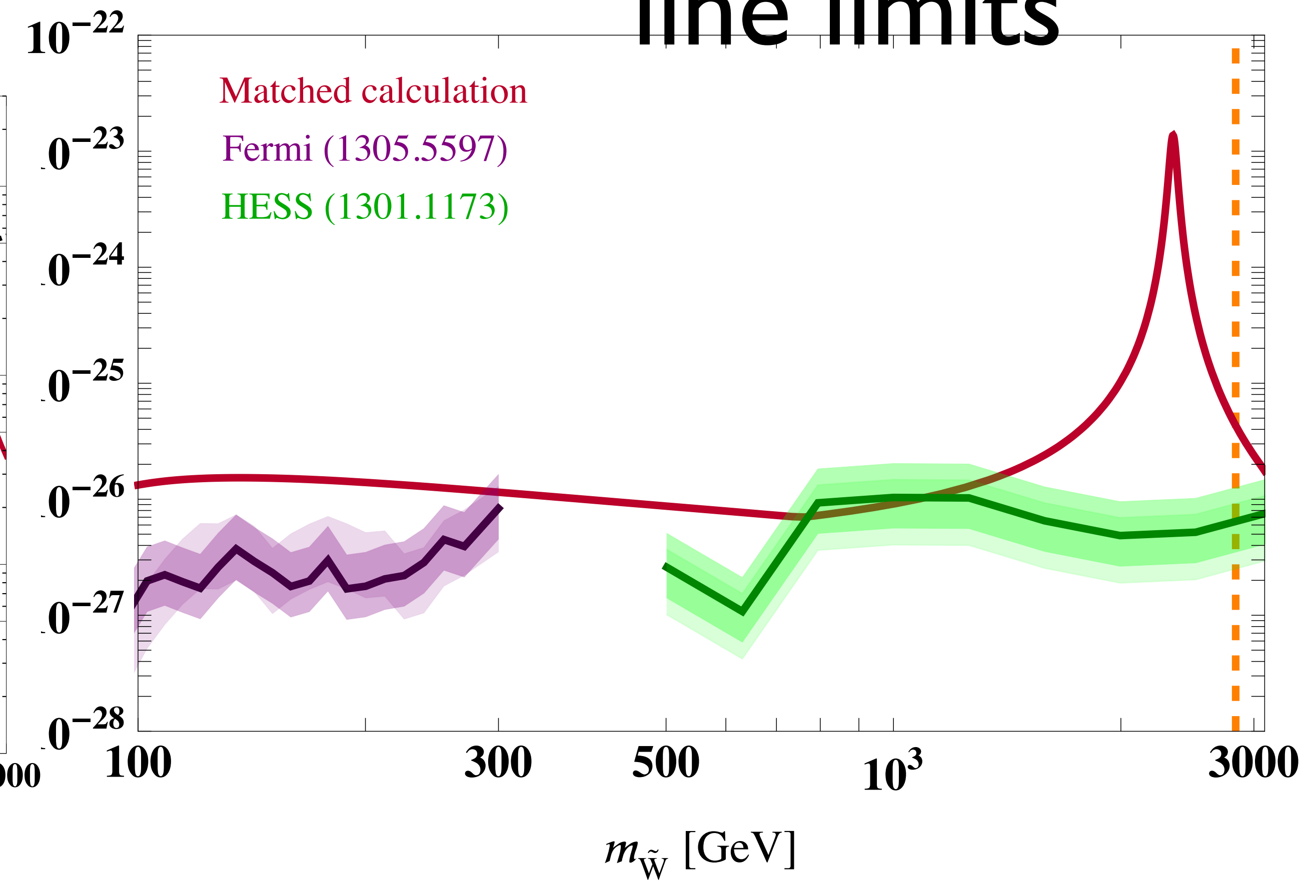
Jet cuts	Lepton bins	$\not{E}_T$ cuts
$p_T(1) > 1200$ GeV	0-bin: $p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 1000$ GeV
$\lvert\eta(1)\rvert < 2.4$	$1, 2$-bin: $40 > p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 2000$ GeV
$p_T(2) > 200$ GeV	0-bin: $p_T(\mu) > 20$ GeV and $\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 2250$ GeV
$\lvert\eta(2)\rvert < 4.5$	$1, 2$-bin: $40 > p_T(\mu) > 20$ GeV and $\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 2500$ GeV
$n_{\text{jet}} \leq 2$	0-bin: $p_T(\tau) > 40$ GeV and $\lvert\eta(\tau)\rvert < 2.3$	$\not{E}_T > 2750$ GeV
$\Delta\phi(1, 2) < 2.5$		$\not{E}_T > 3000$ GeV
		$\not{E}_T > 3250$ GeV
		$\not{E}_T > 3500$ GeV
		$\not{E}_T > 3750$ GeV
		$\not{E}_T > 4000$ GeV
		$\not{E}_T > 5000$ GeV

10 GeV < pT lepton < 30 GeV

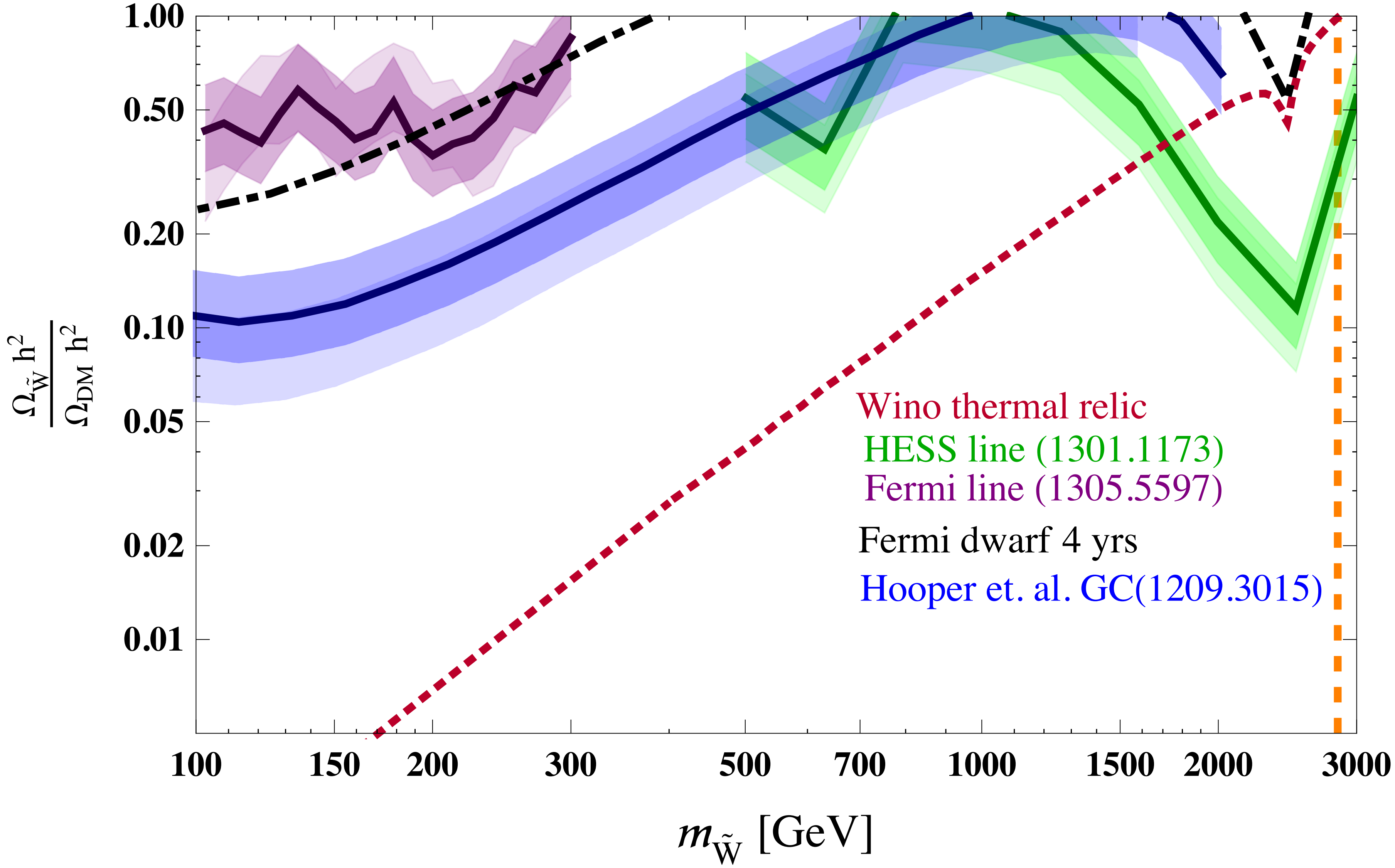
continuum limits



line limits



Wino, interplay with indirect det.



Fan, Reece, 1307.4400

See also, Cohen, Lisanti, Pierce, Slatyer, 1307.4082