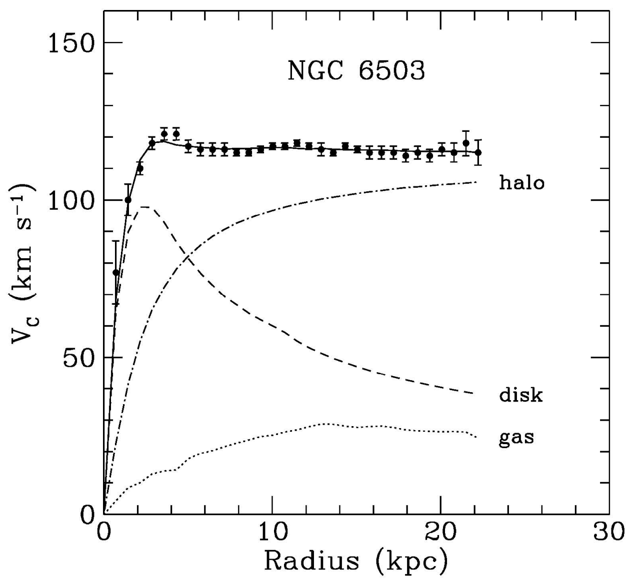
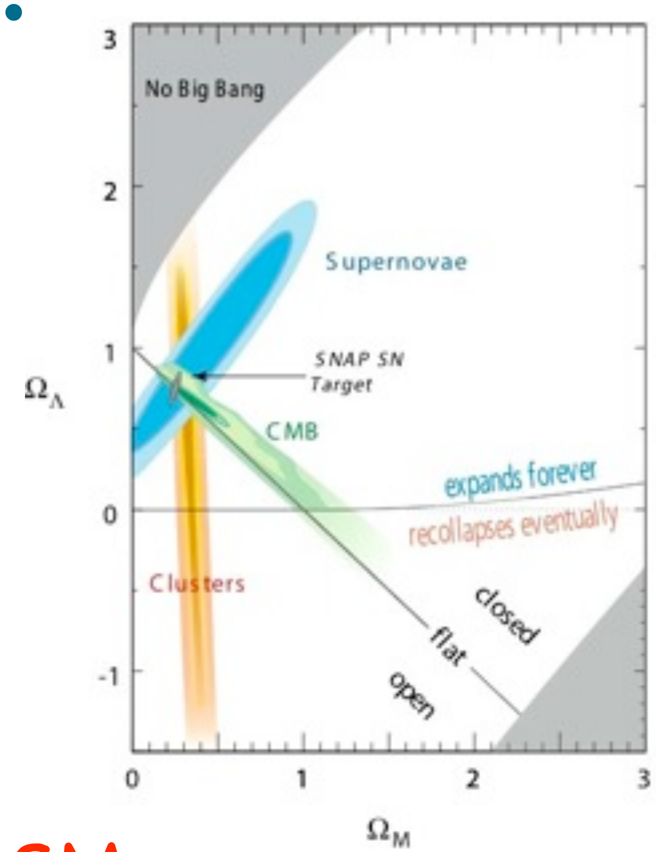
WIMP dark matter at 100 TeV

Lian-Tao Wang
University of Chicago

BSM Opportunities at 100 TeV, CERN, Feb 11, 2014

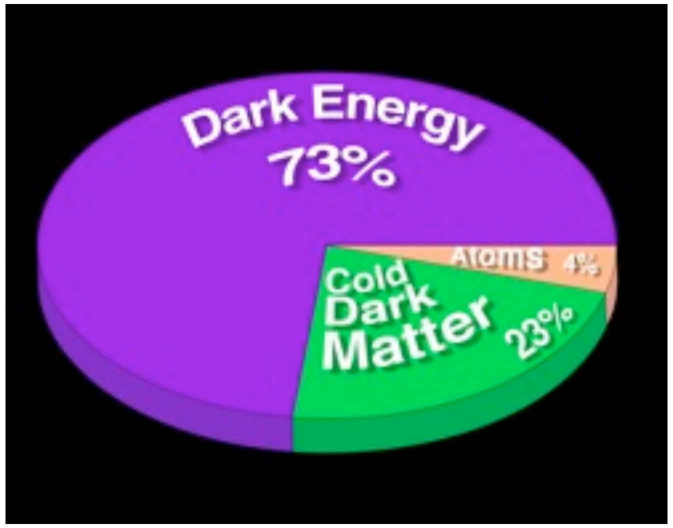
We have solid evidence for dark matter:



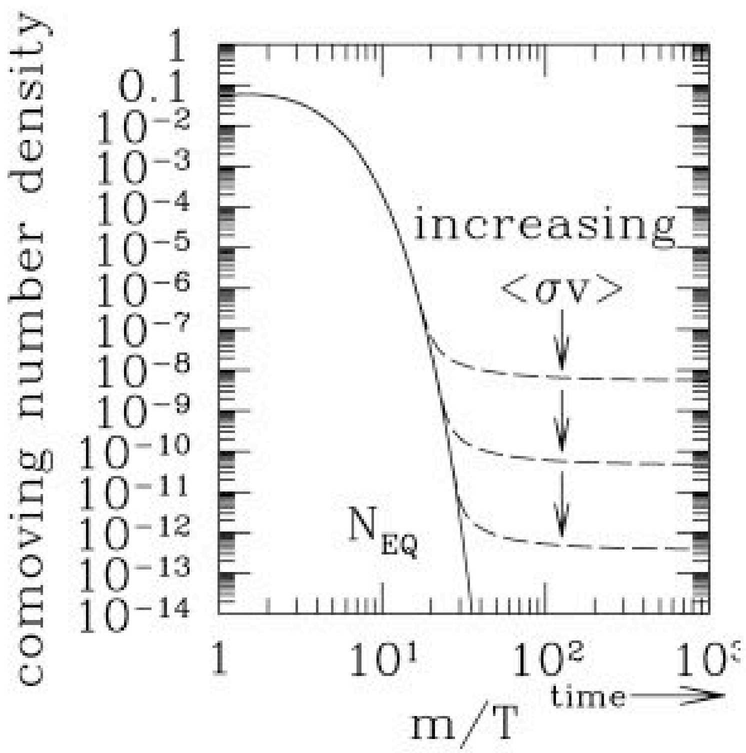


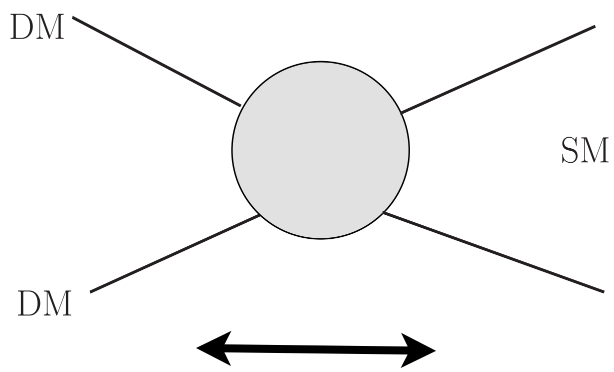
Only NP beyond SM discovered so far.

- Exists
- gravitates.
- is dark.



TeV dark matter: WIMP miracle.





Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$

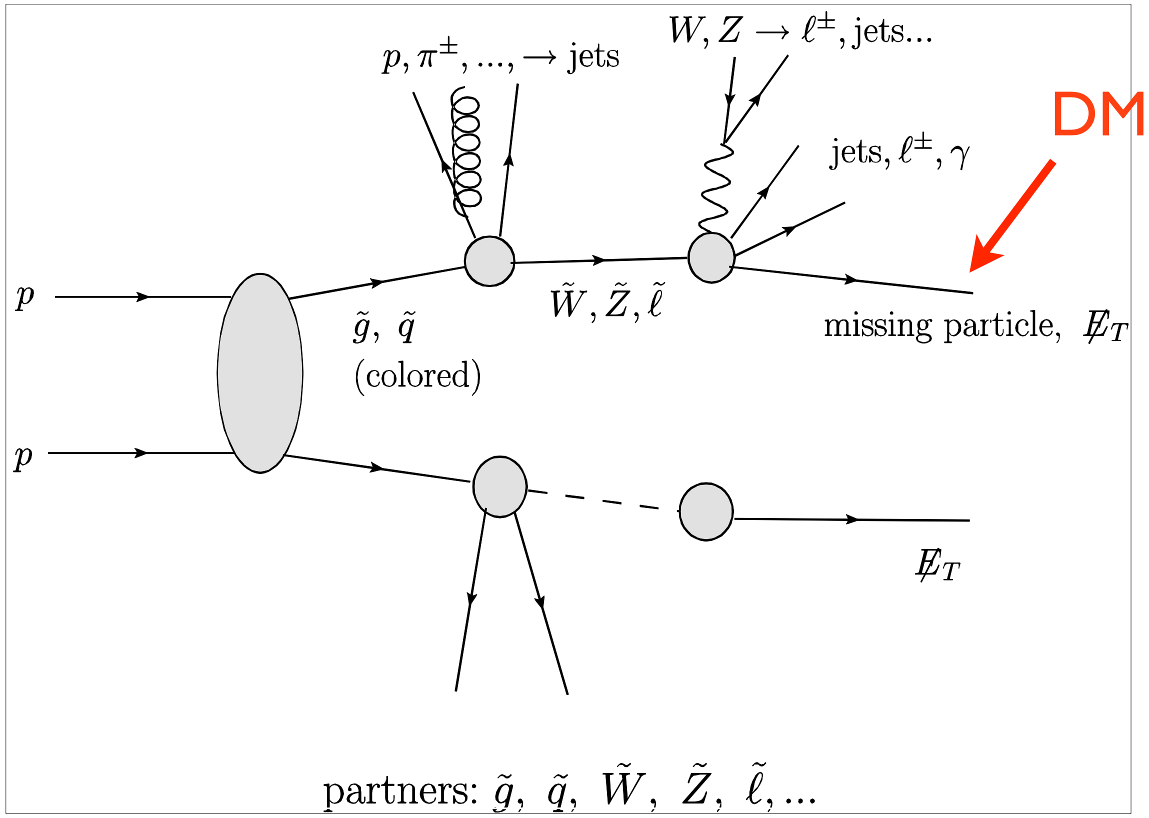
- To get the right relic abundance

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

- A major hint of TeV scale new physics.

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

“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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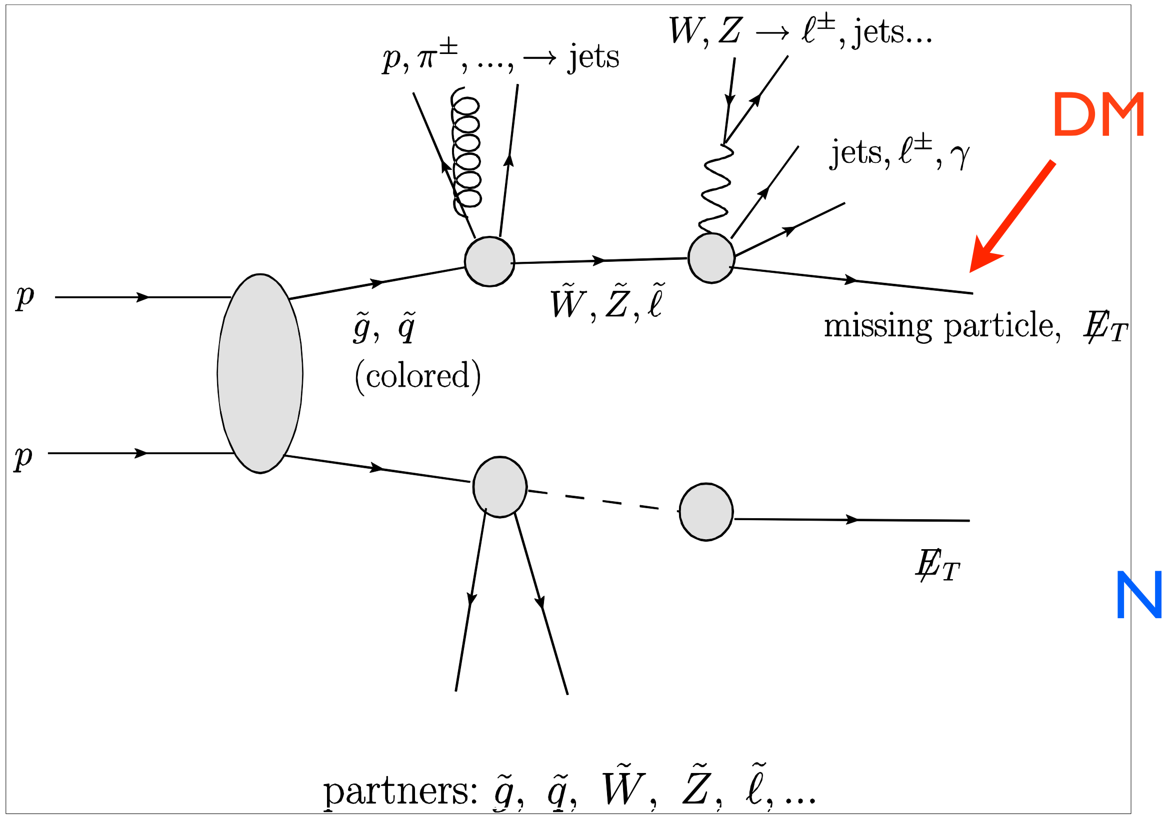
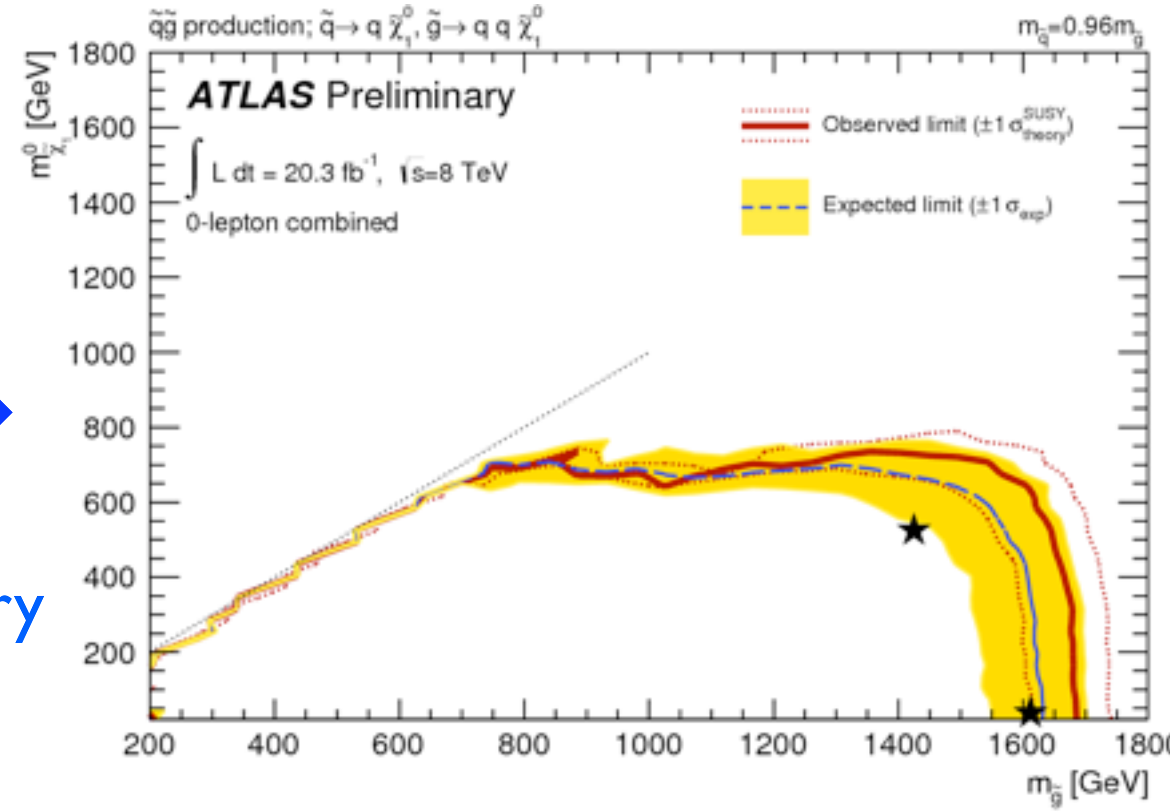


No discovery yet



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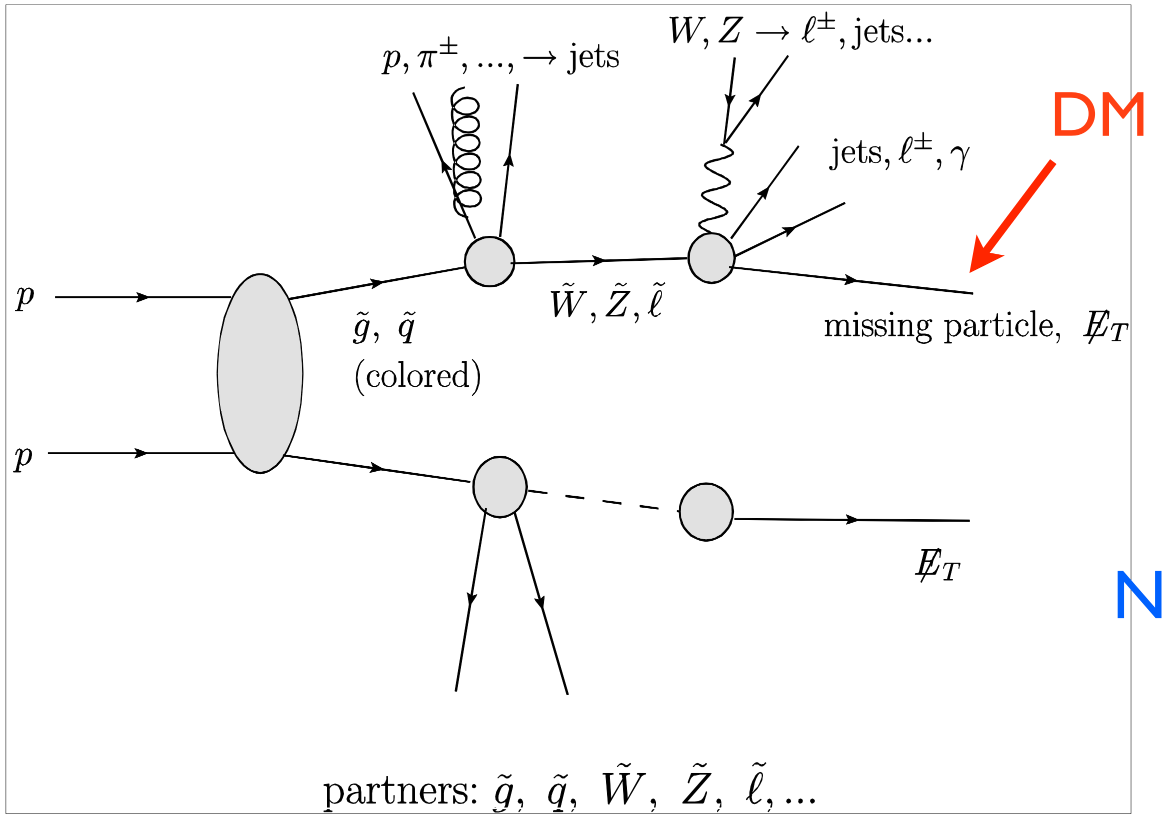

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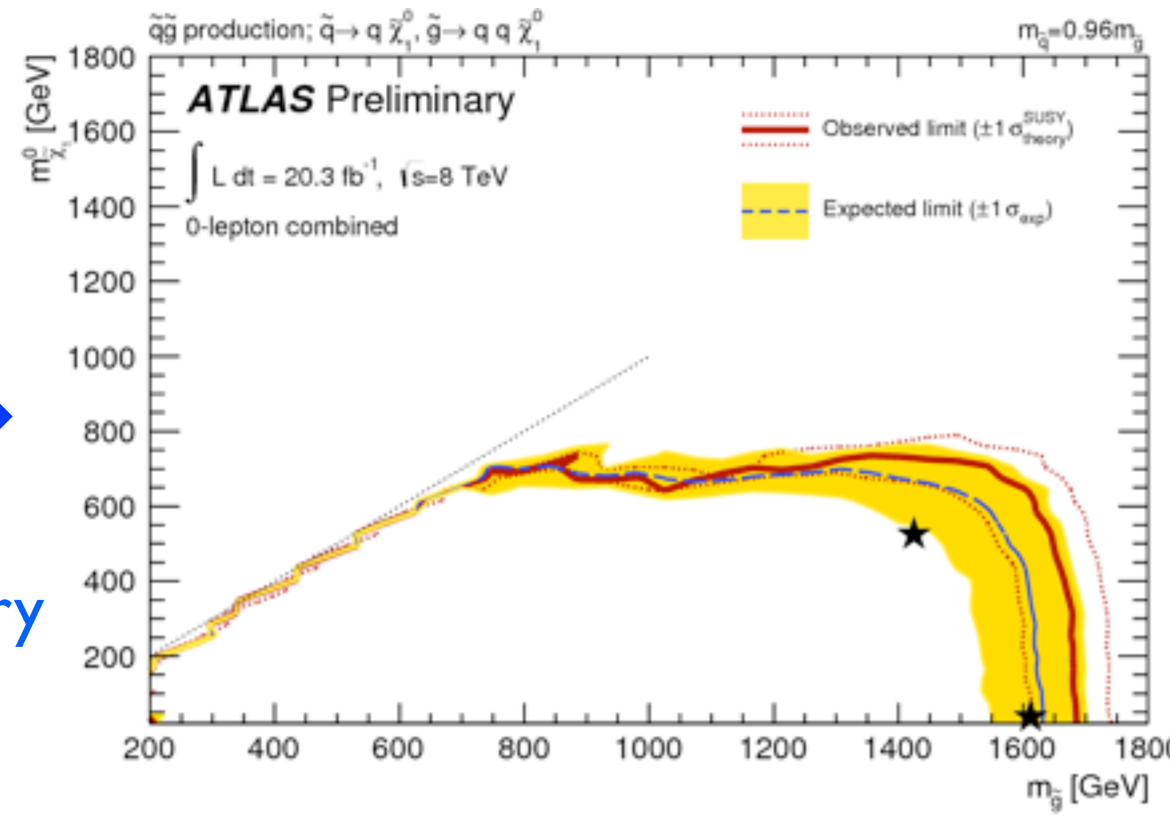
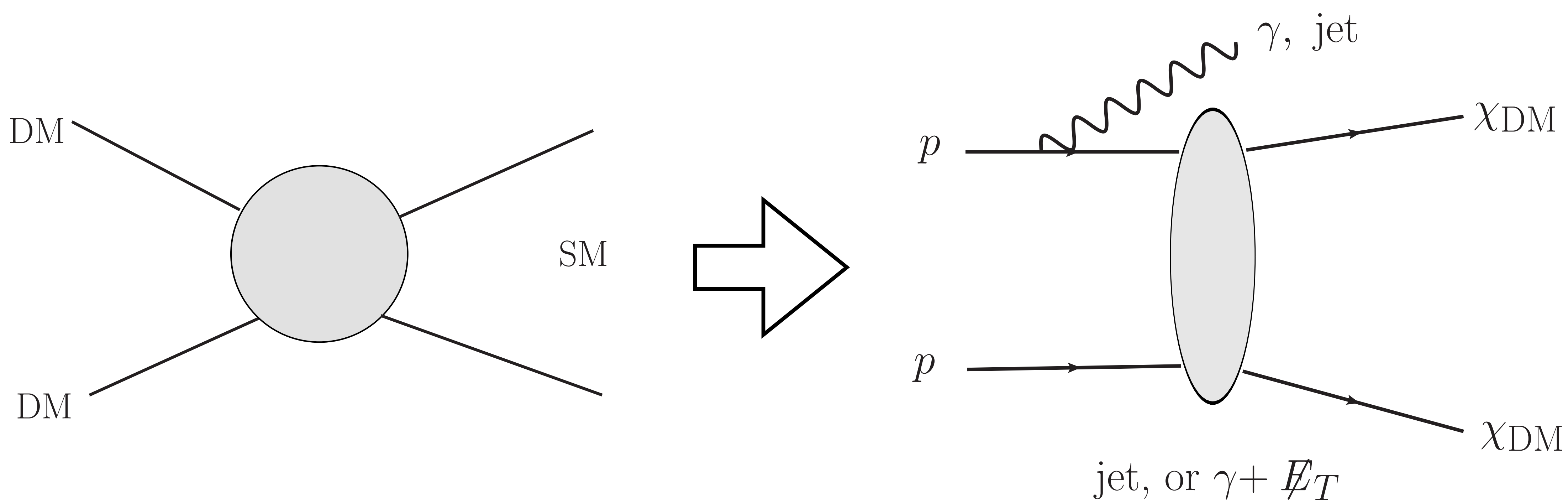


Of course, still plausible at the LHC, will keep looking.
Higher energy ⇒ higher reach

Back to the basics

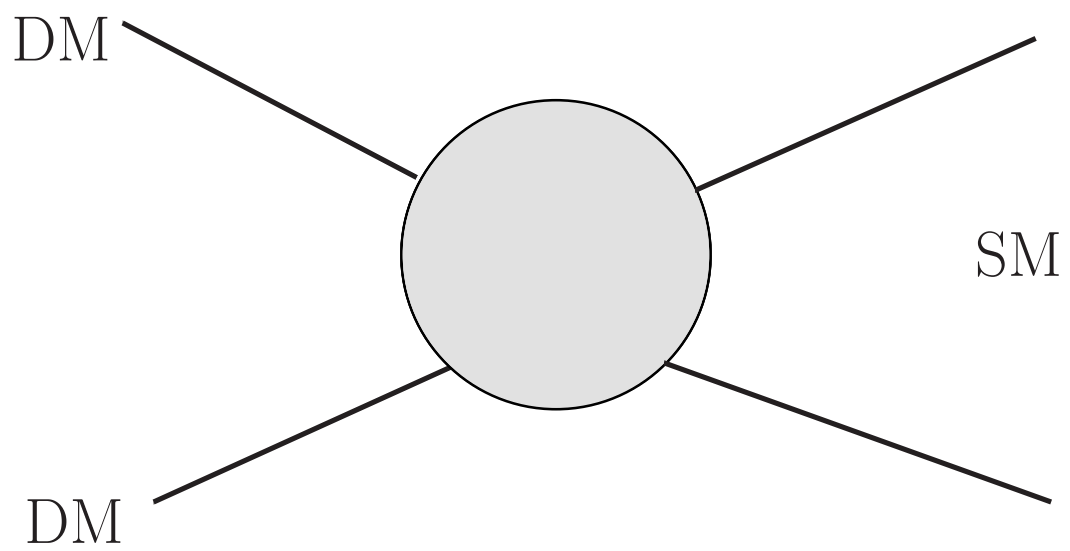
- pair production + additional radiation.



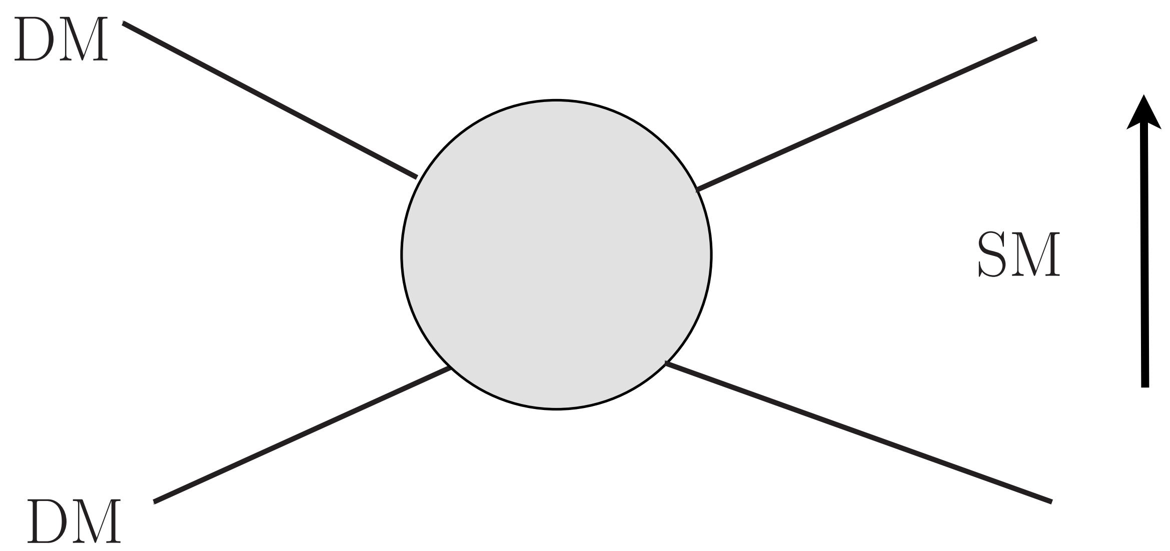
- Mono-jet, mono-photon, mono-...

- Have become "Standard" LHC searches.

Effective operator approach



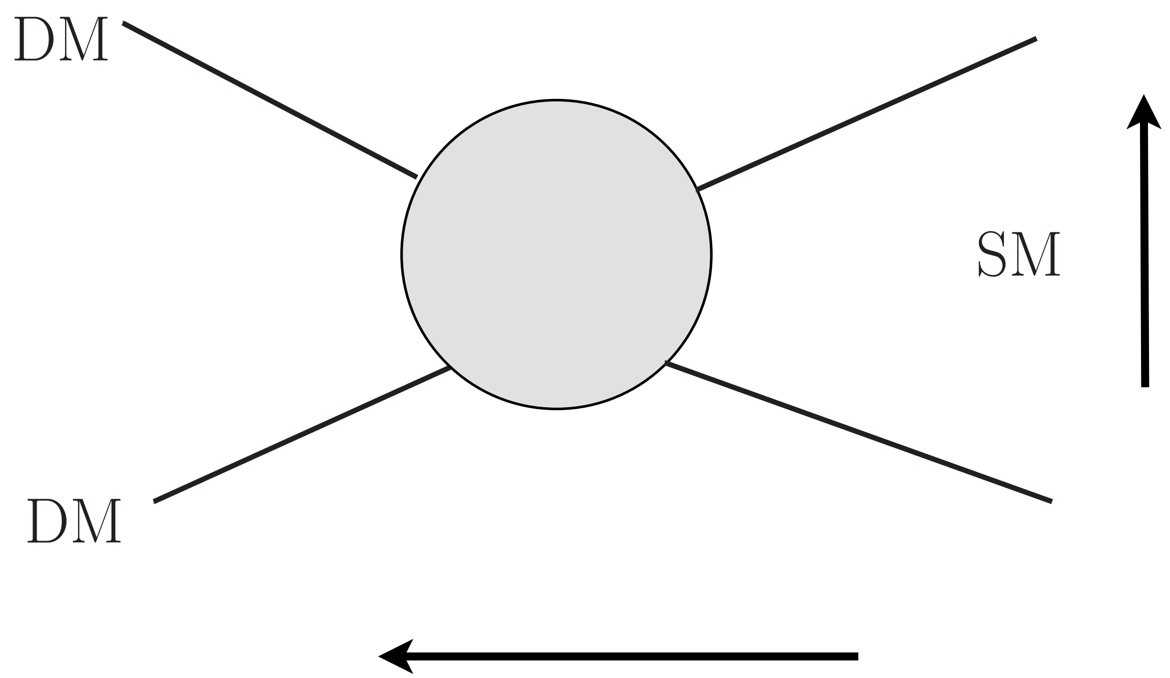
Effective operator approach



momentum exchange
q~100 MeV << m_Φ
effectively,

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

Effective operator approach



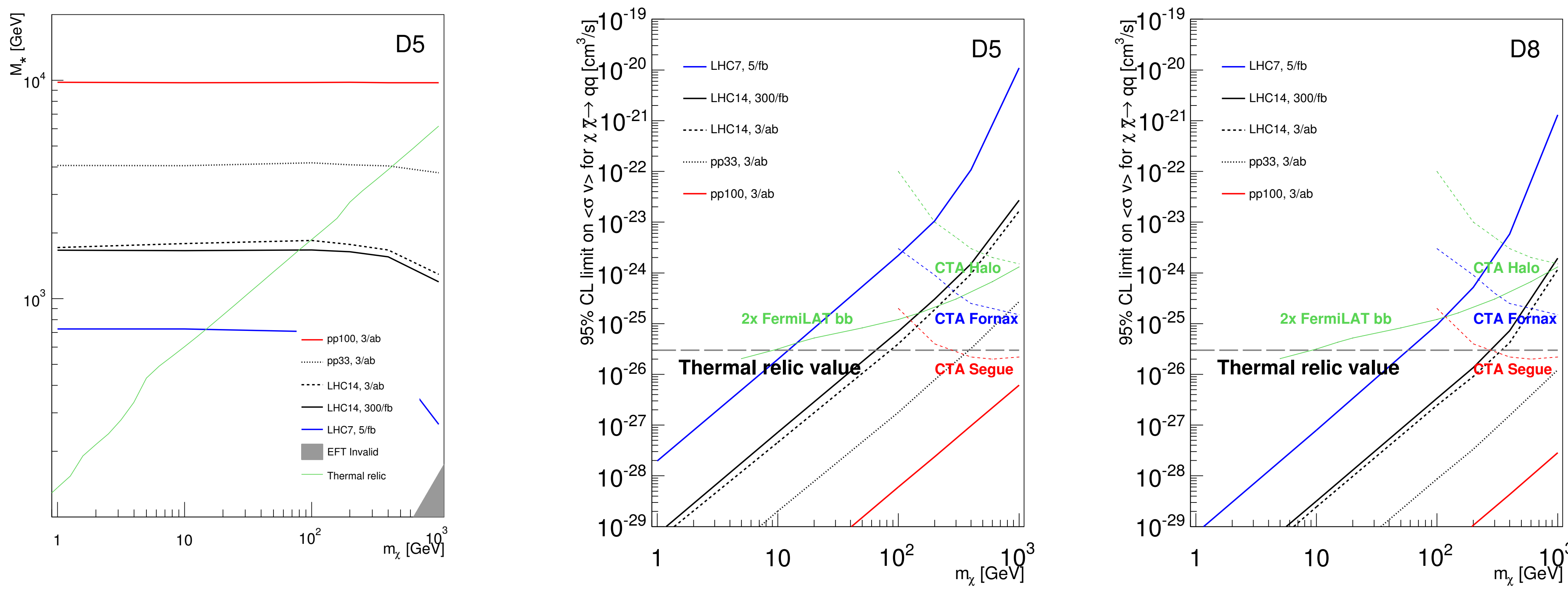
momentum exchange
q~100 MeV << m_Φ
effectively,

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

Use colliders to constrain and probe
the same operator

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

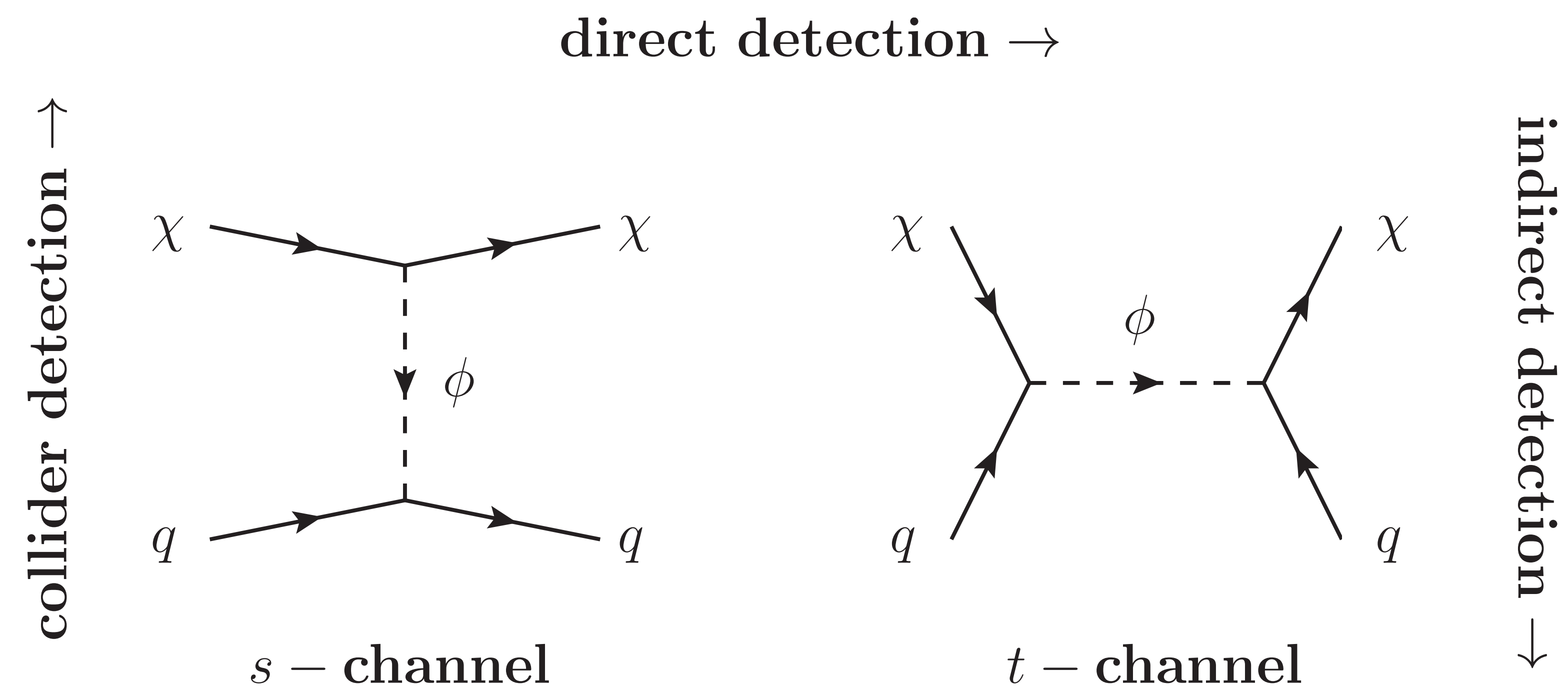
Effective operator approach



Zhou, Berge, LTW, Whiteson, Tait, 1307.5327

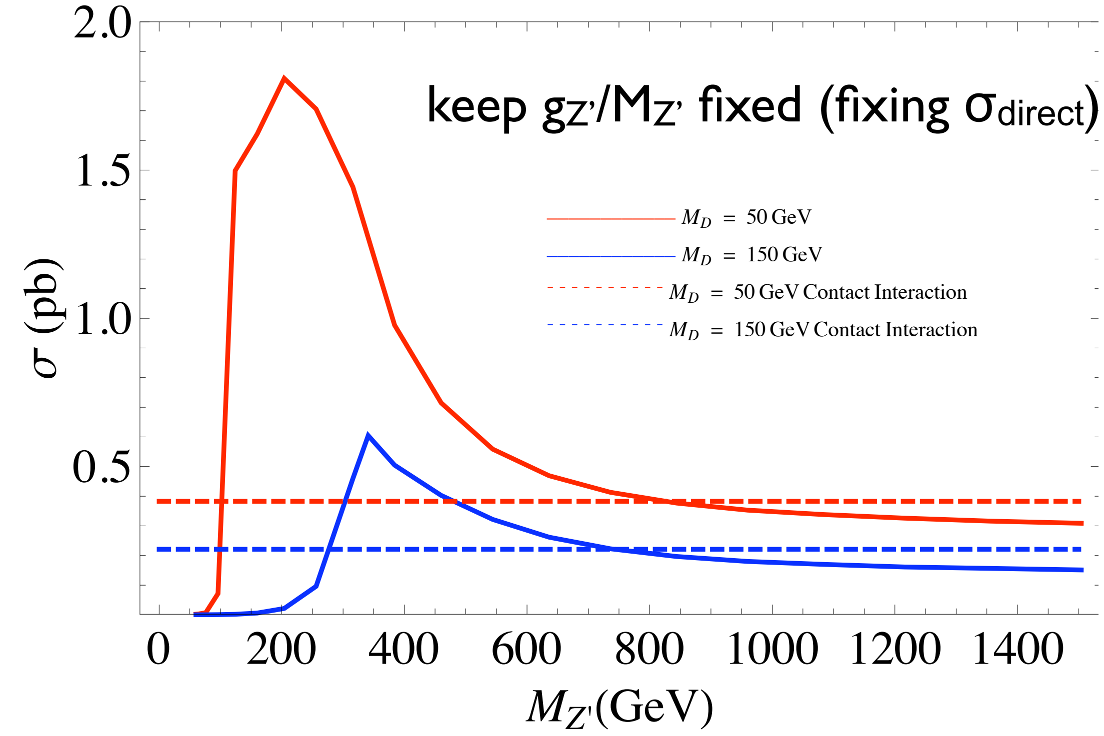
- Effective?
  - Valid? Could be in some parameter region.
  - Representative of possible UV completion? And, representative of possible signals?
    - ☐ Consider possible mediators.

Simplified mediator models



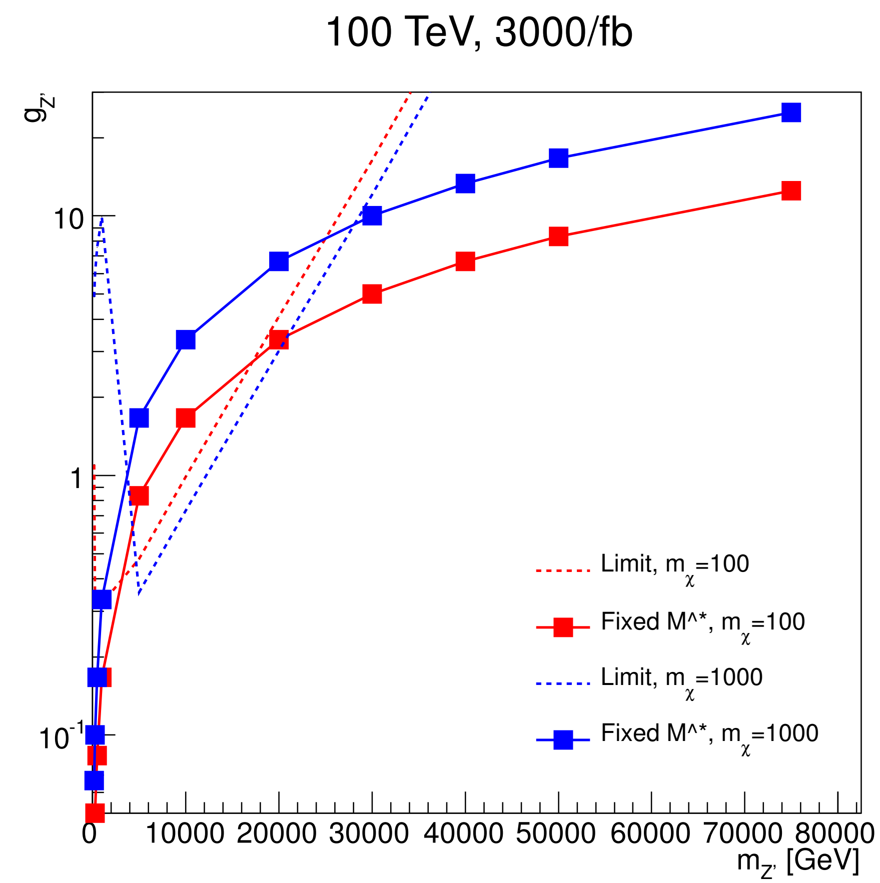
ϕ can be scalar or Z'

ϕ squark like



Tevatron rate, Z' vs effective operator

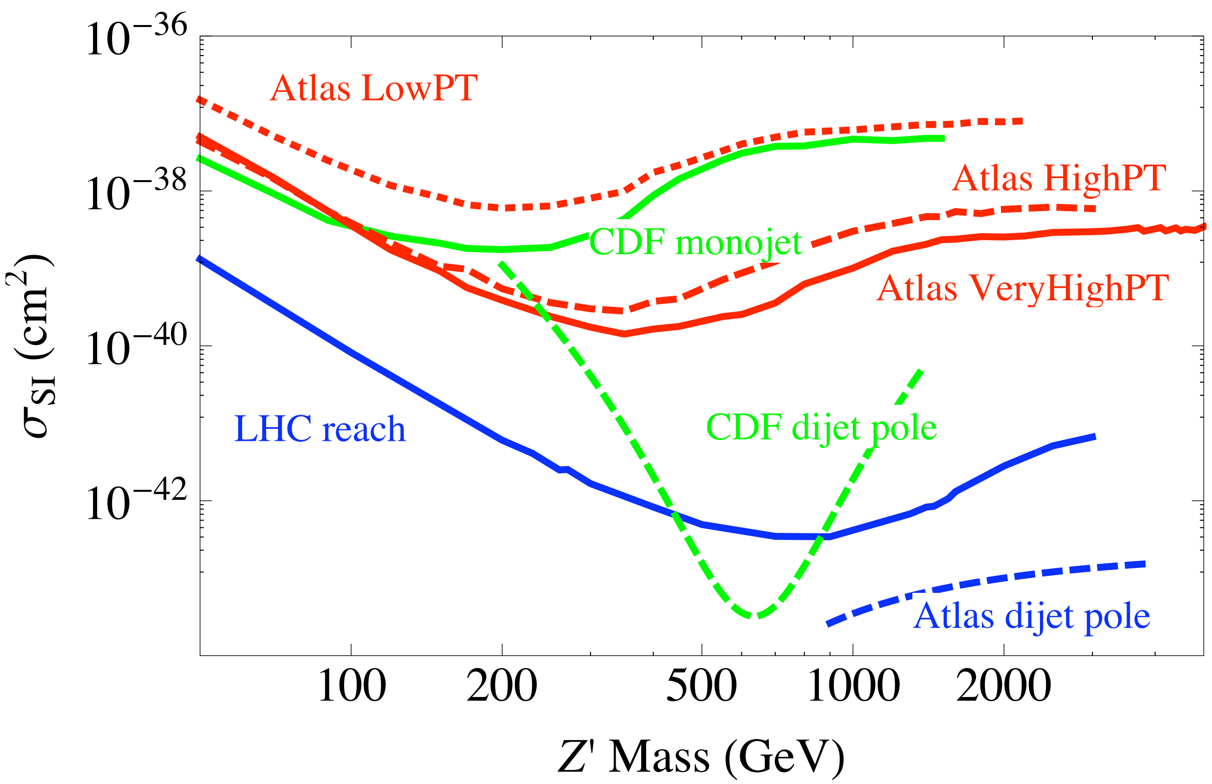
An, Ji, LTW, 1202.2894

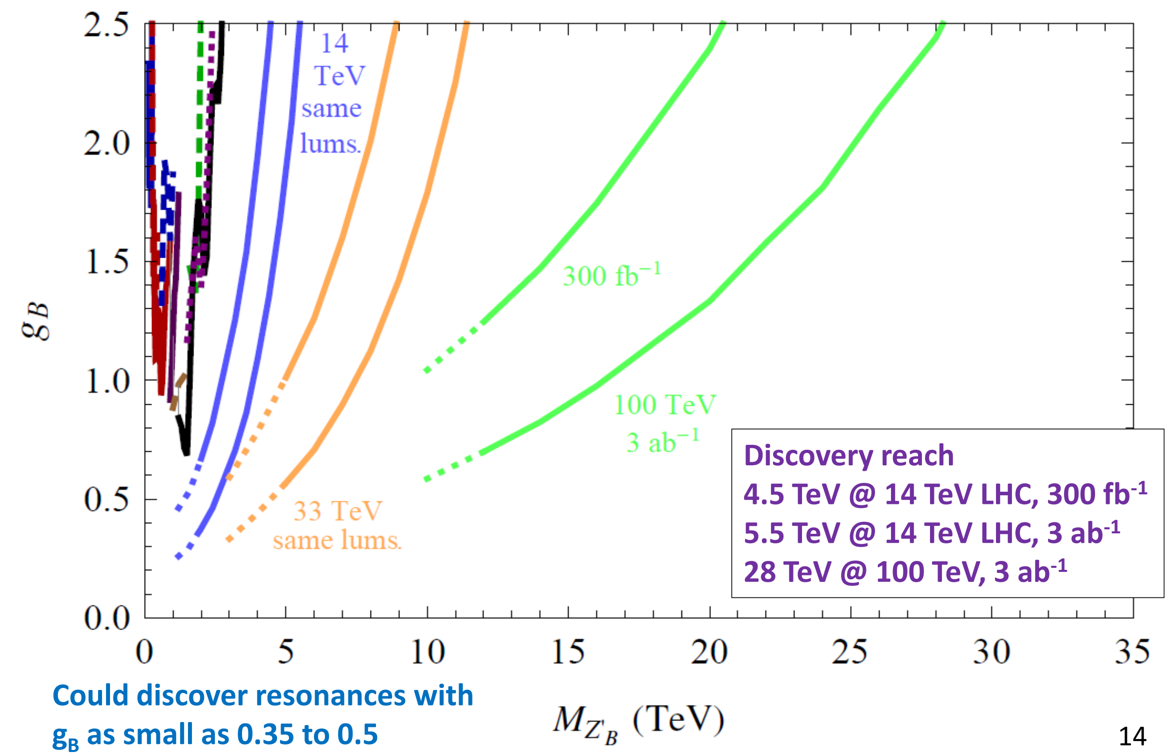


Zhou, Berge, LTW, Whiteson, Tait, 1307.5327

- 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 serves a set of good examples of WIMP candidates even in more general models.
  - Bino ⇔ singlet fermion dark matter
  - Higgsino ⇔ Doublet. Heavy exotic lepton.
  - Wino ⇔ EW Triplet DM
  - Can have co-annihilation regions

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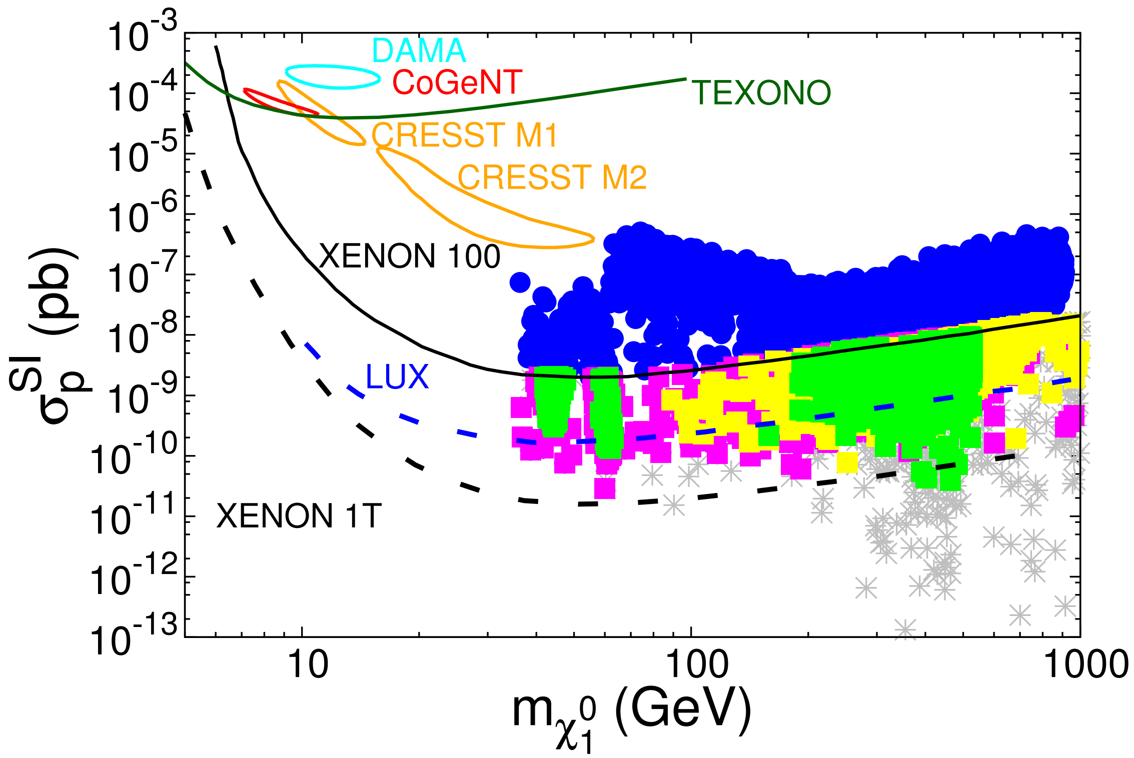
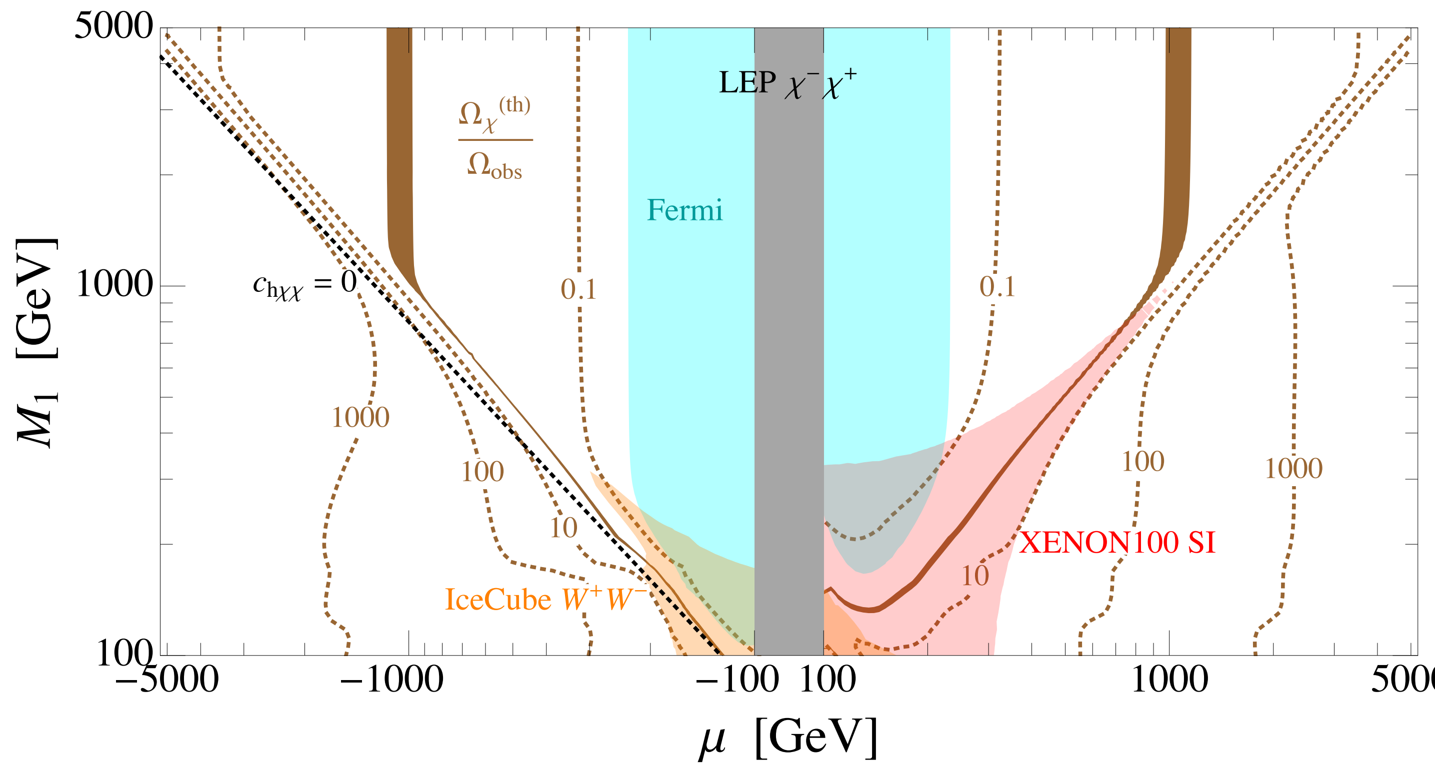
Good starting point to investigate more general WIMP candidates

Narrow parameter space (could still work).



Han, Liu, Natarajan, 1303.3040

Cheung, Hall, Pinner, Ruderman, 1211.4873



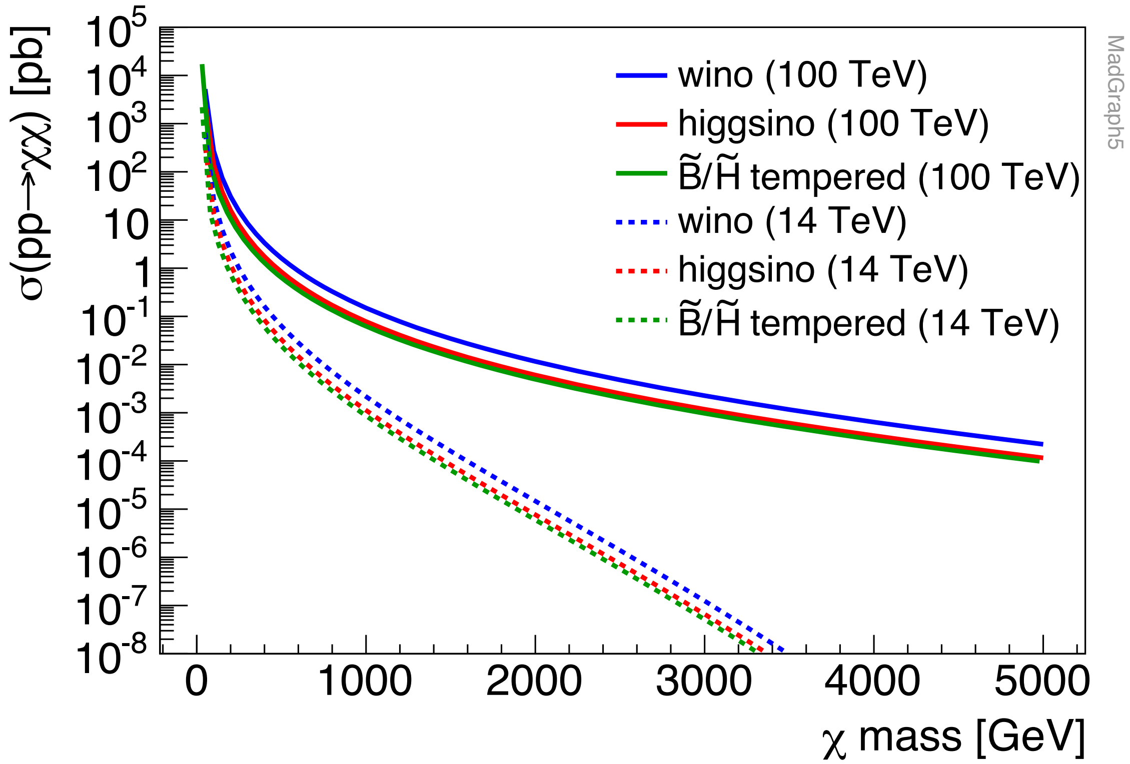
Possible scenarios (not over-closing)

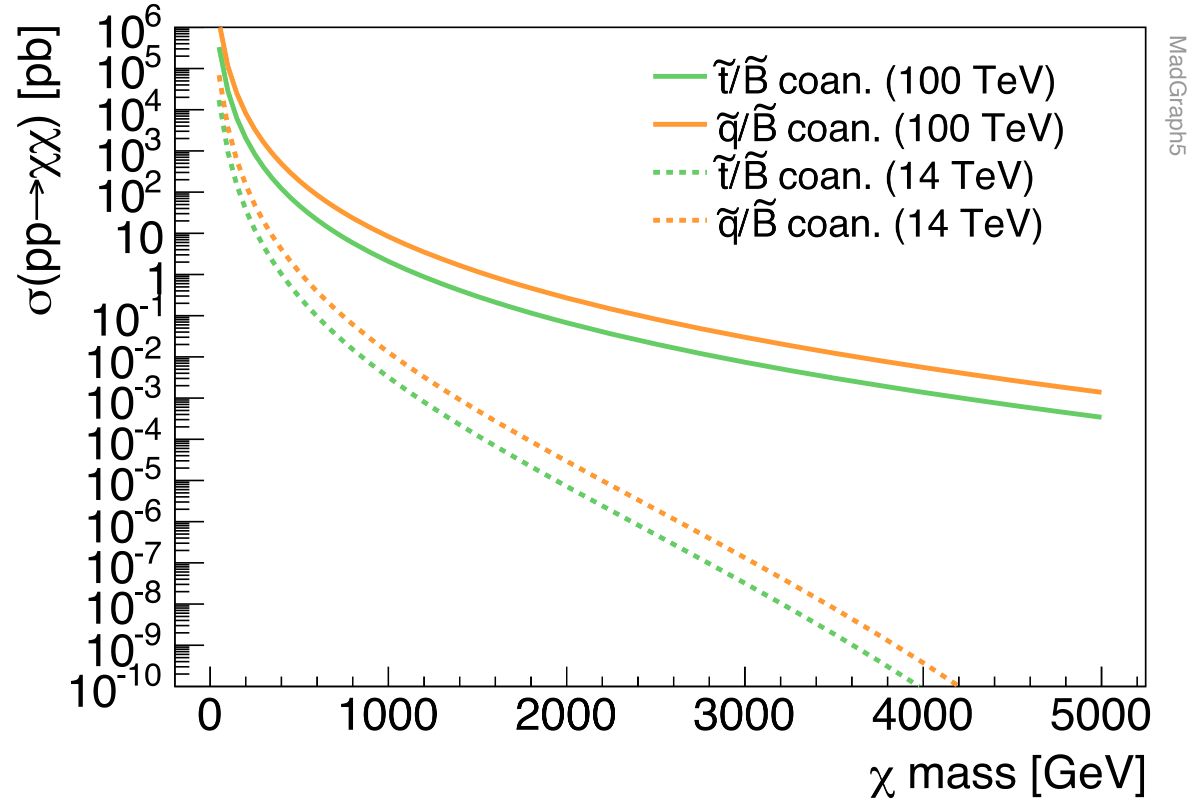
- Higgsino $\lesssim$ TeV
- Wino $\lesssim$ 3 TeV
- Well temper: $\tilde{h},\ \tilde{W}$ / $\tilde{B}$ $\quad \Delta M \sim$ several $\% \times M_{\rm DM}$

  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

14 vs 100 TeV





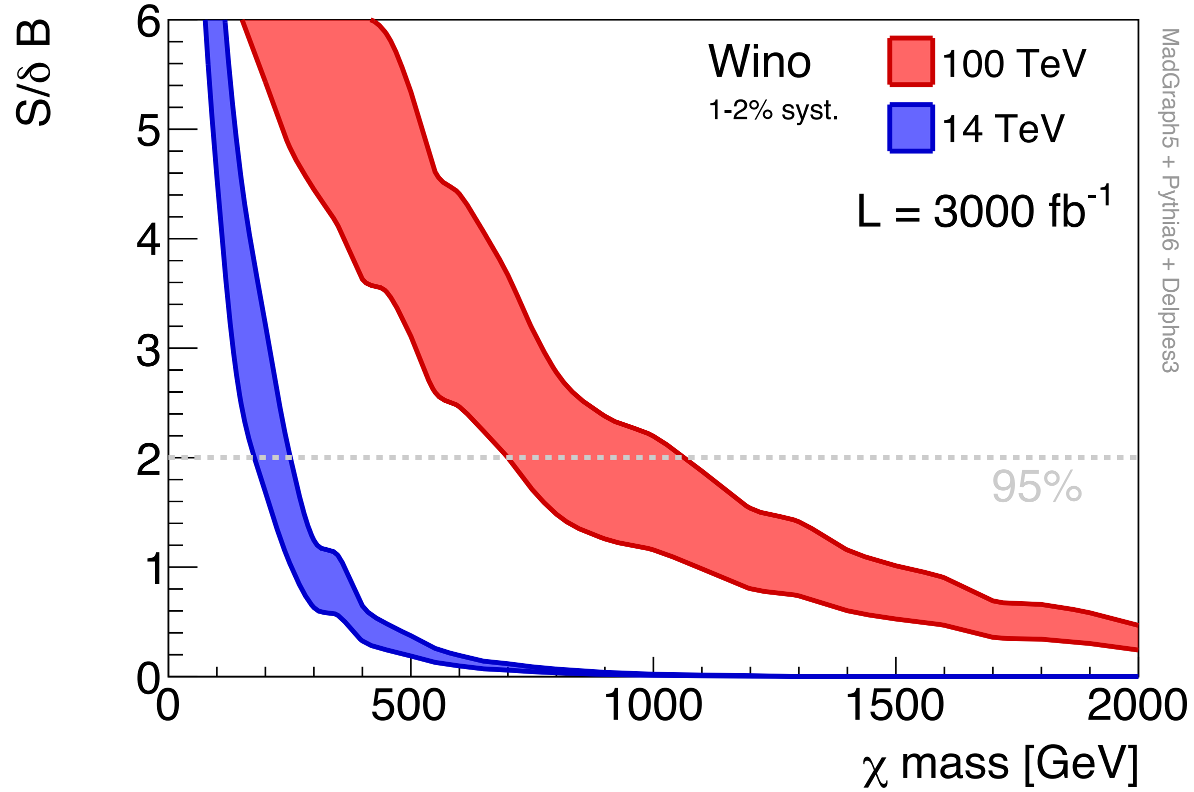
- Higher energy, higher rates

- 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 ...

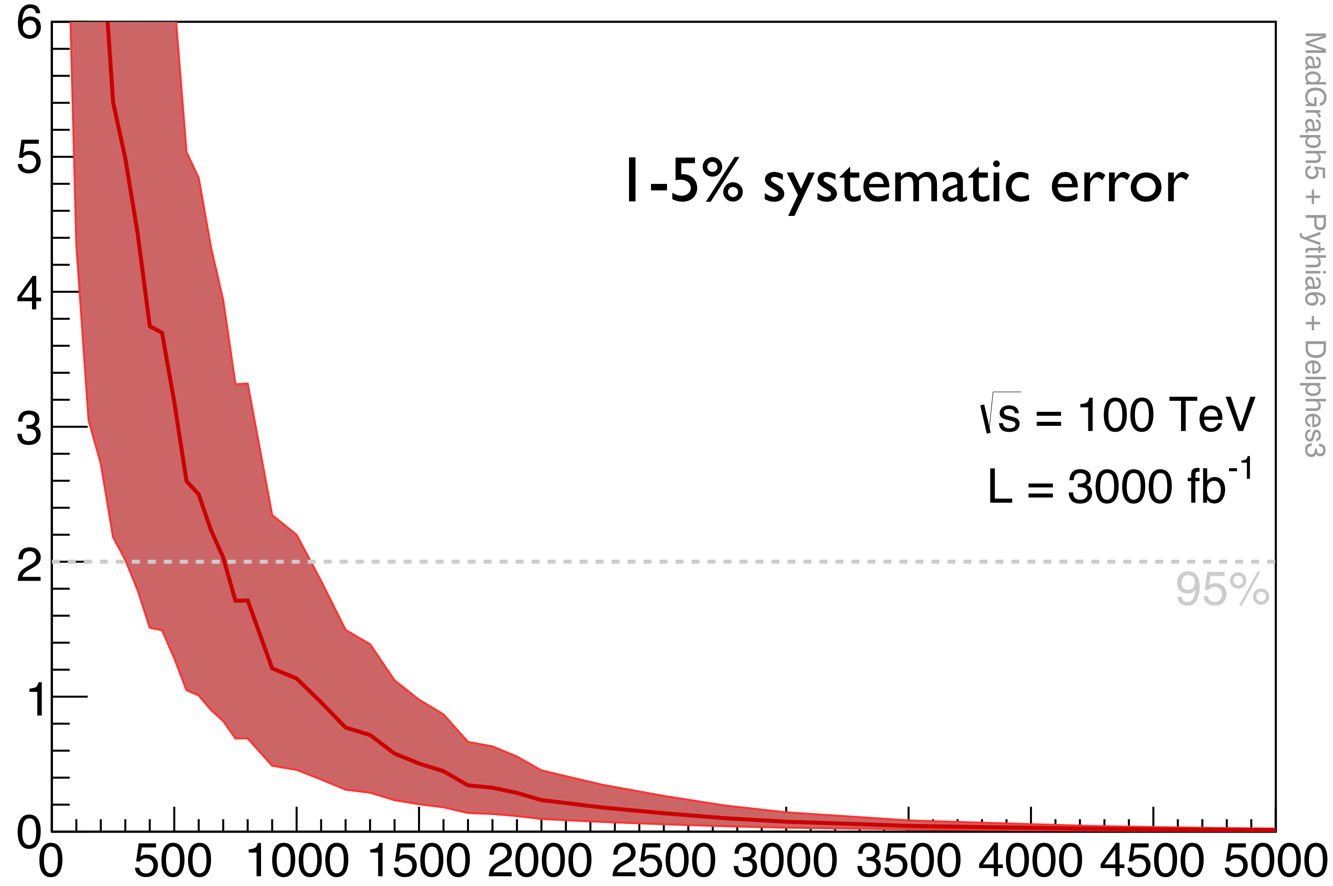
mono-γ and mono-W/Z don't add that much.

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

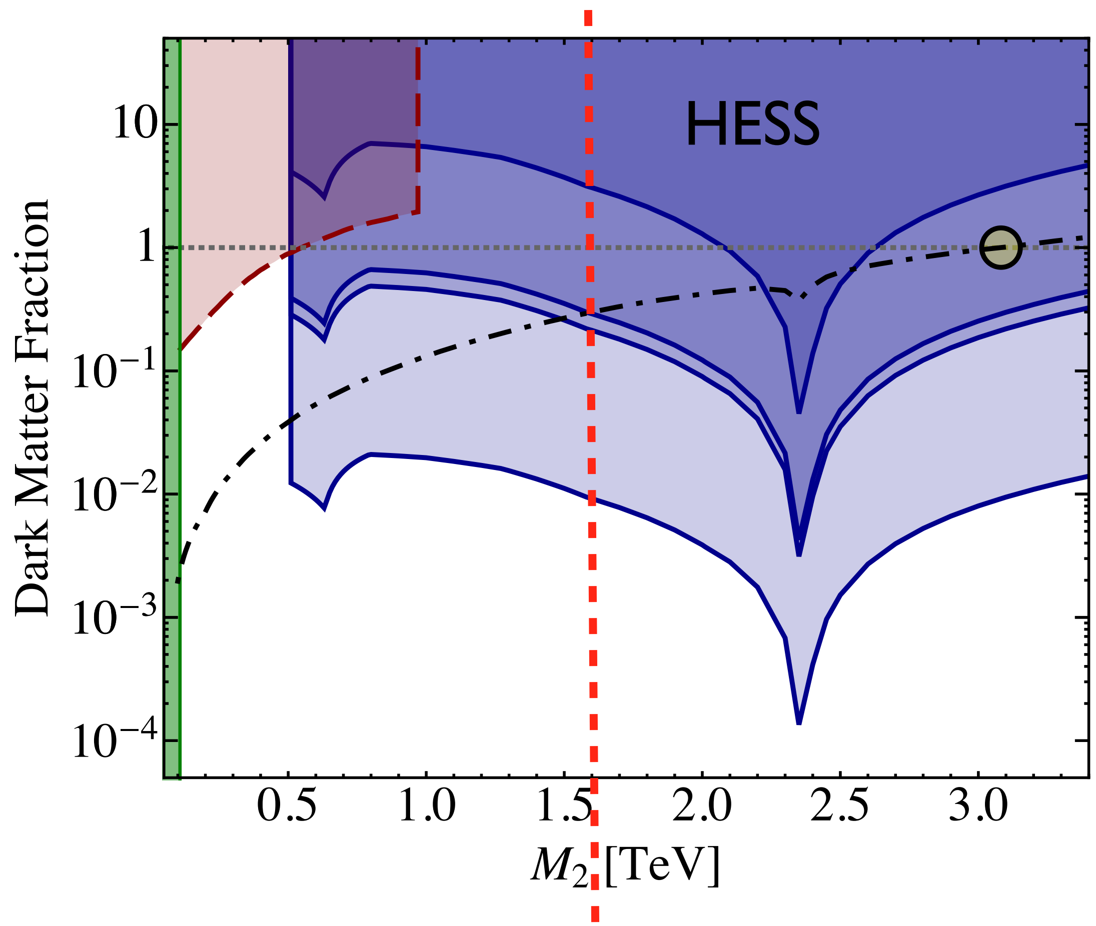


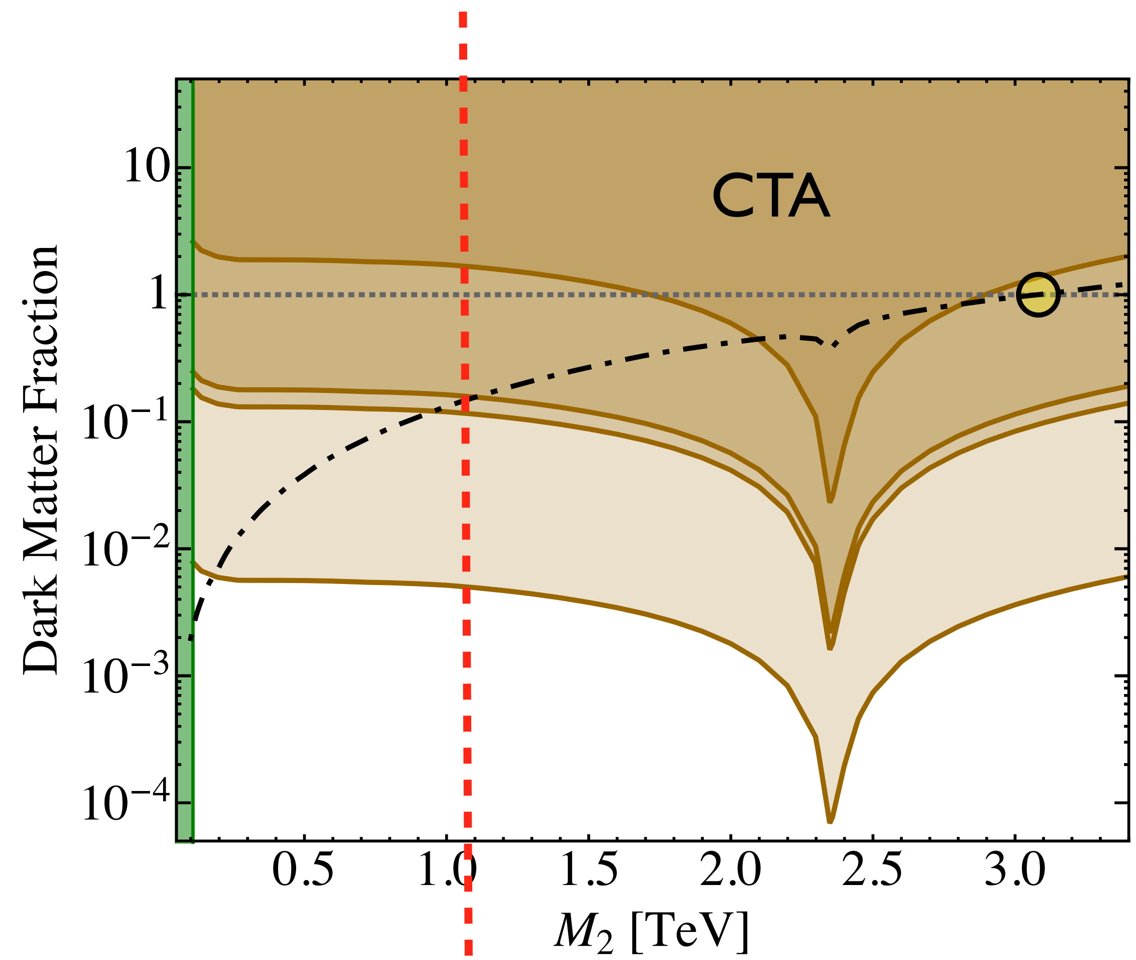
- Dominated by systematical error of background.

- simple scaling with luminosity gives .5% (even remotely realistic?)

- Useful to keep in mind in designing detectors.

Wino, interplay with indirect detection

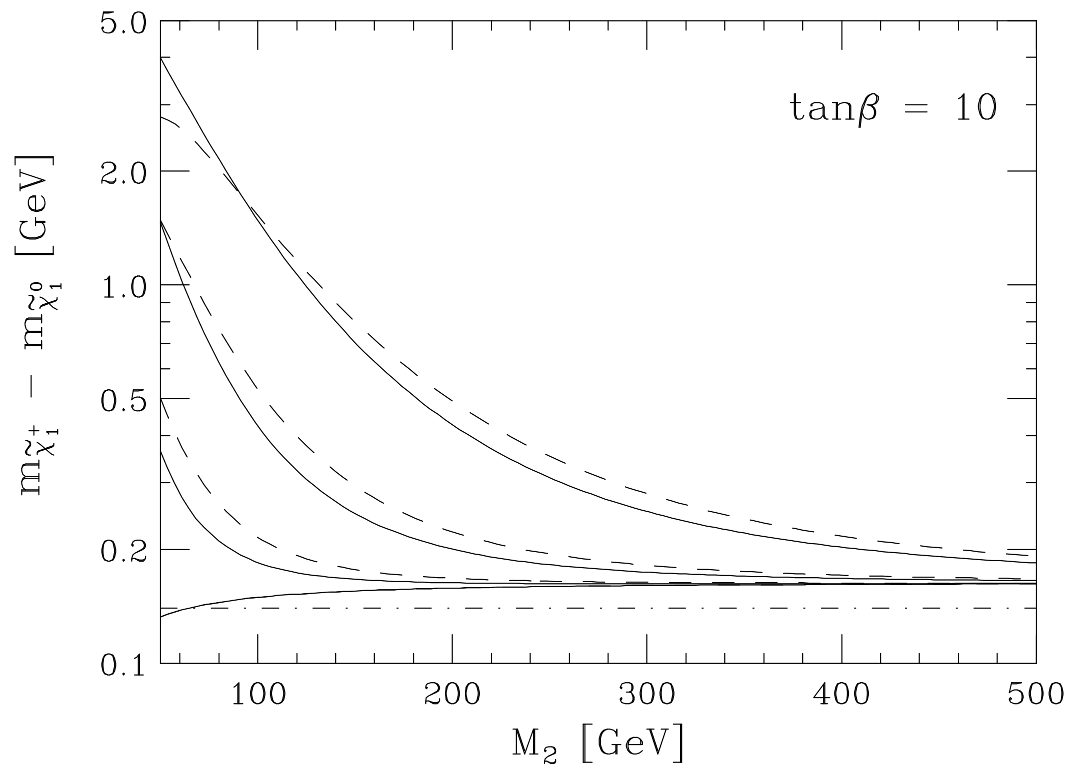




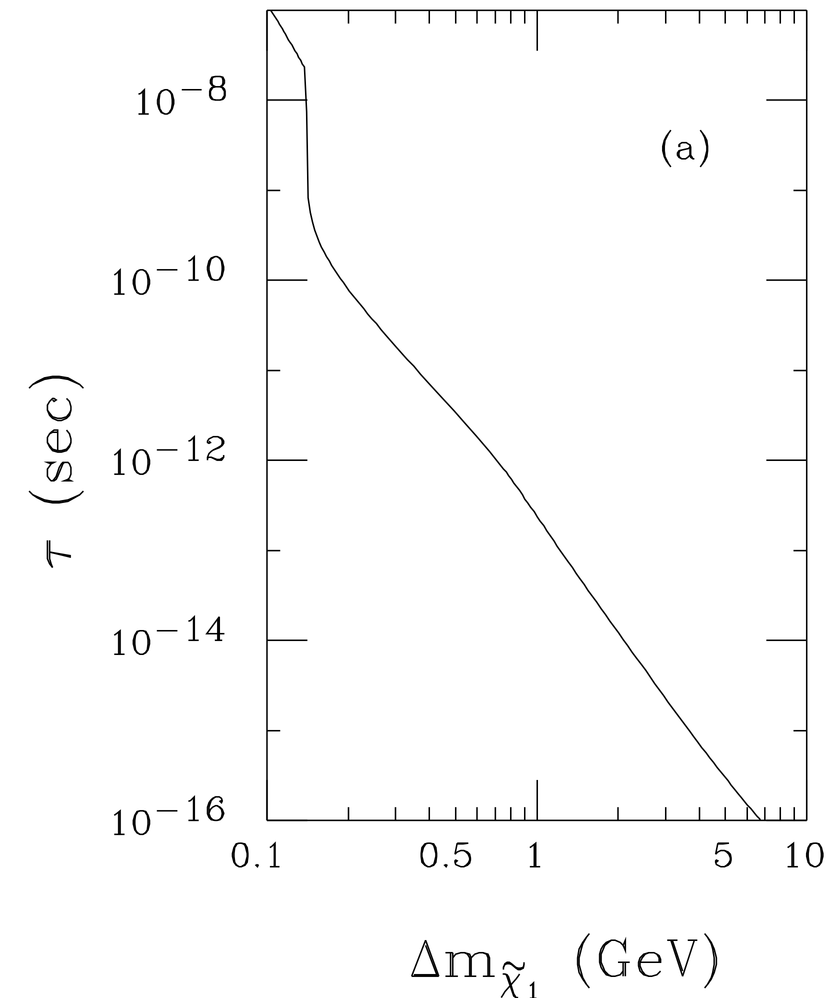
Cohen, Lisanti, Pierce, Slatyer, 1307.4082

See also Fan, Reece, 1307.4400

Wino decay



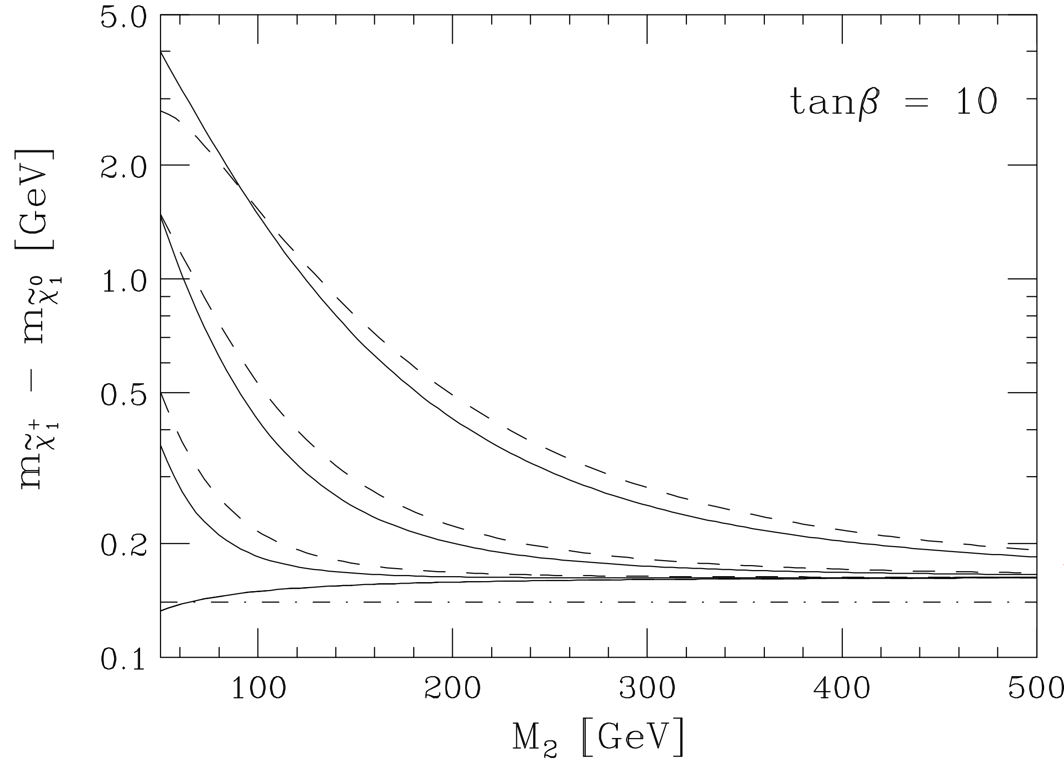
Gherghetta, Giudice and Wells, hep-ph/9904378



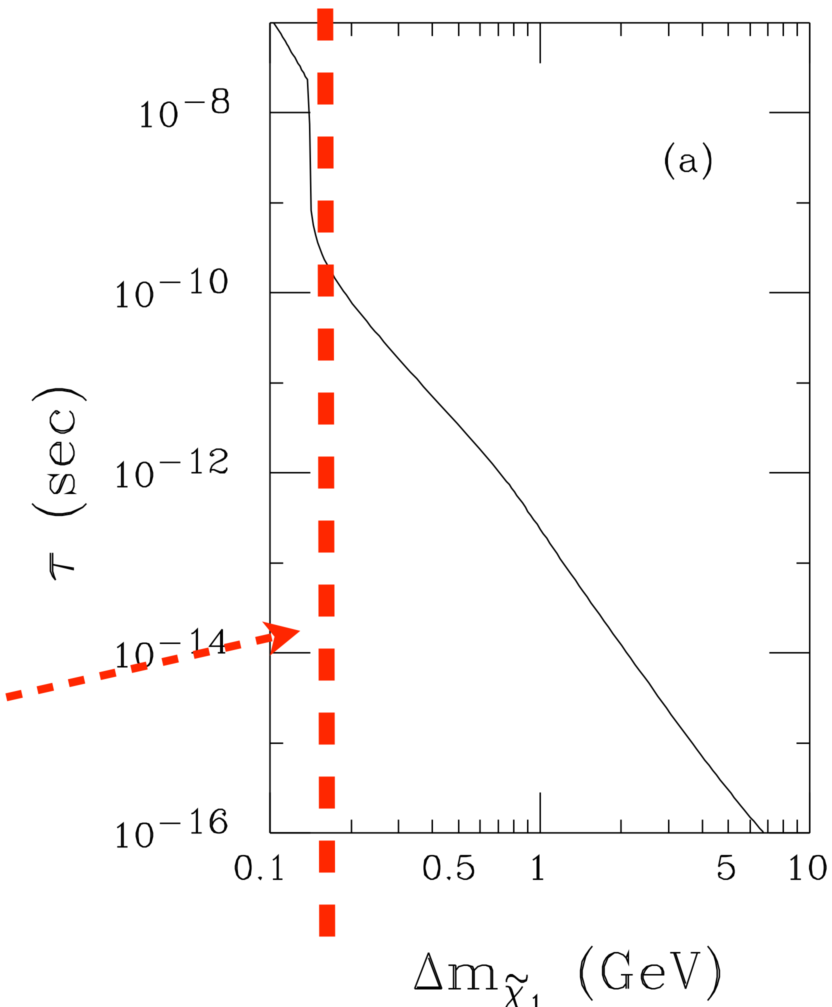
Chen, Drees and Gunion, hep-ph/9902309

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

Wino decay



Gherghetta, Giudice and Wells, hep-ph/9904378



Chen, Drees and Gunion, hep-ph/9902309

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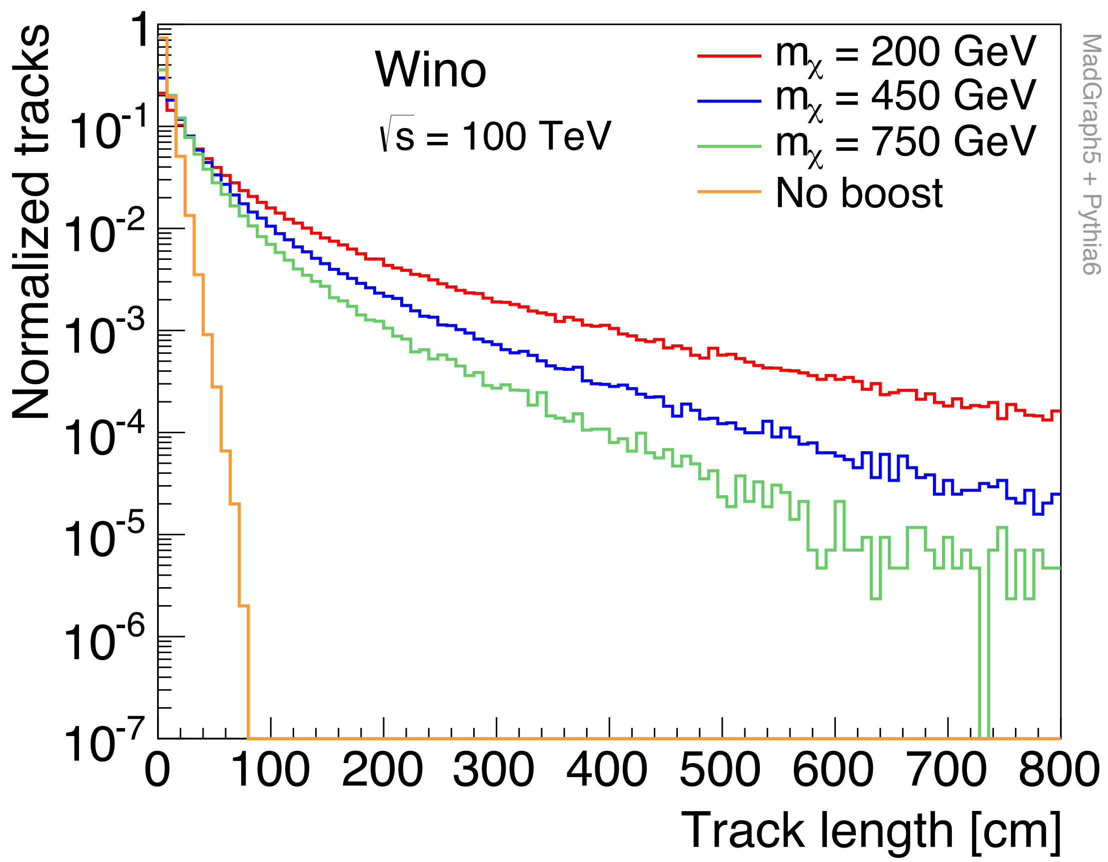
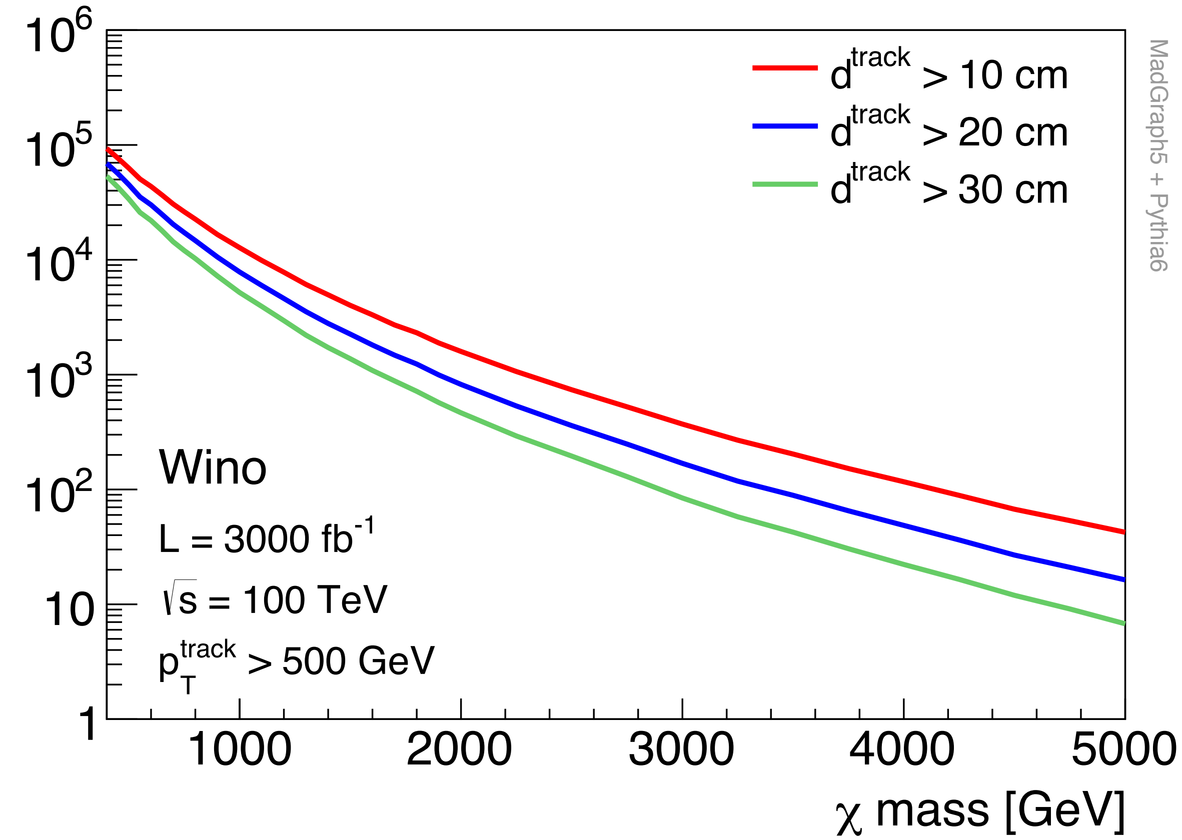
Rates (with long tracks)





- Disappearing track, stub, kink...
- Long lived
- 100 TeV have a better chance: production, boost...

Disappearing track + background

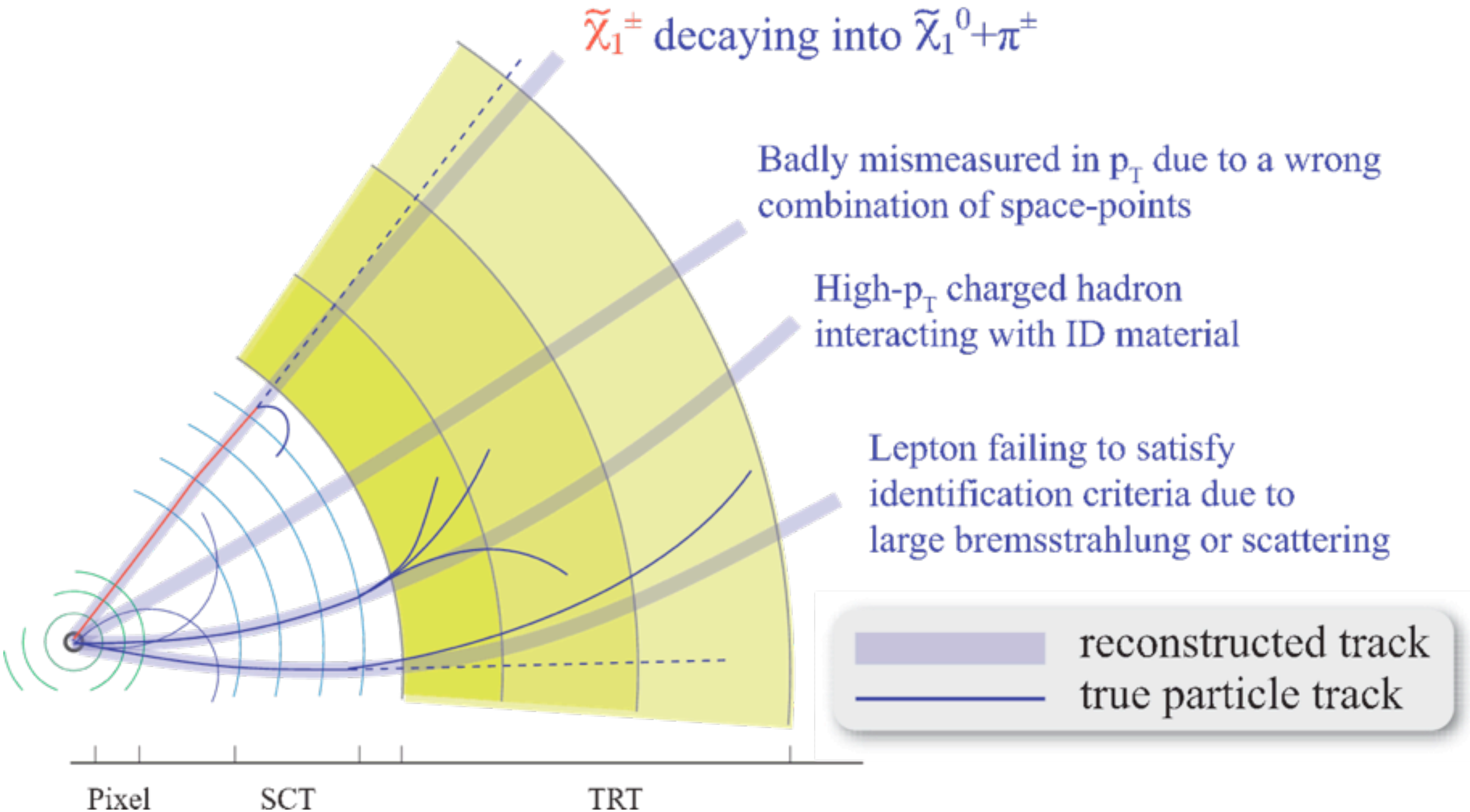
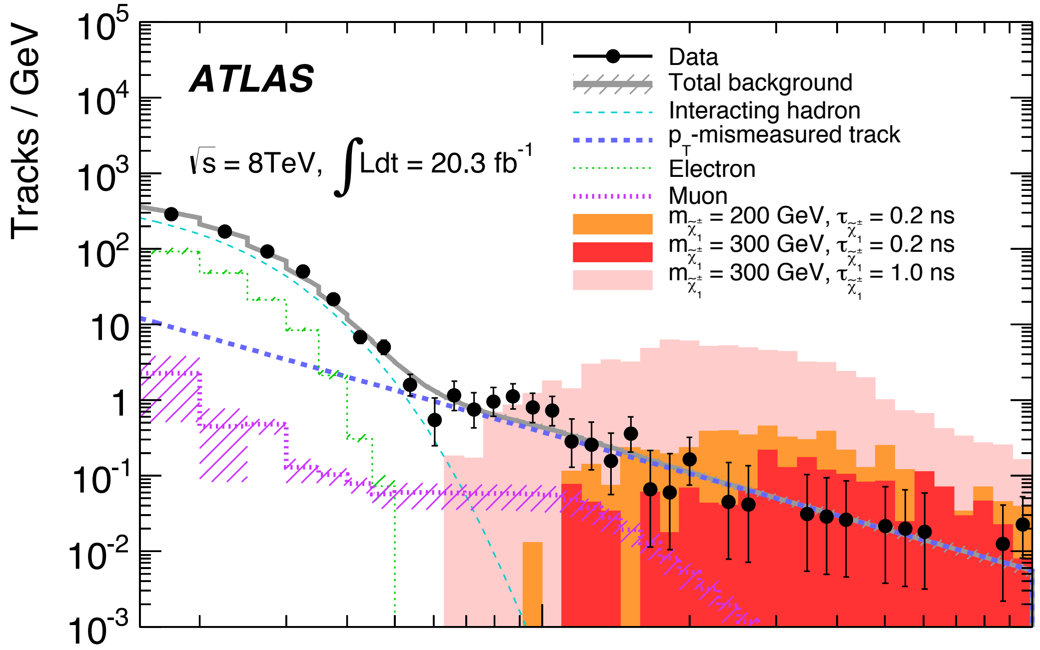
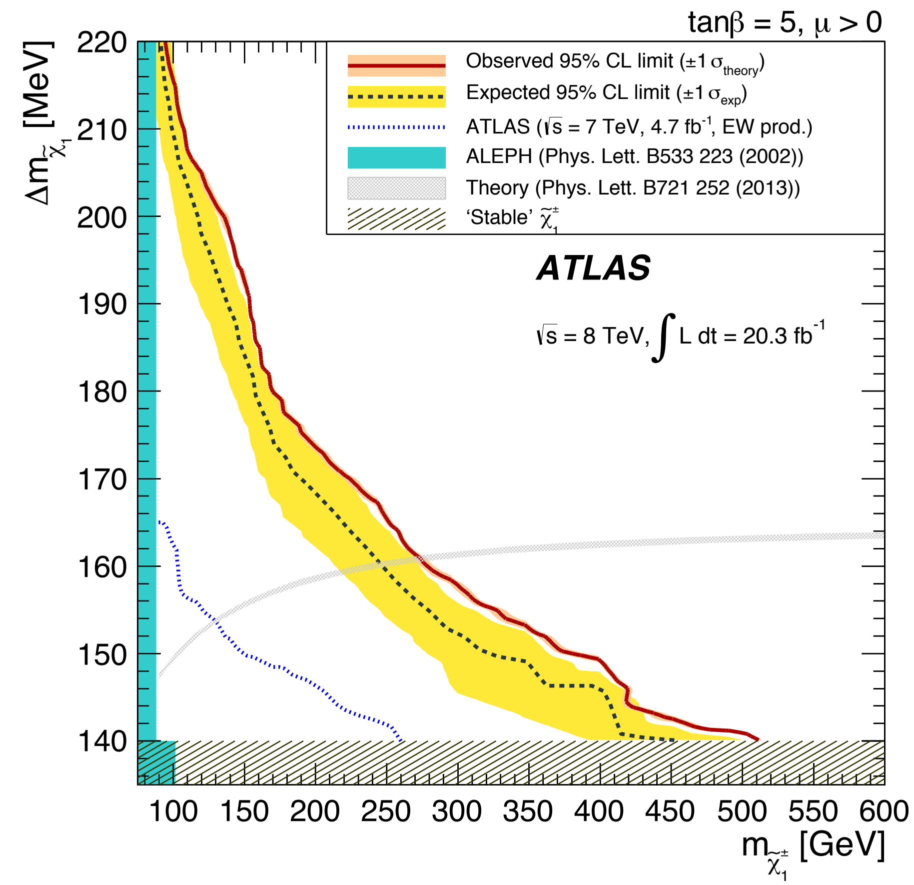


Figure from ATLAS disappearing track search twiki

ATLAS search

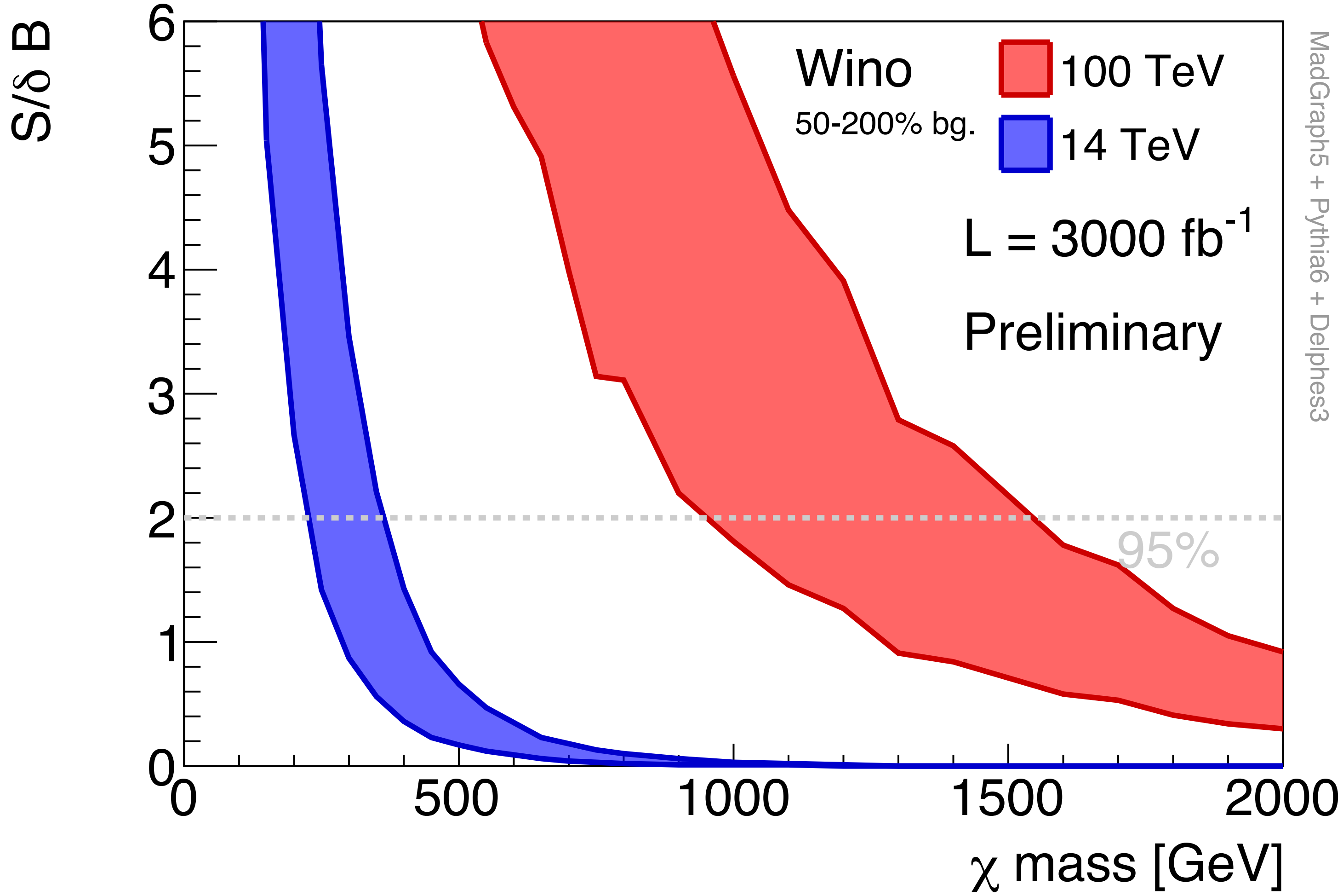
ATLAS, 1310.3675





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

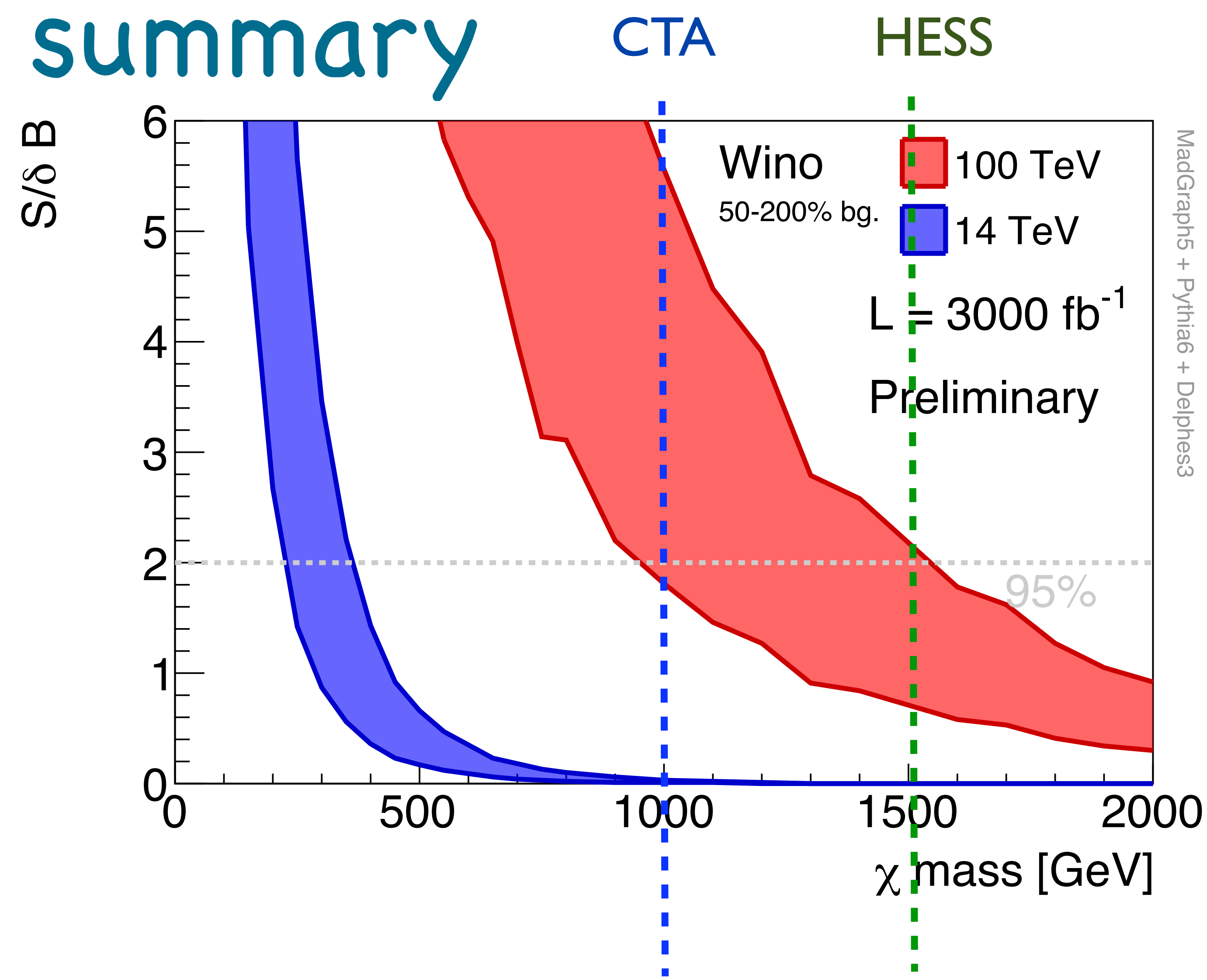
(Rough) Extrapolation from ATLAS search



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

- Band: varying background estimate by 2 either way.

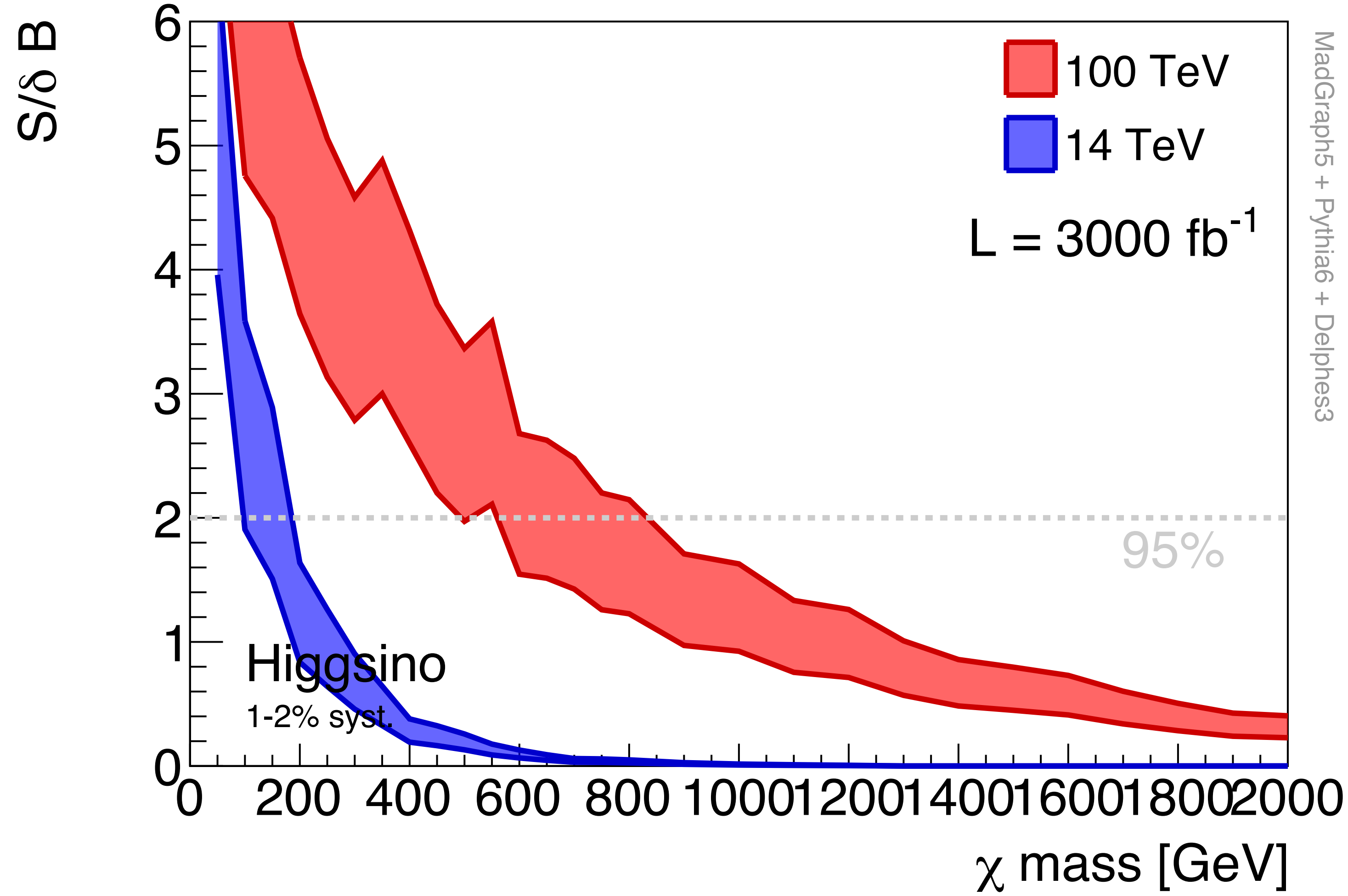
Wino summary



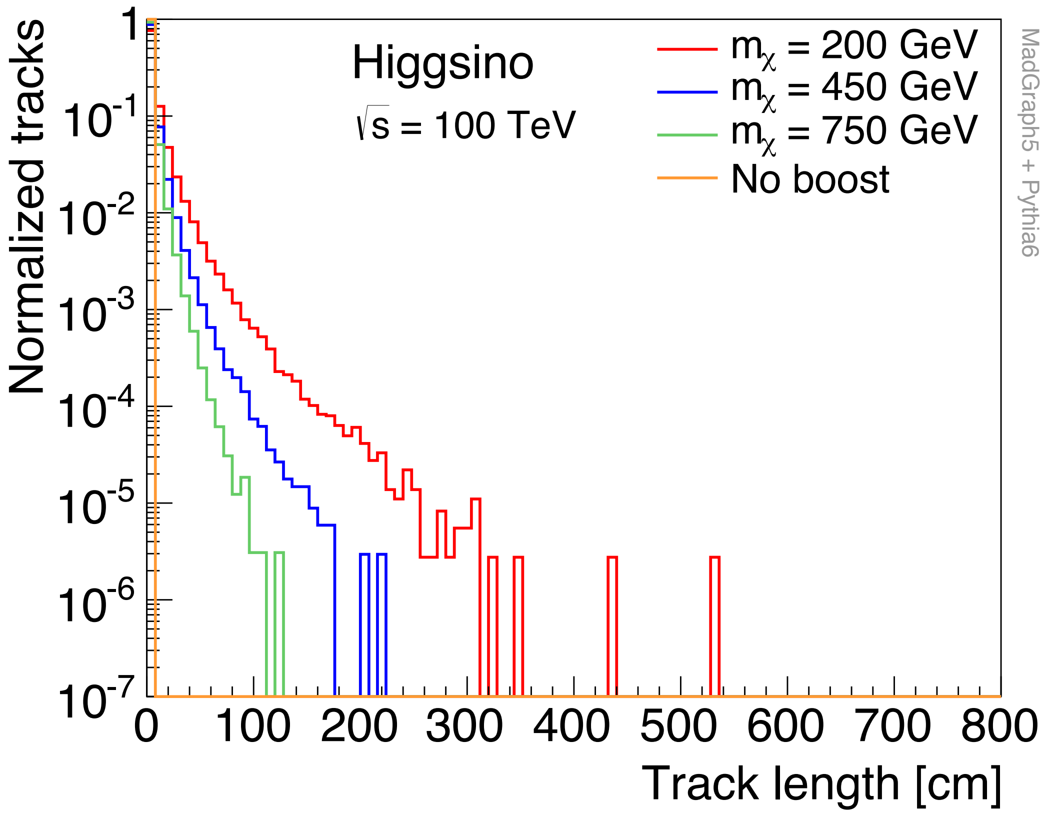
– In combination with indirect detection, there is hope to "completely cover" the wino parameter space.

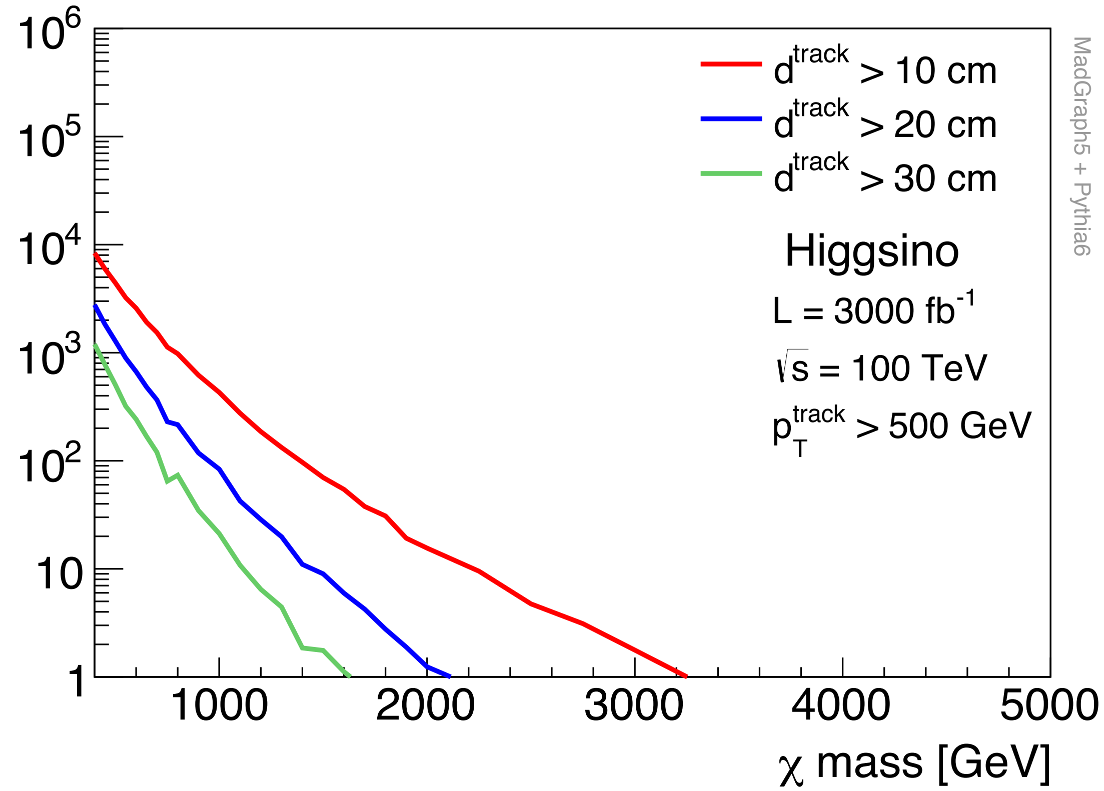
Higgsino

Mono-jet


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

Tracks?

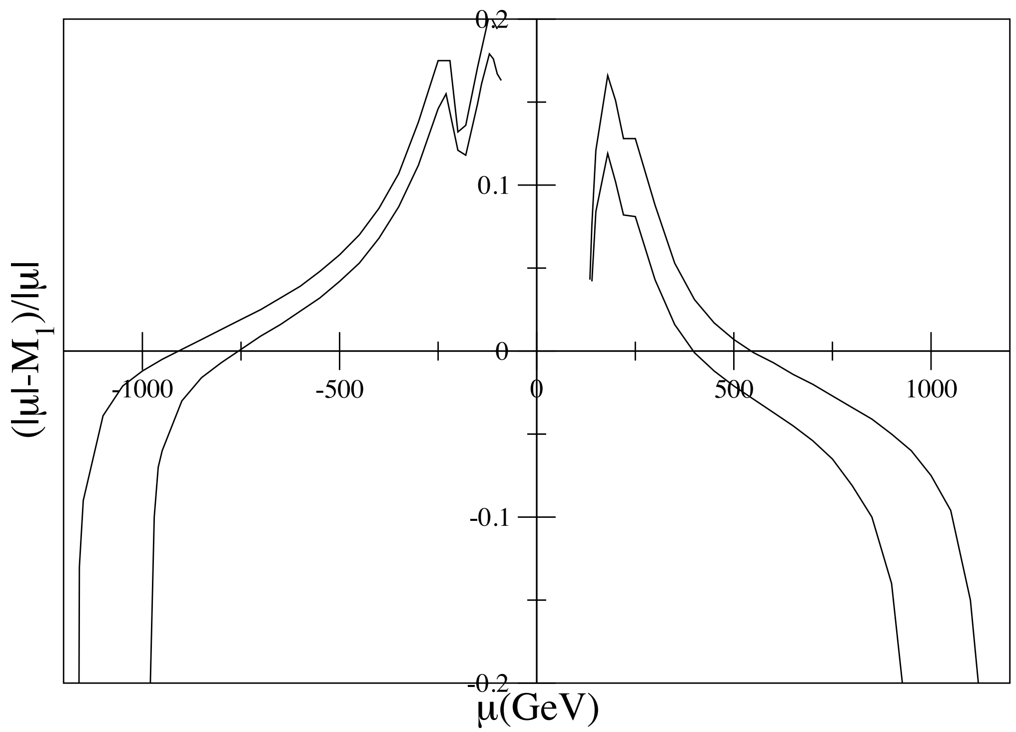


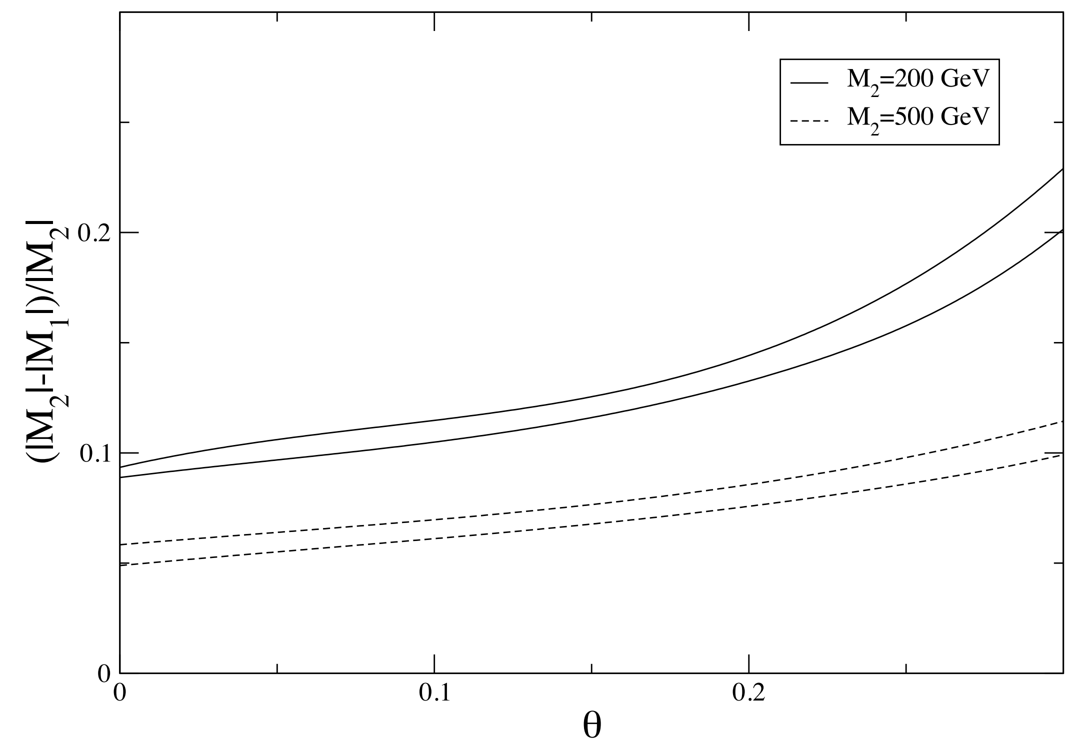


- Depends on how the design
  - How long the track needs to be?
  - Background discrimination?

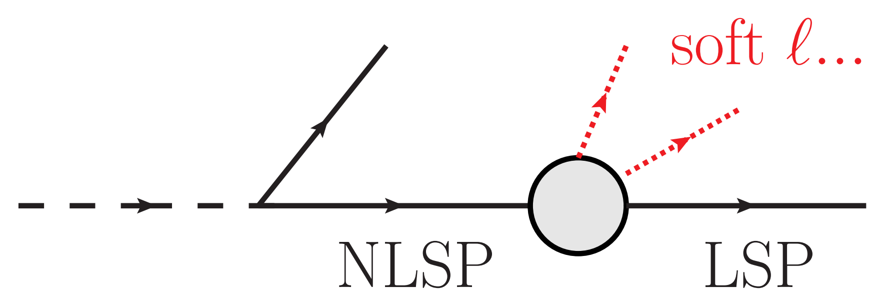
Well-tempered

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



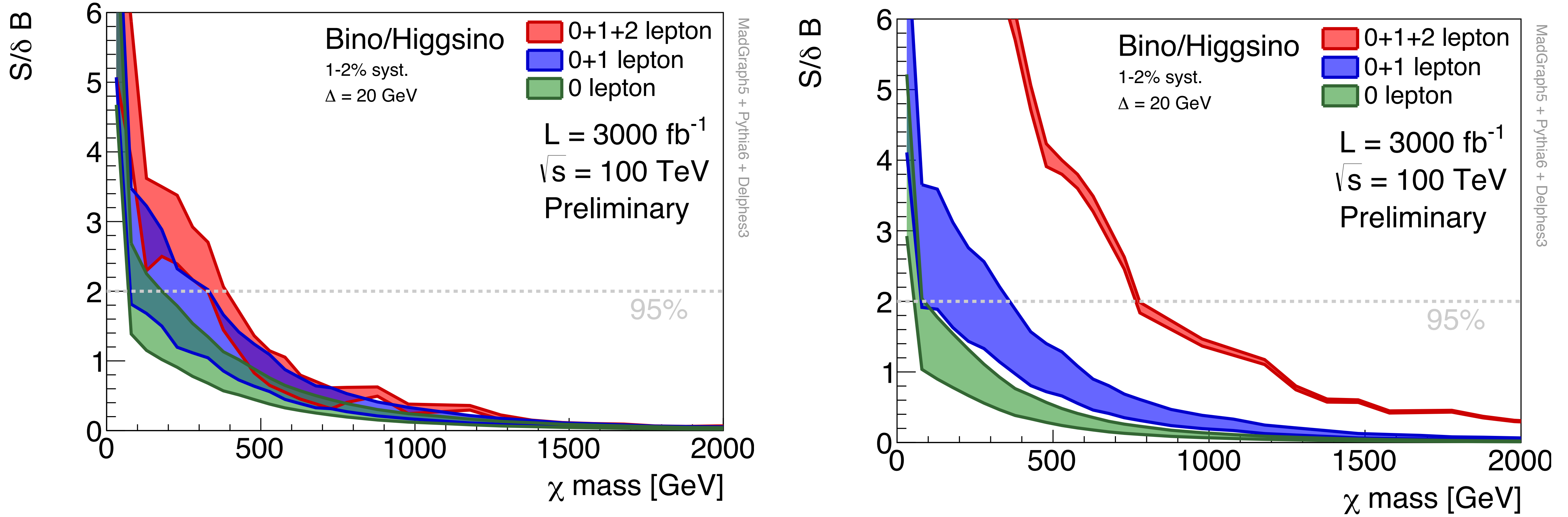


- Adding soft lepton



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

Well-tempered, mono-jet + soft lepton



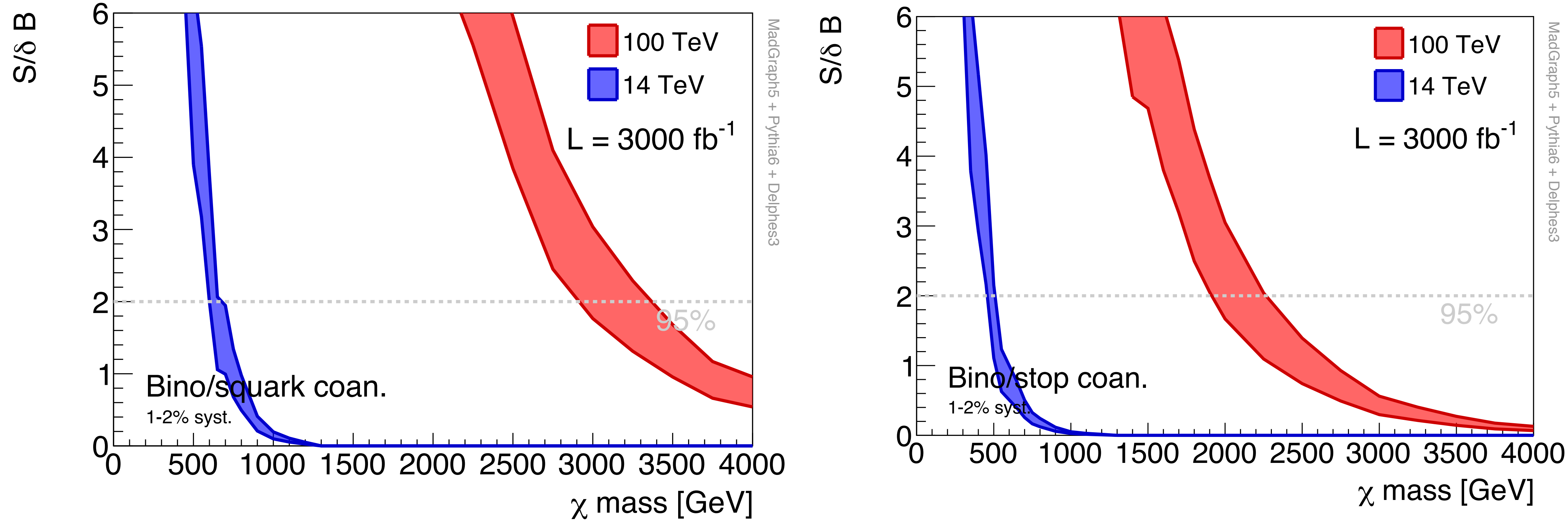
20 GeV < pT lepton < 40 GeV

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.
  - 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.
  - Heavy flavor, VBF ...

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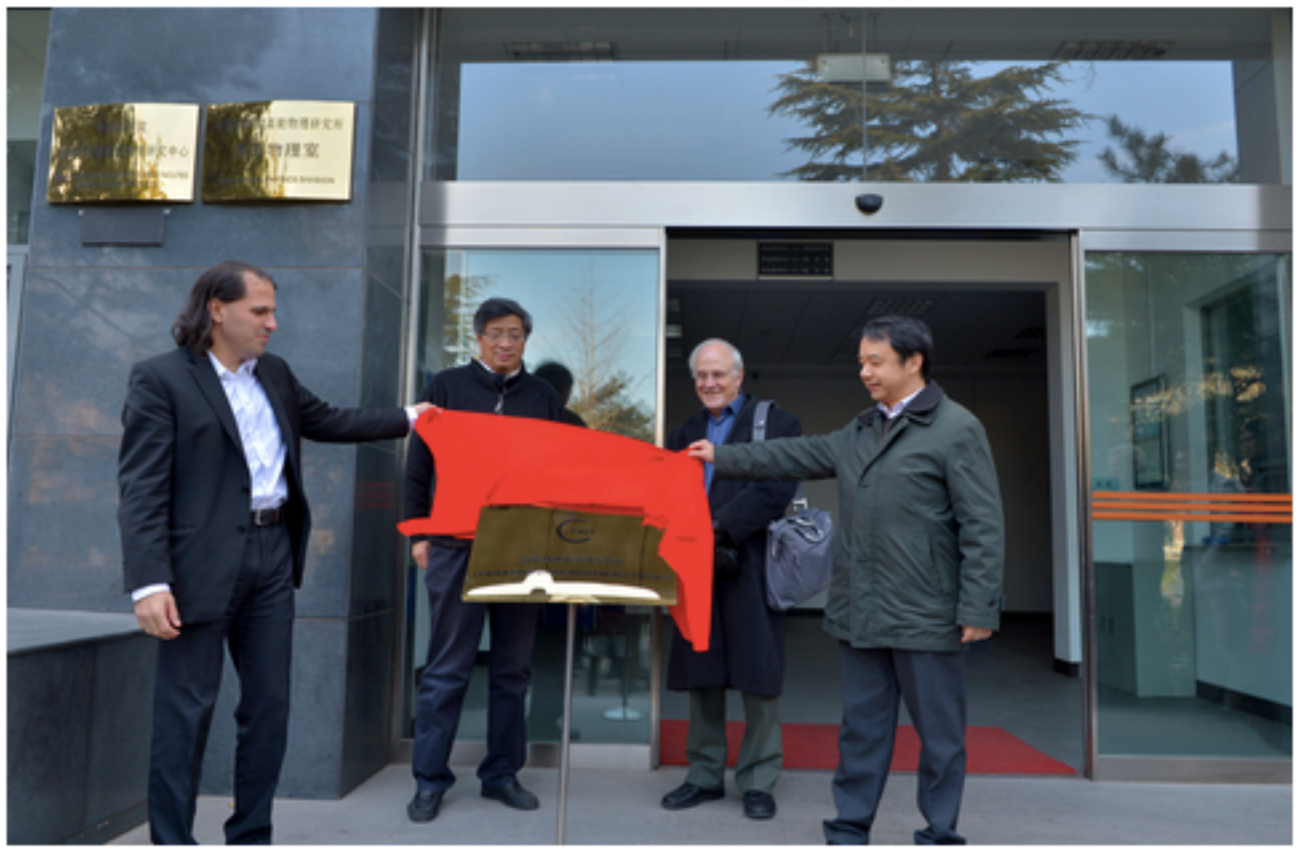


http://cfhep.ihep.ac.cn/
http://beijingcenterfuturecollider.wikispaces.com/

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	$\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 250$ GeV
$\lvert\eta(1)\rvert < 2.4$	$p_T(\mu) > 10$ GeV and	$\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 300$ GeV
$p_T(2) > 30$ GeV	$p_T(\tau) > 20$ GeV and	$\lvert\eta(\tau)\rvert < 2.3$	$\not{E}_T > 350$ GeV
$\lvert\eta(2)\rvert < 4.5$			$\not{E}_T > 400$ 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	$\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 300$ GeV
$\lvert\eta(1)\rvert < 2.4$	$p_T(\mu) > 20$ GeV and	$\lvert\eta(\mu)\rvert < 2.1$	$\not{E}_T > 350$ GeV
$p_T(2) > 60$ GeV	$p_T(\tau) > 20$ GeV and	$\lvert\eta(\tau)\rvert < 2.3$	$\not{E}_T > 400$ GeV
$\lvert\eta(2)\rvert < 4.5$			$\not{E}_T > 450$ 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

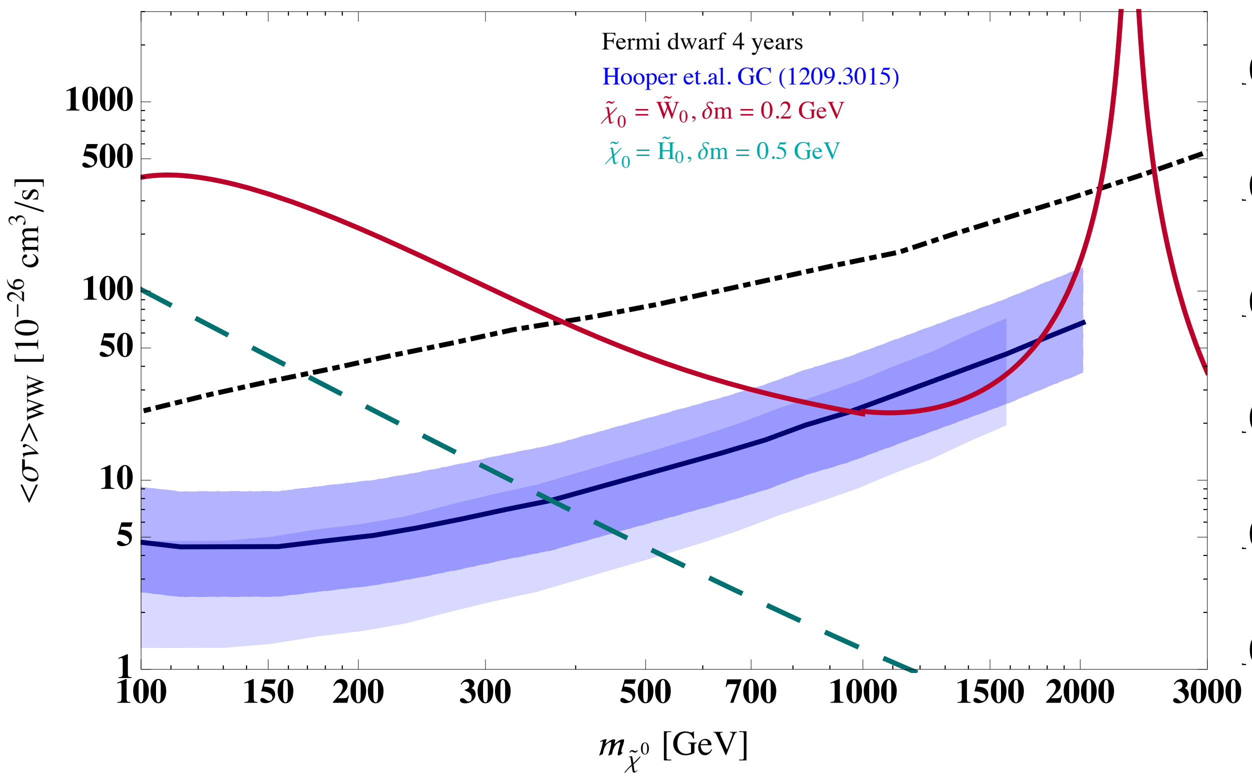
Cuts, soft lepton

$\sqrt{s} = 100$ TeV

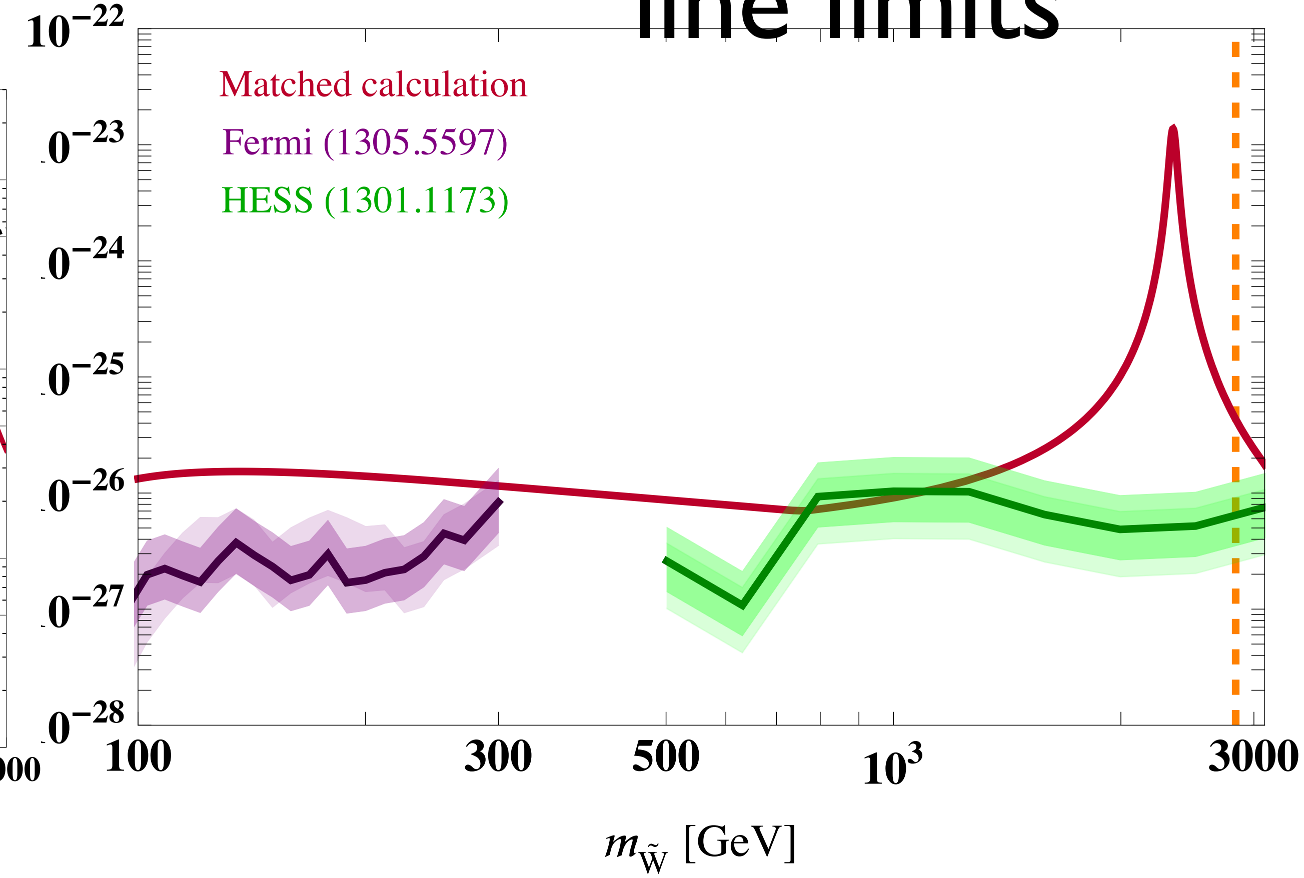
Jet cuts	Lepton bins	$\not{E}_T$ cuts
$p_T(1) > 1200$ GeV	0-bin: $p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 1000$ GeV
$\lvert\eta(1)\rvert < 2.4$	$1,2$-bin: $40 > p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not{E}_T > 2000$ GeV
$p_T(2) > 200$ GeV	0-bin: $p_T(\mu) > 20$ GeV 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
$n_{\text{jet}} \le 2$	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

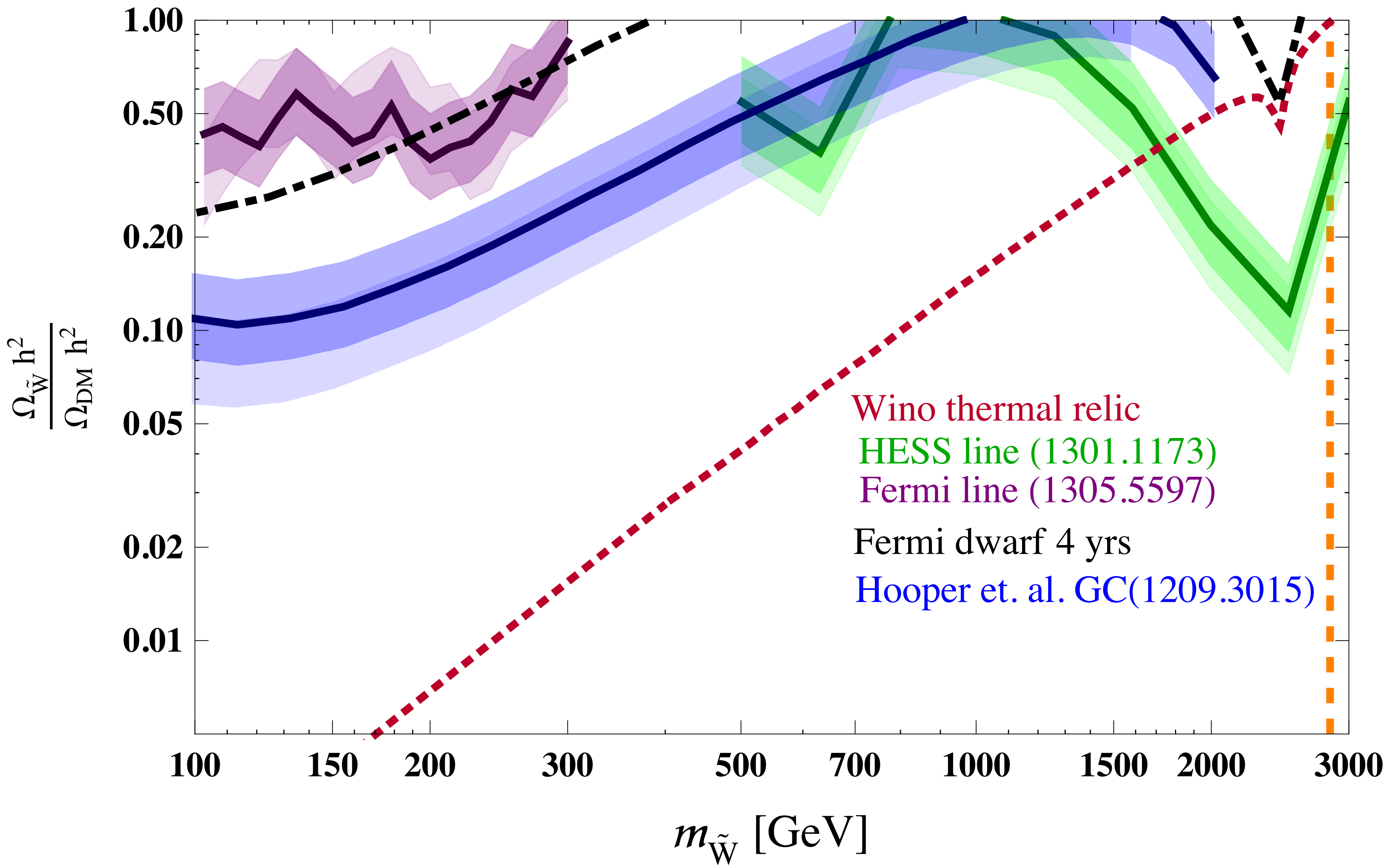
continuum limits



line limits



Wino, interplay with indirect det.



Fan, Reece, 1307.4400

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