WIMP dark matter at 100 TeV

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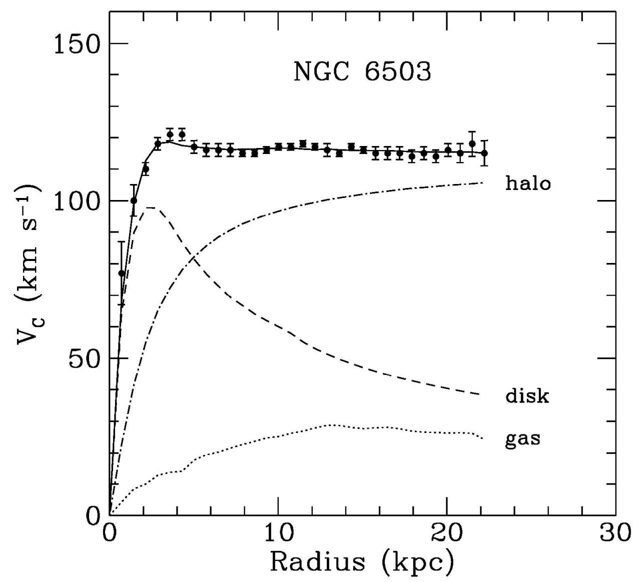
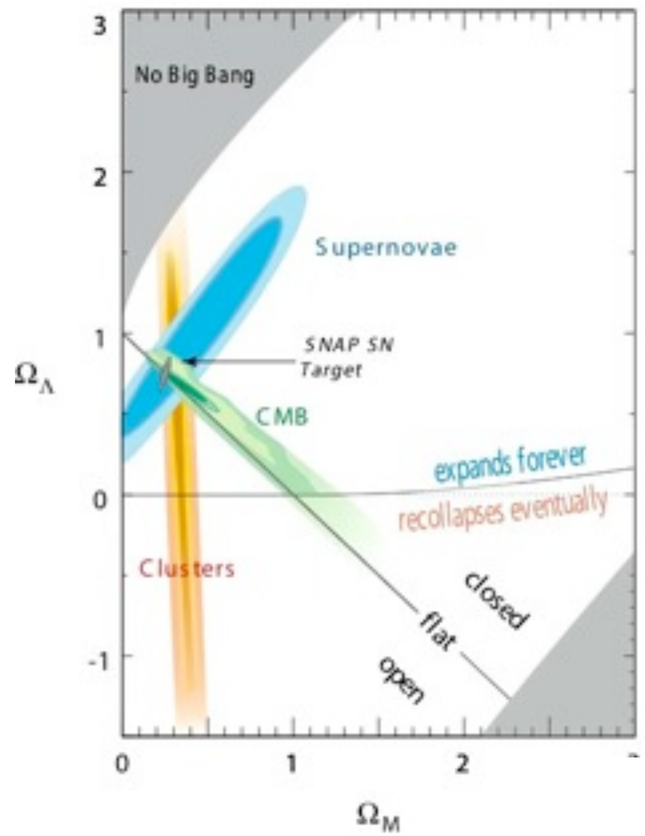
University of Chicago

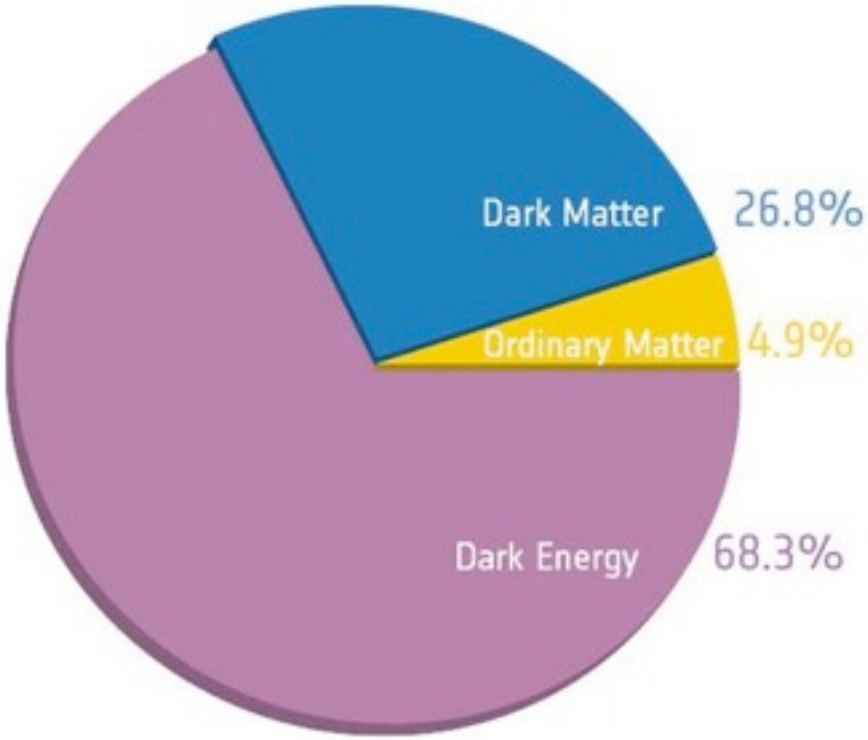
March 24, 2014

We have solid evidence for dark matter:





Only NP beyond SM discovered so far!



Dark matter candidate?

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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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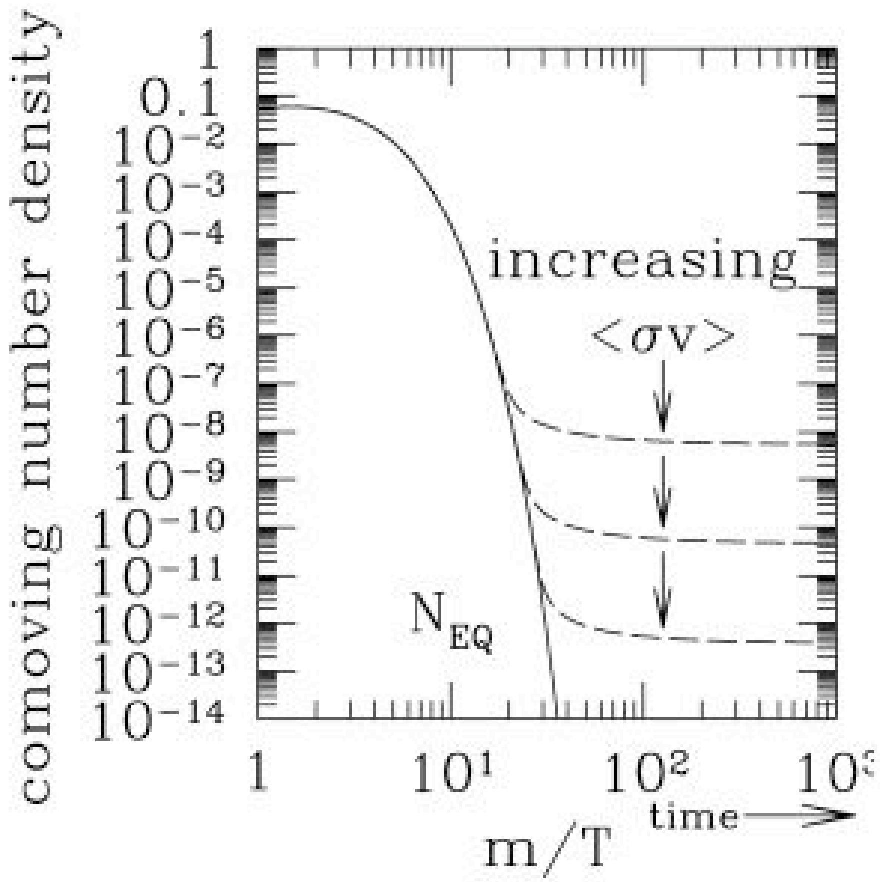
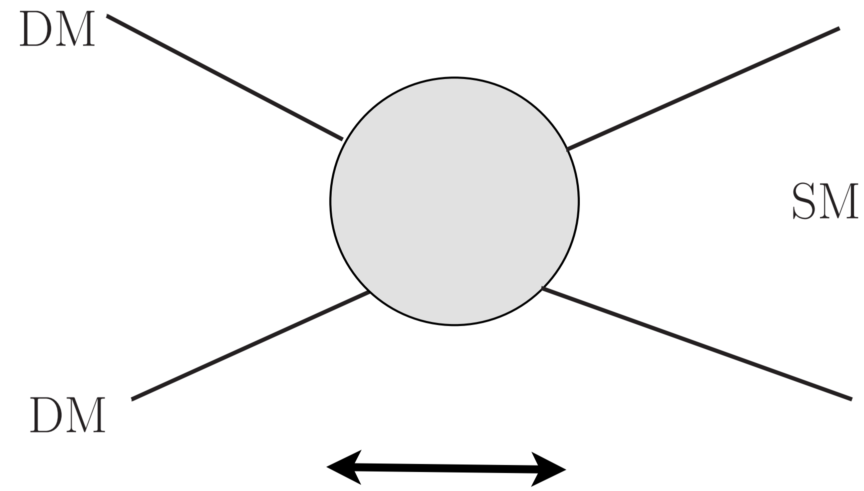
WIMP

WIMP miracle



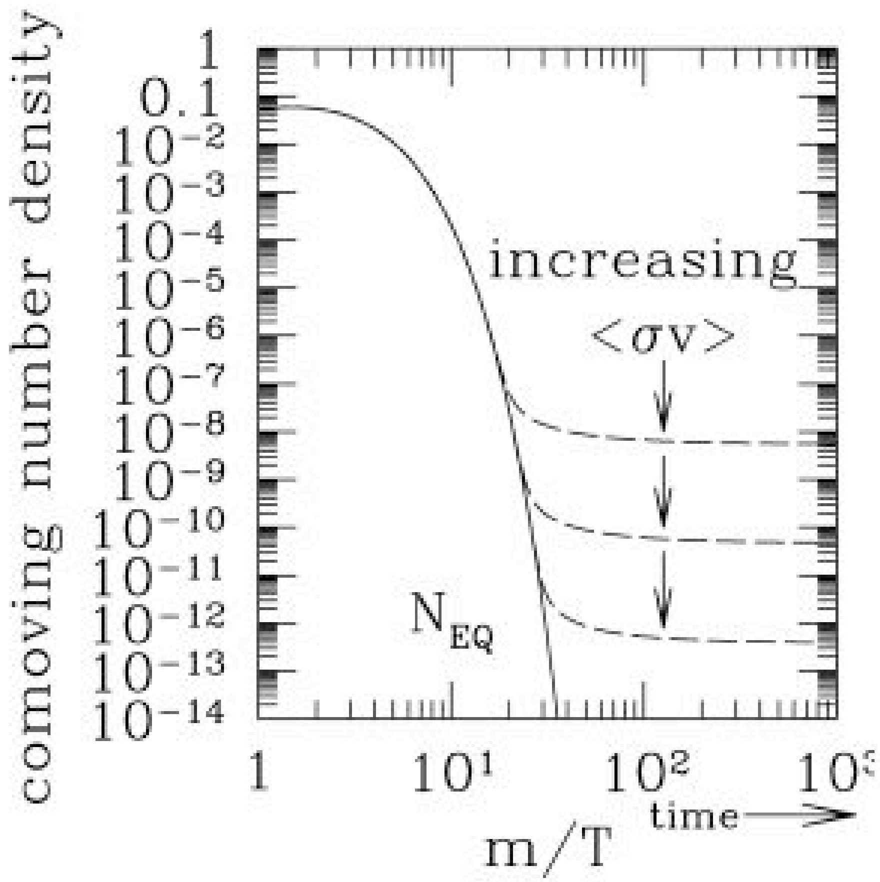


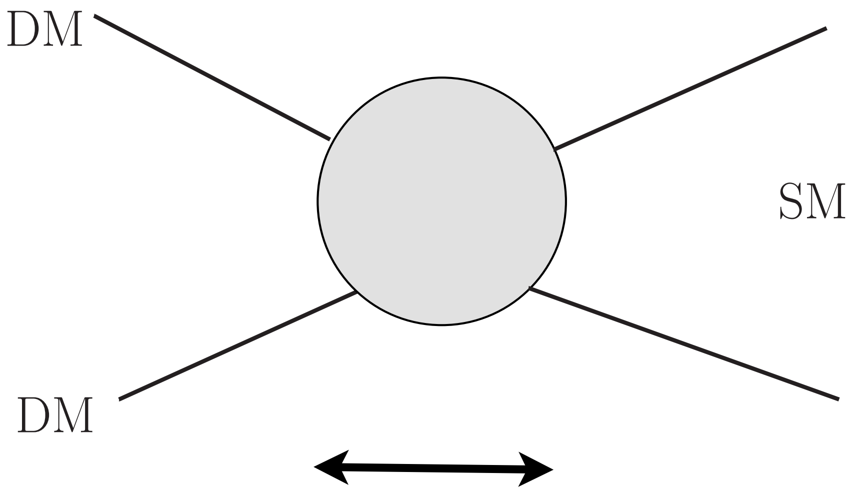
$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- 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





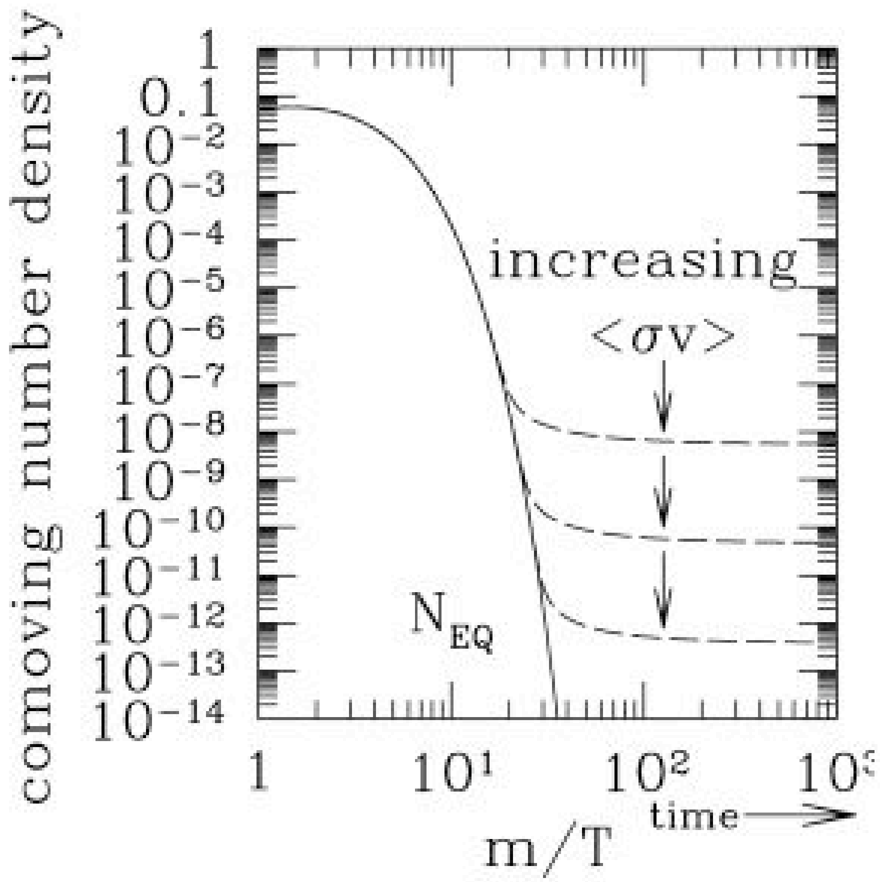
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

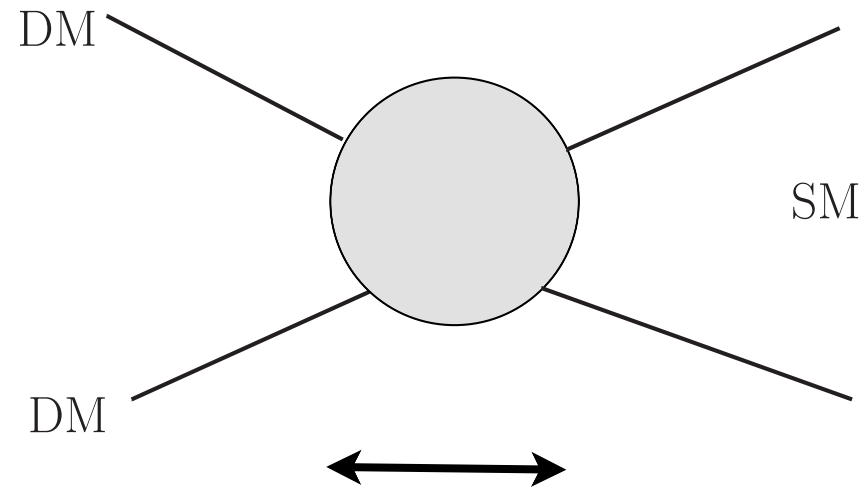
- More precisely, to get the correct relic abundance

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

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

WIMP miracle





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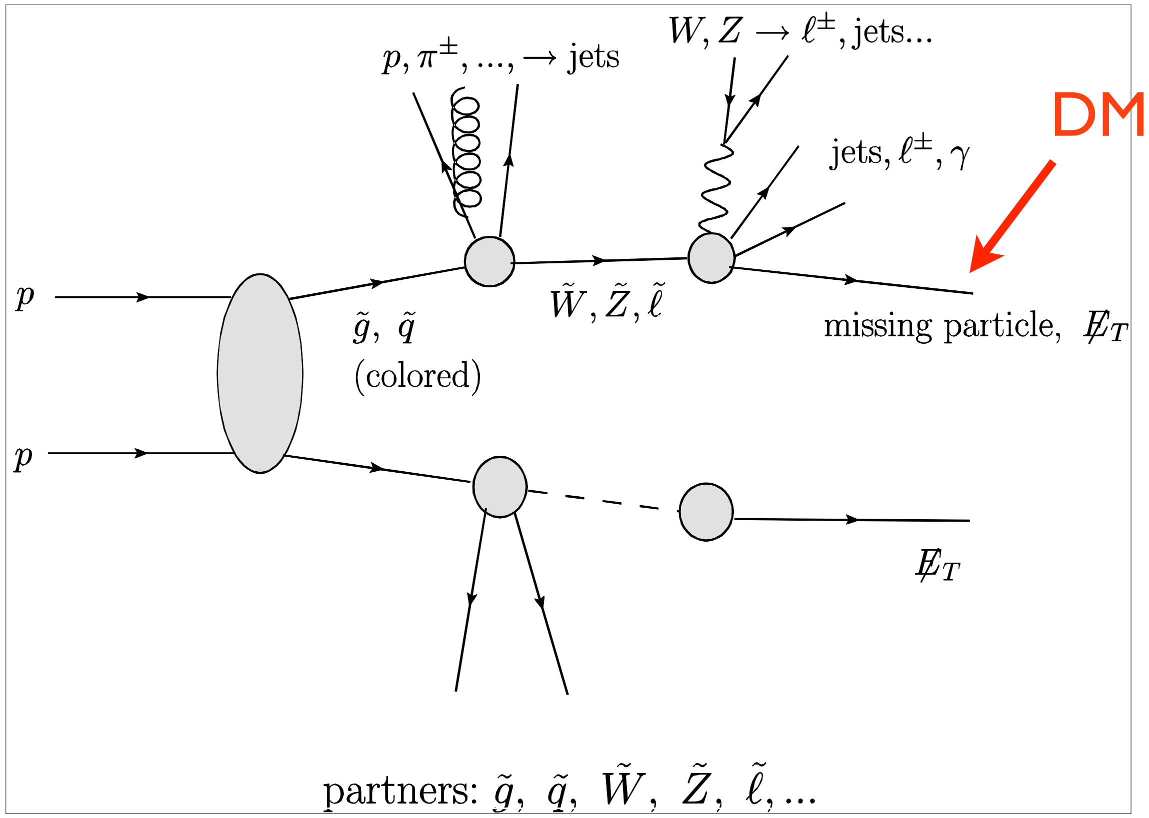
Will use 100 TeV for comparison here.

“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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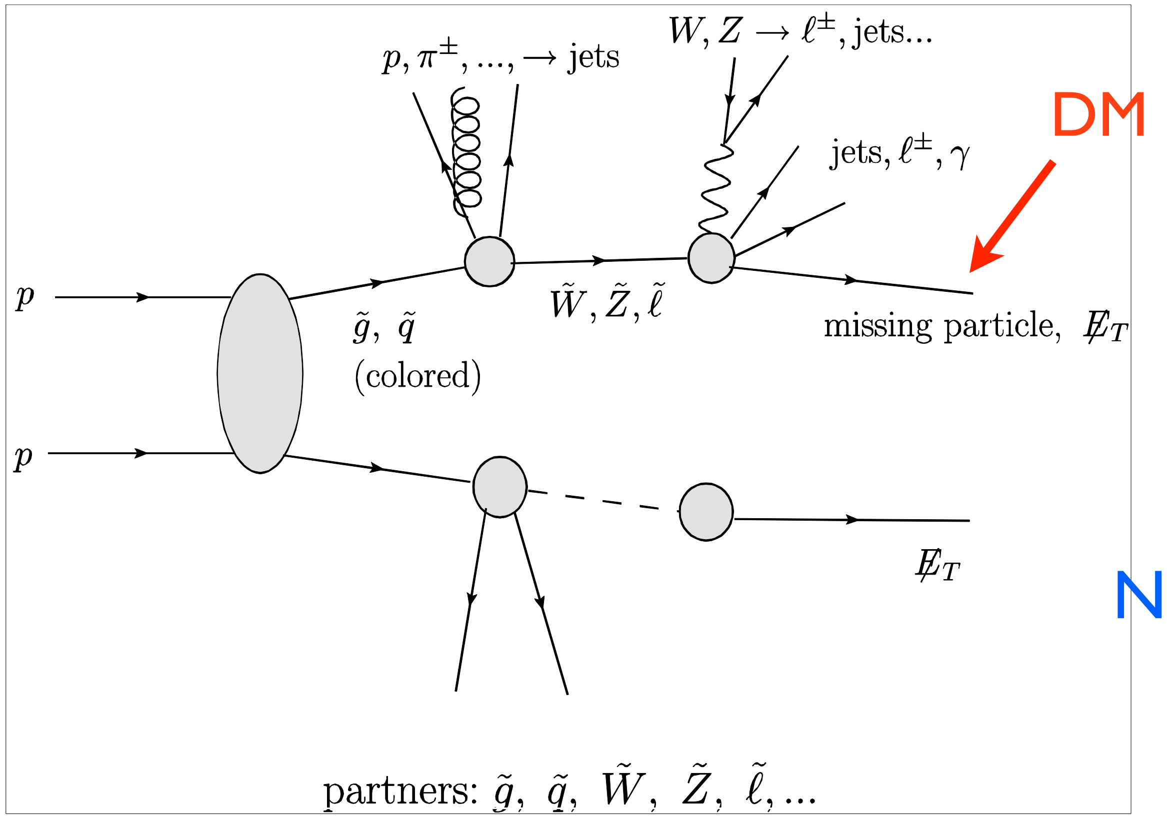
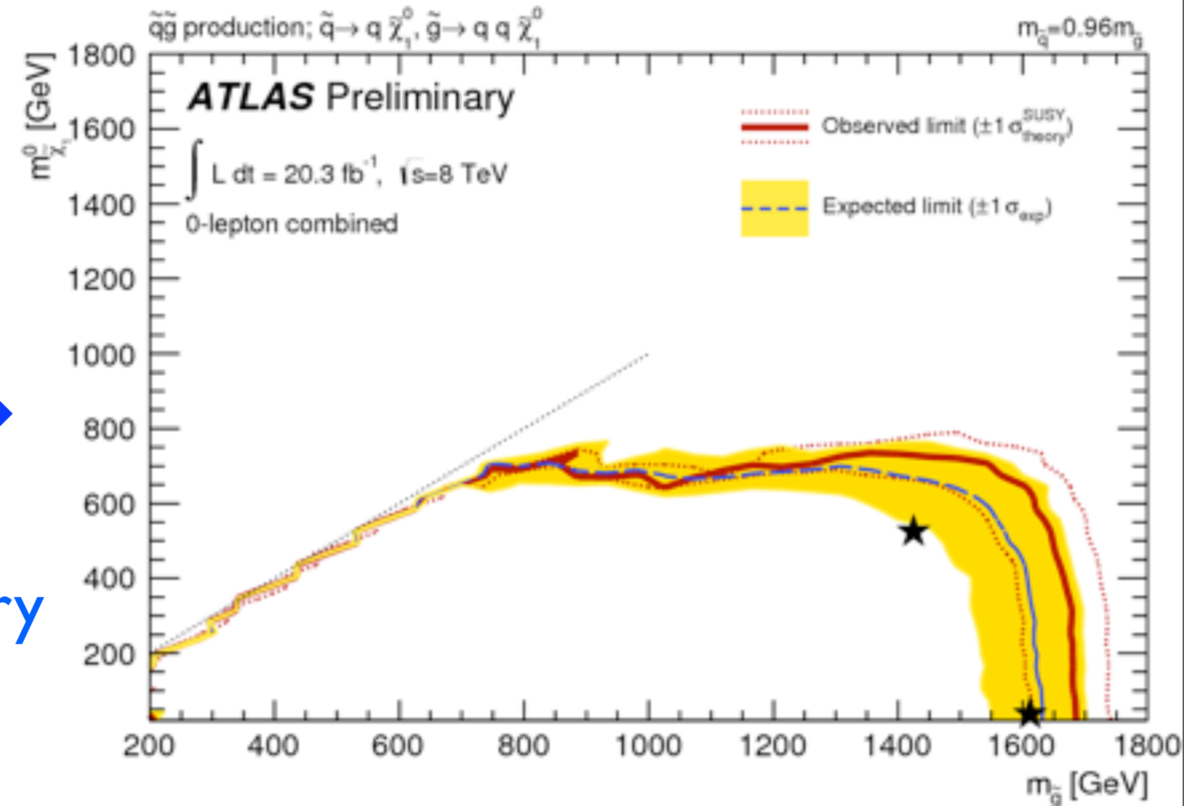


No discovery yet



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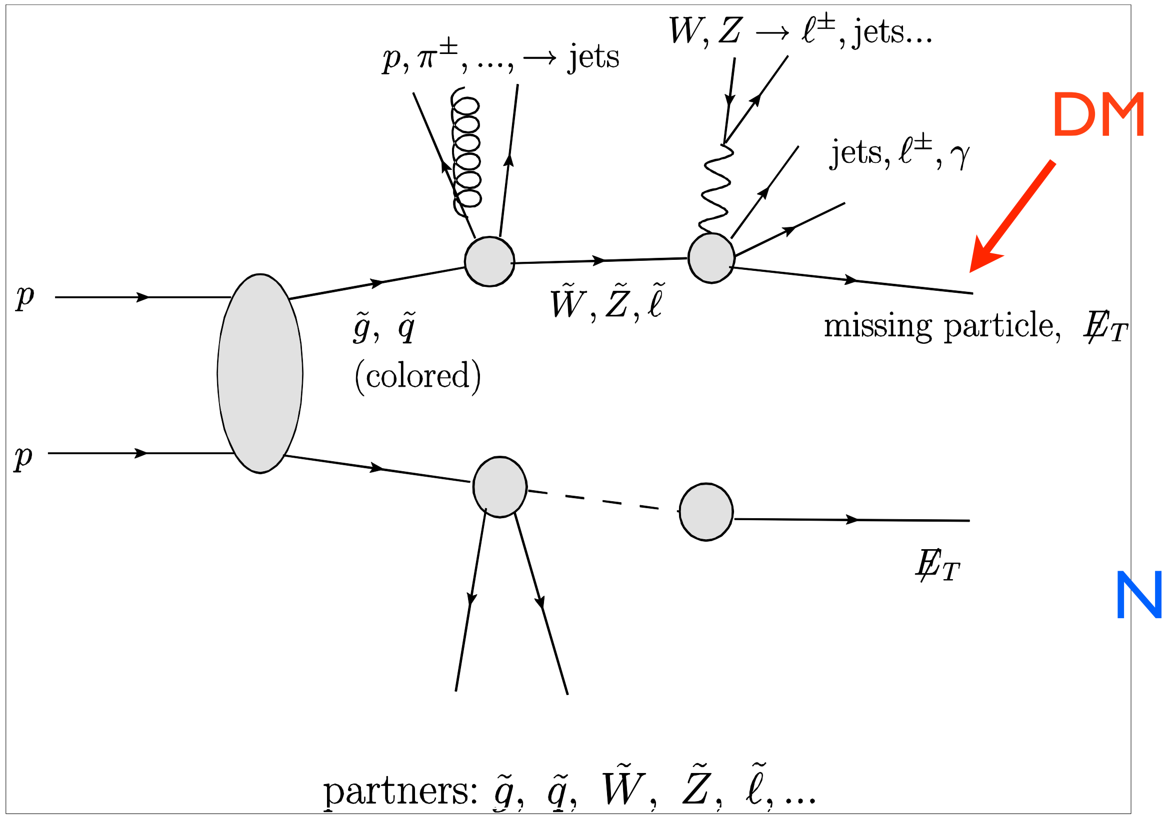

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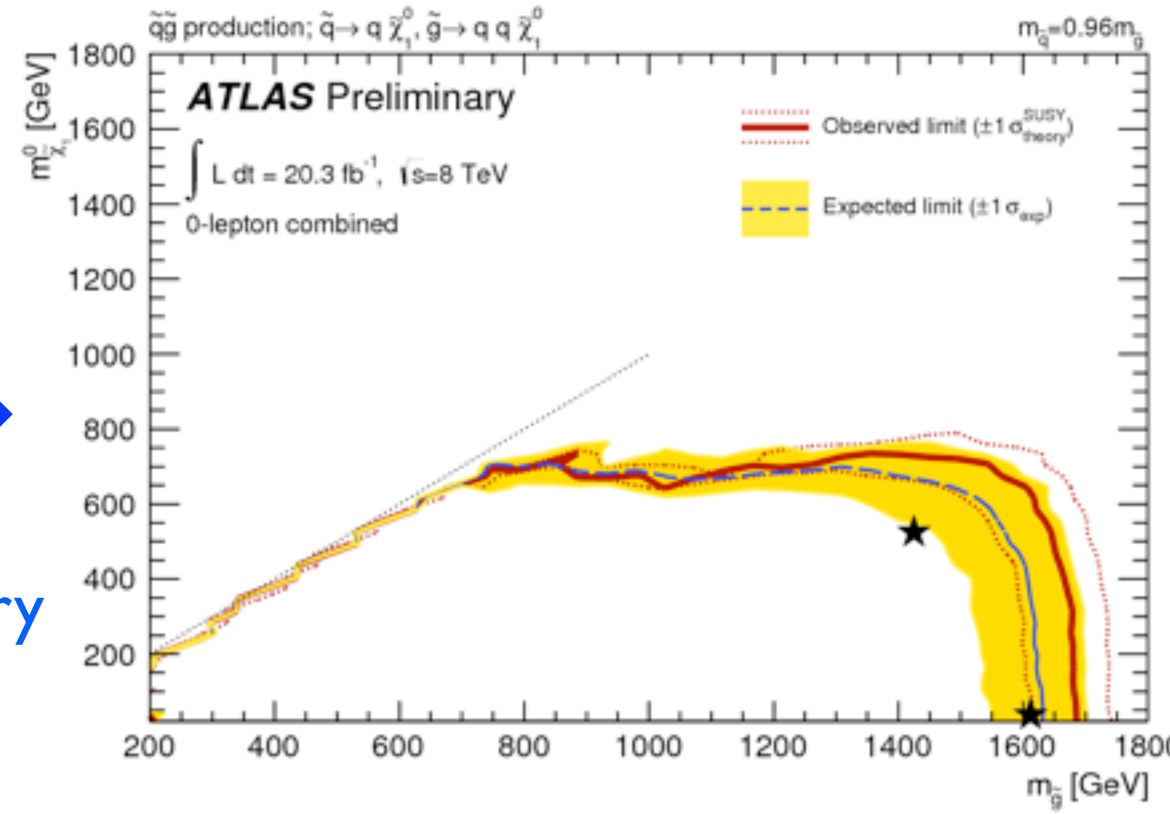
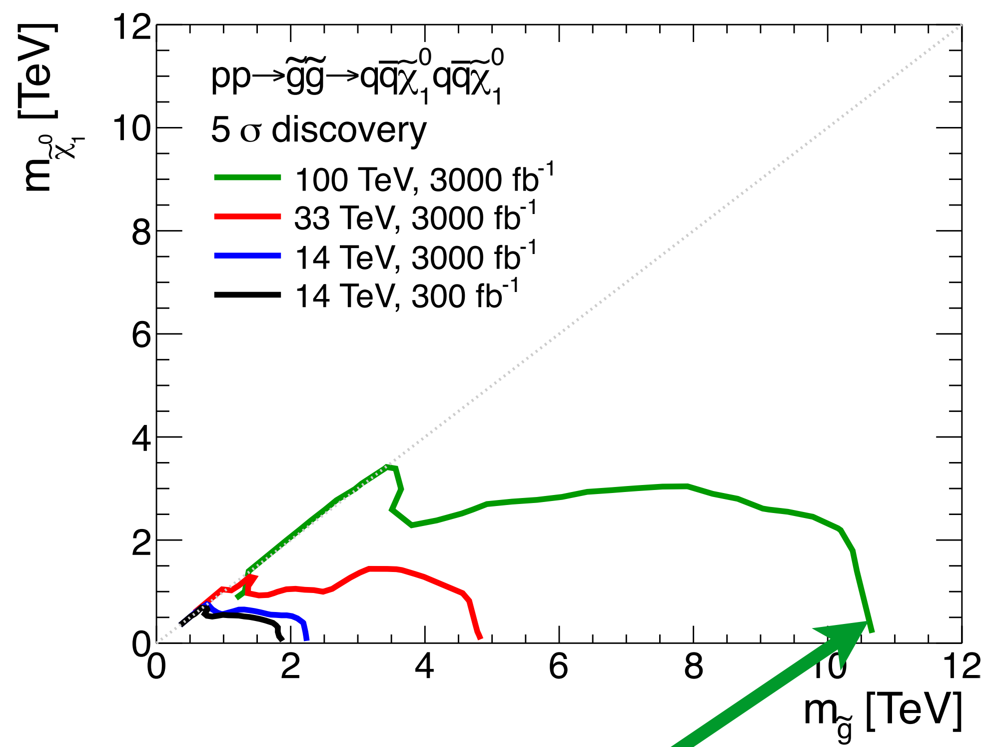
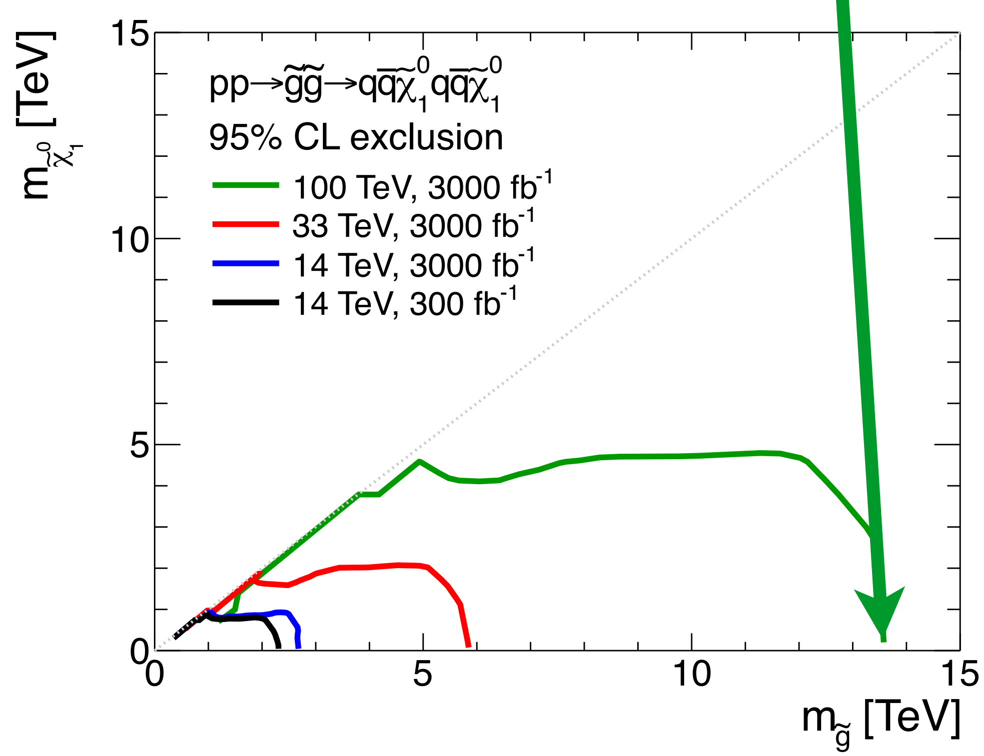


Of course, still plausible at the LHC, will keep looking.
Higher energy ⇒ higher reach

Higher energy



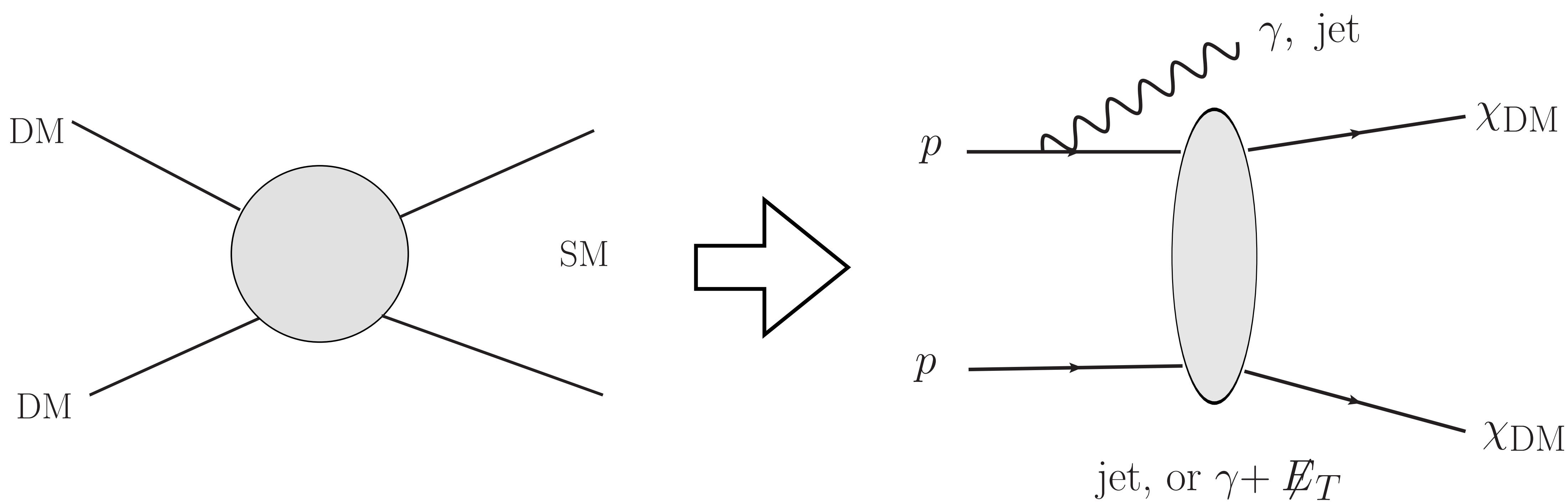


Exclude 13.5 TeV gluino! (with 60 events)

Discover 11 TeV gluino!

Back to the basics

- pair production + additional radiation.



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

- Have become “Standard” LHC searches.

In general

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?

–

Focusing on simplified 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

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

- Coannihilation:

Common feature:
very small mass splitting "compressed"

$\tilde{h},\ \tilde{W}$ —— $\Delta M \sim$ several % $\times M_{\rm DM}$ —— $\tilde{B}$

$\tilde{\tau},\ \tilde{q},\ \tilde{t},\dots$ —— $\Delta M \sim$ several % $\times M_{\rm DM}$ —— $\tilde{B}$

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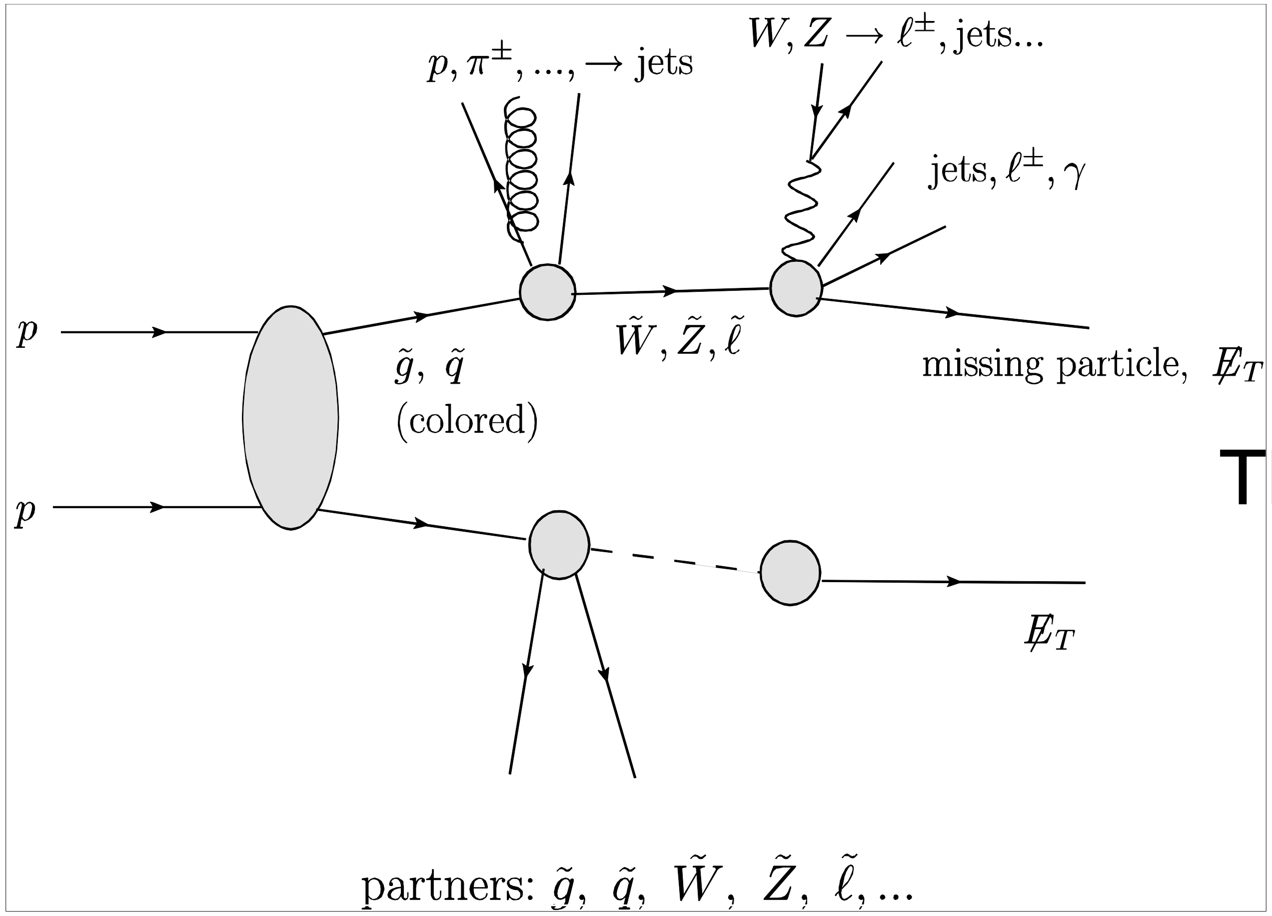
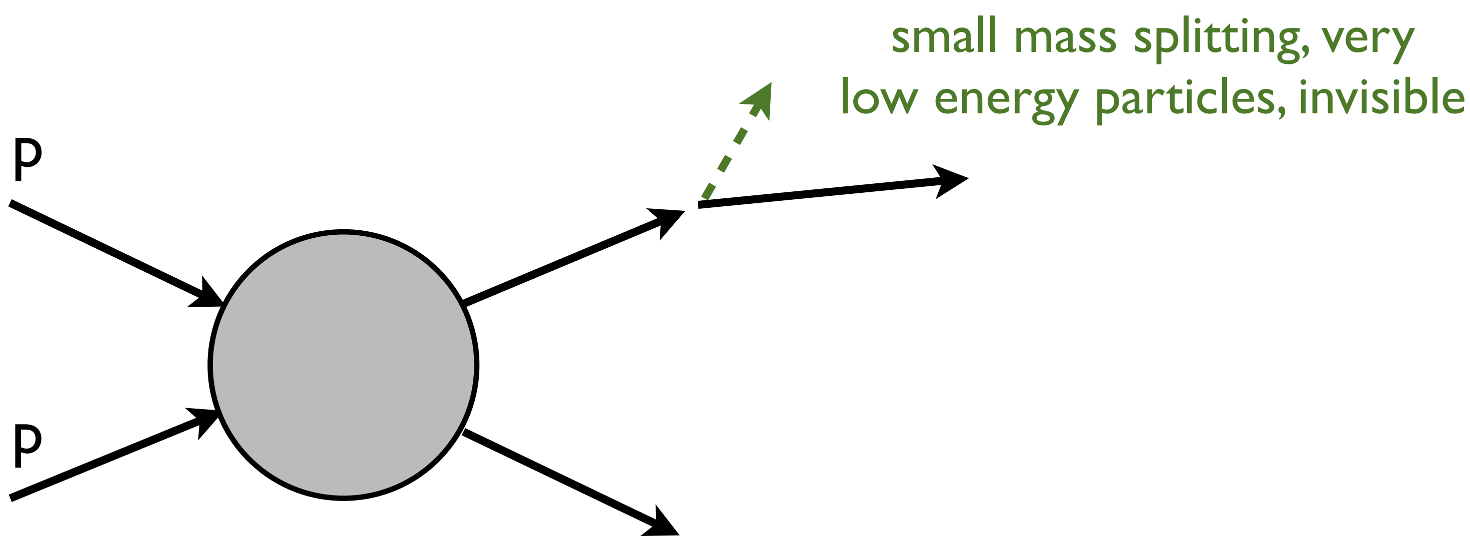
SUSY DM signal in the compressed case



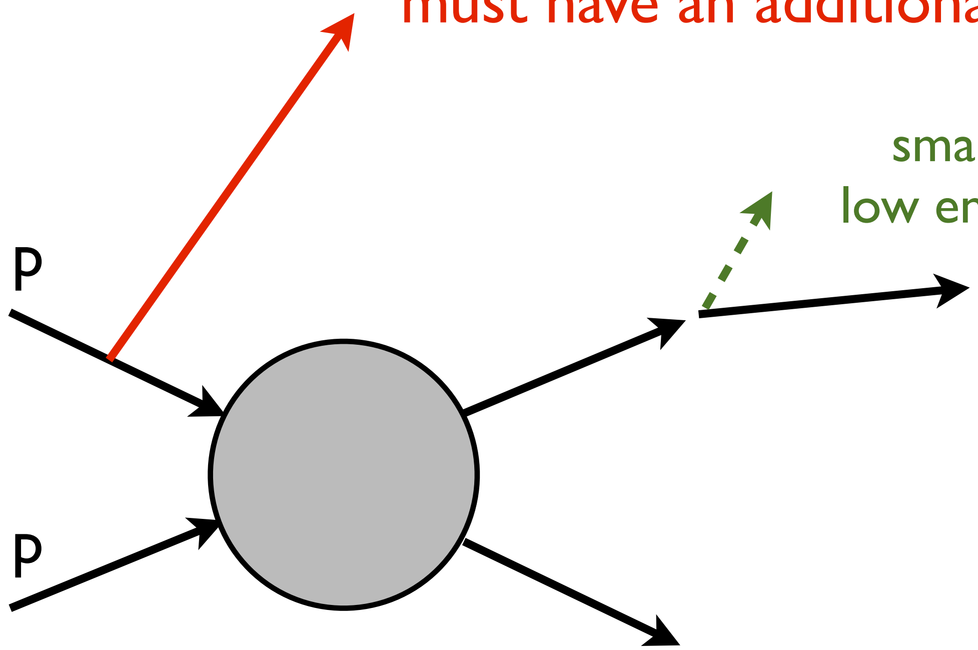
The "usual" story

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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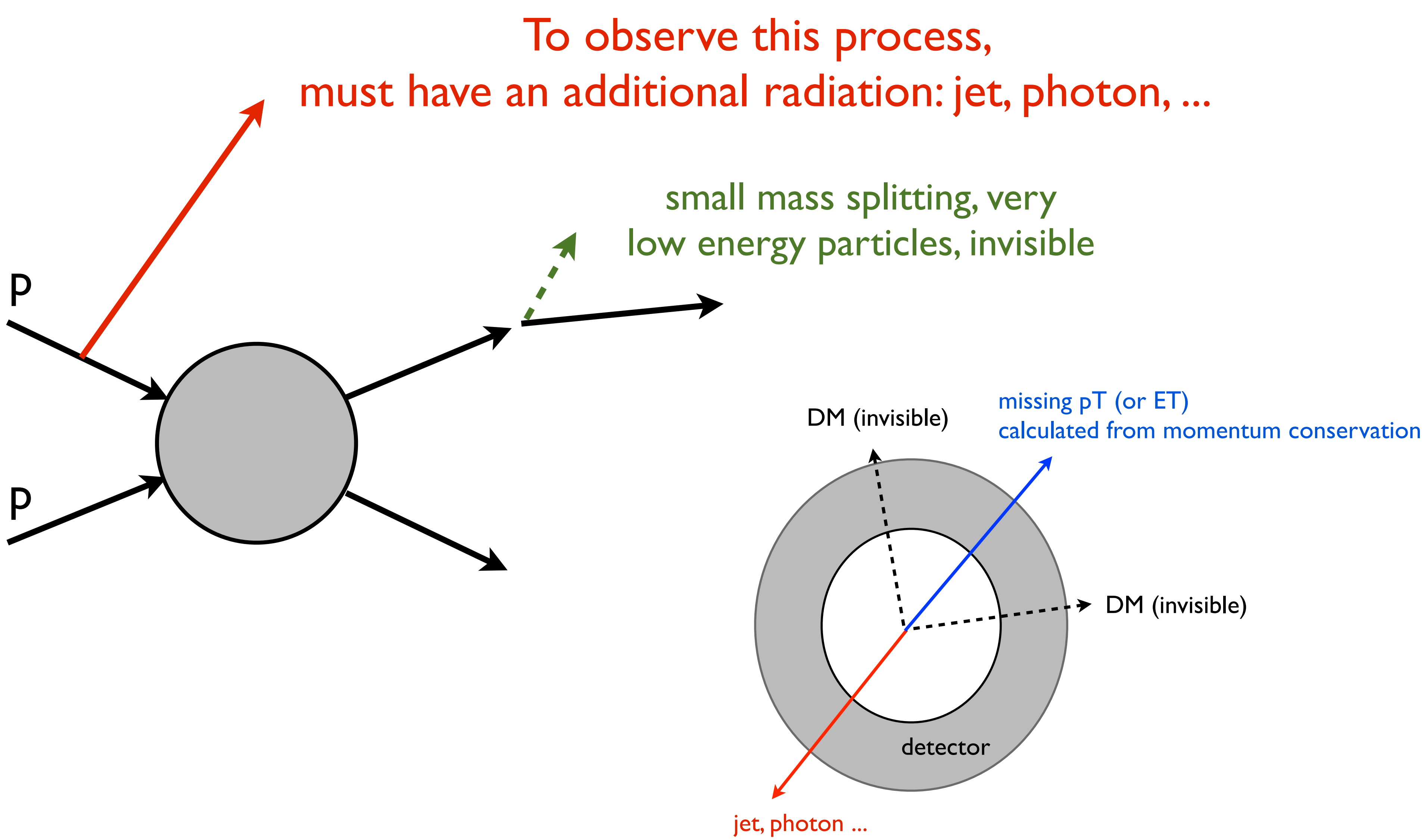
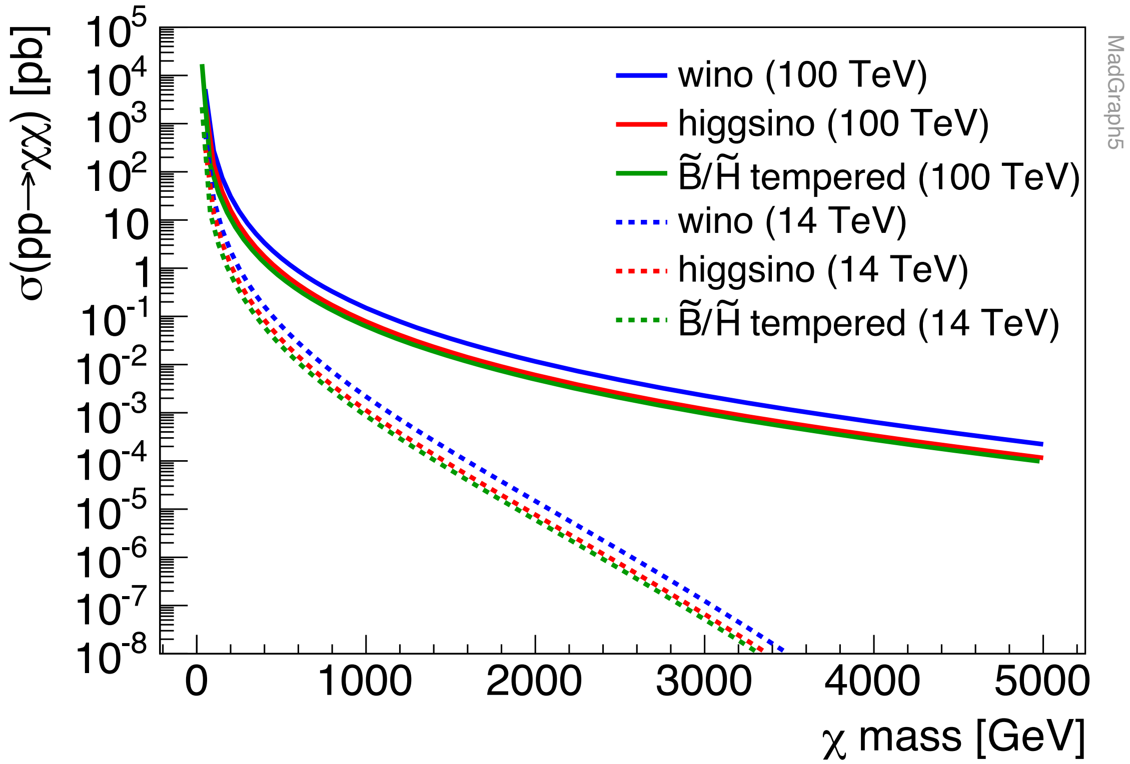
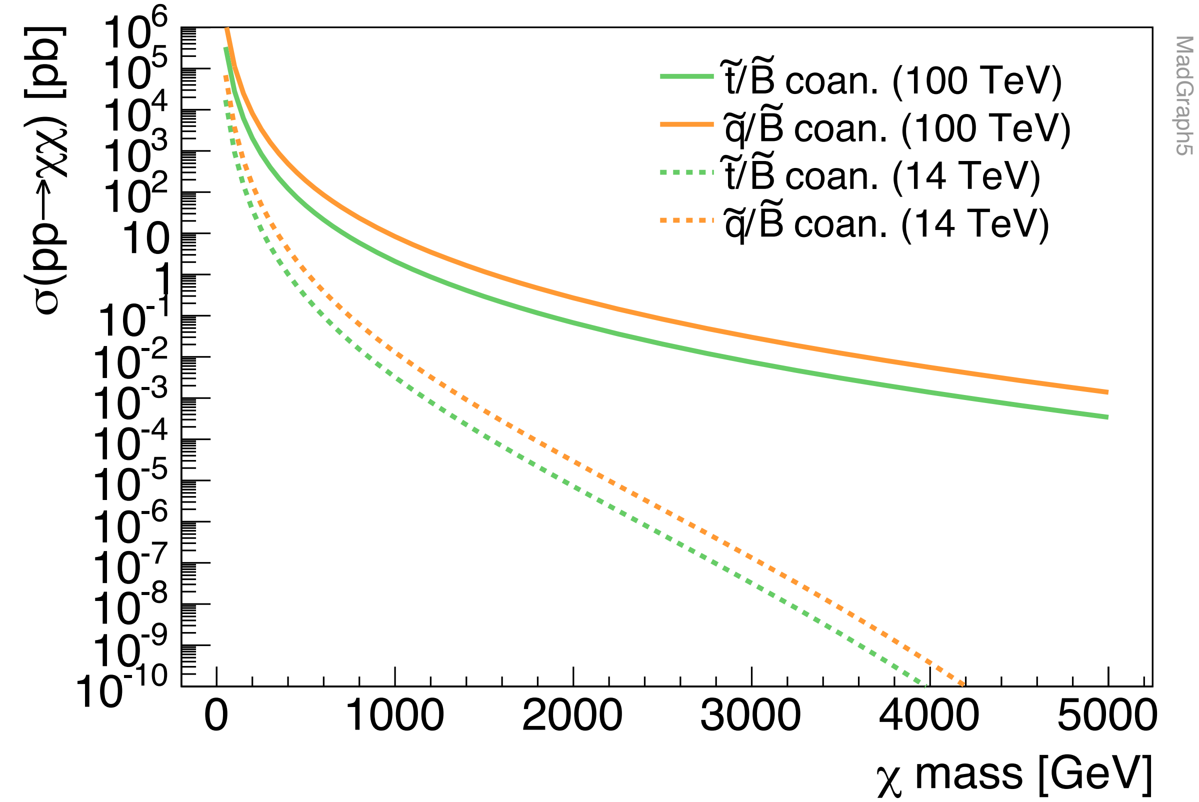


- mono-jet, mono-photon...

14 vs 100 TeV



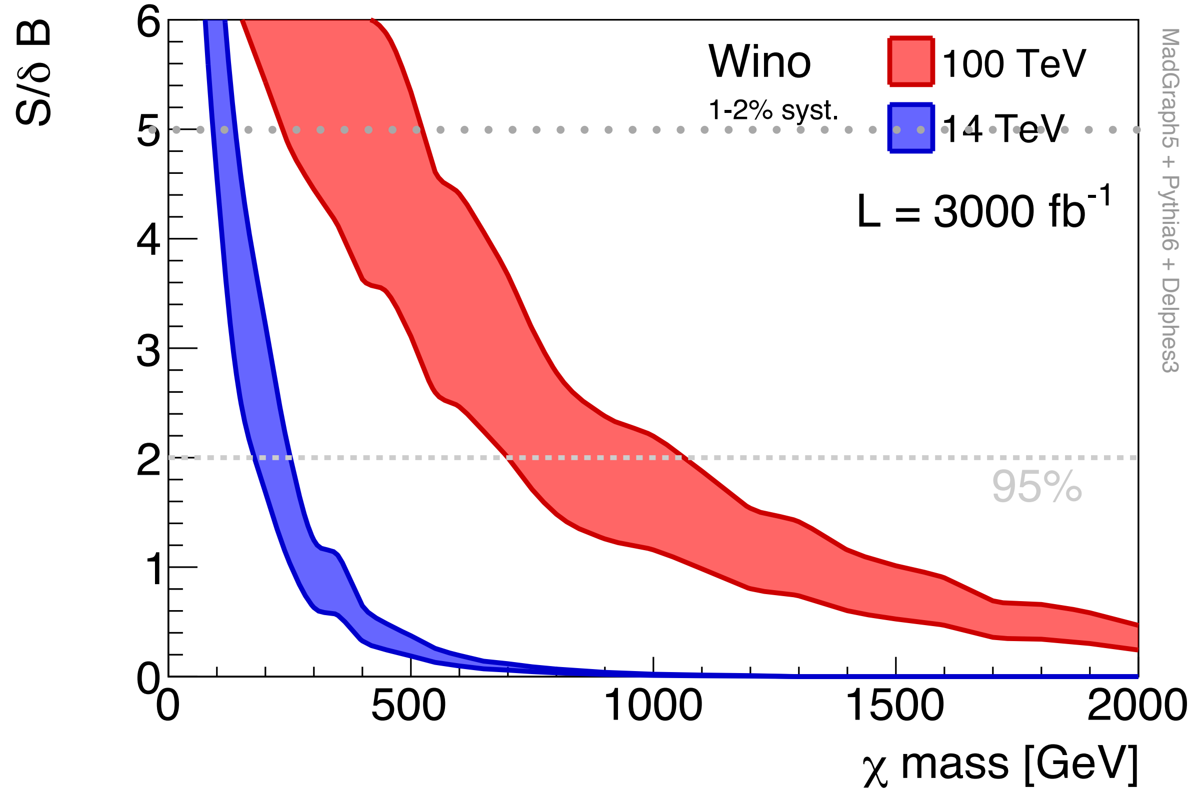


- Higher energy, higher rates

- Expecting large improvement from 14 to 100.

Wino: 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.

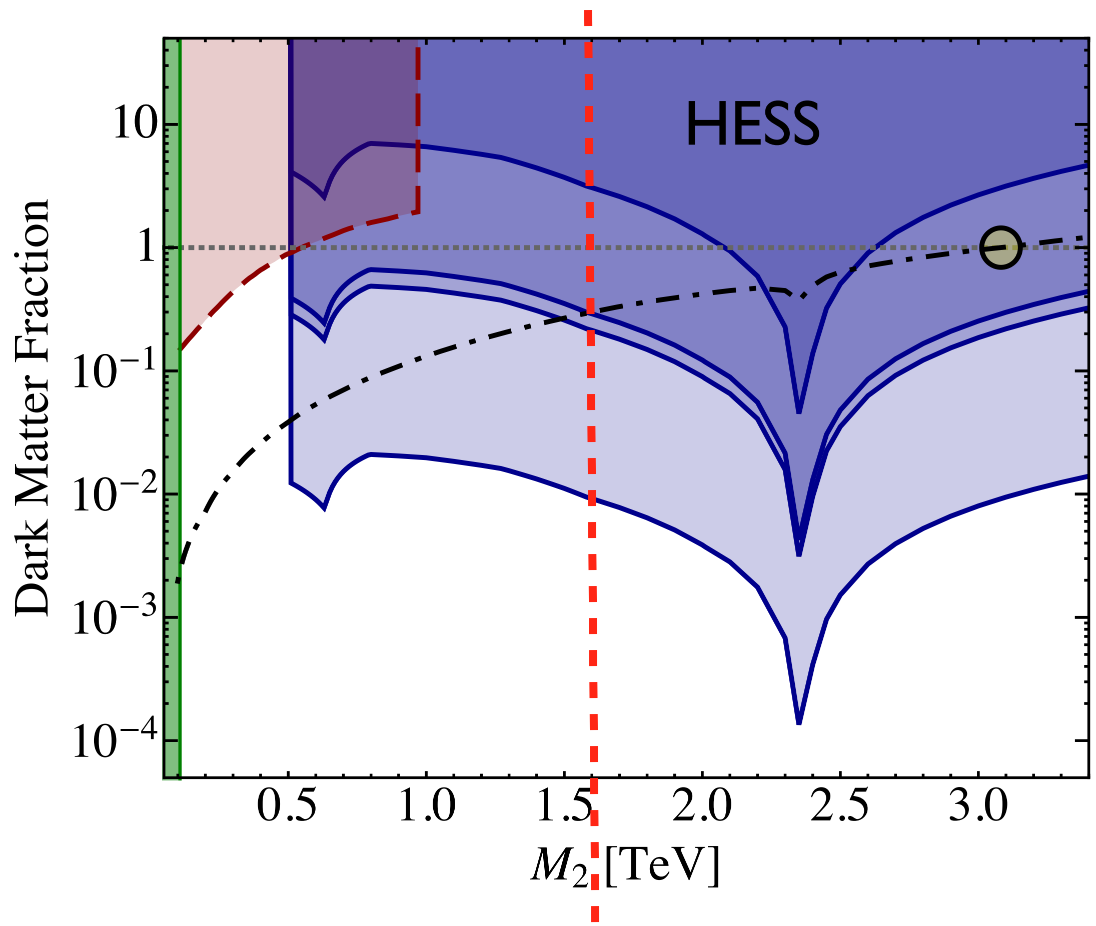
significance: $$\frac{S}{\sqrt{B+\lambda^2 B^2+\gamma^2 S^2}},\ \lambda=(1-2)\%, \gamma=10\%$$

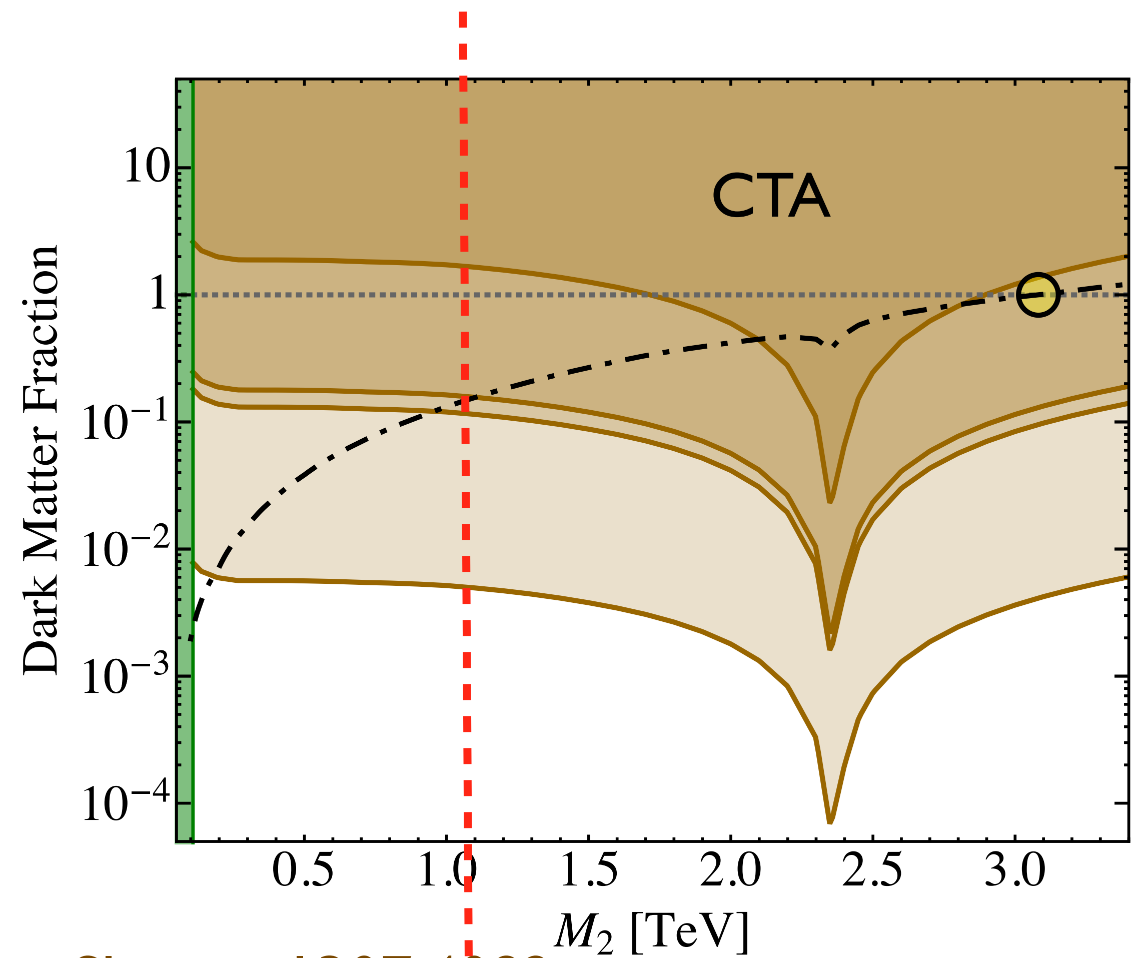
Band: varying systematic error of background, λ, between 1-2%

– 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

Wino, interplay with indirect detection



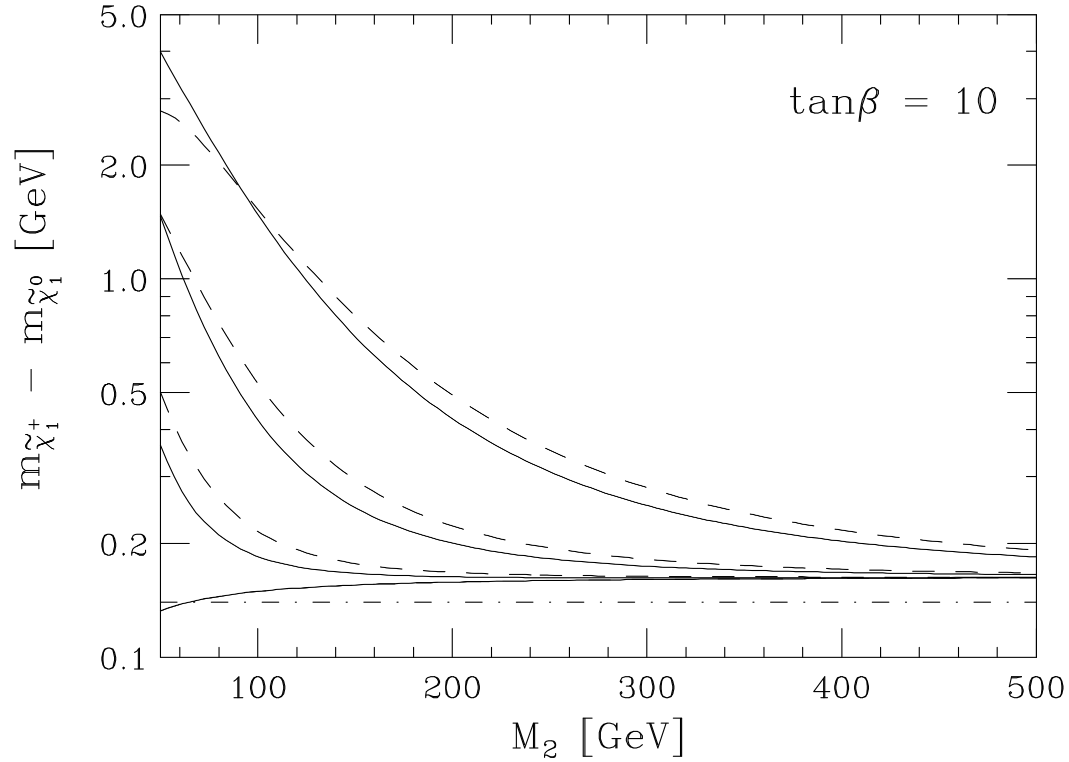


Cohen, Lisanti, Pierce, Slatyer, 1307.4082

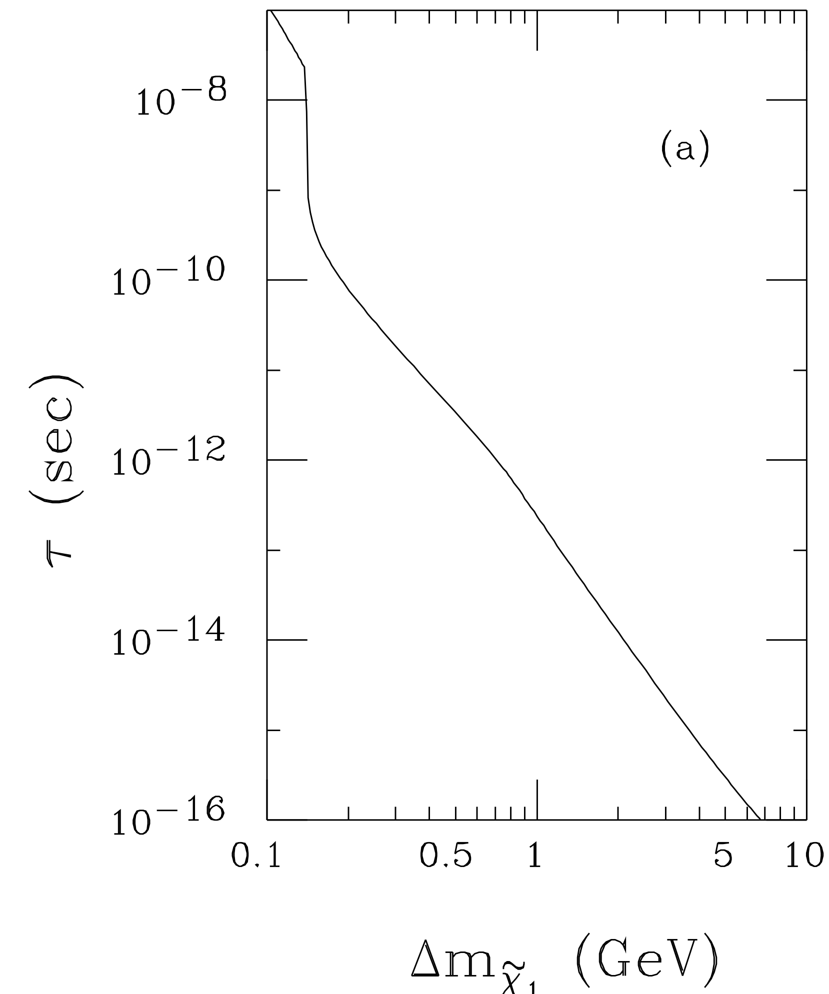
See also Fan, Reece, 1307.4400

Large uncertainties, however.

Wino decay



Gherghetta, Giudice and Wells, hep-ph/9904378

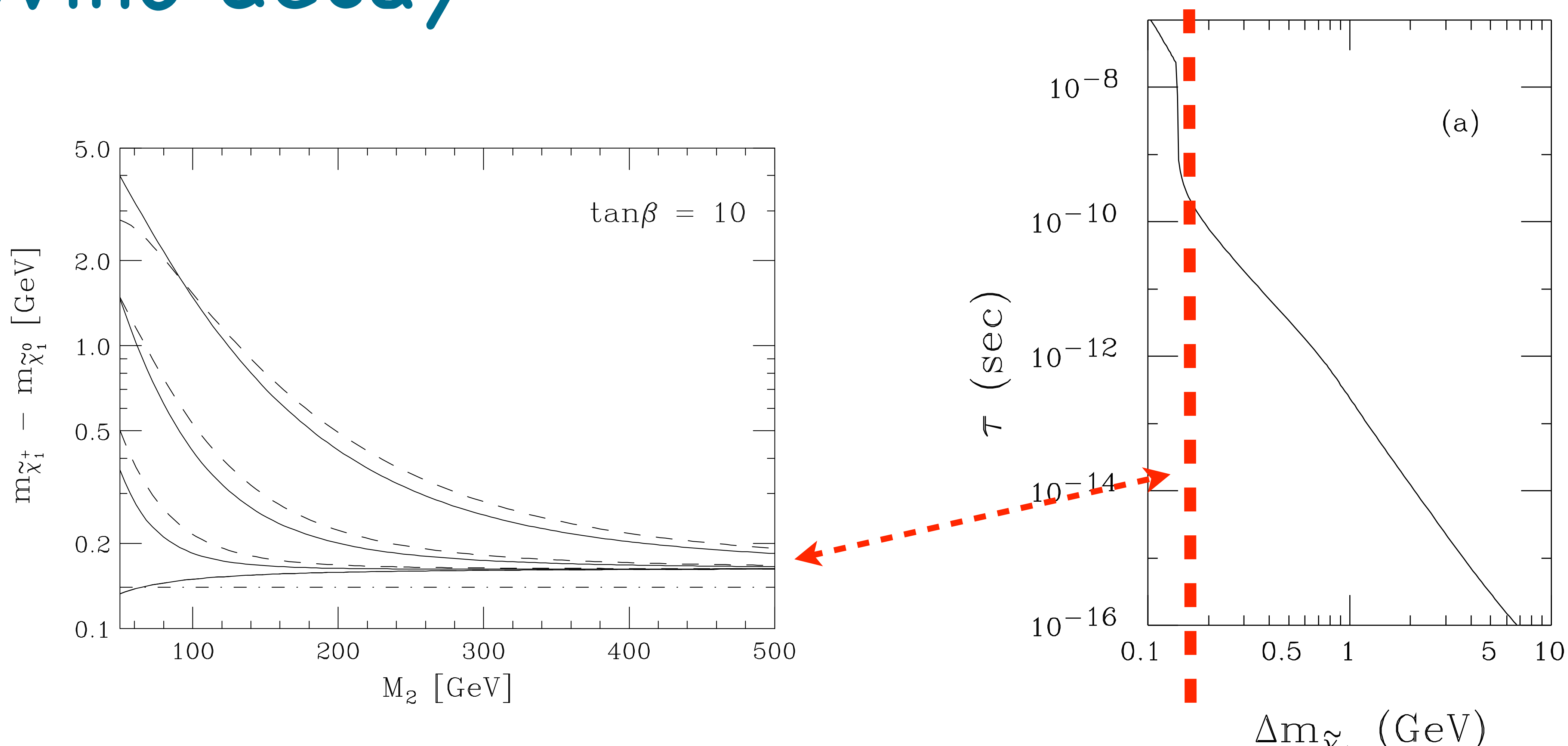


Chen, Drees and Gunion, hep-ph/9902309

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

- Charge track ≈ 10(s) cm

Wino decay



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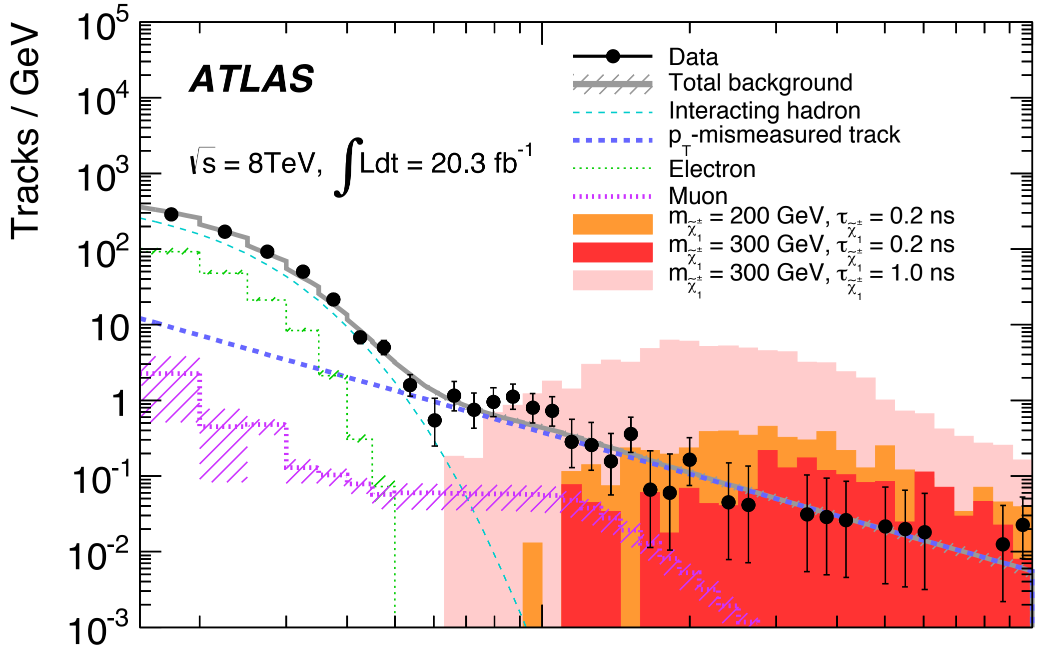
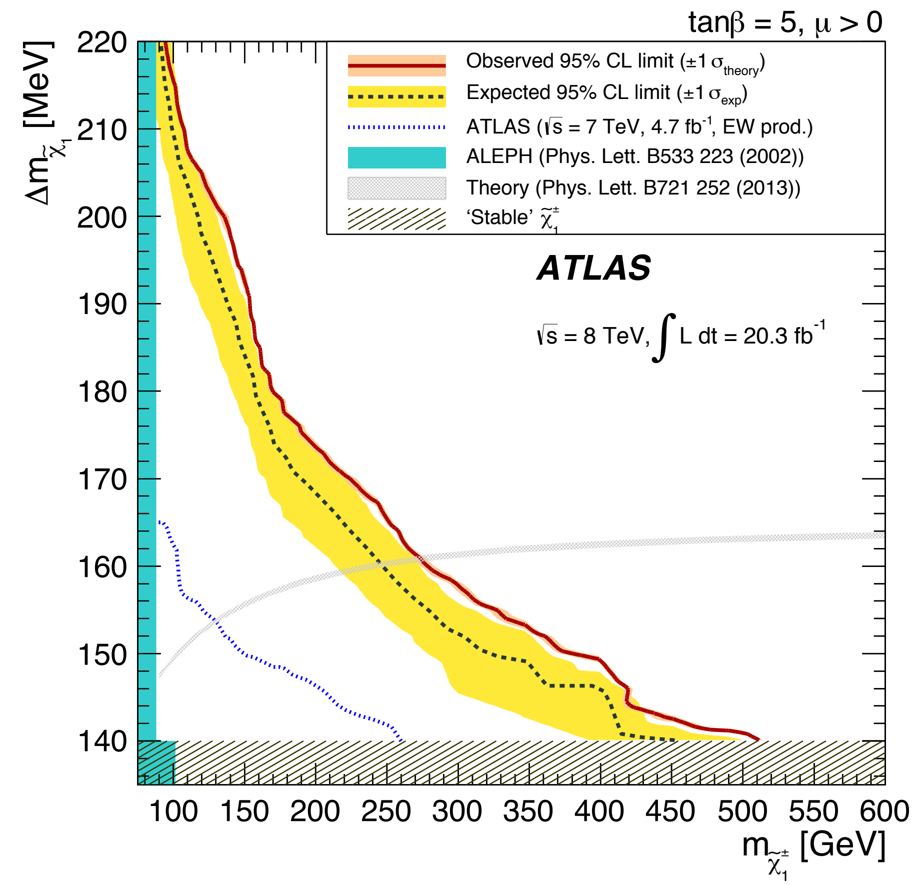
ATLAS search

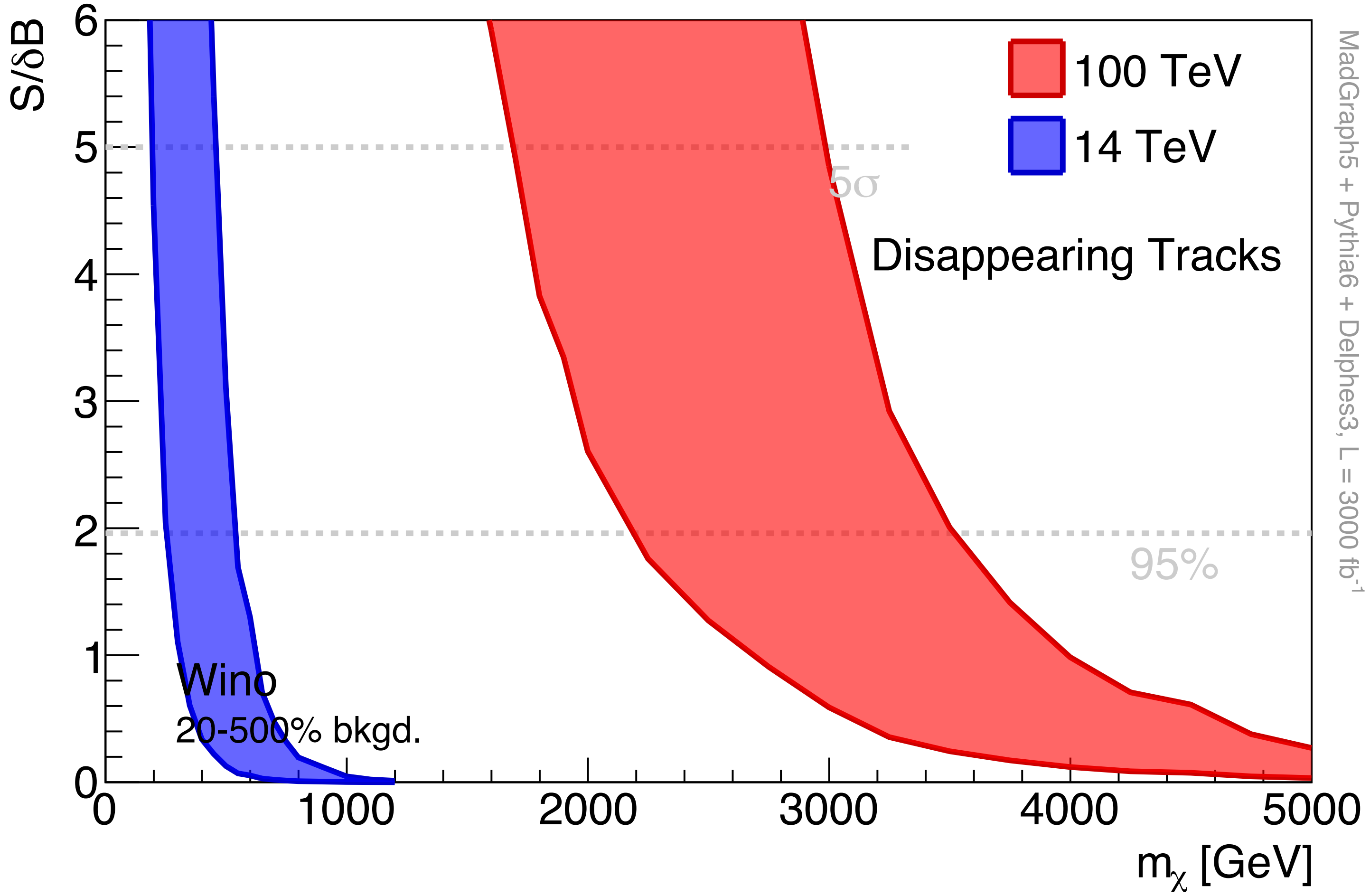
ATLAS, 1310.3675





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

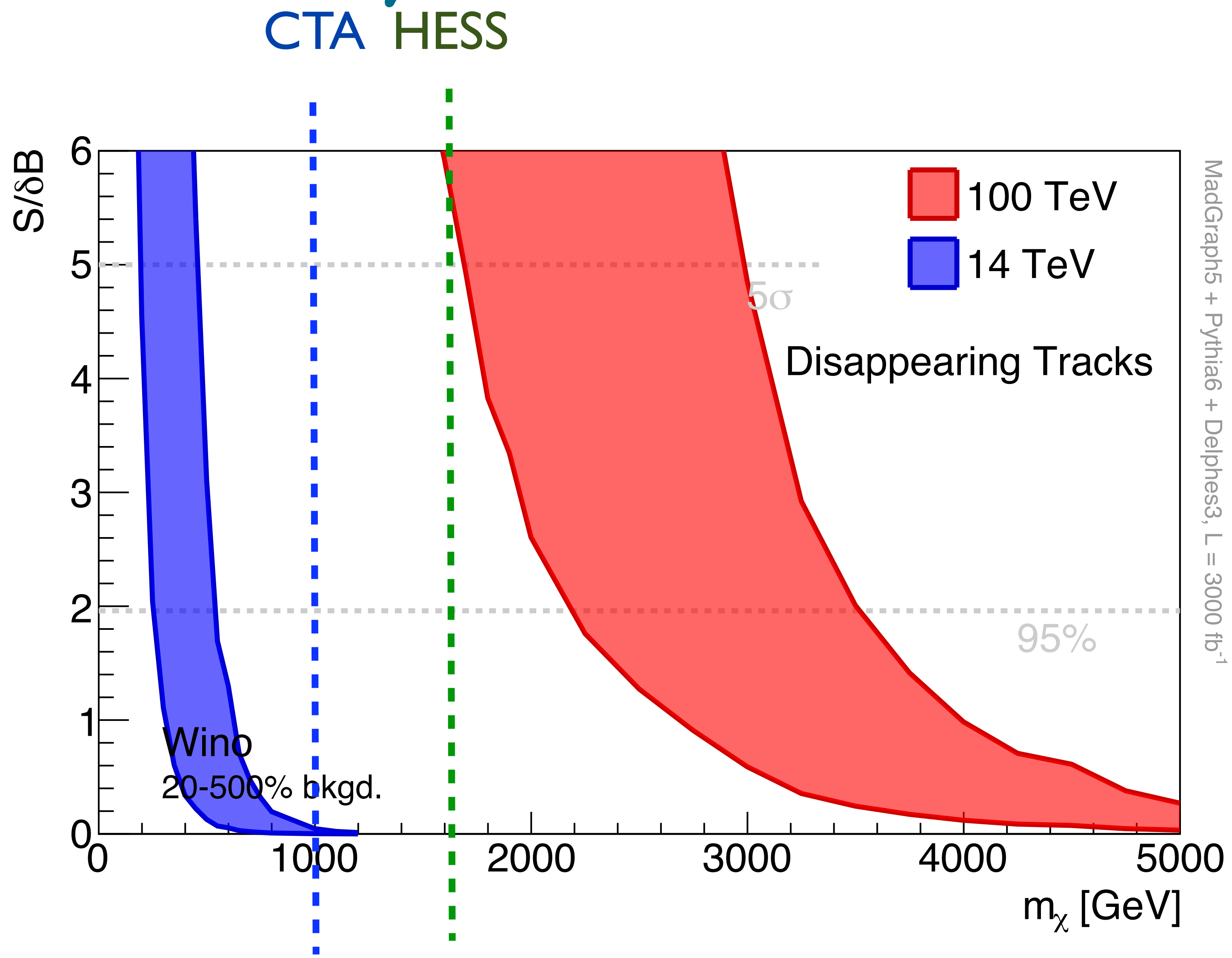
(Rough) Extrapolation from ATLAS search



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

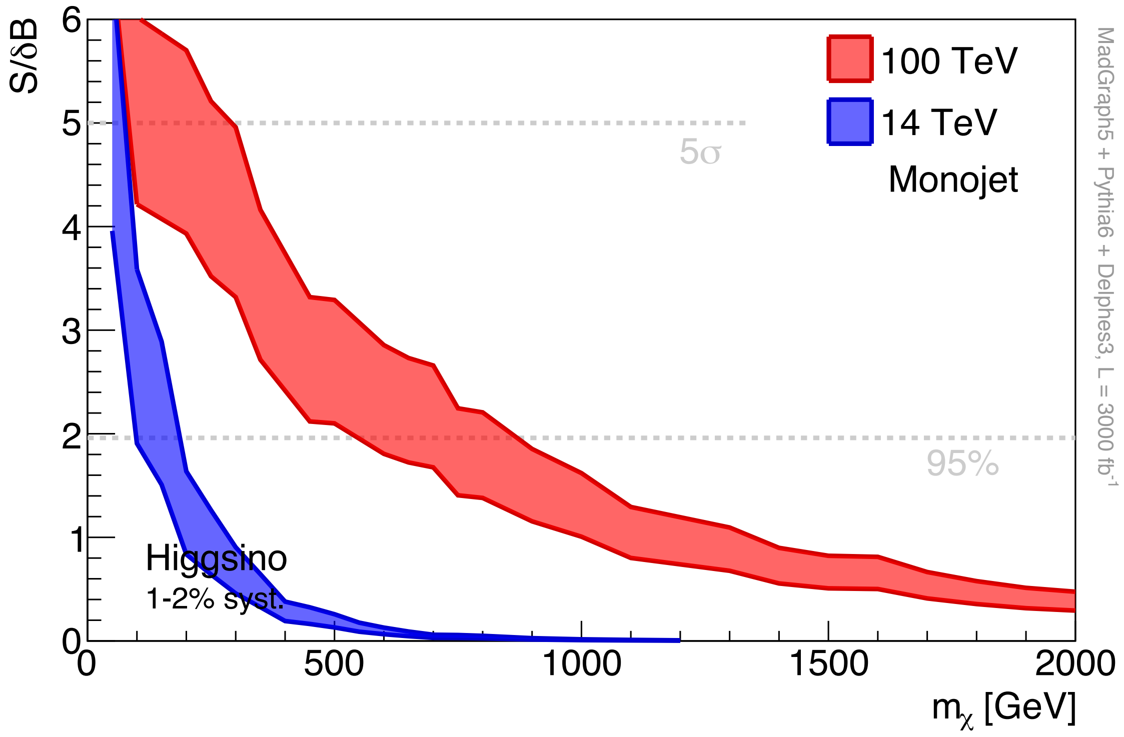
- Band: varying background estimate by 5 either way.

Wino summary

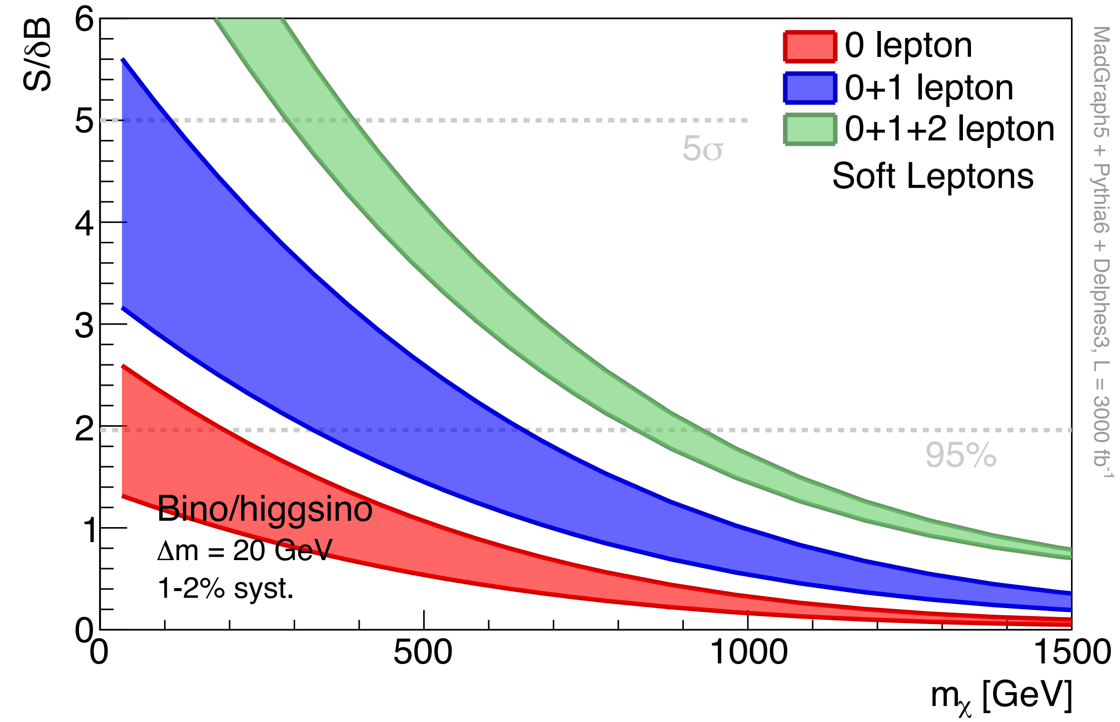


- There is hope to "completely cover" the wino parameter space.

Additional cases

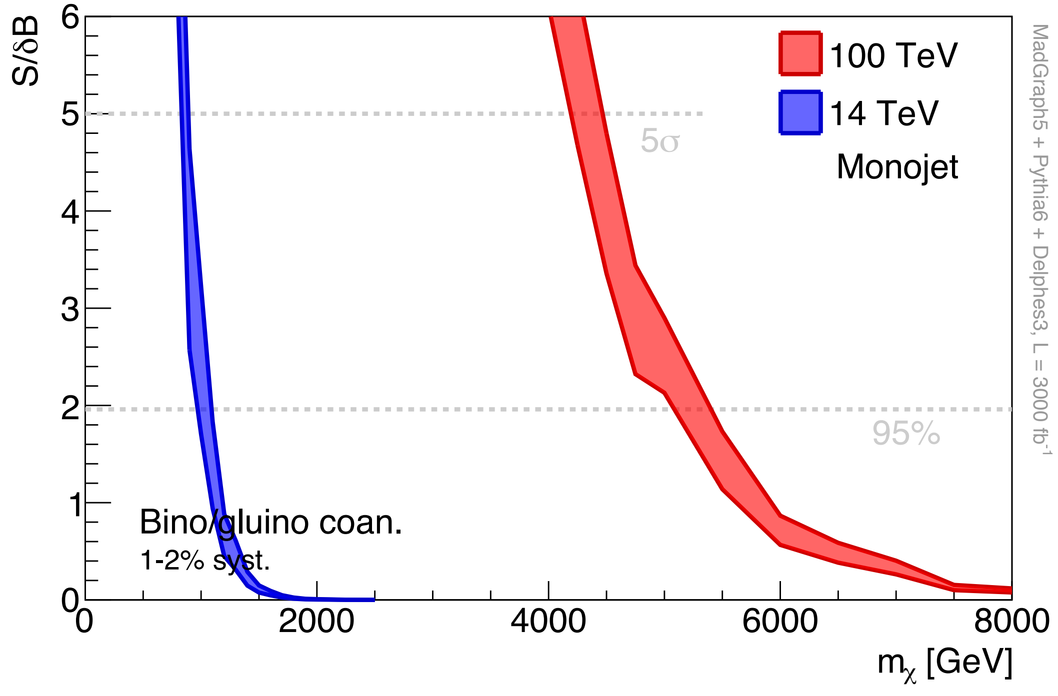


Higgsino

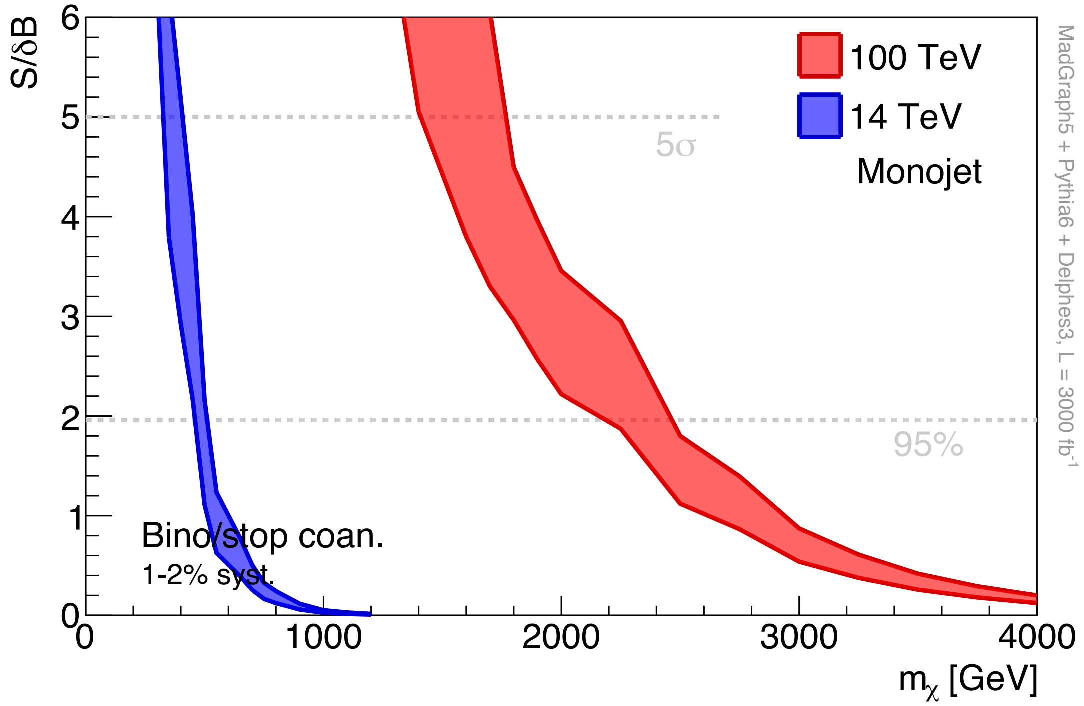


Compressed, Δm=20 GeV, with soft lepton

Additional cases



Coannhilation, gluino



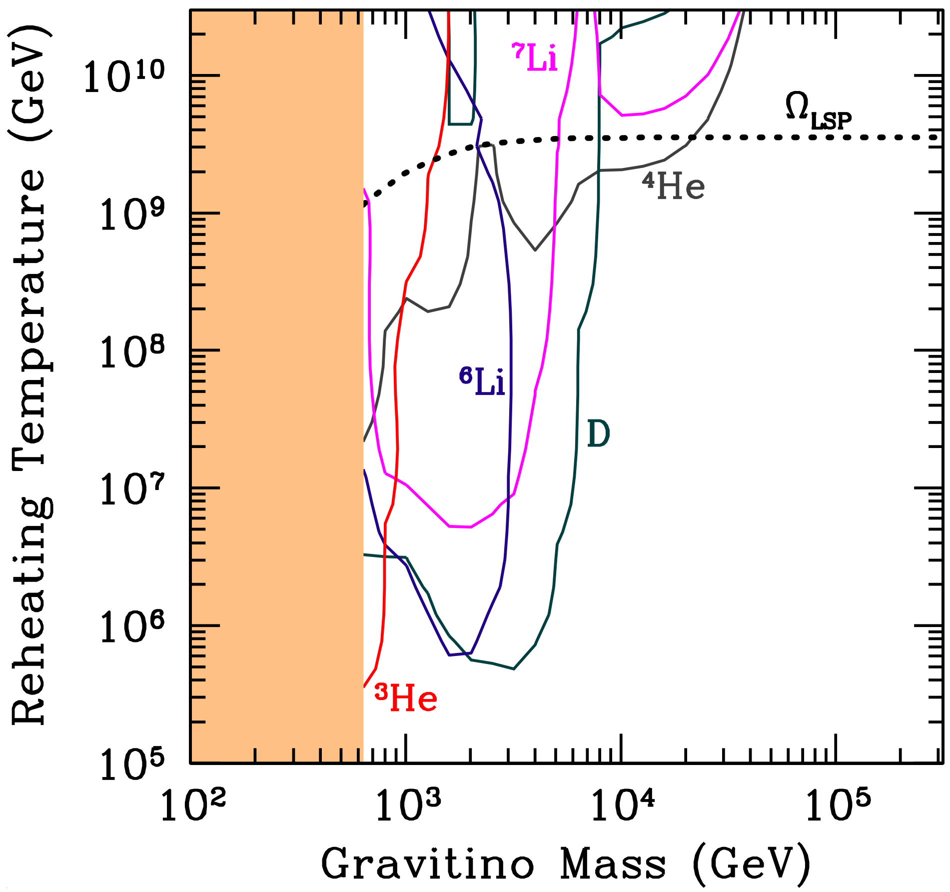
Coannhilation, stop

Conclusion and outlook

- Covering WIMP parameter space a major motivation for going to higher energies.
- 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?

BTW, an implication of r=0.1-0.2.

- High scale inflation.
  - $V_{inflation} \approx (10^{16}\ \mathrm{GeV})^4$, $m_{inflaton} \approx 10^{-6}\ M_{Pl}$.
  - High reheating temp. $T_{RH} \approx (\alpha_{eff})^{1/2}\ 10^{-5} M_{Pl}$.
  - High SUSY breaking scale, heavy superpartners.

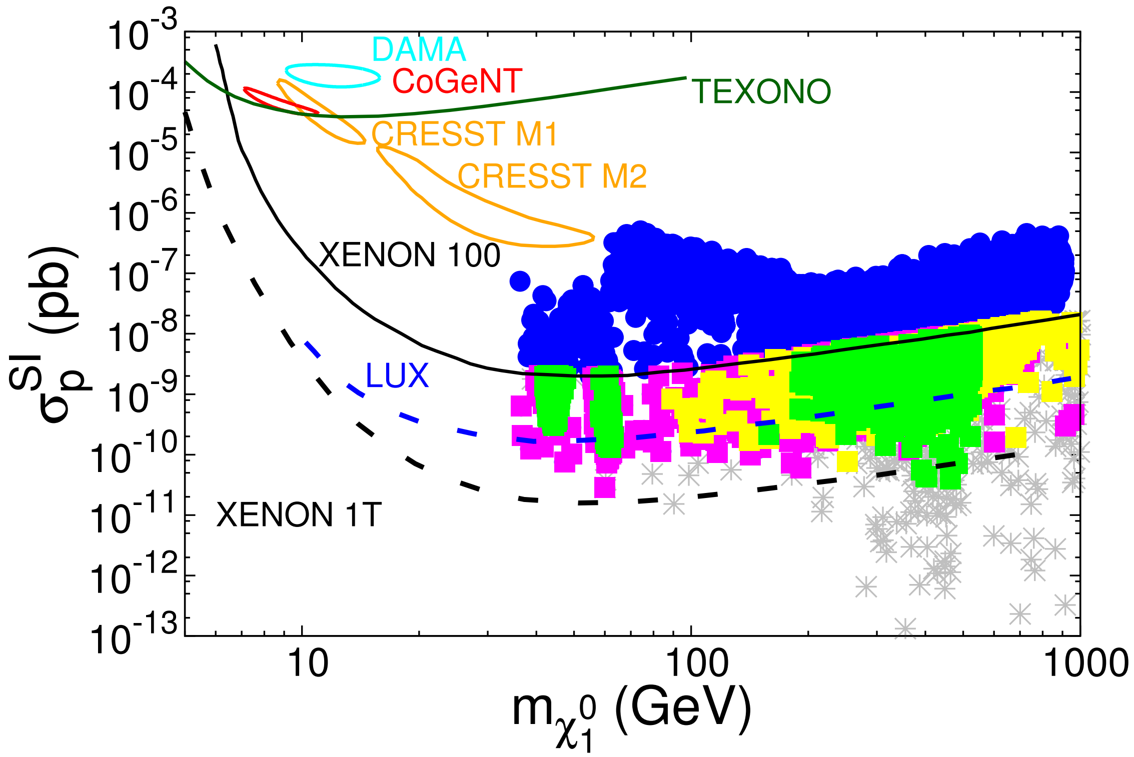


Moroi et al, 2008

- $m_{gravitino} \sim$ 10 TeV
- In many cases:
  - $m_{squark,slepton.} \sim m_{gravitino}$
- Need go beyond LHC.

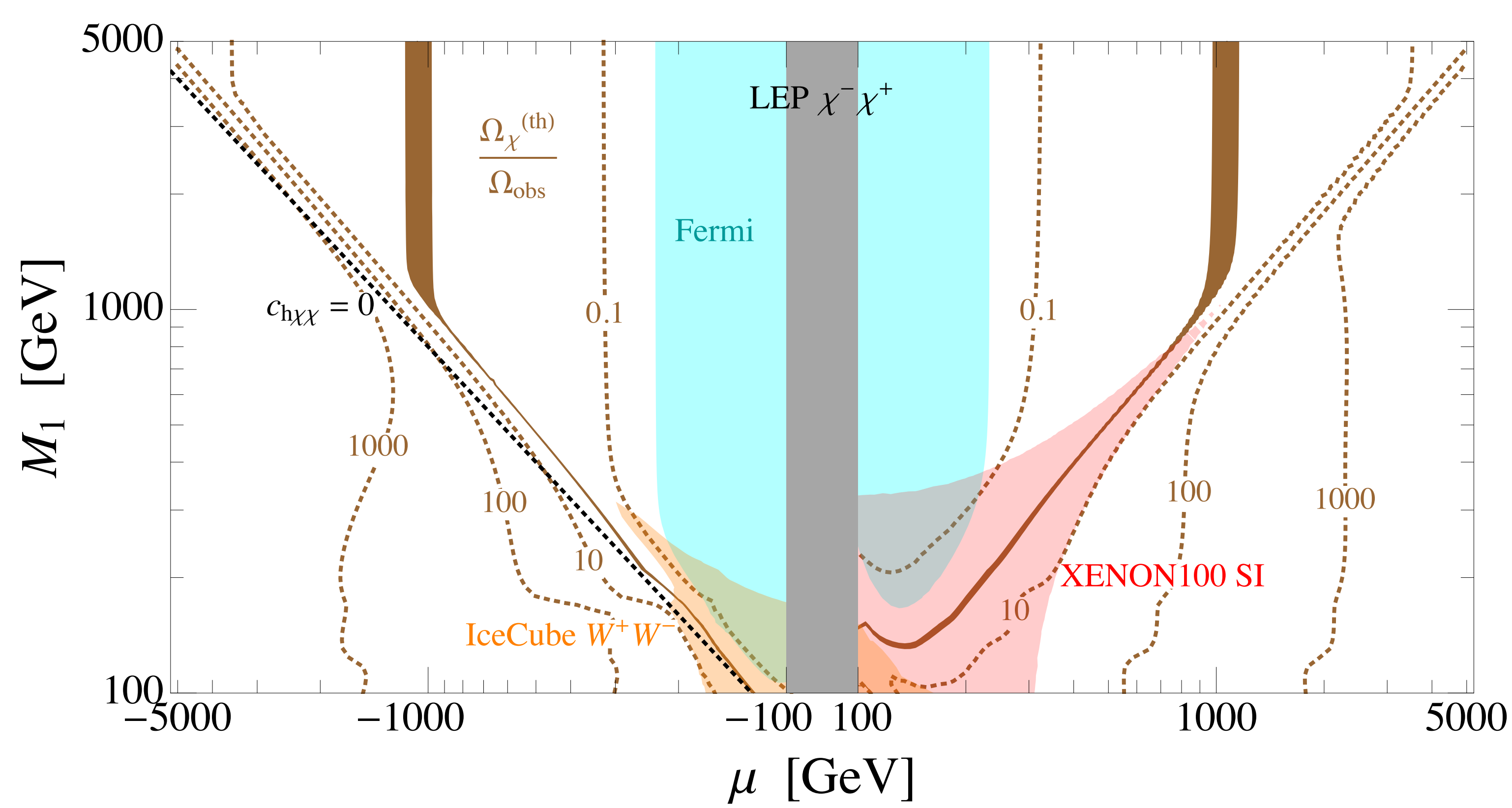
extras

Narrowing parameter space.



Han, Liu, Natarajan, 1303.3040

Cheung, Hall, Pinner, Ruderman, 1211.4873



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
$n_{\text{jet}} \le 2$			$\not{E}_T > 450$ 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
$n_{\text{jet}} \le 2$			$\not{E}_T > 500$ 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
$n_{\rm jet} \leq 2$			$\not\!\!E_T > 2400$ 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
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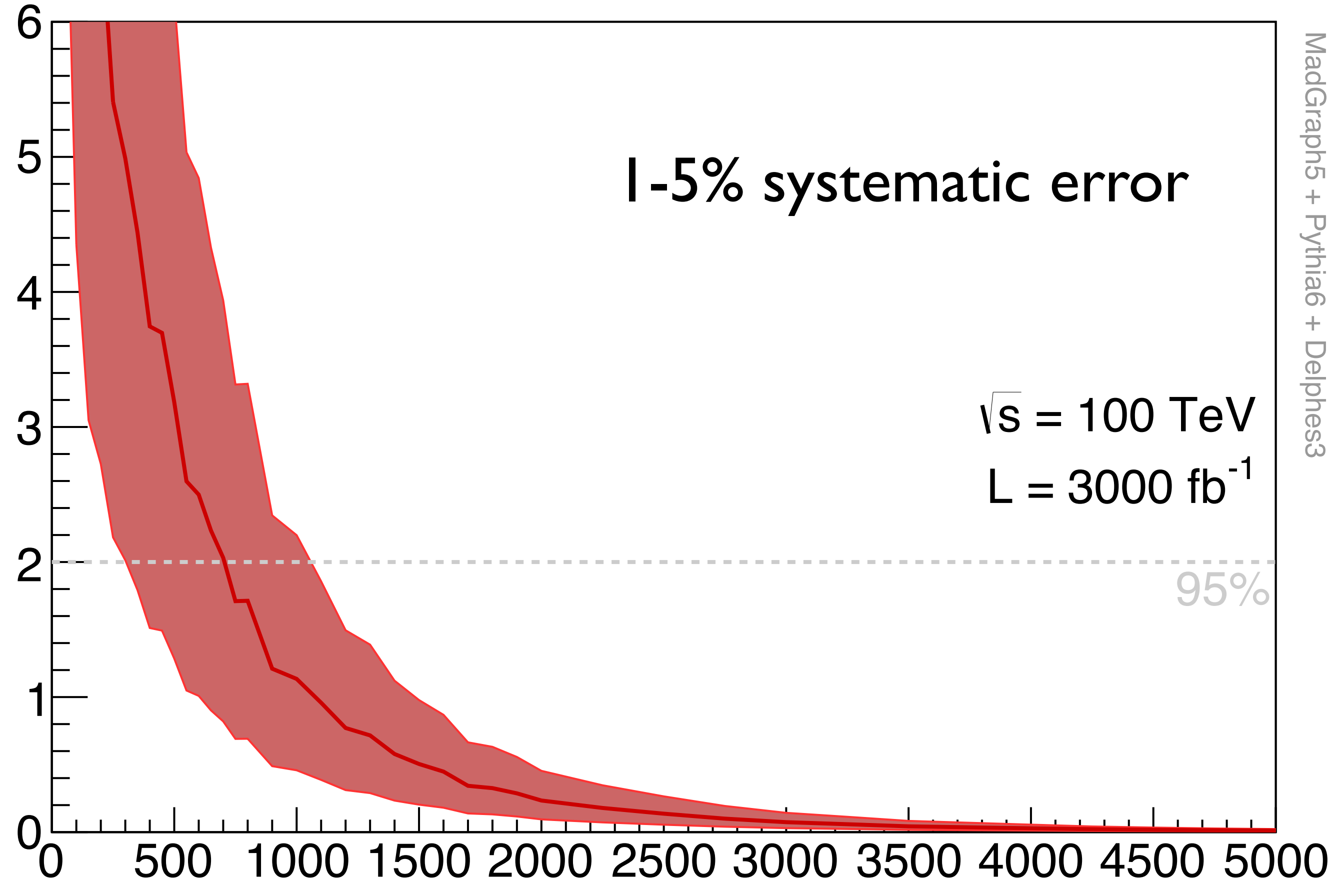
$p_T(1) > 300$ GeV	0-bin: $p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not\!\!E_T > 300$ GeV
$\lvert\eta(1)\rvert < 2.4$	1, 2-bin: $50 > p_T(e) > 20$ GeV and $\lvert\eta(e)\rvert < 2.5$	$\not\!\!E_T > 350$ GeV
$p_T(2) > 60$ GeV	0-bin: $p_T(\mu) > 20$ GeV and $\lvert\eta(\mu)\rvert < 2.1$	$\not\!\!E_T > 400$ 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
$n_{\text{jet}} \leq 2$	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 $\vert\eta(e)\vert < 2.5$	$\not{E}_T > 1000$ GeV
$\vert\eta(1)\vert < 2.4$	1, 2-bin: $40 > p_T(e) > 20$ GeV and $\vert\eta(e)\vert < 2.5$	$\not{E}_T > 2000$ GeV
$p_T(2) > 200$ GeV	0-bin: $p_T(\mu) > 20$ GeV and $\vert\eta(\mu)\vert < 2.1$	$\not{E}_T > 2250$ GeV
$\vert\eta(2)\vert < 4.5$	1, 2-bin: $40 > p_T(\mu) > 20$ GeV and $\vert\eta(\mu)\vert < 2.1$	$\not{E}_T > 2500$ GeV
$n_{\text{jet}} \leq 2$	0-bin: $p_T(\tau) > 40$ GeV and $\vert\eta(\tau)\vert < 2.3$	$\not{E}_T > 2750$ 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



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

Disappearing track + background

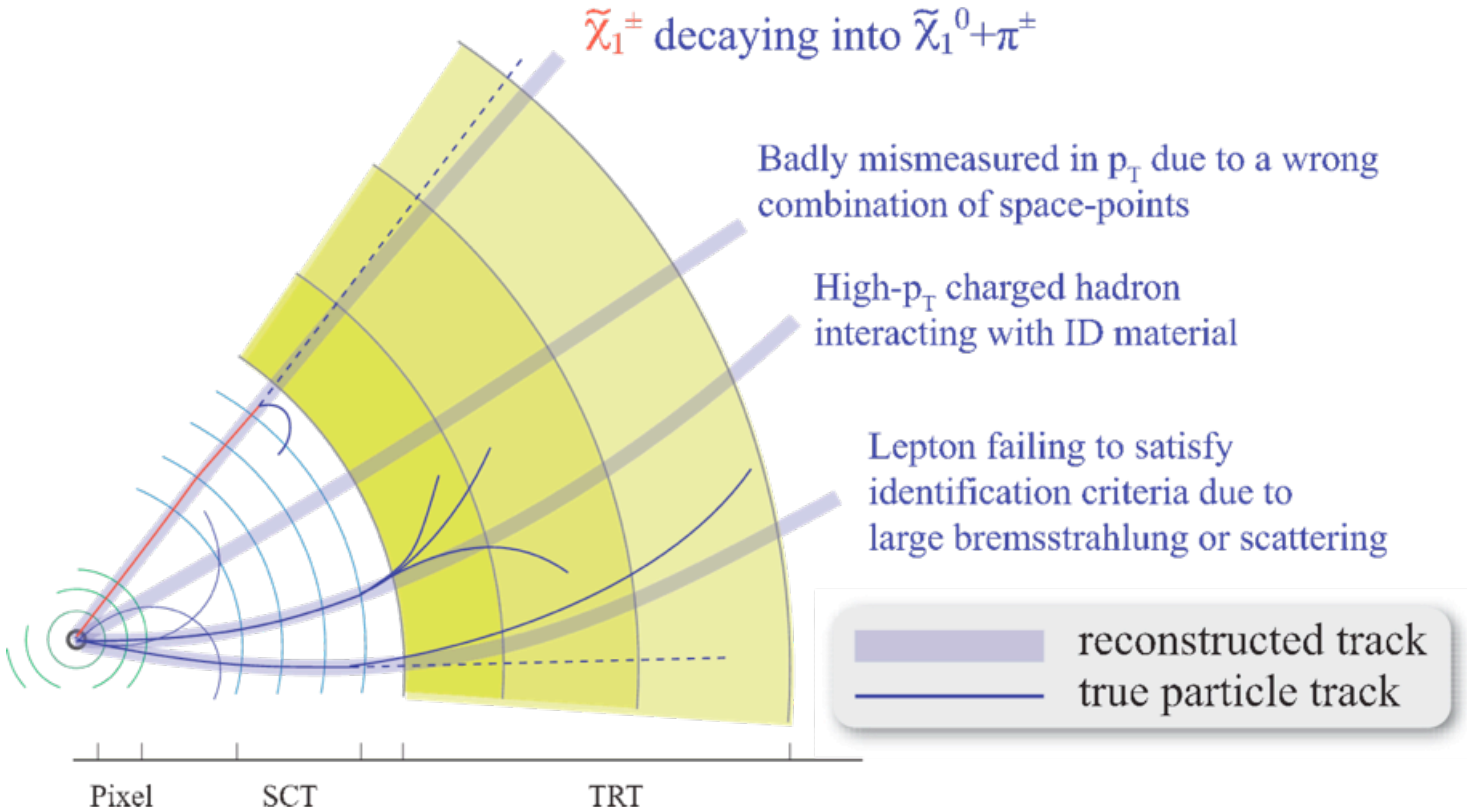


Figure from ATLAS disappearing track search twiki