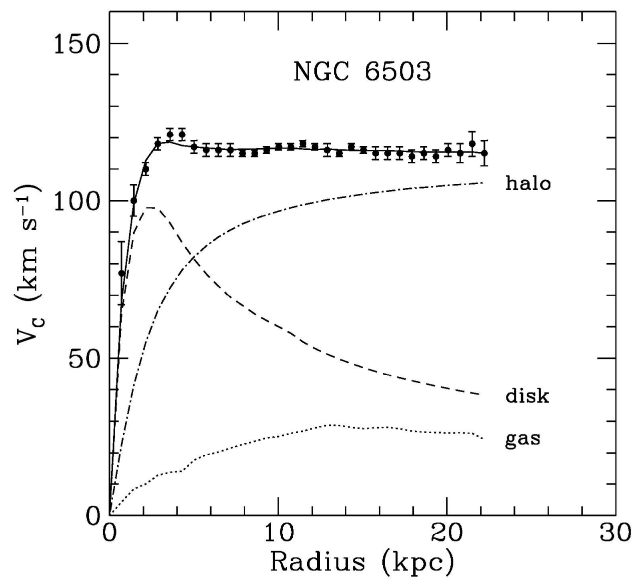
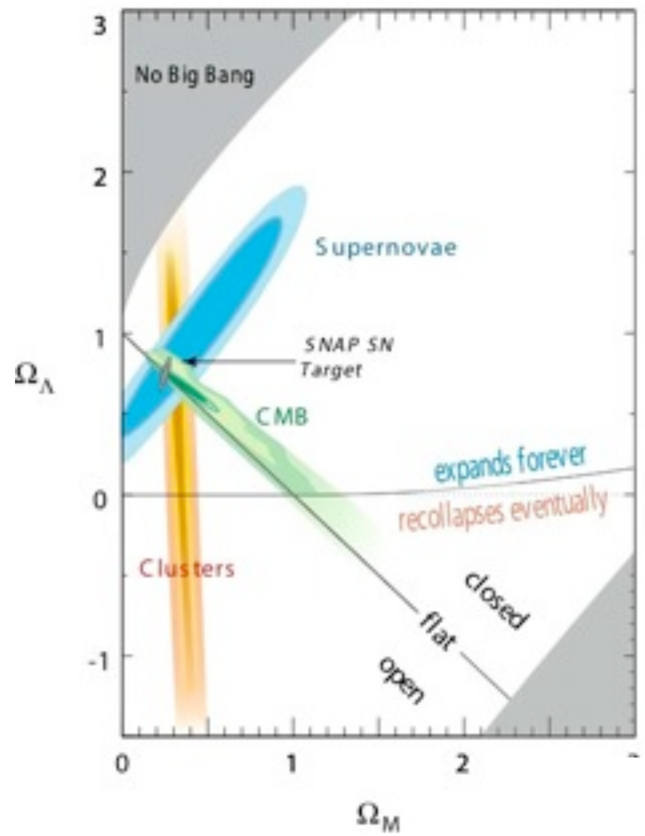
WIMP Dark matter at Future Circular Colliders

Lian-Tao Wang
University of Chicago

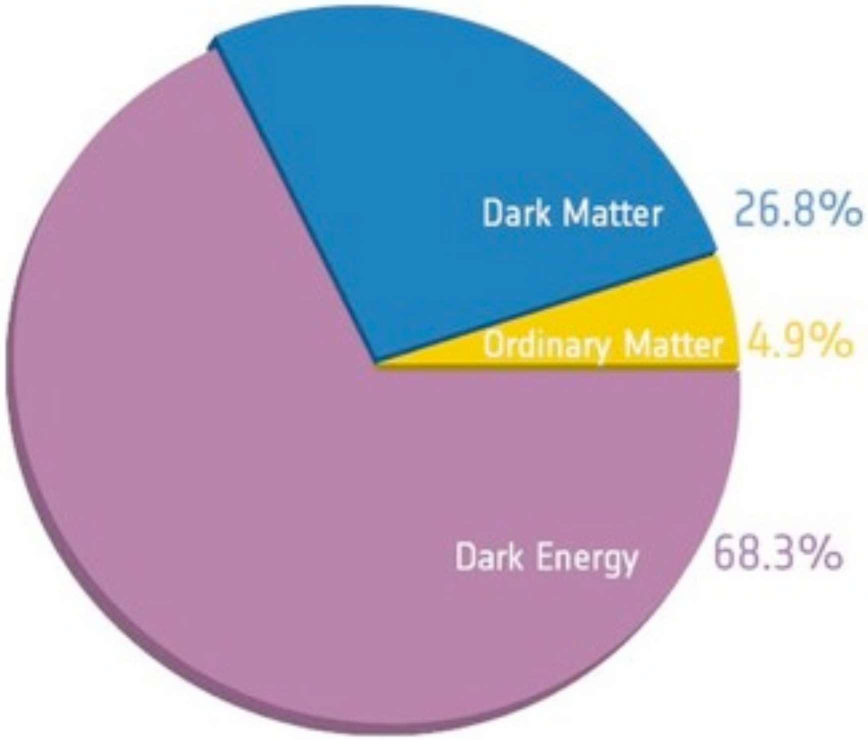
FCC week. Washington DC, March 26, 2015

We have solid evidence for dark matter:





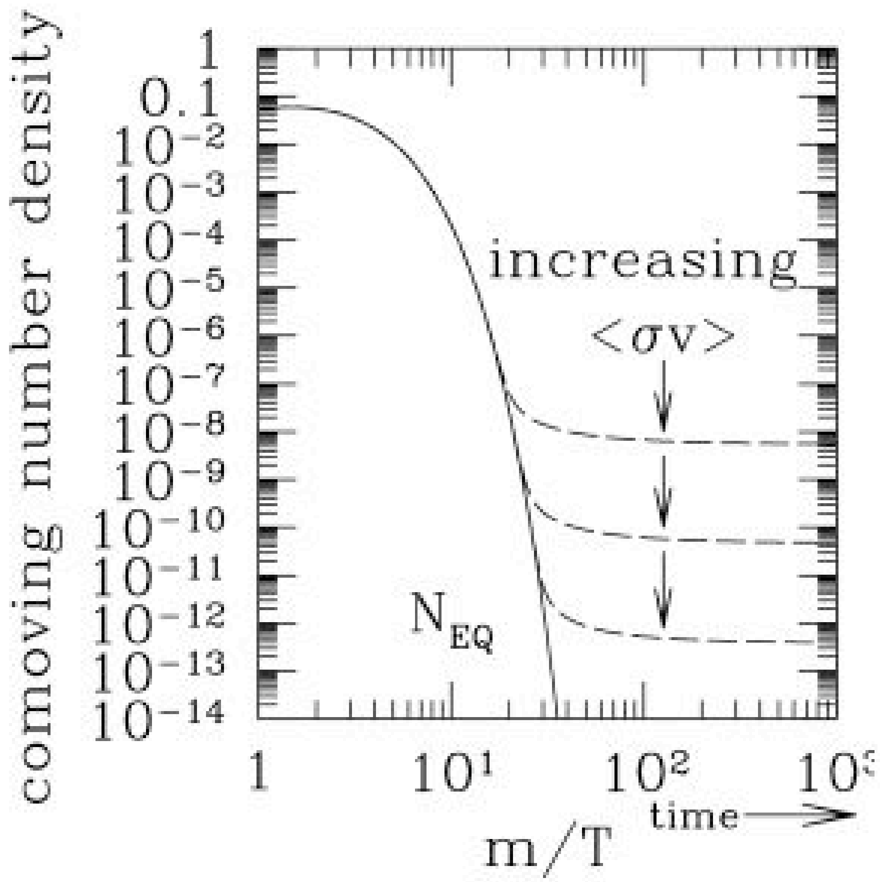
The challenge is to understand its identity.

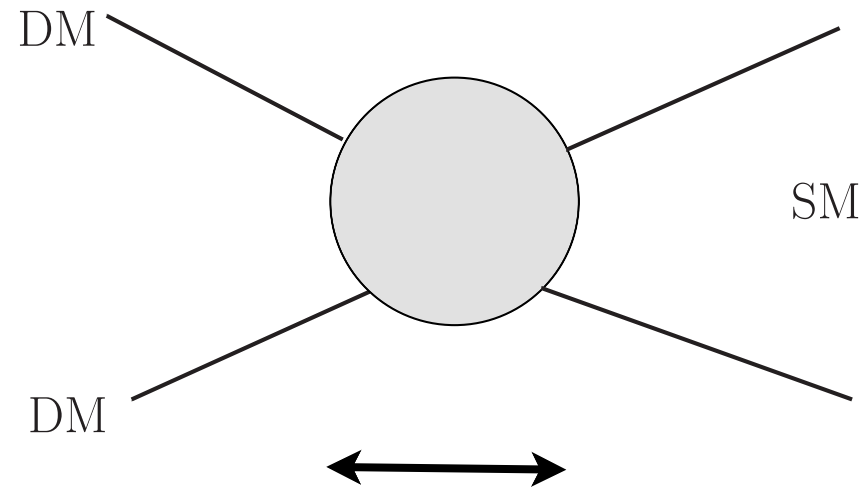


Dark matter candidate?

- We know very little. Vast range of possibilities
  - Can be 10^{-31} GeV to 10^{48} GeV.
- WIMPs
  - A compelling story.
  - Most relevant for the collider searches.
- Other candidates, axion, sterile neutrino...
  - Interesting. Another talk. I will focus on testing WIMP here.

WIMP miracle



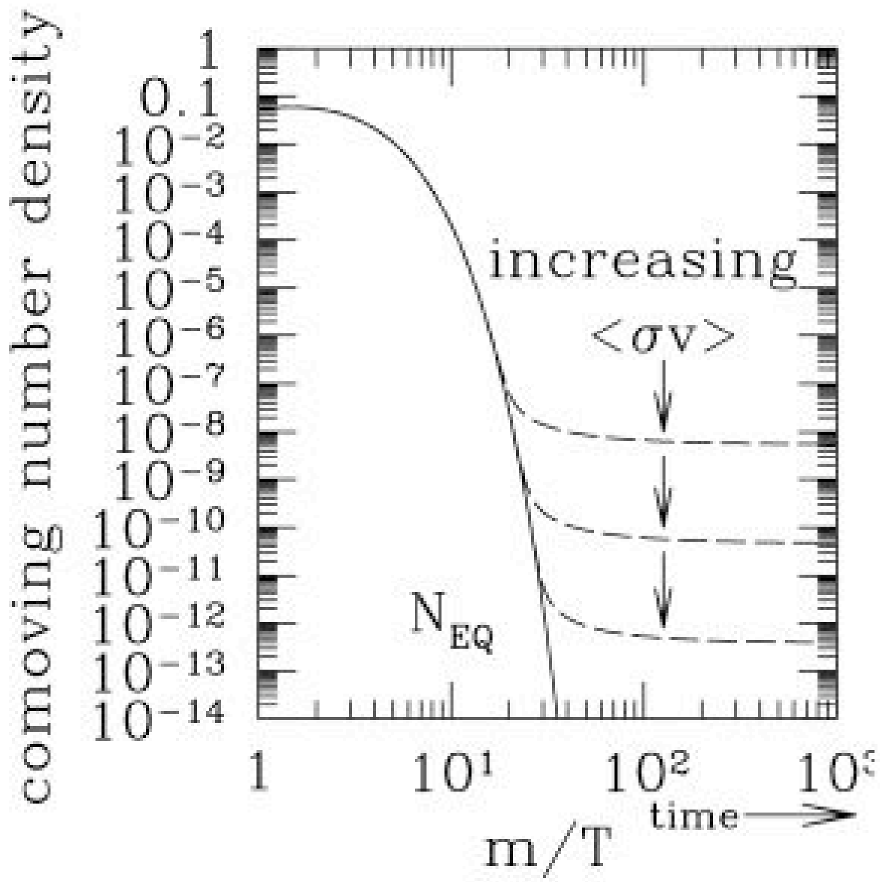


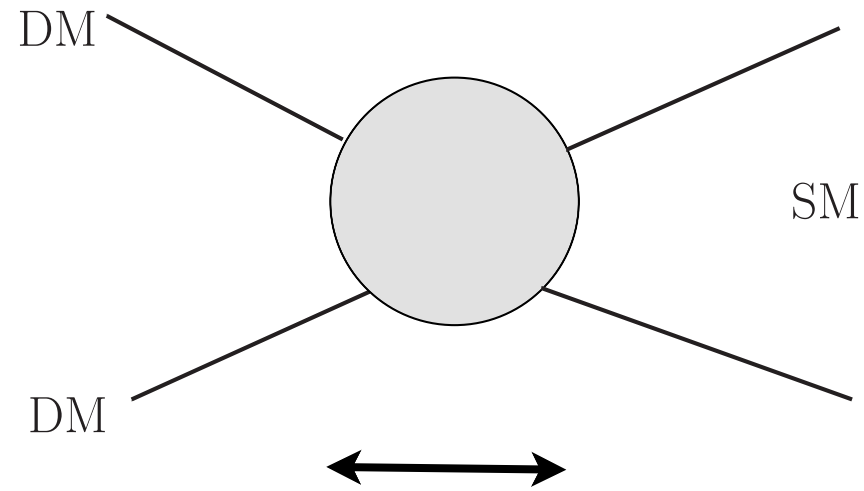
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- 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





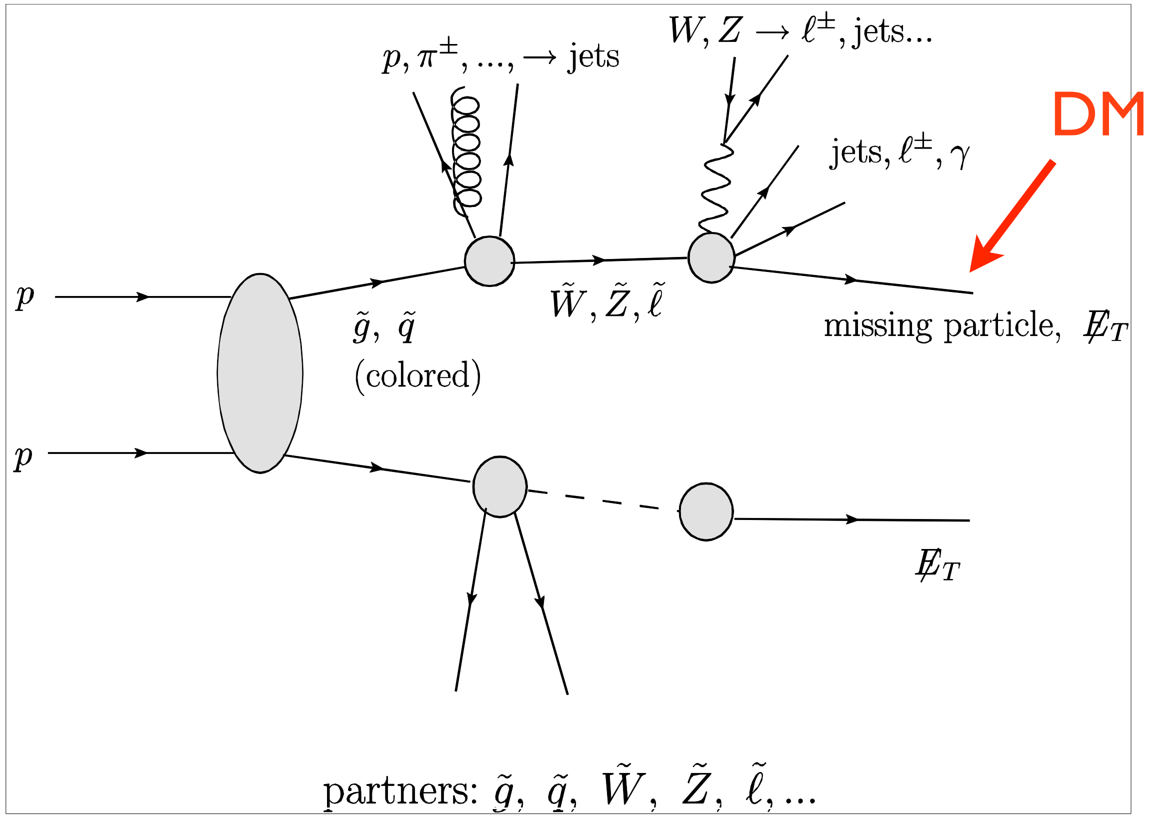
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- 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.

“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.

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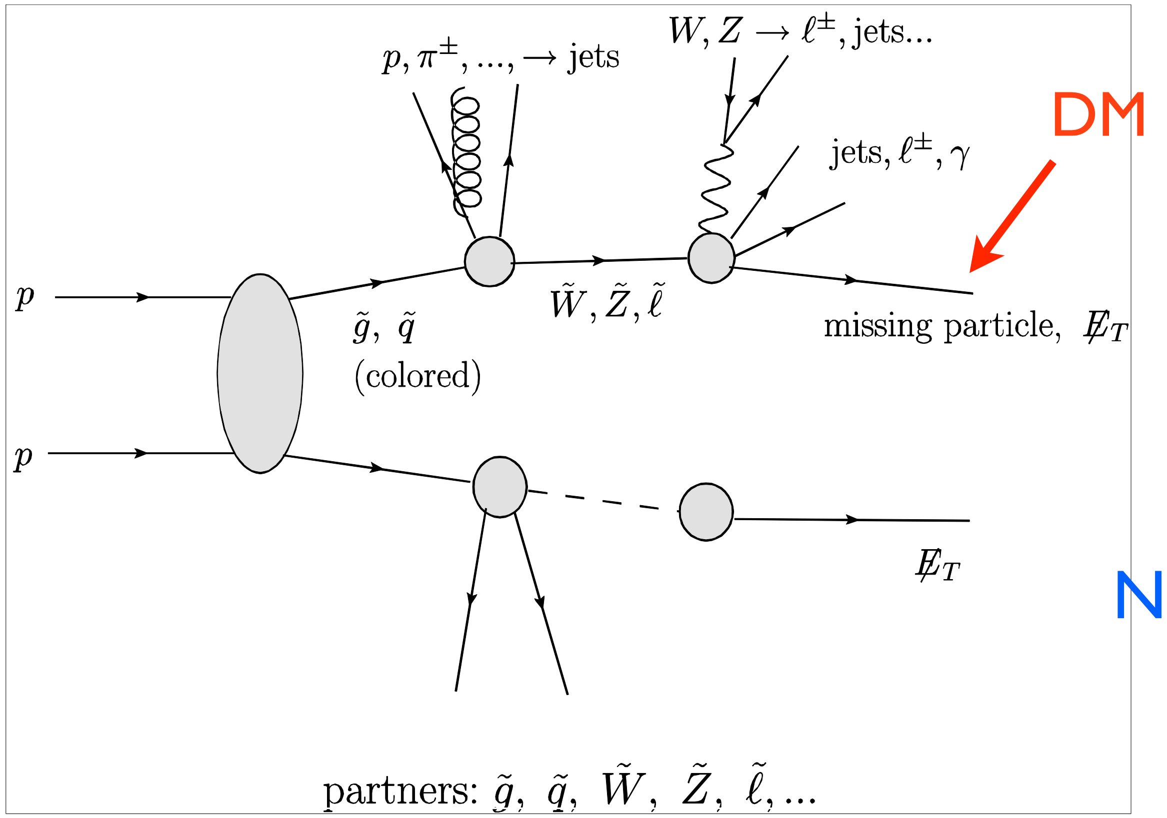
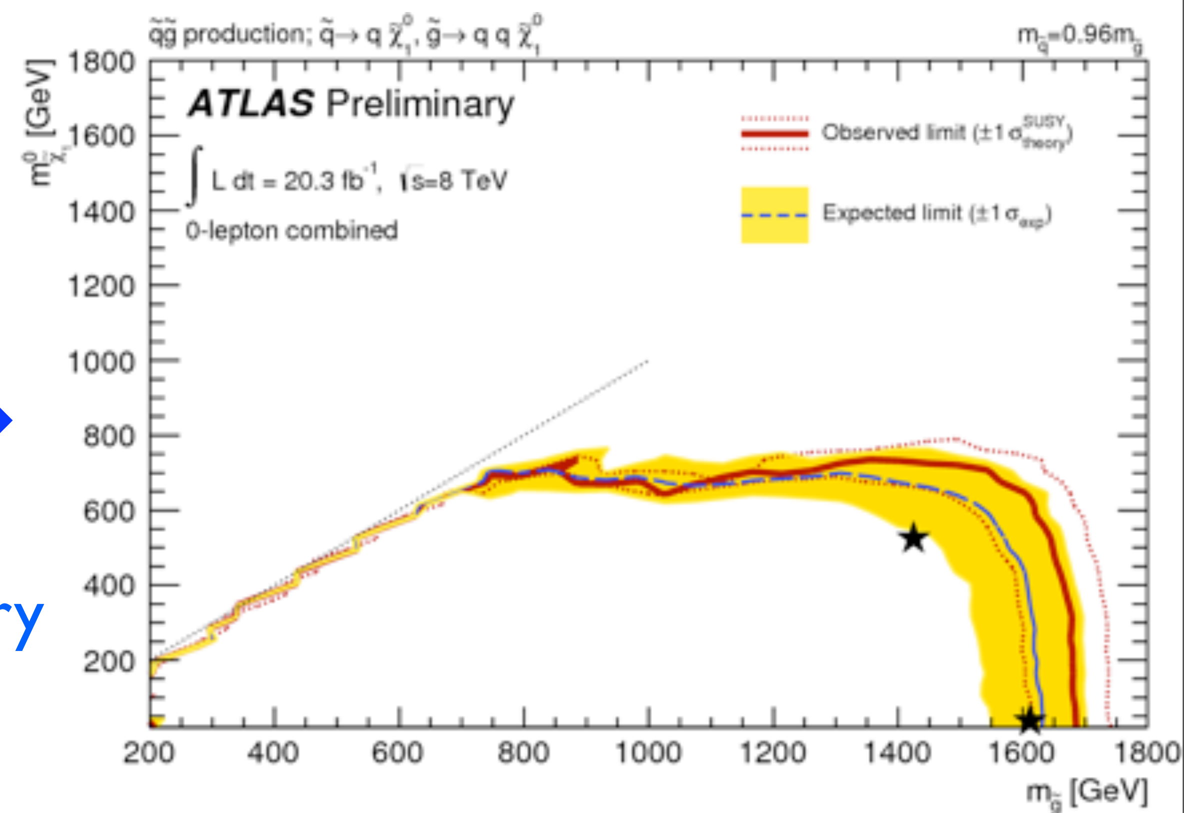


SUSY, UED, etc.

No discovery yet



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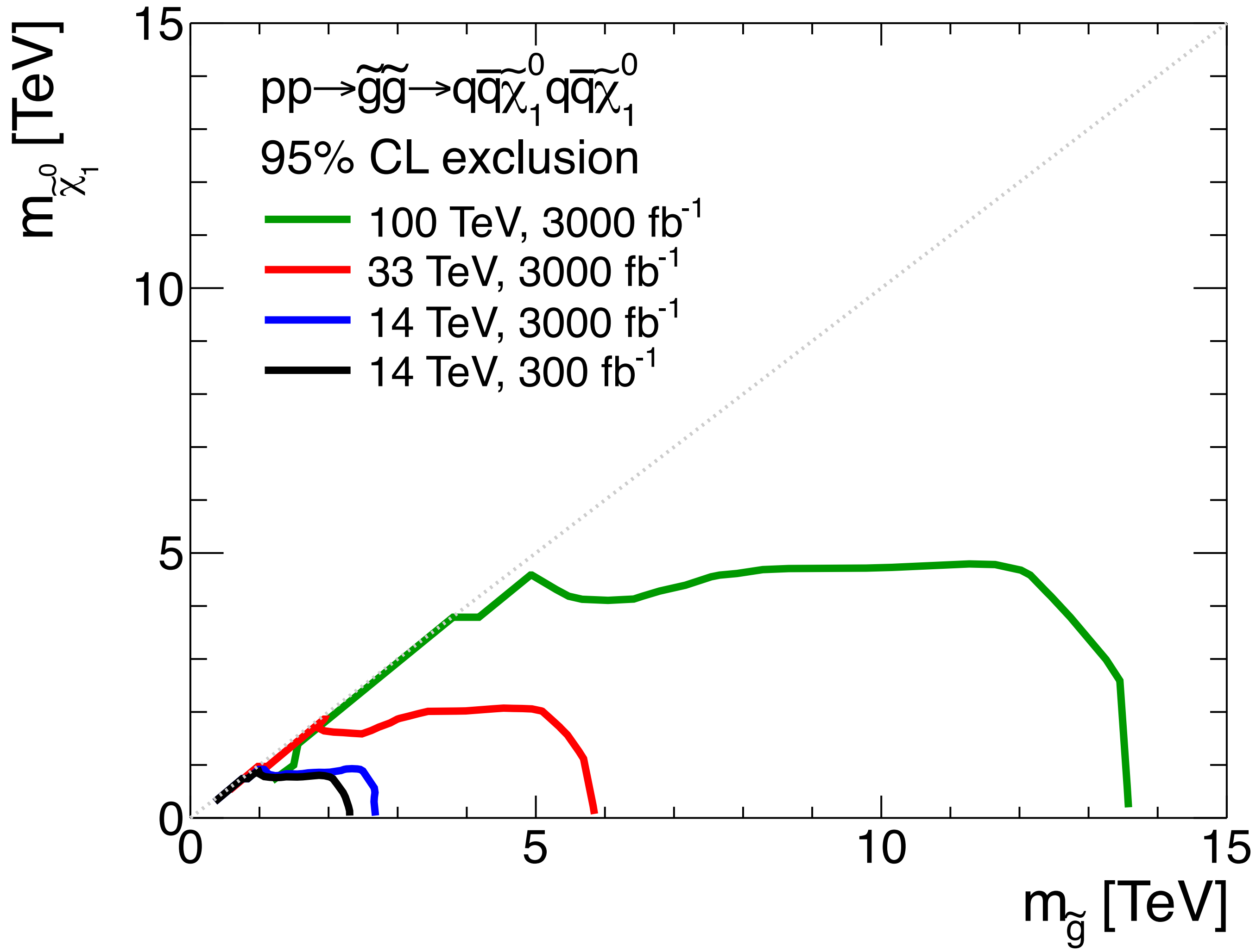
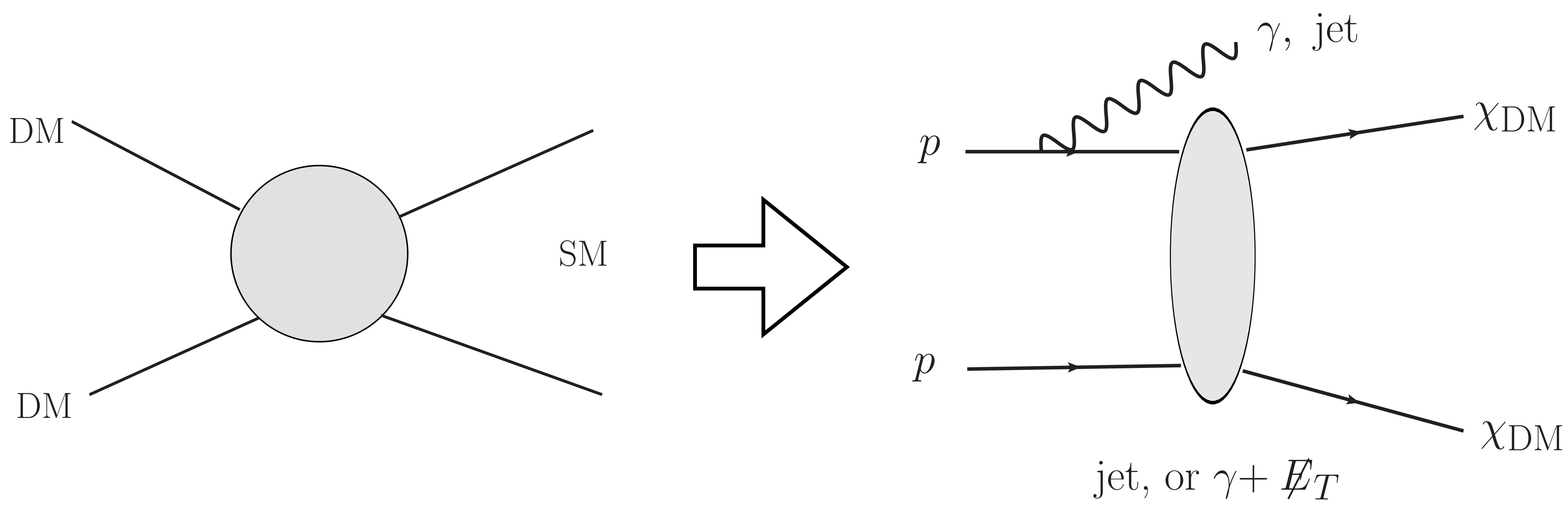


Of course, still plausible, will keep looking.
Higher energy ⇒ higher reach

Back to basics

- pair production + additional radiation.

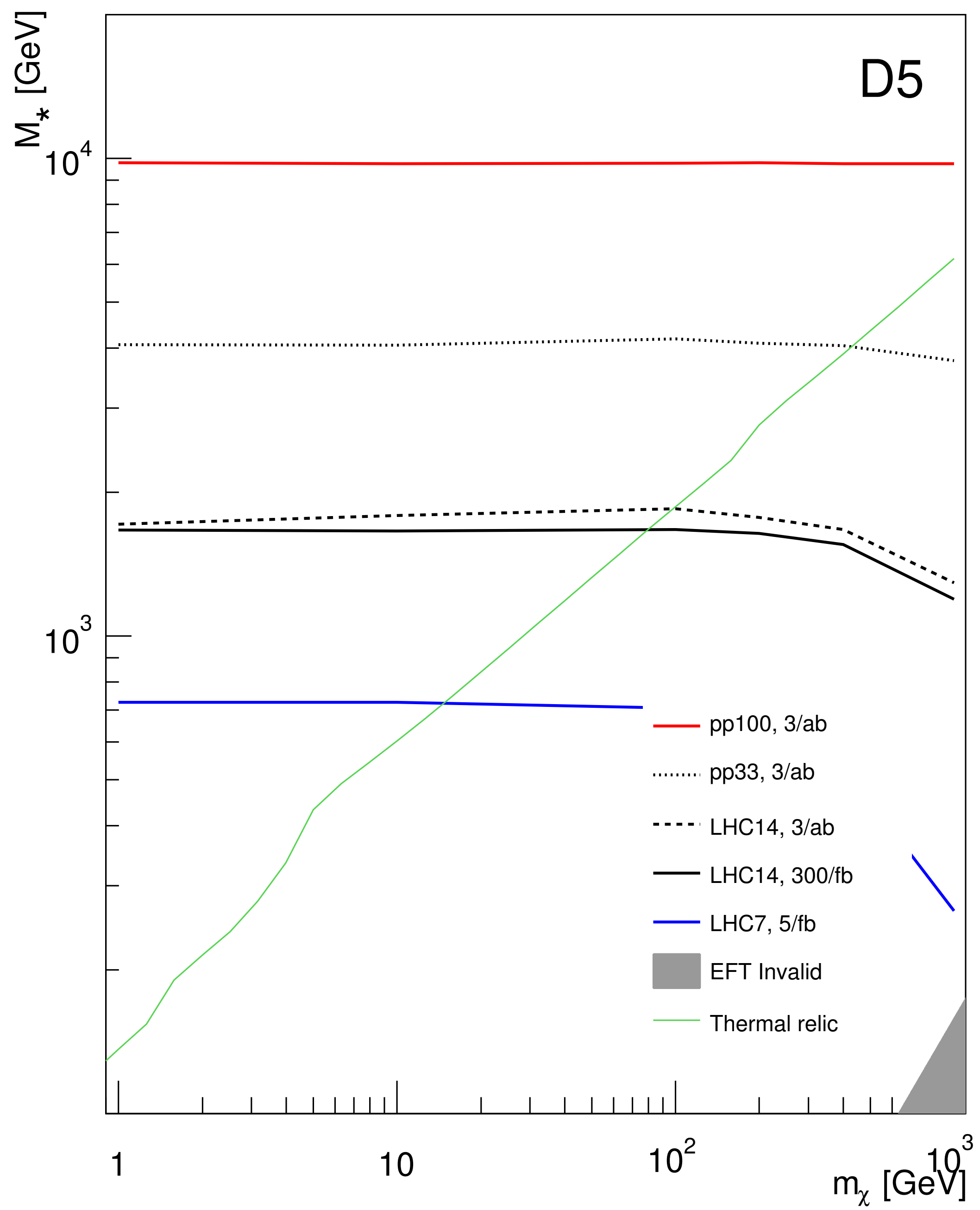


- Mono-jet, mono-photon, mono-...

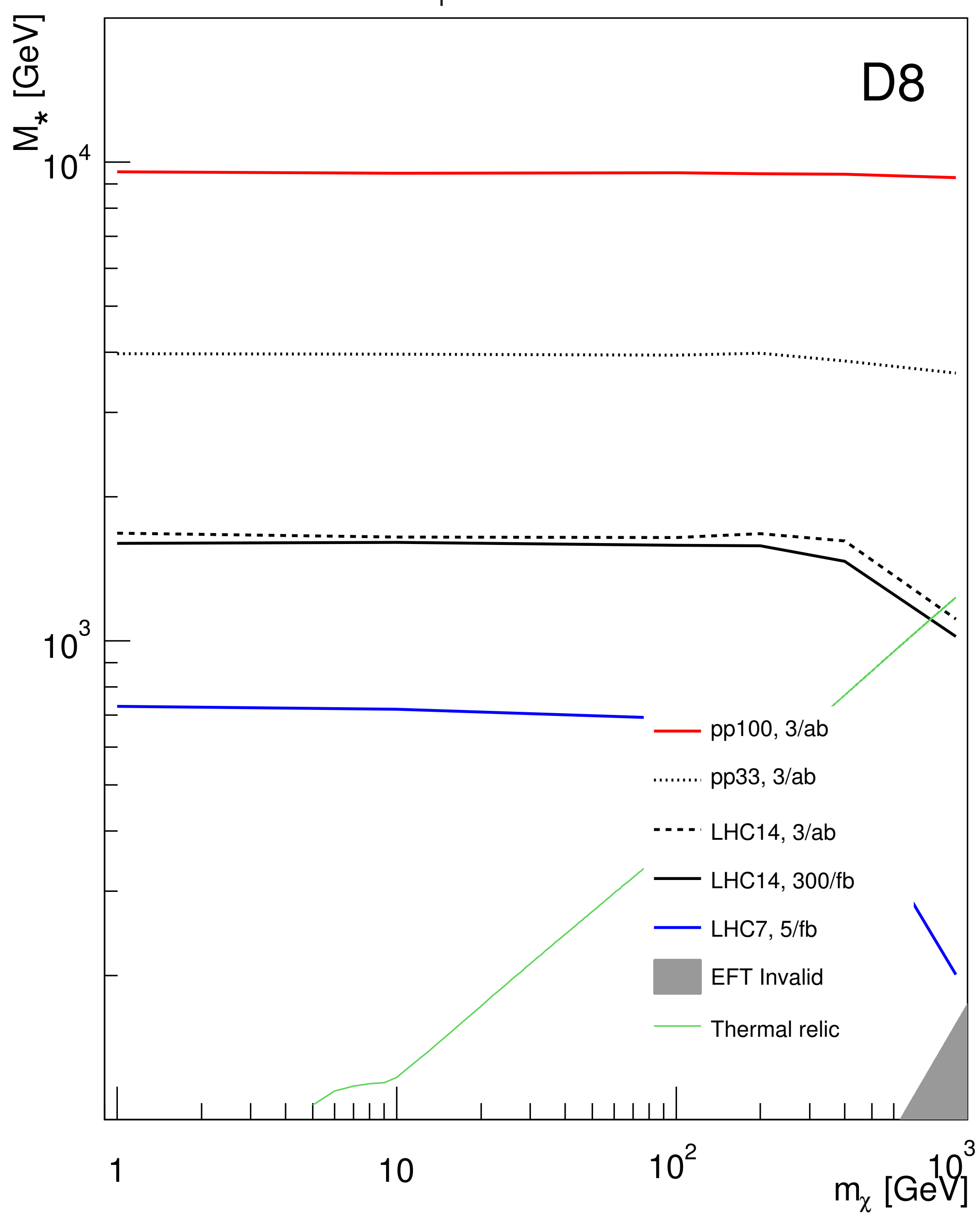
- Have become "Standard" LHC searches.

At future colliders

D5 $\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$

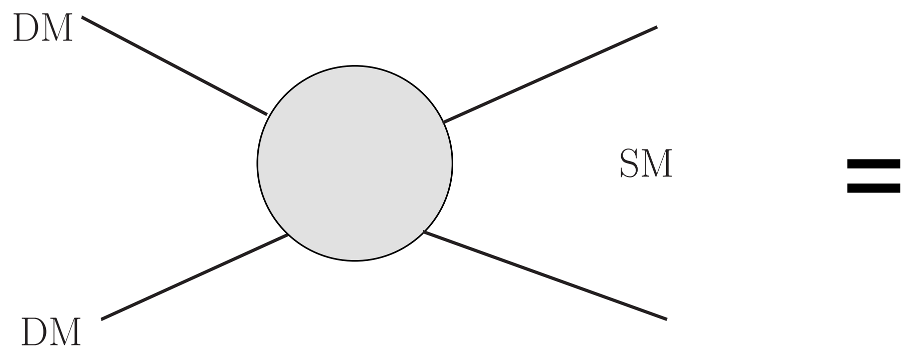


D8 $\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$



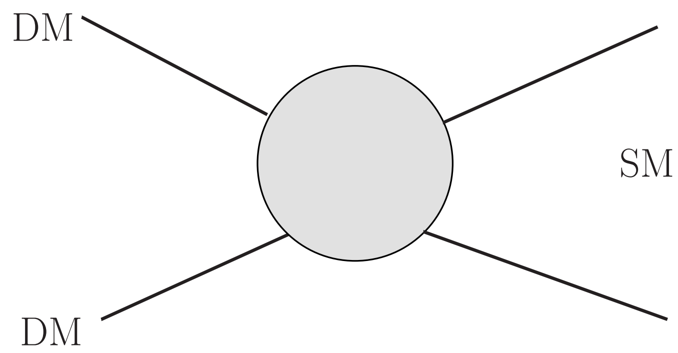
Snowmass, 2013

Going beyond the EFT



- Valid as field theory?
  - Already questionable in run 1, will be quite problematic at for run 2.
  - Much worse at 100 TeV. Overestimation of the reach.
- At the same time, missing other physics opportunities, such as additional states to look for.

Going beyond the EFT



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

- Valid as field theory?
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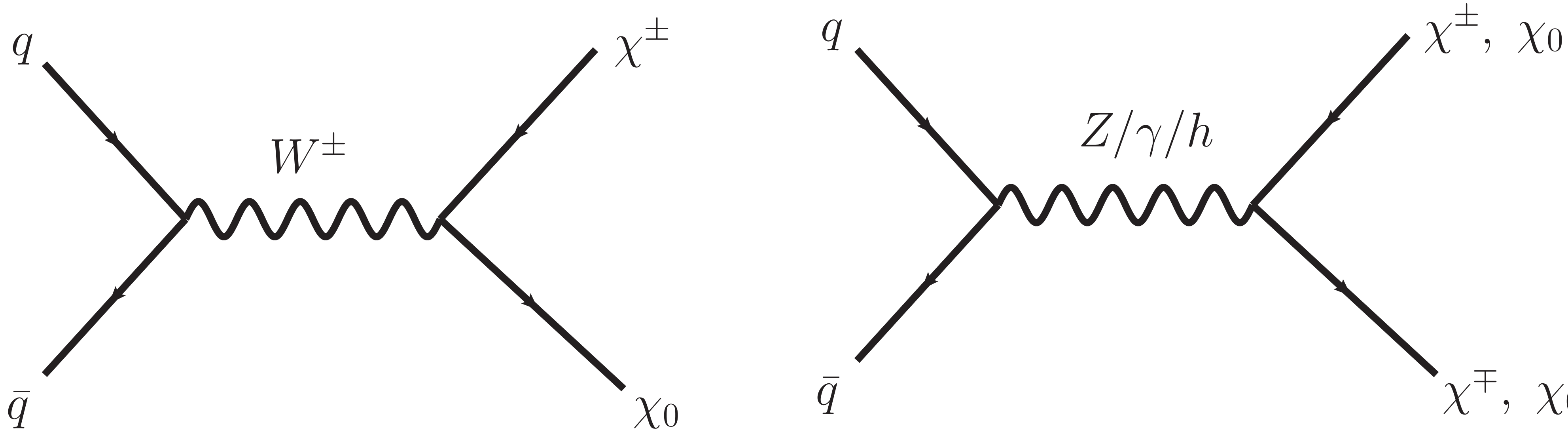
Two simple ways of going beyond

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

- Singlet dark matter + new mediator

DM part of a weak multiplet



- Mediated by W/Z/h.
- Additional charged states.

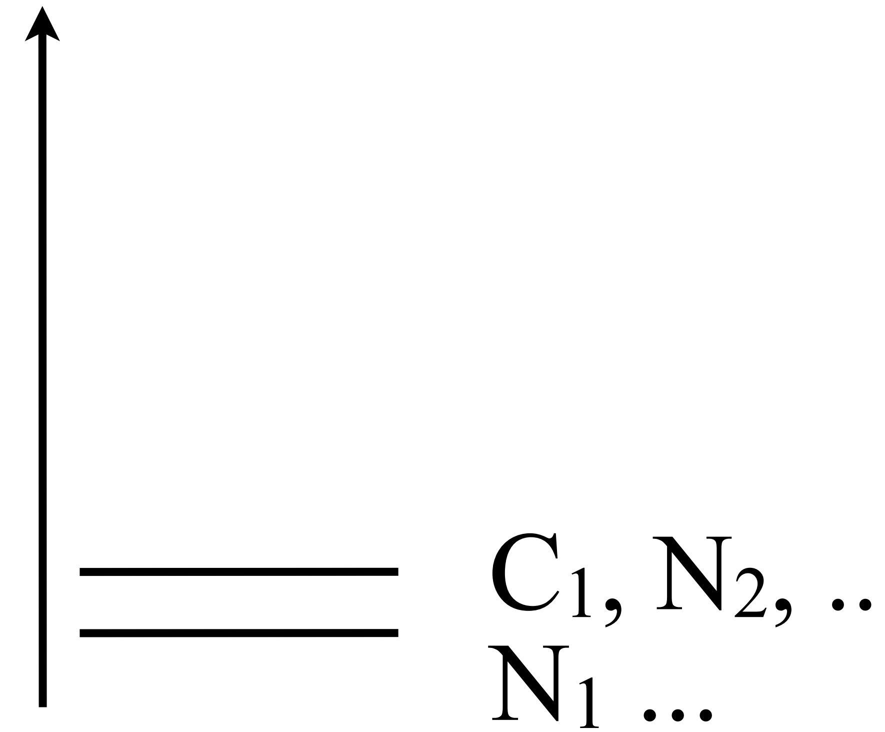
SUSY as an example

- 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

Two different cases

Compressed/degenerate
e.g., pure wino, pure Higgsino, Well temper...

Relying on
ISR: mono-jet, mono-photon...
Soft lepton, displaced tracks



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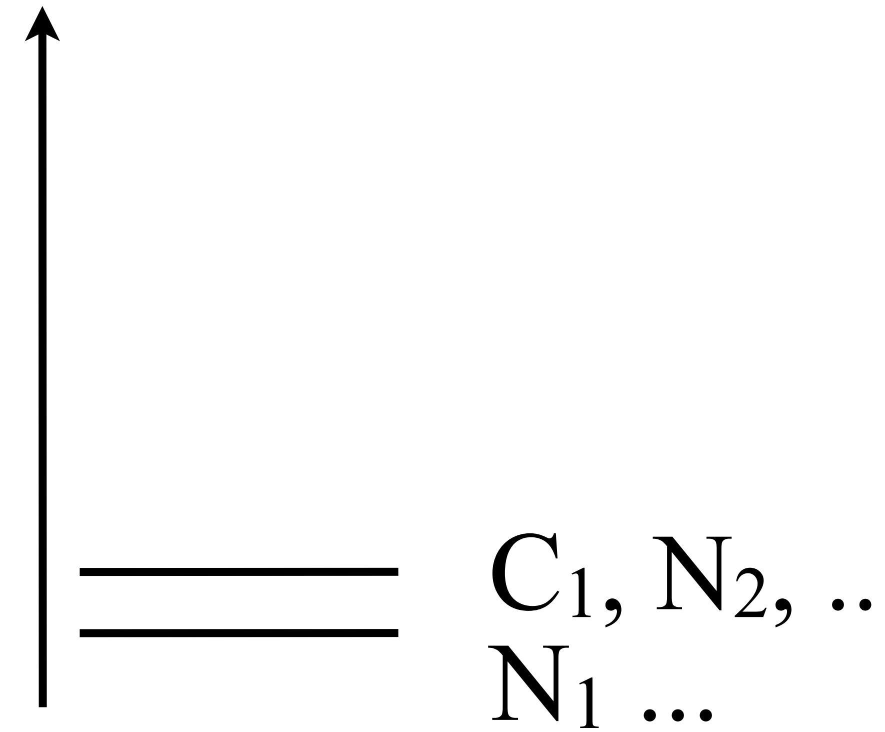
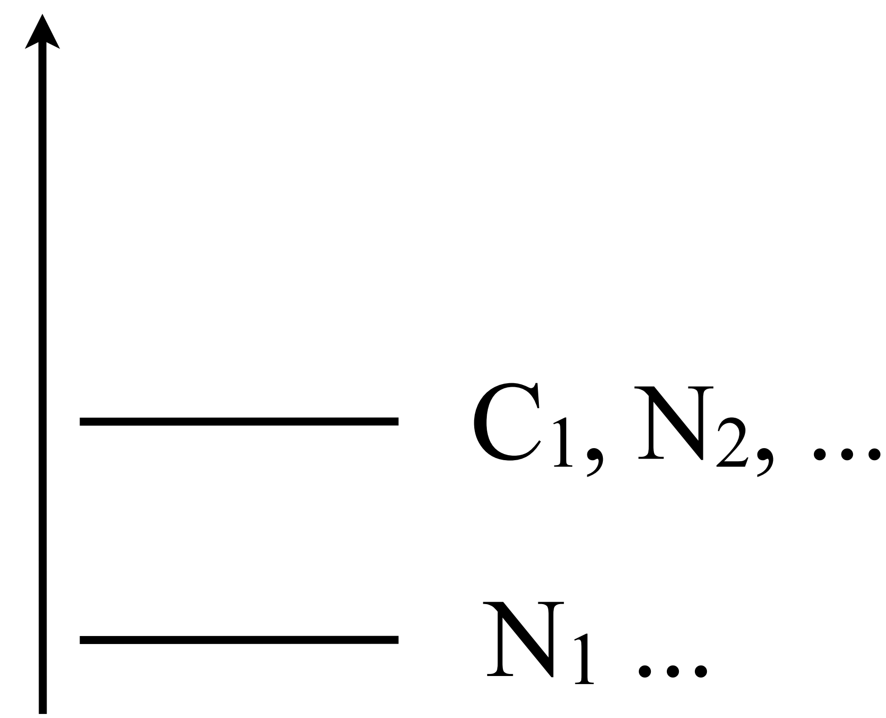


Larger separation in mass spectrum
Cascade decay gives multilepton signal.



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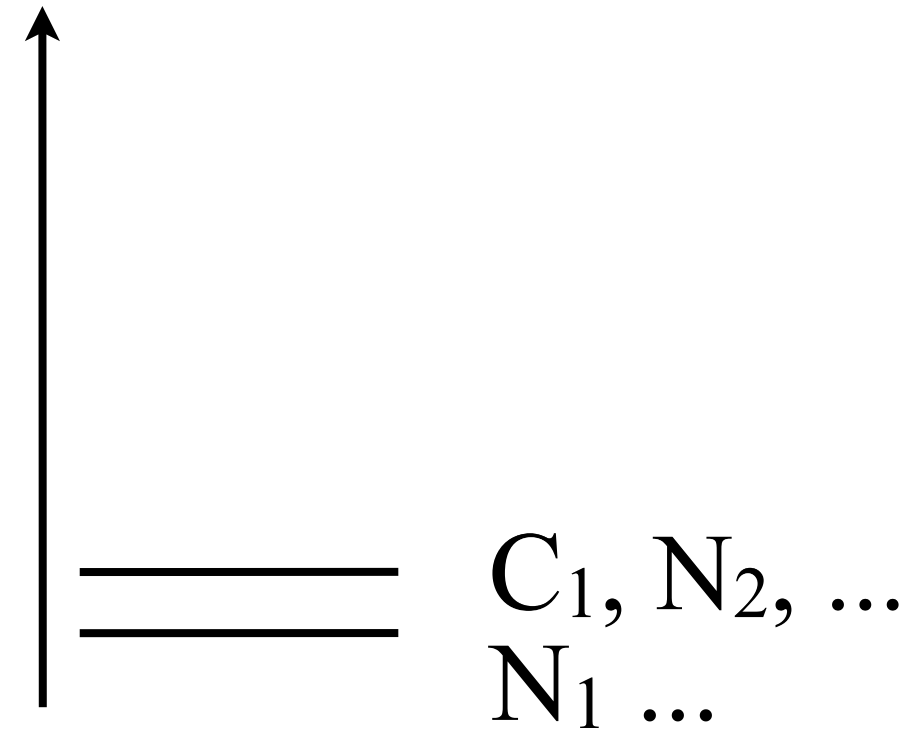

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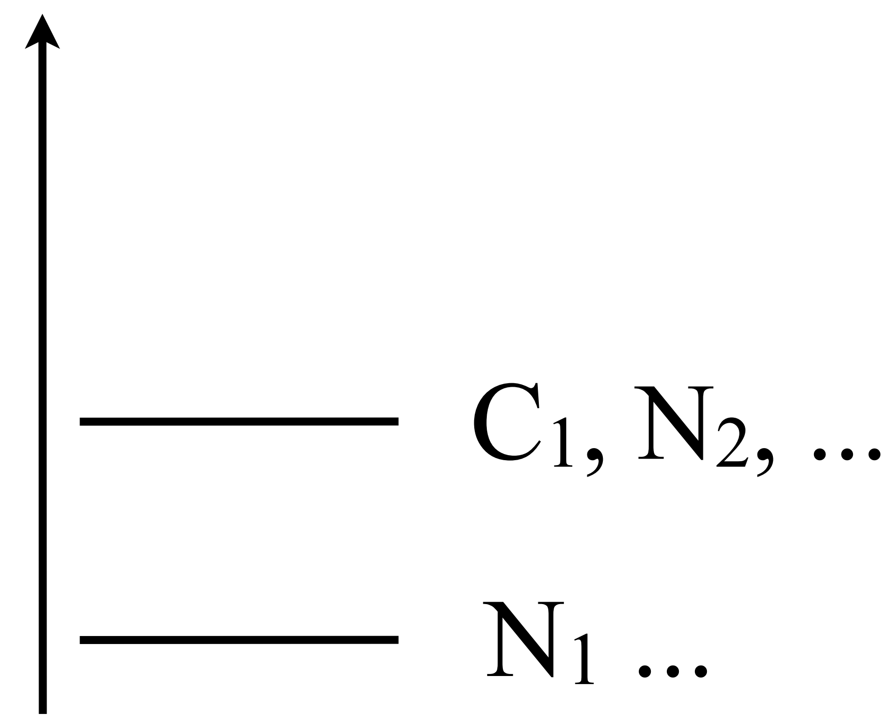
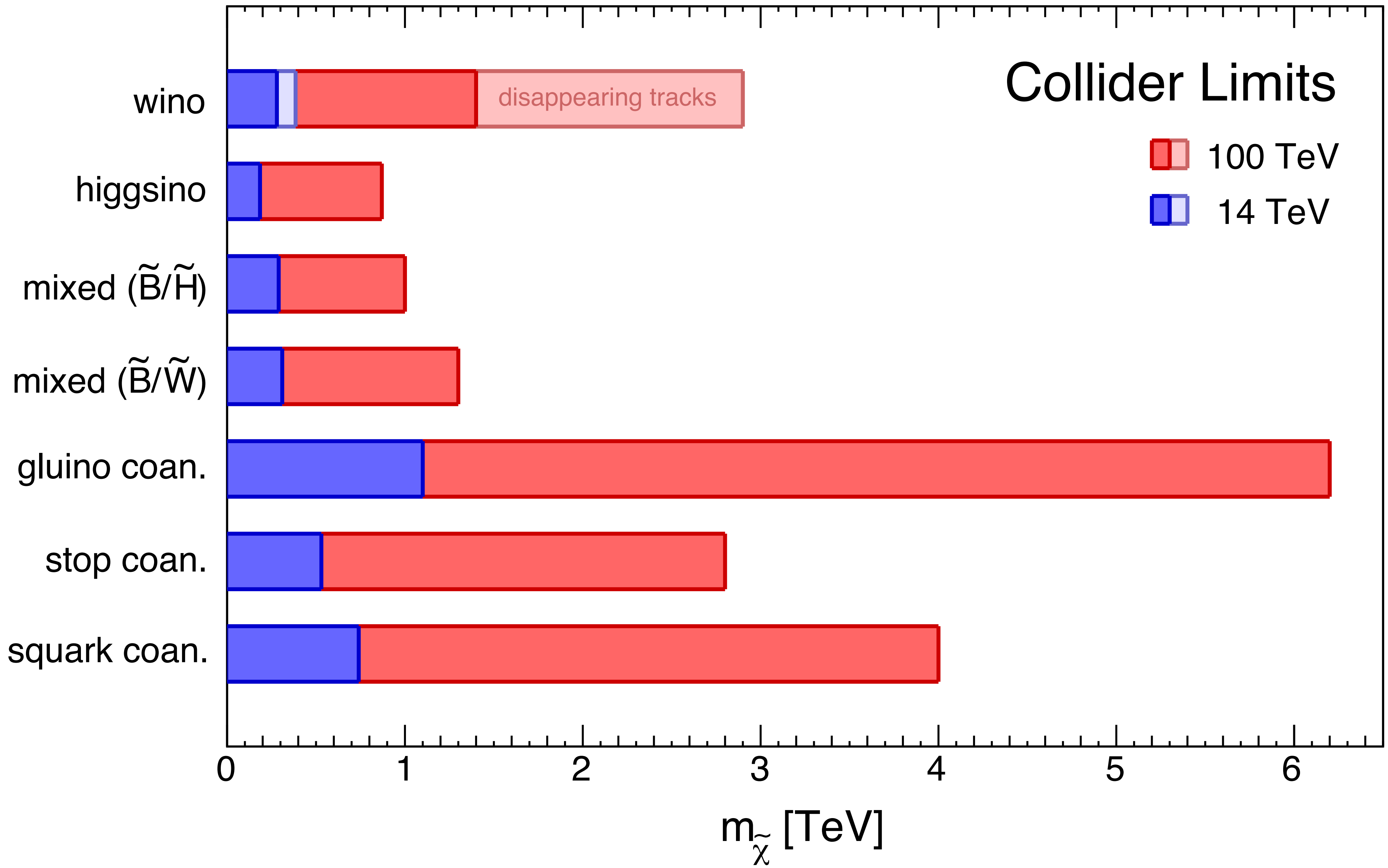


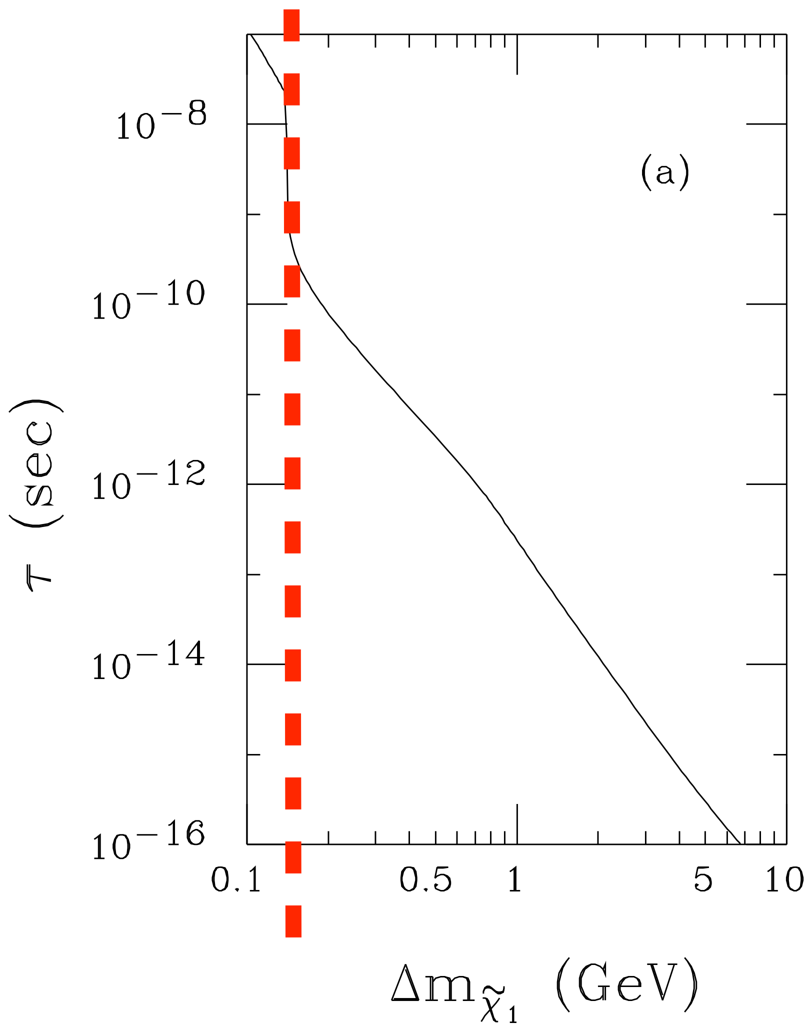
Matthew Low, LTW

Mono-jet



- Significant step beyond the LHC.

Disappearing track



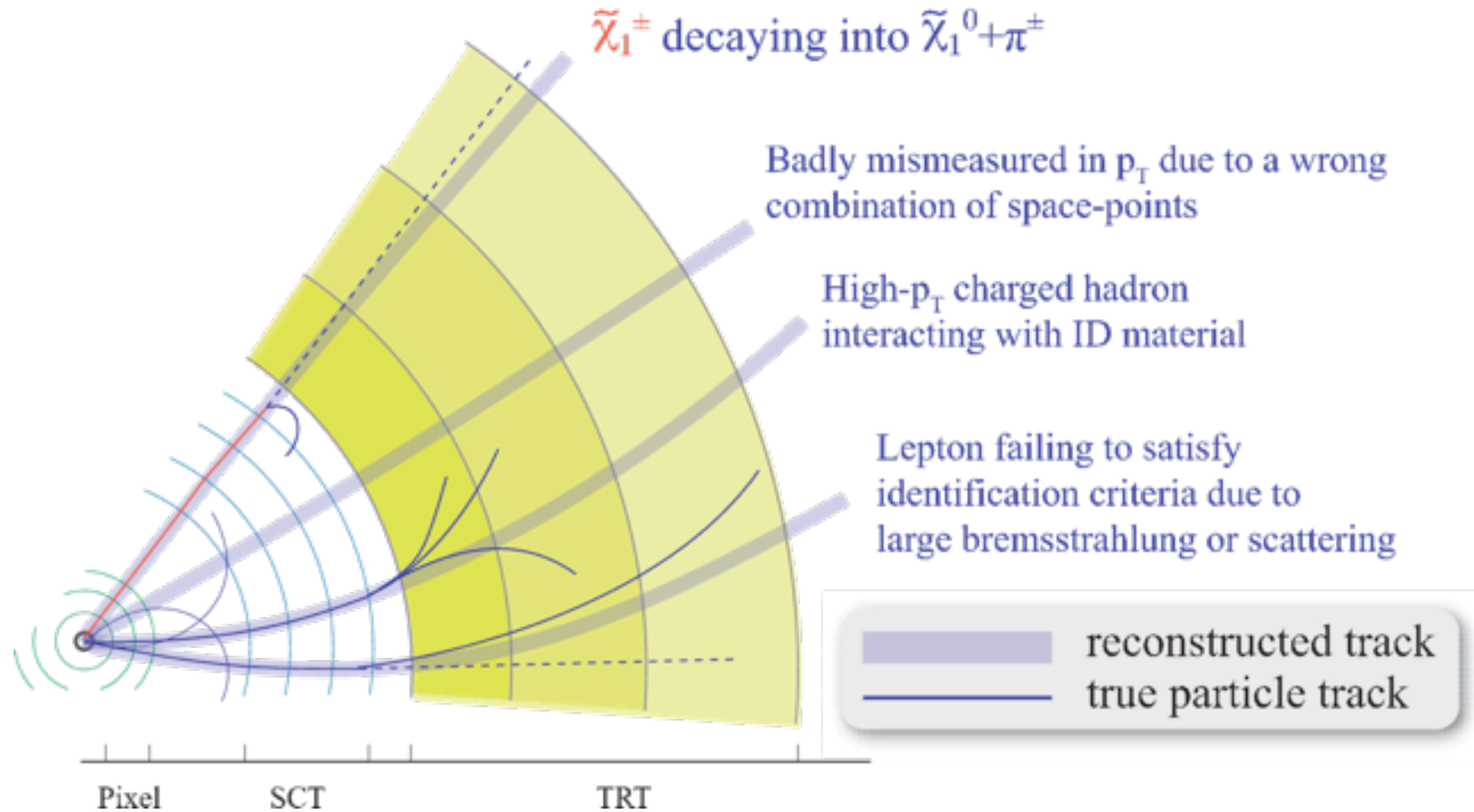
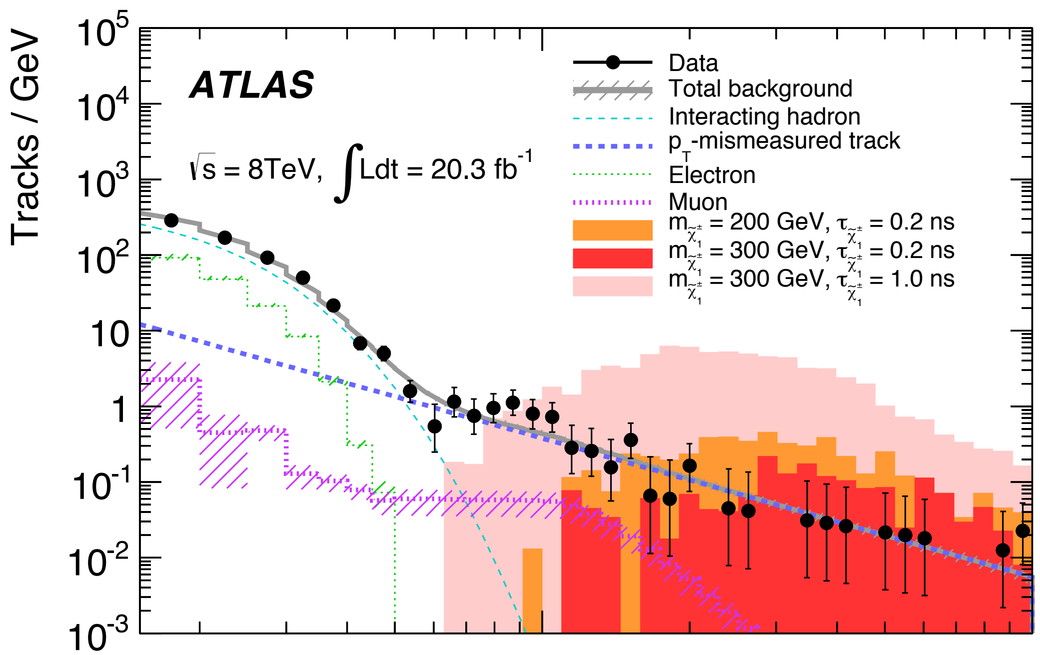


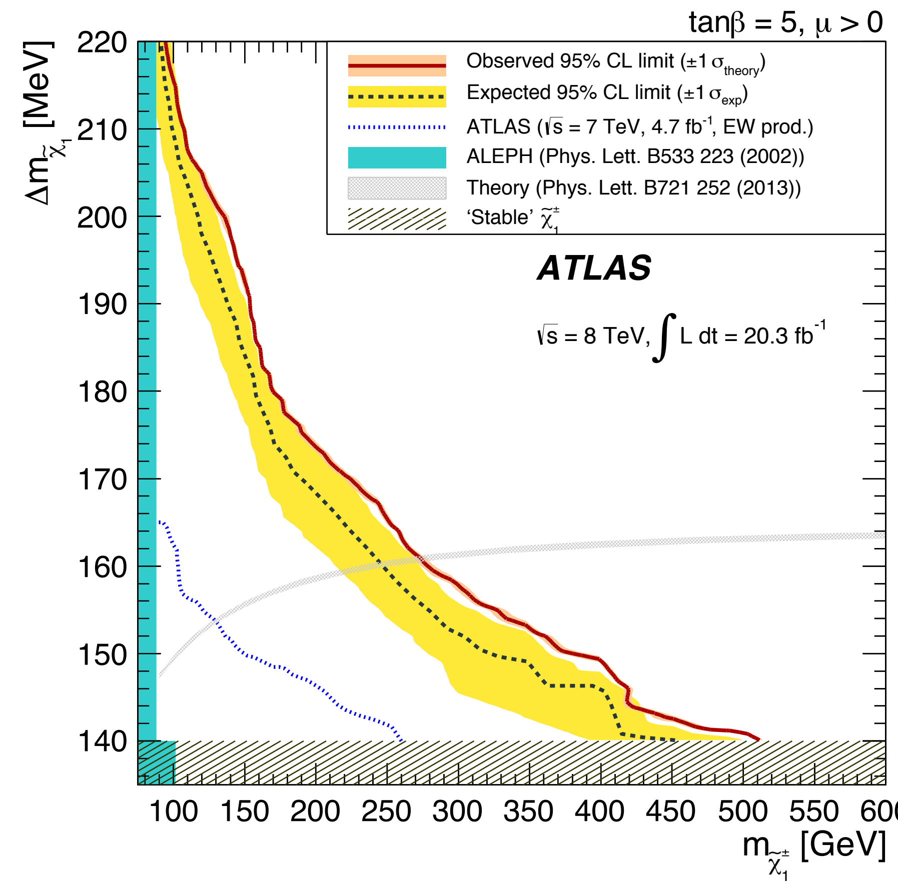
Figure from ATLAS disappearing track search twiki

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

ATLAS search

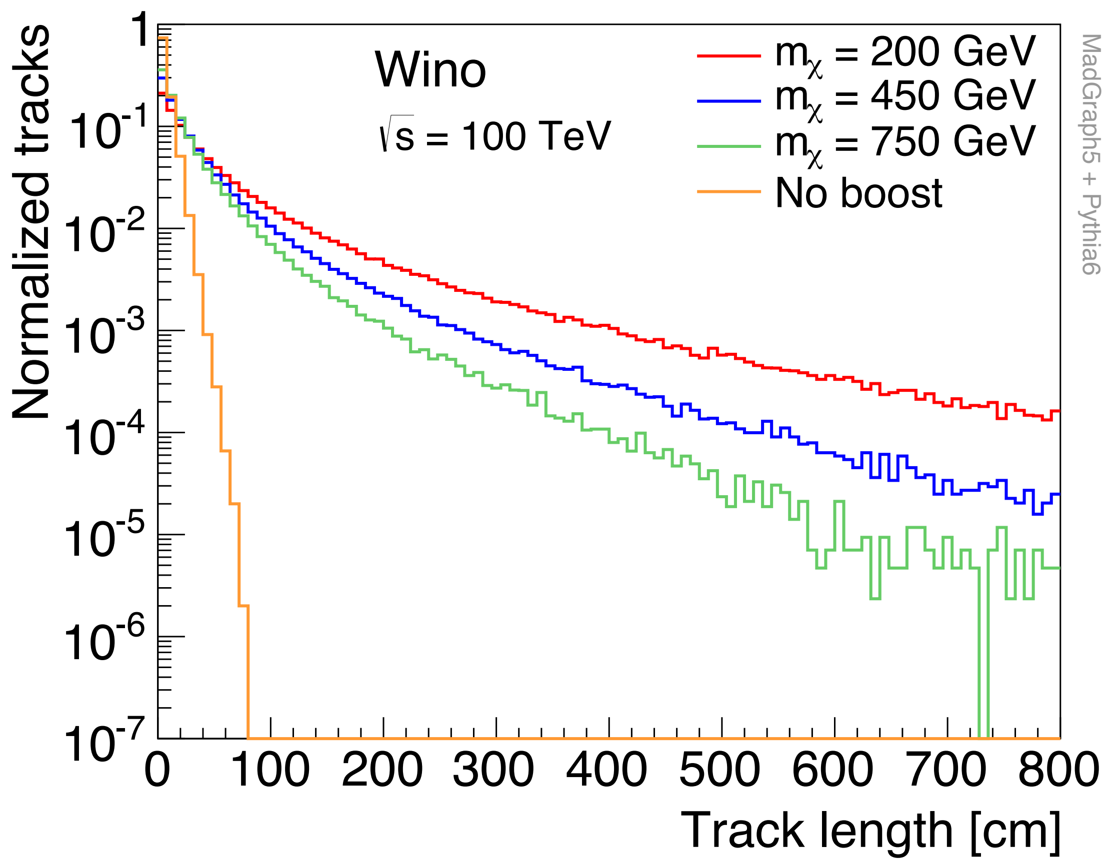
ATLAS, 1310.3675

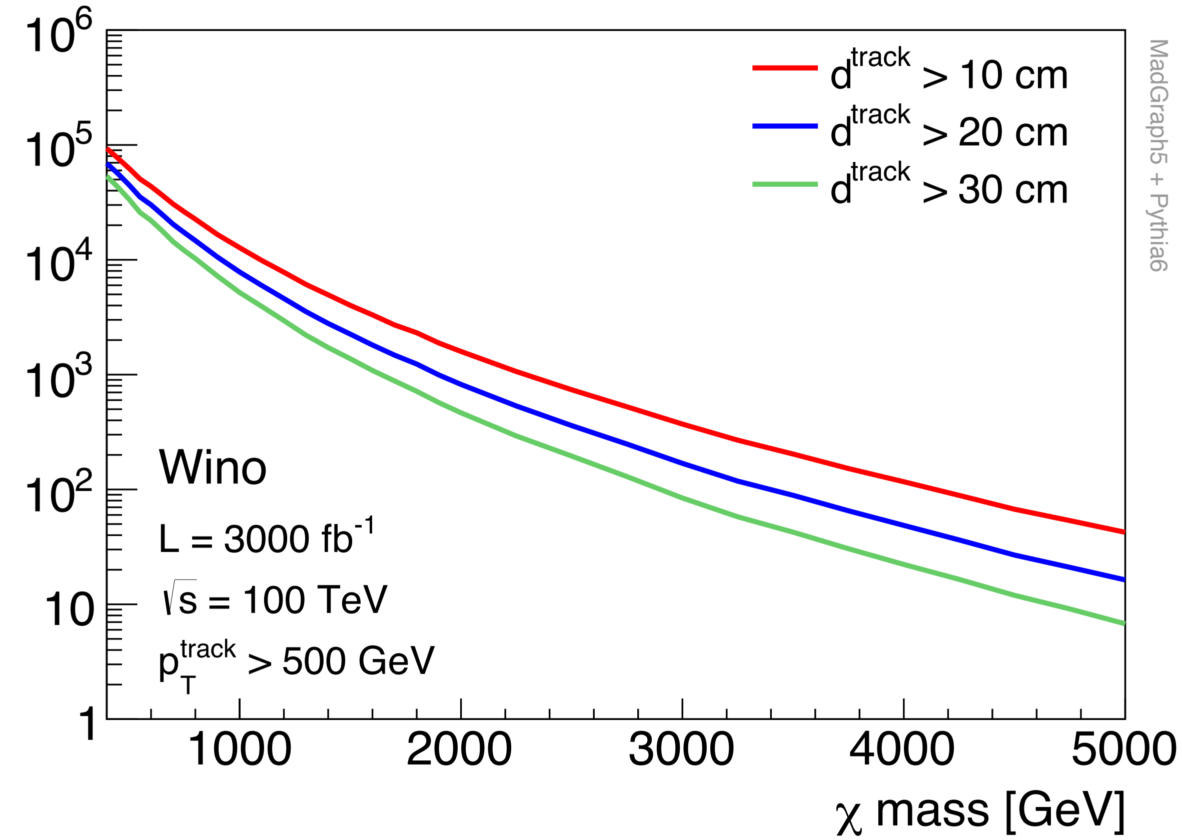




- Essentially free of physics background.
- Dominated by p_T mis-measured tracks.
- Very promising reach, much better than mono-jet

Rates (with long tracks)

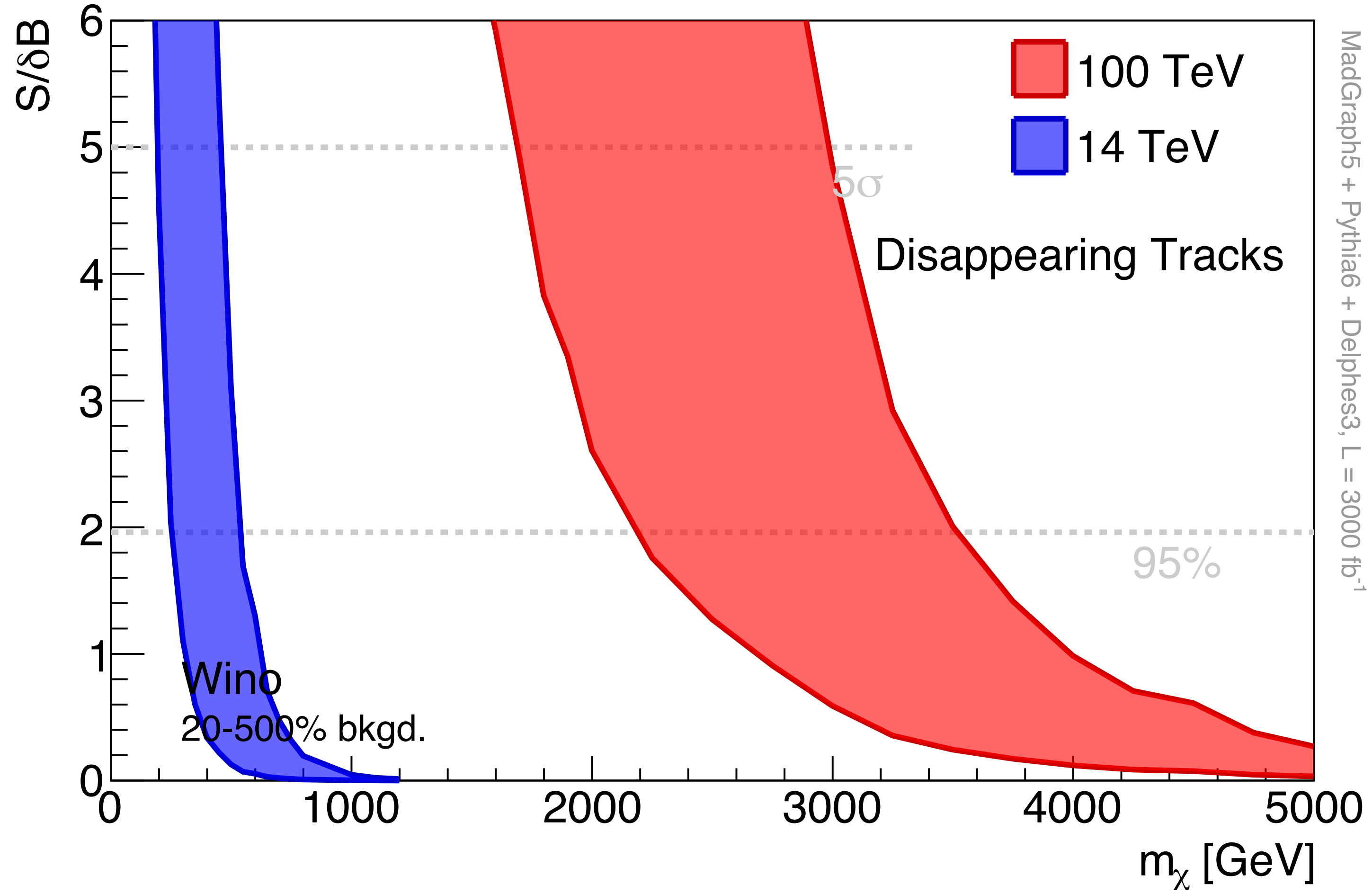




- Disappearing track, stub, kink...

- Could also be long lived

(Rough) Extrapolation from ATLAS search

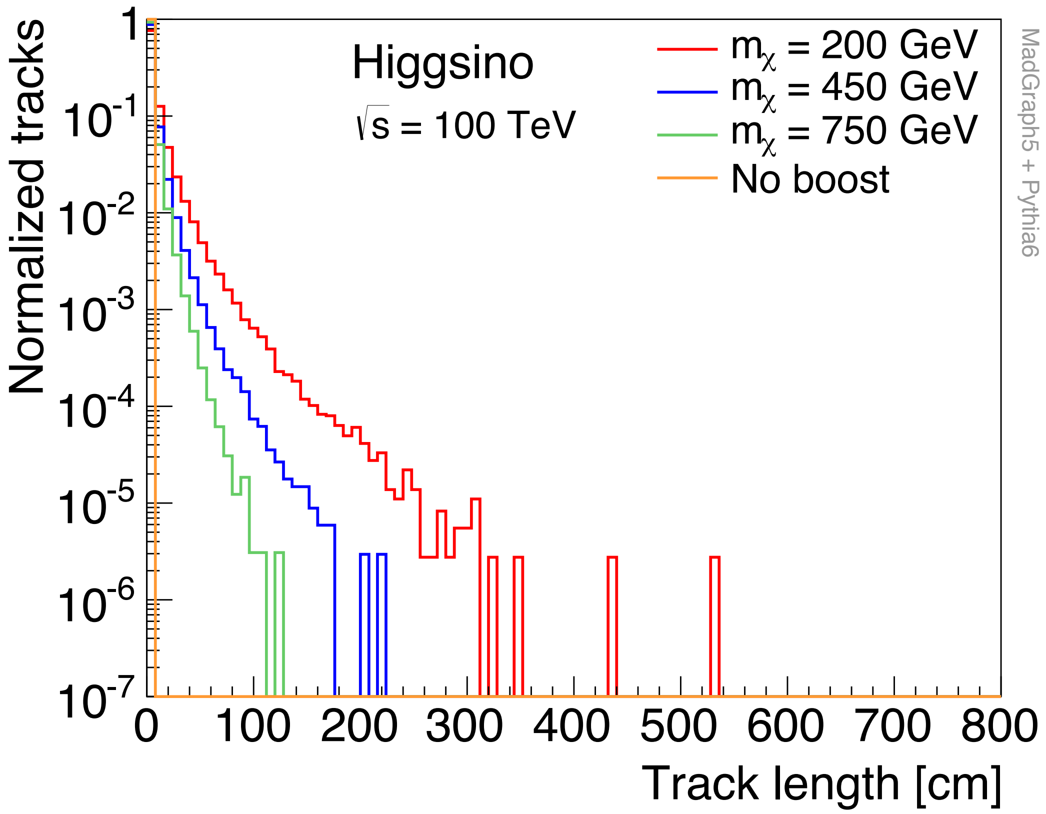


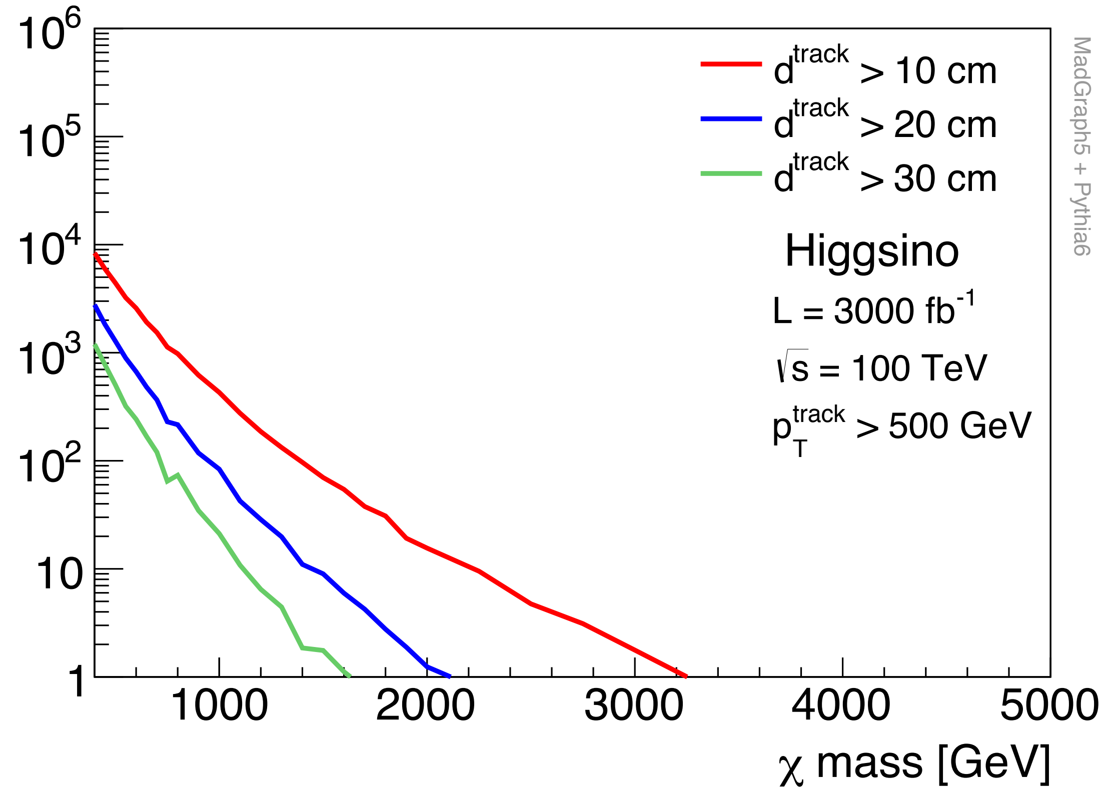
- Scale the ATLAS background rates according to hard jet + MET rates.

- Band: varying background estimate by 5 either way.

More from Phil Harris' talk

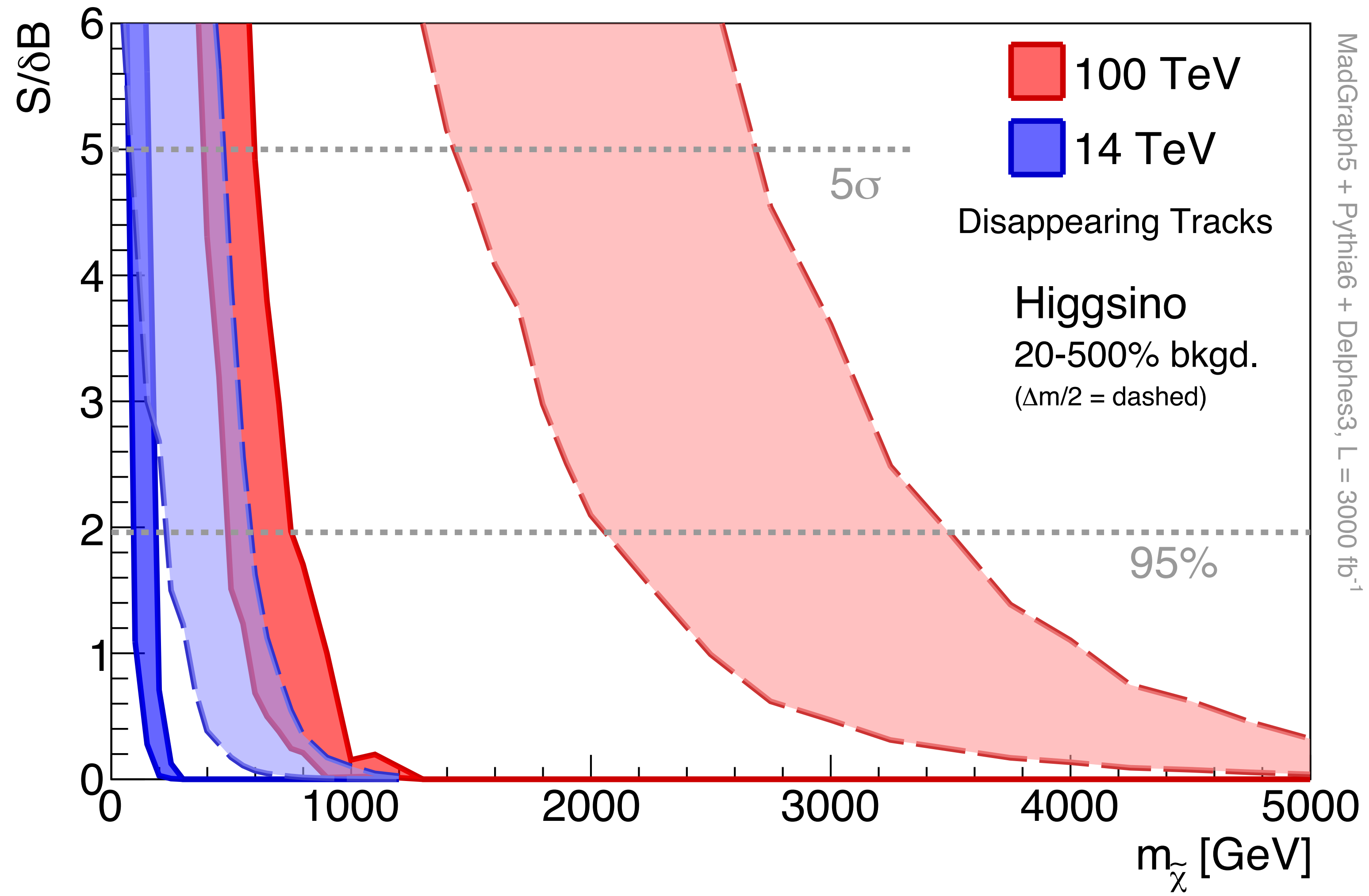
Do something about Higgsino?





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

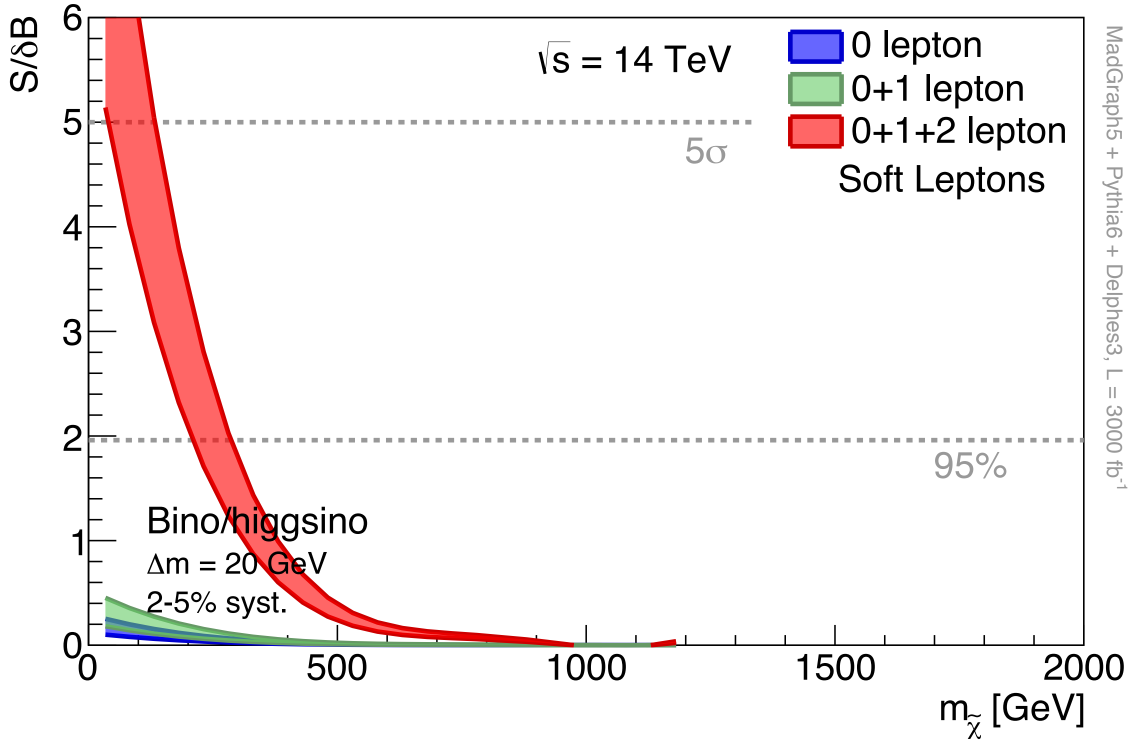
Higgsino with smaller mass splitting



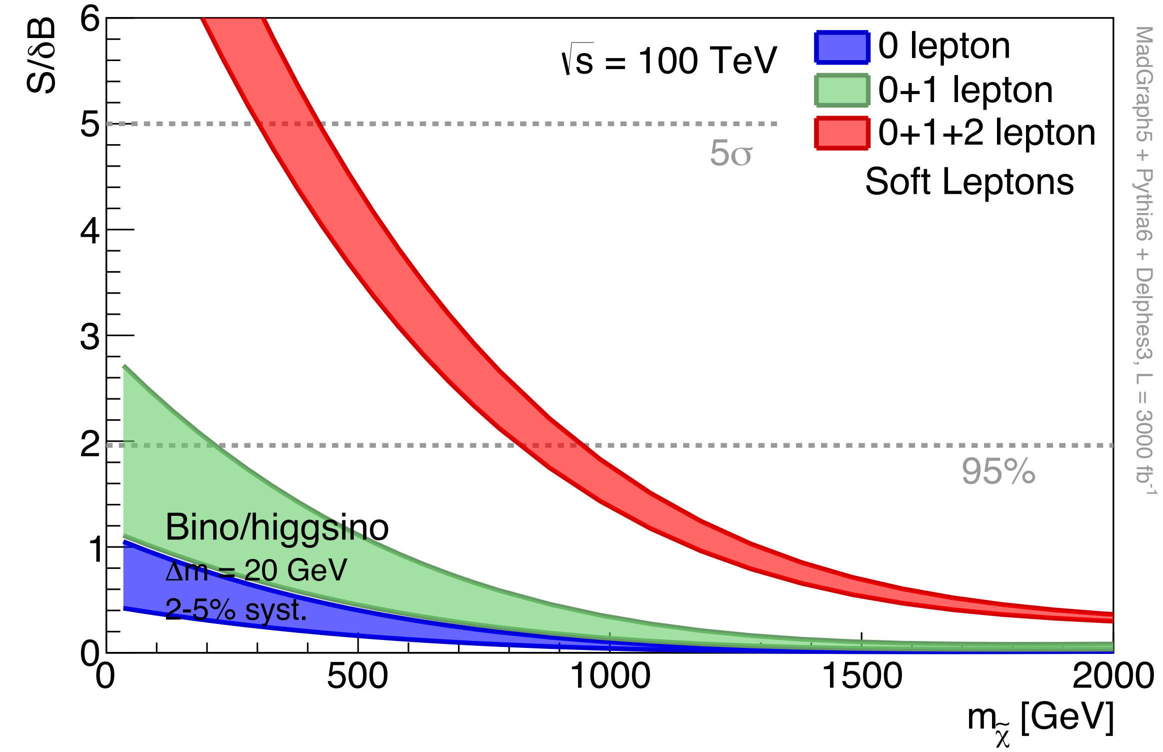
Splitting can be changed easily from dim-5 operator

$$\frac{c}{M}(h^\dagger \tilde{H}_u)(h\tilde{H}_d) \sim \frac{m_Z^2}{M}$$

Well-tempered, mono-jet + soft lepton



20 GeV < pT lepton < 40 GeV



10 GeV < pT lepton < 30 GeV

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

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

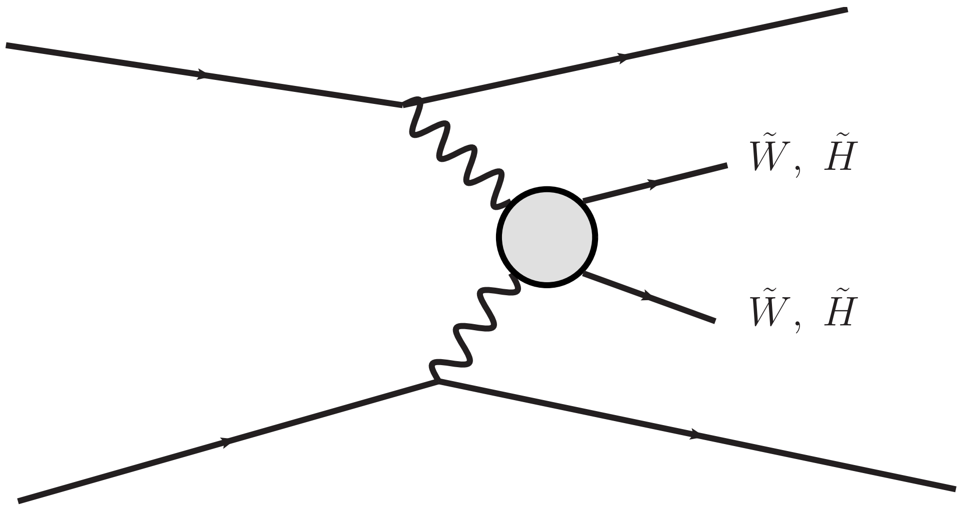
$\tilde{B}$

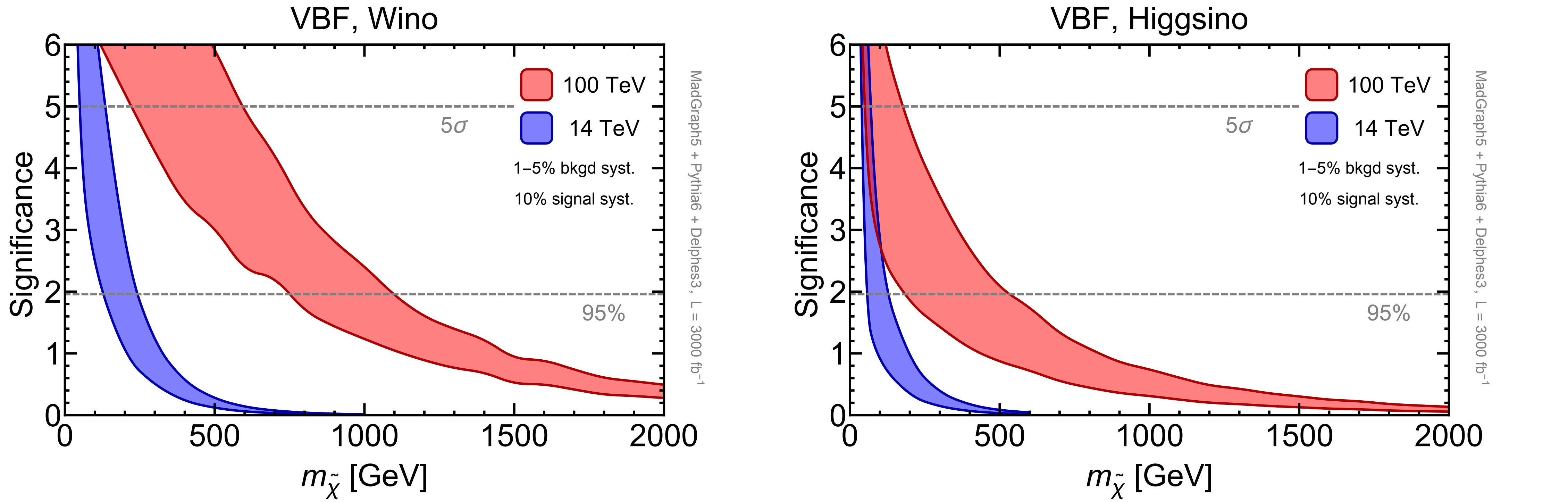
- Important to add soft lepton. S/B is O(1).
- Tailored Detector design and trigger strategy?

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

Vector boson fusion.

Cirelli, Sala, Taoso, 1407.7058
A. Berlin, T. Lin, M. Low, LTW, 1502.05044



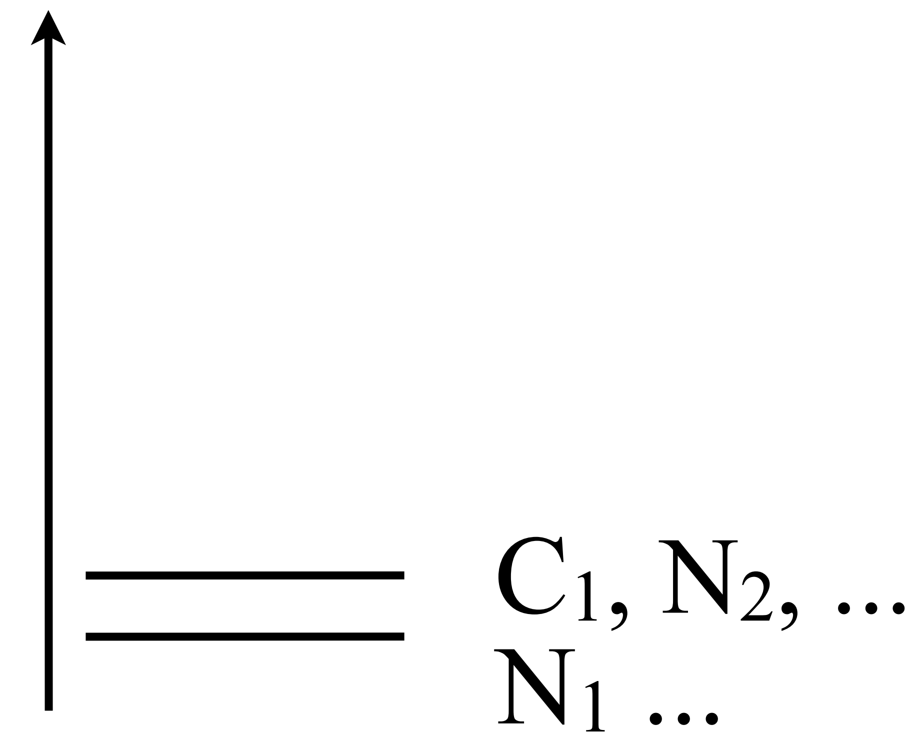


Weaker limit, useful for cross check

Two different cases

Compressed/degenerate
e.g., pure wino, pure Higgsino, Well temper...

Relying on
ISR: mono-jet, mono-photon...
Soft lepton, displaced tracks



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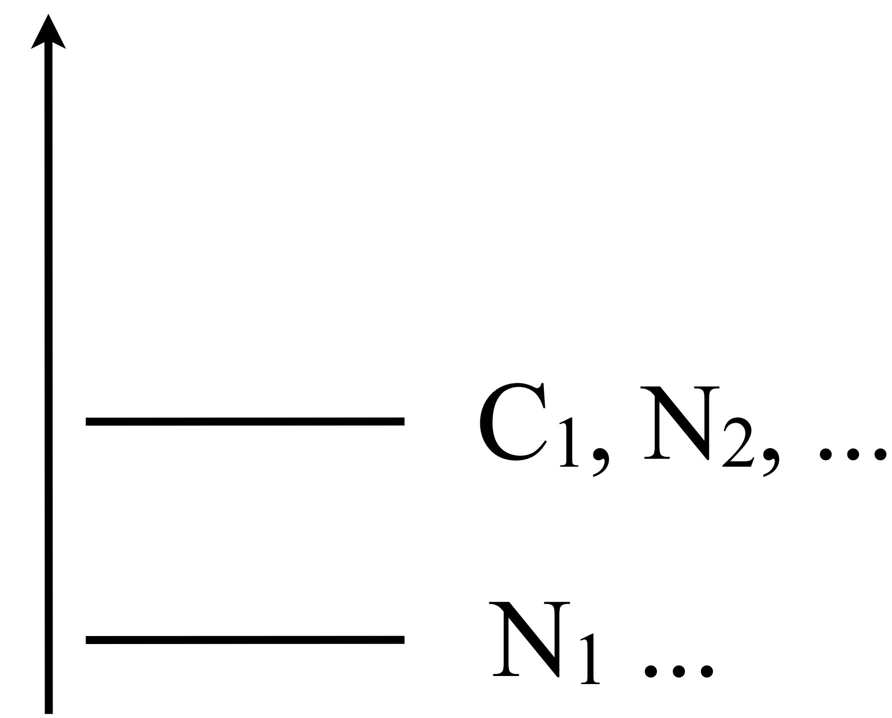
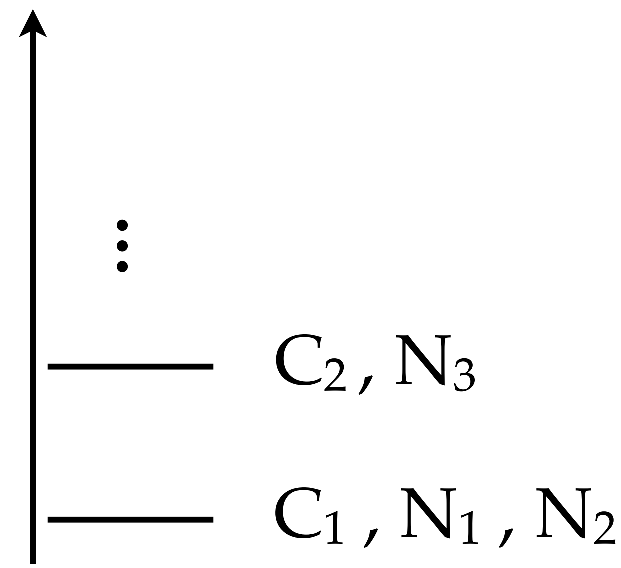
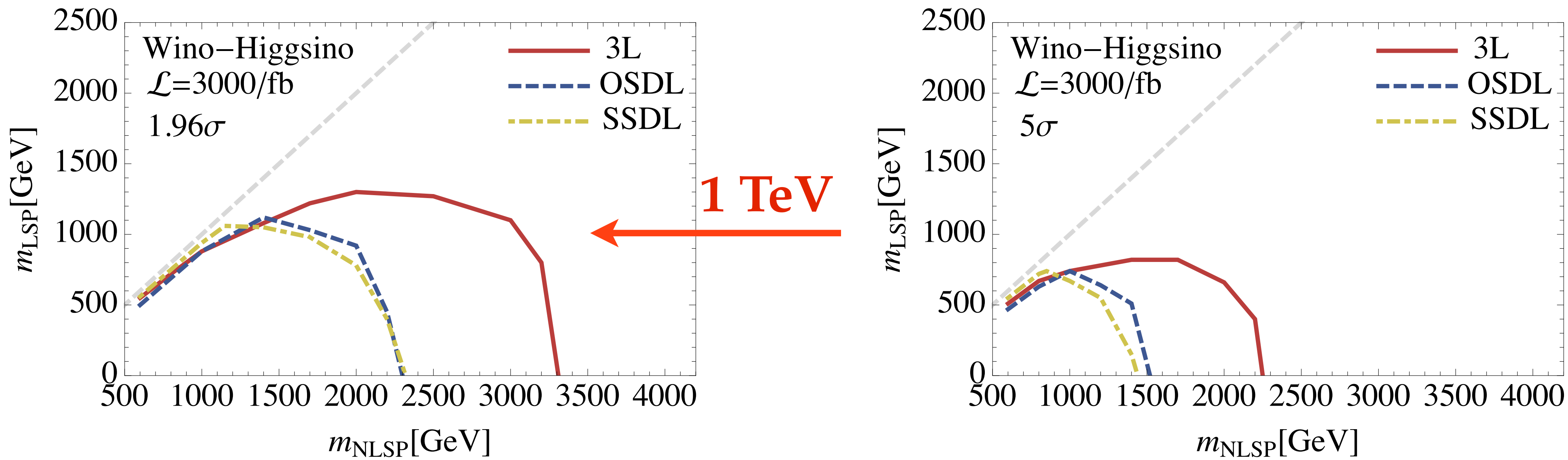


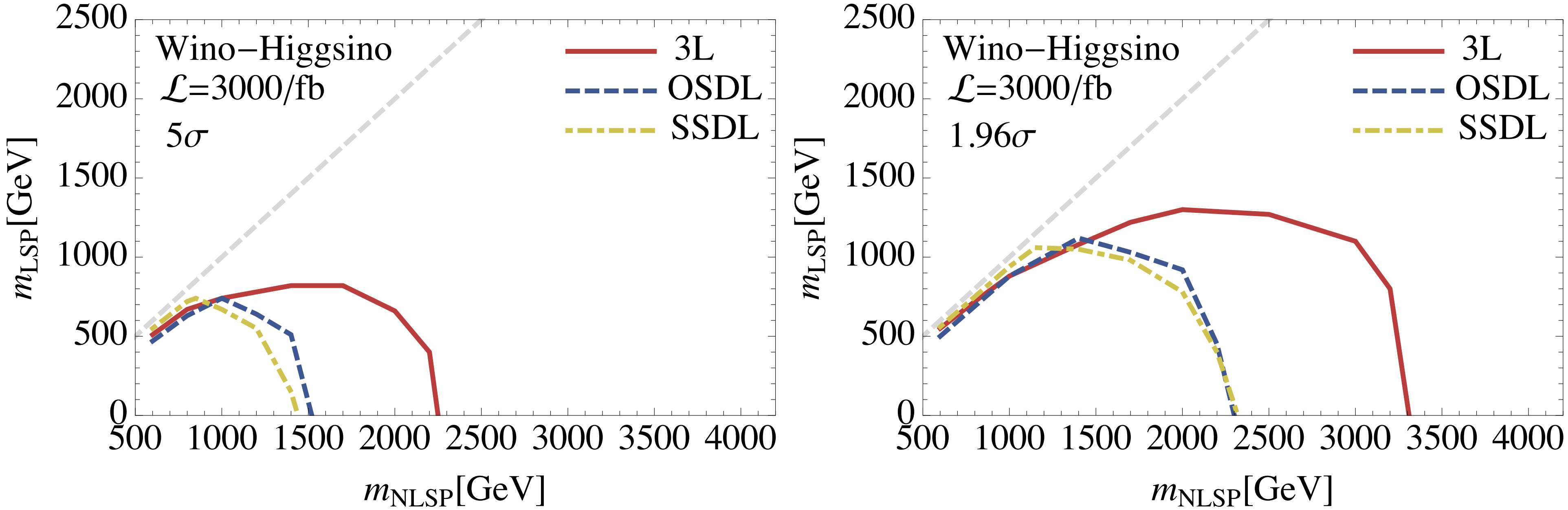
Wino/Higgsino

- Rate ~ wino production
- BR($N_3 \rightarrow N_{1,2}\, h$) ≃ 1/3
- BR($N_3 \rightarrow N_{1,2}\, Z$) ≃ 1/3
- BR($N_3 \rightarrow C_1\, W$) ≃ 1/3



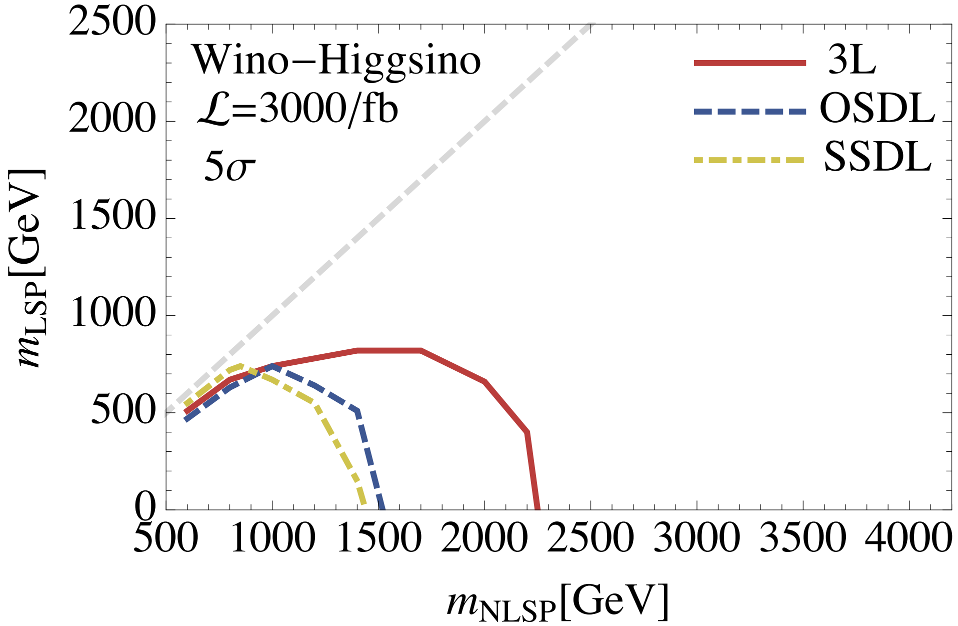


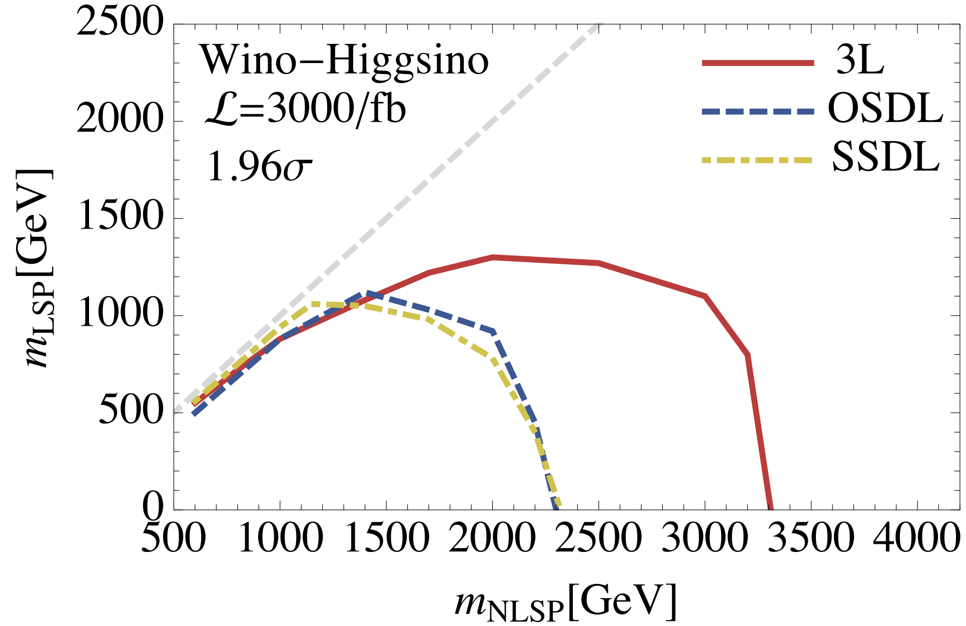
Wino/Higgsino



Leading channel: tri-lepton signal, from $N_2 \to ZN_1$ plus $C_1 \to WN_1$

Wino/Higgsino





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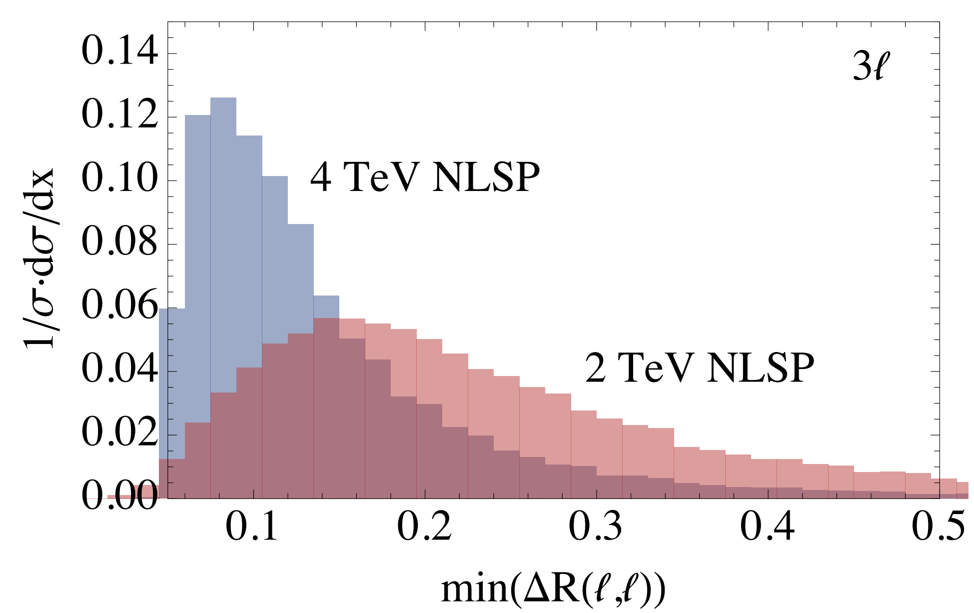
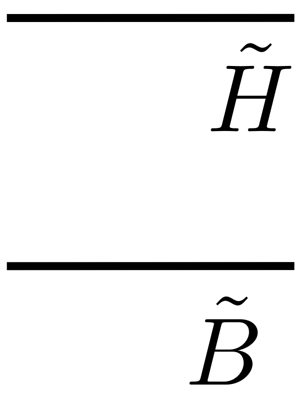
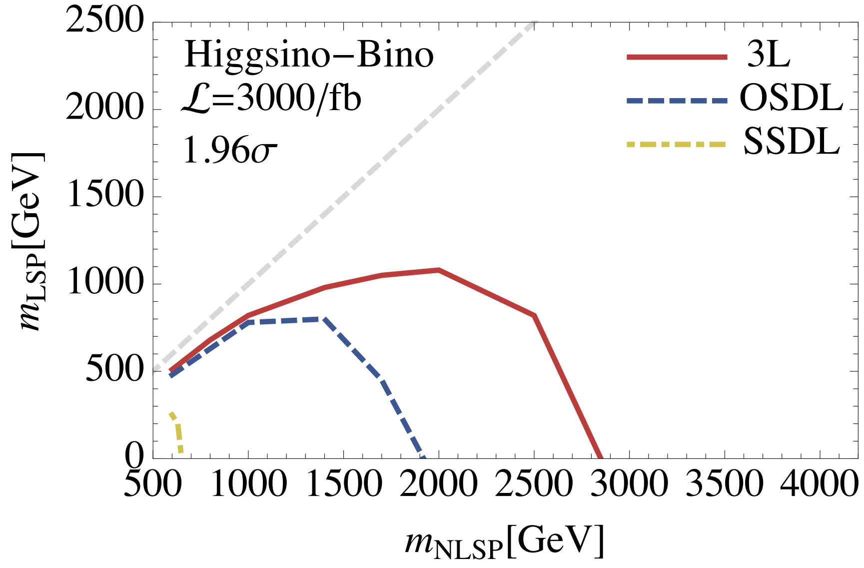
Large mass splitting, boosted W/Z. Challenging for letpon ID and isolation.

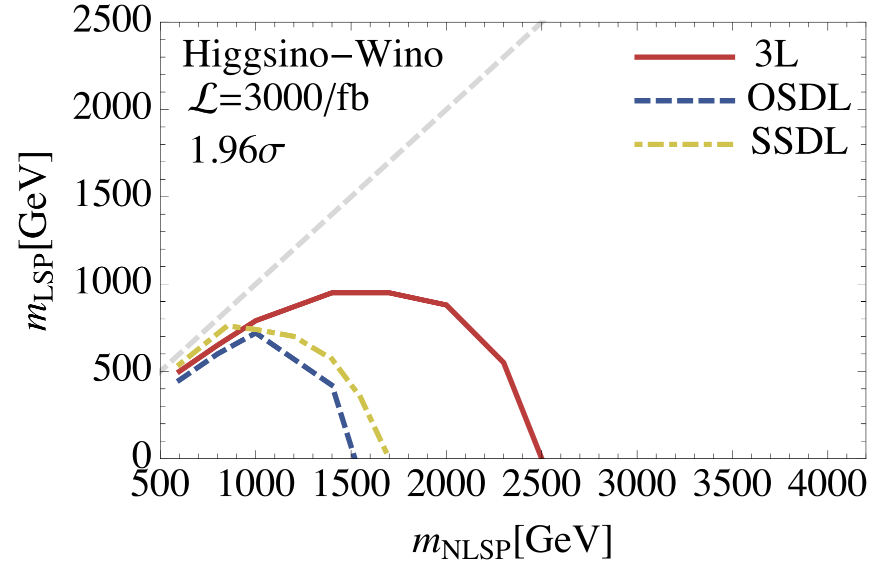


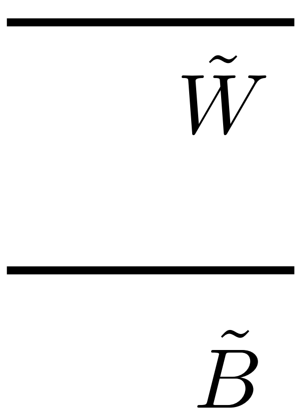
Cascades

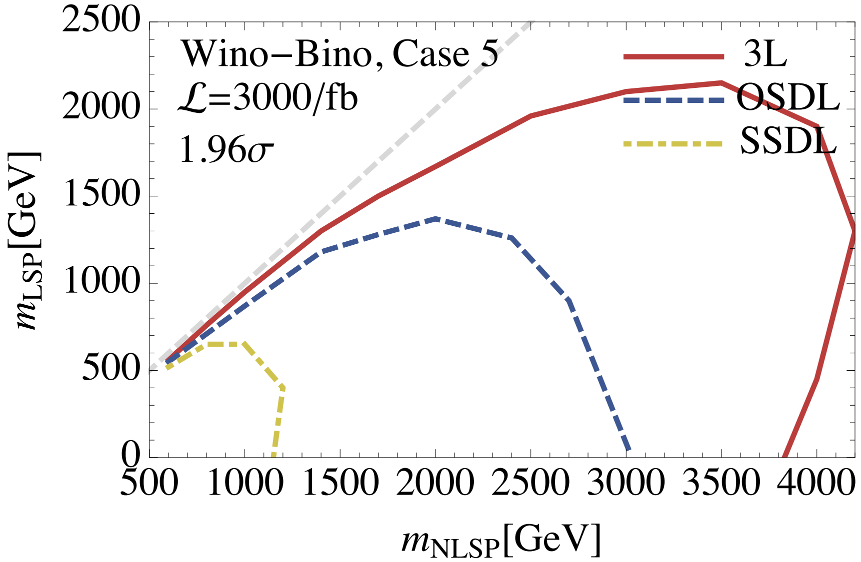
Gori, Jung, LTW, Wells, 1410.6287
Archaya, Bozek, Pongkitivanichkul, Sakurai, 1410.1532

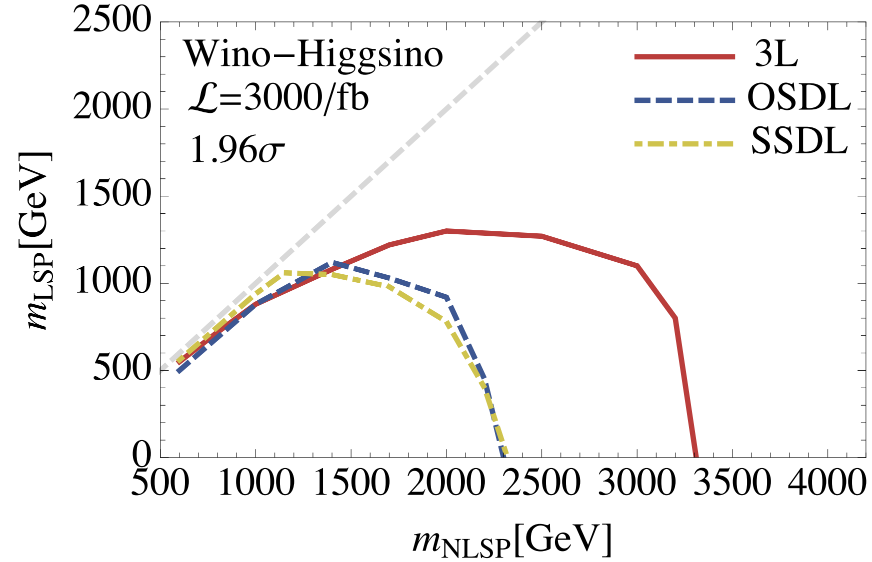








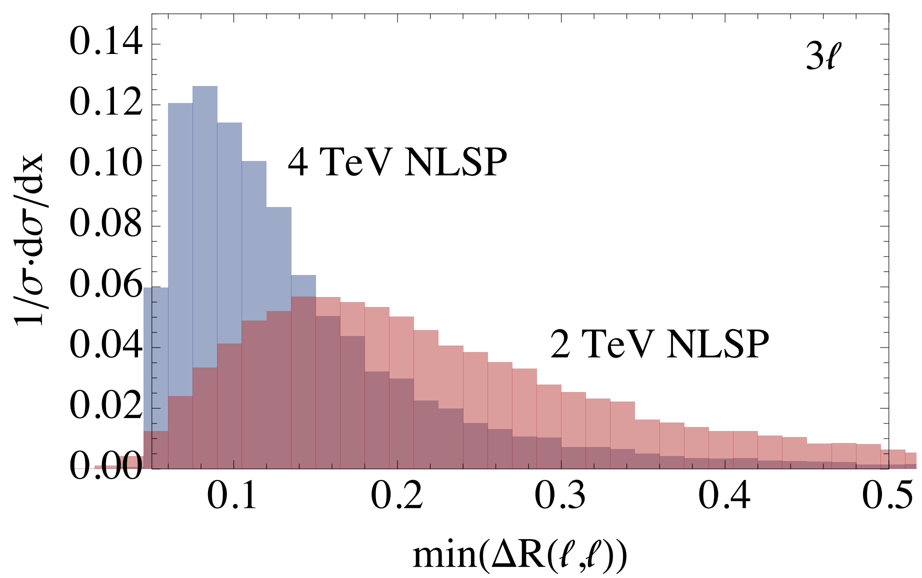


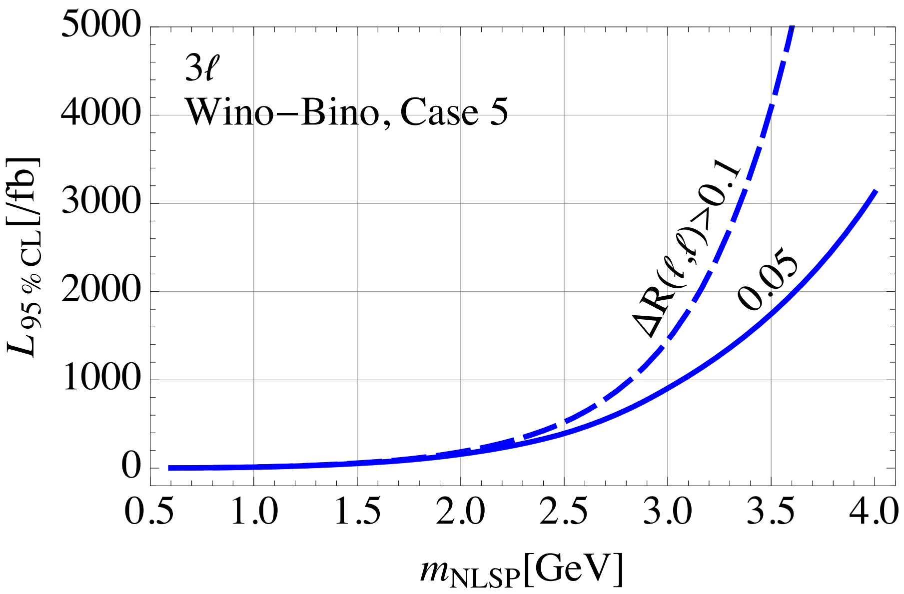


Decay ⇒multi leptons ⇒ stronger limits, multi TeV

Food for thought

Boosted W/Zs. High resolution, less stringent lepton isolation.





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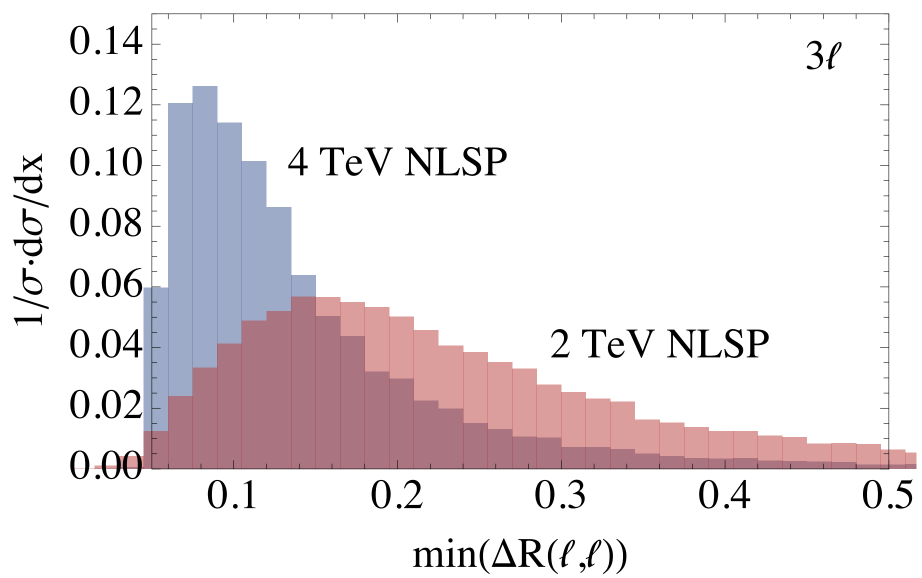

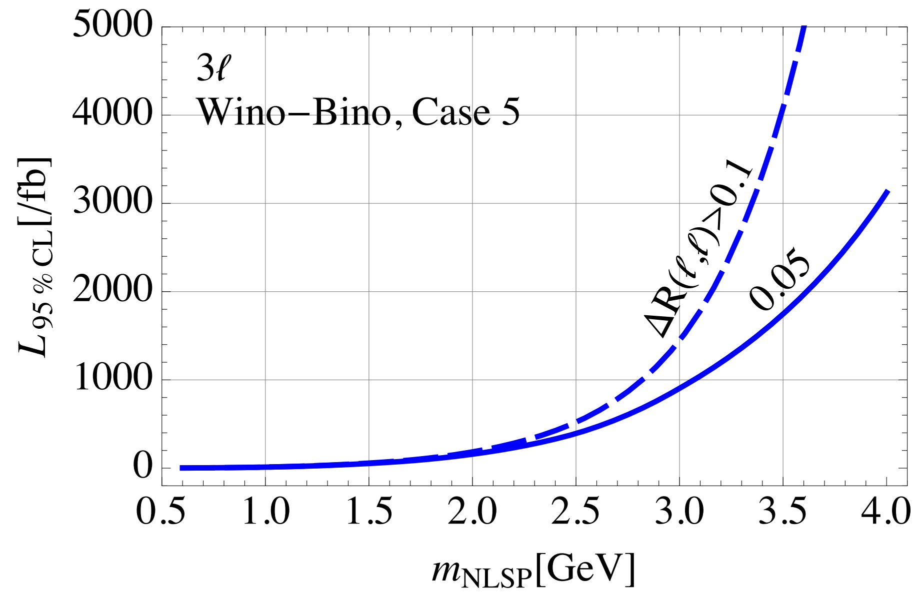

Compressed spectrum generic.
Dedicated detector to id soft lepton, displaced tracks better?

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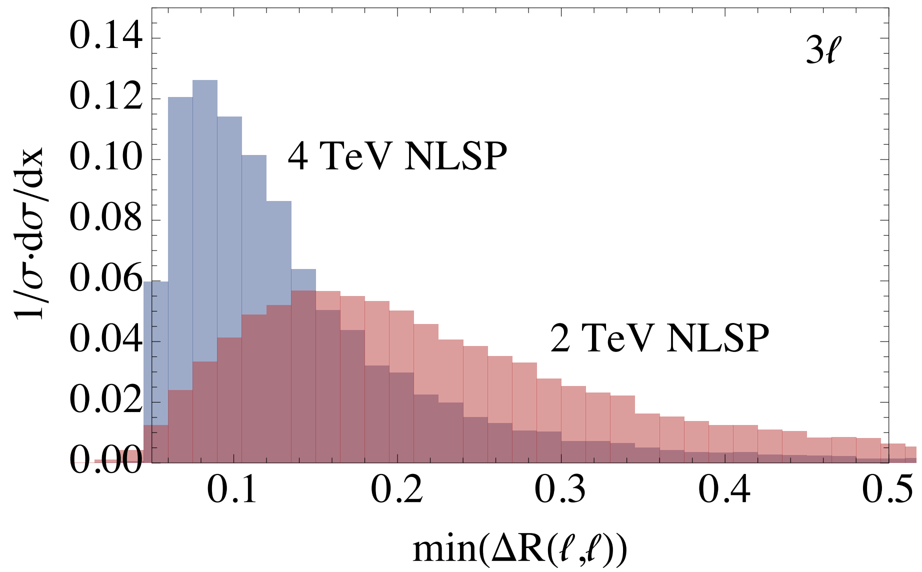

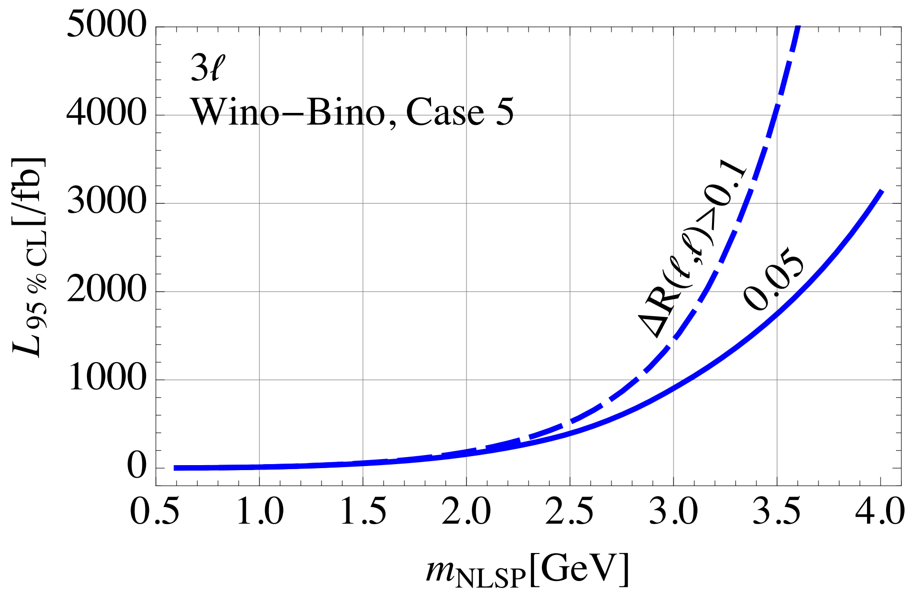

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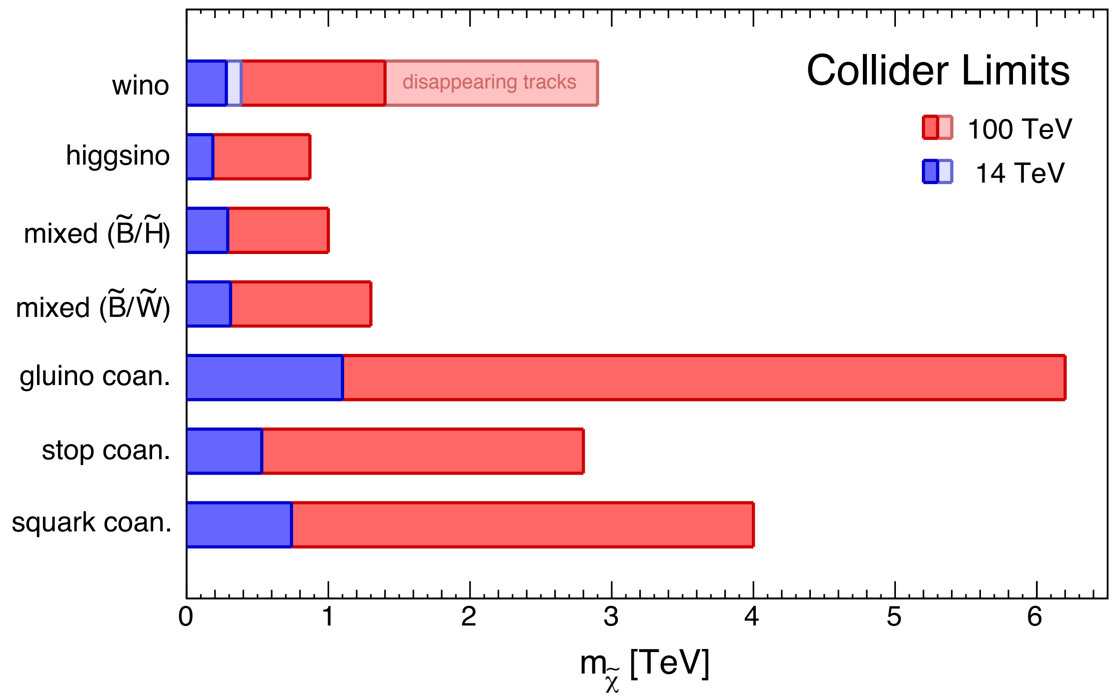
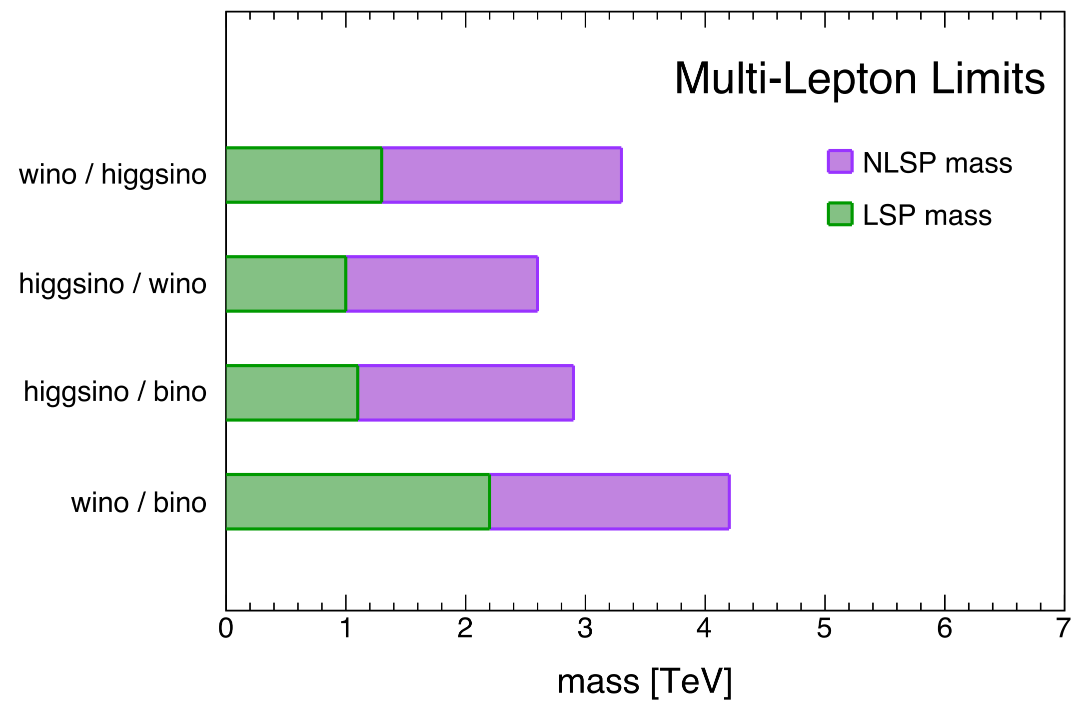
Dark matter signal simpler. Typically no/low jet activities.
Lepton optimized detector?
Write less to tape, trigger more?

WIMP searches at colliders

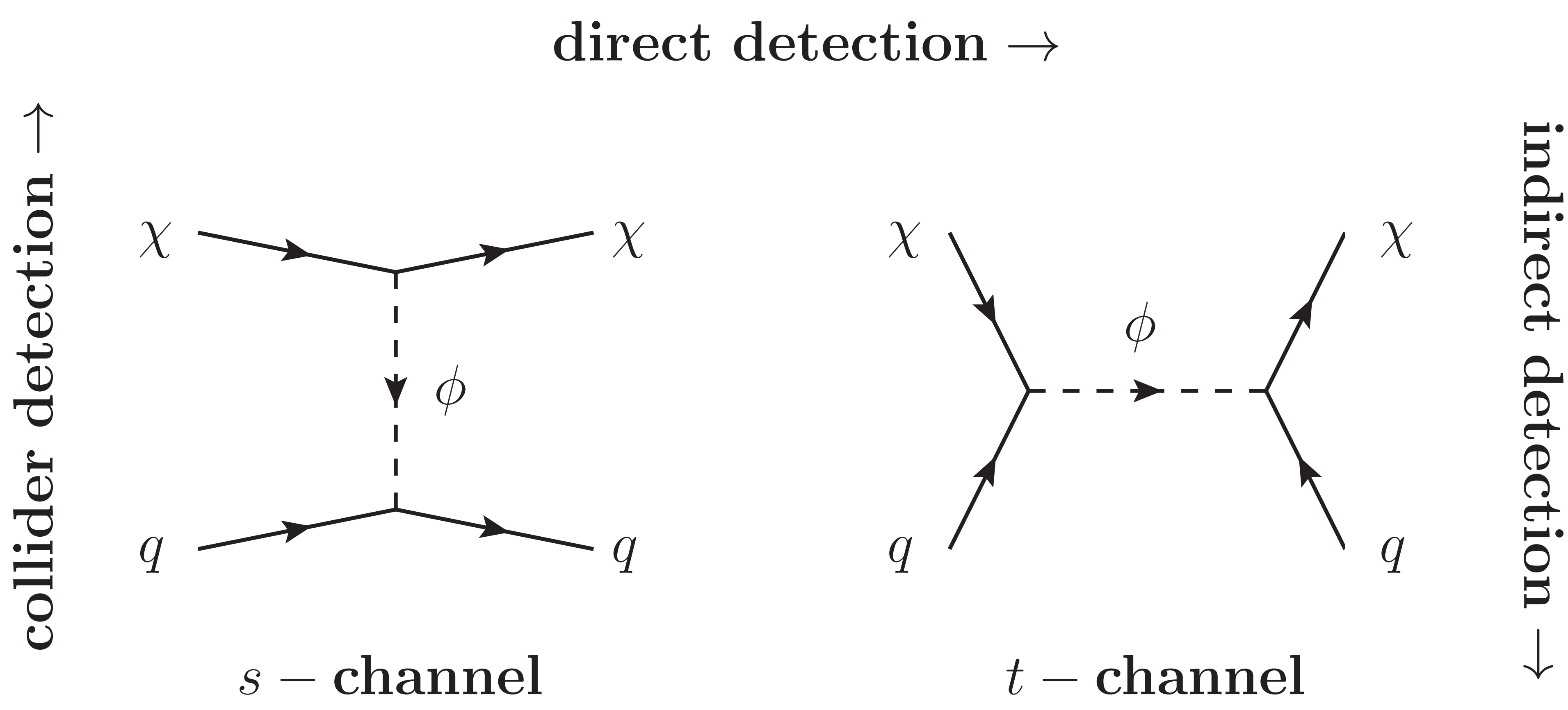




$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

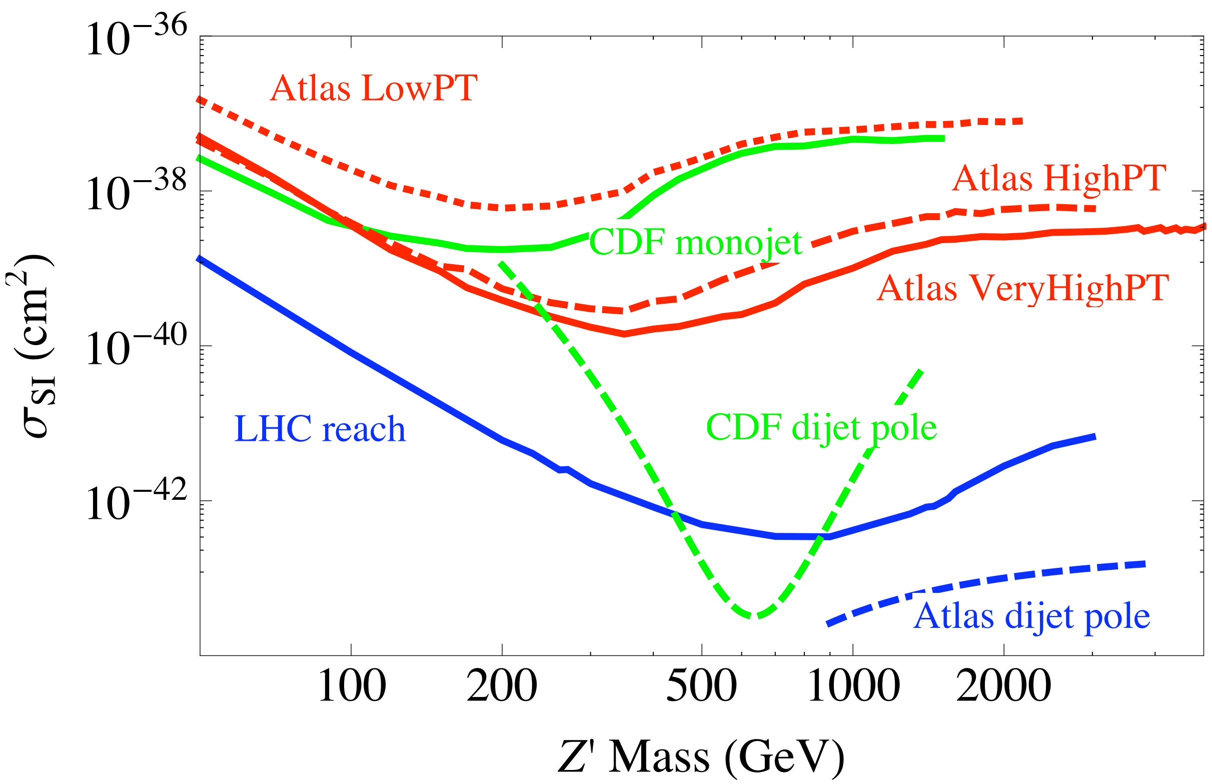
2. Simplified mediator models

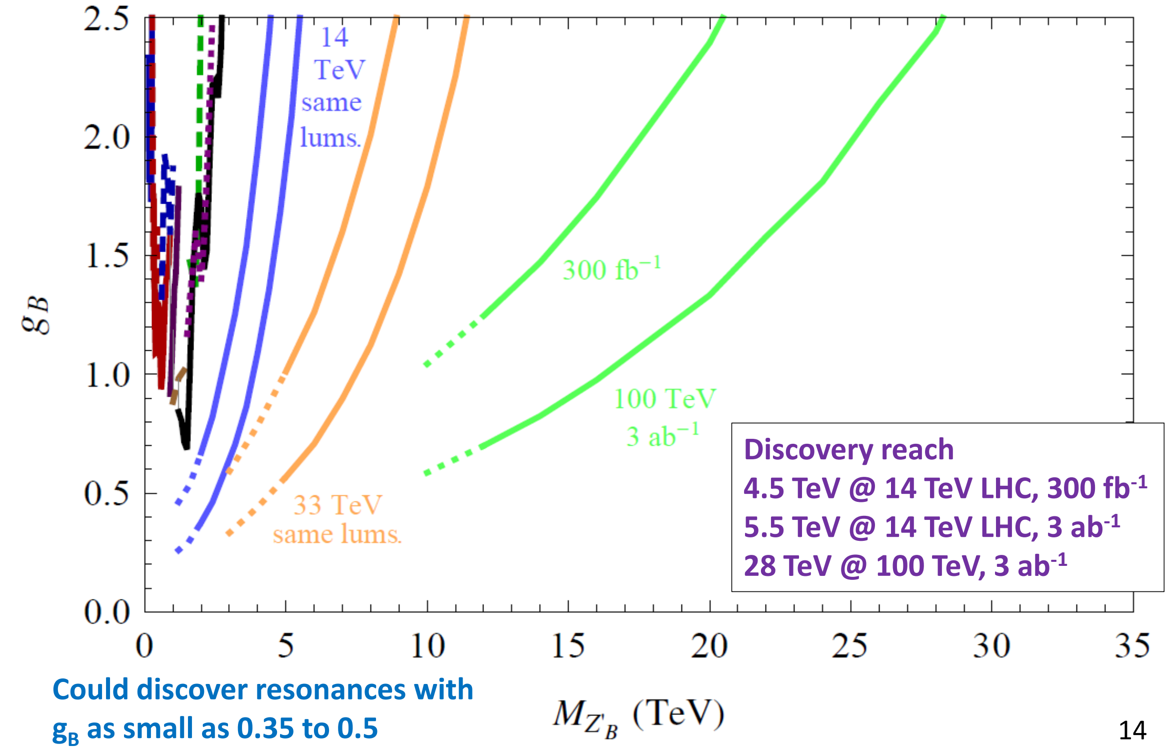


- can be scalar or Z'
- squark like

More from Phil Harris' talk

Possible to discover the mediator first!





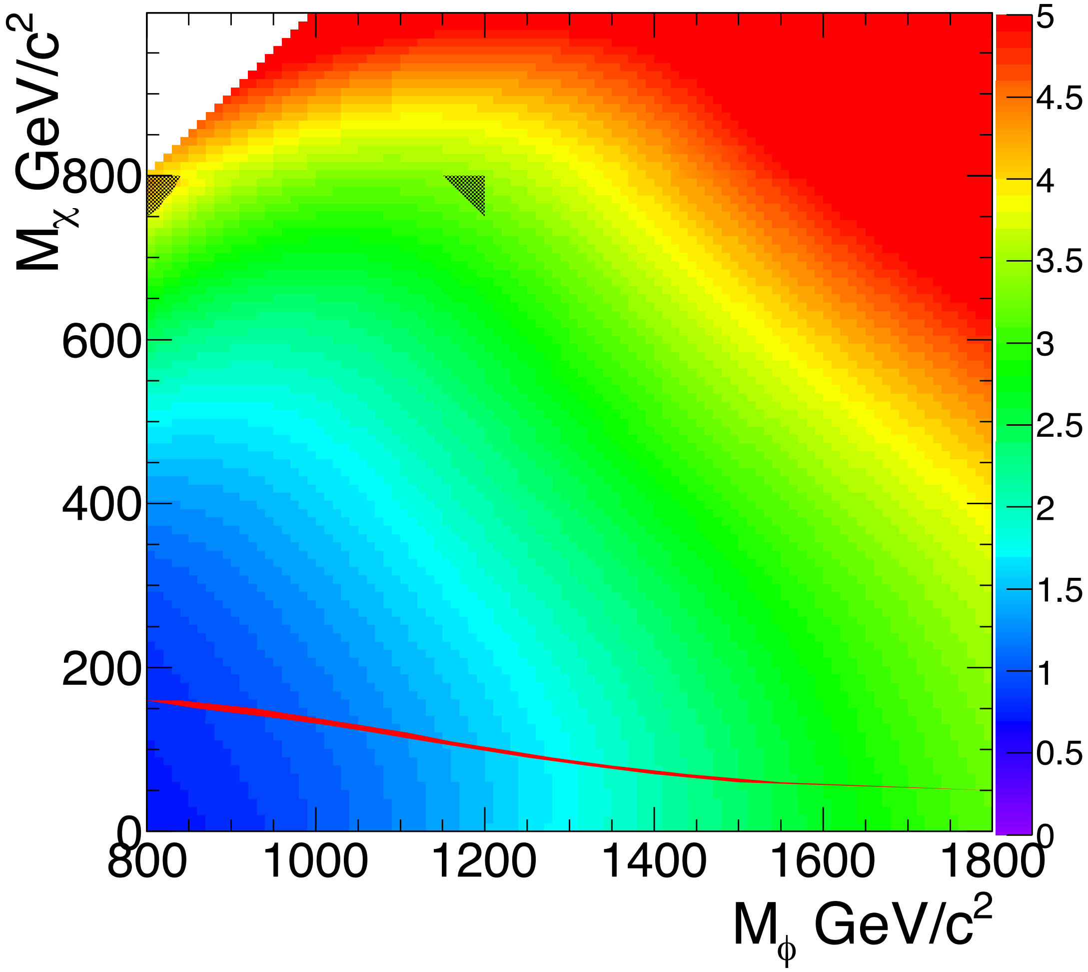
An, Ji, LTW, 1202.2894 Assume $g_{Z'} = g_D$

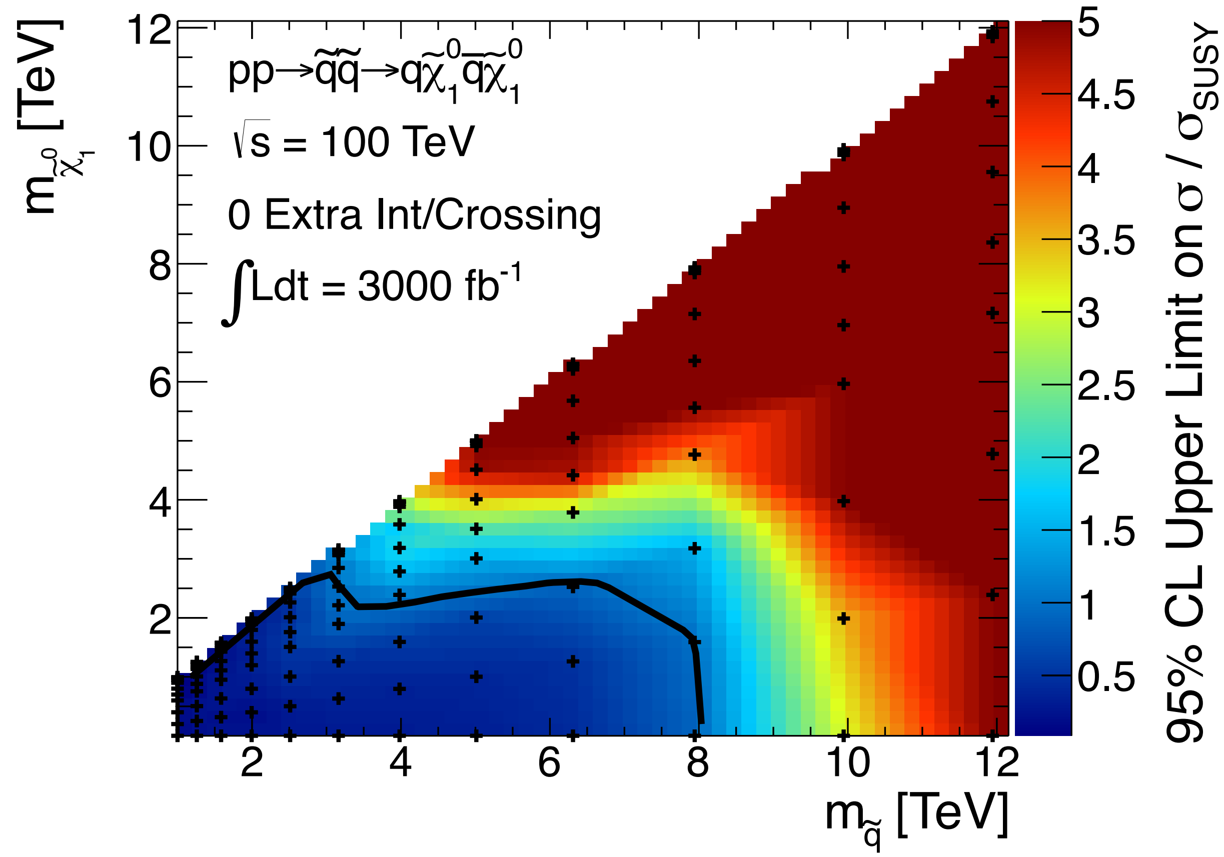
Felix Yu, 2013

Reaches

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

Dirac   Contours, limits on coupling λ_q





In general, the processes involving mediator direct production give strongest limit.

Stronger limit come from squark search (gray) or CMS-style monojet search.

Haipeng An, Hao Zhang, LTW, 1308.0592

Conclusions

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.

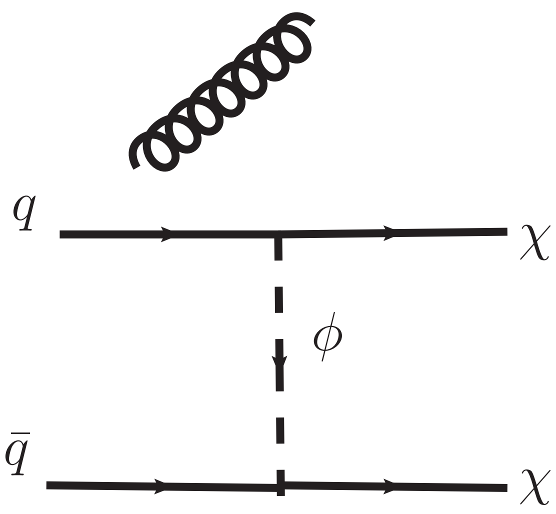
Conclusion

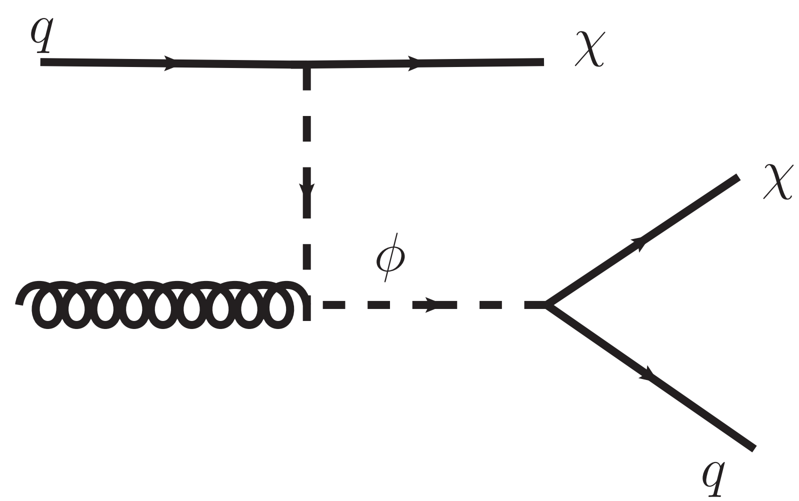
- The search for WIMP dark matter is largely out of the reach for the LHC.
  - LHC 14: reach to about a couple hundred GeV.
- 100 TeV pp Collider significantly enhance the reach, a fact of 5-7 enhancement.
- More detailed studies necessary. New ideas needed: more channels, detector design...
- At the same time, it is clear that this should be one of the main motivations for going to a 100 TeV pp collider.

extras

Collider searches

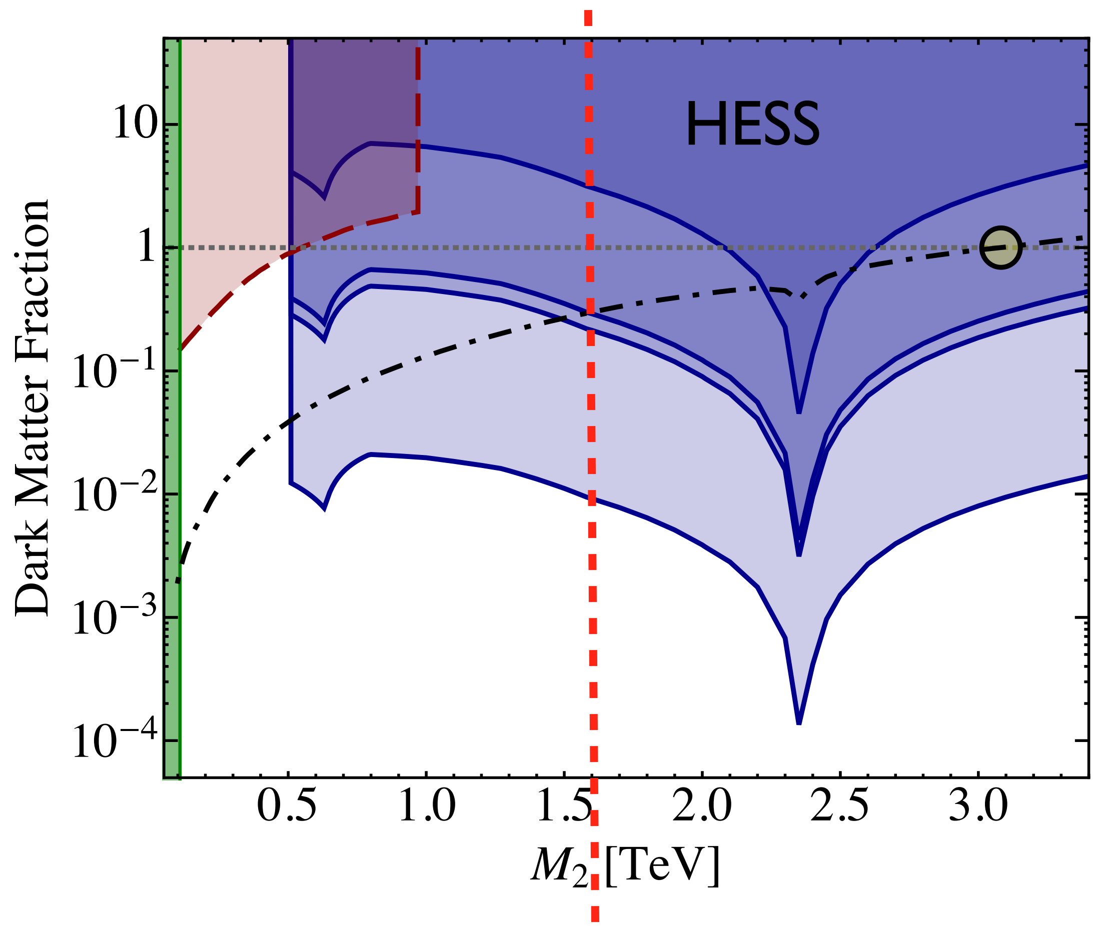
$$\mathcal{L}_\chi = \lambda_q \bar{\chi} \phi^* q + h.c.$$

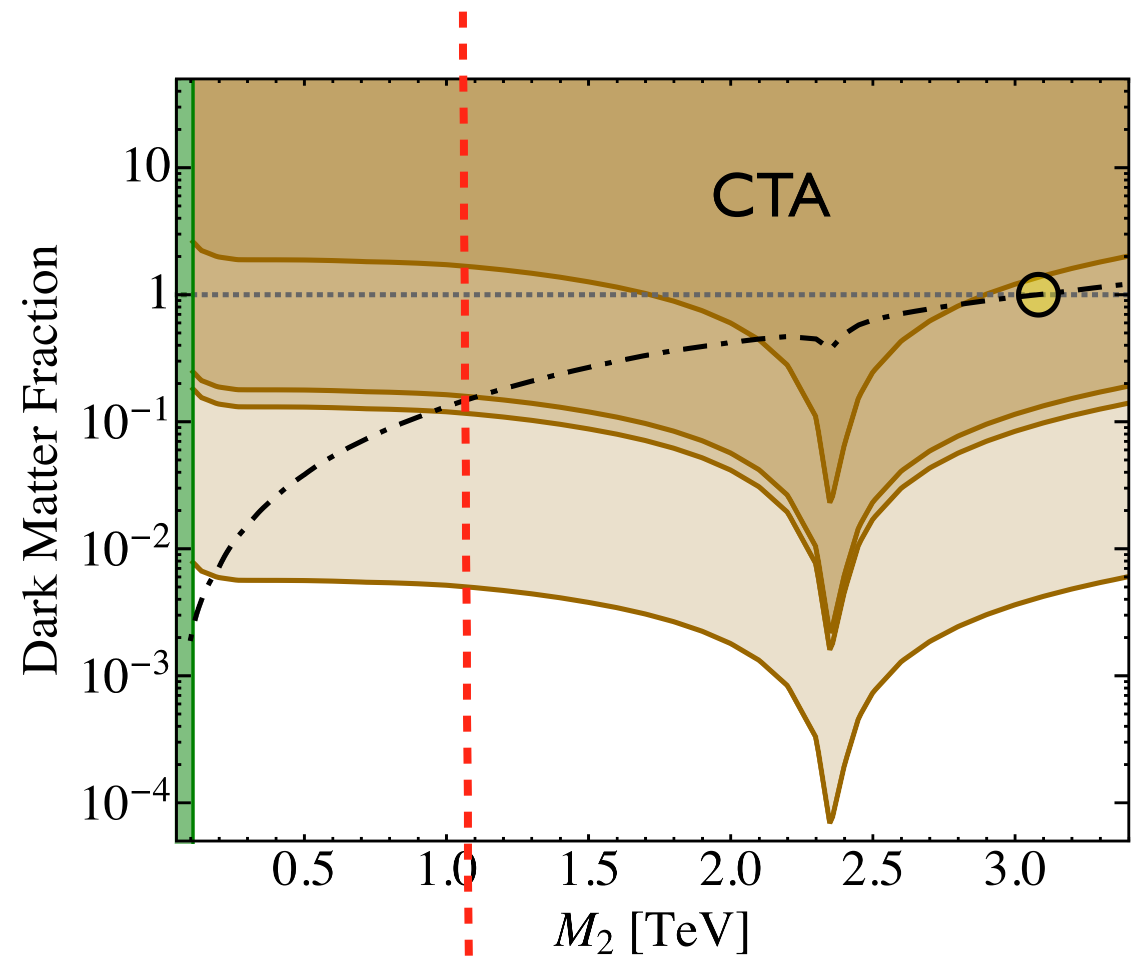




- 2 kinds of contributions for monojet.
- pp$\to\chi\phi$ gives harder (mono)jet!

Wino, interplay with indirect detection

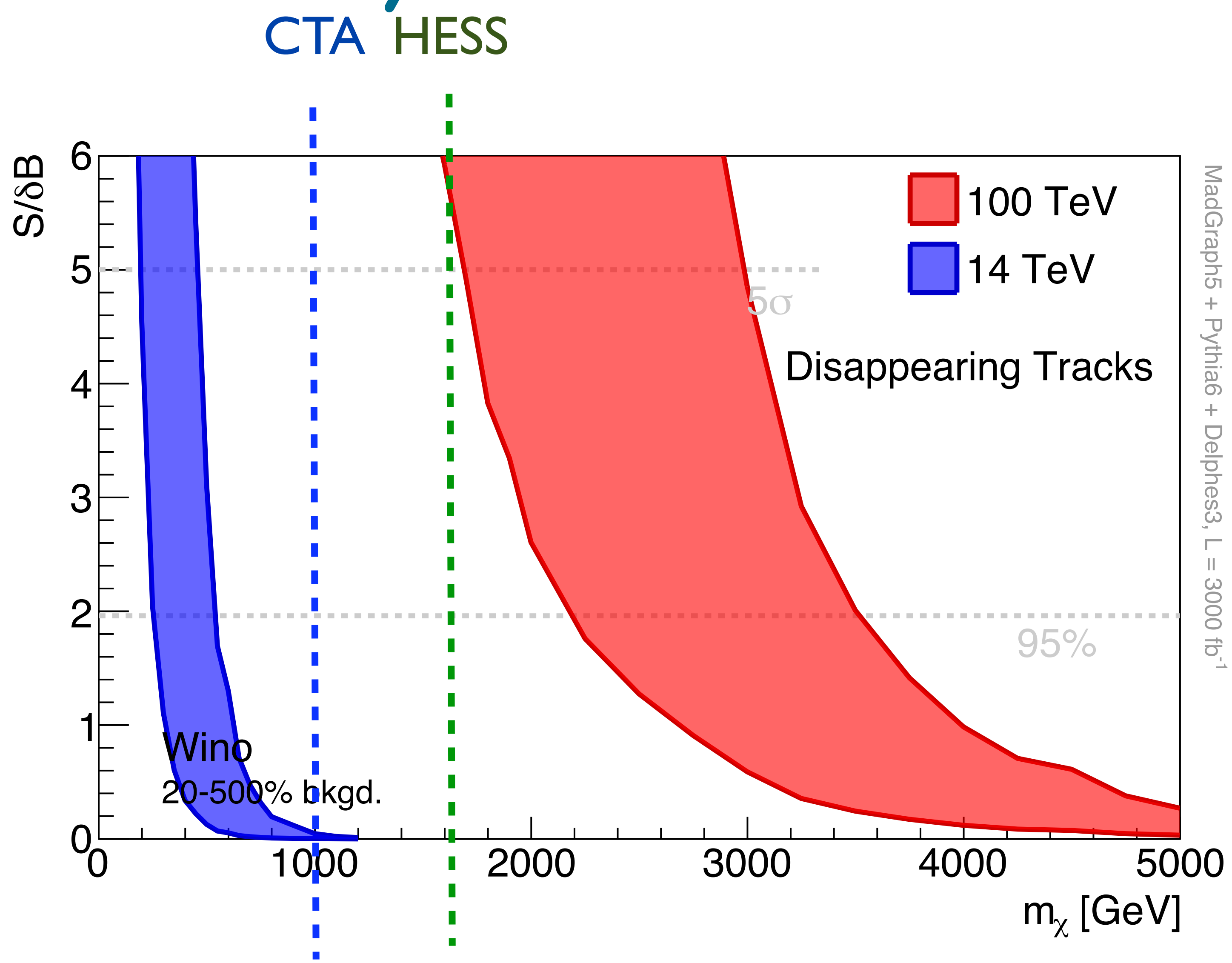




Cohen, Lisanti, Pierce, Slatyer, 1307.4082

See also Fan, Reece, 1307.4400

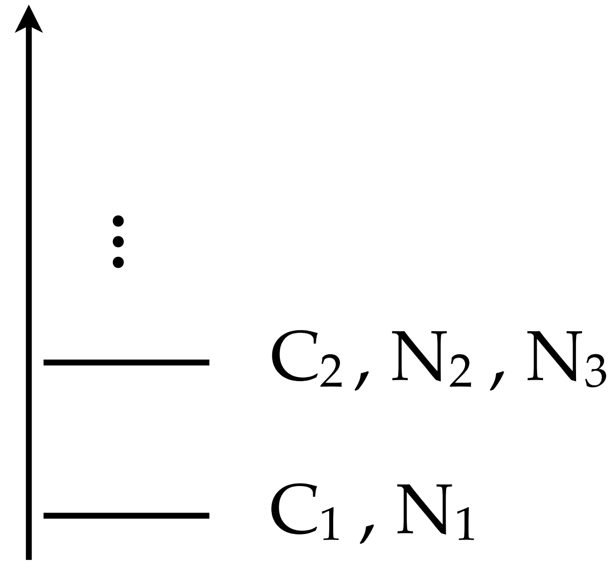
Wino summary

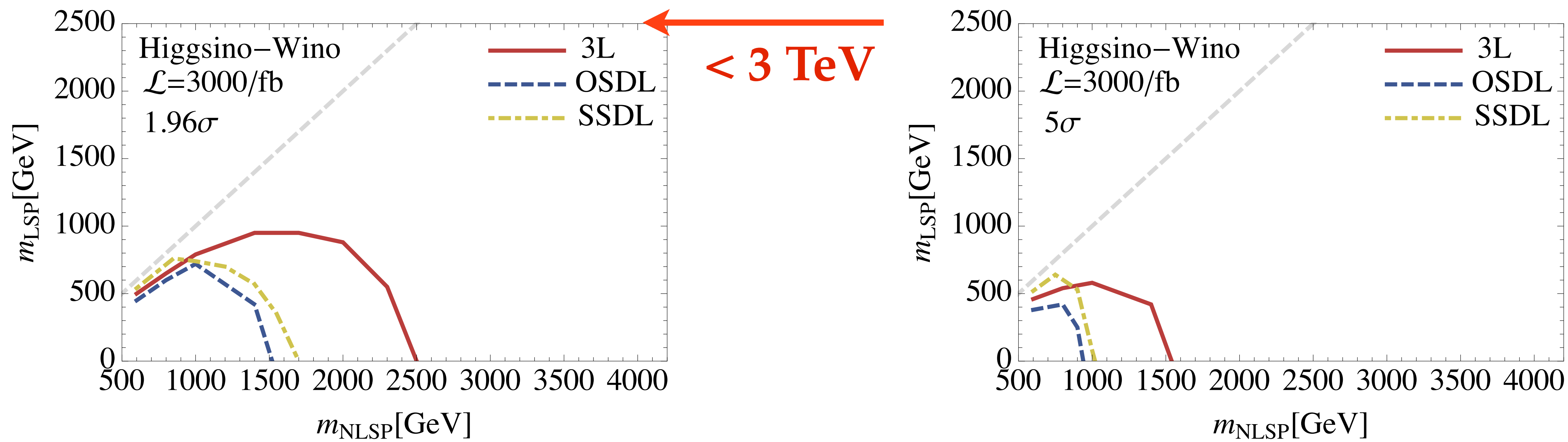


- Completely cover the wino parameter space.

Higgsino/Wino

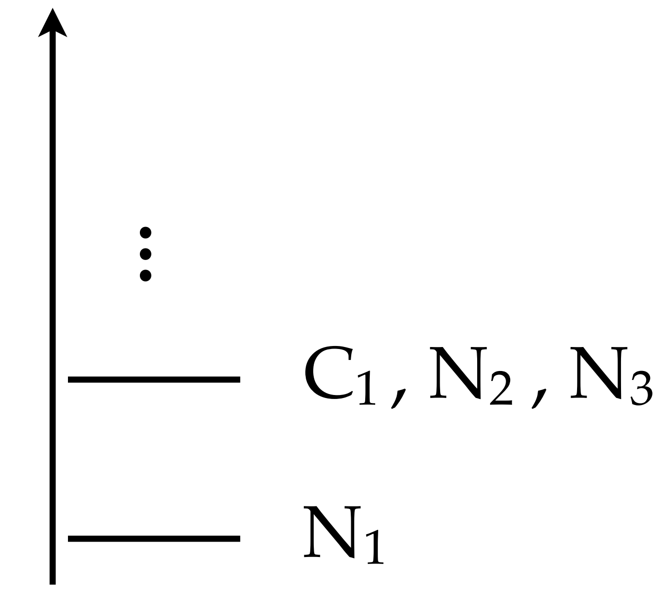
- Rate ~ Higgsino production
- $BR(N_{2,3} \to N_1\, h) \simeq 1/4$
- $BR(N_{2,3} \to N_1\, Z) \simeq 1/4$
- $BR(N_{2,3} \to C_1\, W) \simeq 1/2$

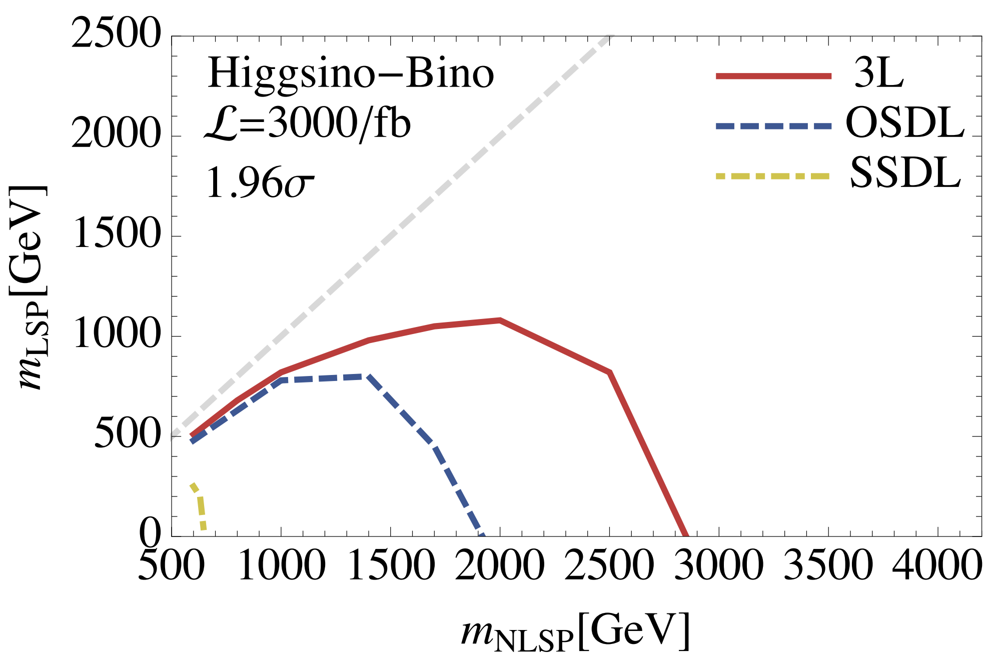


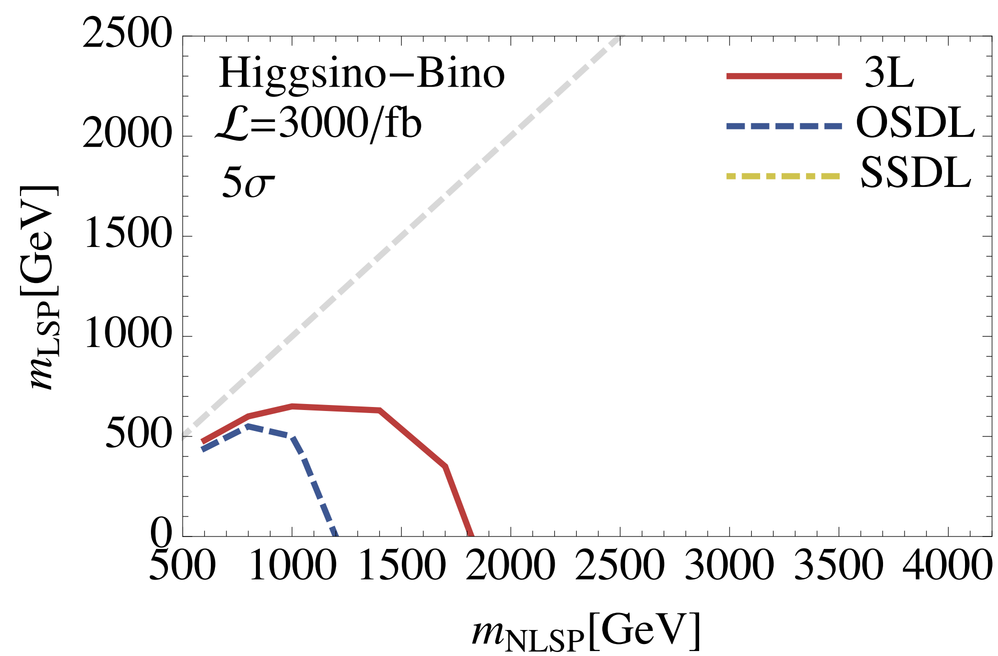


Higgsino/bino

- Rate ~ Higgsino production
- $BR(N_{2,3} \rightarrow N_1\, h) \simeq 1/2$
- $BR(N_{2,3} \rightarrow N_1\, Z) \simeq 1/2$



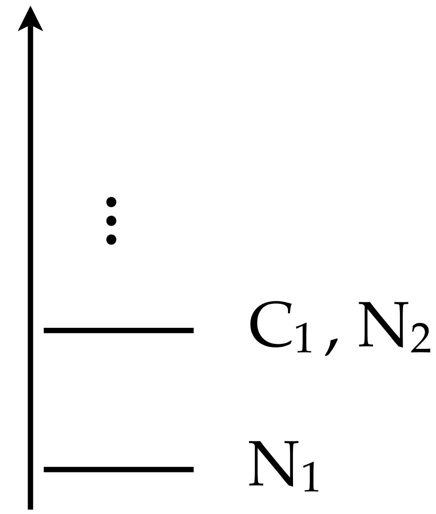


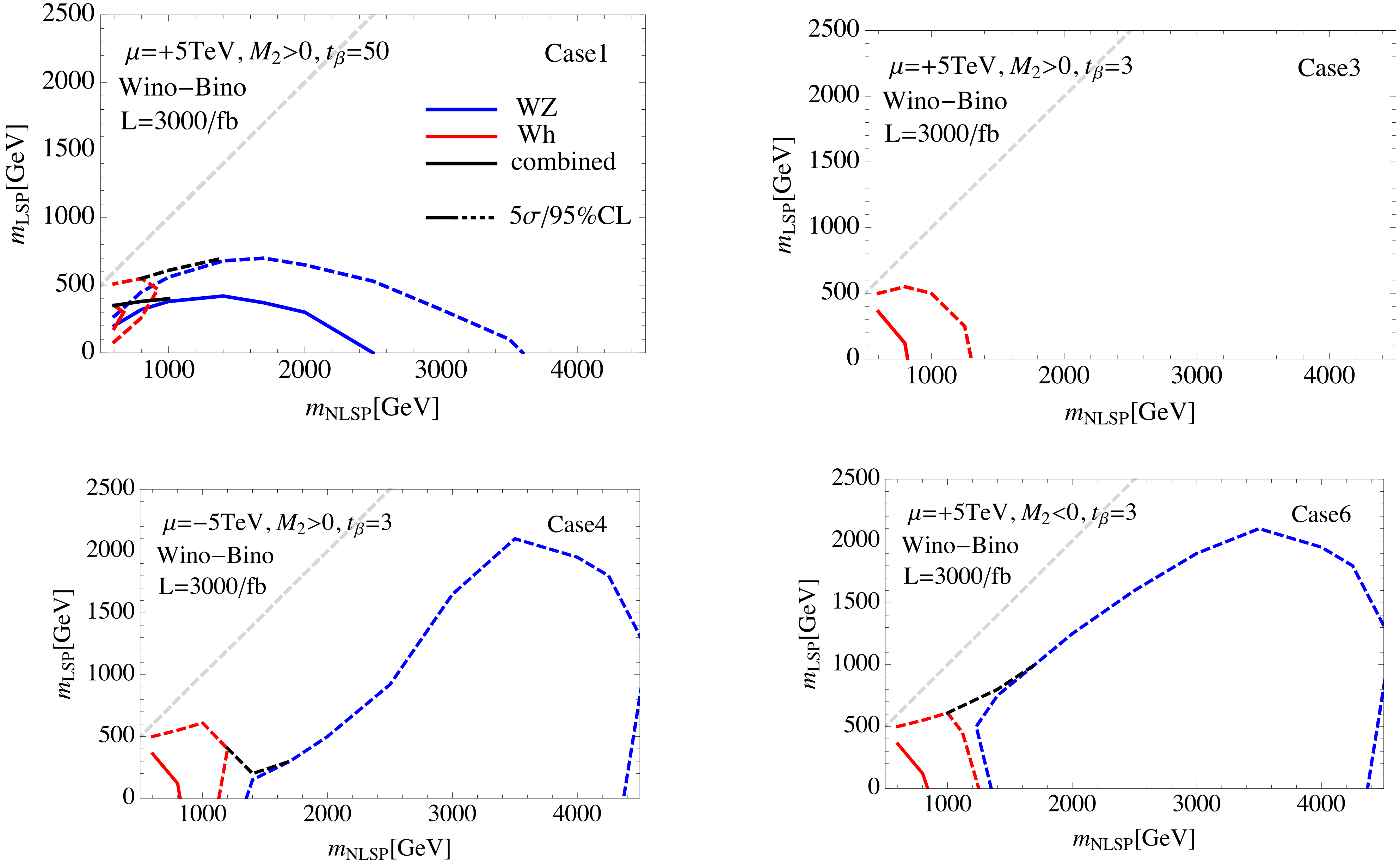


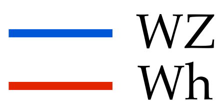
Wino/bino

BRs depend on t_β, sign(μM_2), sign$(M_2 M_1)$

$$\frac{\Gamma(\tilde{W}^0 \to \tilde{B}^0 Z)}{\Gamma(\tilde{W}^0 \to \tilde{B}^0 h)} \simeq \frac{c_{2\beta}^2 M_2^2}{(2\mu s_{2\beta} + M_2 + M_1)^2 (1 + 2M_1/M_2)} \simeq \frac{M_2^2}{4\mu^2 t_{2\beta}^2}$$

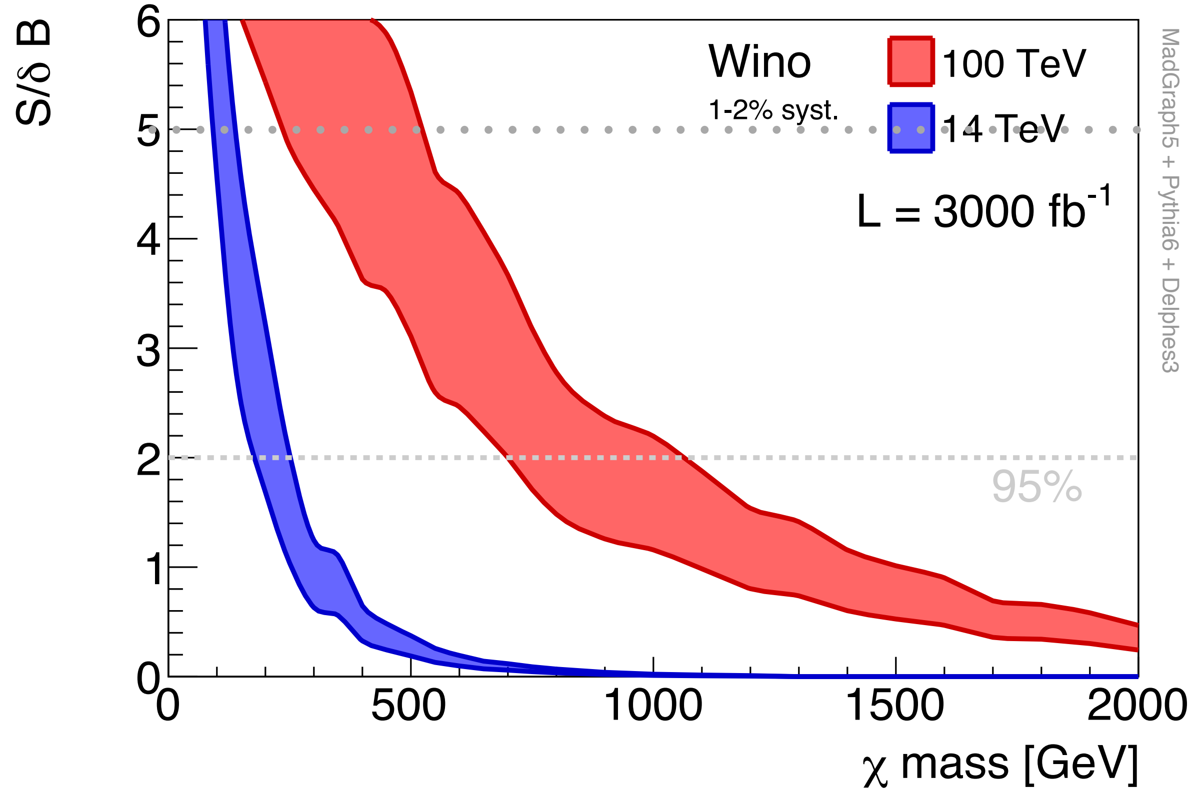






Example: Wino. Monojet channel

Matthew Low, LTW, 2014



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

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

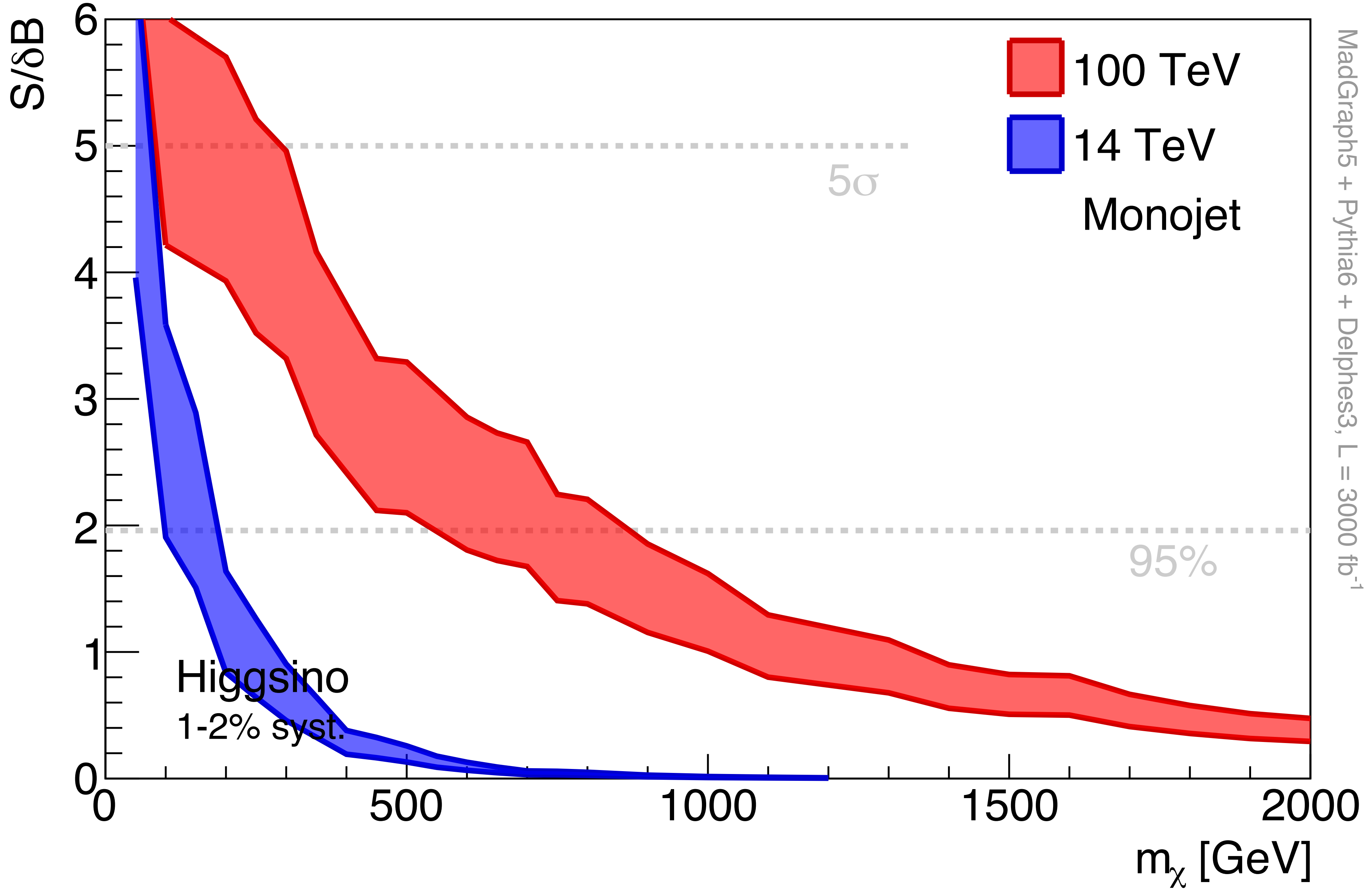
significance: $$\frac{S}{\sqrt{B+\lambda^2 B^2+\gamma^2 S^2}}, \ \lambda=(1-2)\%, \gamma=10\%$$

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

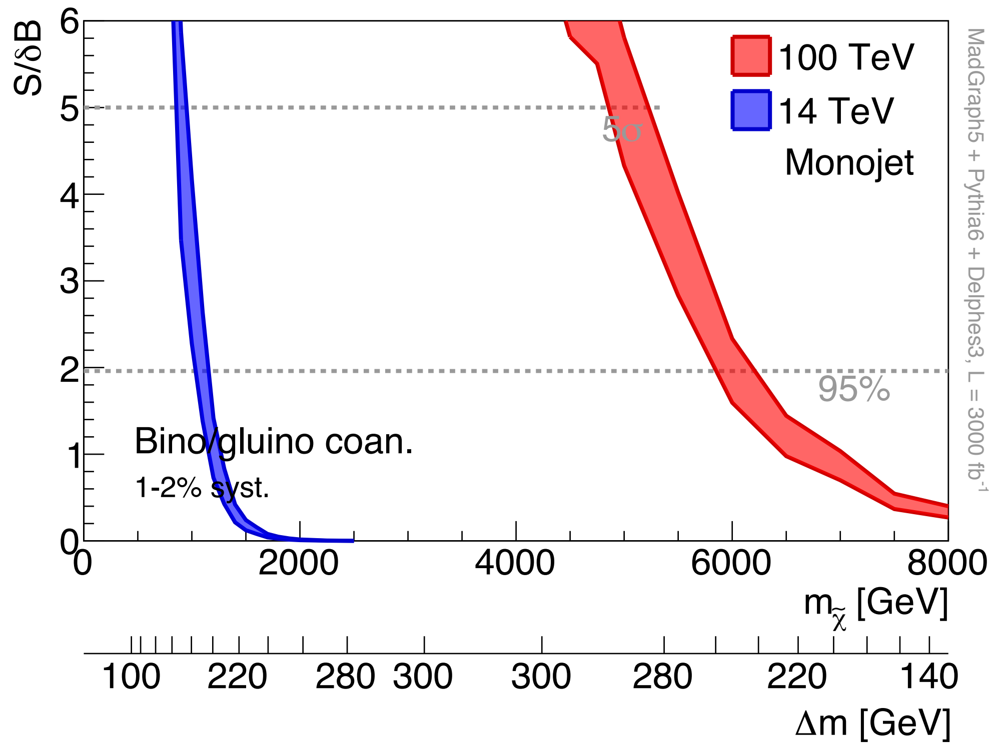
- A factor of 4-5 enhancement from 14 to 100 TeV.

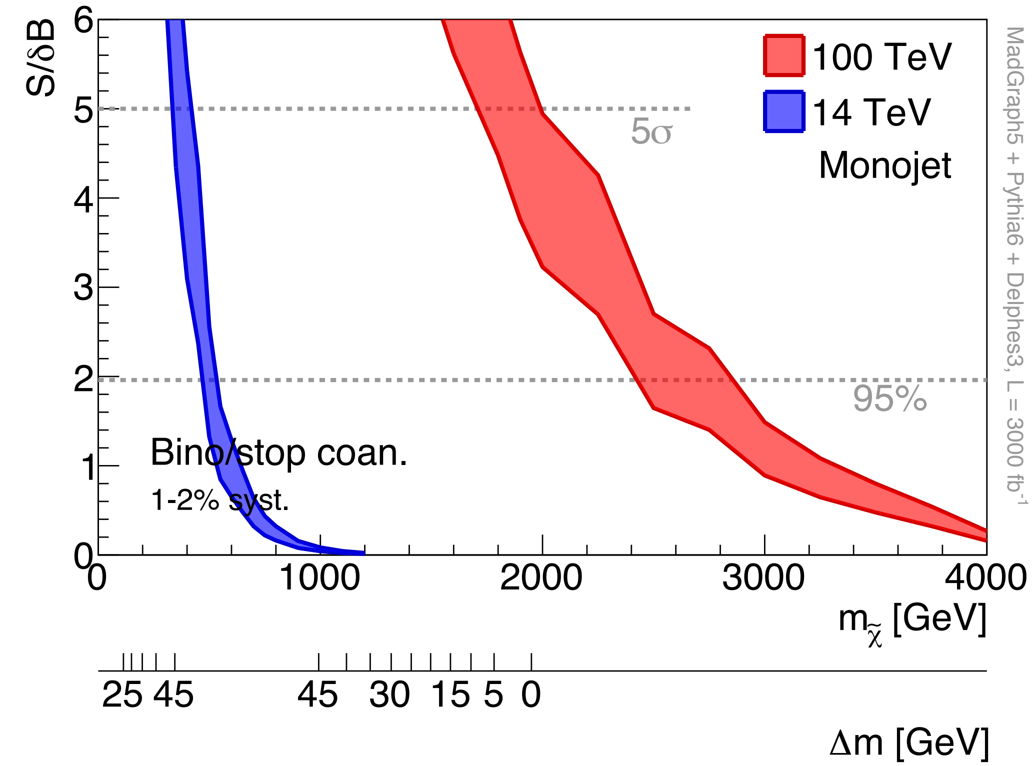
Recent works on mono-jet for electroweak-inos
Schwaller, Zurita, 1312.7350
Baer, Tata, 1401.1162
Han, Kribs, Martin, Menon, 1401.1235

Mono-jet for Higgsino



Co-annihilation, monojet





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

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

$\tilde B$

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