Particle Dark Matter at Hadron Colliders

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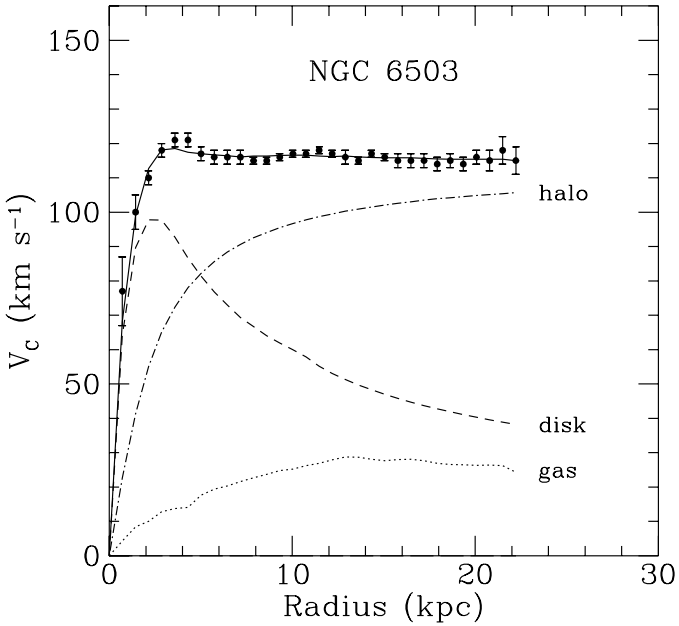
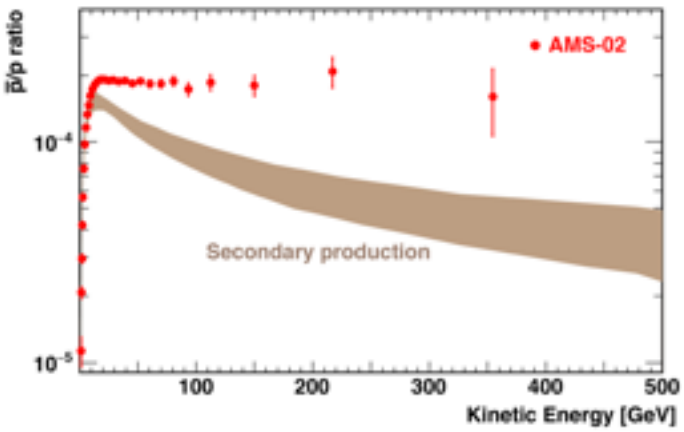
DIS 2015

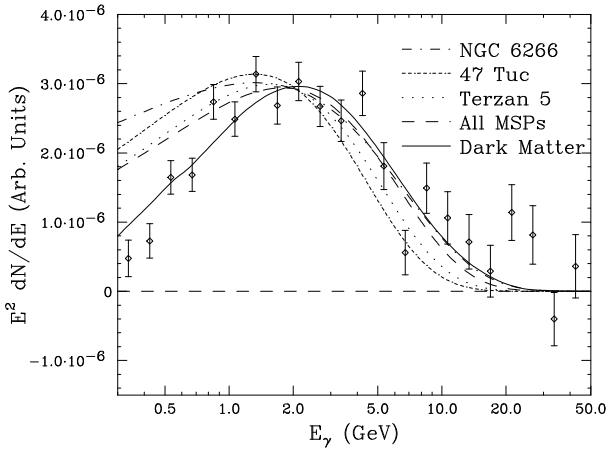
*including results from **1404.0682** and **1502.05044***

Dark matter exists...

- ... in galaxies
- ... in galaxy clusters
- ... in structure formation, in lensing, in the CMB, ...
- ... and has been observed?







Particle dark matter

- WIMP miracle / coincidence

$$\Omega_{\rm DM} \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{M_{\rm DM}^2}{g_{\rm eff}^4}$$

- Relic abundance

$$M_{\rm DM} \lesssim 1.8 \text{ TeV} \left(\frac{g_{\rm eff}^2}{0.3} \right)$$

- BSM models usually predicts parity stabilizes some new particles
  (e.g. R-parity, T-parity, KK parity, twin parity)

- Visible matter = particles

Ways we observe dark matter

- direct detection

  LUX, PICO, Xenon1T, DarkSide, LZ, ...

  Snowmass Review (1310.8327)

- indirect detection *(talk by Varun Vaidya)*

  Fermi, HESS, CTA, ...

  Conrad (1411.1925)

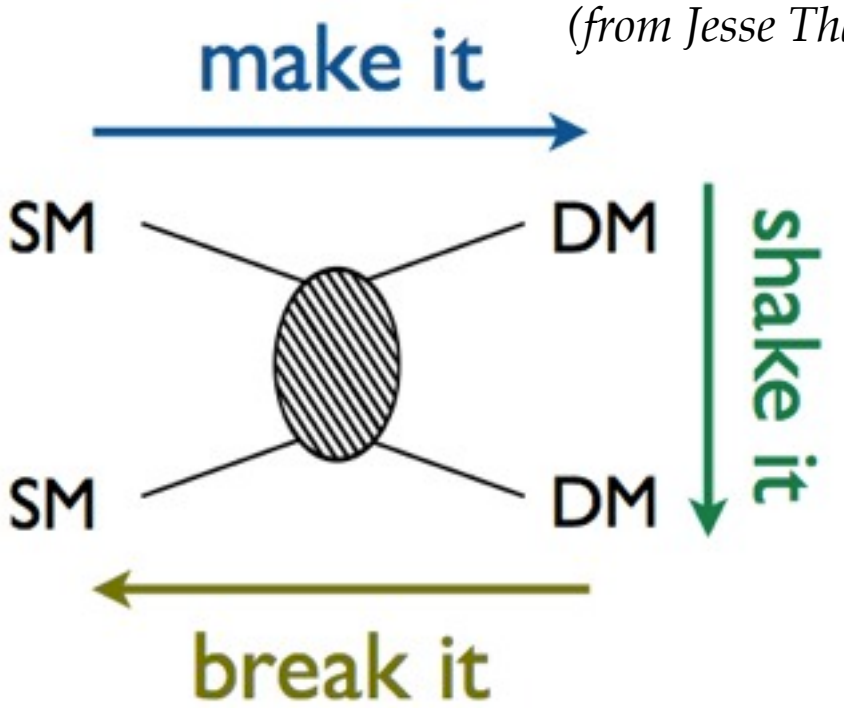
- lepton colliders

  LEP, ILC?, FCC-ee?, CEPC?, ...

- hadron colliders

  UA2, Tevatron, LHC, FCC-hh?, SPPC?, ...

(from Jesse Thaler)



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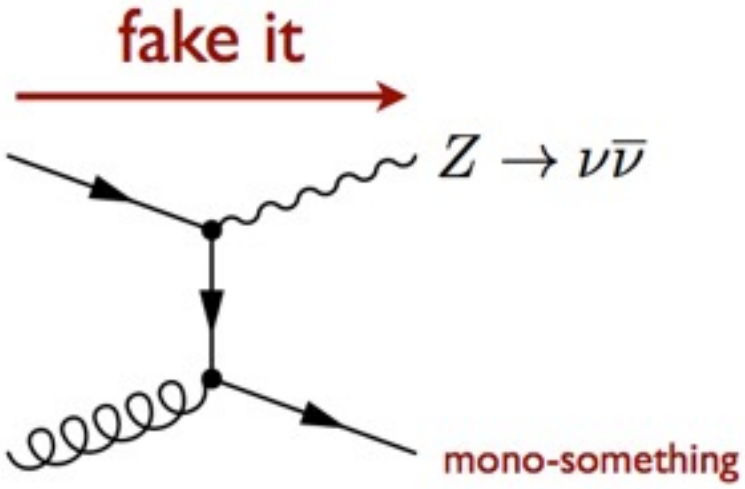


Possible approaches

- **Simplified models (EFT)**
- Simplified models (mediators)
- Electroweak multiplets

Added:

χ dark matter

Parameterize with effective operators

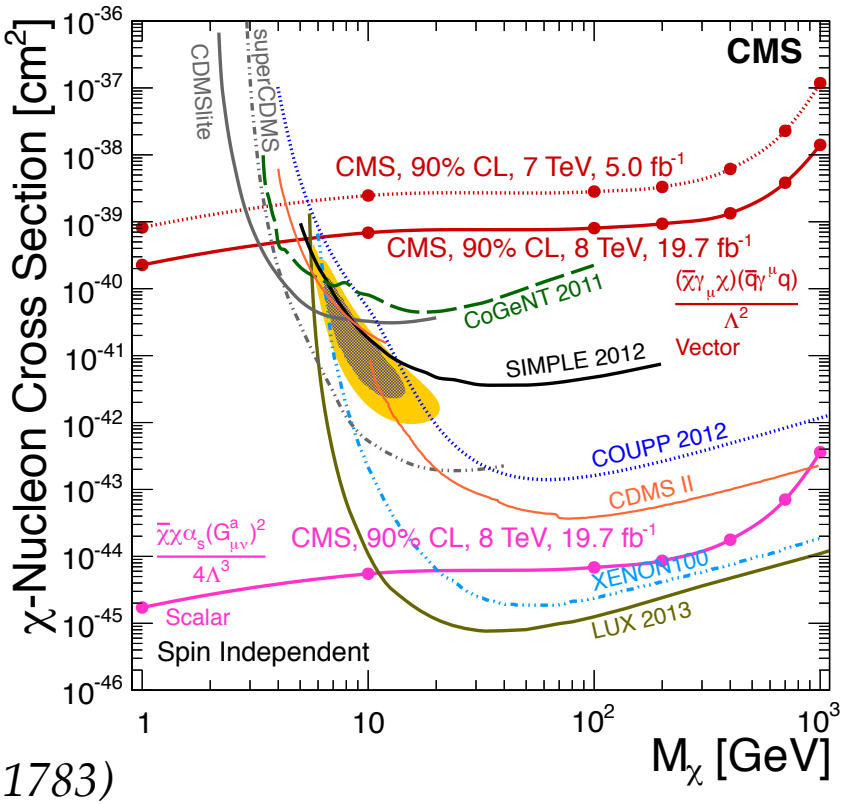
D5: $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$

D6: $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$

D7: $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$

D8: $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$

CMS monojet search, 8 TeV, 20 /fb (1408.3583)
ATLAS monojet search, 8 TeV, 20 /fb (1502.01518)



See e.g. Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (1008.1783)

Possible approaches

- Simplified models (EFT)
- **Simplified models (mediators)**
- Electroweak multiplets

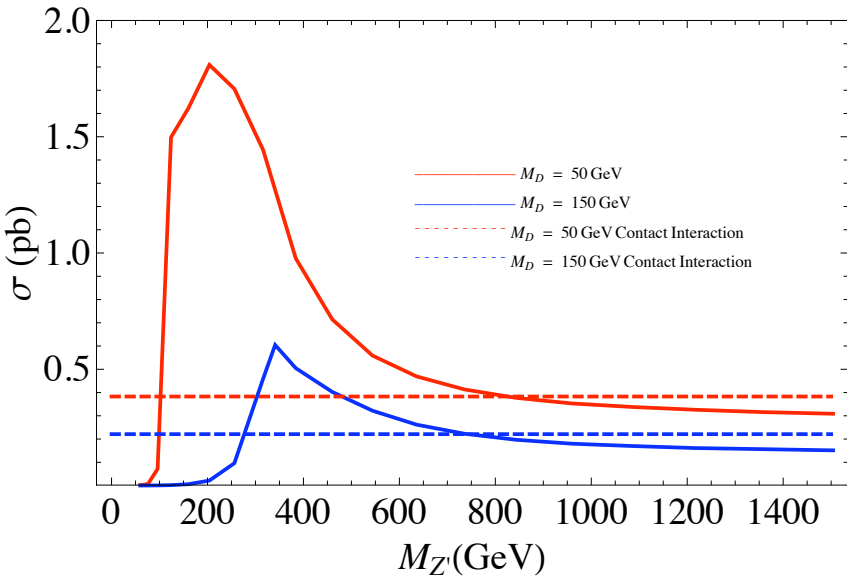
Added:

χ dark matter

Z' mediator

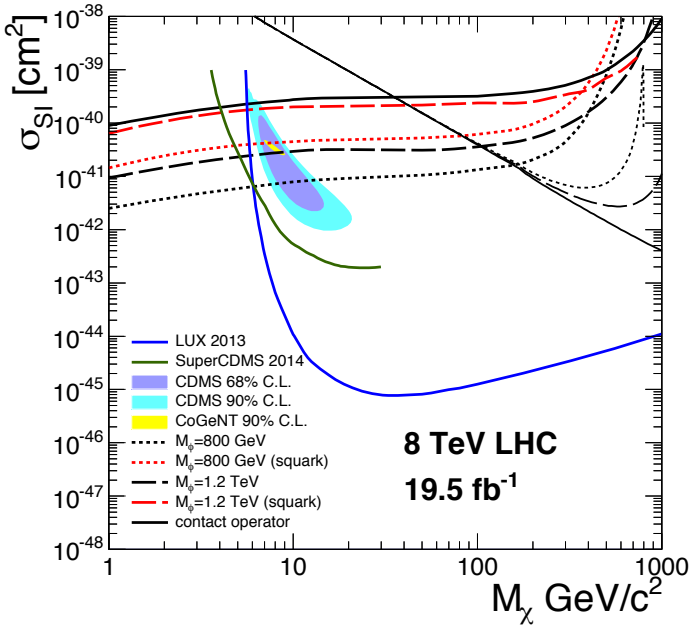
Include mediator in spectrum

- s-channel: neutral vector



See e.g. An, Wang, Zhang (1308.0592)

- t-channel: colored scalar



See e.g. An, Ji, Wang (1202.2894)

Possible approaches

- Simplified models (EFT)
- Simplified models (mediators)
- **Electroweak multiplets**

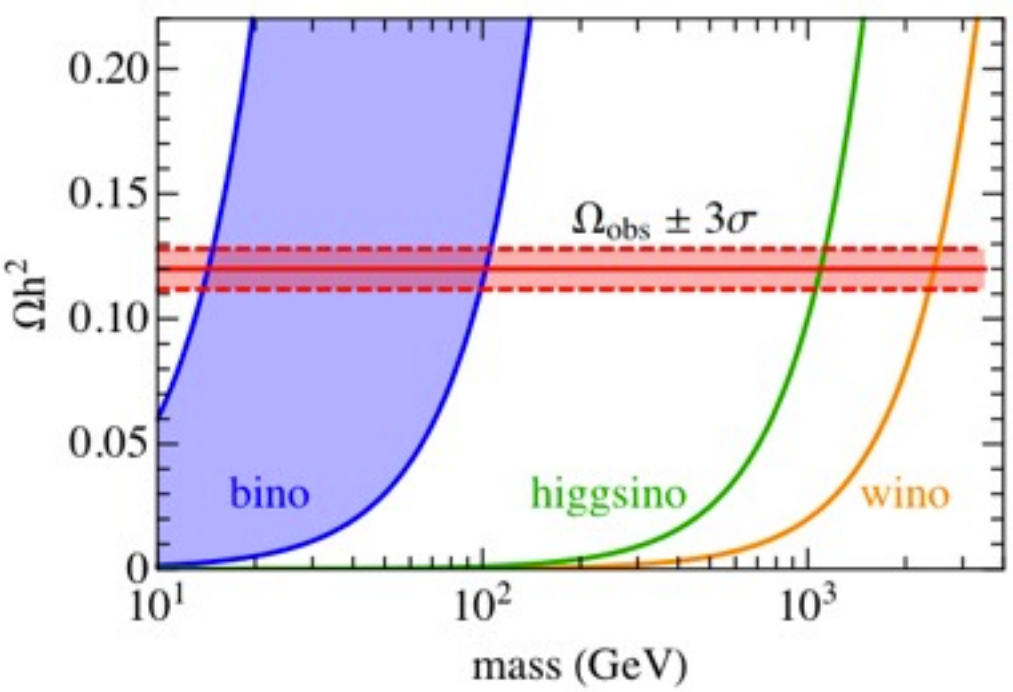
Added:

χ dark matter
(neutralino)

SUSY provides canonical examples

- Doublet (higgsino)
- Triplet (wino)
- Singlet (bino)

  co-annihilating with:
  - gluinos
  - stops
  - squarks



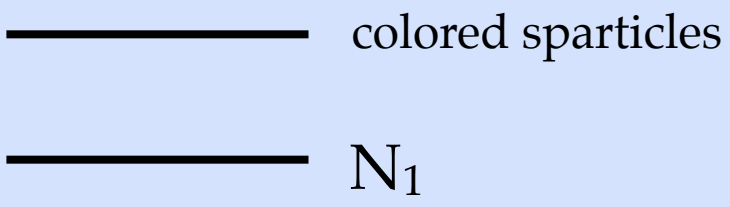
See also Arkani-Hamed, Delgado, Giudice (hep-ph/0601041)

Possible approaches

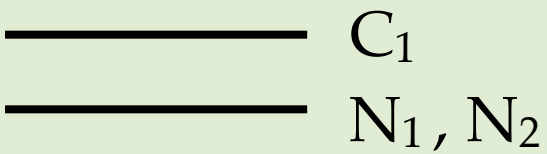
- Simplified models (EFT)
- Simplified models (mediators)
- **Electroweak multiplets**

Mass splittings are generic

- Singlet (bino)
  + coannihilator

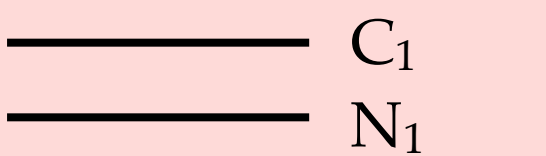


- Doublet (higgsino)



$$\Delta M = \alpha_2 M_w \sin^2(\theta_w/2)$$
$$\simeq 355 \text{ MeV}$$

- Triplet (wino)



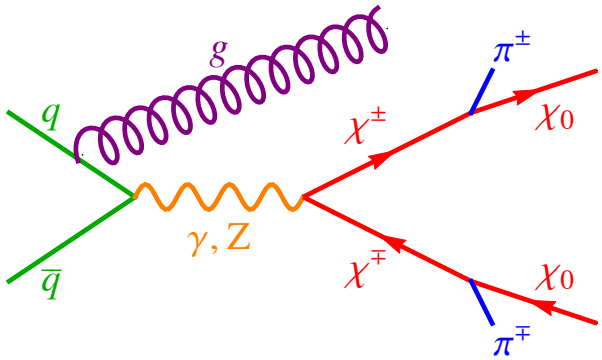
$$\Delta M = \alpha_2 (M_z/2) \sin^2(\theta_w)$$
$$\simeq 166 \text{ MeV}$$

See also Cirelli, Fornengo, Strumia (hep-ph/0512090)

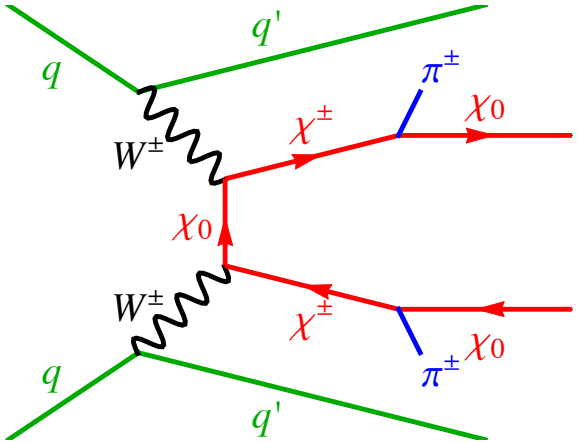
At hadron colliders

Produce it

- intermediate W / Z

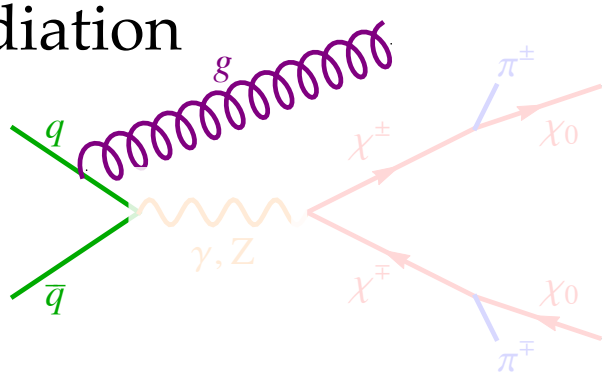


- incoming W / Z

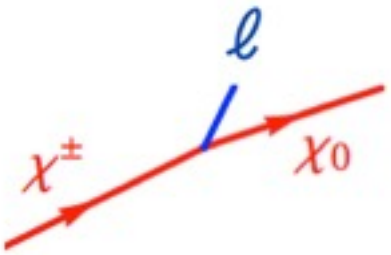


Detect it

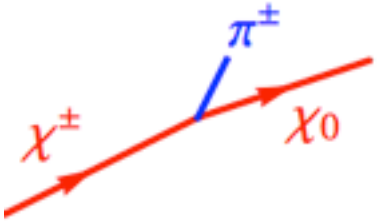
- radiation



- leptonic decay



- hadronic decay



Challenges

- small rates

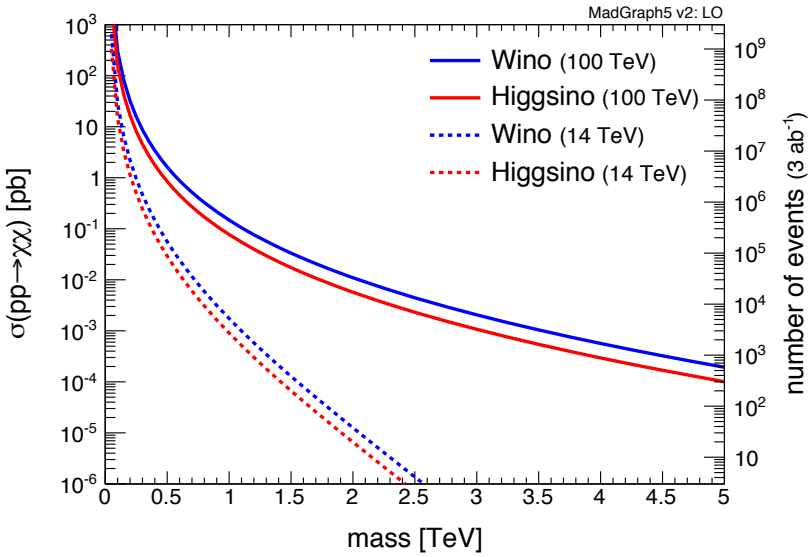
  100 TeV may be a necessity

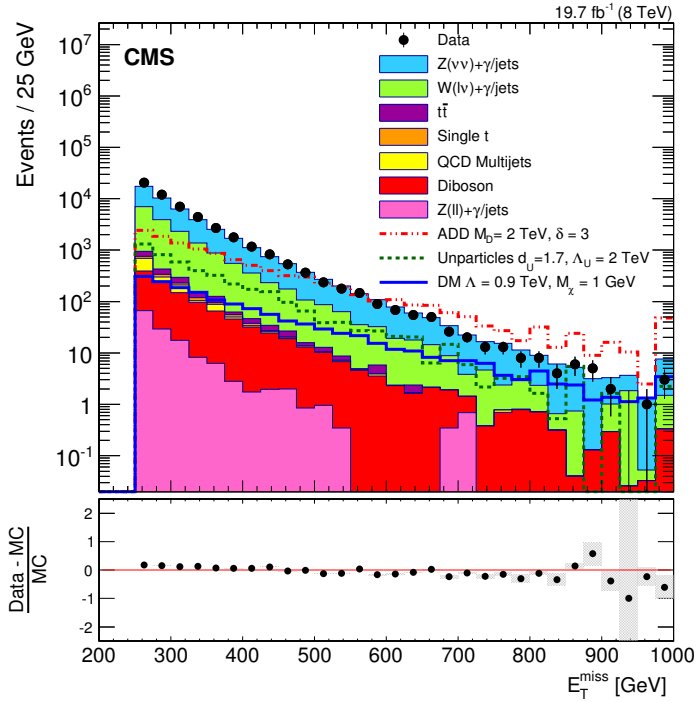
- large backgrounds*

  neutrinos are invisible in colliders

- (controlling systematics)

  errors compound in missing energy



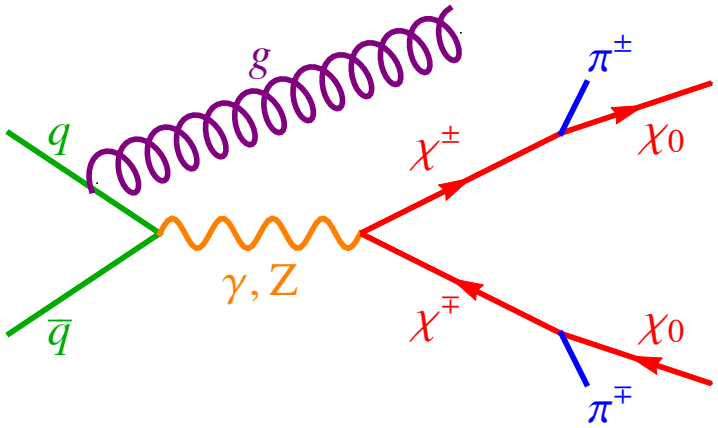


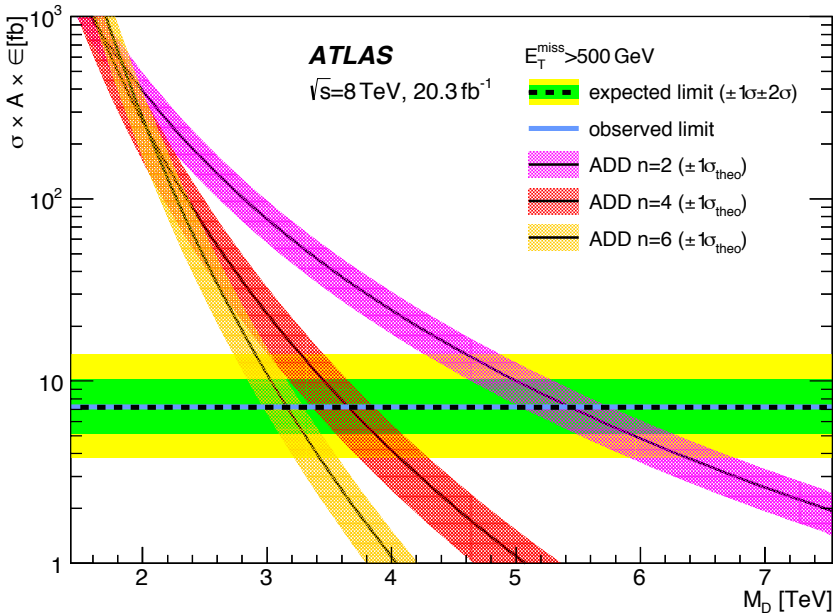
CMS monojet search, 8 TeV, 20 /fb (1408.3583)

ATLAS monojet search, 8 TeV, 20 /fb (1502.01518)

Searches: Monojet

- One or more hard jets and missing energy





Backgrounds:

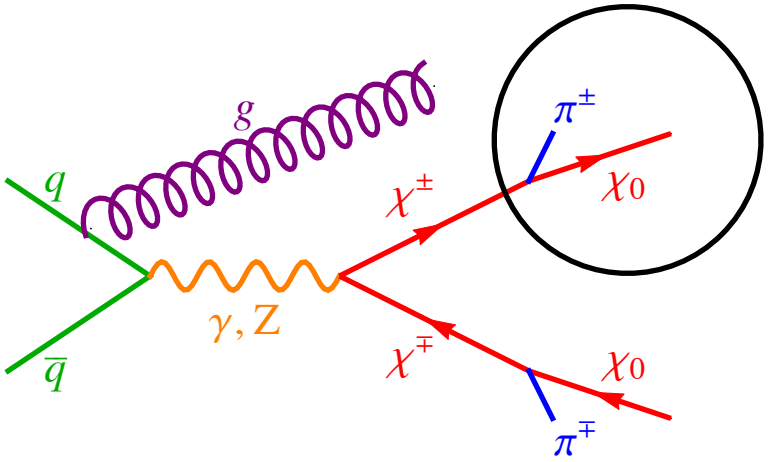
- **Z(νν) + jets**
- W(ℓν) + jets
- ttbar + jets
- Z(ℓℓ) + jets
- single top
- multijet
- detector-related

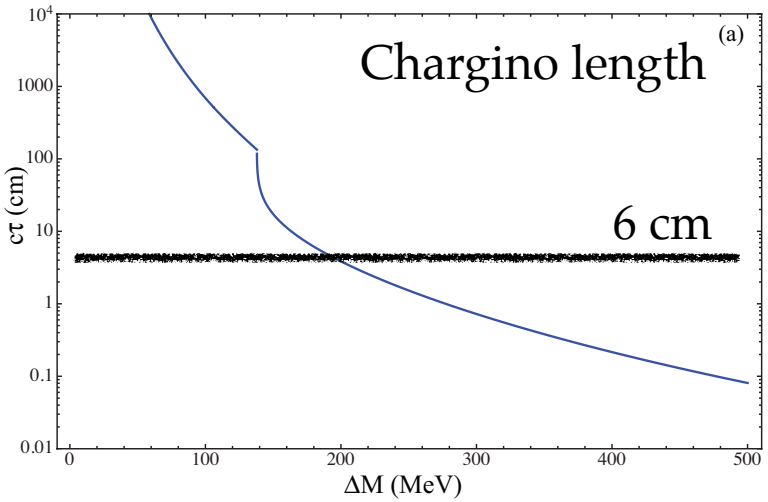
CMS monojet search, 8 TeV, 20 /fb (1408.3583)

ATLAS monojet search, 8 TeV, 20 /fb (1502.01518)

Searches: Disappearing tracks

- Chargino track which disappears as it decays to neutralino and soft pion





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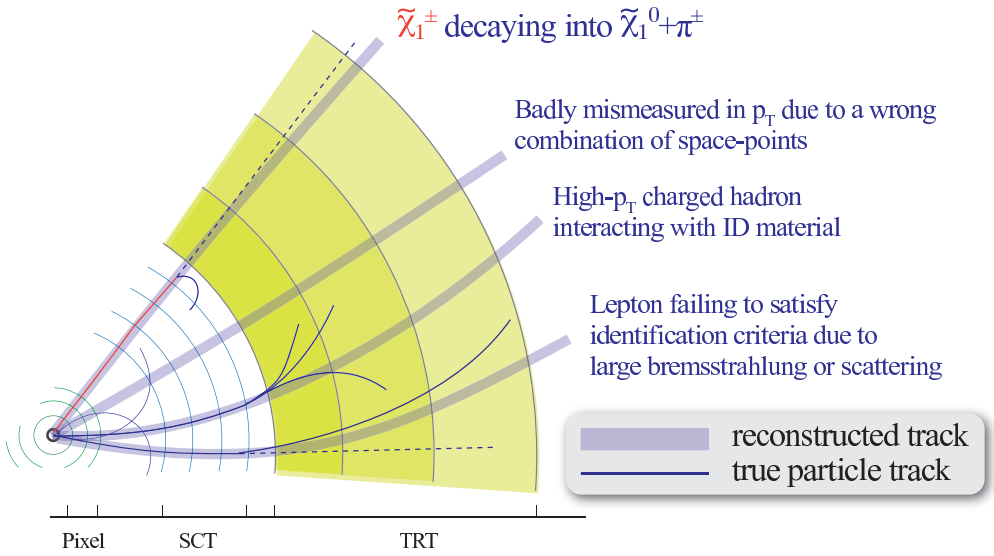

from Buckley, Randall, Shuve (0909.4549)

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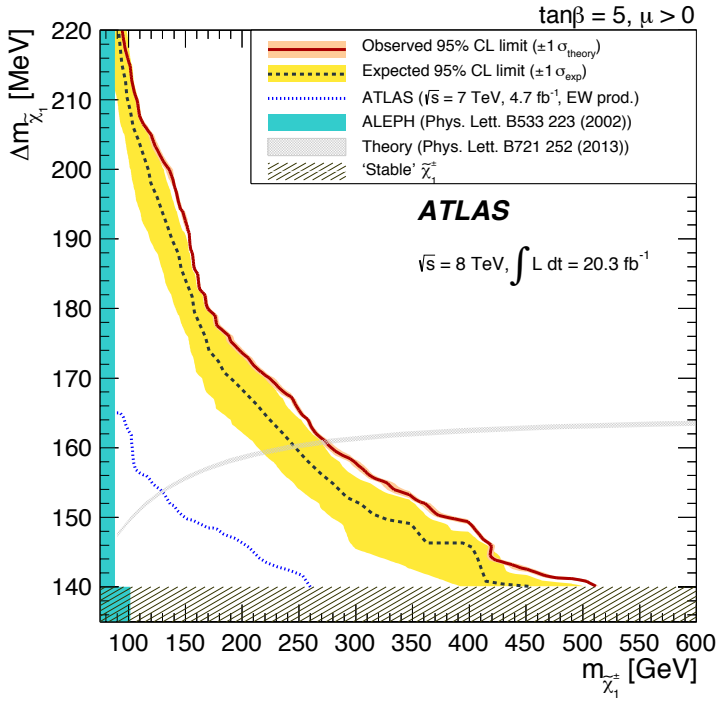
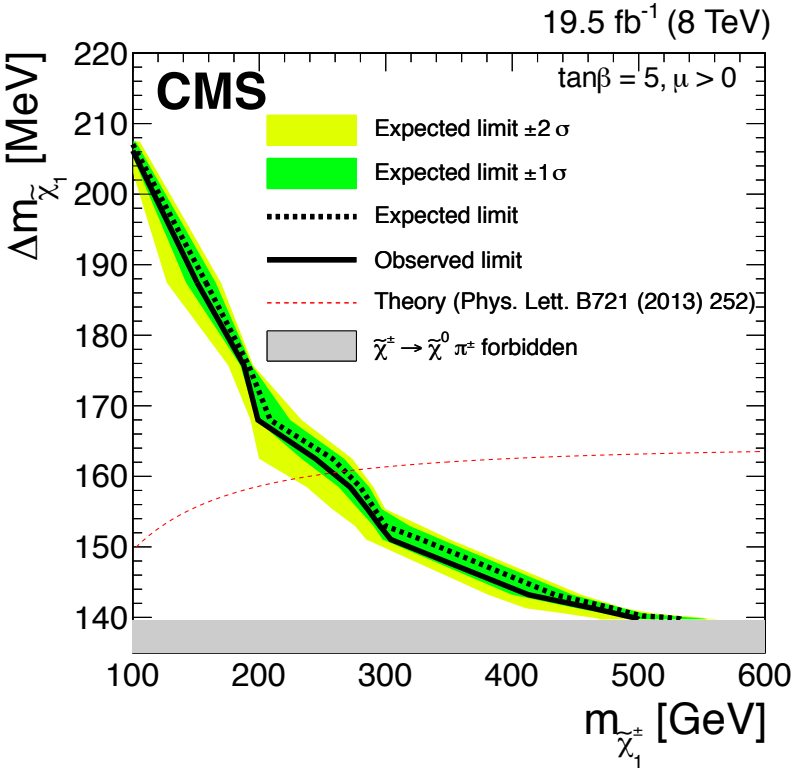




CMS disappearing tracks search, 8 TeV, 20 /fb (1411.6006)

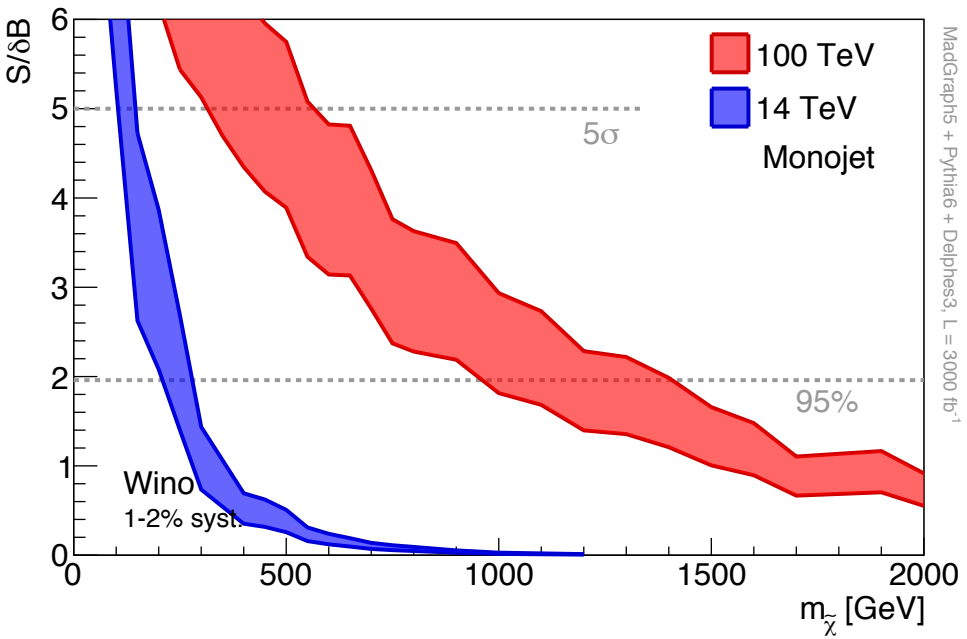
ATLAS disappearing search, 8 TeV, 20 /fb (1310.3675)

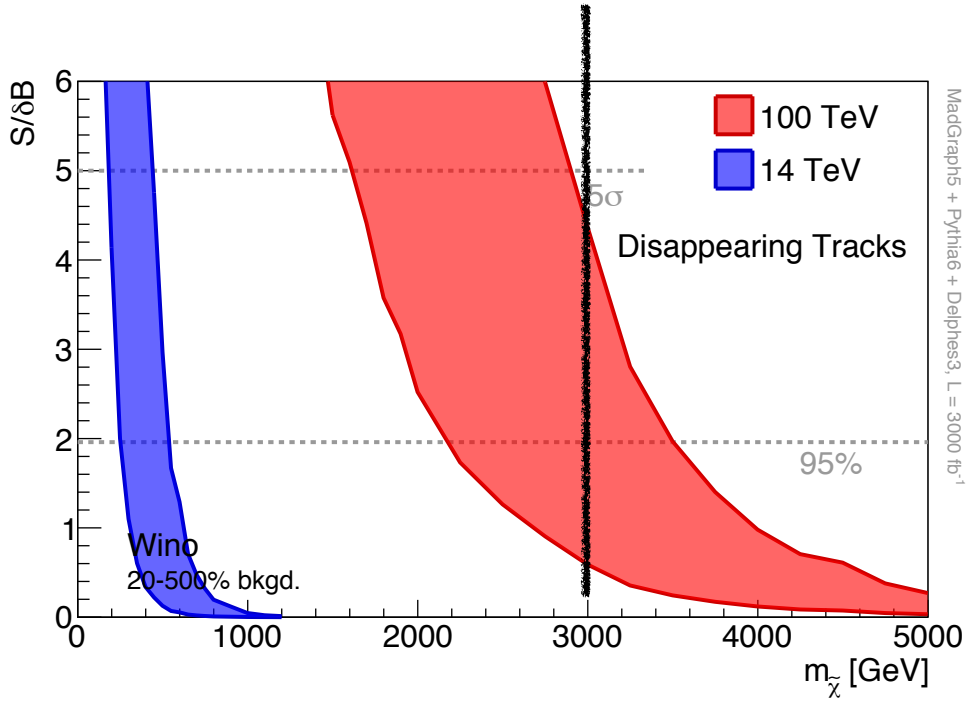
Winos

ML, Wang (1404.0682)
Berlin, Lin, ML, Wang (1502.05044)

- 1 neutralino, 1 chargino, $\Delta M \simeq 166$ MeV
- UV splitting at dim-7
- 100 TeV could cover thermal winos!

thermal wino





See also Cirelli, Sala, Taoso (1407.7058)

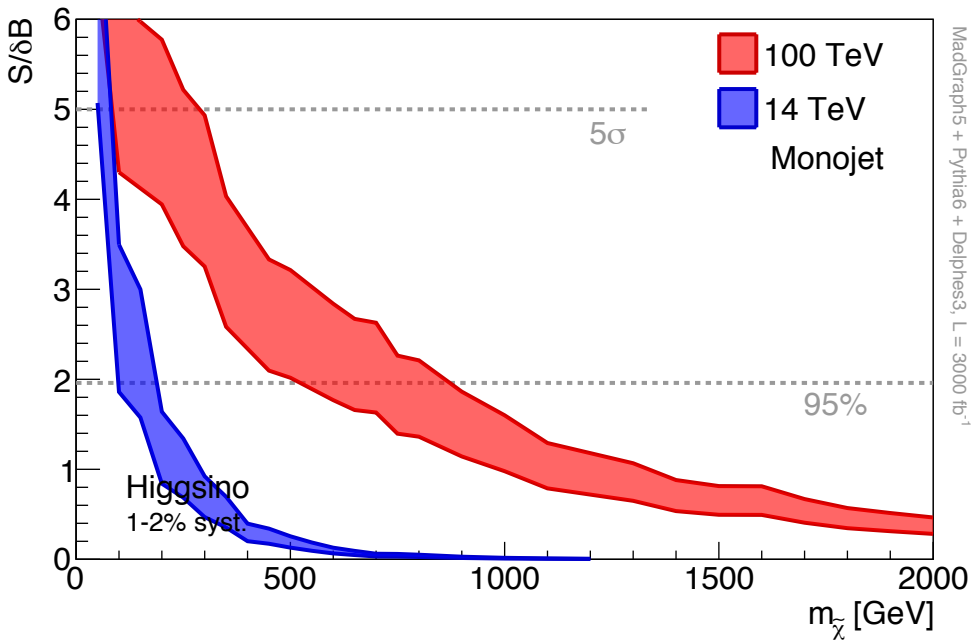
Higgsinos

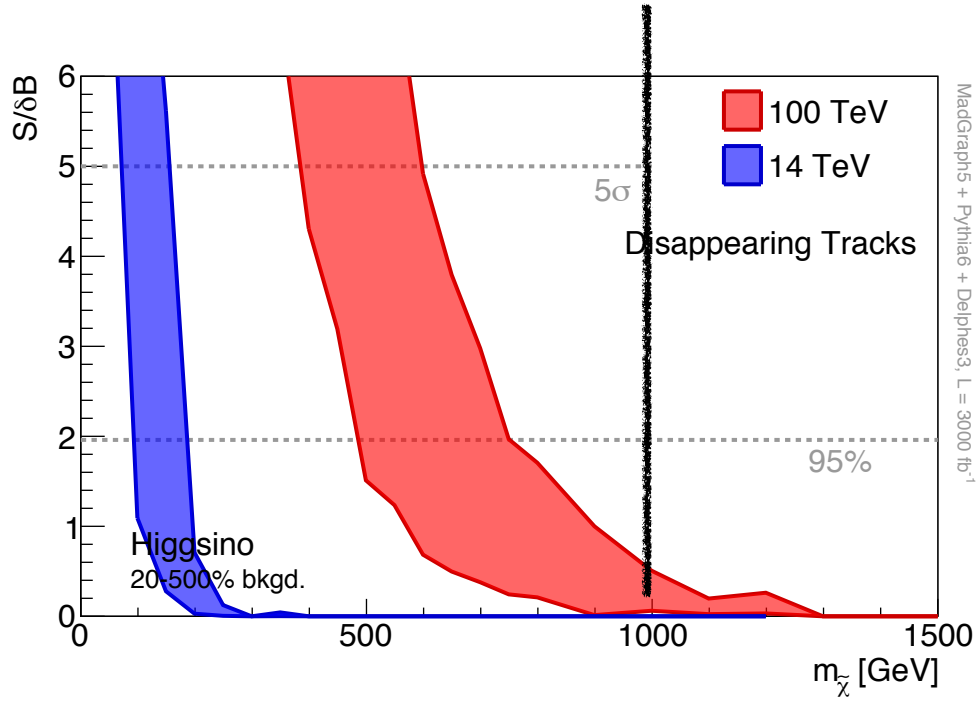
ML, Wang (1404.0682)
Berlin, Lin, ML, Wang (1502.05044)

- 2 neutralinos, 1 chargino, $\Delta M \simeq 355$ MeV
- UV splitting at dim-5
- Requires other states to probe (even at 100 TeV)

See Gori, Jung, Wang, Wells (1410.6287)

thermal higgsino





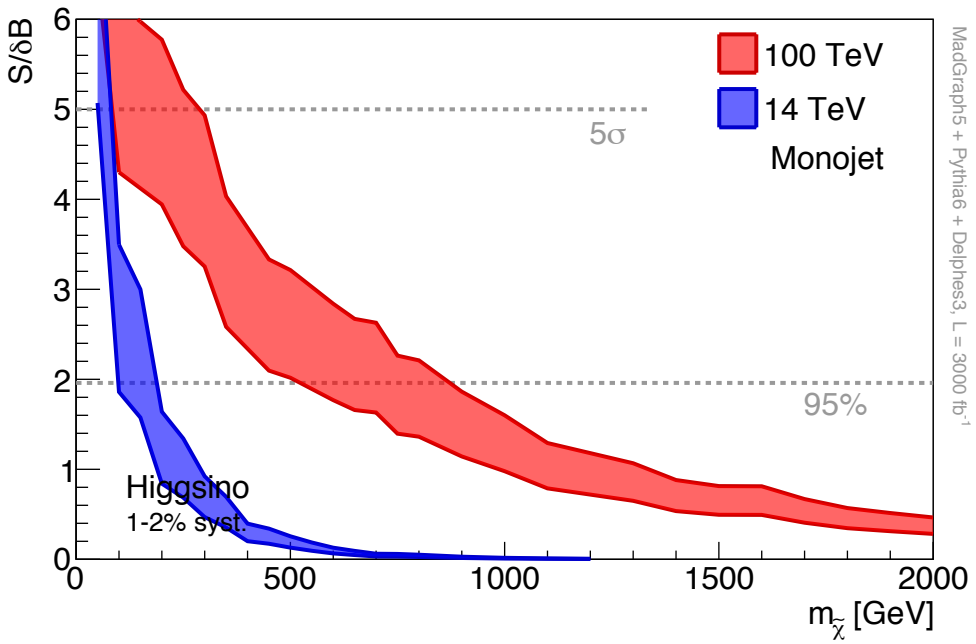
Higgsinos

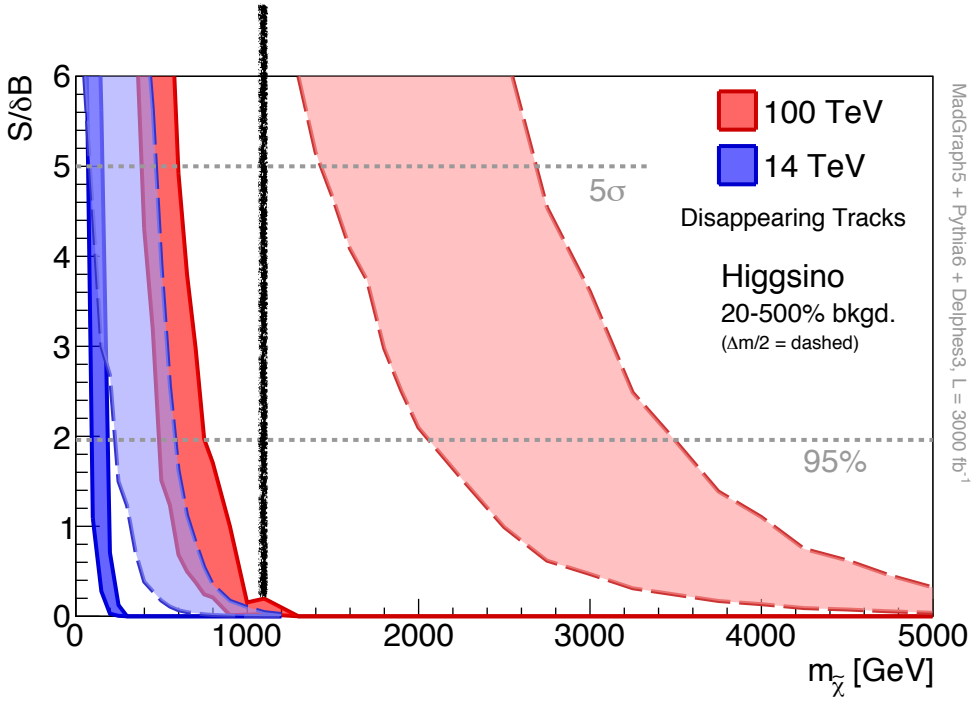
ML, Wang (1404.0682)
Berlin, Lin, ML, Wang (1502.05044)

- UV splitting at dim-5

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

thermal higgsino



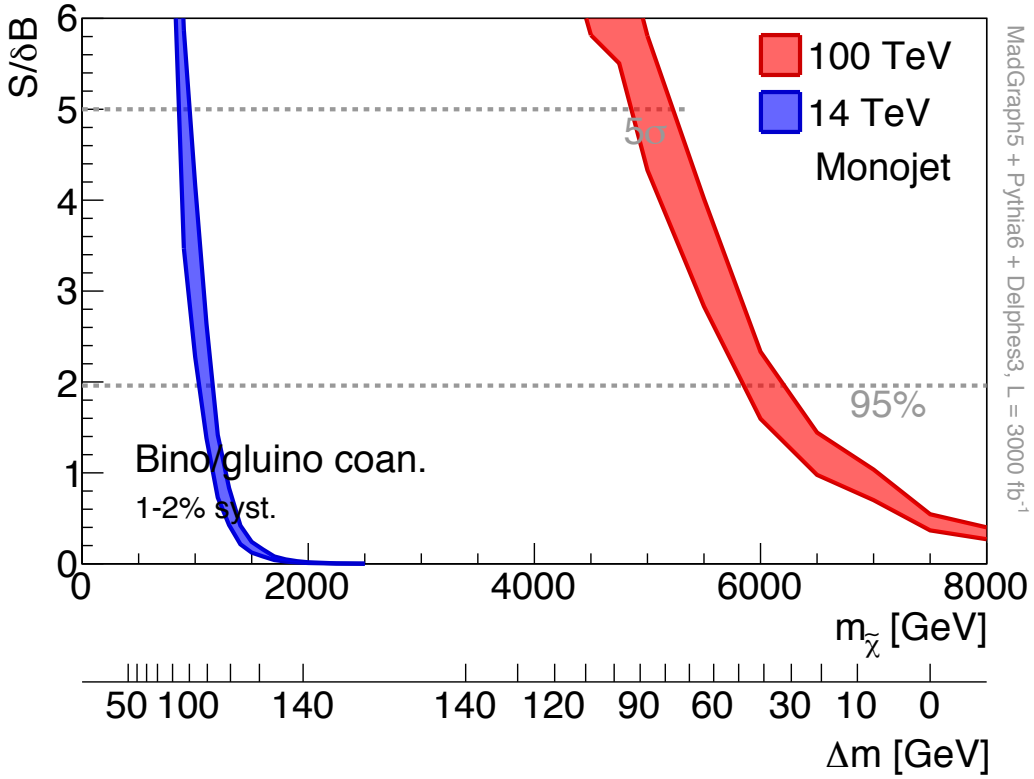


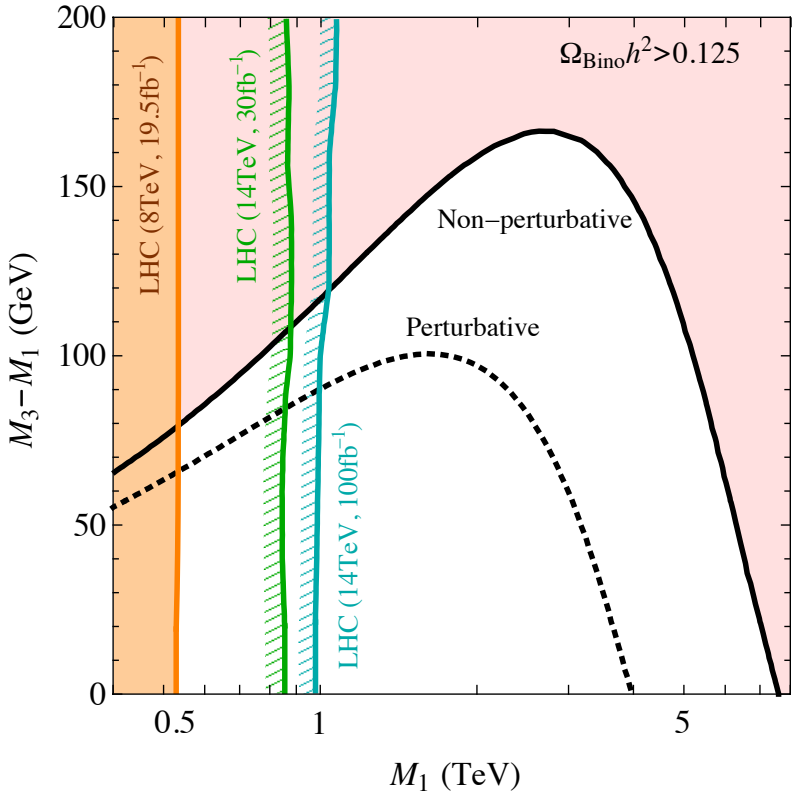
See also CEPC-SppC pre CDR (to appear)

Gluino/bino coannihilation

ML, Wang (1404.0682)

- 1 neutralino, 8 gluinos
- *Conservative*: assuming decay products undetected



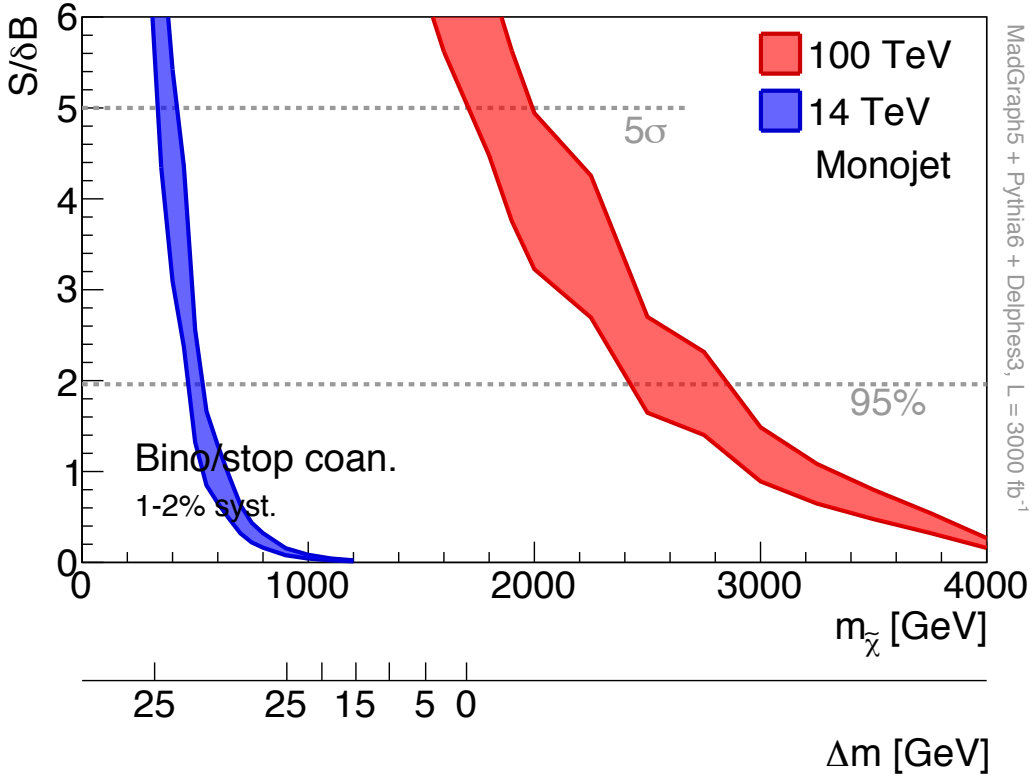


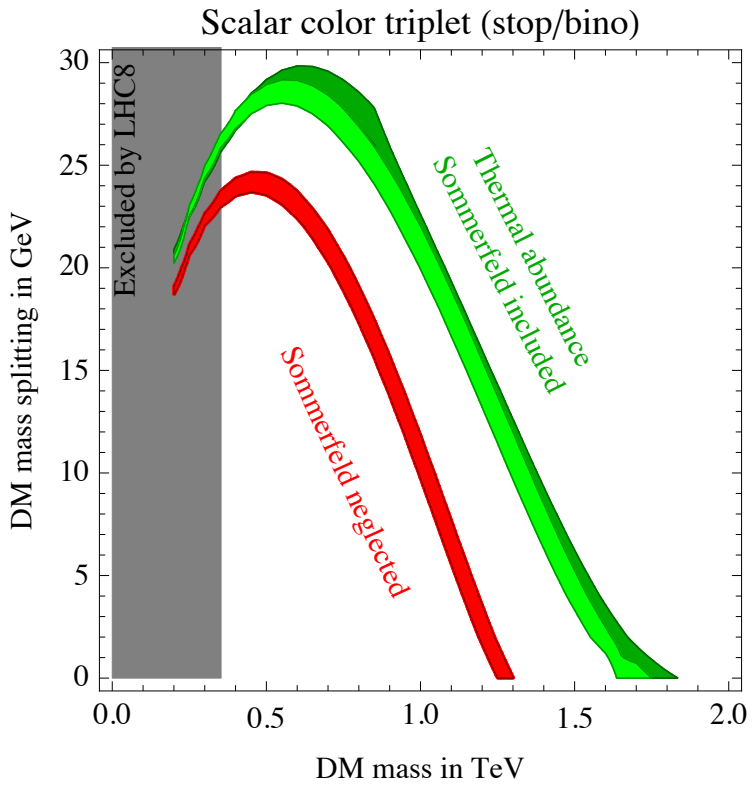
See De Simone, Giudice, Strumia (1402.6287), Harigaya, Kaneta, Matsumoto (1403.0715)

Stop/bino coannihilation

ML, Wang (1404.0682)

- 1 neutralino, 1 stop
- *Conservative*: assuming decay products undetected





See De Simone, Giudice, Strumia (1402.6287), Ibarra, Pierce, Shah, Vogl (1501.03164)

Summary

- Simplified models (EFT)

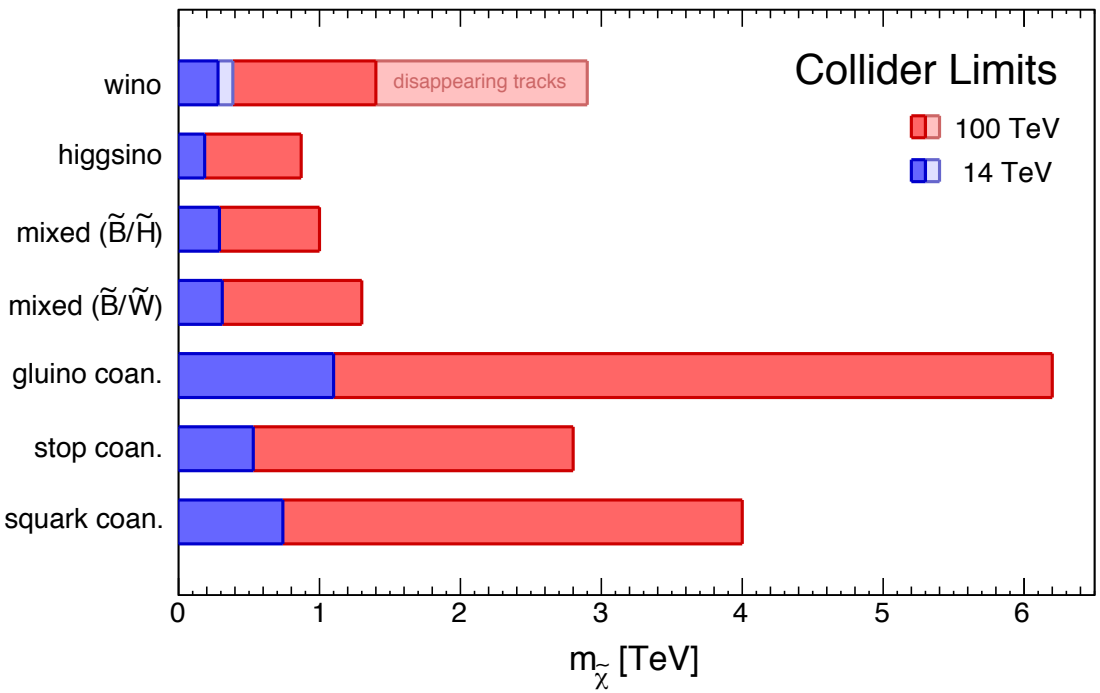
  model independent, careful with EFT validity

- Simplified models (mediators)

  s-channel, t-channel, etc.

- Electroweak multiplets

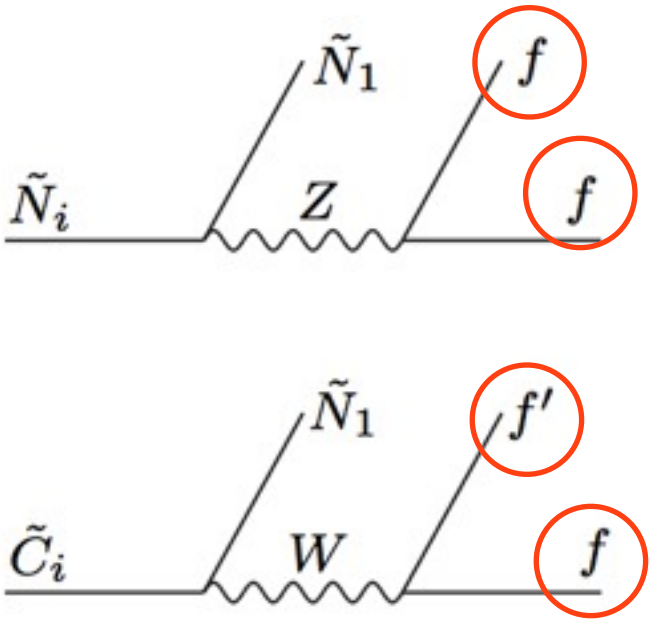
  exploit charged-neutral splittings: tag soft objects



Backup Slides

Other searches: Soft leptons

- Small chargino-neutralino splitting
- Look for soft leptons using hard jet as trigger
- Can bin the search in number of leptons (n=0,1,2)

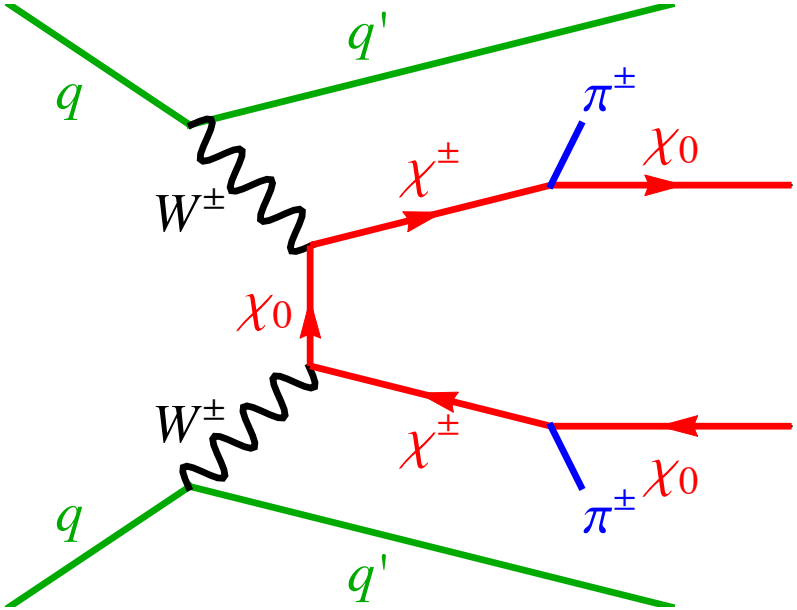


Backgrounds:

- **Z(νν) + jets**
- **W(ℓν) + jets**
- **W(ℓν) W(ℓν) + jets**
- ttbar + jets
- Z(ℓ ℓ) + jets
- single top
- multijet
- detector-related

Other searches: Vector boson fusion

- Tag two forward jets
- Veto on central jets
- Look for soft pions?



Backgrounds:

- **Z(νν) + jets**
- **W(ℓν) + jets**
- ttbar + jets

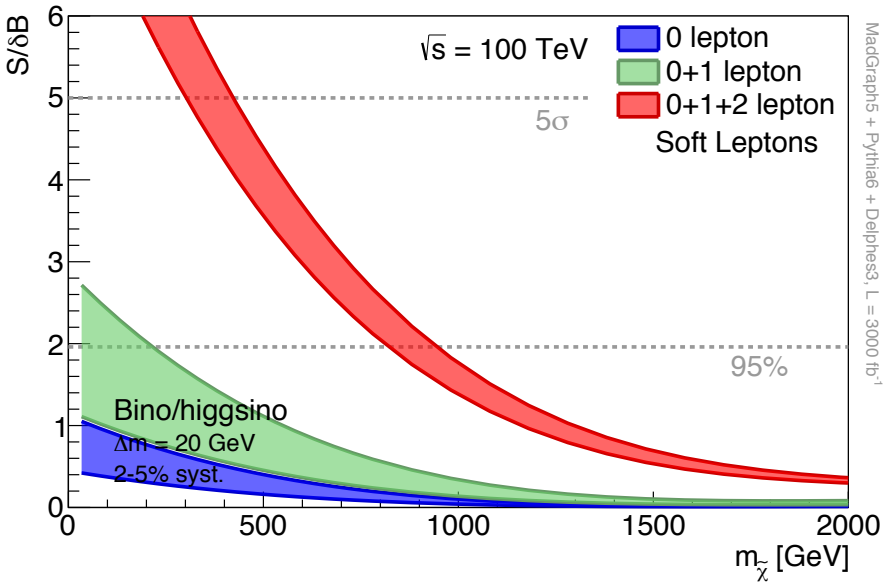
See also Cirelli, Sala, Taoso (1407.7058), Delannoy et al. (1304.7779, 1308.0355), Datta et al. (hep-ph/0109071, hep-ph/0111012)

Mixed electroweakinos

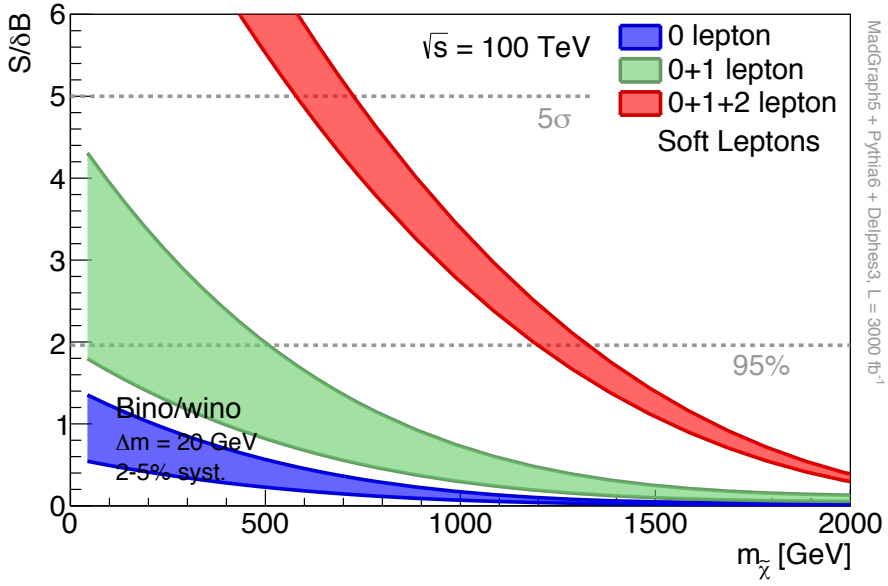
ML, Wang (1404.0682)

- 2/3 neutralinos, 1 chargino
- mass splitting: $\Delta m = m(\tilde{\chi}^{\pm}) - m(\tilde{\chi}^{0}) \simeq 20\ \mathrm{GeV}$
- tag low p_T leptons $10\ \mathrm{GeV} < p_{T,\mathrm{lepton}} < 30\ \mathrm{GeV}$
- since $p_{\mathrm{lepton}} \sim \Delta m$

Bino/higgsino

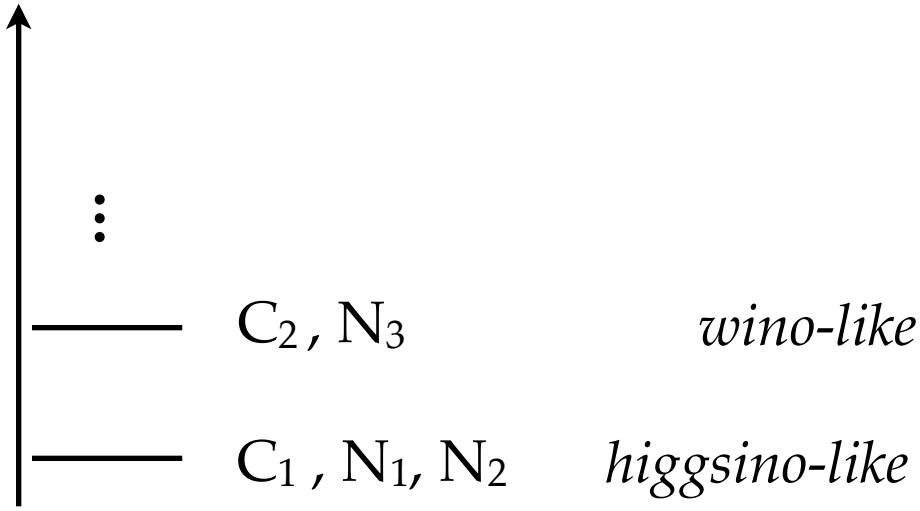


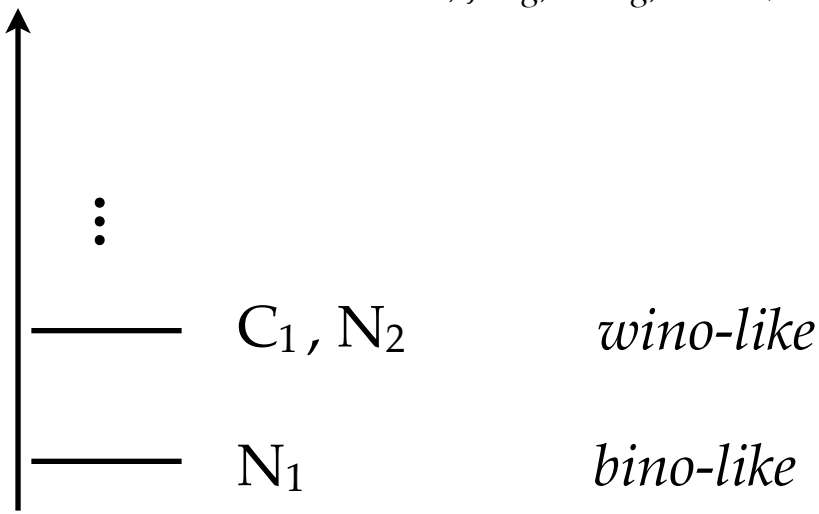
Bino/wino

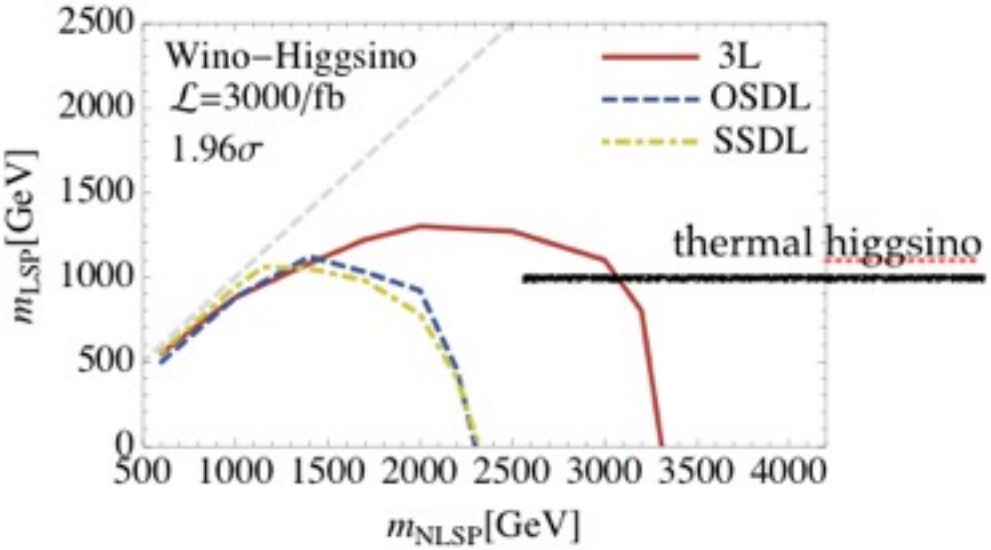


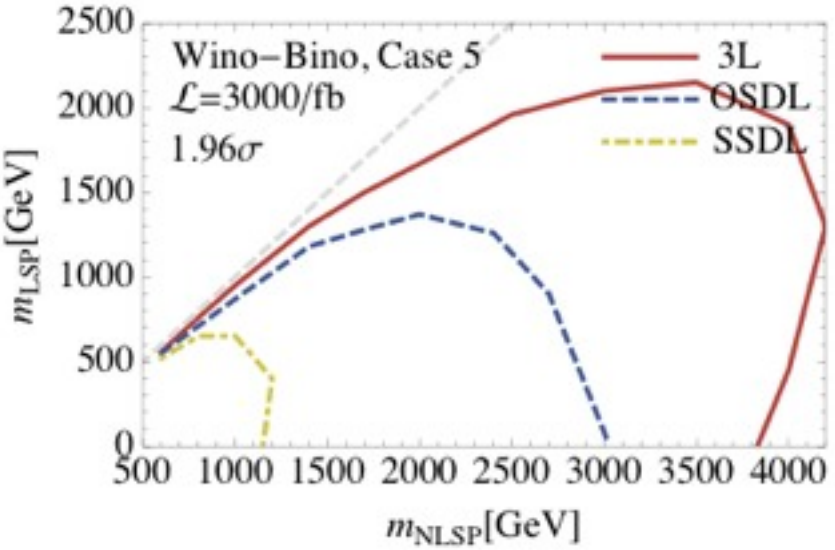
Electroweakino cascades

Gori, Jung, Wang, Wells (1410.6287)



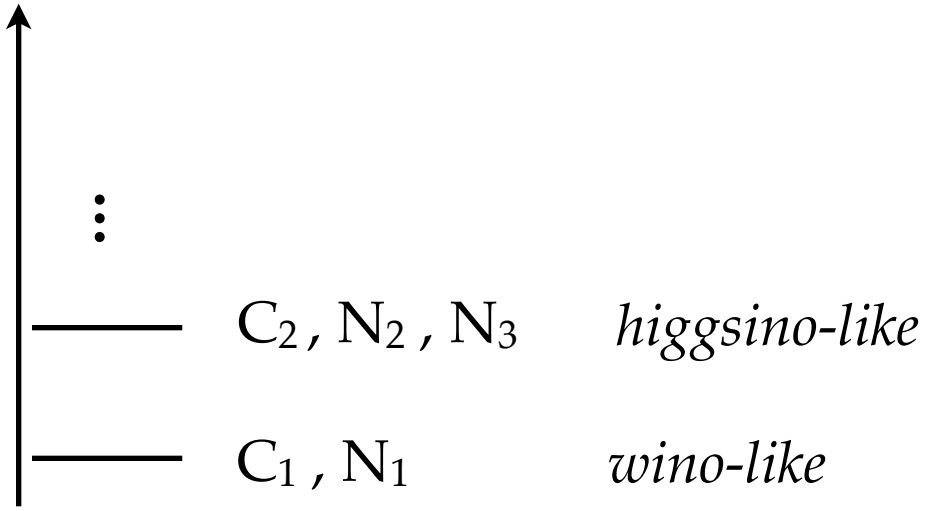


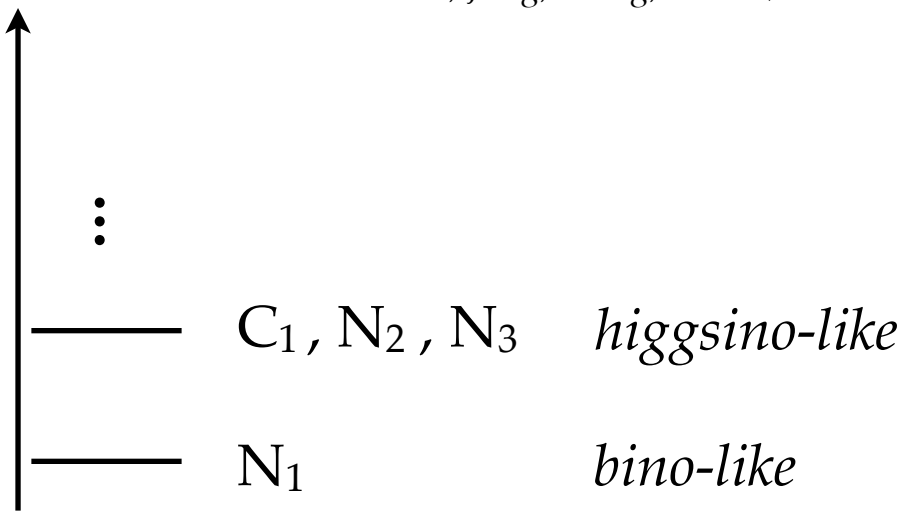


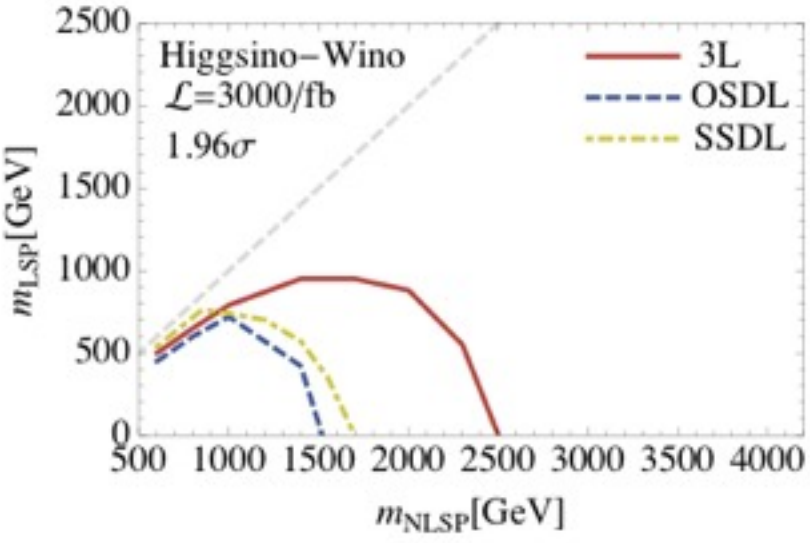


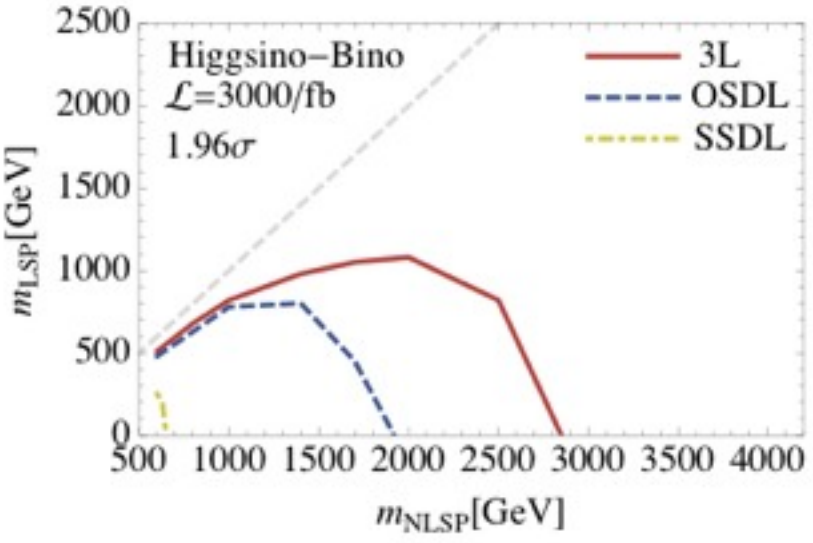
Electroweakino cascades

Gori, Jung, Wang, Wells (1410.6287)





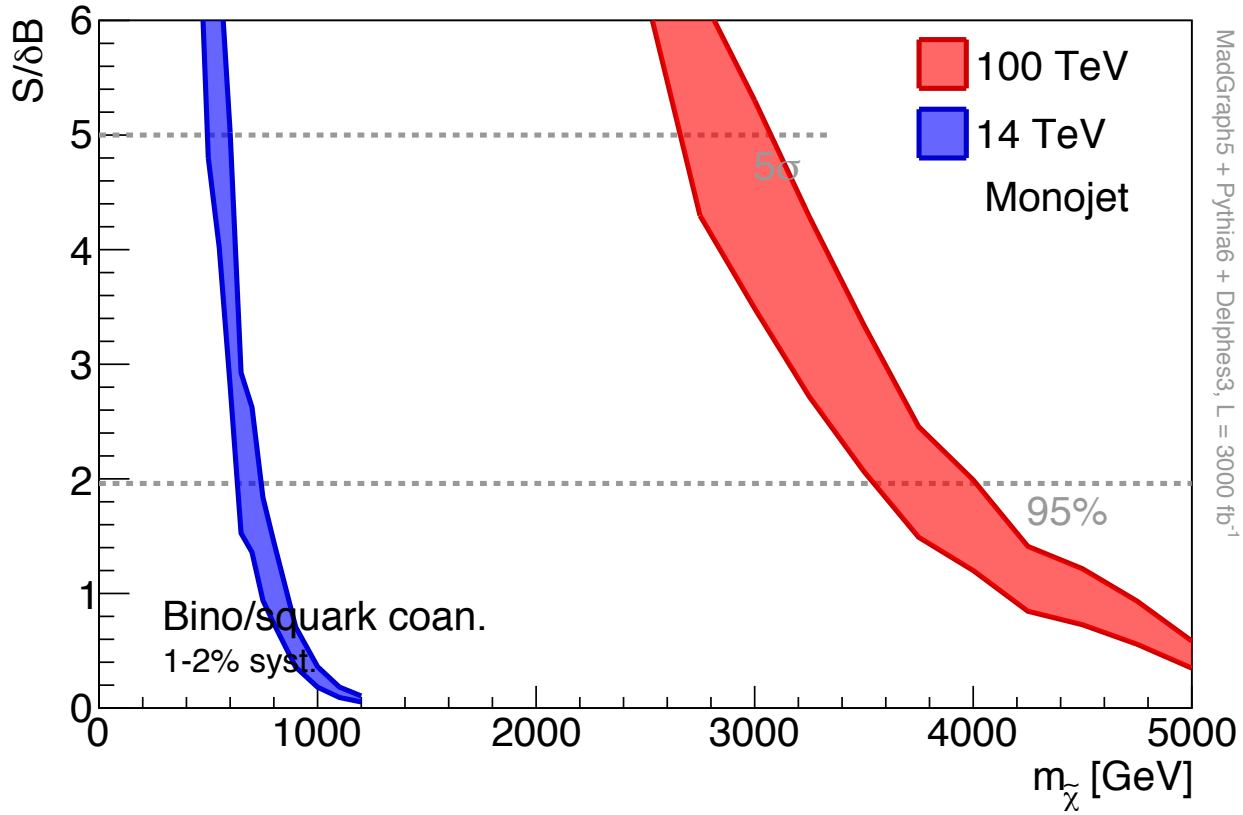




Squark coannihilation

ML, Wang (1404.0682)

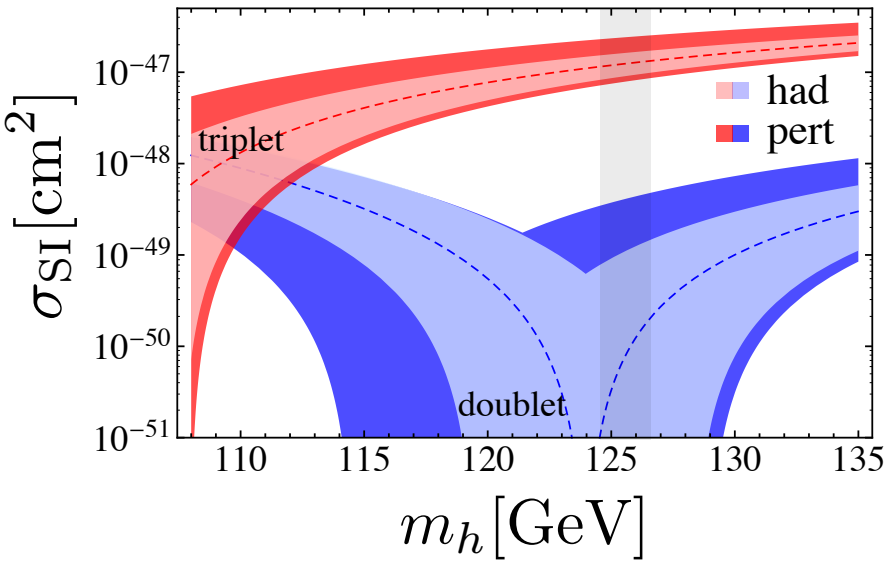
- 1 neutralino, 4 squarks (u, d, s, c)
- *Conservative*: assuming decay products undetected



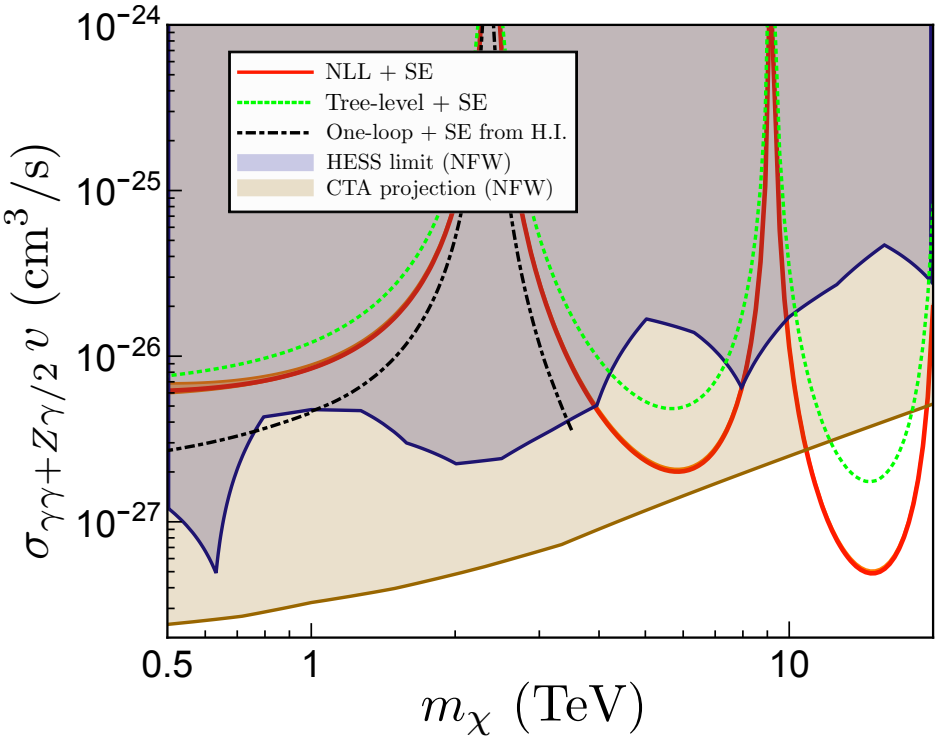
Winos: (in)direct detection

Wino: $\sigma_{\rm SI} = 1.3 \times 10^{-47}\ {\rm cm}^2$

Higgsino: $\sigma_{\rm SI} \lesssim 10^{-48}\ {\rm cm}^2$



See Hill, Solon (1309.4092), Hisano, Ishiwata, Nagata, et al. (hep-ph/0407168, 1004.4090, 1007.2601, 1104.0228, 1210.5985 1504.00915)



See Reece, Fan (1307.4400), Cohen, Lisanti, Pierce, Slatyer (1307.4082), Bauer, Cohen, Hill, Solon (1409.7392), Ovanesyan, Slatyer, Stewart (1409.8294), Baumgart, Rothstein, Vaidya (1409.4415,1412.8698)