Higgsino / Wino search

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Plan

1. Higgsino and Wino Dark Matter
   Motivation, Direct Constraint

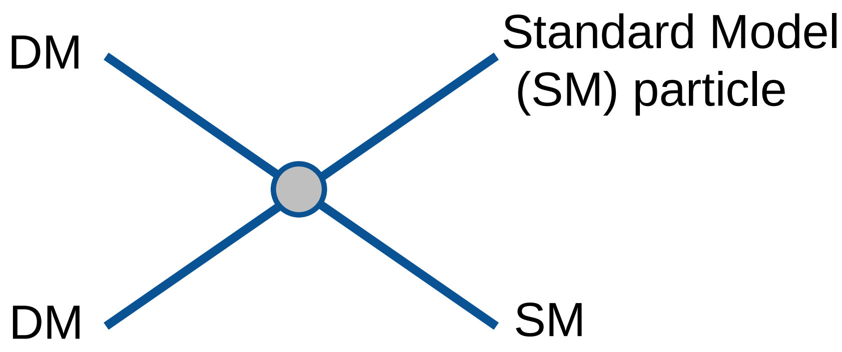
2. Constraint from Indirect Detection
   Uncertainties from cosmology and astrophysics

3. Collider Search
   Wino/Higgsino Mass Spectrum, Decay, Long-lived particle

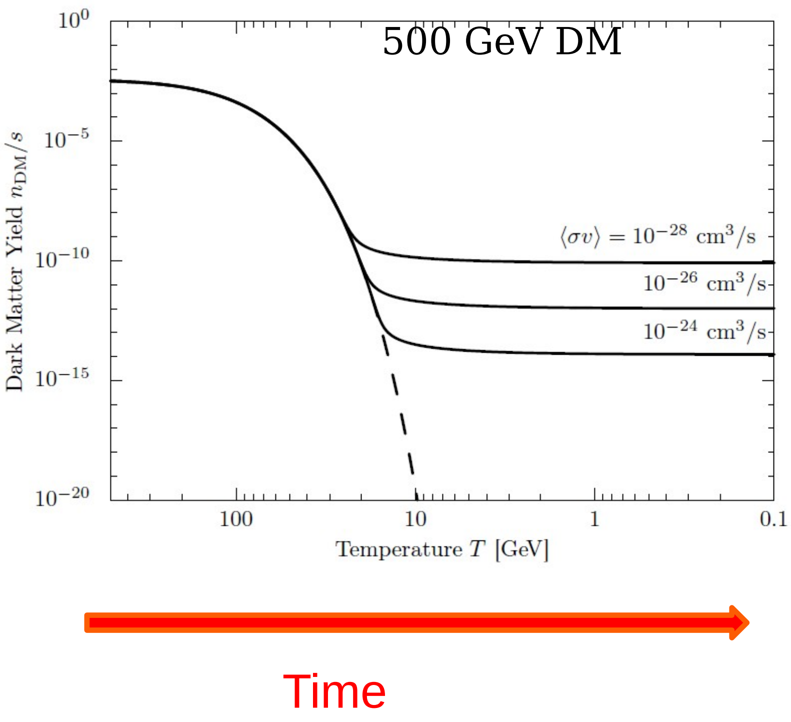
4. Summary

WIMP Dark Matter

Weakly Interacting Massive Particle



DM abundance



WIMP Miracle

$$\Omega_{\rm DM} \simeq 0.2 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ {\rm cm}^3/{\rm s}} \right)^{-1}$$

$$10^{-26}\ {\rm cm}^3/{\rm s} \simeq 10^{-9}\ {\rm GeV}^{-2} \sim \frac{\pi \alpha^2}{m_{\rm DM}^2}$$

$$m_{\rm DM} < O(1)\ {\rm TeV}$$

TeV-scale physics beyond Standard Model!

WIMP DM in Supersymmetry

Wino: $SU(2)_L$ gaugino

$$\chi_1^0 = \tilde{B} + \tilde{W}^0 + \tilde{H}_u^0 + \tilde{H}_d^0$$

Bino: $U(1)_Y$ gaugino

Higgsino: SUSY partner of Higgs

WIMP DM in Supersymmetry

Wino: $SU(2)_L$ gaugino

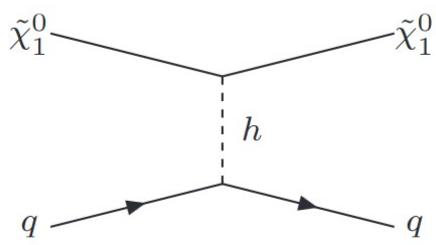
$$\chi_1^0 = \underbrace{\tilde{B}}_{\text{Bino}} + \overbrace{\tilde{W}^0}^{\text{Wino}} + \underbrace{\tilde{H}_u^0 + \tilde{H}_d^0}_{\text{Higgsino}}$$

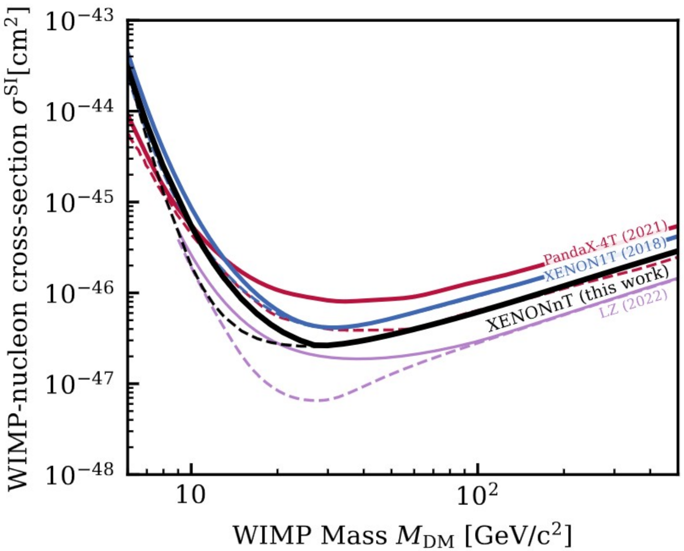
Bino: $U(1)_Y$ gaugino

Higgsino: SUSY partner of Higgs

O(1) admixture is disfavored by direct detection.

$$\sigma_{\rm SI} \sim {\rm Mixing}^2 \times 10^{-43}\ {\rm cm}^2$$





WIMP DM in Supersymmetry

Wino: SU(2)$_L$ gaugino

$$\chi_1^0 = \underbrace{\tilde{B}}_{\text{Bino}} + \overbrace{\tilde{W}^0}^{\text{Wino}} + \underbrace{\tilde{H}_u^0 + \tilde{H}_d^0}_{\text{Higgsino}}$$

Bino: U(1)$_Y$ gaugino

Higgsino: SUSY partner of Higgs

SUSY WIMP = almost pure Bino, Wino or Higgsino.

What is Higgsino?

- (pseudo)Dirac fermion
- Hypercharge |Y|=1/2
- SU(2) doublet $\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$
- <1 TeV $\Omega h^2 \simeq 0.1 \left(\frac{m_{\widetilde{H}}}{1.1 \text{ TeV}} \right)^2$

Why Higgsino?

In SUSY model

- Higgsino is the most important particle of Electroweak naturalness.
  - Focus point, natural SUSY.
- Higgsino mass μ is not SUSY breaking parameter.
  - Maybe quite different from sfermion and gaugino masses.
- Natural SUSY DM candidate for correct abundance.

Model-Independent Dark Matter

- The simplest gauge-portal minimal dark matter.
- Small number of parameters.

What is Wino

- Majorana fermion $\widetilde{W}$
- Hypercharge Y=0
- $SU(2)_L$ triplet $\begin{pmatrix} \widetilde{W}^+ \\ \widetilde{W}^0 \\ \widetilde{W}^- \end{pmatrix}$
- Mass < 3 TeV

[Hisano, Matsumoto, Nagai, Saito & Senami, 06]

Why Wino?

In SUSY model

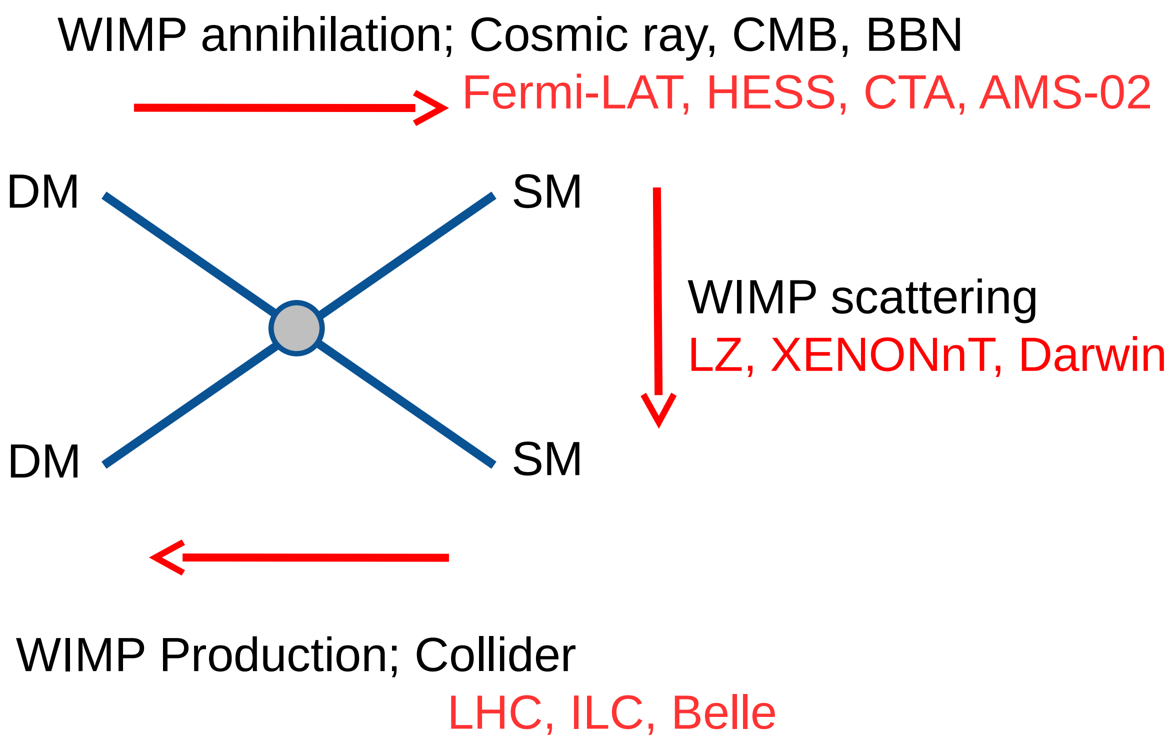
- Natural prediction of anomaly mediation model.
  - Minimal split, spread SUSY, pure gravity,….
- Wino mass needs SUSY breaking and R-symmetry breaking.
  - Maybe quite different from sfermion and Higgsino masses.
- Natural SUSY DM candidate for correct abundance.

Model-Independent Dark Matter

- The simplest gauge-portal minimal dark matter.
- Small number of parameters.

Constraint from Indirect Detection

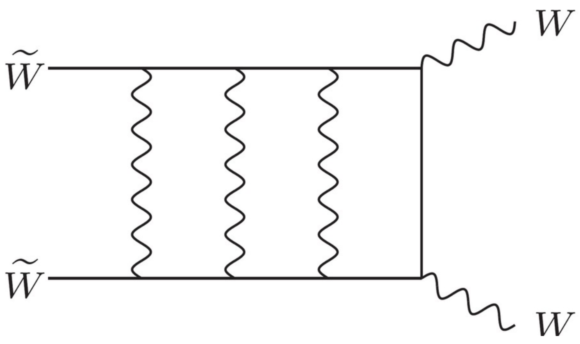
WIMP Detection



Cosmic-ray Constraint

Wino and Higgsino have gauge interaction.

→ Significant signals from DM annihilation.



But, there are large cosmological and astrophysical uncertainties.

WIMP Abundance

Higgsino/Wino is Whole Component of DM?

Yes

No

Only Thermal Relic?

Mixed DM

e.g., (thermal) Higgsino/Wino + Axion

Yes

No

1 TeV Higgsino

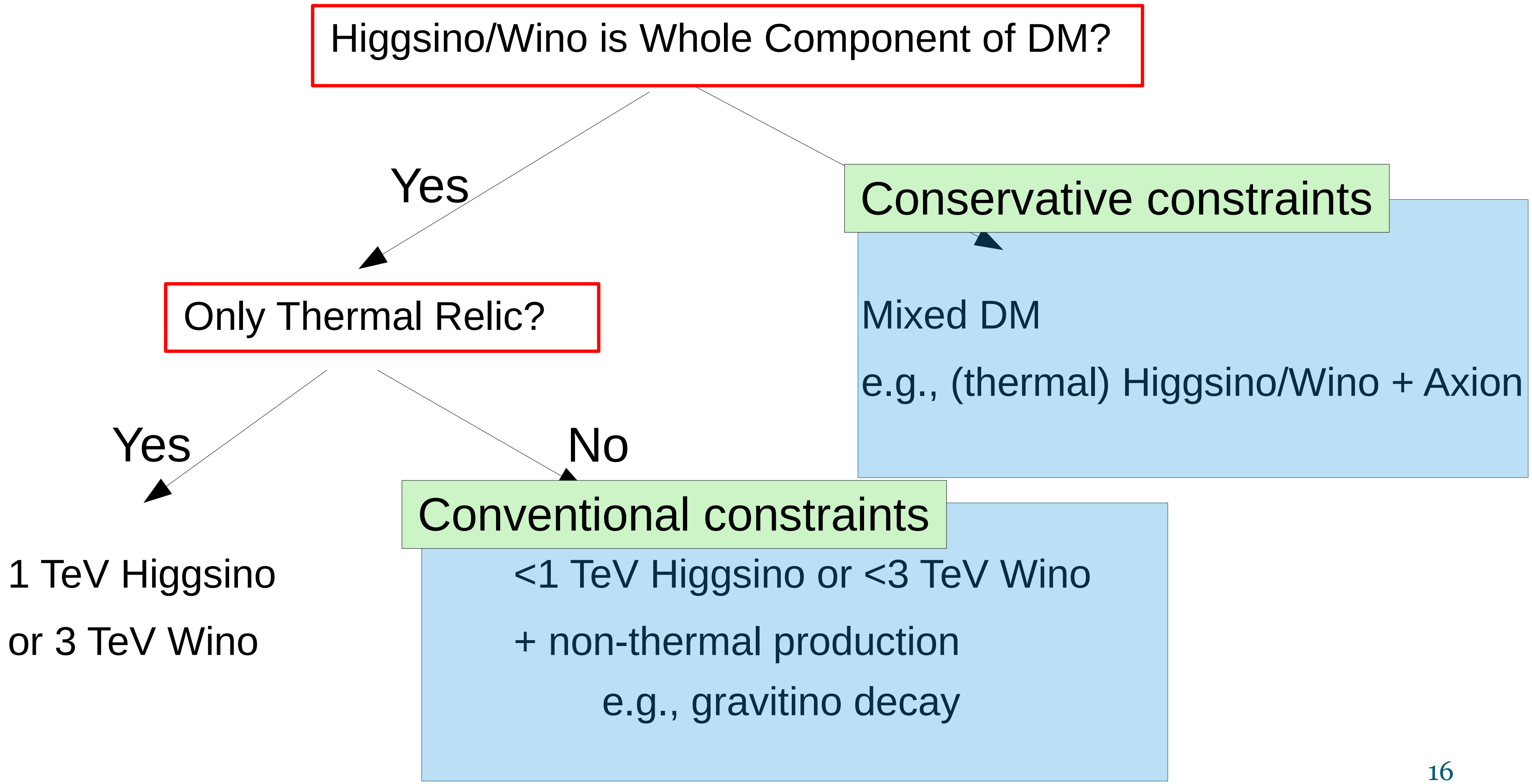
or 3 TeV Wino

<1 TeV Higgsino or <3 TeV Wino

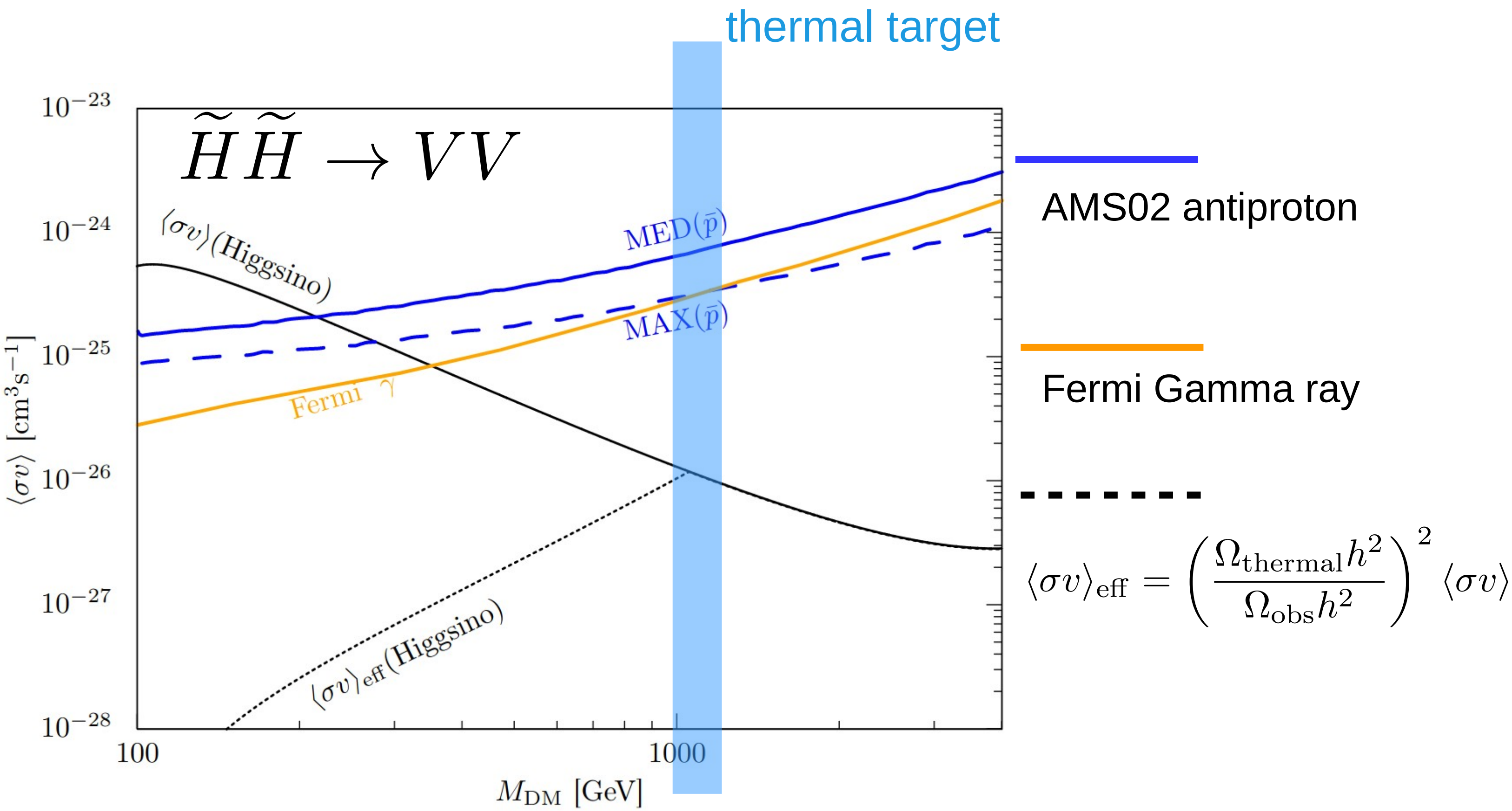
+ non-thermal production

e.g., gravitino decay

WIMP Abundance



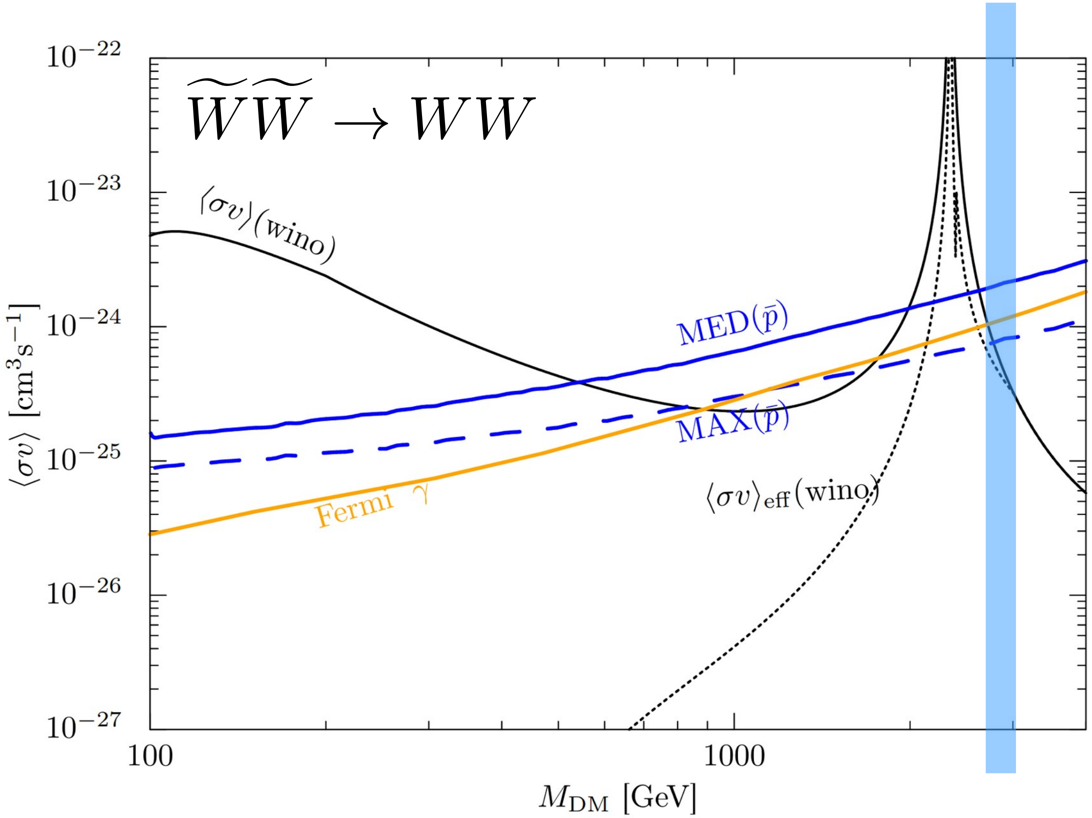
Higgsino Case



$$\langle\sigma v\rangle_{\rm eff} = \left(\frac{\Omega_{\rm thermal}h^2}{\Omega_{\rm obs}h^2}\right)^2 \langle\sigma v\rangle$$

Wino Case

thermal target

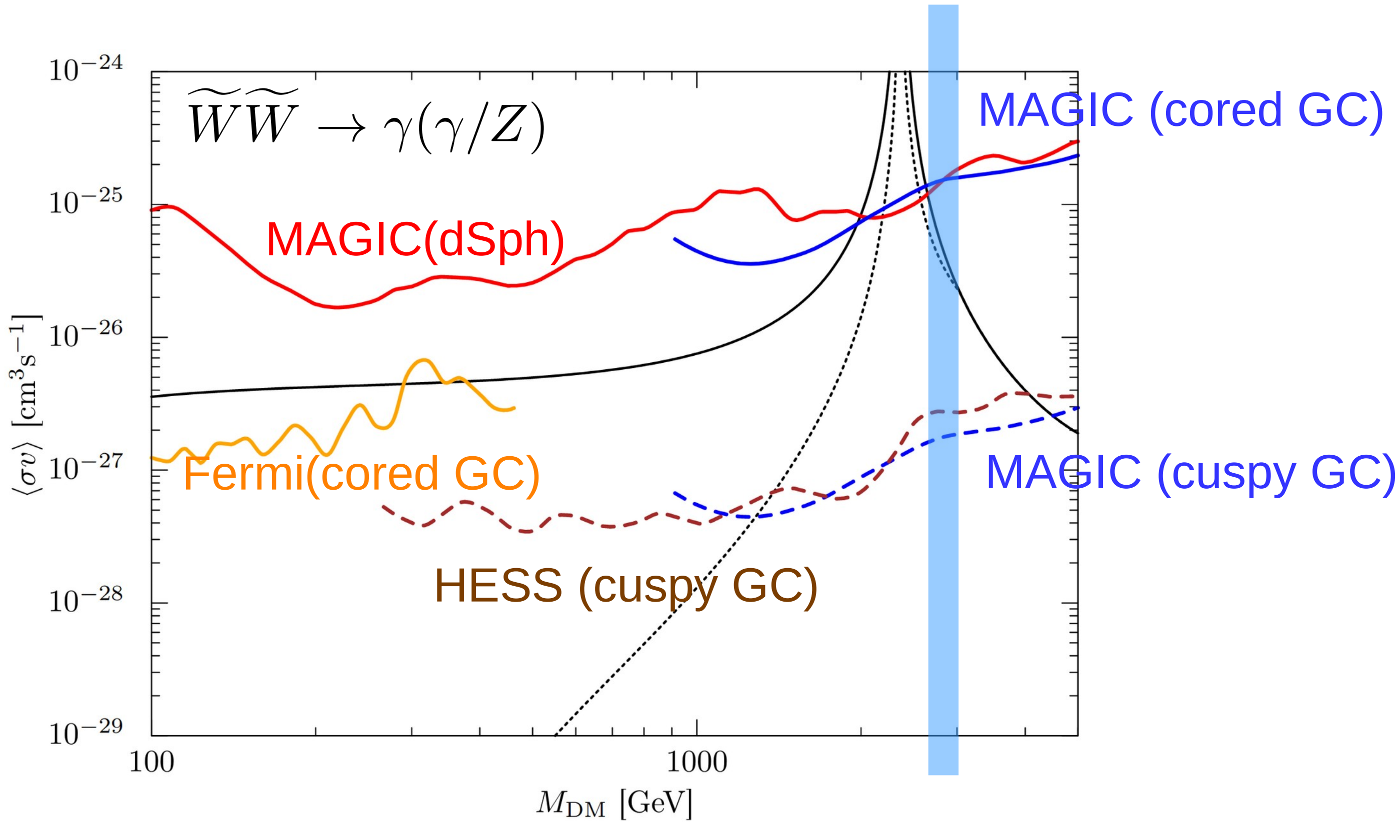


AMS02 antiproton

Fermi Gamma ray

$$\langle \sigma v \rangle_{\rm eff} = \left(\frac{\Omega_{\rm thermal} h^2}{\Omega_{\rm obs} h^2} \right)^2 \langle \sigma v \rangle$$

Line Search for Wino



GC: galactic center

Constraint of Indirect Search

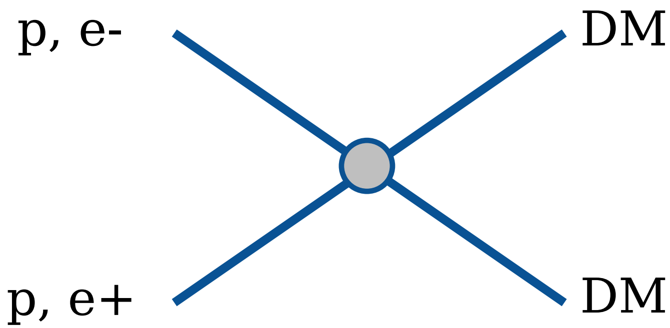
	Conventional constraint $(\Omega_{\chi_1^0} h^2 = 0.12)$	Conservative constraint $(\Omega_{\chi_1^0} h^2 = \Omega_{\chi_1^0}^{\text{thermal}} h^2)$
Higgsino	$M_{\widetilde{H}} \lesssim 300 \text{ GeV}$	N/A
Wino	$M_{\widetilde{W}} \lesssim 800 \text{ GeV}$ +resonance region~ 2 TeV	resonance region~ 2 TeV

Strongly depends on cosmological and astrophysical assumptions.

Collider searches are free from these uncertainties

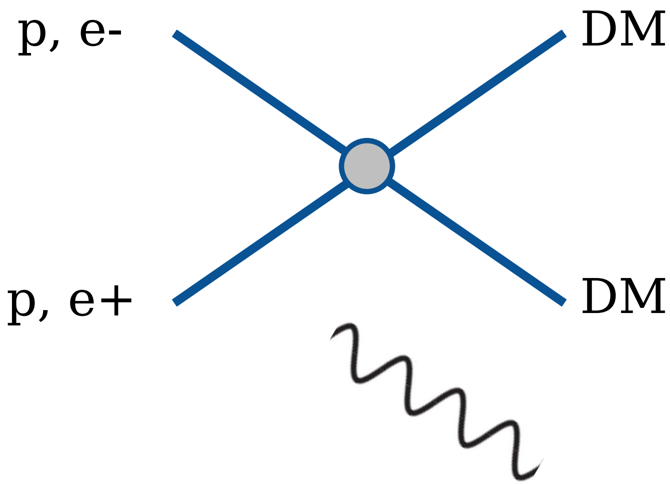
Collider Search

Collider Signals of DM



DM is invisible

Collider Signals of DM

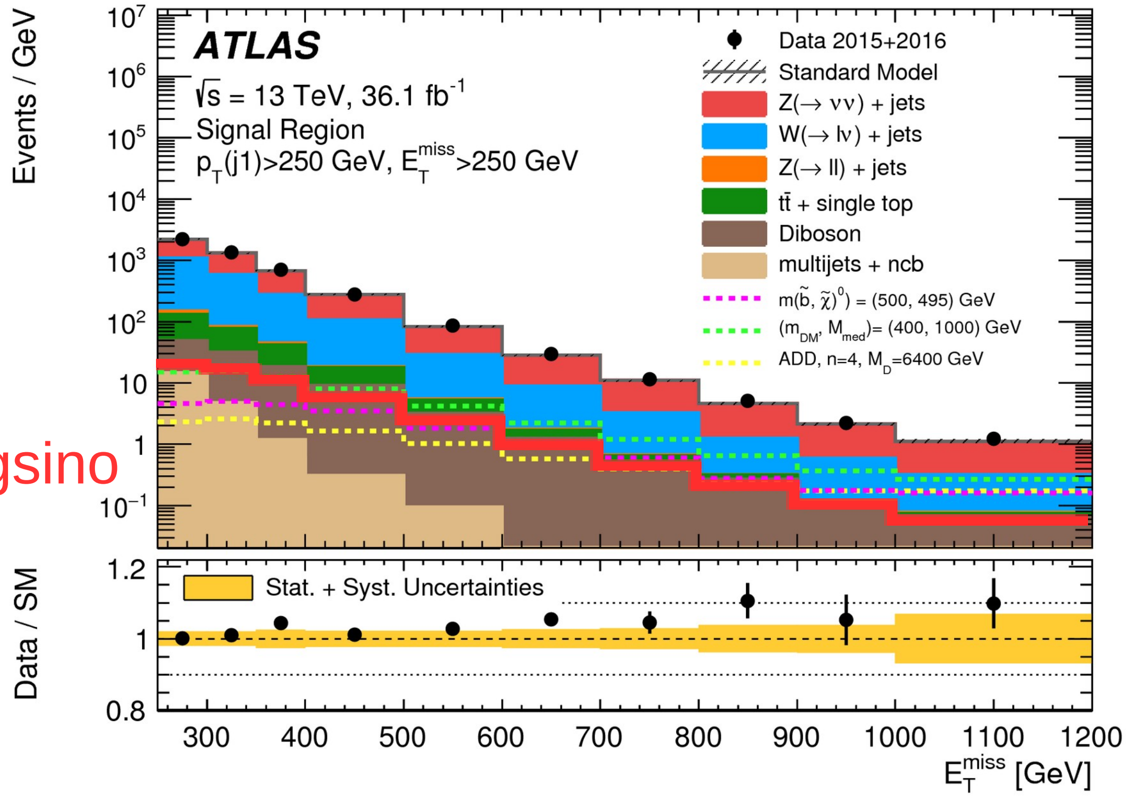


DM is invisible

Additional objects are needed
to see DM.
Missing energy (MET) search

gluon photon, …

Mono-jet Signatures

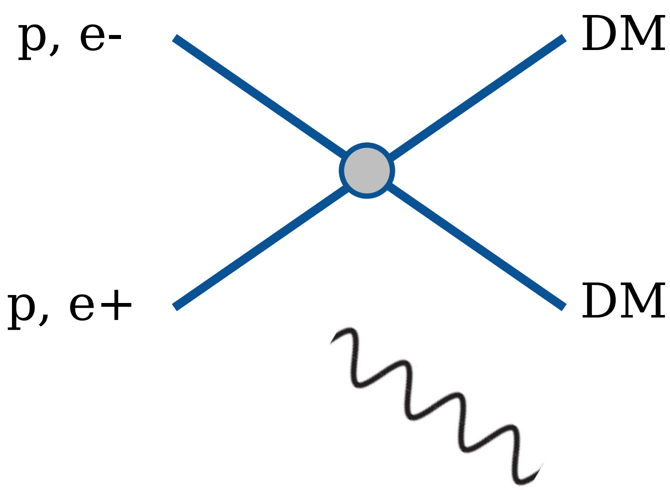


100 GeV Higgsino

$\sigma \sim 10^4$ fb

Difficult to see Higgsino/Wino signal

Collider Signals of DM



DM is invisible

Additional objects are needed to see DM.
Missing energy (MET) search

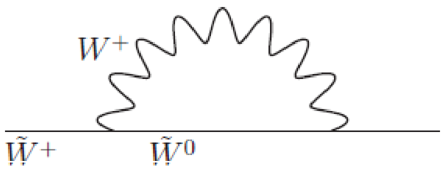
gluon photon, …

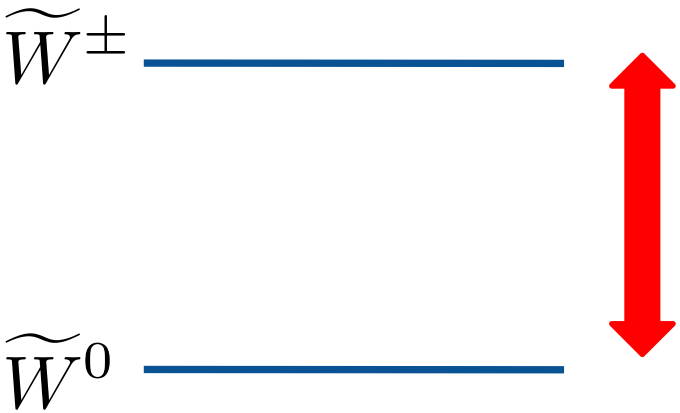
New observable are needed for efficient BG reduction

Decay of heavier Higgsino/Wino component

Wino Search

Wino Spectrum





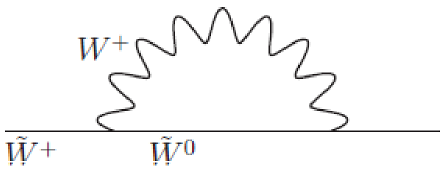
Radiative correction

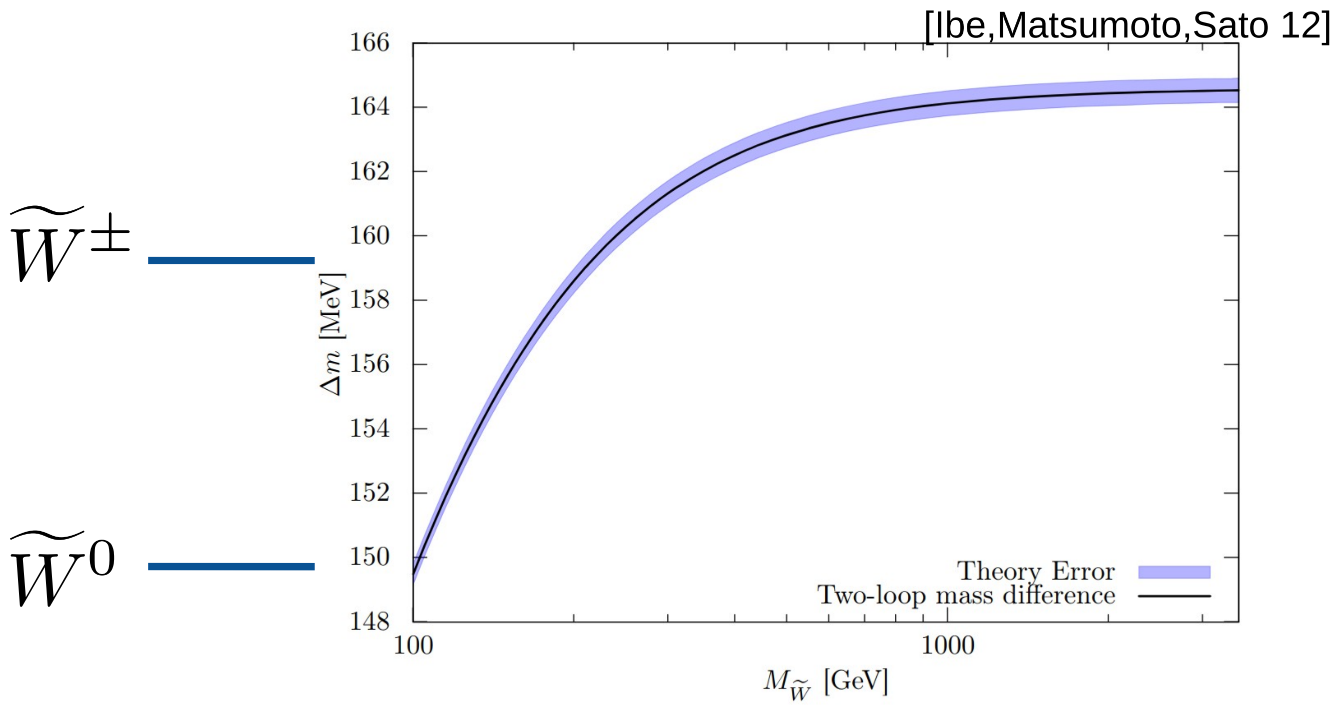
$$\Delta m \simeq 165 \text{ MeV}$$

$$\mathcal{O}\left(\frac{\alpha}{4\pi} m_Z\right)$$

$$c\tau(\widetilde{W}^{\pm} \to \widetilde{W}^{0}\pi^{\pm}) \simeq 7 \text{ cm} \left(\frac{\Delta m}{165 \text{ MeV}}\right)^{-3}$$

Wino Spectrum





$$c\tau(\widetilde{W}^{\pm} \to \widetilde{W}^{0}\pi^{\pm}) \simeq 7 \text{ cm} \left(\frac{\Delta m}{165 \text{ MeV}}\right)^{-3}$$

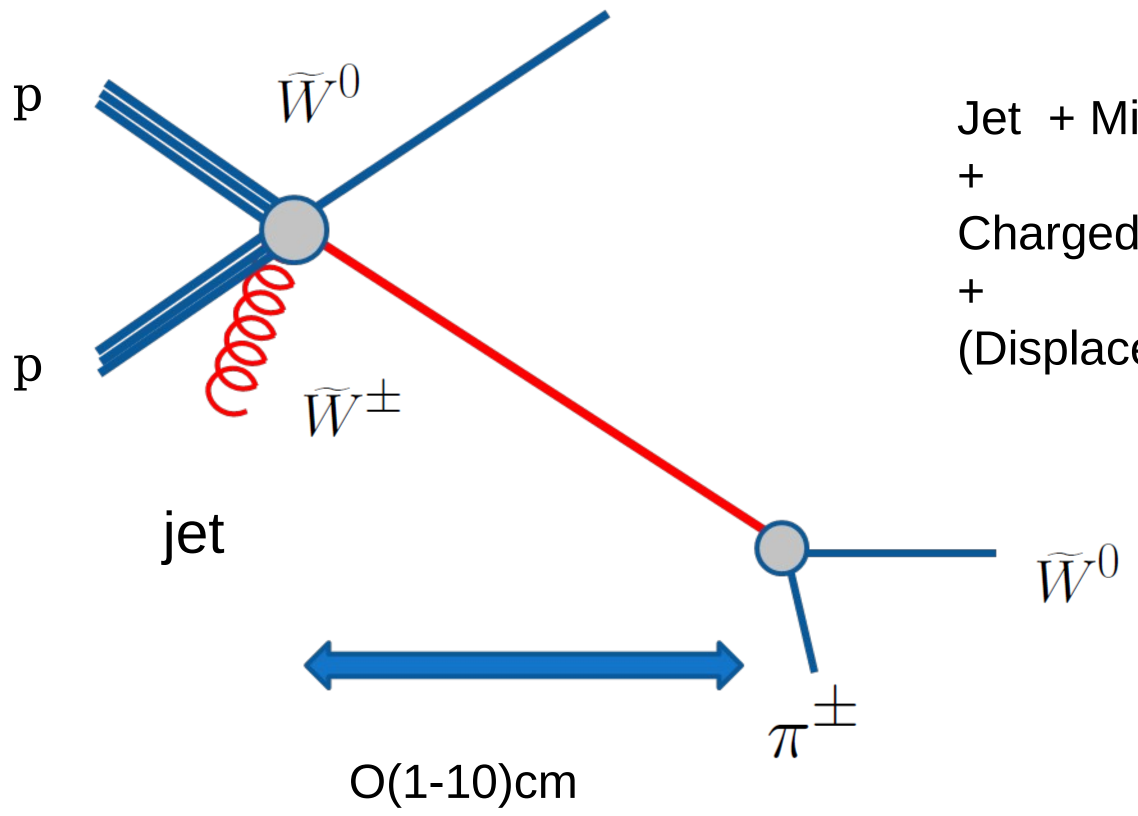
Mass Split from Mixing

Higgsino/Bino mixing also affects the mass split, but its size is small.

$$\Delta m|_{\text{mixing}} \sim 10\ \text{MeV} \frac{1}{\tan\beta} \left(\frac{\mu}{1\ \text{TeV}}\right)^{-2} \left(\frac{M_{\text{Bino}}}{1\ \text{TeV}}\right)^{-1}$$

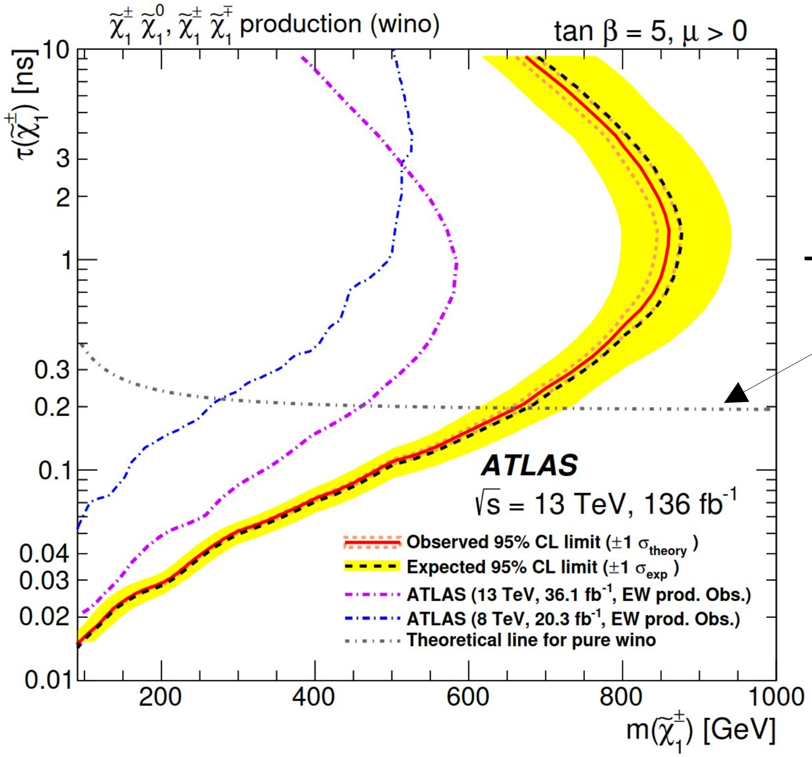
⇒ Completely pure Wino is reasonable treatment for pheno study.

Direct LHC Signals



Jet + Missing energy
+
Charged track
+
(Displaced)Soft pion

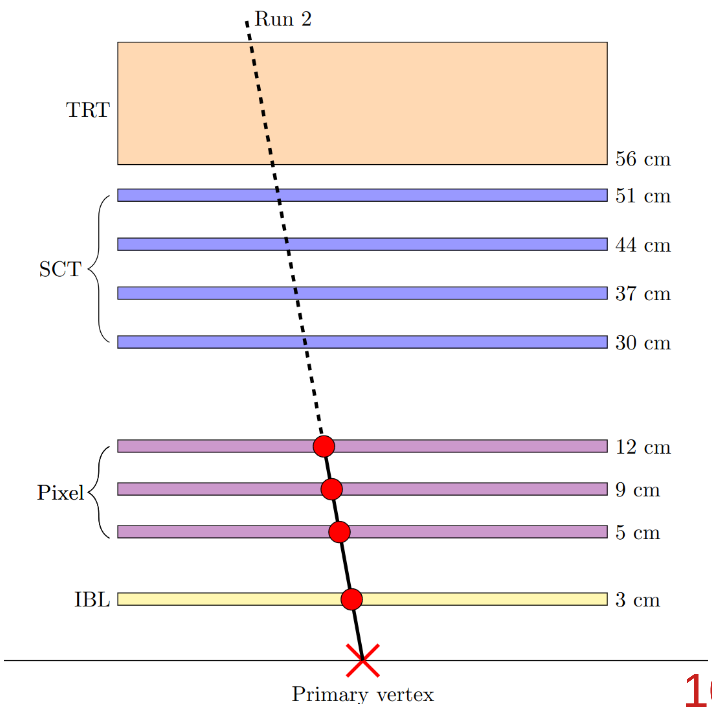
LHC Search by ATLAS



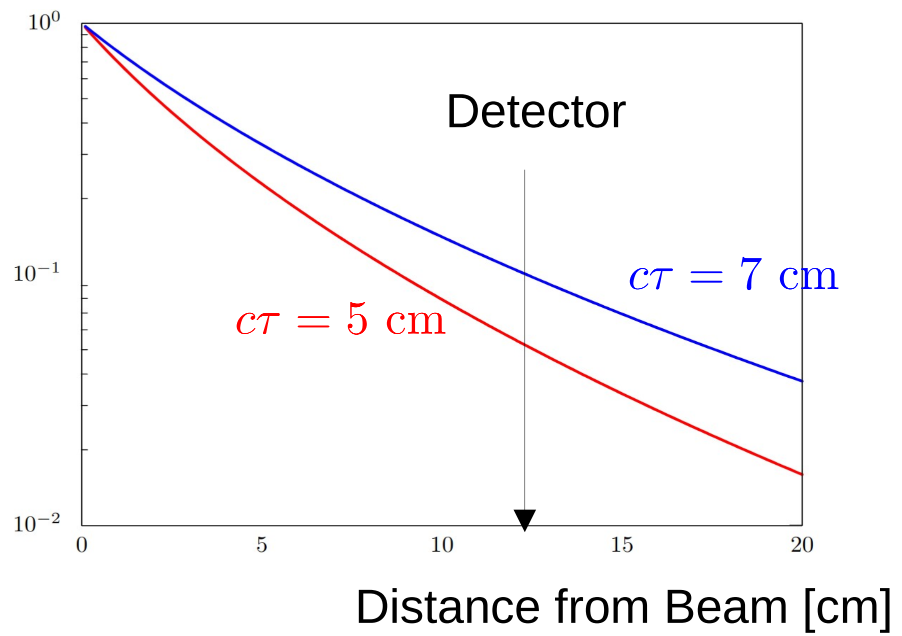
Theory prediction

Direct LHC Signals

ATLAS detector



Survival Probability

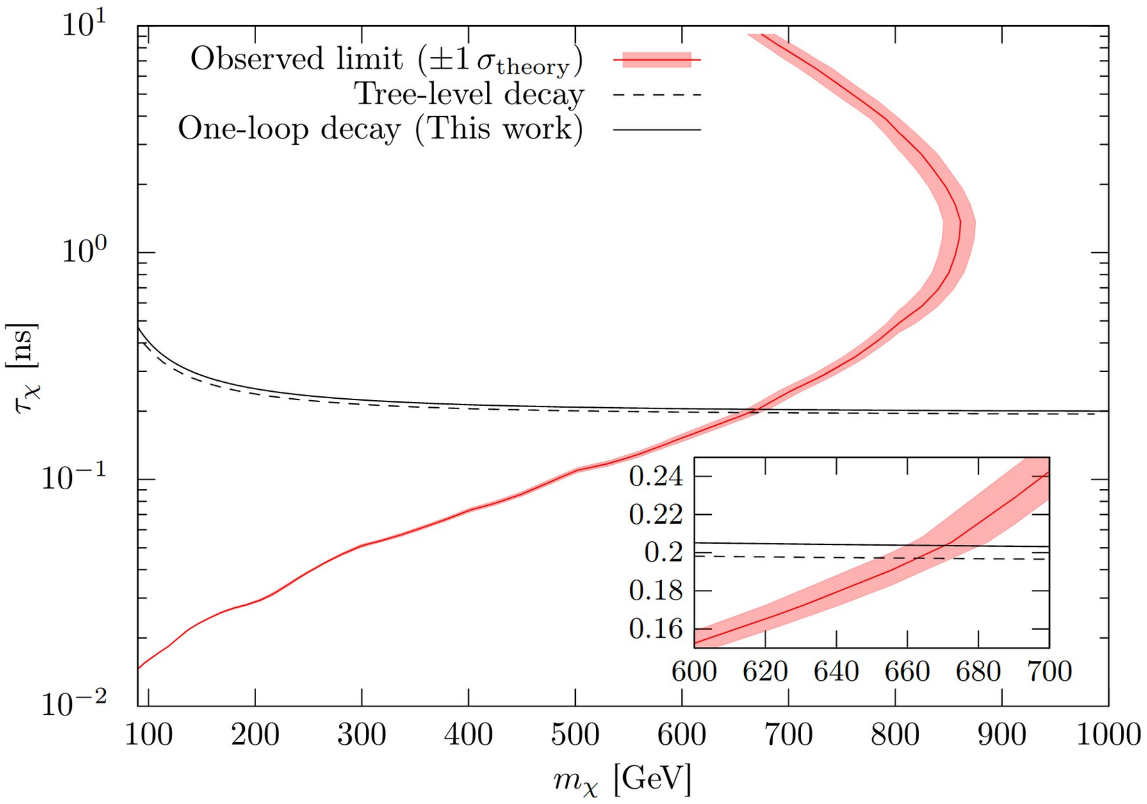


10% error of lifetime → 50% error of signal.

Precise estimation of decay rate is crucial!

see Yuhei Nakayama's poster

Impact on LHC Search



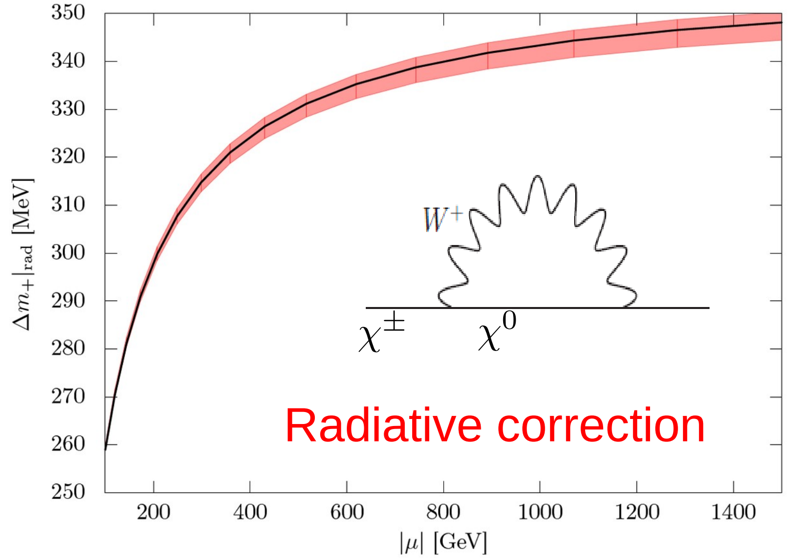
10 GeV shift

Higgsino Search

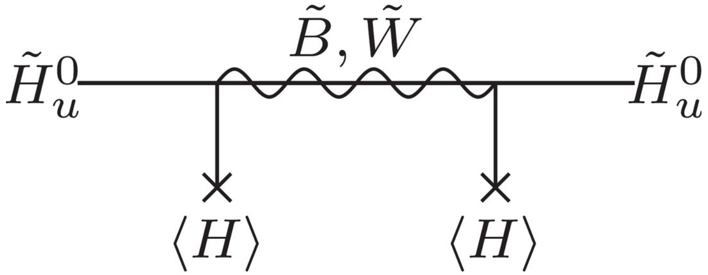
Pure Higgsino Spectrum

$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \chi_D^0 \quad \chi^\pm$$ two Dirac Fermions

Mass difference



Higgsino Spectrum (with gaugino)



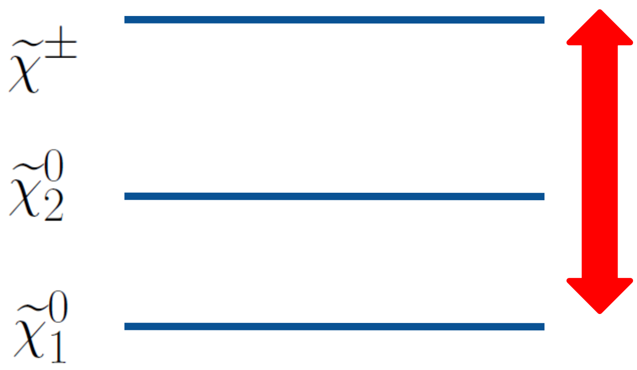
With Gauginos, fermion number is violated.

$$\chi_D^0 \Rightarrow \tilde{\chi}_1^0 \quad \tilde{\chi}_2^0$$

Dirac fermion into two Majorana fermions.

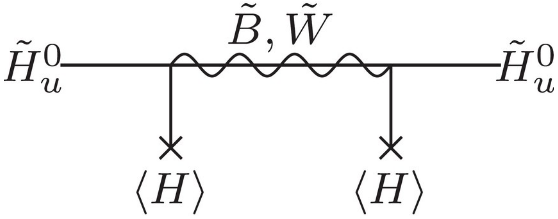
Higgsino Spectrum (with gaugino)

$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$

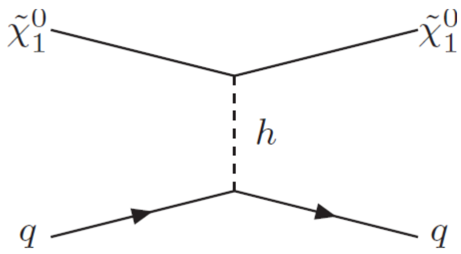


$$\Delta m \sim \frac{m_W^2}{m_{\rm gaugino}} = O(100)\ \mathrm{MeV} \left(\frac{m_{\rm gaugino}}{10\ \mathrm{TeV}}\right)^{-1}$$

Gaugino induced Observables

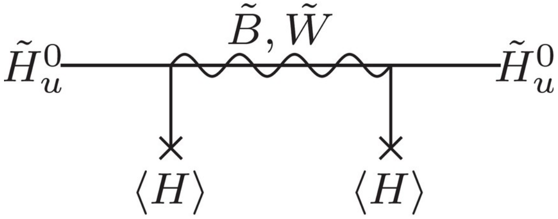


Mass splitting $\Delta m \propto M_{\text{gaugino}}^{-1}$



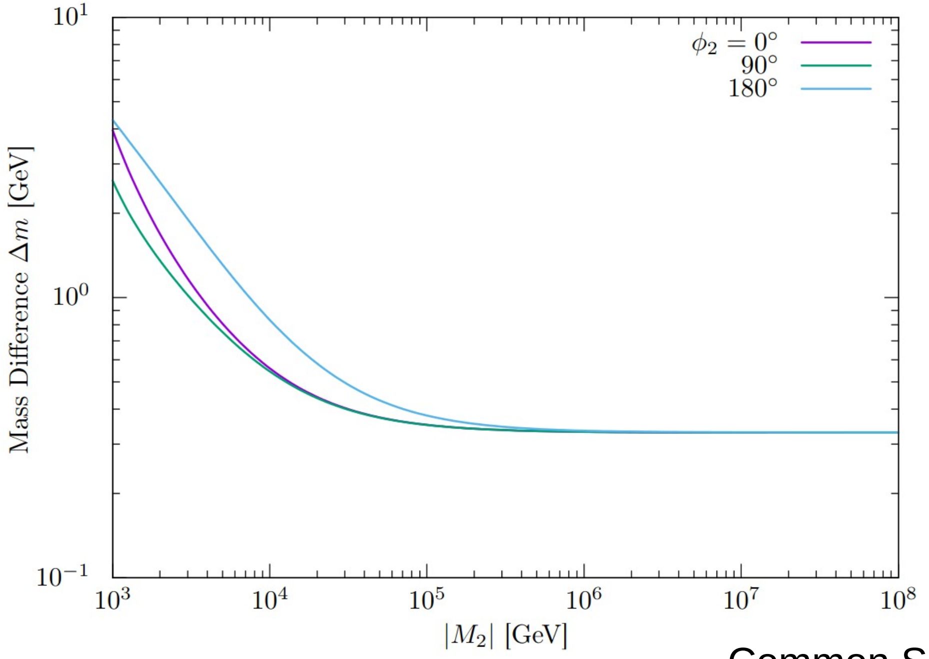
DM direct detection $\sigma_{\text{SI}} \propto M_{\text{gaugino}}^{-2}$

Charged-Neutral Mass Splitting



Mass splitting $\Delta m \propto M_{\text{gaugino}}^{-1}$

$m_{\chi^\pm} - m_{\chi_1^0}$

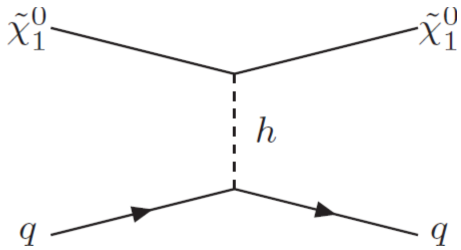


radiative correction

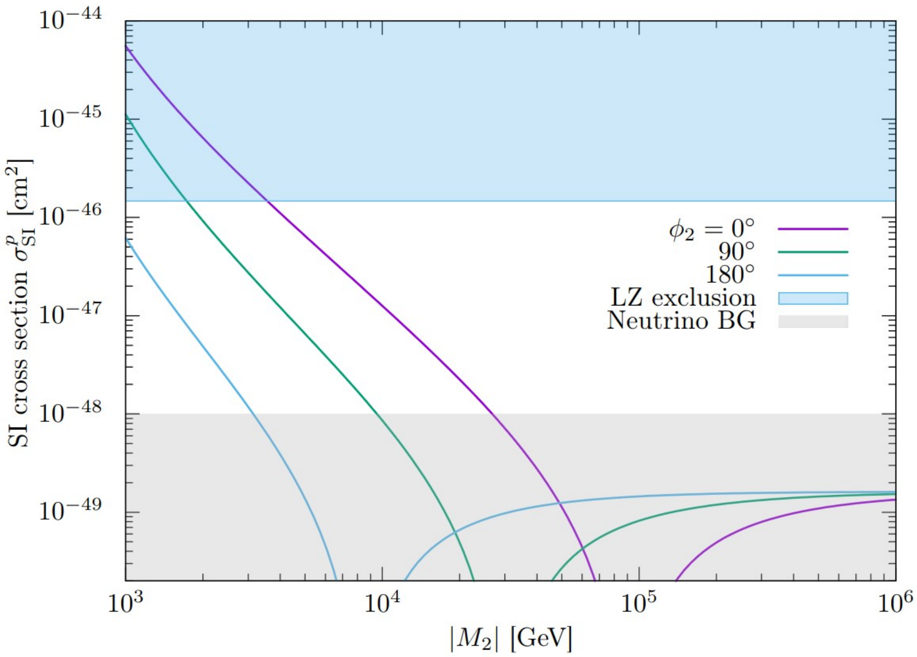
$\tan\beta = 2$

Common SUSY breaking mass

Direct Detection



DM direct detection $\sigma_{\rm SI} \propto M_{\rm gaugino}^{-2}$



500 GeV Higgsino

$\tan\beta = 2$

Common SUSY breaking mass

Correlation

These observables are controlled by gaugino mass

↓

Strong correlation among these observables

$$m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}_1^0} \sim \underbrace{\Delta m_\pm^{\rm rad}}_{\sim 350\ \rm MeV} + 170\ {\rm MeV} \left(\frac{\sigma^{\rm SI}}{10^{-48}\ {\rm cm}^2} \right)^{1/2}$$

for large tanb

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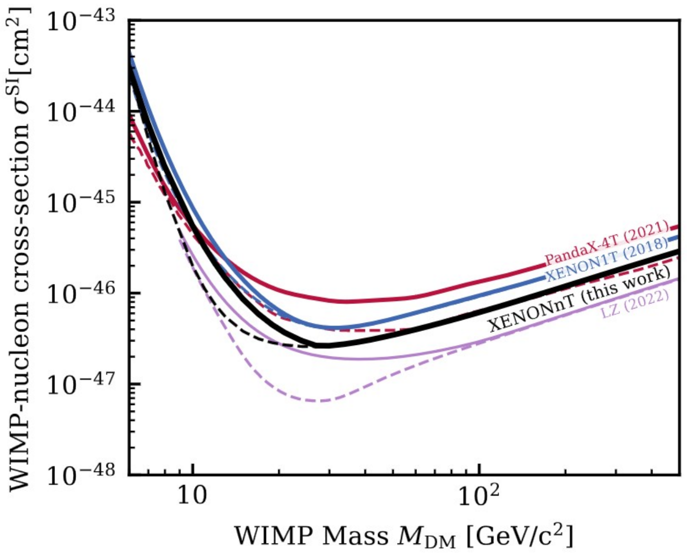
for large tanb

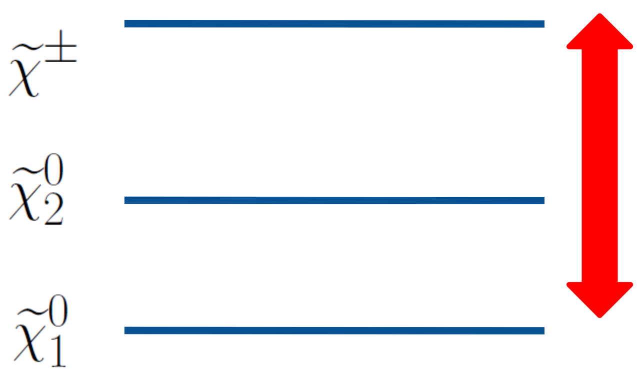
LZ constraint

$$\Delta m < O(1)\ \mathrm{GeV}$$



Viable Higgsino Spectrum

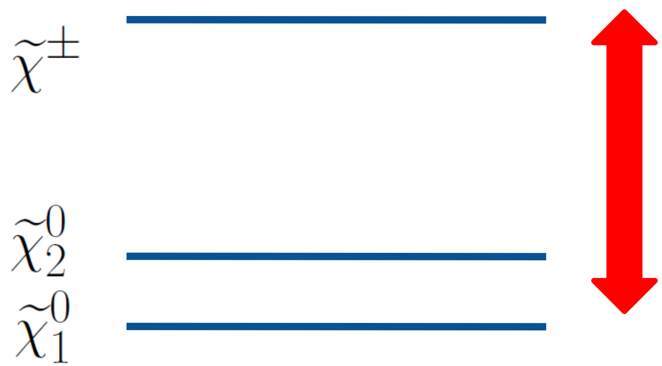
$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \quad \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$

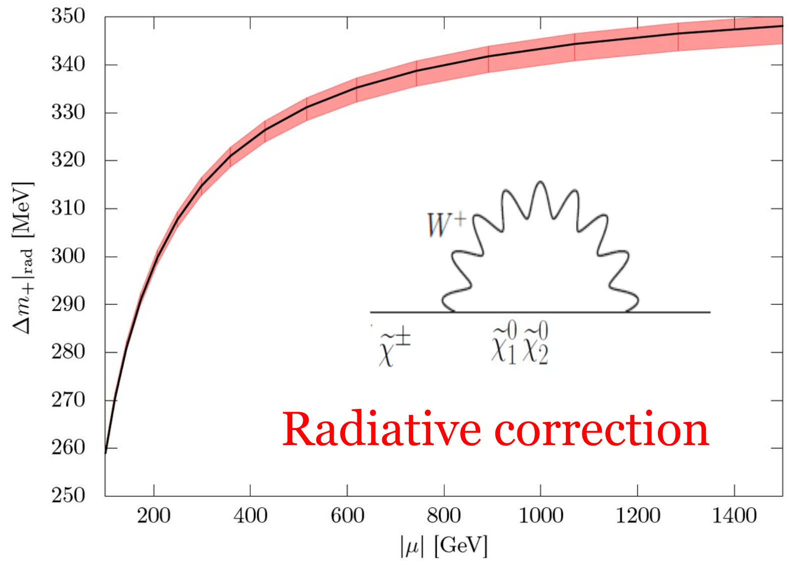


$$\Delta m < O(1)\ \mathrm{GeV}$$

Almost Pure Higgsino Spectrum

$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \quad \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$



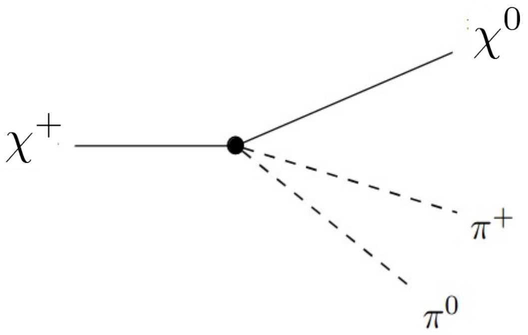


$$c\tau(\tilde{\chi}^\pm \to \tilde{\chi}^0 \pi^\pm) = 1.1\ \text{cm} \left(\frac{\Delta m_+}{300\ \text{MeV}} \right)^{-3} \left[1 - \frac{m_{\pi^\pm}^2}{\Delta m_+^2} \right]^{-1/2}$$

Higgsino Decay

Higgsino-like DM ~300 MeV – 2 GeV from gaugino mixing

For mass difference 500 MeV, lepton and multi-meson decay modes are important.

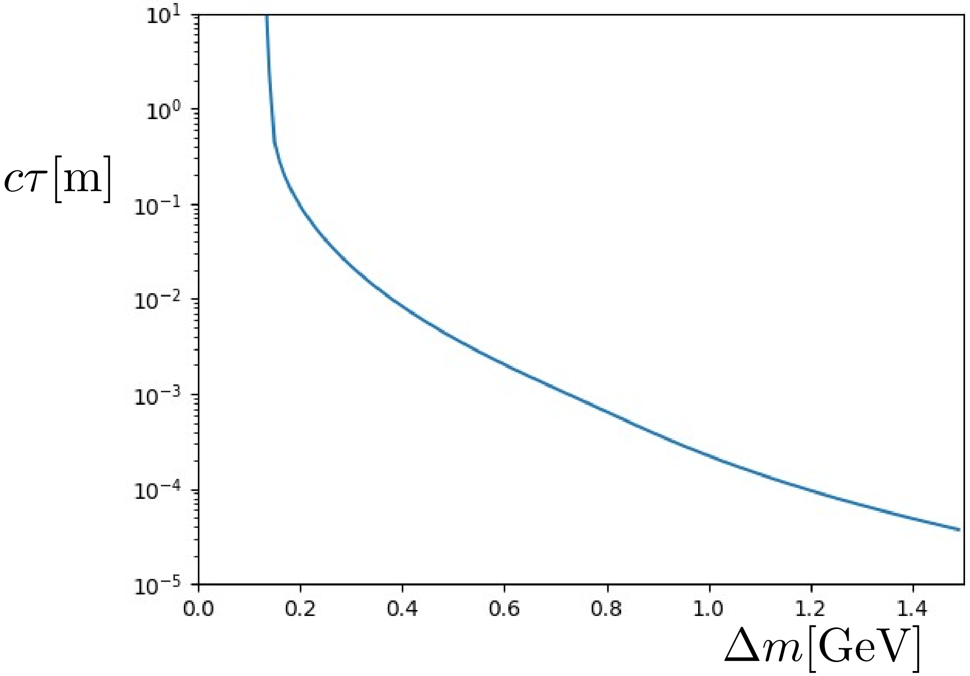


Charged Higgsino Decay

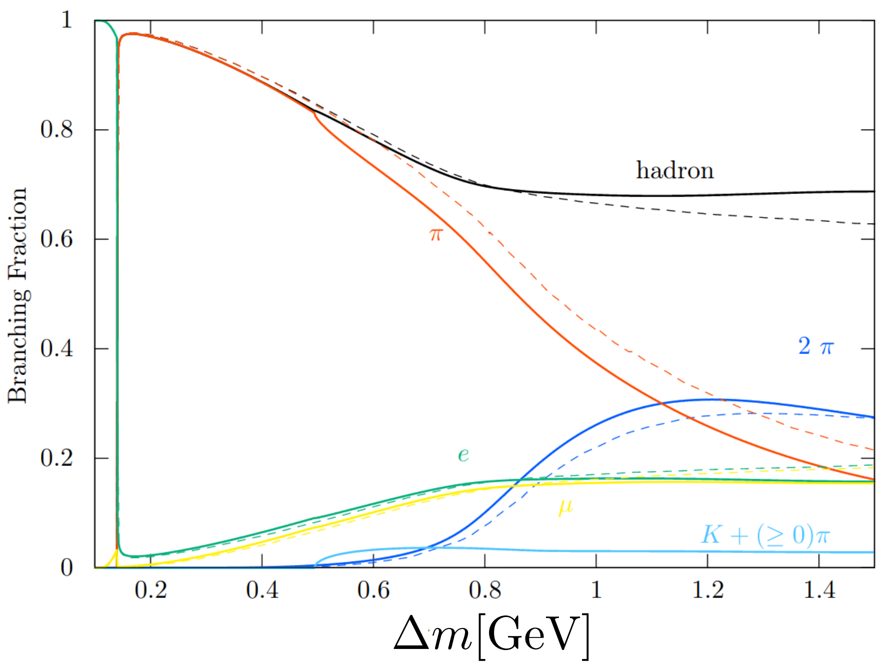
With NLO and latest QCD data

[Ibe, Nakayama, SS, to appear]

Decay length



Branching fraction



~ 20-50 % difference from ISAJET

Charged Higgsino Decay

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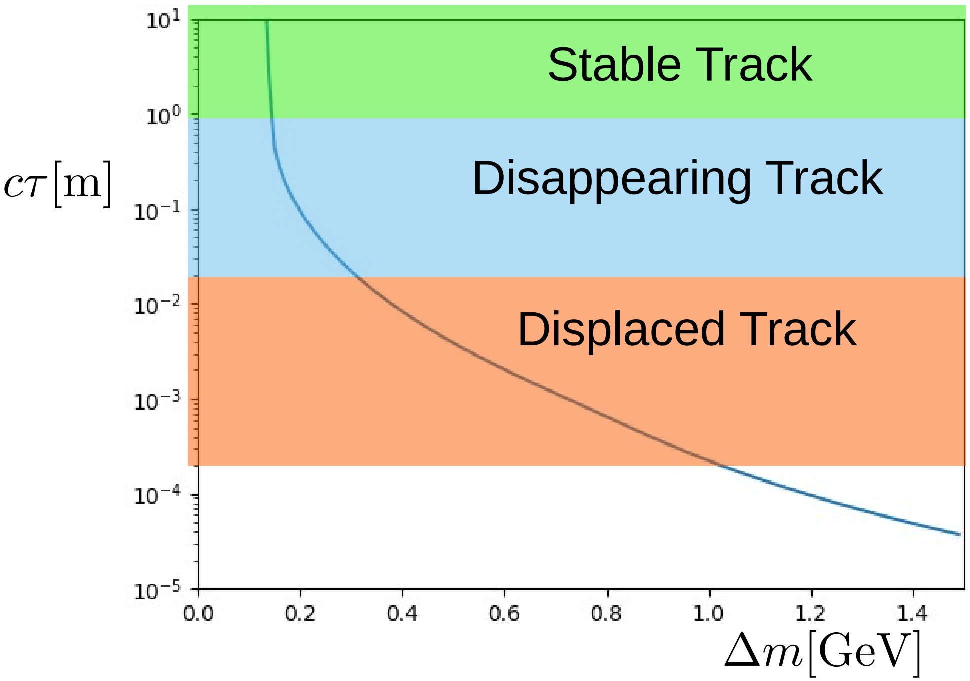
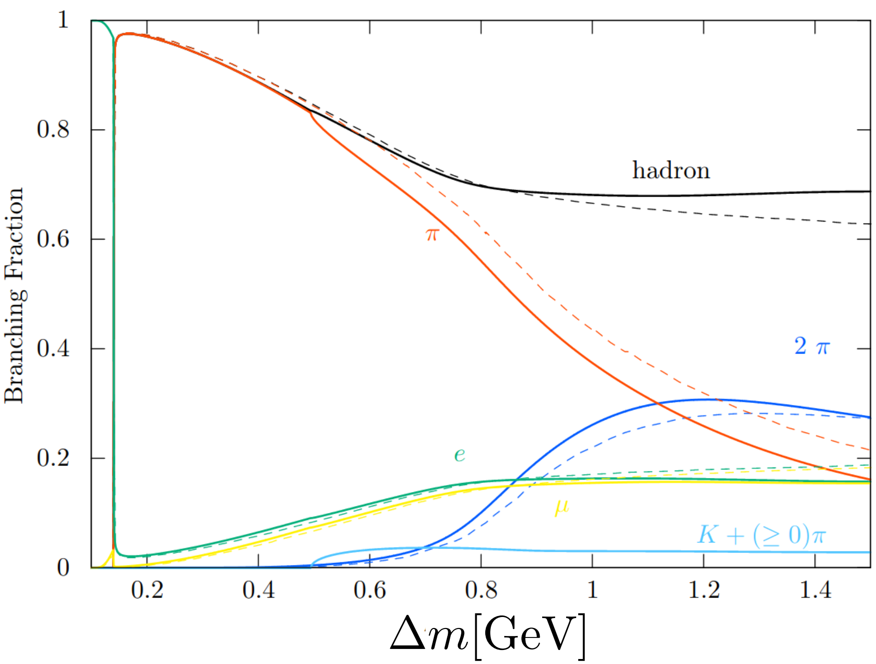
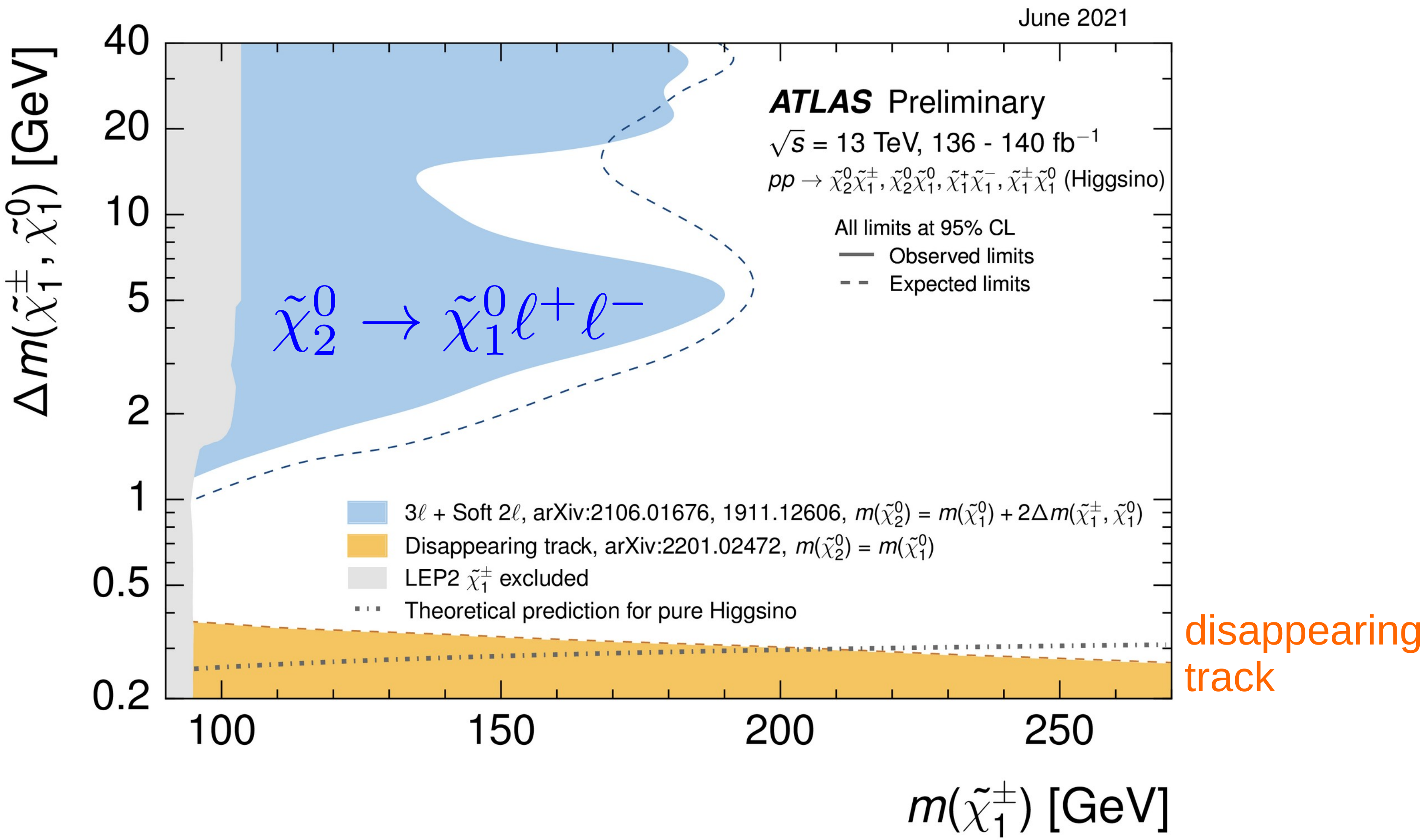


Branching fraction

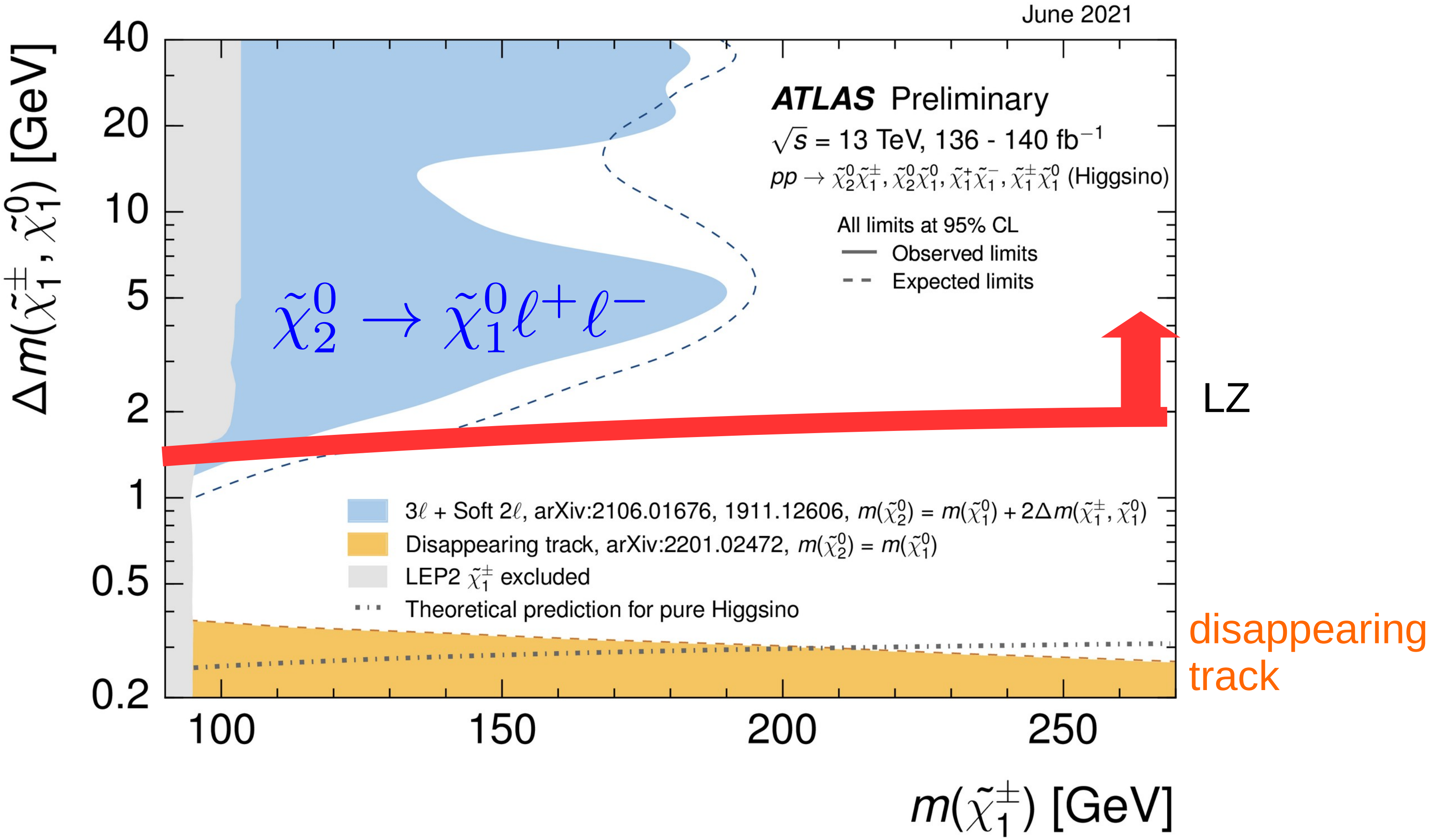


~ 20-50 % difference from ISAJET

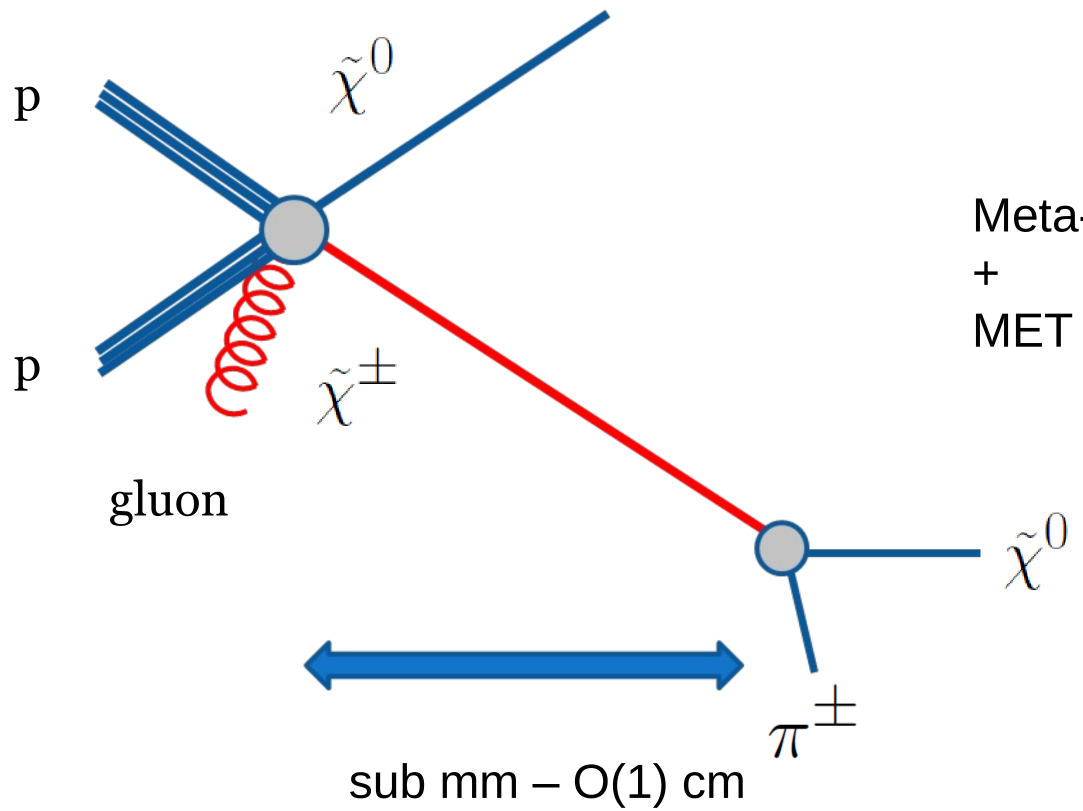
Current Constraint(higgsino)



Current Constraint(higgsino)

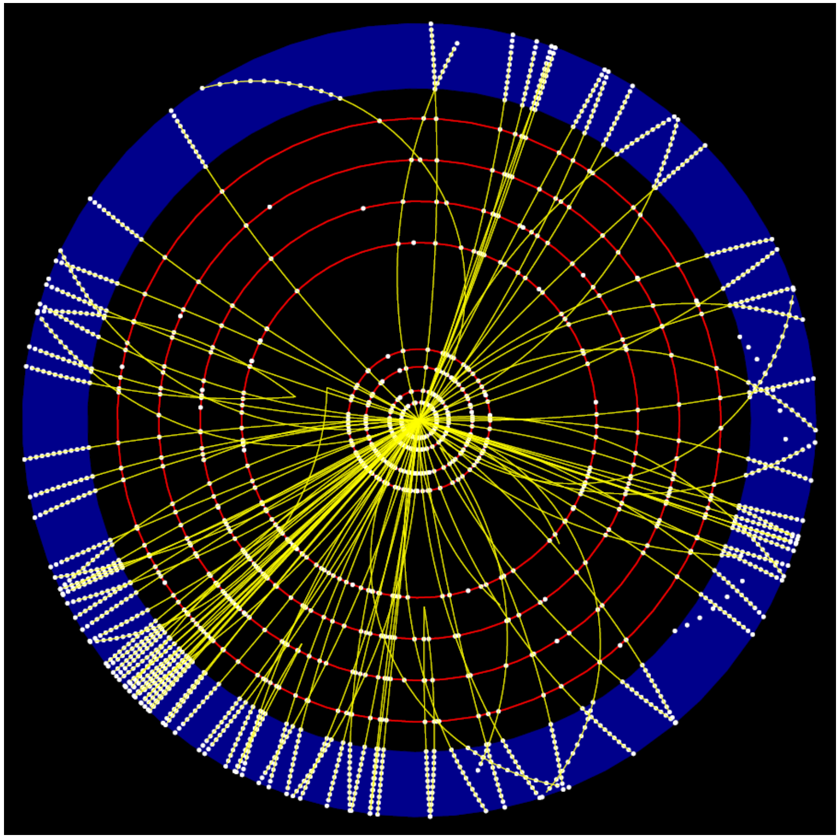


LHC Signals



Meta-stable track
+
MET

Event Display



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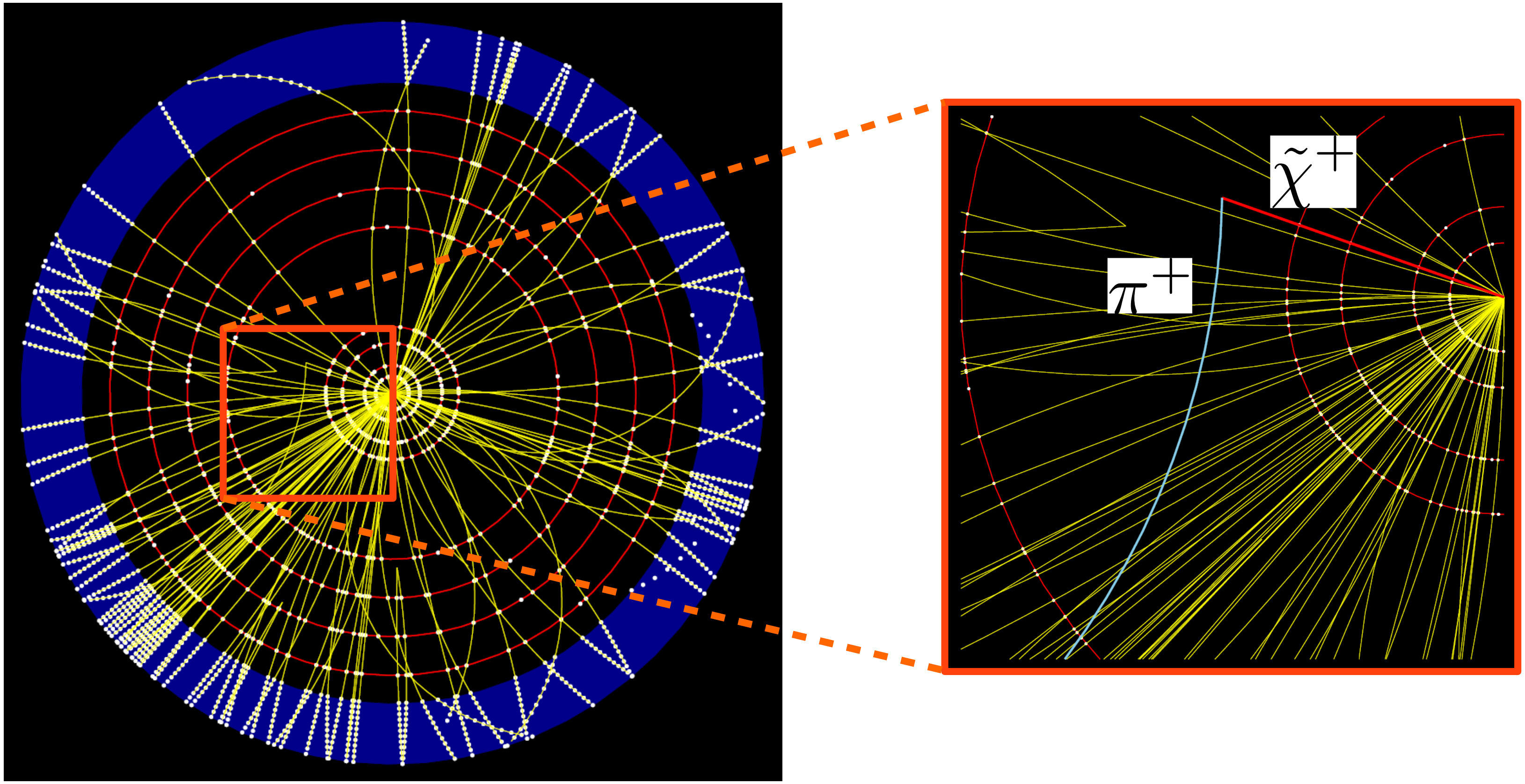

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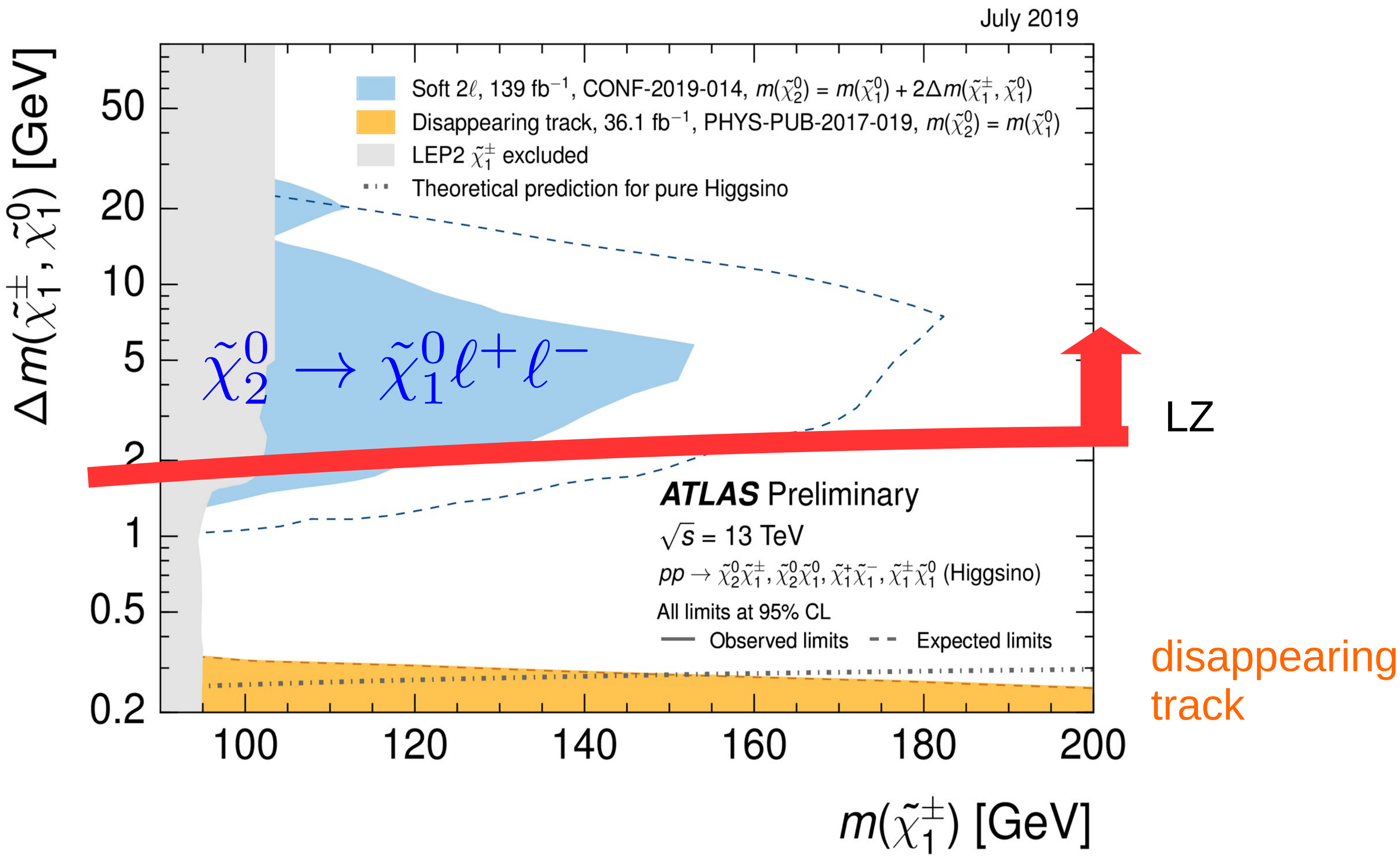
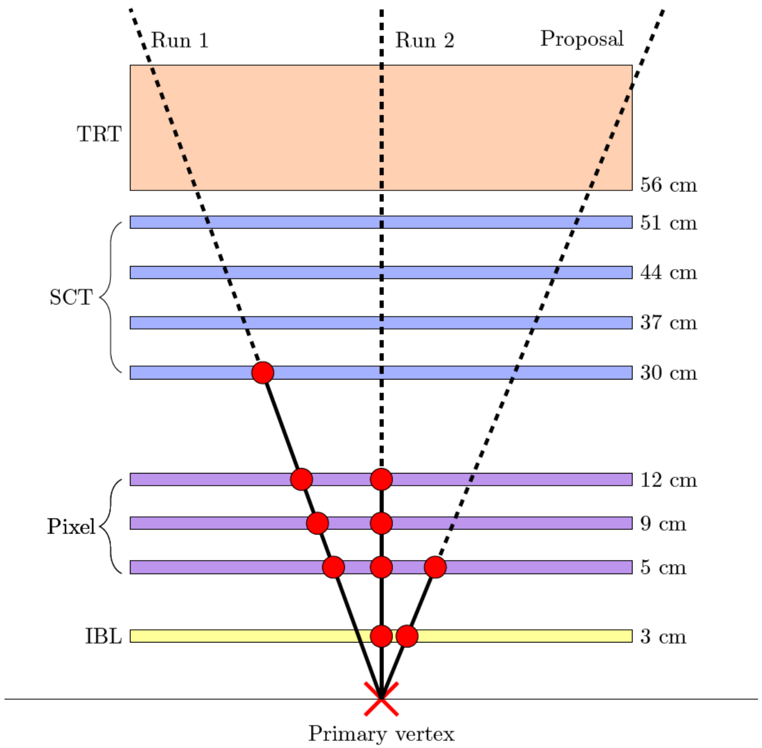
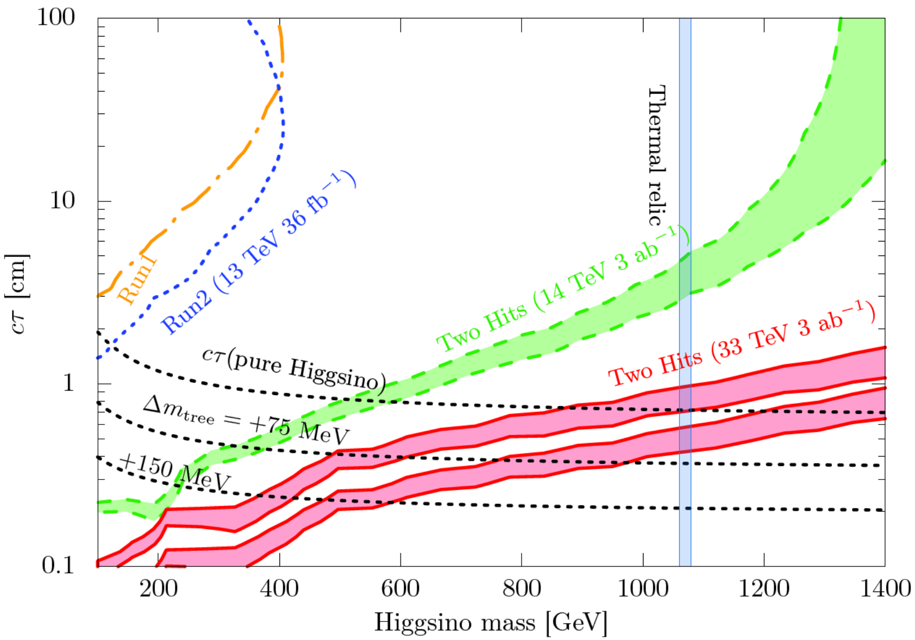


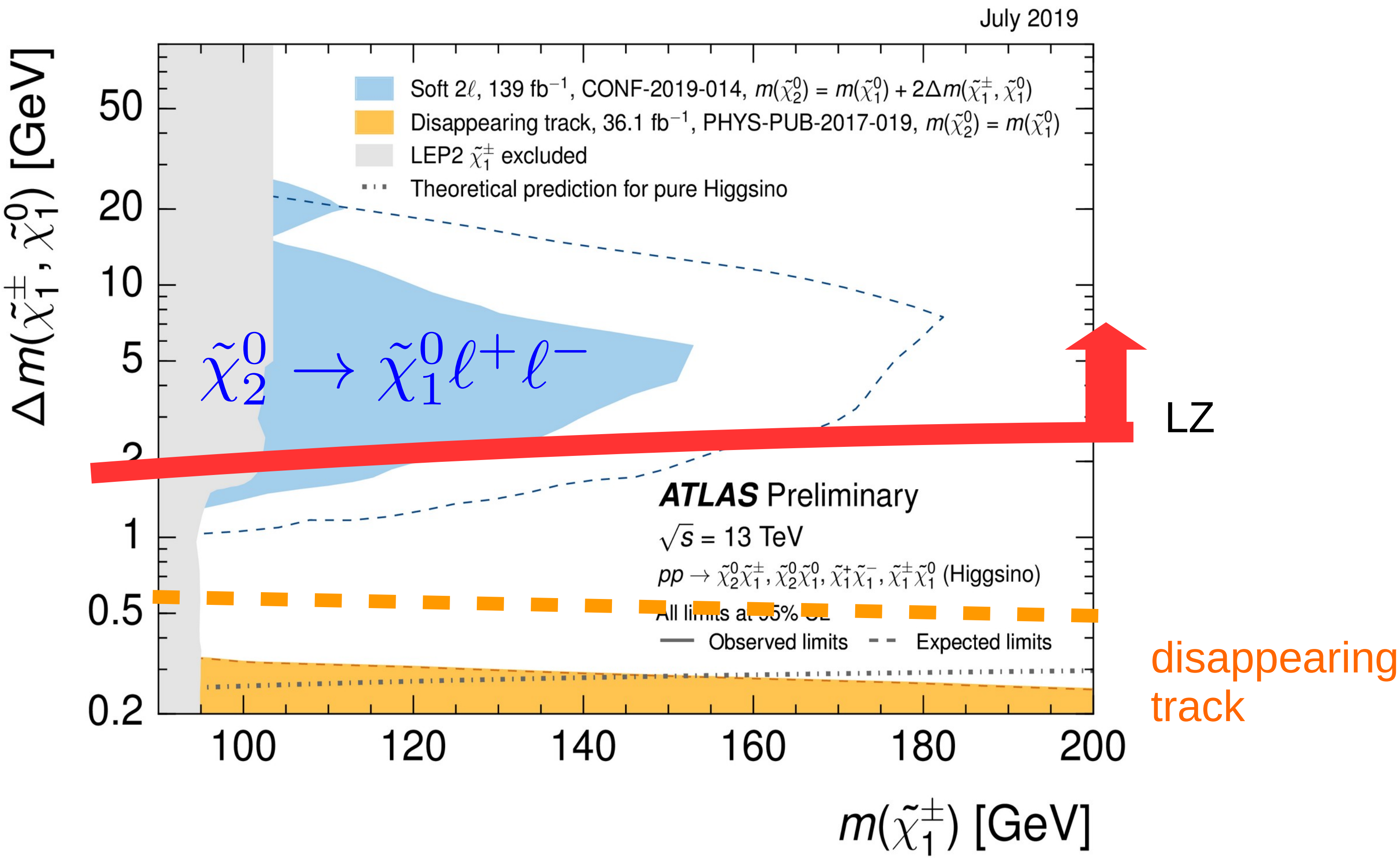
Improving Track Reconstruction



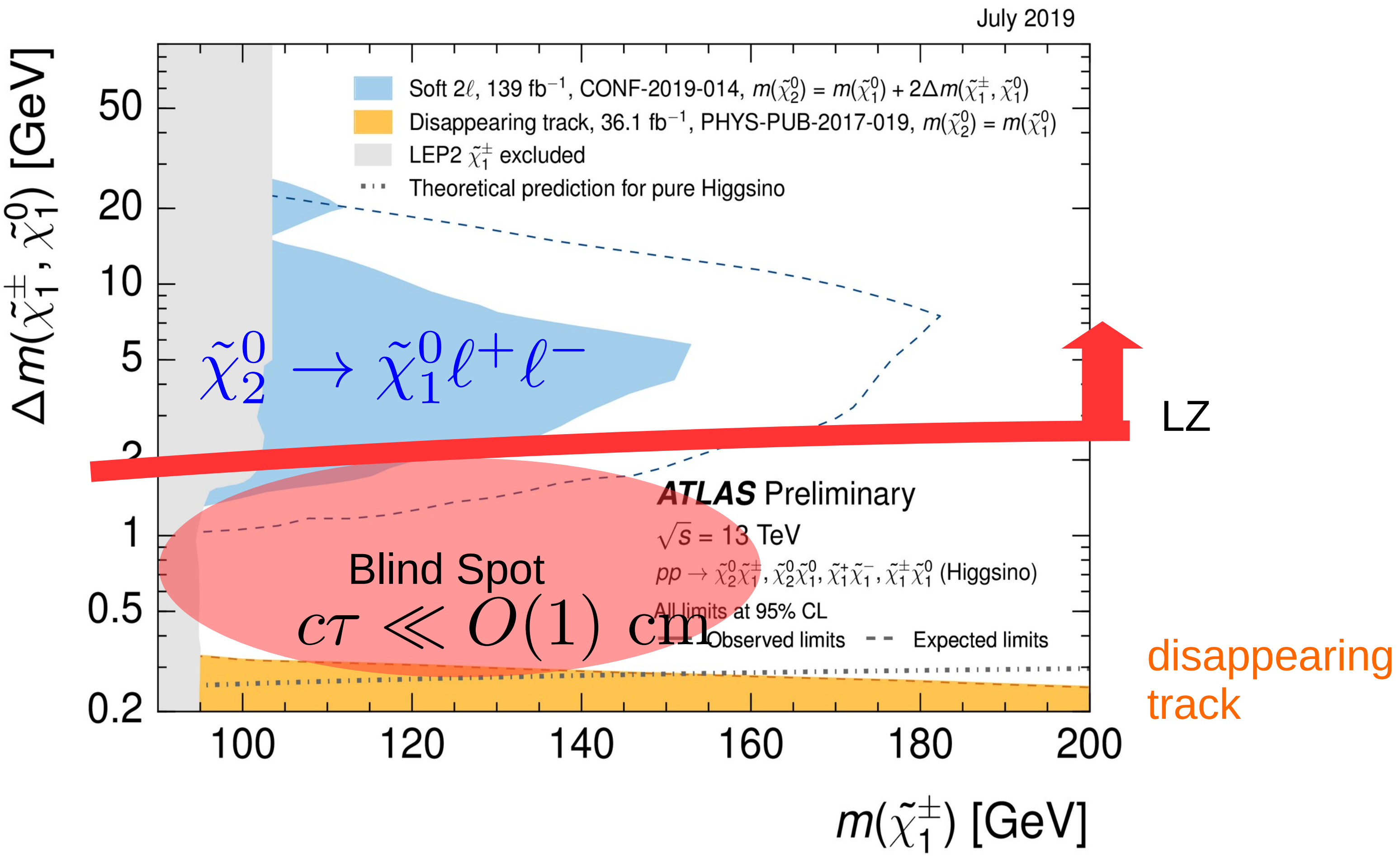


[H. Fukuda, N. Nagata, H. Otono & SS 2017]

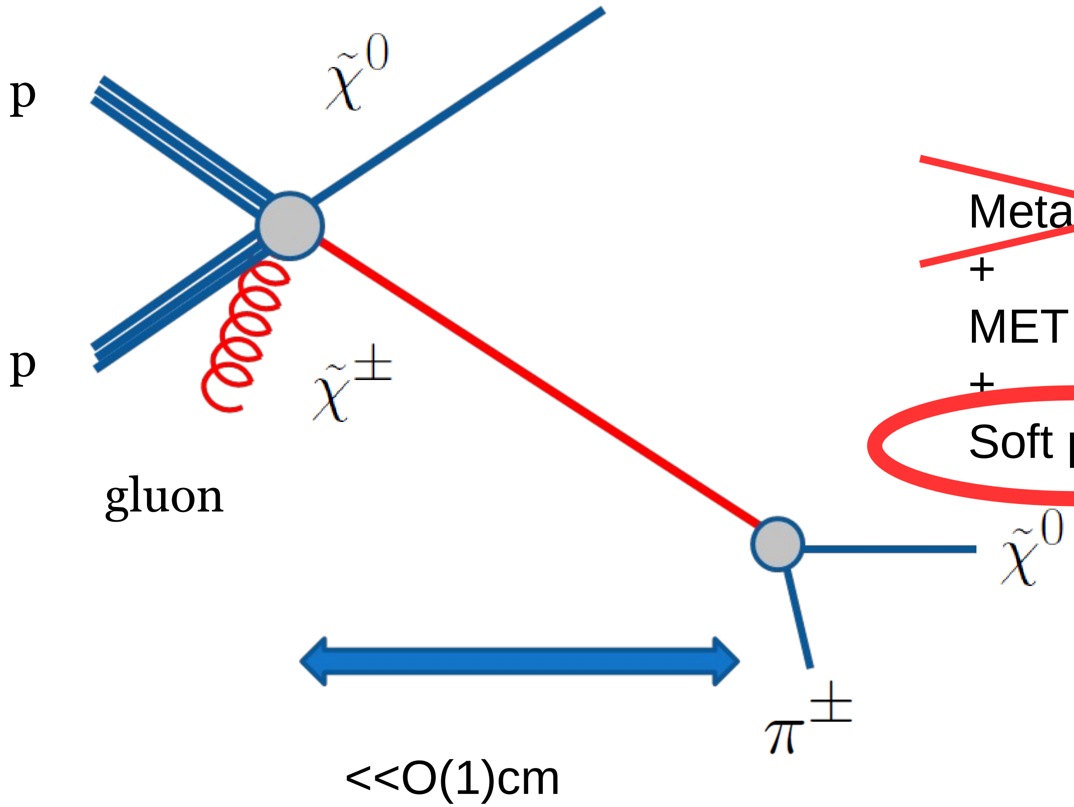
Current Constraint(higgsino)



Current Constraint(higgsino)

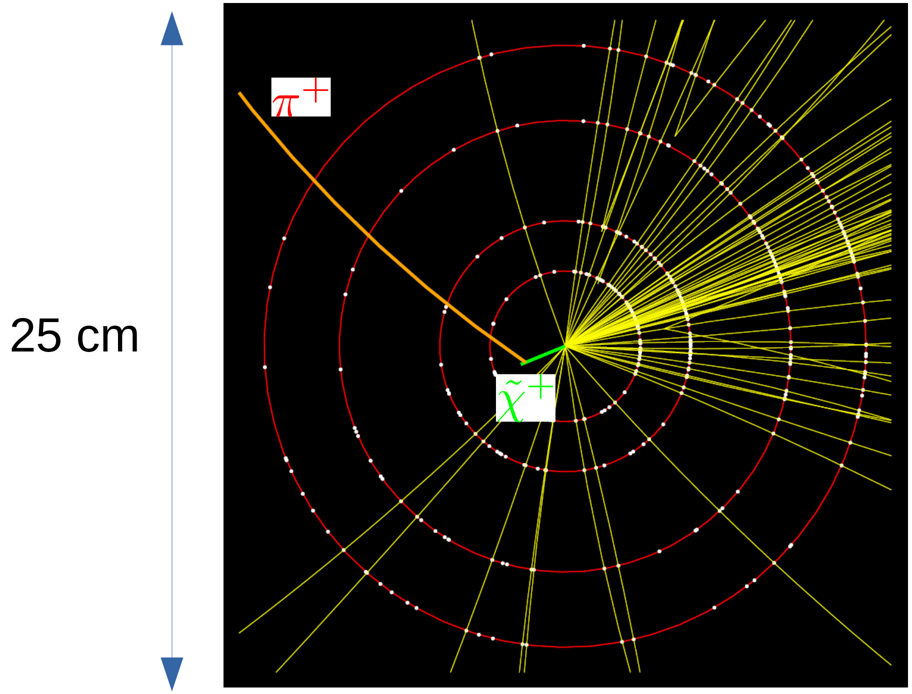


LHC Signals

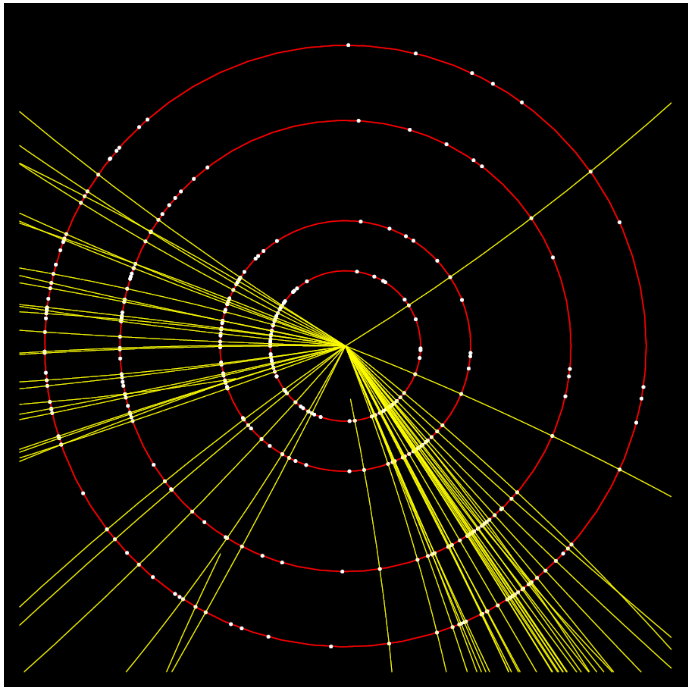


~~Meta-stable track~~
+
MET
+
Soft pion?

Event Display

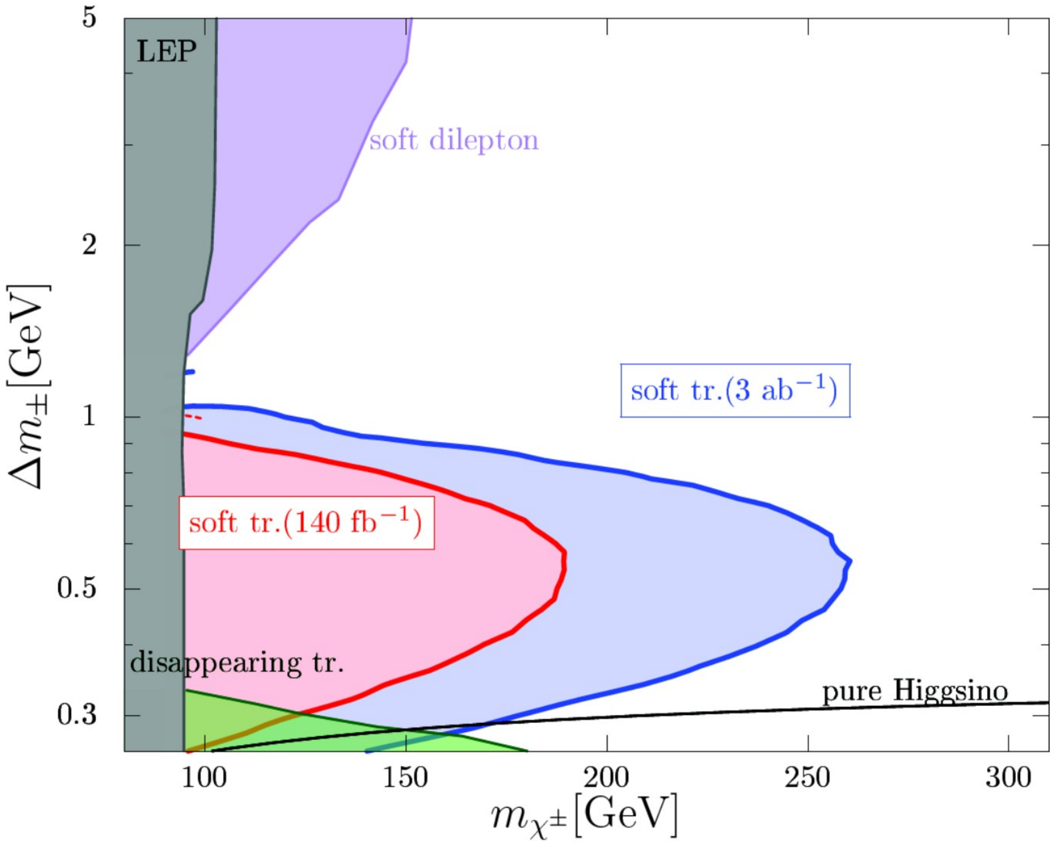


Signal



BG (Z > νν)

Result



Run2 # of BG ~ 250.

Summary and Prospects

- Wino/Higgsino dark matter has various experimental signatures:
  - (In)direct detection, collider, precision physics.

- Strong dependence on the mass splitting structure in collider search
  - Potential improvement of collider searches:
    - Exotic tracks
    - Use of vector boson fusion (VBF).
    - Indirect search of Wino/Higgsino loop in SM processes.
      - Off-shell production can be tested via precision measurement.
      - Strongest search for Higgsino/Wino in lepton colliders, such as e+e- ILC, mu+mu+ μTRISTAN.
- Application to more generic gauge-portal minimal DM.