Cornering Higgsino at the LHC

Satoshi Shirai (Kavli IPMU)

Based on

H. Fukuda, N. Nagata, H. Oide, H. Otono, and SS,
“Higgsino Dark Matter in High-Scale Supersymmetry,” JHEP 1501 (2015) 029,
“Higgsino Dark Matter or Not,” Phys.Lett. B781 (2018) 306
“Cornering Higgsino using Soft Displaced Track”, Phys.Rev.Lett. 124 (2020) 10,101801

1. Higgsino Dark Matter

Viable parameter region

2. Current Status of Higgsino @LHC

Mono-jet, dilepton, disappearing track

3. Prospect of Higgsino

Use of soft track

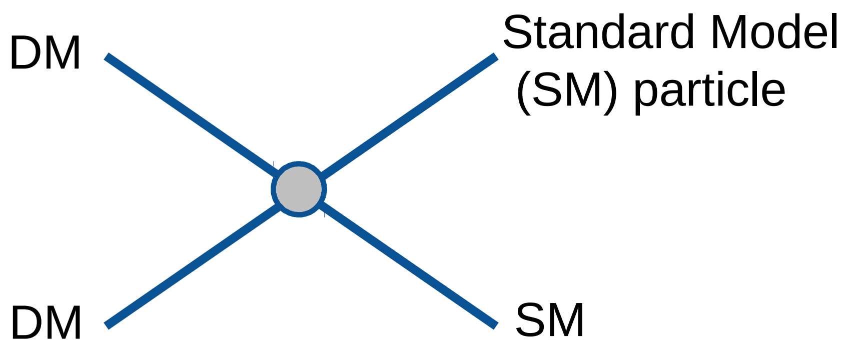
4. Summary

DM Candidates

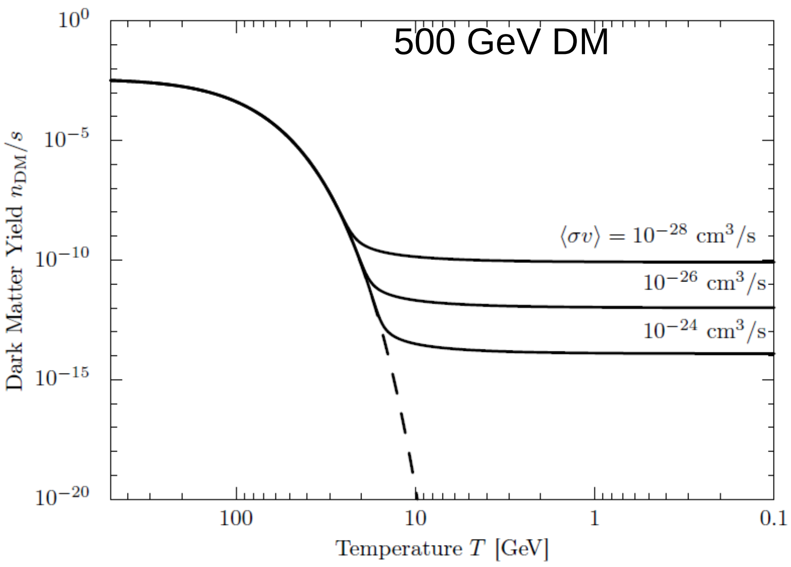
- Axion
- (Primordial) Black hole
- WIMP
- Others…

WIMP Dark Matter

Weakly Interacting Massive Particle



DM abundance



Time

WIMP Miracle

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

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

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

So Many WIMP Candidates...

- Bino
- Wino
- Higgsino
- KK photon
- T-odd Photon
- Technibaryon
- Minimal 5plet fermion
- Minimal singlet scalar
- Minimal 7plet scalar
- …

Why Higgsino.

- Higgsino is the most important particle of Electroweak naturalness
  - Focus point, natural SUSY
- Natural SUSY DM candidate for correct abundance
  - Higgsino or Wino
- The simplest gauge-portal minimal dark matter.
- Rich signature at direct/indirect dark matter search.

- Rich signature at LHC.
  - LHC search technology is also applicable to broad BSM

What is Higgsino?

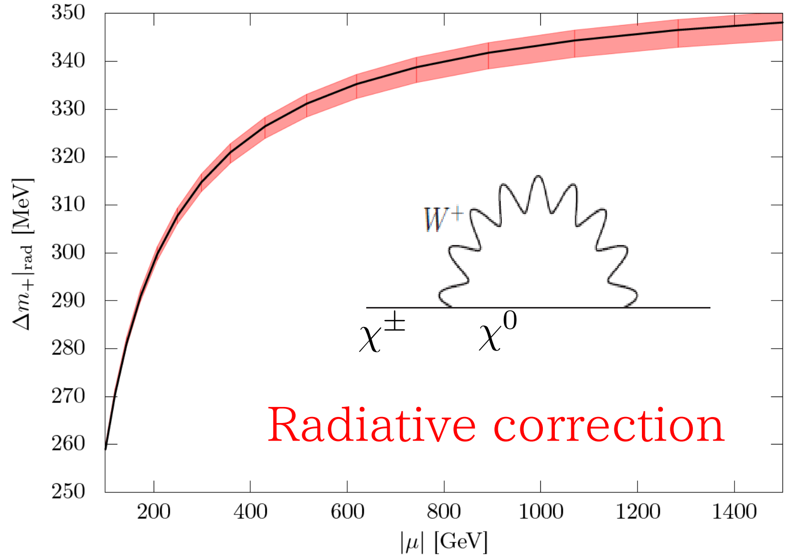
Higgsino is

- (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 $\Omega h^2 \simeq 0.1 \left(\frac{m_{\widetilde{H}}}{1.1\ \mathrm{TeV}} \right)^2$

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

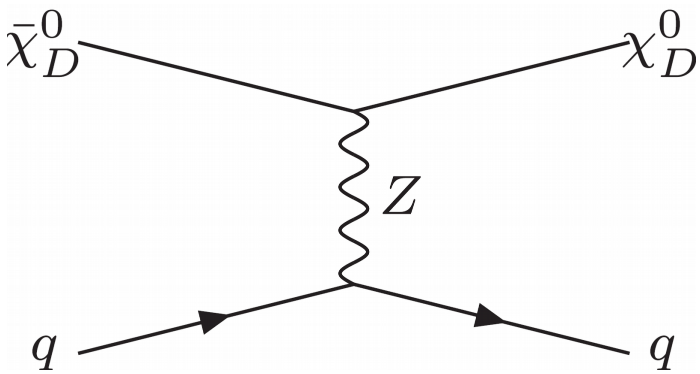


Pure Higgsino DM is Dead

DM is neutral Dirac Fermion

$$\bar{\chi}_D^0 \gamma^\mu \chi_D^0 Z_\mu$$

HUGE spin-independent cross section



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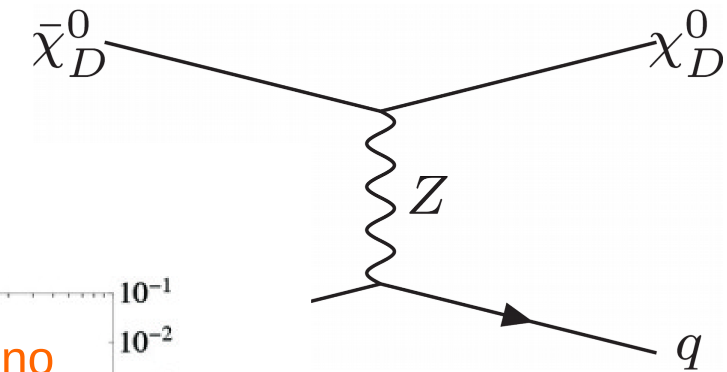
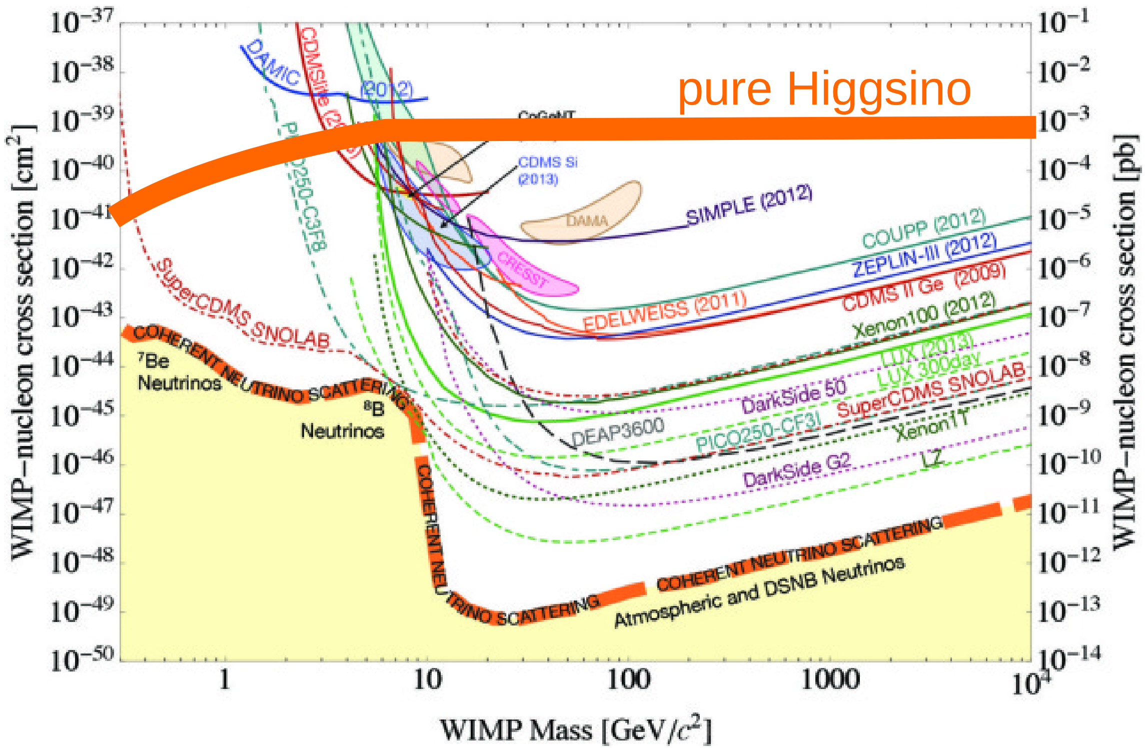
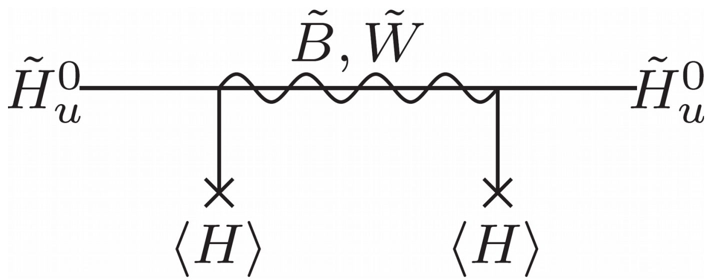




Higgsino Spectrum (with gaugino)



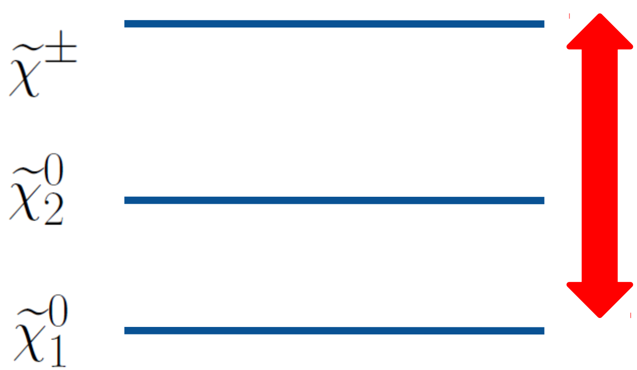
With Gauginos, fermion number is violated

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

Dirac fermion into two Majorana fermions

Higgsino Spectrum (with gaugino)

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



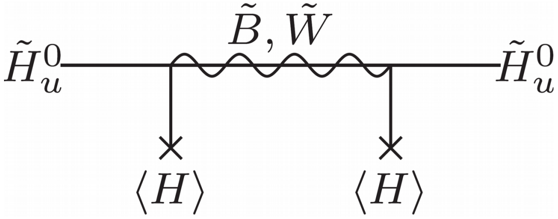
$$\Delta m \sim \frac{m_W^2}{m_{\rm gaugino}} = O(100)\ \mathrm{MeV} \left(\frac{m_{\rm gaugino}}{10\ \mathrm{TeV}}\right)^{-1}$$

Higgsino Spectrum (with gaugino)

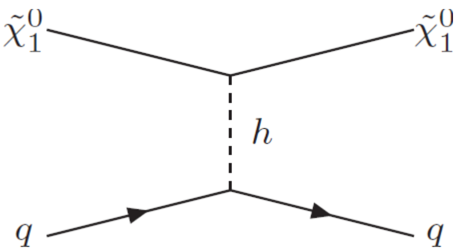
$$\bar{\chi}_D^0 \gamma^\mu \chi_D^0 Z_\mu \quad \Rightarrow \quad \begin{array}{l} \bar{\chi}_1^0 \gamma^\mu \chi_2^0 Z_\mu \neq 0 \\ \bar{\chi}_1^0 \gamma^\mu \chi_1^0 Z_\mu = 0 \end{array}$$

No SI elastic cross section via Z-boson

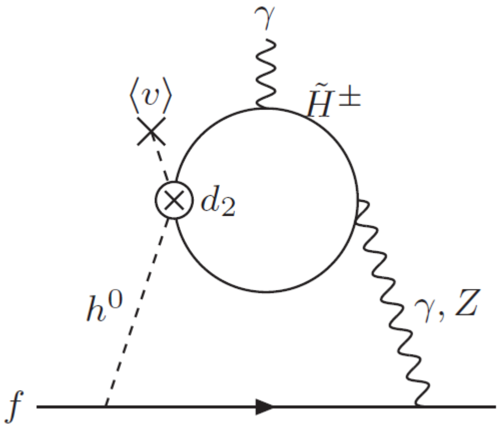
Gaugino induced Observables



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



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



SM fermion EDM $d_e \propto M_{\text{gaugino}}^{-1}$

Correlation

These observables are controlled by gaugino mass

$\Downarrow$

Strong correlation among these observables

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

for large tanb

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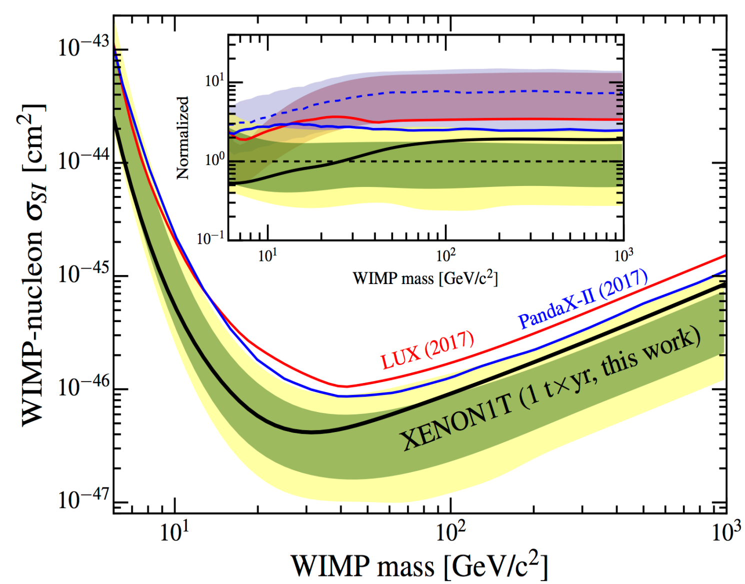
for large tanb

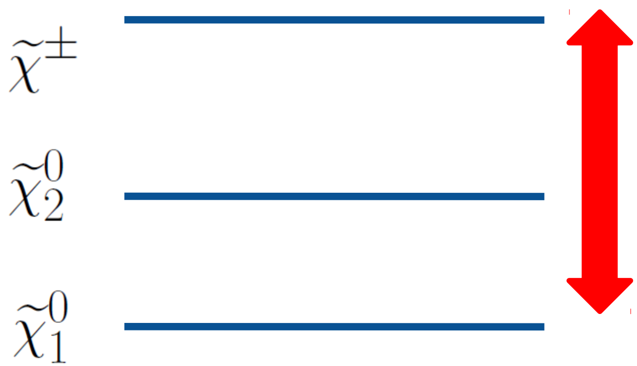
XENON1T constraint

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



Viable Higgsino Spectrum

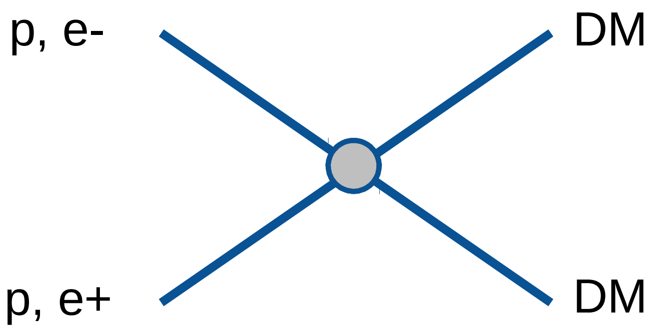
$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \quad \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$



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

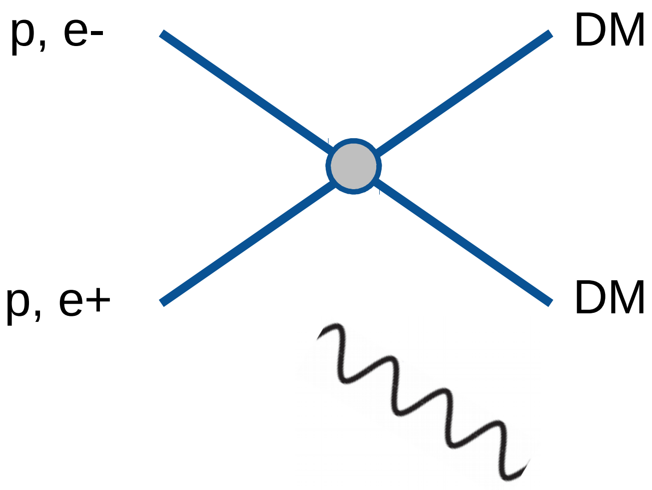
Current Status of Higgsino @LHC

Collider Signals of DM



DM is invisible

Collider Signals of DM



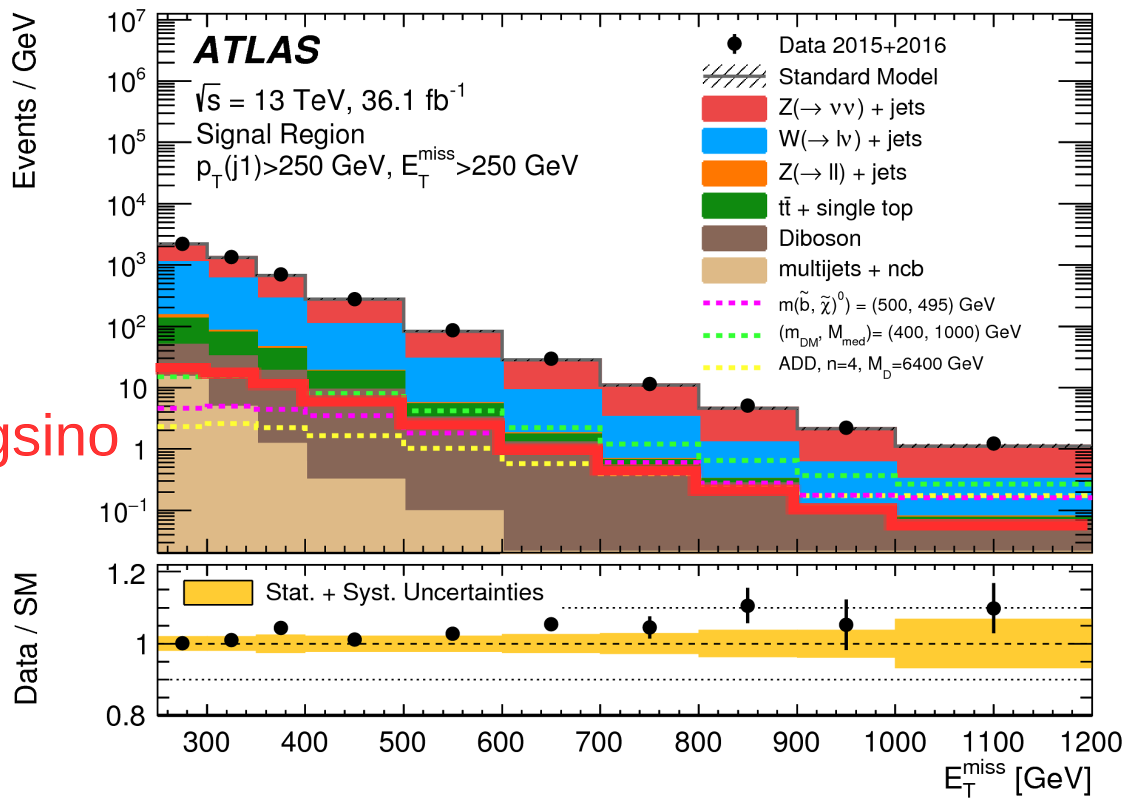
DM is invisible

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

gluon photon, …

Mono-jet Signatures

100 GeV Higgsino



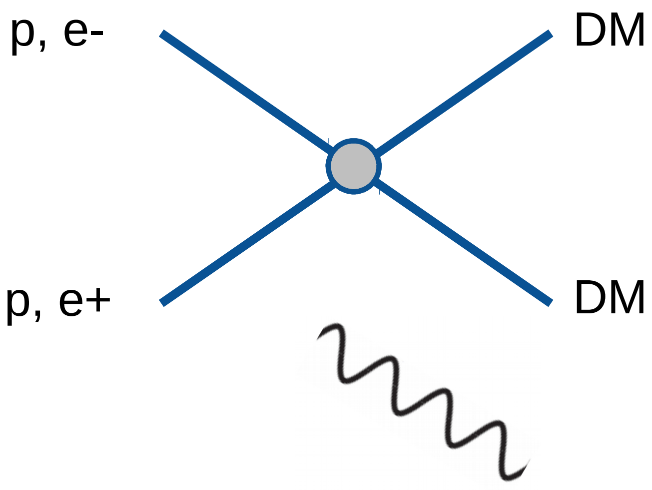
difficult to Higgsino signal

Constraints from MET

Searches via monojet give NO constraint on Higgsino

			Run 2 ~100 fb^{-1}
100 GeV Higgsino Cross section	~10,000 fb		10^6 production
1 TeV Higgsino	~	1 fb	100 production

Collider Signals of DM



DM is invisible

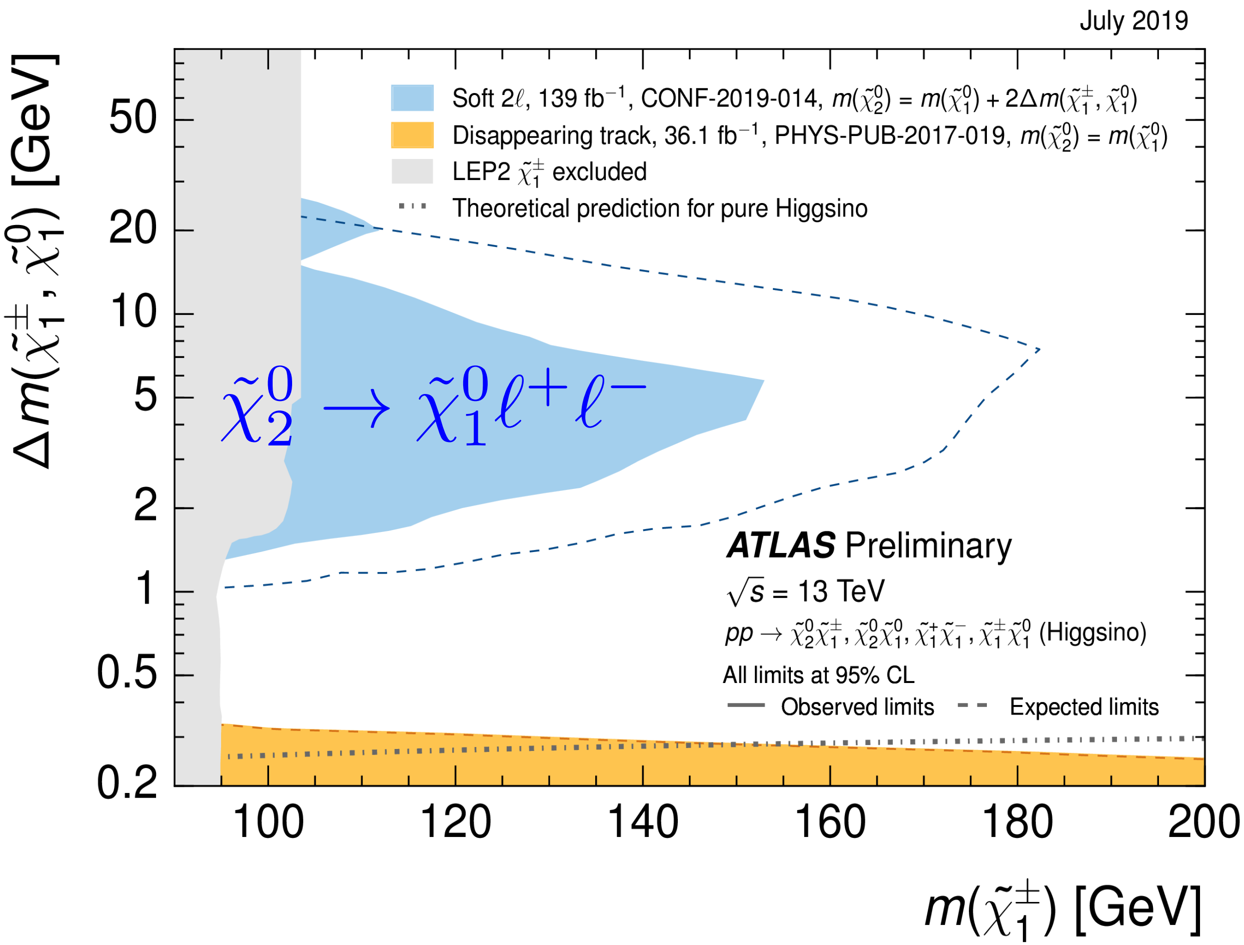
Additional objects are needed
to see DM.
Missing energy (MET) search

gluon photon, …

New observable are needed for efficient BG reduction

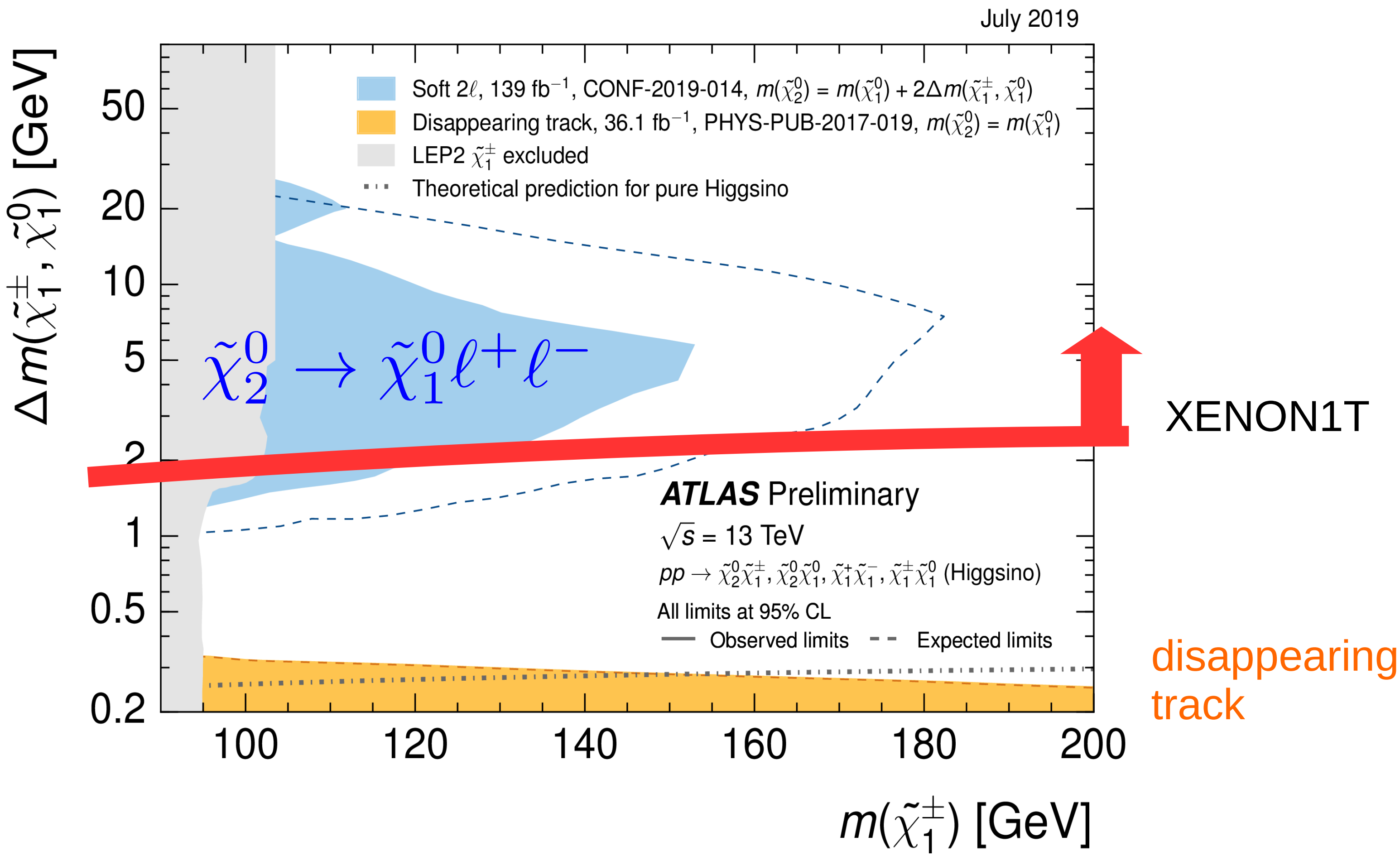
Decay of heavier Higgsino component

Current Constraint(higgsino)



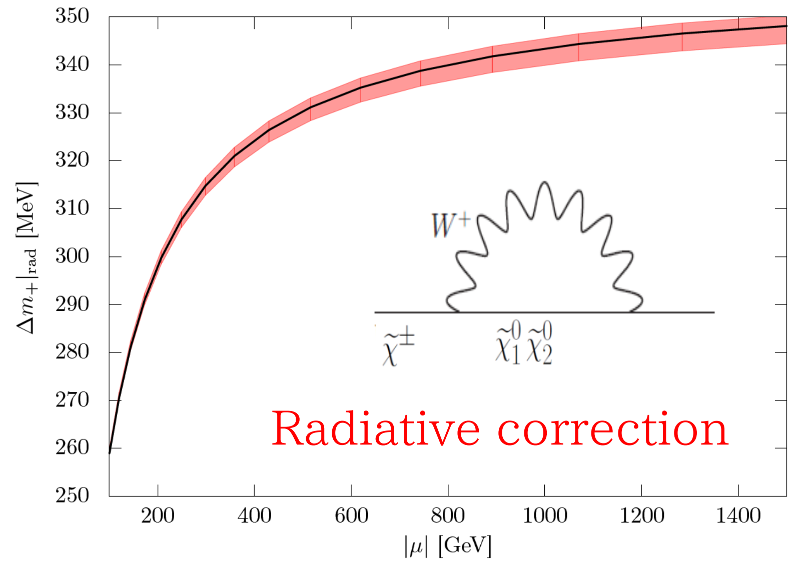
disappearing track

Current Constraint(higgsino)



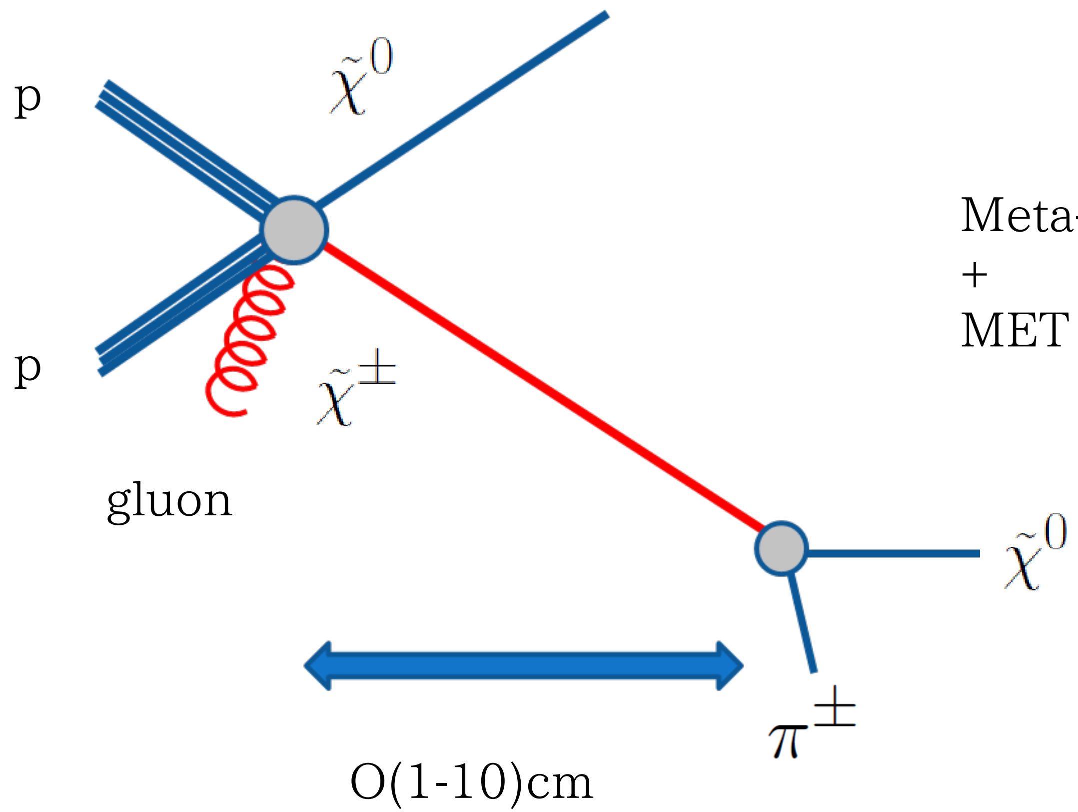
Almost Pure Higgsino Spectrum

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



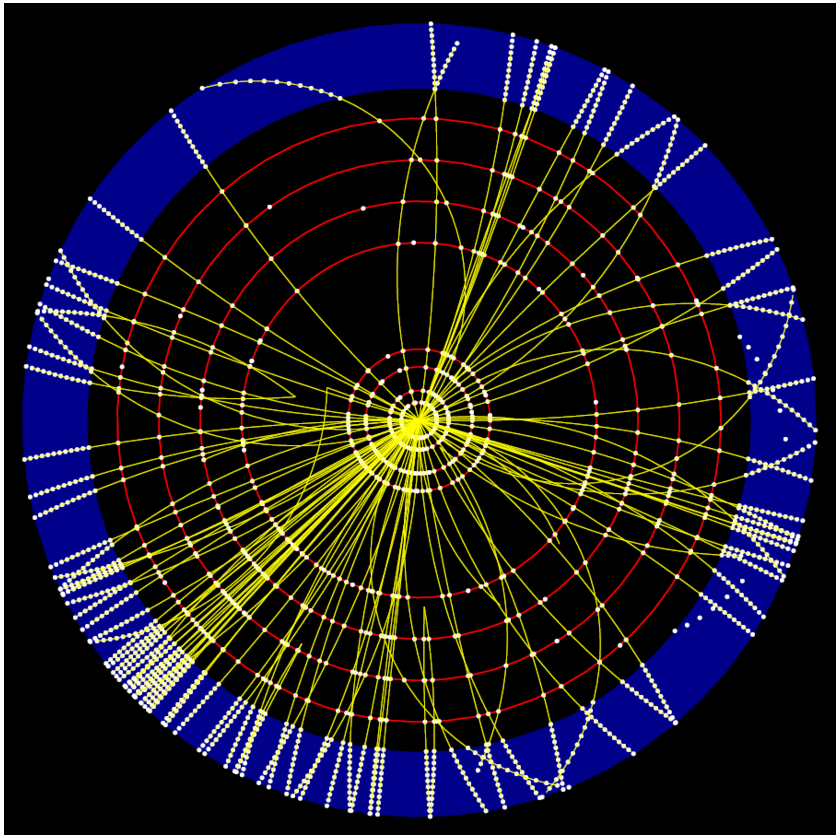
$$c\tau(\tilde{\chi}^\pm \to \tilde{\chi}^0 \pi^\pm) = 1.1 \text{ cm} \left(\frac{\Delta m_+}{300 \text{ MeV}}\right)^{-3} \left[1 - \frac{m_{\pi^\pm}^2}{\Delta m_+^2}\right]^{-1/2}$$

LHC Signals

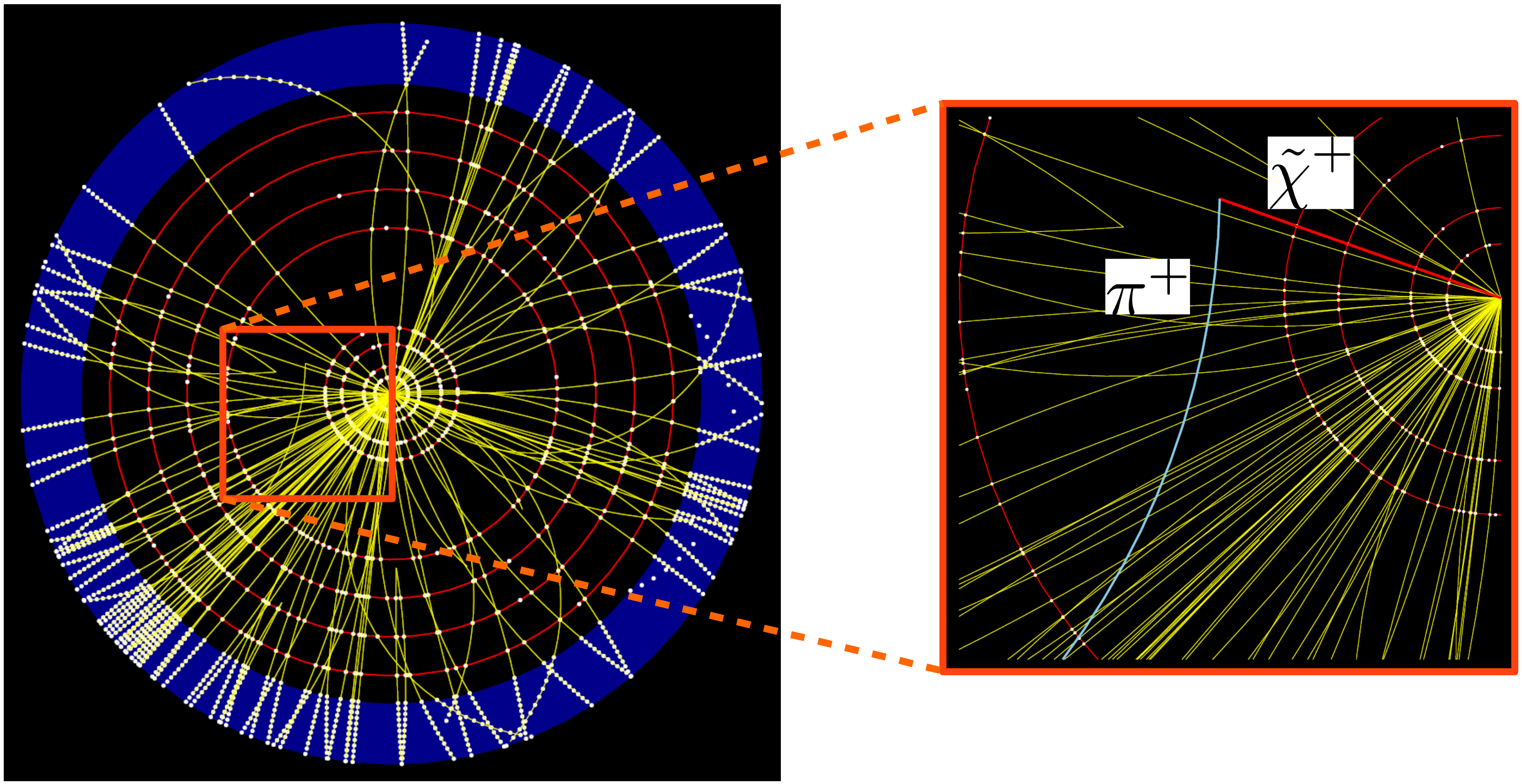


Meta-stable track
+
MET

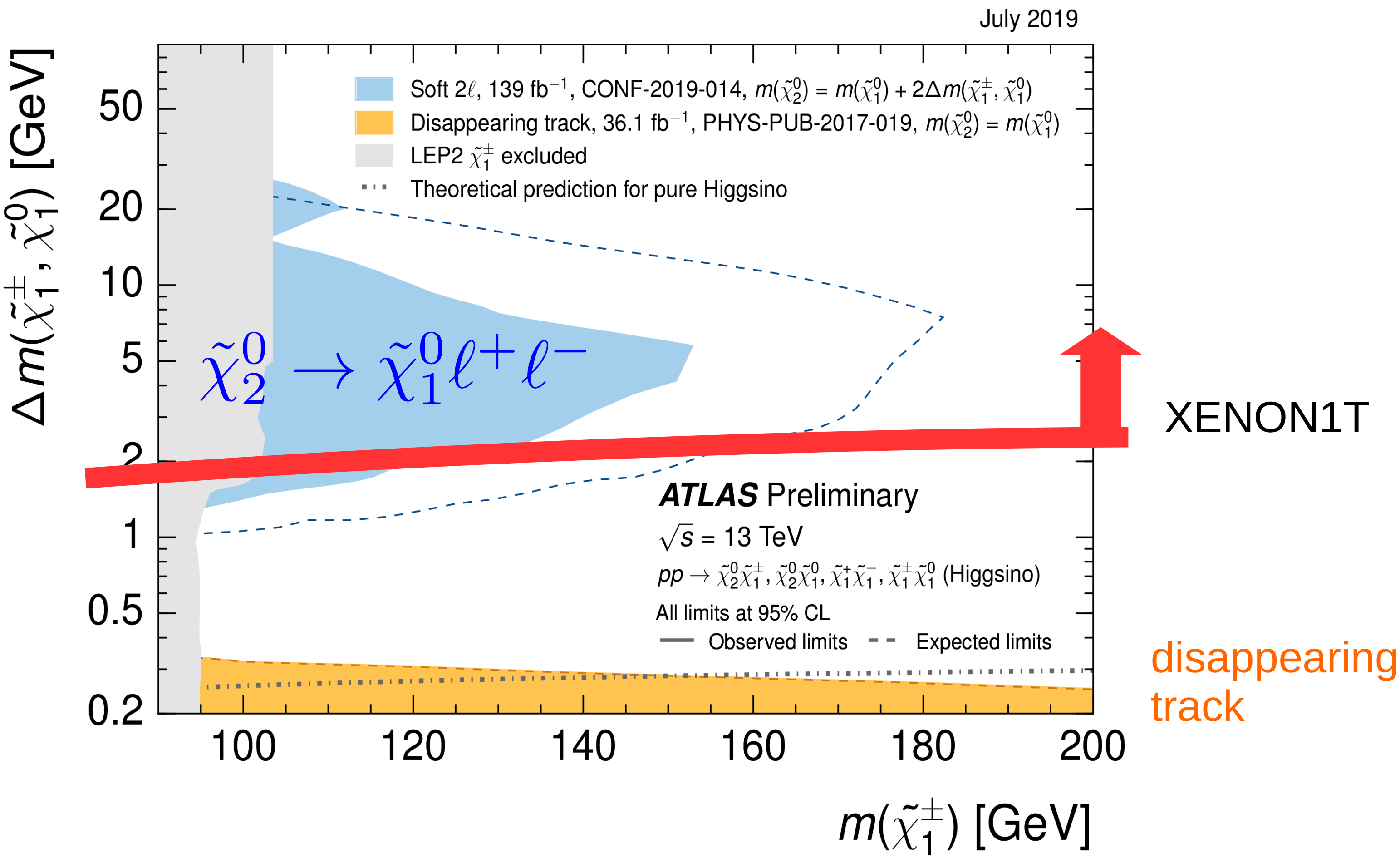
Event Display



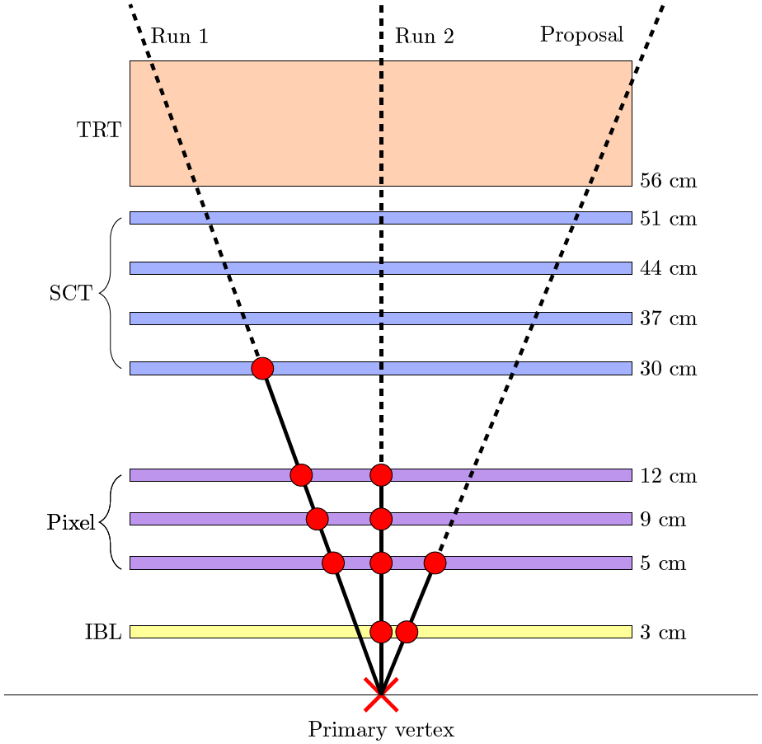
Event Display

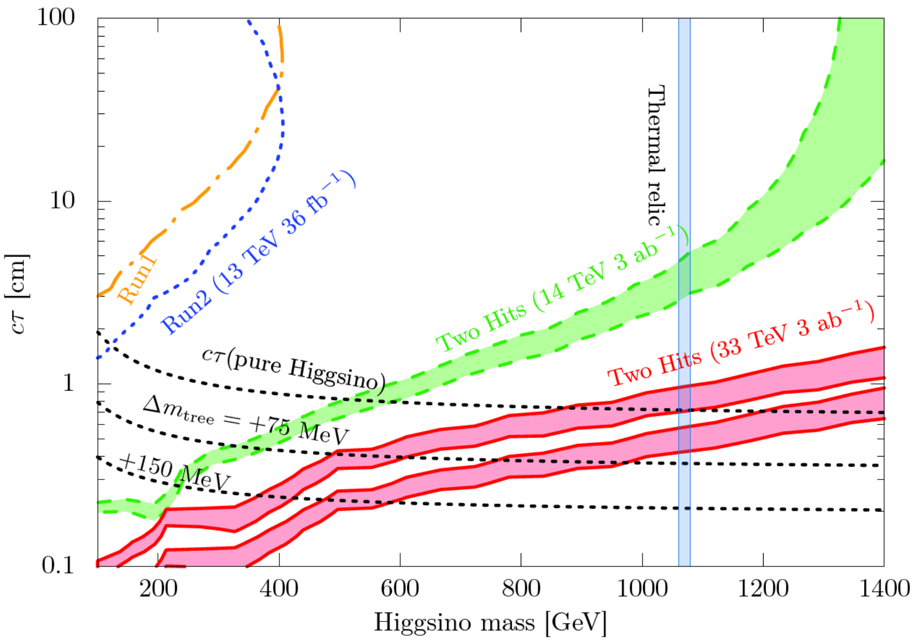


Current Constraint(higgsino)



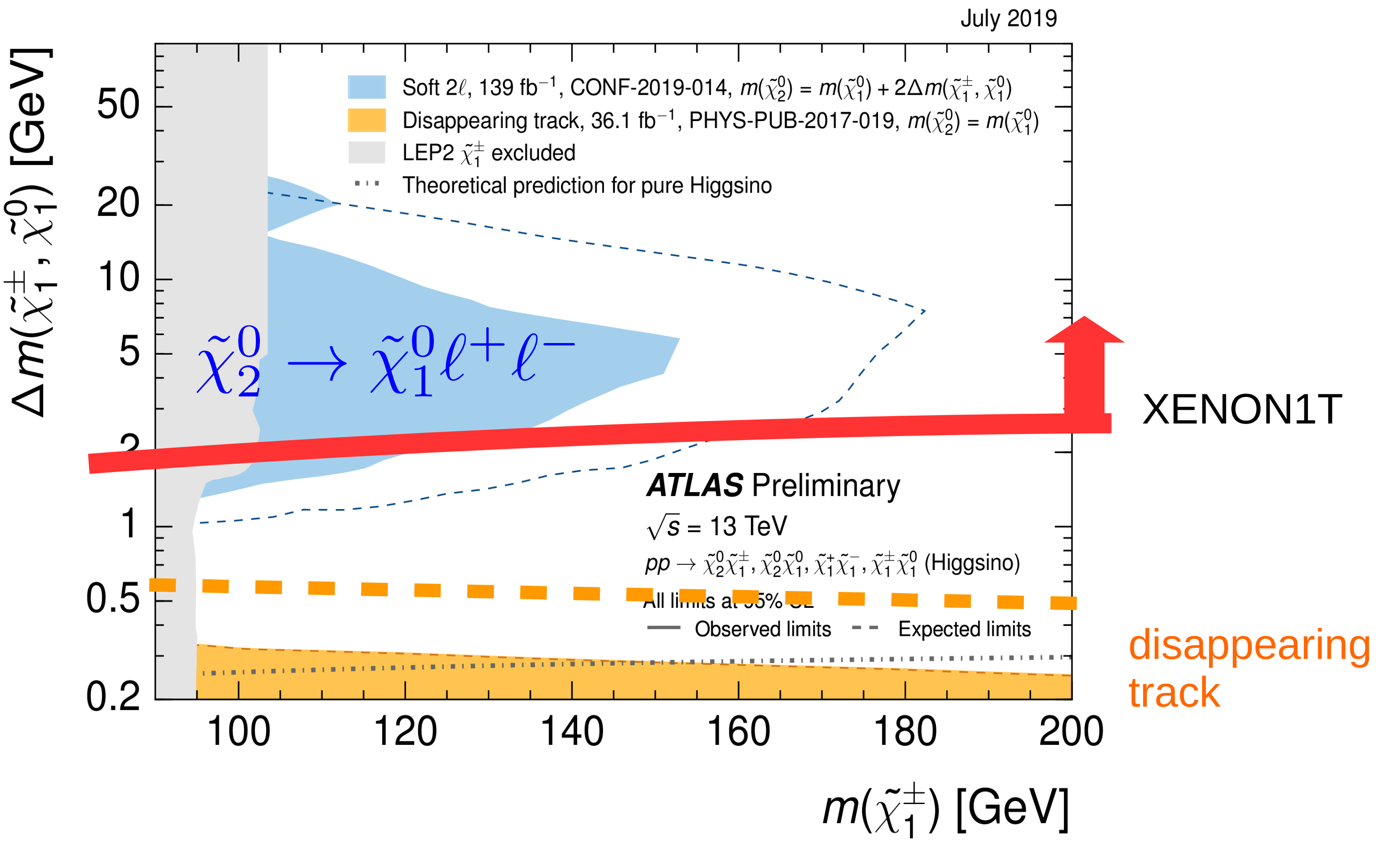
Improving Track Reconstruction



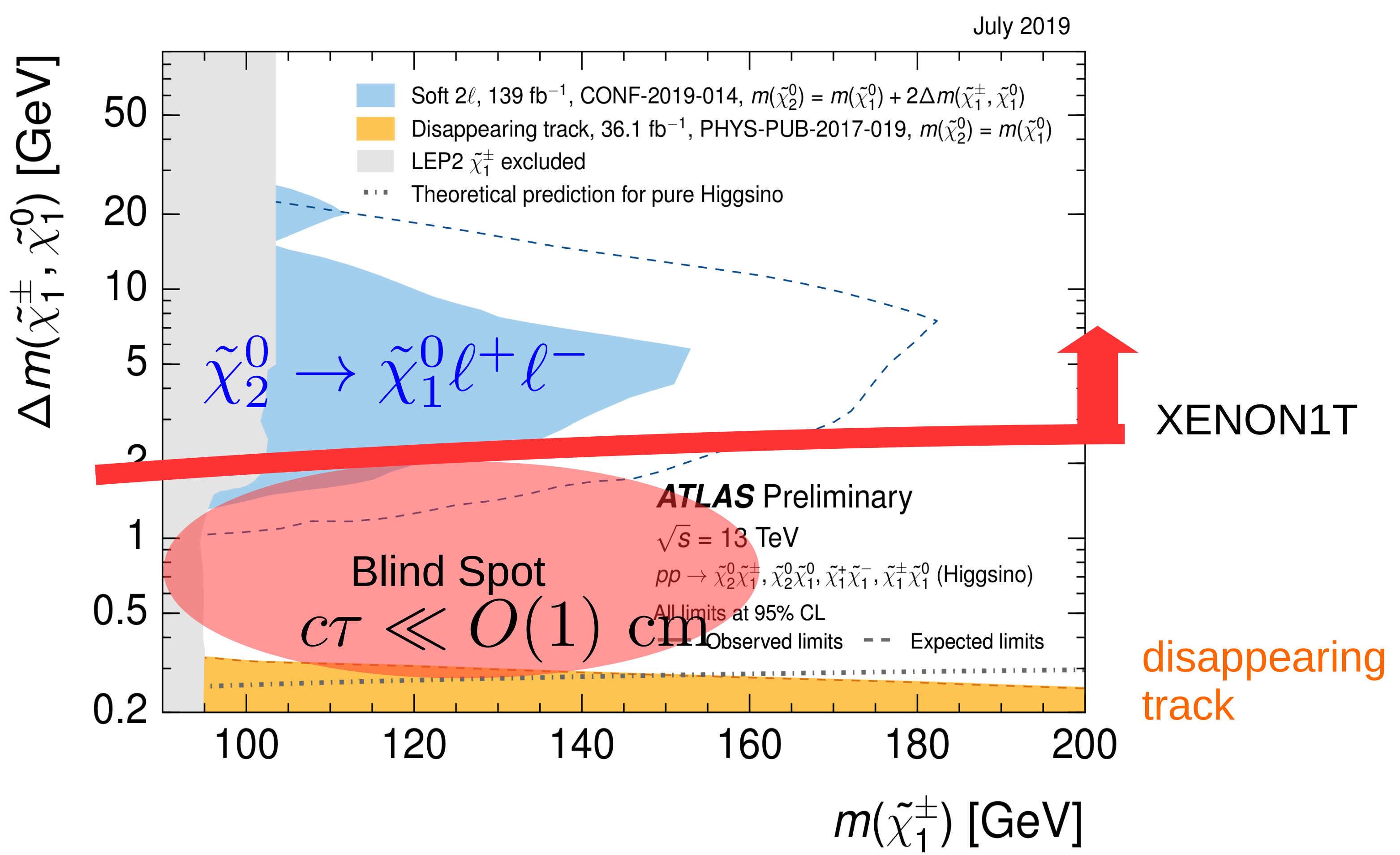


[H. Fukuda, N. Nagata, H. Otono & SS 2017]

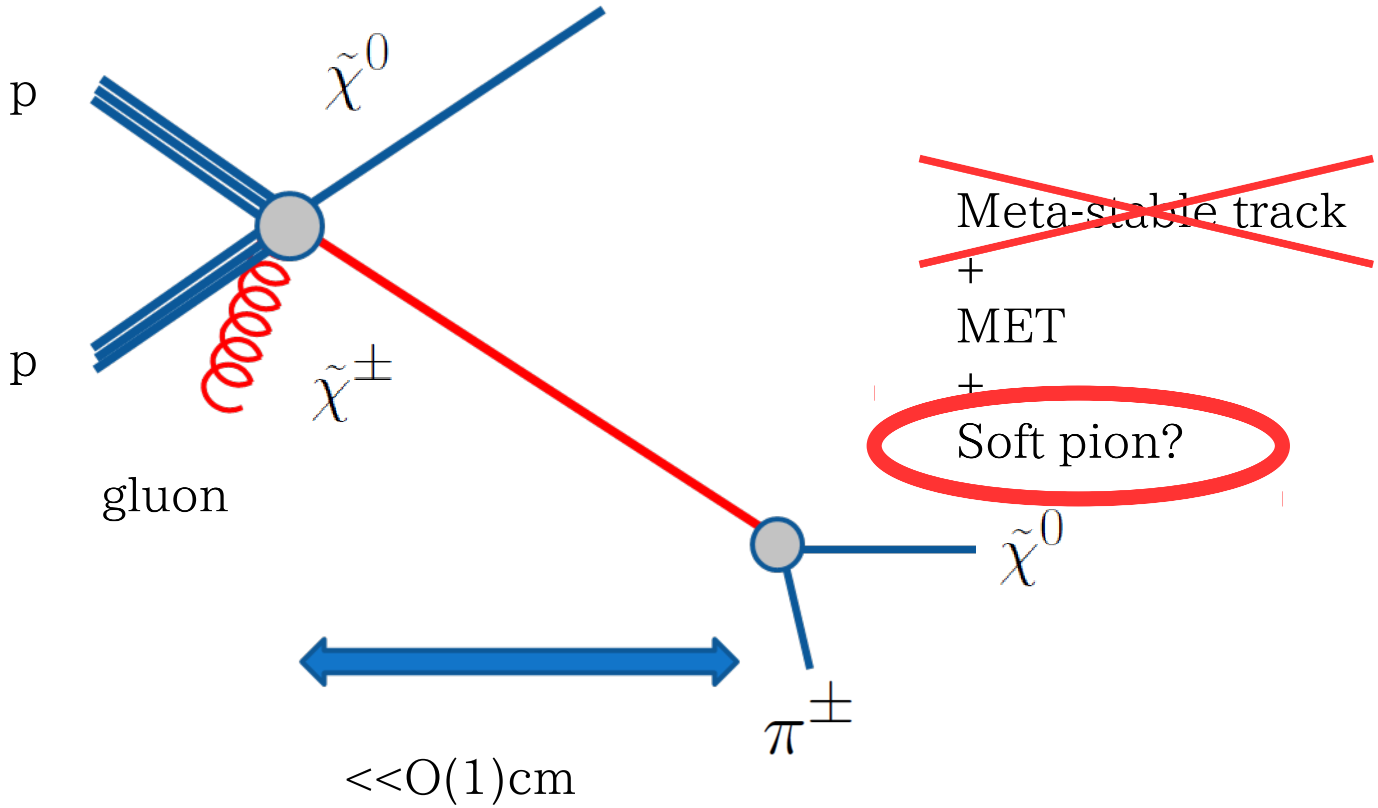
Current Constraint(higgsino)



Current Constraint(higgsino)



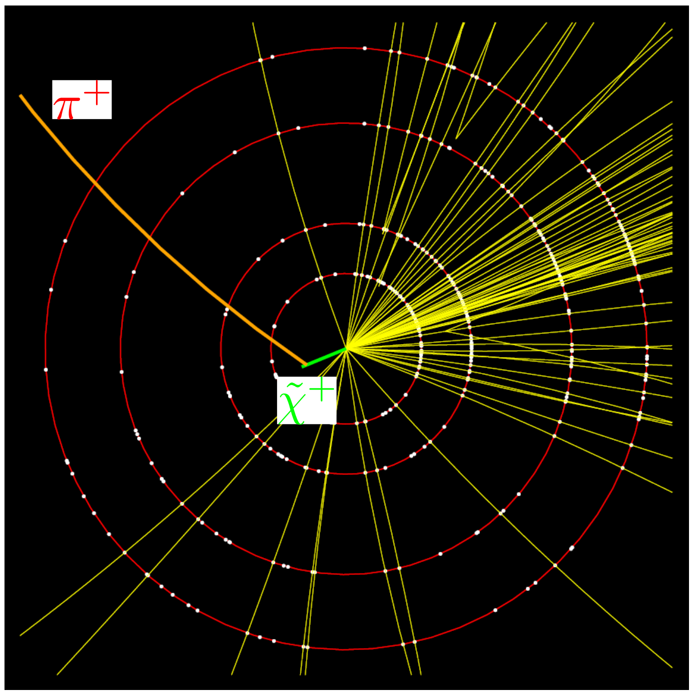
LHC Signals


p
p
$\tilde{\chi}^0$
$\tilde{\chi}^\pm$
gluon
$\tilde{\chi}^0$
$\pi^\pm$
<<O(1)cm
~~Meta-stable track~~
+
MET
+
Soft pion?

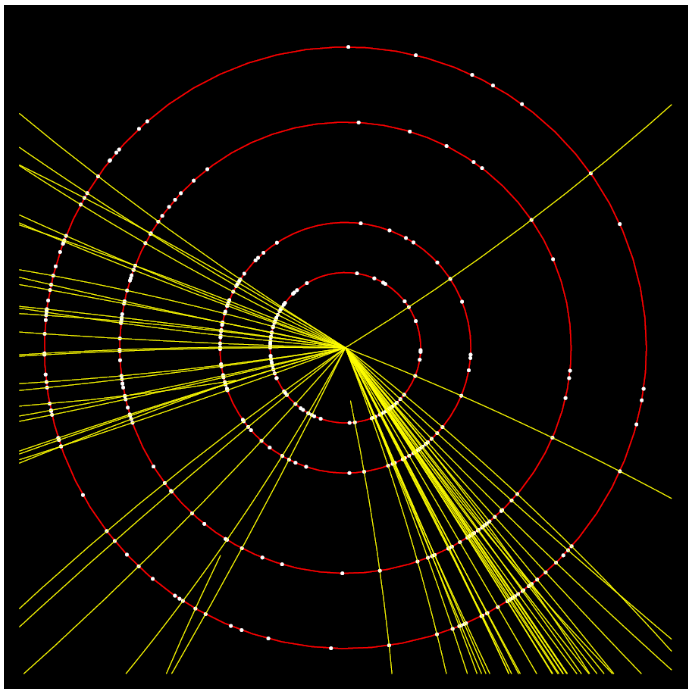
Use Soft Track

Event Display

25 cm

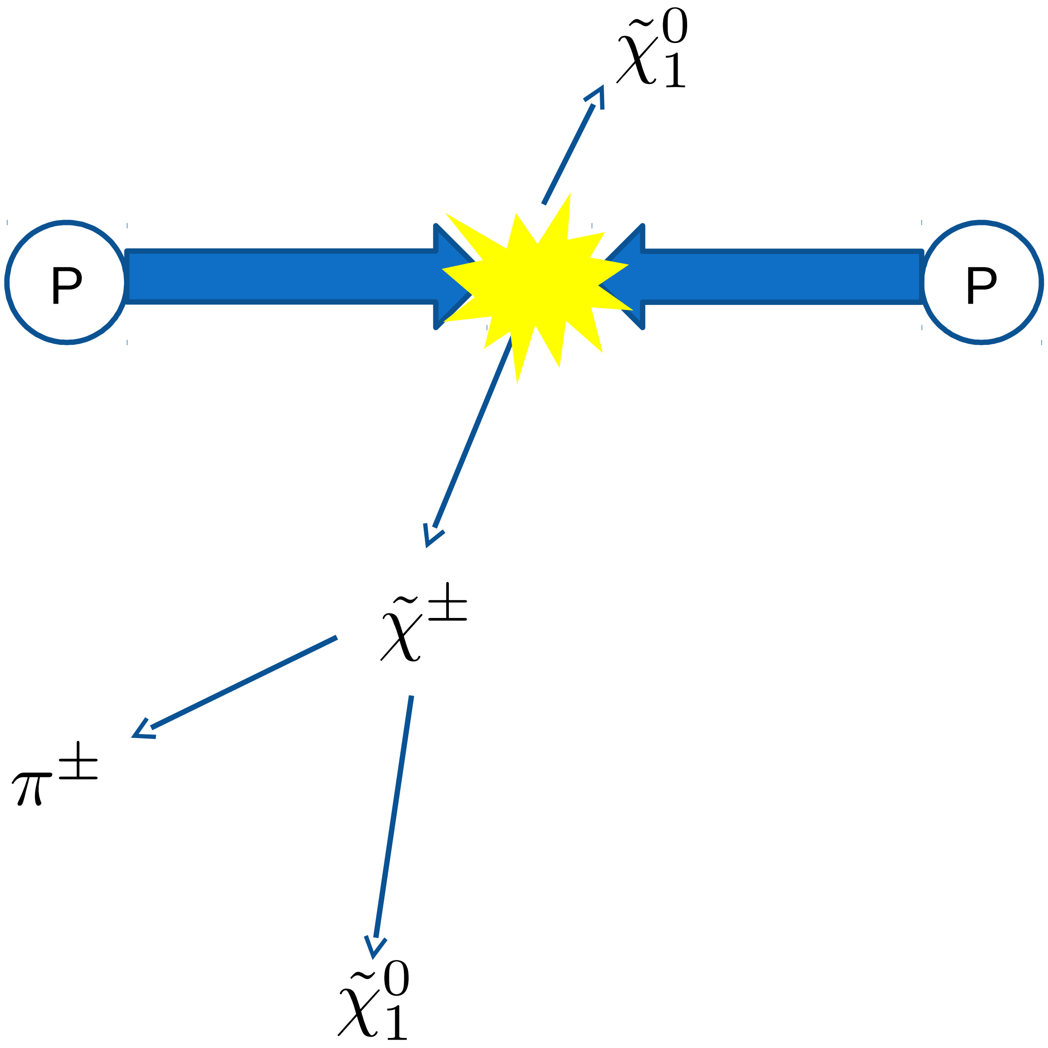


Signal

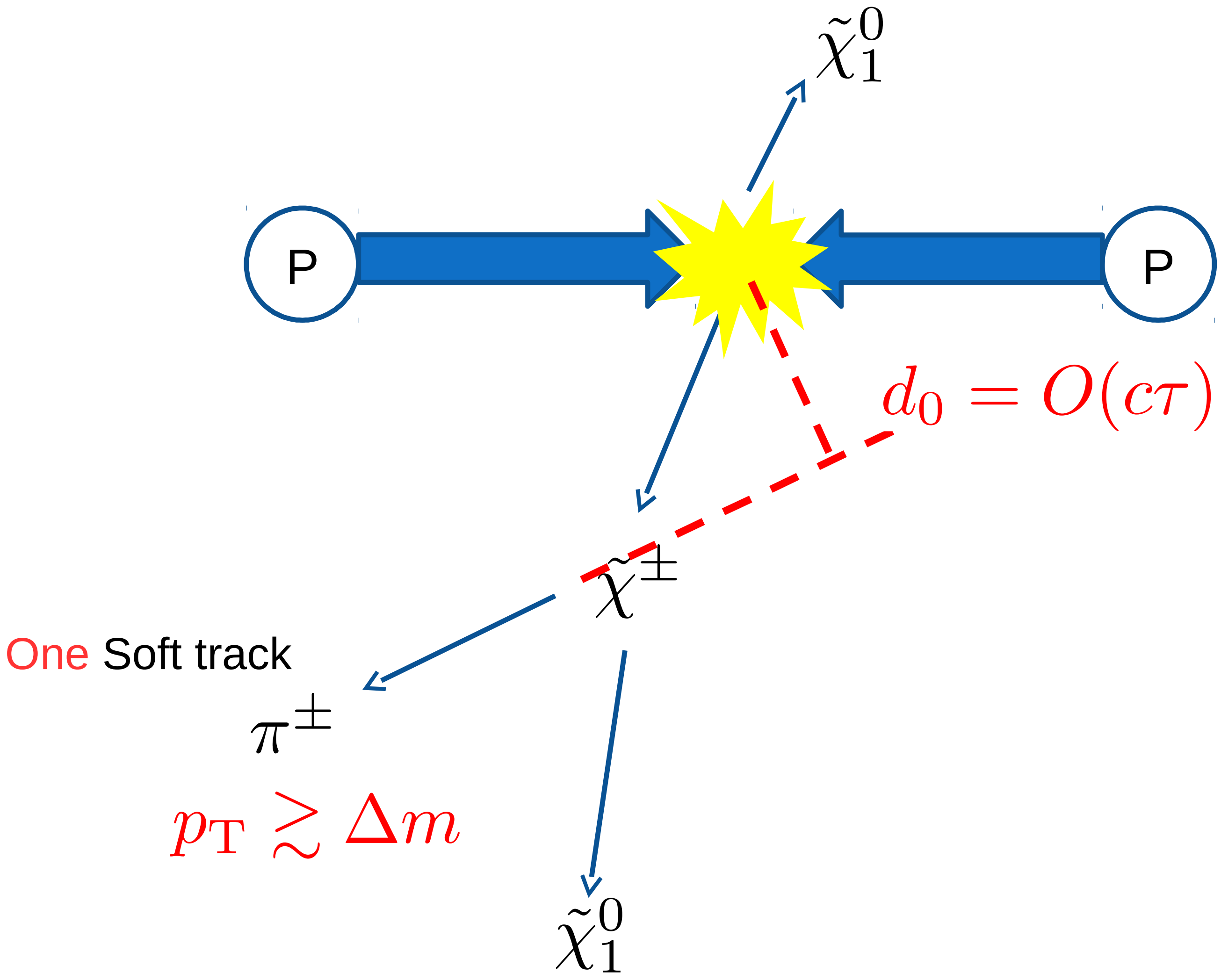


BG (Z > vv)

Signal

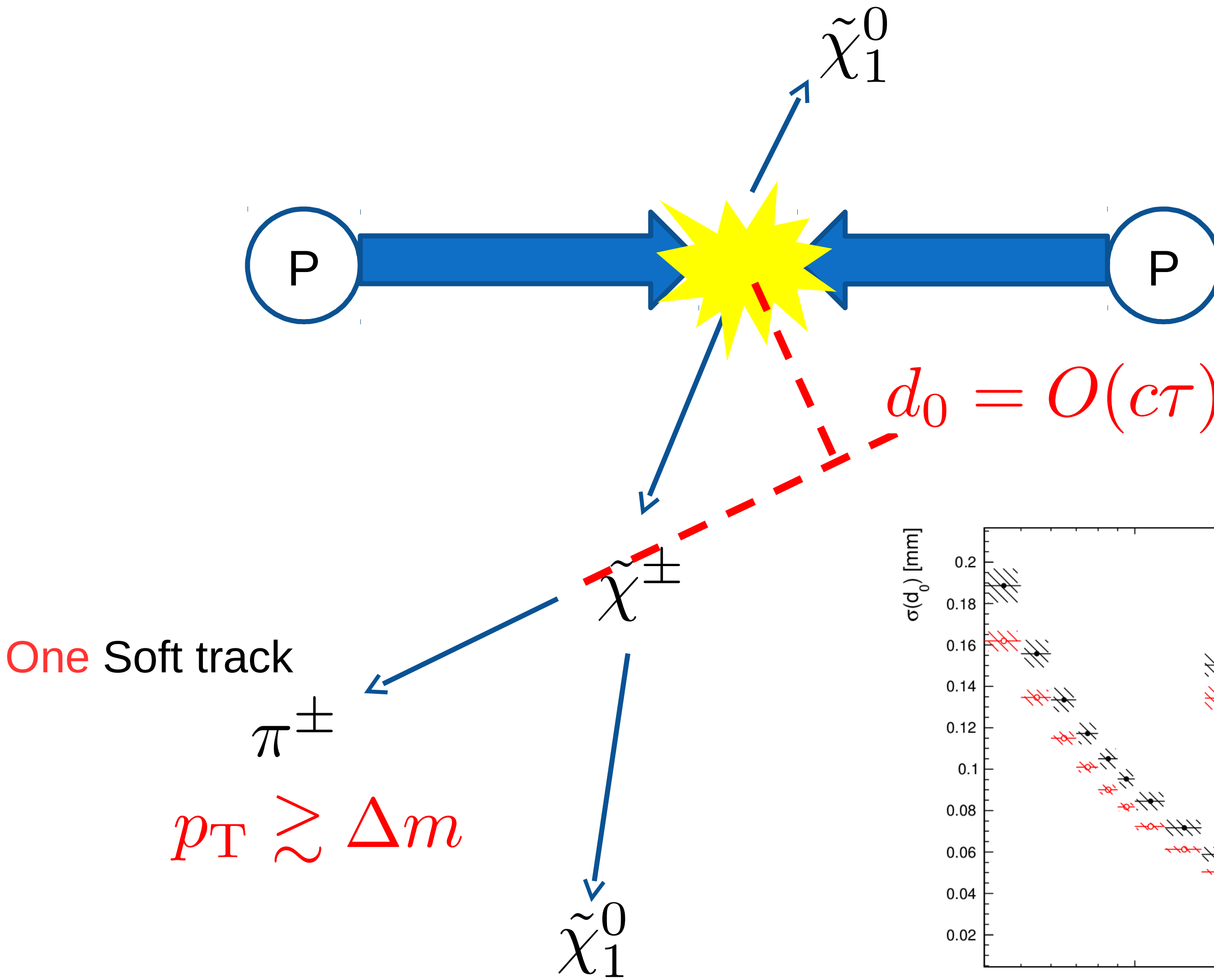


Signal

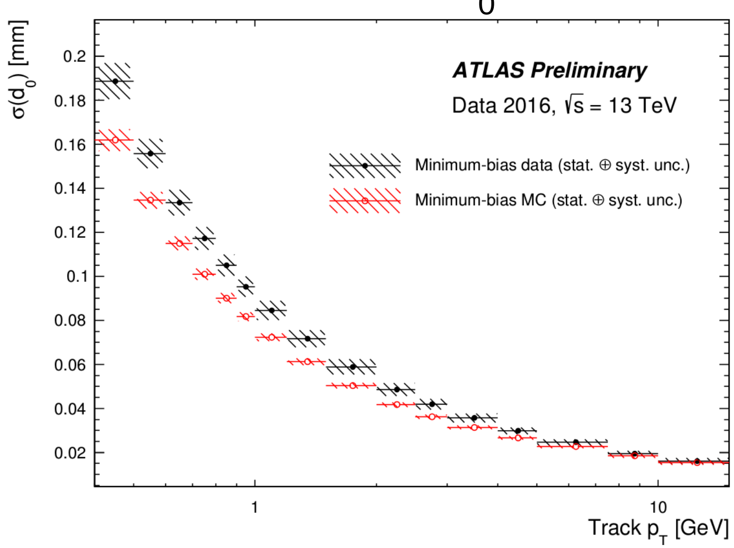


$\tilde{\chi}_1^0$
P
P
$d_0 = O(c\tau)$
$\tilde{\chi}^{\pm}$
One Soft track
$\pi^{\pm}$
$p_{\mathrm{T}} \gtrsim \Delta m$
$\tilde{\chi}_1^0$

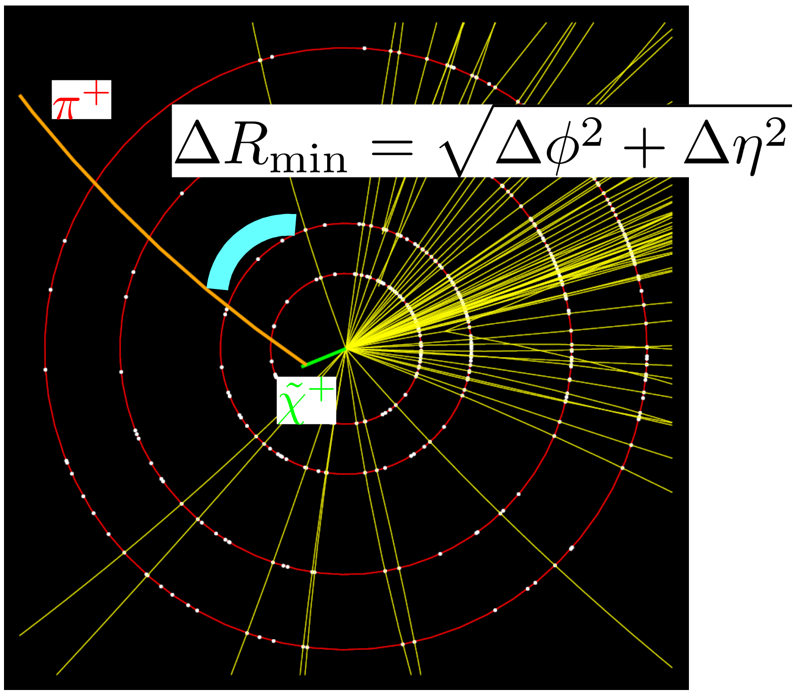
Signal



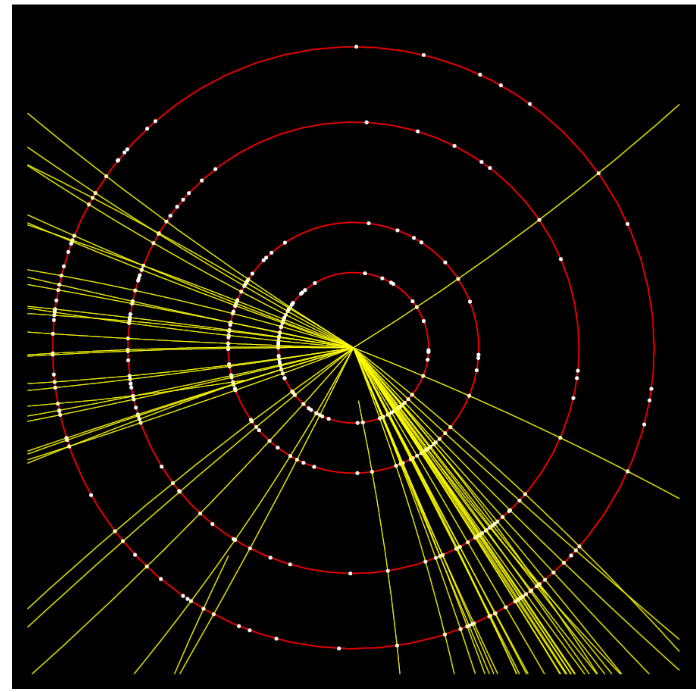
d$_0$ resolution



Event Display



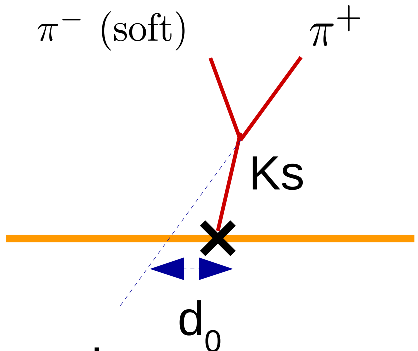
Signal

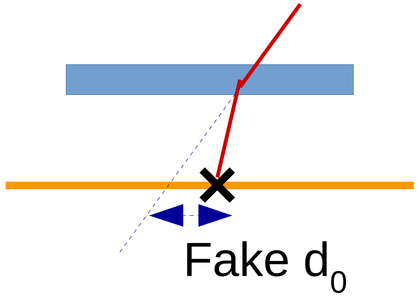


BG (Z > νν)

Background

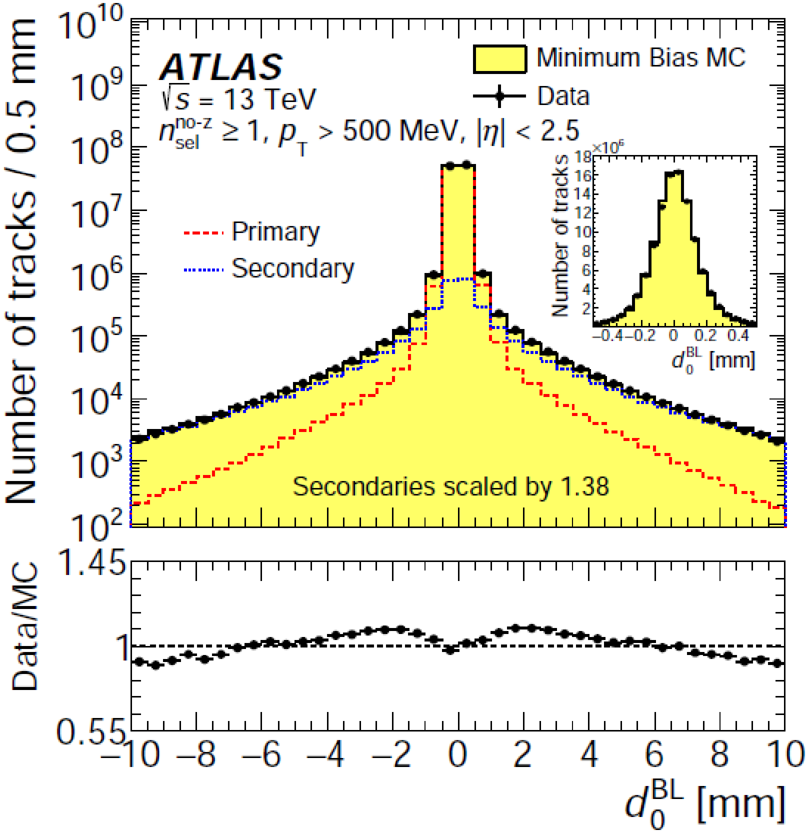
- Main BG event: Mono boson production: Z > νν
- O(100) tracks per event
- Tracks tend to be soft
- Most of tracks are close to each other
- Secondary track: long-lived particles decay: Ks, strange baryon
  - Large impact parameter
- Primary track of large angle scattering with detector material:
  - Fake track with large impact parameter



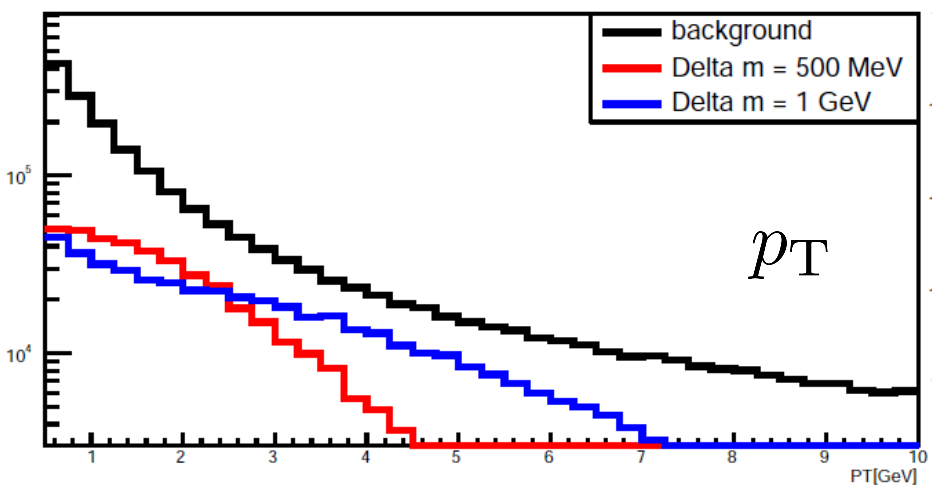


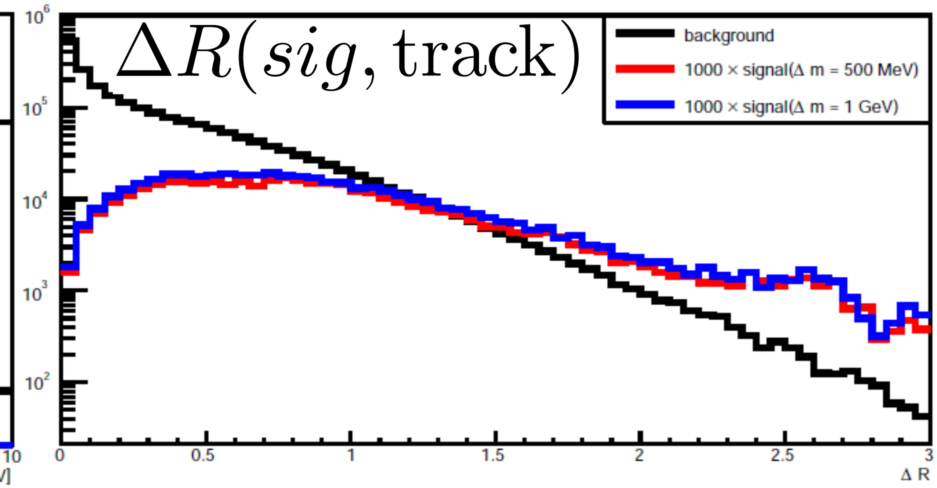
Background

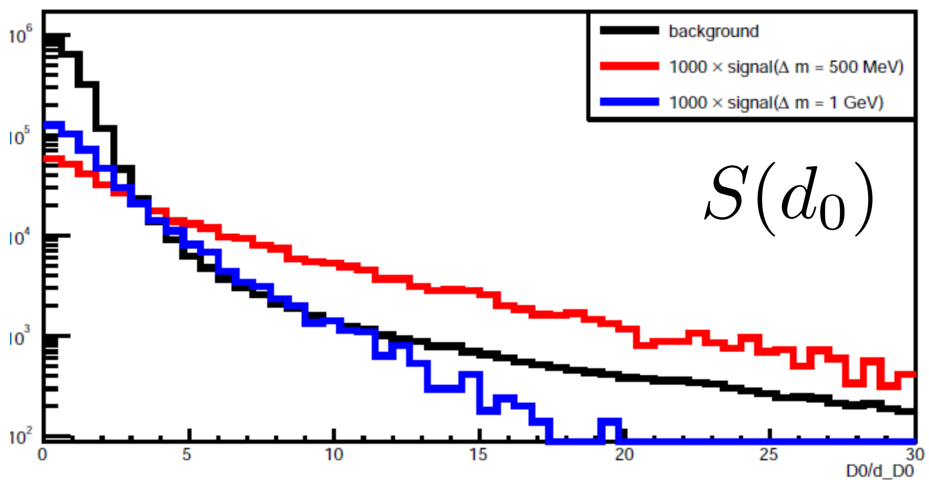
- Main BG event: Mono boson p
- O(100) tracks per event
- Tracks tend to be soft
- Most of tracks are close to eac
- Secondary track: long-lived pa
    - Large impact parameter
- Primary track of large angle sc
    - Fake track with large impa



Background vs Signal





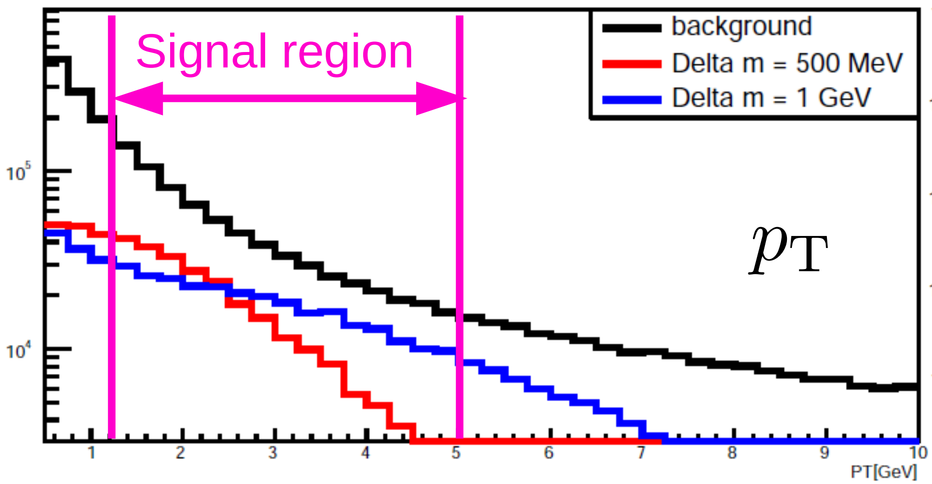


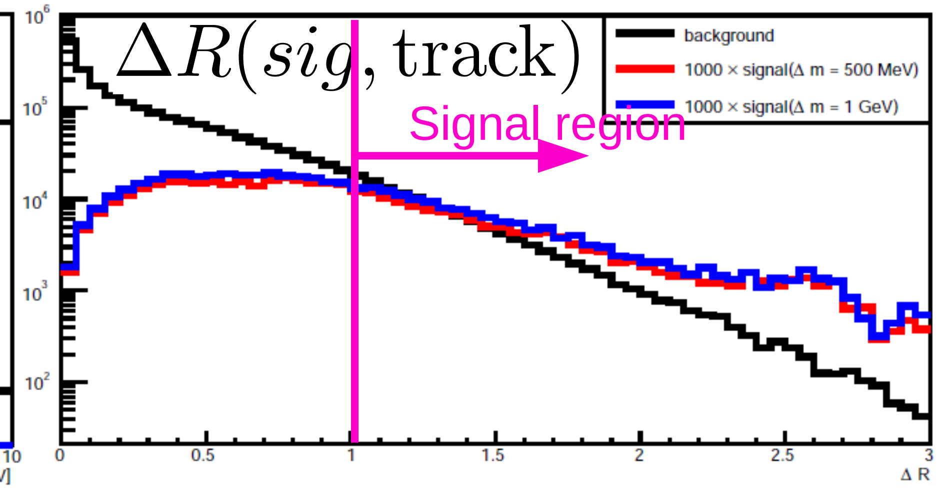
Signal: 150 GeV Higgsino

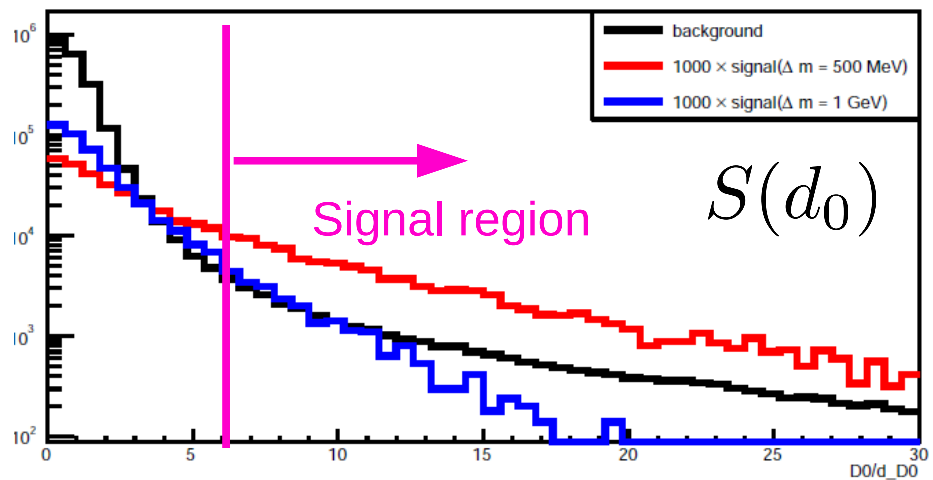
Delta m = 500 MeV: red line
ctau = 2 mm

Delta m = 1 GeV : blue line
ctau = 0.1 mm

Background vs Signal







Signal: 150 GeV Higgsino

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ctau = 2 mm

Delta m = 1 GeV : blue line
ctau = 0.1 mm

Event Selection

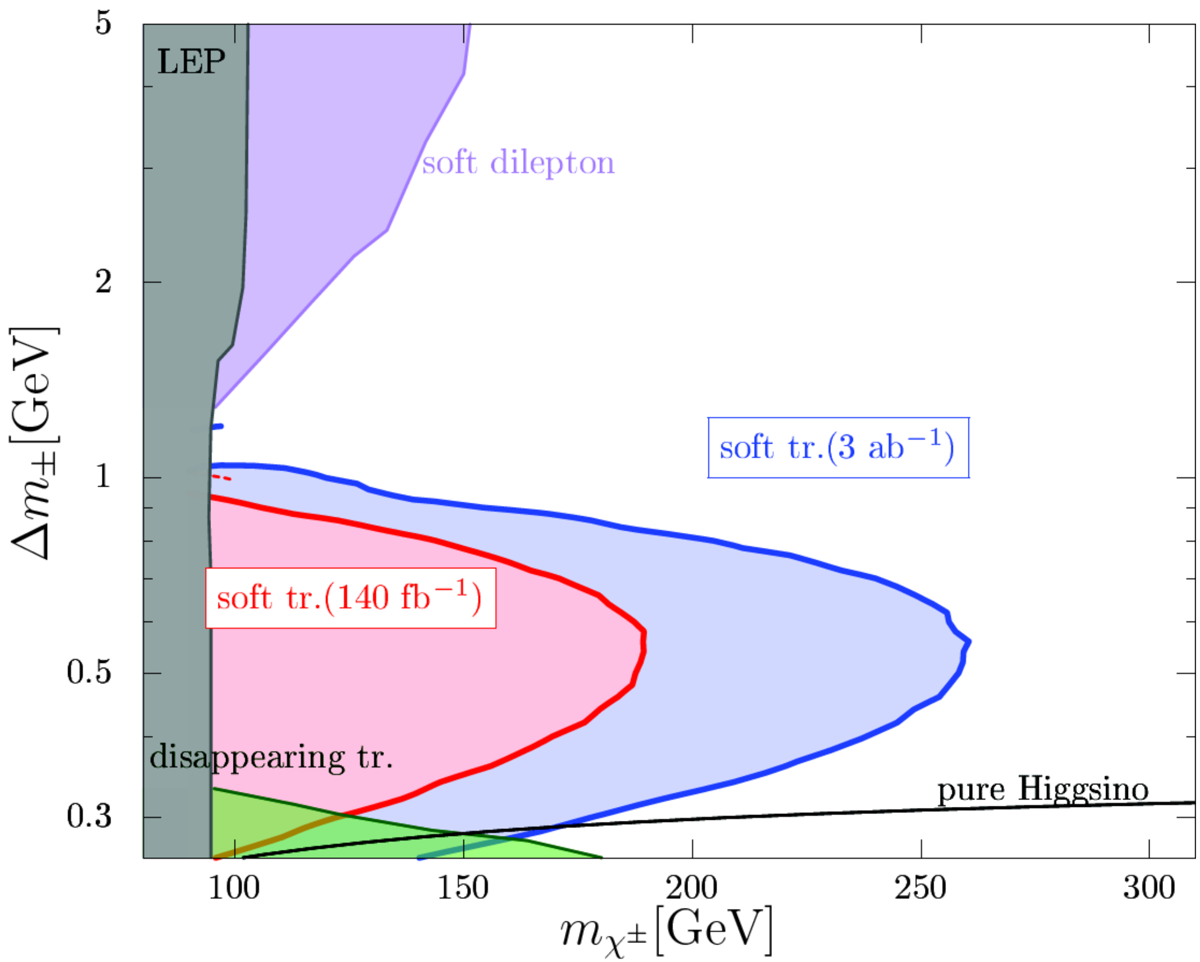
“Mono-jet event” with MET>500 GeV and Signal track satisfying

- Basic Selection: $1.2 < p_{\mathrm{T}} < 5$ GeV; $|\eta| < 1.5$; $|\Delta z_0 \sin(\theta)| < 1.5$, $|d_0| < 10$ mm, and IBL hit
- Isolation: The candidate track is separated by $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 1$ for any tracks with $p_{\mathrm{T}} > 1$ GeV
- Displacement: The transverse impact parameter of the candidate is large: $S(d_0) \equiv |d_0|/\sigma_{d_0} > 6$.
- Alignment to MET direction: $\Delta\phi(\mathrm{trk.}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) < 1$.

Acceptance rate for
Higgsino with 0.5 GeV Delta M ~ 5%.
Background ~ 0.5%
50%: Kshort, Sigma,..., 30%: Mis-measurement, 20% Pileup

Result

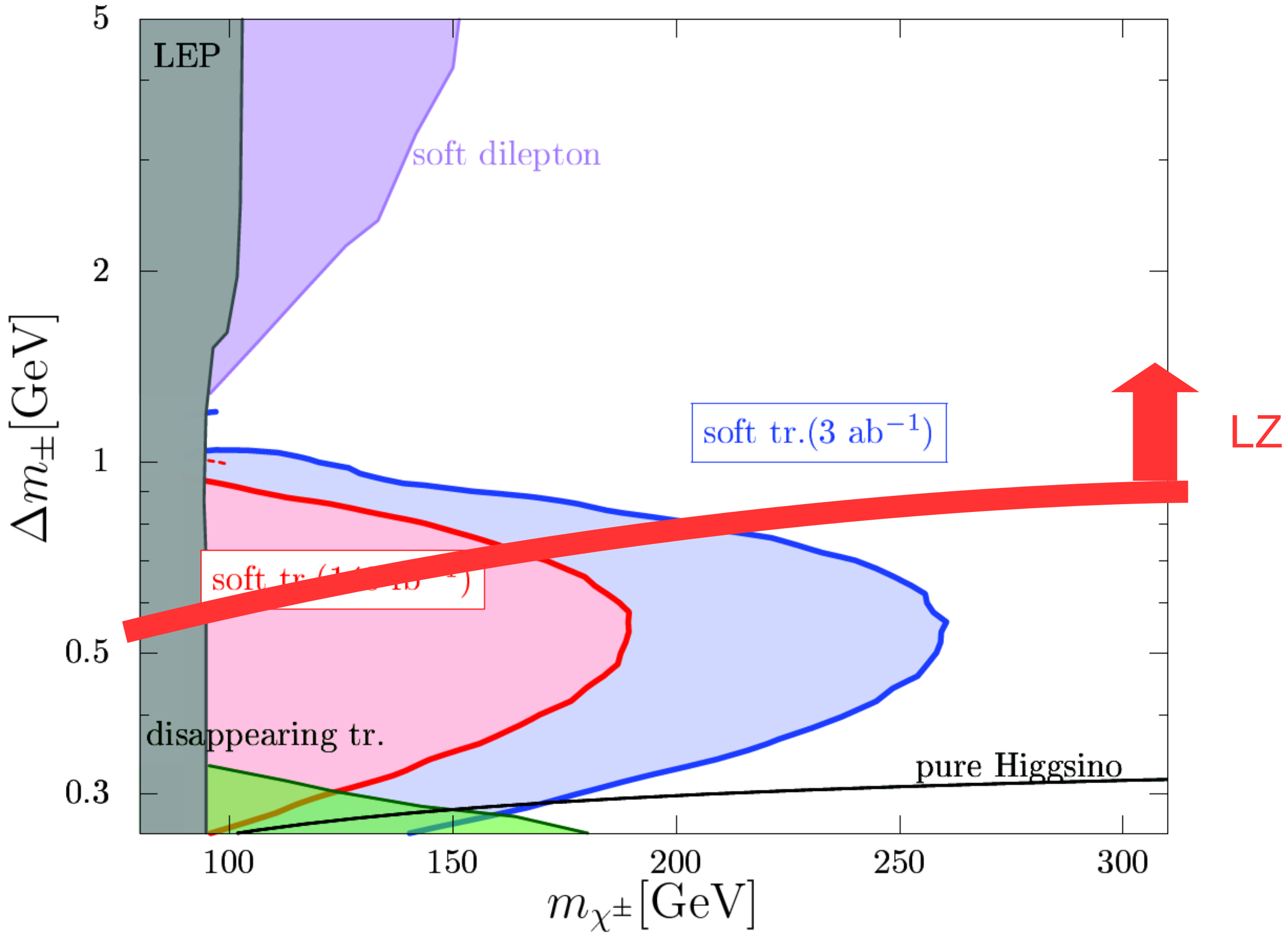
[H. Fukuda, N. Nagata, H. Oide, H. Otono && SS, 2019]



Run2 # of BG ~ 250.

Result

[H. Fukuda, N. Nagata, H. Oide, H. Otono && SS, 2019]

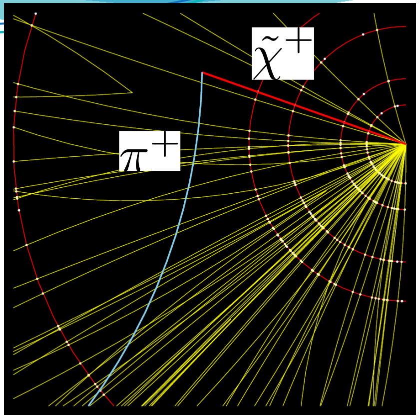


Run2 # of BG ~ 250.

Summary

- Compressed Higgsino has phenomenological importance
- Higgsino DM likely provides meta-stable particles
  - Complementray to DM direct detecion
  - Disappearing track
  - Soft tracks
    - Can fill “Delta M” gap region

Outlook



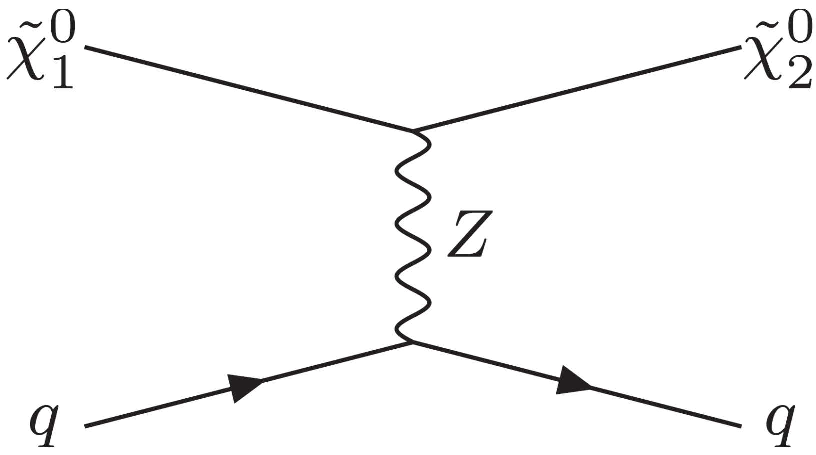
- Combination with shorter disappearing track

- Measurement of the Mass difference

- Application to real data is ongoing

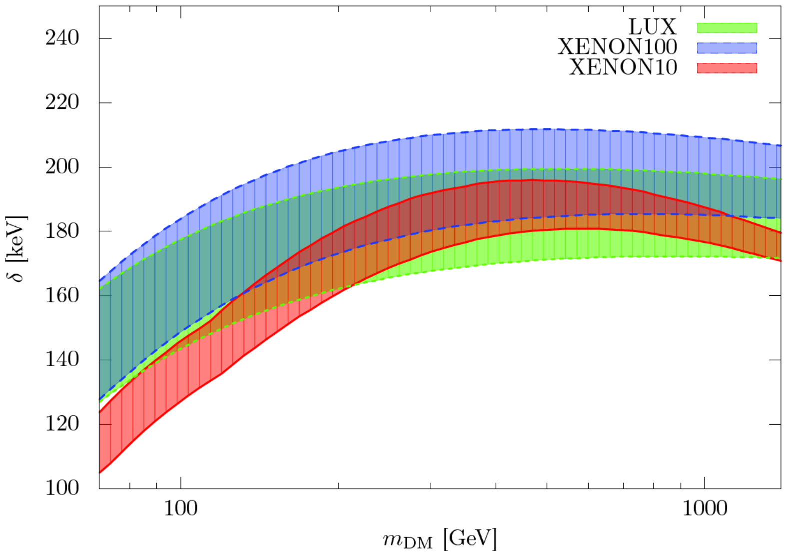
- Application to other BSM models:
  Slepton coannihilation, minimal DM, wino.

Inelastic Scattering



In DM direct detection,
the recoil energy is O(100) keV

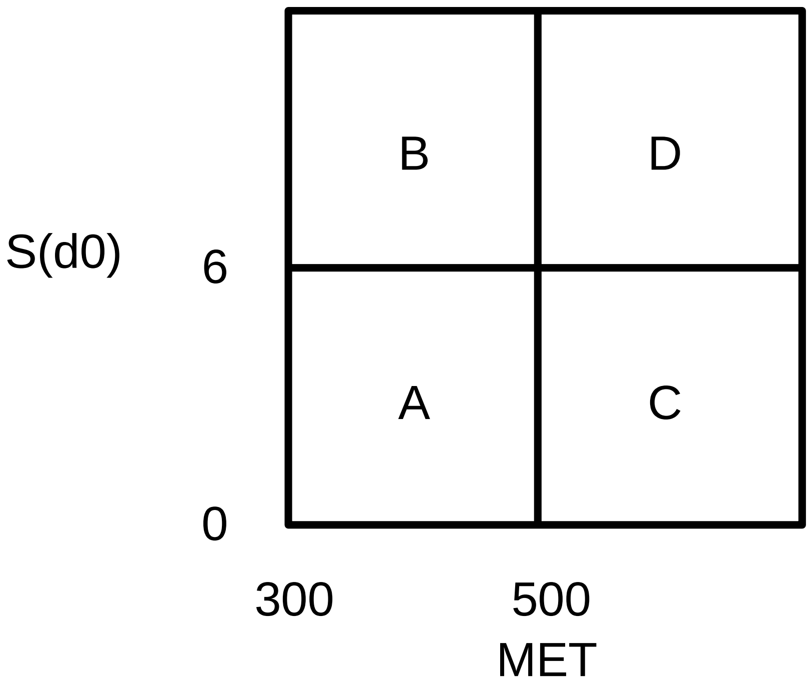
Mass difference < O(100) keV is excluded



ABCD Method

In reality, we need data drive background estimation.

Acceptance rate of Signal track is almost independent on MET.



A, B, C: Control regions:
D: Signal region

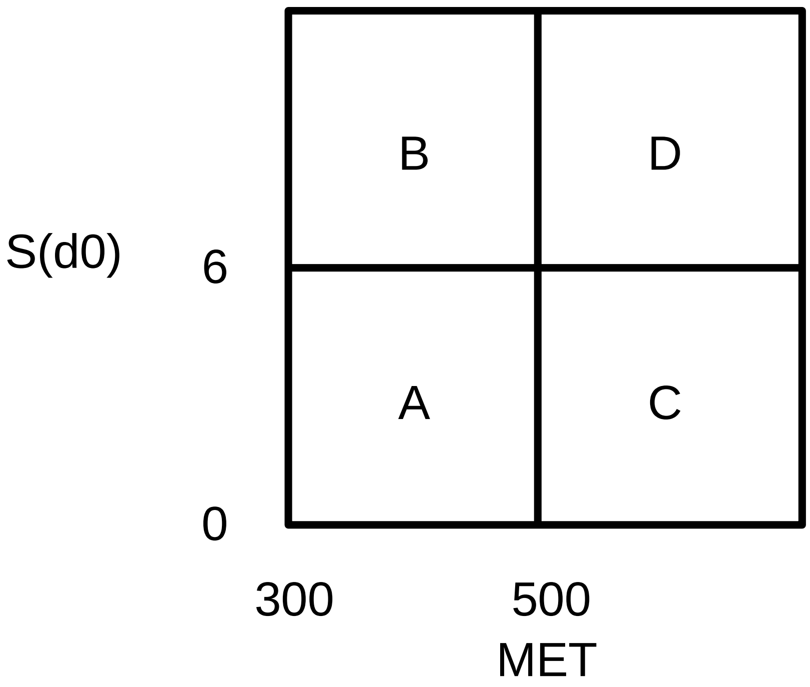
By using observed data for A, B ,C
we can estimate # of signal region D

D = B x C / A

ABCD Method

In reality, we need data drive background estimation.

Acceptance rate of Signal track is almost independent on MET.



Mock data

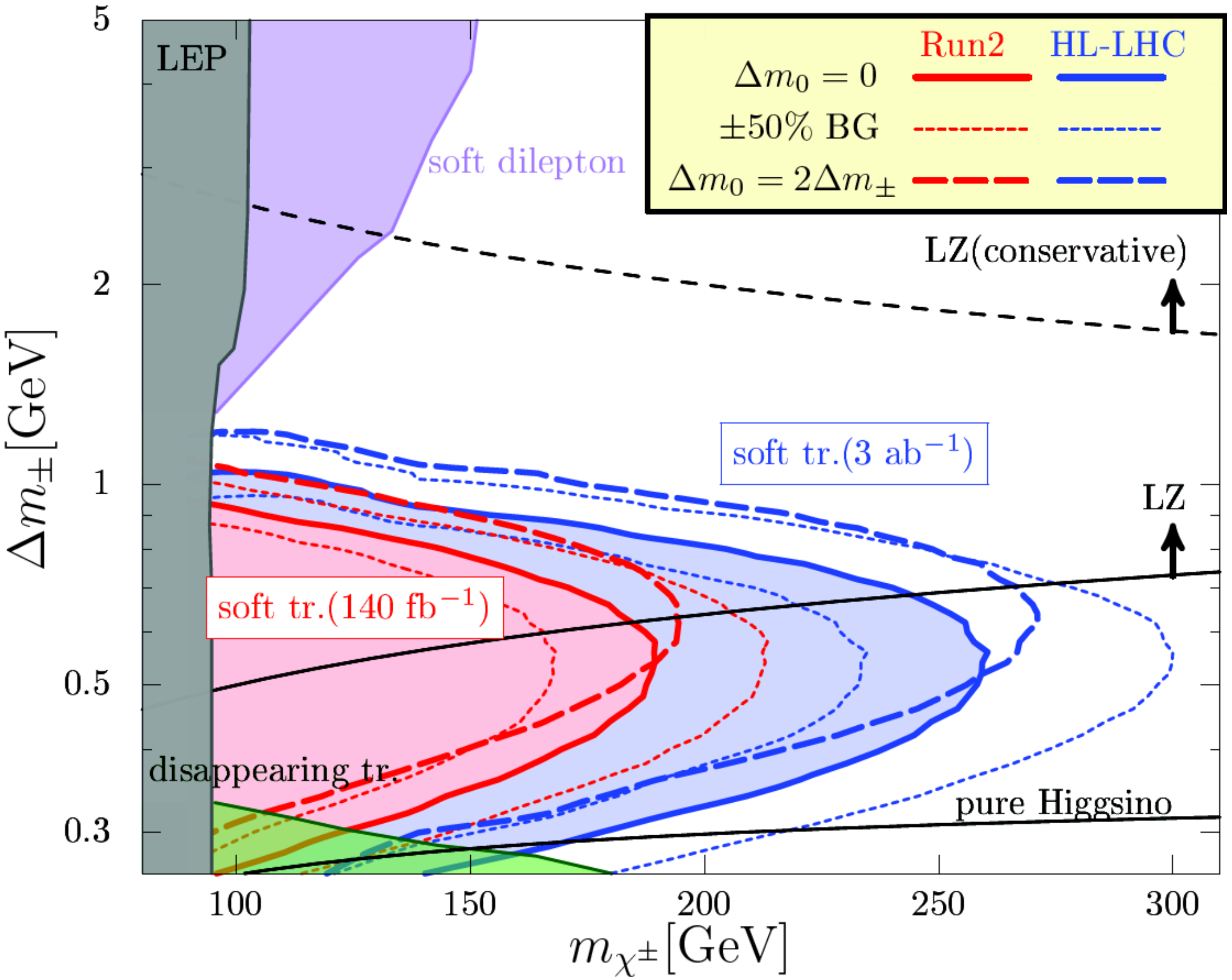
Pythia8 Run2
A: 103302
B: 2574
C: 10691
D: 261

Estimation by ABCD method:

D = B x C / A
= 266 +-6

BG systematic error ~3%.

Full Result



LEP
soft dilepton
Run2
HL-LHC
$\Delta m_0 = 0$
±50% BG
$\Delta m_0 = 2\Delta m_\pm$
LZ(conservative)
soft tr.(3 ab^{-1})
LZ
soft tr.(140 fb^{-1})
disappearing tr.
pure Higgsino
5
2
1
0.5
0.3
100
150
200
250
300
$\Delta m_\pm$[GeV]
$m_{\chi^\pm}$[GeV]

Event Display