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: Use of Soft Displaced Track ”, arXiv:1910.08065

1. Higgsino Dark Matter

2. Current Status of Higgsino @LHC

   mono-jet, dilepton, disappearing track

3. Prospect of Higgsino

   Use of soft track

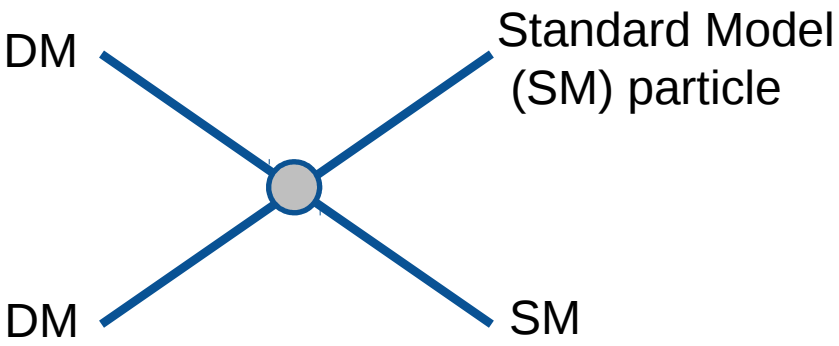
4. Summary

DM Candidates

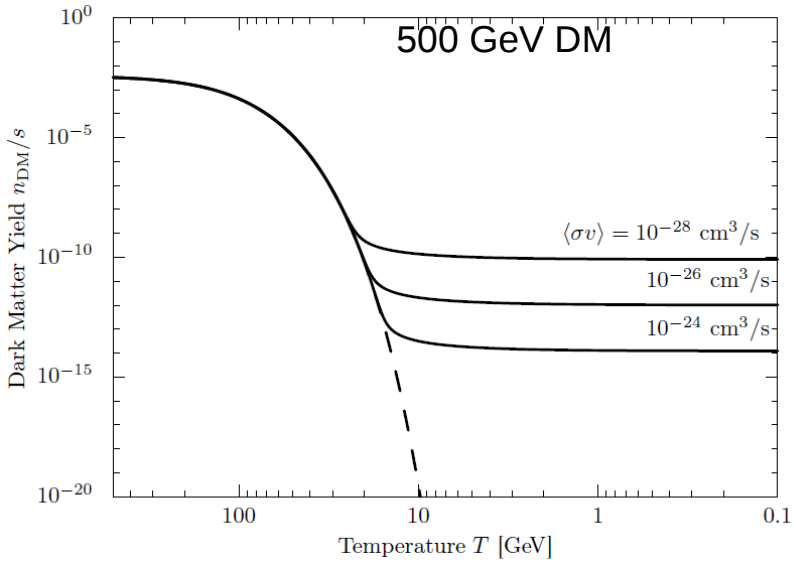
- Axion
- (Primordial) Black hole
- WIMP
- Others…

WIMP Dark Matter

Weakly Interacting Massive Particle



DM abundance



Time

WIMP Miracle

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

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

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

What is Higgsino?

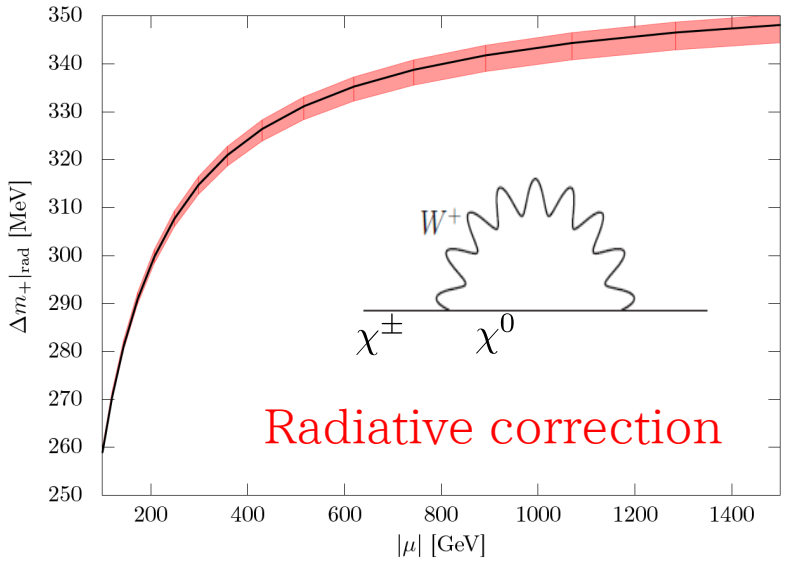
Higgsino is

- (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

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

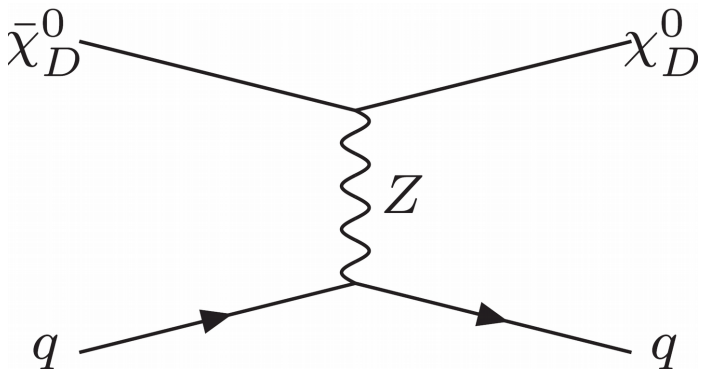
two Dirac Fermions



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

Pure Higgsino DM is Dead

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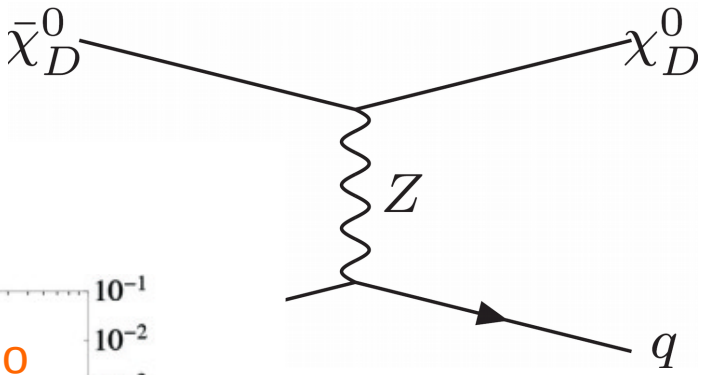
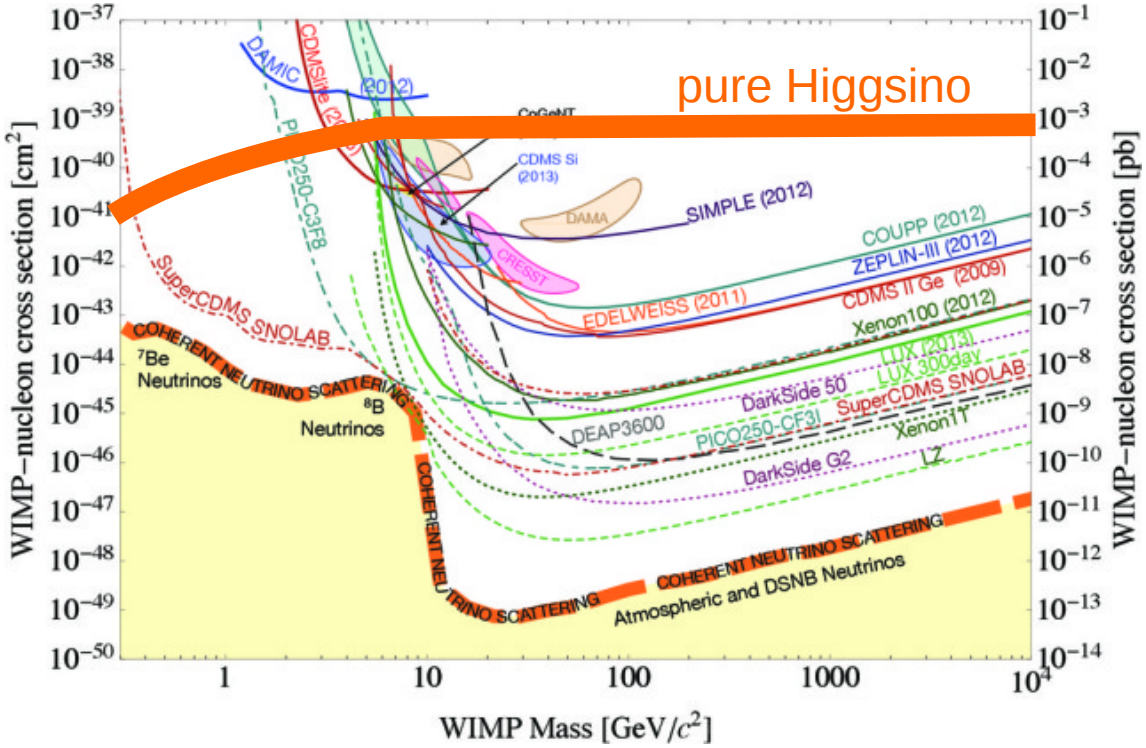
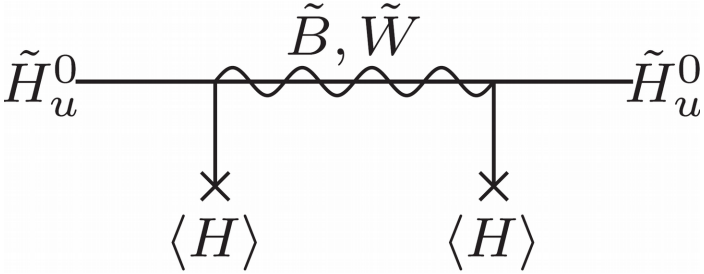




Higgsino Spectrum (with gaugino)



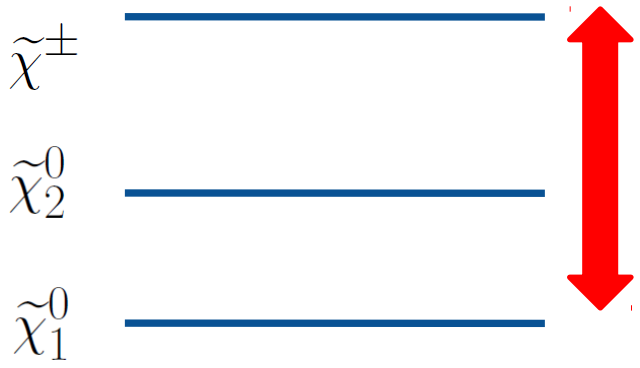
With Gauginos, fermion number is violated

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

Dirac fermion into two Majorana fermions

Higgsino Spectrum (with gaugino)

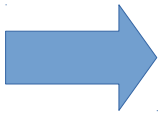
$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \quad \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$



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

Higgsino Spectrum (with gaugino)

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



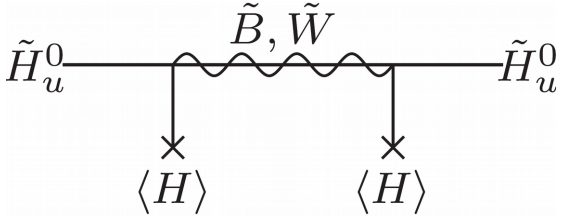
$$\bar{\chi}_1^0 \gamma^\mu \chi_2^0 Z_\mu$$

$$\bar{\chi}_1^0 \gamma^\mu \chi_1^0 Z_\mu = 0$$

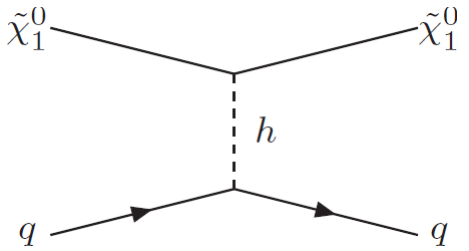
No SI elastic cross section via Z-boson

[N. Nagata & SS 2015]

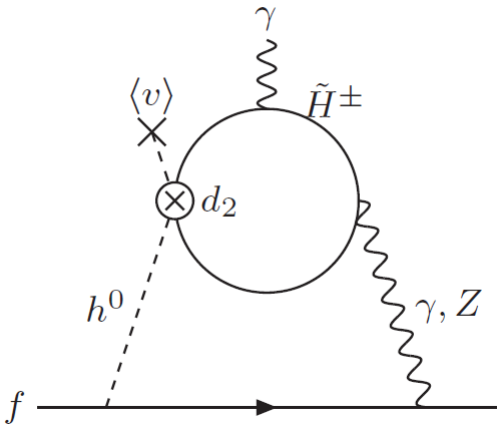
Gaugino induced Observables



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



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



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

Correlation

These observables are controlled by gaugino mass

Strong correlation among these observables

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

for large tanb

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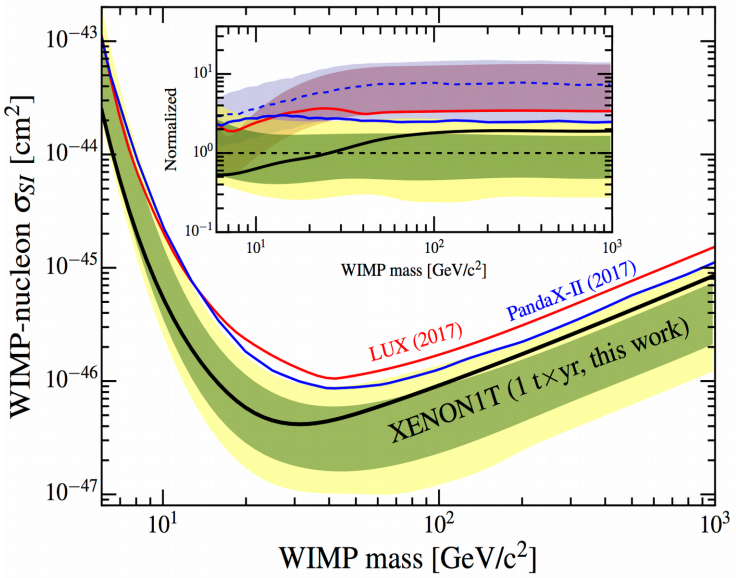
$$\sim 350\ {\rm MeV}$$

for large tanb

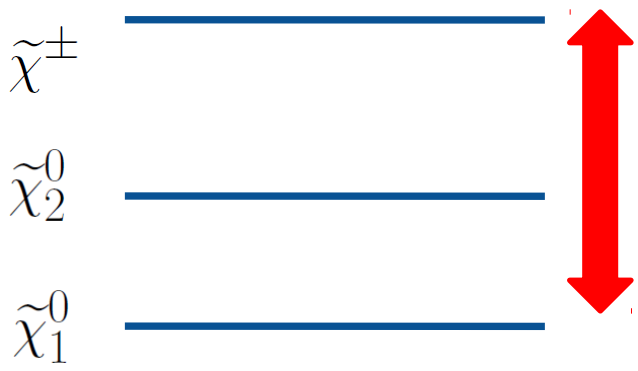
XENON1T constraint

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



Viable Higgsino Spectrum

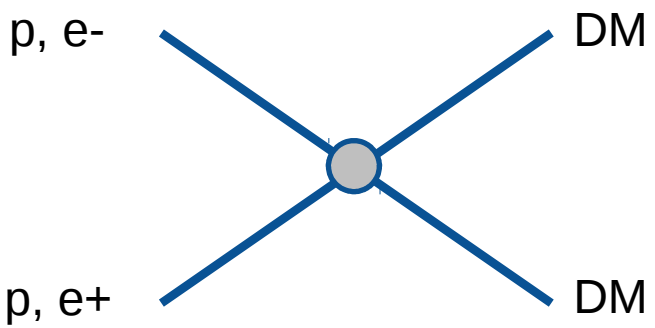
$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \quad \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$



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

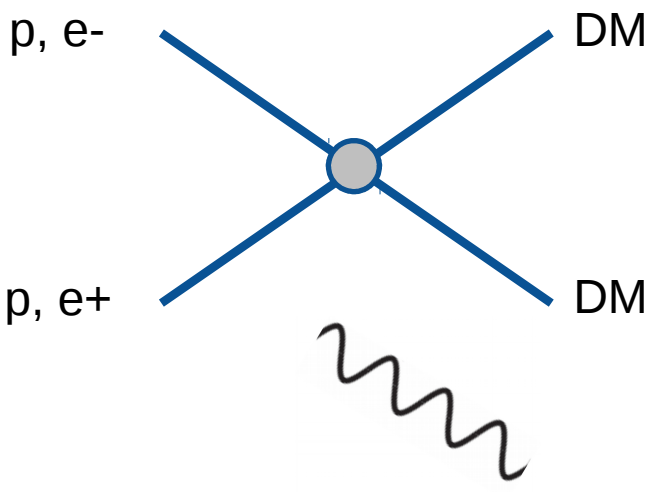
Current Status of Higgsino @LHC

Collider Signals of DM



DM is invisible

Collider Signals of DM



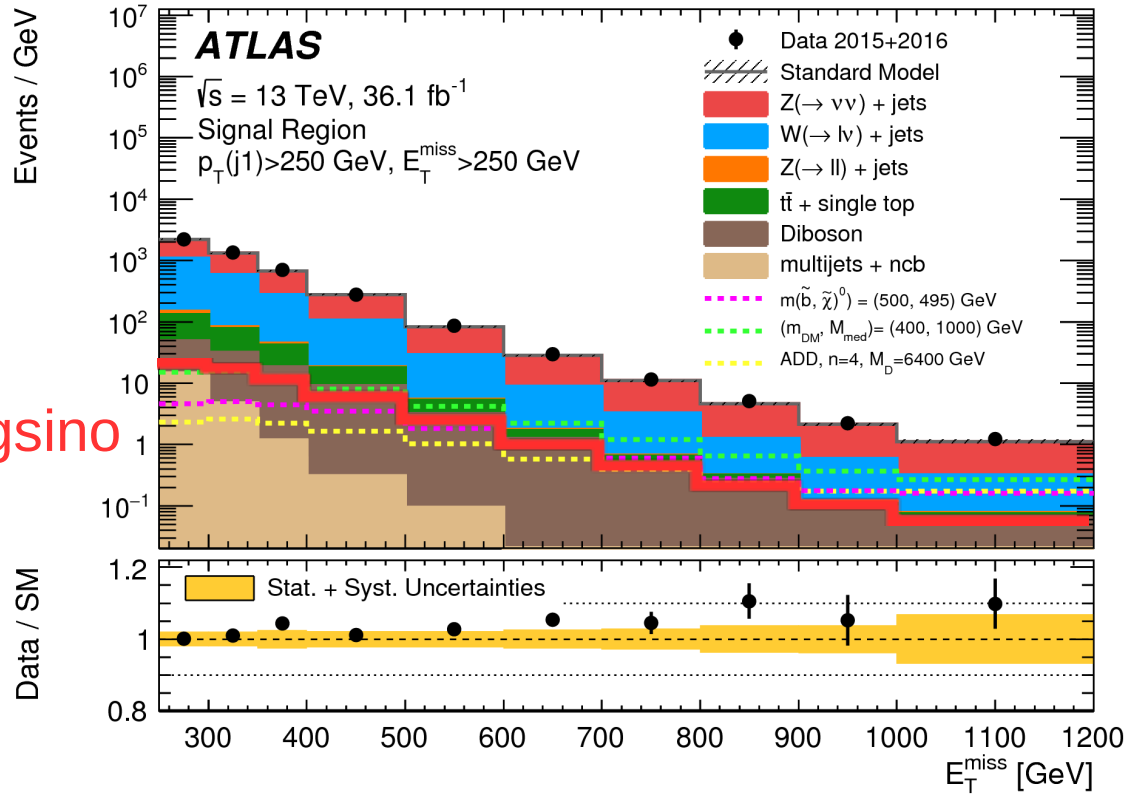
DM is invisible

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

gluon photon, …

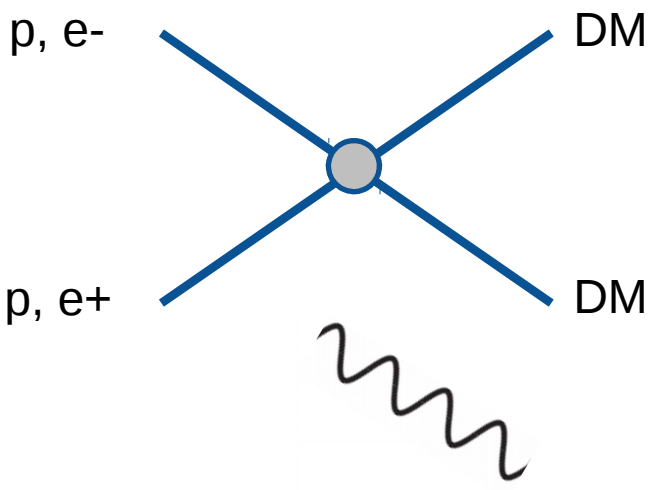
Mono-jet Signatures

100 GeV Higgsino



difficult to Higgsino signal

Collider Signals of DM



DM is invisible

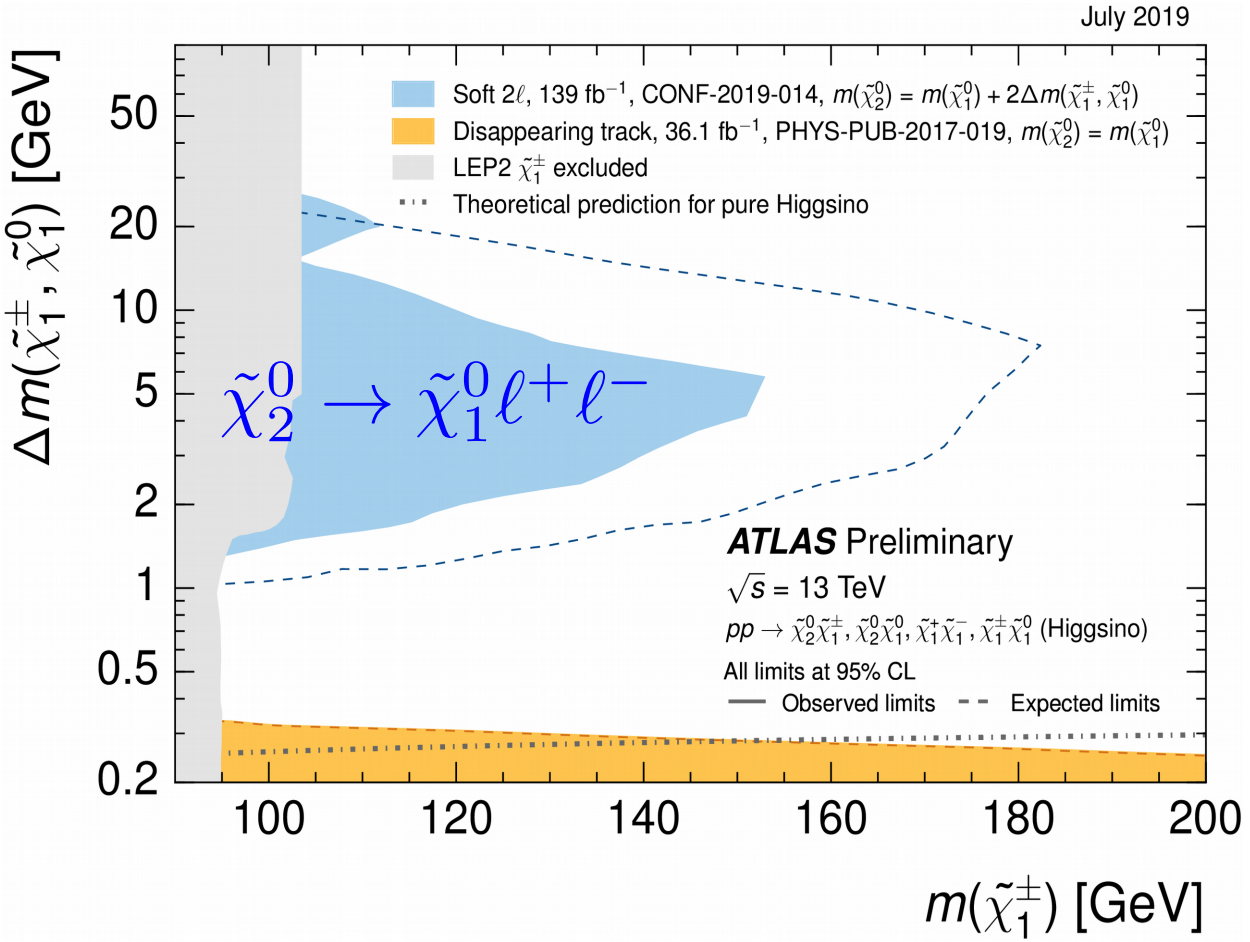
Additional objects are needed to see DM.
Missing energy (MET) search

gluon photon, …

New observable are needed for efficient BG reduction

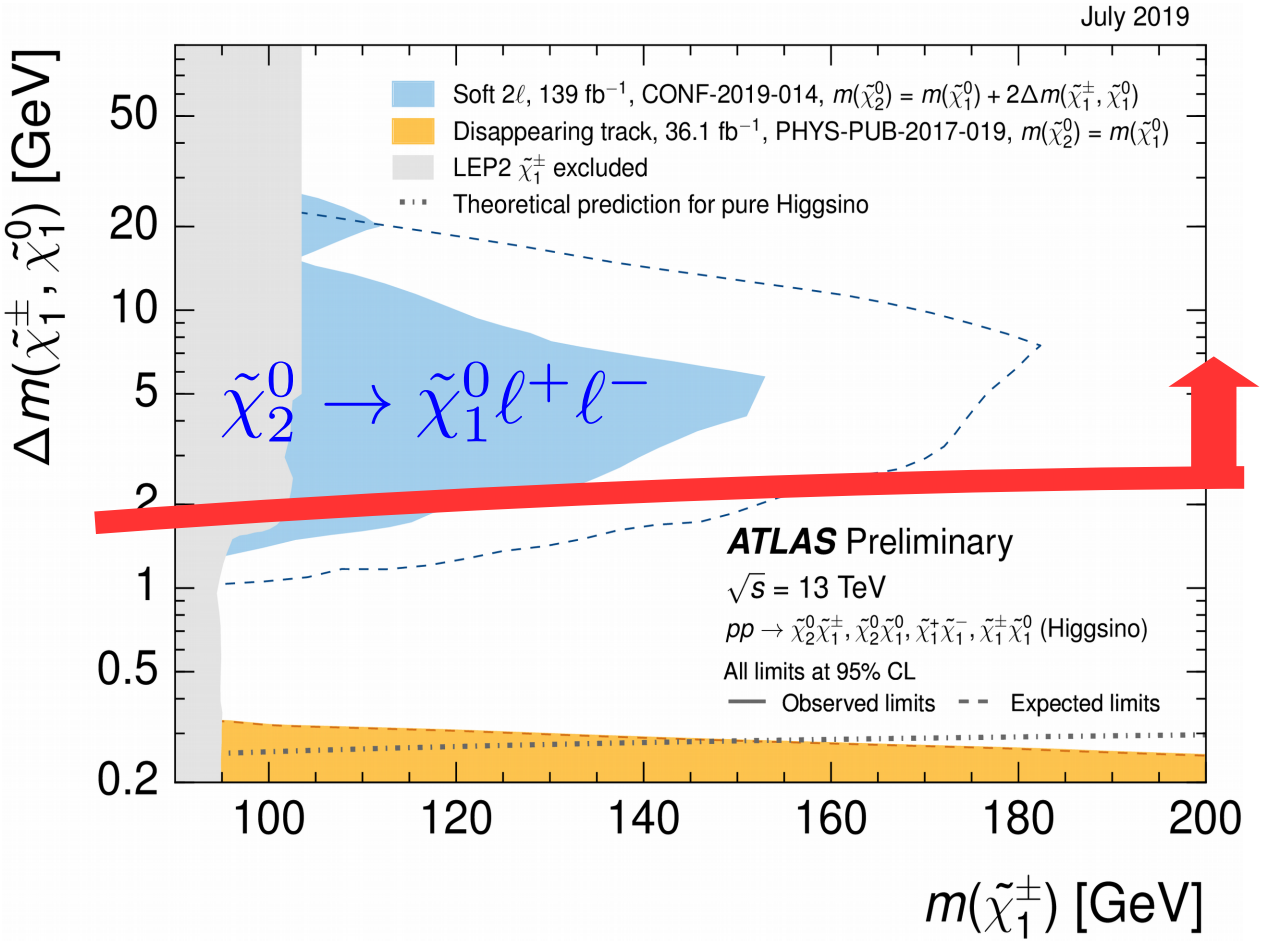
Decay of heavier Higgsino component

Current Constraint(higgsino)



disappearing track

Current Constraint(higgsino)

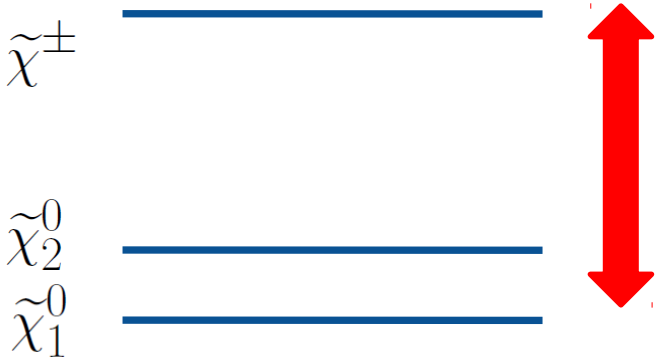


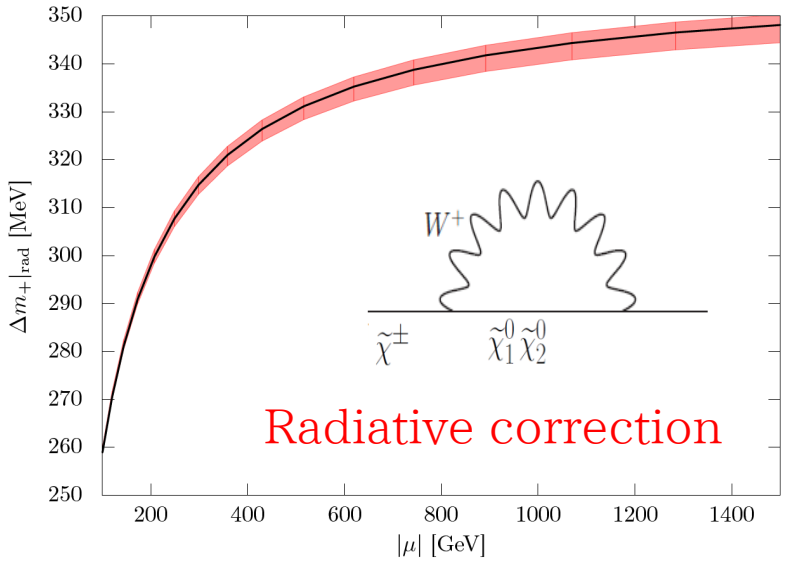
XENON1T

disappearing track

Almost Pure Higgsino Spectrum

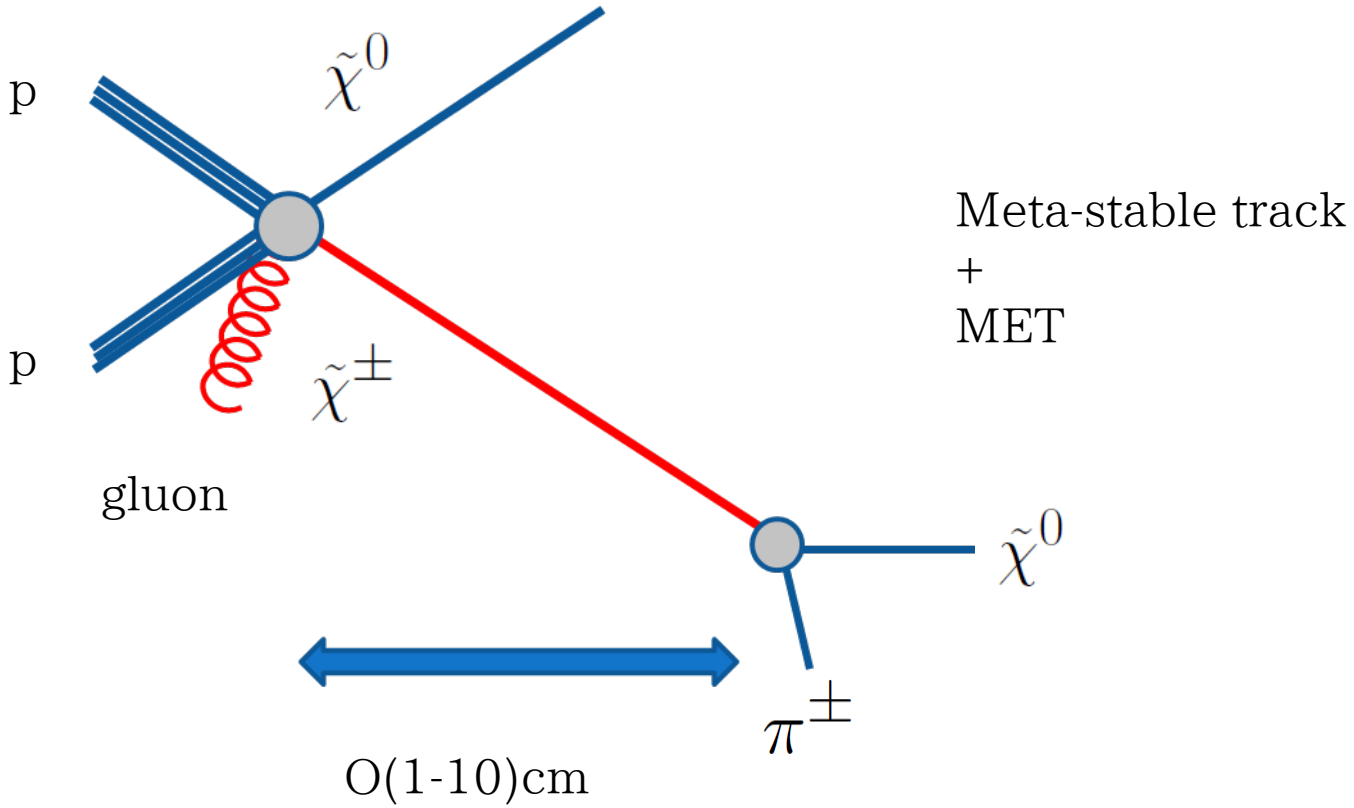
$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$



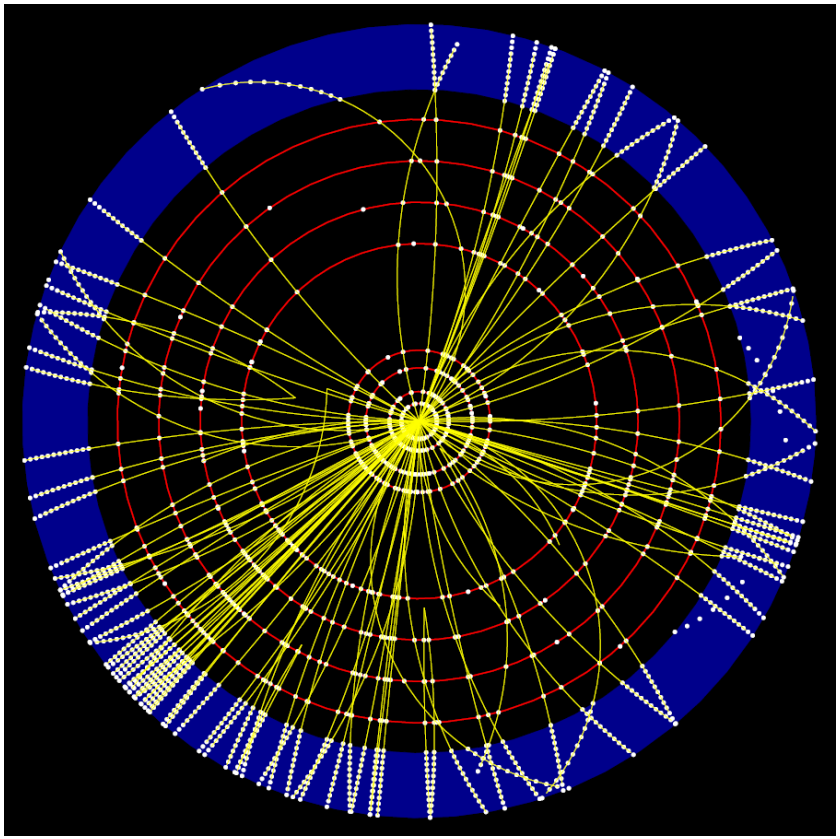


$$c\tau(\tilde{\chi}^\pm \to \tilde{\chi}^0 \pi^\pm) = 1.1 \text{ cm} \left(\frac{\Delta m_+}{300 \text{ MeV}}\right)^{-3} \left[1 - \frac{m_{\pi^\pm}^2}{\Delta m_+^2}\right]^{-1/2}$$

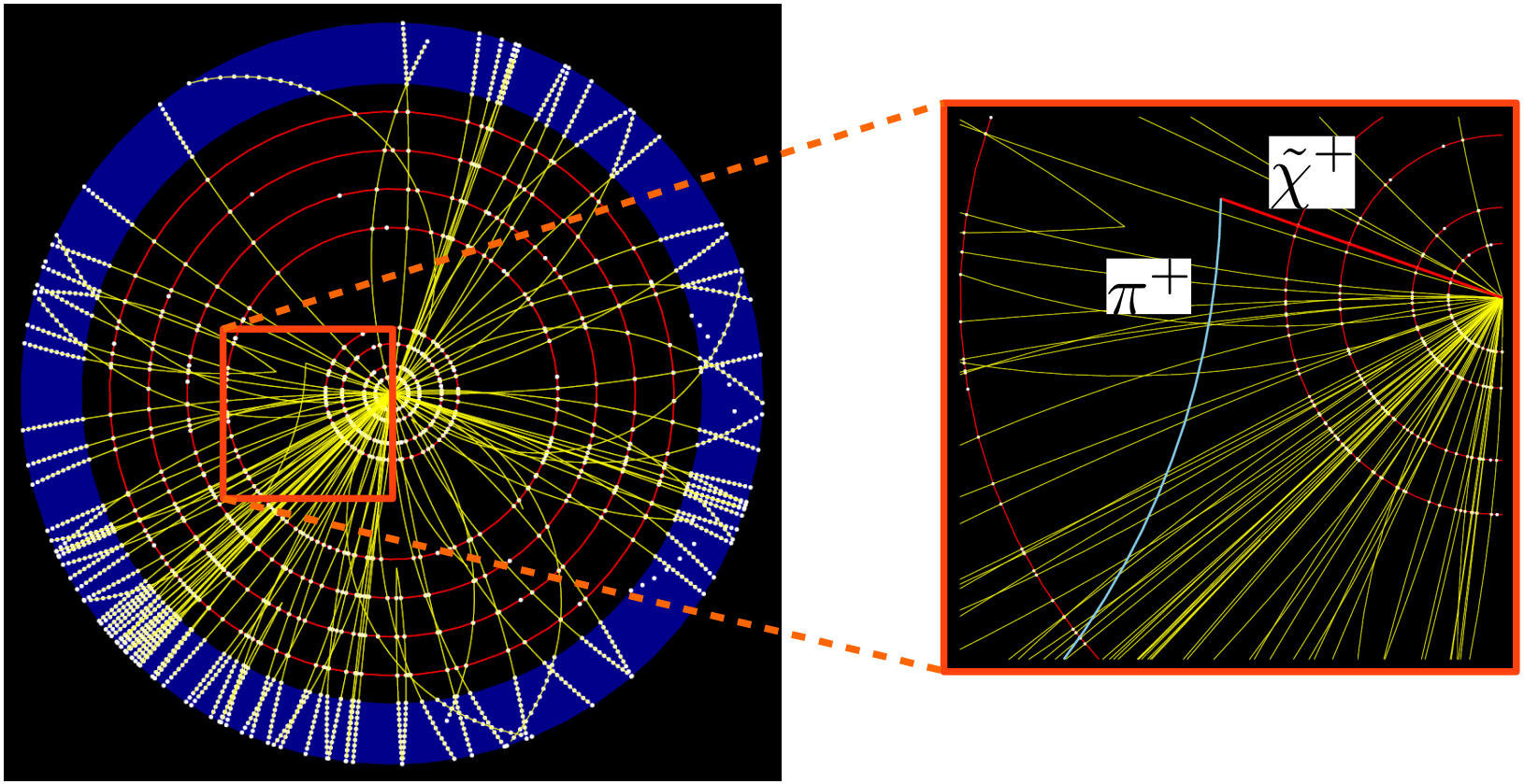
LHC Signals


p
p
$\tilde{\chi}^0$
$\tilde{\chi}^{\pm}$
gluon
$\tilde{\chi}^0$
$\pi^{\pm}$
O(1-10)cm
Meta-stable track
+
MET

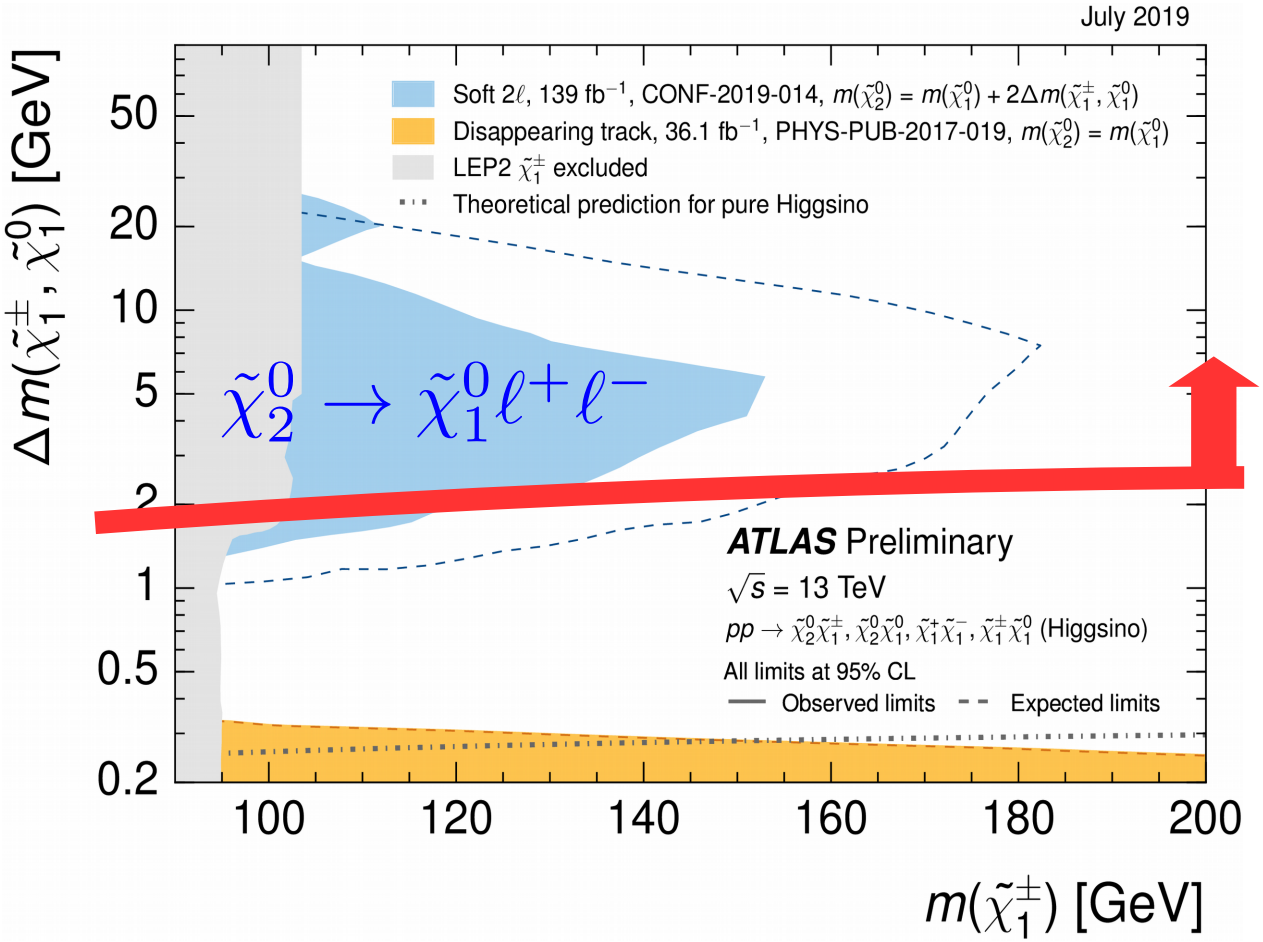
Event Display



Event Display



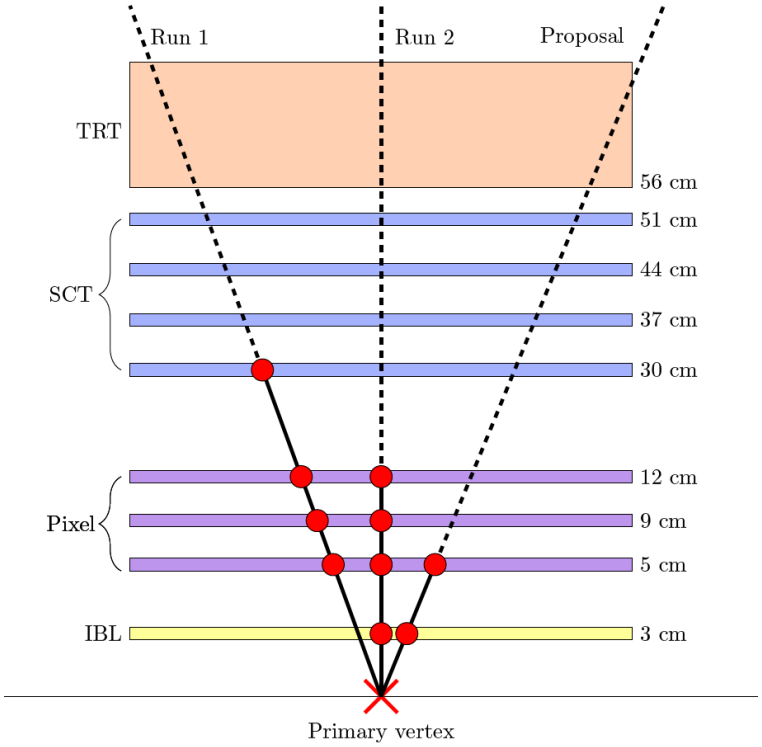
Current Constraint(higgsino)

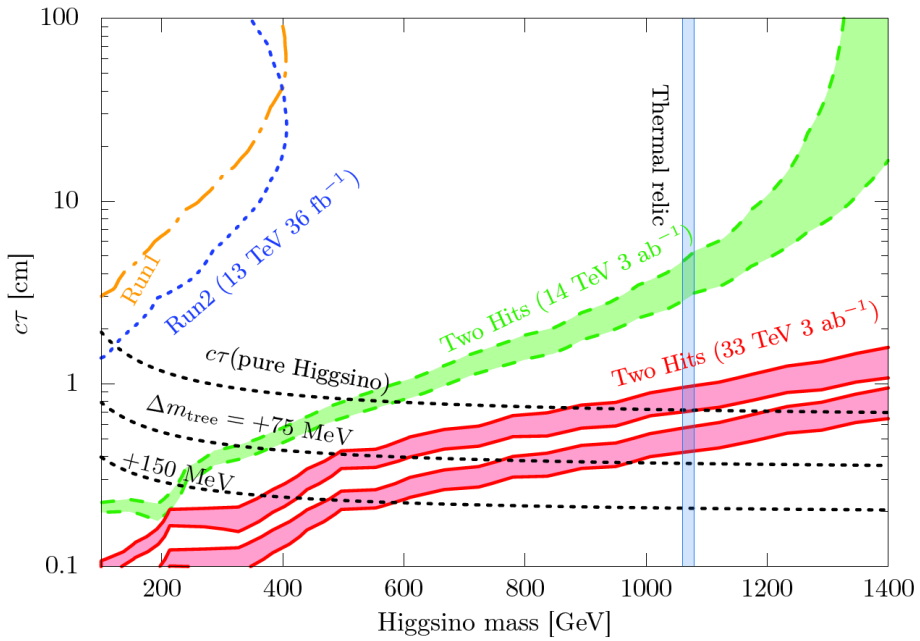


XENON1T

disappearing track

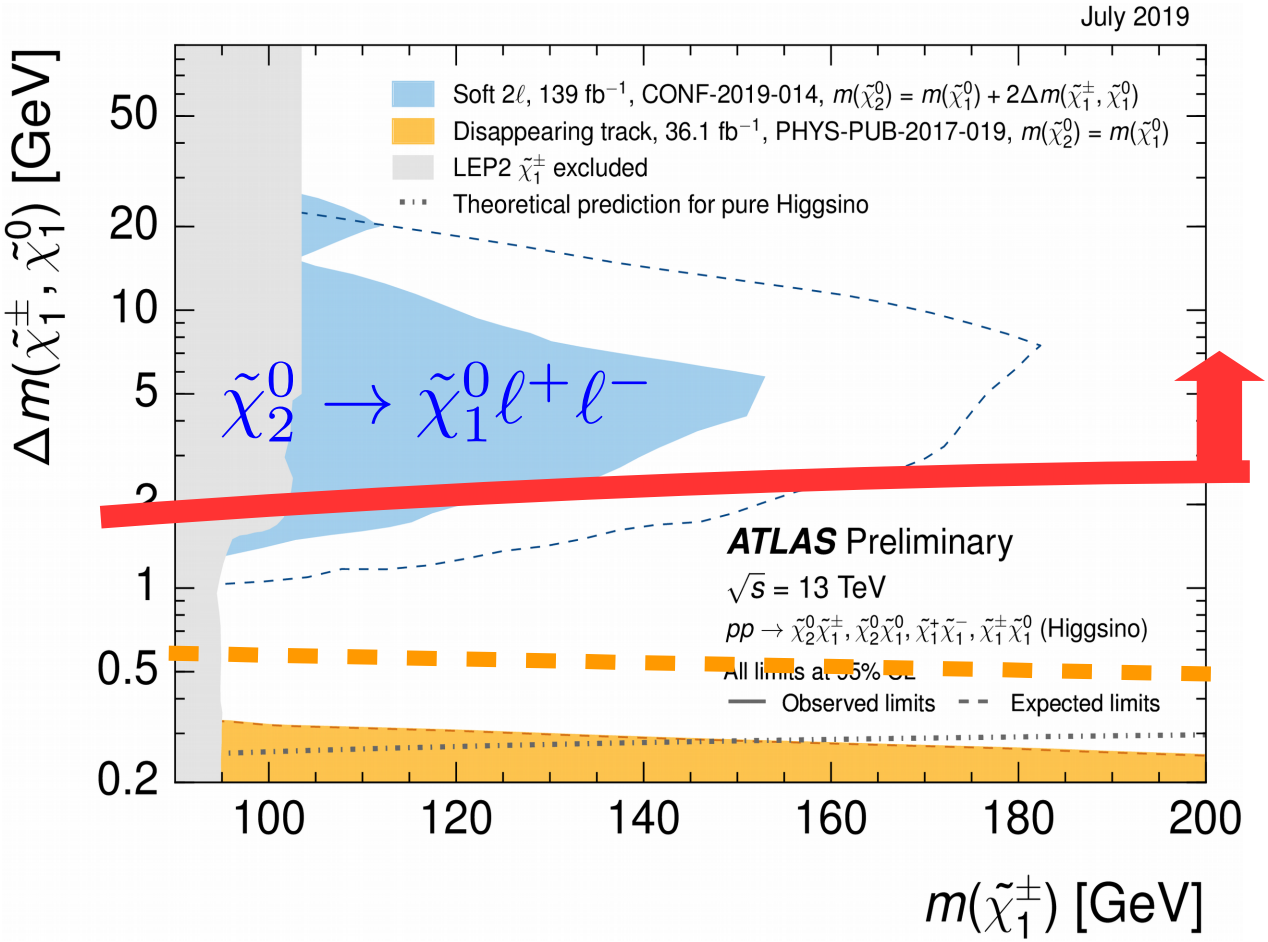
Improving Track Reconstruction





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

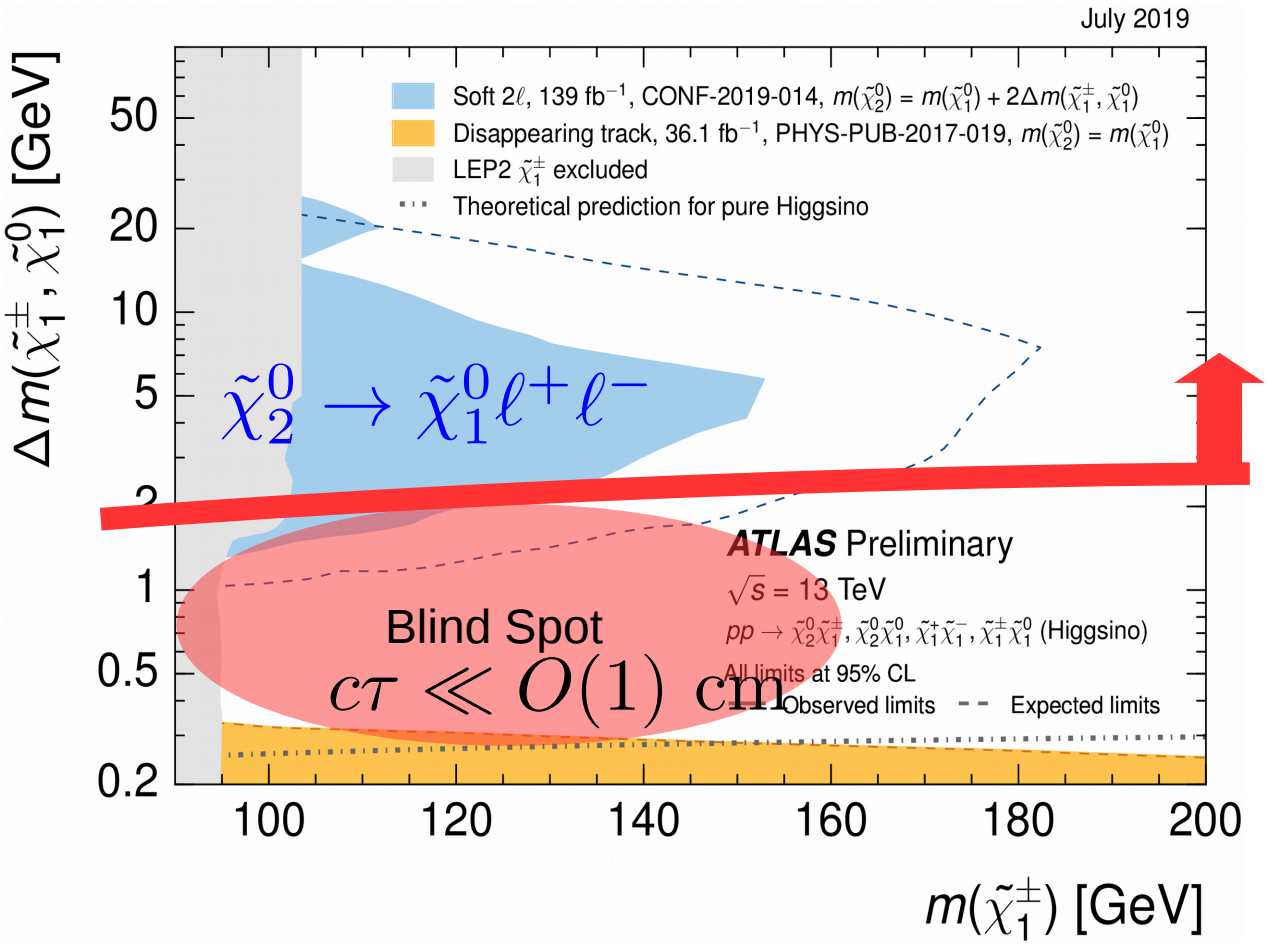
Current Constraint(higgsino)



XENON1T

disappearing track

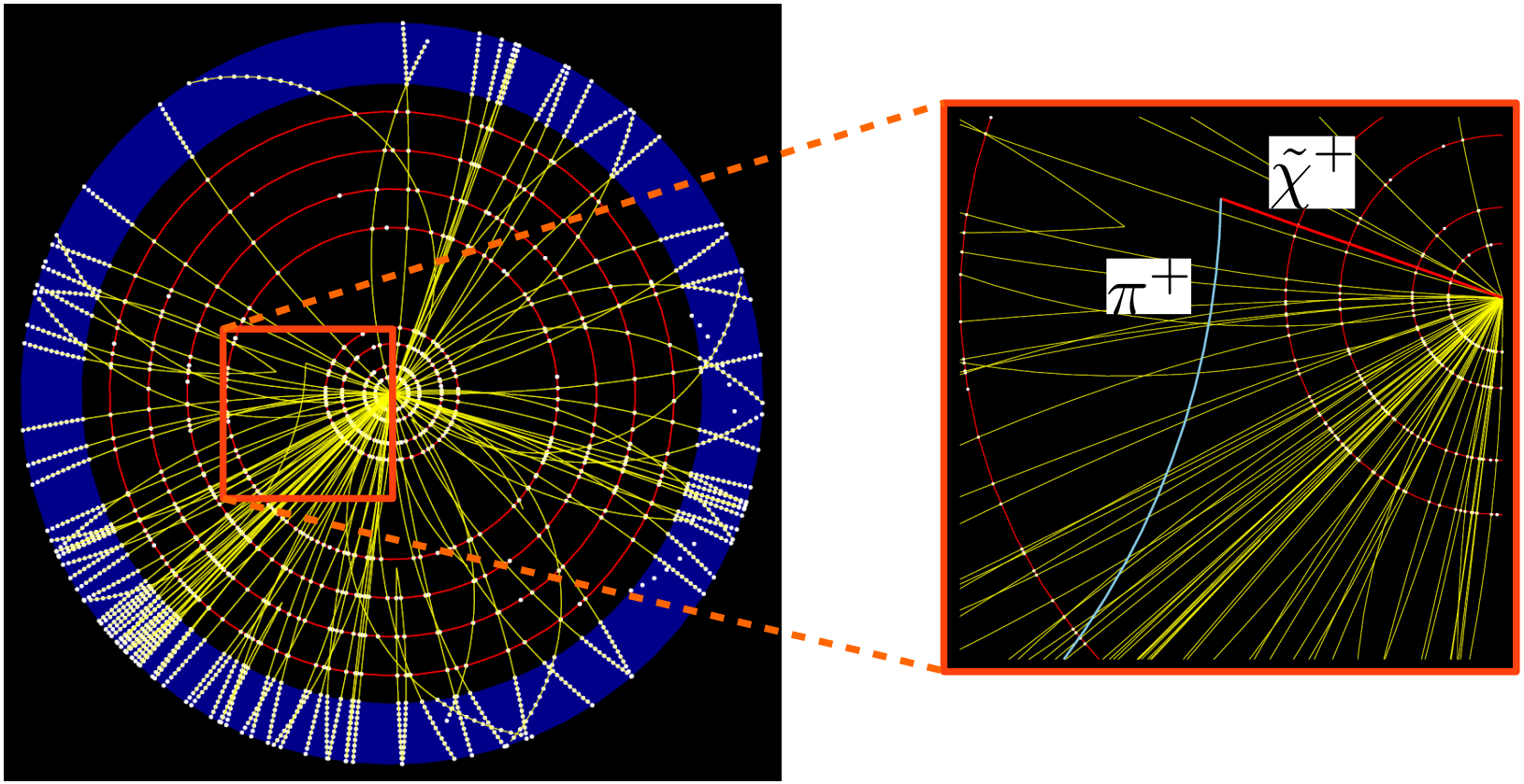
Current Constraint(higgsino)



XENON1T

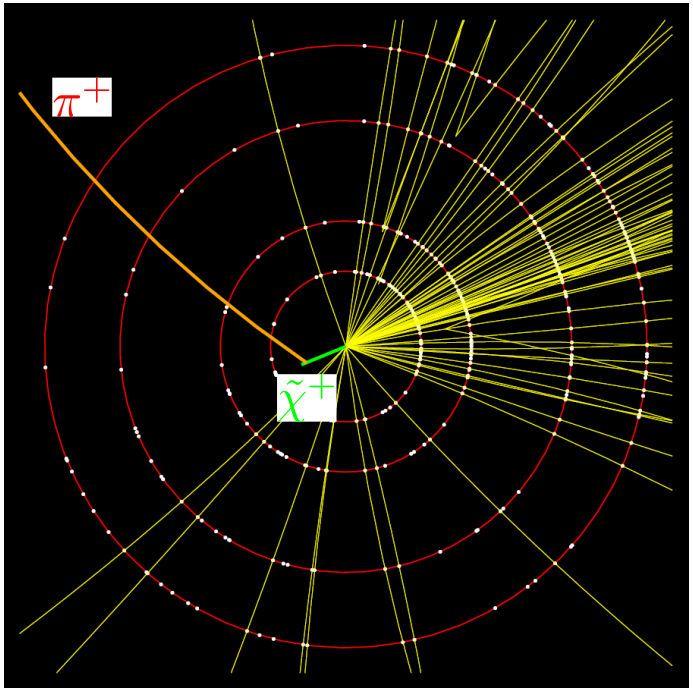
disappearing track

Event Display

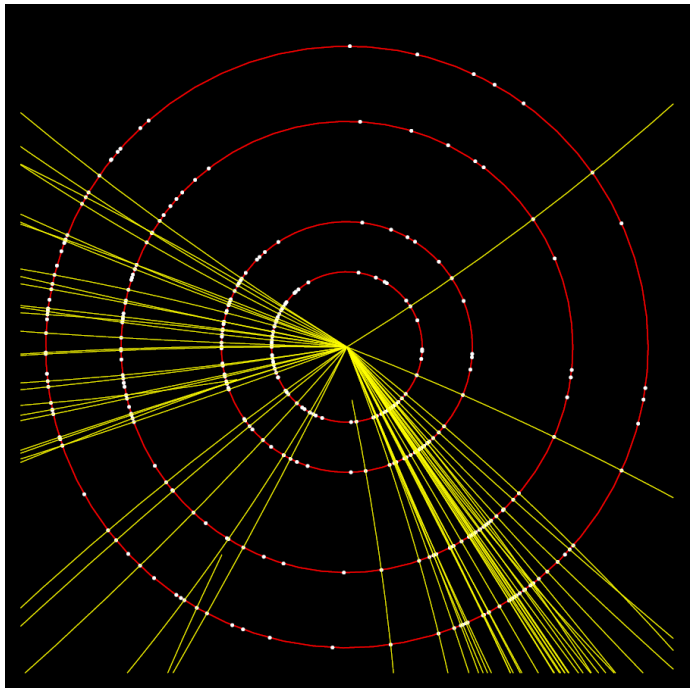


Use Soft Track

Event Display

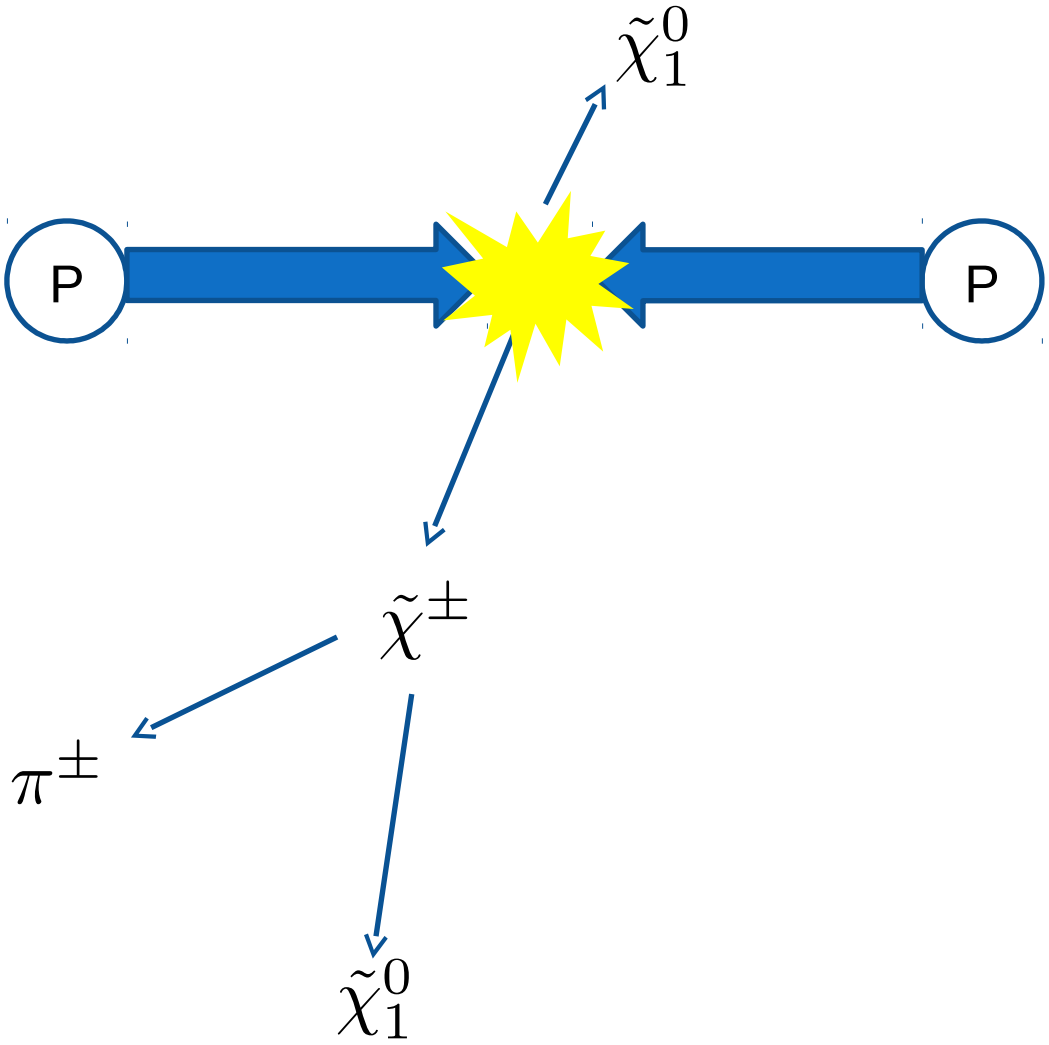


Signal

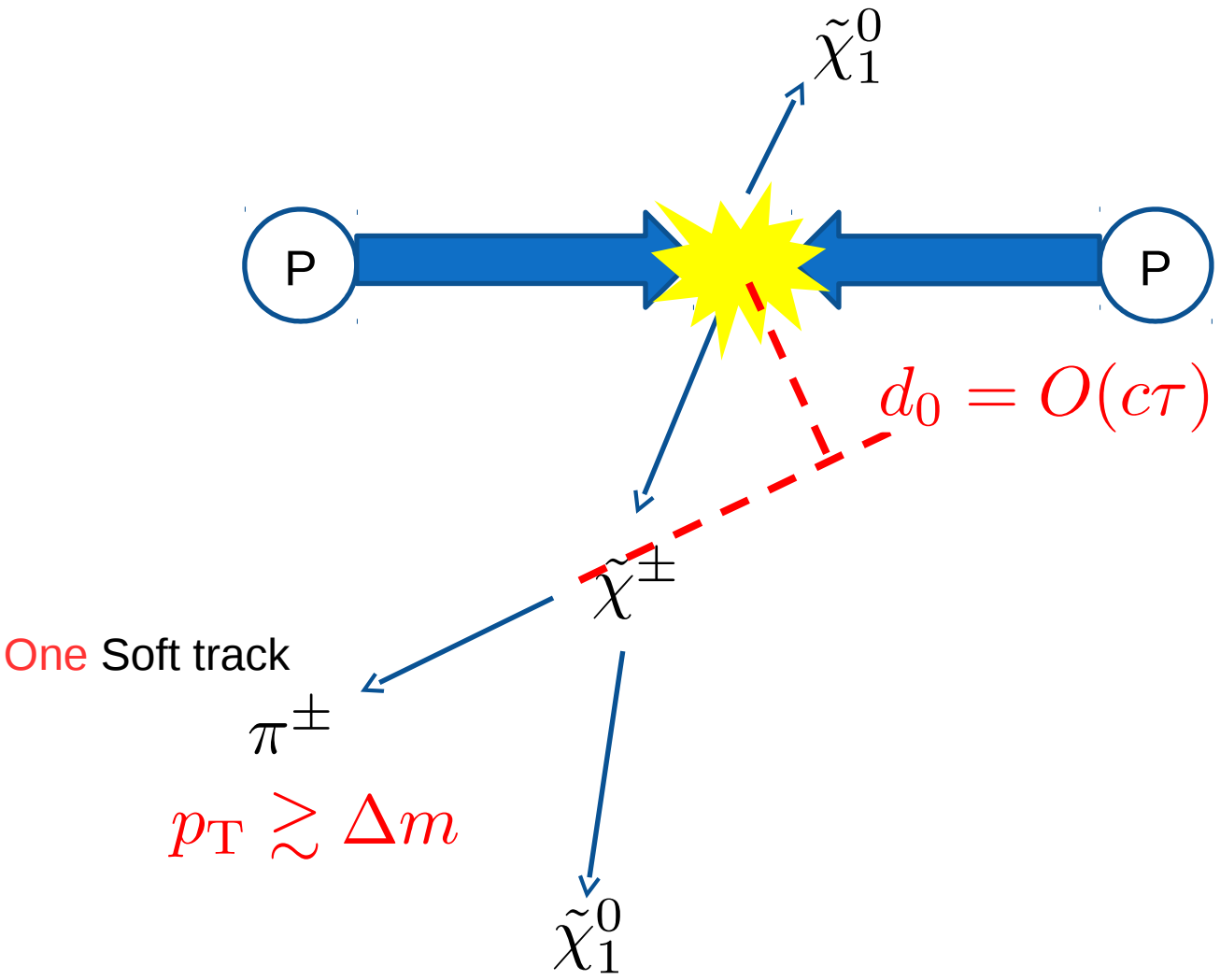


BG (Z > νν)

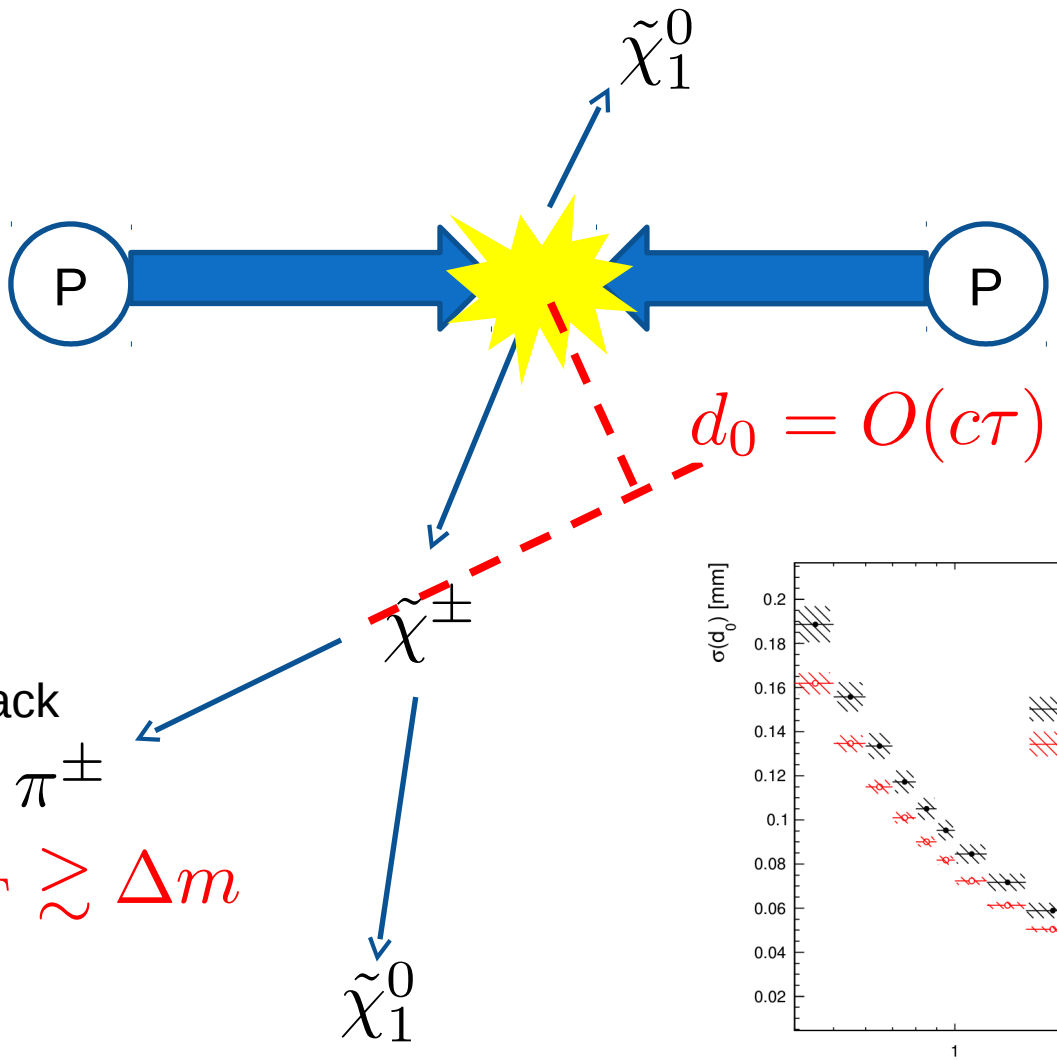
Signal



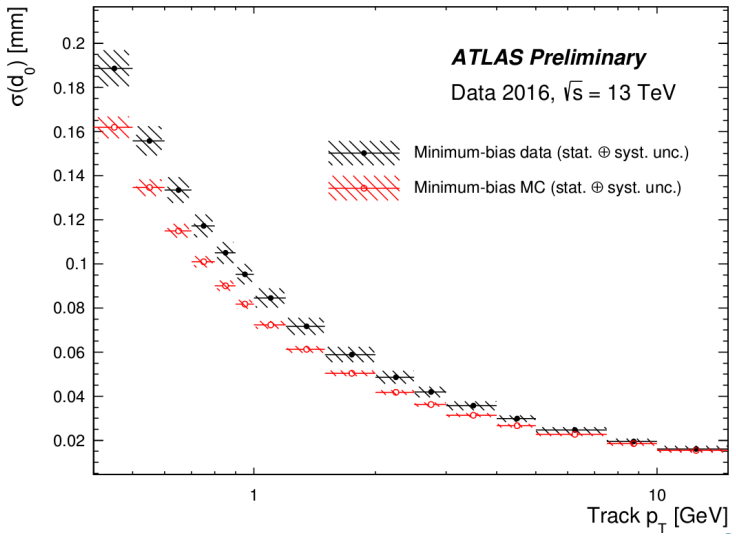
Signal


$\tilde{\chi}_1^0$
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



d0 resolution



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

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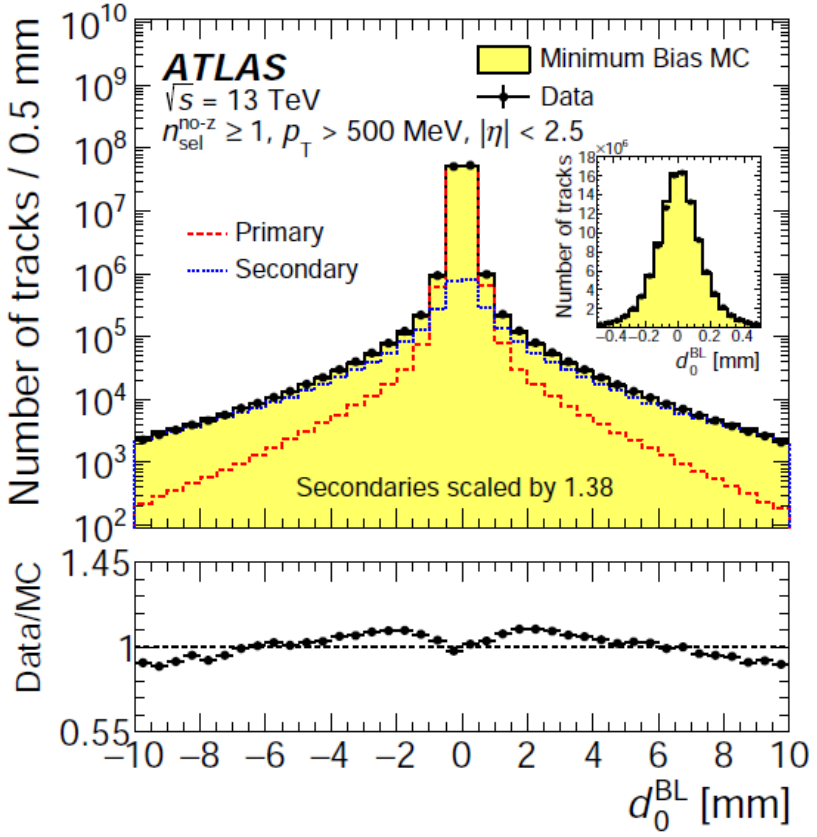
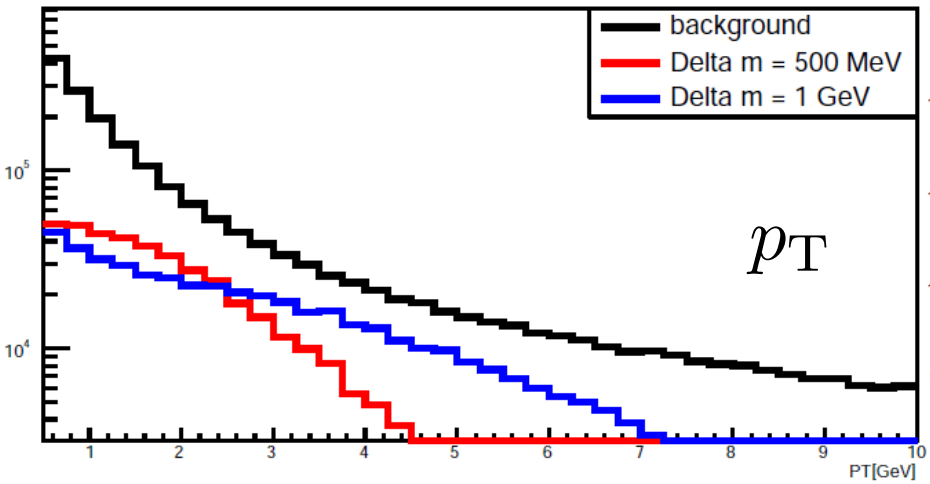
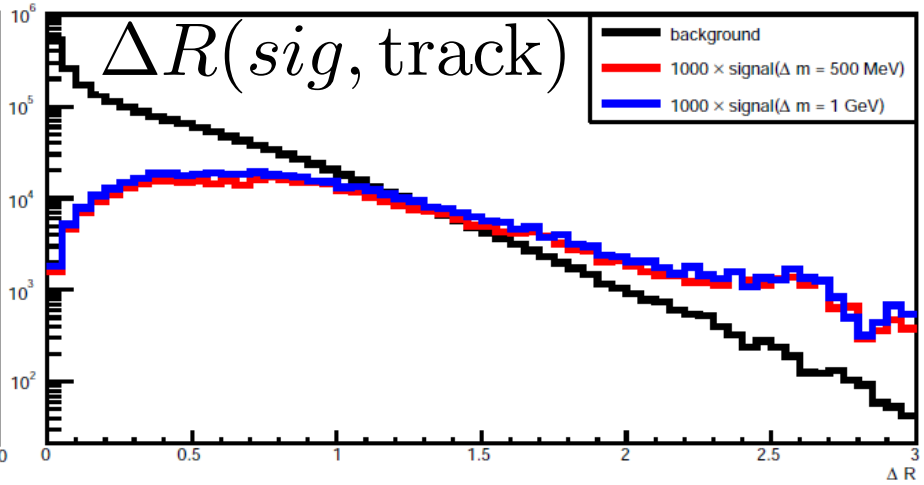
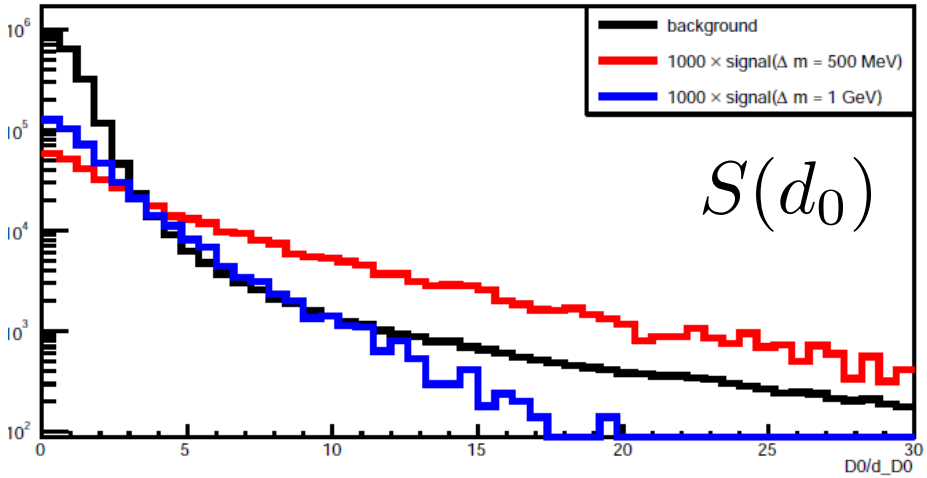


Background vs Signal





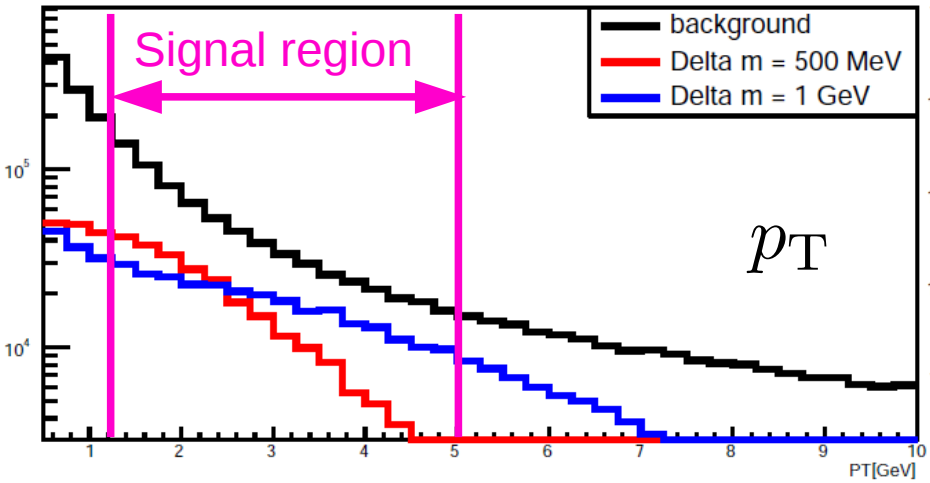


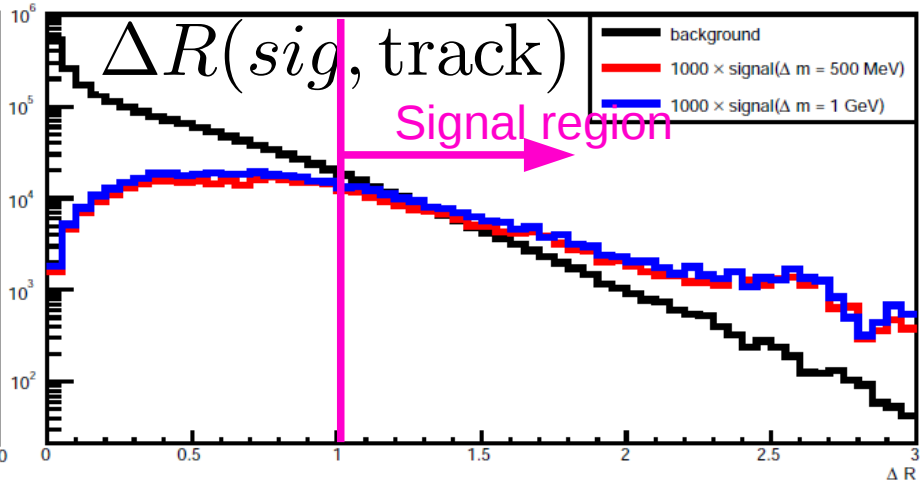
Signal: 150 GeV Higgsino

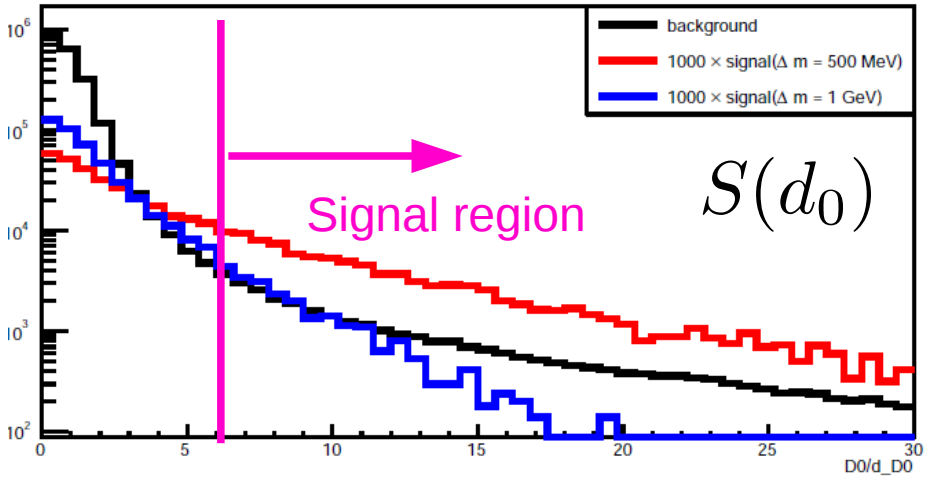
Delta m = 500 MeV: red line
ctau = 2 mm

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

Background vs Signal







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Event Selection

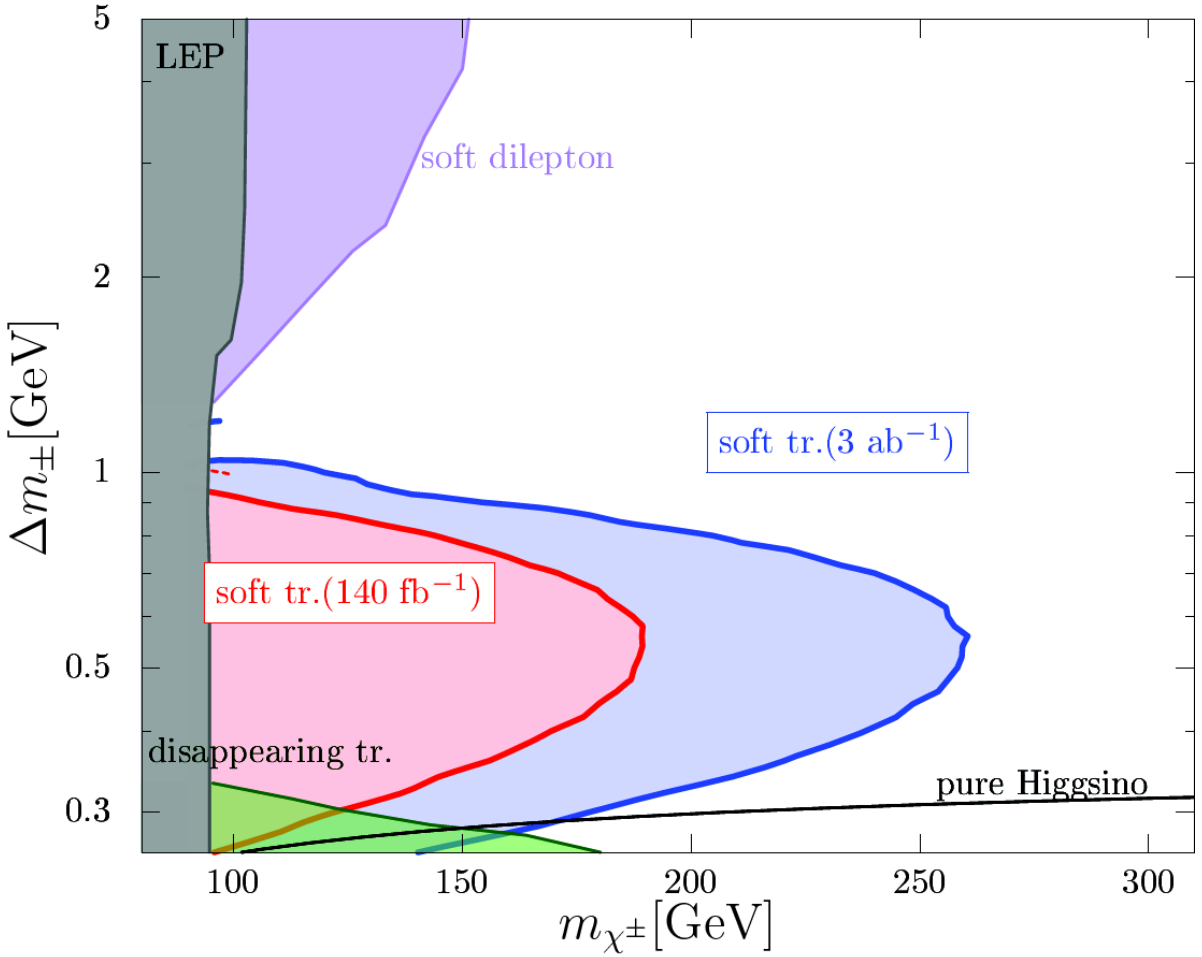
"Mono-jet event" with MET>500 GeV and Signal track satisfying

- 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

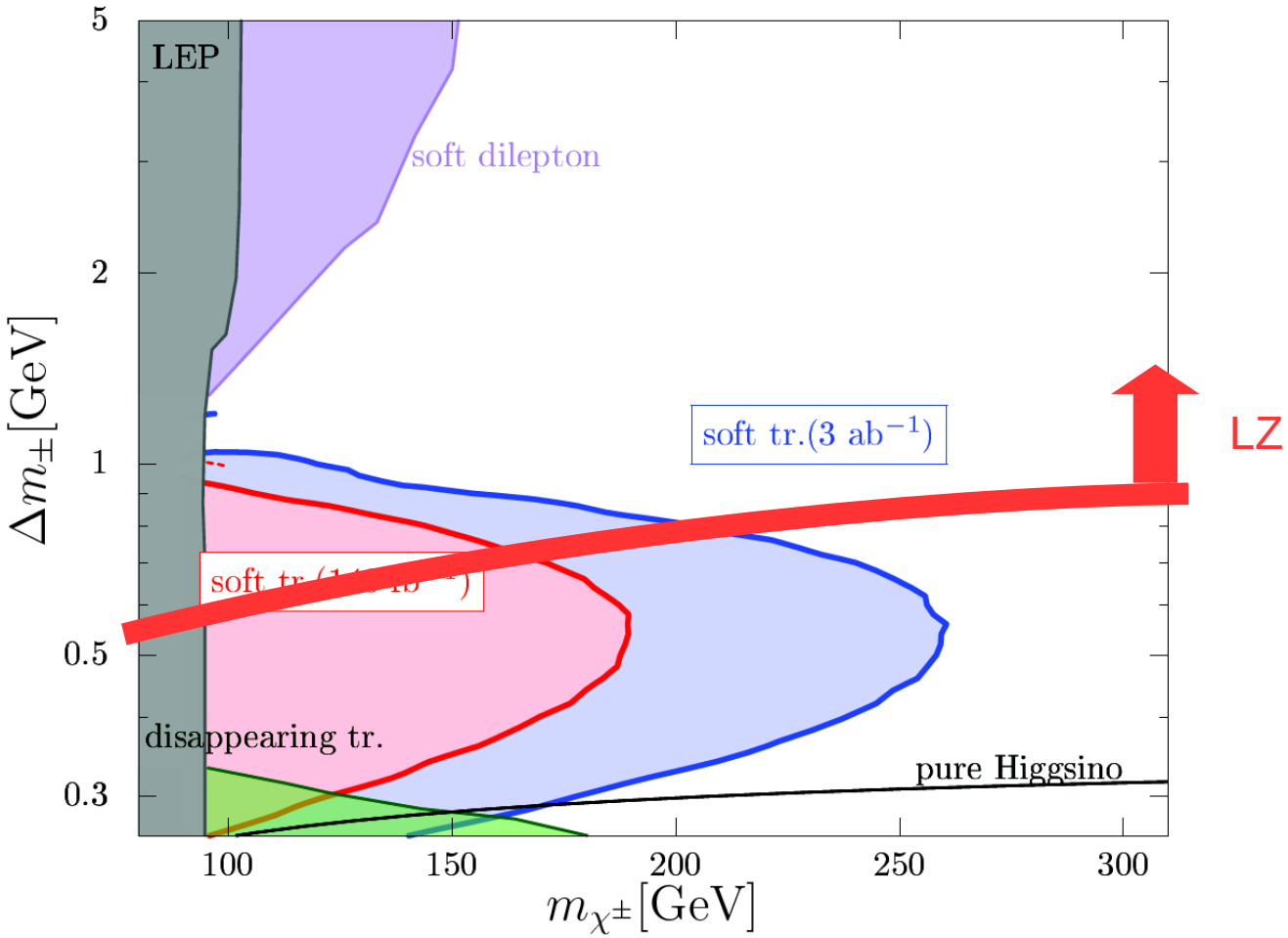
[H. Fukuda, N. Nagata, H. Oide, H. Otono, && SS, 2019]



Run2 # of BG ~ 250.

Result

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



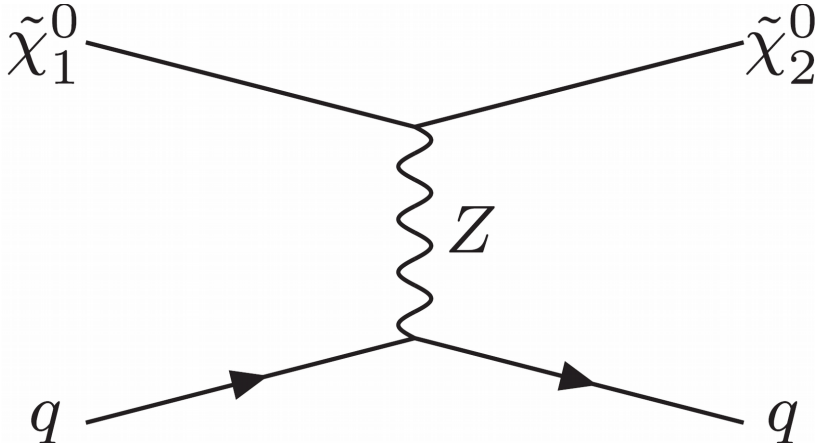
Run2 # of BG ~ 250.

Summary

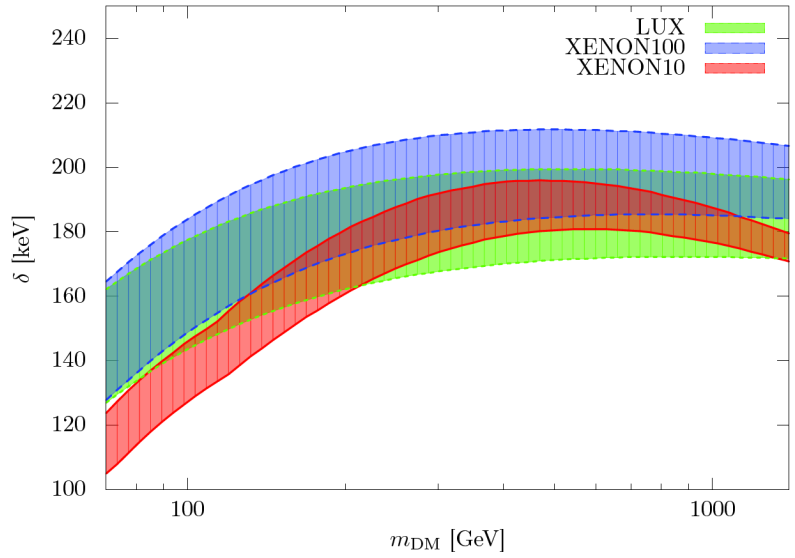
- Compressed Higgsino has phenomenological importance

- Higgsino DM likely provide meta-stable particles
  - Complementray to DM direct detecion
  - Disappering track
  - Soft tracks
    - Can fill “Delta M” gap region
- Application to other BSM models:
  Slepton coannihilation, minimal DM, wino.

Inelastic Scattering



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

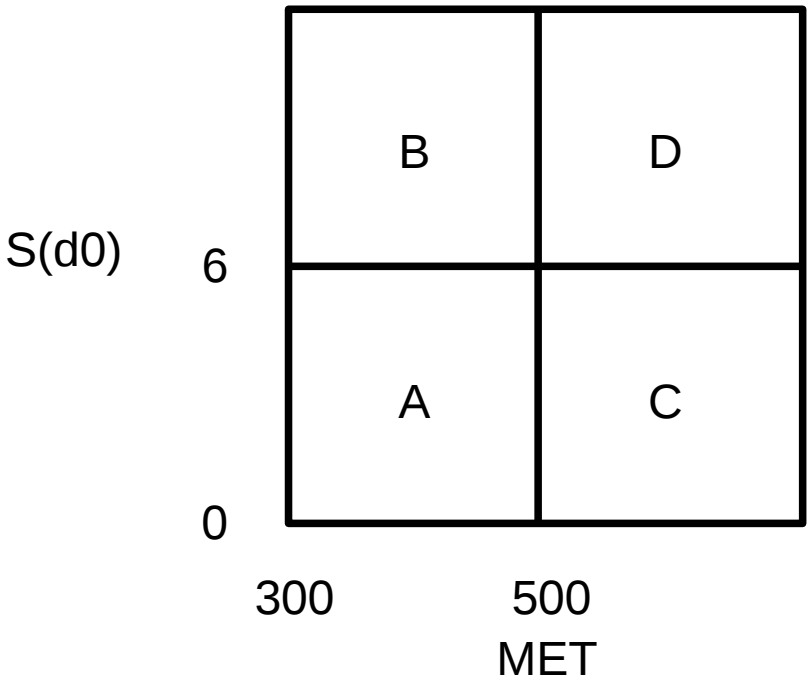


Mass difference < O(100) keV is excluded

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

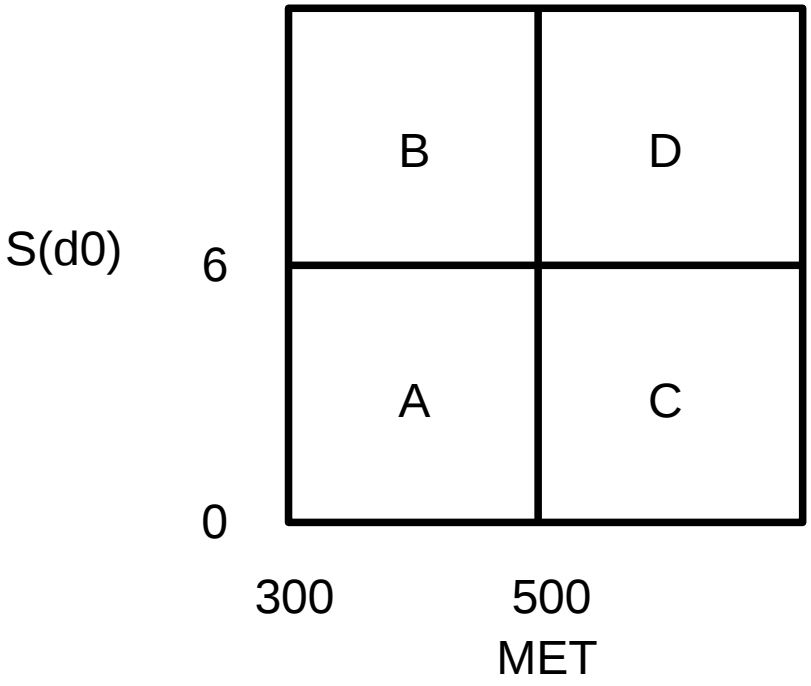
By using observed data for A, B ,C
we can estimate # of signal region D

$D = B \times C / A$

ABCD Method

In reality, we need data drive background estimation.

Acceptance rate of Signal track is almost independent on MET.



Mock data

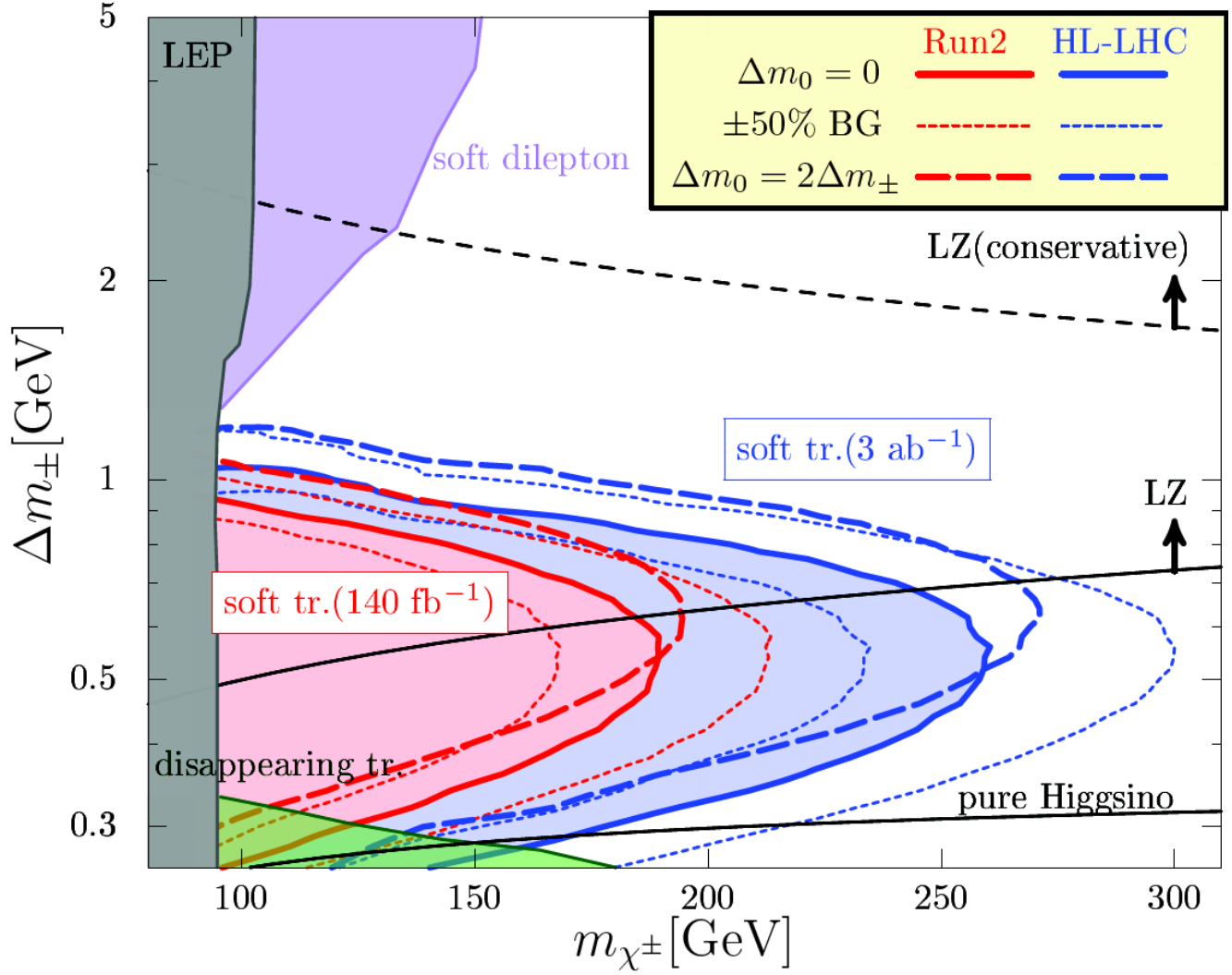
Pythia8 Run2
A: 103302
B: 2574
C: 10691
D: 261

Estimation by ABCD method:

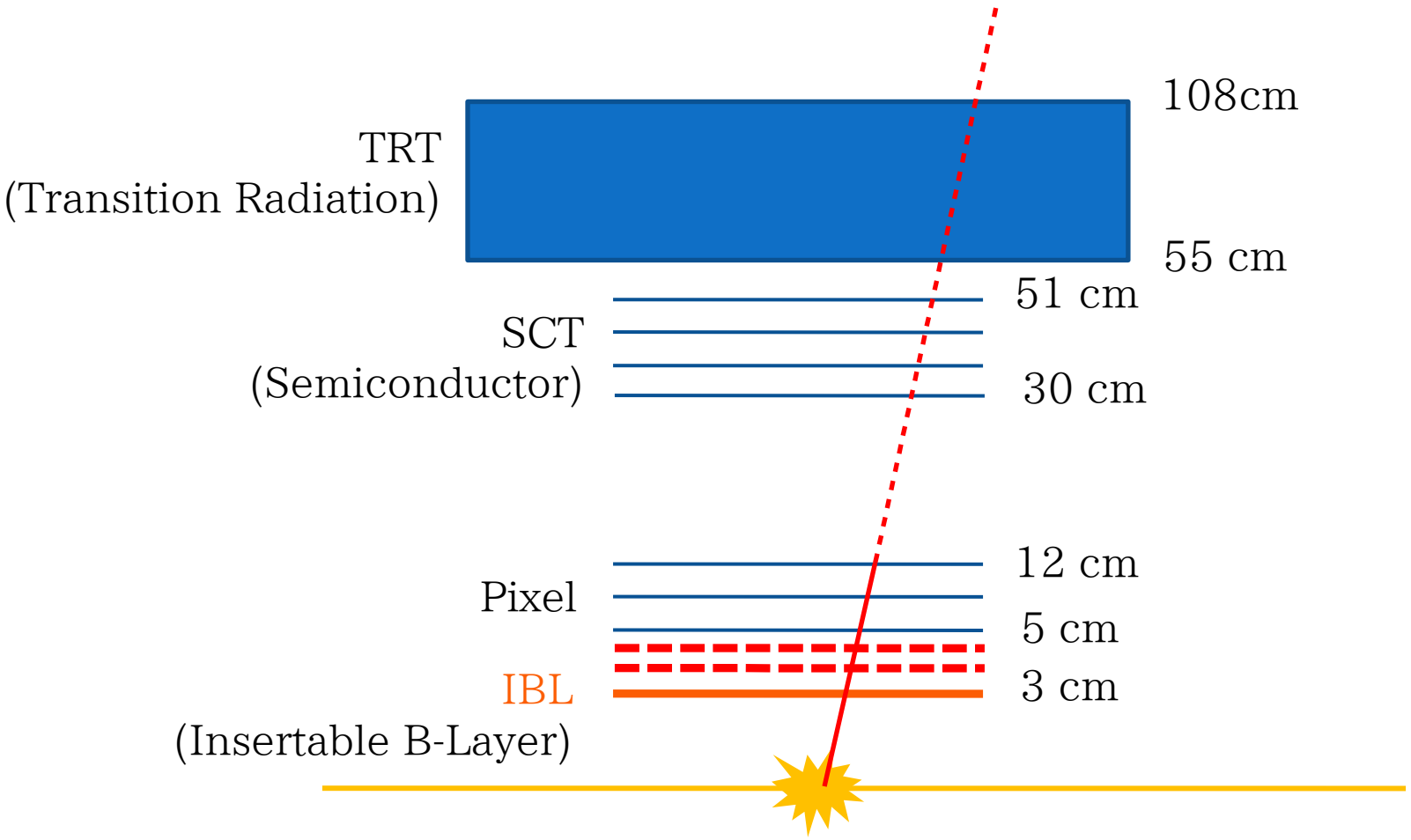
D = B x C / A
= 266 +-6

BG systematic error ~3%.

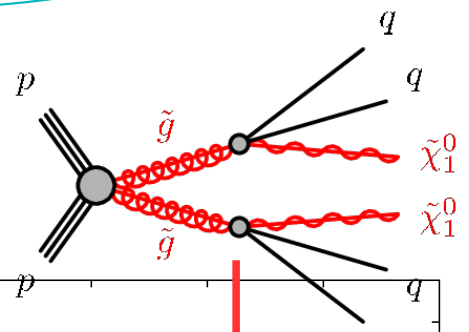
Full Result


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

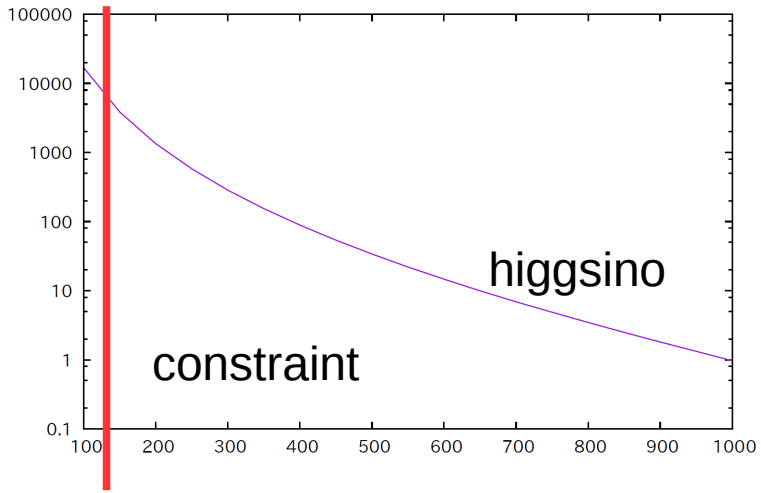
Tracker for Run???

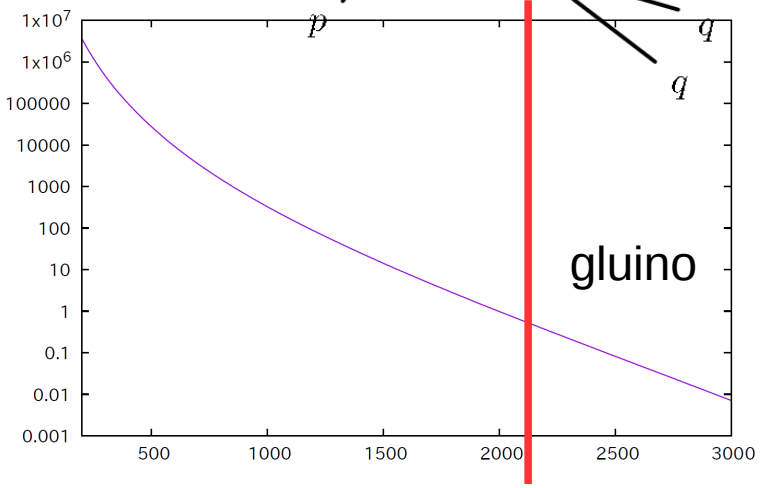


WIMP is hard target



cross section [fb]





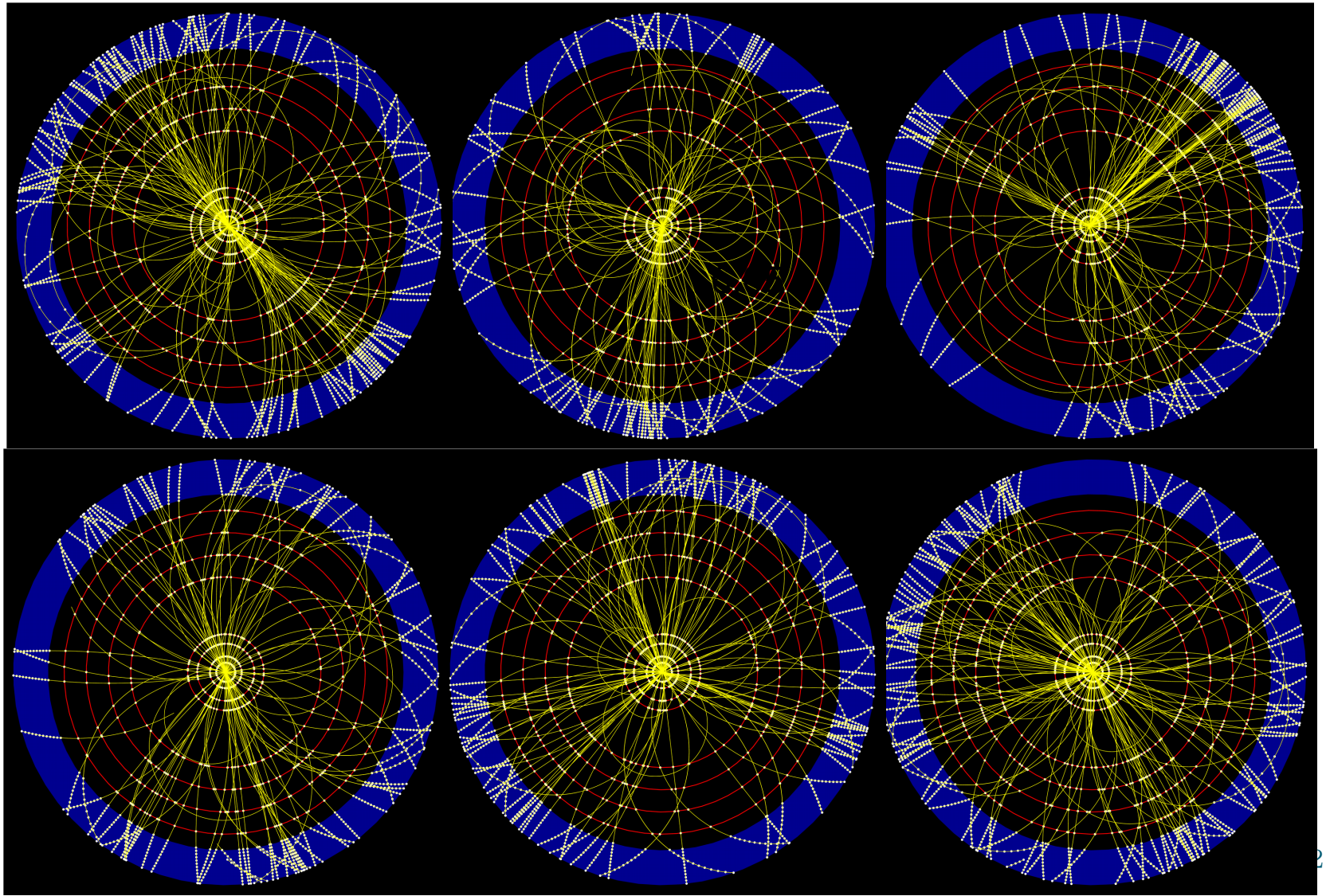
mass [GeV]

O(10^5) particle production

O(10) particle production

Efficient BG reduction and/or new observable are needed

Which is DM signature?



Which is DM signature?

DM signal