WIMP Dark Matter at Collider

Satoshi Shirai (Kavli IPMU)

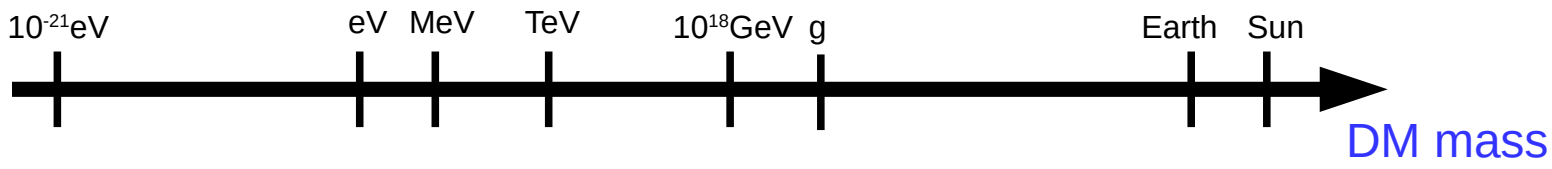
DM Should be...

- Stable.
- Weakly Interacting.
- Cold.
- Production mechanism.

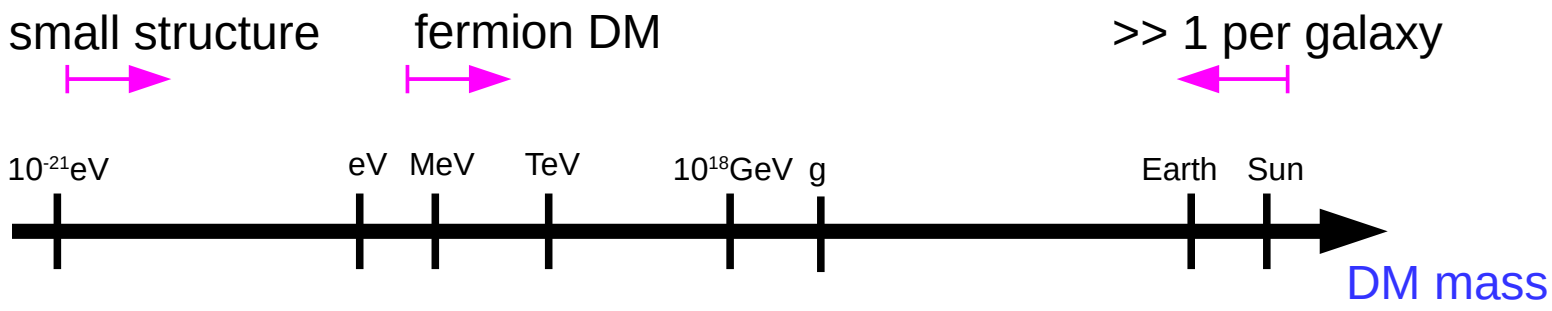
  20% of total energy of Universe

$$\Omega_{\mathrm{DM}} \sim 0.2$$

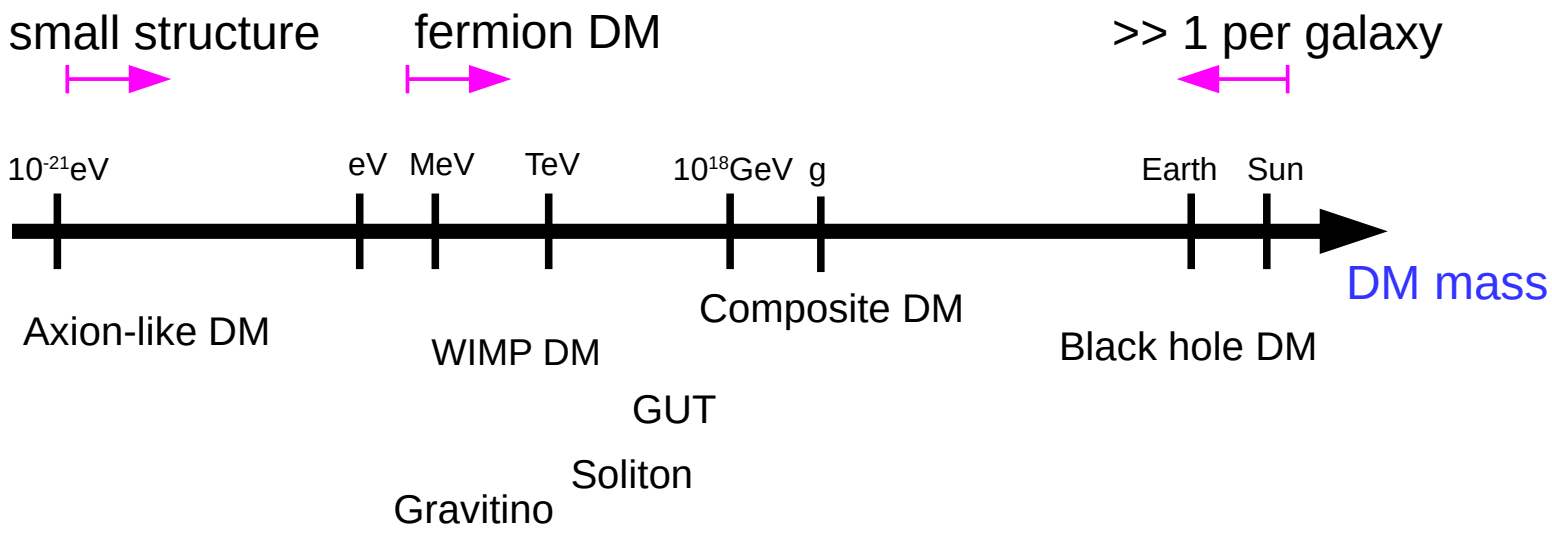
DM Landscape



DM Landscape



DM Landscape



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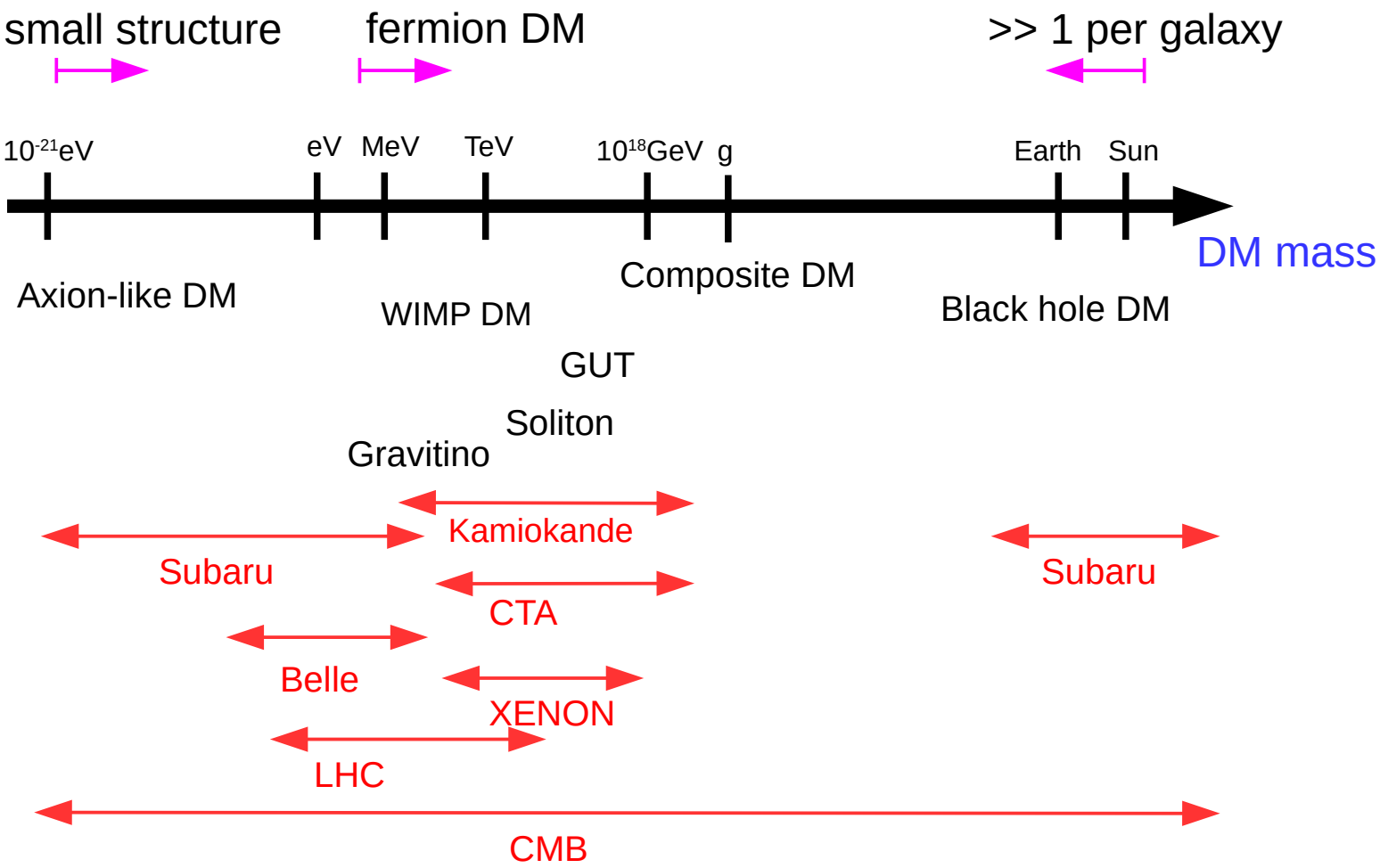

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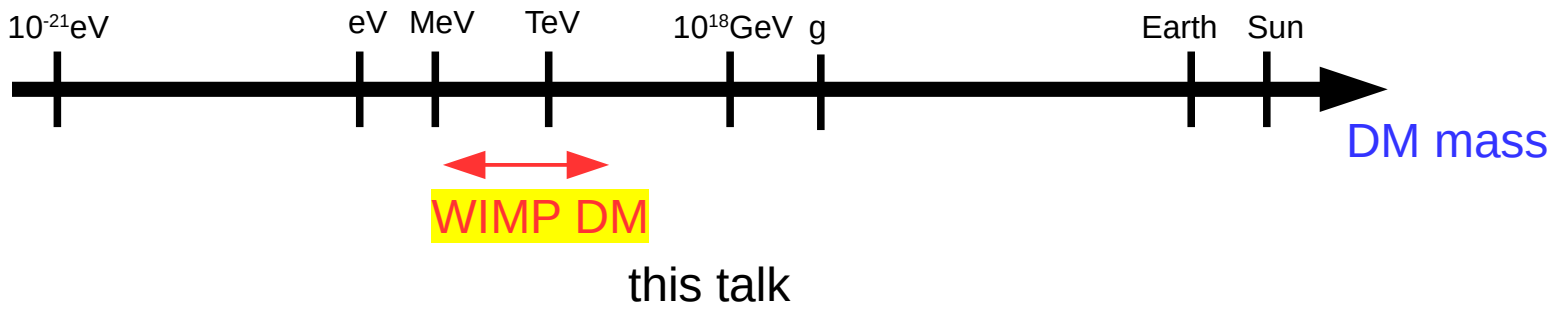


WIMP (Weakly Interacting Massive Particle):

MeV → 100 TeV scale.

New physics at weak scale likely includes WIMP candidates.

Contents

1. WIMP Dark Matter
   - Motivation, DM abundance, signals.
   - Minimal dark matter model.

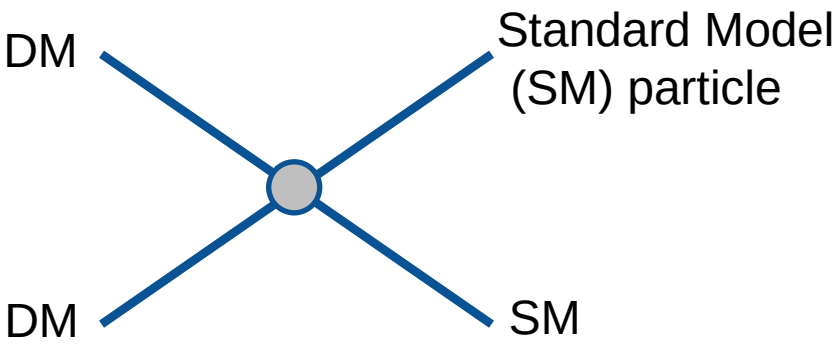
2. LHC Search
   - Missing energy and exotic tracks.

3. Indirect Search at Collider
   - DM search without DM production.
   - Precision measurement.
   - LHC, ILC, muon-collider.

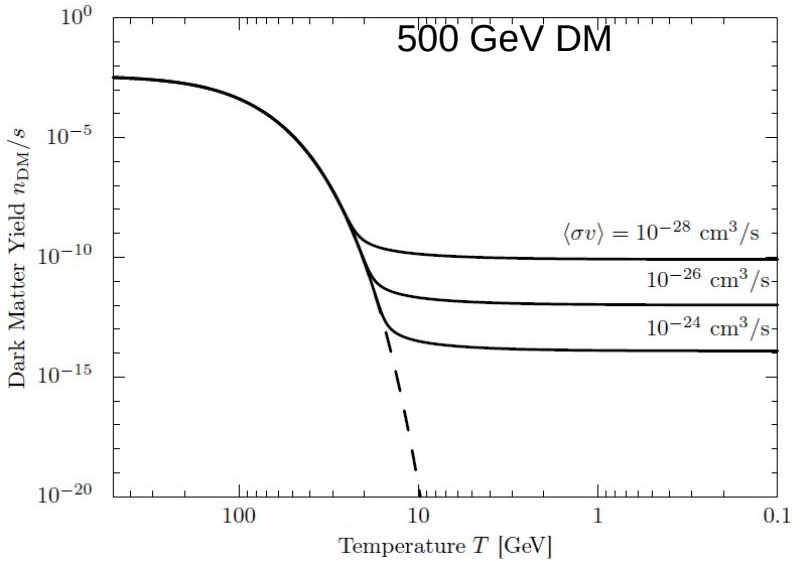
WIMP Dark Matter

WIMP Dark Matter

Weakly Interacting Massive Particle



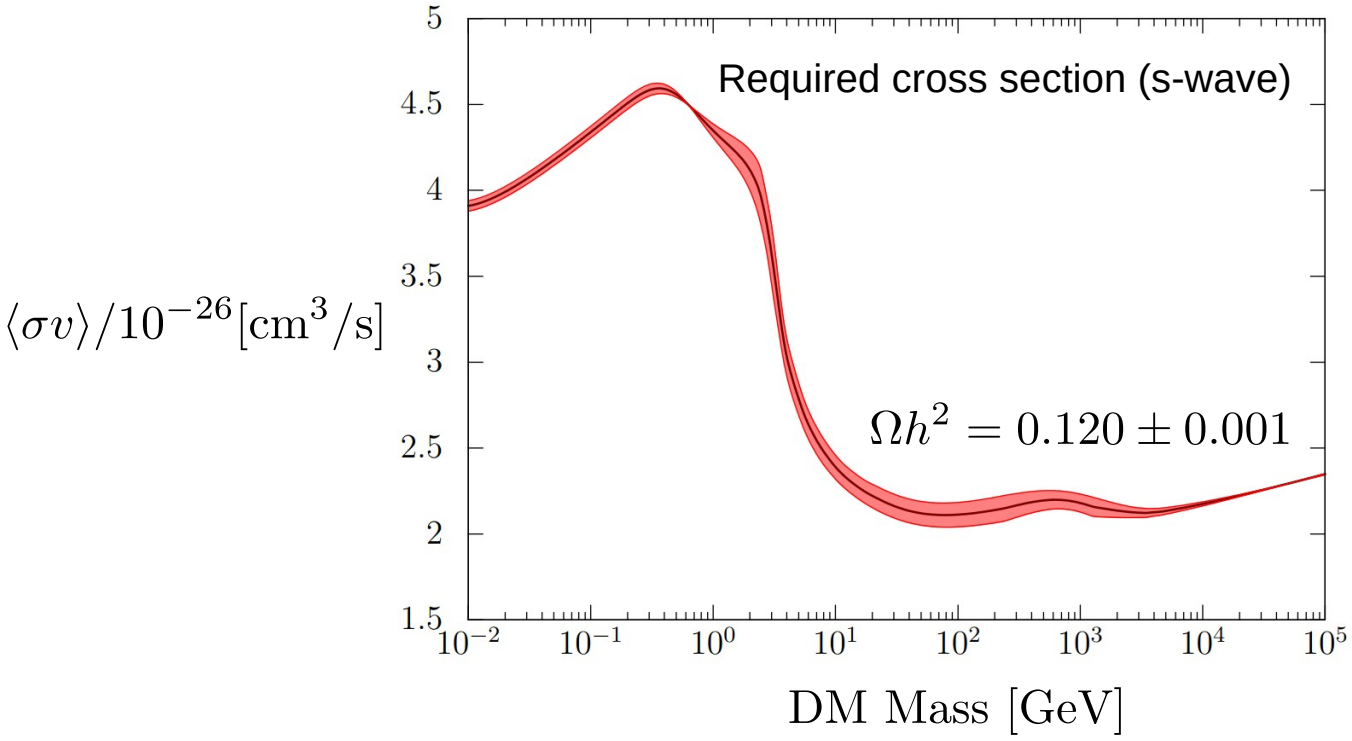
DM abundance



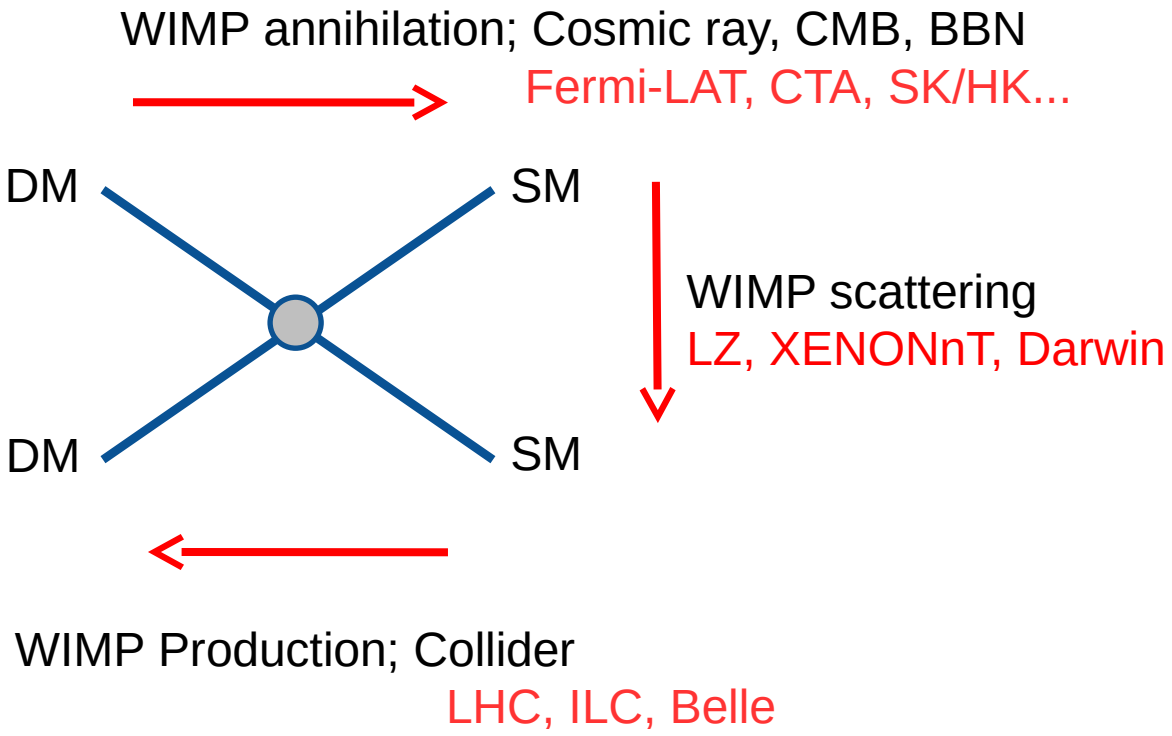
Time

WIMP Cross Section

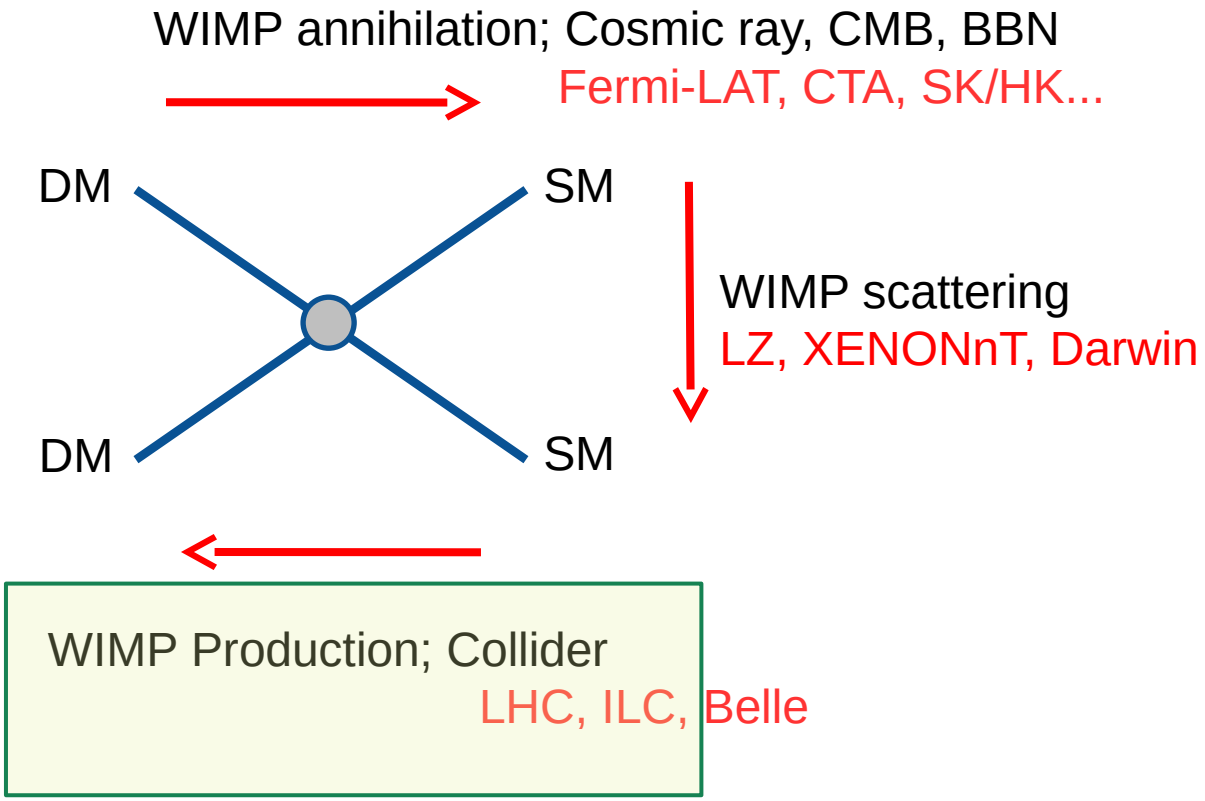
$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ {\rm cm}^3/{\rm s}} \right)^{-1}$$



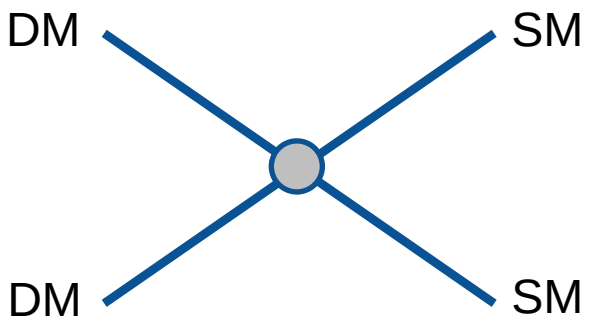
WIMP Detection



WIMP Detection

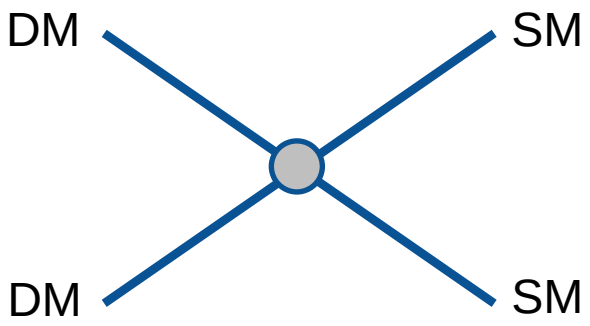


Coupling of DM and SM



Need to identify DM–SM interaction for precise signal prediction.

Coupling of DM and SM



Need to identify DM–SM interaction for precise signal prediction.

So many possibilities of DM-SM interactions….

- SUSY?
  - MSSM?, NMSSM?, ….
    AMSB?, SUGRA?
- Extra Dimension?
  - # of dimension, geometry of compactification,
- ….

(Almost) Minimal WIMP Model

Add one DM particle to SM.

Higgs Portal dark matter

Scalar DM S coupling to Higgs boson.

Gauge Portal dark matter

Scalar or fermion DM charged weak interaction.
Higgsino, Wino, 5plet, …

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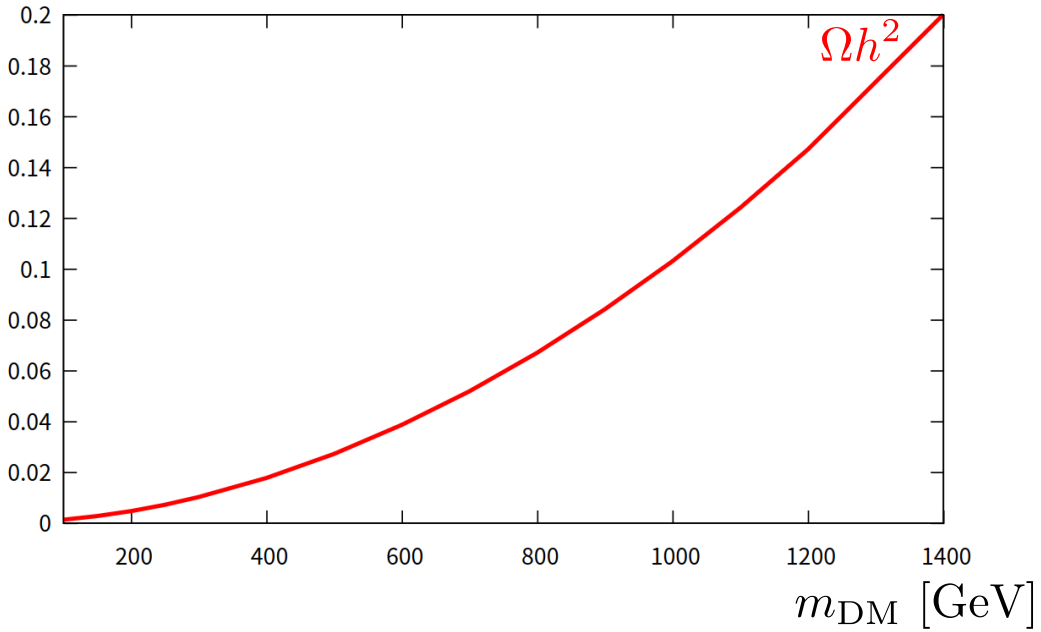
What is Higgsino?

Higgsino is

- (pseudo)Dirac fermion
- Hypercharge |Y|=1/2
- SU(2)doublet $\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$
- <1 TeV

What is Higgsino?

Higgsino is

- 

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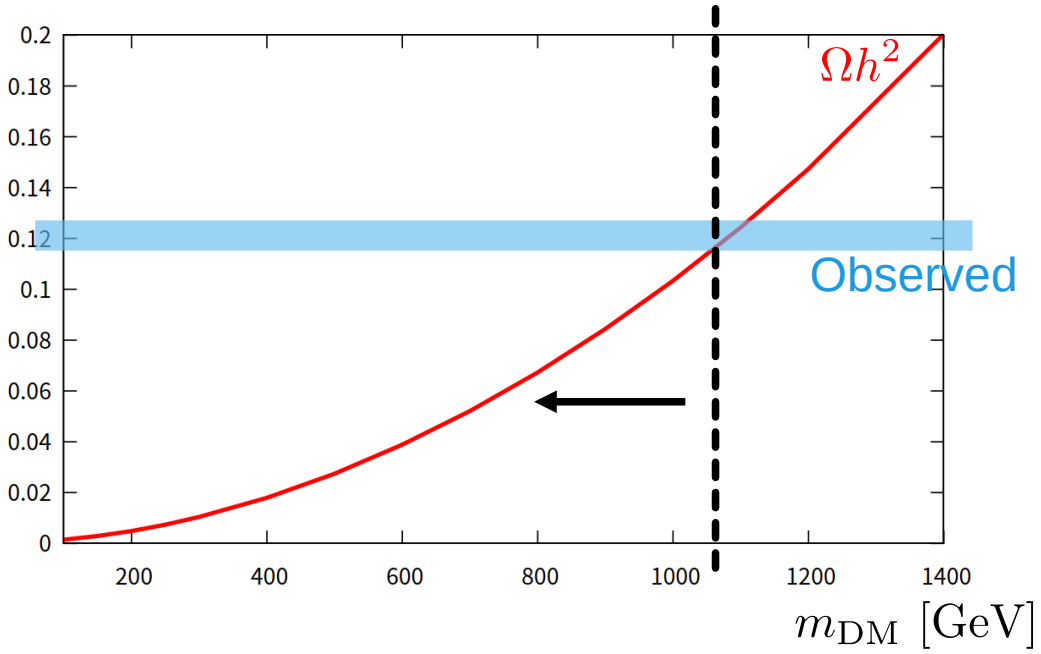
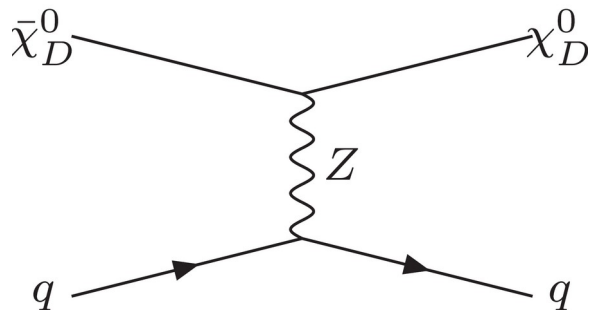
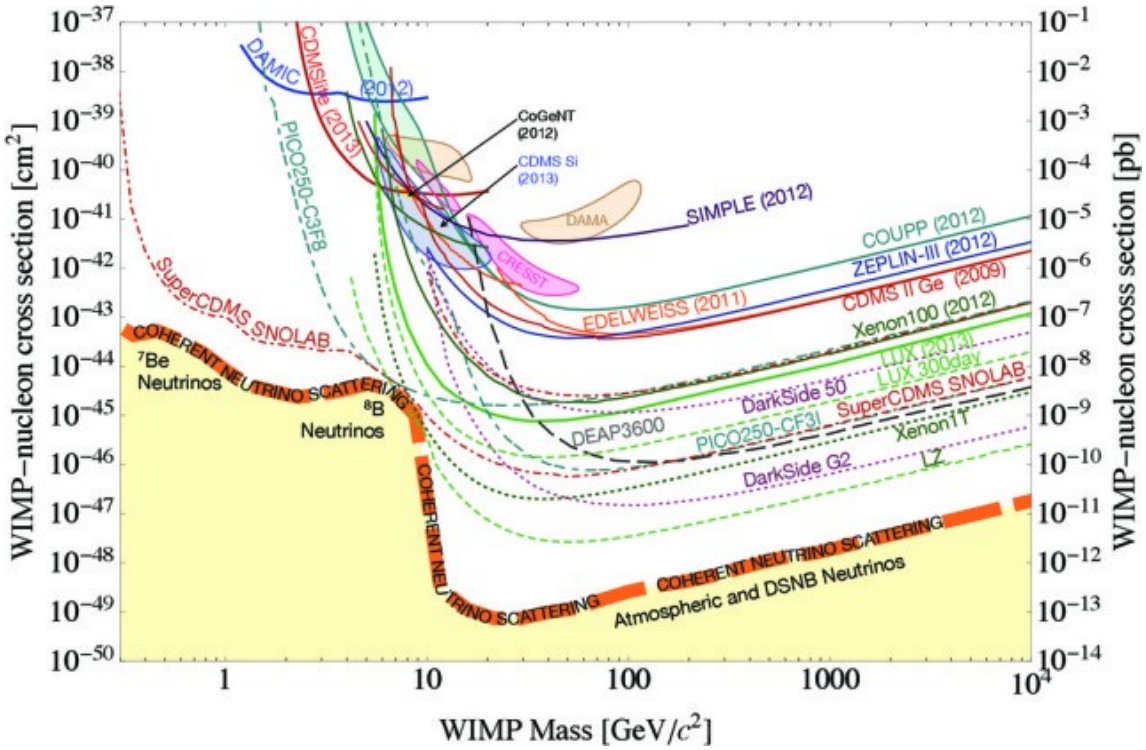


- <1 TeV

Pure Higgsino DM





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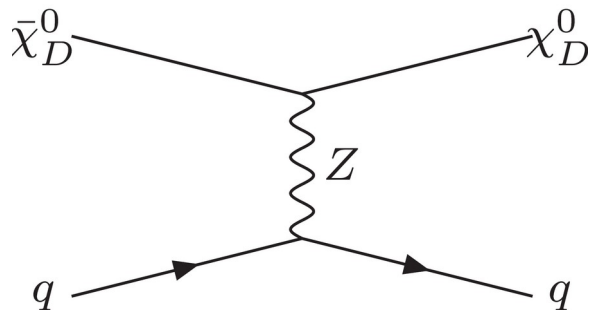

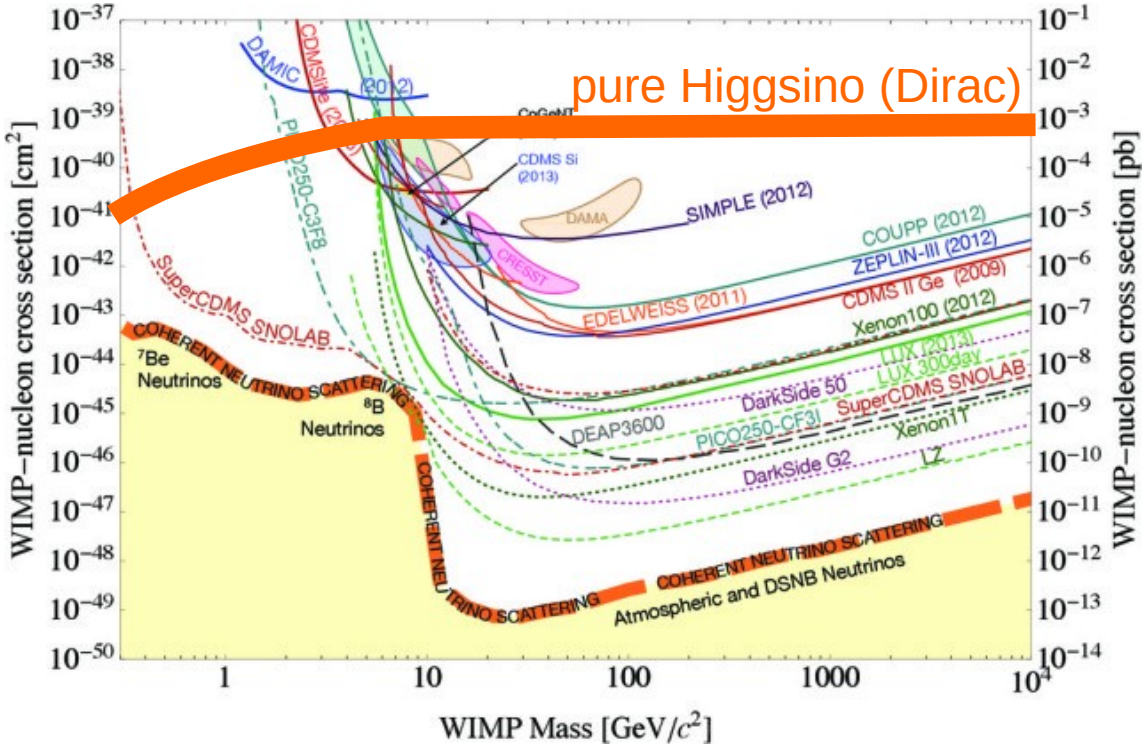

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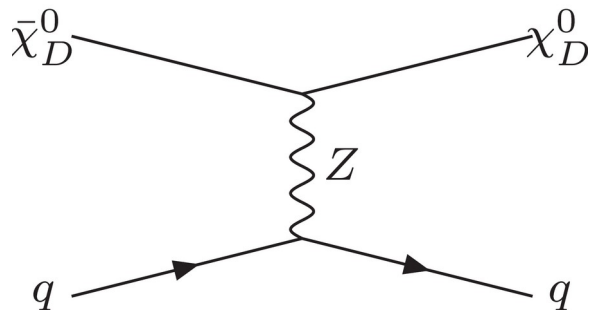
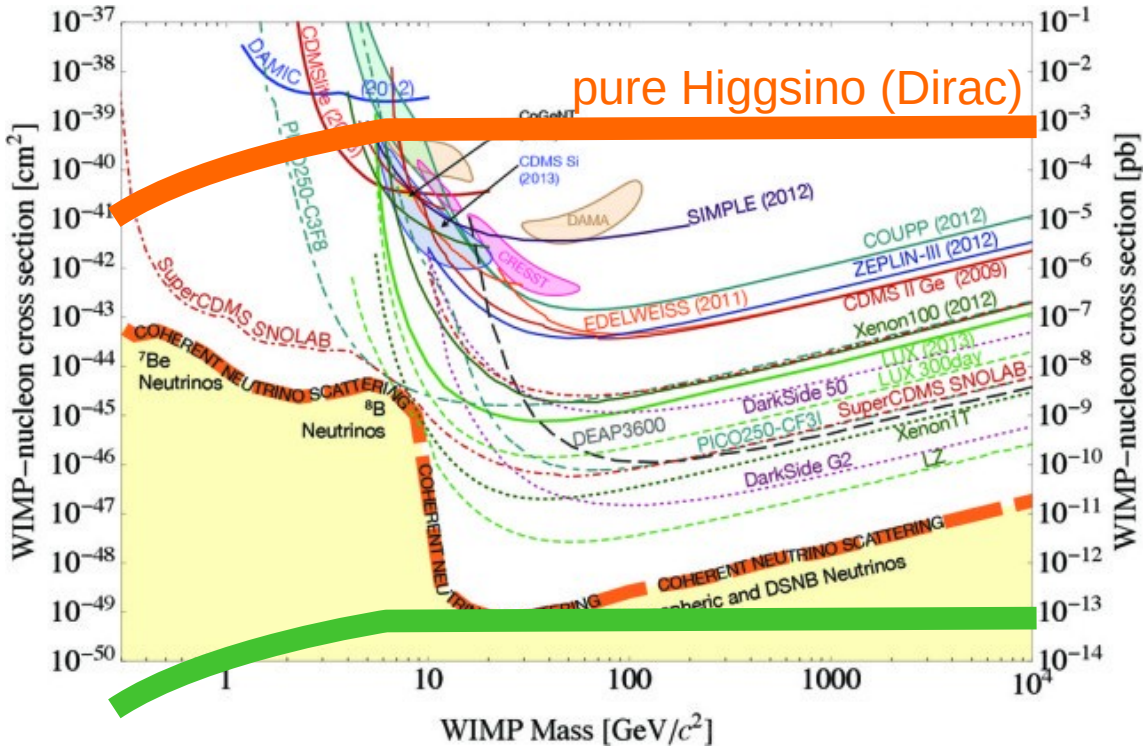


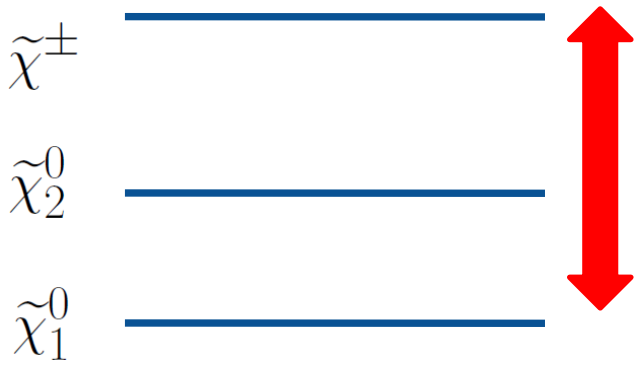


99.999% Higgsino

Majorana Fermion

Higgsino Spectrum (with gaugino)

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



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

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. $m_{\rm DM},\ \Delta m$

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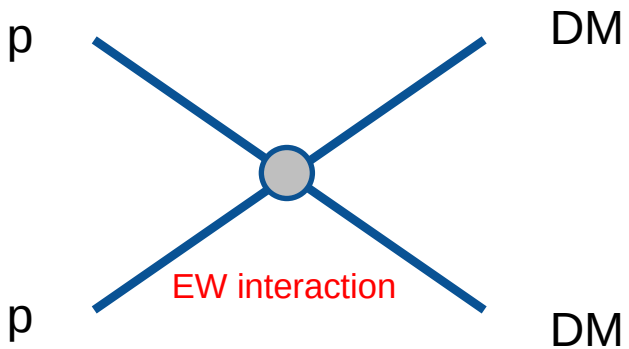
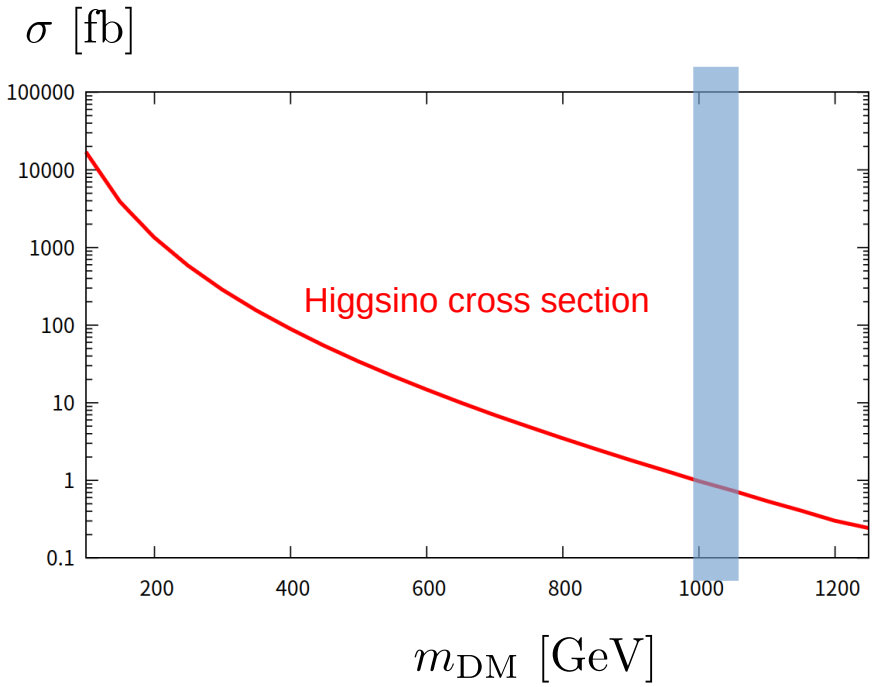
LHC Search

DM Production at LHC





Current LHC integrated luminosity 150 fb^{-1}

DM Production at LHC

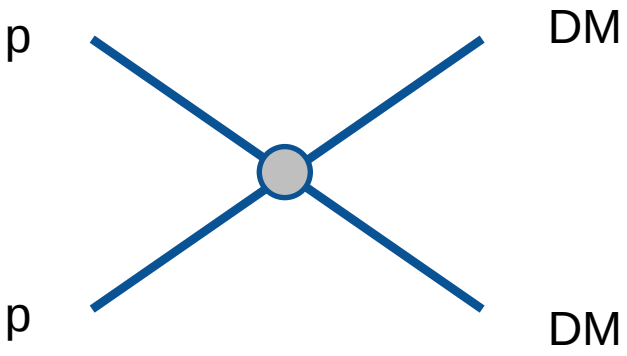
Good:

- Even 1 TeV Higgsino, production is possible:
  ~100 production with LHC data 100 fb^{-1}.

Bad:

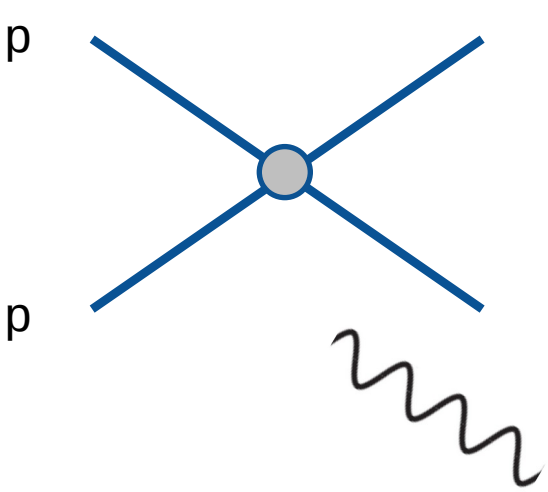
- DM is invisible and detection is not possible.
- SM background is much larger.

Collider Signals of DM



DM is invisible

Collider Signals of DM

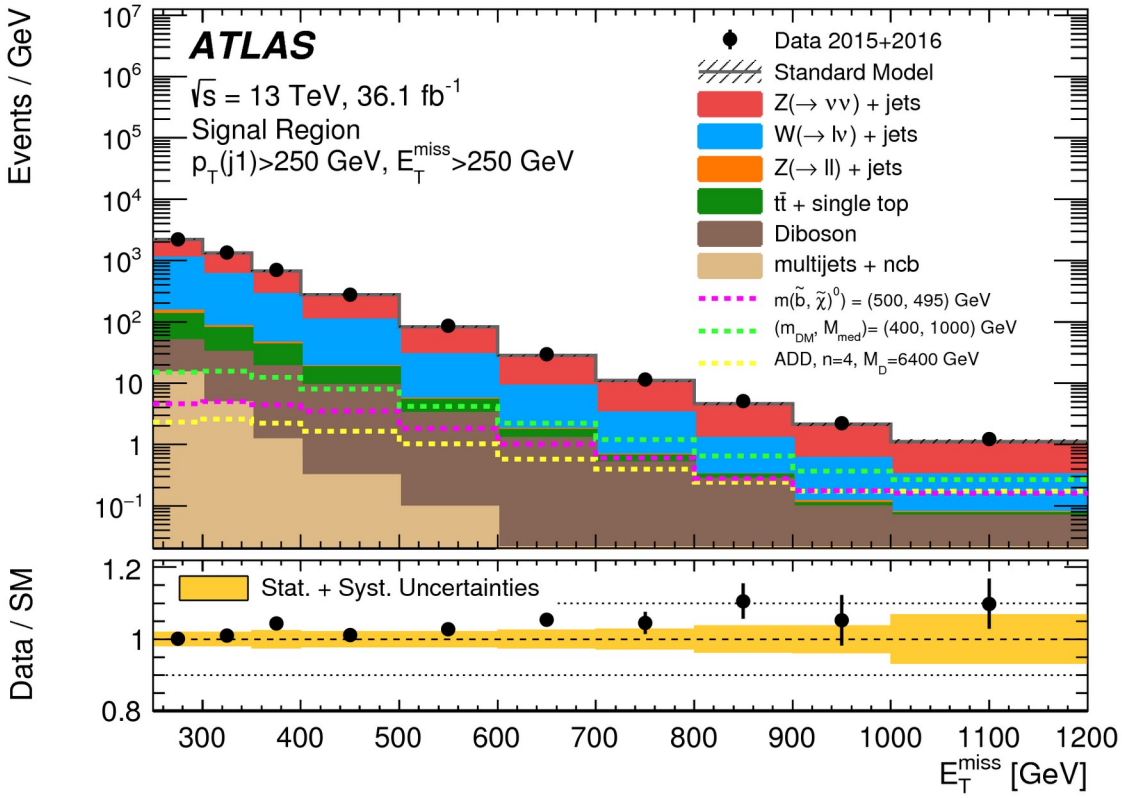


DM is invisible

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

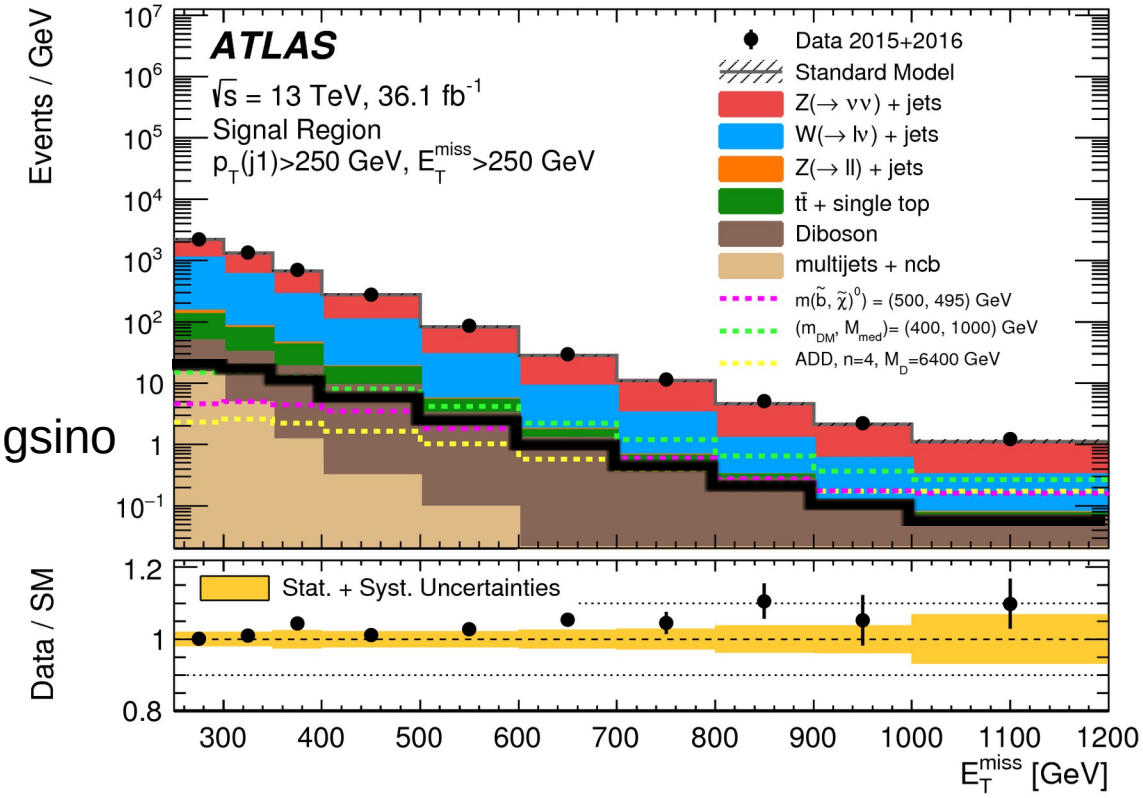
gluon photon, …

Missing Energy Signatures



Missing Energy Signatures

100 GeV Higgsino



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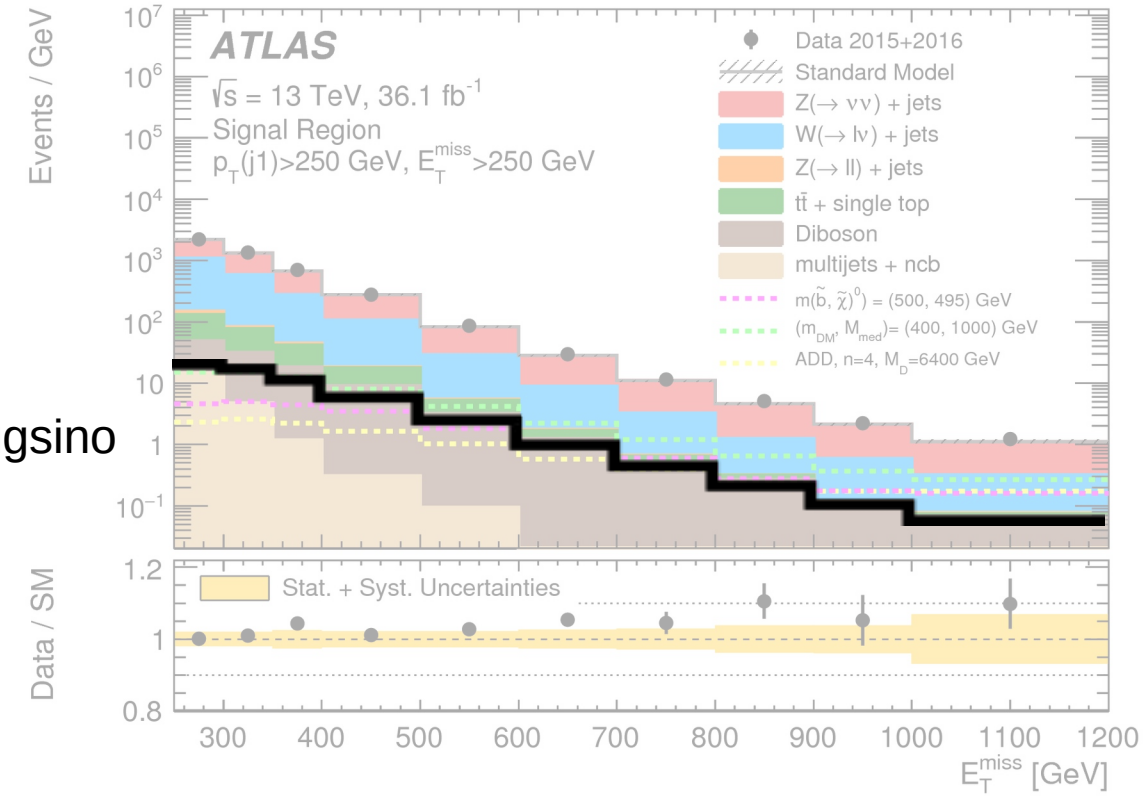
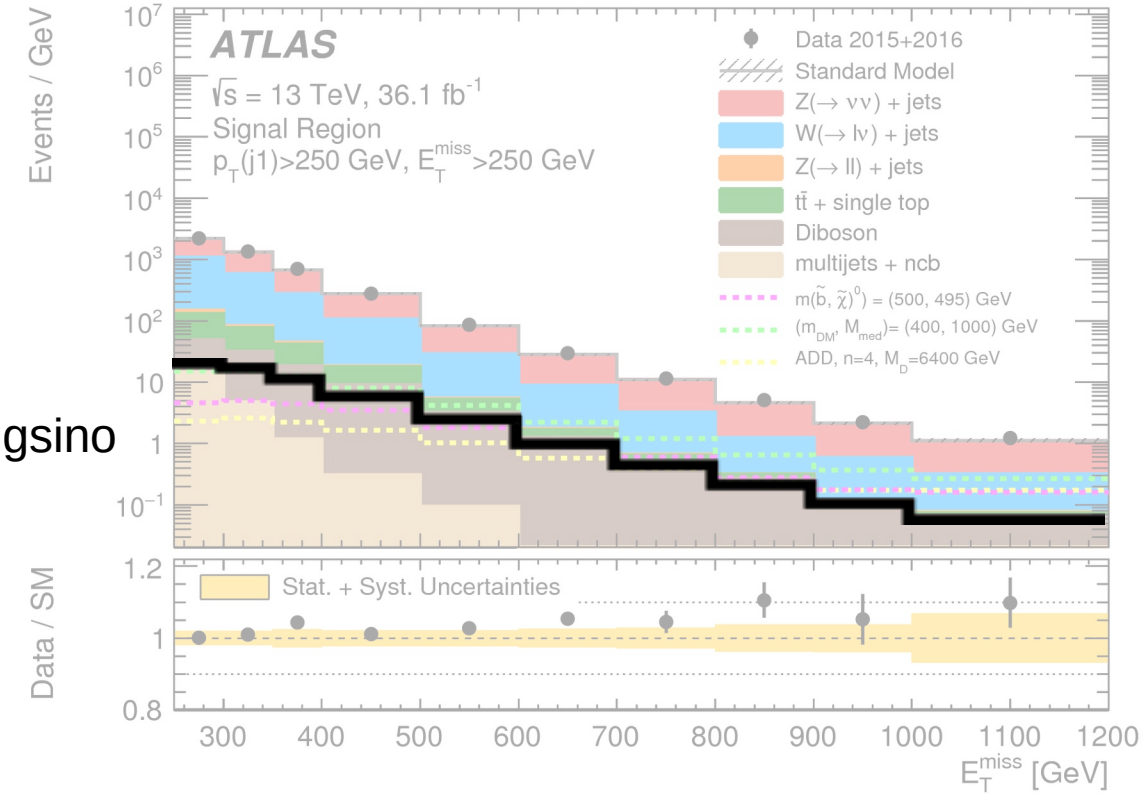


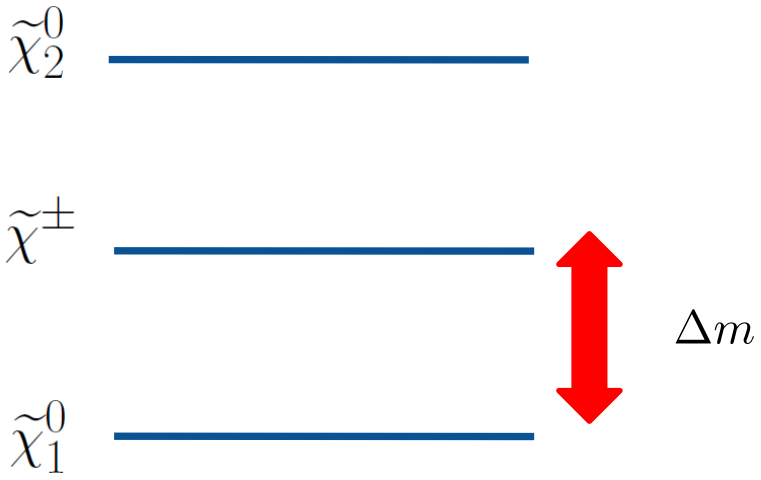
Missing Energy Signatures

100 GeV Higgsino



Simple strategy with jet and missing energy is not useful.

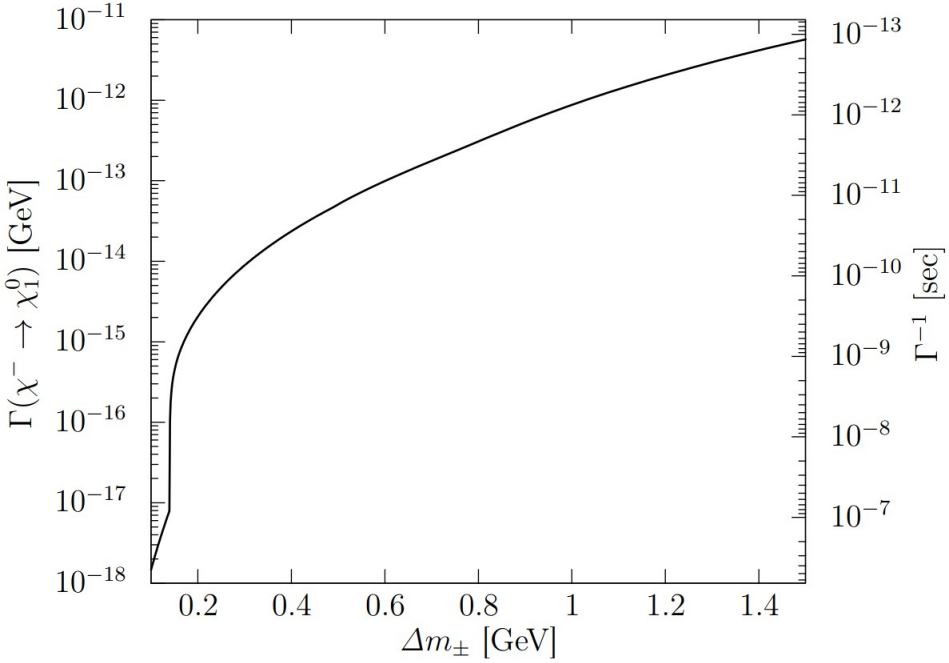
Heavier Higgsino Component



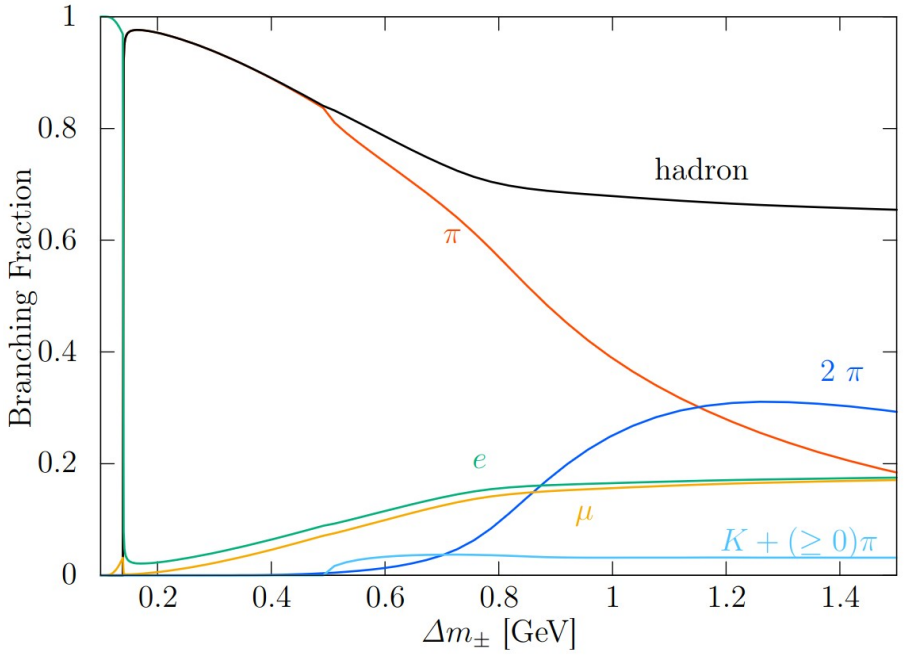
- For small Δ m, charged competent is long-lived.
  - ➡ Heavy charged track.
- For large Δ m, high-energy lepton from decay of heavier Higgsino.
  - ➡ High-energy lepton.

Decay of Higgsino

Decay Rate

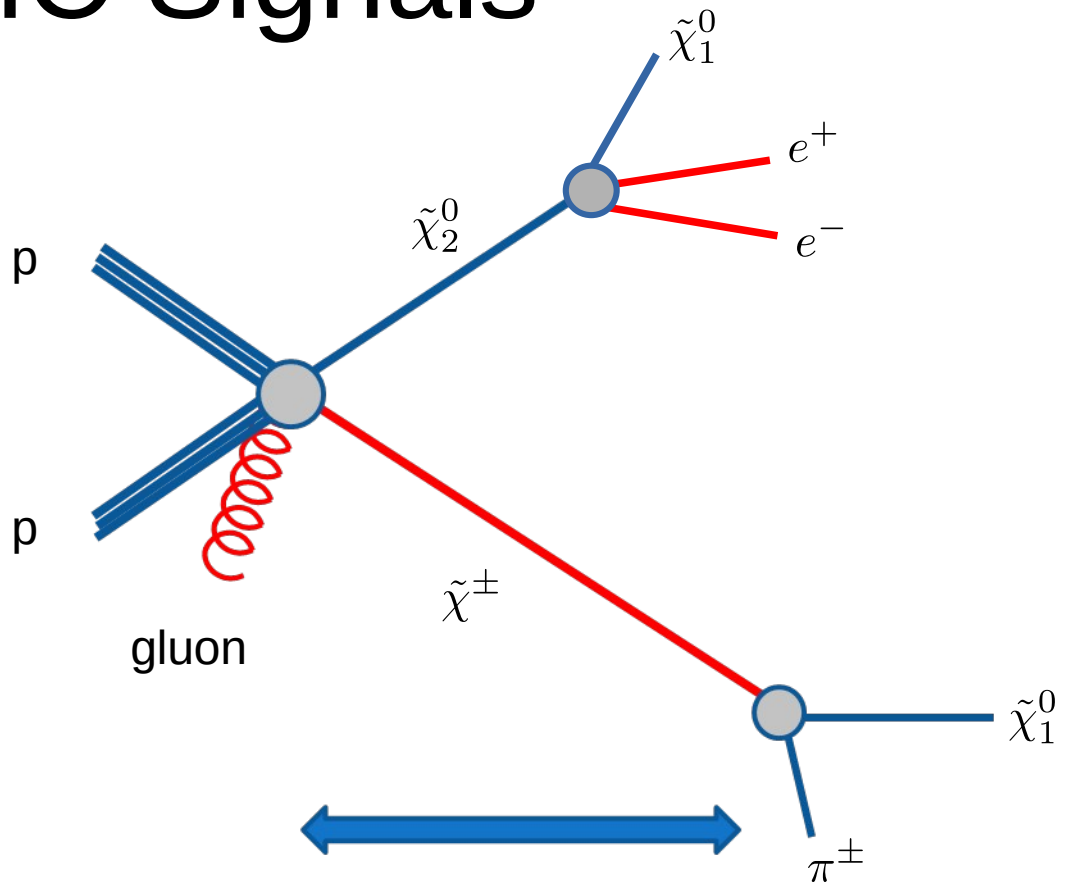


Branching Fraction



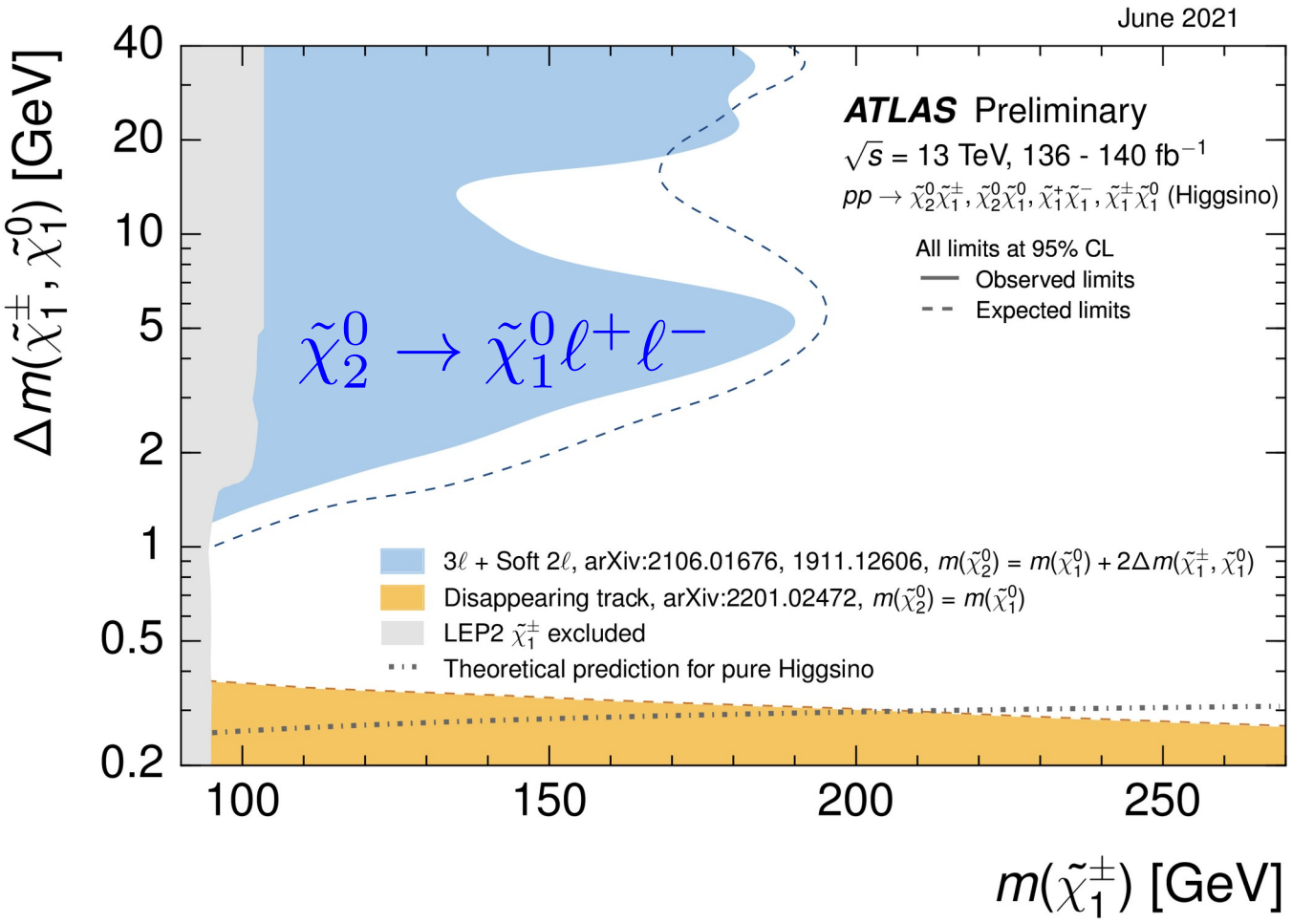
[Ibe,Nakayama,SS, 23]

LHC Signals



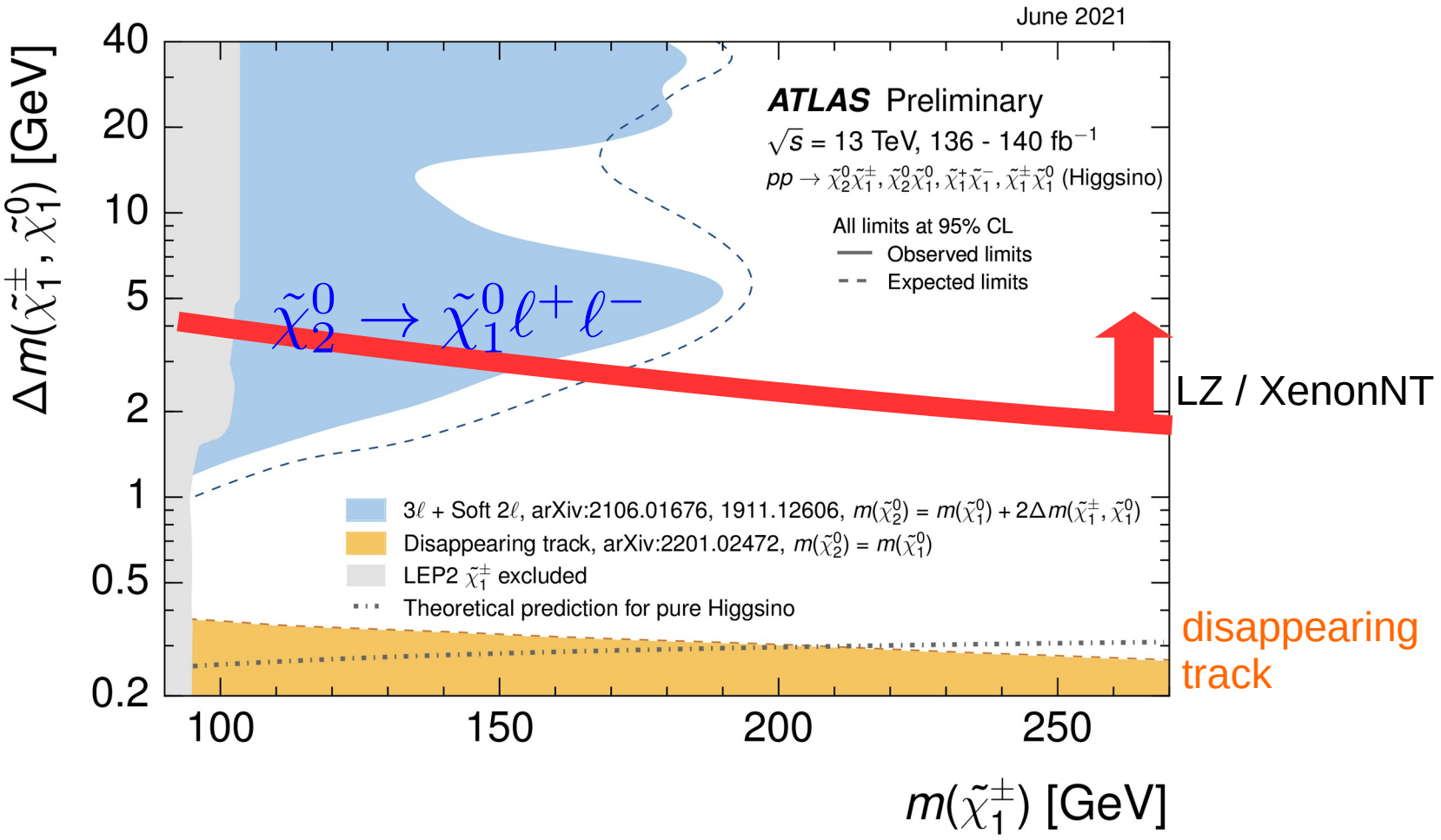
Missing energy
+
Heavy charged track
+
Leptons.

Current Constraint



disappearing track

Current Constraint



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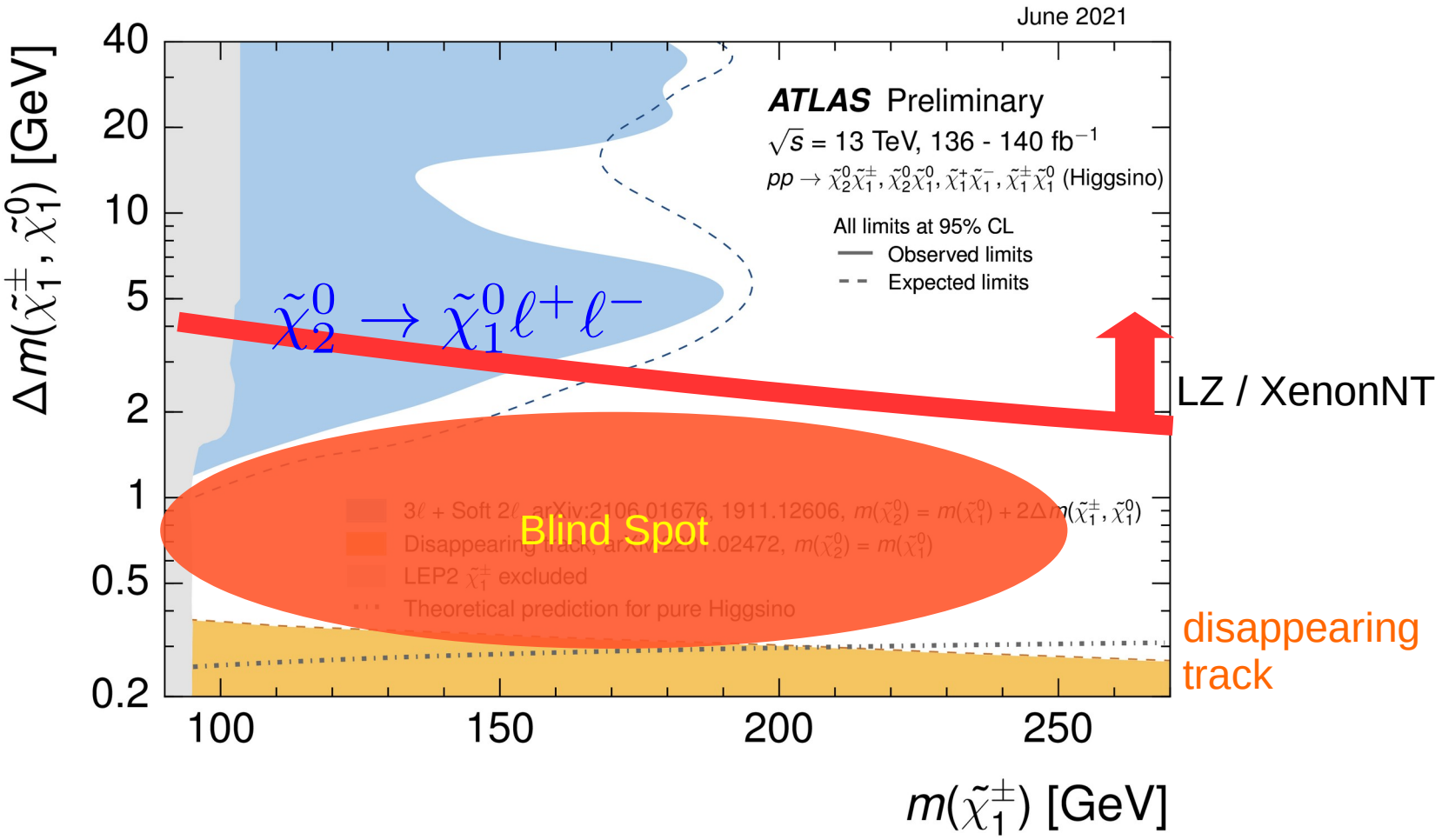
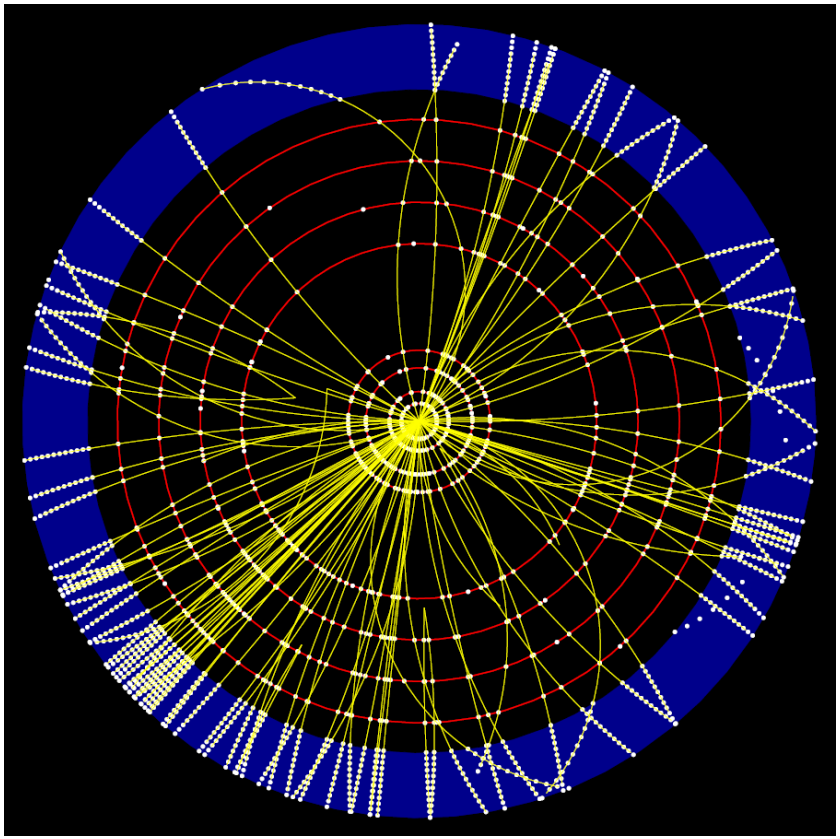


Event Display



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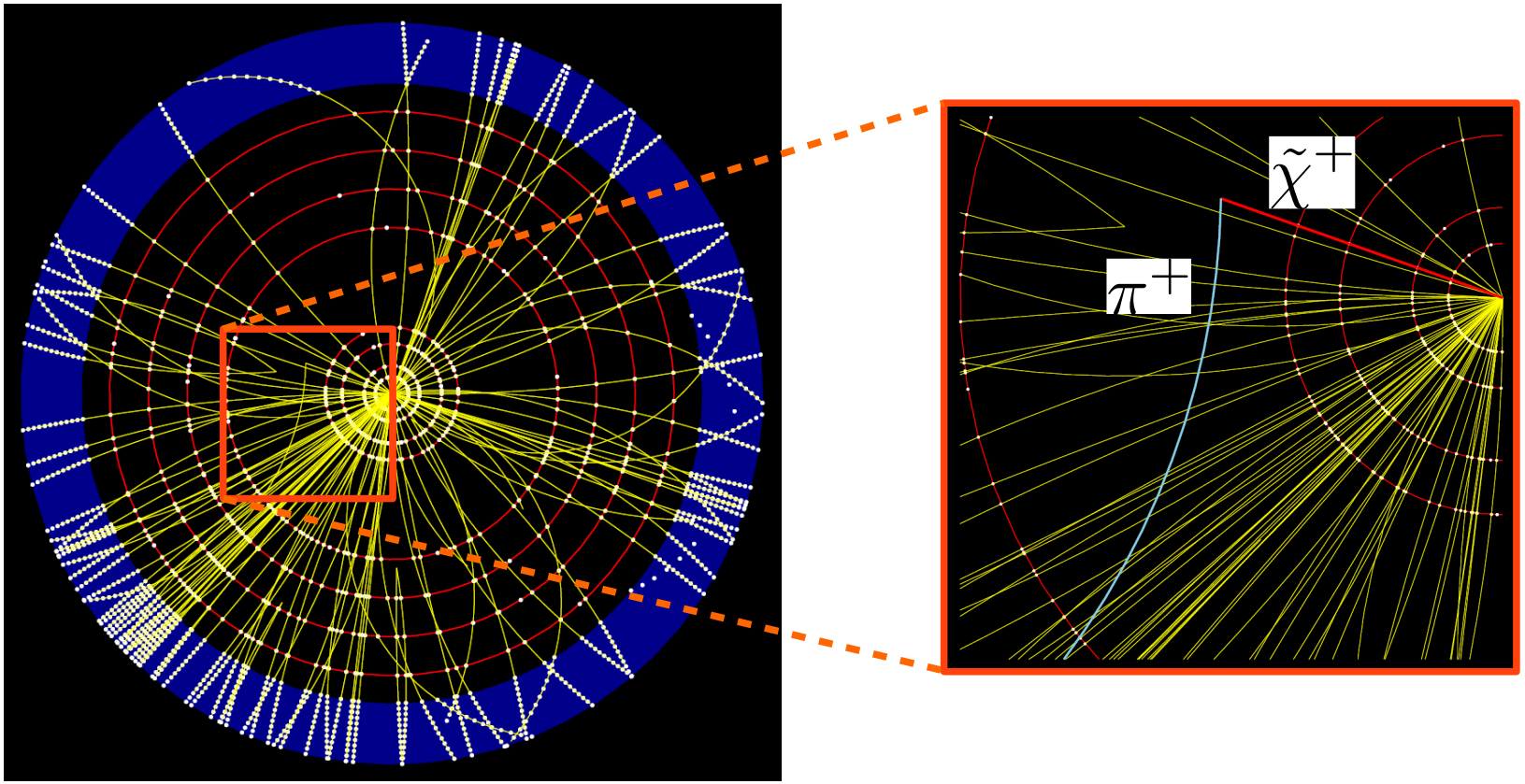

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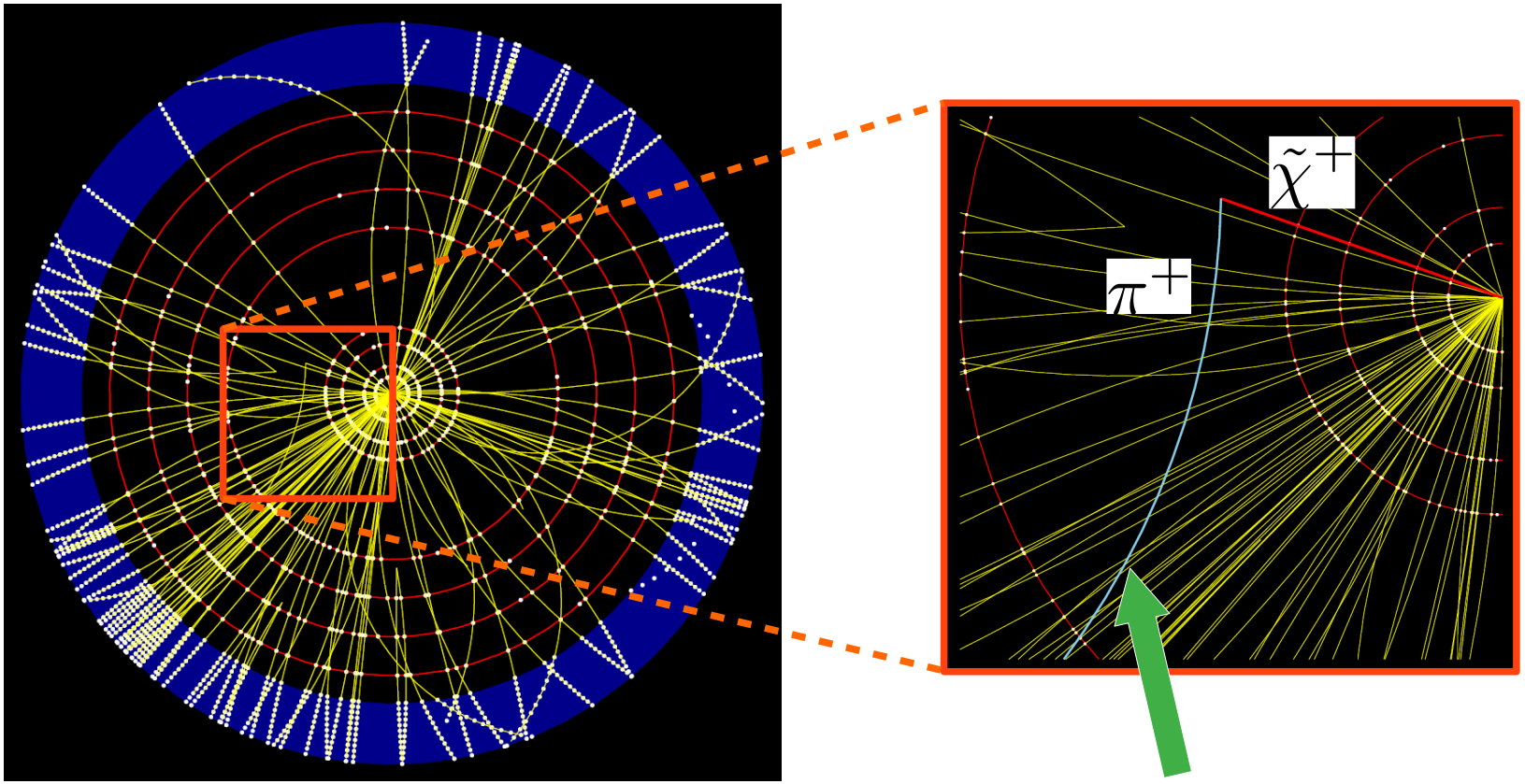


New tag of DM event.

Signal vs Background

SM background:

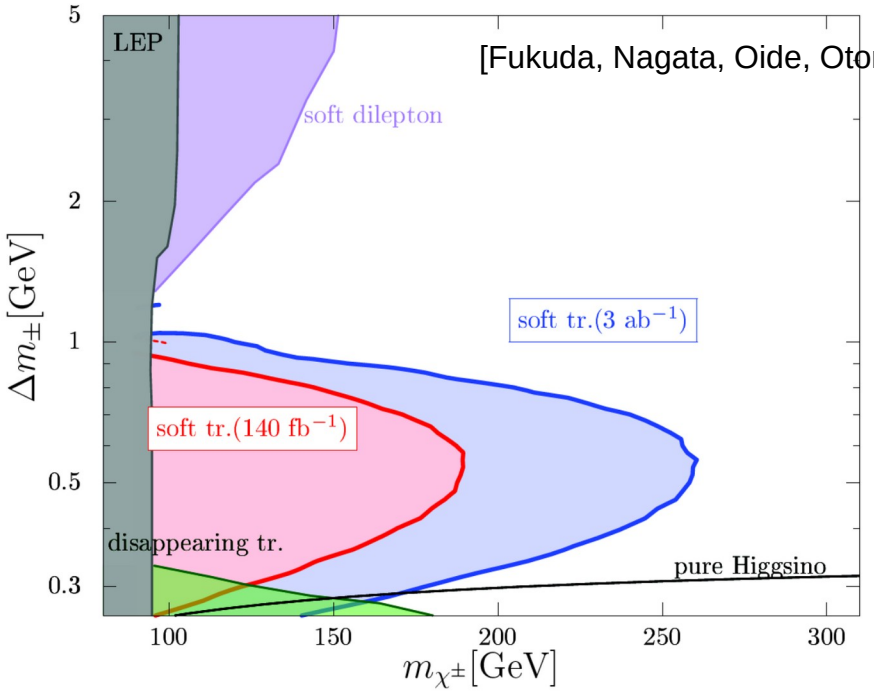
- Mono boson production: Z > νν.
- O(100) tracks per event from soft QCD.
  - Most of tracks are close to each other.

DM signal:

- Signal track is isolated from other tracks.
- Large displacement.

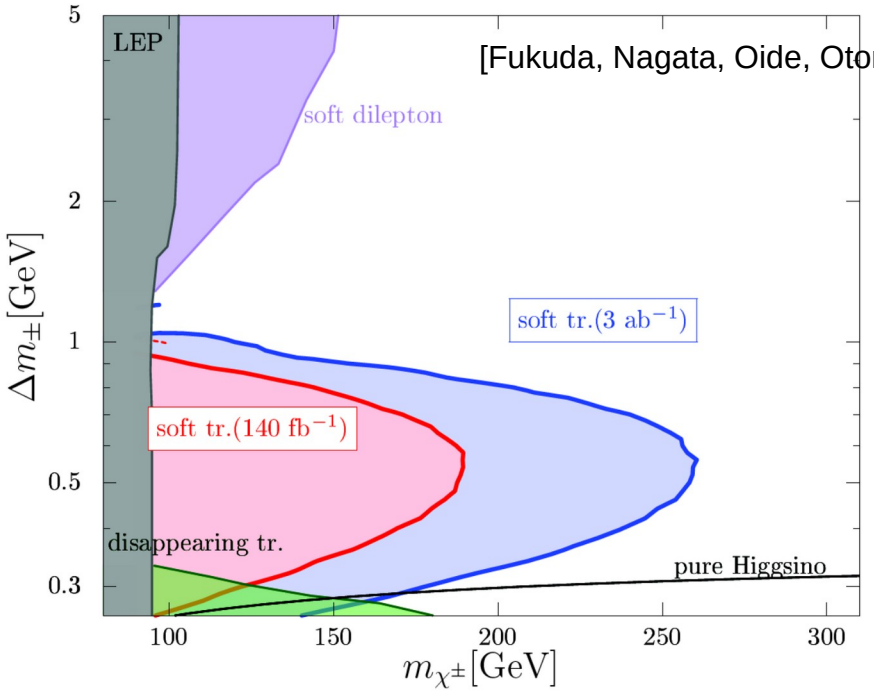
Construction of event selection.

Soft-Track Search



[Fukuda, Nagata, Oide, Otono & SS, 19]

Soft-Track Search

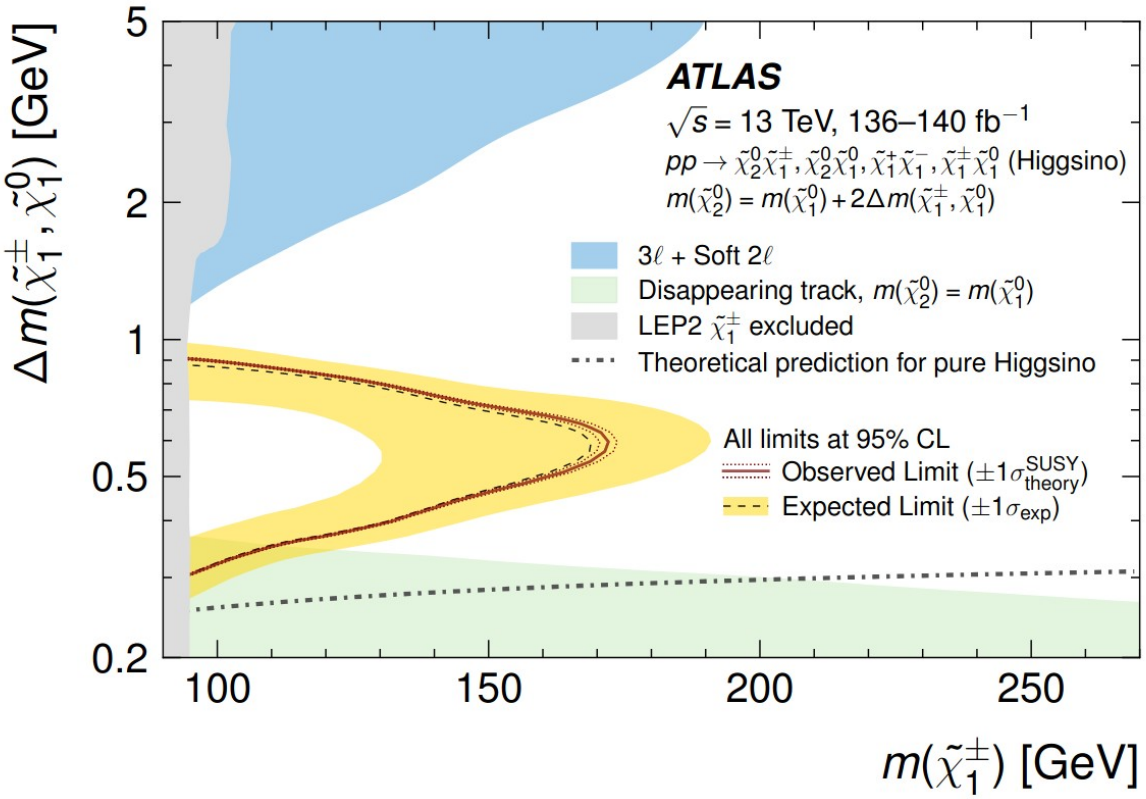


[Fukuda, Nagata, Oide, Otono & SS, 19]

ATLAS public result is now out!

Soft-Track Search

[ATLAS Collaboration, 2401.14046]



Indirect Detection at Collider

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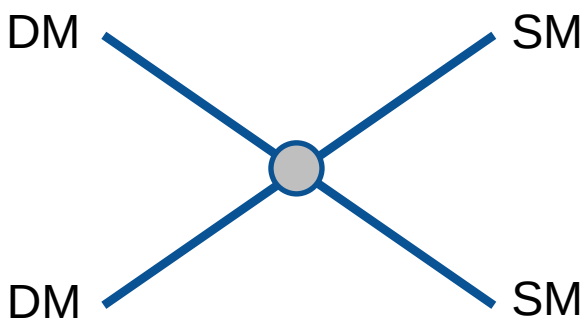

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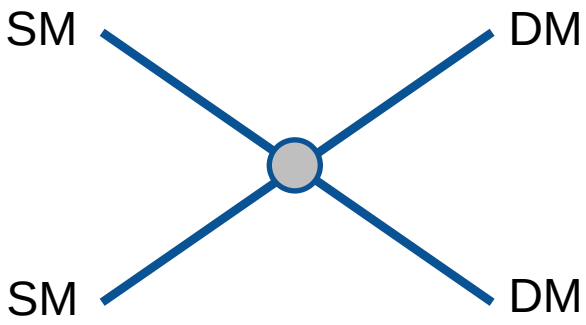

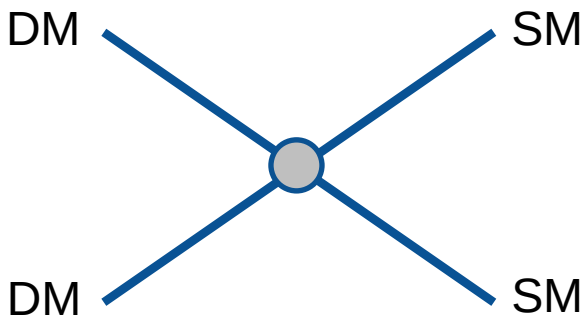

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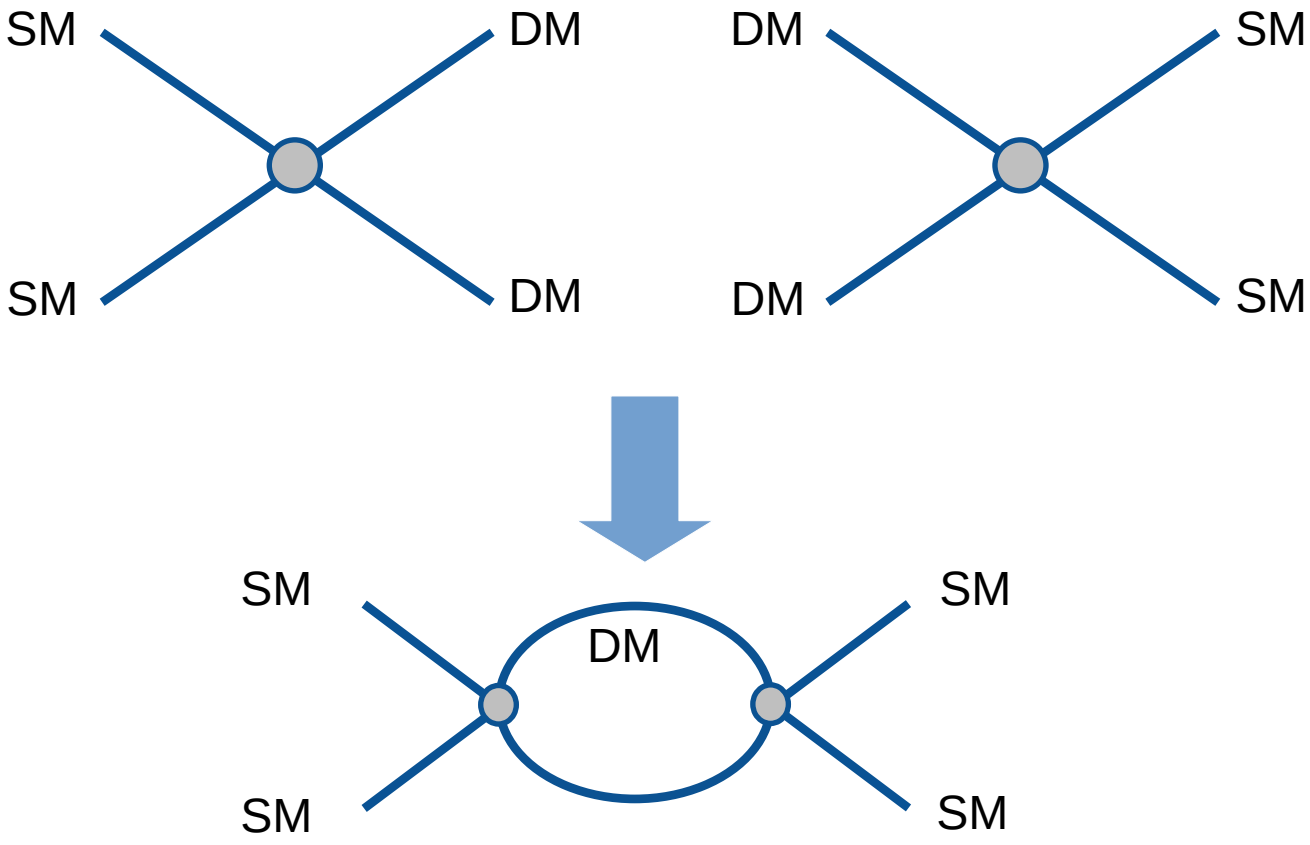

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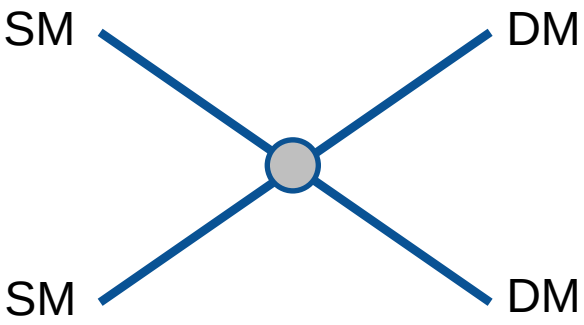
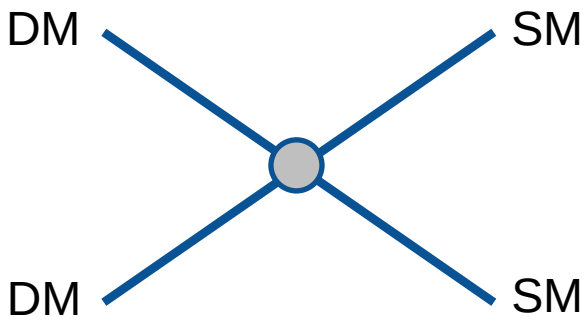
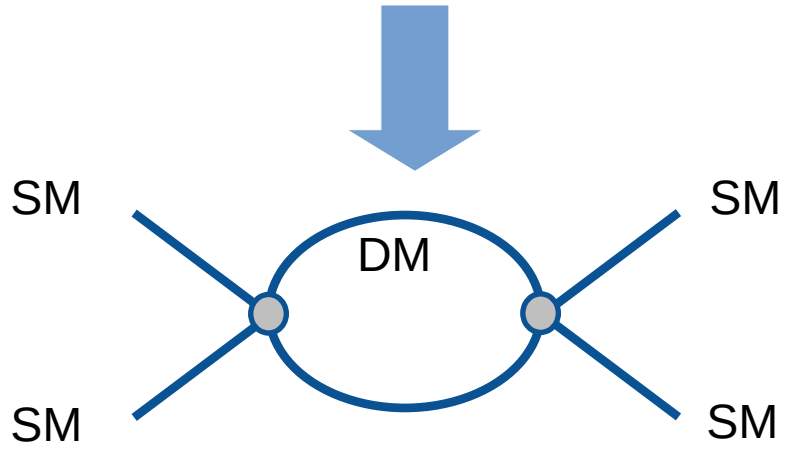




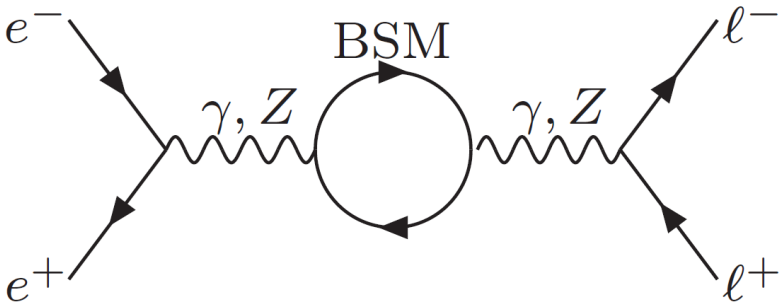


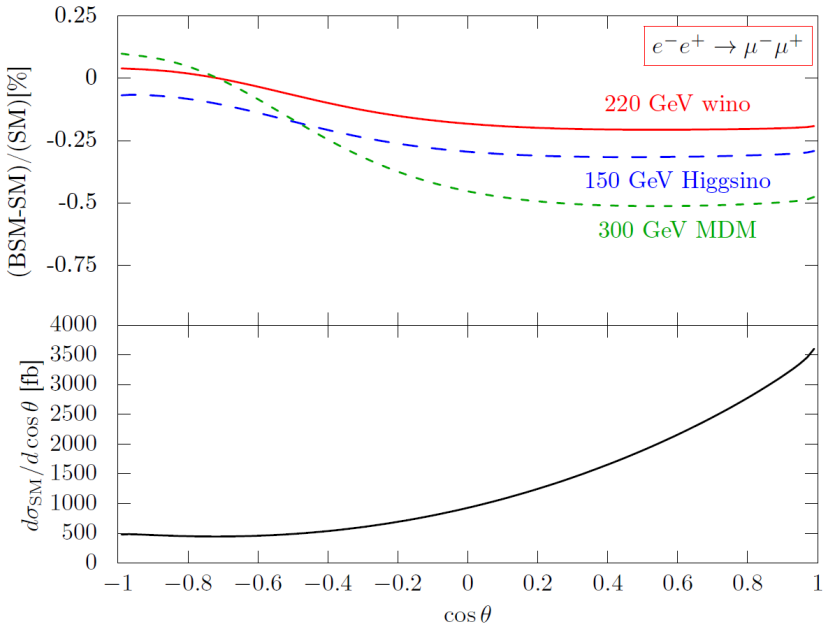
DM Loop effect

Precision measurement of Standard Model

Lepton Collider

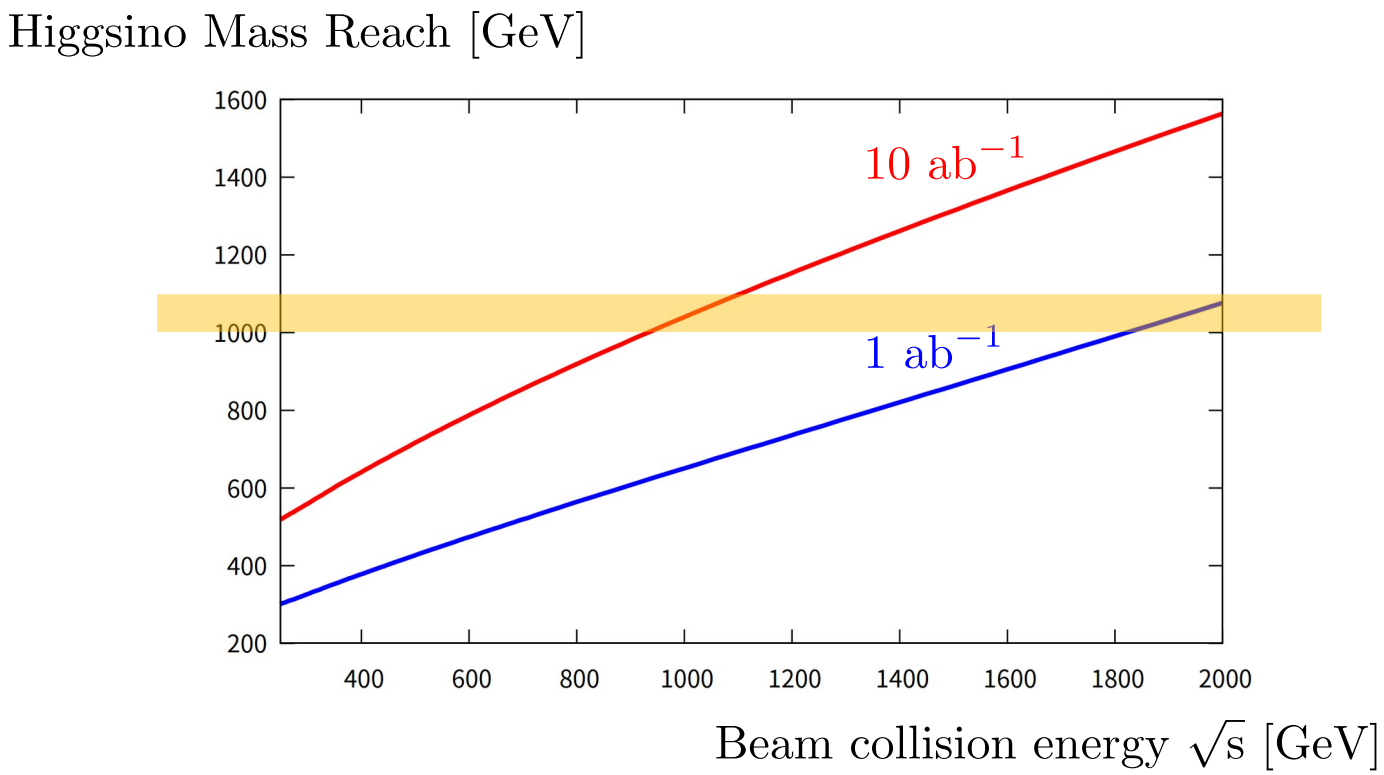
[Harigaya, Ichikawa,Kundu, Matsumoto & SS, 15]





Precision measurement at future lepton collider ILC can probe subtle effects.

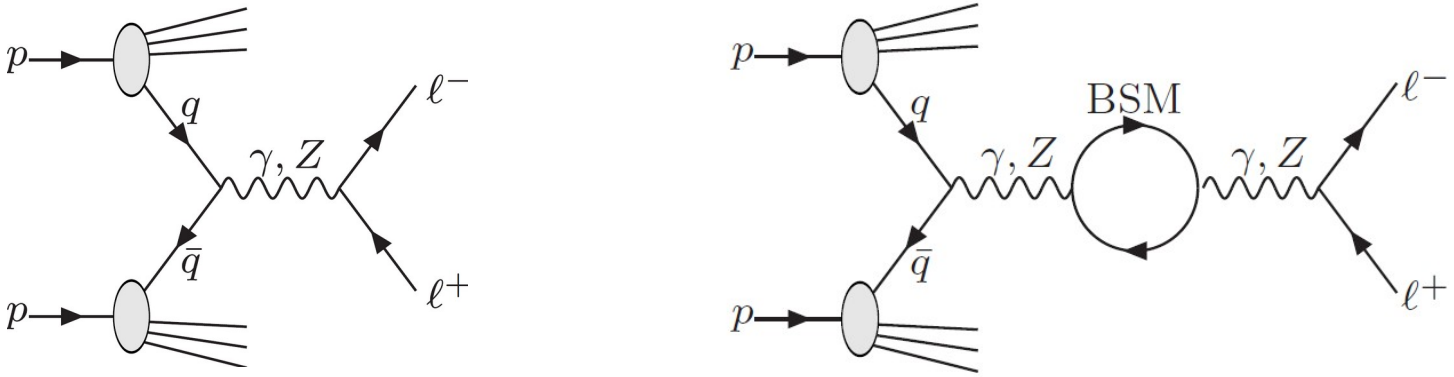
ILC Search for Heavy Higgsino



Sensitivity is better than direct production mode.
Can probe DM mass larger than beam energy.

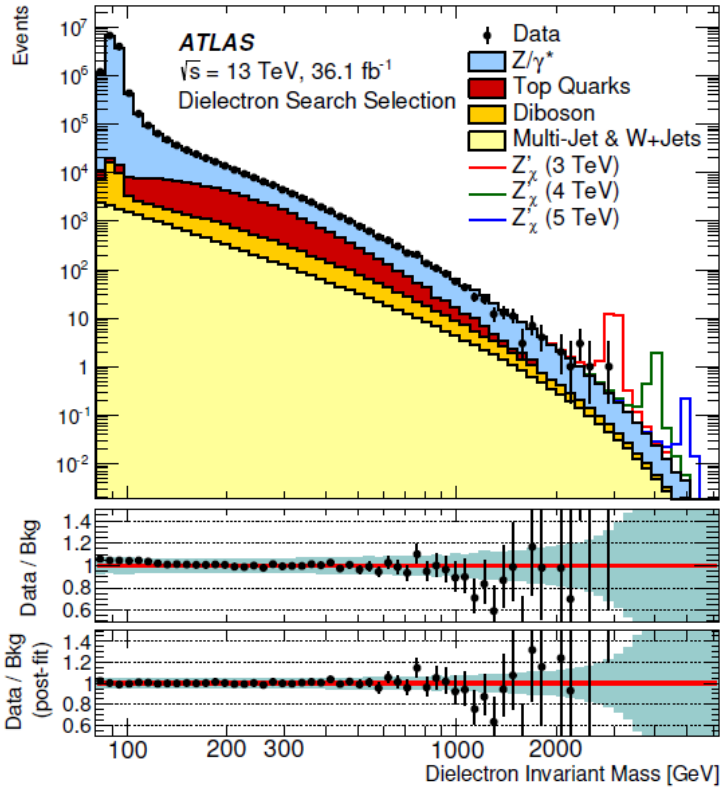
Indirect Probe at LHC

[Matsumoto, SS & Takeuchi, 17,18]
[Katayose, Matsumoto & SS, 20]

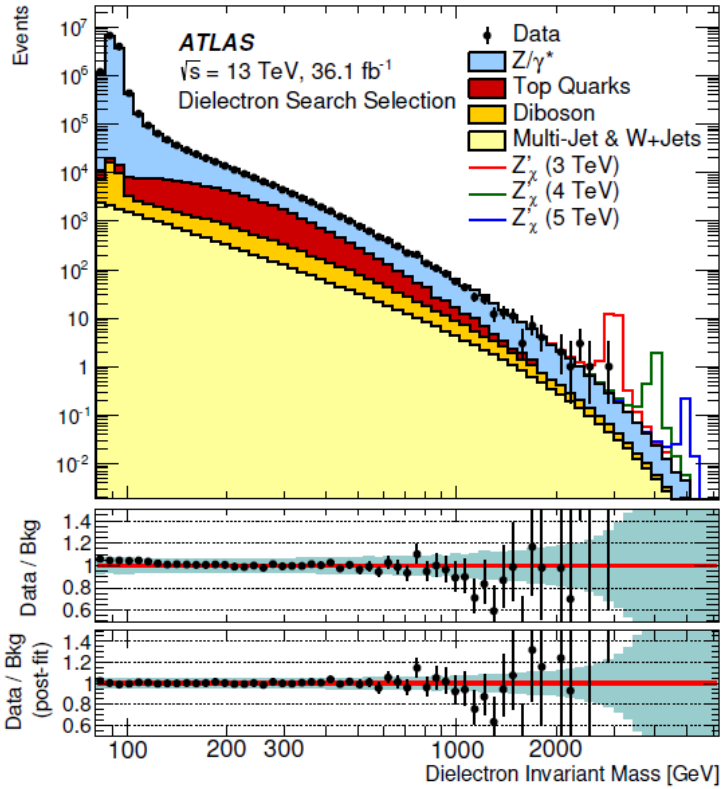


BSM loop affects the Drell-Yan process by O(1)%.

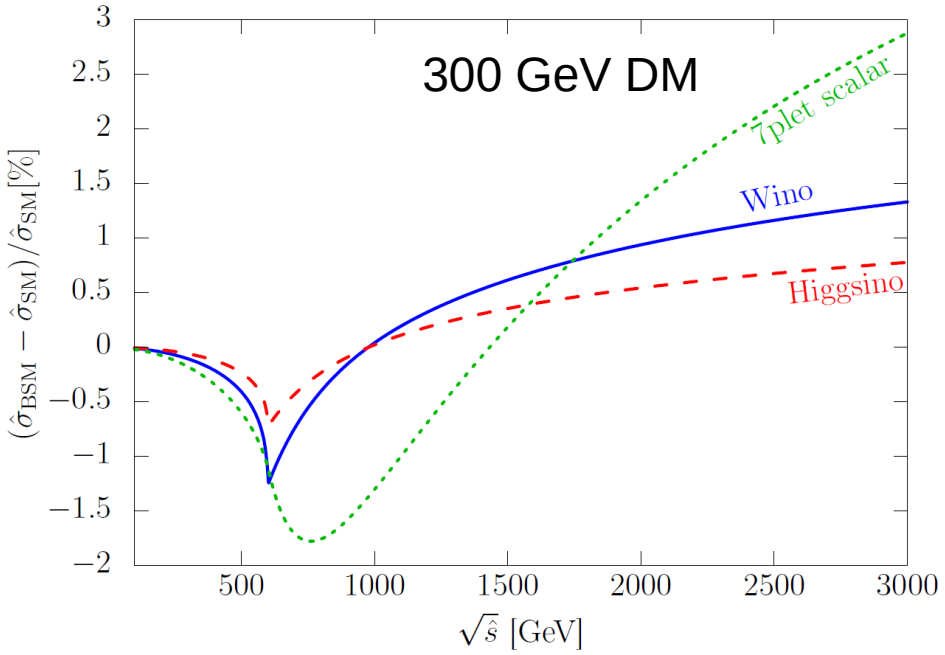
Indirect Probe at LHC



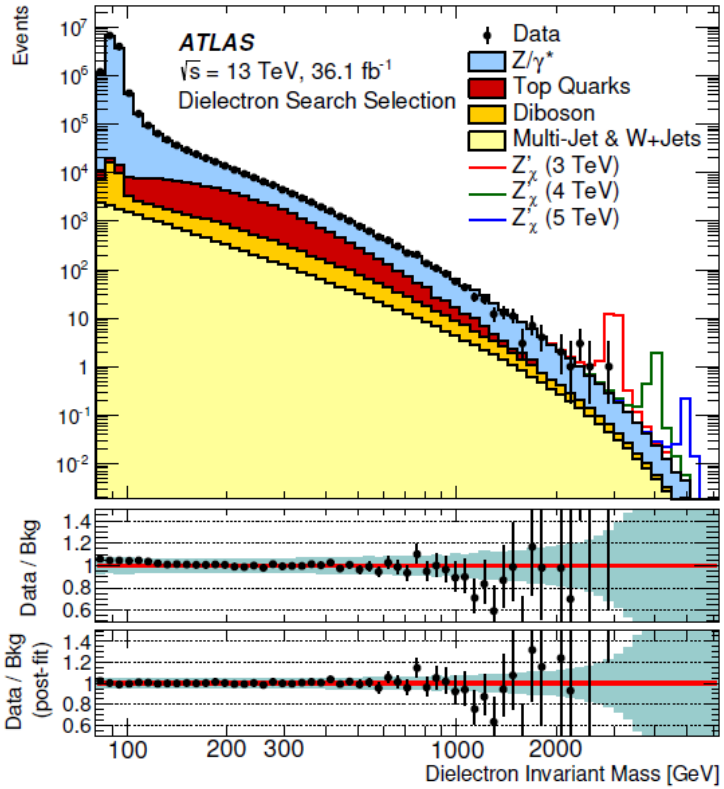
Indirect Probe at LHC



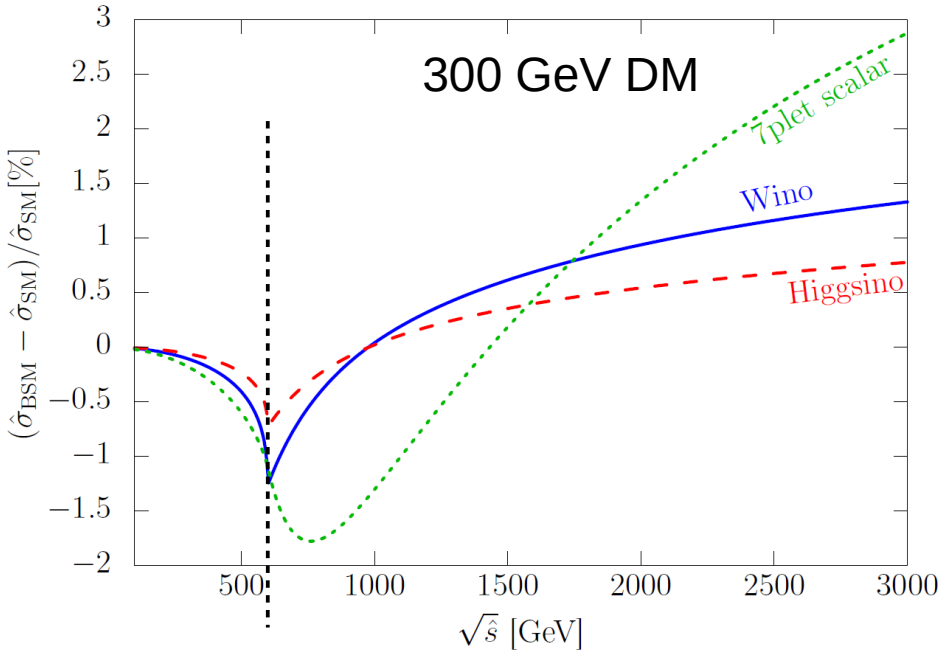
Correction from BSM



Indirect Probe at LHC



Correction from BSM

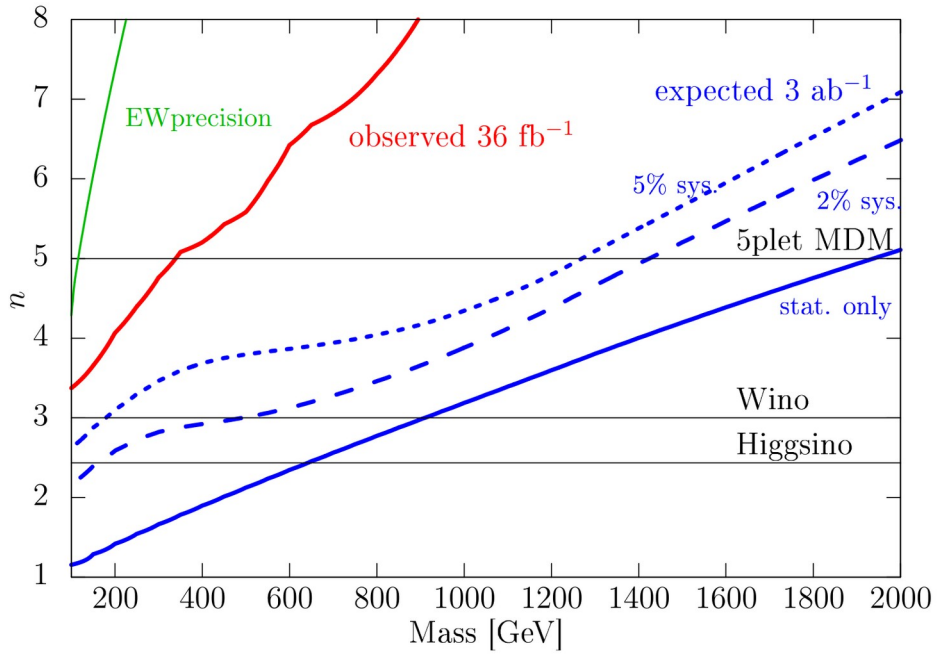


$2 \times m_{\rm DM}$

Constraints and Prospects

of SU(2) representation

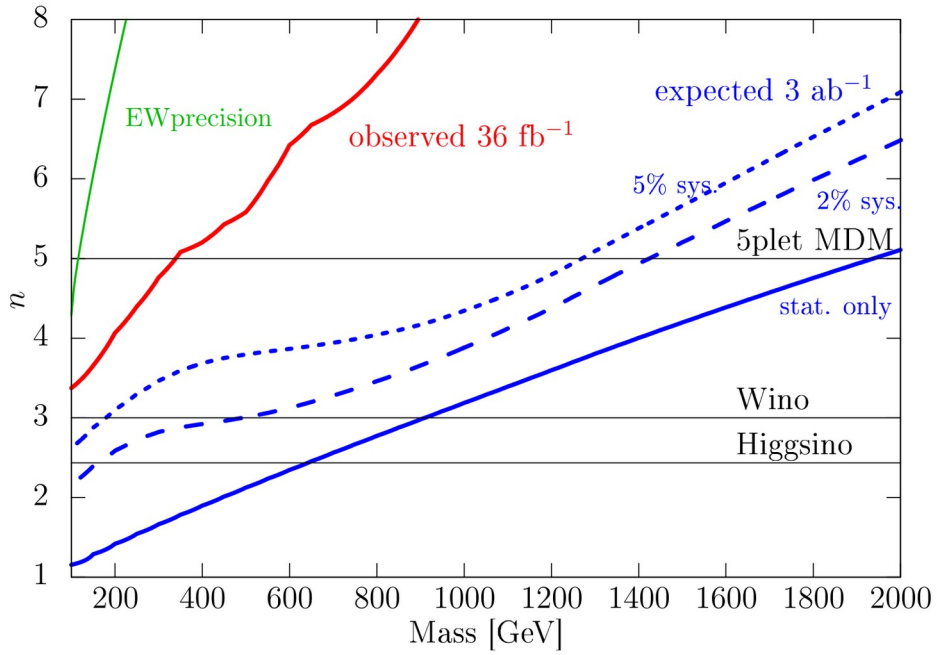
mono-lepton signal



Constraints and Prospects

of SU(2) representation

mono-lepton signal

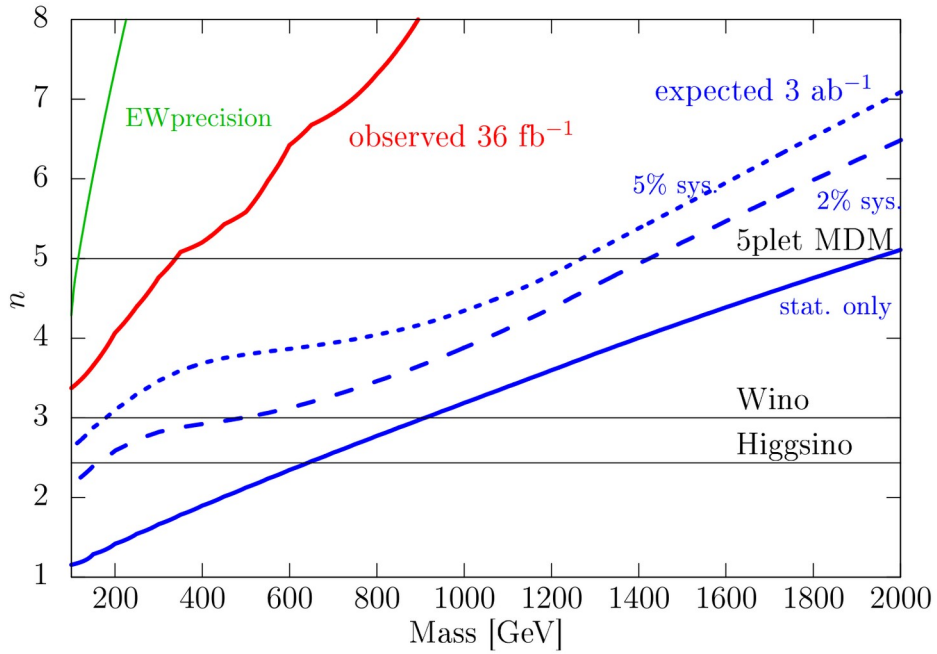


Optimistic setup: 600 GeV Higgsino at future LHC

Constraints and Prospects

of SU(2) representation

mono-lepton signal



Optimistic setup: 600 GeV Higgsino at future LHC

Pessimistic setup: 150 GeV Higgsino

μTRISTAN

$\mu^+\mu^+$ Collider by using technology of μ^+ beam for g-2 measurement at J-PARC. [Hamada+, 2201.06664]

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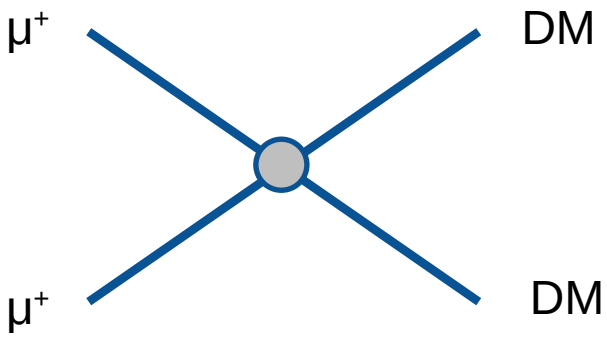
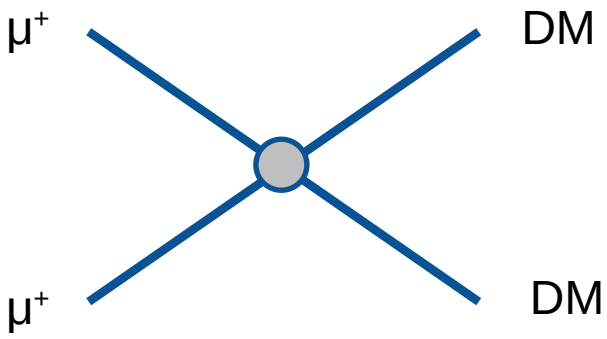
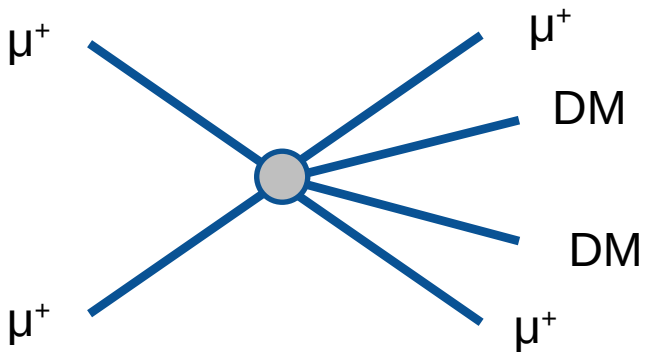


Lepton number is violated.

μTRISTAN

$\mu^+\mu^+$ Collider by using technology of μ^+ beam for g-2 measurement at J-PARC. [Hamada+, 2201.06664]



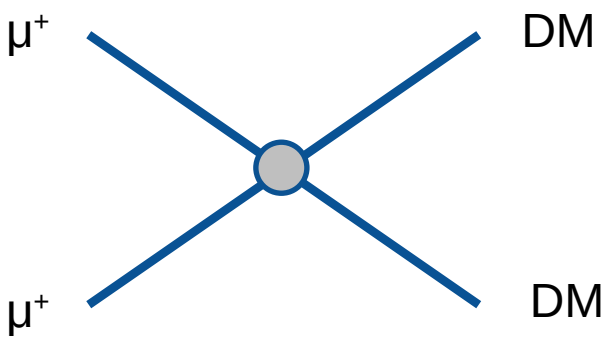


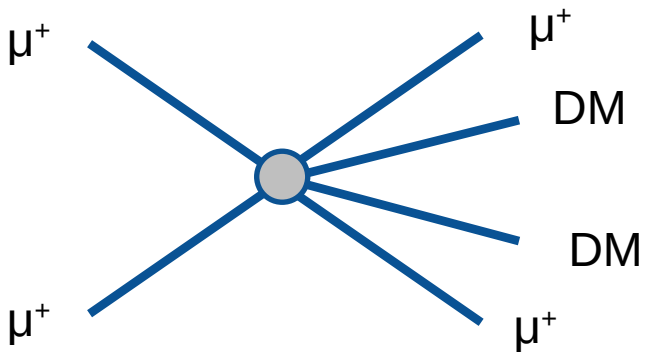
Lepton number is violated.

Reducing cross section.

μTRISTAN

$\mu^+\mu^+$ Collider by using technology of μ^+ beam for g-2 measurement at J-PARC. [Hamada+, 2201.06664]





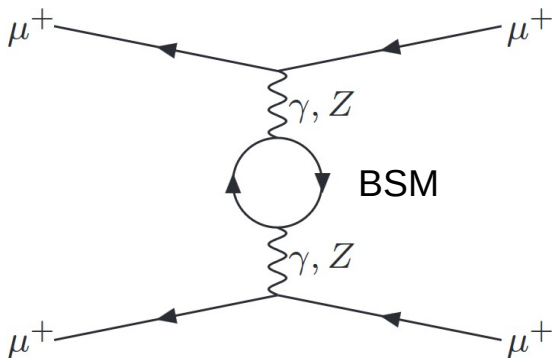
Lepton number is violated.

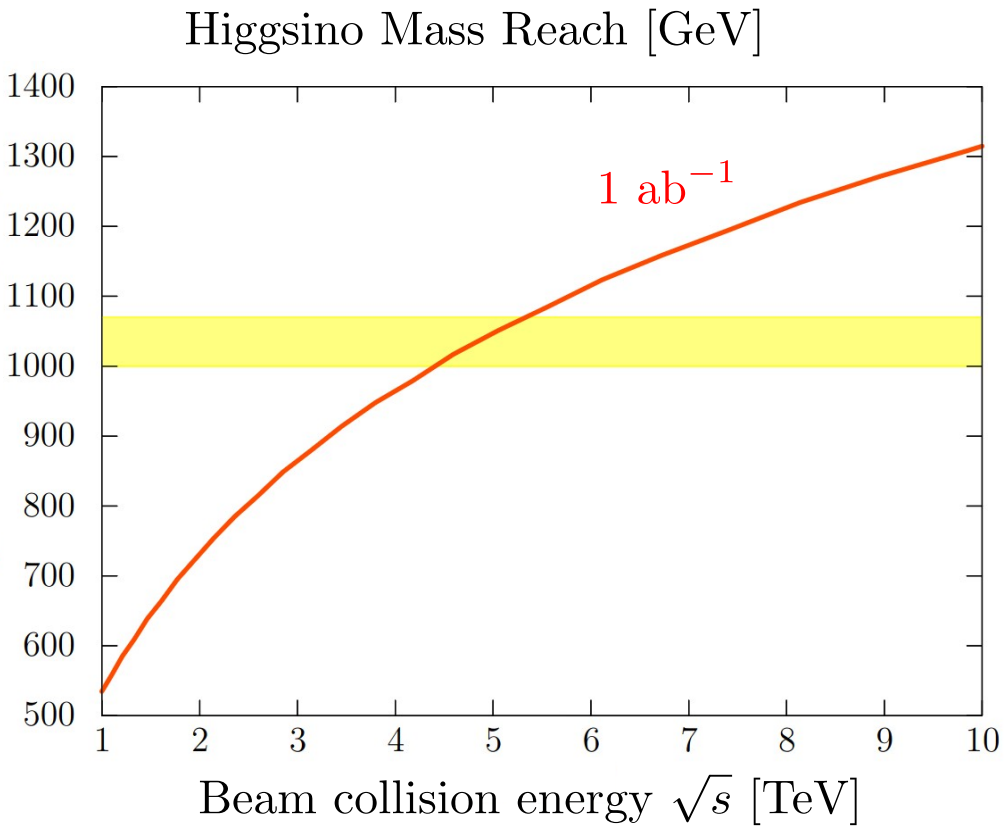
Reducing cross section.

10 TeV collision energy ➡ 1 TeV Higgsino

Indirect Probe of μTRISTAN

[Okabe & SS, 23]
[Fukuda, Moroi, Niki & Wei, 23]





Summary and Prospects

- Exotic tracks can significantly improve DM search.
  - Disappearing charged tracks for pure-Higgsino / Wino.
  - (Displaced) soft pion.
    - LEP, ATLAS search.
    - TODO; ILC, muon-collider, μTRISTAN.
- Indirect search can probe DM without specifying decay chain.
  - May outperform direct production.
  - Needs good understanding both theoretical and experimental systematics.