Search for compressed higgsinos using low-momentum mildly-displaced tracks

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LLP2024: Fourteenth workshop of the Long-Lived Particle Community

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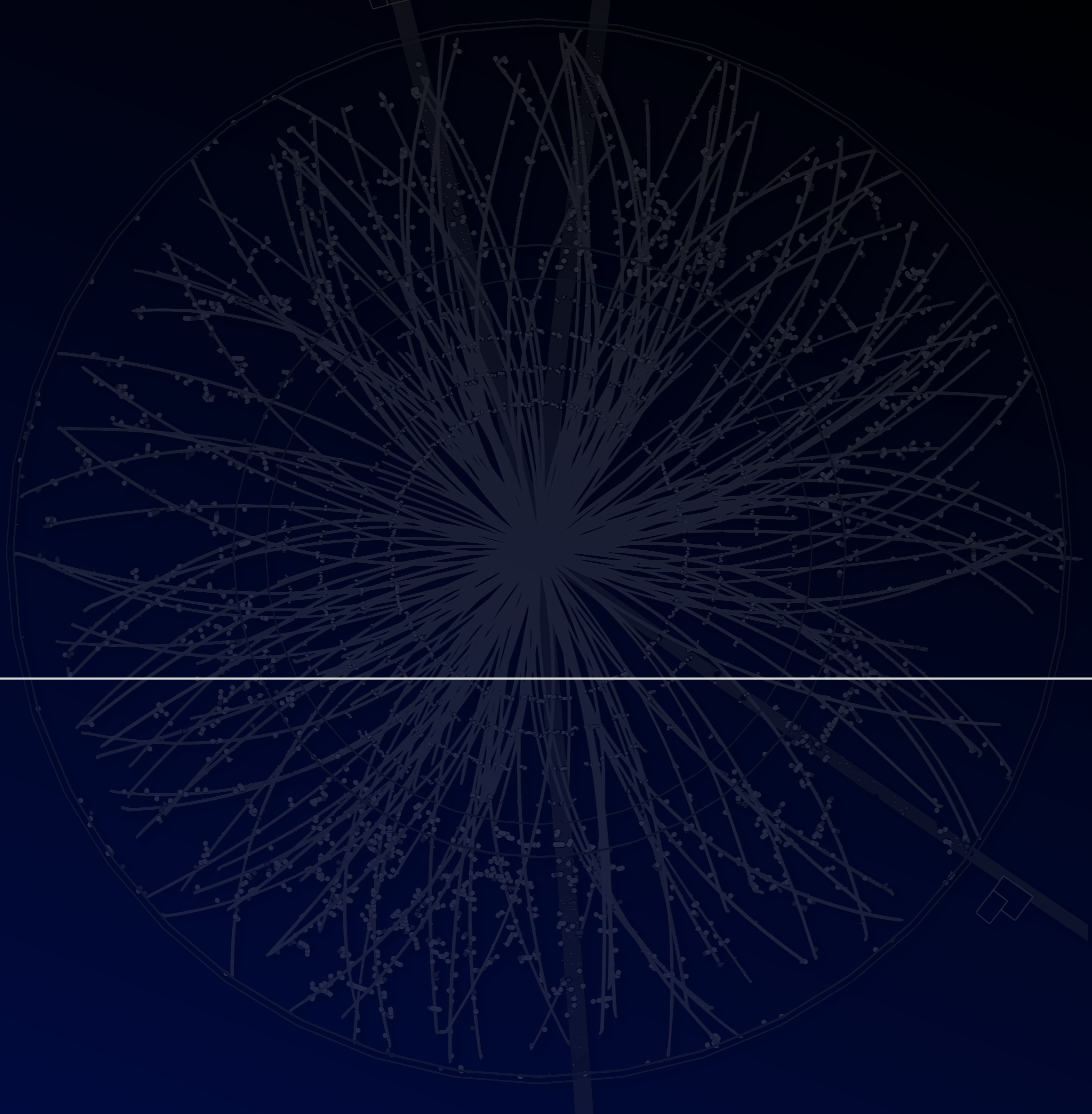
INTRODUCTION

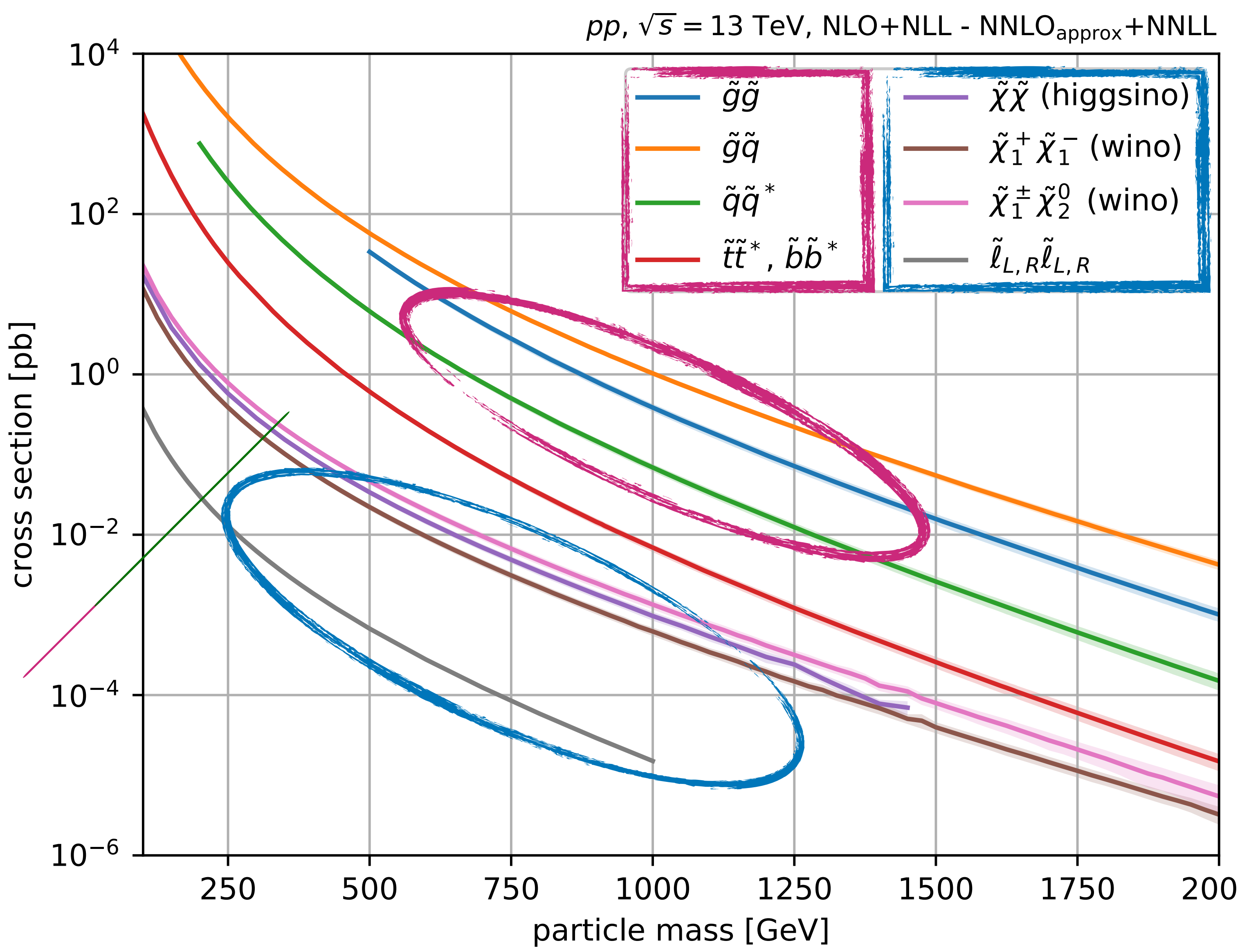


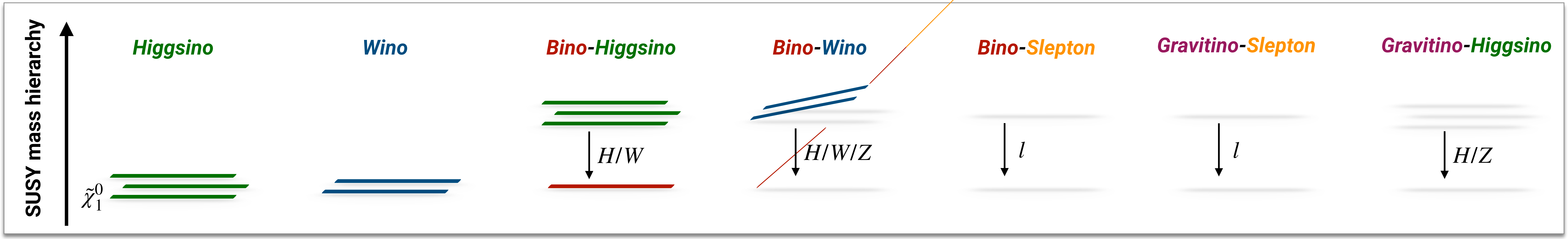
SUSY Searches in LHC

- **Strong production** & **Electroweak production** in LHC
  - *Large cross section*
  - *Energetic jet activities*
  - *Small cross section*
  - *Small mass splitting*
    - *soft objects*

- **Different search strategies for different Lightest SUSY Particle (LSP)**
  - Various mass hierarchies predicted from various motivations
    - *Naturalness, dark matter, SUSY breaking model etc.*

SUSY production cross section in LHC





Broad program of searches targetting different final states ➡ Focus on "light Higgsinos" in this talk

Electroweak Naturalness

- In the MSSM, the following equation holds by requiring minimization of the Higgs potential

Minimization condition

$$\frac{\partial V}{\partial H_u^0} = \frac{\partial V}{\partial H_d^0} = 0 \quad \Rightarrow \quad -\frac{m_Z^2}{2} = \underbrace{|\mu^2|}_{\text{Higgsino mass}} + m_{H_u}^2$$

Higgsino mass is close to the electroweak scale ($\mathcal{O}(100)$ GeV) ("Electroweak Naturalness")

- If the bino & wino mass are decoupled ($\mu \ll M_1, M_2$), light charginos & neutralinos ($\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$) are pure higgsinos

➡ **Higgsinos form a "compressed mass spectrum"**

Higgsino-like LSP

$|\mu| \ll M_1, M_2$

$m_{\tilde{\chi}_1^\pm} \sim \mu$

$m_{\tilde{\chi}_{1,2}^0} \sim \mu$

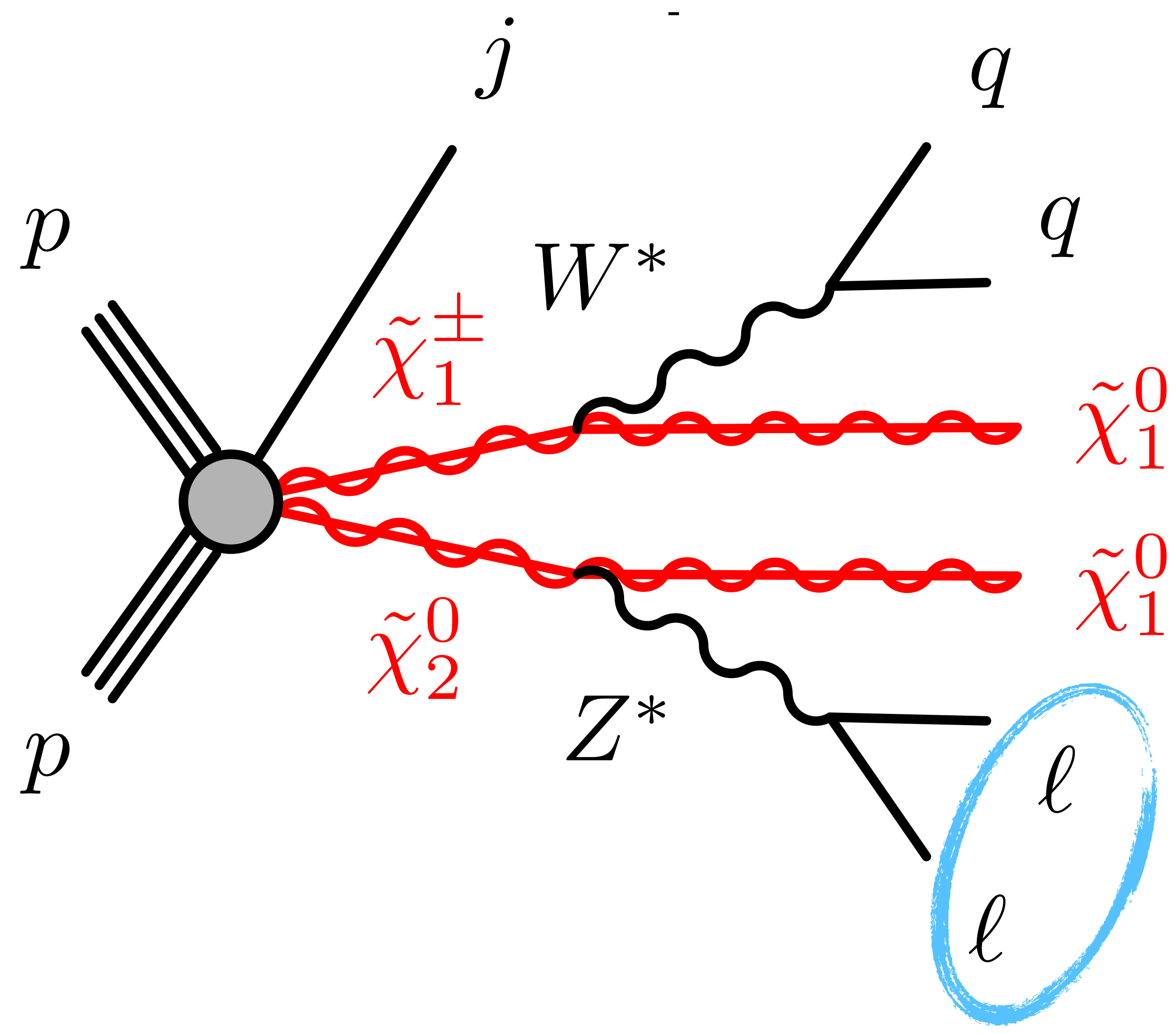
Higgsino Searches by Collider Experiments

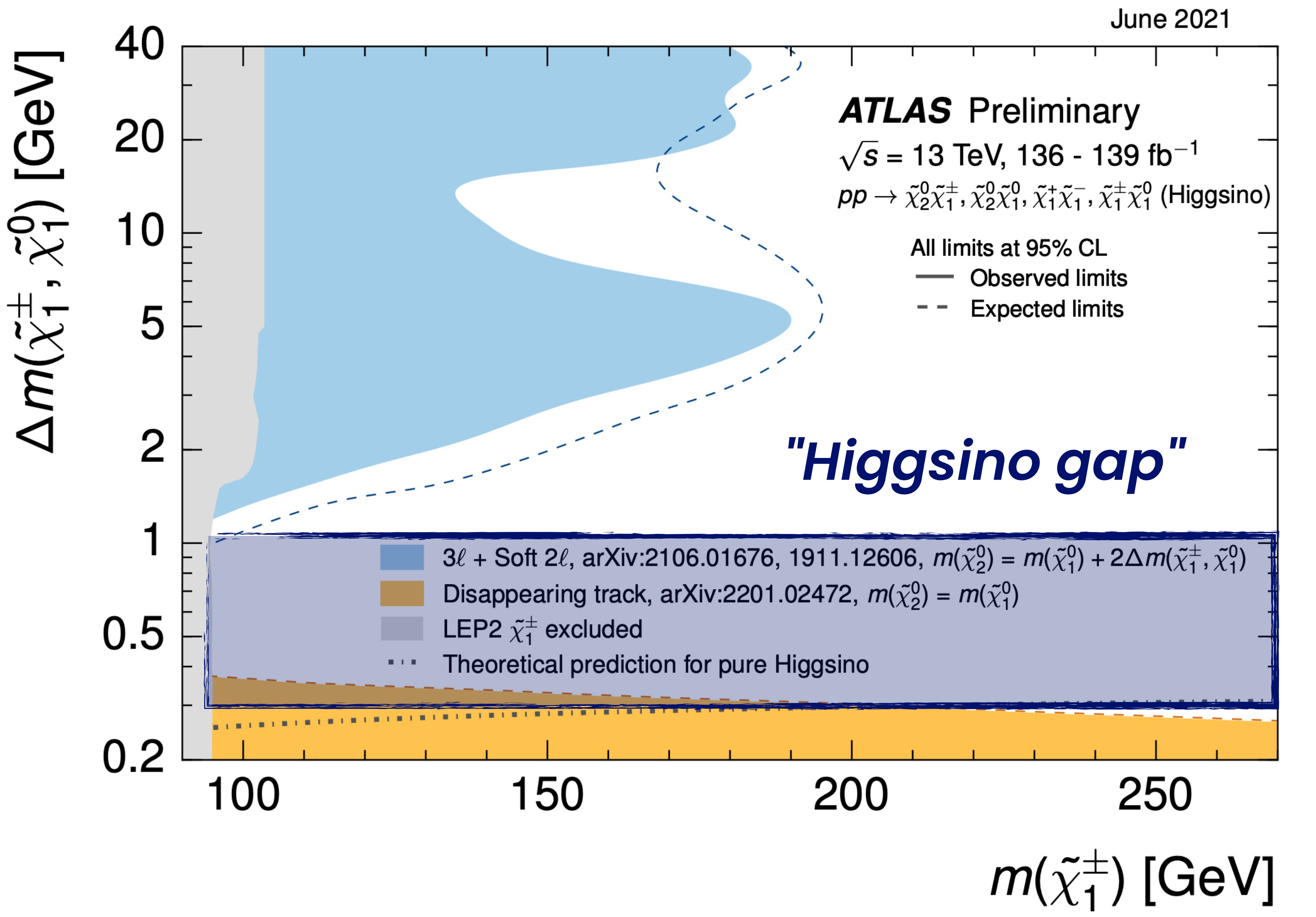
Compressed higgsino states explored by existing searches (Soft 2L + Disappearing track)

- **Soft 2-lepton** : Leptons too soft to be reconstructed
- **Disappearing track** : $\tilde{\chi}_1^{\pm}$ lifetime is too short to pass enough inner detector layers

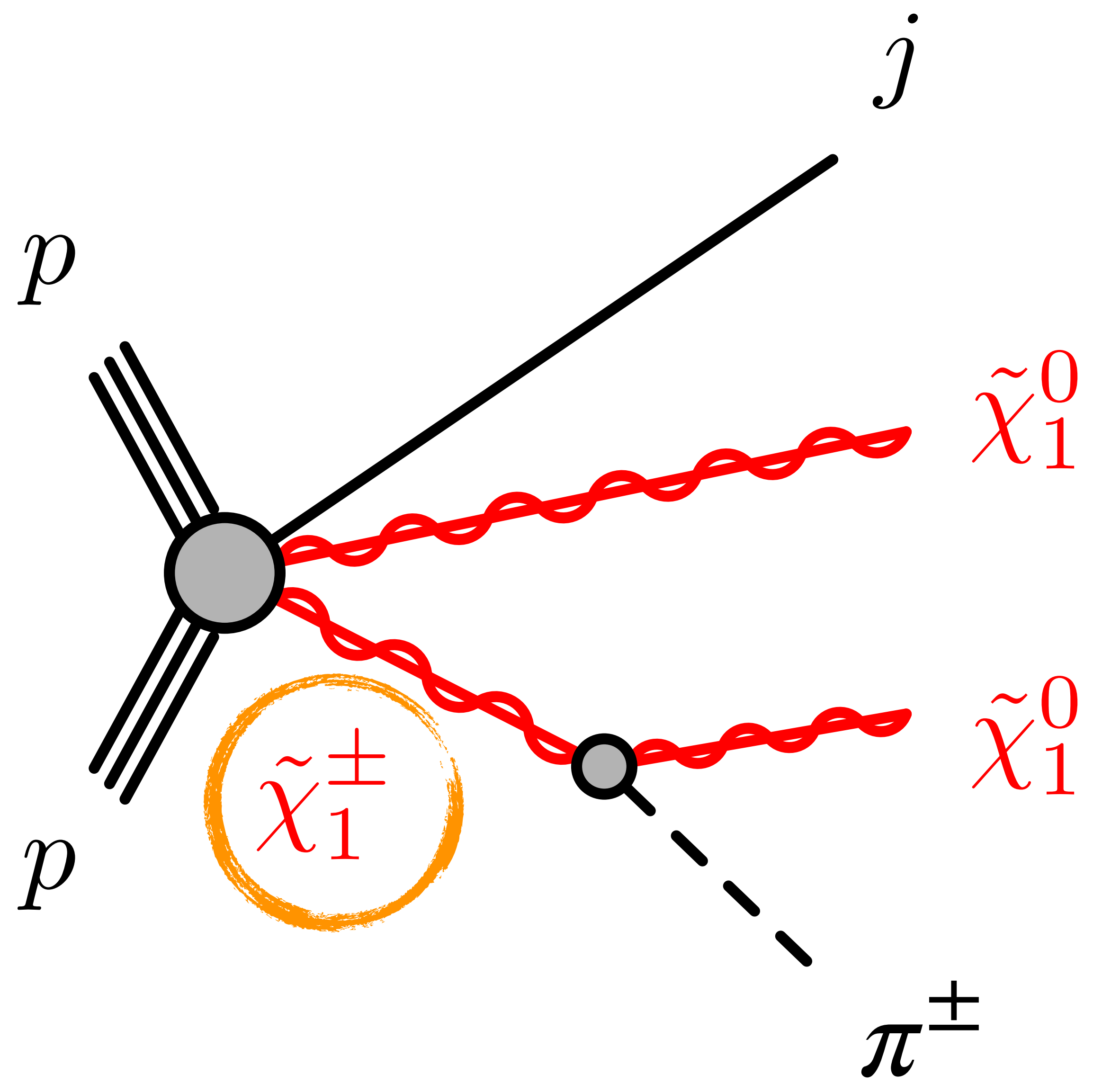
➡ **New analysis method required to cover the compressed mass region ("Higgsino gap")**

Soft 2-lepton





Disappearing track

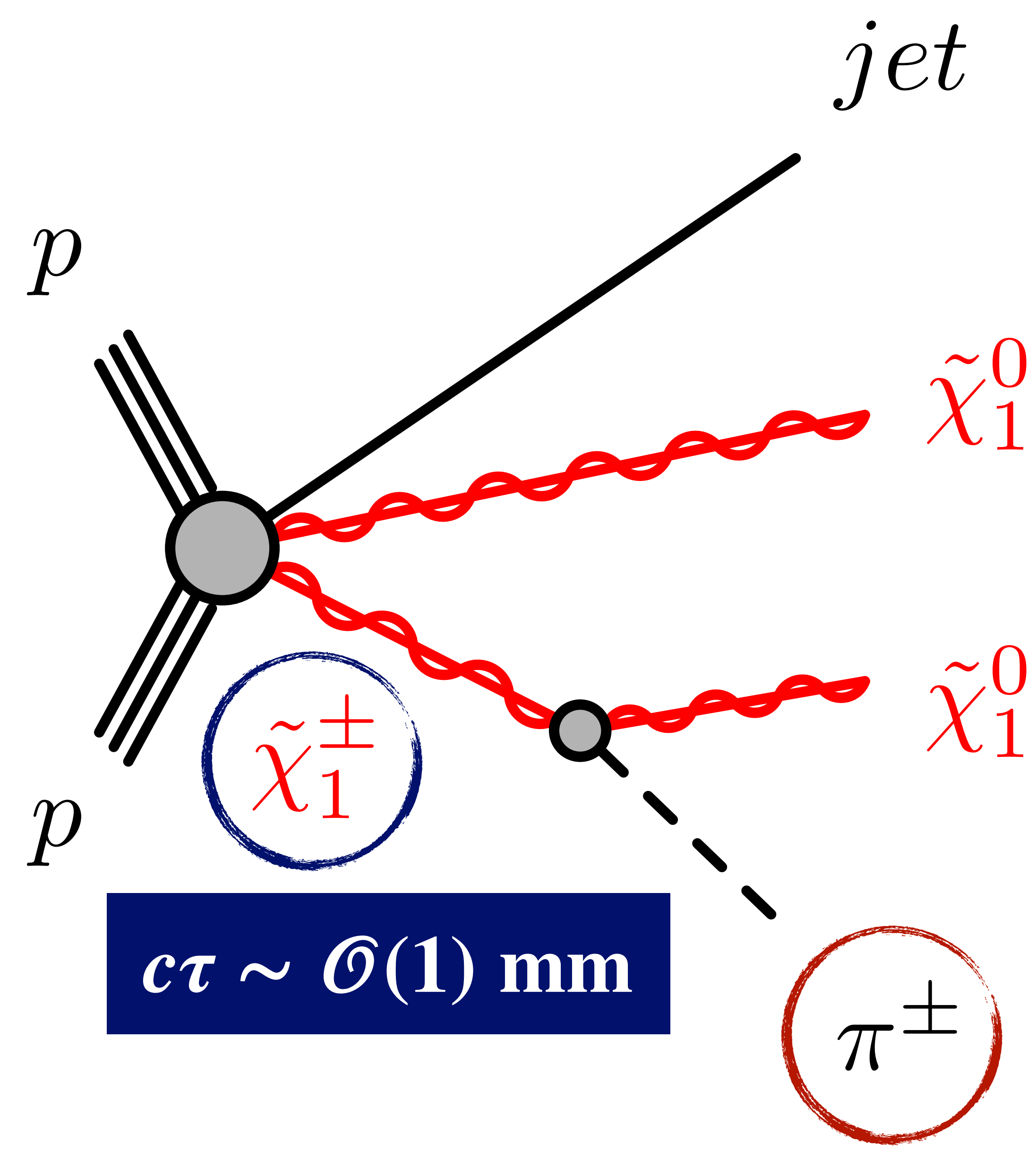


Analysis Strategy

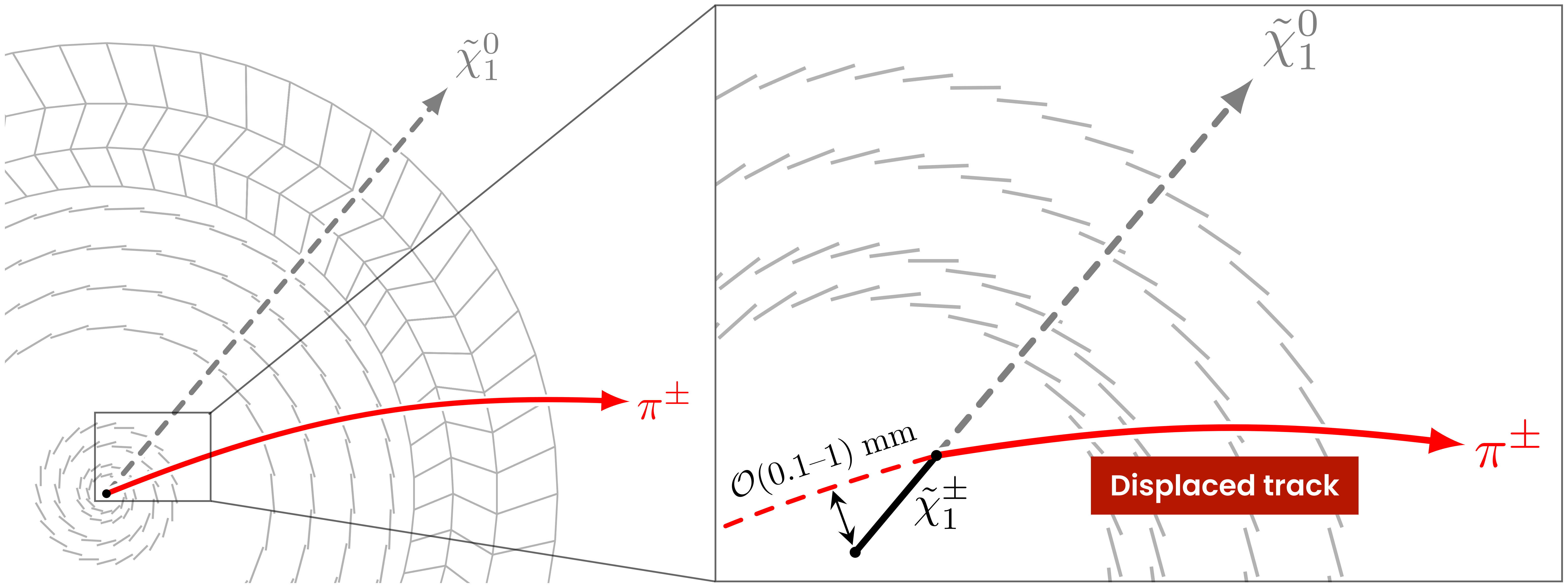
In the Higgsino gap region, $\tilde{\chi}_1^\pm$ acquire a lifetime of order $c\tau \sim \mathcal{O}(1)$ mm

- $\tilde{\chi}_1^\pm$ decay produce tracks with slightly large impact parameters (d_0)
- Identify $\tilde{\chi}_1^\pm$ decay tracks by requiring a **"mildly displaced track"** : $S(d_0) = |d_0|/\sigma(d_0)$
  - Idea from the "cornering higgsino" paper [H. Fukuda et al., Phys. Rev. Lett. 124, 101801 (2020)]

Signal diagram



Schematics of the "mildly displaced track"

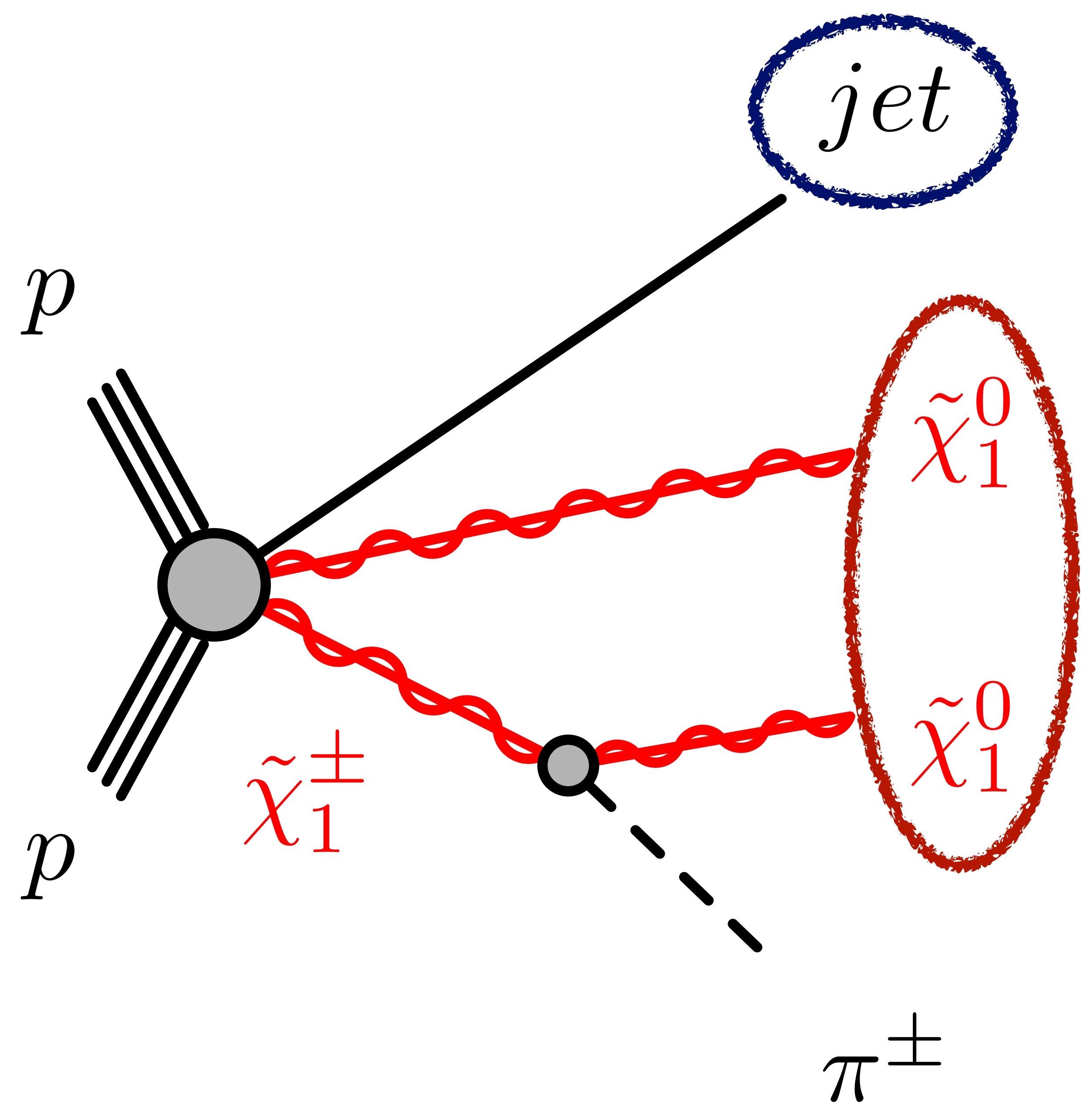


ANALYSIS : EVENT SELECTION

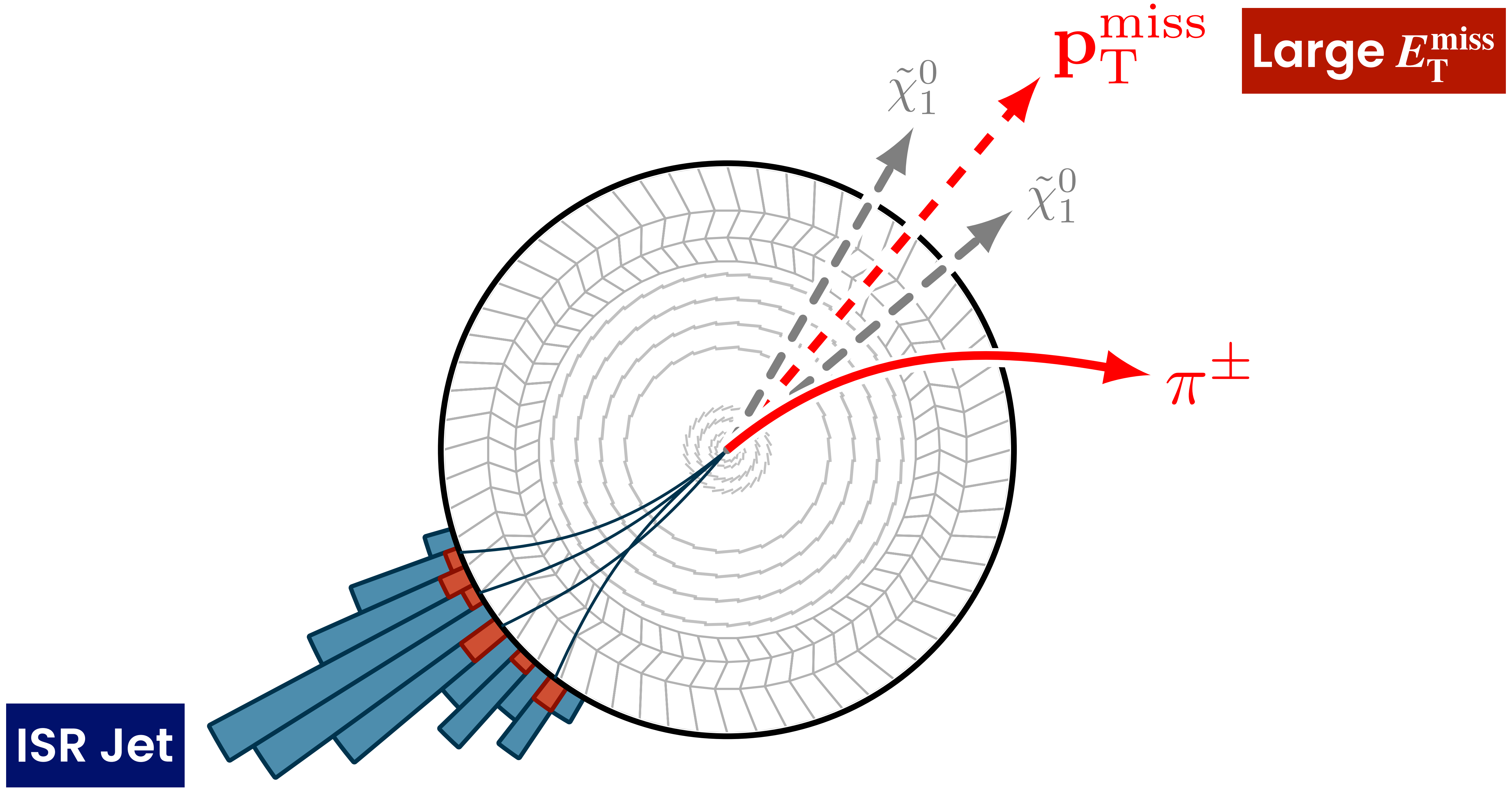
Event Selection

Large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the LSP

- Require **Initial State Radiation (ISR)** topology to boost the SUSY system
- Trigger events and suppress background by requiring a **large $E_{\mathrm{T}}^{\mathrm{miss}}$**



Feynman diagram

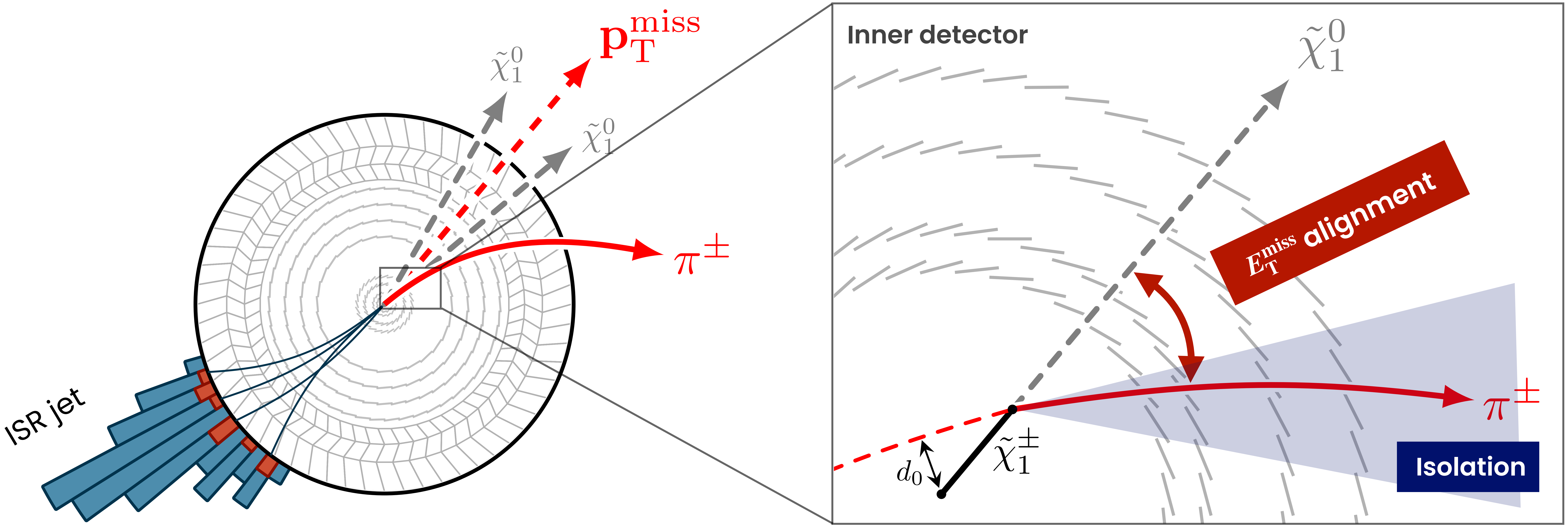


Schematics of "jets+$E_{\mathrm{T}}^{\mathrm{miss}}$" topology

Track Selection

Displaced track from the chargino decay

- **E_T^{miss} alignment** : $\tilde{\chi}_1^\pm$ boosted in the opposite direction of the ISR jet ➡ Track aligned with E_T^{miss}
- **Track Isolation** : To reduce tracks from long-lived SM particles (τ lepton, strange hadrons), which produce multiple decay products, require isolated tracks

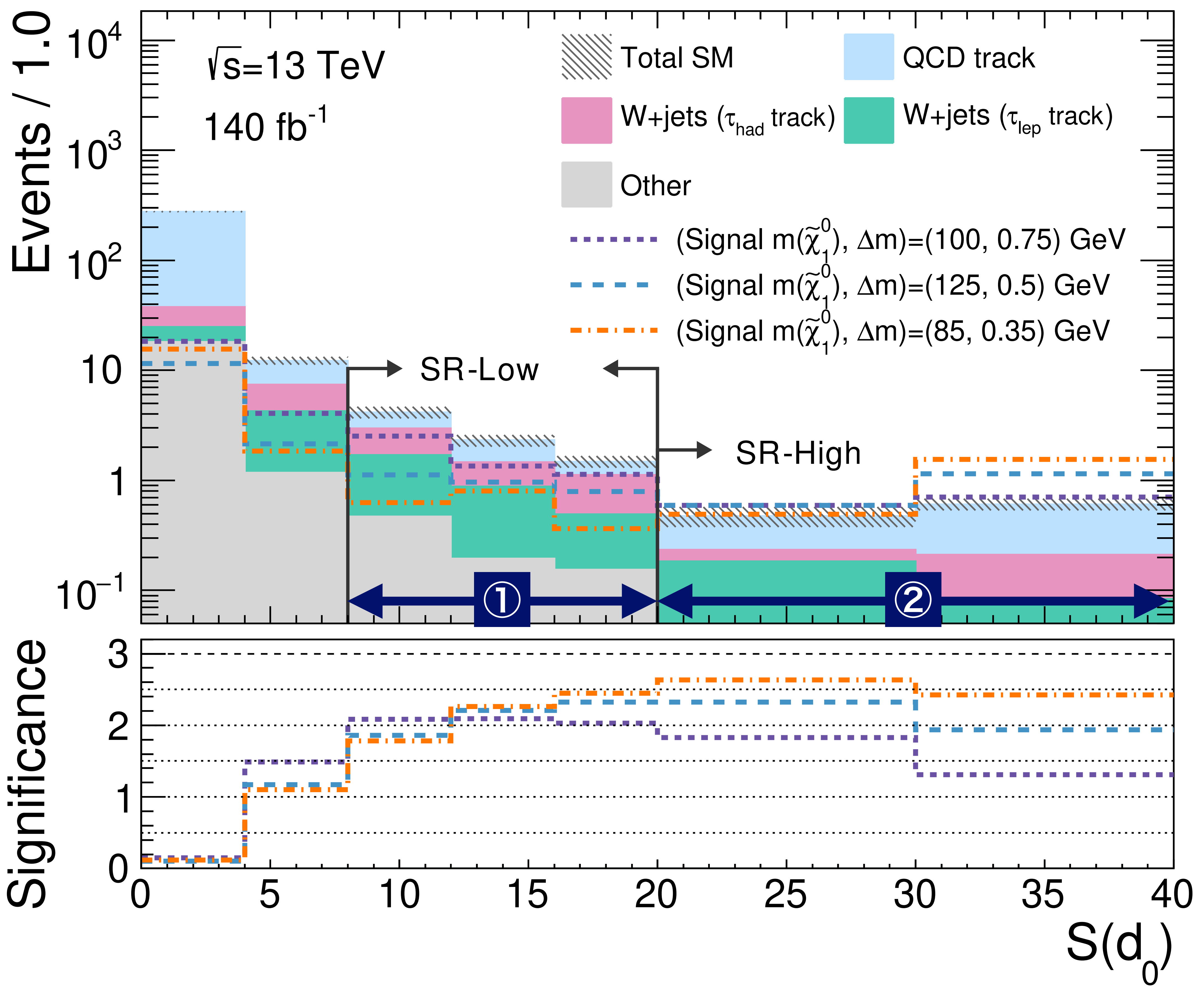


Signal Region Definition

- Require additional selections to improve sensitivity and define SRs
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 600$ GeV ⬅ Large $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $2.0 < p_{\mathrm{T}} < 5.0$ GeV ⬅ Low-momentum track
  - $S(d_0) > 8$ ⬅ Displaced track

- SR subdivided into two $S(d_0)$ orthogonal bins to target different $\tilde{\chi}_1^{\pm}$ lifetime (= mass splitting)
  - ① **SR-Low** : $S(d_0) \in [8, 20]$
  - ② **SR-High** : $S(d_0) \in [20, \infty]$

Track $S(d_0)$ distribution



ANALYSIS : BACKGROUND ESTIMATION

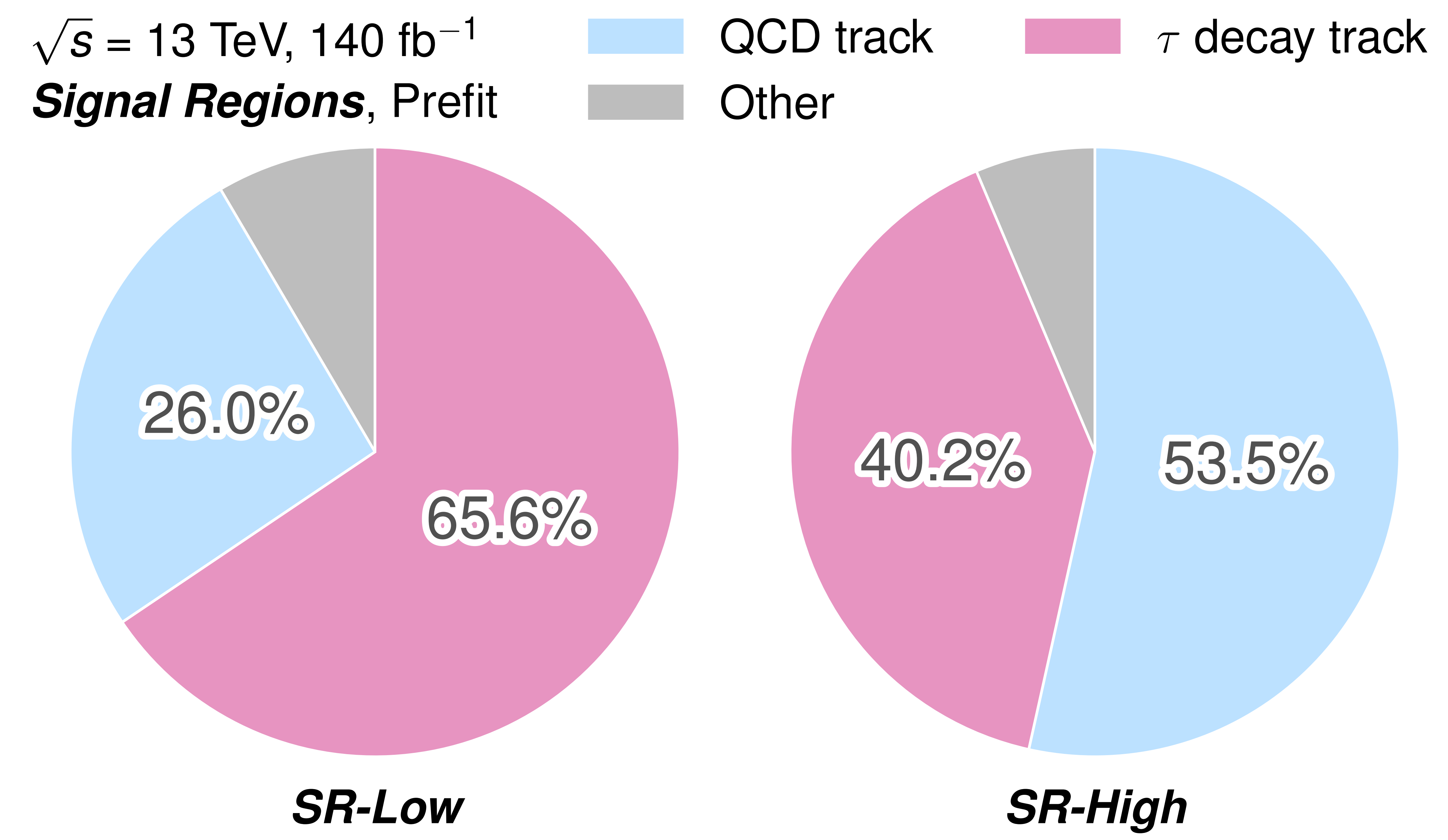
Background Estimation : Overview

Background : Large E_T^{miss} + Displaced track with large $S(d_0)$

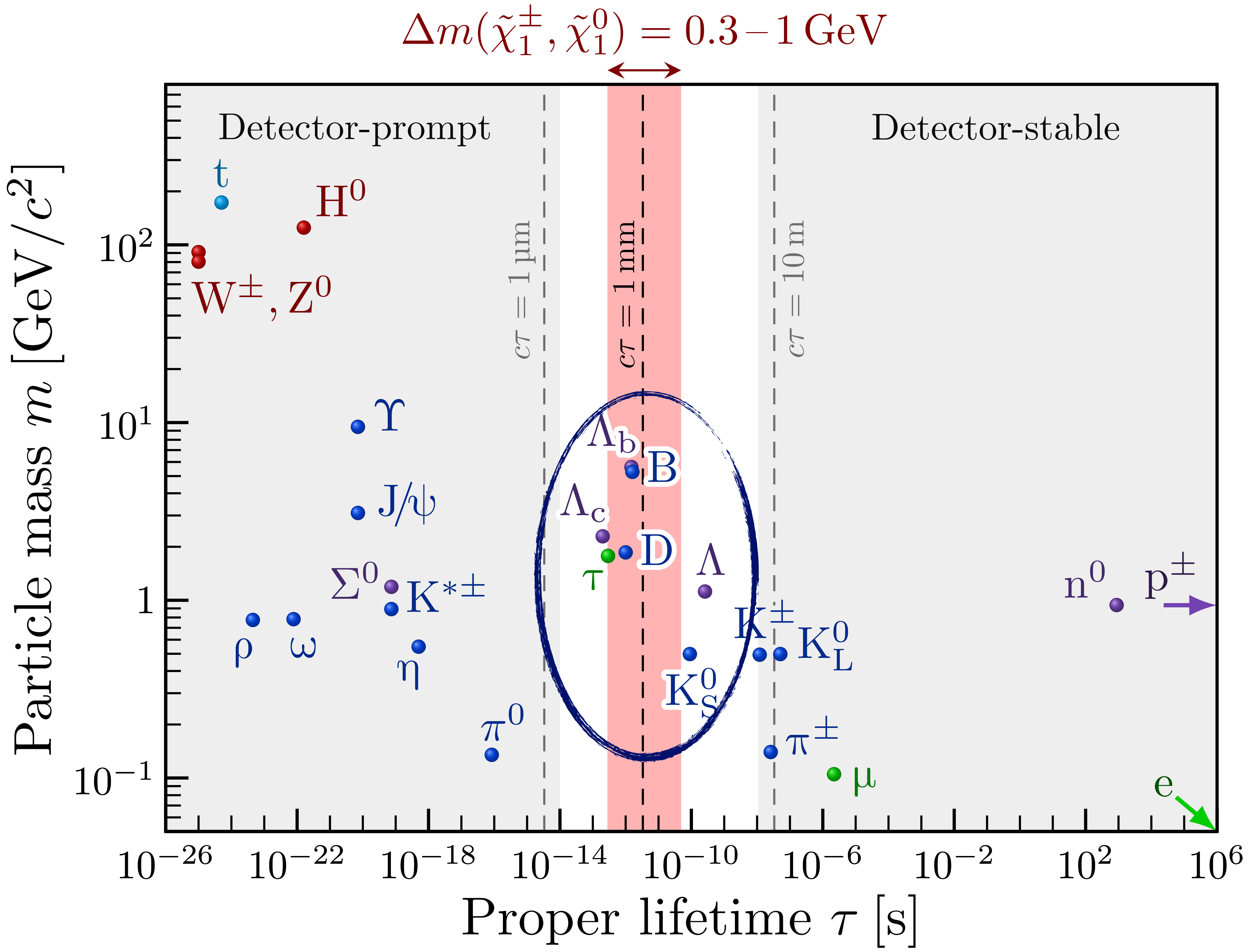
- $Z \to \nu\nu, W \to \ell\nu$: **Tracks from B/D or Strange hadrons (QCD track)** ➡ **Data-driven**
- $W \to \tau\nu$: **Tracks from leptonic & hadronic τ decays (τ decay track)** ➡ **Semi data-driven**

Estimation method

Background composition in the SRs



Lifetime of SM particles

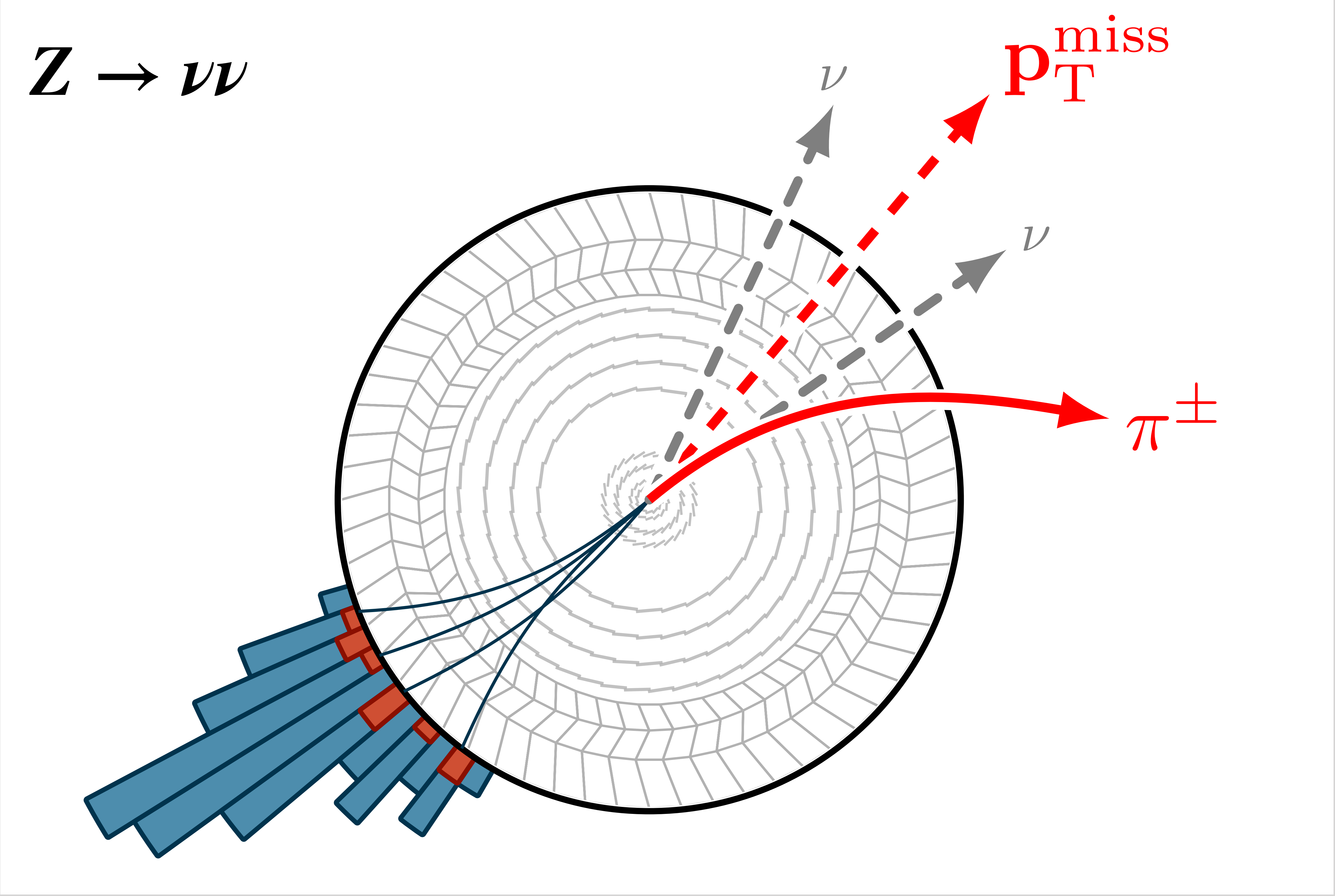


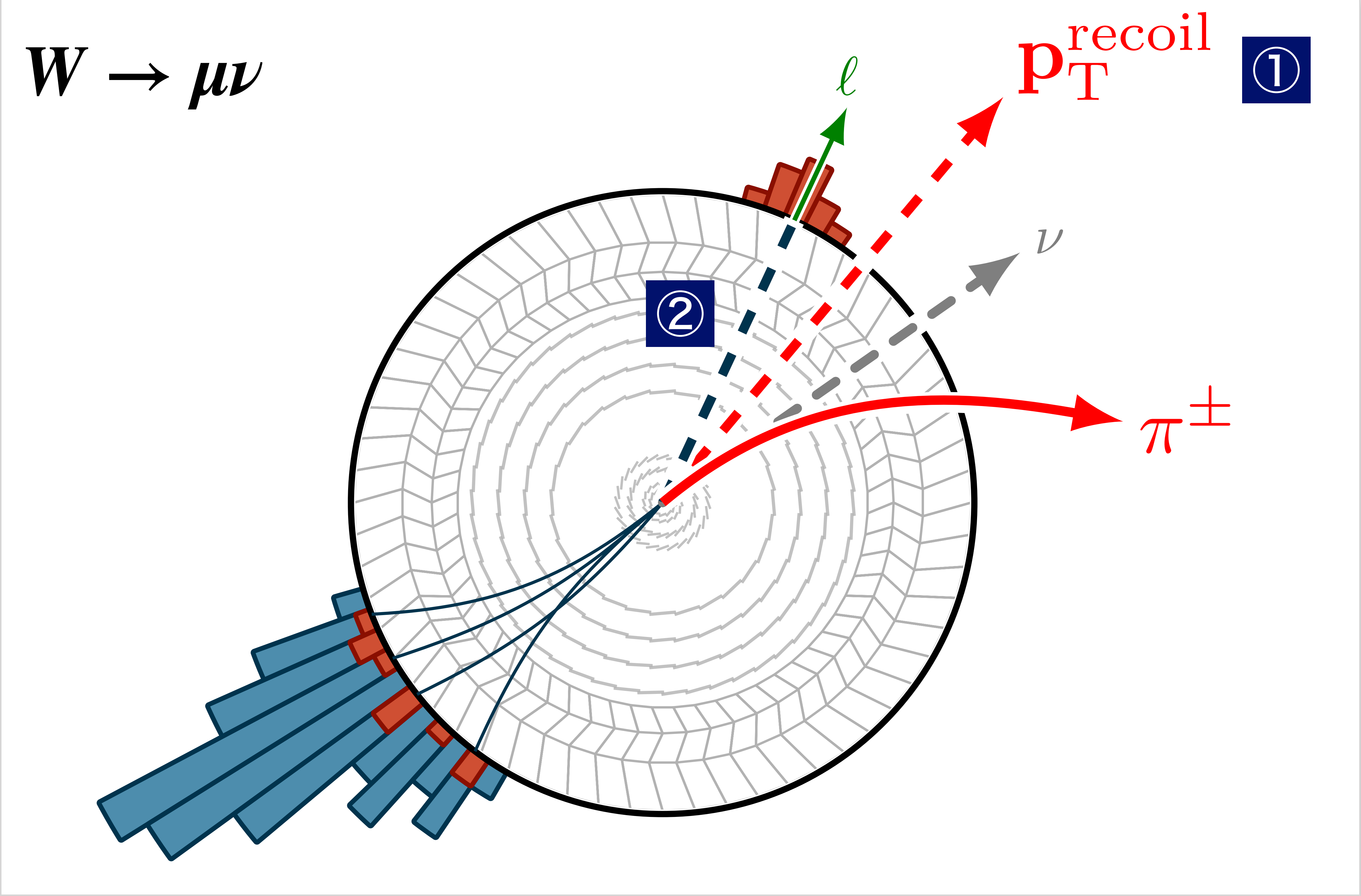
Background Estimation Method : QCD Tracks

The $S(d_0)$ distribution of QCD tracks are difficult to model ➡ Extract distribution from data

- QCD tracks not from the W/Z bosons ➡ **$Z+\text{jets}$ and $W+\text{jets}$ have the same $S(d_0)$ distribution**
- Extract distribution from $W \to \mu\nu$ CR ➡
  - ① Use $\mathbf{p}_\mathrm{T}^\mathrm{recoil} \equiv \mathbf{p}_\mathrm{T}^\mathrm{miss} + \mathbf{p}_\mathrm{T}(\mu)$ as a proxy of W boson p_T
  - ② Remove tracks around the muon*

*$\Delta R(\mu, \text{track}) < 0.04$





Background Estimation Method : Tau Decay Tracks

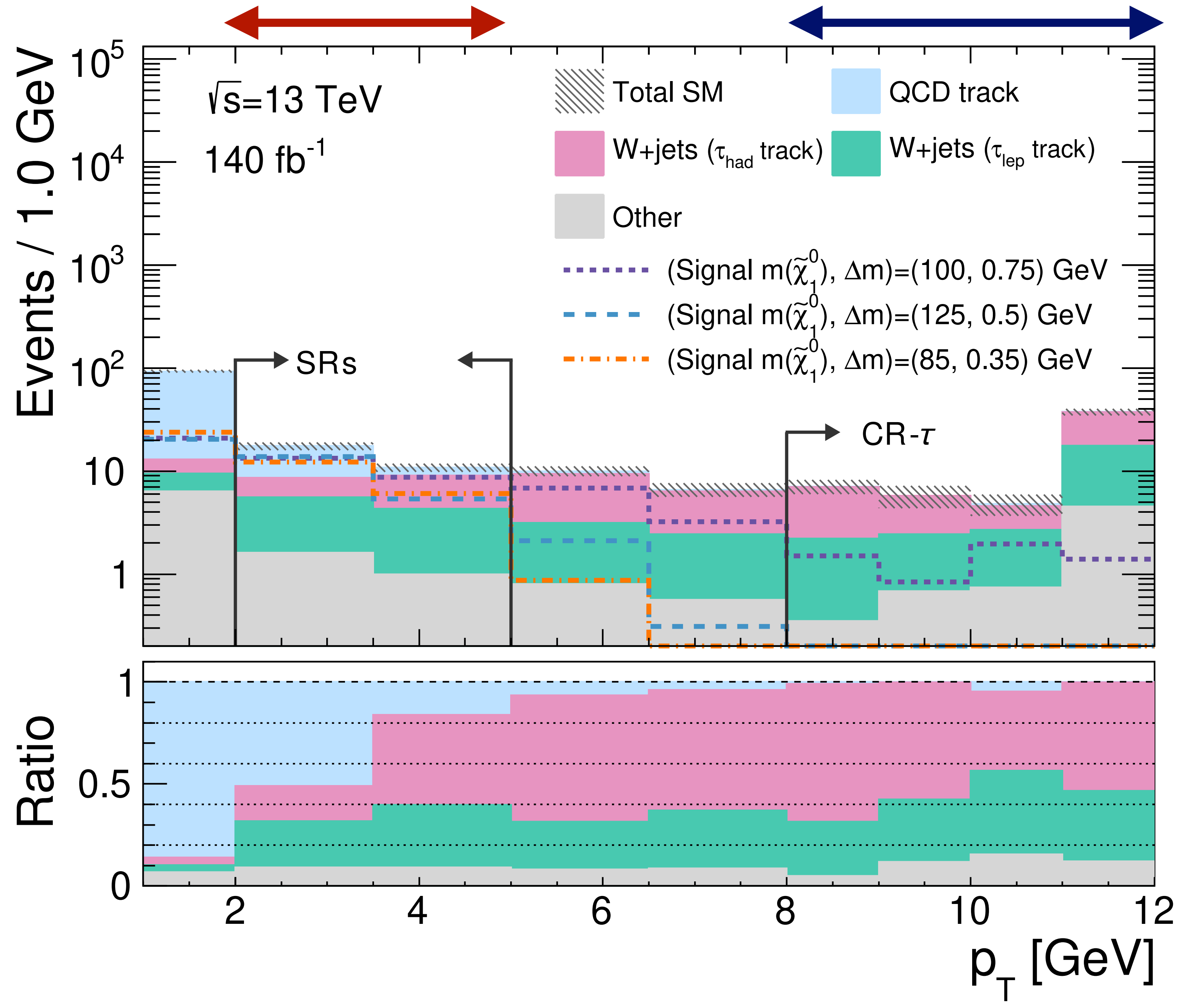
- Two CRs to normalize the τ decay track MC

  ① Hadronic tau CR : Shift track p_{T} range from SR ([2:5] GeV → [8:20] GeV)

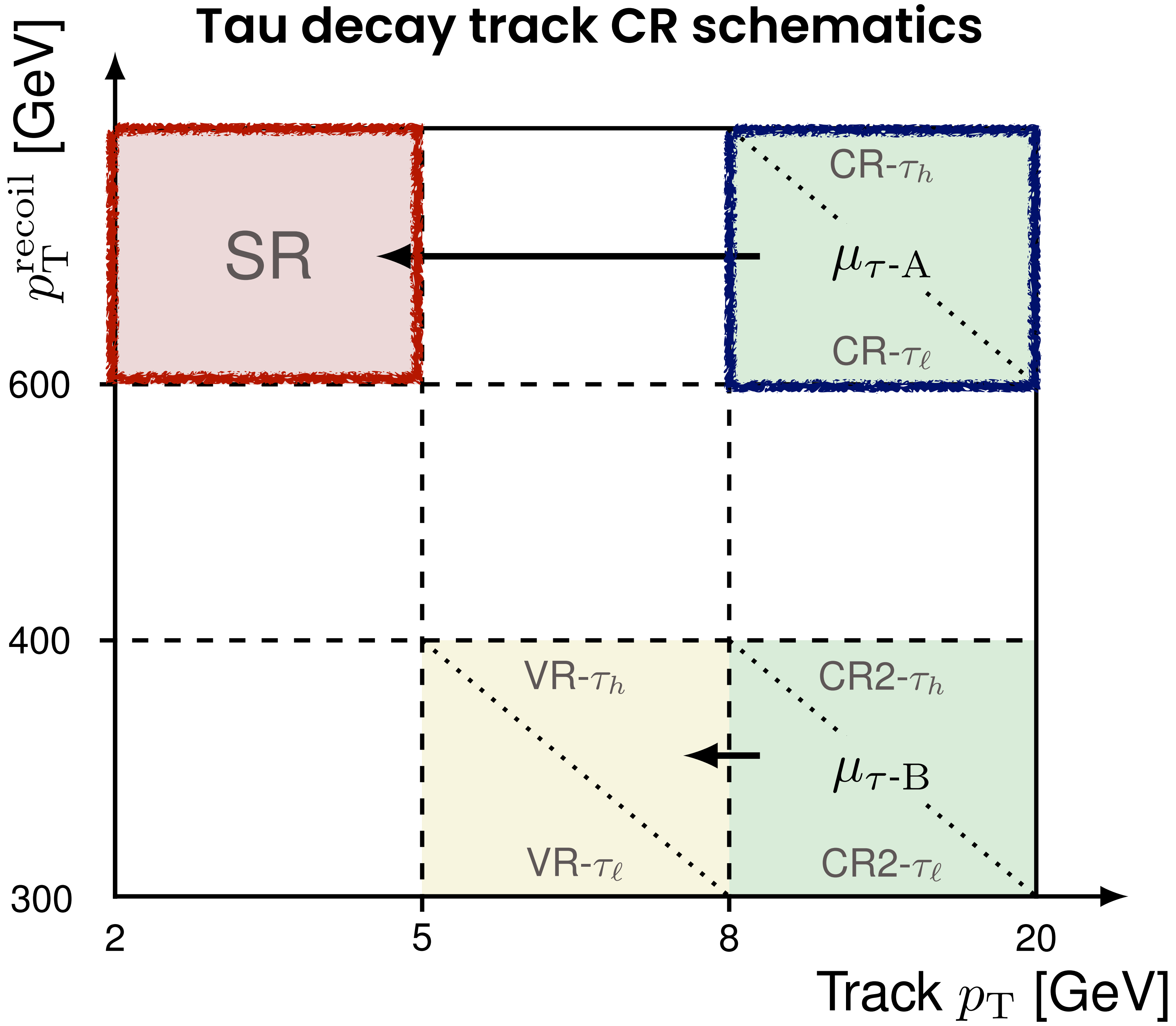
  ② Leptonic tau CR : Require displaced muon $(S(d_0) > 3)$

➡ **Calculate scale factor in high-p_{T} range** and **correct τ decay track in the SR**

Track p_{T} distribution



Tau decay track CR schematics

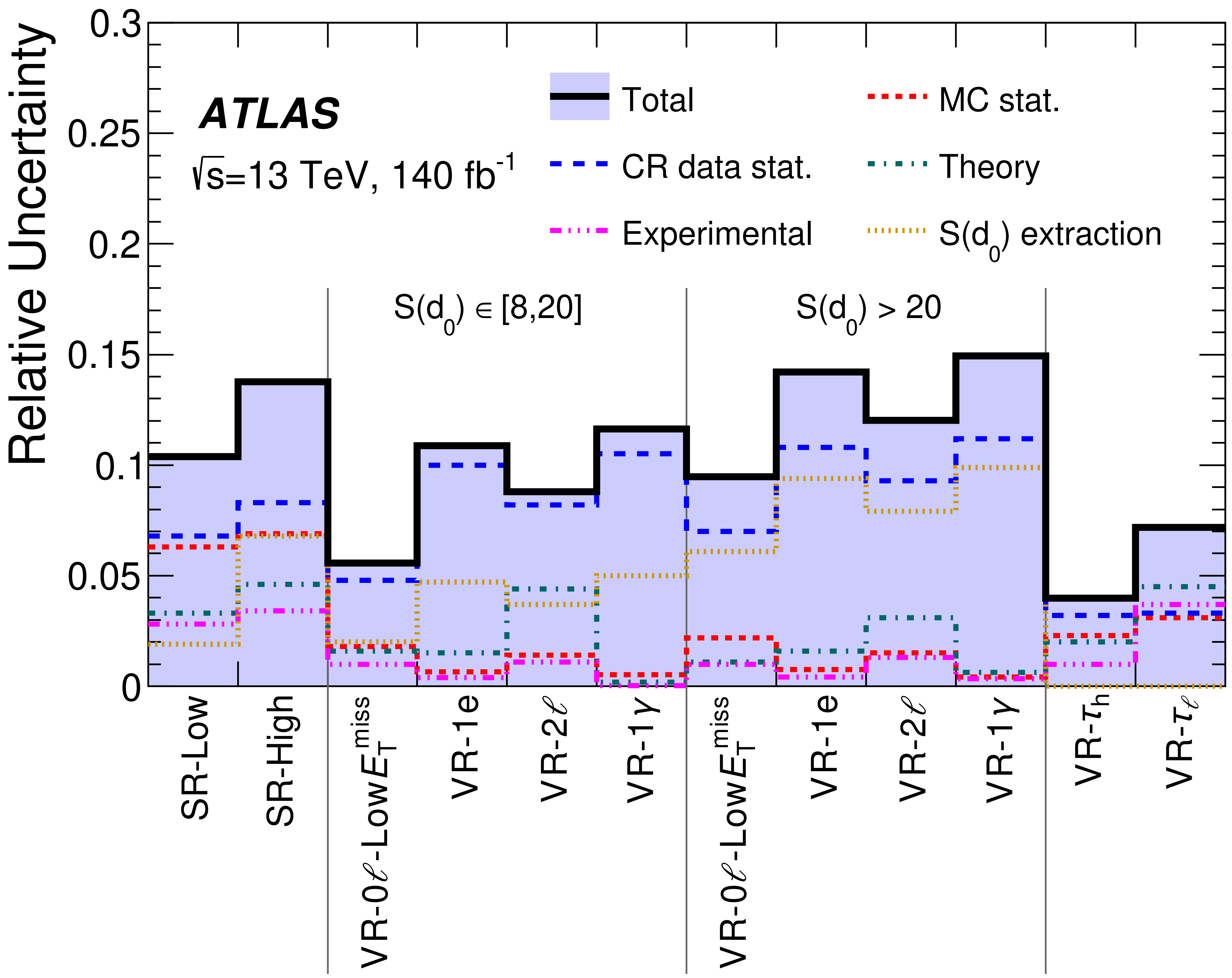


Systematic Uncertainty & Validation Results

Systematic uncertainties in the SRs

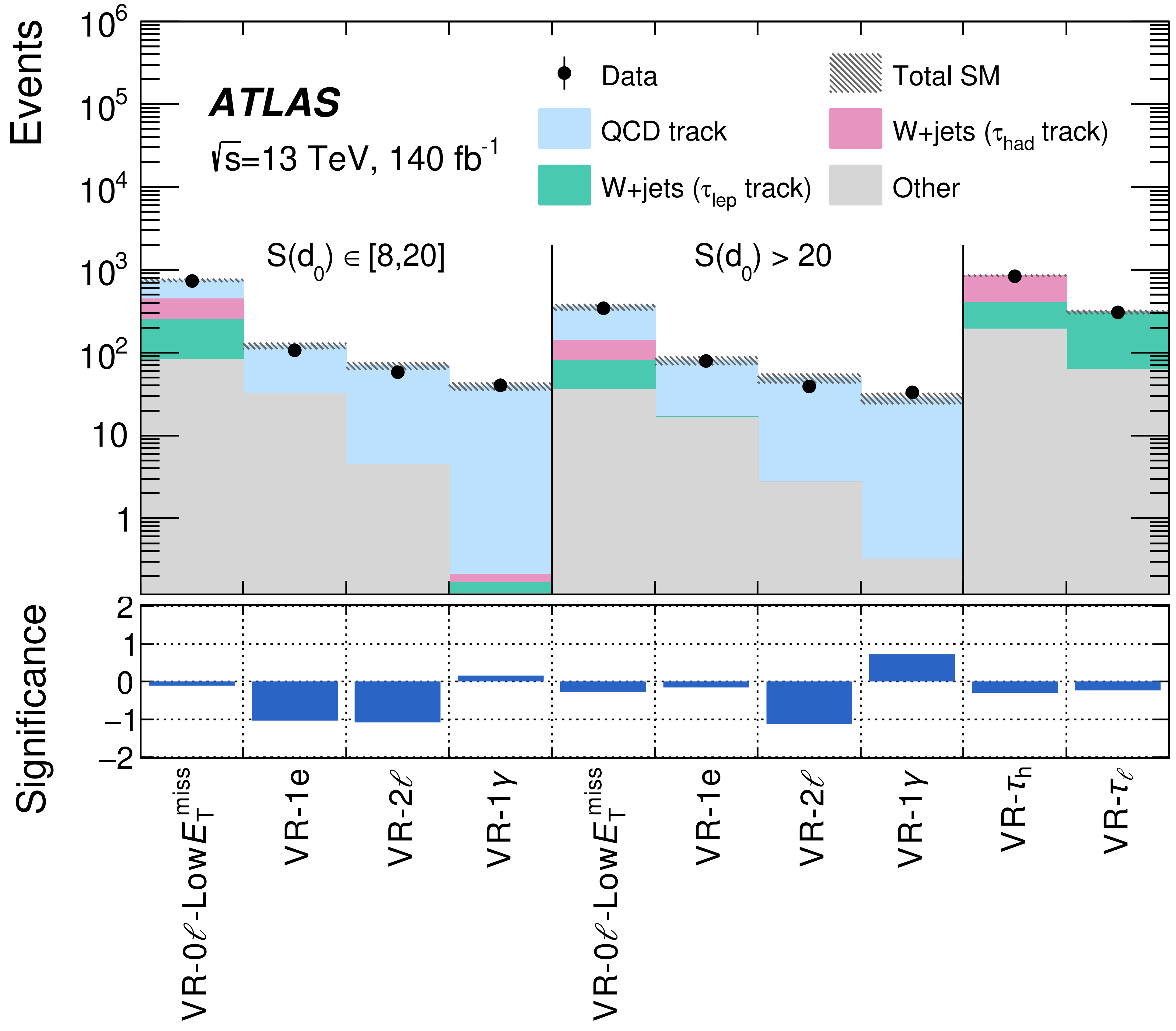
- SR-Low : ~11%
- SR-High : ~14%

} CR statistics + MC statistics

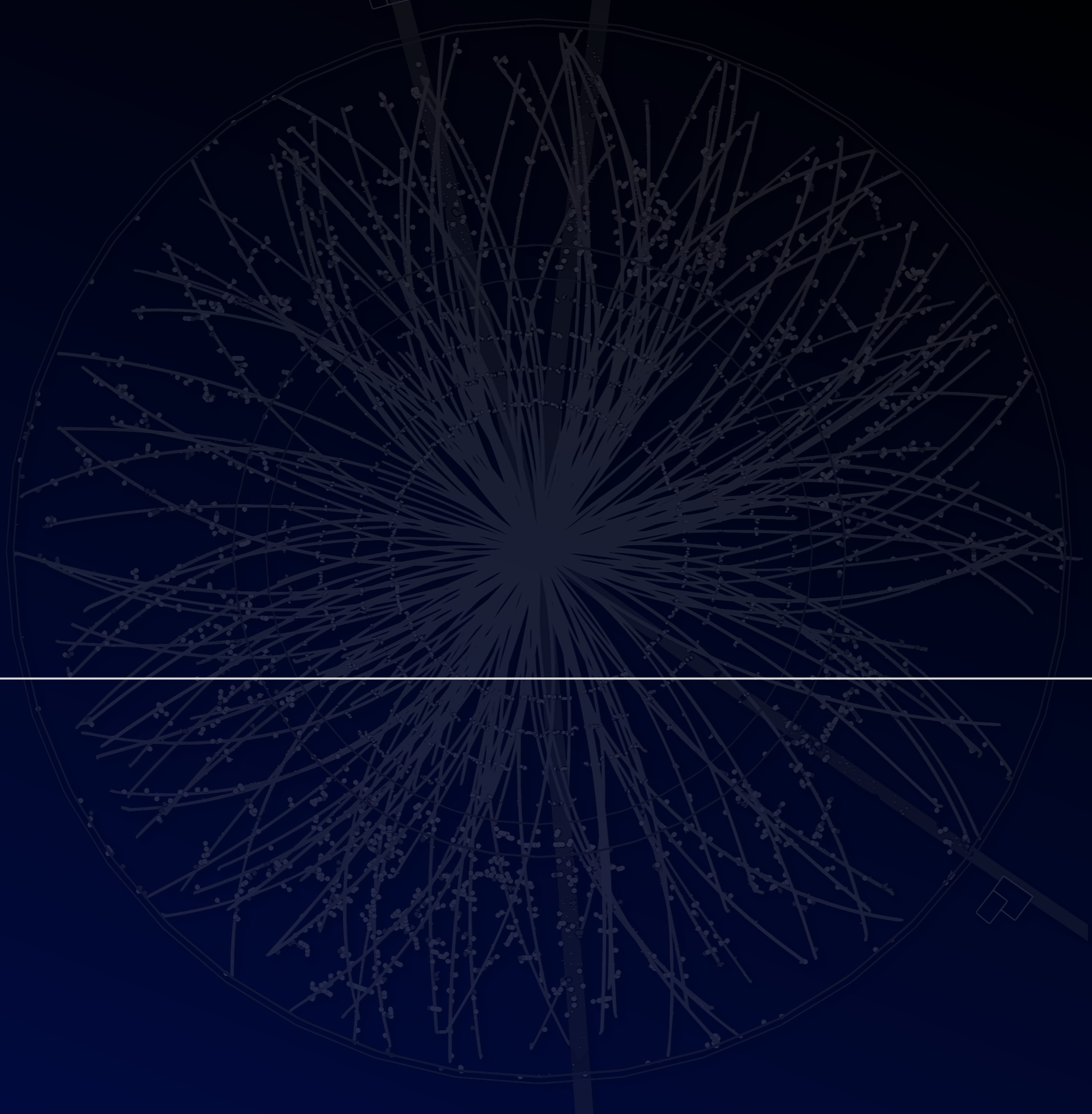


Validation of BG estimation method

- In each VR, the expected and observed yields are consistent within the uncertainty



RESULTS



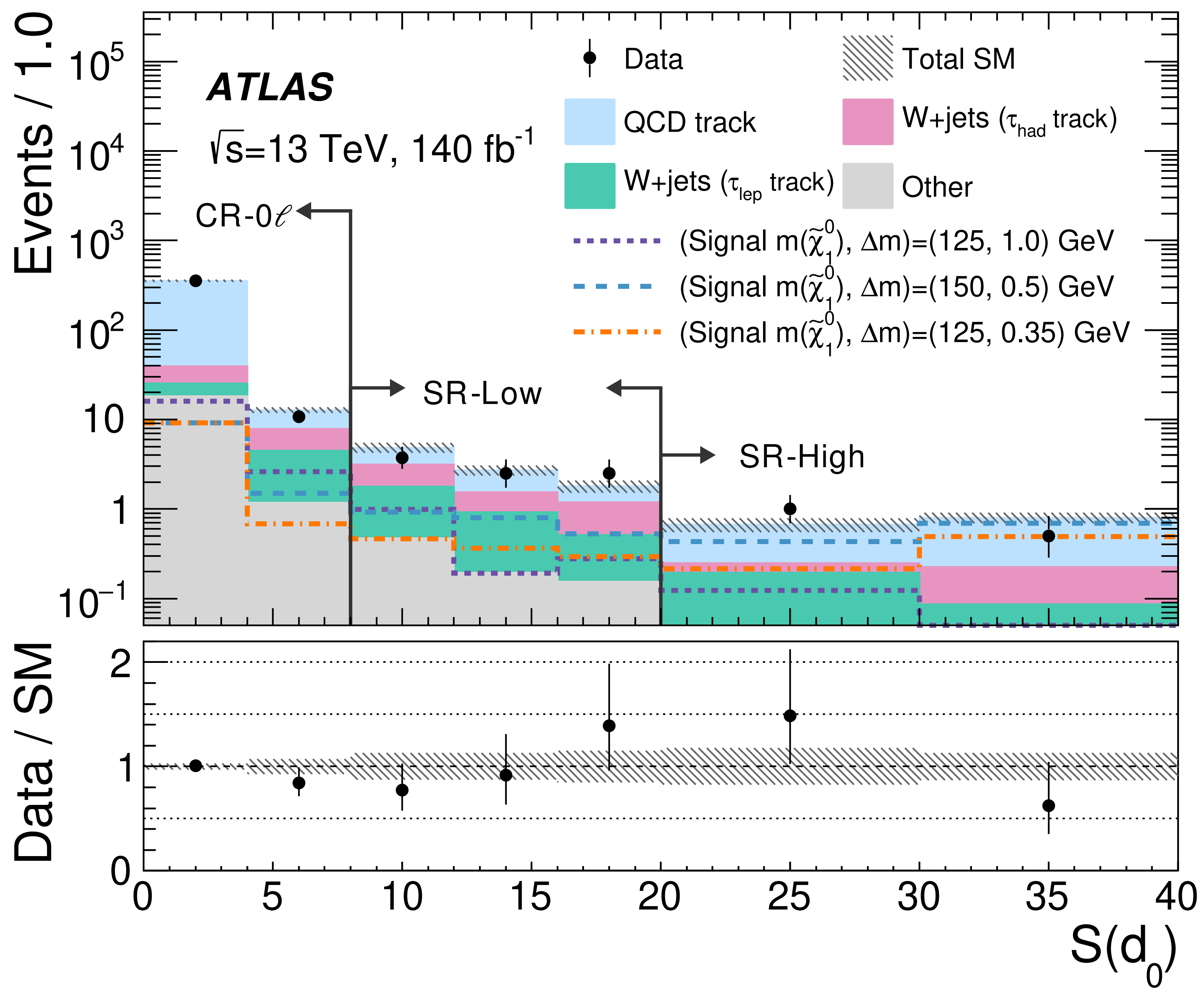
Unblinded Results

No significant data excess in both SRs

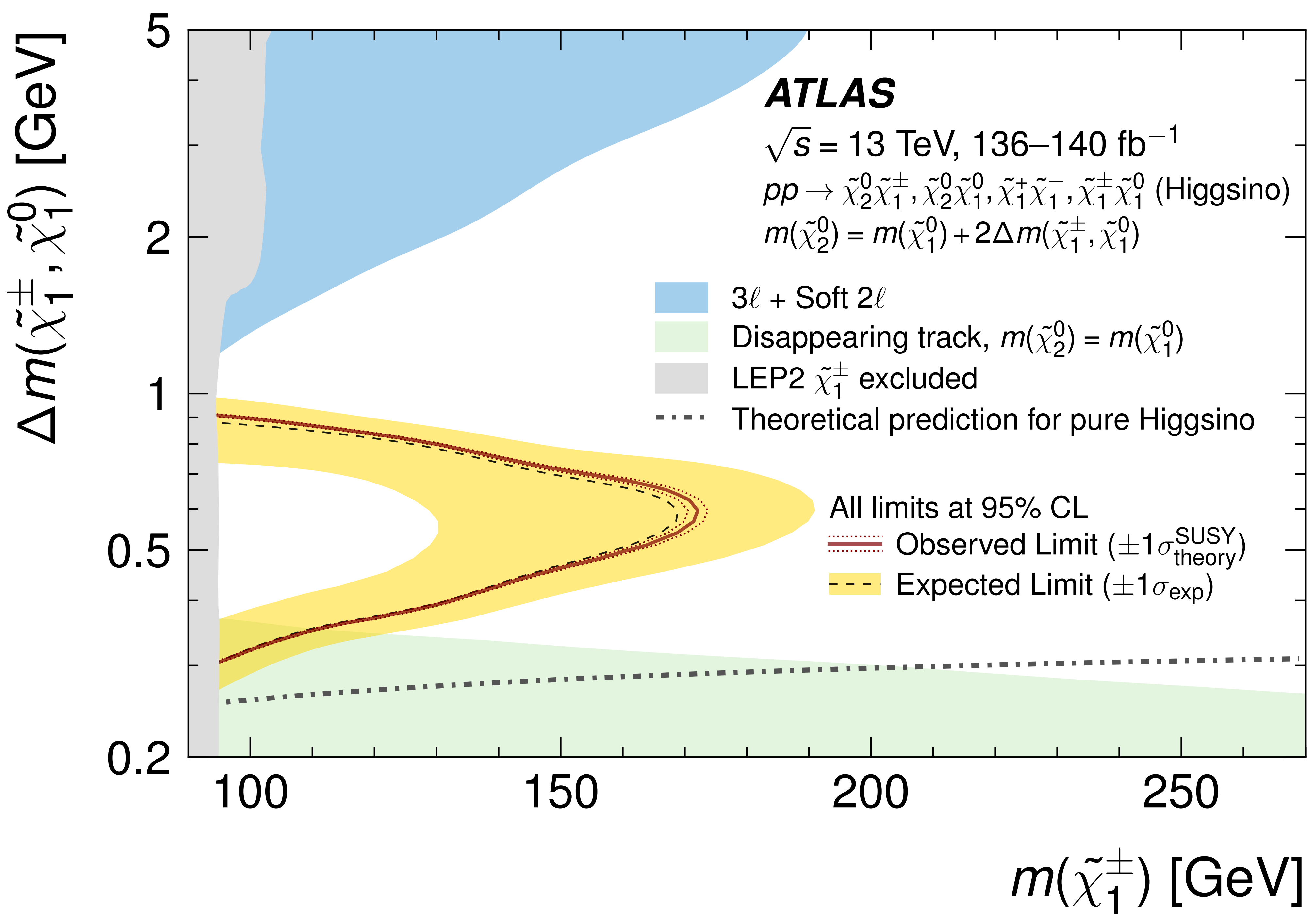
➡ Covered the higgsino gap ($0.3\ \text{GeV} < \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{0}) < 0.9\ \text{GeV}$), with a maximum reach of 170 GeV in the chargino mass

	SR-Low	SR-High
Observed data	35	15
SM prediction	37 ± 4	14.8 ± 2.0
QCD track	14.0 ± 1.7	10.0 ± 1.6
$W(\rightarrow \tau_{\ell}\nu)$+jets	9.6 ± 1.6	2.0 ± 0.6
$W(\rightarrow \tau_{h}\nu)$+jets	10.6 ± 2.0	1.9 ± 0.8
Others	3.2 ± 0.7	0.8 ± 0.4

Track $S(d_0)$ distribution



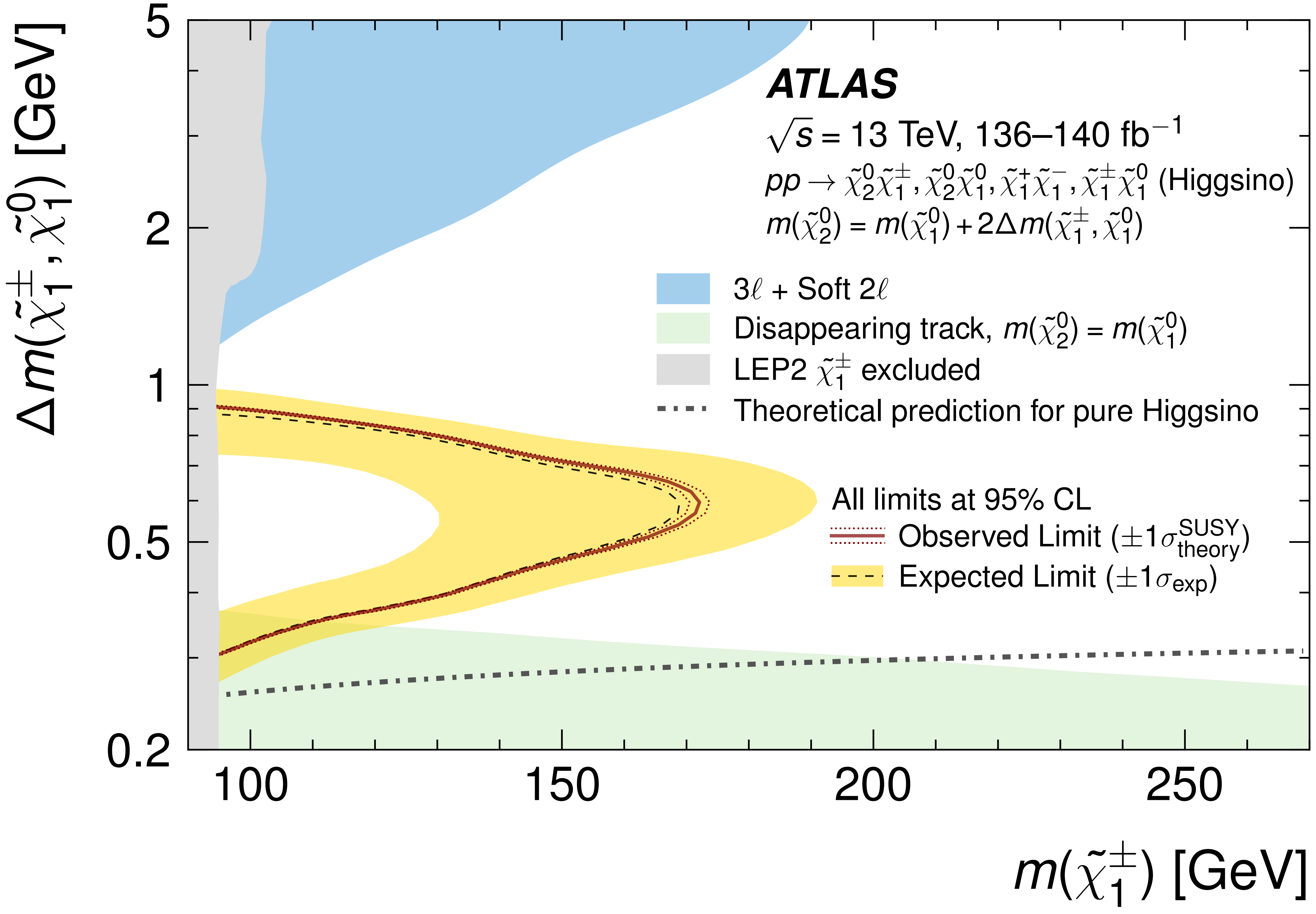
Exclusion limits (overlayed with previous analyses)



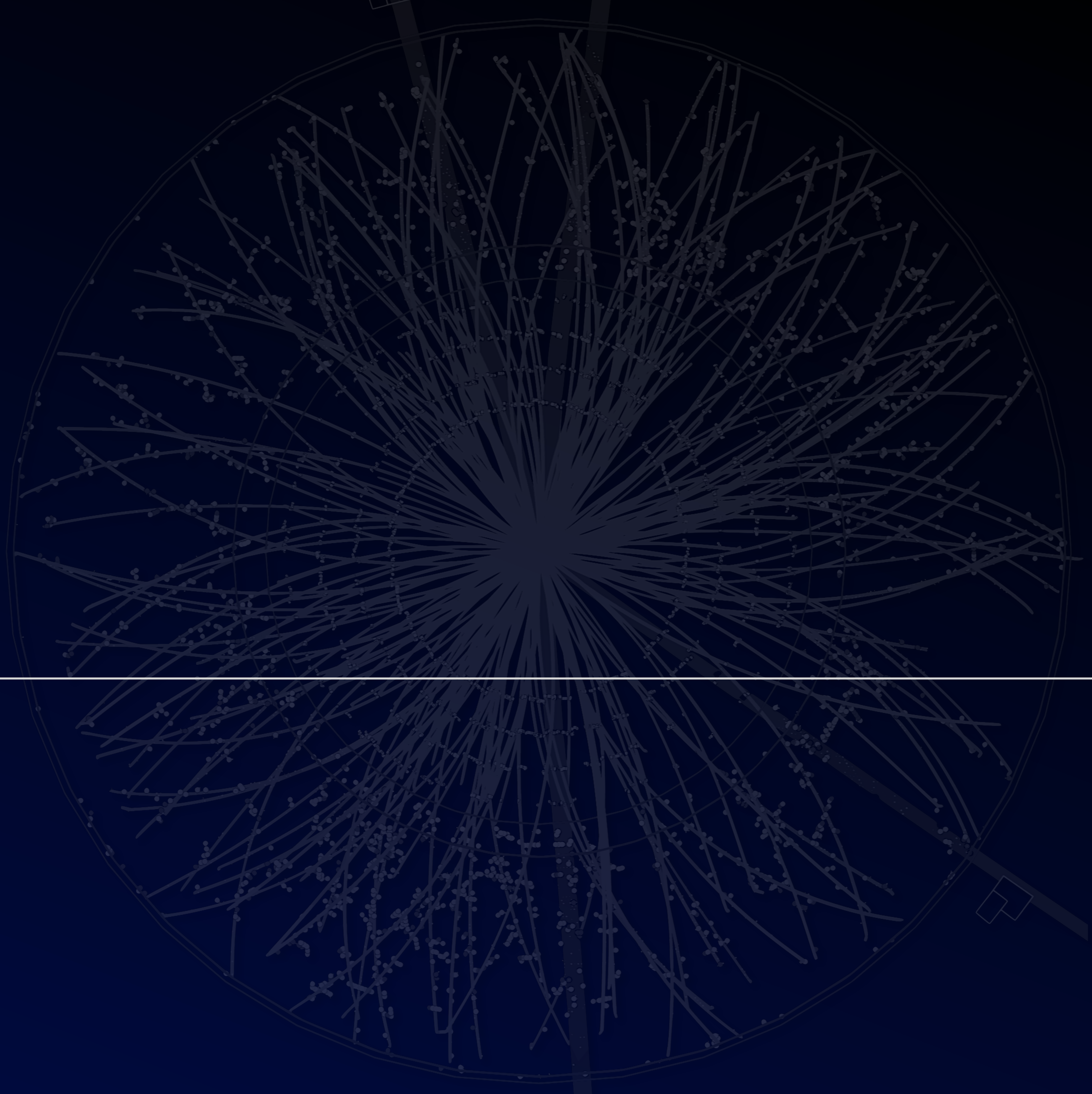
Summary

- Light Higgsinos are motivated by "Electroweak Naturalness"
- **Performed the first displaced track search to explore the "higgsino gap"**
- No significant data excess beyond the SM expectation
  - ➡ **Exceed the LEP limit in the higgsino gap for the first time**

Phys. Rev. Lett. 132 (2024) 221801



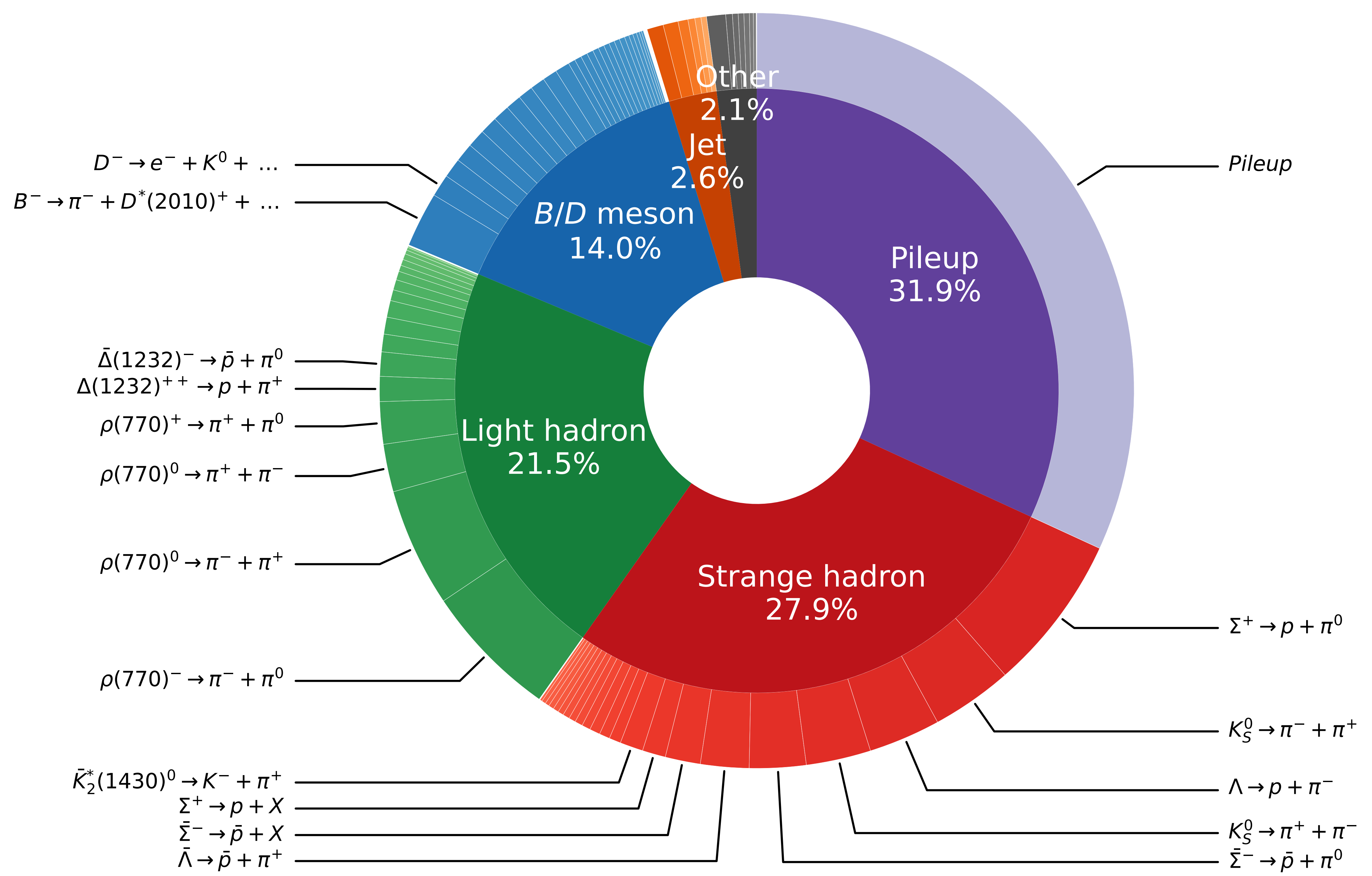
BACKUP



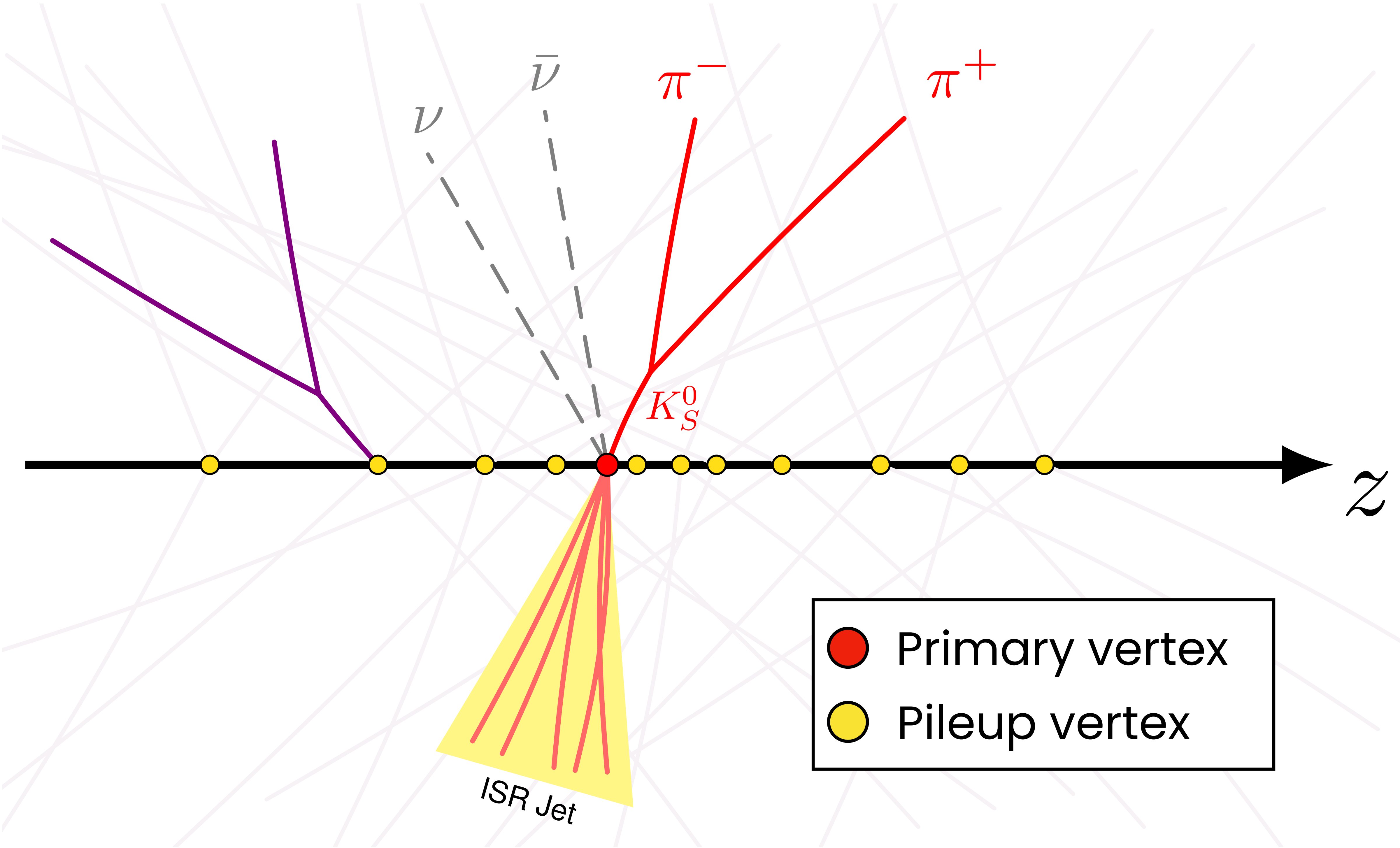
Background : QCD Track

- QCD tracks are mainly from the Pileup vertex **or** Strange hadrons
  - Modeling of QCD events are difficult ➡ Estimate QCD tracks using only data

QCD track composition in SR-High



Schematics of QCD tracks in a $Z \to \nu\nu$ event

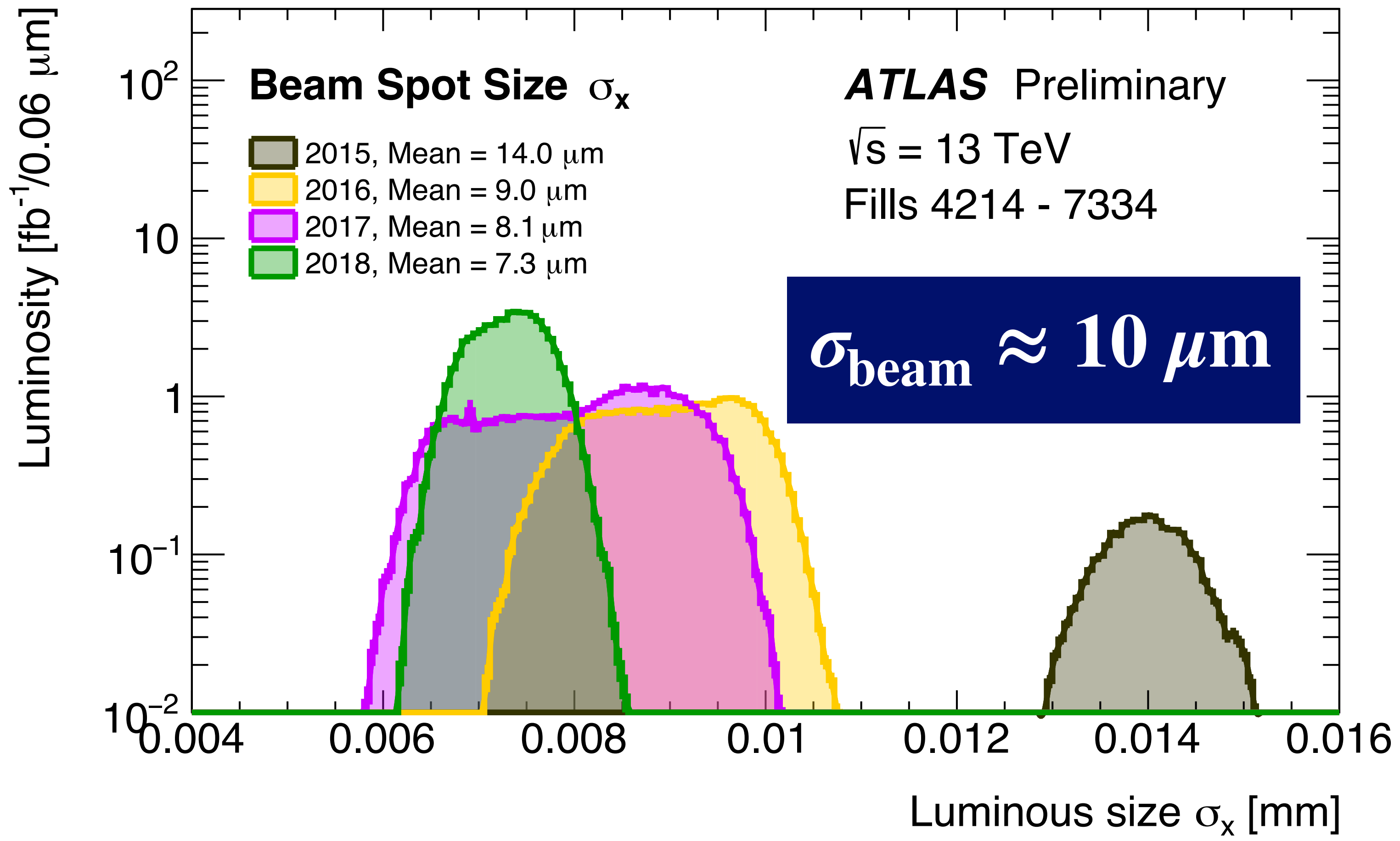


Track Resolution

- Use the impact parameter significance to identify chargino decay tracks : $S(d_0) = d_0/\sigma(d_0)$

$$\sigma(d_0)^2 = \sigma_{\text{beam}}^2 + \sigma_{\text{track}}^2 \begin{cases} \sigma_{\text{beam}} : \text{Beam spot uncertainty} \\ \sigma_{\text{track}} : \text{Track fit uncertainty} \end{cases}$$

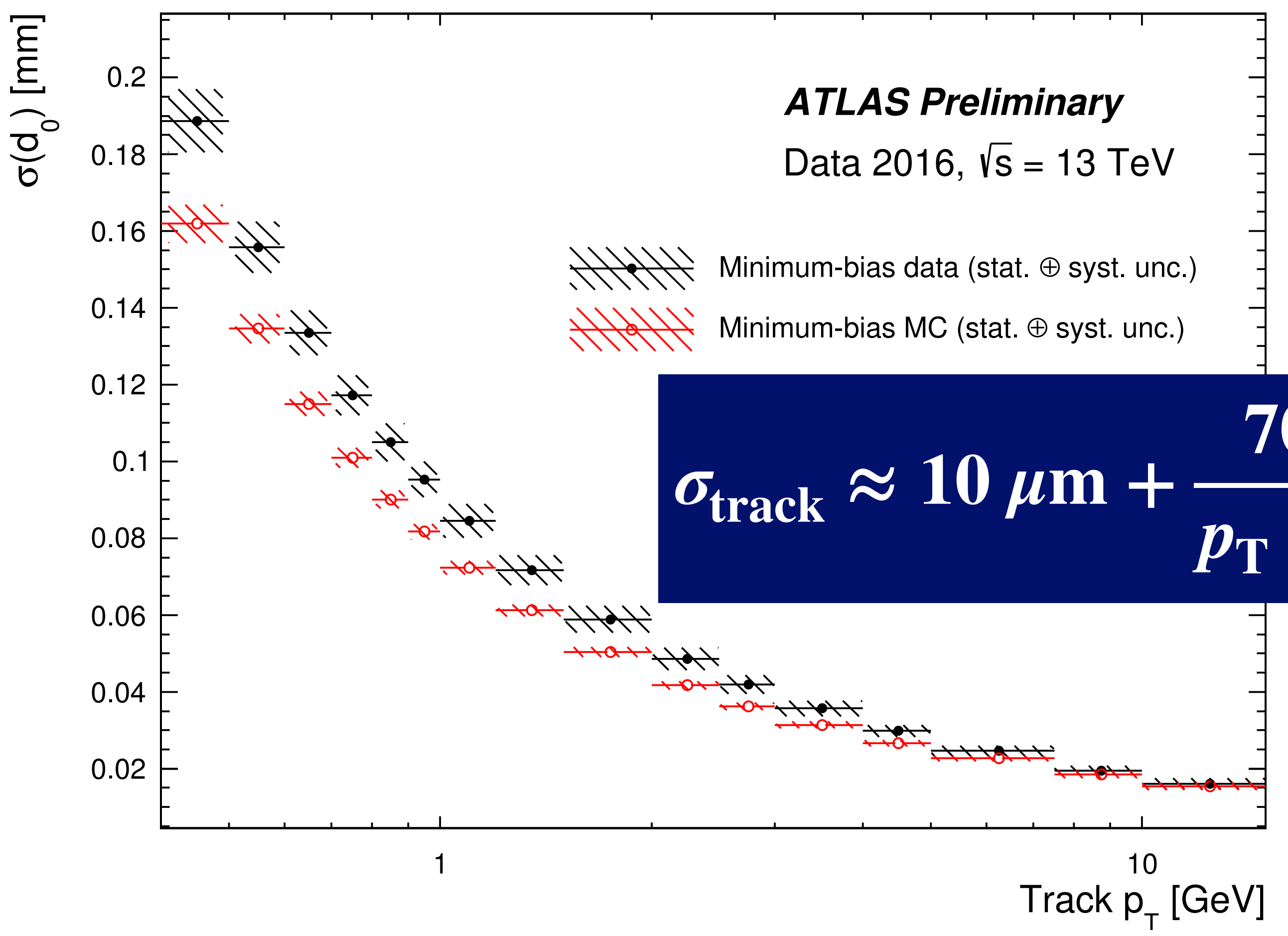
σ_{beam}



$\sigma_{\text{beam}} \approx 10\ \mu m$

$\oplus$

σ_{track}



$$\sigma_{\text{track}} \approx 10\ \mu m + \frac{70\ \mu m}{p_T\ [\text{GeV}]}$$

=

$\sigma(d_0)$

$$\sigma(d_0) \approx 14\ \mu m + \frac{70\ \mu m}{p_T\ [\text{GeV}]}$$

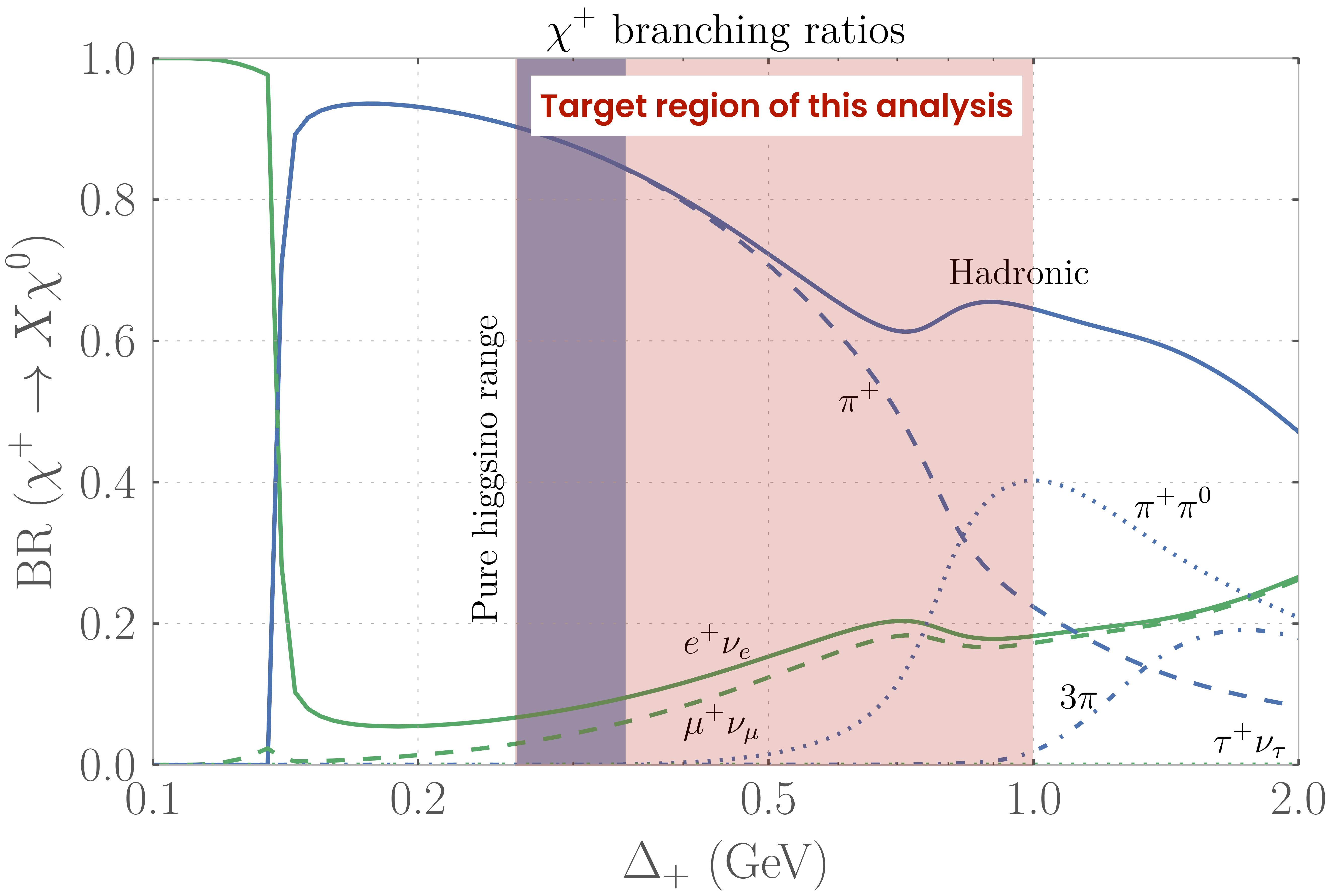
Tracks with a few GeV

$$\sigma(d_0) \approx 20 - 100\ \mu m$$

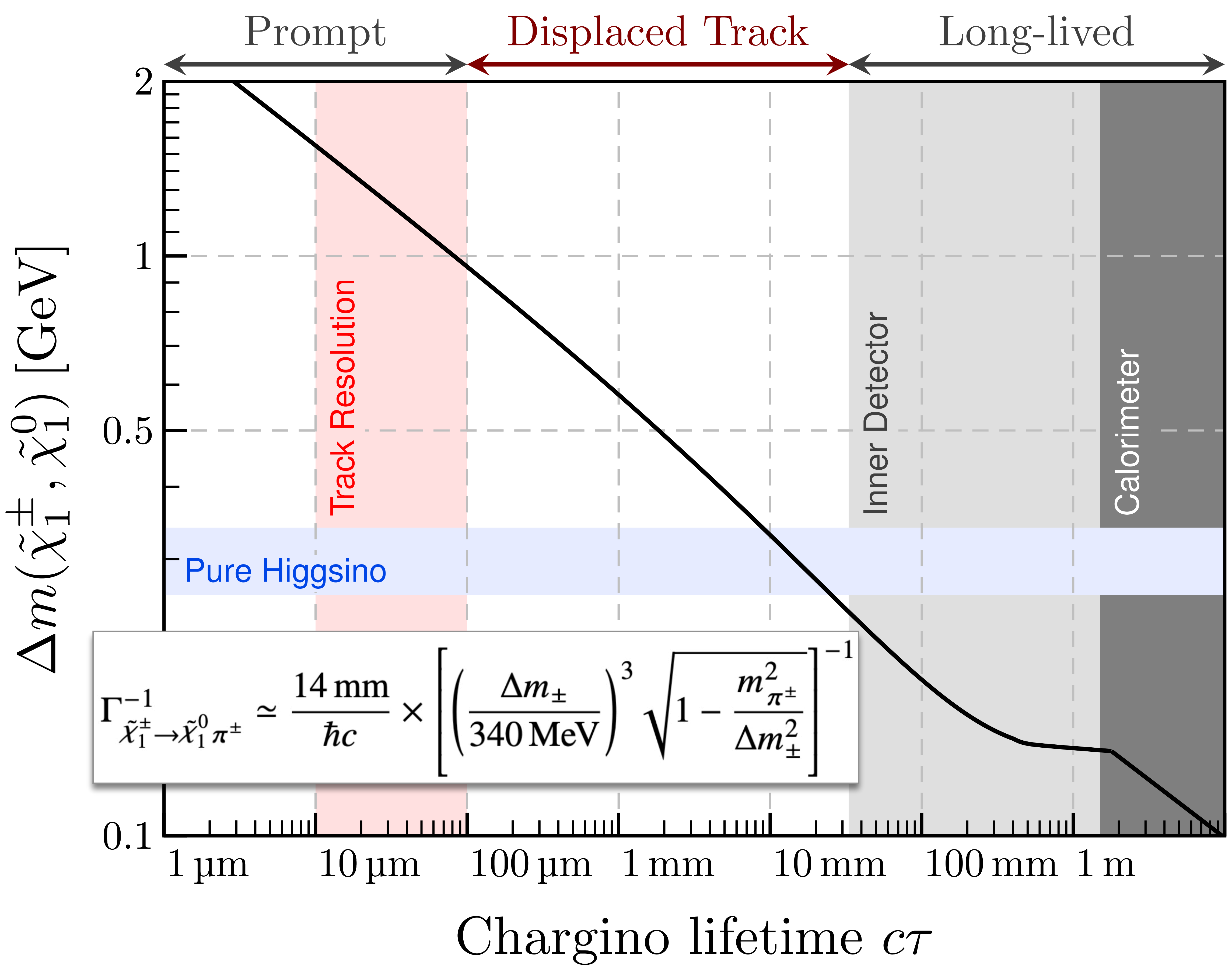
The chargino lifetime is $c\tau \approx \mathcal{O}(1)$ mm ➡ Distinguish prompt decay tracks using the track $S(d_0)$

Chargino Branching Ratio & Lifetime

Chargino branching ratio

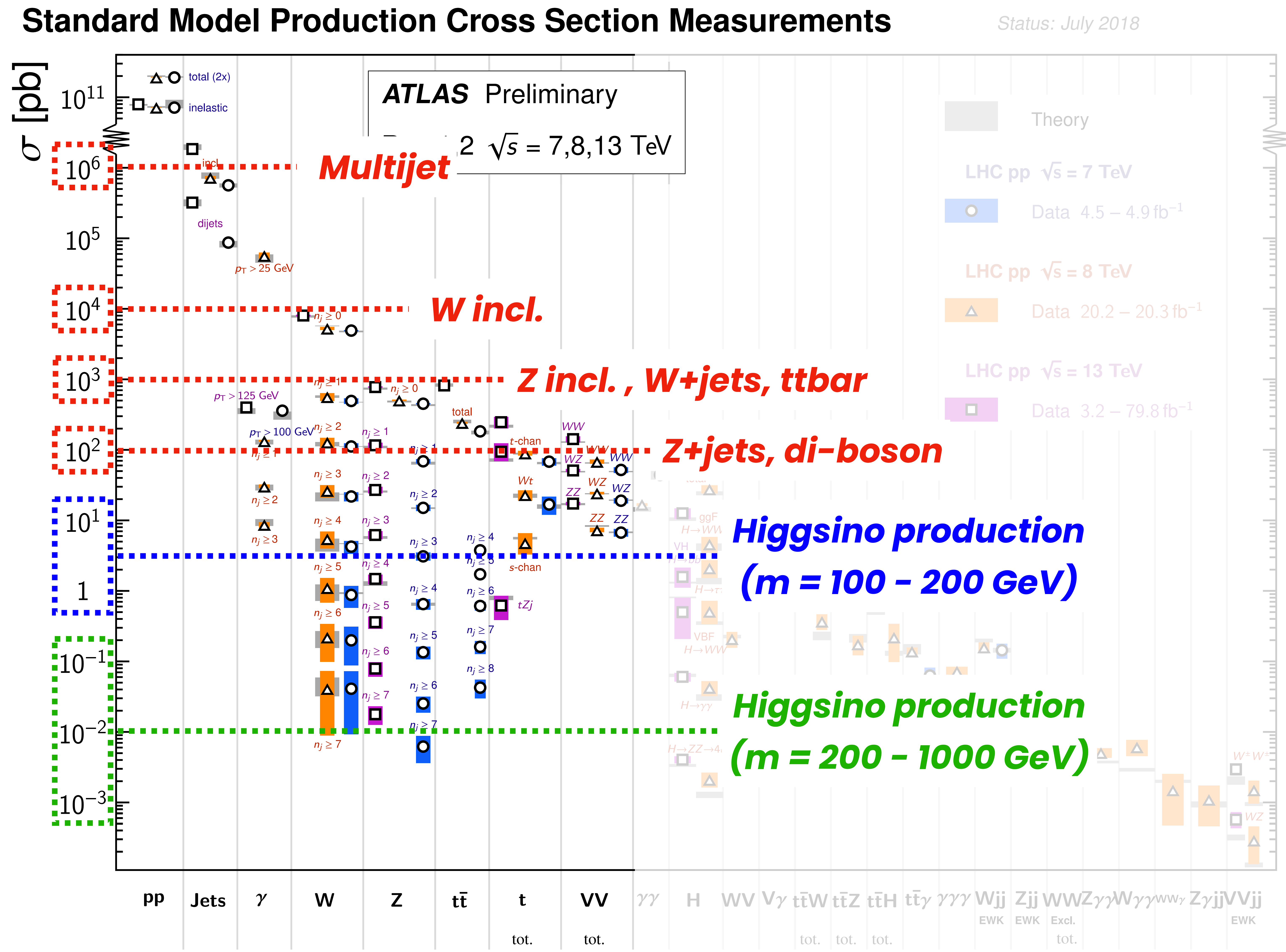


Chargino lifetime



$$\Gamma^{-1}_{\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm} \simeq \frac{14\,\mathrm{mm}}{\hbar c} \times \left[\left(\frac{\Delta m_\pm}{340\,\mathrm{MeV}}\right)^3 \sqrt{1-\frac{m_{\pi^\pm}^2}{\Delta m_\pm^2}} \right]^{-1}$$

Signal & Background Cross-section



Multijet

W incl.

Z incl. , W+jets, ttbar

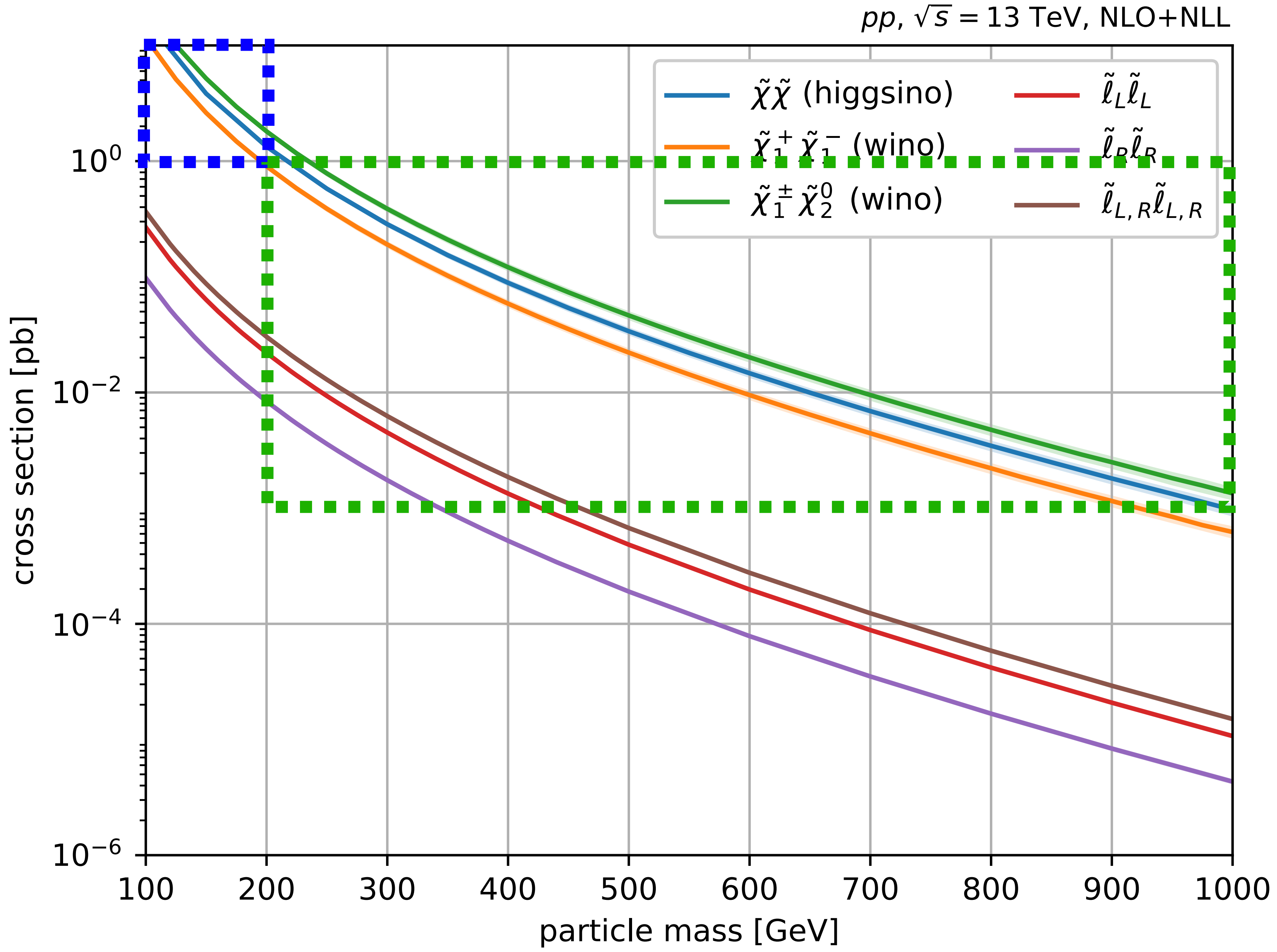
Z+jets, di-boson

Higgsino production
(m = 100 - 200 GeV)

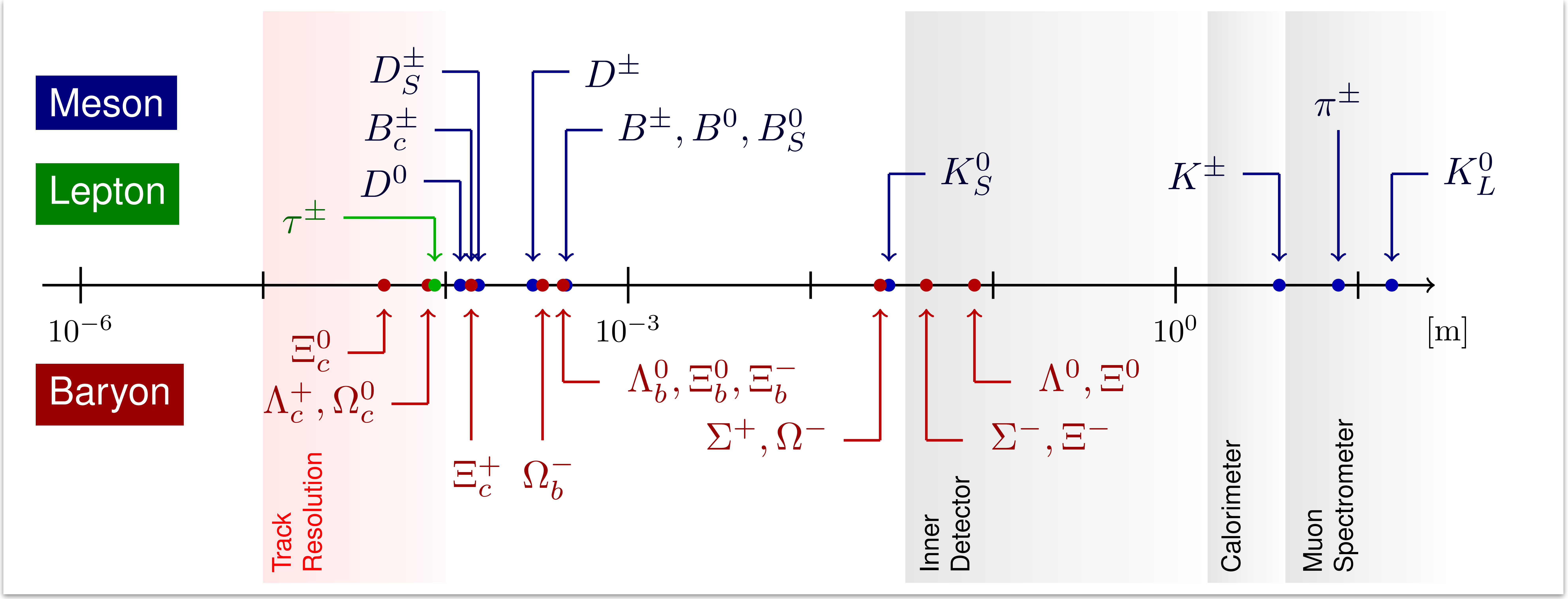
Higgsino production
(m = 200 - 1000 GeV)

- Full Run 2 data (149 fb^{-1})
  - ➡ $\mathcal{O}(10^5 - 10^6)$ signal events

Electroweak SUSY signal cross-sections

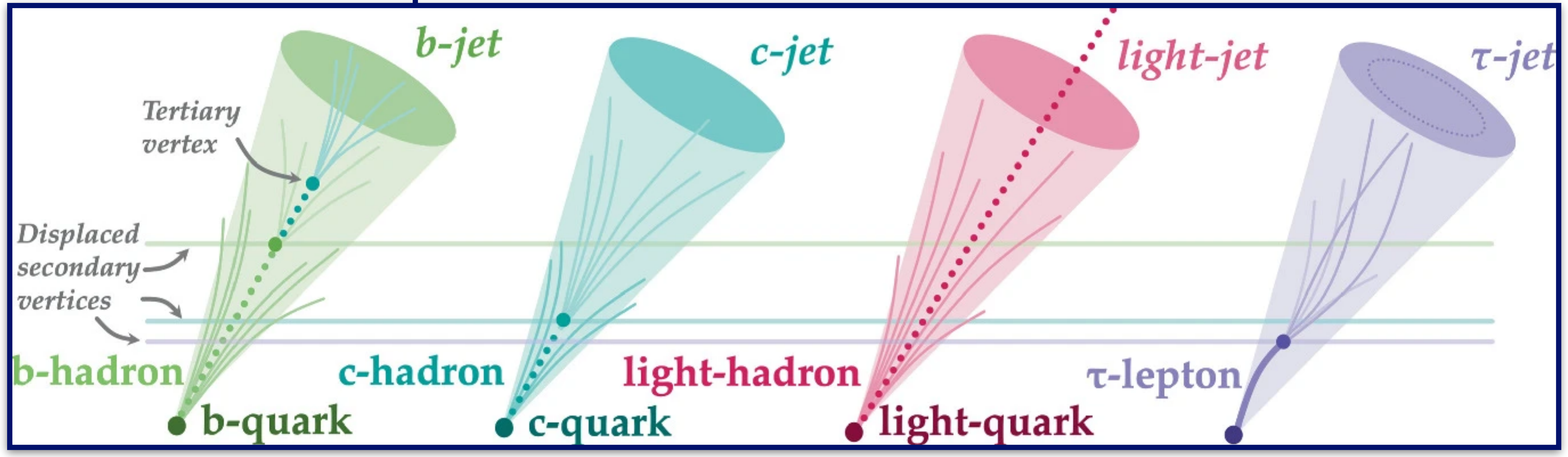


SM Particle Lifetime

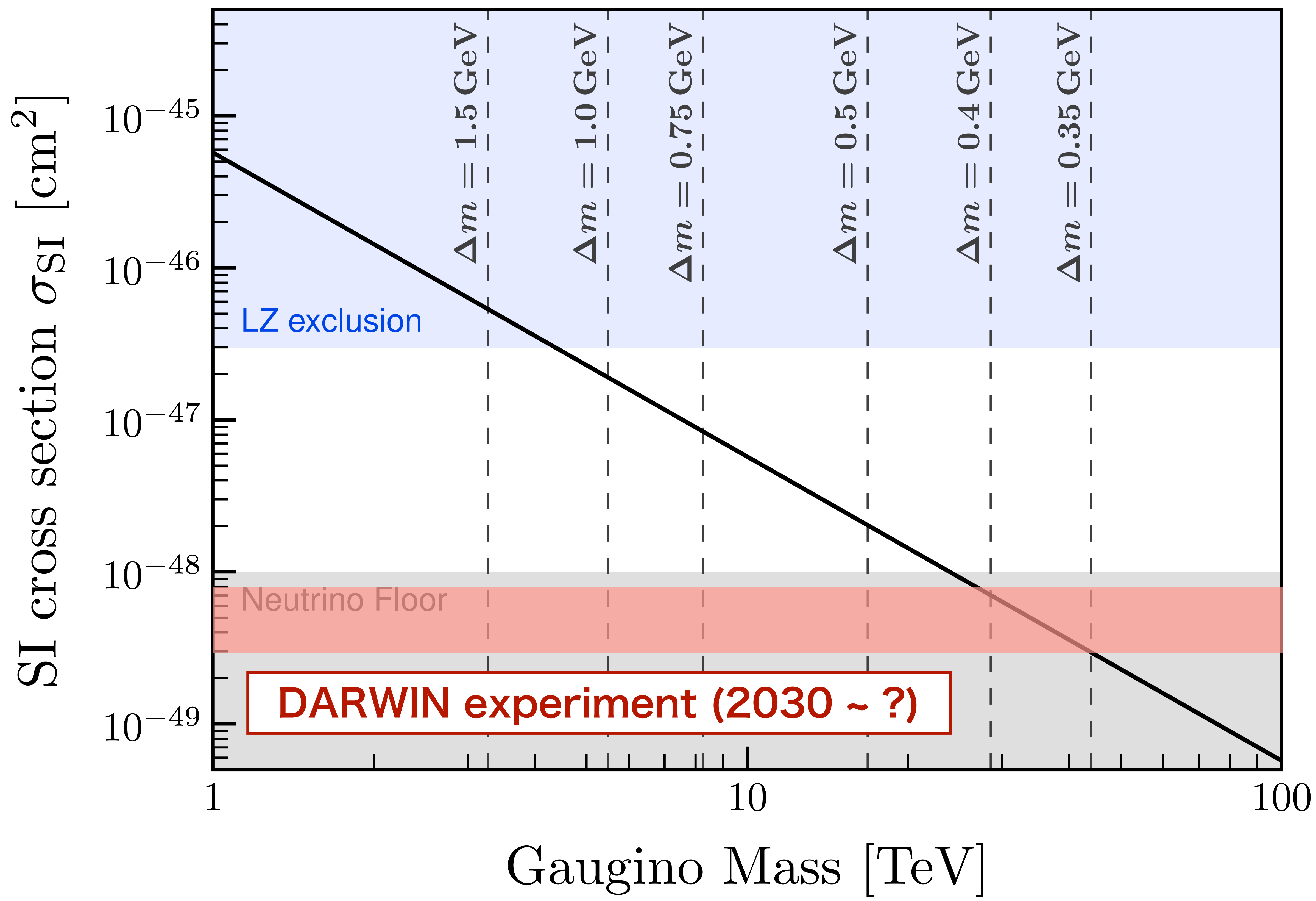


Flavor tagging ($c\tau \sim \mathcal{O}(10-100)\ \mu m$)

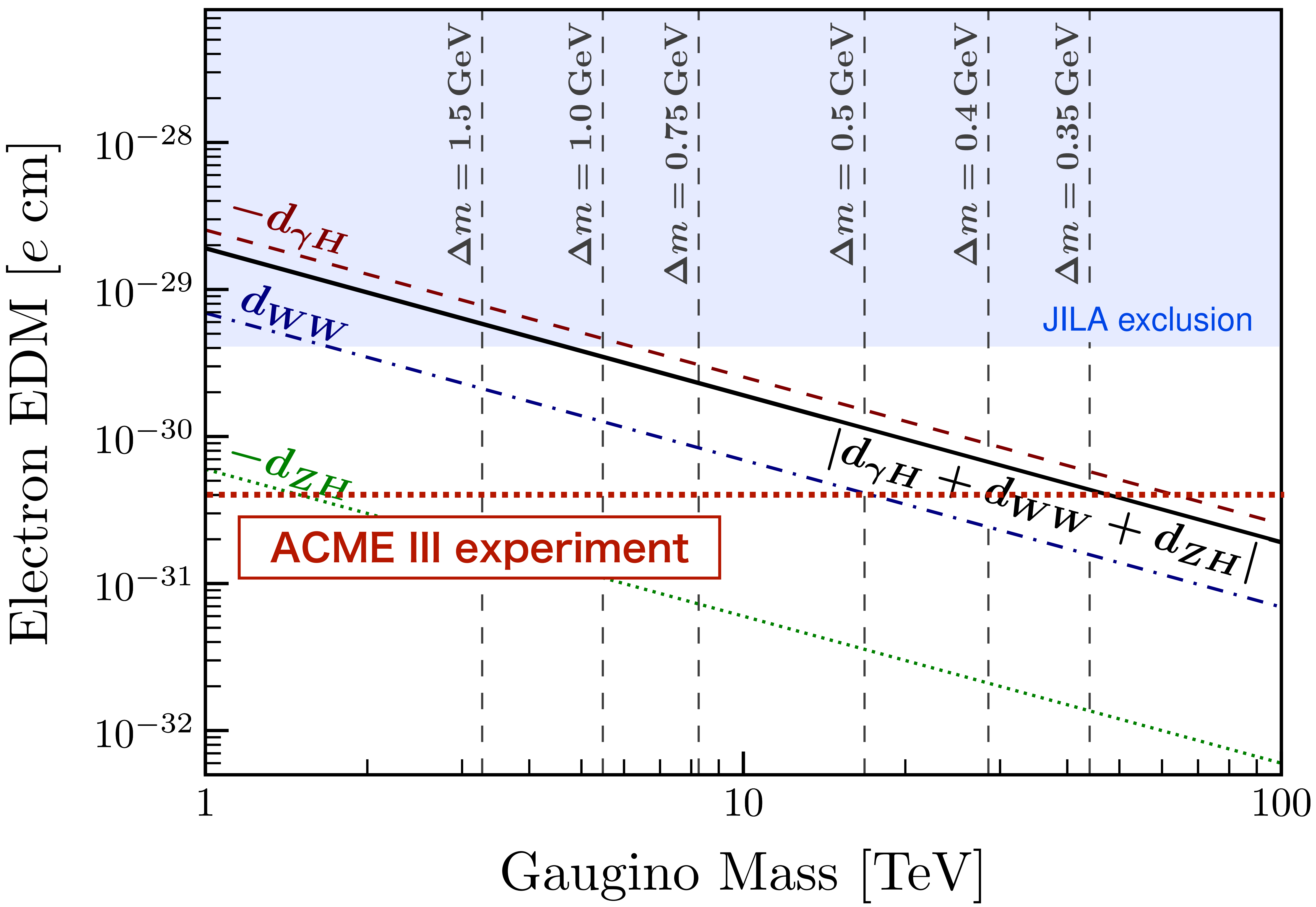
Secondary vertex reconstruction



Limits by Direct Detection & Electron EDM



Limits from direct detection



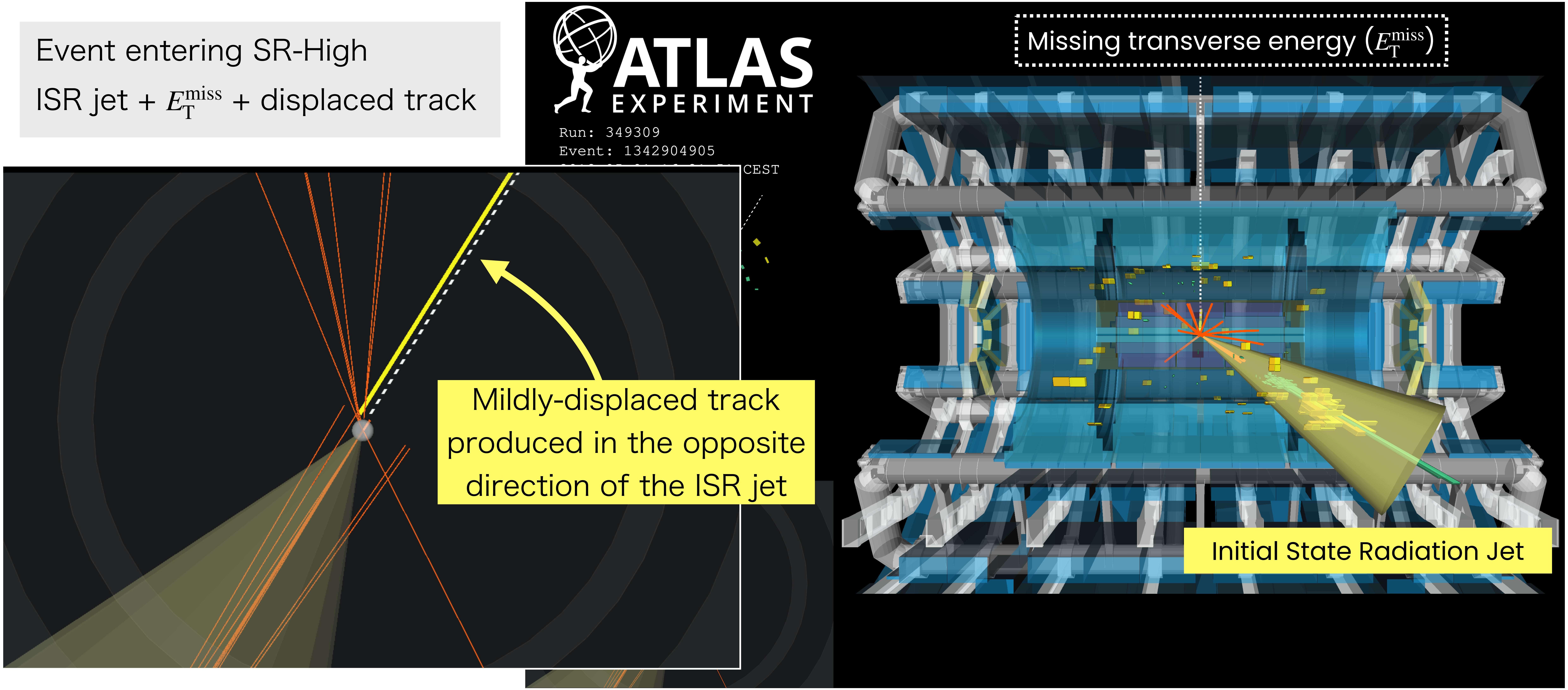
Limits from electron EDM

SM prediction by CKM matrix $\mathcal{O}(10^{-40})$ e cm

Event Display

Event entering SR-High

ISR jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ + displaced track



Missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)

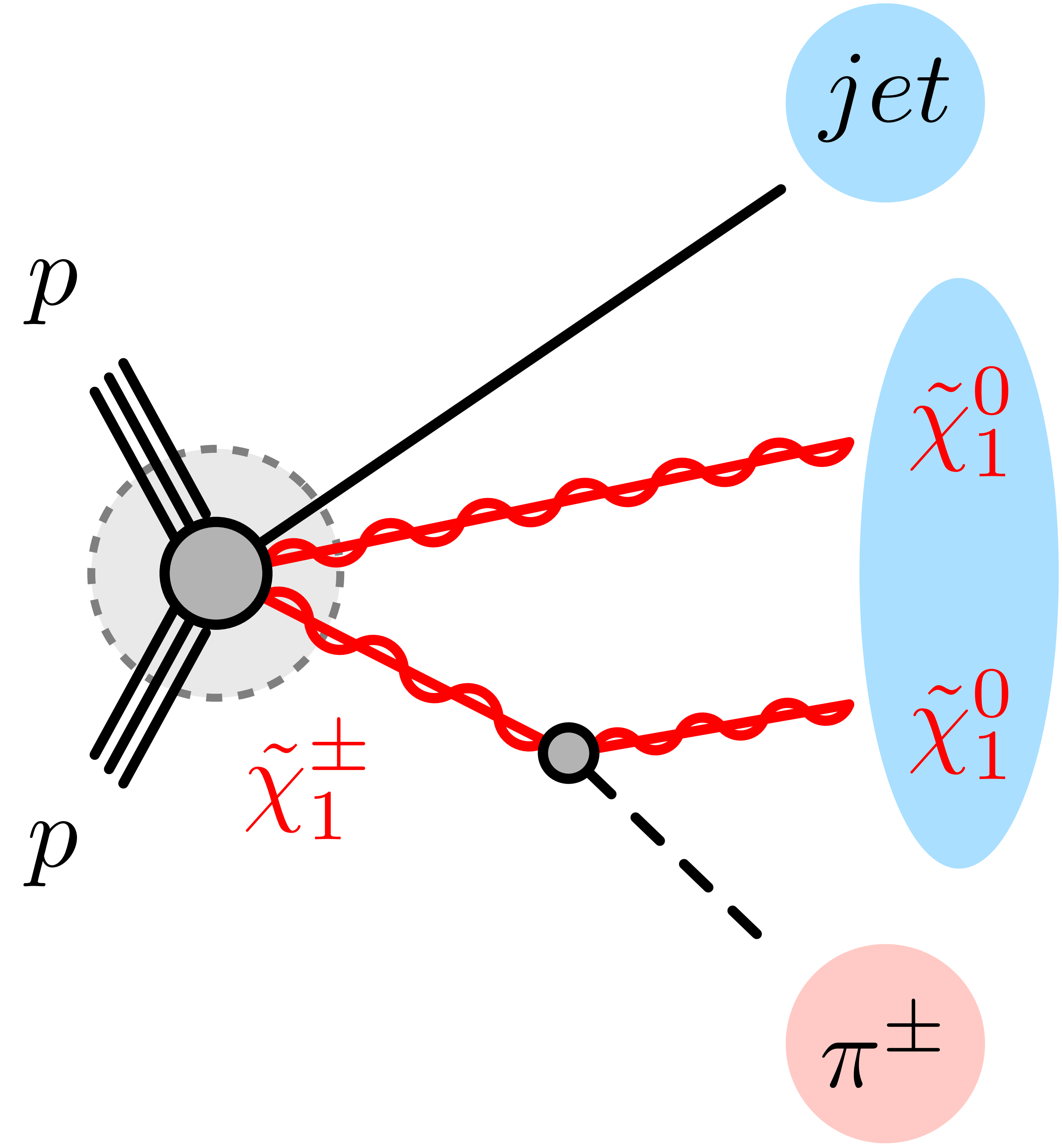
Mildly-displaced track produced in the opposite direction of the ISR jet

Initial State Radiation Jet

EVENT & TRACK SELECTION

Number of Events : Signal

- Cut flow for signal process with $(m(\chi_1^0), \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)) = (150, 0.5)$ GeV



Initial number of events : **140 k events**

↓ 5.8%

Jets+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature : **8.1 k events**

↓ 86%

Filtering (Lepton veto etc.) : **7.0 k events**

↓ 49%

Signal track selection : **3.4 k events**

↓ 6.6%

$E_{\mathrm{T}}^{\mathrm{miss}} > 600$ GeV : **223 events**

↓ 28%

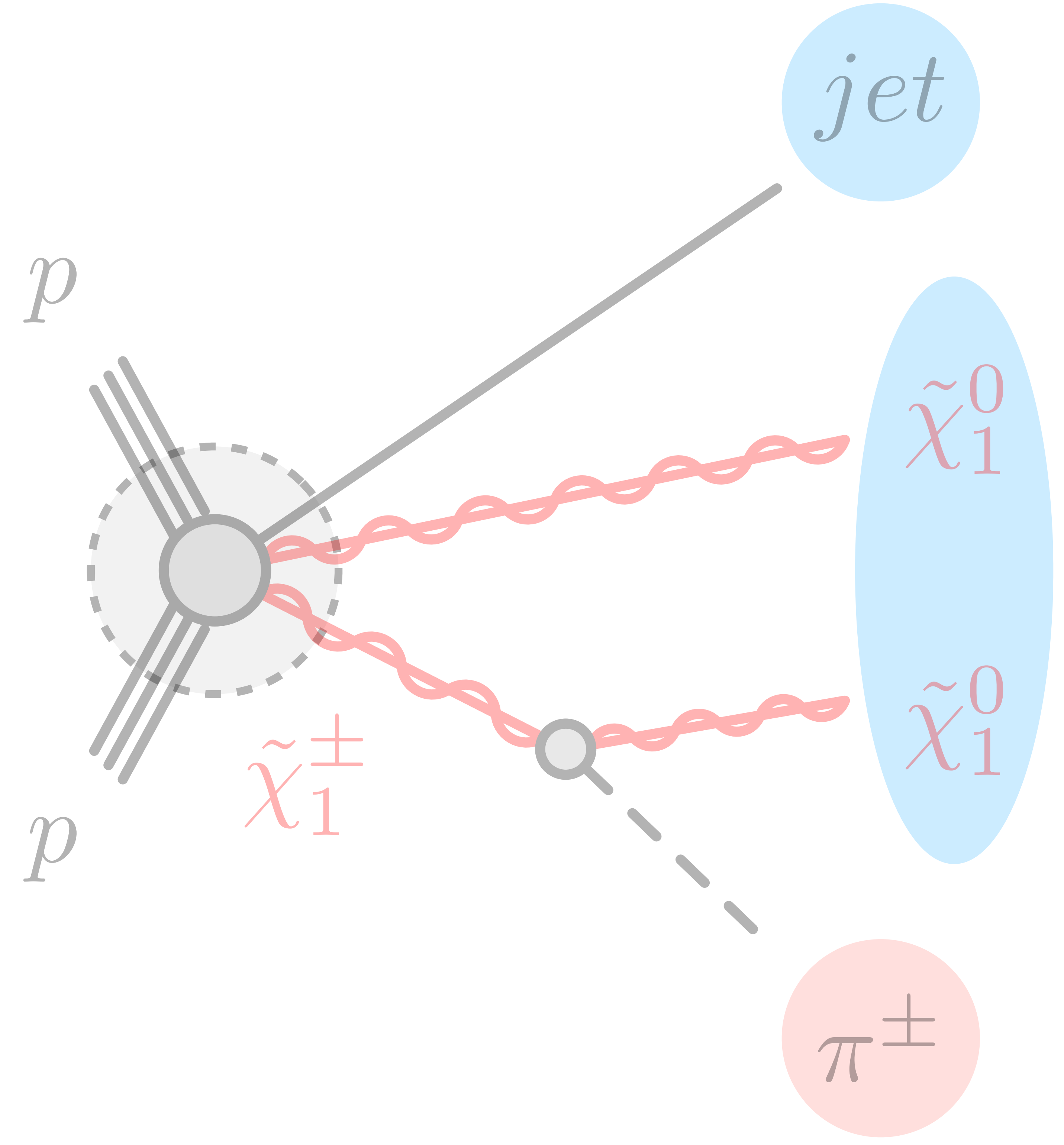
Low-momentum tracks : **63 events**

↓ 32%

Mildly-displaced track signature : **20 events**

Number of Events : Background

- Cut flow for background processes



Initial number of events : **18 M events**

7.8%

Jets+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature : **1.4 M events**

32%

Filtering (Lepton veto etc.) : **450 k events**

40%

Signal track selection : **180 k events**

3.6%

$E_{\mathrm{T}}^{\mathrm{miss}} > 600$ GeV : **6.5 k events**

18%

Low-momentum tracks : **1.2 k events**

3.6%

Mildly-displaced track signature : **43 events**

HIGH LUMINOSITY LHC (HL-LHC)

Inner Detector Upgrade

- Current inner detector consists of Pixels + Strips + TRT
  - Replaced by **all-silicon tracker (Inner Tracker; ITk)** for HL-LHC

① **Increased coverage**

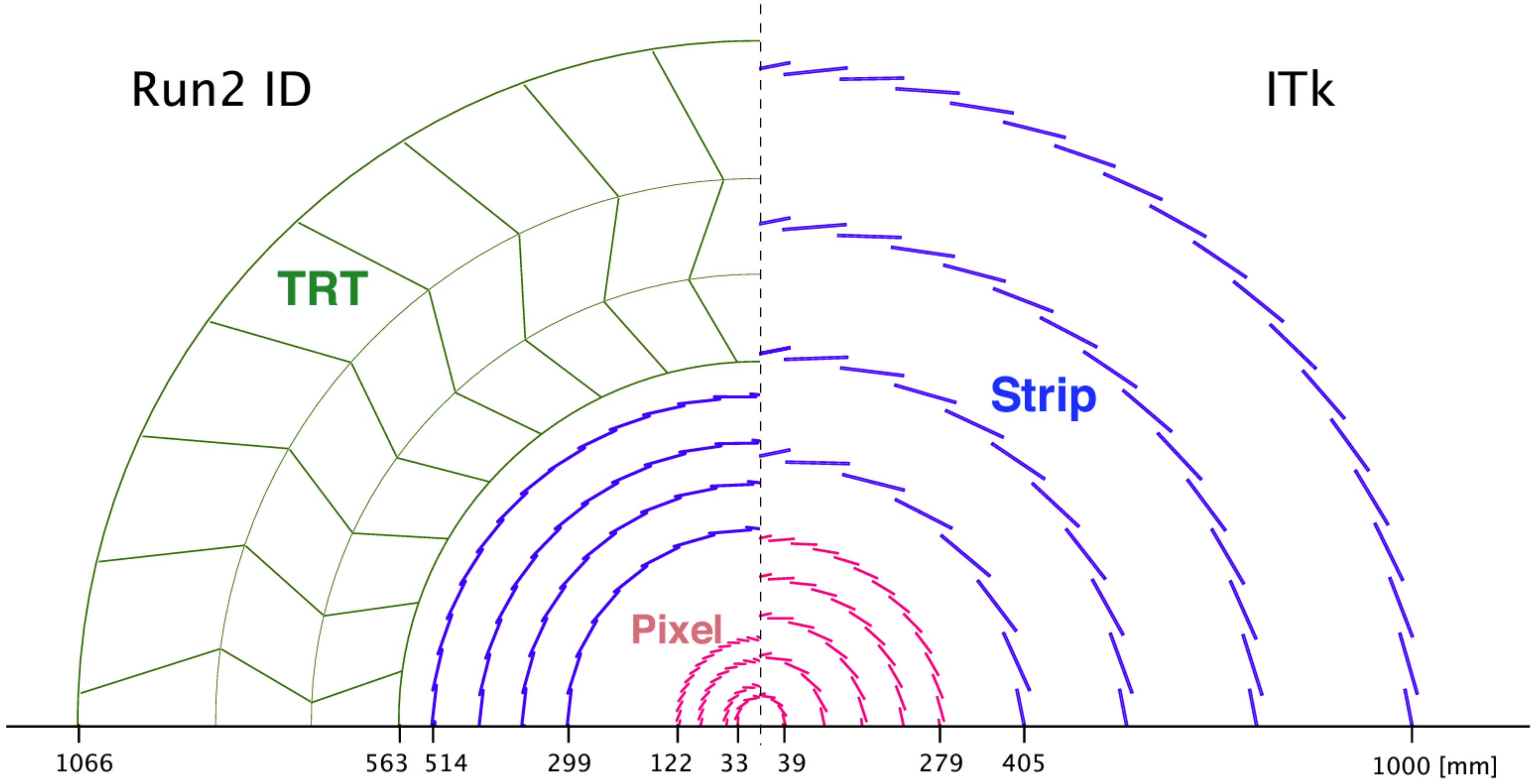
- $|\eta| < 2.5$ ➡ $|\eta| < 4$

② **Reduced pixel pitch**

- IBL : $50 \times 250\ \mu\mathrm{m}^2$ ➡ $25 \times 100\ \mu\mathrm{m}^2$
- Other : $50 \times 400\ \mu\mathrm{m}^2$ ➡ $50 \times 50\ \mu\mathrm{m}^2$

③ **Lower material budget**

- Maximum of 5% X_0 ➡ 2% X_0

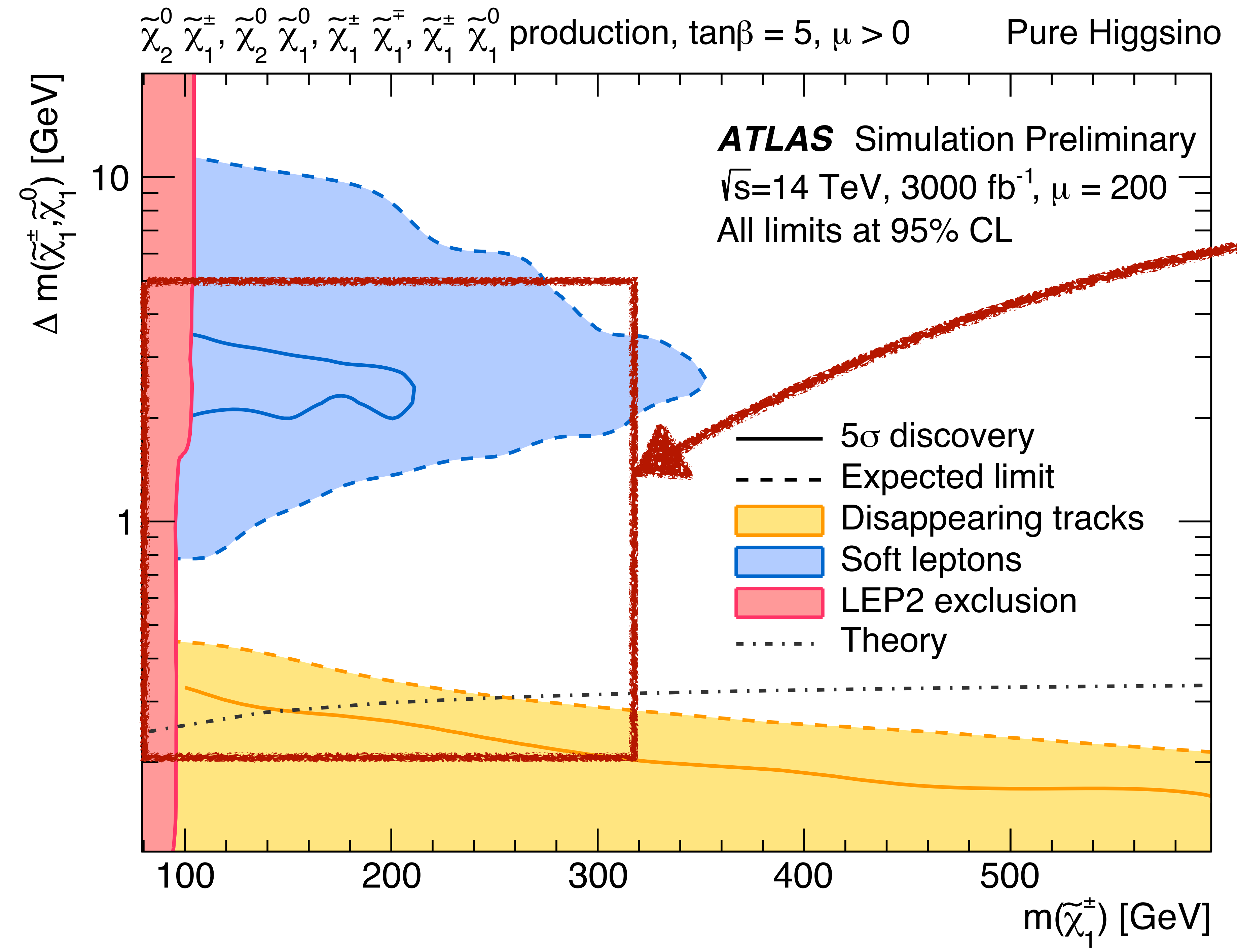


Expected Sensitivity in the HL-LHC

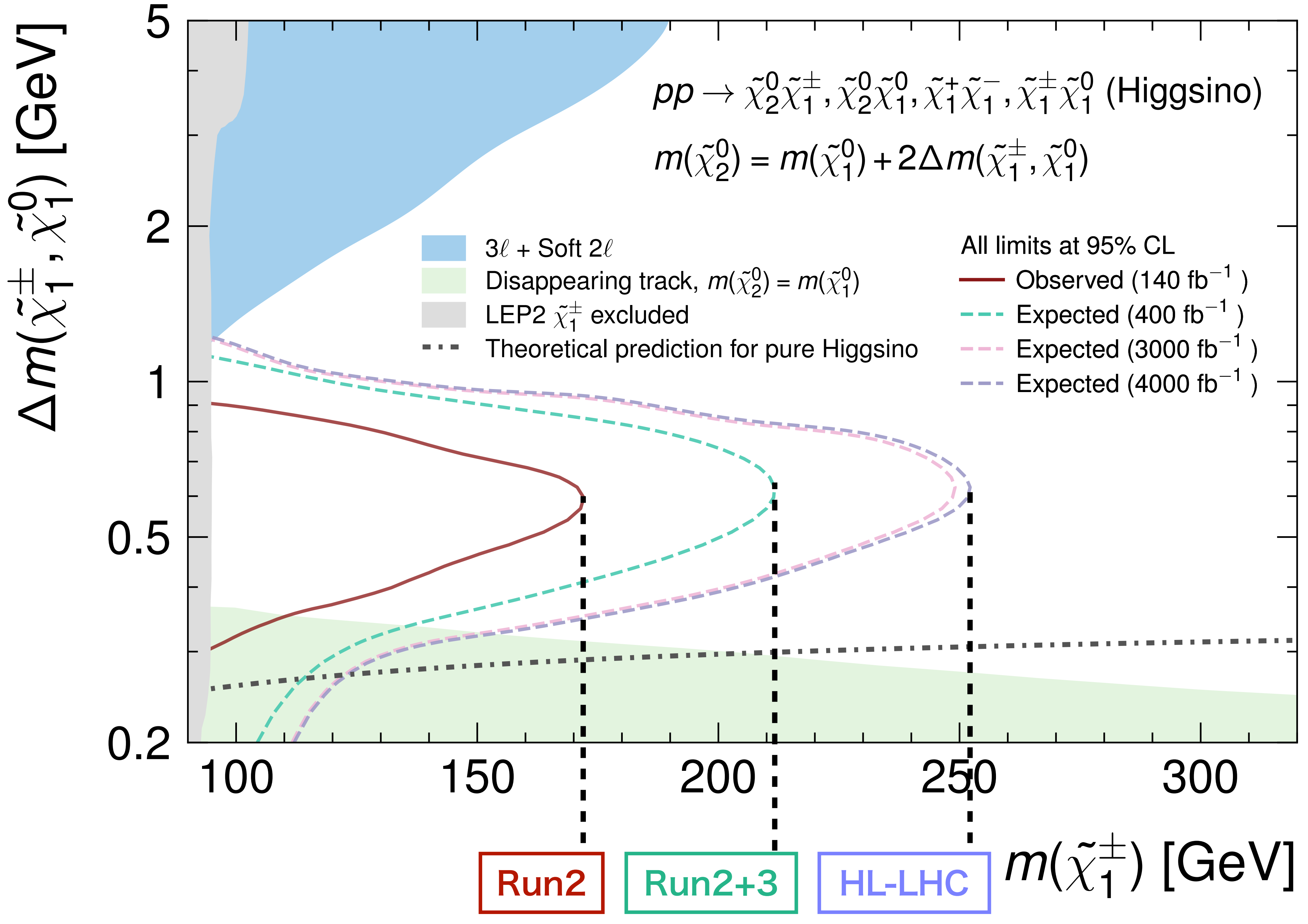
- The High-Luminosity LHC (HL-LHC) is scheduled to start from 2029
  - Expected to obtain about 3000 - 4000 fb^{-1} in 10 years (~20 times the Run 2 statistics)

➡ **Chargino mass reach extended to ~250 GeV with current analyses**

Expected sensitivity of the soft-2L & disappearing track analysis



Expected sensitivity of the displaced track analysis



Expected Sensitivity in the HL-LHC

Considered 3 types of background tracks

① **Fake tracks** : Tracks reconstructed by random combinations

➡ Negligible in the ITk geometry 👍

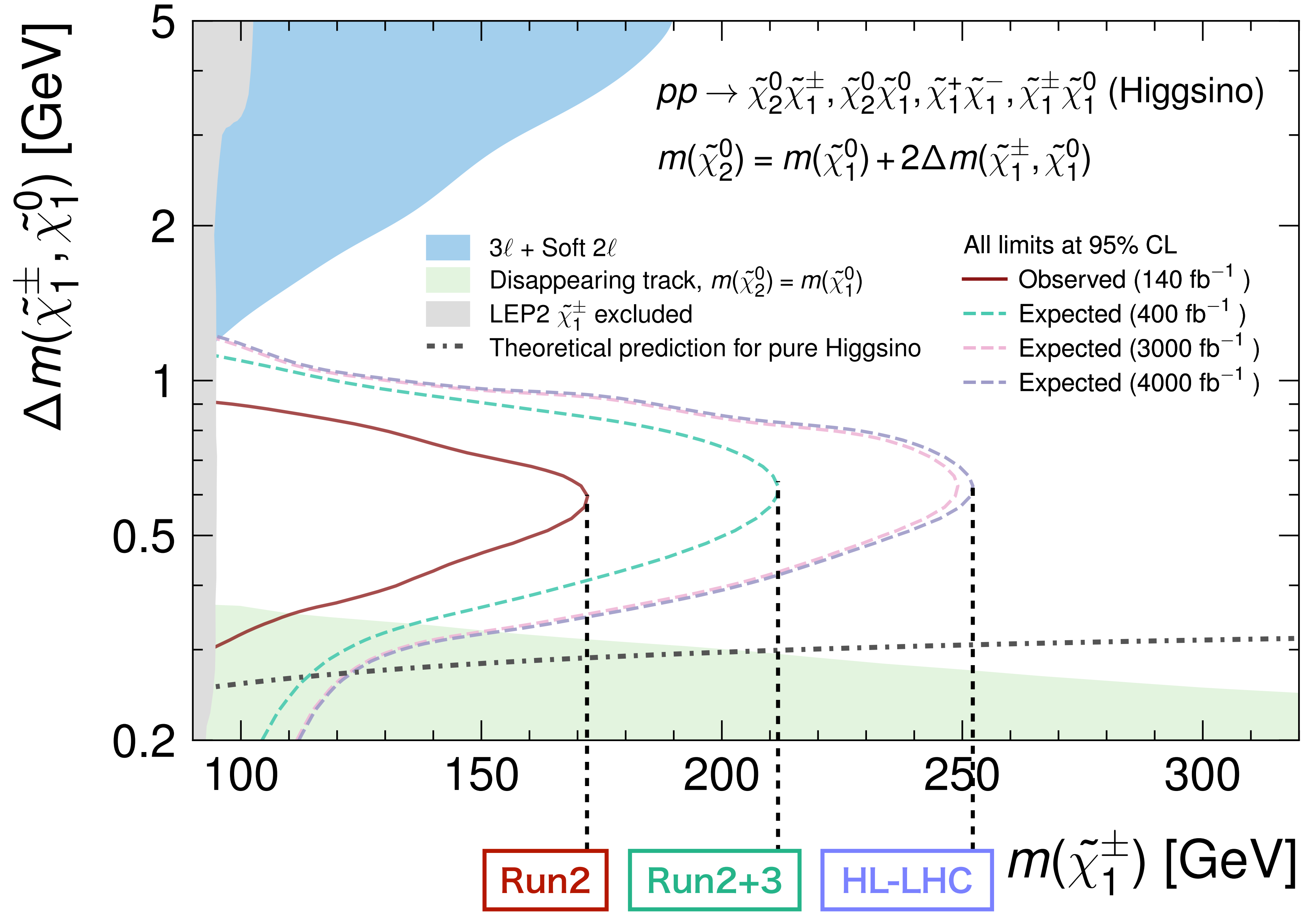
② **Primary tracks** : Tracks from the primary vertex

➡ Efficiency and d_0 resolution of low-p_{T} track remains almost the same overall 👍

③ **Pileup tracks** : Tracks from pileup vertices

➡ Need to account for increase of pileup ✋

Expected sensitivity of this analysis



③ is reweighted so that the pileup effect is comparable with the case of <μ> = 200

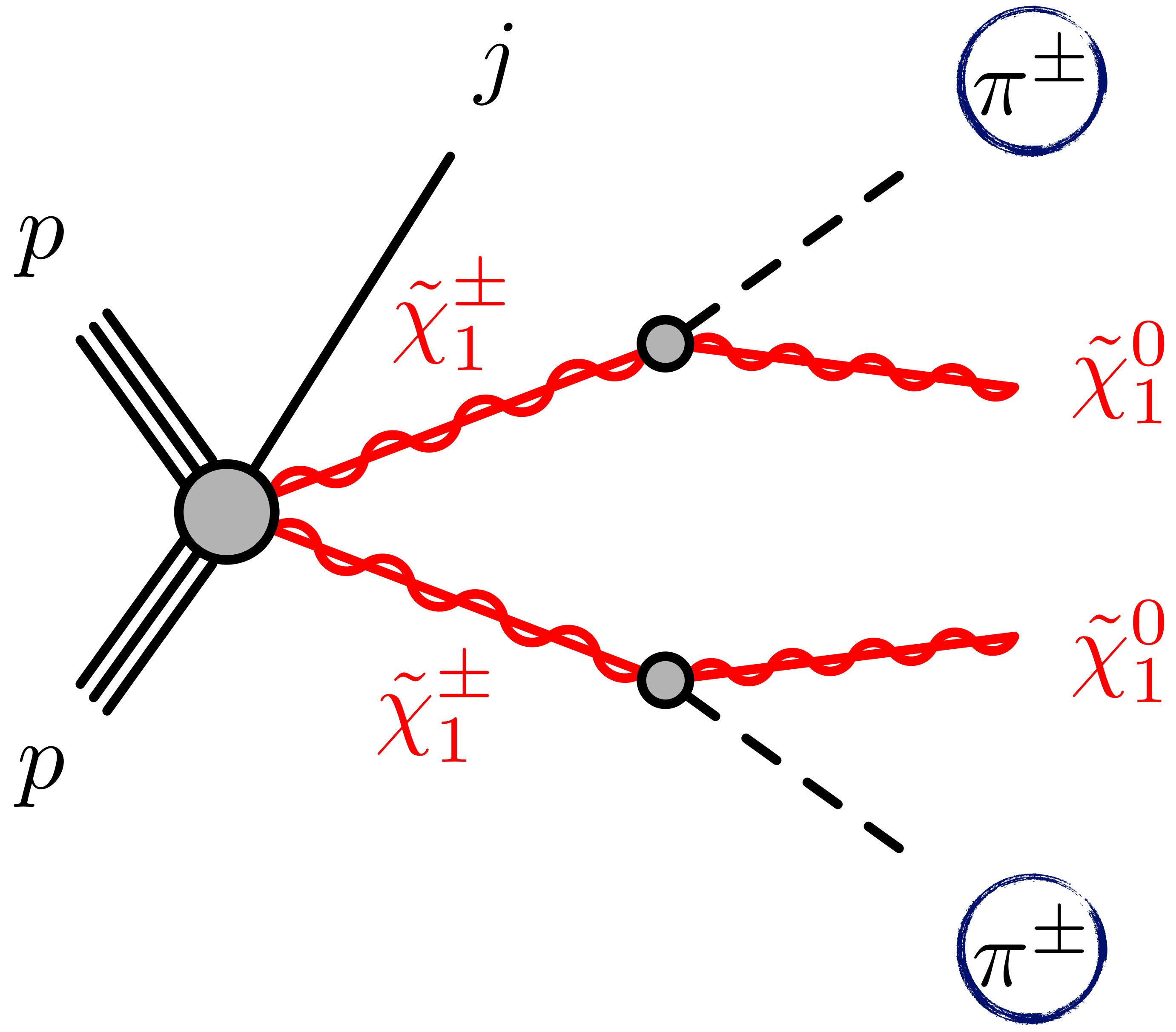
Search Methods Using Mildly-Displaced Tracks

- Tighter selections can be applied since signal events increase in the HL-LHC

  ➡ **Require two mildly-displaced tracks** for further background suppression

① Target tracks from $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production

Signal efficiency quite low since lifetime of two charginos are independent



② Target tracks from $\tilde{\chi}_2^0$ decay

When $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \sim 1.0\ \mathrm{GeV}$, $\mathrm{BR}(\tilde{\chi}_0^2 \to \tilde{\chi}_0^1 \pi^+\pi^-) \sim 40\,\%$

➡ Reconsruct mildly-displaced vertex with two tracks