Search for higgsinos in compressed mass spectra using a low-momentum displaced track with the ATLAS detector

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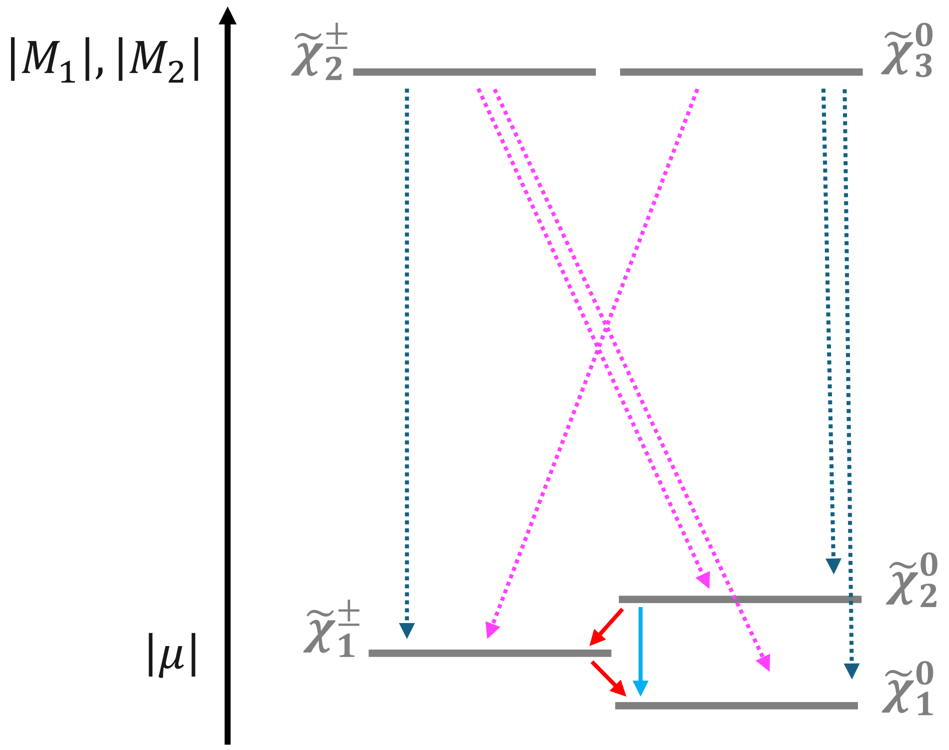
Theorethical motivation

What are higgsinos?

- Fermionic supersymmetric partners of the Higgs boson.
  - The lightest neutral ($\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$) and the lightest charged ($\tilde{\chi}_1^{\pm}$) mass eigenstates form a nearly **mass-degenerate triplet** of **Higgsino-like mass eigenstates** if $|\mu| \ll |M_1|, |M_2|$.

Which higgsinos?

In the pure Higgsino limit (bino and wino decoupled in mass), radiative corrections induce a **small mass splitting** $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \approx$ 250–400 MeV.

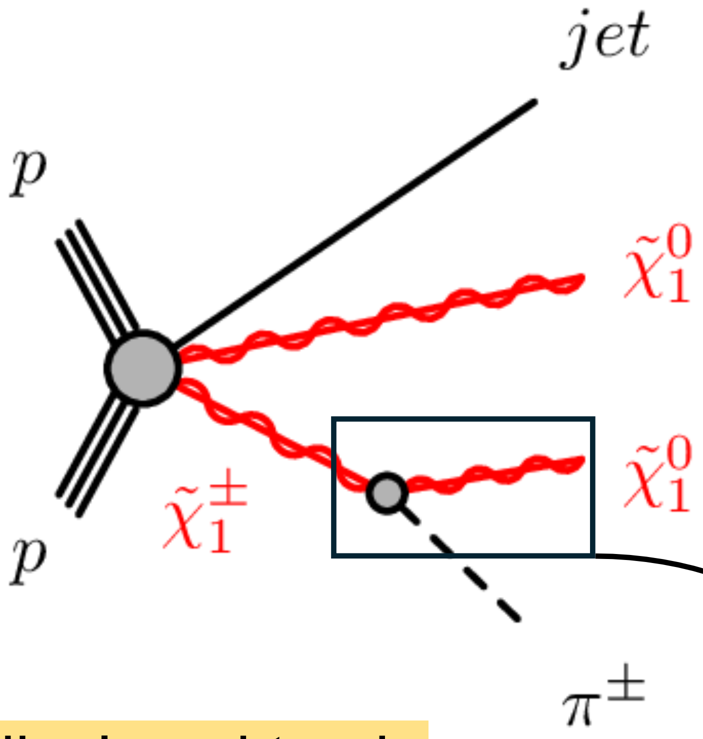


Why higgsinos?

The natural solution of the hierarchy problem requires the higgsinos to be around the electroweak scale.

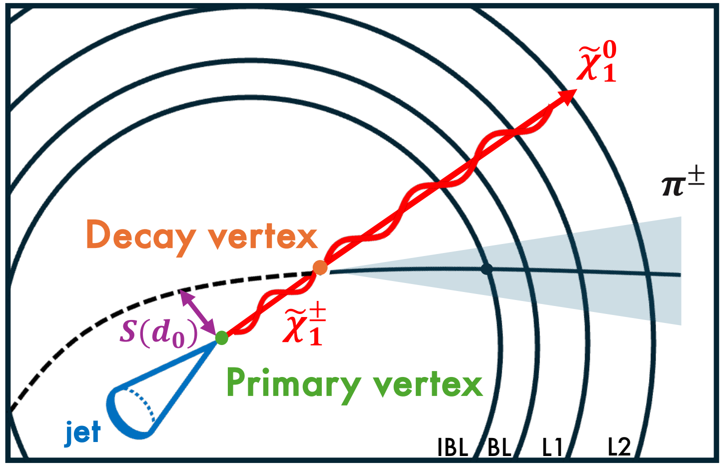
Experimental signature

Search proposed by [1]
[Phys. Rev. Lett. **124**, 101801 (2020)]



Initial state radiation jet to boost the system forward.

Missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ to account for invisible particles and the boosted jet recoiling.



Decay length:
$c\tau \sim \mathcal{O}(0.1 - 1)$ mm,
well within the first ATLAS pixel layer but still measurable.

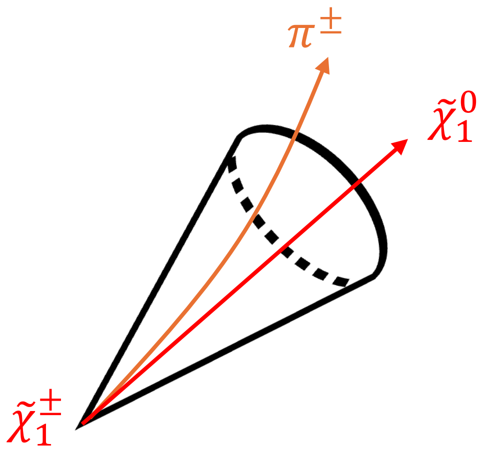
A displaced track associated to a charged pion $\pi^{\pm}$ arising from the $\tilde{\chi}_1^{\pm}$ decay into a $\tilde{\chi}_1^0$.

Large significance of the transverse impact parameter $S(d_0)$ to account for the track displacement.

Signal tracks

Signal tracks associated to low p_T displaced $\pi^{\pm}$ arising from $\tilde{\chi}_1^{\pm}$ decaying into $\tilde{\chi}_1^0$.

All events are required to satisfy a Mono-jet signature, all tracks a soft displaced track selection.



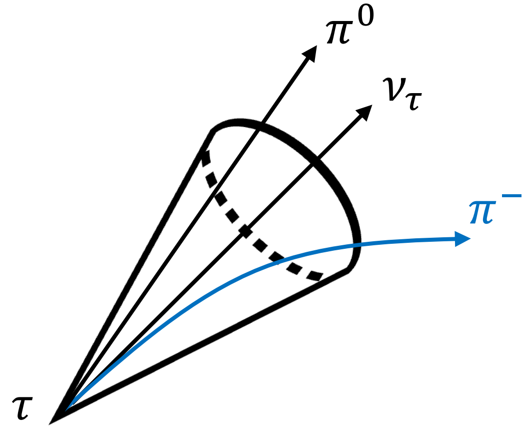
Mono-jet signature

- Leading jet with $p_{\mathrm{T}} > 250$ GeV and $|\eta| < 2.5$
- min $\left[\Delta\phi\left(\text{any jet}, E_{\mathrm{T}}^{\text{miss}}\right)\right] > 0.4$
- No leptons or photons
- $N_{\text{jets}} \leq 4$
- $E_{\mathrm{T}}^{\text{miss}} > 600$ GeV

Soft displaced track selection

- *Soft*: 2 GeV $< p_{\mathrm{T}} <$ 5 GeV, $|\eta| < 1.5$
- *Displaced*: $S(d_0) > 8$, $|d_0| < 10$ mm and $|z_0 \sin\theta| < 3$ mm.
- *Isolated* by any other track with $p_{\mathrm{T}} > 1$ GeV within $\Delta R = 0.4$.
- $E_{\mathrm{T}}^{\text{miss}}$ *alignment*: $\Delta\phi\left(\text{track}, E_{\mathrm{T}}^{\text{miss}}\right) < 0.4$.
- *Quality*: `TightPrimary` working point, $N_{\text{hits}}^{\text{IBL}} > 0$, not matched to Λ^0, K_S^0 decay vertex.

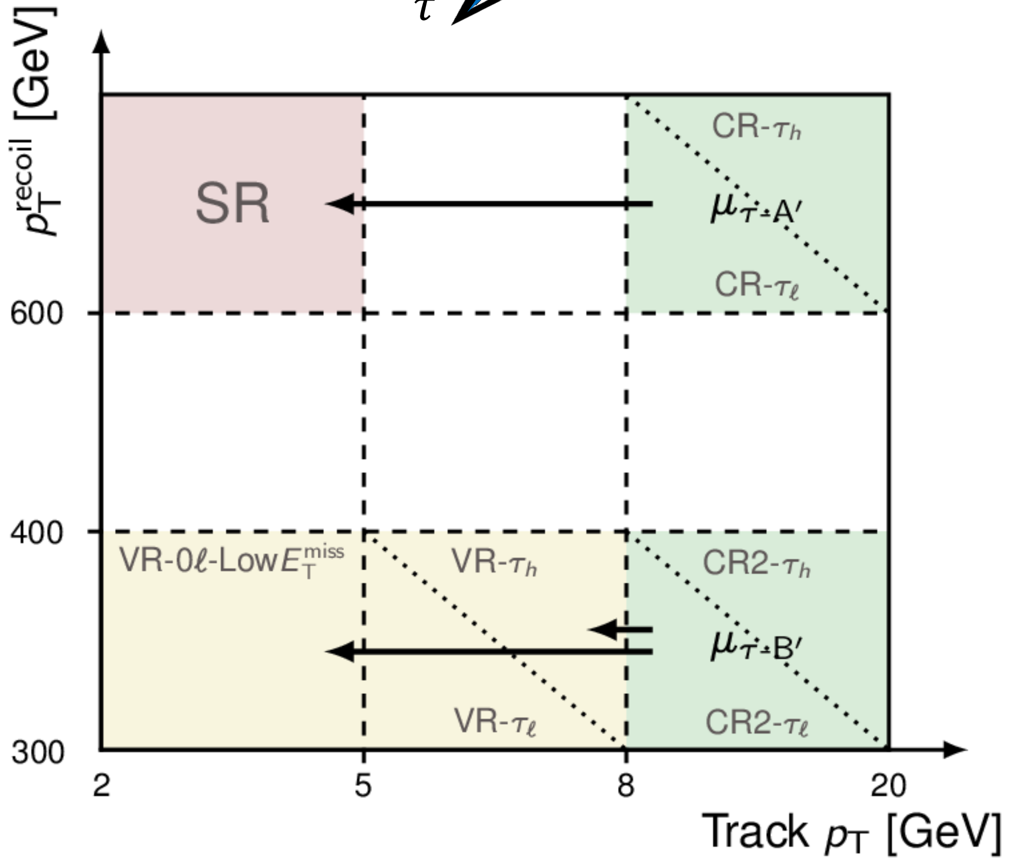
τ track background



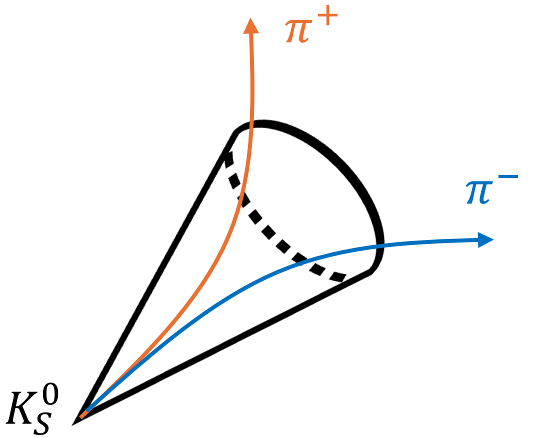
τ tracks associated to pions or leptons from decays of low-p_T τ leptons in W+jets events.

Estimation via Monte Carlo simulation normalisation to data. *Note:* τ tracks tend to have a harder p_T spectrum than signal ones.

- Control Regions (CRs) defined by requiring $8 <$ track p_T $[\mathrm{GeV}] < 20$.
- CR-τ_h and CR-τ_ℓ for hadronic τ_h or leptonic τ_ℓ decays, defined by requiring 0 or 1 leptons, respectively.
- Validation Regions (VRs) defined in a lower $p_\mathrm{T}^\mathrm{recoil} = |p_\mathrm{T}(\ell) + p_\mathrm{T}^\mathrm{miss}|$ phase space to increase the background purity.



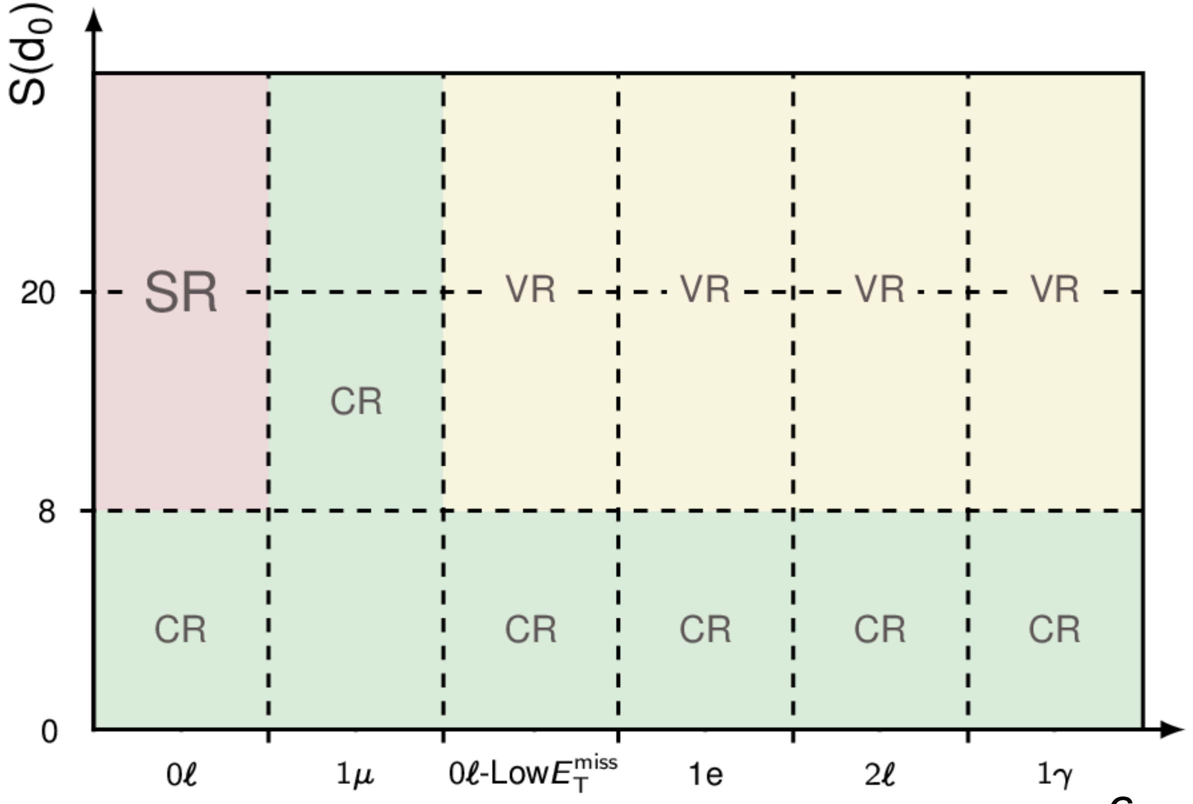
QCD track background



QCD tracks from decays of heavy particles (Λ^0, K_S^0, etc.) in pileup or underlying events in *W*/*Z*+jets.

Data-driven ABCD background estimation:

- $S(d_0)$ distribution extracted from data events in CR-1μ, mostly populated by *W*($\rightarrow \mu\nu$)+jets .
- Background normalized in CR-0ℓ to obtain the estimate in the Signal Region (SR), where the main physics process is $Z(\rightarrow \nu\nu)$+jets.
- VRs in 1e, 2ℓ and 1γ for the validation in other processes.

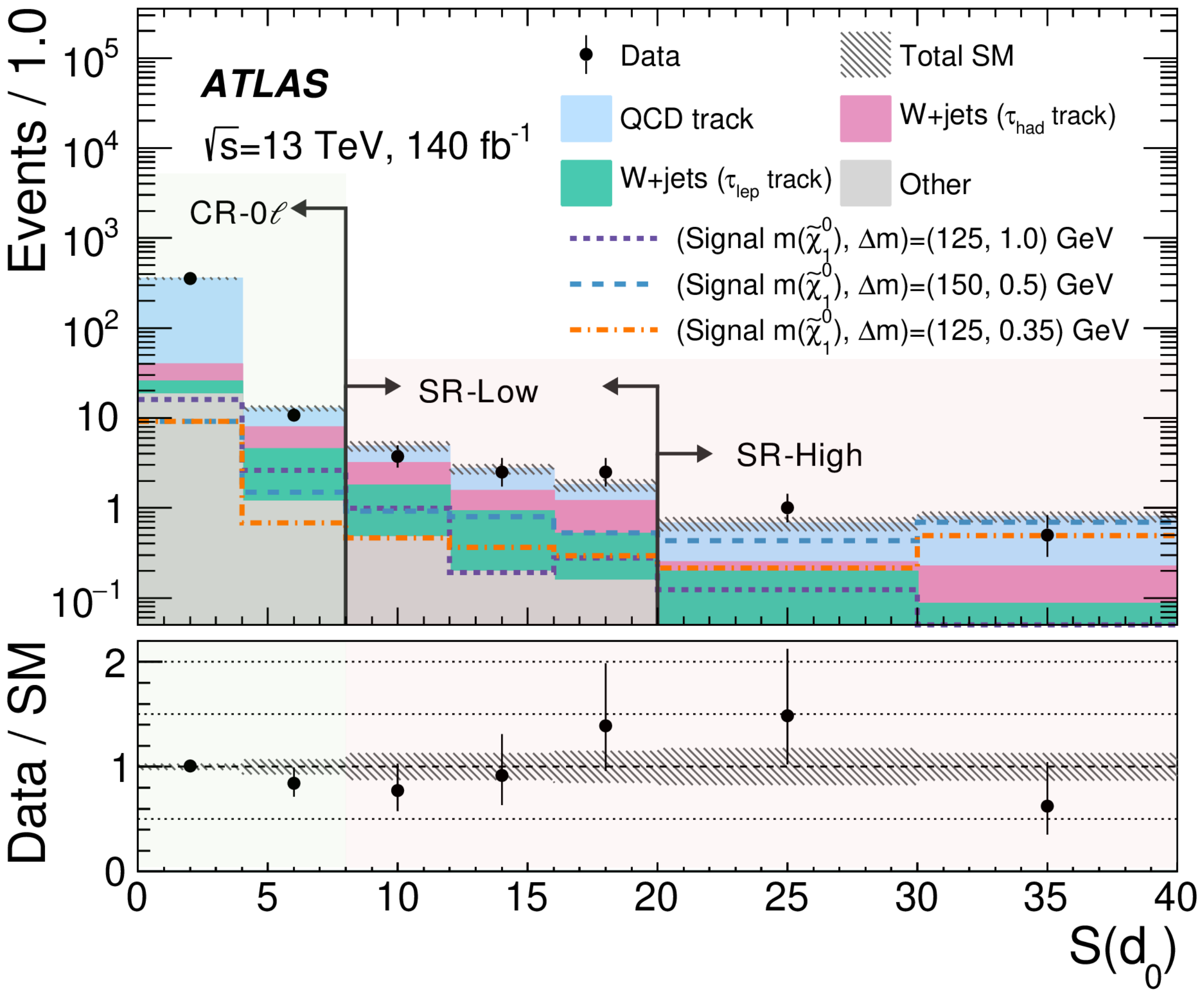


Time to unblind!

Two different SRs:

- SR-Low $(8 < S(d_0) < 20)$
- SR-High $(S(d_0) > 20)$

	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
$W(\to \tau_\ell \nu) + \text{jets}$	9.6 ± 1.6	2.0 ± 0.6
$W(\to \tau_h \nu) + \text{jets}$	10.6 ± 2.0	1.9 ± 0.8
Others	3.2 ± 0.7	0.8 ± 0.4



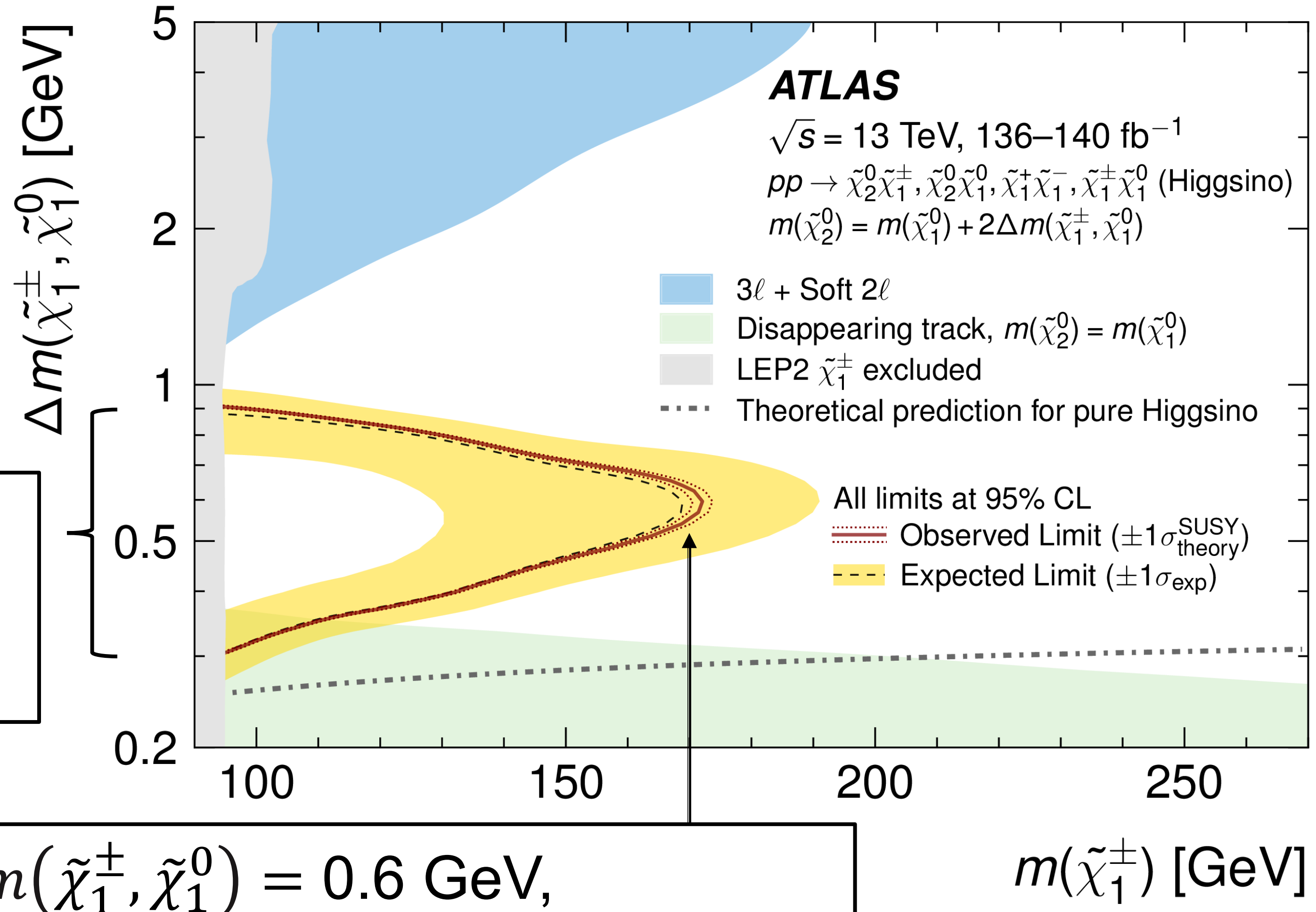
No significant deviations of the observed data from the standard model predictions.

Results

Good agreement between data and MC simulation

→ Exclusion limits set at 95% confidence level for the simplified higgsino model.

Higgsinos excluded in the range of mass splittings $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ between 0.3 GeV and 0.9 GeV.



For $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 0.6$ GeV,
the $\tilde{\chi}_1^{\pm}$ is excluded with a mass up to 170 GeV.

Conclusions

ATLAS paper of this search [2]
Phys. Rev. Lett. **132**, 221801(2024)

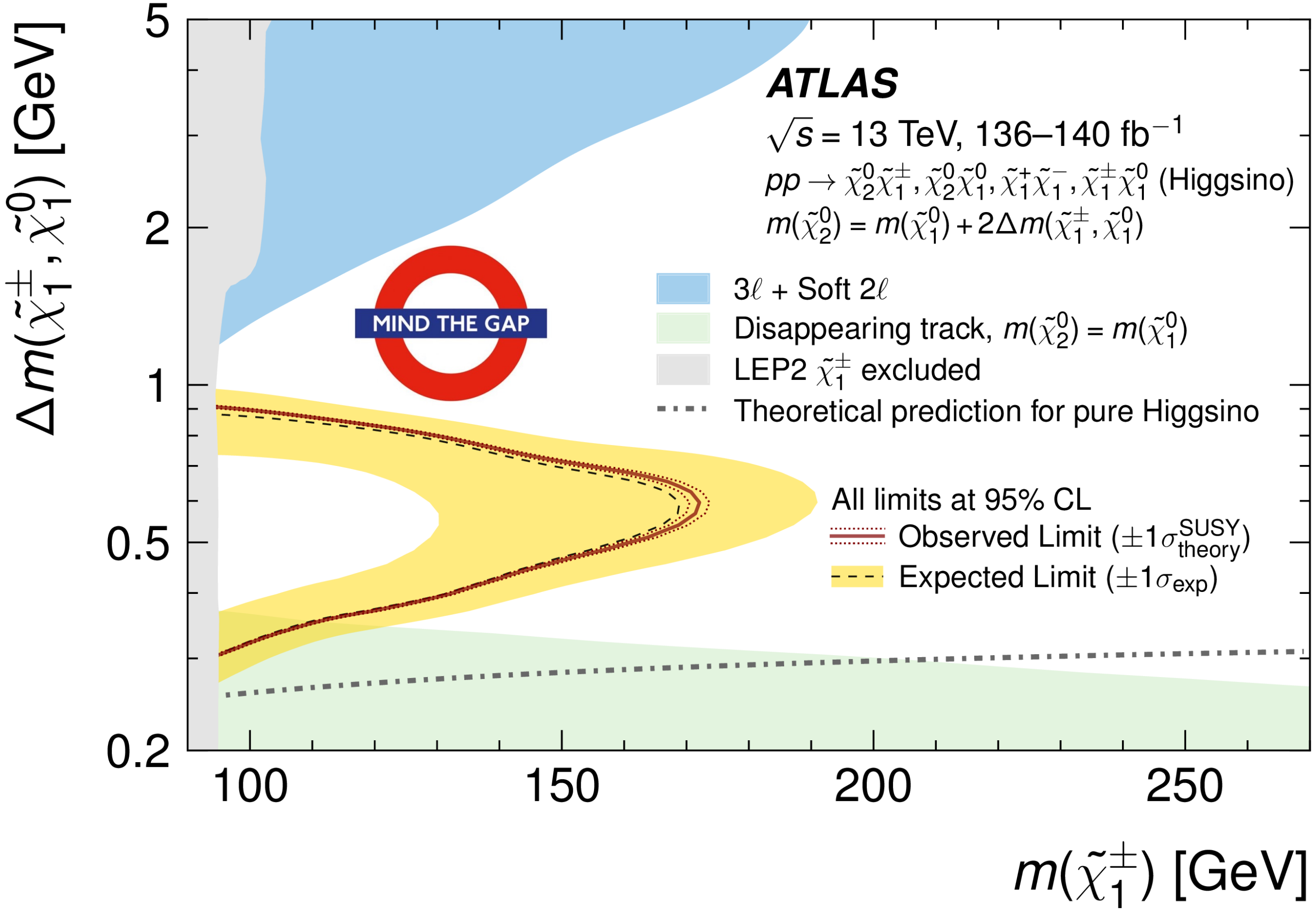
New ATLAS search for compressed higgsinos

→ Higgsinos with mass splittings between 0.3 GeV and 0.9 GeV have been excluded at 95% confidence level for the first time since LEP.

« Just the beginning »
→ other compressed searches are being prepared!

« Where is SUSY hiding? »

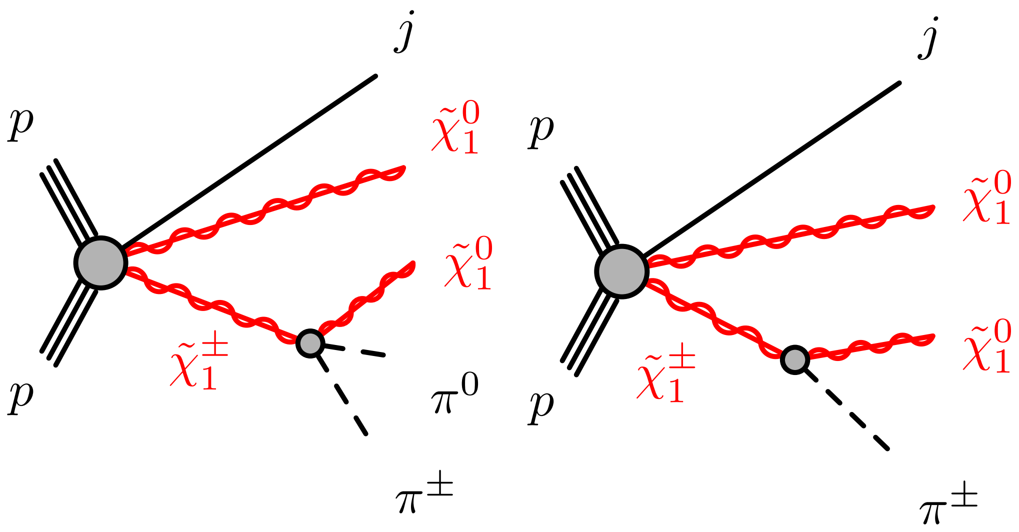
Extensive dataset collected in Run 3 will shed light into it.



Backup

Signal models

Six higgsino signal processes considered: $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$.



$\tilde{\chi}_1^\pm$ supposed to have a mass halfway between the $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_1^0$ masses as from Phys. Lett. B 372 (1996) 253-258 [3],

$$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = \frac{1}{2}\left(1 - \frac{\varepsilon \sin 2\beta}{4}\right)\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) + \mathcal{O}\left(\frac{1}{M^2}\right).$$

Mass splittings

The mass splitting $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ for higgsinos is given by the tree-level mixing with other heavier particles (wino and bino) and by electroweak radiative corrections [1],

$$\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = \Delta m^{\mathrm{tree}}(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) + \Delta m^{\mathrm{rad}}(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$$

where:

$$\Delta m^{\mathrm{tree}}(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \simeq \frac{M_Z^2}{2}\left|\frac{\cos^2\theta_W}{M_2} + \frac{\sin^2\theta_W}{M_1}\right| + \sin 2\beta M_Z^2\left(\frac{\cos^2\theta_W}{M_2} - \frac{\sin^2\theta_W}{M_1}\right)$$

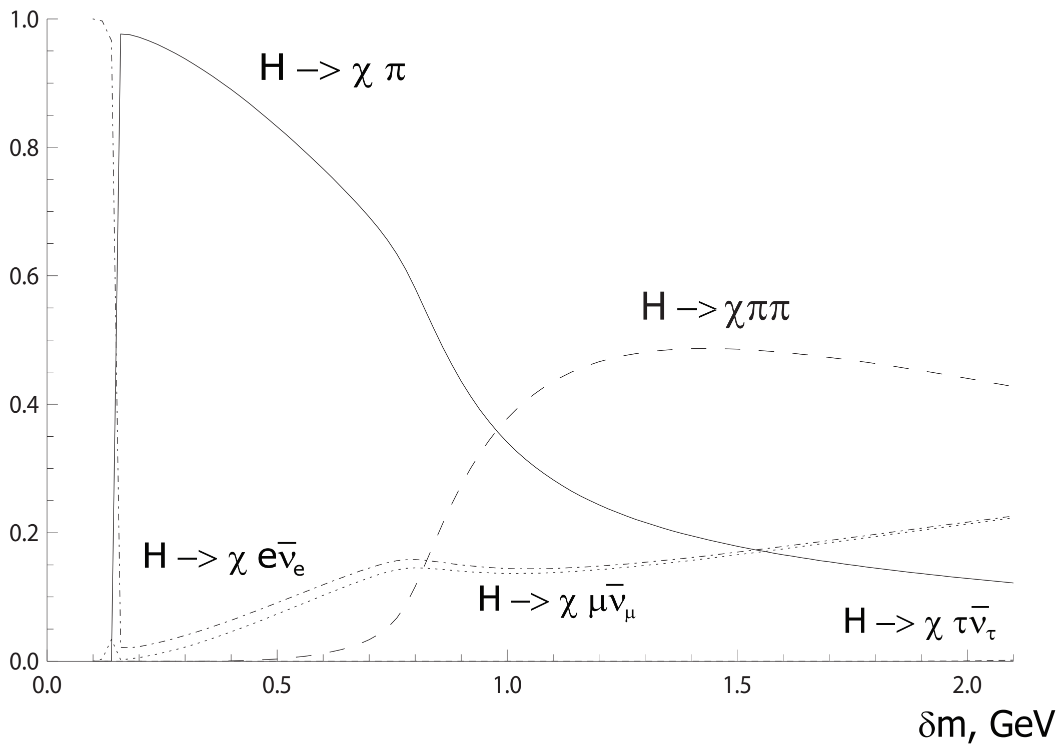
if $\mu \gg M_Z$

$$\Delta m^{\mathrm{rad}}(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \simeq \frac{\alpha_2 \mu \sin^2\theta_W}{2\pi}\int_0^1 \mathrm{d}t\,(1+t)\ln\left[1 + \frac{M_Z^2(1-t)}{\mu^2 t^2}\right] \simeq \frac{\alpha_2 M_Z}{2}\sin^2\theta_W \simeq 354\ \mathrm{MeV}.$$

Branching ratios

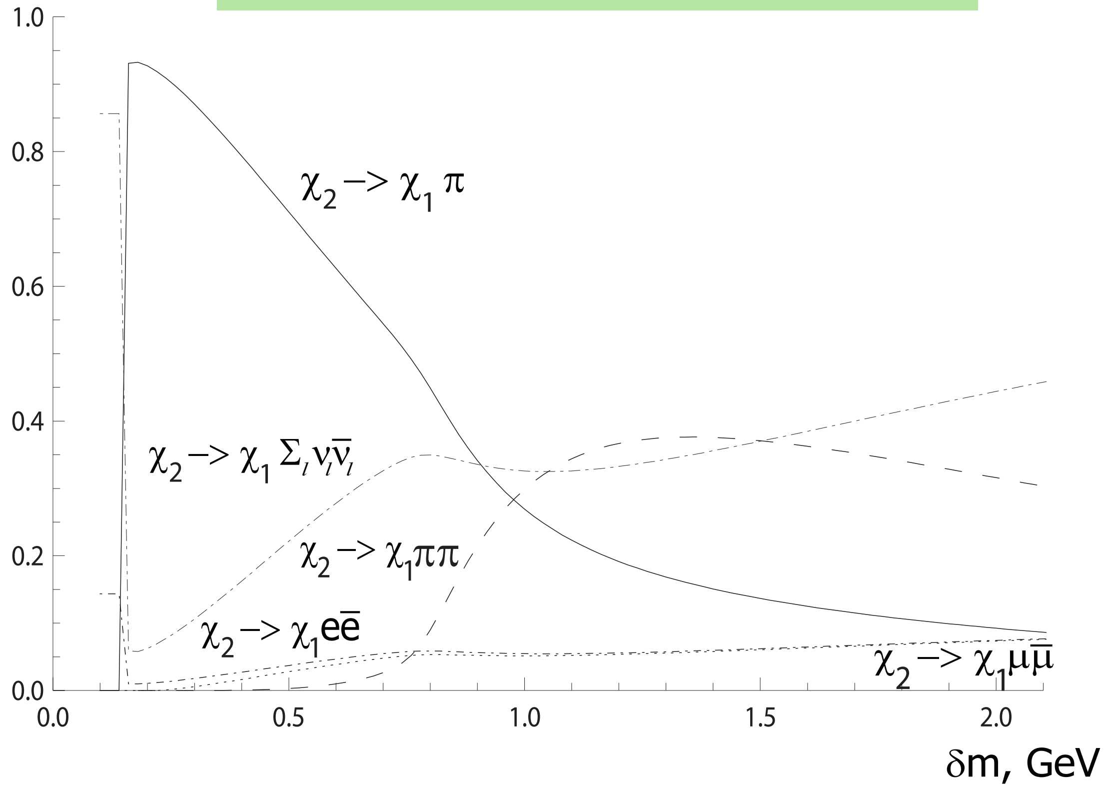
Int. J. Mod. Phys. A 24, 6051 (2009) [4]

BR for $\tilde{\chi}_1^{\pm} \to \pi^{\pm}\tilde{\chi}_1^0$



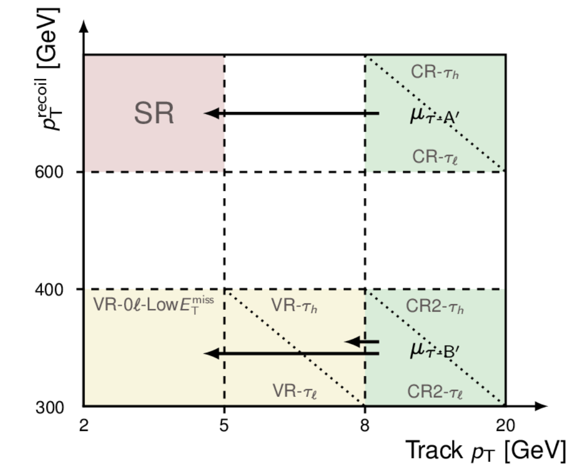
$BR(\tilde{\chi}_1^{\pm} \to \pi^{\pm}\tilde{\chi}_1^0) \sim 80\%$ for $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 0.5$ GeV

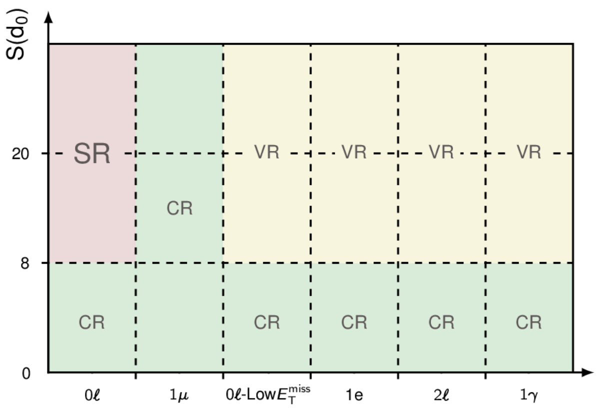
BR for $\tilde{\chi}_2^0 \to \pi^0\tilde{\chi}_1^0$



$BR(\tilde{\chi}_2^0 \to \pi^0\tilde{\chi}_1^0) \sim 70\%$ for $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 0.5$ GeV

Selection of the analysis regions



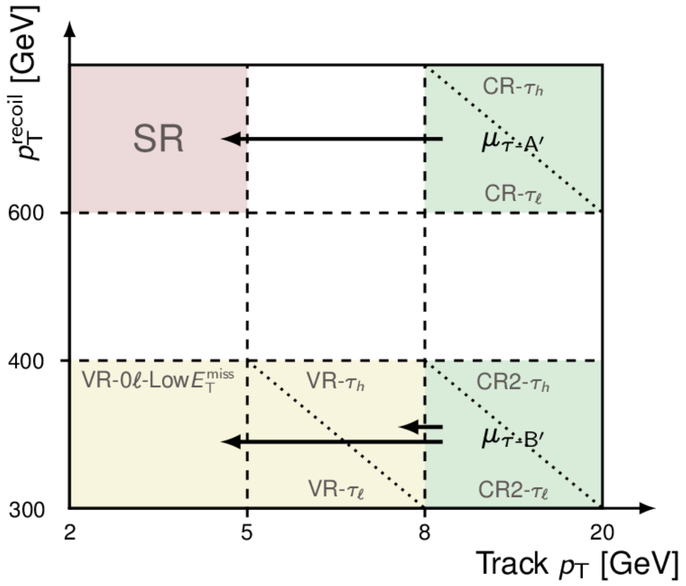


Variable	SR	CR-τ_h	CR-τ_ℓ	VR(CR2)-τ_h	VR(CR2)-τ_ℓ
N_ℓ	= 0	= 0	= 1	= 0	= 1
m_T [GeV]	–	–	< 50	–	< 50
p_T^{recoil} [GeV]	> 600	> 600		[300,400]	
Track p_T [GeV]	[2,5]	[8,20]		[5,8] ([8,20])	
Track $S(d_0)$	> 8	> 3		> 3	

Variable	SR (CR-0ℓ)	CR-1μ	VR(CR)-0ℓ−lowE_T^{miss}	VR(CR)-1e	VR(CR)-2ℓ	VR(CR)-1γ
Trigger	E_T^{miss}	E_T^{miss}	E_T^{miss}	Single-e	E_T^{miss} or Single-e	Single Photon
$N(e)$	= 0	= 0	= 0	= 1	–	= 0
$N(\mu)$	= 0	= 1	= 0	= 0	–	= 0
$N(e$ or $\mu)$	= 0	= 1	= 0	= 1	= 2	= 0
N_γ	= 0	= 0	= 0	= 0	= 0	= 1
$p_T(\ell_1)$ [GeV]	–	> 10	–	> 30	$p_T(\mu) > 10$ ($p_T(e) > 30$)	–
$p_T(\ell_2)$ [GeV]	–	–	–	–	> 10	–
m_{ll} [GeV]	–	–	–	–	[66.2, 116.2]	–
m_T [GeV]	–	[56, 106]	–	[56, 106]	–	–
p_T^{recoil} [GeV]	> 600	> 300	[300, 400]	> 300	> 300	> 600
Track $S(d_0)$	> 8 (< 8)	–	> 8 (< 8)			

τ track background

- The $W(\rightarrow \mu\nu)$+jets MC sample is normalized to the data in CR-τ_h and CR-τ_ℓ to obtain the estimate in the SR in $p_{\mathrm{T}}^{\mathrm{recoil}} > 600$ GeV phase space.
  - The MC normalization factor for the τ track background is 1.1 ± 0.1, derived from a fit under the background-only hypothesis.
- The extrapolation over the track p_{T} is validated in VRs-τ_h and VRs-τ_ℓ, where the intermediate $5 <$ track p_{T} [GeV] < 8 range is selected.
  - To avoid signal contamination in the VRs, the $p_{\mathrm{T}}^{\mathrm{recoil}}$ selection is shifted to $300 < p_{\mathrm{T}}^{\mathrm{recoil}}$ [GeV] < 400.
  - To validate the track p_{T} extrapolation in an isolated way, the estimates in the VRs are obtained by normalizing the MC in CRs denoted as (CR2-τ_h and CR2-τ_ℓ) with the same shifted $p_{\mathrm{T}}^{\mathrm{recoil}}$ requirement.
- To acquire larger data statistics, the $S(d_0)$ selection is loosened to $S(d_0) > 3$.



Purity of τ track background $> 90\%$.

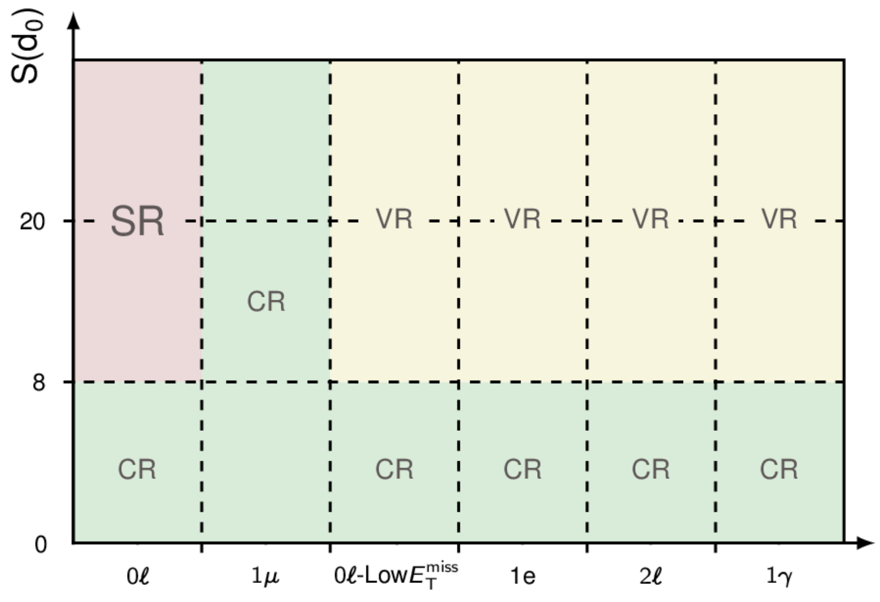
QCD track background

- The breakdown of the hadron components in the pileup jets or underlying events do not strongly depend on the details of the hard collision process.

  → It is possible to use CR-1μ, mostly populated by $W(\rightarrow \mu\nu)$+jets and CR-0ℓ, mostly populated by $Z(\rightarrow \nu\nu)$+jets, to estimate the QCD track background via the ABCD method.

- $W(\rightarrow e\nu)$+jets validated in VRs with $1e$,
  $Z(\rightarrow \ell\ell)$+jets validated in VRs with 2ℓ,
  γ + jets and multijet QCD validated in VRs with 1γ.

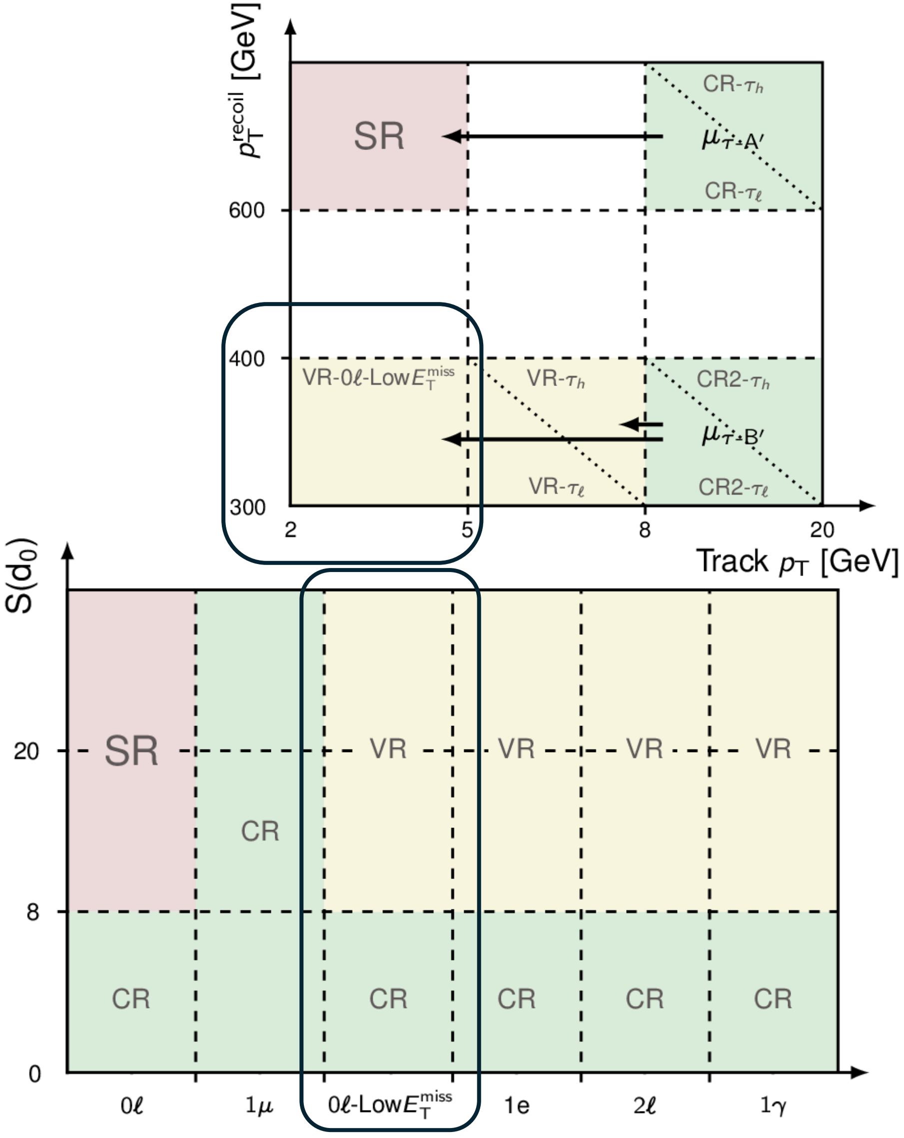
- The $p_{\mathrm{T}}^{\mathrm{recoil}}$ is used as a proxy for the p_{T} of the $W/Z/\gamma$ boson, and it assumes the definitions:
  - $p_{\mathrm{T}}^{\mathrm{recoil}} = E_{\mathrm{T}}^{\mathrm{miss}}$ in 0ℓ regions,
  - $p_{\mathrm{T}}^{\mathrm{recoil}} = |p_{\mathrm{T}}(\ell = e/\mu) + p_{\mathrm{T}}^{\mathrm{miss}}|$ in 1e/1μ regions,
  - $p_{\mathrm{T}}^{\mathrm{recoil}} = |p_{\mathrm{T}}(\ell_1) + p_{\mathrm{T}}(\ell_2) + p_{\mathrm{T}}^{\mathrm{miss}}|$ in 2ℓ regions,
  - $p_{\mathrm{T}}^{\mathrm{recoil}} = |p_{\mathrm{T}}(\gamma) + p_{\mathrm{T}}^{\mathrm{miss}}|$ in 1γ regions.



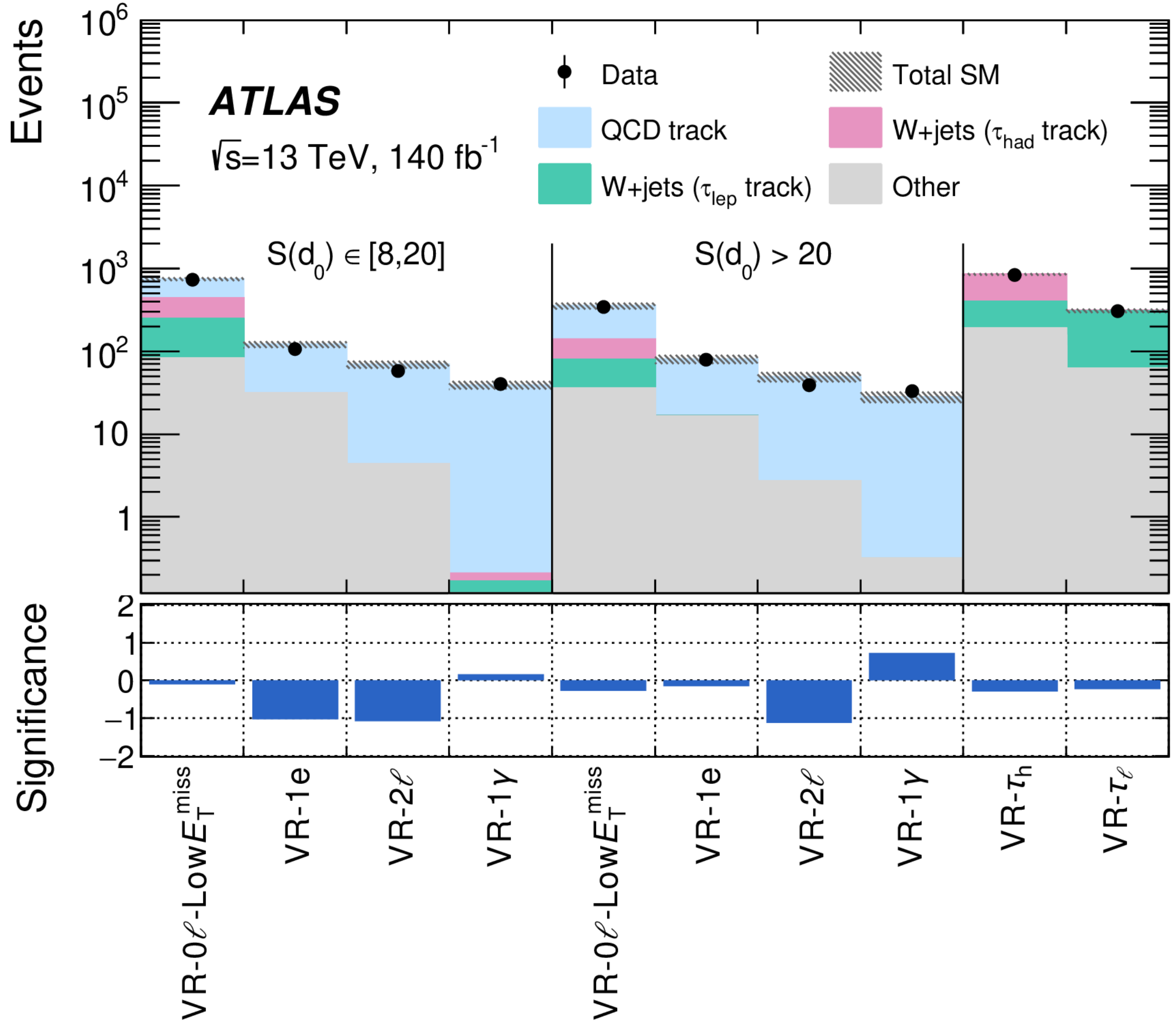
Purity of QCD track background > 90%.
Exception: regions with 1γ, ~30% multijet QCD.

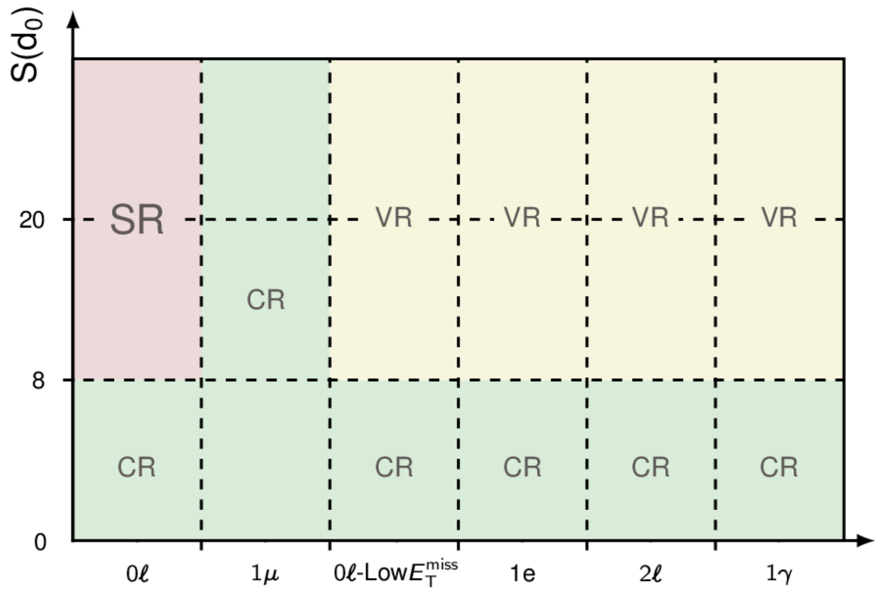
Hybrid τ track and QCD track validation

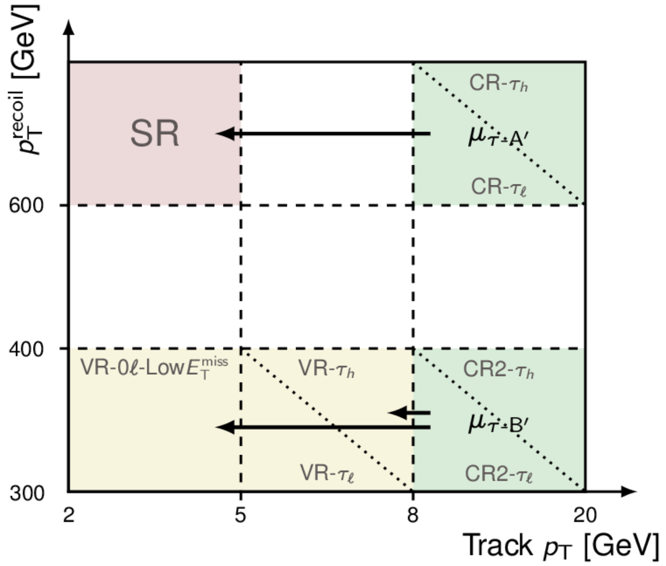
- VR-0ℓ-Low$E_{\mathrm{T}}^{\mathrm{miss}}$: simultaneous validation of the τ track and QCD track backgrounds, for which the contributions are almost equal.
- VR-0ℓ-Low$E_{\mathrm{T}}^{\mathrm{miss}}$ defined in the 0ℓ phase space with a lower $E_{\mathrm{T}}^{\mathrm{miss}} = p_{\mathrm{T}}^{\mathrm{recoil}}$ requirement, $300 < p_{\mathrm{T}}^{\mathrm{recoil}}$ [GeV] < 400, as for the VR-τ_h and VR-τ_ℓ .
- τ track background in VR-0ℓ-Low$E_{\mathrm{T}}^{\mathrm{miss}}$ estimated by normalizing the MC in CR2-τ_h and CR2-τ_ℓ , which are defined in the higher $8 <$ track p_{T} [GeV] < 20 phase space.
- QCD track background in VR-0ℓ-Low$E_{\mathrm{T}}^{\mathrm{miss}}$ estimated by the ABCD method, where the $S(d_0)$ shape is extracted from CR-1μ and normalized to CR-0ℓ-Low$E_{\mathrm{T}}^{\mathrm{miss}}$.



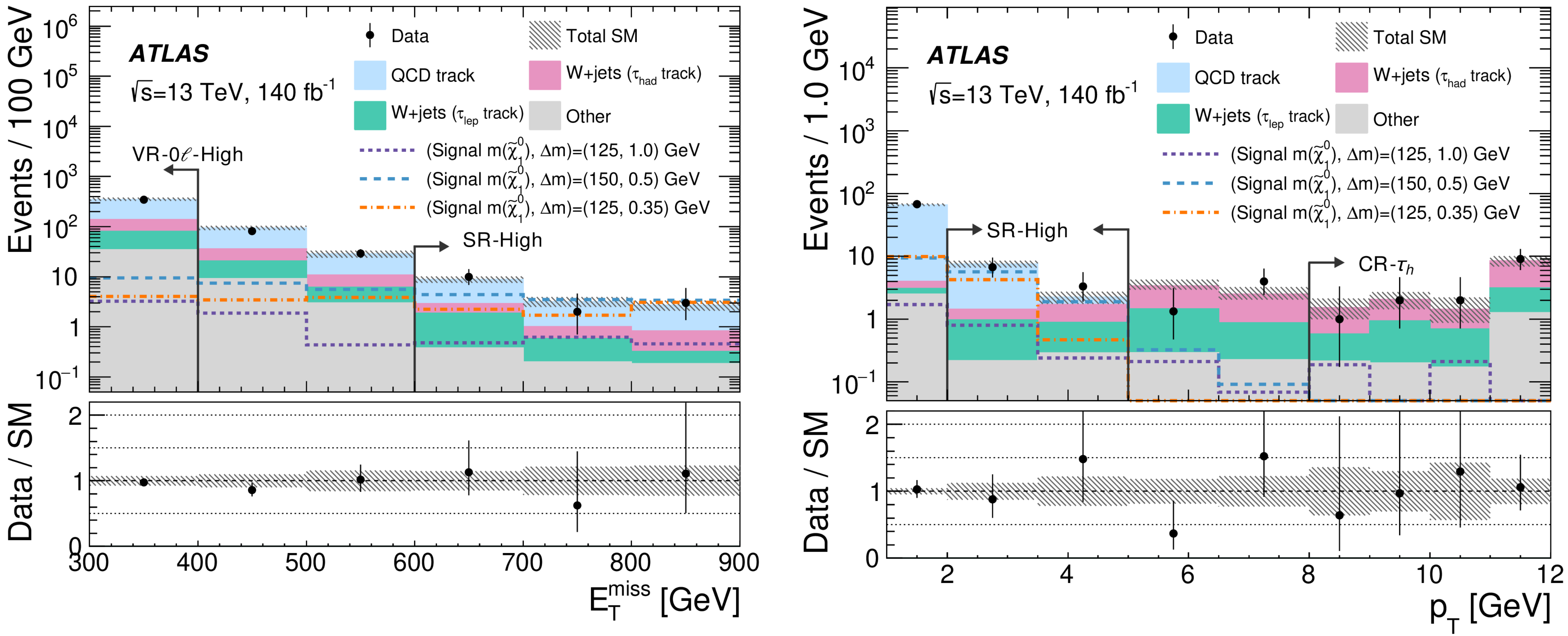
Validation regions



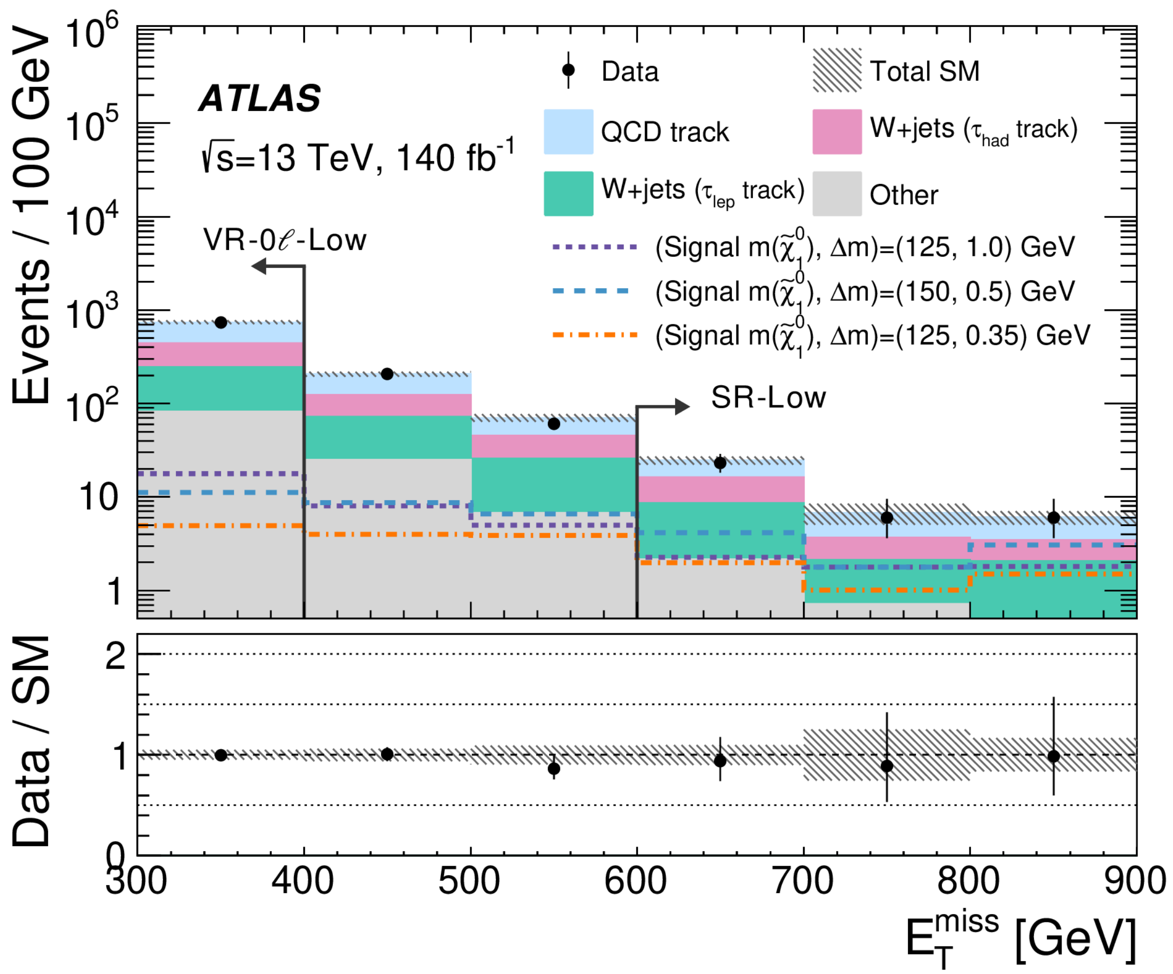


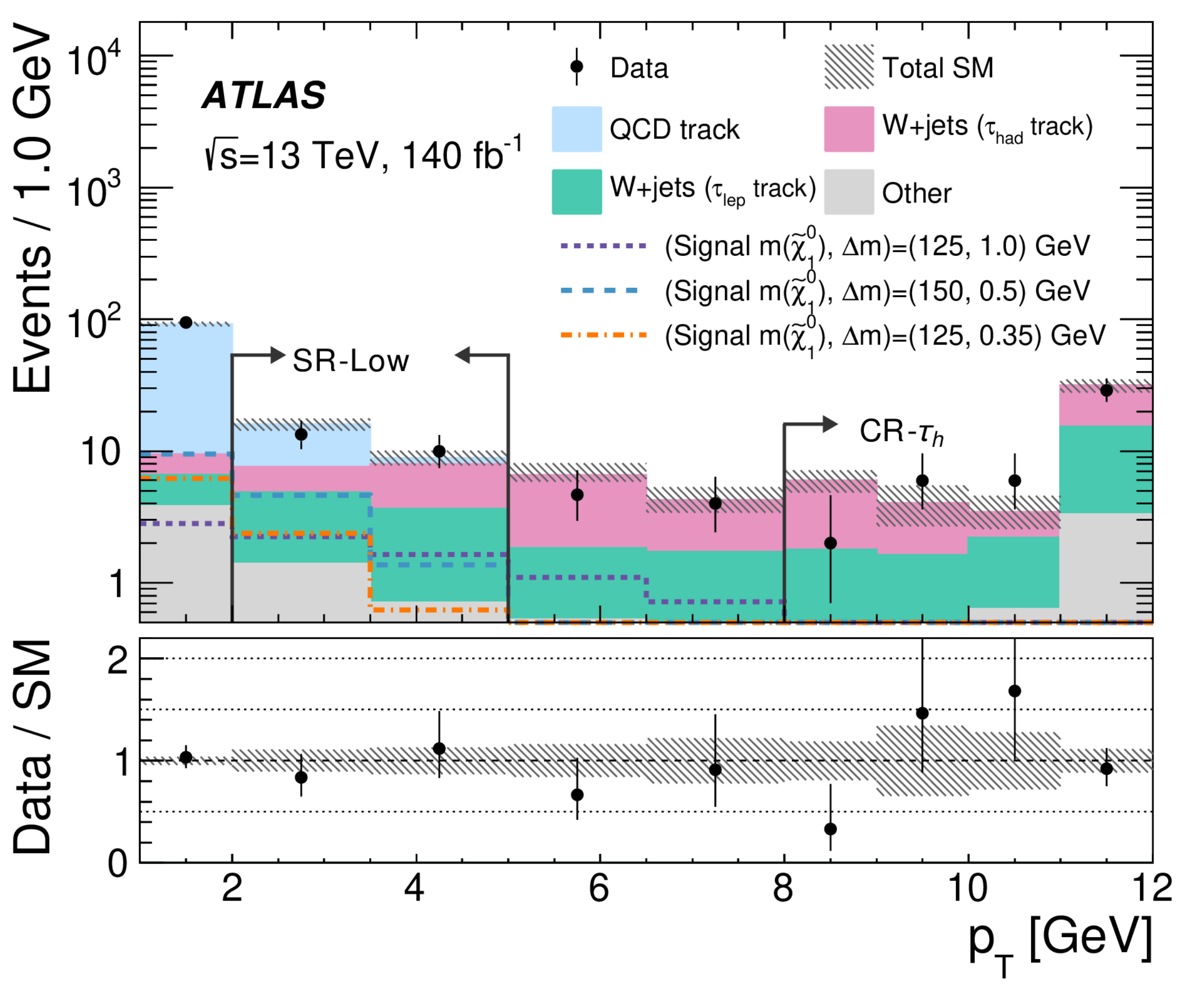


SR-High selection

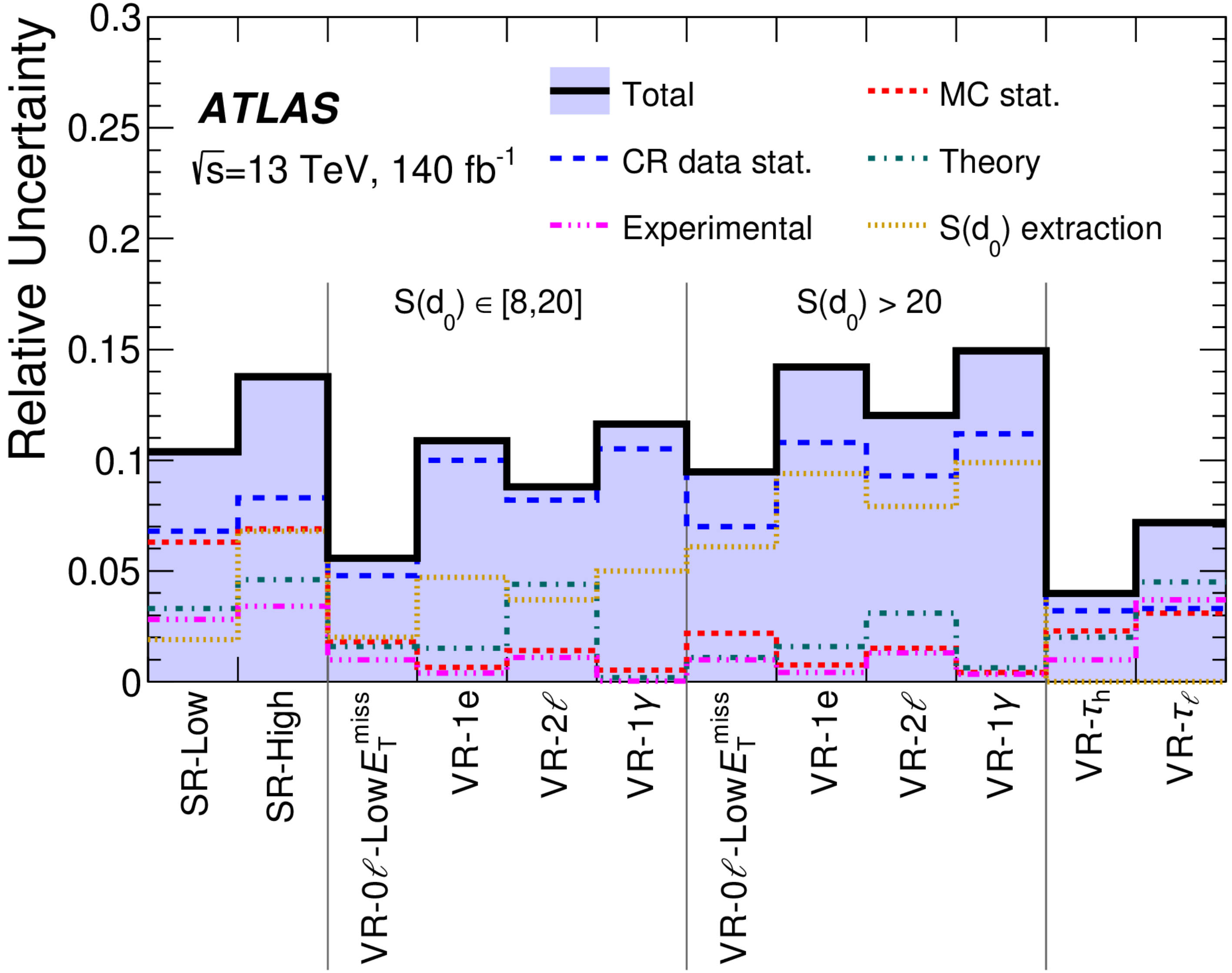


SR-Low selection

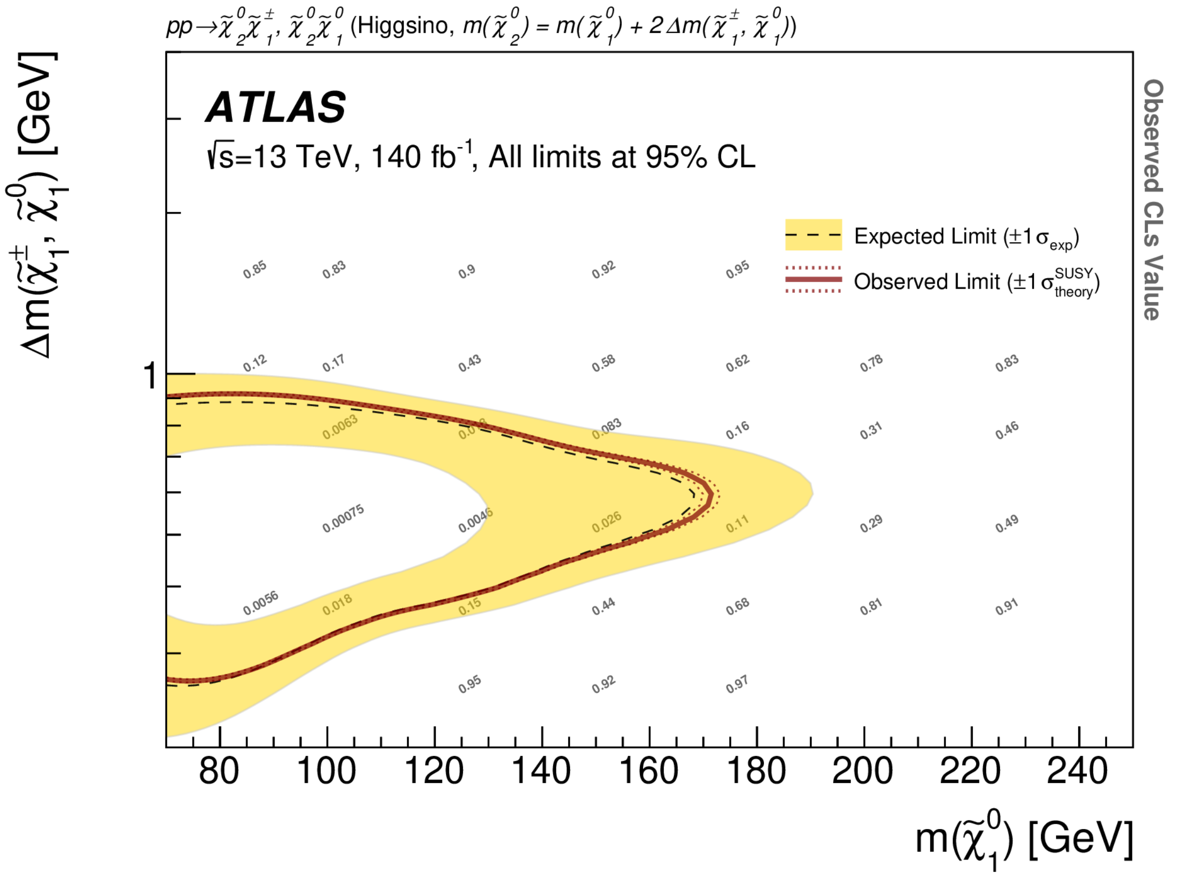


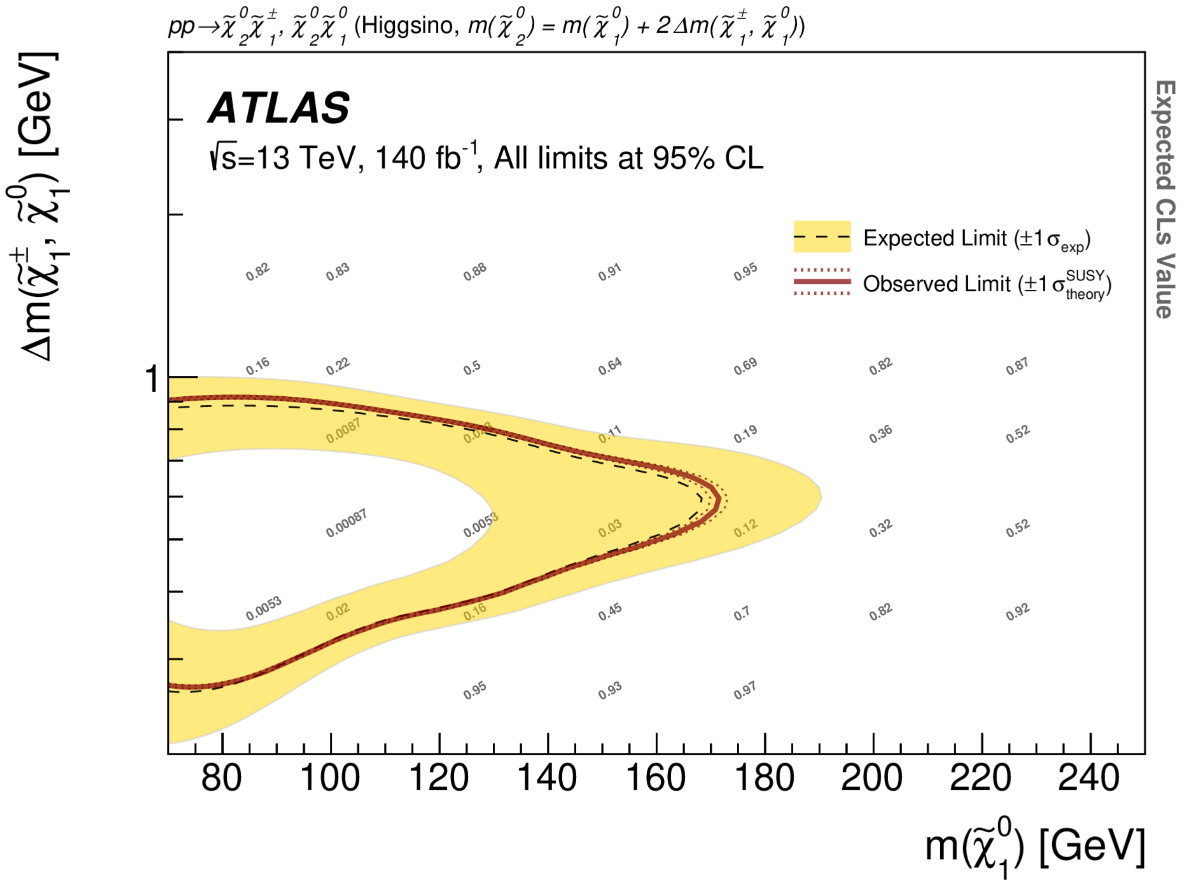


Systematic uncertainties

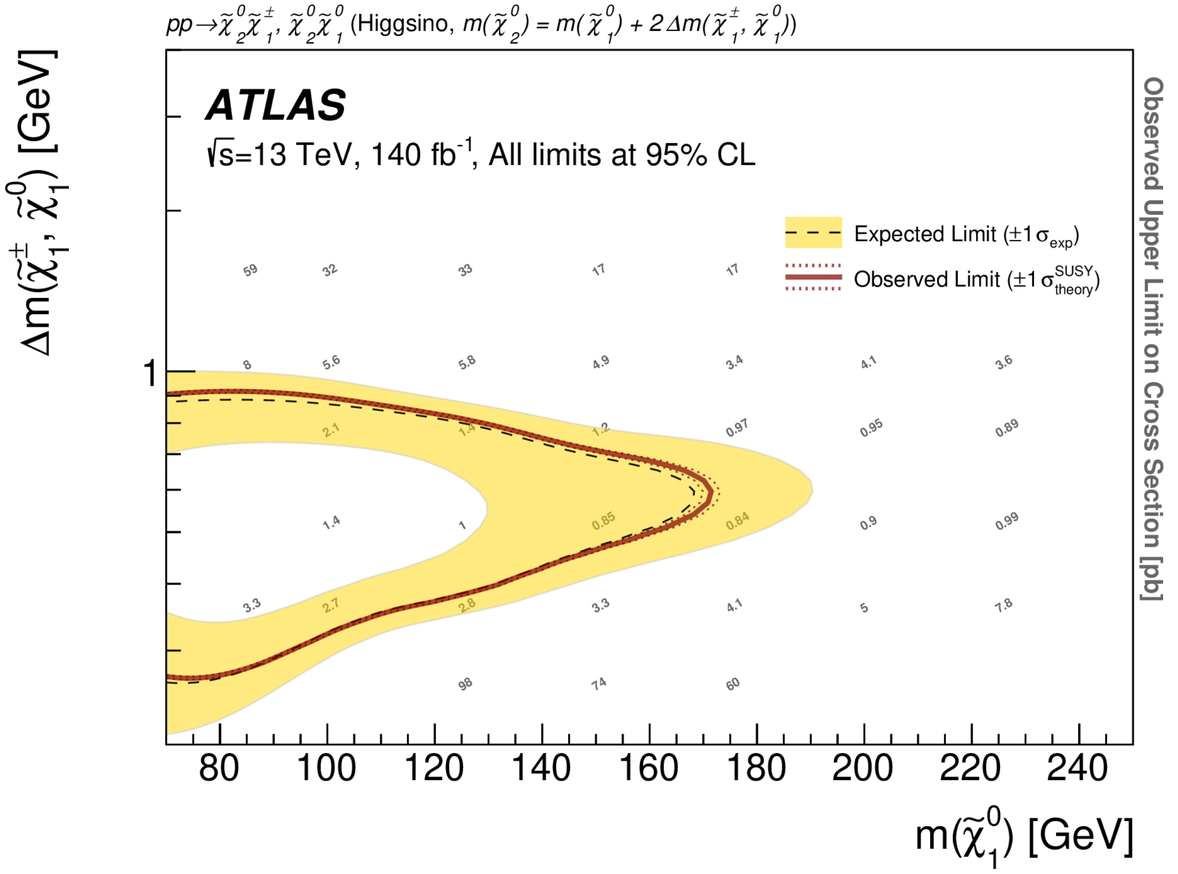


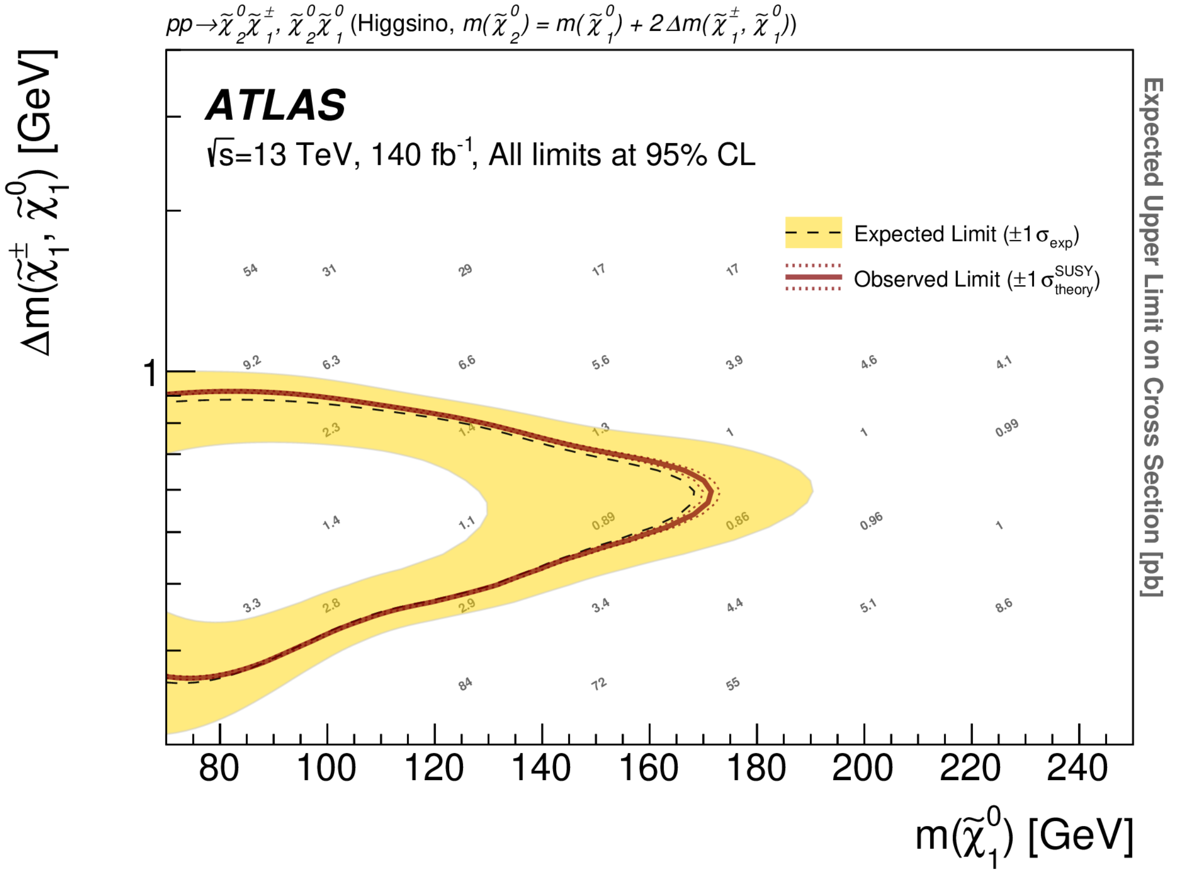
Observed and expected CLs





Observed and expected upper limits on the cross section





ATLAS EXPERIMENT

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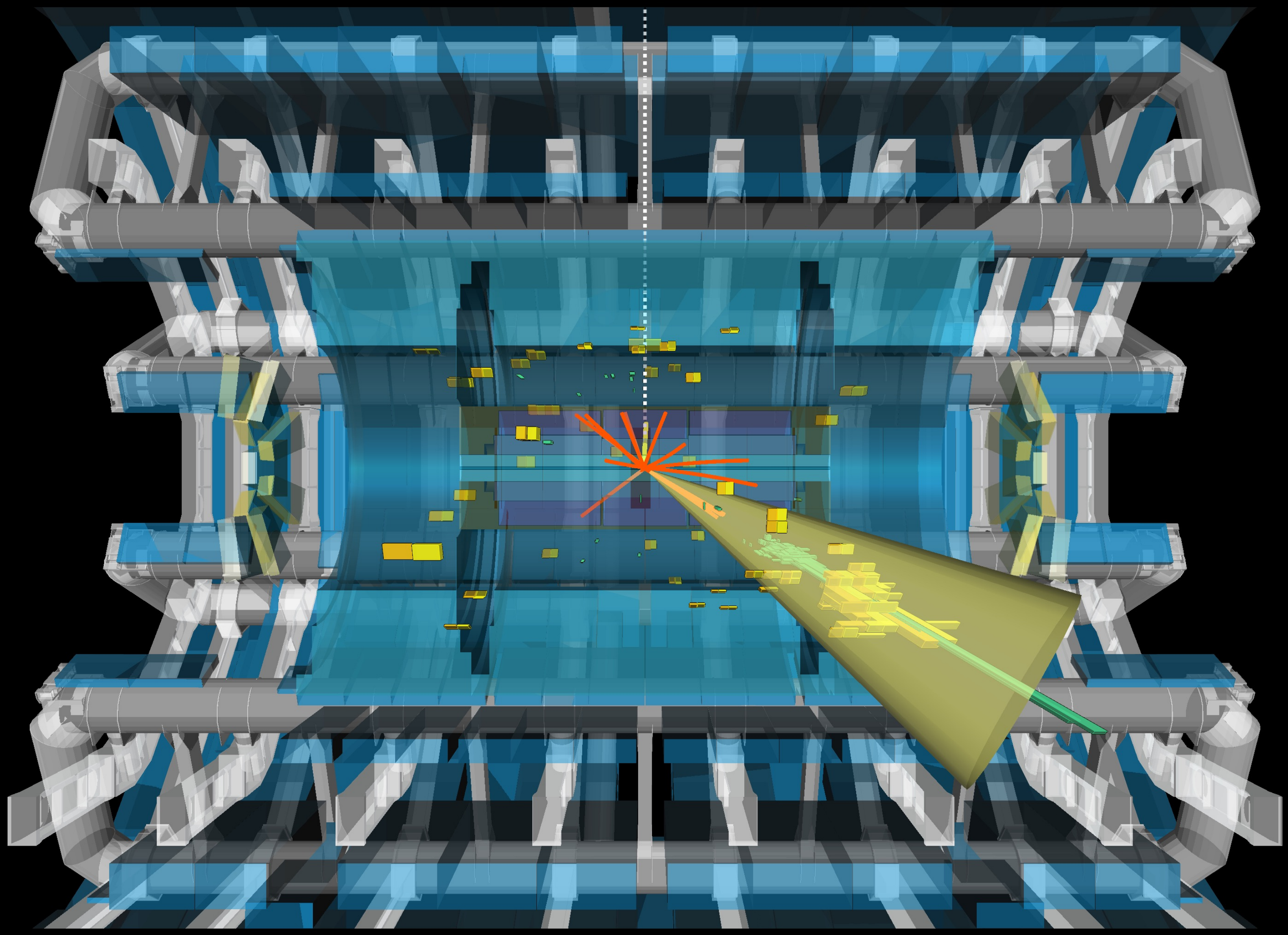
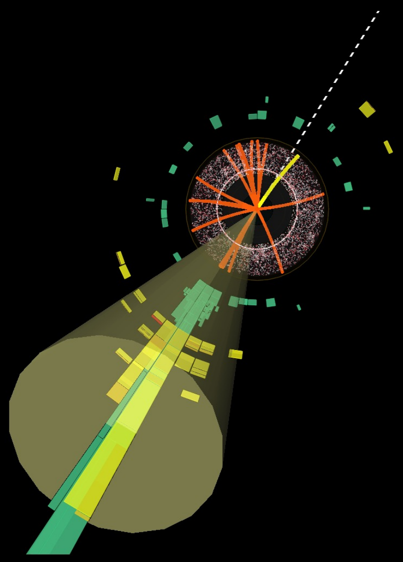
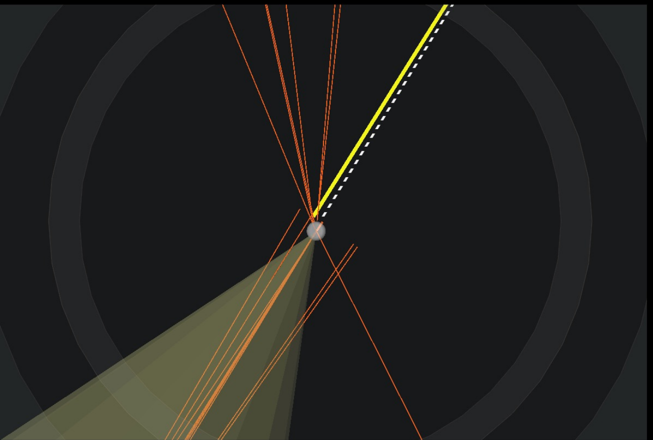
Event: 1342904905
2018-05-01 16:21:51 CEST







References

[1] H. Fukuda, N. Nagata, H. Oide, H. Otono, S. Shirai, «*Cornering Higgsino: Use of Soft Displaced Track*», Phys. Rev. Lett. 124, 101801 (2020).

[2] ATLAS Collaboration, «*Search for Nearly Mass-Degenerate Higgsinos Using Low-Momentum Mildly Displaced Tracks in pp Collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS Detector*», Phys. Rev. Lett. **132**, 221801(2024).

[3] G. F. Giudice, A. Pomarol, «*Mass degeneracy of the higgsinos*», Phys. Lett. B 372 (1996) 253-258.

[4] R. Pasechnik, V. A. Beylin, V. I. Kuksa, and G. M. Vereshkov «*Neutralino-nucleon interaction in the split SUSY scenario of the dark matter*», Int. J. Mod. Phys. A 24, 6051 (2009).