Compressed SUSY searches in ATLAS

LHCP 2018 - Bologna

Joana Machado Miguéns

University of Pennsylvania

on behalf of the ATLAS Collaboration

June 7th 2018

Why compressed

just a few examples...

naturalness in MSSM (tree level)

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

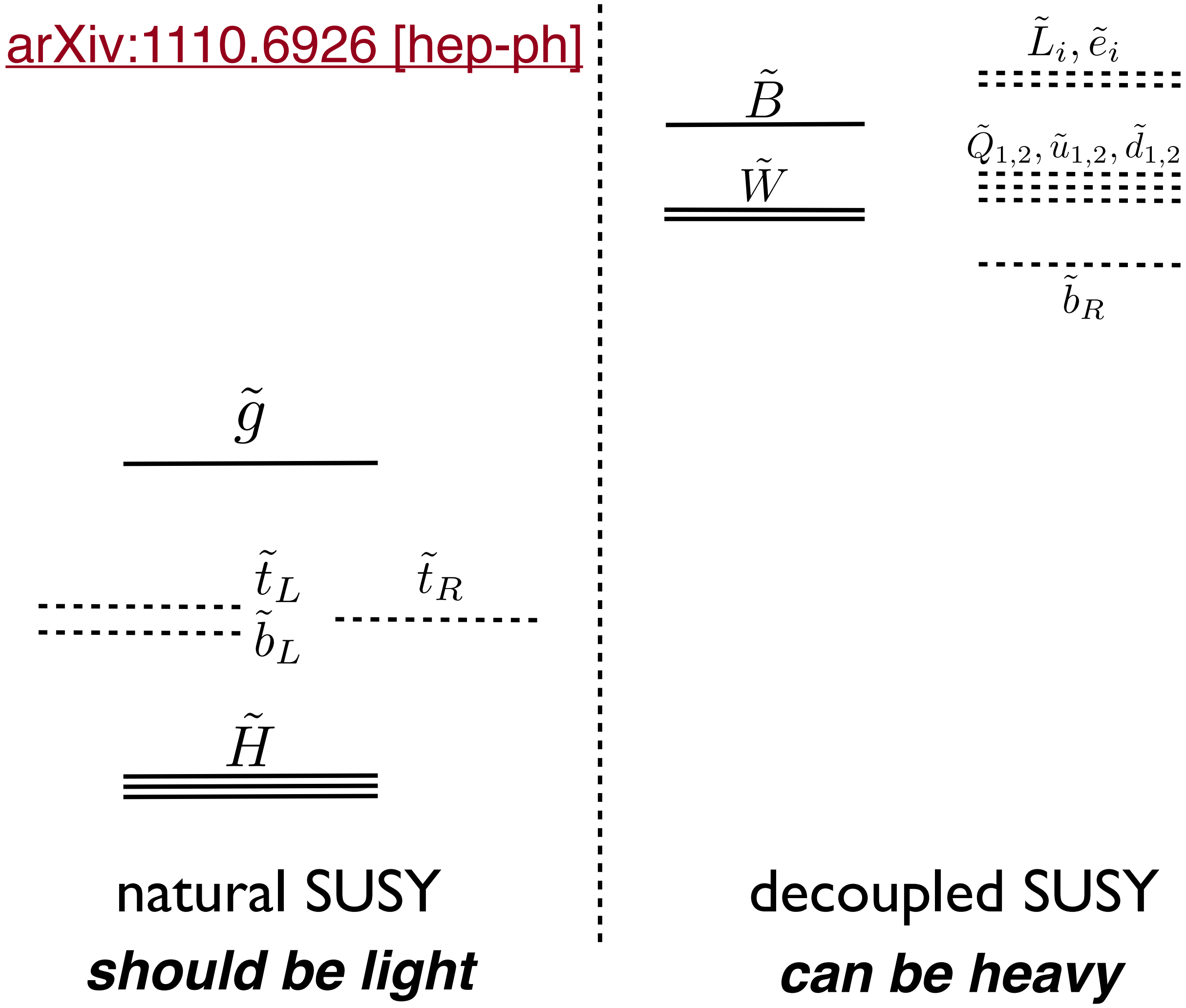
two-loop correction to m_H from gluinos

one-loop correction to m_H from stops

μ controls Higgsino masses

Natural SUSY mass spectrum

arXiv:1110.6926 [hep-ph]



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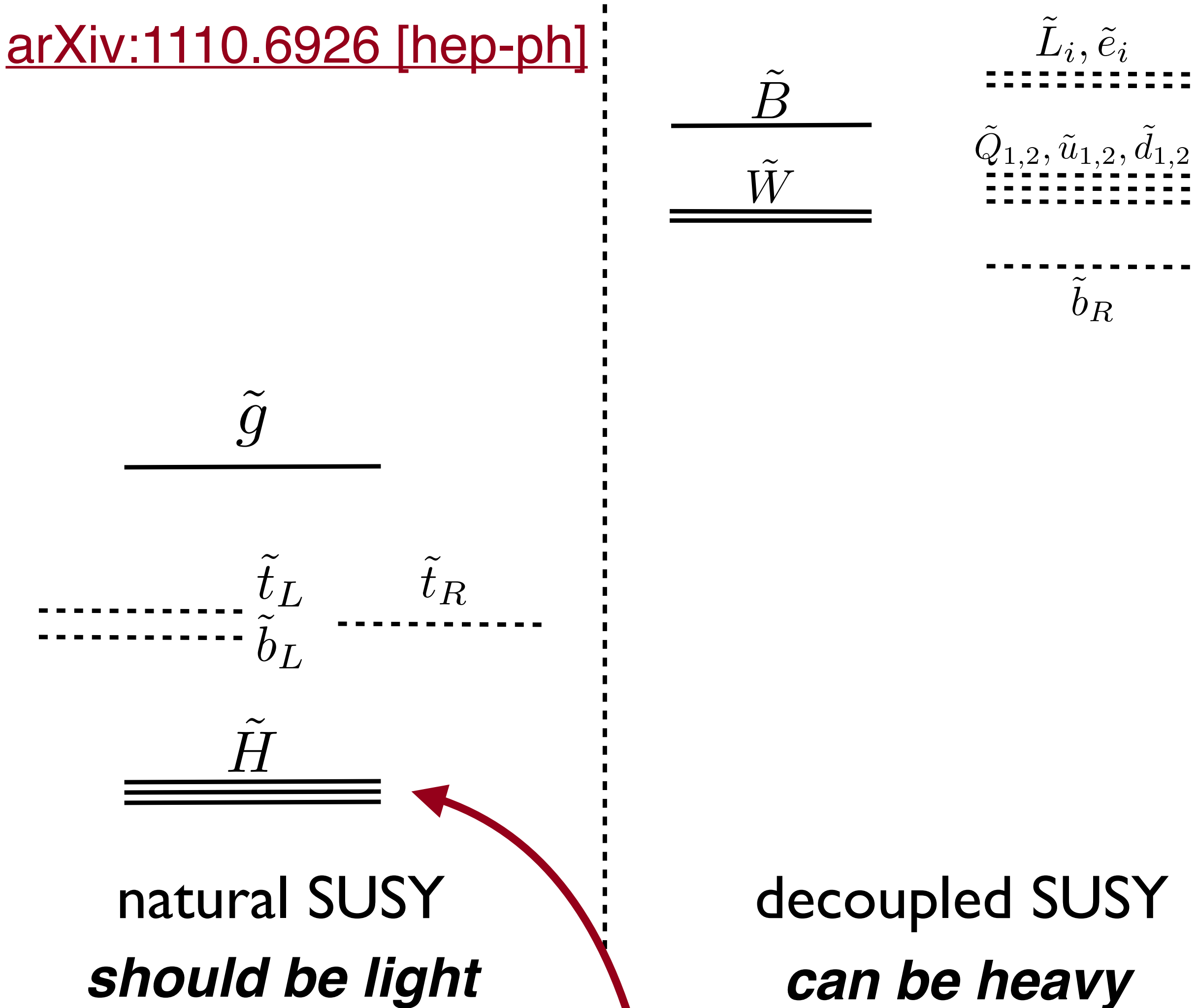

higgsino LSPs motivated by naturalness & naturally compressed

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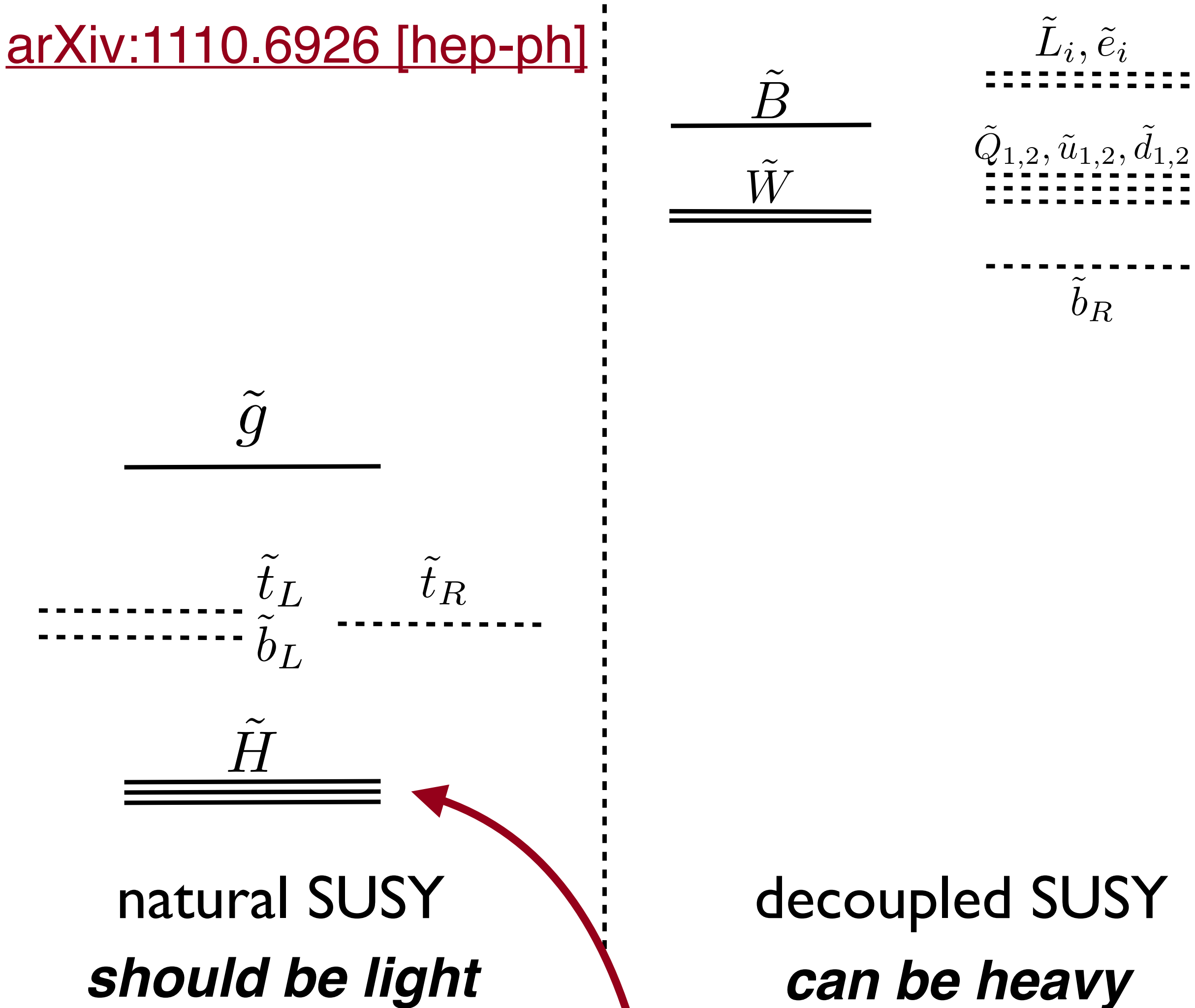

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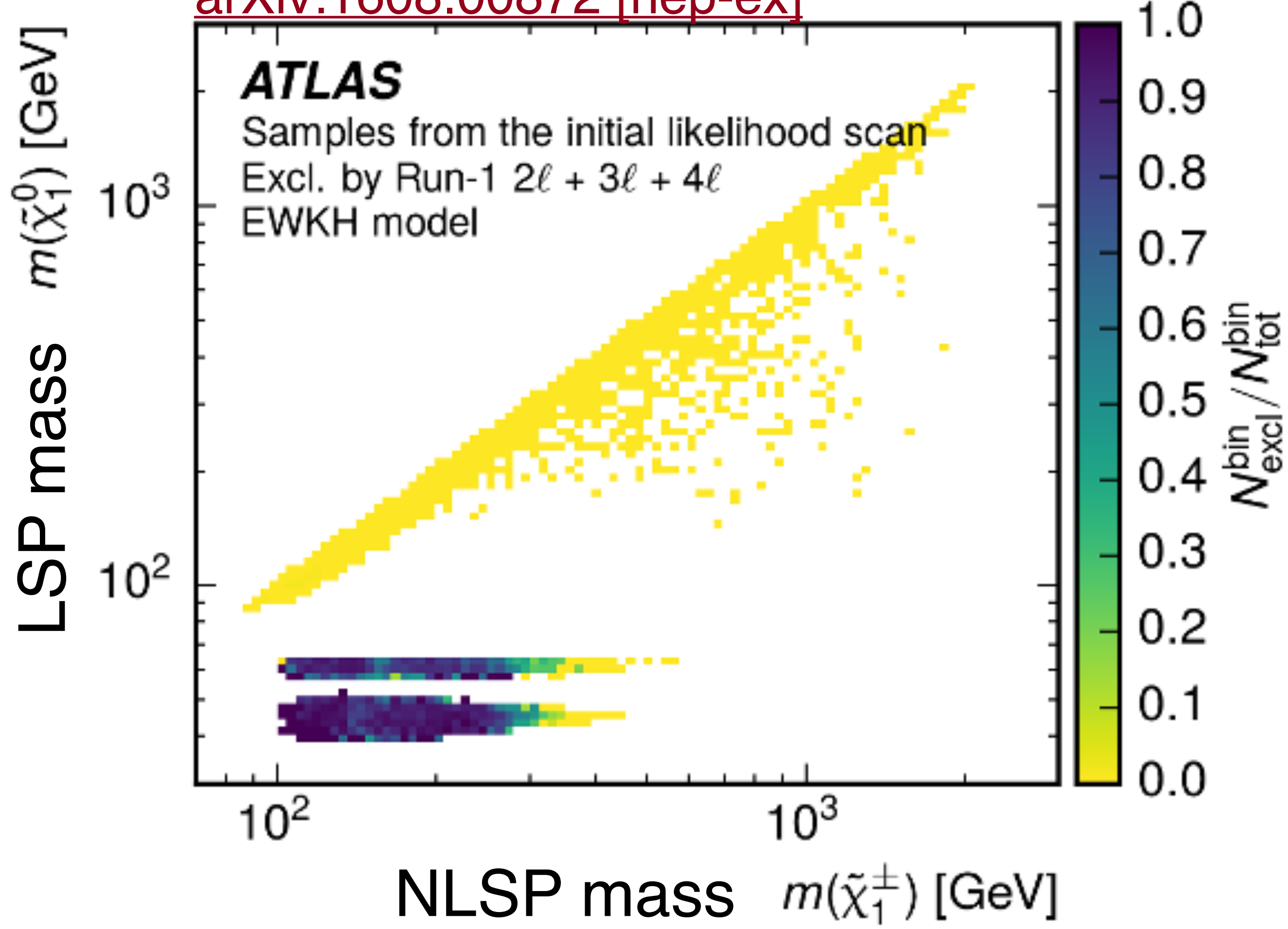

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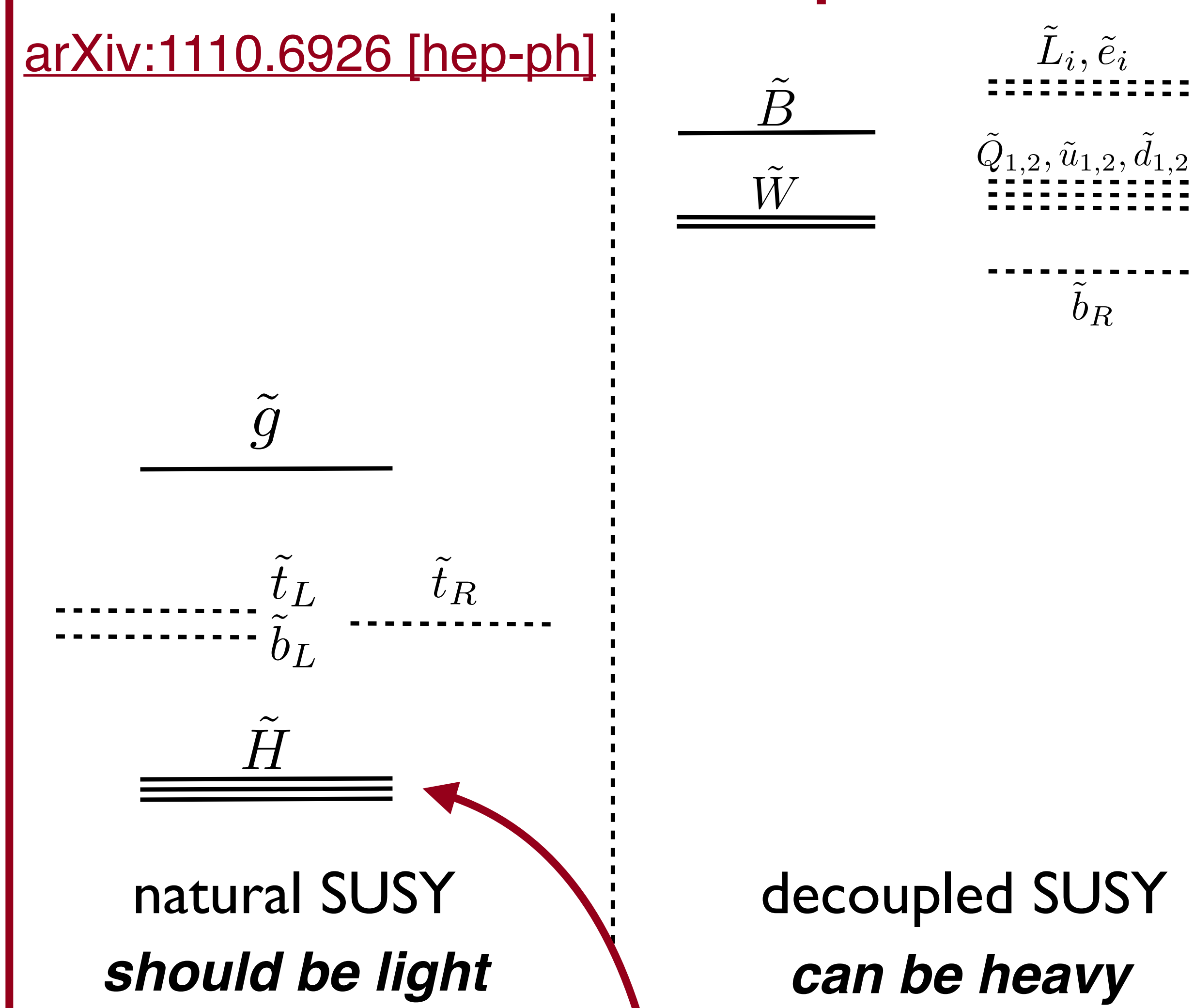

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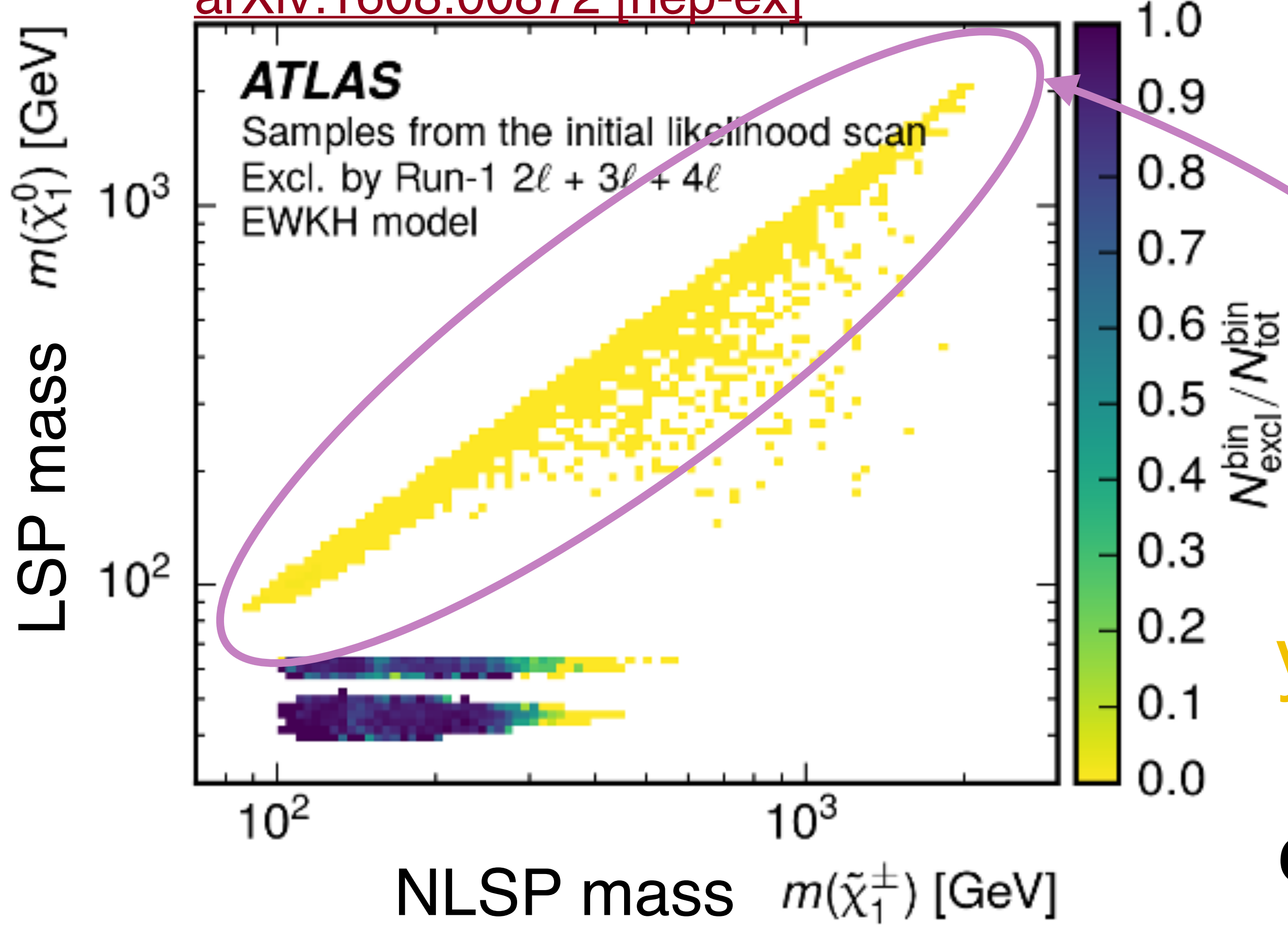

higgsino LSPs motivated by naturalness & naturally compressed

yellow means not excluded
clear gap in sensitivity for compressed SUSY models

Why compressed

and from S. Heinemeyer talk yesterday

Where we will find SUSY

If SUSY exists: it sould explain $(g-2)_\mu$!

$\Rightarrow$ there should be (relatively) light EW SUSY particles!

masterCODE

1.) pMSSM11 fit to all existing data

[2017]

$\Rightarrow$ predictions of fit to all data: light EW particles

$\Rightarrow$ mass hierarchy: $M_1 \sim M_2 < \mu$

$\Rightarrow$ problem for the LHC: compressed spectra

2.) "natural SUSY" with low fine-tuing [*H. Baer et al. '17*]

$\Rightarrow$ prediction: light EW particles (possible)

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Compressed searches

Will focus on searches for **EWK production** of SUSY particles

check out J. Long, Y. Nakahama and B. Petersen's talks for strong production

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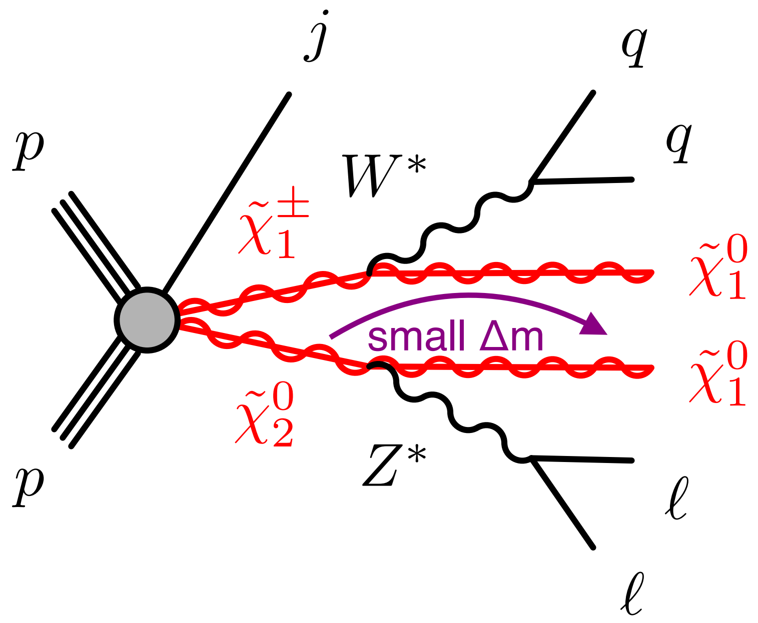
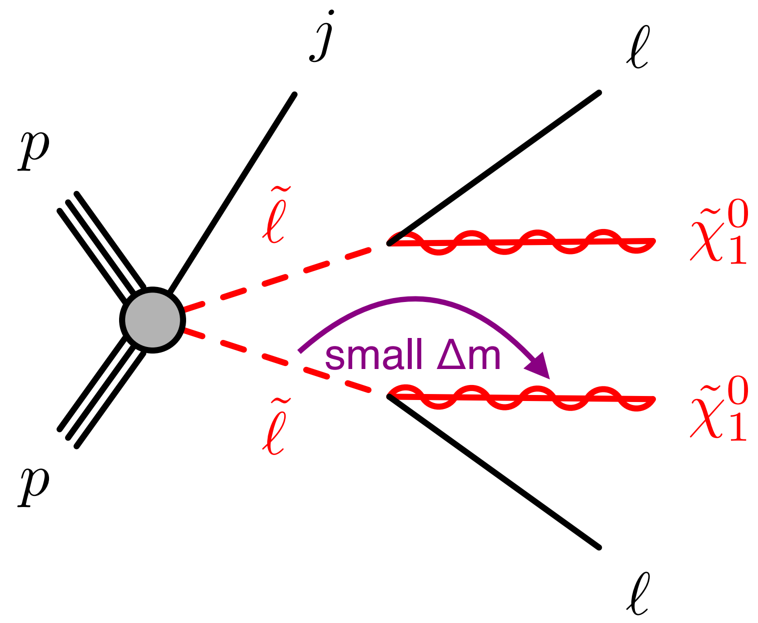
2 soft leptons ($e^+e^-/\mu^+\mu^-$)

compressed EWKinos



compressed sleptons



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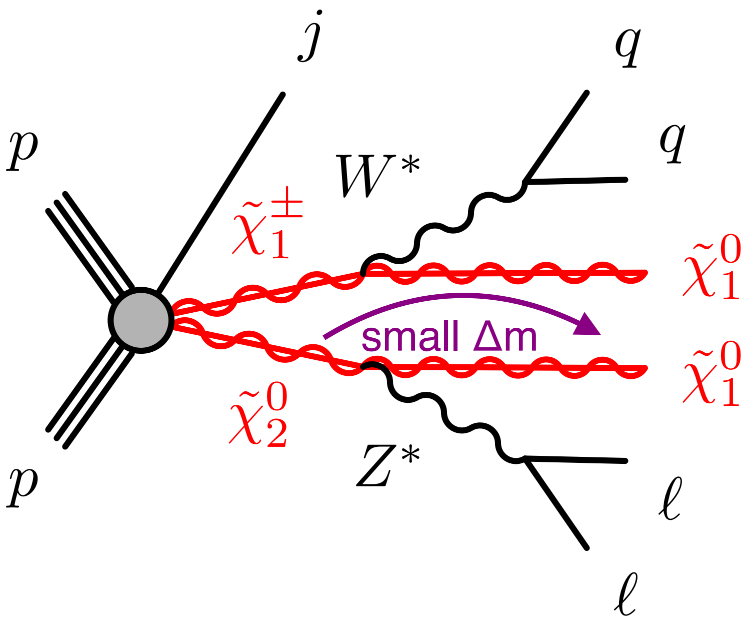

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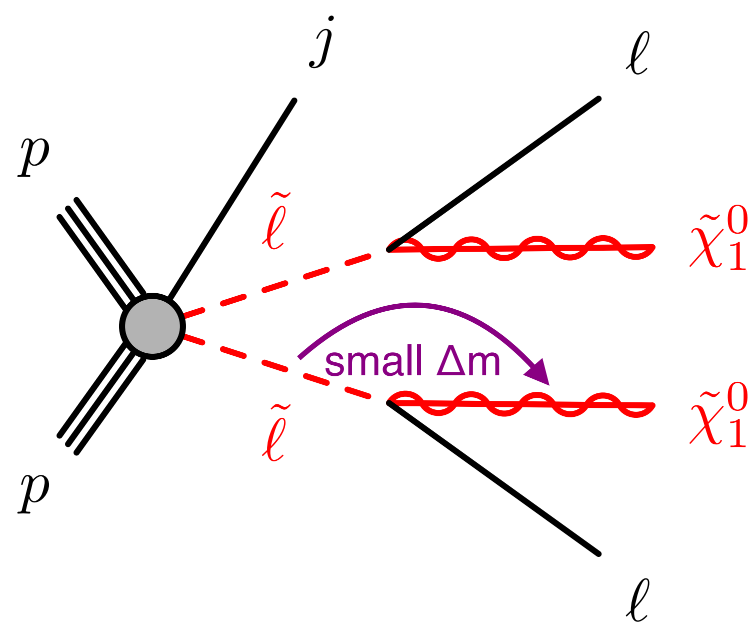
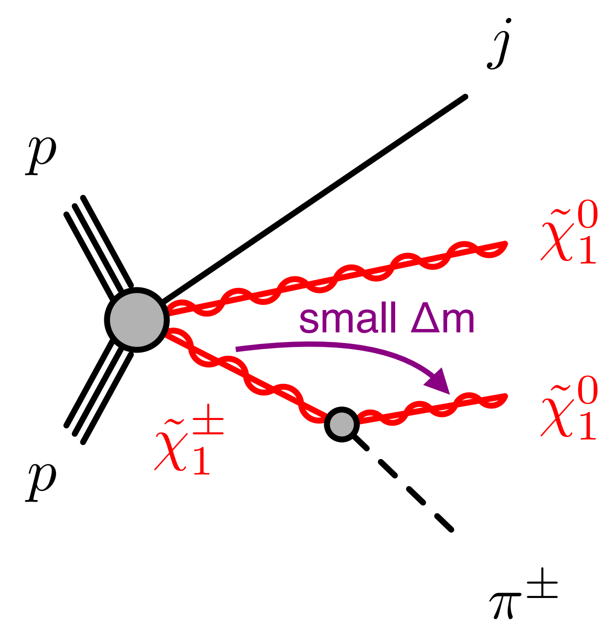


disappearing track

long-lived EWKinos



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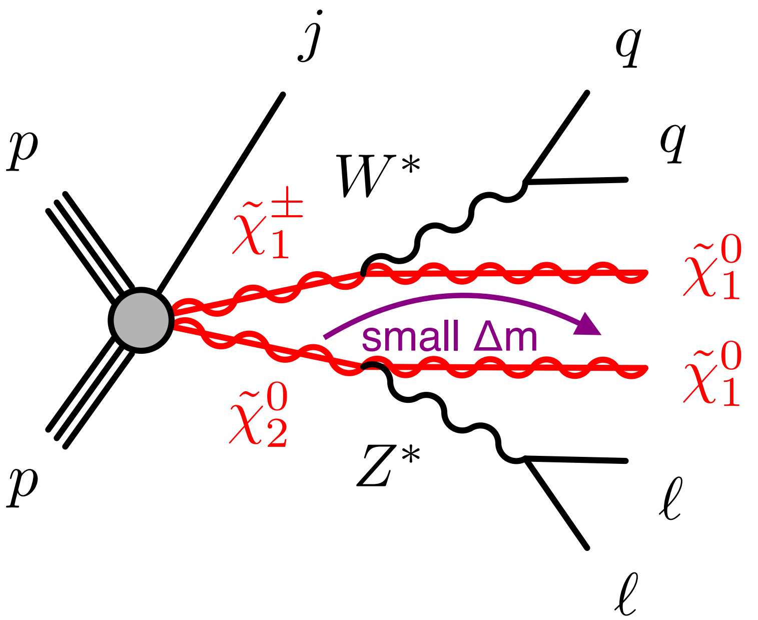

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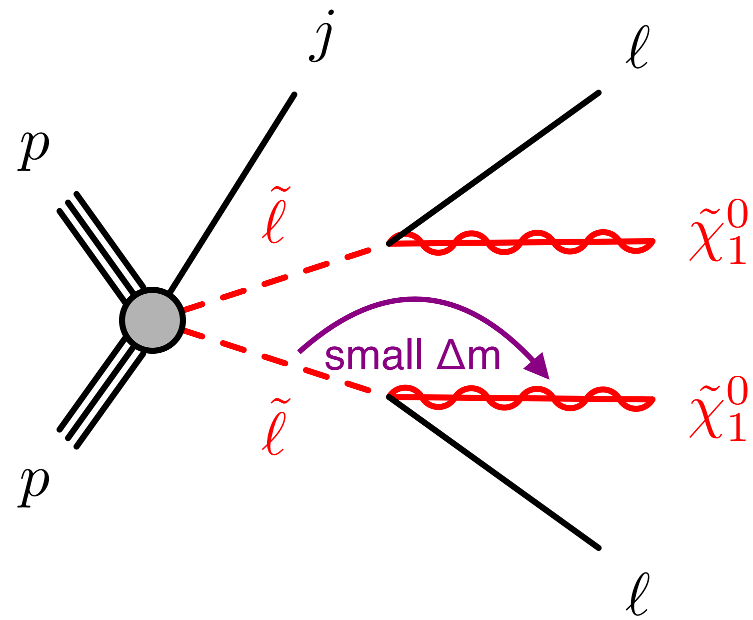

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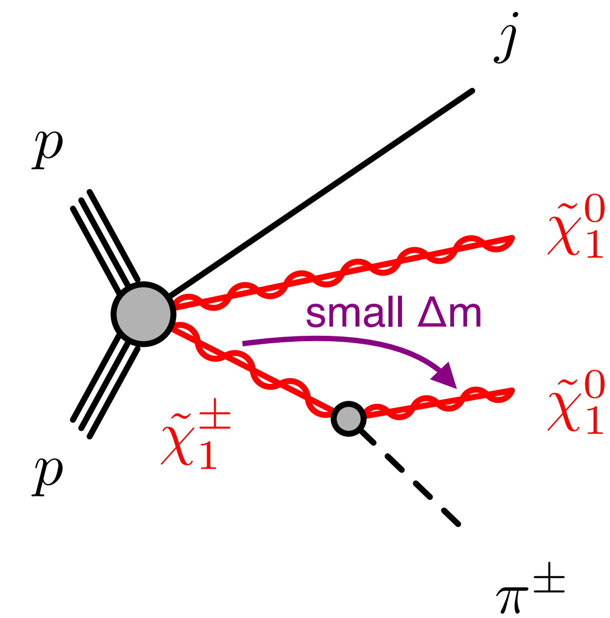

exploit distinct features from decay products

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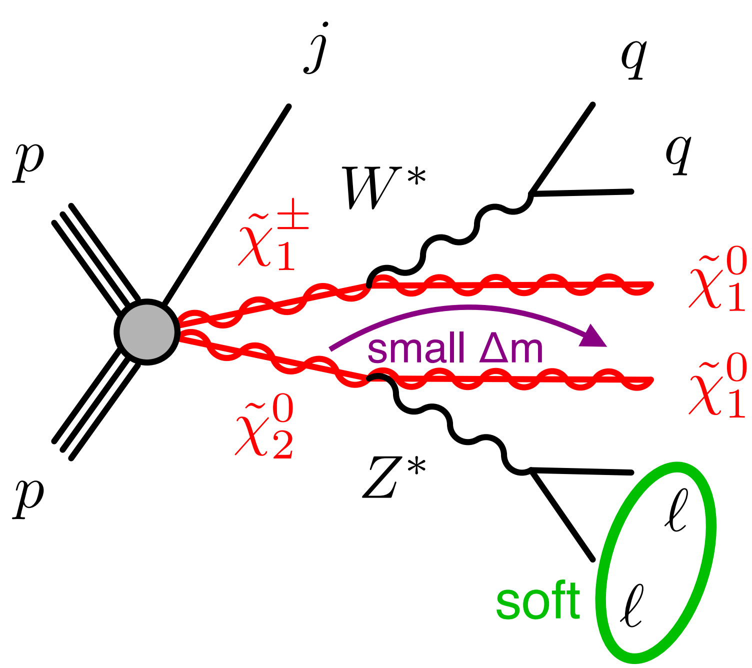

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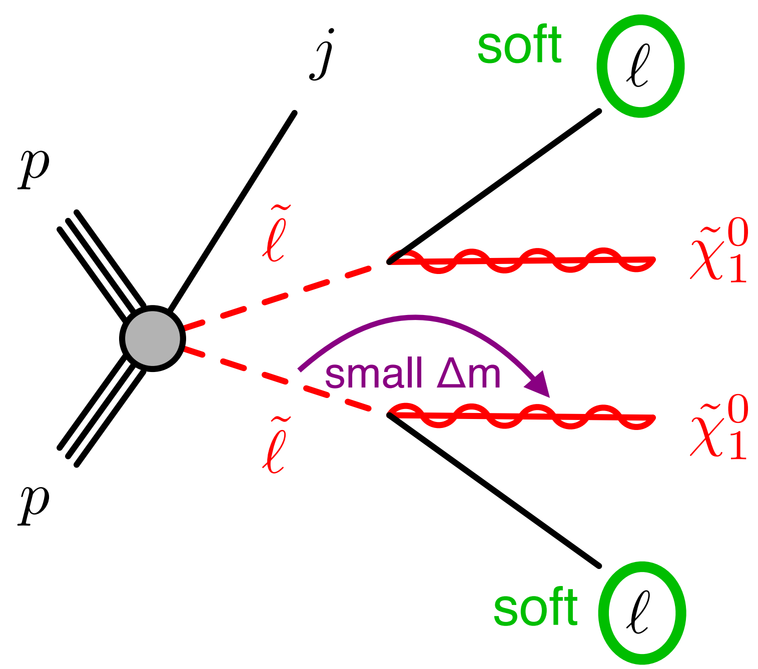

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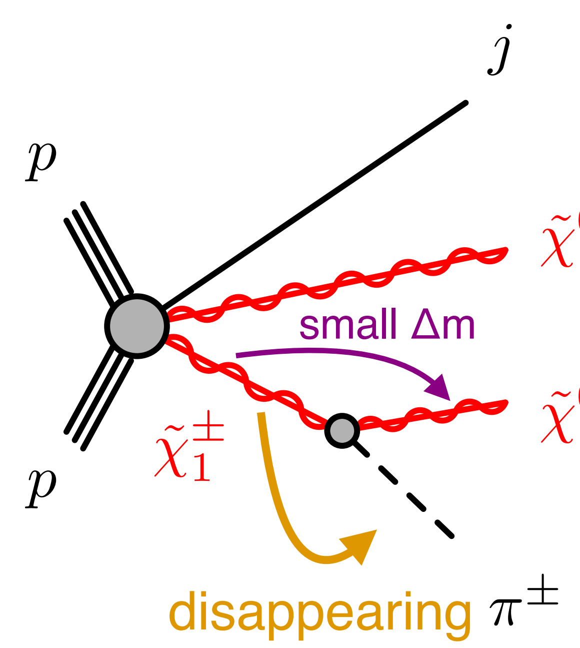

exploit distinct features from decay products

soft lepton mass edges and disappearing tracks

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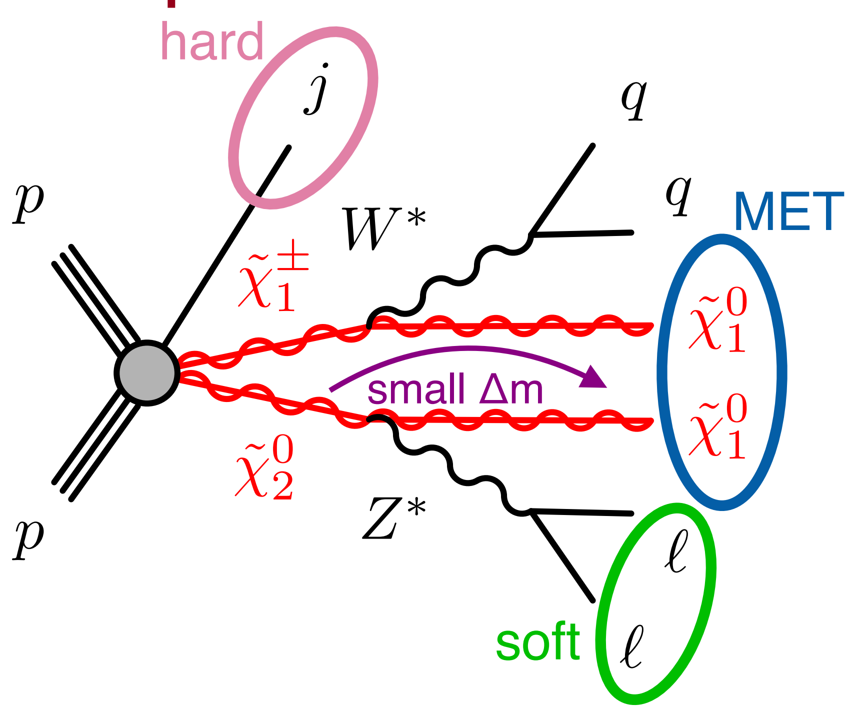

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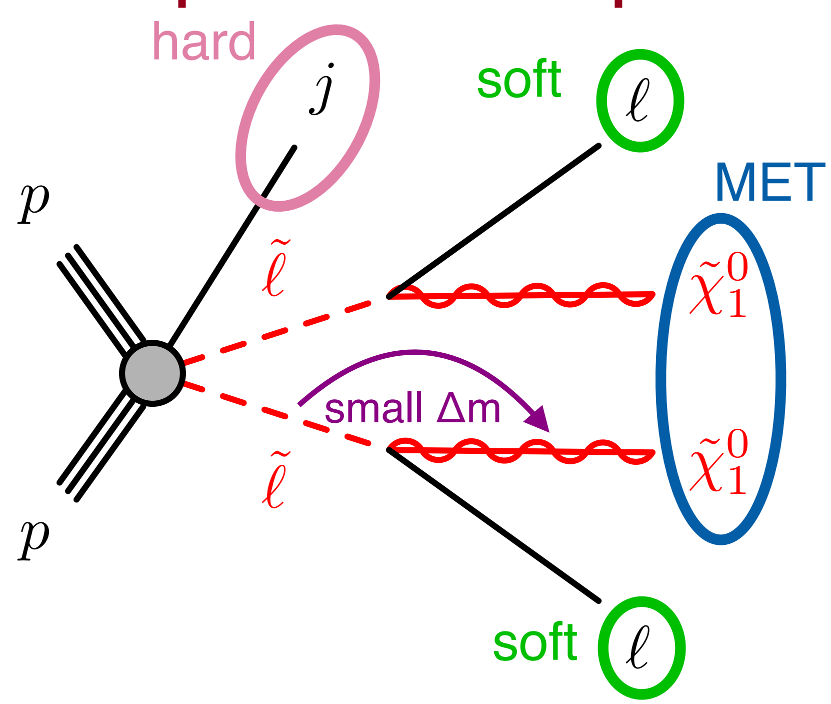

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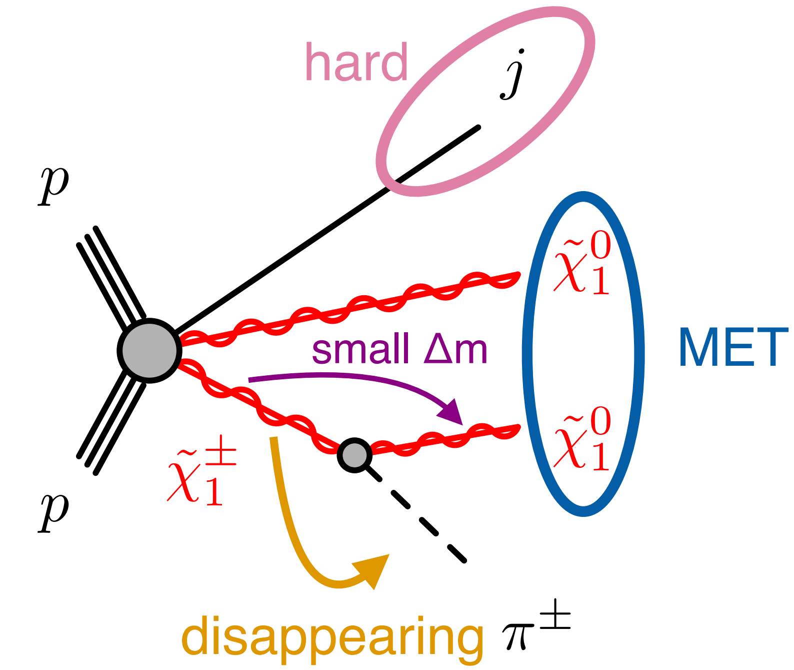
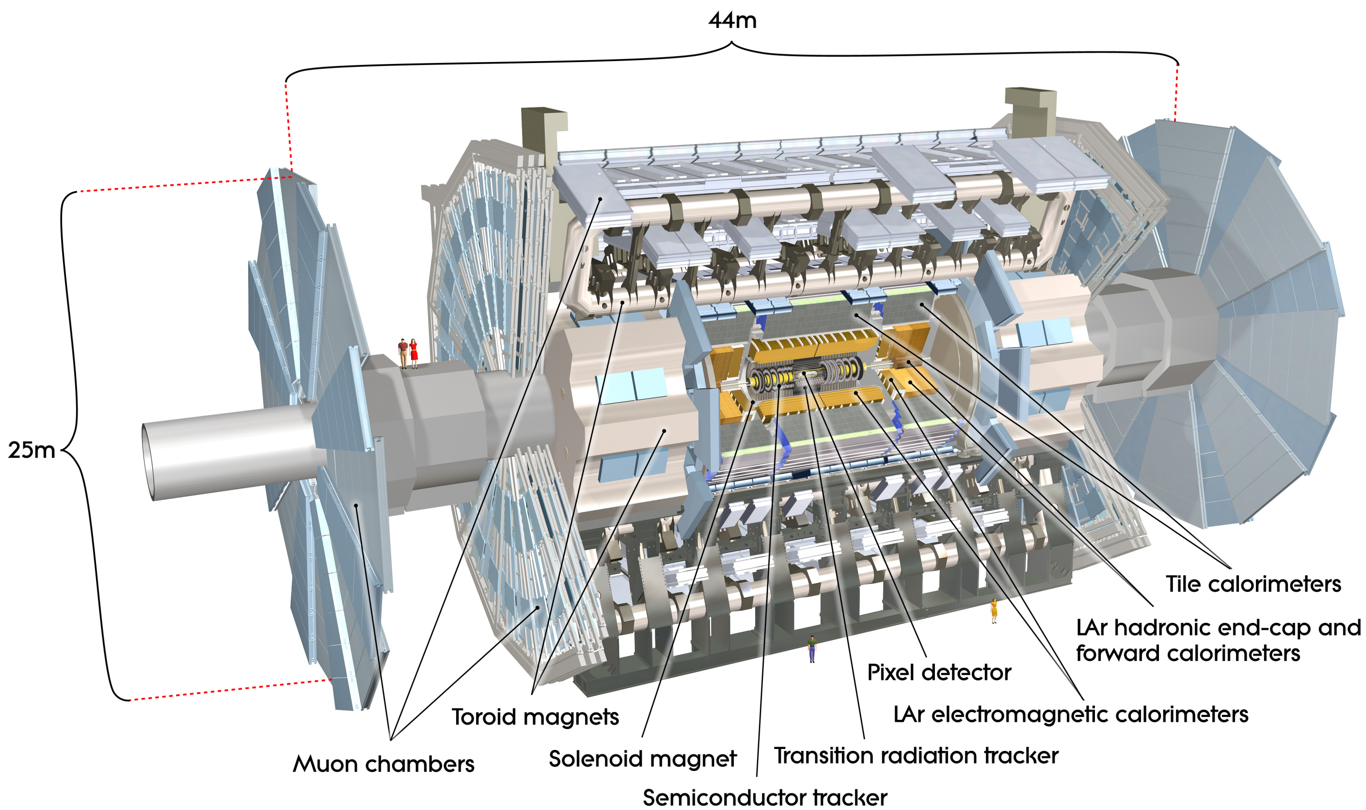


exploit distinct features from decay products

soft lepton mass edges and disappearing tracks

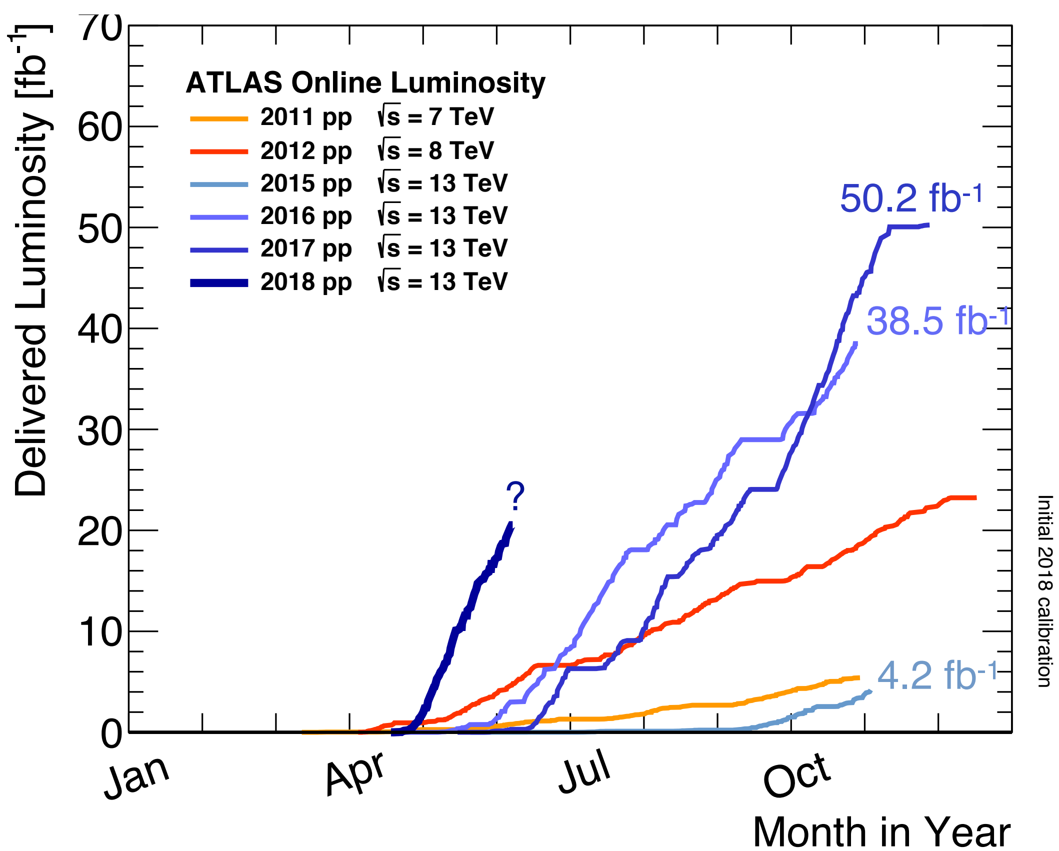
ISR jet selection enhances MET from soft LSPs

ATLAS: A Toroidal LHC ApparatuS



major upgrades for Run 2

detectors (e.g. **IBL**), trigger, DAQ, reconstruction



excellent performance under challenging LHC conditions

peak lumi 2.14 x 10^{34} cm^{-2} s^{-1}

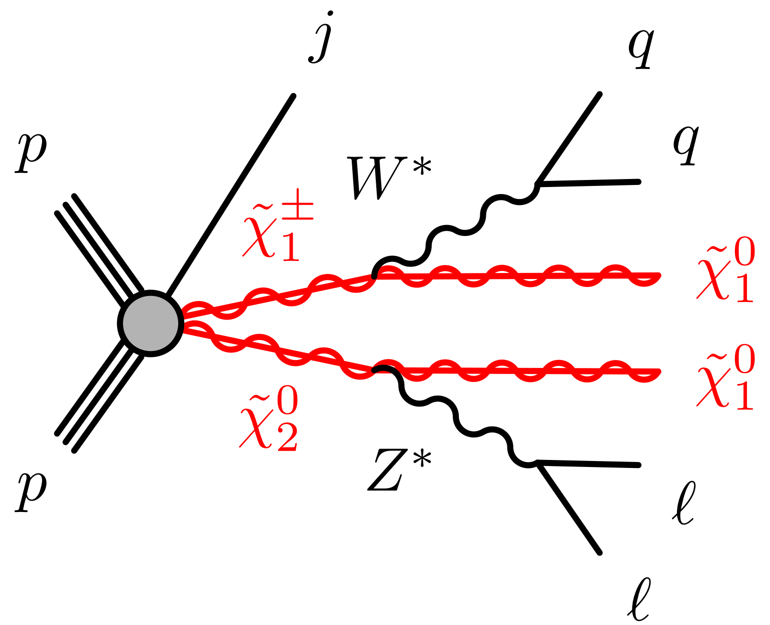
over 64 interactions per crossing

analyses use 36 fb^{-1} of 13 TeV pp LHC data collected by ATLAS

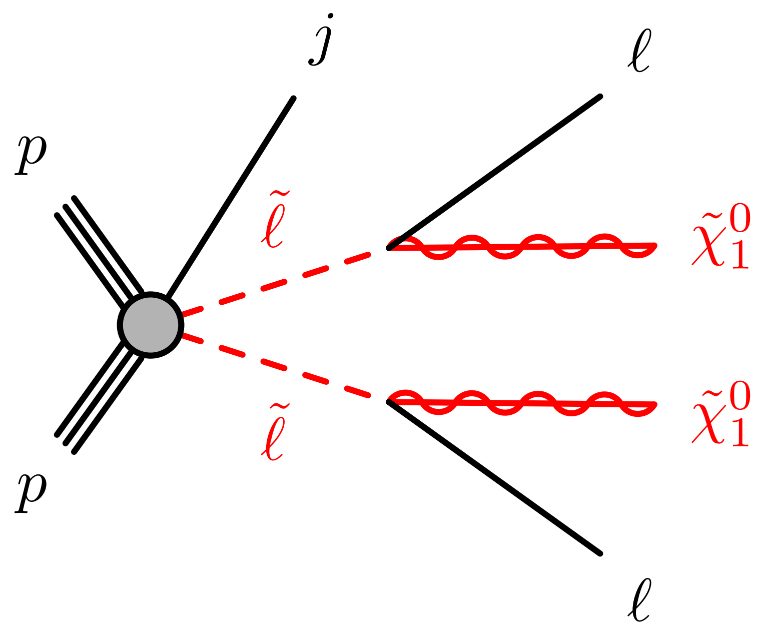
2015 + 2016

2 soft leptons ($e^+e^-/\mu^+\mu^-$)

Phys. Rev. D 97, 052010 (2018)

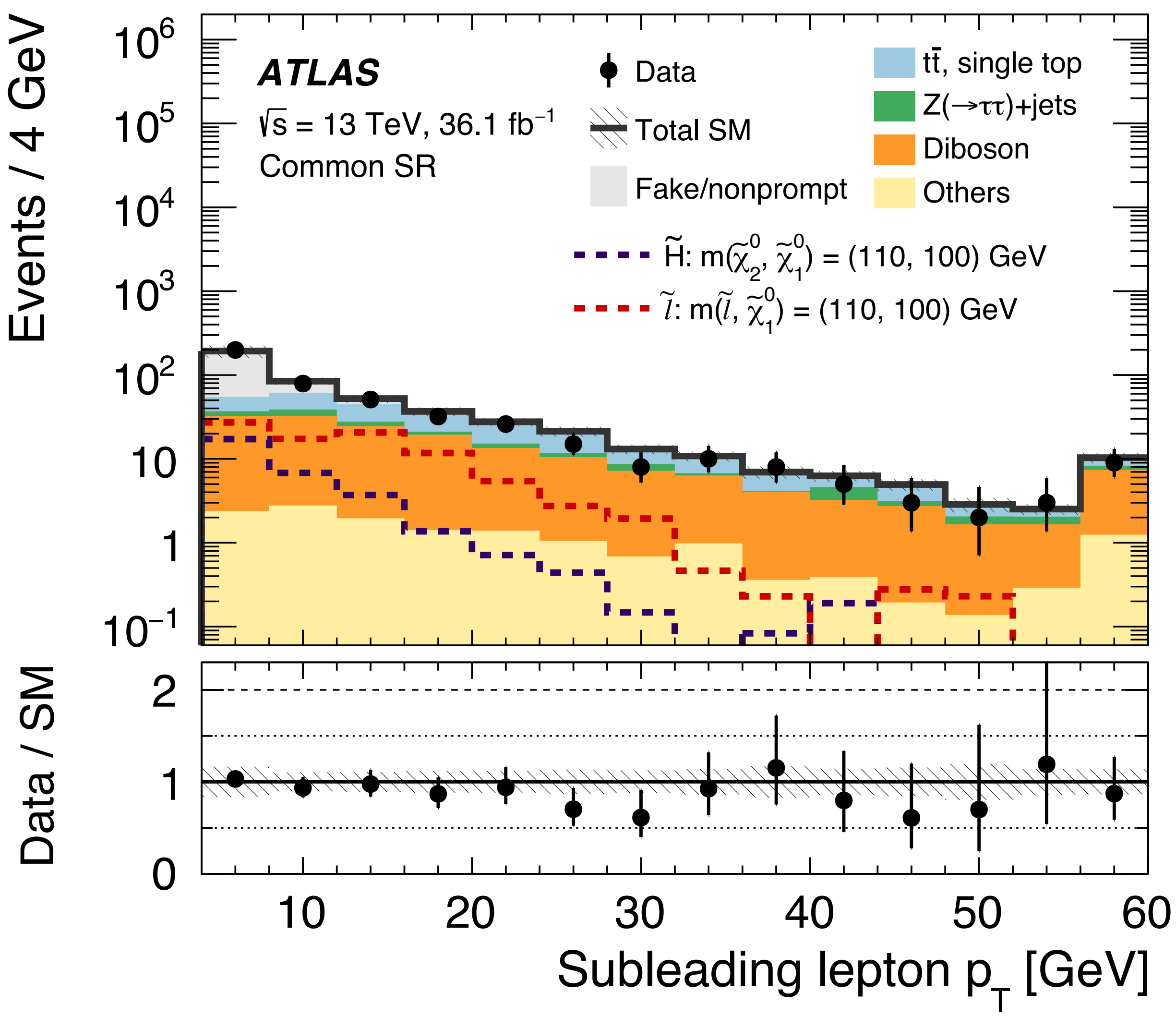


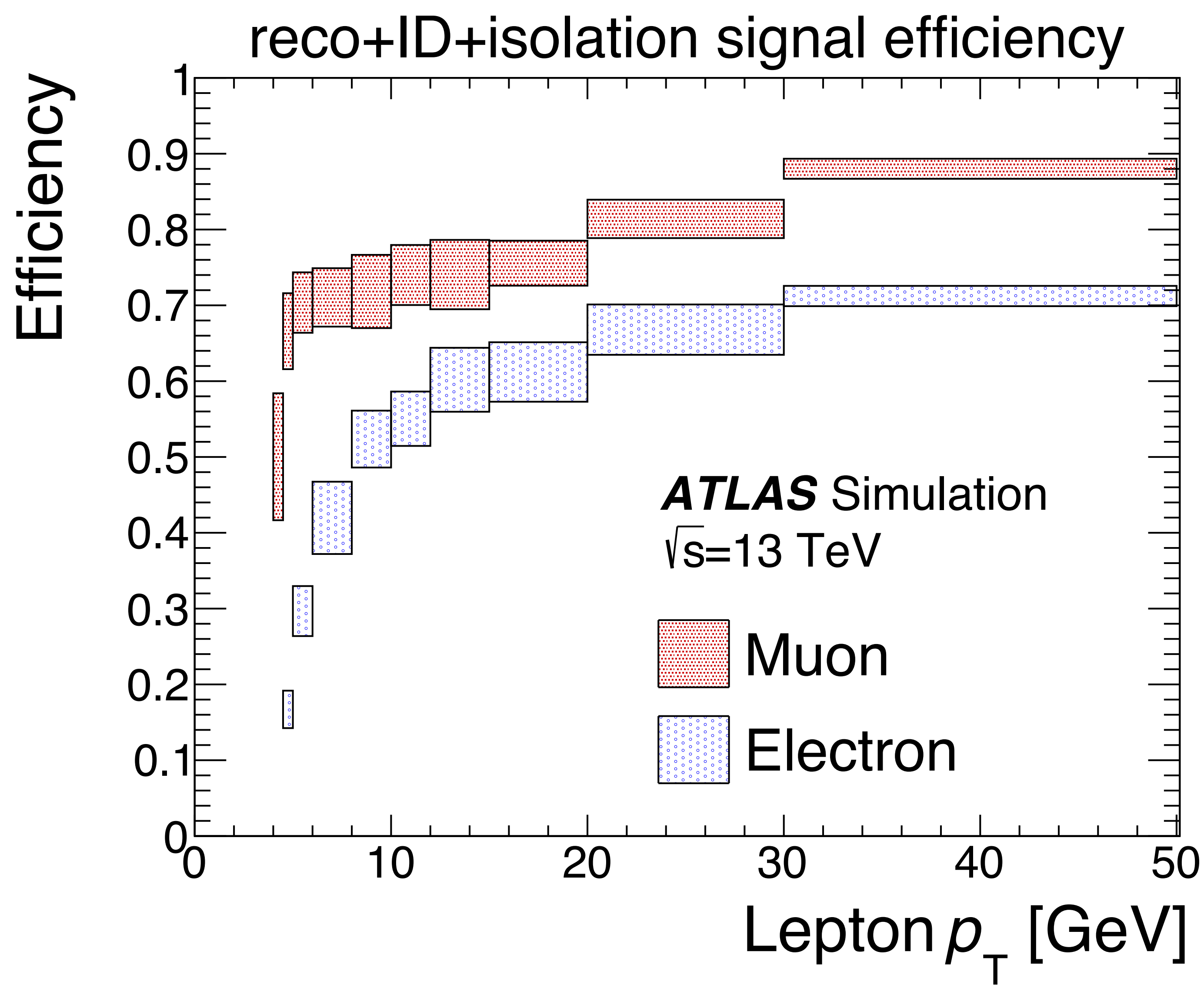
compressed EWKinos



compressed sleptons

Soft leptons



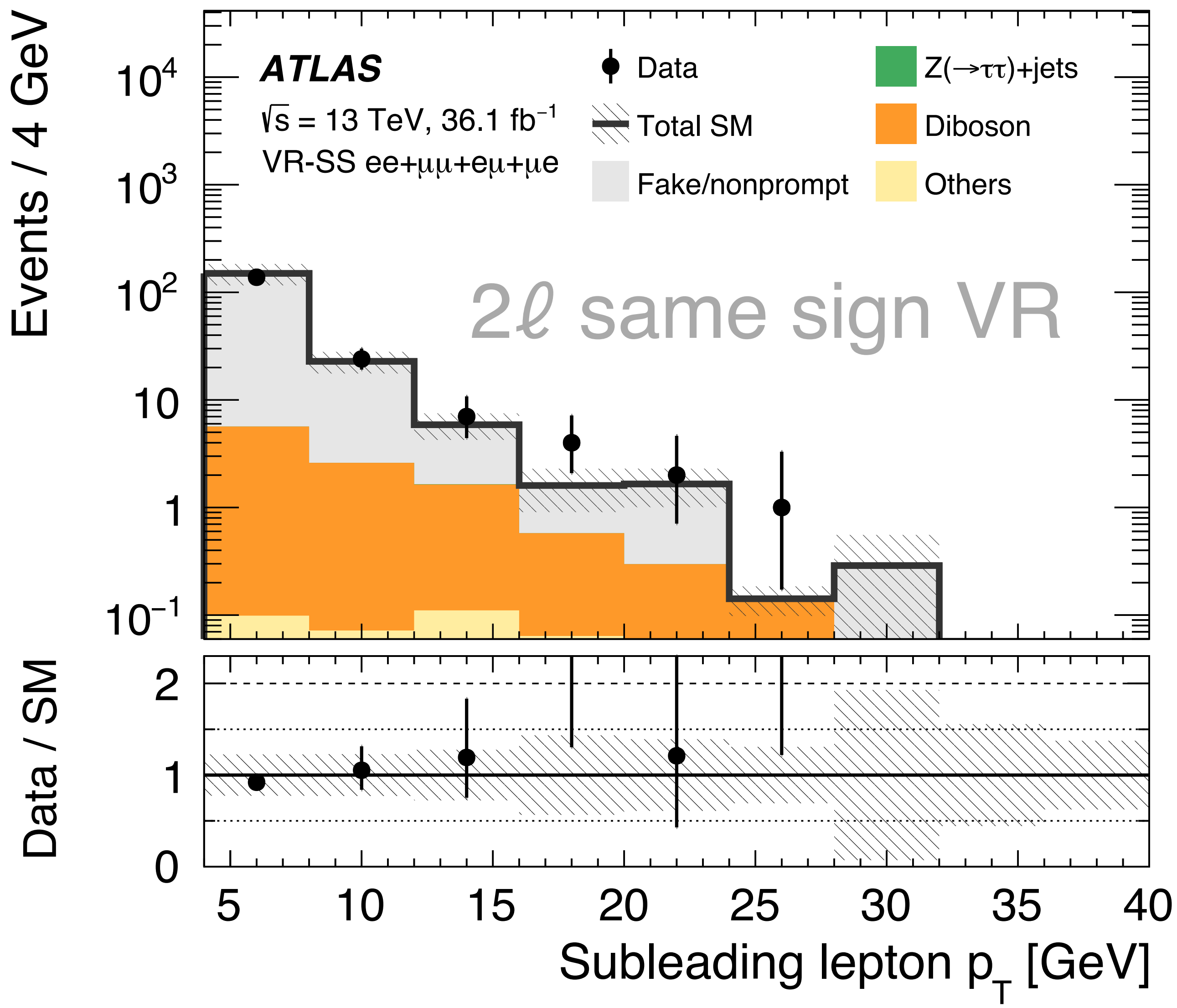


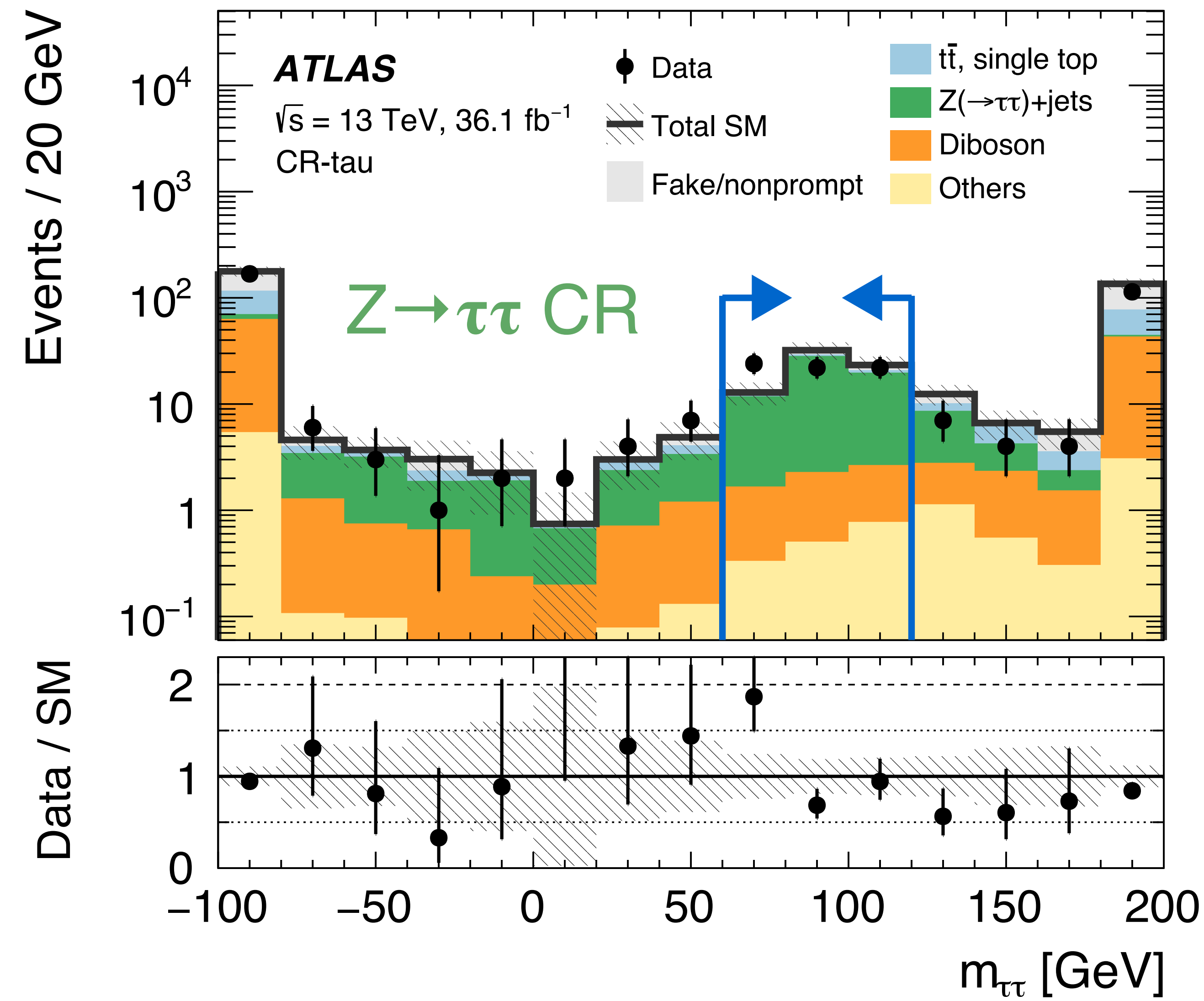
small Δm means very **soft** decay products ($p_T \sim \Delta m/2$)

ATLAS is pushing lepton reconstruction to very low p_T

analysis uses 4 GeV muons and 4.5 GeV electrons!

Backgrounds



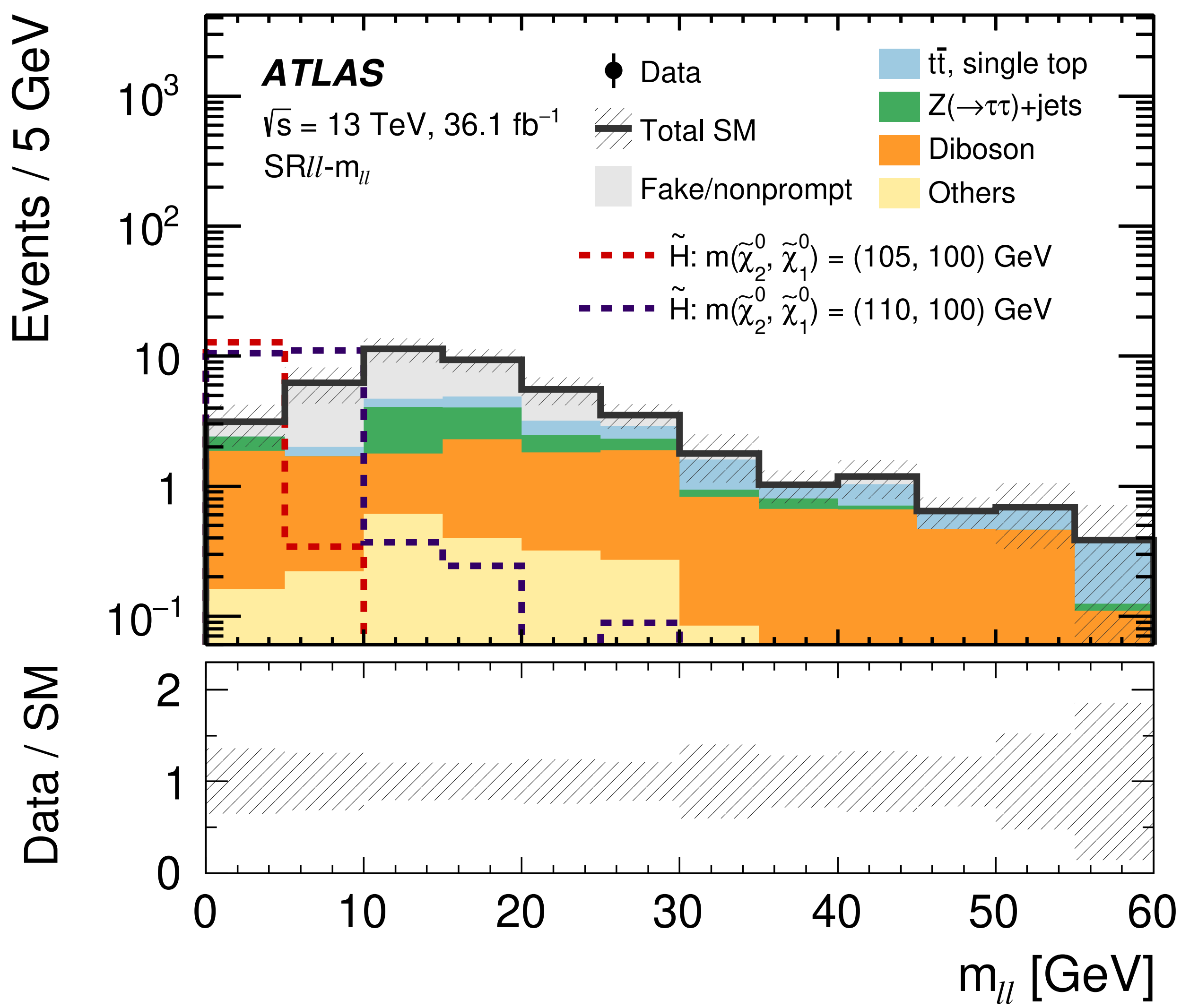


fake lepton bkgs dominant at low p_T & estimated entirely from data using "Fake Factor" method

Z→ττ & **top quark** bkgs normalized to data in dedicated control regions

data used as much as possible to estimate backgrounds

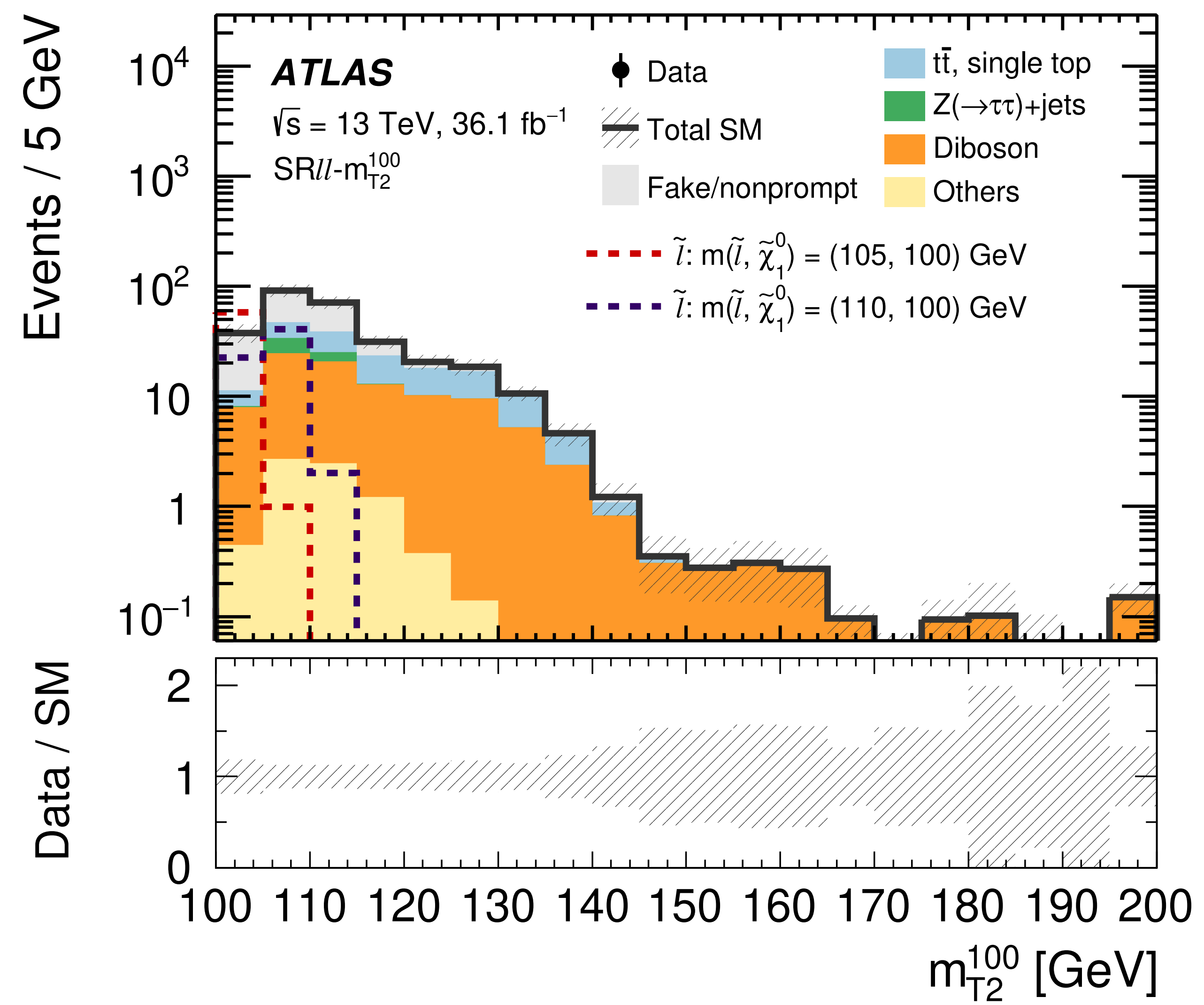
Distinct signatures



kinematic endpoint at

$m_{\ell\ell}$ = Δm from

N2 → N1 decay

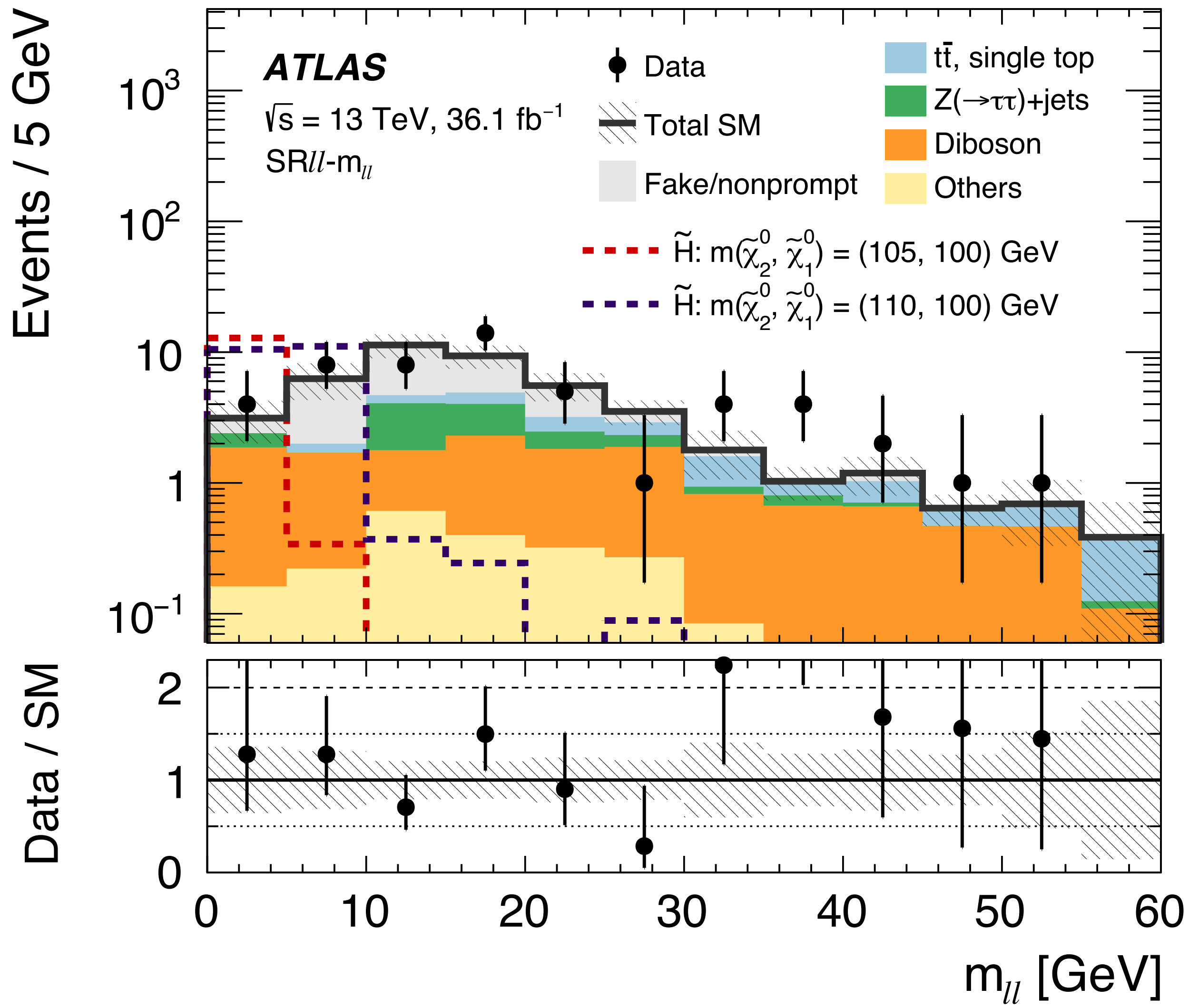


kinematic endpoint at

m_{T2} = 100 + Δm from

slepton → N1 decay

Distinct signatures



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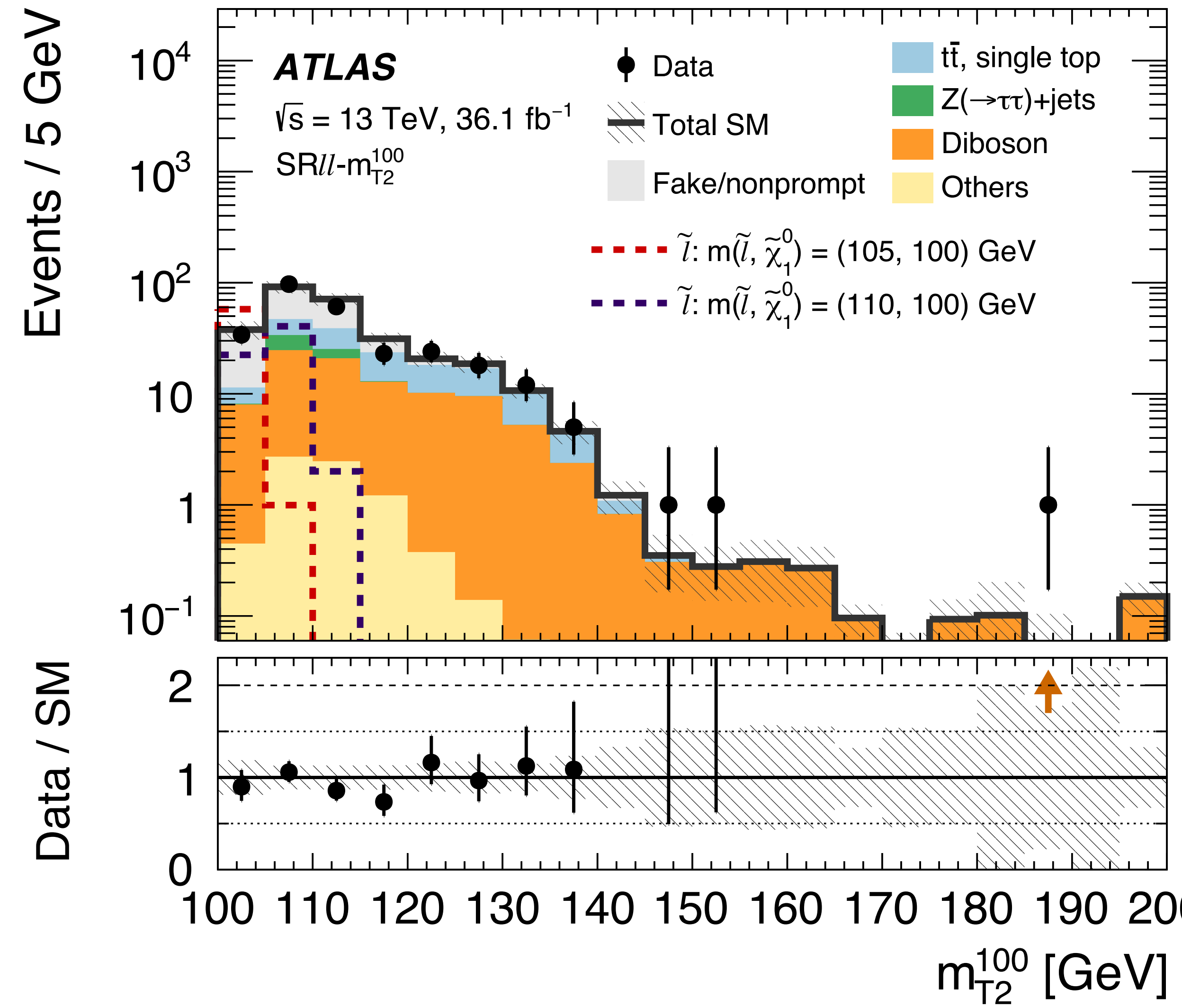

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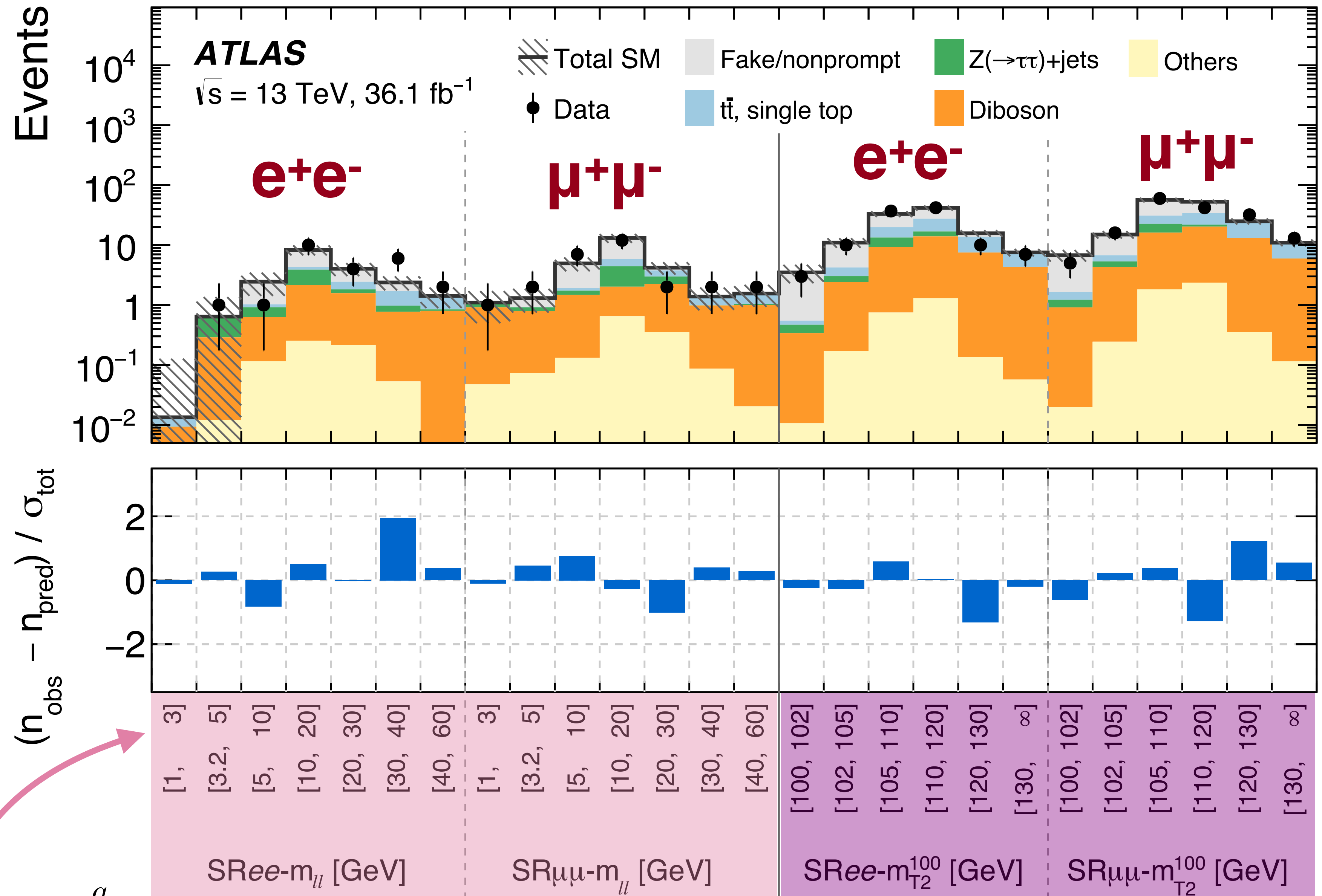
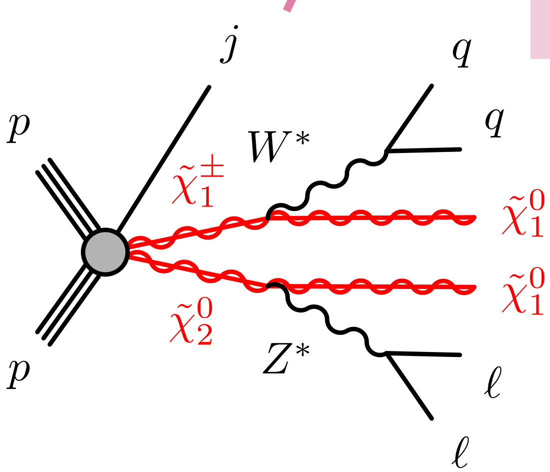
shape fits in $m_{\ell\ell}$ and m_{T2} used to improve sensitivity

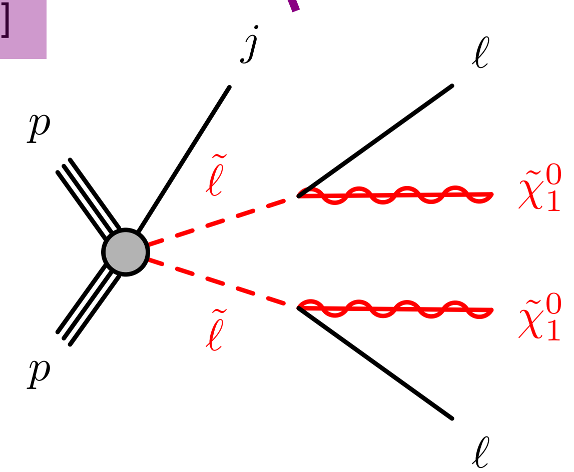
Results



EWKino $m_{\ell\ell}$ SRs

slepton m_{T2} SRs





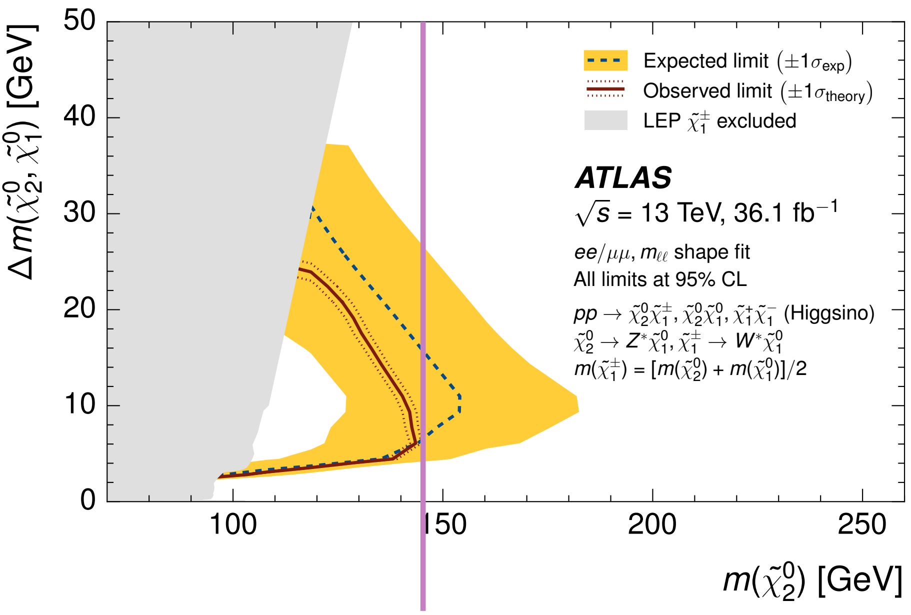
no significant excess seen over the background prediction

Interpretation

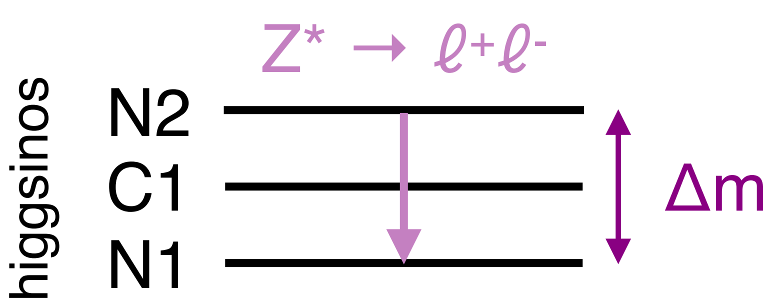
higgsino LSP

motivated by

naturalness



m(higgsino) ~ 145 GeV

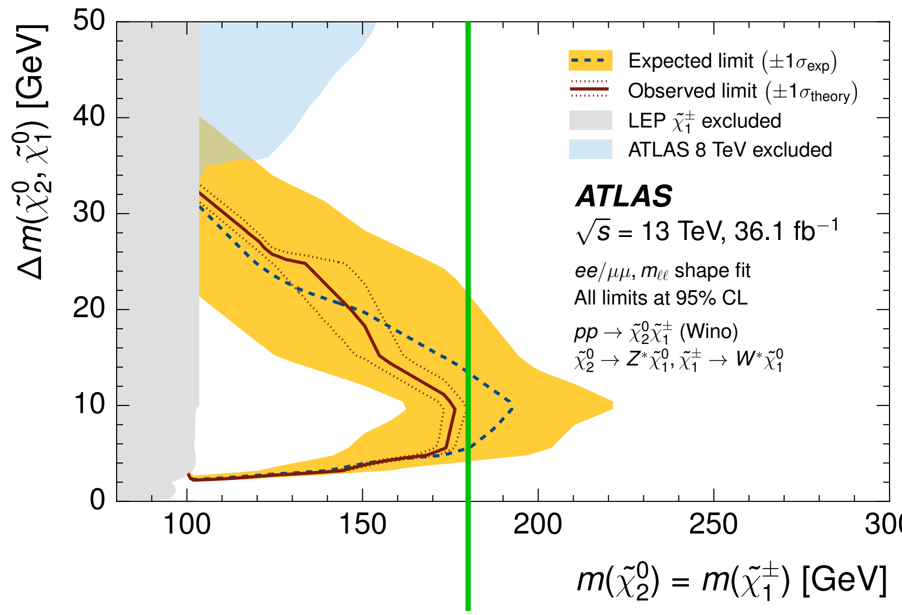


Δm as low as 3 GeV

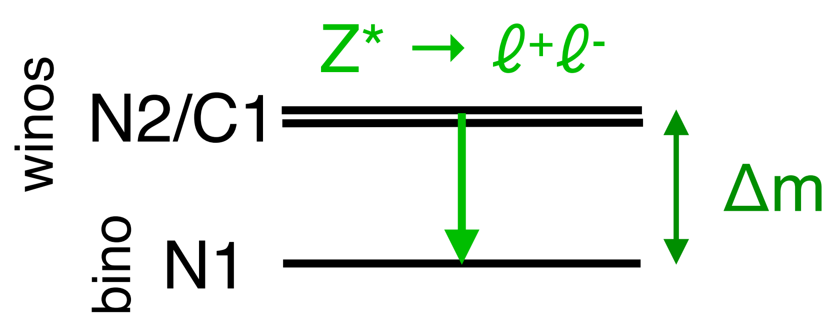
wino NLSP/bino LSP

motivated by

DM relic abundance



m(wino) ~ 180 GeV

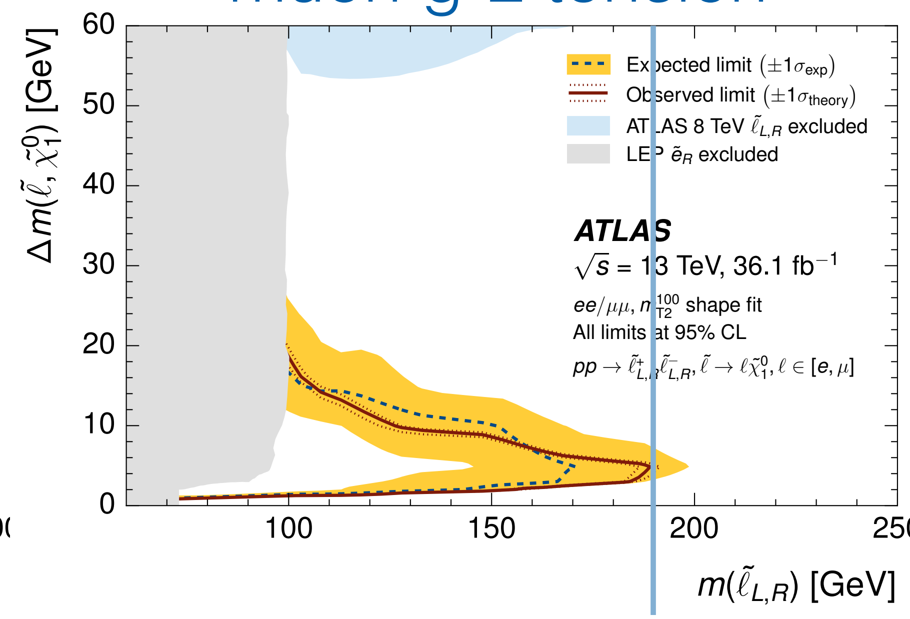


Δm as low as 2.5 GeV

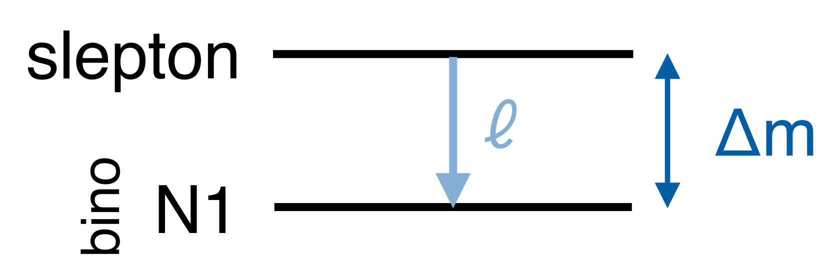
slepton NLSP/Bino LSP

motivated by

muon g-2 tension



m(slepton) ~ 190 GeV



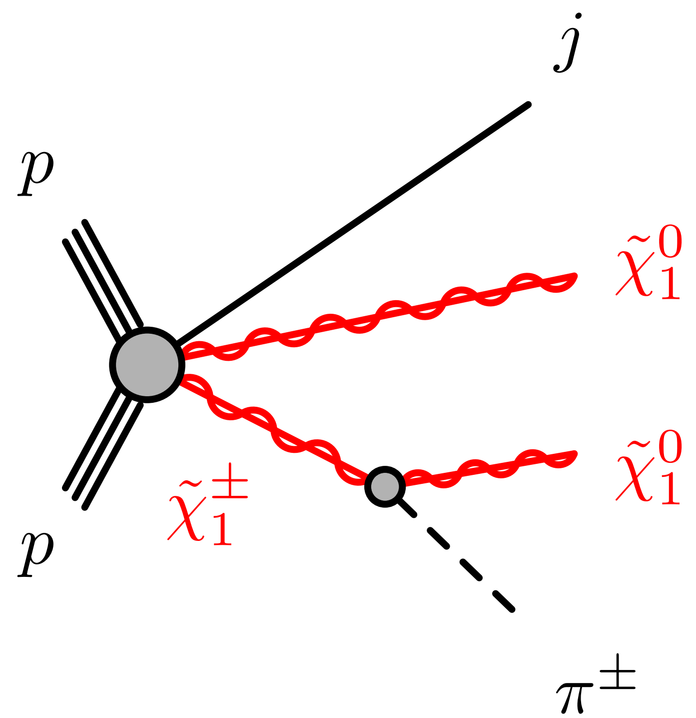
Δm as low as 1 GeV

first direct limits on Higgsino since LEP! (also from CMS)

disappearing track

arXiv:1712.02118 [hep-ex]

ATL-PHYS-PUB-2017-019



long-lived EWKinos

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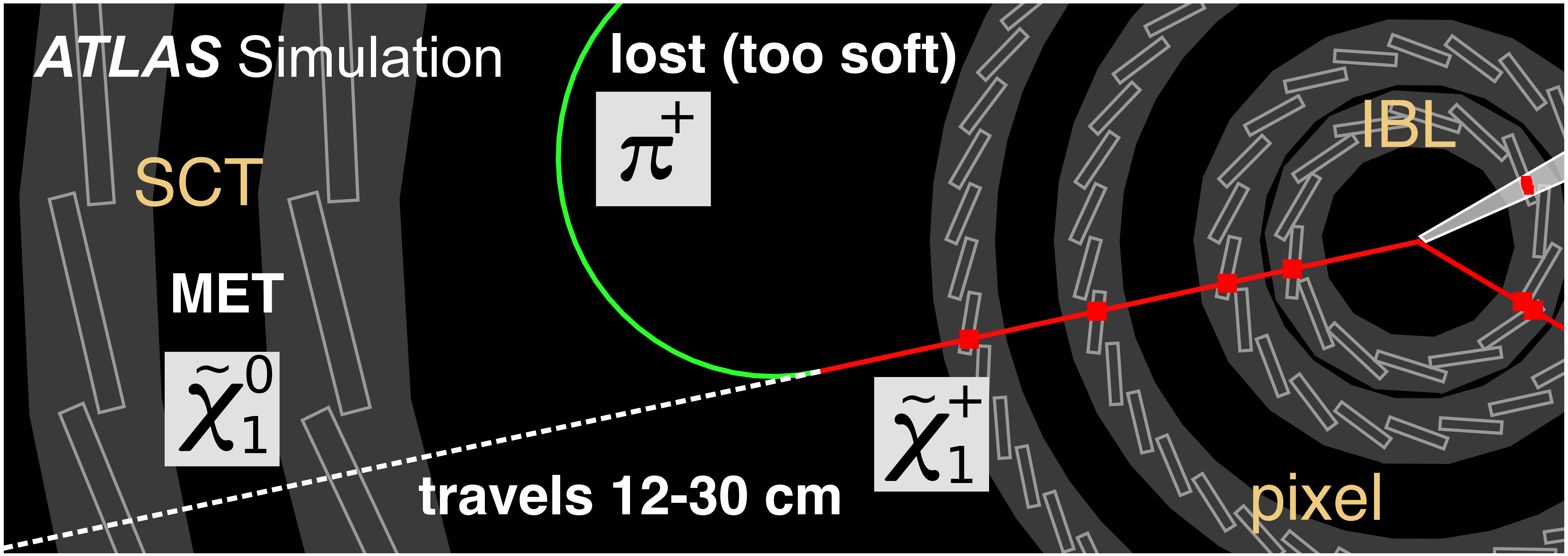


ultra compressed EWKinos can be **long-lived**

e.g. c**τ** ~ 1.5 cm (0.05 ns) for Higgsinos with Δm ~ 300 MeV

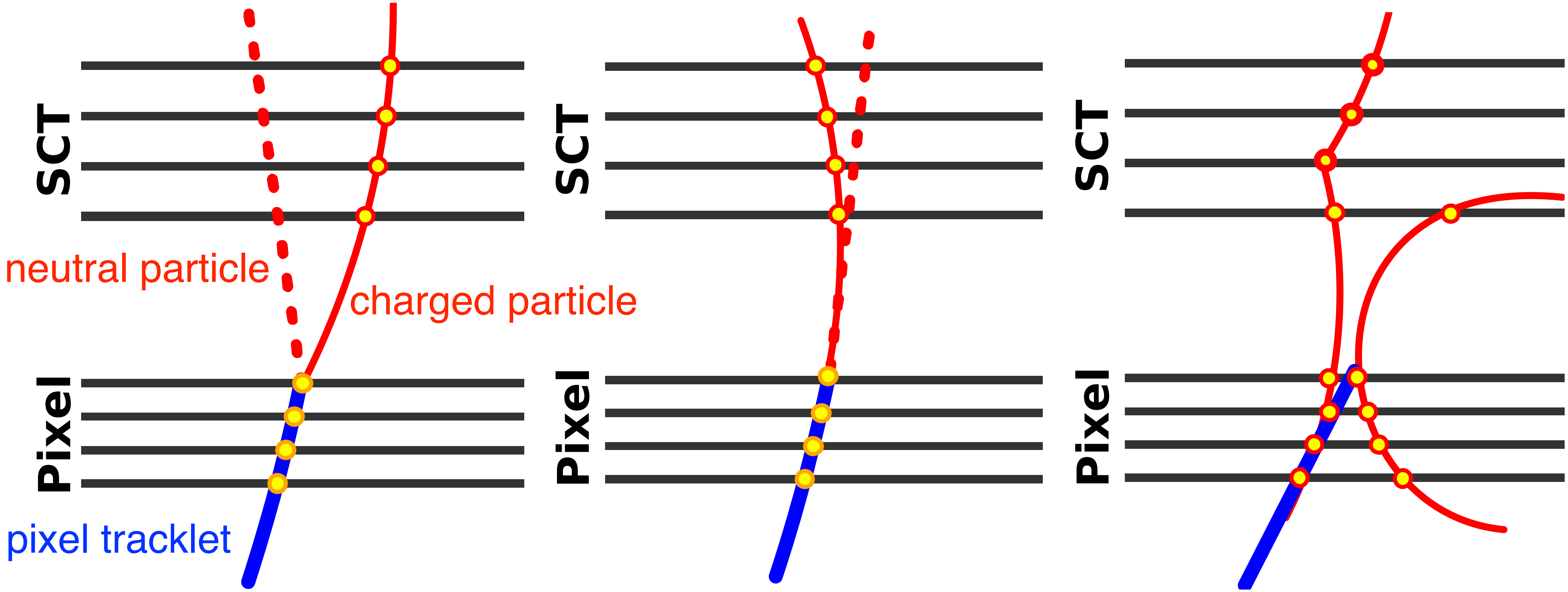
look for **"tracklets"** in ATLAS pixel layers

veto hits in the silicon strips - track *disappears* once C1 decays

new IBL in Run 2 allows for shorter tracks

increased sensitivity to shorter lifetimes compared to Run 1

Tracklet backgrounds

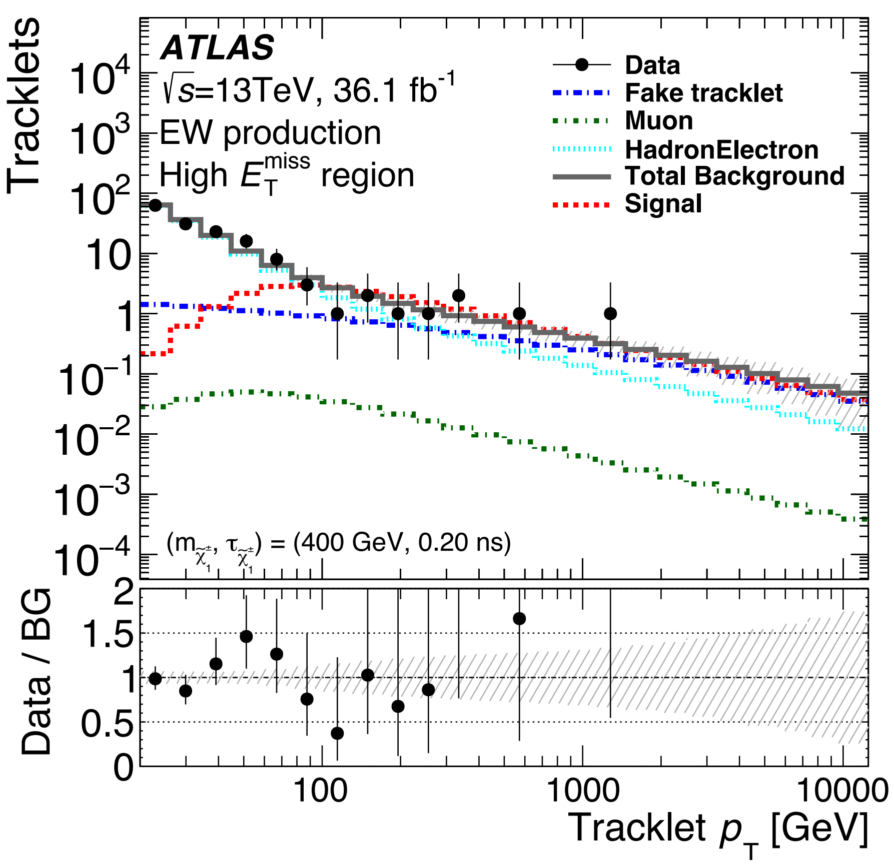


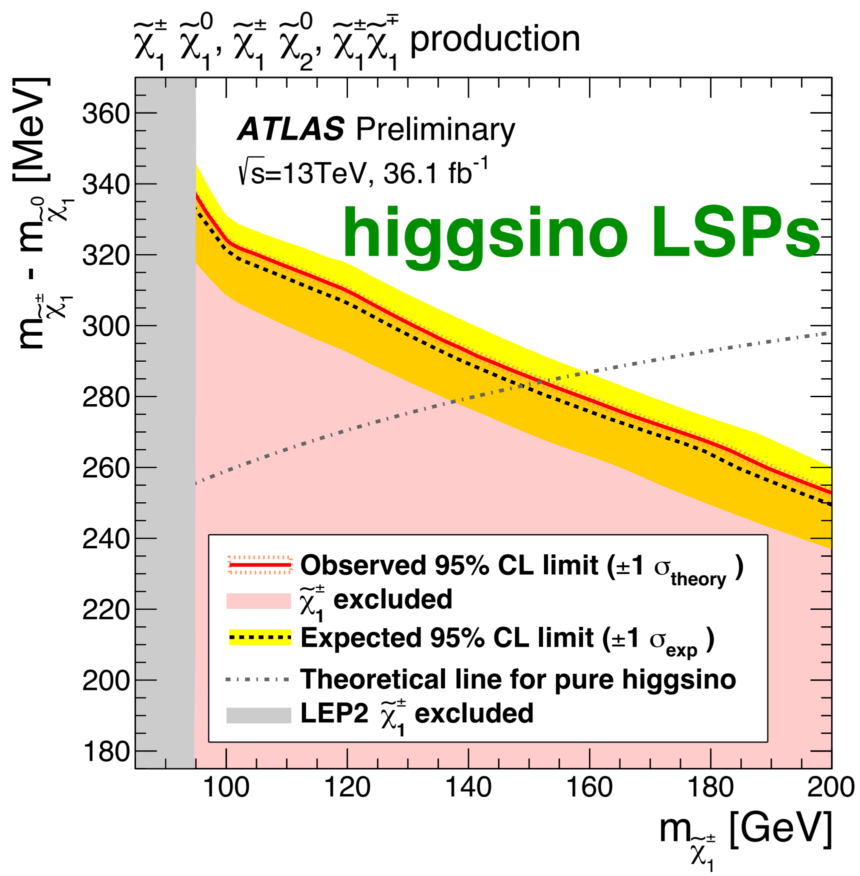
hadron undergoes hard scattering or lepton emits a photon - pixel and SCT hits not associated to the same track

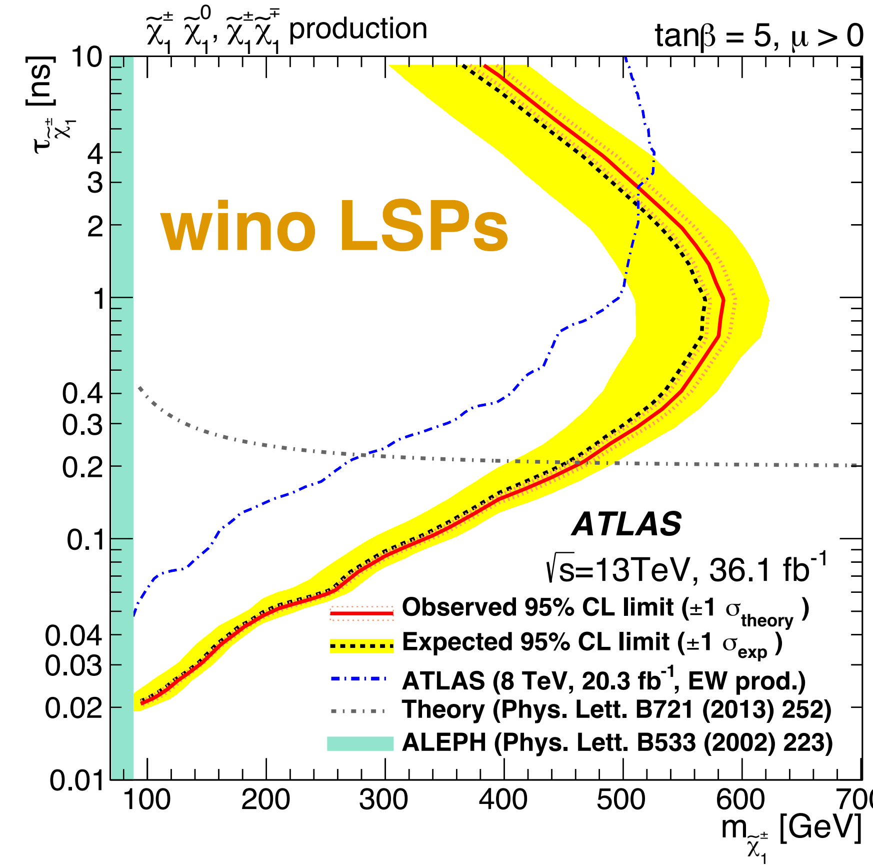
nearby particles generate random combinations of hits

bkgs reduced with isolation & track quality requirements estimated from data templates constrained at low MET

Results and interpretation







no excess seen over the background prediction

pure higgsino LSPs with **Δm ~ 275 MeV** excluded up to 152 GeV

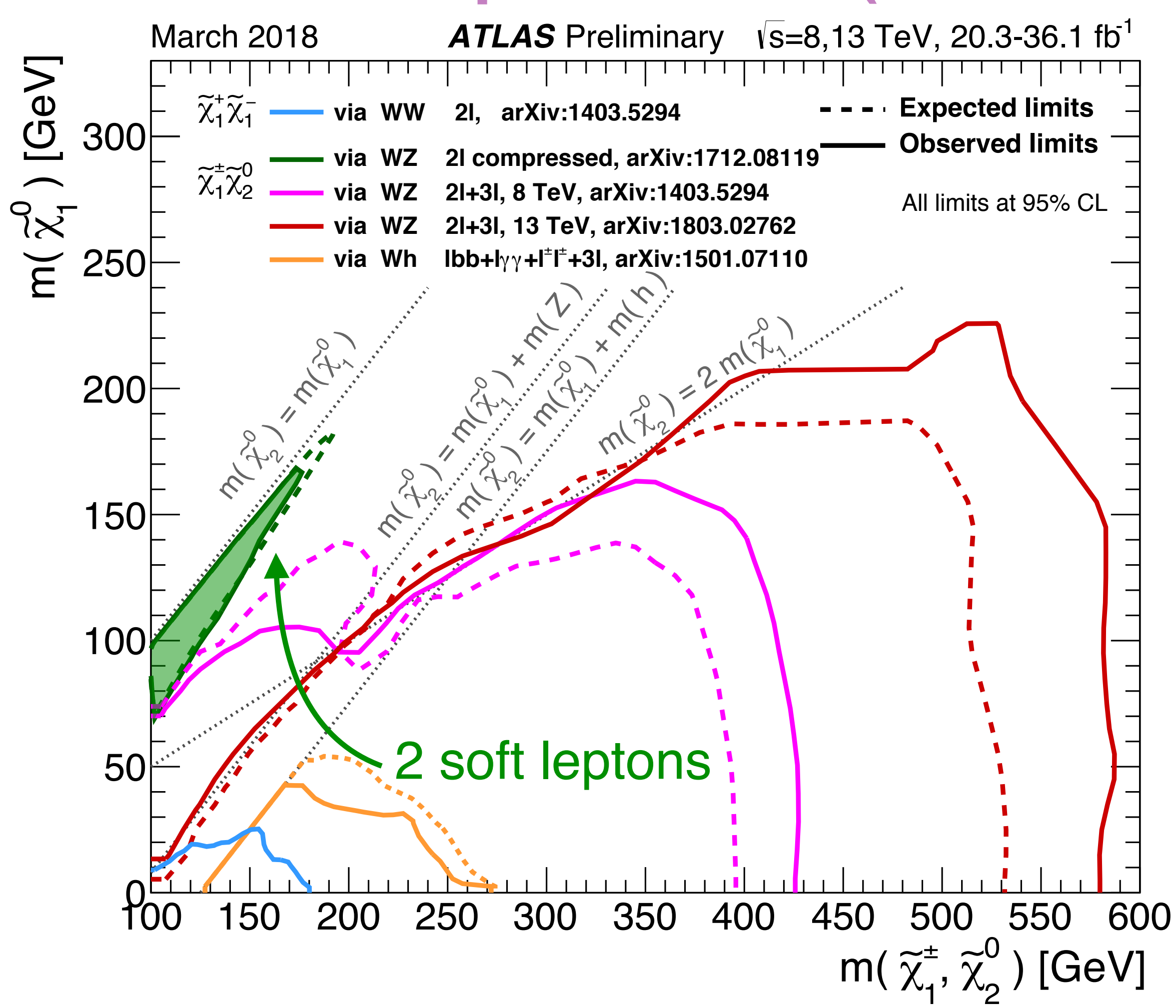
pure wino LSPs with **Δm ~ 160 MeV** excluded up to 460 GeV

Summary and Conclusions

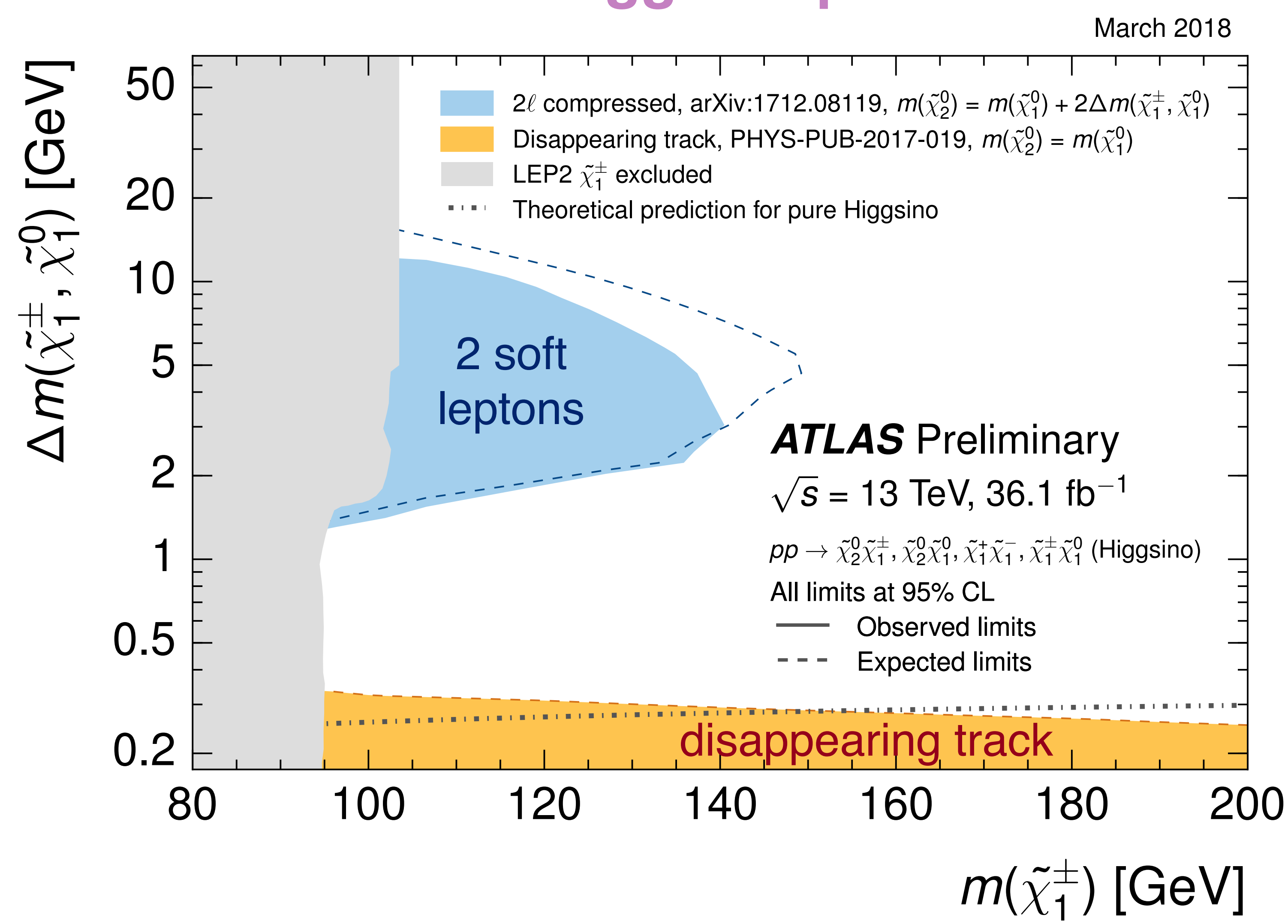
Summary of EWK searches

many more [here]...

limits on wino production (bino LSP)



limits on higgsino production

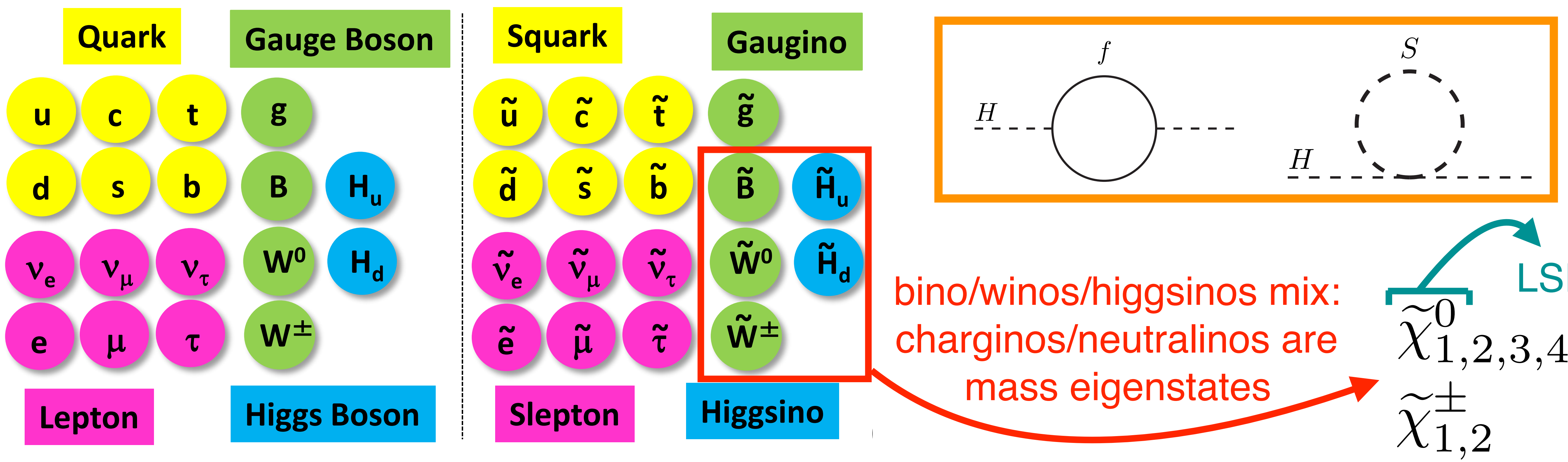


ATLAS limits on **compressed SUSY** particles **filling in the sensitivity gaps** and extending to regions **not probed since LEP**!

no signs of SUSY yet but ATLAS continues to take data so stay tuned

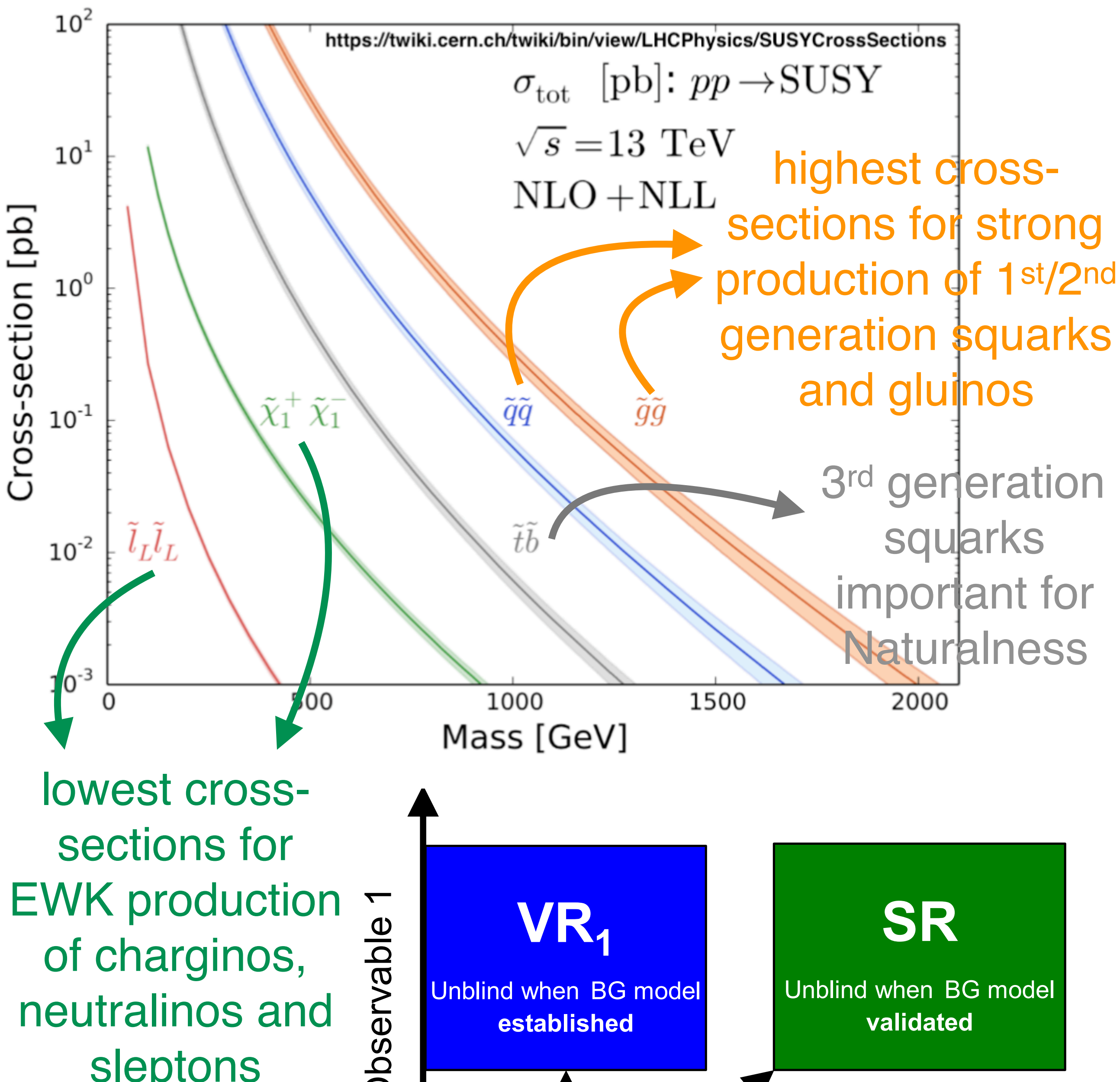
Back-up

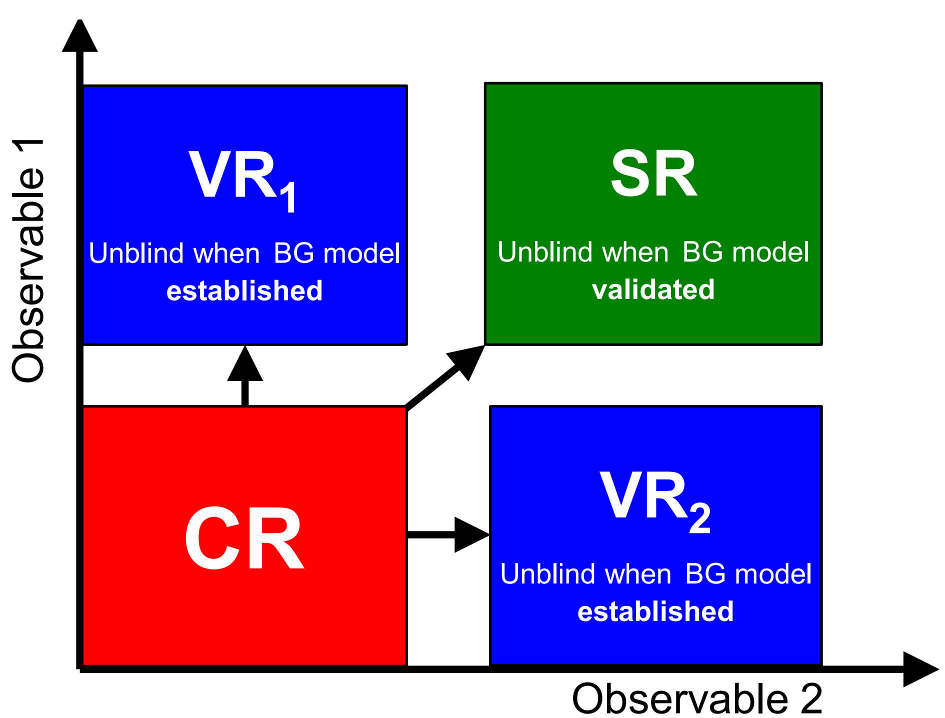
Supersymmetry (SUSY)



- Fundamental symmetry between **fermions** and **bosons** that presents solutions to some *problems* of the SM:
  - SUSY particles provide opposite-sign loop corrections to the Higgs mass, **canceling out quadratic divergencies**
  - If R-parity = $(-1)^{3(B-L)+2s}$ conserved, Lightest SUSY particle (LSP) is stable and natural **Dark Matter** candidate
  - Achieve **unification** of gauge couplings at $M_{GUT} \approx 10^{16}$ GeV

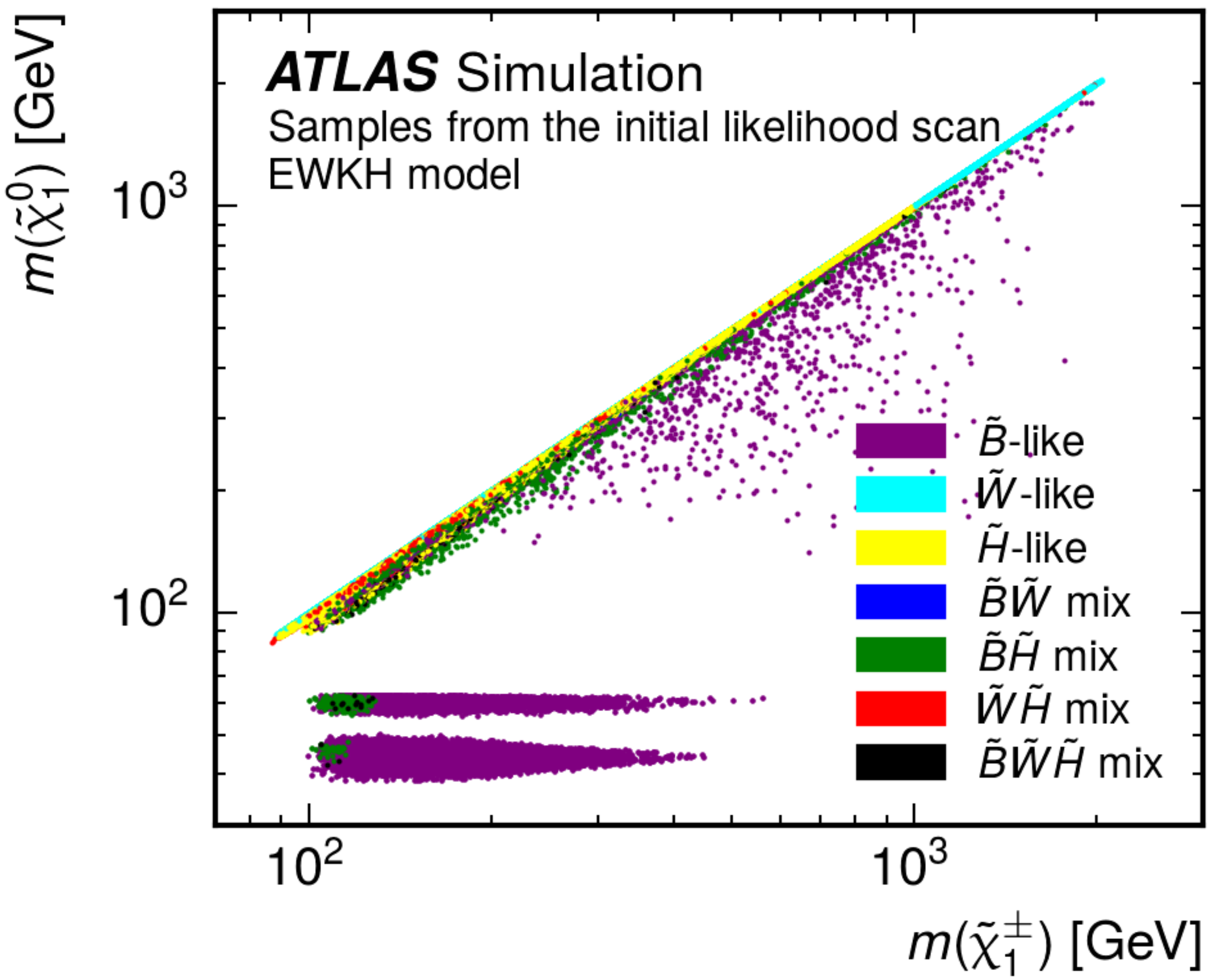
How to search for SUSY

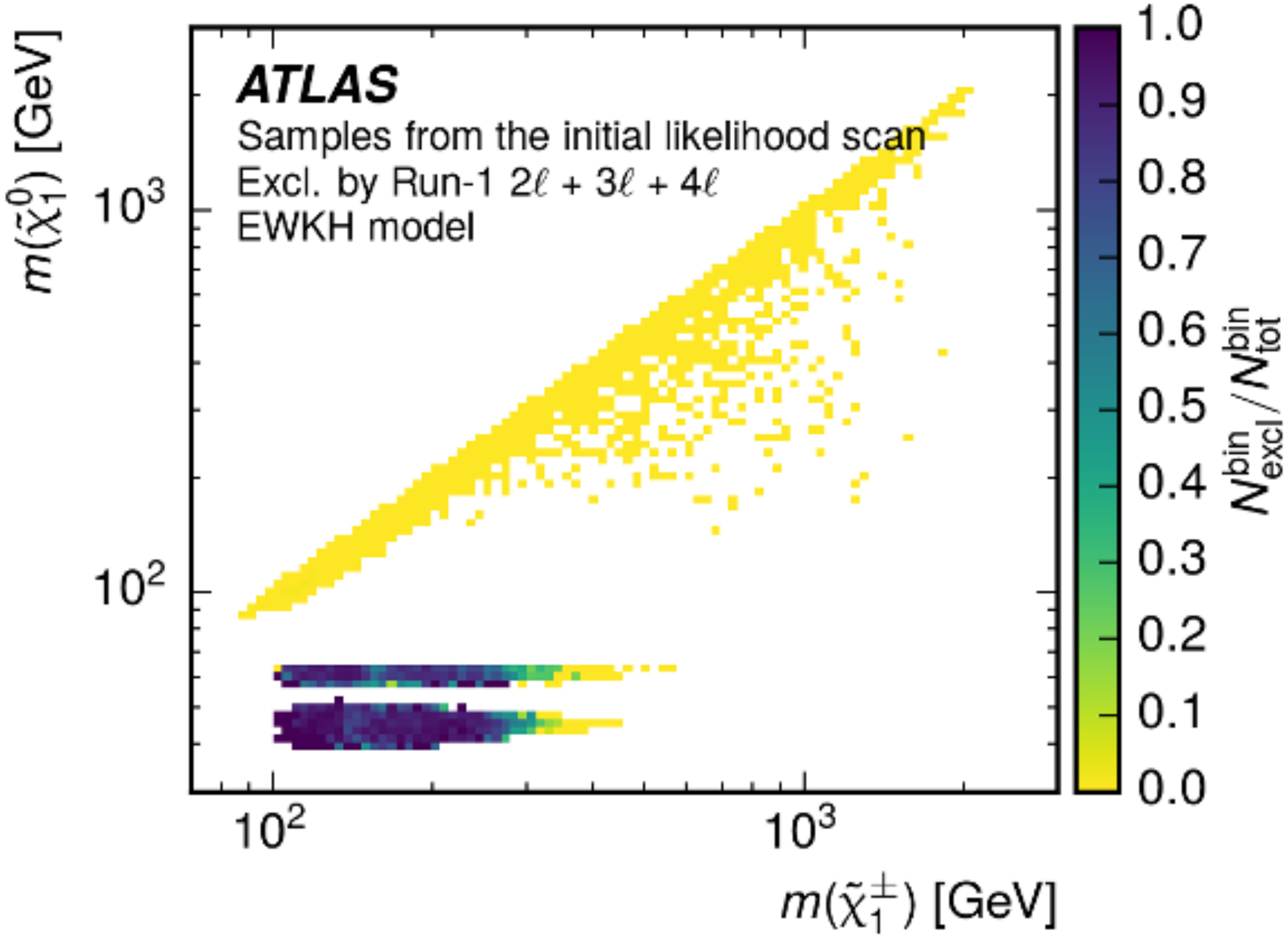




- Make **assumptions** on mass spectra and use **simplified models** to define signatures and guide searches
  - *R-parity conservation - **RPC***: pair-produced SUSY particles decaying to LSP
  - *R-parity violation - **RPV***: LSP decays to SM particles
- **Signal regions** built with high S/B using discriminating variables
- Backgrounds:
  - Irreducible predicted from MC or normalized in **control regions**
  - Reducible estimated from data-driven methods
  - Checked in **validation regions**

Dark matter interpretation of ATLAS Run 1 searches



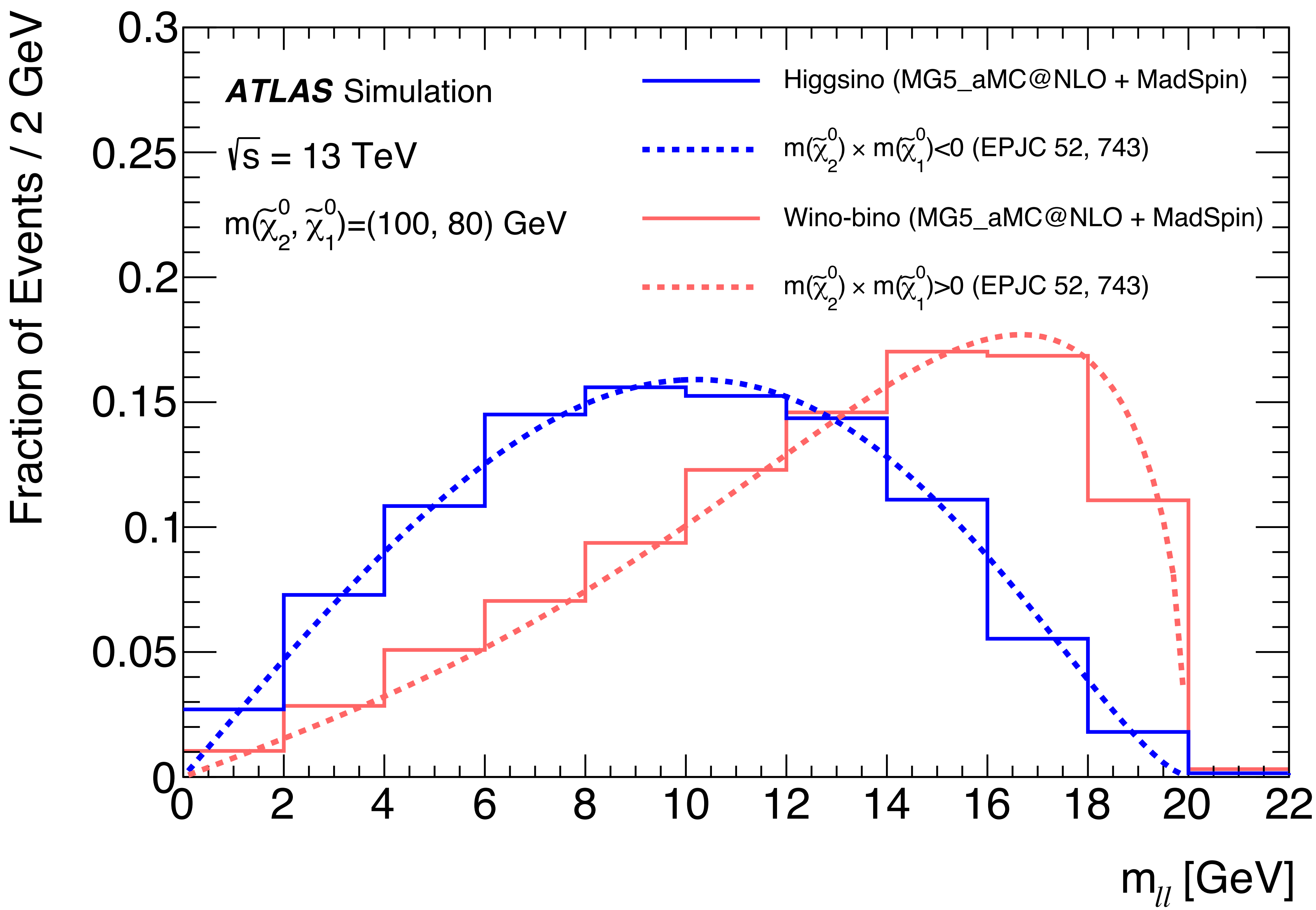


2 soft leptons MC samples

Process	Matrix element	Parton shower	PDF set	Cross-section
$Z^{(*)}/\gamma^* + \text{jets}$	SHERPA 2.2.1		NNPDF 3.0 NNLO [86]	NNLO [87]
Diboson	SHERPA 2.1.1 / 2.2.1 / 2.2.2		NNPDF 3.0 NNLO	Generator NLO
Triboson	SHERPA 2.2.1		NNPDF 3.0 NNLO	Generator LO, NLO
$t\bar{t}$	POWHEG-BOX v2	PYTHIA 6.428	NLO CT10 [88]	NNLO+NNLL [89,90,91,92]
t (s-channel)	POWHEG-BOX v1	PYTHIA 6.428	NLO CT10	NNLO+NNLL [93]
t (t-channel)	POWHEG-BOX v1	PYTHIA 6.428	NLO CT10f4	NNLO+NNLL [94,95]
$t + W$	POWHEG-BOX v1	PYTHIA 6.428	NLO CT10	NNLO+NNLL [96]
$h(\rightarrow \ell\ell, WW)$	POWHEG-BOX v2	PYTHIA 8.186	NLO CTEQ6L1 [97]	NLO [98]
$h + W/Z$	MG5_aMC@NLO 2.2.2	PYTHIA 8.186	NNPDF 2.3 LO	NLO [98]
$t\bar{t} + W/Z/\gamma^*$	MG5_aMC@NLO 2.3.3	PYTHIA 8.186	NNPDF 3.0 LO	NLO [64]
$t\bar{t} + WW/t\bar{t}$	MG5_aMC@NLO 2.2.2	PYTHIA 8.186	NNPDF 2.3 LO	NLO [64]
$t + Z$	MG5_aMC@NLO 2.2.1	PYTHIA 6.428	NNPDF 2.3 LO	LO [64]
$t + WZ$	MG5_aMC@NLO 2.3.2	PYTHIA 8.186	NNPDF 2.3 LO	NLO [64]
$t + t\bar{t}$	MG5_aMC@NLO 2.2.2	PYTHIA 8.186	NNPDF 2.3 LO	LO [64]

- Signal samples generated at LO using MG5_aMC@NLO with up to two extra partons and showered with Pythia8
- Resummino at NLL+NLO used to compute the cross-sections
- Madspin used for the decays of the EWK samples
- Lepton BRs computed using SUSY-HIT

2 soft leptons EWKino $m_{\ell\ell}$



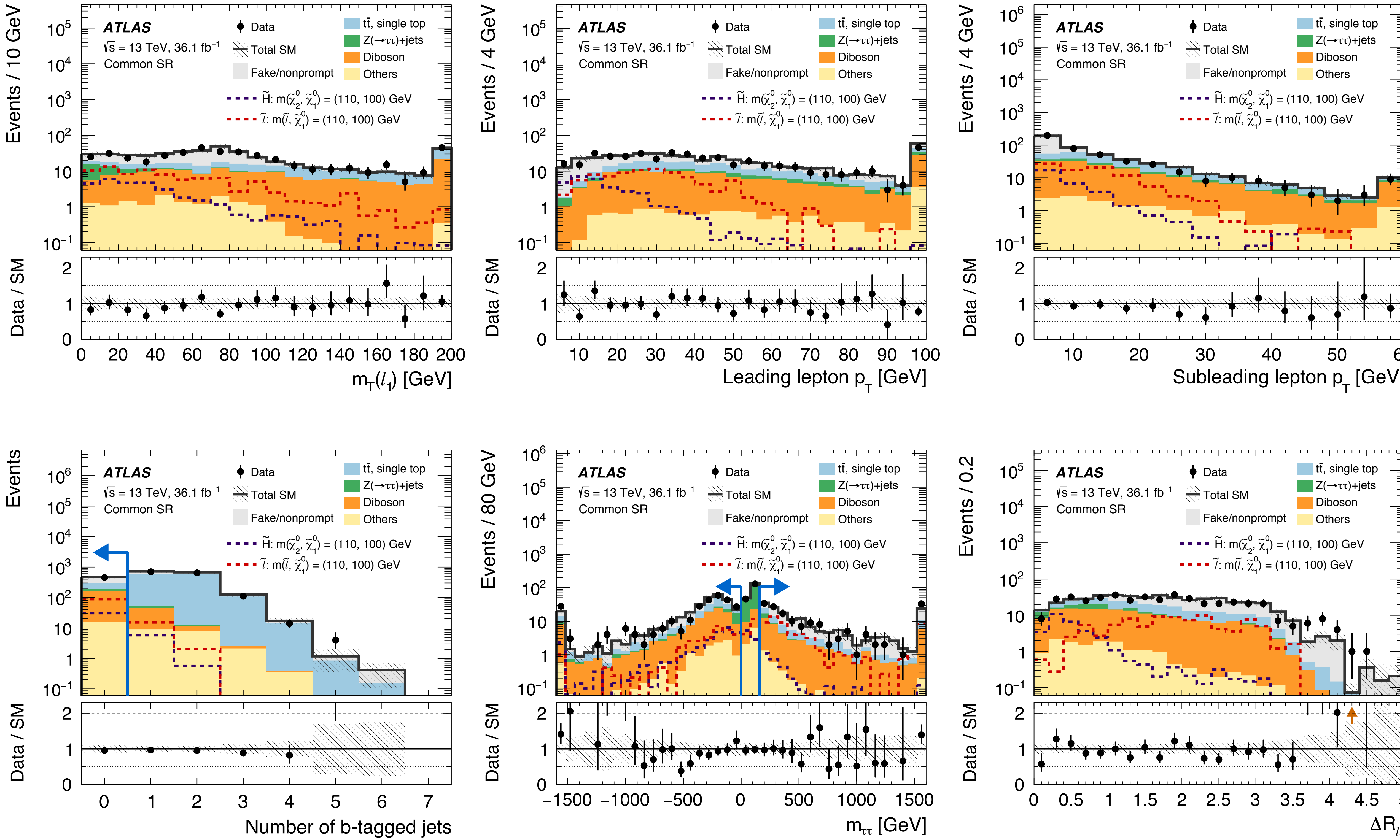
Wino cross-sections = 4 x Higgsino cross-sections

2 soft leptons event selection

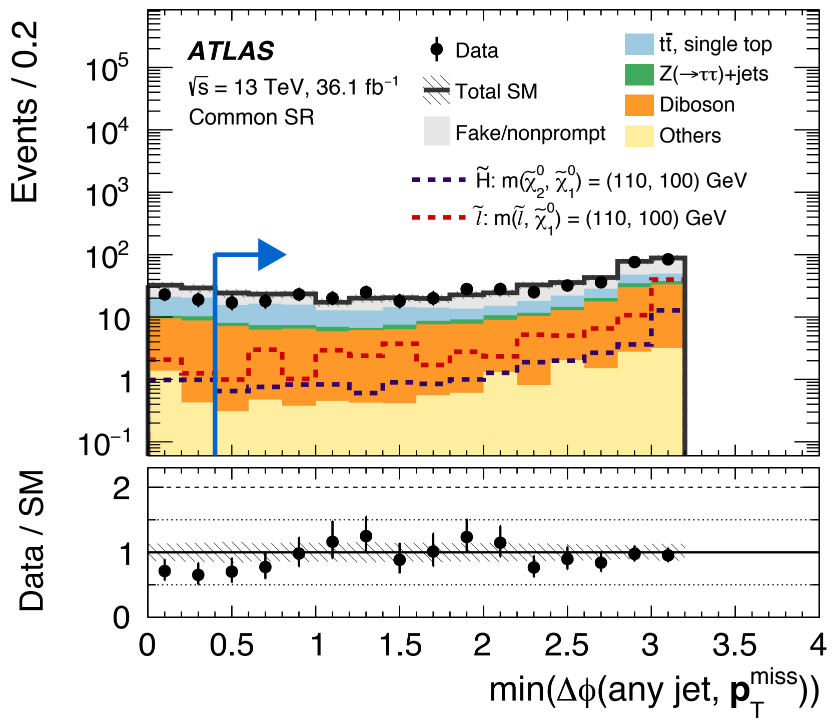
Variable	Common requirement	
Number of leptons	$= 2$	
Lepton charge and flavor	e^+e^- or $\mu^+\mu^-$	
Leading lepton $p_T^{\ell_1}$	> 5 (5) GeV for electron (muon)	
Subleading lepton $p_T^{\ell_2}$	> 4.5 (4) GeV for electron (muon)	
$\Delta R_{\ell\ell}$	> 0.05	
$m_{\ell\ell}$	$\in [1, 60]$ GeV excluding $[3.0, 3.2]$ GeV	
E_T^{miss}	> 200 GeV	
Number of jets	≥ 1	
Leading jet p_T	> 100 GeV	
$\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$	> 2.0	
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_T^{\text{miss}}))$	> 0.4	
Number of b-tagged jets	$= 0$	
$m_{\tau\tau}$	< 0 or > 160 GeV	
	Electroweakino SRs	Slepton SRs
$\Delta R_{\ell\ell}$	< 2	—
$m_T^{\ell_1}$	< 70 GeV	—
$E_T^{\text{miss}}/H_T^{\text{lep}}$	$> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\ GeV}\right)$	$> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\ GeV} - 100\right)\right)$
Binned in	$m_{\ell\ell}$	m_{T2}^{100}

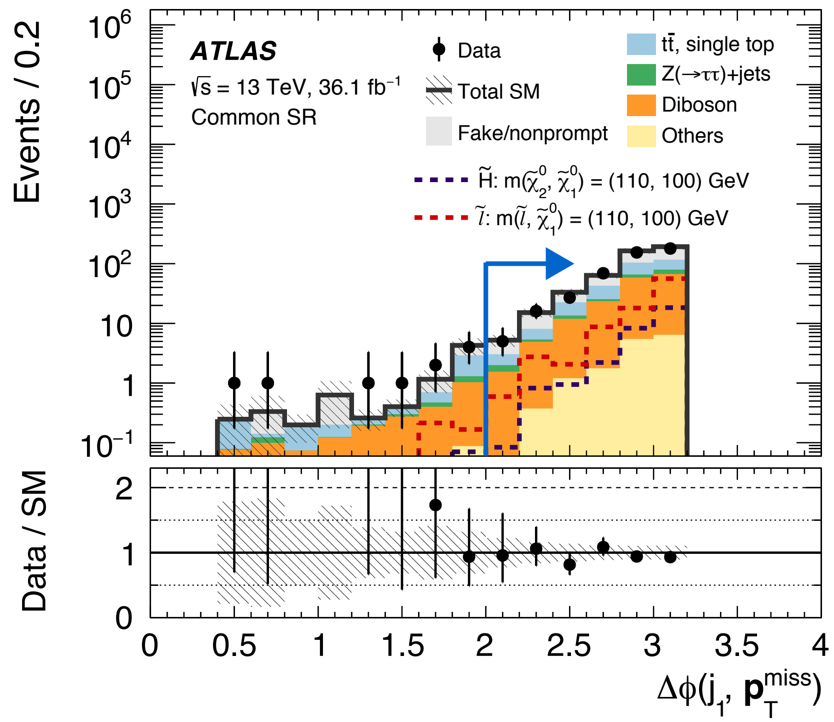
$$m_{T2}^{m_\chi}\left(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}}\right) = \min_{\mathbf{q}_T}\left(\max\left[m_T\left(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T, m_\chi\right), m_T\left(\mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T, m_\chi\right)\right]\right)$$

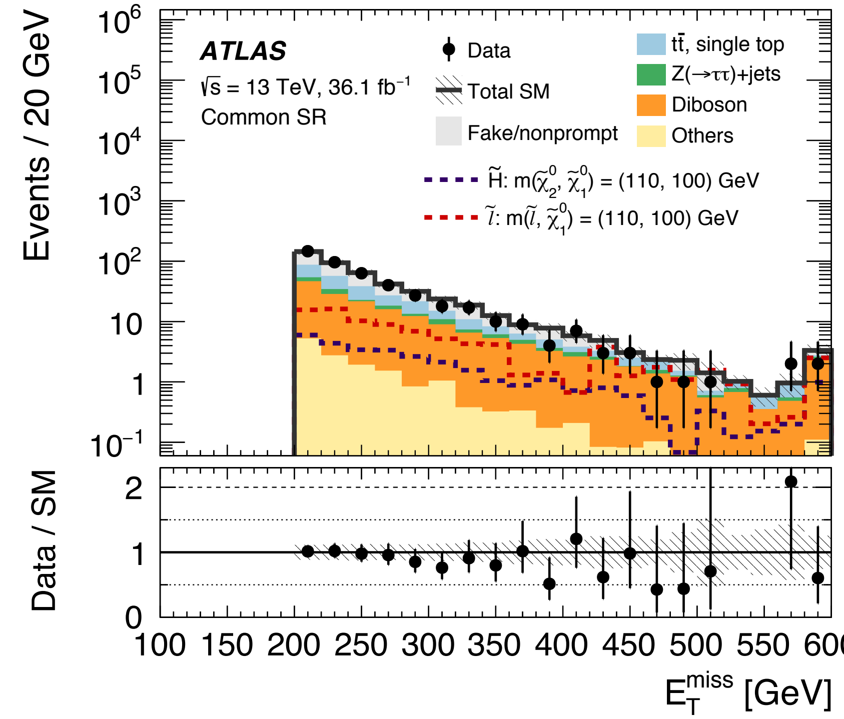
2 soft leptons event selection

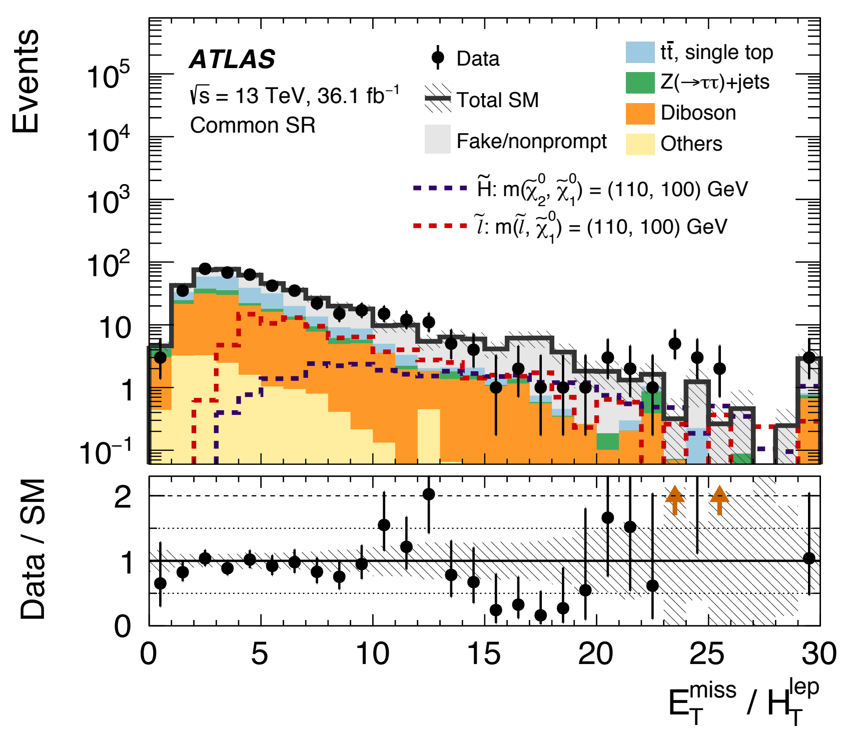


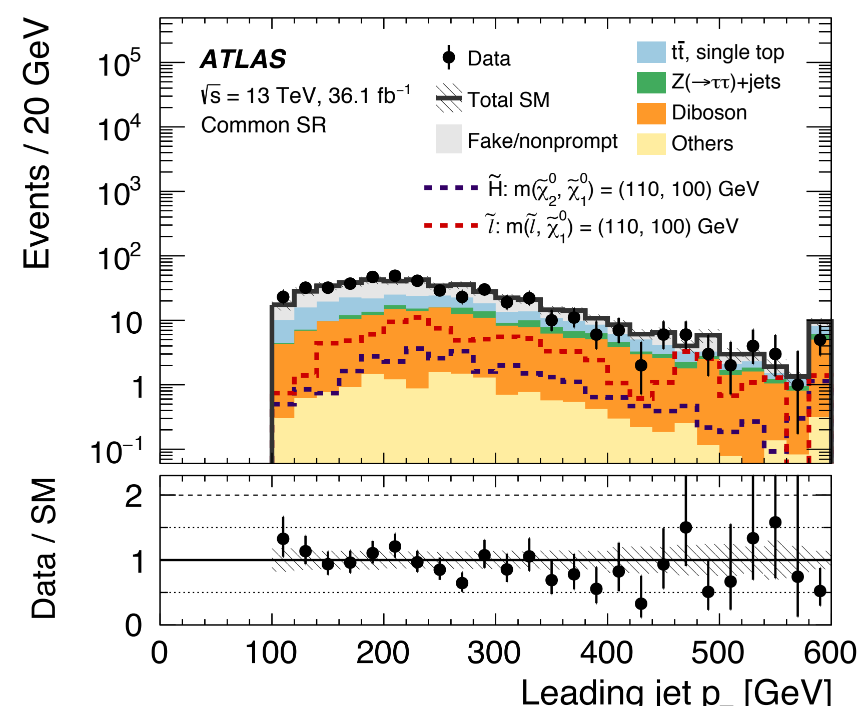
2 soft leptons event selection



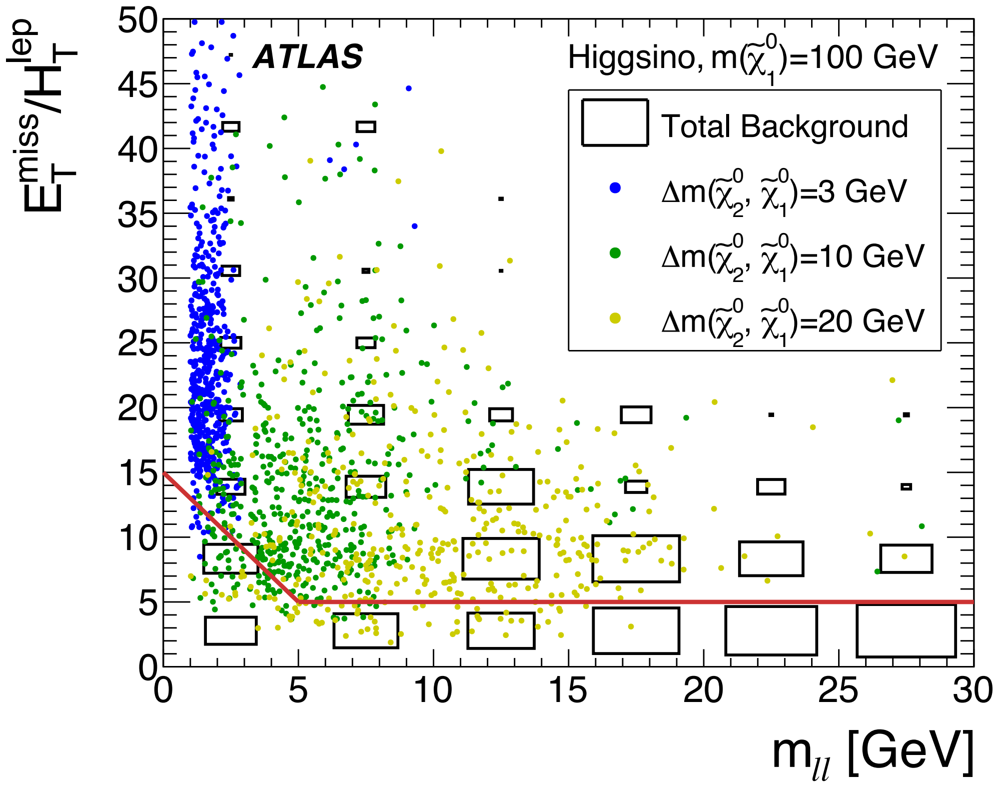


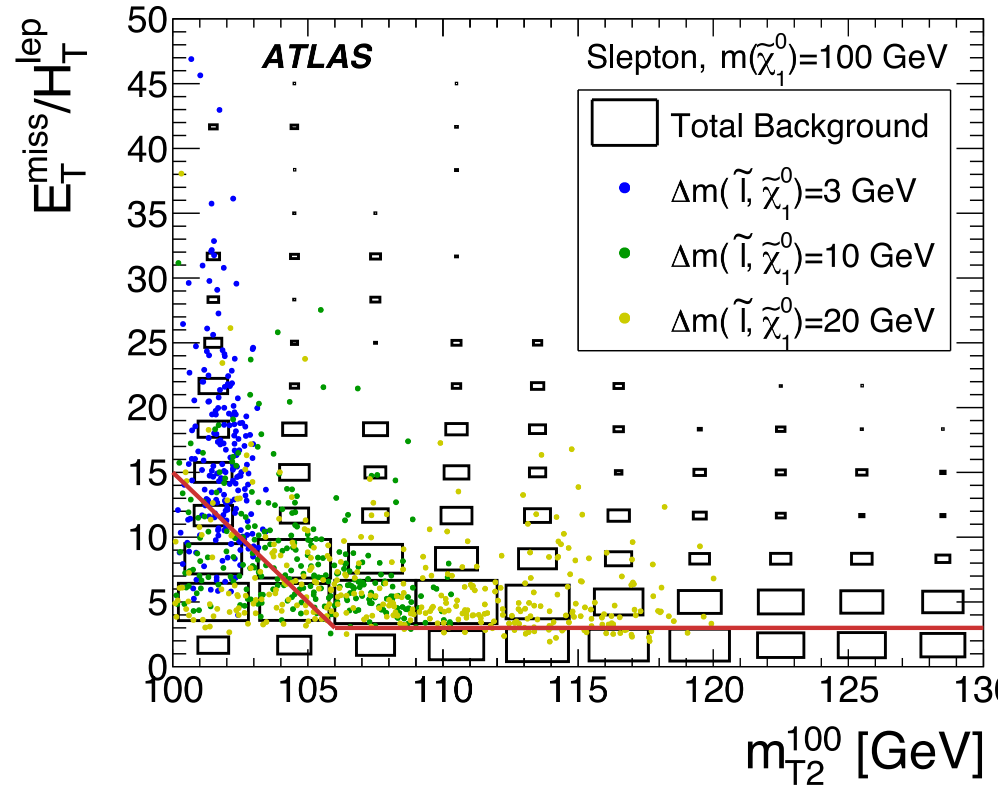


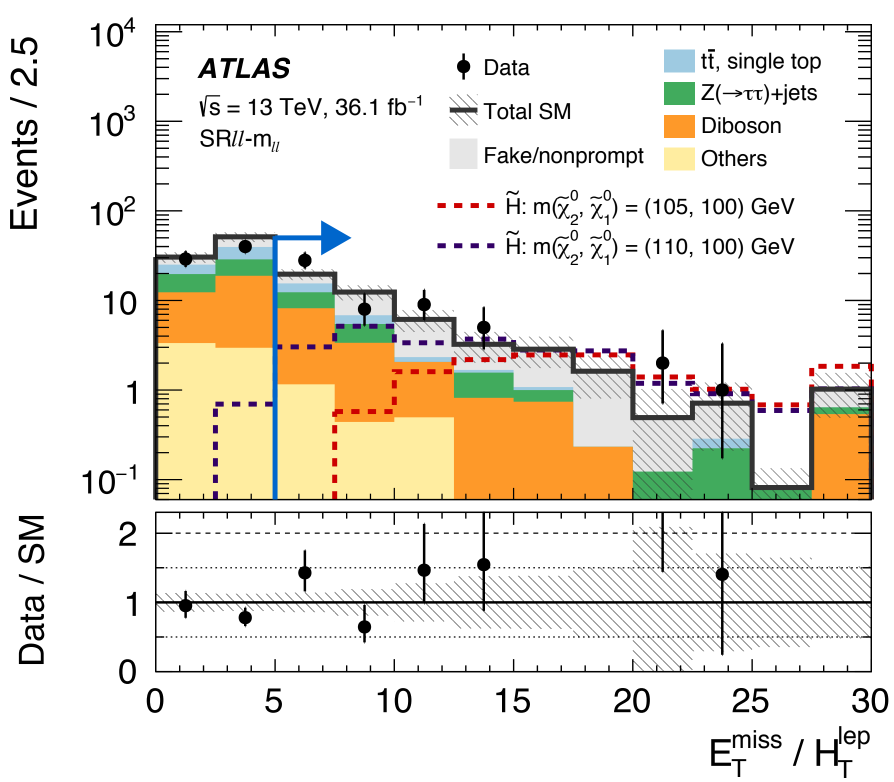


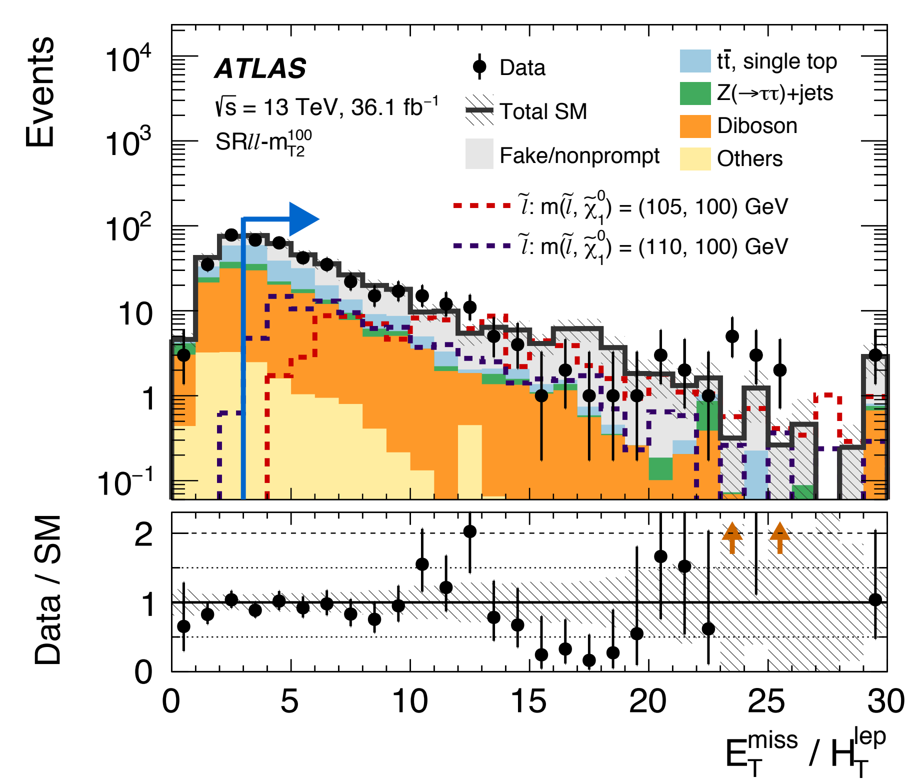


2 soft leptons MET/HT^{lep}









2 soft leptons CRs and VRs

Region	Leptons	E_T^{miss}/H_T^{lep}	Additional requirements
CR-top	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	> 5	≥ 1 b-tagged jet(s)
CR-tau	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$\in [4, 8]$	$m_{\tau\tau} \in [60, 120]$ GeV
VR-VV	$e^\pm e^\mp$, $\mu^\pm\mu^\mp$, $e^\pm\mu^\mp$, $\mu^\pm e^\mp$	< 3	
VR-SS	$e^\pm e^\pm$, $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, $\mu^\pm e^\pm$	> 5	
VRDF-$m_{\ell\ell}$	$e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$> \max\left(5, 15 - 2\frac{m_{\ell\ell}}{1\ GeV}\right)$	$\Delta R_{\ell\ell} < 2$, $m_T^{\ell_1} < 70$ GeV
VRDF-m_{T2}^{100}	$e^\pm\mu^\mp$, $\mu^\pm e^\mp$	$> \max\left(3, 15 - 2\left(\frac{m_{T2}^{100}}{1\ GeV} - 100\right)\right)$	

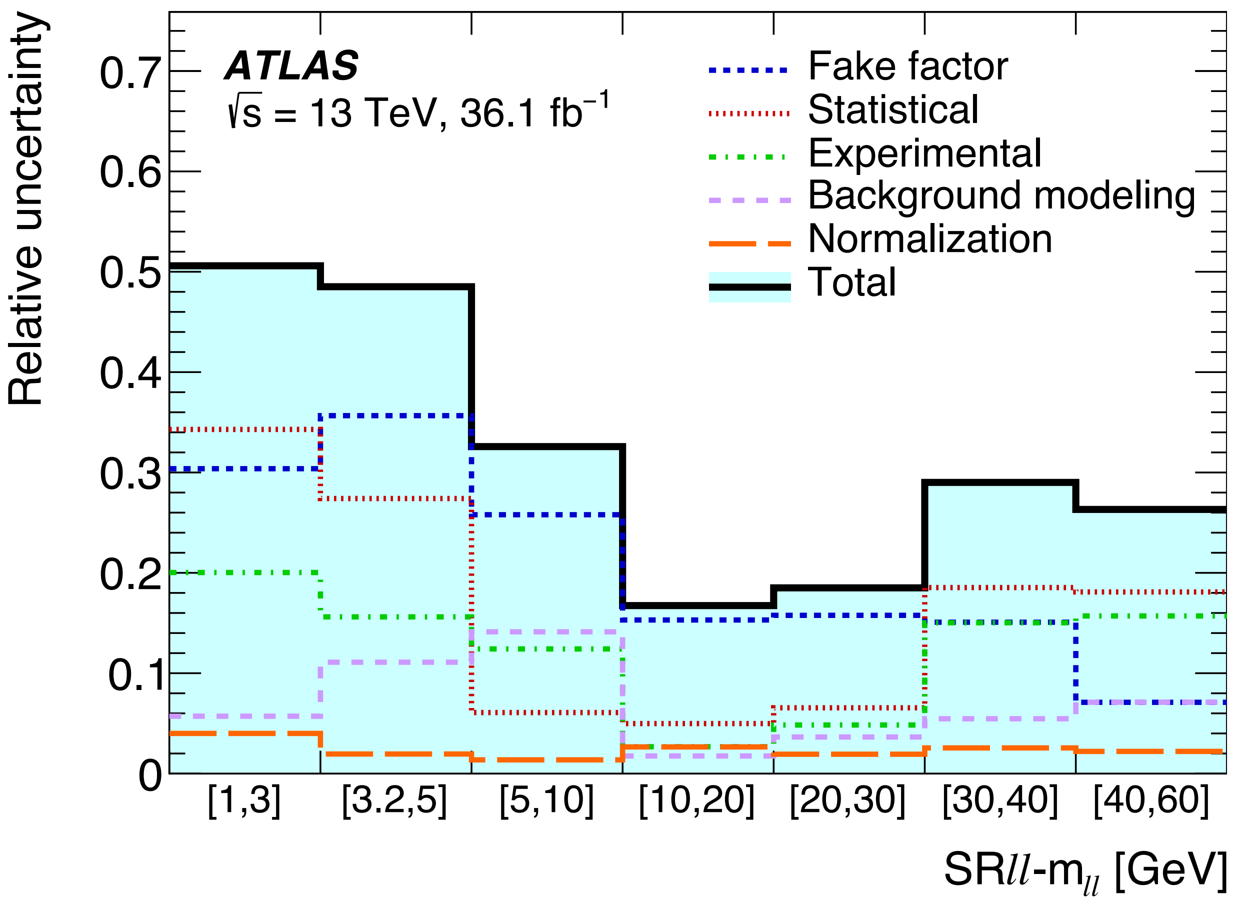
$$m_{\tau\tau} = \text{sign}\left(m_{\tau\tau}^2\right)\sqrt{\left|m_{\tau\tau}^2\right|}$$

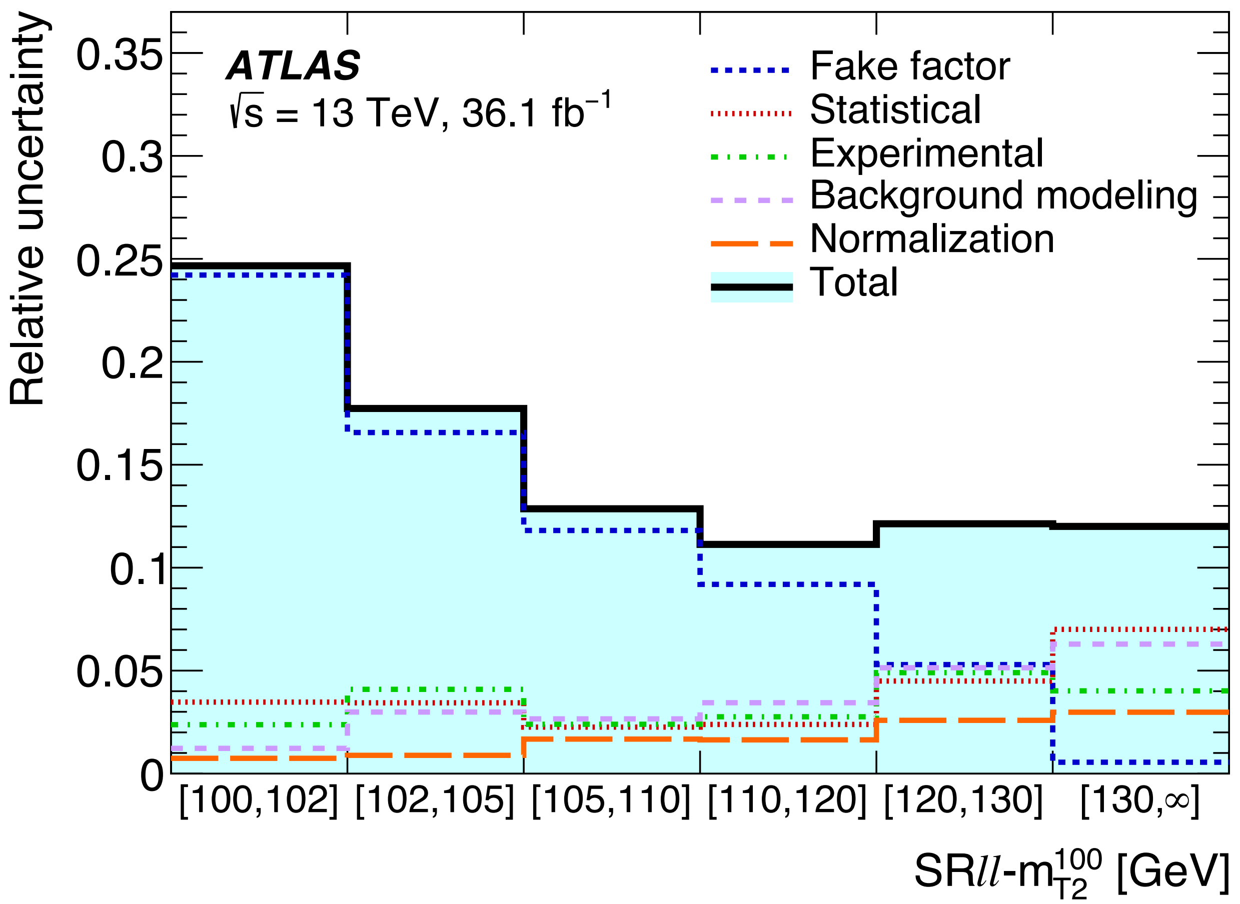
$$m_{\tau\tau}^2 \equiv 2p_{\ell_1} \cdot p_{\ell_2}(1 + \xi_1)(1 + \xi_2)$$

ξ_i obtained by solving $\mathbf{p}_T^{miss} = \xi_1 \mathbf{p}_T^{\ell_1} + \xi_2 \mathbf{p}_T^{\ell_2}$

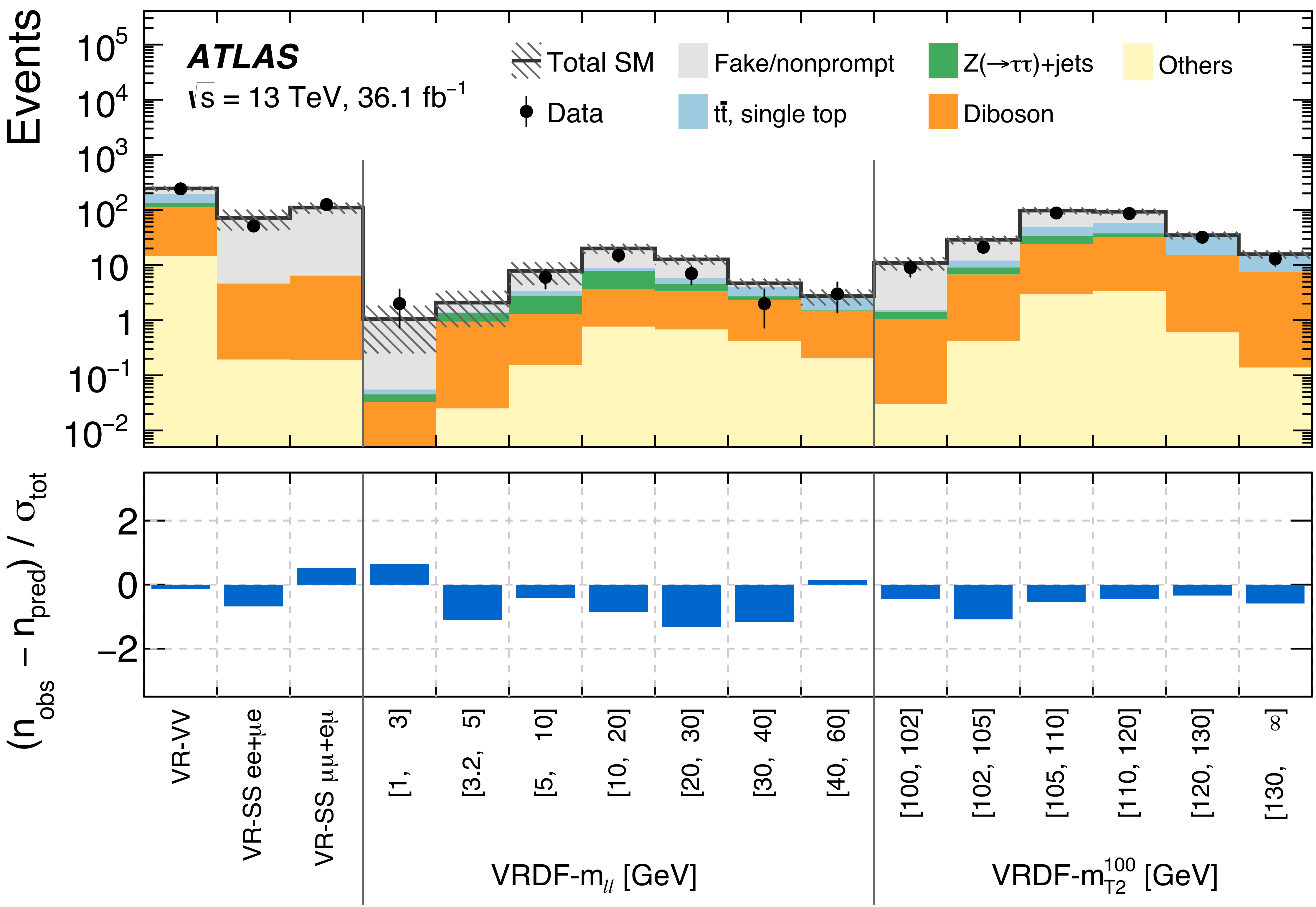
m$\tau\tau$ negative when one of the leptons points in the opposite direction of pTmiss

2 soft leptons uncertainties

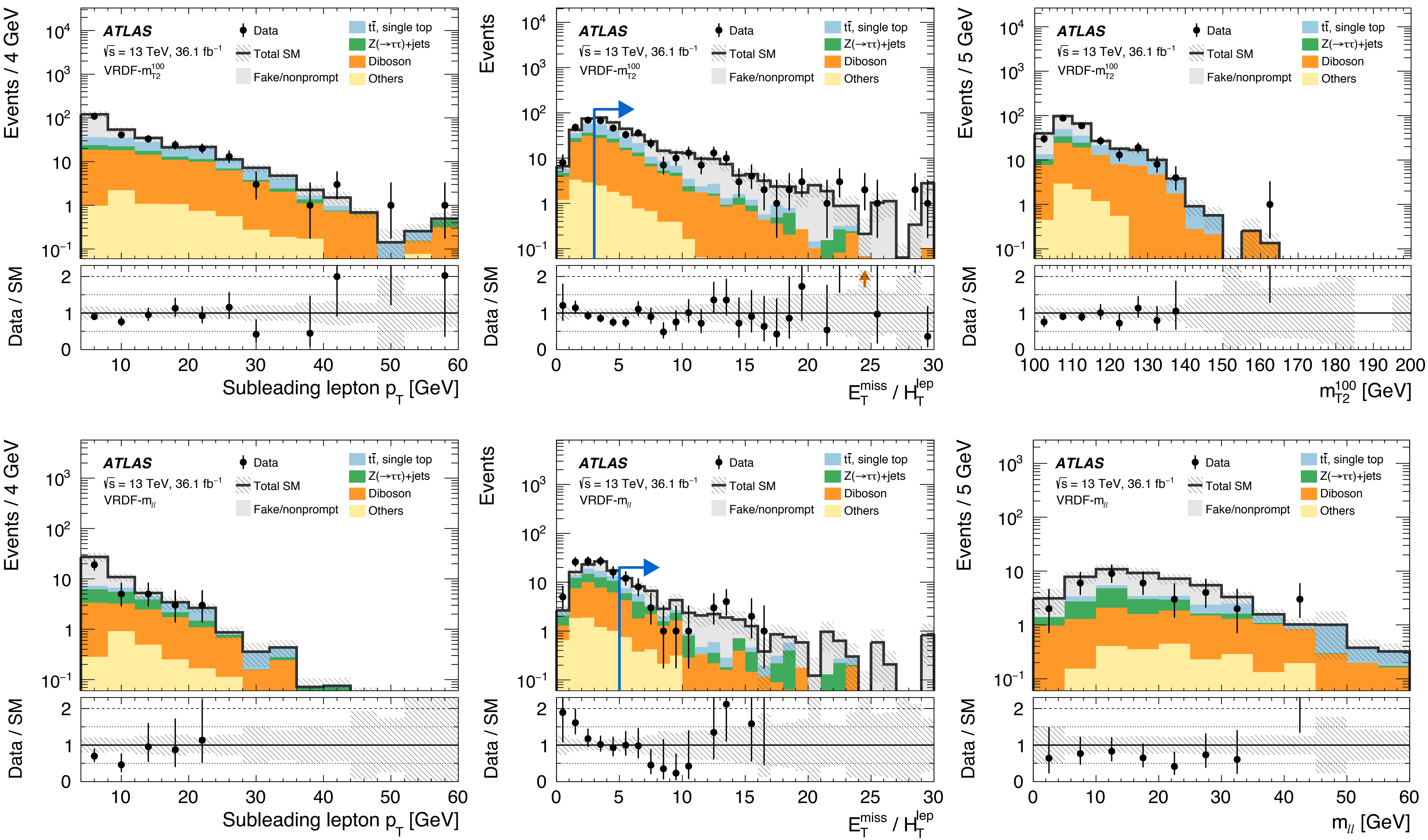




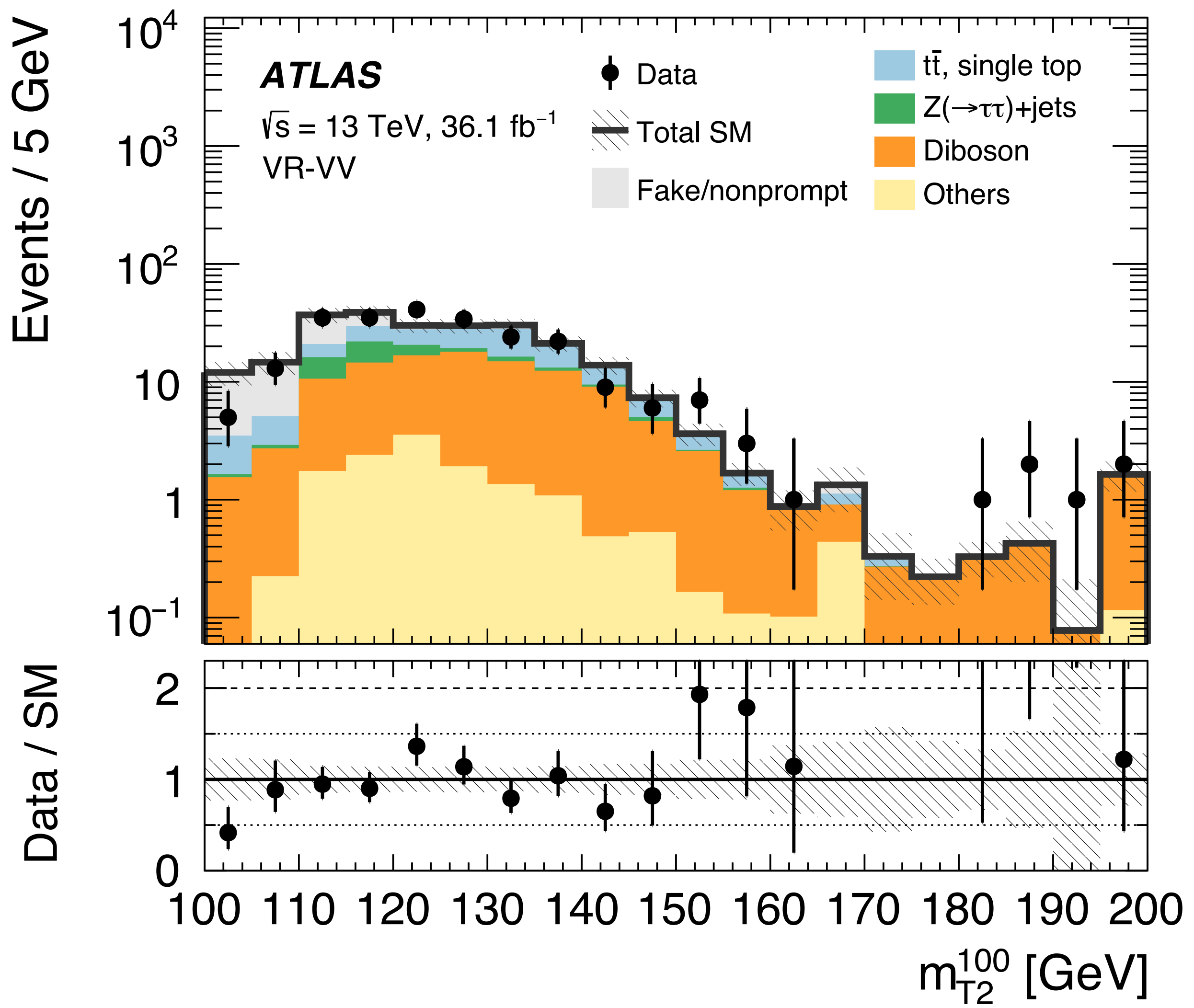
2 soft leptons VRs

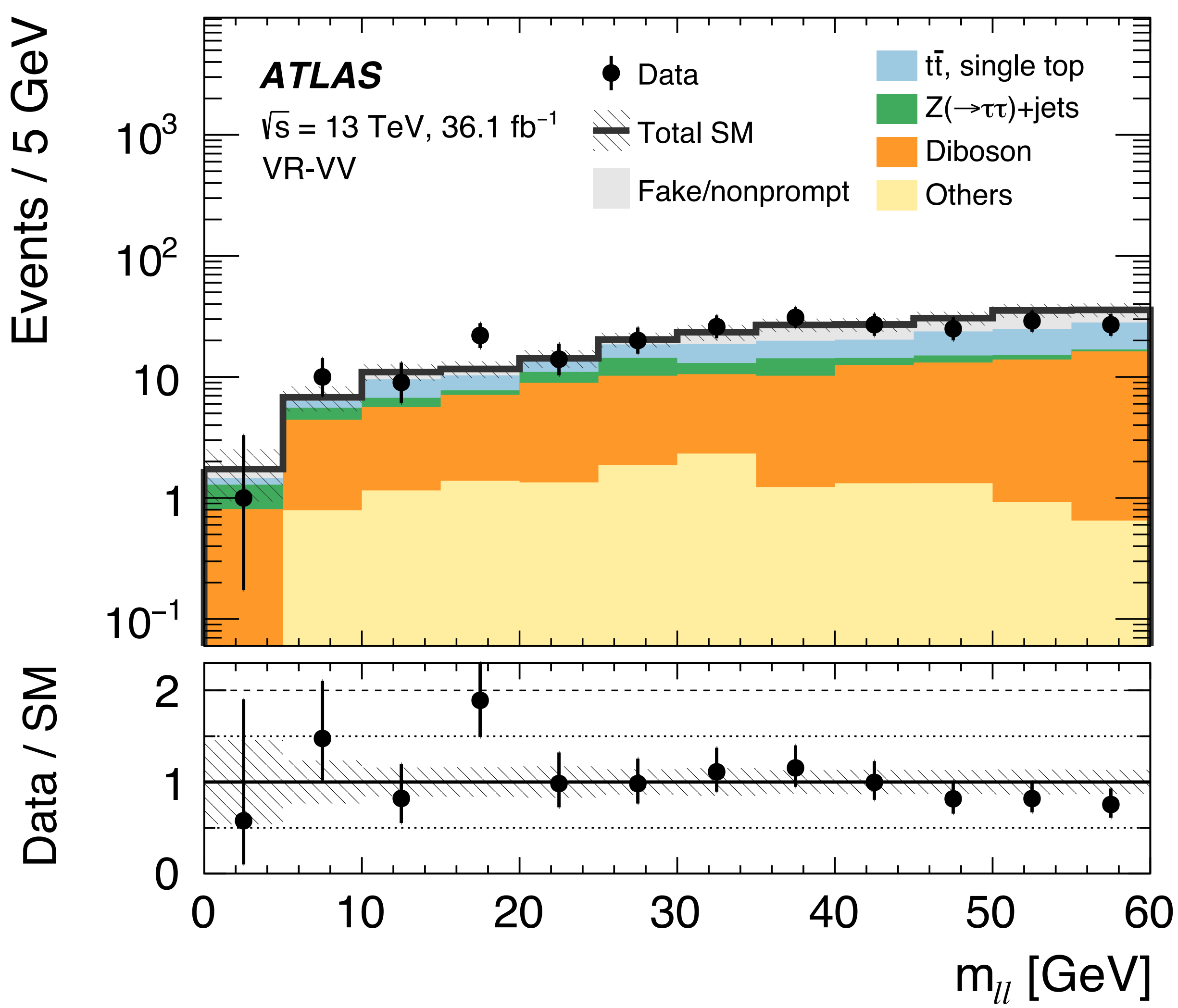


2 soft leptons VR-DF

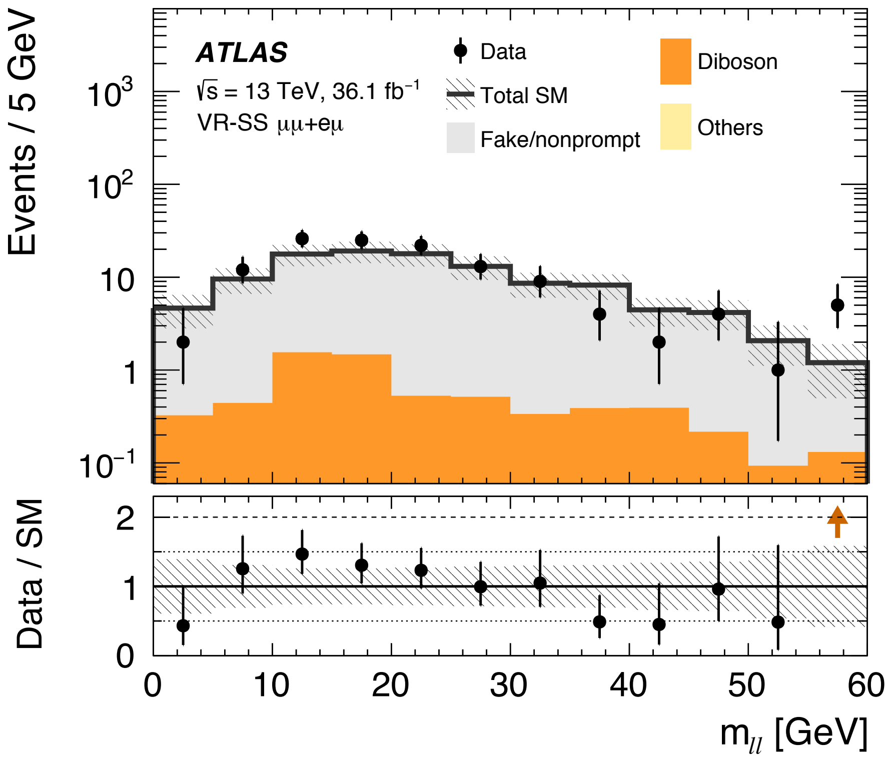


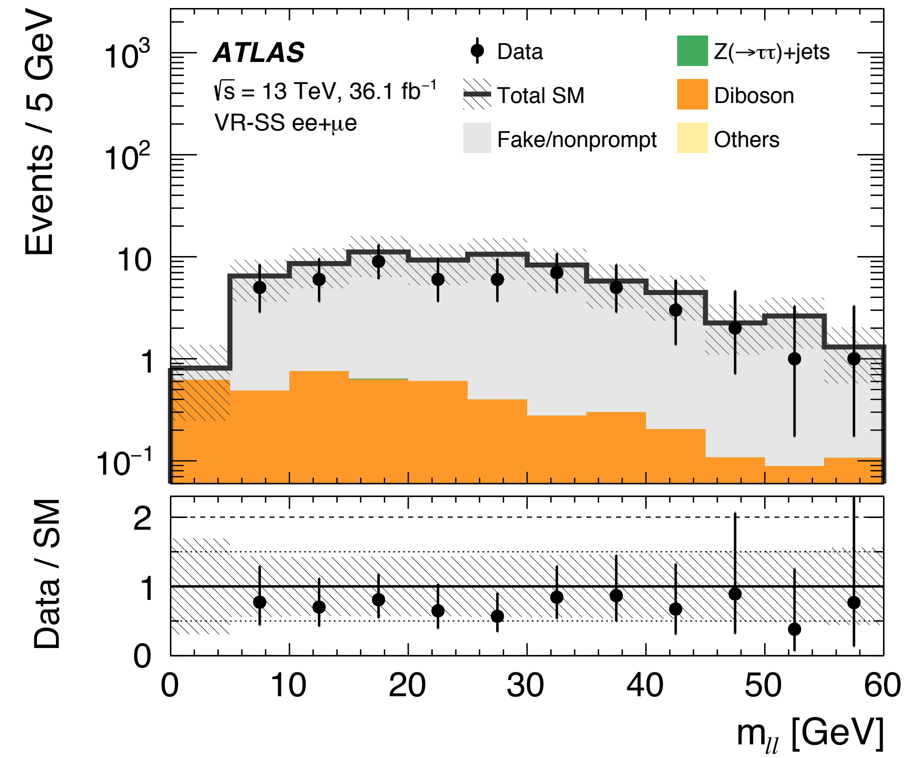
2 soft leptons VR-VV

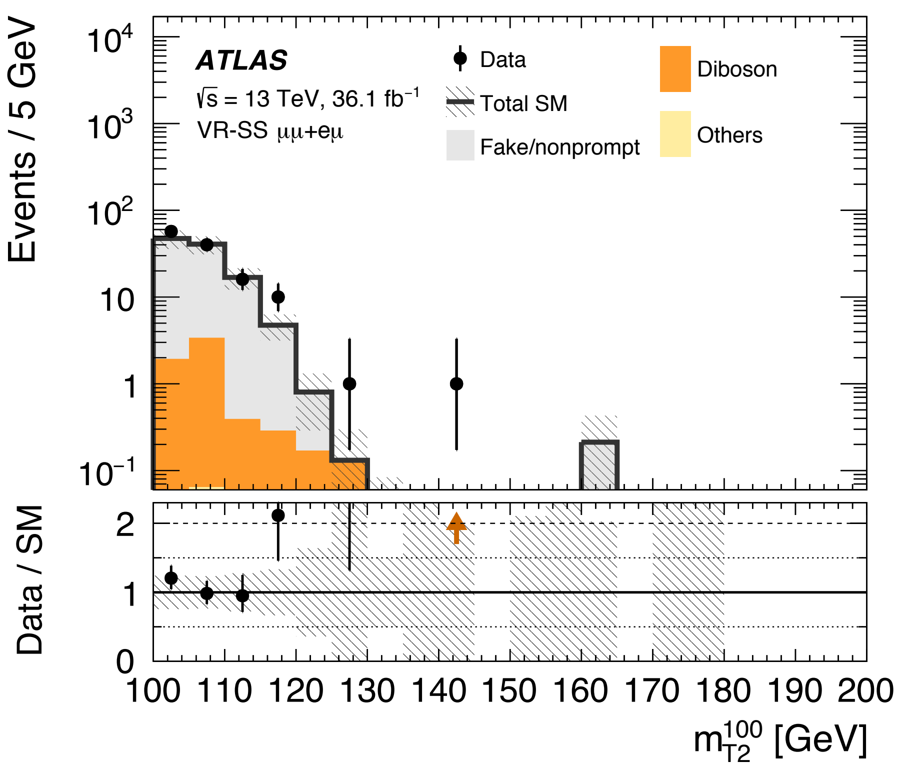


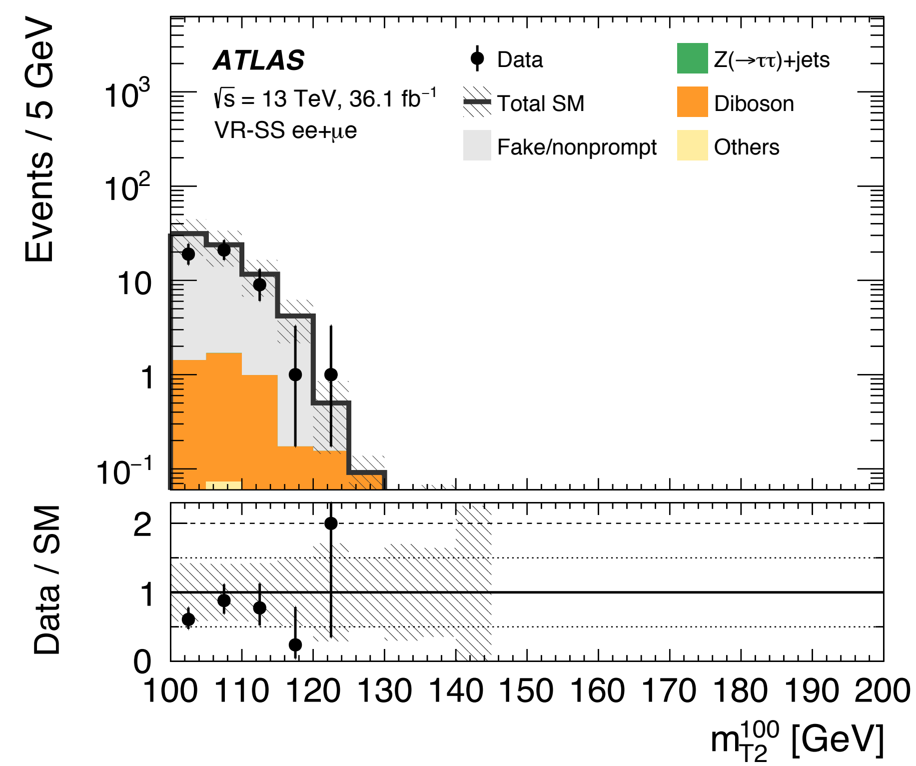


2 soft leptons VR-SS

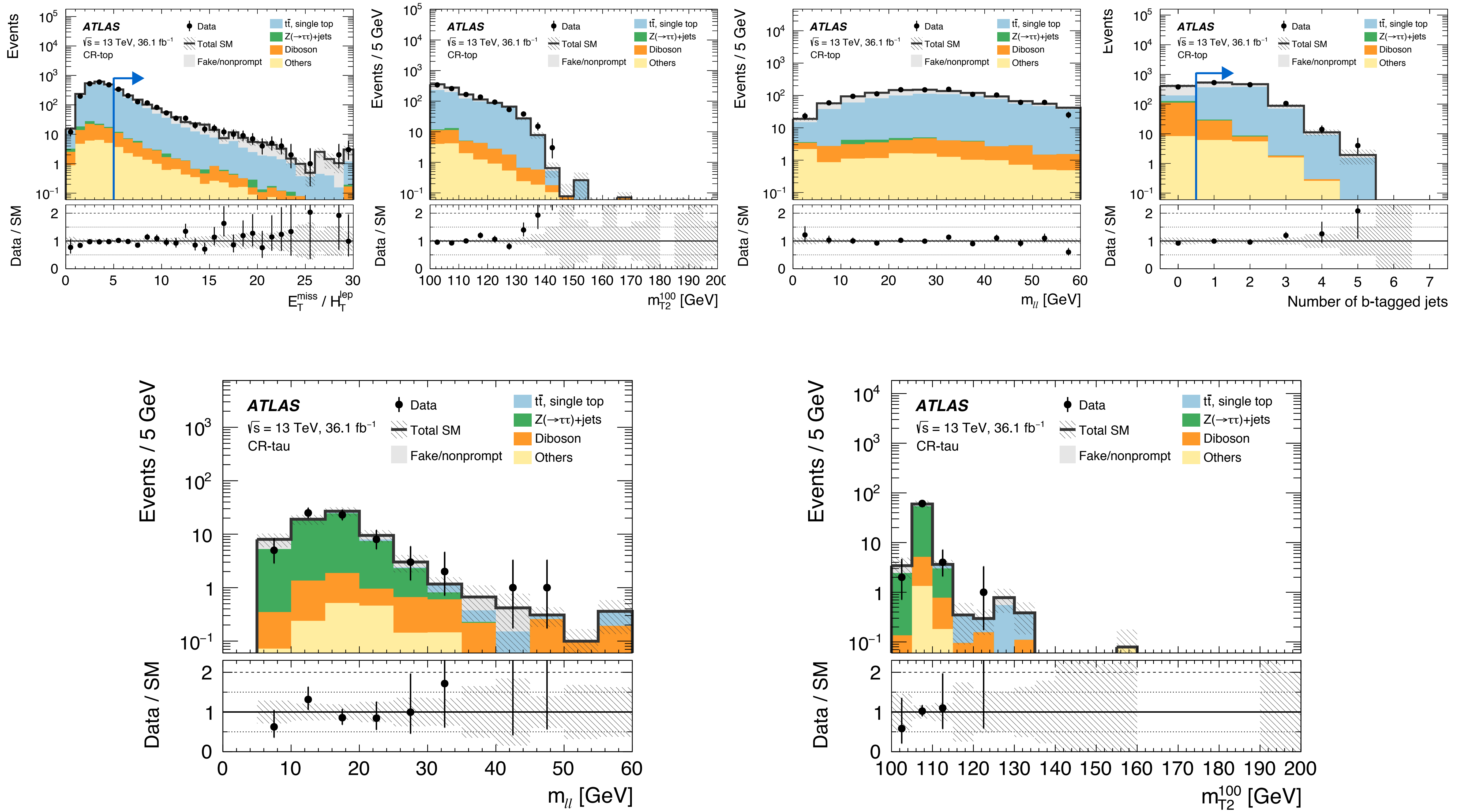




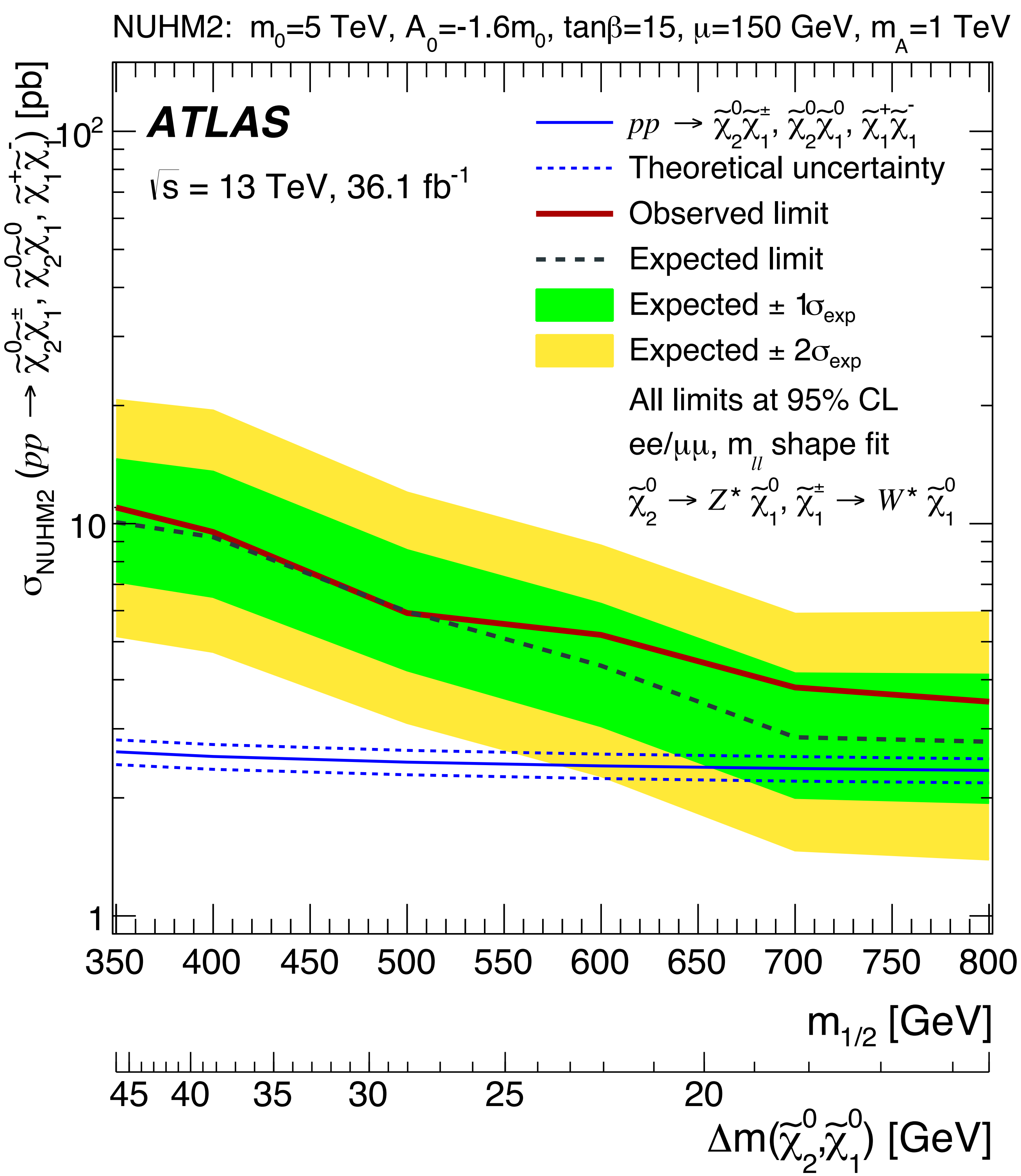




2 soft leptons CRs



2 soft leptons NUHM2 limits



disappearing track higgsino lifetimes

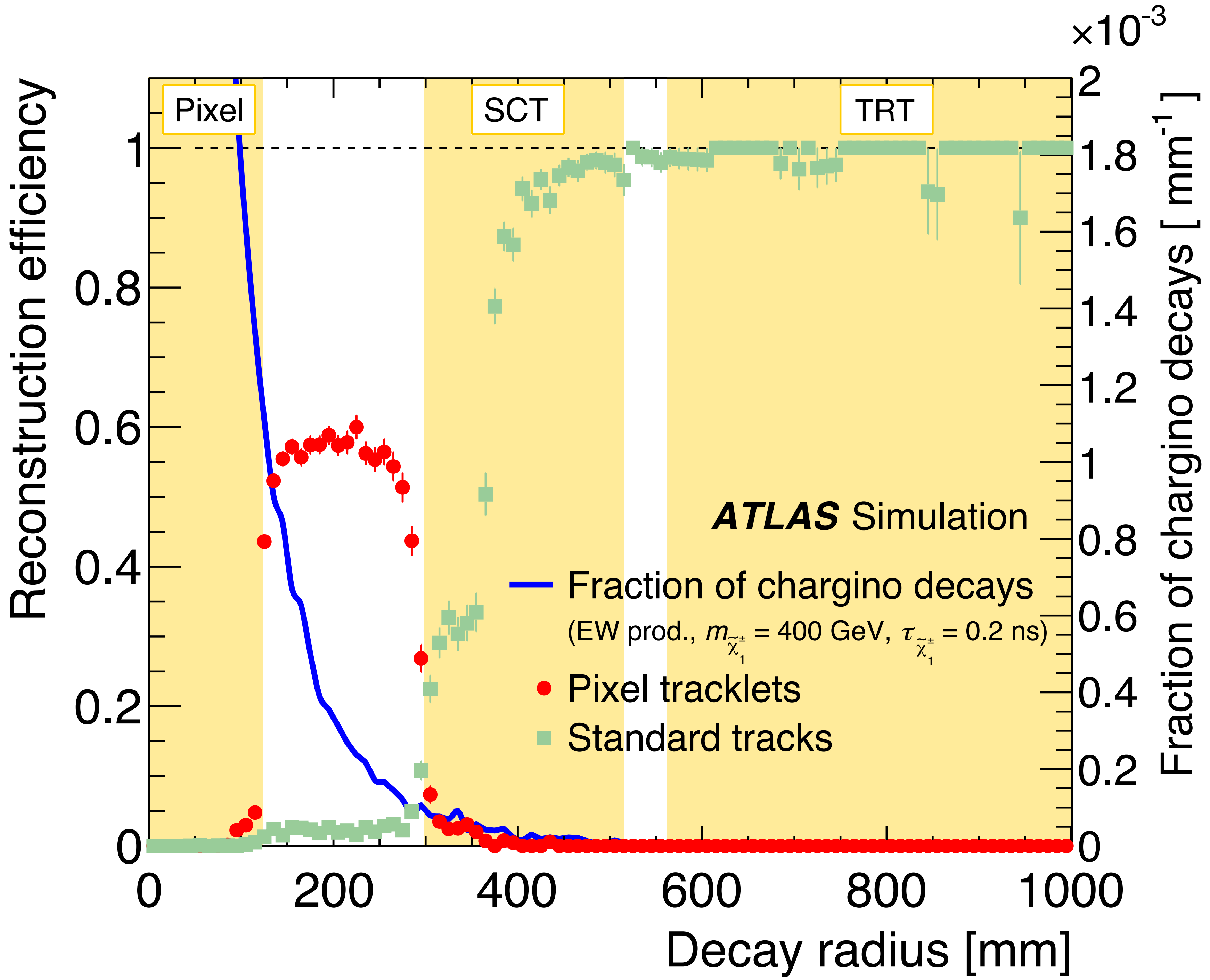
$$c\tau[\mathrm{mm}] \sim 7 \times \left[\left(\frac{\Delta m \left(\tilde{\chi}_1^{\pm}, \tilde{\chi}_{1,2}^{0} \right)}{340\,\mathrm{MeV}} \right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m \left(\tilde{\chi}_1^{\pm}, \tilde{\chi}_{1,2}^{0} \right)^2}} \right]^{-1}$$

Example lifetimes:

μ = 100 GeV ⟹ Δm = 257 MeV, so cτ = 19.3 mm

μ = 1 TeV ⟹ Δm = 355 MeV, so cτ = 6.7 mm

disappearing track tracklet reconstruction efficiency



disappearing track event selection

Selection requirement	Electroweak channel	
	Observed	Expected signal
Trigger	434 559 704	1276 (0.20)
Jet cleaning	288 498 579	1181 (0.19)
Lepton veto	275 243 946	1178 (0.19)
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jet requirements	2 697 917	579.1 (0.092)
Isolation and p_{T} requirement	464 524	104.2 (0.017)
Geometrical $\lvert\eta\rvert$ acceptance	339 602	83.6 (0.013)
Quality requirement	6134	29.6 (0.0047)
Disappearance condition	154	24.1 (0.0038)

For Wino signal point: $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (400\ \text{GeV}, 0.2\ \text{ns})$

MET and jet requirements:
- MET > 140 GeV
- at least one jet with p_T > 140 GeV
- Δϕ > 1.0 between MET and up to four leading jets with p_T > 50 GeV

Isolation and p_T requirements:
- ΔR > 0.4 between tracklet and any jet with p_T > 50 GeV or MS track
- $p_{\mathrm{T}}^{\mathrm{cone40}}/p_{\mathrm{T}} < 0.04$
- Candidate tracklet must be highest p_T track or tracklet in event, and have p_T > 50 GeV

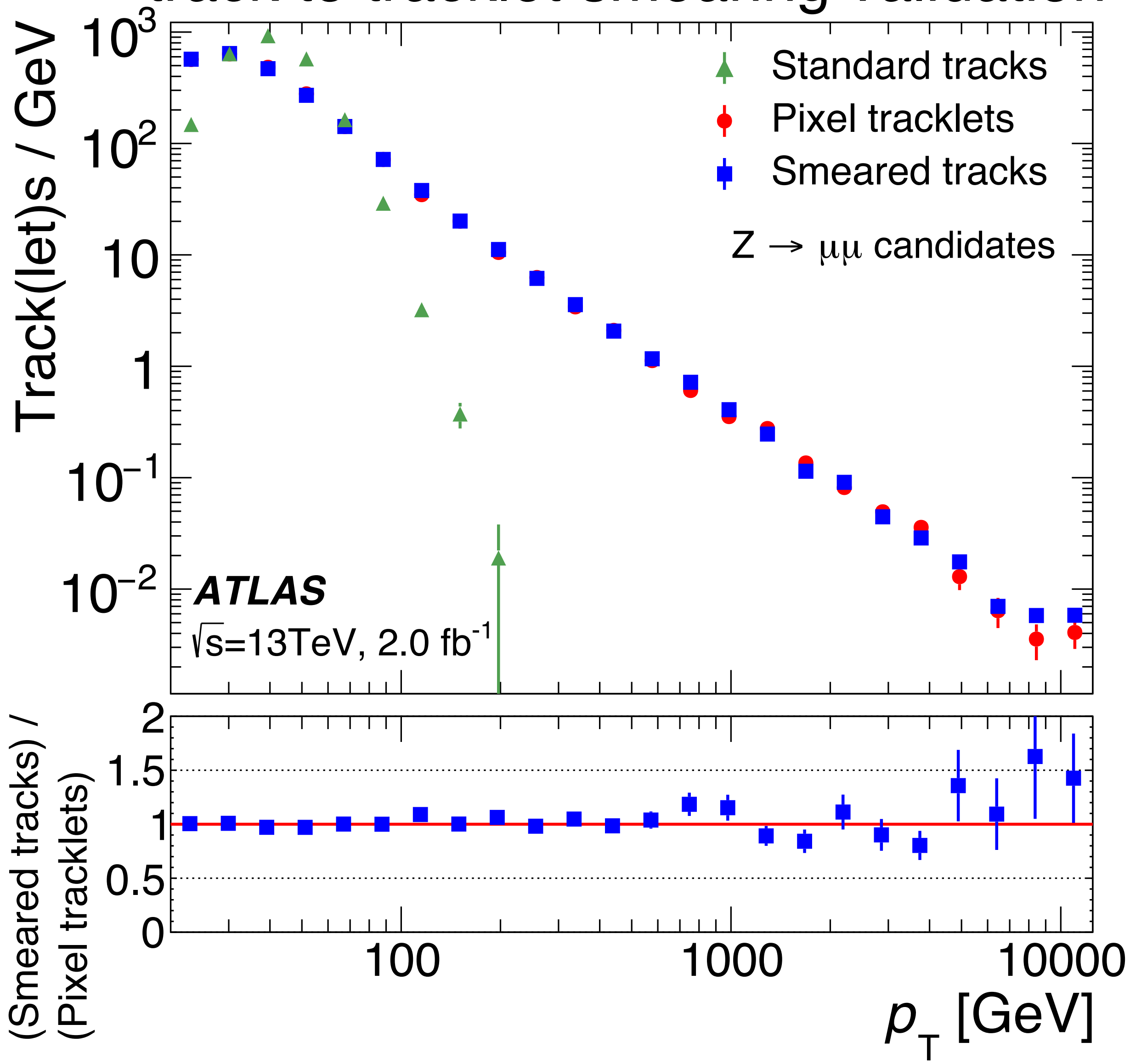
Quality requirement:
- Hits on all four pixel layers; zero holes
- Zero "low quality" hits
- $|d_0|/\sigma(d_0) < 2$, $|z_0 \sin(\theta)| < 0.5$ mm
- Fit χ^2 probability > 10%

Geometrical lηl acceptance: 0.1 < |η| < 1.9

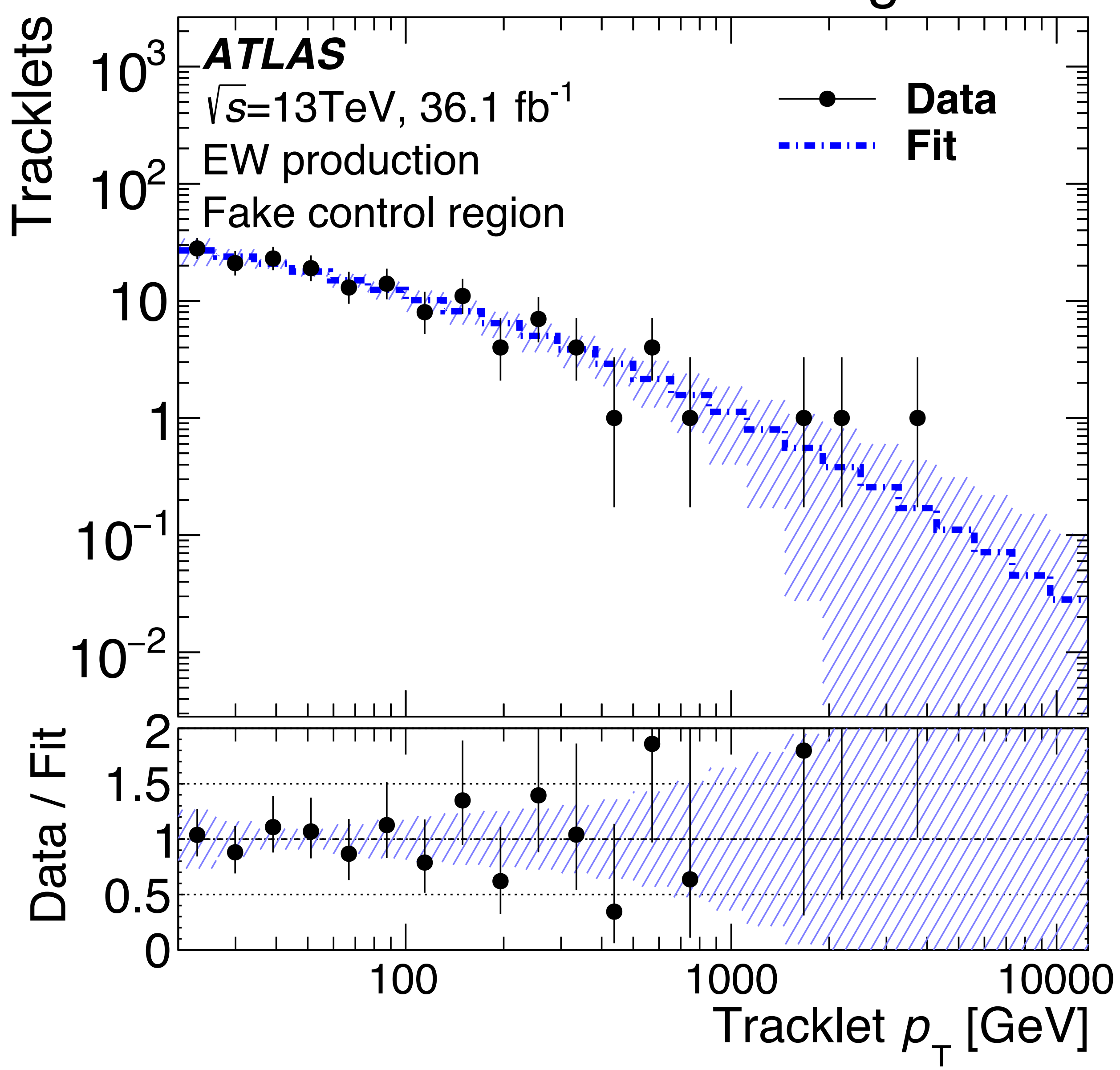
Disappearance condition: zero SCT hits associated to tracklet

disappearing track backgrounds

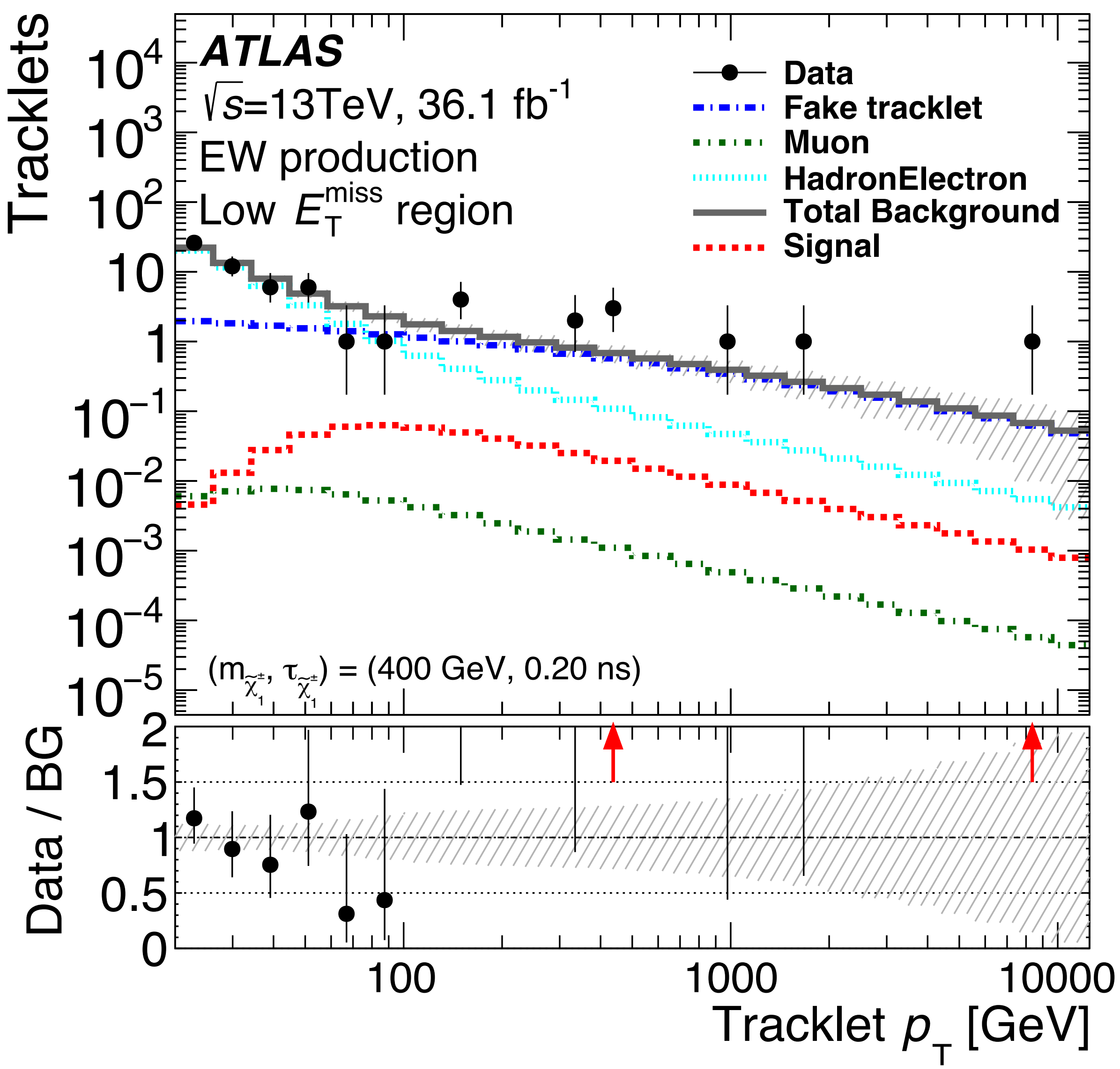
track to tracklet smearing validation

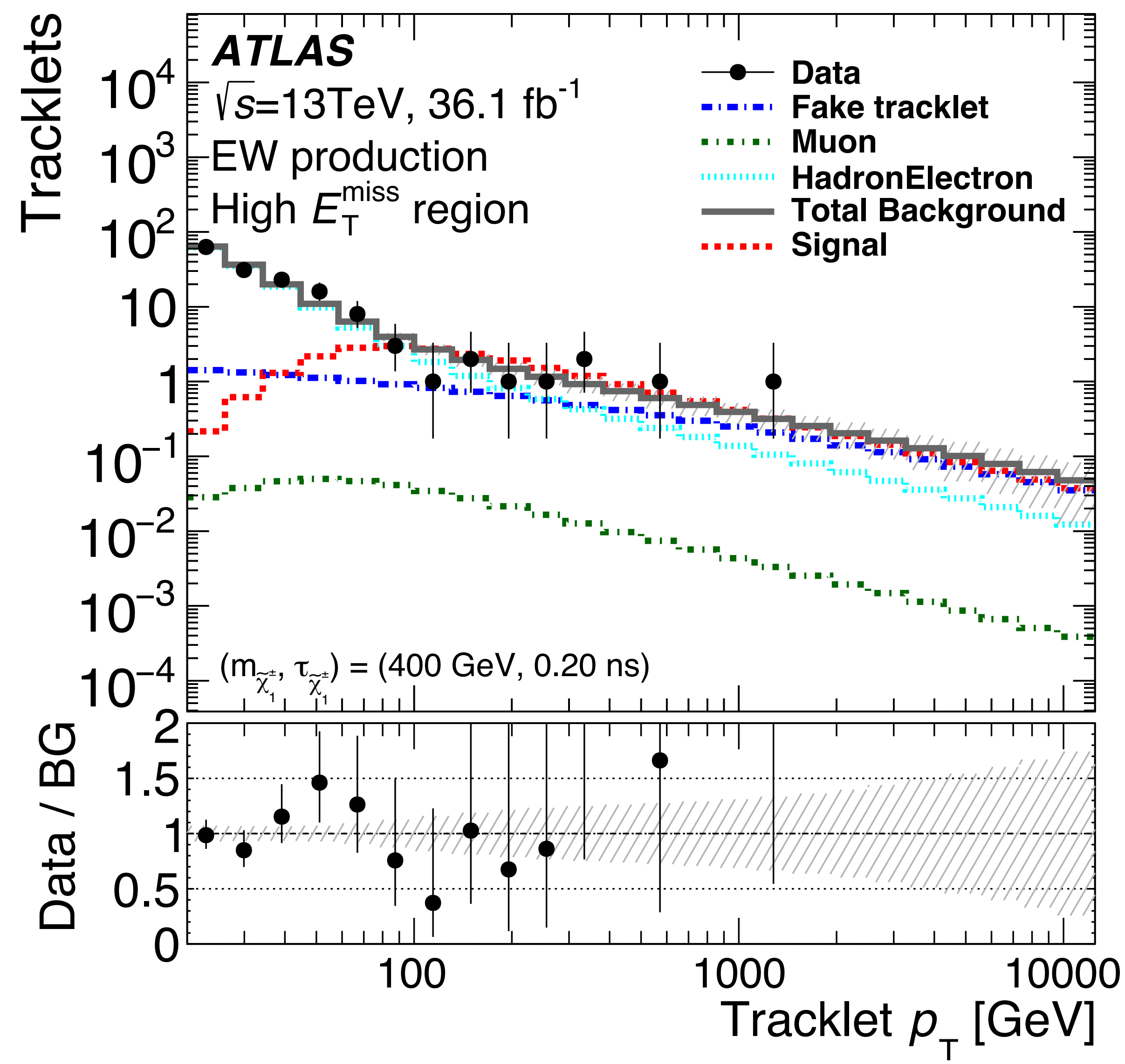


fake tracklet control region



disappearing track fitted regions

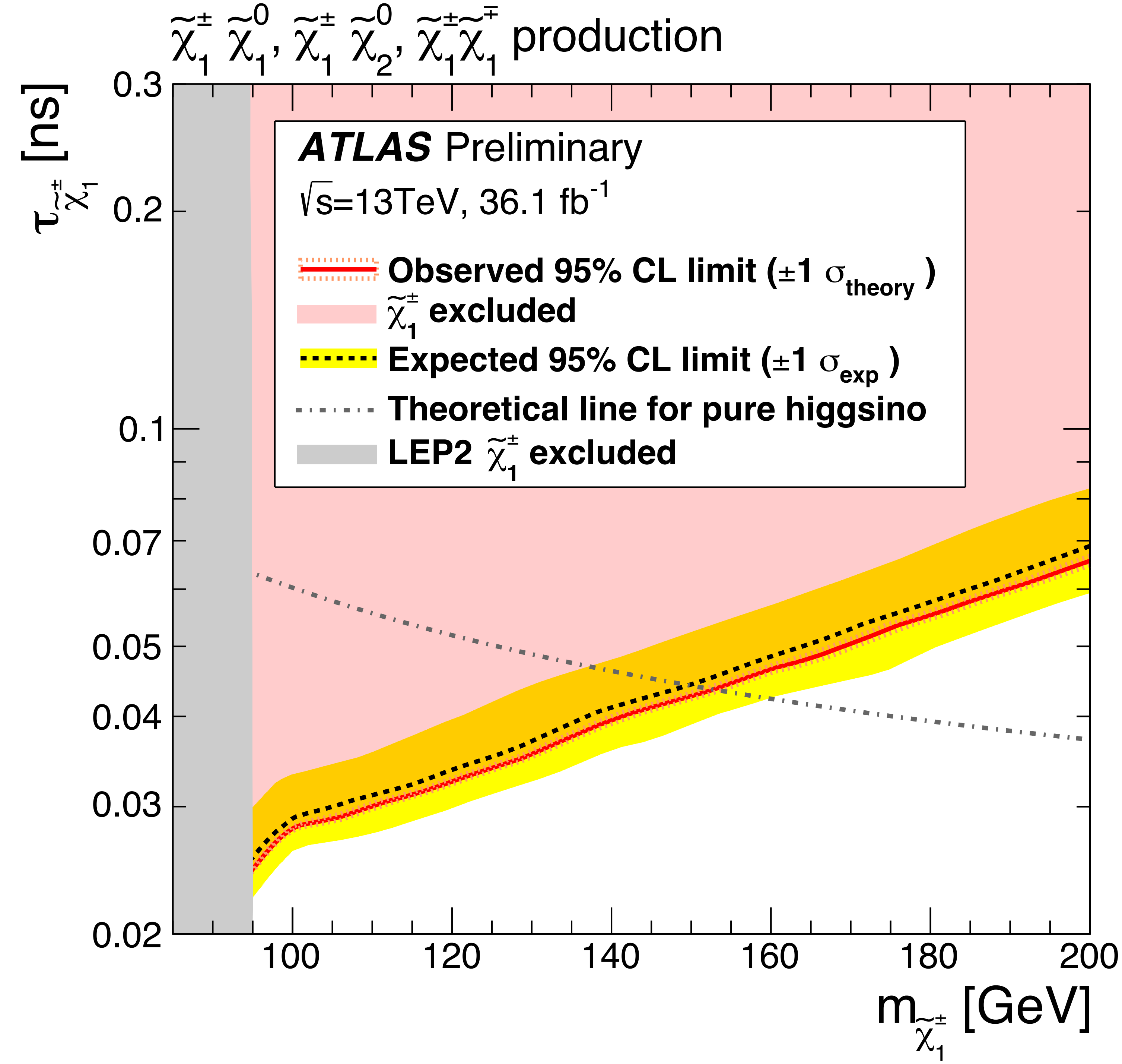




disappearing track uncertainties

Parameter	Electroweak channel [%]	Strong channel [%]
Expected signal events	11	13
α in signal p_{T} resolution function	0.8	1.5
σ in signal p_{T} resolution function	5.3	7.2
$\log r_{\mathrm{ABCD}}$	15	<0.1
α in background p_{T} resolution function	5.0	1.2
σ in background p_{T} resolution function	2.2	5.0
p_0 parameter of the fake-BG p_{T} function	2.5	<0.1
p_1 parameter of the fake-BG p_{T} function	8.5	0.1
Expected number of muon events	0.5	0.9

disappearing track pure higgsino limits



disappearing track yields

Number of observed events		
	9	
Number of expected events		
Hadron+electron background	6.1	$\pm$ 0.6
Muon background	0.15	$\pm$ 0.09
Fake background	5.5	$\pm$ 3.3
Total background	11.8	$\pm$ 3.1
Number of expected signal events for the higgsino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = $ **(160 GeV, 0.05 ns)**		
	10.3	$\pm$ 2.1
Number of expected signal events for the wino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = $ **(400 GeV, 0.2 ns)**		
	13.5	$\pm$ 2.1