Search for chargino-neutralino production using an emulated recursive jigsaw reconstruction technique with the ATLAS detector

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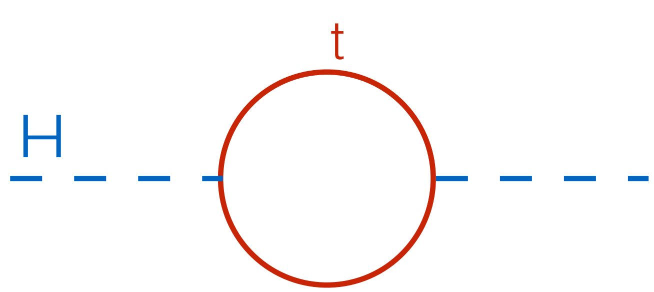
ATLAS
EXPERIMENT

Open questions of the Standard Model

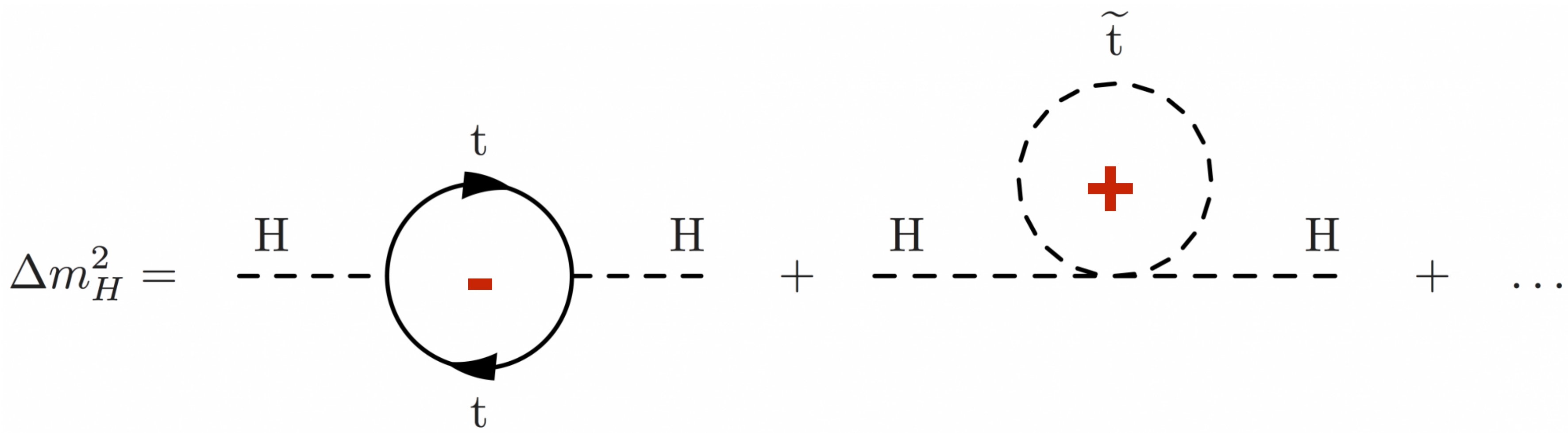
- The Standard Model (SM) has been successful at the LHC
- However there are questions that remain unanswered
  - What is Dark Matter?
  - Why is the Higgs mass so light?
    - Quadratic divergences in the corrections of the Higgs mass



$$\Delta m_H^2 \propto \Lambda_{UV}^2 \sim M_p$$

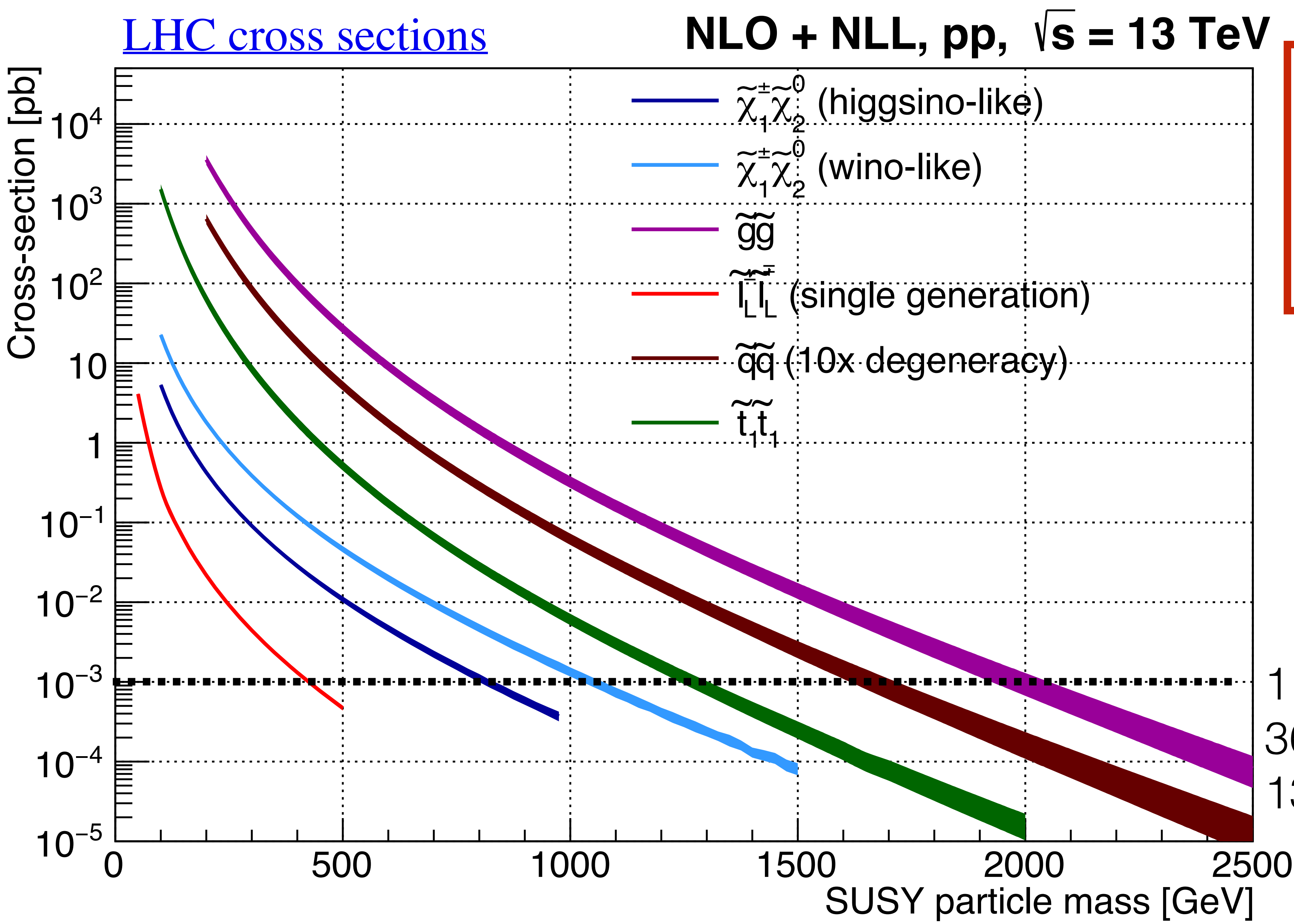
Supersymmetry as a proposed solution

- **Symmetry** between the bosons and the fermions
  - Partner particles to the SM particles with half spin difference
- Fine tuning: opposite sign loop corrections to cancel quadratic divergence



- Dark matter: if R-parity where baryon - lepton numbers (B-L) conserved
  - Lightest SUSY particle (LSP) is **stable** -> candidate for dark matter!

SUSY production cross sections



Strong production

- gluino
- squark
- stop

EWK production

- wino production
- higgsino production
- sleptons

1 event per fb^{-1}

36 events in 2015+16

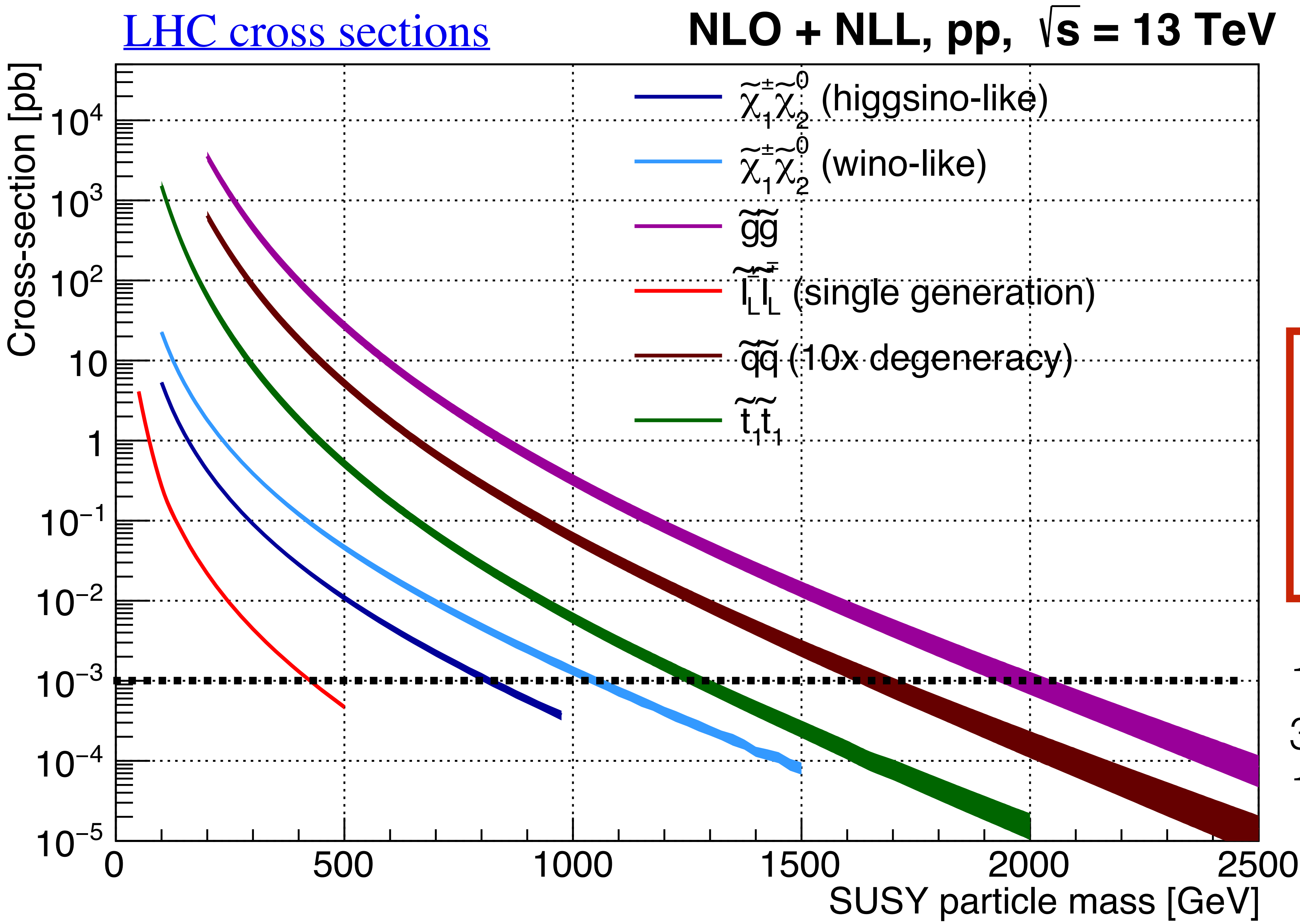
139 events in Run 2 (2015-18)

Squark and gluinos have the largest cross section

But… strong SUSY tightly constrained using simplified models

What's next?

[LHC cross sections](#)



Strong production

- gluino
- squark
- stop

EWK production

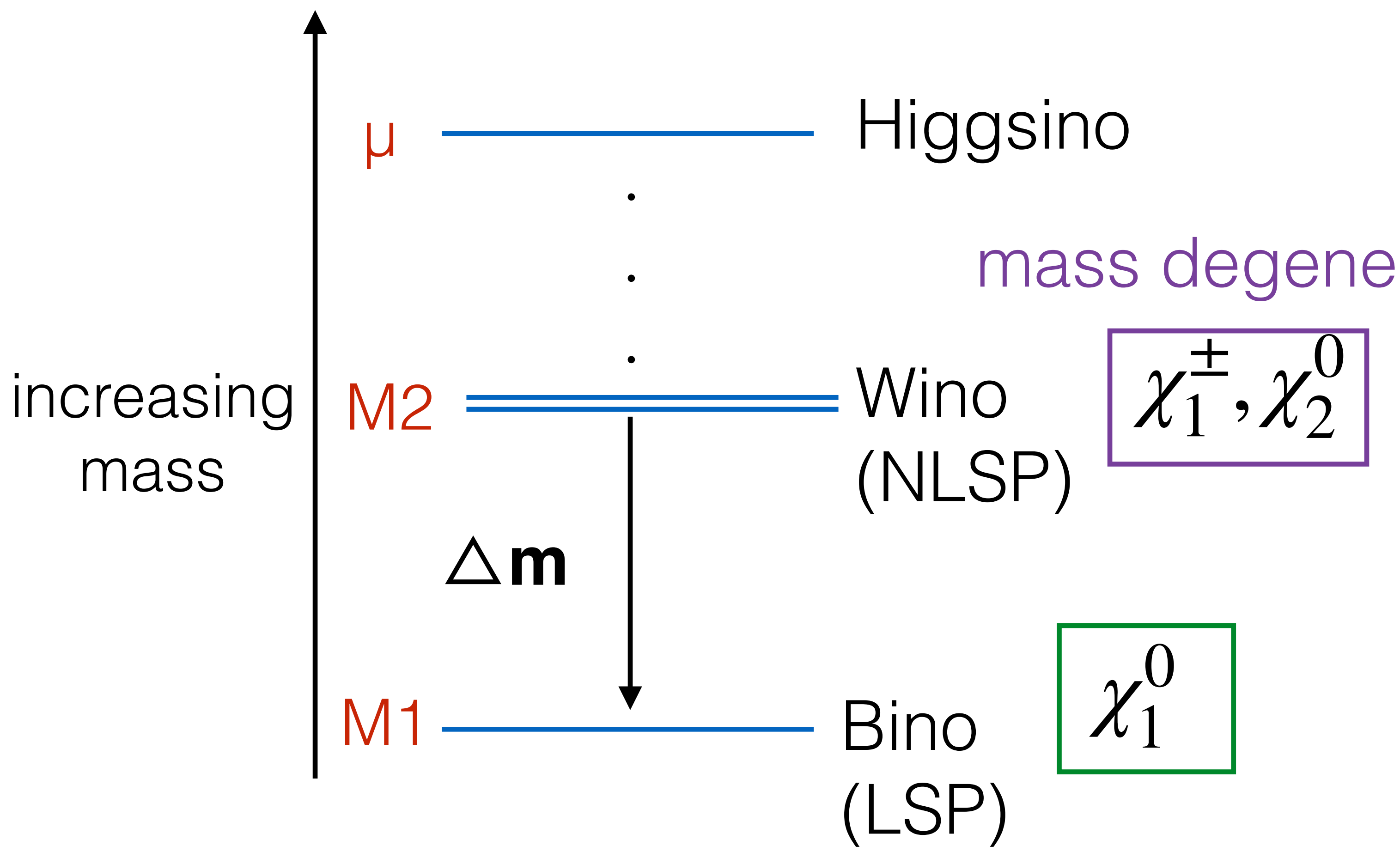
- wino production
- higgsino production
- sleptons

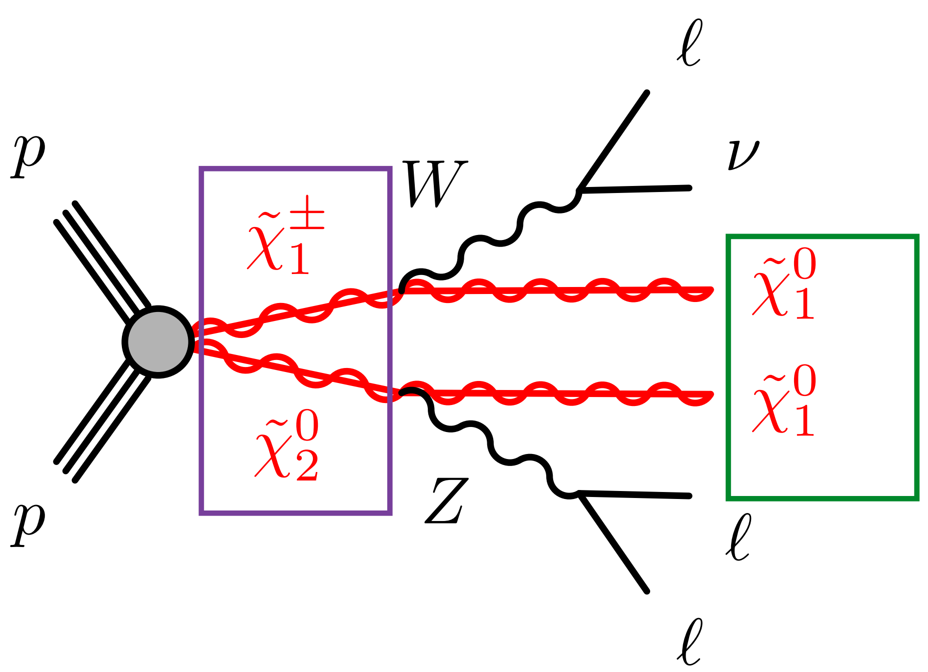
1 event per fb^{-1}
36 events in 2015+16
139 events in Run 2

Electroweak (EWK) production of SUSY next natural place to look!
This can lead to signatures with multiple leptons and missing energy

Model considered: direct Wino production

| M1 | < | M2 | << | μ |

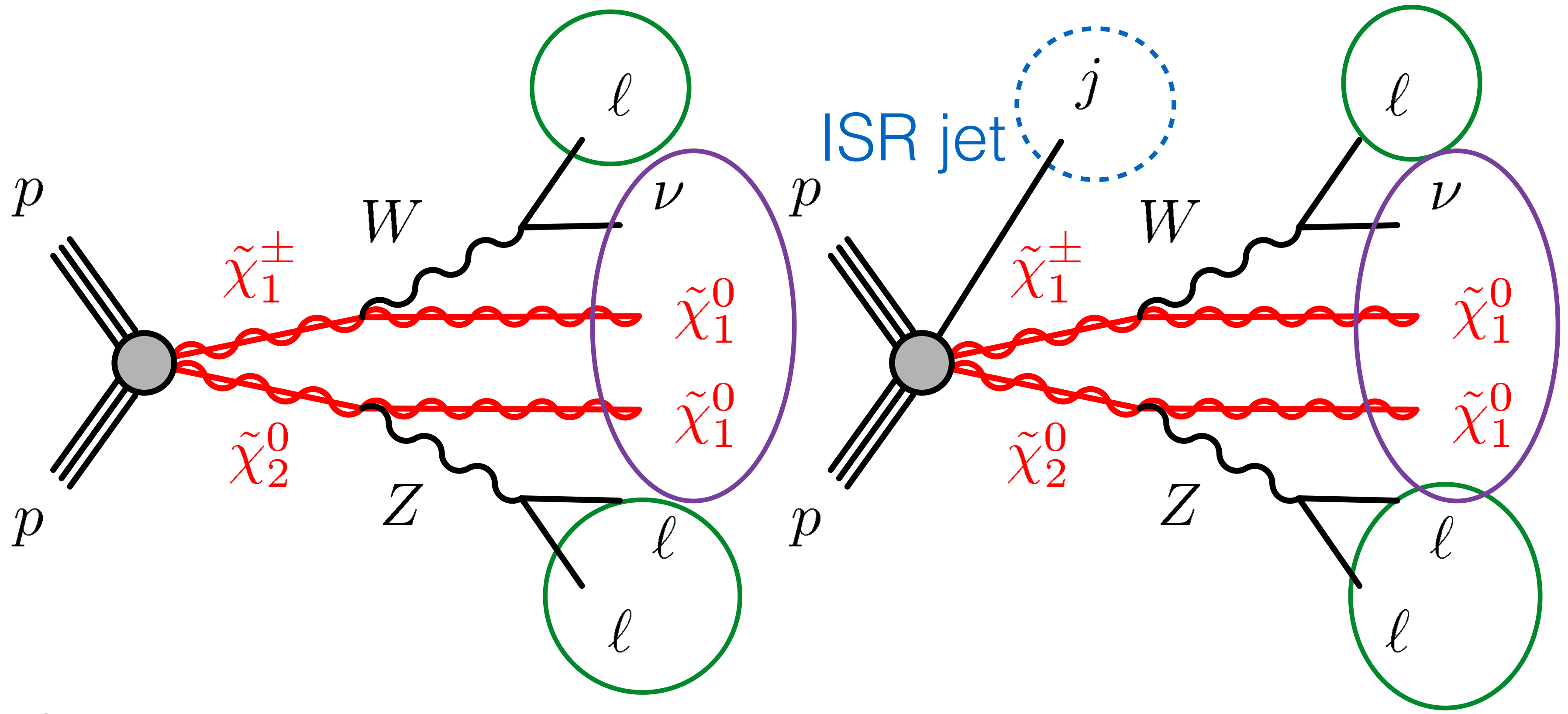




- Larger cross-section than other EWK production
- Can give correct Dark Matter Relic abundance
- Simplified models make the following assumptions:
  - **No mixing** between SUSY mass parameters
  - 100% branching fraction from sparticle to particle

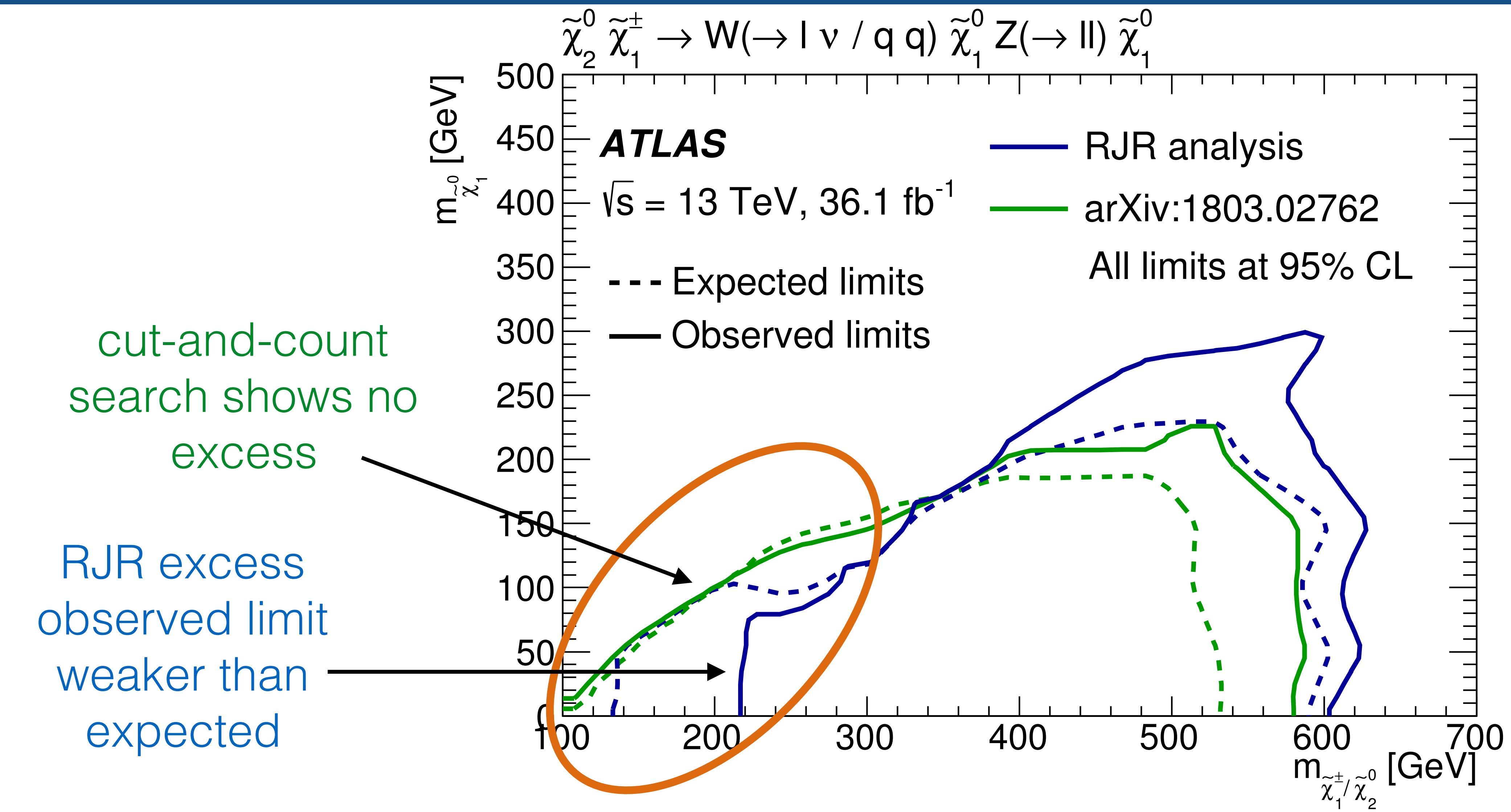
Diagram for search discussed

Production of charginos and neutralinos
decaying via on-shell *W* and *Z* to 3 leptons and missing energy



- Search strategy:
  - 1 same flavor, opposite charge pair of leptons with invariant mass consistent with the Z-mass
  - 2 orthogonal signal regions: jet veto, region with at least one jet (ISR)
- Background estimation:
  - *WZ* (dominant) and top backgrounds estimated with a control region
  - *Z*+jets and *Z*+γ where jet/γ fake a lepton estimated using a data-driven method

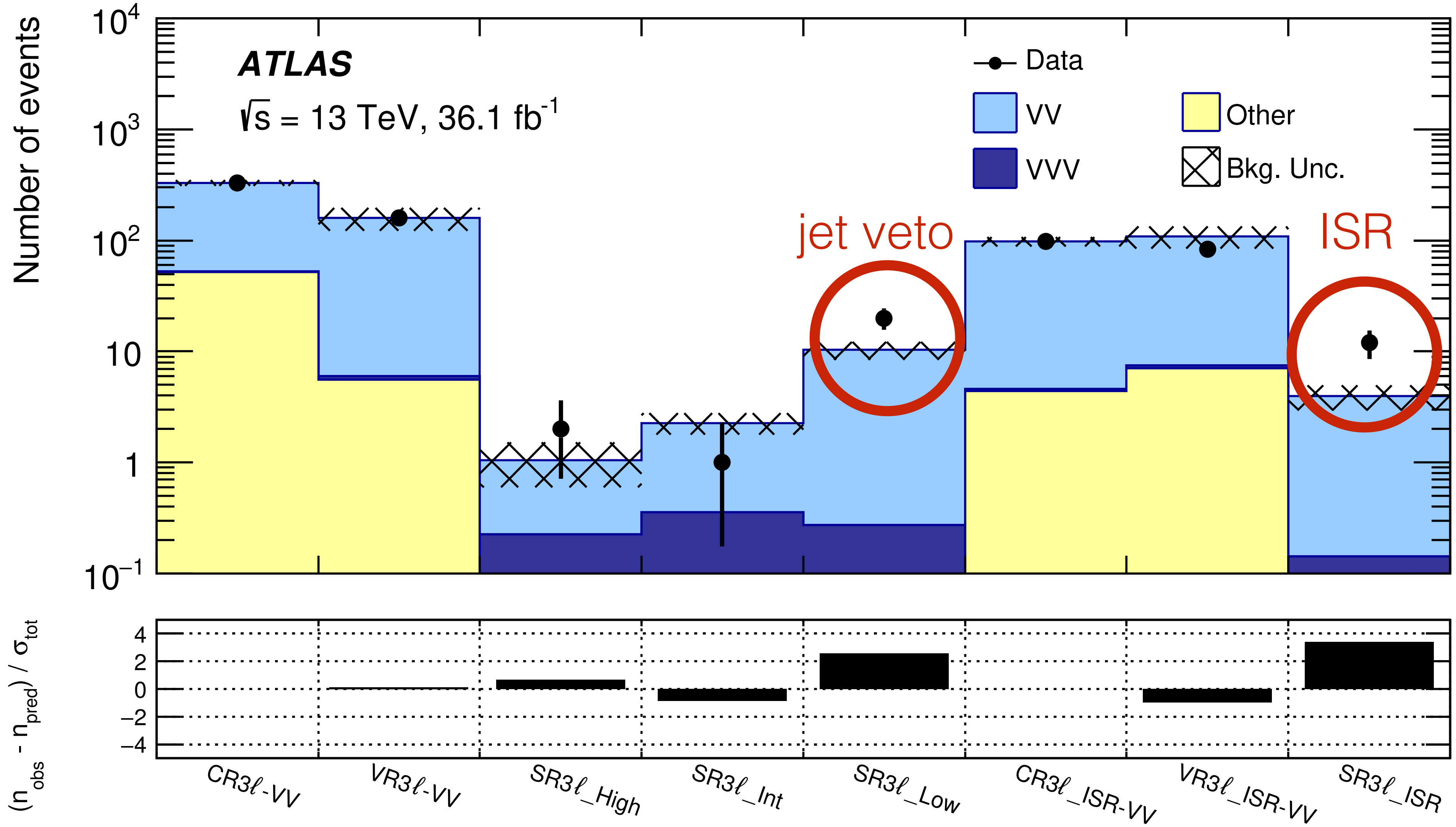
Motivation



arXiv:1806.02293

- Two independent efforts pursued with 2015+2016 data
  - cut-and-count and Recursive Jigsaw (RJR)
- RJR saw excesses in two orthogonal bins targeting models with $\Delta m \sim m(Z)$
  - cut-and-count analysis did not see these excesses

Motivation for search



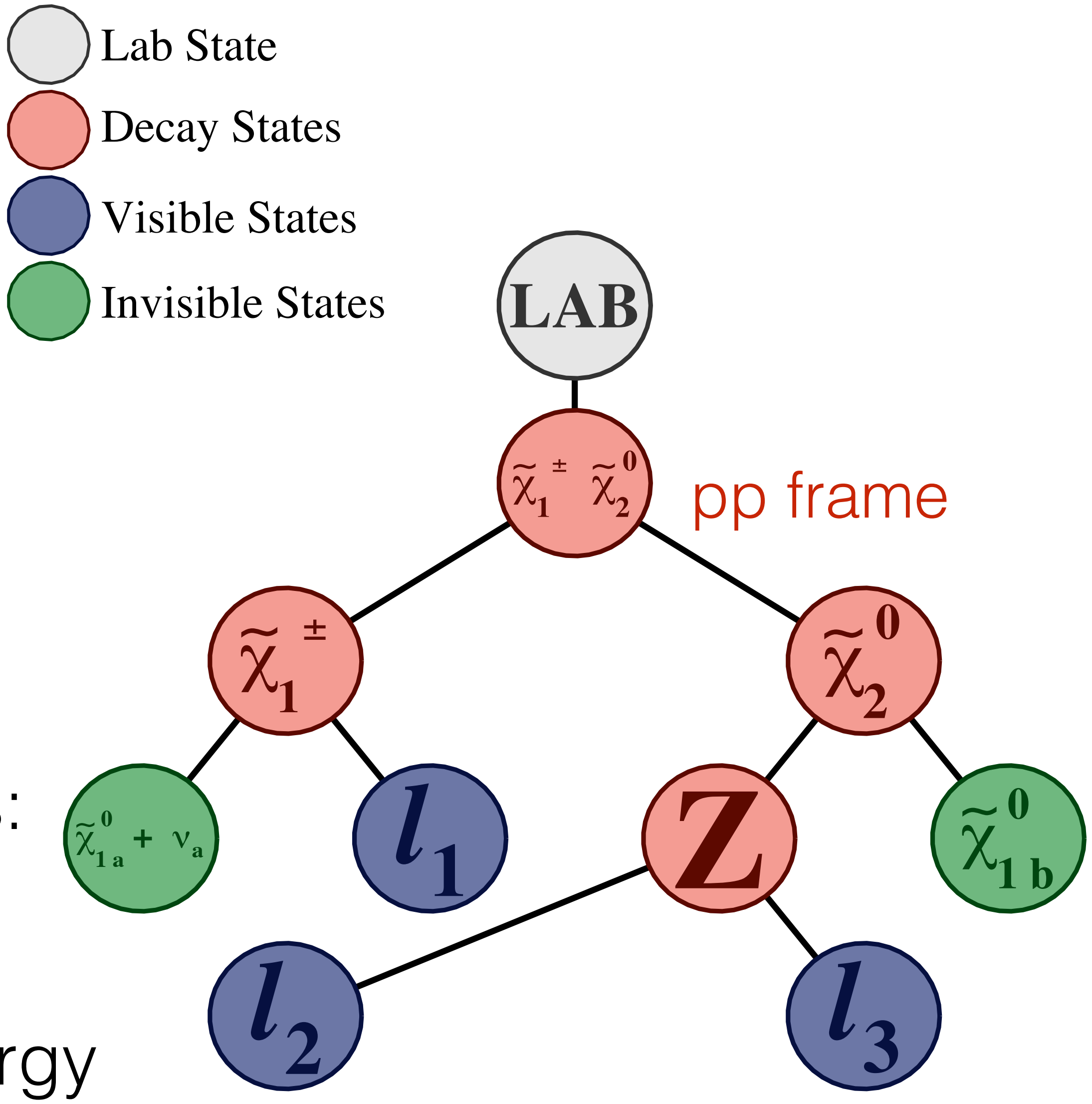
[arXiv:1806.02293](https://arxiv.org/abs/1806.02293)

Significance
- jet veto region: 2.1
- ISR region: 3.0

- Excess in two orthogonal bins in search using: jet veto and ISR
- Developed new analysis technique: emulated RJR (eRJR)
  - Explore the intersection between the conventional and RJR analyses
  - Reproduce the RJR technique using simplified, lab frame variables
- Expand the analysis to include the full Run 2 dataset (139 fb^{-1})

Overview of RJR technique

- RJR technique separates event into a tree
- Two types of objects are present:
  - Visible: 3 leptons
  - Invisible: 2 neutralinos and 1 neutrino



- Use iterative mass minimization
  - Assign objects to each frame
  - Unknowns associated with invisible objects:
    - Mass of the invisible particles
    - Longitudinal momenta
    - How they contribute to total missing energy
- Boost back to each frame

- Calculate kinematic variables in each frame

arXiv:1705.10733
arXiv:1806.02293

Overview of eRJR technique

- Translate RJR variables into lab frame variables with minimal assumptions
- Difference in assumptions:
  - In eRJR, mass of the invisible system is 0, no splitting of the invisible system
  - In eRJR, all signal jets are part of the ISR system while in RJR, ISR jets selected to boost against the leptons and missing energy frame
- For example

$$p_T^I \leftrightarrow E_T^{miss}$$

$$\frac{p_T^{PP}}{p_T^{PP} + HT_{3,1}^{PP}} \leftrightarrow \frac{p_T^{\text{soft}}}{p_T^{\text{soft}} + m_{\text{eff}}^{3\ell}}$$

p_T^I = transverse momentum of the invisible particles

p_T^{PP} = vector sum of transverse momenta of all objects in sparticle-sparticle frame (PP)

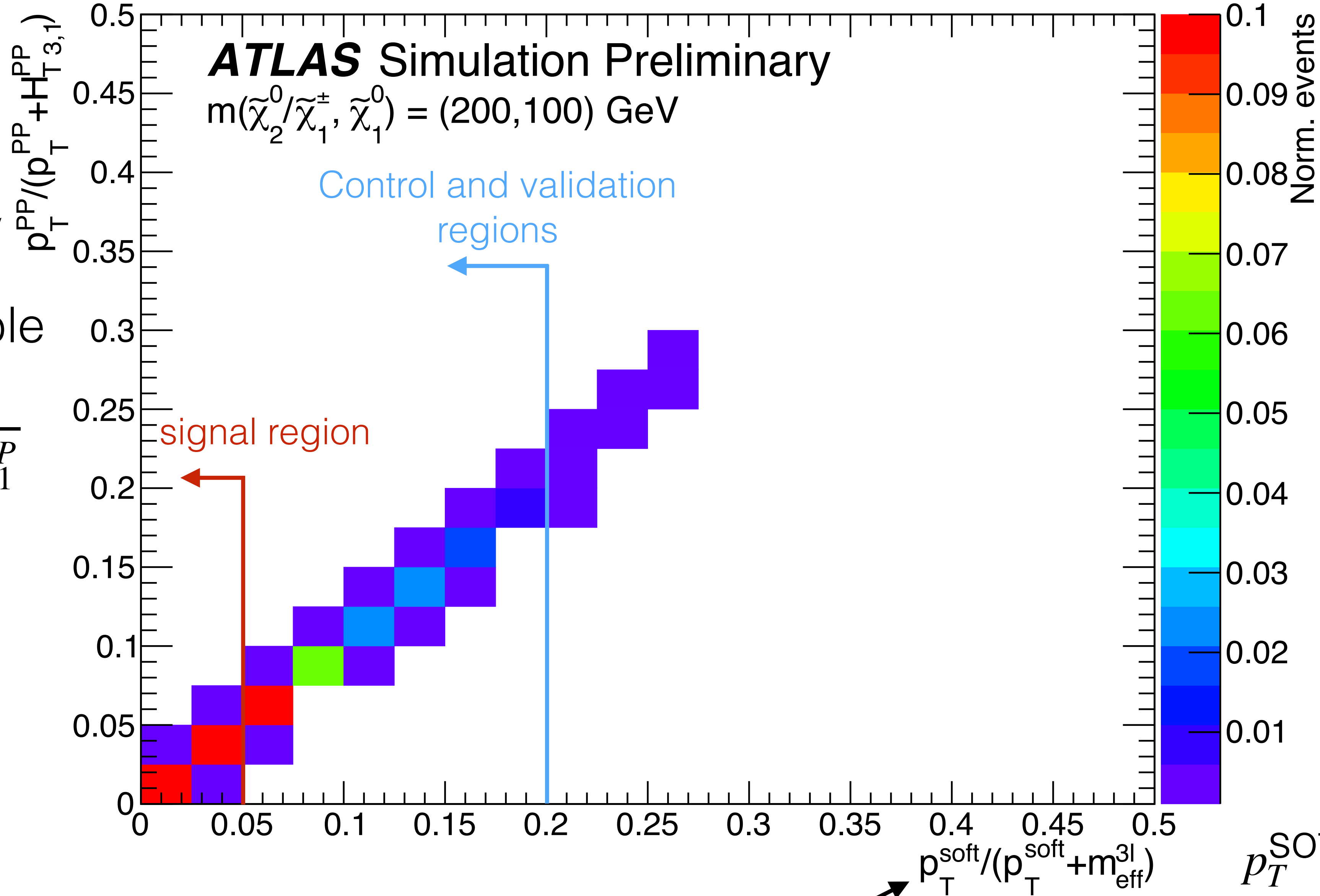
$$HT_{n,m}^F = \sum_{i=1}^{n} |\vec{p}^{\,F}_{T\,\text{vis},i}| + \sum_{j=1}^{m} |\vec{p}^{\,F}_{T\,\text{inv},j}|$$

$p_T^{soft}, m_{eff}^{3\ell}$ = respectively vectorial and scalar sum of transverse momenta of the 3 leptons and missing energy

Correlating RJR and eRJR

RJR variable

$$\frac{p_T^{PP}}{p_T^{PP} + H_{3,1}^{PP}}$$



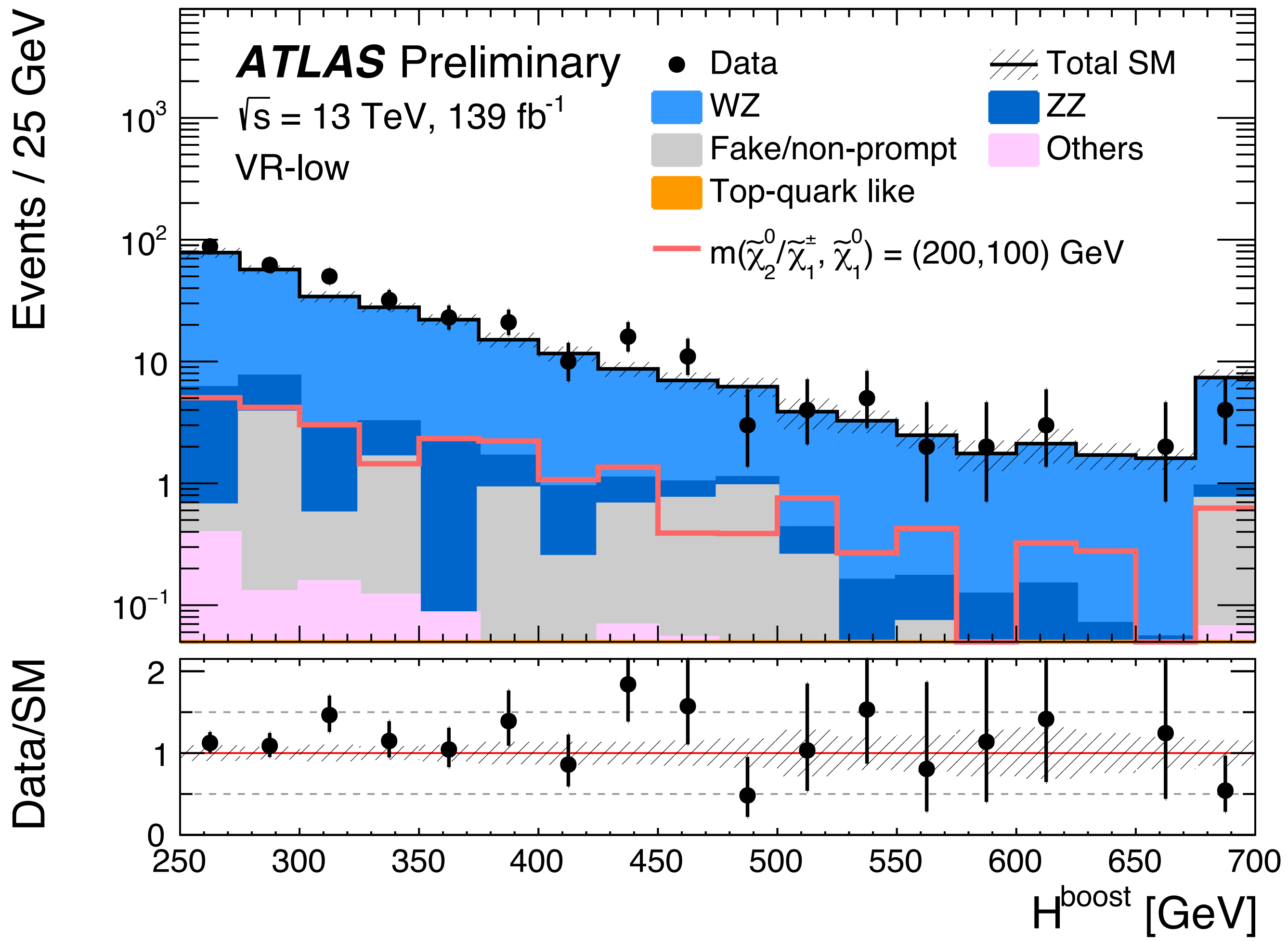
eRJR variable

$$\frac{p_T^{\rm soft}}{p_T^{\rm soft} + m_{\rm eff}^{3\ell}}$$

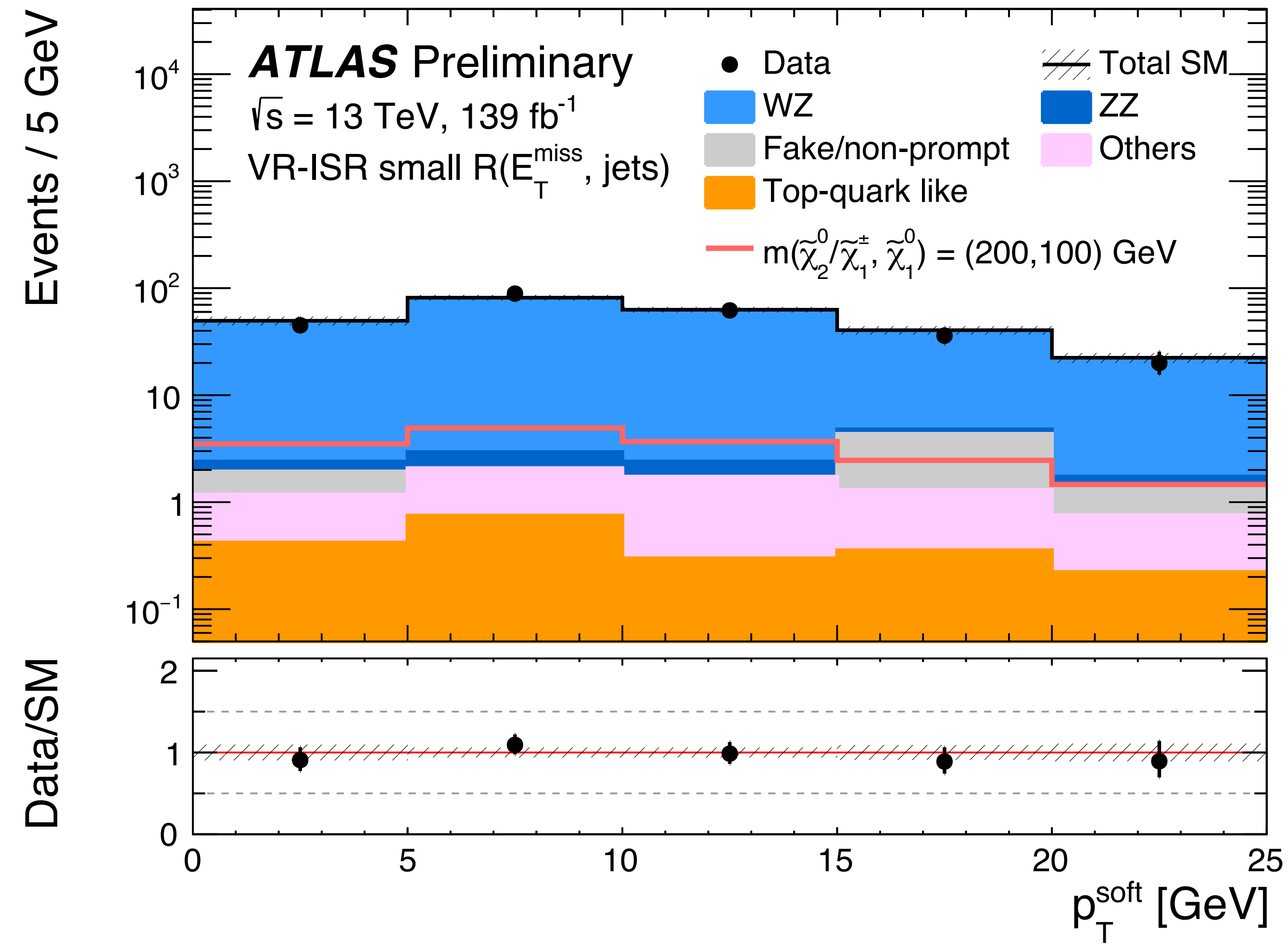
- Distributions are event-by-event comparison of RJR and eRJR variables
- Good correlation between RJR and eRJR mimic variables
- eRJR replicates well the RJR analysis with minimal assumptions!

Background modeling for eRJR search

VR low



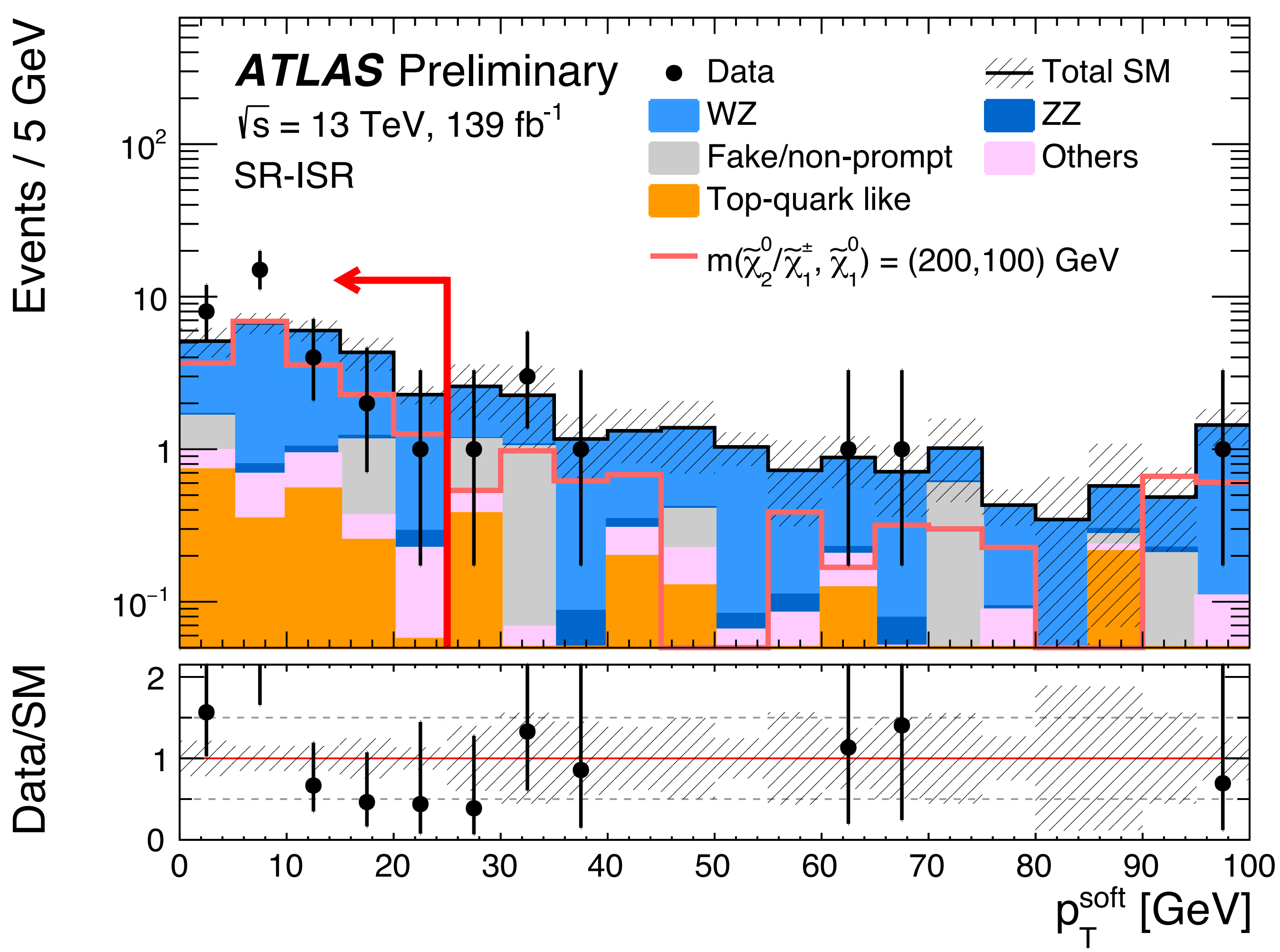
VR-small R(MET, jets)

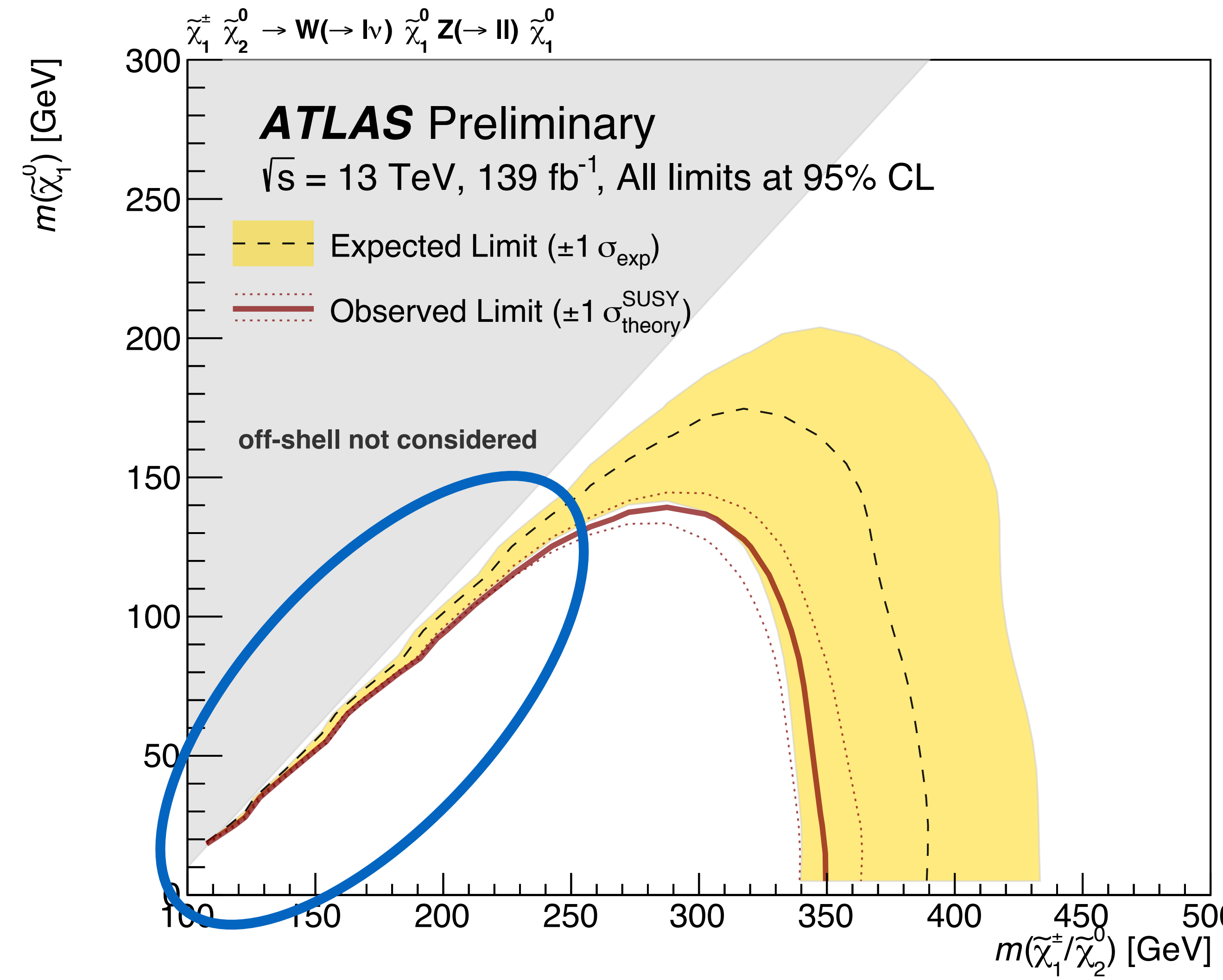


Good background modeling!

Result

Signal channel	N_{obs}	N_{exp}	σ_{vis}[fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$ (Z)
SR-low	51	46 ± 5	0.16	22.0	$20.7^{+6.2}_{-4.3}$	0.27 (0.60)
SR-ISR	30	23.0 ± 2.2	0.13	18.0	$12.1^{+5.3}_{-2.0}$	0.10 (1.27)





- No longer have significant excess!

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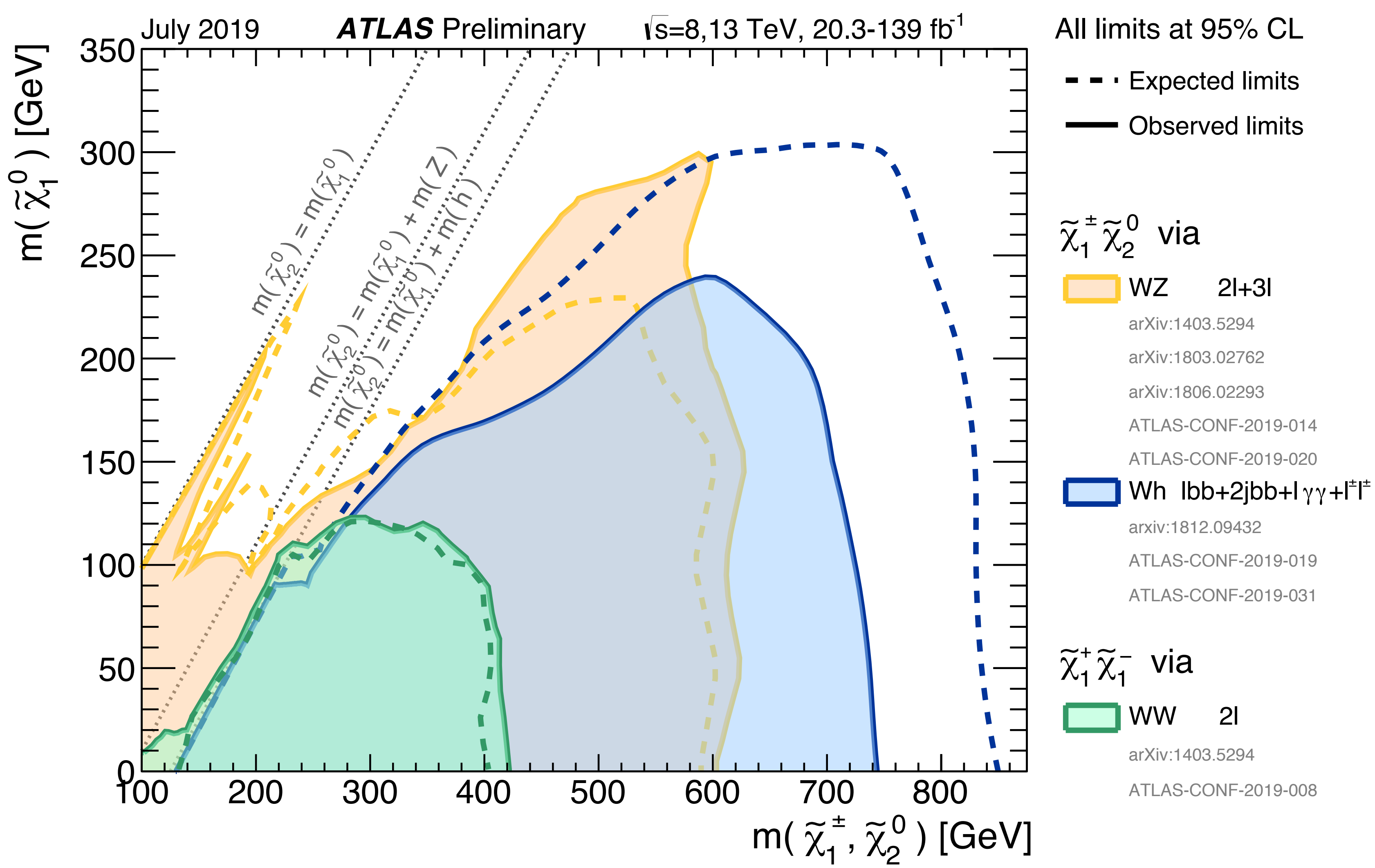
Conclusion

- EWK SUSY is well-motivated and interesting as LHC collects more data
- Developed new technique to study RJR phase space: eRJR
    - No significant excess observed with full Run 2 dataset
    - We are currently working on the publication for this work
- Plenty of phase space left to cover, maybe SUSY could be hiding there!



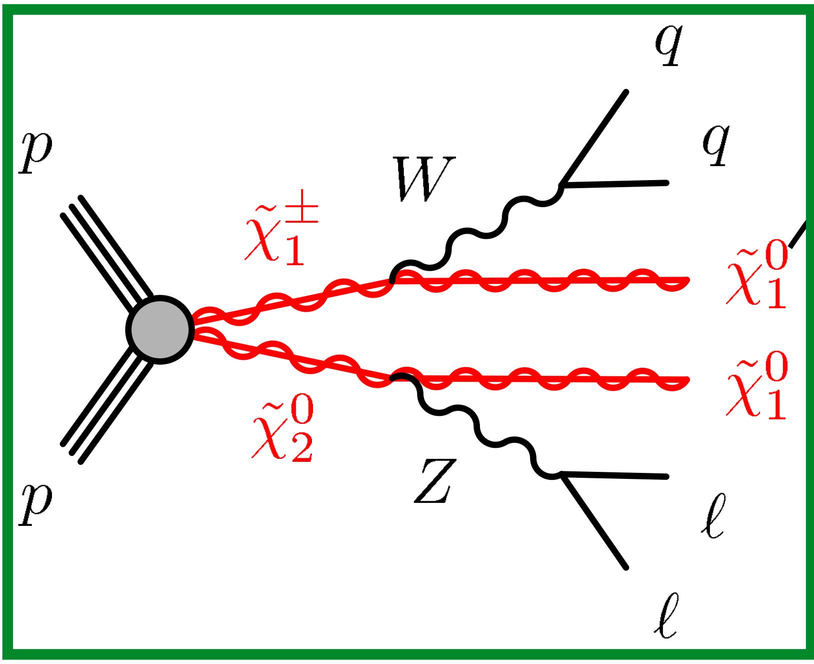
SUSY summary plots

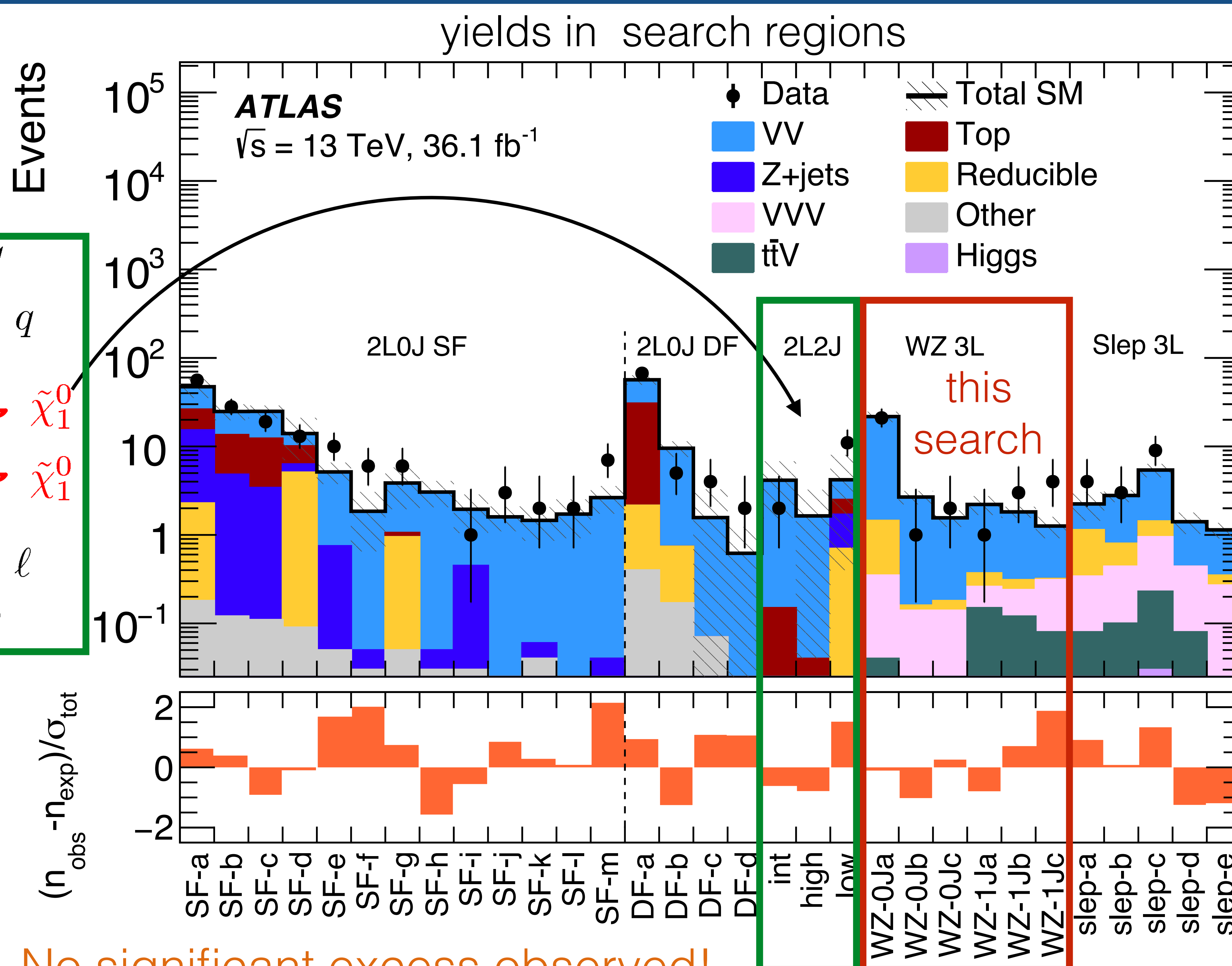
Thank you for your attention. Any questions?

Hello,
is it me you're looking for?

BACKUP

Results

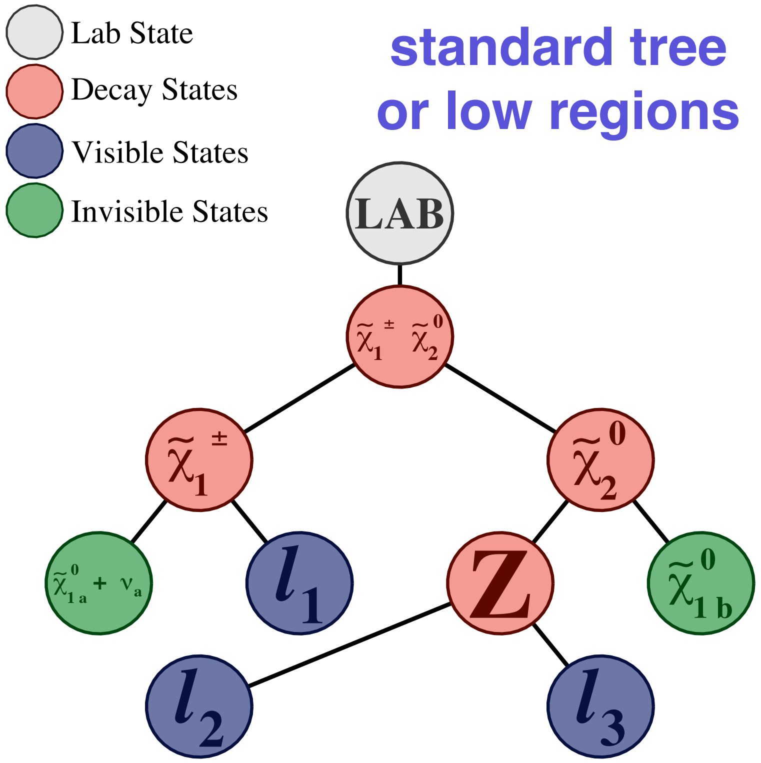




No significant excess observed!

Can set limit on the masses of SUSY particles

Translation of standard tree variables



standard tree or low regions

Variables calculated in lab frame:

- p_T^{soft} = (lep1 + lep2 +lep3 + MET).Pt()
- m_{eff}^{3l} = lep1.Pt() + lep2.Pt() + lep3.Pt() + MET.Pt()

Variable calculated in PP frame

- H^{boost} = lep1.P() + lep2.P() + lep3.P() + MET.P()
  - Includes full momentum of MET
  - Calculate Z-component of MET, assuming mass of invisible is 0
    - RJ mass estimation: $M_I^2 = M_V^2 - 4M_{Va}^2 M_{Vb}^2$
  - Boost to PP frame

Note: *m_{eff}^{3l} and H^{boost} are calculated in different frames*

Calculating z-component of MET and boost

- In order to emulate some RJ variables, need to boost to PP frame
- But first, need to determine z-component of MET
- Determining pZ of the invisible system described: arXiv:1705.10733

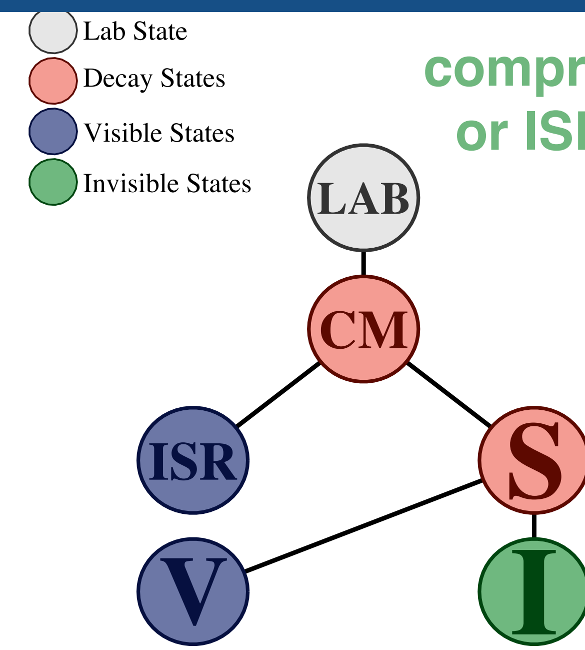
$$p_{I,||} = p_{V,||} \frac{\sqrt{(p_{I,\perp})^2 + m_I^2}}{\sqrt{(p_{V,\perp})^2 + m_V^2}}, p_{V,||} = (\ell_1 + \ell_2 + \ell_3).Pz(), assume : m_I = 0$$

- Boost is given by:

$$\vec{\beta}_{PP}^{\,lab} = \frac{\vec{p}_{PP}^{\,lab}}{E_{PP}^{\,lab}} = \frac{\vec{p}_V^{\,lab} + \vec{p}_I^{\,lab}}{E_V^{\,lab} + \sqrt{|\vec{p}_I^{\,lab}|^2 + M_I^2}}, assume : M_I = 0$$

Translation of compressed tree variables

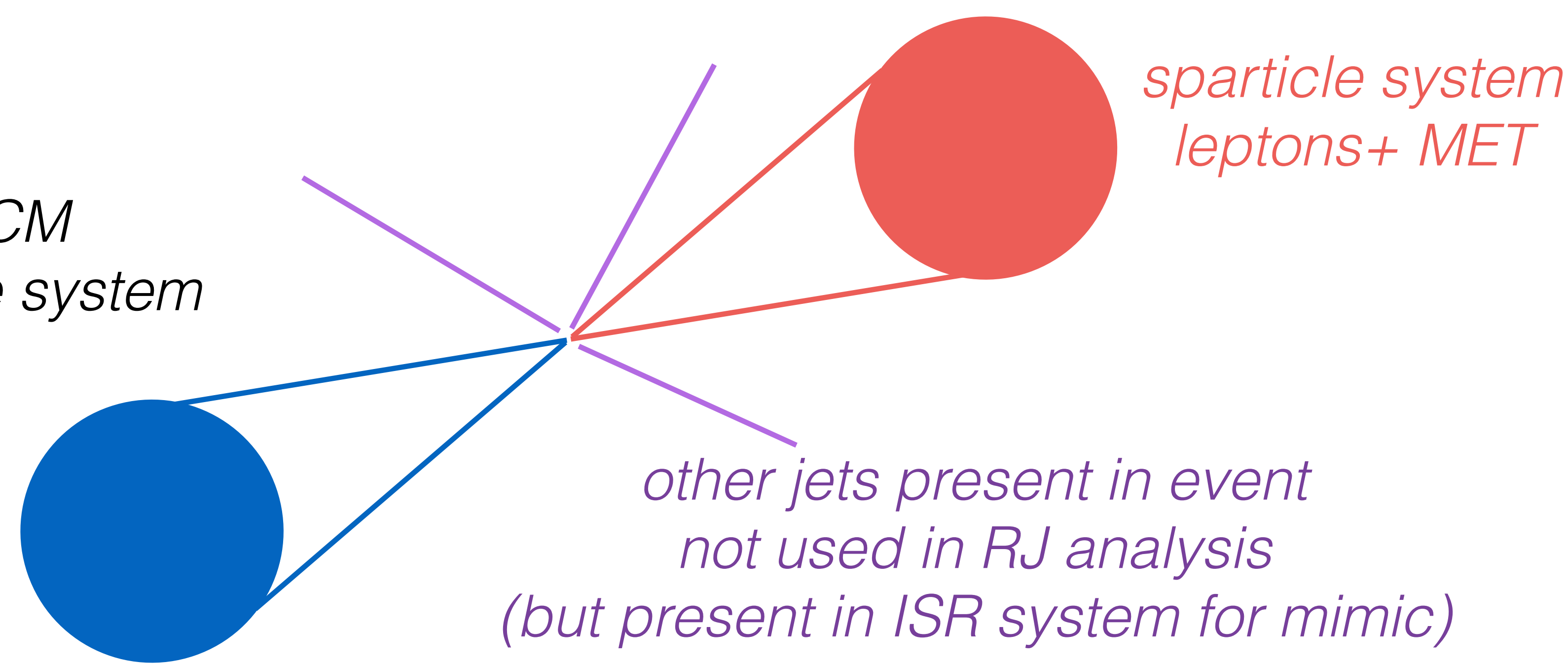
All these variables are calculated in the lab frame
- ISR = vector sum of jets
- p_T^{soft} = (lep1 + lep2 +lep3+ ISR + MET).Pt()
- p_T^{jet} = ISR.Pt()
- R(MET, jet) = $\frac{MET \cdot \overrightarrow{ISR}}{(p_T^{ISR})^2}$



compressed tree or ISR regions

Another difference between RJ and RJ mimic is selection of jets
- RJ mimic considers ISR to be all signal jets
- RJ selects jets in ISR frame, discounts others

Select jets to minimize mass in CM
jets chosen to recoil against sparticle system



SR/CR/VR definitions

Selection Criteria

Low-mass Region	$p_T^{\ell_1}$ [GeV]	$p_T^{\ell_2}$ [GeV]	$p_T^{\ell_3}$ [GeV]	m_{T} [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	H^{boost} [GeV]	$\frac{m_{\mathrm{eff}}^{3\ell}}{H^{\mathrm{boost}}}$	$\frac{p_{\mathrm{T}}^{\mathrm{soft}}}{p_{\mathrm{T}}^{\mathrm{soft}}+m_{\mathrm{eff}}^{3\ell}}$
CR-low	> 60	> 40	> 30	$\in (0, 70)$	> 40	> 250	> 0.75	< 0.2
VR-low	> 60	> 40	> 30	$\in (70, 100)$	-	> 250	> 0.75	< 0.2
SR-low	> 60	> 40	> 30	> 100	-	> 250	> 0.9	< 0.05

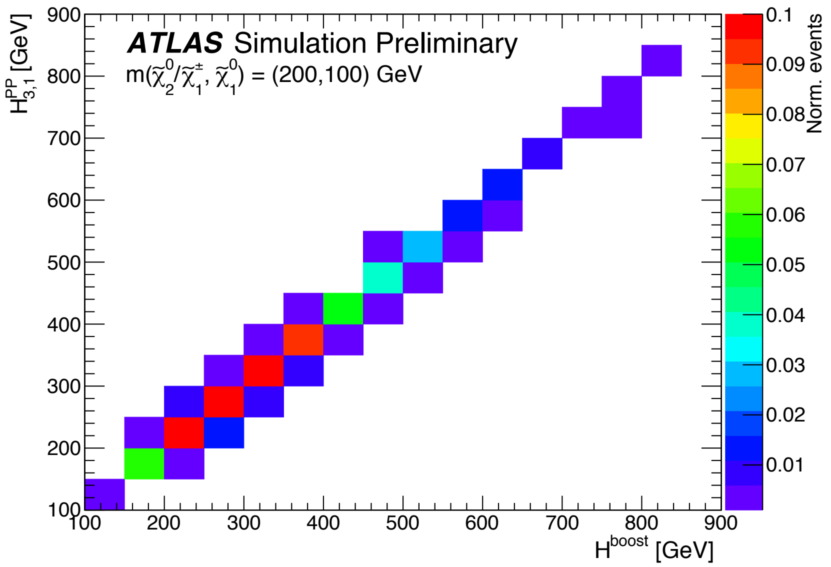
ISR Region	$p_T^{\ell_1}$ [GeV]	$p_T^{\ell_2}$ [GeV]	$p_T^{\ell_3}$ [GeV]	m_{T} [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\lvert\Delta\phi\left(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)\rvert$	$R\left(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)$	$p_{\mathrm{T}}^{\mathrm{jets}}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{soft}}$ [GeV]
CR-ISR	> 25	> 25	> 20	< 100	> 60	> 2.0	$\in (0.55, 1.0)$	> 80	< 25
VR-ISR	> 25	> 25	> 20	> 60	> 60	> 2.0	$\in (0.55, 1.0)$	> 80	> 25
VR-ISR-small $p_{\mathrm{T}}^{\mathrm{soft}}$	> 25	> 25	> 20	> 60	> 60	> 2.0	$\in (0.55, 1.0)$	< 80	< 25
VR-ISR-small $R\left(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)$	> 25	> 25	> 20	> 60	> 60	> 2.0	$\in (0.30, 0.55)$	> 80	< 25
SR-ISR	> 25	> 25	> 20	> 100	> 80	> 2.0	$\in (0.55, 1.0)$	> 100	< 25

- Region definitions kept as close as RJR published result

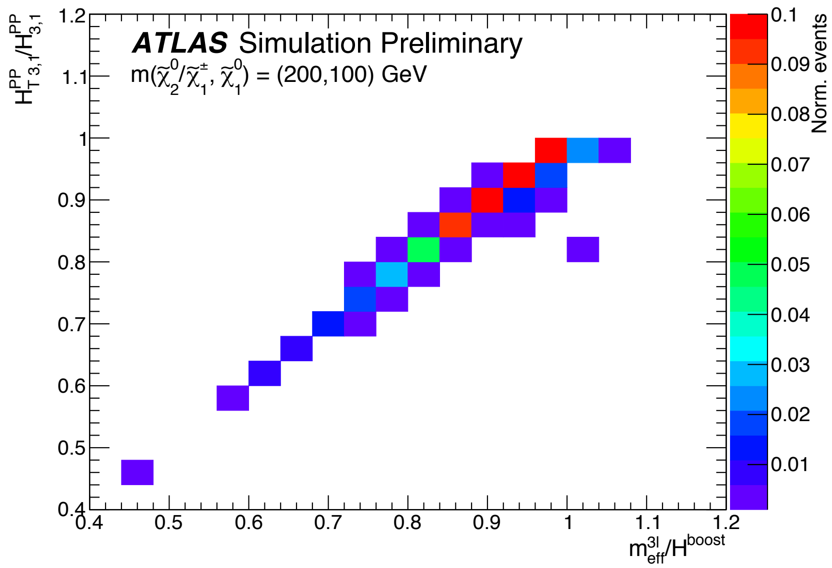
Correlating RJR and eRJR using WZ

low

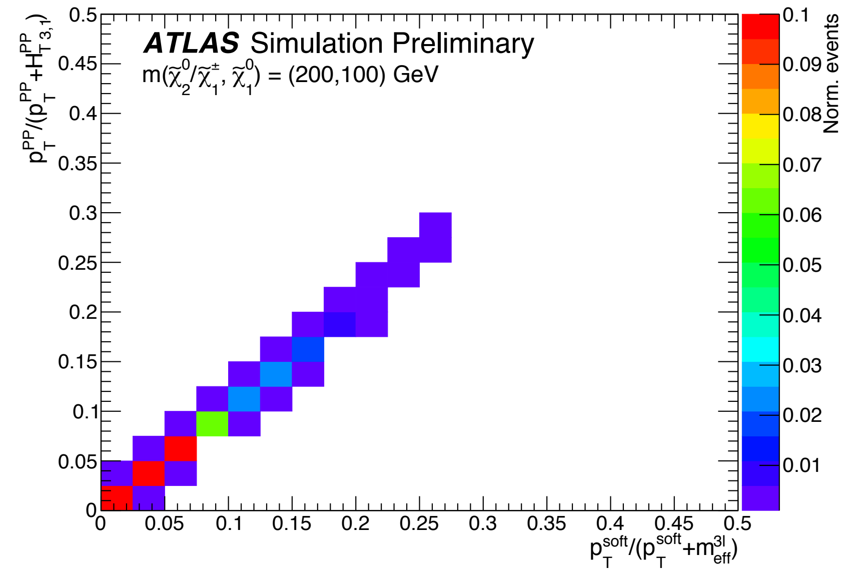
H^{boost}



m_{3l}^{eff}/H^{boost}

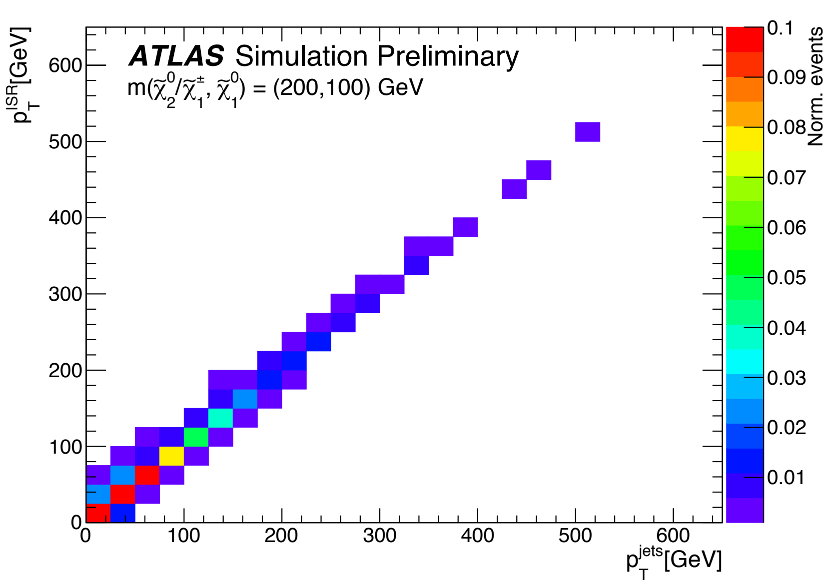


$p_T^{soft}/(p_T^{soft}+m_{3l}^{eff})$

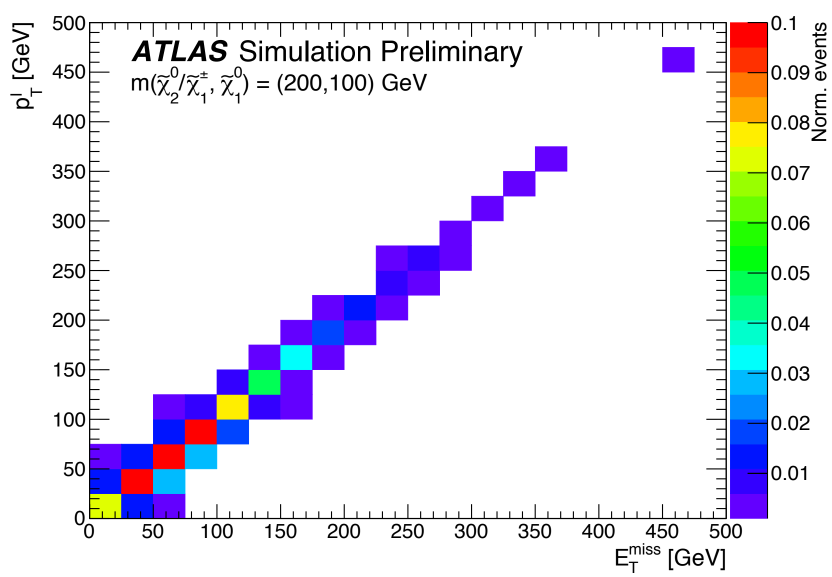


ISR

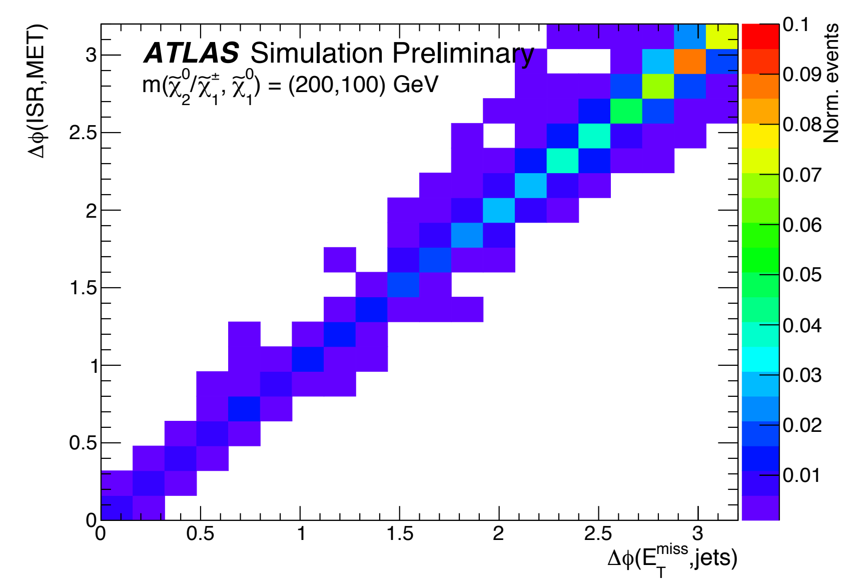
p_T^{jets}



MET



$|\Delta\phi(\text{MET, jets})|$



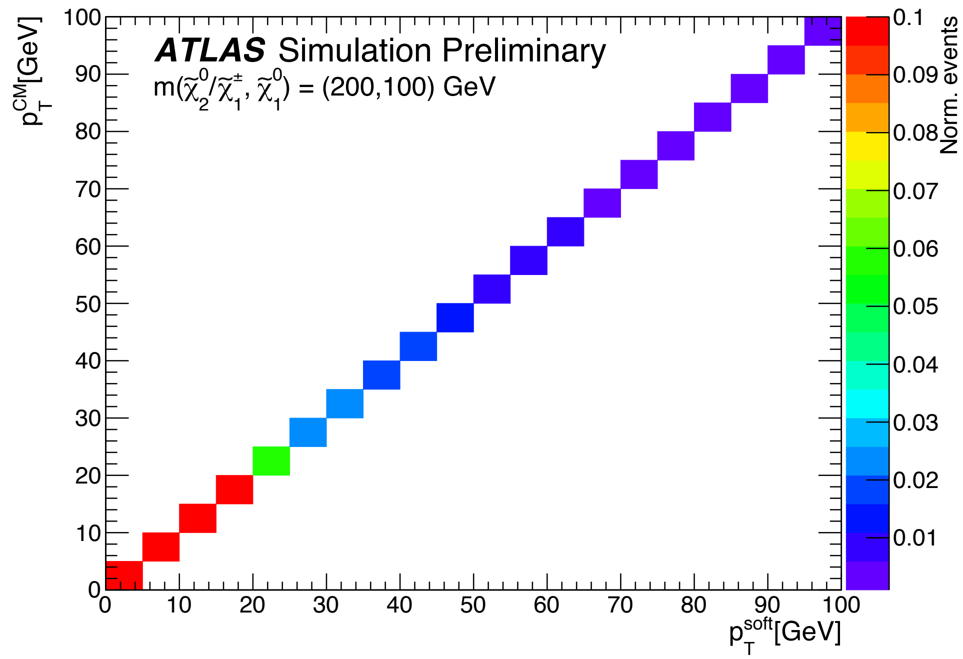
Good correlation between RJR (y-axis) and eRJR(x-axis) variables for signal

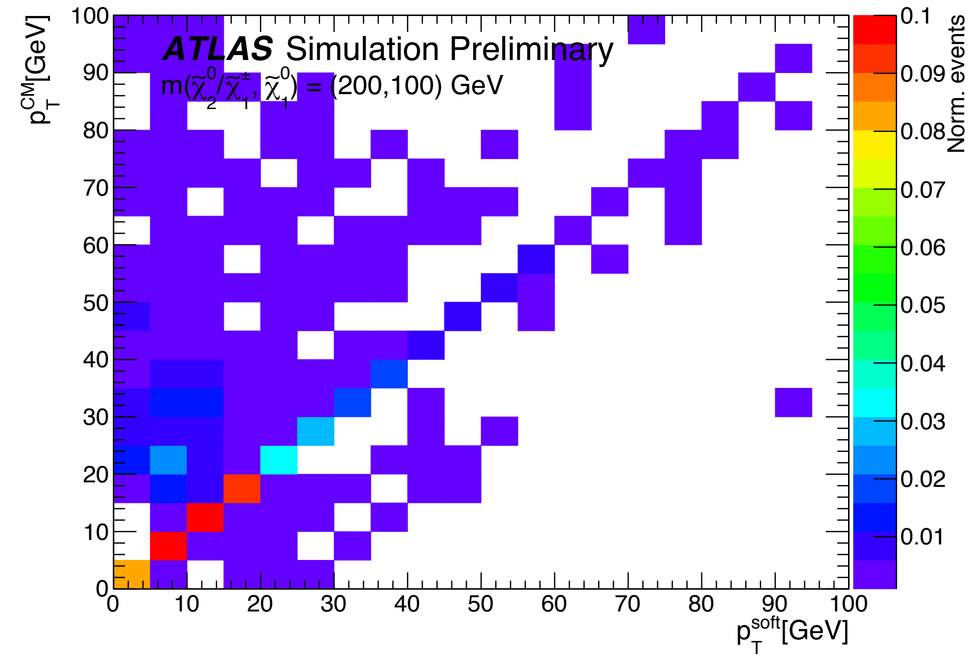
Correlating RJR and eRJR using *WZ*

Njets =1

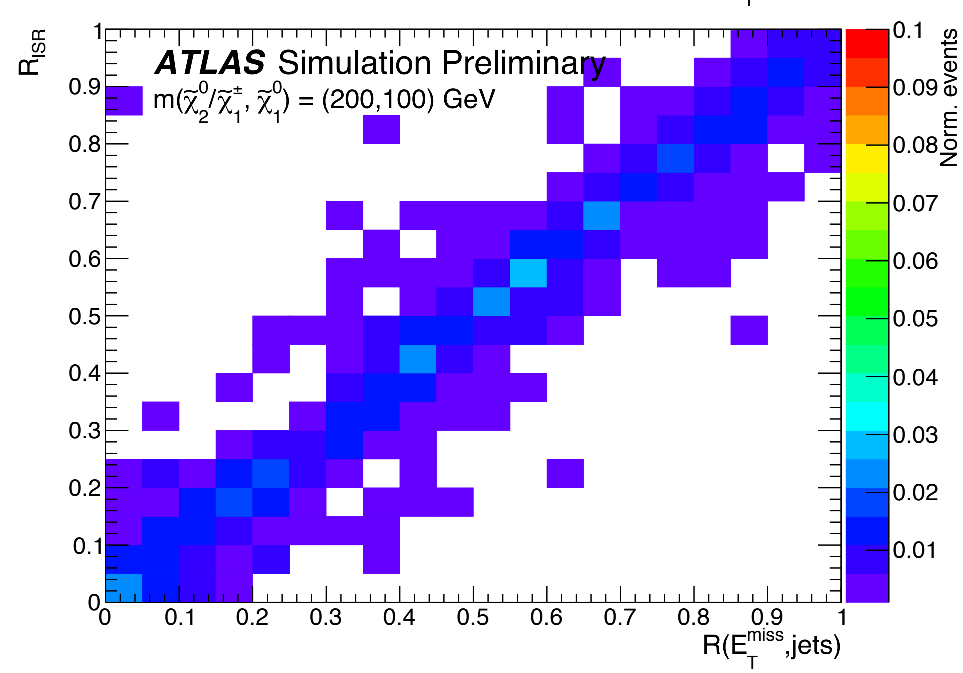
Njets >1

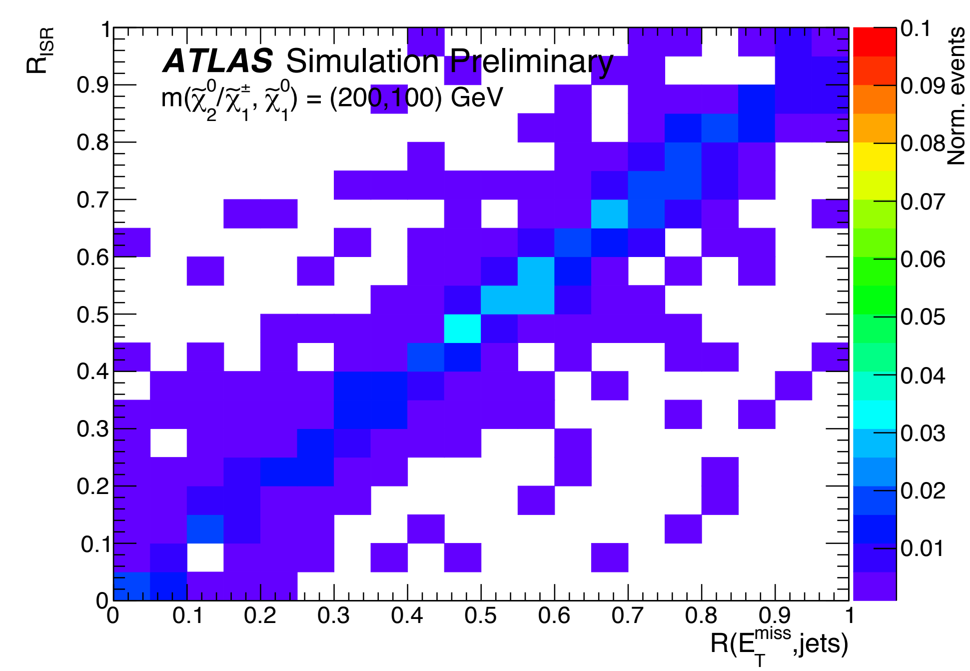
p_T^{soft}





R(MET, jets)





- Emulation of p_T^{soft} not as correlated due to difference in ISR jet selection

CR and VR yields

low-mass regions

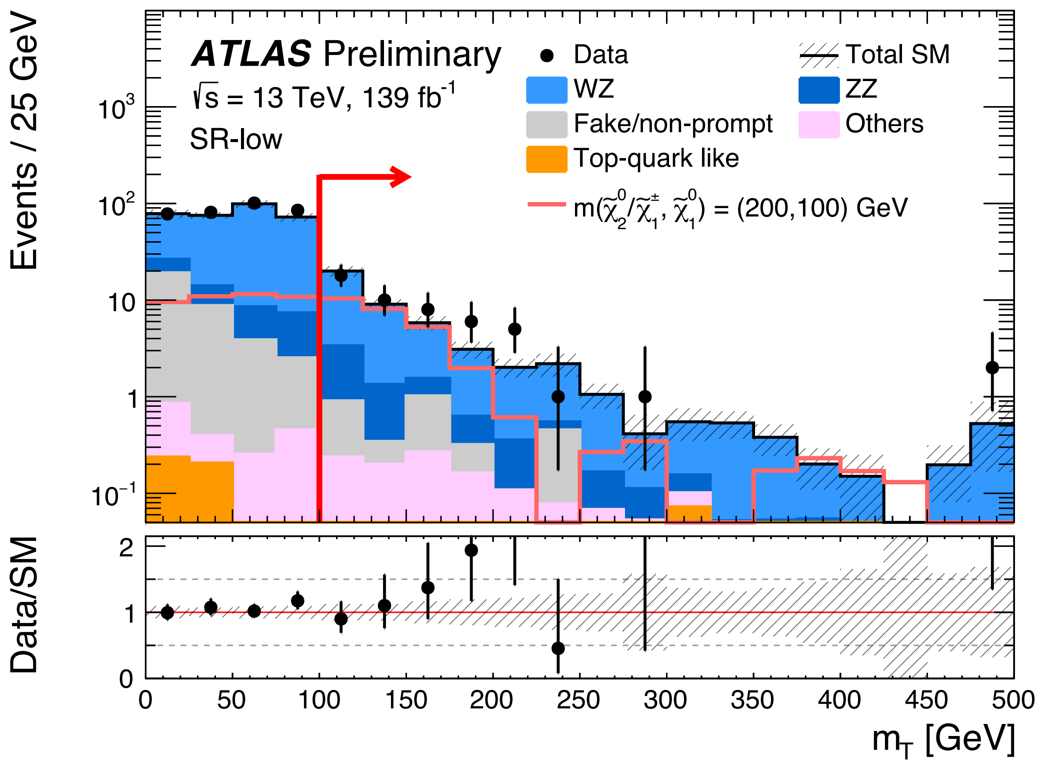
	CR-low	VR-low
Observed events	412	338
Fitted SM events	412 ± 20	291 ± 19
WZ	343 ± 27	262 ± 21
ZZ	19.2 ± 1.7	18.2 ± 1.6
Others	3.1 ± 1.9	1.3 ± 0.9
Top-quark like	0.5 ± 0.4	$0.02^{+0.25}_{-0.02}$
Fake/non-prompt leptons	46 ± 17	9 ± 5

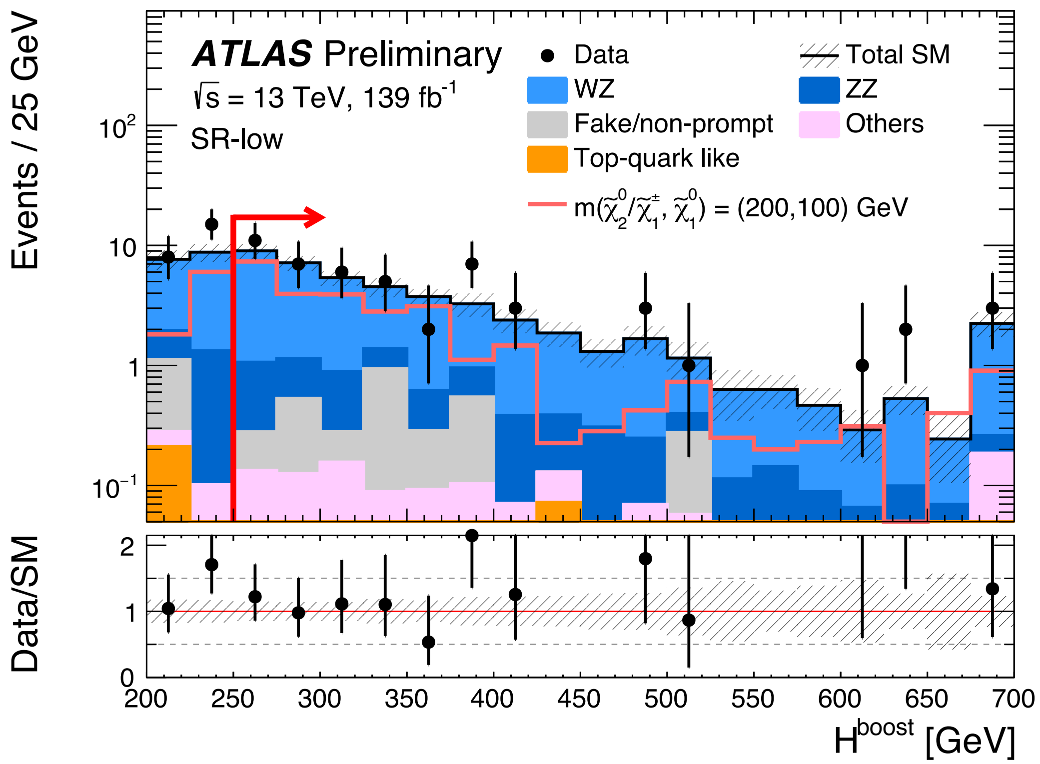
ISR regions

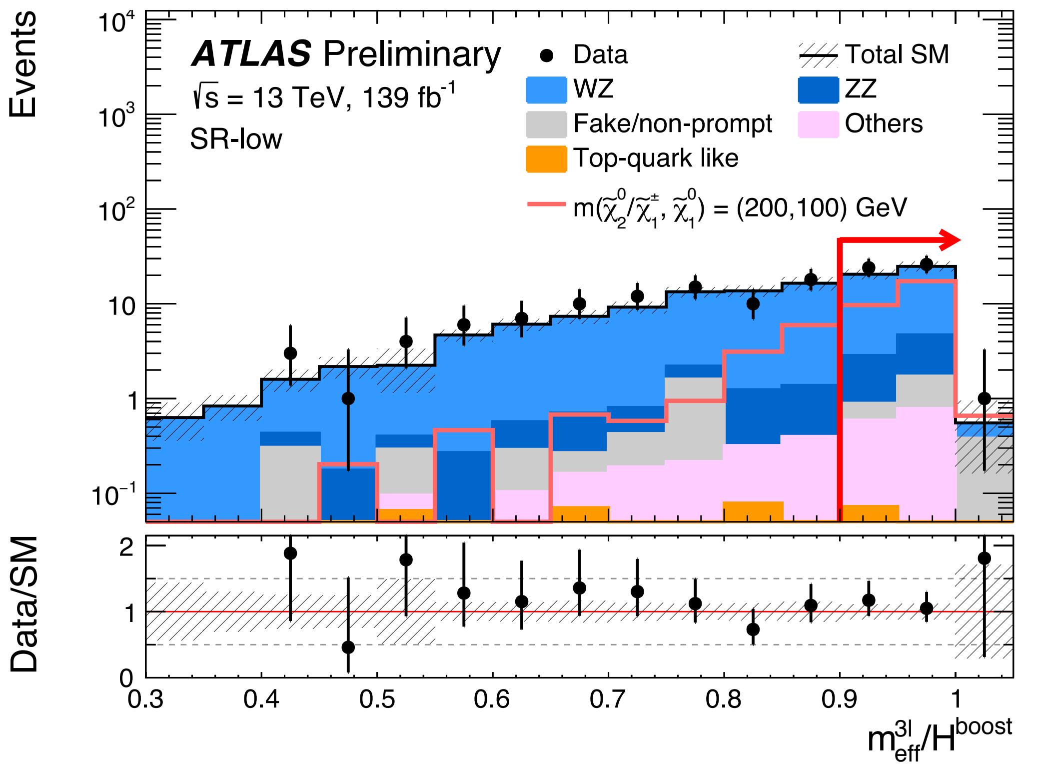
	CR-ISR	VR-ISR	VR-ISR-small $p_{\mathrm{T}}^{\mathrm{soft}}$	VR-ISR-small $R\left(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)$
Observed events	442	101	72	252
Fitted SM events	442 ± 21	107 ± 18	94 ± 7	256 ± 14
WZ	411 ± 22	97 ± 17	88 ± 7	242 ± 13
ZZ	9.1 ± 0.8	2.1 ± 0.5	2.6 ± 0.4	2.7 ± 0.5
Others	9 ± 5	4.8 ± 2.5	1.8 ± 1.1	5.0 ± 2.5
Top-quark like	4.8 ± 1.6	2.7 ± 1.1	1.5 ± 1.1	2.0 ± 1.0
Fake/non-prompt leptons	9 ± 5	$0.01^{+0.18}_{-0.01}$	$0.5^{+1.5}_{-0.5}$	3.7 ± 3.4

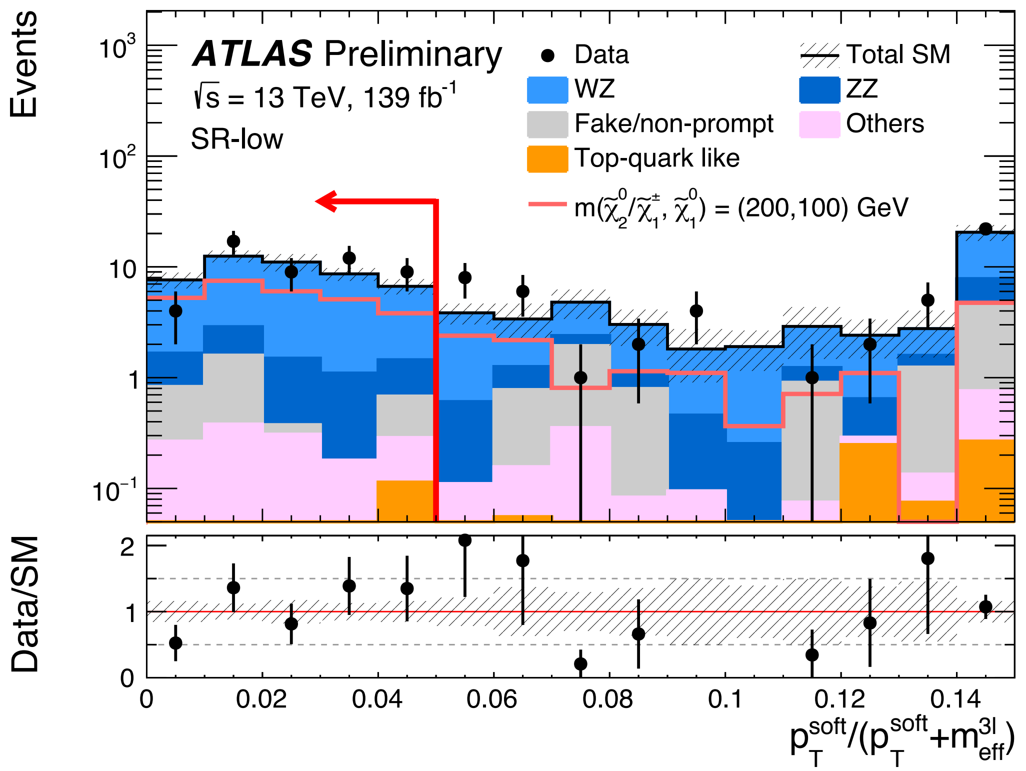
- *WZ* NF is 0.84 ± 0.07 for low-mass regions, 0.94 ± 0.05 for ISR regions

SR low distributions



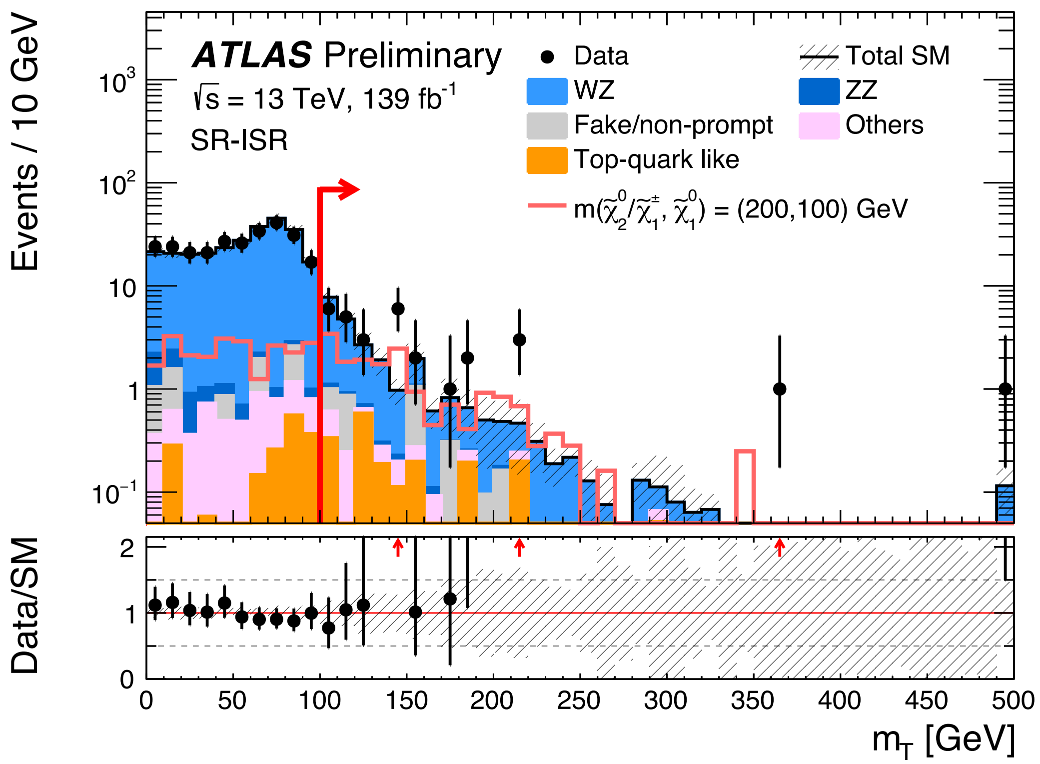


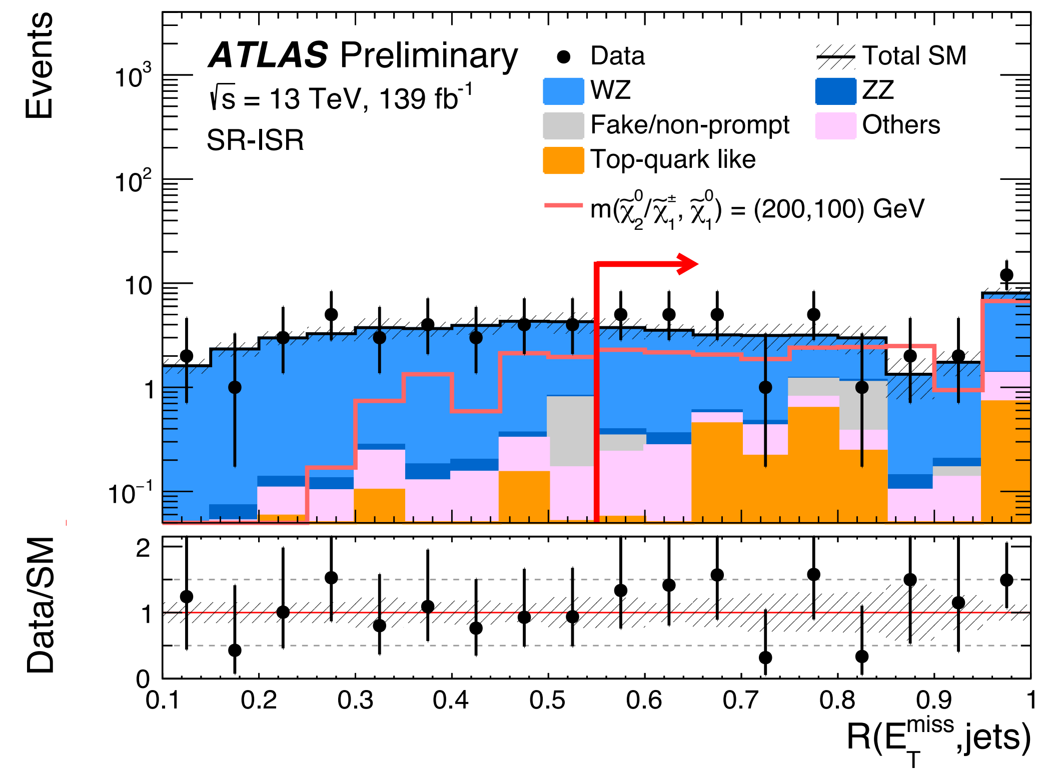


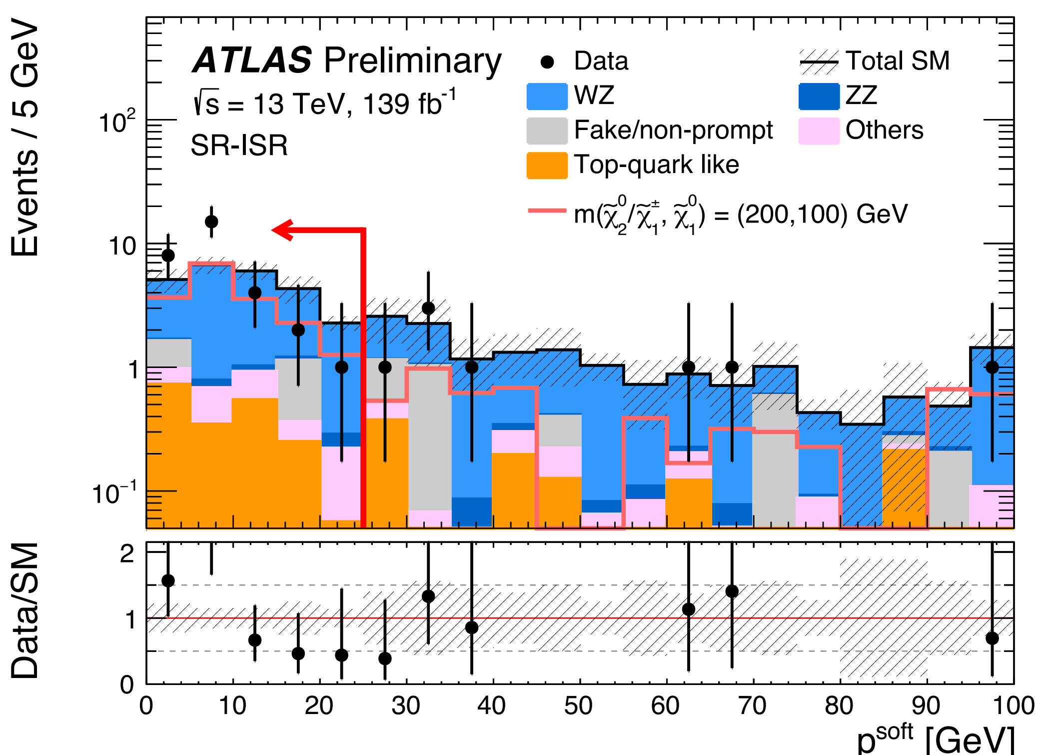


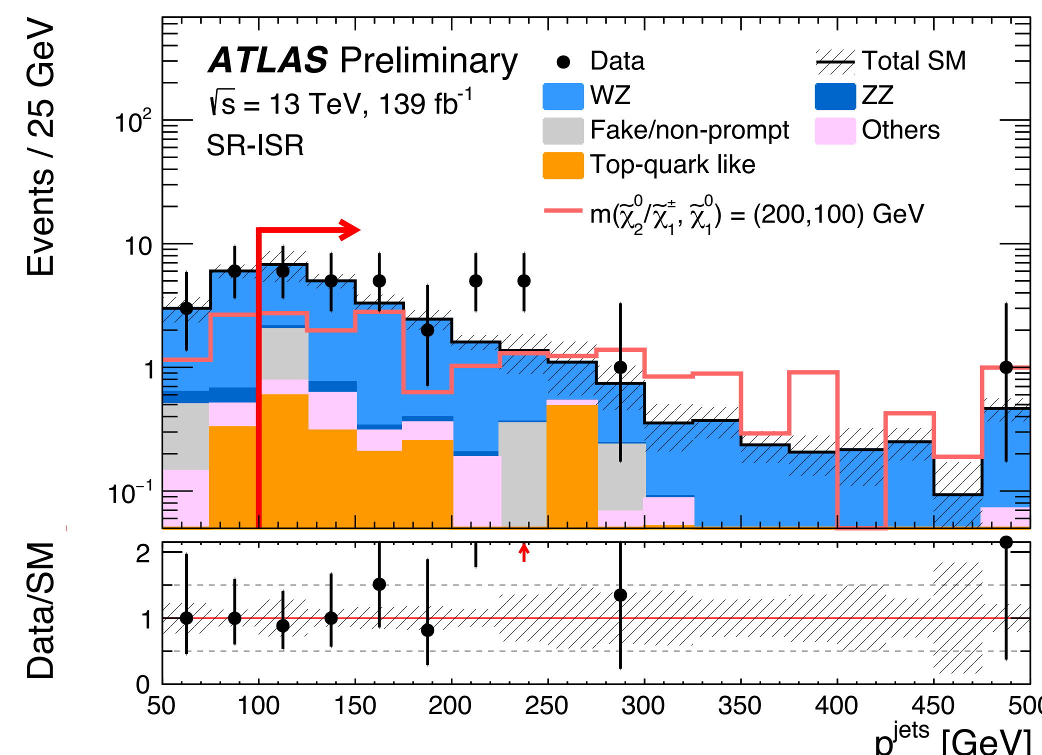
- No significant excess in SR low

SR ISR distributions





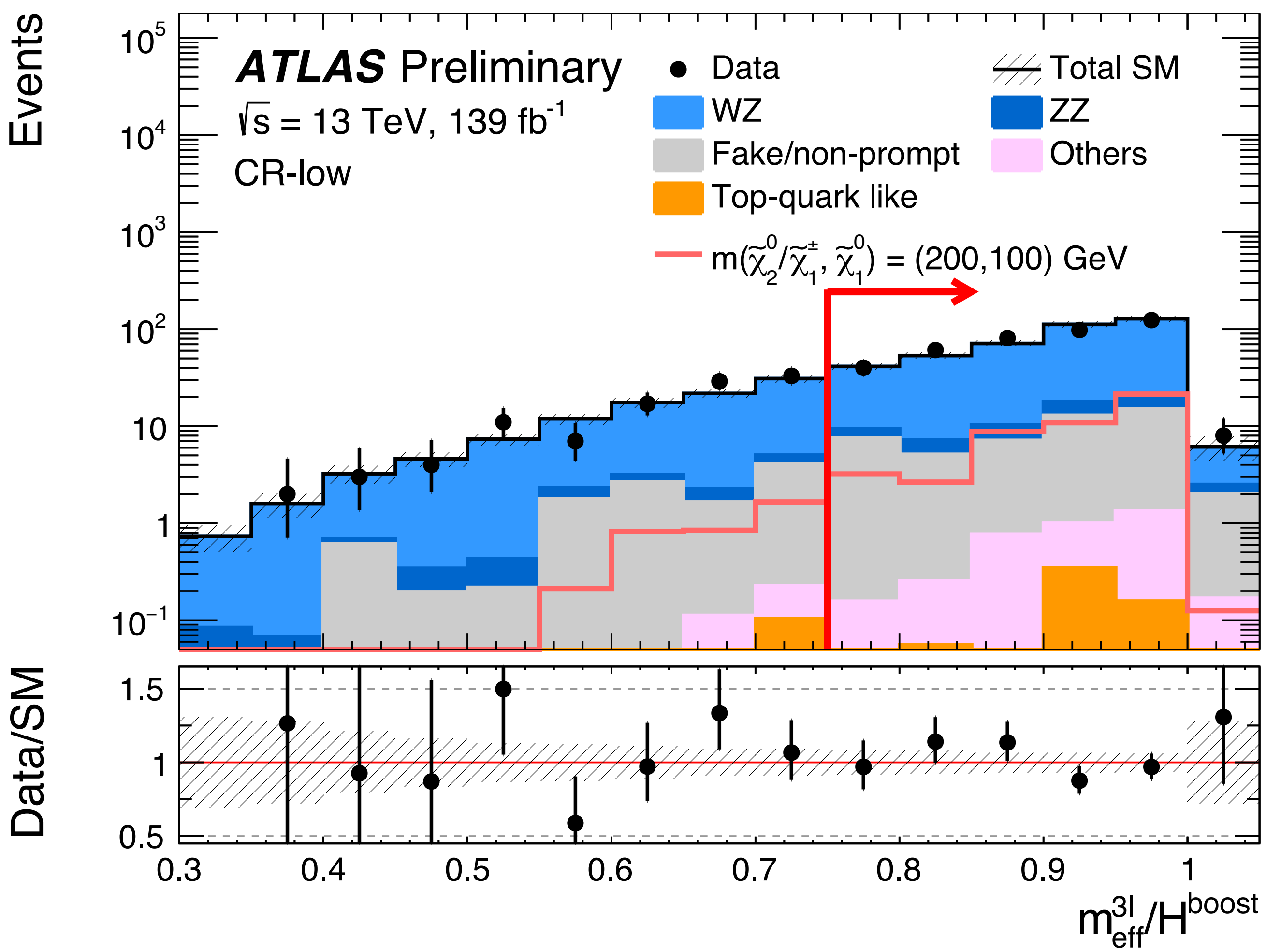




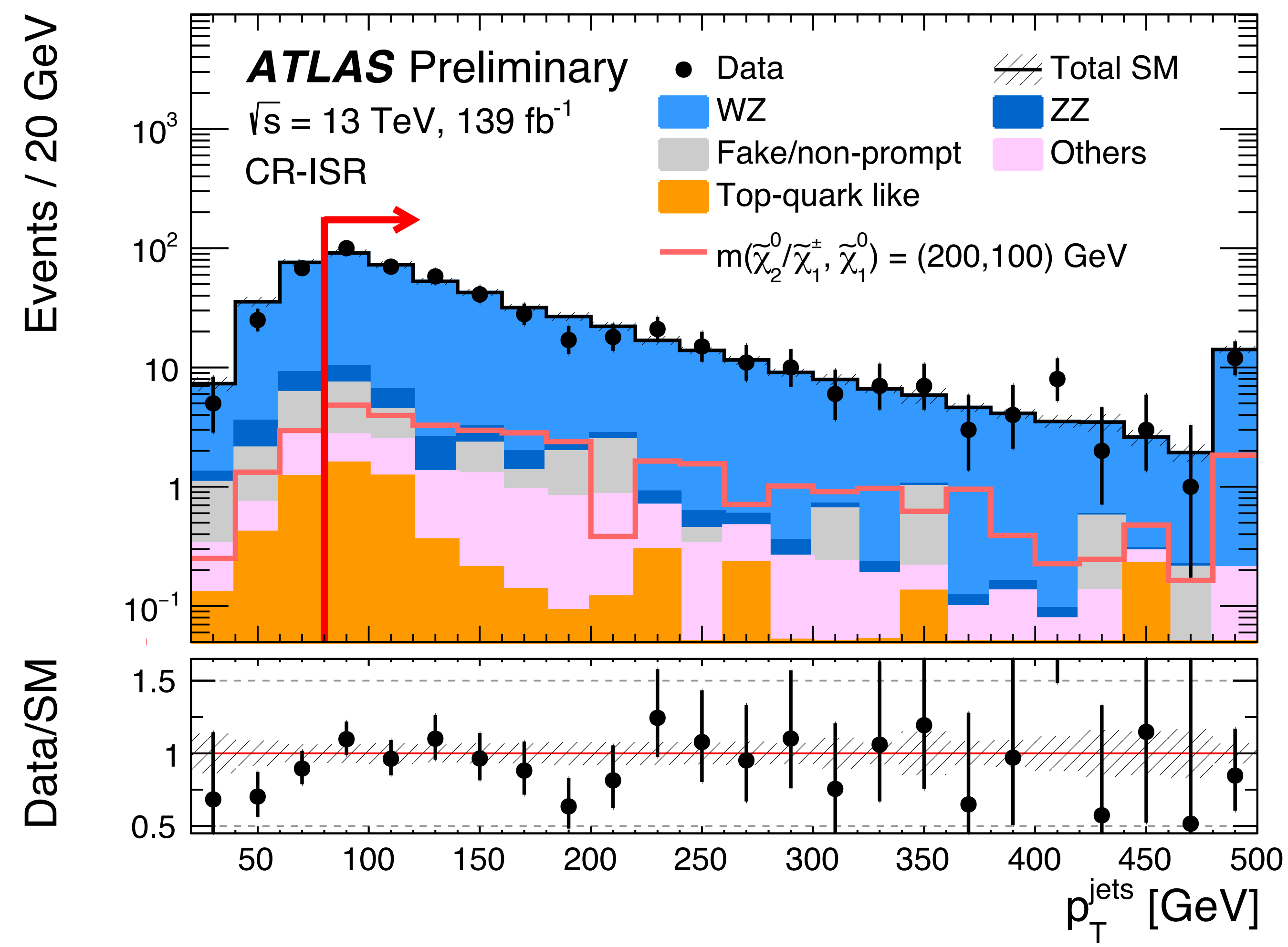
- Slight excess in SR ISR, which does not appear to match the signal model

Control Region distributions

CR low



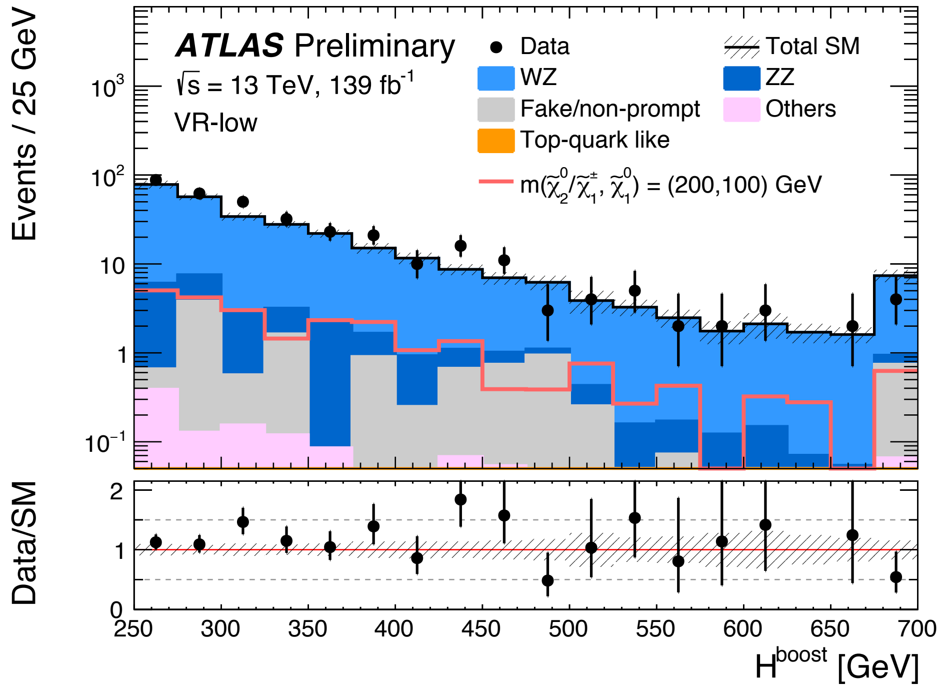
CR ISR



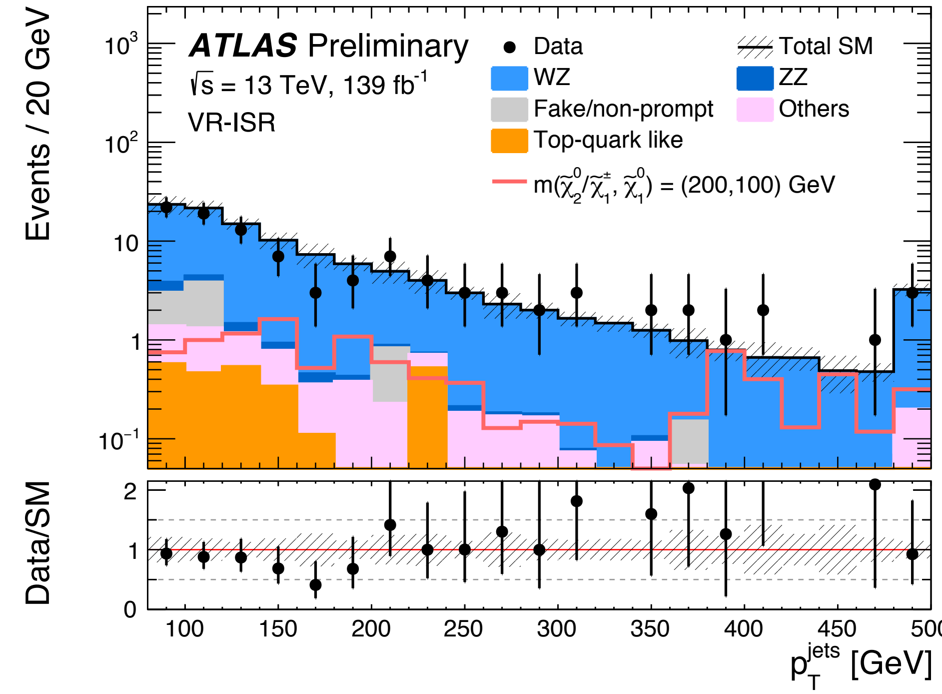
- Good background modeling

Background modeling for eRJR search

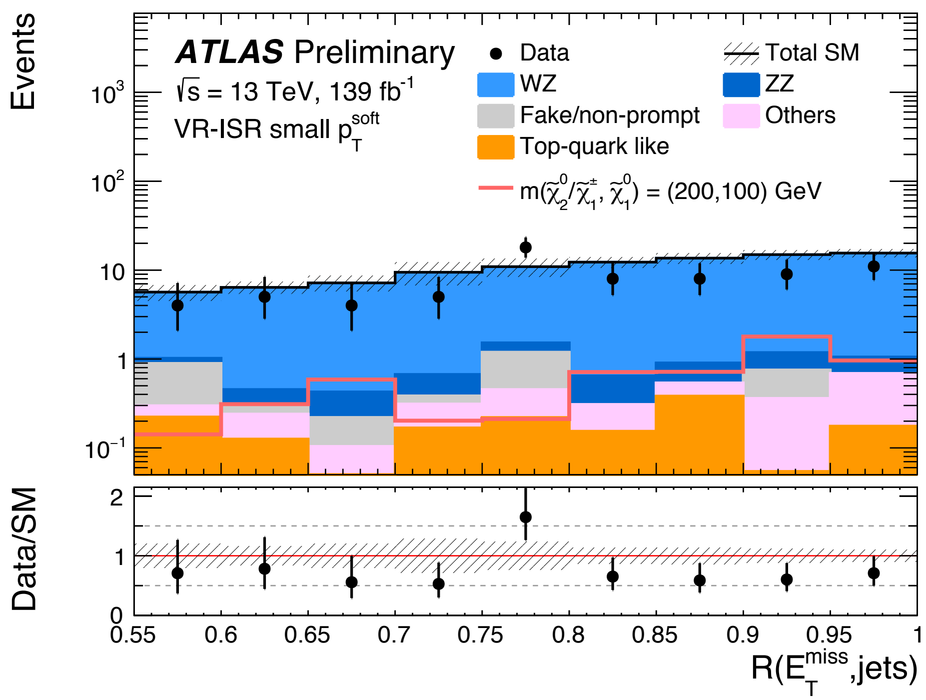
VR low



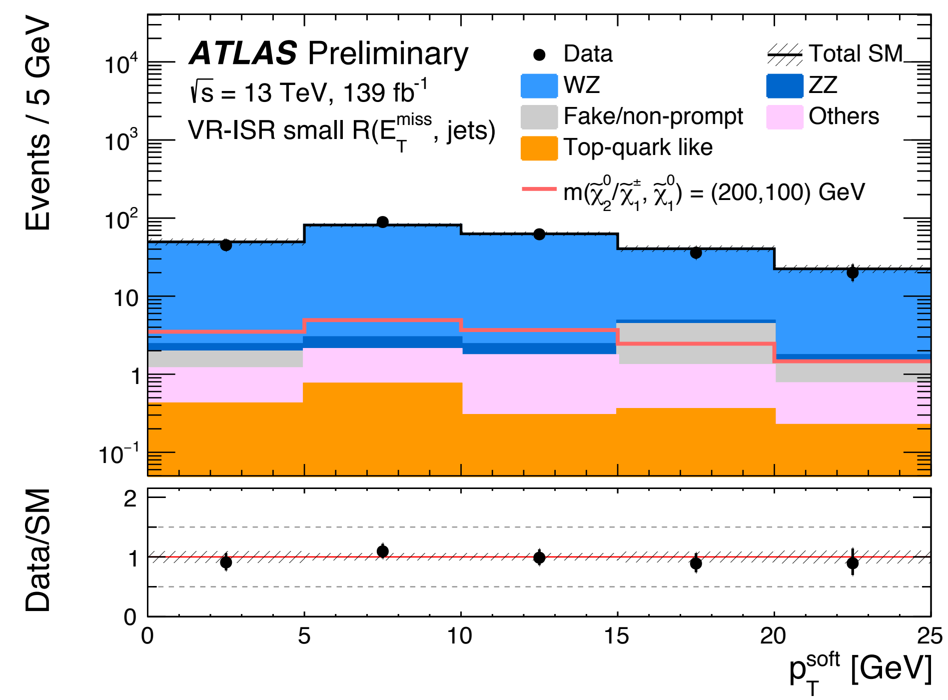
VR ISR



VR-small p_T^{soft}

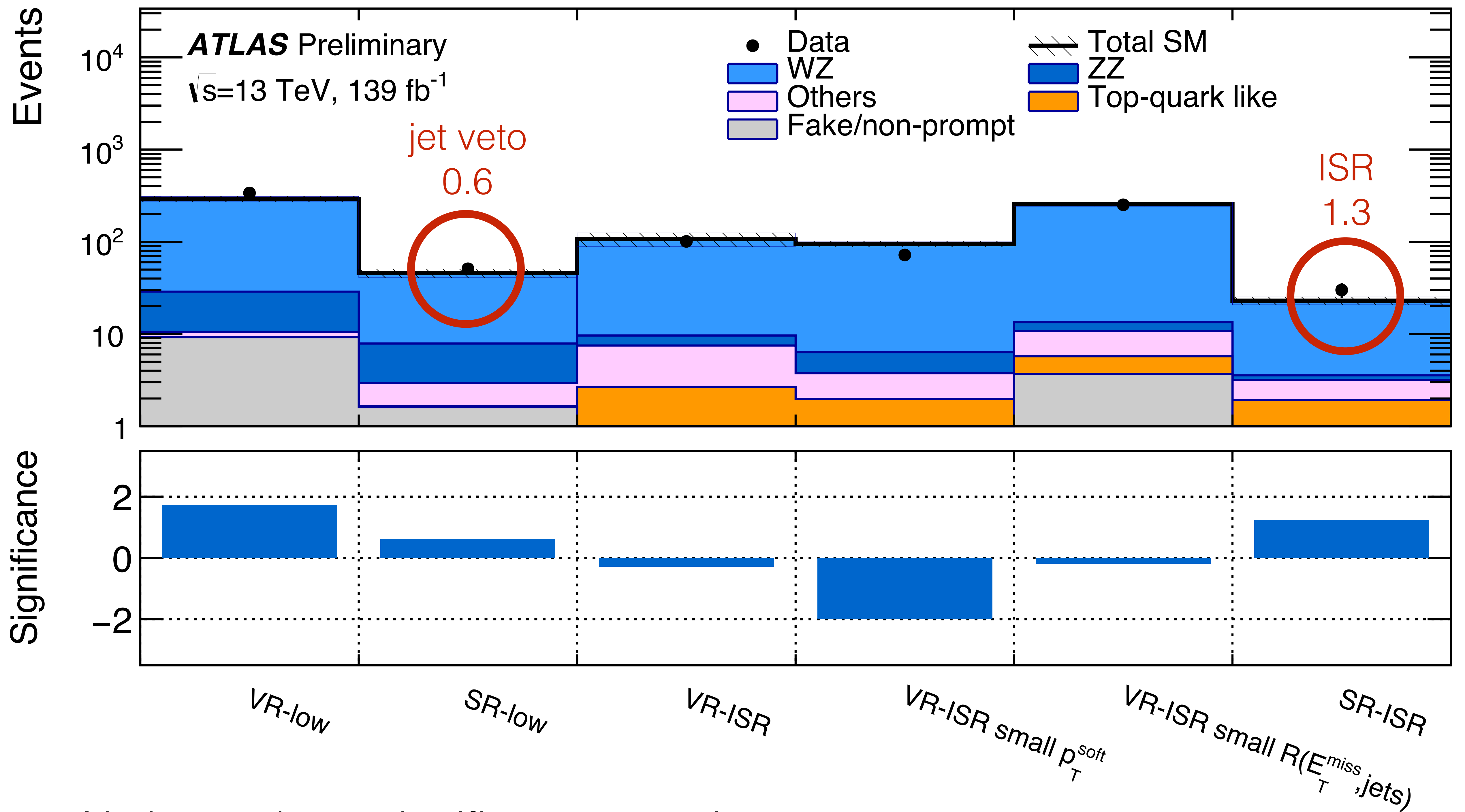


VR-small R(MET, jets)



- Good background modeling

Result



- No longer have significant excess!

CP Systematics

- Jet: jet energy scale and resolution
- Electron and Muon
  - Momentum scale and resolution, uncertainties on scale factors
- missing energy:
  - propagation of uncertainties on p_T of objects
  - uncertainties on resolution of track-based soft term
- Luminosity: uncertainty for combined 2015-18 is 1.7%

Uncertainty in signal regions	SR-low	SR-ISR
Jet energy scale and resolution	7.0%	6.8%
WZ Normalization	6.6%	4.6%
$E_{\mathrm{T}}^{\mathrm{miss}}$	3.3%	2.6%
MC Statistics	2.9%	4.0%
Anti-ID CR Stats	2.7%	0.22%
WZ Theory	1.9%	1.3%
30% uncertainty on other backgrounds	1.4%	2.7%
Fake factor estimation	1.1%	$< 0.01\%$
Muon momentum scale and resolution	0.37%	0.04%
Electron energy scale and resolution	0.24%	0.30%
Pileup	0.17%	0.96%
Top-quark like background estimation	0.02%	1.4%
Flavor Tagging	0.02%	0.39%