Searching for the Invisible using cross-section ratios

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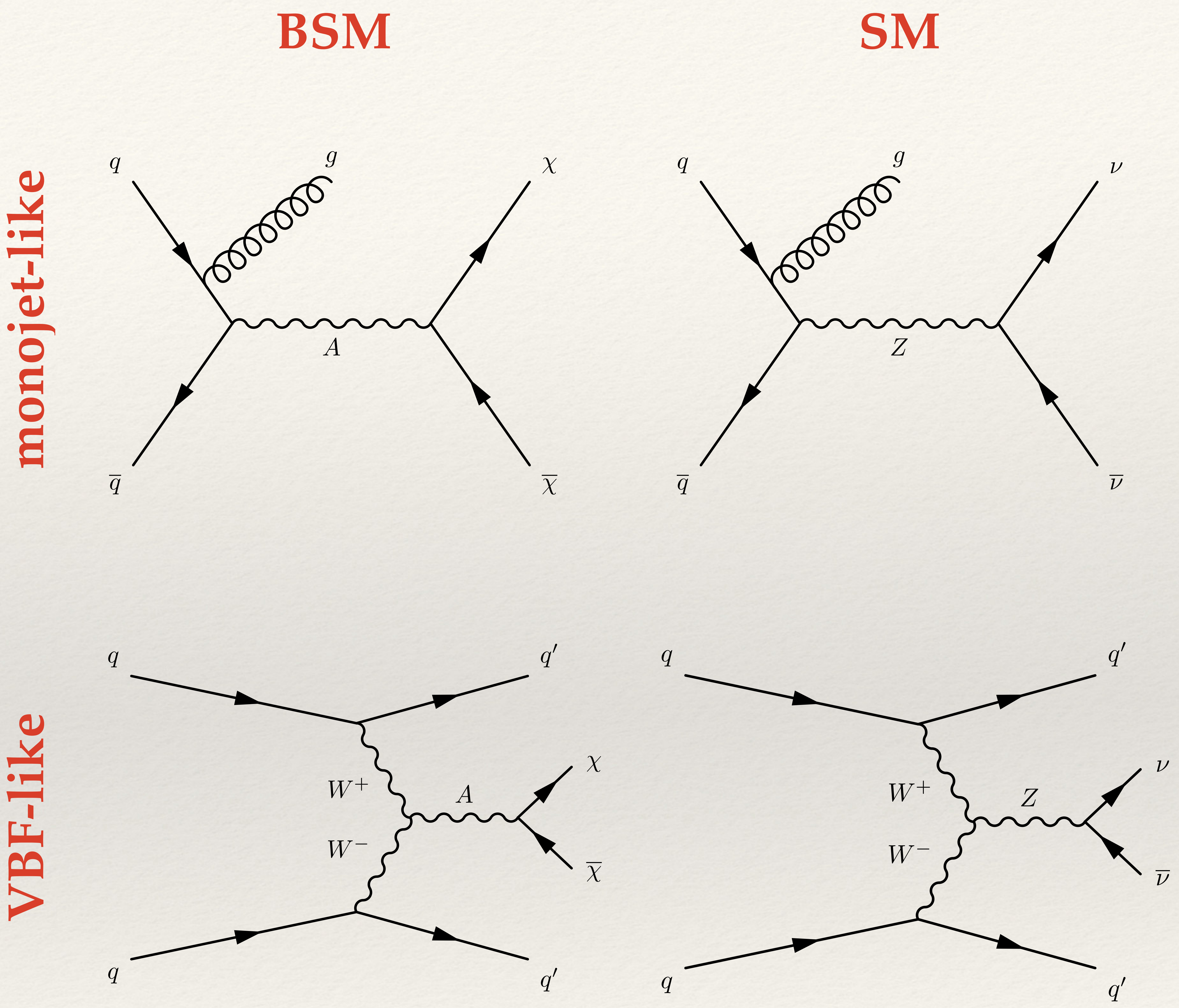
Motivation

- Dark Matter candidates could be produced at the LHC.
- Can be inferred via momentum imbalance in the transverse plane if produced in association with SM objects (e.g. jets).
- Dark Matter + jets production has an identical signature to $Z \to \nu\bar{\nu} + \text{jets}$ process (or $W \to l\nu + \text{jets}$ with out-of-acceptance lepton).

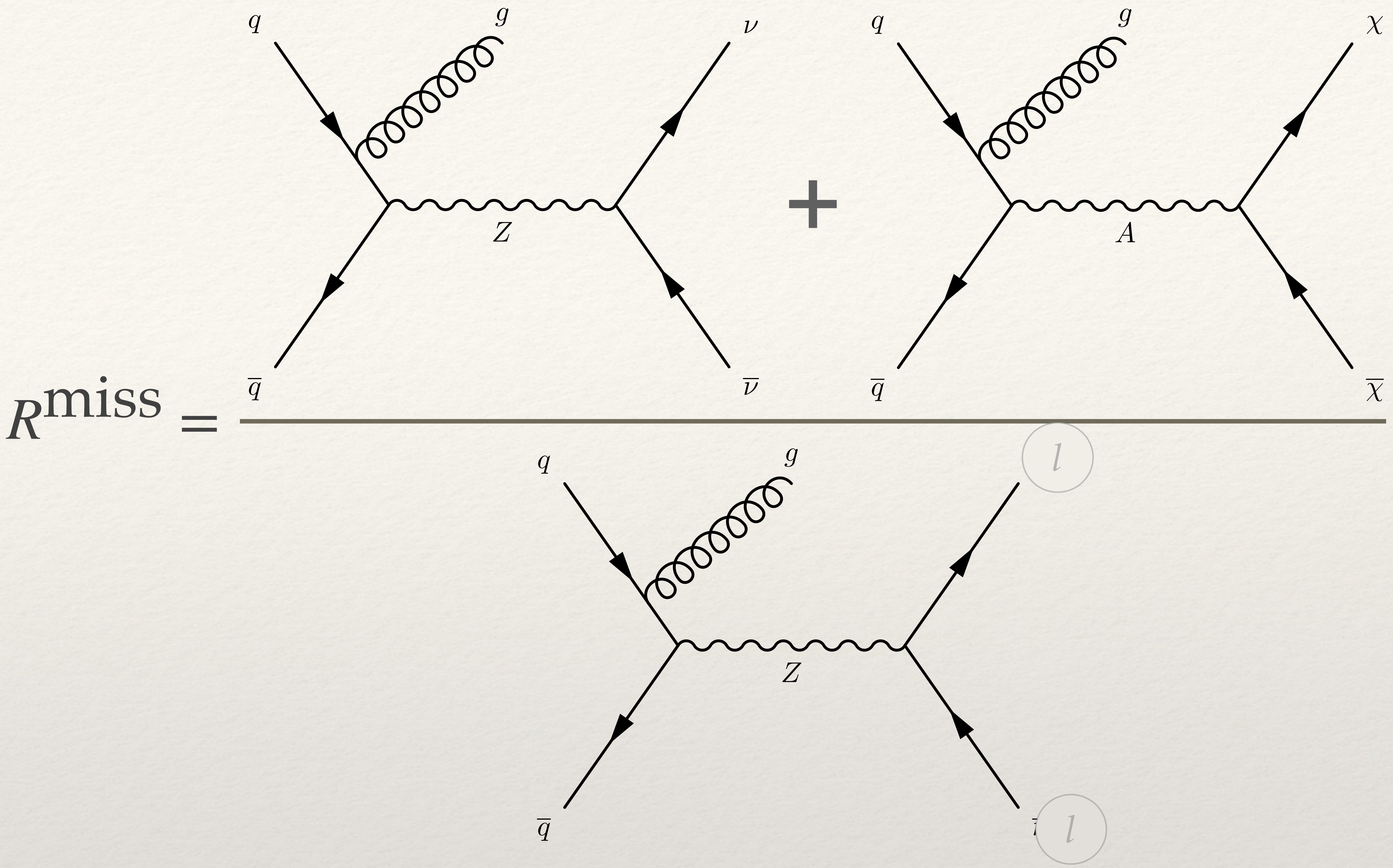


The idea: Visible regions and Ratio construction

- SM diagrams similar to the invisible decay of the Z boson:
    - $Z \rightarrow l^+l^- + \text{jets}$
    - $W \rightarrow l\ \nu + \text{jets}$
- Measure two ratios in addition to the individual processes:

$$R^{\text{miss}} = \frac{p_{\text{T}}^{\text{miss}} + \text{jets}}{p_{\text{T}}^{\text{miss}} + l + \text{jets}} \qquad R^{\text{miss}} = \frac{p_{\text{T}}^{\text{miss}} + \text{jets}}{l^+l^- + \text{jets}}$$

- Select leptons and then mark as invisible.
- Presence of BSM physics with a $p_{\text{T}}^{\text{miss}} + \text{jets}$ signature will lead to deviations from the ratio as predicted by the SM.



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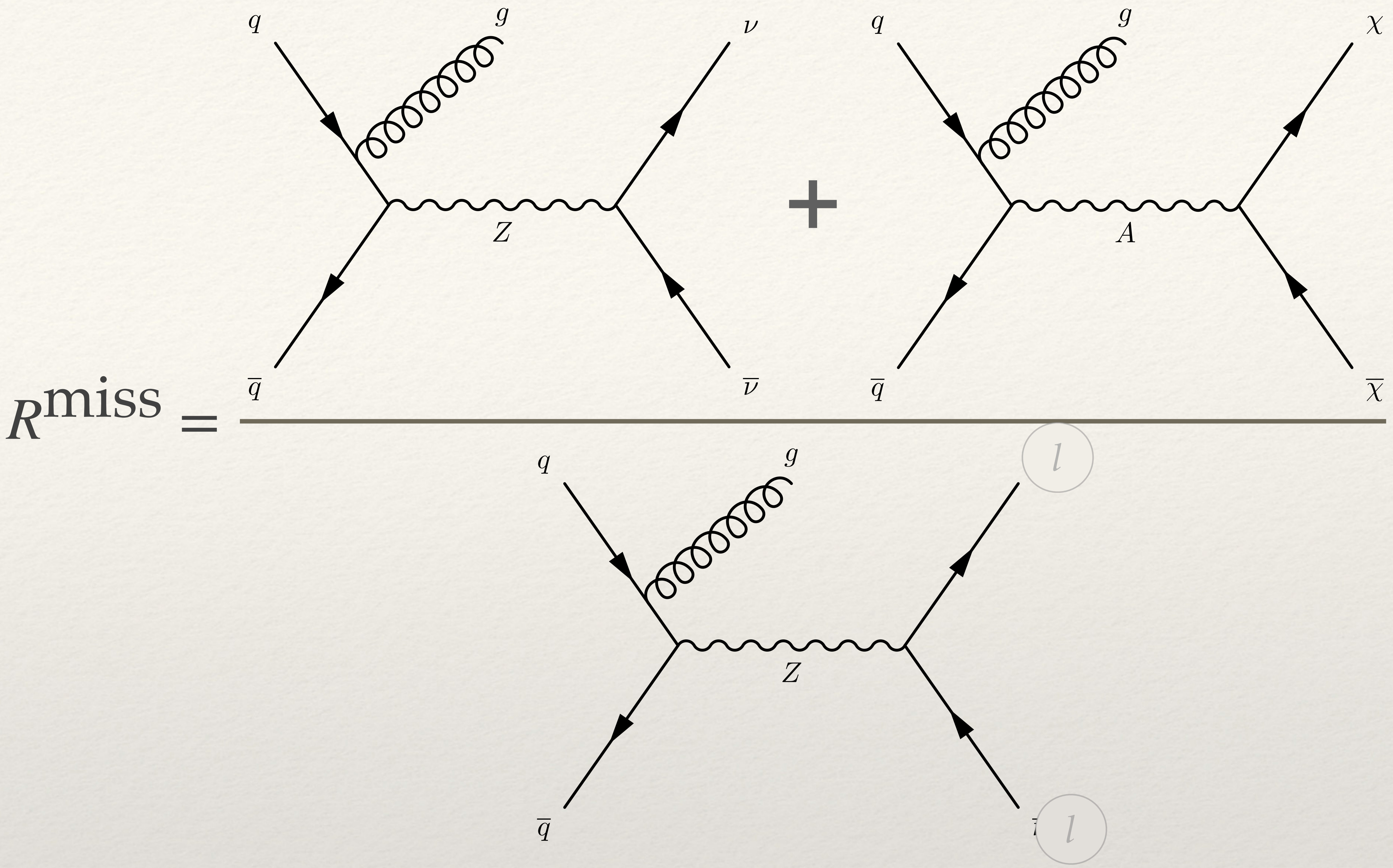
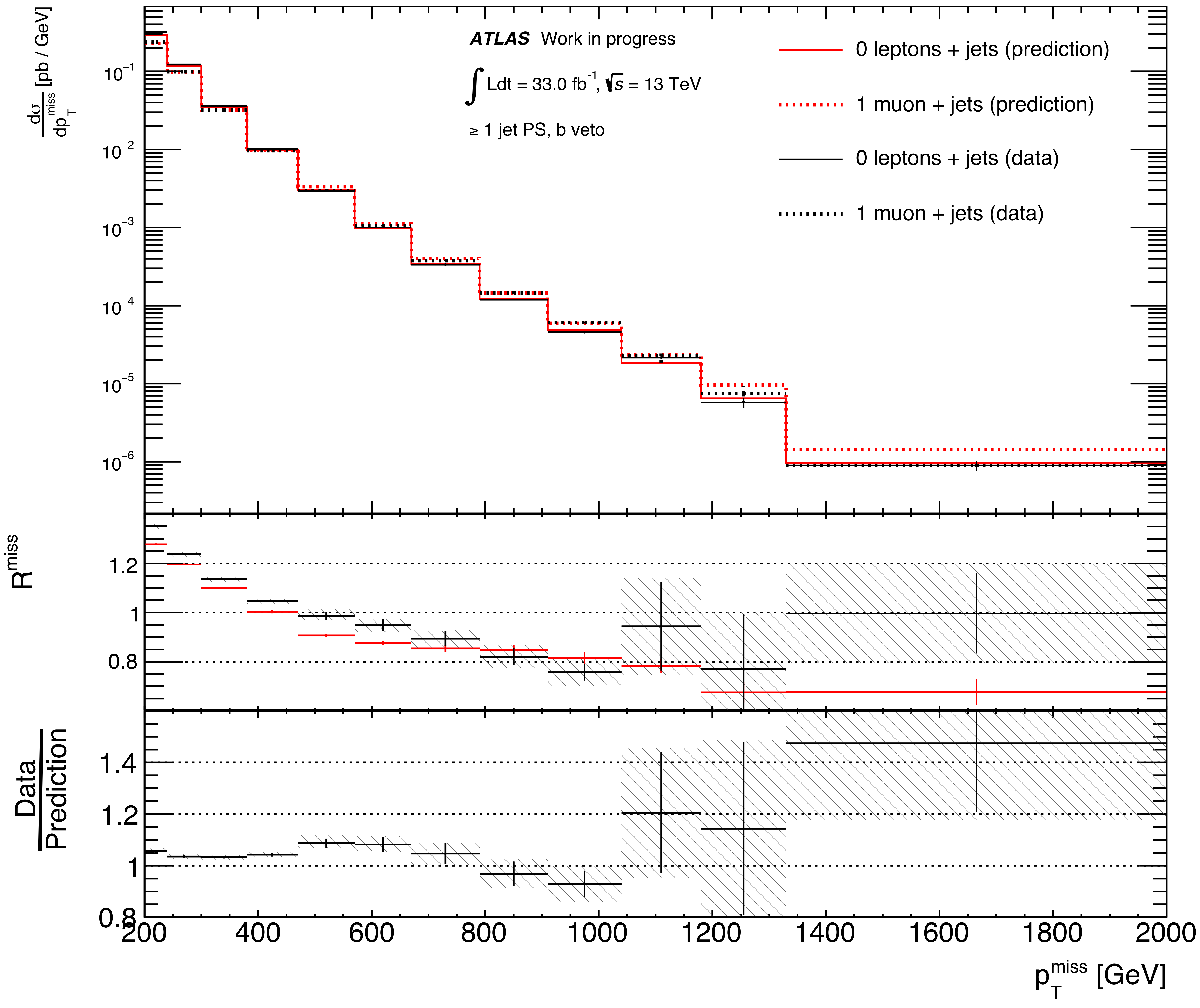


- Cancellations of most theoretical and experimental uncertainties in the ratio.

- Ratio is measured differentially.

- Results are corrected for detector effects.

Double Ratio: p_T^{miss}

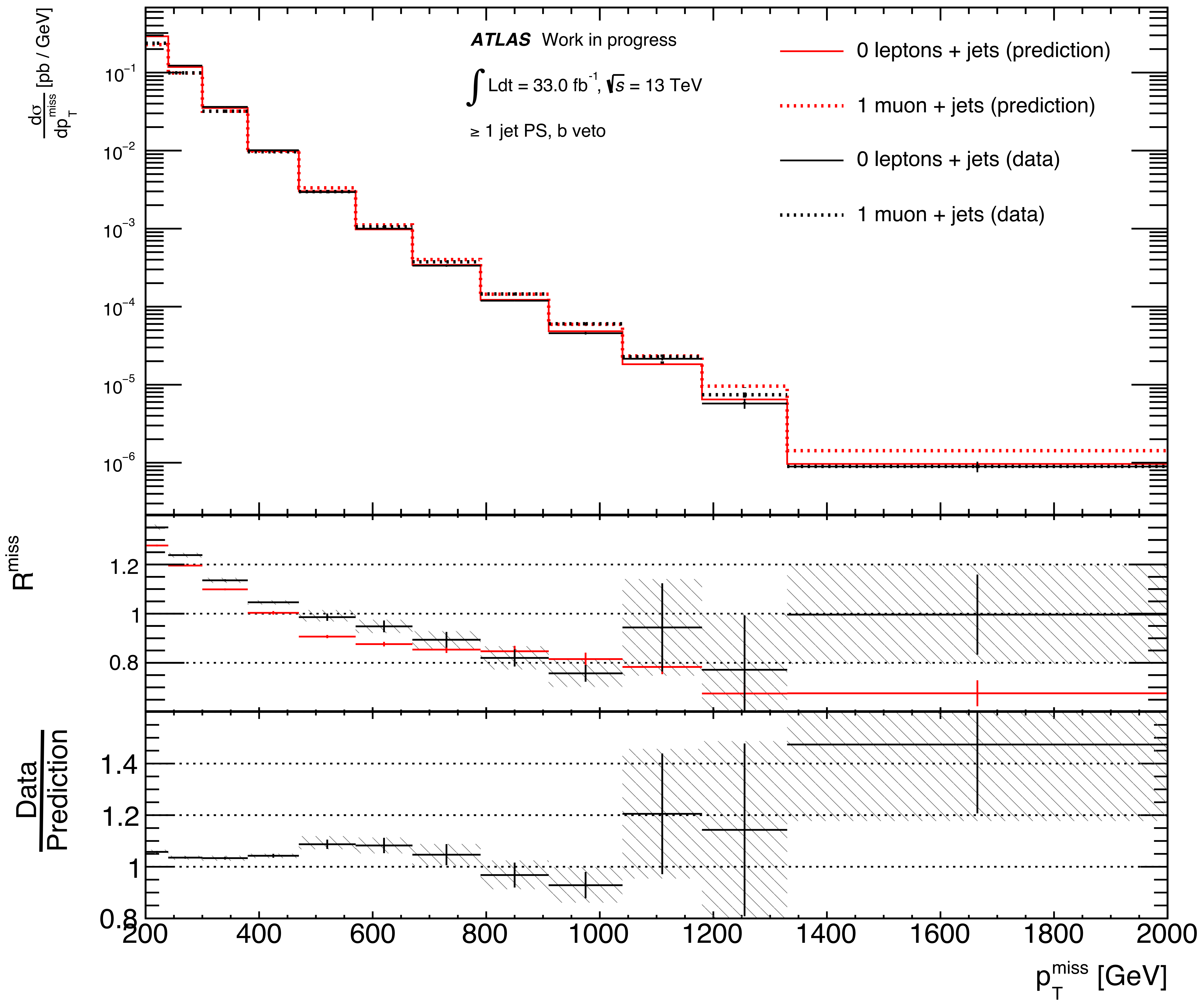


- Differential cross-sections of the 0-lepton Signal Region and 1-muon Control Region as a function of p_T^{miss} in the monojet-like phase space.
- Multijet background not included in the simulation ➡ Data excess in first bin.

$$R^{miss} = \frac{p_T^{miss} + \text{jets}}{p_T^{miss} + \mu + \text{jets}}$$

- Theoretical uncertainties not included.

Double Ratio: p_T^{miss}



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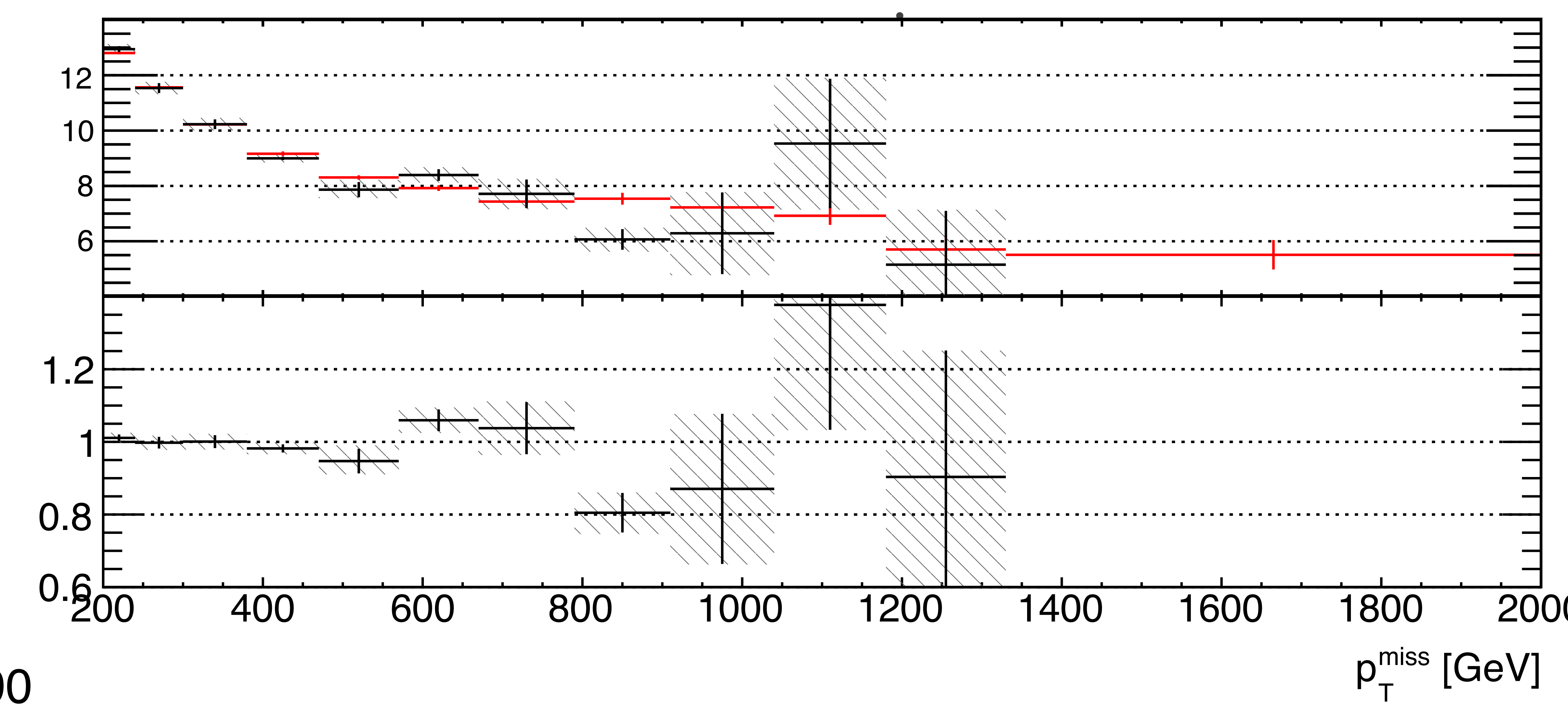
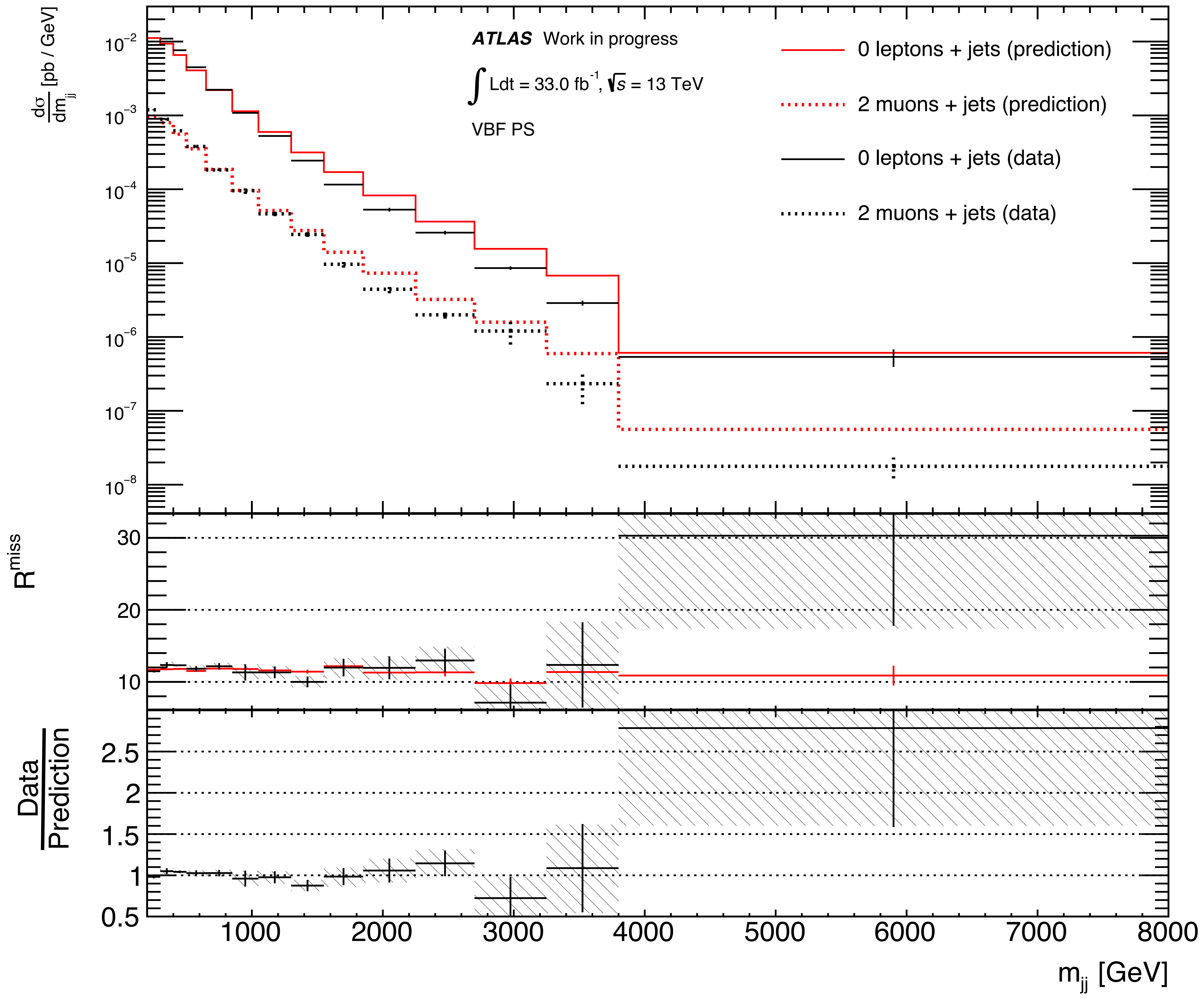


Double Ratio: m_{jj}

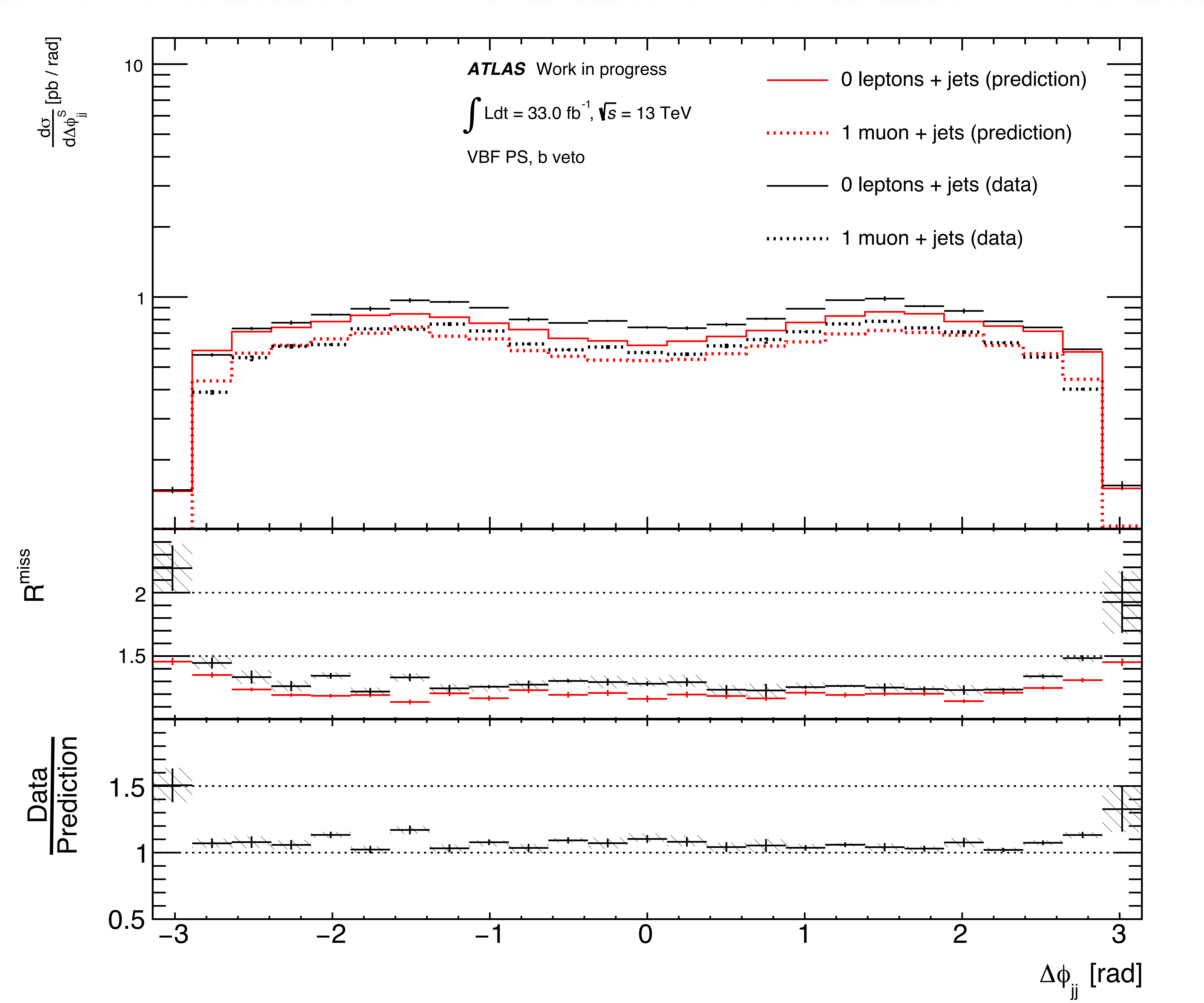


- Differential cross-sections of the 0-lepton Signal Region and 2-muon Control Region as a function of m_{jj} in the VBF phase space.
- Good agreement between measured and predicted ratio.

$$R^{\text{miss}} = \frac{p_T^{\text{miss}} + \text{jets}}{\mu^+\mu^- + \text{jets}}$$

- Poor modelling of the m_{jj} distribution in both the numerator and denominator largely cancels out in the ratio.

Double Ratio: $\Delta\Phi_{jj}$



- Differential cross-sections of the 0-lepton Signal Region and 1-muon Control Region as a function of $\Delta\Phi_{jj}$ in the VBF phase space.
- Multijet background not included in the simulation ➡ Data excess at edges of distribution.

$$R^{\text{miss}} = \frac{p_T^{\text{miss}} + \text{jets}}{p_T^{\text{miss}} + \mu + \text{jets}}$$

- Poor modelling of the $d\Phi_{jj}$ distribution in both the numerator and denominator largely cancels out in the ratio.
- Theoretical uncertainties not included.

Summary and future plans

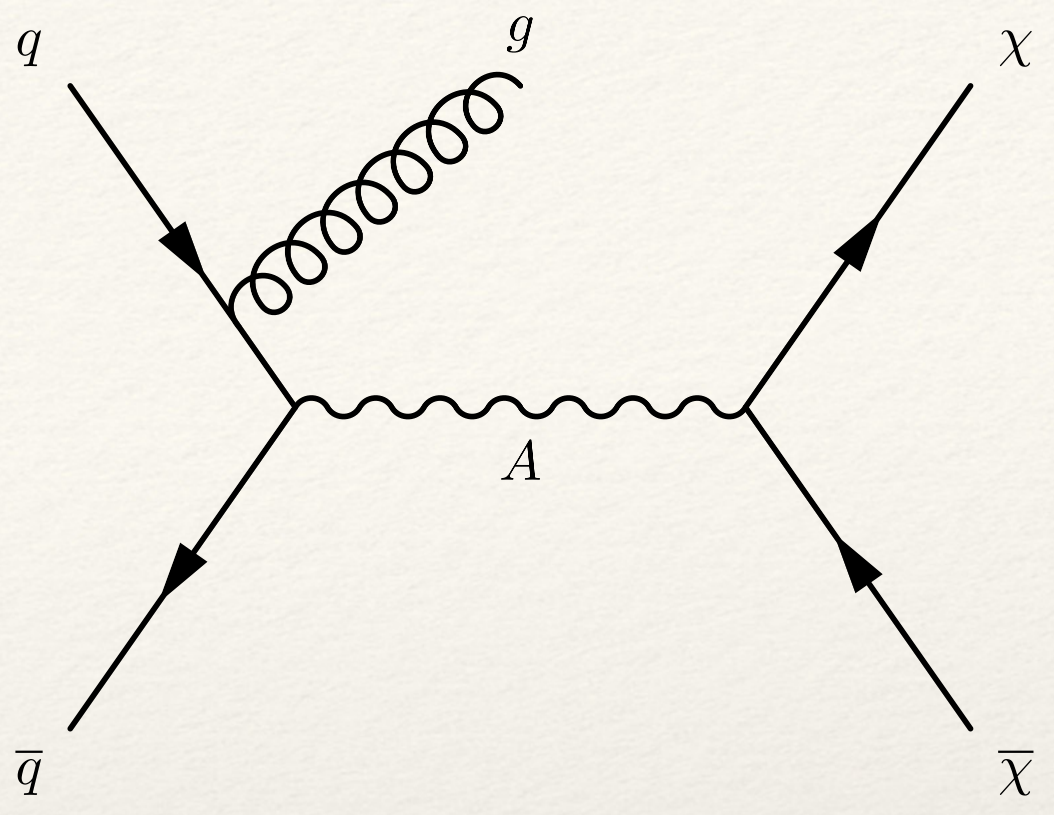
- Measuring a Signal region with a $p_{\mathrm{T}}^{\mathrm{miss}} + \mathrm{jets}$ final state signature.
- Constraining it with Control regions containing visible objects.
- Results are corrected for detector effects.
- Optimising regions using the 2016 dataset - will be using full dataset collected at the ATLAS detector between 2015 and 2018 (~136 fb^{-1}).
- Aiming to measure more Signal and Control regions, phase spaces and kinematic distributions.

Backup

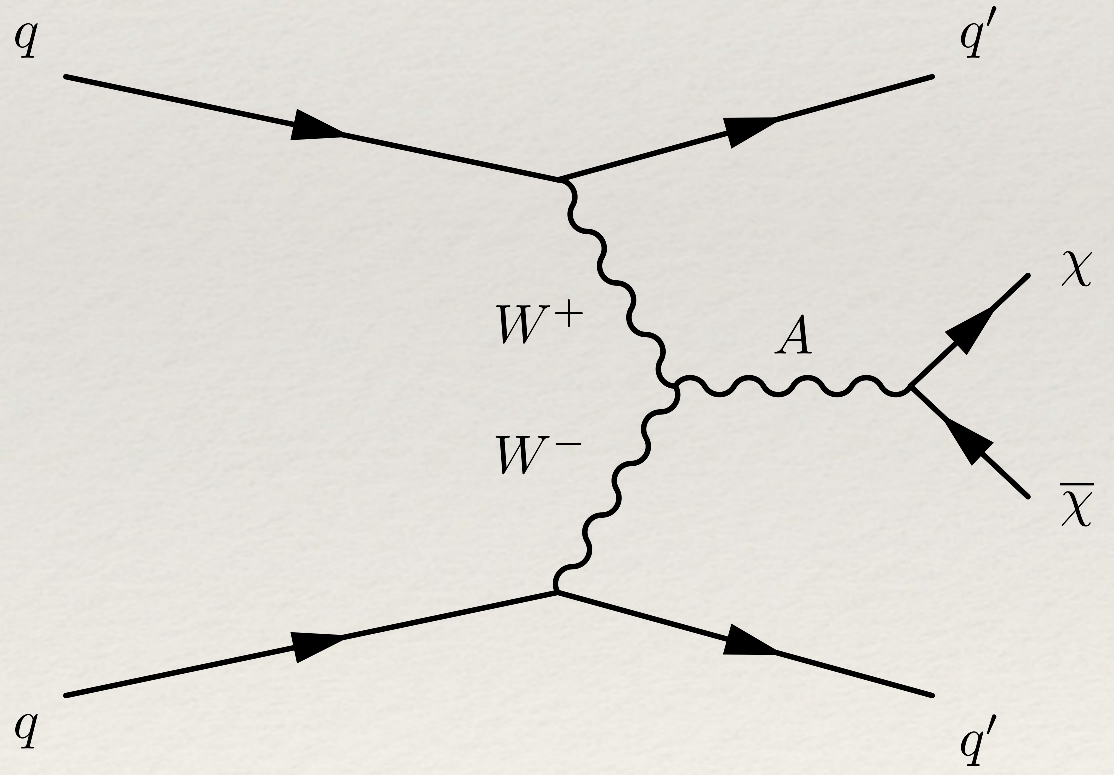
Phase-space definition

Signal and Control Regions			
	≥ 1 jet	VBF	2-jet Inclusive
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV		
(additional) lepton veto	e, μ with $p_{\mathrm{T}} > 7$ GeV and $\lvert\eta\rvert < 2.5$		
Jet $\lvert y\rvert$	< 4.4		
Jet p_{T}	> 30 GeV		
$\Delta\phi_{\mathrm{jet_i},p_{\mathrm{T}}^{\mathrm{miss}}}$	> 0.4, for the four leading jets		
Leading jet p_{T}	> 120 GeV	> 80 GeV	> 120 GeV
Subleading jet p_{T}	-	> 50 GeV	> 50 GeV
Leading jet $\lvert\eta\rvert$	< 2.4	-	-
m_{jj}	-	> 200 GeV	> 70 GeV
Δy_{jj}	-	> 1.0	-
Jet-gap requirement	-	no additional jets	-
2-lepton Control Region			
Lepton pair	Opposite sign, same-flavour pair of e^+e^- or $\mu^+\mu^-$		
Leading lepton p_{T}	> 80 GeV		
Subleading lepton p_{T}	> 7 GeV		
Lepton $\lvert\eta\rvert$	< 2.5		
$\lvert m_{ll} - m_Z\rvert$	< 25 GeV		
1-lepton Control Region			
Lepton	single lepton: e^+, e^-, μ^+or μ^-		
Leading lepton p_{T}	> 7 GeV for μ , 25 GeV for e		
Lepton $\lvert\eta\rvert$	< 2.5		
Jets	b-veto		

monojet-like



VBF-like



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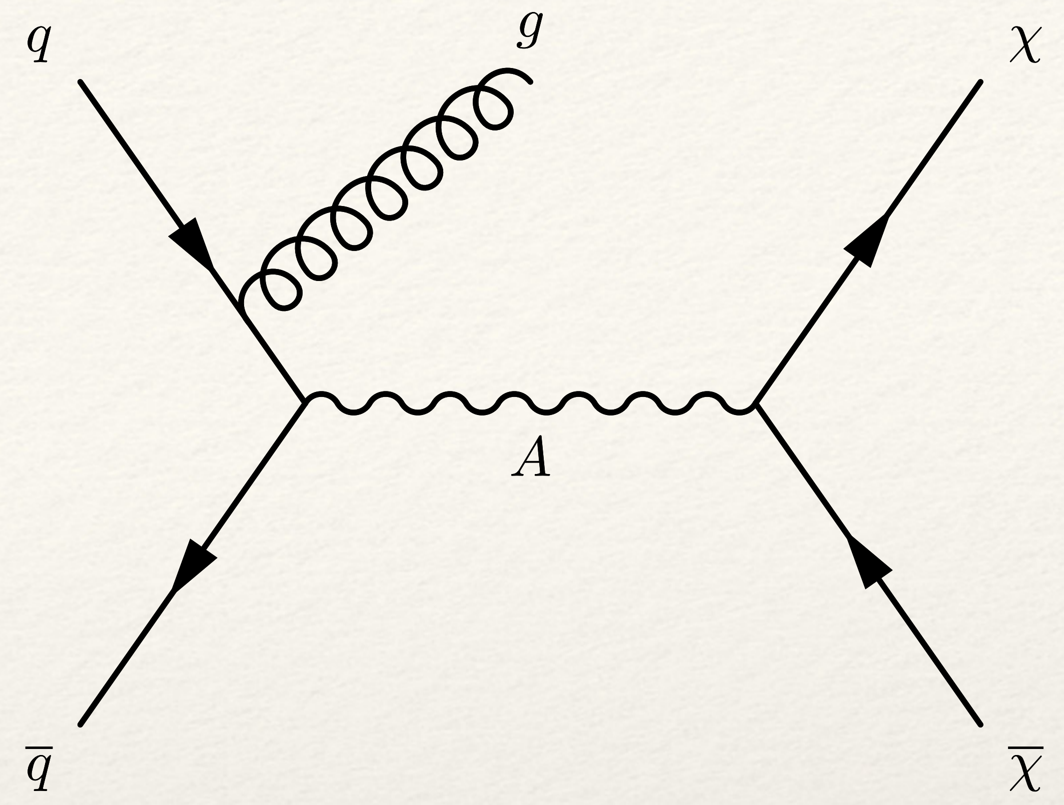

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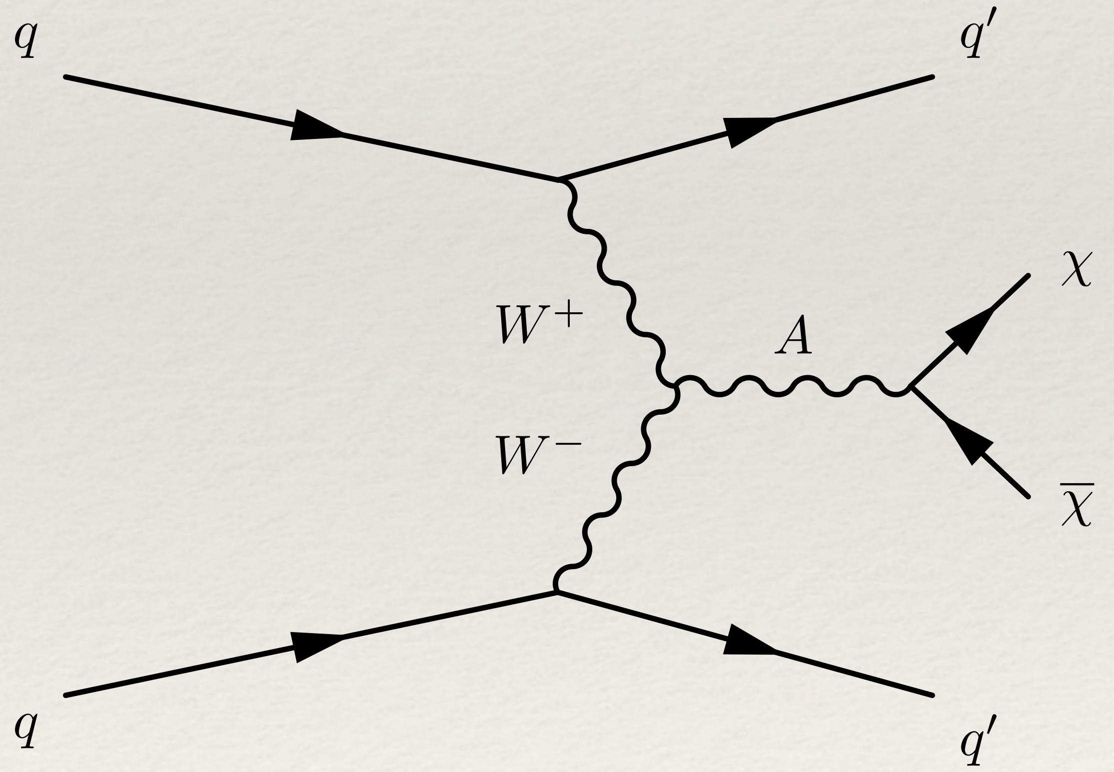


Reco object selection

Muons

- $p_T > 7$ GeV and $|\eta| < 2.5$
- **Working points:**
  - Selection tool: Loose
  - Isolation tool: LooseTrackOnlyIso
  - Efficiency tool: Loose
- Include in OR (default)

Electrons

- $p_T > 7$ GeV and $|\eta| < 2.47$ (excluding crack)
- **Working points:**
  - Likelihood: LHMedium
  - Isolation tool: LooseTrackOnly
- Include in OR (default)

Jets

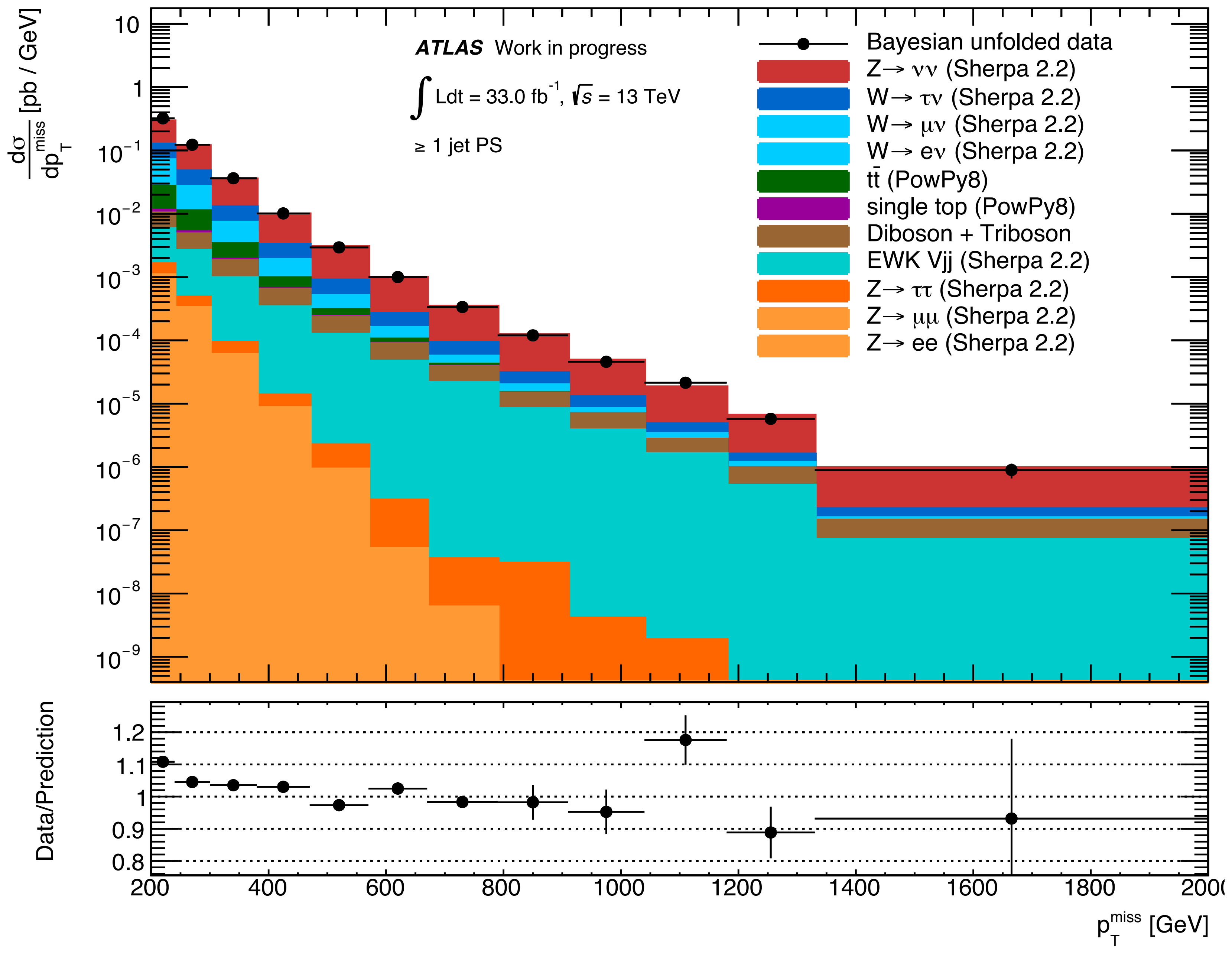
- $p_T > 30$ GeV , $|y| < 4.4$
- Using AntiKt4EMTopo jets
- **Working points:**
  - JVT efficiency tool: Medium
  - FJVT tool OP: Tight
  - Jet cleaning: LooseBad
- Include in OR (default)
- **B-tagging:**
  - TaggerName: MV2c10
  - Sel. Tool OP: HybBEff_77
  - Eff. Tool OP: FixedCutBEff_77
  - Reduction point: Tight
  - $p_T > 20$ GeV , $|\eta| < 2.5$

MET

- Using the default configuration of the METmaker tool
- DoRemoveMuonJet: true
- Using FJVT
- JetSelection: Tight

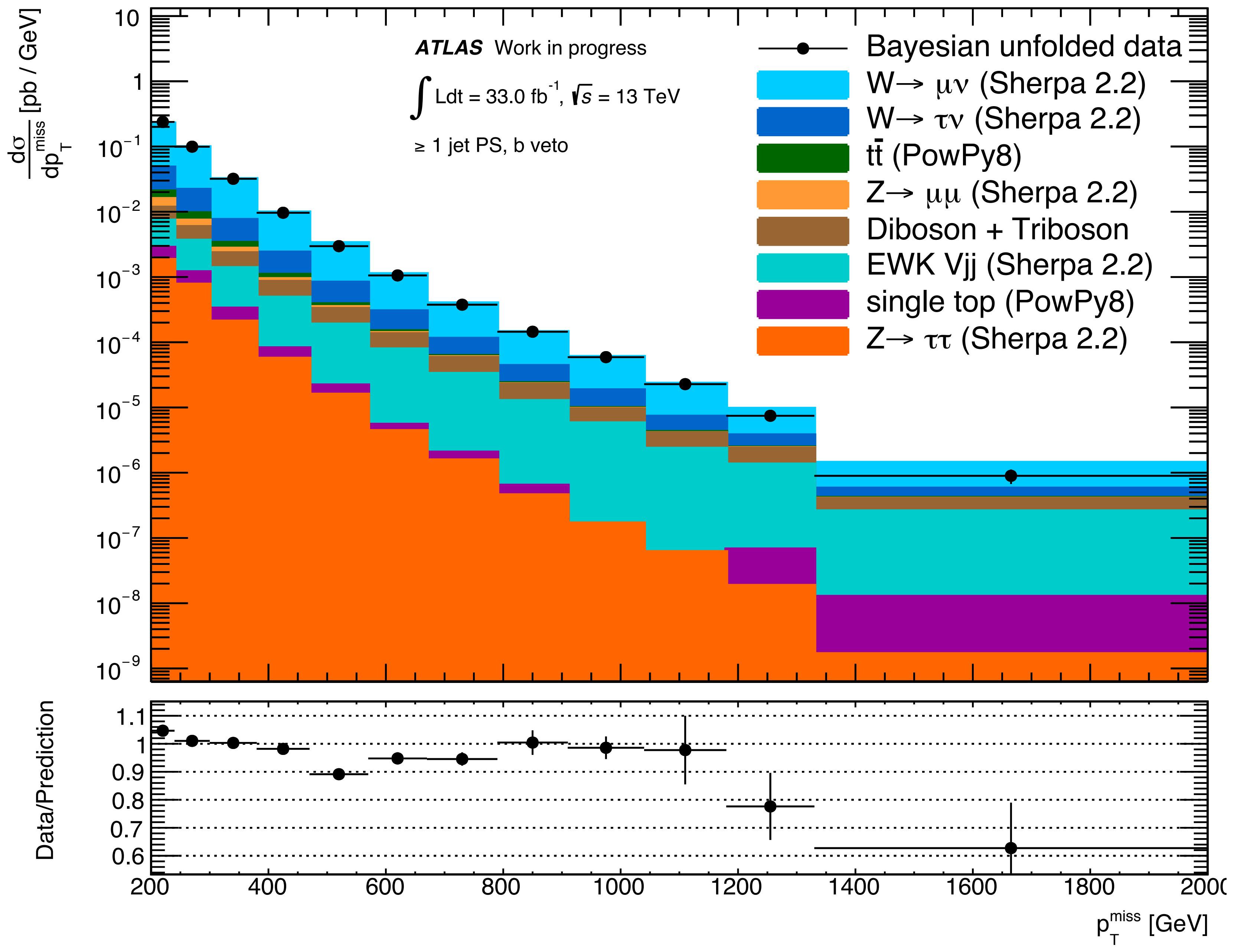
Final-state particle regions using the 2016 dataset

0-lepton SR



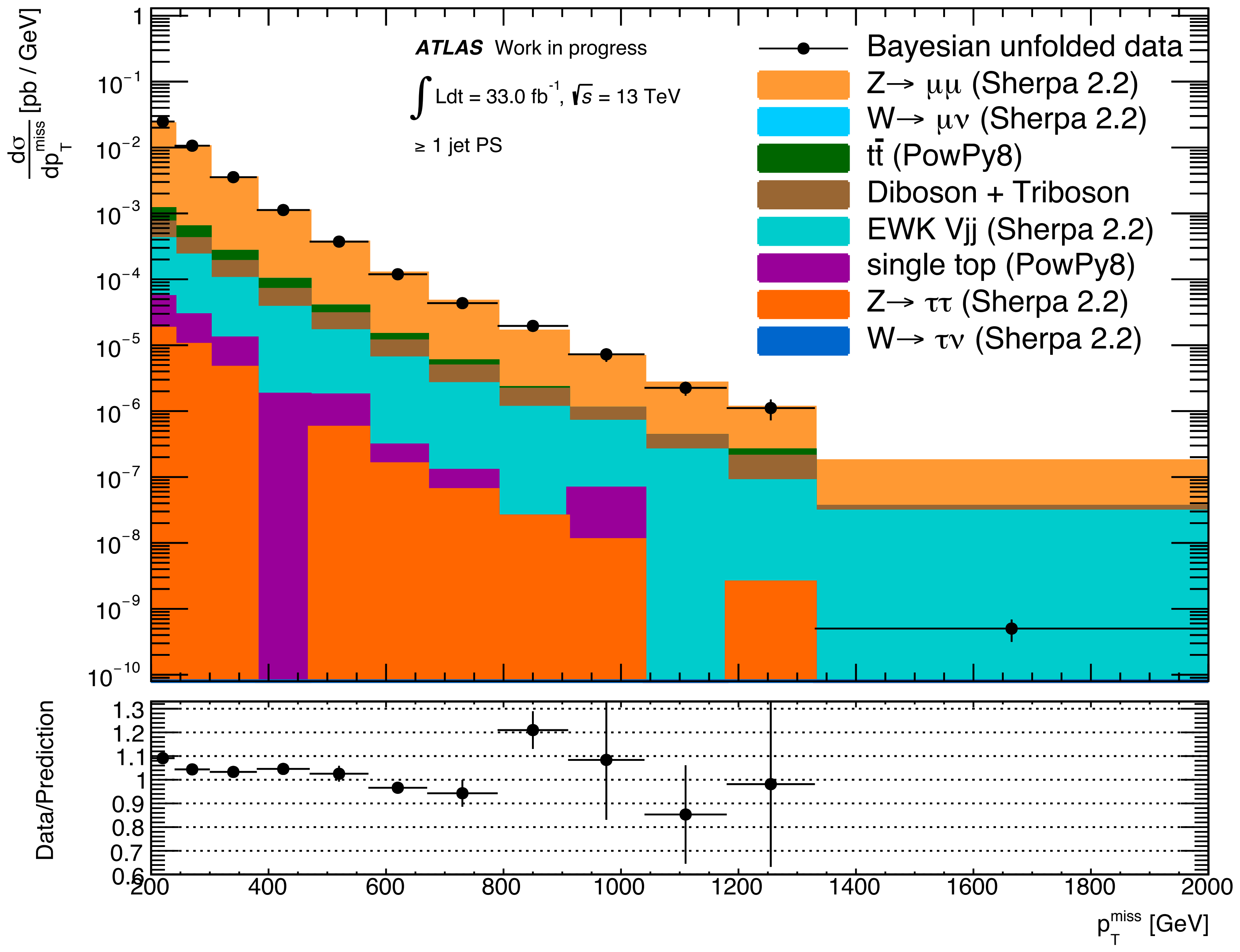
- Exactly 0 leptons required, veto events with additional leptons.
- Multijet background not included.

1-muon SR



- Exactly one muon, veto events with additional leptons.
- p_T^{miss} observable includes muon p_T (treated as invisible) ➡ acts as a proxy for the W boson p_T.
- Veto events with b-jets to suppress top contributions.

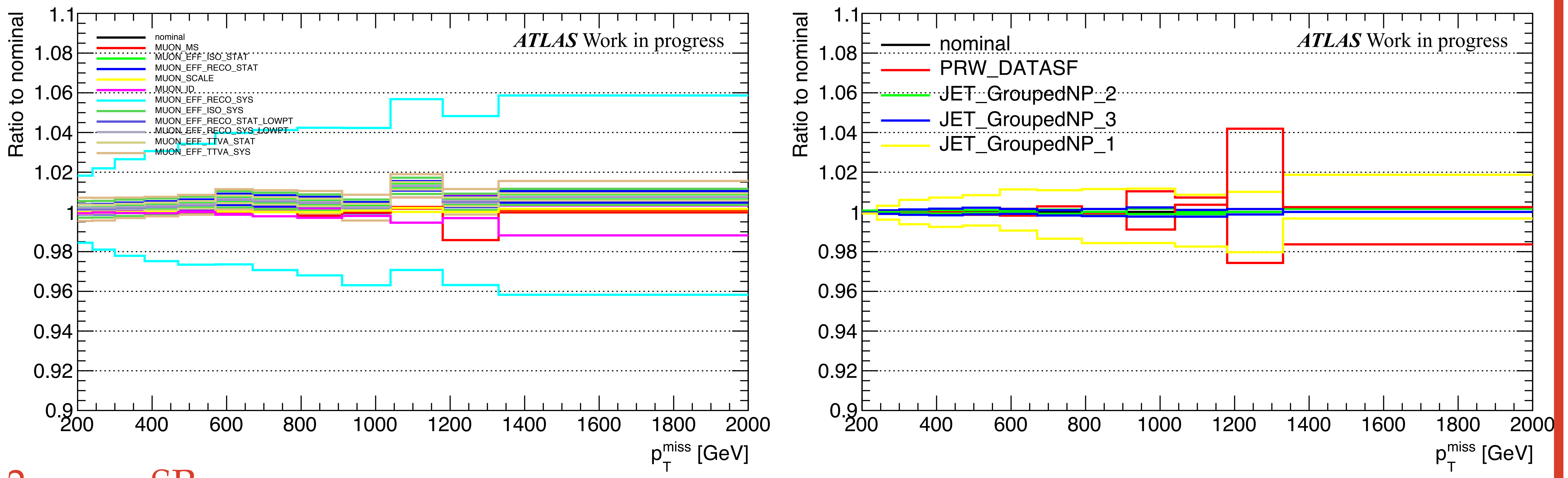
2-muon SR



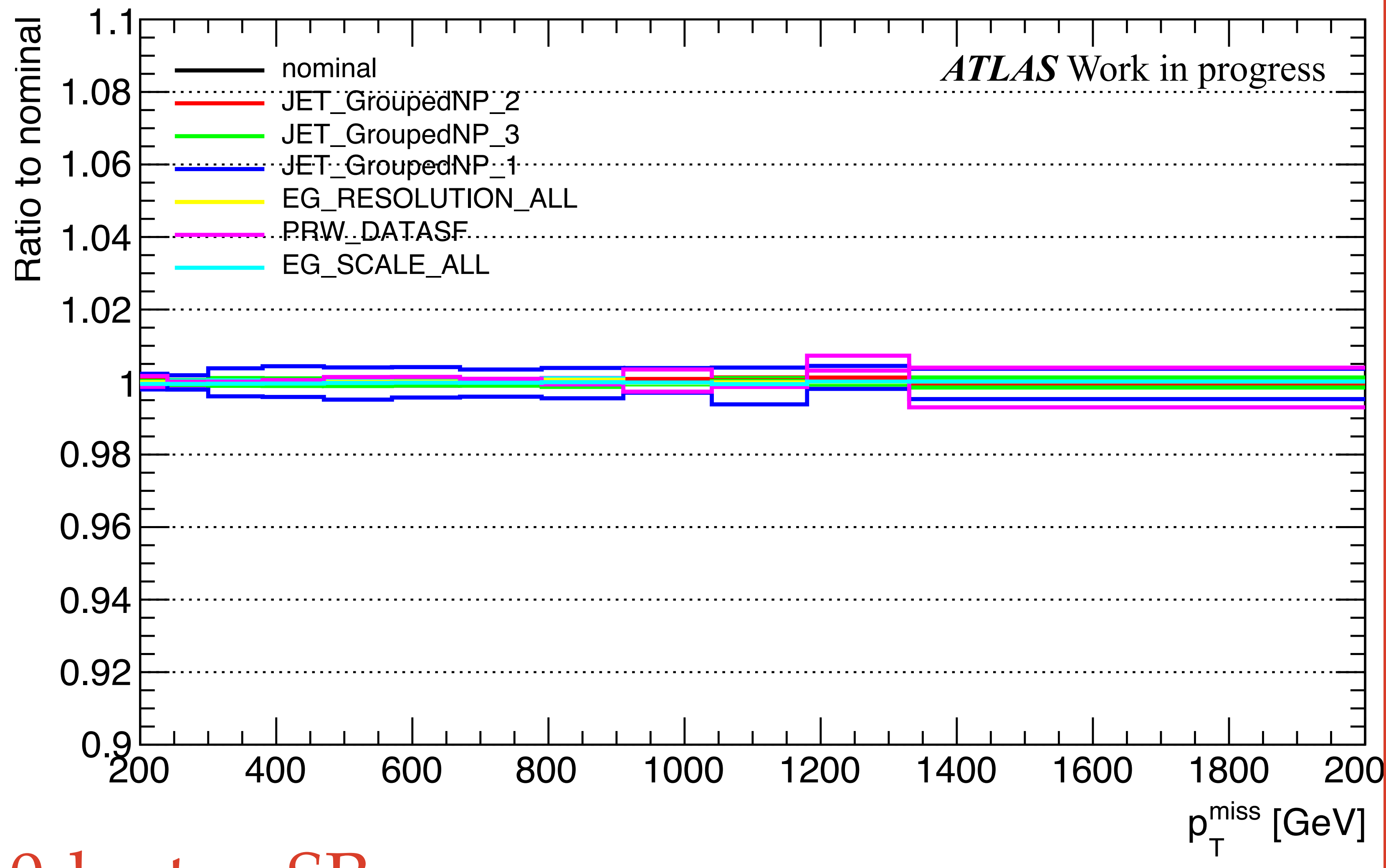
- Exactly one opposite-charge muon pair, veto events with additional leptons.
- 66 GeV < m_{ll} < 116 GeV
- p_T^{miss} observable includes muon p_T (treated as invisible) ➡ acts as a proxy for the Z boson p_T.

Systematic Uncertainties

1-muon SR

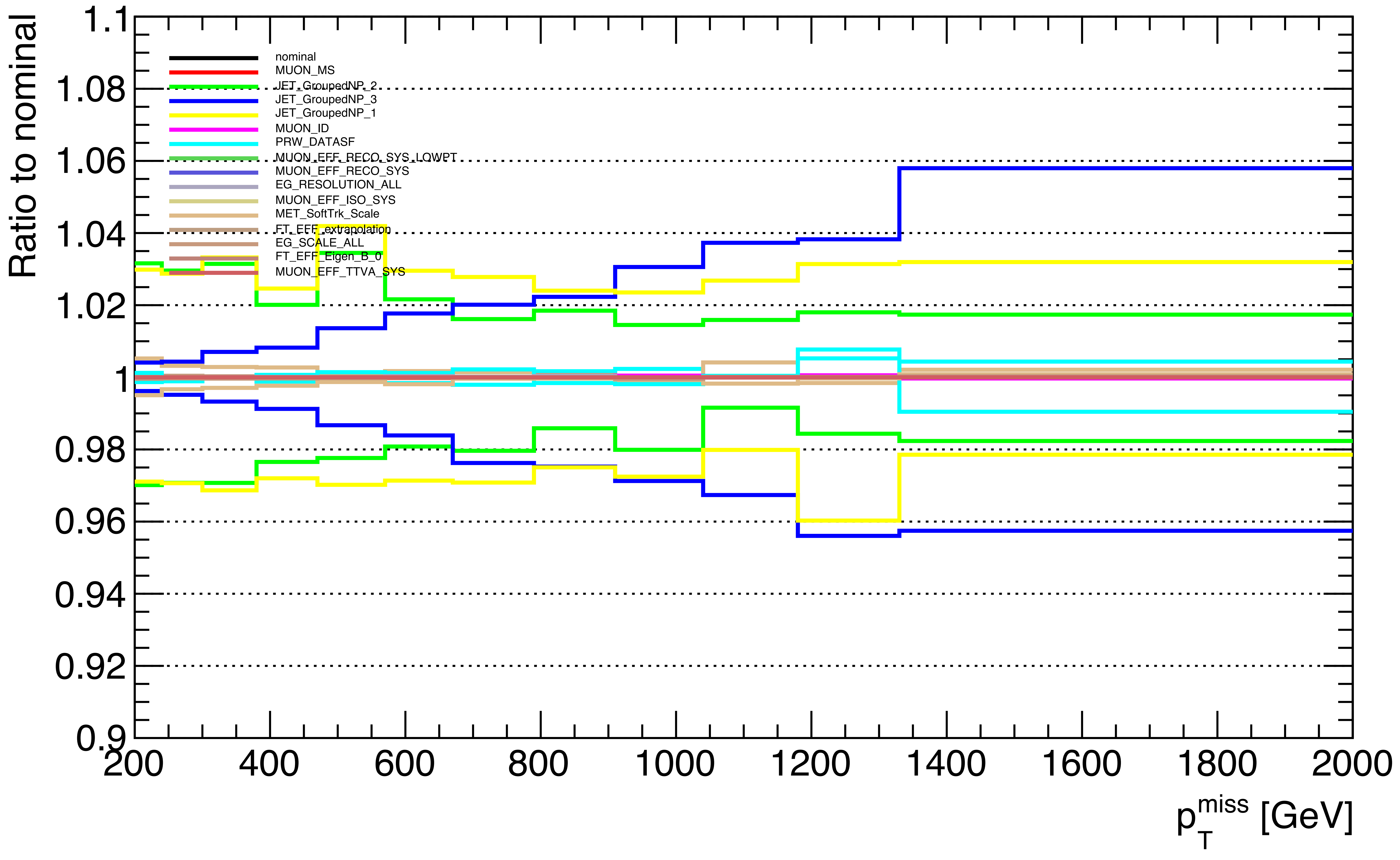


2-muon SR

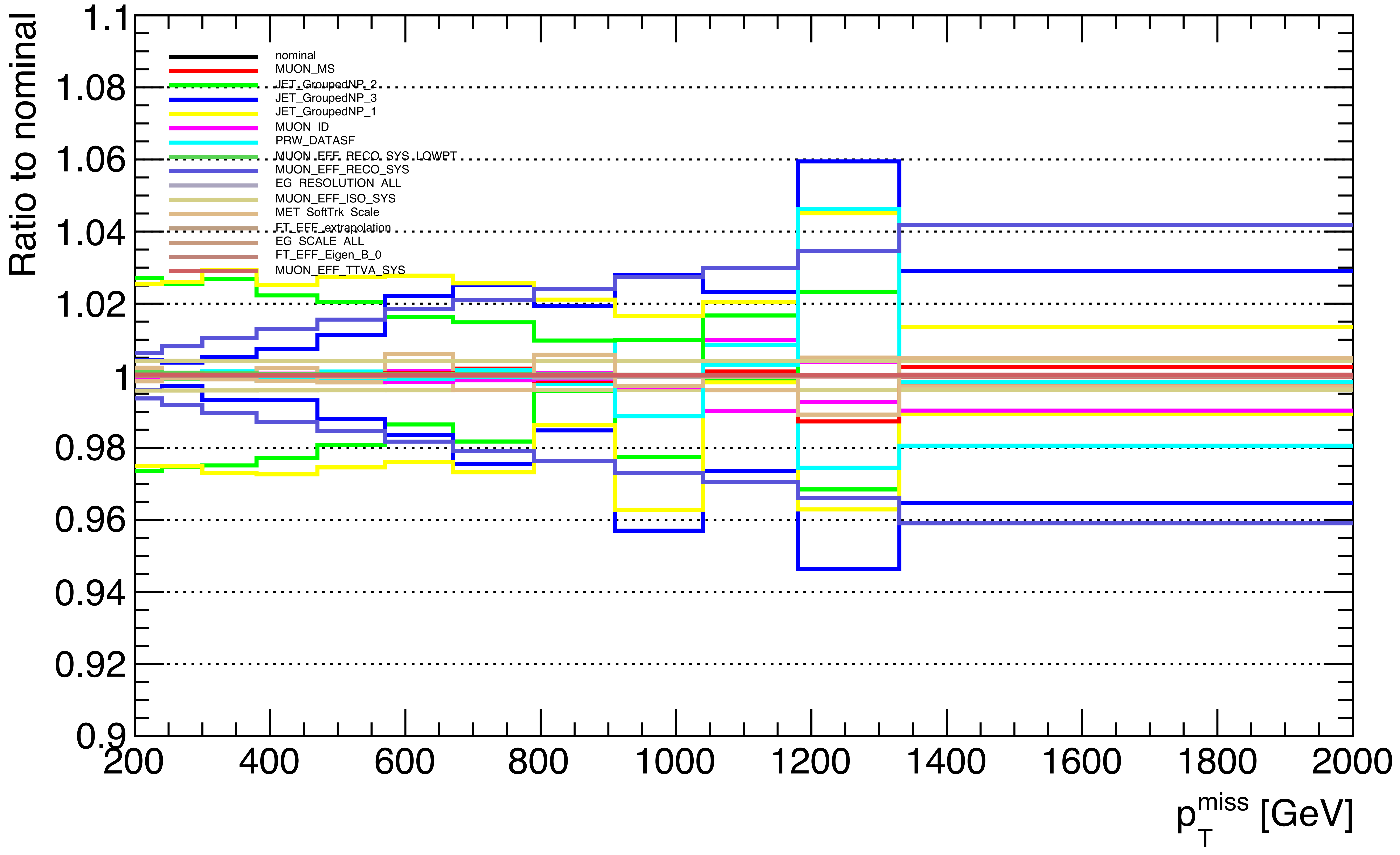


0-lepton SR

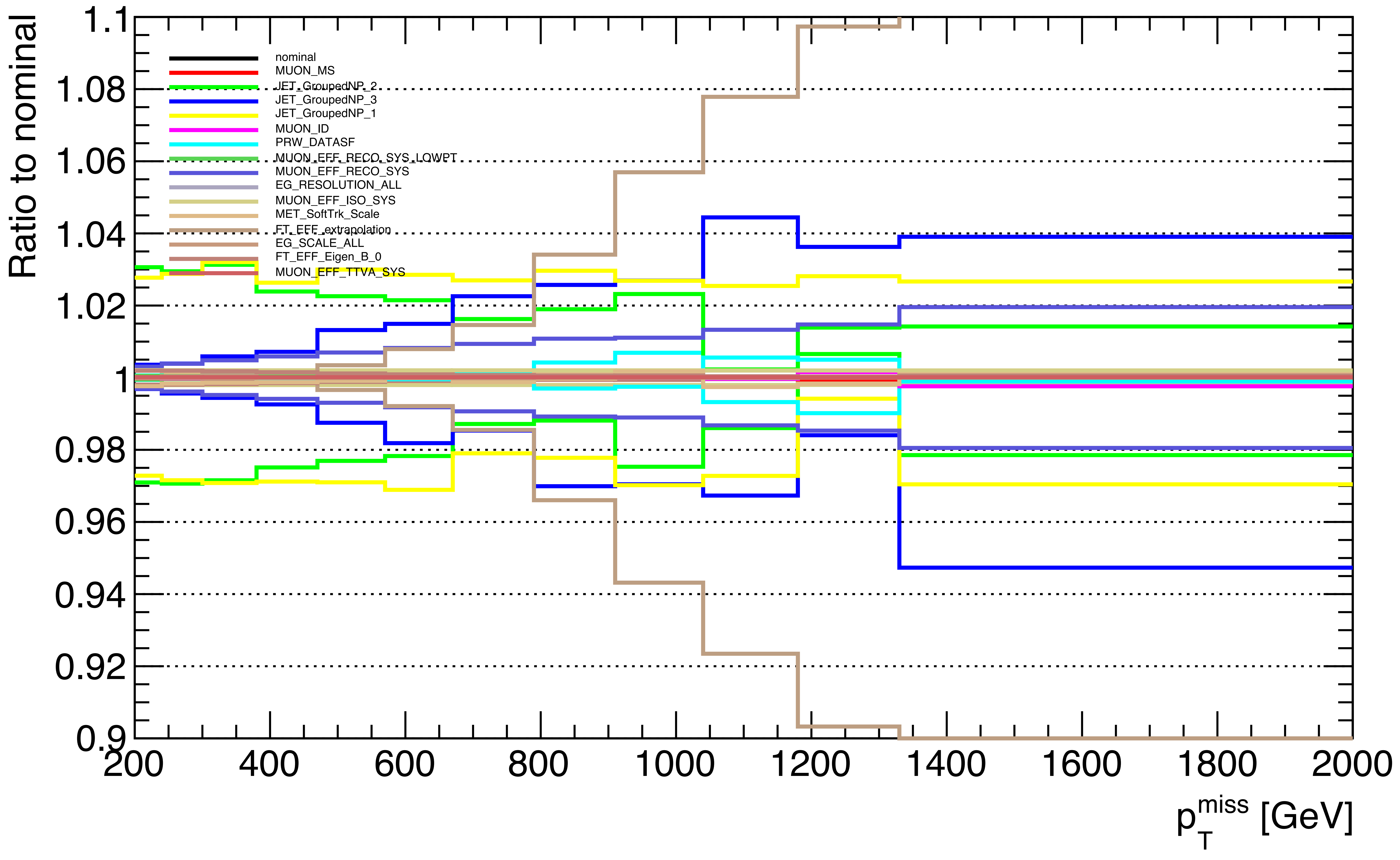
Systematic Uncertainties: 0-lepton Signal Region



Systematic Uncertainties: 2-muon Control Region



Systematic Uncertainties: 1-muon Control Region

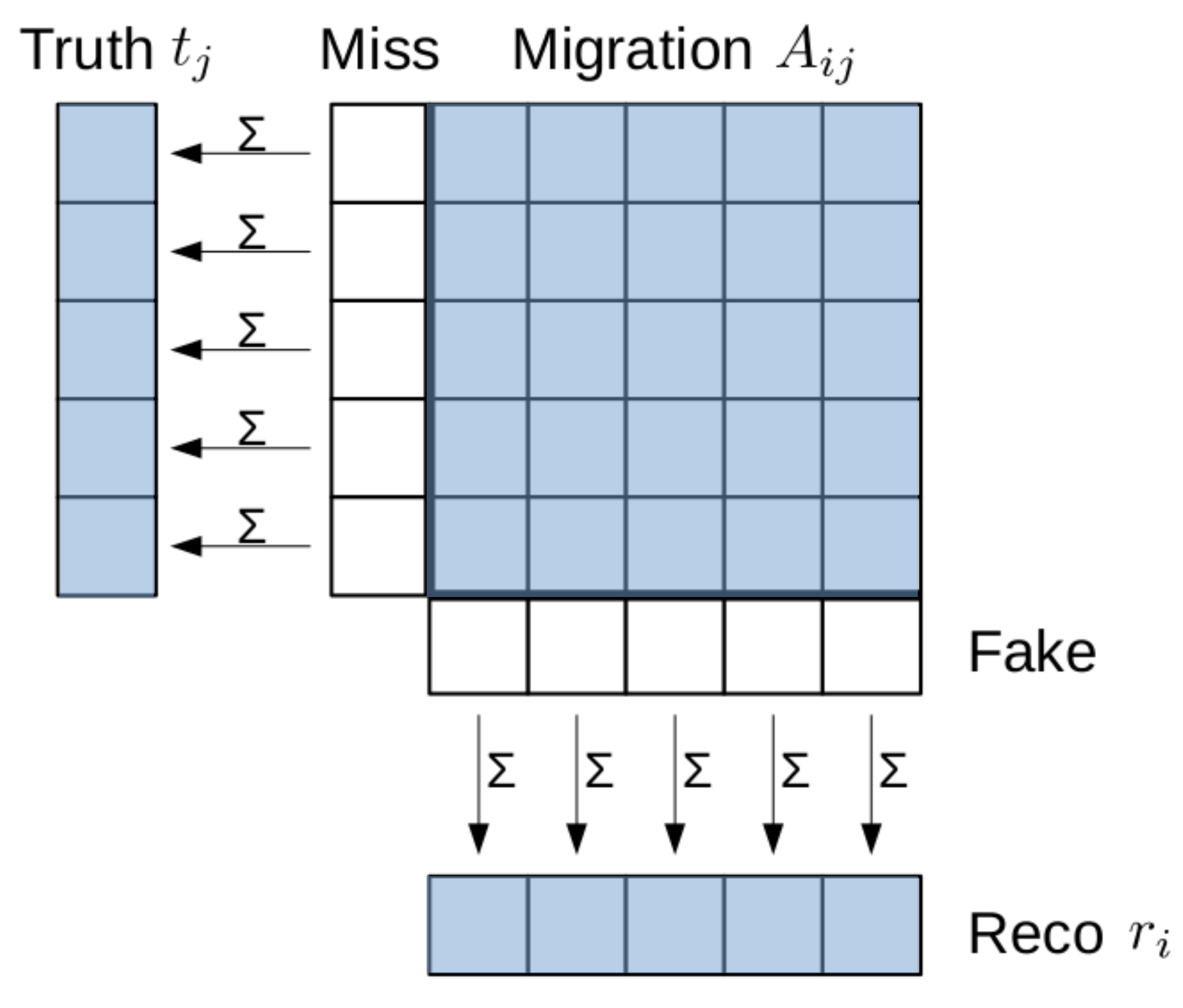


Bayesian unfolding

- Fill a response matrix with events which pass **both** the reco and particle-level event selection.
- The response matrix represents the probability of a measured spectrum given an underlying true distribution (particle-level MC)
- Correct for detector-level events which did not fall in the particle-level fiducial region definition (**Fakes)**.
- Correct for efficiency and acceptance losses when going from particle-level to detector-level (**Miss).**
- Use Bayes' theorem to find the probability of an underlying true spectrum given the measured spectrum.

↓

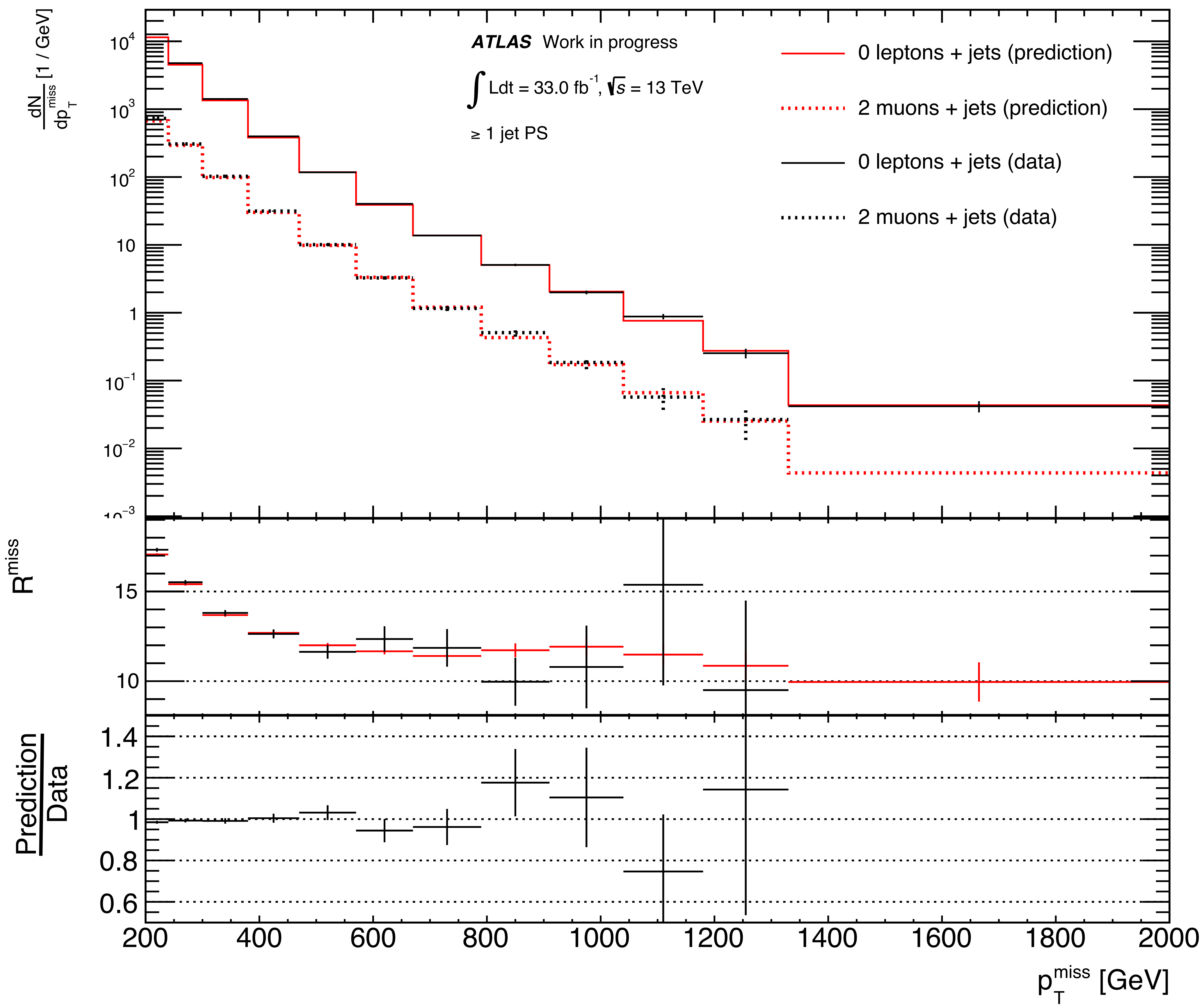
🎉 **the unfolding matrix** 🎉

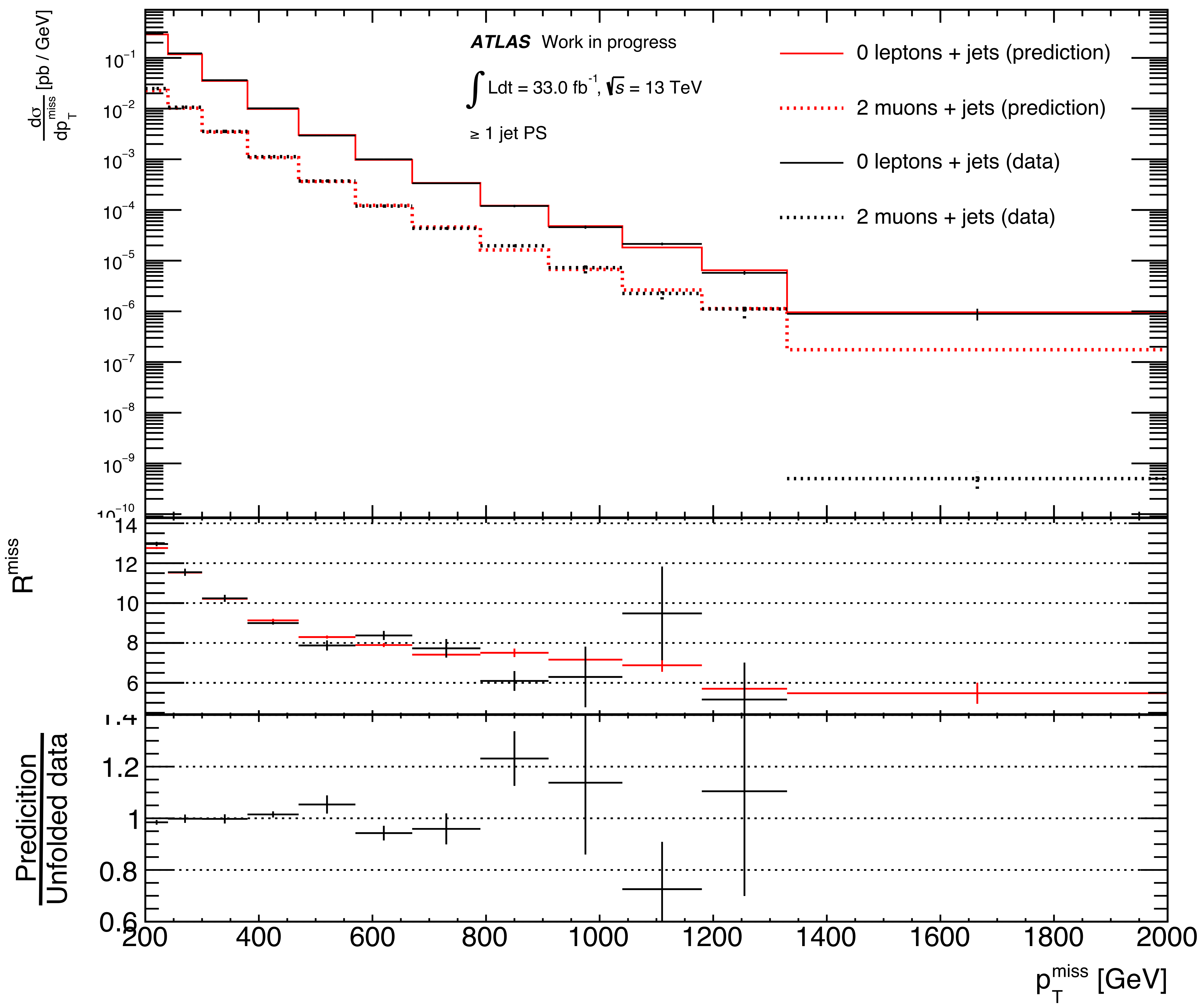


MET in monojet-like PS

Ratios: 0-lepton / 2-muon: met in monojet-like PS

Unfold

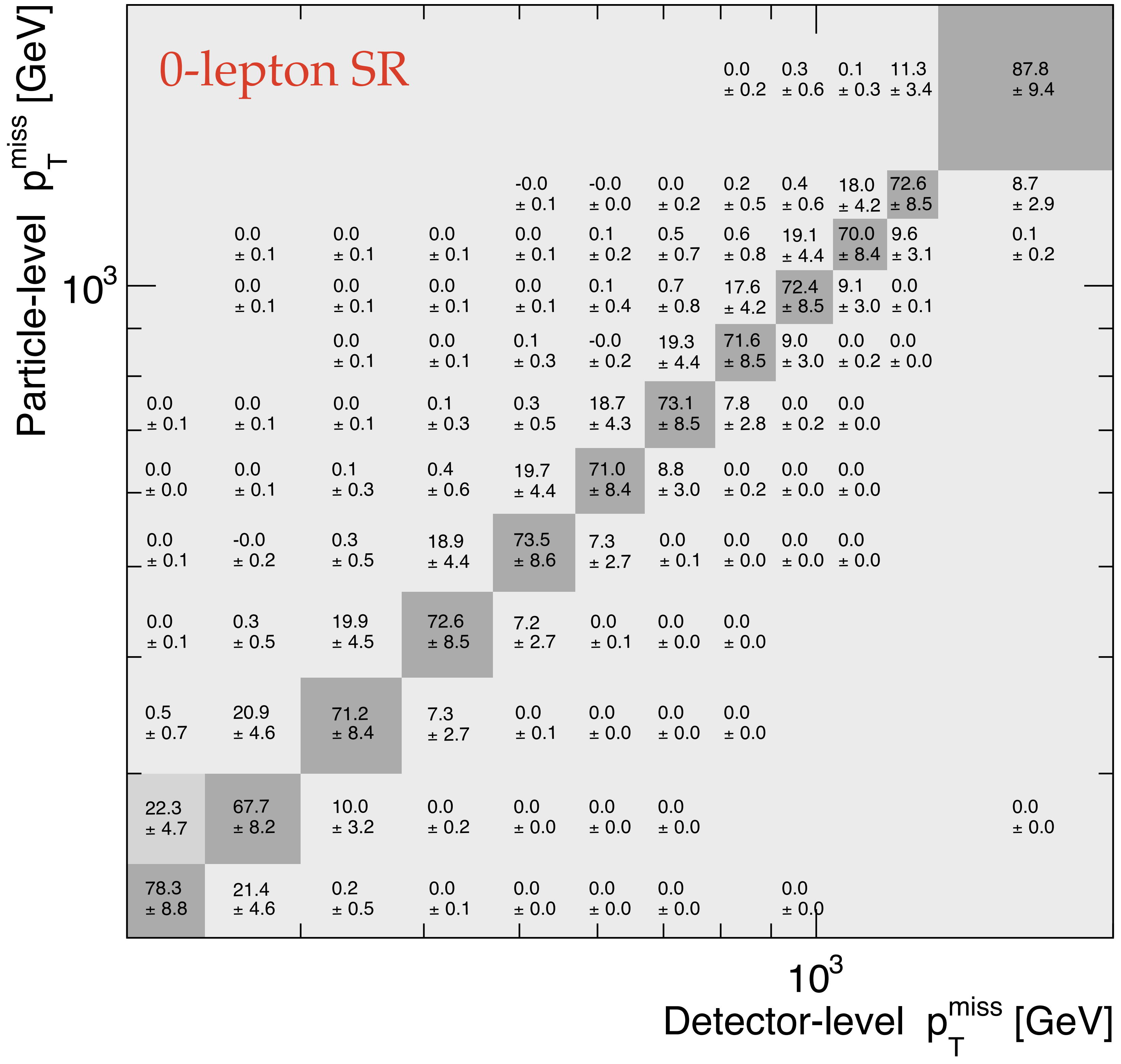


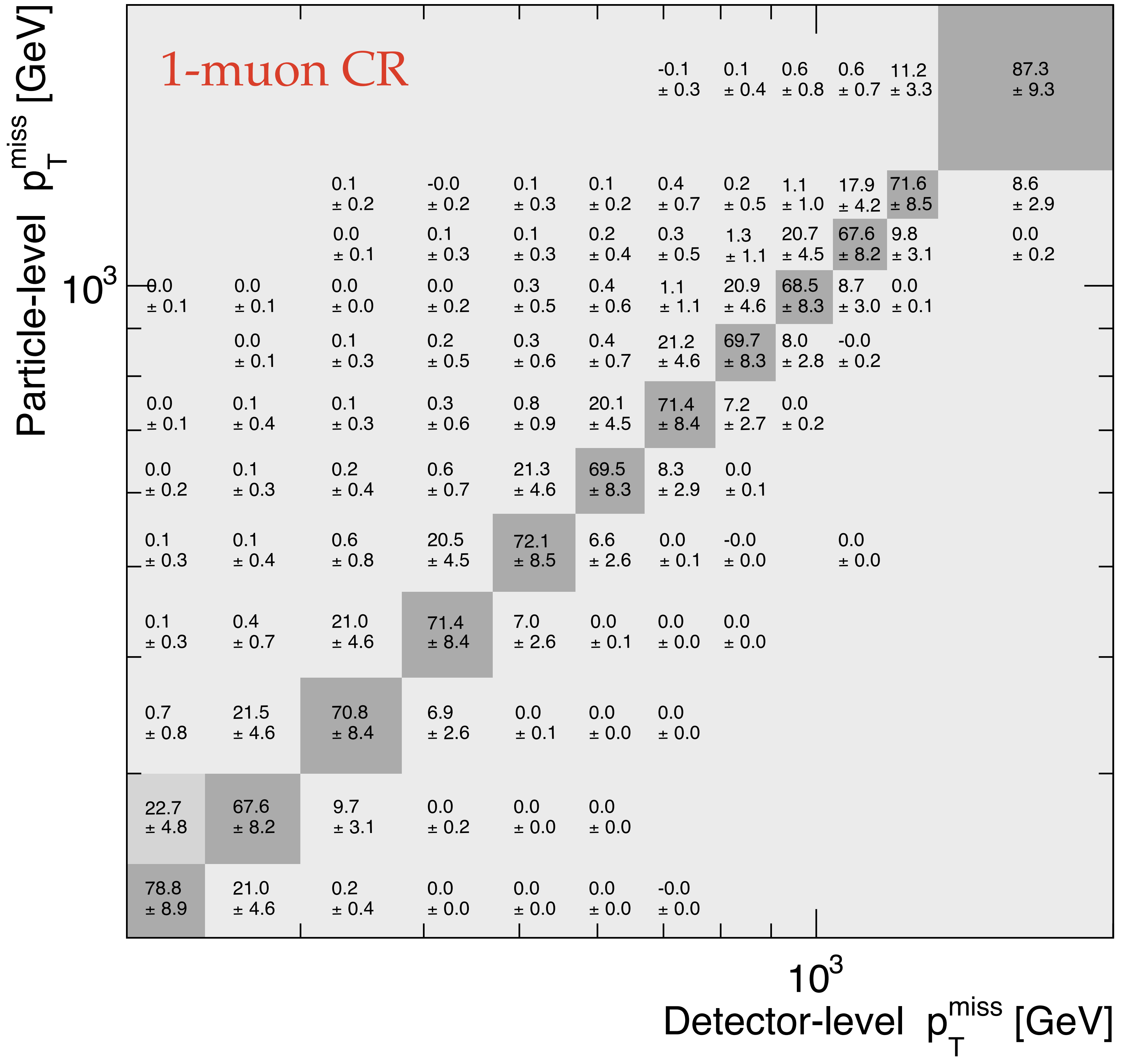


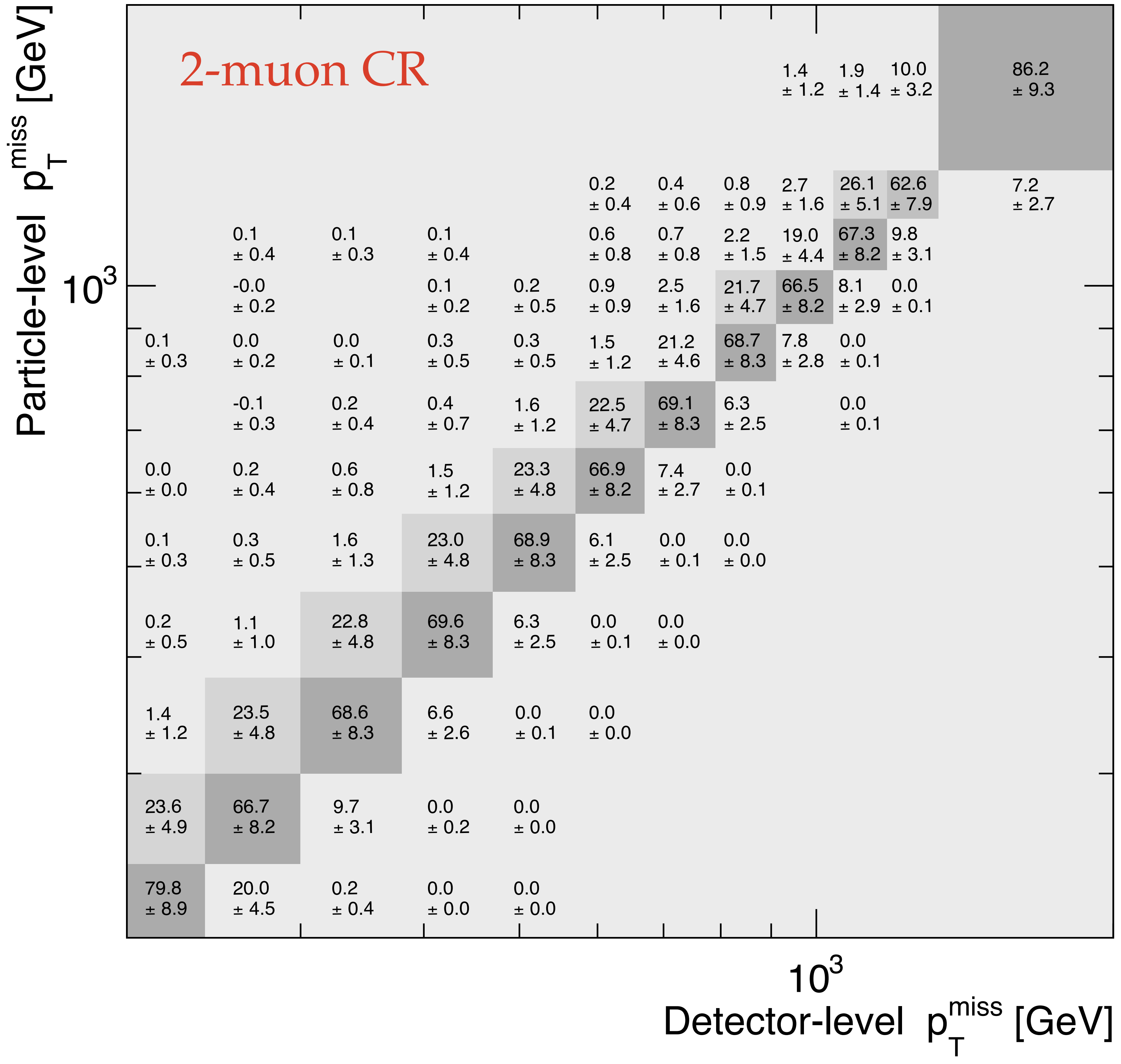
Ratios: 0-lepton / 1-muon: met in monojet-like PS

Unfold

Response matrices



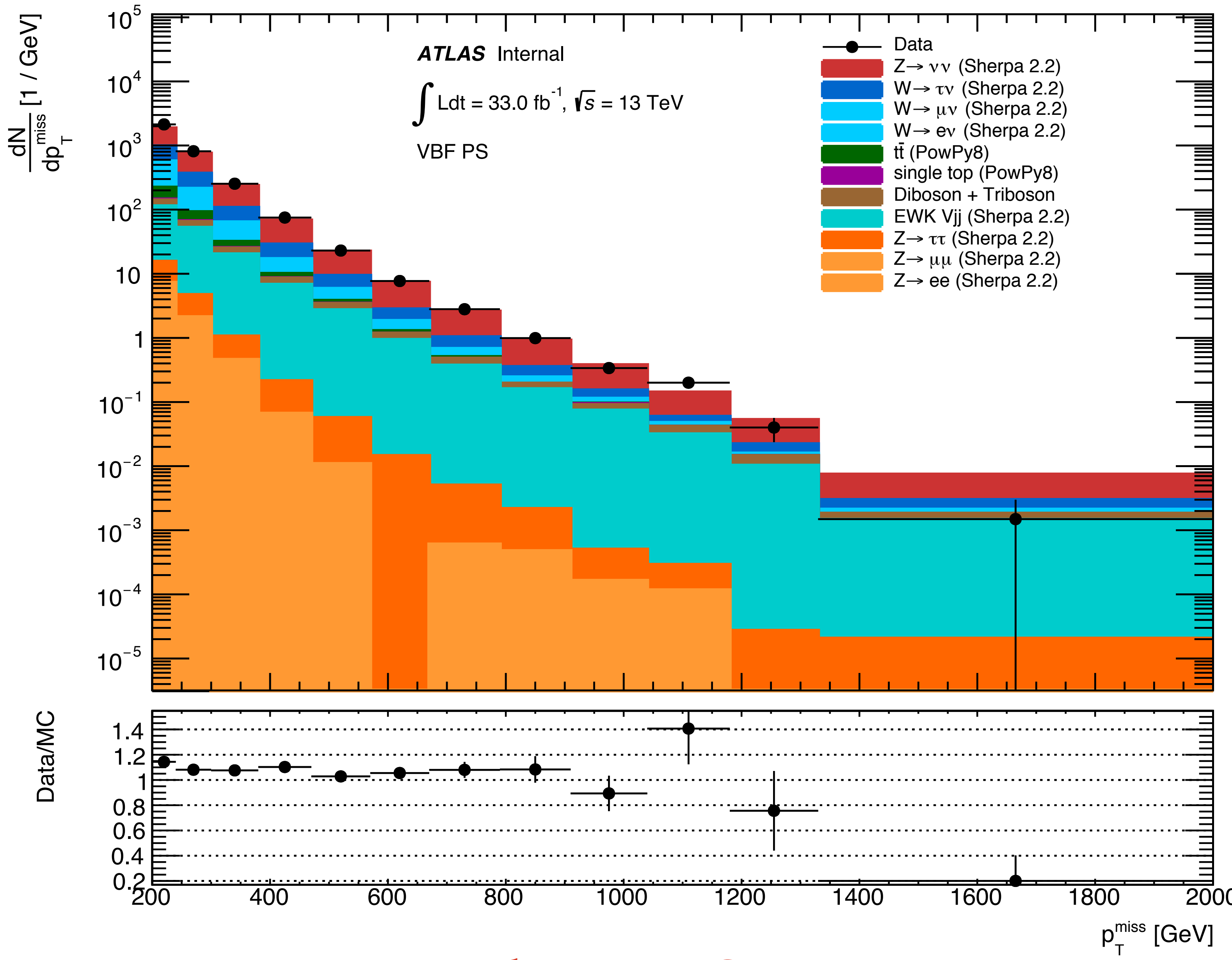


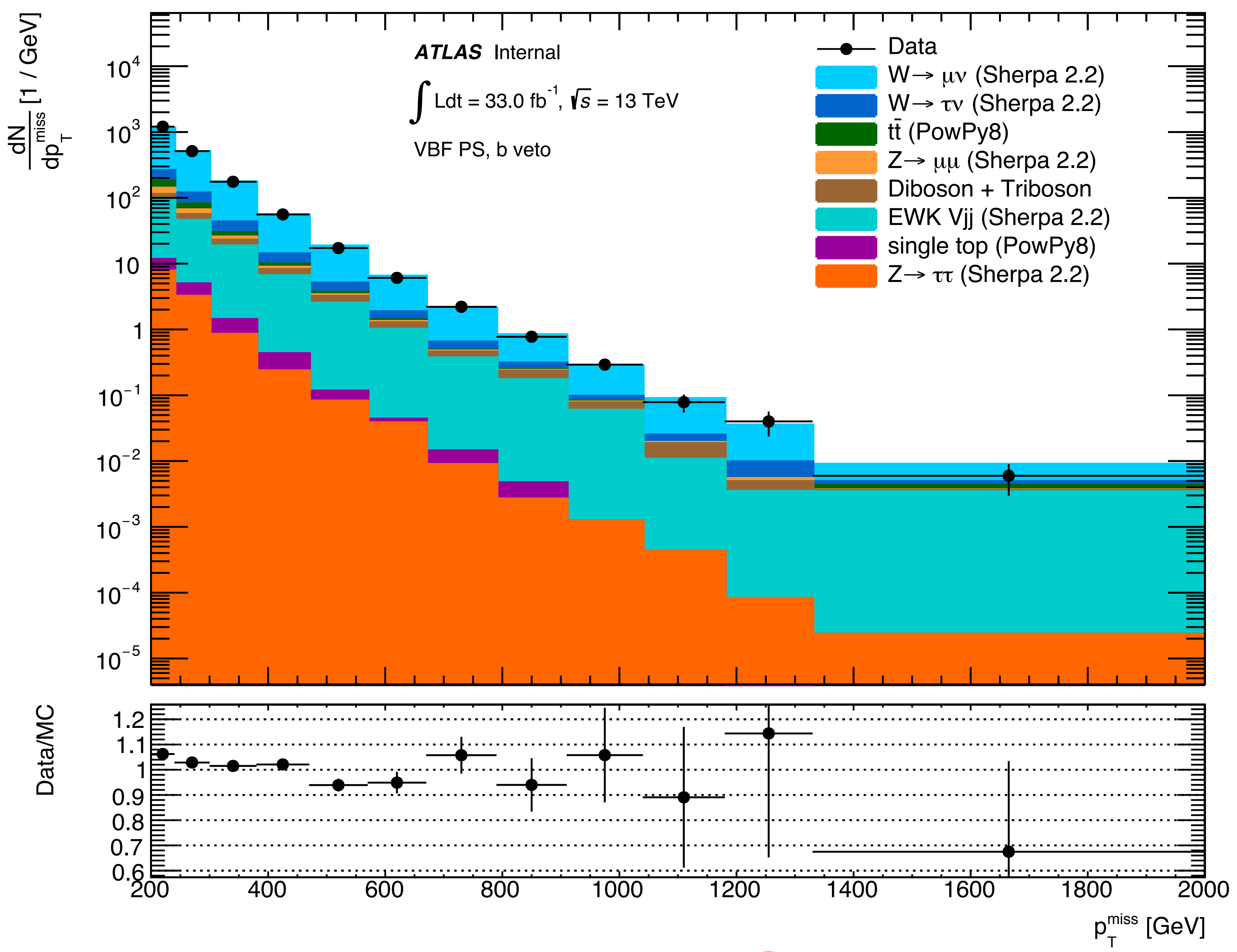


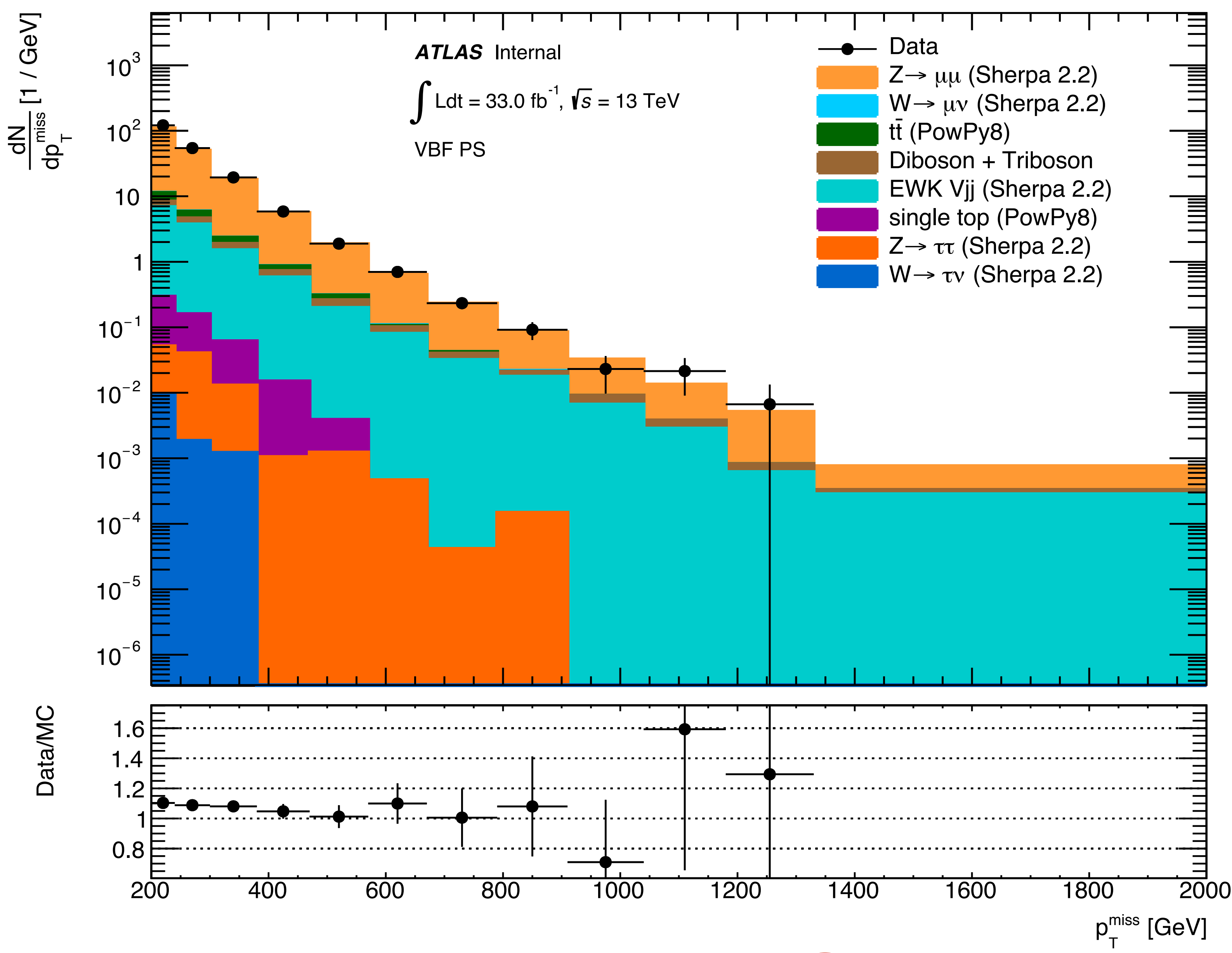
- Showing bin migrations when unfolding from reco to particle level
- Using Bayesian unfolding

MET in VBF

Detector-level





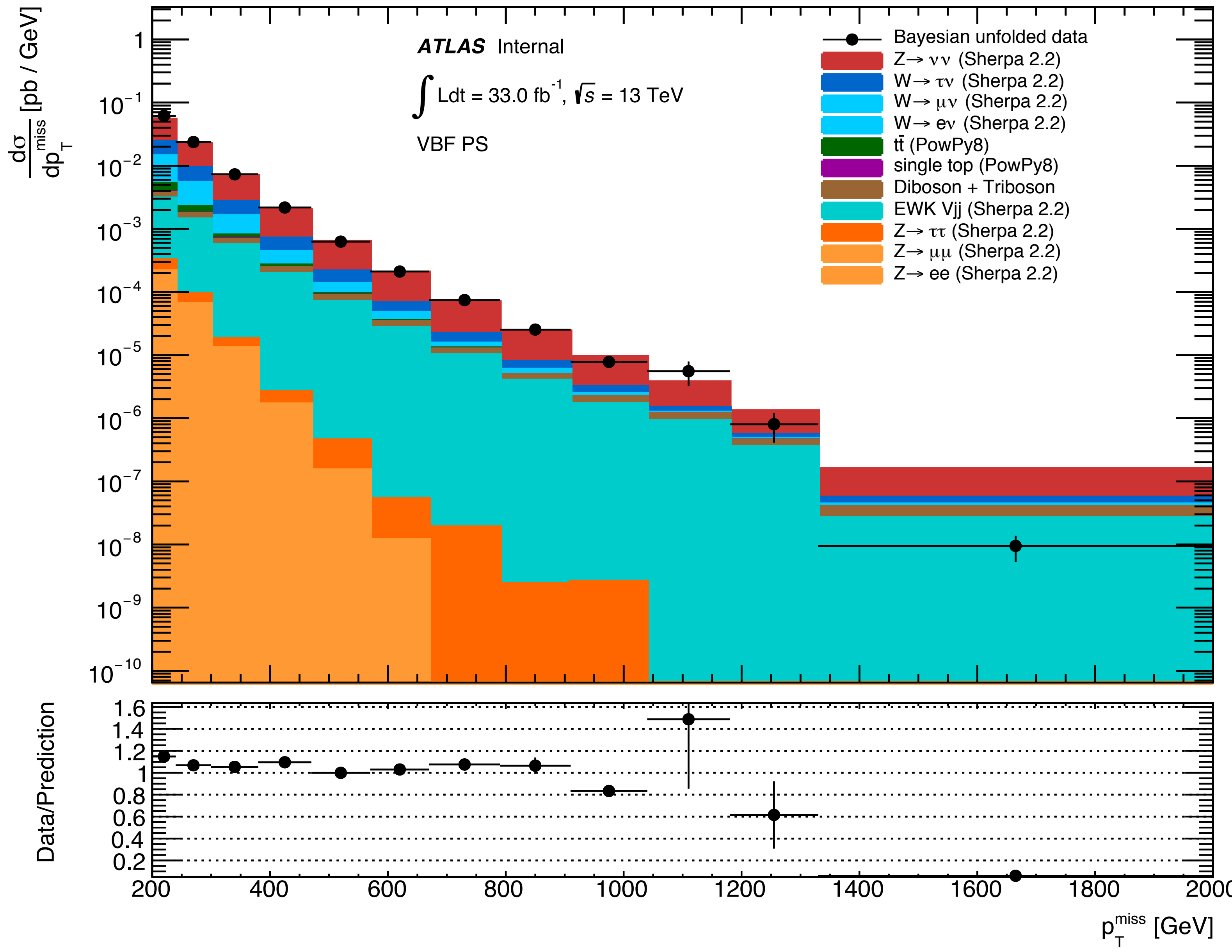


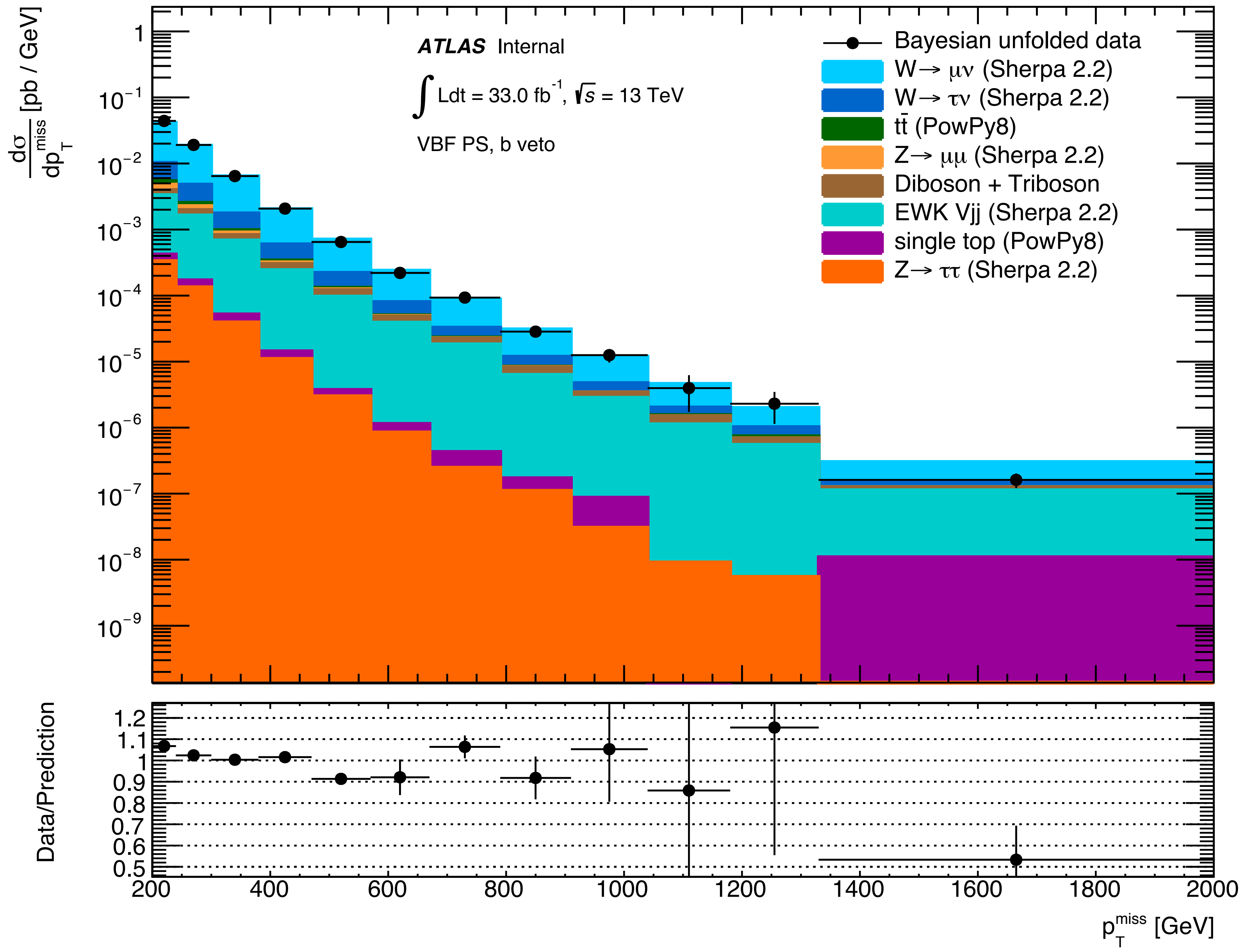
0-lepton SR

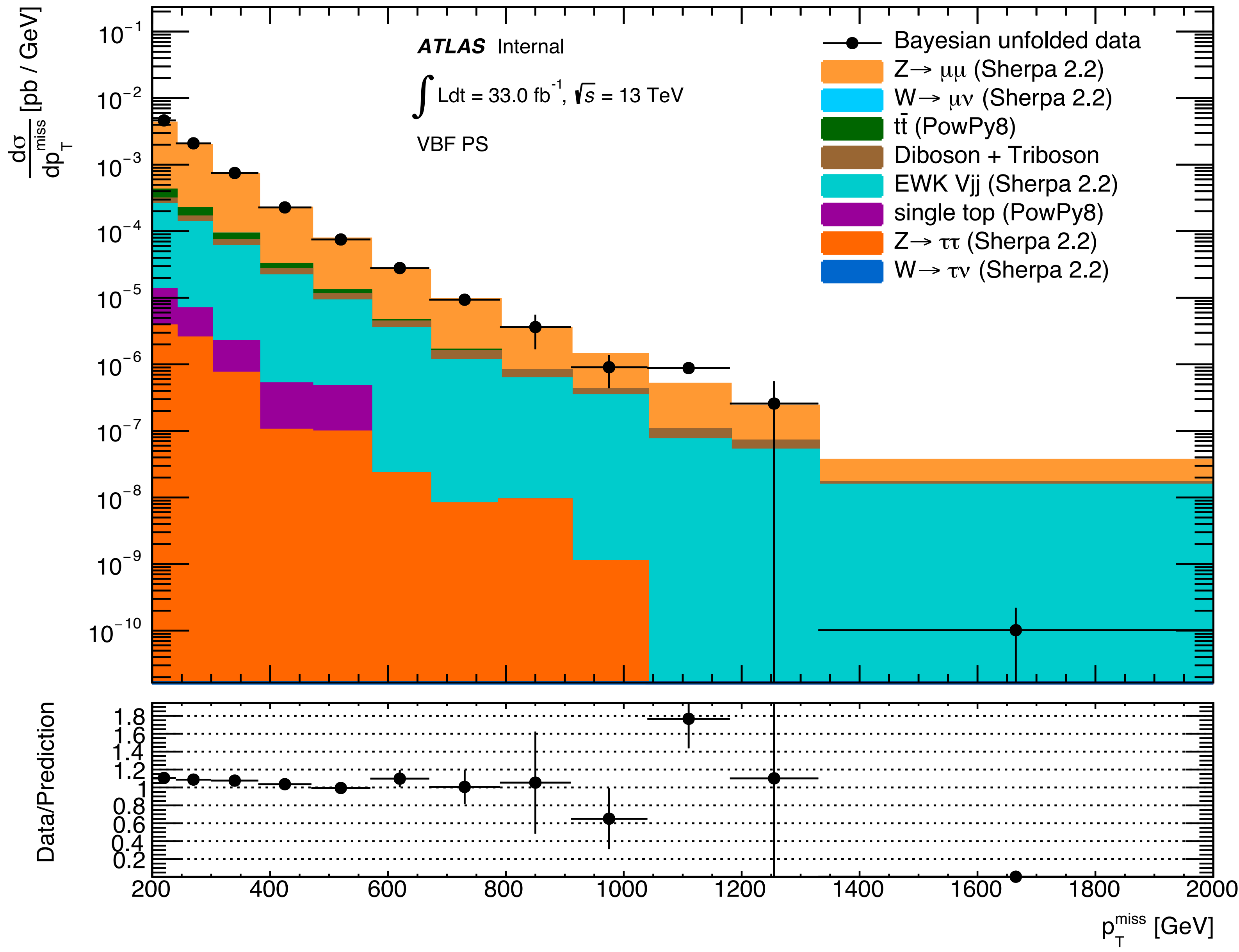
1-muon CR

2-muon CR

Unfolded

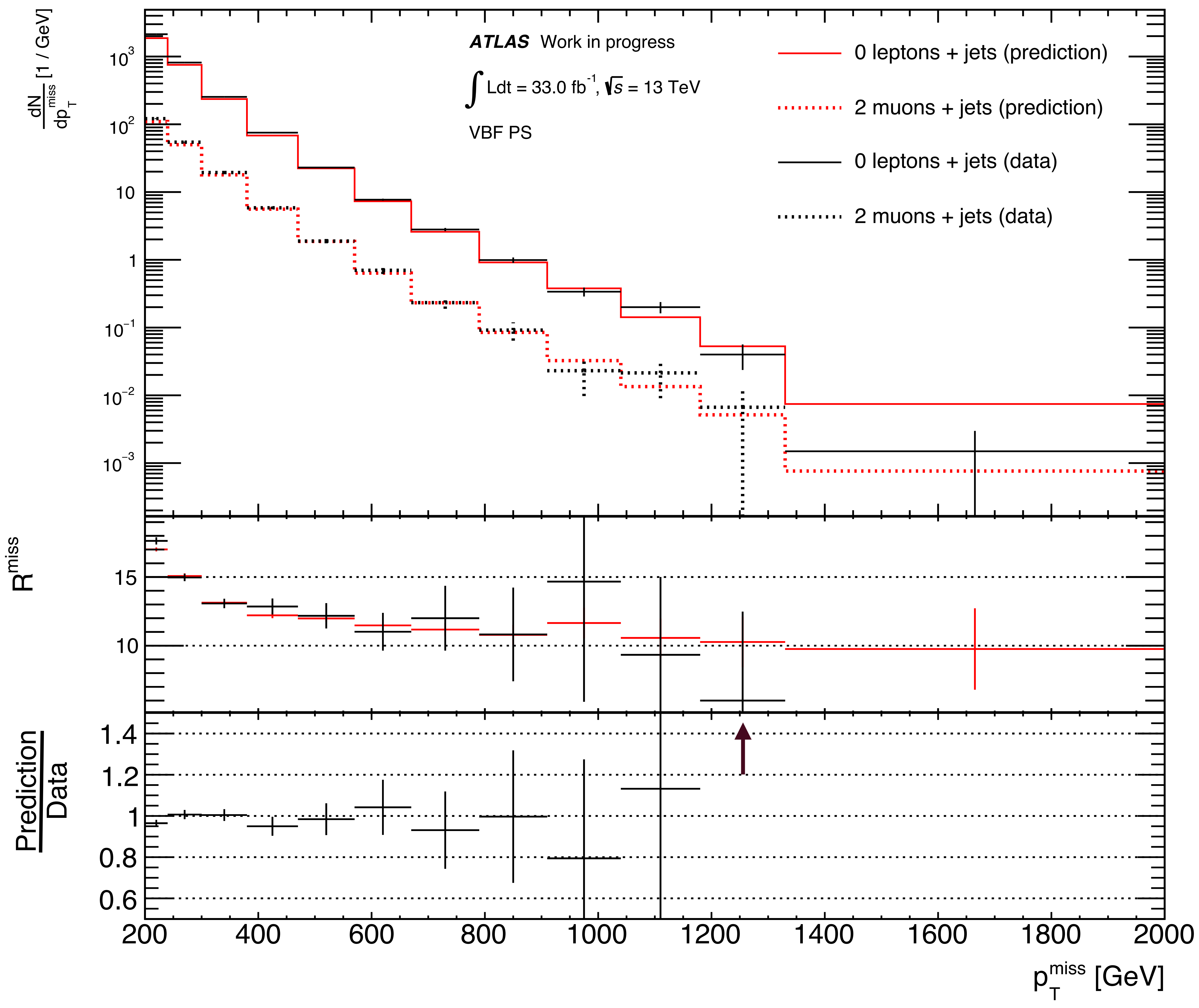


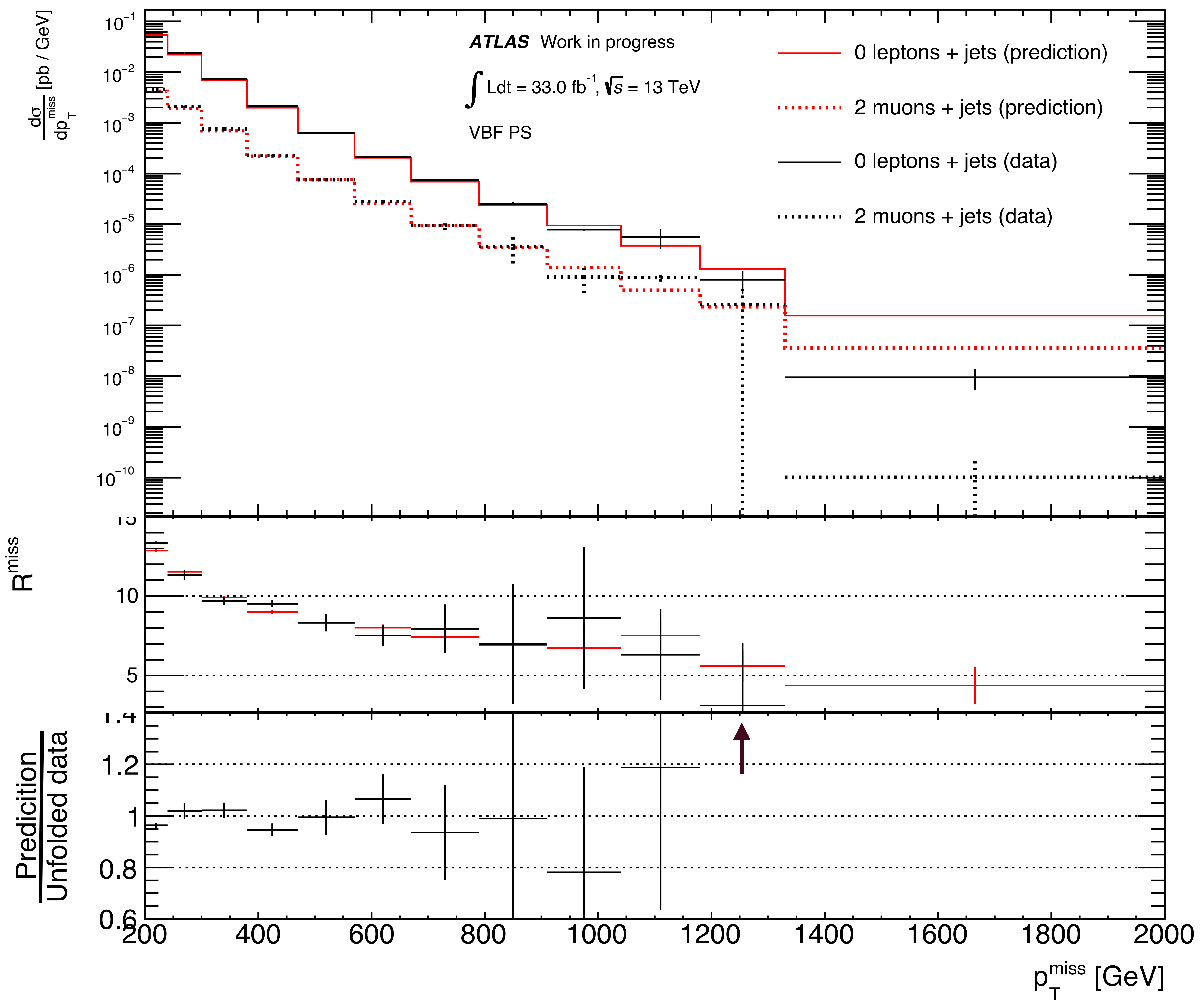




Ratios: 0-lepton / 2-muon: met vbf

Unfold





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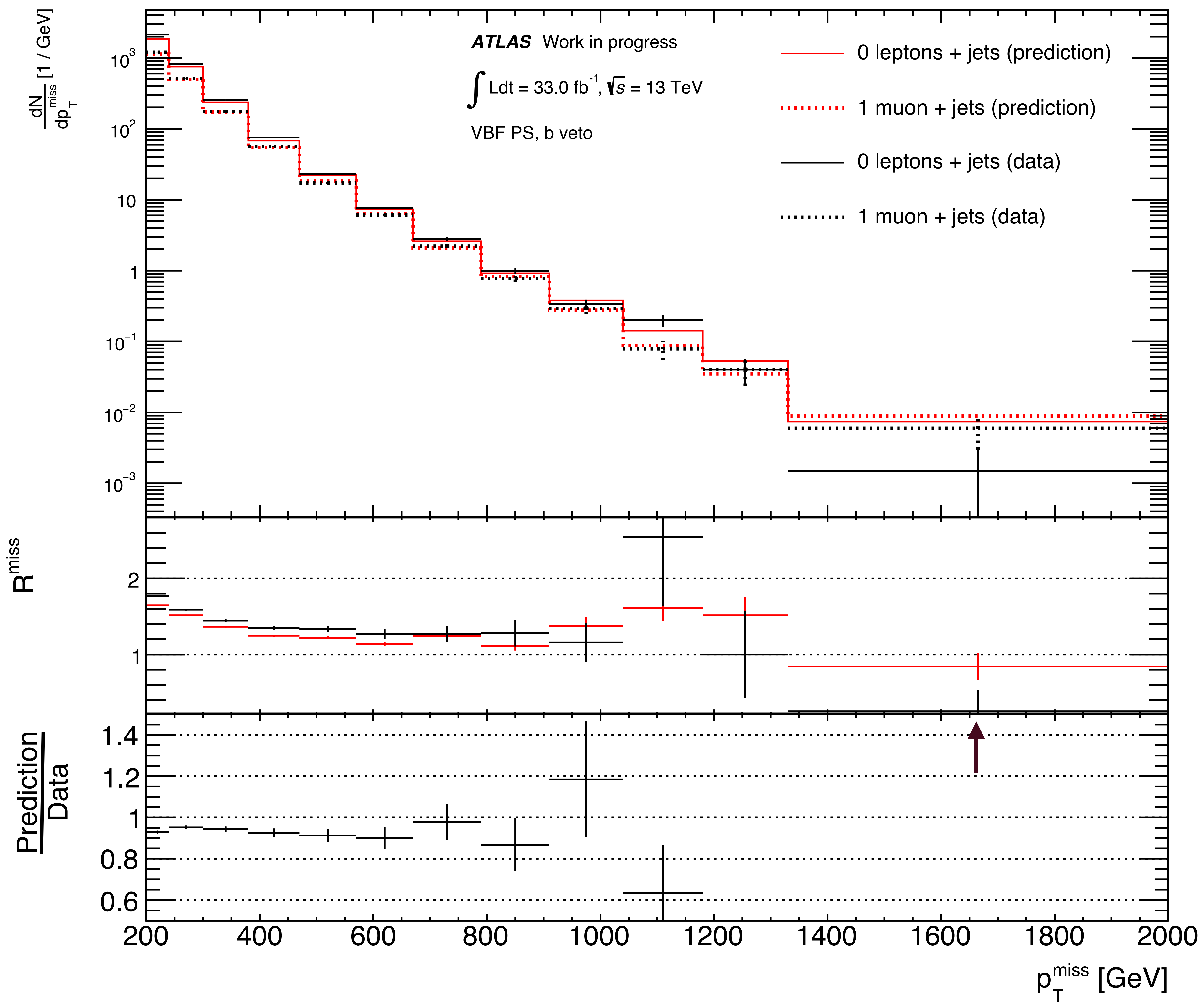
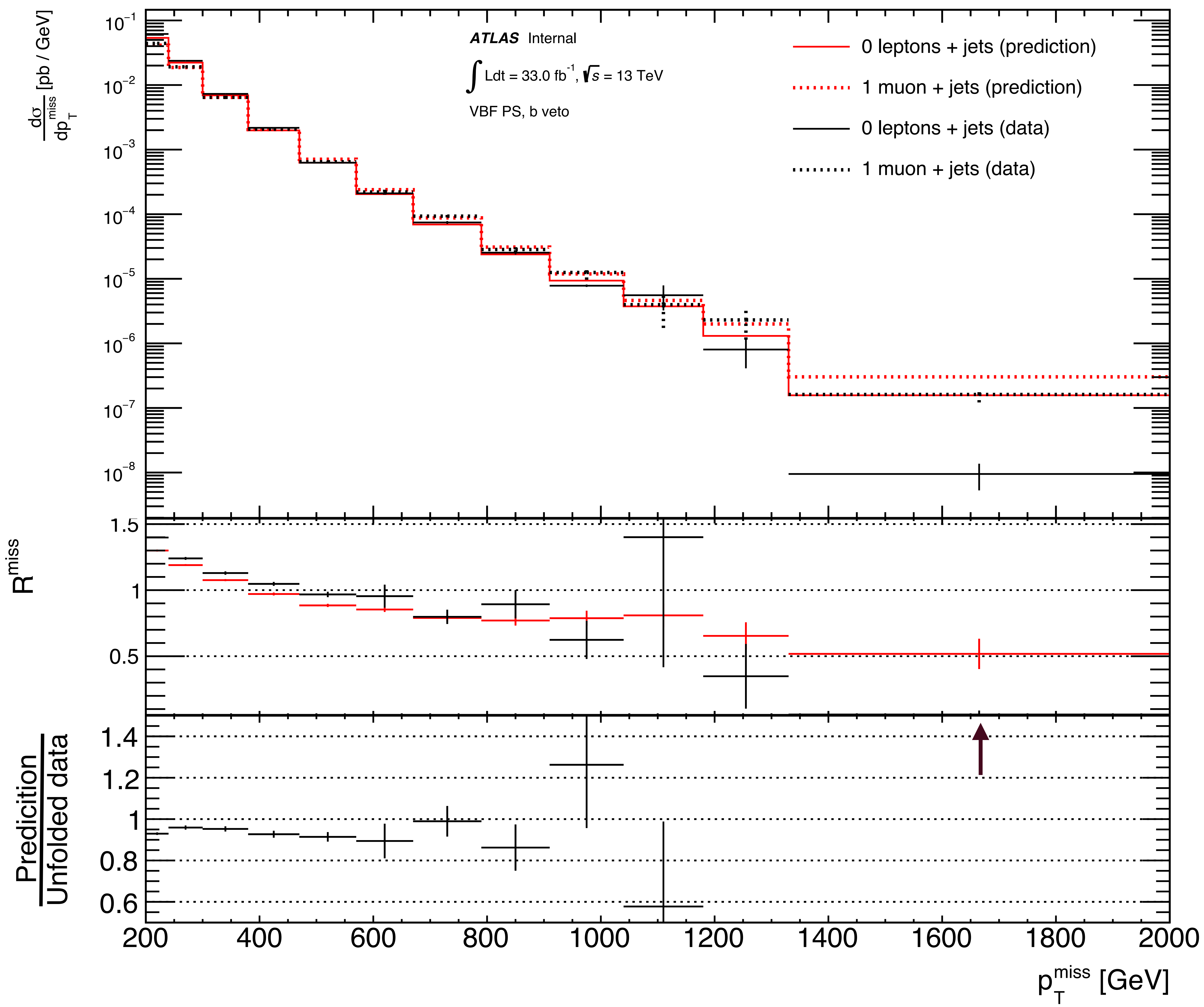
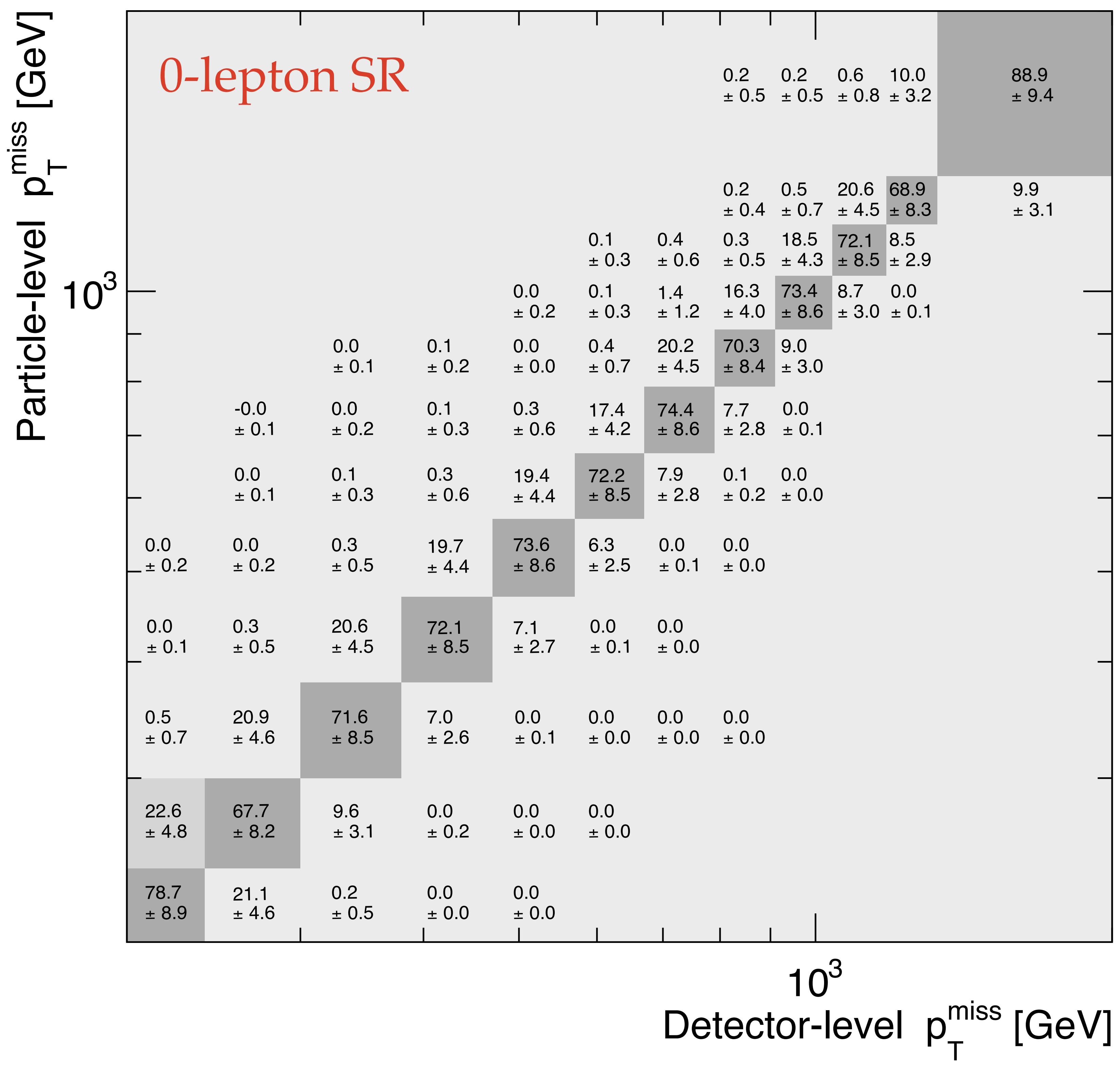
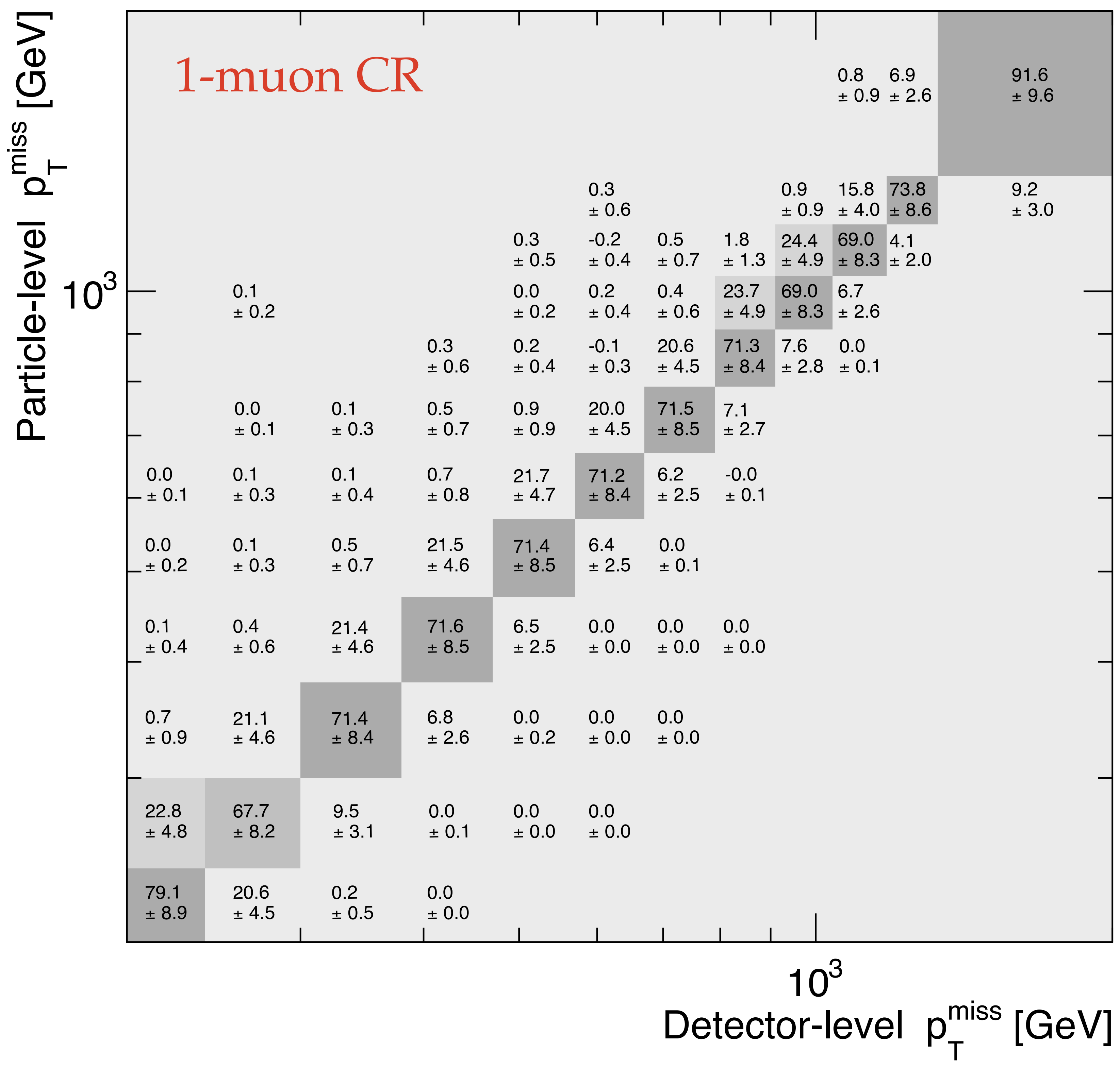
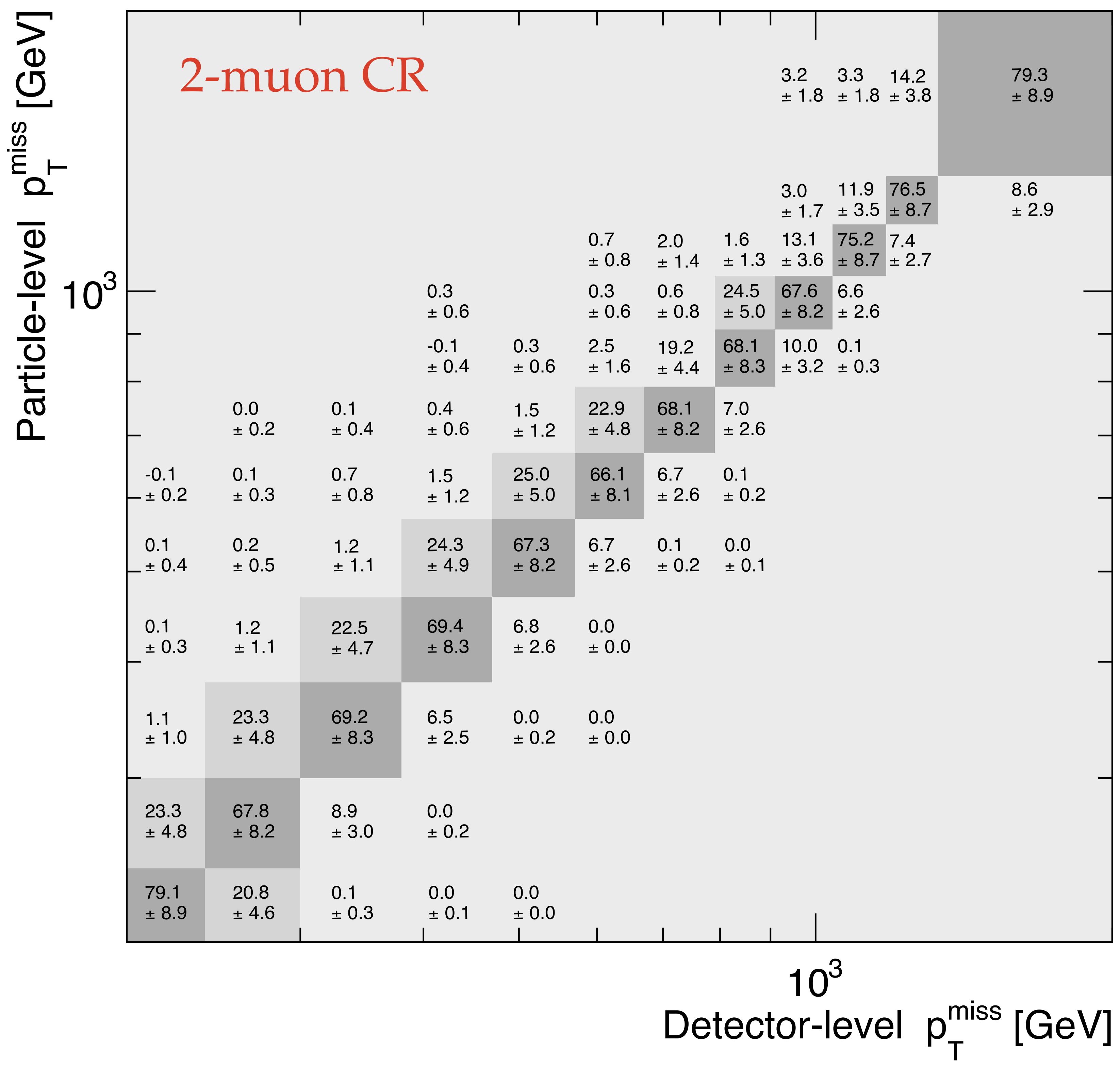




Response matrices







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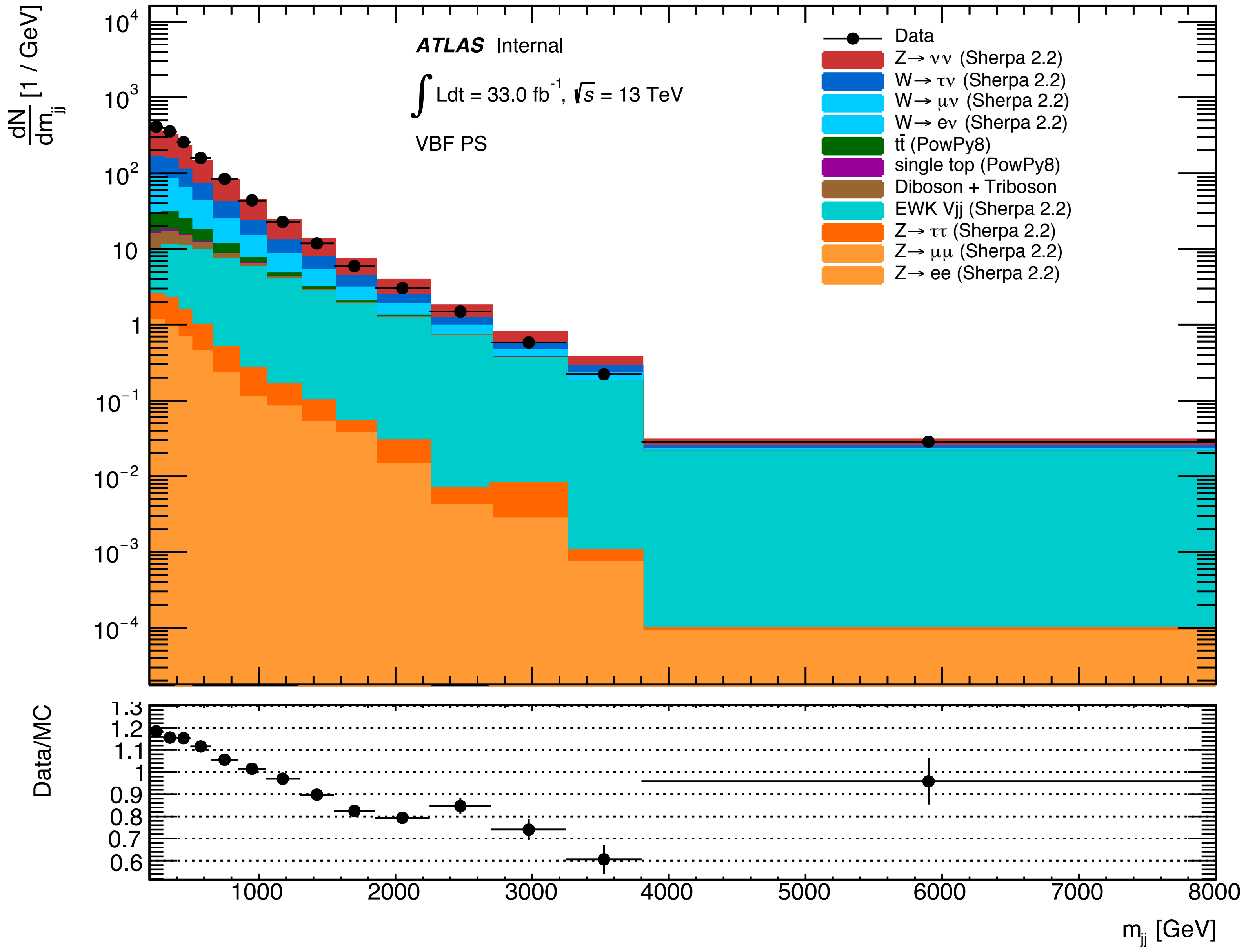
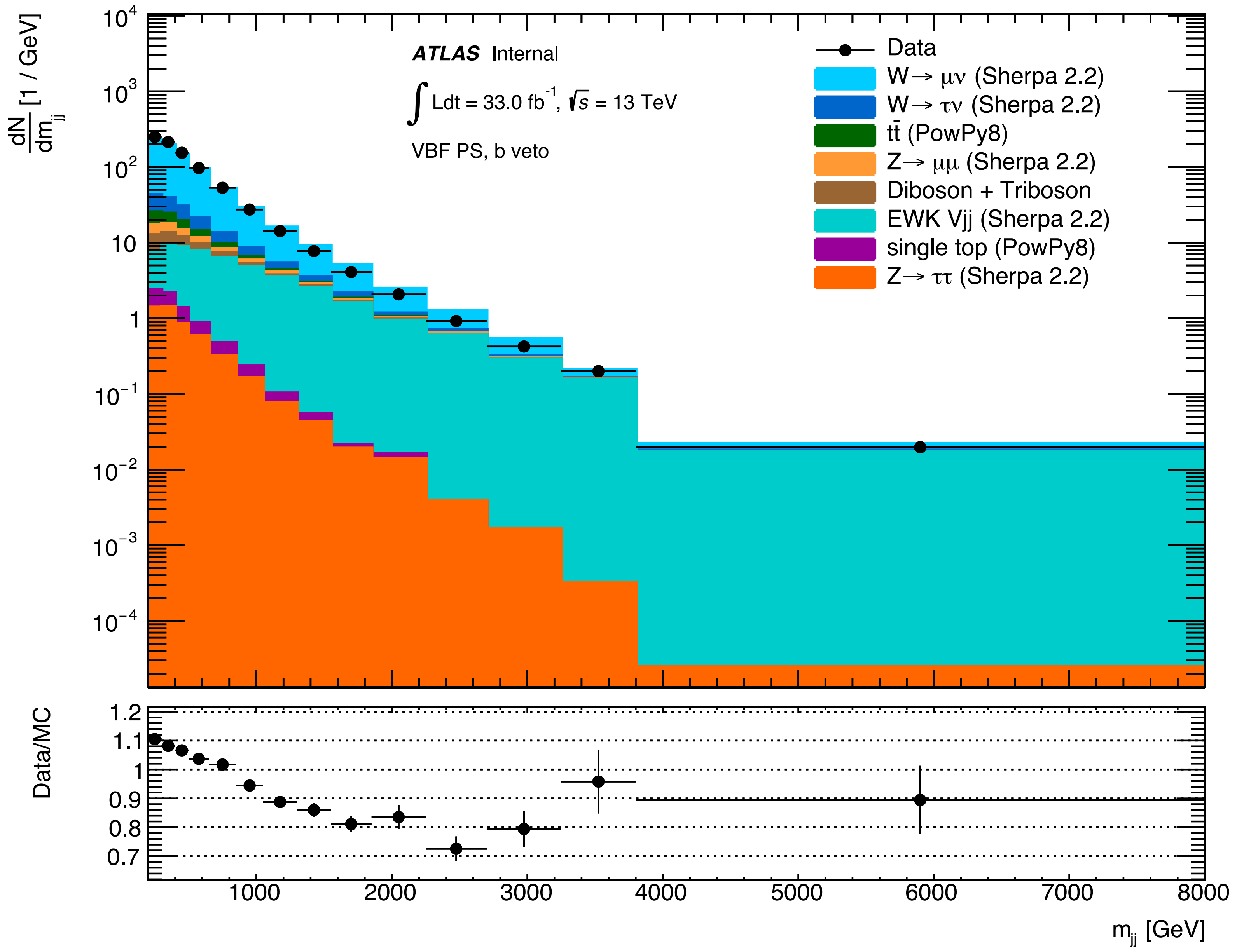
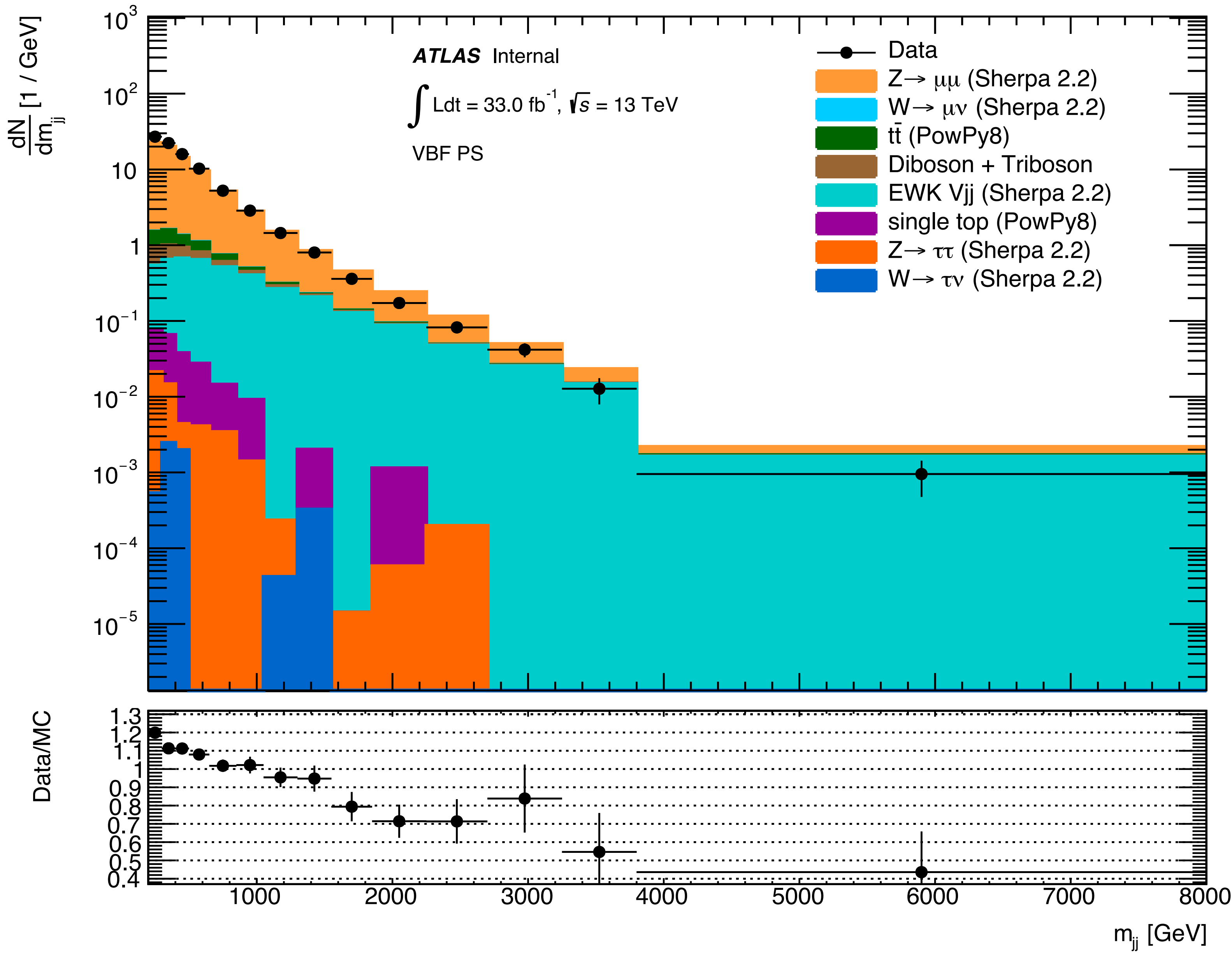
m_{jj} in VBF

Detector-level







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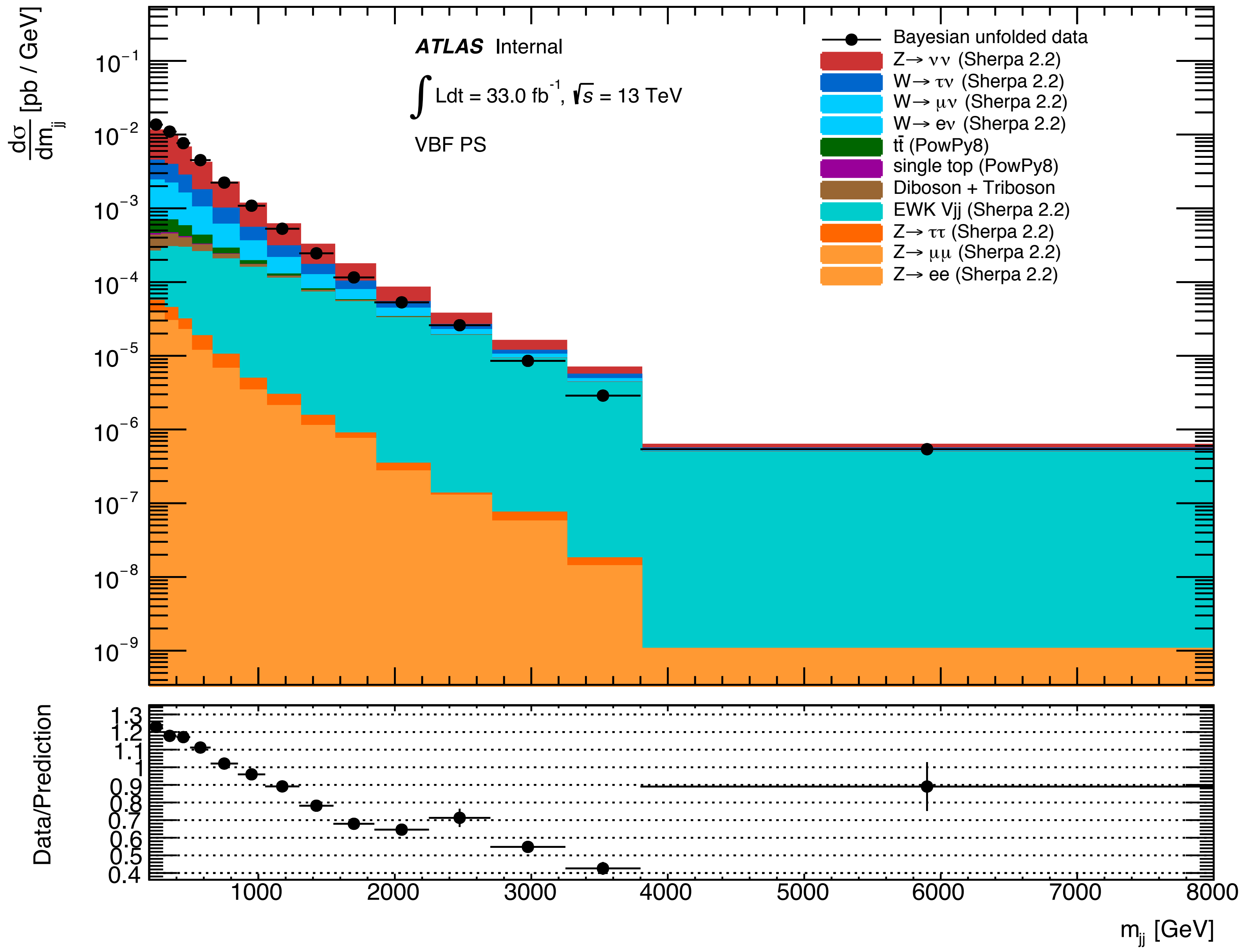

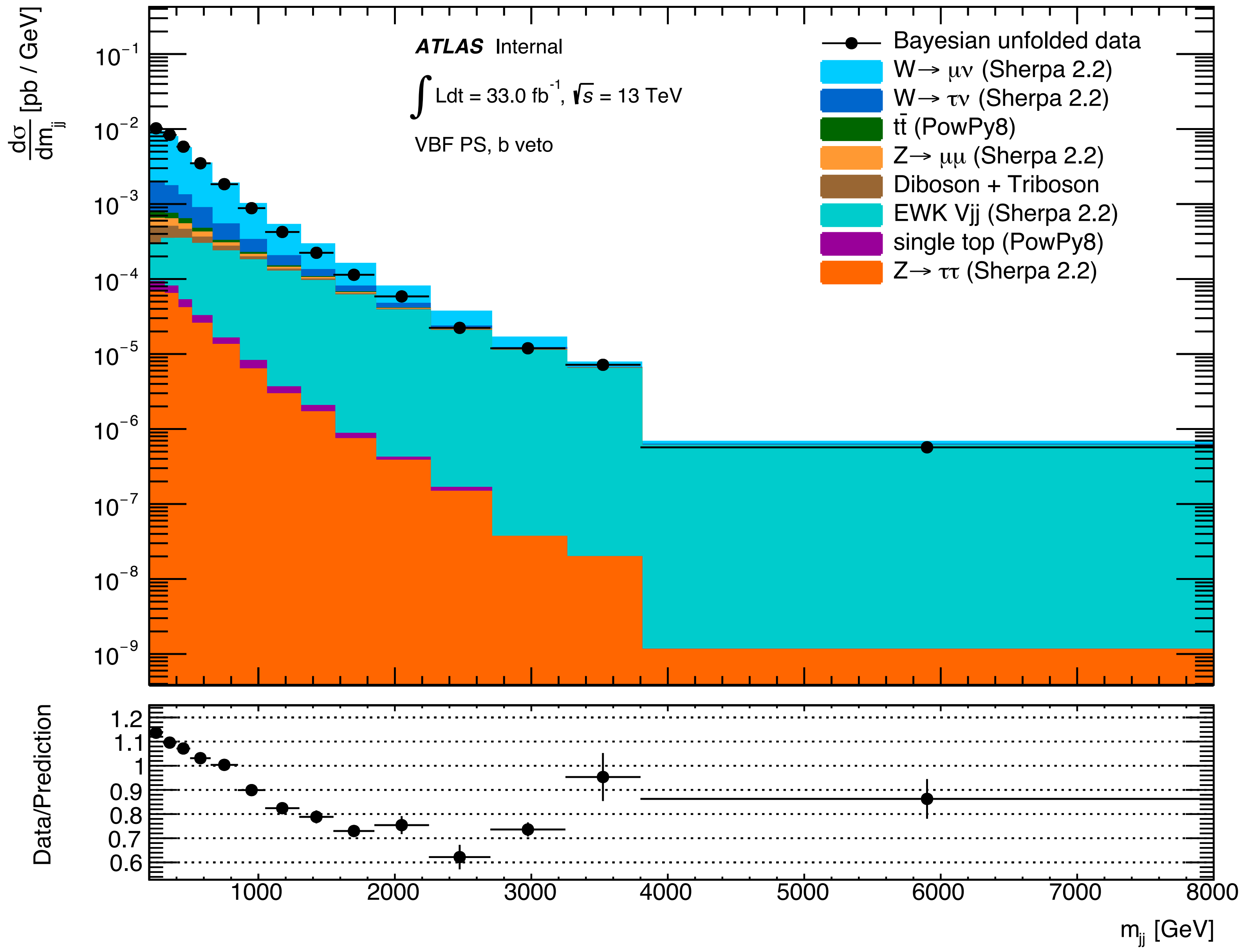

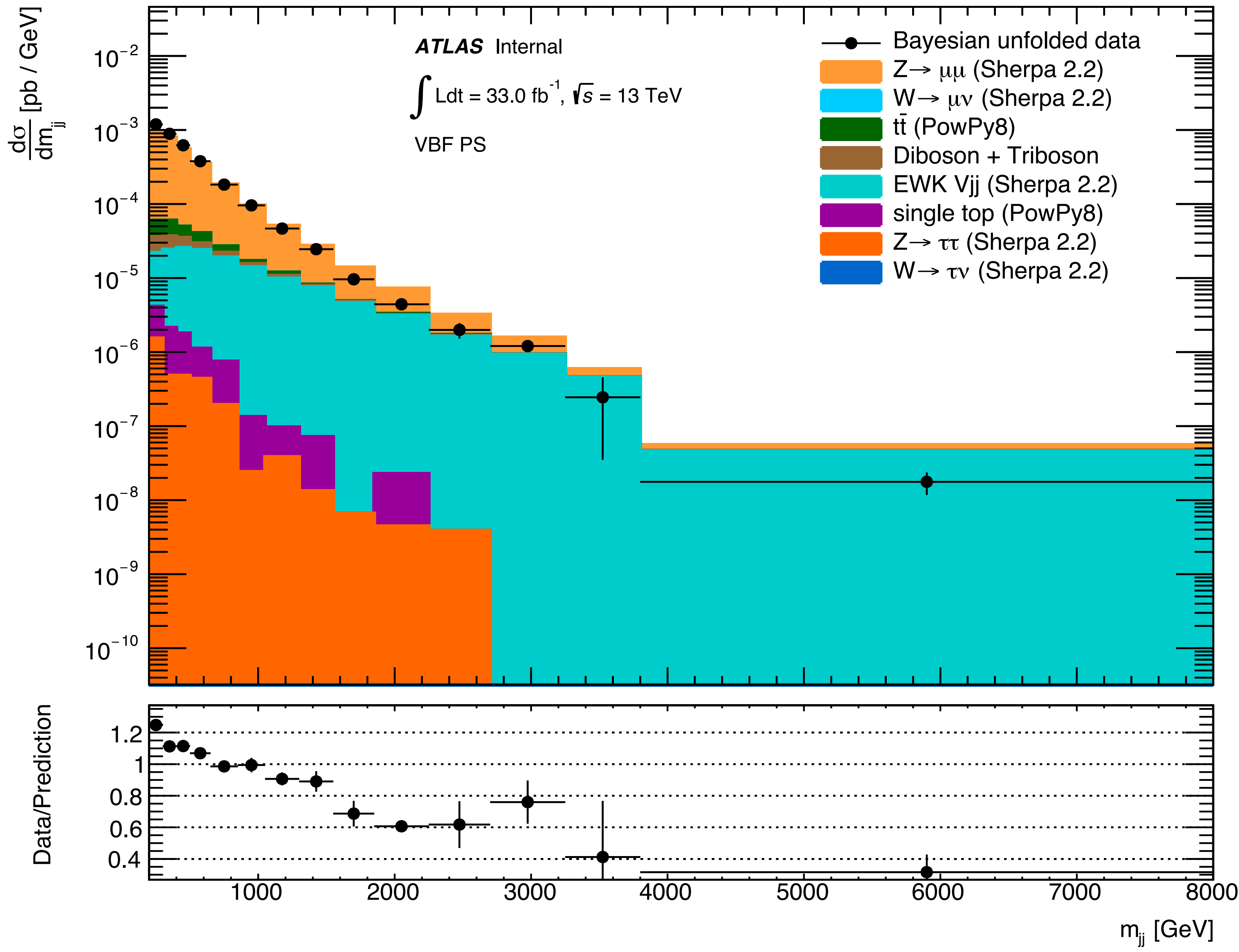

Ratios: 0-lepton / 2-muon: mjj vbf

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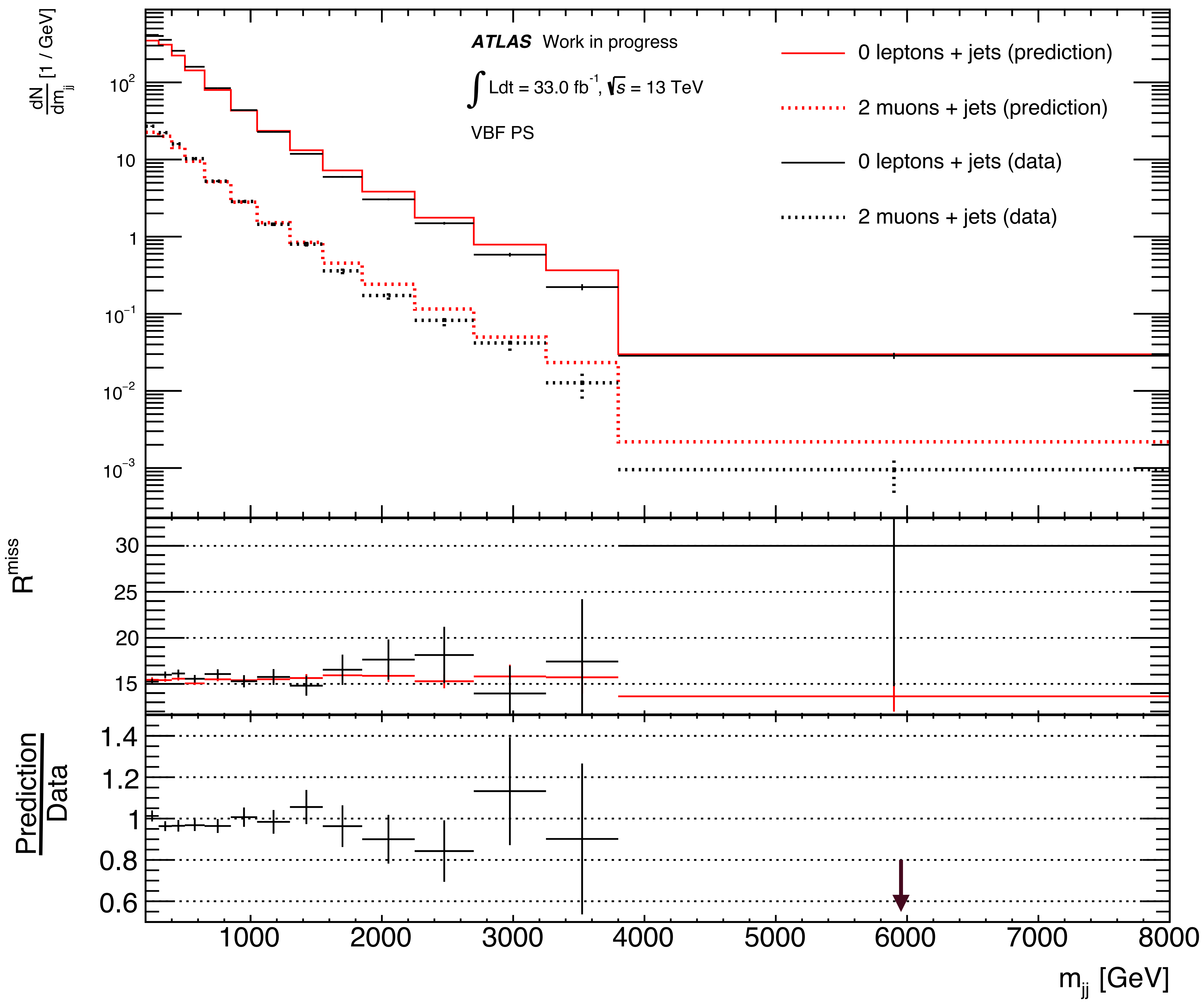

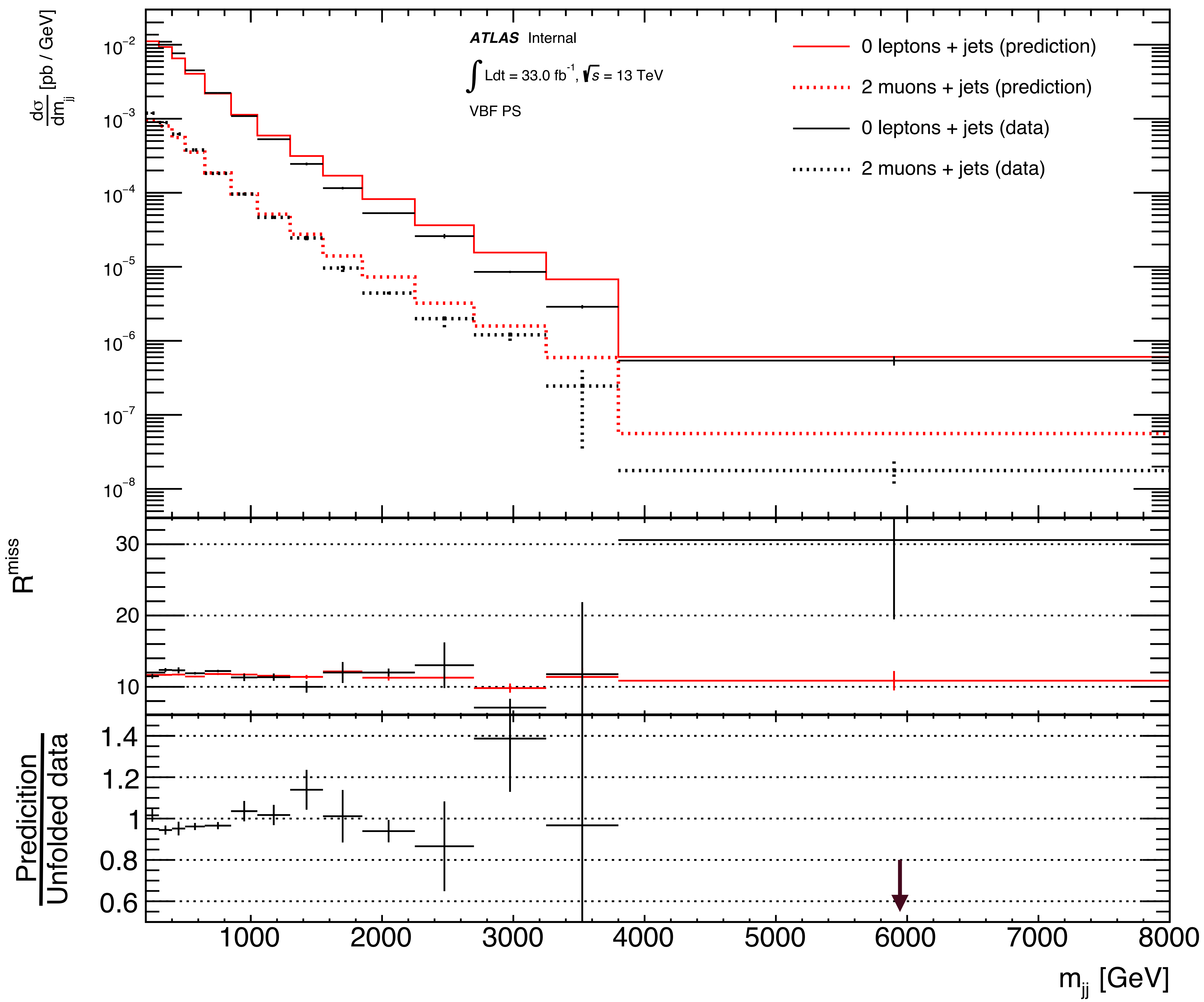

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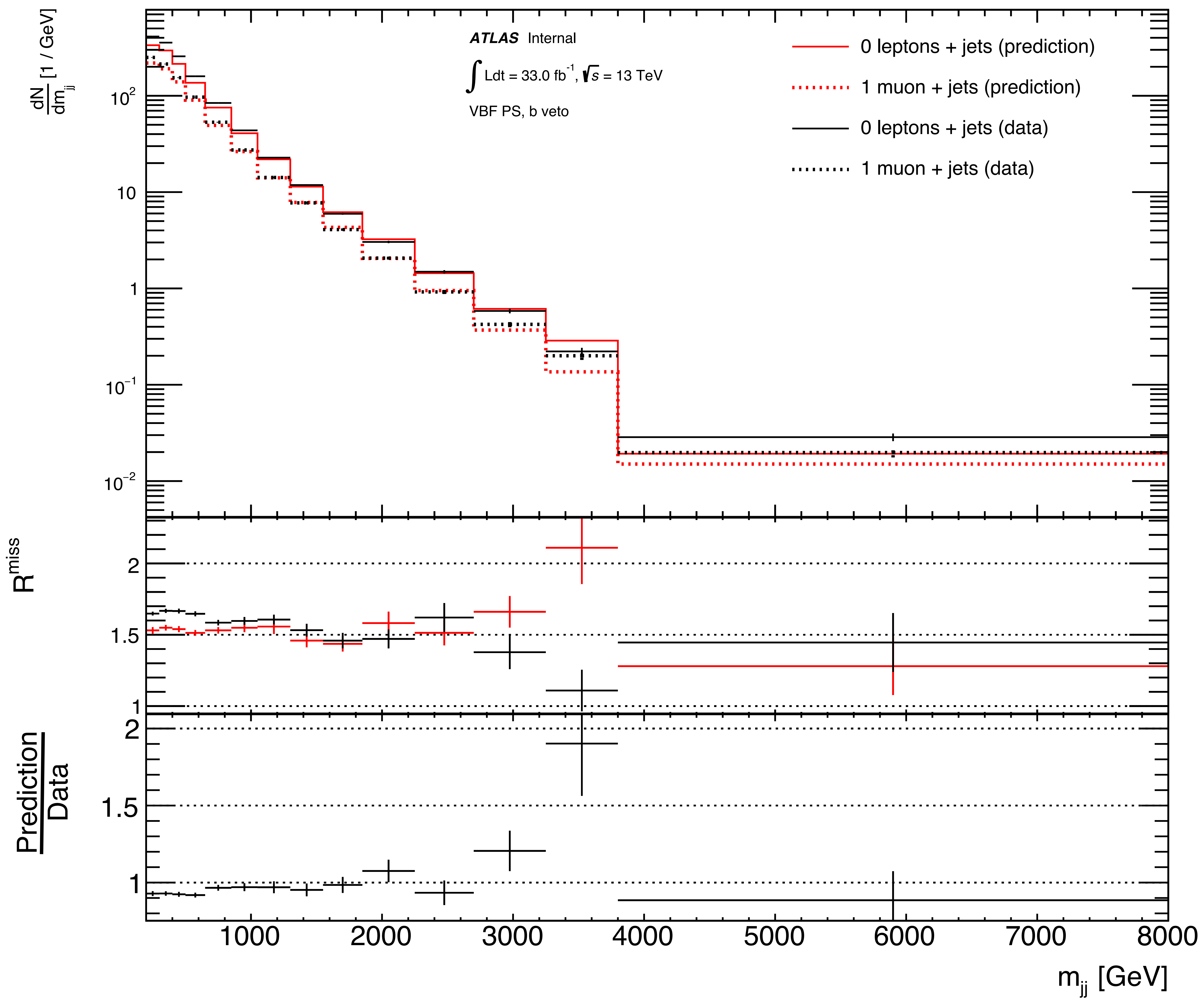
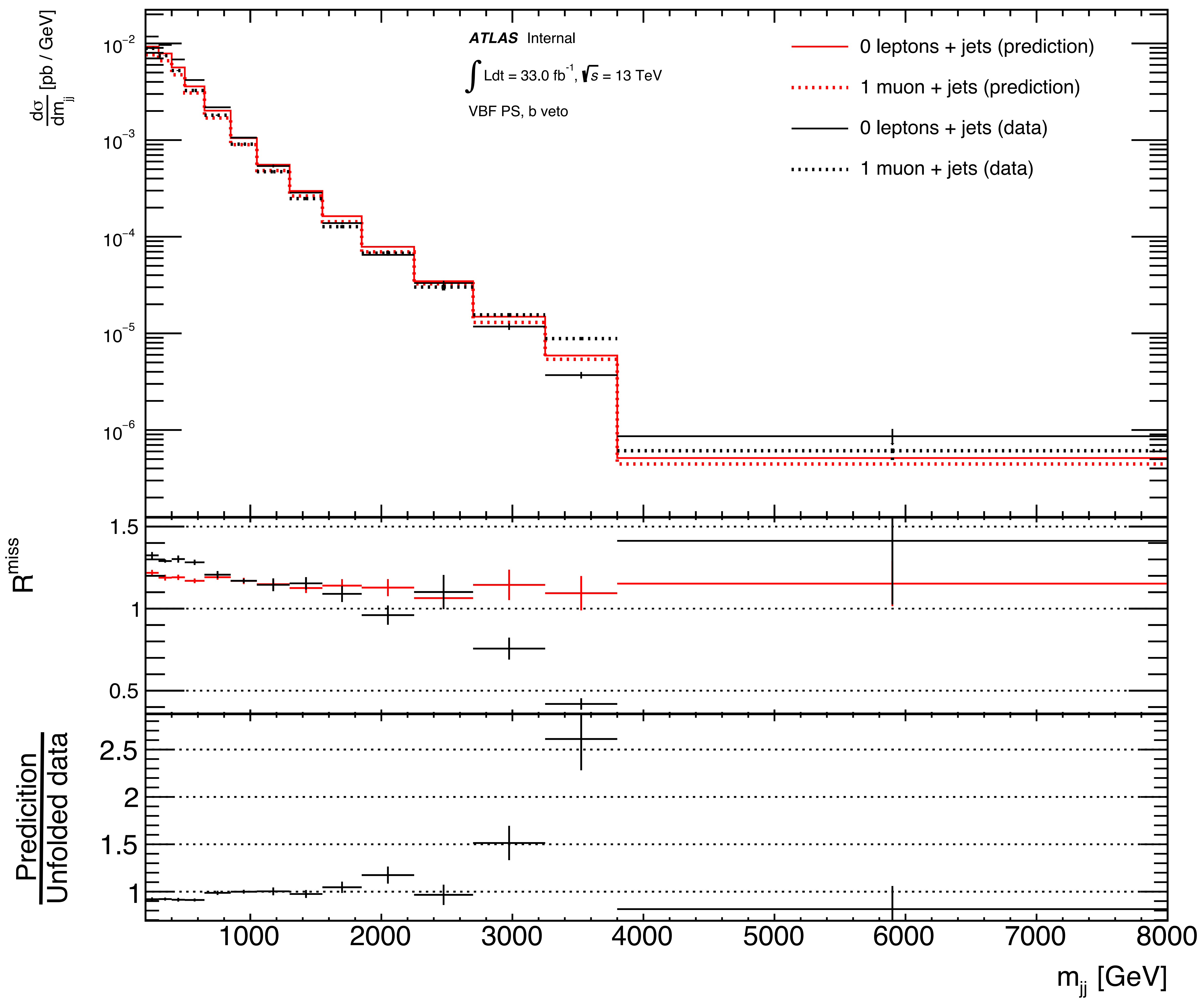
Unfold



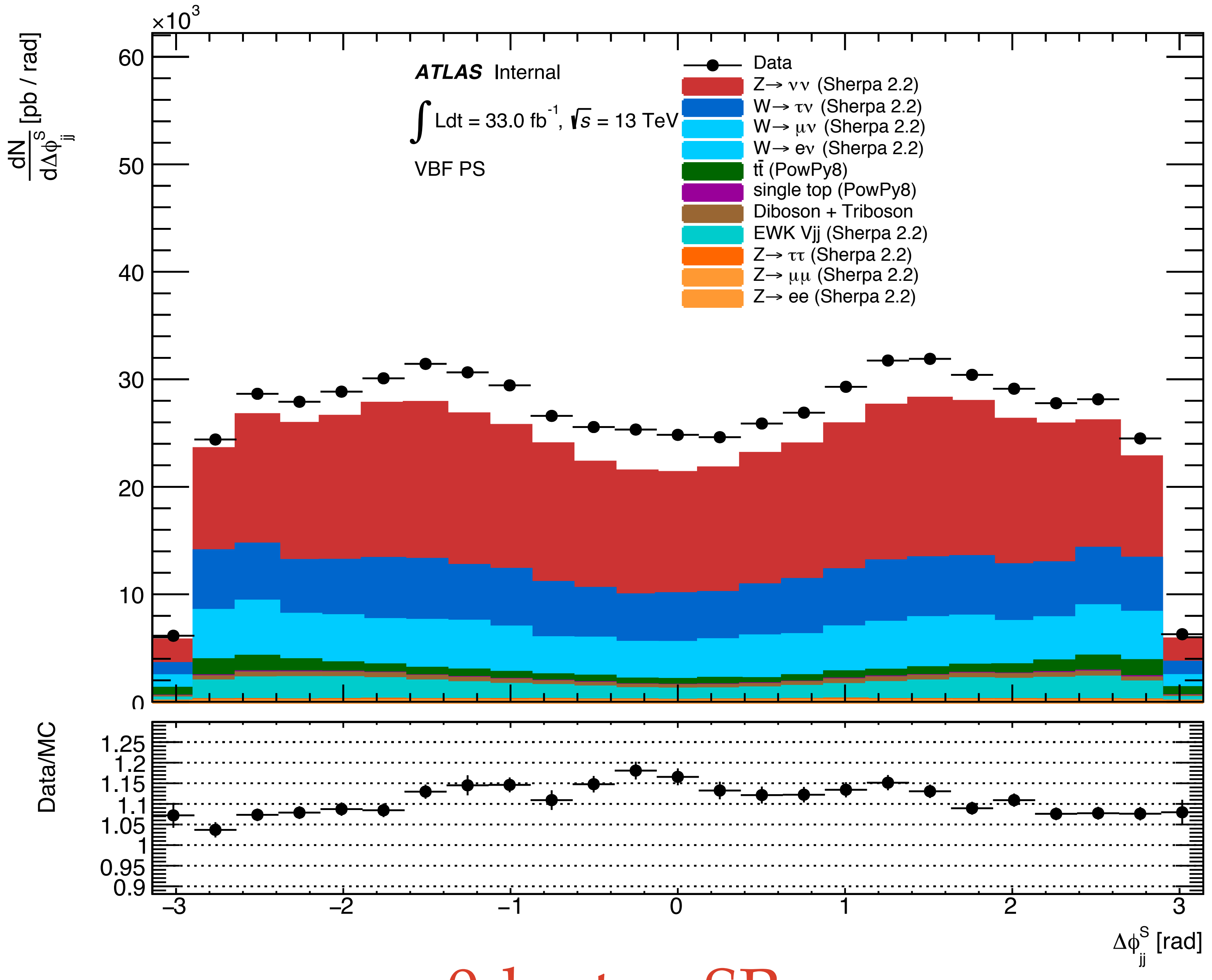


Response matrices

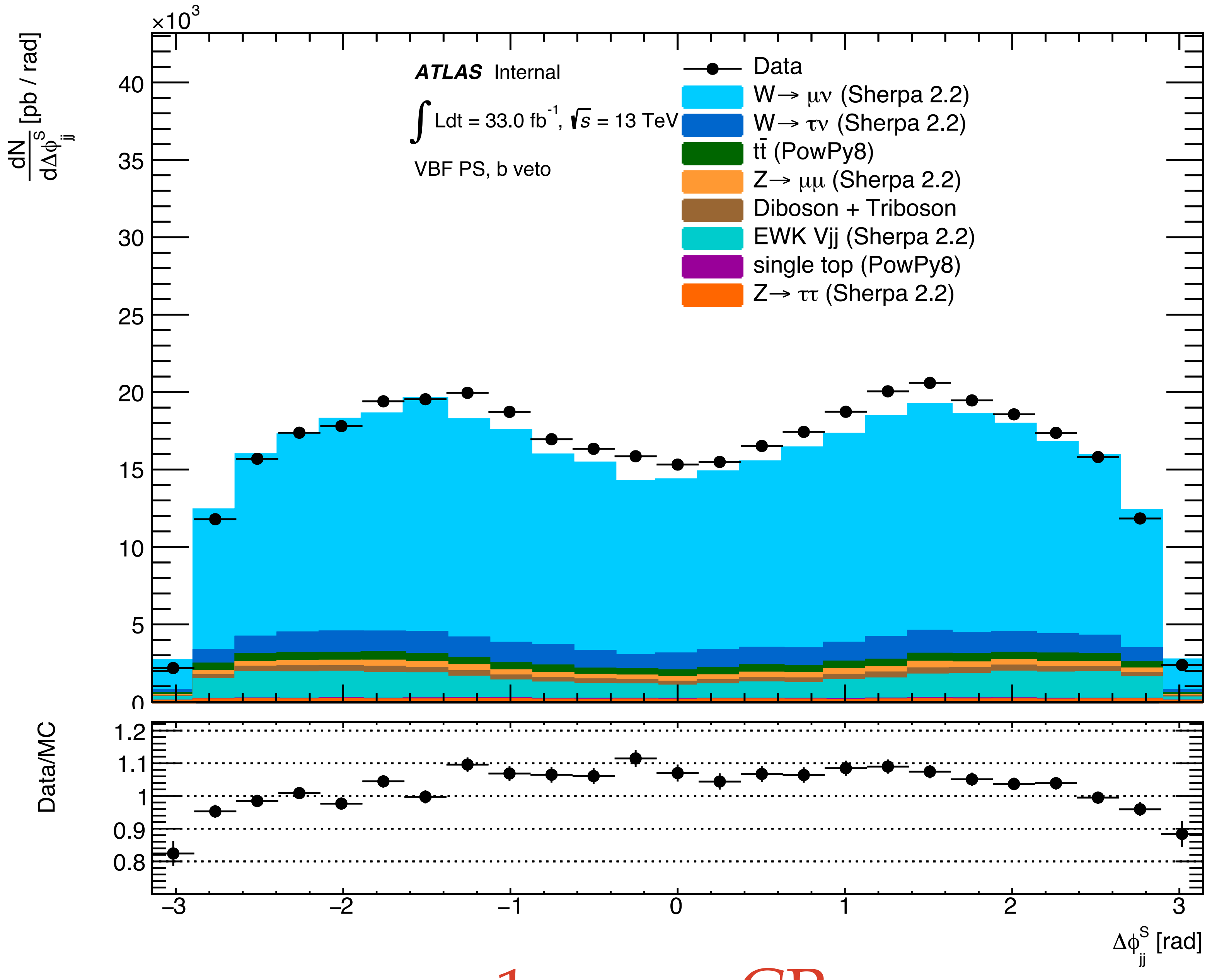
- Showing bin migrations when unfolding from reco to particle level

dPhi in VBF

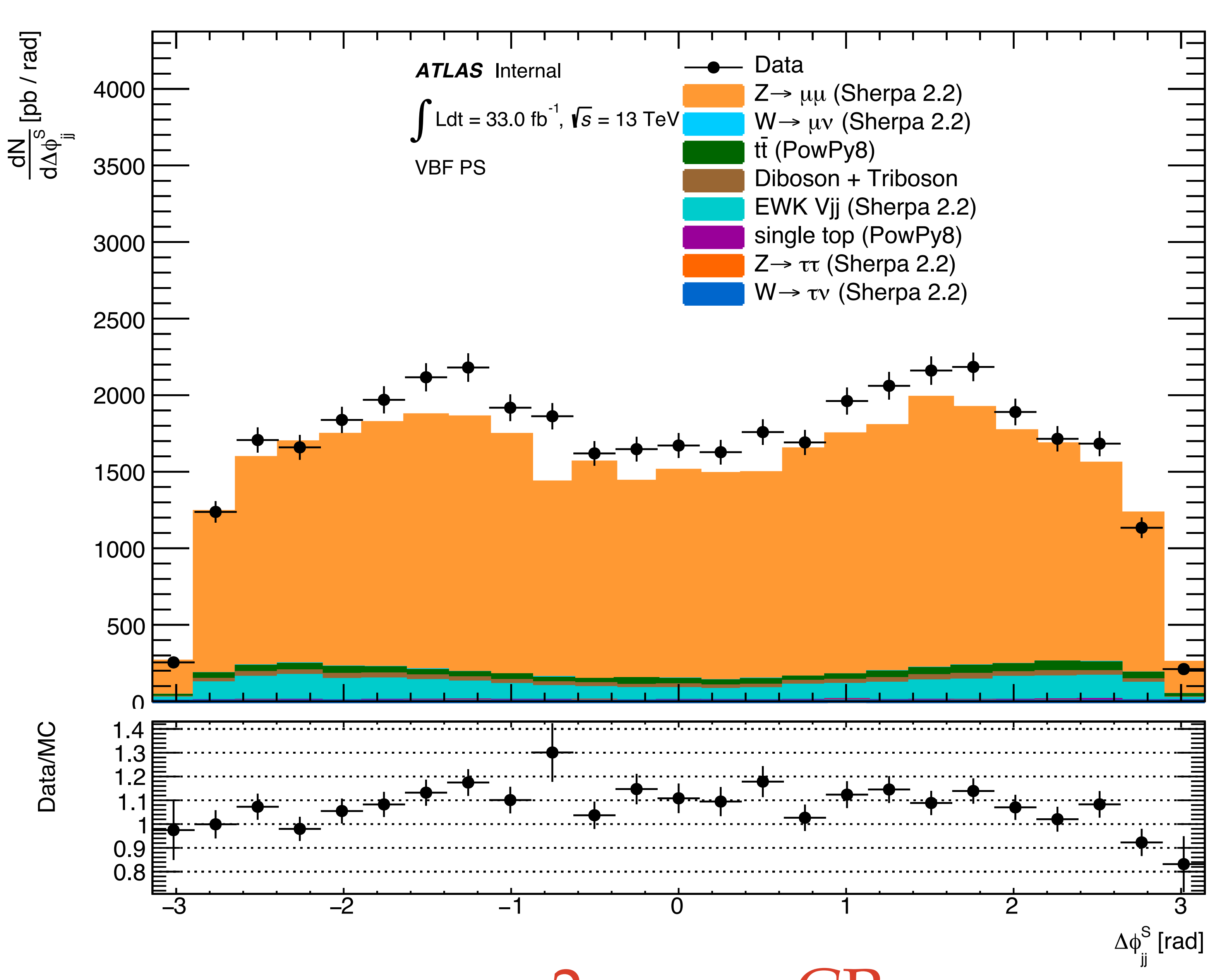
Detector-level



0-lepton SR

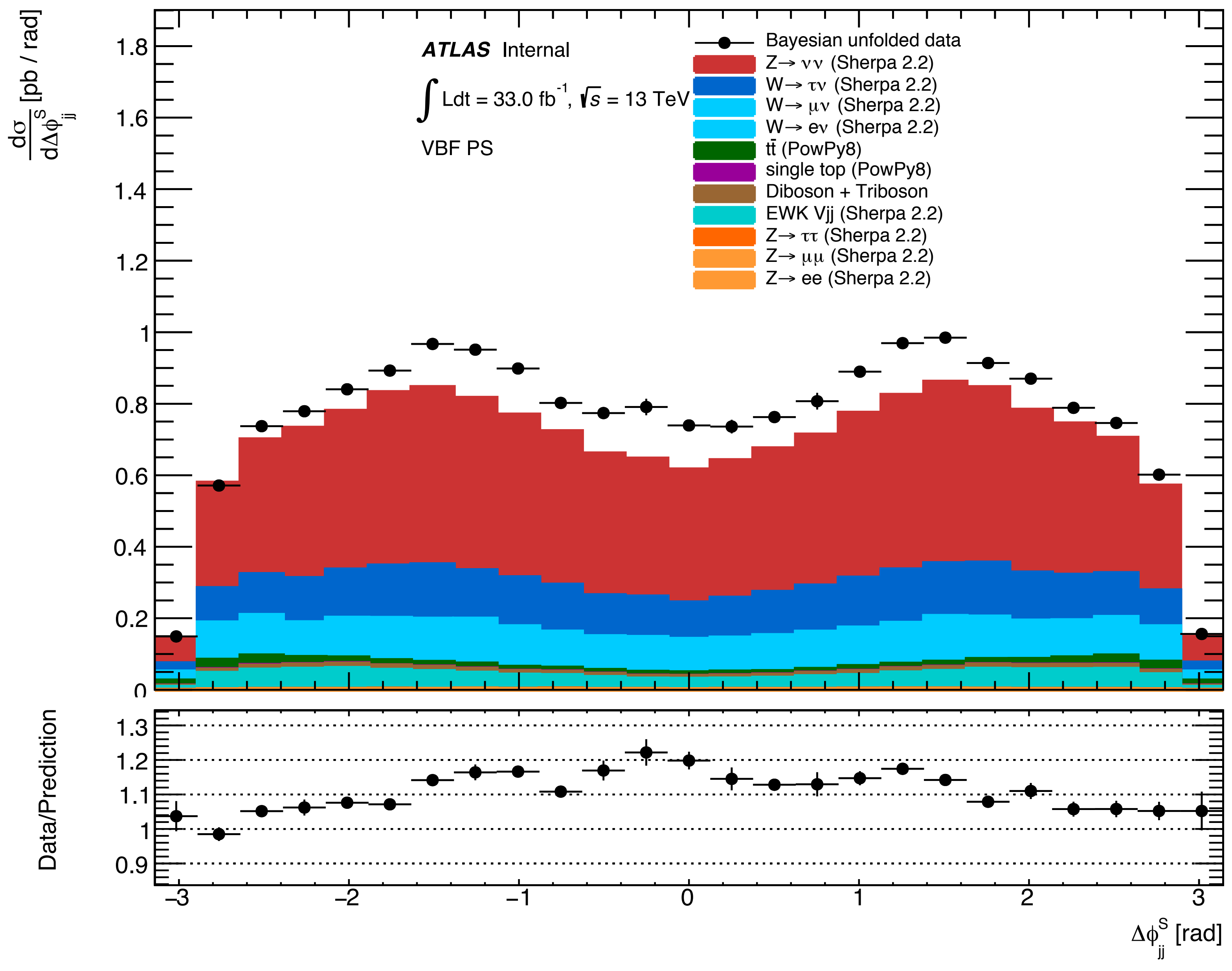


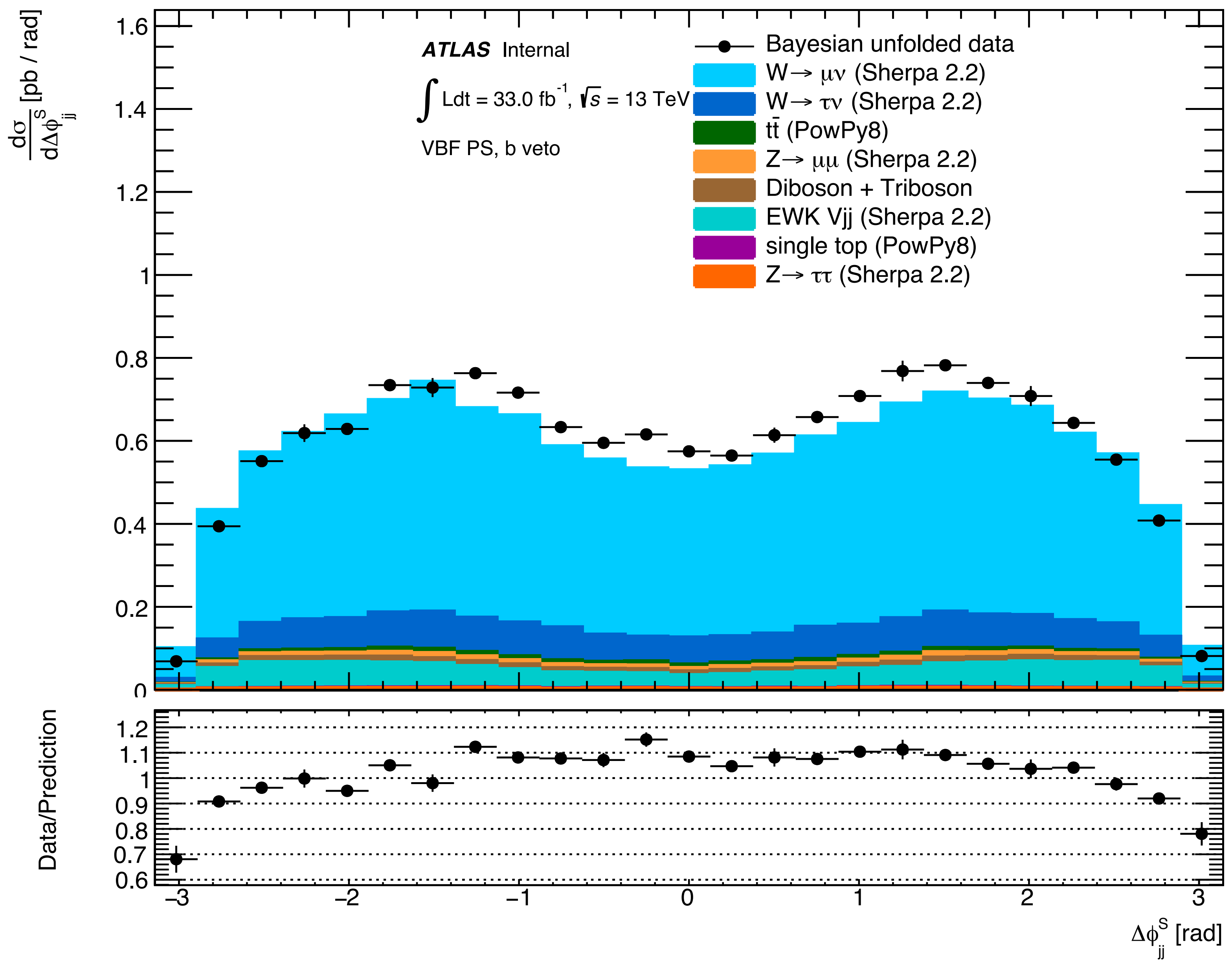
1-muon CR

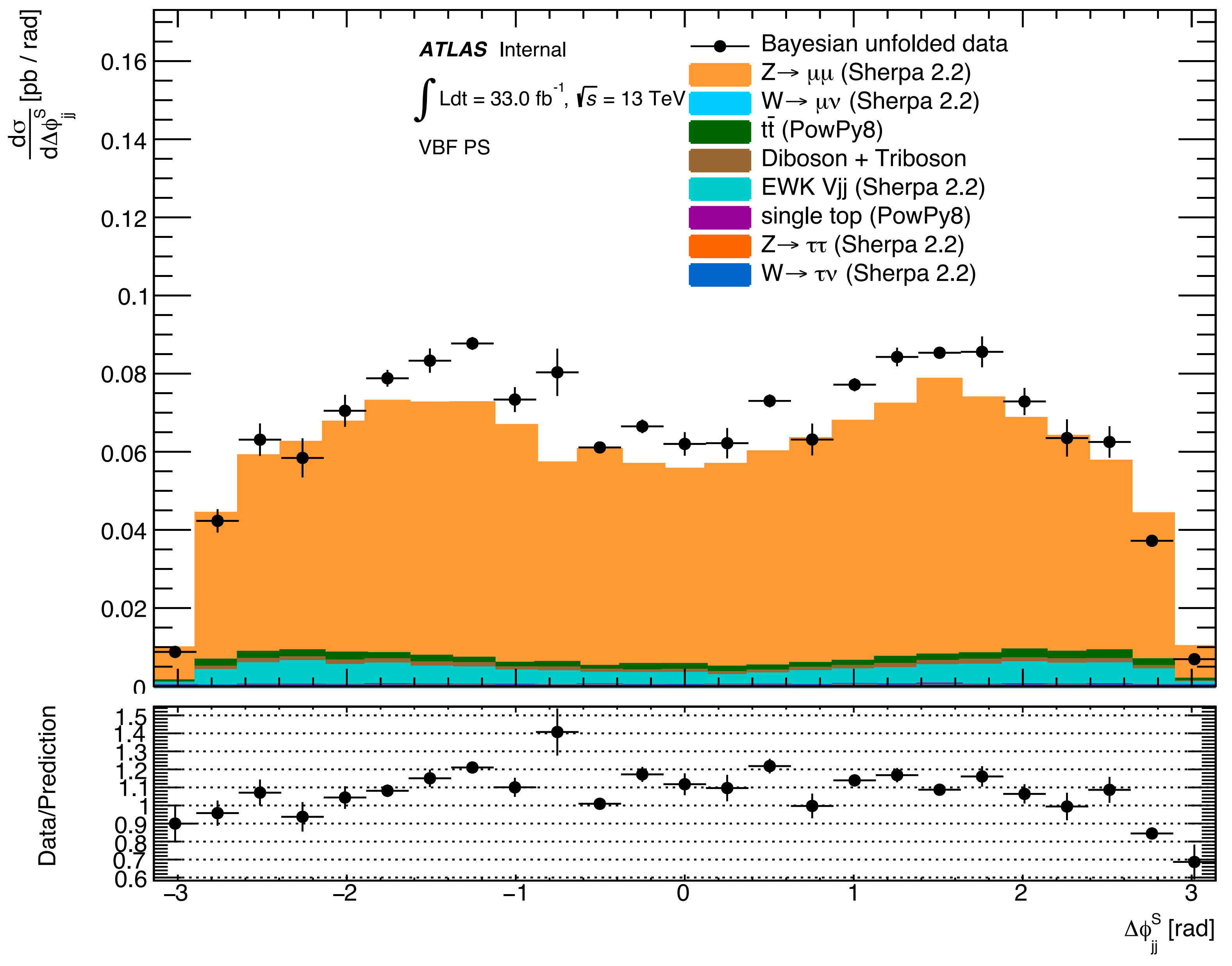


2-muon CR

Unfolded

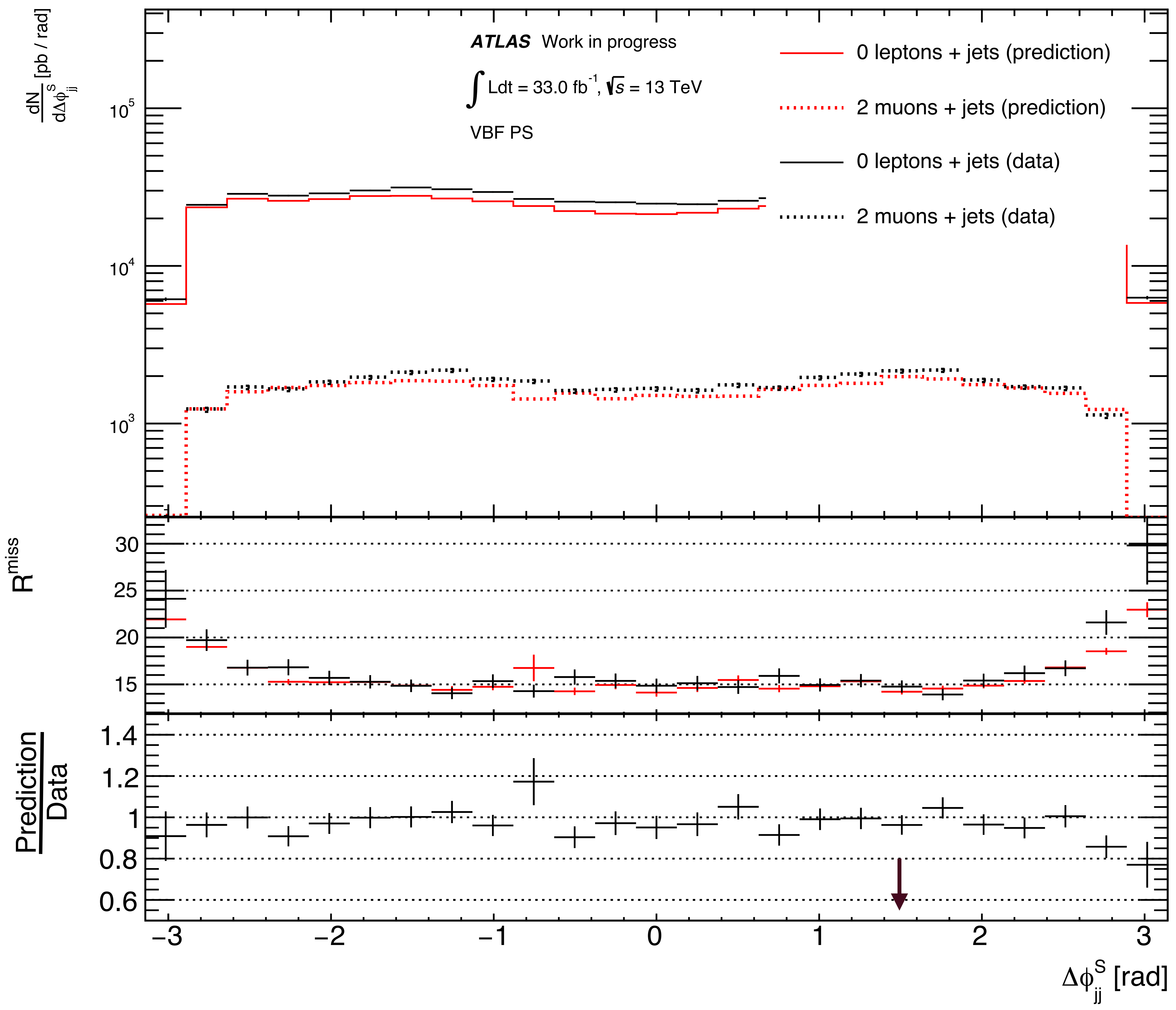


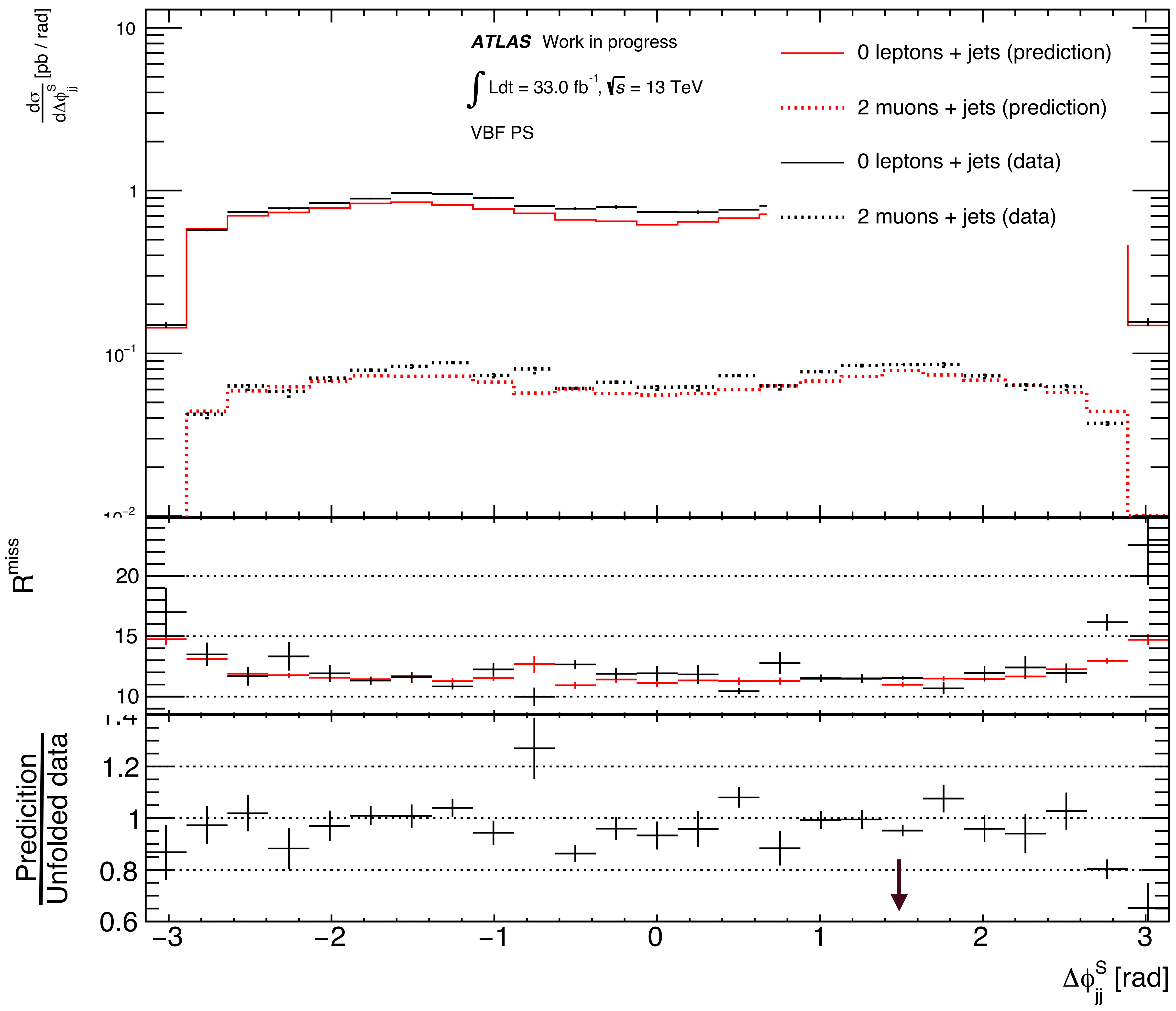




Ratios: 0-lepton / 2-muon: dPhi vbf

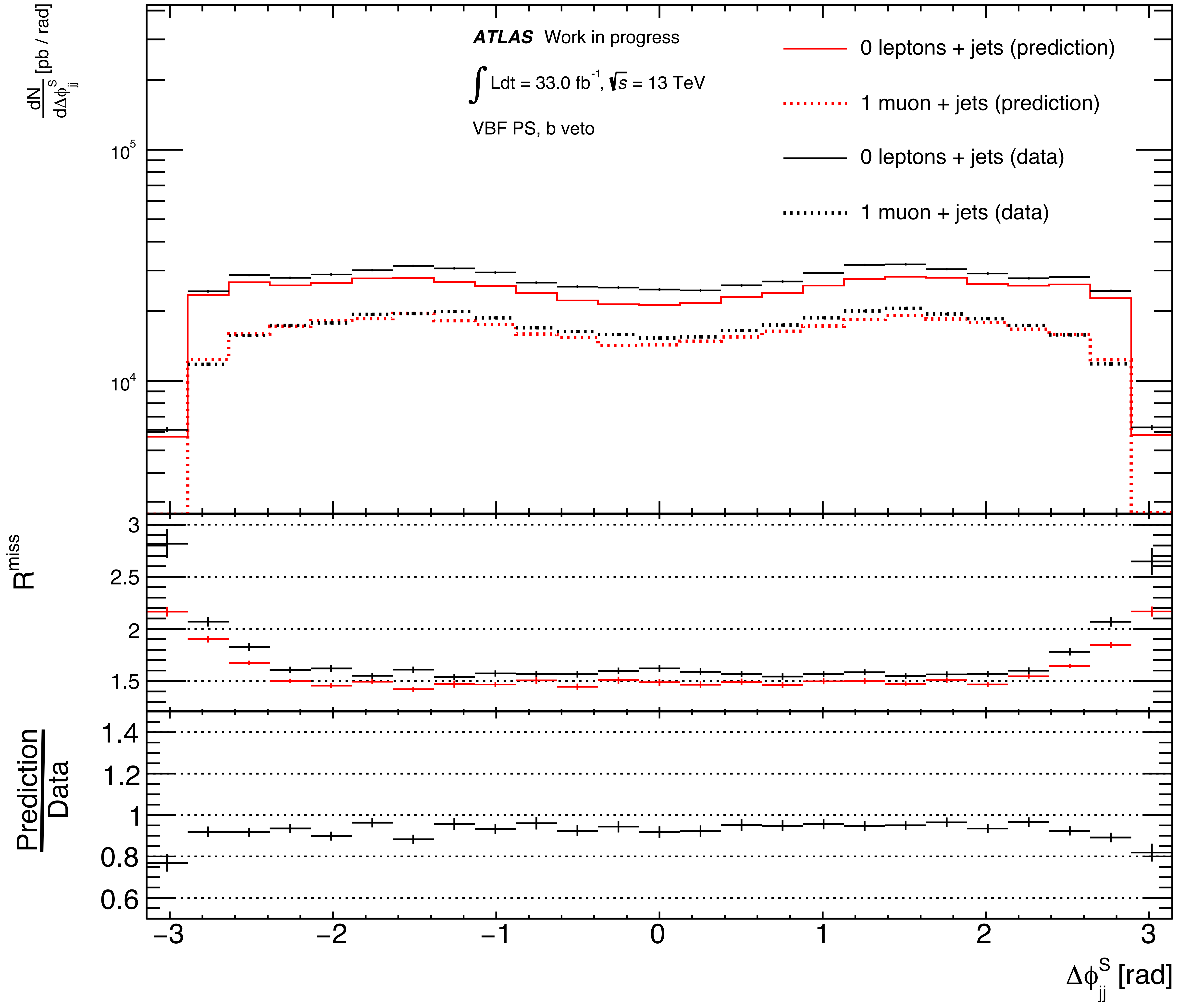
Unfold

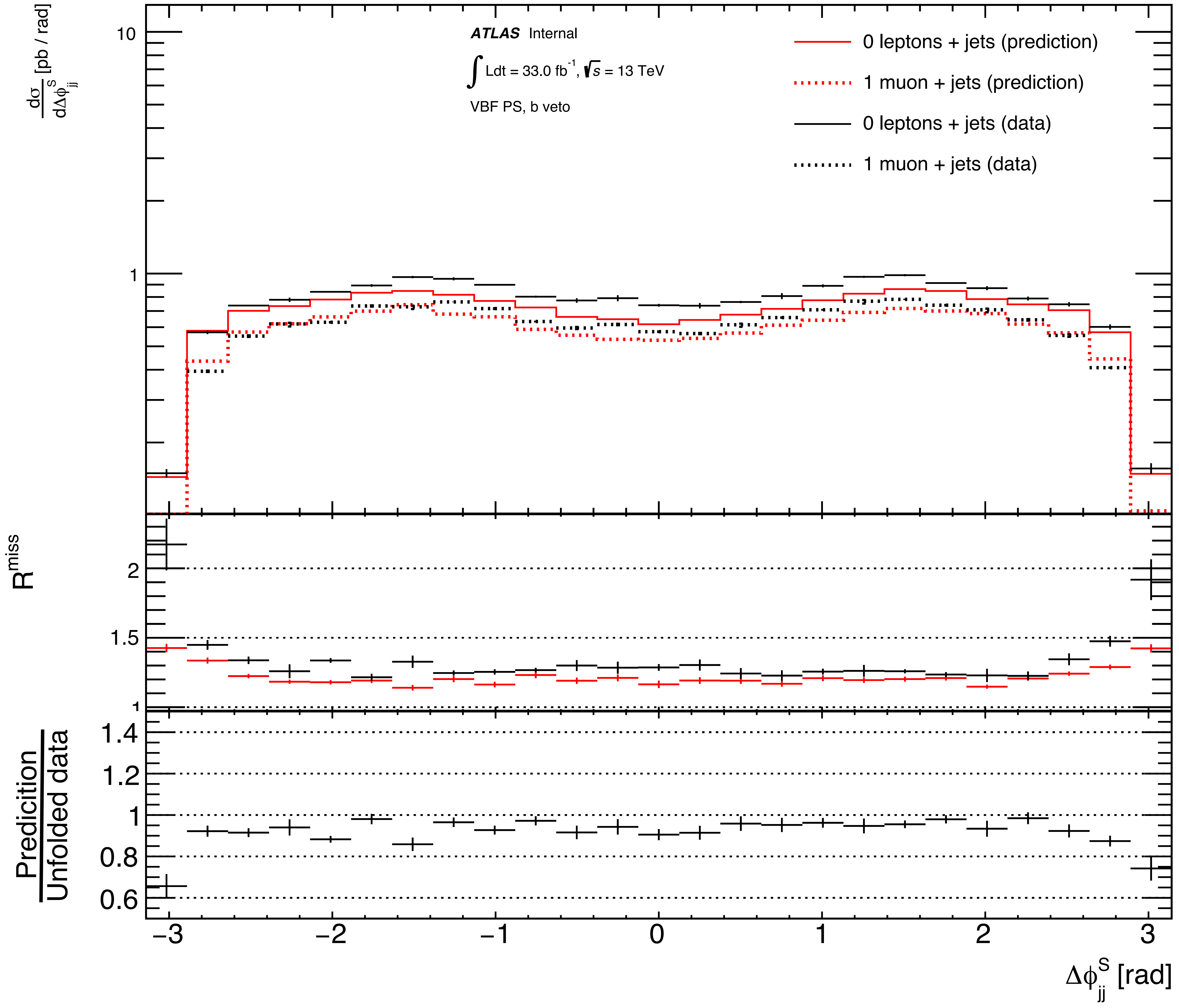




Ratios: 0-lepton / 1-muon: dPhi vbf

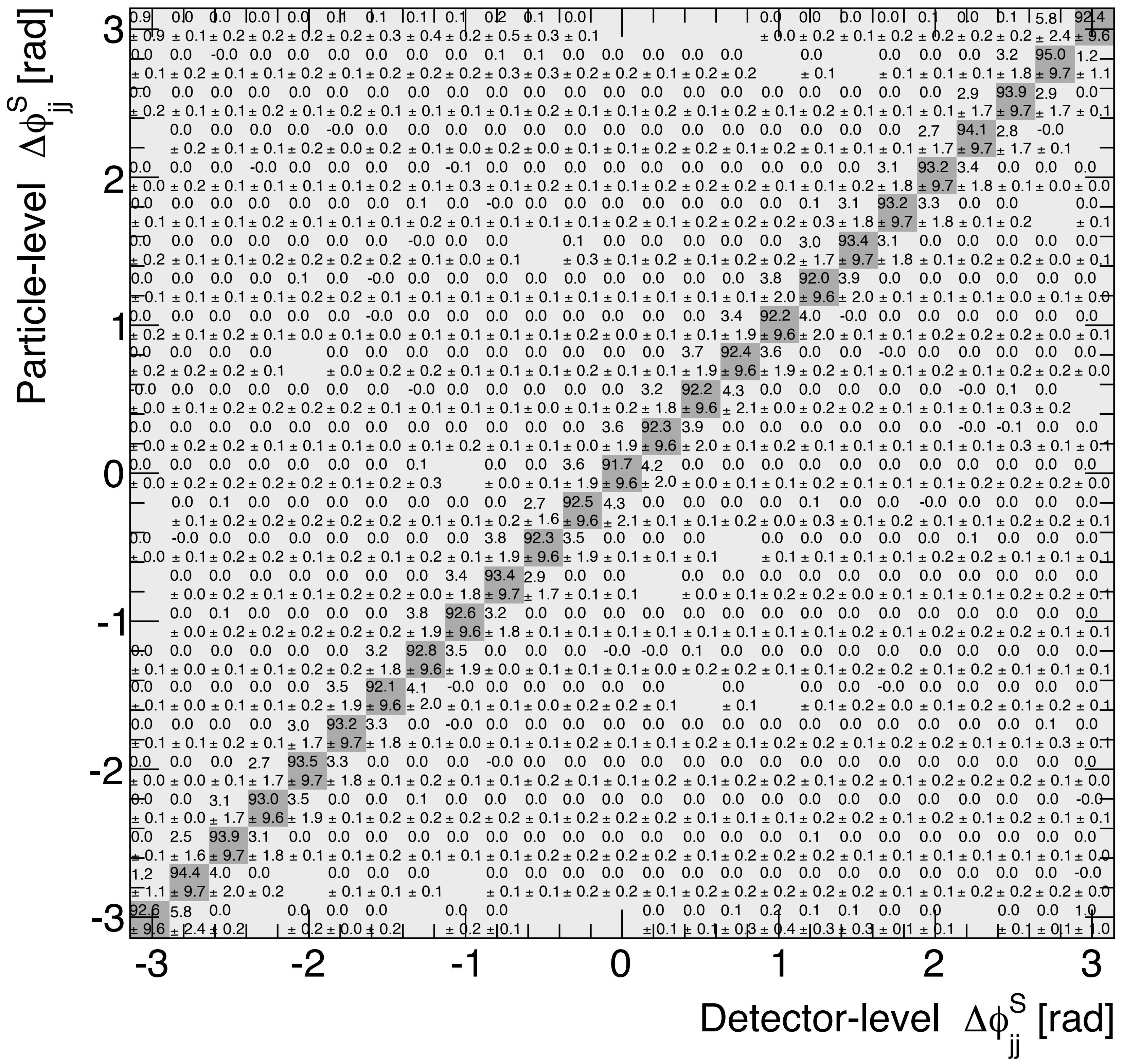
Unfold



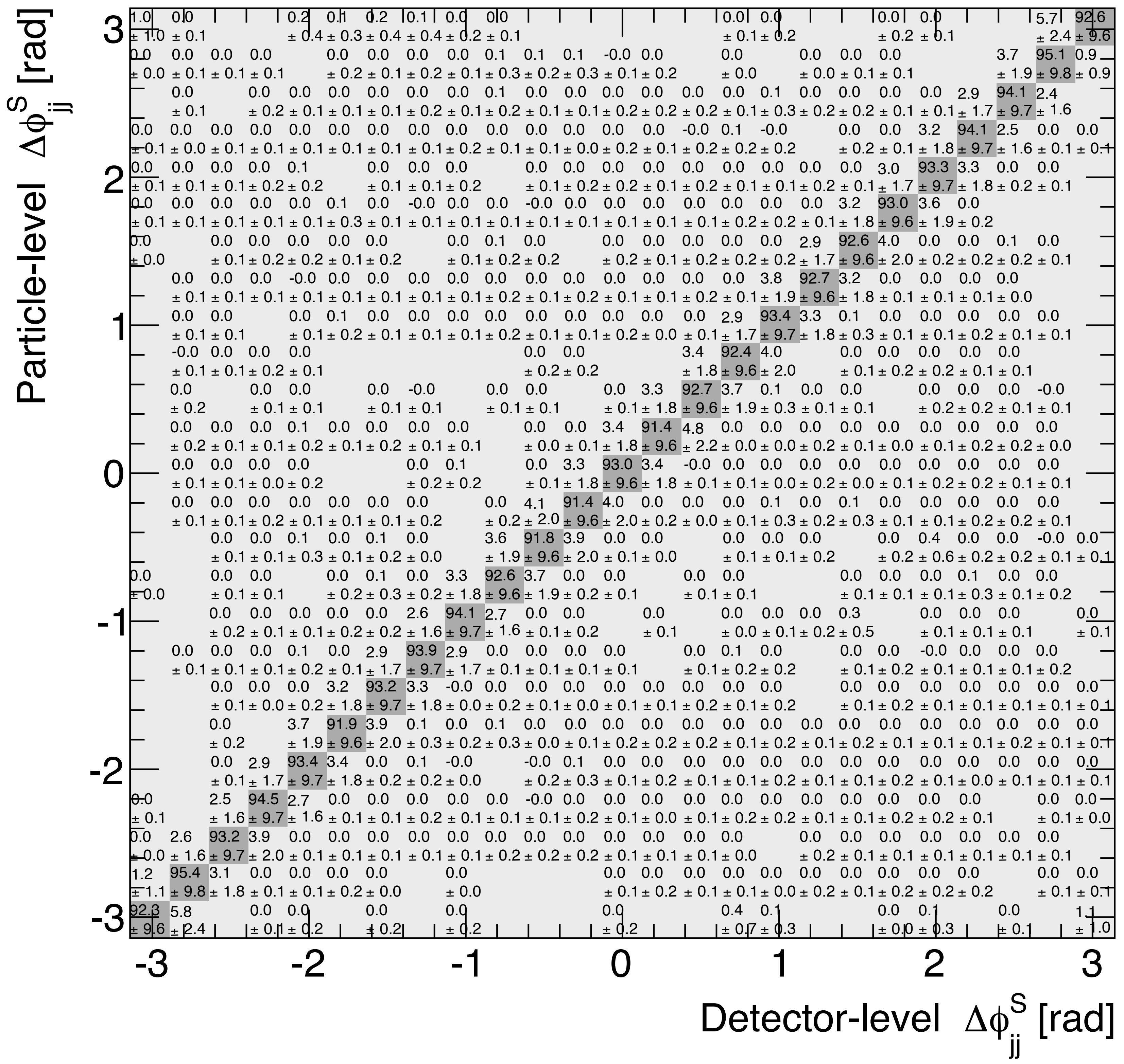


Response matrices

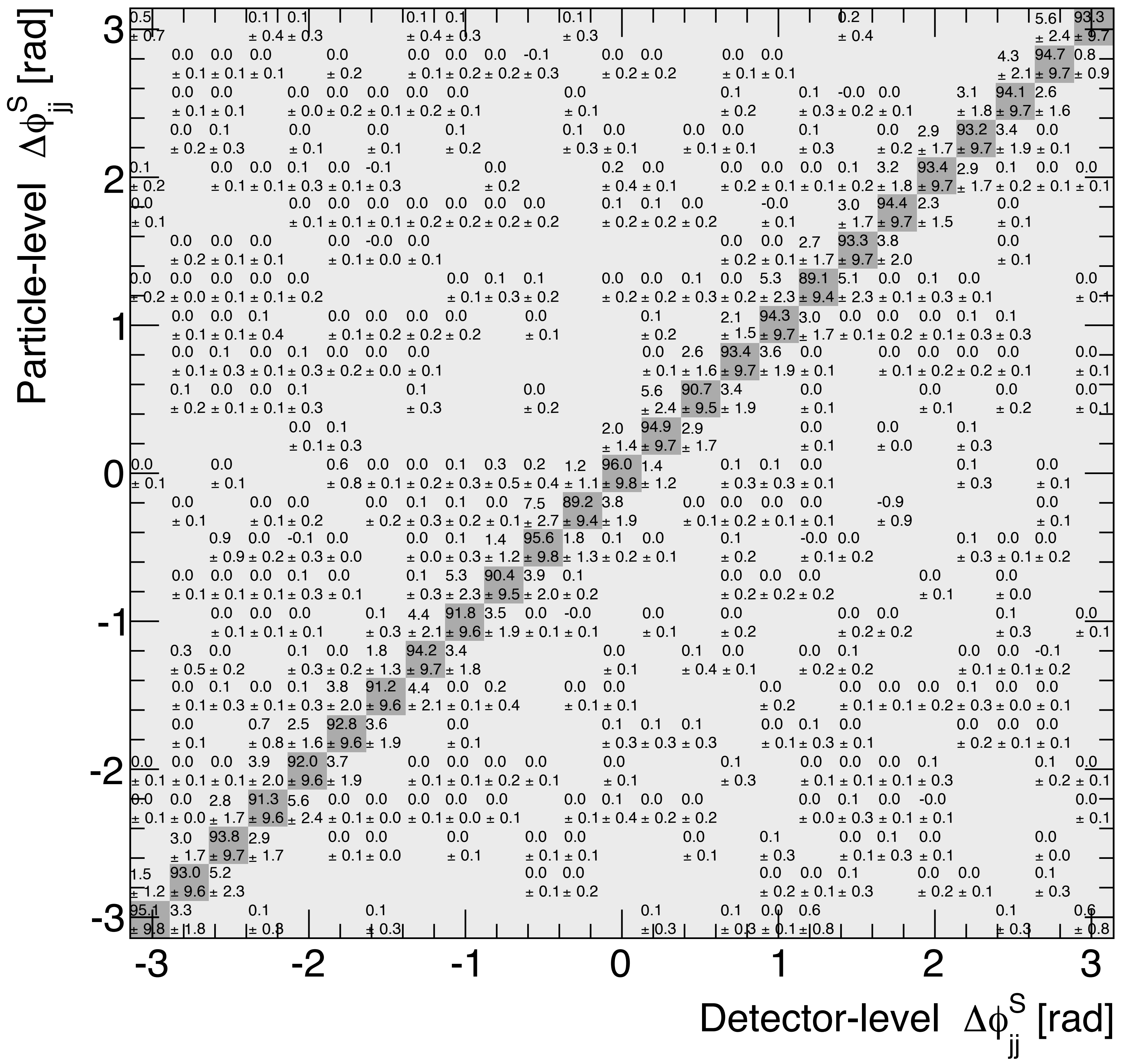
0-lepton SR



1-muon CR

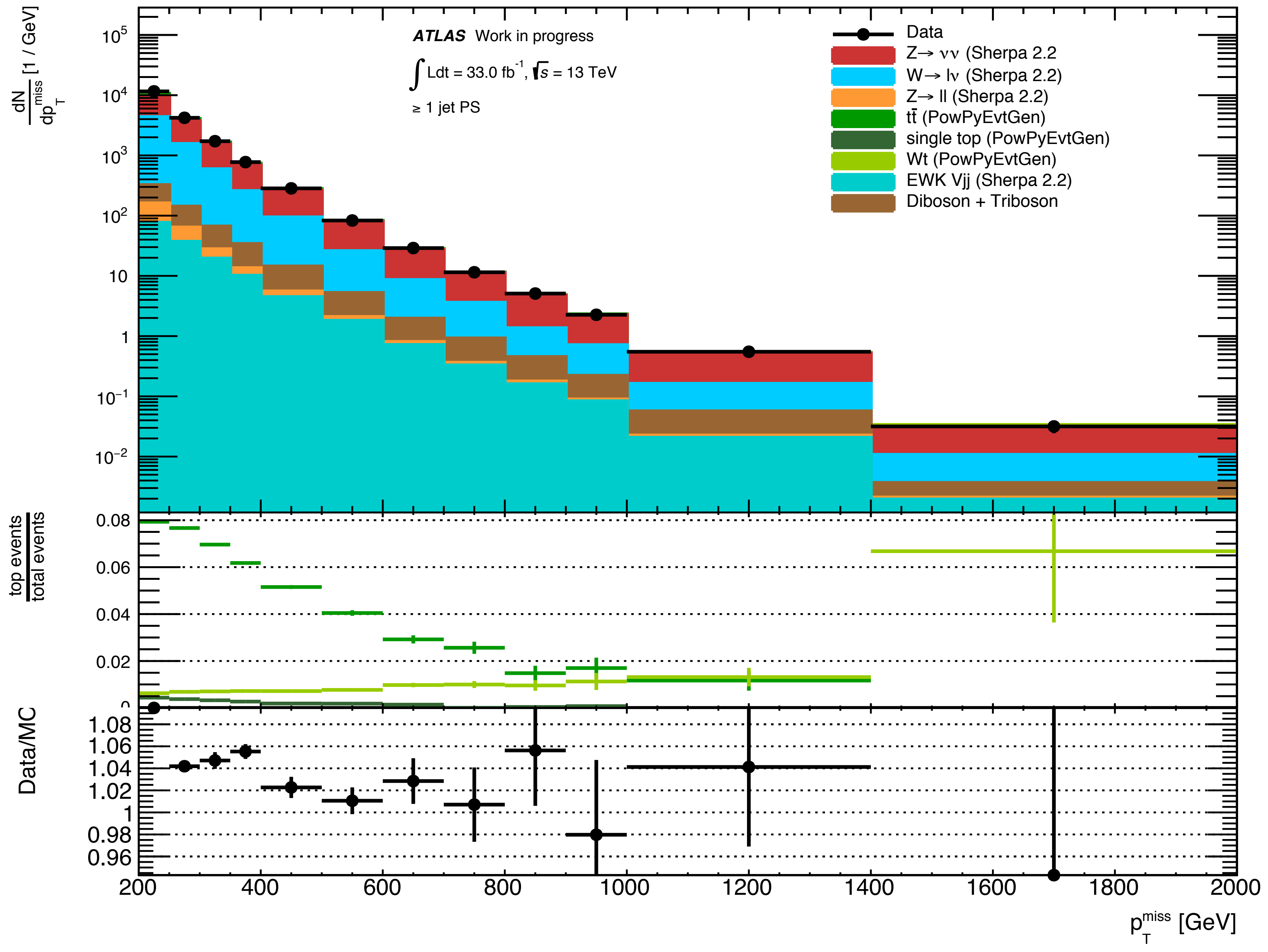


2-muon CR

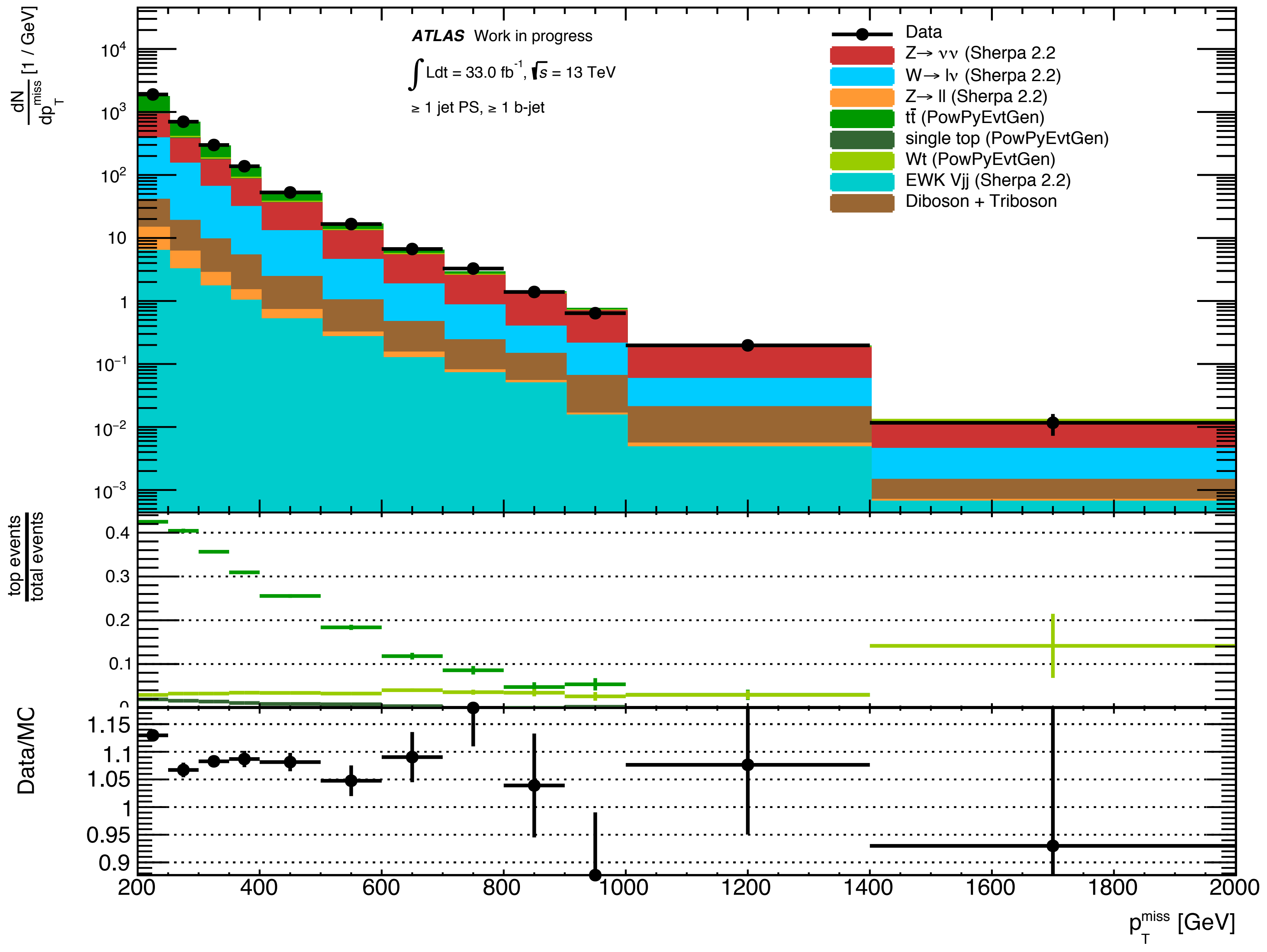


- Showing bin migrations when unfolding from reco to particle level

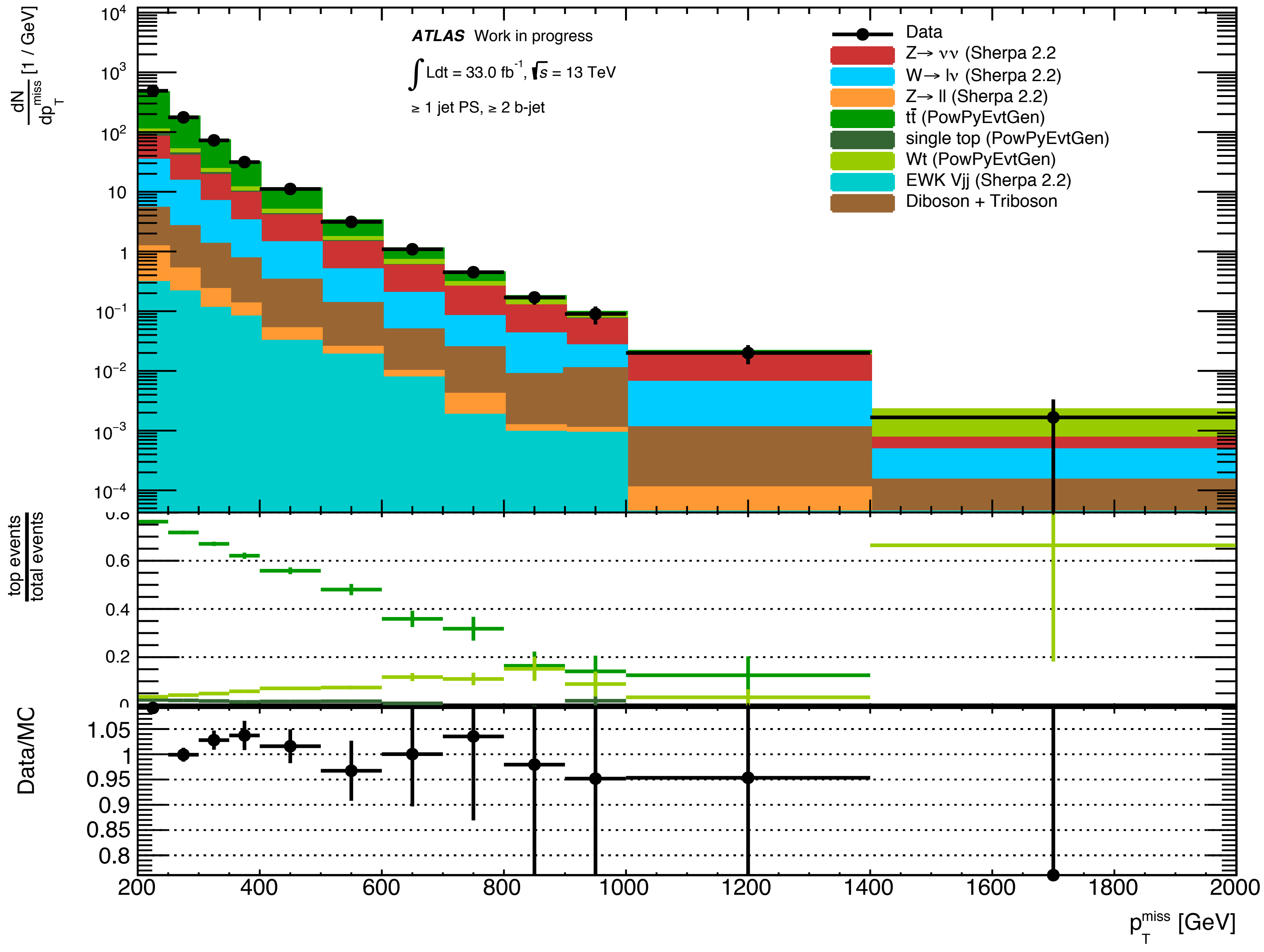
Data/MC comparisons : 0-lepton top enhanced control region



No b-jet requirement



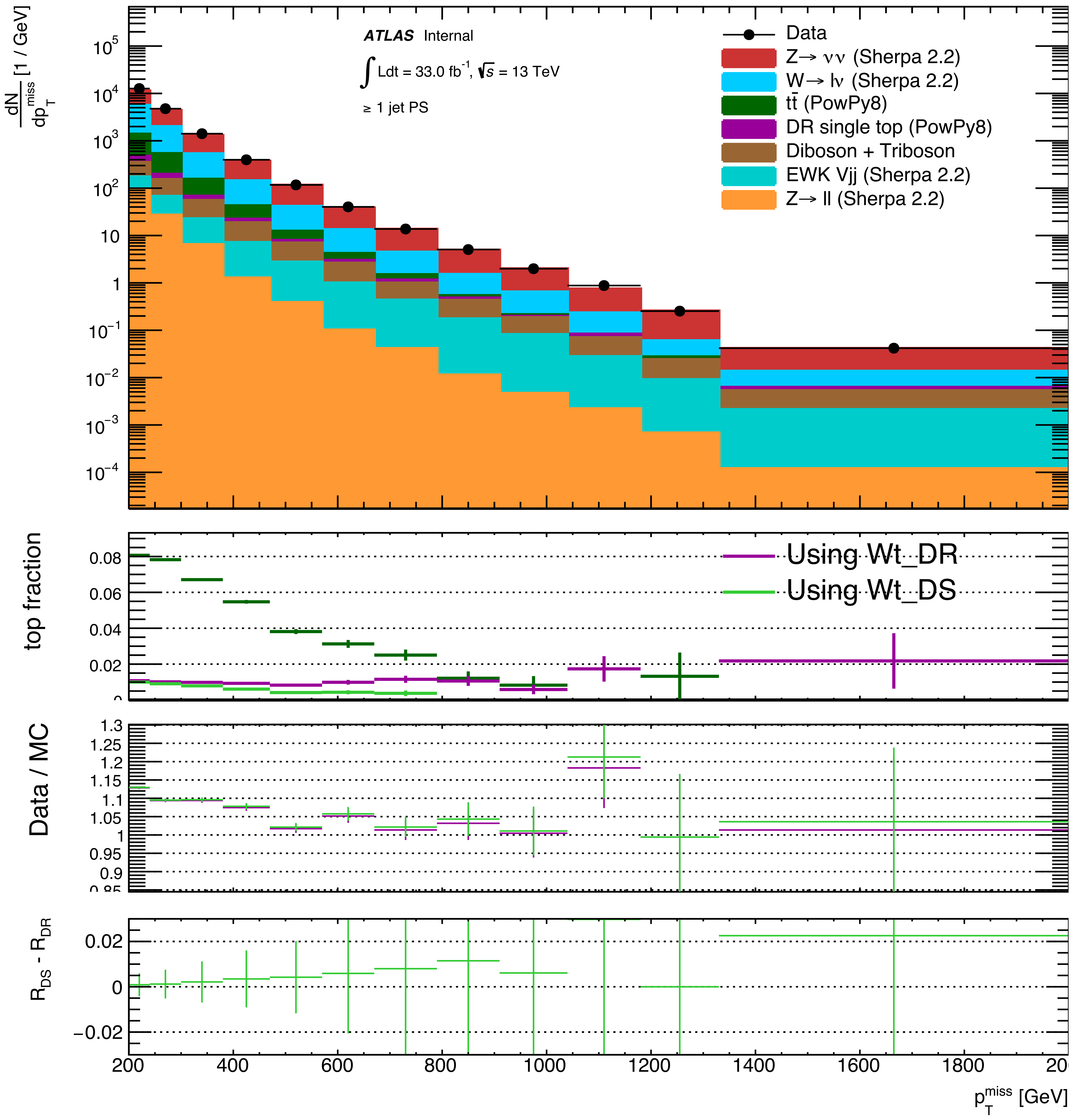
≥ 1 b-jets



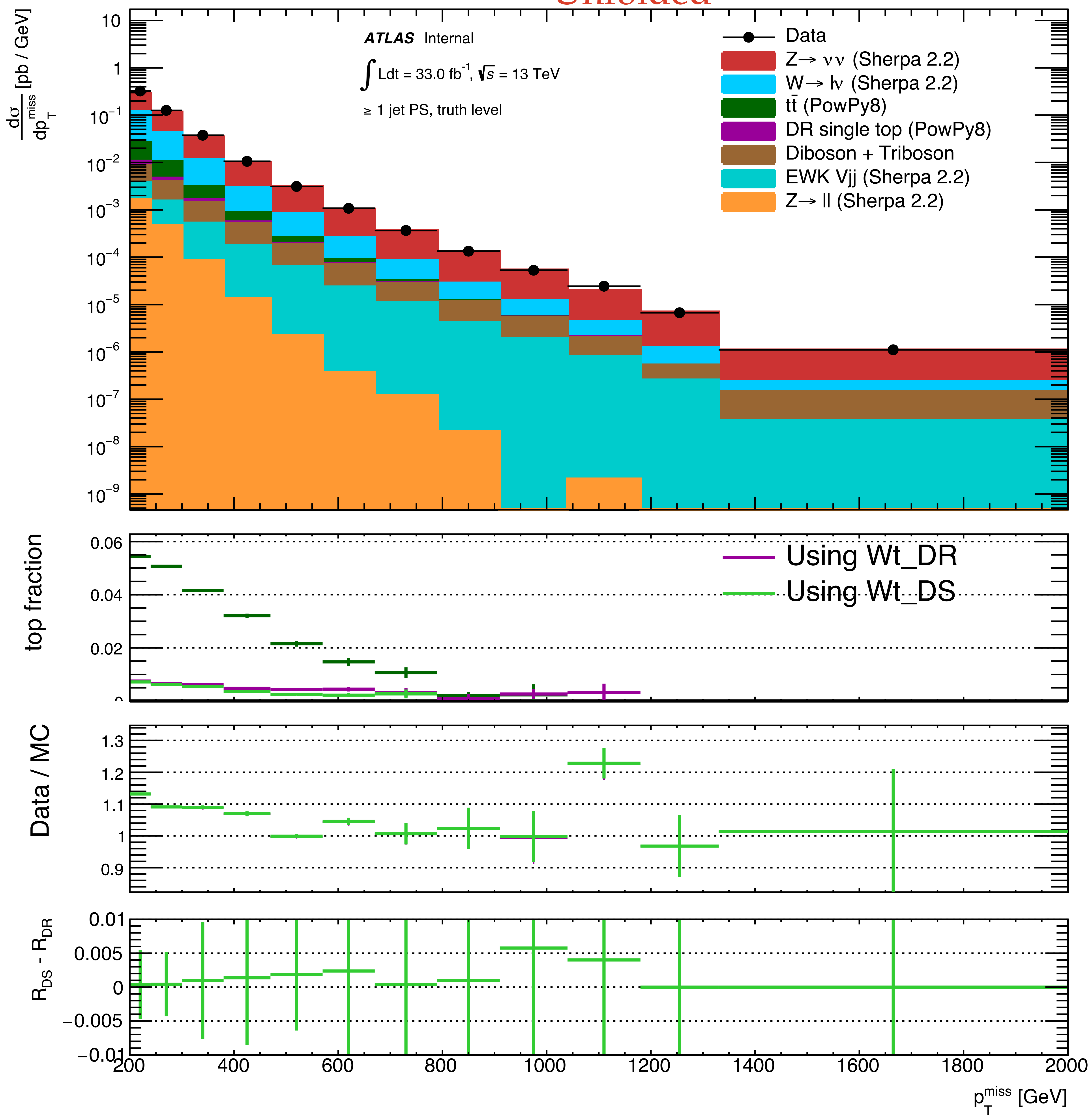
≥ 2 b-jets

- Main top contribution comes from ttbar.

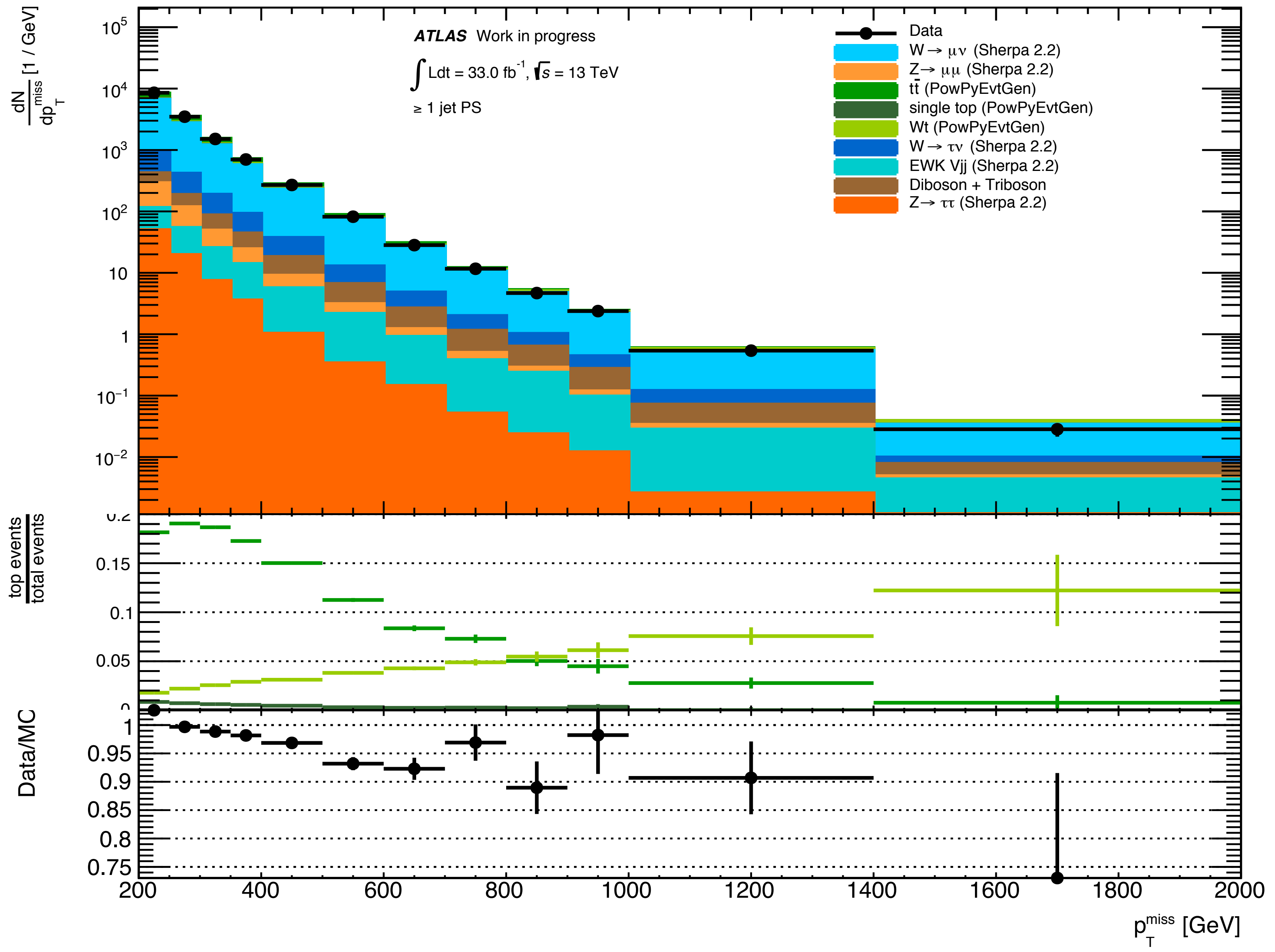
0-lepton SR : DR vs DS single-top



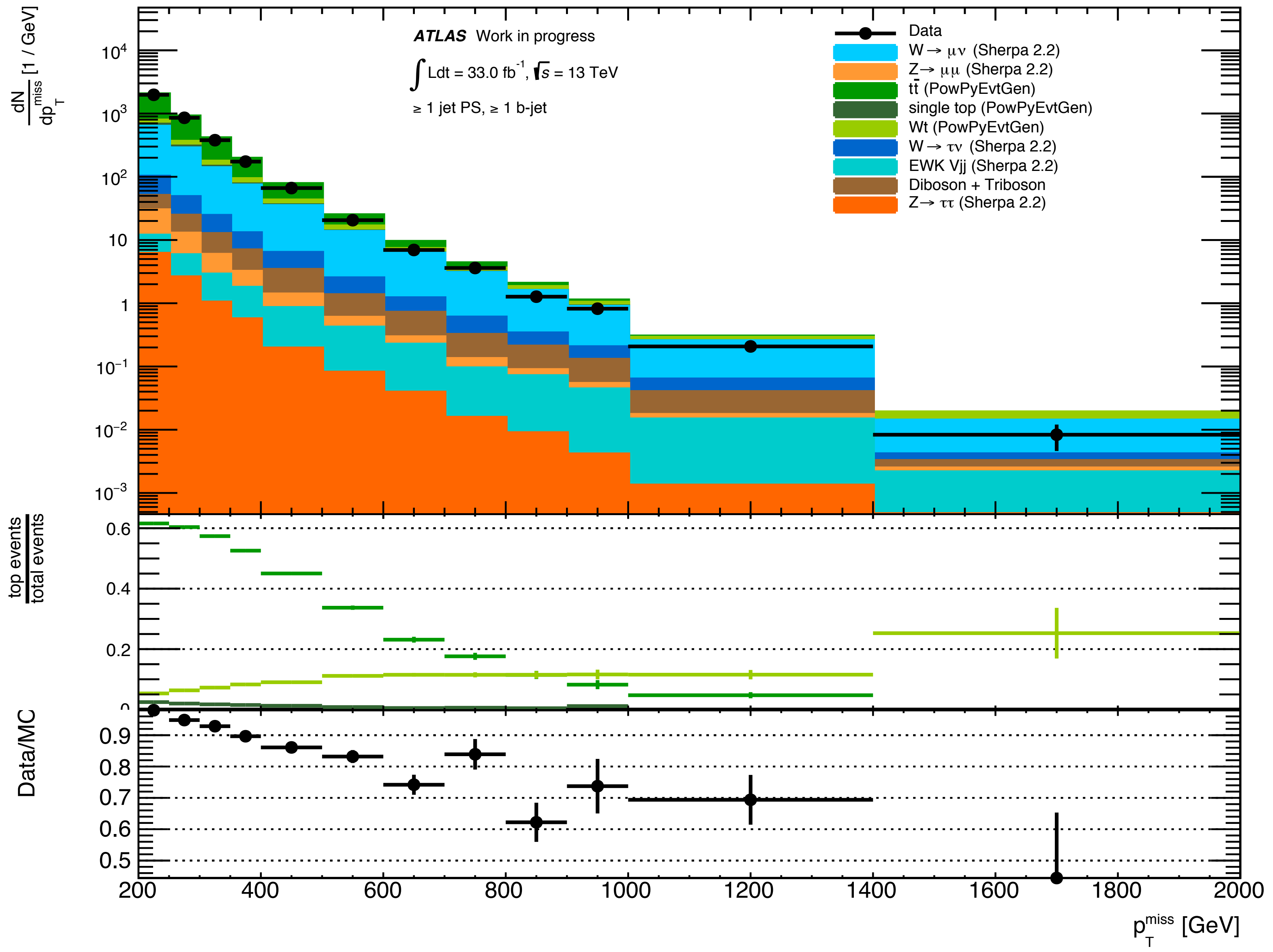
Unfolded



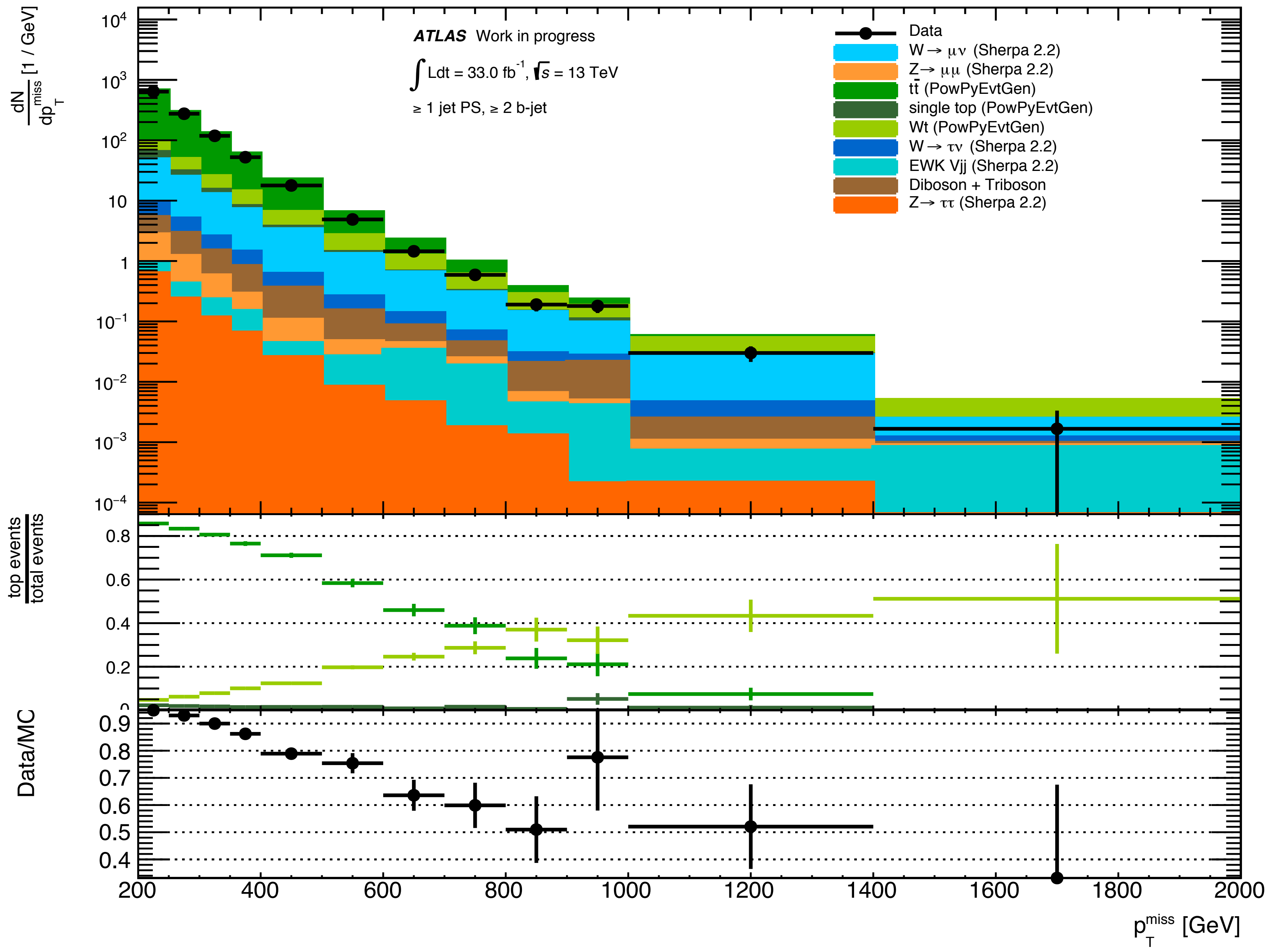
Data/MC comparisons : 1-muon top enhanced control region



No b-jet requirement



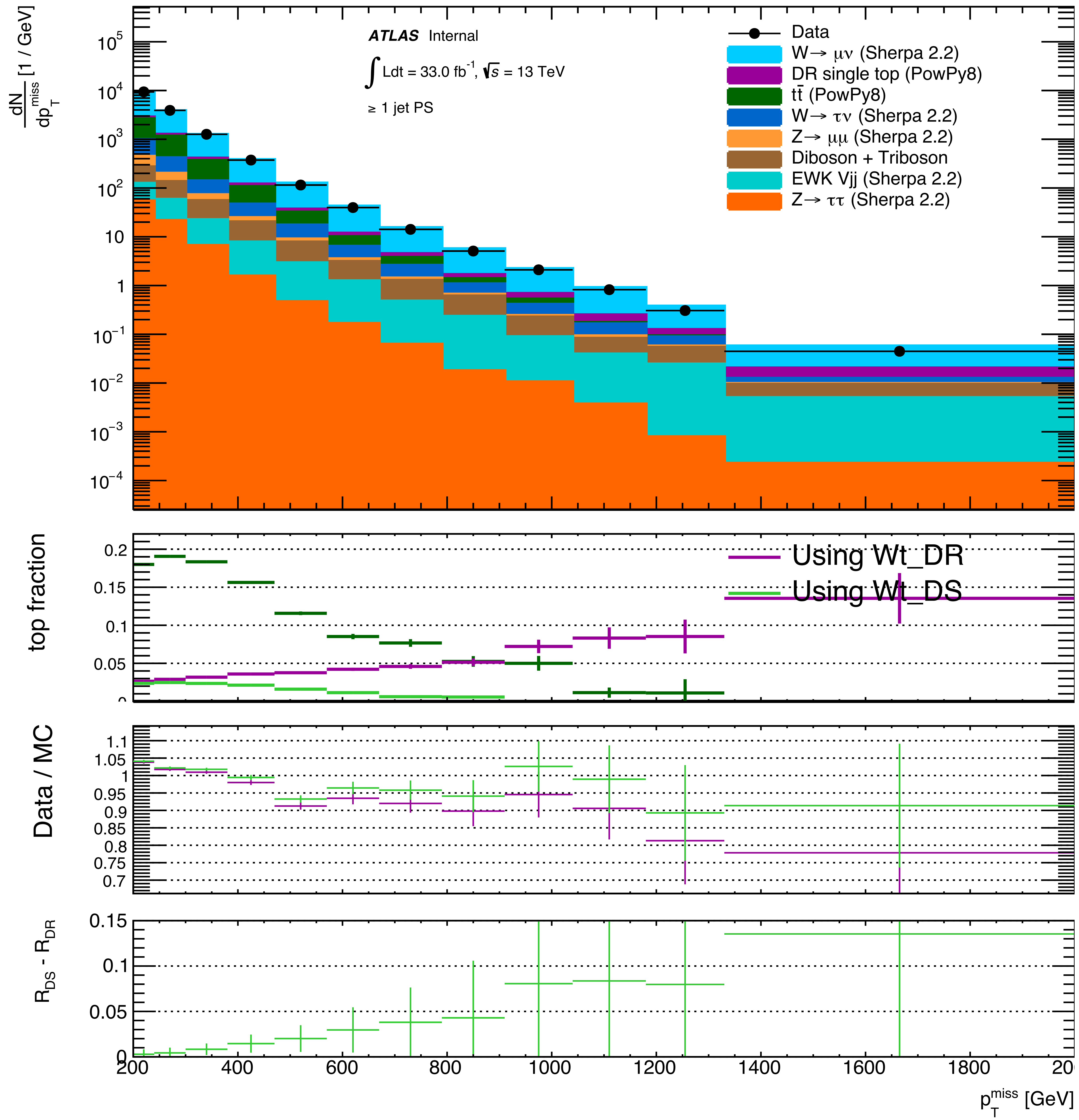
≥ 1 b-jets



≥ 2 b-jets

- Larger Wt contributions ➡ worse Data/MC agreement.
- Options for 1-lepton CR:
  - Include b-veto ➡ additional b-tagging systematics but smaller top modelling uncertainties.
  - Remove b-veto ➡ larger top modelling uncertainties but no b-tagging systematics (cleaner cancelation of uncertainties in the ratio).
- Need to study different Wt modelling methods: diagram subtraction VS diagram removal.

1-muon CR (b-jet inclusive): DR vs DS single-top



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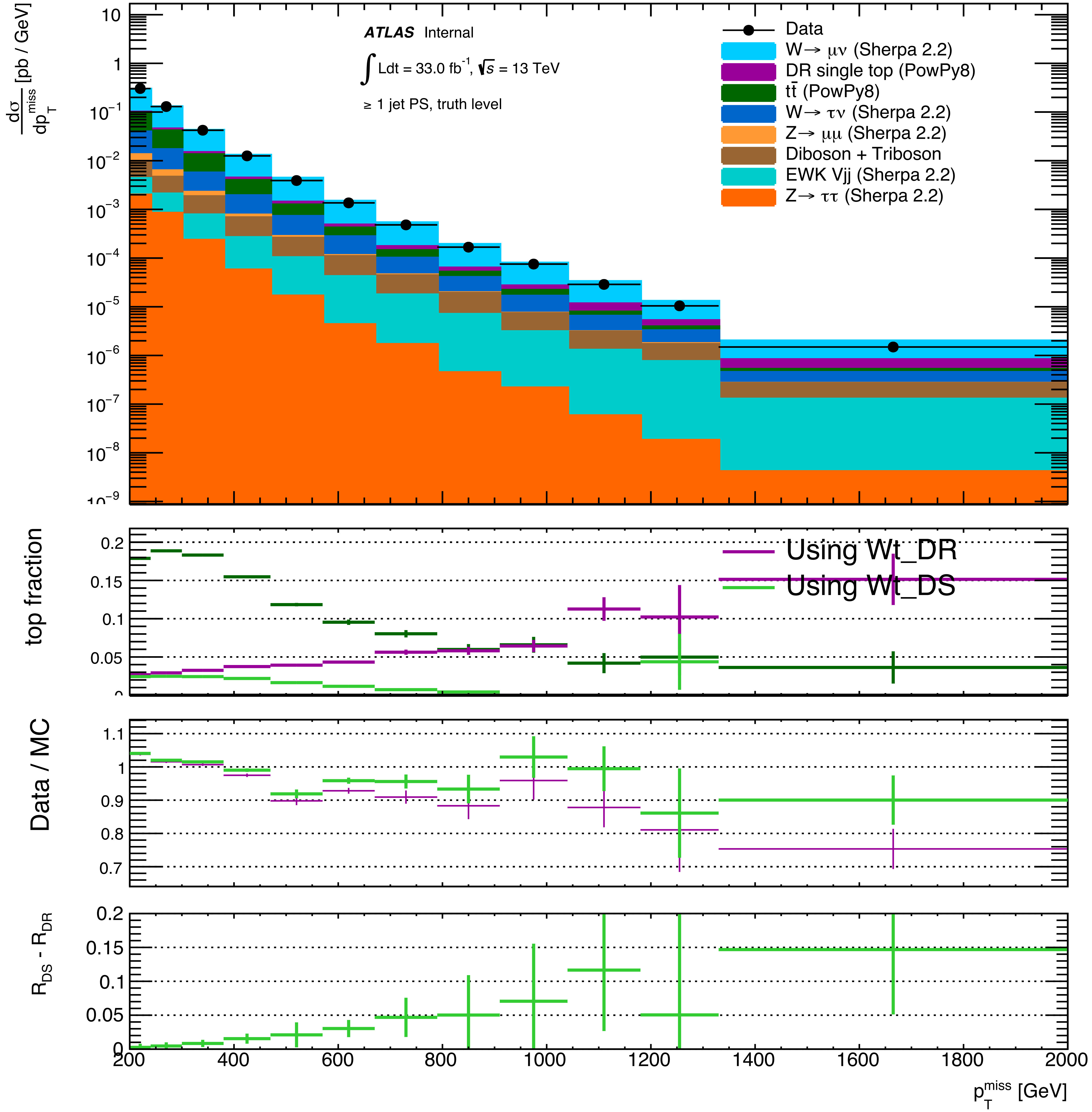
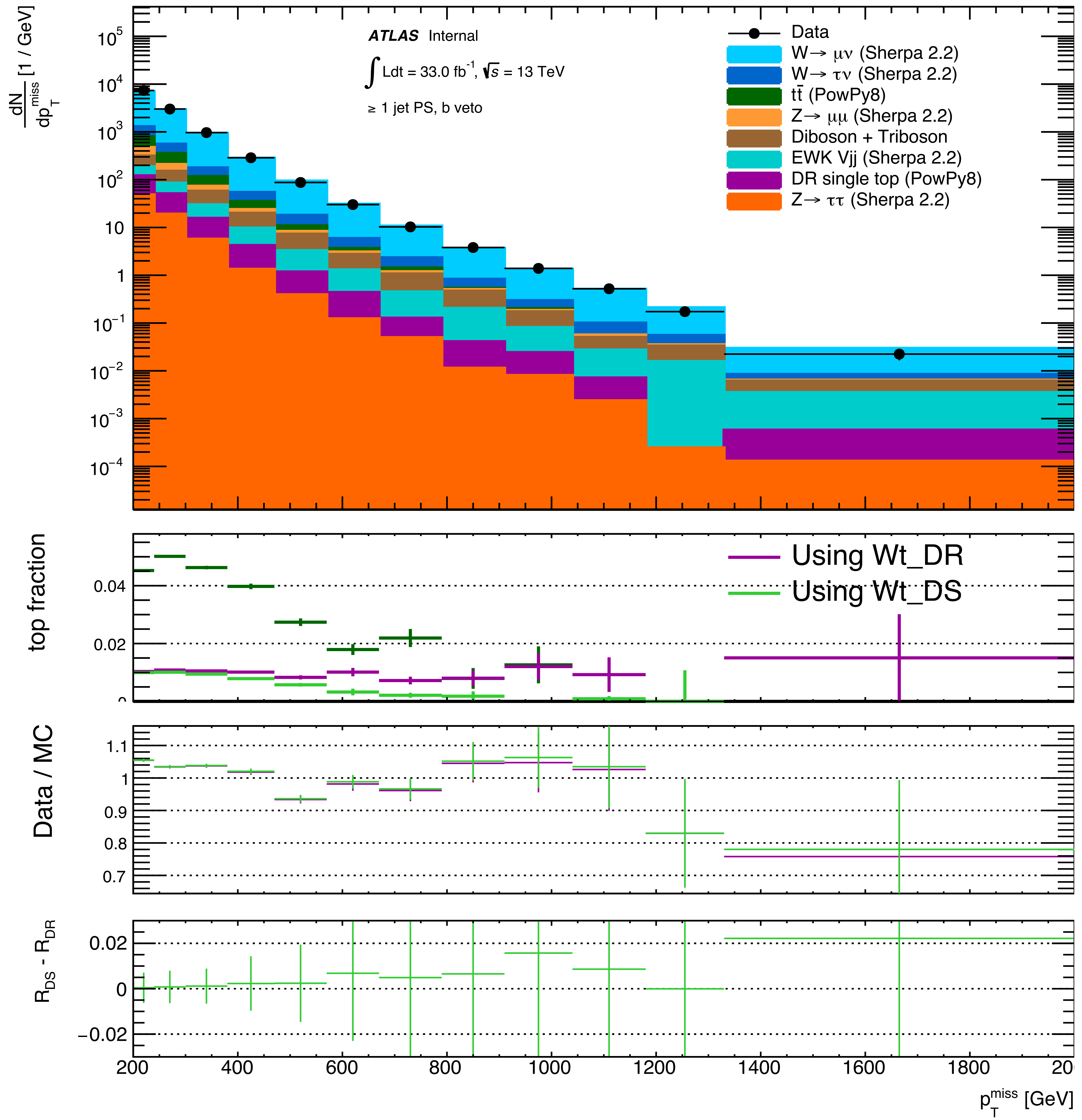


1-muon CR (b-veto): DR vs DS single-top



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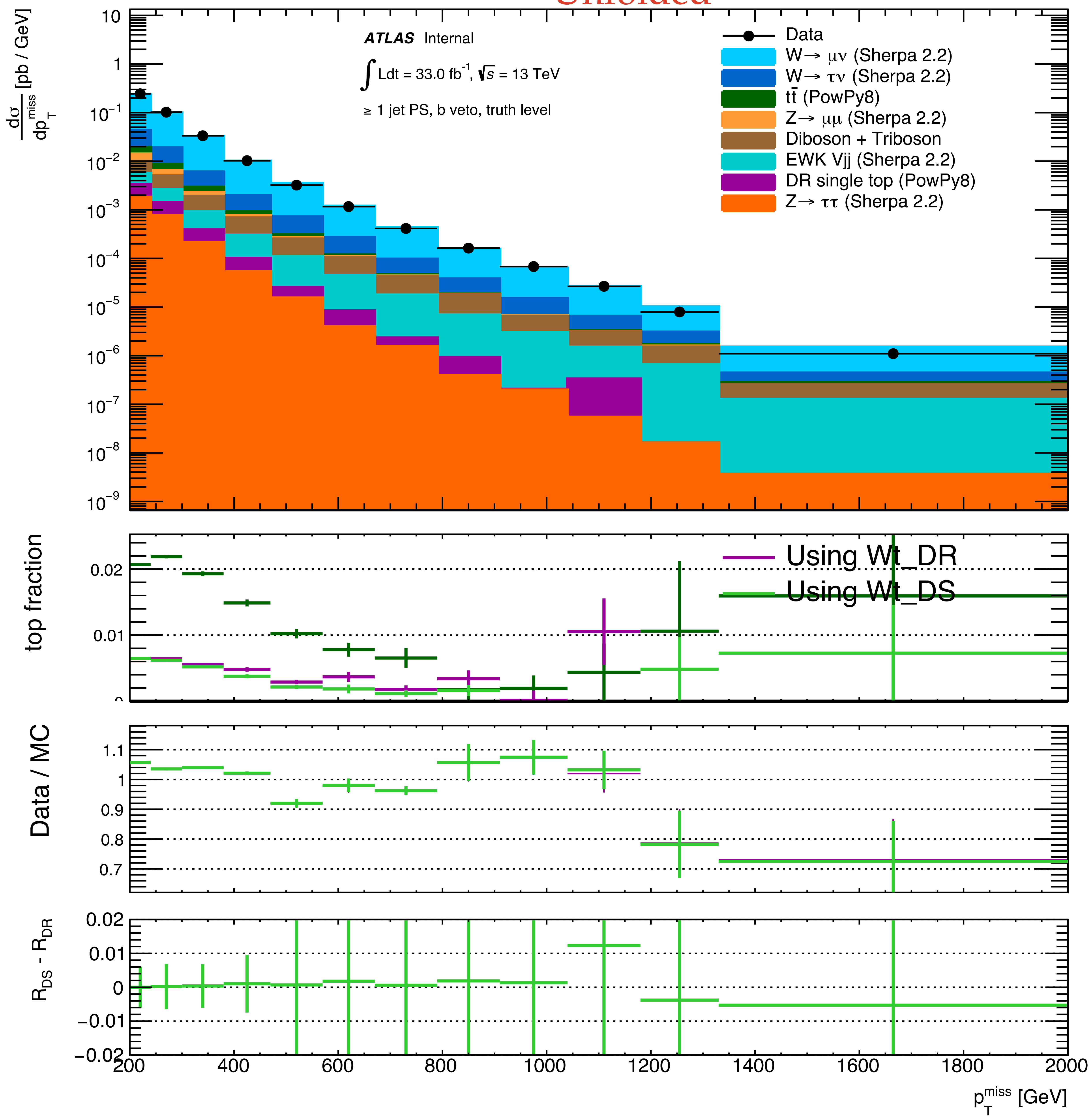
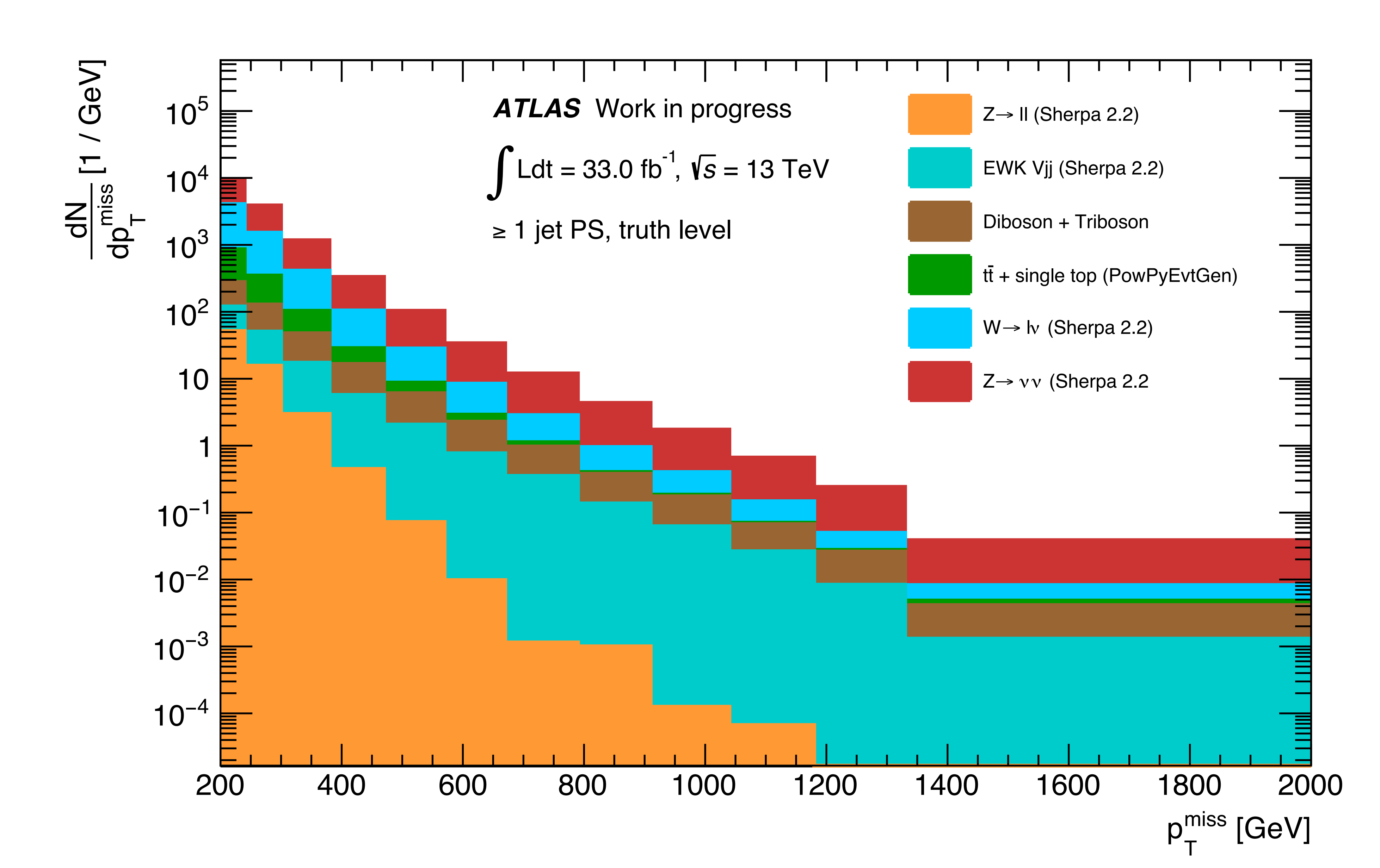
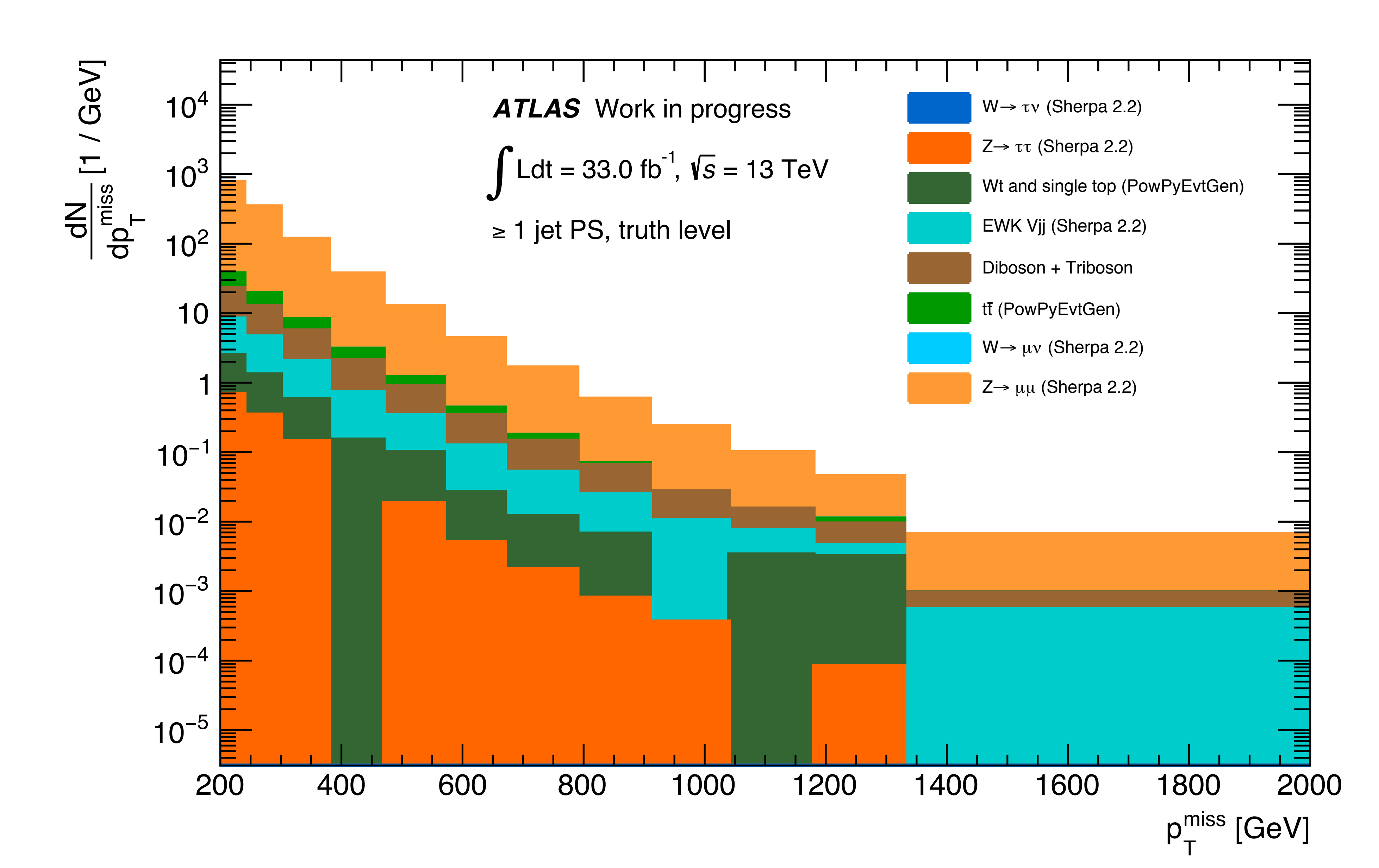


Particle level ratios

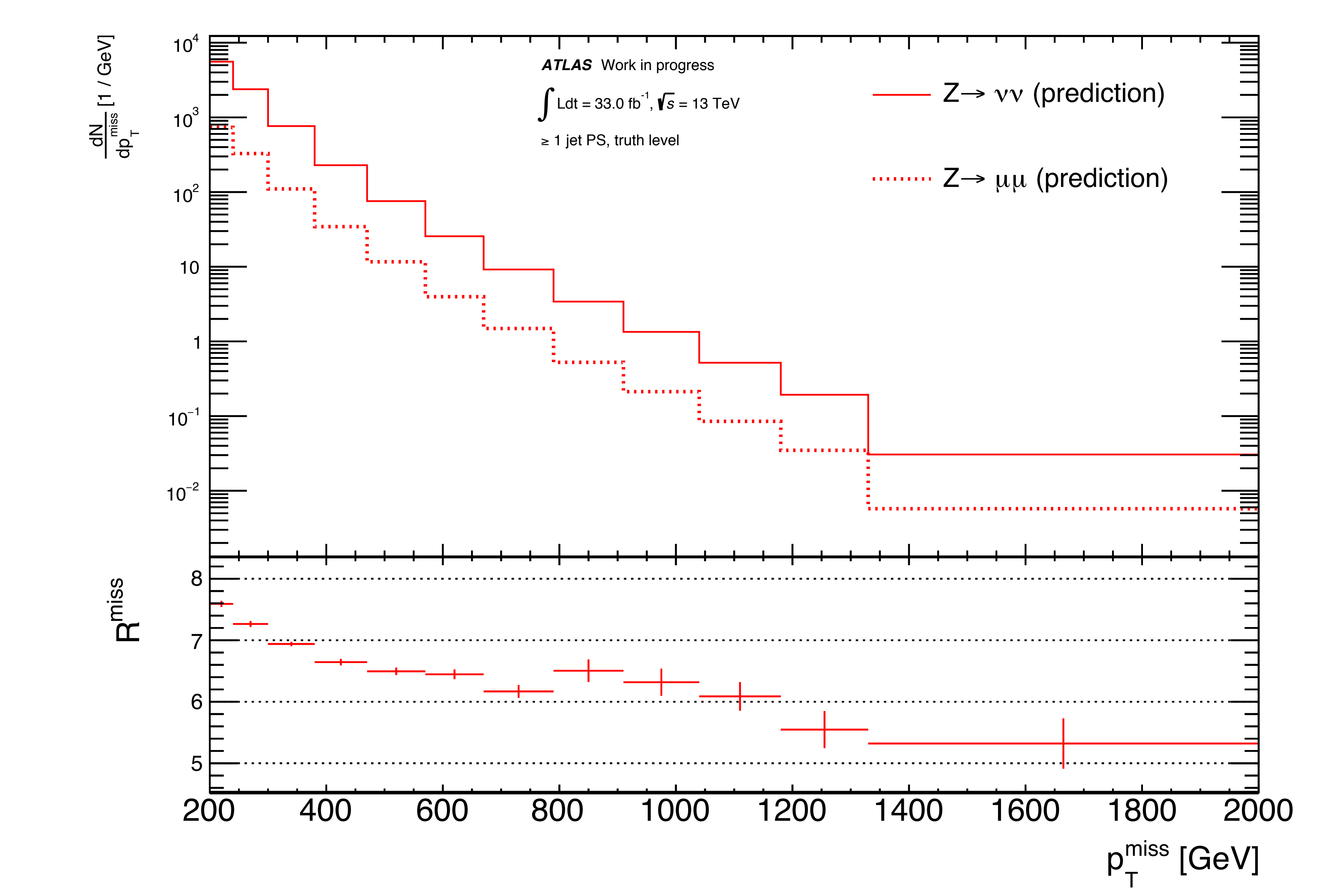
SR truth stack



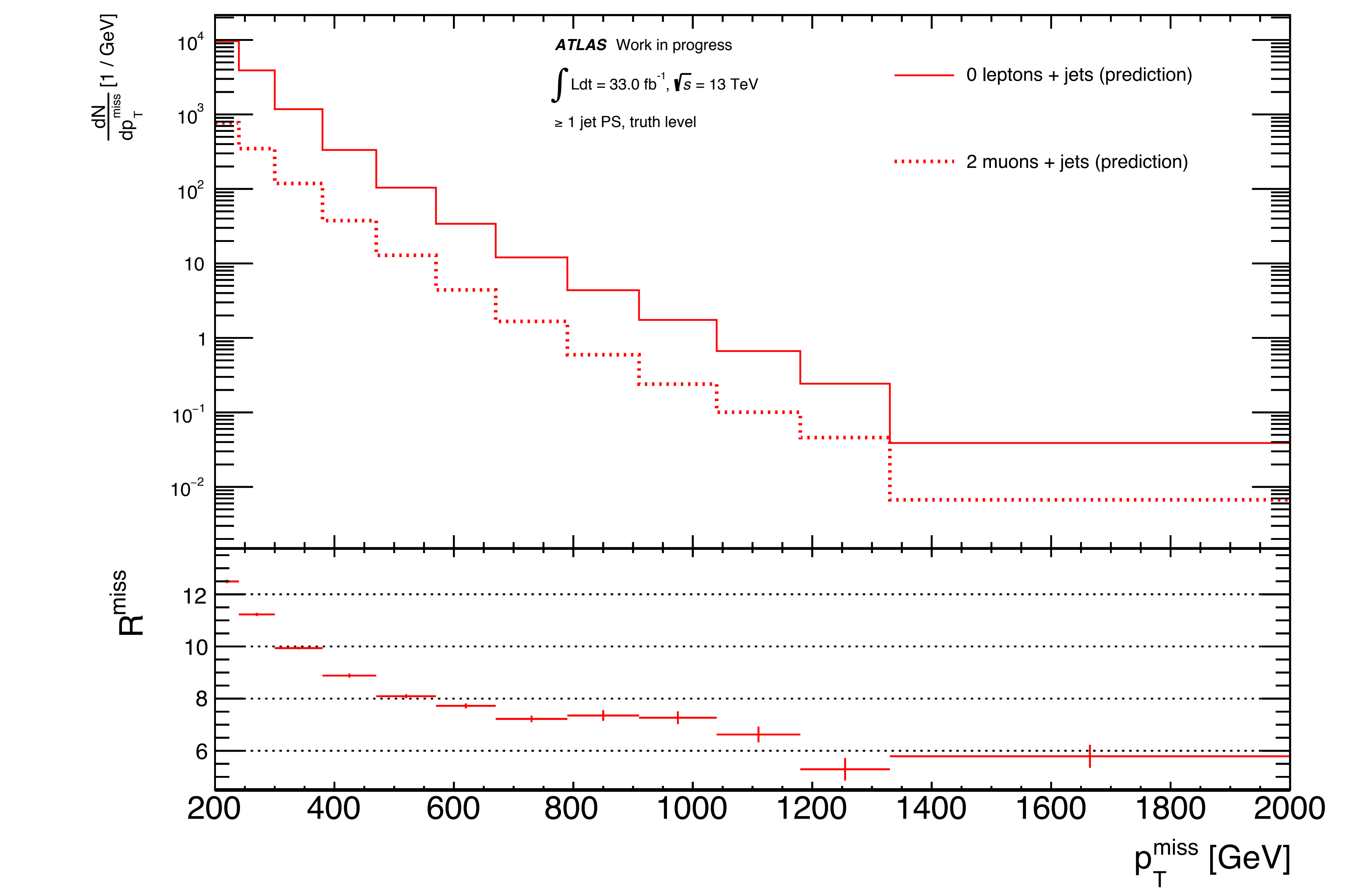
2-muon CR truth stack



Non-fiducial

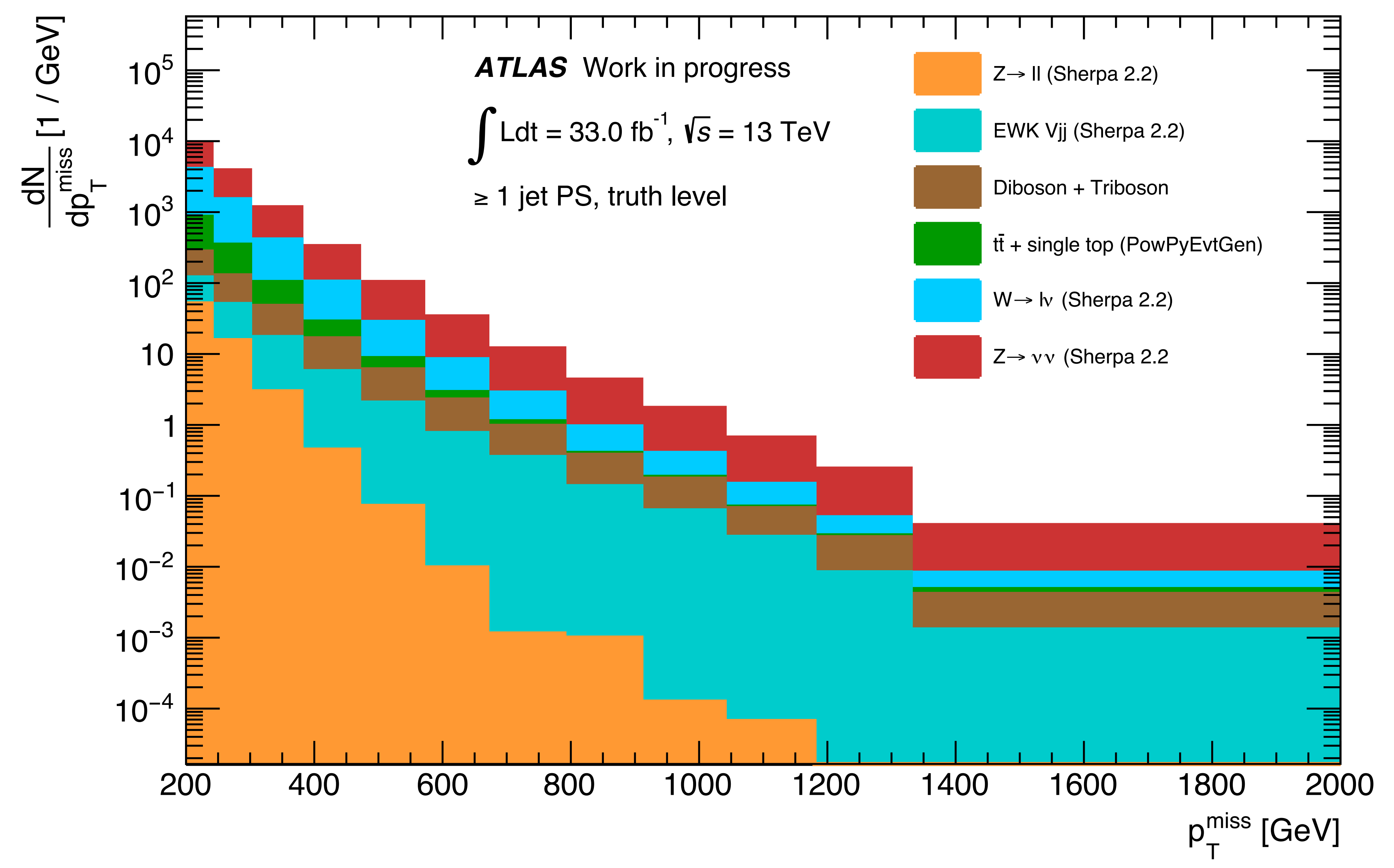


Fiducial

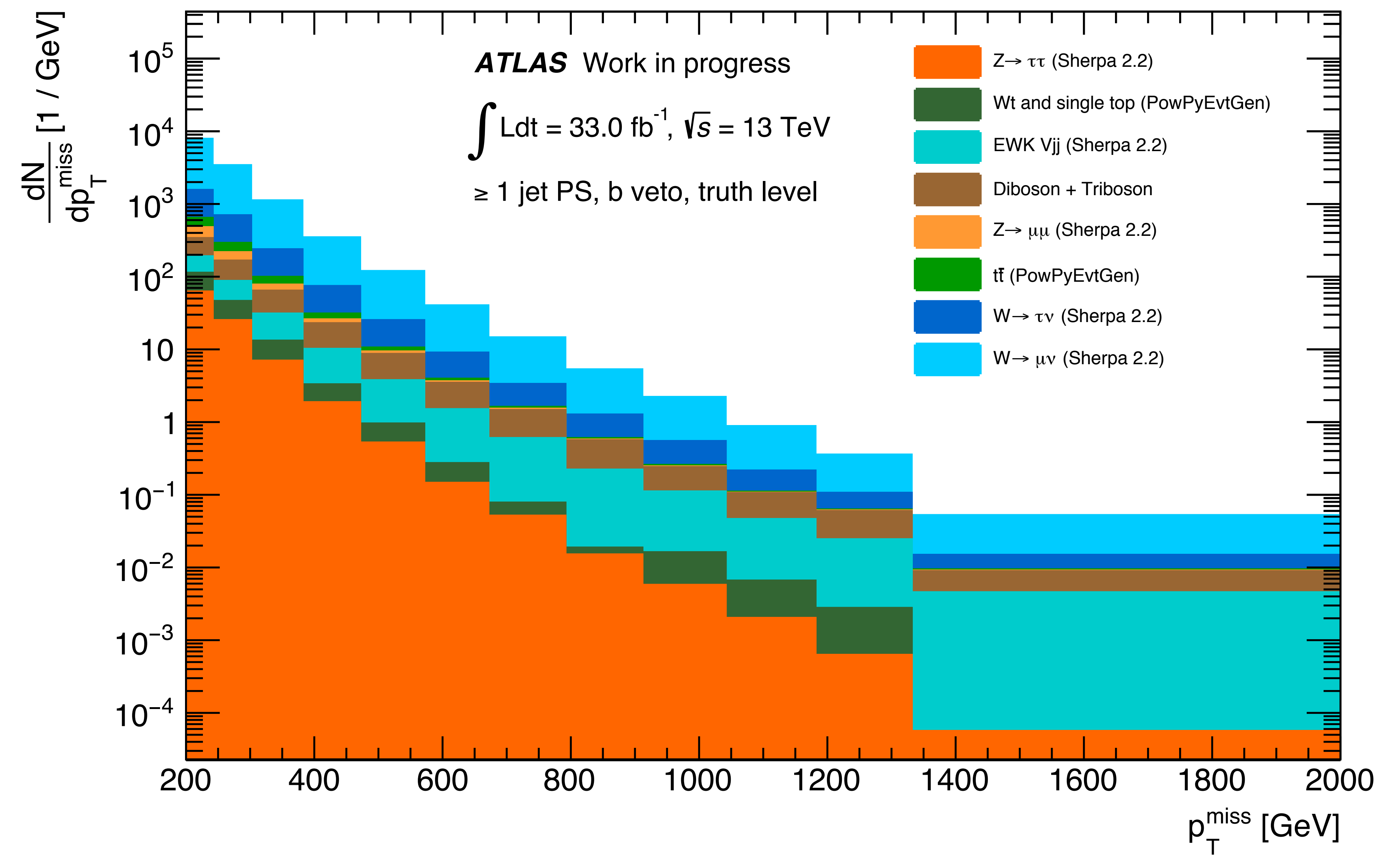


Particle level ratios

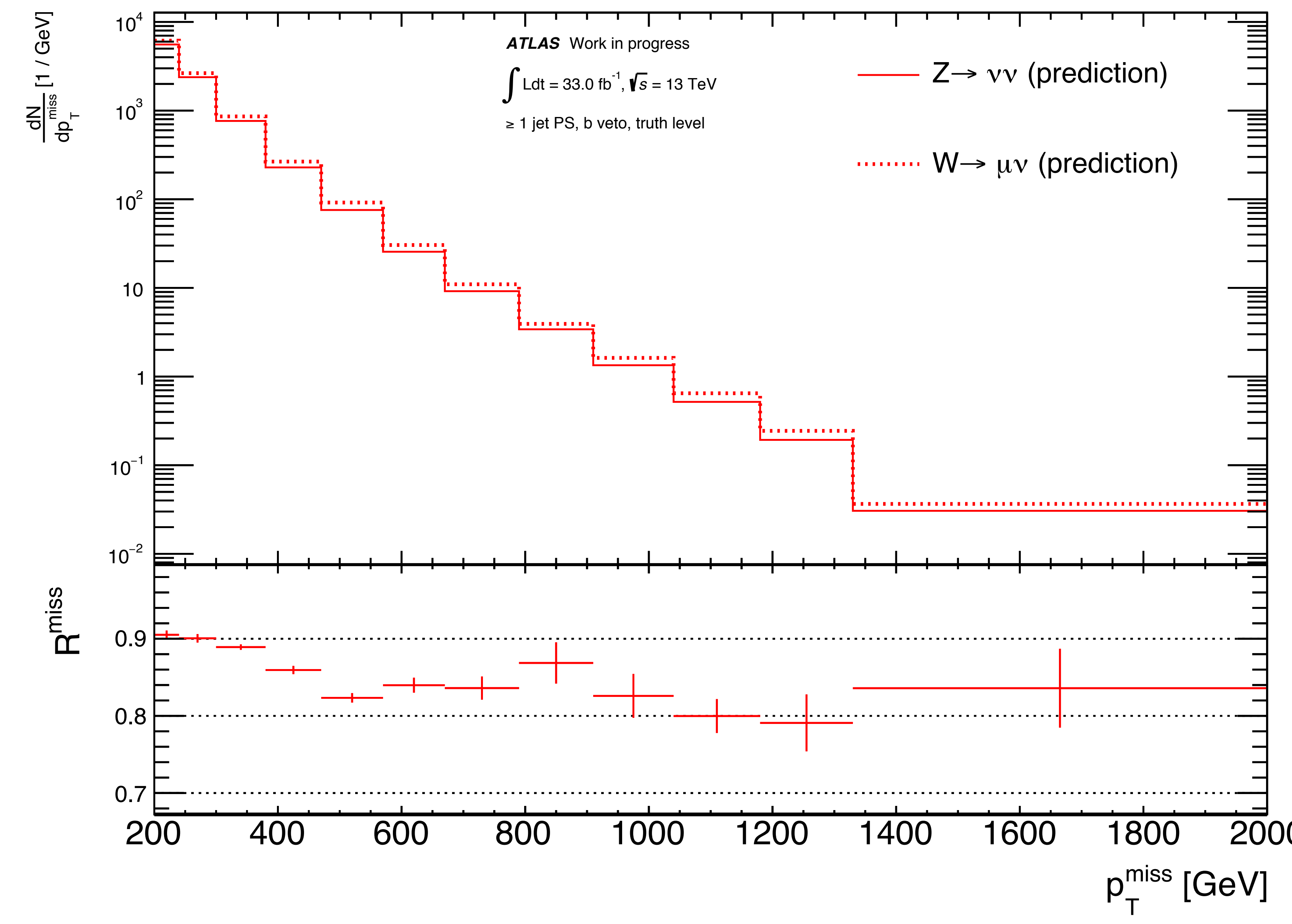
SR truth stack



1-muon CR truth stack



Non-fiducial



Fiducial