

$t\bar{t}\gamma$ differential cross section measurements at 13 TeV with the ATLAS detector

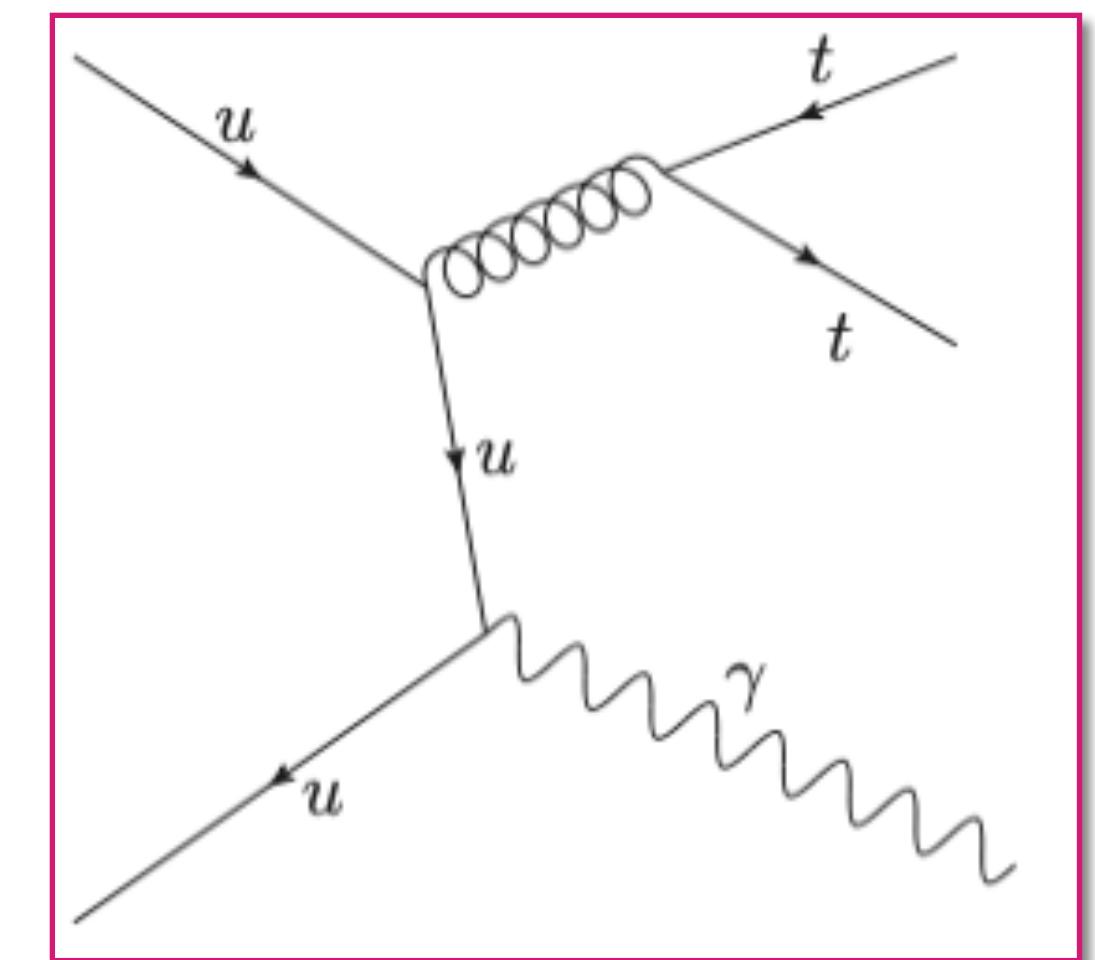
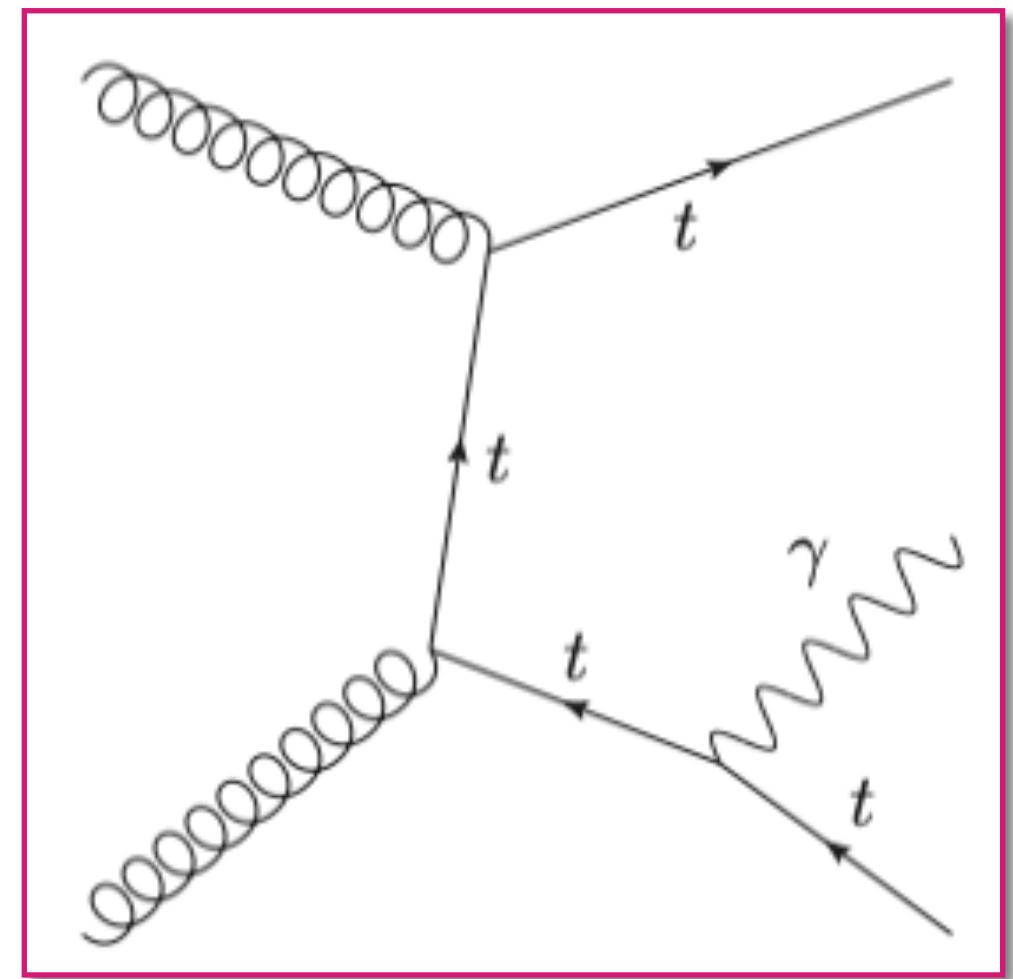
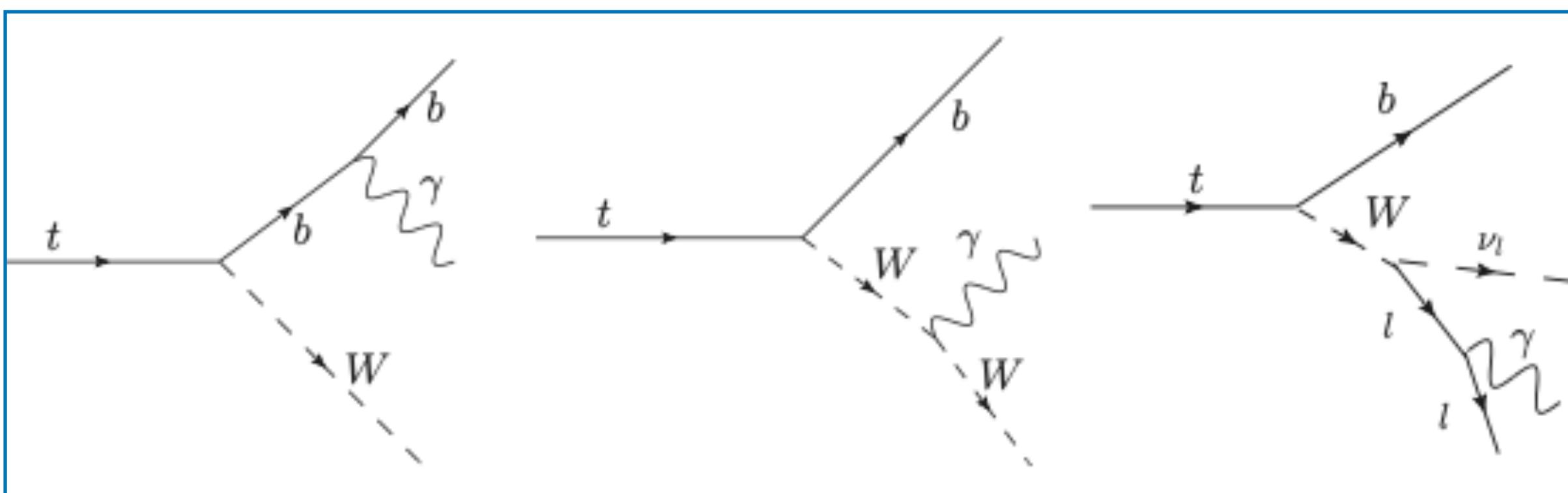
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Physics at the Terascale
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Introduction



- ▶ $t\bar{t}\gamma$ probes the coupling between top quark and photon
- ▶ This topology is sensitive to new physics through anomalous dipole moment of top quark and also in the context of EFT
- ▶ Measurement is being performed using 139 fb^{-1} data collected by ATLAS detector in pp collision at $\sqrt{s} = 13 \text{ TeV}$
- ▶ Semi-leptonic and dileptonic final state of the $t\bar{t}$ pair. **This talk focuses on semileptonic channel** ($e+jets$, $\mu+jets$)
- ▶ $t\bar{t}\gamma$ events with photon radiated during top quark pair production or from initial parton considered as signal
- ▶ $t\bar{t}\gamma$ events with photon emitted from decay products of top quark pair considered as background



Signal and Background simulation



Signal process: $pp \rightarrow t\bar{t}\gamma$

- ▶ Simulated at NLO as 2->3 process using Madgraph_aMC@NLO

Background process:

- ▶ Decay of $t\bar{t}\gamma$ is simulated as 2->7 process at LO
- ▶ K-factor of 1.50 is used for scaling to NLO cross section
- ▶ Other background process:
 $t\bar{t}$, $V + \text{jets}$, $V\gamma + \text{jets}$, $VV\gamma$, $t\bar{t}V\gamma$, $t + \gamma$

Background categorization based on photon source:

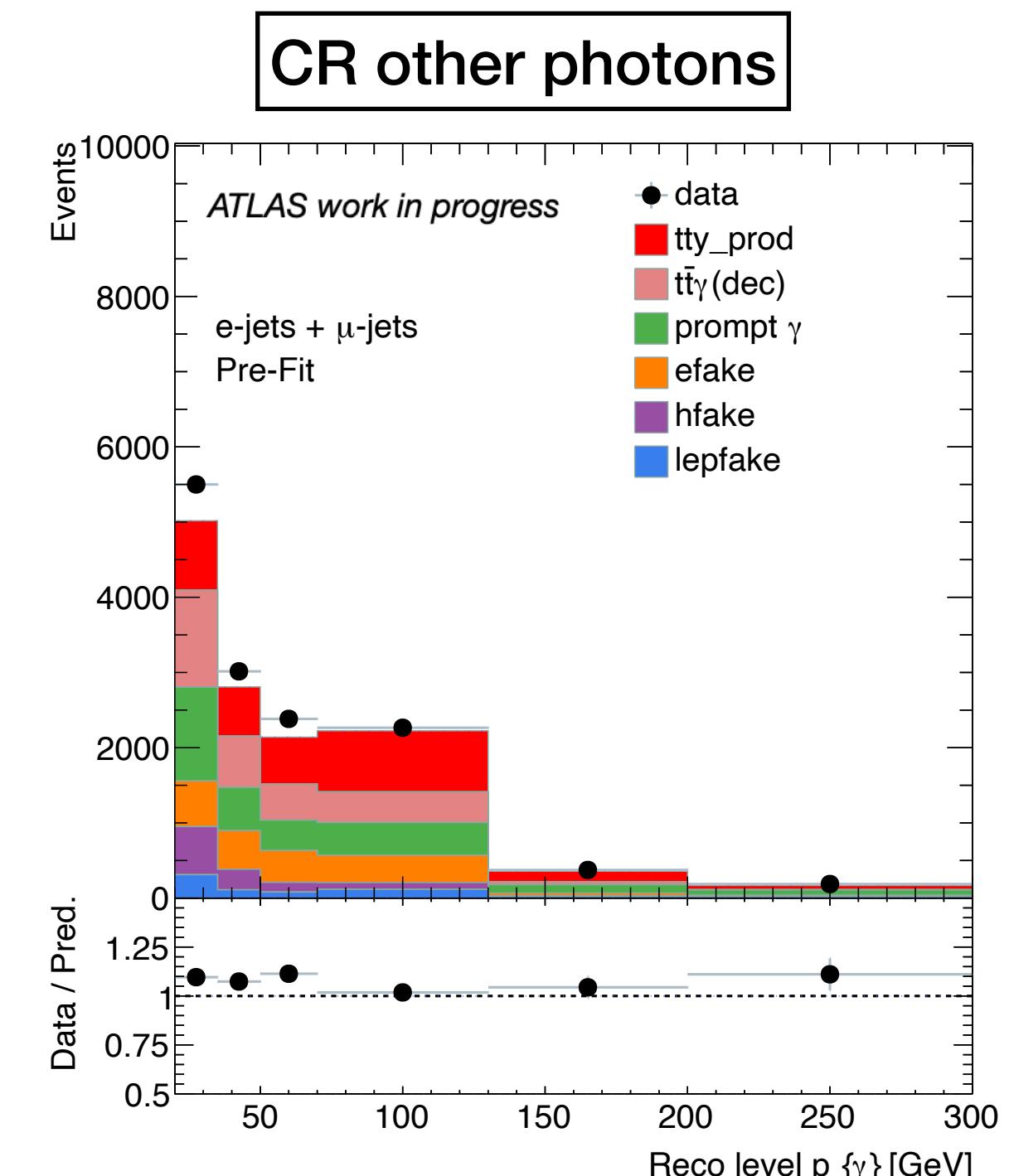
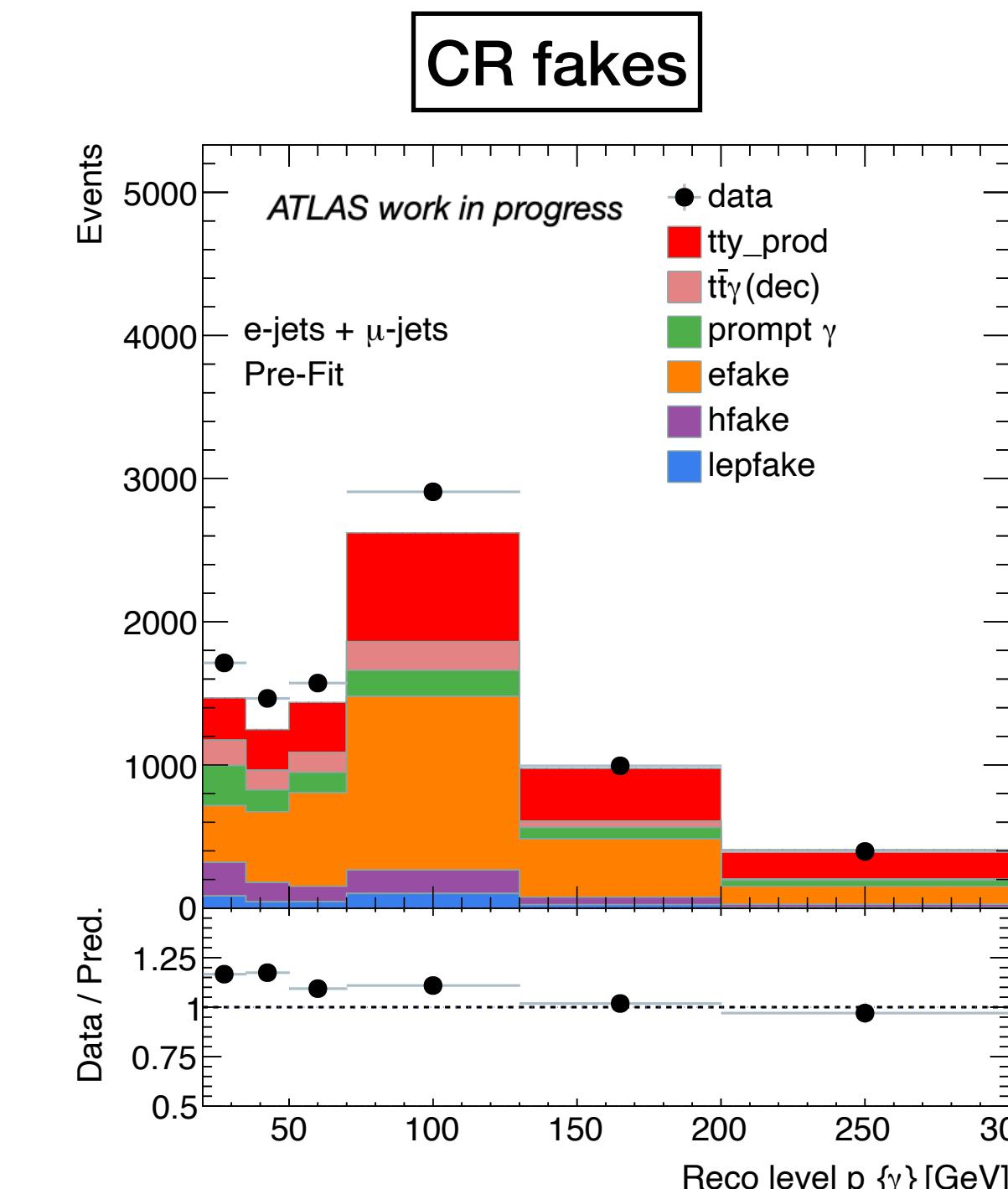
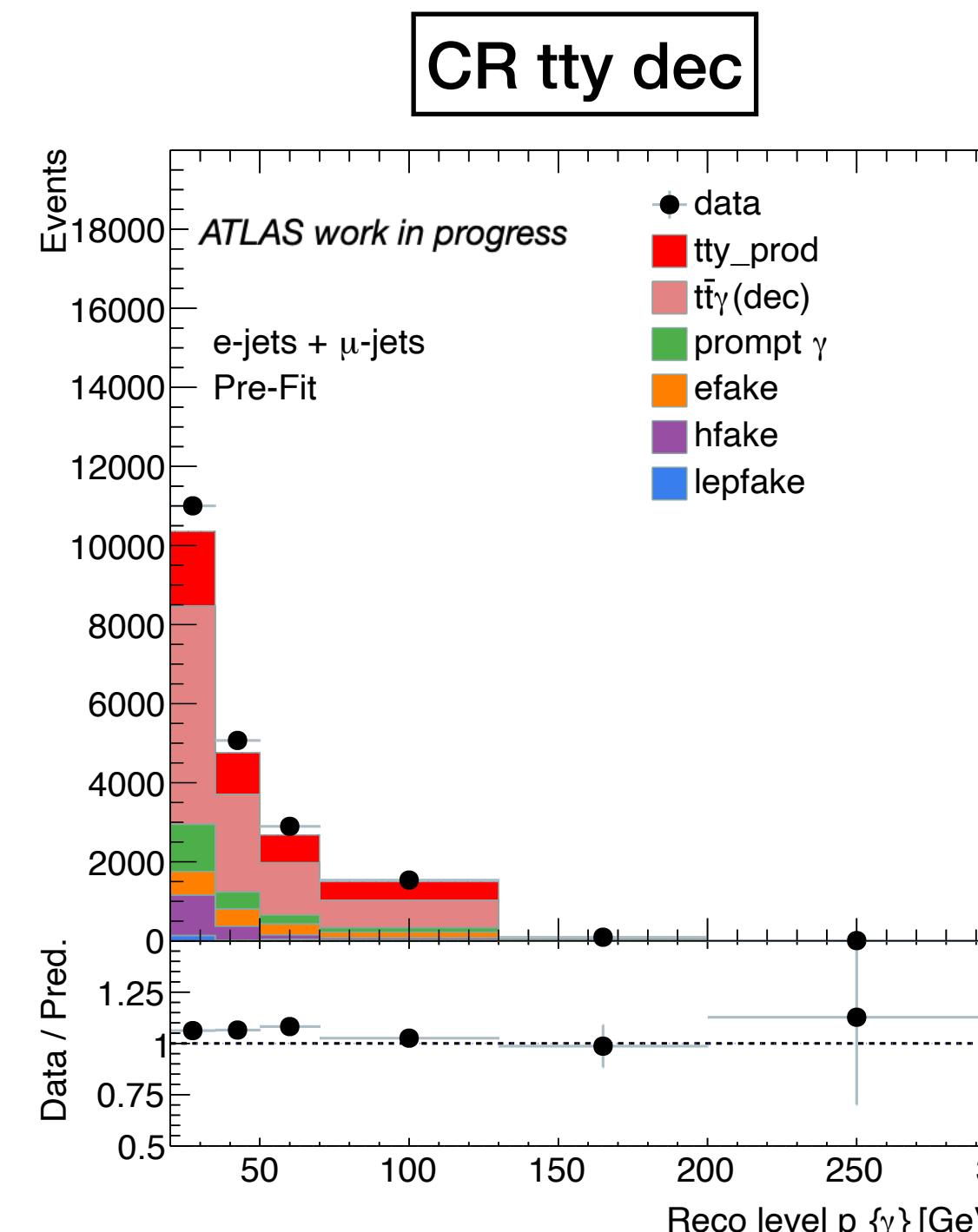
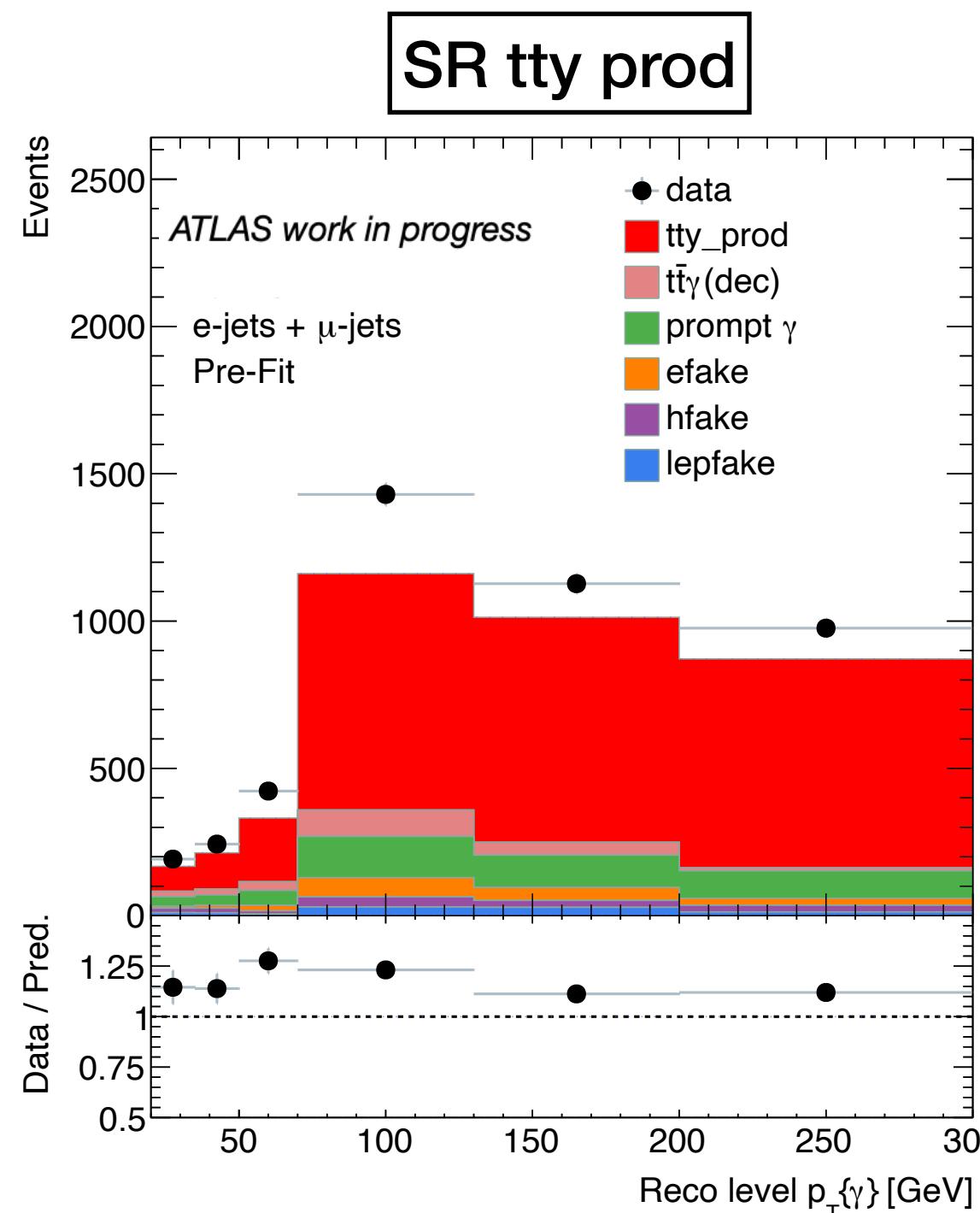
- ▶ **Prompt γ :** truth match to photon from lepton/quark/bosons
- ▶ **Non-prompt γ :**
electron mis-reconstructed as photon ($e \rightarrow \gamma$ fake)
jet mis-reconstructed as photon,
photon coming from hadron decay
(hadron fake)

Event selection



Channel	$e + jets$	$\mu + jets$
Common	$1e$	1μ
Photon	$1\gamma p_T > 20 \text{ GeV}$	
Jet	≥ 4	
b-jet	≥ 1	
$m(e, \gamma)$	Not in $[86.19, 96.19] \text{ GeV}$	
$\Delta R(\gamma, l)$		> 0.4

- ▶ Signal and control regions defined by means of multi classification NN



Non-prompt background processes

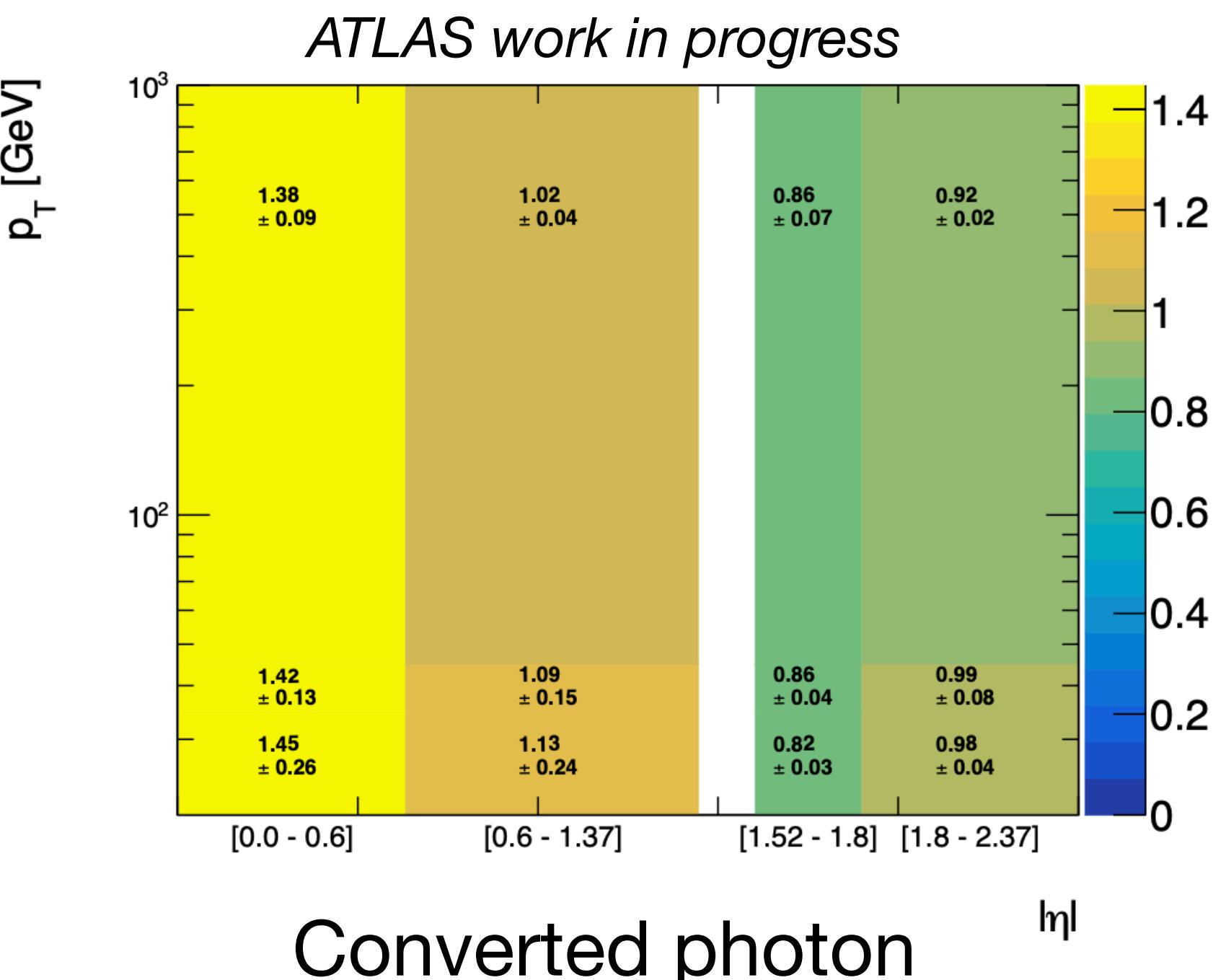
- ▶ Backgrounds with non-prompt objects estimated from data

$e \rightarrow \gamma$ fake:

- ▶ electron mis-reconstructed as photon
- ▶ Tag and probe approach is used
- ▶ Using $Z \rightarrow e^+e^-$, ee and $e\gamma$ CRs are defined in data and MC
- ▶ Fake rate (FR) is calculated both in data and MC,

$$\text{FR}^{data/MC} = \frac{N_{e\gamma}^{data/MC}}{N_{ee}^{data/MC}} \cdot \frac{FR^{data}}{FR^{MC}}$$

- ▶ FR scale factor = $\frac{FR^{data}}{FR^{MC}}$
- ▶ 2D FR scale factor is estimated in p_T , $|\eta|$
 - ▶ estimated for converted and unconverted photon



Converted photon

| η |

Fiducial phase space



Differential cross-section measured at particle level in a fiducial phase space close to the selection at reconstruction level

- ▶ Exactly one lepton with $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
 - ▶ Leptons dressed using photons found within $\Delta R < 0.1$
- ▶ Jet Clustered using anti – k_T algorithms with radius $\Delta R = 0.4$,
with $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$, $\text{njets} \geq 4$
- ▶ One or more b-quark jet $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
 - ▶ b-quark jets identified using ghost-matching procedure
- ▶ $\Delta R(l, \gamma) > 0.4$

Differential cross section measurement



- ▶ Measurements for the following variables

$$p_T(\gamma), |\eta(\gamma)|, \min\Delta R(\gamma, l), \min\Delta R(\gamma, b), \min\Delta R(l, j), p_T(j1)$$

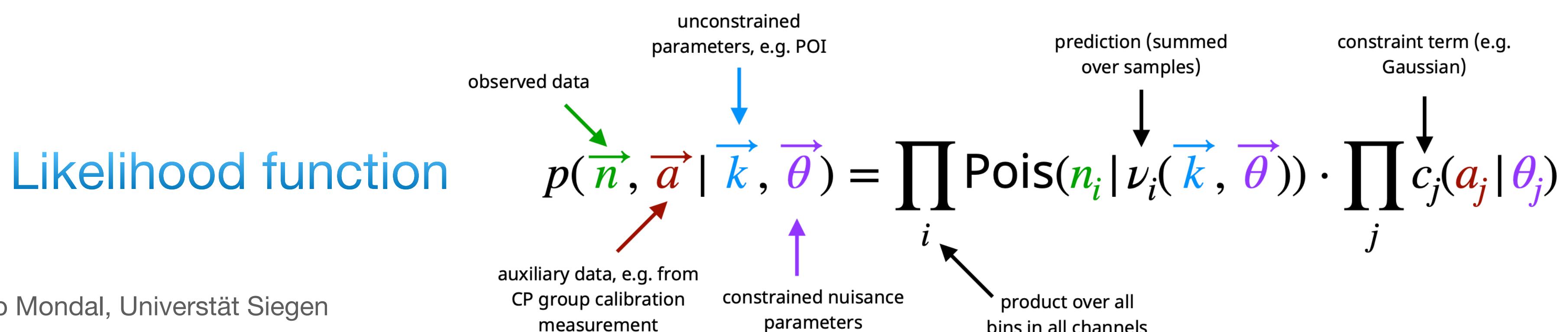
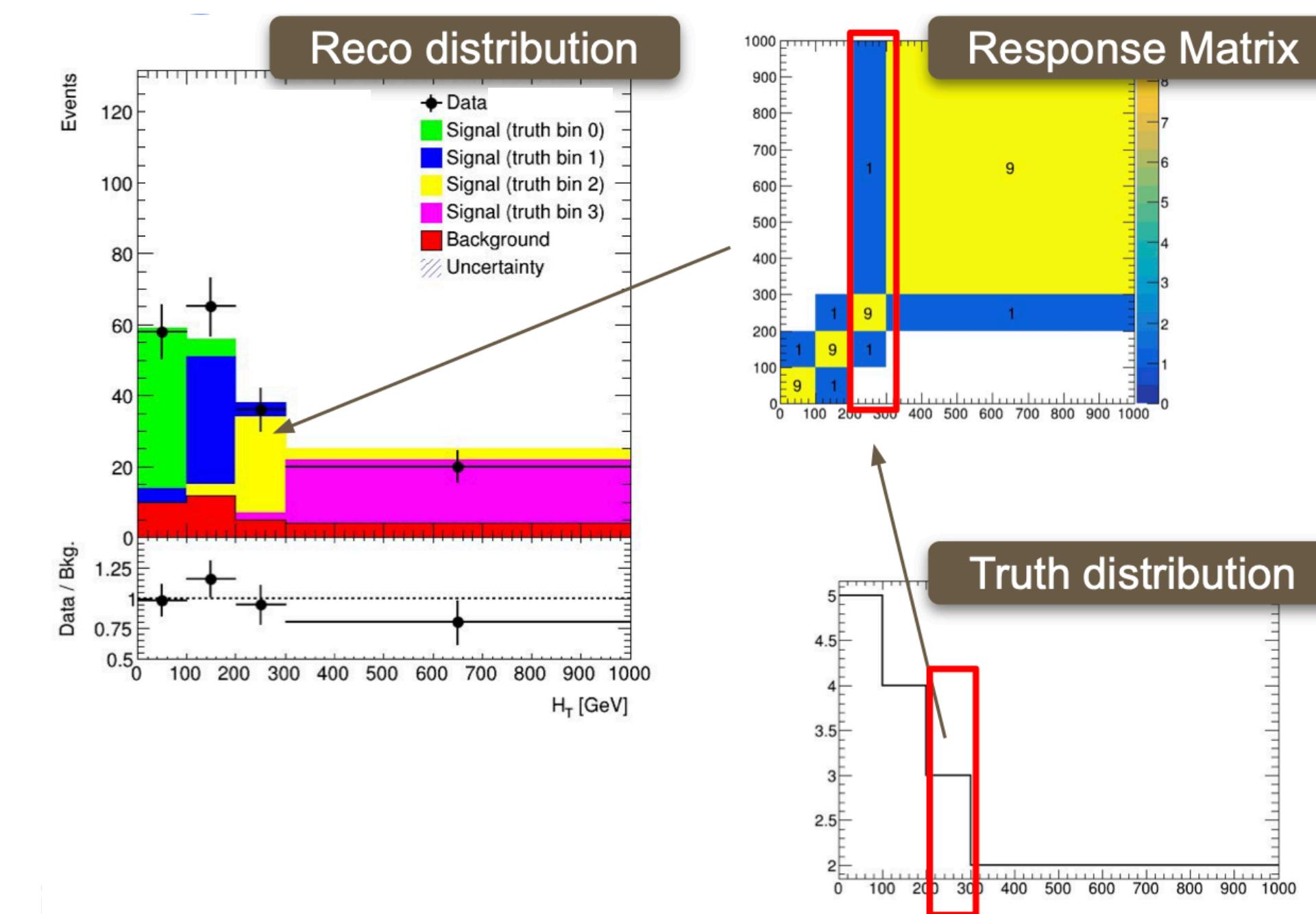
- ▶ Detector response and acceptance effects are represented by response matrix
- ▶ Differential cross section evaluated by applying unfolding procedure (next slide):
 - ▶ Unregularized profile likelihood unfolding

Fit and unfolding strategy



- Each bin of signal distribution at particle level is folded using response matrix to obtain distribution at reconstruction level
- A normalization factor (free parameter) is assigned to each bin at particle level
- Profile likelihood fit to the reco level distribution to fit signal normalization factors: adjust truth bin contents -> unfolded distribution
- Uncertainties are incorporated to the likelihood model as nuisance parameters with proper constraints

Toy example



Systematic Uncertainties



Experimental sources:

- The jet energy scale and jet energy resolution
- Lepton and photon identification, reconstruction and isolation
- b-jet tagging
- Pileup modelling
- Trigger
- Integrated luminosity
- Uncertainty in $e \rightarrow \gamma$ fake, hadron fake, lepton fake estimation

Systematic Uncertainties



Background normalization: for background processes estimated with MC

- $t\bar{t}\gamma$ decay: $\pm 20\%$ arising from the uncertainty in NLO/LO k-factor
- $W\gamma, t\bar{t}$: $\pm 20\%$
- $Wt\gamma, Z\gamma, t\bar{t}V$, Diboson: $\pm 50\%$

Theoretical uncertainties: for signal and background processes

- Sources related to the matrix element calculation of the hard scattering process
 - The uncertainty from PDFs
 - QCD renormalization and factorization scales
- Sources related to the modelling of the parton shower and underlying events

Results



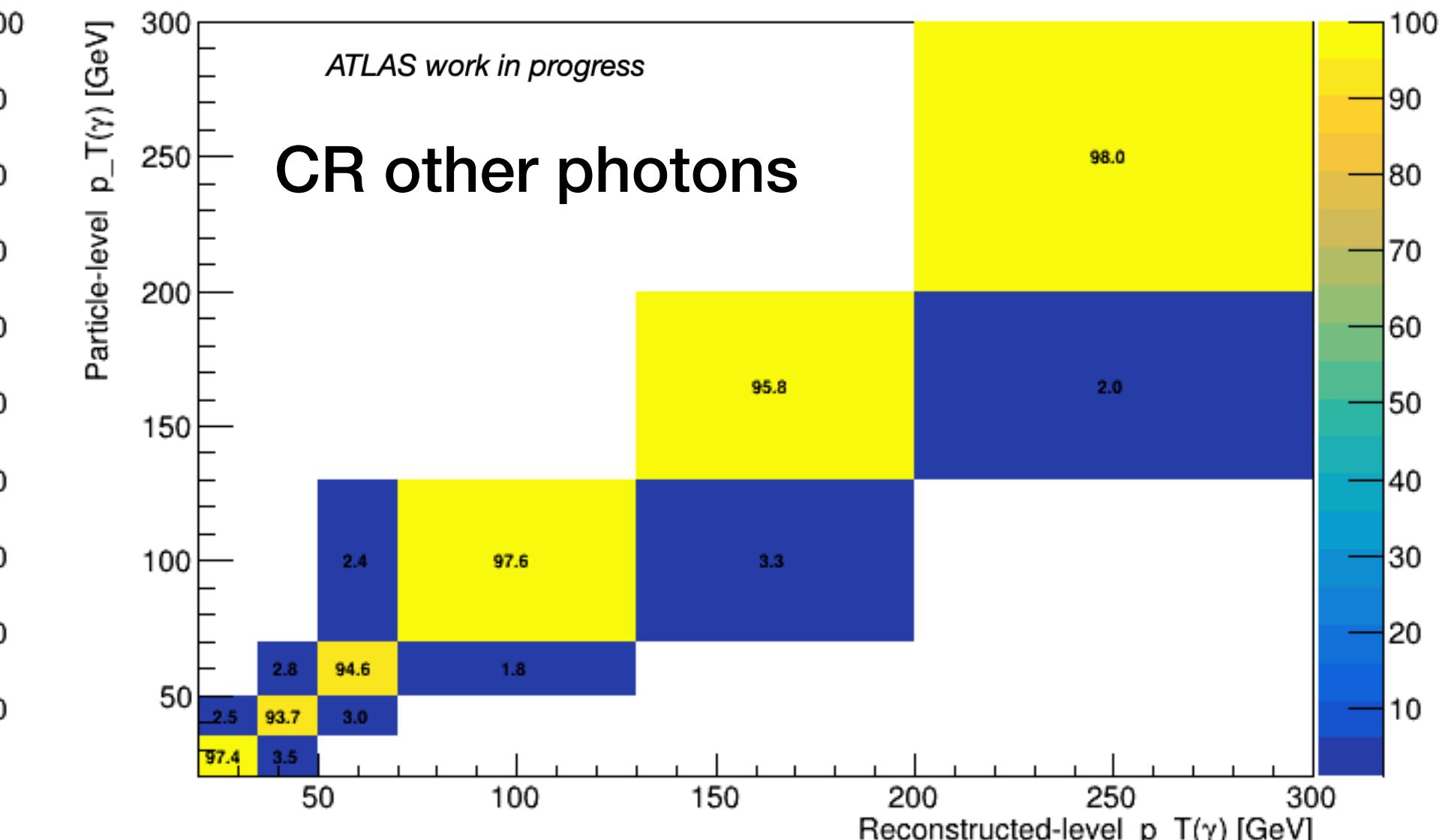
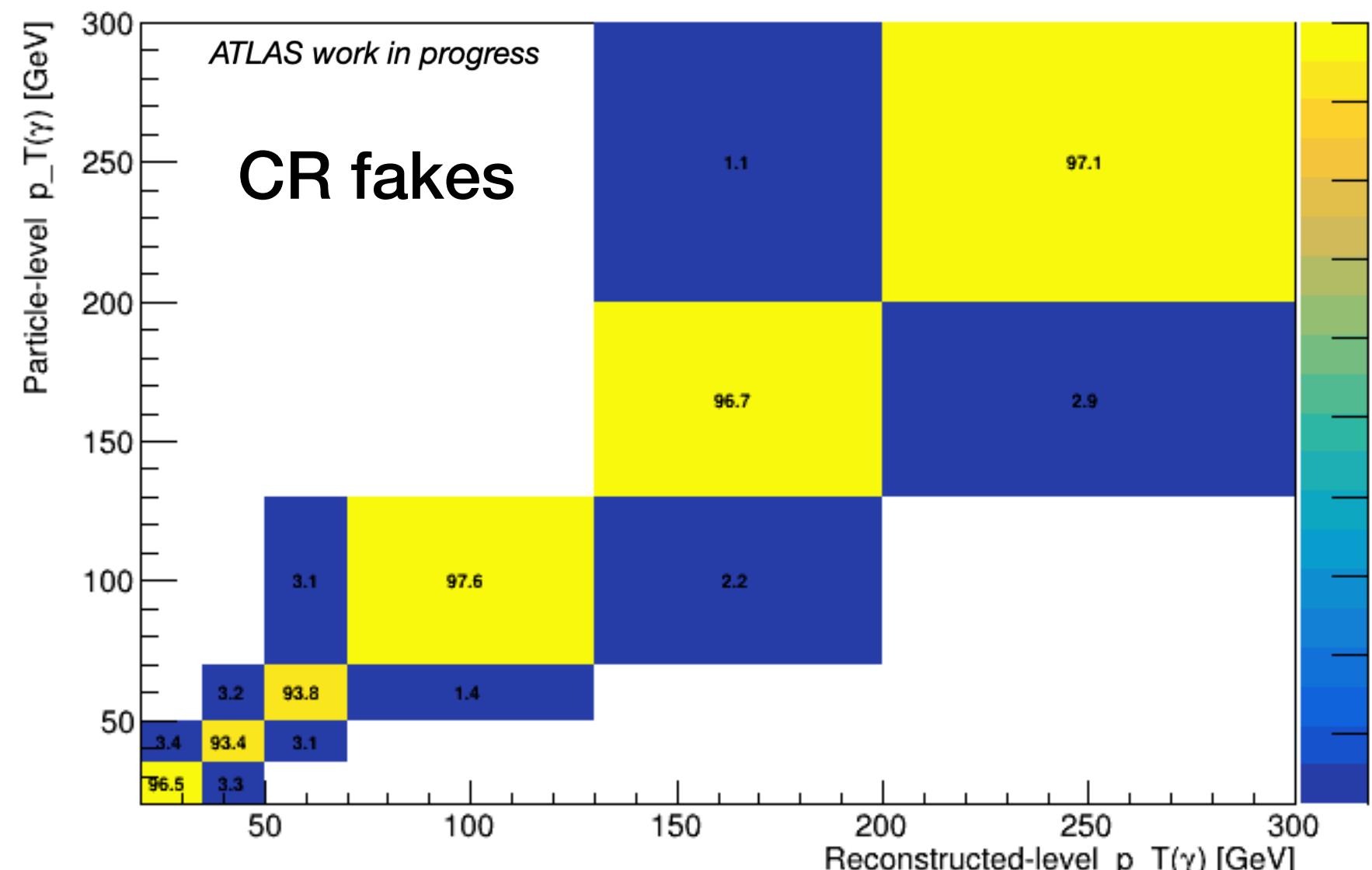
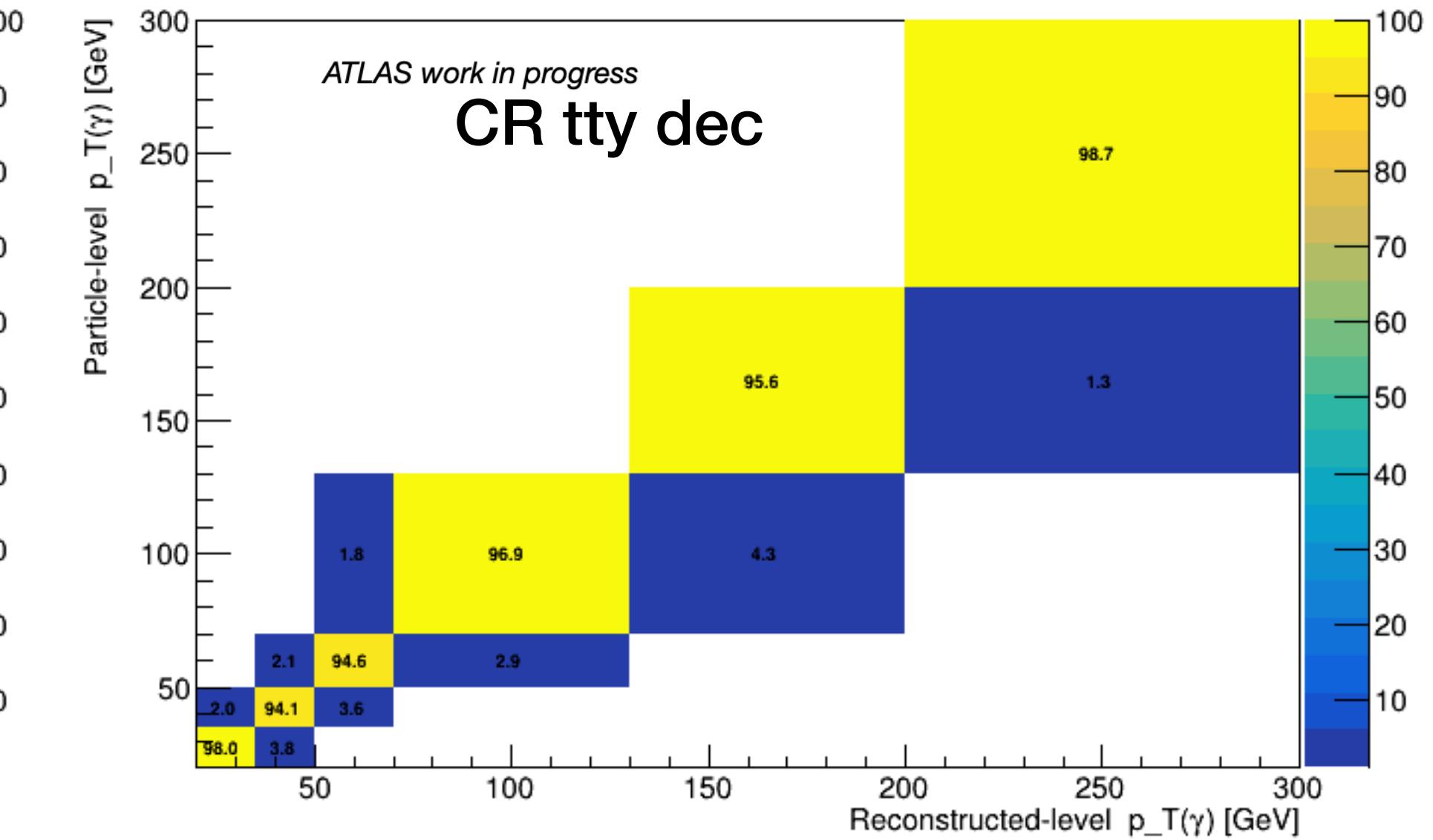
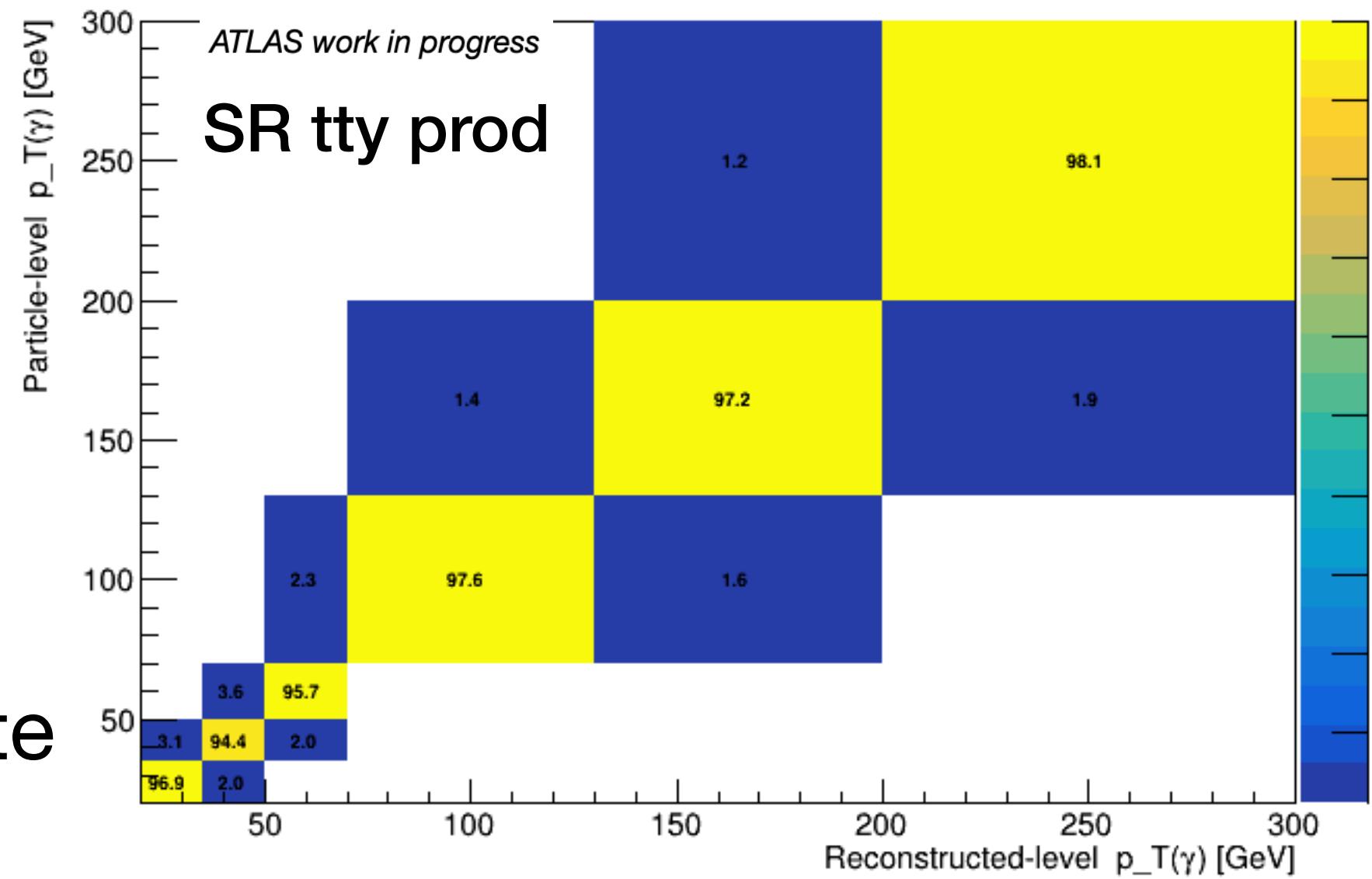
- ▶ Showing results of fit to Asimov data (pseudo data)
- ▶ Showing: migration matrix, absolute differential cross-section, ranking plot of syst. uncertainties with largest impact

Migration matrices

From particle level to different regions at reco level



~ 4% of the events migrate
to neighbouring bins



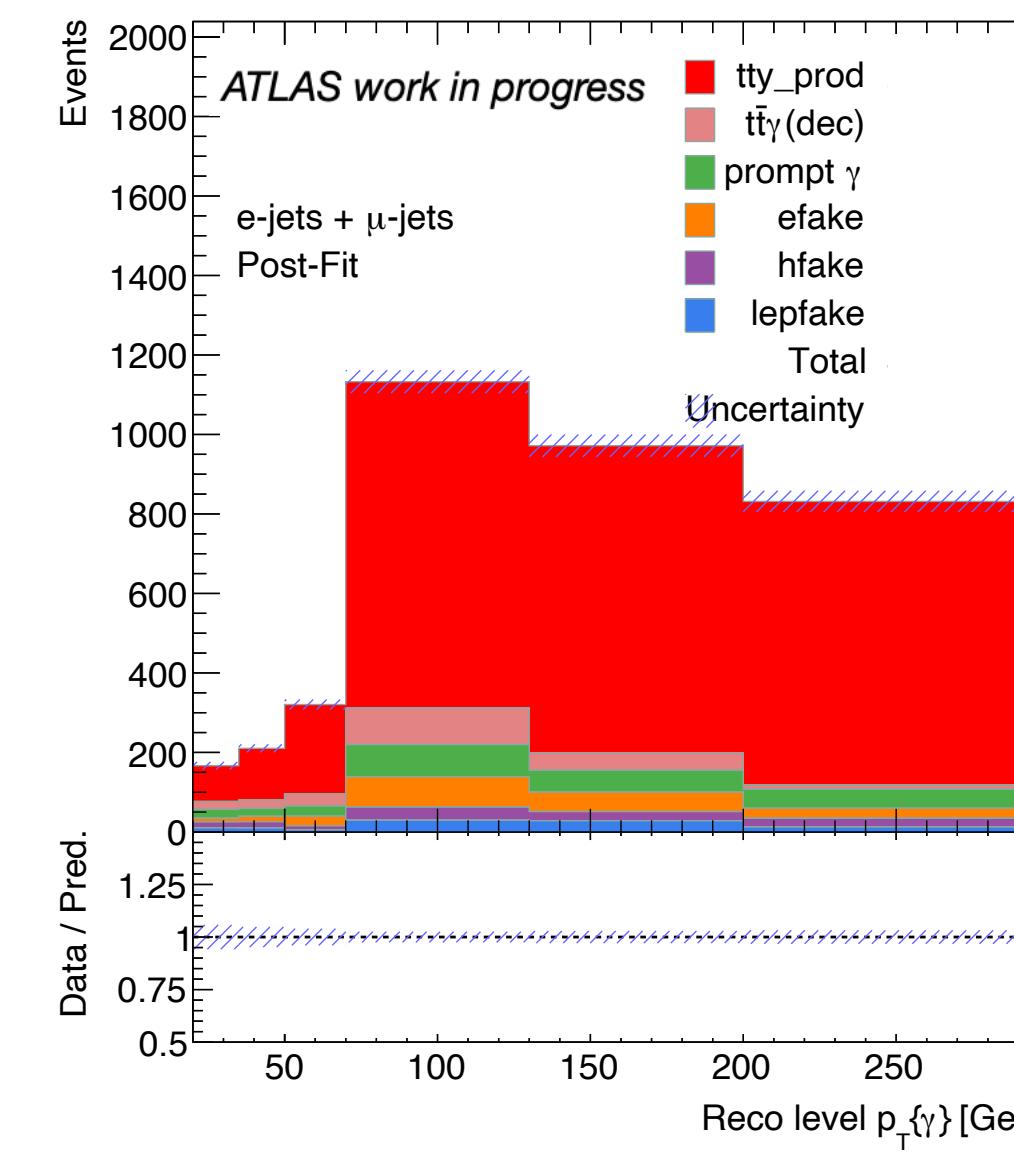
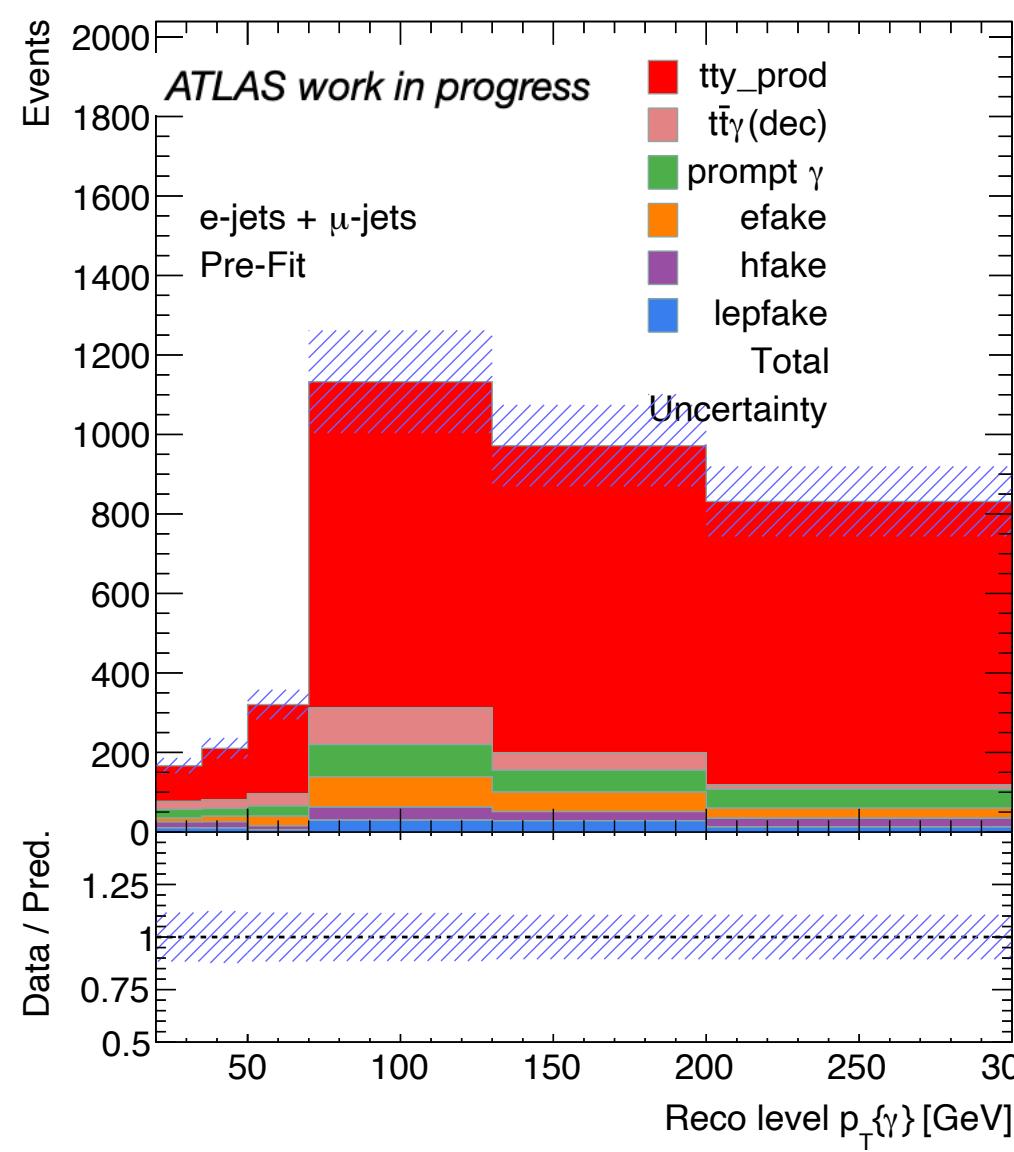
Pre-fit and post-fit distributions



pre-fit

SR tty prod

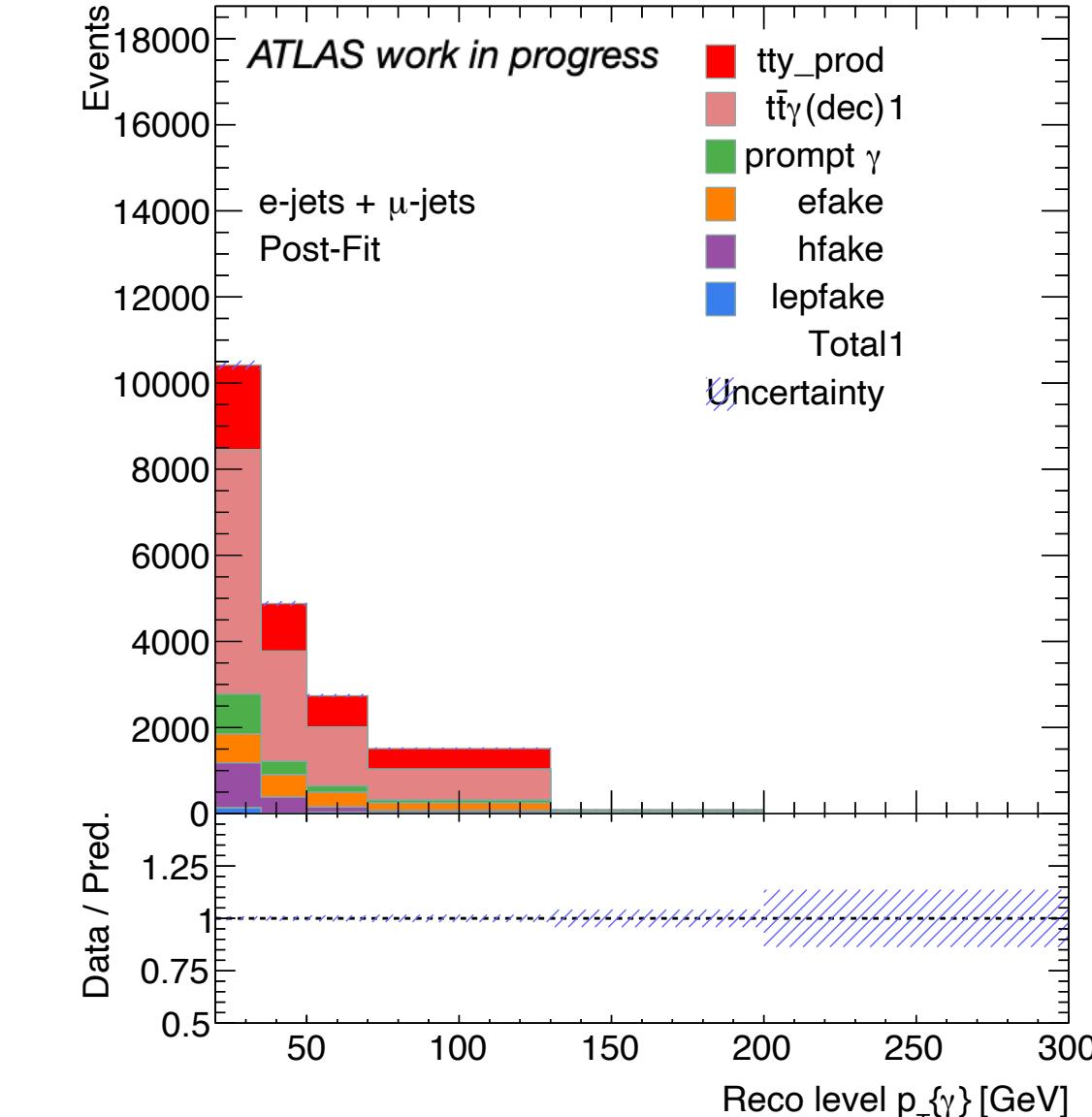
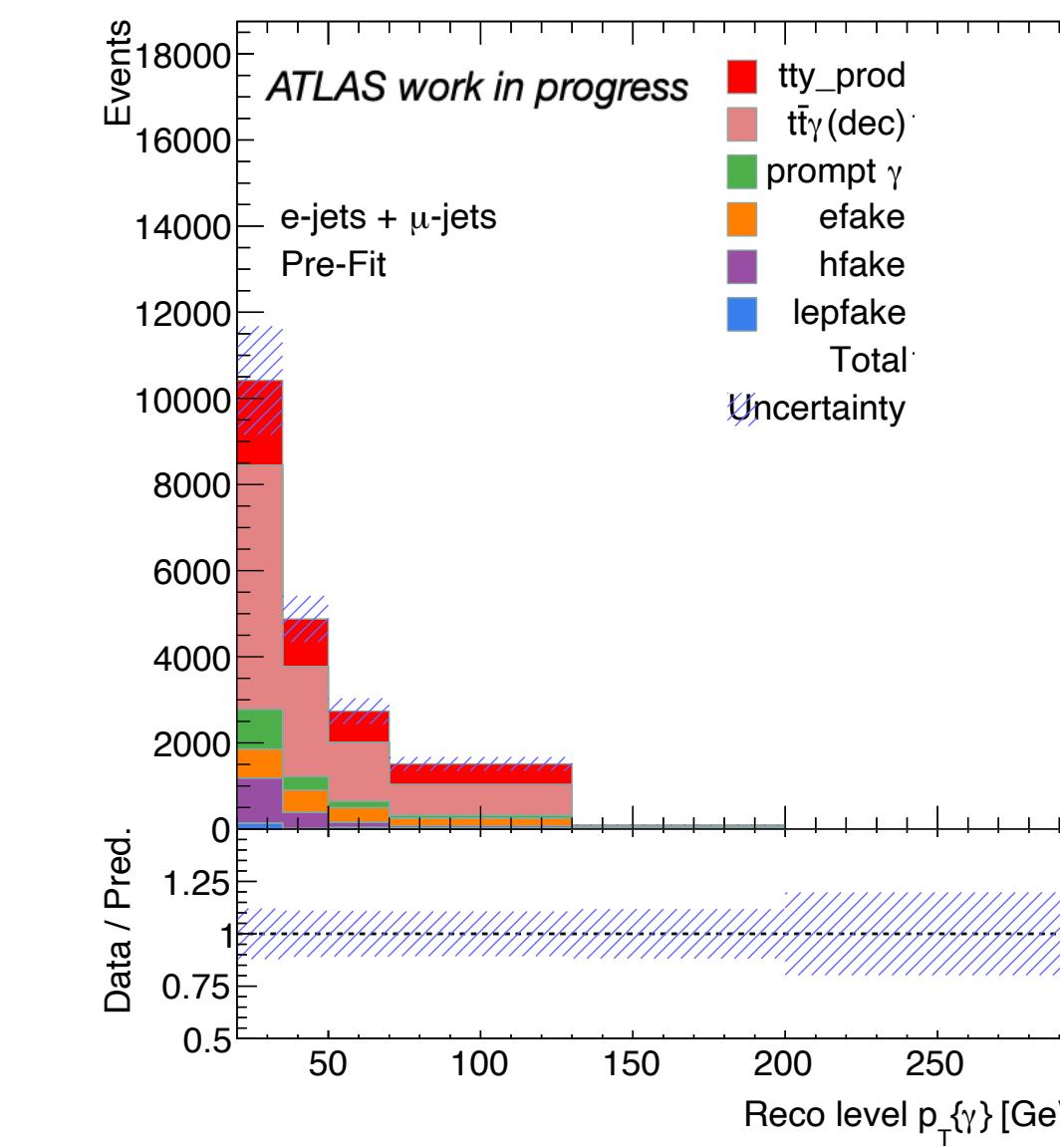
post-fit



pre-fit

CR tty dec

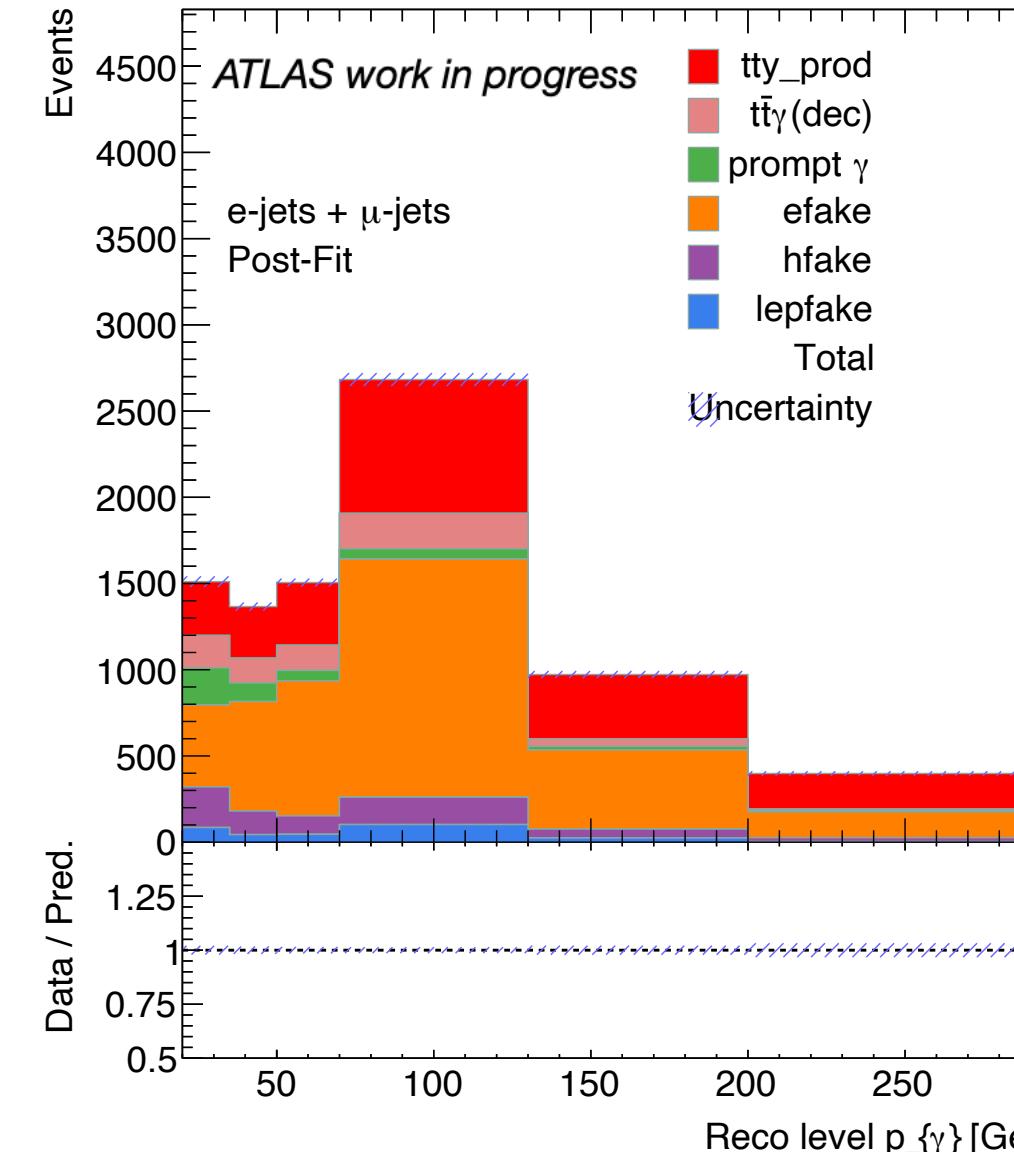
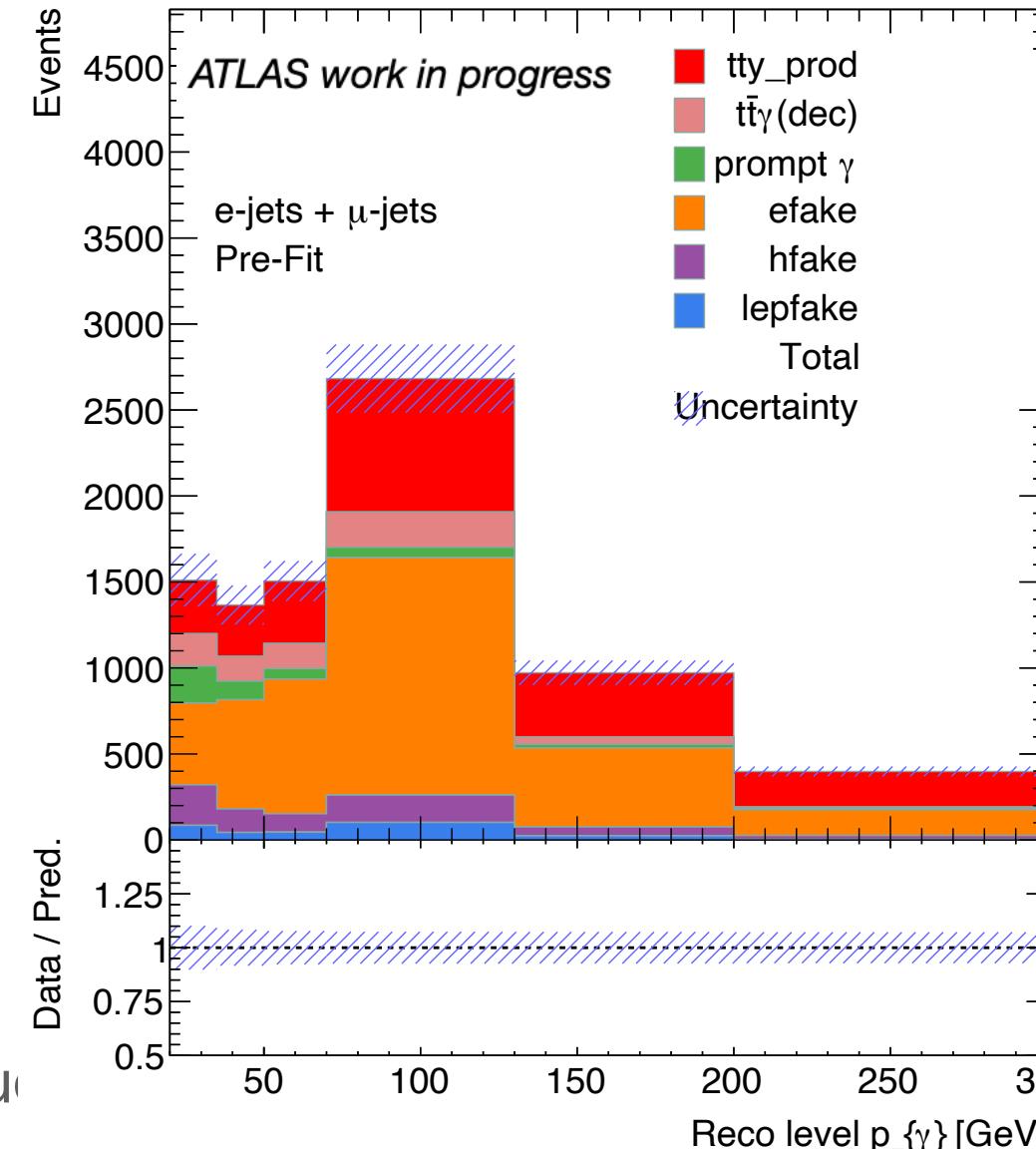
post-fit



pre-fit

CR fakes

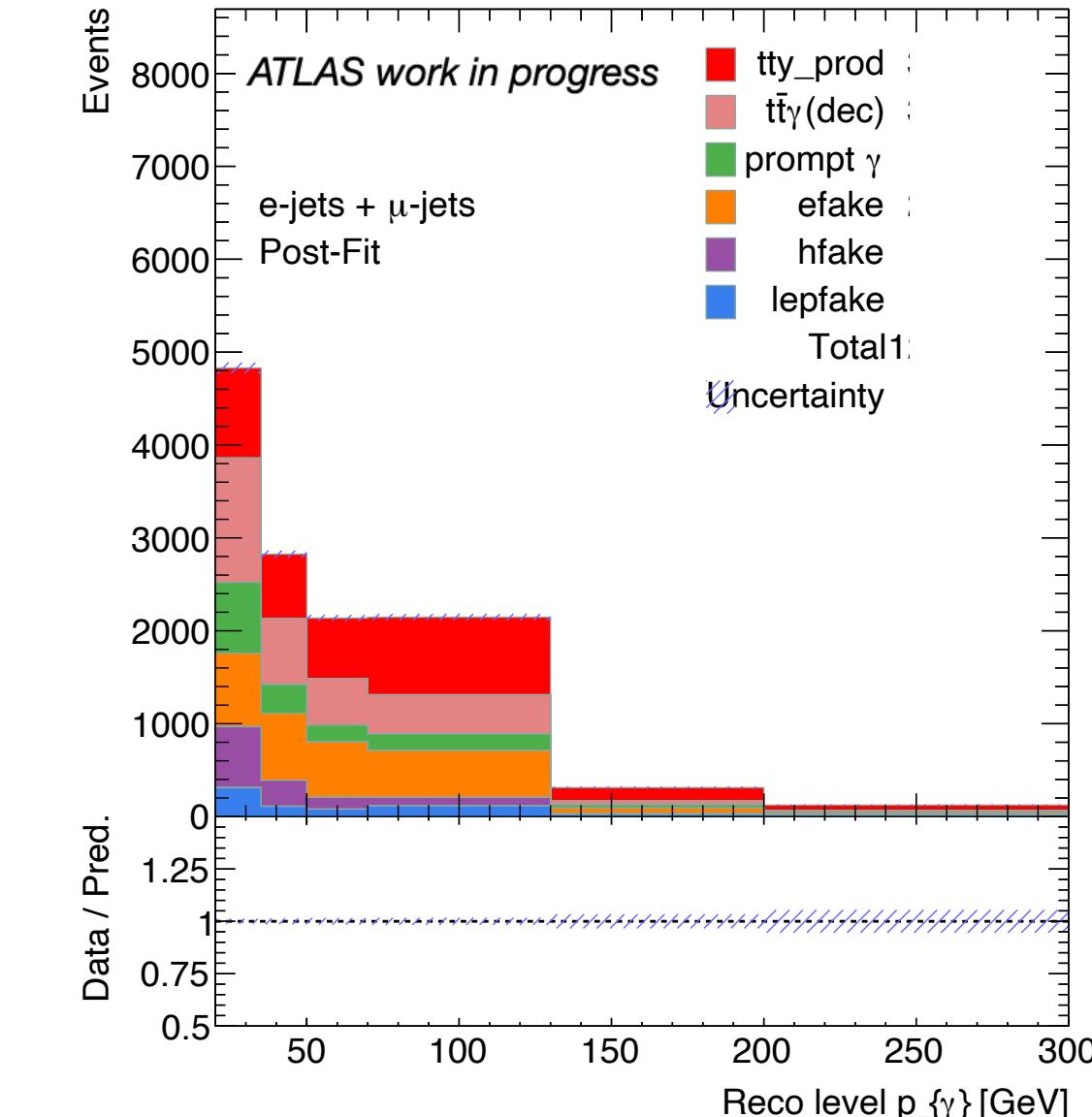
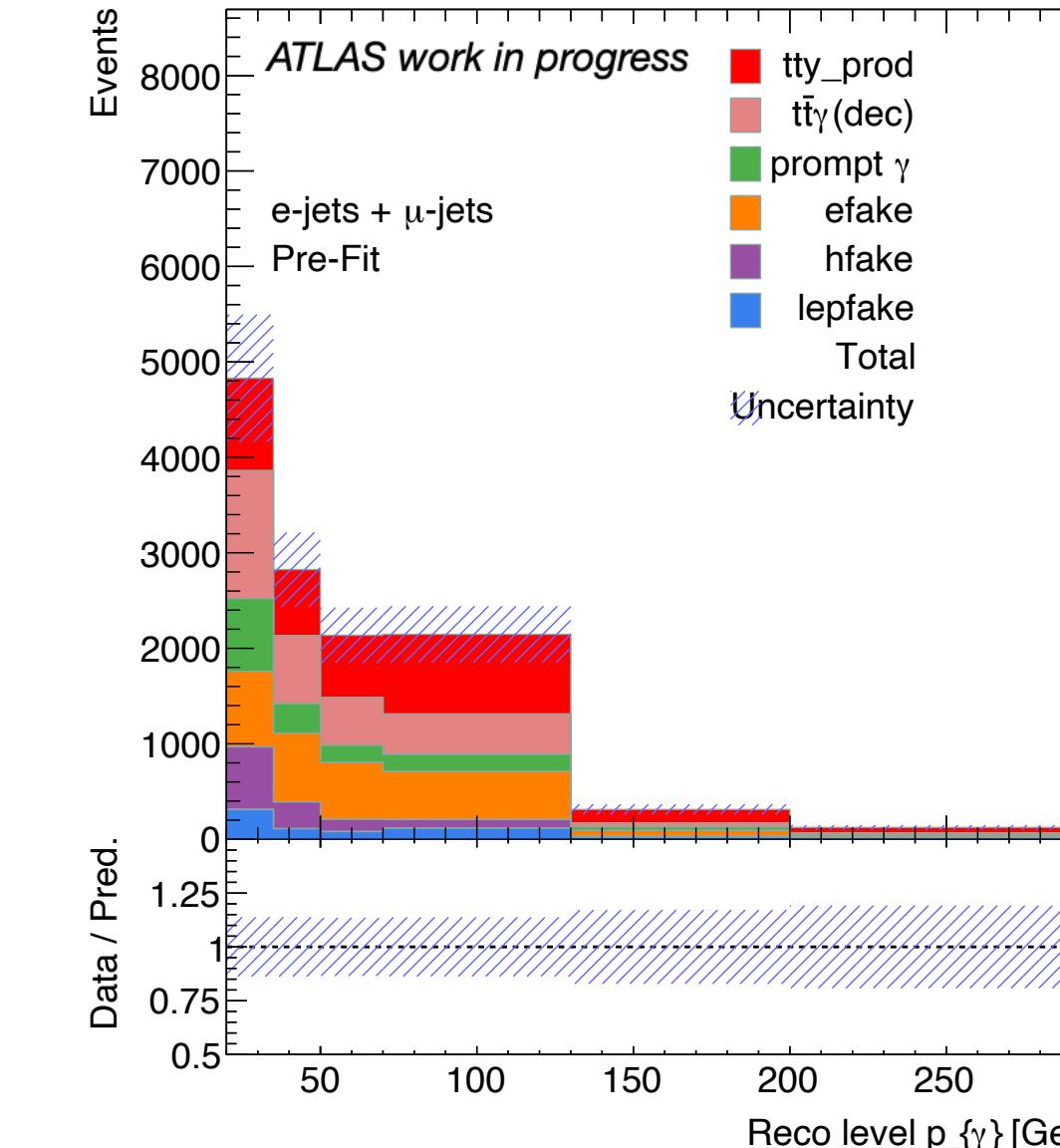
post-fit



pre-fit

CR other photons

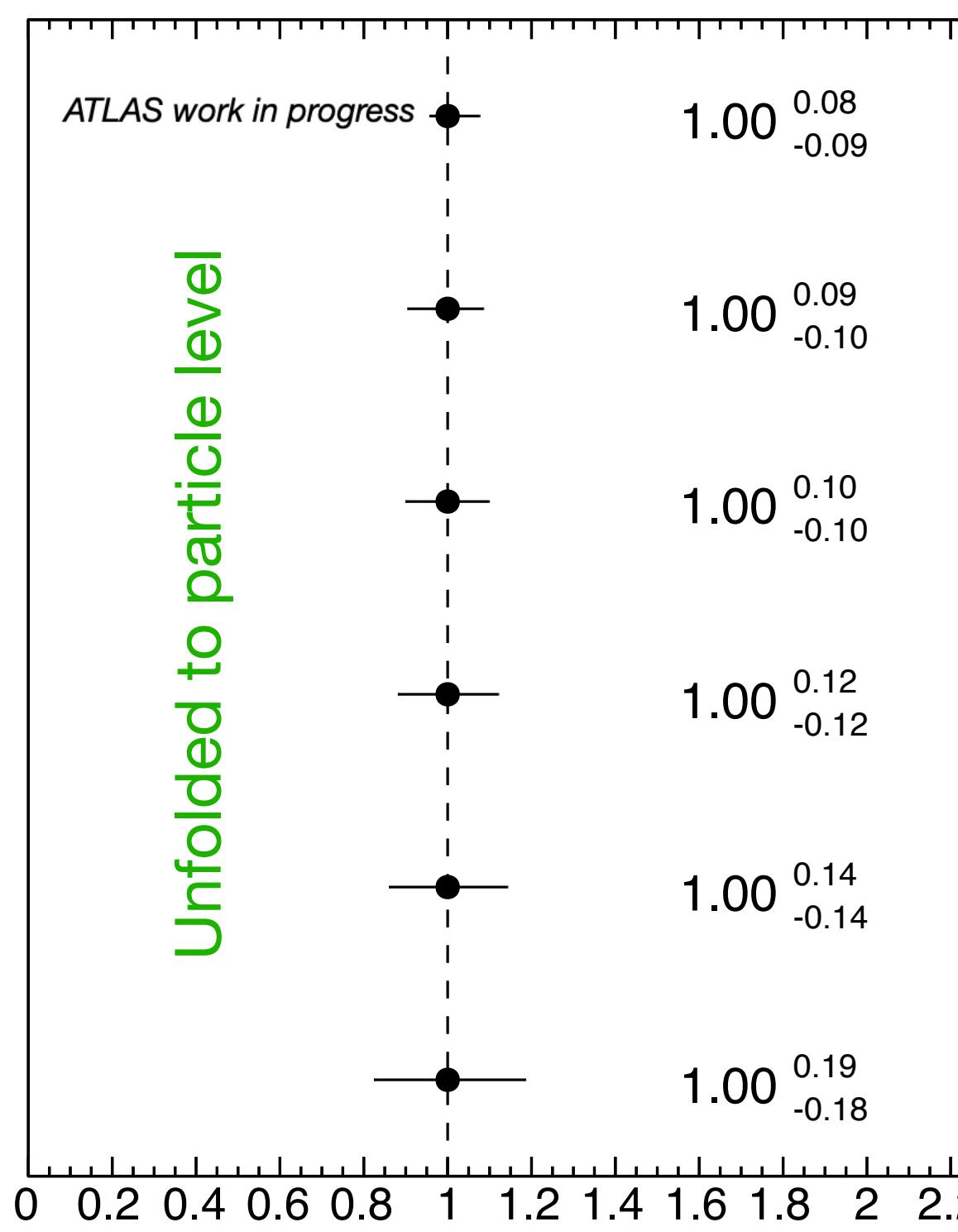
post-fit



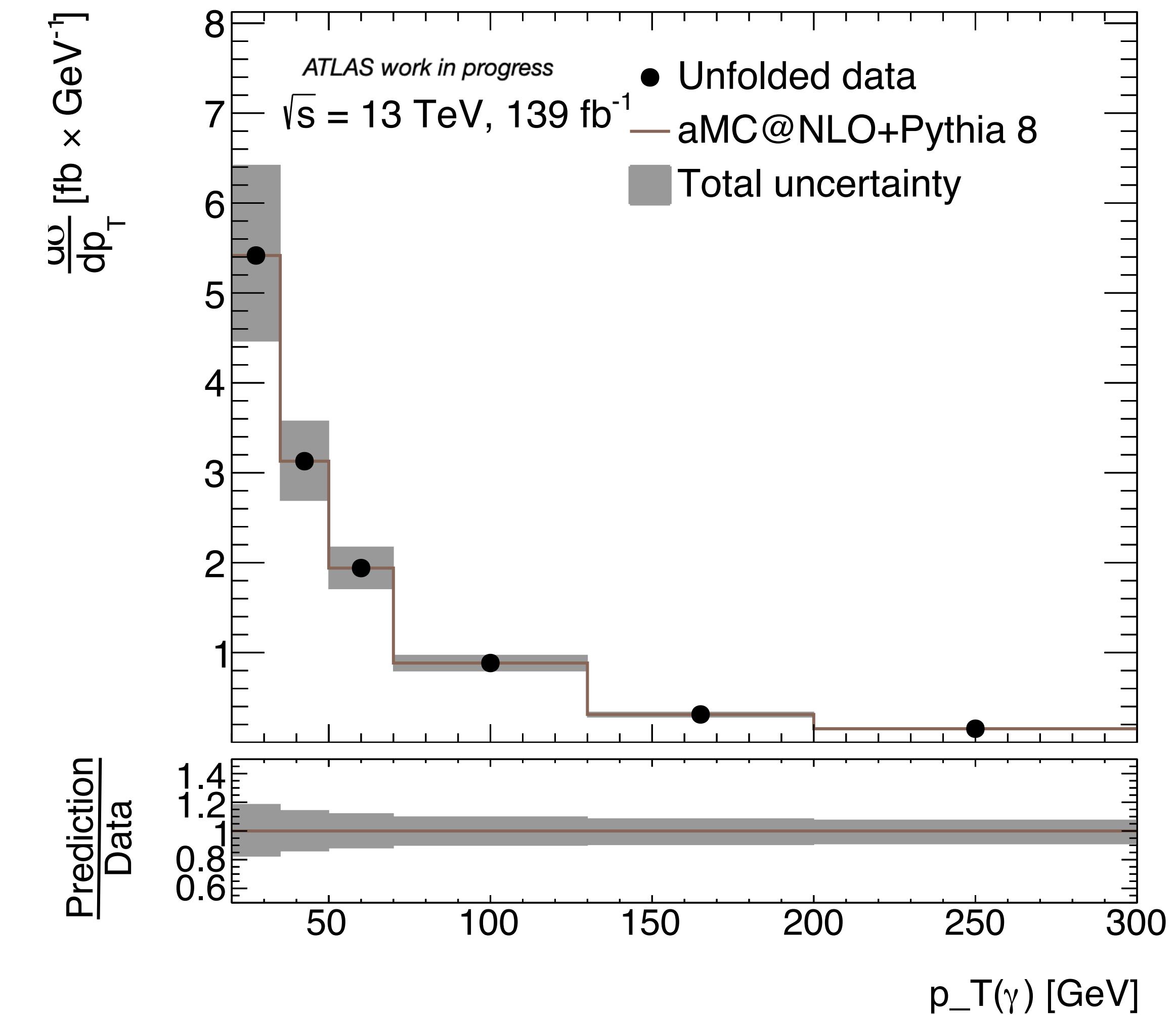
Unfolded distribution at particle level



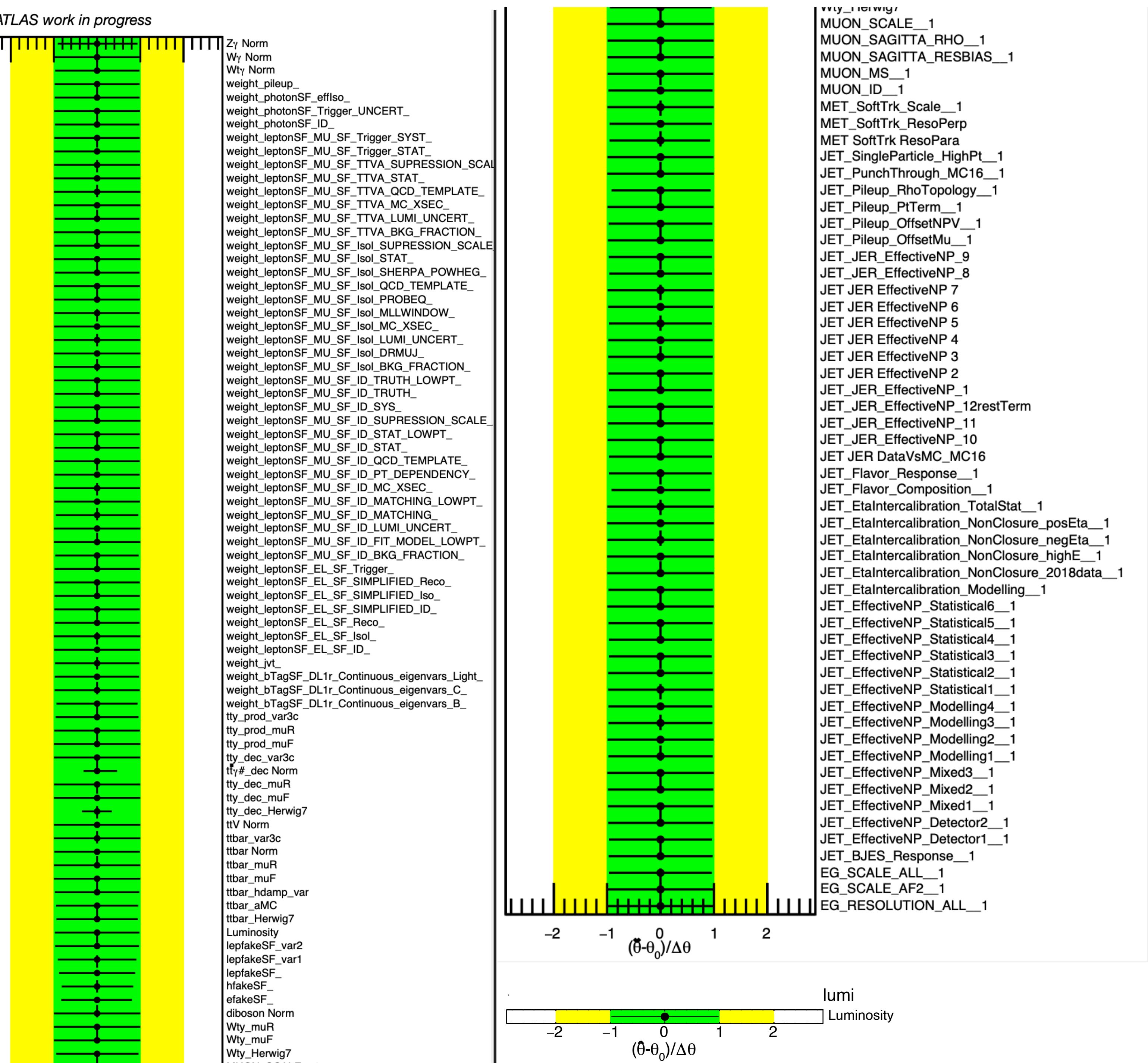
- ▶ Fit performed to the Asimov dataset
- ▶ Uncertainties on norm factors ranges from 8% to 19%



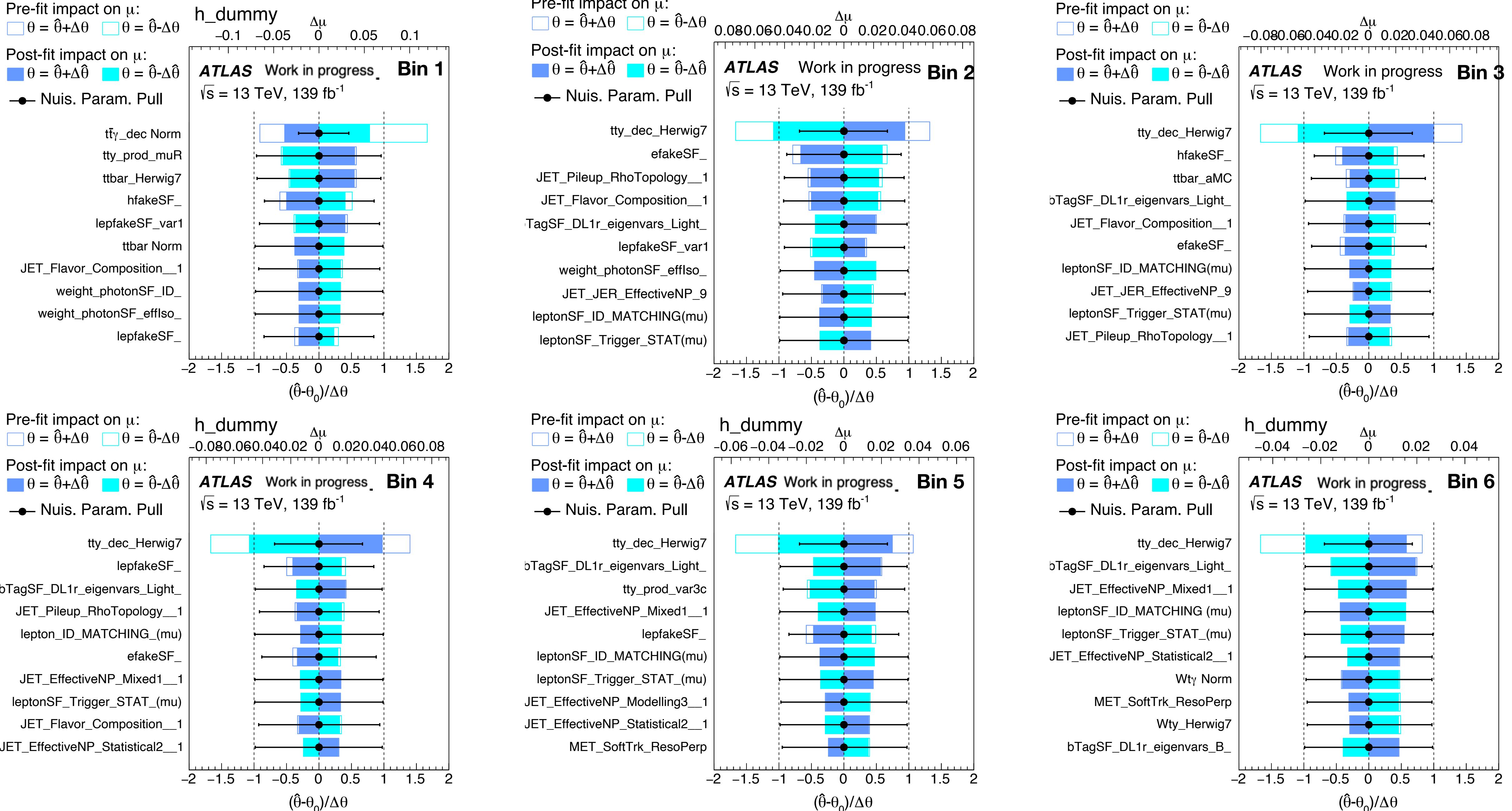
Unfolding Unfolded Truth Bin 6
Unfolding Unfolded Truth Bin 5
Unfolding Unfolded Truth Bin 4
Unfolding Unfolded Truth Bin 3
Unfolding Unfolded Truth Bin 2
Unfolding Unfolded Truth Bin 1



Nuisance parameters during fit



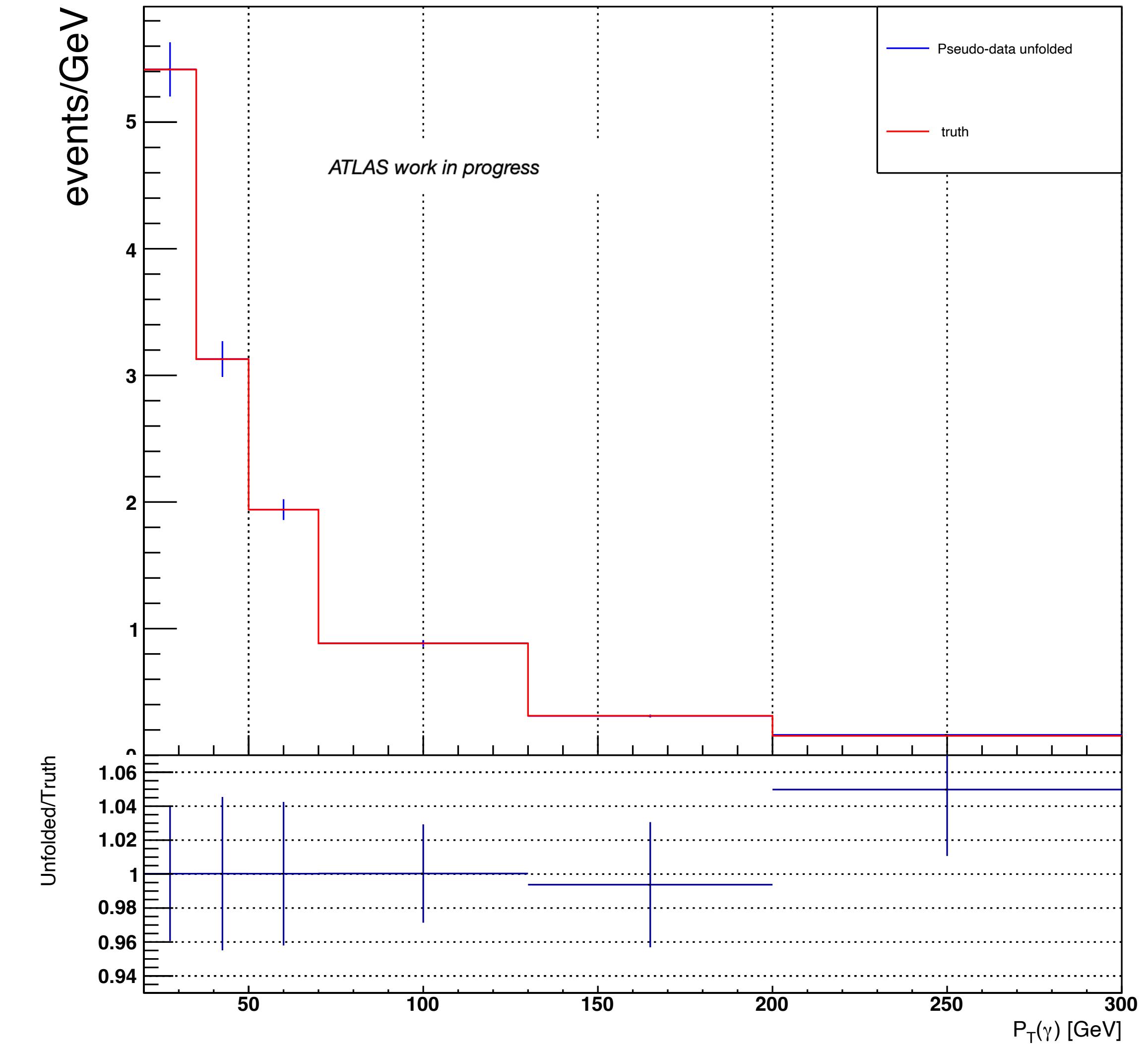
Ranking of nuisance parameters



Unfolding tests

Closure test

- Aim is to identify any technical problems of the implementation of the procedure
- Pseudo-data (distribution at reconstruction level) unfolded using nominal MC sample and response matrix
- Unfolded spectra is compared with truth spectra
- Unfolding procedure perfectly corrects the detector response



Unfolding tests

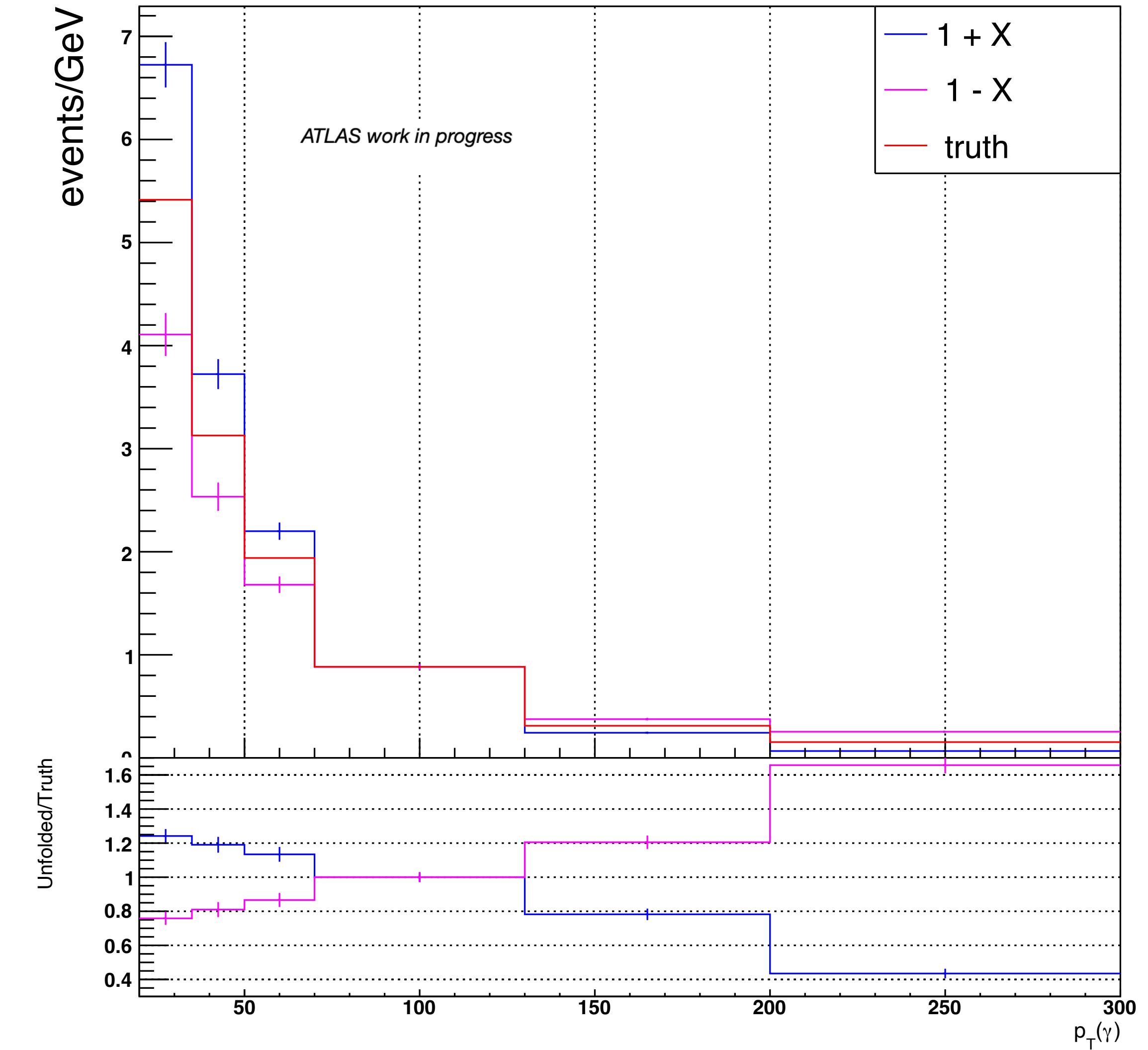
Stress test

- Aim is to check if unfolding procedure is biased to any specific shape
- Reco level signal distribution is reweighted

$$\text{weight} = 1 + y \times \frac{100 - i}{300} = 1 + y \times X$$

where, i is the bin centre, $y = -1, 1$

- Reweighted pseudo-data distribution is unfolded using the nominal MC sample



Summary



- ▶ Presented ongoing differential cross section measurement of $t\bar{t}\gamma$ process in single lepton channel using 139 fb^{-1} data
- ▶ Measurement at particle-level in a fiducial region
- ▶ Results will be used to set limits on top-photon EFT coefficients

Backup

Correlation among NPs

	Unfolding Unfolded Truth Bin 1	Unfolding Unfolded Truth Bin 2	Unfolding Unfolded Truth Bin 3	Unfolding Unfolded Truth Bin 4	Unfolding Unfolded Truth Bin 5	Unfolding Unfolded Truth Bin 6	EG_SCALE_ALL_1	JET_EffectiveNP_Mixed1_1	ET_EffectiveNP_Modelling1_1	ET_EffectiveNP_Modelling3_1	ET_EffectiveNP_Statistical2_1	JET_Flavor_Composition_1	JET_Flavor_Response_1	JET_JER_EffectiveNP_9	JET_Pileup_RhoTopology_1	JET_SingleParticle_HighPt_1	MET_SoftTrk_ResoPerp	MUON_ID_1	MUON_MS_1	MUON_SAGITTA_RHO_1	Wt_Herwig7	efakeSF_	hfakeSF_	Luminosity	ttbar_Herwig7	ttbar_aMC	ttbar_hdamp_var	ttbar_Norm	tty_dec_Herwig7	tty_prod_muR	tty_prod_var3c	L1r_Continuous_eigenvars_B_	_Continuous_eigenvars_Light_	1SF_SF_SF_ID_MATCHING_	SF_ID_MATCHING_LOWPT_	onSF_SF_SF_ID_MC_XSEC_	leptonSF_SF_SF_ID_STAT_	MU_SF_ID_TRUTH_LOWPT_	onSF_SF_ISOL_PROBEQ_	J_SF_ISOL_QCD_TEMPLATE_	onSF_SF_TRIGGER_STAT_	weight_photonSF_ID_	weight_photonSF_effIso_	Wt_Norm	Zt_Norm
Unfolding Unfolded Truth Bin 1	100.0	82.1	77.0	72.9	61.7	59.4	3.3	5.0	-12.8	-6.9	7.2	-18.6	11.8	-6.6	-17.5	5.9	-6.0	-8.0	4.9	-5.8	-1.9	9.4	-16.5	-7.0	17.7	-7.9	-1.0	-14.9	8.0	19.7	-7.0	4.4	12.3	2.6	-8.3	5.9	5.2	5.8	5.7	5.8	7.8	-19.2	-17.5	-8.0	-2.2
Unfolding Unfolded Truth Bin 2	82.1	100.0	83.3	84.6	72.0	67.2	7.5	9.8	-11.4	-8.0	9.5	-17.1	10.2	-10.6	-17.7	7.7	-9.3	-8.7	7.0	-7.7	-2.2	-19.0	3.7	-6.8	7.5	-7.8	-0.9	2.3	33.1	10.8	-9.4	8.0	14.5	7.6	-11.8	7.8	8.8	7.7	7.6	7.7	11.4	-3.7	-16.2	-5.4	-7.7
Unfolding Unfolded Truth Bin 3	77.0	83.3	100.0	86.8	75.1	69.7	6.5	10.5	-8.1	-7.3	10.9	-13.6	8.3	-10.4	-11.7	8.8	-9.5	-8.9	8.3	-8.7	-4.3	-14.8	-16.8	-2.0	2.0	-15.7	-1.8	4.8	42.0	10.0	-5.0	7.7	14.6	7.0	-12.8	8.8	9.3	8.8	8.6	8.8	12.5	0.8	-8.7	-4.6	6.9
Unfolding Unfolded Truth Bin 4	72.9	84.6	86.8	100.0	80.7	76.7	4.3	14.7	-7.1	-10.2	12.8	-12.1	7.6	-9.2	-13.8	10.2	-12.2	-9.8	9.6	-10.2	-9.2	-16.0	-4.8	-0.9	-0.4	-12.2	1.5	5.5	45.7	4.4	-9.4	10.5	17.8	6.8	-15.3	10.2	10.2	10.1	10.2	14.9	1.3	-11.1	-6.2	8.8	
Unfolding Unfolded Truth Bin 5	61.7	72.0	75.1	80.7	100.0	78.8	-3.1	17.2	-4.0	-12.3	13.1	-12.8	5.1	-9.1	-12.6	11.0	-12.4	-10.9	10.5	-10.9	-12.4	-11.3	1.2	-1.8	-0.5	-7.9	0.6	5.1	31.8	0.4	17.9	12.6	20.4	5.4	-16.7	-11.0	9.8	11.0	10.8	10.9	16.1	0.8	-8.8	-10.7	5.0
Unfolding Unfolded Truth Bin 6	59.4	67.2	69.7	76.7	78.8	100.0	-11.4	17.0	-2.7	-11.7	12.6	-9.1	3.4	-8.1	-11.8	10.9	-12.4	-11.1	10.1	-10.8	-12.6	6.3	-2.2	-2.6	-0.9	-7.8	2.0	4.6	24.6	-3.6	8.5	14.2	21.4	4.7	-16.4	-10.9	9.4	10.9	10.7	10.8	15.7	-1.2	-13.3	-14.6	3.1
EG_SCALE_ALL_1	3.3	7.5	6.5	4.3	-3.1	11.4	100.0	-0.4	-0.6	-0.2	-5.3	-1.1	0.8	-0.2	2.3	-2.5	-3.8	0.1	-2.3	2.5	-4.3	4.8	-3.1	-2.2	0.8	1.3	0.4	-0.2	14.5	0.5	3.0	0.5	-4.9	0.3	0.3	2.5	-1.1	-2.5	-2.5	-2.4	0.3	2.9	-2.6	2.5	1.5
JET_EffectiveNP_Mixed1_1	5.0	9.8	10.5	14.7	17.2	17.0	-0.4	100.0	-0.0	1.9	-1.0	-0.3	-0.9	3.2	-1.5	1.5	2.2	-1.4	1.6	1.2	1.6	3.1	-0.4	-3.0	-2.9	-0.9	0.9	7.9	-1.1	1.8	0.1	-0.5	-2.0	1.6	-3.5	-1.6	-1.6	-0.5	0.5	-2.0	-0.9				
ET_EffectiveNP_Modelling1_1	-12.8	-11.4	-8.1	-7.1	-4.0	-2.7	-0.6	-0.0	100.0	-0.2	0.3	-5.7	1.4	-1.2	-5.6	0.6	-0.2	-0.8	1.0	-0.6	-0.2	-1.1	-4.9	-1.3	-2.4	0.1	-0.2	-0.8	3.3	-1.0	0.1	0.0	1.3	-2.6	-0.6	0.6	0.6	0.5	-1.1	-1.6	-1.8	-1.0			
ET_EffectiveNP_Modelling3_1	-6.8	-8.0	-7.3	-10.2	-12.3	-11.7	-0.2	1.9	-0.2	100.0	-0.9	-1.1	0.3	-4.9	2.3	2.2	1.0	-5.3	2.0	-2.2	0.8	1.6	-0.8	0.2	-0.1	0.2	-0.1	-1.3	-2.7	-0.2	3.4	-1.9	2.1	2.8	2.2	2.2	1.9	2.7	0.1	0.4	0.6				
ET_EffectiveNP_Statistical2_1	7.2	9.5	10.9	12.8	13.1	12.6	-5.3	-1.0	0.3	-0.9	100.0	-1.0	-0.8	-0.1	1.3	-2.1	-1.1	-0.3	-2.0	2.1	-1.4	-0.3	-1.3	-1.8	-1.3	-0.2	0.5	7.4	-1.0	1.7	-0.2	-4.2	-2.3	1.4	2.1	-2.0	-2.1	-2.0	-1.5	2.0	1.9	1.2	2.0		
JET_Flavor_Composition_1	-18.6	-17.1	-13.6	-12.1	-12.8	9.1	-1.1	-0.3	-5.7	-1.1	-1.0	100.0	9.3	-0.2	-21.8	-0.7	2.1	0.2	0.3	0.7	2.2	1.3	-12.5	-6.8	-4.2	-0.4	-1.0	-0.3	11.0	-6.7	0.3	3.1	2.4	1.3	1.8	0.7	-4.0	-0.7	-0.7	-2.1	-5.4	-5.7	-5.8	-1.8	
JET_Flavor_Response_1	11.8	10.2	8.3	7.6	5.1	3.4	-0.8	-0.9	1.4	0.3	-0.8	9.3	100.0	0.2	9.2	-0.2	-0.4	0.1	-0.5	0.2	-1.1	2.1	4.0	2.1	-1.0	-0.2	-2.7	-0.4	0.7	-0.2	1.8	2.6	-2.1	-1.3	-0.2	0.0	0.2	2.8	2.0	1.8	3.0				
JET_JER_EffectiveNP_9	-6.6	-10.6	-10.4	-9.2	-9.1	-8.1	-0.2	-0.2	-1.2	-4.9	-0.1	-0.2	0.2	0.2	100.0	2.4	2.7	-1.6	-5.7	3.3	-2.7	-1.5	4.1	-2.1	1.0	0.6	1.2	1.2	-1.0	-0.2	0.9	-3.4	0.2	0.8	-3.0	-2.7	3.4	2.7	2.7	3.0	1.9	-0.2	0.3	1.6	
JET_Pileup_RhoTopology_1	-17.5	-17.7	-11.7	-13.8	-12.6	-11.8	2.3	-1.5	-5.6	2.3	-1.3	-21.8	9.2	-2.4	100.0	1.1	2.4	-3.1	-0.3	1.1	3.4	-2.7	14.2	-7.5	-4.4	-2.5	1.4	0.7	-12.6	-7.0	1.1	5.0	4.5	2.2	2.8	1.2	-5.8	-1.1	-1.1	-3.1	-8.0	-5.4	-8.3	-2.5	
JET_SingleParticle_HighPt_1	5.9	7.7	8.8	10.2	11.0	10.9	-2.5	-1.5	0.6	2.2	-2.1	-0.7	0.2	2.7	-1.1	100.0	-0.9	2.5	-2.2	2.2	-0.8	-1.1	-0.4	-1.5	-0.7	-0.5	0.0	0.5	5.7	-1.1	2.1	1.5	-1.8	-2.7	1.9	2.2	-2.2	-2.2	-1.9	-0.5	-1.1	0.0	0.7		
MET_SoftTrk_ResoPerp	-6.0	-9.3	-9.5	-12.2	-12.4	-12.4	-3.8	1.5	-0.2	1.0	-1.1	2.1	0.4	-1.6	2.4	-0.9	100.0	-0.1	-0.7	0.8	-8.1	3.9	-2.0	-1.6	0.8	-2.7	0.1	0.3	4.8	1.9	0.														

Gamma factors

ATLAS work in progress

