ARC-author meeting for *TOP-25-003*

Ying AN, Maria Aldaya, Hugo Becerril, Abideh Jafari, Andreas Meyer

30 Sep 2025

Analysis overview

- Pre-approval presentation: talk on 02/04/2025
- Pre-approved: 17/09/2025
- Latest AN note: AN2023_188_v7
- Paper draft: TOP-25-003-paper-v1
- Q&A twiki: Full track of comments
- CMS-PUB talk: TOP-25-003
- Object review: All GL except for *combine tool lacking standard systematic naming*

Available on the CMS information server **CMS AN-23-188**

CMS Draft Analysis Note

The content of this note is intended for CMS internal use and distribution only

2025/09/19
Archive Hash: untracked
Archive Date: 2025/09/19

Measurement of single top and $t\bar{t}$ production cross sections in association with a photon in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

Ying An[1], Maria Aldaya[1], Hugo Alberto Becerril Gonzalez[1], Abideh Jafari[2], and Andreas Meyer[1]

[1] DESY, Hamburg, Germany
[2] Isfahan University of Technology, Isfahan, Iran

DRAFT

Abstract

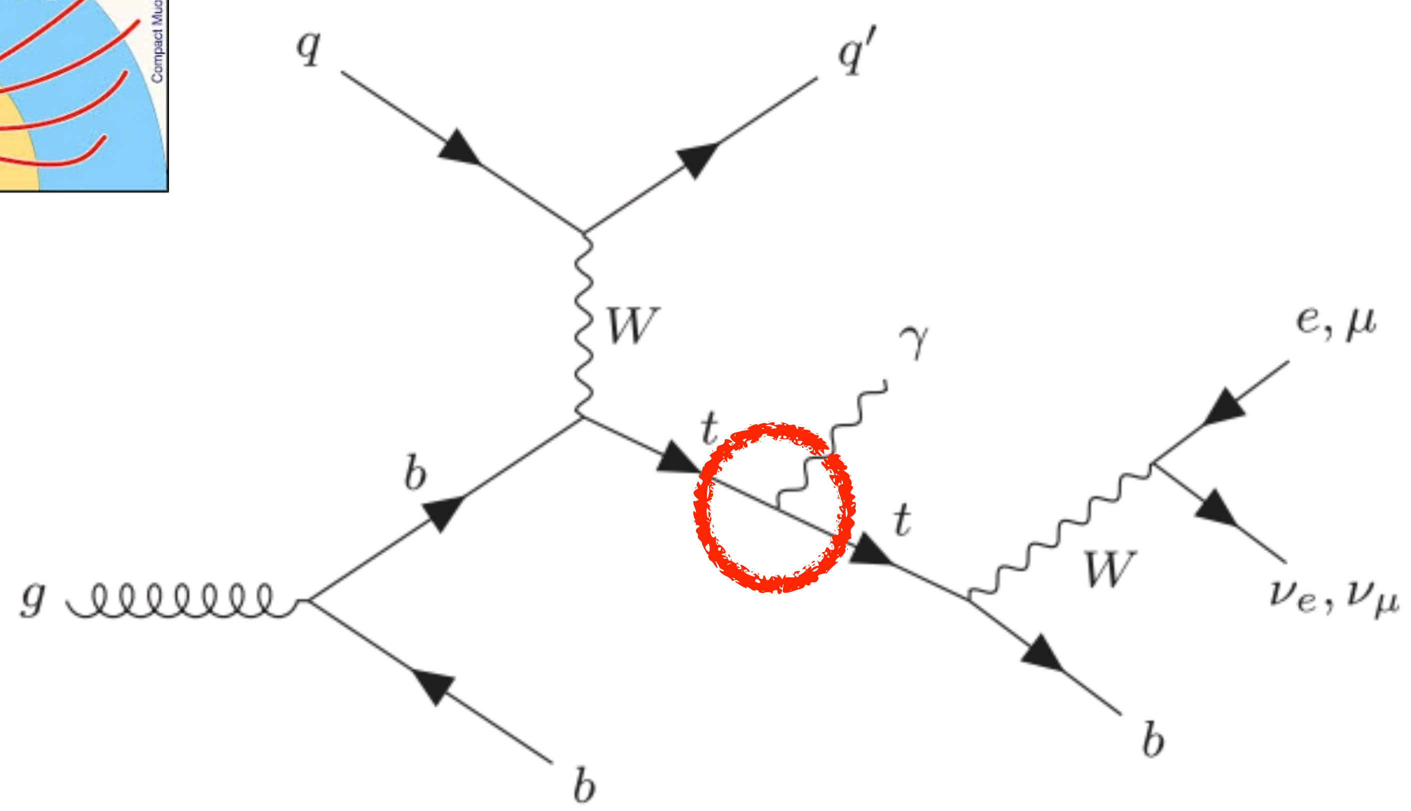
This note presents the study of measuring $t\bar{t}$ and single top in association with a photon production simultaneously. Both the inclusive and differential cross sections are measured in proton-proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$, based on the data recorded by the CMS experiment, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$. Measurements are performed in events with a well-isolated, highly energetic lepton (electron and muon), at least two jets from the hadronization of quarks, and an isolated photon, as well as moderate missing transverse momentum. The photon emitted from the initial state radiation, top quark, and top quark decay products are simulated in separate samples. The particle level differential cross sections are measured as functions of the leading photon transverse momentum (p_T^{γ}), the leading lepton transverse momentum (p_T^{ℓ}), the angular separation between the leading lepton and photon ($\Delta R(\ell,\gamma)$), $m_{\ell\gamma}$, the pseudorapidity of the leading jet not passing the btagging discriminator (η_{lightj}), and the number of jets (N_{jets}). The parton-level differential cross sections of $\Delta R(t,\gamma)$ and the charge of the top quark decaying to the lepton topology are presented in addition.

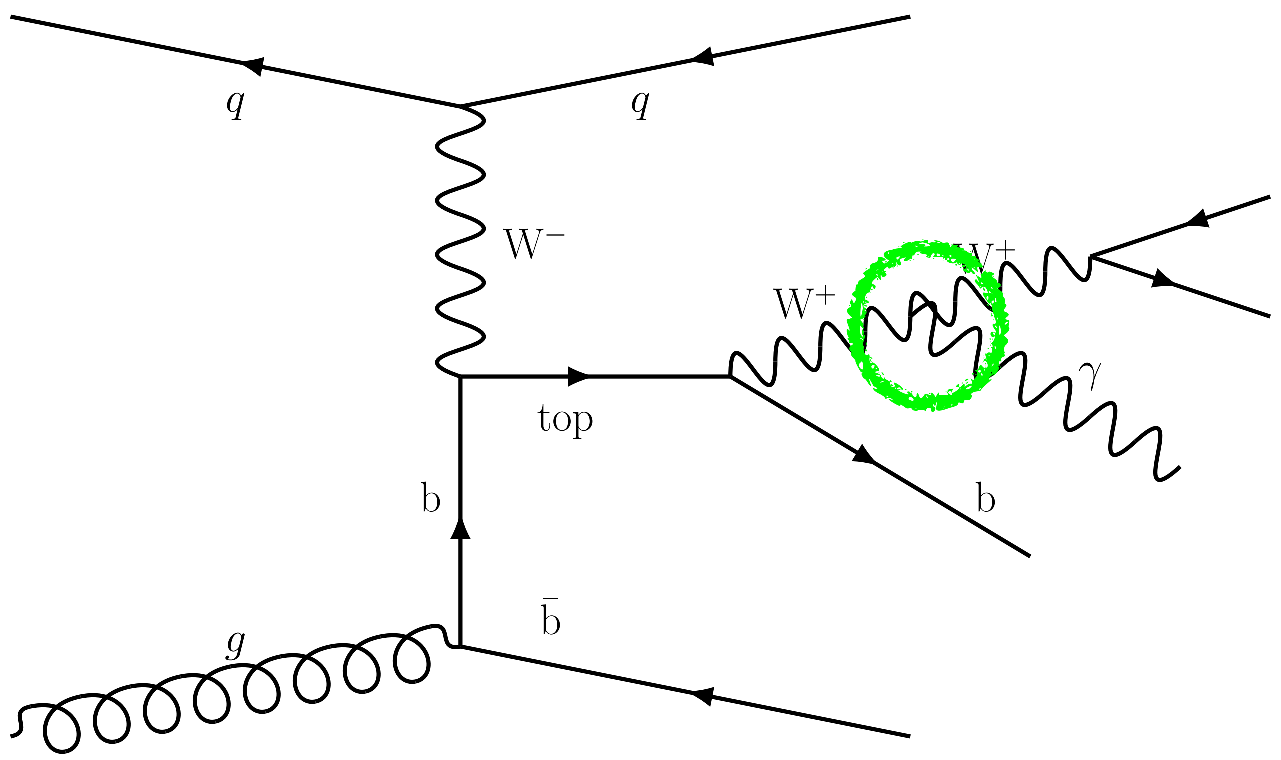
This box is only visible in draft mode. Please make sure the values below make sense.

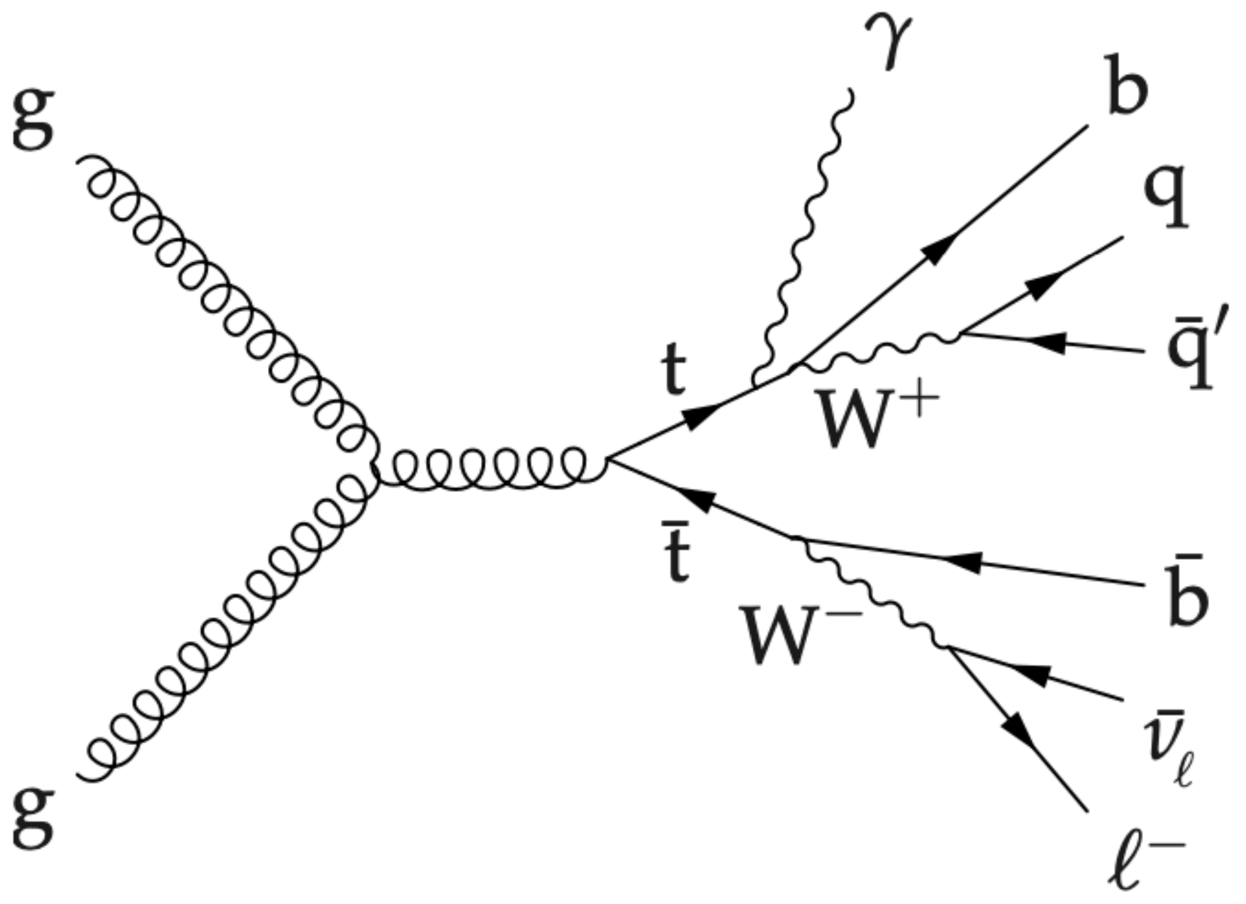
PDFAuthor:	Ying AN, Maria Aldaya, Hugo Becerril, Abideh Jafari, Andreas Meyer
PDFTitle:	Cross section measurements of single top and ttbar in association with a photon production
PDFSubject:	CMS
PDFKeywords:	CMS, single top, top-photon coupling

Please also verify that the abstract does not use any user defined symbols

Physics motivation





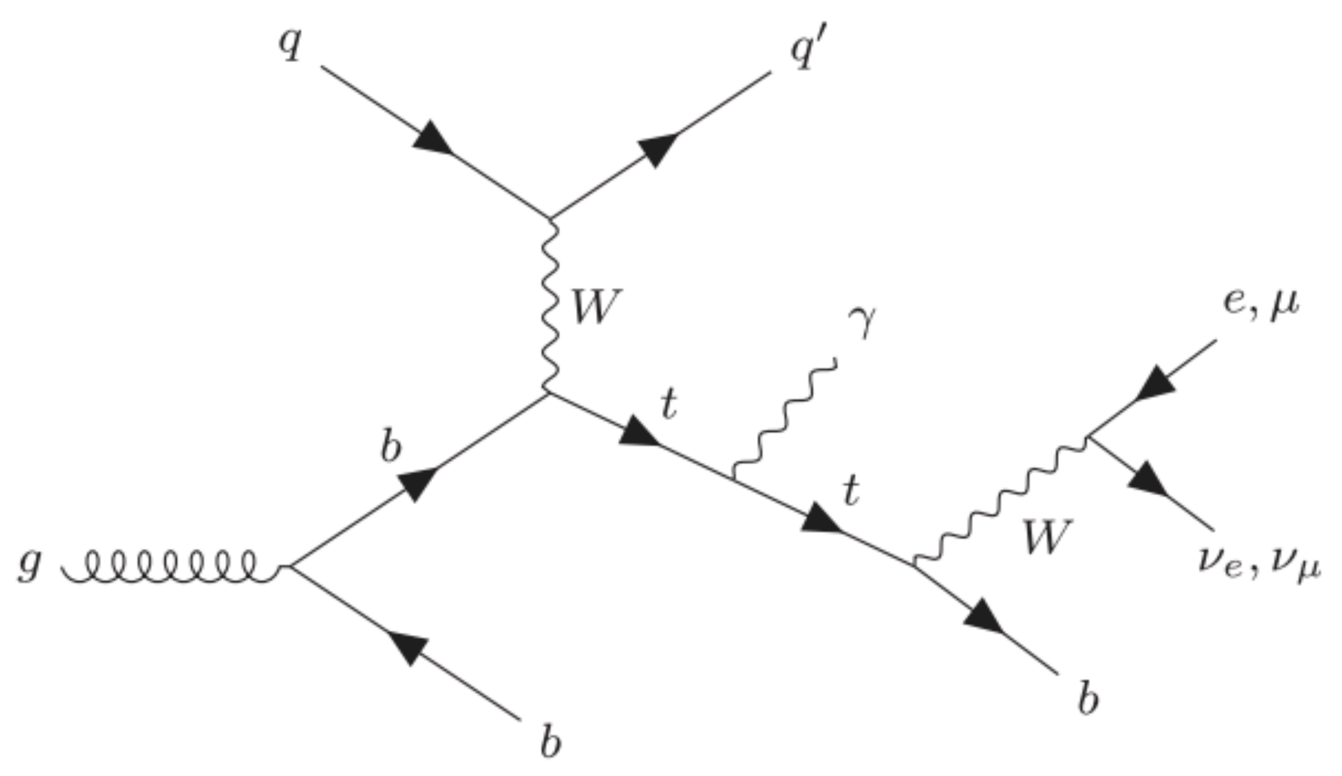


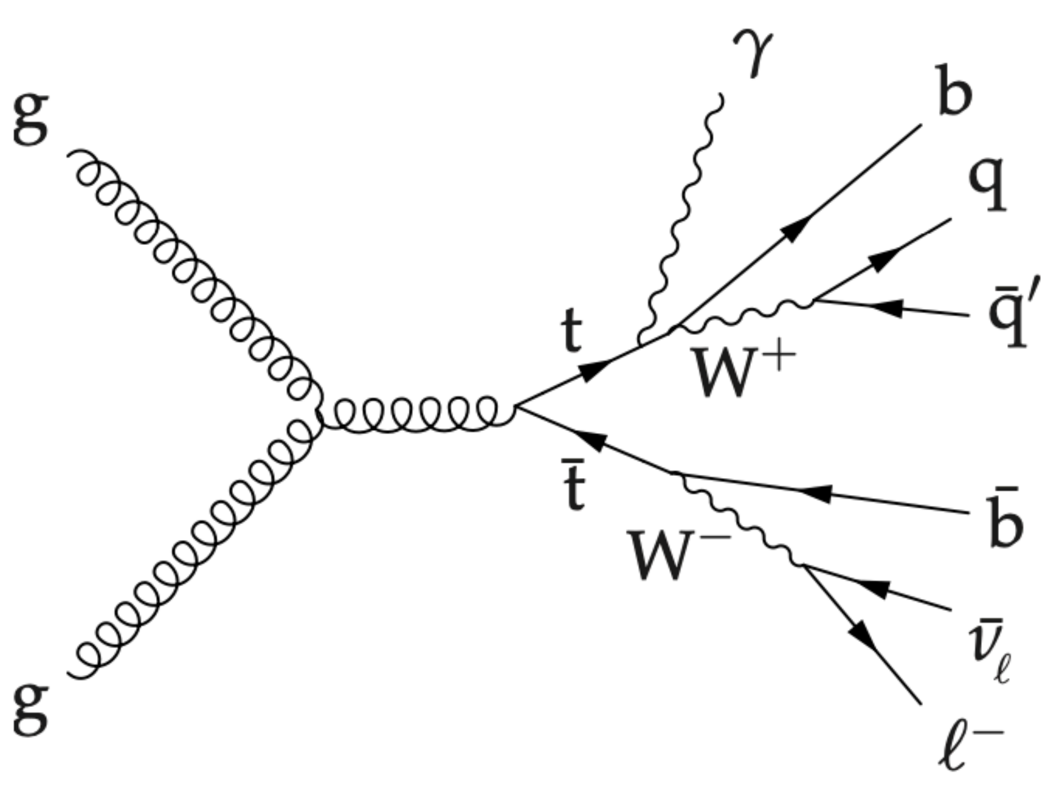
- The $t\gamma q$ process is observed by ATLAS. CMS so far only has evidence for tγq, **first-ever tγq differential** cross sections and **simultaneous tγq+ttγ** cross section
- These processes represent a direct probe of the top-photon coupling
  - Precise measurements provide a stringent test of SM predictions
  - Anomalous top-photon electroweak coupling via EFT fit to tγq+ttγ

Simultaneous measurement of the tγq+ttγ

- Full set of correlations between the two processes
- Possible for a more straightforward EFT interpretation
- Compatible precision of ttγ results in TOP-18-010

Methodology and strategy





Signal events (**N_ℓ=1, N_γ ≥1, N_j≥2, N_b≥1):** *exactly 1 lepton, at least 1 photon, at least 2 jets, of which at least 1 is b-jet*

Separate signal and background: Train BDT to separate tγq, $t\bar{t}\gamma$ and others

Background estimation/constraint (<u>$t\bar{t}\gamma$ as signal</u>):

- Simulation: V+Jets/Vγ+Jets, tW/tWγ, TTV, VV
- Data-Driven backgrounds:
  - j→γ (nonprompt γ), j→ℓ (nonprompt ℓ), double nonprompt, and e→γ (ele misID)
- Define proper control regions
  - Constrain normalisations of main and data-driven backgrounds

Sample and trigger

- **Data:** Full Run-II dataset SingleMuon and SingleElectron (EGamma)
- **Trigger:** Single electron and muon trigger → SFs are ready for these HLT paths

- Signal MCs are sum of separated samples with photon from both decay and production
  - TGJets_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8
  - ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8
  - ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8

  } tγq default

  - TTGJets_Lminus(plus)Nu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8
  - TTGamma_SingleLept_TuneCP5 13TeV-madgraph-pythia8 with k-factor of 1.71

  } ttγ default

  - ☆ TTGJets_Lminus(plus)Nu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8
  - ☆ TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8

  } ttγ alternative

  — provided for differential fits to be compared to the data

- Phase space overlap removal of samples is applied
- Full MC sample list can be found in AN note

Sample and trigger — signal photon definition

- **Definition refers to TOP-23-002**

Update after pre-approval talk

- Good photon passing Table 6 is classified into categories shown in Table 7

Item		Requirement
|pdgId|		22
status		1 → stable particle
Mother		No meson or hadron in ancestor particle list
p_T^γ		> 20 GeV
$\|\eta^\gamma\|$		< 2.5
$\Delta R(\text{part}, \gamma)$	> 0.1	with all status $= 1$ and $p_T > 5$ GeV particle-level particles but not ν or γ
$\Delta R(\ell, \gamma)$	> 0.4	with all status $= 1$ and $p_T > 5$ GeV particle-level leptons

Table 6: List of requirements to define a good generator-photon at particle-level.

Mother particle	Decay photon	Production photon
lepton mother	Yes	No
W or b mother of t → Wb	Yes	No
t mother of t → t	Yes	No

Table 7: The definition of classifying production and decay photons from the collection of good generator-photons at the particle level.

- TGJets_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8 → **production photon**
- ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8 → **decay photon**
- ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8 → **decay photon**

} tγq default

- TTGJets_Lminus(plus)Nu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8 → **production photon**
- TTGamma_SingleLept_TuneCP5 13TeV-madgraph-pythia8 with k-factor of 1.71 → **decay photon**

} ttγ default

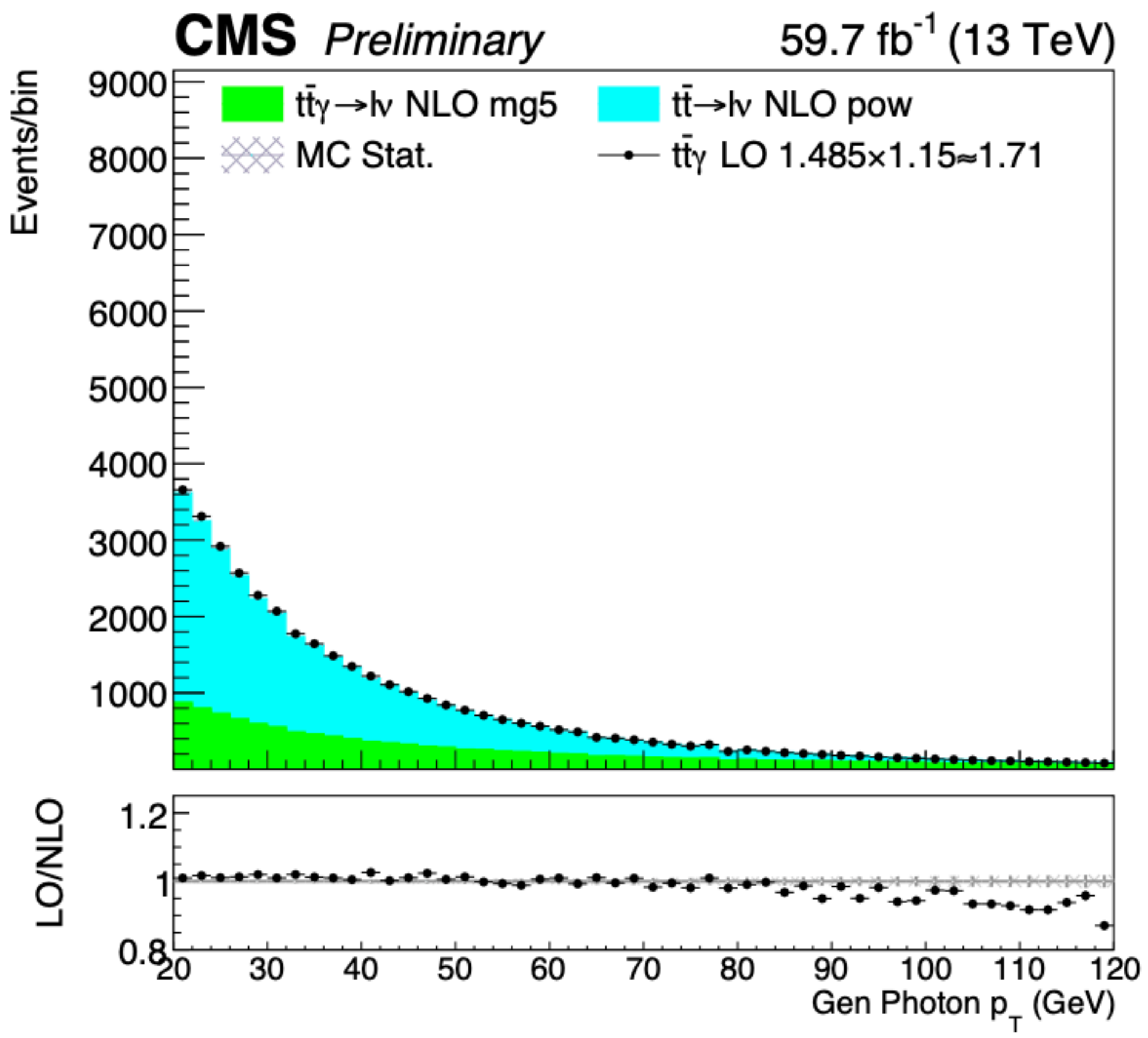
- TTGJets_Lminus(plus)Nu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8 → production photon
- TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8 → decay photon

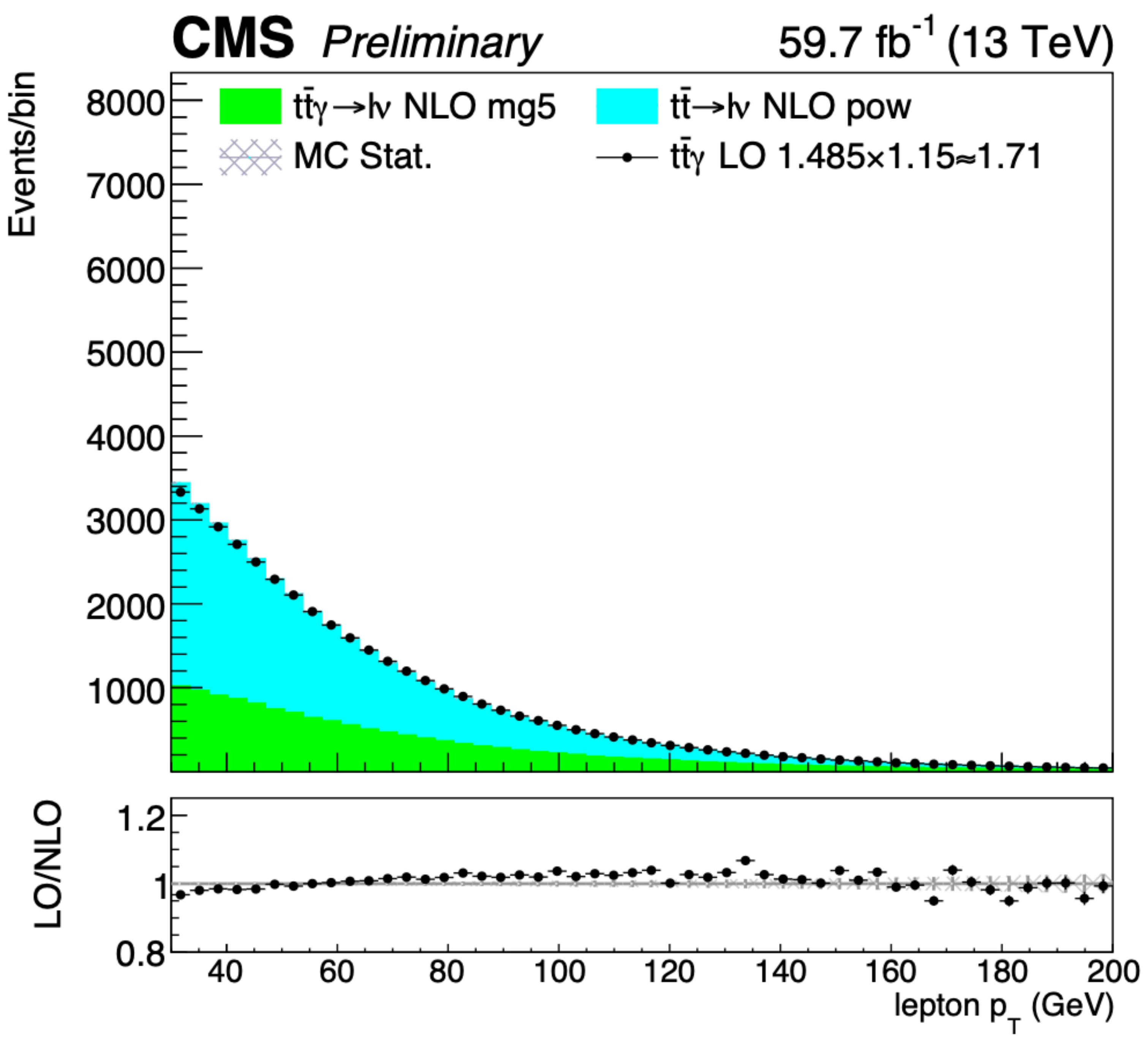
} ttγ alternative

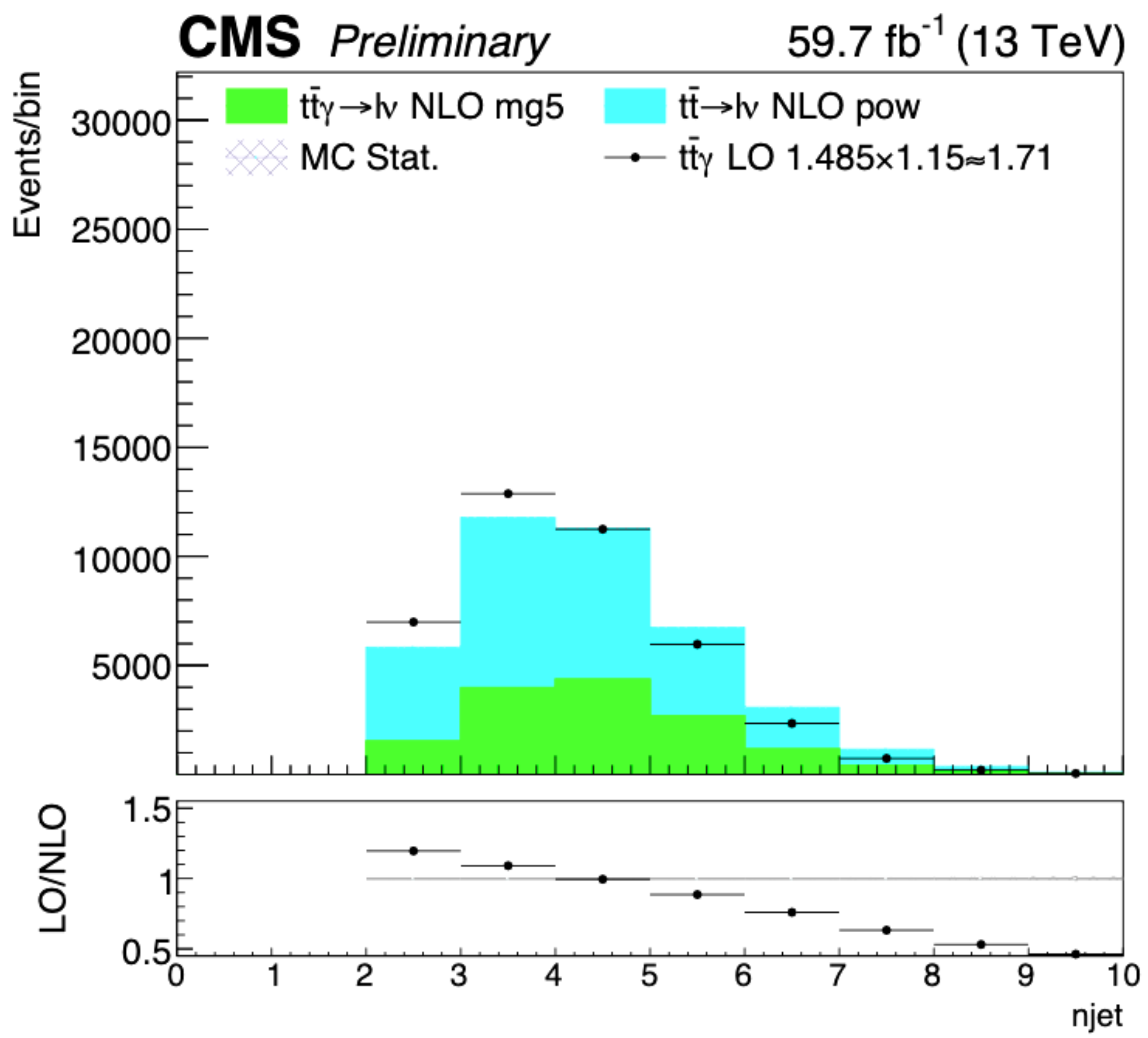
Sample and trigger — $t\bar{t}\gamma$ signal

- The k-factor of 1.71 is derived in fiducial region at particle level by comparing the ***full LO ttγ*** with the ***sum of prod. γ*** from NLO MG5+Pythia8 ***and decay γ*** from NLO Powheg+Pythia8, **documented in AN v7 in Fig. 3 of Sec 3.2**
  - Show good agreement in lepton and photon p_T
  - Show different trends in N_{jets} → NLO has more events when $N_{jets} \geq 4$

→ The value of 1.71 is consistent with the theoretical paper in https://www.arxiv.org/abs/1102.1967







Selection & correction

Electron	Good
p_T/GeV	> 35
$\|\eta\|$	< 2.5 not in ECAL gap
ID	cut-based medium ID
Others	Impact (d_{xy},d_z)

Muon	Good
p_T/GeV	> 30
$\|\eta\|$	< 2.4
ID	cut-based tight ID
Iso	Tight Iso (<0.15)

Photon	Good
p_T/GeV	> 20
$\|\eta\|$	< 2.5 not in ECAL gap
ID	cut-based medium ID
Ele-veto	pixel seed veto

JetMET	Jet	b-jet	MET
p_T/GeV	> 30	> 30	> 20
$\|\eta\|$	< 4.7	< 2.5	—
Type	AK4CHS	AK4CHS	PFMET
ID	tight jet ID Pileup ID (jet p_T<50)	medium deepjet ID	—

Signal requirements:

- Event ≥ 1 good PV and pass MET Filters and pass high-level trigger
- Exactly one lepton
  - Reject events containing extra ℓ with veto lepton requirement
- At least one photon
- At least two jet with at least one being b-jet
- $\Delta R(\ell,\gamma) > 0.4$, $\Delta R(\ell,j) > 0.4$, $\Delta R(\gamma,j) > 0.4$
- MET p_T > 20 GeV

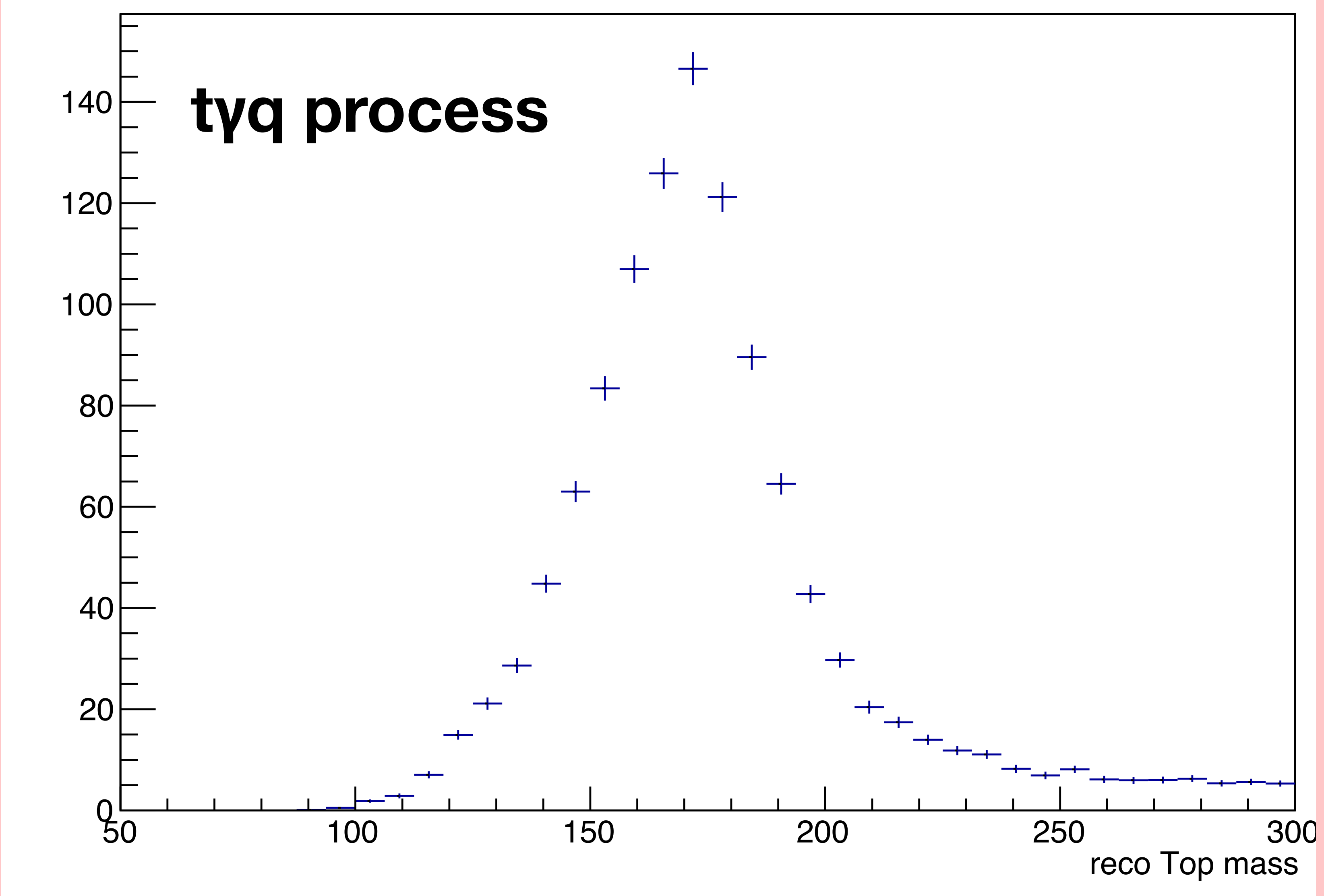
Applied correction:

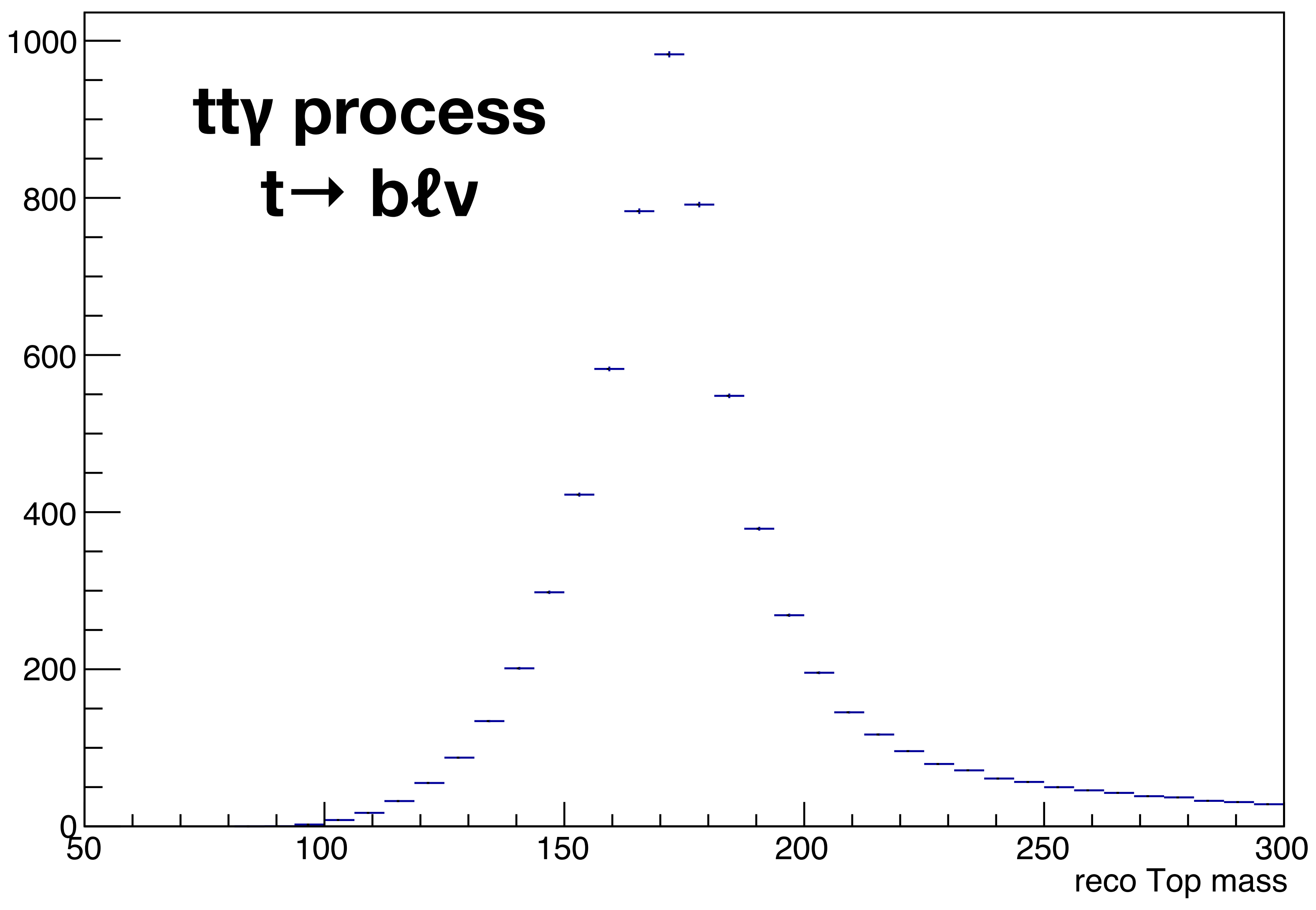
- Pileup reweighting
- L1 prefiring (2016 and 2017 MCs)
- Lepton energy correction
- Lepton ID/ISO/RECO/HLT scale factors
- e/γ energy scale/smearing
- Photon ID/Pixel Seed Veto scale factors
- Jet energy correction
- Jet pileup ID scale factors
- b-jet ID scale factors

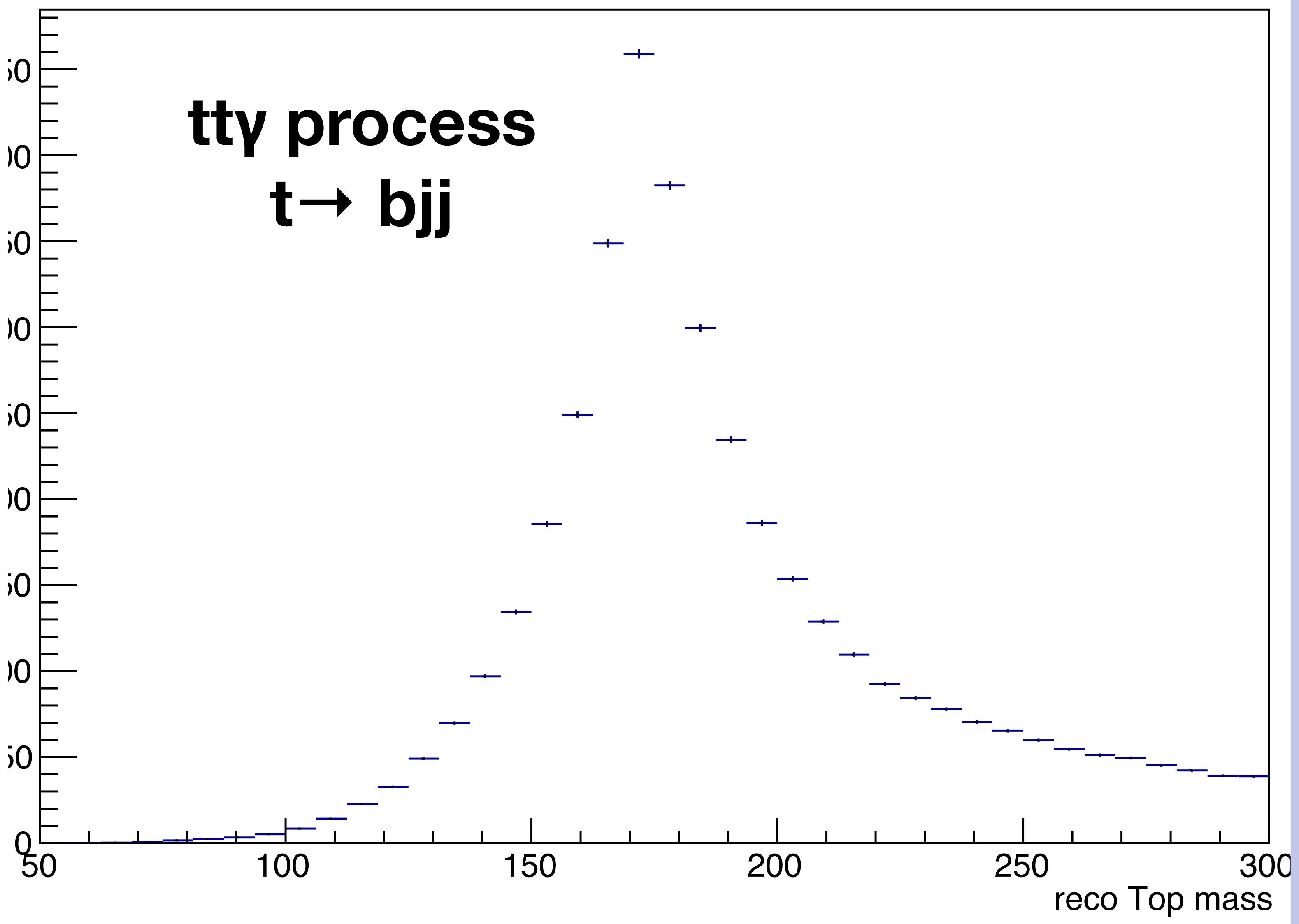
Top reconstruction

- **Method refer to TOP-23-004 and TOP-24-015**
- Chi-square minimisation is performed
- Leptonic and hadronic top quarks are reconstructed depending on the available objects
- If the reconstruction is not possible, give a default value -10

$$\chi^2_{\mathrm{t,lep}} = \left(\frac{m_{\ell\nu\mathrm{b}} - m_{\mathrm{t}}}{\sigma_{\mathrm{t,lep}}}\right)^2 \qquad \chi^2_{\mathrm{t,had}} = \left(\frac{m_{\mathrm{bjj}} - m_{\mathrm{t}}}{\sigma_{\mathrm{t,had}}}\right)^2 \qquad \chi^2_{\mathrm{t}} = \left(\frac{m_{\ell\nu\mathrm{b}} - m_{\mathrm{t}}}{\sigma_{\mathrm{t,lep}}}\right)^2 + \left(\frac{m_{\mathrm{bjj}} - m_{\mathrm{t}}}{\sigma_{\mathrm{t,had}}}\right)^2$$

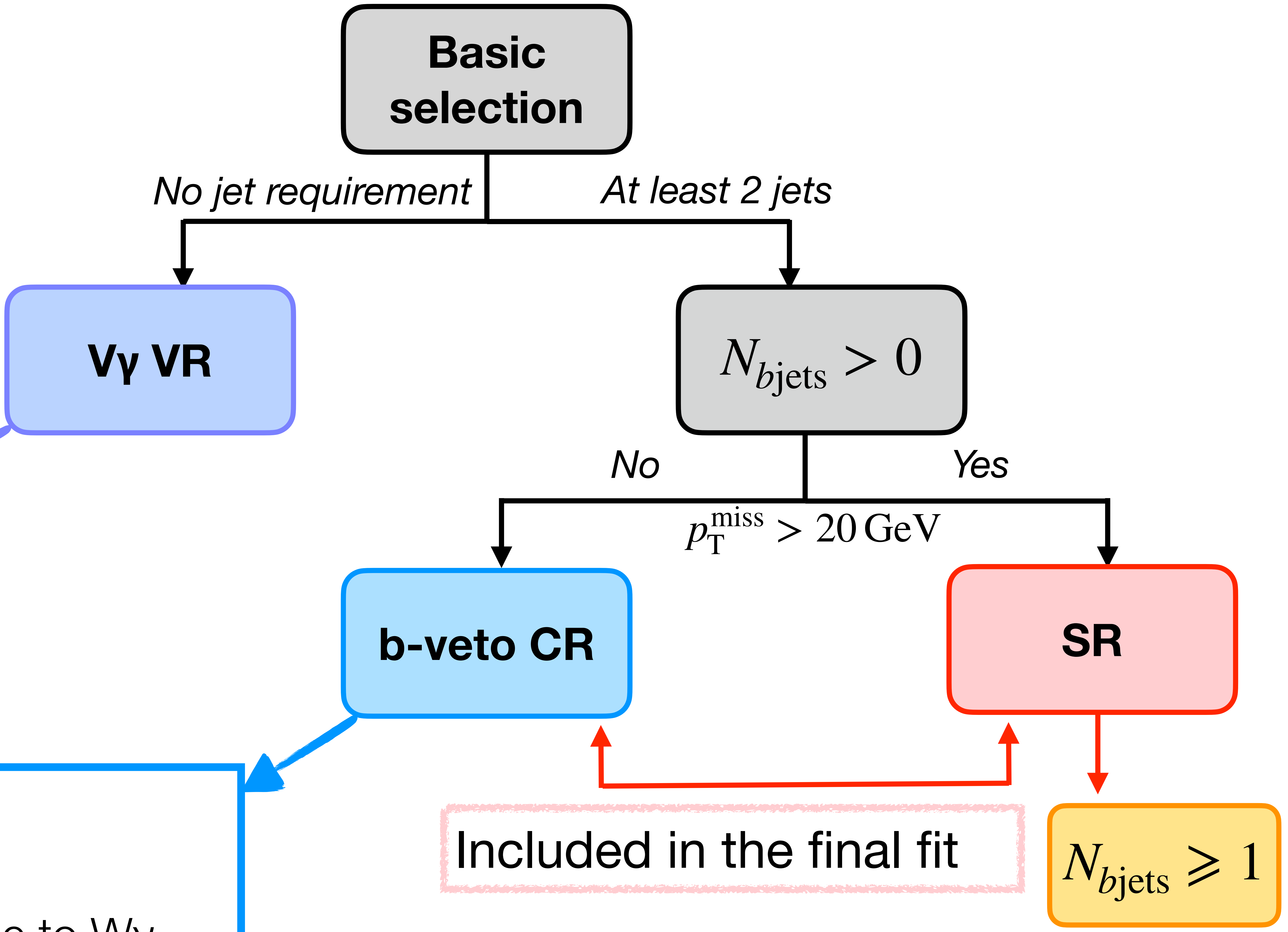






Event categorisation

Baseline selection	A. Exactly one lepton with $p_T^{\mu/e}>$ 30 (35) GeV, $\lvert\eta\rvert < 2.4$ (2.5) B. Pass single e(μ) HLT paths C. At least one photon with $p_T^{\gamma}>$ 20 GeV in the barrel or endcap



Vγ validation region

- Nonprompt γ contribution is comparable
- Very large statistics is helpful to validate corresponding background normalisation

Wγ enriched region

- Nonprompt ℓ contribution is visible
- Nonprompt γ contribution is comparable to Wγ
- Constrain the corresponding background normalisation by correlating the same systematic uncertainty in the SR

Events are further separated to **e channel** and **μ channel**

Event yields

Process	Muon channel		Electron channel	
	Pre-fit	Post-fit	Pre-fit	Post-fit
$t\gamma q$	3341.6	3737.0	2081.8	2360.1
$t\bar{t}\gamma$+jets	19223.3	19920.0	13296.7	13801.3
$t\gamma q$ out	203.9	200.5	116.6	117.3
$t\bar{t}\gamma$+jets out	251.1	254.5	127.3	126.8
Nonprompt γ	15555.6	15262.9	11206.3	11165.1
Nonprompt ℓ	1727.5	1933.6	2627.1	2963.4
Double Nonprompt	2653.7	2706.6	2620.9	2800.2
$t\bar{t}\gamma \to 2\ell$	10708.0	10548.3	7404.8	7334.3
$t\bar{t}\gamma \to 2\ell$ misID	7157.7	9433.0	5023.26	6659.1
$W\gamma$+jets	6135.7	6767.0	4243.4	4596.9
$Z\gamma$+jets	2521.5	2617.6	1855.0	1938.8
$tW\gamma$	1901.3	1871.4	1364.9	1376.1
Z+jets	43.9	31.2	5518.9	7135.3
Others	622.5	673.9	442.6	491.2
Other misID	468.6	608.6	469.3	607.4
Sum of prediction	72516.0 ± 3427.6	76566.2 ± 1162.6	58398.9 ± 3222.0	63464.6 ± 414.6
Sum of data	76477 ± 276		63592 ± 252	

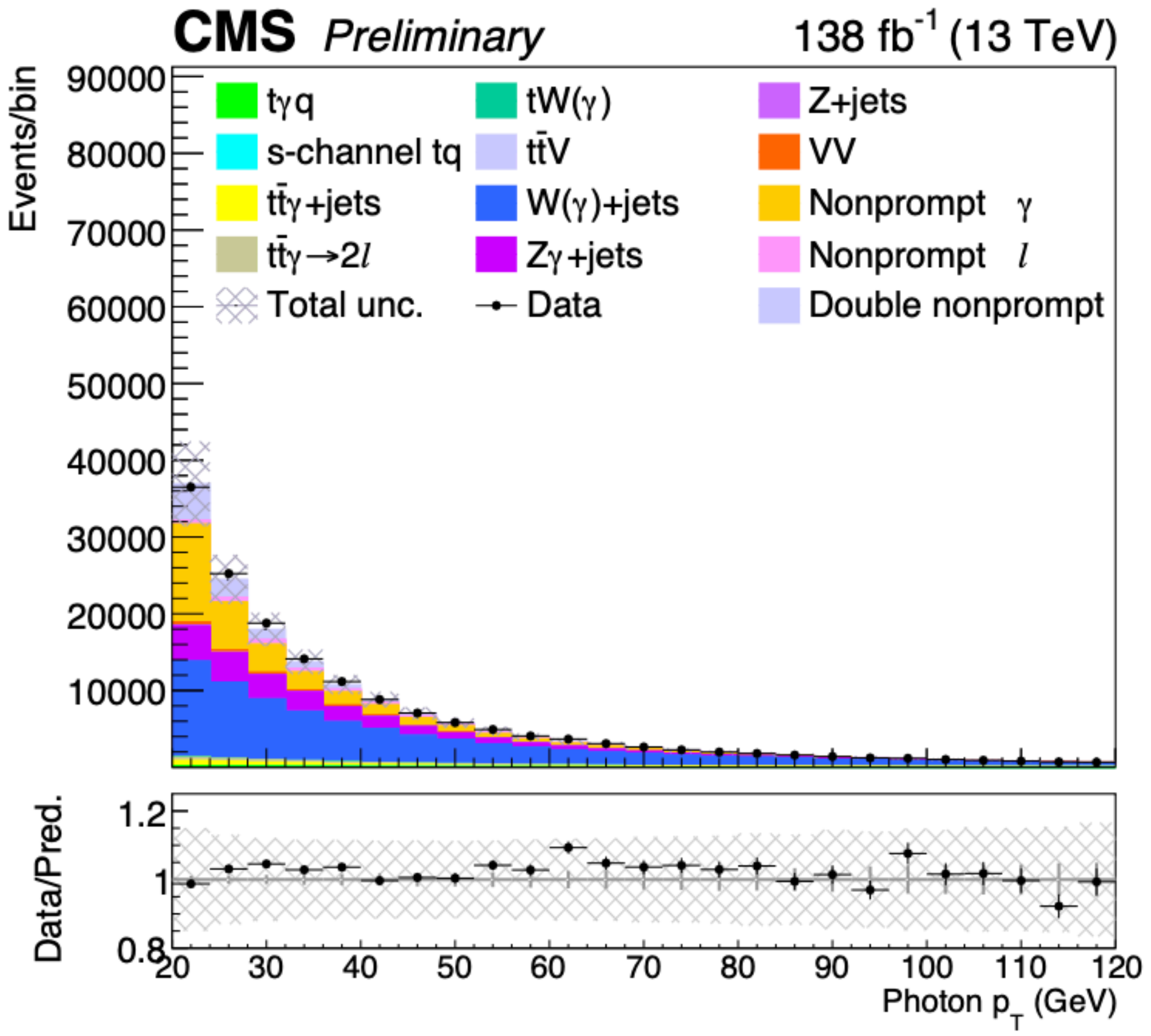
The ele misID estimation in the final fit:

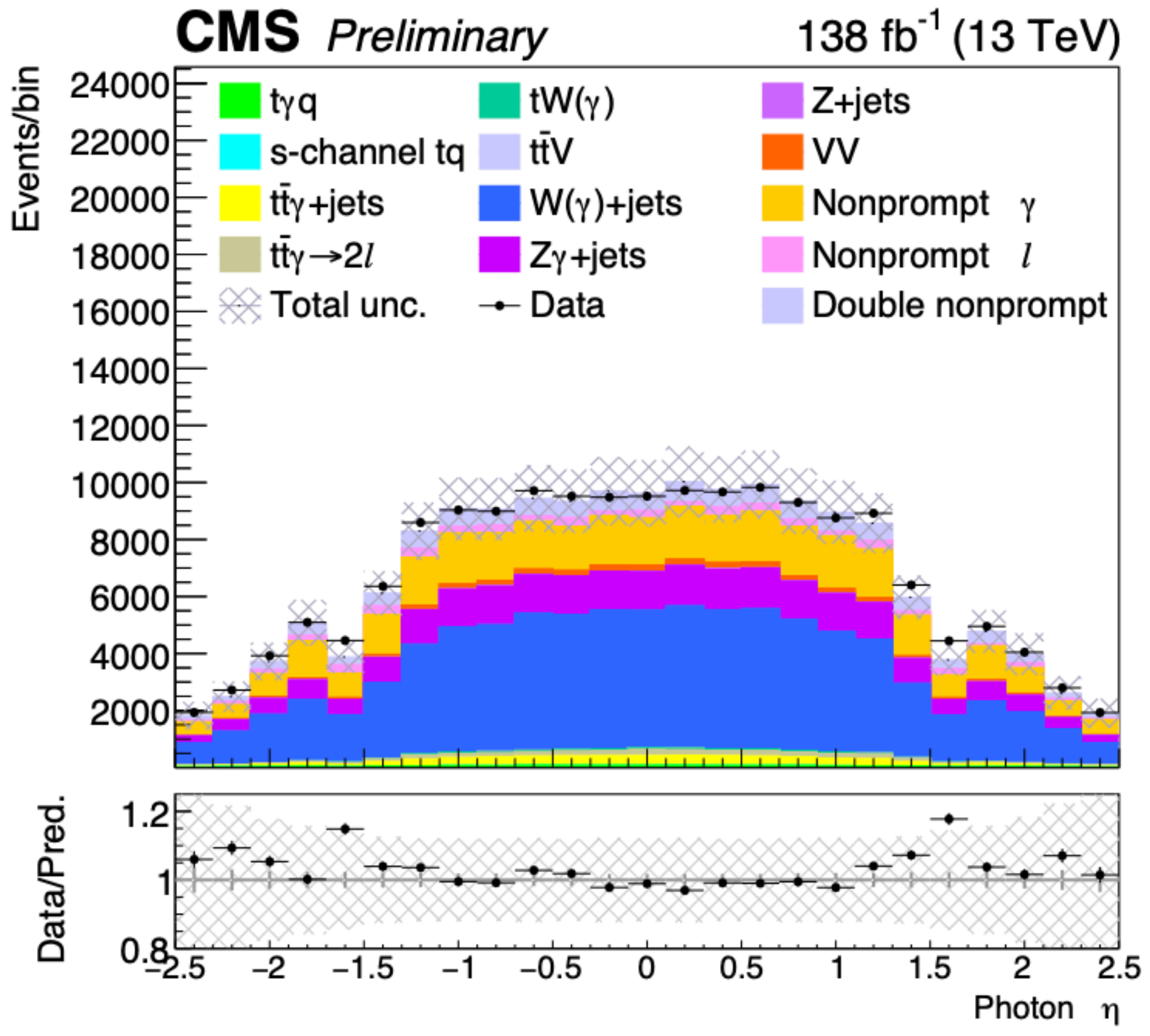
1. Float the Z+jets normalisation as rateParam for electron channel
2. Float the ttγ→2ℓ misID and the remaining total misID (signal not included) as rateParam for electron and muon channel

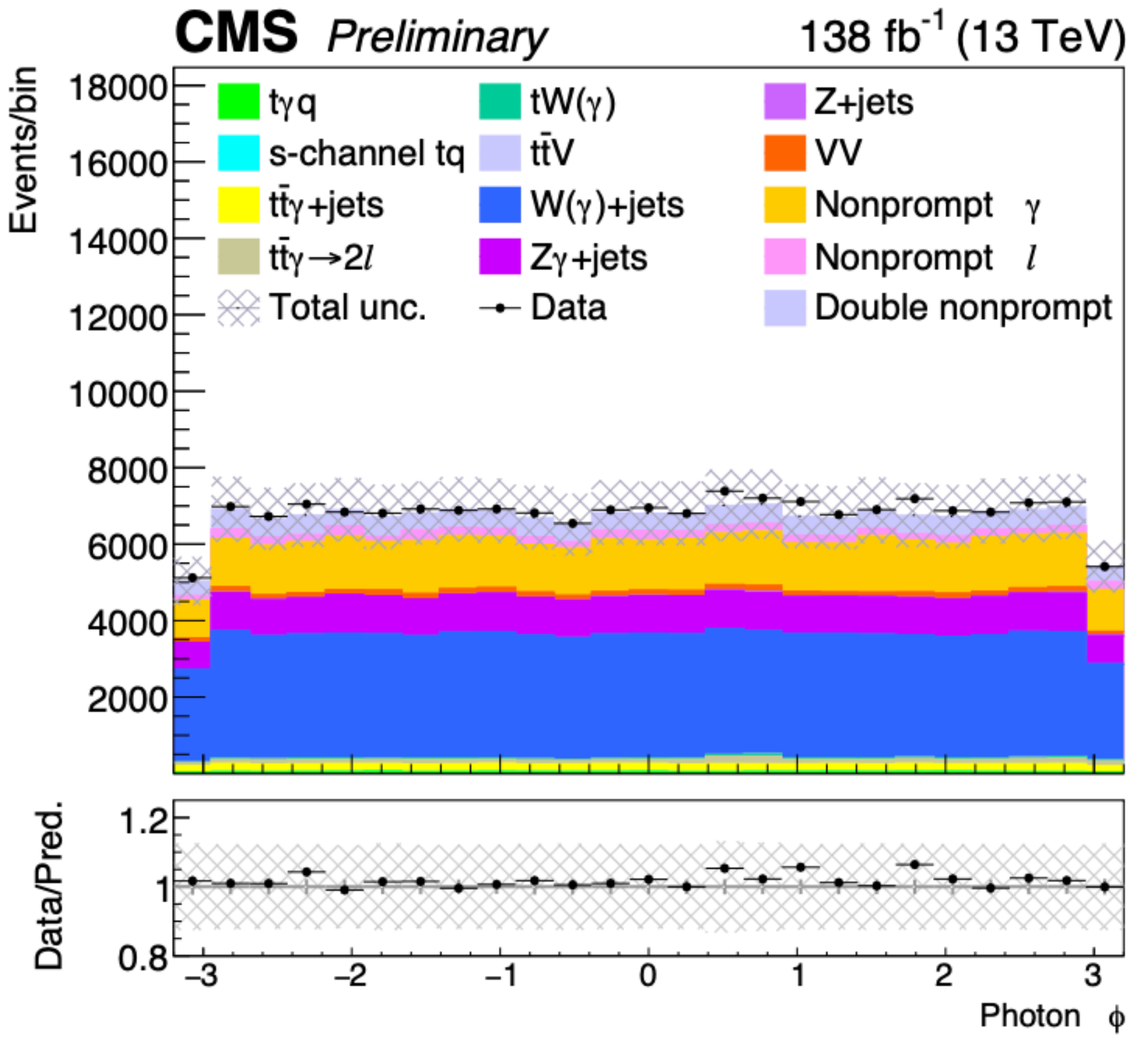
- Uncorrelated across years and jet flavour channels.
- Correlated between lepton flavour channels.

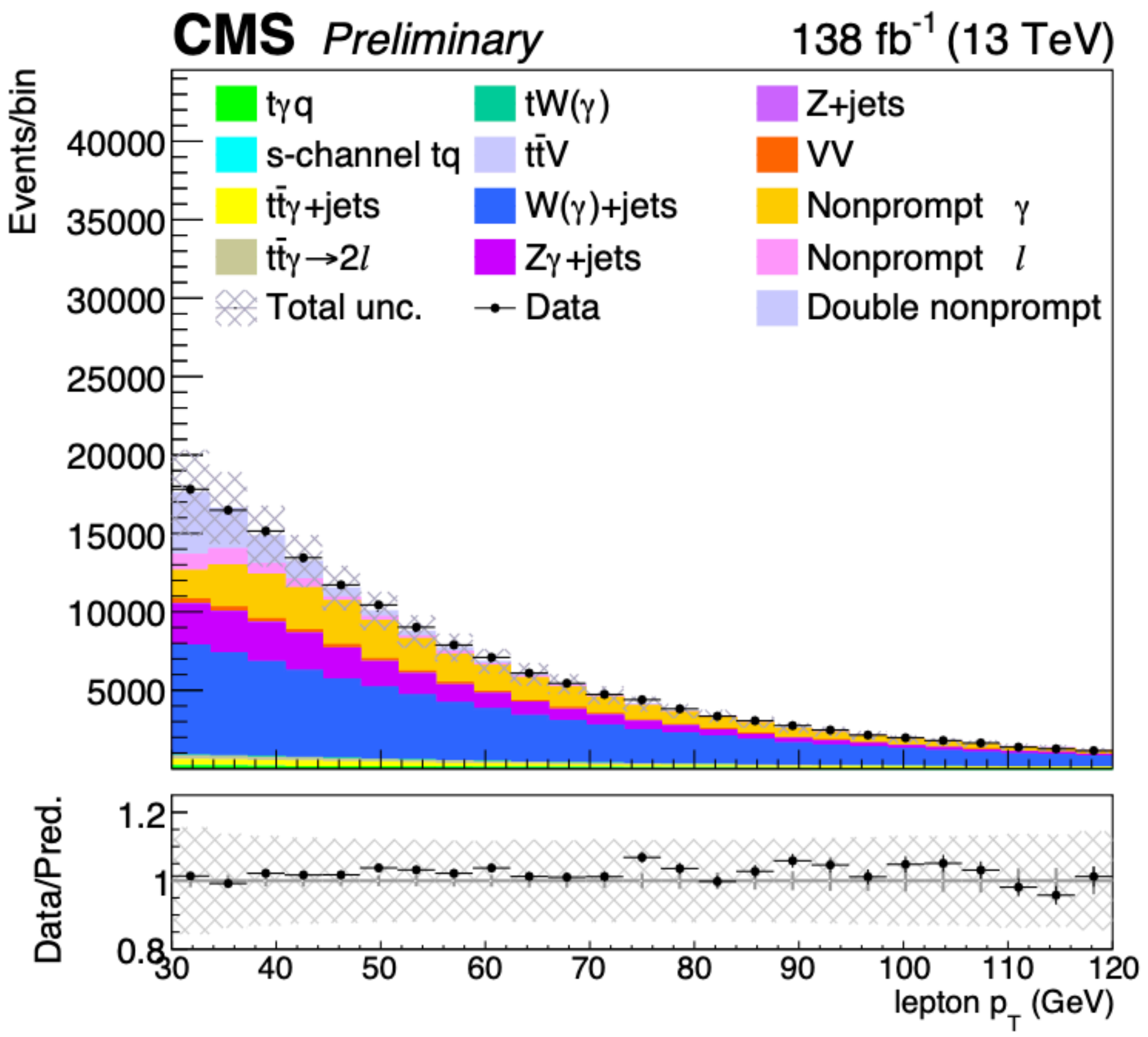
Update after pre-approval talk

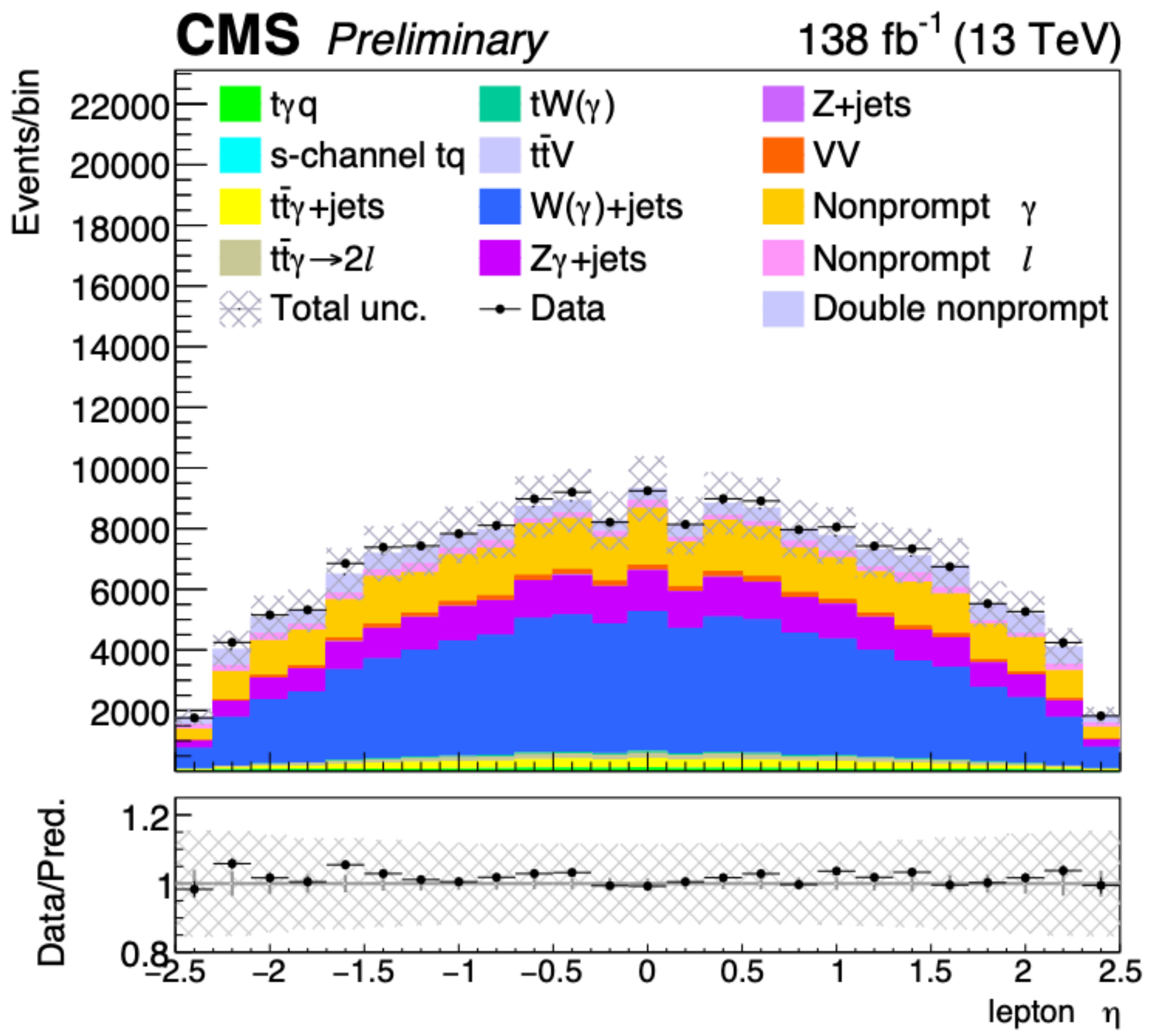
Control plots — μ channel

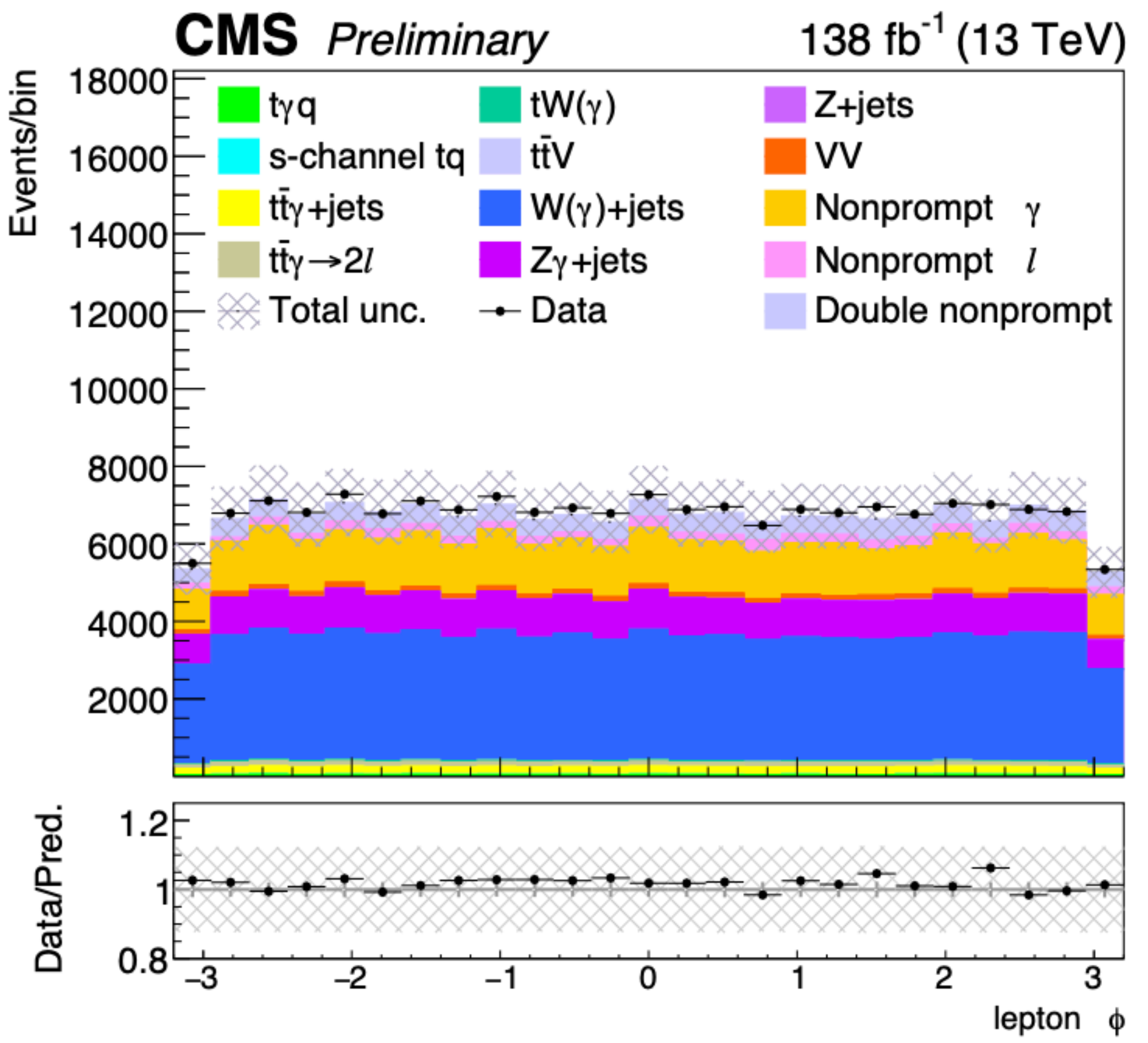




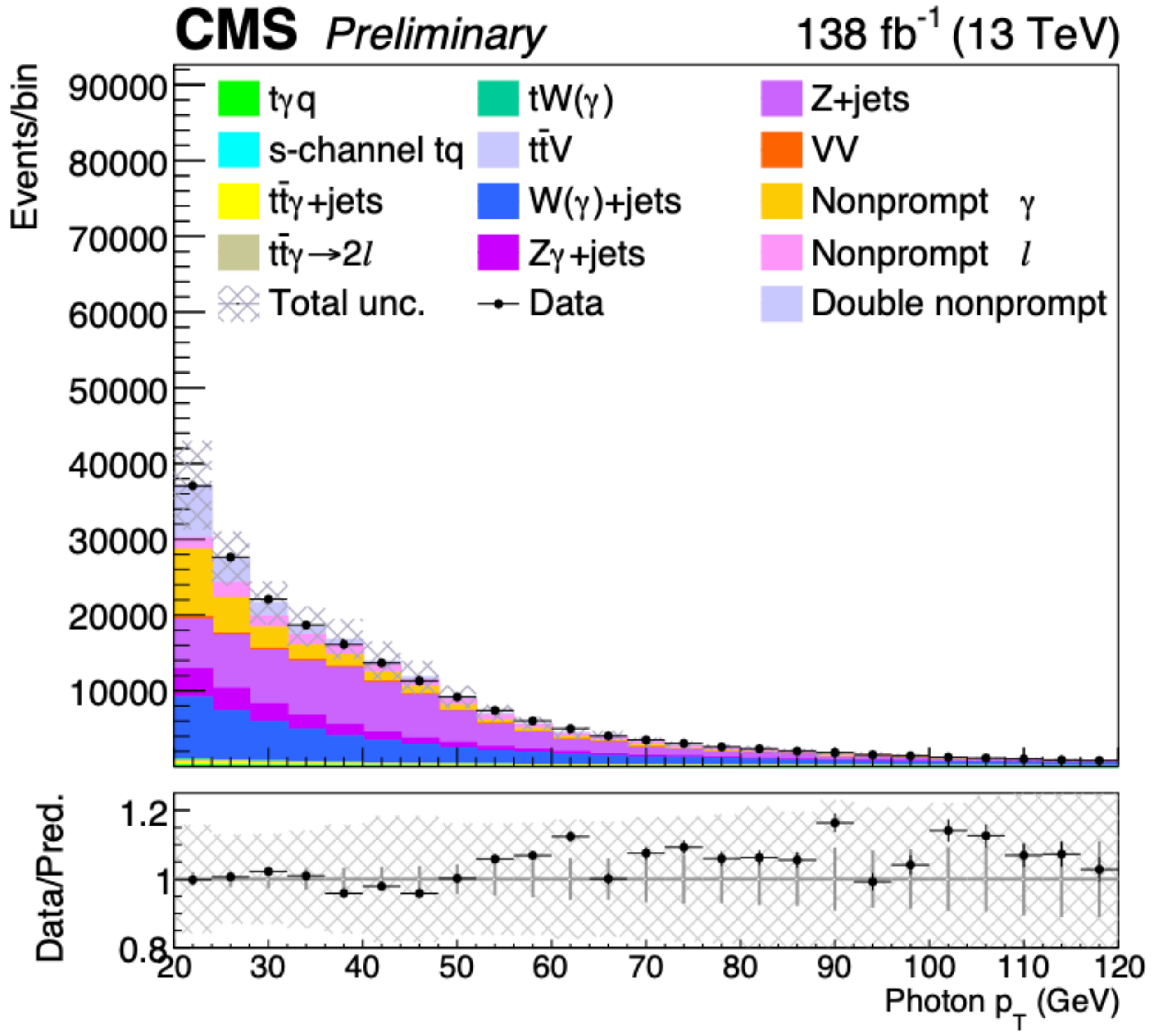


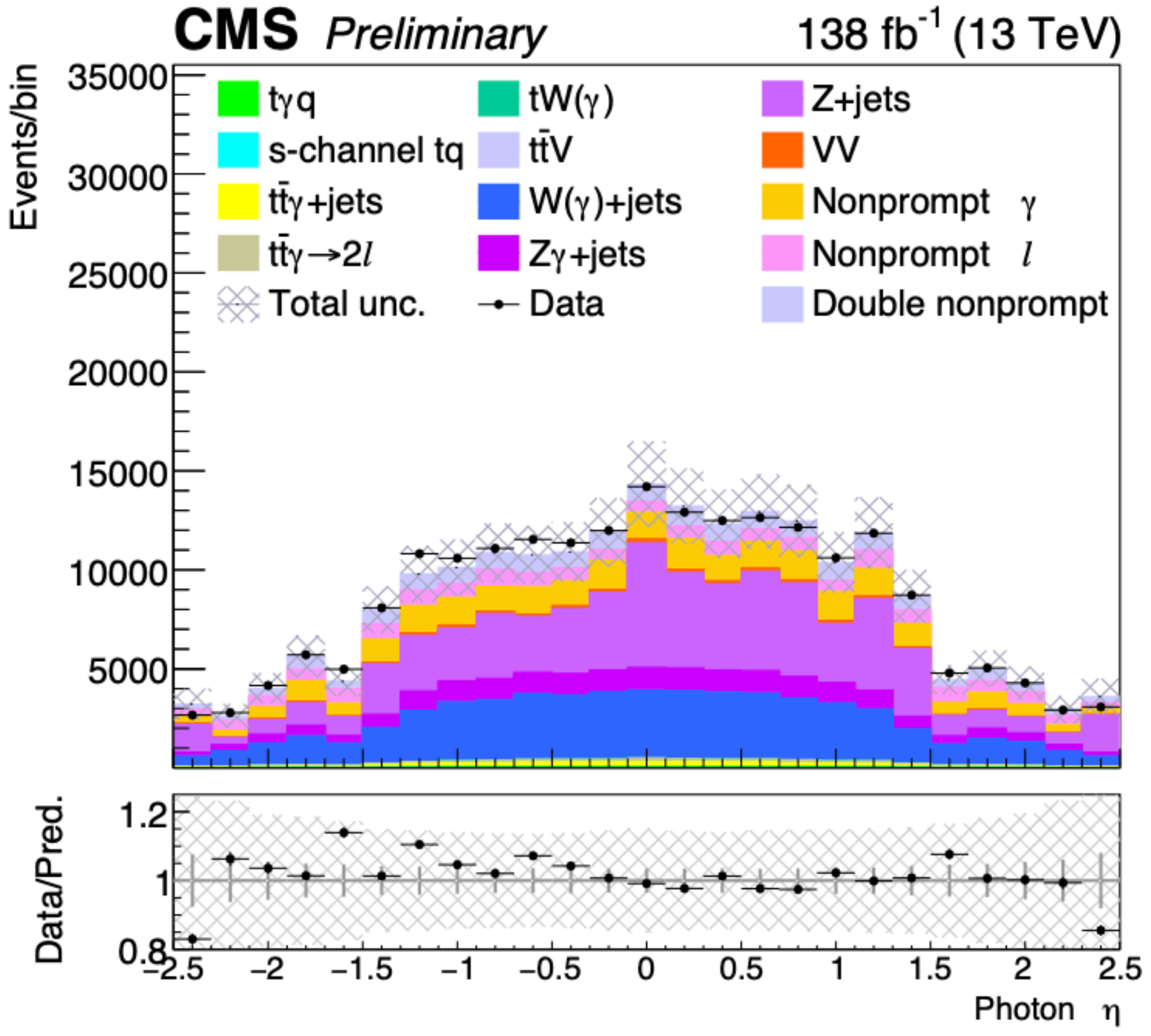


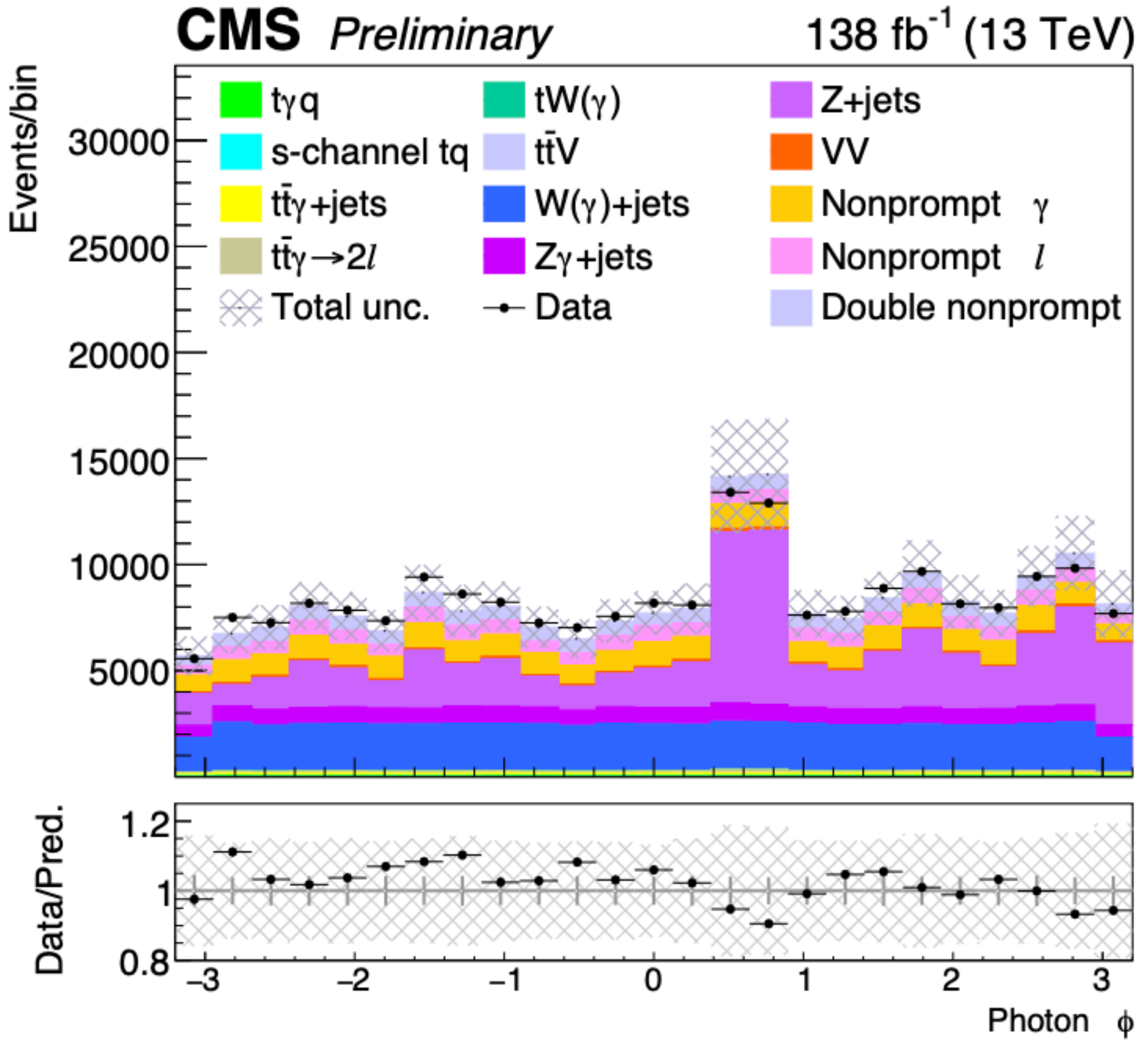


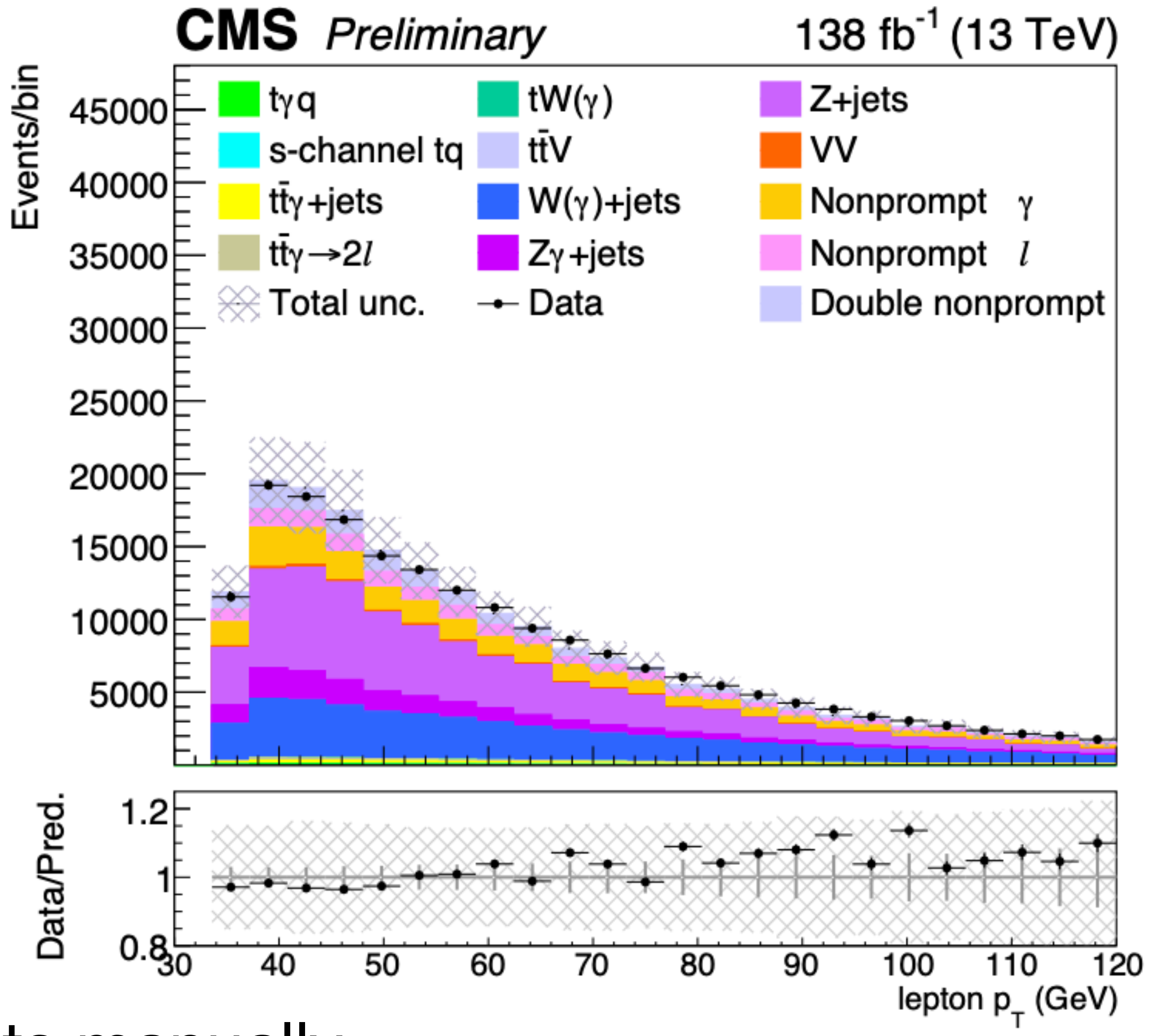


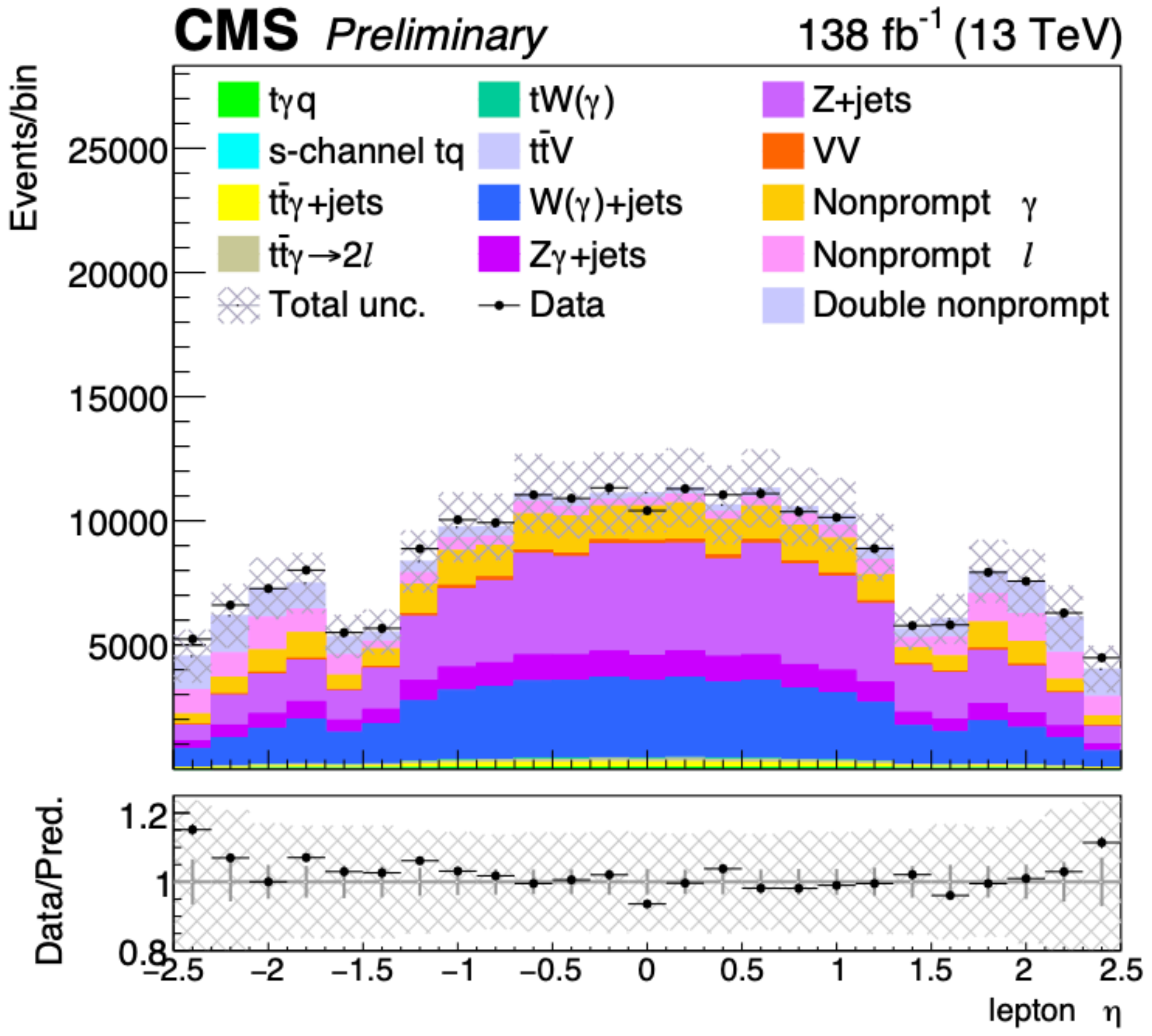
Control plots — e channel

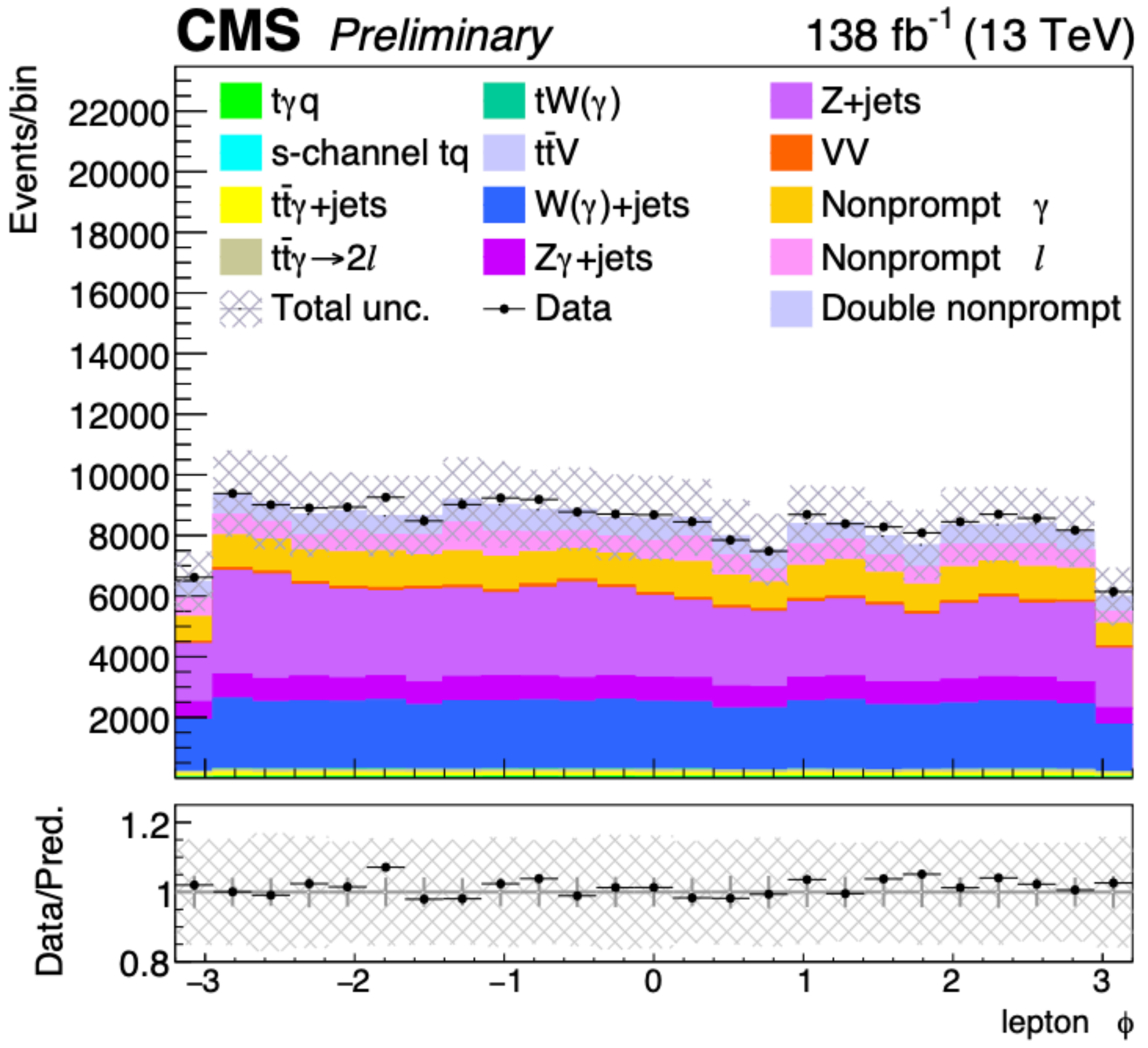










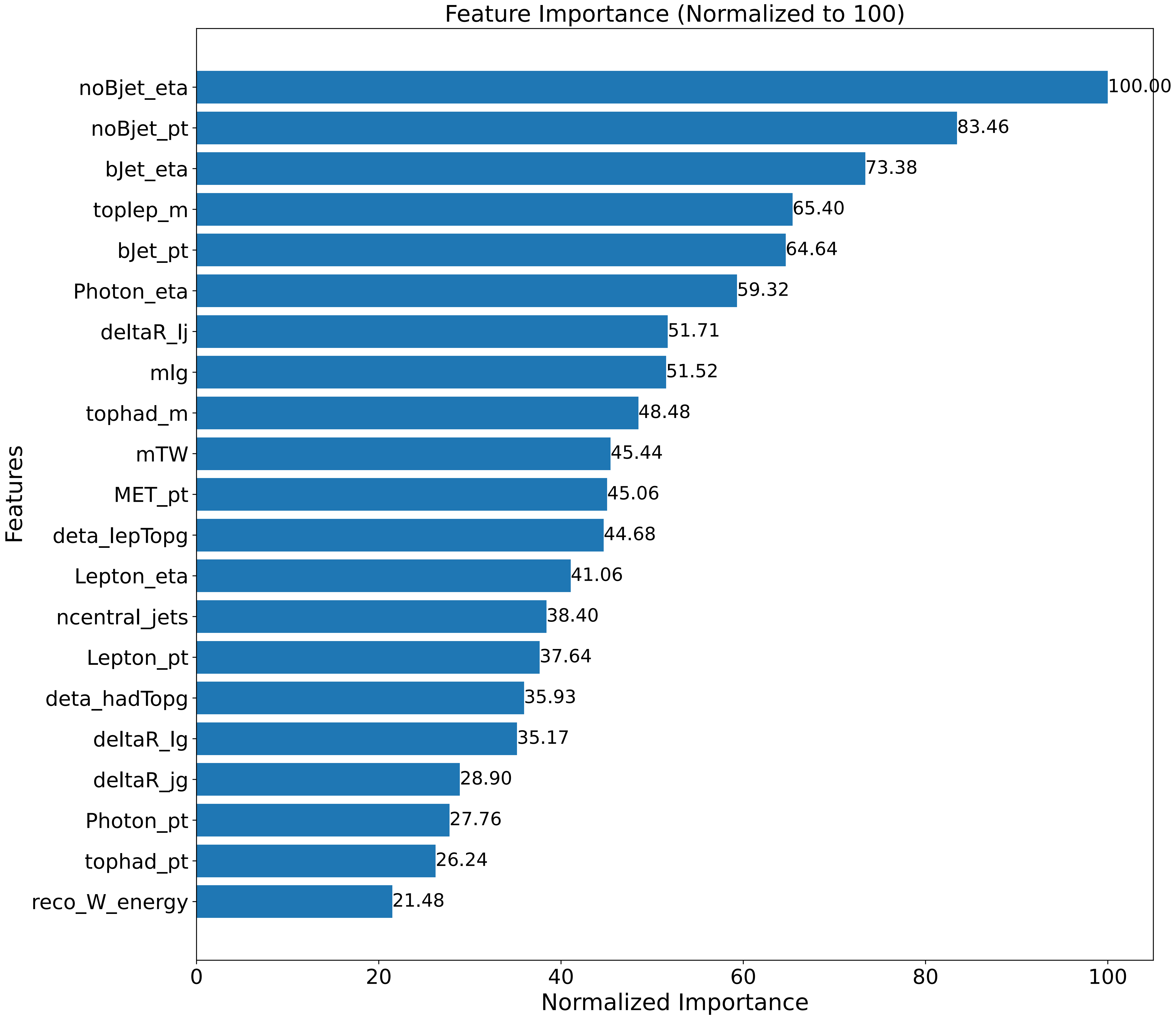


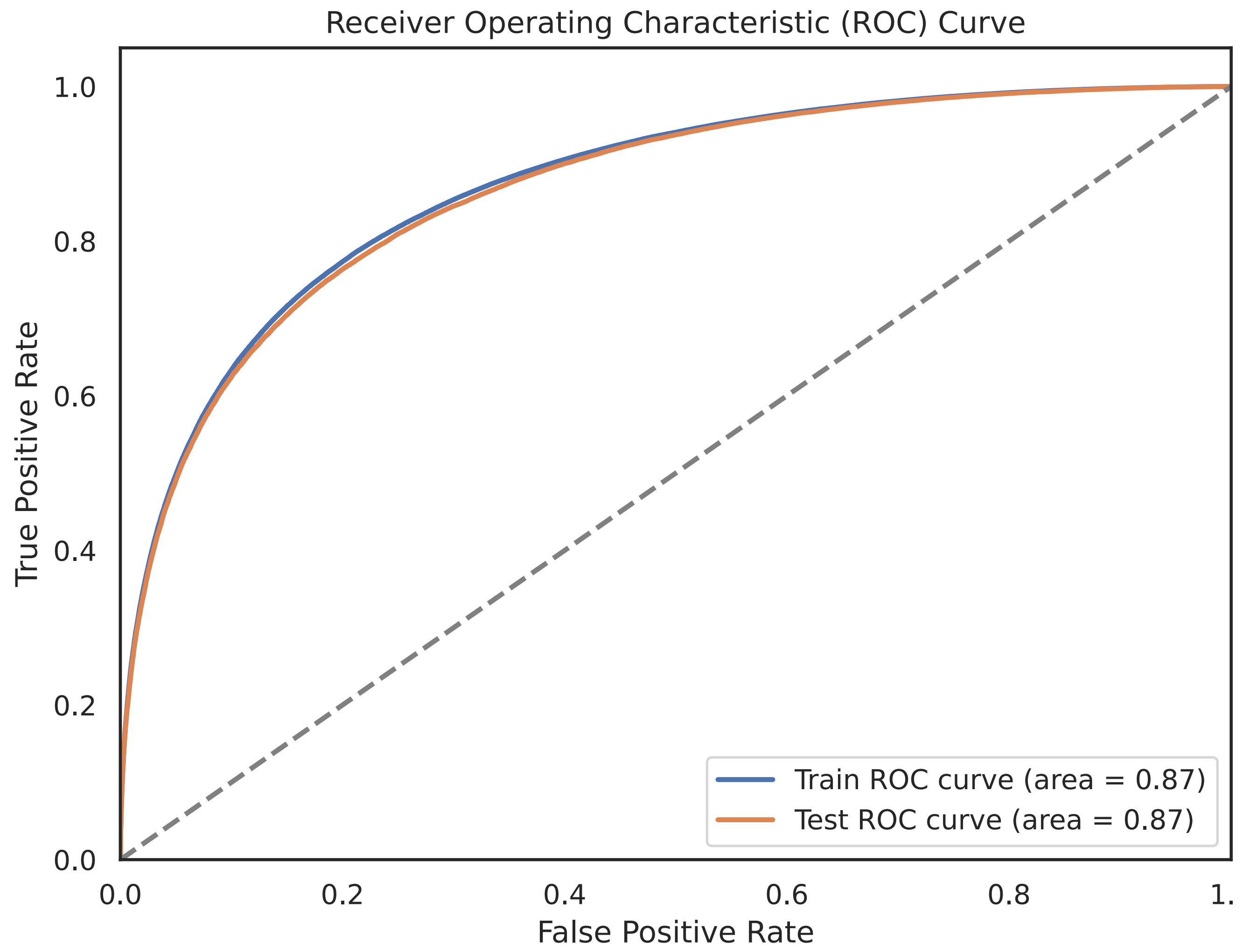
Normalising Z+jets manually

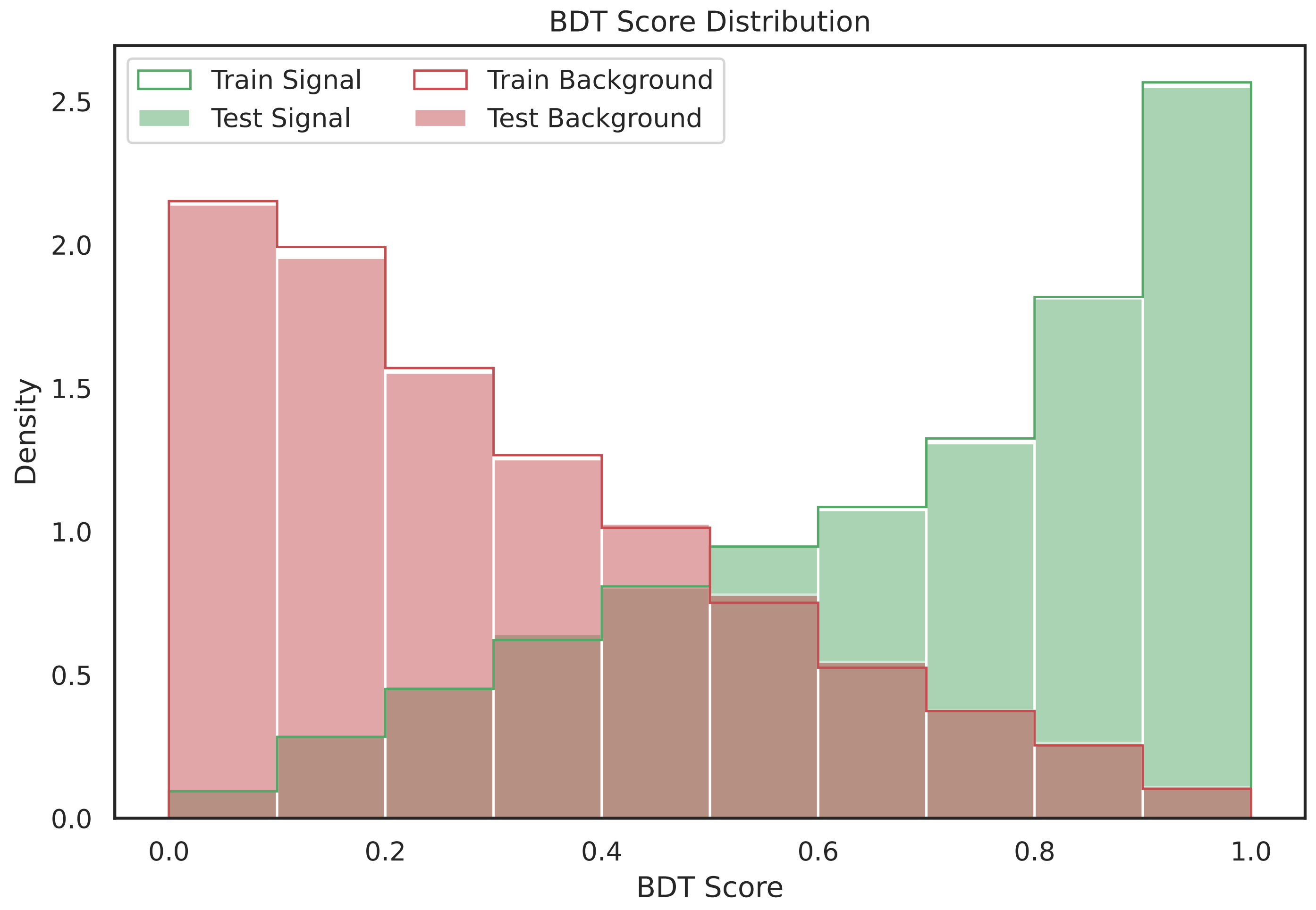
BDT training

A BDT is trained in the signal region with tγq production photon as signal and others as backgrounds

- Using simulation events
- Train one model for different lepton channels and years



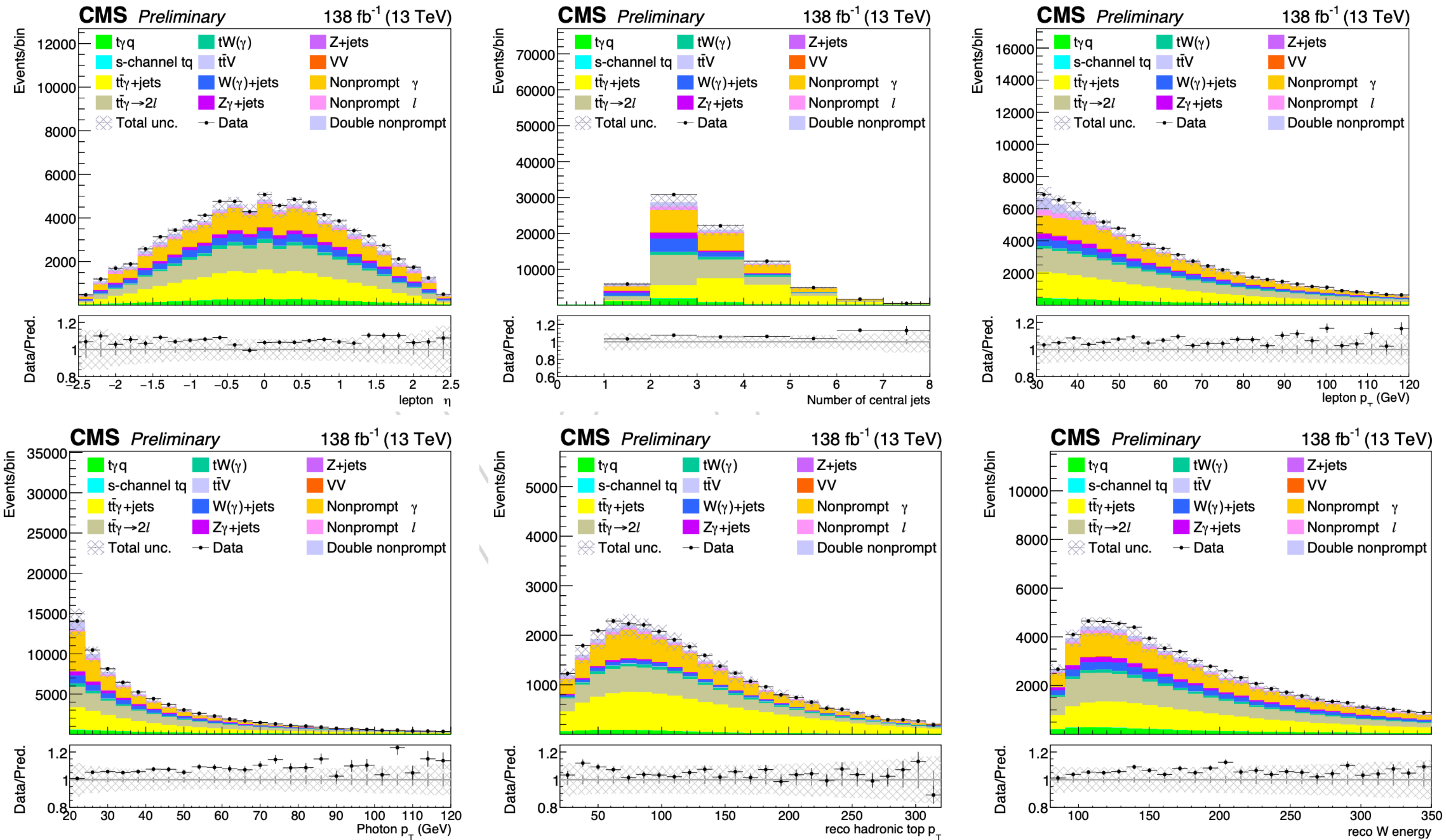




- Hyper-parameters tuned by HYPEROPT package
- Total 21 input features checked in partial SR of BDT<0.5 (before unblinding)
- Train and test matched well with ROC ~ 87%

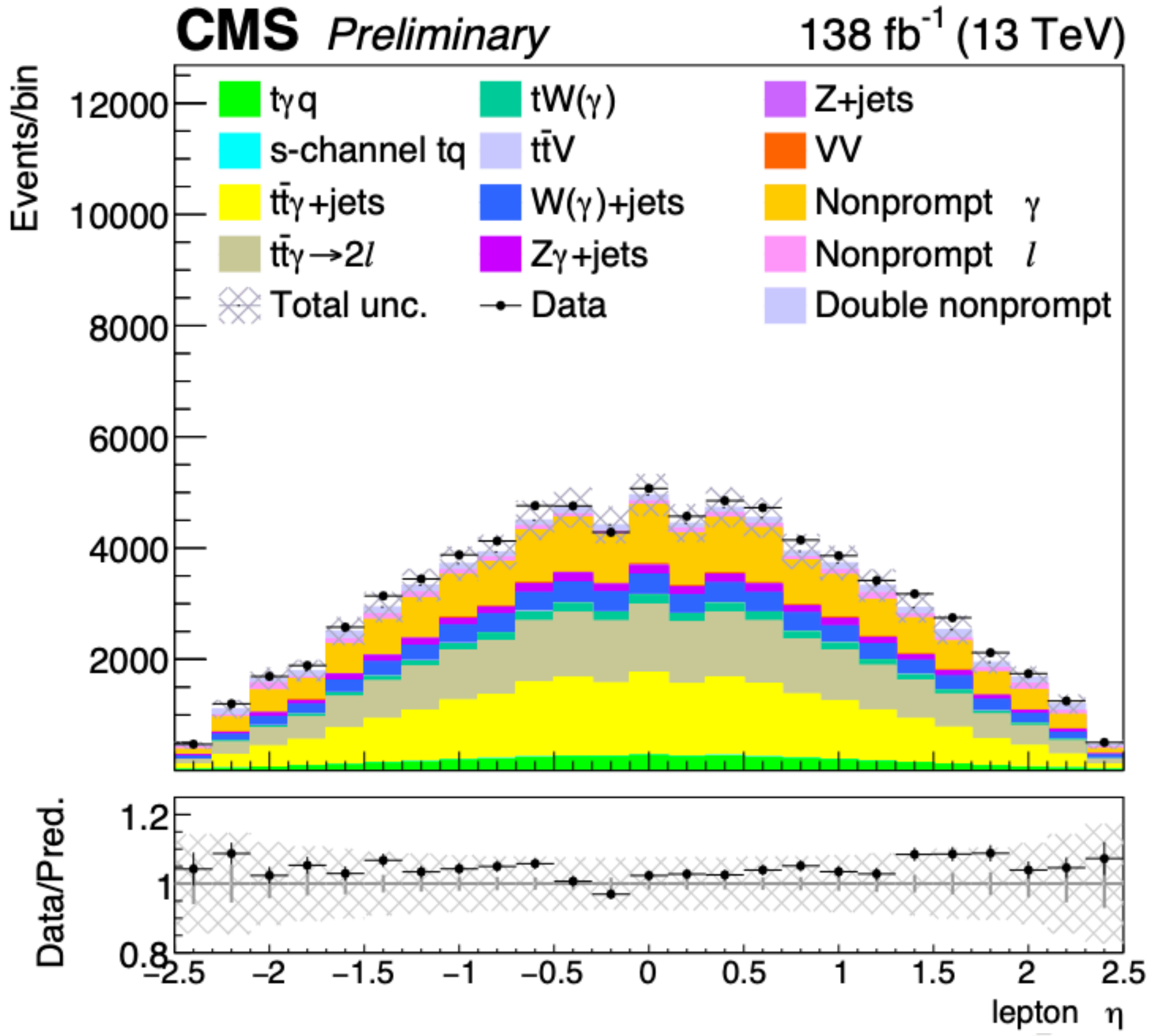
Unblind plots for SR

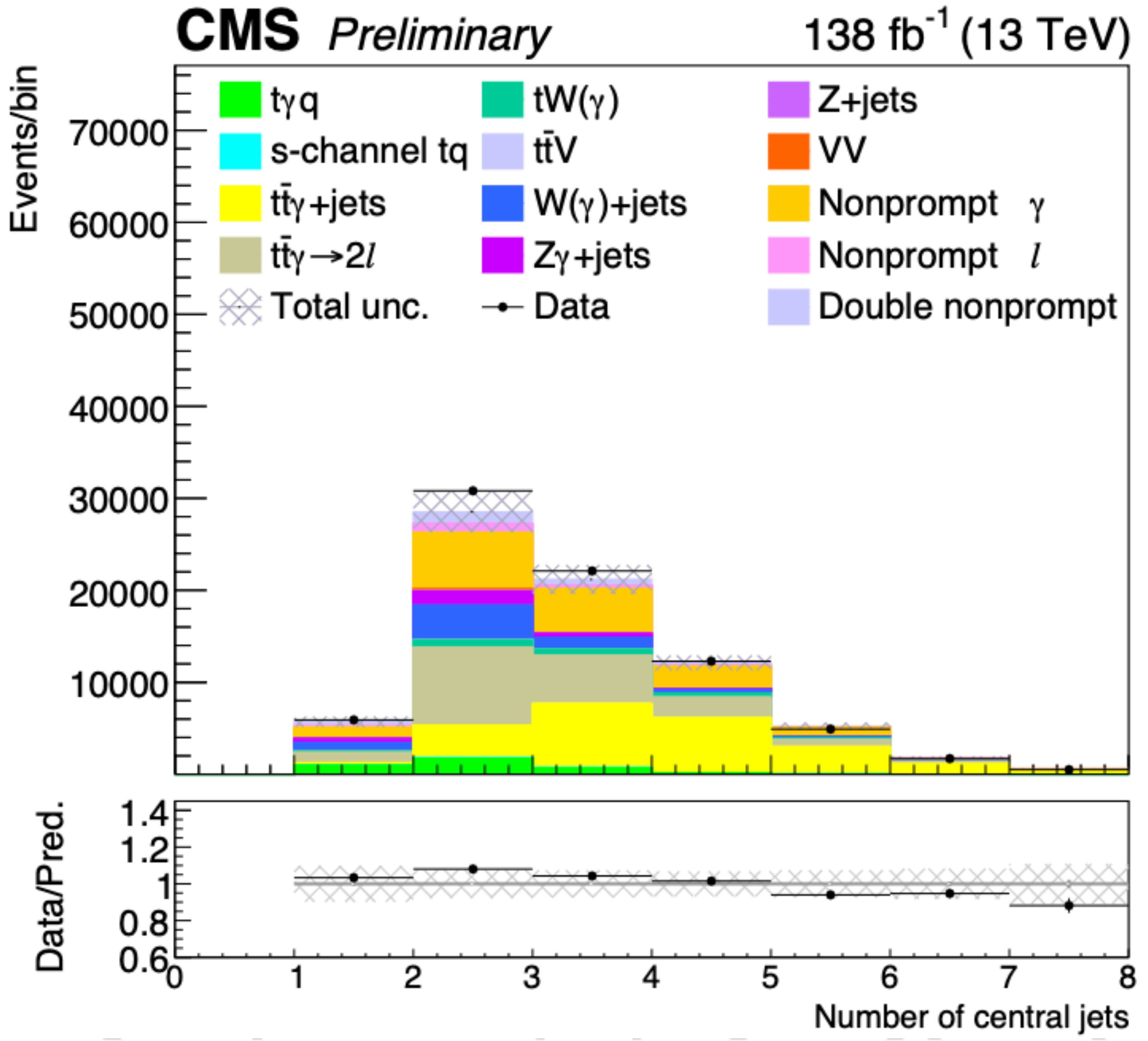
- TTGJets_Lminus(plus)Nu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8
- TTGamma_SingleLept_TuneCP5 13TeV-madgraph-pythia8 with k-factor of 1.71

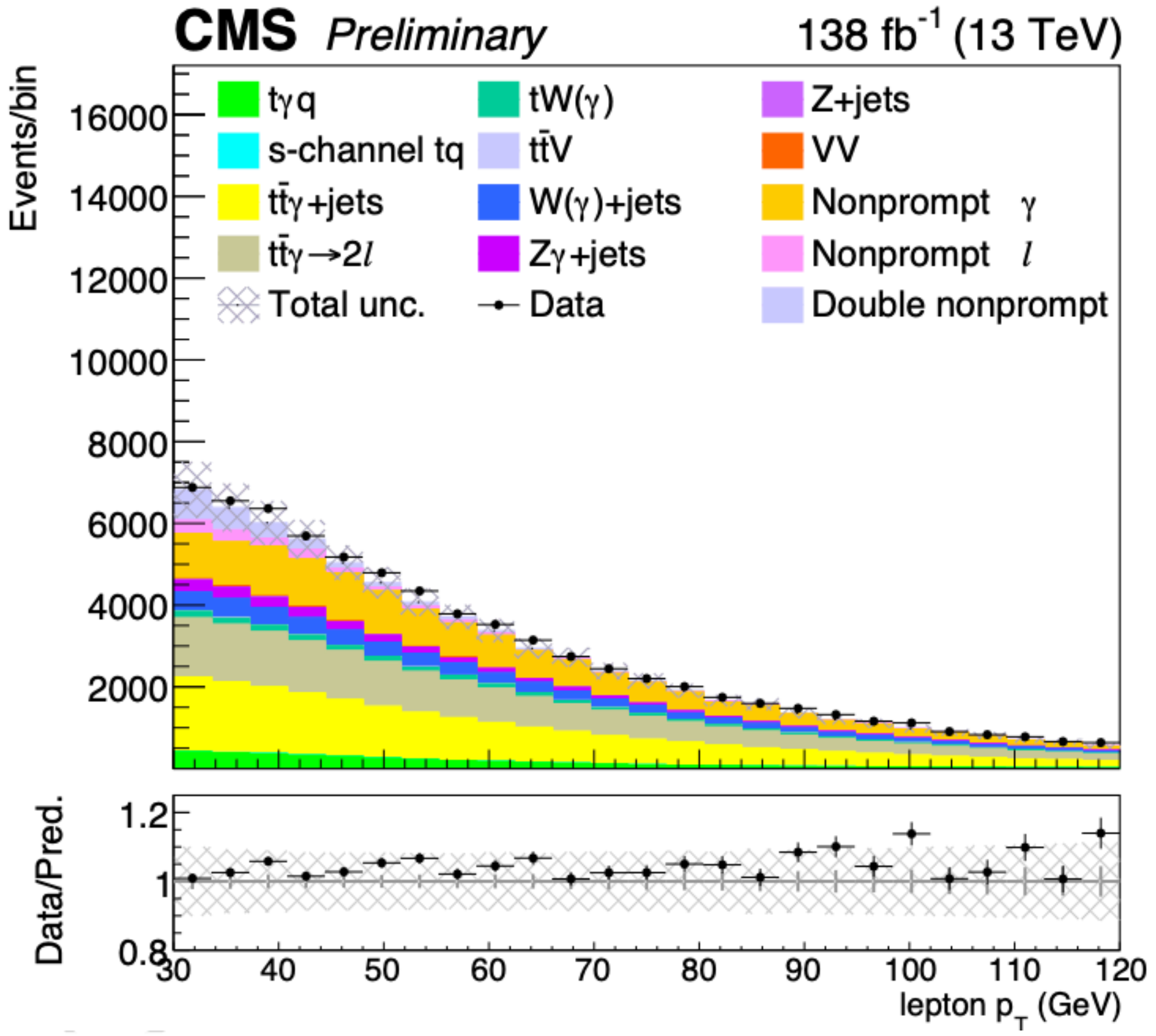


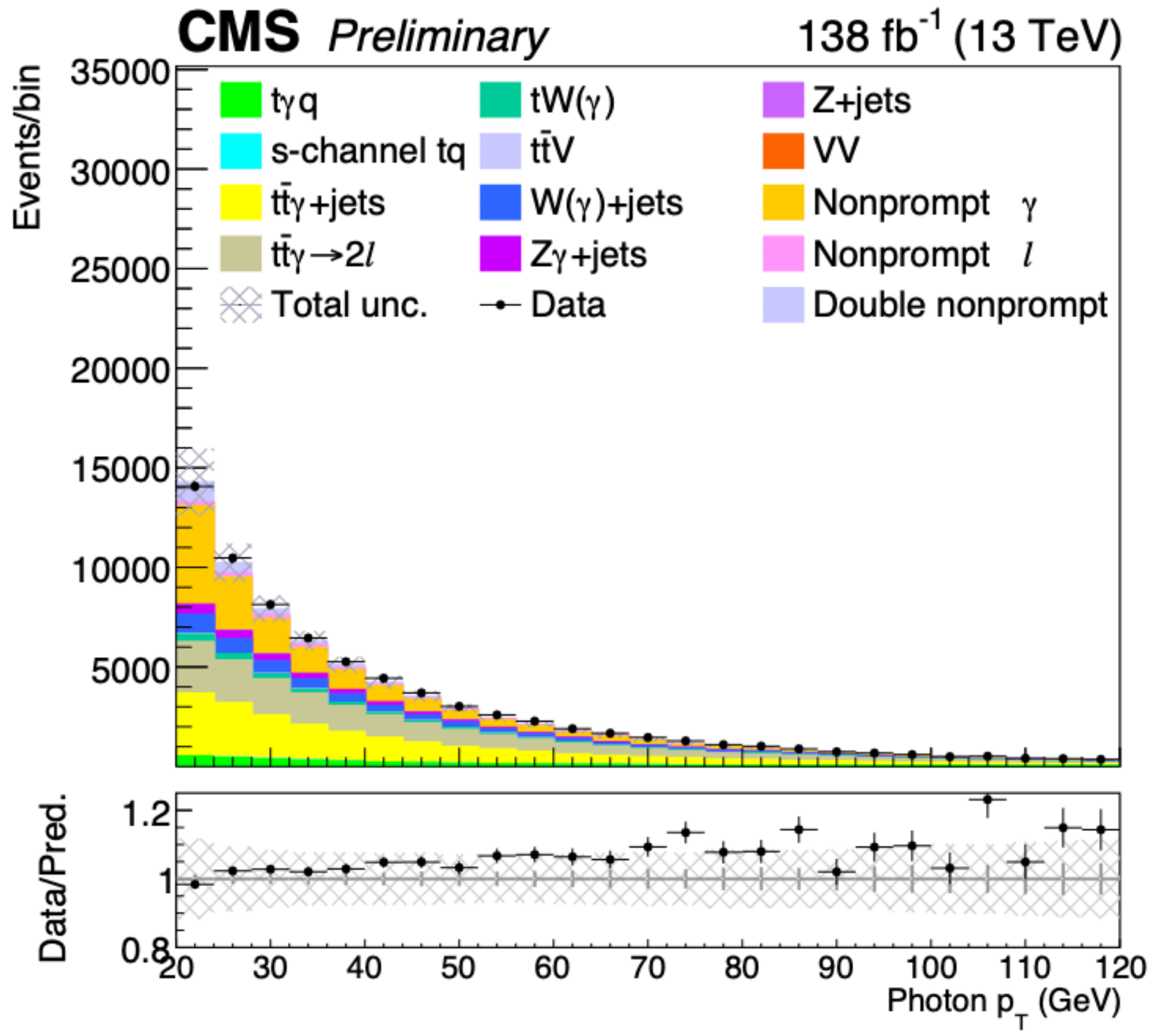
Unblind plots for SR

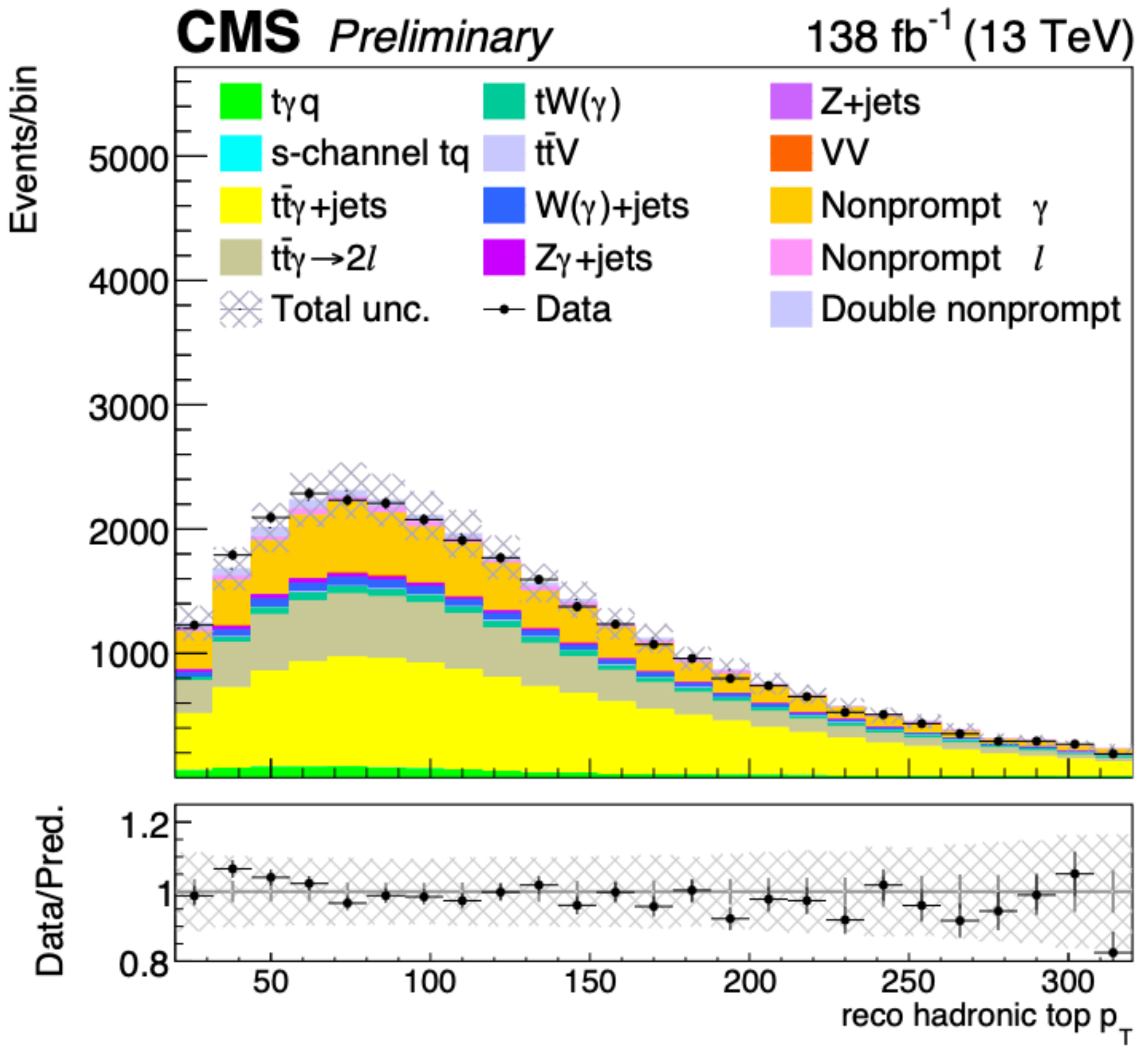
- TTGJets_Lminus(plus)Nu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8
- TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8

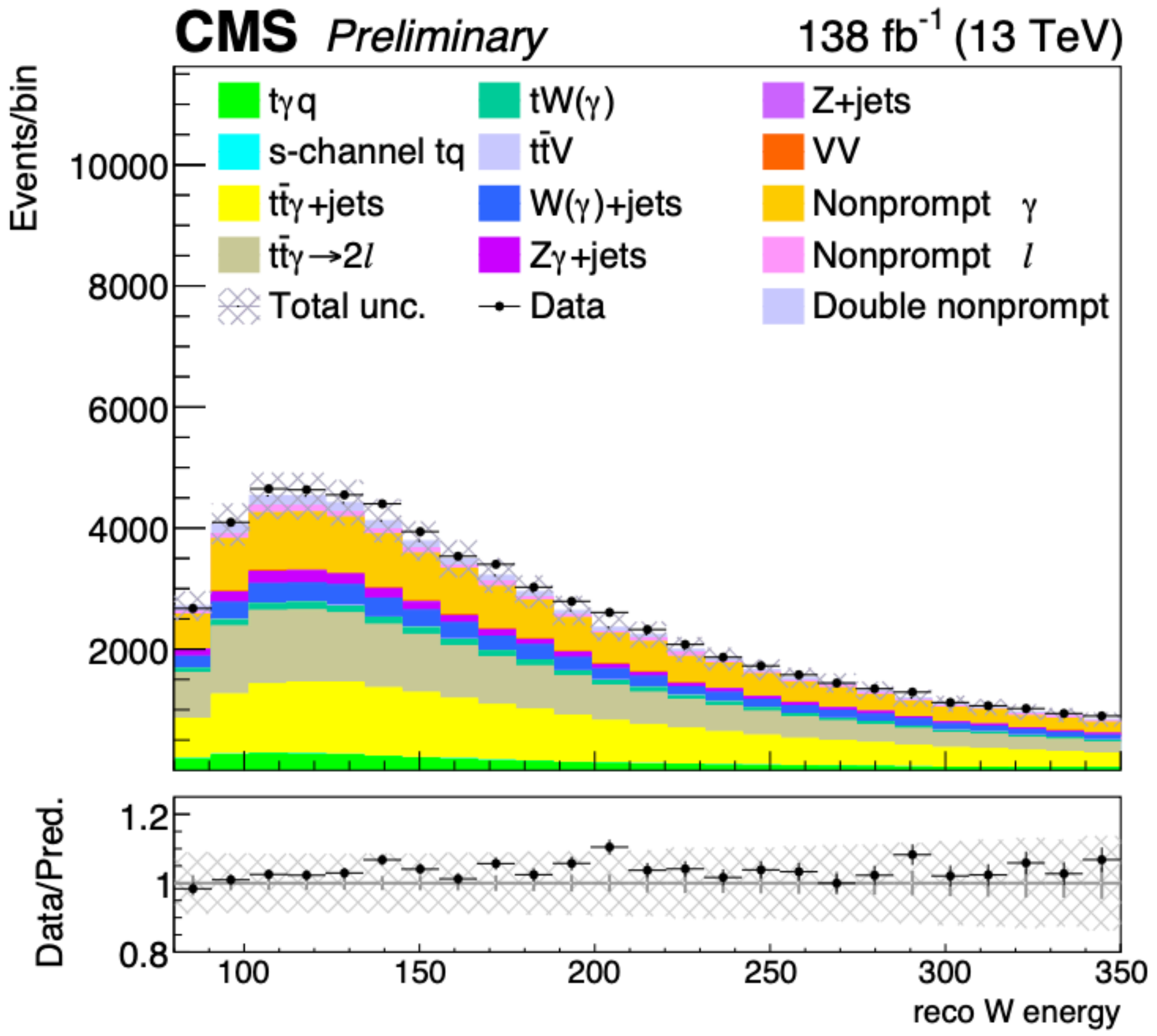












Theoretical systematics

- Renormalisation and factorisation
- PDF → splited
- PDF α_s (if provided)
- Parton shower (FSR, ISR)

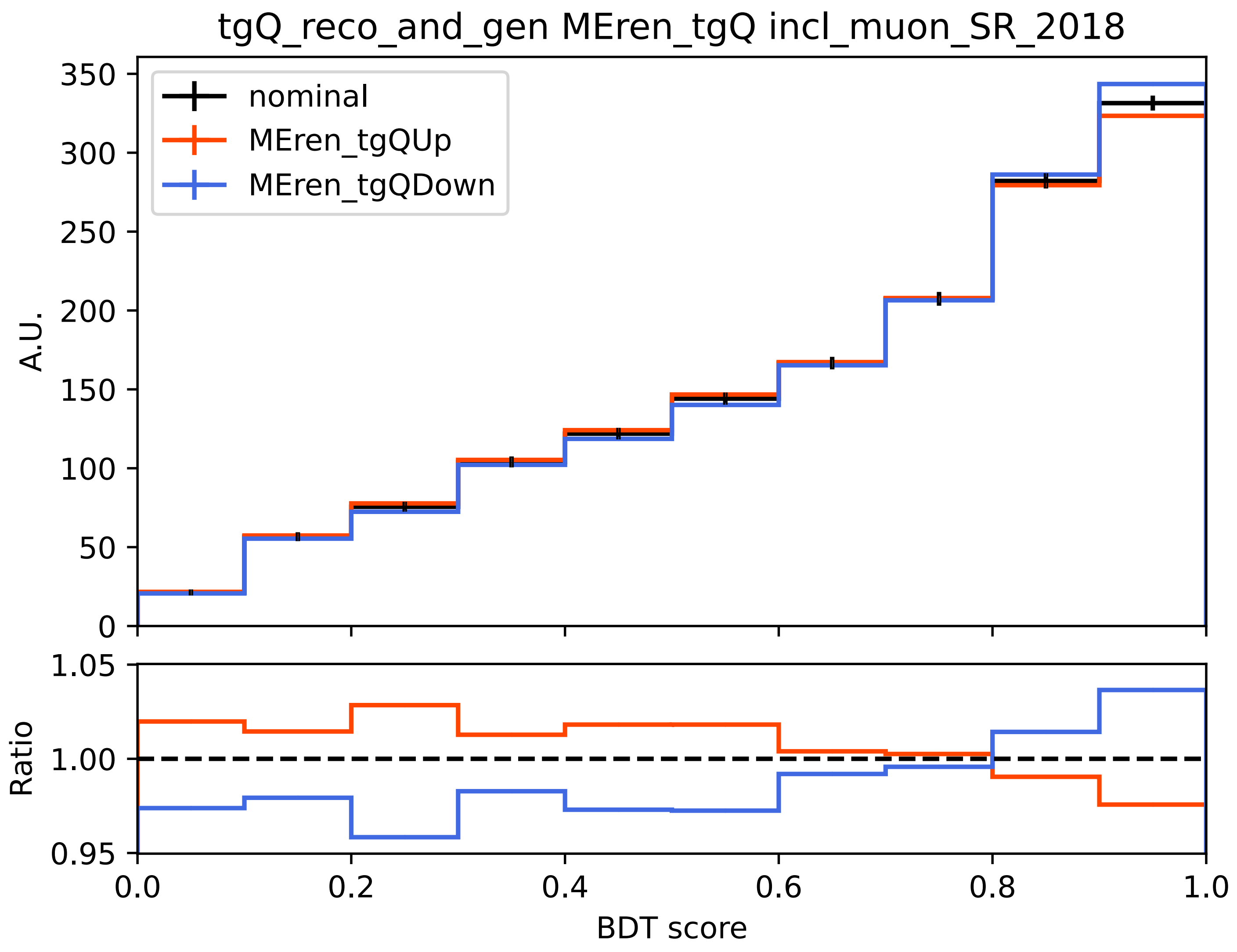
→ *Normalization effect removed*

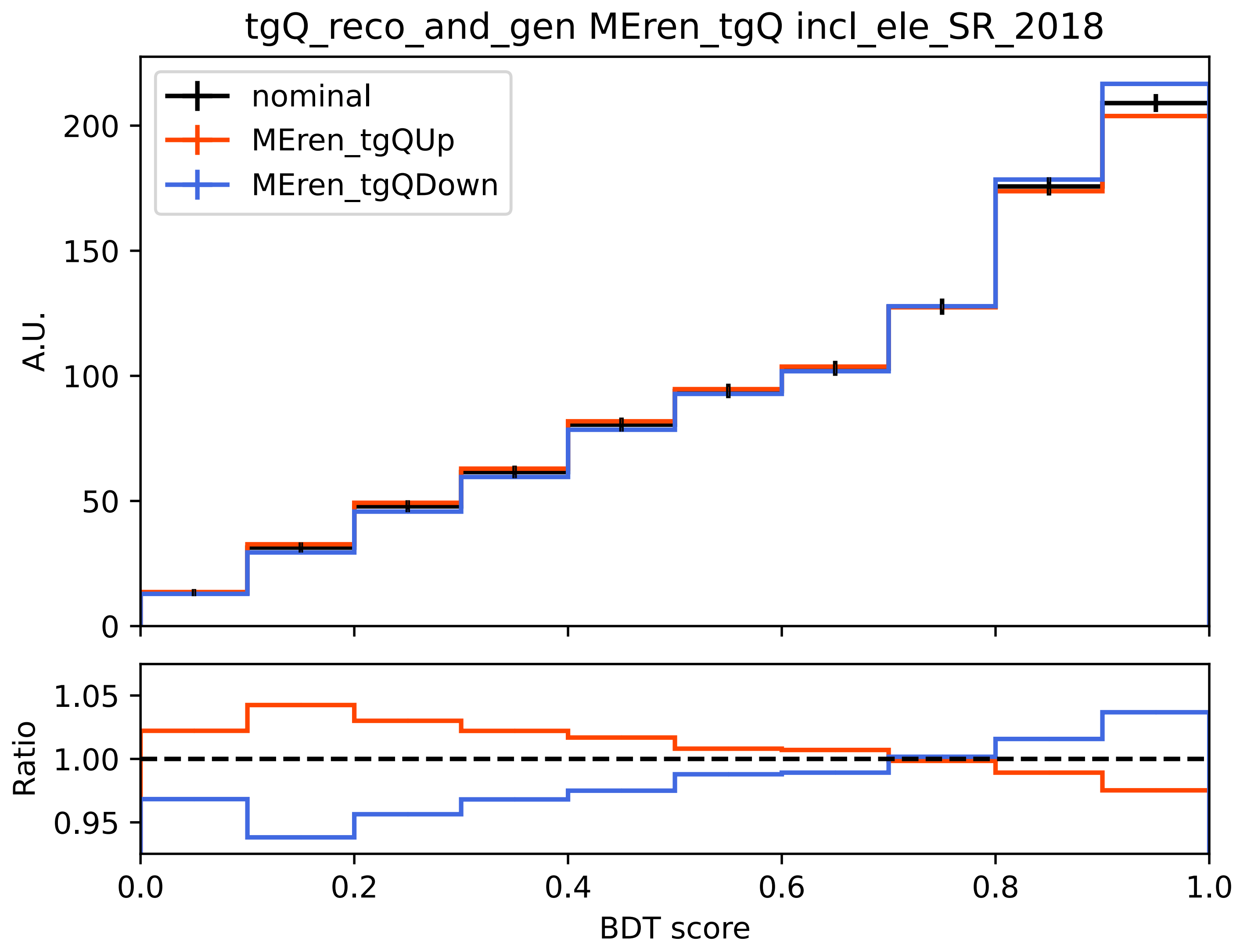
- Uncertainty on fraction of production and decay photons for tγq and ttγ signals

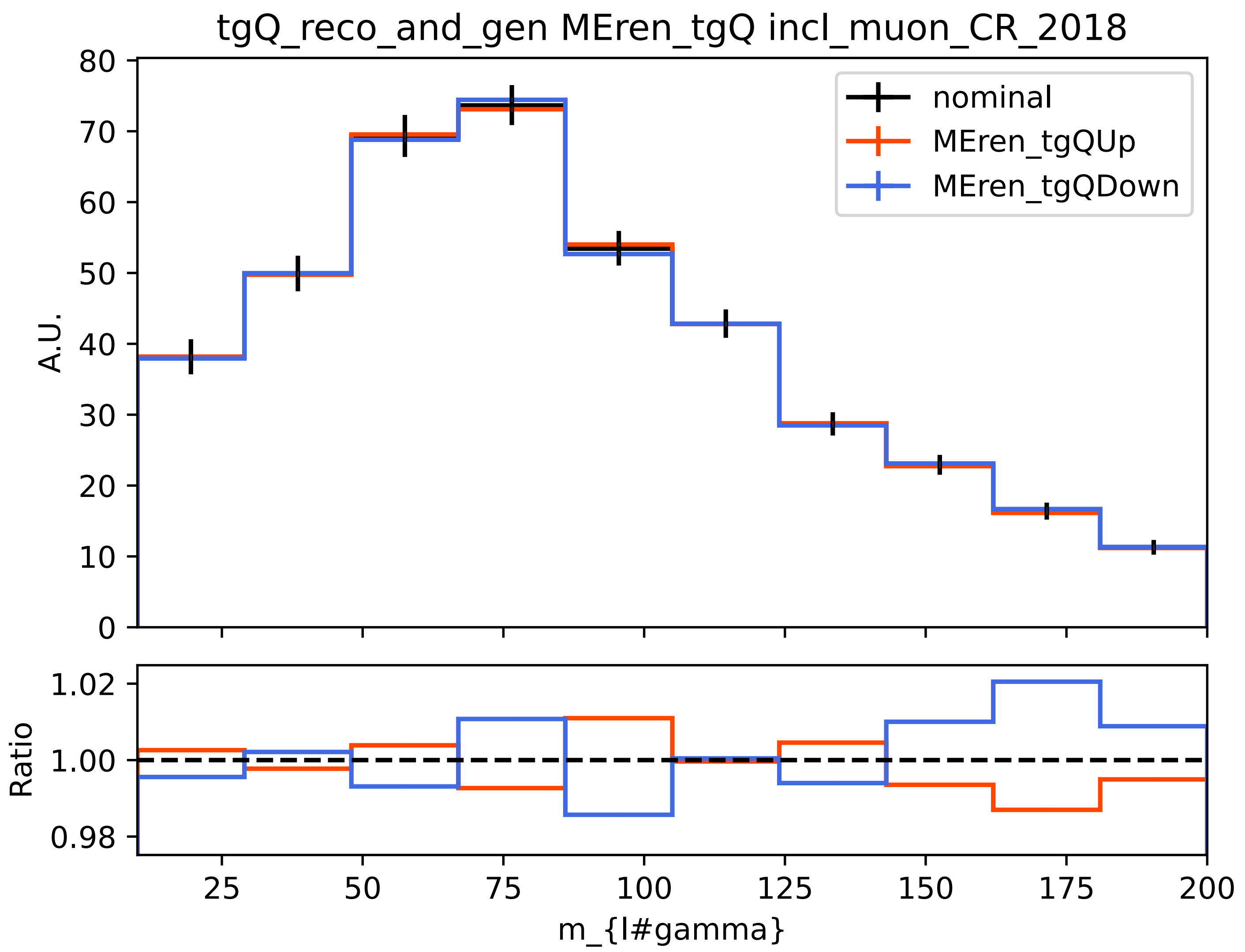
  Documented in AN v7 Sec 8.3.1

Update after pre-approval talk

- Cross sections for minor backgrounds → VV, ttV, etc.
  - When the lnN XS uncertainty considered, the above theoretical uncertainty is not applied







Experimental systematics

- Luminosity
- PU
- L1 pre-firing (2016 and 2017) → split to Muon and ECAL parts
- Lepton ID/ISO/reco/HLT
- Photon ID/veto scale factors → photon ID split to syst. (rate+shape) and stat. parts
- Pileup Jet ID/Btagging SFs
- Jet energy scale and resolution → split JES (LOWESS smooth for some of them)
- Uncluster MET energy
- Nonprompt photon → *introduce next slide*
- Nonprompt lepton → *introduce next slide*
- Shape uncertainty on jet multiplicity → *introduce next slide*
- **rateParam for ele misID**

Update after pre-approval talk

Experimental systematics — Nonprompt data-driven

$$n^{\mathrm{SR}}_{\mathrm{nonprompt}\,\gamma} = \sum_{\mathrm{ij}} (\mathrm{data}^{\mathrm{ij}}_{\mathrm{B}} \times \mathrm{fake\ rate}^{\mathrm{ij}}_{\gamma} \times k^{\mathrm{ij}}_{\mathrm{MC}}) - \sum_{\mathrm{ij}} ((\mathrm{prompt} + \mathrm{ele\ mis.})\,\gamma\,\mathrm{MC}^{\mathrm{ij}}_{\mathrm{B}} \times \mathrm{fake\ rate}^{\mathrm{ij}}_{\gamma} \times k^{\mathrm{ij}}_{\mathrm{MC}})$$

$$n^{\mathrm{SR}}_{\mathrm{nonprompt}\,\ell} = \sum_{\mathrm{ij}} (\mathrm{data}^{\mathrm{ij}}_{\mathrm{CR}} \times \mathrm{fake\ rate}_{\ell}) - \sum_{\mathrm{ij}} (\mathrm{prompt}\ \ell\ \mathrm{MC}^{\mathrm{ij}}_{\mathrm{CR}} \times \mathrm{fake\ rate}_{\ell})$$

$$n^{\mathrm{SR}}_{\mathrm{double\ nonprompt}} = \sum_{\mathrm{ij}} (\mathrm{data}^{\mathrm{ij}}_{\mathrm{double\ CR}} \times \mathrm{fake\ rate}_{\ell} \times \mathrm{fake\ rate}_{\gamma} \times k_{\mathrm{MC}}) - \sum_{\mathrm{ij}} (\mathrm{prompt}\ \ell\gamma\ \mathrm{MC}^{\mathrm{ij}}_{\mathrm{double\ CR}} \times \mathrm{fake\ rate}_{\ell} \times \mathrm{fake\ rate}_{\gamma} \times k_{\mathrm{MC}})$$

We consider the following uncertainties for nonprompt data-driven:

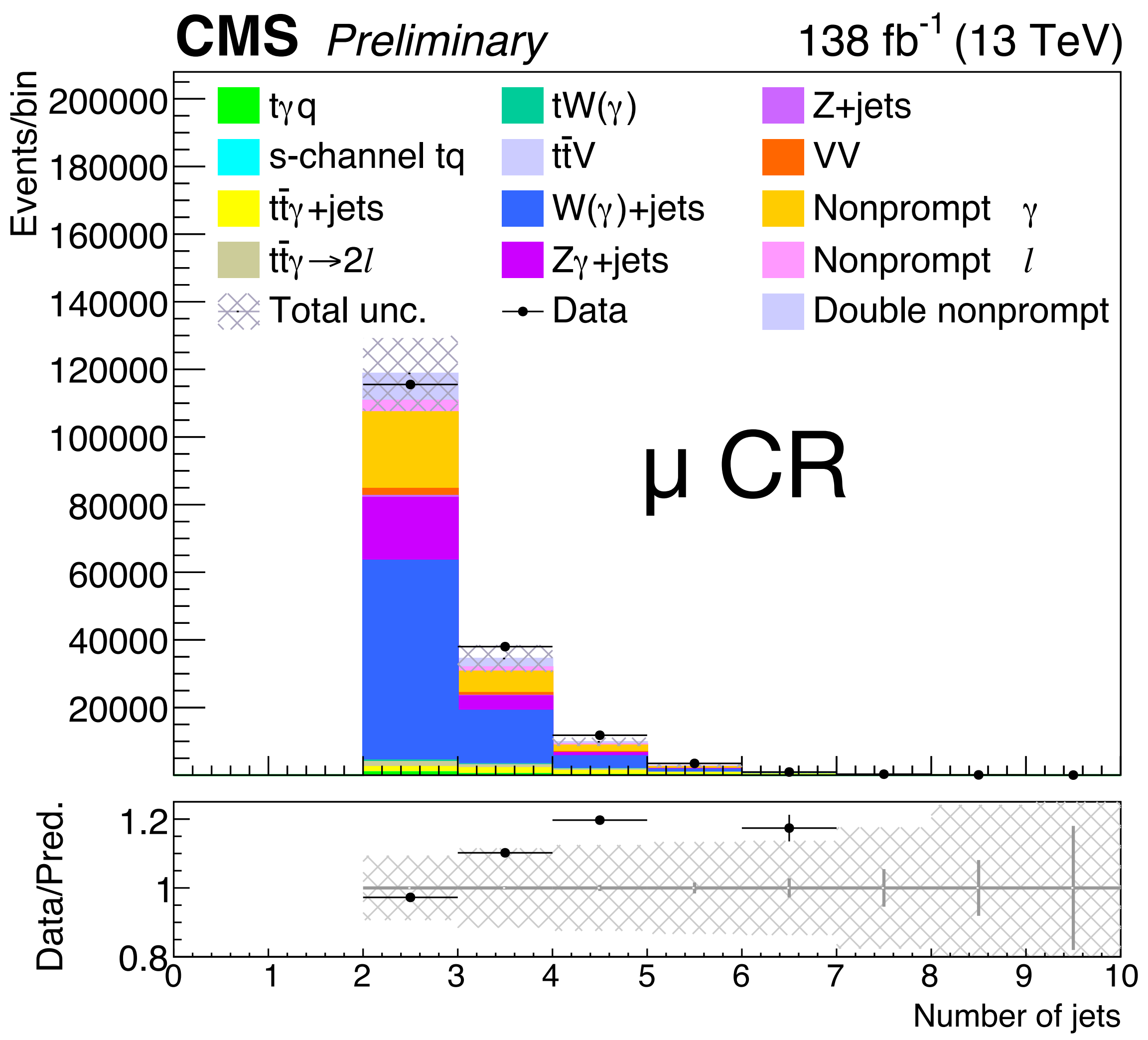
- Fake rate calculated in different sideband region → difference to nominal as uncertainty
- Fake rate calculated in different η binning → difference to nominal as uncertainty
- Prompt subtraction with variation of 10%
- k_{MC} factor uncertainty by comparing values in data and MC → for nonprompt γ and double nonprompt

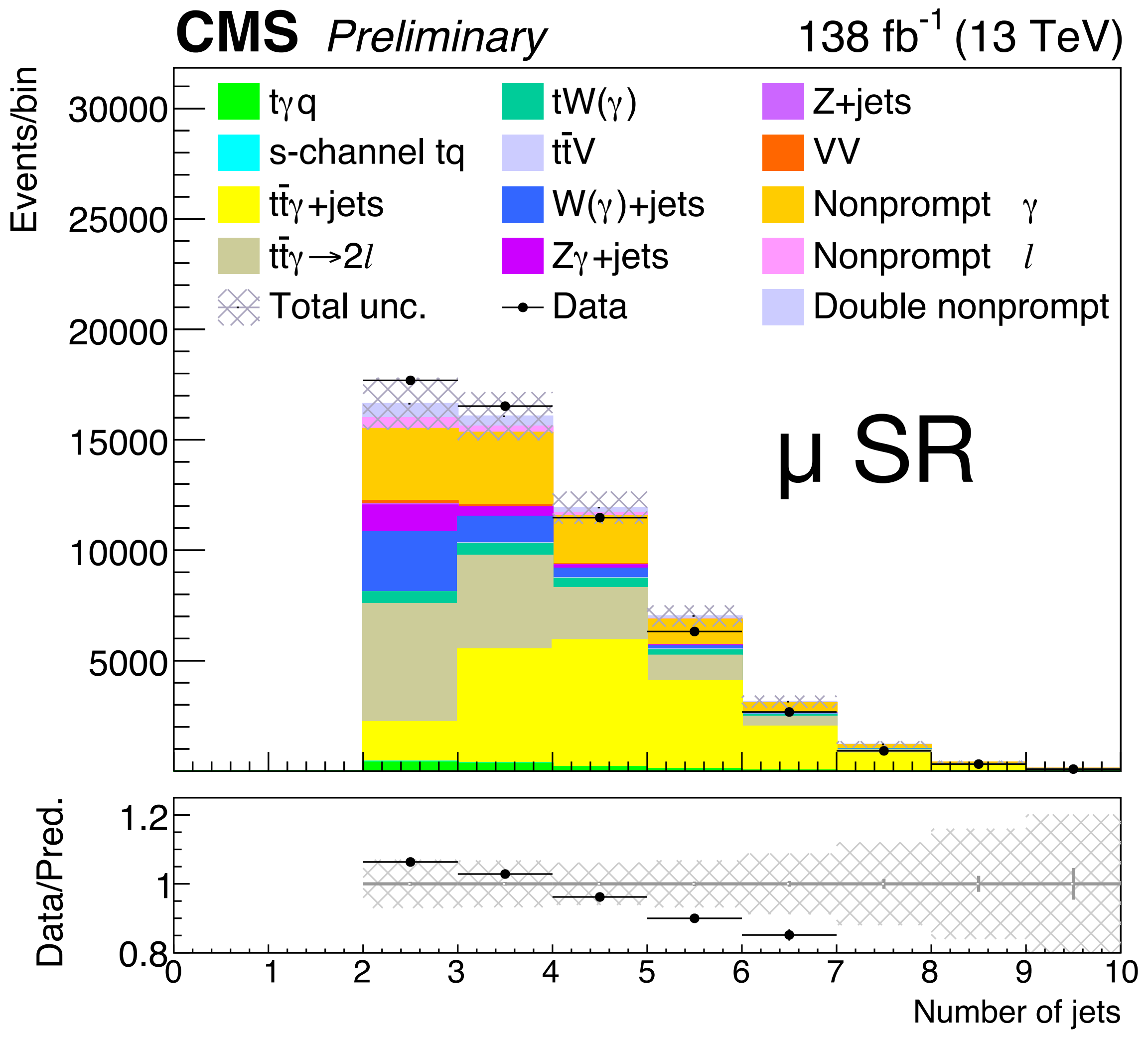
Update after pre-approval talk

Experimental systematics — shape uncertainty on N_{jets}

Update after pre-approval talk

Without N_{jets} shape uncertainty applied

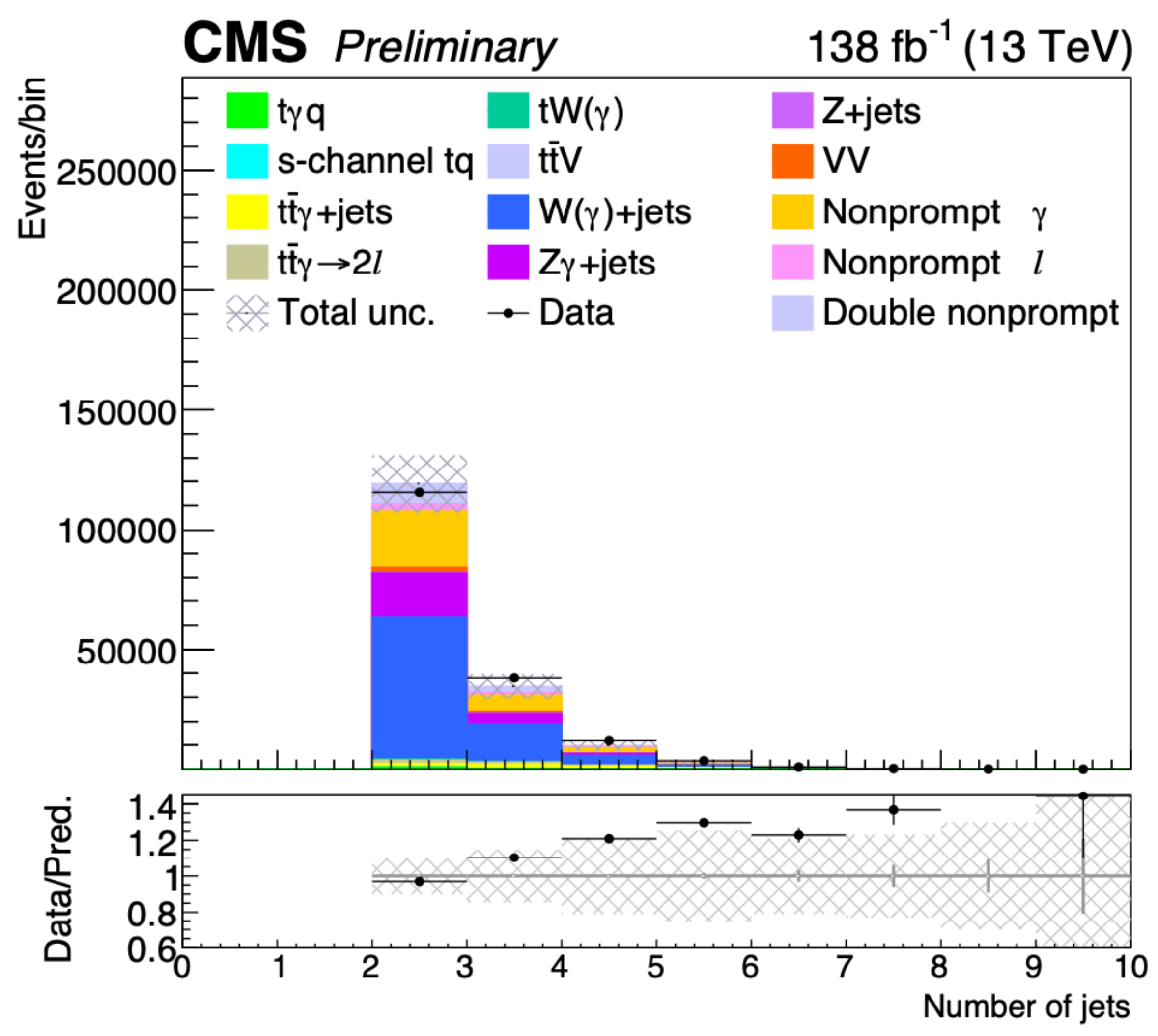


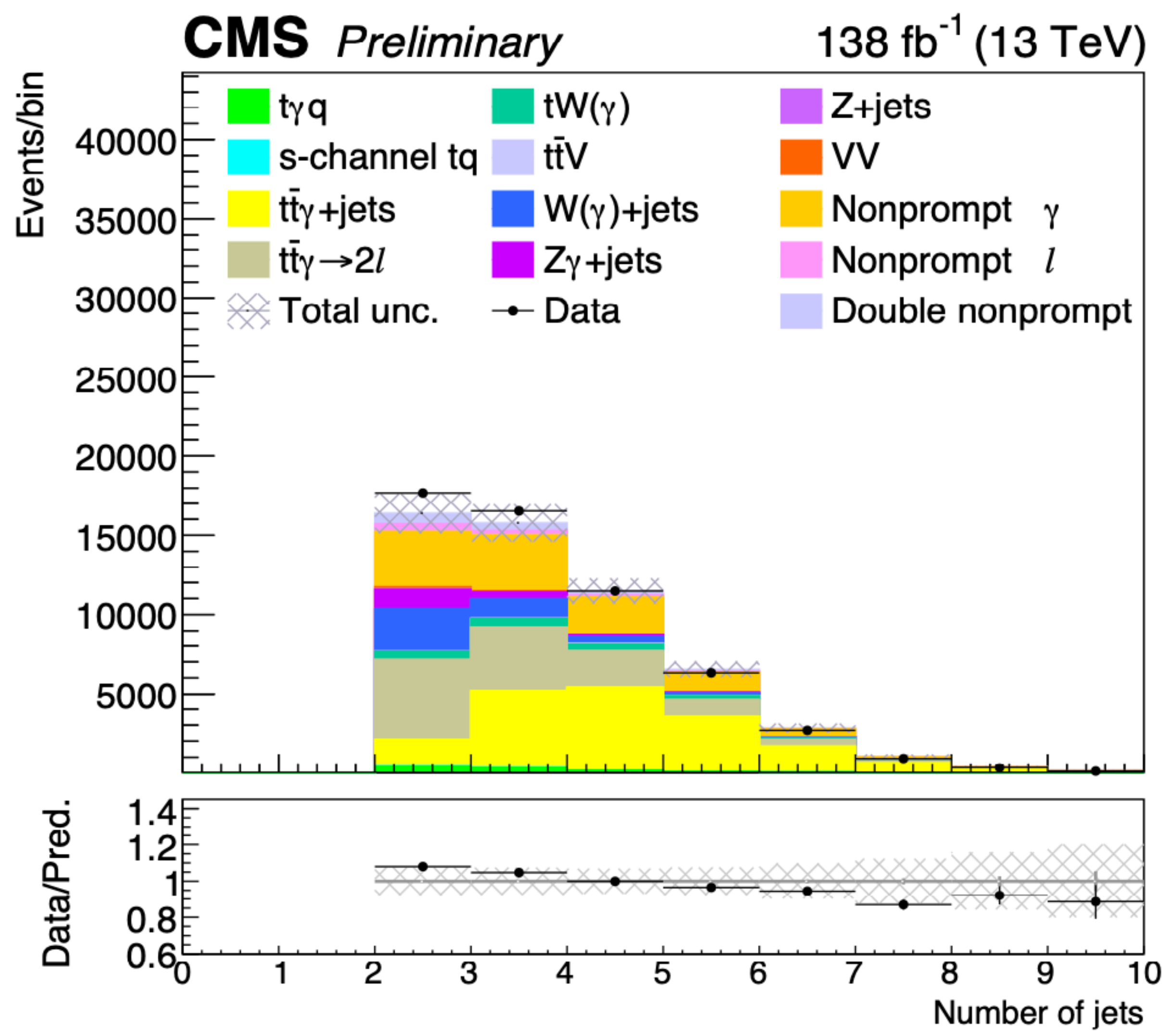


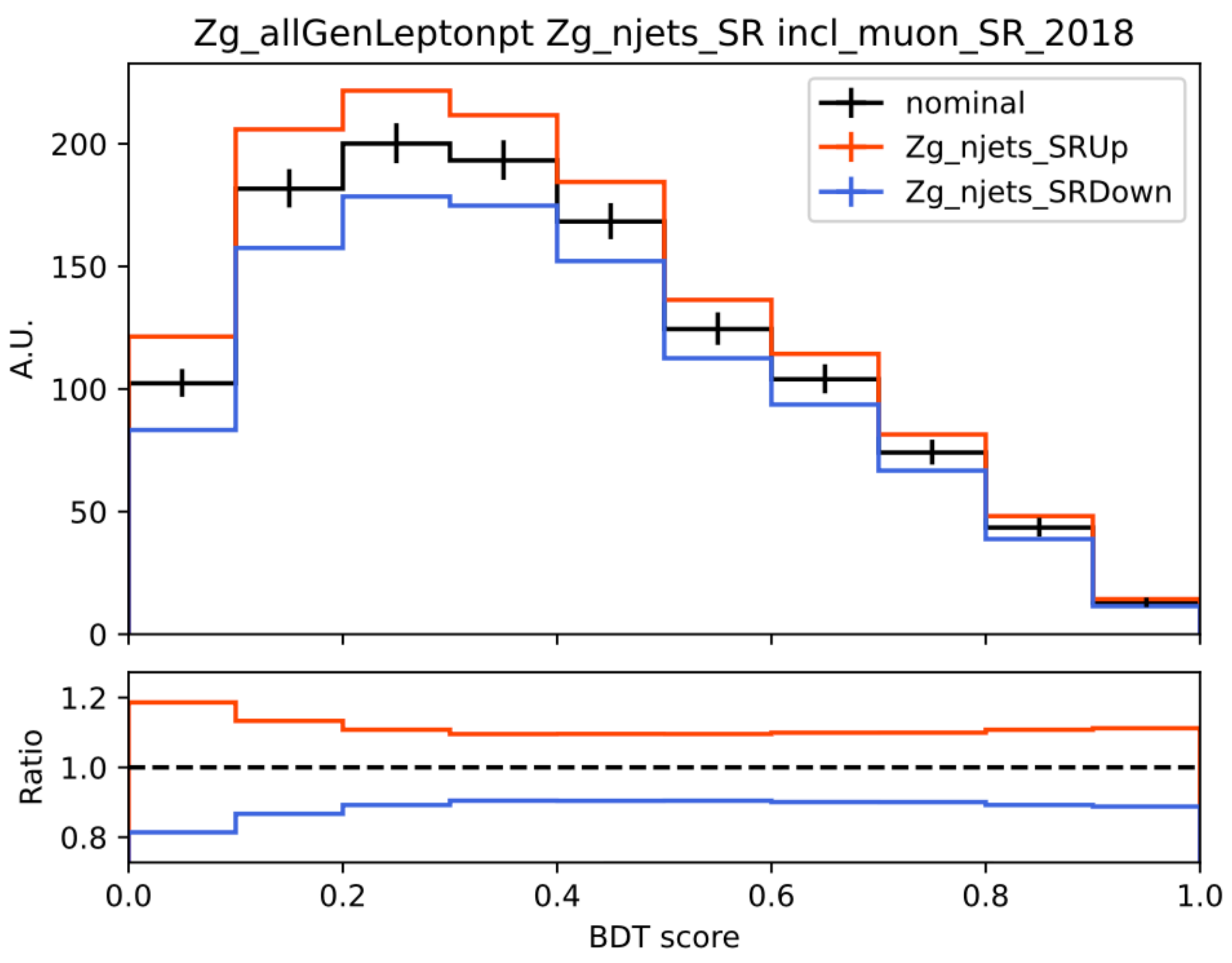
- This uncertainty consideration is triggered by different Data/Pred. trend in CR and SR
- Uncertainty on jet multiplicity from Zγ and Wγ for muon channel, Z+jets included for electron channel

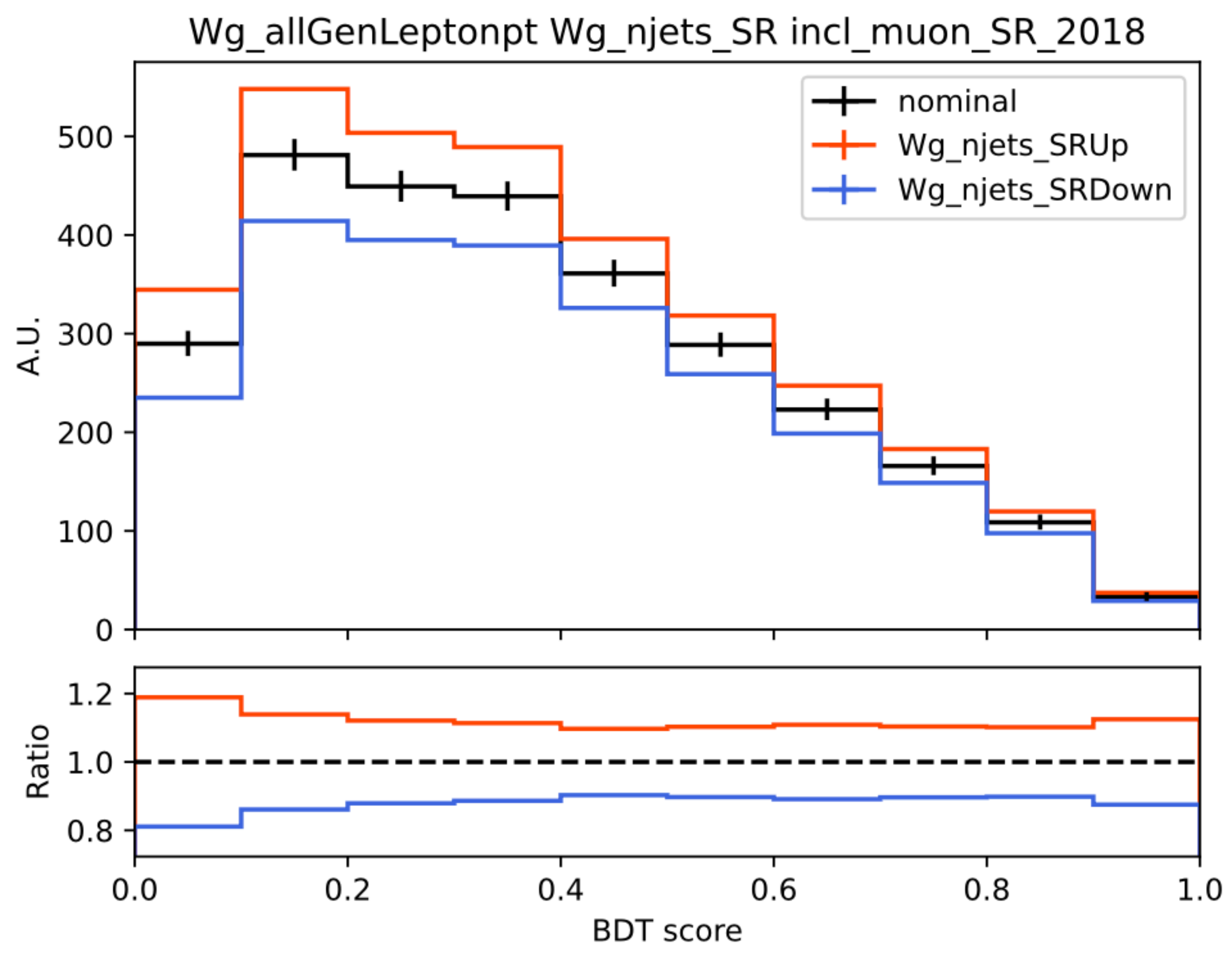
1. Calculate symmetric variations by using the sum of Wγ and Zγ (Z+jets) that the +1σ variation in the sum of Wγ and Zγ (Z+jets) can cover the data and prediction disagreement
2. The uncertainties are calculated as a function of jet multiplicity distribution in the binning of [2, 3, 4, 5, 6, ∞]
3. The same uncertainties calculated in the b-veto CR are applied to the SR

With N_{jets} shape uncertainty applied









Simultaneous inclusive fit

- Perform a simultaneous fit for events in the **signal** and **b-veto control regions**

Update after pre-approval talk

  - The signal region uses the unrolled 2D distribution of BDT score and $\Delta R(\ell, \gamma)$ → 5 bins from 0 to 1 and [0.4, 1.2, 2.0, 2.8, ∞]
  - The control region uses the $m_{\ell\gamma}$ distribution → 10 bins from 10 to 200 GeV (overflow included)
- POIs are signal strengths of $t\gamma$q and $t\bar{t}\gamma$
  - *Signal events out of fiducial are regarded as backgrounds but have same uncertainties as the real signal events*
- All systematic uncertainties are considered

Table 1: A summary of the selection used in different regions.

CR	SR	Fiducial region
Pass the single lepton HLT		X
At least one good PV		X
$N^{\text{reco}}_{\text{loose}\,\ell} = 1$ ($p^{\ell}_{\text{T}} > 10\,\text{GeV}$)		$N^{\text{gen}}_{\ell} = 1$
$N^{\text{reco}}_{\gamma} \geq 1$		$N^{\text{gen}}_{\gamma} = 1$
$N^{\text{reco}}_{\text{jets}} \geq 2$		$N^{\text{gen}}_{\text{jets}} \geq 2$
$p^{\ell}_{\text{T}} > 30\,(35)\,\text{GeV}$ and $\lvert\eta\rvert < 2.4\,(2.5)$		
$p^{\gamma}_{\text{T}} > 20\,\text{GeV}$ and $\lvert\eta\rvert < 2.5$		
$p^{\text{j}}_{\text{T}} > 30\,\text{GeV}$ and $\lvert\eta\rvert < 4.7$		
$\Delta R(\ell,\gamma) > 0.4$, $\Delta R(\ell,\text{jets}) > 0.4$		
$\Delta R(\gamma,\text{jets}) > 0.4$		$\Delta R(\gamma,\text{jets}) > 0.1$
$N_{\text{bjets}} = 0$	$N_{\text{bjets}} \geq 1$	X
$p^{\text{miss}}_{\text{T}} > 20\,\text{GeV}$		X

$$\mu^{\text{exp.}}_{\text{t}\gamma\text{q}} = 1.00^{+0.080}_{-0.078} = 1.00^{+0.067}_{-0.065}\,(\text{syst})\;^{+0.044}_{-0.044}\,(\text{stat}),$$

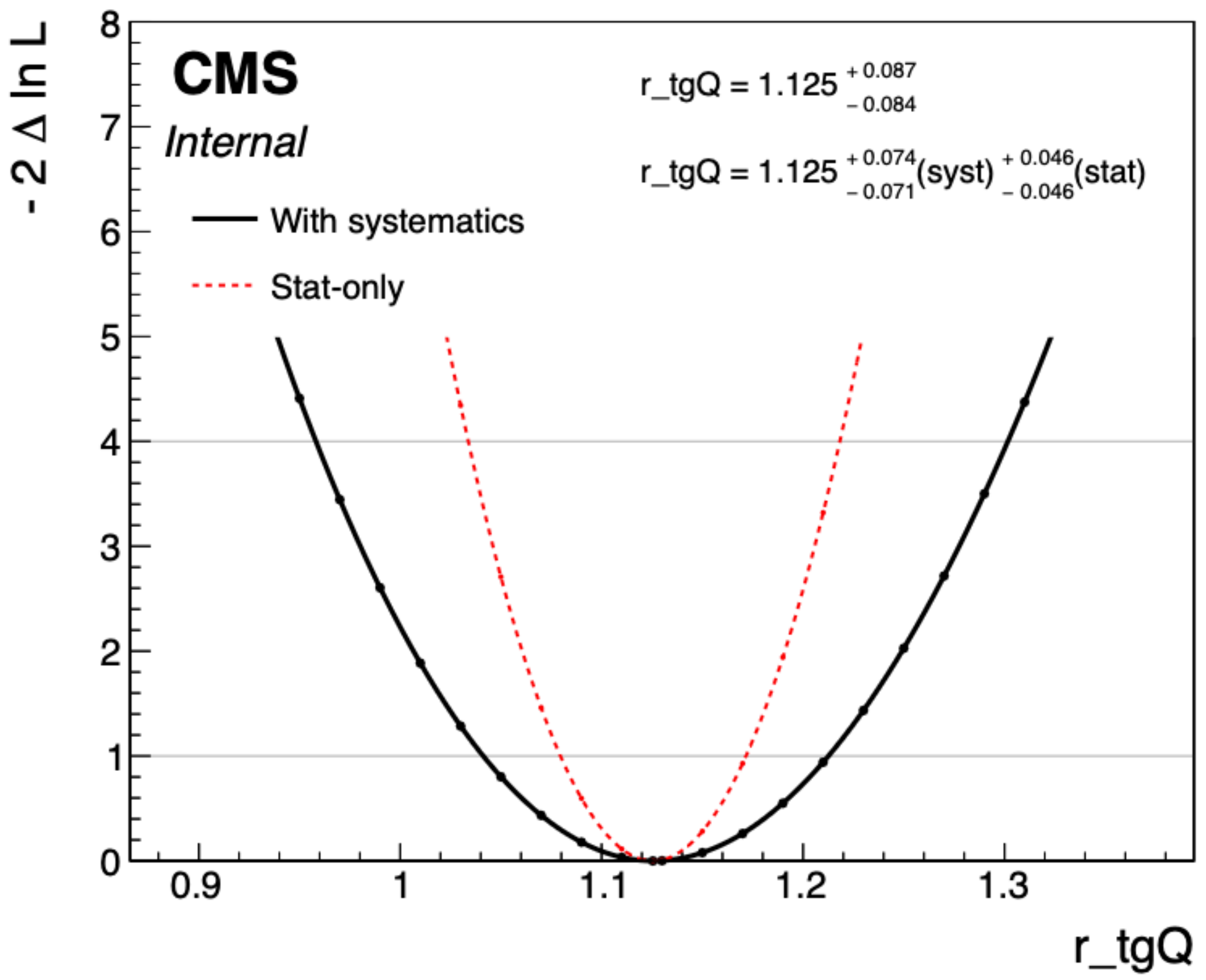
$$\mu^{\text{exp.}}_{\text{t}\bar{\text{t}}\gamma} = 1.00^{+0.061}_{-0.059} = 1.00^{+0.058}_{-0.056}\,(\text{syst})\;^{+0.021}_{-0.021}\,(\text{stat})$$

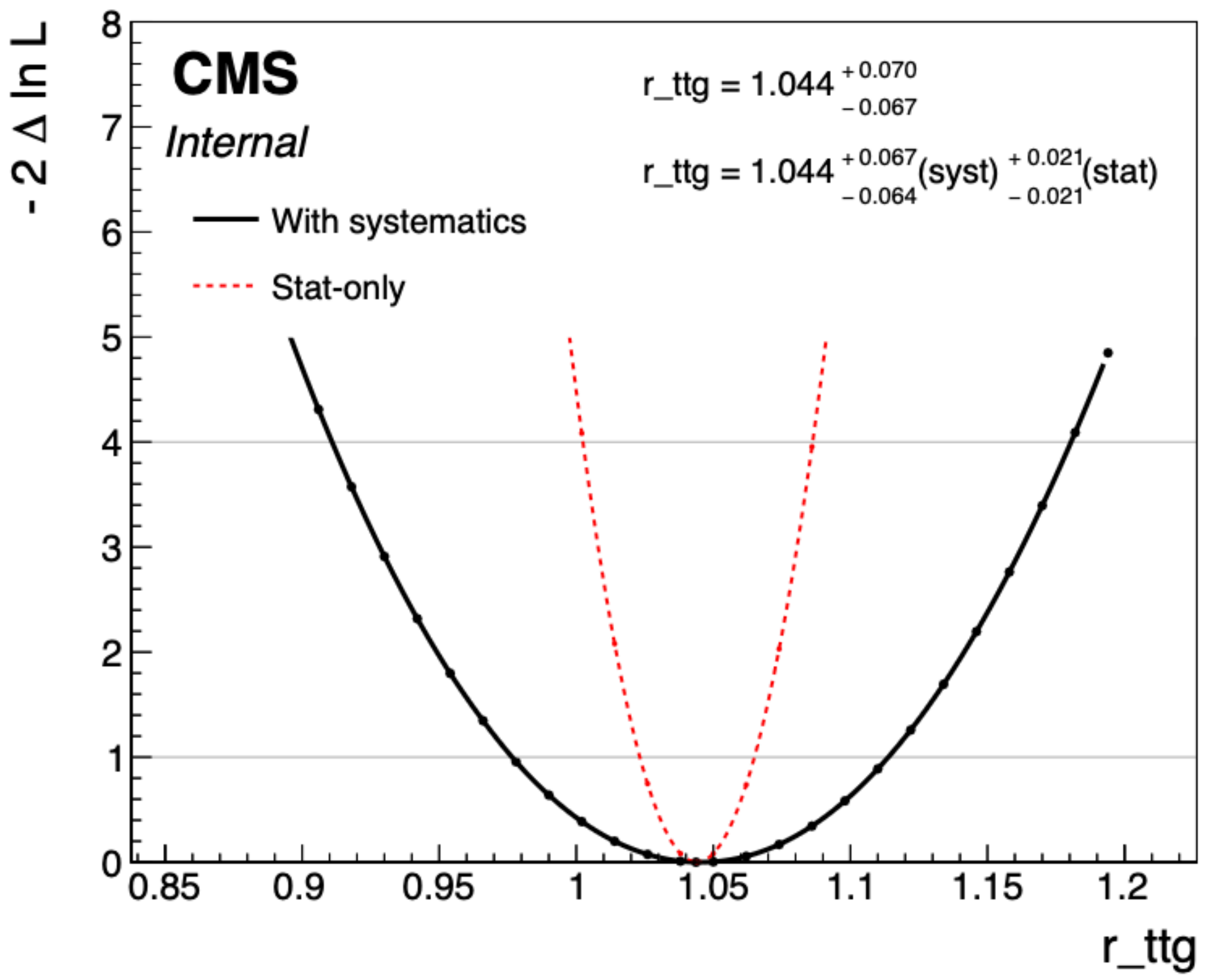
$$\mu^{\text{obs.}}_{\text{t}\gamma\text{q}} = 1.125^{+0.087}_{-0.084} = 1.125^{+0.074}_{-0.071}\,(\text{syst})\;^{+0.046}_{-0.046}\,(\text{stat}),$$

$$\mu^{\text{obs.}}_{\text{t}\bar{\text{t}}\gamma} = 1.044^{+0.070}_{-0.067} = 1.07^{+0.067}_{-0.064}\,(\text{syst})\;^{+0.021}_{-0.021}\,(\text{stat})$$

$$\sigma^{\text{mea.}}_{\text{tot.}\,\text{t}\gamma\text{q}} = \hat{\mu}_{\text{t}\gamma\text{q}} \times \sigma^{\text{fid}}_{\text{tot.}\,\text{t}\gamma\text{q}} = 233.51^{+18.1}_{-17.4}\ \text{fb}$$

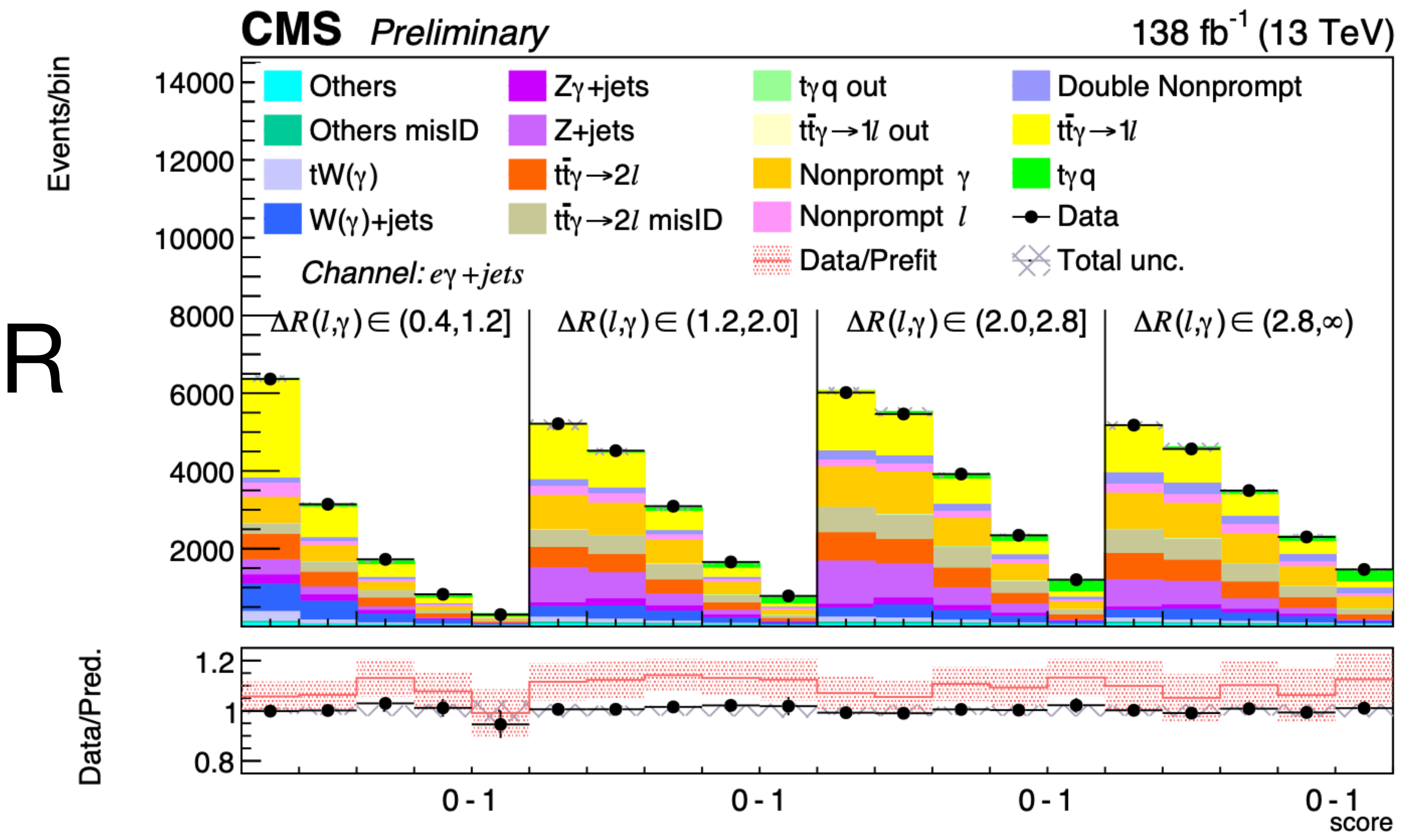
$$\sigma^{\text{mea.}}_{\text{tot.}\,\text{t}\bar{\text{t}}\gamma} = \hat{\mu}_{\text{t}\bar{\text{t}}\gamma} \times \sigma^{\text{fid}}_{\text{tot.}\,\text{t}\bar{\text{t}}\gamma} = 1430.18^{+95.89}_{-91.78}\ \text{fb}$$

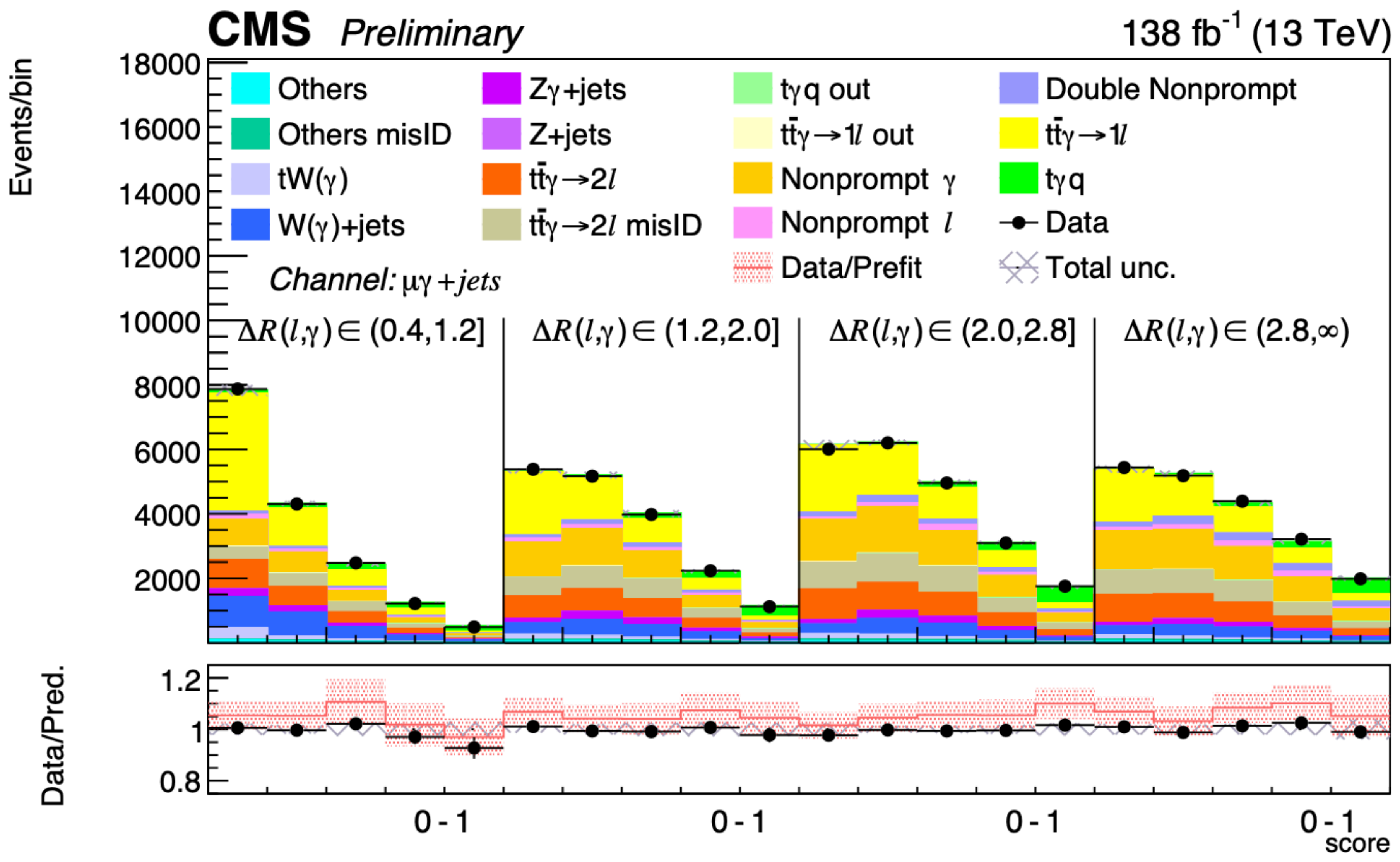




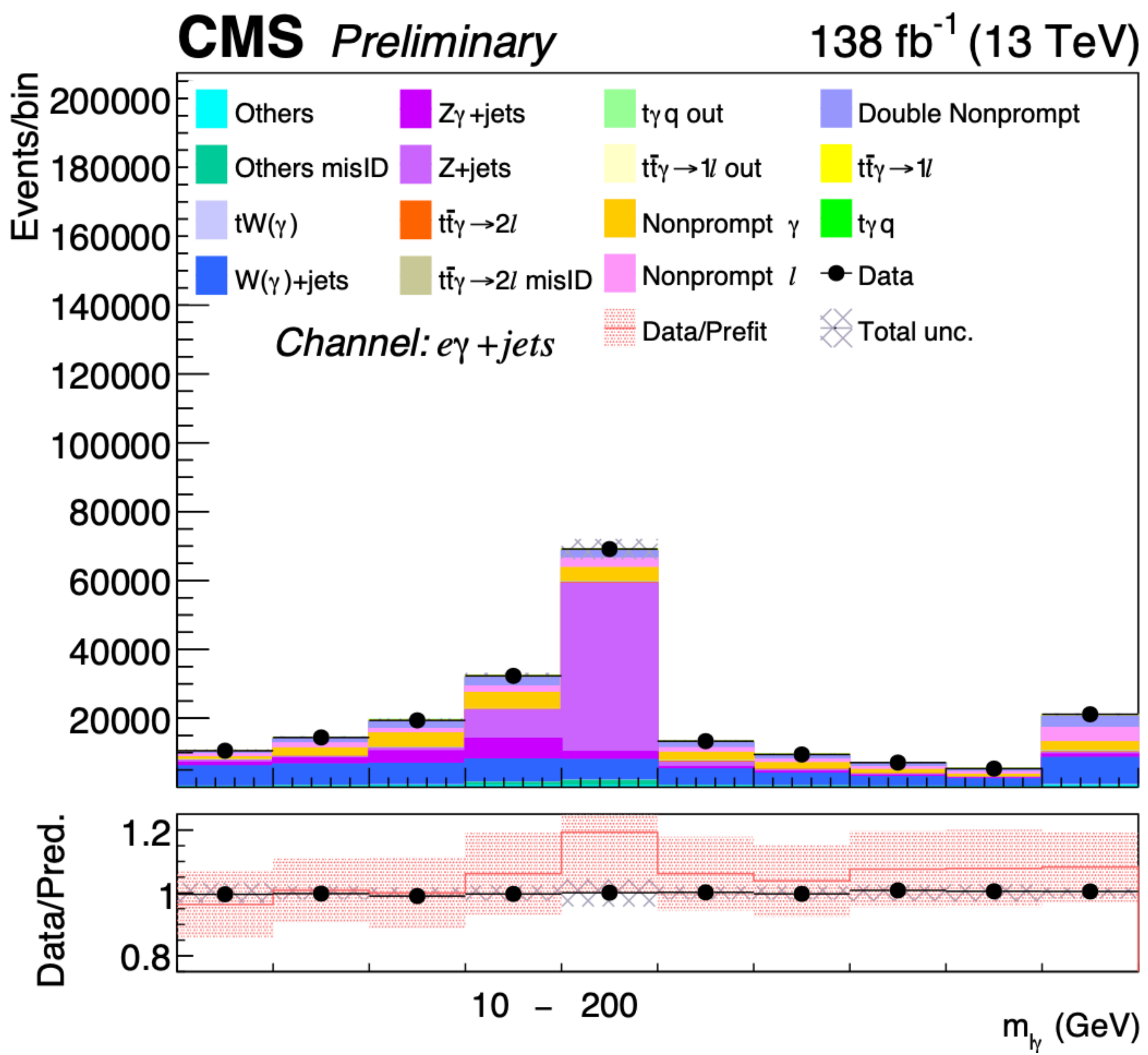
Simultaneous inclusive fit

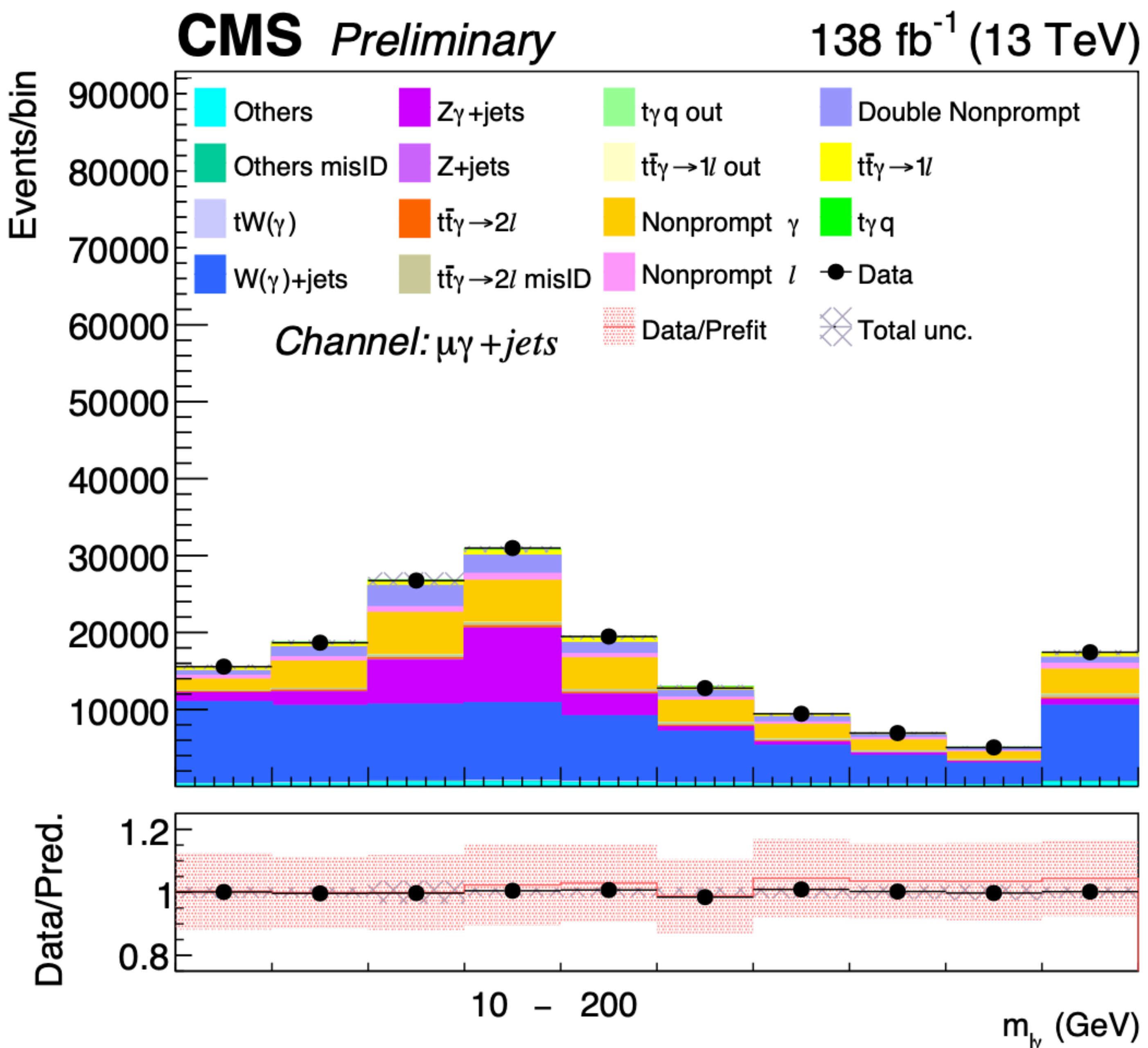
Post-fit SR



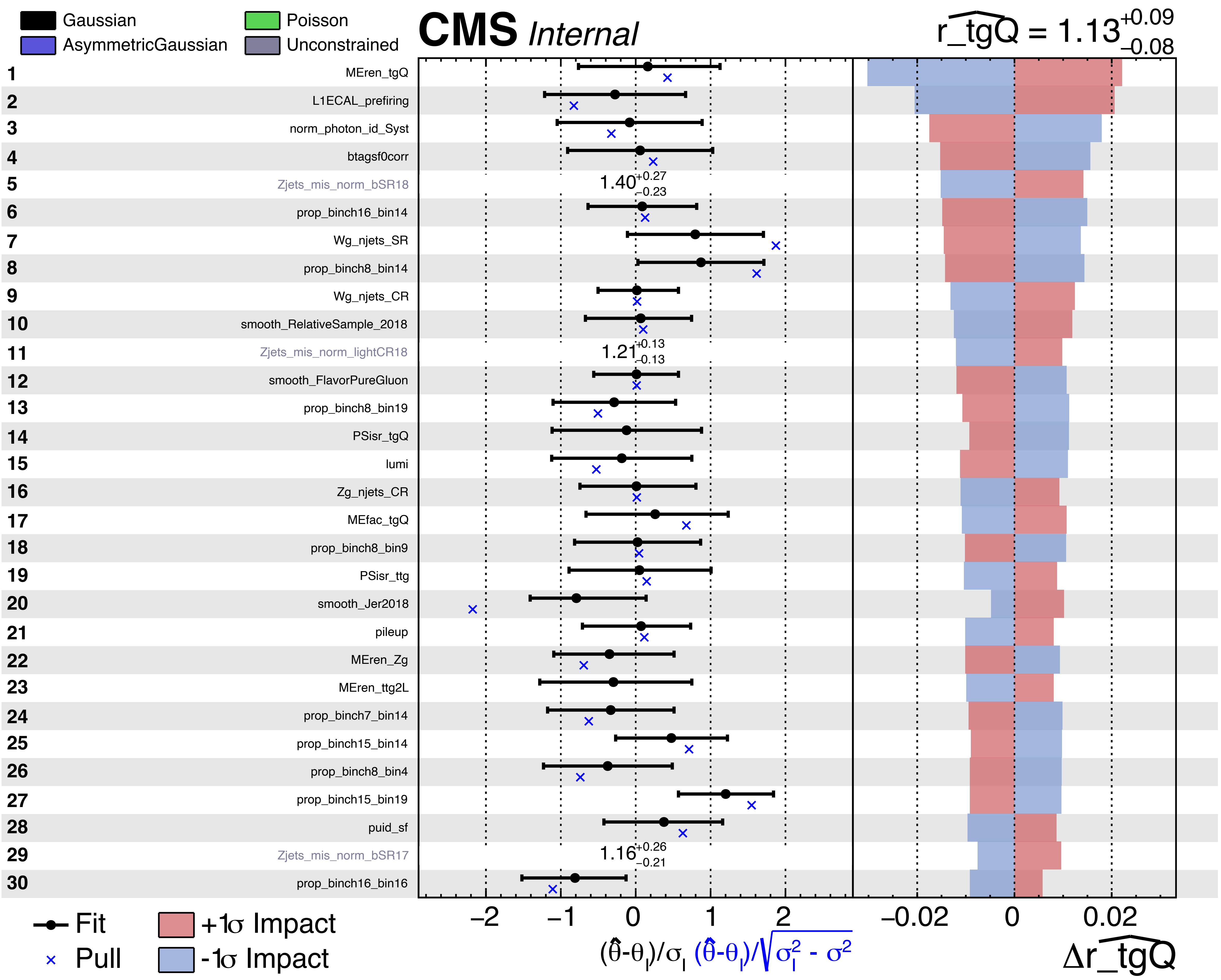


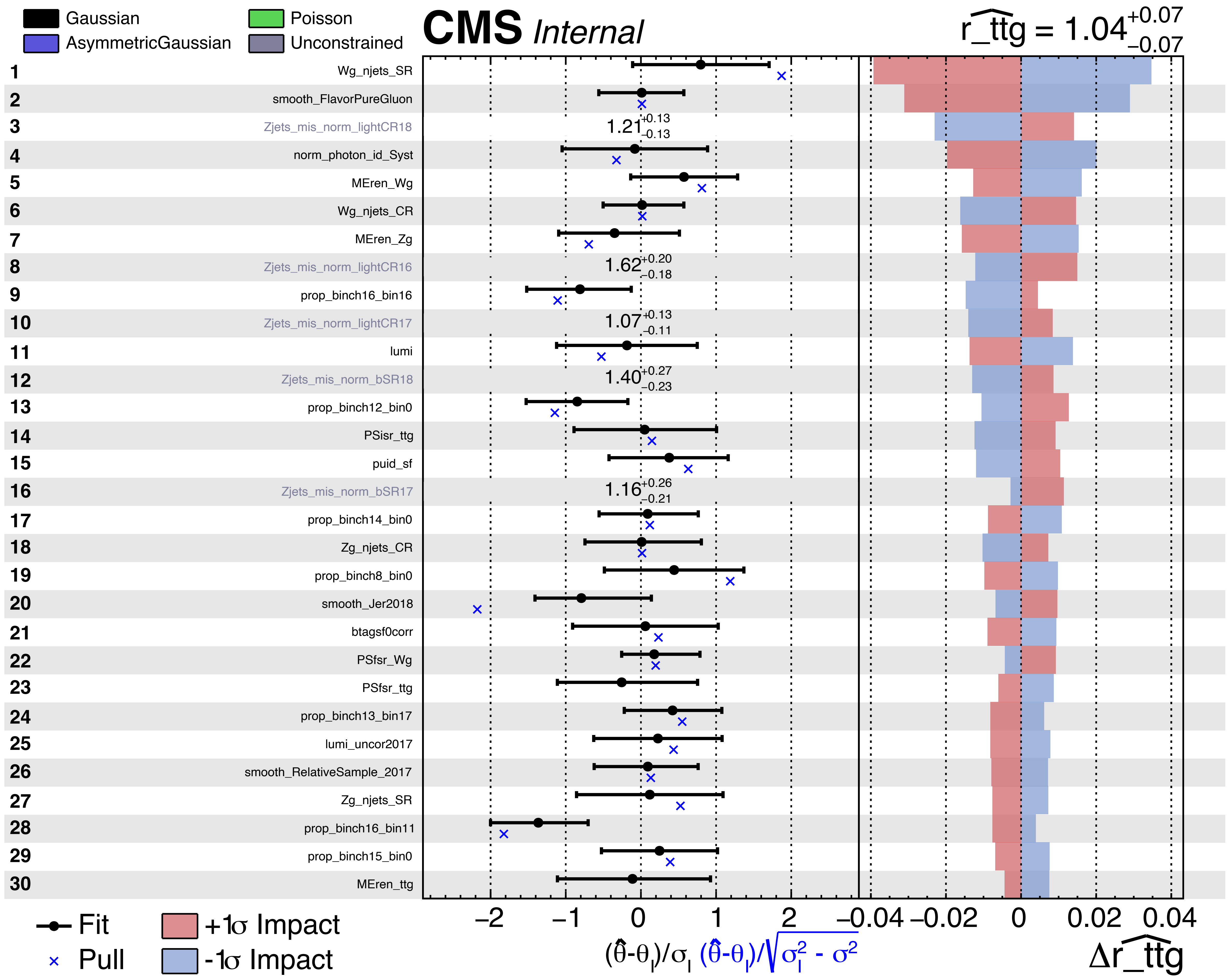
Post-fit CR





Simultaneous inclusive fit — impact plots

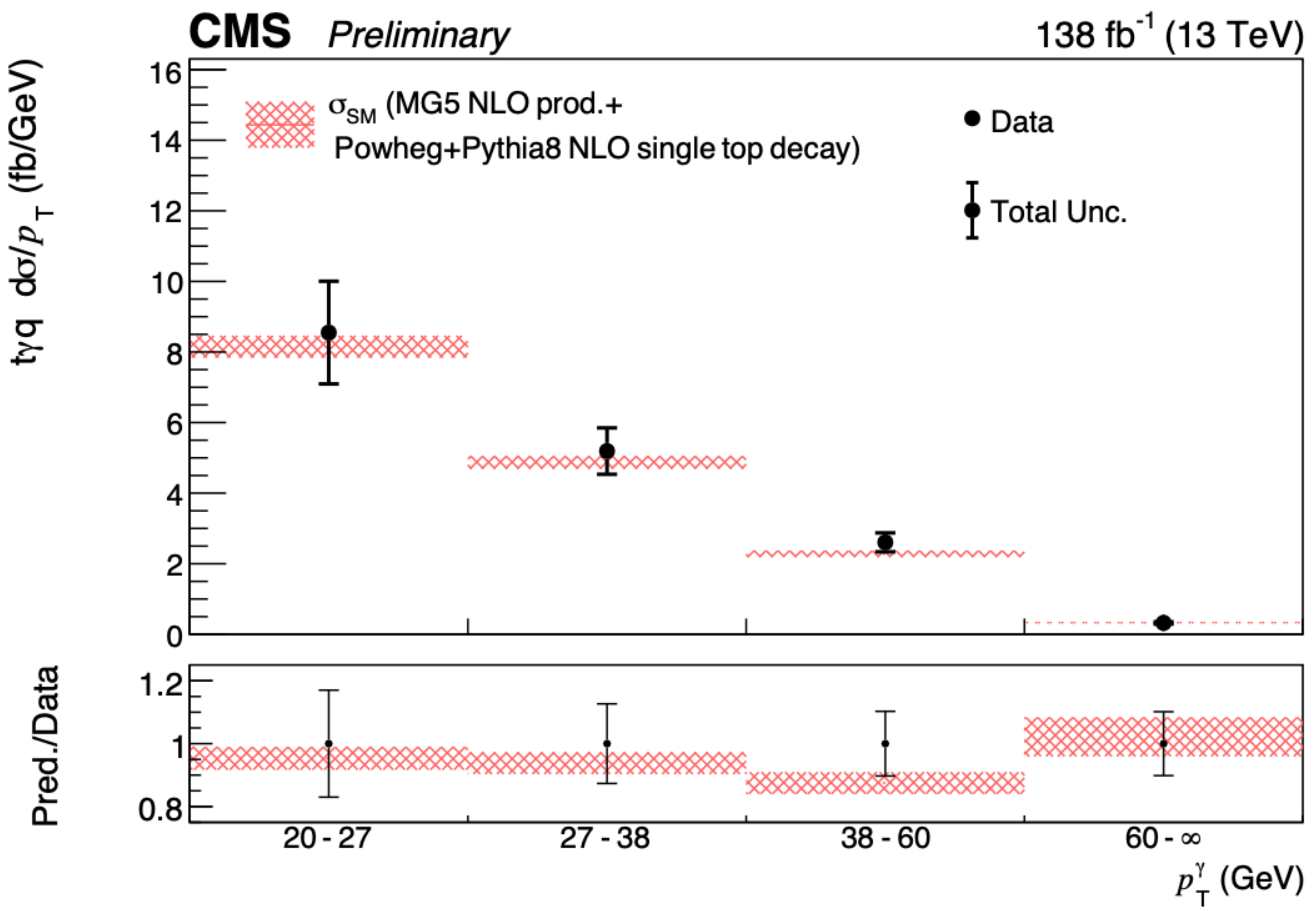


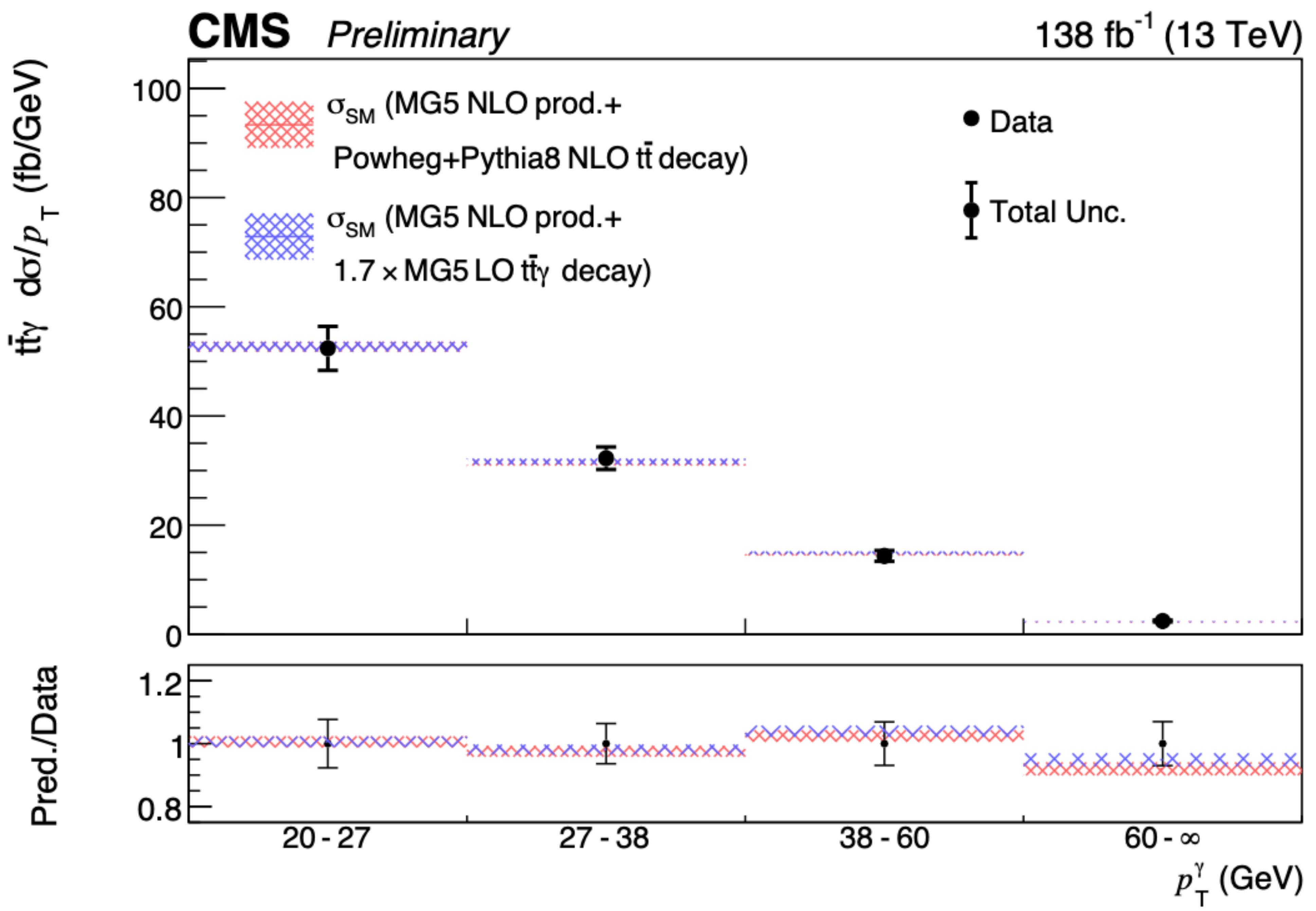


Simultanesous differential fit

- Maximum-likelihood unfolding using BDT in different reconstructed variables bins
- Other setups are same as the inclusive fit
- Photon p_T, lepton p_T, $m_{\ell\gamma}$, <u>$\Delta R(\ell,\gamma)$, $\eta_{light\ j}$, N_{jets}</u> are measured at particle level
- <u>$\Delta R(t_\ell,\gamma)$ and leptonic top quark charge</u> are measured at parton level
- Very diagonal response matrix, no regularisation needed

Update after pre-approval talk



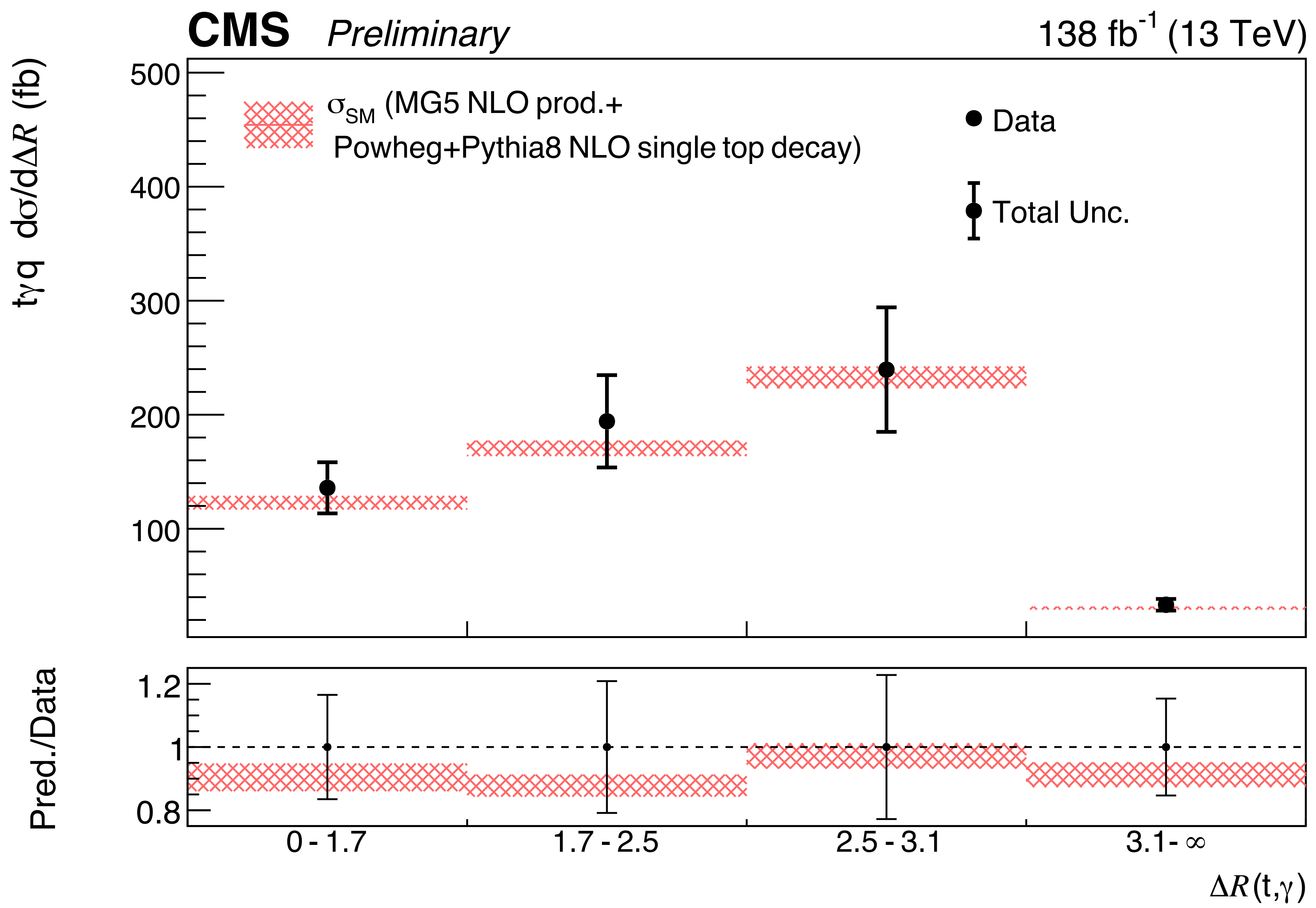


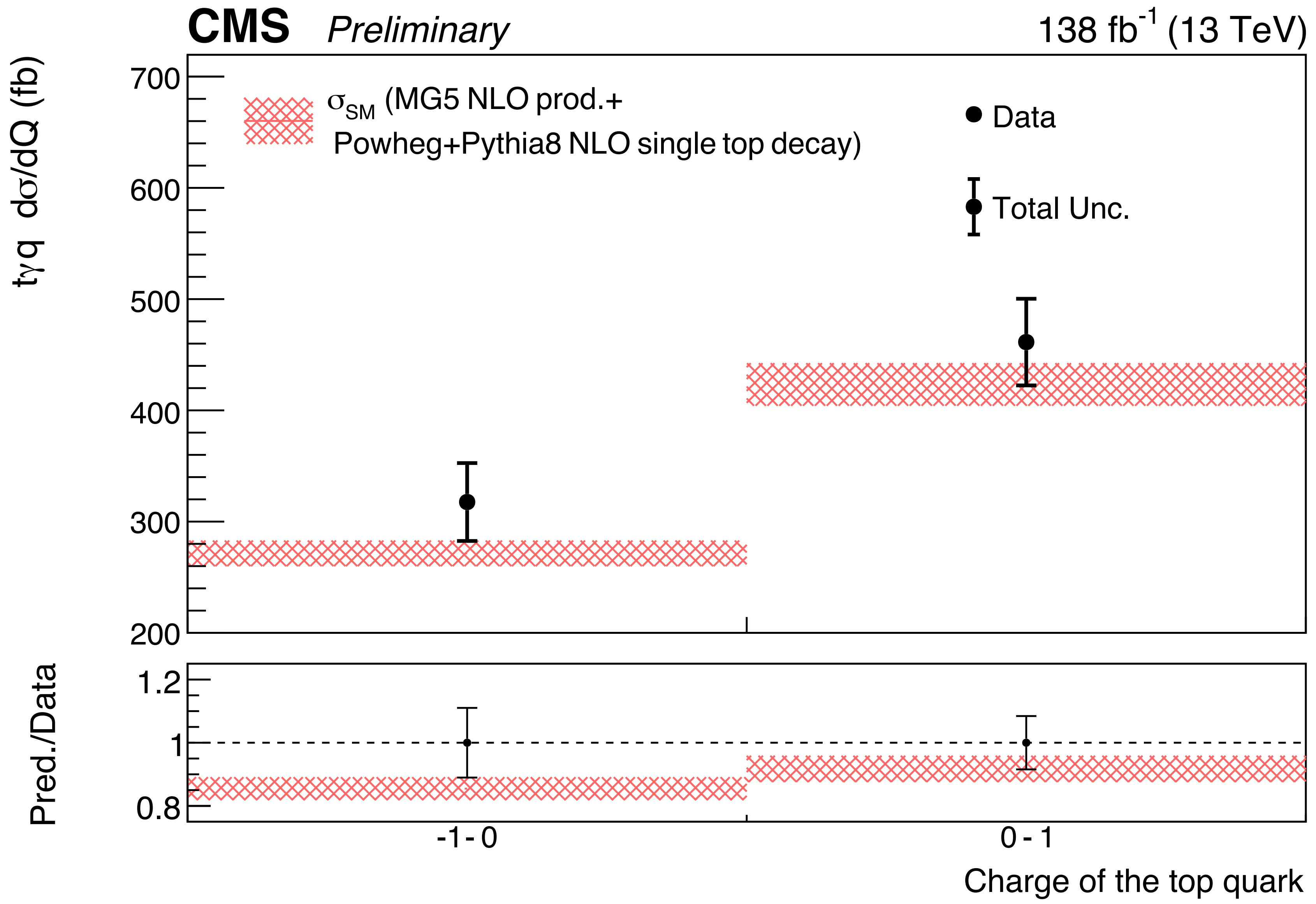
Simultanesous differential fit

Differential XS for tγq measured at particle level

Simultanesous differential fit

Differential XS for tγq measured at parton level

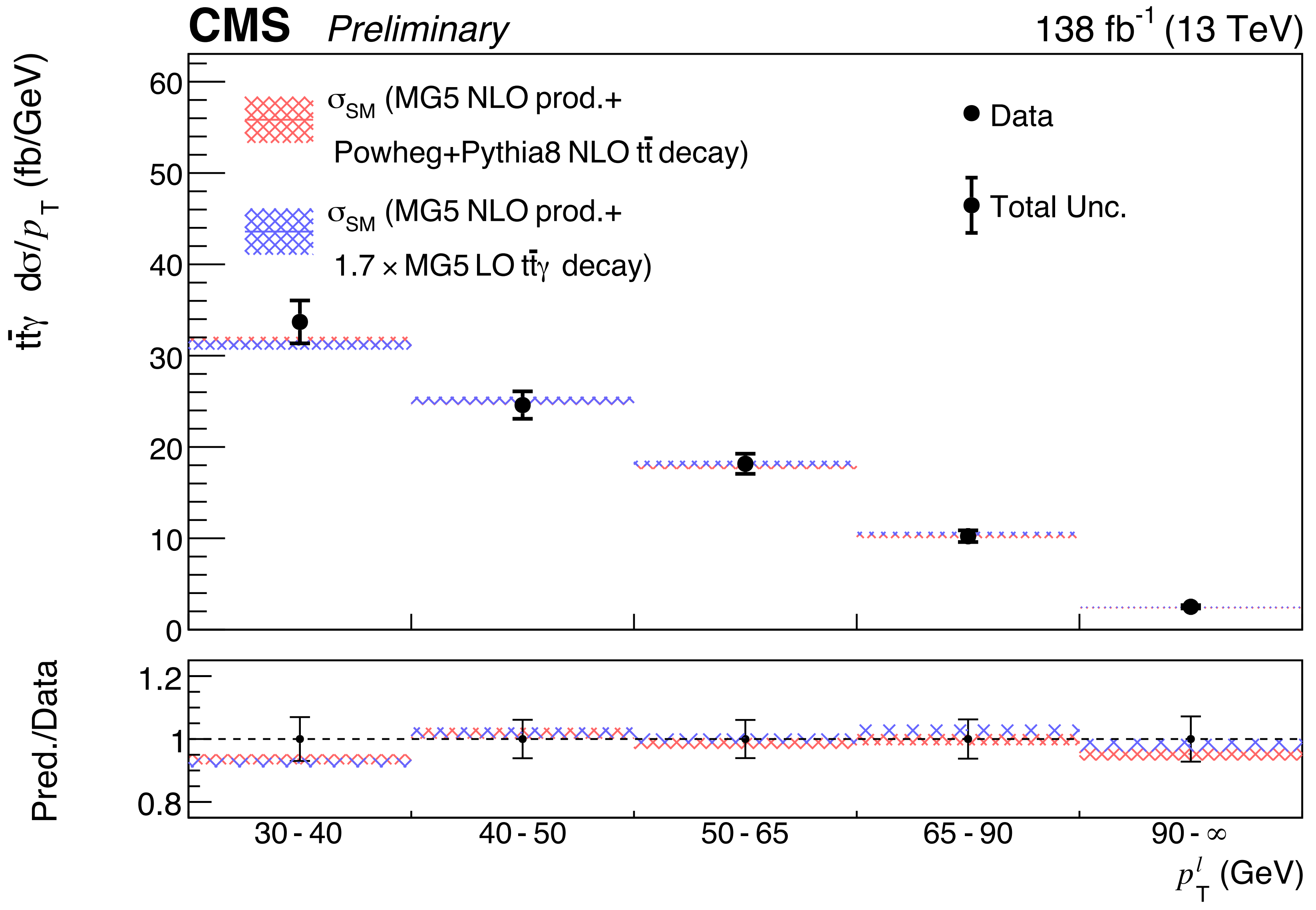


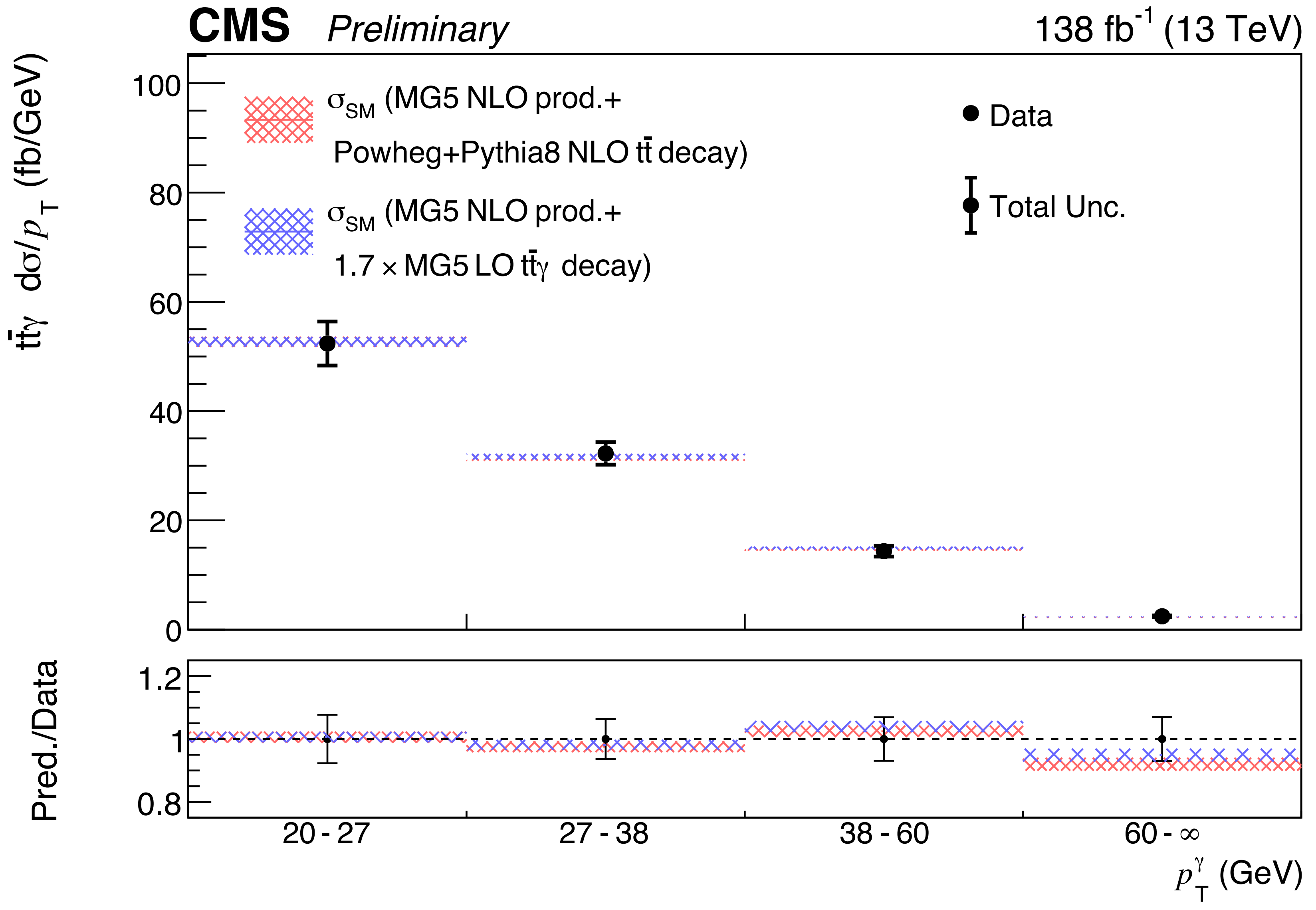


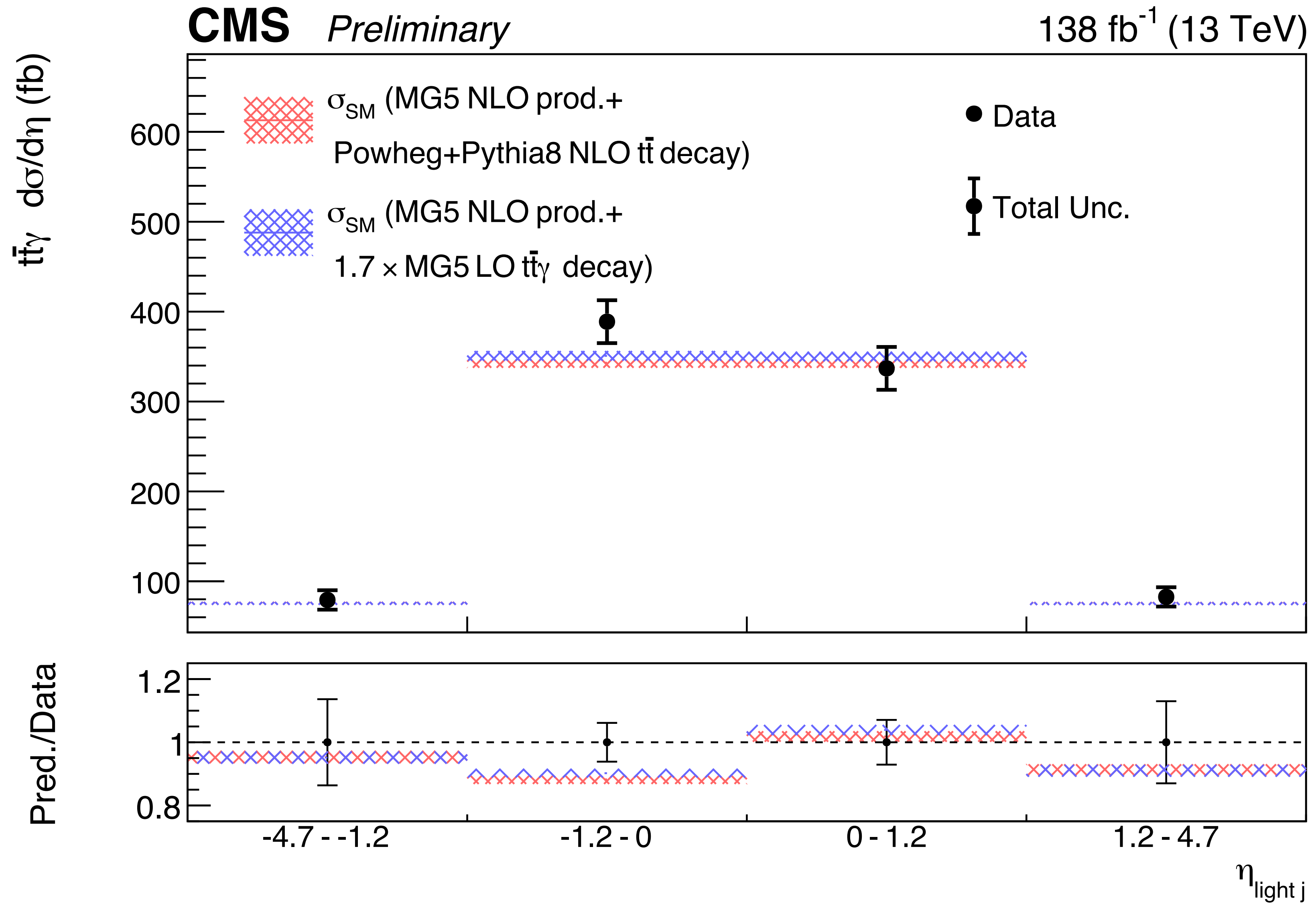
Variables	Bin	$\mu \pm \Delta\mu$	Predicted σ/fb	Predicted dσ/fb	Observed dσ/fb
p_T^{γ}	20–27	$1.049^{+0.179}_{-0.178}$	57.04 ± 2.18	8.15 ± 0.31	8.55 ± 1.45
	27–38	$1.066^{+0.136}_{-0.134}$	53.58 ± 2.03	4.87 ± 0.18	5.19 ± 0.66
	38–60	$1.143^{+0.119}_{-0.116}$	50.27 ± 2.07	2.28 ± 0.09	2.61 ± 0.27
	60–200	$0.979^{+0.101}_{-0.098}$	46.67 ± 2.42	0.33 ± 0.02	0.33 ± 0.03
p_T^{ℓ}	30–40	$0.958^{+0.131}_{-0.129}$	63.04 ± 2.43	6.30 ± 0.24	6.04 ± 0.82
	40–50	$1.168^{+0.129}_{-0.127}$	46.74 ± 1.82	4.67 ± 0.18	5.46 ± 0.60
	50–65	$0.938^{+0.124}_{-0.121}$	44.50 ± 1.85	2.97 ± 0.12	2.78 ± 0.36
	65–90	$1.205^{+0.148}_{-0.143}$	33.22 ± 1.46	1.33 ± 0.06	1.60 ± 0.19
	90–200	$1.168^{+0.172}_{-0.164}$	20.05 ± 1.05	0.18 ± 0.01	0.21 ± 0.03
$m_{\ell\gamma}$	10–50	$0.757^{+0.133}_{-0.129}$	43.68 ± 1.79	1.09 ± 0.04	0.83 ± 0.14
	50–75	$0.957^{+0.134}_{-0.131}$	44.34 ± 1.68	1.77 ± 0.07	1.70 ± 0.24
	75–95	$1.009^{+0.169}_{-0.163}$	32.04 ± 1.29	1.60 ± 0.06	1.62 ± 0.27
	95–140	$1.165^{+0.126}_{-0.123}$	42.88 ± 2.02	0.95 ± 0.04	1.11 ± 0.12
	140–200	$1.100^{+0.119}_{-0.116}$	44.61 ± 2.38	0.74 ± 0.04	0.82 ± 0.09
$\Delta R(\ell,\gamma)$	0.4–1.2	$0.854^{+0.143}_{-0.138}$	40.70 ± 1.69	50.87 ± 2.11	43.44 ± 7.15
	1.2–2.0	$1.043^{+0.132}_{-0.127}$	46.87 ± 1.92	58.58 ± 2.40	61.10 ± 7.59
	2.0–2.8	$1.256^{+0.132}_{-0.122}$	59.58 ± 2.60	74.48 ± 3.25	93.55 ± 9.46
	2.8–10	$1.153^{+0.142}_{-0.137}$	60.40 ± 2.78	8.39 ± 0.39	9.67 ± 1.17
$\eta_{\text{light j}}$	-4.7– -1.2	$1.003^{+0.108}_{-0.105}$	72.03 ± 3.13	20.58 ± 0.89	20.64 ± 2.19
	-1.2–0.0	$1.412^{+0.537}_{-0.500}$	31.63 ± 1.37	26.36 ± 1.15	37.22 ± 13.67
	0.0–1.2	$1.908^{+0.551}_{-0.532}$	31.94 ± 1.41	26.61 ± 1.18	50.78 ± 14.41
	1.2–4.7	$1.008^{+0.123}_{-0.121}$	71.95 ± 3.15	20.56 ± 0.90	20.72 ± 2.51
N_{jets}	2–3	$1.344^{+0.116}_{-0.115}$	117.39 ± 5.07	117.39 ± 5.07	157.78 ± 13.56
	3–4	$0.690^{+0.153}_{-0.150}$	63.55 ± 2.86	63.55 ± 2.86	43.85 ± 9.63
	4–10	$0.279^{+0.310}_{-0.303}$	26.61 ± 2.51	4.44 ± 0.42	1.24 ± 1.36
$\Delta R(t,\gamma)$	0.0–1.7	$1.106^{+0.186}_{-0.179}$	208.87 ± 10.11	122.86 ± 5.95	135.89 ± 22.42
	1.7–2.5	$1.139^{+0.241}_{-0.234}$	136.42 ± 5.42	170.53 ± 6.77	194.23 ± 40.50
	2.5–3.1	$1.029^{+0.239}_{-0.230}$	139.69 ± 5.72	232.82 ± 9.54	239.57 ± 54.60
	3.1–10	$1.096^{+0.170}_{-0.166}$	209.76 ± 8.96	30.40 ± 1.30	33.32 ± 5.11
top quark charge	-1–0	$1.170^{+0.131}_{-0.127}$	271.47 ± 11.49	271.47 ± 11.49	317.62 ± 35.02
	0–1	$1.090^{+0.094}_{-0.090}$	423.28 ± 19.10	423.28 ± 19.10	461.37 ± 38.94

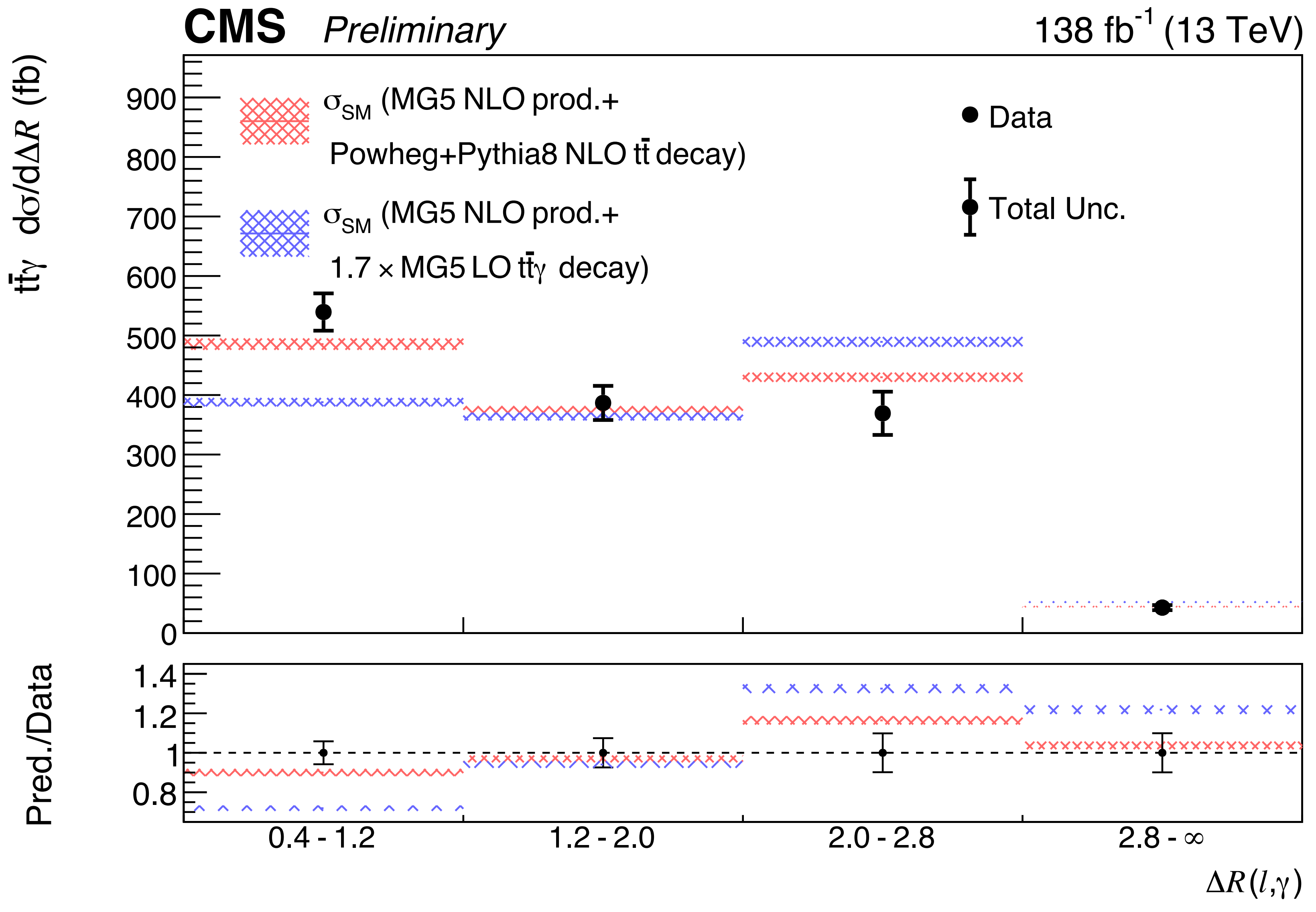
Simultanesous differential fit

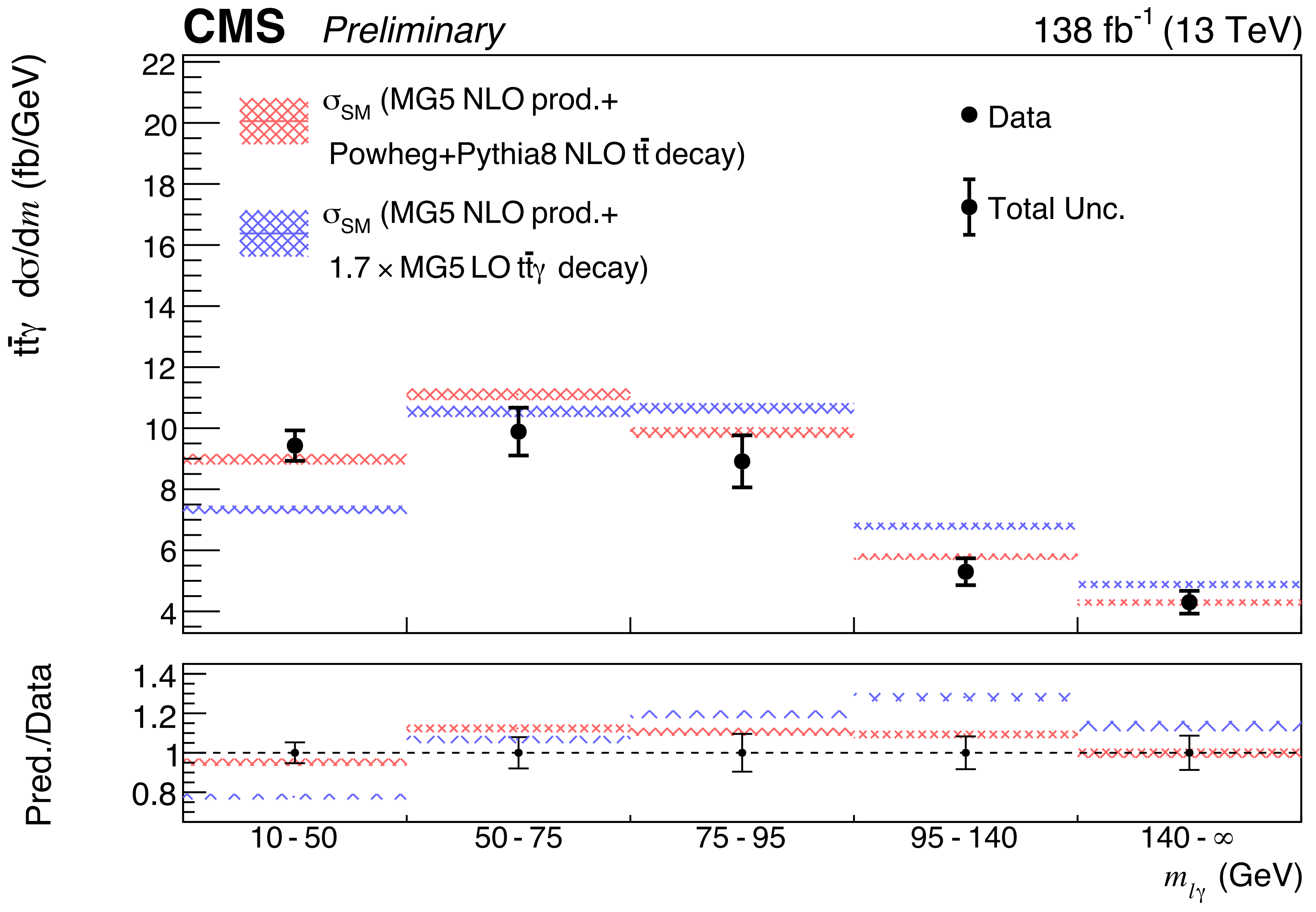
Differential XS for ttγ measured at particle level

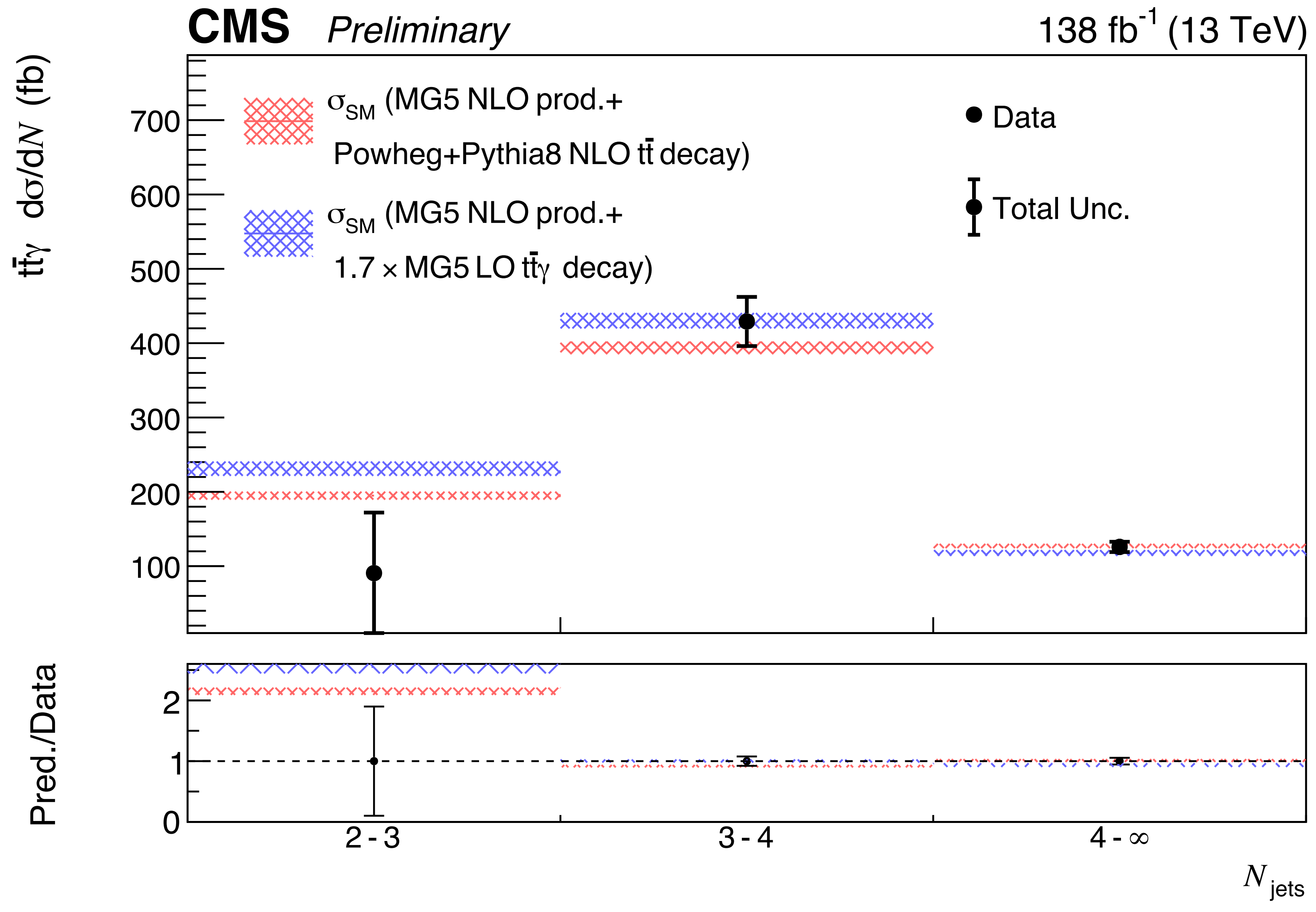






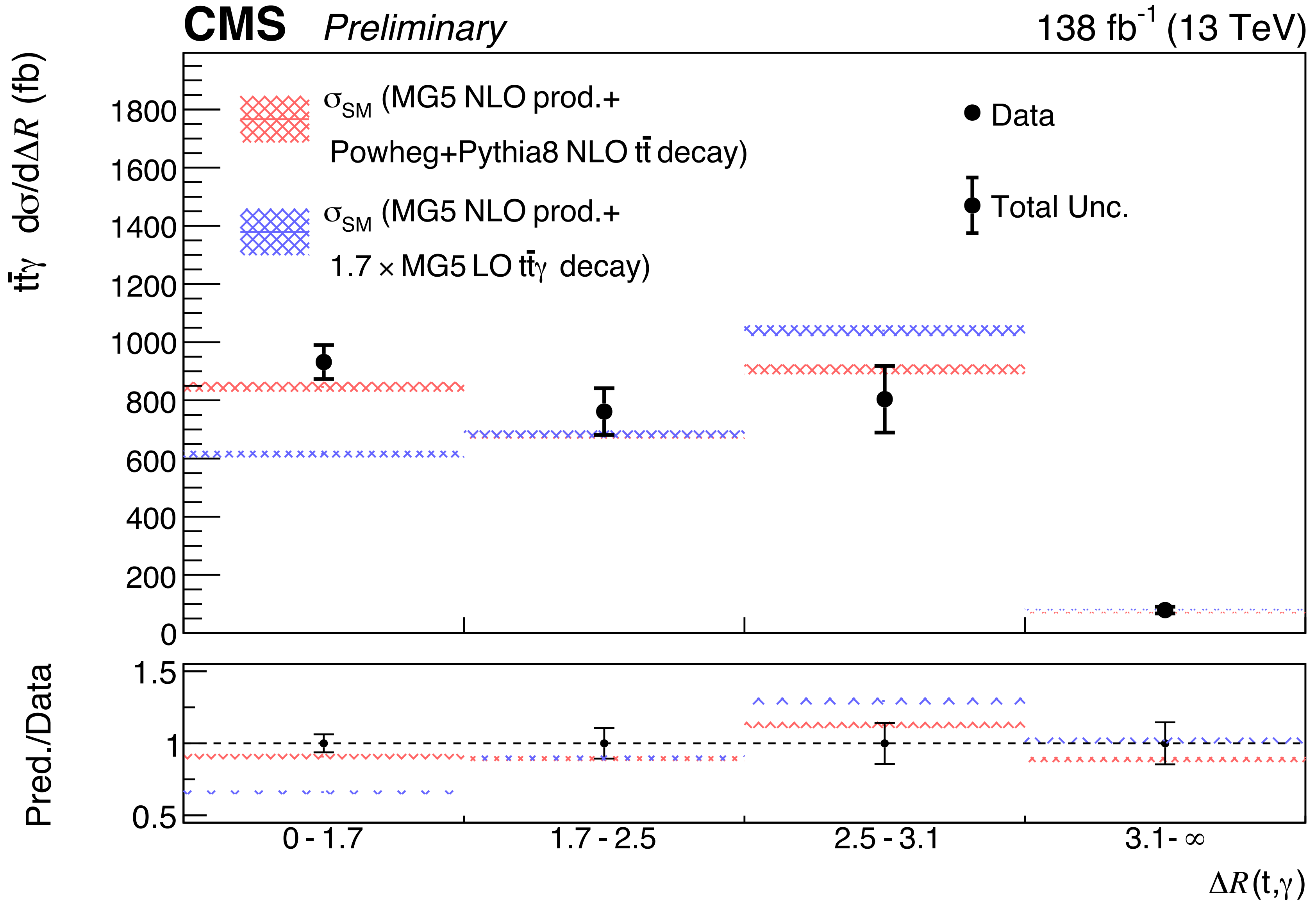


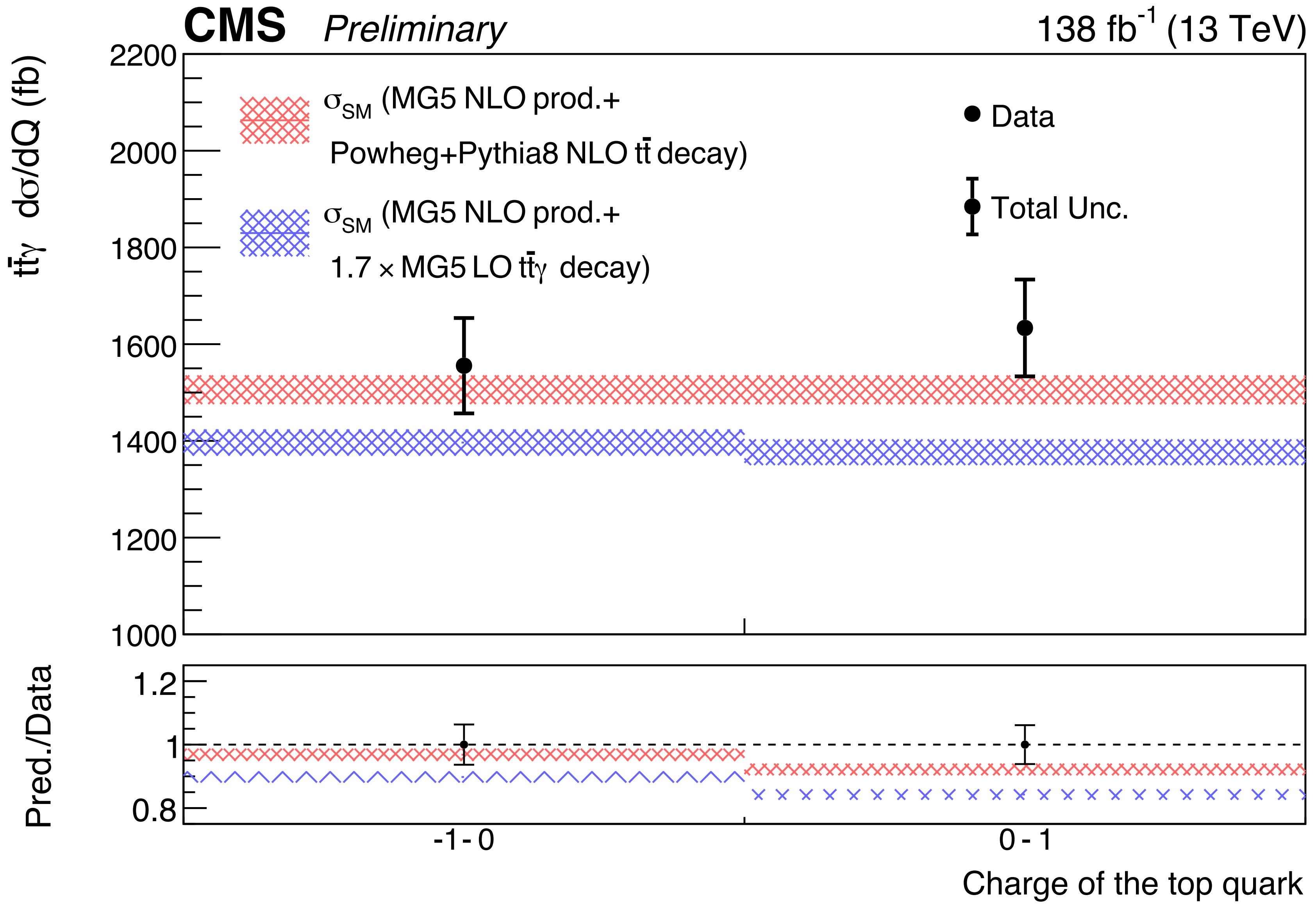




Simultanesous differential fit

Differential XS for ttγ measured at parton level



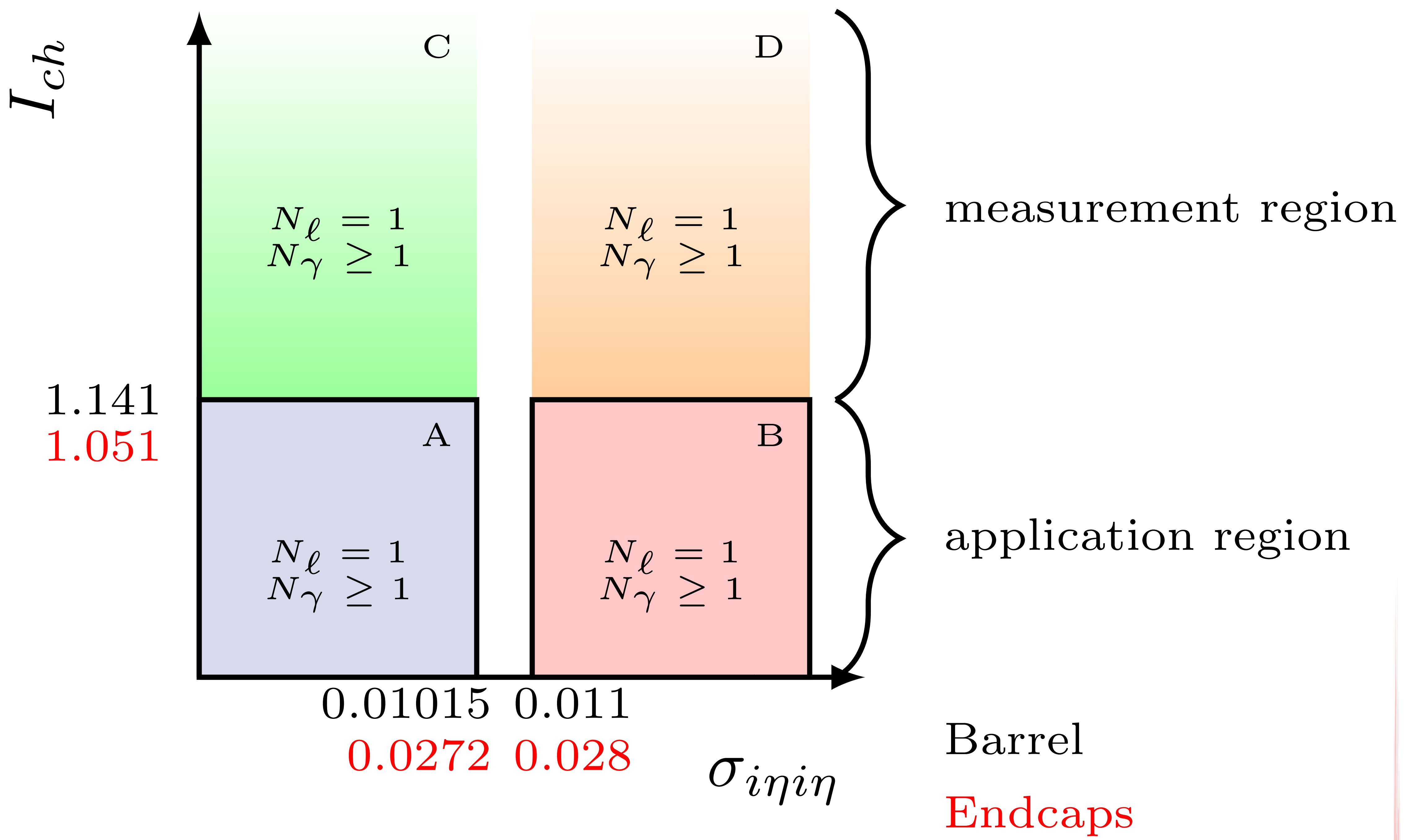


Variables	Bin	$\mu \pm \Delta\mu$	Predicted σ/fb	Predicted dσ/fb	Observed dσ/fb
p_T^γ	20–27	$0.994^{+0.077}_{-0.076}$	368.88 ± 5.95	52.70 ± 0.85	52.38 ± 4.03
	27–38	$1.025^{+0.066}_{-0.065}$	348.12 ± 5.66	31.65 ± 0.51	32.44 ± 2.07
	38–60	$0.976^{+0.068}_{-0.067}$	328.56 ± 5.49	14.93 ± 0.25	14.58 ± 1.01
	60–200	$1.087^{+0.078}_{-0.074}$	322.73 ± 6.76	2.31 ± 0.05	2.51 ± 0.18
p_T^ℓ	30–40	$1.069^{+0.076}_{-0.073}$	311.73 ± 5.01	31.17 ± 0.50	33.32 ± 2.32
	40–50	$0.982^{+0.060}_{-0.060}$	250.91 ± 4.01	25.09 ± 0.40	24.64 ± 1.51
	50–65	$1.014^{+0.062}_{-0.061}$	272.82 ± 4.41	18.19 ± 0.29	18.44 ± 1.12
	65–90	$1.002^{+0.063}_{-0.062}$	263.07 ± 4.44	10.52 ± 0.18	10.54 ± 0.66
	90–200	$1.050^{+0.076}_{-0.075}$	269.75 ± 5.64	2.45 ± 0.05	2.57 ± 0.19
$m_{\ell\gamma}$	10–50	$1.050^{+0.056}_{-0.055}$	293.37 ± 5.16	7.33 ± 0.13	7.70 ± 0.41
	50–75	$0.890^{+0.071}_{-0.070}$	263.75 ± 4.41	10.55 ± 0.18	9.39 ± 0.74
	75–95	$0.904^{+0.087}_{-0.086}$	212.90 ± 3.46	10.65 ± 0.17	9.62 ± 0.92
	95–140	$0.915^{+0.077}_{-0.075}$	305.72 ± 5.06	6.79 ± 0.11	6.22 ± 0.52
	140–200	$1.002^{+0.089}_{-0.085}$	292.54 ± 6.44	4.88 ± 0.11	4.89 ± 0.42
$\Delta R(\ell,\gamma)$	0.4–1.2	$1.111^{+0.065}_{-0.064}$	310.37 ± 5.55	387.96 ± 6.94	431.02 ± 25.02
	1.2–2.0	$1.032^{+0.078}_{-0.075}$	291.02 ± 5.07	363.78 ± 6.33	375.42 ± 27.83
	2.0–2.8	$0.859^{+0.085}_{-0.084}$	391.46 ± 6.49	489.33 ± 8.12	420.33 ± 41.35
	2.8–10	$0.964^{+0.094}_{-0.097}$	375.44 ± 6.60	52.14 ± 0.92	50.27 ± 4.98
$\eta_{\text{light j}}$	-4.7– -1.2	$1.049^{+0.143}_{-0.143}$	264.04 ± 5.37	75.44 ± 1.53	79.14 ± 10.79
	-1.2–0.0	$1.133^{+0.070}_{-0.069}$	420.96 ± 6.38	350.80 ± 5.32	397.46 ± 24.38
	0.0–1.2	$0.982^{+0.070}_{-0.069}$	420.01 ± 6.37	350.01 ± 5.30	343.71 ± 24.33
	1.2–4.7	$1.097^{+0.142}_{-0.143}$	263.27 ± 5.34	75.22 ± 1.53	82.52 ± 10.72
N_{jets}	2–3	$0.465^{+0.419}_{-0.417}$	231.17 ± 9.54	231.17 ± 9.54	107.49 ± 96.63
	3–4	$1.090^{+0.085}_{-0.083}$	430.23 ± 10.31	430.23 ± 10.31	468.95 ± 36.14
	4–10	$0.990^{+0.057}_{-0.052}$	706.89 ± 22.48	117.82 ± 3.75	116.64 ± 6.42
$\Delta R(t,\gamma)$	0.0–1.7	$1.101^{+0.070}_{-0.068}$	1045.86 ± 18.52	615.21 ± 10.89	677.35 ± 42.45
	1.7–2.5	$1.118^{+0.120}_{-0.116}$	547.26 ± 9.82	684.07 ± 12.27	764.79 ± 80.72
	2.5–3.1	$0.887^{+0.128}_{-0.125}$	623.95 ± 10.89	1039.91 ± 18.15	922.40 ± 131.55
	3.1–10	$1.127^{+0.165}_{-0.163}$	556.04 ± 10.70	80.59 ± 1.55	90.82 ± 13.22
top quark charge	-1–0	$1.033^{+0.066}_{-0.065}$	1396.57 ± 26.80	1396.57 ± 26.80	1442.66 ± 91.48
	0–1	$1.085^{+0.067}_{-0.066}$	1376.54 ± 26.46	1376.54 ± 26.46	1493.55 ± 91.54

Backup

Background estimation — Nonprompt γ

- Under the selection of exactly one lepton and at least one photon $N_\ell=1$, $N_\gamma \geq 1$
- The ABCD regions are built by varying the charge isolation and $\sigma_{i\eta i\eta}$
- Assuming the nonprompt photon performance in C and D is similar with in A and B, the nonprompt photon fake rate can be estimated and corrected by the following equations

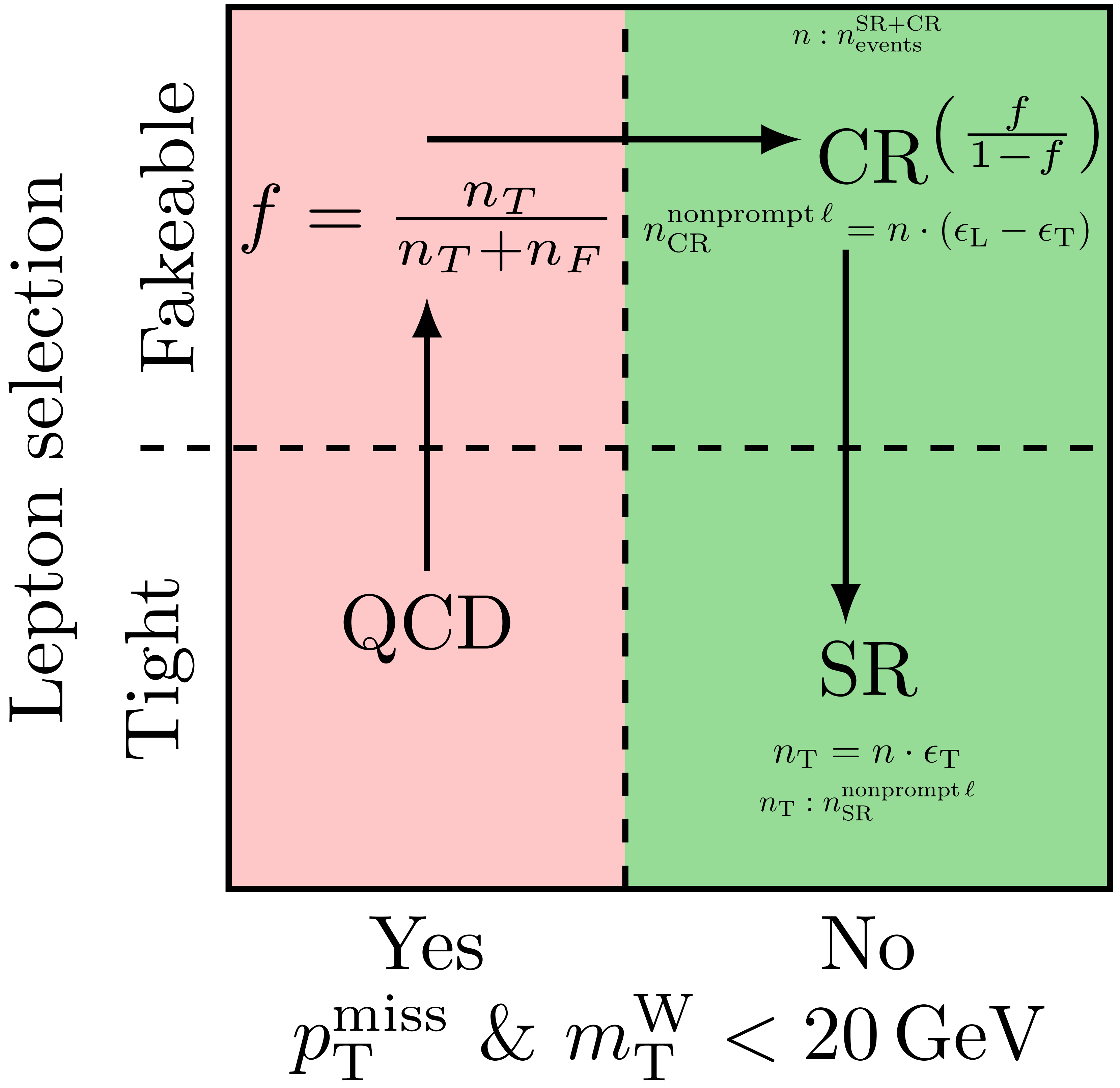


$$\text{fake rate}^{ij} = \frac{\text{Data}_C^{ij} - (\text{prompt} + \text{ele mis.})\,\text{MC}_C^{ij}}{\text{Data}_D^{ij} - (\text{prompt} + \text{ele mis.})\,\text{MC}_D^{ij}}$$

$$k_{MC}^{ij} = \frac{\text{nonprompt MC}_A^{ij}}{\text{nonprompt MC}_B^{ij}} \div \frac{\text{nonprompt MC}_C^{ij}}{\text{nonprompt MC}_D^{ij}}$$

$$\text{nonprompt contribution} = \sum_{ij} (\text{data}_B^{ij} \times \text{fake rate}^{ij} \times k_{MC}^{ij}) - \sum_{ij} ((\text{prompt} + \text{ele mis.})\,\text{MC}_B^{ij} \times \text{fake rate}^{ij} \times k_{MC}^{ij})$$

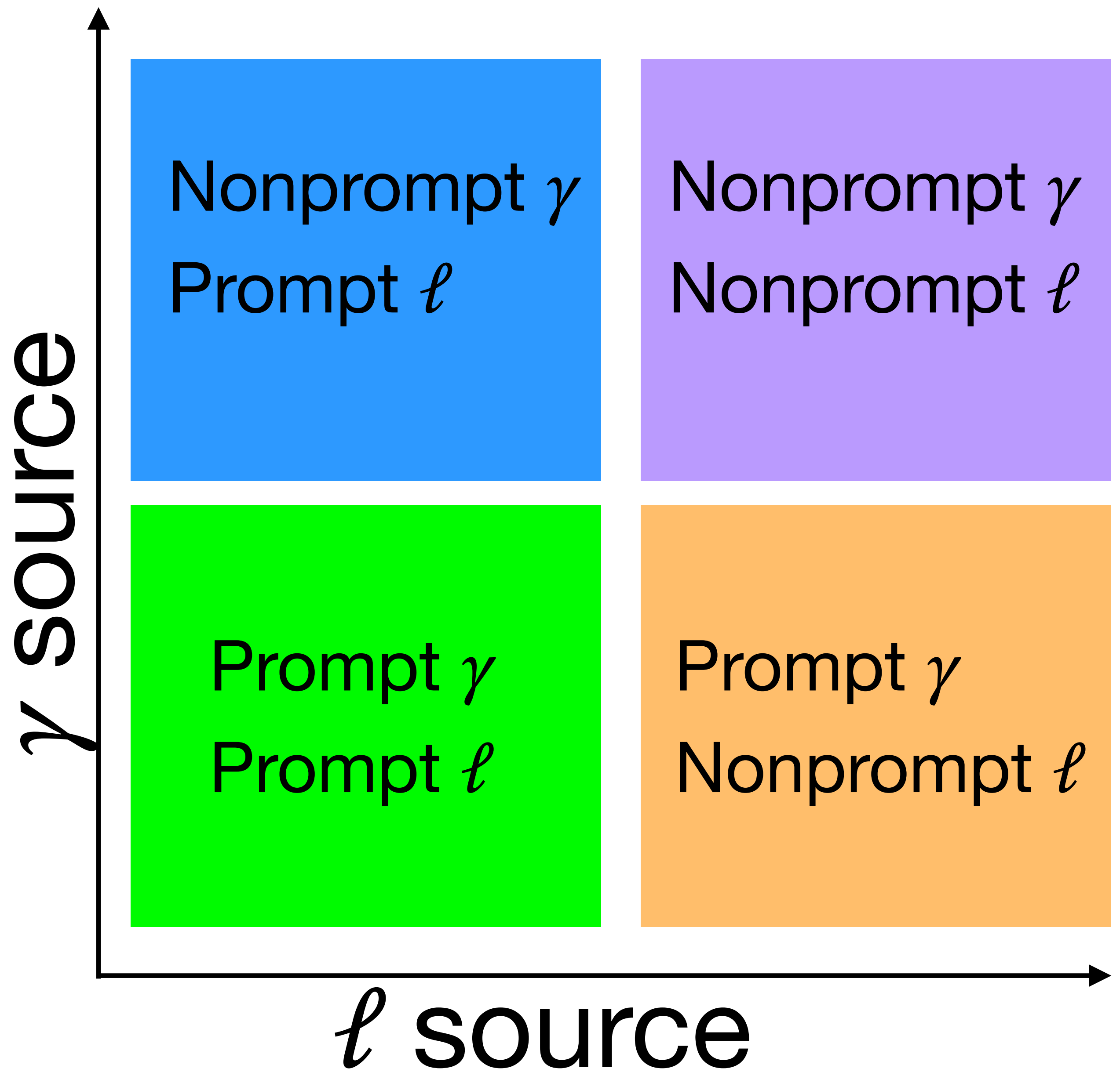
Background estimation — Nonprompt ℓ



1. Build QCD jet-enriched region with requirements of
   - Exactly one lepton
   - $p_{\text{T}}^{\text{miss}} < 20$ GeV and $m_{\text{T}}^{\text{W}} < 20$ GeV
   - At least one jet with $p_{\text{T}} > 30$ GeV and $\Delta R(\ell,j) > 0.4$
2. Measure the tight-to-loose rate $f = \dfrac{n_T}{n_T + n_F}$
   - n_T the number of leptons passing tight ℓ ID in QCD jet-enriched region
   - n_F the number of leptons passing fakeable ℓ ID in QCD jet-enriched region
3. Build nonprompt ℓ data-driven CR with fakeable ℓ ID and apply to SR with weights $f/(1-f)$

$$n_{\text{nonprompt}\,\ell}^{\text{SR}} = \sum_{\text{ij}} \left(\text{data}_{\text{CR}}^{\text{ij}} \times \frac{f^{\text{ij}}}{1-f^{\text{ij}}}\right) - \sum_{\text{ij}} \left(\text{prompt}\,\ell\,\text{MC}_{\text{CR}}^{\text{ij}} \times \frac{f^{\text{ij}}}{1-f^{\text{ij}}}\right)$$

Background estimation — Double Nonprompt



- **Method refer to SMP-19-002 and SMP-21-011**

The nonprompt γ enriched region is with γ_{CR} and ℓ_{SR} selection, after weights applied, the estimation is made up of:

- Nonprompt γ_{CR} + prompt ℓ_{SR} → a.1 √
- Prompt γ_{CR} + prompt ℓ_{SR} → a.2
- Prompt γ_{CR} + nonprompt ℓ_{SR} → a.3
- Nonprompt γ_{CR} + nonprompt ℓ_{SR} → a.4

The nonprompt ℓ enriched region is with γ_{SR} and ℓ_{CR} selection, after weights applied, the estimation is made up of:

- Prompt γ_{SR} + nonprompt ℓ_{CR} → b.1 √
- Prompt γ_{SR} + prompt ℓ_{CR} → b.2
- Nonprompt γ_{SR} + prompt ℓ_{CR} → b.3
- Nonprompt γ_{SR} + nonprompt ℓ_{CR} → b.4

If we only consider these two data-driven samples, contributions between a.4 and b.4 are **double counted**. And we don't want any nonprompt γ contribution appearing in the nonprompt ℓ estimation like the b.3, vice versa.

The double nonprompt enriched region is with γ_{CR} and ℓ_{CR} selection, with products of fake ℓ and γ weights applied, the estimation is made up of:

- Nonprompt γ_{CR} + nonprompt ℓ_{CR} → c.1 √
- Prompt γ_{CR} + prompt ℓ_{CR} → c.2
- Prompt γ_{CR} + nonprompt ℓ_{CR} → c.3
- Nonprompt γ_{CR} + prompt ℓ_{CR} → c.4

- **Weighted CR Nonprompt ℓ (γ) → Nonprompt ℓ (γ) in SR**

c.1 ≈ Nonprompt γ_{SR} + Nonprompt ℓ_{SR} ≈ a.4 ≈ b.4

c.3 ≈ Prompt γ_{CR} + Nonprompt ℓ_{SR} ≈ a.3

c.4 ≈ Nonprompt γ_{SR} + Prompt ℓ_{CR} ≈ b.3

a.2, b.2 and c.2 can be subtracted from simulation

We want a.1 + b.1 + c.1

Background estimation — Double Nonprompt

If we subtract double nonprompt from each nonprompt γ and ℓ, and add double nonprompt again:

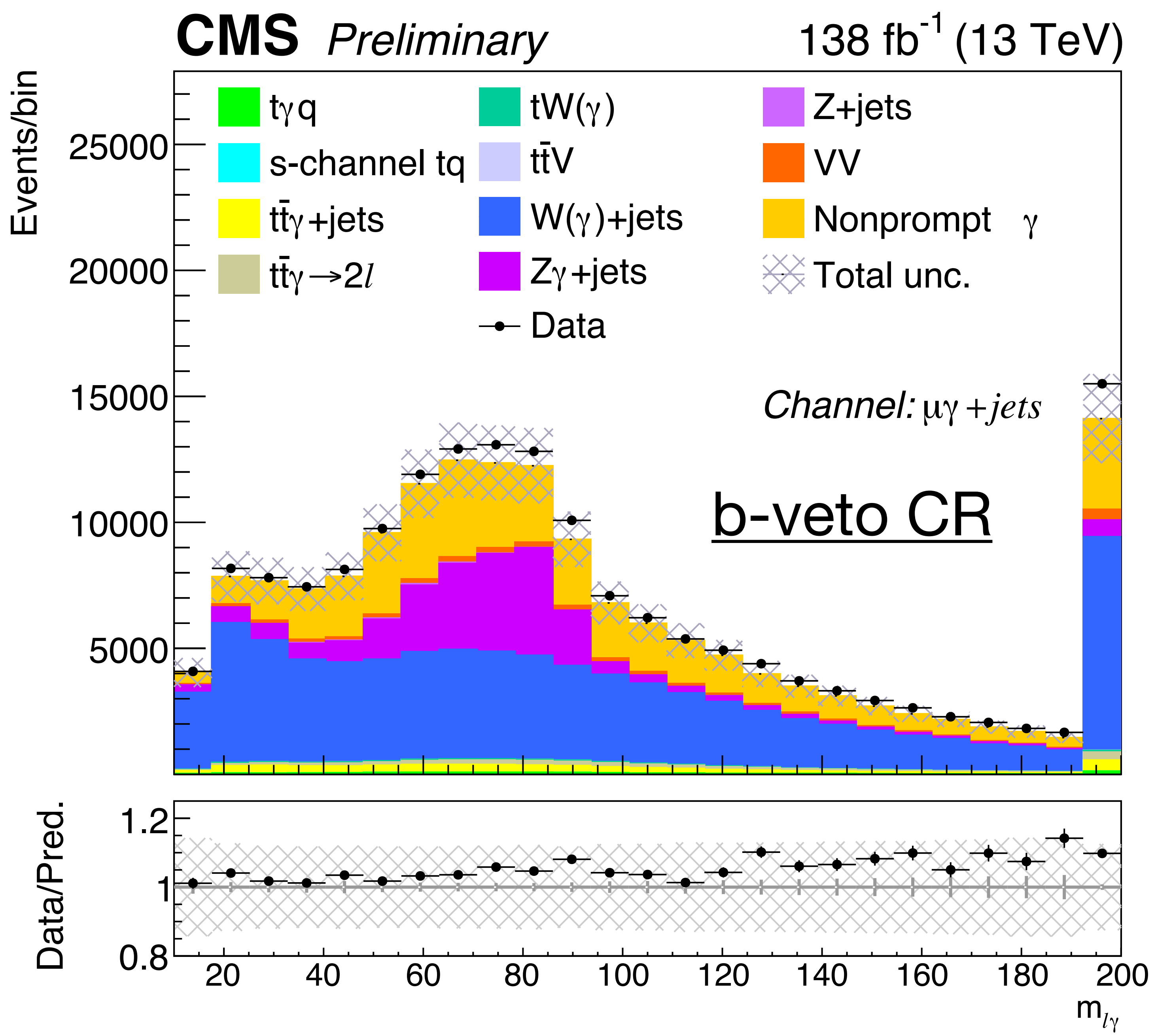
- c.1 ≈ a.4 ≈ b.4
- c.3 ≈ a.3
- c.4 ≈ b.3

$$(N_{\mathrm{nonprompt}\gamma} - N_{\mathrm{double\ nonprompt}}) + (N_{\mathrm{nonprompt}\ell} - N_{\mathrm{double\ nonprompt}}) + N_{\mathrm{double\ nonprompt}}$$

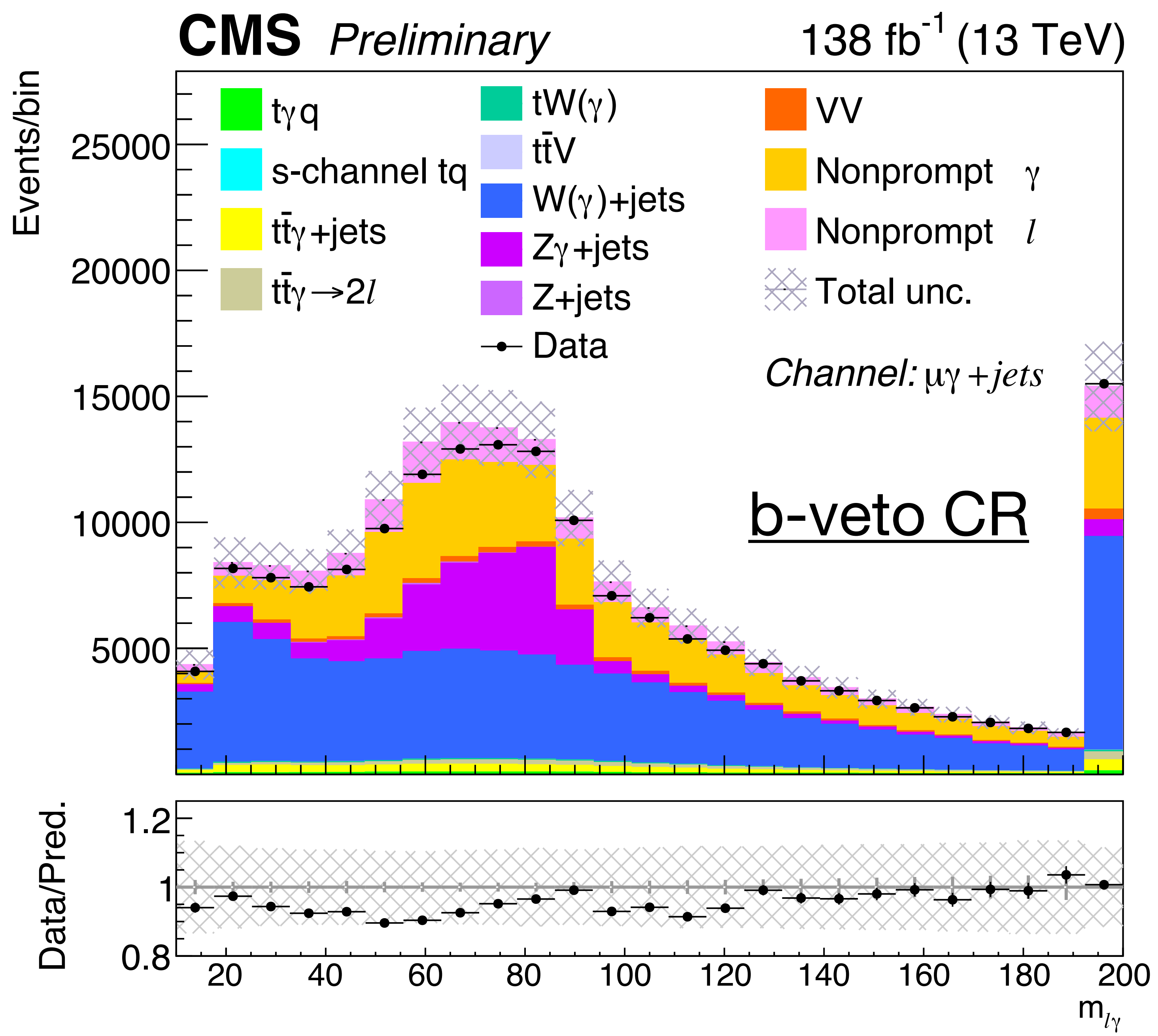
$$= \mathrm{a.1} + \mathrm{b.1} + \mathrm{c.1}$$

In this way, we get the pure nonprompt γ and ℓ as well as the double nonprompt

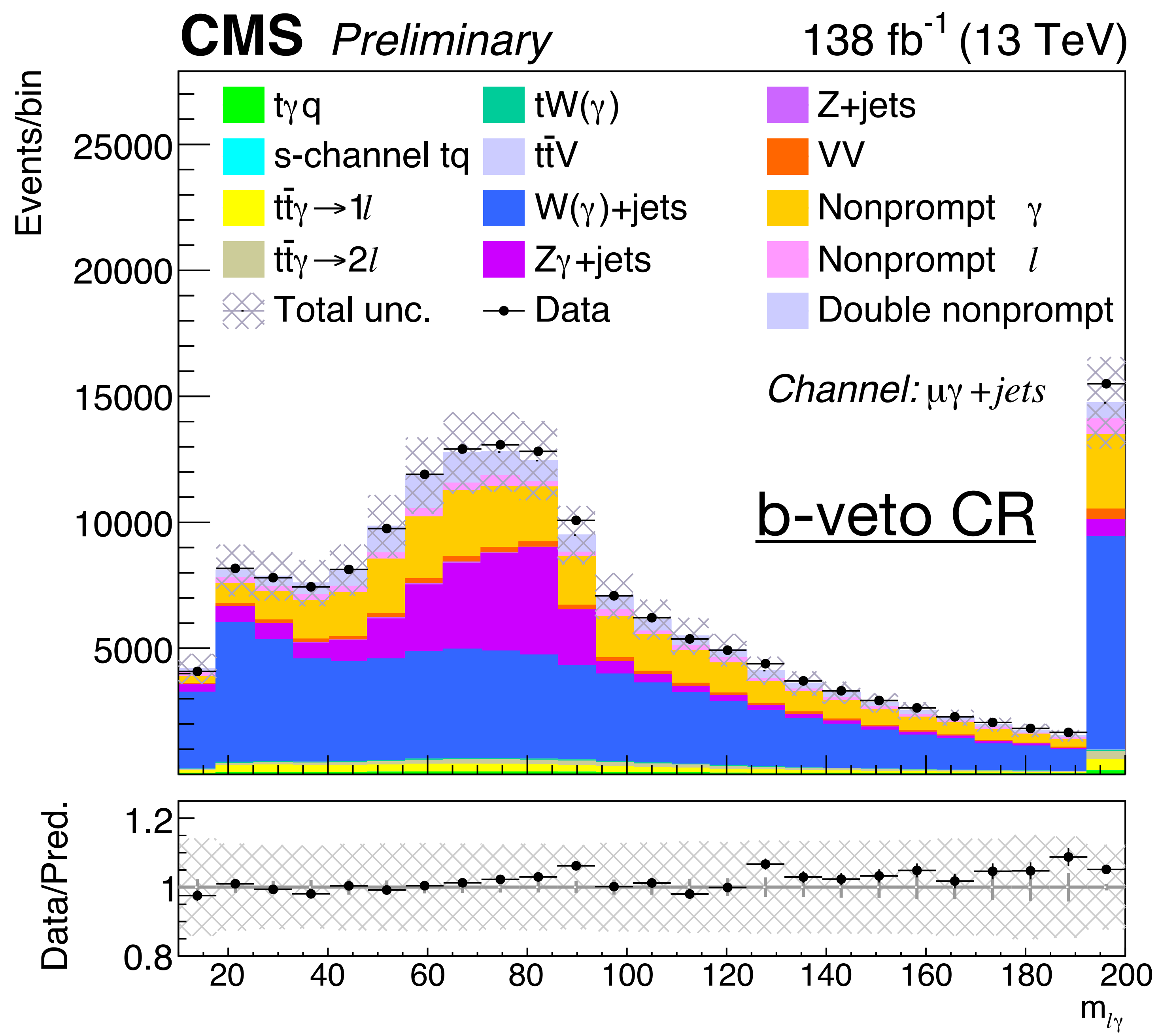
Only nonprompt γ



Nonprompt γ + Nonprompt ℓ

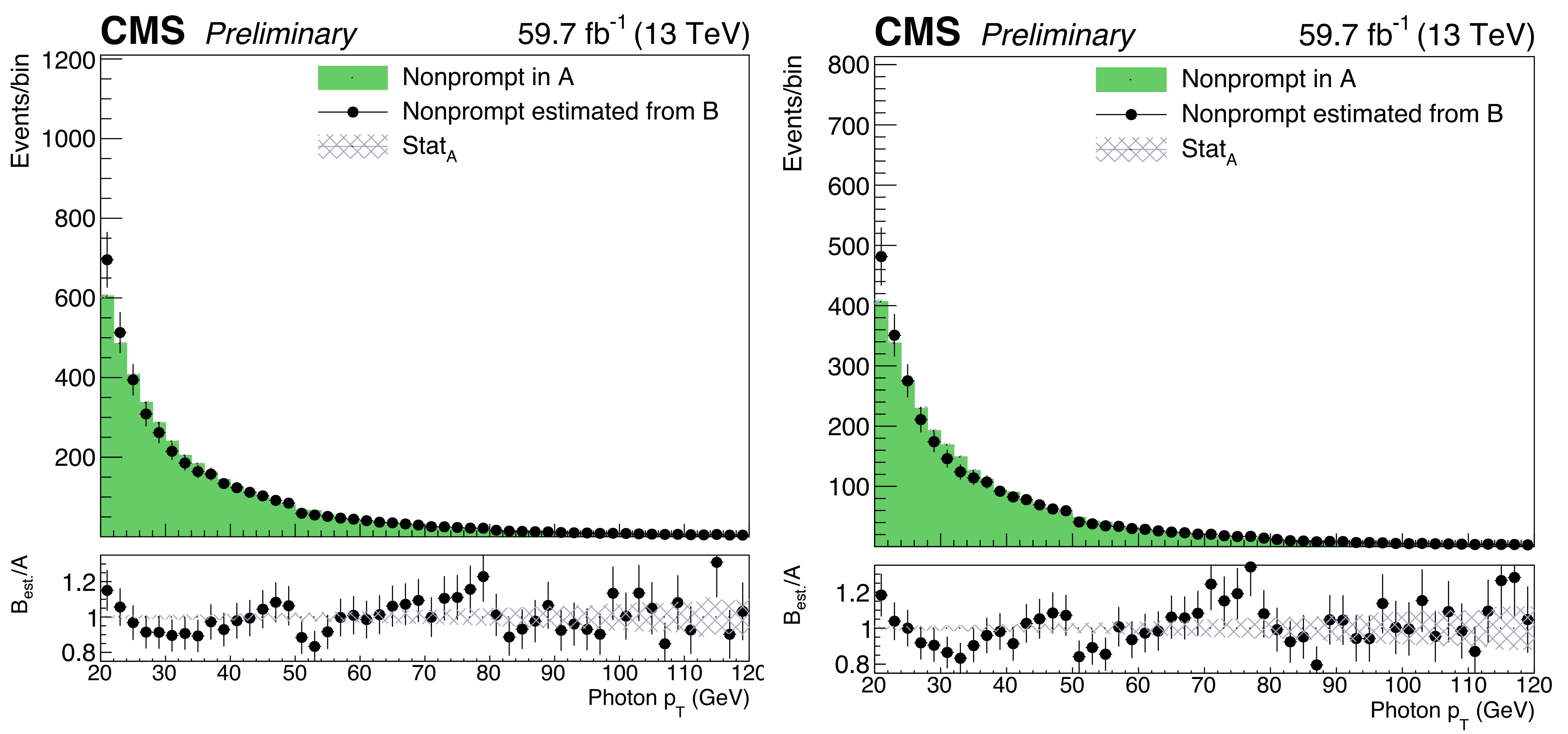


Nonprompt γ + Nonprompt ℓ + Double Nonprompt (with overlap removal)

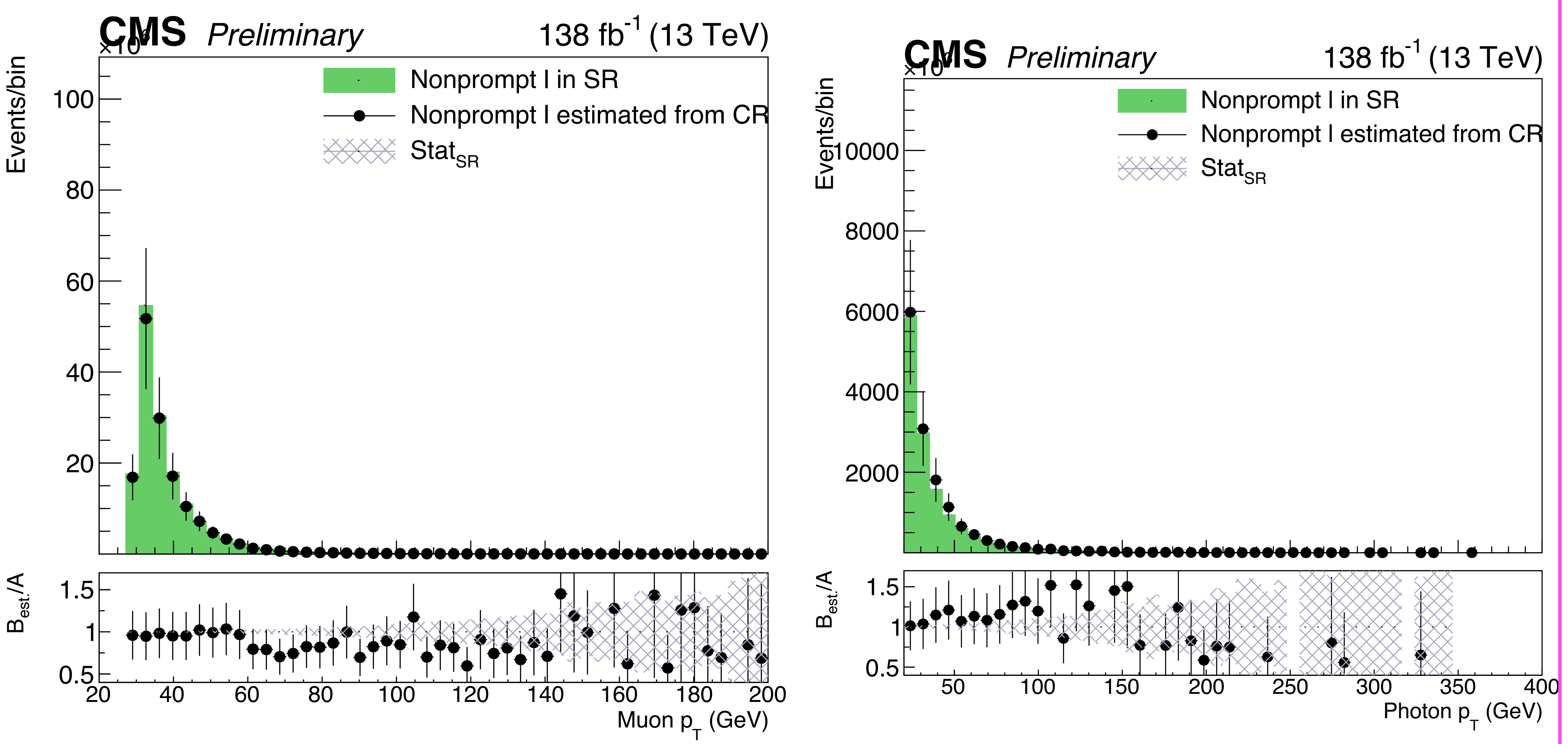


Background estimation — Nonprompt Closure

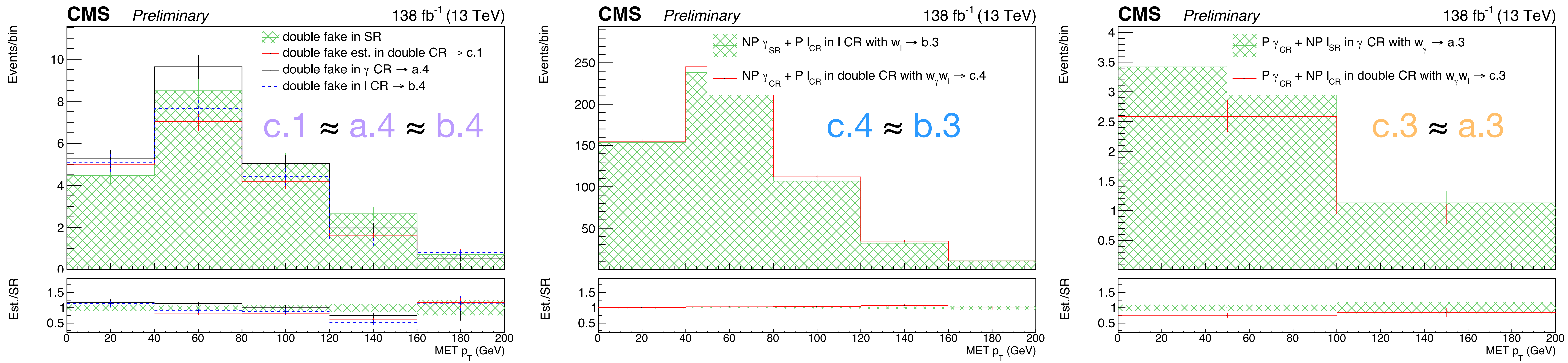
- Nonprompt γ closure by using ttbar MC



- Nonprompt ℓ closure by using QCD MC

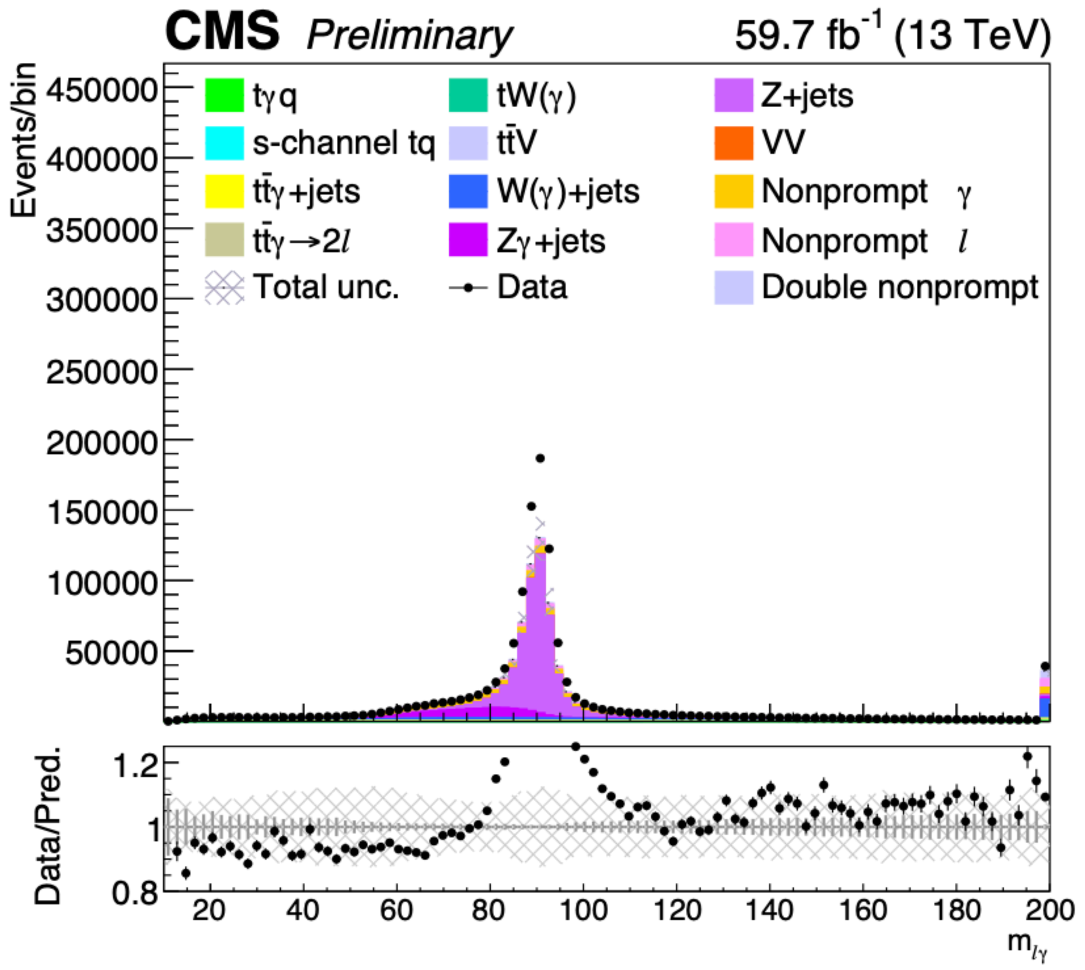


- Double nonprompt closure by using ttbar MC

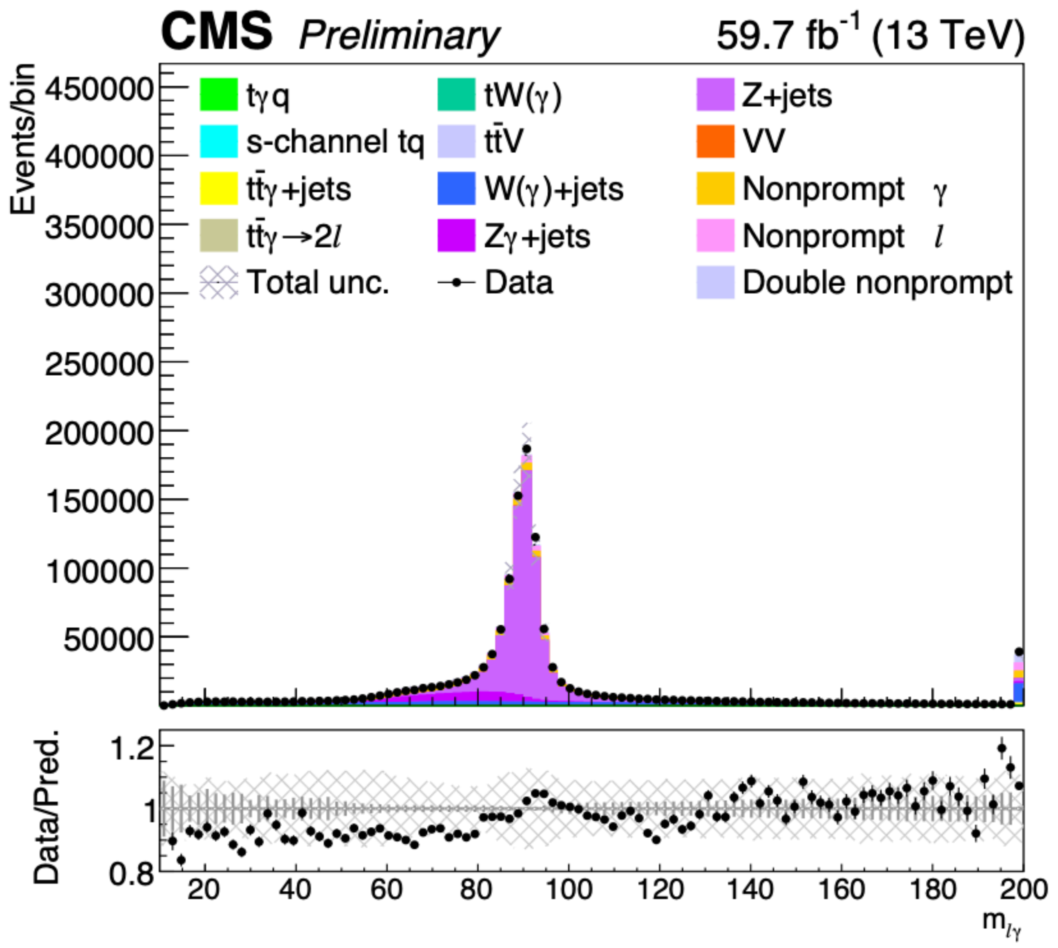


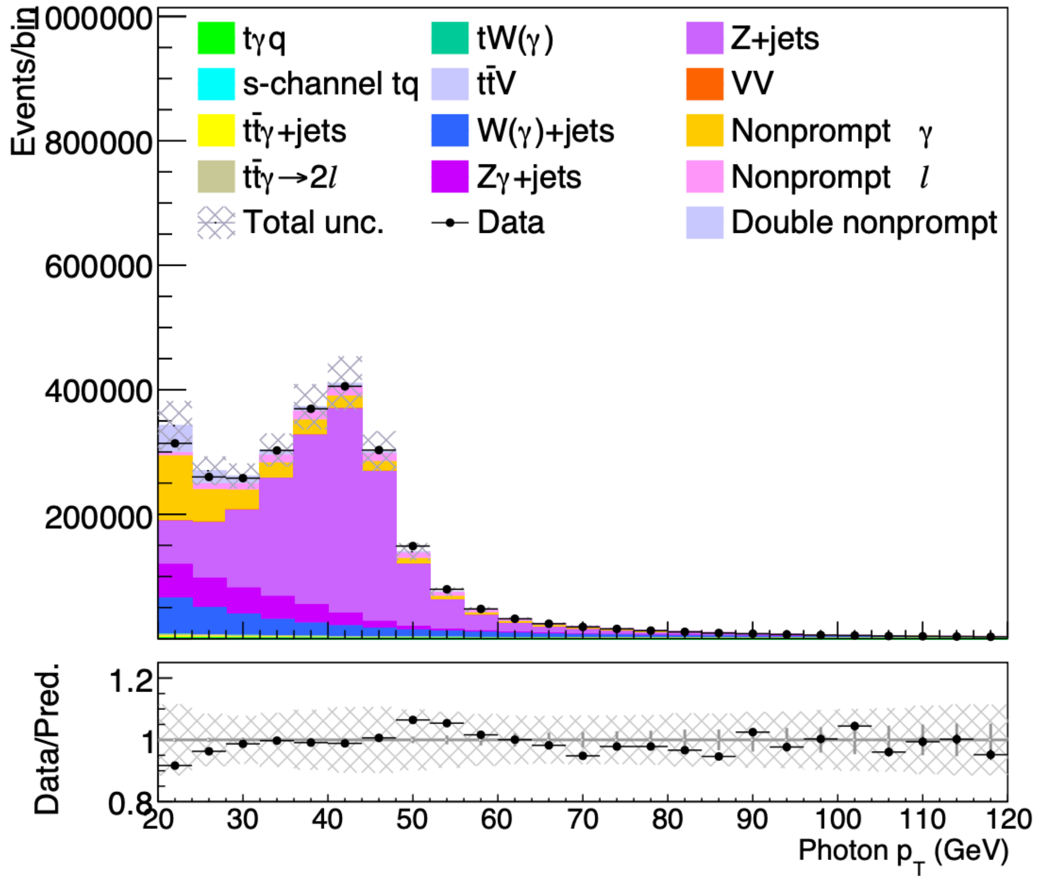
Background estimation — ele misID validation

- Validation by checking agreement in Vγ VR where ele misID mainly from Z+jets
  - The agreement in muon channel is acceptable
  - In the electron channel, disagreement can be cure by ***normalisation factor*** *derived from $m_{l\gamma}$ distribution*
  - → <u>No shape mismodeling, agreement can be fixed by a simple normalization factor</u>



Normalizing Z+jets →





- Validation by performing fit for Vγ events by regarding Wγ as signal