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ttbb modeling for ttH ATLAS+CMS

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On behalf of the ATLAS and CMS collaborations

10th edition of the Large Hadron Collider Physics Conference

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ATLAS EXPERIMENT

CMS
Compact Muon Solenoid

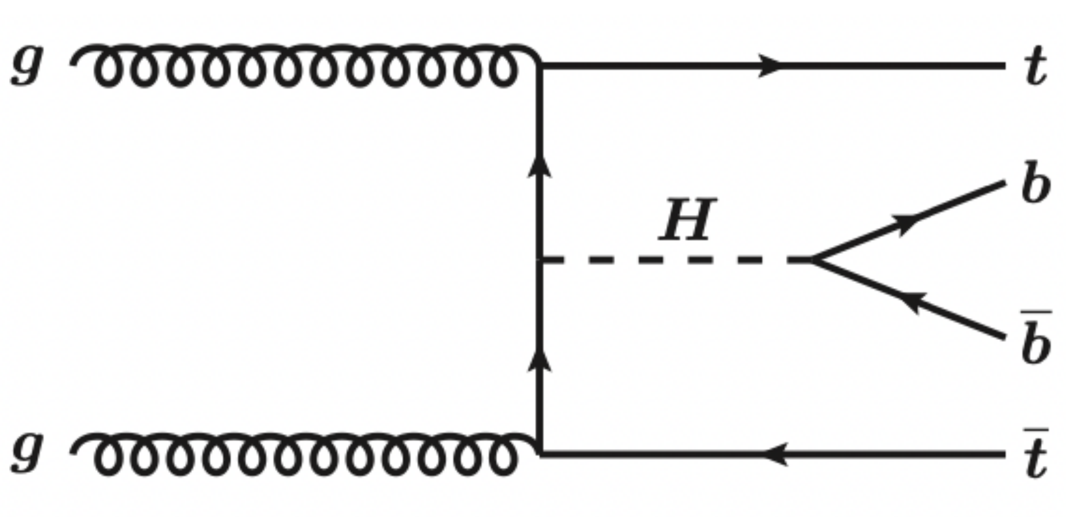
Outline

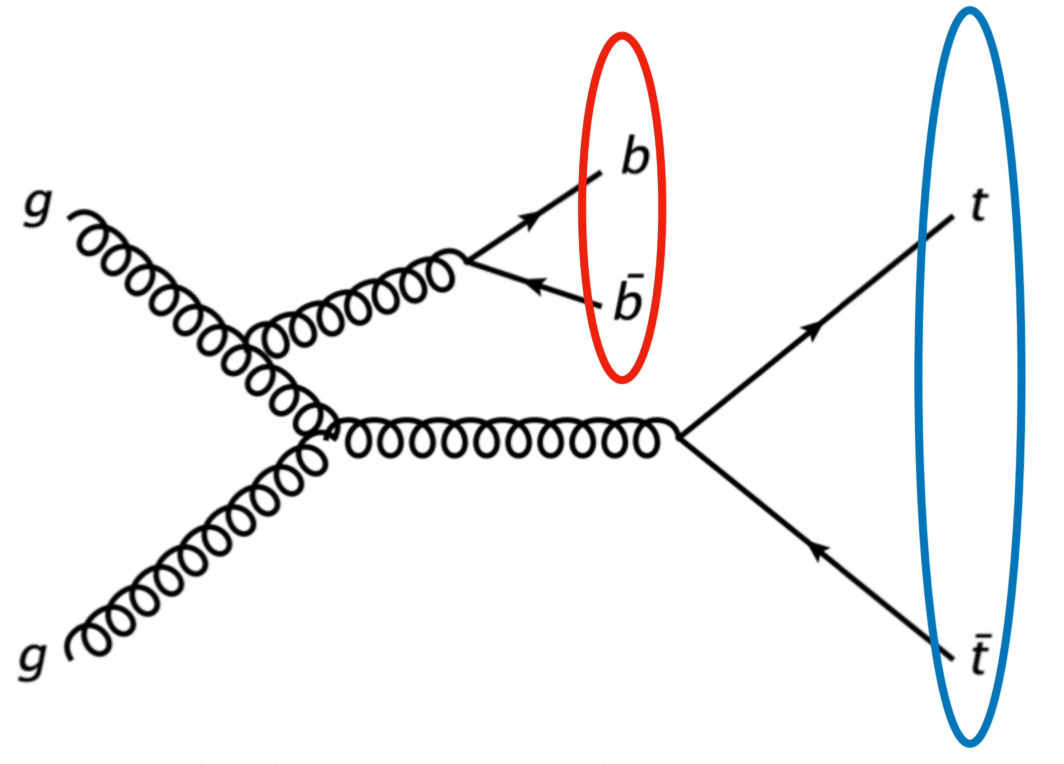
- Overview of the ttbb modelling, a cornerstone for ttH(H→bb) analyses, will be given.
- Following results will be covered:

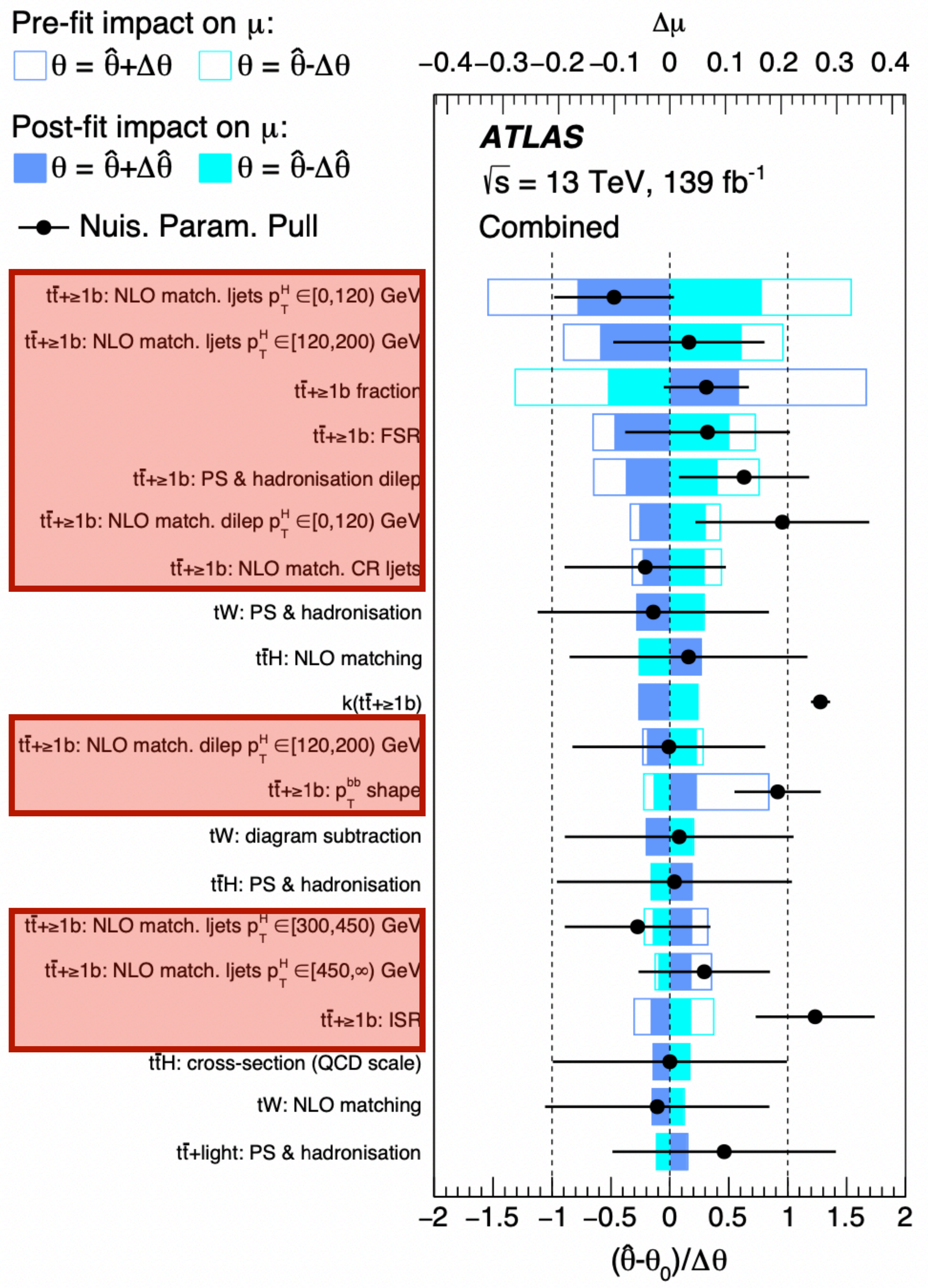
	ATLAS EXPERIMENT	CMS
ttH(H→bb) analysis	**HIGG-2020-23 (139 ifb)**	**CMS-PAS-HIG-18-030 (78 ifb)**
ttbb measurement	**JHEP 1904 (2019) 046 (36.1 ifb)**	**JHEP 07 (2020) 125 (35.9 ifb: leptonic)** **Phys. Lett. B 803(2020)135285 (all-had)**
ttbb modeling studies	**ATLAS and CMS comparisons:** **LHC top WG meeting 23-24 Nov**	
	ATL-PHYS-PUB-2022-006 (modeling optimisation)	

Introduction

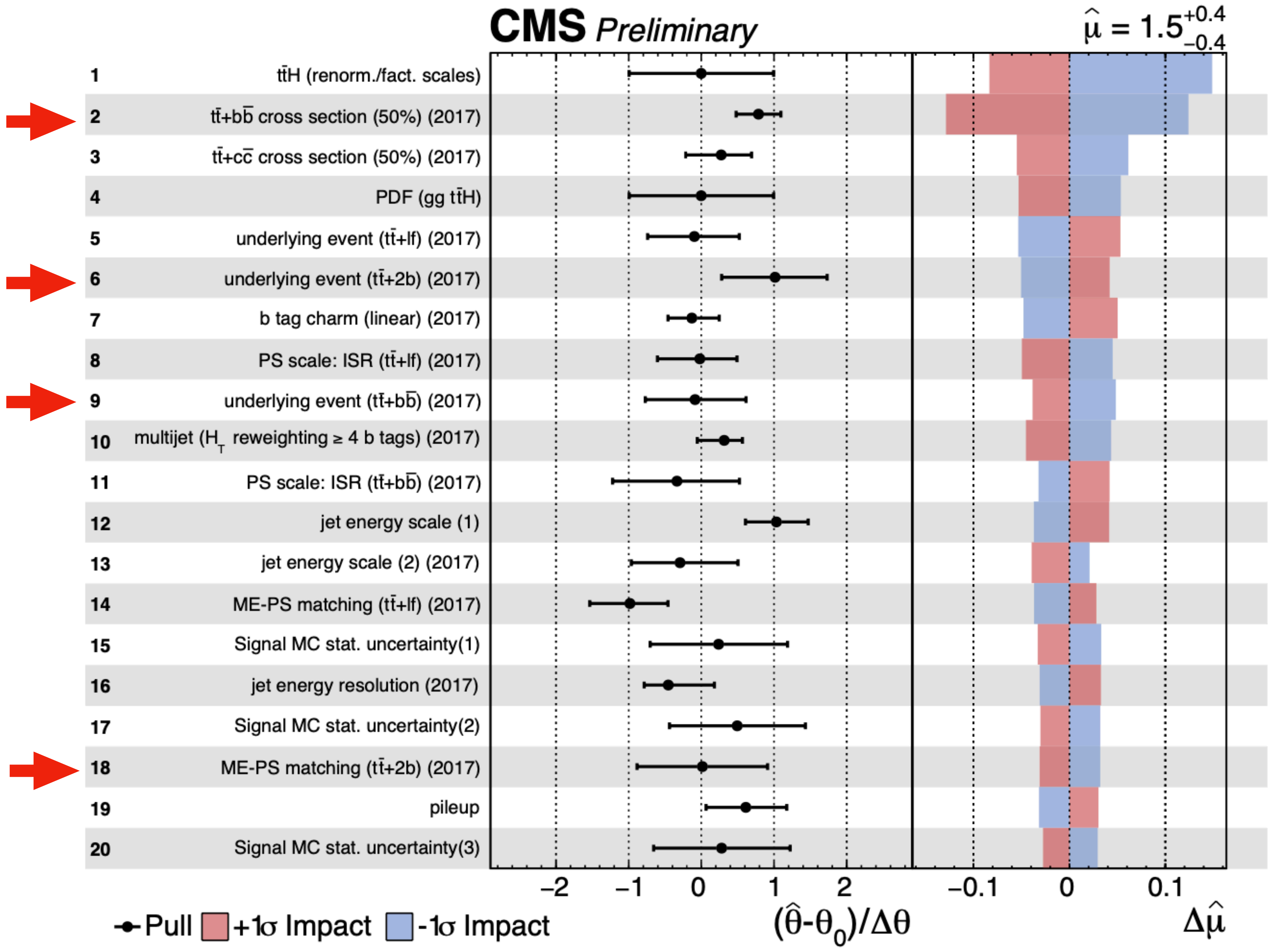
- **ttbb** production is a **challenging** process to model
  - multi-scale nature (m_{bb} ~ 10 GeV to m_{tt} ~350GeV) —> gap between tt and bb
  - significant differences among available MC predictions especially in bb modelling —> **large theoretical uncertainties**
- **Overwhelming and irreducible background** in ttH(H->bb) analysis: more details in Luisa Carvalho's and Angela Giraldi's talks
  - **ttbb modeling uncertainties** are the limiting factor of sensitivity in this analysis







HIGG-2020-23



CMS-PAS HIG-18-030

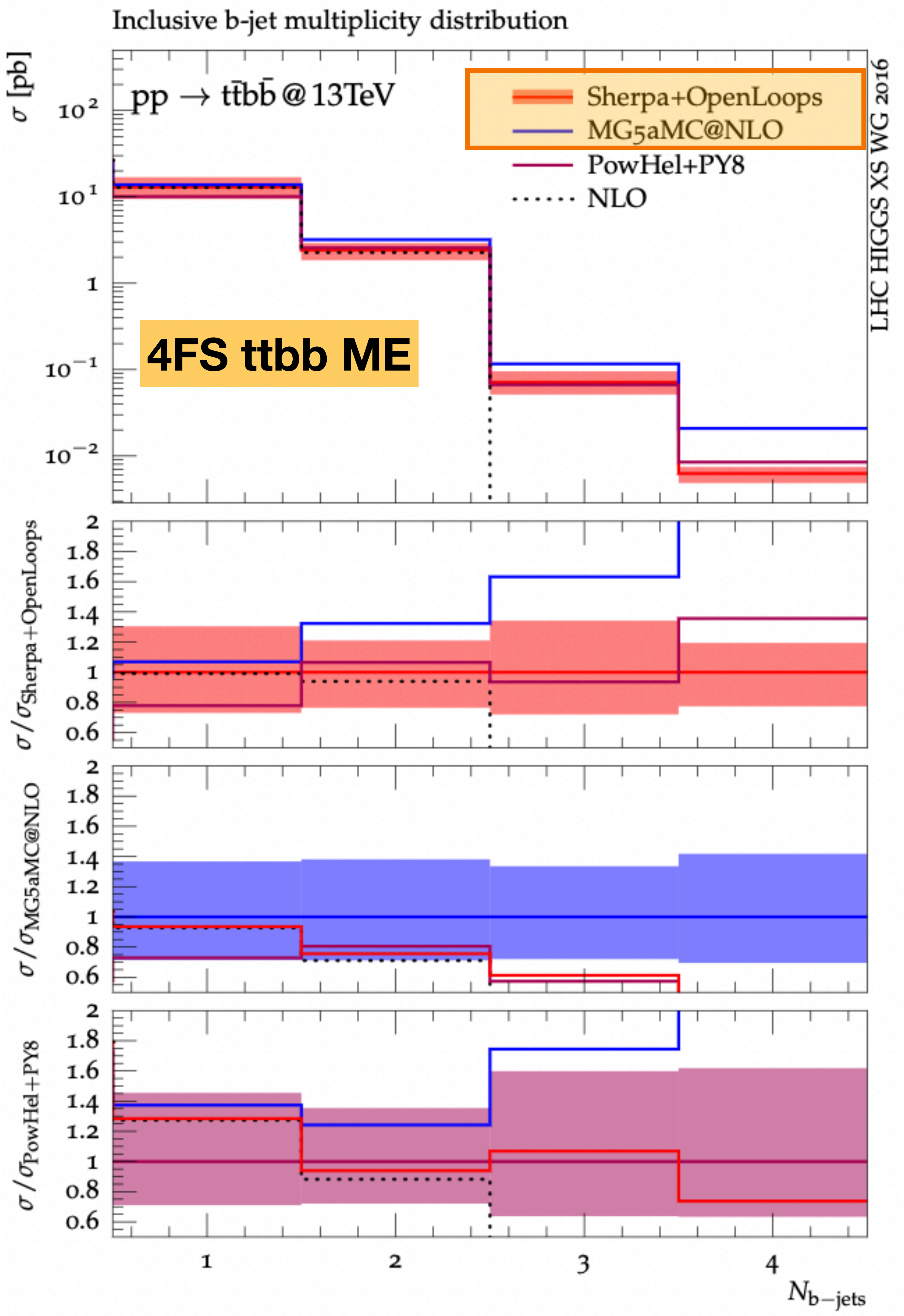
ttbb modeling @ LHC

- There are **two main approaches** to model ttbb:
  - **tt ME with Five-flavour scheme PDFs (5FS):**
    - *Inclusive* NLO+PS tt sample with additional b-quarks described by the Parton Shower (g->bb splitting)
    - *Multi-leg merged* tt+jets sample with additional b's from higher order MEs or Parton shower

  → b-quarks considered as massless in MEs

  → historically used in MC predictions for LHC
  - **ttbb ME with Four-flavour scheme PDFs (4FS):**
    - NLO+PS ttbb using MEs with massive b-quarks
    - Recently becoming nominal for ttbb description
  - Several tools available to the experiments for generating ttbb predictions:
    - **ME Generators**: POWHEG, SHERPA, MG5aMC@NLO,..
    - **Parton showers**: PYTHIA8, HERWIG, ..

YR4(arXiv:1610.07922)



ttbb modelling @ ATLAS (full Run 2 ttH(H->bb) analysis)

- **ttbb 4FS prediction** generated with **POWHEG+PYTHIA8** setup used as **nominal** for $tt+\geq 1b$ modelling:

Scales used: $\mu_R = \sqrt[4]{m_T(t) \, . \, m_T(\bar{t}) \, . \, m_T(b) \, . \, m_T(\bar{b})}$, $\mu_F = 0.5 \times \sum_{i=t,\bar{t},b,\bar{b},j} m_T(i)$, $h_{damp} = 0.5 \times \sum_{i=t,\bar{t},b,\bar{b}} m_T(i)$

- Alternative tt 5FS predictions were used for $tt+\geq 1c$ and $tt+$ light modelling and to assign uncertainties to $tt+\geq 1b$

Scales used: $\mu_R = \mu_F = m_T(t)$ and h_{damp}(POWHEG) $= 1.5 m_t$

- Modelling uncertainties assigned to $tt+\geq 1b$:
  - ISR (including ME scale) and FSR variations
    → based on 4FS
  - PS & hadronisation and NLO matching procedure
    → derived from 5FS and applied to nominal 4FS
  - Additional uncertainty on $tt+\geq 1b$ subcomponents fractions ($tt+1b$,$tt+\geq 2b$) was applied (from 5FS).

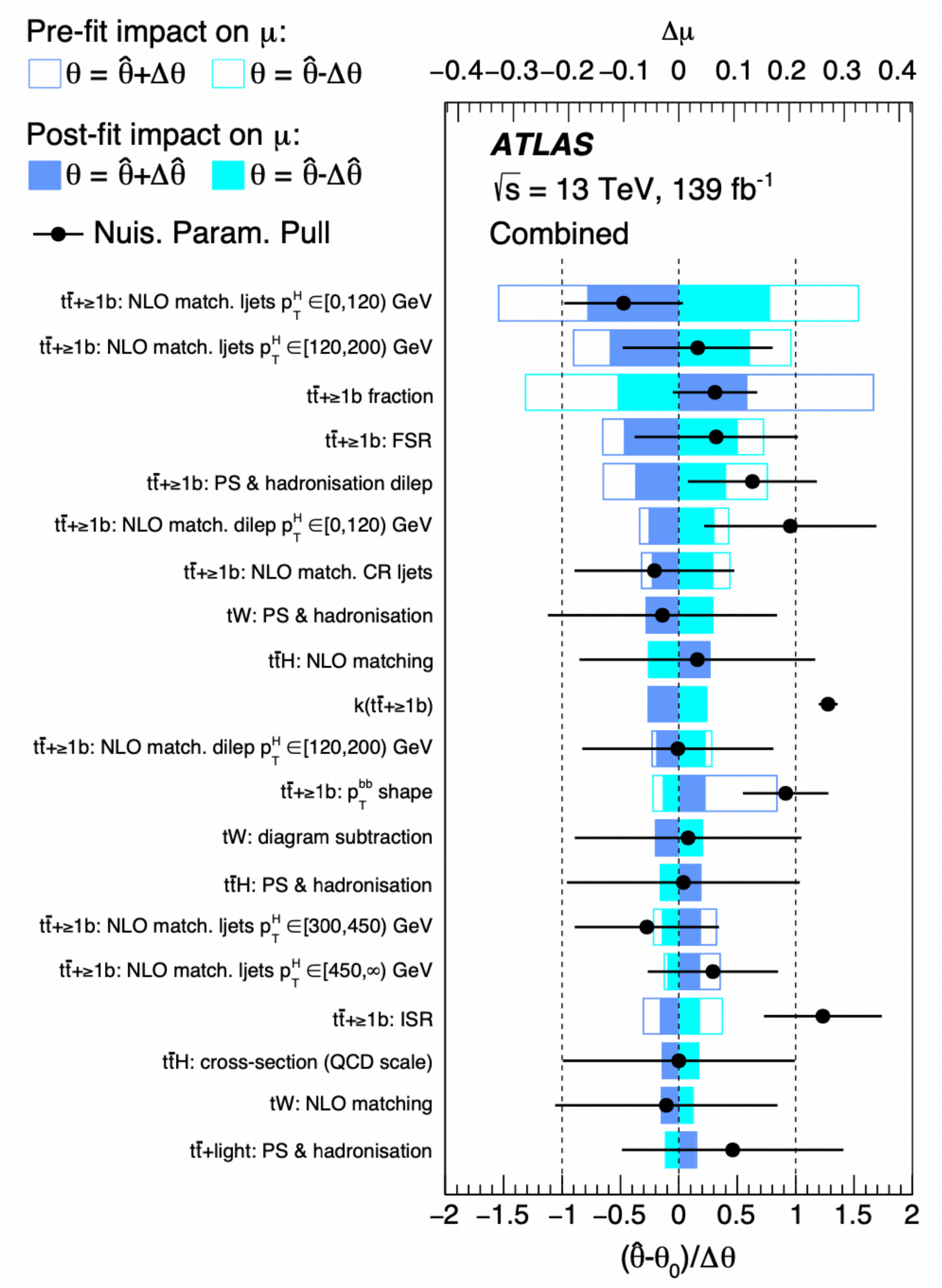
→ $tt+\geq 1b$ **normalisation** is left to **free-float** in the fit (fractions in alternative samples reweighed to match the nominal)

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}$ + light
$t\bar{t}+\geq 1b$ normalisation	Free-floating		$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1c$ normalisation	$\pm 100\%$		$t\bar{t}+\geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia 8 vs Powheg Box+Pythia 8		All
PS & hadronisation	Powheg Box+Herwig 7 vs Powheg Box+Pythia 8		All
ISR	Varying α_s^{ISR} (PS), μ_r & μ_f (ME)	in Powheg Box Res+Pythia 8	$t\bar{t}+\geq 1b$
		in Powheg Box+Pythia 8	$t\bar{t}+\geq 1c$, $t\bar{t}$ + light
FSR	Varying α_s^{FSR} (PS)	in Powheg Box Res+Pythia 8	$t\bar{t}+\geq 1b$
		in Powheg Box+Pythia 8	$t\bar{t}+\geq 1c$, $t\bar{t}$ + light
$t\bar{t}+\geq 1b$ fractions	Powheg Box+Herwig 7 vs Powheg Box+Pythia 8		$t\bar{t}+1b$, $t\bar{t}+\geq 2b$
p_T^{bb} shape	Shape mismodelling measured from data		$t\bar{t}+\geq 1b$

HIGG-2020-23

ttbb modelling @ ATLAS (full Run 2 ttH(H->bb) analysis)

- $tt + \geq 1b$ normalisation factor measured to be: **1.28 ± 0.08 —>** data favours a larger $tt + \geq 1b$ production cross-section
- **ttbb background modelling** is the **leading source of uncertainty** impacting the ttH(H->bb) measurement
  - large pulls associated with $tt + \geq 1b$ modelling also observed: e.g ISR, NLO matching
- $tt + \geq 1b$ modelling still drives the sensitivity despite significant improvement in corresponding theoretical knowledge
  - compared to previous measurement based on 36 ifb (Phys. Rev. D 97 (2018) 072016)



Uncertainty source	$\Delta\mu$	
Process modelling		
$t\bar{t}H$ modelling	+0.13	−0.05
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ NLO matching	+0.21	−0.20
$t\bar{t} + \geq 1b$ fractions	+0.12	−0.12
$t\bar{t} + \geq 1b$ FSR	+0.10	−0.11
$t\bar{t} + \geq 1b$ PS & hadronisation	+0.09	−0.08
$t\bar{t} + \geq 1b$ p_T^{bb} shape	+0.04	−0.04
$t\bar{t} + \geq 1b$ ISR	+0.04	−0.04
$t\bar{t} + \geq 1c$ modelling	+0.03	−0.04
$t\bar{t}$ + light modelling	+0.03	−0.03
tW modelling	+0.08	−0.07
Background-model statistical uncertainty	+0.04	−0.05
Total systematic uncertainty	+0.30	−0.28
$t\bar{t} + \geq 1b$ normalisation	+0.04	−0.07
Total statistical uncertainty	+0.20	−0.20
Total uncertainty	+0.36	−0.34

HIGG-2020-23

ttbb modeling @ CMS (2016+2017 ttH(H->bb) analysis)

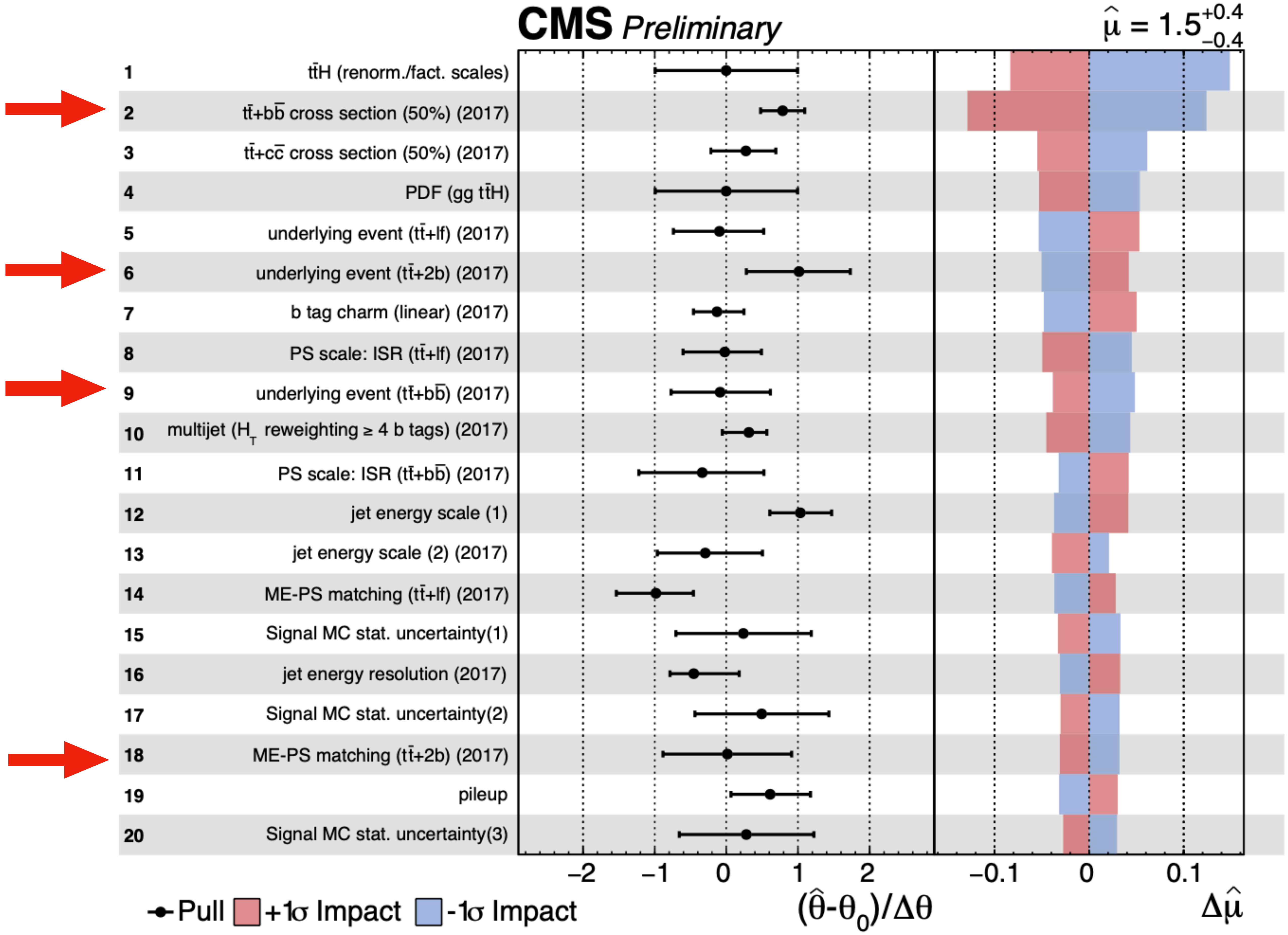
- $tt + jets$ **5FS prediction** generated with POWHEG+PYTHIA8 setup used as **nominal** for $tt + \geq 1b$ modelling**:**
  - Scales used: $\mu_R = \mu_F = m_T(t)$ and $h_{damp} = 1.379m_t$
  - Normalised to NNLO+NNLL inclusive cross-section
- $tt + \geq 1b$ divided to 3 contributions: tt+bb, tt+2b, tt+b—> **50% norm uncertainty on each process**
- Systematics (shape and rate): ME and PS scale variations (ISR and FSR), NLO matching (h_{damp} variation), UE tune, PDF.
- No dedicated comparison of different MC generators (2-point systematics) was used as uncertainty.

Source	Type	Remarks
Renorm./fact. scales ($t\bar{t}$)	rate	Scale uncertainty of NNLO $t\bar{t}$ prediction
$t\bar{t}$+hf cross sections	rate	Additional 50% rate uncertainty of $t\bar{t}$+hf predictions
PDF shape variations ($t\bar{t}H$, $t\bar{t}$)	shape	Based on the NNPDF variations, same for $t\bar{t}H$ and additional jet flavours
μ_R scale ($t\bar{t}$)	shape	Renormalisation scale uncertainty of the $t\bar{t}$ ME generator (POWHEG), same for additional jet flavours
μ_F scale ($t\bar{t}$)	shape	Factorisation scale uncertainty of the $t\bar{t}$ ME generator (POWHEG), same for additional jet flavours
PS scale: ISR ($t\bar{t}$)	shape	Initial state radiation uncertainty of the PS (for $t\bar{t}$ events), independent for additional jet flavours
PS scale: FSR ($t\bar{t}$)	shape	Final state radiation uncertainty of the PS (for $t\bar{t}$ events), independent for additional jet flavours
ME-PS matching (tt)	rate	NLO ME to PS matching, *hdamp* [51] (for tt events), independent for additional jet flavours
Underlying event ($t\bar{t}$)	rate	Underlying event (for $t\bar{t}$ events), independent for additional jet flavours

CMS-PAS-HIG-18-030

ttbb modeling @ CMS (2016+2017 ttH(H->bb) analysis)

- $tt + jets$ uncertainties namely $tt + \geq 1b$ have a **large impact on the measurement**
  - smaller compared to ATLAS (where it is driven by NLO matching 2-point systematic)
  - tt+bb XS highly ranked and pulled up—> **consistent with larger cross-section favoured by data**
  - pulls also observed on $tt + \geq 1b$ UE and ISR



CMS-PAS-HIG-18-030

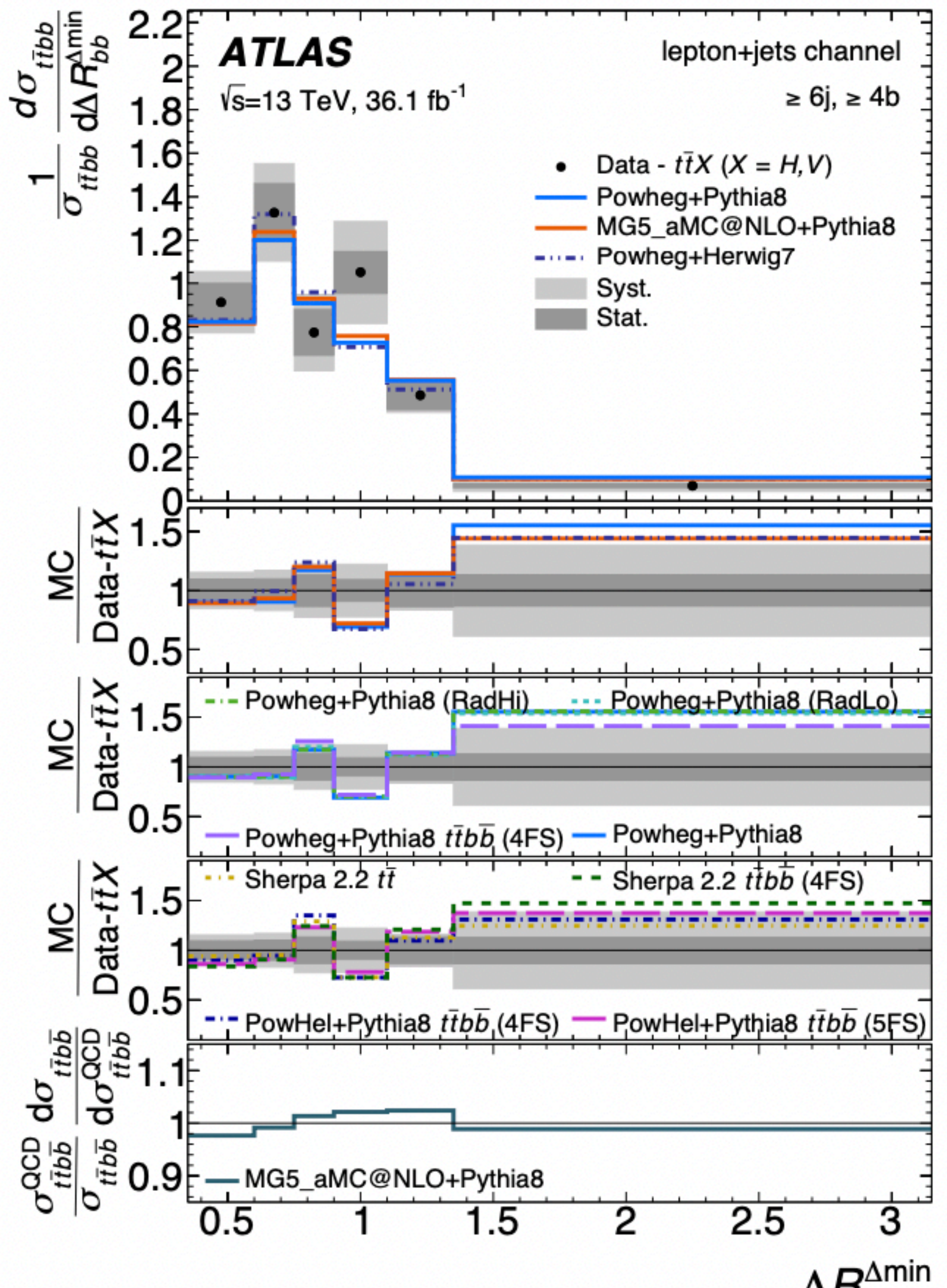
Uncertainty source	$\Delta\hat{\mu}$
Total experimental	$+0.15/-0.13$
b tagging	$+0.08/-0.07$
jet energy scale and resolution	$+0.05/-0.04$
Total theory	$+0.23/-0.19$
signal	$+0.15/-0.06$
tt̄+hf modelling	$+0.14/-0.15$
QCD background prediction	$+0.10/-0.08$
Size of simulated samples	$+0.10/-0.10$
Total systematic	$+0.28/-0.25$
Statistical	$+0.15/-0.15$
Total	$+0.32/-0.29$

ttbb measurements @ATLAS and CMS

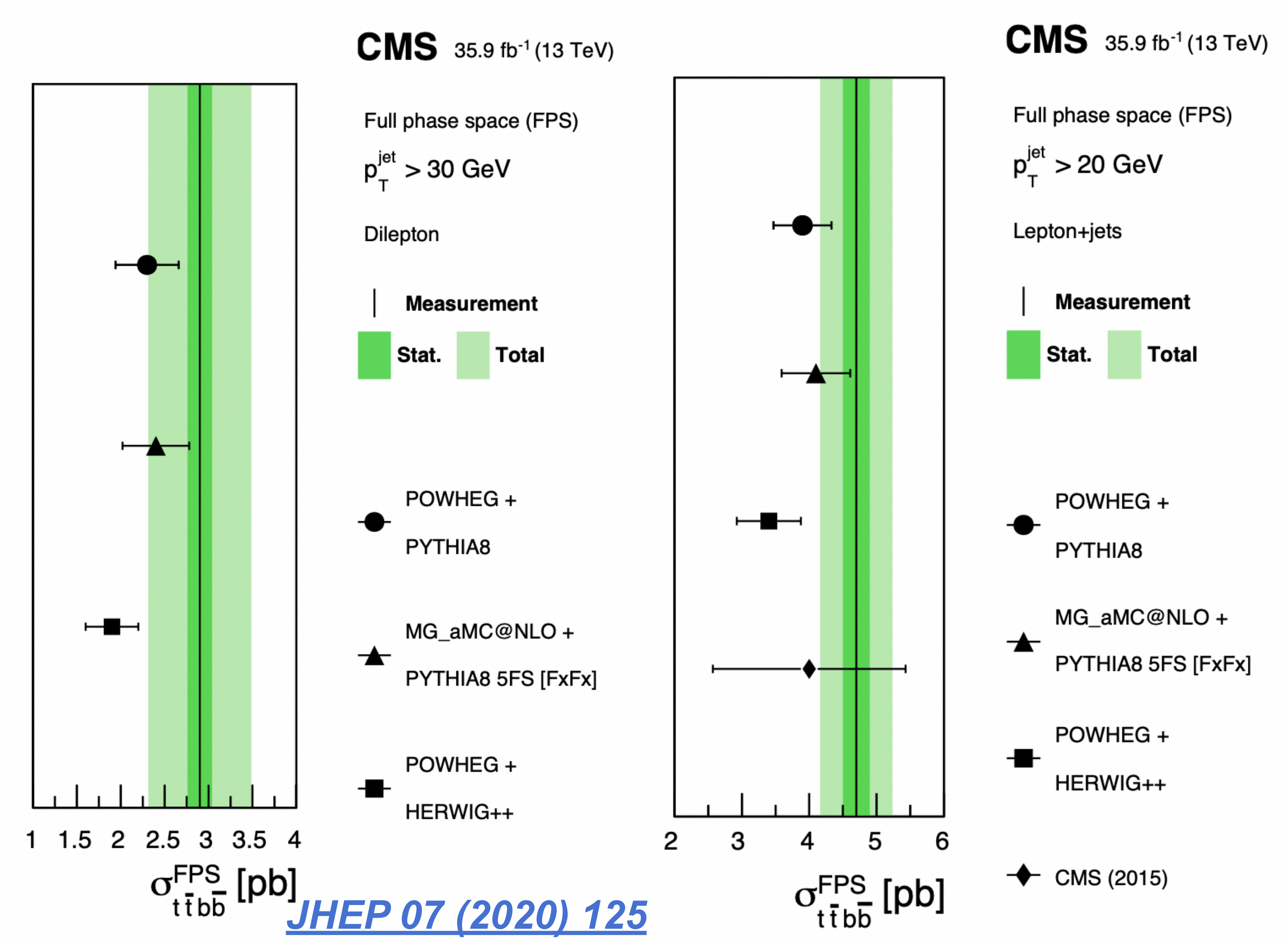
- Measurements of ttbb carried out to provide inputs for MC modelling improvements
  - Performed in ttHbb-like phase space (e.g requiring ≥ 3 or ≥ 4 b-jets)
  - Inclusive fiducial (and full phase space @CMS) measurements available across channels

—> differential measurements also available in lepton channels so far.

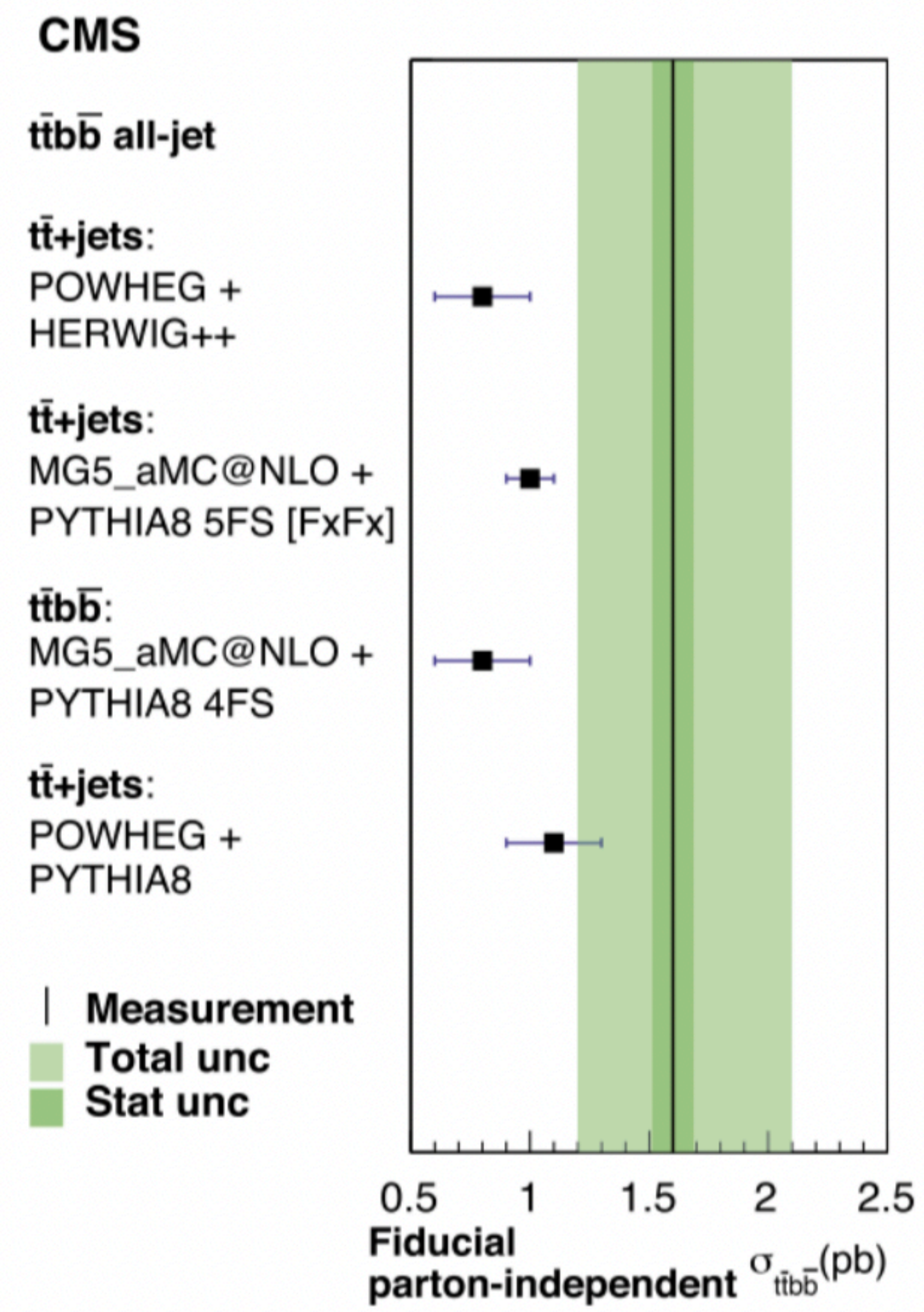
- Measured cross-sections found larger than predictions (30-40%)
  - Consistent with ttHbb results
  - Data cannot yet distinguish among most models despite improved precisions
  - Need to enhance precision further to be sensitive to modelling differences.



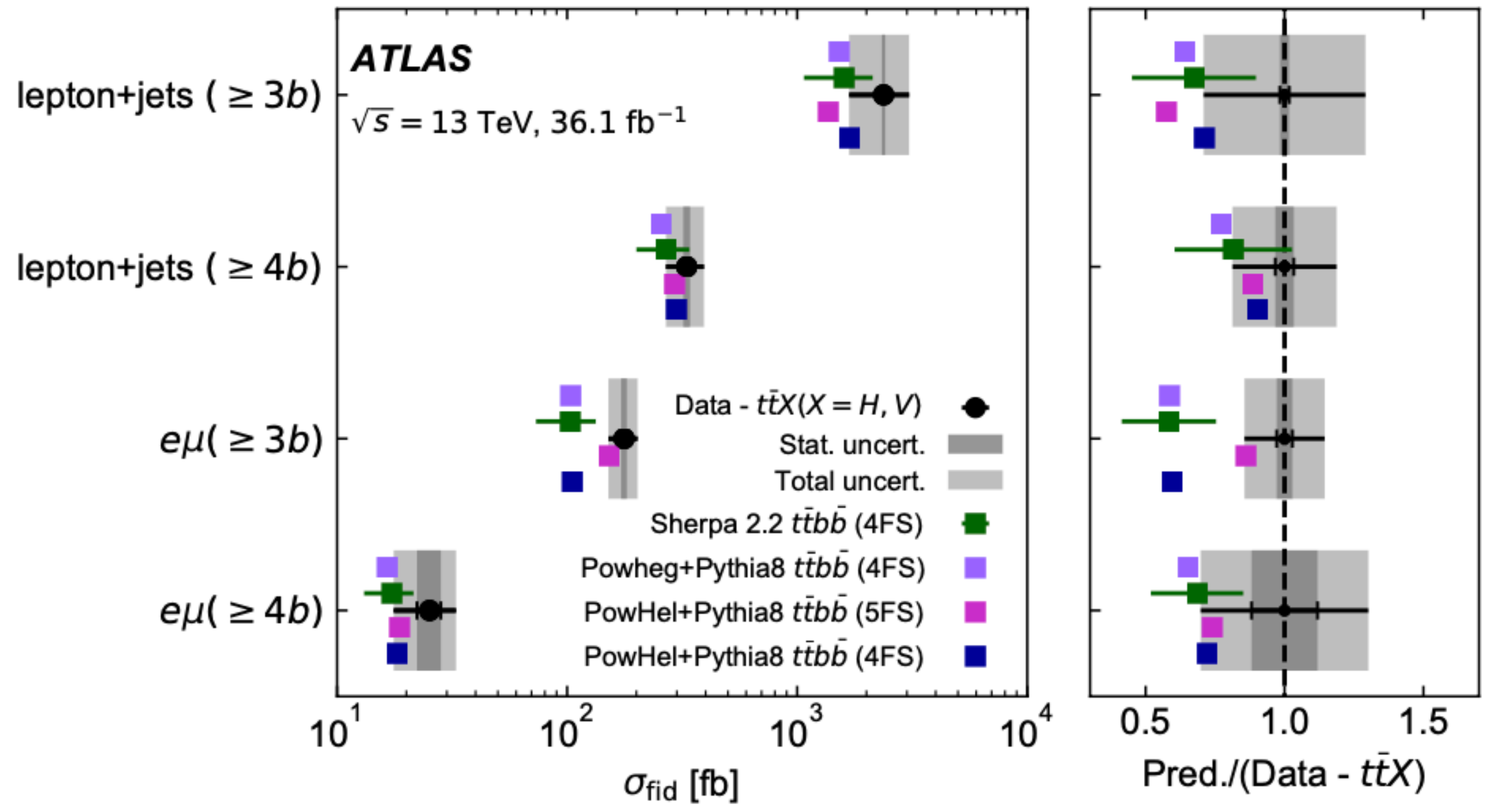
JHEP 1904 (2019) 046



JHEP 07 (2020) 125



Phys. Lett. B 803 (2020) 135285



ATLAS vs CMS comparisons

- Efforts launched within LHC Higgs WG since 2019 to compare the modelling of ttbb among the two experiments
  - in view of a **full Run 2 ttHbb ATLAS + CMS combination**
  - **goal**: understand possible differences at generator level in the experiments's setups

    → decide on a **common strategy for the ttbb treatment**
- Comparisons performed at the particle level in a ttHbb-like phase space and common between ATLAS and CMS
  - using tt and ttbb predictions used in last rounds of **Run 2 ttHbb analyses**

    → **Updated results** using latest predictions from ATLAS and CMS are in preparation and will be available soon.
  - comparisons performed in the single lepton channel (≥ 4 jets and ≥ 3 b-jets)

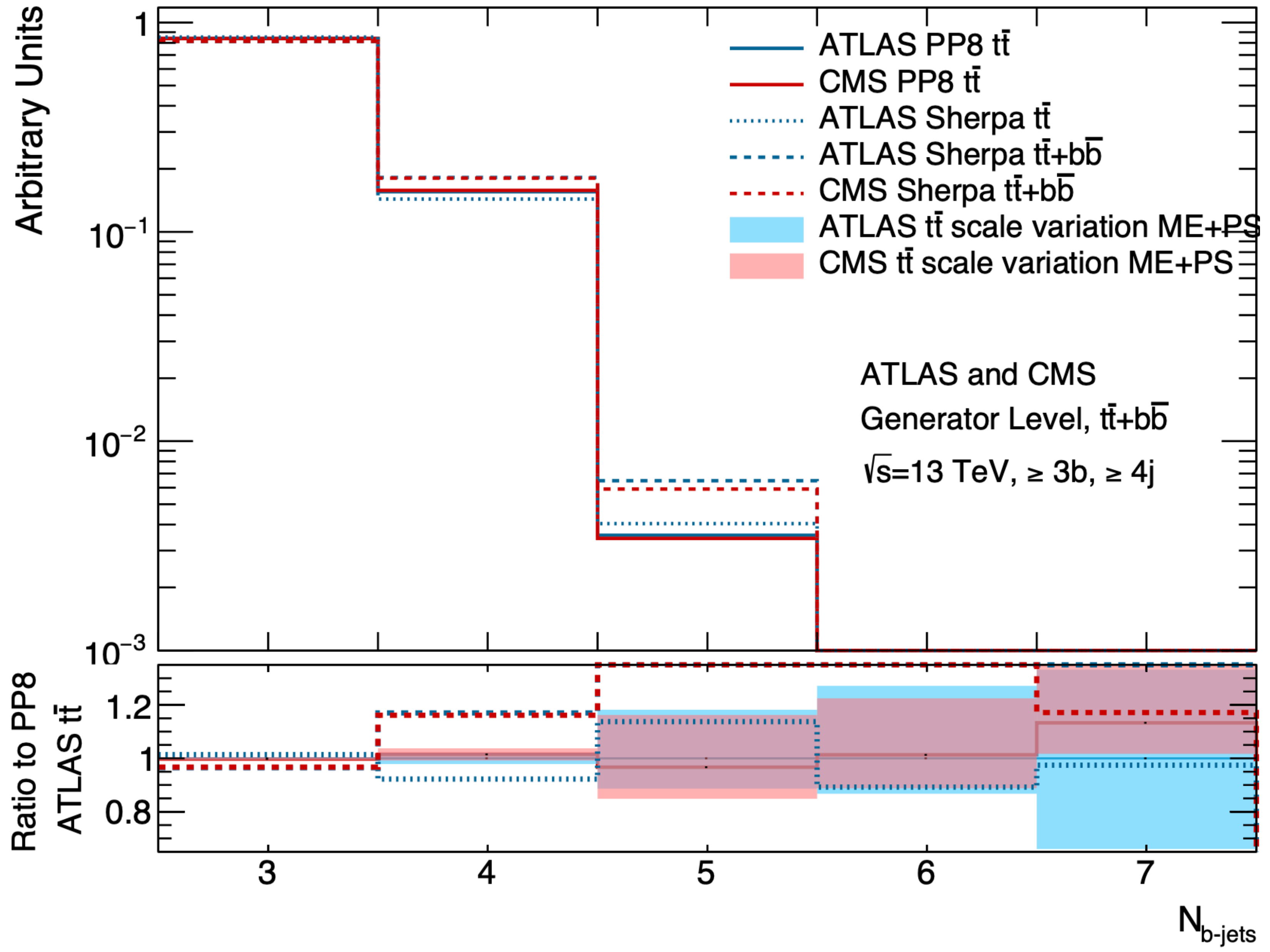
LHC Top WG meeting

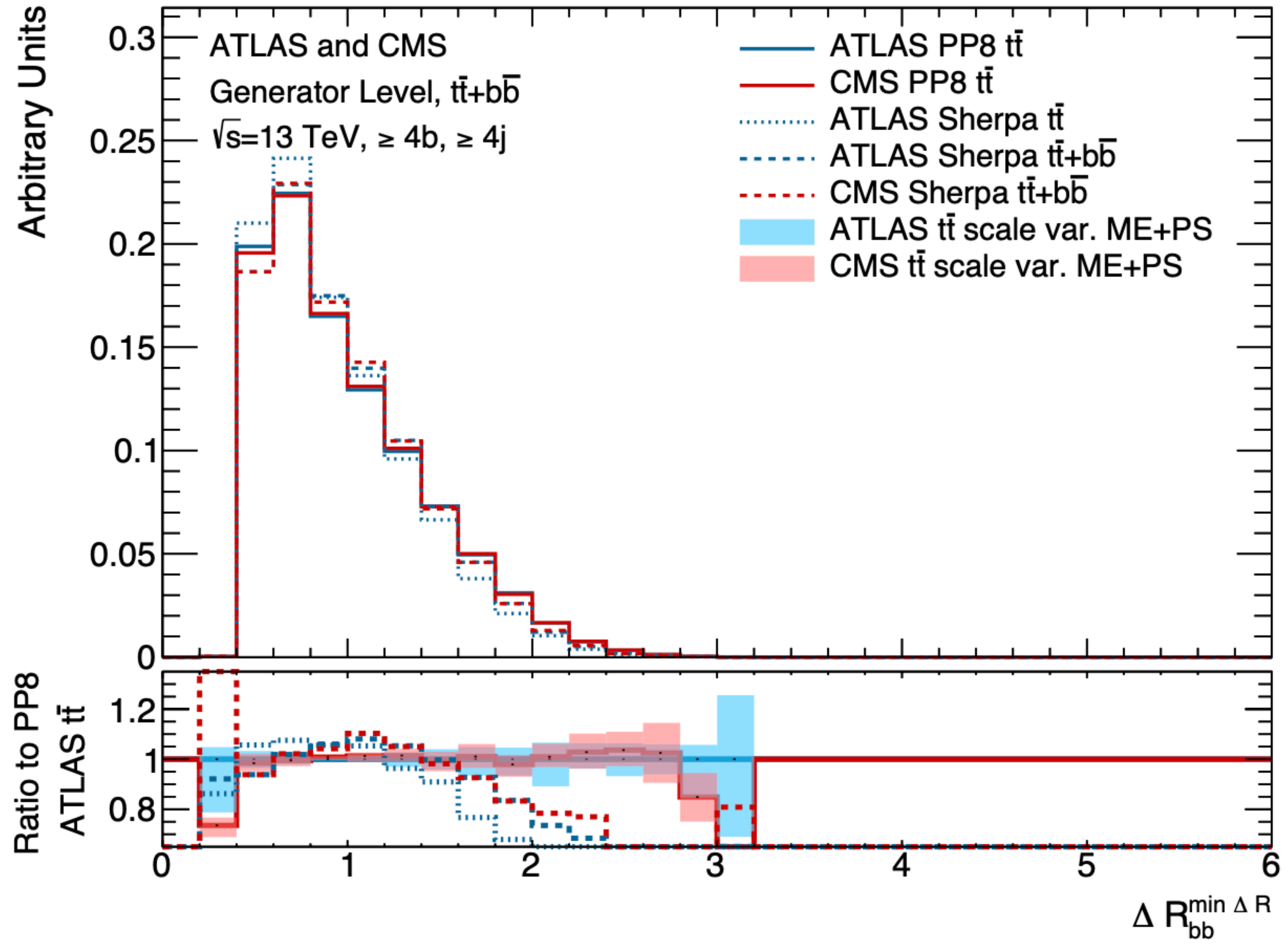
Experiment	Process	Generator	ME order	Shower	Tune	PDF set	h_{damp}	Cross section [pb]
ATLAS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	A14 [6]	5FS NNPDF3.0 NLO [7]	$1.5 \cdot m_{top}$	451.78 [8–13]
ATLAS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	A14 [6]	5FS NNPDF3.0 NLO [7]	$3.0 \cdot m_{top}$	451.78 [8–13]
CMS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	CP5 [14]	5FS NNPDF3.1 NLO [7]	$1.379 \cdot m_{top}$	451.78 [8–13]
CMS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	CP5 [14]	5FS NNPDF3.1 NLO [7]	$0.874 \cdot m_{top}$	451.78 [8–13]
CMS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	CP5 [14]	5FS NNPDF3.1 NLO [7]	$2.305 \cdot m_{top}$	451.78 [8–13]
ATLAS	$t\bar{t}+b\bar{b}$	Powheg-Box-Res [15–17]	NLO	Pythia 8 [5]	A14 [6]	4FS NNPDF3.0 NLO as 0118 [7]	$\Sigma_{i=t,\bar{t},b\bar{b}} m_T(i)$	16.89
CMS	$t\bar{t}+b\bar{b}$	Powheg-Box-Res [15–17]	NLO	Pythia 8 [5]	CP5 [14]	4FS NNPDF3.1 NLO as 0118 [7]	$1.379 \cdot m_{top}$	23.87
ATLAS	$t\bar{t}+b\bar{b}$	Sherpa 2.2.1 [16, 18, 19]	NLO	Sherpa	Sherpa default [20]	4FS NNPDF3.0 NNLO as 0118 [7]	–	14.21
CMS	$t\bar{t}+b\bar{b}$	Sherpa 2.2.4 [16, 18, 19]	NLO	Sherpa	Sherpa default [20]	4FS NNPDF3.0 NNLO as 0118 [7]	–	14.01
ATLAS	$t\bar{t}$	Sherpa 2.2.1 [21, 22]	tt+0,1NLO +2,3,4@LO	Sherpa	Sherpa default	5FS NNPDF3.0 NNLO [7]	–	451.78 [8–13]

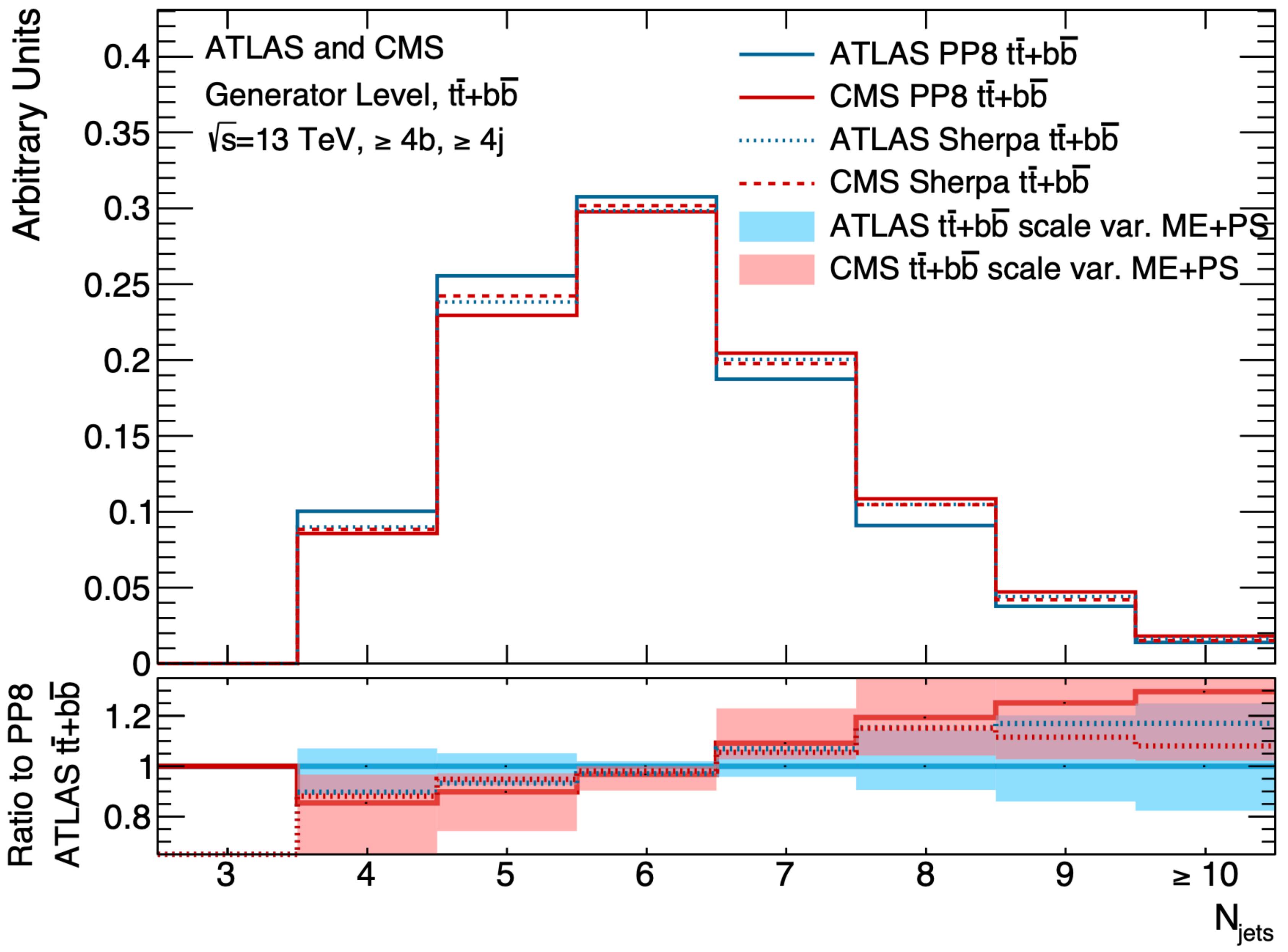
Samples considered in the comparisons

ATLAS vs CMS comparisons

LHC Top WG meeting





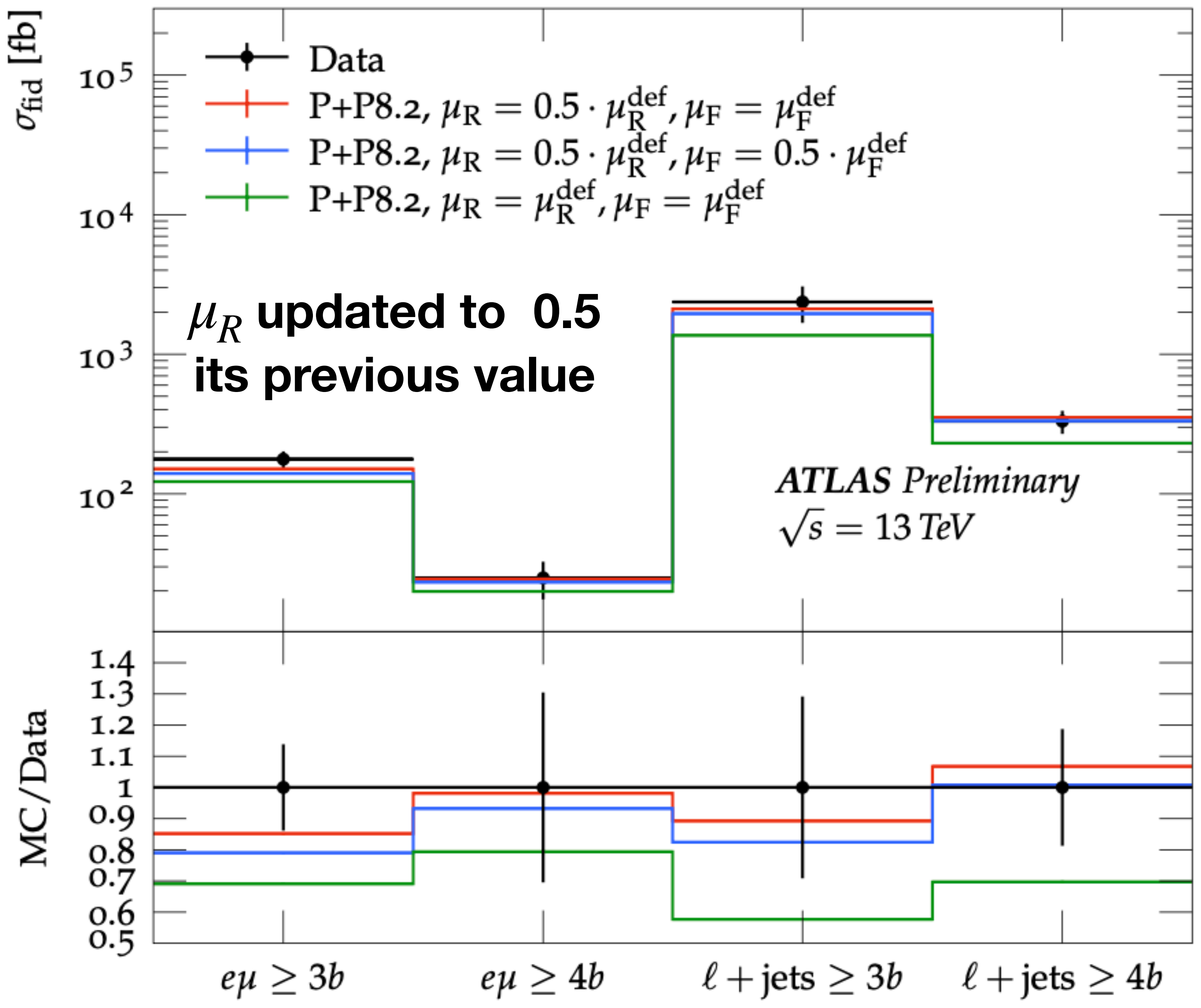


- Very good agreement between ATLAS and CMS in tt samples → both nominal distributions and scale variation size.
  - both ME scale and PS variations included in uncertainty bands except for Sherpa ttbb w/ ME variations only shown
- Large differences between Sherpa and POWHEG+PYTHIA8 tt predictions in $\Delta R_{bb}^{min \Delta R}$.
- Differences observed between ATLAS and CMS for POWHEG+PYTHIA8 ttbb distributions and scale variations
  - CMS has a larger scale variation for POWHEG+PYTHIA8 ttbb
  - CMS scale is a factor 2 lower than ATLAS in these comparisons (cf. backup)
- good agreement for Sherpa ttbb however which also agree with CMS POWHEG+PYTHIA8 ttbb

ttbb modelling optimisation @ ATLAS

- After first full Run 2 ttHbb and ttbb measurements, detailed studies of available MC predictions were carried out
  - Provide **recommendations for the nominal ttbb prediction** to be used in next round of ttHbb analysis (legacy Run 2)
  - **Explore impact of different modeling effects as inputs for the systematics scheme.**
- Parameters of the **nominal 4FS POWHEG+PYTHIA8** prediction were **revisited and optimised**
  - **POWHEG**: scales, h_{damp} and h_{bzd} choice, top quarks decay handling, negative weights reduction (factor 2)
  - **PYTHIA8**: p_T definition for matching, ISR shower recoil

—> **comparison** at both **parton and particle levels** as well as to **unfolded data** were used in these studies.



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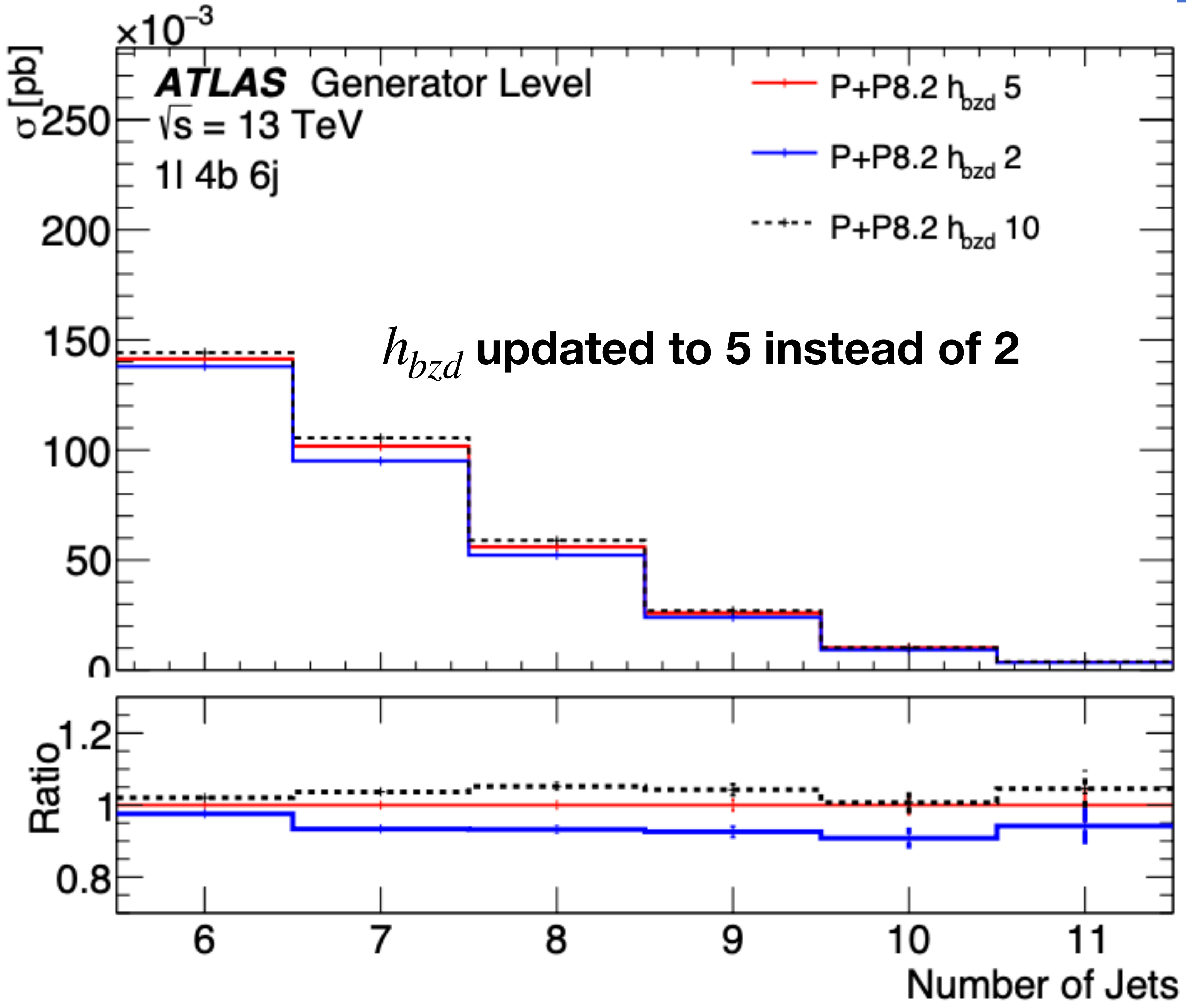
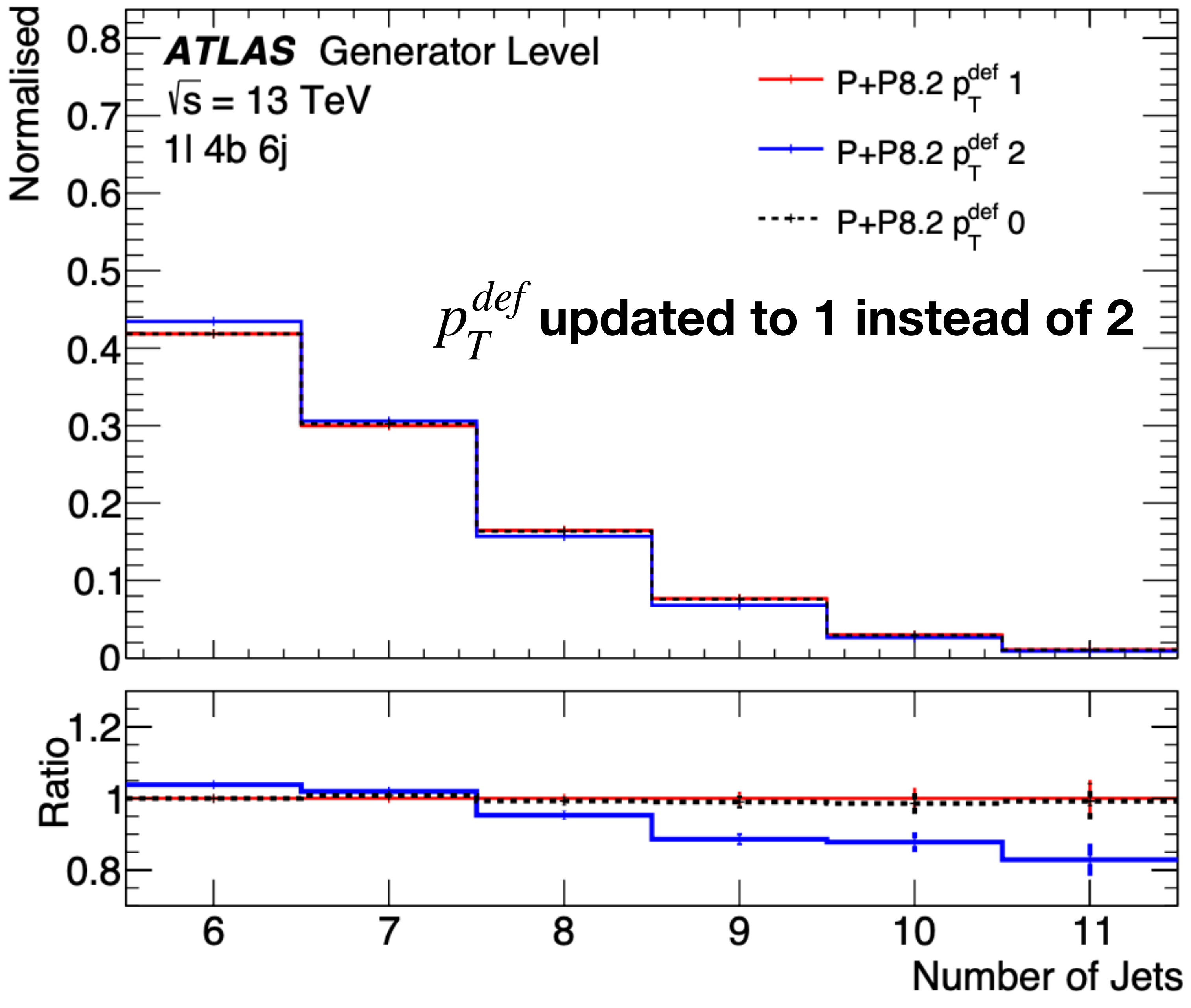
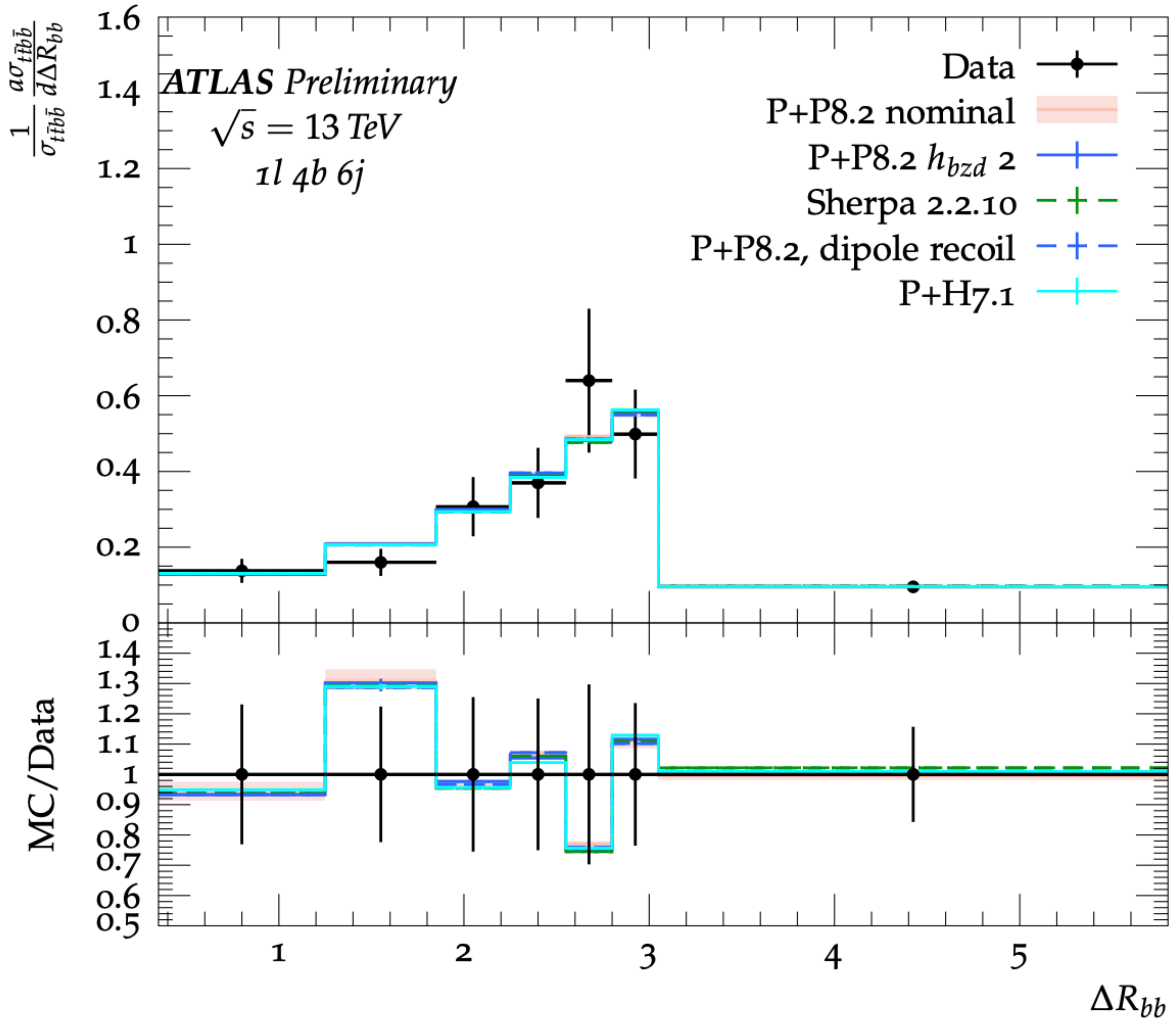


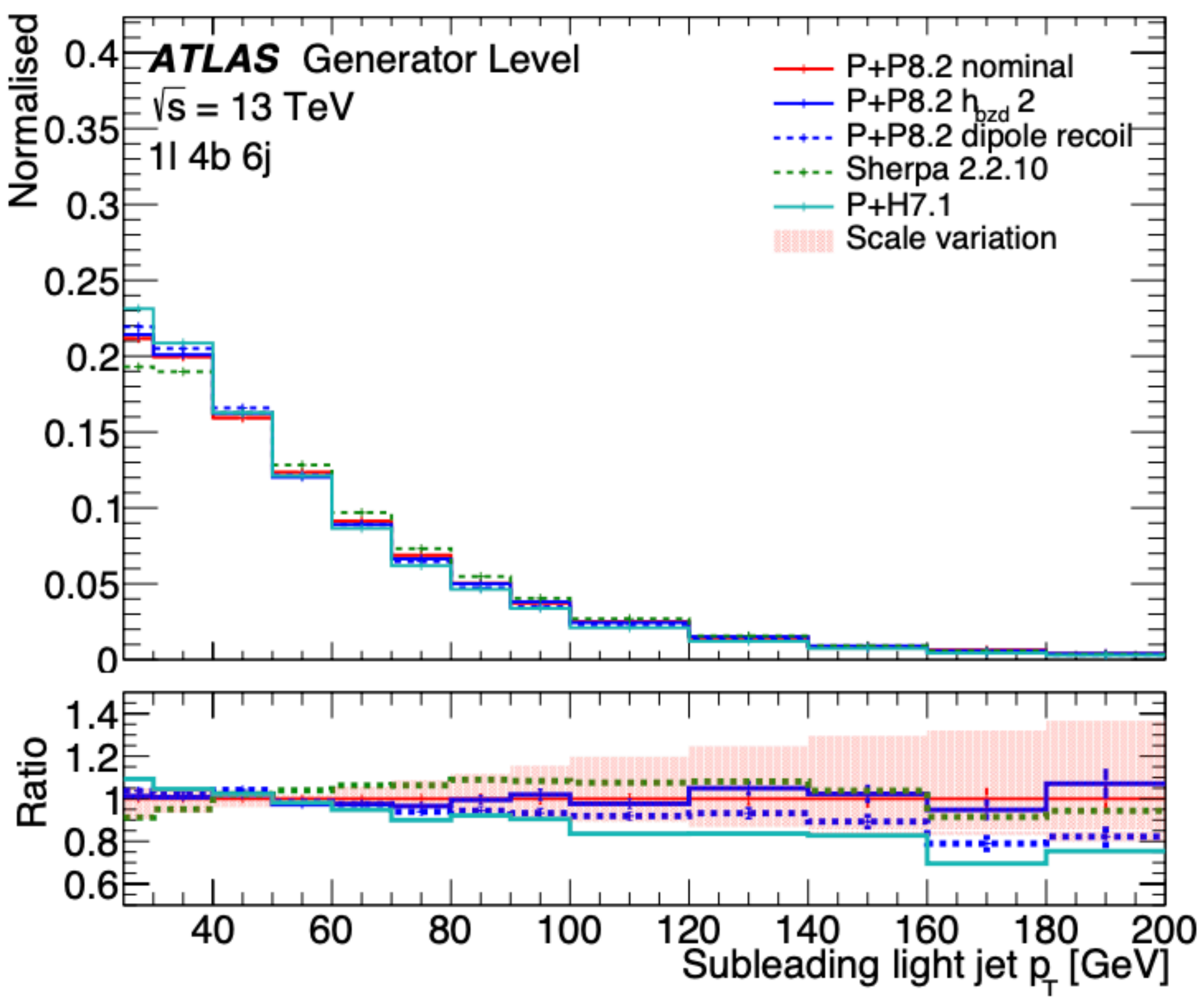


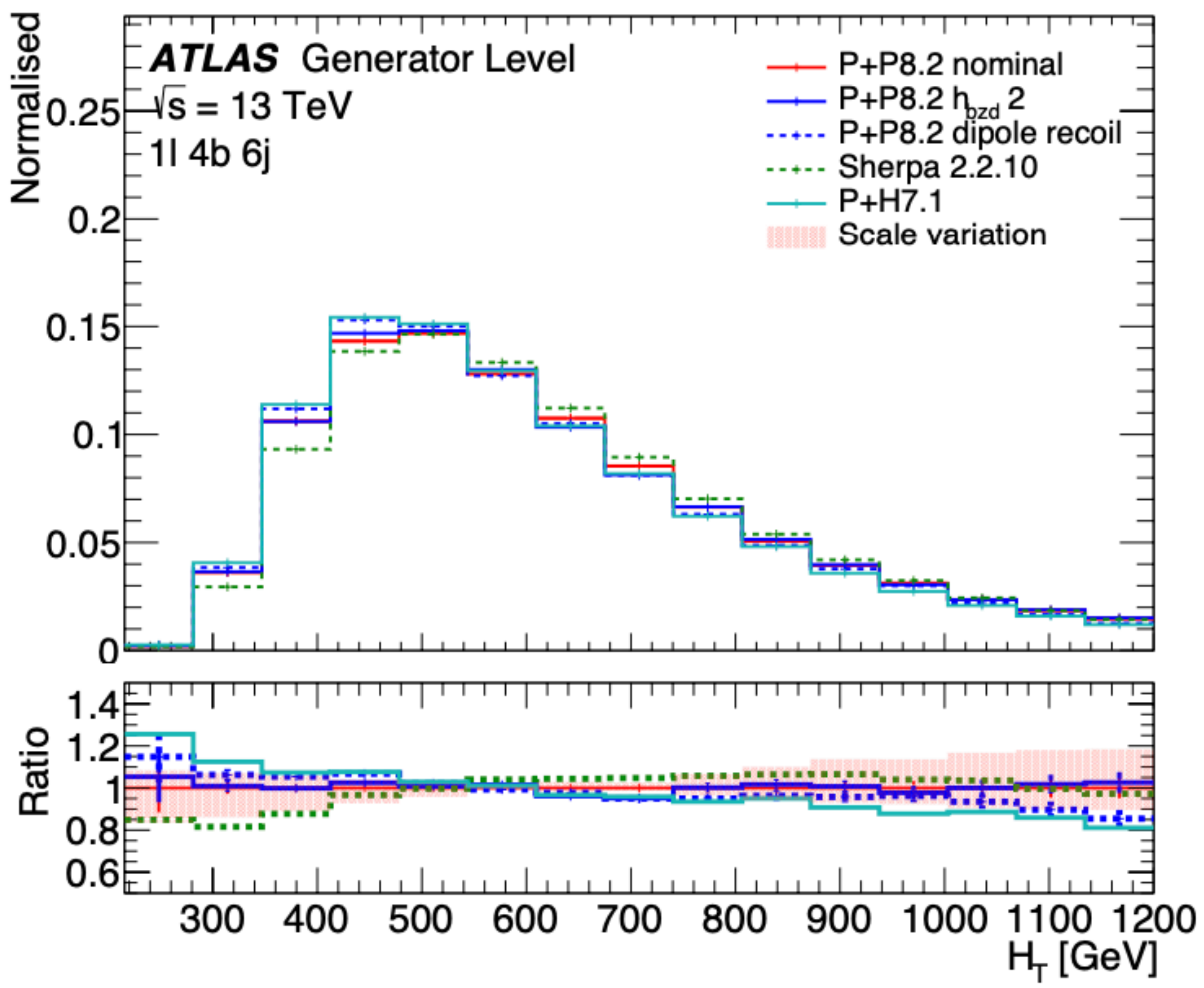
ttbb modelling optimisation @ ATLAS

- Optimised nominal prediction was compared to **alternative 4FS predictions**:
  - **NLO matching and generator choice**: SHERPA
  - **PS calculation**: POWHEG+HERWIG7, POWHEG+PYTHIA8 w/ dipole recoil/ **w/** $h_{bzd} = 2$
- **Shape** differences among predictions found small for b-jets from MEs observables: up to 10%
  - differences increase to 20% for observables related to additional light radiation from PS.

ATL-PHYS-PUB-2022-006







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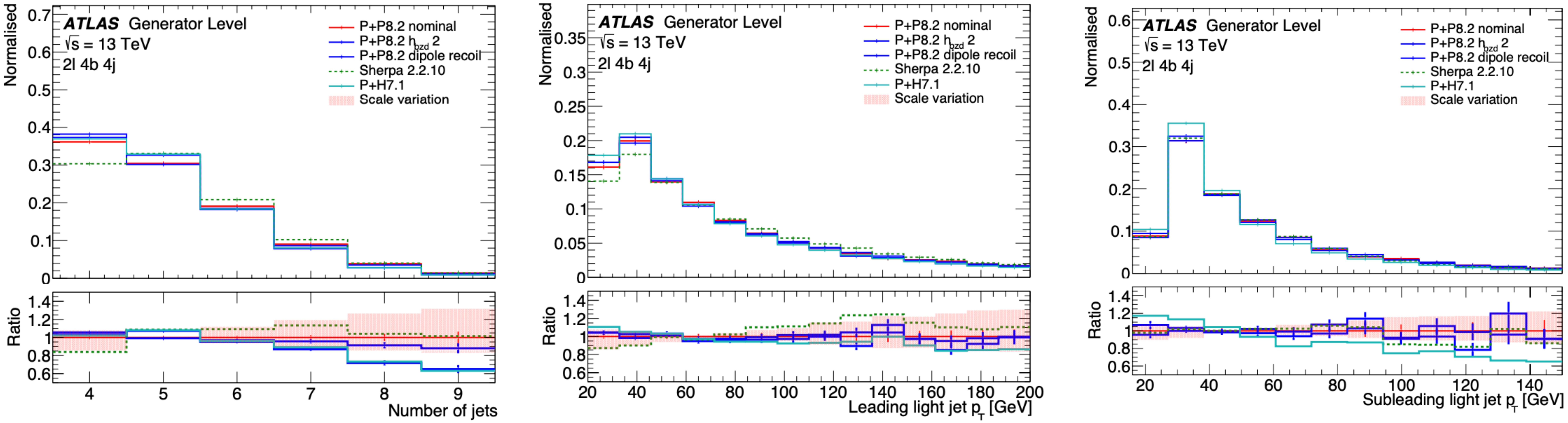


Summary

- **ttbb process is theoretically challenging to model—> multi-scale problem**
  - Traditionally relying on 5FS description but recently moving towards 4FS
  - Significant differences exist among available predictions especially in bb modelling
  - Main limiting factor of sensitivity for ttHbb measurement for both ATLAS and CMS
- **Efforts ongoing within LHC Higgs WG to adopt a common ttbb treatment between ATLAS and CMS**
  - In view of a full Run 2 ttHbb combination between the two experiments
- **Dedicated studies @ATLAS to optimise the pre-fit 4FS modelling of ttbb were presented**
  - Implementing the improved theoretical knowledge and making use of unfolded ttbb data
  - Different modelling effects explored to inform the systematic model for ongoing legacy analysis
  - Largest modelling differences after optimisations observed for additional light radiation (beyond bb)

Backups

ATLAS vs CMS comparisons

- Efforts launched within LHC Higgs WG since 2019 to compare the modelling of ttbb among the two experiments
  - in view of a **full Run 2 ttHbb ATLAS + CMS combination**
  - **goal**: understand possible differences at generator level in experiments' setups

    → decide on a **common strategy for the ttbb treatment**
- Comparisons performed at the particle level in a ttHbb-like phase space and common between ATLAS and CMS
  - First comparisons using ATLAS tt and ttbb predictions used in **partial Run 2 ttHbb analyses**

    —> updated results using latest predictions from ATLAS and CMS are in preparation and will be available soon.
  - comparisons performed in the single lepton fiducial volume ($\ell + \geq 4$ jets)

ATL-PHYS-PUB-2019-043

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}$	PowHeg v2	NLO	Pythia 8	5FS NNPDF3.0 NLO	A14
$t\bar{t} + b\bar{b}$	Powheg-Box-Res	NLO	Pythia 8	4FS NNPDF30_nlo_as_0118_nf_4	A14
$t\bar{t} + b\bar{b}$	Sherpa 2.2.1	NLO	Sherpa	4FS NNPDF30_nlo_as_0118_nf_4	Sherpa default
$t\bar{t}$	Sherpa 2.2.1	tt+0,1NLO+2,3,4@LO	Sherpa	5FS NNPDF3.0 NNLO	Sherpa default

Samples considered in the comparisons

POWHEG parameters

- μ_F: defines available phase space for QCD radiation.
- R: real emission, Rs: singular part, Rf finite part, F damping function: steers transition between Rs and Rf regions
- h_{damp}: regulates the high p_T emission against which the ttbb system recoils. Event weight changes from Rs to Rf when p_T of the order of h_{damp}
- $\mathscr{R}$: infrared (soft and collinear) approximation of full matrix element
- h_{bzd} (bornzerodamp): steers amount of events ending up in finite region: lower values lead to more events in Rf

$$R_s = F \cdot R$$
$$R_f = [1 - F]R,$$

$$F = F_{\text{damp}} \cdot F_{\text{bzd}}$$

$$F_{\text{damp}} = \frac{h^2_{\text{damp}}}{h^2_{\text{damp}} + p^2_{\text{T}}}.$$

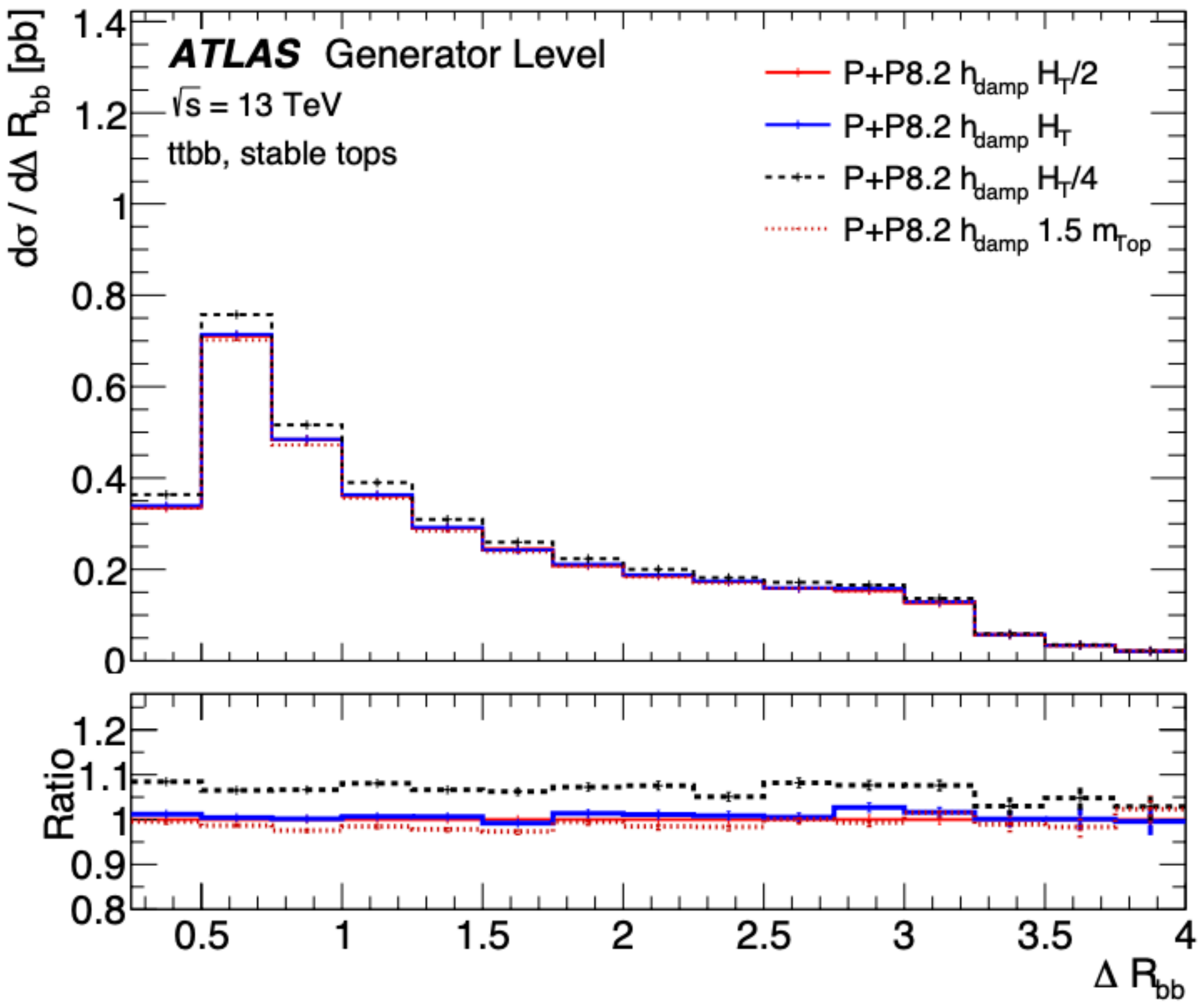
$$F_{\text{bzd}} = \theta\left(\text{h}_{\text{bzd}} - \frac{R}{\mathcal{R}}\right)$$

- Top decay handling: calculated by both POWHEG and MadSpin preserving spin correlations (same precision). POWHEG preferred and chosen for technical reasons—> compatibility with ttH generation.
- Negative weights: folding method in MC integration used to reduce fraction of negative weighted events by a factor of 2 with an acceptable increase of production time of 55%

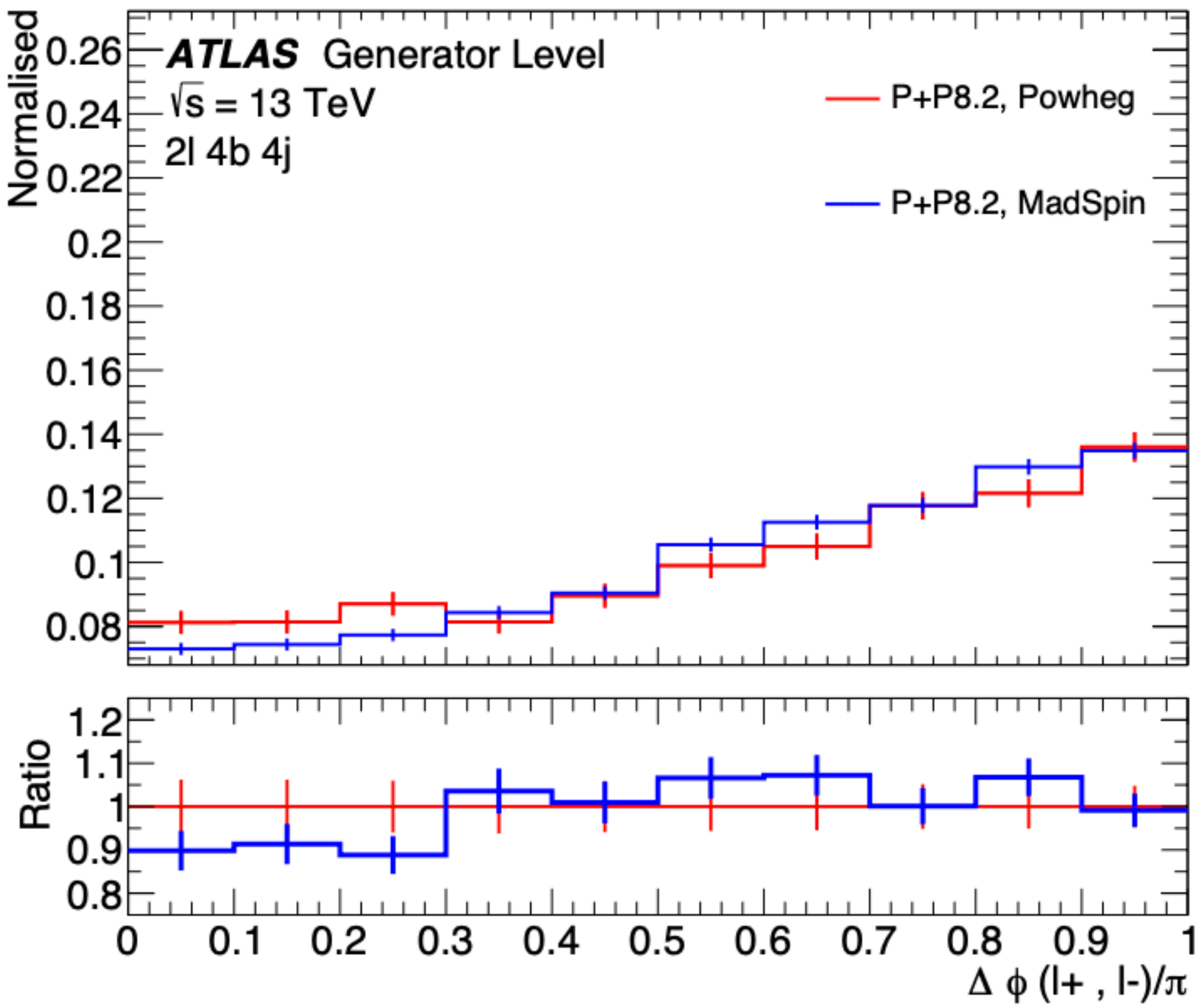
POWHEG +PYTHIA8 matching parameters

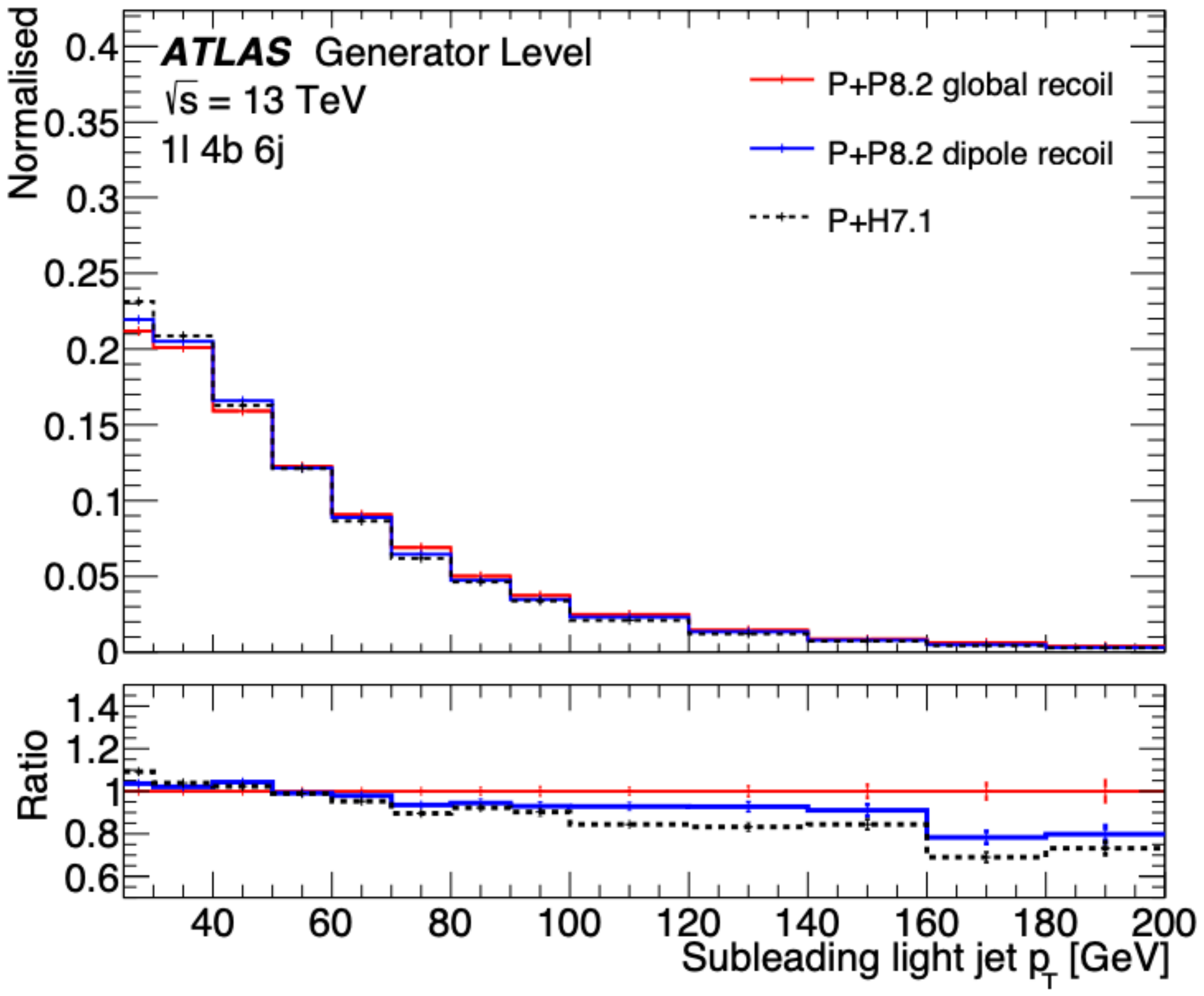
- p_T^{def}: sets the definition used for the calculation of the hardness criterion for the shower veto w.r.t ME (POWHEG).

ttbb modeling studies (hdamp optimisation)

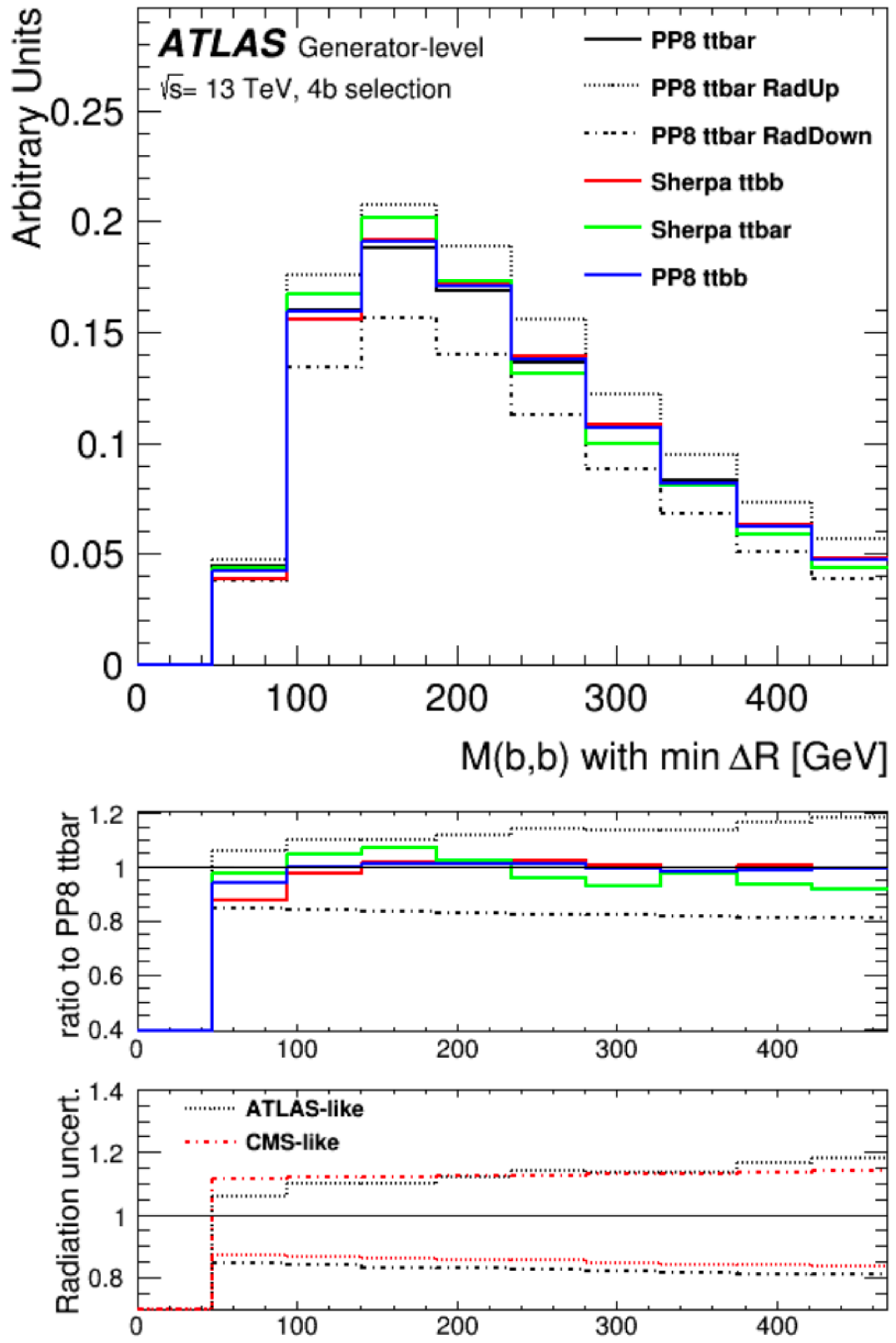


ttbb modeling studies (Decay handling, recoil)





ATLAS vs CMS comparisons



ATLAS vs CMS comparisons (scale choices)

LHC Top WG meeting

Sample	Scale ATLAS	Scale CMS
POWHEG +PYTHIA 8 (5FS $t\bar{t}$)	$\mu_{R,F} = \sqrt{m_t^2 + p_{T,t}^2}$	
POWHEG-BOX-RES +PYTHIA 8 (4FS $t\bar{t} + b\bar{b}$)	$\mu_R = \sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{2}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$	$\mu_R = \frac{1}{2}\sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{4}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$
SHERPA 2.2.4 (4FS $t\bar{t} + b\bar{b}$)		$\mu_R = \sqrt{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{4}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$
SHERPA 2.2.1 (4FS $t\bar{t} + b\bar{b}$)	$\mu_R = \sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{2}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$	
SHERPA 2.2.1 (5FS $t\bar{t}$)	$\mu_{R,F} = \sqrt{0.5 \cdot (m_{T,t}^2 + m_{T,\bar{t}}^2)}$ (core scale in CKKW-like scale choice)	-
Scale variation ME	$\mu_{R,F} = 0.5$ and $\mu_{R,F} = 2.0$	
ISR variation (PS, PP8)	Var3c A14 tune[1]	vary α_S^{ISR}, 0.5 and 2.0
FSR variation (PS, PP8)	vary α_S^{FSR}, 0.5 and 2.0	

ATLAS vs CMS comparisons

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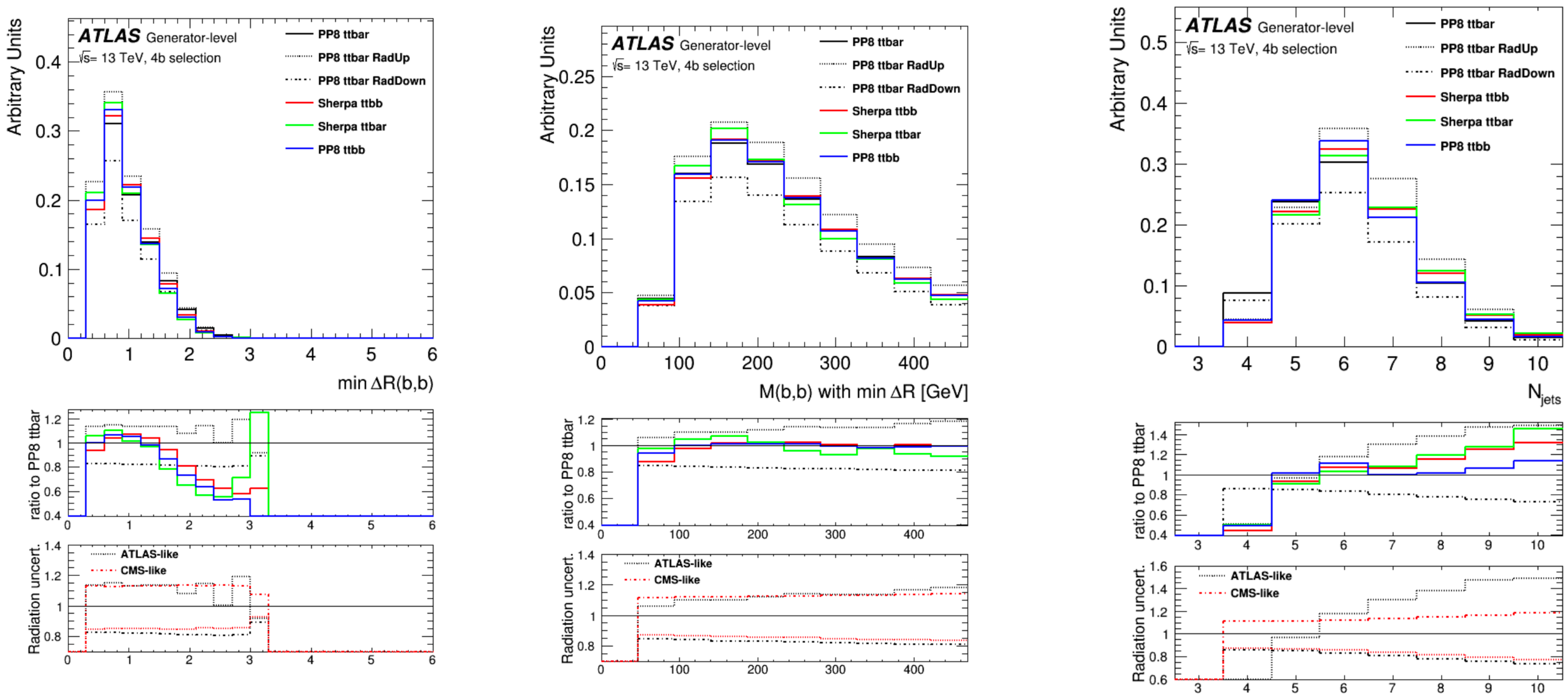

- Two approaches for the radiation variations in the inclusive 5FS POWHEG+PYTHIA8 are checked:
  - ATLAS-like: ME scales and A14 tune varied simultaneously (including h_{damp} for up variation)
  - CMS-like: ME scales and PDF tune variations summed in quadrature (no h_{damp} variation)
- Differences between 5FS POWHEG+PYTHIA8 and alternative generators are observed
  - can be larger than uncertainties given by the radiation variations
  - Large Poor agreement at large jet multiplicities

ttbb modelling optimisation @ ATLAS

Table 1: Configurations used for the MC generation.

Generator	ME order	PS	PDF	Tune
POWHEG BOX RES	NLO	PYTHIA 8.244	NNPDF3.1 nnlo Nf4	A14
	NLO	HERWIG 7.1.6	NNPDF3.1 nnlo Nf4	H7.1.6 default
SHERPA 2.2.10	NLO	SHERPA	NNPDF3.0 nnlo Nf4	SHERPA default

Parameter	previous value	new default value
PDF	NNPDF3.0 nnlo Nf4	NNPDF3.1 nnlo Nf4
Scale choice[a] [b]	$\mu_R^{def} = \sqrt[4]{\prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}}$ $\mu_F^{def} = \frac{1}{2}[\sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i}]$	$\mu_R = 0.5 \cdot \mu_R^{def}$ $\mu_F = \mu_F^{def}$
h_{bzd}	2	5
h_{damp}	$H_T/2$	$H_T/2$
Decay handling	MadSpin	POWHEG
PYTHIA8 POWHEG:$pTdef$	2	1
PYTHIA8 SpaceShower:dipoleRecoil	off (global recoil)	off (global recoil)