Measurement of tt+bb and news on its simulation

June 3rd 2019, LHC Discussion

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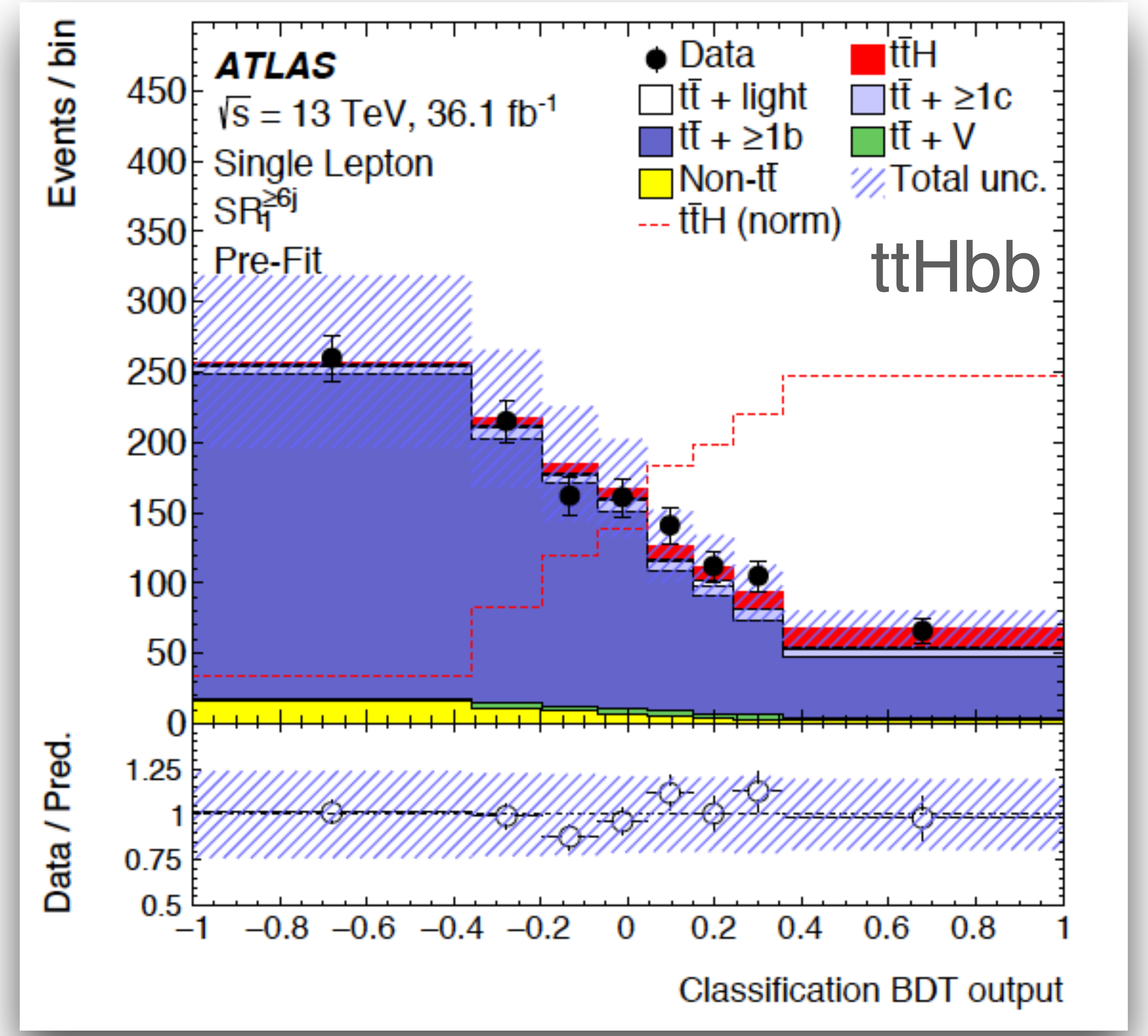
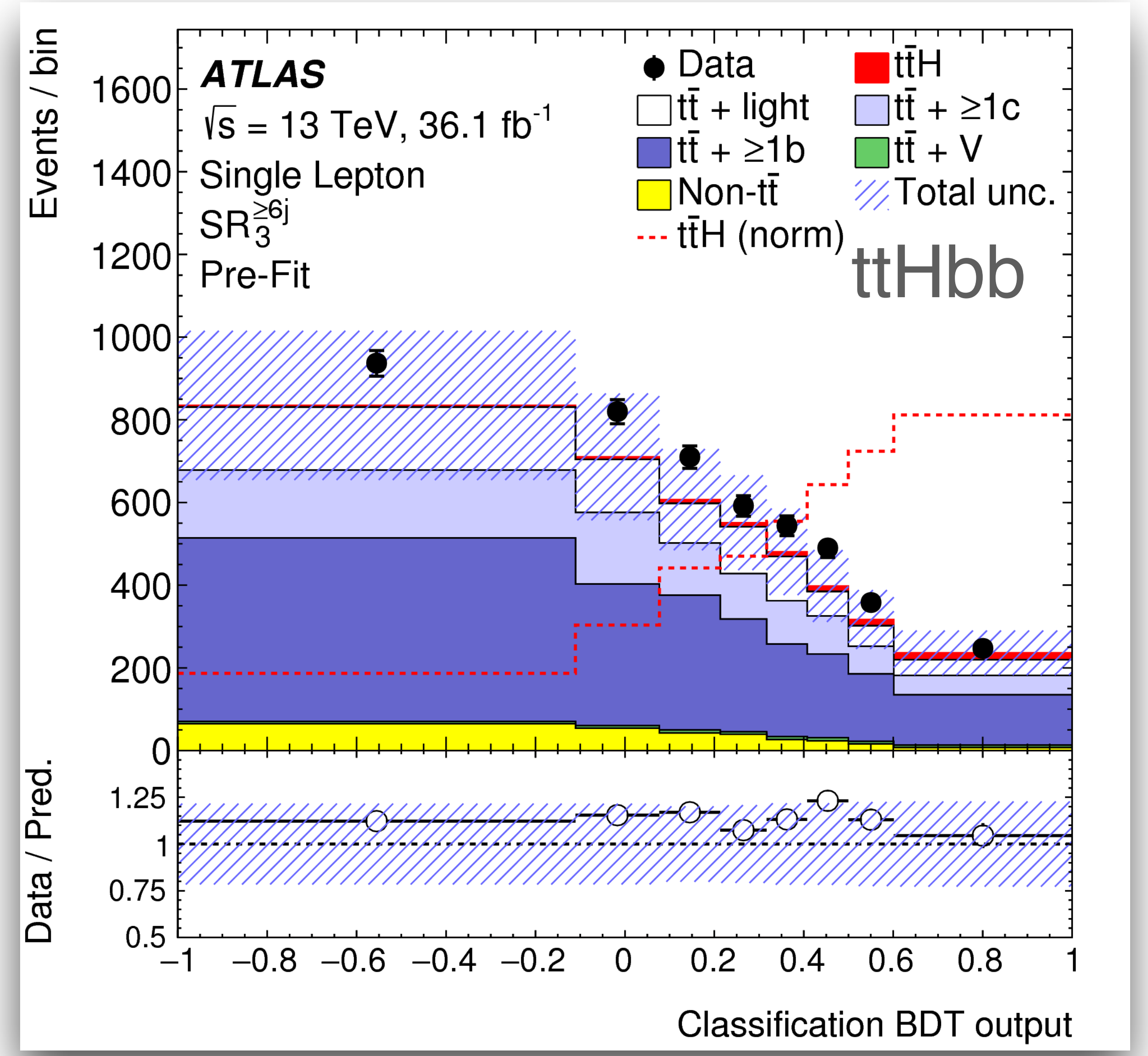
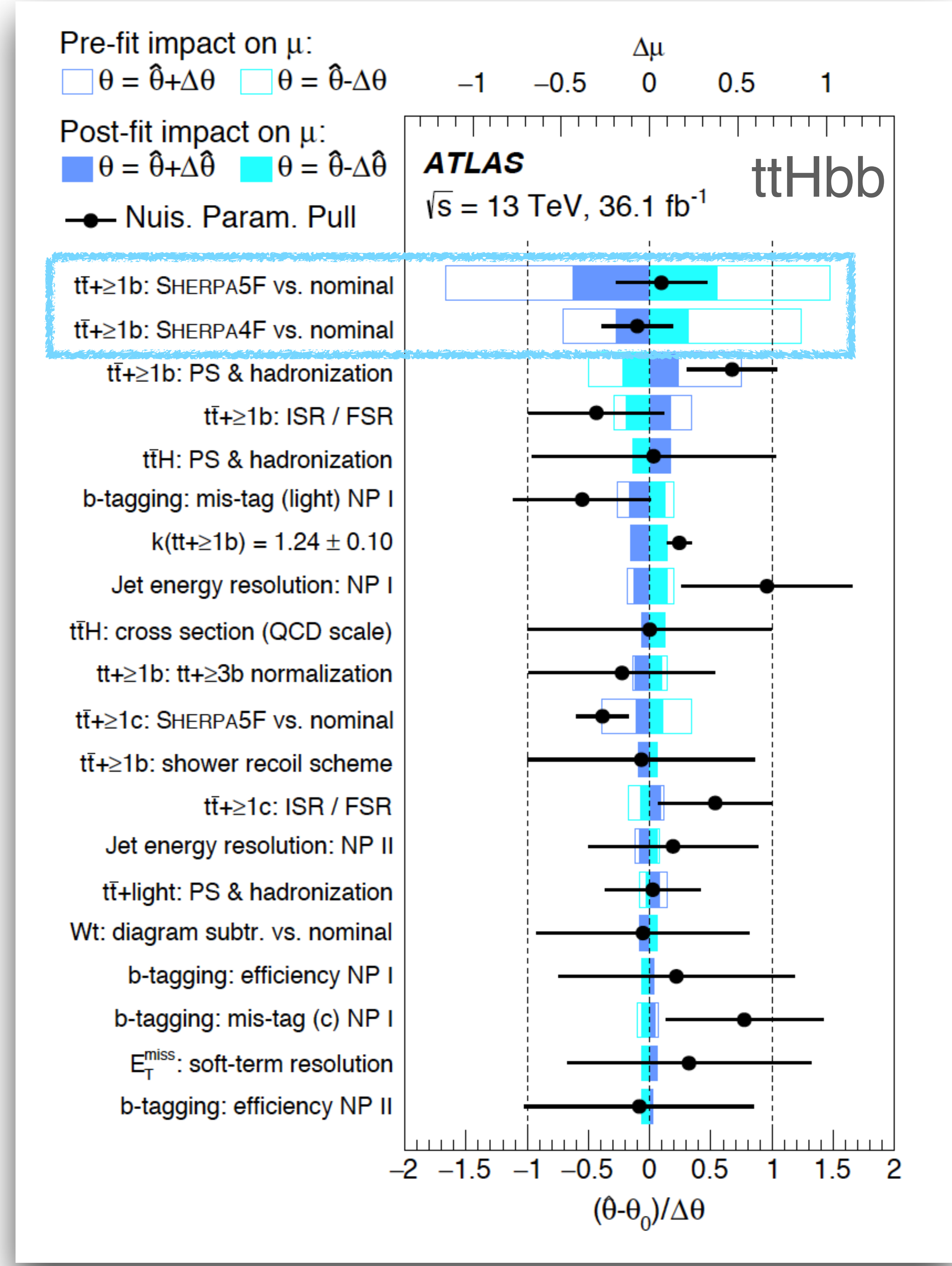
Motivation

- tt+HF tt+Heavy Flavour production is large and irreducible background limiting the precision of ttH (H->bb) measurements and searches.
- In the most signal like region, signal yields are ~20% over 80% ttbb background; only ~5-8% of all ttbb events are in this region
    - low uncertainty on the background modelling in total and in the tails of the differential distributions is mandatory to measure ttH signal
- Provide measurements to better understand QCD HF production; constrain MC models for ttbb
- Depending on the signal region definition, tt+light and tt+charm jets are non-negligible background
    - Development in simulation: Inclusive prediction of jet production in top pair events including precise b-pair production desired

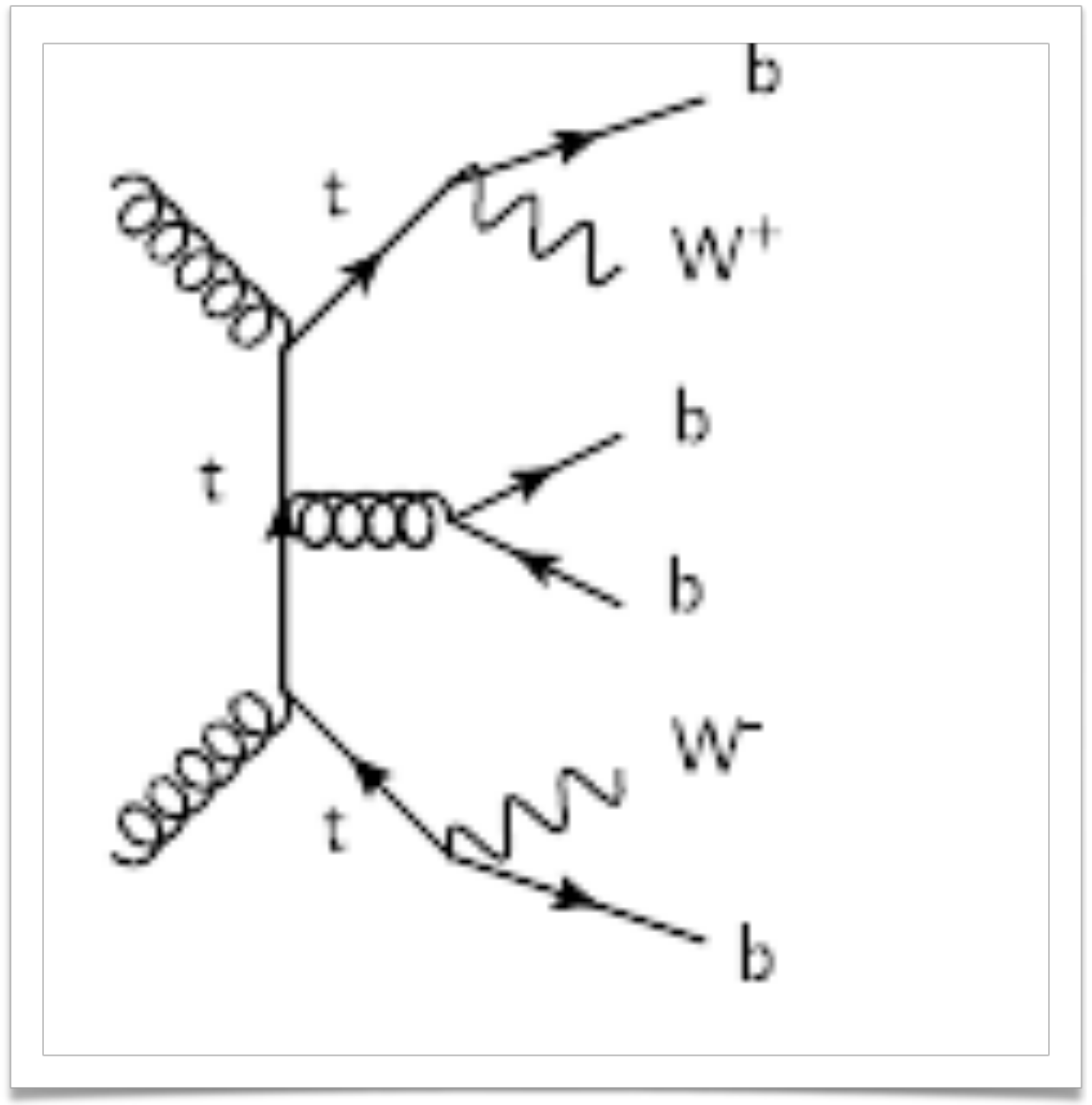






What are the theoretical difficulties to calculate tt+HF?

- Complex calculations:
  - >= 8 parton final state
  - >= 6 colored partons
- Multiple scales between 5 GeV and 500 GeV
- Large scale dependence



Different approaches to predict full events:

- tt ME@NLO + g->bb in PS (5FS)
- tt+0,1,2 ME@NLO massless b-quarks (5FS)
- ttbb ME@NLO with massive b-quarks (4FS)
- Fusing of 4FS and 5FS

Observables to separate ttbb from ttH(H->bb)

- Known separating features between tt+HF and ttHbb are dR between b-jets, mass of bb system and HT
- ML algorithm may also pick-up on correlations between observables and on particular event topologies
  - good description of full event important

BDT dilepton channel

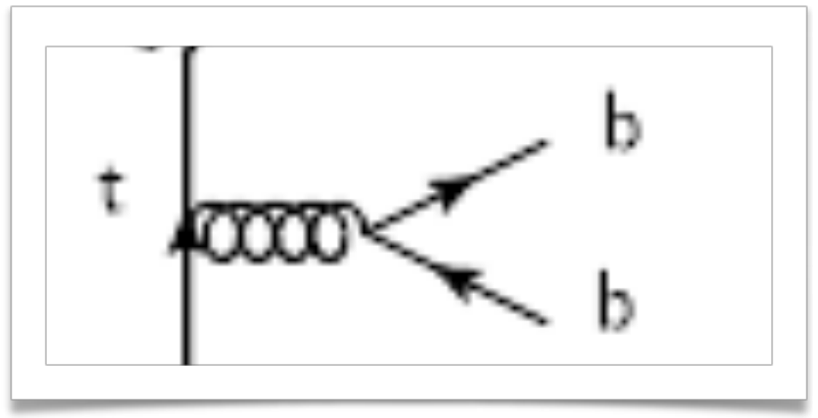
Variable	Definition	$SR_1^{\geq 4j}$	$SR_2^{\geq 4j}$	$SR_3^{\geq 4j}$
General kinematic variables				
$m_{bb}^{\min}$	Minimum invariant mass of a b-tagged jet pair	✓	✓	-
$m_{bb}^{\max}$	Maximum invariant mass of a b-tagged jet pair	-	-	✓
$m_{bb}^{\min \Delta R}$	Invariant mass of the b-tagged jet pair with minimum ΔR	✓	-	✓
$m_{jj}^{\max p_T}$	Invariant mass of the jet pair with maximum p_T	✓	-	-
$m_{bb}^{\max p_T}$	Invariant mass of the b-tagged jet pair with maximum p_T	✓	-	✓
$\Delta\eta_{bb}^{avg}$	Average $\Delta\eta$ for all b-tagged jet pairs	✓	✓	✓
$\Delta\eta_{\ell,j}^{\max}$	Maximum $\Delta\eta$ between a jet and a lepton	-	✓	✓
$\Delta R_{bb}^{\max p_T}$	ΔR between the b-tagged jet pair with maximum p_T	-	✓	✓
$N_{bb}^{Higgs\ 30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓	-
$n_{jets}^{p_T>40}$	Number of jets with $p_T > 40$ GeV	-	✓	✓
Aplanarity$_{b\text{-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [99] built with all b-tagged jets	-	✓	-
H_T^{all}	Scalar sum of p_T of all jets and leptons	-	-	✓

BDT l+jets channel

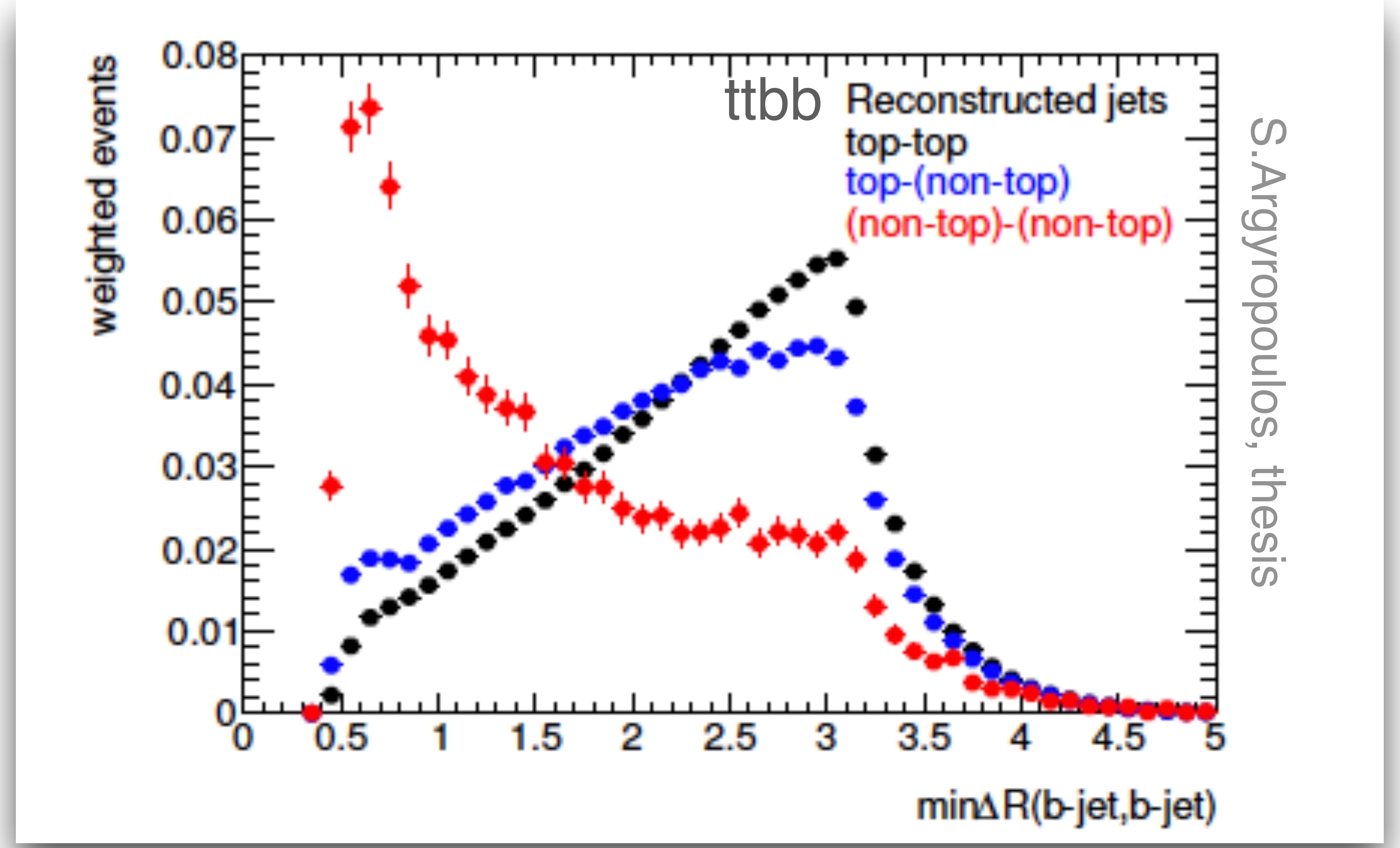
Variable	Definition	$SR_{1,2,3}^{\geq 6j}$	$SR_{1,2}^{5j}$
General kinematic variables			
ΔR_{bb}^{avg}	Average ΔR for all b-tagged jet pairs	✓	✓
$\Delta R_{bb}^{\max p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	✓	–
$\Delta\eta_{jj}^{\max}$	Maximum $\Delta\eta$ between any two jets	✓	✓
$m_{bb}^{\min \Delta R}$	Mass of the combination of two b-tagged jets with the smallest ΔR	✓	–
$m_{jj}^{\min \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	–	✓
$N_{bb}^{Higgs\ 30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓
H_T^{had}	Scalar sum of jet p_T	–	✓
$\Delta R_{\ell,bb}^{\min}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [99] built with all jets	✓	✓
H_1	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓

Measure these observables at particle level

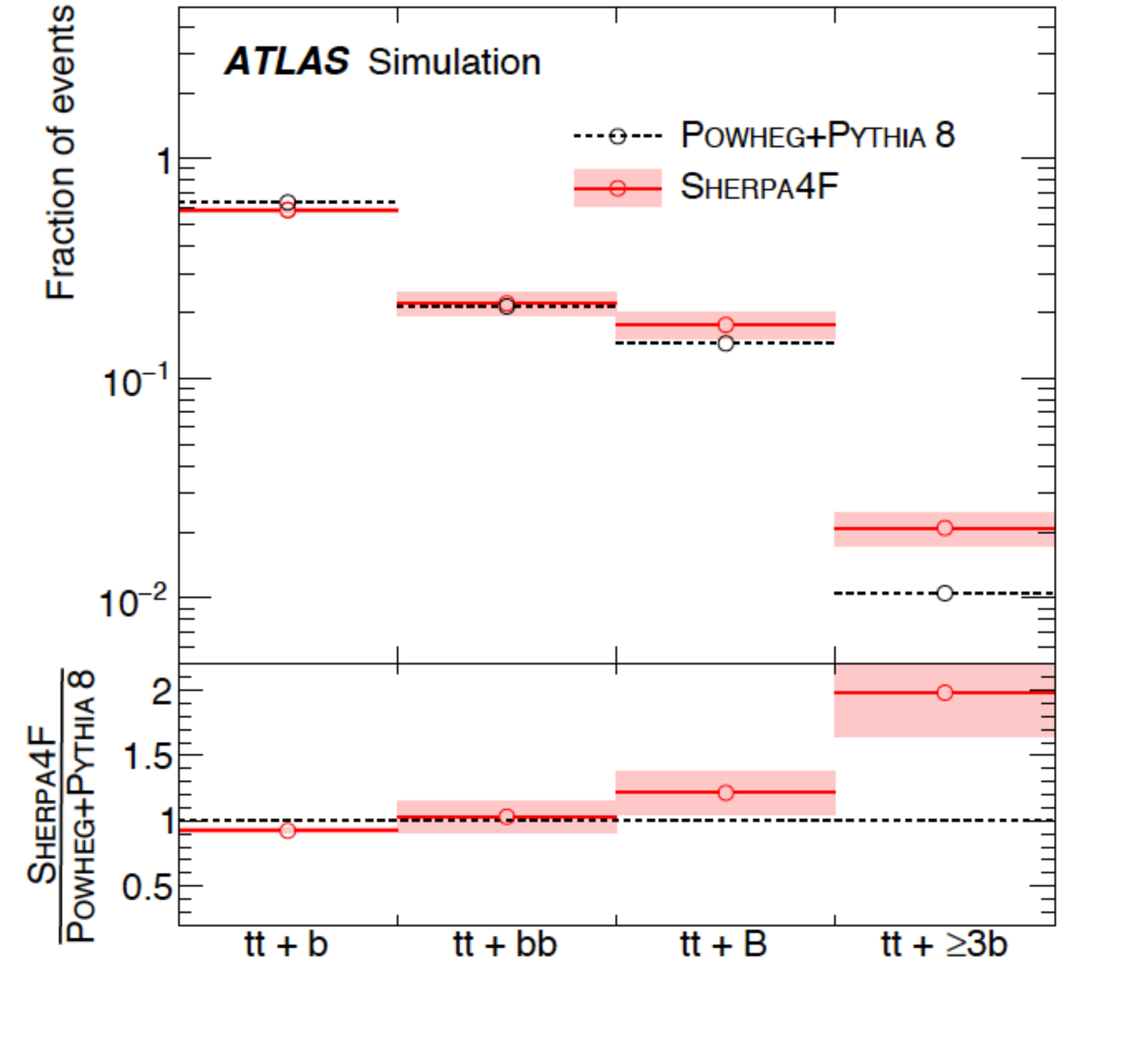
Angular distribution of gluon splitting



- The angular distributin of gluon splitting may have significant experimental effects:
  - For DR(bb)->0 both additional b-quarks (B-hadrons) might be contained in one jet "ttB"
  - Large DR g->bb splitting may lead to b-jet due to loss of the other b-jet outside detector acceptance "ttb"
- Different topologies of additional b-jets have different separation power in ttHbb (e.g. ttB more signal like, ttb more background like)
- Measurement of xsec for >= 3b and >=4b



ttHbb selection

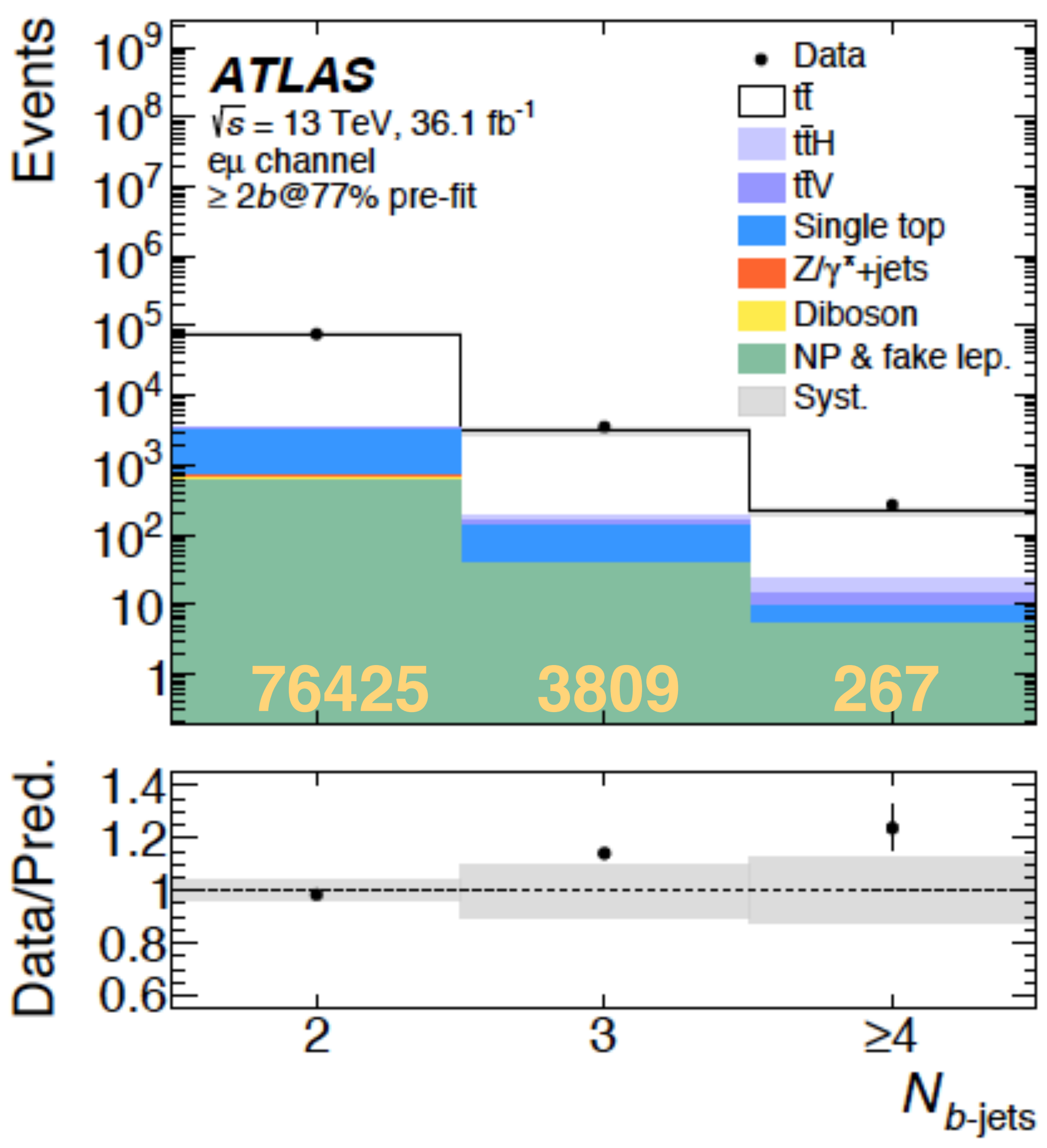


ttbb measurement @ 13 TeV

Measure b-jet pair production in ttbar events without selecting production channel or identifying b-jets origin

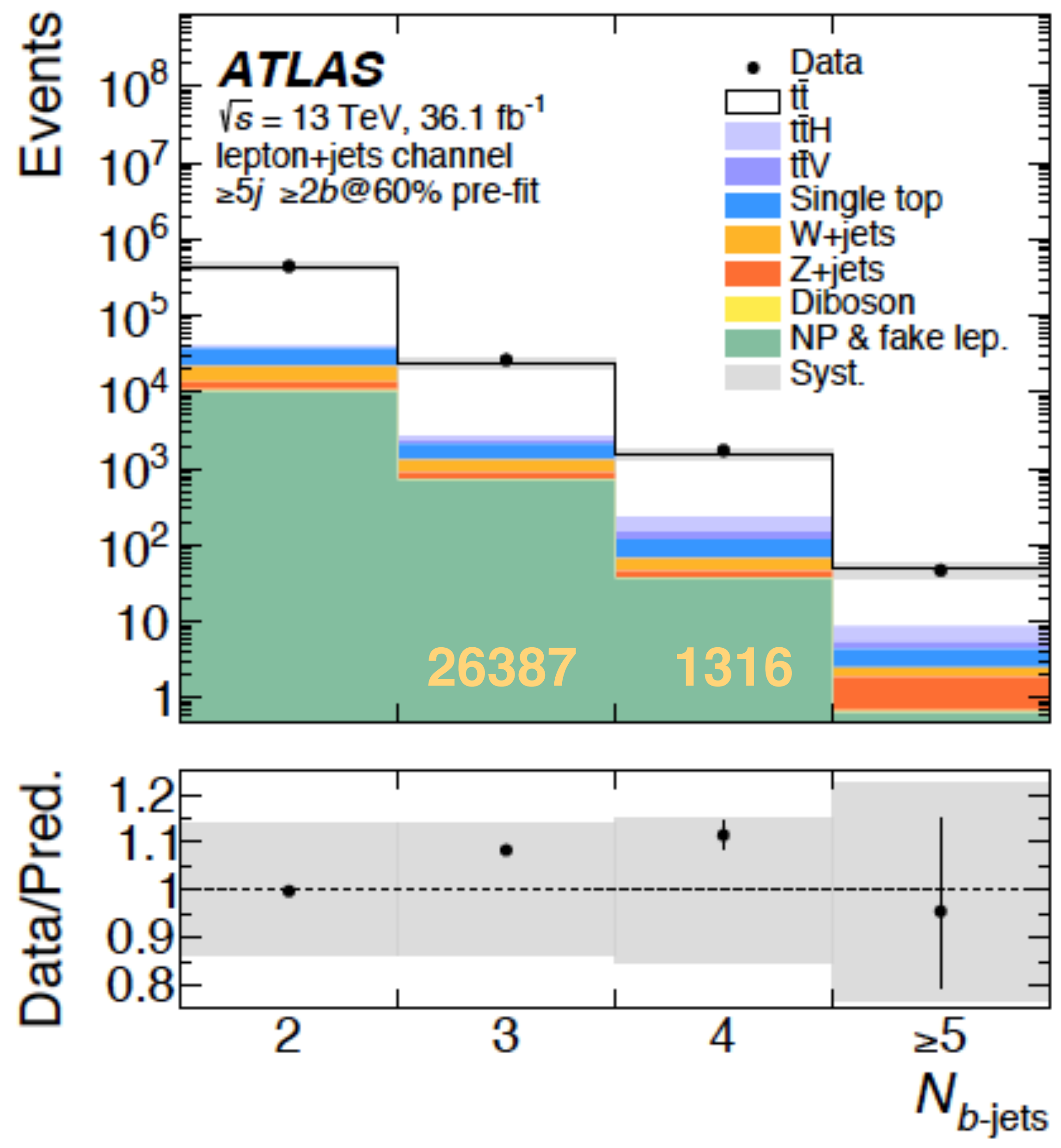
em-channel:

- e, m with pT>27GeV, OS, b-jets @ 77% WP, b-jet pT>25 GeV
- Very low background
- differential measurements in 3b



Lepton+jets channel:

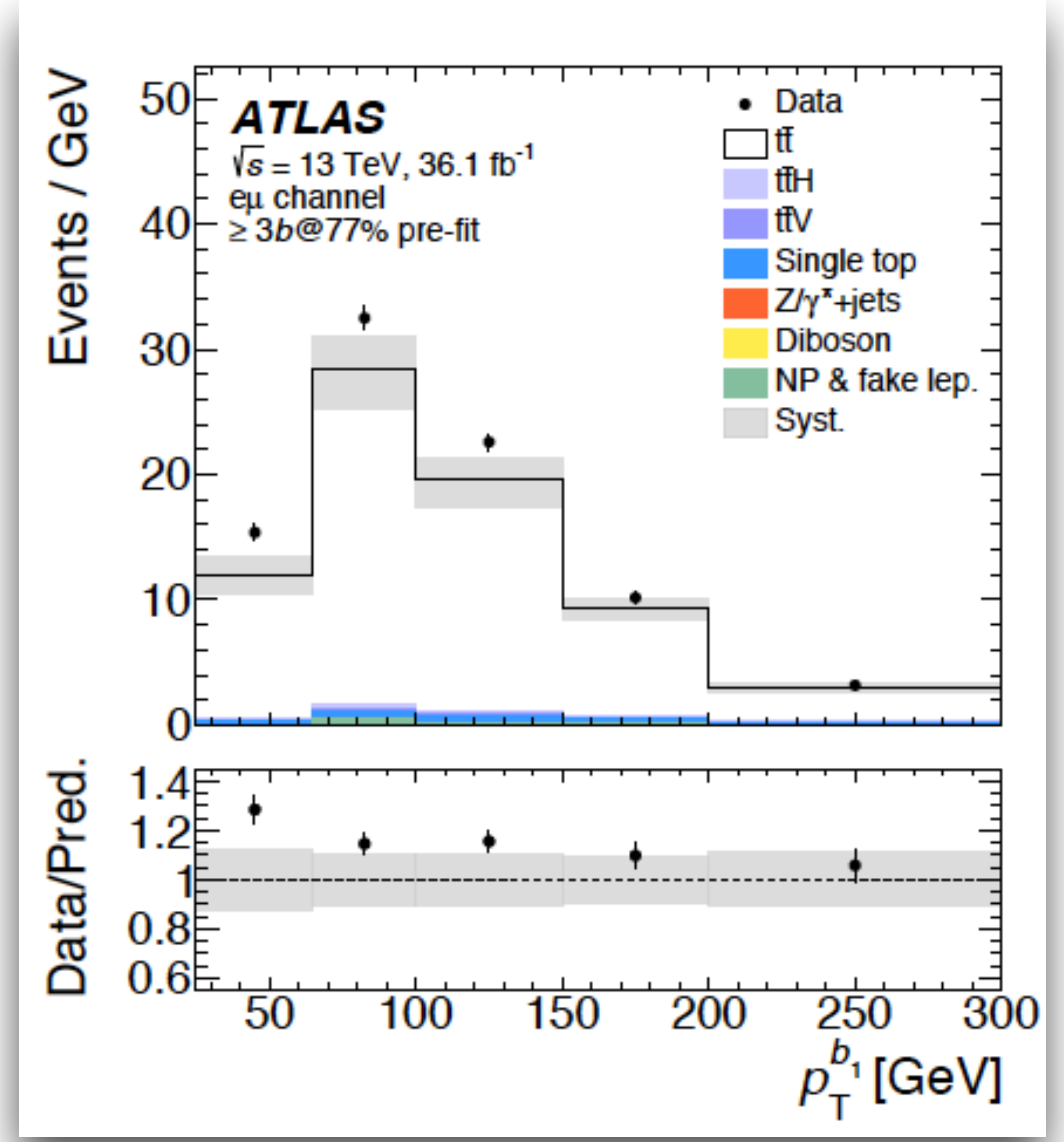
- exactly 1 e or m with pT>27GeV, 5 jets with pT>25 GeV, b-jets@60% WP
- background for additional b-jets from W->cs decays
- high stats to measure differential distributions in 4b



ttbb measurement @ 13 TeV

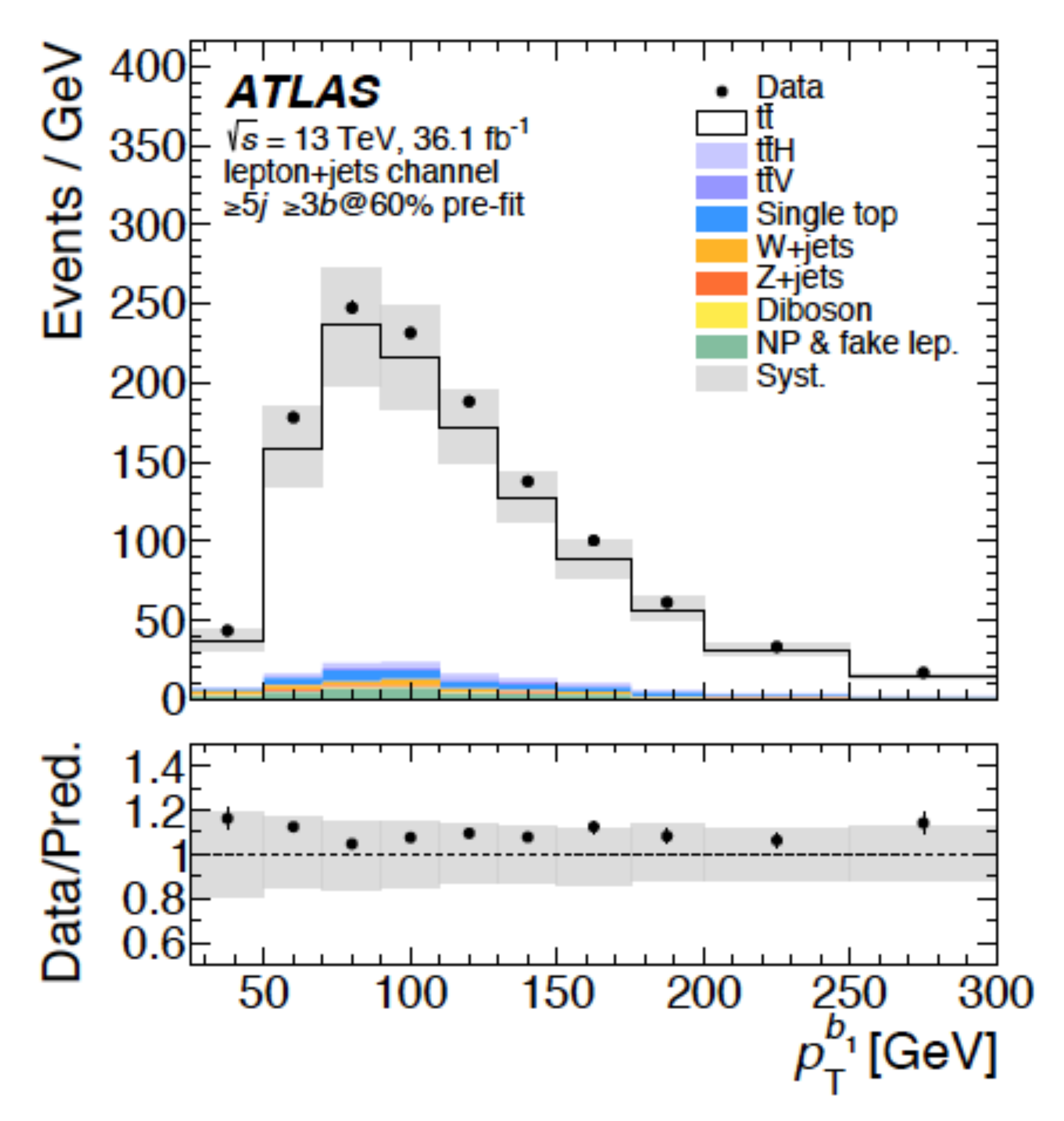
em-channel

Experimental uncertainties on b-jets ~10%



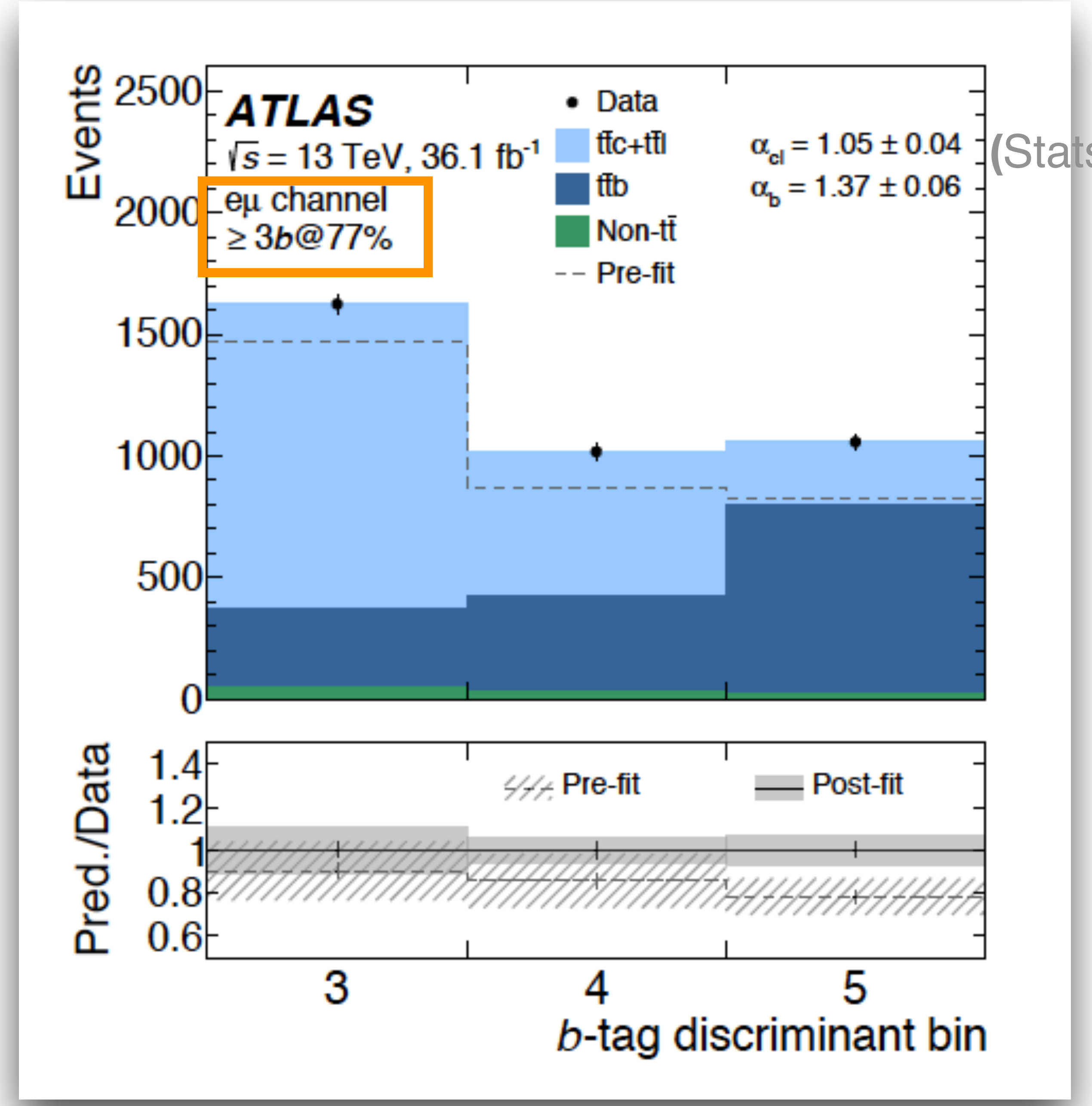
Lepton+jets channel:

Experimental uncertainties on b-jet ~15-20%



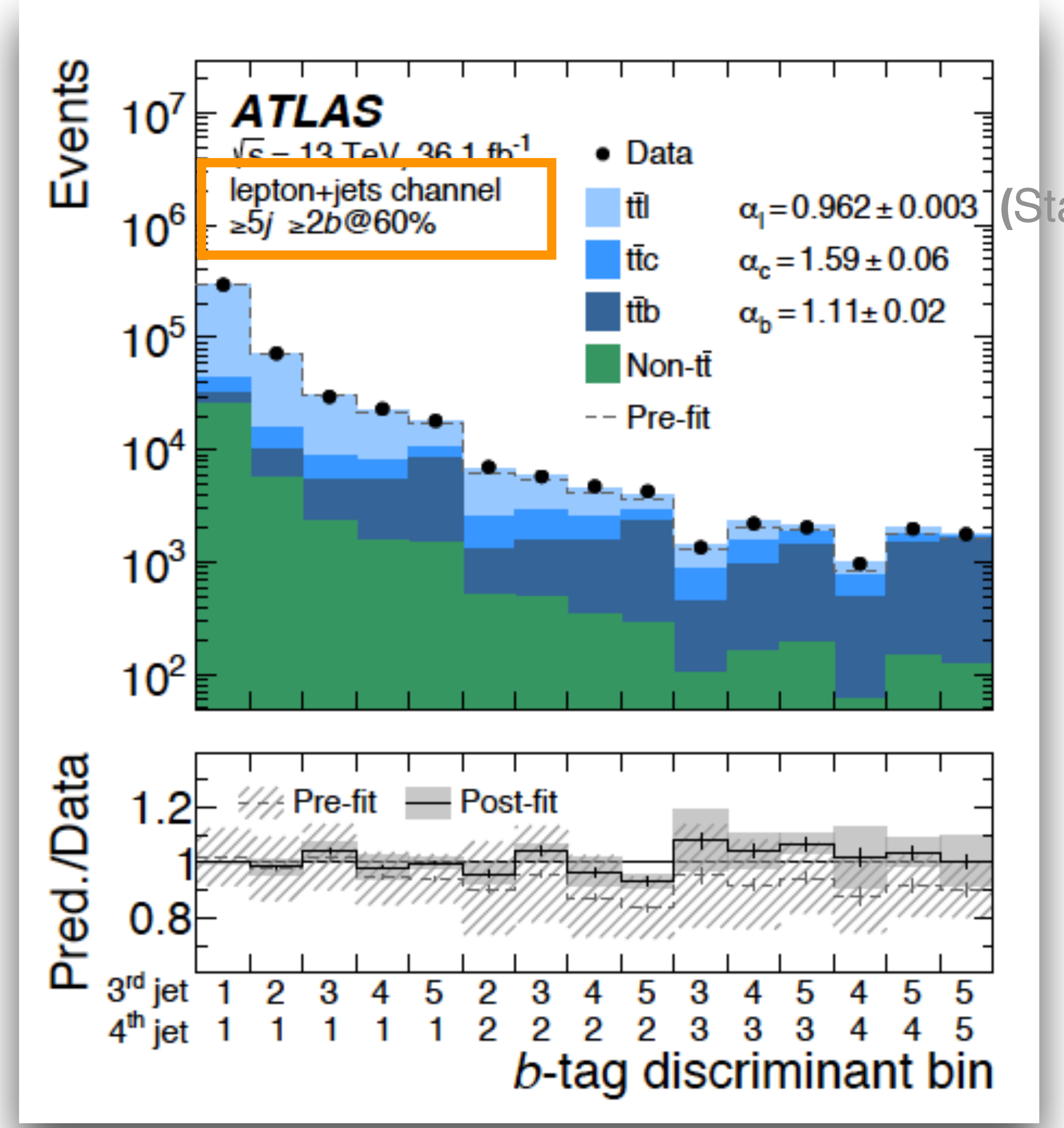
Determination of flavour of additional jets

- B-tagging efficiency known from calibration but mistag efficieny for charm- and light-jets and xsec for ttcc poorly known
- Perform binned likelihood template fit to determine background from tt+jets and tt+charm
- Categorise events according to particle level jets into templates of ttc, ttl, ttb and background



(Stats)

b-tag bins: efficiency
1: 100-85%
2: 85-77%
3: 77-70%
4: 70-60%
5: 60- 0%



(Stats)

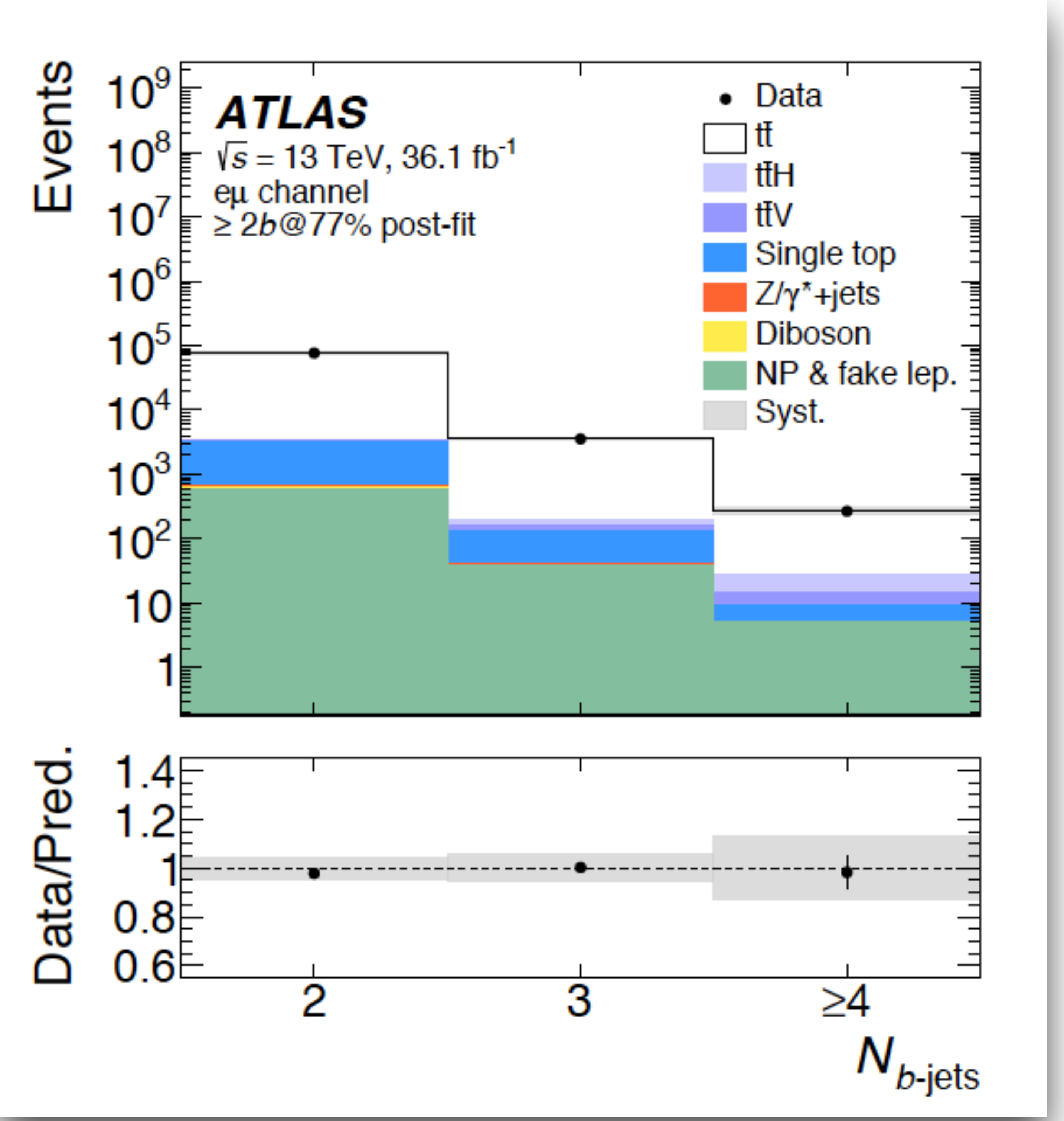
$$\nu_k(\alpha_b, \alpha_{cl}) = \alpha_b N^k_{t\bar{t}b} + \alpha_{cl}\left(N^k_{t\bar{t}c} + N^k_{t\bar{t}l}\right) + N^k_{\text{non-}t\bar{t}}$$

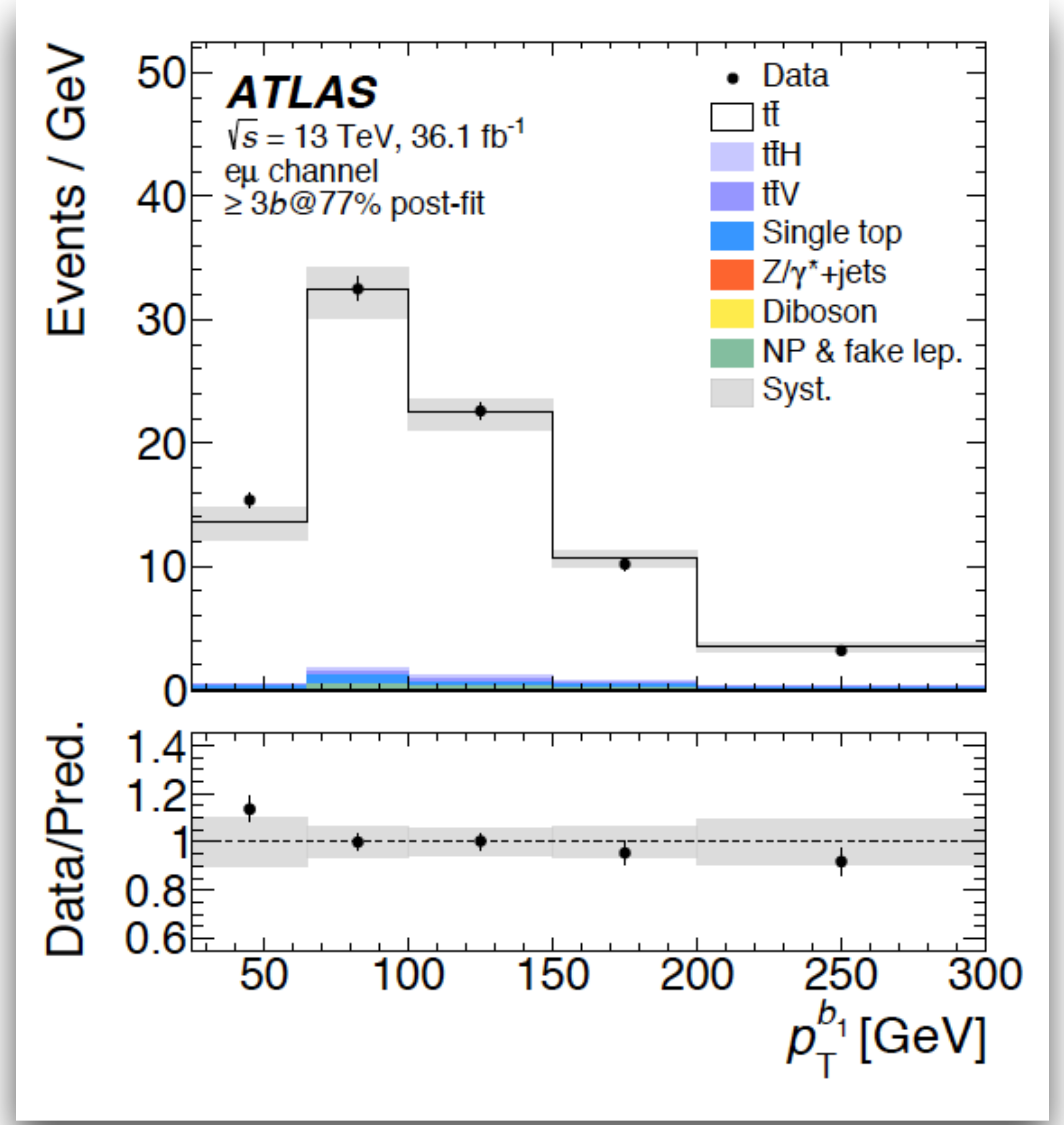
- Fit performed in measurement phase space
- Uncertainty from variation of ttc template by 40% => systematic uncertainty of a_b=11%, a_{cl}=7%

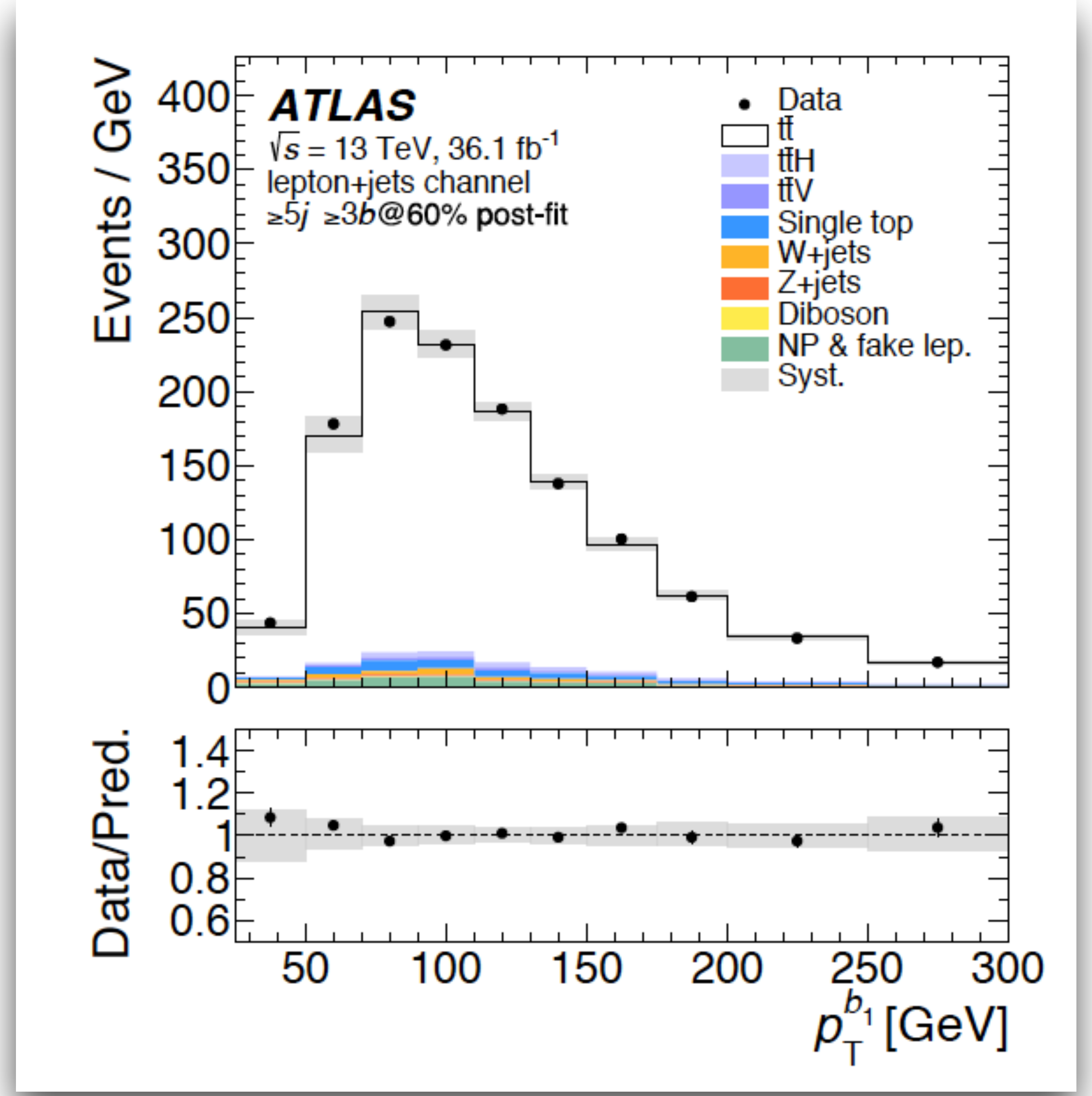
$$\nu_k(\alpha_b, \alpha_c, \alpha_l) = \alpha_b N^k_{t\bar{t}b} + \alpha_c N^k_{t\bar{t}c} + \alpha_l N^k_{t\bar{t}l} + N^k_{\text{non-}t\bar{t}}$$

- Fit performed in all b-tagging bins
- Systematic uncertainty from varying MC models for templates

Reconstruction level distributions with flavour scale factors







Good agreement with data also in differential distributions of measured phase space

Unfolding

- Unfolding is done in fiducial phase space to stable final state particles with life time >30ps.
- Signal consists of QCD production of ttbb+ttHbb+ttVbb
- Final state leptons and jets are required to have pT>25GeV and |eta|<2.5, b-jets are defined as containing a B-hadron with pT> 5GeV

$$\frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X^i} = \frac{N^i_{\mathrm{unfold}}}{\mathcal{L}\,\Delta X^i} = \frac{1}{\mathcal{L}\,\Delta X^i\, f^i_{\mathrm{eff}}} \sum_j \mathcal{M}^{-1}_{ij}\, f^j_{\mathrm{matching}}\, f^j_{\mathrm{accept}}\, f^j_{t\bar{t}b}\,(N^j_{\mathrm{data}} - N^j_{\mathrm{non}\text{-}t\bar{t}\text{-bkg}})$$

$$f^j_{\mathrm{matching}} = \frac{N^j_{t\bar{t}b,\mathrm{reco}\wedge\mathrm{part}\wedge\mathrm{matched}}}{N^j_{t\bar{t}b,\mathrm{reco}\wedge\mathrm{part}}}$$

$$f^j_{t\bar{t}b} = \frac{\alpha_b N^j_{t\bar{t}b,\mathrm{reco}}}{\alpha_b N^j_{t\bar{t}b,\mathrm{reco}} + \mathcal{B}^j}$$

em channel

$$\mathcal{B}^j = \alpha_{cl}\left(N^j_{t\bar{t}c,\mathrm{reco}} + N^j_{t\bar{t}l,\mathrm{reco}}\right)$$

l+jets channel

$$\mathcal{B}^j = \alpha_c N^j_{t\bar{t}c,\mathrm{reco}} + \alpha_l N^j_{t\bar{t}l,\mathrm{reco}}$$

\

$$\sigma^{\mathrm{fid}} = \int \frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X}\mathrm{d}X = \frac{\sum N^i_{\mathrm{unfold}}}{\mathcal{L}}$$

Uncertainties

Estimate detector effects from varying input distributions and performing flavour fit+unfolding

Estimate modelling uncertainties by replacing MC but keeping unfolding corrections from nominal MC; take particle level difference to nominal sample

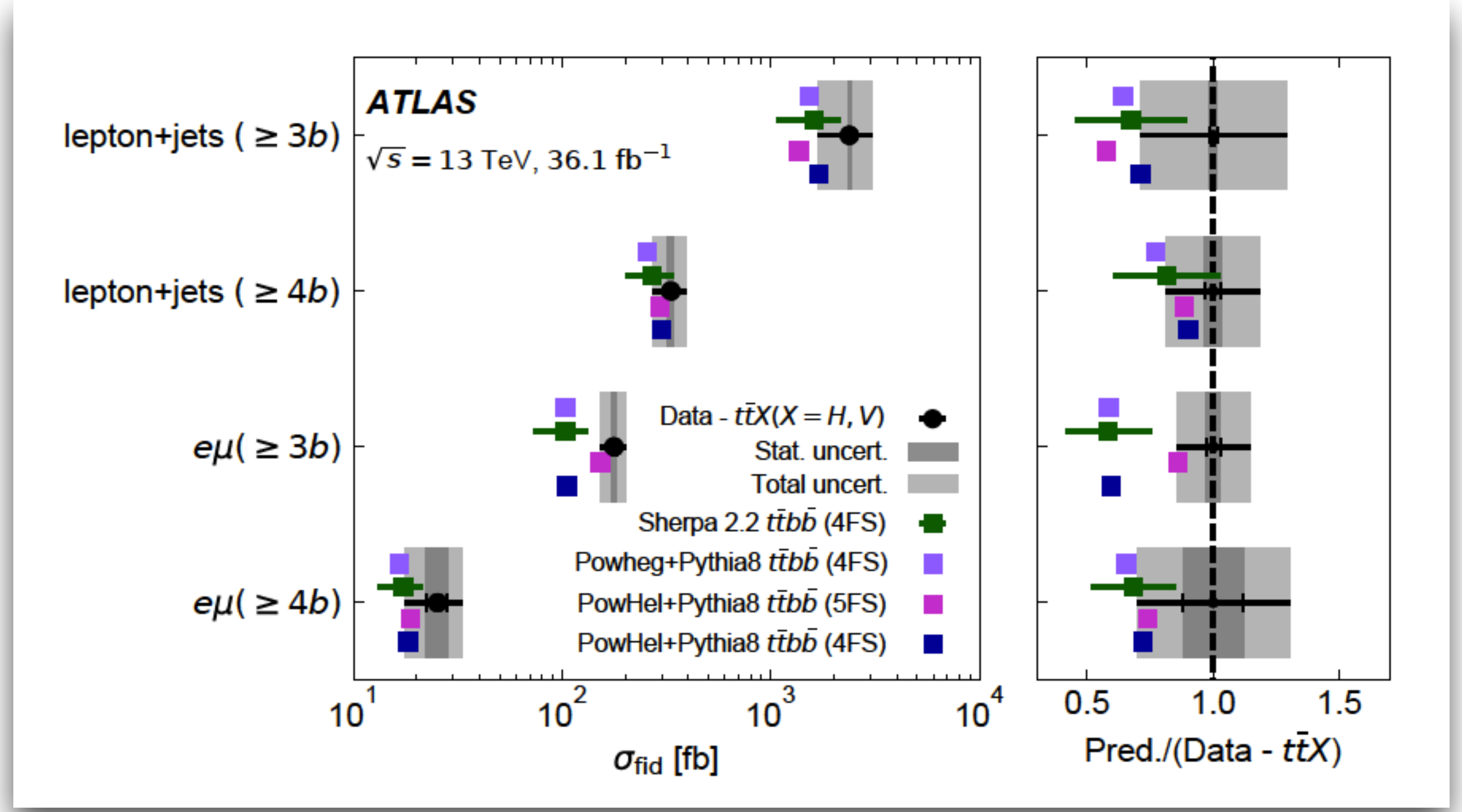
Source	Fiducial cross-section phase space $e\mu$ $\geq 3b$ unc. [%]	$e\mu$ $\geq 4b$ unc. [%]	lepton + jets $\geq 5j, \geq 3b$ unc. [%]	lepton + jets $\geq 6j, \geq 4b$ unc. [%]
Data statistics	2.7	9.0	1.7	3.0
Luminosity	2.1	2.1	2.3	2.3
Jet	2.6	4.3	3.6	7.2
b-tagging	4.5	5.2	17	8.6
Lepton	0.9	0.8	0.8	0.9
Pile-up	2.1	3.5	1.6	1.3
$t\bar{t}c$ fit variation	5.9	11	-	-
Non-$t\bar{t}$ bkg	0.8	2.0	1.7	1.8
Detector+background total syst.	8.5	14	18	12
Parton shower	9.0	6.5	12	6.3
Generator	0.2	18	16	8.7
ISR/FSR	4.0	3.9	6.2	2.9
PDF	0.6	0.4	0.3	0.1
$t\bar{t}V/t\bar{t}H$	0.7	1.4	2.2	0.3
MC sample statistics	1.8	5.3	1.2	4.3
$t\bar{t}$ modelling total syst.	10	20	21	12
Total syst.	13	24	28	17
Total	13	26	28	17

Powheg+Pythia8 vs Powheg+Herwig7
Powheg+Pythia8 vs Sherpa 2.2.1
Powheg+Pythia8 RadHi/RadLo

Xsec varied within measured uncertainties

Measurement uncertainties dominated by systematics

Inclusive fiducial cross section



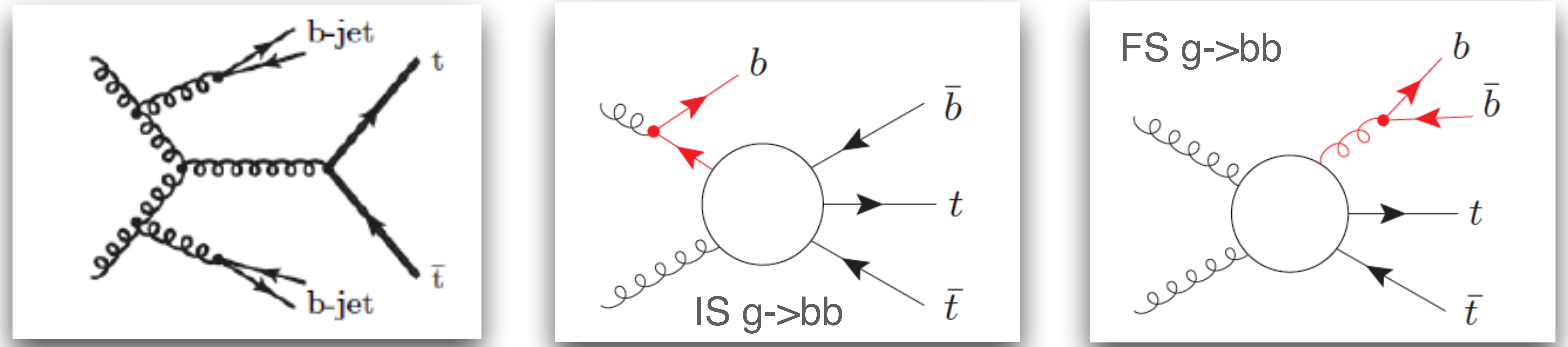
- MC Models of ttbb ME in 4FS predict lower xsec than data
- Effect is bigger for phase space with >=3b
- Modelling of small angle gluon splitting (B-jets)? b-jet p_T too low? Missing ISR contributions?

MGaMC@NLO 4F ttbb
Matchbox+Herwig 4F ttbb
Sherpa 4FS, 1309.5912
PowHel 4FS
Powheg-Box-Res ttbb, 1802.00426

ttbb ME@NLO with massive b-quarks (4FS)

Advantage:

- ME@NLO calculation has less uncertainty than LO PS calculation
- Due to massive b-quarks soft gluon splitting doesn't have a singularity at collinear splittings
  - full phase space covered by ME
- Covers also double soft gluon splittings
  - estimated in Higgs region up to 30%



Caveat:

- $\alpha_S \ln(m_b/Q)$ terms that arise from IS g->bb splittings are not resummed through the PDF evolution.
  - Powheg study: $\alpha_S \ln(m_b/Q)$ not relevant for low mass region, compensated by interference effects for H region in ttHbb
- No prediction for the inclusive top pair production including additional light and charm jets

Further MC predictions for ttbb

tt ME@NLO + g->bb in PS

Large theoretical uncertainties due to additional b-quark production in LO PS

PS tuned to tt+jets, top pt,… ATLAS data with decent agreement in jet inclusive distributions

ATLAS samples:

- Powheg+Pythia8 (ttbar nominal, RadHi, RadLo)
- Powheg+Herwig7
- MC@NLO+Pythia8

(N)LO tt+0,1,2 ME + PS (5FS)

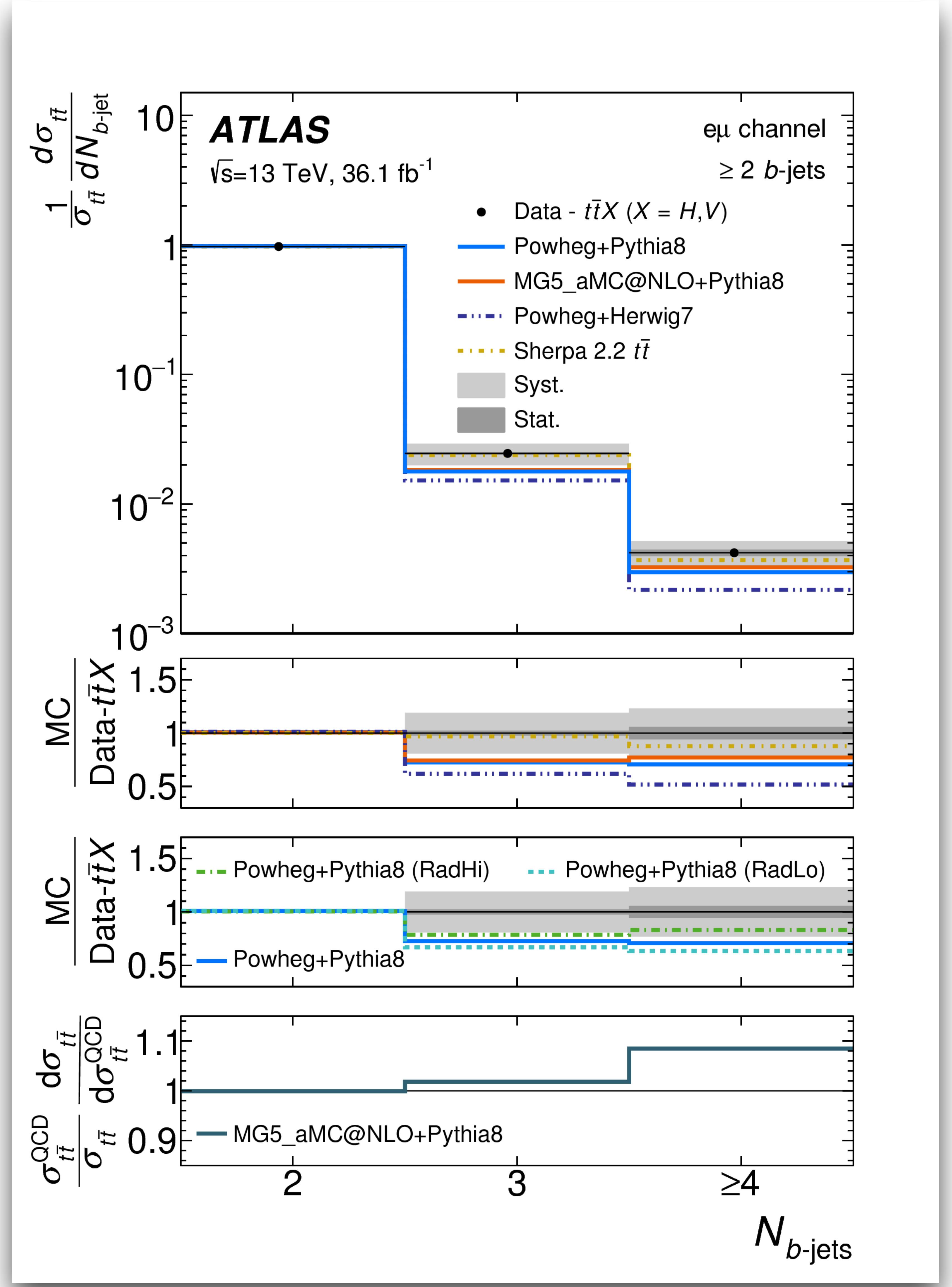
ME calculation of QCD radiation more precise than PS
α_S ln(m_b/Q) terms from IS g->bb splittings are resummed through the PDF evolution
Prediction inclusive in flavour of additional jets

But even though ttbb (with m_b=0) is availble at ME, most events have b-jets from PS (study in 1802.00426)

- Gluon->bb typically softer than 1st and 2nd splitting
- At $m_{bb} \sim m_H$ still almost 50% b-jets from PS (tt+0b)

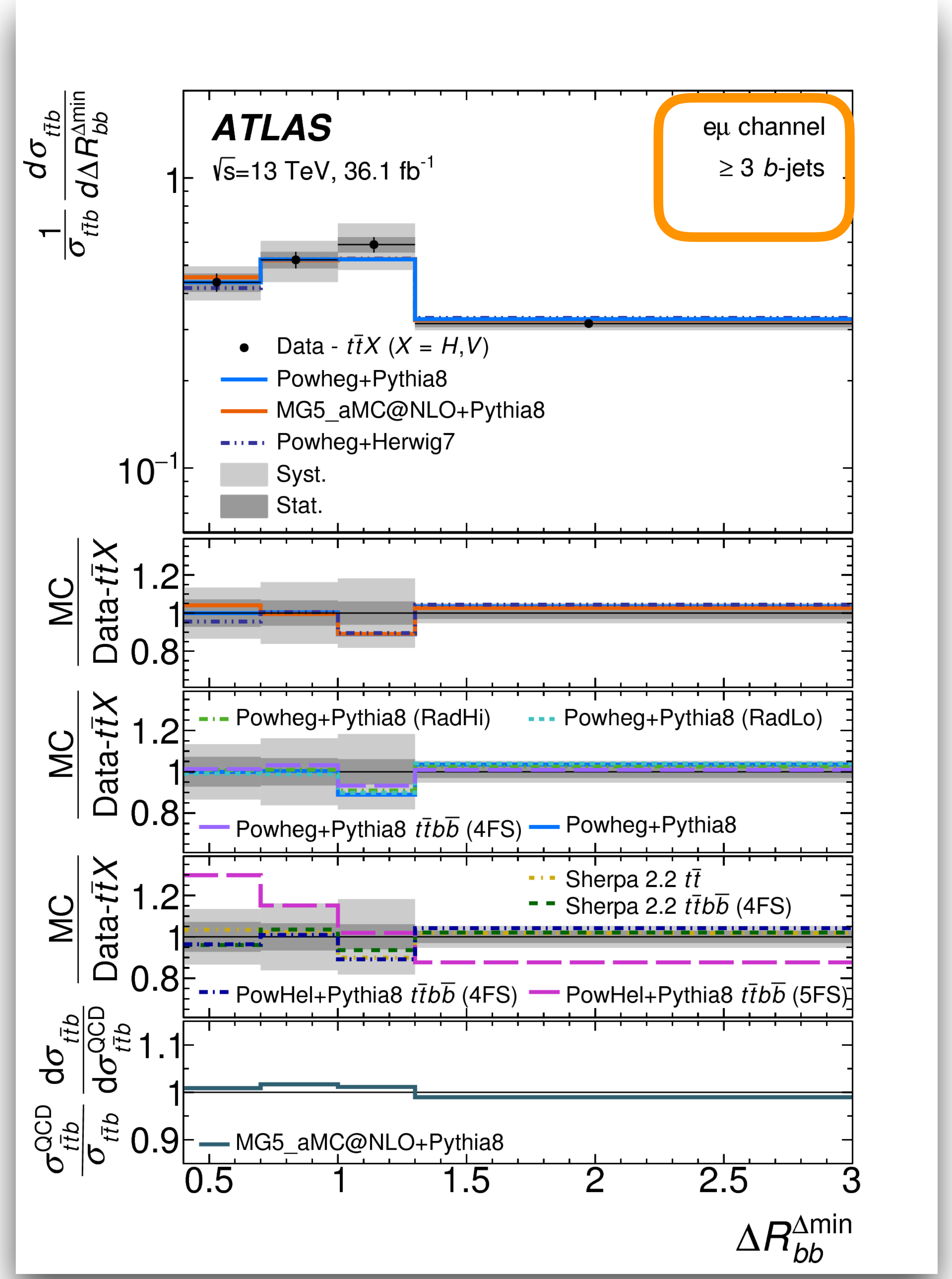
ATLAS sample: Sherpa 2.2 (5FS)

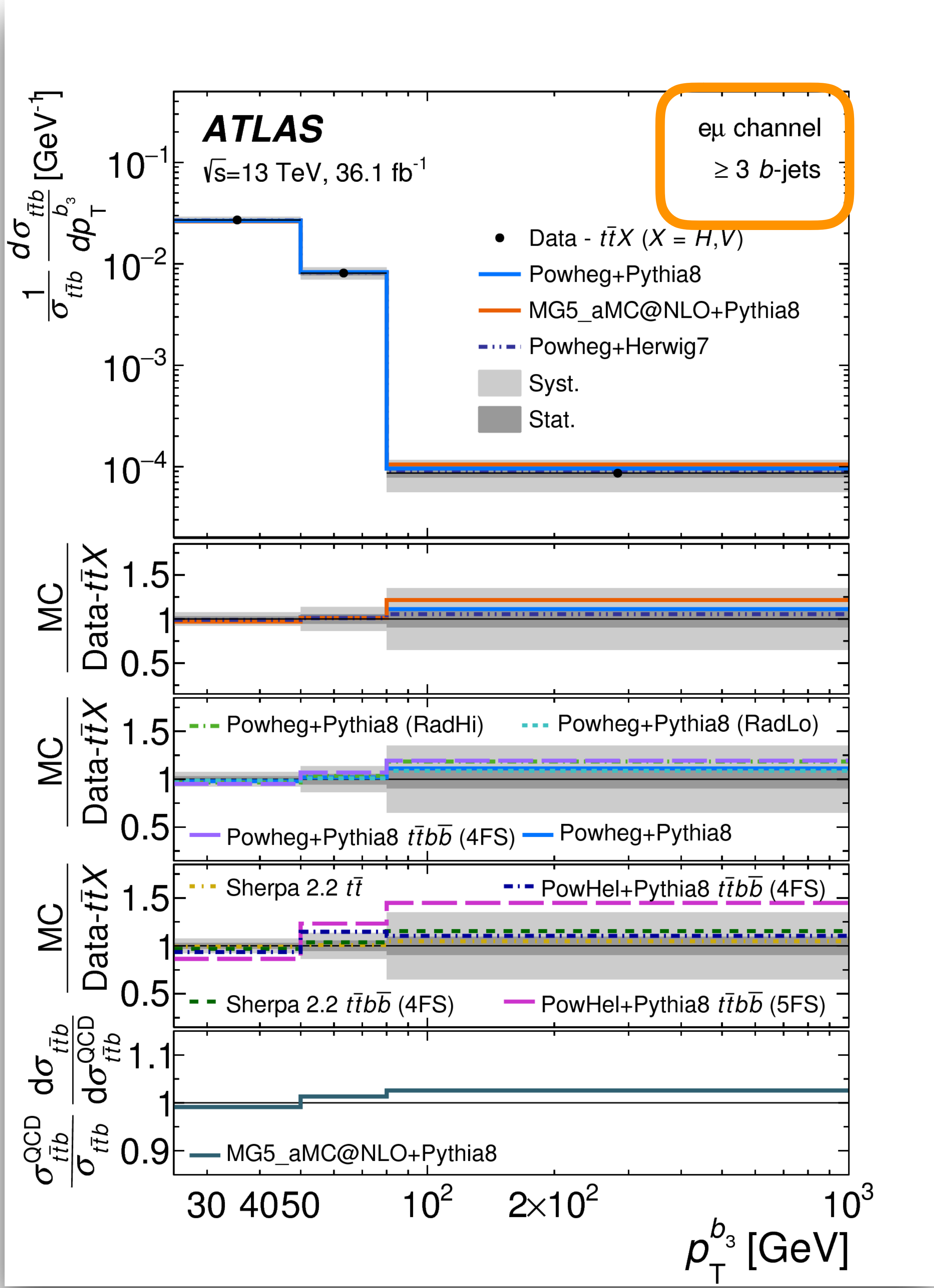
ATLAS ttbb measurements differential in b-jet multiplicity

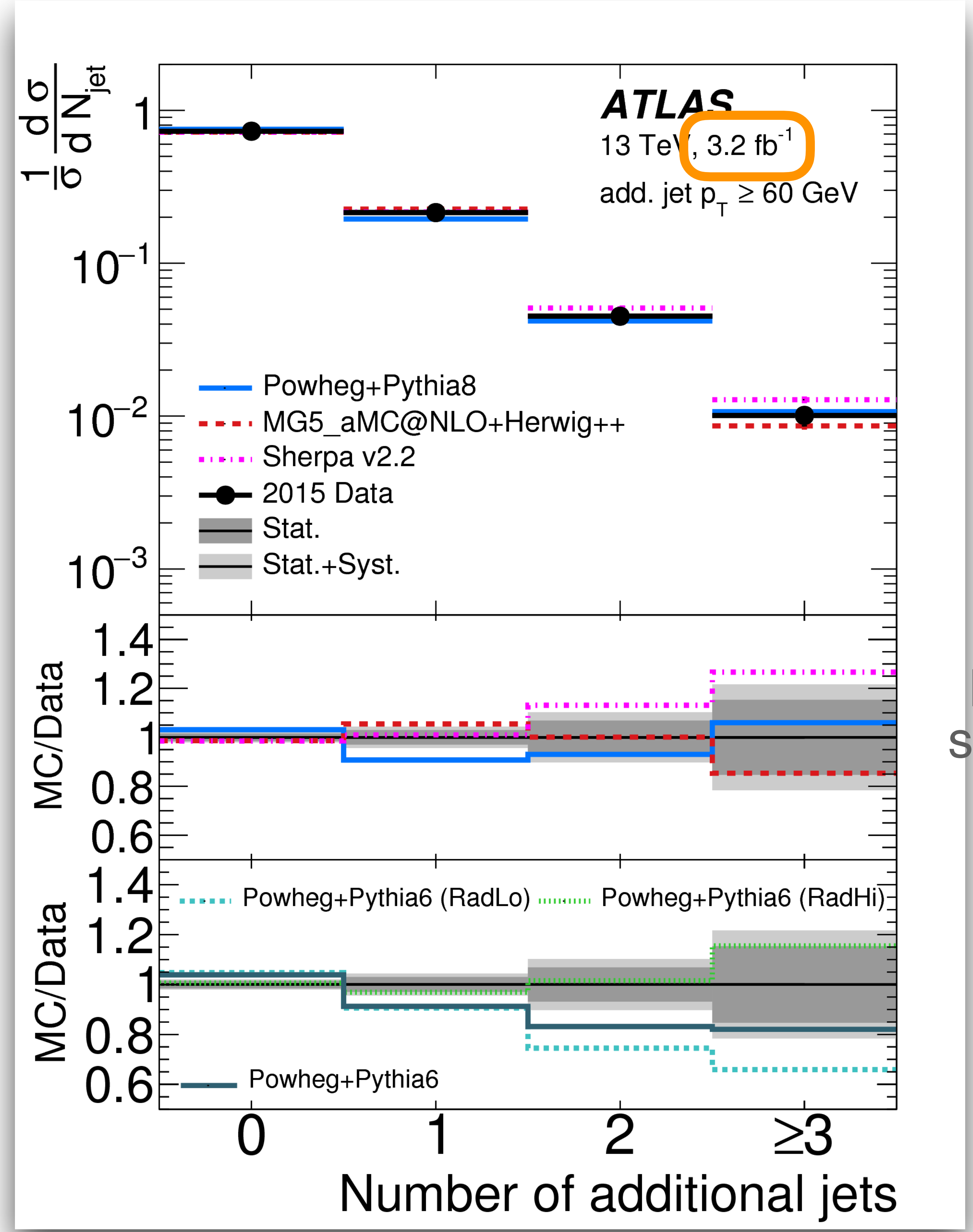


- >Powheg+Pythia8 and all other MC with b-quark production only from PS predicts too few additional b-jets($N_{b\text{-jets}}$>=3)
- >QCD scale in PS not able to fix this
- >Very good agreement over the full phase space for Sherpa 2.2 5FS based on ME with ttj@NLO + 4 partons@LO

ATLAS: differential kinematic distributions, dilepton (>=3b)







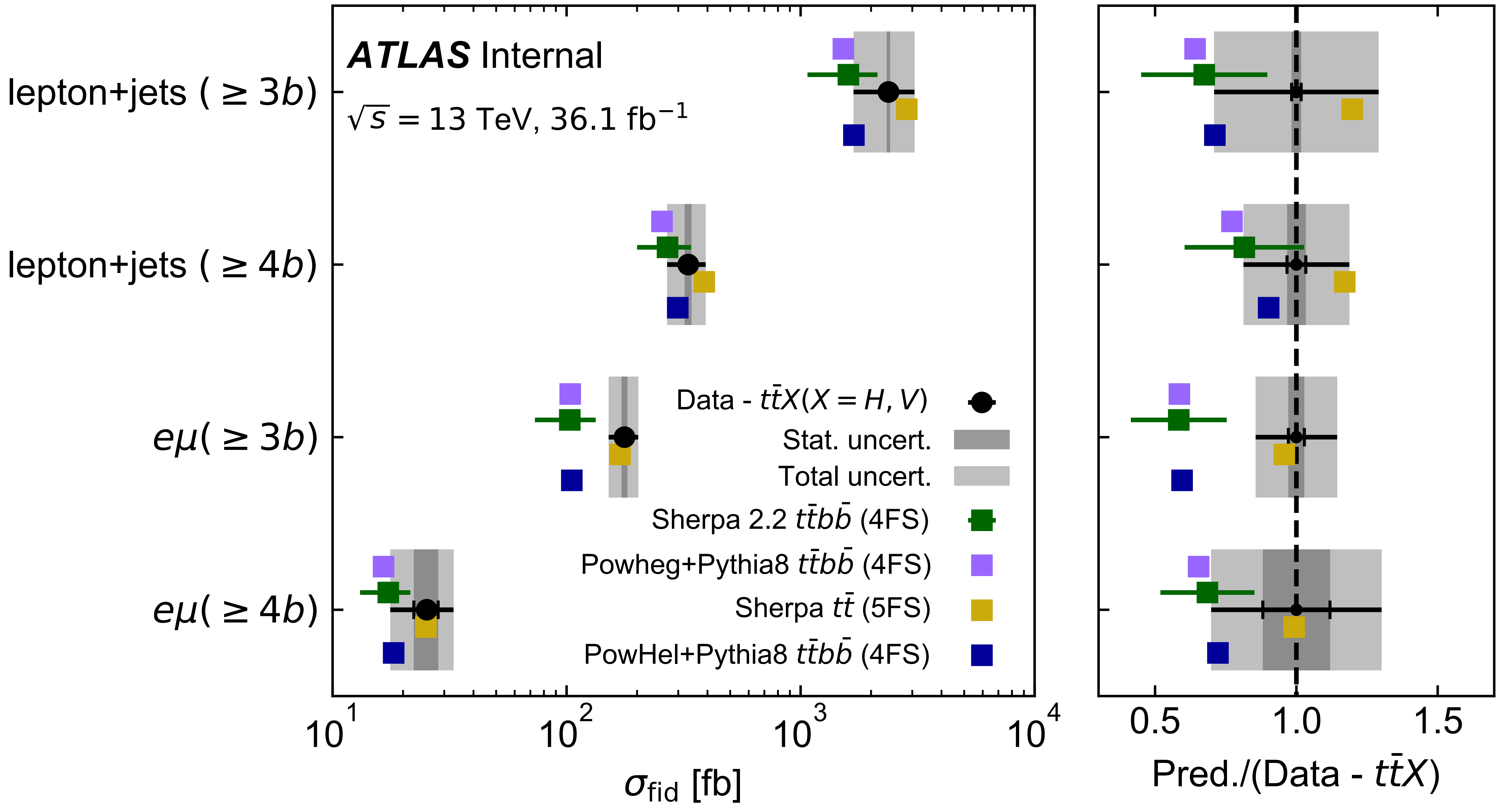
precision statistically limited

> PowHel 5FS is excluded by the differential measurement

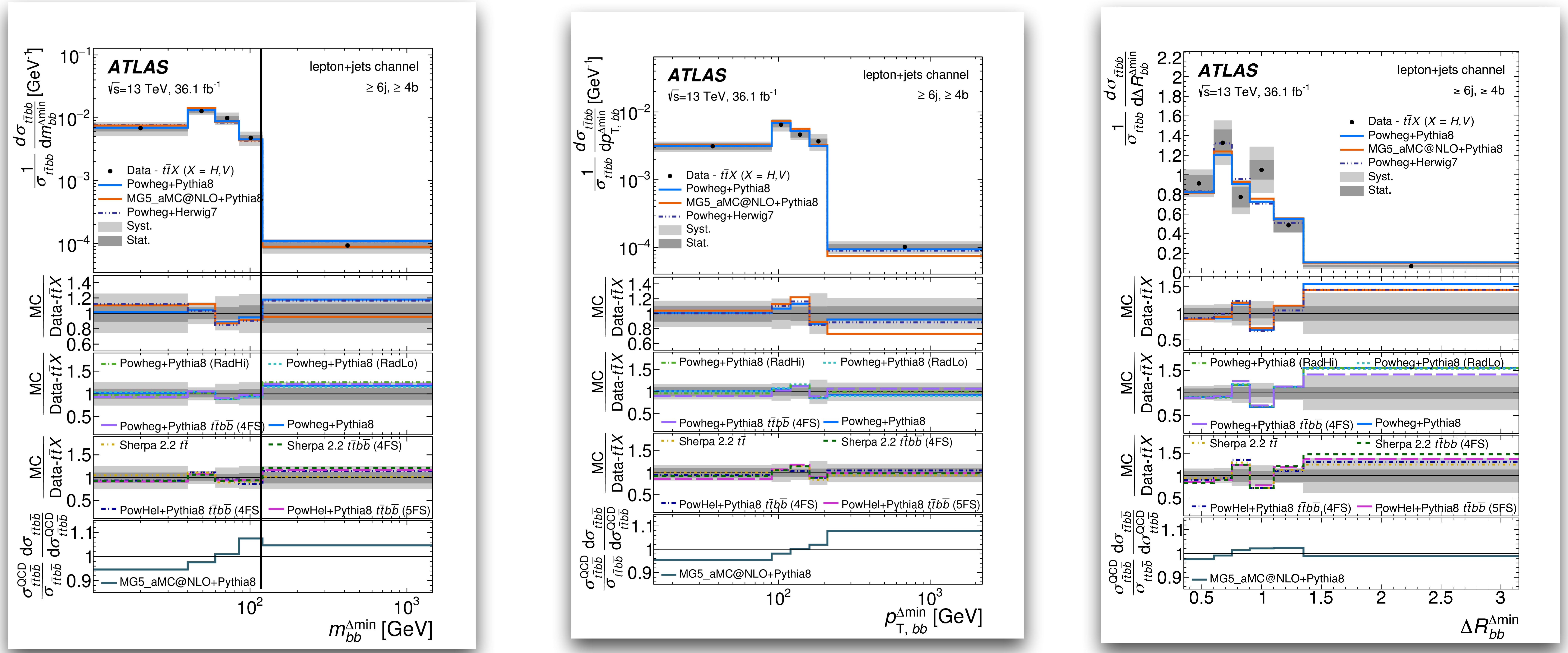
> All other MC models agree with data and their variations is significantly less than the measurement uncertainty

> Sherpa 2.2 tt (= 5FS) describes all ttbb observables well simultaneously (however predicts too many light jets)

Inclusive xsecs compared to Sherpa 5FS



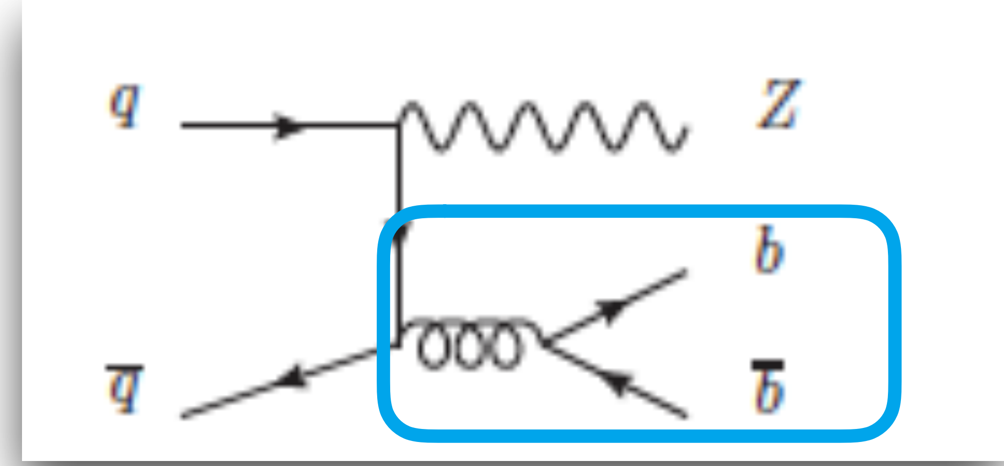
ATLAS differential kinematic distributions 4b (l+jets)

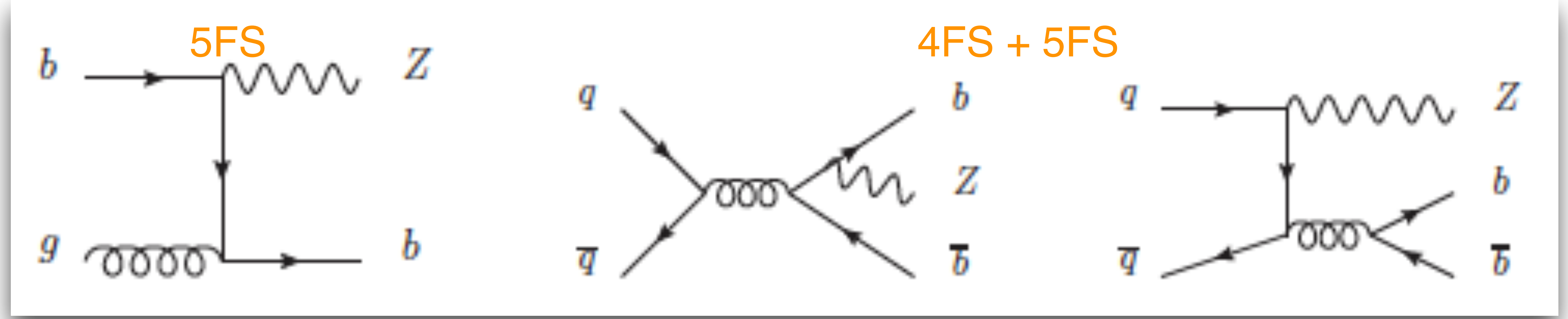


- Close to ttHbb signal region
- Normalised fiducial cross sections agree with all MC models
- Variations between models significantly smaller than experimental uncertainties

Other ways to constrain models of g->bb splitting?

- Measure g->bb in a more “pure” event topology: Zbb
- Caveat: this process comes also with other production modes

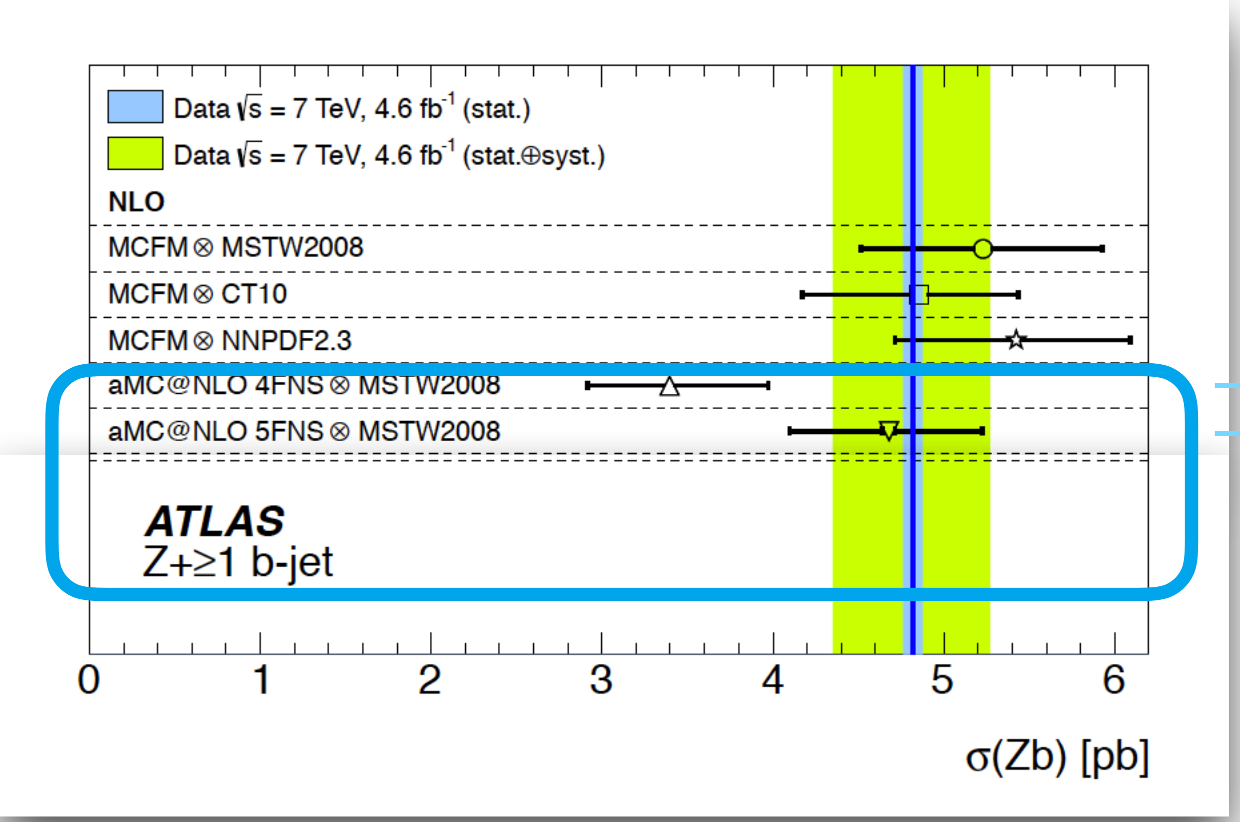


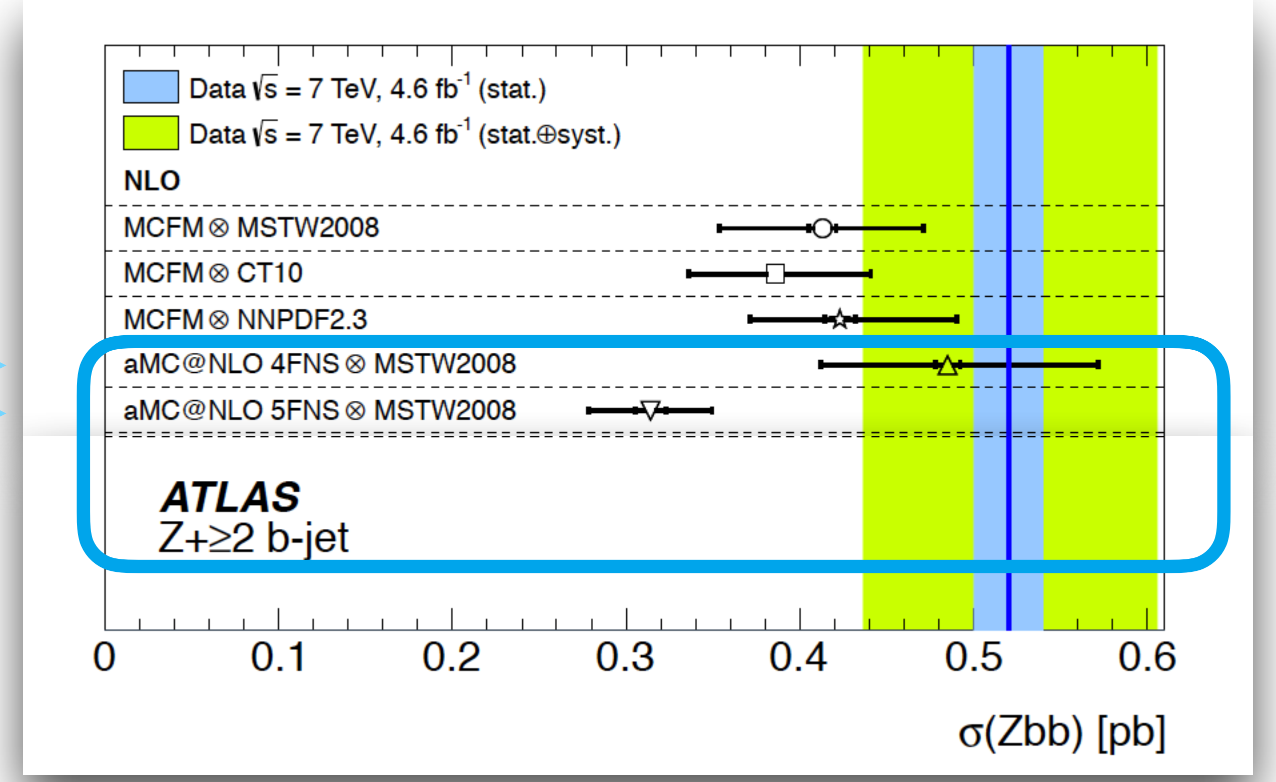


Enhanced in Z+1b
Used to determine b-quark PDF

Enhanced in Z+2b

ATLAS measurements @ 7 TeV prefer 4FS for Z+2b, 5FS for Z+1b

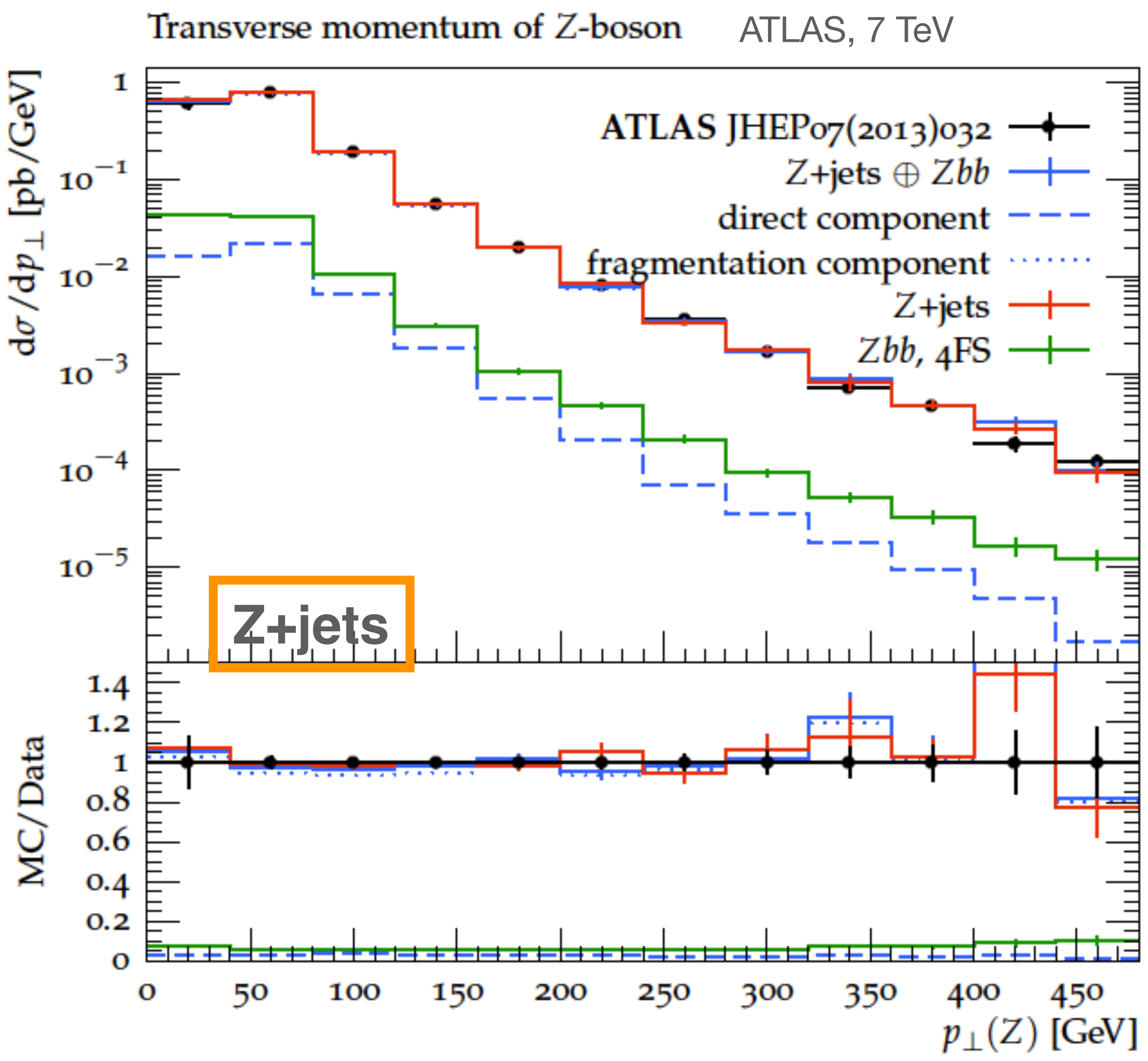




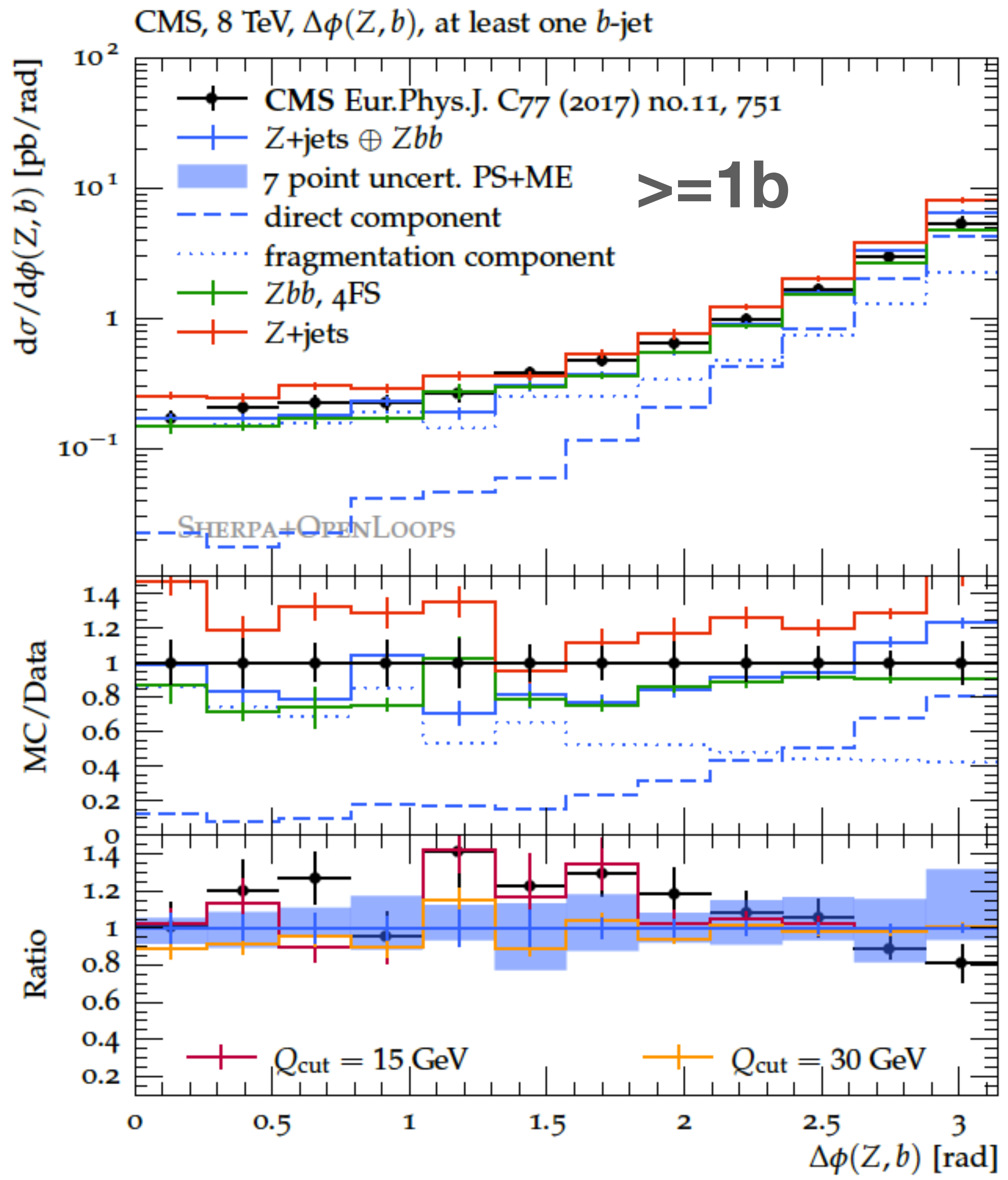
S.Höche, J.Krause, F.Siegert
arXiv:1904.09382v1

New algorithm: Fusing of 4FS + 5FS for HF production

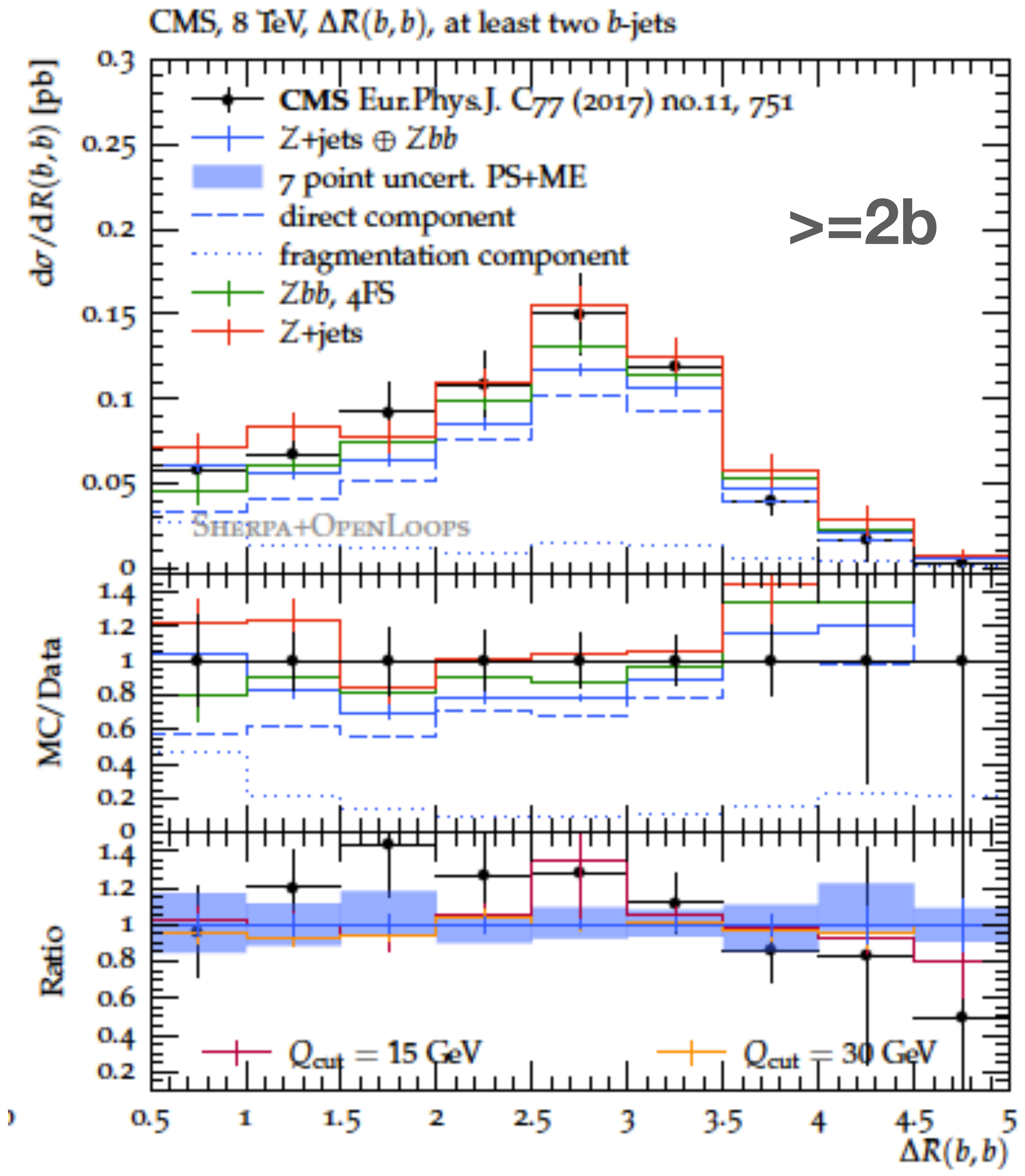
- Development of new algorithm in Sherpa
- Control fragmentation component in Z+jets events and both components in Z+b-jets eventt



(a) The transverse momentum of the Z boson.



(d) The azimuthal distance between the leading b-jet and the Z-boson.



- Algorithm to incorporate 4FS and 5FS calculations and smooth transition between them!

J.Katzy, J.Krause, C.Pollard, F.Siegert
Work in progress

Application of Fusing of 4FS + 5FS for HF production in ttbar

Goal:

- Better description of ttbar with additional b and light jet radiation in ME => reduced uncertainty
- Description of tt+jets inclusive in jet flavour

Algorithm:

1. HFOR a la multi-leg merging:
    - Cluster fully showered event using reverse shower
    - Look at leading 2 emission:
        - Heavy flavour -> keep from ttbb+PS simulation
        - Light flavour -> keep from tt+jets MEPS@NLO simulation

      => Sub(sub) leading g->bb splitting not from ttbb ME but from ttjjj ME or from PS

2. Embed ttbb as merged contribution to tt+jets MEPS@NLO

3. Match 4FS/5FS in a_S and PDF

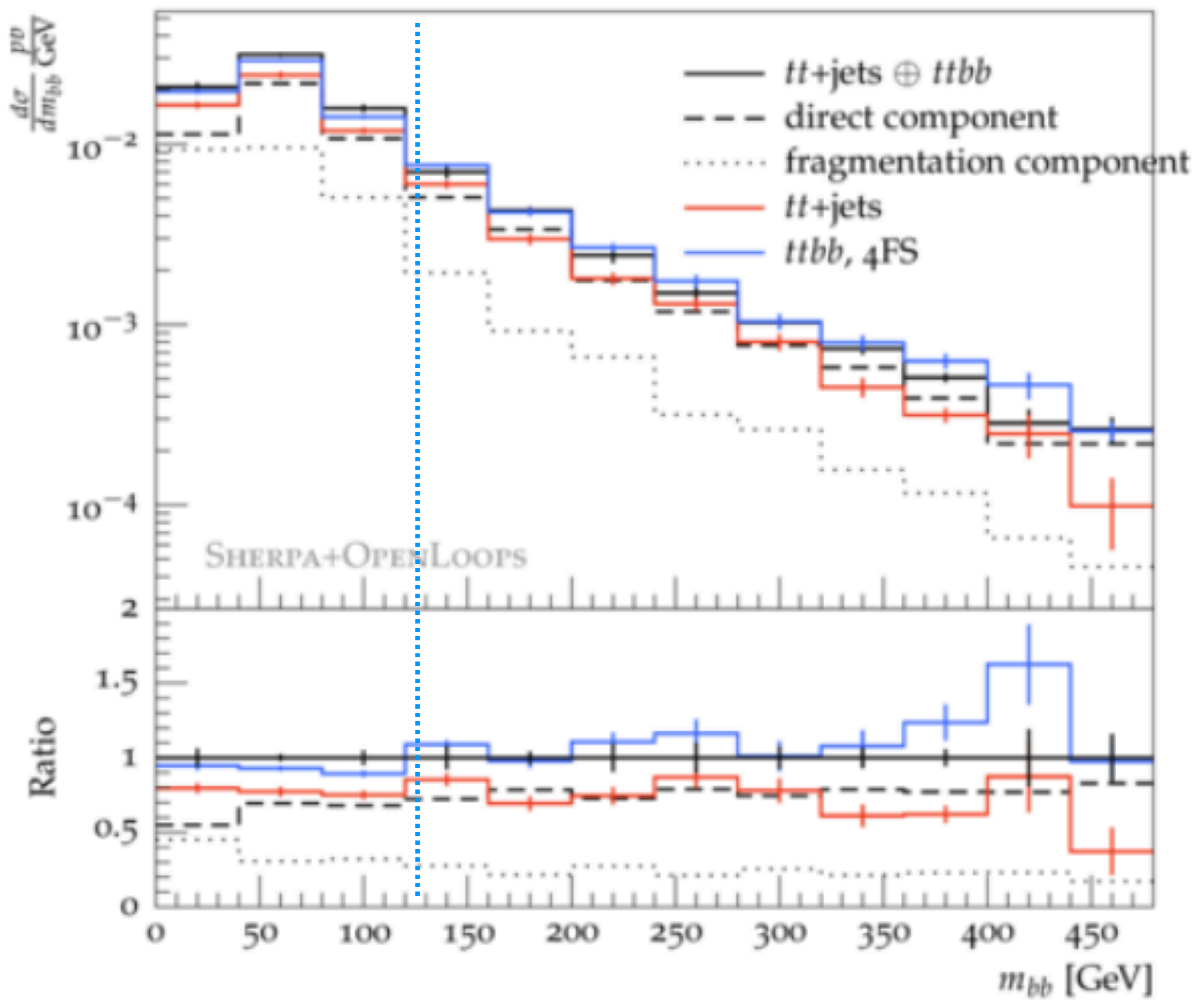
J.Katzy, J.Krause, C.Pollard, F.Siegert

Work in progress

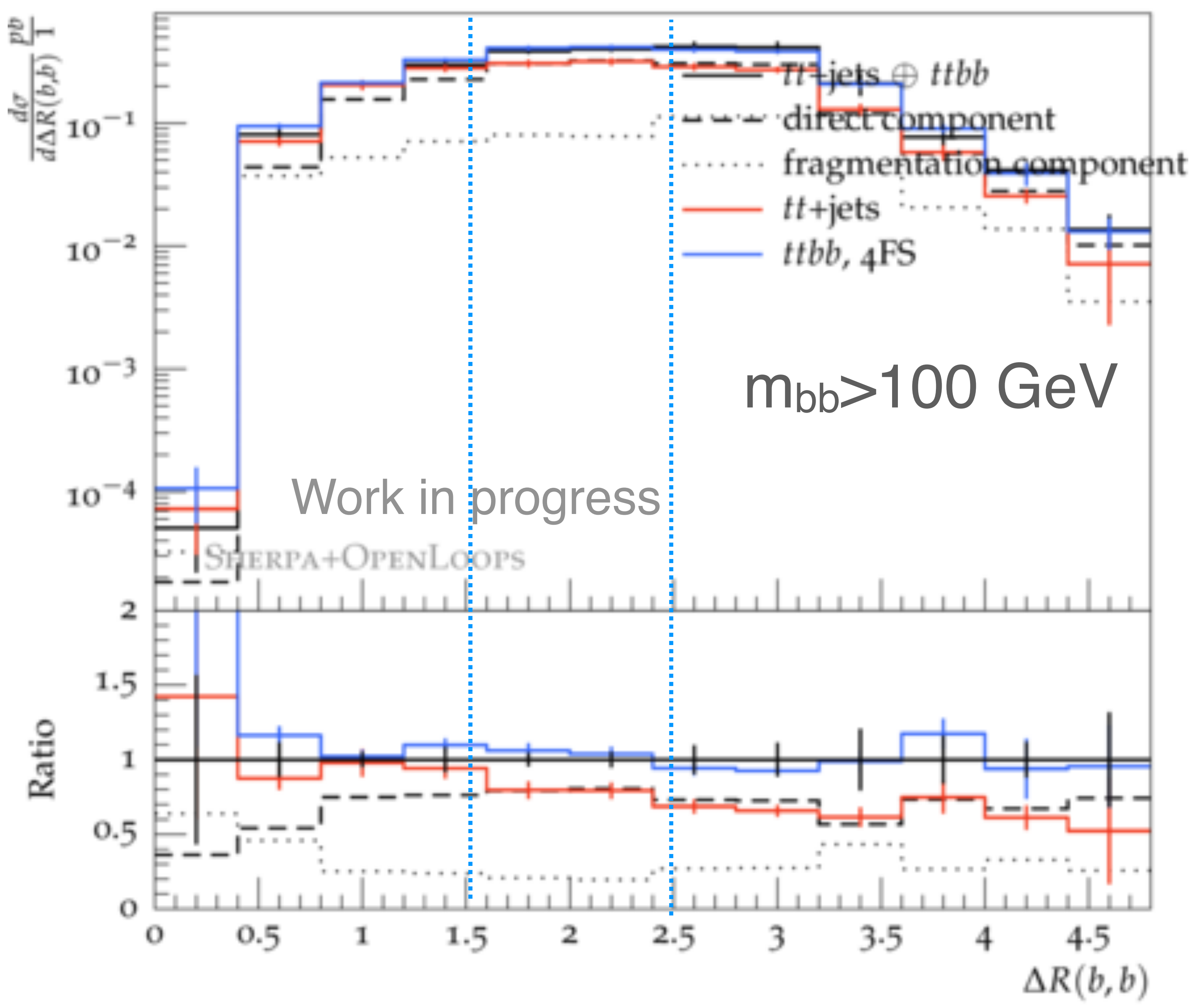
Fusing algorithm for ttbb+ttjj predictions

- Direct component in fused sample: ttbb ME@NLO in 4FS component in fused sample
- Fragmentation component in fused sample: g->bb PS splitting and b-jets from tt+jets (m_b=0)
- Compare to tt+jets 5FS and ttbb 4FS standalone calculations

Undecayed tops



Undecayed tops



- At 1.5 < DR(bb) <2.5 (Higgs region) 80% direct component
- At Higgs mass region still significant contributions from fragmentation component

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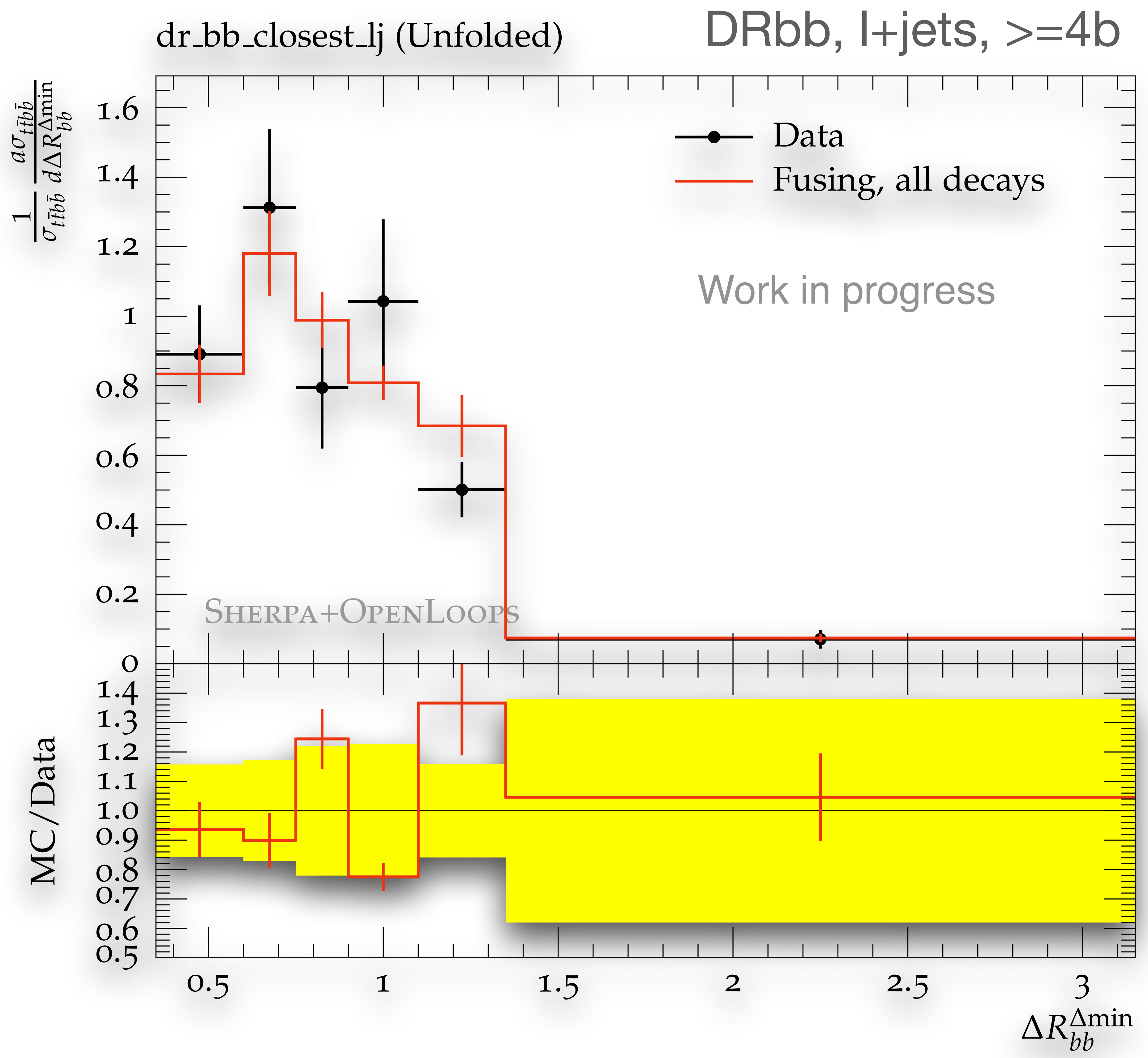
Work in progress

Fusing compared to ttbb measurement

- Decayed tops, PS+hadronisation in Sherpa 2.2.6



Summary and Conclusion

- ttbb rare process, first differential measurements exist with 32fb-1 (ATLAS) and 2.3 fb-1 (CMS) but lack stats
  - With full Run2 more observables are possible and improved analysis techniques will give smaller uncertainties

- Predictions of tt+HF involve many theoretical aspects
  - New algorithm “fusing” applied to ttbb + tt+jets

- Constraining ttbb background for ttHbb is a challenging but not hopeless task with many new ideas to be explored experimentally and in phenomenology

BACK-UP

Monte Carlo samples

Generator sample	Process	Matching	Tune	Use
Powheg-Box v2 + Pythia 8.210	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 1.5m_t$	A14	nom.
MadGraph5_aMC@NLO + Pythia 8.210	$t\bar{t} + V/H$ NLO	MC@NLO	A14	nom.
Powheg-Box v2 + Pythia 8.210 RadLo	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 1.5m_t$	A14Var3cDown	syst.
Powheg-Box v2 + Pythia 8.210 RadHi	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 3.0m_t$	A14Var3cUp	syst.
Powheg-Box v2 + Herwig 7.01	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 1.5m_t$	H7UE	syst.
Sherpa 2.2.1 $t\bar{t}$	$t\bar{t}$ +0,1 parton at NLO +2,3,4 partons at LO	MePs@Nlo	Sherpa	syst.
MadGraph5_aMC@NLO + Pythia 8.210	$t\bar{t}$ NLO	MC@NLO	A14	comp.
Sherpa 2.2.1 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}b\bar{b}$ NLO	MC@NLO	Sherpa	comp.
PowHel + Pythia 8.210 (5FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\text{damp}} = H_T/2$	A14	comp.
PowHel + Pythia 8.210 (4FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\text{damp}} = H_T/2$	A14	comp.
Powheg-Box v2 + Pythia 8.210 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\text{damp}} = H_T/2$	A14	comp.

Binned Maximum Likelihood Fit

$$\mathcal{L}(\vec{\alpha}|x_1,\ldots,x_n) = \prod_k^n \frac{e^{-\nu_k(\vec{\alpha})}\nu_k(\vec{\alpha})^{x_k}}{x_k!}$$

em channel

$$\nu_k(\alpha_b,\alpha_{cl}) = \alpha_b N^k_{t\bar{t}b} + \alpha_{cl}\left(N^k_{t\bar{t}c} + N^k_{t\bar{t}l}\right) + N^k_{\text{non-}t\bar{t}}$$

l+jets channel

$$\nu_k(\alpha_b,\alpha_c,\alpha_l) = \alpha_b N^k_{t\bar{t}b} + \alpha_c N^k_{t\bar{t}c} + \alpha_l N^k_{t\bar{t}l} + N^k_{\text{non-}t\bar{t}}$$

Template fit event categorization

Table 4: Event categorisation (for the definition of the MC templates) based on the particle-level selections of *b*-jets, *c*-jets and light-flavour jets.

Category	$e\mu$	lepton + jets
$t\bar{t}b$	$\geq$3 *b*-jets	$\geq$3 *b*-jets
$t\bar{t}c$	$<$ 3 *b*-jets and $\geq$ 1 *c*-jet	$<$ 3 *b*-jets and $\geq$ 2 *c*-jets
$t\bar{t}l$	events that do not meet above criteria	events that do not meet above criteria

includes
< 3b-jet + 1 c-jet
Which are from W->cs decays to 85%

Unfolding

$$\frac{d\sigma^{\text{fid}}}{dX^i} = \frac{N^i_{\text{unfold}}}{\mathcal{L}\,\Delta X^i} = \frac{1}{\mathcal{L}\,\Delta X^i\, f^i_{\text{eff}}} \sum_j \mathcal{M}^{-1}_{ij}\, f^j_{\text{matching}}\, f^j_{\text{accept}}\, f^j_{t\bar{t}b}\, (N^j_{\text{data}} - N^j_{\text{non-}t\bar{t}\text{-bkg}})$$

$$f^j_{t\bar{t}b} = \frac{\alpha_b N^j_{t\bar{t}b,\text{reco}}}{\alpha_b N^j_{t\bar{t}b,\text{reco}} + \mathcal{B}^j}$$

$$f^j_{\text{matching}} = \frac{N^j_{t\bar{t}b,\text{reco}\wedge\text{part}\wedge\text{matched}}}{N^j_{t\bar{t}b,\text{reco}\wedge\text{part}}}$$

em channel

$$\mathcal{B}^j = \alpha_{cl}\left(N^j_{t\bar{t}c,\text{reco}} + N^j_{t\bar{t}l,\text{reco}}\right)$$

l+jets channel

$$\mathcal{B}^j = \alpha_c N^j_{t\bar{t}c,\text{reco}} + \alpha_l N^j_{t\bar{t}l,\text{reco}}$$

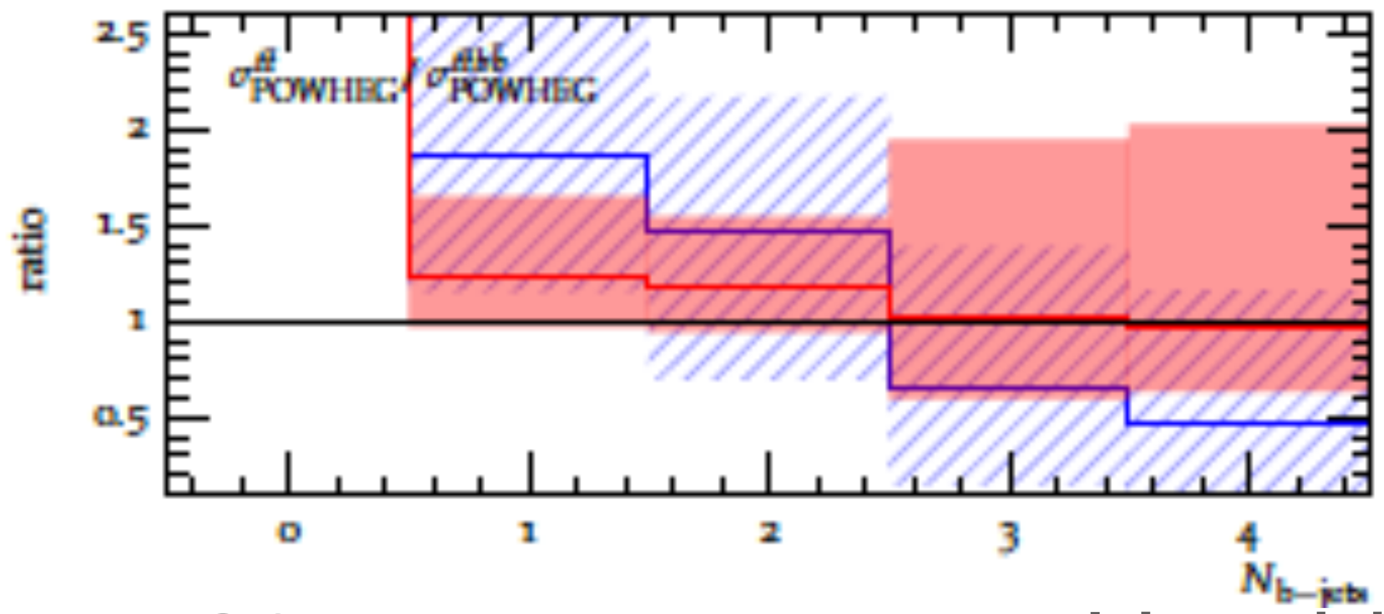
$$f^i_{\text{eff}} = \frac{N^i_{t\bar{t}b,\text{part}\wedge\text{reco}\wedge\text{matched}}}{N^i_{t\bar{t}b,\text{part}}}$$

$$f^j_{\text{accept}} = \frac{N^j_{t\bar{t}b,\text{reco}\wedge\text{part}}}{N^j_{t\bar{t}b,\text{reco}}}$$

$$\sigma^{\text{fid}} = \int \frac{d\sigma^{\text{fid}}}{dX} dX = \frac{\sum N^i_{\text{unfold}}}{\mathcal{L}}$$

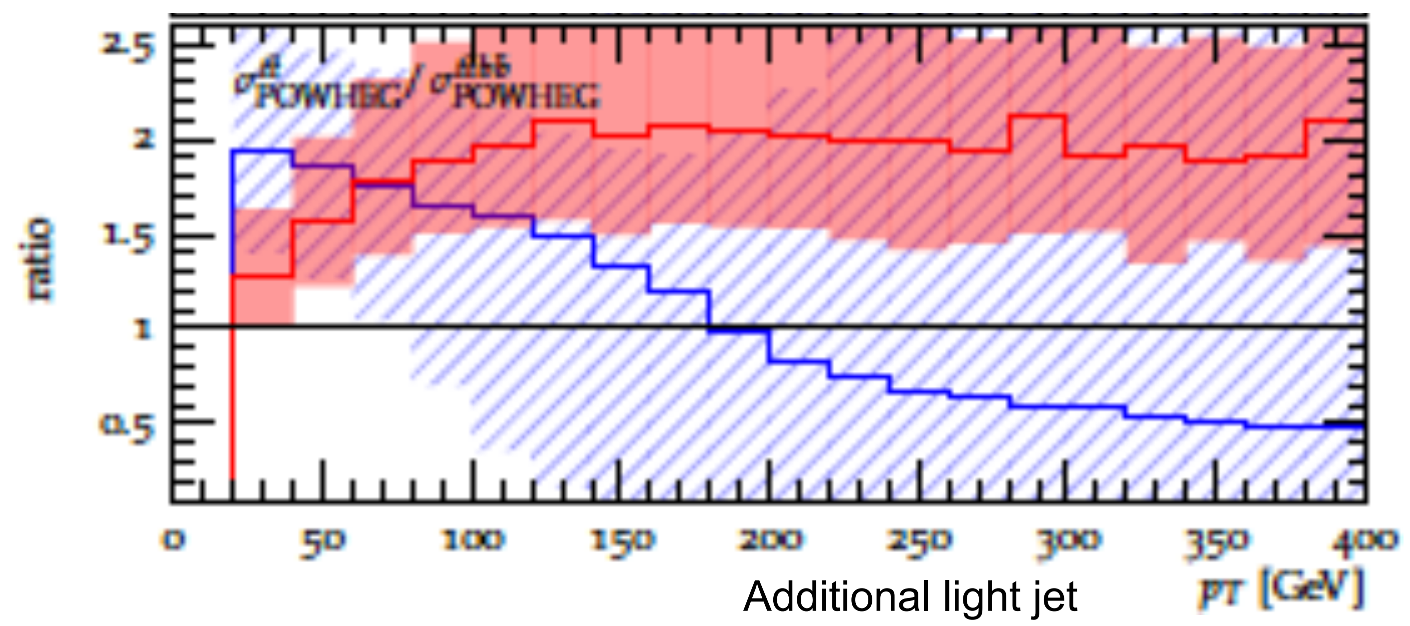
ttbb vs tt+PS

Ttbb PowHeg paper



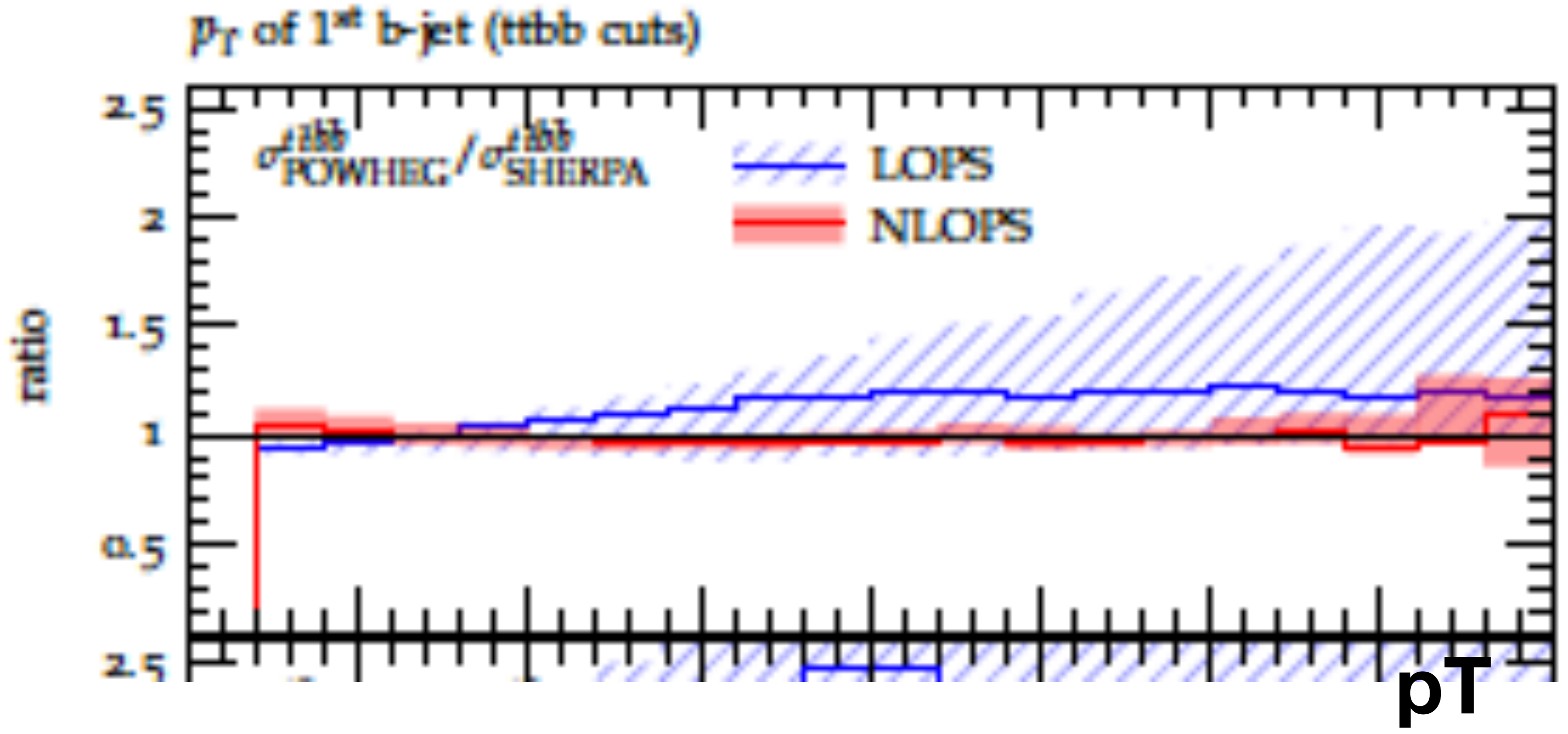
~20% more events with additional b-jets

Large uncertainties (20-30%)



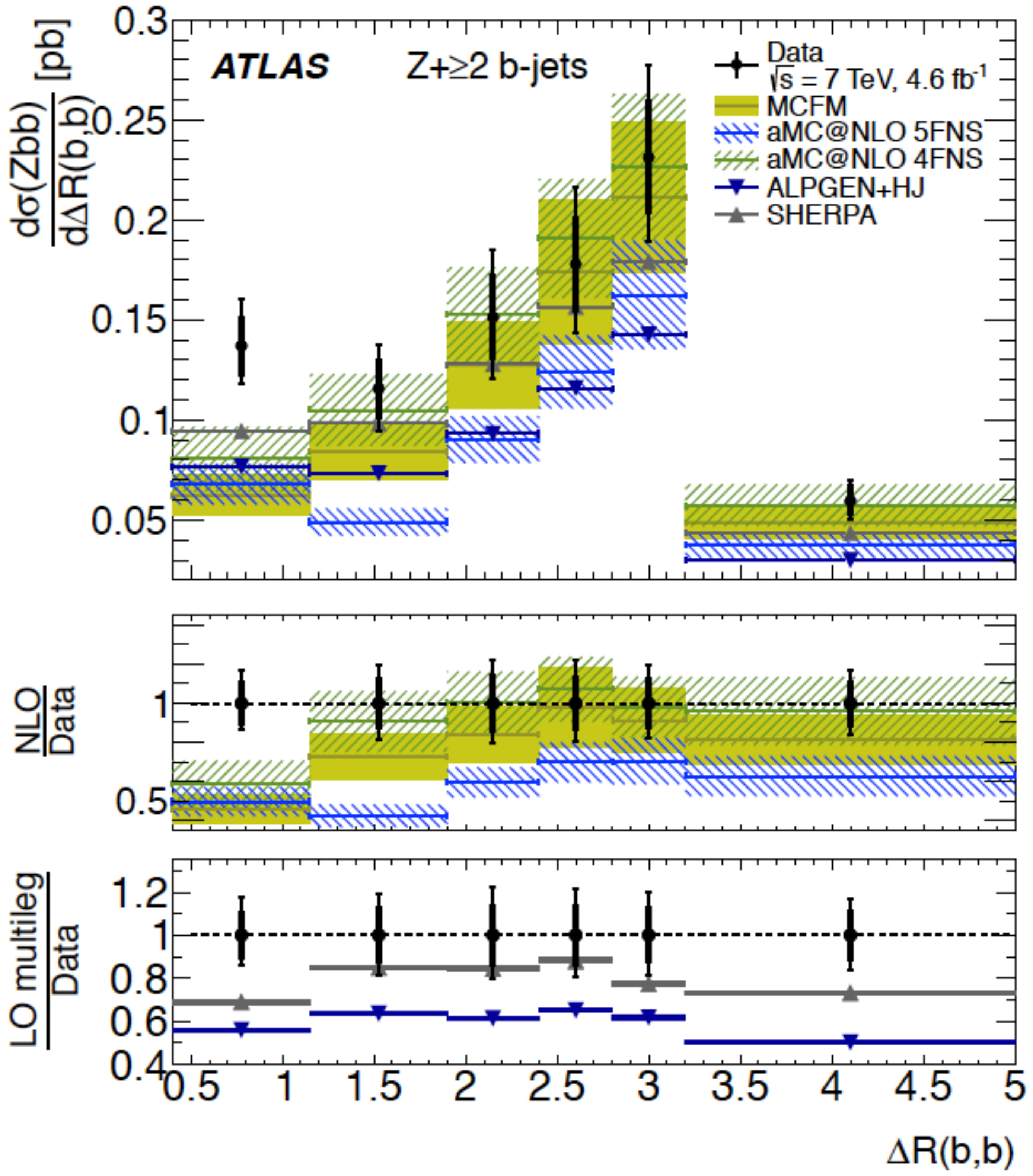
Significant changes in light jet pt

PS uncertainty doesn’t cover the ttbb ME predictions



Different ttbb ME@NLO calculations agree with each other

DRbb in Z+bb


ATLAS
Z+≥2 b-jets
Data
√s = 7 TeV, 4.6 fb-1
MCFM
aMC@NLO 5FNS
aMC@NLO 4FNS
ALPGEN+HJ
SHERPA
dσ(Zbb)/dΔR(b,b) [pb]
NLO/Data
LO multileg/Data
ΔR(b,b)

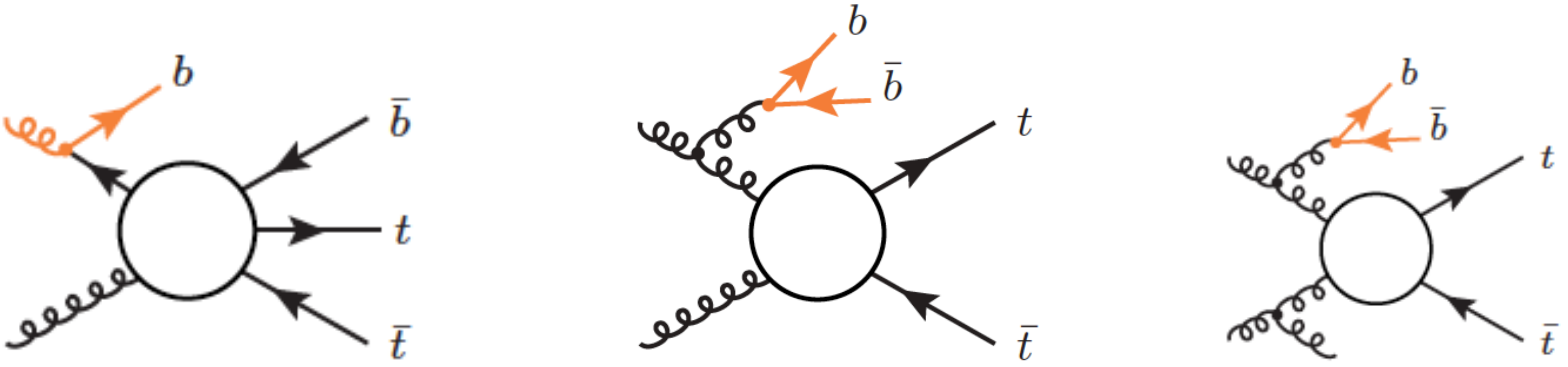
Event yields 36 fb-1

Table 2: Predicted and observed $e\mu$ channel event yields in $2b$, $\geq 3b$ and $\geq 4b$ selections. The quoted errors are symmetrised and indicate total statistical and systematic uncertainties in predictions due to experimental sources.

Process	$2b$	$\geq 3b$	$\geq 4b$
Signal ($t\bar{t} + t\bar{t}H + t\bar{t}V$)	74 400 ± 2 900	3 200 ± 310	210 ± 29
$t\bar{t}$	74 200 ± 2 900	3 100 ± 310	190 ± 29
$t\bar{t}H$	45.3 ± 6.6	36.5 ± 7.0	9.4 ± 3.3
$t\bar{t}V$	190 ± 16	33.5 ± 6.7	4.4 ± 2.2
Background	3 150 ± 810	140 ± 53	9.2 ± 5.6
Single top	2 460 ± 540	96 ± 32	4.1 ± 2.5
NP and fake lep.	600 ± 600	43 ± 43	5.1 ± 5.1
Z/γ^*+jets	53 ± 13	1.3 ± 0.3	0.07 ± 0.02
Diboson	38 ± 20	1.0 ± 1.1	$<$ 0.01
Expected	77 600 ± 3 000	3 320 ± 320	216 ± 30
Observed	76 425	3 809	267

MC predictions for ttbb

ME@NLO
PS



tt ME@NLO + g->bb in PS (5FS)

- Large theoretical uncertainties due to additional b-quark production in LO PS
- PS tuned to tt+jets, top pt,… ATLAS data with decent agreement in jet inclusive distributions

ATLAS nominal samples in this scheme (and CMS ttHbb samples):

- Powheg+Pythia8 (ttbar nominal + ttbar filtered for additional b-jet)
- Powheg+Herwig7
- MC@NLO+Pythia8

Powheg ttbb paper

(N)LO tt+0,1,2 ME + PS

Phenomenological study in PowHeg ttbb paper:

- Even though ttbb (with m_b=0) is availble at ME, most events have b-jets from PS
- Gluon->bb typically softer than 1st and 2nd splitting
- At $m_{bb} \sim m_H$ still almost 50% b-jets from PS (tt+0b)