Vector bosons + heavy flavours: lessons learned in ATLAS Run 1

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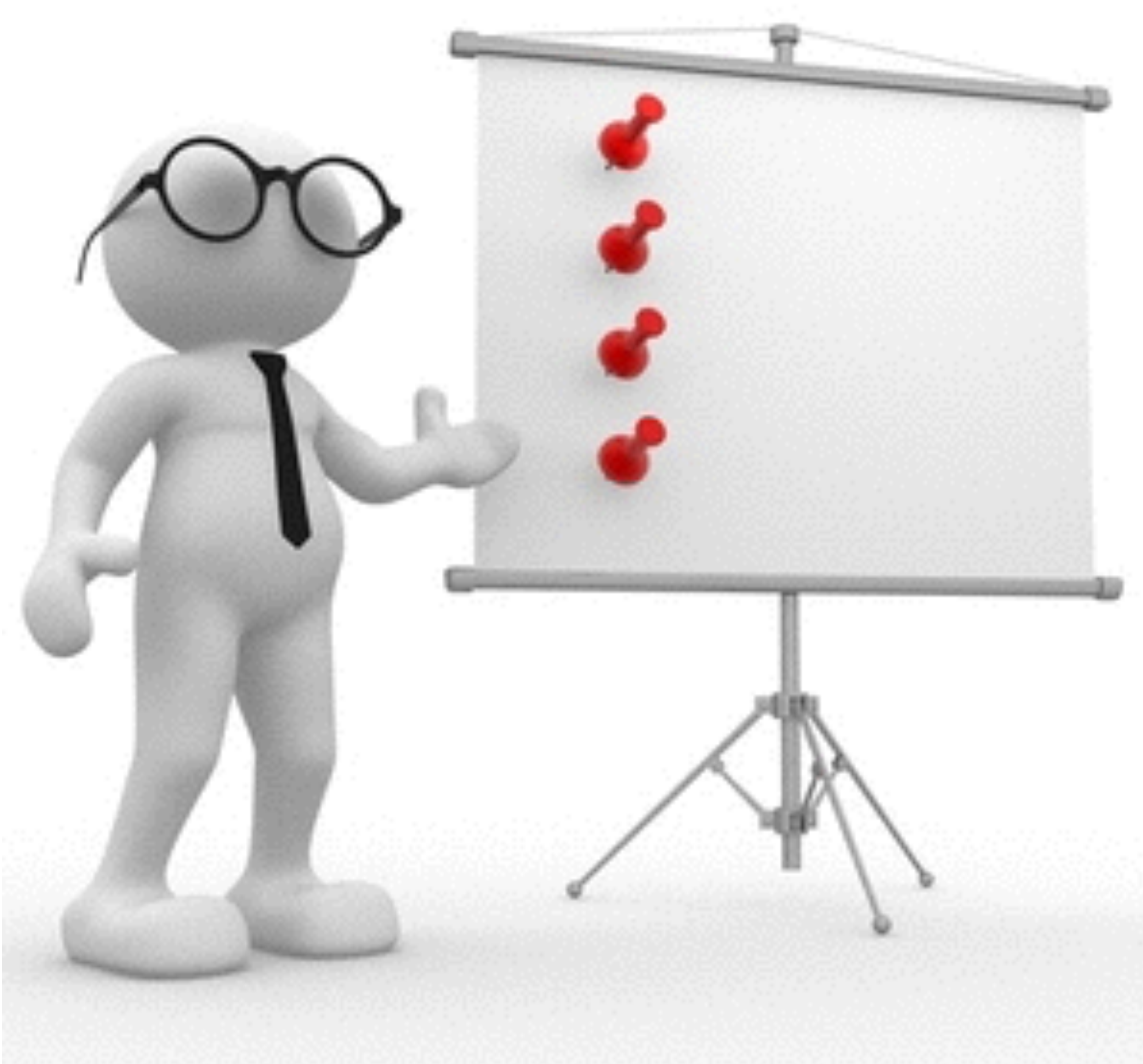
Outline



- Introduction
- The main client: VH(H→bb)
- W+b @ 7 TeV
- Z+b(b) @ 7 TeV
- Diversion: W+c @ 7 TeV
- Conclusions

Introduction

- ***Why is the measurement of V+HF important?***
  - Theory-wise, I guess you know ;-) , I will present what we tried to address analysis by analysis
  - Try to address here main experimental motivation
- Let's concentrate on what we can measure (and have already measured)
- ***Idea***: have two complementary talks (this and Josh's tomorrow)
  - *In this talk: where we're at ⇒ what we already measured during Run 1, and experimental motivations for measurements*
  - *In Josh's talk (he will illustrate this better..): where we're going ⇒ plans and first ATLAS results V+hf - related*

..some experimental motivation to start with!

The "main client" (experimentally)

- *VH(H→bb) analysis is the main "client" for these measurements*

- *Z+bb and W+bb are irreducible backgrounds, and the modelling of V+b is also important for a good modelling of the control regions*

- ATLAS Run 1 analysis (based on full 7+8 TeV dataset) uses a BDT, trained in 12 different categories: 3 "lepton channels" ($\nu\nu$, $\ell\nu$, $\ell\ell$), 2 or 3 jet exclusive, high and low p_T^V

Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
$\boxed{m_{bb}}$	×	×	×
$\boxed{\Delta R(b_1, b_2)}$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$\boxed{MV1c(b_1)}$	×	×	×
$\boxed{MV1c(b_2)}$	×	×	×
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

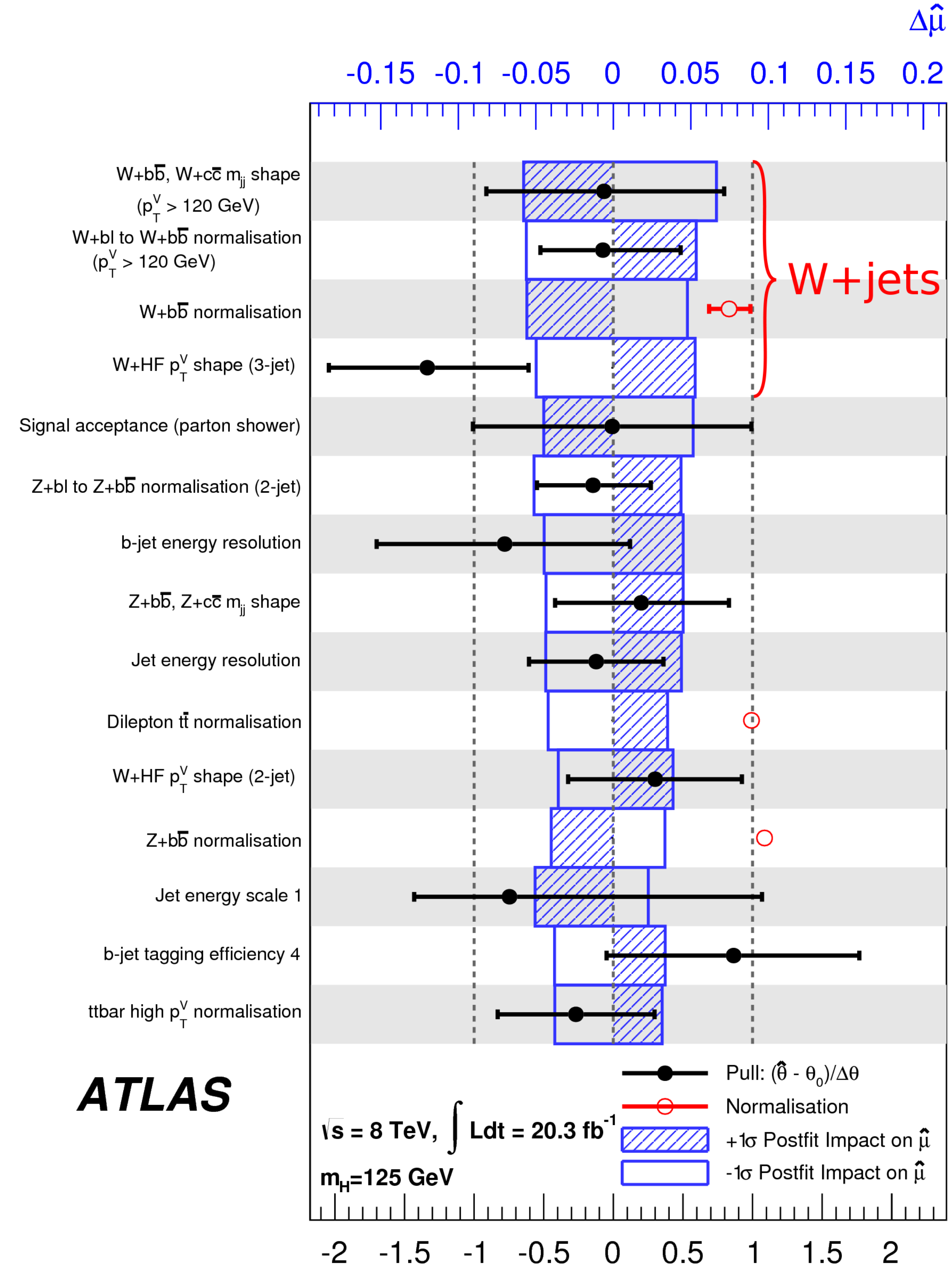
Profile likelihood fit with large number of categories (including regions with only 1 b-tagged jet or 0 tagged jets, to constrain the background normalisations) to extract the signal

VH(bb) guidelines for V+HF future measurements

- ***Main source of uncertainty in the analysis comes from the V+HF modelling***, mainly in the W channel, where feedback from measurement is lacking more

- ***Message to take:*** very important to reduce uncertainty on the predictions: our duty for Run 2 (see Josh's talk)

- *Relevant variables for differential measurement of W+b and W+bb (planned for ATLAS Run 2) m_{bb}, p_T^V, $\Delta R(b,b)$*



W+b analysis in Run 1

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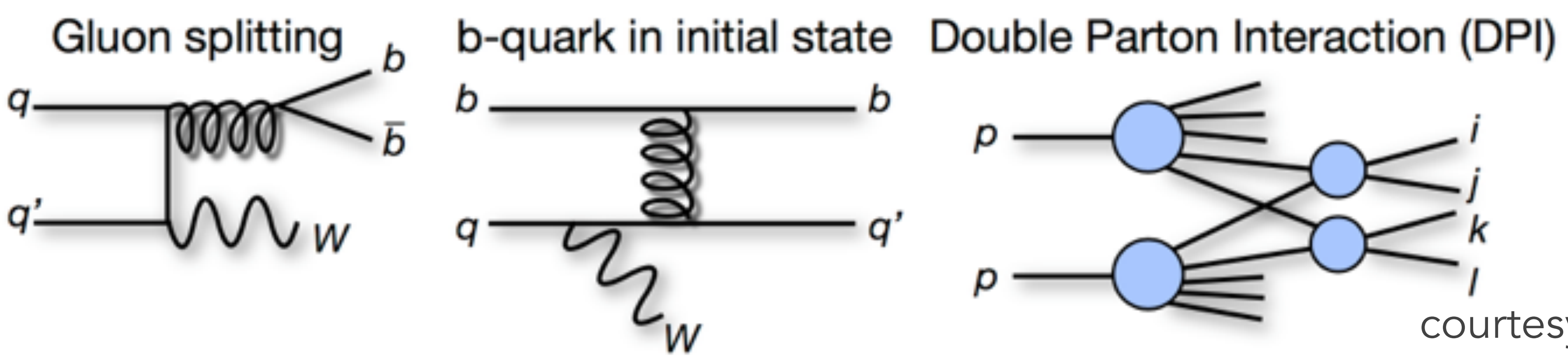
W+b - Dataset and strategy

- ***Performed on 4.6 fb^{-1} of data collected @ 7 TeV***

- Probing mainly following processes:



courtesy of Y. Ninomiya

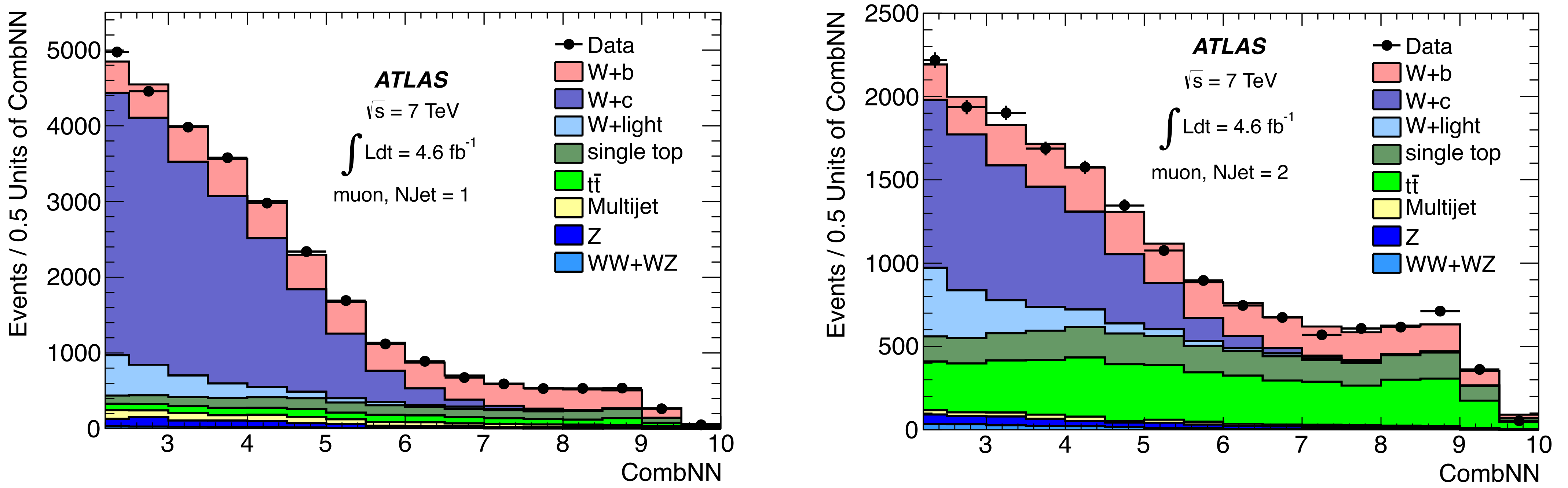
σ_{fid}	==1 b-jet ⇒ reject top bkgr Jet multiplicities: 1, 2, and 3 jets	$d\sigma_{fid}/dp_T^b$	==1 b-jet Jet multiplicities: 1, and 2 jets

b-tagging (Run 1 version, but see more in Hanna's talk tomorrow):

- multivariate combination of different algorithms, examining IP, SV and b—>c decay chains

W+b - Backgrounds and uncertainties

- Most background derived with *data driven* techniques in control regions (top, EW, QCD multijet)
- *Signal extraction based on template likelihood fit to b-tagging discriminant variable*



Sources of *uncertainties* (and measurement limiting factors):

- Statistics: 7-10% uncertainty
- Systematics: 20-25% mainly driven by JES/JER, MC modelling, and ISR and FSR evaluation, affecting the top

⇒ ***main points to be addressed for Run 2 measurement!***

W+b - Cross section results

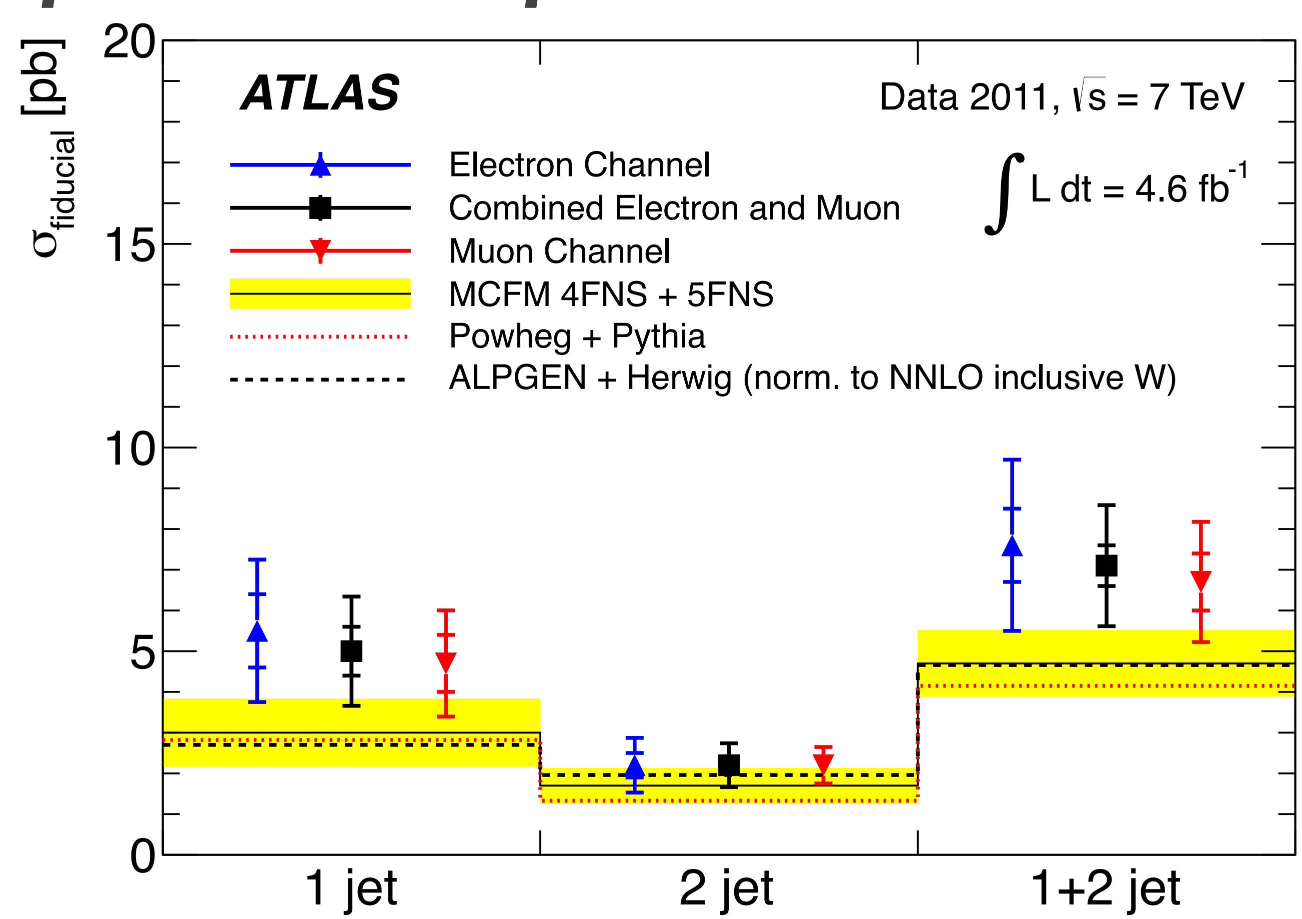
Comparison with different predictions: MCFM (5FNS), Powheg and Alpgen (4FNS)

Correction factors applied to the predictions for:

- ➡ non-perturbative effects (4% in 1-jet bin, 8% in 2-jet bin)
- ➡ DPI (~25% of the total cross section, mainly in low momentum 1-jet bin)

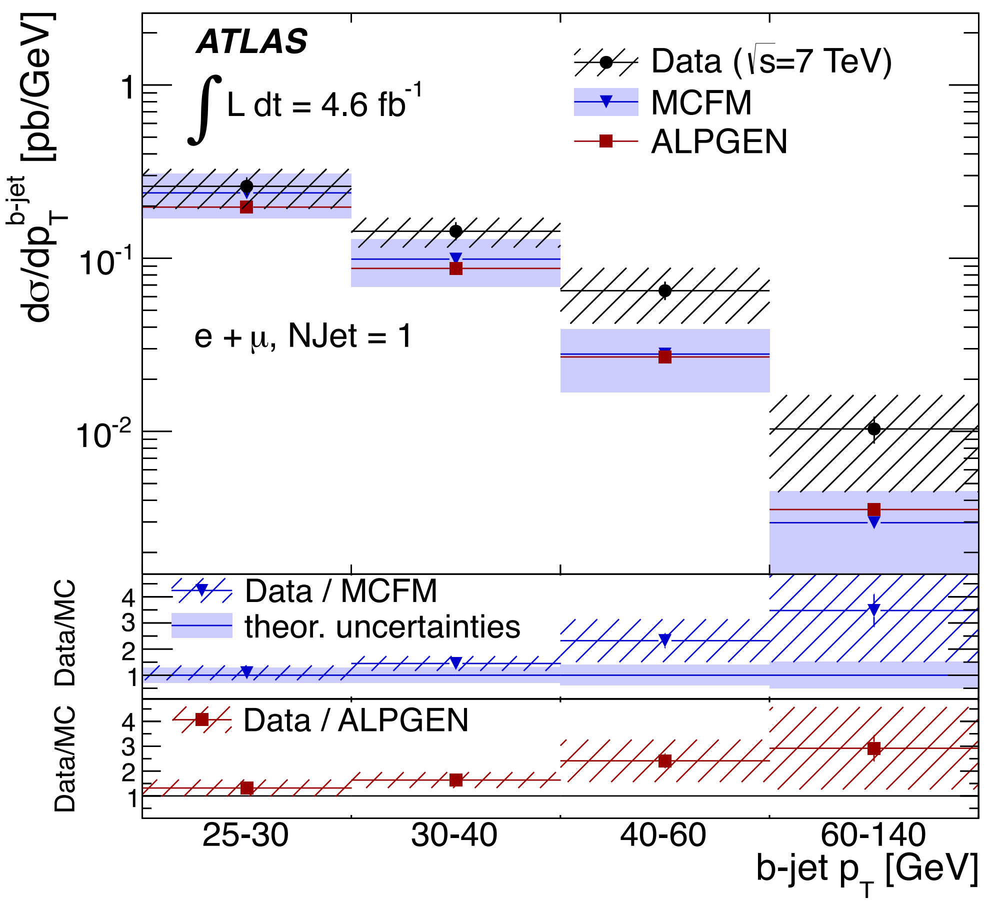
Fiducial cross section comparison to predictions:

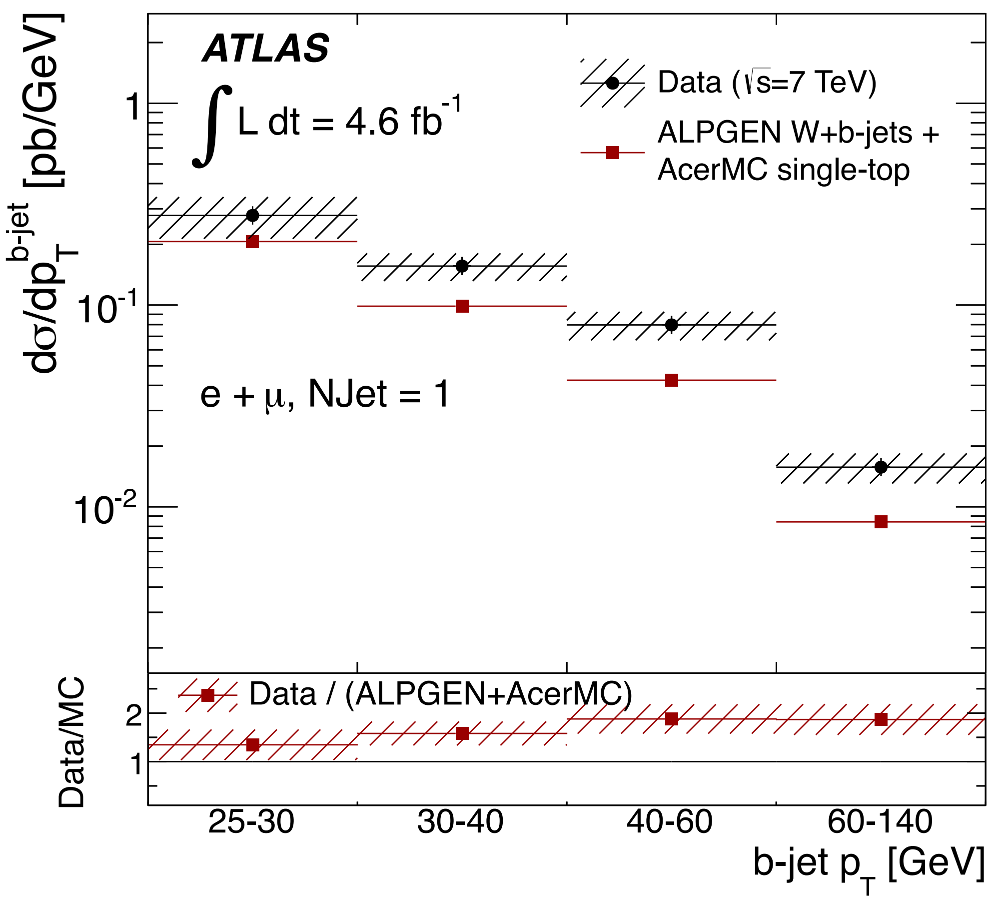
- ➡ 1-jet bin: underestimate wrt data (~1.5 sigma less)
- ➡ 2-jet bin: good agreement
- ➡ all the predictions agree within the uncertainties



W+b - Differential cross section

Differential cross section in b-jet p_T calculated with and w/o subtracting the single top contamination (very large)





- ***Discrepancy growing as a function of p_T***, but large statistical uncertainty
- Study with single top included seems to vouch for this discrepancy, with a reduced stat uncertainty in the higher pt bins

Z+b(b) analysis in Run 1

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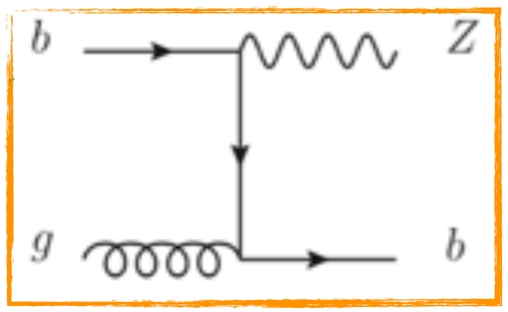
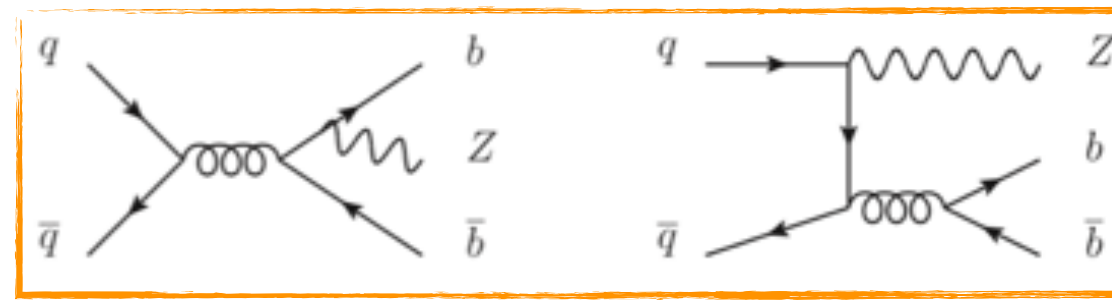
Z+b(b) - Dataset and strategy

Measurement performed on same dataset as W+b (7 TeV, 4.6 fb-1)



Z+≥1 b-jet
b is initial state parton:
5FNS



Z+≥2 b-jet
Present in both 4 and 5FNS

Total cross section + large pool of differential distributions → feedback to generators

dσ/dx	x
1 b-tag	y^Z, p_T^Z, y^b, p_T^b, $\Delta R^{Z,b}$, $\Delta\Phi^{Z,b}$, $y_{boost}^{Z,b}$
2 b-tags	y^Z, p_T^Z, m_{bb}, ΔR_{bb}

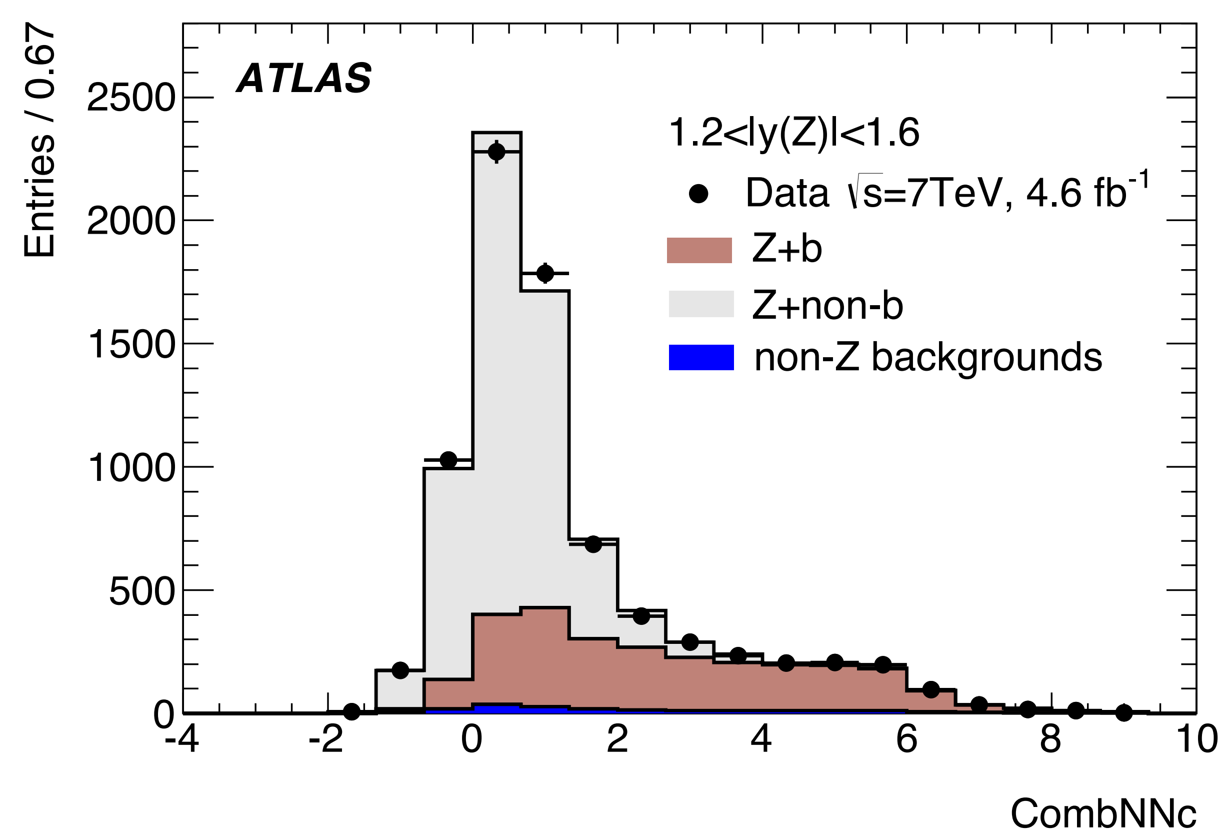
Z+b(b) - Background and systematics

- ***Background treatment:***
  - top and diboson from simulation
  - QCD multijet from data
  - *template fit to b-tag discriminant to extract signal and contribution of mis-tagged events of W+light and c-jets*

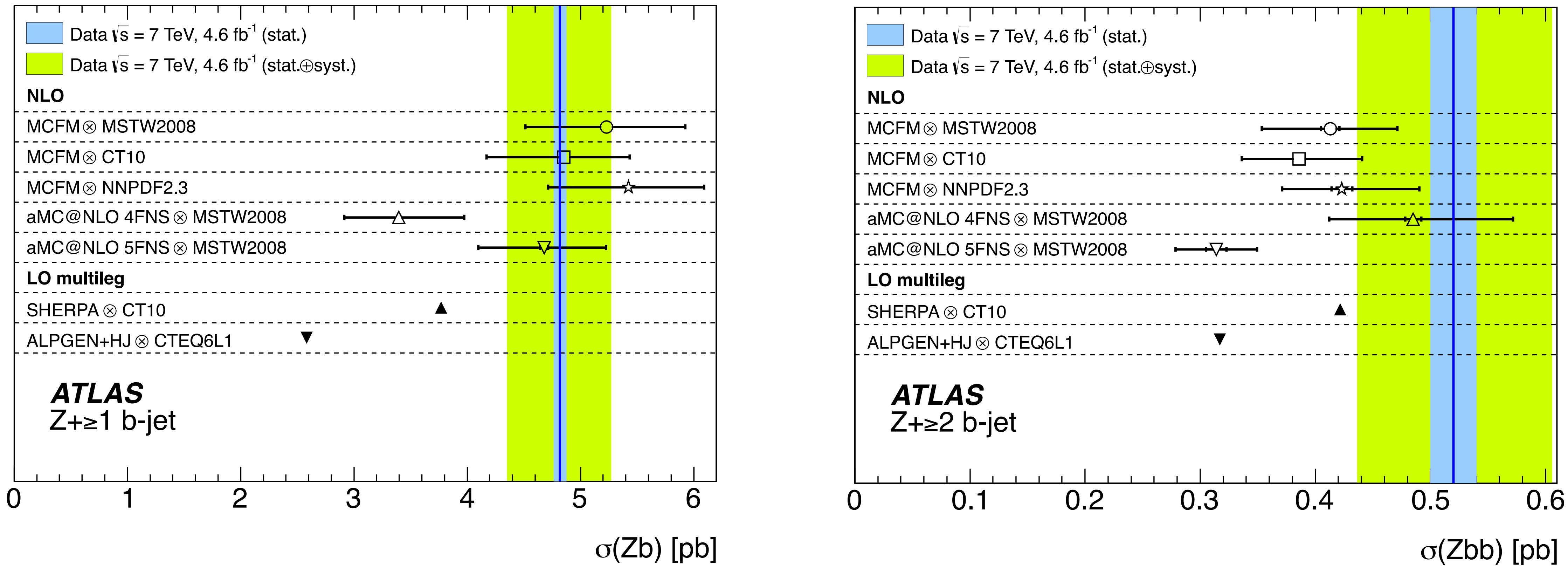
Dominant uncertainties and limiting factors (to be addressed in Run 2 analysis):

- Dominant systematic uncertainties from flavour fit, b-tagging and JES
- 2 b-jet region dominated by statistical uncertainties in the differential distributions

Example template fit in one of the y(Z) intervals



Z+b(b) - Cross section measurement

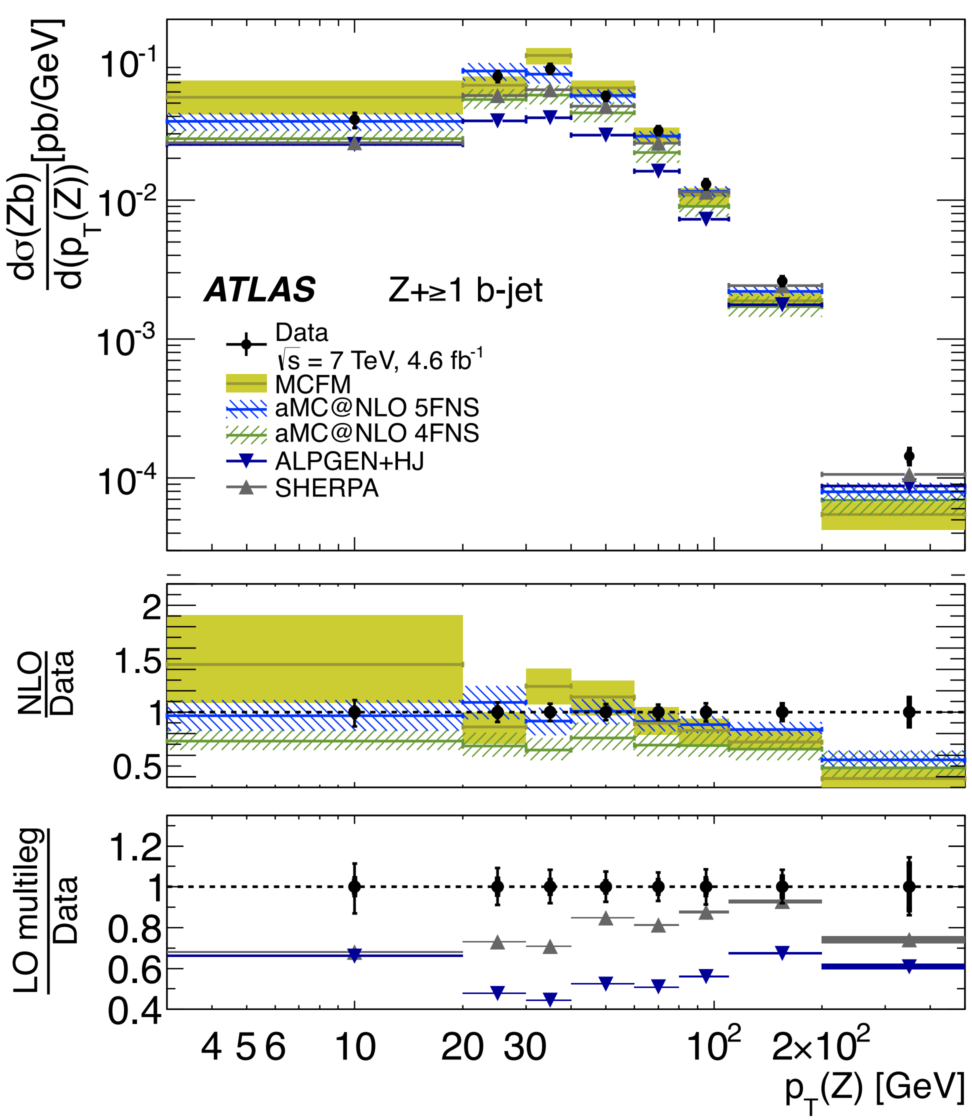


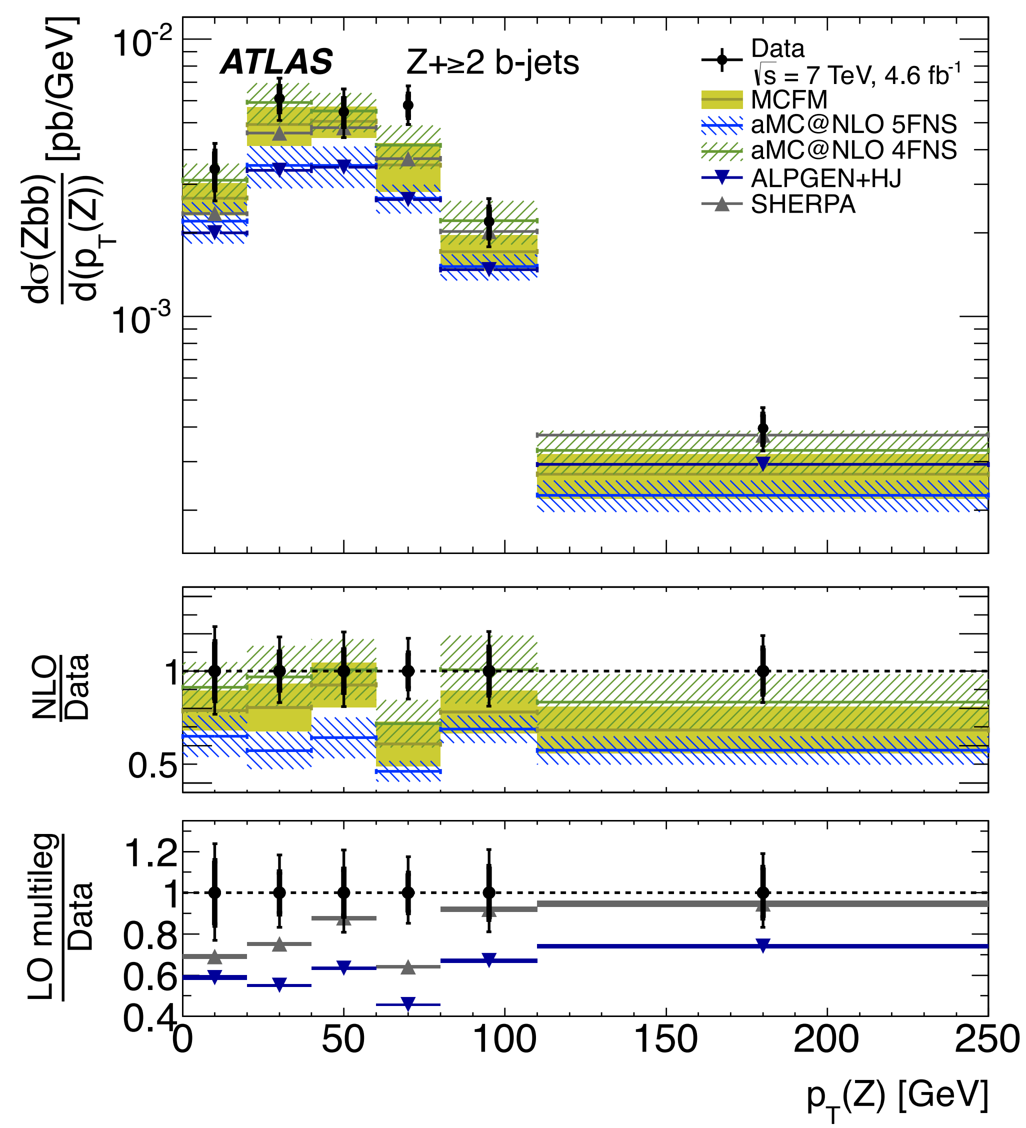
- ***Different predictions compared:***
  - *MCFM* (fixed order NLO for Z+≥1 b and Z+≥2b, 5FNS, massless b's)
    - compared different PDF sets, within 1 sigma (th) from one another - relatively good agreement in 1 b-jet case
  - *aMC@NLO* (NLO ME for Z+bb, 4FNS, massive b's)
    - good agreement for Z+bb, > 2sigma off for Z+1b
  - *aMC@NLO* (NLO ME for Z+1b, 5FNS, massless b's)
    - good agreement for Z+1b, and large underestimate for Z+bb

Z+b(b) - $d\sigma/dp_T^Z$

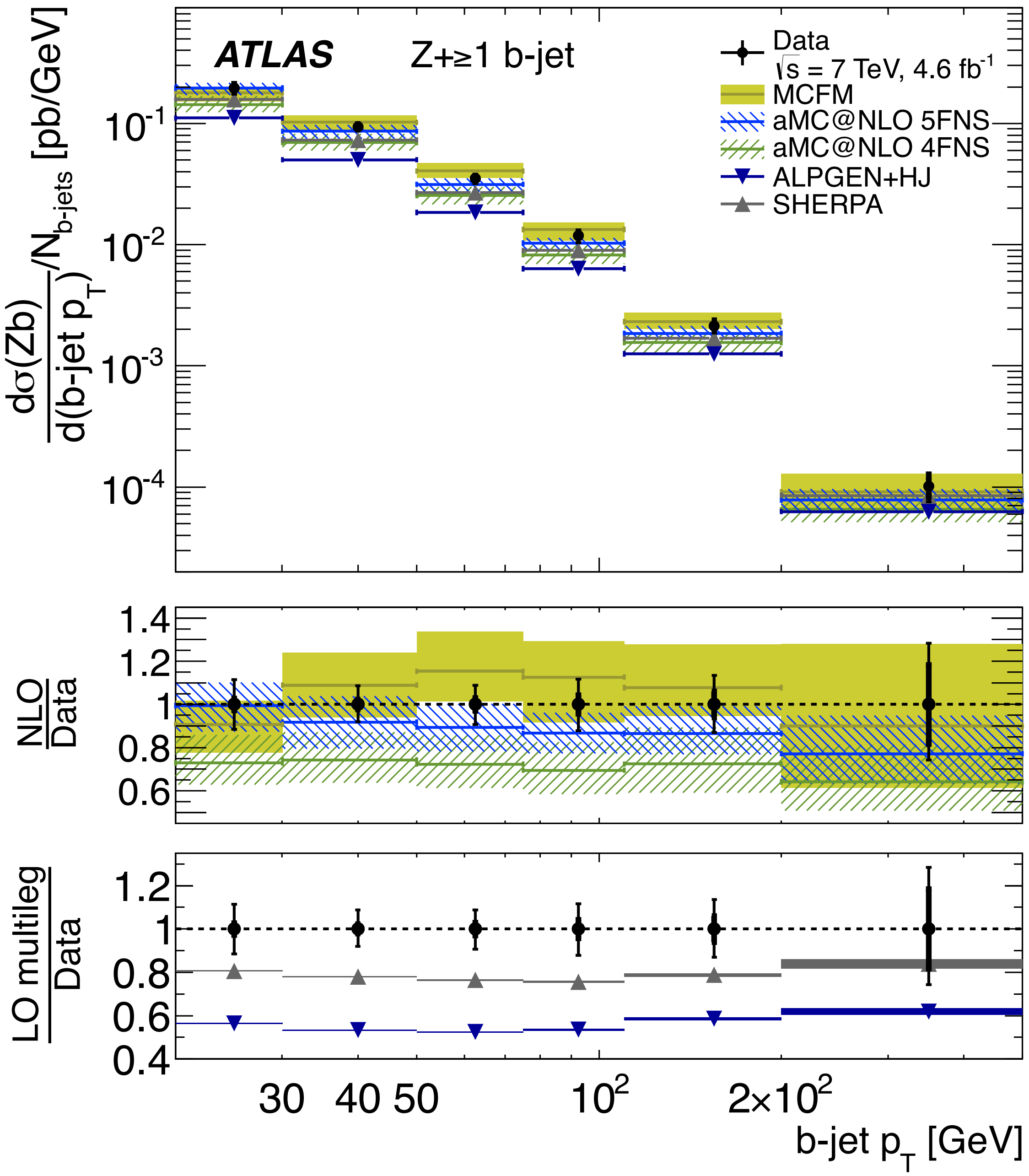
- ***Differential x sections compared to same MC's described in previous slide + LO multi leg (shown on plots without applying k-factors):***
  - Alpgen (4FNS)
  - Sherpa (5FNS) 1.4.1

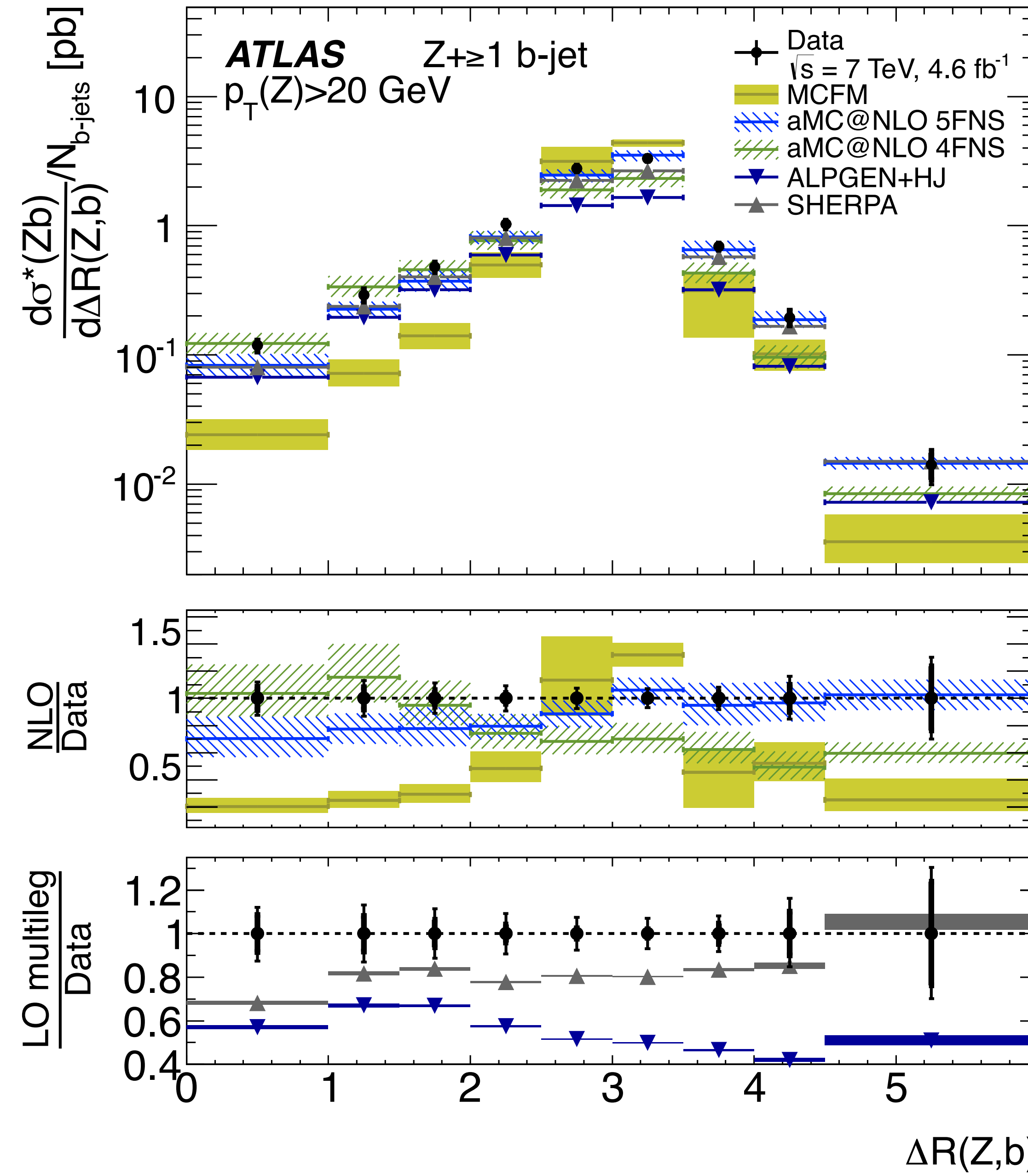
- *Discrepancy with respect to NLO predictions at high p_T^Z → to be addressed with new Run 2 measurement!*





Z+b(b) - $d\sigma/dp_T^b$ and $d\sigma/d\Delta R(Z,b)$

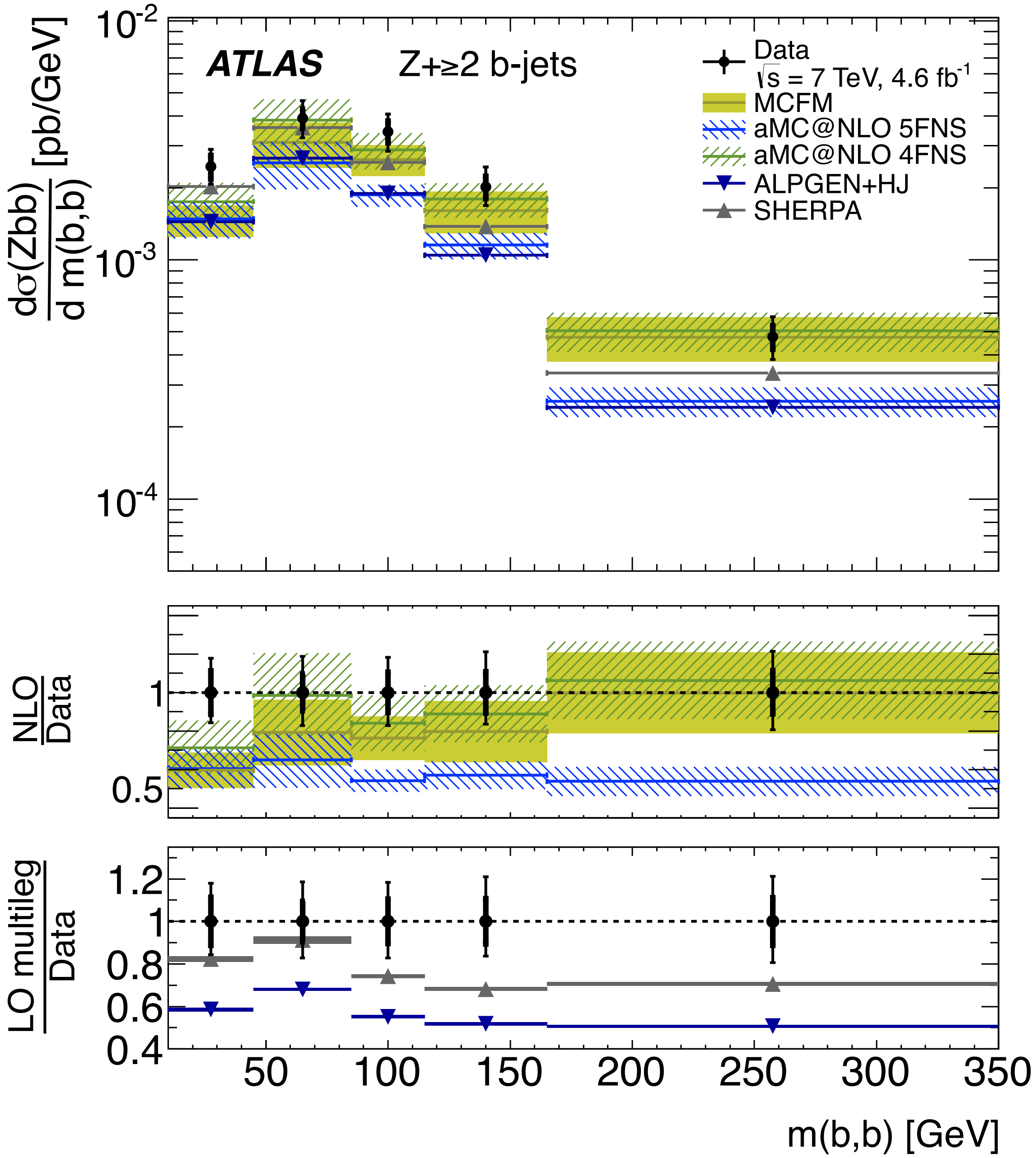


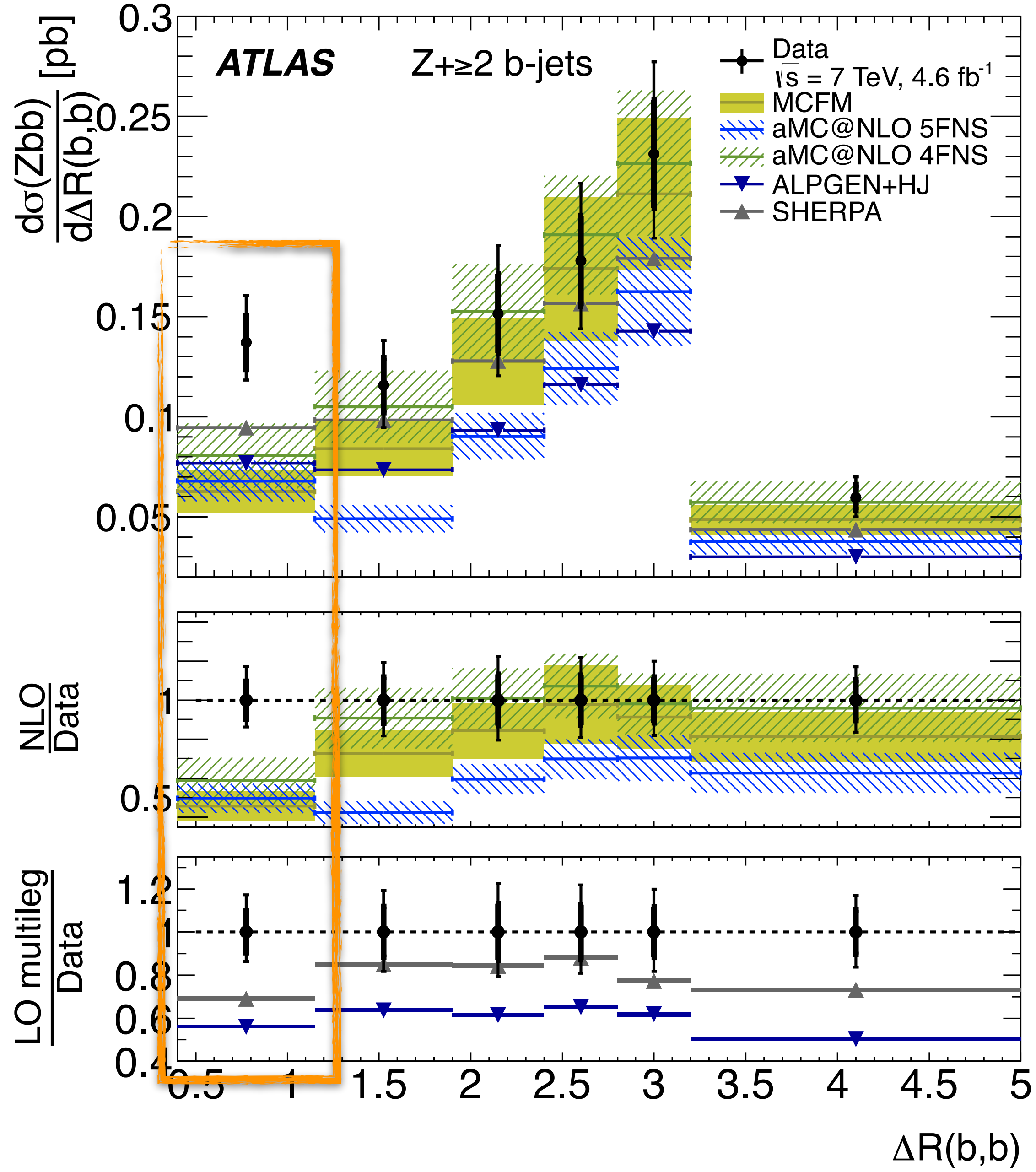


MC and data agree within the uncertainty

MCFM bad modelling because of 1 parton case ($\Delta\Phi(Z,b)=\pi$ by construction, fixed order calculation with up to 2 outgoing partons)

Z+b(b) - dσ/dm$_{bb}$ and dσ/dΔR(b,b)





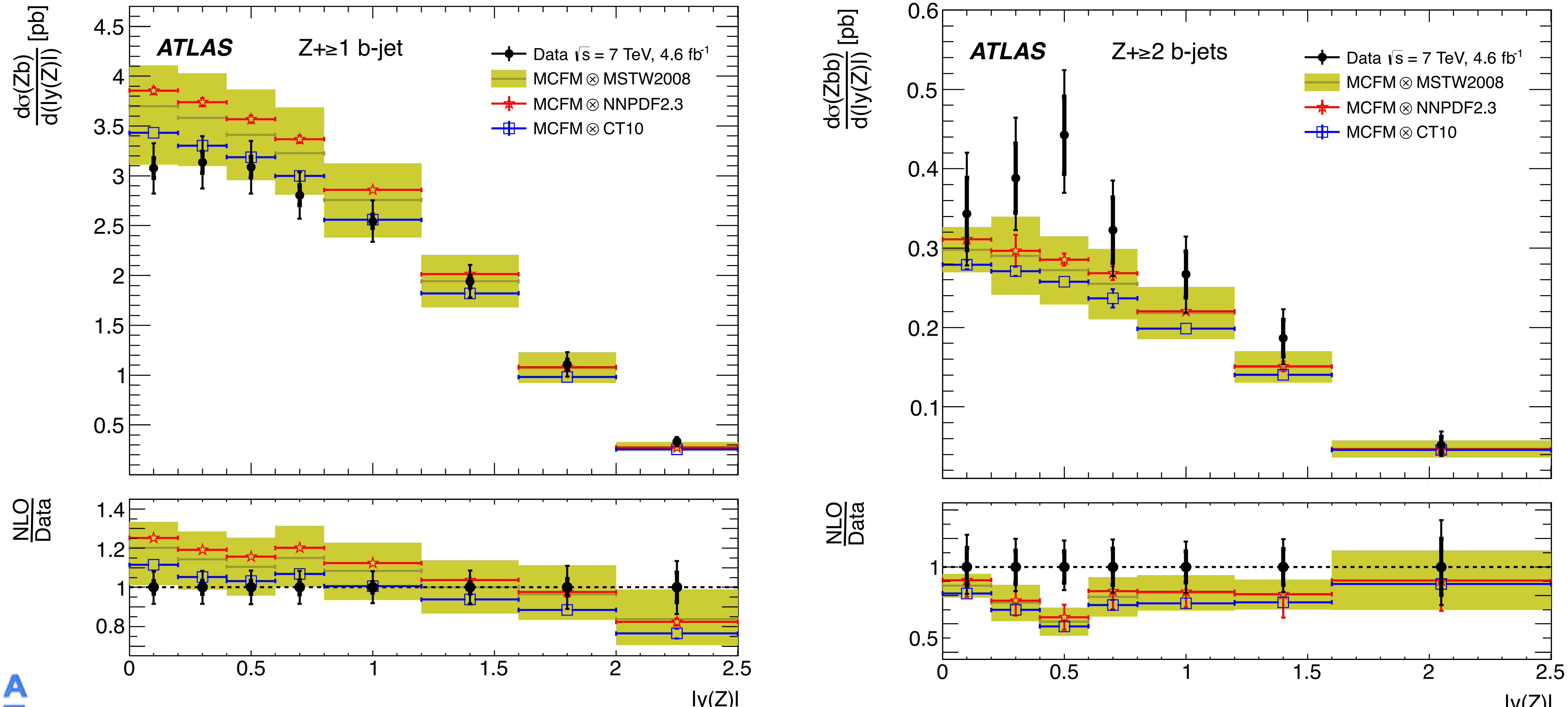
Low ΔR(b,b) large discrepancy!

Testing here gluon splitting to bb!!! → very interesting to be followed up in Run 2!!

Z+b(b) - Checking pdf's

Z rapidity most sensitive distribution to pdf's → still hard to make a statement because of large scale uncertainties

Trend of predictions with respect to data similar between different pdf's



Short digression:
a different V+HF analysis

W+c in Run 1

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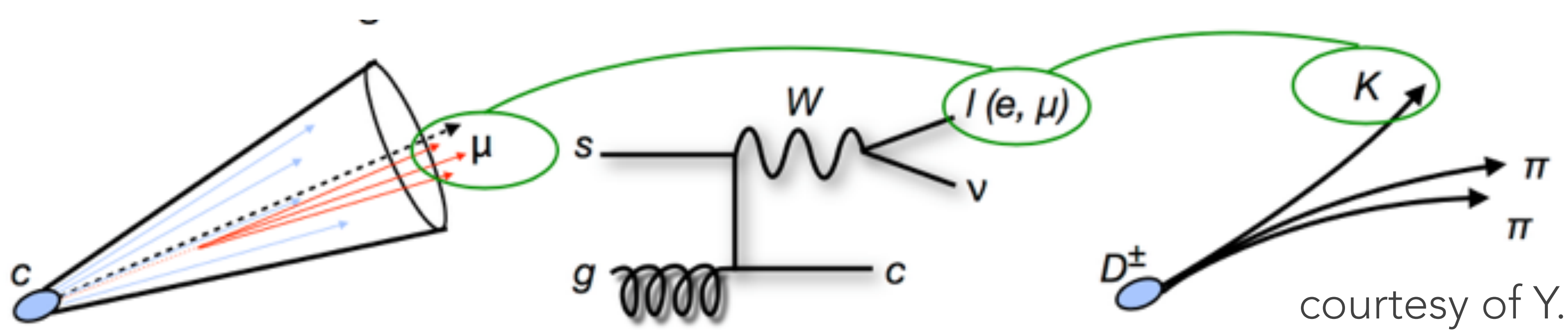
W+c - Dataset, motivation and strategy

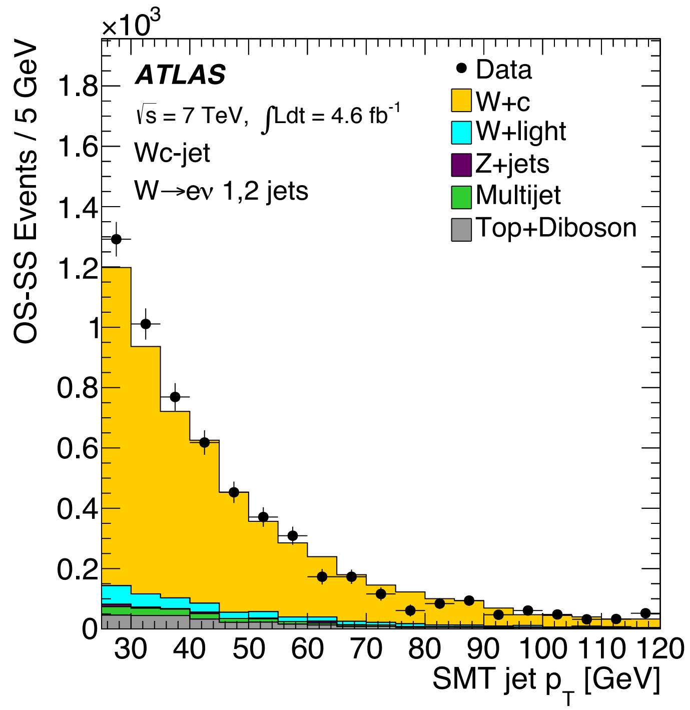
- *Measurement performed on the same 7 TeV dataset*
- ***Probe for strange PDF***
  - Provides info on SU(3) flavour symmetry
    - is the symmetry of the sea broken by strange quark mass?
    - (how) does it depend on x?
- ***2 analyses*** to extract c-component in the final state
  - soft muon tagging of the jet
  - use D hadrons
- Charge correlation between W and c used for background suppression (OS-SS)

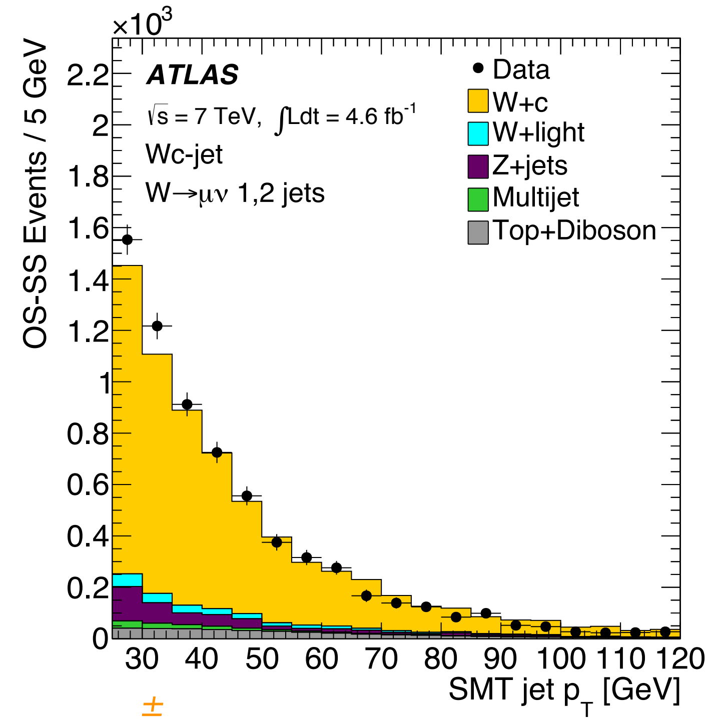


courtesy of Y. Ninomiya

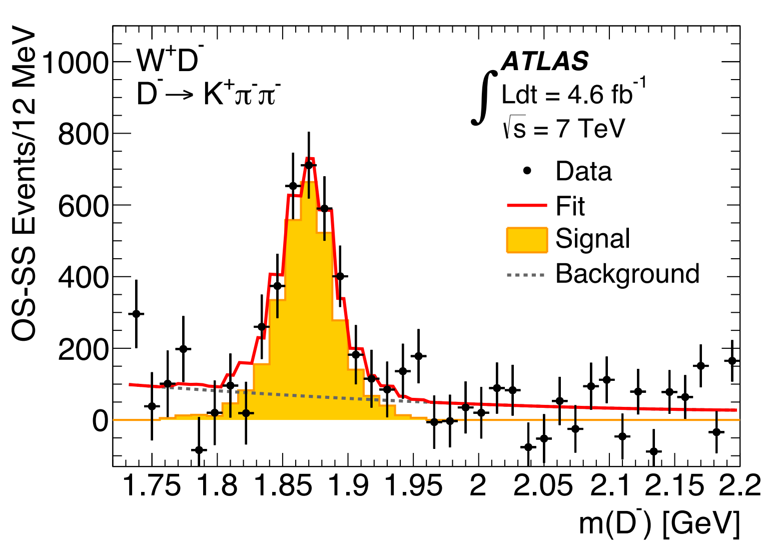
W+c - Analysis description

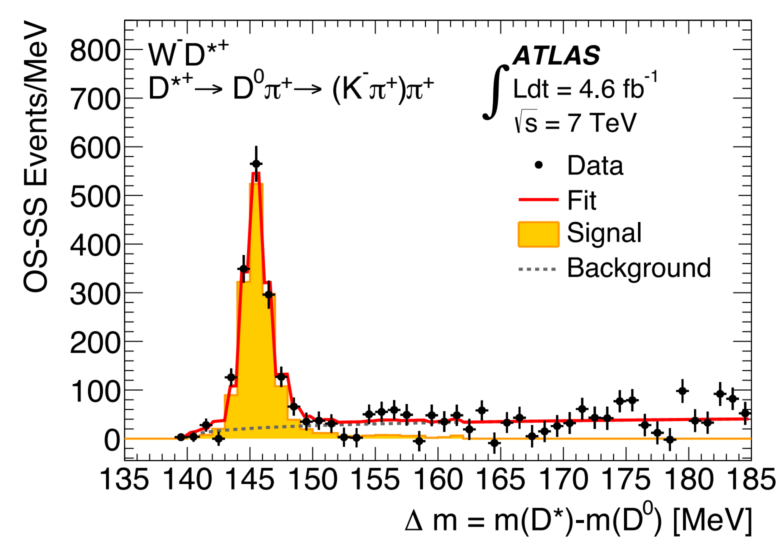
- *W+c-jet based on cut and count of OS and SS events*
- Main background estimated using data, smaller via MC



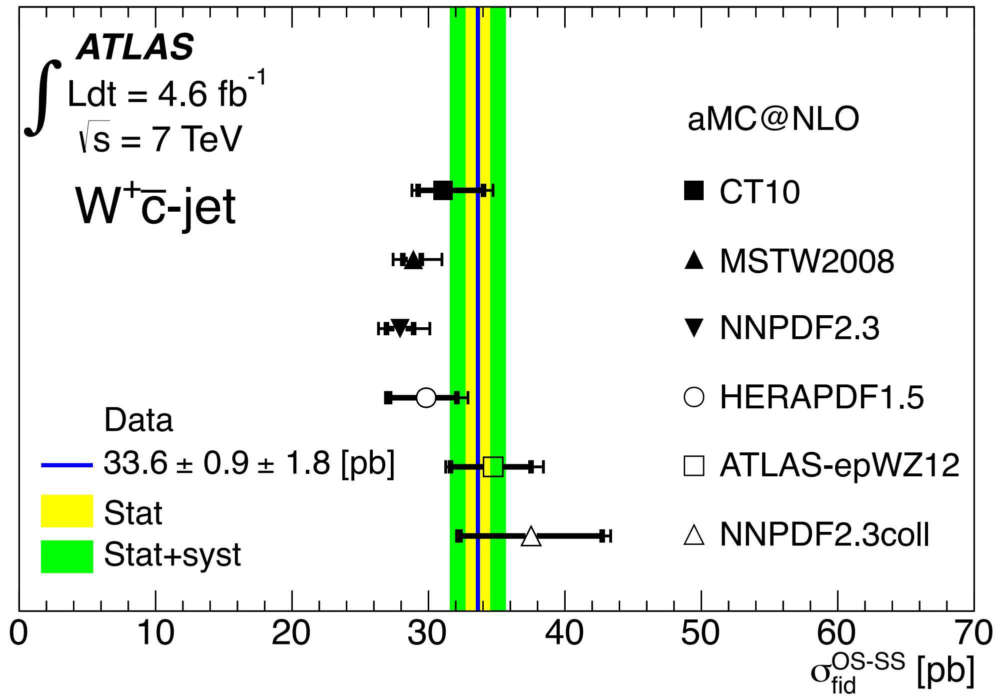


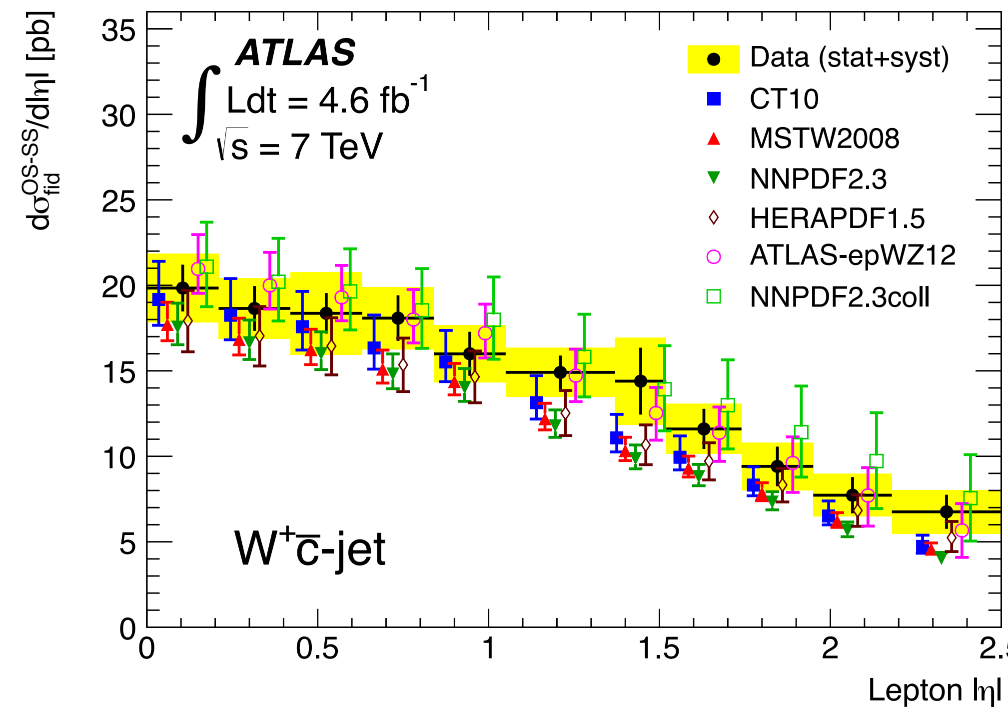
- *W+c hadron based on exclusive reconstruction of $D^{\pm}$ and D* mesons in different decay channels*
- Fit mass of D+- or mass difference (D*-D^{0})

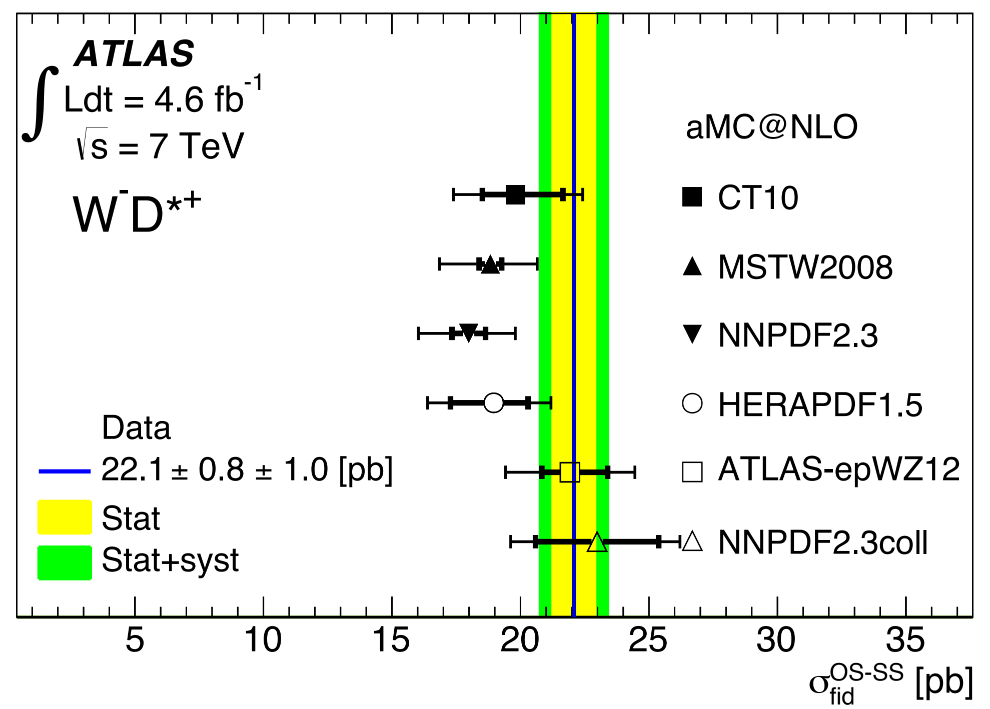


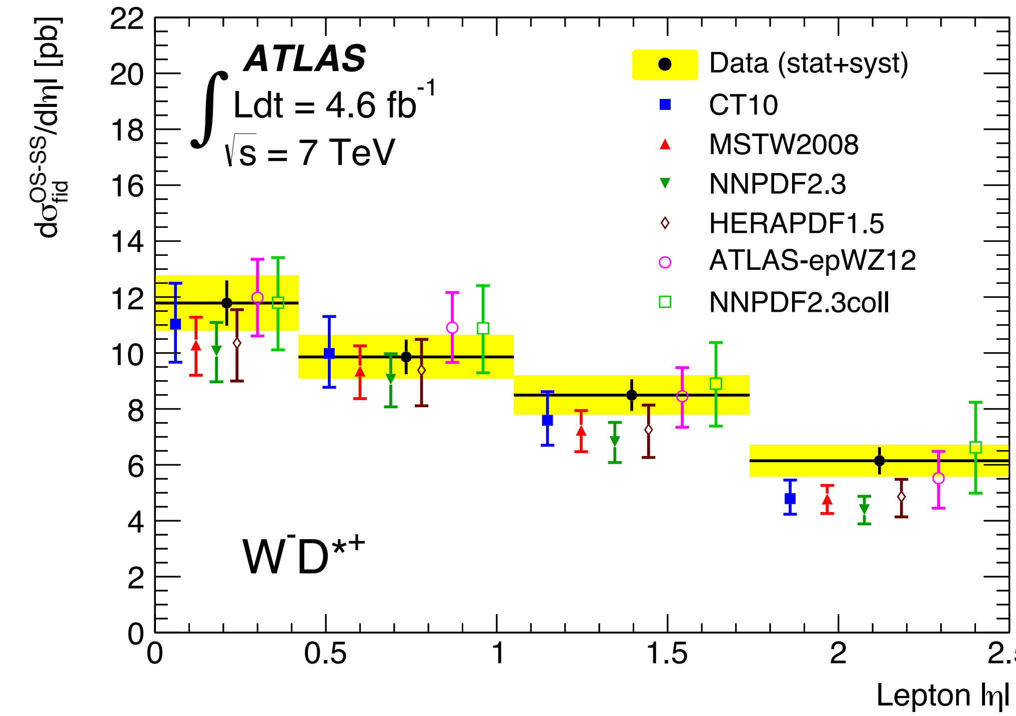


W+c - Results









PDFs with symmetric light quark sea (ATLAS-epWZ12) are favoured by the data

Conclusions

- ***Need to revisit asap the V+b(b) measurement (in progress)***
  - Very complete Z channel analysis @ 7 TeV
  - Less information from W+b analysis - follow up and *measurement of W+bb needed!*
  - Very important for Higgs analysis (and not only!!! Many BSM analyses have V+b's final states)
  - *Try and go as low as possible in $\Delta R(b,b)$ for the Z case → probe even more the gluon splitting*

- Interesting results from the W+c analysis, *hinting towards symmetric light quark sea in PDF's* - will be followed up

- ***…more on plans and where we stand now and what we plan in Josh talk!***

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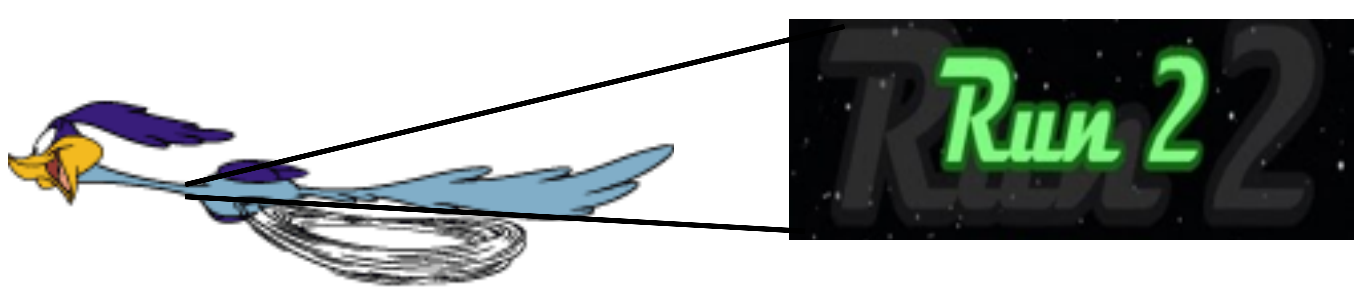

Thank you!

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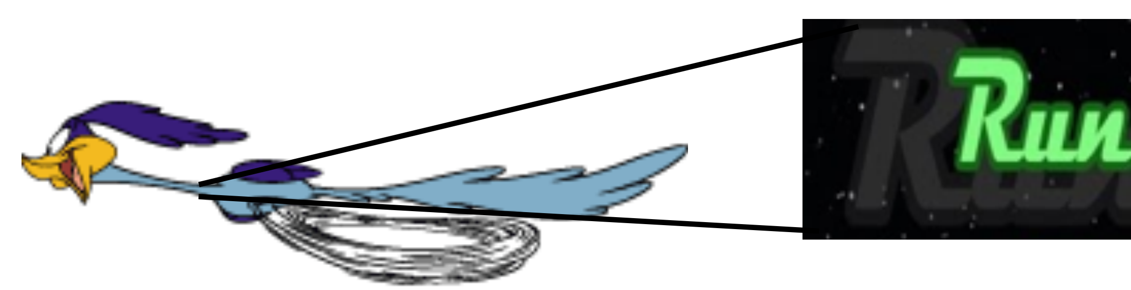
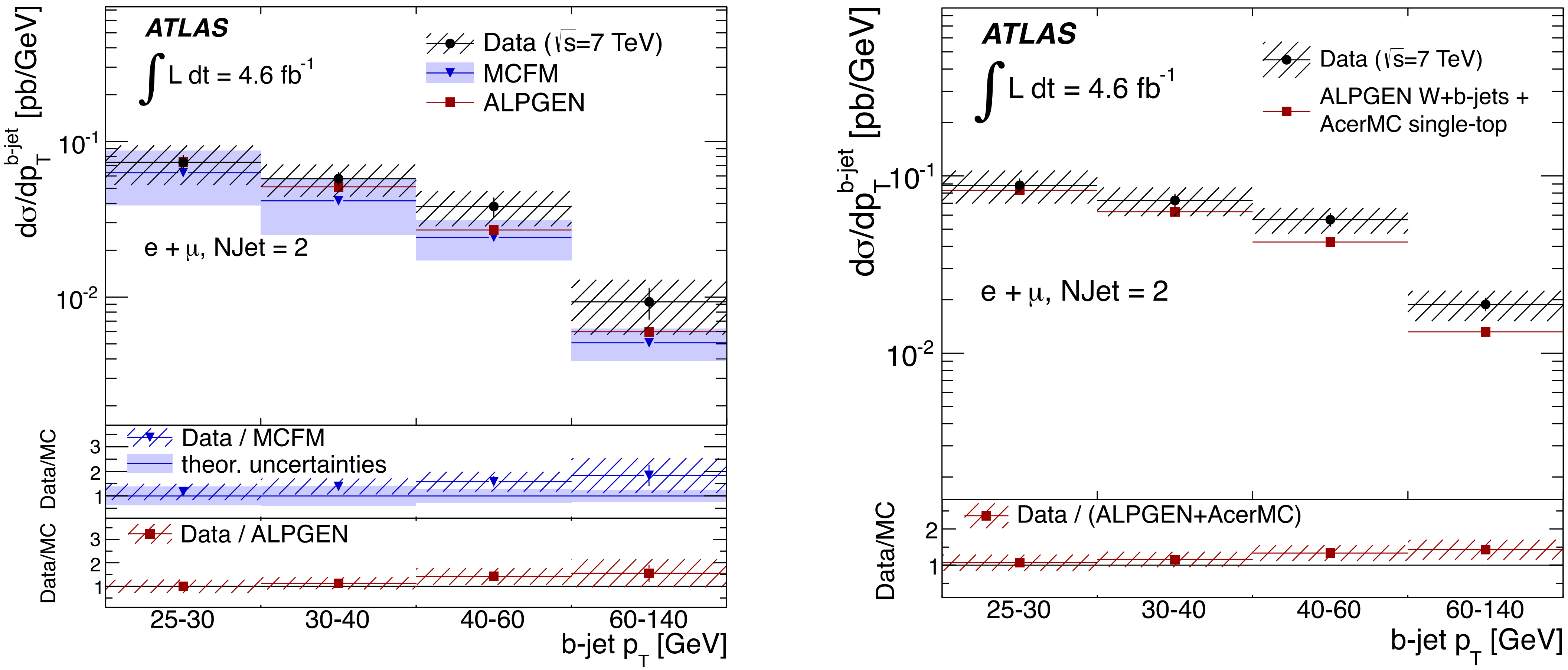


BACKUP

Z+bb - differential cross sections

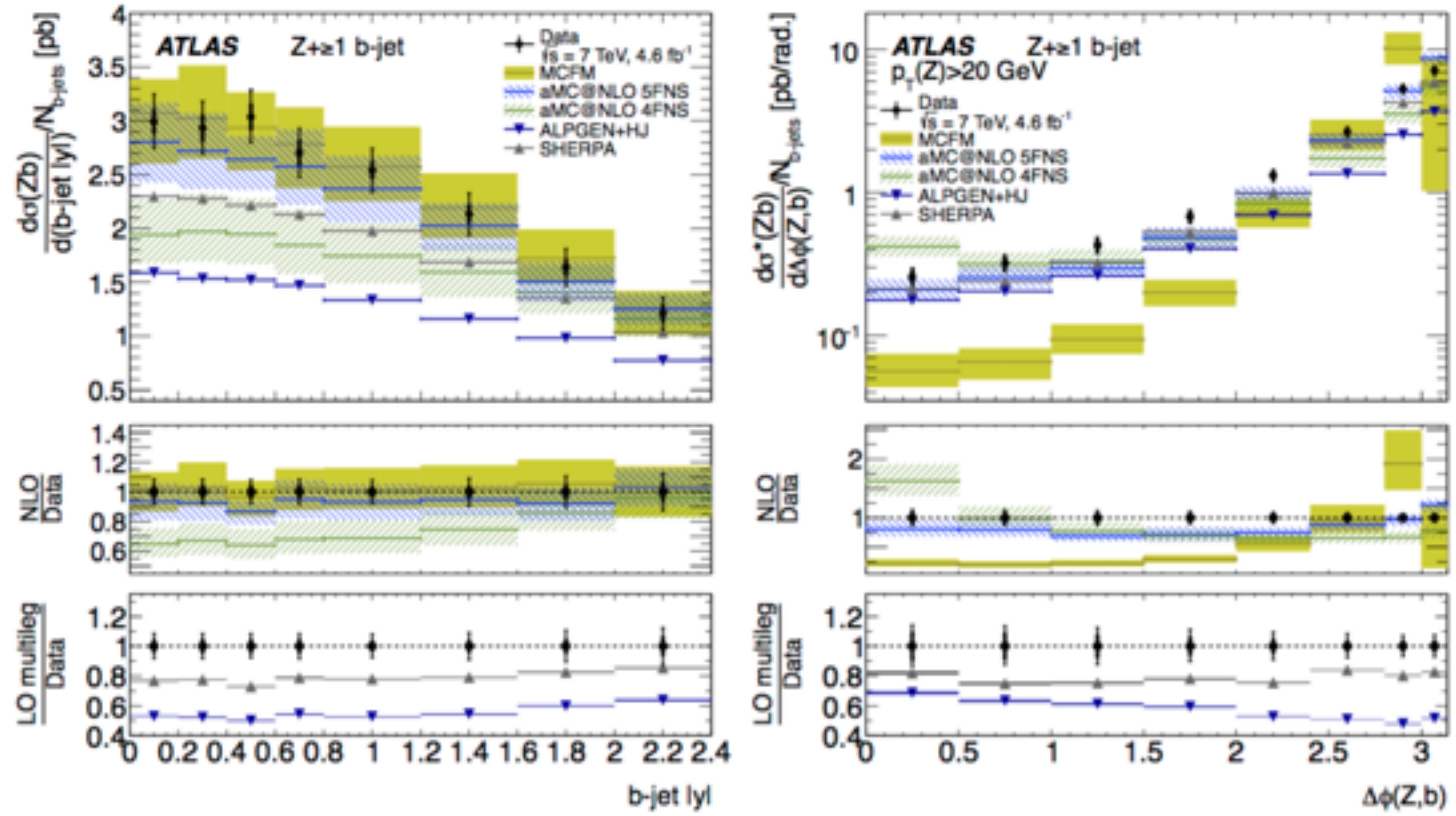
Differential cross section in b-jet pt calculated with and w/o subtracting the single top contamination (very large)



- ➡Discrepancy growing as a function of pt, but large statistical uncertainty
- ➡Study with single top included seems to vouch for this discrepancy, with a reduced stat uncertainty on the higher pt bins

Z+b(b) – further info

- Z+b probes b-quark content of proton
- Z+bb background for Higgs associated production and BSM searches
- Jets are tagged with Neural Net b-tagging using jet kinematics and impact parameter information
- Differential cross sections in 12 observables compared to NLO JHEP10(2014)141
- Iterative Bayesian (1-tag) and fiducial/efficiency (2-tag) unfolding to particle-level
- Fixed-order MCFM discrepant at $\Delta\Phi = \pi$. Likely because it includes at most 2 outgoing partons in association with Z



		$\sigma(Zb)$[fb]	$\sigma(Zb) \times N_{b\text{-jet}}$ [fb]	$\sigma^*(Zb) \times N_{b\text{-jet}}$[fb]	$\sigma(Zbb)$[fb]
	Data	$4820 \pm 60^{+360}_{-380}$	$5390 \pm 60 \pm 480$	$4540 \pm 55 \pm 330$	$520 \pm 20^{+74}_{-72}$
	MCFM⊗MSTW2008	$5230 \pm 30^{+690}_{-710}$	$5460 \pm 40^{+740}_{-740}$	$4331 \pm 30^{+400}_{-480}$	$410 \pm 10^{+60}_{-60}$
5FNS	MCFM⊗CT10	$4850 \pm 30^{+580}_{-680}$	$5070 \pm 30^{+640}_{-710}$	$4030 \pm 30^{+350}_{-450}$	$386 \pm 5^{+55}_{-50}$
	MCFM⊗NNPDF23	$5420 \pm 20^{+670}_{-710}$	$5660 \pm 30^{+720}_{-740}$	$4490 \pm 30^{+380}_{-460}$	$420 \pm 10^{+70}_{-50}$
	aMC@NLO 4FNS⊗MSTW2008	$3390 \pm 20^{+580}_{-480}$	$3910 \pm 20^{+660}_{-560}$	$3290 \pm 20^{+580}_{-460}$	$485 \pm 7^{+80}_{-70}$
	aMC@NLO 5FNS⊗MSTW2008	$4680 \pm 40^{+550}_{-580}$	$5010 \pm 40^{+590}_{-620}$	$4220 \pm 40^{+460}_{-510}$	$314 \pm 9^{+30}_{-30}$
5FNS	SHERPA⊗CT10	3770 ± 10	4210 ± 10	3640 ± 10	422 ± 2
4FNS	ALPGEN+HJ⊗CTEQ6L1	2580 ± 10	2920 ± 10	2380 ± 10	317 ± 2

JHEP10(2014)141

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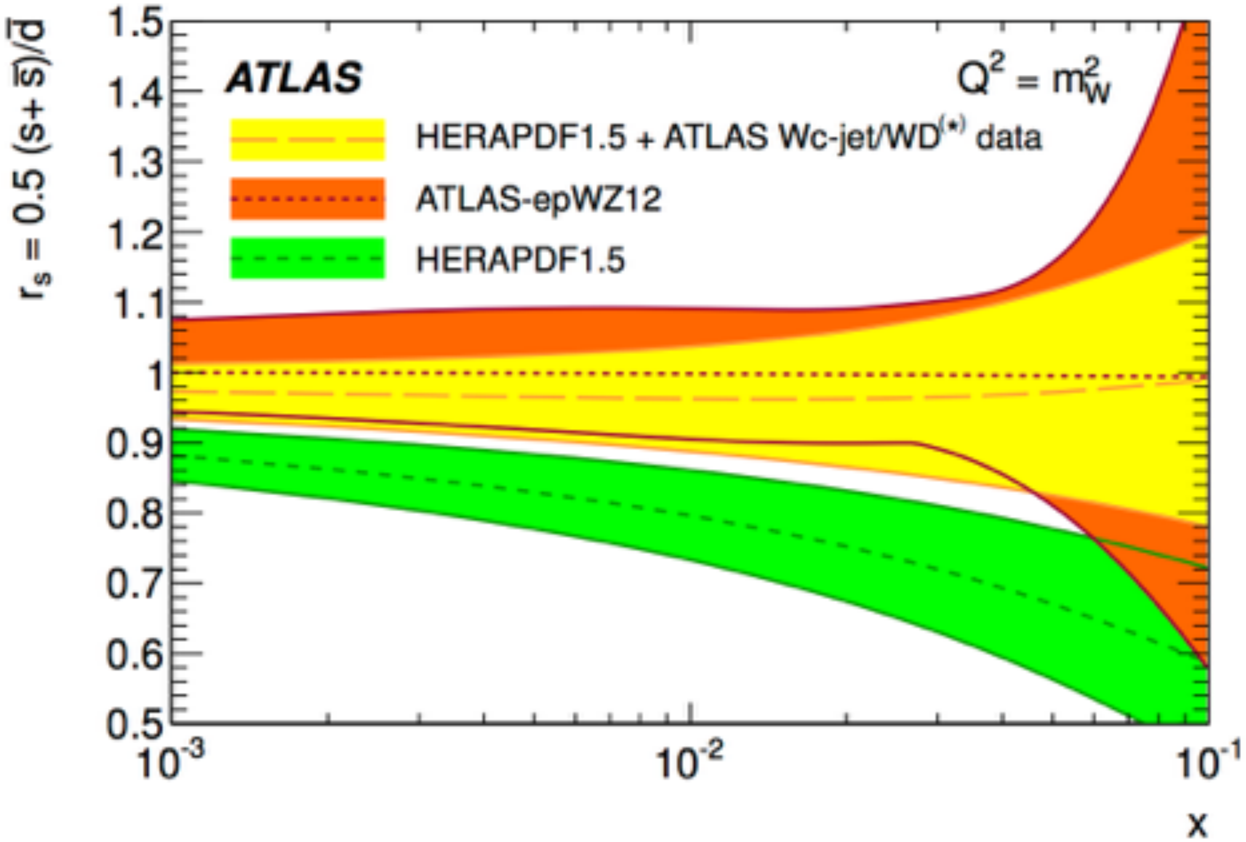
courtesy of B. Brau

W+c – r_s

- Determine strange suppression r_s using HERAPDF1.5 set, best fit value:
  - $r_s \equiv 0.5(s+\bar{s})/\bar{d} = f_s/(1-f_s) = 0.96^{+0.16\,+0.21}_{-0.18\,-0.24}$



- ATLAS Wc-jet/WD(*) data favor a symmetric light-quark sea in agreement with inclusive W, Z fit (ATLAS-epWZ12)

courtesy of Y. Ninomiya

VH(Hbb) - modelling uncertainties

Signal	
Cross section (scale)	1% ($q\bar{q}$), 50% (gg)
Cross section (PDF)	2.4% ($q\bar{q}$), 17% (gg)
Branching ratio	3.3 %
Acceptance (scale)	1.5%–3.3%
3-jet acceptance (scale)	3.3%–4.2%
p_{T}^{V} shape (scale)	S
Acceptance (PDF)	2%–5%
p_{T}^{V} shape (NLO EW correction)	S
Acceptance (parton shower)	8%–13%
Z+jets	
Zl normalisation, 3/2-jet ratio	5%
Zcl 3/2-jet ratio	26%
Z+hf 3/2-jet ratio	20%
Z+hf/Zbb ratio	12%
$\Delta\phi(\mathrm{jet}_1, \mathrm{jet}_2)$, p_{T}^{V}, m_{bb}	S
W+jets	
Wl normalisation, 3/2-jet ratio	10%
Wcl, W+hf 3/2-jet ratio	10%
Wbl/Wbb ratio	35%
Wbc/Wbb, Wcc/Wbb ratio	12%
$\Delta\phi(\mathrm{jet}_1, \mathrm{jet}_2)$, p_{T}^{V}, m_{bb}	S
$t\bar{t}$	
3/2-jet ratio	20%
High/low-p_{T}^{V} ratio	7.5%
Top-quark p_{T}, m_{bb}, $E_{\mathrm{T}}^{\mathrm{miss}}$	S
Single top	
Cross section	4% (s-,t-channel), 7% (Wt)
Acceptance (generator)	3%–52%
m_{bb}, $p_{\mathrm{T}}^{b_1}$	S
Diboson	
Cross section and acceptance (scale)	3%–29%
Cross section and acceptance (PDF)	2%–4%
m_{bb}	S
Multijet	
0-, 2-lepton channels normalisation	100%
1-lepton channel normalisation	2%–60%
Template variations, reweighting	S