Differential Measurements of b-jets in Association with a Z boson with the ATLAS Detector at the LHC

RPM Mark Tibbetts

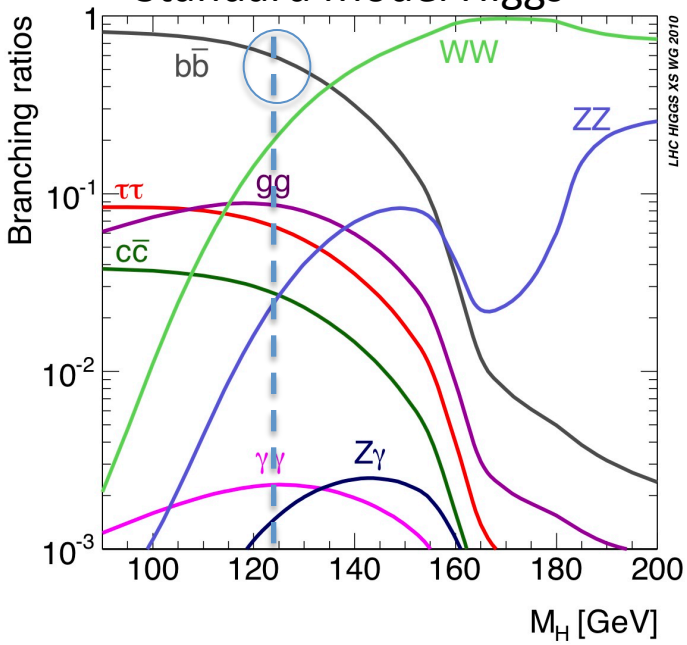
16th October 2014

Outline

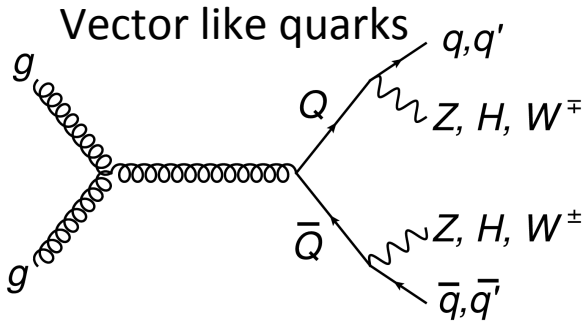
- **Introduction**
- LHC & ATLAS
- Luminosity measurement
- Z+b-jets cross-section measurement
- Conclusions

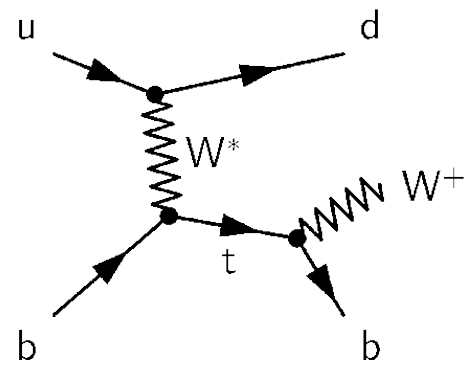
b quarks at the TeV scale

Standard Model Higgs

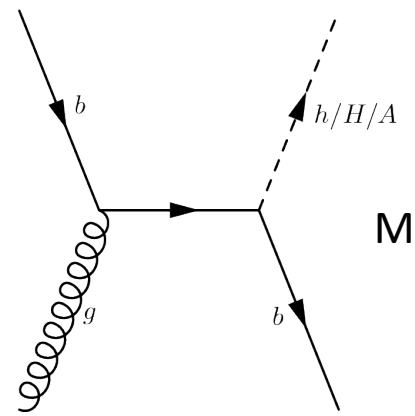


Vector like quarks





Single top

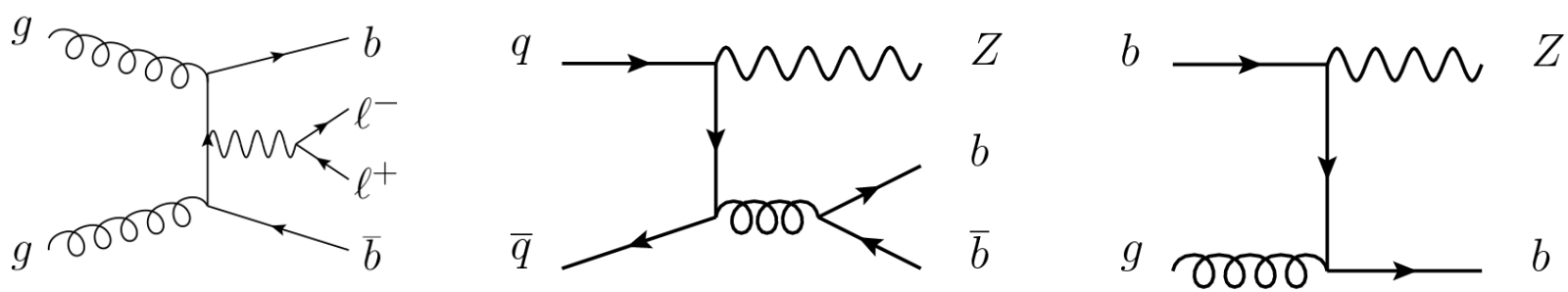


MSSM Higgs

- **At TeV scale many signatures of interest have b quarks in the (initial and) final state**
- Important to understand processes containing b quarks!

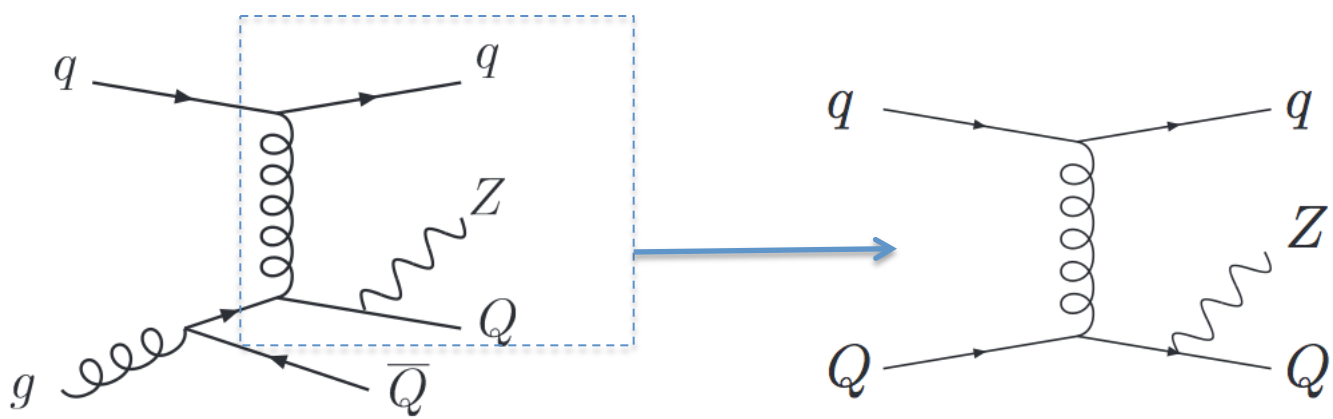
Flavor scheme with Z+b-jets

Z+b(b):



- **4 flavor number scheme (4FNS)**
  - b quark does not contribute to proton wave-function
- **5 flavor number scheme (5FNS)**
  - Reordering of perturbation series initial state logs resumed into b-PDF
  - LO diagrams one order lower in αs wrt 4FNS: easier to calculate to higher order!
- To all orders 4FNS and 5FNS agree, at given order differences can occur

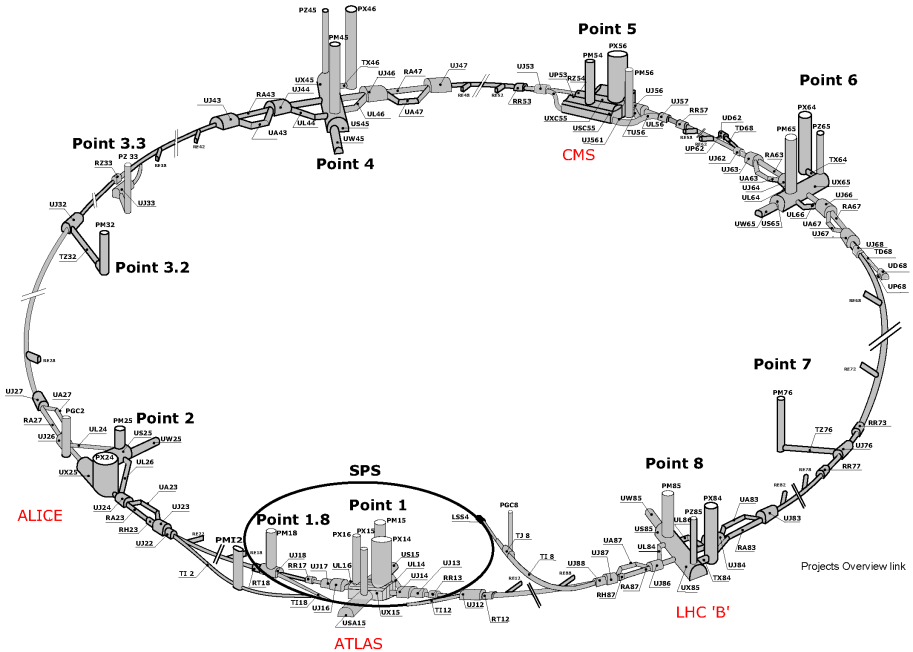
Z+b(b)+j:



Outline

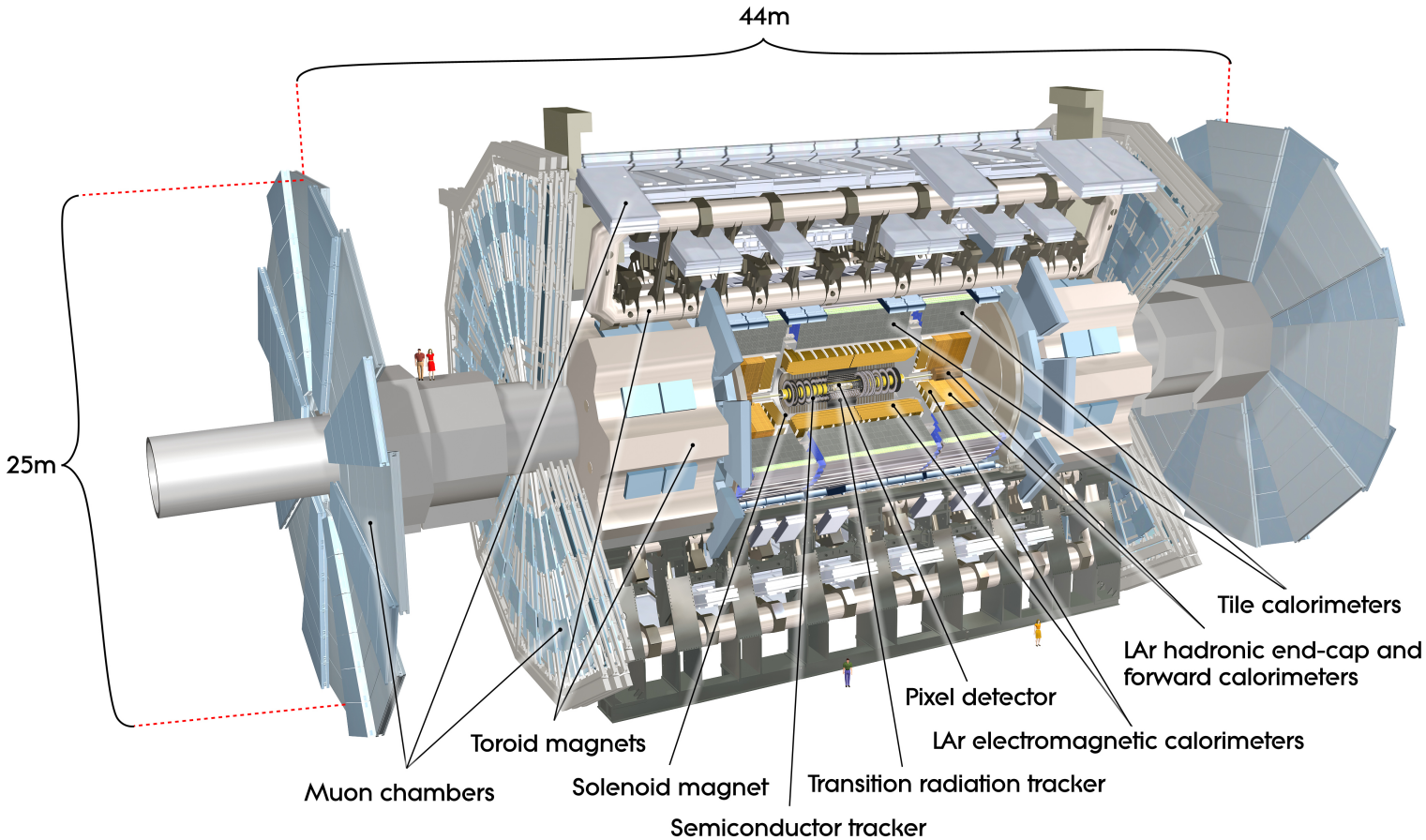
- Introduction
- **LHC & ATLAS**
- Luminosity measurement
- Z+b-jets cross-section measurement
- Conclusions

The LHC Experiment



- **pp collider** near Genève, CH with 27km circumference, 11245.5Hz revolution frequency, 3564 25ns slots per revolution
  - Also PbPb & pPb collisions
- **To date:**
  - 2010/11: 3.5TeV per beam; 2012: 4TeV per beam
  - Up to 1368 colliding bunches with 50ns spacing (11 'trains')

The ATLAS Detector

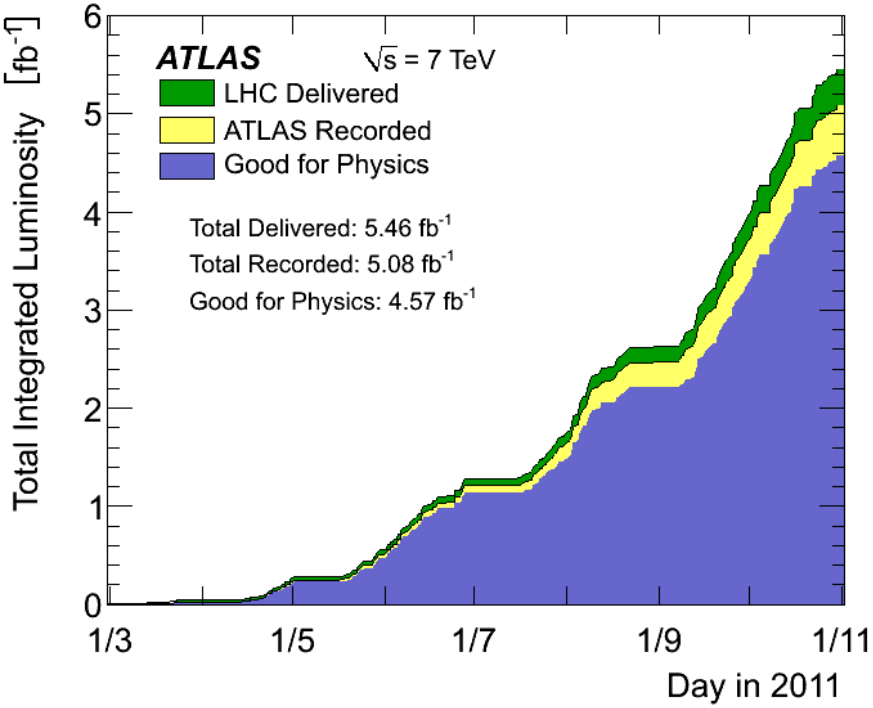


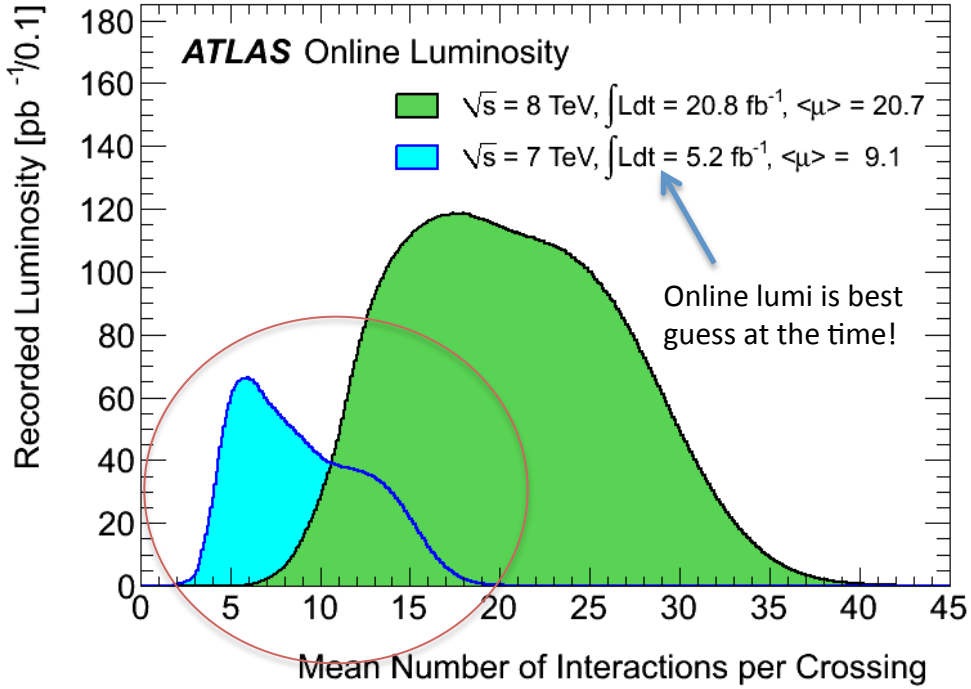
- Tracking to |η|<2.5
- Close to full solid angle coverage from calorimeters: |η|<4.9
- Independent muon tracking to |η|<2.7
- Trigger output ~400Hz, unprescaled e,μ triggers with pT~20GeV

Outline

- Introduction
- LHC & ATLAS
- **Luminosity measurement**
- Z+b-jets cross-section measurement
- Conclusions

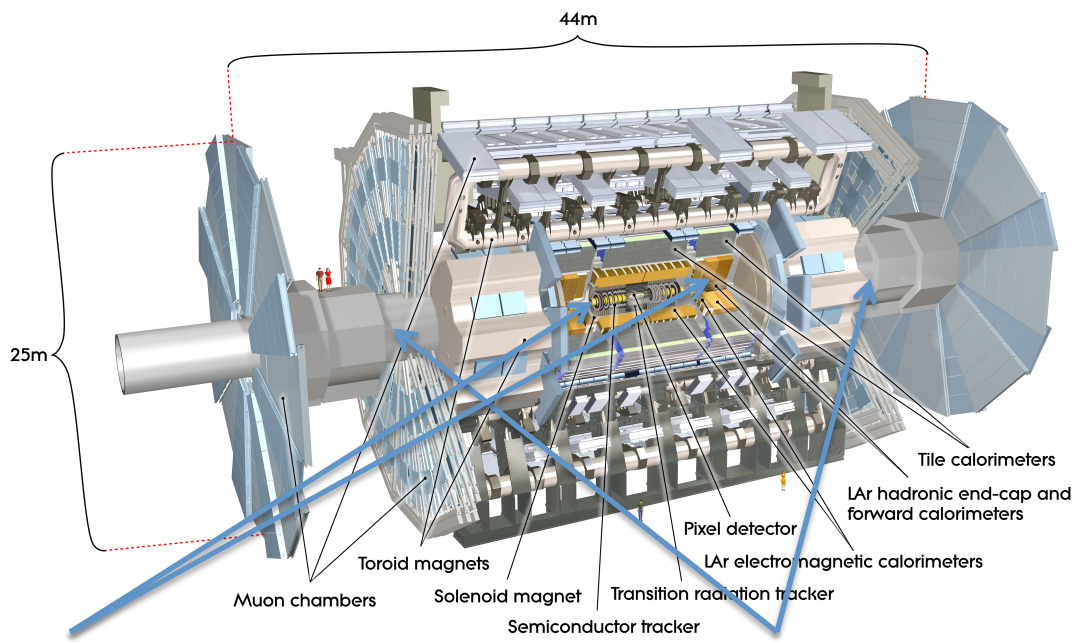
Luminosity and pileup

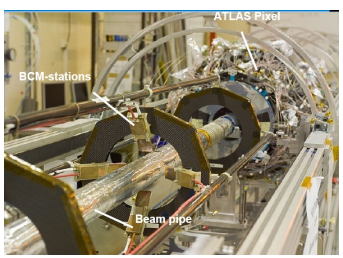




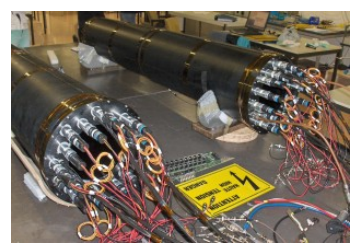
- **To date majority of Standard Model analyses based on 2011 data** (including this talk)
- **High precision calibration of luminosity scale**
- Pileup (# of pp collisions per bunch crossing) smaller in 2011 wrt to 2012 but not insignificant

Measuring Luminosity: Detectors





- **Beam conditions monitor (BCM)**
  - Diamond sensors |η|~4.2
  - Per bunch (25ns) resolution



- **"LUCID"**
  - Cherenkov tubes 5.6<|η|<6.0
  - Per bunch (25ns) resolution

- Per bunch detectors directly calibrated
- Cross-check with relative response from other 'bunch integrated' detectors
  - Tile calorimeter, forward calorimeter

Luminosity calibration

Inelastic interactions per bunch crossing (BC)

$$L = \frac{\mu n_b f_r}{\sigma_{inel}} = \frac{\mu_{vis} n_b f_r}{\sigma_{vis}}$$

Visible rate for given detector/algorithm

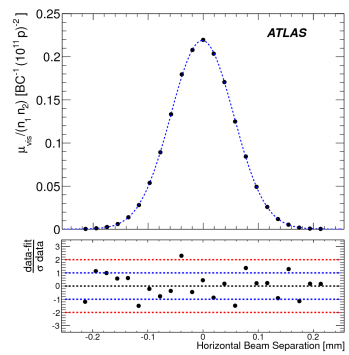
Algorithm calibration constant to be measured

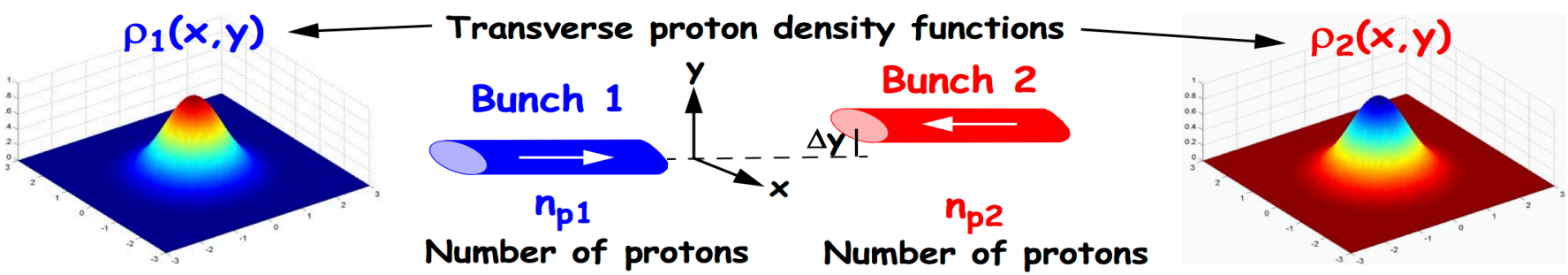
Calibrate in van der Meer beam separation scans:

Bunch charge product

$$L = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \qquad \Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int \mu_{vis}(x)\,dx}{\mu_{vis}(0)}$$

Convolved beam profile



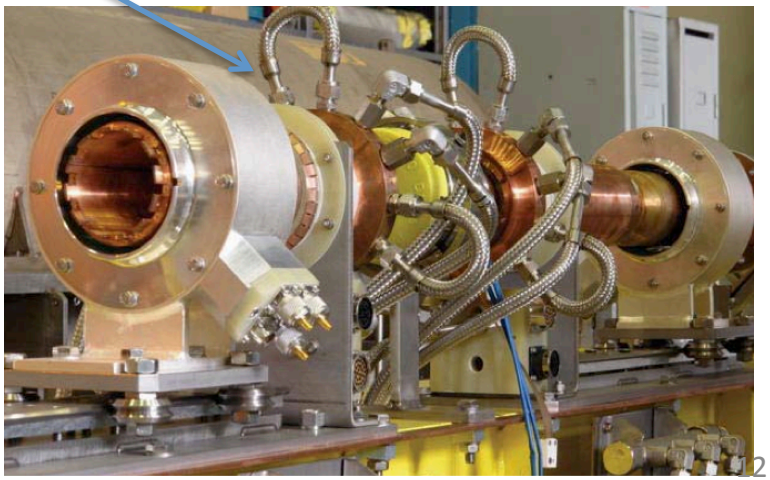


LHC bunch current measurement

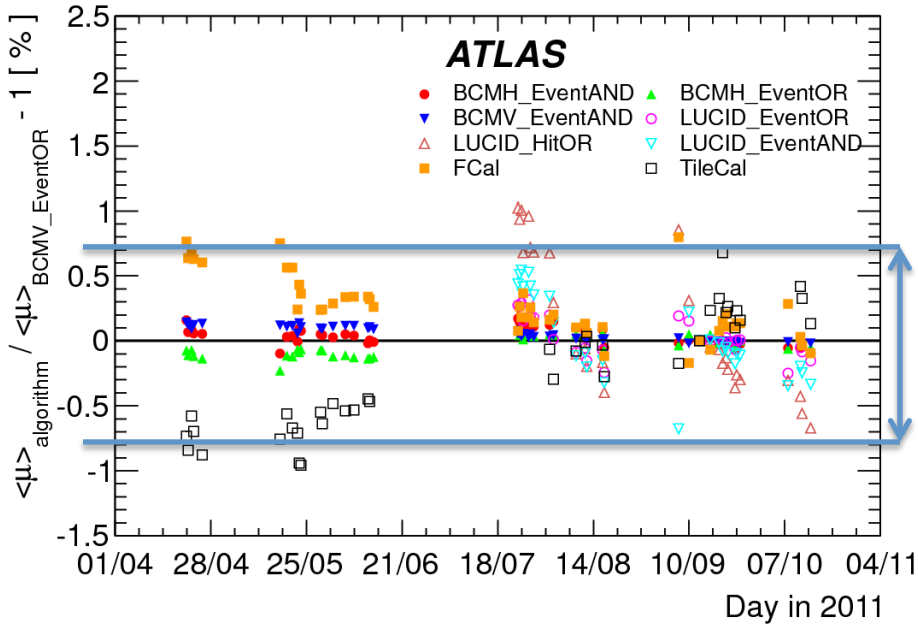
- Uncertainty from LHC bunch current normalization group analysis
- DCCT: High accuracy measures integrated charge
  - Baseline offset ~10^9 protons
  - Scale determined from precision current source
- FCBT: Relative charge fraction bunch by bunch

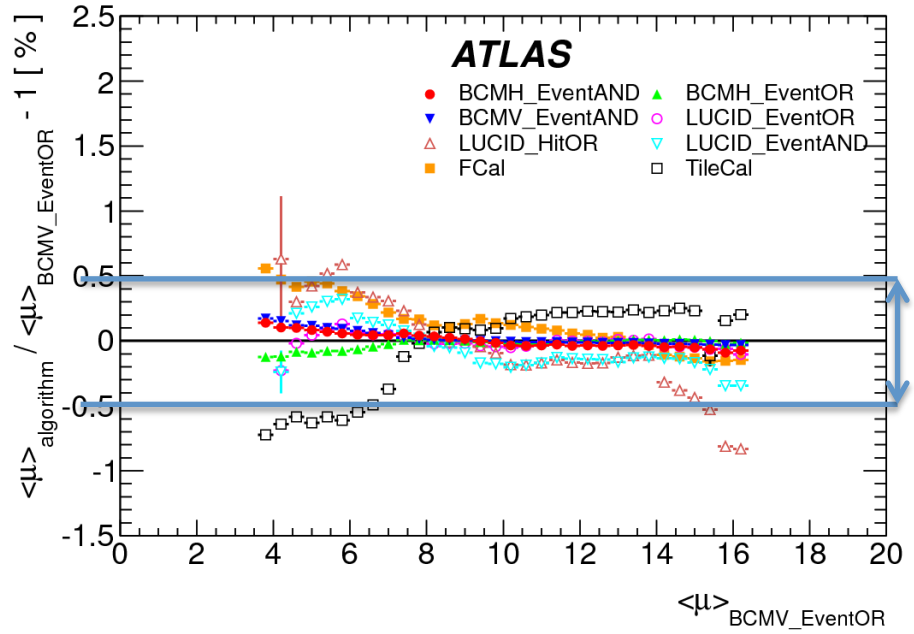
Scan Number	I	II–III	IV–V	VII–VIII
LHC Fill Number	1059	1089	1386	1783
DCCT baseline offset	3.9%	1.9%	0.1%	0.10%
DCCT scale variation	2.7%	2.7%	2.7%	0.21%
Bunch-to-bunch fraction	2.9%	2.9%	1.6%	0.20%
Ghost charge and satellites	-	-	-	0.44%
Total	5.6%	4.4%	3.1%	0.54%

← 2010 → 2011



Luminosity Stability





- **Redundancy of measurements gives confidence in luminosity stability**
- Long term stability compares integrated luminosity per LHC fill
  - Consistency to +/-0.7%
- Short term stability (μ-dependence) compares measured luminosity as a function of μ both across the year and in a dedicated run
  - Both inputs indicate μ-dependent stability to +/-0.5%

Luminosity uncertainty

Uncertainty Source	$\delta\mathscr{L}/\mathscr{L}$ 2010	2011
Bunch Population Product	3.1%	0.5%
Other *vdM*		
Calibration Uncertainties	1.5%	1.4%
Afterglow Correction		0.2%
BCM Stability		0.2%
Long-Term Stability	0.5%	0.7%
μ Dependence	0.5%	0.5%
Total	3.5%	1.8%

- Single largest improvement from 2010 to 2011 is bunch charge product uncertainty
- **In 2011 achieve luminosity scale uncertainty of 1.8%**

Outline

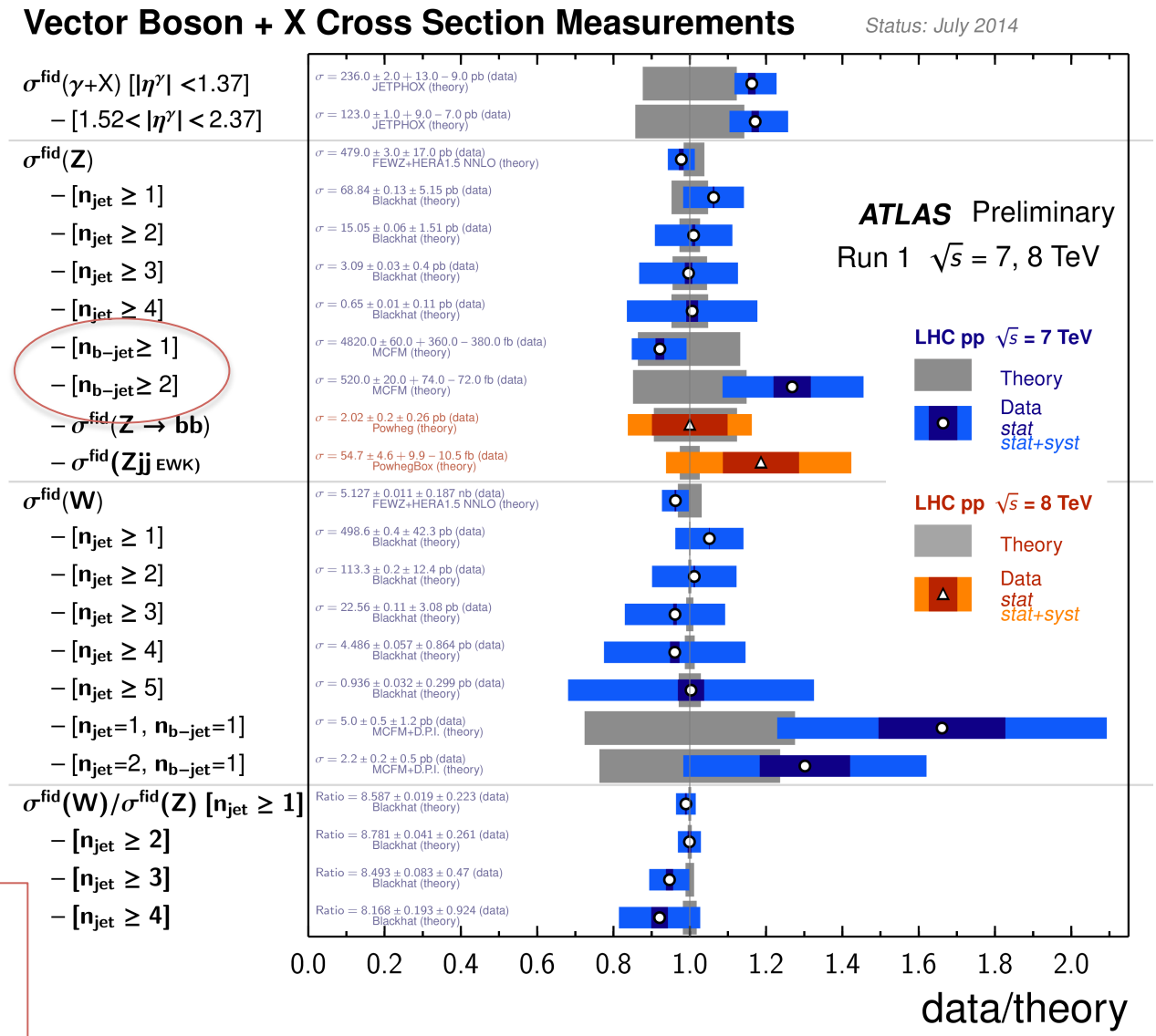
- Introduction
- LHC & ATLAS
- Luminosity measurement
- **Z+b-jets cross-section measurement**
- Conclusions

V+jets as a probe of QCD at ATLAS

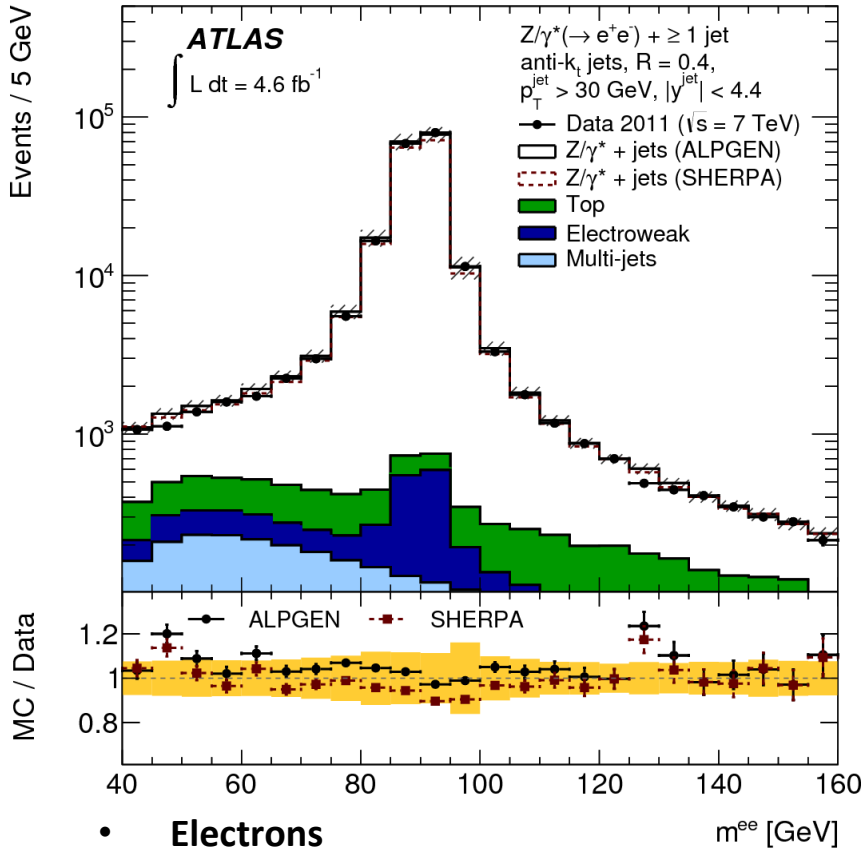
- **Abundance of results from 7 TeV pp data**

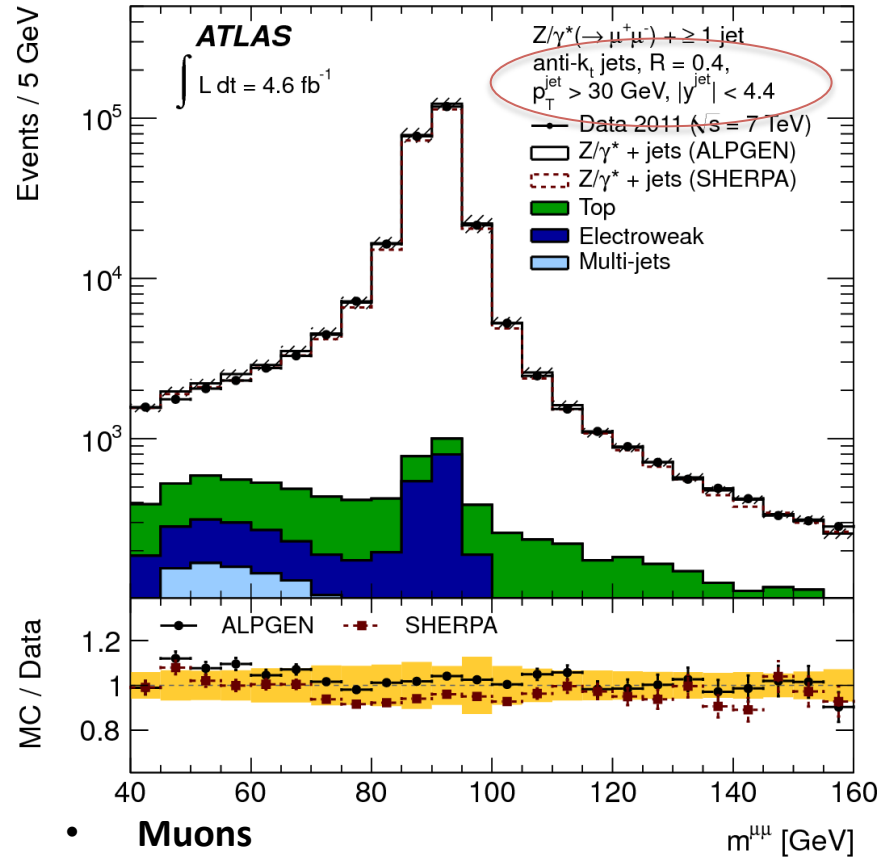
- **W+jets & Z+jets:**
  Numerous differential kinematic distributions
- **R_{jets}:**
  Differential ratios W+jets/Z+jets to reduce uncertainties
- **Also:**
  W+c sensitive to s-PDF;
  Zjj & Z->bb at 8 TeV
- **Heavy flavor:**
  First differential distributions;
  4F vs 5F & b-PDF
  THIS TALK Z+b-jets!

Reminder! **Jets**: collimated clusters of particles can be thought as synonymous with quarks & gluons from collision



Selecting Z boson (+jets) events





- **Electrons**
  - Dielectron trigger, ET>20GeV; |η|<2.47
  - Track matched to cluster; quality requirements
- **Muons**
  - Single muon trigger, pT>20GeV; |η|<2.4
  - Isolated inner detector track matched to muon spectrometer track
- **General**
  - Impact parameter requirements to reject leptons from heavy flavor
  - Mulitjet background estimated from data control regions with relaxed quality/isolation requirements
  - For Z+jets, pT threshold high to reduce pileup allows extended angular coverage to |y|<4.4

Analysis strategy for Z+b-jets

Select data events, extract b-jet yield & convert to particle level cross-sections

Z+b-jets:	Particle level selection
Lepton	p_T>20 GeV; $\|\eta\|$<2.5
Z->ll	76<m_{ll}<106 GeV
b-jets	p_T>20 GeV; $\|y\|$<2.4 ΔR(l,jet)>0.5 ΔR(b-hadron,jet)<0.3

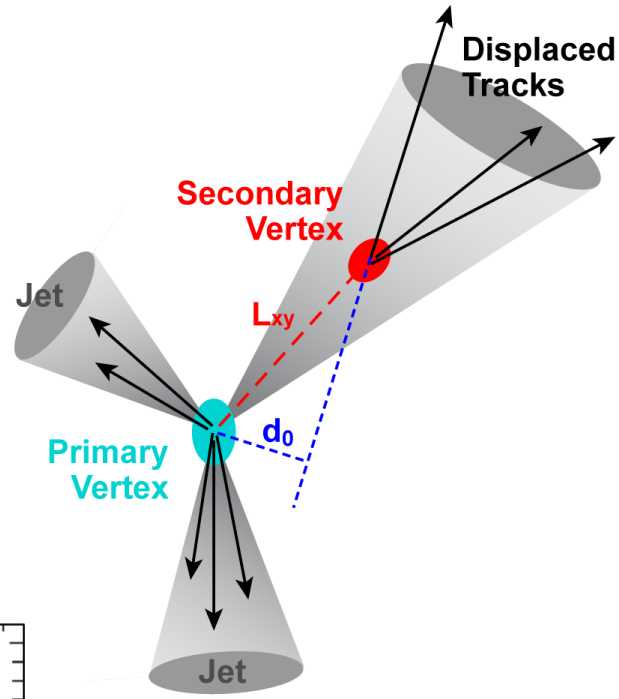
Narrow to suppress top background

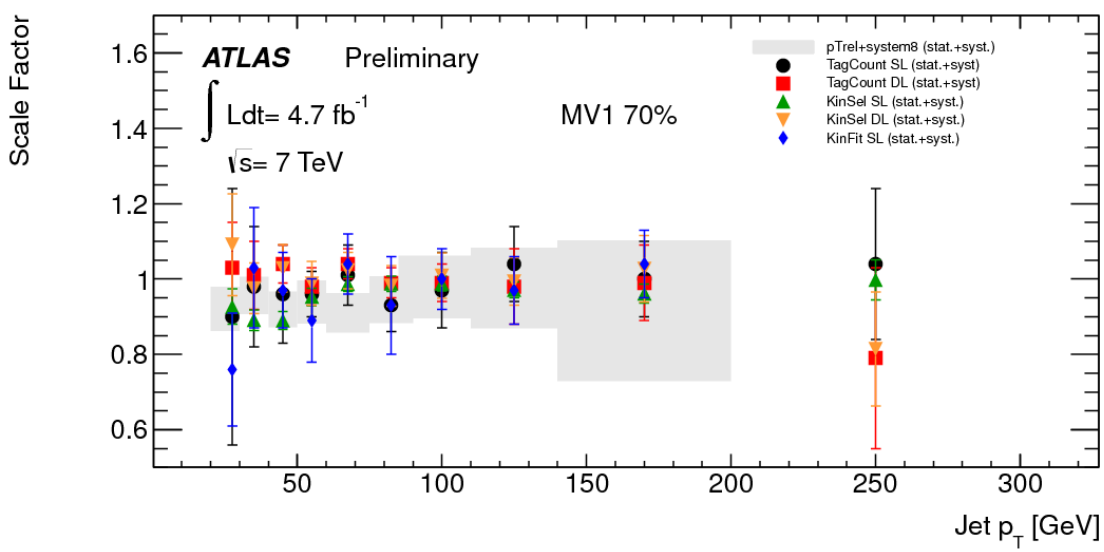
- **Probe pQCD heavy flavor calculations**
- Z+≥1b-jet differential cross-sections
  - b-jet pT & |y|
  - Z boson pT & |y|
  - Z, b-jet separations $\Delta\varphi$, Δy, ΔR, y_{boost}
- Z+≥2b-jets differential cross-sections
  - Z boson pT & |y|
  - Leading jets ΔR, mbb

- **Selection of jets**
  - Restrict jets to tracking volume
  - Reject pileup based on tracks associated to 'primary' vertex
  - Allows pT threshold reduction to 20GeV
- **Extracting b-jet yields in data:**
  - Flavor tag jets to enrich b-jet content
  - Fit to flavor sensitive discriminant
- **Unfolding to particle level**
  - Choose particle fiducial region to closely match data selection

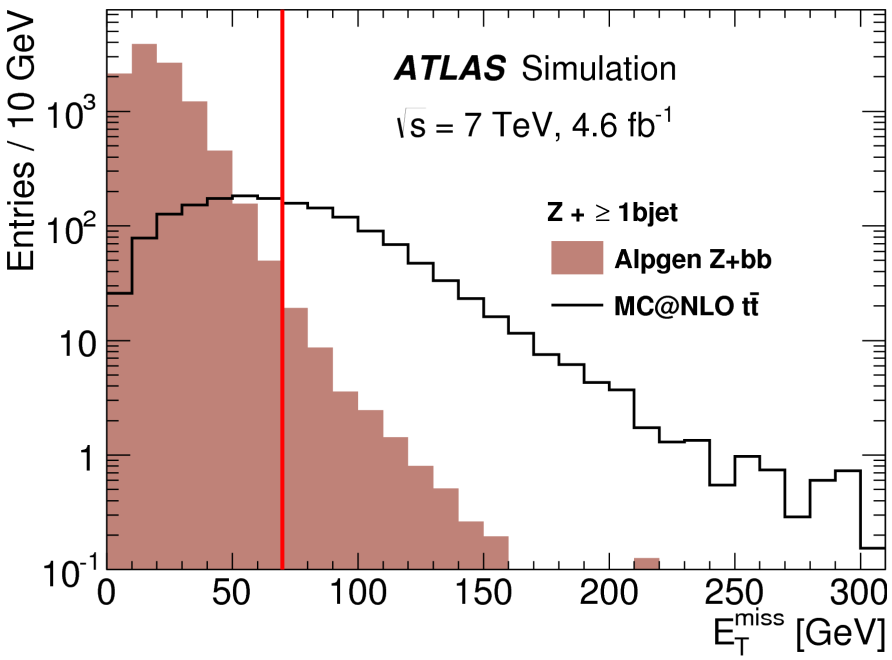
Heavy flavor tagging

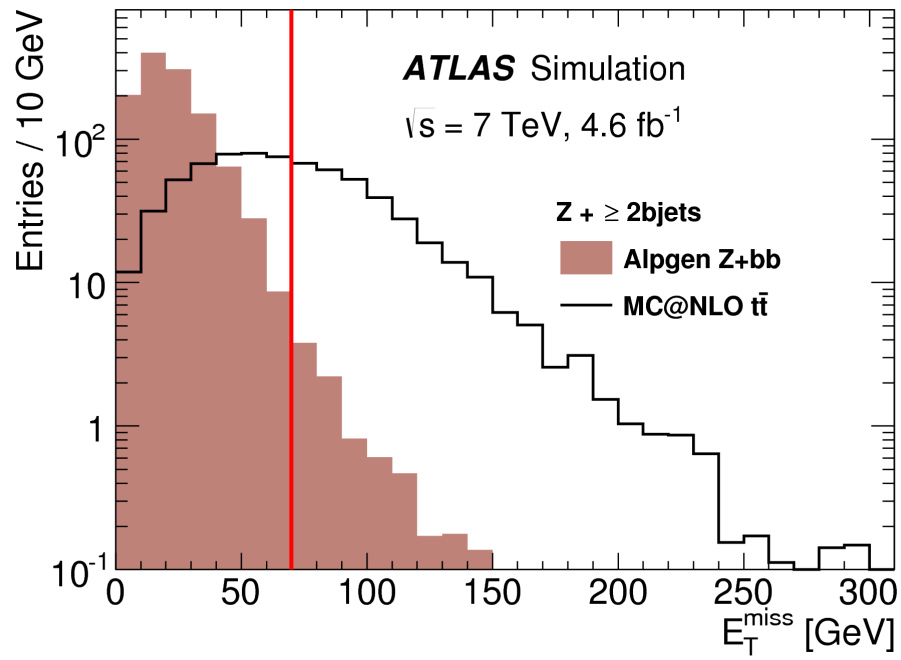
- **Long lifetime of weakly decaying b-hadrons**
- Tracks in b-jets can reconstruct secondary vertex & have larger average IP wrt to primary vertex
- Combine SV & IP information into multivariate classifier to select more b-like jets
- Correct simulation efficiency using data control regions enriched in b-jets with associated systematic uncertainty
- Similar 'mistag' scale factors derived from charm and 'light' jet data control regions





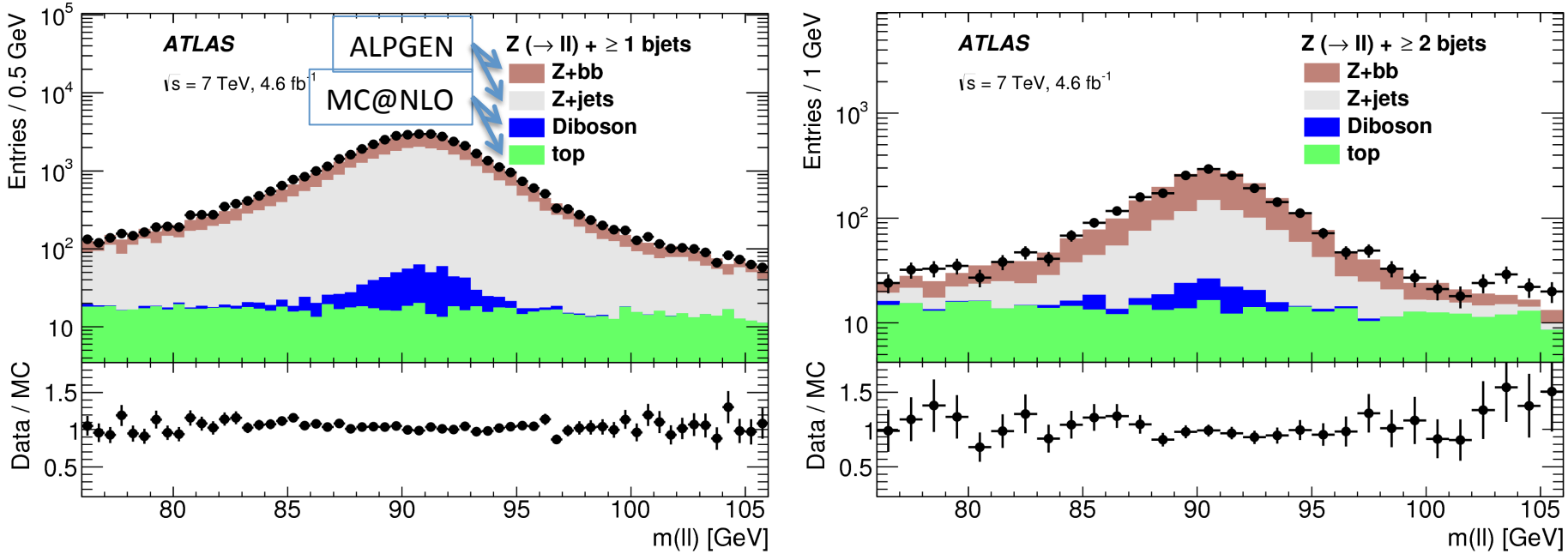
Reducing background from top pairs





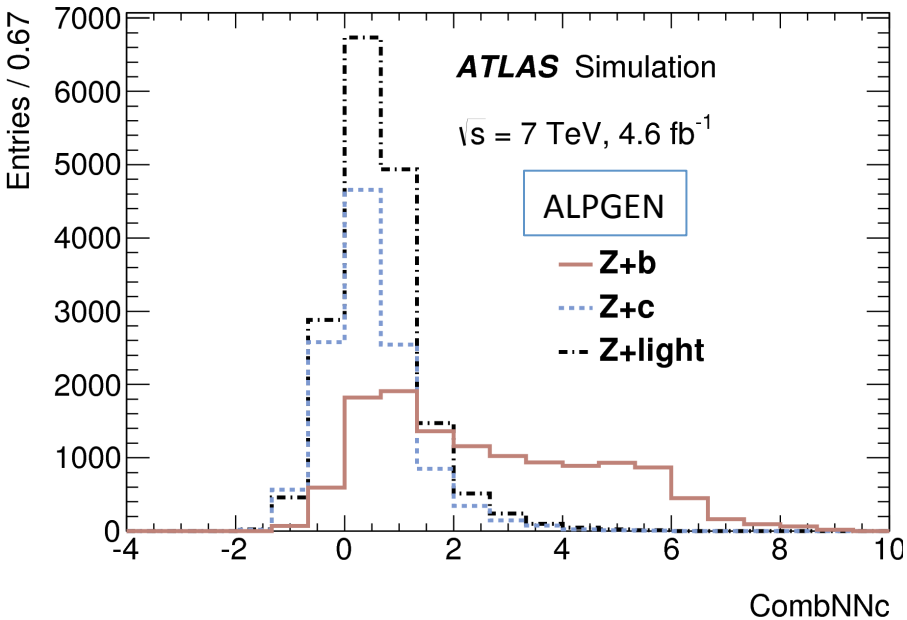
- **b-jet tagging enhances the relative top pair background in Z+jets events**
  - Particularly where both W bosons decay to same flavor leptons
- **Exploit presence of neutrino(s)** in top events to reduce by factor of ~2 by requiring events have missing transverse momentum E_T<70GeV
  - Preserves >99% of signal

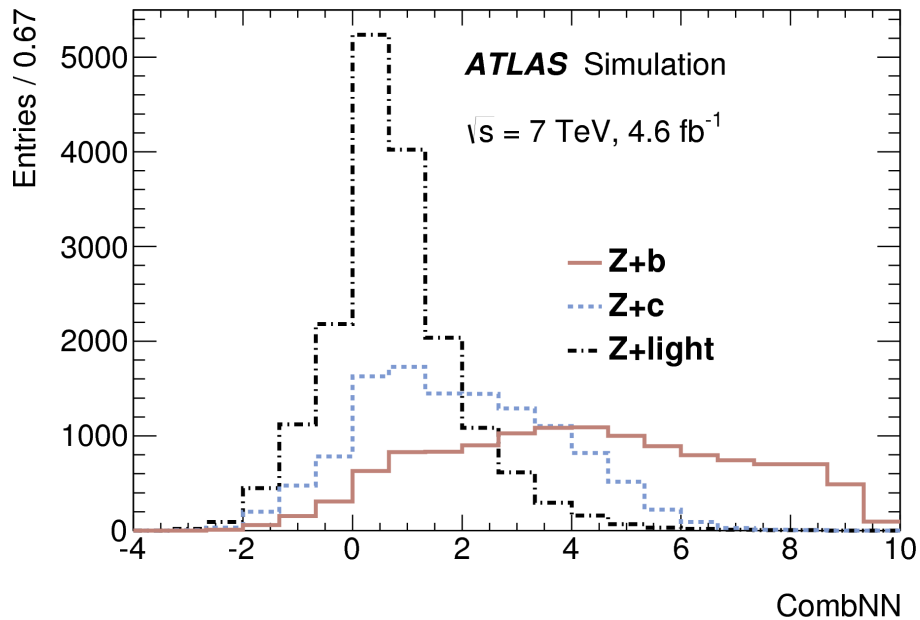
Sample composition



- After signal selection non Z+jets backgrounds form ~3% (~18%) of data yield in Z+1 b-jet (Z+2 b-jets) events
  - Residual background from multijets measured but essentially negligible
- **Dominant background from light & charm jets mistagged as b-jets in Z+jets events**
  - Don't trust flavor fractions from simulation: fit yields using data

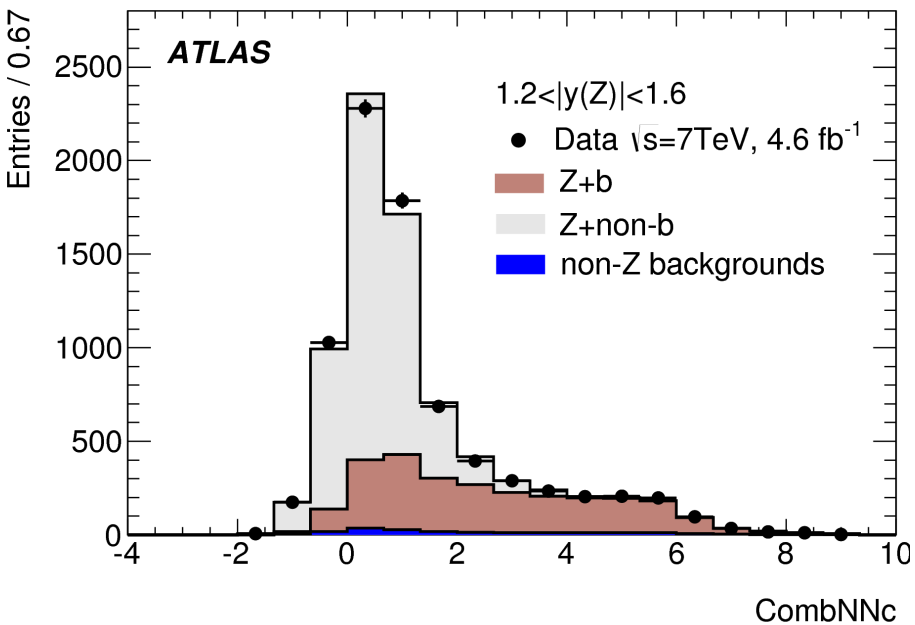
Discriminating jet flavor

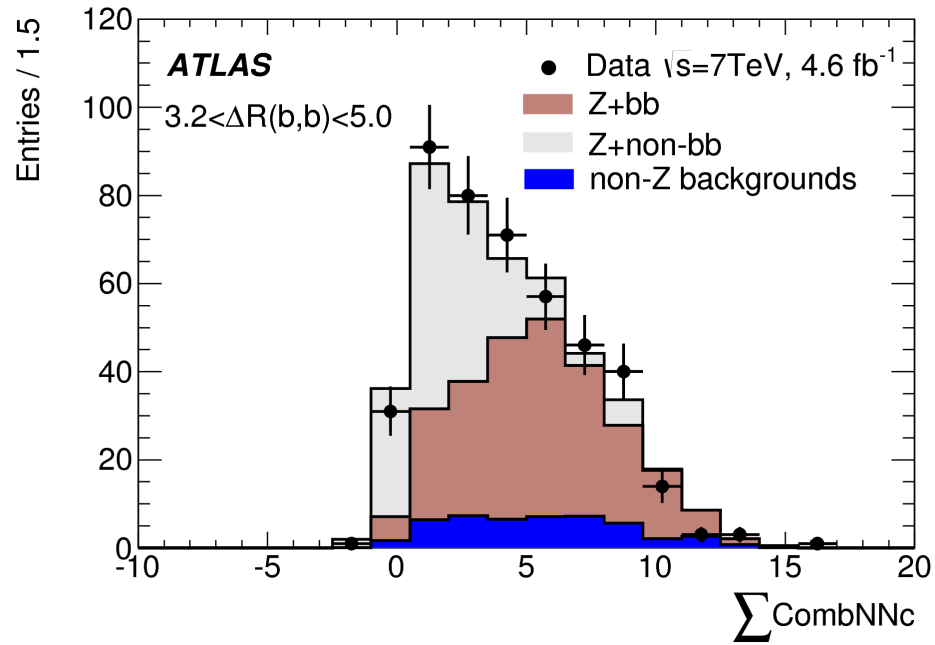




- **Output of multivariate b-jet classifiers can separate jet flavor in selected Z+jets events**
- **'CombNNc'**: neural network classifier trained to separate b-jets and charm jets
  - Charm & light jets have similar shape reducing uncertainty from relative charm/light ratio
- Alternative distribution **'CombNN'**: same inputs to separate b-jets & light jets
  - Use as a cross-check for fits based on ComnNNc
- Derive fit templates from simulation
- Combine electron & muon channels to maximize statistical precision

Heavy flavor fits

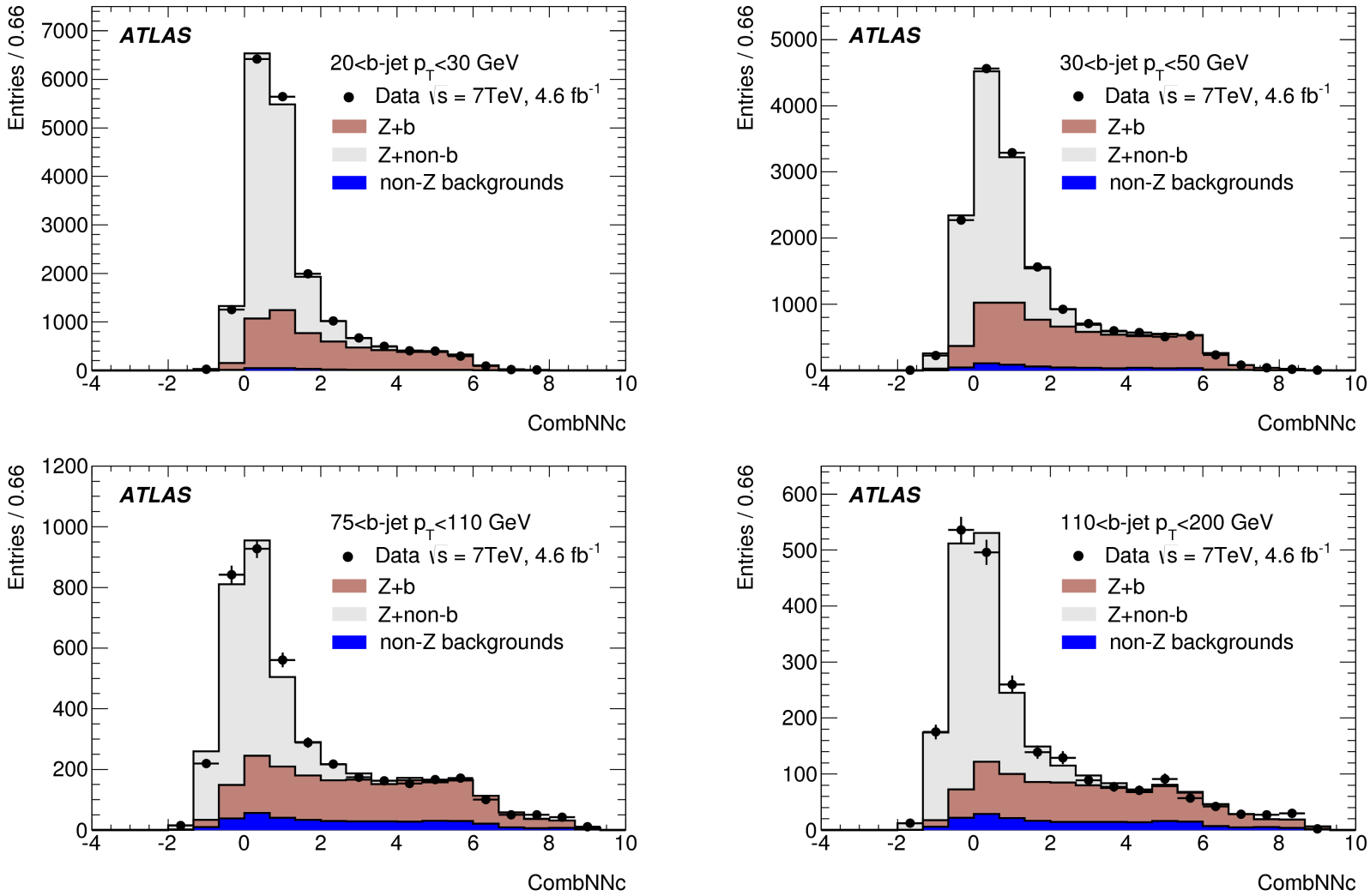




- **Z+≥1 b-jet**
  - Inclusive: all tagged jets
  - Fiducial: lead pT tagged jet
  - Non Z+jets backgrounds fixed to predicted yields
  - Charm & light combined into single template assuming relative fraction from MC
  - Float Z+b-jet & Z+non-b-jet yields
- **35% of data events are Z+b**

- **Z+≥2 b-jets**
  - 2 lead pT tagged jets
  - Non Z+jets backgrounds fixed to predicted yields
  - Non-bb combinations combined into single template
    - b+X components fixed from data control fits
  - Float Z+bb & Z+non-bb yields
- **47% of data events are Z+bb**

Differential analysis



Each differential bin makes independent fit to data; integral cross-checked with inclusive fit

Extracting particle level cross-sections

$$\sigma_i \times Br(Z \rightarrow ll) = \frac{m_i \times N^i_{fit}}{L \times \varepsilon_i}$$

Fitted yield in data

Luminosity

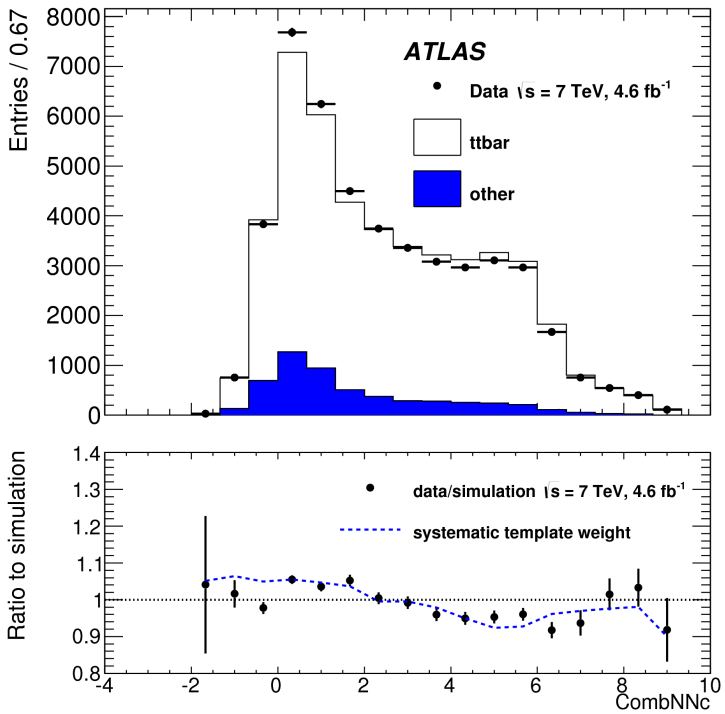
Matching correction

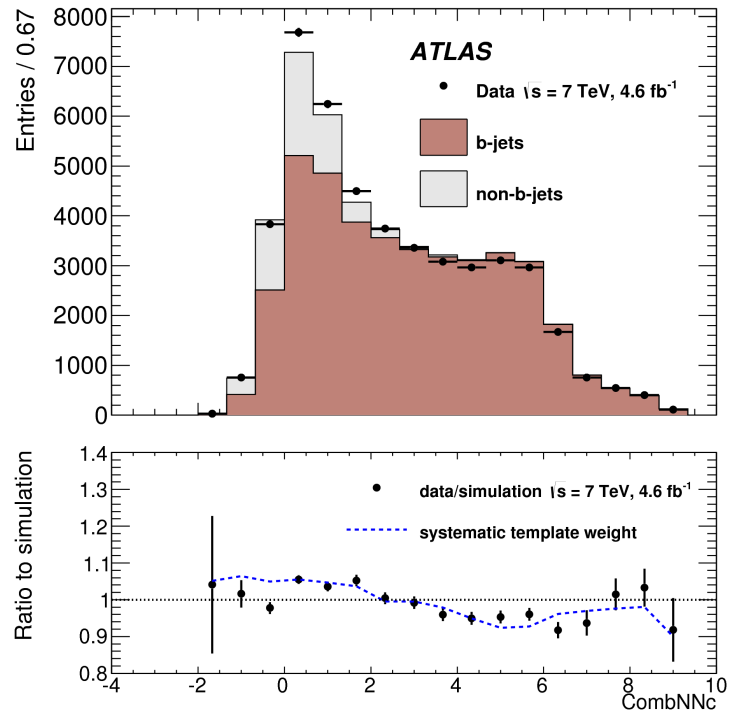
$$m_i = \frac{N^{reco}_{matched}}{N^{reco}_{all}}; \varepsilon_i = \frac{N^{particle}_{matched}}{N^{particle}_{all}}$$

Efficiency correction

- **Fitted yields in data unfolded to particle level cross-sections using full detector simulation**
- Reconstructed events 'matched' to particle events to derive resolution & efficiency corrections
  - i.e., lepton & b-jet reco. efficiency, migration outside fiducial region, etc.
- Differential cross-sections extracted with full Bayesian iterative treatment of bin by bin migrations
- Unfold electron & muon channels simultaneously
  - Cross-checked by unfolding channels separately and comparing consistency, agreement within 2 sigma in all bins

Systematics: Fit templates





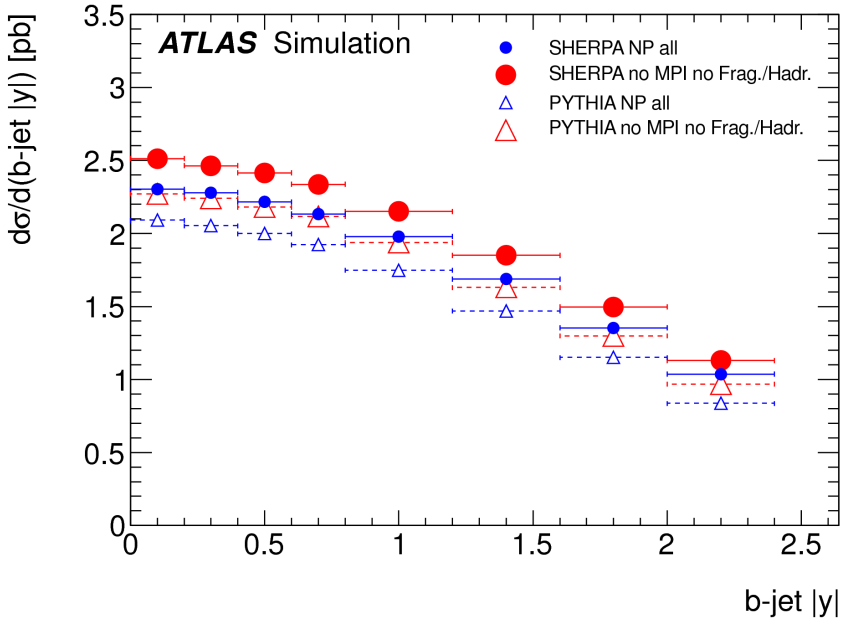
- **Uncertainty in b-jet template shape forms dominant systematic**
- Cross-checked in b-jet enriched data control region of top pair events
- Difference between data/MC in control region used to reweight signal templates to assign systematic
  - No strong evidence of kinematic dependence of this ratio in the control region

Systematics: Summary

Source of uncertainty	$\sigma(Zb)$[%]	$\sigma(Zbb)$[%]
b-jet tagging efficiency	3.4	9.8
c-jet mistag rate	0.2	2.3
light-jet mistag rate	0.4	0.6
JES	2.9	4.7
JER	0.3	0.7
b-jet template shape	4.8	4.8
c-jet template shape	0.2	0.6
light-jet template shape	0.9	0.9
b-jet template scale factor	N/A	2.3
MPI	2.5	0.8
gluon splitting	1.2	1.5
background normalisation	1.1	3.6
$t\bar{t}$ modelling	0.0	2.9
MC sample size	1.0	1.4
lepton efficiency, scale and resolution	1.2	1.2
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.1	0.6
luminosity	1.8	1.8
total	7.7	14.0

- Other significant systematics include b-tagging efficiency and jet energy scale
- Signal modeling:
  - MPI fraction varied by +/-50%; jets with 2 b-hadrons varied by +/-100%
- **Systematics dominate fiducial measurements**
- Differentially systematic & statistical components for most part comparable

Theoretical predictions: MCFM



Renormalization & Factorization scales:

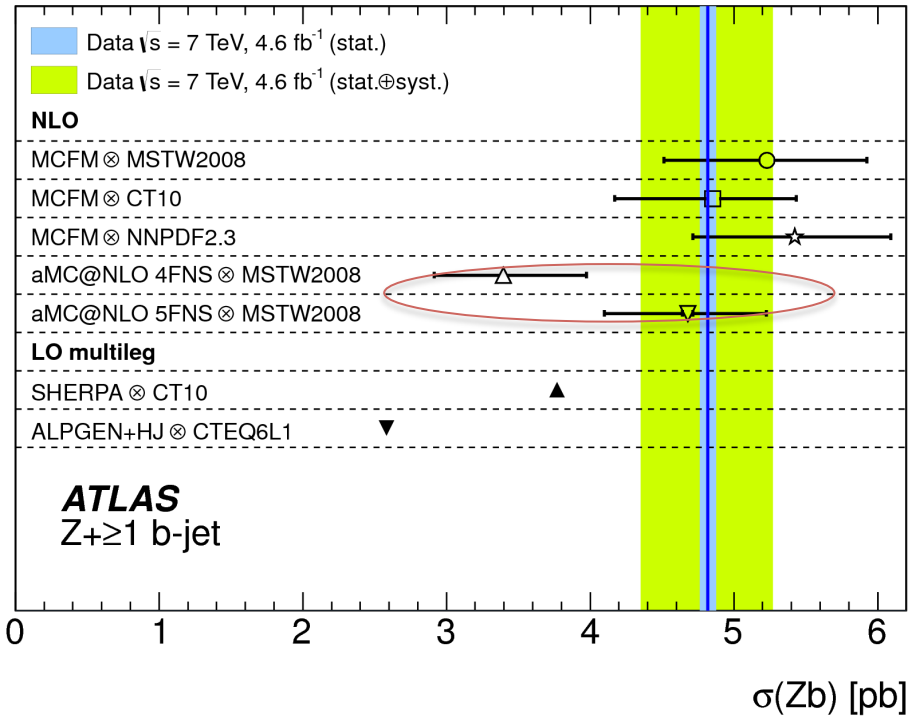
$$\sqrt{m(Z)^2 + p_T(Z)^2}$$

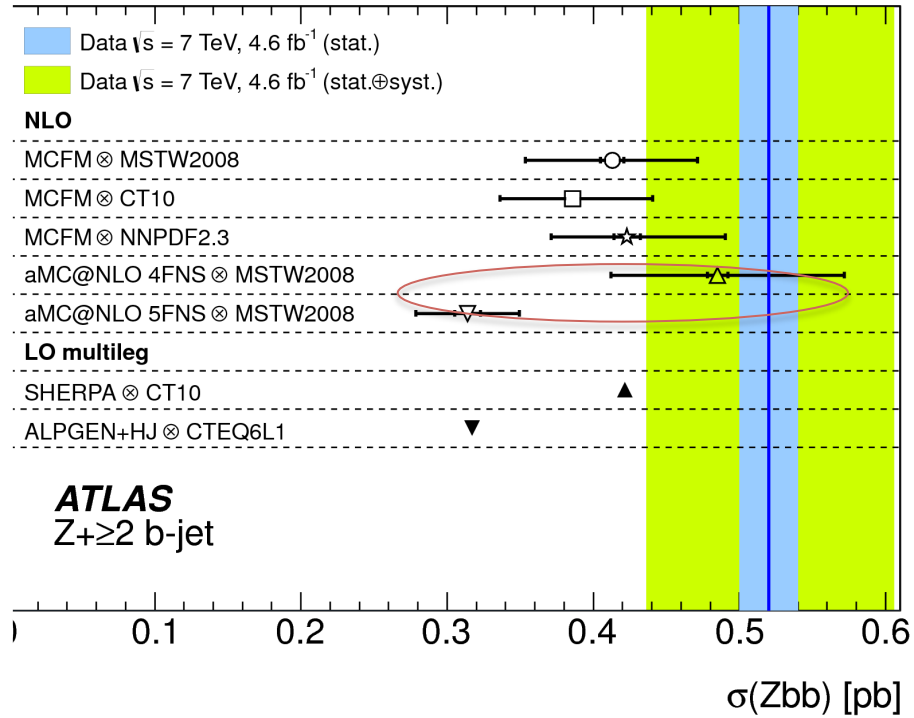
- **Fixed order parton level prediction at NLO combining different sub-processes**
  - Correct to particle level using pythia cross-checked with Sherpa for NP effects
- Inclusion of b mass depends on sub-process
- Uncertainties from scale (x2 variation), PDF, αs, NP corrections
  - **Scale dominates, total uncertainty ~10-15%**

Theoretical predictions: aMC@NLO

- **Particle level NLO prediction**
  - Interfaced to HERWIG++
  - Same choice of scale as MCFM
- Fully inclusive Z+bb prediction in 4FNS with b mass
- Calculate Z+jets in 5FNS and extract predicted heavy flavor cross-sections, massless b
- Only scale uncertainty calculated, ~10% comparable magnitude between schemes
  - **4FNS**: Dominated by renormalization scale
  - **5FNS**: Dominated by opposite variations of renormalization & factorizations scales

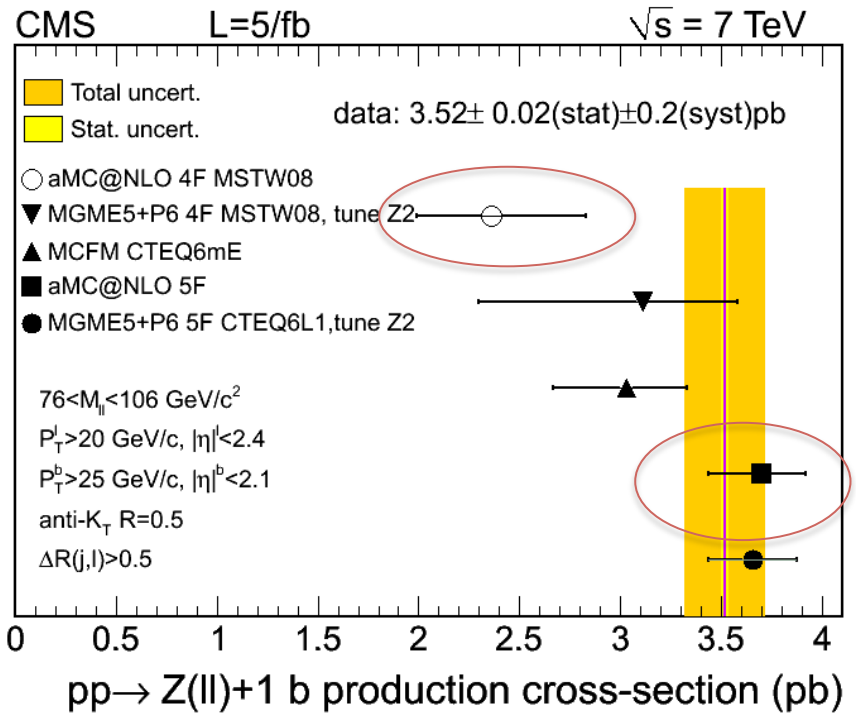
Results: Fiducial cross-sections

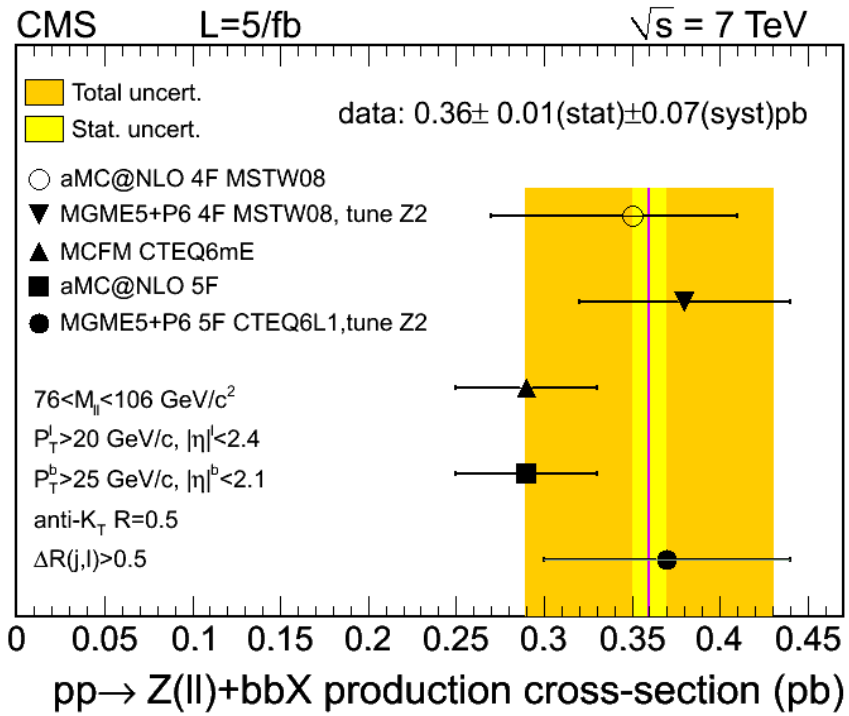




- 5F NLO for Zb describes data well
  NLO matrix element for Zbb in 4F underestimates
- NLO matrix element for Zb in 5F low since it is LO Zbb
- Choice of PDF set has no strong influence on theory prediction wrt data measurement

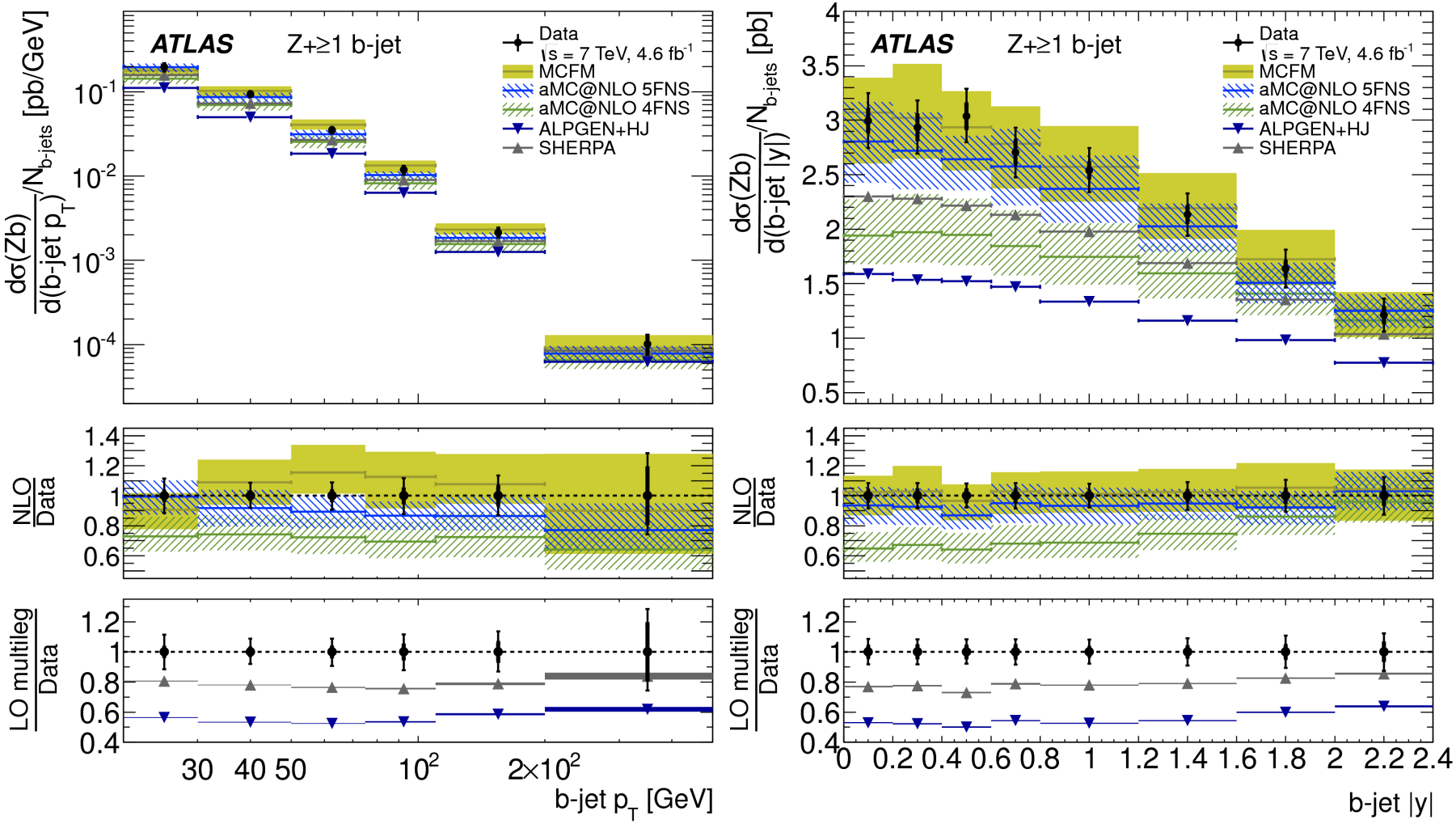
Results: Consistency with CMS





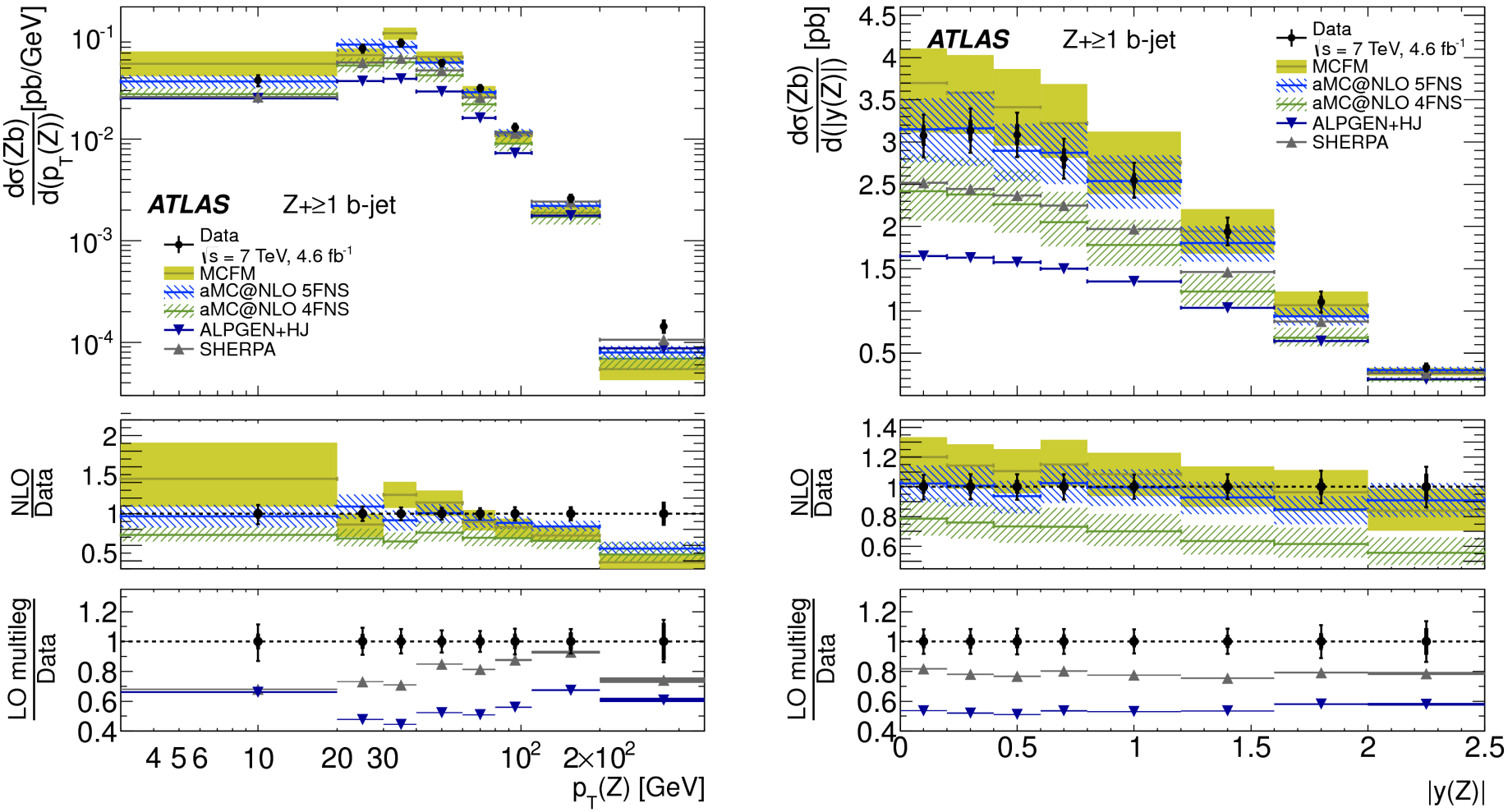
- CMS measure slightly narrower fiducial region
  - Similar order of magnitude difference between Z+≥1 b-jet and Z+≥2 b-jets
  - Experimental systematics comparable
  - **Observe consistent behavior of aMC@NLO 4F vs 5F for Z+≥1 b-jet**
  - aMC@NLO 5F more consistent with data for Z+≥ 2 b-jets

Results: Z+1 b-jet differential



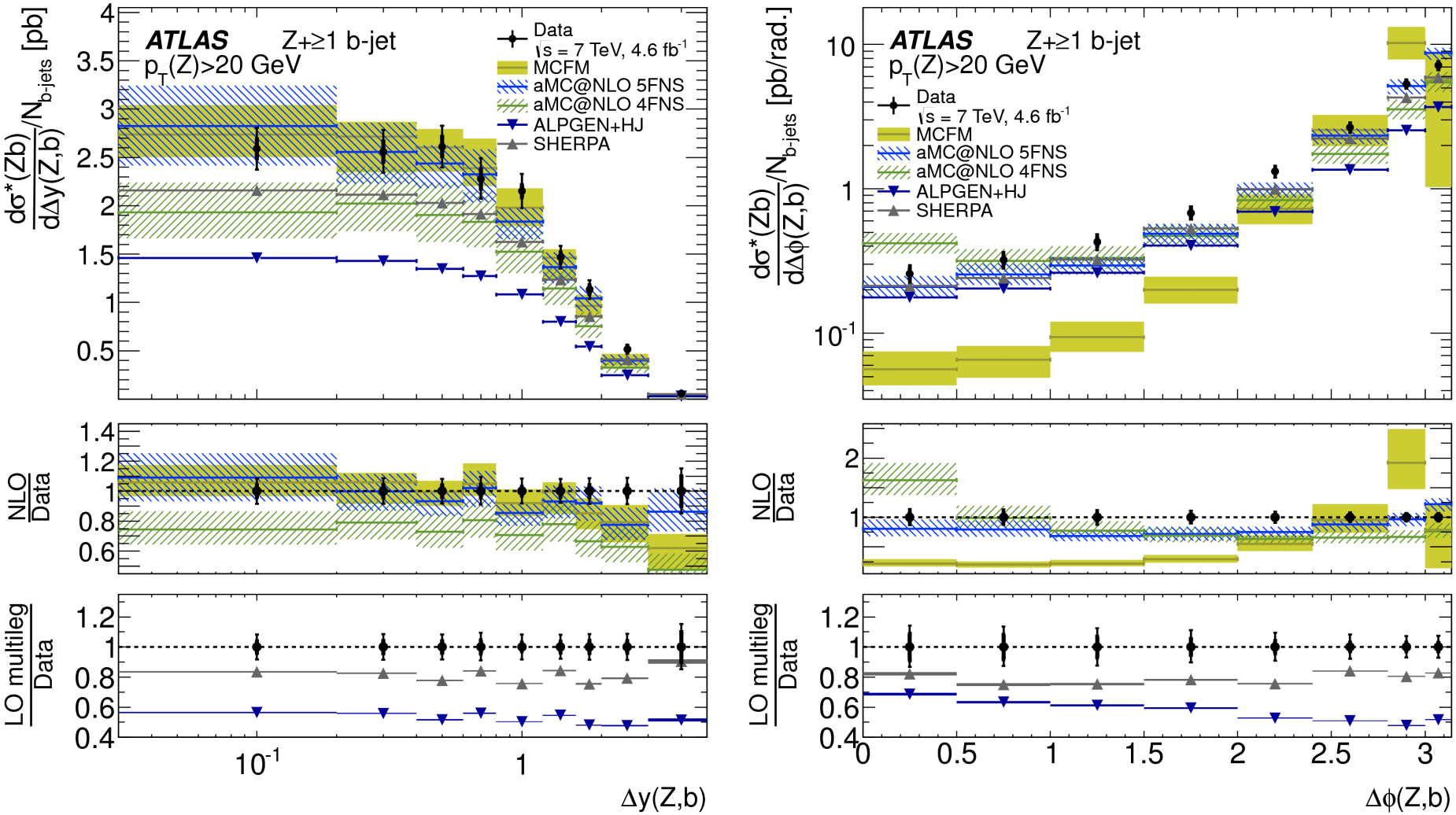
- b-jet pT well modeled over 3 orders of magnitude
- 4FNS underestimates central rapidities

Results: Z+1 b-jet differential



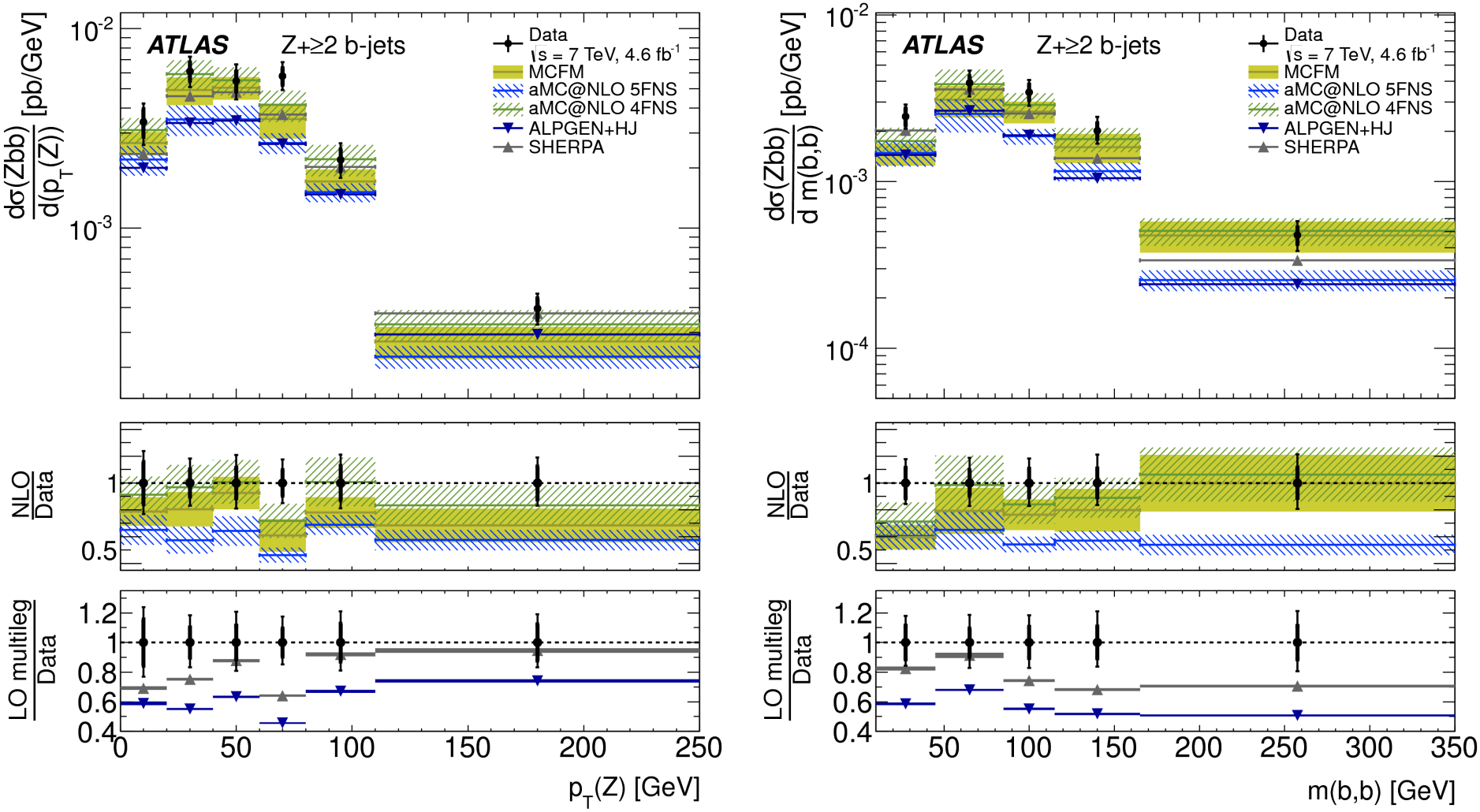
- Reasonable description of Z boson kinematics
- Some deviation at high Z pT
- Slope in MCFM rapidity prediction wrt data

Results: Z+1 b-jet differential



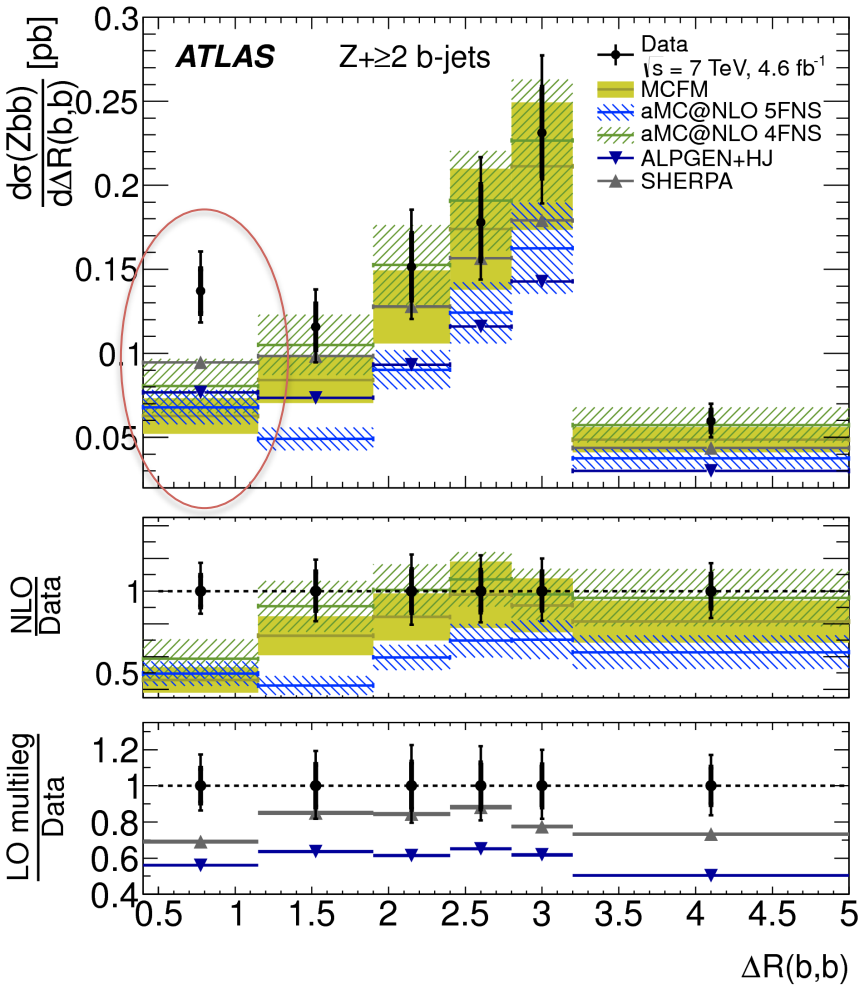
- Boson b-jet rapidity gap modeled well for most part
- Fixed order parton level breaks down for dΦ due to kinematics
  - Better regulated by full particle level predictions

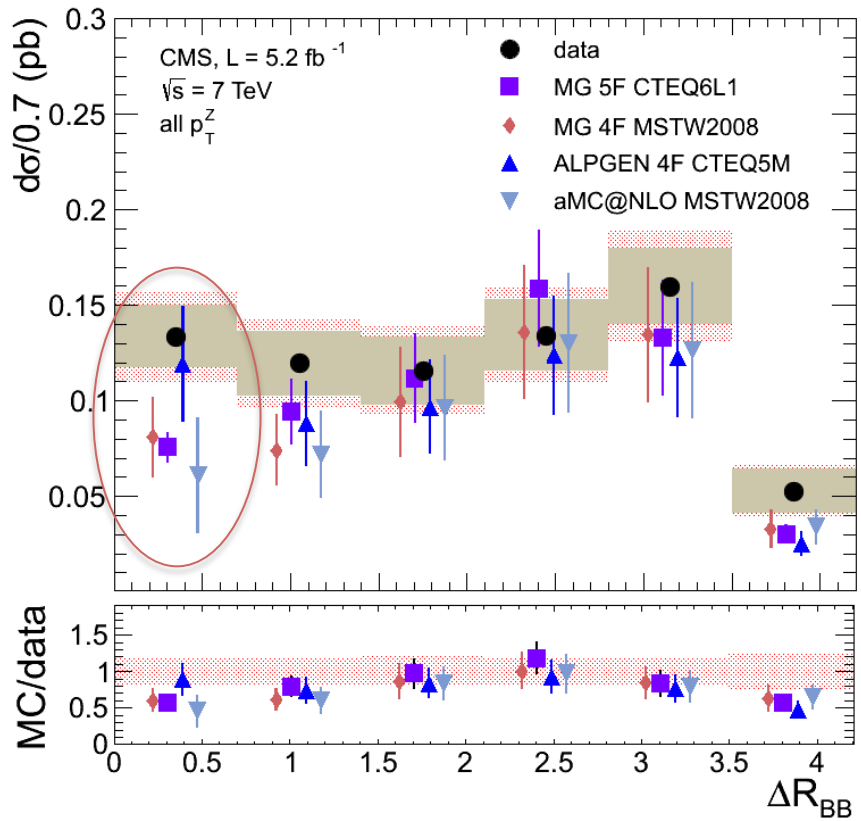
Results: Z+2 b-jets differential



- Z+2b-jets differential measurements more statistically limited
- Distributions well modeled by LO and NLO

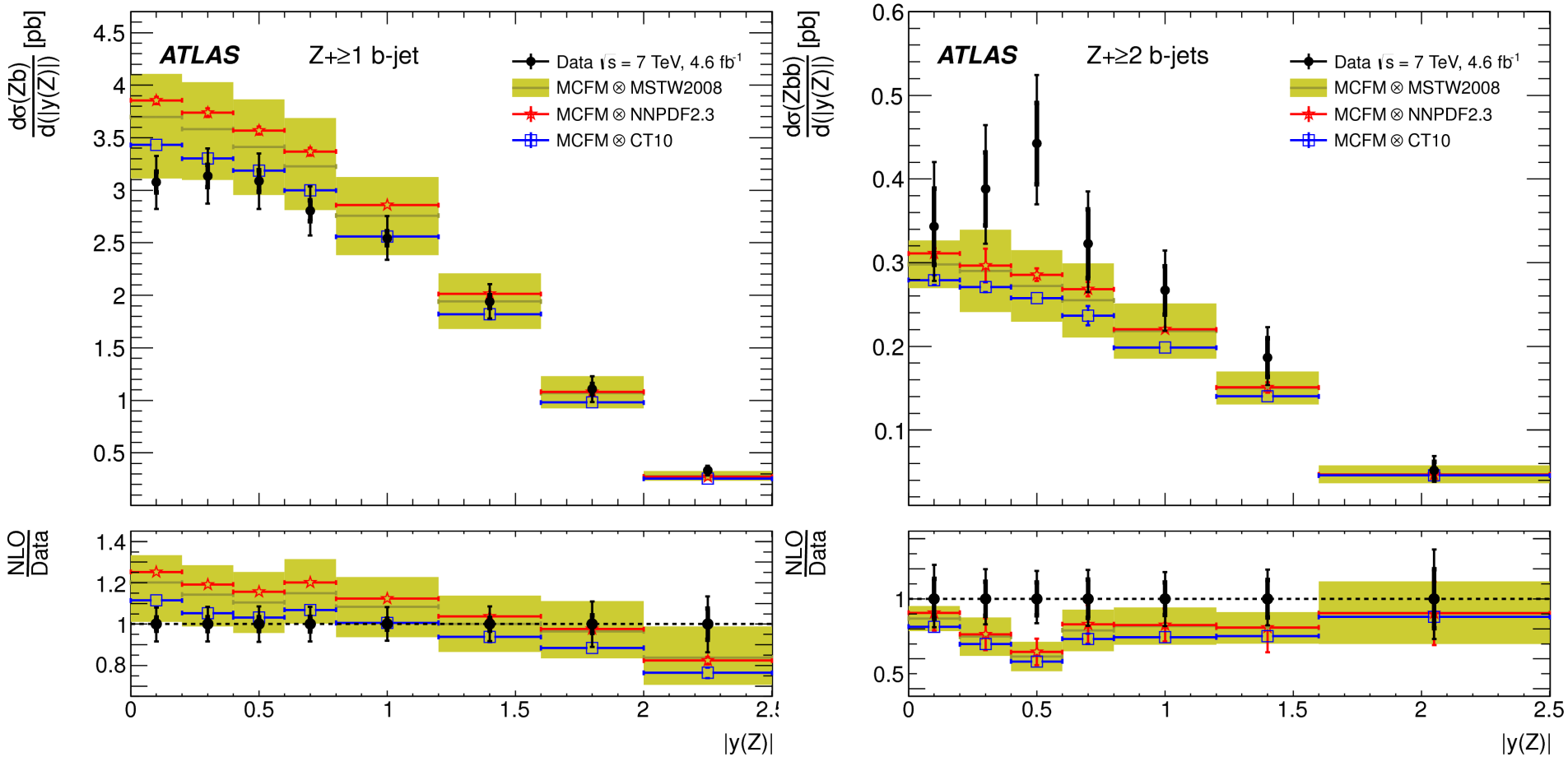
Angular separation between b-jets





- Angular separation of b-jets shows some discrepancy where NPCs are important
- Comparable results from CMS 2 b-hadron analysis
- Interesting to see with higher statistics data

Results: Sensitivity to b-PDF



- Z rapidity variable most sensitive to b-PDF
- Large scale uncertainty make it difficult to discriminate PDF sets
- Factor 2 or more reduction in scale uncertainty would improve sensitivity

Outline

- Introduction
- LHC & ATLAS
- Luminosity measurement
- Z+b-jets cross-section measurement
- **Conclusions**

Future prospects

- **Larger 2012 data largely unexplored in terms of V+b-jets cross-section measurements**
  - Increased statistics could address issues such as dR(b,b)
  - Limited time to analyze before start of Run 2
- NNLO cross-sections in 5FNS may soon be available
- Associated Higgs production ZH(bb) will move towards observation & differential analysis in Run 2: updated analysis of Z+b-jets at 13TeV essential
- Possible spin off: measurement of Z+charm
  - Intrinsic charm in proton?

Summary

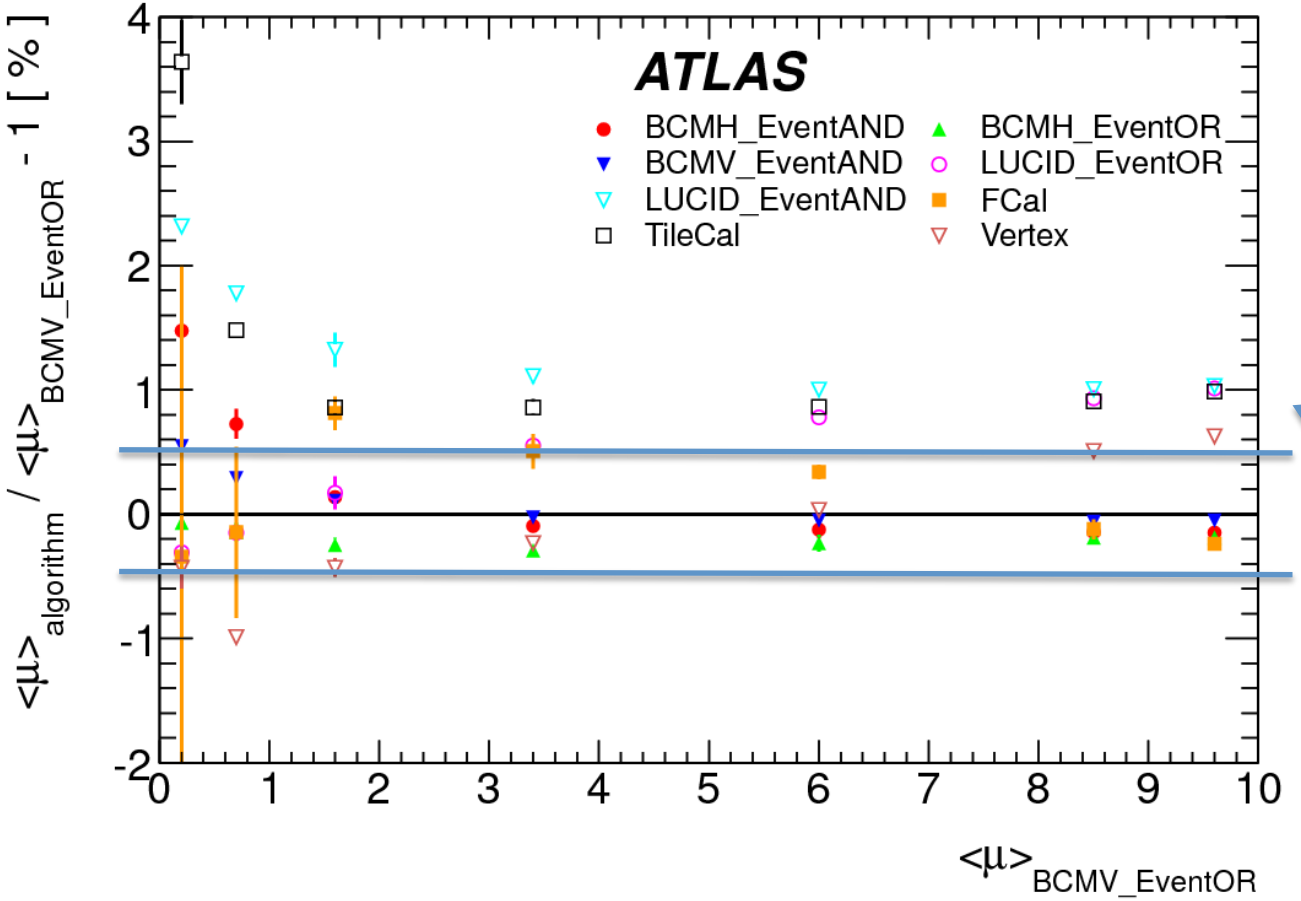
- **Excellent luminosity precision achieved in Run 1 at ATLAS**
- **First differential measurements of Z+b-jets at ATLAS using 2011 data**
  - Flavor scheme dependence of predictions can be understood with data
  - Full particle level NLO calculations improve angular shape modeling wrt fixed order parton level NLO calculations
  - Higher statistics analysis needed to better understand possible discrepancies in modeling b-jet angular separation
- **Sensitivity to b-PDF currently limited due to large scale uncertainties even from NLO predictions**

References

- **Selected Z+b-jets theory**
  - F. Maltoni, G. Ridolfi, and M. Ubiali, "**b-initiated processes at the LHC: a reappraisal**" arXiv:1203.6393 [hep-ph]
  - R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, R. Pittau, and P. Torrielli, "**W and Z/γ* boson production in association with a bottom-antibottom pair**" arXiv:1106.6019 [hep-ph]
  - J. M. Campbell, R. Ellis, F. Maltoni, and S. Willenbrock, "**Production of a Z boson and two jets with one heavy quark tag**" arXiv:hep-ph/0510362
- **ATLAS Luminosity**
  - ATLAS Collaboration, "**Improved luminosity determination in pp collisions at √s=7TeV using the ATLAS detector at the LHC**" arXiv:1302.4393 [hep-ex]
- **ATLAS Z+(b-)jets Standard Model Measurements**
  - ATLAS Collaboration, "**Measurement of differential production cross-sections for a *Z* boson in association with *b*-jets in 7 TeV proton-proton collisions with the ATLAS detector**" arXiv:1407.3643 [hep-ex]
  - ATLAS Collaboration, "**Measurement of the production cross section of jets in association with a Z boson in pp collisions at √s=7TeV with the ATLAS detector**" arXiv:1304.7098 [hep-ex]
- **CMS Z+b(b) Measurements**
  - CMS Collaboration, "**Measurement of the production cross sections for a Z boson and one or more b jets in pp collisions at √s=7TeV**" arXiv:1402.1521 [hep-ex]
  - CMS Collaboration, "**Measurement of the cross section and angular correlations for associated production of a Z boson with b hadrons in pp collisions at √s=7TeV**" arXiv:1310.1349 [hep-ex]

Backup

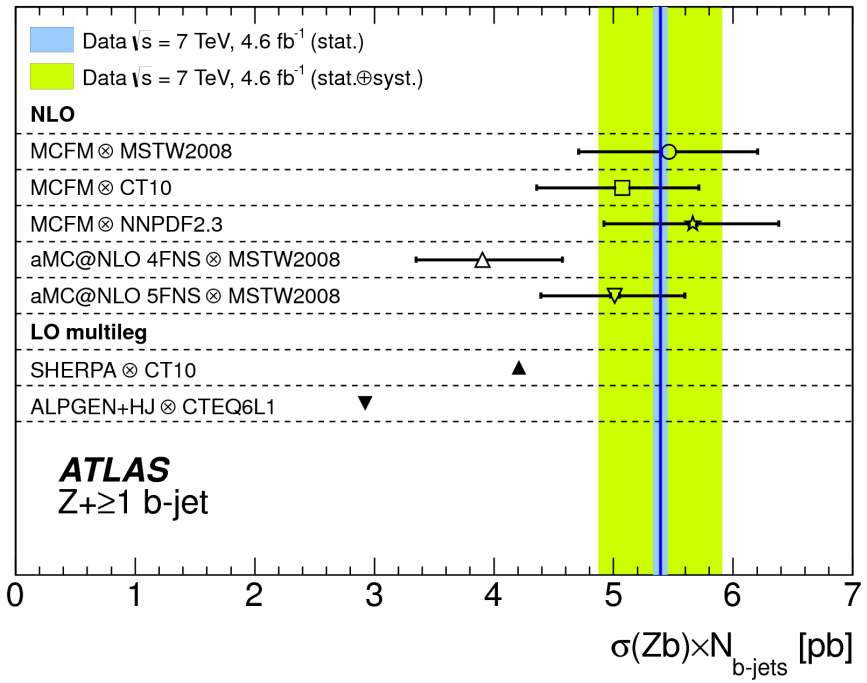
Luminosity Stability

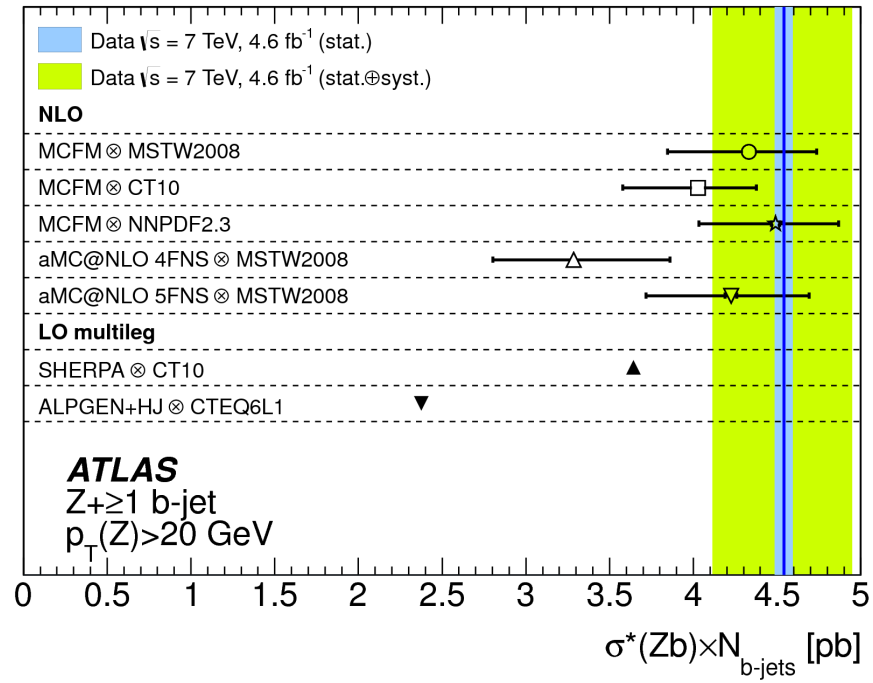


NB offset is artifact of long term stability

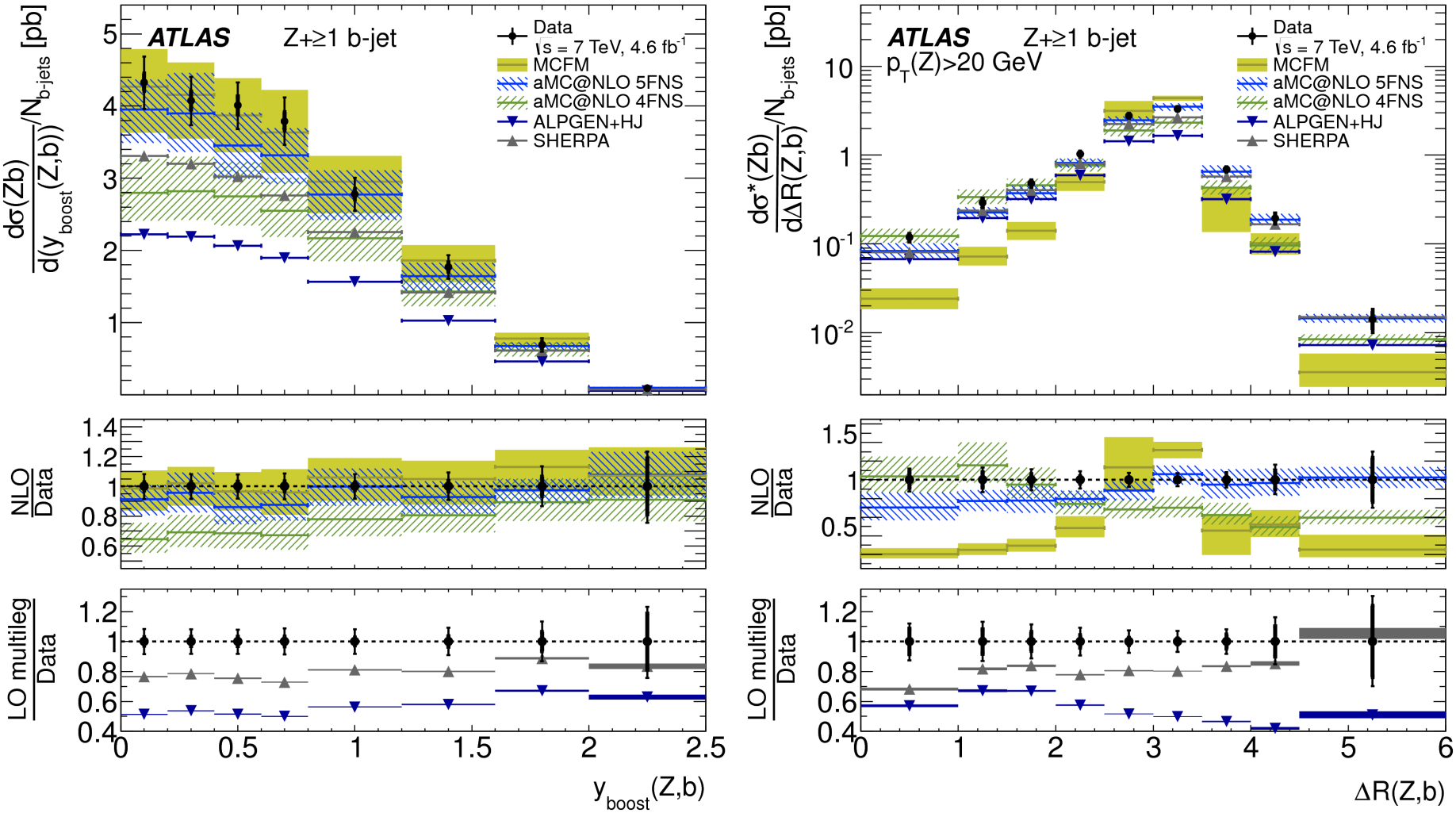
μ-dependence stability in single, dedicated LHC fill

Results: Z+1 b-jet inclusive





Results: Z+1 b-jet differential



Results: Z+2 b-jet differential