Cross section measurements of heavy flavour quarks production in association with a vector boson at hadron colliders

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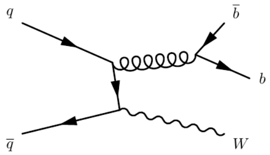
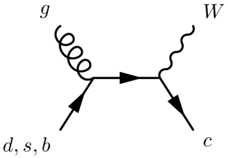
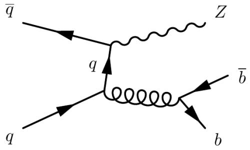
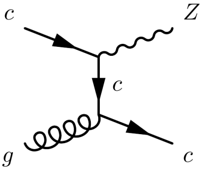


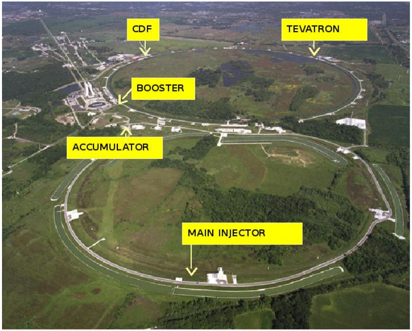


- $W+$ jets and $Z+$ jets at hadron colliders: theory vs experiments
- $W/Z+$ heavy flavour jets: motivation
- Identification of $W/Z+$heavy flavour jets final states: heavy flavour tagging
- Measurements:
  - $W + c$
  - $W + b$
  - $Z + b$
- Outlook and conclusion



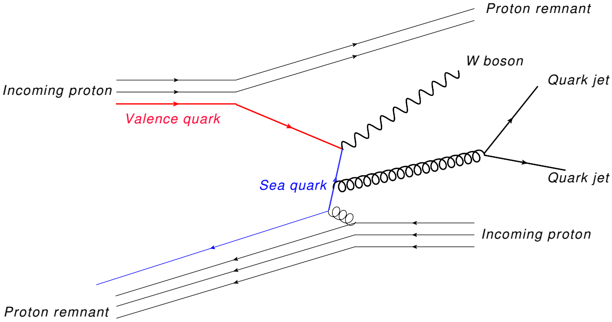


W/Z + jets production at hadron colliders



- $p\bar{p}$ collisions @ 1.96 TeV (Run II)
- Run II: 10 fb^{-1}

- pp collisions
- 2010: 40 pb^{-1} @ 7 TeV
- 2011: 5 fb^{-1} @ 7 TeV
- 2012: 25 fb^{-1} @ 8 TeV



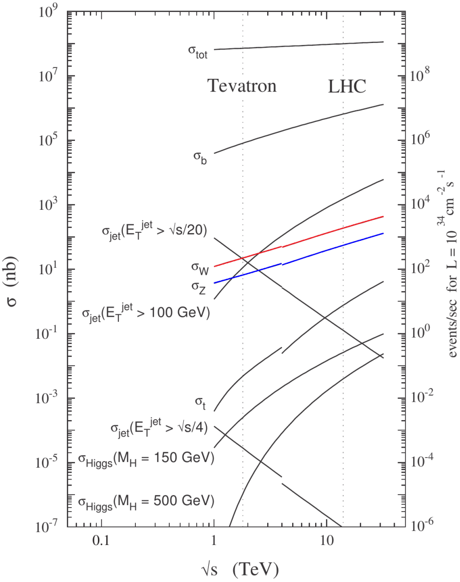
Structure of the proton

- Valence: uud, Sea: $q\bar{q}$ pairs $+g$
- Quark densities described by parton density functions (PDF)
  - fundamental input for calculations
  - PDF uncertainty reduction crucial for measurements and searches
- LHC and Tevatron look at different phase space
  - *pp* more sensitive to sea
  - 7 TeV wider x sensitivity wrt 1.96

Collision modelling

- Pile-up
  - e.g. LHC 2011 dataset $\rightarrow$ average 9 collisions/ bunch crossing
  - challenge for detectors
- Multiple Parton Interactions
  - significant uncertainty in the predictions
  - published determination in data with W + 2 jets @ LHC
  - significant impact to W/Z+hf

Vector boson production at hadron colliders

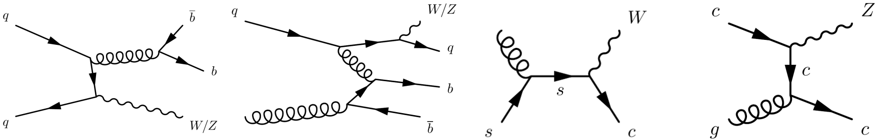


- High statistics @ Tevatron and LHC
- Clear signature leptonic decays
  - → high background rejection
- Huge cross section wrt many processes
  - top physics, Higgs Boson, SUSY/BSM...

$W+$ jets and $Z+$ jets

$W+$ jets and $Z+$ jets are an ideal laboratory for pQCD physics

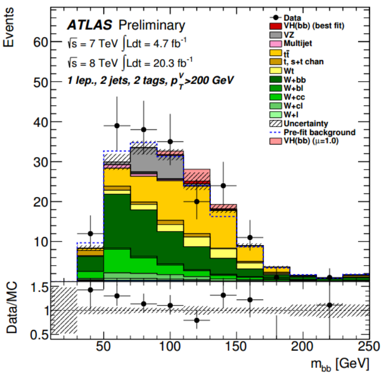
- W/Z + N jets proportional to α_s^N at lowest order
- EW + QCD mixture: relatively low number of diagrams, pQCD calculation possible for high N^{jets}
- Experimentally clear signature and high rate

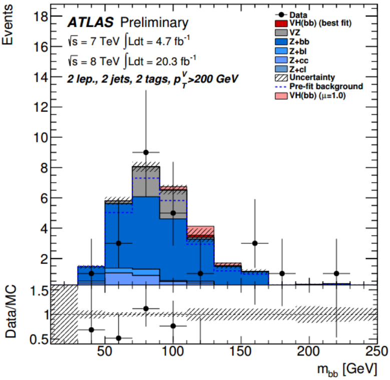


- Fundamental input for comprehension of QCD in hadron collision
  - perturbative calculation and non-perturbative evolution
  - treatment of heavy flavour quarks in the initial state
- Probe the strange and heavy flavour content of the proton $\rightarrow$ PDFs
- Significant background for top, Higgs, SUSY

  need reliable description $\rightarrow$ MC tuning

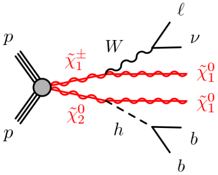
ATLAS-CONF-2013-079, search for VH with $H \to b\bar{b}$





W/Z+hf: background for new physics

Many SUSY and new physics searches are in final states with W/Z+hf



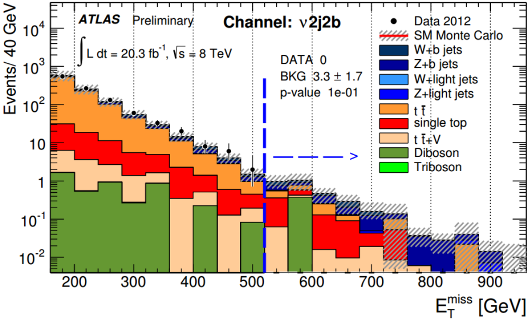
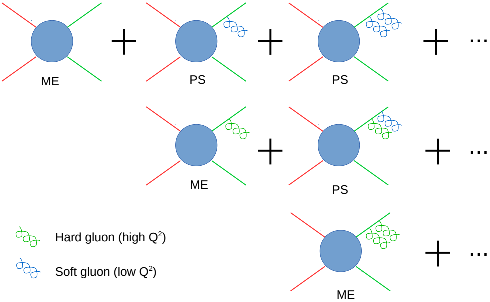
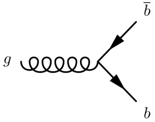


Figure 11: $E_T^{\rm miss}$ distribution for the event class with 2 jets, 2 b-jets and $E_T^{\rm miss}$ ($\nu 2j2b$). The dashed vertical line and the arrow indicate the region of interest which has the smallest p-value (0.097) for this event class.

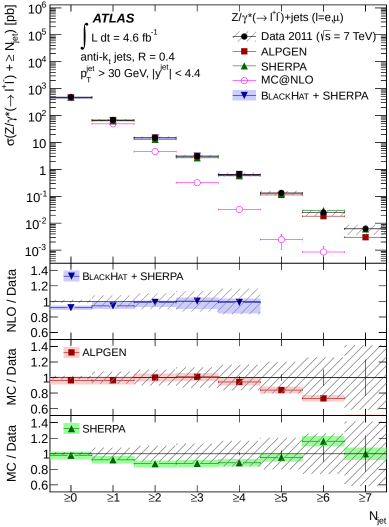
ATLAS-CONF-2014-006, A general search for new phenomena with the ATLAS

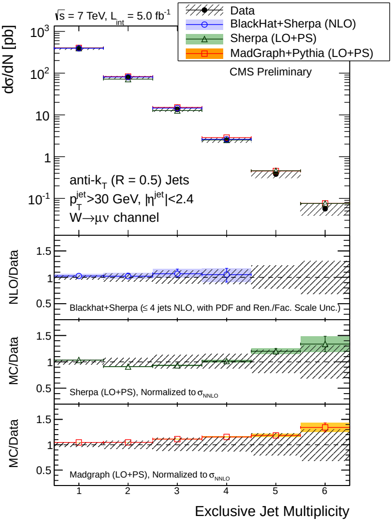


- Matrix Elements: hard Q^2, Parton Shower: soft Q^2 ...
  $\rightarrow$ arbitrary distinction
- ME-PS matching needed to avoid double-counting: CKKW, MLM, ...
  $\rightarrow$ significant differences between matching schemes (e.g. for $Z+$ jets), measurements used for tuning
- Ad-hoc procedures applied to avoid double counting for heavy-flavours
  e.g. $W + b\bar{b}$ (ME) vs W+0 jet + $b\bar{b}$ (PS)
  ME $\rightarrow$ wide angle, PS $\rightarrow$small angle



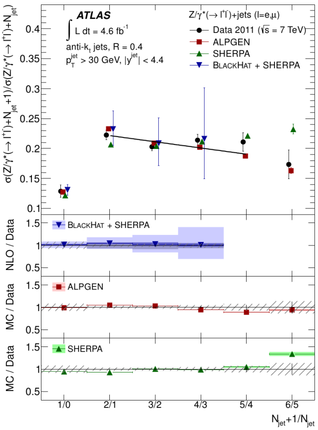
- PS vs ME has significant impact on $b\bar{b}$ ΔR and p_T spectra
- Difficult interfacing theory with exp.: *b-jet* can be associated to more than 1 quark, description of hadronization...



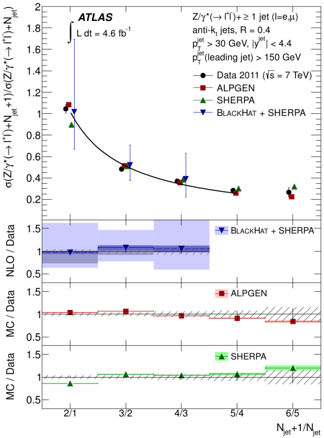


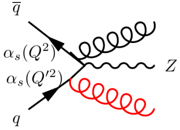
- $W+$ jets and $Z+$ jets measured with high precision
- Reached high jets multiplicities

leading jet with p_T >30 GeV



leading jet with p_T >150 GeV





- $R_n = \sigma^{n+1\ jets}/\sigma^n$
- R_n at LHC between two patterns: $R_{(n+1)/n} \approx$ constant and $R_{(n+1)/n} \propto (1/n)$
- Second behaviour expected to emerge when introducing large scale differences

Challenge for predictions and measurements: test of "extreme" kinematics regions, i.e. regions with large higher order corrections

For scaling patterns see arXiv:1208.3676 [hep-ph]

Blackhat predictions Phys. Rev. D 82 (2010) 074002 and Phys. Rev. D 85 (2012) 031501

W/Z + heavy flavour jets: calculation scheme

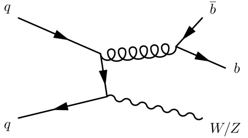
$W+$ b-jets different contributions at NLO

1. $q\bar{q} \rightarrow Wbb$
2. $q\bar{q} \rightarrow Wbbg$
3. $gq \rightarrow Wbbq$
4. $bq \rightarrow Wbq$
5. $bq \rightarrow Wbqg$
6. $bg \rightarrow Wbqq$

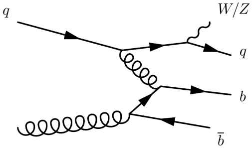
- Contributions 1-3 must be calculated with $m_b \neq 0$ to avoid divergencies in $g \rightarrow b\bar{b}$ splitting
- Contributions 4-6 exist in the 5-flavour-number scheme (5FNS), where b are present in the initial state with their own PDF

  on the other side, in the 4-flavour-number scheme (4FNS) only *udscg* have their PDF, b quarks are produced only by gluon splitting
- Calculations performed with different assumptions on the calculation scheme have significant differences (e.g. see later $Z+$ b-jets)
- Double parton interactions also give significant contribution

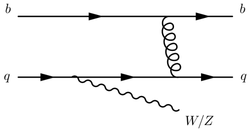
$q\bar{q} \rightarrow Wbb$



$gq \rightarrow Wbbq$



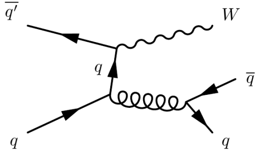
$bq \rightarrow Wbq$ in the 5FNS



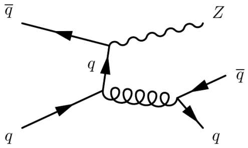
Measuring W/Z + (heavy flavour) jets

Signal and background processes

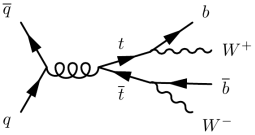
$W+$ jets



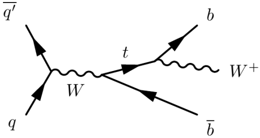
$Z+$ jets



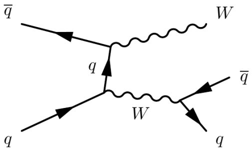
$t\bar{t}$: critical for measurements with $b-jets$



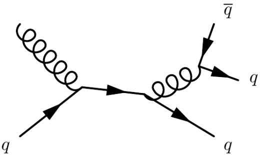
Single-top: difficult to estimate in data



Diboson: hard to estimate in data



QCD multi-jet: high rejection, but huge cross section. Must be estimated in data

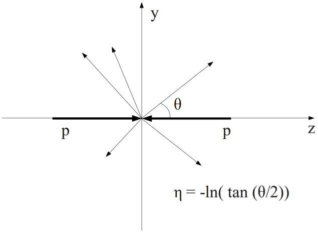


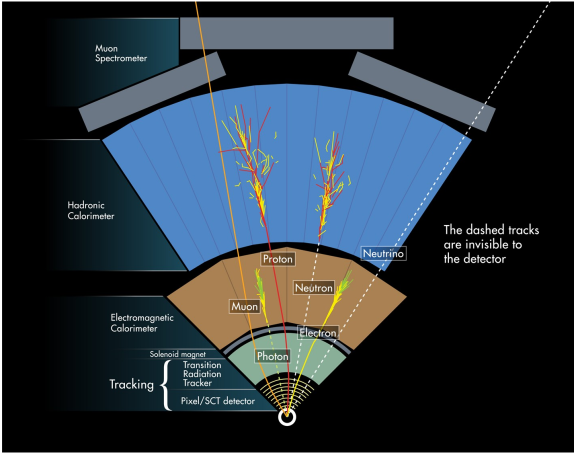
$\sqrt{s}$ not fixed, transverse quantities must be used:

- Transverse energy E_T
- Transverse momentum p_T
- Transverse missing energy $E_T^{\mathrm{miss}} \rightarrow$ **neutrinos**

Angular variables defined:

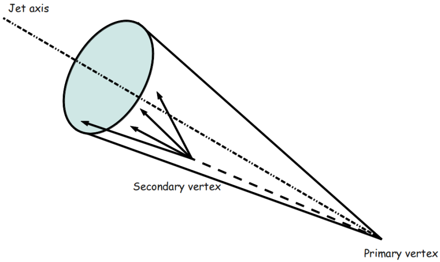
- ϕ around the beams
- θ in the beams plane $\rightarrow \eta$





- W/Z leptonic decays selected, leptons $p_T > 20 - 30$ GeV
- Jets reconstructed with clustering algorithm from deposition in calorimeters (*anti-k_T* @LHC)
- For *b*-jet identification critical vertex reconstruction

b-jet identification



Jets originated from *b*-hadrons can be selected (TAGGED) using:

- long lifetime ($c\tau \approx$0.5 mm) $\rightarrow$ displaced secondary vertex (SV), impact paramter of tracks in jet
- high mass ($>$5 GeV) $\rightarrow$ invariant mass of tracks associated to SV
- kinematics
- number of tracks in the jet
- cascade vertices
- ...

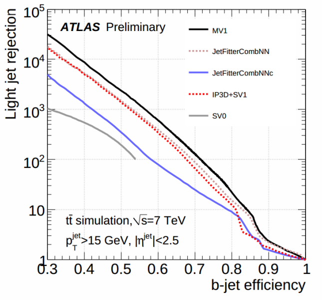
Jets are tagged with:

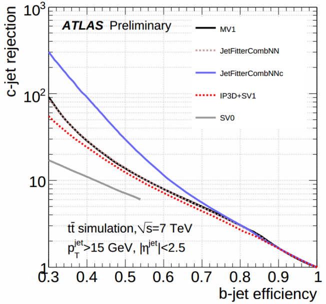
- SV tagger / impact parameter tagger
- Multivariate tagger
- Neural network combination of simple taggers

Challenge

- *c*-hadrons have smaller masses ($\approx$2 GeV) but only slightly lower decay length ($c\tau \approx$0.1-0.3 mm)
- $\rightarrow$ *b*-jet vs *c*-jet discrimination is the challenge for taggers

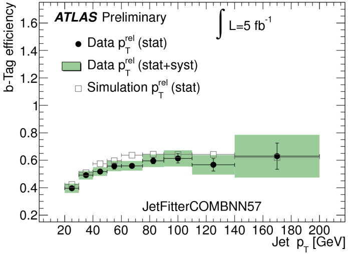
b-jet identification efficiency

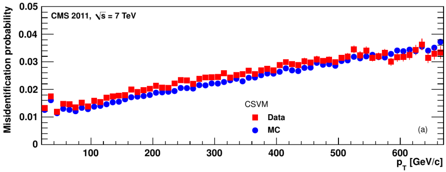




- Taggers define discriminating variables
- Working point selected optimising analysis. In measurements presented in this talk:
  - ϵ_b ≈50% (depends on jet p_T)
  - c-jet rejection factor ≈ 10
  - light-jet rejection factor > 100

Tagger calibration in data





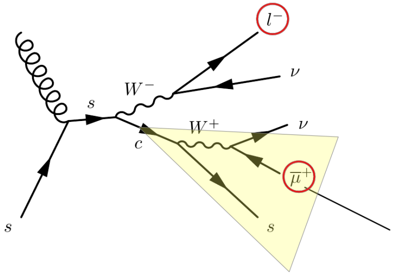
- Taggers @ LHC calibrated in different kinematics regions, taking into account correlations on uncertainties
- Efficiency measured in data
  - multi-jet sample, using orthogonal tagger
  - soft-muon tagged jet sample
  - $t\bar{t}$ sample
- Mistag rate for light-jets measured in data in negative-tagged event or using low-mass SV
- Challenging mistag rate of c-jets $\rightarrow$ it can be measured in $W + c$ events

Selection of a $W + c$ sample

Two main c identification techniques:

- c-jet tagged using semimuonic decays of charmed mesons (low BR, clear signature)

  $\rightarrow$ soft muon inside jet
- reconstruction of D/D^* meson in detector tracker
  - $D^+ \rightarrow K^-\pi^+\pi^-$ (9%)
  - $D^{*+} \rightarrow D^0\pi^+$ (68%) with $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^0$ or $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$



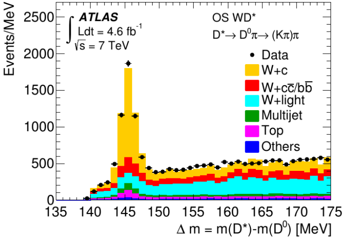
- Charge of W from selected e/μ
- Charge of c from reconstructed D meson or from soft muon charge

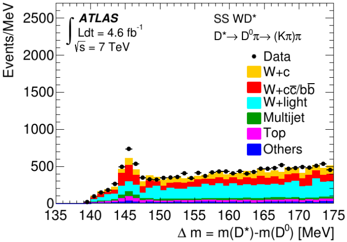
Selected events classified in Same Sign (SS) and Opposite Sign (OS):

- $N^{OS} = N^{signal} + N^{bkg}_{OS}$
- $N^{SS} = N^{bkg}_{SS}$
- Since $N^{bkg}_{OS} \approx N^{bkg}_{SS} \rightarrow N^{OS} - N^{SS} \approx N^{signal}$

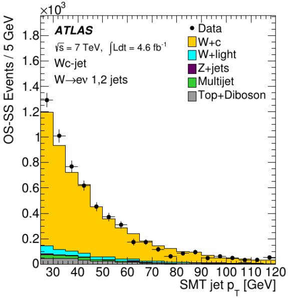
$N^{OS} - N^{SS}$ yield dominated by $W + c$ signal (70-80% contribution)

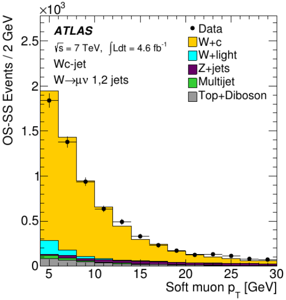
$W + c$ sample





Background contribution ≈ symmetric in OS/SS, signal totally asymmetric.

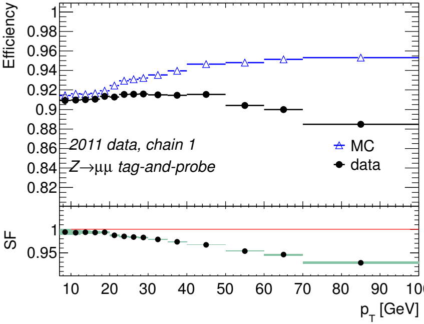




After OS-SS subtraction, sample dominated by signal. Residual contribution estimated in data (QCD, $t\bar{t}$, $Z+$ jets) or simulated.

- *c*-jet selected requiring muon with $p_T > 4\text{GeV}$ with $\Delta R < 0.5$ from jets
- cut on muon track quality (χ^2_{match} between ID and MS) to enhance light-jets rejection
- calibration of muon selection efficiency in $Z \to \mu\mu$ data sample
- mistag rate calibrated in multijet sample

Efficiency of soft muon selection in data and MC



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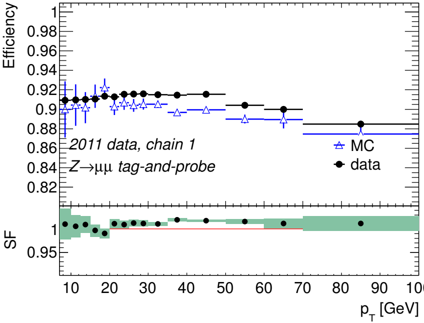
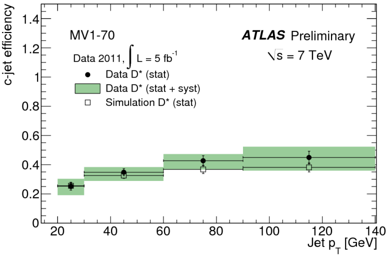
Efficiency of soft muon selection in data and MC

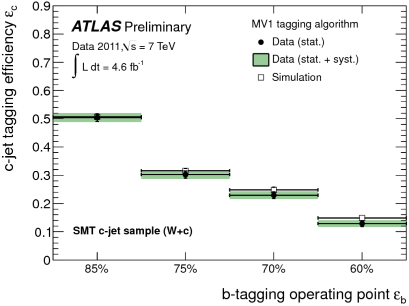
considering a realistic alignment in MC significantly improves data/MC agreement



b-jet mistag rate due to *c*-jets can be measured in clean sample of *c*-jets using $W+$ *c*-jet events



Measurement in $W+D$ sample
ATLAS-CONF-2012-039



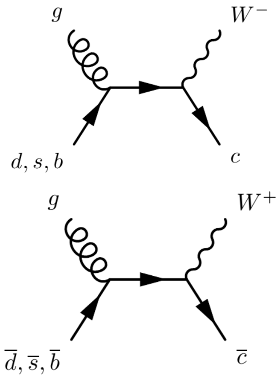
Measurement in $W+c$ sample
ATLAS-CONF-2013-109

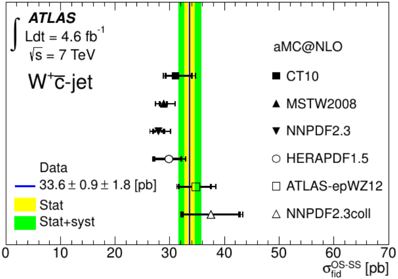
$W + c$ cross section measurements

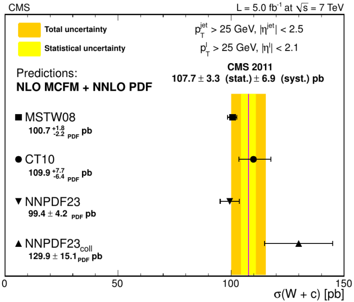
- CMS **JHEP02 (2014) 013**: 2011 data, 5 fb^{-1} @ 7 TeV
- ATLAS **arXiv:1402.6263**: 2011 data, 4.6 fb^{-1} @ 7 TeV
- CDF **Phys.Rev.Lett. 110 (2013) 7, 071801**: Run II data, 4.3 fb^{-1} @ 1.96 TeV

$W + 1\ c$ production

- totally dominated by production diagrams with s in the initial state $\rightarrow$ sensitive to s PDF
- $W^+\overline{c}/W^-c$ constrains $s/\overline{s}$ asymmetry

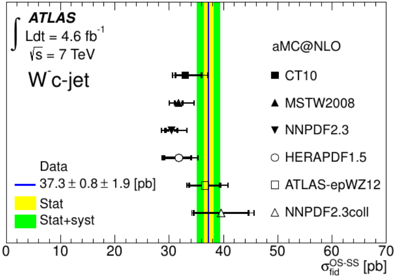


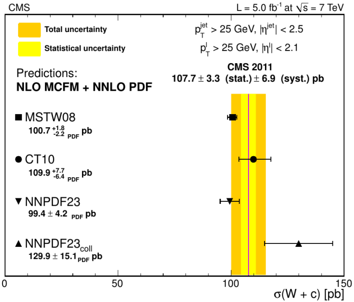




- ATLAS results favour PDF fits with higher s quark content
- CMS more consistent with PDF fit lower s quark content
- Cannot do a direct comparison of results
  - different phase space
  - different strategy for $W + D$: no jet reconstruction (ATLAS) vs jet tagging (CMS)
- Significant systematic uncertainties due to
  - Jet energy measurement
  - QCD, $W+$ jets background estimation
  - c quark fragmentation (fragmentation fraction, function)
  - c-hadron decay (BR, kinematics)

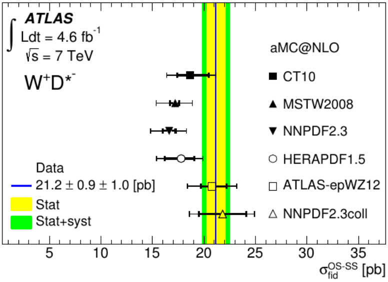
$W + c$ results: cross section

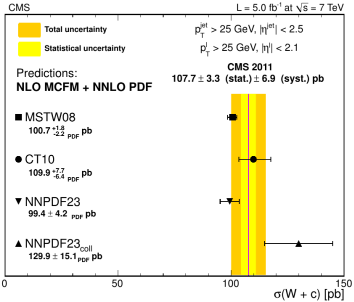




- ATLAS results favour PDF fits with higher s quark content
- CMS more consistent with PDF fit lower s quark content
- Cannot do a direct comparison of results
  - different phase space
  - different strategy for $W + D$: no jet reconstruction (ATLAS) vs jet tagging (CMS)
- Significant systematic uncertainties due to
  - Jet energy measurement
  - QCD, $W+$ jets background estimation
  - c quark fragmentation (fragmentation fraction, function)
  - c-hadron decay (BR, kinematics)

$W + c$ results: cross section





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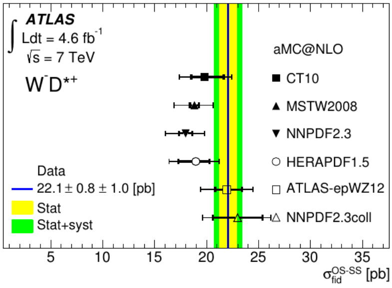

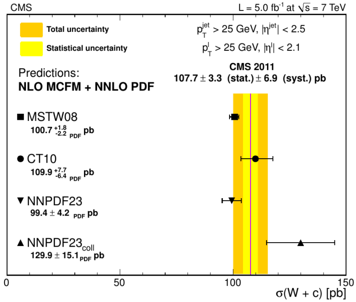

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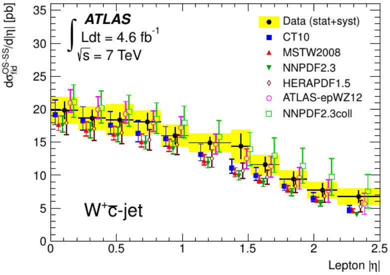
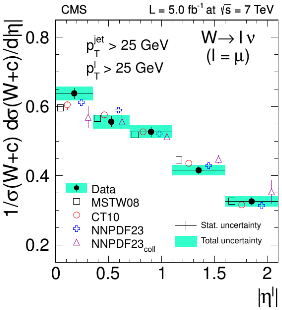
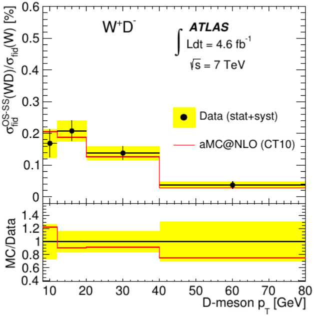
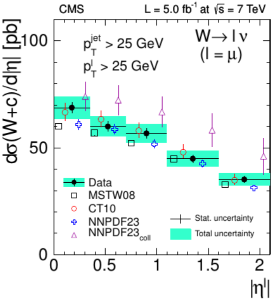
$W + c$ results: differential cross section

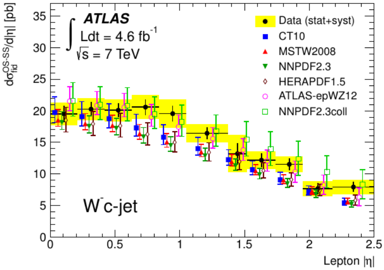


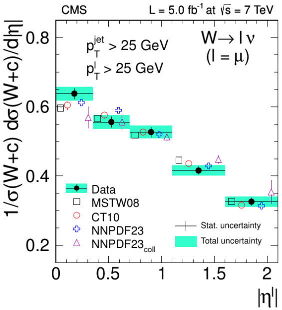


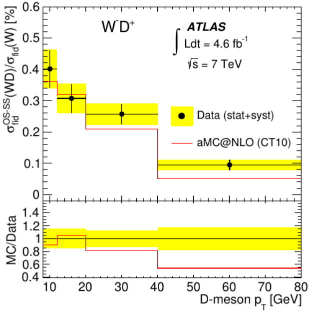


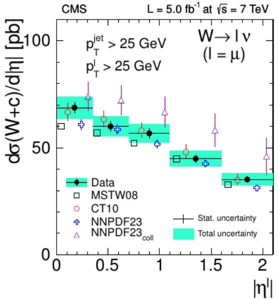


Differential meas. fundamental for PDF determination: probe different x regions



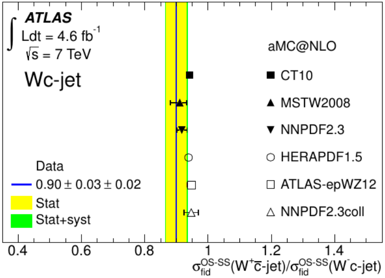


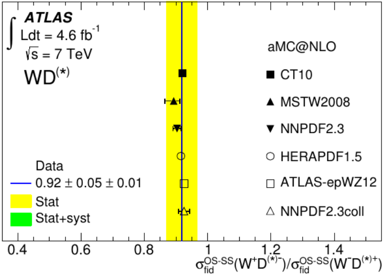


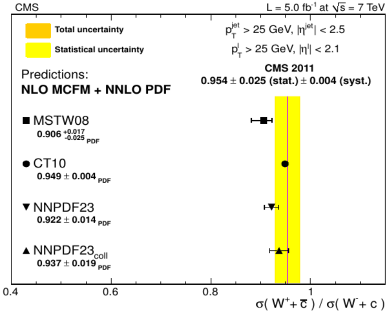


Differential meas. fundamental for PDF determination: probe different x regions

$W+c$ results: $W^+\overline{c}/W^-c$ cross section ratio

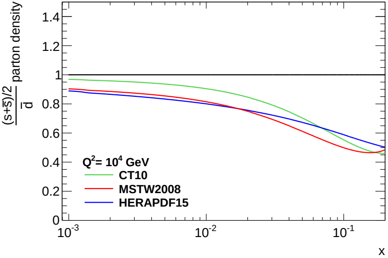






- Most systematics uncertainties cancelled in $W^+\overline{c}/W^-c$ ratio
- Measurement, sensitive to $s/\overline{s}$ asymmetry, is statistically limited

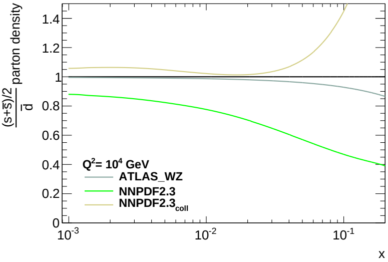
- s PDF known with relatively high uncertainties
- SU(3) $\rightarrow$ PDF(s)=PDF($\bar{s}$)=PDF($\bar{d}$)
- Non-perturbative QCD effects $\rightarrow$ possible PDF(s)$\neq$PDF(d) and also PDF($\bar{s}$)$\neq$PDF(s)
- Strongest constraints to s PDF from neutrino DIS experiment, suffering from modelling of c fragmentation and nuclear corrections
- Fits to these data suggest s-PDF suppressed wrt to d PDF at high x



Different PDF fits (CT10, MSTW, HERA in the plot) predict different levels of SU(3) restoration at small x (LHC region)

- s PDF known with relatively high uncertainties
- SU(3) $\rightarrow$ PDF(s)=PDF($\bar{s}$)=PDF($\bar{d}$)
- Non-perturbative QCD effects $\rightarrow$ possible PDF(s)$\neq$PDF(d) and also PDF($\bar{s}$)$\neq$PDF(s)
- Strongest constraints to s PDF from neutrino DIS experiment, suffering from modelling of c fragmentation and nuclear corrections
- Fits to these data suggest s-PDF suppressed wrt to d PDF at high x

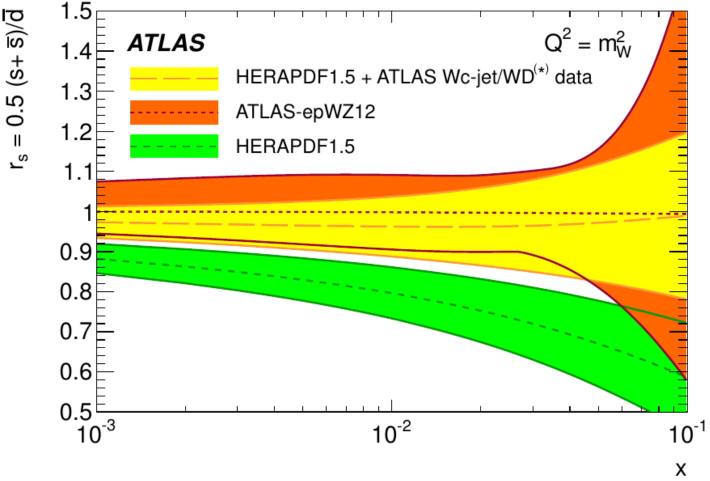
- Some fits to NuTeV ν DIS results also introduce $s/\bar{s}$ asymmetry
- Results based only on collider data (HERA + ATLAS W,Z inclusive) predict no $s/\bar{d}$ suppression



PDF(s)/PDF(d) shown for

- *NNPDF* fit, taking into account ν DIS
- $NNPDF_{coll}$ based solely on collider data
- *ATLAS* – *PDF* based on HERA data + ATLAS W,Z inclusive measurements

$W + c$ results: r_s measurement



Comparison of ATLAS result with HERA PDF including ν DIS results and with PDF with HERA+LHC results only

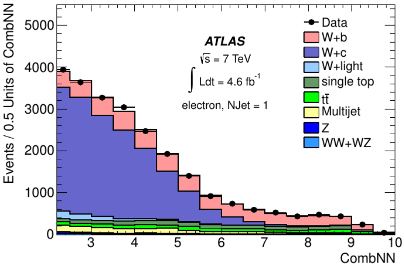
W + b-jets

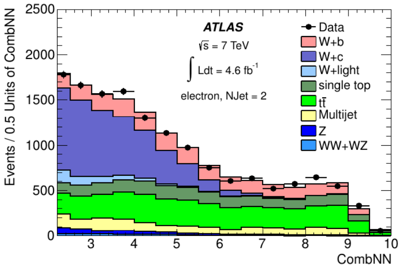
$W+$ b-jets

- CDF **Phys.Rev.Lett. 104 (2010) 131801**: Run II data, 1.9 fb^{-1} @1.96 TeV
- D0 **Phys. Lett. B718 (2013) 1314-1320**: Run II data, 6.1 fb^{-1} @ 1.96 TeV
- ATLAS **JHEP 06 (2013) 084**: 2011 data, 4.6 fb^{-1} @ 7 TeV

  $\rightarrow$ previous result **Phys.Lett. B707 (2012) 418-437**: 2010 data, 36 pb^{-1} @ 7 TeV
- CMS **arXiv:1312.6608 , submitted to Phys.Lett. B**: 2011 data, 5.0 fb^{-1} @ 7 TeV

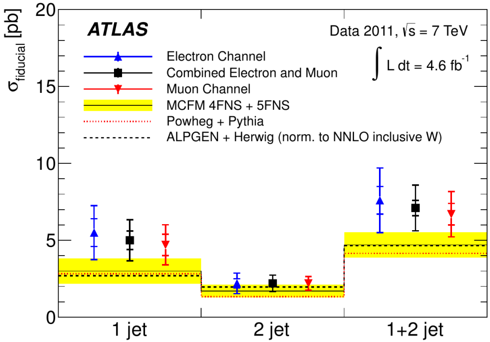
$W+$ b-jets measurement

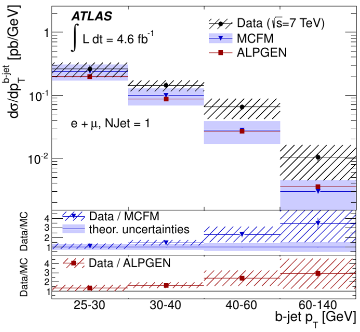




- Complementary measurements from ATLAS and CMS
  - ATLAS: selection W + 1 b-tagged jet + 0-1 jet (any)
  - CMS: selection W + 2 b-tagged jets
- b-jets, c-jets, light-jets fraction in selected events determined with fit to discriminant variable
- control of c-jets component is one of the biggest challenges for the measurement
- $t\bar{t}$, single-top, QCD multi-jet determined with similar technique in complementary data samples

$W+$ b-jets: results ATLAS JHEP 06 (2013) 084





- Measured cross section compared with LO+PS and NLO predictions
- Comparison with Powheg(ME) + Pytha(PS), Alpgen (ME) + Herwig (PS), both with 4FNS item Comparison with MCFM in 5FNS. Prediction at parton level, crorected using factor from Powheg+Pythia sample
- Differential cross section vs jet p_T also measured
- Dominant uncertainties: Jet energy scale and resolution, b-jet selection efficiency
- 25% contribution to $\sigma_{predicted}$, mostly at low p_T, due to Double Parton Interactions, with high uncertainty (40% from ATLAS $W+2$ jets DPI measurement)

$W+$ b-jets: summary of results

All cross sections are fiducial, numbers quoted are $\sigma^{fid} \times BR(W \rightarrow \ell\nu)$
Different fiducial phase space, direct comparison of measurements not possible.
Recent results solve tension with prediction observed in early measurements

- CDF result: $W+$ b-jets jet-level cross section, $p\bar{p}$ 1.96 TeV

Measurement	Cross section [pb]	NLO prediction [pb]
$W+$ 1+ b-jets	2.74 ± 0.50	1.22 ± 0.14

- ATLAS results: W + 1 b-jet + 0-1 additional jets, pp 7 TeV

Measurement	Cross section [pb]	MCFM NLO prediction [pb]
W+1 b-jet	5.0 ± 1.3	$3.01^{+0.83}_{-0.62}$
W+1 b-jet +1 jet	2.2 ± 0.5	$1.69^{+0.43}_{-0.27}$

- CMS result: W + 2 b-jets, pp 7 TeV

Measurement	Cross section [pb]	MCFM NLO prediction [pb]
W+2 b-jets	0.53 ± 0.12	0.55 ± 0.06

- D0 result: W + at least 1 b-jet, $p\bar{p}$ 1.96 TeV

Measurement	Cross section [pb]	MCFM NLO prediction [pb]
$W+$ b-jets	1.05 ± 0.12	$1.34^{+0.41}_{-0.34}$

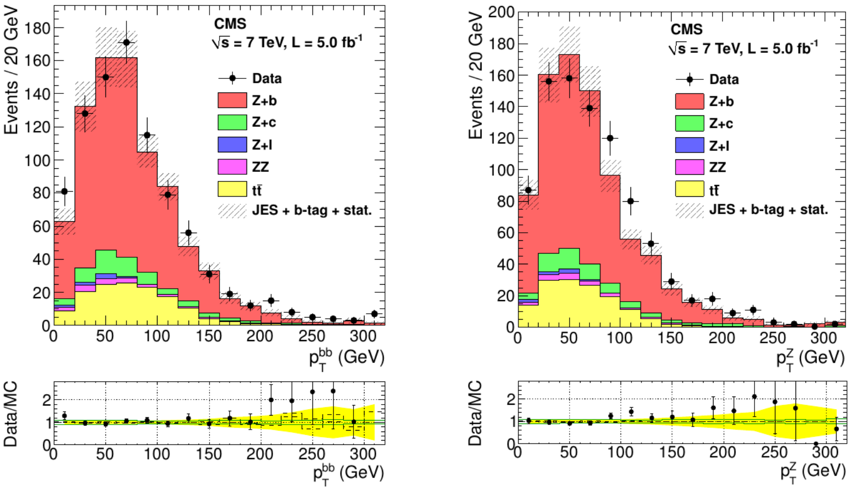
$Z + b$-jets

$Z+$ b-jets

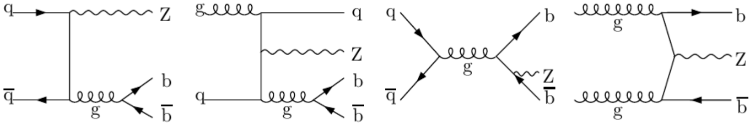
- CDF preliminar $Z+$ b-jets/Z and $Z+$ b-jets/$Z+$ jets, **note 10594**: Run II data, 7.9 fb^{-1} @ 1.96 TeV
    - $\rightarrow$ previous result **Phys. Rev. D 79, 052008 (2009)**, 2.0 fb^{-1}
- D0 $Z+$ b-jets/$Z+$ jets ratio, **Phys. Rev. D 87, 092010 (2013)**: Run II data, 9.7 fb^{-1} @ 1.96 TeV
- ATLAS **Phys.Lett. B706 (2012) 295-313**: 2010 data, 36 pb^{-1} @ 7 TeV
- CMS **JHEP06 (2012) 026**: 2011 data, 2.2 fb^{-1} @ 7 TeV
- CMS $Z + b\bar{b}$ angular correlations, **JHEP12 (2013) 039**: 2011 data, 5.2 fb^{-1} @ 7 TeV
- CMS **arXiv:1402.1521, submitted to JHEP**: 2011 data, 5 fb^{-1} @ 7 TeV

Cross section	Measured	MadGraph (5F)	aMC@NLO (5F)	MCFM (parton level)	MadGraph (4F)	aMC@NLO (4F)
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.07	$0.29^{+0.04}_{-0.04}$	$0.29^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.08}_{-0.06}$
σ_{Z+b} (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.24	$3.99^{+0.25}_{-0.29}$	$3.23^{+0.34}_{-0.40}$	$3.49^{+0.52}_{-0.91}$	$2.71^{+0.52}_{-0.41}$
$\sigma_{Z+b/Z+j}$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.11	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

- Results provided for Z+1 b-jet and $Z+2$ b-jets important to get full picture
- Comparison with different predictions
  - uncertainties on MadGraph 5FNS treated taking into account correlations are significantly smaller
  - biggest discrepancies in predictions are between 4FNS and 5FNS
  - MCFM predictions at parton level, but difference with measurements not due to hadronization (correction factor <1)
  - significant discrepancy with aMC@NLO in 4FNS
- Measurements at same level of precision of predictions

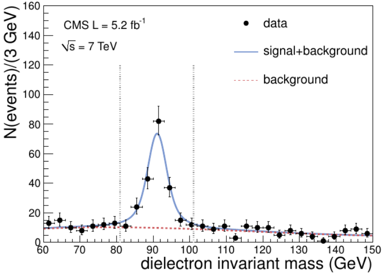


- p_T spectra harder in measurements than predictions

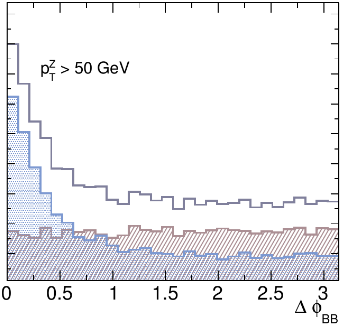


(a) (b) (c) (d)

- Angular correlation of $b\bar{b}$ pair in $Z + b\bar{b}$ production interesting as described with significant theoretical uncertainties
- E.g. in 2HDM studies, with $\phi_1 \to Z\phi_2$ and $\phi_2 \to b\bar{b}$ if $m_{\phi_1} - m_{\phi_2}$ is large b quarks are collinear
- Measurement done with identification of b-hadrons from displaced vertex, independently of jet reconstruction
- $qq, qg \to ZbbX$ and and $gg \to ZbbX$ give different distributions in different kinematics regions



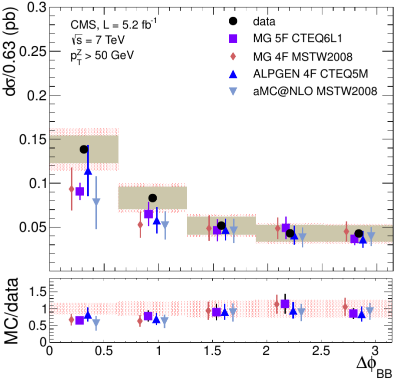
background estimation form sidebands of mass distribution



Contribution of

- $qq, qg \rightarrow ZbbX$ diagrams (brown)
- $gg \rightarrow ZbbX$ diagrams (blue)

as a function of $\Delta\phi_{b\bar{b}}$



Measured and predited cross section as a function of $\Delta\phi_{b\bar{b}}$

Data/MC agreement is worse in low $\Delta\phi_{b\bar{b}}$ region (i.e. for collinear B hadrons)

- $W+$ jets and $Z+$ jets studied with high precision at the Tevatron and Large Hadron Collider
- Predictions and Monte Carlo simulation have been tested, finding in general good agreement, with potential for improvement/tuning especially in “extreme” kinematic regions
  - scale uncertainties are a limiting uncertainty for predictions
- $W+$ b-jets and $Z+$ b-jets results at level of precision of predictions
  - good agreement of integrated results, shown possible tension in kinematics description
  - results sensitive to difference between 4-flavour and 5-flavour calculation schemes
  - tuning of $g \to b\bar{b}$ MC description possible exploiting experimental results
- $W + c$ results provide fundamental constraints for s quark PDF, which needs to be included in PDF fits
  - ATLAS favouring enhanced s content of the proton, while CMS prefers a lower s quark PDF

Outlook

What do we want to learn in the near future: 2012 LHC dataset

- For $W+$ jets and $Z+$ jets main interest in "extreme" kinematics regions (high boson/jet $\mathrm{p_T}$ high E_T^{miss} ,...) and for events with large scale differences (e.g. leading jet with very hight $\mathrm{p_T}$)
  - large higher order corrections play important role in those regions, must test pQCD
  - these regions are interesting for searches, need reliable description of $W+$ jets and $Z+$ jets
- $W + c$ results could significantly improve with bigger dataset
  - c tagging and jet energy measurements are dominant systematics for the measurement
  - also background determination suffer from limited statistics
  - $W^+\overline{c}/W^-c$, sensitive to $s/\overline{s}$ PDF asymmetry, is statistically limited
- An improvement in $W+$ b-jets and $Z+$ b-jets differential measurements could be a probing test for MC description
  - furthermore, potentially these final states can probe b PDF for the 5 flavour scheme

Outlook

Next LHC run

- LHC run II @ 13-14 TeV
- Will need new round of MC tuning with measurements, for $W+$ jets and $Z+$ jets possible with early data
- One of the challenge (especially for W) will be in the definition of a suitable trigger menu $\rightarrow W + D$ could be difficult
- Top background will become even more relevant
- For heavy flavour tagging jet substructure will be studied more closely

Theoretical developments

- With recent development of automatised code for NLO calculations, we can expect many processes calculated with NLO accuracy (V+ n jets...)
- Heavy flavour tagging will soon need more solid theoretical ground (IR, collinear safe definition of jet flavour, dependence on fragmentation/hadronization, ...)