QCD with Jets and Heavy Flavor in pp and PbPb Collisions in ATLAS

QCD@Work

Wednesday June 29, 2016

Robert Keyes

On behalf of the

ATLAS Collaboration

Outline

Standard Model

- Inclusive W & Z at 13TeV
- Inclusive Z P_T at 8TeV
- Inclusive Photons at 8TeV

B-Physics

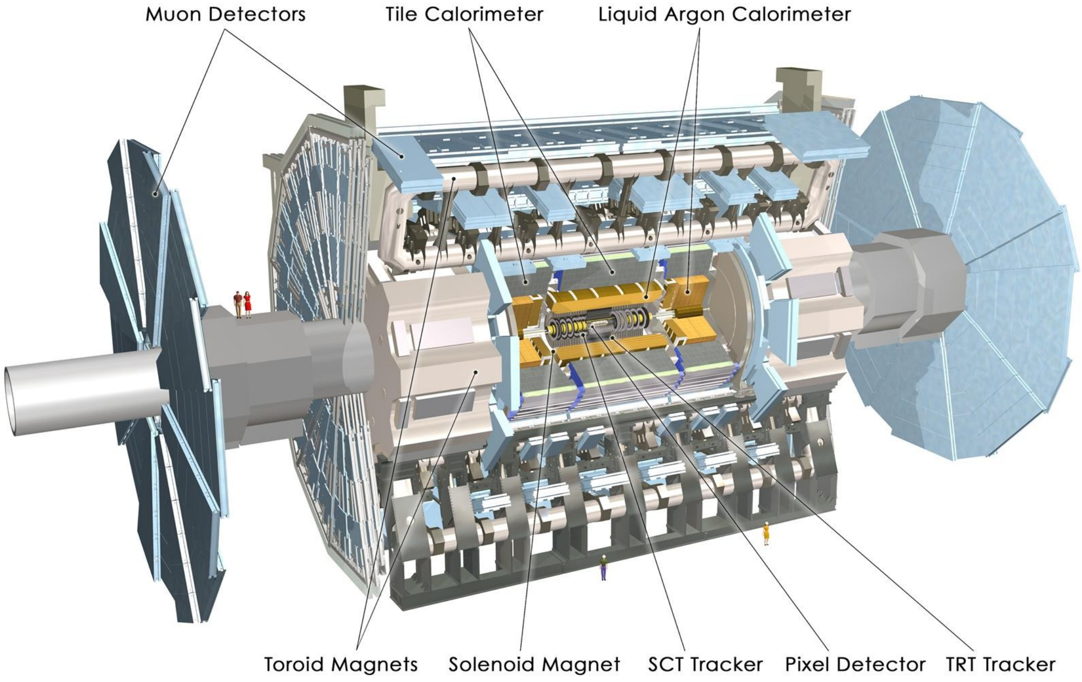
- J/ψ and ψ(2s) at 7&8TeV
- Prompt/Non-prompt J/ψ at 13TeV
- Open Charm Production at 7TeV

Heavy Ions

- Internal Jet Structure in Pb-Pb
- Dijet P_T Correlations in Pb-Pb
- Heavy Flavor Muons in Pb-Pb

QCD@ATLAS

- Multipurpose detector
- A broad physics program
- Many interesting QCD results



This talk covers a small selection, check out the ATLAS Heavy Ion, Standard Model and B-Physics public results pages for more results

Inclusive W & Z at 13TeV

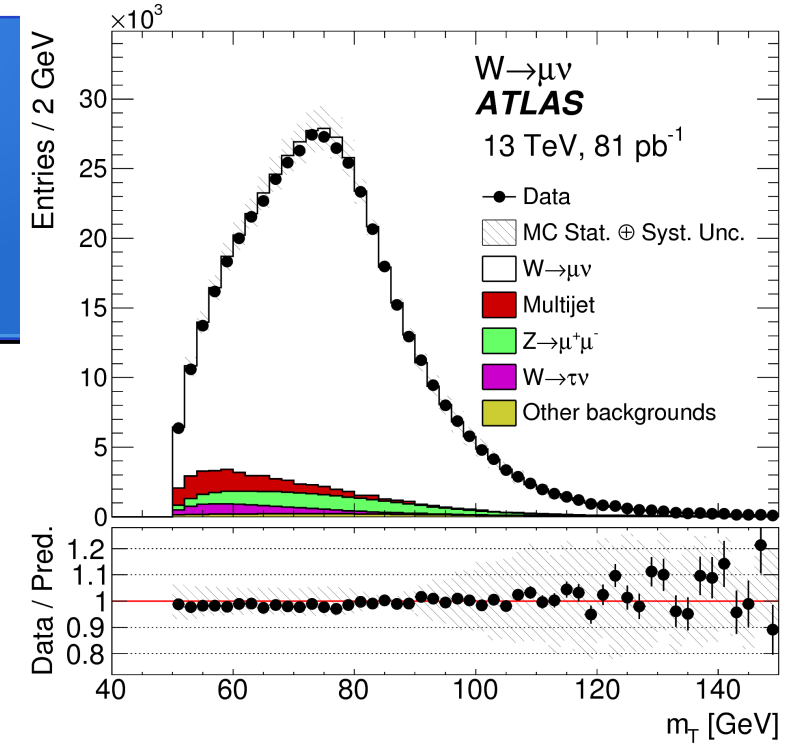
arXiv:1603.09222 (submitted to PLB)

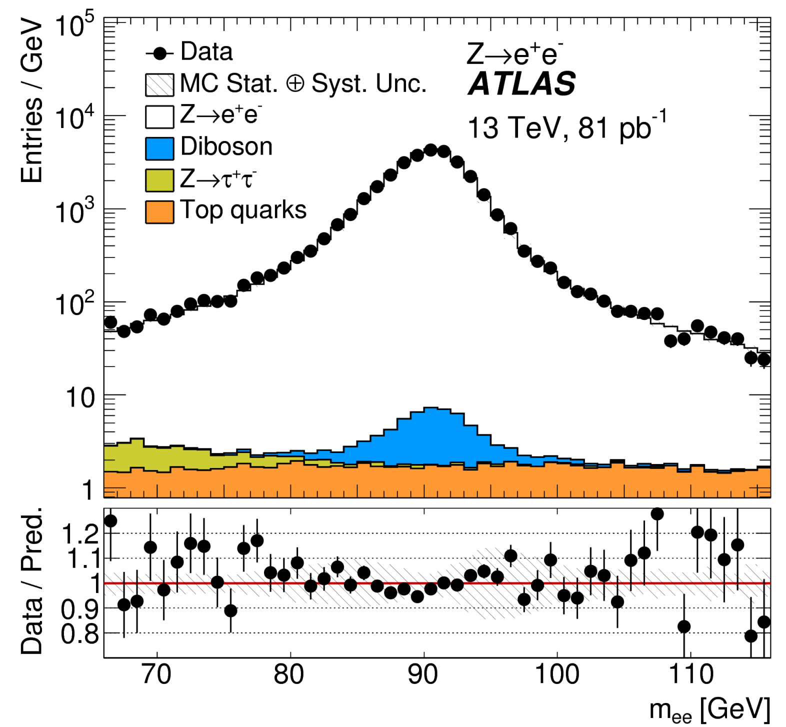
Why

- Benchmark for QCD and EW processes
- Sensitive to the PDF
- Run 2 x-section enhanced by factor of 2

How

- Considers leptonic decays
  - Single lepton+MET for W
  - Dilepton events falling in Z mass window
- Backgrounds
  - W: Multijet, Z → ee, W → τν
  - Z: Diboson (WW), Z → ττ, Top

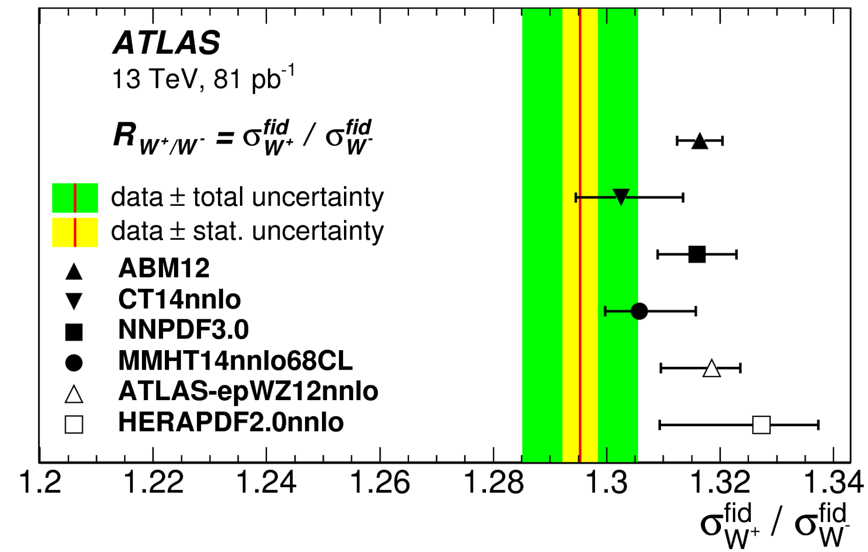


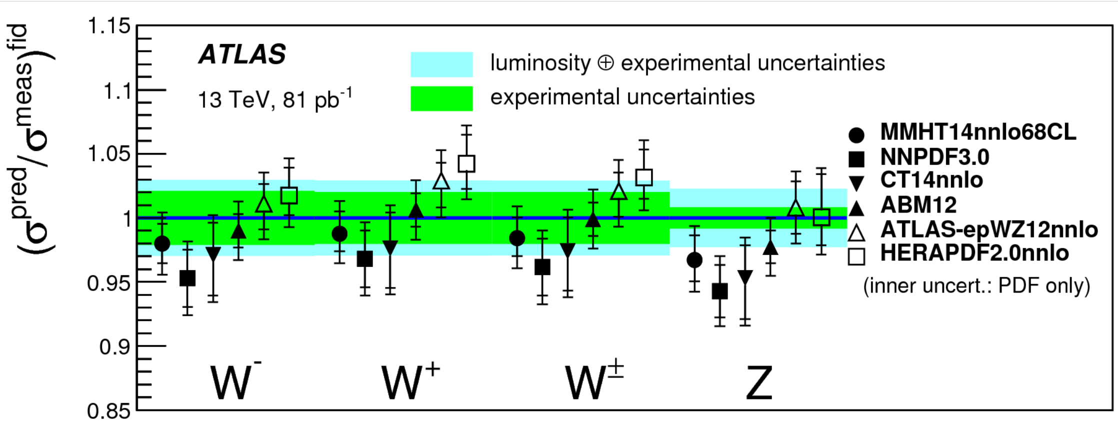


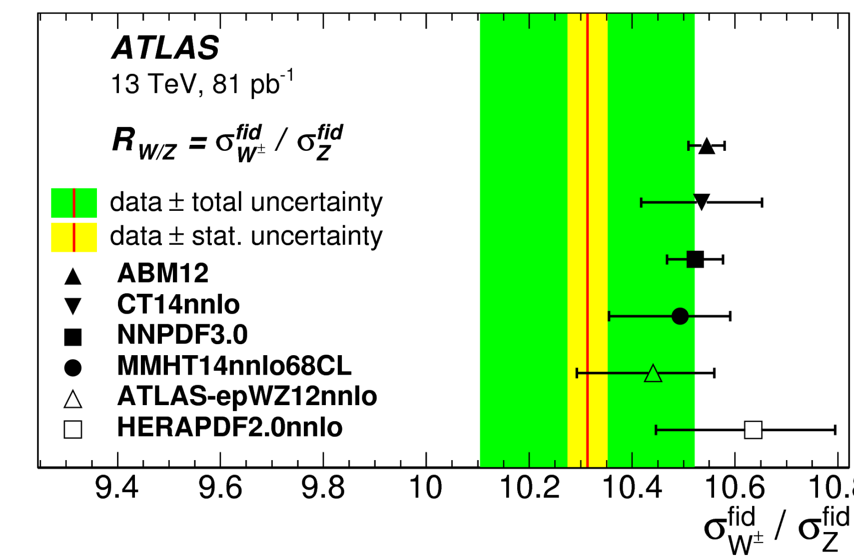
Inclusive W & Z at 13TeV

Result

- Agreement with NNLO QCD and NLO EW corrections
- e and μ channels measured separately and found to be consistent
- Updated lumi uncertainty of 2.1%
- W+/W- ratio has 0.8% uncertainty, displaying tension in PDF predictions







Inclusive Z P_T at 8TeV

Eur. Phys. J. C 76(5), 1-61 (2016)

Why

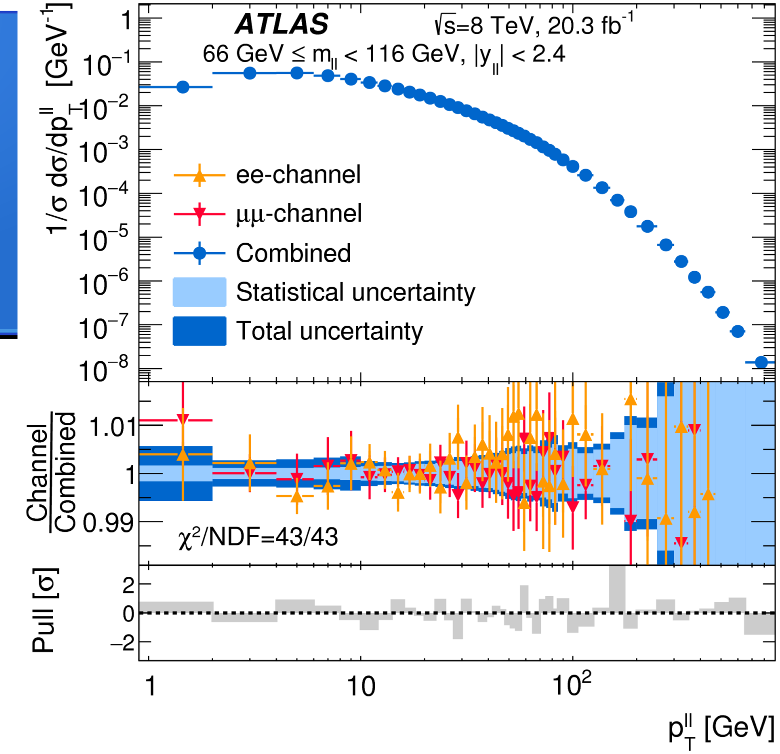
- Comprehensive test of QCD at all levels
  - Low P_T: soft-gluon resummation
  - High P_T: fixed-order pQCD+PS and EWK corrections
  - Ingredient for W-boson mass
- W and Z bosons constitute significant background in many analysis
  - Data driven Z P_T corrections implemented in many analyses

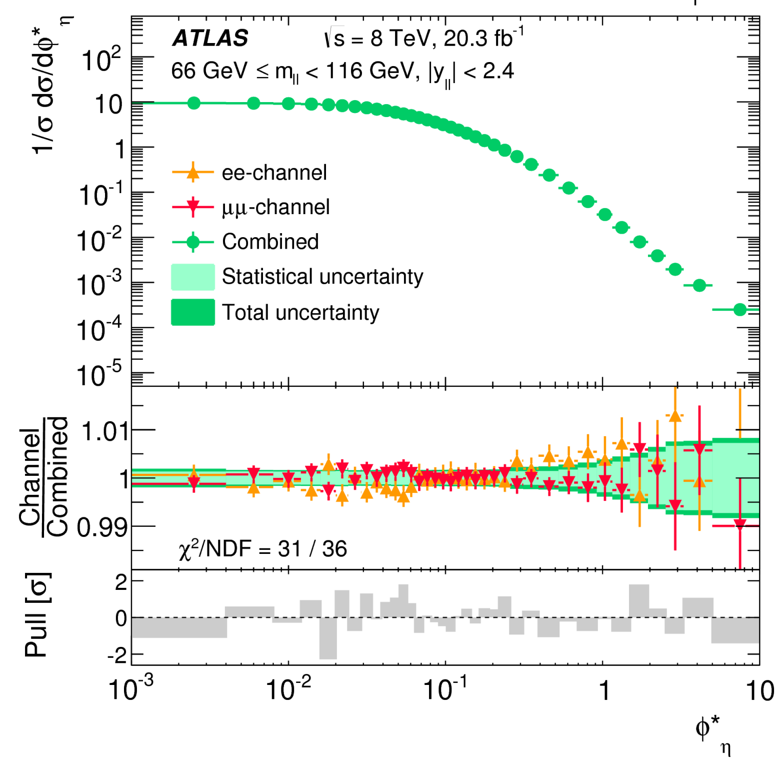
How

- Dilepton final state precisely measures P_T
  - No neutrino
  - Low background
- Angular φ^* reduces P_T resolution uncertainty
  - Especially at low P_T

$$\varphi^*_\eta = \tan\left(\frac{\pi - \Delta\varphi}{2}\right) \cdot \sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

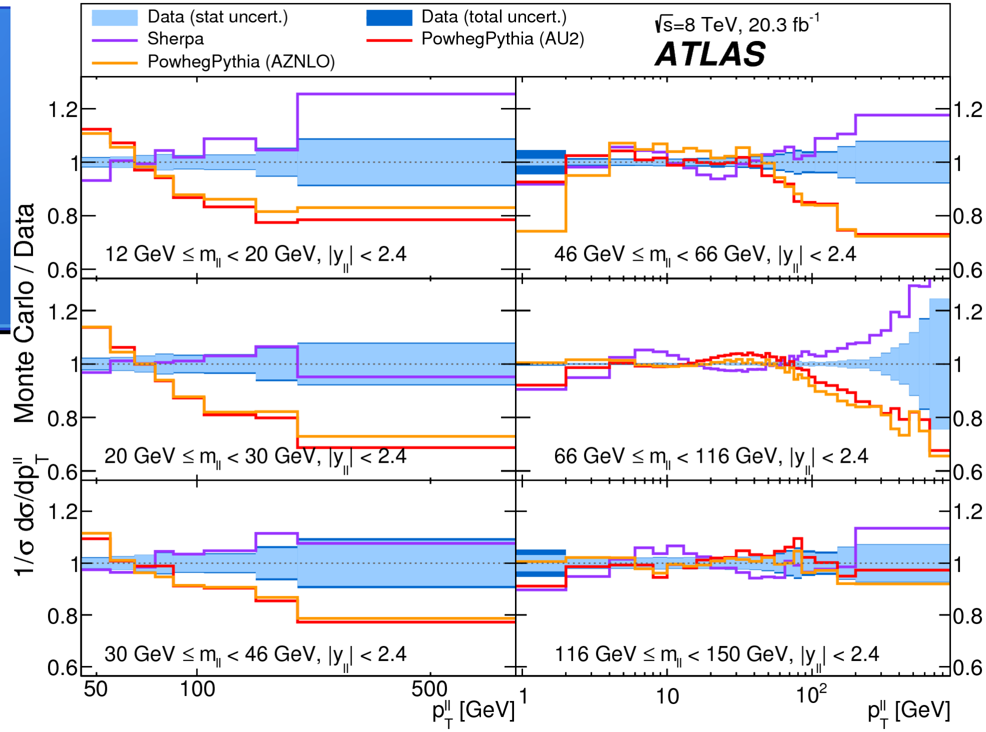


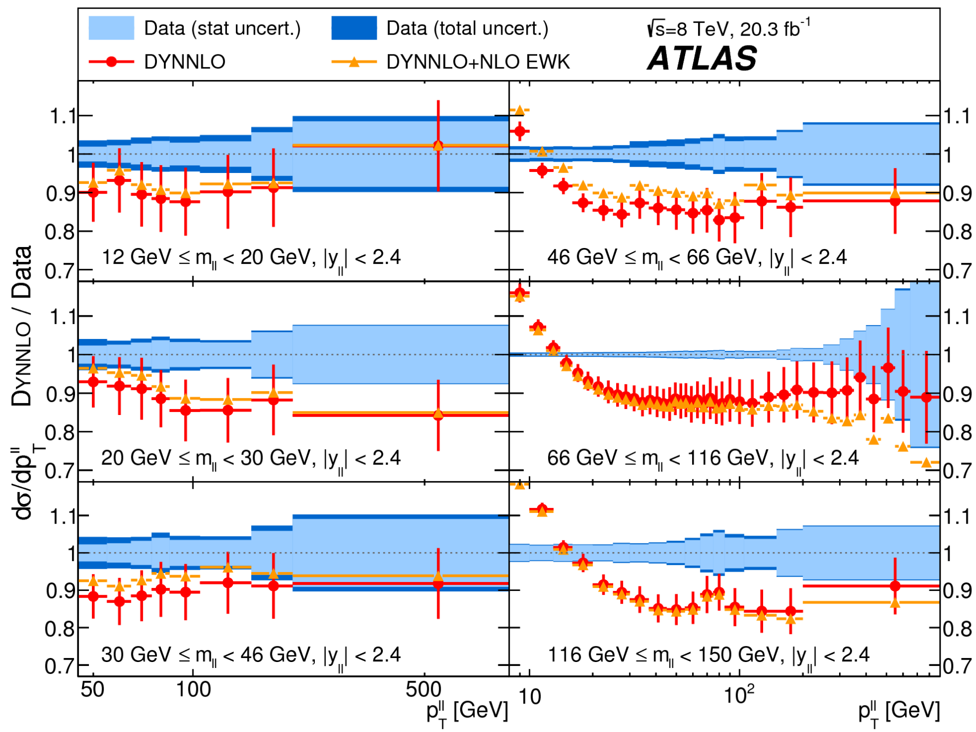


Inclusive Z P_T MC Comparisons

Result

- Comparisons to:
  - **MC Generator** predictions (PYTHIA, SHERPA)
    - Poor description of high P_T tail
  - **DYNNLO**
    - Better description of high P_T tail
    - Constant offset
    - EW corrections were quantified
  - ResBos
    - Low P_T and phi regions well described
    - Different kinematic regions demonstrate different φ* distribution, this is well described





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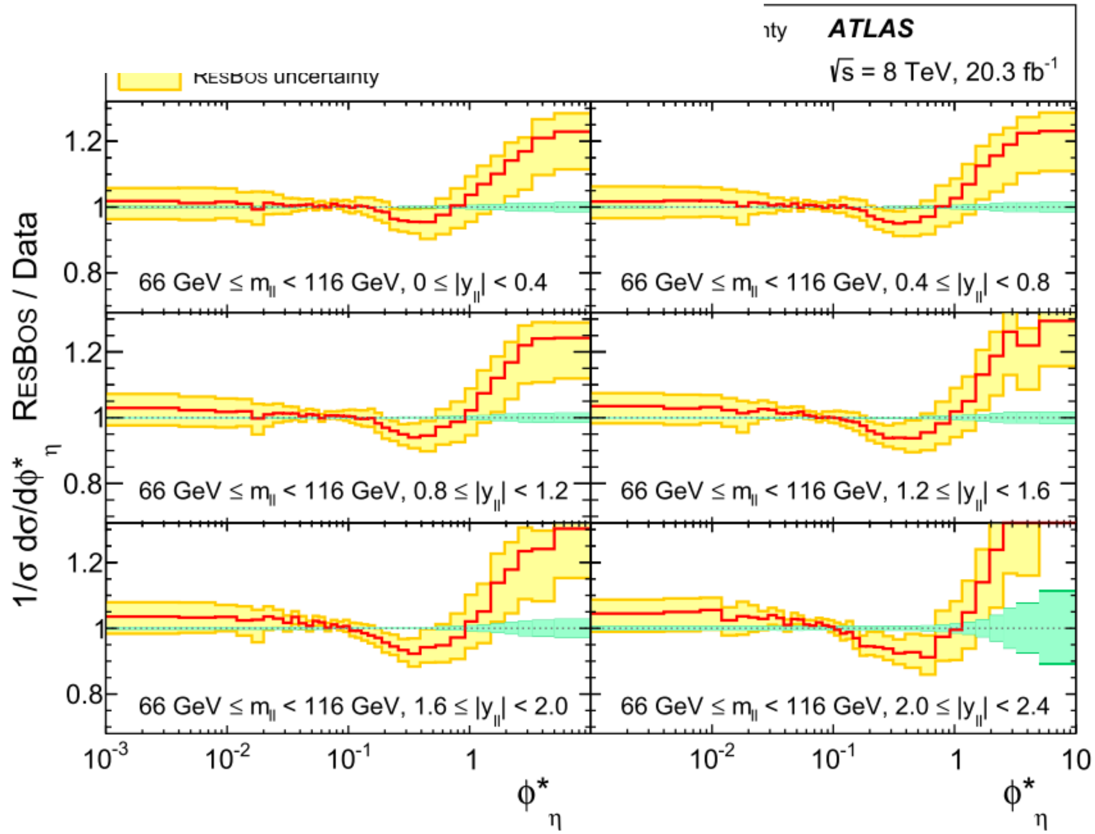
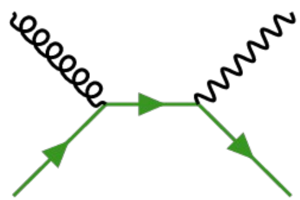


Inclusive Photons at 8TeV

arXiv:1605.03495

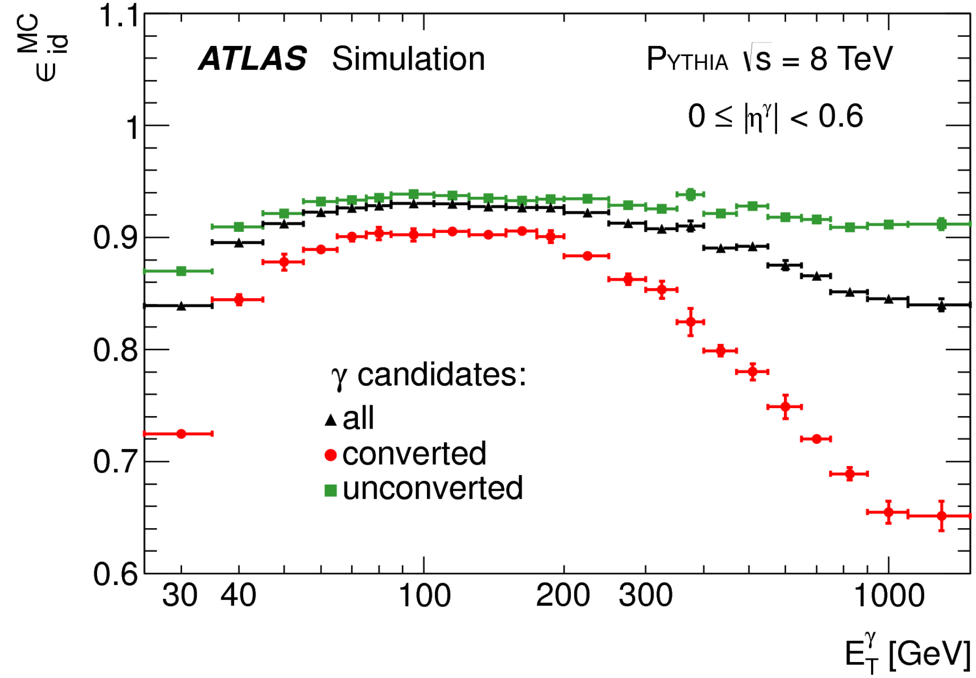
Why

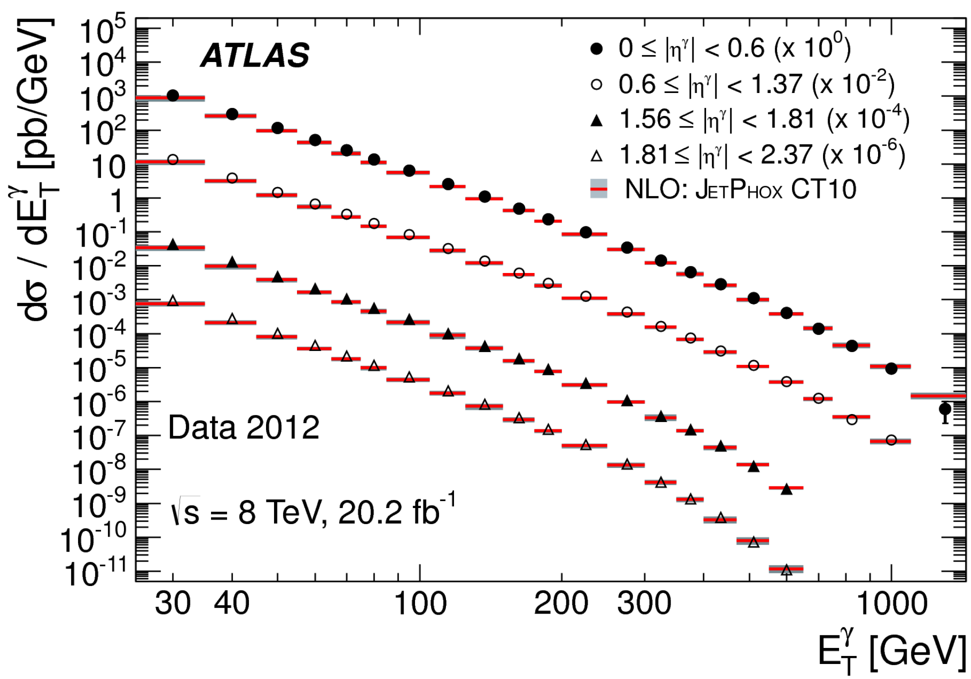
- Clean probe of hard parton level dynamics
- Probe of gluon PDF



How

- EM shower shape and depth used to identify photon candidates
- Tracker used to veto electrons and reconstruct converted photon vertices ($|\eta| < 2.37$)
- Isolated calorimetric signals
  - Discriminates "fragmentation" photons
- Theory predictions
  - JetPhox (NLO)
  - PeTeR (NLO+NNNLL ~ NNLO)

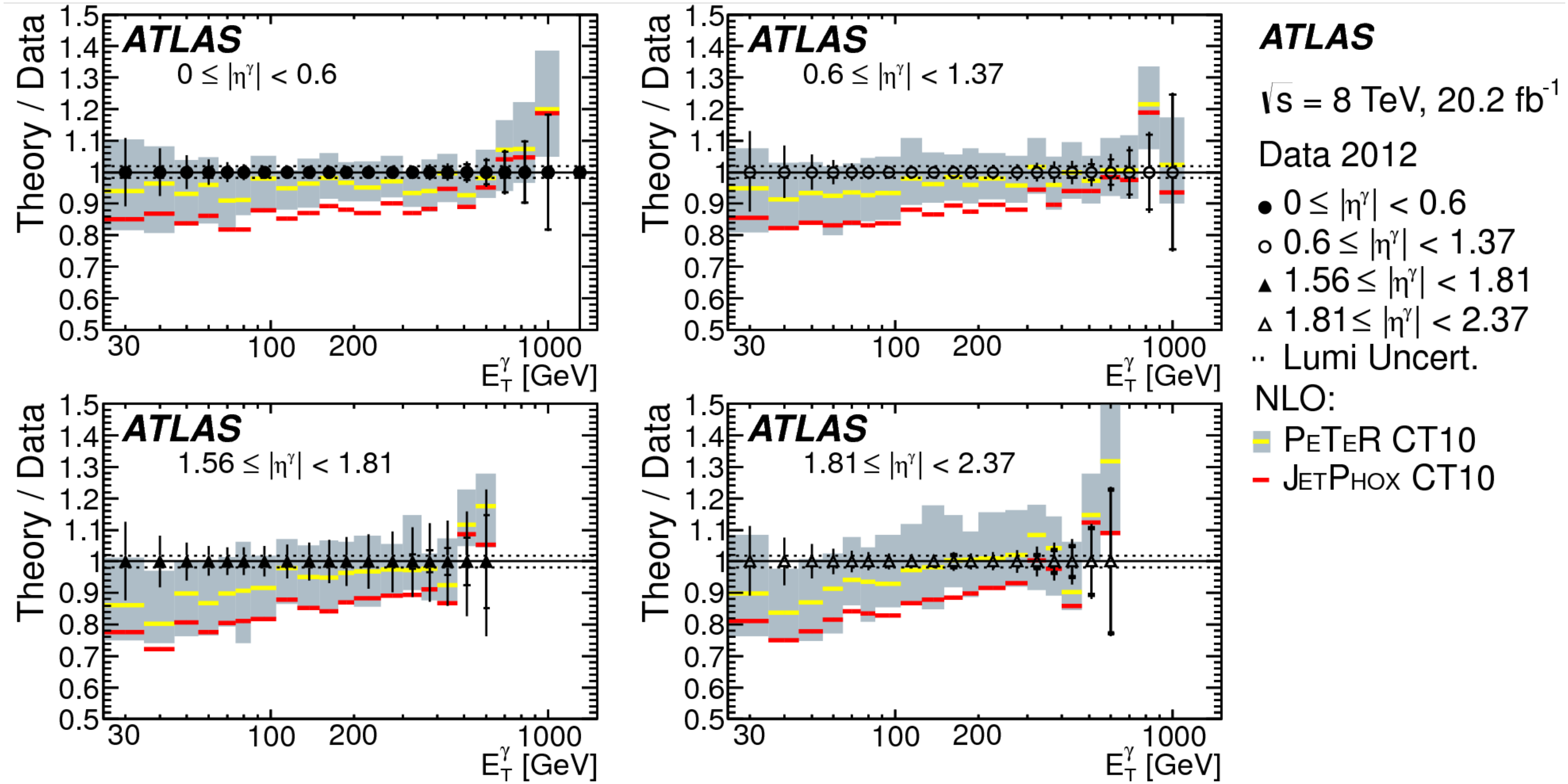




Inclusive Photons at 8TeV

Result

- Significant improvement of experimental uncertainties
- Good shape agreement with NLO (JetPHOX)
- NLO+NNNLL (PeTeR) agrees in both shape and normalization
- Low Et fragmentation most challenging
- Provides constraint on global PDF fit



J/ψ and ψ(2s) at 7&8TeV

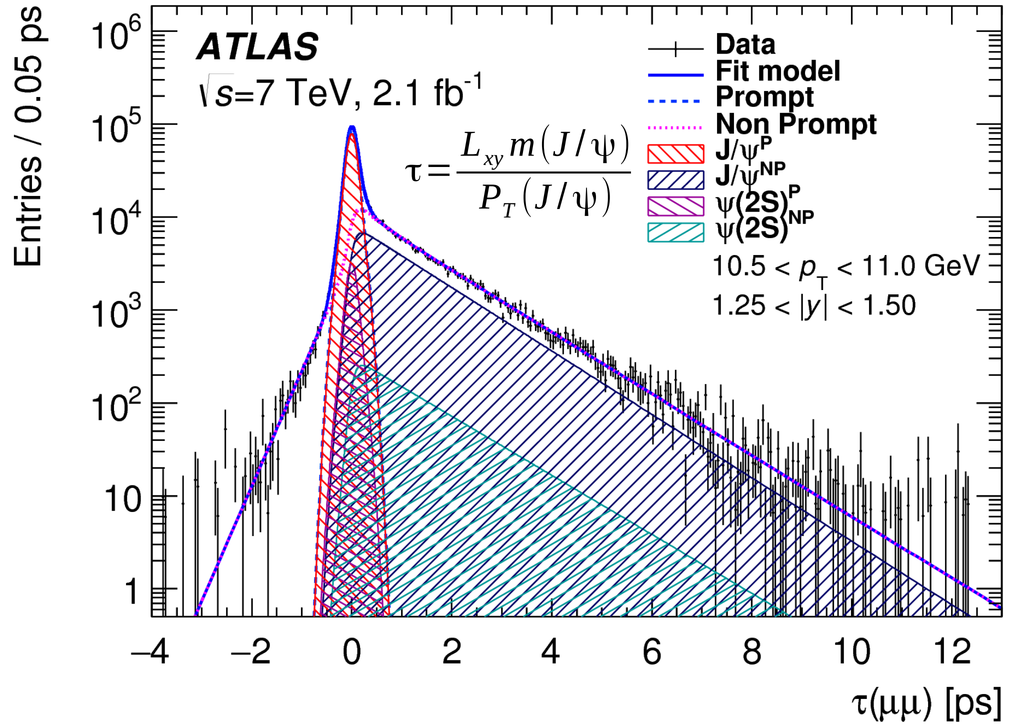
Eur.Phys.J. C76 (2016) 5, 283

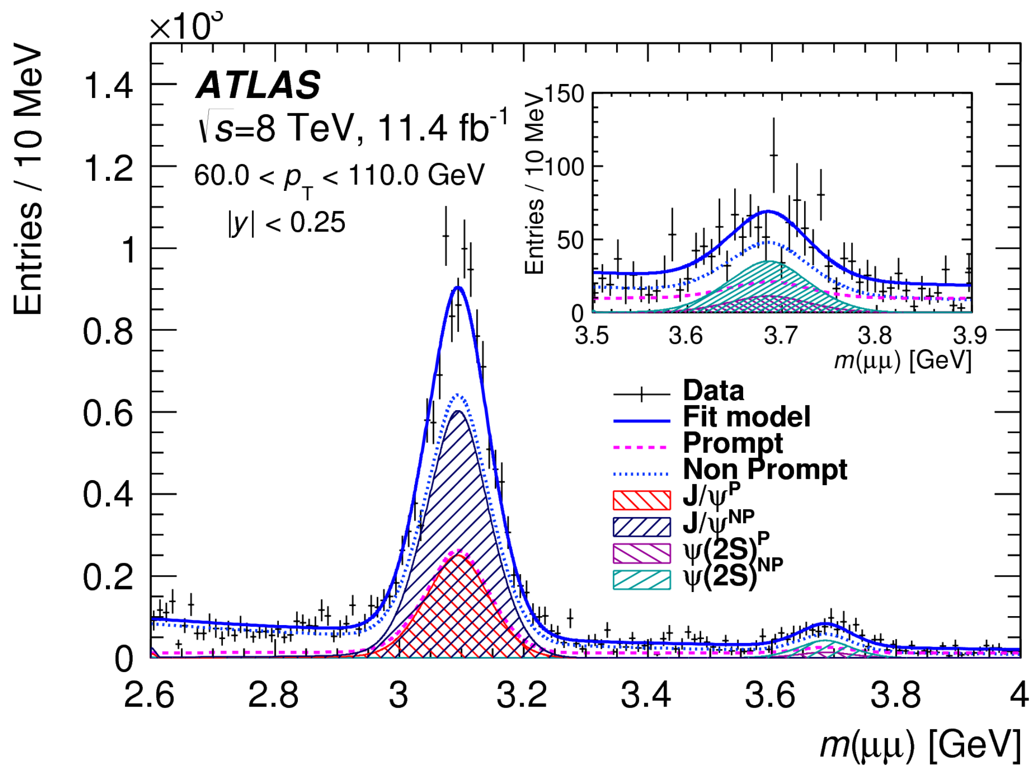
Why

- QCD bound states (quarkonia) probe the perturbative non-perturbative boundary
- Produced via:
  - **Prompt:** Direct production in hard scatter or decays from higher quarkonium states (Perturbative)
  - **Non-prompt:** Production in B-hadron decay (Perturbative → Non-Perturbative)
- ψ(2S) is the only vector charmonium state that is mostly direct

How

- Use di-muon decays
  - Clean reconstruction and efficient triggering
- Construct pseudo-proper time variable τ
- Perform 2D MLL fit to mass and τ
  - τ discriminates prompt from non-prompt
  - Mass discriminates signal from background



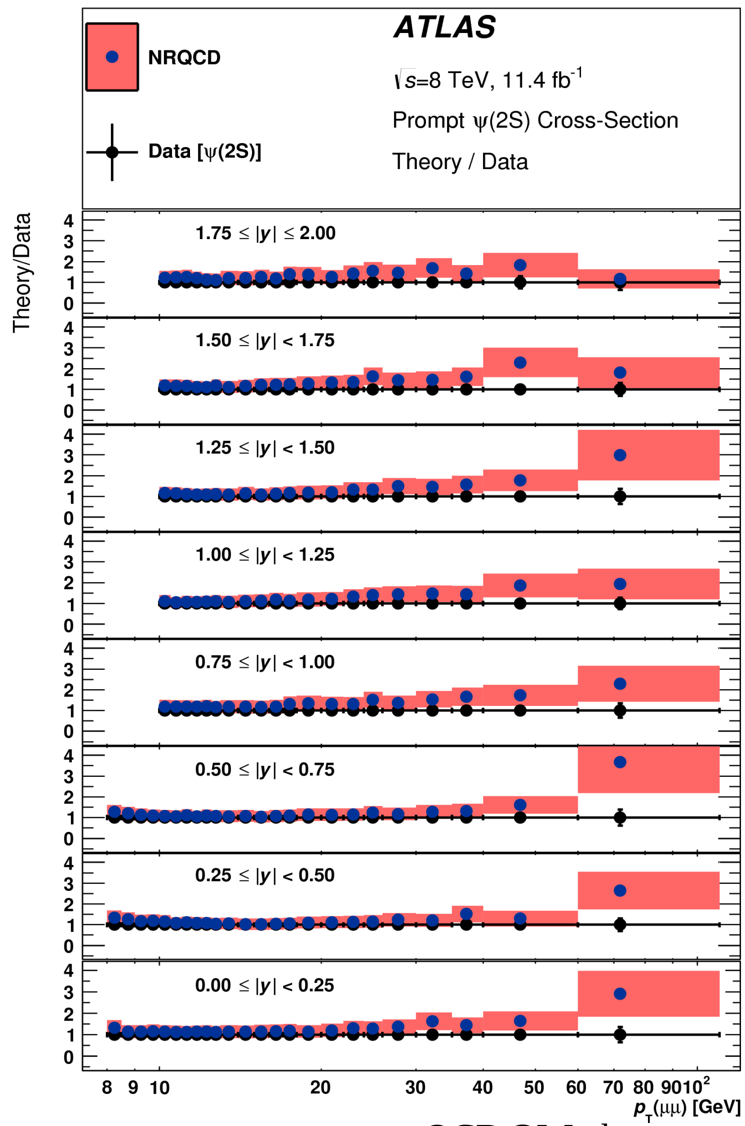


J/ψ and ψ(2s) at 7&8TeV

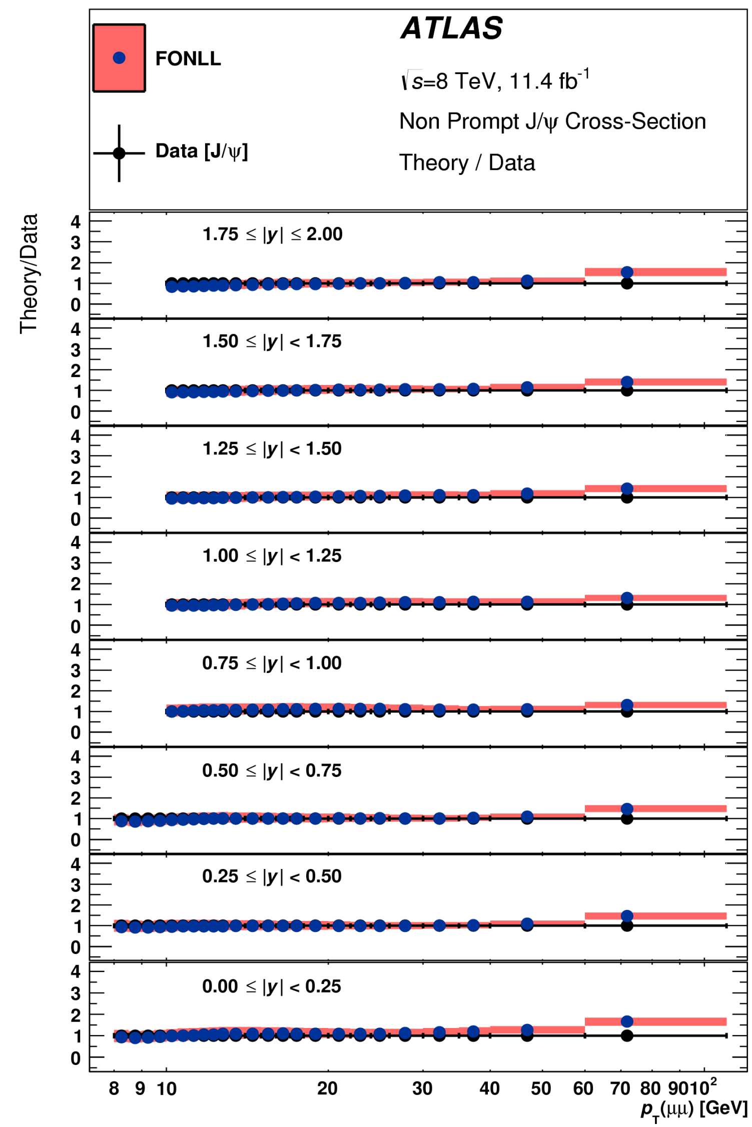
Result

- Agrees well with other experiments
- Prompt agrees with NLO NRQCD calculation
- Non-prompt comparison to FONLL:
  - J/ψ spectra slightly softer than calculation
  - ψ(2s) yields lower than calculation, however good shape agreement

Prompt ψ(2s)



Non-Prompt J/ψ



Prompt/Non-Prompt Ratio J/ψ at 13TeV

Eur.Phys.J. C76 (2016) 5, 283

Why

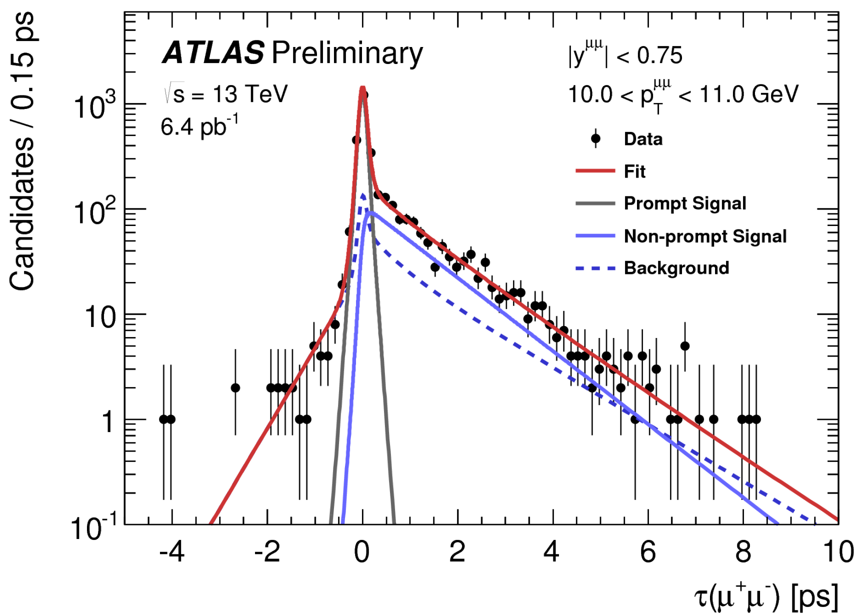
- IBL upgraded for Run 2
  - Enhanced heavy flavor capabilities
- First result, more to come
  - Ratio is less sensitive to efficiencies and luminosity

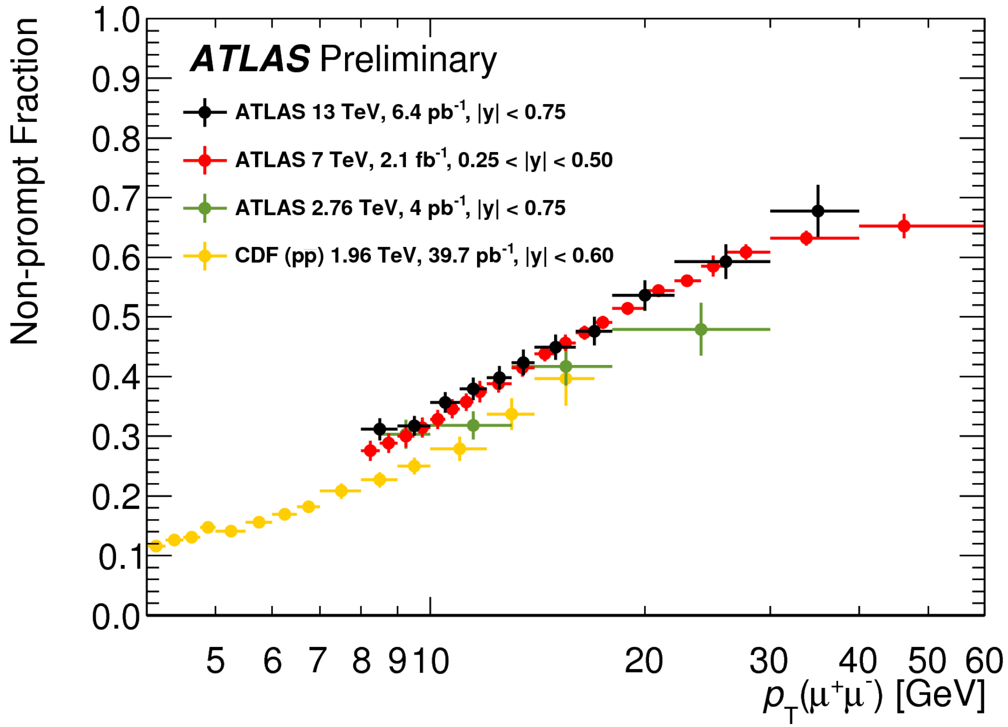
How

- Similar methodology to Run 1 J/ψ measurements

Result

- Consistent results and no variations in different pseudo-rapidity regions
- Promising first look at Run 2





Open Charm Production at 7TeV

	LEP data
$f(c \to D^{*+})$	$0.236 \pm 0.006 \pm 0.003$
$f(c \to D^{+})$	$0.225 \pm 0.010 \pm 0.005$
$f(c \to D_s^{+})$	$0.092 \pm 0.008 \pm 0.005$
$f(b \to D^{*\pm})$	$0.221 \pm 0.009 \pm 0.003$
$f(b \to D^{\pm})$	$0.223 \pm 0.011 \pm 0.005$
$f(b \to D_s^{\pm})$	$0.138 \pm 0.009 \pm 0.006$

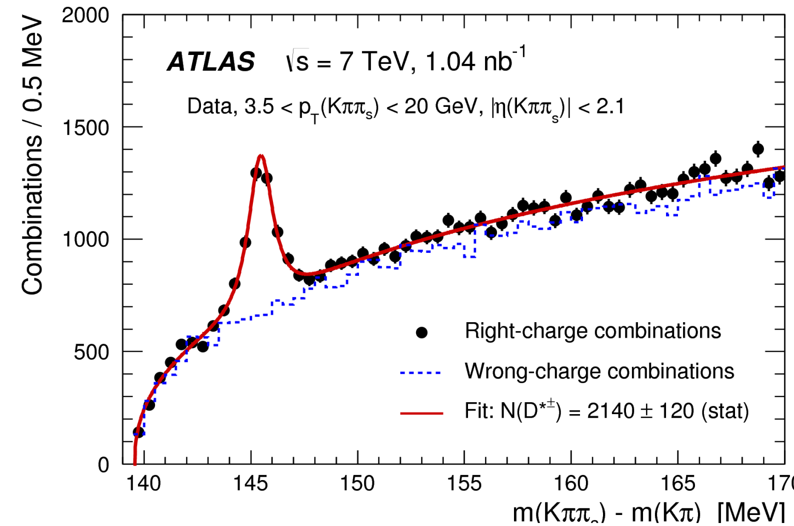
Nucl.Phys. B907 (2016) 717

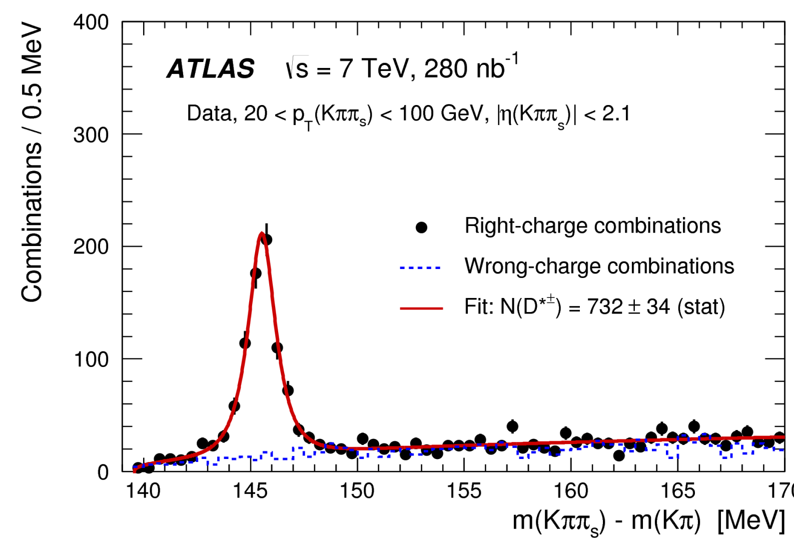
Why

- D mesons arise in c and b fragmentation
  - Test pQCD calculations for HF production
  - Calculations at NLO+NLL
- Verify proton structure functions and m_q
- HF constraints are important for electroweak Higgs sector and other searches
- Open flavor in ATLAS:
  - Large cross section
  - Clean signatures making use of precise tracking and vertexing

How

- Minimum bias triggers for low pT, jet triggers for high pT
  - 3.5 < pT < 20 GeV and 20 GeV < pT < 100 GeV
- $D^{*\pm}$, $D^{\pm}$ and $D^{\pm}_s$ mesons
  - Reconstruct KKπ and Kππ final states

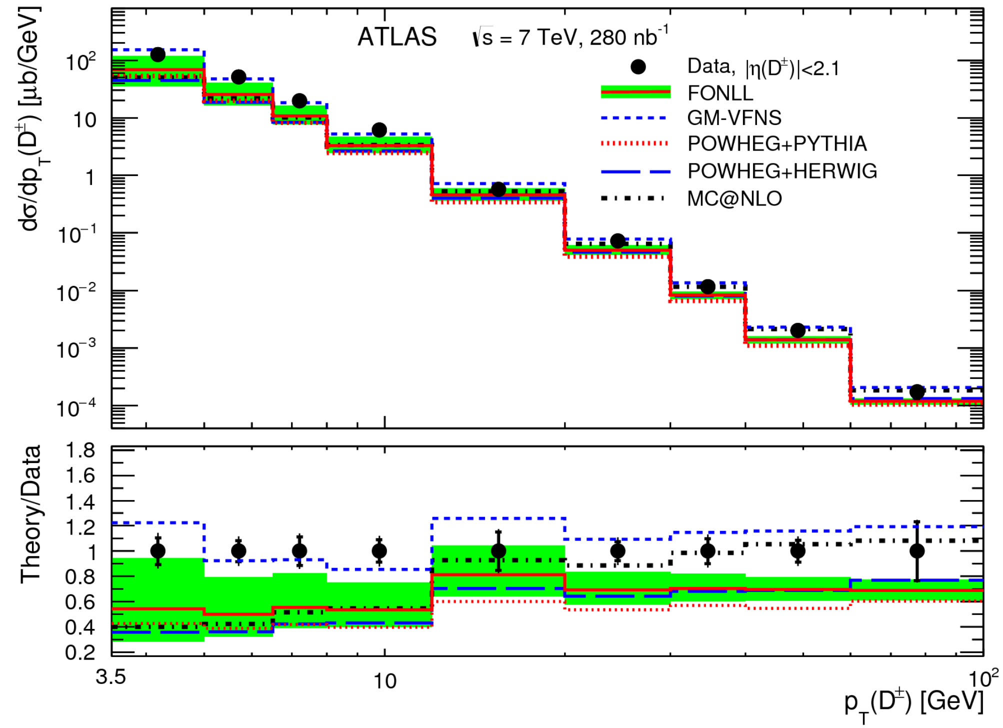


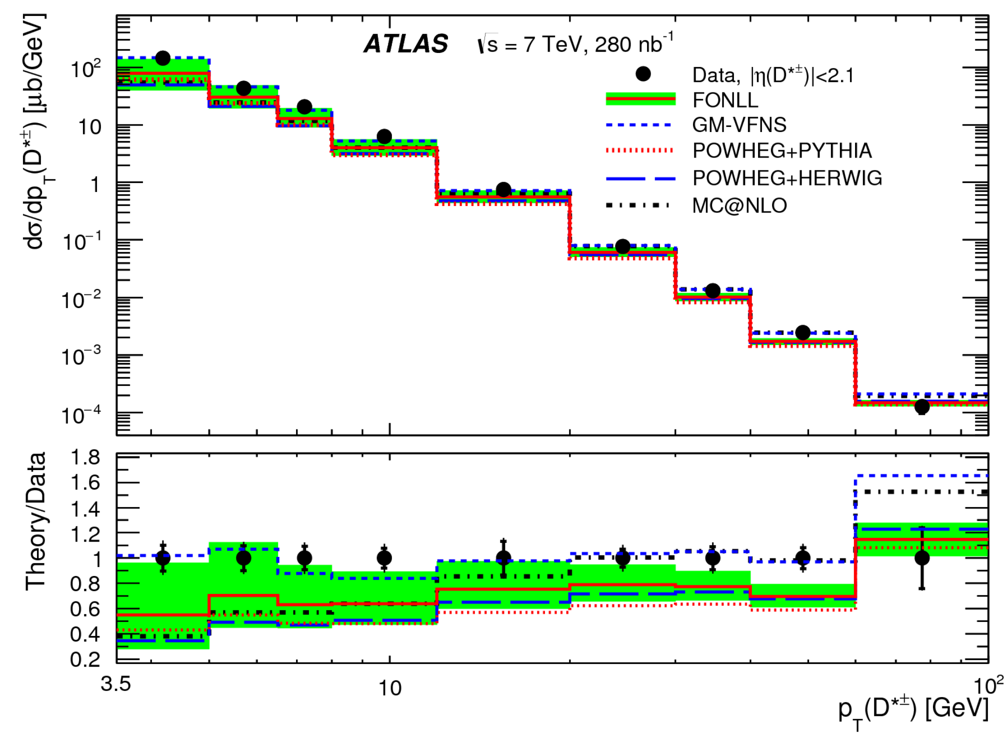


Open Charm Prod. at 7TeV

Results

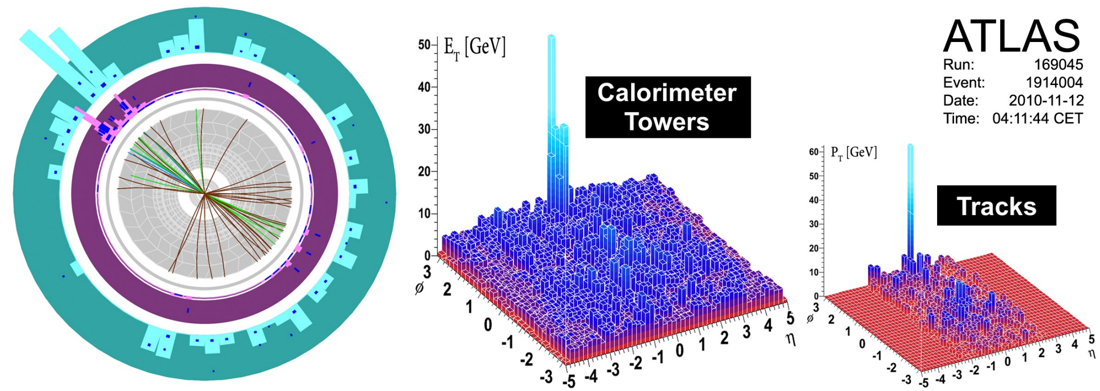
- Compared to various QCD predictions
  - Generally below the data
  - MC@NLO shows deviations in shape while FONLL and POWHEG look better
- Total Cross section consistent with ALICE
  - JHEP 07 (2012) 191
- Strangeness suppression factor and charged non-strange vector D-meson fraction consistent with ALICE and LEP
  - Phys. Lett. B 718 (2012) 279
  - Eur. Phys. J. C 38 (2005) 447
  - Eur. Phys. J. C 44 (2005) 351
  - JHEP 07 (2007) 074
  - JHEP 09 (2013) 058

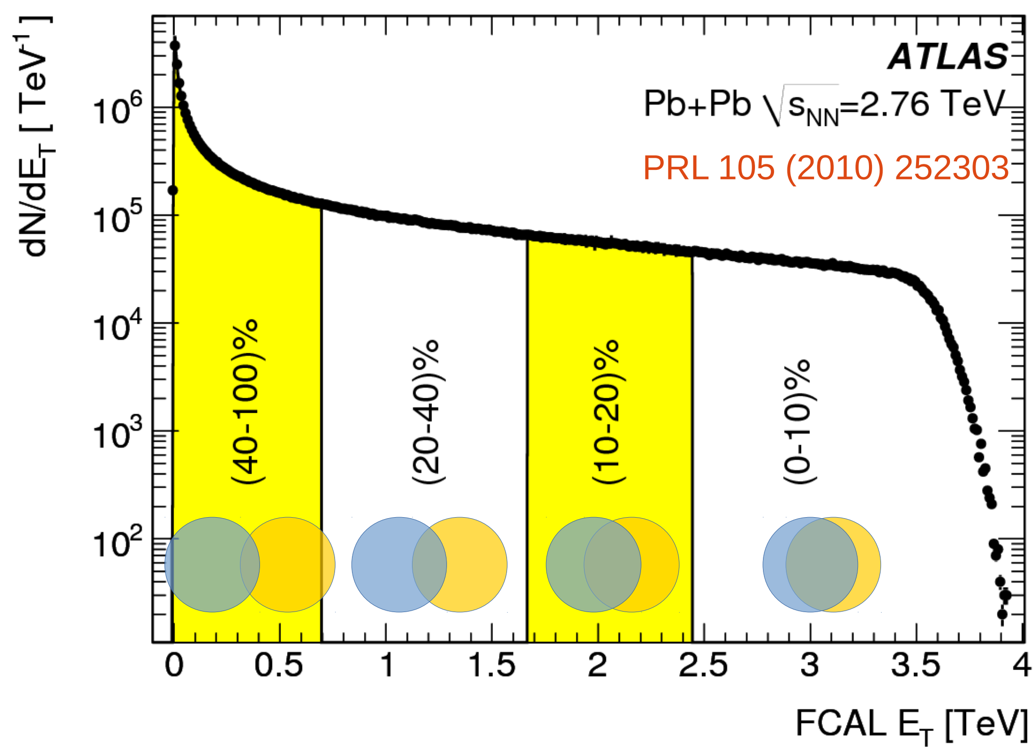




Heavy Ions in ATLAS

- Quark Gluon Plasma (QGP): Hot and dense medium of strong nuclear matter with deconfined color charges
- New testing ground for QCD
  - Jet quenching
- Results most often compared to pp results
- **Centrality**: Measure of the participating nucleons in a collision
  - Forward detectors (FCal) measure total E_T
  - More energy in the forward region means more participating nucleons
- Events collected using minimum bias+jet trigger
  - +Muons for heavy flavor





Dijet Asymmetry in PbPb at 2.76TeV

ATLAS-CONF-2015-052

Why

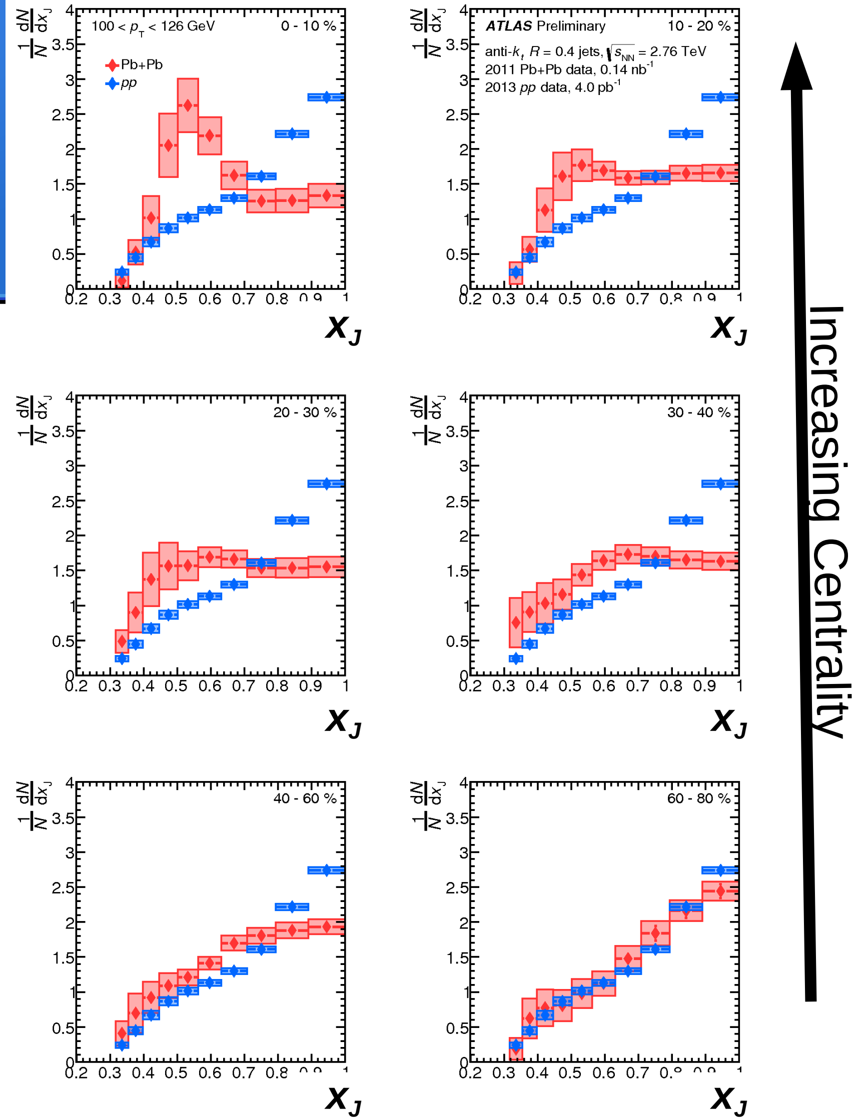
- Hard scatter high P_T jets let us probe the QGP
- Jet Quenching has been established but not well understood

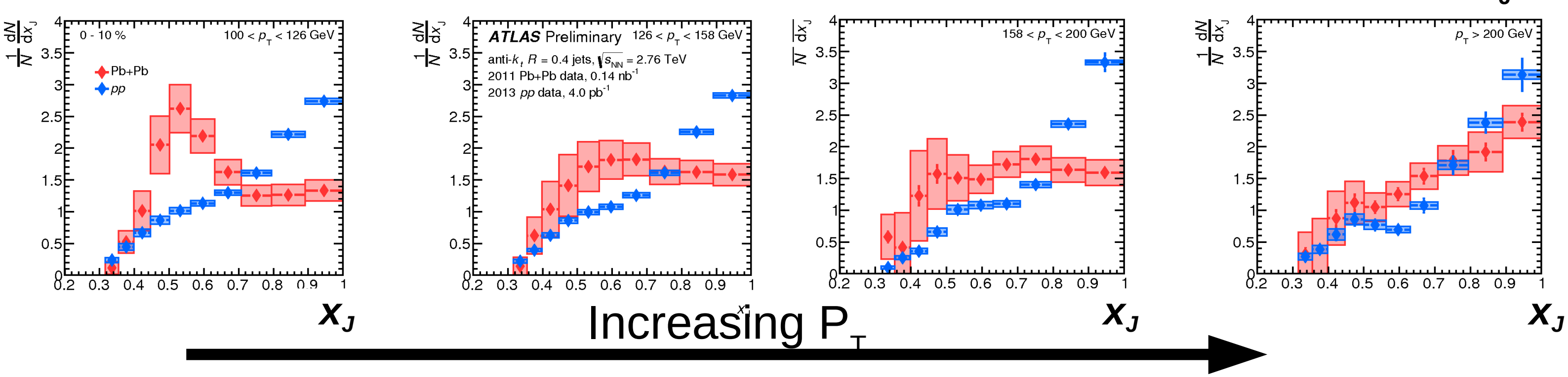
How

- 2D unfolding accounting for migrations of each jet
- P_T balance, $\boldsymbol{x_J = P_T^2/P_T^1}$, as a function of centrality and P_T^{Lead}

Result

- PbPb shows strong deviation from pp
  - Peaked at $x_J=0.5$ indicating strong imbalance
- Asymmetry grows with centrality and shrinks with P_T
- Important benchmark





Internal Jet Structure in PbPb at 2.76TeV

ATLAS-CONF-2015-055

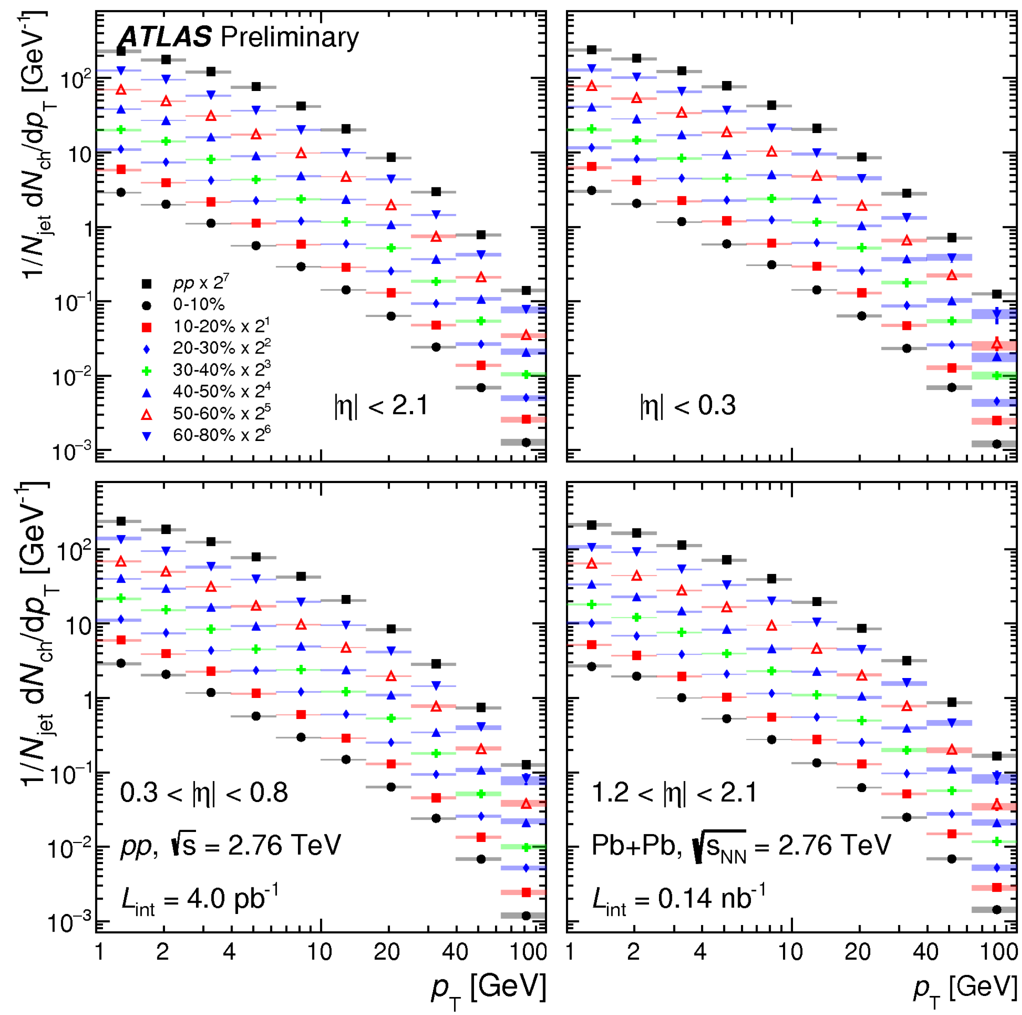
Why

- Better understand jet quenching by probing internal jet structure
- To help constrain jet quenching models and in-medium modifications of parton showers

How

- Jet fragments measured down to 1GeV
- Yields corrected for tracking efficiency
- Jet fragmentation functions as a function of:
  - Longitudinal momentum z
  - Transverse momentum P_T

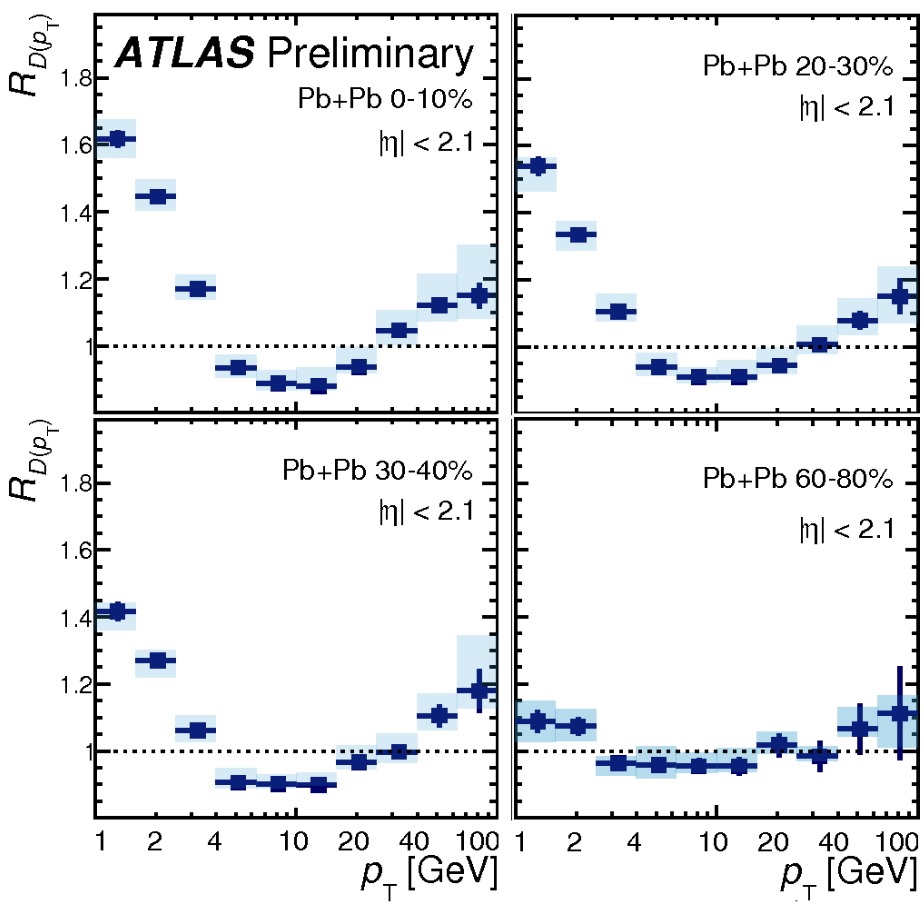
$$D(p_T) = \frac{1}{N_{jet}} \frac{dN_{ch}(p_T)}{dp_T}$$



Internal Jet Structure in PbPb at 2.76TeV

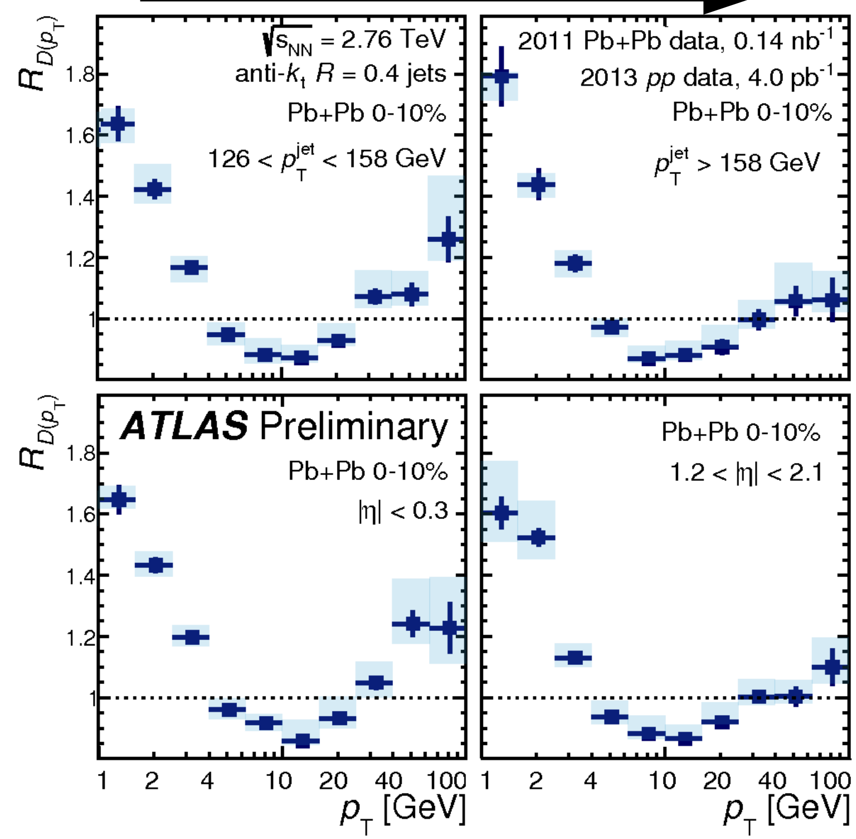
Resulting Fragmentation Yields

- Enhanced for $1 < p_T^{ch} < 4$ GeV and $p_T^{ch} > 25$ GeV
- Reduced for $4 < p_T^{ch} < 25$ GeV
- Effects diminish in peripheral collisions



- P_T^{Jet} dependence only observed as an enhancement suppression at high P_T^{ch} and z for large P_T^{Jet}
- η dependence only observed as an enhancement suppression at high P_T^{ch} and high z for large η

Increasing P_T^{Jet}



Increasing |η|

Heavy Flavor μ in PbPb at 2.76TeV

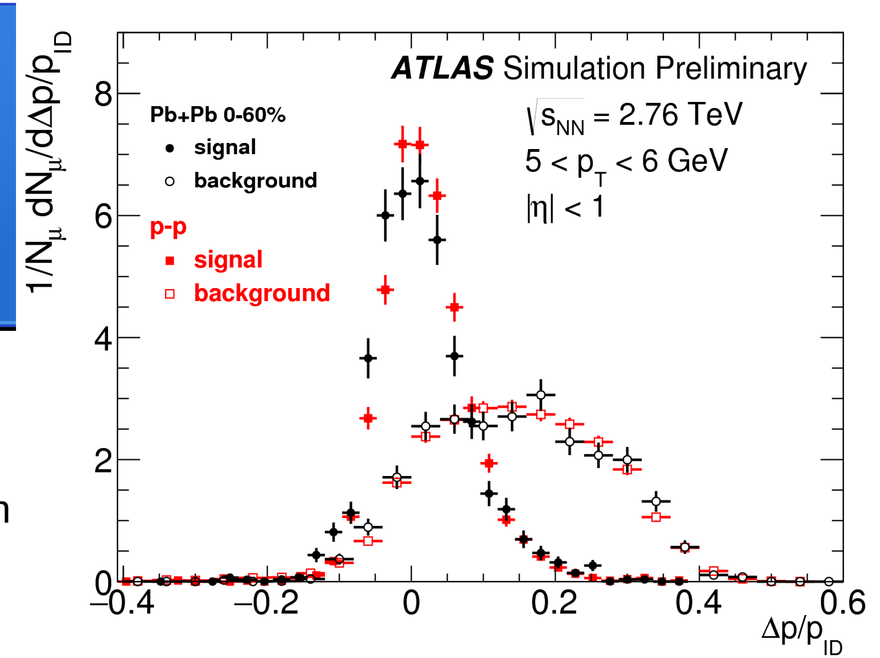
ATLAS-CONF-2015-053

Why

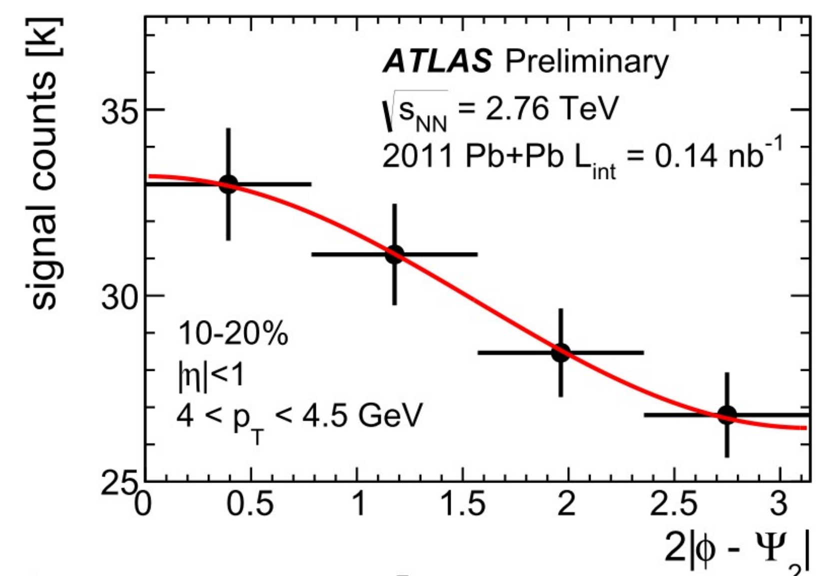
- HF created in the hard scatter and subsequently interact with the medium
  - Masses much larger than temperature
  - Early production that can be perturbatively calculated
- HF yields gives window into HF in-medium energy loss

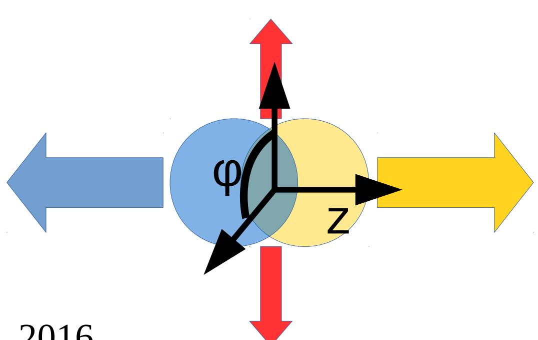
How

- Identify prompt muons (not from π/K decay)
  - Uses discriminating variable based on muon energy loss between inner detector and muon system $\Delta P/P_{ID}$
- Measure the Nuclear Modification Factor R_{AA} comparing yields to pp
- Measure the azimuthal anisotropy
  - 2^{nd} order Fourier coefficient in azimuthal shape captures elliptic flow



$$\frac{\Delta p}{p_{\rm ID}} = \frac{p_{\rm ID} - p_{\rm MS} - \Delta p_{\rm calo}(p, \eta, \phi)}{p_{\rm ID}}$$



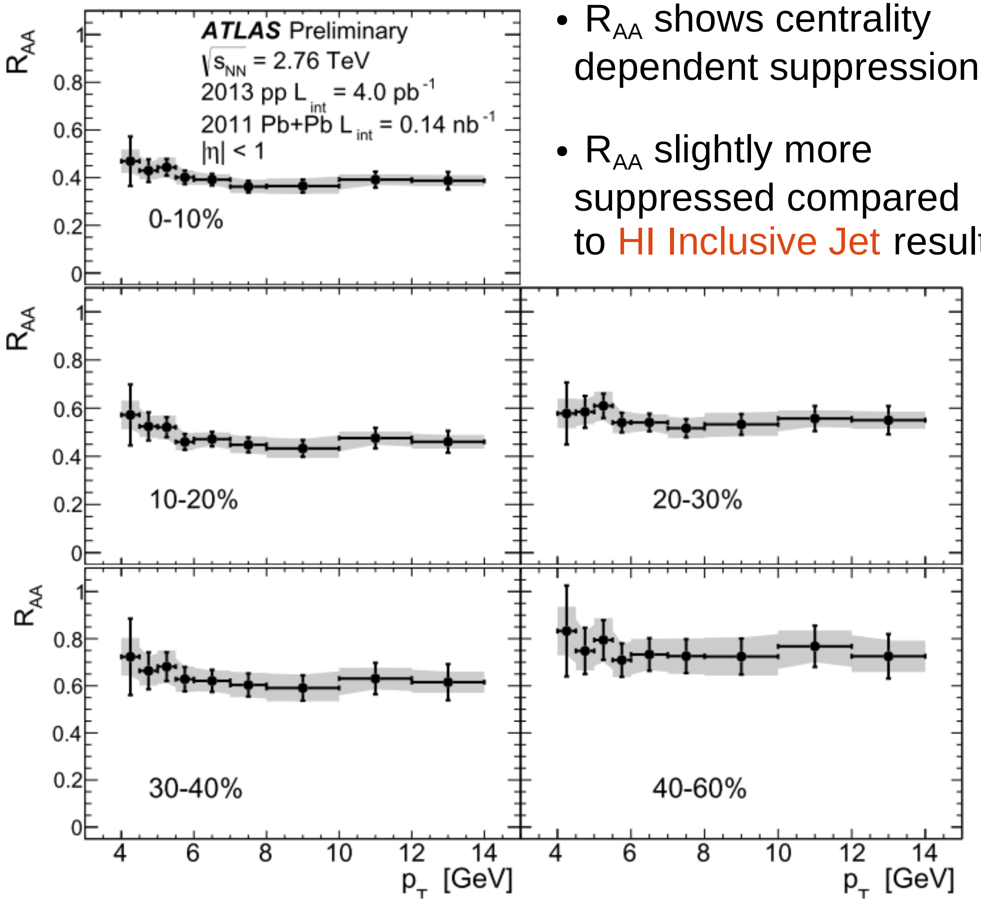


$$\frac{dN}{d\phi} = N_0\left[1 + 2v_2^{\rm obs}\cos(2(\phi - \Psi_2))\right]$$

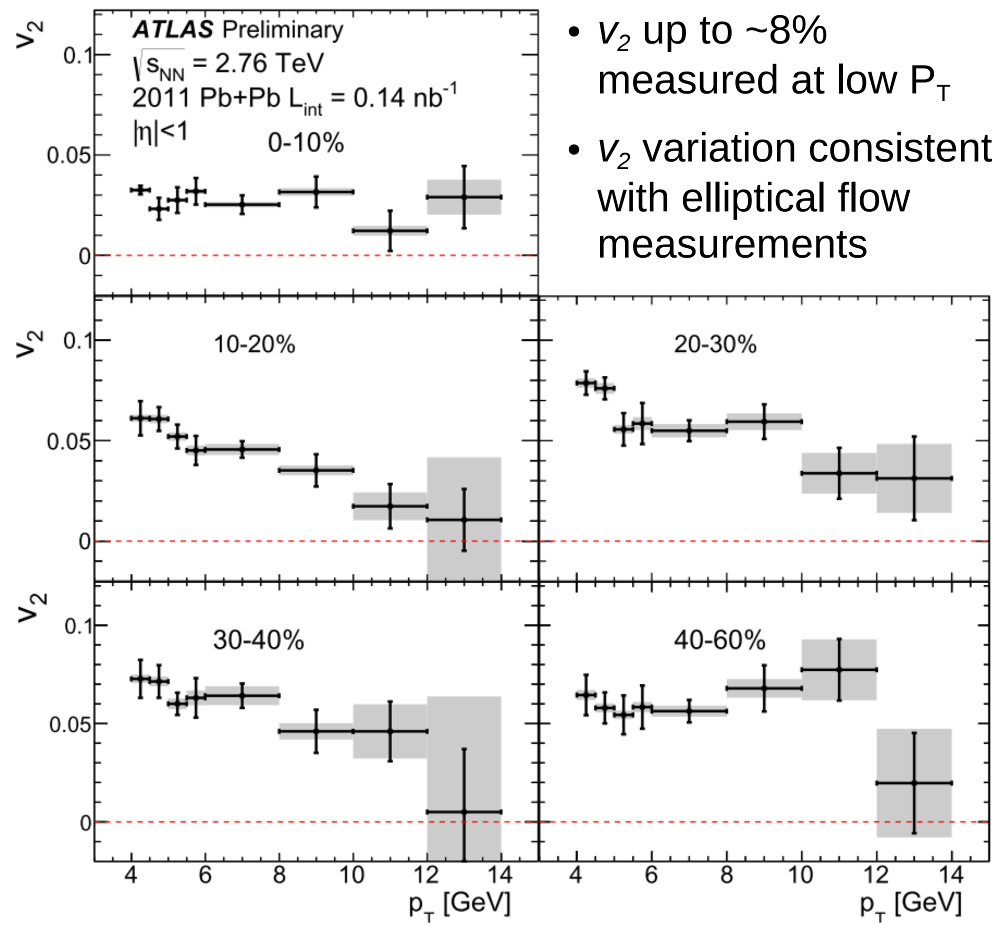
Heavy Flavor μ in PbPb at 2.76TeV

Results

- These findings are consistent with, and much more precise, than similar forward measurements performed by ALICE (2.5<y<4)



- R_{AA} shows centrality dependent suppression
- R_{AA} slightly more suppressed compared to HI Inclusive Jet result



- v_2 up to ~8% measured at low P_T
- v_2 variation consistent with elliptical flow measurements

Conclusions

- ATLAS has a diverse program studying QCD in the SM, heavy flavor and HI contexts
- This talk is a small snapshot
- ATLAS is performing well providing new and extended measurements as well as cross checks with other experiments and previous results
- Simulations have been improving, still some discrepancies so these and future studies are well motivated
- Stay tuned!

Thank you for your attention!

Backup

Inclusive W and Z at 8TeV

Uncertainties:

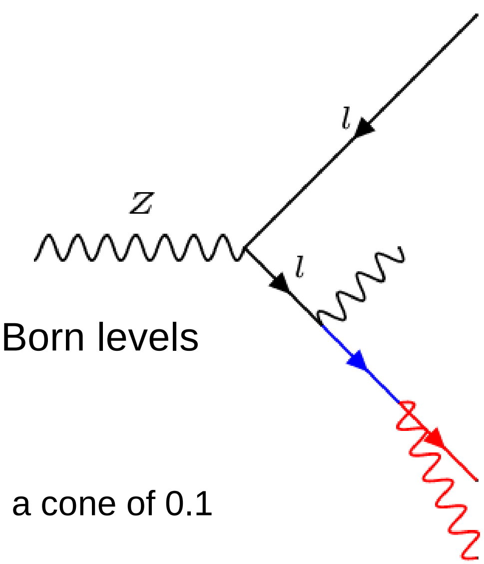
$\delta C/C$ [%]	$Z \to e^+e^-$	$W^+ \to e^+\nu$	$W^- \to e^-\bar{\nu}$	$Z \to \mu^+\mu^-$	$W^+ \to \mu^+\nu$	$W^- \to \mu^-\bar{\nu}$
Lepton trigger	0.1	0.3	0.3	0.2	0.6	0.6
Lepton reconstruction, identification	0.9	0.5	0.6	0.9	0.4	0.4
Lepton isolation	0.3	0.1	0.1	0.5	0.3	0.3
Lepton scale and resolution	0.2	0.4	0.4	0.1	0.1	0.1
Charge identification	0.1	0.1	0.1	–	–	–
JES and JER	–	1.7	1.7	–	1.6	1.7
$E_{\mathrm{T}}^{\mathrm{miss}}$	–	0.1	0.1	–	0.1	0.1
Pile-up modelling	< 0.1	0.4	0.3	< 0.1	0.2	0.2
PDF	0.1	0.1	0.1	< 0.1	0.1	0.1
Total	1.0	1.9	1.9	1.1	1.8	1.8

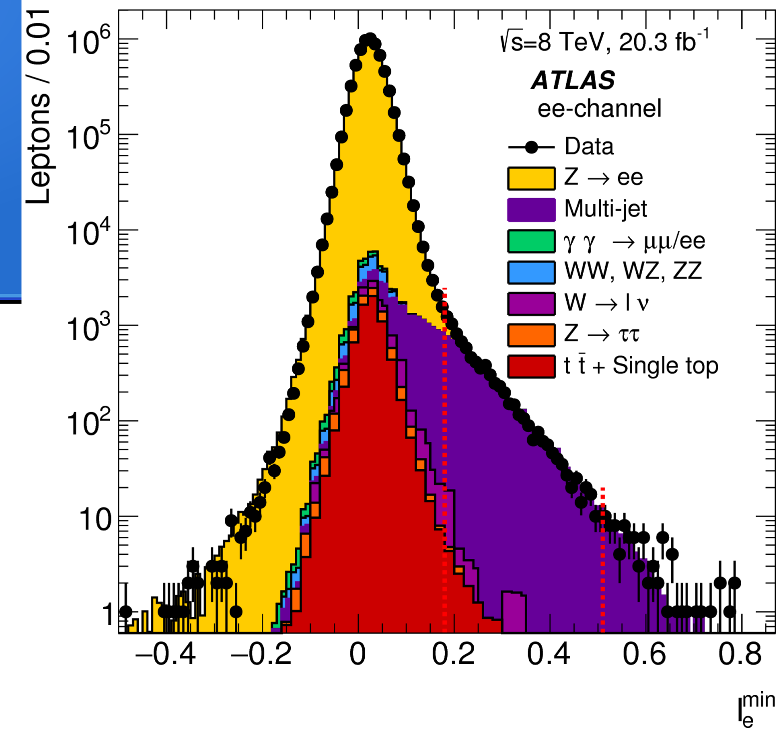
Table 1: Relative systematic uncertainties (%) in the correction factors C in the different channels.

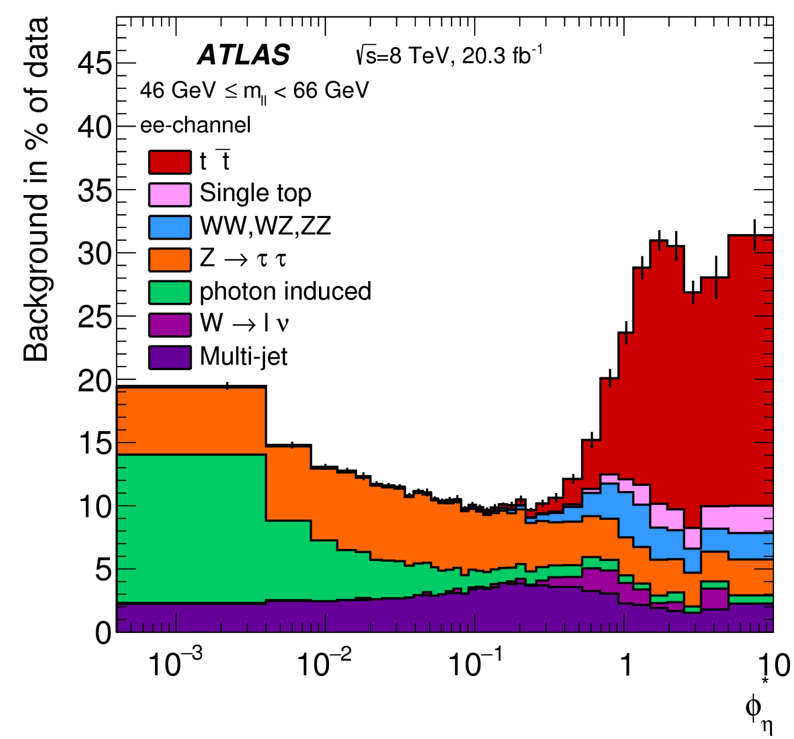
Inclusive Z P_T at 8TeV

How

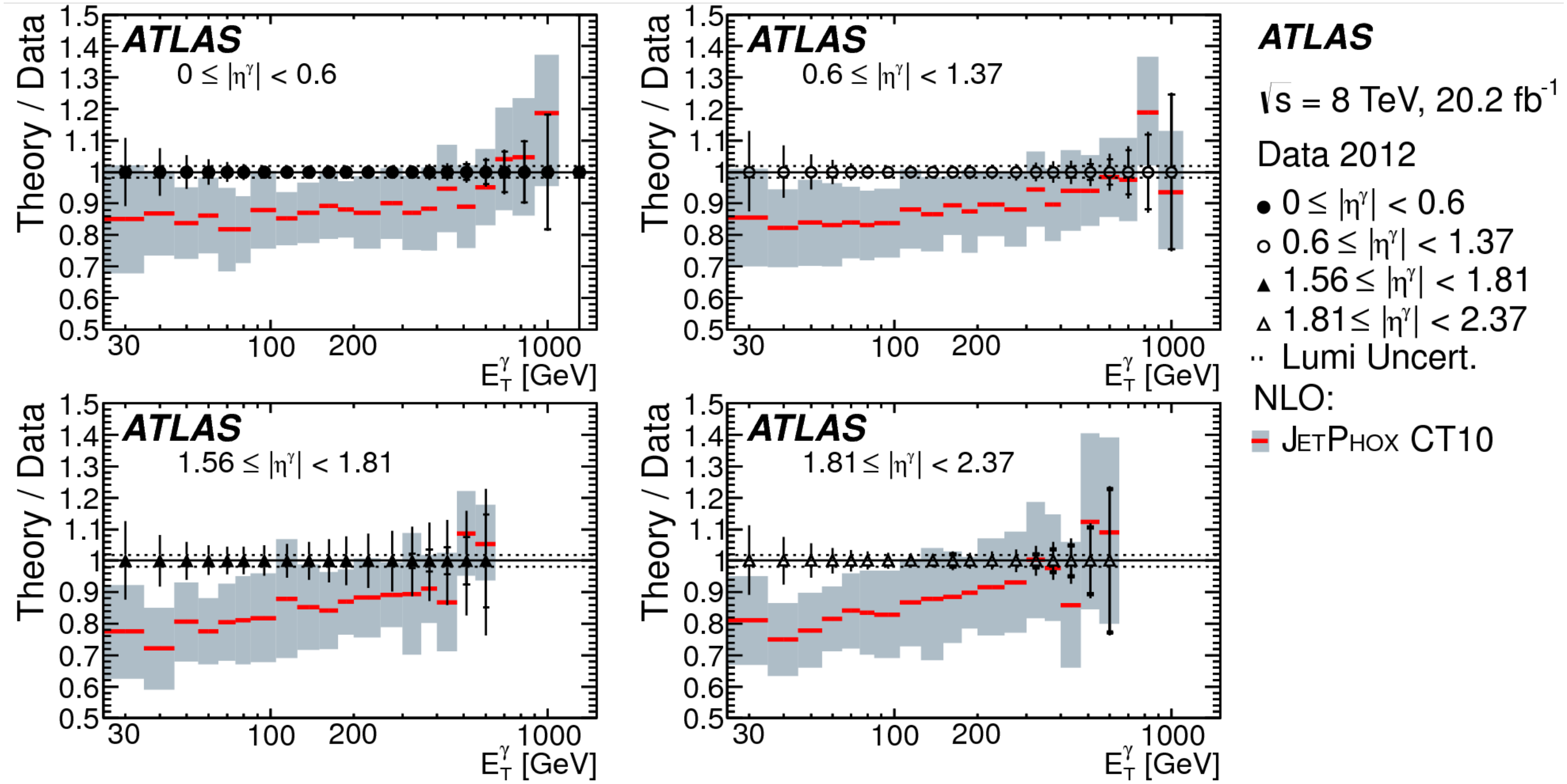
- Fiducial region:
  - pT > 20 GeV, |η| < 2.4
- Kinematic regions:
  - m_{ll}: 46-66-116-150, 3(6 in peak) $|y^{ll}|$ bins
  - m_{ll}: 12-20-30-46 GeV, p_T^{ll} only
- Data modeled background
  - Multijet: Isolation variable template fit using control region templates
- MC Modeled Backgrounds
  - Ttbar, single top
  - Z → tautau
  - W → lepton+nu
  - WW, WZ, ZZ
  - Photons
- Reported at Bare, Dressed and Born levels
  - Born: For NNLO comparisons
  - Bare: After lepton FSR
  - Dressed: Including FSR photons in a cone of 0.1







Inclusive Photons: JetPHOX



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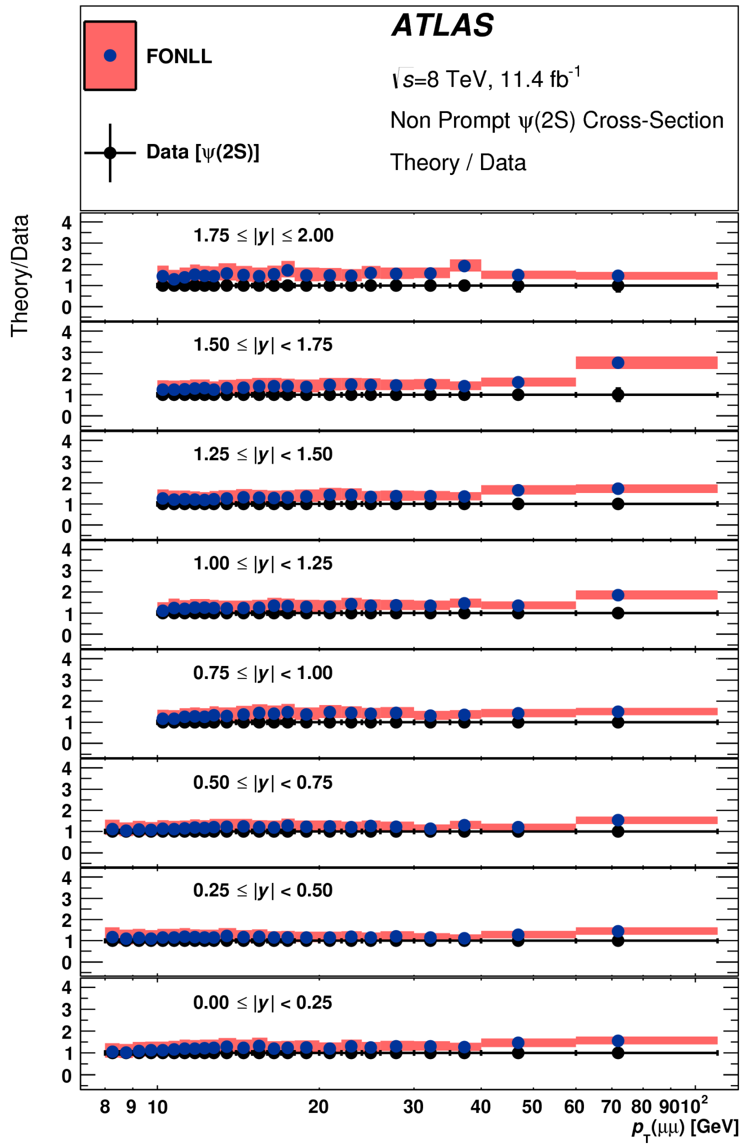
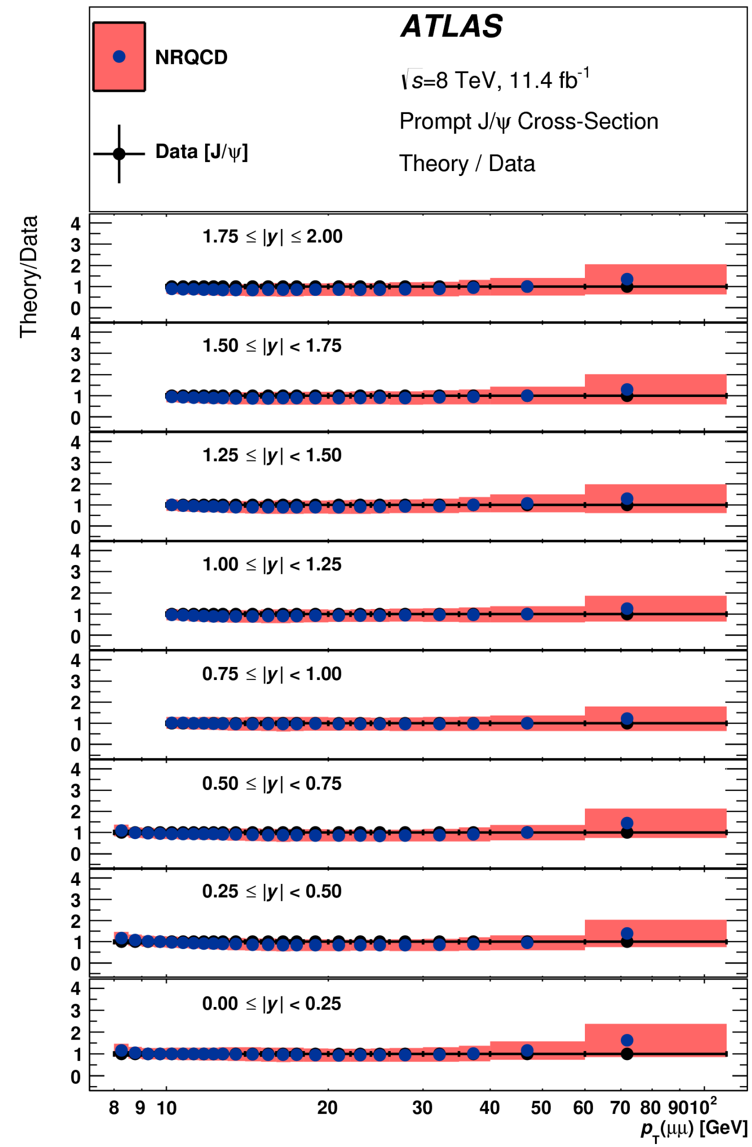
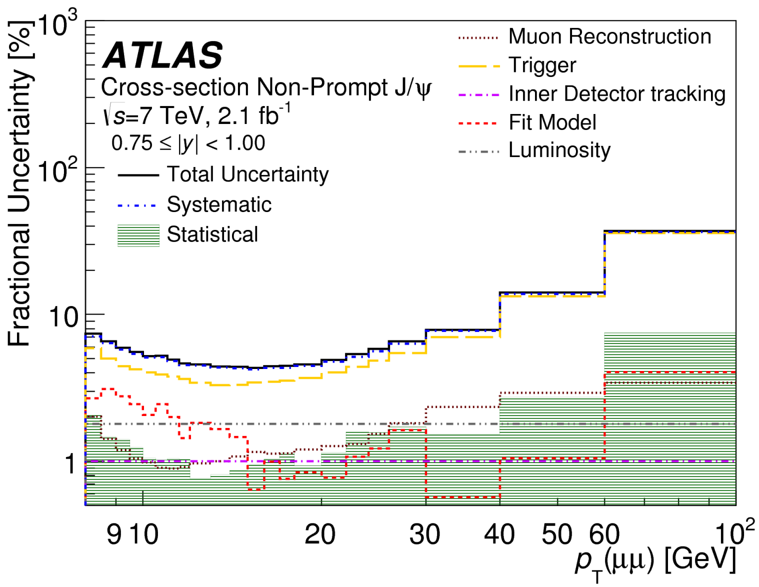
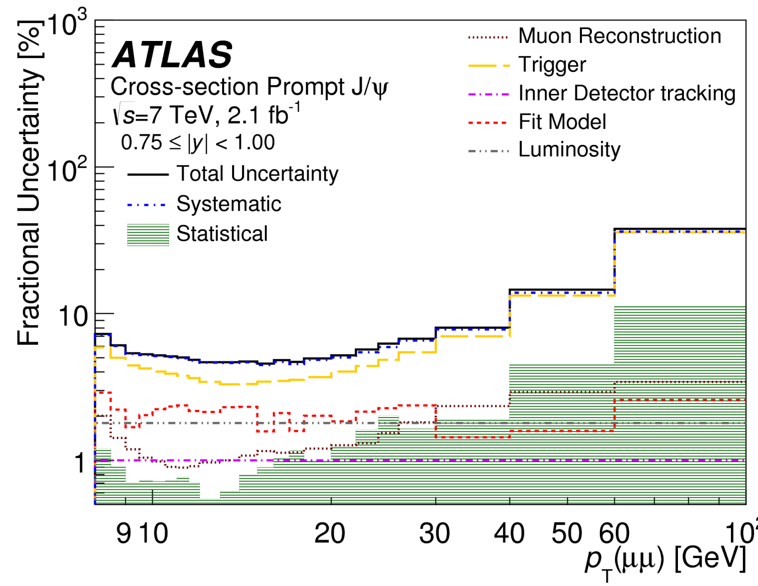
  - J/ψ spectra slightly softer than calculation
  - ψ(2s) yields lower than calculation, however good shape agreement

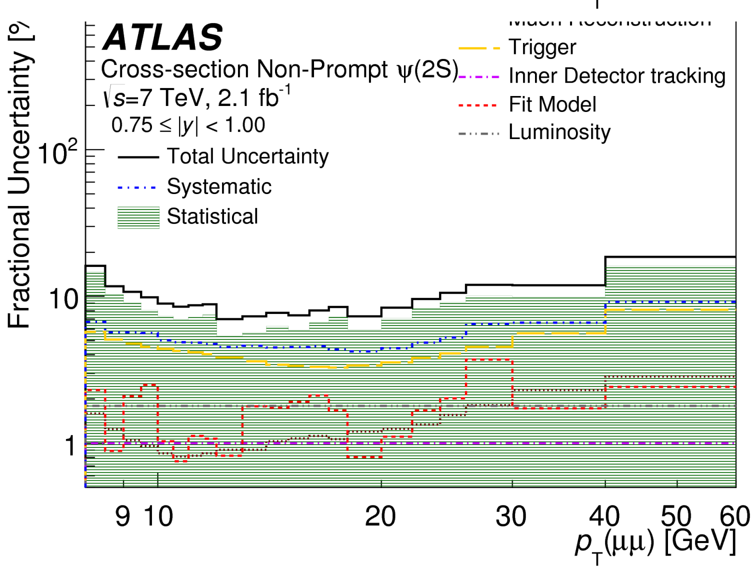


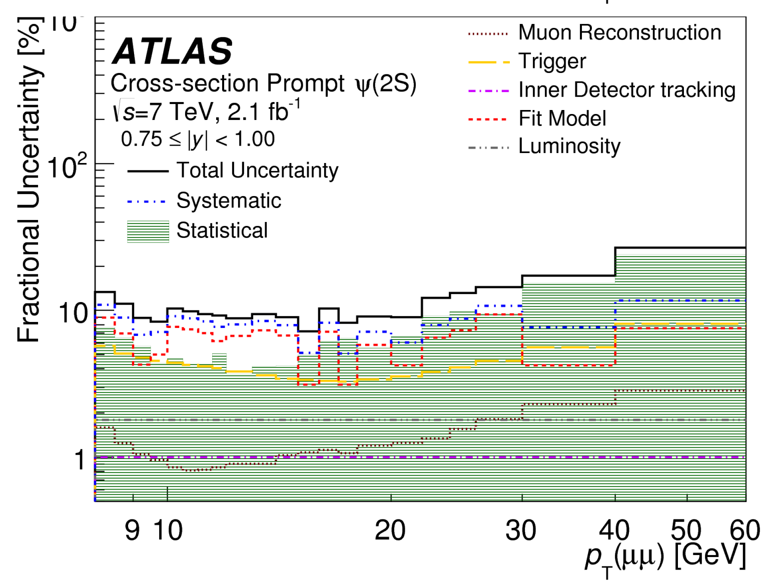


J/ψ and ψ(2s) at 7&8TeV









J/ψ and ψ(2s) at 7&8TeV

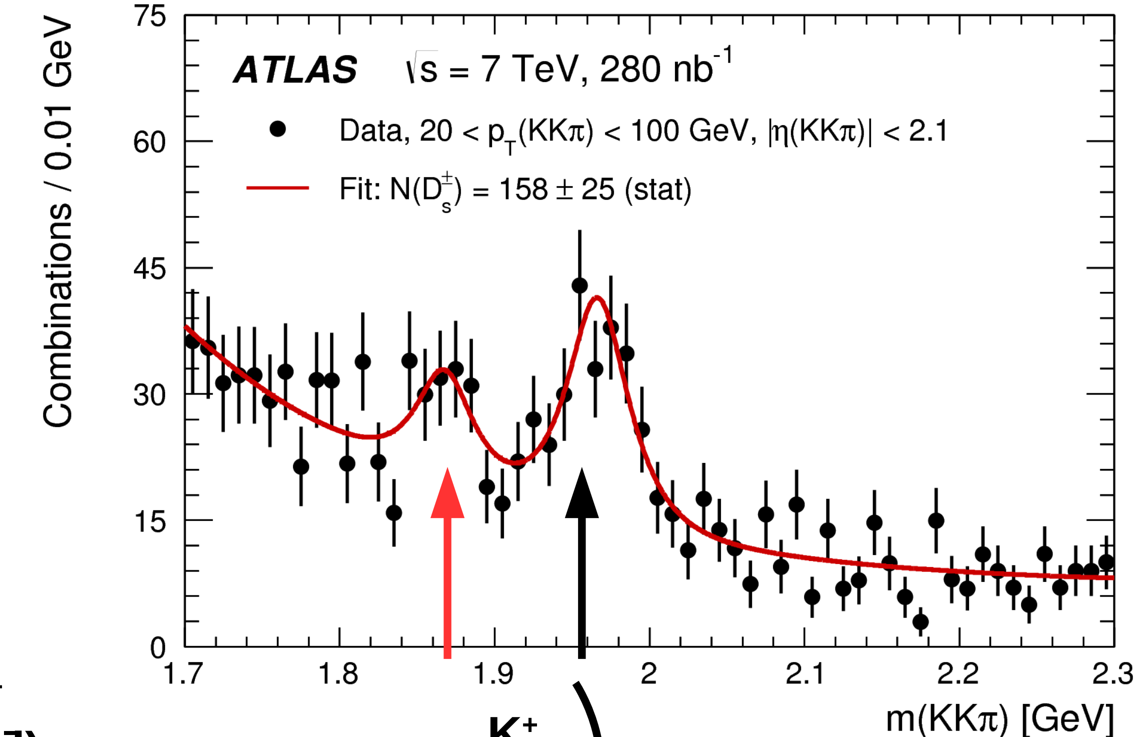
Table 3 Summary of the minimum and maximum contributions along with the median value of the systematic uncertainties as percentages for the prompt and non-prompt ψ cross-section results. Values are quoted for 7 and 8 TeV data

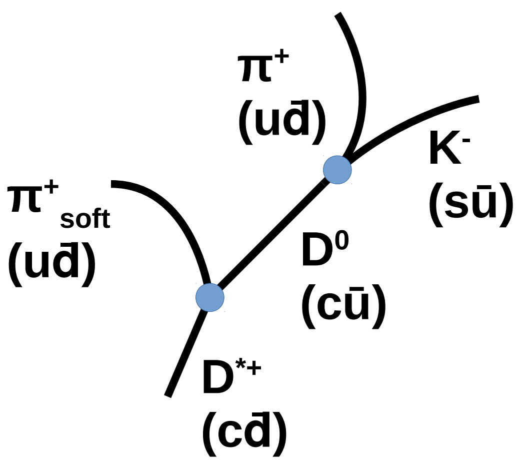
	7 TeV (%)			8 TeV (%)		
Source of systematic uncertainty	Min	Median	Max	Min	Median	Max
Luminosity	1.8	1.8	1.8	2.8	2.8	2.8
Muon reconstruction efficiency	0.7	1.2	4.7	0.3	0.7	6.0
Muon trigger efficiency	3.2	4.7	35.9	2.9	7.0	23.4
Inner detector tracking efficiency	1.0	1.0	1.0	1.0	1.0	1.0
Fit model parameterizations	0.5	2.2	22.6	0.26	1.07	24.9
Bin migrations	0.01	0.1	1.4	0.01	0.3	1.5
Total	4.2	6.5	36.3	4.4	8.1	27.9

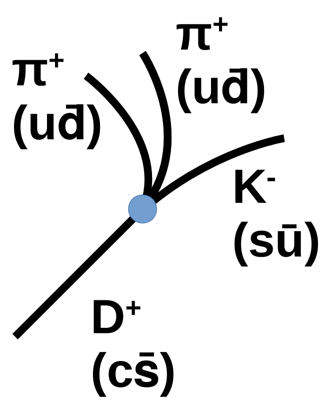
Open Charm Production at 7TeV

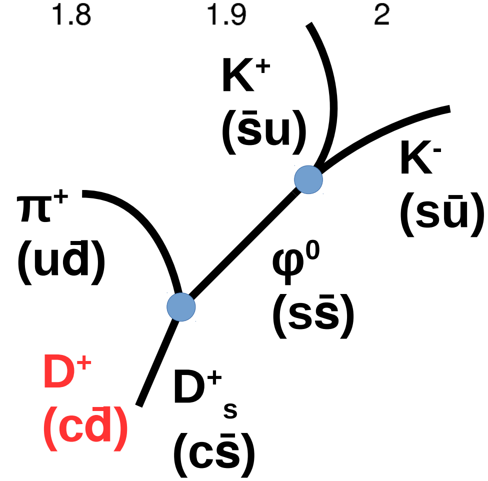
How

- Decay topology reconstruction assuming masses for all constituents
- Vertex fit quality requirement
- Other decay length and vertex position cuts









Open Charm Production at 7TeV

The strangeness-suppression factor is calculated as the ratio of the $\sigma^{tot}_{c\bar{c}}$ (D^+_s) to the sum of $\sigma^{tot}_{c\bar{c}}$ (D^{*+}) and that part of $\sigma^{tot}_{c\bar{c}}$(D^+) which does not originate from D^{*+} decays:

$$\gamma_{s/d} = \frac{\sigma^{\text{tot}}_{c\bar{c}}(D_s^+)}{\sigma^{\text{tot}}_{c\bar{c}}(D^{*+}) + \sigma^{\text{tot}}_{c\bar{c}}(D^+) - \sigma^{\text{tot}}_{c\bar{c}}(D^{*+}) \cdot (1 - \mathcal{B}_{D^{*+} \to D^0 \pi^+})} = \frac{\sigma^{\text{tot}}_{c\bar{c}}(D_s^+)}{\sigma^{\text{tot}}_{c\bar{c}}(D^+) + \sigma^{\text{tot}}_{c\bar{c}}(D^{*+}) \cdot \mathcal{B}_{D^{*+} \to D^0 \pi^+}}$$

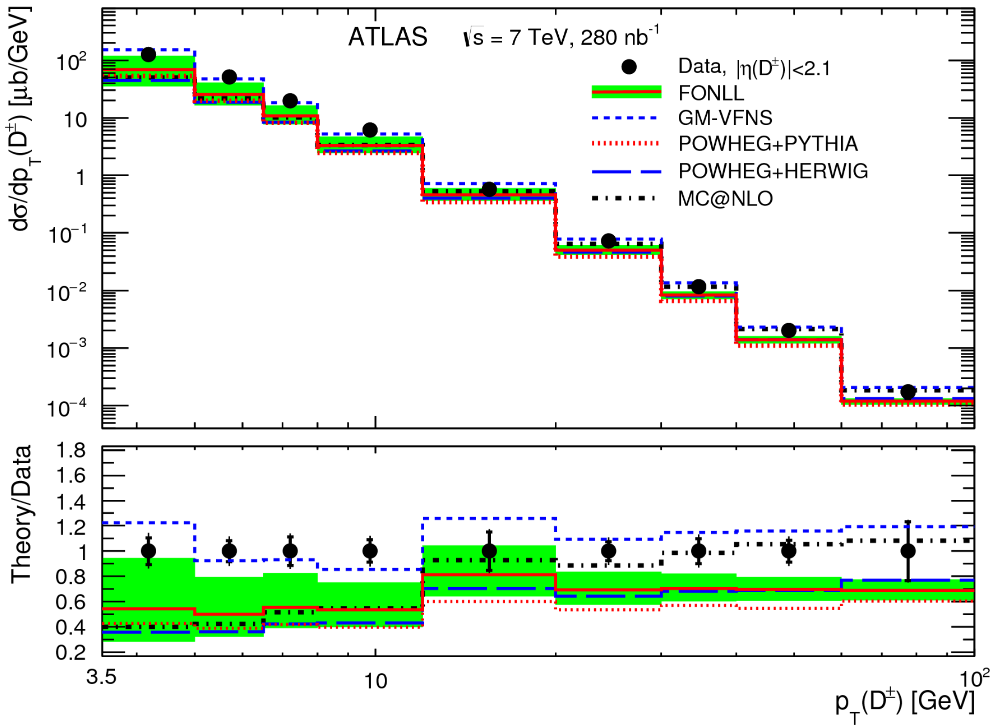
The fraction of charged non-strange D mesons produced in a vector state is calculated as the ratio of $\sigma^{tot}_{c\bar{c}}$ (D^{*+}) to the sum of $\sigma^{tot}_{c\bar{c}}$ (D^{*+}) and that part of $\sigma^{tot}_{c\bar{c}}$ (D^+) which does not originate from D^{*+} decays:

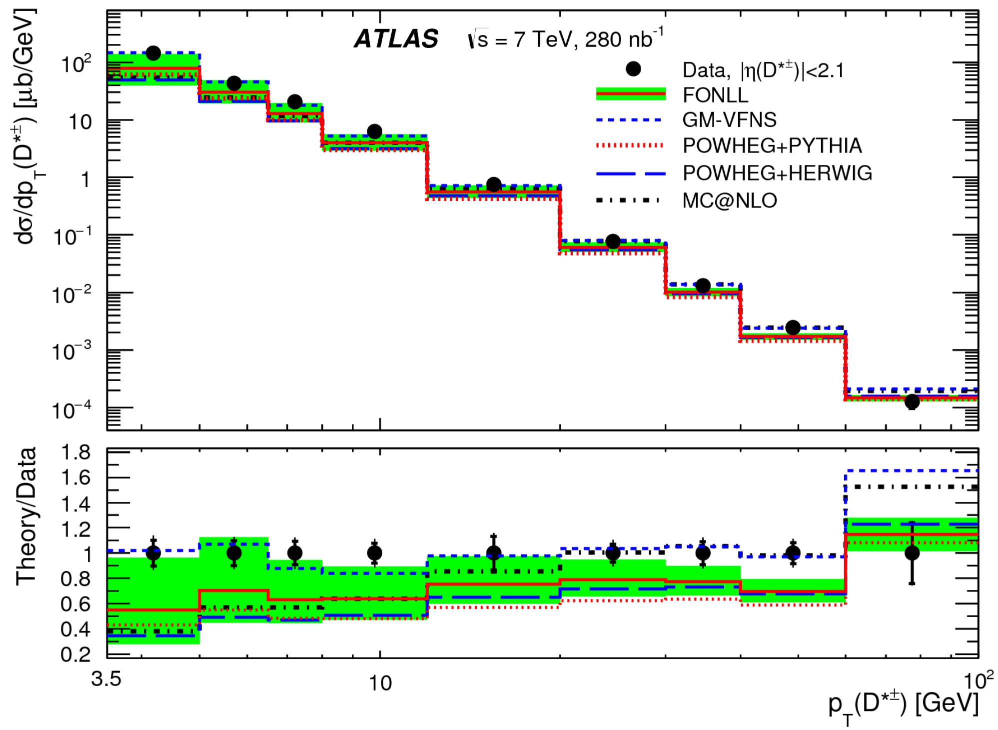
$$P_{\text{v}}^{d} = \frac{\sigma^{\text{tot}}_{c\bar{c}}(D^{*+})}{\sigma^{\text{tot}}_{c\bar{c}}(D^{*+}) + \sigma^{\text{tot}}_{c\bar{c}}(D^+) - \sigma^{\text{tot}}_{c\bar{c}}(D^{*+}) \cdot (1 - \mathcal{B}_{D^{*+} \to D^0 \pi^+})} = \frac{\sigma^{\text{tot}}_{c\bar{c}}(D^{*+})}{\sigma^{\text{tot}}_{c\bar{c}}(D^+) + \sigma^{\text{tot}}_{c\bar{c}}(D^{*+}) \cdot \mathcal{B}_{D^{*+} \to D^0 \pi^+}}$$

Open Charm Prod. at 7TeV

Detailed Results

- Total Cross section:
  - ATLAS: $\sigma^{tot}_{c\bar{c}}$ = 8.6 ± 0.3 (stat) ± 0.7 (syst) ± 0.3 (lum) ± 0.2 (ff)$^{+3.8}_{-3.4}$ (extr) mb
  - ALICE: $\sigma^{tot}_{c\bar{c}}$ =8.5 ± 0.5 (stat)$^{+1.0}_{-2.4}$ (syst) ± 0.3 (lum) ± 0.2 (ff) $^{+5.0}_{-0.4}$ (extr) mb
- Strangeness suppression factor:
  - ATLAS: 0.26 ± 0.05 (stat) ± 0.02 (syst) ± 0.02 (br) ± 0.01 (extr)
  - LEP: 0.24 ± 0.02 ± 0.01 (br)
- Charged non-strange vector D-meson fraction:
  - ATLAS: 0.56 ± 0.03 (stat) ± 0.01 (syst) ± 0.01 (br) ± 0.02 (extr)
  - LEP: = 0.61 ± 0.02 ± 0.01 (br)





Open Charm Prod. at 7TeV

Detailed Results

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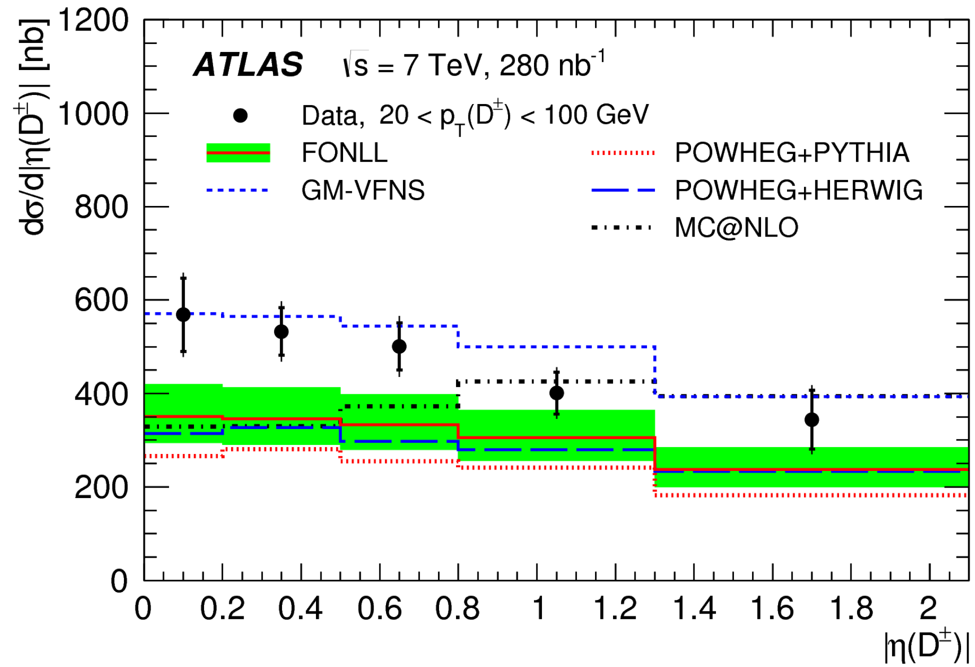
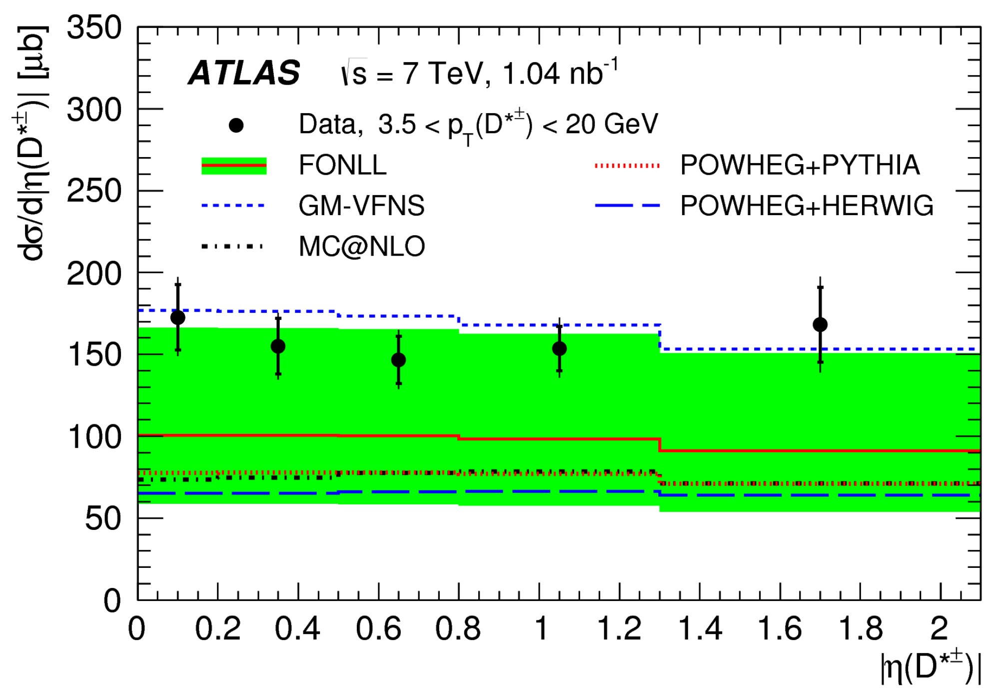
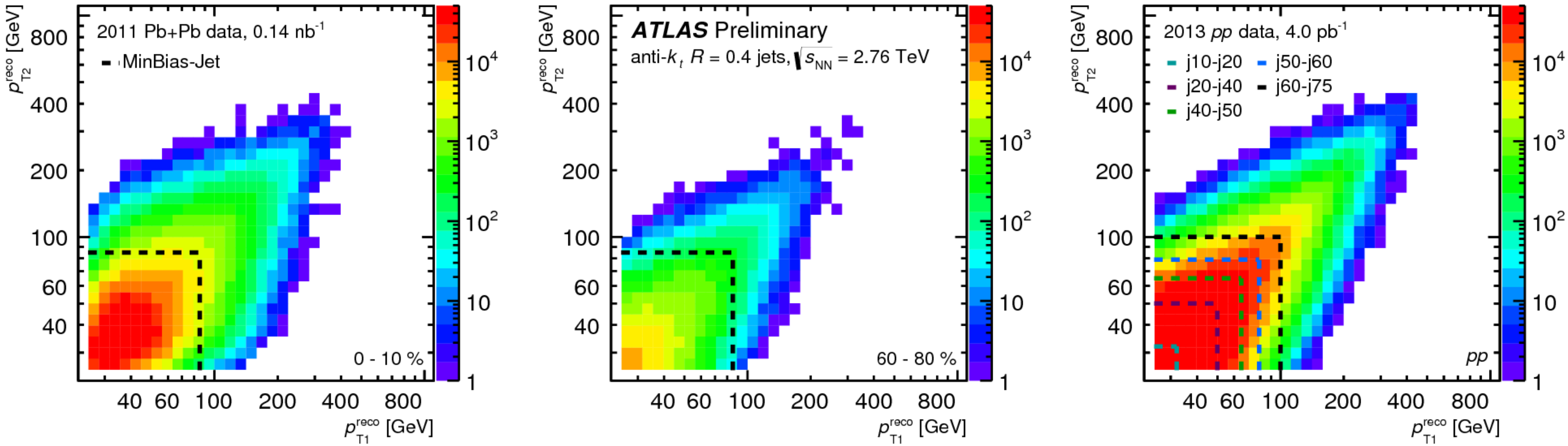




Open Charm Uncertainties

Source	$\sigma^{vis}(D^{*\pm})$		$\sigma^{vis}(D^{\pm})$		$\sigma^{vis}(D_s^{\pm})$	
	Low-p_T	High-p_T	Low-p_T	High-p_T	Low-p_T	High-p_T
Trigger (δ_1)	-	$^{+0.9}_{-1.0}\%$	-	$^{+0.9}_{-1.0}\%$	-	$^{+0.9}_{-1.0}\%$
Tracking (δ_2)	$\pm 7.8\%$	$\pm 7.4\%$	$\pm 7.7\%$	$\pm 7.4\%$	$\pm 7.6\%$	$\pm 7.4\%$
D selection (δ_3)	$^{+2.8}_{-1.6}\%$	$^{+1.7}_{-1.4}\%$	$^{+1.6}_{-1.0}\%$	$^{+0.9}_{-0.6}\%$	$^{+2.6}_{-1.6}\%$	$^{+1.1}_{-0.9}\%$
Signal fit (δ_4)	$\pm 1.3\%$	$\pm 0.9\%$	$\pm 1.3\%$	$\pm 1.5\%$	$\pm 6.4\%$	$\pm 5.3\%$
Modelling (δ_5)	$^{+1.0}_{-1.7}\%$	$^{+2.7}_{-2.3}\%$	$^{+2.3}_{-2.6}\%$	$^{+2.9}_{-2.4}\%$	$^{+1.7}_{-2.4}\%$	$^{+2.8}_{-2.4}\%$
Size of MC sample (δ_6)	$\pm 0.6\%$	$\pm 0.9\%$	$\pm 0.8\%$	$\pm 0.8\%$	$\pm 2.9\%$	$\pm 3.1\%$
Luminosity (δ_7)	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$
Branching fraction (δ_8)	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 2.1\%$	$\pm 2.1\%$	$\pm 5.9\%$	$\pm 5.9\%$

Dijet Asymmetry Unfolding



Heavy Flavor μ in PbPb at 2.76TeV

v_2 Defined:

$$v_2 = \frac{v_2^{\text{obs}}}{\text{Res}\{2\Psi_2\}}, \quad \text{Res}\{2\Psi_2\} = \langle \cos(2(\Psi_2 - \Phi_2)) \rangle_{\text{evts}}$$

$$q_{2,x} = \frac{\Sigma E_{\mathrm{T},i} \cos(2\phi_i) - \langle \Sigma E_{\mathrm{T},i} \cos(2\phi_i) \rangle_{\text{evts}}}{\Sigma E_{\mathrm{T},i}},$$

$$q_{2,y} = \frac{\Sigma E_{\mathrm{T},i} \sin(2\phi_i) - \langle \Sigma E_{\mathrm{T},i} \sin(2\phi_i) \rangle_{\text{evts}}}{\Sigma E_{\mathrm{T},i}},$$

$$\tan(2\Psi_2) = \frac{q_{2,y}}{q_{2,x}}$$

Uncertainties:

p_{T} interval	$4<p_{\mathrm{T}}<5$ GeV		$6<p_{\mathrm{T}}<10$ GeV		$10<p_{\mathrm{T}}<14$ GeV	
Centrality	0–10%	40–60%	0–10%	40–60%	0–10%	40–60%
Muon selection cuts [%]	2	1	2	2	2	5
p_{MS} cuts [%]	1	4	0	0	0	0
Background Template variation [%]	1	2	2	3	3.5	40
p_{T} resolution [%]	1	0	4	2	25	70
EP resolution [%]	2.5	4	2.5	4	2.5	4

Table 2: Relative systematic uncertainties on the heavy flavor muon v_2, quoted in percent, for selected p_{T} and centrality intervals. They are averaged over p_{T} intervals that are larger than the intervals used for the measurement.