

Overview of ATLAS Heavy Flavor Measurements

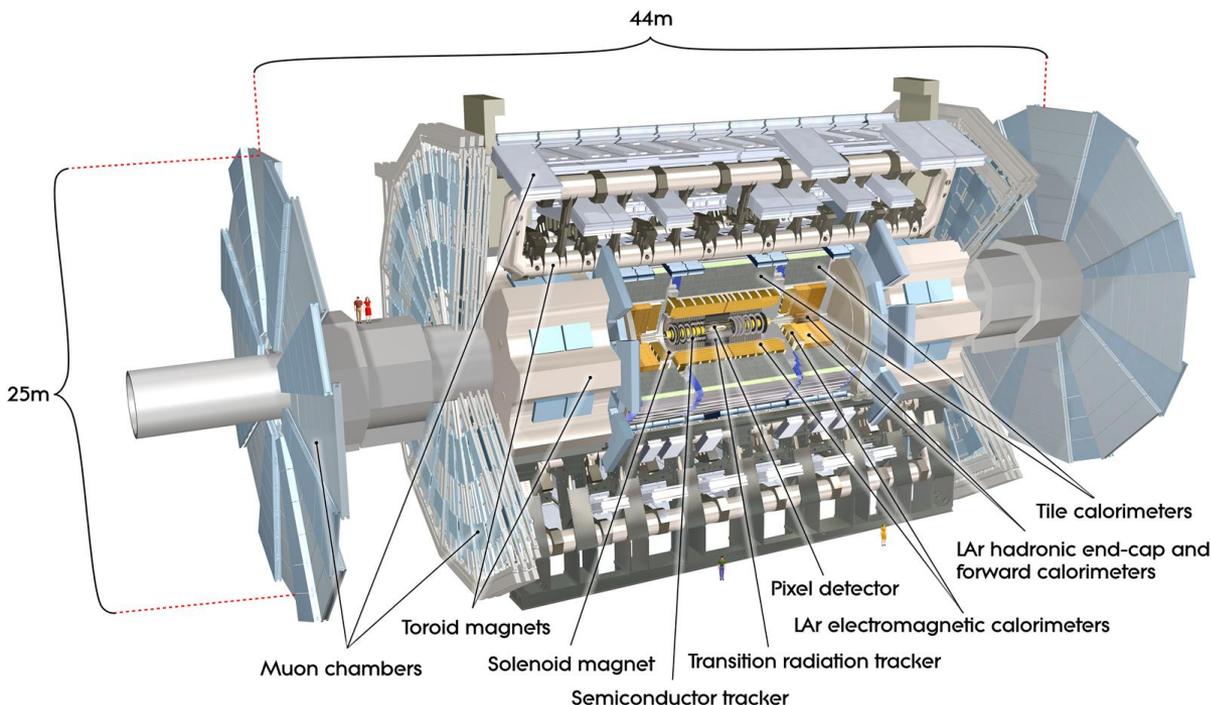
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- I. Introduction to ATLAS
- II. b-Hadron Pair Production Cross-section
- III. Prompt J/ψ Pair Production Cross-section
- IV. $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ and $X(3872) \rightarrow J/\psi\pi^+\pi^-$ Production
- V. Angular Analysis of $B_d^0 \rightarrow K^*\mu^+\mu^-$ Decays

Introduction

The 4 most recent public results in B-Physics from ATLAS, all using LHC pp data collected at $\sqrt{s} = 8$ TeV, and released in 2017.



ATLAS from inside to out:

- Inner detector (pixel, silicon microstrips, straw-tube TRT) $|\eta| < 2.5$, surrounded by a 2T axial B field from the solenoid
- Sampling calorimeters (LAr EM $|\eta| < 3.2$; Scint tile HAD $|\eta| < 3.2$; LAr HAD $1.5 < |\eta| < 4.9$)
- Air core toroids provide B field for Muon drift tubes + cathode strip chambers (muon tracking to $|\eta| < 2.7$) and resistive plate + thin gap chambers (triggering to $|\eta| < 2.4$)

Measurement of b-hadron Pair Production Cross-section*

Message: This total cross section is measured: $\sigma\left(B\left(\rightarrow J/\psi\left[\rightarrow\mu^+\mu^-\right]+X\right)B\left(\rightarrow\mu+X\right)\right)$

Using it, 8 differential cross sections are obtained:

- $\frac{1}{\sigma} \frac{d\sigma}{d\Delta R(J/\psi\mu)}$ separation between the J/ψ and the third μ in the azimuth-rapidity plane
- $\frac{1}{\sigma} \frac{d\sigma}{dm(J/\psi\mu)} [\text{GeV}^{-1}]$ mass of the J/ψμ system
- $\frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi(J/\psi\mu)} [\text{rad}^{-1}]$ azimuthal separation Δφ between the J/ψ and the third μ
- $\frac{1}{\sigma} \frac{d\sigma}{dp_T(J/\psi\mu)}$ transverse momentum p_T of the 3-muon system
- $\frac{1}{\sigma} \frac{d\sigma}{d\Delta y(J/\psi\mu)}$ rapidity separation Δy between the J/ψ and the third μ

the list continues.....

- $$\frac{1}{\sigma} \frac{d\sigma}{dy_{boost} (J/\psi\mu)}$$

magnitude y_{boost} of the avg. rapidity of the J/ψ and the third μ

- $$\frac{1}{\sigma} \frac{d\sigma}{dp_T^{\mu\mu\mu} / m^{\mu\mu\mu}}$$

ratio of the p_T to the invariant mass of the 3-muon system,

- $$\frac{1}{\sigma} \frac{d\sigma}{dm^{\mu\mu\mu} / p_T^{\mu\mu\mu}}$$

and its inverse

These differential cross sections are compared to predictions from several event generators.

Motivation:

- Factorization of QCD calculations into parton distribution functions, hard matrix elements, and soft parton shower components allows the heavy (b) quark mass to be introduced at *different stages*.
- *Several schemes are possible* for inclusion of the heavy quark masses
- Previous analyses of heavy flavor production highlighted disagreements *among* theoretical predictions and *between* predictions and data. *This analysis constrains the options*.
- The region of small-angle $b\bar{b}$ production is *especially sensitive* to details of the calculations but has previously been *only loosely constrained* by data.
- Searches for Higgs produced in association with a vector boson (VH) and decaying to $b\bar{b}$ *rely on the modeling* of the background $b\bar{b} + V$

Details of the analysis (1)

- **Trigger:** 2 oppositely charged muons with a common vertex, $p_T(\mu) > 4 \text{ GeV}$, $|\eta(\mu)| < 2.4$, $2.5 < m(\mu\mu) < 4.3 \text{ GeV}$
- **Integrated luminosity** = 11.4 fb^{-1}
- **Primary vertex:** ≥ 2 tracks, each with $p_T > 400 \text{ MeV}$, with largest summed p_T^2 .
- **Form the muon candidates:**
 - use combined inner detector and muon spectrometer tracks
 - $p_T(\mu) > 6 \text{ GeV}$, $|\eta(\mu)| < 2.5$
- **J/ ψ candidates:**
 - opposite-sign muon pairs with $|\eta(\mu)| < 2.3$ and directional correspondence with the trigger-level candidate
 - $2.6 < m(\mu\mu) < 3.5 \text{ GeV}$
 - If multiple candidates per event, choose the one with mass closest to J/ψ_{PDG} .
- **Third muon:** choose the highest- p_T one not included in the J/ ψ reconstruction.
- **The J/ ψ and the third μ may come from feed-down or cascade.**
- **The data are first compared to these simulations:**
 - Inclusive b-hadron pairs from **PYTHIA8.186** (2->2 matrix element with parton shower); CTEQ6L1 pdf, AU2 tune; b quarks are massless in the pdf but the mass is reinstated during the shower; pile-up included with PYTHIA8 + MSTW2008 pdf + A2 tune.
 - $pp \rightarrow b\bar{b}$ simulated with HERWIG++, CTEQ6L1, UE-EE5 tune; b-quarks are massive in the matrix element and in the parton shower.
- 4-momenta of photons near muon ($\Delta R_\eta(\mu, \gamma) < 0.1$) added to muon

Analysis details (2)

Corrections:

- for trigger efficiency including vertex recon and spatial overlap of muons
- for muon reconstruction efficiency
- To collect the J/ψ 's produced in decays of b-hadrons:
 - Define L_{xy} : transverse distance between primary vertex (PV) and dimuon vertex, signed positively for momentum pointing away from primary vertex.
 - Define pseudo-proper decay time:
$$\tau \equiv \frac{L_{xy} \cdot m(J/\psi_{PDG})}{p_T(\mu^+ \mu^-)}$$
 - J/ψ 's from most b decays are non-prompt, so to optimize for signal events, require $\tau > 0.25$ mm/c.
 - simultaneous maximum likelihood fit to the distributions of dimuon mass and τ .
- Extract # non-prompt J/ψ 's.

Analysis details (3)

- To **select the third muon**, reject bkg: prompt muons, muons from charged π/K decay, fake muons from decay in flight and hadron shower leakage, muons combined with continuum (false) J/ψ , and muons in pile-up.
- **Discriminate third-muon signal from bkg with a simultaneous fit on 2 observables:**
 - **transverse impact parameter significance**

$$S_{d_0} \equiv d_0 / \sigma_{d_0}$$

(d_0 is distance of closest approach of the muon track to the PV in the r - ϕ projection, with sign given by the sign of the angular momentum of the track around the beam at point of closest approach)

- **Output of a boosted decision tree** using kinematic variables related to track deflection significance, momentum balance, and $|\eta|$.
- **Subtract 3 remaining irreducible bkg** from fitted yields:
 - $B_c \rightarrow J/\psi + \mu + X$ (very small, taken from simulation)
 - Semileptonic decays of c-hadrons not resulting from b-hadron feed-down
 - “Sail through” charged π/K : traverses the detector to the muon spectrometer without interacting or decaying (mimics a muon, taken from simulation)

Analysis details (4)

Corrections:

- for the τ requirement: extrapolate to full range
- for detector resolution on momentum and η of muons. Issue: migration between bins and in/out of fiducial volume.

Repeat for every kinematic bin for each differential cross section.

Systematic uncertainties:

- Muon efficiency corrections to data
- J/ψ model
- Background components in the fits

Statistical uncertainties:

- On the data statistics
- On the third-muon templates taken from simulation

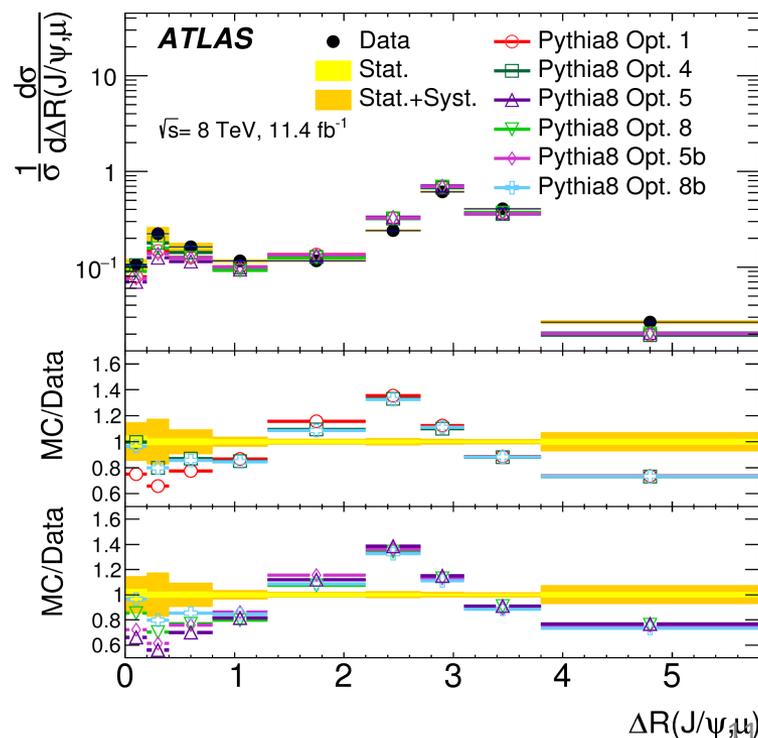
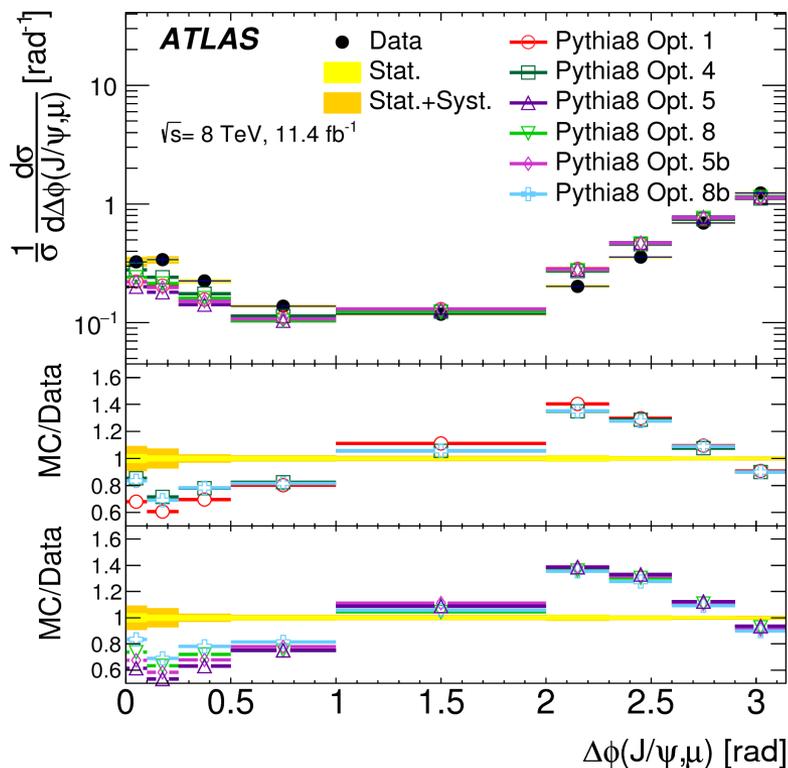
Luminosity uncertainty: 1.9%

Result 1: $\sigma\left(B(\rightarrow J/\psi[\rightarrow \mu^+\mu^-]+X)B(\rightarrow \mu+X)\right) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst}) \text{ nb.}$

Result 2: Is the scale of α_s during splitting set by *relative p_T* or by *mass*?
Compare differential cross sections using 6 options in PYTHIA8 for the $g \rightarrow b\bar{b}$ splitting kernel (dominates small angle b-hadron production).

PYTHIA8 does not reproduce the shape of the angular distributions for any of the 6 options.

Some of the options of splitting function form and α_s scale fit better to the mass or ΔR distributions. Example:



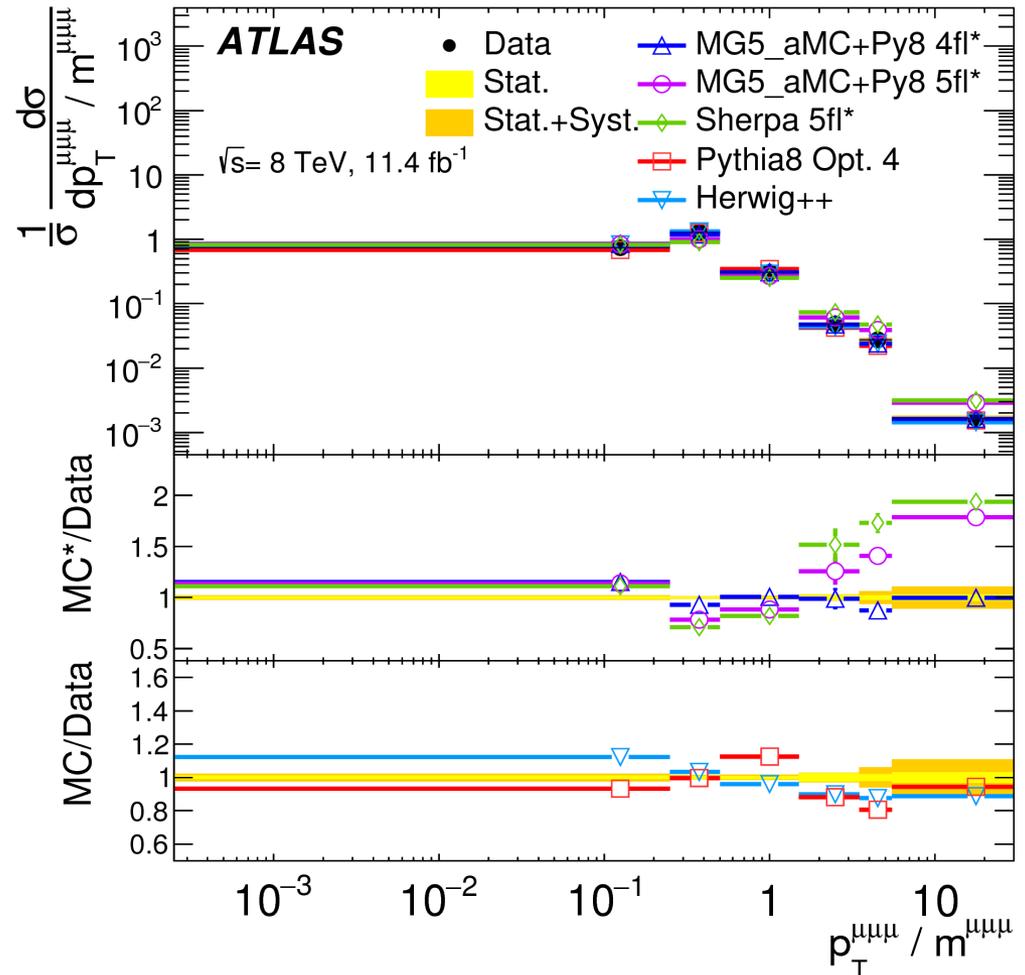
Result 3:

Extend the comparison of data to HERWIG++, SHERPA, and MADGraph5_AMC@NLOv2.2.2 + PYTHIA8.186 parton shower model.

These cover a range of matrix elt calculations and parton shower models.

Consider options with 4 or 5 massless flavors. Compare all of these to PYTHIA8.

- HERWIG++ reproduces the ΔR and $\Delta\phi$ graphs best.
- 4-massless flavors models ΔR and $\Delta\phi$ better than 5.
- Δy spectrum is well modeled by MadGraph and SHERPA
- All models reproduce y_{boost} well.
- 5-massless flavor MadGraph models low mass distribution better than 4,
- but 4-massless flavor MadGraph models high p_T/m best.



Conclusions:

- Considering all distributions, the 4-massless flavor prediction from MadGraph5_AMC@NLO+PYTHIA8 best describes the data.
- Predictions of PYTHIA8 and HERWIG++ are comparable.
- Among PYTHIA8 options studied, the p_T -based splitting kernel is best.

Measurement of Prompt J/ψ Pair Production Cross-section*

Message: The cross section for production of 2 prompt centrally-produced J/ψ mesons is measured. *“Prompt” means: produced at a point consistent with the primary vertex, not as a product of the decay of a long-lived hadron.*

Differential cross sections are produced as a function of:

- p_T of the lower- p_T meson (called “J/ψ₂”) - Measurements use subleading meson J/ψ₂ to access full kinematic region.
- di-J/ψ p_T
- di-J/ψ mass
- Δy between the 2 mesons
- $\Delta\phi$ between the 2 mesons

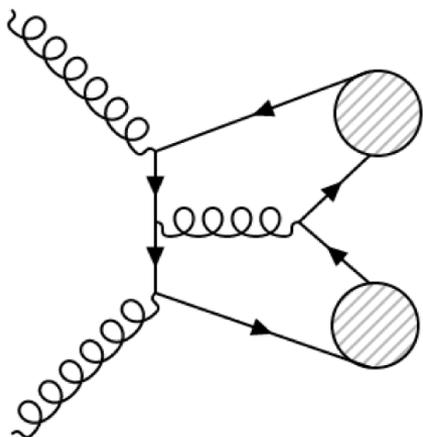
Characterization of kinematic correlations between the 2 J/ψ’s is used to extract the fraction of prompt pair events arising from **double parton scattering**.

Total and double parton scattering cross sections are compared with predictions.

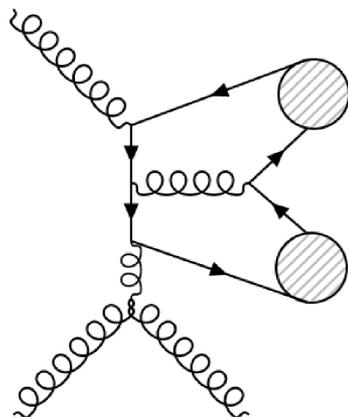
The **effective cross section** of a double parton scattering is measured.

This is the first such measurement at 8 TeV, and it probes a different kinematical range from previous (1.96 TeV and 7 TeV) measurements.

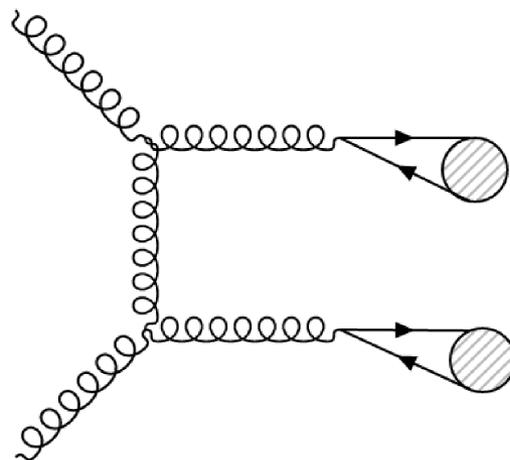
What the events look like: each shaded circle is a J/ψ meson.
 Di- J/ψ 's can be produced from single parton (g-g) scattering (“SPS”) or from double parton scattering (“DPS”).



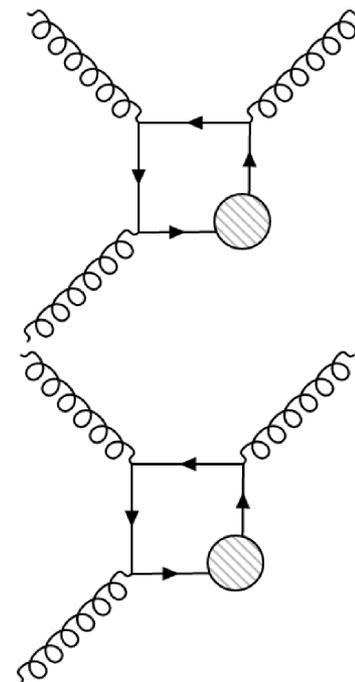
LO SPS



NLO SPS, color singlet J/ψ



LO SPS, color octet $c\bar{c}$



DPS

Motivation:

Goal #1: measure the *fraction of events that result from double parton scattering*. The DPS cross section is sensitive to the spatial distribution of gluons in the proton.

Goal #2: use the fraction of DPS events f_{DPS} to *measure the effective cross section of DPS*. Effective cross section is:

$$\sigma_{eff} = \frac{1}{2} \frac{\sigma_{J/\psi}^2}{f_{DPS} \cdot \sigma_{J/\psi J/\psi}}$$

It relates the production cross section of the 2 individual interactions to the total production cross section. Testing correlations of non-perturbative origin between the partons in a DPS may improve understanding of non-perturbative QCD.

Goal #3: DPS can be modeled and subtracted to *provide input to SPS quarkonium production models*. Quarkonium production is a background to new physics searches. Make comparisons between the data and various production models using different techniques to compute di- J/ψ production at LO, NLO, NLO color singlet NRQCD without loops (NLO*), and intrinsic parton transverse momentum fractions.

Details of the analysis (1)

- Integrated luminosity = 11.4 fb^{-1}
- Accept prompt-prompt mesons produced directly or through feed-down from $\psi(2S)$ decay
- Dimuon trigger, each muon's $p_T > 4 \text{ GeV}$; $2.5 < m(\mu^+\mu^-) < 4.3 \text{ GeV}$
- Reconstruction:
 - ≥ 3 muons in the muon spectrometer data
 - Record $|d_z|$ of 2 J/ψ decay vertices projected onto the beam axis
 - $|\eta^\mu| < 2.3$, $p_T^\mu > 2.5 \text{ GeV}$
 - $2.8 < m(\mu\mu) < 3.4 \text{ GeV}$
 - $|y^{J/\psi}| < 2.1$, $p_T^{J/\psi} > 8.5 \text{ GeV}$
- For each J/ψ candidate, find the signed transverse decay length L_{xy} (recall from page 8)
- Because J/ψ mass resolution is worse in forward region, measure cross section separately for 2 rapidity regions: $|y^{J/\psi}| < 1.05$ (“central”) and $1.05 < |y^{J/\psi}| < 2.1$ (“forward”)

Analysis details (2)

Signal extraction procedure:

- **Weight each event** by efficiency of trigger, reconstruction, and selection, and by geometrical acceptance.
- **First find *all* di- J/ψ events:**
 - Build a 2-d distribution of the $m(J/\psi_1)$ vs. $m(J/\psi_2)$ from inclusive single J/ψ events. Signal for each J/ψ is modeled by Crystal Ball function, bkg (muons from semileptonic decays of b-hadrons and from continuum) is modeled by polynomial
 - Fit the data to this 2-d probability density function. Subtract this non- J/ψ bkg. What remains is inclusive di- J/ψ signal (prompt and non-prompt).
- To **extract only prompt-prompt (“PP”) events from that inclusive di- J/ψ sample:**
 - Construct 2 L_{xy} probability distributions from the inclusive J/ψ sample – one for prompt-prompt and one for nonprompt-nonprompt. **Prompt events have L_{xy} consistent with resolution, non-prompt with an exponential (decay constant τ).** Mixed prompt-nonprompt events are negligible.
 - Classify events according to the rapidity bins (central or forward) of the 2 J/ψ 's and apply bin-specific decay constants τ to the exponentials.
 - For each event, plot L_{xy} of J/ψ_1 versus L_{xy} of J/ψ_2 and compare it to the PP and NP-NP PDFs, then classify it.
- Divide the PP-weighted PDF by the full PDF to get the likelihood that the event is PP as a function of its mesons' values for L_{xy} and rapidity.
- **Subtract pileup bkg: remove events with $|d_z| > 1.2$ mm.**

Analysis details (3)

- **Determine DPS fraction:**

- Construct a **data-driven DPS template** by combining J/ψ mesons from different random events in the di- J/ψ sample.
- Construct a **data-driven SPS template** by subtracting the DPS template from the di- J/ψ samples' Δy vs. $\Delta\phi$ distribution.
- Normalize the DPS sample to the data in the region $\Delta y > 1.8$ and $\Delta\phi < \pi/2$ (where SPS is negligible).

- Construct weights $w_{DPS(SPS)}(\Delta\phi, \Delta y) = \frac{N_{DPS(SPS)}(\Delta\phi, \Delta y)}{N_{Data}(\Delta\phi, \Delta y)}$

- For every event, apply these weights, apply the PP weight, fit to template of $m(J/\psi_1)$ vs. $m(J/\psi_2)$ in bins of the chosen variable, **extract PP SPS signal and PP DPS signals, compute f_{DPS} .**
- For this fixed f_{DPS} , **compare distribution to LO DPS and NLO* SPS model distributions.**
- **Extract effective cross section**

Analysis details (4)

Corrections:

- Dimuon trigger efficiency including (1) correlations between vtx resolution and opposite-sign requirement and (2) muons overlapped and unresolvable by the trigger
- Muon recon efficiency
- Kinematic acceptance (from simulation – effect of p_T and η cuts on fiducial region)
- Signal efficiency on d_z and L_{xy} .
- p_T -dependence of reconstructed mass and mass resolution of J/ψ

Systematic uncertainties:

Trigger selection, muon recon, kinematic acceptance, mass model developed from inclusive J/ψ sample, J/ψ mass and width bias function of p_T , prompt-prompt model (from inclusive J/ψ sample) dependence on p_T , pile-up, J/ψ to dimuon branching fraction, luminosity, DPS model and binning.

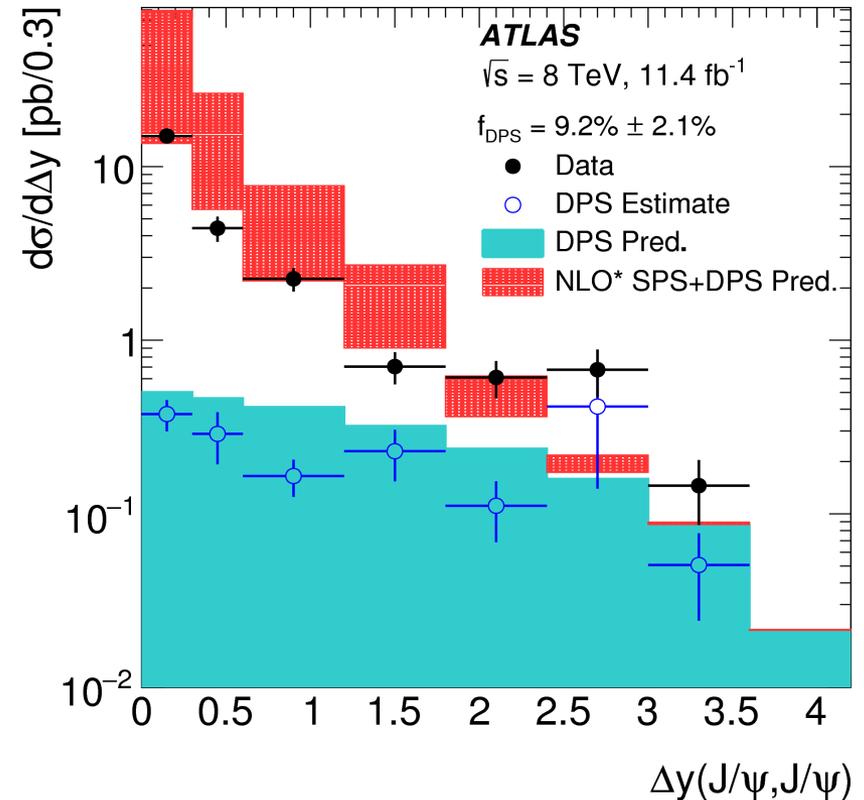
Results:

- Prompt-prompt cross sections measured:

$$\sigma_{central}(J/\psi J/\psi) = 82.2 \pm 8.3 \text{ (stat.)} \pm 6.3 \text{ (syst.)} \pm 0.9 \text{ (BF)} \pm 1.6 \text{ (lumi) pb}$$

$$\sigma_{forward}(J/\psi J/\psi) = 78.3 \pm 9.2 \text{ (stat.)} \pm 6.6 \text{ (syst.)} \pm 0.9 \text{ (BF)} \pm 1.5 \text{ (lumi) pb}$$

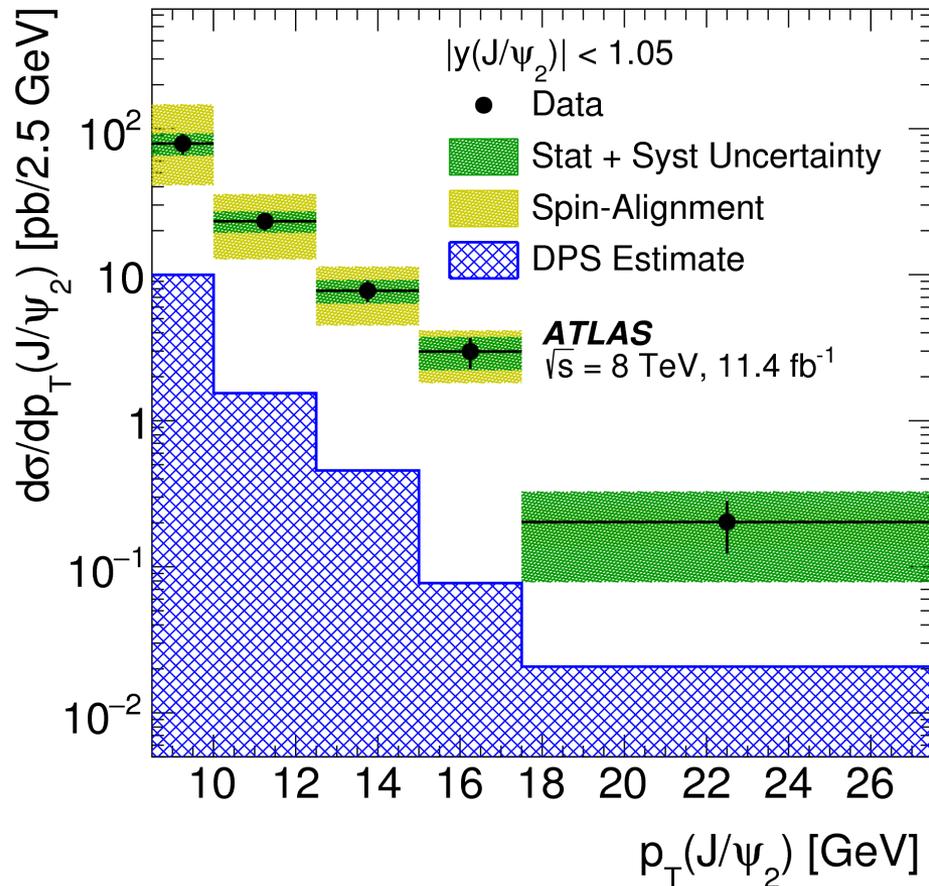
- Data are compared to theoretical distributions.[§] *Shapes of DPS distributions are consistent with models.* For SPS, the data distributions in Δy , $|\Delta\phi|$, $m(J/\psi J/\psi)$, and $p_T(J/\psi J/\psi)$ are wider than predicted by the NLO calculation.
- Data and predictions especially diverge for $\Delta y > 1.8$. This may indicate a large effect due to k_T or contributions via feed-down from color-singlet $\psi(2S)$.



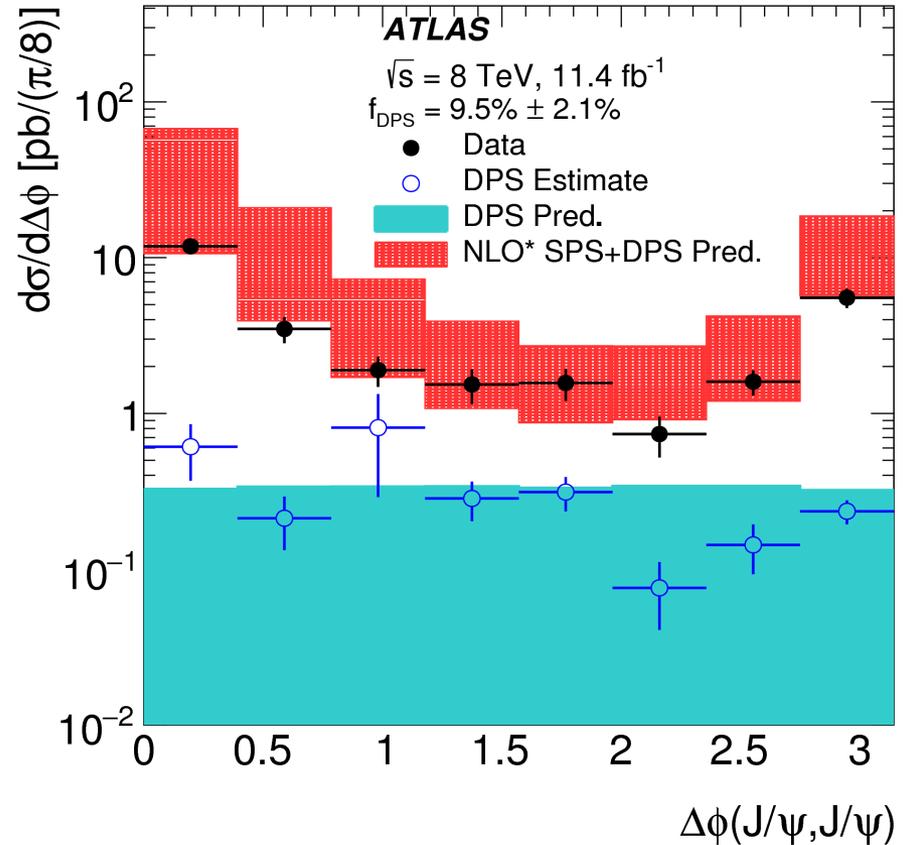
[§]LO DPS: C. Borschensky and A. Kulesza, arXiv: 1610.00666 [hep-ph];

NLO* SPS: J.P. Lansbert, H.S. Shao, Phys. Lett. B 751, 479 (2015) and PRL 111, 122001 (2013).

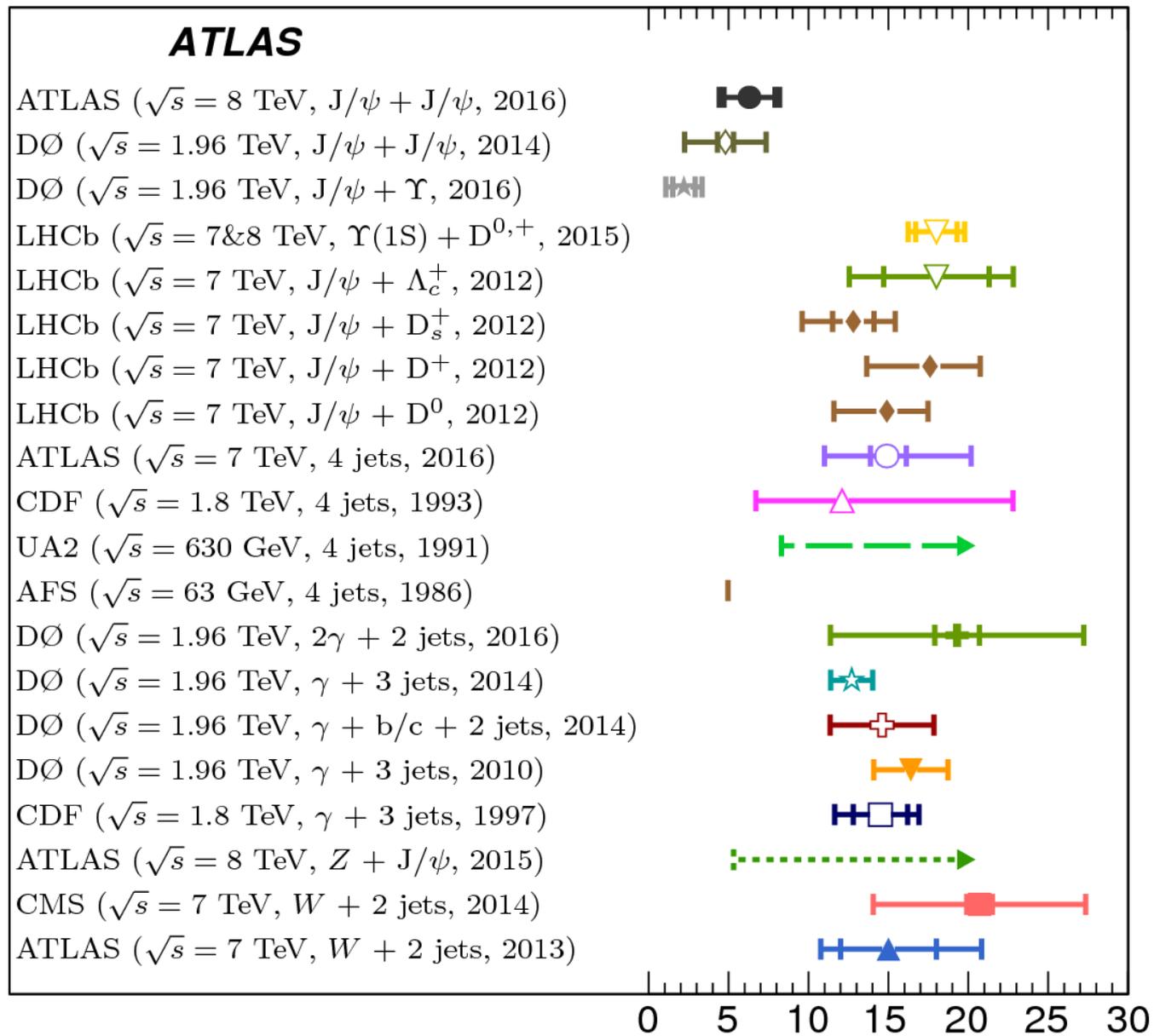
$f_{DPS} = (9.2 \pm 2.1 \text{ (stat)} \pm 0.5 \text{ (syst)})\%$,
 consistent with model predictions, for
 example:



NLO* with LO DPS+NLO color
 singlet SPS w/o loops generally
 describes data well, for example:



Experiment (energy, final state, year)



$$\sigma_{eff} = (6.3 \pm 1.6 \text{ (stat)} \pm 1.0 \text{ (syst)} \pm 0.1 \text{ (BF)} \pm 0.1 \text{ (lumi)}) \text{ mb}$$

σ_{eff} [mb]

Measurements of $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ and $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ Production*

Message:

Differential cross sections of $X(3872)$ and $\psi(2S)$ are measured and compared to models, for *prompt and non-prompt* production.

The *ratio of production cross sections* $X(3872)/\psi(2S)$ is measured.

The fraction of non-prompt $X(3872)$ and the fraction of non-prompt $\psi(2S)$ are measured.

The non-prompt *$X(3872)$ sample requires 2 lifetimes* in the fit. The short lifetime component involves $X(3872)$'s produced in B_c decays.

The *invariant mass of the dipion* system in the $J/\psi \pi^+ \pi^-$ final state is measured and found to be consistent with the process $\rho^0 \rightarrow \pi^+ \pi^-$.

*JHEP 01 (2017) 117.

Motivation:

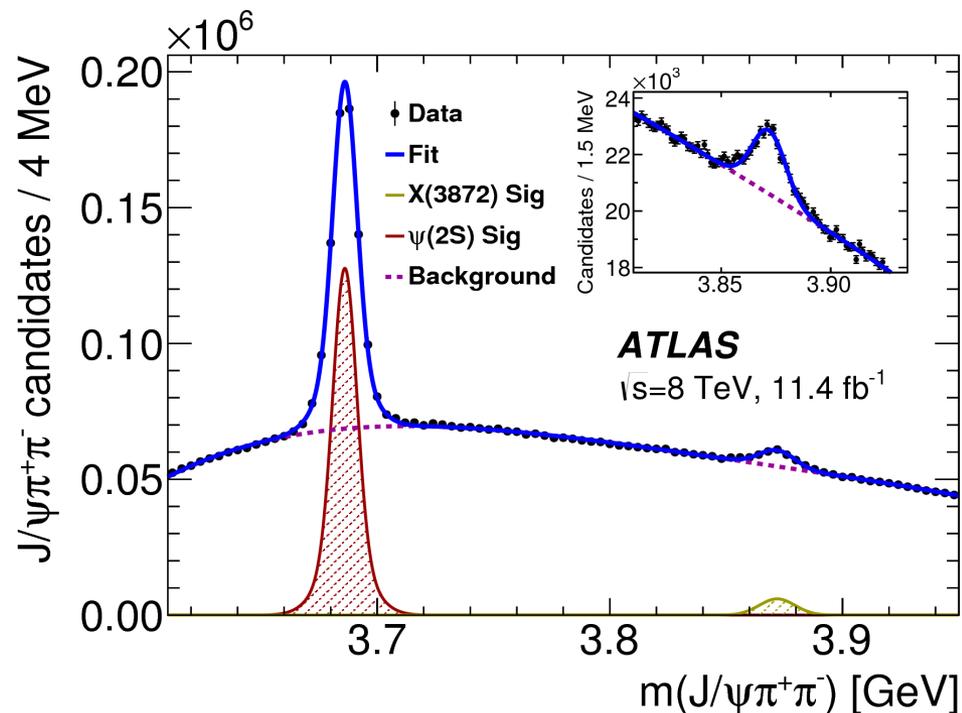
This study examines:

- the production mechanisms for these hidden charm states: direct versus feed-down from one or more heavy hadrons.
- the production mechanism of the dipion in the final state

The current best model for the X(3872) is a mixed $\chi_{c1}(2P) - D^0 \bar{D}^{*0}$ state.

Details of the analysis (1)

- Integrated luminosity = 11.4 fb^{-1}
- **Trigger:** dimuons fitted to a common vertex
- **Reconstruction:**
 - Muons well matched to trigger objects
 - $p_T(\mu) > 4 \text{ GeV}$, $|\eta(\mu)| < 2.3$, $m(\mu\mu)$ within $m_{J/\psi} \pm 120 \text{ MeV}$
- **Find $J/\psi\pi^+\pi^-$ candidates:**
 - Constrain $m(\mu\mu)$ to $m(J/\psi)_{\text{PDG}}$, then assign pion masses to 2 additional oppositely charged non-muon tracks and fitted to a common vertex with the muons. $p_T(\pi) > 0.6 \text{ GeV}$, $|\eta(\pi)| < 2.4$.
 - $J/\psi\pi^+\pi^-$ rapidity $|y| < 0.75$;
 $10 < p_T < 70 \text{ GeV}$.
 - $\Delta R(J/\psi, \pi^\pm) < 5$: the angular distance between momenta of the dimuon system and each candidate.
 - Require: $Q = m(J/\psi\pi^+\pi^-) - m(J/\psi) - m(\pi\pi) < 0.3 \text{ GeV}$: suppresses combinatorial bkg while saving 90% of signal.



Analysis details (2)

- Bin candidates in p_T .
- Weight each candidate for p_T - and η -dependent selection and recon efficiencies
- Subdivide candidates in each p_T bin according to pseudo-proper lifetime where

$$\tau = \frac{L_{xy} m}{c p_T}$$

$$L_{xy} = \frac{\vec{L} \cdot \vec{p}_T}{p_T}$$

\vec{L} is the vector pointing from the PV to the $J/\psi\pi^+\pi^-$ vertex.

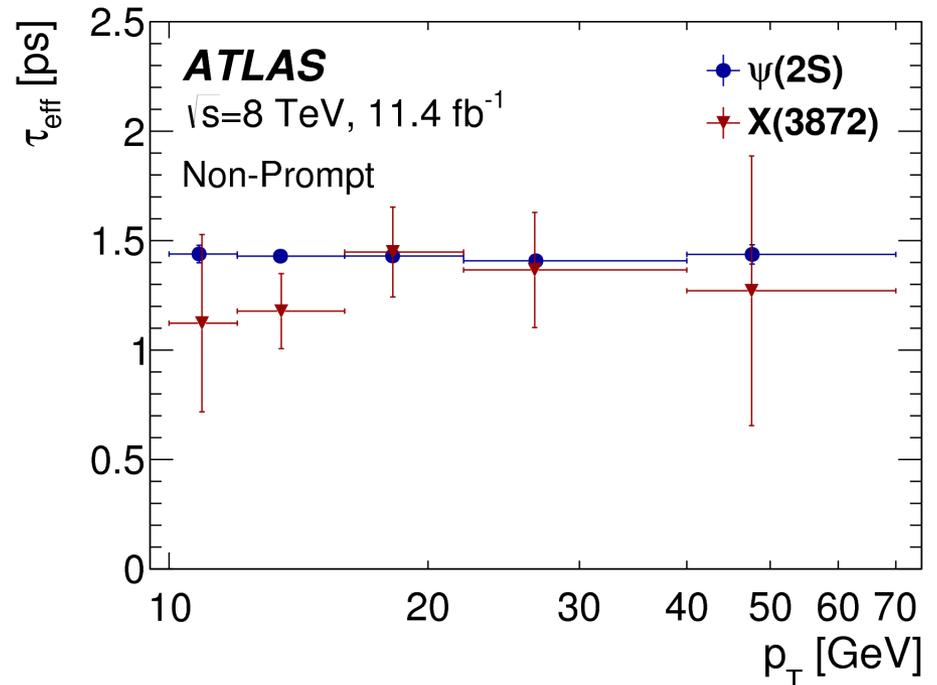
- Define 4 lifetime intervals.
- Fit data distribution in each lifetime interval to a function with 2 double-Gaussian signal functions (the $\psi(2S)$ and the $X(3872)$), polynomial bkg. Extract signal yields Y .

Analysis details (3)

- Apply yields Y to find double differential cross sections \times branching ratios, for $i = X(3872)$ or $\psi(2S)$:

$$B(i \rightarrow J / \psi \pi^+ \pi^-) B(J / \psi \rightarrow \mu^+ \mu^-) \cdot \frac{d^2 \sigma(i)}{dp_T dy} = \frac{Y(i)}{\Delta p_T \Delta y \int L dt}$$

- First fit data in each p_T bin assuming one prompt component and one non-prompt (τ_{eff}) component. Observe: τ_{eff} is different for low- p_T $X(3872)$ decays. Do these proceed by a different mechanism?



Analysis details (4) and results:

- Try 2 lifetimes for the non-prompt decays. (Short component: from B_c decays, long component from all other B^\pm , B^0 , B_s , and b-baryons.)
 - Observe: no short-lived non-prompt component in $\psi(2S)$ production.
 - For $X(3872)$, short-lived non-prompt fraction is 25%:

$$\frac{\sigma(pp \rightarrow B_c) \cdot B(B_c \rightarrow X(3872))}{\sigma(pp \rightarrow \text{non-prompt } X(3872))} = (25 \pm 13 \text{ (stat)} \pm 2 \text{ (syst)} \pm 5 \text{ (spin)})\%$$

- Measure ratio:

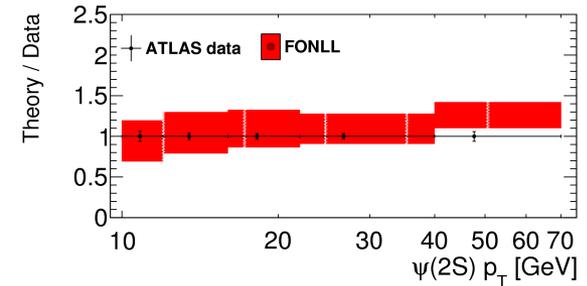
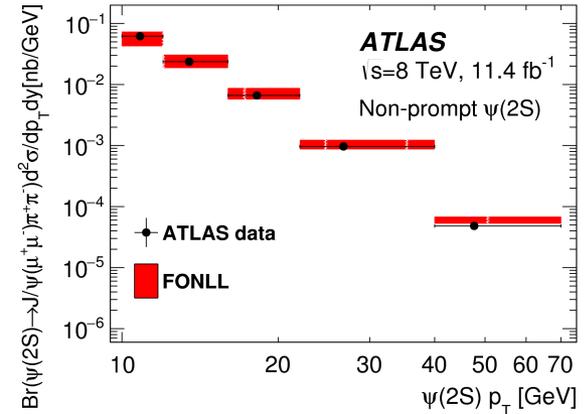
$$R = \frac{B(B \rightarrow X(3872) + \text{any}) \cdot B(X(3872) \rightarrow J / \psi \pi^+ \pi^-)}{B(B \rightarrow \psi(2S) + \text{any}) \cdot B(\psi(2S) \rightarrow J / \psi \pi^+ \pi^-)} = (3.57 \pm 0.33 \pm 0.11) \times 10^{-2}$$

This ratio is below the value inferred from the ratio of Tevatron data (numerator) to the world average of branching fractions (denominator): 0.18 ± 0.08 .

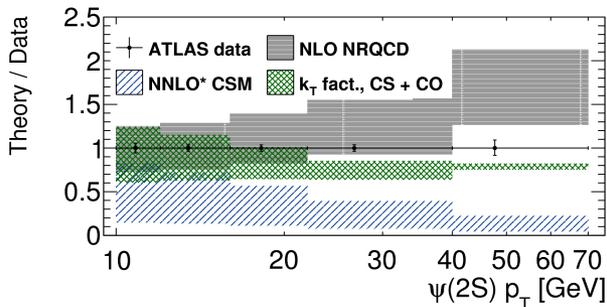
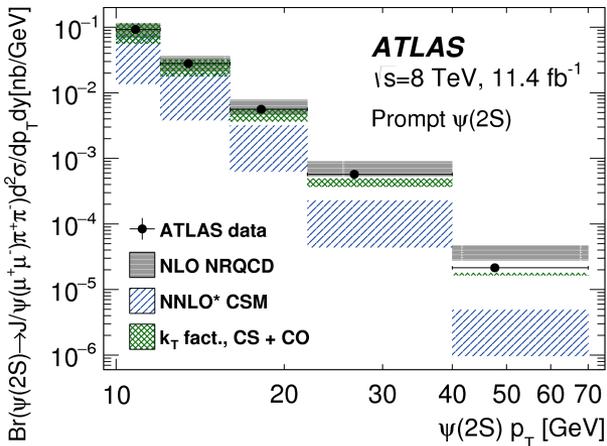
Results on differential cross sections:

For $\psi(2S)$ prompt and non-prompt:

- Generally good agreement between data and NLO NRQCD using long distance matrix elements derived from Tevatron data, below highest p_T
- k_T factorization model including color-octet contributions tuned on 7 TeV CMS data + color singlet contributions describes data well but underestimates at highest p_T .
- NNLO* color singlet model agrees at low p_T .

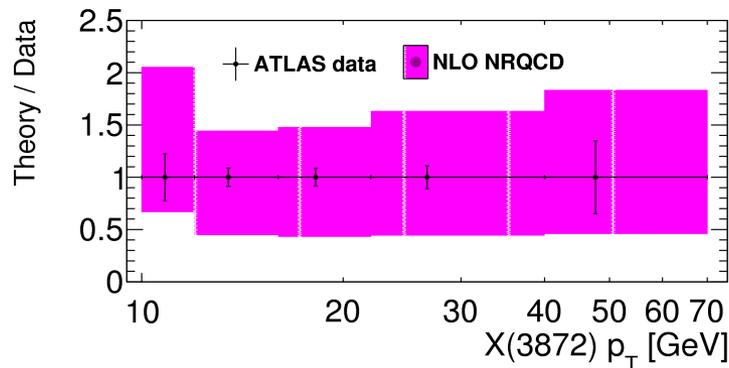
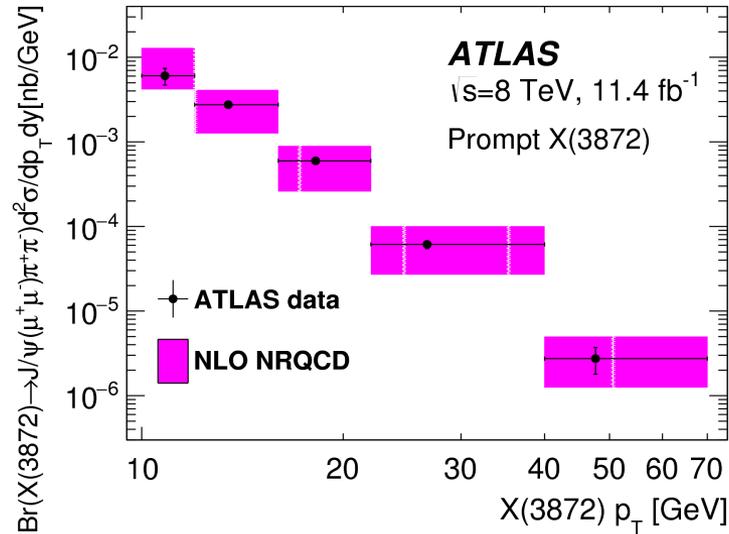


For non-prompt $\psi(2S)$:
good agreement with FONLL over full p_T range

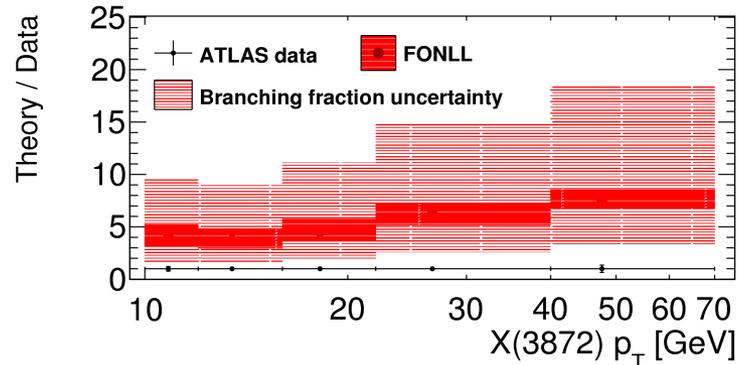
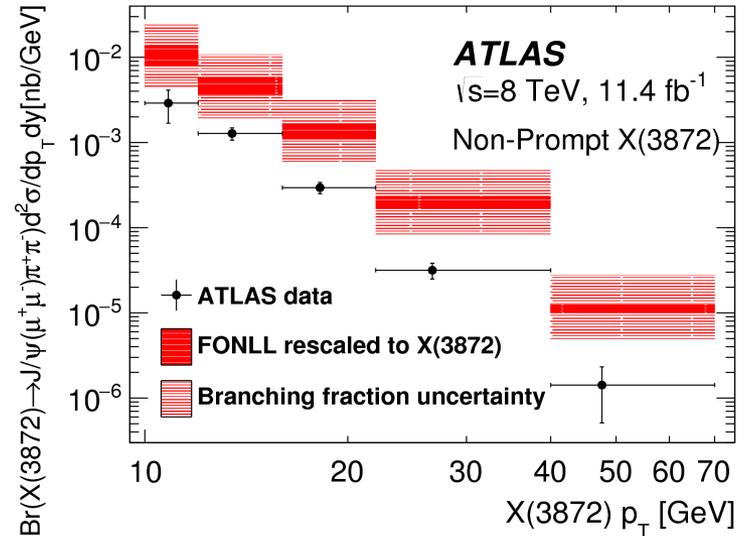


Results on differential cross sections, continued:

For prompt X(3872): described adequately by NRQCD as $\chi_{c1}(2P) - D^0 \bar{D}^{*0}$ mixture

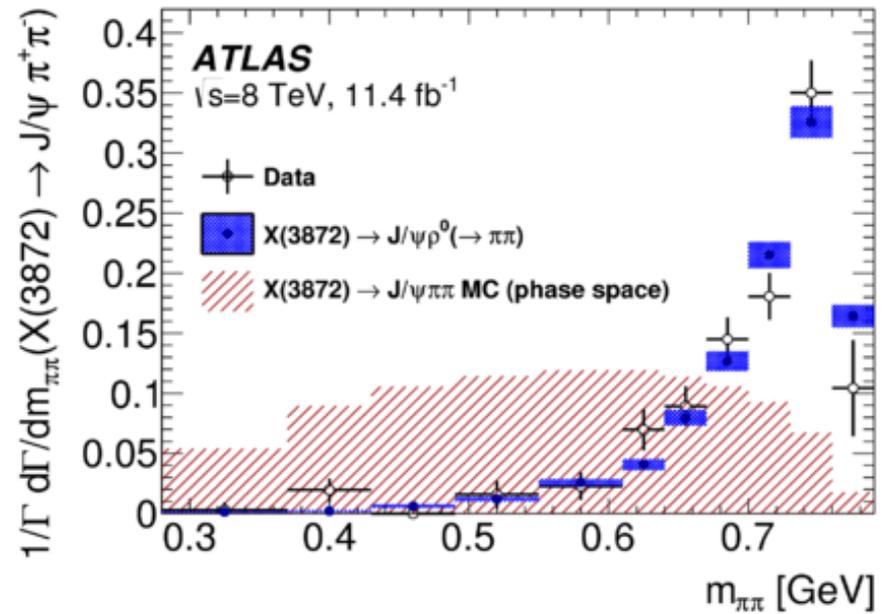
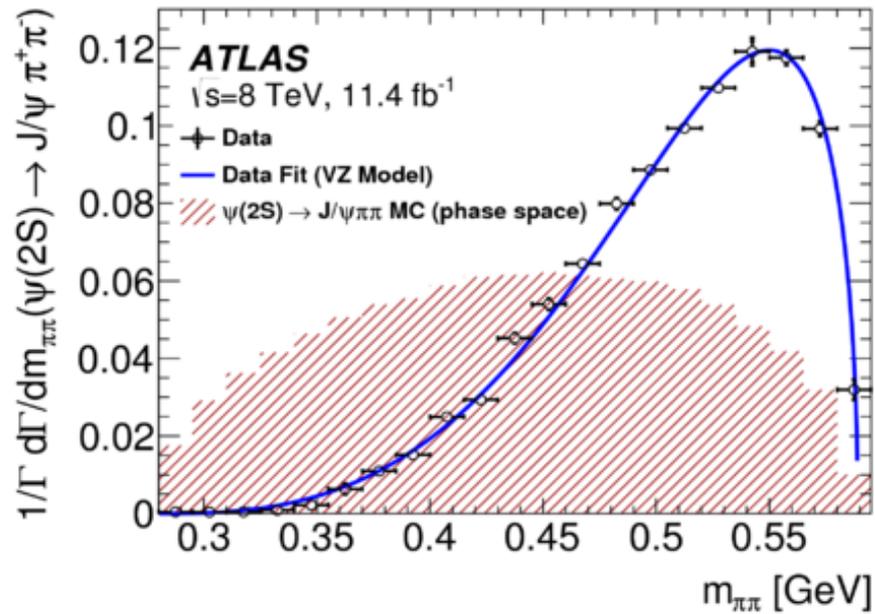


For non-prompt X(3872): FONLL model overestimates data by factor 4-8, increasing with p_T



Results on differential cross sections, continued:

Using the normalized differential decay width in bins of dipion invariant mass, we see that phase space decay is disfavored: **the pion production occurs through $\rho^0 \rightarrow \pi^+\pi^-$** .



Angular Analysis of $B_d^0 \rightarrow K^* (\rightarrow K^+ \pi^-) \mu^+ \mu^-$ Decays*

The message:

The **longitudinal polarization of the K^*** is measured and compared to theoretical predictions.

This polarization can be influenced by *penguin diagrams involving new physics*.

Hadron form factors dominate the prediction at leading order.

LHCb has adopted *a method[§] for minimizing uncertainties in hadron form factors* in this measurement. LHCb observes[¶] a 3.4 sigma deviation from Standard Model calculations. The LHCb method is used here.

*ATLAS-CONF-2017-023 (3 April 2017).

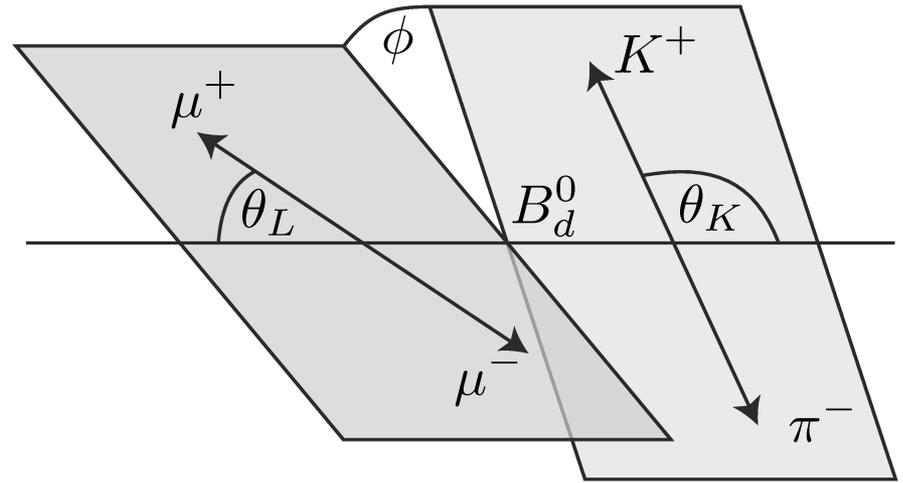
§LHCb Collaboration, PRL 111 (2013) 191801.

¶LHCb Collaboration, JHEP 02 (2016) 104.

The method:

- 3 angular variables:
 - θ_K , between the K^+ and the direction opposite the B_d , in the K^* frame
 - θ_L , between the μ^+ and the direction opposite the B_d , in the dimuon frame
 - ϕ , between the two decay planes formed by the $K\pi$ and dimuon systems, in the B_d frame.

- Measure:



$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_L d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[F_L \cos^2 \theta_K + \frac{3(1-F_L)}{4} \sin^2 \theta_K + \frac{1-F_L}{4} \sin^2 \theta_K \cos 2\theta_L \right. \\ \left. - F_L \cos^2 \theta_K \cos 2\theta_L + S_3 \sin^2 \theta_K \sin^2 \theta_L \cos 2\phi \right. \\ \left. + S_4 \sin 2\theta_K \sin 2\theta_L \cos \phi + S_5 \sin 2\theta_K \sin \theta_L \cos \phi \right. \\ \left. + S_6 \sin^2 \theta_K \cos \theta_L + S_7 \sin 2\theta_K \sin \theta_L \sin \phi \right. \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_L \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_L \sin 2\phi \right]$$

The familiar forward-backward asymmetry is given by $A_{FB} = 3S_6/4$.

- The method to reduce hadronic form factor dependence is this: the S_i depend on the form factors and have significant uncertainty at LO. *Transform the S_i using ratios constructed to cancel the form factor dependence at LO:*

$$P_1 = \frac{2S_3}{1 - F_L}$$

$$P_2 = \frac{2}{3} \frac{A_{FB}}{1 - F_L}$$

$$P_3 = -\frac{S_9}{1 - F_L}$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}$$

- All these parameters depend on the invariant mass squared of the dilepton system (q^2), *so analyze data in 6 partially-overlapping q^2 bins.*

Analysis details:

- Integrated luminosity = 20.3 fb^{-1}
- Trigger: 1, 2, or 3 muons
- Reconstruct muons: $p_T > 3.5 \text{ GeV}$, $|\eta| < 2.5$
- Require: $\mu^+\mu^-$ reconstruct to a common vertex
- Candidate kaon, pion tracks: $p_T > 0.5 \text{ GeV}$ [no dedicated particle ID in ATLAS]
- Select K^* mesons: $p_T(K^*) > 3.0 \text{ GeV}$, $m(K\pi)$ within $[846,946] \text{ MeV}$.
- Reconstruct B candidate:
 - Flavor assigned from K charge.
 - Vertex K^* with $\mu^+\mu^-$
 - Require consistent vectors: vector from PV to B_d decay vertex, and B_d momentum vector
- Suppress combinatorial bkg with lifetime significance cut: $\tau(B_d)/\sigma_\tau > 12.5$
- Suppress partially recon decays with tight lower cut around nominal B_d mass:
 $5150 < m(K\pi\mu\mu) < 5700 \text{ MeV}$
- to eliminate extra candidates per event, choose best match to $m(K^*)_{\text{PDG}}$, and best B vertex fit.
- q^2 bin range: $[0.04,6.0]$ excluding $[9.8,1.1]$ (to remove ϕ resonance)
- Compare data to a model using maximum likelihood, for Gaussian signal, with parameters taken from a control region, and 4 bkg components
- To overcome low statistics, a “folding procedure” of transformations is used that exploits trigonometric relations among the angular parameters.

The models:

- Ciuchini et al. (CFFMPSV)¹ – QCD factorization framework to perform consistency checks of the LHCb data with theory expectations
- Descotes-Genon et al. (DHMV)² – QCD factorization
- Jäger and Camalich (JC)³ - QCD factorization, focus on impact of long distance corrections using a helicity amplitude approach

Results:

Good agreement except in 3 q^2 bins: P'_4 and P'_5 in q^2 bin [4.0,6.0] and P'_8 in q^2 bin [2.0,4.0].

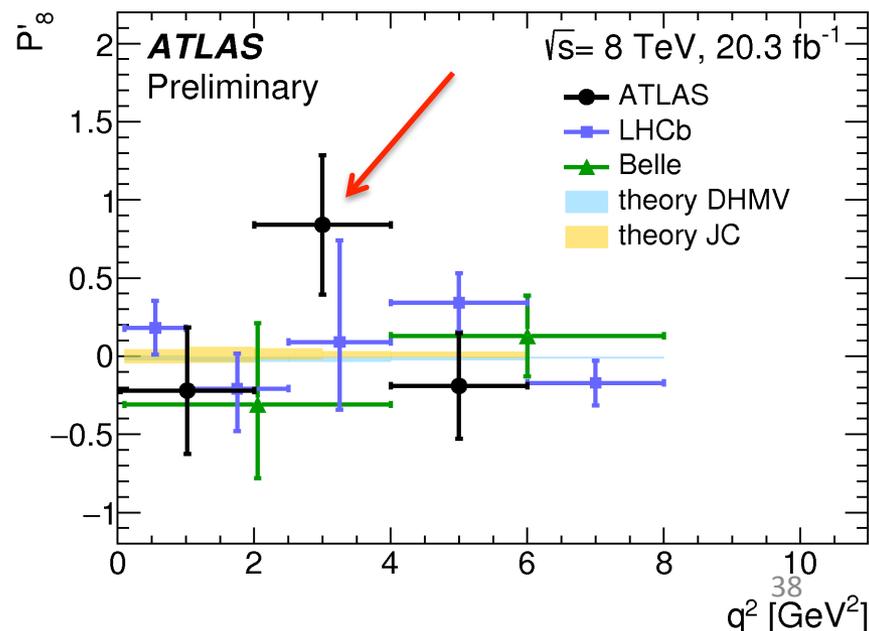
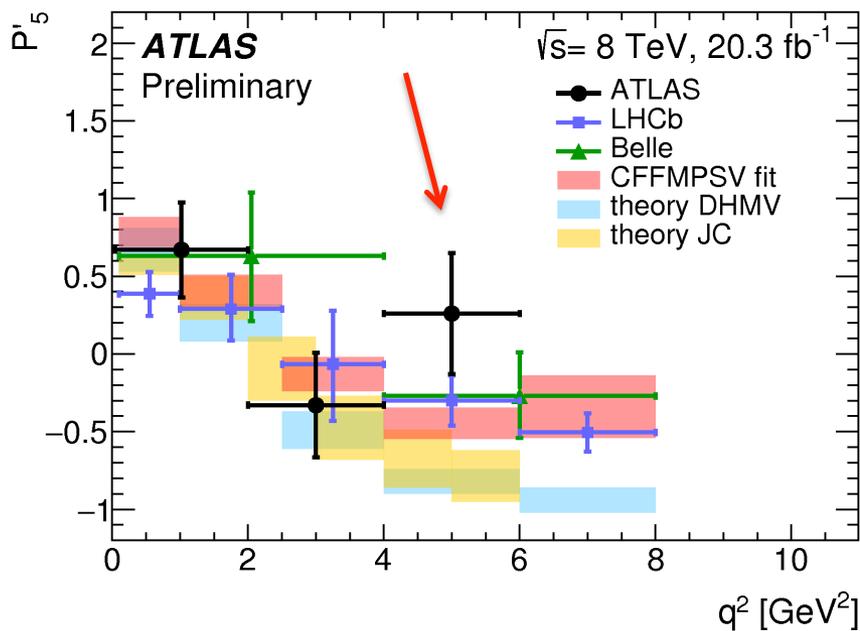
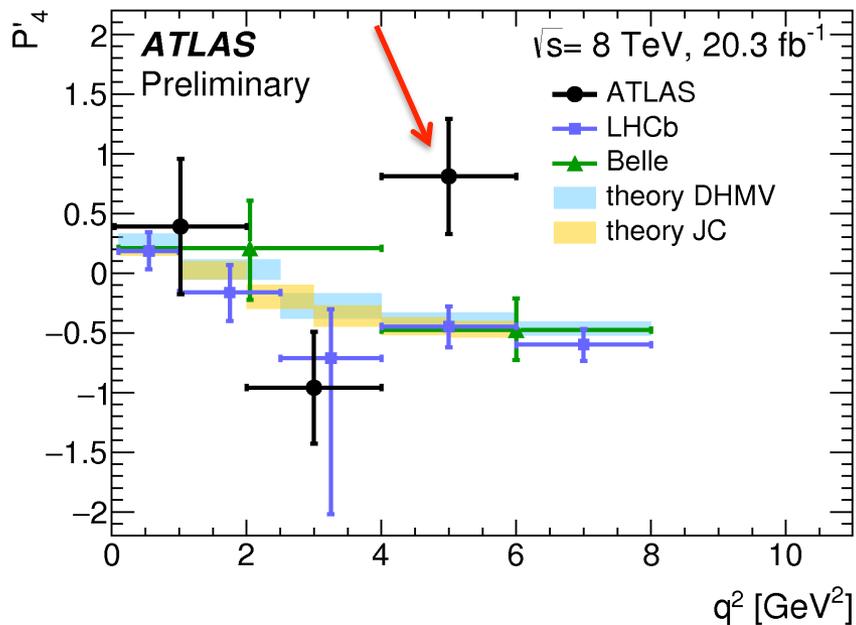
The P'_4 (P'_5) deviations are consistent with the LHCb observation and are 2.5 (2.7) sigma from the DHMV model. All measurements are within 3 sigma of the SM theory band. They are also compatible with the LHCb result.

¹ JHEP 06 (2016)116, arXiv: 1512.07157 [hep-ph]

² JHEP 12 (2014) 125, arXiv: 1407.8526 [hep-ph]

³ JHEP 05 (2013) 043, arXiv: 1212.2263 [hep-ph]; PRD 93 (2016) 014028, arXiv: 1412.3183 [hep-ph]

The 3 noted deviations,
for ATLAS and LHCb
data and theoretical
models



Summary

ATLAS presents 4 measurements using data recorded at $\sqrt{s} = 8$ TeV at the LHC. All are compared to contemporary models.

- **Differential cross sections for b-hadron pair production** – *to improve the theoretical description of quarkonium production and to facilitate background subtractions in new physics searches.*
- **Prompt J/ψ pair production differential cross sections** – *to characterize double parton scattering as a probe of the gluon distribution in the proton, and to investigate correlations in the non-perturbative regime.*
- **Differential production cross sections for $\psi(2S)$ and $X(3872)$, both observed in decays to $J/\psi\pi^+\pi^-$** – *a study of production mechanisms through examination of prompt and non-prompt signals.*
- **An angular analysis of $B_d^0 \rightarrow K^*\mu^+\mu^-$ decays** – *a potential probe of new physics contributions through penguin diagrams.*