Overview of ATLAS Heavy Flavor Measurements

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III. Prompt J/ψ Pair Production Cross-section
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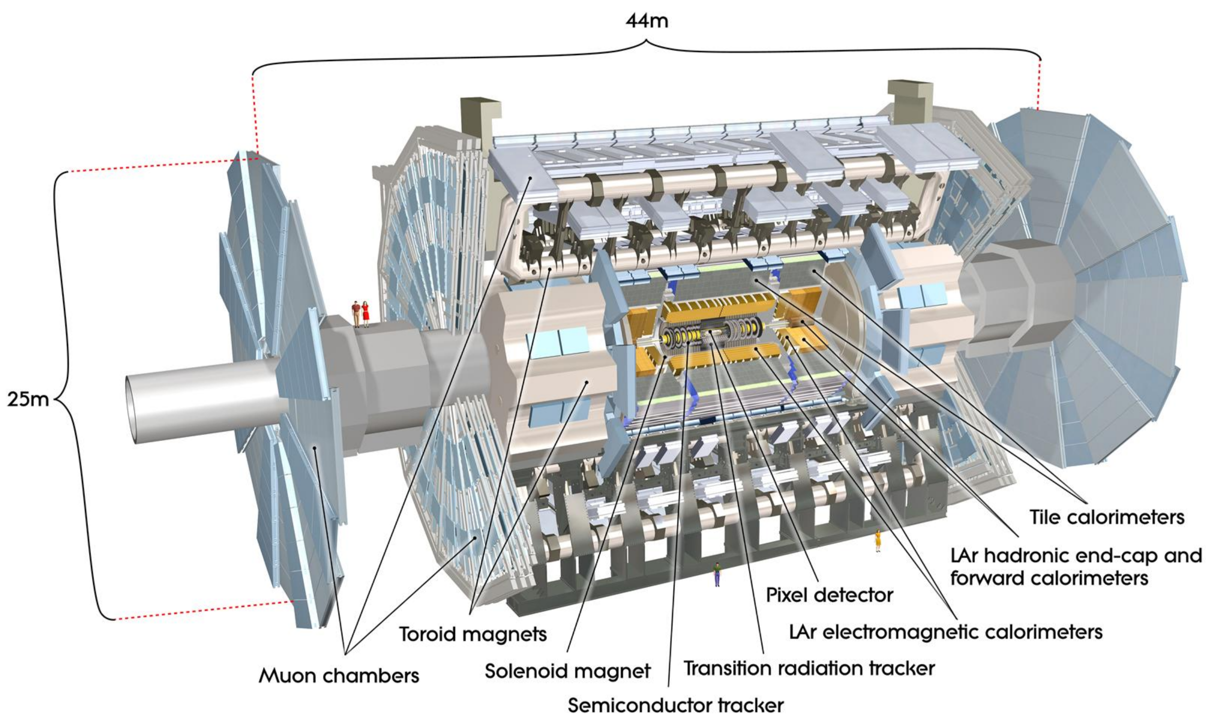
Introduction

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: $\sigma\left(B\left(\to J/\psi\left[\to \mu^+\mu^-\right]+X\right)B\left(\to \mu+X\right)\right)$

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
- $\frac{1}{\sigma}\frac{d\sigma}{dm(J/\psi\mu)}[\mathrm{GeV}^{-1}]$ mass of the J/ψμ system
- $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi(J/\psi\mu)}[\mathrm{rad}^{-1}]$ 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.....

*JHEP 11 (2017) 062.

- $$\frac{1}{\sigma}\frac{d\sigma}{dy_{boost}(J/\psi\mu)}$$ 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, $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.4$, $2.5 < m(\mu\mu) < 4.3$ GeV
- Integrated luminosity = 11.4 fb^{-1}
- Primary vertex: ≥ 2 tracks, each with $p_T > 400$ MeV, with largest summed p_T^2.
- Form the muon candidates:
  - use combined inner detector and muon spectrometer tracks
  - $p_T(\mu) > 6$ 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
  - $2.6 < m(\mu\mu) < 3.5$ 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.
  - $pp \to b\bar{b}$ 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:

$$\tau \equiv \frac{L_{xy} \cdot m\left(J/\psi_{PDG}\right)}{p_T\left(\mu^+\mu^-\right)}$$

  - 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 bkgs: 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 bkgs from fitted yields:
  - $B_c \to J/\psi + \mu + X$ (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

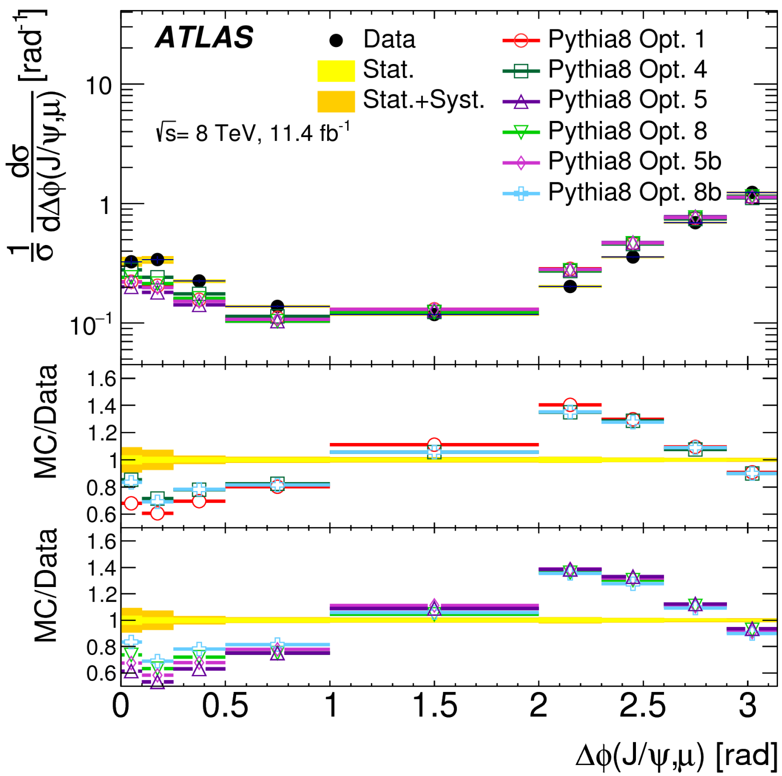
Luminosity uncertainty: 1.9%

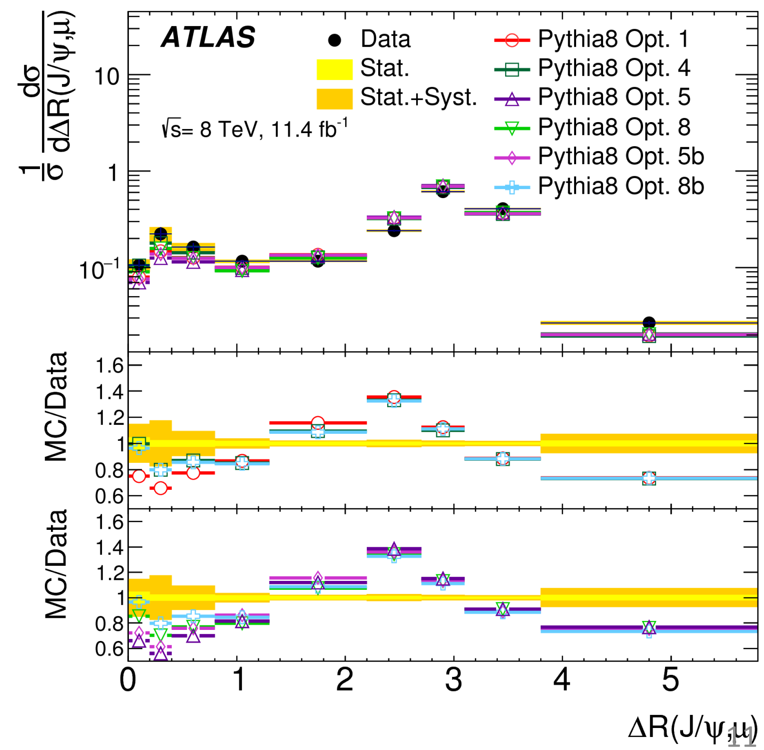
Result 1: $\sigma\left(B\left(\rightarrow J/\psi\left[\rightarrow \mu^{+}\mu^{-}\right]+X\right)B\left(\rightarrow \mu+X\right)\right)=17.7\pm0.1(\text{stat})\pm2.0(\text{syst})$ nb.

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:





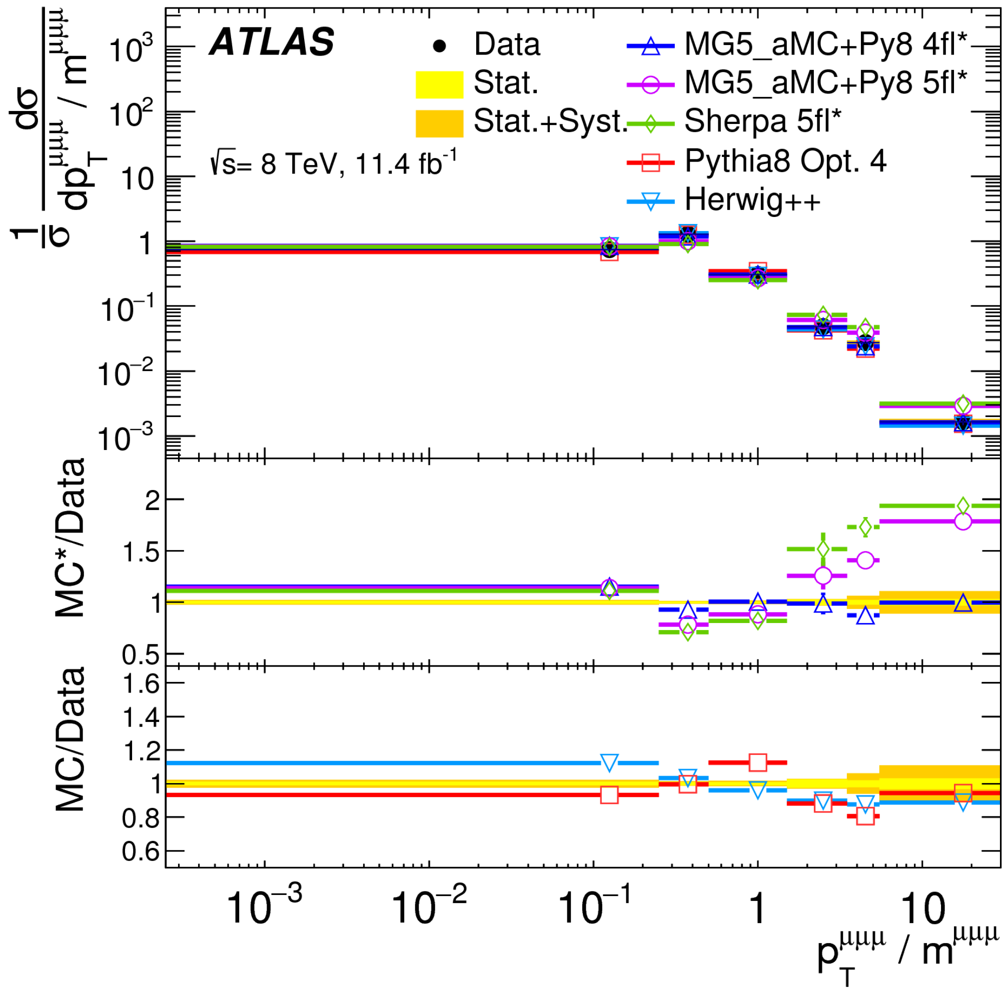
Result 3:

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 element 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/ψ_2") - Measurements use subleading meson J/ψ_2 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.

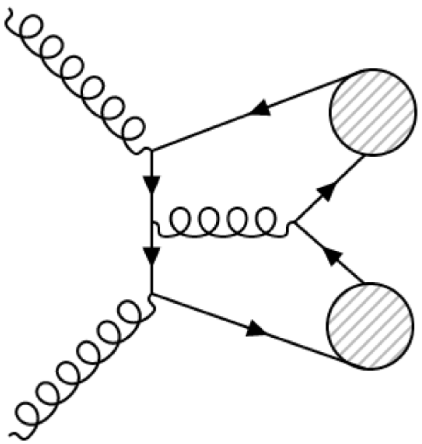
Total and double parton scattering cross sections are compared with predictions.

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

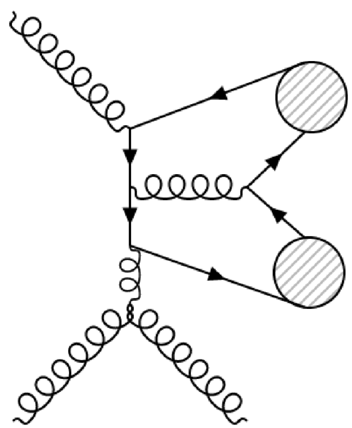
This is the first such measurement at 8 TeV, and it probes a different kinematical range from previous (1.96 TeV and 7 TeV) measurements.

*Eur. Phys. J. C (2017) 77:76.

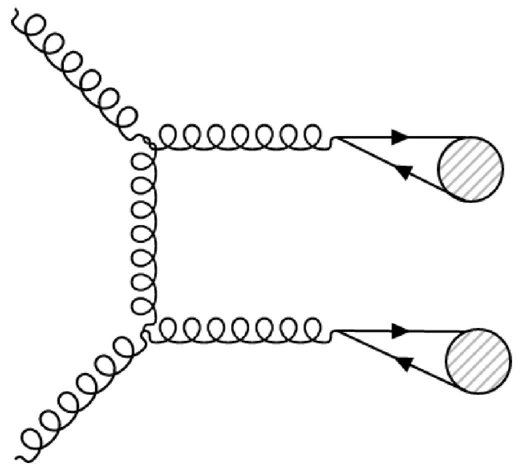
What the events look like: each shaded circle is a J/ψ meson. Di-J/ψ's can be produced from single parton (g-g) scattering ("SPS") or from double parton scattering ("DPS").



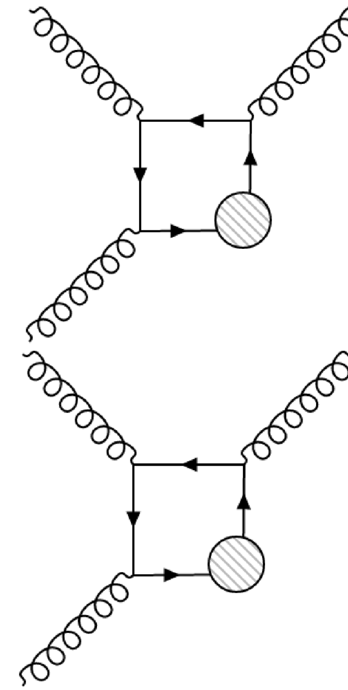
LO SPS



NLO SPS, color singlet J/ψ



LO SPS,
color octet cċ



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 $p_T > 4$ GeV; $2.5 < m(\mu^+\mu^-) < 4.3$ GeV
- Reconstruction:
  - ≥ 3 muons in the muon spectrometer data
  - Record $|d_z|$ of 2 J/ψ decay vertices projected onto the beam axis
  - $|\eta^\mu| < 2.3$, $p_T^\mu > 2.5$ GeV
  - $2.8 < m(\mu\mu) < 3.4$ GeV
  - $|y^{J/\psi}| < 2.1$, $p_T^{J/\psi} > 8.5$ 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/ψ_1) vs. m(J/ψ_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 $w_{DPS(SPS)}(\Delta\phi,\Delta y) = \dfrac{N_{DPS(SPS)}(\Delta\phi,\Delta y)}{N_{Data}(\Delta\phi,\Delta y)}$
  - 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:

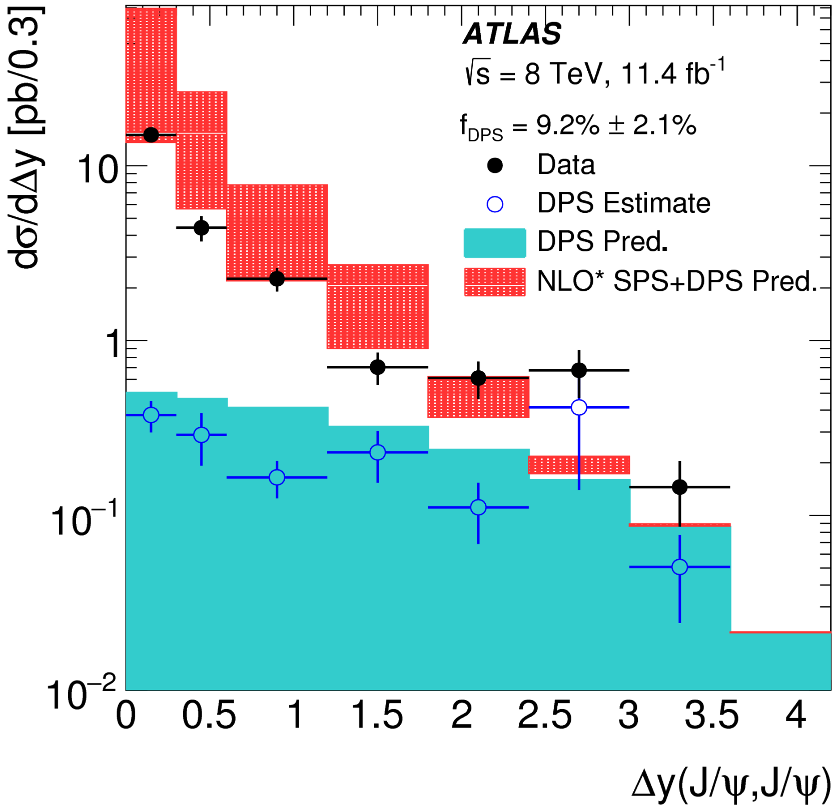
- Prompt-prompt cross sections measured:

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

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

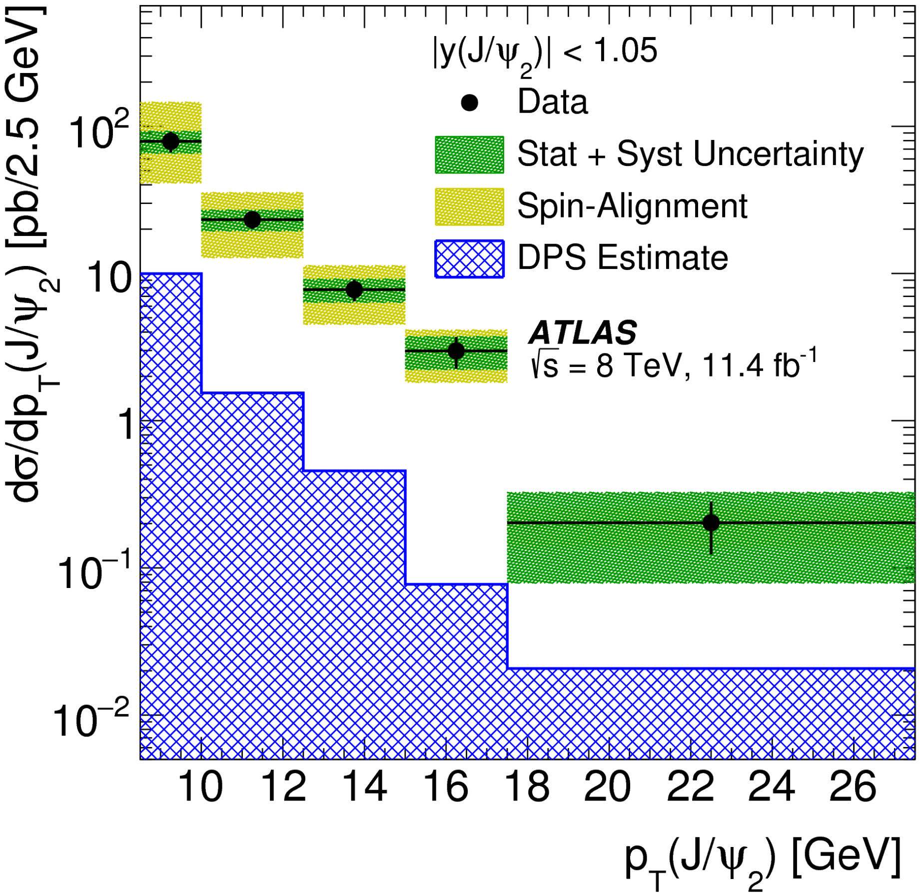
- Data are compared to theoretical distributions.[§] *Shapes of DPS distributions are consistent with models.* For SPS, the data distributions in Δy, $|\Delta\phi|$, $m(J/\psi J/\psi)$, and $p_T(J/\psi J/\psi)$ are wider than predicted by the NLO calculation.

- 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 $\psi(2S)$.

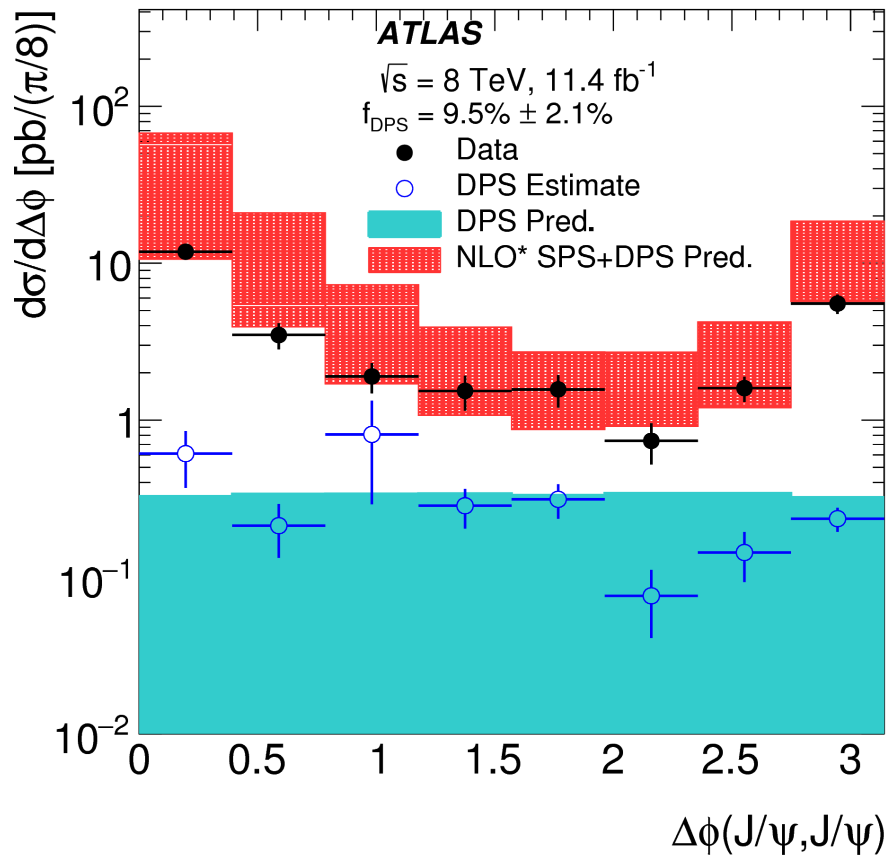


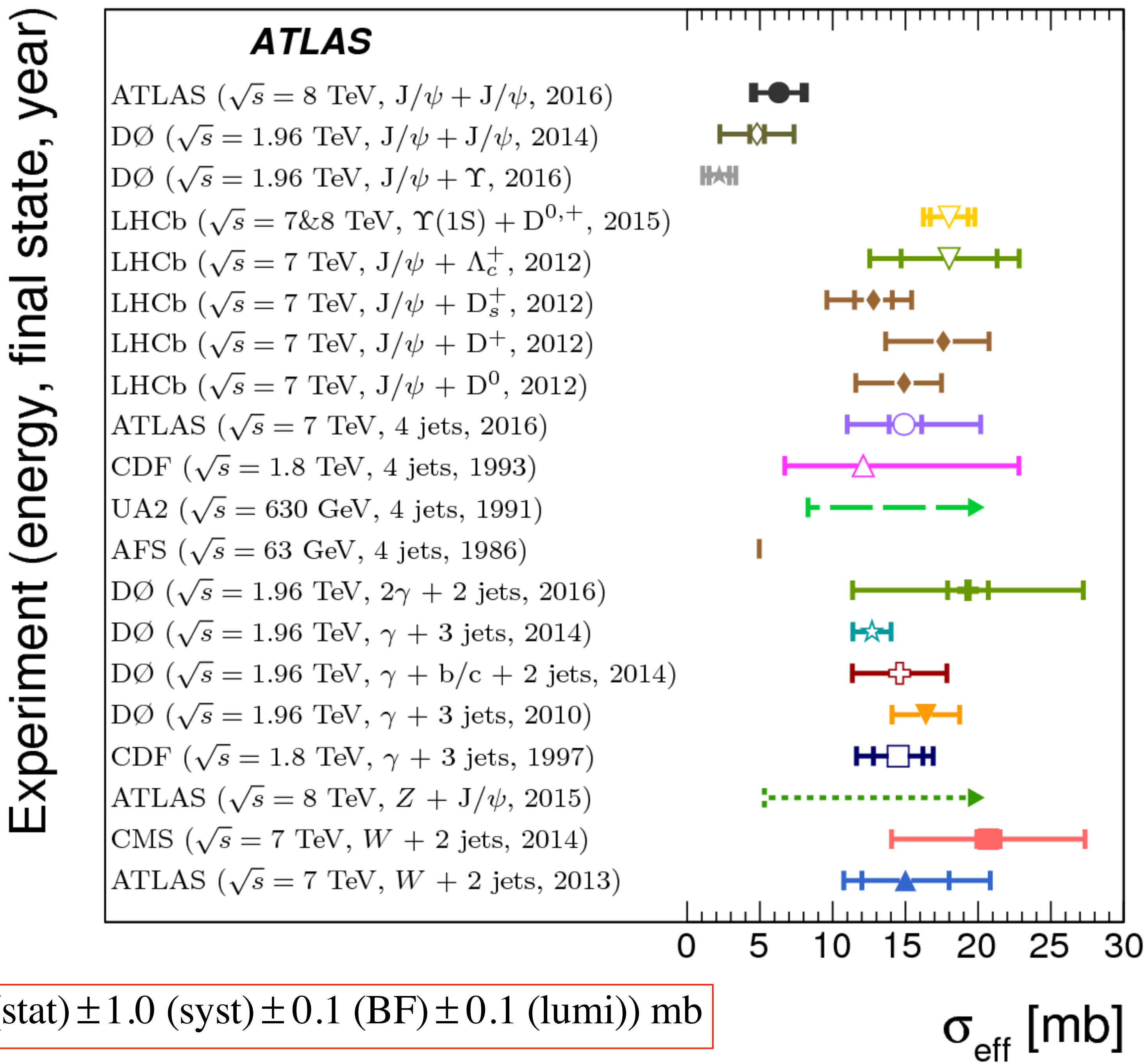
[§]LO DPS: C. Borschensky and A. Kulesza, arXiv: 1610.00666 [hep-ph];
NLO* SPS: J.P. Lansbert, H.S. Shao, Phys. Lett. B 751, 479 (2015) and PRL 111, 122001 (2013).

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



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





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

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

Message:

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

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

The fraction of non-prompt X(3872) and the fraction of non-prompt ψ(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 $\rho^0 \to \pi^+\pi^-$.

*JHEP 01 (2017) 117.

Motivation:

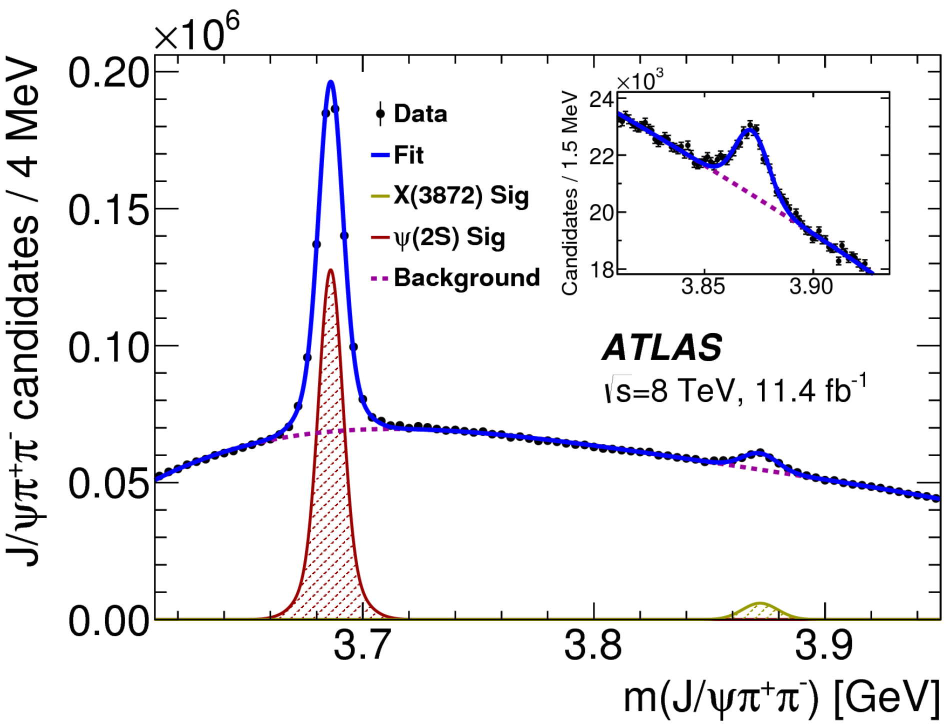
This study examines:

- 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
  - $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.3$, $m(\mu\mu)$ within $m_{J/\psi} \pm 120$ MeV
- Find $J/\psi\pi^+\pi^-$ candidates:
  - Constrain $m(\mu\mu)$ to $m(J/\psi)_{PDG}$, then assign pion masses to 2 additional oppositely charged non-muon tracks and fitted to a common vertex with the muons. $p_T(\pi) > 0.6$ GeV, $|\eta(\pi)| < 2.4$.
  - $J/\psi\pi^+\pi^-$ rapidity $|y| < 0.75$; $10 < p_T < 70$ GeV.
  - $\Delta R(J/\psi,\pi^\pm) < 5$: the angular distance between momenta of the dimuon system and each candidate.
  - Require: $Q = m(J/\psi\pi^+\pi^-) - m(J/\psi) - m(\pi\pi) < 0.3$ 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.

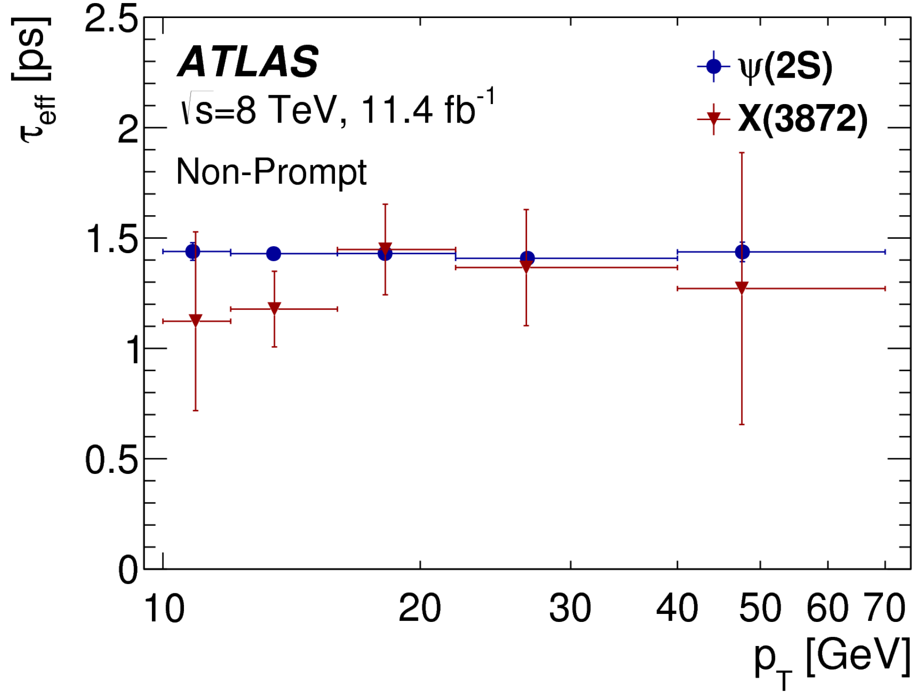
- Define 4 lifetime intervals.
- Fit data distribution in each lifetime interval to a function with 2 double-Gaussian signal functions (the $\psi(2S)$ and the X(3872), polynomial bkg. Extract signal yields Y.

Analysis details (3)

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

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

- 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 ψ(2S) production.
  - For X(3872), short-lived non-prompt fraction is 25%:

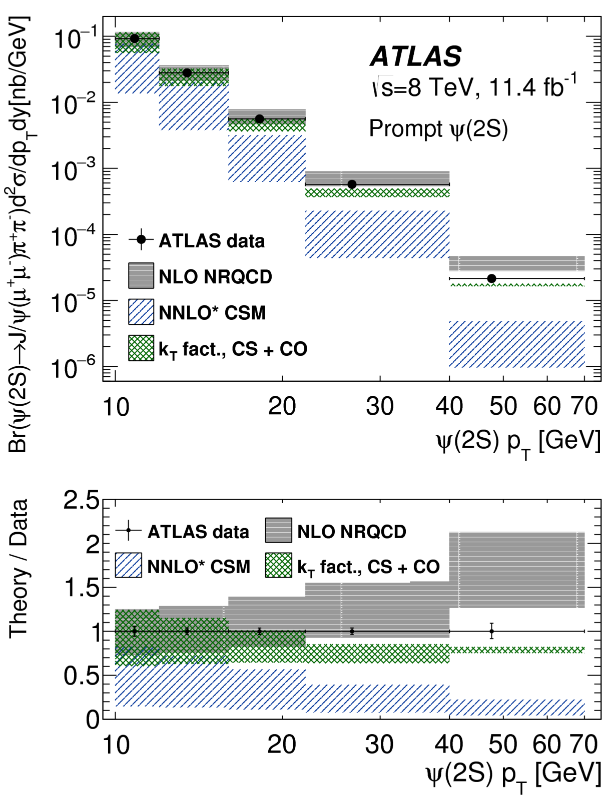
$$\frac{\sigma\left(pp \to B_c\right) \cdot B\left(B_c \to X(3872)\right)}{\sigma\left(pp \to \text{non-prompt } X(3872)\right)} = \left(25 \pm 13 \text{ (stat)} \pm 2 \ (\text{syst}) \pm 5 \ (\text{spin})\right)\%$$

- Measure ratio:

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

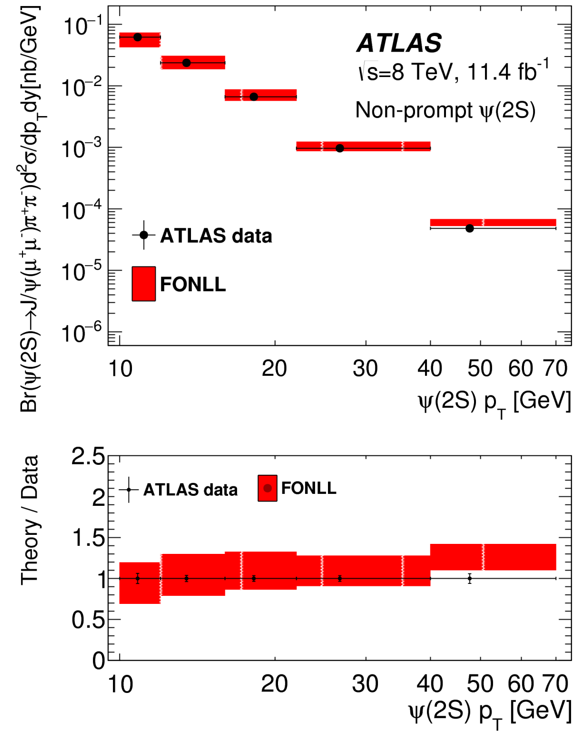
This ratio is below the value inferred from the ratio of Tevatron data (numerator) to the world average of branching fractions (denominator): 0.18 ± 0.08.

Results on differential cross sections:



For prompt ψ(2S):

- 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.

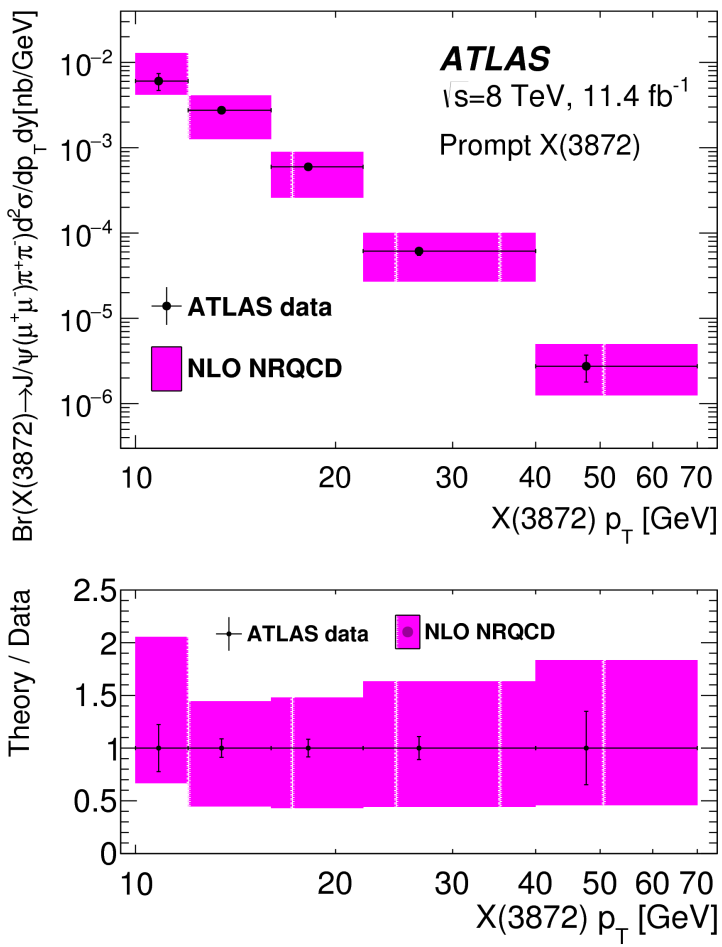


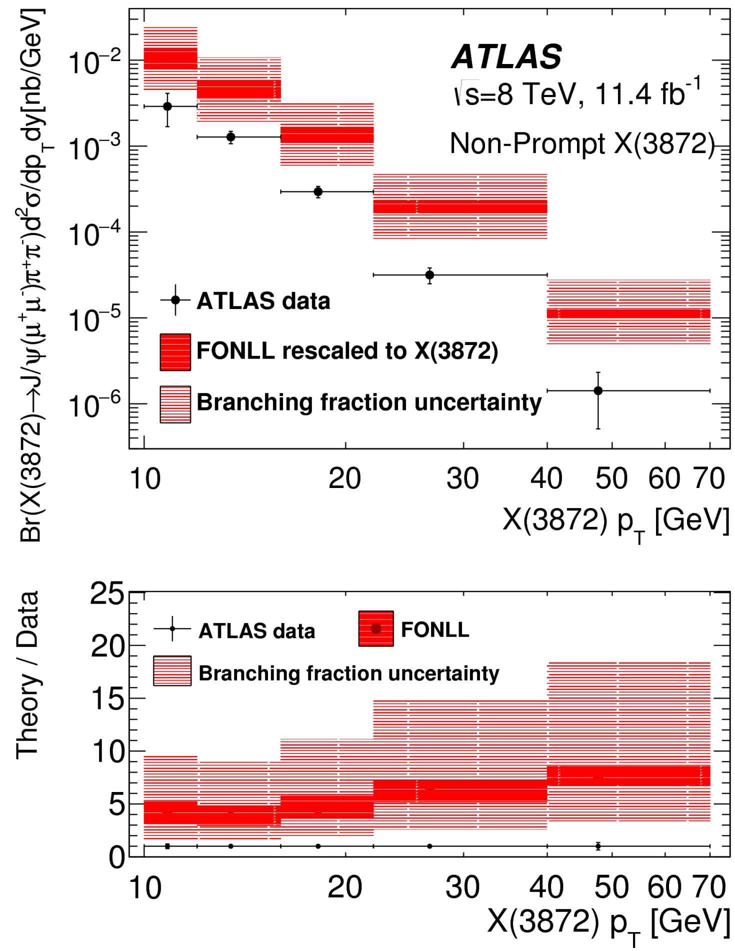
For non-prompt ψ(2S): good agreement with FONLL over full p_T range

Results on differential cross sections, continued:

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

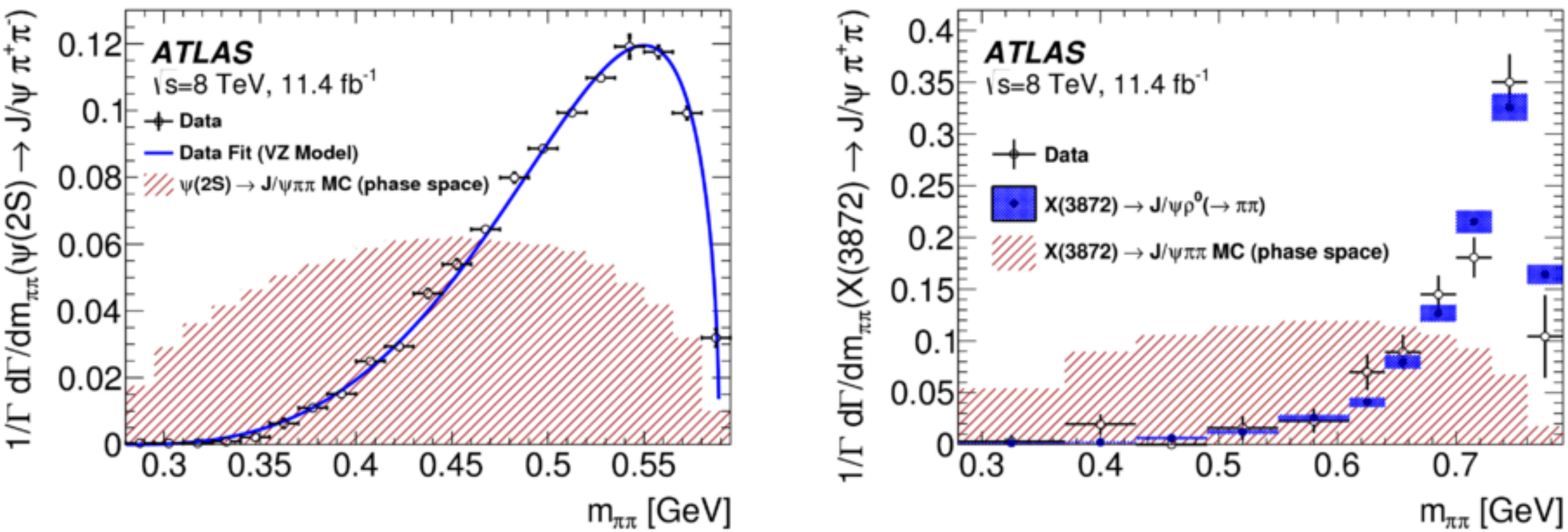
For non-prompt X(3872): FONLL model overestimates data by factor 4-8, increasing with p_T





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 $\rho^0 \to \pi^+\pi^-$.



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

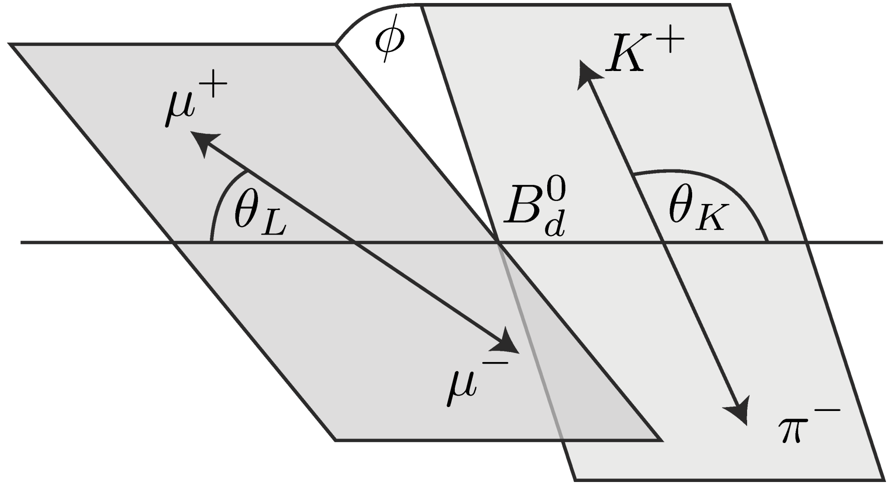
Hadron form factors dominate the prediction at leading order.
LHCb has adopted *a method§ for minimizing uncertainties in hadron form factors* in this measurement. LHCb observes¶ a 3.4 sigma deviation from Standard Model calculations. The LHCb method is used here.

*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:

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

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:*

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

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

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

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

- 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: $p_T > 3.5$ GeV, $|\eta| < 2.5$
- Require: $\mu^+\mu^-$ reconstruct to a common vertex
- Candidate kaon, pion tracks: $p_T > 0.5$ GeV *[no dedicated particle ID in ATLAS]*
- Select K^* mesons: $p_T(K^*) > 3.0$ GeV, $m(K\pi)$ within [846,946] 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: $5150 < m(K\pi\mu\mu) < 5700$ MeV
- to eliminate extra candidates per event, choose best match to $m(K^*)_{PDG}$, 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].

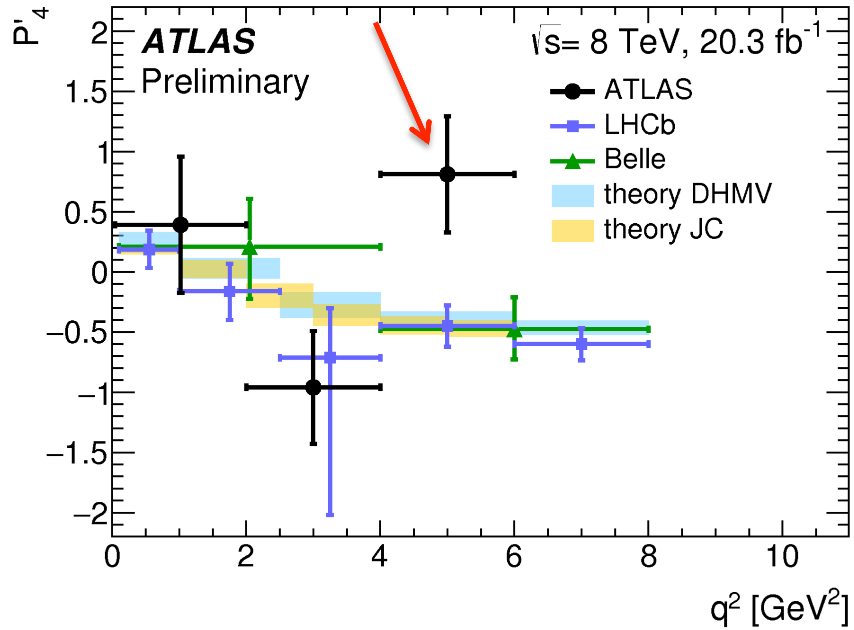
The P'_4 (P'_5) deviations are consistent with the LHCb observation and are 2.5 (2.7) sigma from the DHMV model. All measurements are within 3 sigma of the SM theory band. They are also compatible with the LHCb result.

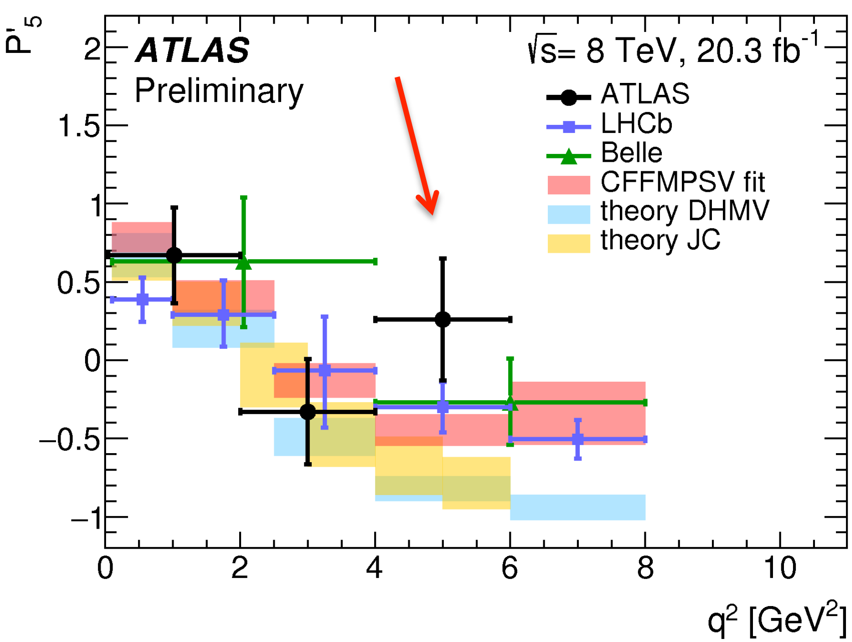
[1] JHEP 06 (2016)116, arXiv: 1512.07157 [hep-ph]

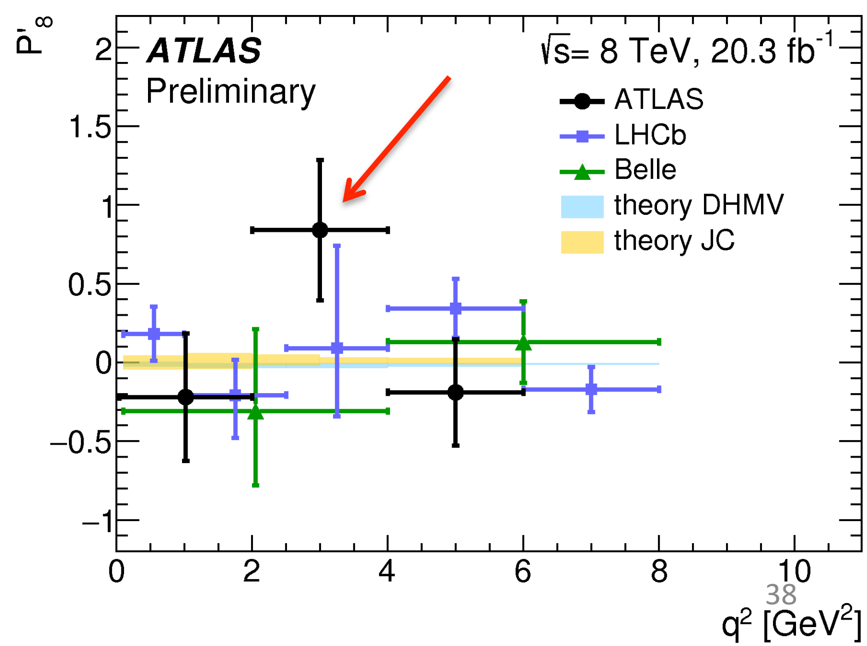
[2] JHEP 12 (2014) 125, arXiv: 1407.8526 [hep-ph]

[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 √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 ψ(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** $B_d^0 \to K^* \mu^+ \mu^-$ **decays** - *a potential probe of new physics contributions through penguin diagrams.*