Overview of ATLAS Heavy Flavor Measurements

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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: 

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

Using it, 8 differential cross sections are obtained:

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

the list continues.....

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magnitude $y_{\text{boost}}$ of the avg. rapidity of the $J/\psi$ and the third $\mu$

\[
\frac{1}{\sigma} \frac{d\sigma}{dy_{\text{boost}} (J/\psi\mu)}
\]

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

\[
\frac{1}{\sigma} \frac{d\sigma}{dp_{T\mu\mu\mu} / m_{\mu\mu\mu}}
\]

and its inverse

\[
\frac{1}{\sigma} \frac{d\sigma}{dm_{\mu\mu\mu} / p_{T\mu\mu\mu}}
\]

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, $|\eta(\mu)| < 2.5$
- **$J/\psi$ 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 $J/\psi_{PDG}$.
- **Third muon**: choose the highest-$p_T$ one not included in the $J/\psi$ reconstruction.
- **The $J/\psi$ and the third $\mu$ 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:

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

- 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 $\tau$.
- Extract # non-prompt J/ψ’s.
Analysis details (3)

- **To select the third muon**, reject bkg: prompt muons, muons from charged $\pi/K$ decay, fake muons from decay in flight and hadron shower leakage, muons combined with continuum (false) $J/\psi$, and muons in pile-up.

- **Discriminate third-muon signal from bkg with a simultaneous fit on 2 observables:**
  - transverse impact parameter significance
    \[ S_{d_0} \equiv \frac{d_0}{\sigma_{d_0}} \]
    
    ($d_0$ is distance of closest approach of the muon track to the PV in the $r$-$\phi$ 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 s** 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 $\pi/K$: traverses the detector to the muon spectrometer without interacting or decaying (mimics a muon, taken from simulation)
Analysis details (4)

Corrections:
- for the $\tau$ requirement: extrapolate to full range
- for detector resolution on momentum and $\eta$ 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
- $J/\psi$ 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: \[ \sigma \left( B \left( \rightarrow J/\psi \left[ \rightarrow \mu^+ \mu^- \right] + X \right) B \left( \rightarrow \mu + X \right) \right) = 17.7 \pm 0.1 \text{(stat)} \pm 2.0 \text{(syst)} \text{ nb.} \]

Result 2: Is the scale of \( \alpha_s \) 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 \( \alpha_s \) scale fit better to the mass or \( \Delta R \) 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 $\Delta R$ and $\Delta \phi$ graphs best.
- 4-massless flavors models $\Delta R$ and $\Delta \phi$ better than 5.
- $\Delta y$ spectrum is well modeled by MadGraph and SHERPA
- All models reproduce $y_{\text{boost}}$ 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.
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
- Δφ 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 $J/\psi$ meson. Di-$J/\psi$’s can be produced from single parton (g-g) scattering ("SPS") or from double parton scattering ("DPS").

LO SPS

NLO SPS, color singlet $J/\psi$

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:

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

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-$J/\psi$ 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 ψ(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 $J/\psi$ 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 $J/\psi$ candidate, find the signed transverse decay length $L_{xy}$ (recall from page 8)
- Because $J/\psi$ 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”)
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 $J/\psi$ mesons from different random events in the di-$J/\psi$ sample.
  - Construct a *data-driven SPS template* by subtracting the DPS template from the di-$J/\psi$ samples’ $\Delta y$ 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 $\eta$ cuts on fiducial region)
- Signal efficiency on $d_z$ and $L_{xy}$
- $p_T$-dependence of reconstructed mass and mass resolution of $J/\psi$

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

- Prompt-prompt cross sections measured:

\[ \sigma_{\text{central}} (J/\psi J/\psi) = 82.2 \pm 8.3 \, \text{(stat.)} \pm 6.3 \, \text{(syst.)} \pm 0.9 \, \text{(BF)} \pm 1.6 \, \text{(lumi)} \, \text{pb} \]
\[ \sigma_{\text{forward}} (J/\psi J/\psi) = 78.3 \pm 9.2 \, \text{(stat.)} \pm 6.6 \, \text{(syst.)} \pm 0.9 \, \text{(BF)} \pm 1.5 \, \text{(lumi)} \, \text{pb} \]

- Data are compared to theoretical distributions. \(^\S\) Shapes of DPS distributions are consistent with models. For SPS, the data distributions in \(\Delta y\), \(|\Delta \phi|\), \(m(J/\psi J/\psi)\), 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 \(\psi(2S)\).

\[ f_{DPS} = (9.2 \pm 2.1 \text{ (stat)} \pm 0.5 \text{ (syst)})\%, \]
consistent with model predictions, for example:
$\sigma_{\text{eff}} = (6.3 \pm 1.6 \text{ (stat)} \pm 1.0 \text{ (syst)} \pm 0.1 \text{ (BF)} \pm 0.1 \text{ (lumi)}) \text{ mb}$
Measurements of $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ 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 $\rho^0 \rightarrow \pi^+ \pi^-$.  

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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 $\eta$-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 (\( \tau_{\text{eff}} \)) component. Observe: \( \tau_{\text{eff}} \) 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%:
    \[ \frac{\sigma(pp \to B_c) \cdot B(B_c \to X(3872))}{\sigma(pp \to \text{non-prompt } X(3872))} = (25 \pm 13 \text{ (stat)} \pm 2 \text{ (syst)} \pm 5 \text{ (spin)})\% \]

- Measure ratio:
  \[ R = \frac{B(B \to X(3872) + \text{any}) \cdot B(X(3872) \to J/\psi \pi^+ \pi^-)}{B(B \to \psi(2S) + \text{any}) \cdot B(\psi(2S) \to J/\psi \pi^+ \pi^-)} = (3.57 \pm 0.33 \pm 0.11) \times 10^{-2} \]

This ratio is below the value inferred from the ratio of Tevatron data (numerator) to the world average of branching fractions (denominator): $0.18 \pm 0.08$. 
Results on differential cross sections:

- **For prompt $\psi(2S)$:**
  - 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 $\psi(2S)$:**
  - 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.


¶LHCb Collaboration, JHEP 02 (2016) 104.
The method:

- 3 angular variables:
  - $\theta_K$, between the $K^+$ and the direction opposite the $B_d$, in the $K^*$ frame
  - $\theta_L$, between the $\mu^+$ and the direction opposite the $B_d$, in the dimuon frame
  - $\phi$, between the two decay planes formed by the $K\pi$ and dimuon systems, in the $B_d$ frame.

- Measure:

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

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:

$$P_1 = \frac{2S_3}{1 - F_L}$$
$$P_2 = \frac{2A_{FB}}{3(1 - F_L)}$$
$$P_3 = -\frac{S_9}{1 - F_L}$$

For $i = 4, 5, 6, 8$:

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

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: \(p_T > 3.5\) GeV, \(|\eta| < 2.5\)
- Require: \(\mu^+\mu^-\) reconstruct to a common vertex
- Candidate kaon, pion tracks: \(p_T > 0.5\) GeV \([\text{no dedicated particle ID in ATLAS}]\)
- 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 \(m(K^*)_{\text{PDG}}\), and best \(B\) vertex fit.
- \(q^2\) bin range: [0.04,6.0] excluding [9.8,1.1] (to remove \(\phi\) 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)\textsuperscript{1} – QCD factorization framework to perform consistency checks of the LHCb data with theory expectations
- Descotes-Genon et al. (DHMV)\textsuperscript{2} – QCD factorization
- Jäger and Camalich (JC)\textsuperscript{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.

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 ψ(2S) and X(3872), both observed in decays to J/ψπ⁺π⁻** - 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.