Recent Heavy Flavor Results from ATLAS

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On behalf of the ATLAS Collaboration

CIPANP 2025
June 9, 2025

Overview

Presenting 3 recent results in heavy flavor physics from ATLAS:

Differential cross-section measurements of $D^{\pm}$ and $D_s^{\pm}$ meson production in p-p collisions at $\sqrt{s} = 13$ TeV[1]

Precision measurement of the B^0 meson lifetime using $B^0 \to J/\psi K^{*0}$ decays[2]

Measurement of the production cross section of J/ψ and $\psi(2S)$[3]

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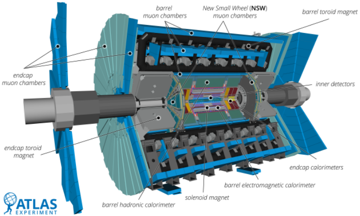
[1] arXiv:2412.15742 (submitted to JHEP)

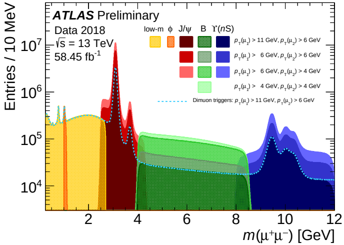
[2] arXiv:2411.09962 (accepted by EPJC)

[3] Eur. Phys. J. C 84 (2024) 169 arXiv:2309.17177

Introduction

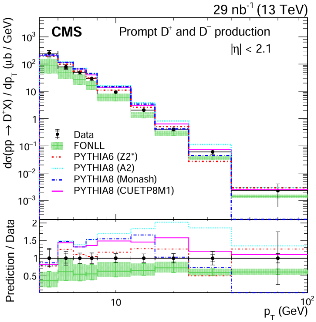
- Cross section and lifetime measurements provide crucial tests of QCD, improve constraints to improve calculation techniques
- Heavy flavor processes are often backgrounds in other experimental searches at the LHC, and improved constraints can aid in, e.g. direct searches for new physics
- Heavy flavor measurements like B lifetime can provide constraints to BSM models
- ATLAS is not designed specifically for flavor physics, but is well-equipped especially to measure final states with muons, with lower-p_{T} dimuons can be triggered utilizing dimuon inv. mass

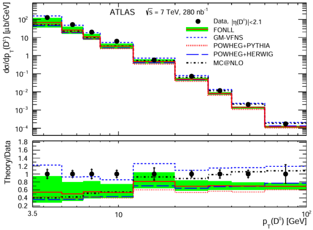




$D^{\pm}/D_s^{\pm}$ Cross Section - Overview

- Charm hadron production is critical input for improving QCD calculations where large theoretical uncertainties exist and for searches for new physics phenomena
- Previous measurements made by ATLAS, CMS, LHCb, and ALICE
  - This measurement marks the first differential measurement in the $D_s^{\pm}$ channel
- New measurement, using $D^{\pm}/D_s^{\pm} \to \phi(\mu^+\mu^-)\pi^{\pm}$ channel, uses $\int \mathcal{L}dt = 137\ \mathrm{fb}^{-1}$ from 2016-18 data
- MC simulations use Pythia 8.212 with LO 2→2 QCD processes, parton showers, and NNPDF2.3LO PDFs, ATLAS A14 tune used for event generation
- Measurements are compared to both general-mass variable-flavor-number scheme (GM-VFNS) and fixed order next-to-leading logarithm (FONLL) predictions





$D^\pm/D_s^\pm$ Measurement Strategy

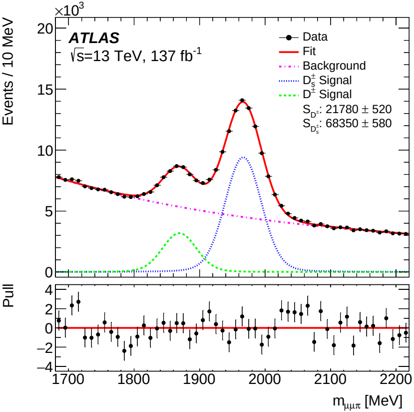
Measurement proceeds in bins of p_T and η

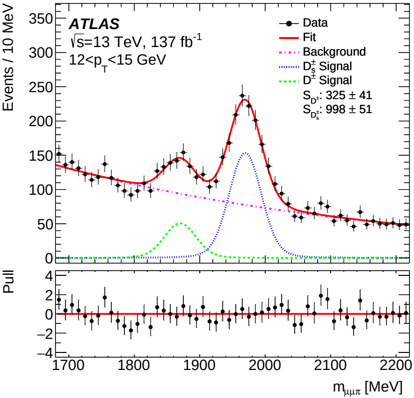
$$\left.\frac{d\sigma}{dp_{\mathrm{T}}(\eta)}\right|_i = \frac{S^i}{\int \mathcal{L}dt \times C^i \times \mathcal{B}(D^\pm/D_s^\pm \to (\phi(\mu^+\mu^-)\pi^\pm) \times \Delta^i p_{\mathrm{T}}(\eta)} \quad (1)$$

Quantity	Description / Value
S^i	Signal yields, extracted from mass fits
$\int \mathcal{L}\,dt$	$137\ \mathrm{fb}^{-1}$
C^i	Reconstruction/selection efficiency, found using MC simulated events, with fraction from $b\bar{b}$ vs. $c\bar{c}$ determined by lifetime fit
$\mathcal{B}(D^\pm/D_s^\pm \to (\phi(\mu^+\mu^-)\pi^\pm))$	PDG value for $D^\pm$, or $\frac{\mathcal{B}(D_s^\pm \to \phi(K^+K^-)\pi^\pm}{\mathcal{B}(\phi \to K^+K^-)} \times \mathcal{B}(\phi \to \mu^+\mu^-)$
$\Delta^i p_{\mathrm{T}}/\eta$	Bin width

$D^\pm/D_s^\pm$ Mass Fit

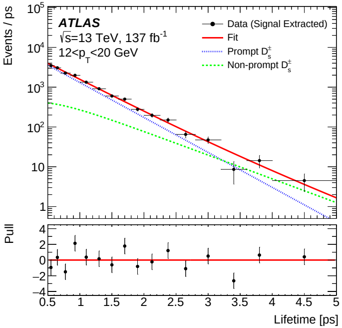
- 2 Voigtian distributions with Gaussian constraint on $m_{D^\pm} - m_{D_s^\pm}$ + quadratic exponential for background
- Fit for each bin in η, p_T, here is one example

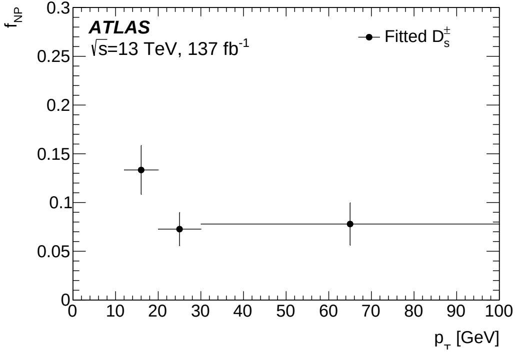




$D^{\pm}/D_s^{\pm}$ Lifetime Fit

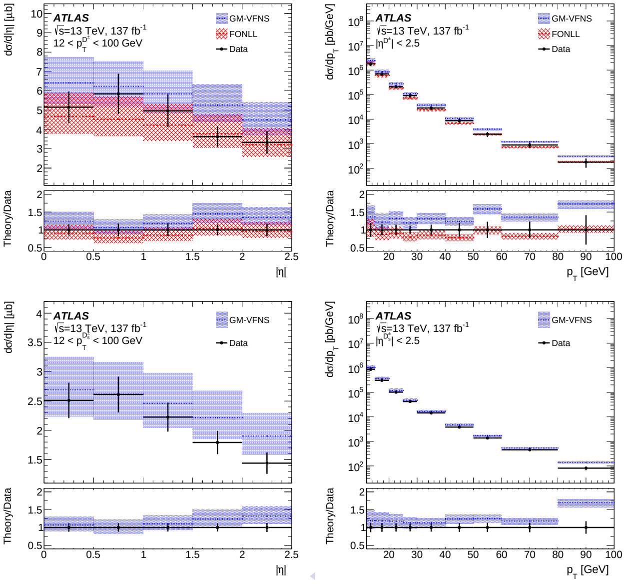
- Pseudo-proper lifetime $\tau = \frac{m_{\mu^+\mu^-\pi} L_{xy}}{p_{\mathrm{T}}}$
- Templates consisting of exponential(s) convolved with Gaussian and error function fit to $b\bar{b}$ and $c\bar{c}$ MC
- Relative fraction is then fit with single-parameter template fit to data in each bin





$D^{\pm}/D_s^{\pm}$ Results

- Good agreement for both models at low p_T for $D^{\pm}$, GM-VFNS is higher at high p_T
- Only GM-VFNS available for $D_s^{\pm}$, predicts higher value throughout, increasing with p_T



B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Overview

- Lifetime measurement is a fundamental property that can test our understanding of the weak interaction - e.g. the difference between B_d/B_s masses due to Pauli interference and weak annihilation
- Theoretical predictions made using QCD sum rules in the Heavy Quark Effective Theory (HQET) or Lattice QCD framework
- After τ is extracted, Γ_d can be calculated w/ parameters from HFLAV
- Γ_d/Γ_s is observable with best theoretical uncertainty, reported using previous measurement of Γ_s by ATLAS

B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Reconstruction

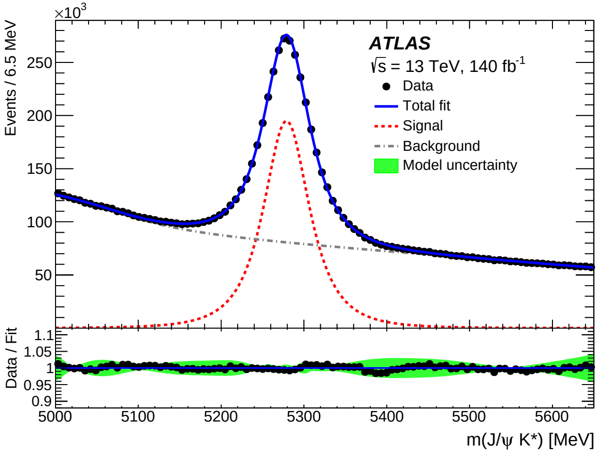
- Pseudo-proper decay time $t = \frac{L_{xy} m_B}{p_{\mathrm{T}}}$
- Fit vertex with 2 oppositely charged muons, then $K^{*0} \to K^+ \pi^-$ fit 2 tracks
- Perform a cascade fit to a common vertex, with J/ψ mass constrained, $\chi^2/\mathrm{ndof} < 3$
- PV is refitted removing tracks from B^0 reconstruction, PV with smallest 3D impact parameter is used
- Simultaneous fit to mass and lifetime performed with:

$$\ln L = \Sigma_i^N w(t_i) \ln[f_{\mathrm{sig}} \mathcal{M}_{\mathrm{sig}}(m_i) \mathcal{T}_{\mathrm{sig}}(t_i, \sigma_i, p_{\mathrm{T}_i}) + (1 - f_{\mathrm{sig}}) \mathcal{M}_{\mathrm{bkg}}(m_i) \mathcal{T}_{\mathrm{bkg}}(t_i, \sigma_i, p_{\mathrm{T}_i})] \quad (2)$$

where $w(t_i)$ are decay time dependent weights based on detector and selection efficiencies f is the fraction of signal events, determined in the fit, and $\mathcal{M}, \mathcal{T}$ are the mass and decay time PDF's

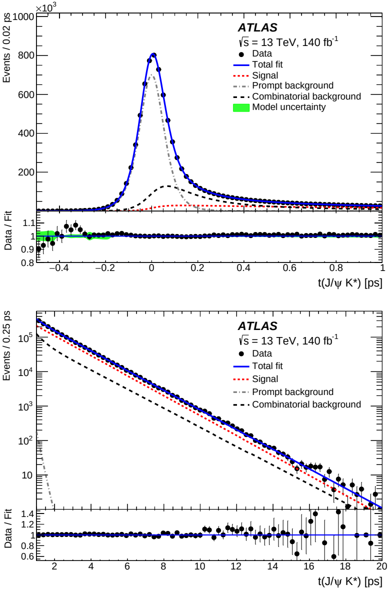
B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Mass Fit

- Signal PDF is Johnson S_U-distribution
- Background modeled with linear + sigmoid function



B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Decay Time Fit

- Consists of signal term + bkg term, both convolution with a sum of 3 Gaussians modeling the proper decay time resolution
- Signal PDF is exponential
- Background is prompt contribution, which is just resolution, plus sum of 3 exponentials, for combinatorial contribution



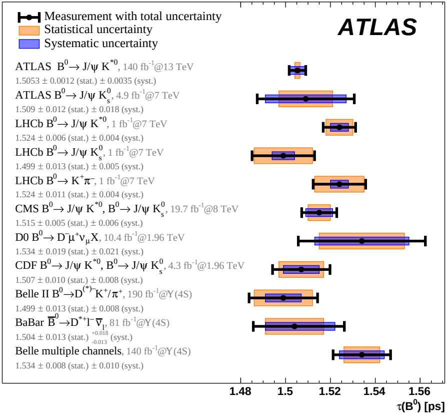
B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Systematics

- Extensive systematic studies were performed, see paper for more details
- Largest contribution comes from mass-time correlation, $1.9\sigma_{\text{stat}}$
- Evaluated by dividing mass sidebands into 6 bins, then fitting for background PDF's only
- This showed linear dependence on mass. New fit is performed with with linear dependence of f_{prompt} on mass is reflected in fit, result is a fit that is different by $1.9\sigma_{\text{stat}}$

Source of uncertainty	Systematic uncertainty [ps]
ID alignment	0.00108
Choice of mass window	0.00104
Time efficiency	0.00130
Best-candidate selection	0.00041
Mass fit model	0.00152
Mass-time correlation	0.00229
Proper decay time fit model	0.00010
Conditional probability model	0.00070
Fit model test with pseudo-experiments	0.00002
Total	0.0035

B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Results

$$
\begin{aligned}
\tau_B^0 &= 1.5053 \pm 0.0012(\text{stat.}) \pm 0.0035(\text{syst.})\text{ps} \\
\Gamma_d &= 0.6639 \pm 0.0005(\text{stat.}) \pm 0.0016(\text{syst.}) \pm 0.0038(\text{ext.})\text{ps}^{-1} \\
\frac{\Gamma_d}{\Gamma_s} &= 0.9905 \pm 0.0022(\text{stat.}) \pm 0.0036(\text{syst.}) \pm 0.0057(\text{ext.})
\end{aligned}
\tag{3}
$$

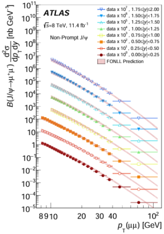


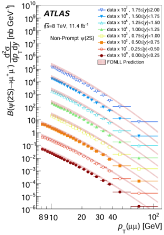
- External uncertainty comes from HFLAV uncertainties from parameters used in the Γ calculations
- Previous ATLAS measurement of Γ_s was used
- This measurement is the most precise to date, compatible with theory and previous measurements

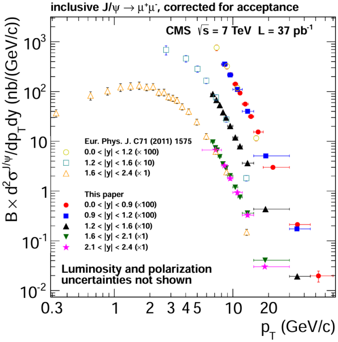
Model	Γ_d/Γ_s
HQE	1.003 ± 0.006
Lattice QCD	1.00 ± 0.02

J/ψ & $\psi(2S)$ Differential Cross Section - Overview

- Models for charmonium production are well constrained by previous measurements of cross section and polarization
- New constraints to help improve models can be added by measuring differential cross section at higher p_T
- New result measures the double-differential cross section for $J/\psi(\psi(2S))$ in a much wider range of transverse momentum, between 8-360 (8-140) GeV
- New p_{T} regime reached using single muon high-p_{T} trigger





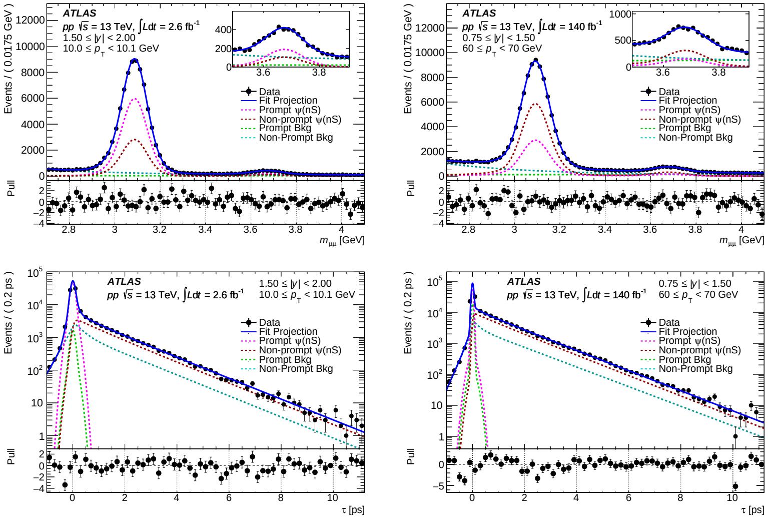


J/ψ & $\psi(2S)$ Differential Cross Section - Overview

- Overall strategy is similar to D meson cross section, with necessary ingredients of yield, efficiencies, and integrated luminosity
- There are 2 regimes in this measurement, distinguished by different triggers:
  - $p_{\mathrm{T}}(\psi) < 60$ GeV - uses dimuon $p_{\mathrm{T}} >$ 4 GeV triggers, 2.6 fb^{-1} of data
  - $p_{\mathrm{T}}(\psi) > 60$ GeV - uses single muon $p_{\mathrm{T}} >$ 52.5 GeV trigger, 140 fb^{-1} of data
- Charmonium states reconstructed from $\psi \to \mu^+\mu^-$ decays
- Fit model consists of 7 terms, with each consisting of a mass PDF times (decay time PDF convolution with resolution function):
  - 4 signal terms, for prompt/non-prompt, $J/\psi/\psi(2S)$
  - 3 background terms describing prompt backgronds and non-prompt same/opposite side backgrounds

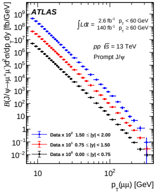
J/ψ & $\psi(2S)$ Differential Cross Section - Fits

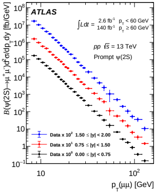
- Some example fits out of the 34 bins of $p_\mathrm{T} \times 3$ bins of $|y|$

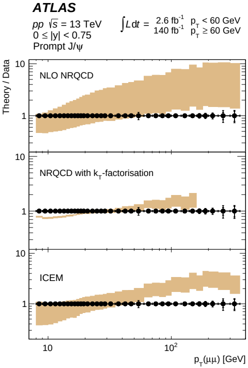


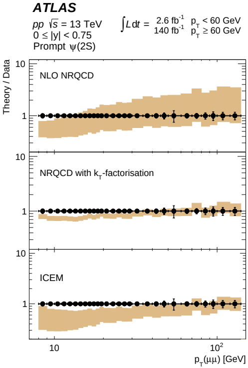
J/ψ & $\psi(2S)$ Differential Cross Section - Prompt Results

- Comparisons made to theory for prompt production w/ 3 different models
- Generally good agreement, at low p_{T} worse at high p_{T} for J/ψ
- Some underestimation at low p_{T} for $\psi(2S)$



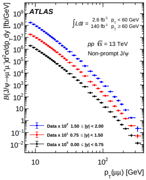


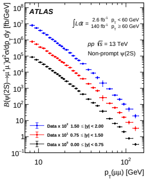


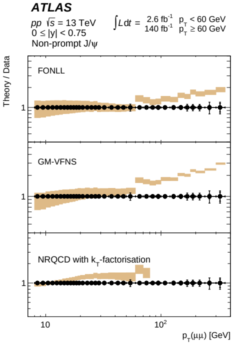


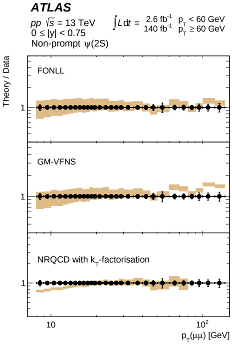
J/ψ & $\psi(2S)$ Differential Cross Section - Non-prompt Results

- Similar results for non-prompt cross section
- Larger divergence at high-p_{T} for J/ψ









Conclusions

$D^{\pm}/D_s^{\pm}$ Differential Cross Section Measurement

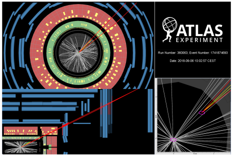
First measurement for $D_s^{\pm}$ and overall improvement from previous ATLAS result

B^0 Lifetime with $B^0 \to J/\psi K^{*0}$

Most precise B^0 lifetime measurement so far, in agreement with SM predictions and previous measurements

J/ψ & $\psi(2S)$ Differential Cross Section

Measurements made for wider p_{T} range provide new inputs for theoretical models



Backup slides

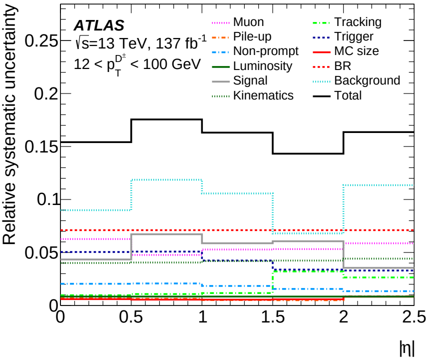
$D^{\pm}/D_s^{\pm}$ Selections

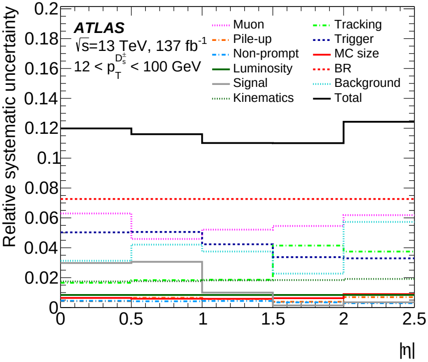
- For possible combination of $\mu^+\mu^-$ track (hypothesized pion), remove 3 tracks, refit PV, then attempt D meson SV fit
- Various selections are made to improve the signal-to-noise ratio
- $\vec{L_t}$ is the vector connecting SV and PV in the transverse plane
- Then $a^0_{xy} = L_T \cos(\theta_{xy})$; $L_{xy} = L_T \sin(\theta_{xy})$

Selection	
Muon objects	Two muons satisfying the *Loose* working point
Track object	One track satisfying the *Loose* working point
Transverse momentum	$p_T^{\mu} > 6\,\mathrm{GeV}$, $p_T^{\pi} > 1\,\mathrm{GeV}$
Total charge	$\lvert Q_{\mathrm{triplet}}\rvert = 1$
Opposite charge muons	$Q_{\mu_1} \times Q_{\mu_2} = -1$
Di-muon invariant mass	$\lvert m_{\mu\mu} - m_{\phi}\rvert < \delta m(\lvert\eta\rvert)$
L_{xy} significance	$\mathrm{Sig}(L_{xy}) > 3$
a^0_{xy} significance	$\lvert\mathrm{Sig}(a^0_{xy})\rvert < 4$
Vertex p-value	$\log(p_0^{\mathrm{vertex}}) > -0.8$
Highest vertex p-value	The vertex with $\mathrm{Max}(p_0^{\mathrm{vertex}})$ in the event

$D^{\pm}/D_s^{\pm}$ Systematic Uncertainty

- Several systematics were considered, summarized in the plot
- Most important uncertainty for most of phase space in $D^{\pm}$ measurement is background modeling (assessed by refitting with simple exponential function)
- Most important in $D_s^{\pm}$ is BR uncertainty





$D^\pm / D_s^\pm$ Inclusive Cross Section

- Fiducial cross section for $|\eta| < 2.1, 20 < p_{\mathrm{T}} < 100 GeV$
- Data are mostly consistent with models within uncertainty

	$D^\pm$ inclusive fiducial cross-section [nb]		
	ATLAS	GM-VFNS	FONLL
	$\sigma \pm \delta_{\text{total}}$	$\sigma \pm \delta_{\text{theory}}$	$\sigma \pm \delta_{\text{theory}}$
$\sqrt{s}$ = 13 TeV	1 690 ± 270	$2\,200^{+310}_{-290}$	$1\,480^{+230}_{-190}$
$\sqrt{s}$ = 7 TeV	888 ± 97	980^{+120}_{-150}	620^{+100}_{-80}
Ratio (13 TeV/7 TeV)	1.9 ± 0.4	2.24 ± 0.04	2.38 ± 0.01

	$D_s^\pm$ inclusive fiducial cross-section [nb]	
	ATLAS	GM-VFNS
	$\sigma \pm \delta_{\text{total}}$	$\sigma \pm \delta_{\text{theory}}$
$\sqrt{s}$ = 13 TeV	810 ± 100	950^{+140}_{-130}
$\sqrt{s}$ = 7 TeV	510 ± 100	470^{+56}_{-69}
Ratio (13 TeV/7 TeV)	1.6 ± 0.4	2.02 ± 0.05

B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Overview

- Lifetime measurement is a fundamental property that can test our understanding of the weak interaction - e.g. the difference between B_d/B_s masses due to Pauli interference and weak annihilation, and is an indirect probe of new physics
- Theoretical predictions made using QCD sum rules in the Heavy Quark Effective Theory (HQET) or Lattice QCD framework
- Ratio of B^0 to B_s^0 is observable with best theoretical uncertainty
- We measure:

$$\tau_{B^0} = \frac{1}{\Gamma_d} \cdot \frac{1}{1-y^2} \left(\frac{1 + 2Ay + y^2}{1 + Ay} \right) \tag{4}$$

- where:

$$A = \frac{R_H^f - R_L^f}{R_H^f + R_L^f} \tag{5}$$

$$\begin{aligned} \langle \Gamma(B^0(t)) \rangle &= \Gamma(B^0(t)) + \Gamma(\bar{B}^0(t)) \\ &= R_H^f \exp(-\Gamma_H t) + R_L^f \exp(-\Gamma_L t) \end{aligned} \tag{6}$$

B^0 Lifetime with $B^0 \to J/\psi K^{*0}$ Reconstruction

- Pseudo-proper decay time $t = \frac{L_{xy} m_B}{p_{\mathrm{T}}}$
- 2 oppositely charged muons, Tight working point ID, fit req $\chi^2/\mathrm{ndof} < 10$ + loose mass selection, which retains 99.7% of candidates
- $K^{*0} \to K^+\pi^-$ fit 2 tracks with both $K^*/\bar{K}^*$ hypotheses (keep the one closer to K^* mass), $p_{\mathrm{T}}[K(\pi)] > 1(0.5)$ GeV
- $p_{\mathrm{T}}(K^{*0}) > 3.5$ GeV, and $846\ \mathrm{MeV} < m < 946\ \mathrm{MeV}$
- We perform a cascade fit to a common vertex, with J/ψ mass constrained, $\chi^2/\mathrm{ndof} < 3$
- PV is refitted removing tracks from B^0 reconstruction, PV with smallest 3D impact parameter is used
- Simultaneous fit to mass and lifetime performed with:

$$\ln L = \Sigma_i^N w(t_i) \ln[f_{\mathrm{sig}} \mathcal{M}_{\mathrm{sig}}(m_i) \mathcal{T}_{\mathrm{sig}}(t_i, \sigma_i, p_{\mathrm{T}_i}) + (1 - f_{\mathrm{sig}}) \mathcal{M}_{\mathrm{bkg}}(m_i) \mathcal{T}_{\mathrm{bkg}}(t_i, \sigma_i, p_{\mathrm{T}_i})] \quad (7)$$

where $w(t_i)$ are decay time dependent weights based on detector and selection efficiencies based on MC, f is the fraction of signal events, determined in the fit, and $\mathcal{M}, \mathcal{T}$ are the mass and decay time PDF's

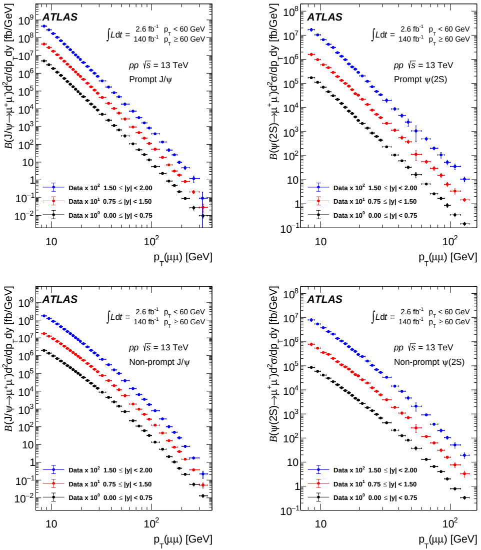
J/ψ & $\psi(2S)$ Differential Cross Section - Overview

- Charmonium states reconstructed from $\psi \to \mu^+\mu^-$ decays
- Fit model consists of 7 terms, with each consisting of a mass PDF times (decay time PDF convolution with resolution function):
  - 4 signal terms, for prompt/non-prompt, $J/\psi/\psi(2S)$
  - 3 background terms describing prompt backgrounds (e.g. Drell-Yan), non-prompt same-side backgrounds (like b-hadron decay) and non-prompt double sided backgrounds (muons originate e.g. from 2 different b-hadrons)
  - Resolution function is a sum of 3 Gaussians
  - Fits summarized in table, where G, CB, δ, E, and P terms correspond to Gaussian, Crystal-Ball, Dirac-δ Exponential and 2nd-order polynomial functions, respectively

i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\delta(\tau)$
2	J/ψ	NP	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\omega_2 E_1(\tau) + (1-\omega_2)E_1(b\tau)$
3	$\psi(2S)$	P	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$E_2(\tau)$
5	Bkg	P	P	$\delta(\tau)$
6	Bkg	NP	$E_3(m)$	$E_4(\tau)$
7	Bkg	NP	$E_5(m)$	$E_6(\|\tau\|)$

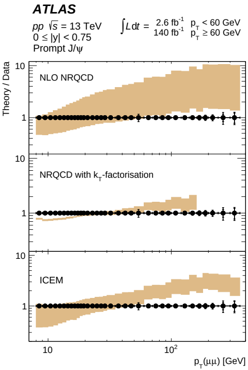
J/ψ & $\psi(2S)$ Differential Cross Section - Results

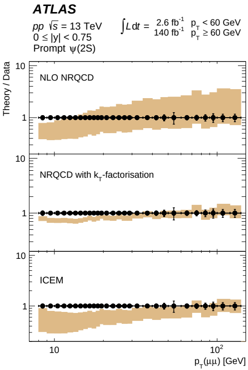
- Measurement results for prompt/non-prompt $J/\psi/\psi(2S)$



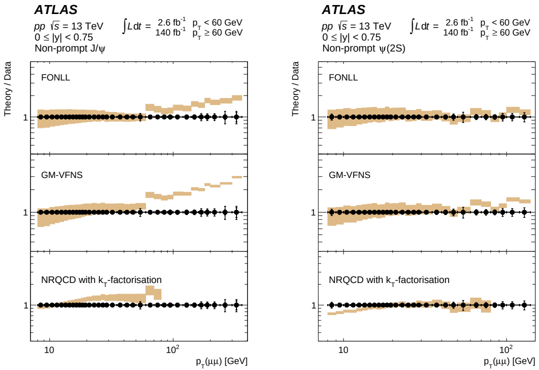
J/ψ & $\psi(2S)$ Differential Cross Section - Results

- Comparisons made to theory for prompt production
- NRQCD: Predictions and largely overlap, some overestimate at hight p_{T}
- k_{T}-factorization model: aims to improve by taking into account transverse degrees of freedom of the initial gluons in the colliding protons. Underestimates data at low-p_{T}
- Improved Color Evaporation Model (ICEM) assigns fixed fraction of the $c\bar{c}$ production cross section below the open charm threshold to individual charmonium states. Predicts harder p_{T} spectra and underestimates cross section for $\psi(2S)$



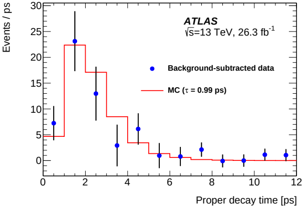


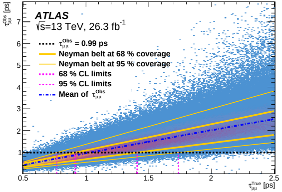
- Models based on PQCD for production of $b\bar{b}$ pair, their hadronization, and decay to charmonium
- FONLL agrees at low p_{T} and diverges at hight p_{T}
- GM-VFNS is similar
- NRQCD with k_{T} factorization reproduce measurement well, but are limited in p_{T} range by the available gluon PDF



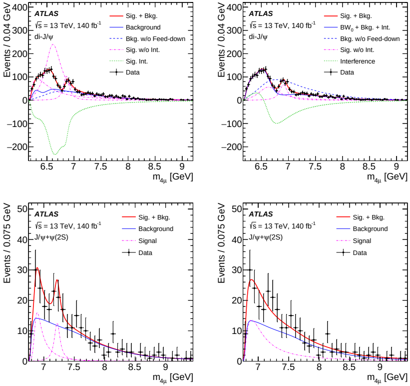
Other Results Since CIPANP 2022

- Measurement of $B_s^0 \to \mu^+\mu^-$ Effective Lifetime[4]
- $\tau = 0.99^{+0.42}_{-0.07}(\text{stat.}) \pm 0.17(\text{syst.})$





- Dicharmonium Spectroscopy with di-J/ψ and $J/\psi + \psi(2S)$[5]
- Observed peak consistent with X(6900) resonance observed by LHCb, plus broader excess at lower mass



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[4] JHEP 09 (2023) 199 arXiv:2308.01171

[5] Phys. Rev. Lett. 131 (2023) 151902 arXiv:2304.08962