Production of Heavy Flavour in ATLAS

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on behalf of the ATLAS collaboration

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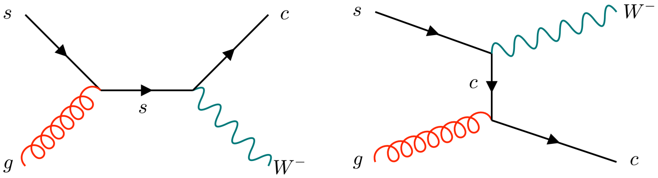
This talk will cover the following analyses:

- Measurement of the production of a W boson in association with a charmed hadron in *pp* collisions at $\sqrt{s} = 13\,\text{TeV}$ with the ATLAS detector CERN-EP-2022-291
- Production of $\Upsilon(nS)$ mesons in $Pb + Pb$ and *pp* collisions at 5.02 TeV....... Phys. Rev. C 107 (2023) 054912

W production in association with a charmed hadron (1/7)

CERN-EP-2022-291

- The production of a W boson in association with a single charm quark is studied using $140\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 13\,\mathrm{TeV}$ pp collisions
- This analysis aims to improve knowledge of parton distribution functions (PDFs) of strange quarks
- In perturbative quantum chromodynamics (QCD), the production of a W boson in association with a single charm quark occurs through the scattering of a gluon and a down-type quark
- The dominant production process at LHC is from $gs \to W^- c$ and its charge conjugate
- $gd \to W^- c (g\bar{d} \to W^+ \bar{c})$ contributes only $\sim 10\%(5\%)$ to the $W^- c (W^+ \bar{c})$ rate
- The leading-order diagrams for $W^- + c$ production are the following:



W production in association with a charmed hadron (2/7)

CERN-EP-2022-291

- The ATLAS measurement examines the W boson in association with the $D^{(*)}$ meson
- Events in which the W boson decays to an electron or a muon ($W \to e\nu$ and $W \to \mu\nu$) are studied and the presence of the charm quark is detected through explicit charmed hadron reconstruction
- The reconstruction relies on different categories of electrons and muons: *baseline*, *loose* and *tight*

	Electrons			Muons		
Features	`baseline`	`loose`	`tight`	`baseline`	`loose`	`tight`
p_{T}	> 20 GeV	> 30 GeV		> 20 GeV	> 30 GeV	
$\lvert\Delta z_0^{\mathrm{BL}} \sin(\theta)\rvert$	< 0.5 mm			< 0.5 mm		
$\lvert d_0^{\mathrm{BL}}/\sigma(d_0^{\mathrm{BL}})\rvert$	< 5			< 3		
Pseudorapidity	$(\lvert\eta\rvert < 1.37) \lvert\lvert (1.52 < \lvert\eta\rvert < 2.47)$			$\lvert\eta\rvert < 2.5$		
Identification	Tight			Tight		
Isolation	No		Yes	No		Yes

- The presence of a reconstructed jet is not required
- Events are required to have exactly one lepton (events with additional leptons are rejected)
- To reduce multijet background, $E_{\mathrm{T}}^{miss} > 30$ GeV and $m_{\mathrm{T}}(W) > 60$ GeV is required

W production in association with a charmed hadron (3/7)

CERN-EP-2022-291

- Events containing c-quarks are identified by explicitly reconstructing charmed mesons in charged, hadronic decay channels
- Two charmed hadron channels are used:
  - $D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$
  - $D^{*+} \rightarrow D^{0}\pi^{+} \rightarrow (K^{-}\pi^{+})\pi^{+}$
- Multiple $D^{(*)}$ candidates are allowed
- The selected events are categorized according to the $b-jet$ multiplicity to separate $W + D^{(*)}$ signal events from the $t\bar{t}$ background with events containing $W \rightarrow cs$ decays
- Events with 0 $b-jets$ are classified as the $W + D^{(*)}$ signal region (**SR**)
- Events with one or more $b-tag$ jets comprise to Top control region (**CR**)

W production in association with a charmed hadron (4/7)

CERN-EP-2022-291

- MC samples are used to construct signal and background mass templates (except for the multijet background):

Category	Normalization	$m(D^{(*)})$ shape
W+$D^{(*)}$ (D^+ channel)	Sherpa 2.2.11	Sherpa 2.2.11
W+$D^{(*)}$ (D^* channel)	Sherpa 2.2.11	aMC@NLO+Py8 (NLO)
W+c^{match} (D^+ channel)	MG+Py8 (CKKW-L)	MG+Py8 (CKKW-L)
W+c^{match} (D^* channel)	Sherpa 2.2.11	Sherpa 2.2.11
W+$c^{\text{mis-match}}$	Sherpa 2.2.11	LIS Sherpa 2.2.11
W+jets (D^+ channel)	Sherpa 2.2.11	LIS Sherpa 2.2.11
W+jets (D^* channel)	MG+Py8 (CKKW-L)	LIS MG+Py8 (CKKW-L)

- MC truth information is used to categorize the events as: **signal** (all tracks match signal decay), **match** (tracks match different hadron species or different channel), **mis-match** (at least one track is matched) and W+**jets** (no track is matched)
- Two background categories are used: **Top** ($t\bar{t}$, single-t, $t\bar{t}X$) and **Others** (di-boson, Z+jets)
- The hadronization rates are reweighted to the world-average values

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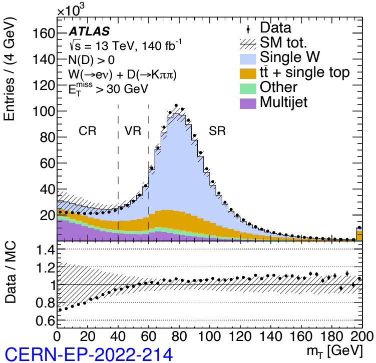
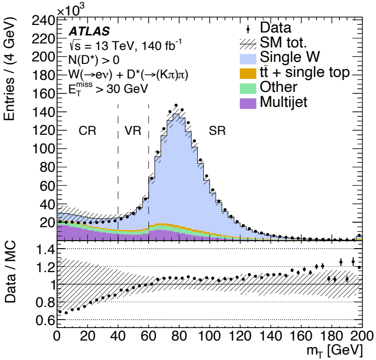
- Multijet background is data driven based on Matrix Method [1]
- It arise if one or more constituents of a jet are misidentified as a prompt lepton
- It is extracted from the fake CR and is extrapolated to the SR
- The validation of the extrapolation is made in the validation region (**VR**)



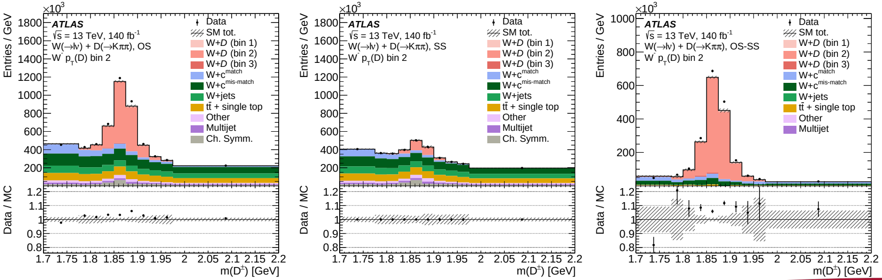


[1] ATLAS Collaboration, CERN-EP-2022-214

W production in association with a charmed hadron (6/7)

CERN-EP-2022-291

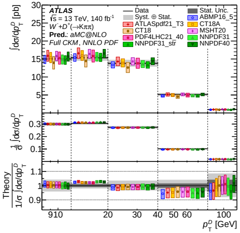
- The analysis exploits the charge correlations of the W boson and the charm quark to enhance the signal (signal has W and $D^{(*)}$ with opposite charge (OS), while background is mostly same sign(SS))
- Signal is extracted by measuring difference in the number of OS and SS candidates
- The signal $W + D^{(*)}$ events are extracted through a profile likelihood fit to the reconstructed secondary vertex mass distribution measuring:
  - absolute fiducial cross-section: $\sigma_{\text{fid}}^{OS-SS}(W^- + D^{(*)})$ and $\sigma_{\text{fid}}^{OS-SS}(W^+ + D^{(*)})$
  - the cross-section ratio: $R_c^{\pm} = \sigma_{\text{fid}}^{OS-SS}(W^+ + D^{(*)})/\sigma_{\text{fid}}^{OS-SS}(W^- + D^{(*)})$
  - differential cross-sections for OS-SS $W^- + D^{(*)}$ and $W^+ + D^{(*)}$

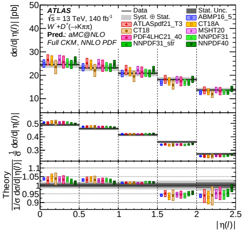


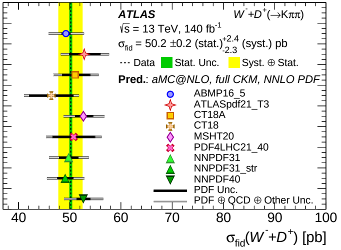
W production in association with a charmed hadron (7/7)

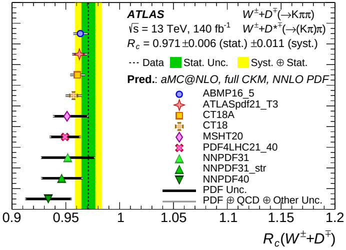
CERN-EP-2022-291

- The differential cross-section is made in 5 bins of $p_{\mathrm{T}}(D^{(*)})$ and 5 bins of $|\eta(l)|$
- Post-fit comparisons between the data and MC distributions
- The precision of ratio measurement is $\sim 1\%$ level
- Extensive systematic uncertainty study was made
- The measured fiducial cross-sections for each of the four channels are compared with the theoretical predictions obtained using different NNLO PDF sets









Channel	$\sigma_{\mathrm{fid}}^{\mathrm{OS-SS}}(W+D^{(*)}) \times B(W \to \ell\nu)$ [pb]
W^-+D^+	50.2 ± 0.2 (stat.) $^{+2.4}_{-2.3}$ (syst.)
W^++D^-	48.5 ± 0.2 (stat.) $^{+2.3}_{-2.2}$ (syst.)
W^-+D^{*+}	51.1 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
W^++D^{*-}	50.0 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
	$R_c^{\pm} = \sigma_{\mathrm{fid}}^{\mathrm{OS-SS}}(W^++D^{(*)})/\sigma_{\mathrm{fid}}^{\mathrm{OS-SS}}(W^-+D^{(*)})$
$R_c^{\pm}(D^+)$	0.965 ± 0.007 (stat.) ± 0.012 (syst.)
$R_c^{\pm}(D^{*+})$	0.980 ± 0.010 (stat.) ± 0.013 (syst.)
$R_c^{\pm}(D^{(*)})$	0.971 ± 0.006 (stat.) ± 0.011 (syst.)

Production of $\Upsilon(nS)$ mesons in $Pb+Pb$ (1/6)

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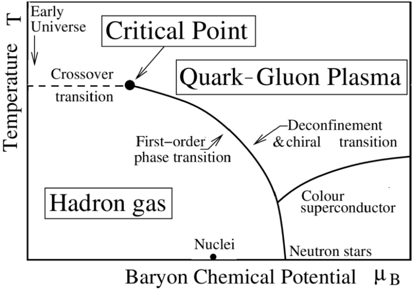
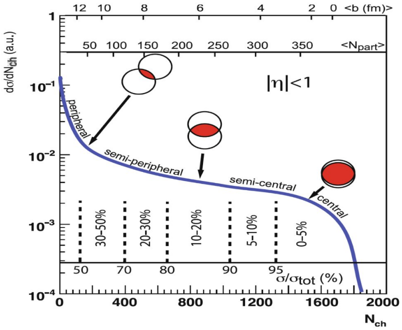
- Quantum chromodynamics (QCD) predicts a phase transition at high temperatures and energy densities and formation of quark–gluon plasma (QGP)
- The transition temperature is measured to be $T_c \sim 155\,\text{MeV}$
- Formation of the QGP and the consequent modification to the heavy-quark potential is expected to lead to different quarkonium states dissolving at different temperatures of the medium
- It was found that the $\Upsilon(1S)$ persists well above T_c, while $\Upsilon(2S)$ dissociates at about $1.1\,T_c$ and $\Upsilon(3S)$ can not exist at temperatures above T_c



Production of $\Upsilon(nS)$ mesons in $Pb+Pb$ (2/6)

Phys. Rev. C 107 (2023) 054912

- ATLAS experiment measured the $\Upsilon(nS)$ production cross-section in pp and $Pb+Pb$ collisions at $\sqrt{s}=5.02\,\mathrm{TeV}$ per nucleon–nucleon pair
- The integrated luminosity of the pp sample collected in 2017 is $0.26\,\mathrm{fb}^{-1}$ while for the *PbPb* sample it corresponds to $0.44\,\mathrm{nb}^{-1}$ in 2015 and $1.38\,\mathrm{nb}^{-1}$ in the 2018 data sample
- The degree of overlap between the two colliding Pb nuclei, called centrality, is estimated based on the transverse energy measured in the forward calorimeter ($\sum E_{\mathrm{T}}^{FCal}$)
- Each centrality class corresponds to a fixed percentile in the $\sum E_{\mathrm{T}}^{FCal}$ distribution of minimum-bias events
- A Monte Carlo Glauber-based model[1] is used to calculate the mean number of participant nucleons $\langle N_{\mathrm{part}}\rangle$ and the mean nuclear overlap function $\langle T_{\mathrm{AA}}\rangle$



[1] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, Glauber modeling in high energy nuclear collisions, Ann. Rev. Nucl. Part. Sci. **57** (2007)

Production of $\Upsilon(nS)$ mesons in $Pb+Pb$ (3/6)

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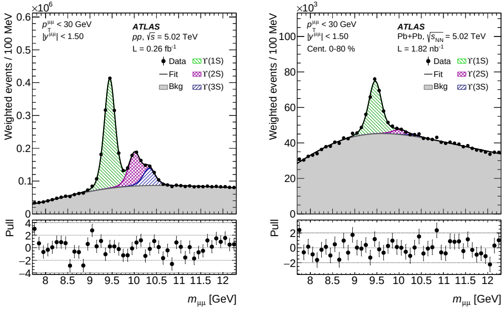
- $\Upsilon(nS)$ states are reconstructed in the $\mu^+\mu^-$ decay channel and their yields are determined via unbinned maximum-likelihood fits to the weighted di-muon invariant mass distributions

$$w_{\text{total}}(\Upsilon(nS)) = \frac{1}{\mathcal{A}(\Upsilon(nS)) \times \epsilon_{\text{reco}}(\mu_1\mu_2) \times \epsilon_{\text{trig}}(\mu_1\mu_2) \times \epsilon_{\text{pvAsso}}(\mu_1\mu_2)},$$

  where ϵ_{pvAsso} is the efficiency related to the primary-vertex association

- The signal shapes are described by a sum of Crystal Ball and Gaussian functions in both *pp* and *PbPb*.



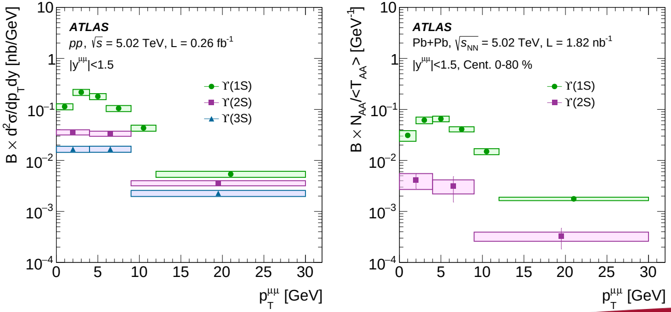
Production of $\Upsilon(nS)$ mesons in $Pb+Pb$ (4/6)

Phys. Rev. C 107 (2023) 054912

- The differential $\Upsilon(nS)$ production cross-sections in *pp* are measured according to the relation

$$\frac{d^2\sigma_{\Upsilon(nS)}}{dp_{\mathrm{T}}^{\mu\mu}dy^{\mu\mu}} \times \mathcal{B}(\Upsilon(nS)\to\mu^+\mu^-) = \frac{N^{\mathrm{corr}}_{\Upsilon(nS)}}{\Delta p_{\mathrm{T}}^{\mu\mu}\times\Delta y^{\mu\mu}\times\int\mathcal{L}dt}$$

- And for the *PbPb* collisions we assume: $N_{AA} = \frac{N^{\mathrm{corr}}_{\Upsilon(nS)}}{\Delta p_{\mathrm{T}}^{\mu\mu}\times\Delta y^{\mu\mu}\times Nevt}$ where N_{evt} is the total number of minimum-bias Pb+Pb collisions in each centrality class

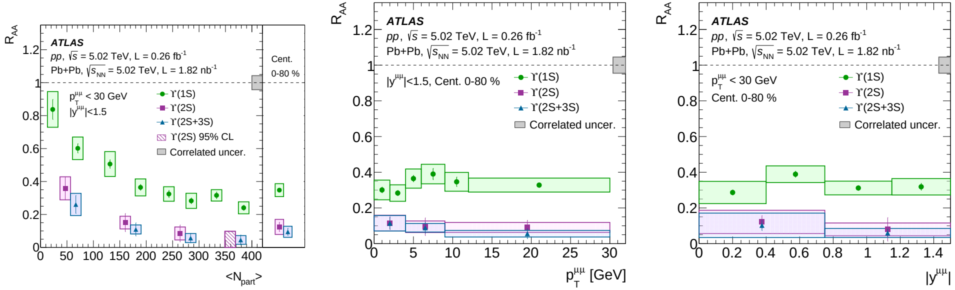


Production of $\Upsilon(nS)$ mesons in $Pb + Pb$ (5/6)

Phys. Rev. C 107 (2023) 054912

- The modifications of bottomonium production yields in *PbPb* collisions relative to the *pp* system are quantified by the nuclear modification factor R_{AA}, which can be defined for each centrality interval as

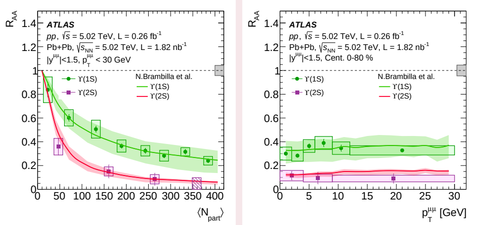
$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma^{pp}}$$



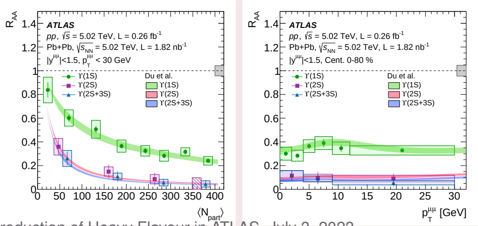
Production of $\Upsilon(nS)$ mesons in $Pb+Pb$ (6/6)

Phys. Rev. C 107 (2023) 054912

N. Brambilla et al.[1]

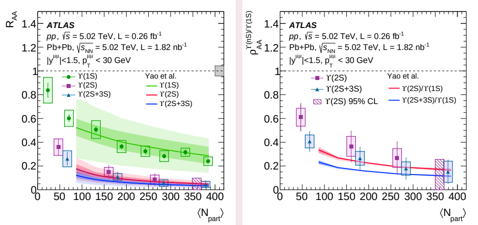


X. Du et al.[2]



- The measured results are compared with the theoretical predictions
- All three models are in agreement with the data within experimental and theoretical uncertainties

X. Yao et al.[3]



[1] N. Brambilla et al., Phys. Rev. D **104** (2021) no.9, 094049
[2] X. Du et al., Phys. Rev. C **96** (2017) no.5, 054901
[3] X. Yao et al., JHEP **01** (2021), 046

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Summary

- Some of the most recent results in heavy flavor physics by ATLAS was presented
- W production in association with charm decay $D^{(*)}$ shows good agreement with the predictions and provides useful constraints upon global PDF fits
- The $\Upsilon(nS)$ production cross-section was measured and nuclear modification factor was compared to various models
- All results shows good agreement with the previous CMS measurement[1]

Clermont-Ferrand

[1]CMS Collaboration,Suppression of Excited Υ States Relative to the Ground State in Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV, Phys. Rev. Lett. **120** (2018) no.14, 142301

Backup slides

W production in association with a charm

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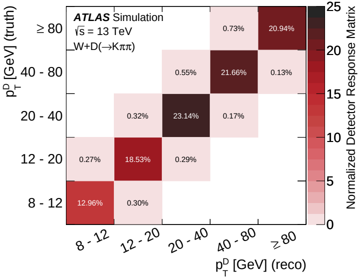
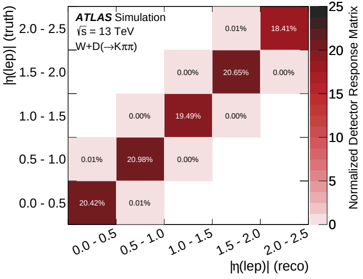
- The $W + D^{(*)}$ measurement is unfolded to "truth" fiducial region defined at MC particle level
- The response matrices are made for differential $p_{\mathrm{T}}(D^{(*)})$ and $|\eta(l)|$ bins





- Events where the reconstructed objects pass the event selection but the truth objects fail the truth fiducial requirements are treated as fakes
- Cases where the reconstructed objects fail the reconstruction fiducial selection but the truth objects pass the truth selection are treated as inefficiencies