Heavy-flavour production measurements in proton-lead and fixed-target collisions at LHCb

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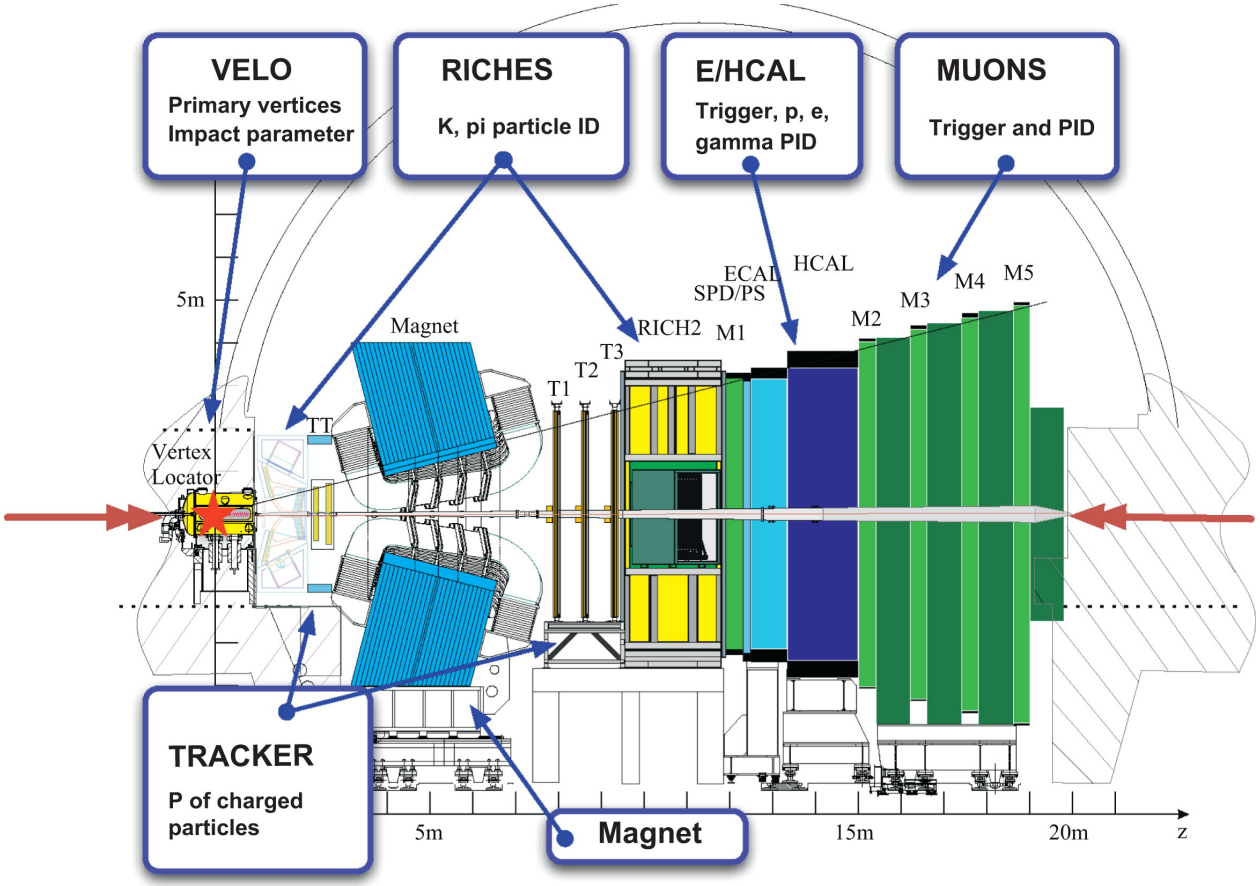
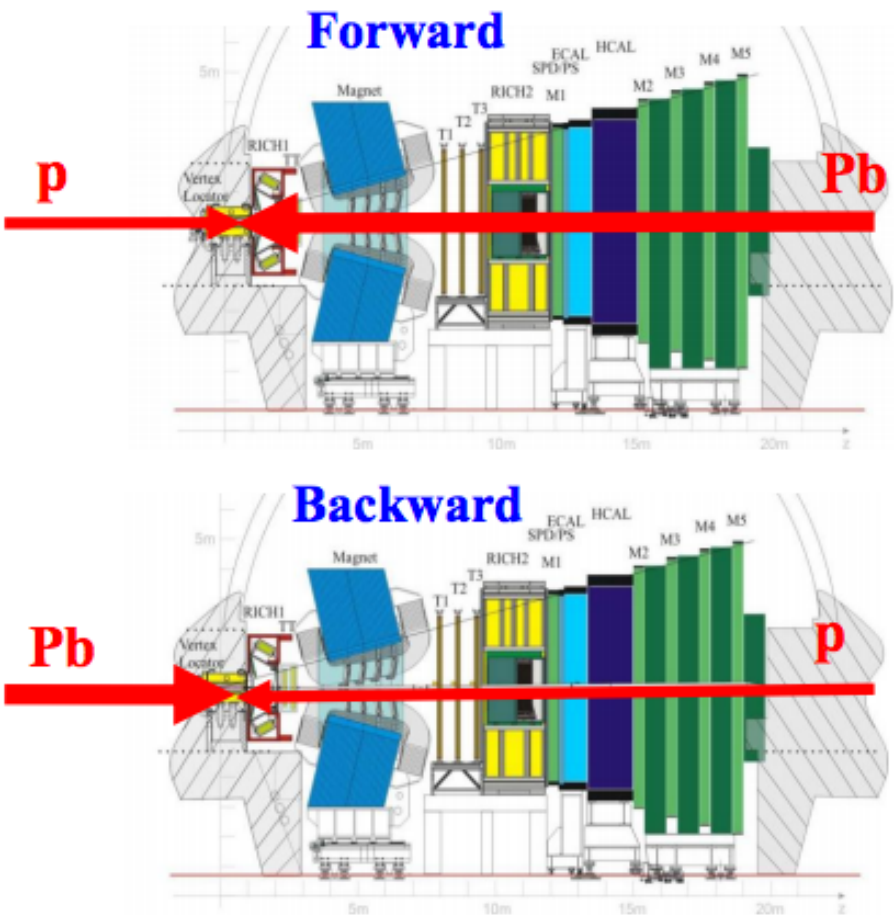
LHCb detector

- LHCb - single armed forward spectrometer, located at LHC
- Acceptance $2 < \eta < 5$
- Proton-proton interaction at up to $\sqrt{s} = 13$ TeV
- Physics goals:
  - Designed for: *CP* violation in *b* and *c* sectors
  - Today: also general purpose physics in forward region



[IJMPA 30, 1530022 (2015)] [2008 JINST 3 S08005]

Proton-lead setup at LHCb



Ion = $^{208}_{82}$Pb

Forward region:

- $y^* = y_{lab} - 0.465$
- pPb: $1.5 < y^* < 4.0$

Backward region:

- $y^* = -(y_{lab} + 0.465)$
- Pbp: $-5.0 < y^* < -2.5$

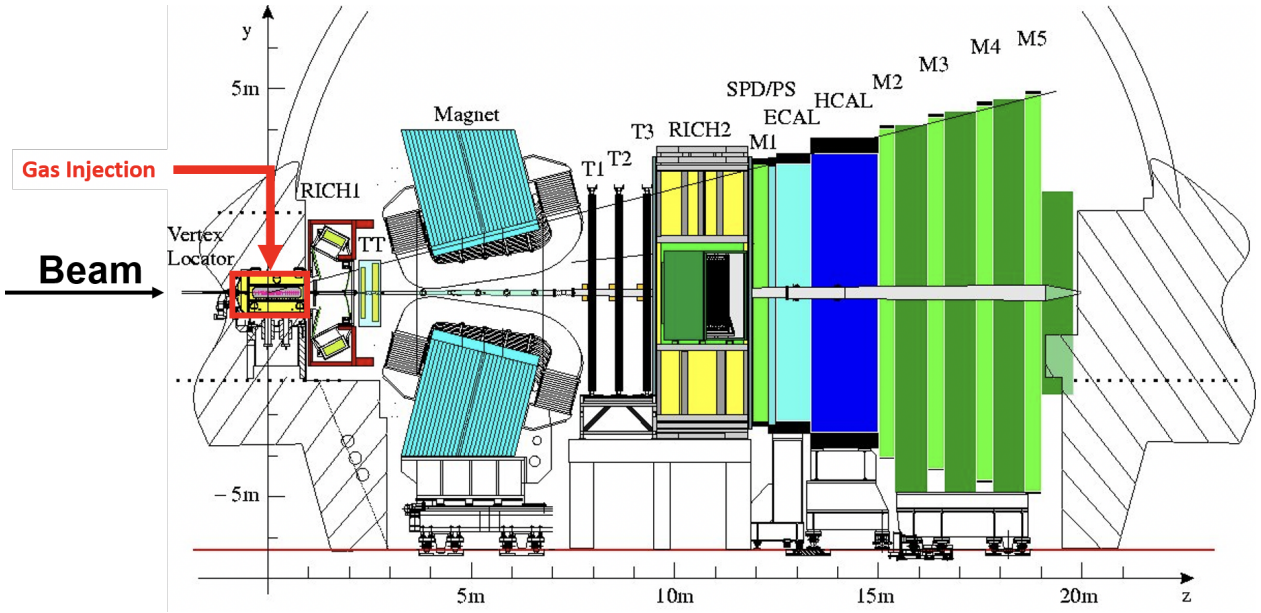
2013 data taking: $\sqrt{s_{NN}} = 5.02$ TeV

- 1.1 nb^{-1} (Fwd), 0.5 nb^{-1} (Bwd)

2016 data taking: $\sqrt{s_{NN}} = 8.16$ TeV

- 13.6 nb^{-1} (Fwd), 20.8 nb^{-1} (Bwd)

Fixed-target setup at LHCb



- Unique capability at LHC: Injecting noble gas (He, Ne, Ar) in the Vertex Locator (VELO)
- Parasitic to the collider mode
- Gas spreads in the beam pipe up to ± 20 m around LHCb
- Use non-colliding bunches
- Access: $\sqrt{s_{NN}} \in [69, 115]$ GeV, backward rapidity in centre-of-mass system

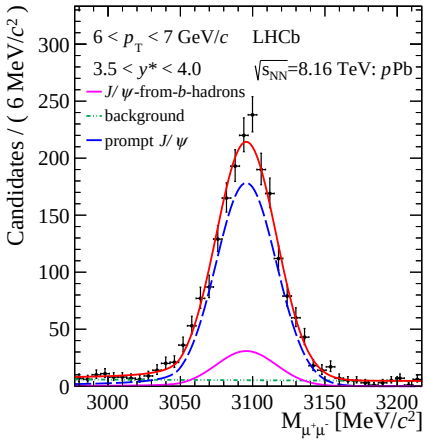
J/ψ production in proton-lead collisions at 8.16 TeV

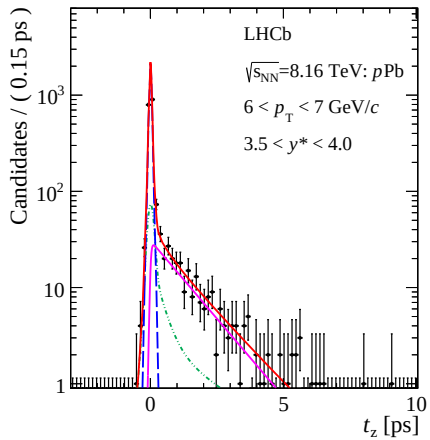
[PLB 774(2017) 159-178]

Signal extraction

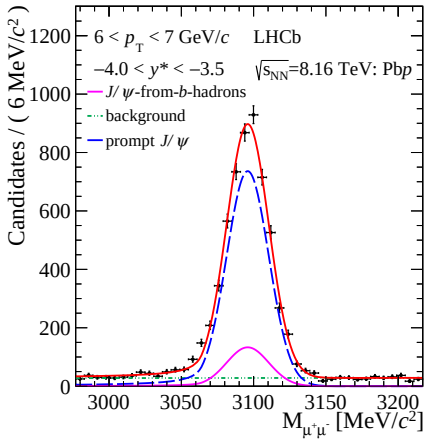
- 2016 pPb collision data, 8.16 TeV
- Prompt J/ψ and J/ψ-from-b are extracted by simultaneous fit of mass and pseudo-proper time: $t_Z = (Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}/p_Z$

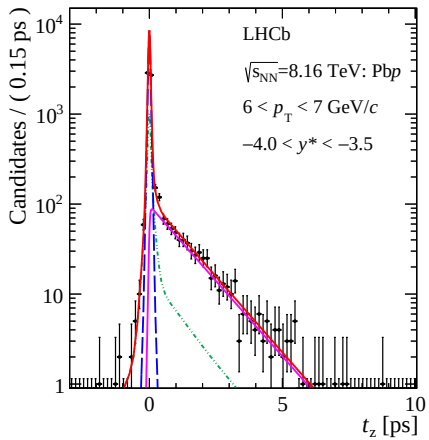
Forward





Backward





Mass distribution:
Signal: Crystal Ball
Background: exponential

t_Z distribution:
Signal: δ (t_Z) for prompt J/ψ;
Exponential for J/ψ-from-b.
Background: empirical function from sideband

Total yields:

	prompt	from-b
Forward:	$\sim 3.8 \times 10^5$;	$\sim 6.7 \times 10^4$
Backward:	$\sim 5.6 \times 10^5$;	$\sim 7.1 \times 10^4$

[PLB 774(2017) 159-178]

Results: J/ψ total cross-sections in pPb

Forward:

$$\sigma_{\text{prompt } J/\psi}(1.5 < y^* < 4.0,\ p_{\mathrm{T}} < 14\ \text{GeV}/c) = 1625 \pm 4 \pm 117\,\mu\text{b},$$
$$\sigma_{J/\psi\text{-from-}b\text{-hadrons}}(1.5 < y^* < 4.0,\ p_{\mathrm{T}} < 14\ \text{GeV}/c) = 276 \pm 2 \pm 20\,\mu\text{b},$$

Backward:

$$\sigma_{\text{prompt } J/\psi}(-5.0 < y^* < -2.5,\ p_{\mathrm{T}} < 14\ \text{GeV}/c) = 1692 \pm 4 \pm 182\,\mu\text{b},$$
$$\sigma_{J/\psi\text{-from-}b\text{-hadrons}}(-5.0 < y^* < -2.5,\ p_{\mathrm{T}} < 14\ \text{GeV}/c) = 209 \pm 1 \pm 22\,\mu\text{b},$$

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Results: J/ψ double differential cross-section

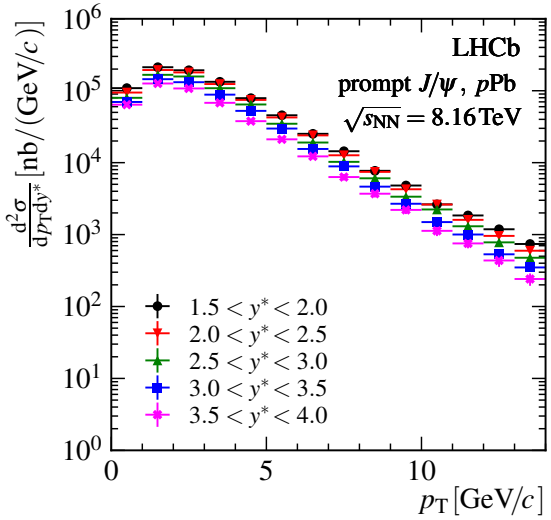
Double-differential cross-section is defined as:

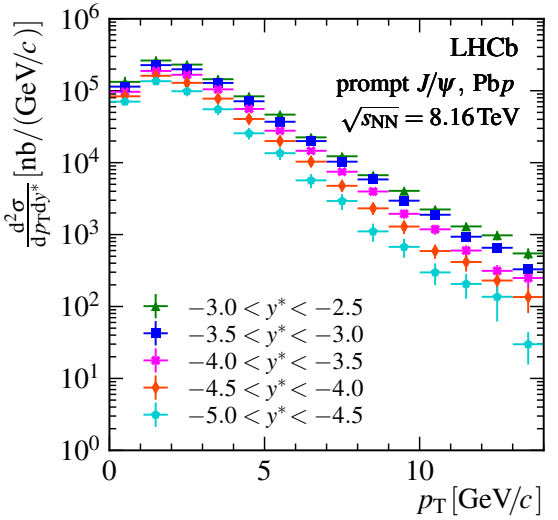
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} = \frac{N(\mathrm{J}/\psi \to \mu^+\mu^-)}{\mathcal{L}\cdot\epsilon_{tot}\cdot\mathcal{B}\cdot\Delta p_\mathrm{T}\cdot\Delta y^*}$$

- N: number of reconstructed prompt J/ψ or J/ψ-from-b;
- $\mathcal{B}$: branching fraction of $J/\psi \to \mu^+\mu^-$ decay ($\sim 6\%$) [PDG];

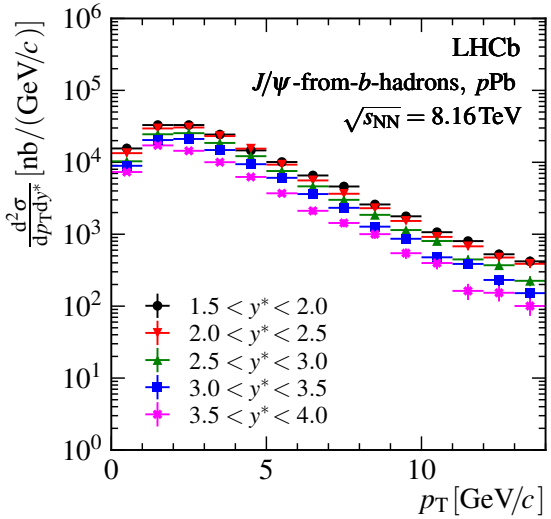
Forward | Backward

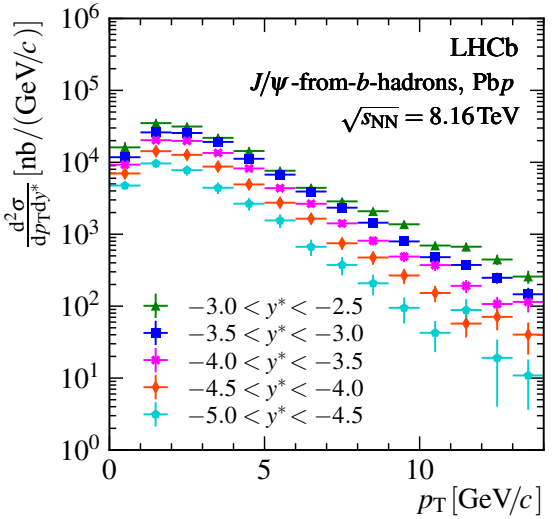
Prompt





From-b





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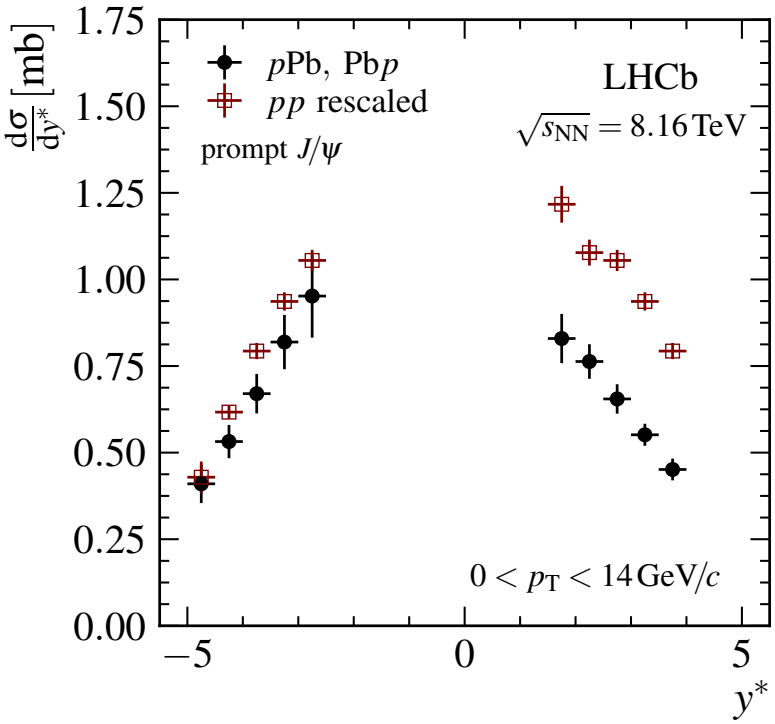
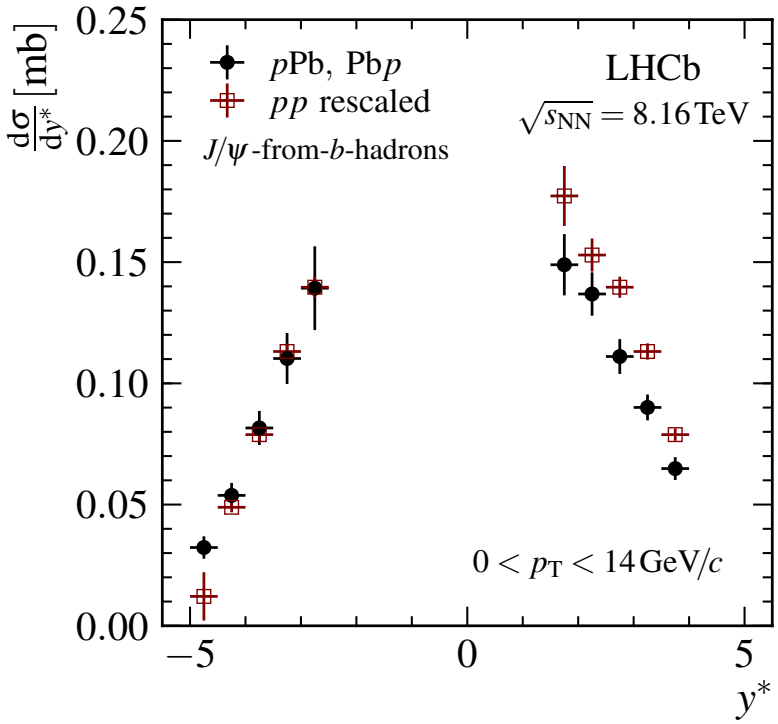
Results: J/ψ differential cross-section

Prompt



From-b



- The cross-sections as a function of y^*, integrated over the p_T
- Sizeable forward-backward asymmetry
- Uncertainties are the quadratic sums of the statistical and systematic components

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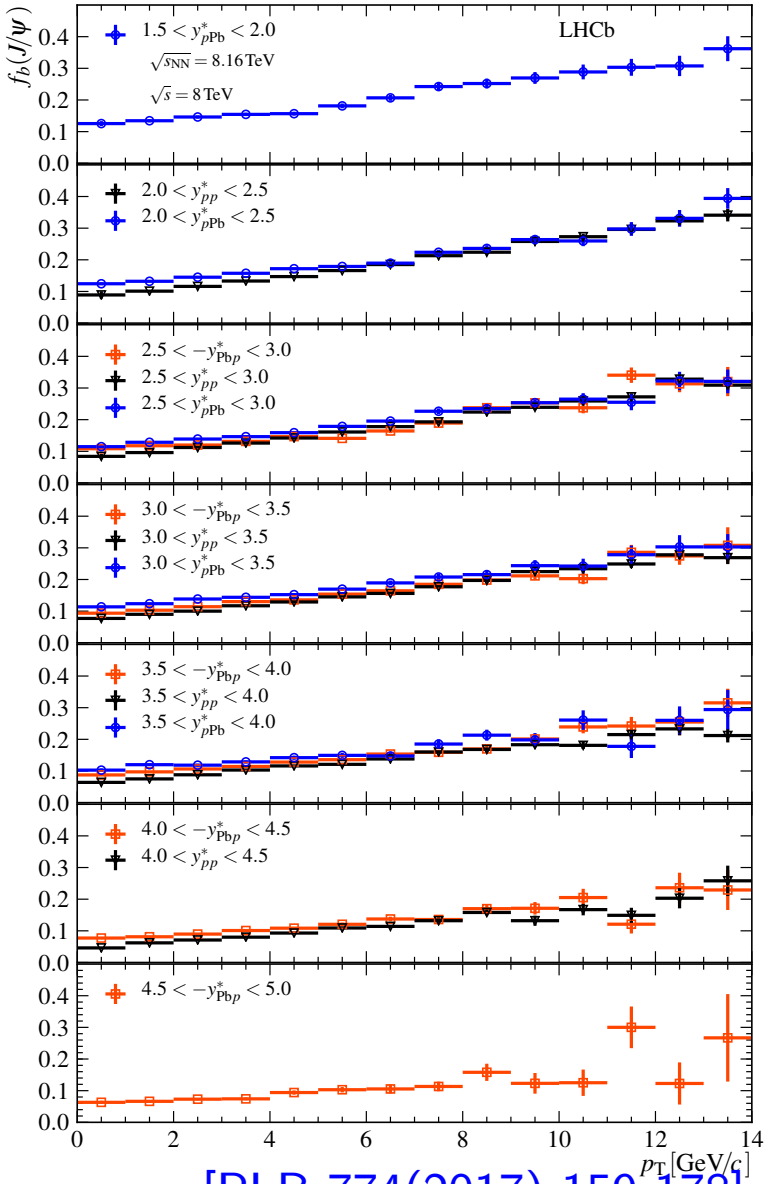
Results: fraction of J/ψ-from-b

- Fraction of J/ψ-from-b is defined as:

$$f_b \equiv \frac{\frac{\mathrm{d}^2\sigma_{J/\psi\text{-from-}b\text{-hadrons}}}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}}{\frac{\mathrm{d}^2\sigma_{\text{prompt } J/\psi}}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} + \frac{\mathrm{d}^2\sigma_{J/\psi\text{-from-}b\text{-hadrons}}}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}}$$

- Comparing pp (black), forward (blue) and backward (red) configurations.
- Similar trends.
- But deviations at low p_T highlight the differences in the nuclear effects on prompt J/ψ and J/ψ-from-b hadrons.



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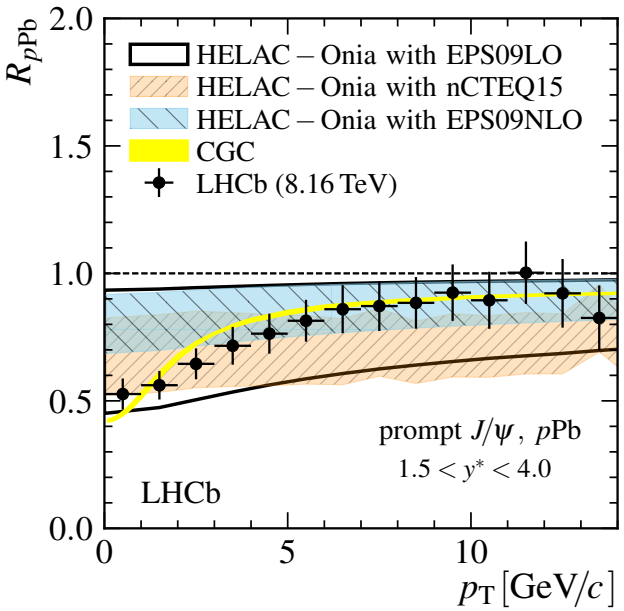
Results: prompt J/ψ nuclear modification factor

Nuclear modification factor is defined as:

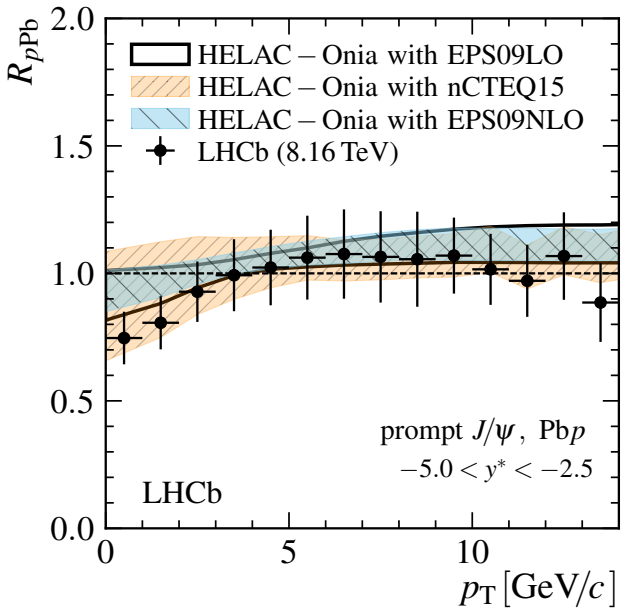
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}, y^*) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}, A = 208$$

- In Fwd: suppression at low p_{T} up to 50%, converging to unity at high p_{T}
- In Bwd: R_{pPb} closer to unity. Intriguing low values in Bwd at low p_{T}
- Overall agreement with theoretical models. Compatible with *p*Pb 5 TeV results.

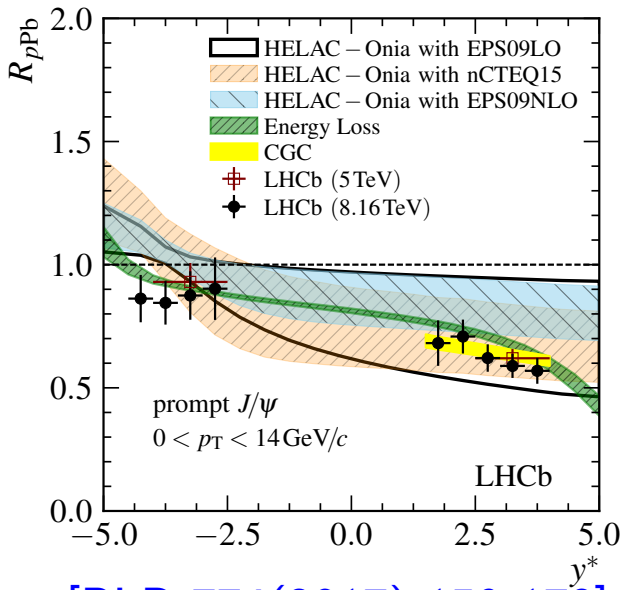
R_{pPb} vs. p_{T}, Forward



R_{pPb} vs. p_{T}, Backward



R_{pPb} vs. y^*



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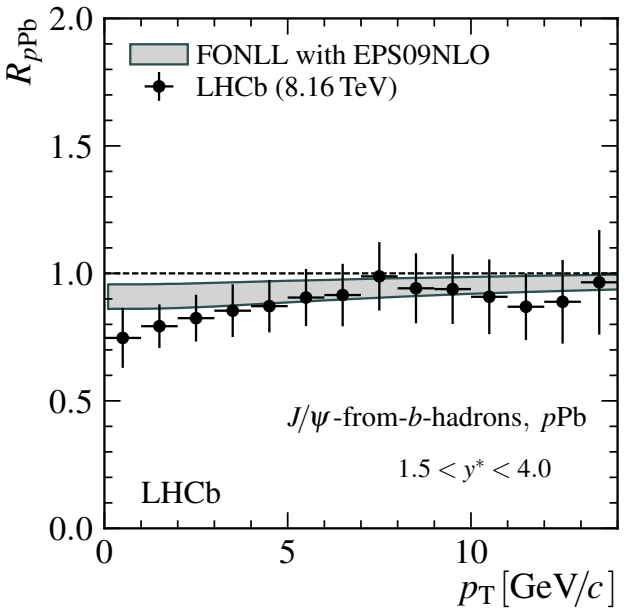
Results: J/ψ-from-b nuclear modification factor

Nuclear modification factor is defined as:

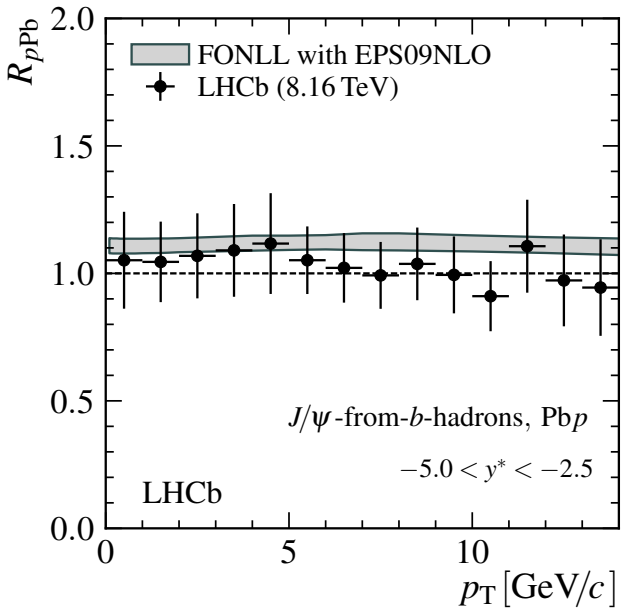
$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}, A = 208$$

- In Fwd: suppression at low p_T up to 30%, converging to unity at high p_T
- In Bwd: R_{pPb} slightly above unity
- Overall agreement with theoretical model. Compatible with pPb 5 TeV results.

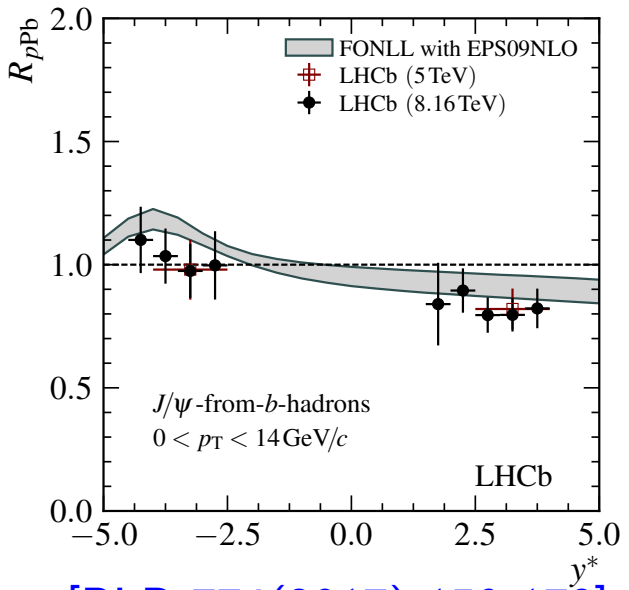
R_{pPb} vs. p_T, Forward



R_{pPb} vs. p_T, Backward



R_{pPb} vs. y^*



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Results: J/ψ forward-backward asymmetry

Forward-backward production ratio is defined as:

$$R_{\rm FB}(p_{\rm T}, y^*) \equiv \frac{\frac{{\rm d}^2\sigma_{p{\rm Pb}}(p_{\rm T}, +|y^*|)}{{\rm d}p_{\rm T}{\rm d}y^*}}{\frac{{\rm d}^2\sigma_{{\rm Pb}p}(p_{\rm T}, -|y^*|)}{{\rm d}p_{\rm T}{\rm d}y^*}}$$

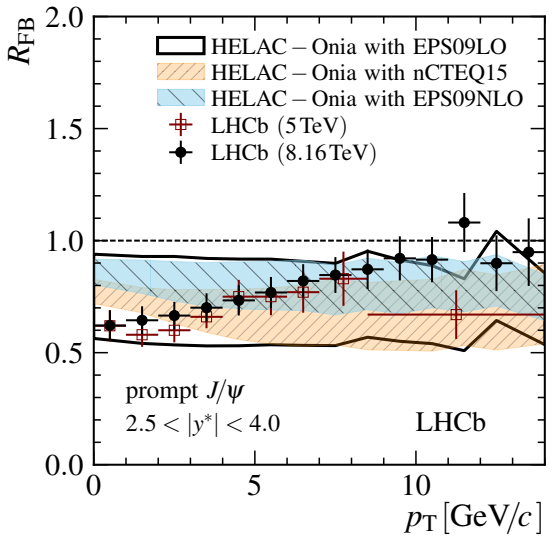
Prompt

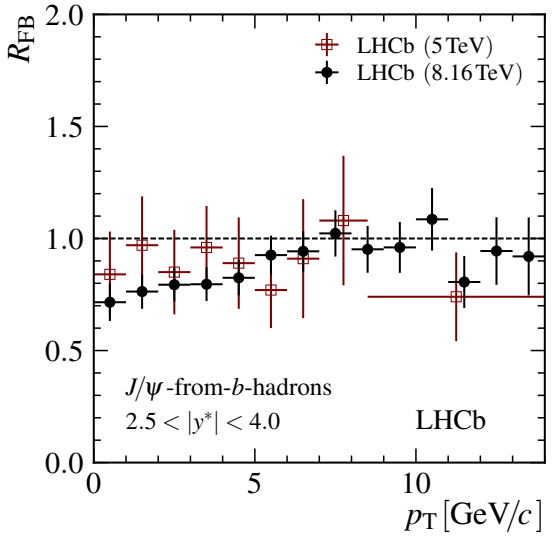
- Clear forward-backward asymmetry for prompt J/ψ, in particular at low $p_{\rm T}$

From-b

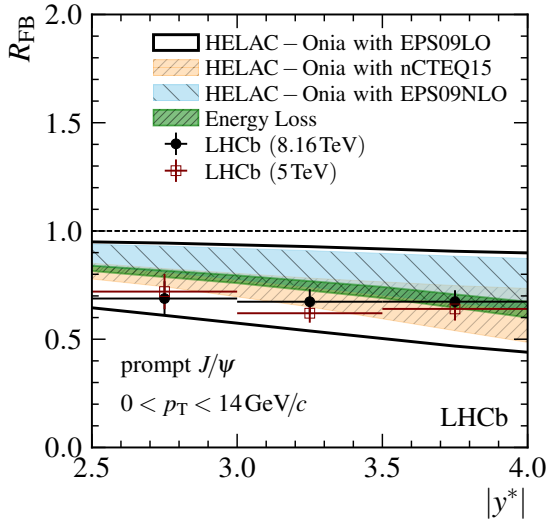
- For J/ψ-from-b: R_{FB} is closer to unity
- Agreement with pPb 5 TeV data within uncertainties

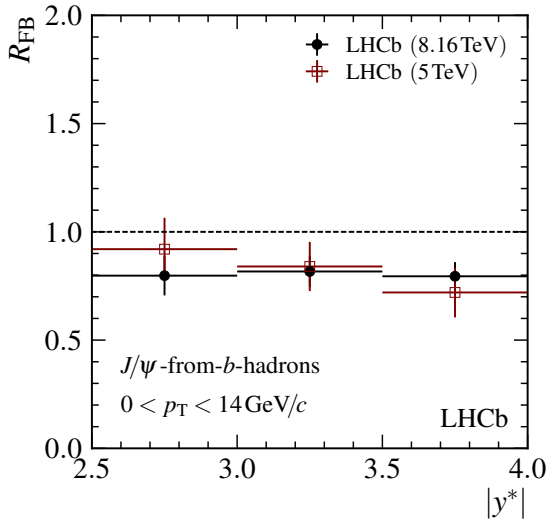
R_{FB} vs. p_T





R_{FB} vs. y^*





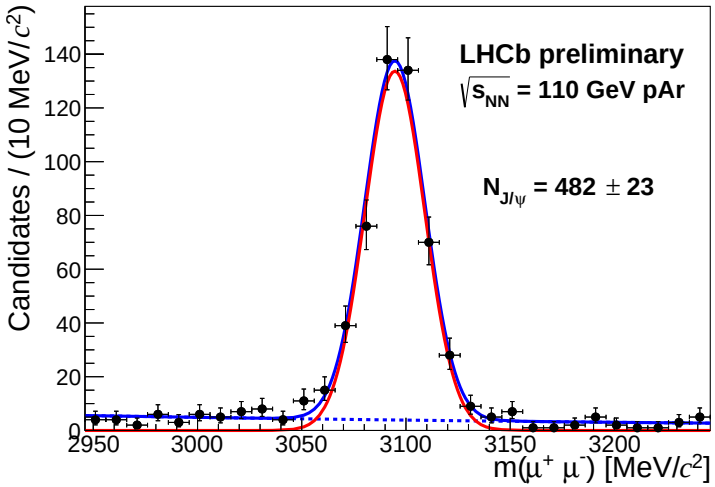
[PLB 774(2017) 159-178]

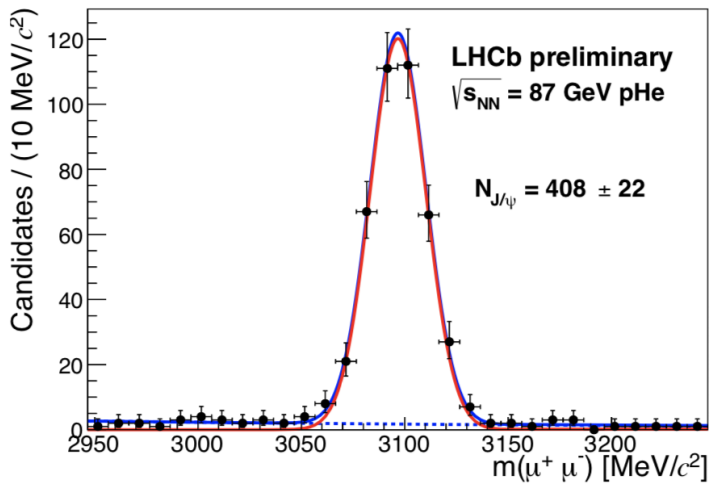
J/ψ production in pAr and pHe data

[LHCB-CONF-2017-001, paper in preparation]

Dataset

- Data collected in 2015 in pAr collisions at $\sqrt{s_{NN}} = 110$ GeV
- Data collected in 2016 in pHe collisions at $\sqrt{s_{NN}} = 86.6$ GeV
- J/ψ selected with Z vertex inside the Vertex Locator, $[-200,+200]$ mm, extracted with Crystal Ball functions





J/ψ and D^0 cross section in pHe

- Luminosity measurement only available for fixed target data starting 2016
- Cross-section measurement has been performed for the pHe sample only
- J/ψ and D^0 total cross-sections per target nucleon, in the full phase-space, are found to be:

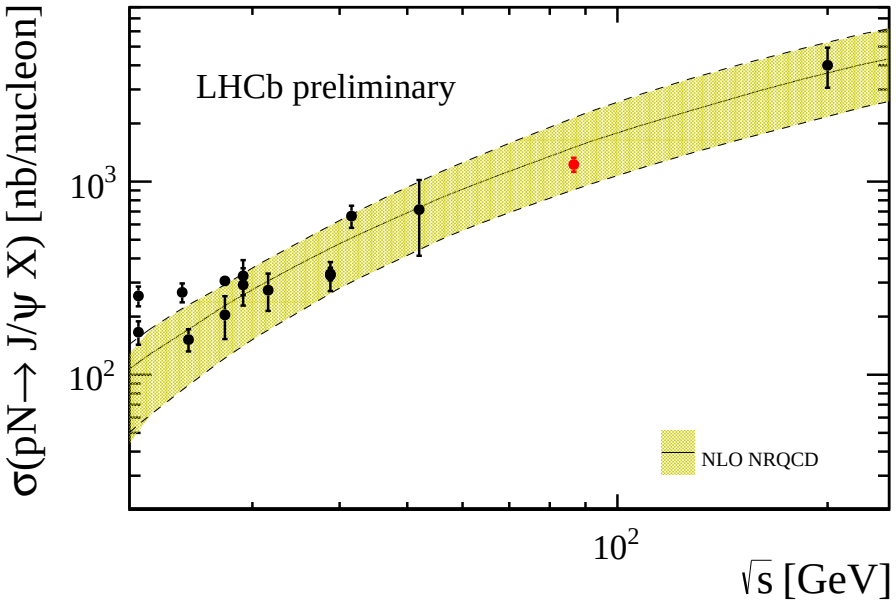
$$\sigma_{J/\psi}^{86.6\ \mathrm{GeV}} = 1225.6 \pm 62.0(stat.) \pm 81.6(syst.)\ \mathrm{nb/nucleon}$$

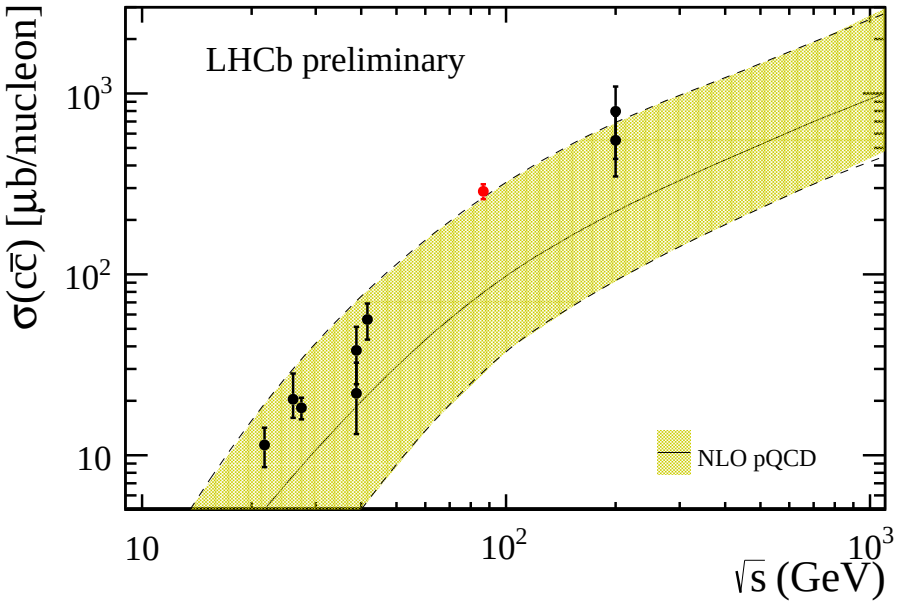
$$\sigma_{D^0}^{86.6\ \mathrm{GeV}} = 156.0 \pm 4.6(stat.) \pm 12.3(syst.)\ \mu\mathrm{b/nucleon}$$

- Scaling the D^0 cross-section with the global fragmentation ratio $f(c \to D^0) = 0.542 \pm 0.024$, $c\bar{c}$ production cross section can be obtained:

$$\sigma_{c\bar{c}}^{86.6\ \mathrm{GeV}} = 287.8 \pm 8.5(stat.) \pm 25.7(syst.)\ \mu\mathrm{b/nucleon}$$

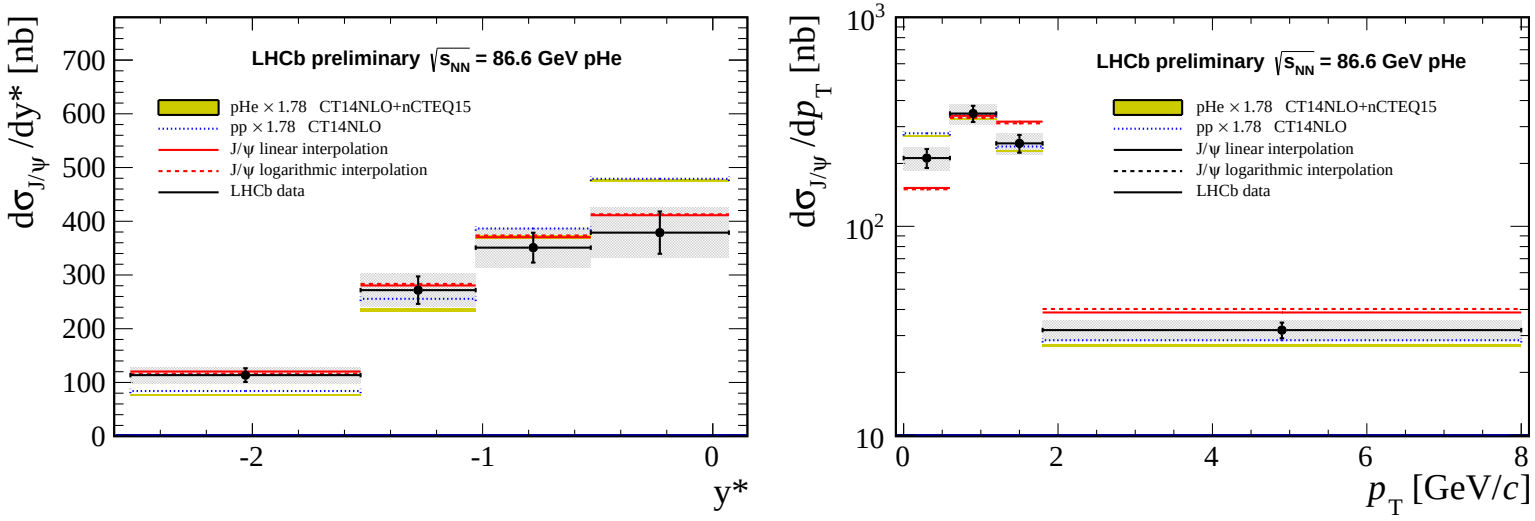
J/ψ and $c\bar{c}$ cross section vs. centre-of-mass energy





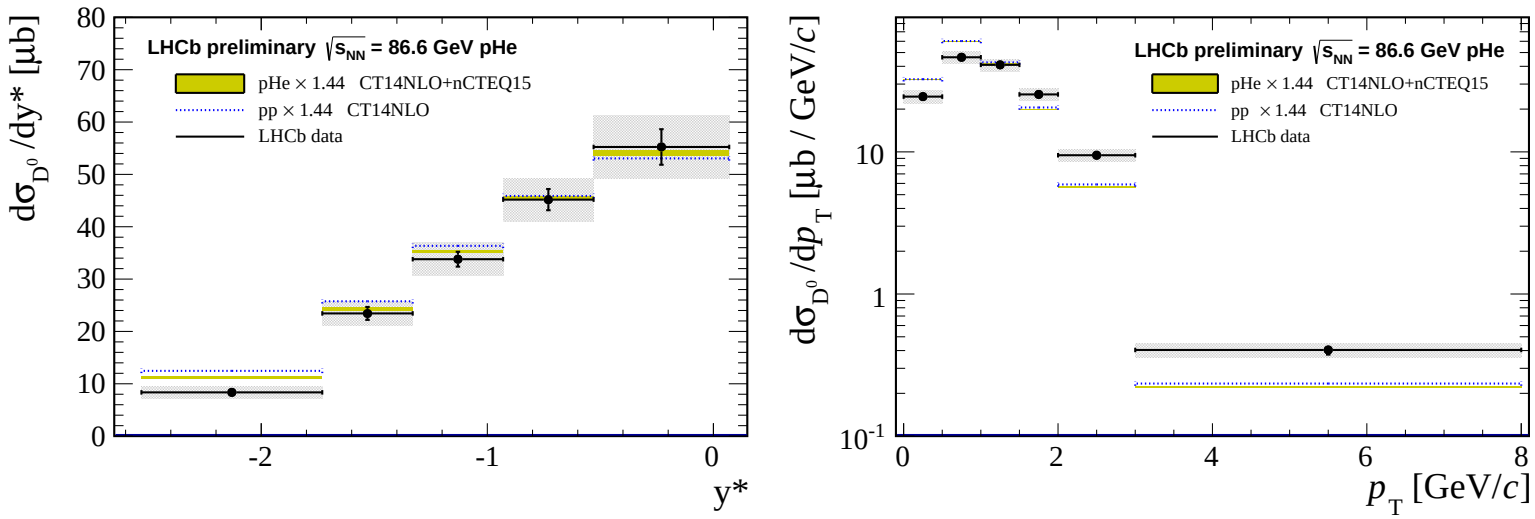
- J/ψ (left) and $c\bar{c}$ (right) cross-section measurements as functions of the centre-of-mass energy
- NLO NRQCD ([PLB 638 (2006) 202], left) and NLO pQCD ([PRC 94 (2016) 054908], right) predictions marked with yellow band
- Red points correspond to the results presented here

J/ψ pHe differential cross section



- Quadratic sum of statistical and uncorrelated systematic uncertainties indicated by vertical lines
- Correlated systematic uncertainties are indicated by open boxes
- HELAC-ONIA [EPJC 77:1 (2017)] predictions for pp (blue line) and pHe (yellow box) overlaid with measurement
- Plain and dashed red lines: phenomenological parametrization [PRL 109 (2012) 122301, PRD 83 (2011) 114036]
- Reasonable agreement with theoretical expectations

D^0 pHe differential cross section



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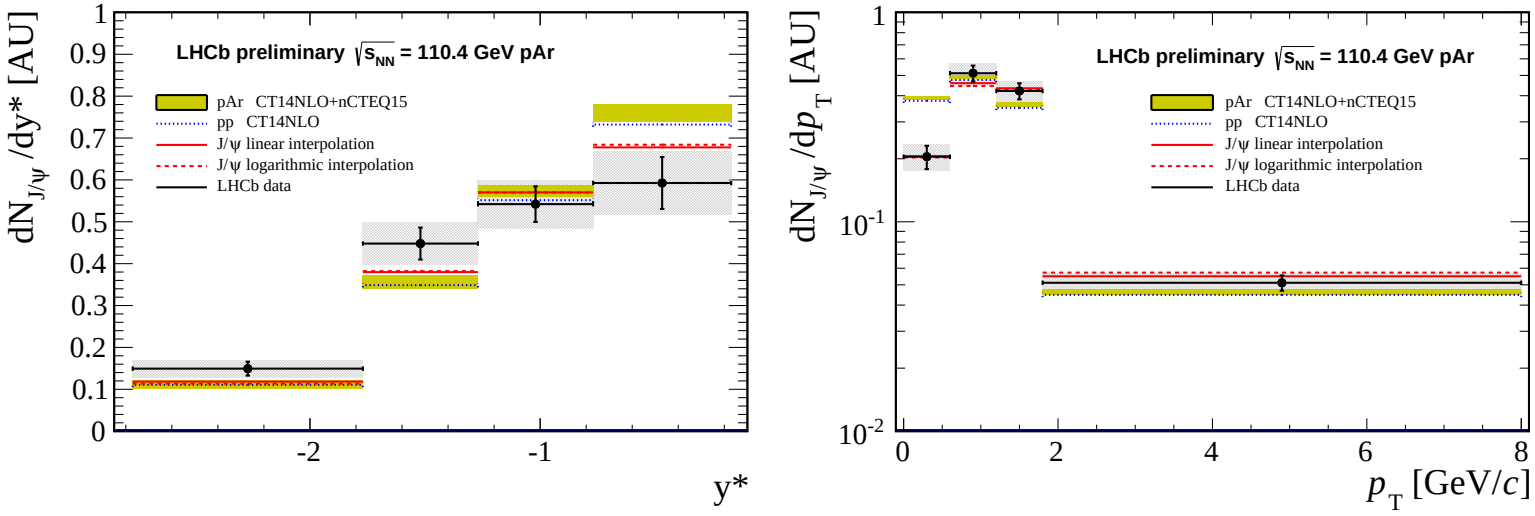
- Correlated systematic uncertainties are indicated by open boxes
- HELAC-ONIA [EPJC 77:1 (2017)] predictions for pp (blue line) and pHe (yellow box) overlaid with measurement
- No strong intrinsic charm contribution is observed
- Reasonable agreement with theoretical expectations

J/ψ pAr differential yields



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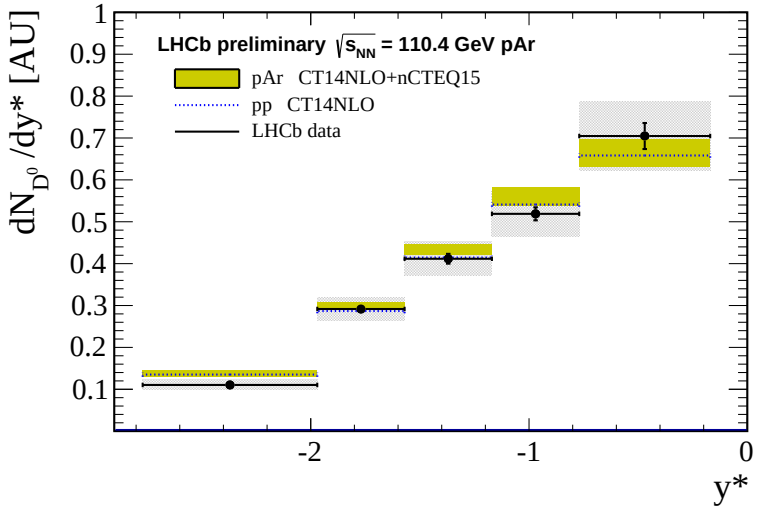
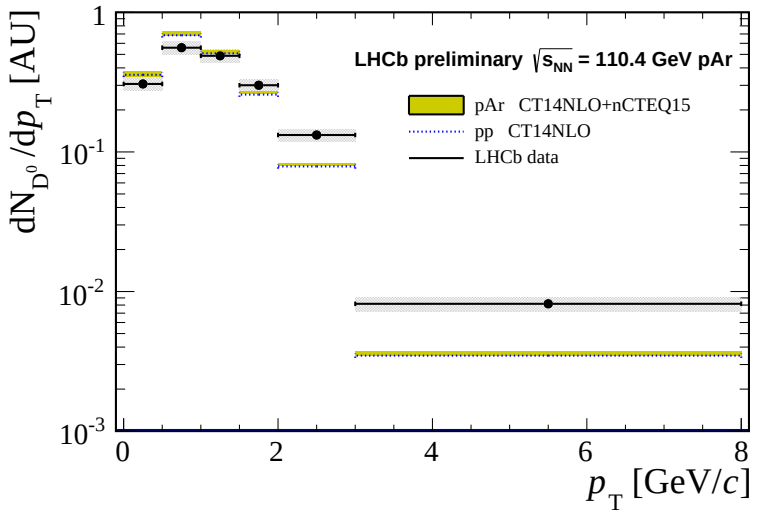
D^0 pAr differential yields





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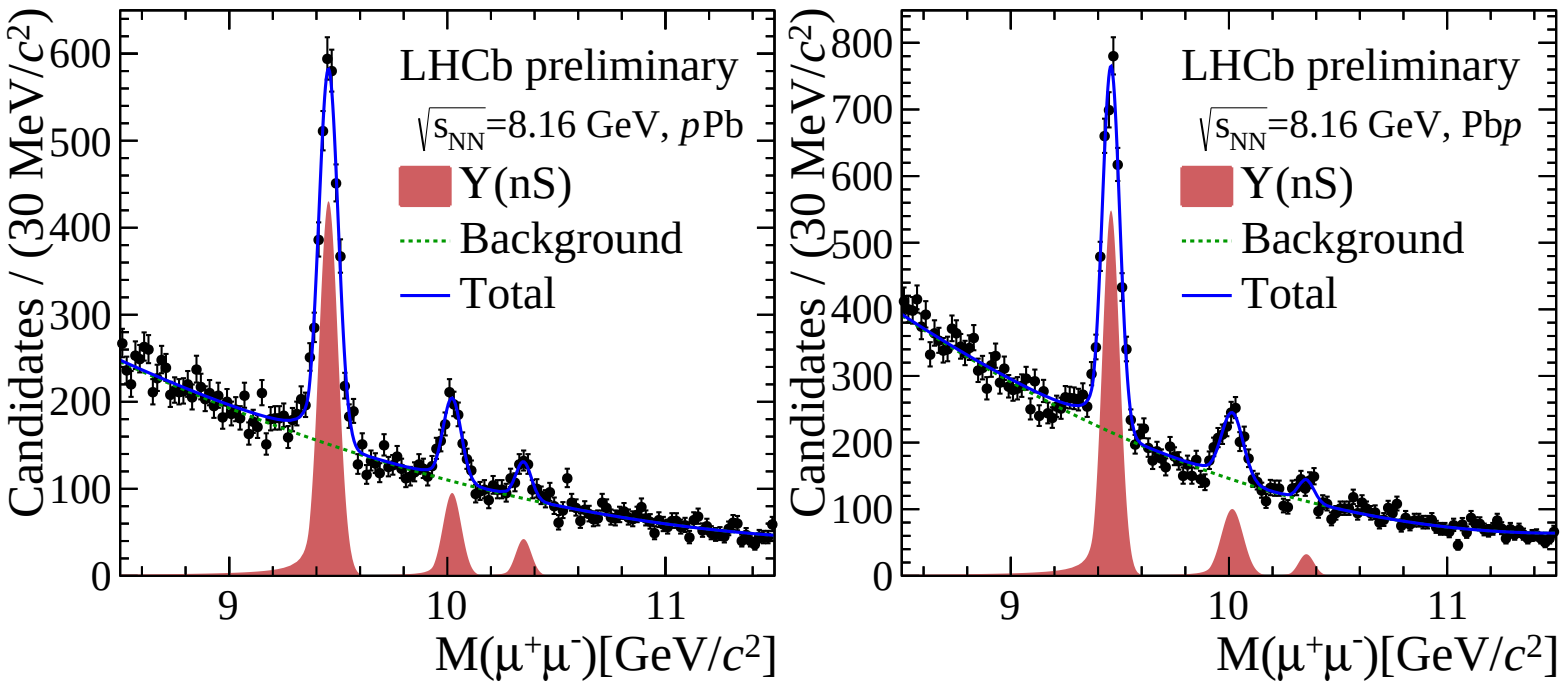
- Reasonable agreement with theoretical expectation

Outlook and conclusions

Other measurements with proton-lead data

LHCb will release $\Upsilon(nS)$ and $\psi(2S)$ measurements soon.



Outlook and conclusions

Proton-lead:

- Production cross-sections of prompt and non-prompt J/ψ in $\sqrt{s_{NN}} = 8.16$ TeV pPb collisions are measured as function of p_{T} and y^*
- Nuclear modification factors and forward-backward asymmetry are measured
- These results can have an impact in constrain models for nuclear effects
- These results will be the reference for the analyses of nucleus-nucleus collisions
- More measurements with $\sqrt{s_{NN}} = 8.16$ TeV are still yet to come ($\psi(2S)$, $\Upsilon(nS)$, ...)

Outlook and Conclusions

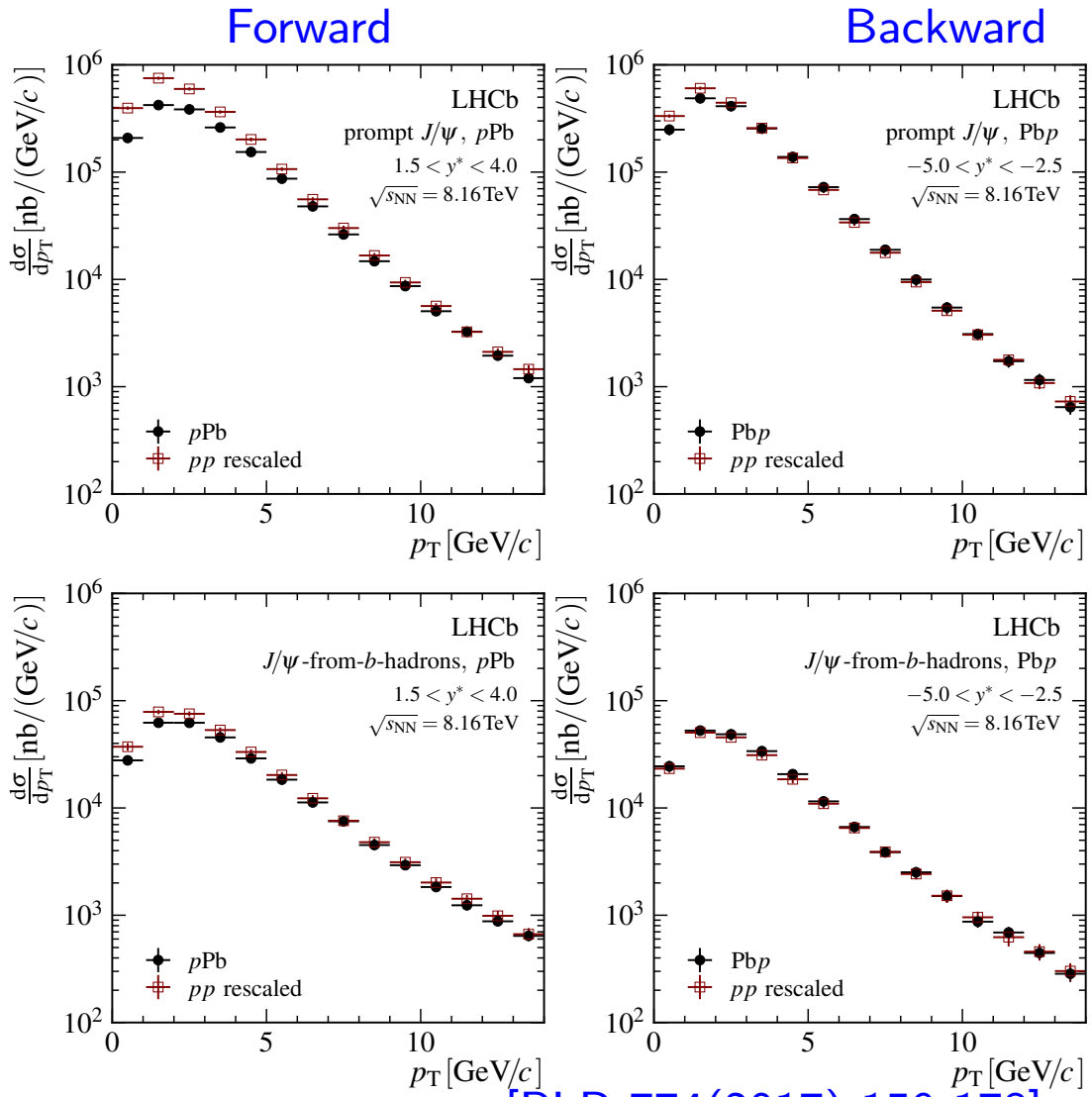
Fixed target:

- Measure ~500 J/ψ in pAr collisions at $\sqrt{s_{NN}} = 110$ GeV and ~400 J/ψ in pHe collisions at $\sqrt{s_{NN}} = 86.6$ GeV
- No strong intrinsic charm contribution is observed within experimental uncertainties
- Demonstrate the feasibility of a heavy-flavor fixed-target program with LHCb
- LHCb can also measure other charm hadrons ($\psi(2S)$...) with future larger data samples

Backup

Results: J/ψ differential cross-section

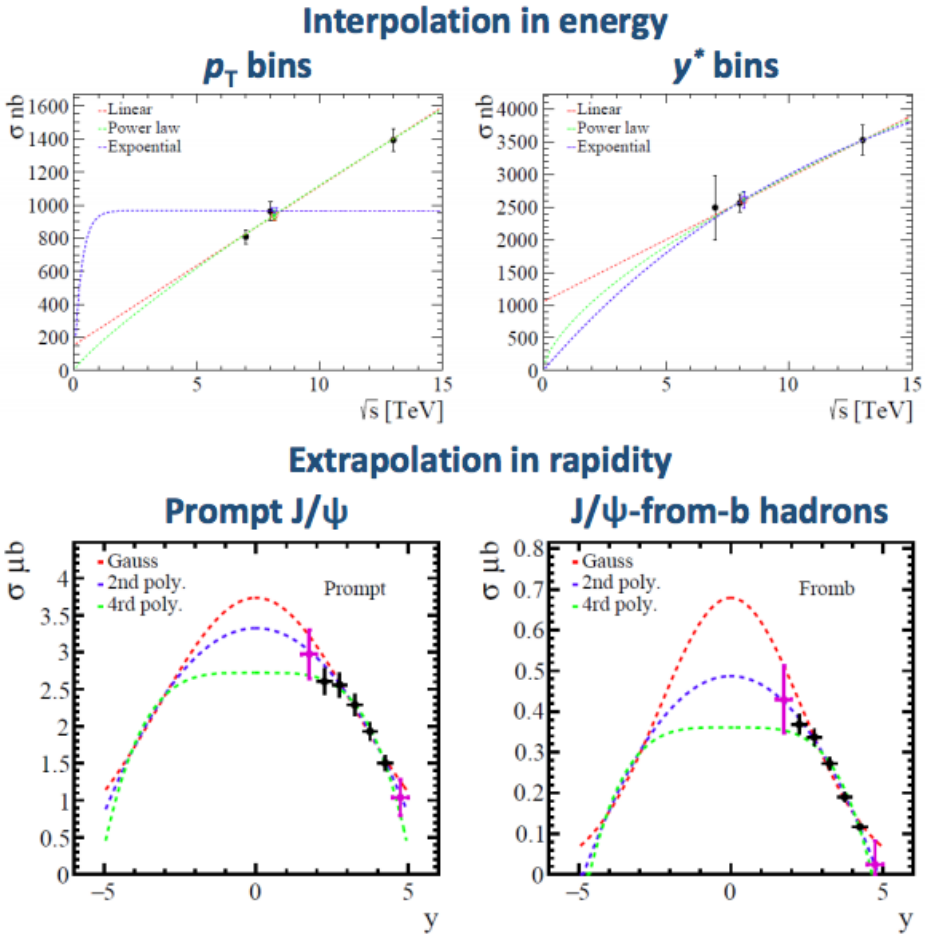
- The cross-section is compared with the reference cross-section for prompt J/ψ and J/ψ-from-b-hadrons production in pp collisions at $\sqrt{s} =$ 8.16 TeV, multiplied by the Pb mass number A = 208
- The cross-sections as a function of p_T, integrated over the range $1.5 < y^* < 4.0$ for pPb and $-5.0 < y^* < -2.5$ for Pbp



[PLB 774(2017) 159-178]

Collision of *pp* at 8.16 TeV reference

- *pp* measurements at 8.16 TeV not available.
- Estimated based on interpolation (in energy), extrapolation (in rapidity outside *pp* coverage) of measurements at 7, 8 and 13 TeV.
- These methods were validated with ALICE and LHCb data [LHCb-CONF-2013-013; ALICE-PUBLIC-2013-002]



Yields and uncertainties

Yields are corrected for different efficiencies

$$Y = \frac{Y^{measured}}{\epsilon}$$

where $Y^{measured}$ is extracted from mass fits and ϵ is combination of geometrical acceptance, trigger, selection, reconstruction, particle identification efficiencies

Source of uncertainties	pAr J/ψ y	pAr J/ψ p_T	pHe J/ψ y	pHe J/ψ p_T
Corr. between bins				
Tracking	1.9%	1.9%	1.1%	1.1%
PID	1.9%	1.8%	1.0%	0.9%
Signal selection	1.4%	1.4%	1.1%	1.1%
Uncorr. betwwen bins				
Signal extraction	(0-0.6)%	(0-0.9)%	(0-0.7)%	(0-0.9)%
MC sample	(1.8-1.9)%	(1.8-2.0)%	(1.8-2.0)%	(1.7-3.4)%
Tracking	(0.3-1.9)%	(0.1-0.2)%	(0.6-1.8)%	(0.2-0.4)%
PID	(0-1.9)%	(0-1.6)%	(0-0.8)%	(0-0.8)%
Stat. uncertainties	(7.8-11.1)%	(8.4-12.7)%	(7.9-11.3)%	(8.6-10.4)%