Open heavy flavor production at LHCb

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on behalf of the LHCb collaboration

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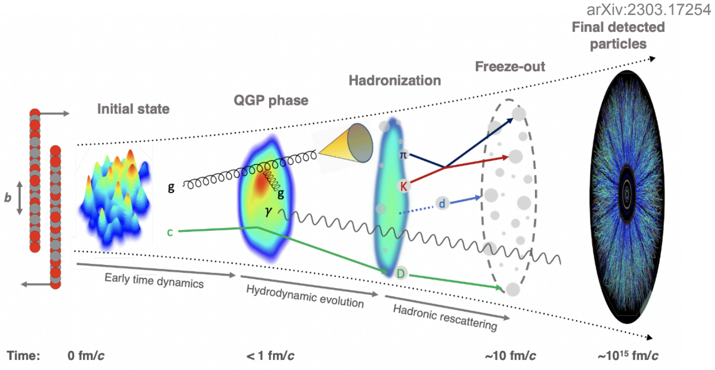
1. Physics background
2. LHCb detector
3. Open heavy flavour results with LHCb
   - Λ_b^0/B^0 production ratio in pp collisions at $\sqrt{s} = 13\,\text{TeV}$
   - Open charm production in pPb collisions
   - Open charm production in fixed-target collisions
4. Summary and prospect

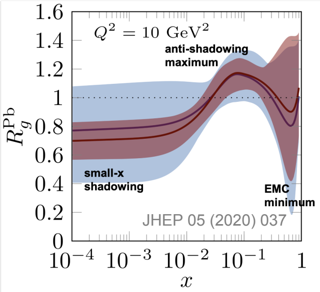
Heavy flavour in heavy-ion collisions

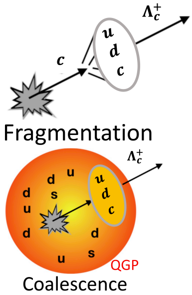
- Heavy quarks are excellent probes in heavy-ion collisions
  - Produced in hard processes at early stage of collisions
  - Experience the evolution of the nuclear medium due to their long lifetime



Heavy flavour in heavy-ion collisions

- Heavy quarks are excellent probes in heavy-ion collisions
  - Produced in hard processes at early stage of collisions
  - Experience the evolution of the nuclear medium due to their long lifetime
- Nuclear matter effects in heavy flavour production
  - Nuclear shadowing
  - Multi-parton scattering
  - Hadronisation in medium (fragmentation / coalescence)

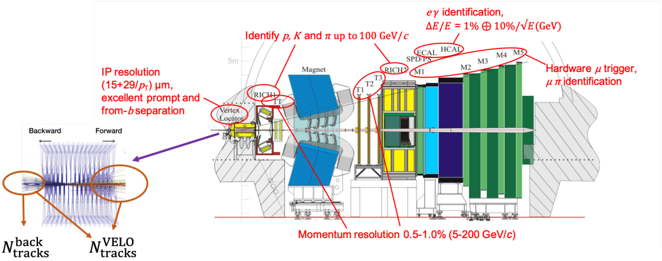




LHCb detector in Run2

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Single-arm forward spectrometer, covering the pseudo-rapidity range of $2 < \eta < 5$
- Designed for studying particles containing b or c quarks
- A general purposed detector collecting pp/pPb/PbPb data, providing unique fix-target mode at the LHC

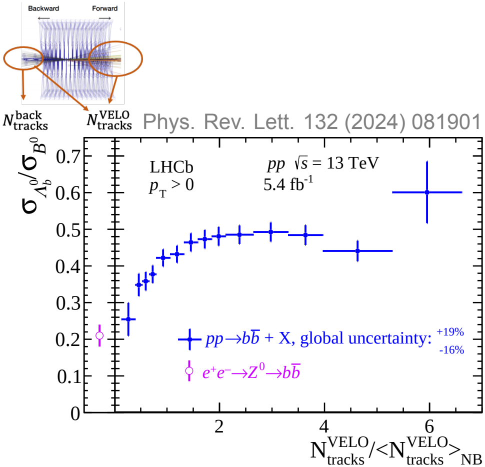


- Provide excellent track finding, vertex reconstruction and particle identification (PID)

Λ_b^0/B^0 production ratio in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

Λ_b^0/B^0 ratio versus multiplicity

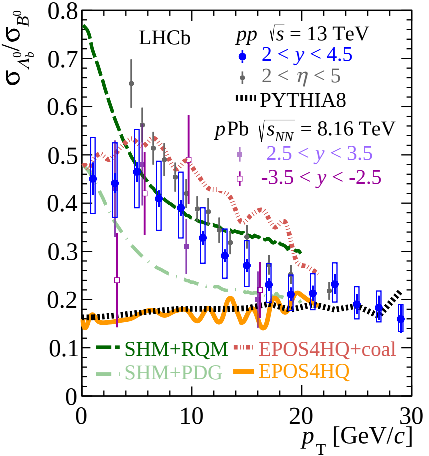
- Enhanced baryon production considered as a signature of quark coalescence
- Quark wave-function overlap enhanced by multiple parton scatterings and high particle density



- $R_{\Lambda_b^0/B^0}$ reach e^+e^- result as multiplicity goes lower
- Significant increasing trend of Λ_b^0/B^0 with multiplicity, suggesting the contribution from coalescence in addition to fragmentation in b quark hadronisation

Λ_b^0/B^0 ratio versus p_{T}

Phys.Rev.Lett. 132 (2024) 081901

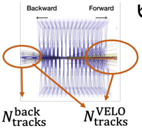


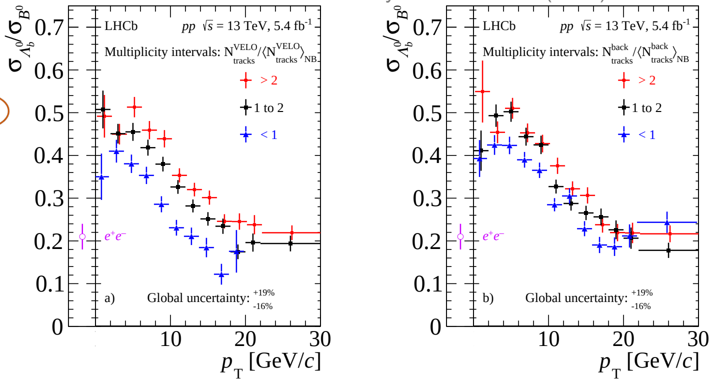
LHCb pp: Phys.Rev.D 100, 031102(R) (2019)
LHCb pPb: Phys.Rev.D 99, 052011 (2019)
SHM: Phys.Rev.Lett. 131, 012301 (2023)
EPOS4HQ: Phys.Rev.D 109 (2024) 5, 054011
PYTHIA8: Comput.Phys.Commun. 178, 852 (2008)

- $R_{\Lambda_b^0/B^0}$ enhanced at low p_{T} observed, where coalescence is expected to dominate
- In agreement with previous LHCb pp and pPb measurements
- Statistical hadronisation model (SHM) with relativistic quark model (RQM) gives better description than with PDG data by considering Λ_b^0 feed-down from excited baryons
- EPOS4HQ reproduces the enhancement at low p_{T} by incorporating coalescence

Λ_b^0/B^0 ratio versus p_T in different multiplicity intervals

Phys.Rev.Lett. 132 (2024) 081901





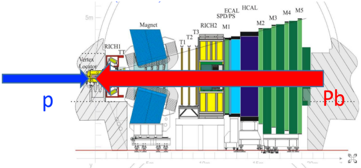
- $R_{\Lambda_b^0/B^0}$ shows a stronger dependence on normalised $N_{\text{tracks}}^{\text{VELO}}$ (forward tracks dominant) than $N_{\text{tracks}}^{\text{back}}$ (backward tracks only), which indicates that coalescence may be induced by interactions with particles around b quarks
- $R_{\Lambda_b^0/B^0}$ enhancement at low p_T observed
- Pronounced ordering of $R_{\Lambda_b^0/B^0}$ with multiplicity at intermediate p_T
- $R_{\Lambda_b^0/B^0}$ at high $p_T \rightarrow e^+e^-$

Open charm production in pPb collisions

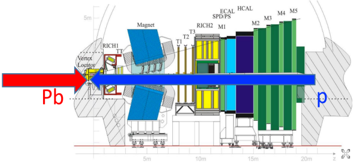
LHCb pPb data

- Asymmetric pPb data taken in 2013 and 2016 with $\sqrt{s_{\mathrm{NN}}} = 5.02$ and $8.16\,\mathrm{TeV}$, including two collision configurations

pPb: forward



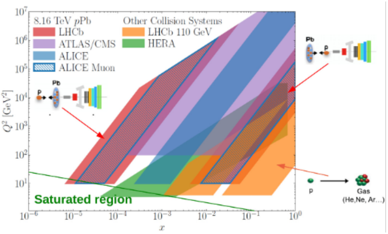
Pbp: backward



- Rapidity boosted in lab frame by 0.465
- Rapidity coverage:

$$p\mathrm{Pb} : 1.5 < y^* < 4.0$$
$$\mathrm{Pb}p : -5.0 < y^* < -2.5$$

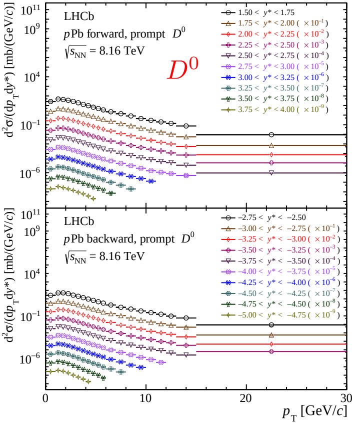
- Covering both shadowing and anti-shadowing regions

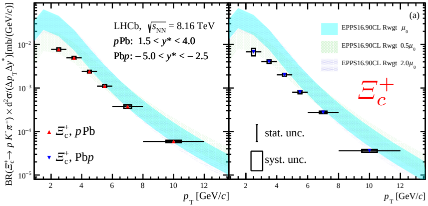


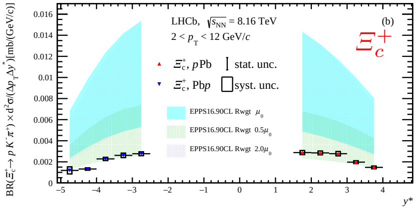
Open charm production cross-section in pPb

- D^0, D^+, D_s^+ and Ξ_c^+ production measured in pPb collisions
- Prompt D^0 and Ξ_c^+ production cross-sections at $\sqrt{s_{\rm NN}} = 8.16$ TeV

D^0: Phys. Rev. Lett. 131 (2023) 102301
Ξ_c^+: Phys. Rev. C 109 (2024) 044901







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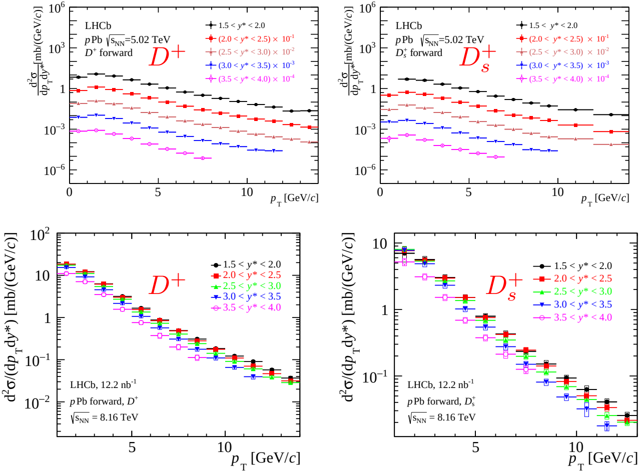
- Prompt D^+ and D_s^+ production cross-sections at $\sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$ and $8.16\,\text{TeV}$

5TeV: JHEP 01 (2024) 070
8TeV: arXiv:2311.08490



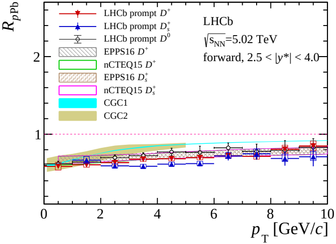
Nuclear modification factor

- Nuclear modification factor obtained by comparing with pp reference

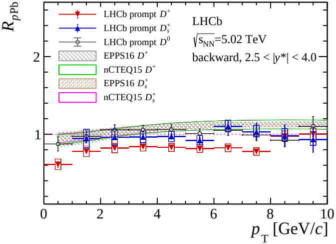
$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*) \equiv \frac{1}{A} \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_{\mathrm{T}}, y^*)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}$$

- pp reference derived from LHCb 5 TeV and 13 TeV D meson production
- $R_{p\mathrm{Pb}}(D^+)$ and $R_{p\mathrm{Pb}}(D_s^+)$ at 5.02 TeV

LHCb 5 TeV D^0: JHEP 10 (2017) 090
EPPS16 : Eur.Phys.J.C77 (2017) 3, 163
nCTEQ15 : Phys.Rev.D 93 (2016) 8, 085037



LHCb 5 TeV D^+ and D_s^+: JHEP 01 (2024) 070
CGC1: Nucl.Phys.Proc 2017, 289-290
CGC2: Phys.Rev.D 98 (2018) 7, 074025



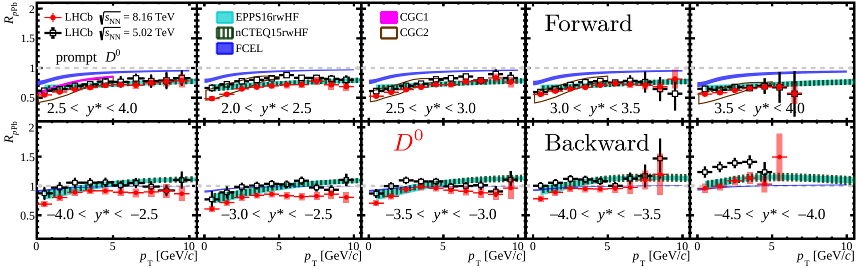
- Significantly suppressed $R_{p\mathrm{Pb}}$ at forward rapidity, suggesting the existence of nuclear shadowing
- $R_{p\mathrm{Pb}}(D^+)$ more suppressed at backward rapidity than other D mesons and nPDF calculations

$R_{p\mathrm{Pb}}(D^0)$ in (p_{T}, y^*)

- $R_{p\mathrm{Pb}}(D^0)$ at 8.16 TeV in different rapidity intervals

LHCb 5 TeV D^0: JHEP 10 (2017) 090
EPPS16 : Eur.Phys.J.C77 (2017) 3, 163
nCTEQ15 : Phys.Rev.D 93 (2016) 8, 085037

FCEL: JHEP 01 (2022) 164
CGC1: Nucl.Phys.Proc 2017, 289-290
CGC2: Phys.Rev.D 98 (2018) 7, 074025



- $R_{p\mathrm{Pb}}(D^0)$ in forward regions in general agreement with CGC and nPDF models
- Stronger suppression for $R_{p\mathrm{Pb}}(D^0)$ at lowest p_{T} in forward rapidity than nPDF calculations, possibly due to the exsistence of fully coherent energy loss (FCEL) effects besides nuclear shadowing
- More suppressed $R_{p\mathrm{Pb}}(D^0)$ at high p_{T} in backward region than nPDF models, indicating additional initial or final state effects

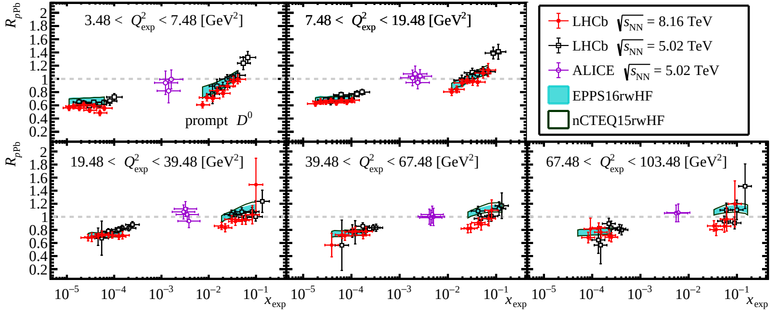
$R_{p\text{Pb}}(D^0)$ in (x, Q^2)

- The experimental proxies x_{exp} and Q^2_{exp} used for comparing results in different energy and kinematic regions

$$x_{\text{exp}} \equiv 2\frac{\sqrt{p_{\text{T}}{}^2(D^0) + M^2(D^0)}}{\sqrt{s_{\text{NN}}}}e^{-y^*} \text{ and } Q^2_{\text{exp}} \equiv p_{\text{T}}{}^2(D^0) + M^2(D^0)$$

LHCb 8 TeV D^0: Phys. Rev. Lett. 131 (2023) 102301
LHCb 5 TeV D^0: JHEP 10 (2017) 090
ALICE 5 TeV D^0: JHEP 12 (2019) 092

EPPS16 : Eur.Phys.J.C77 (2017) 3, 163
nCTEQ15 : Phys.Rev.D 93 (2016) 8, 085037



- Consistency between LHCb results at 5.02 TeV and 8.16 TeV in (x, Q^2) space
- Stronger suppression than nPDF calculations in $x \sim 0.01$ at larger Q^2

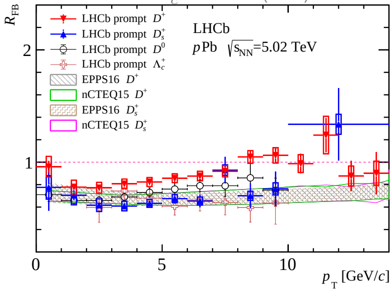
Forward backward production ratio

- Forward-backward production ratio defined as

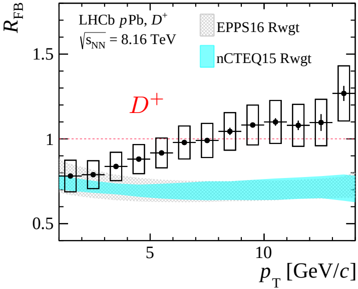
$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, +|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_{\mathrm{T}}, -|y^*|)/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*}$$

- $R_{\mathrm{FB}}(D^+)$ and $R_{\mathrm{FB}}(D_s^+)$ at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ and $8.16\,\mathrm{TeV}$

LHCb 5 TeV D^+ and D_s^+: JHEP 01 (2024) 070
LHCb 5 TeV D^0: JHEP 10 (2017) 090
LHCb 5 TeV Λ_c^+: JHEP 02 (2019) 102



LHCb 8 TeV D^+: arXiv:2311.08490
EPPS16 : EPJC 77 (2017) 3, 163
nCTEQ15 : Phys.Rev.D 93 (2016) 8, 085037

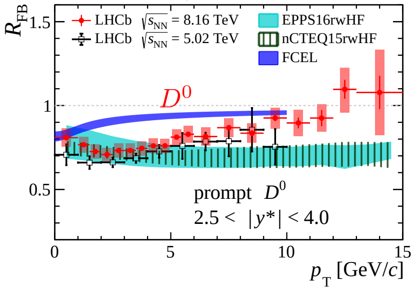


- Significant suppression at low p_{T}, in agreement with nPDF predictions
- $R_{\mathrm{FB}}(D^+)$ goes higher than nPDF predictions with increasing p_{T}, while for other charm hadrons, R_{FB} is consistent with the flat trend from nPDF models
- Consistency $R_{\mathrm{FB}}(D^+)$ bewteen 5.02 TeV and 8.16 TeV

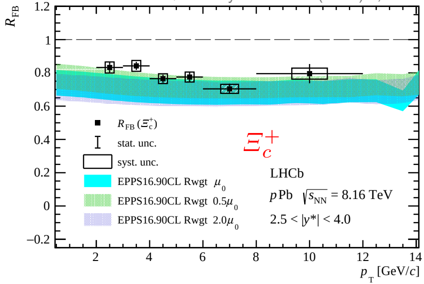
D^0 and Ξ_c^+ $R_{\rm FB}$ of at 8.16 TeV

- $R_{\rm FB}(D^0)$ and $R_{\rm FB}(\Xi_c^+)$ versus $p_{\rm T}$ at $\sqrt{s_{\rm NN}} = 8.16\,{\rm TeV}$

LHCb 8 TeV D^0: Phys. Rev. Lett. 131 (2023) 102301
LHCb 8 TeV Ξ_c^+: Phys. Rev. C 109 (2024) 044901



FCEL: JHEP 01 (2022) 164
EPPS16 : EPJC 77 (2017) 3, 163
nCTEQ15 : Phys.Rev.D 93 (2016) 8, 085037



- $R_{\rm FB}(D^0)$ shows an increasing trend with $p_{\rm T}$ and goes towards unity at high $p_{\rm T}$, consistent with $R_{\rm FB}(D^+)$ with higher precision
- $R_{\rm FB}(\Xi_c^+)$ shows no dependence on $p_{\rm T}$, in agreement with nPDF calculations but conflicting with D mesons

Open charm production in fixed-target collisions

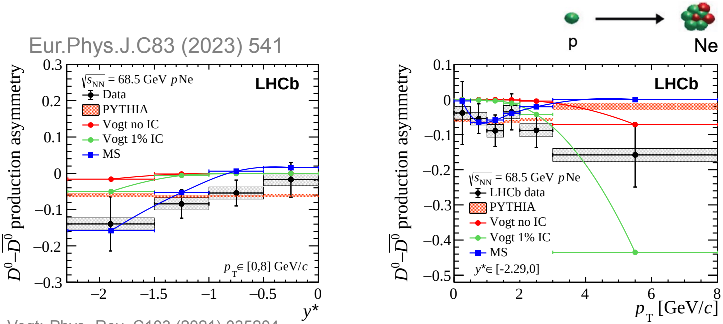
D^0-$\overline{D}^0$ production asymmetry in 68.5 GeV pNe

- D^0-$\overline{D}^0$ production asymmetry defined as

$$\mathcal{A}_{\text{prod}} = \frac{Y_{\text{corr}}(D^0) - Y_{\text{corr}}(\overline{D}^0)}{Y_{\text{corr}}(D^0) + Y_{\text{corr}}(\overline{D}^0)}$$

- Intrinsic charm of the nucleon and charm quark recombination involving high-x partons can contribute to the asymmetry
  - *Intrinsic* charm: $c\bar{c}$ pairs as sea quarks of nucleons rather than from gluon splitting

Eur.Phys.J.C83 (2023) 541

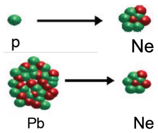


Vogt: Phys. Rev. C103 (2021) 035204
PYTHIA: Comput. Phys. Commun. 178 (2008) 852 MS: Phys. Lett. B835 (2022) 137530

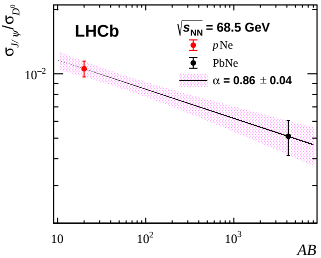
- Largest negative asymmetry of $\sim 15\%$ at $y^* \approx -2$
- MS model with 1% intrisic charm and 10% recombination in good agreement with data

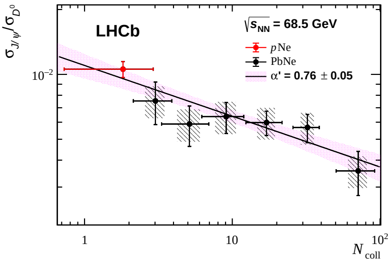
$J/\psi\,/D^0$ ratio in 68.5 GeV pNe and PbNe

- $J/\psi\,/D^0$ ratio measured as a function of collision size
  - AB: product of beam and target atomic mass number
  - N_{coll}: number of binary nucleon-nucleon collisions



Eur.Phys.J.C83 (2023) 658





- Initial state effects on $c\bar{c}$ production canceled, which gives a power-law dependence on collision size as $R_{J/\psi\,/D^0} \propto (AB)^{\alpha-1}$ or $(N_{\mathrm{coll}})^{\alpha'-1}$
- The suppression with increasing collision size leads to $\alpha < 1$ and indicates additional nuclear effects of J/ψ than D^0 mesons
- Consistency of decreasing trend across pNe, peripheral PbNe and central PbNe collisions, with no evindence of anomalous suppression or QGP formation

Summary and prospect

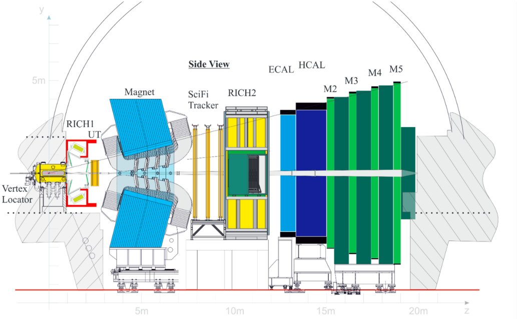
- The LHCb experiment provides excellent reconstruction on heavy flavour particles in pp, pPb and fixed-target experiments, which brings new insights on partonic structure of nucleon and hadronisation mechanisms
  - Enhancement of Λ_b^0/B^0 ratio with increasing multiplicity observed at intermediate p_{T}, suggesting the exsistence of quark coalescence in b quark hadronisation in pp collisions
  - Nuclear shadowing and forward-backward production asymmetry observed for all species of charm hadrons in pPb collisions
  - D^0 production and $J/\psi/D^0$ ratio measured in fixed-target pNe and PbNe collisions, where no evidence for anomalous suppression or exsistence of hot nuclear medium is seen
- More on strangeness production ratios (D_s^+/D^+, Ξ_c^+/Λ_c^+) see **Clara's talk**
- More central data samples with higher statistics available, thanks to Run3 data-taking and LHCb upgrade

Thanks

Backups

LHCb detector at Run3

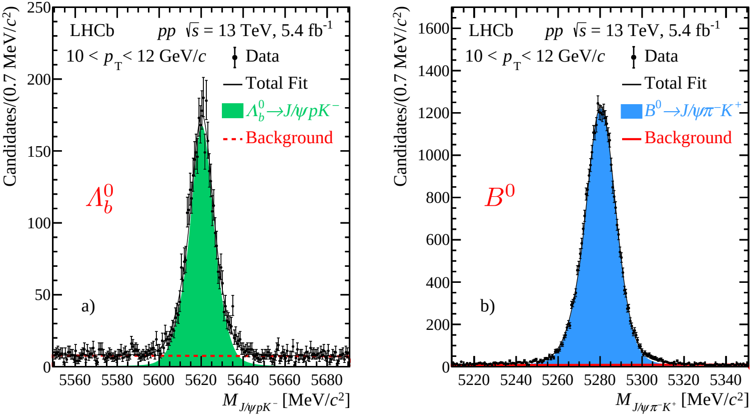
CERN-LHCC-2012-007



- Collision rate at 40 MHz
- Pile-up factor $\mu \approx 5$
- New tracking system:
  - Silicon upstream detector (UT)
  - Scintillating tracking fibre (SciFi)
- Full software trigger:
  - Remove L0 triggers
  - Read out the full detector at 40 MHz

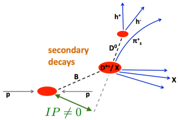
Λ_b^0 and B^0 invariant mass peaks

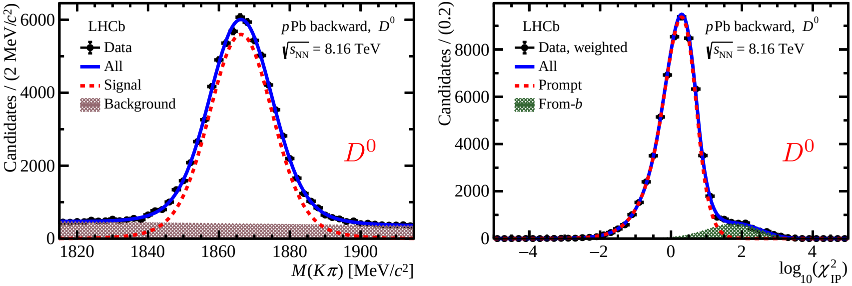
- Reconstructed with $\Lambda_b^0 \to J/\psi\, pK^-$ and $B^0 \to J/\psi\, \pi^- K^+$ channels



Prompt yield extraction

- Production mechanisms different for charm and beauty quarks. Necessary to separate prompt and from-b charm hadrons
- Fit to impact parameter (IP) for prompt yield extraction ($\chi^2_{\rm IP} \sim {\rm IP}/\sigma_{\rm IP}$)





Prompt Ξ_c^+ production in pPb at 8.16 TeV

- **First** measurement of Ξ_c^+ baryons in heavy-ion collisions
- $\Xi_c^+[usc](\Lambda_c^+[udc]) \to pK^-\pi^+$ channels employed