Recent developments in open heavy-flavour physics: ALICE highlights

Samrangy Sadhu for the ALICE Collaboration
University of Bonn, Germany

Heavy quarks: a unique probe of QGP

- **Heavy quarks: charm and beauty, predominantly produced by the parton-parton hard scattering in heavy-ion/hadronic collisions -> perturbative Quantum Chromodynamics (pQCD) can be applied.**
- **In heavy-ion collisions: a quark-gluon plasma (QGP) state is produced**
  - **-> Heavy quarks are produced before QGP formation (t_{QGP} ~ 1 fm/c and $t_Q \leq 1/2m_Q \leq 0.1$ fm/c)**
  - **-> Identity is preserved while traversing the medium**
  - **-> Experience the complete evolution of system**

Charm

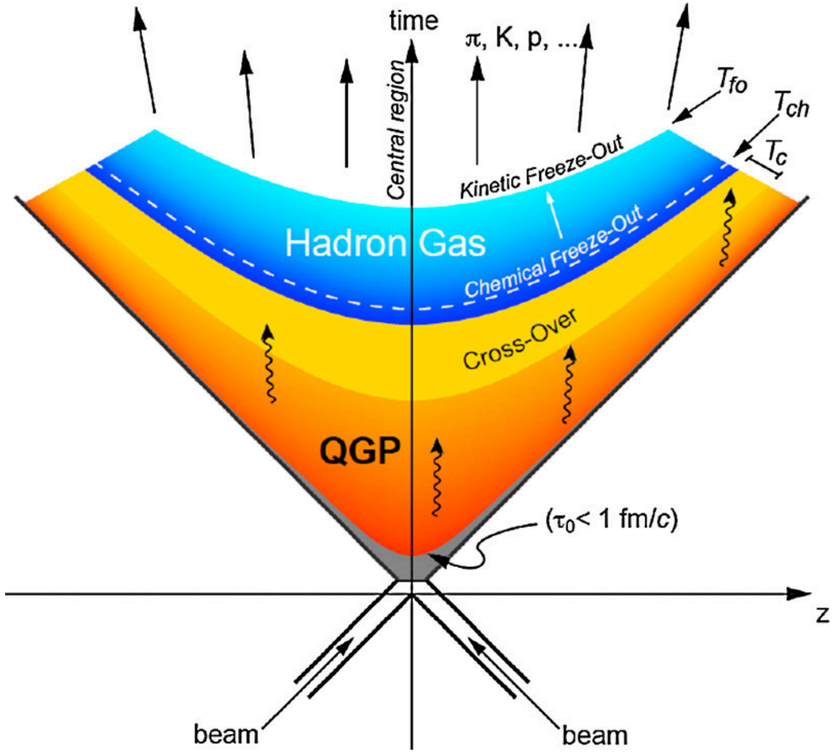
m_c ~ 1.3 GeV/c^2

$t_c \leq$ 0.08 fm/c

Beauty

m_b ~ 4.2 GeV/c^2

$t_b \leq$ 0.03 fm/c



- **Energy loss of partons traversing the QGP is expected to occur via inelastic processes : radiative energy loss via medium-induced gluon radiation**
- **Elastic processes : interactions with the QGP constituents**

★ **Therefore, heavy quarks act as important tools for characterizing the medium formed in heavy-ion collisions.**

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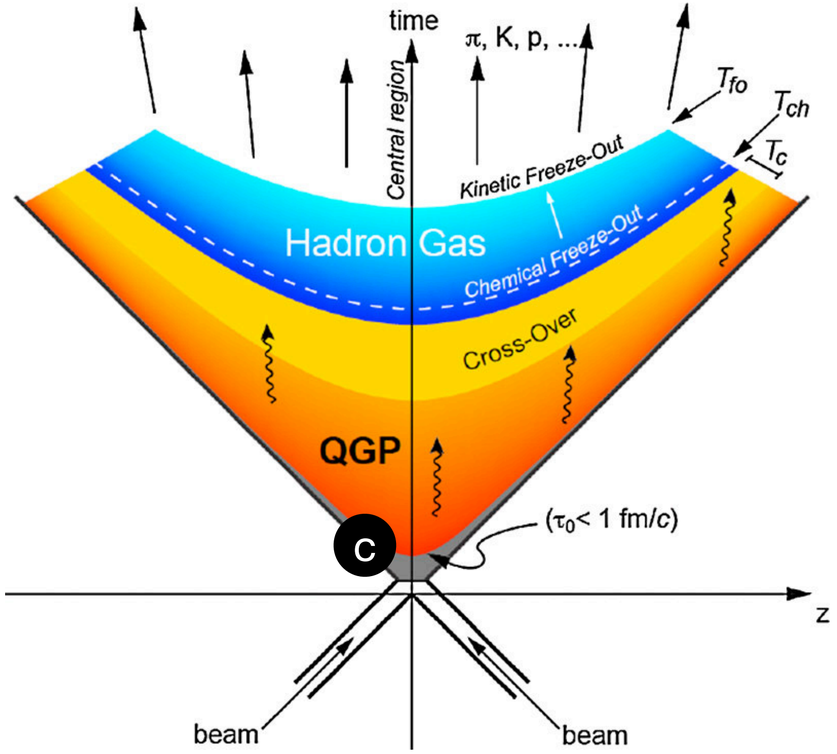

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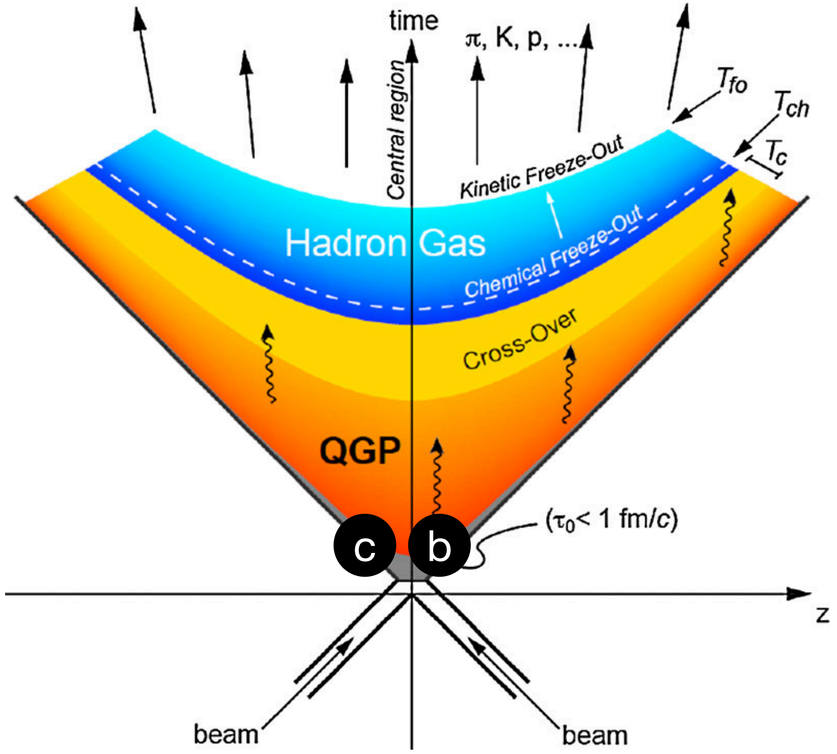

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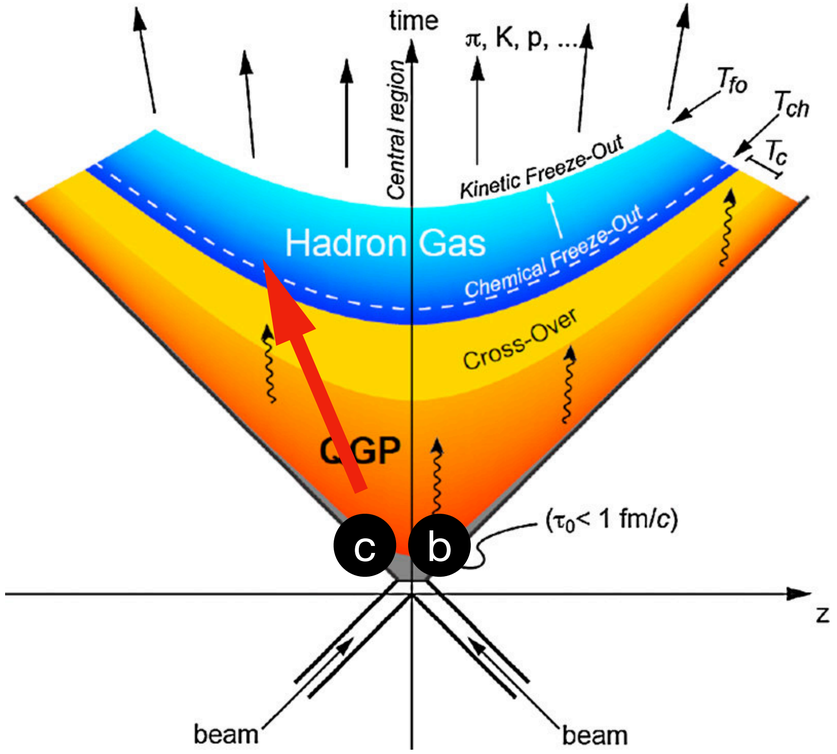

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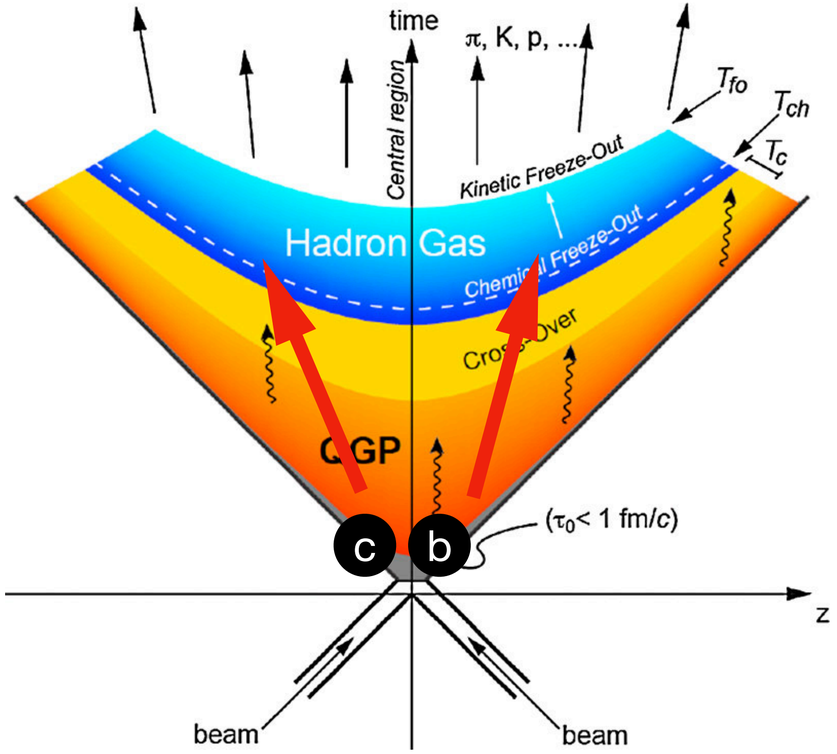

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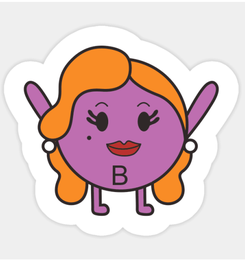

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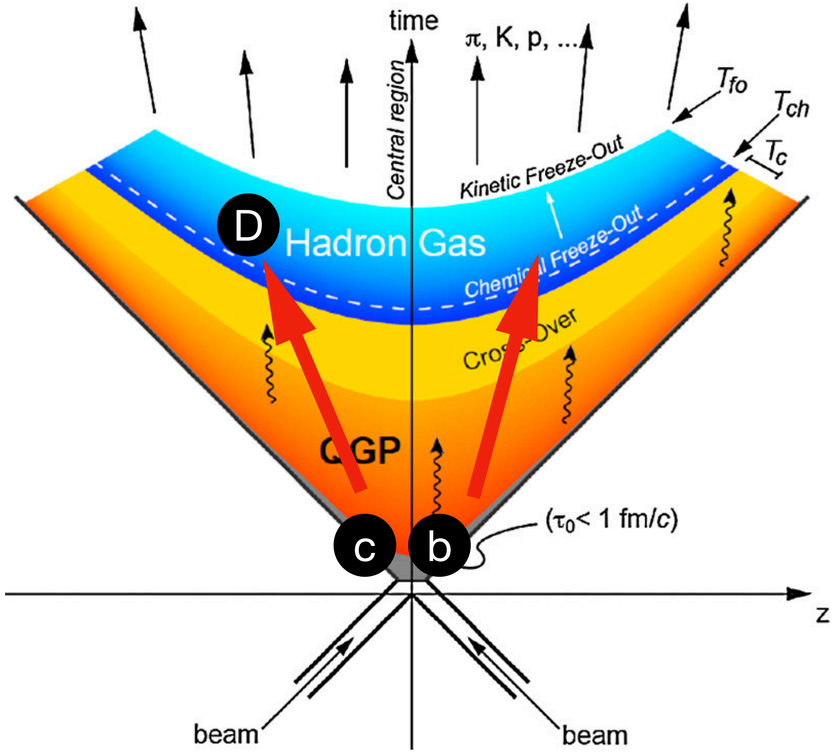

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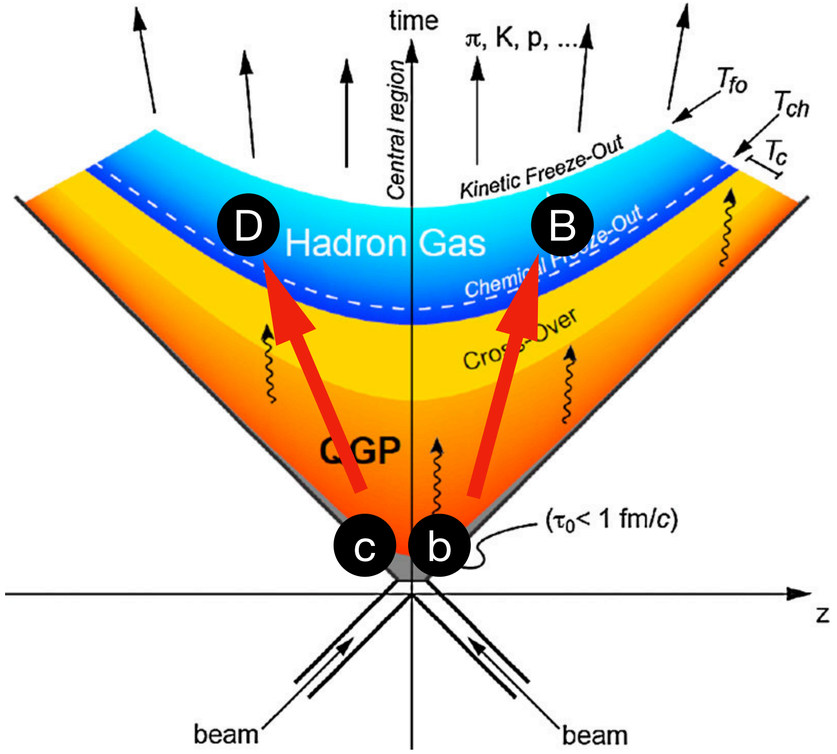

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Heavy flavour hadrons in small systems

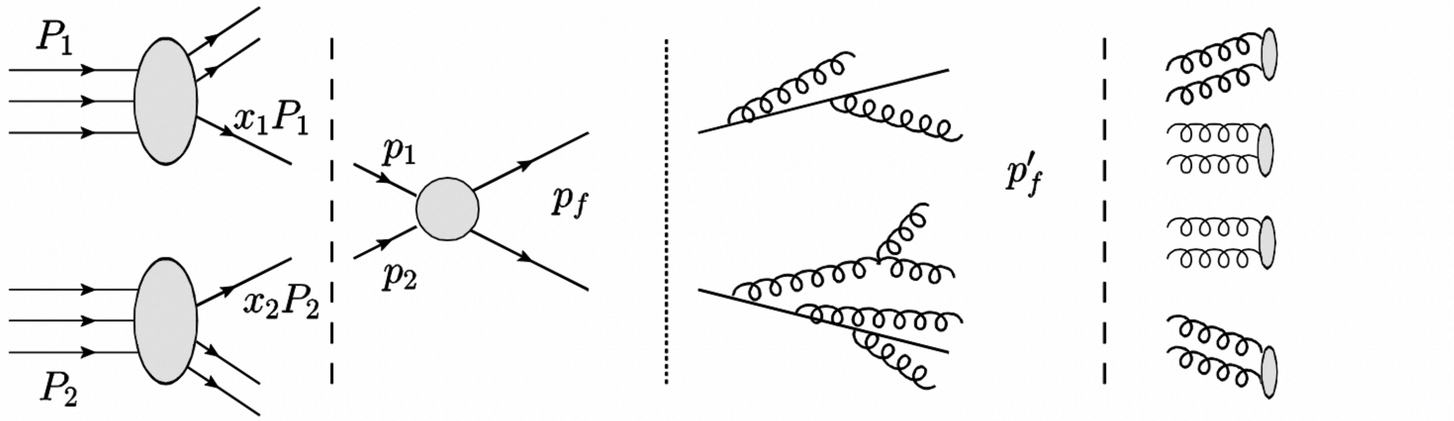
Production of heavy-quark hadrons can be calculated using the factorization approach :

$$\frac{\mathrm{d}\sigma^{\mathrm{H}_c}}{\mathrm{d}\sigma^{\mathrm{H}_c}_{p_\mathrm{T}}}(p_\mathrm{T};\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F) \otimes \frac{\mathrm{d}\sigma^{c}}{\mathrm{d}p^{c}_\mathrm{T}}(x_1,x_2;\mu_R,\mu_F) \otimes D_{\mathrm{c}\to H_c}(z=\frac{p_{\mathrm{H}_c}}{p_c},\mu_F)$$

Parton distribution functions (PDFs) | **Hard scattering cross section (pQCD)** | **Fragmentation function (hadronisation)**

Assumed to be universal across collision systems

Physics Procedia 51 (2014) 25 – 30



non-perturbative | perturbative | perturbative | non-perturbative

$f_i(x_i,\mu_F)$ pdf | $d\hat{\sigma}$ hard x-sec. | parton shower | hadronization

Initial condition from data

non-perturbative
phenomenology + fit to data (e^+e^-, e^-p)

Measurements of heavy flavour particles :

- Test the perturbative QCD (pQCD) calculations
- Provide input for the data driven non-perturbative QCD (npQCD) quantities

Study of heavy-flavour physics in different collision systems

In small systems:

pp collisions:
- Test pQCD calculations
- Study heavy-flavour quark production and hadronization
- Reference for p—Pb and Pb—Pb systems

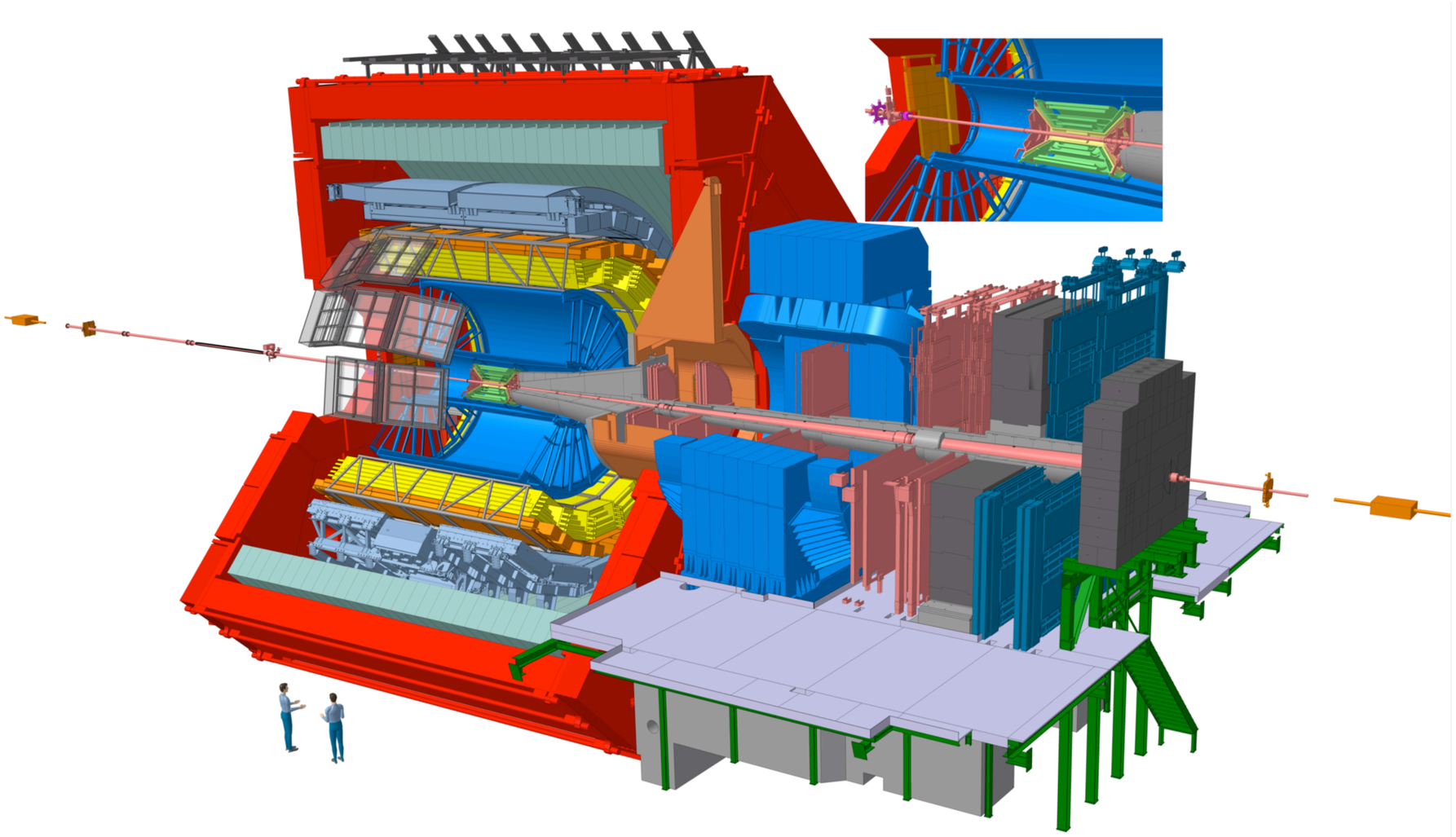
p—Pb collisions:
- Study cold nuclear matter (CNM) effects
- Possible collective effects ?

In heavy-ion system:

Pb—Pb collisions:
- Sensitivity to the energy-loss mechanism of heavy quarks (radiative processes)
- Diffusion motion of heavy quarks via multiple low-momentum transfer interaction with QGP constituents
- Possible modification of the quark hadronization and collective effects

This talk:
- Physics from Pb-Pb, p-Pb and pp collision systems.
- What's new from Run 2 and Run 3 ?
- Plans for Run 4 onwards

ALICE apparatus (run 2)



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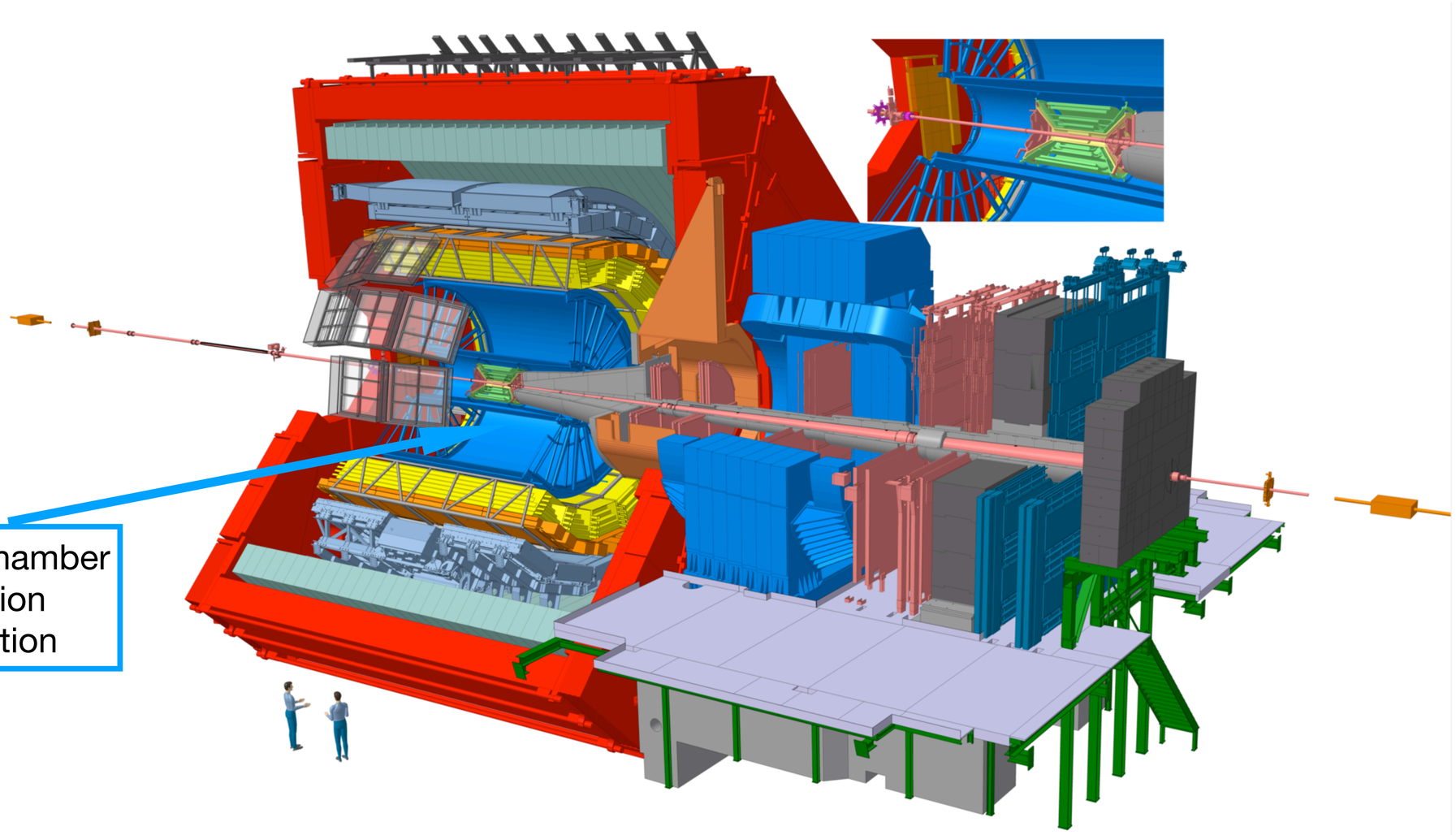
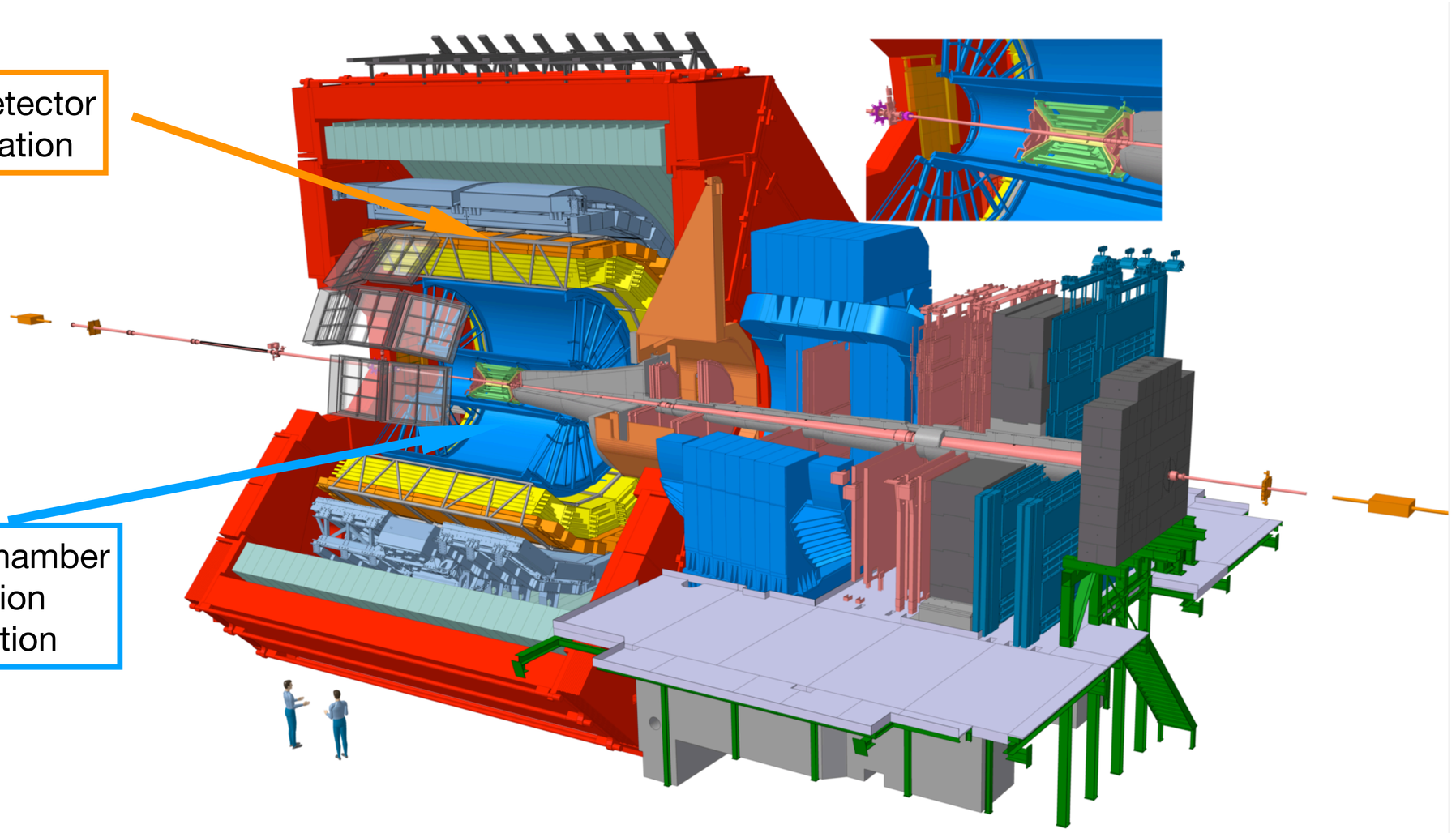


Time **P**rojection **C**hamber
- track reconstruction
- particle identification

ALICE apparatus (run 2)

Time-**O**f-**F**light detector
- particle identification



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- trigger
- particle identification

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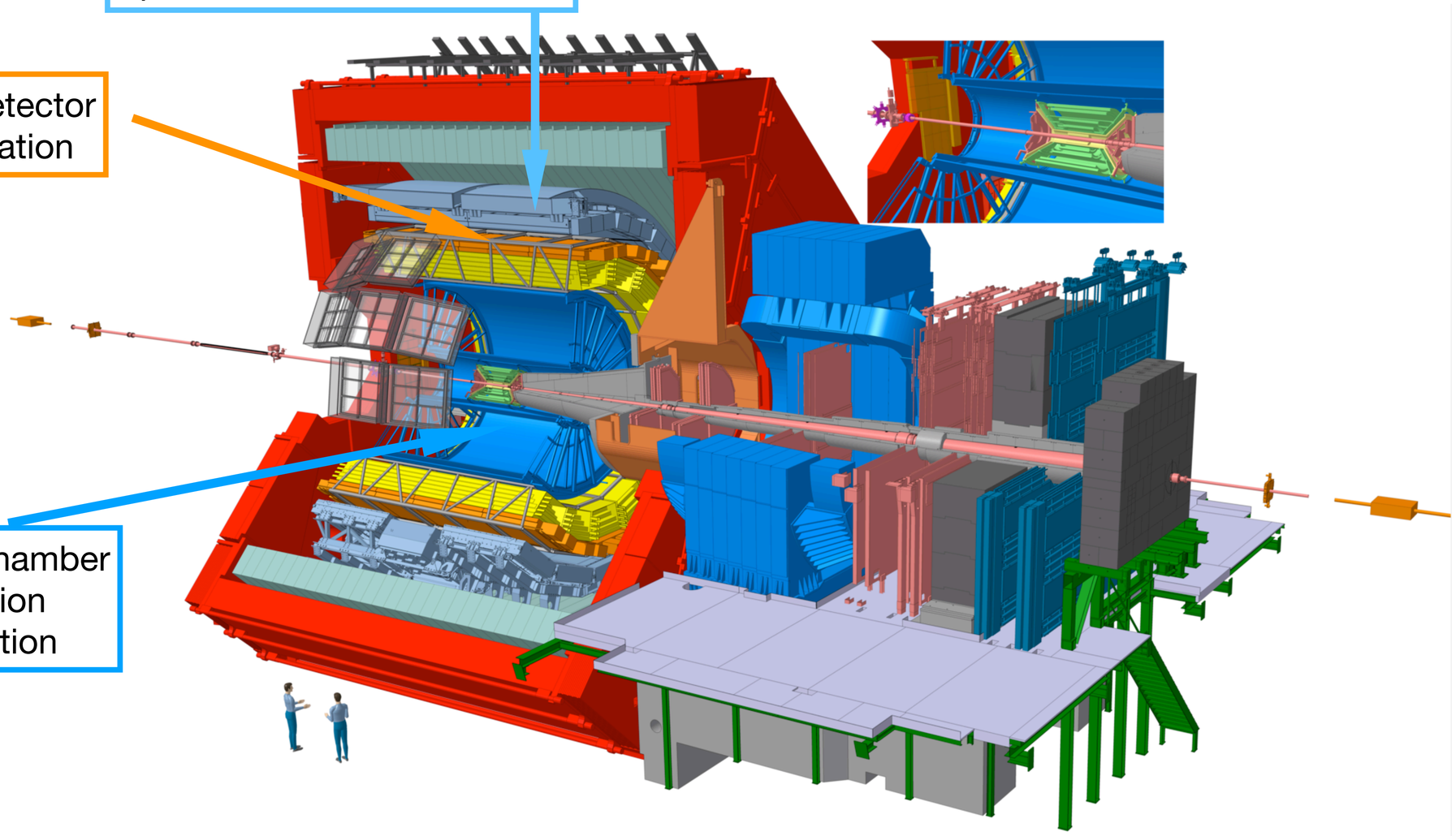

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- vertex determination

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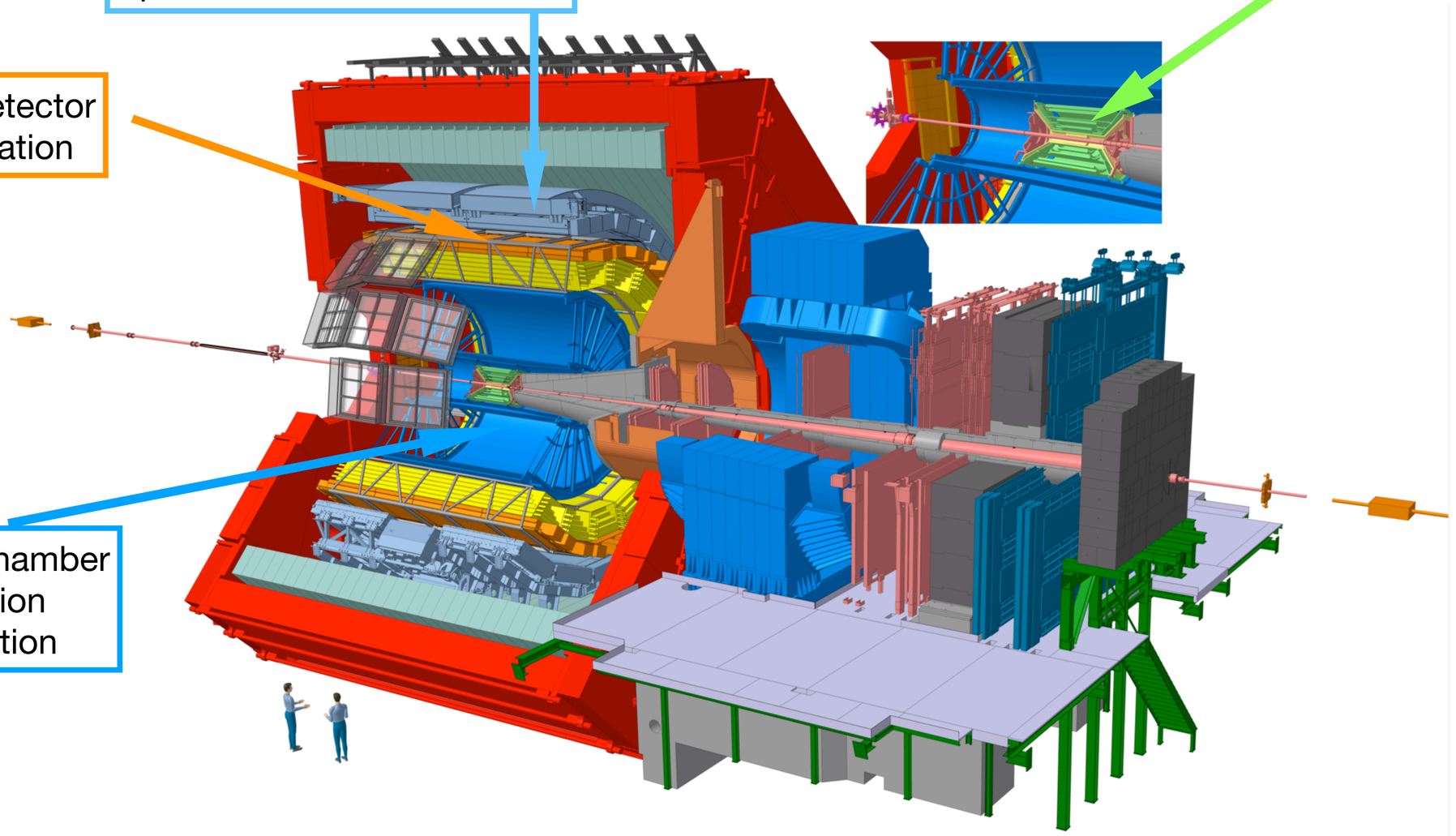

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V0 detector
- trigger
- centrality estimation
- event plane estimation

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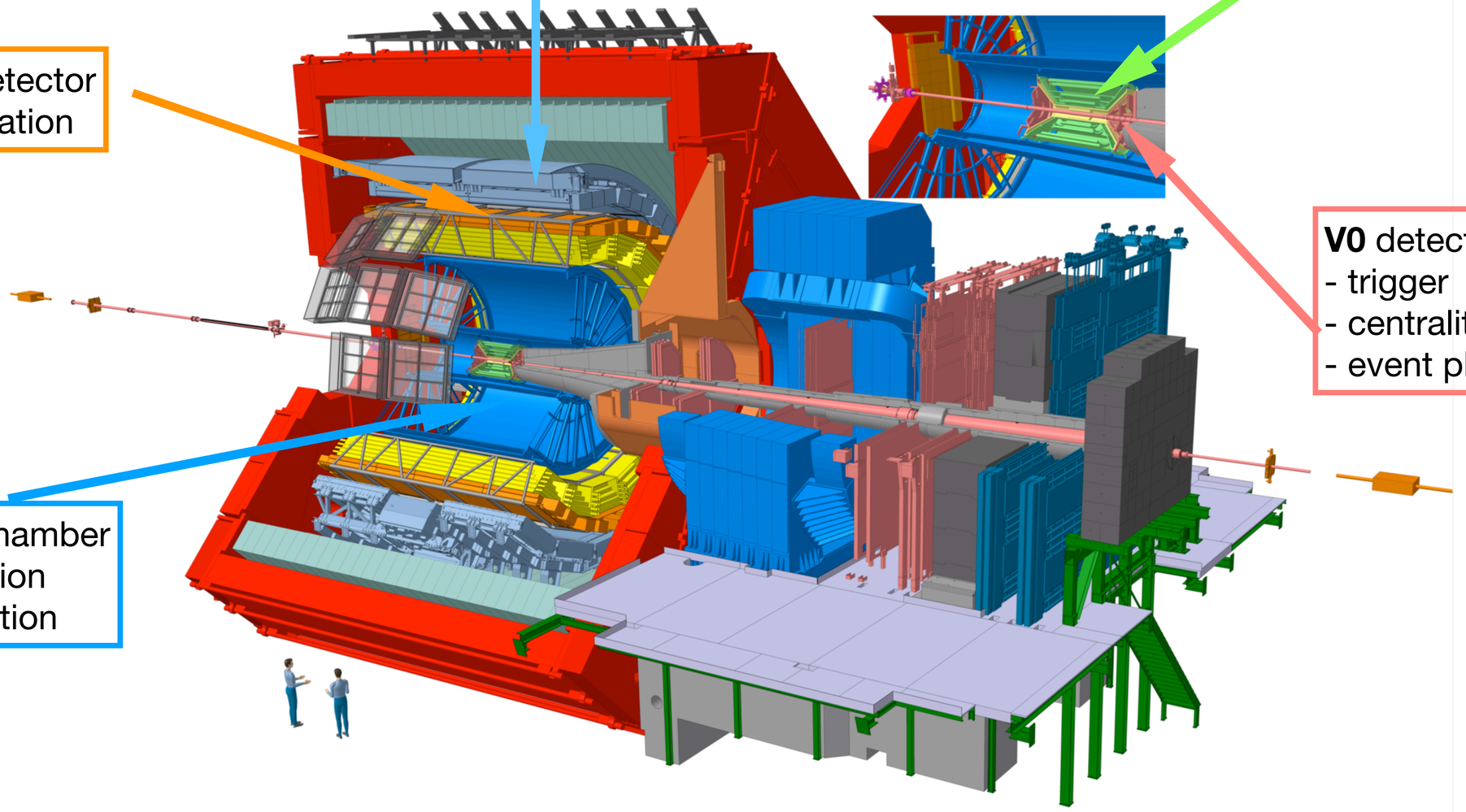
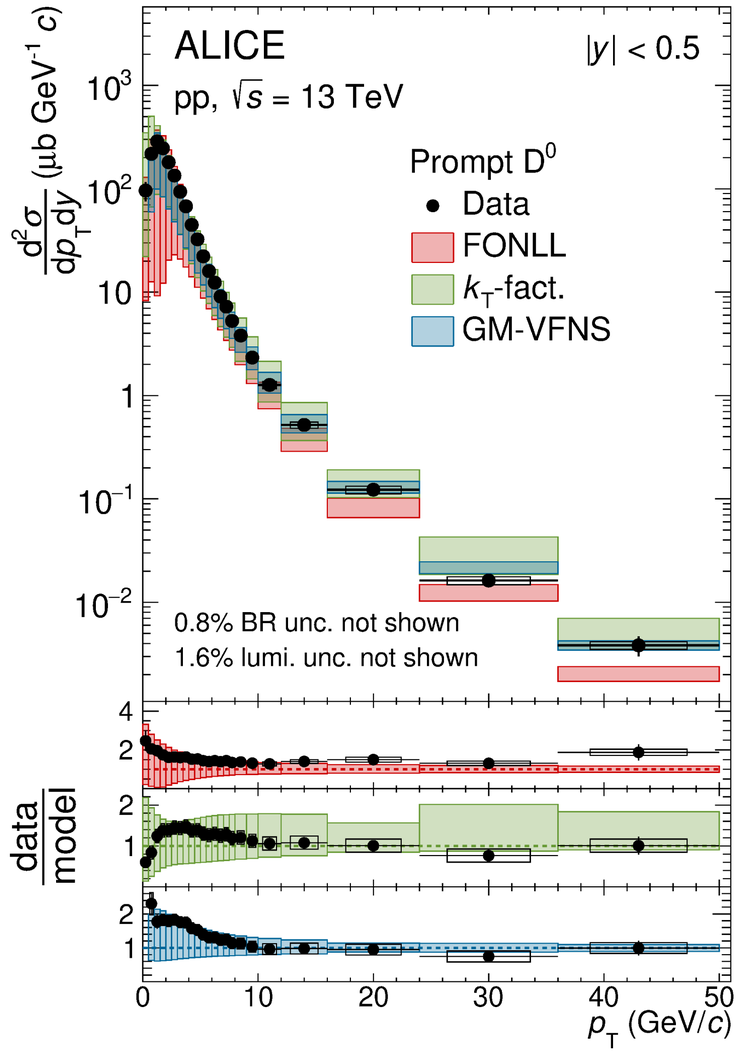


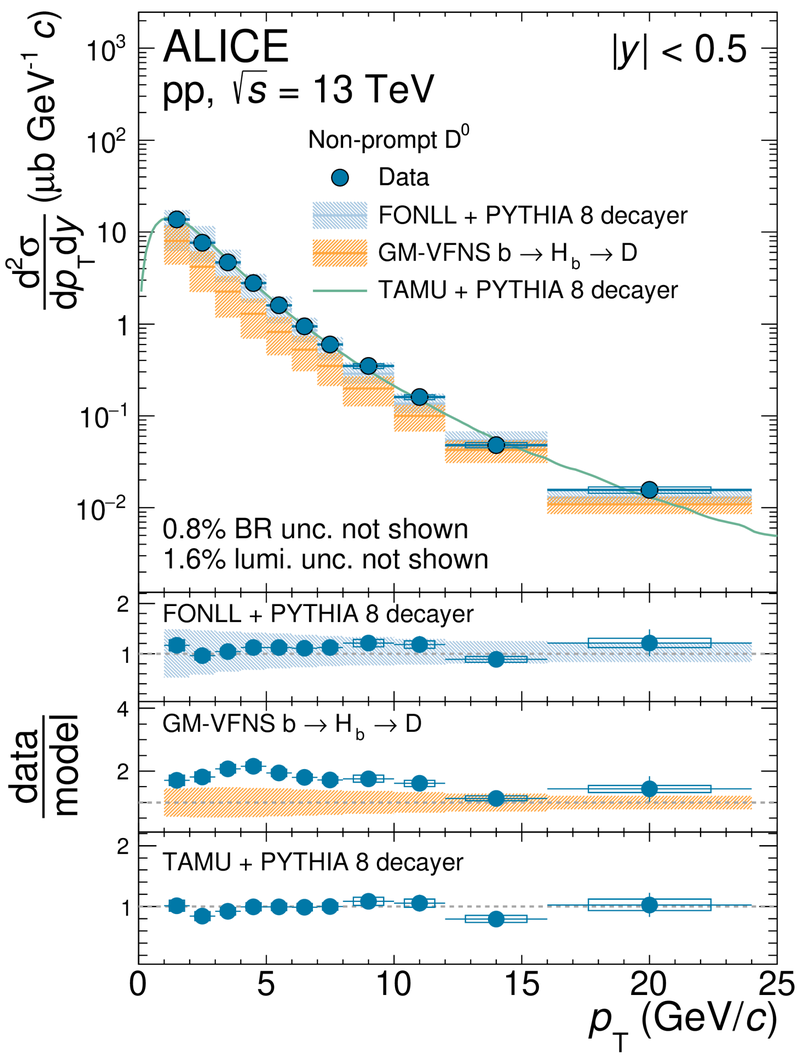
Cross-section measurements of charm and beauty

JHEP 12 (2023) 086



ALI-PUB-567836

JHEP 10 (2024) 110



ALI-PUB-586555

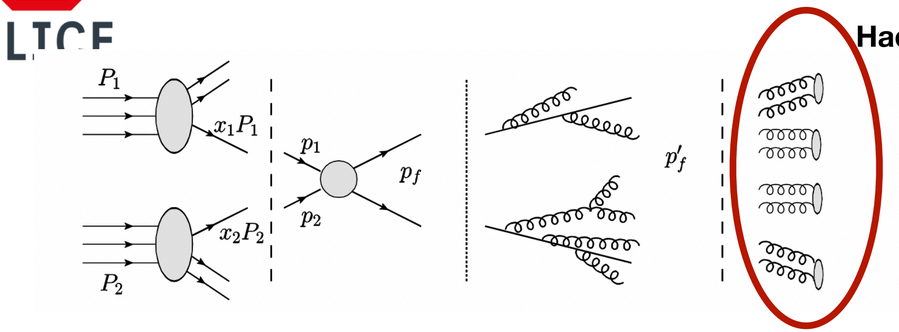
Prompt charm hadron:
hadrons from c-quark hadronization or from the decay of excited charm hadrons

Non-prompt charm hadron:
charm hadrons from beauty-hadron decays

- p_T-differential cross sections described by pQCD calculations (FONLL, kT-factorization, GM-VFNS) ➡ Good agreement within uncertainties

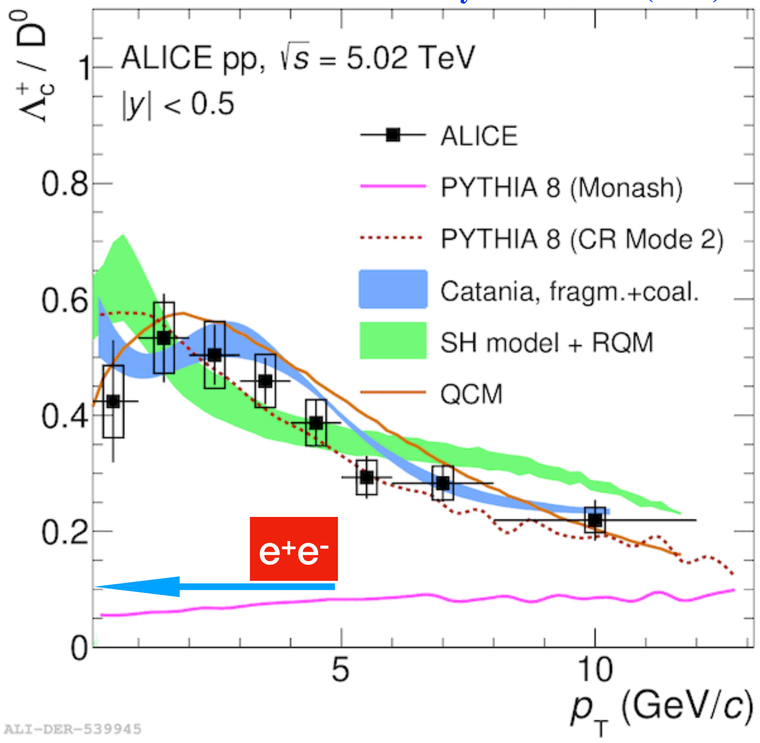
FONLL : JHEP 05 (1998) 007, JHEP 10 (2012) 137
kT-factorization : Phys. Rev. D 104 (2021) 094038
GM-VFNS : JHEP 12 (2017) 021, Nucl. Phys. B 925 (2017) 415–430

Prompt Λ_c^+/D⁰ ratio : Questioning the Universality



Measurements of the baryon-to-meson yield ratio -> p_T-dependent enhancement of Λ_c^+/D⁰ ratio in pp w.r.t. e⁺e⁻

Phys. Rev. C 107 (2023) 064901



LEP: (0.113 ± 0.013 ± 0.006) EPJC 75 (2015) 19

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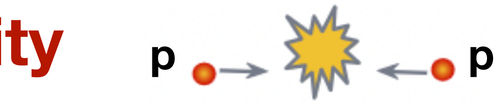

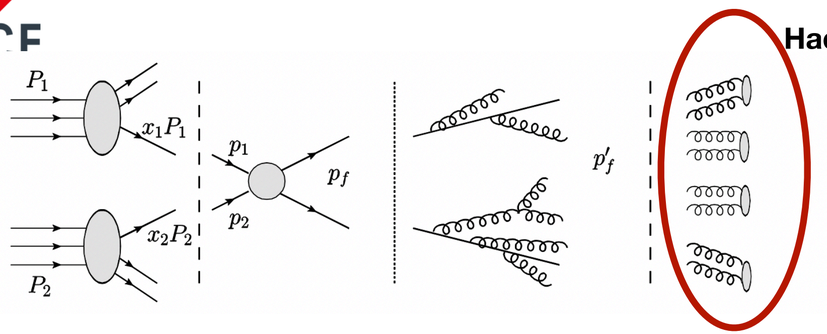

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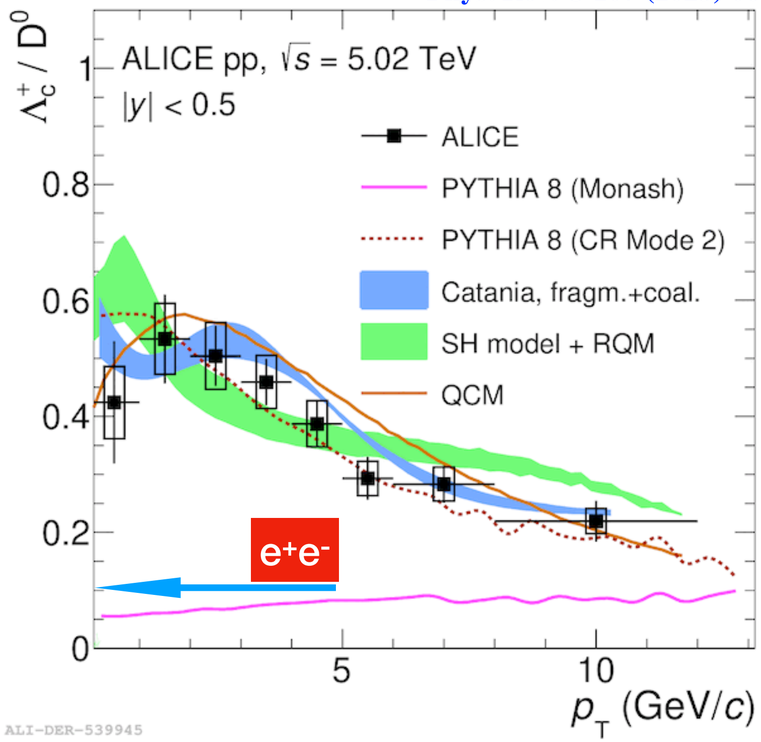

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Eur. Phys. J. C 74 (2014) 3024

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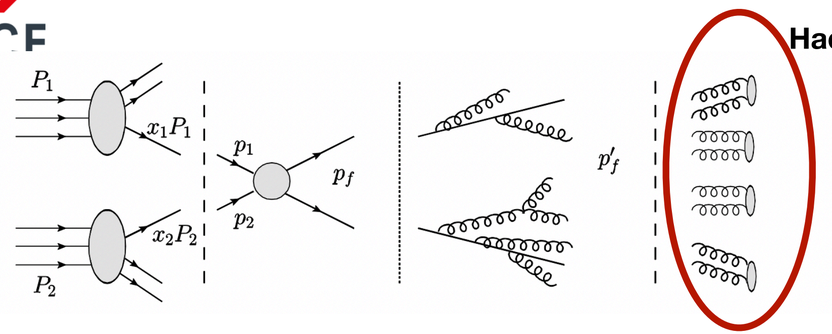

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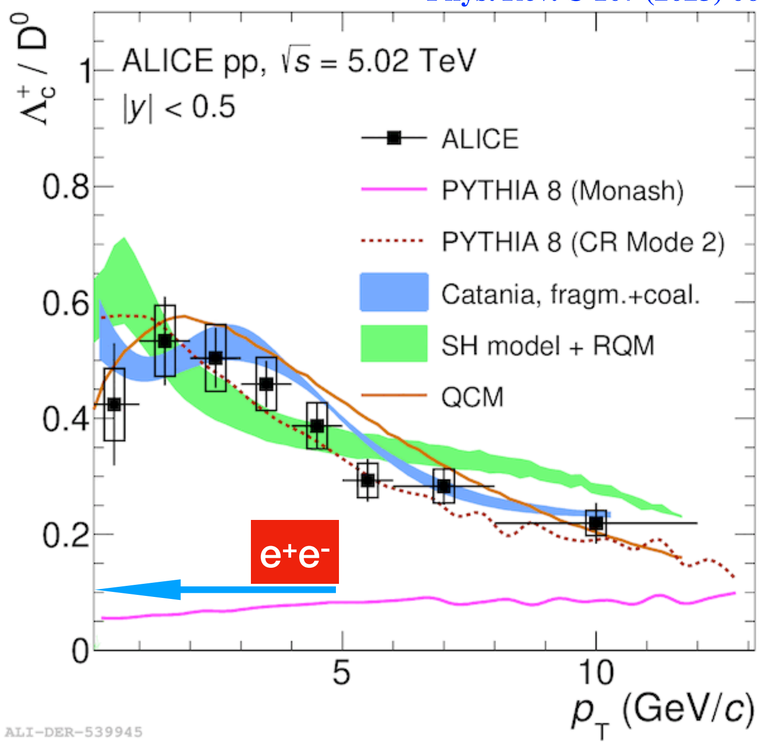

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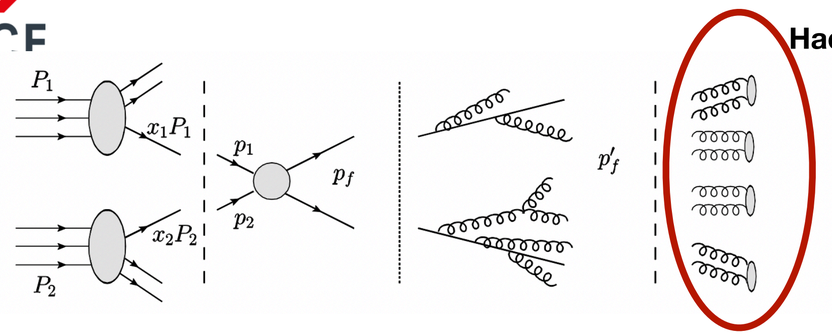

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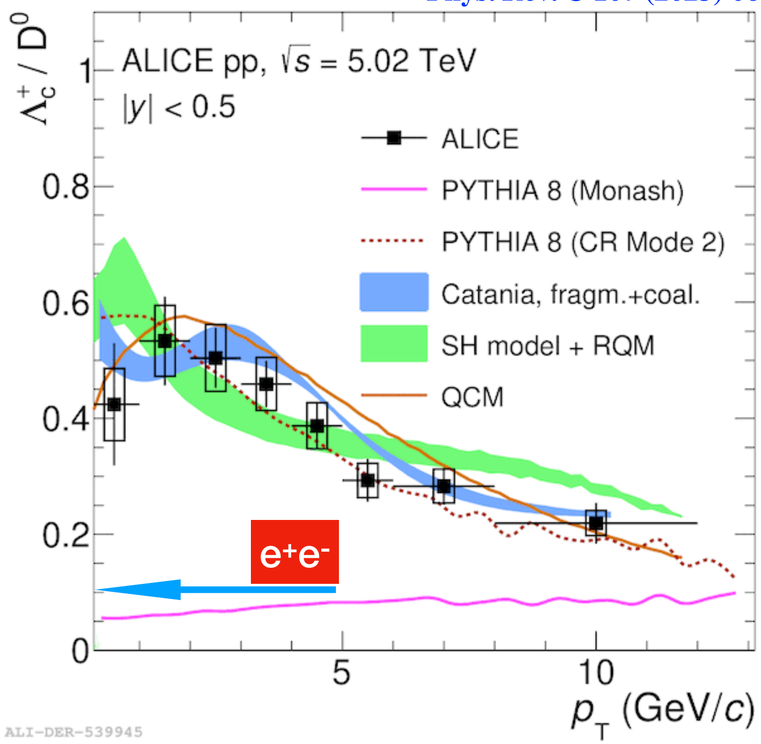

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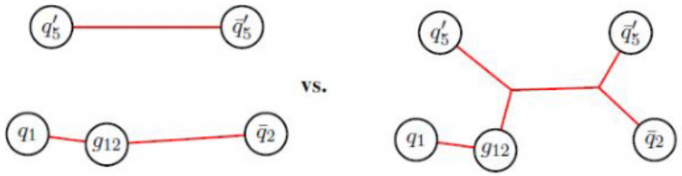
JHEP 08 (2015) 003



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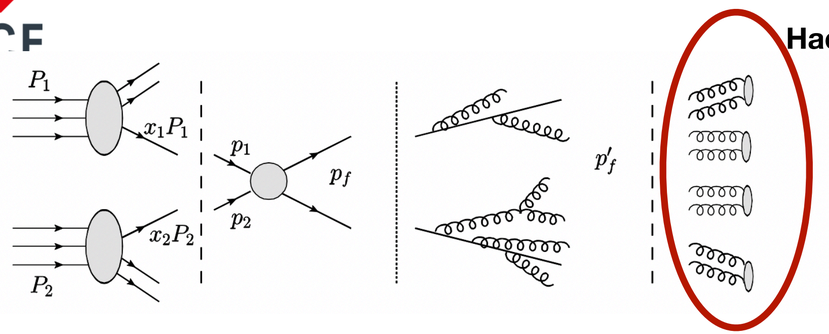

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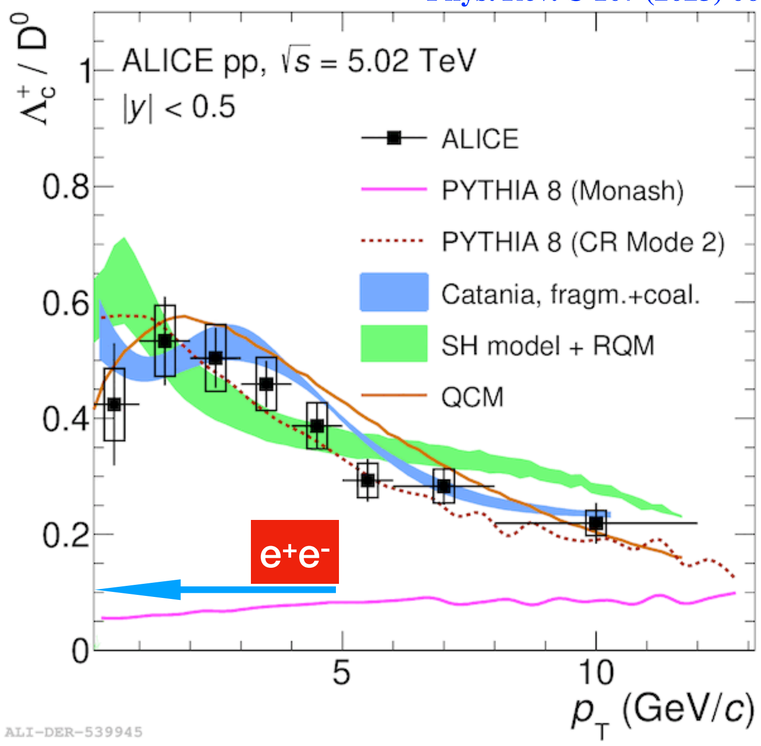

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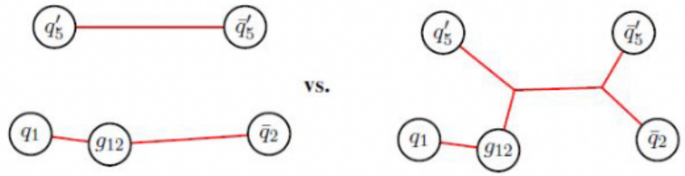
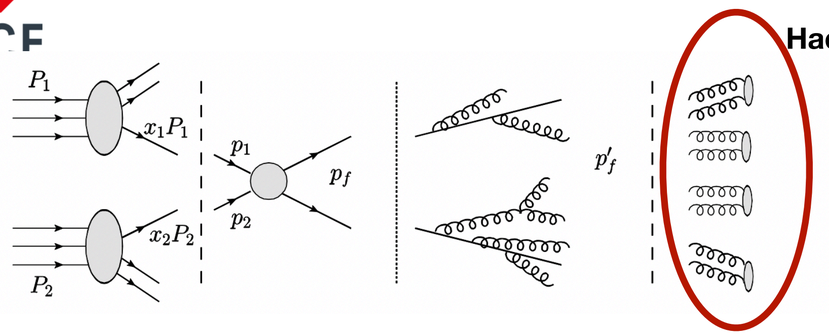


Increased feed-down from an augmented set of excited charm baryons (Statistical Hadronisation model + Relativistic Quark model)

Phys. Lett. B 795 (2019) 117–121

Prompt Λ_c^+/D⁰ ratio : Questioning the Universality

p → ✸ ← p



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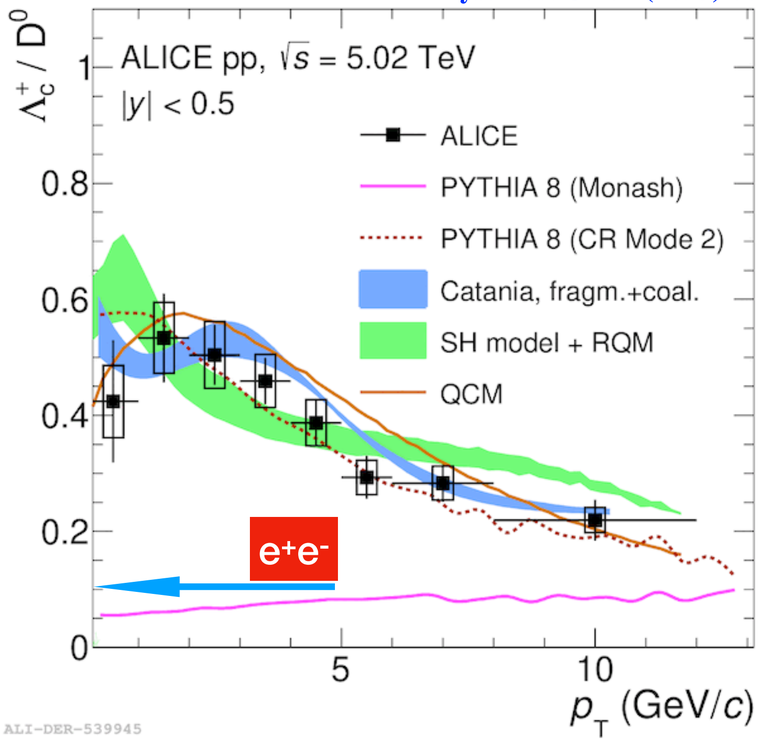
Phys. Rev. C 107 (2023) 064901

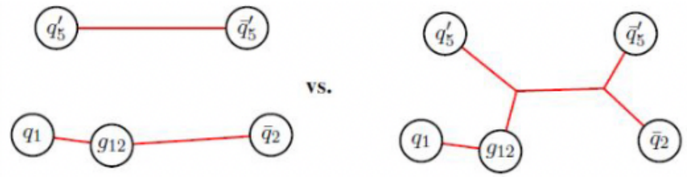


LEP: (0.113 ± 0.013 ± 0.006) EPJC 75 (2015) 19

Models based on fragmentation functions evaluated from e⁺e⁻ collisions underestimate the data (PYTHIA 8 Monash)
Eur. Phys. J. C 74 (2014) 3024

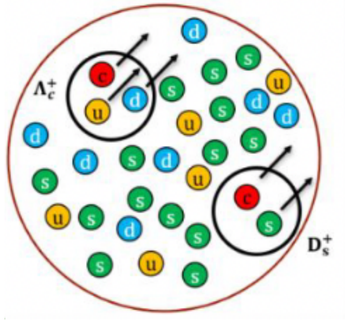
Different hadronization mechanisms proposed:

Color reconnection beyond leading color (PYTHIA 8 CR Mode 2)
JHEP 08 (2015) 003

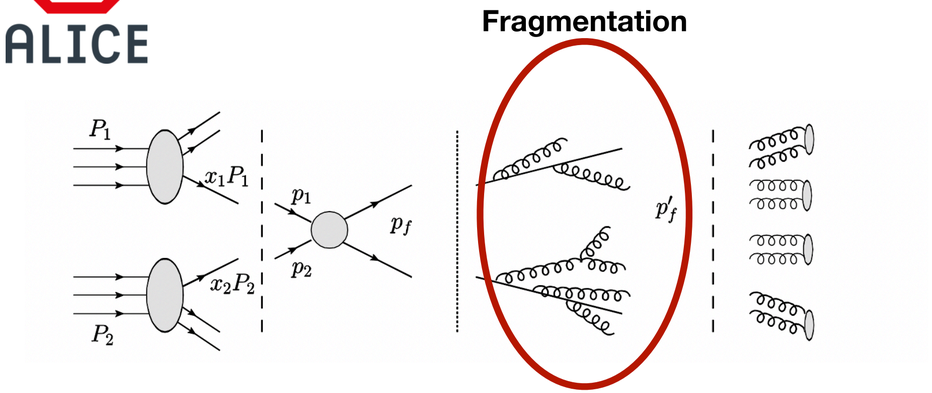


Increased feed-down from an augmented set of excited charm baryons (Statistical Hadronisation model + Relativistic Quark model)
Phys. Lett. B 795 (2019) 117–121

Hadronization via coalescence and fragmentation in a thermalised system of gluons, light quarks and antiquarks (Catania, Quark (re)Combination Model)
Phys. Lett. B 821 (2021) 136622, Eur. Phys. J. C 78 (2018) 344



Charmed-hadron tagged jets



Regarding fragmentation, additional insights compared to single-particle studies are offered by:

→ Charm-hadron tagged jets

→ Azimuthal correlations of charm hadrons with charged particles

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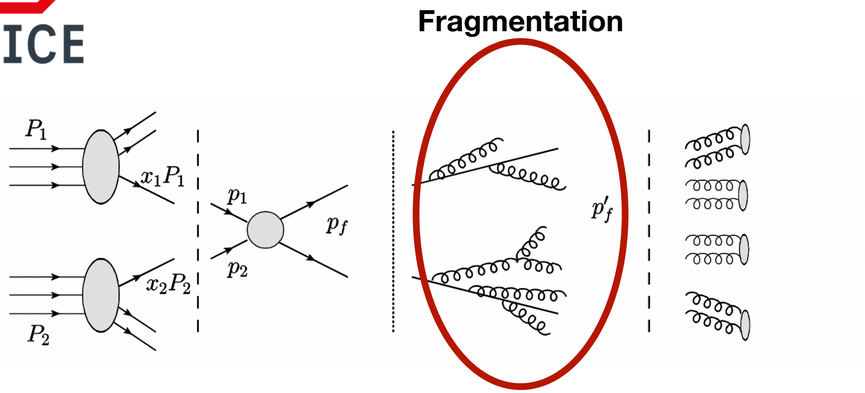

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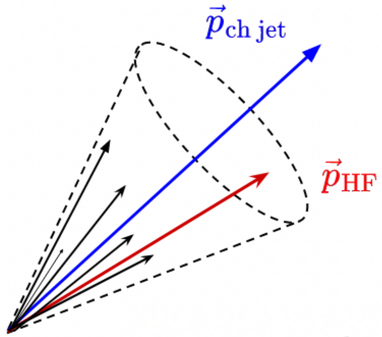
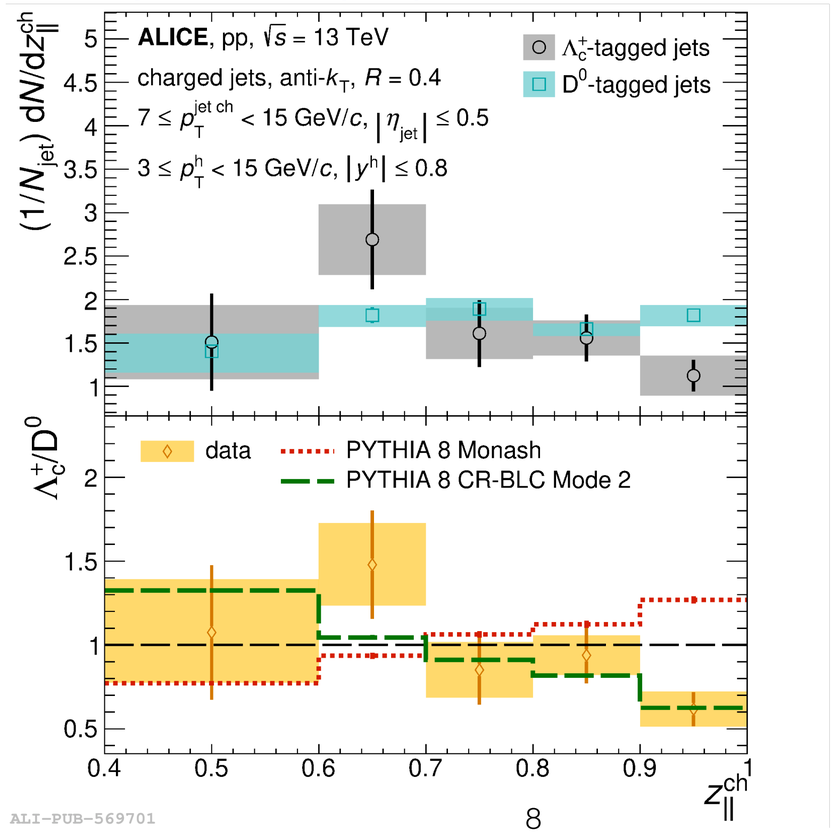
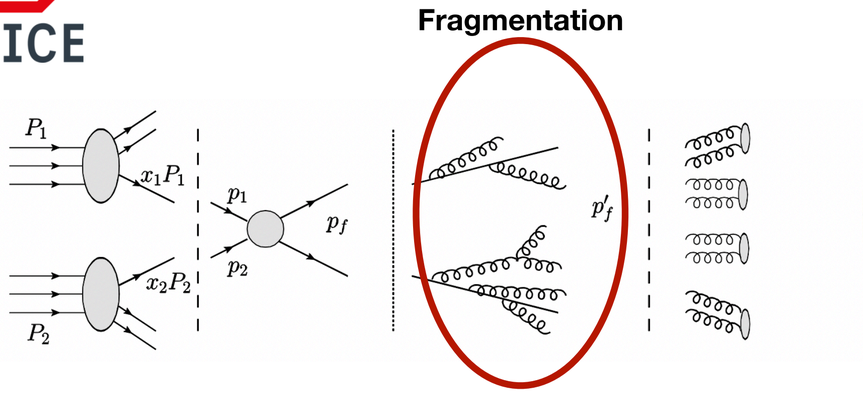


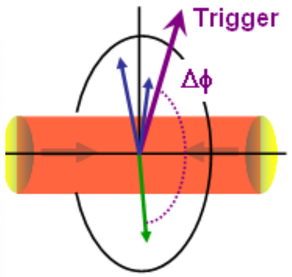
$$z_{\parallel}^{\mathrm{ch}} = \frac{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{D^0}}}{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{ch\,jet}}}$$

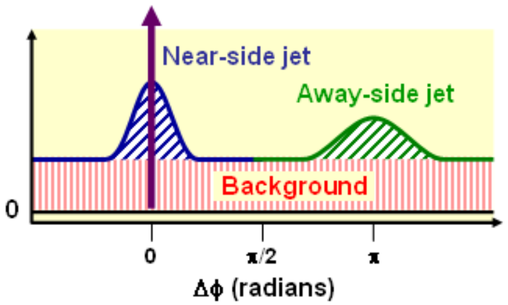
Phys. Rev. D109 (2024) 072005



Charmed-hadron tagged jets







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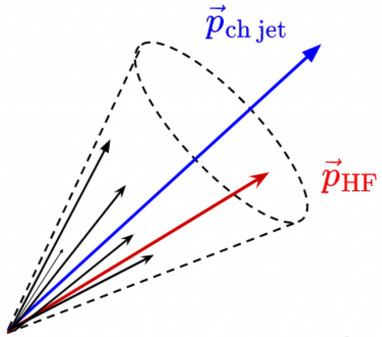

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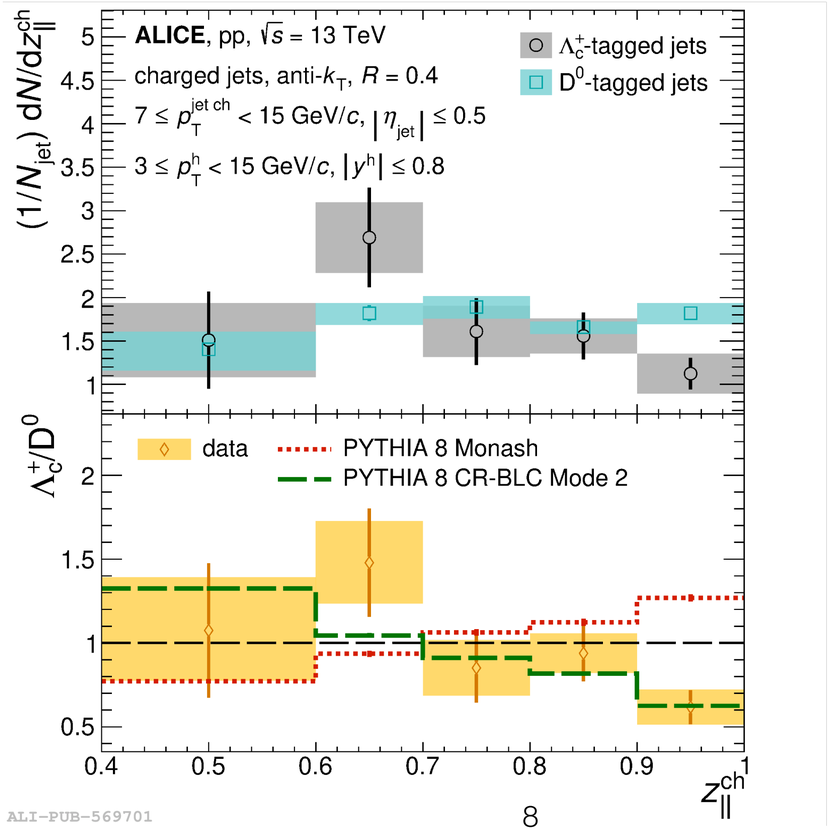
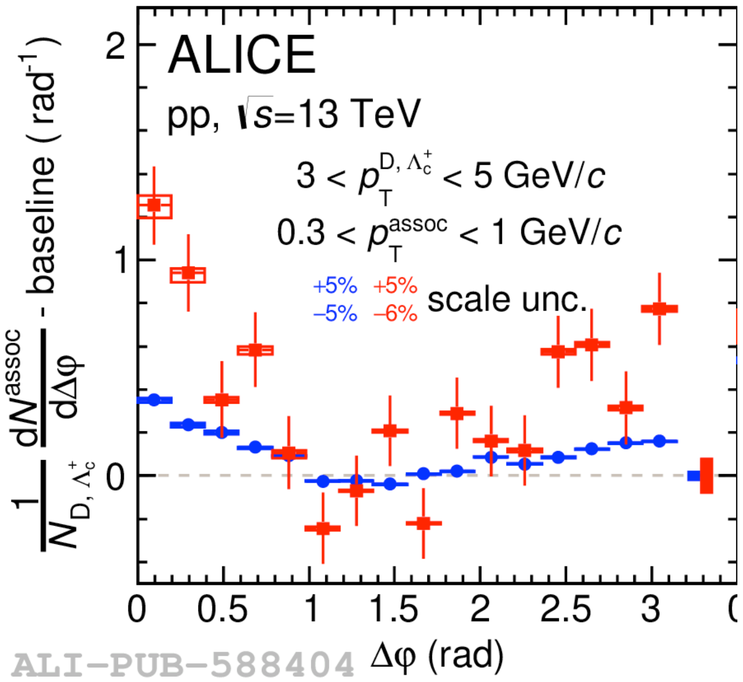
Phys. Rev. D109 (2024) 072005



arXiv:2411.10104



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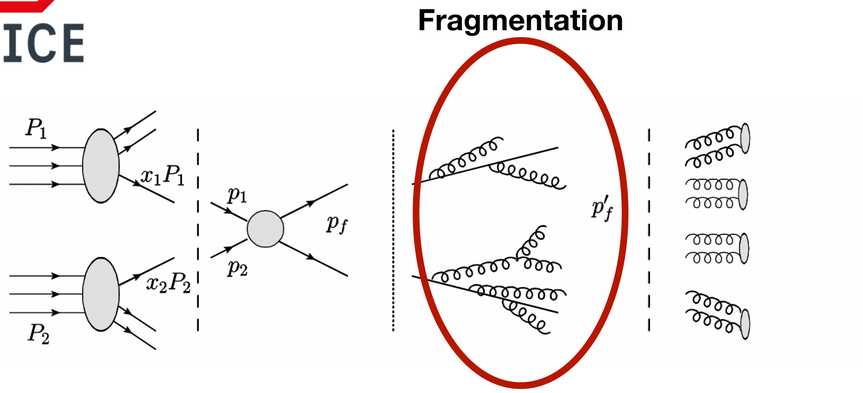

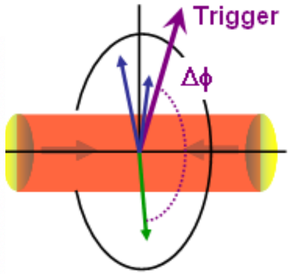

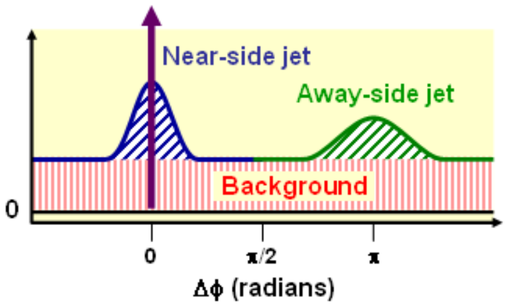

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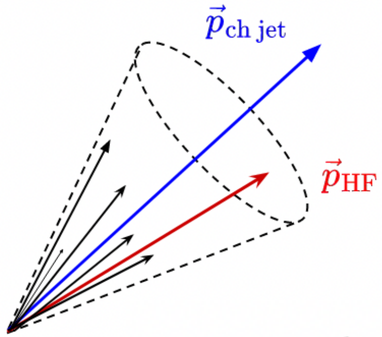

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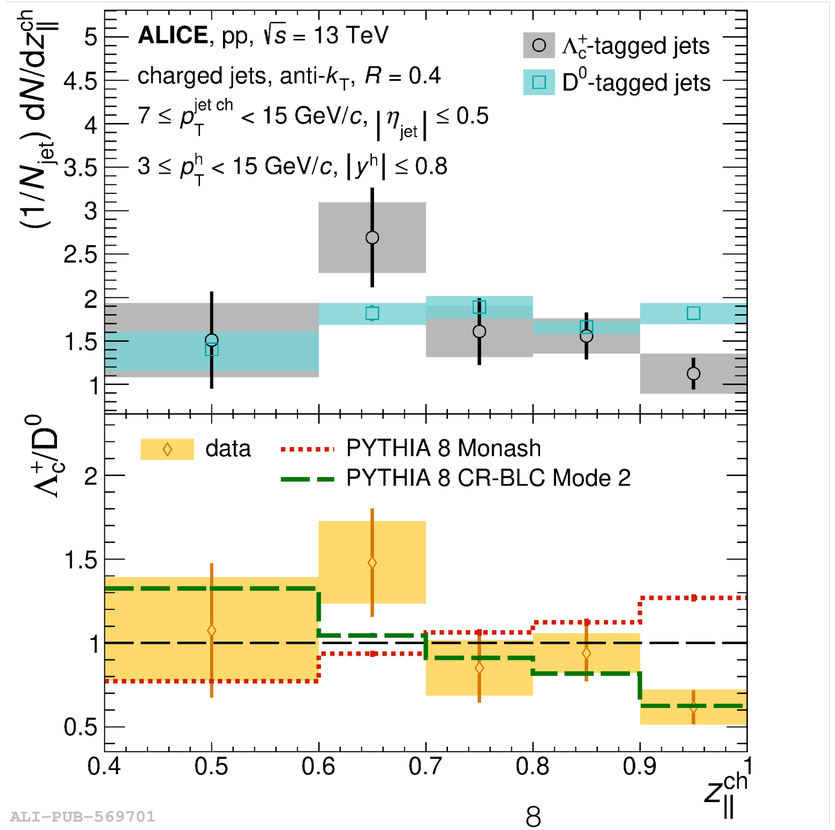
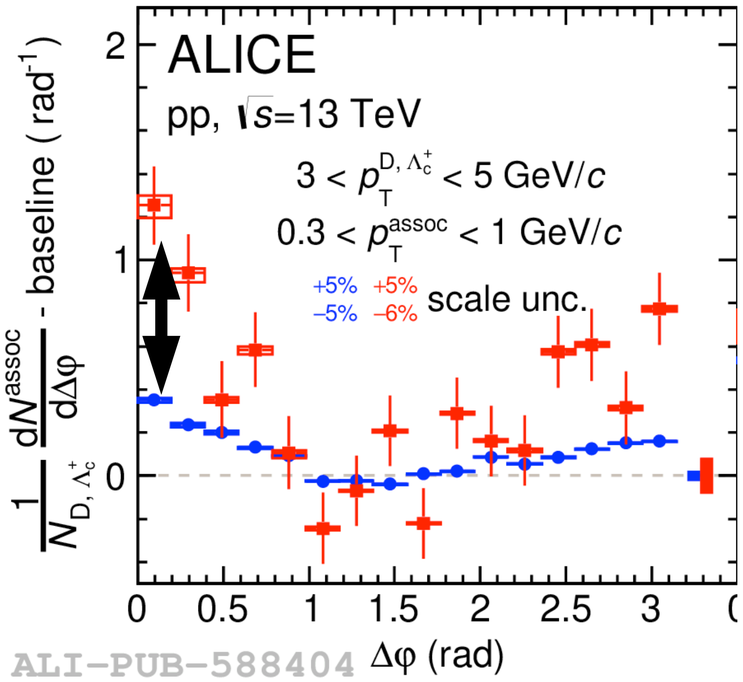
Phys. Rev. D109 (2024) 072005



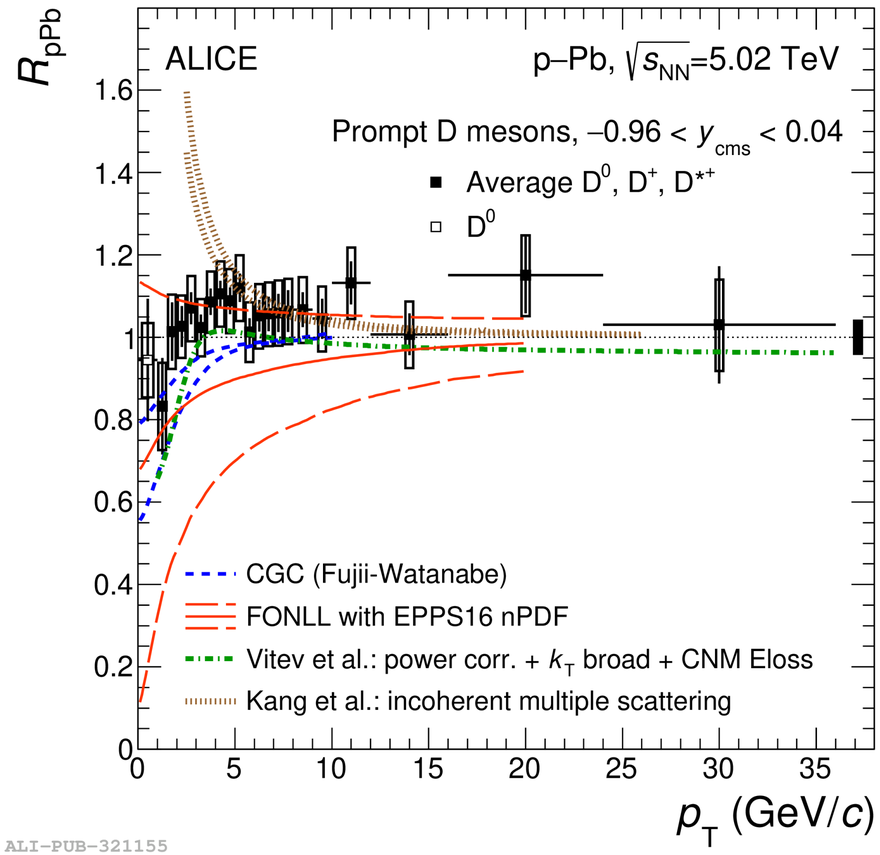
arXiv:2411.10104



Indication that charm fragmentation into Λ_c^+ is softer and produces more collinear-associated particles compared to fragmentation into D^0

Charm hadron measurement in p—Pb collisions

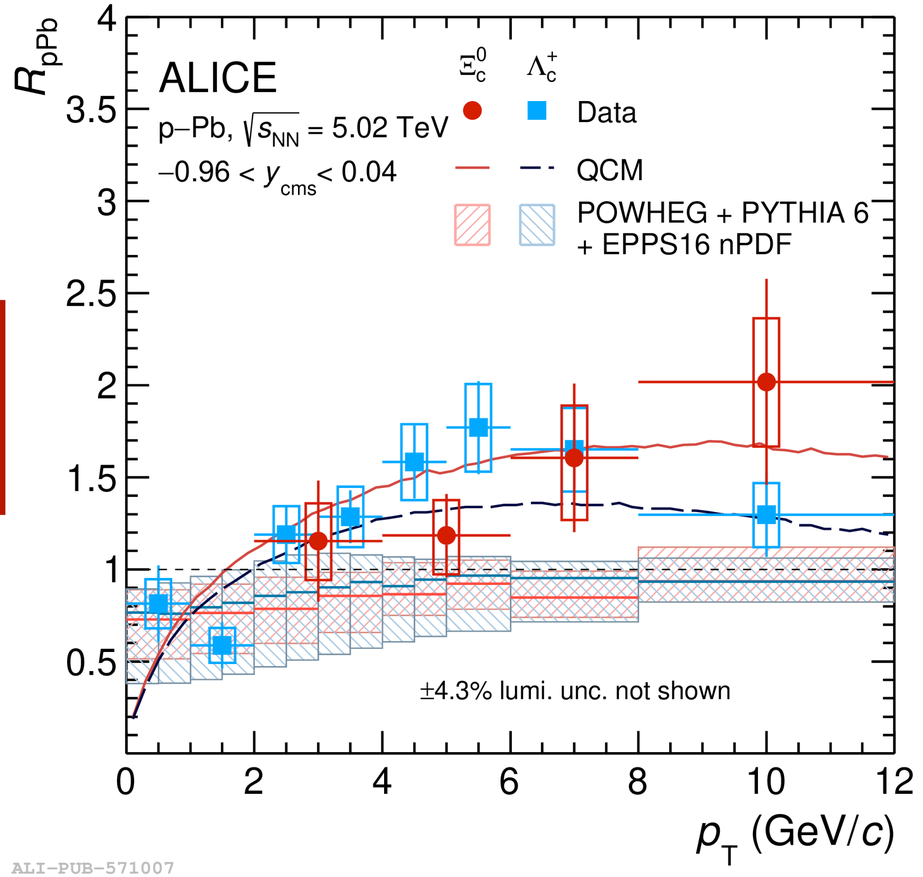
JHEP 12 (2019) 92



ALI-PUB-321155

$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

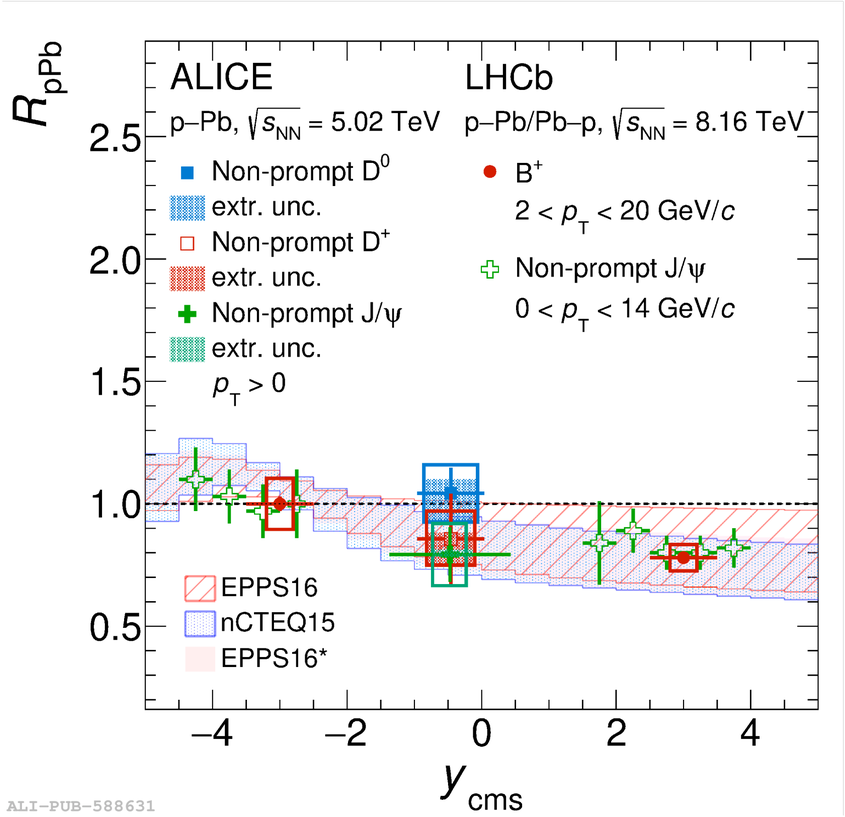
arXiv:2405.14538



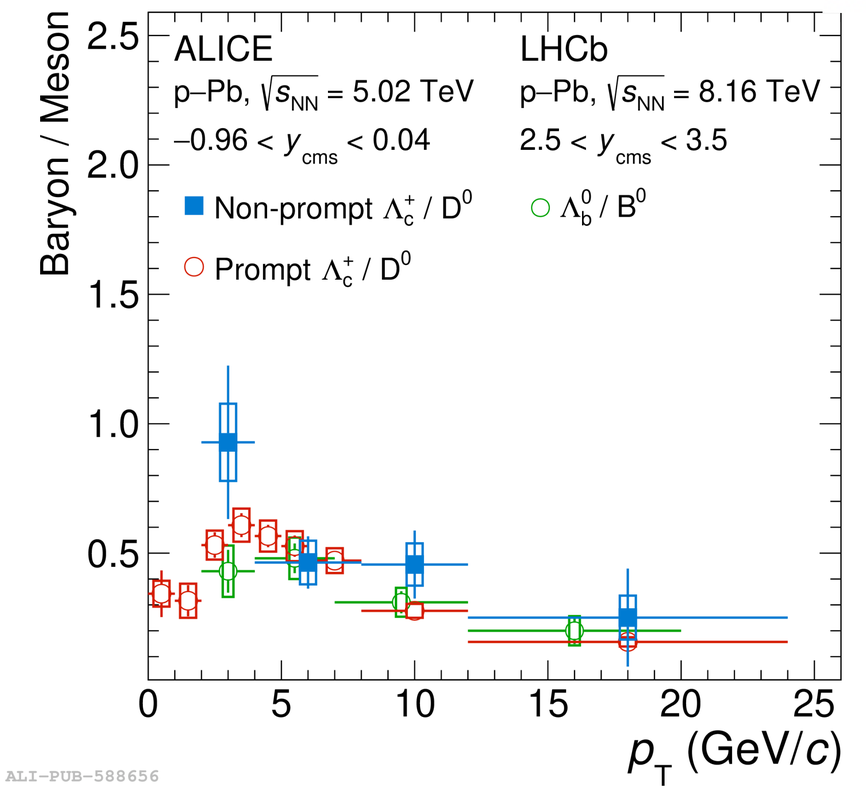
ALI-PUB-571007

- D-meson R_{pPb} is compatible with unity and compared to model predictions including CNM effects
- Both Λ_c^+ and Ξ_c^0 R_{pPb} are compatible within uncertainties → similar modification of the production in p–Pb collisions
  - ✓ R_{pPb} of Ξ_c^0 is larger than unity → no conclusion of increasing trend with p_T due to large uncertainties
  - ✓ Models underestimate the data (only Λ_c^+ R_{pPb} is described below 2 GeV/c)

Beauty hadron measurement in p—Pb collisions



JHEP 11 (2024) 148



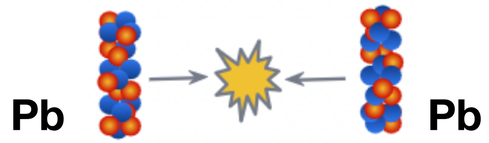
p_T-integrated R_{pPb} of non-prompt D^0 and J/ψ measured:

- ✓ Suppression at forward rapidity whereas compatible with unity at backward rapidity
- ✓ Good agreement with model predictions based on nuclear PDFs, within uncertainties -> no hot medium effects

Compared with LHCb:

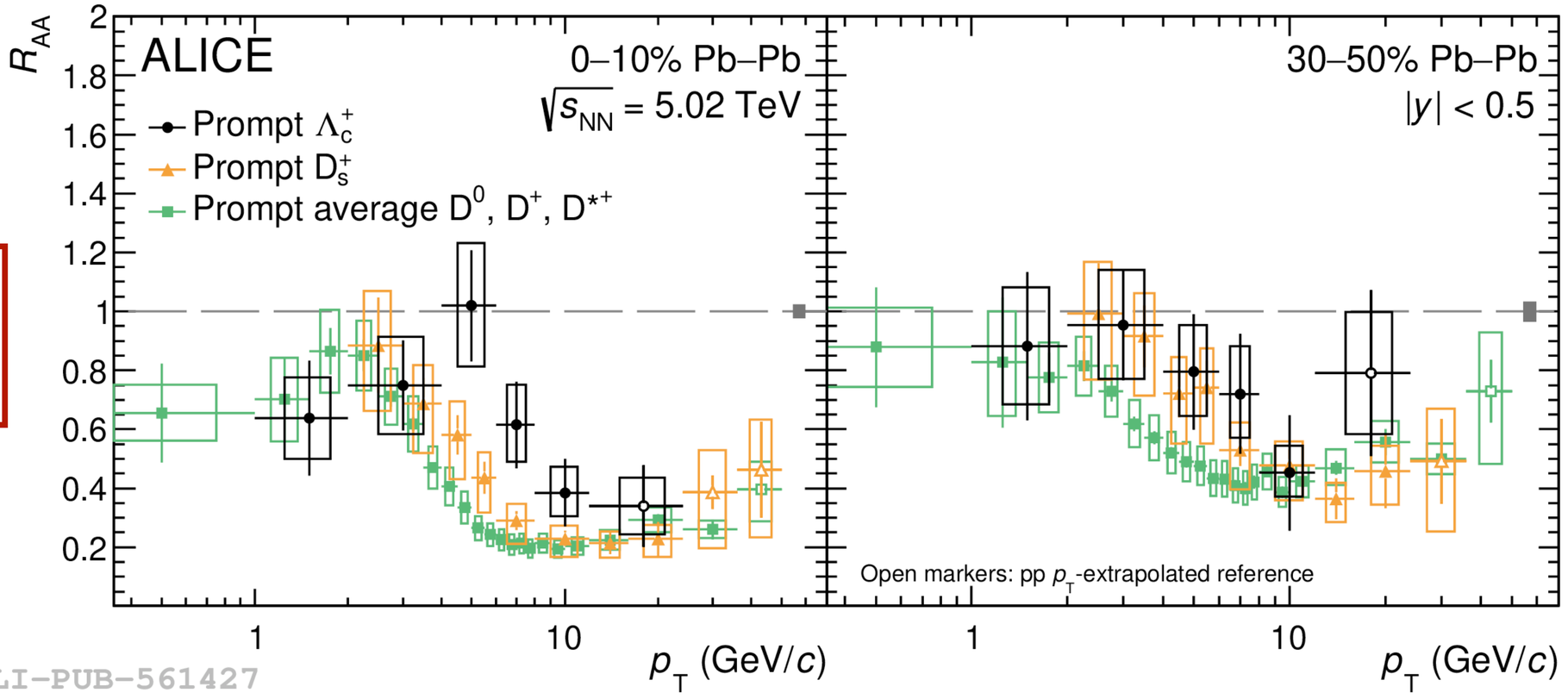
- ✓ Similar dependency on p_T within experimental uncertainties

R_{AA} of charm hadrons in Pb-Pb collisions



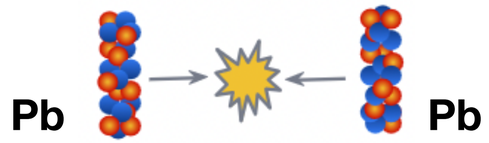
Phys. Lett. B 839 (2023) 137796

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{Y_{AA}}{Y_{pp}}$$



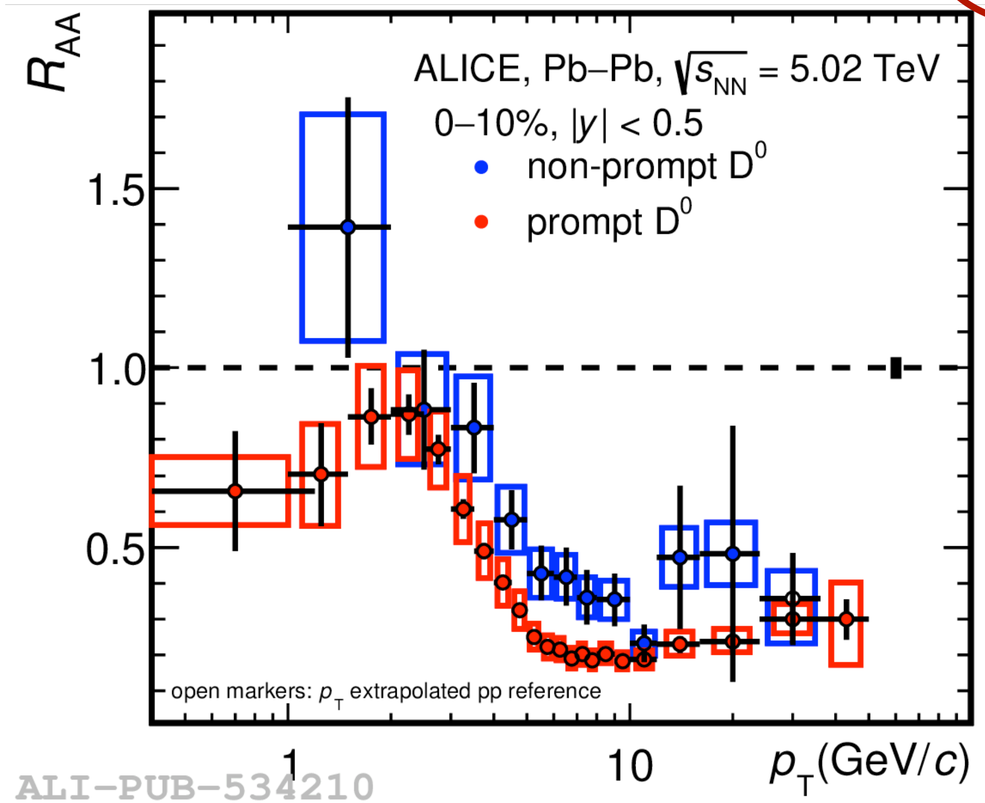
- Suppression of all charm species from $p_T > 6$ GeV/c for 0–10% and from $p_T > 4$ GeV/c for 30–50% → Interaction of charm quarks with the medium
- Hint of a hierarchy $R_{AA}(D^0) < R_{AA}(D_s^+) < R_{AA}(\Lambda_c^+)$ in $4 < p_T < 8$ GeV/c in 0–10%, while less pronounced in 30–50%
- For $p_T > 10$ GeV/c, all R_{AA} are compatible within uncertainties

Beauty Quark Energy Loss in Pb-Pb



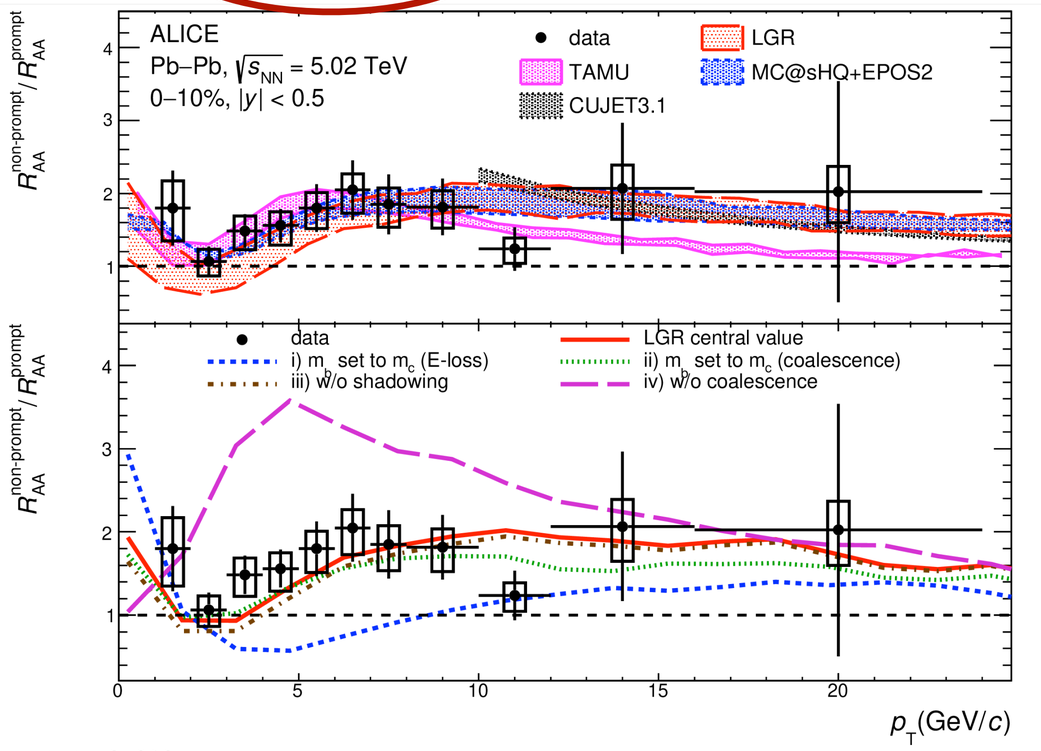
Beauty quark interaction and energy loss in the QGP → less diffusion and longer relaxation time than charm

$$\Delta E(g) > \Delta E(u, d, s) > \Delta E(c) > \Delta E(b) => R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$



ALI-PUB-534210

JHEP 12 (2022) 126

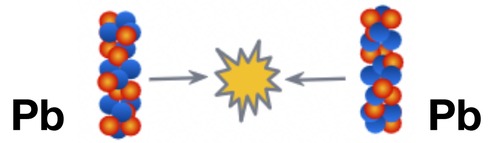


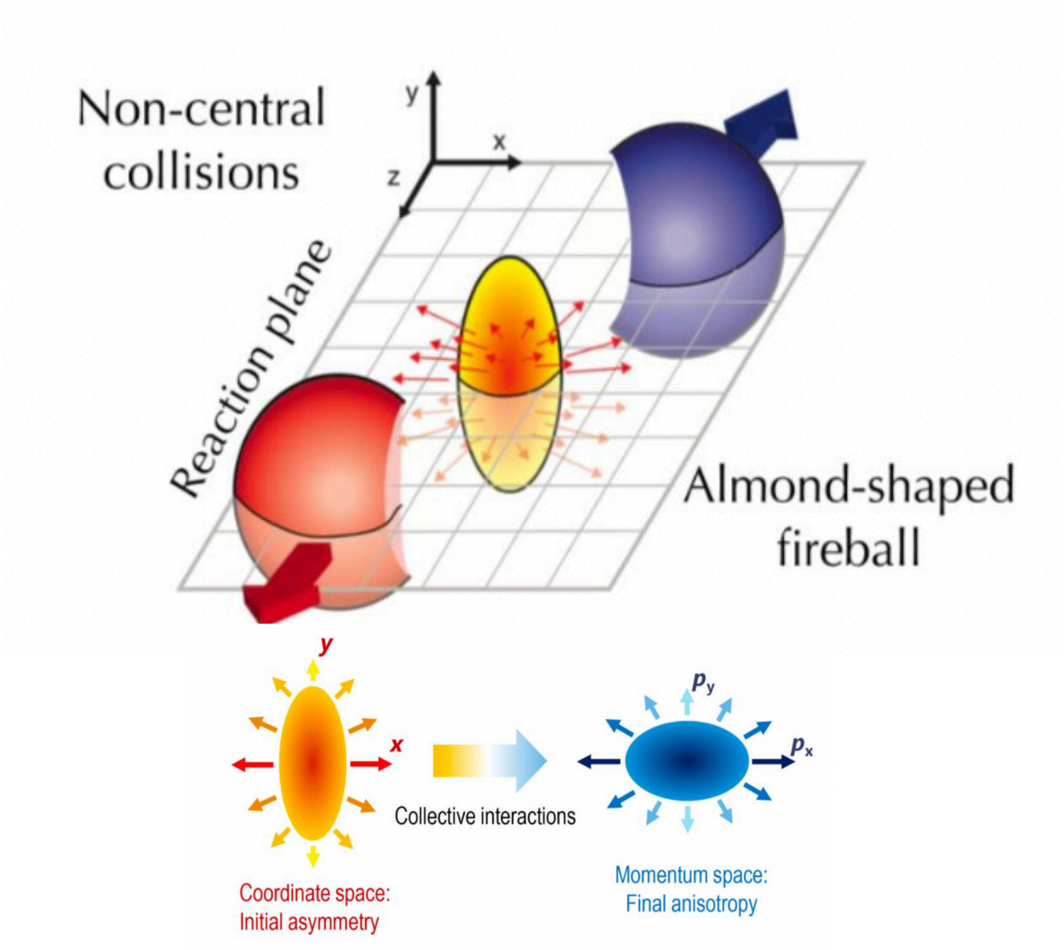
ALI-PUB-534213

- Intermediate p_T (5-20 GeV/c): R_{AA}(b) > R_{AA}(c)
- High p_T: R_{AA}(b) ~ R_{AA}(c) within large uncertainties

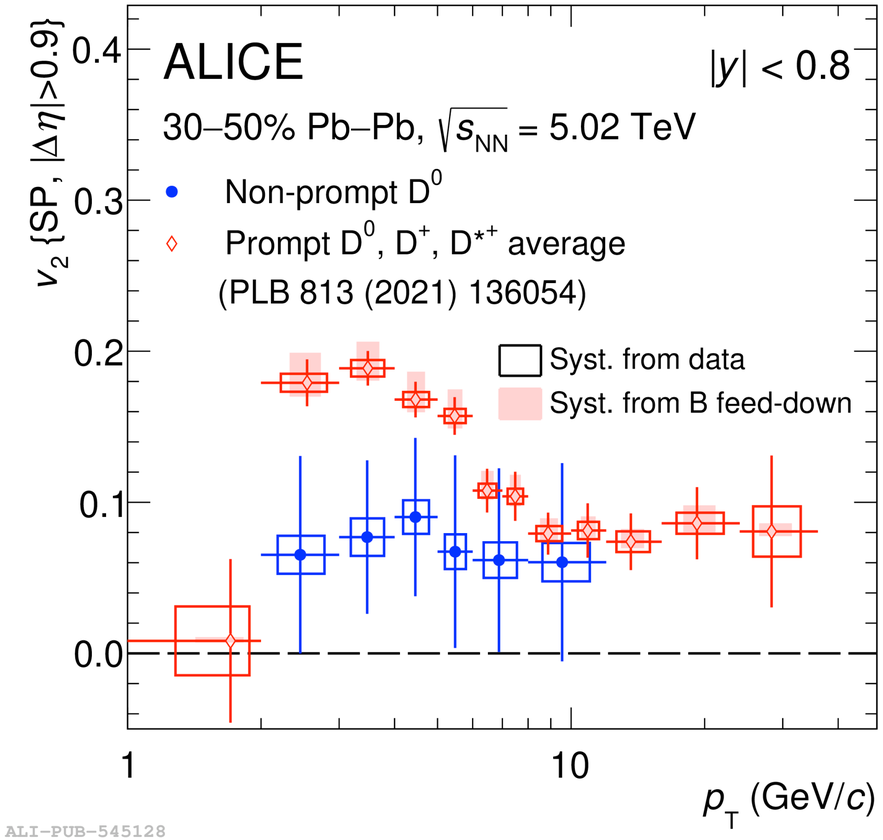
- Described by models: smaller b quark energy loss due to dead cone for gluon radiation
- Dip due to formation of D and B mesons via coalescence hardening the D p_T spectra

Elliptic flow (v_2) of charm and beauty quarks





EPJC 83 (2023) 1123



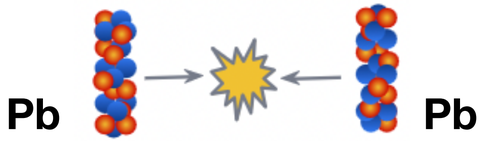
ALI-PUB-545128

Fourier decomposition of the azimuthal distribution of particles :

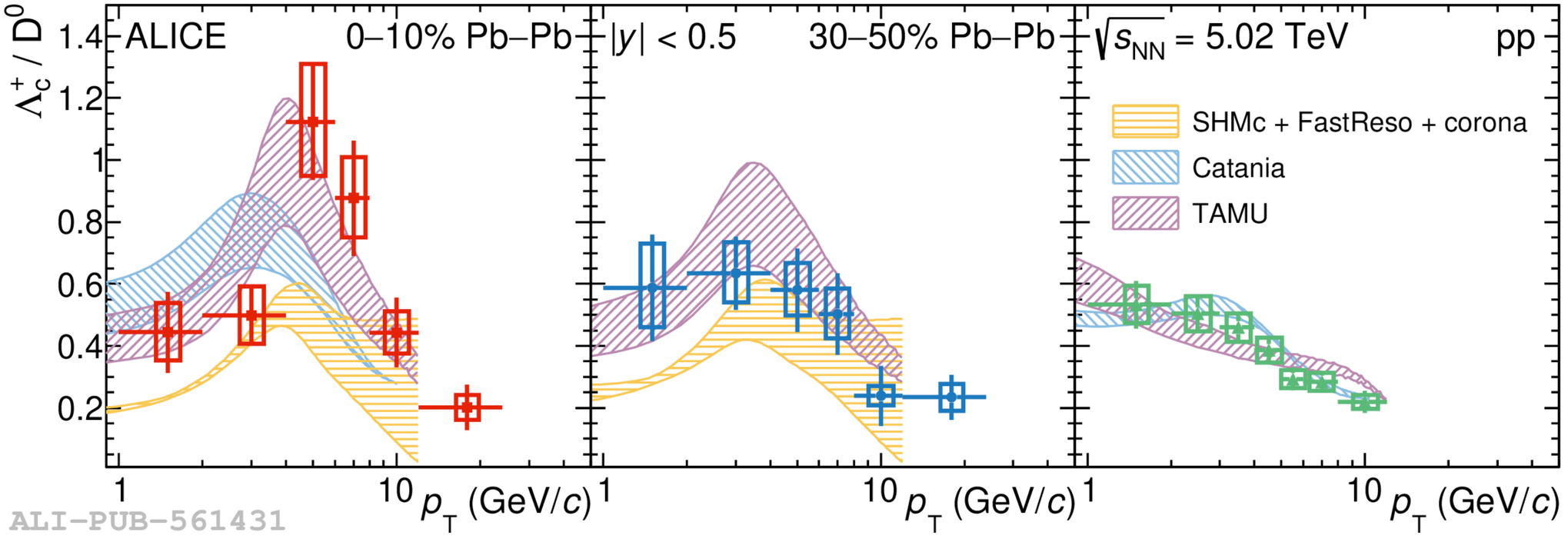
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \text{ , } v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

- v_2(b->D^0) < v_2(D) : Different degree of participation between charm and beauty quarks in the medium expansion

Baryon production : Λ_c^+/D^0 ratio in Pb-Pb collisions



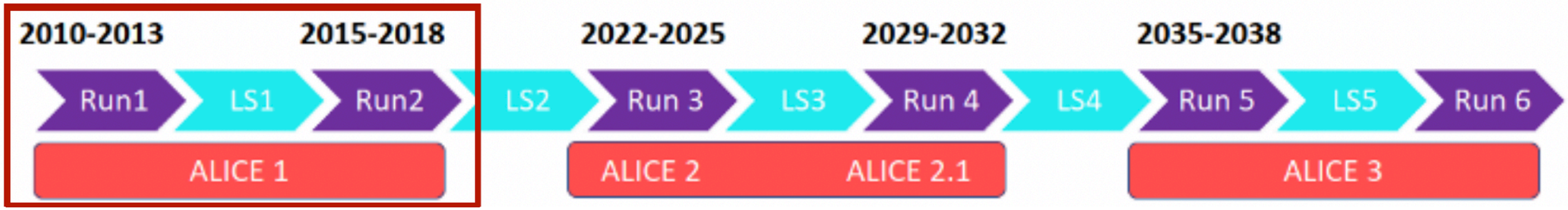
Phys. Lett. B 839 (2023) 137796



- Ratio increases from pp to semicentral and central Pb–Pb collisions at the intermediate p_T region
- Compare to different model predictions
  - ✓ SHMc : describes the ratio in semicentral collisions and underestimate the data in $4 < p_T < 8$ GeV/c in central collisions
  - ✓ Catania : underestimates the data in the intermediate p_T region
  - ✓ TAMU : reproduce the magnitude and shape of the data, and better description within uncertainties

SHMc : **JHEP 07 (2021) 035**
Catania : **Phys. Lett. B 821 (2021) 136622** (pp)
EPJC 78 (2018) 348 (Pb–Pb)
TAMU : **Phys. Lett. B 795 (2019) 117–121** (pp)
Phys. Rev. Lett. 124 (2020) 042301 (Pb–Pb)

Summary from run 2



In pp collisions :

- Production cross section described by pQCD calculations
- Fragmentation function universality is violated in pp collisions
  - Hadronization via recombination is dominant at low p_T

In p–Pb collisions :

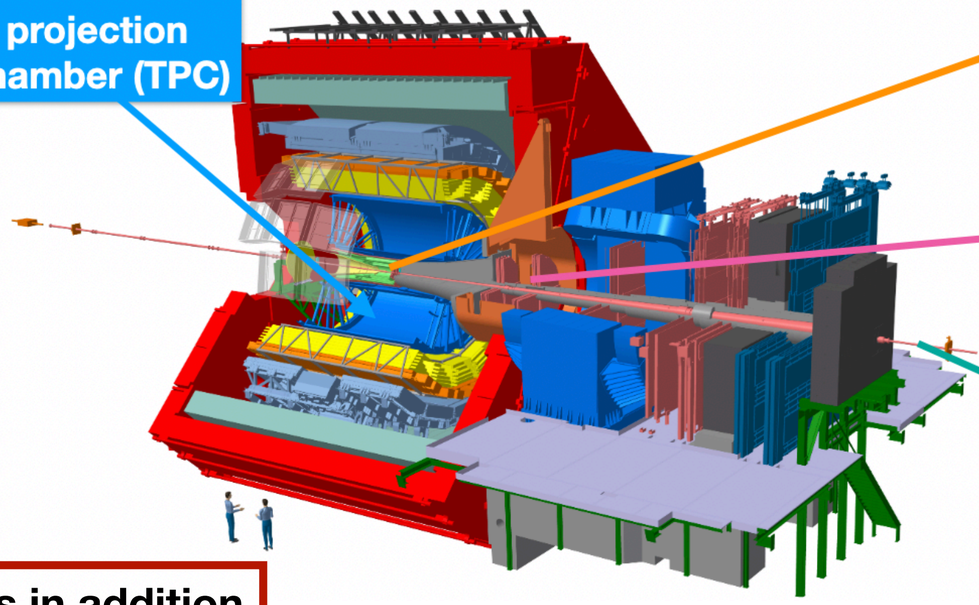
- Heavy-quark production is not significantly affected by CNM effects
- Enhanced baryon production in p–Pb collisions w.r.t pp collisions in the intermediate p_T region

In Pb–Pb collisions :

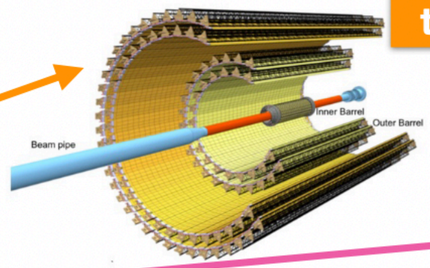
- Baryon enhancement depends on the event multiplicity
- Both charm and beauty quarks lose energy in the medium
  - Beauty quarks lose less energy than charm quarks
- Heavy quarks participate in a hydrodynamically expanding medium, $v_2(\mathrm{HF}) > 0$
  - $v_2(\mathrm{c}) > v_2(\mathrm{b})$

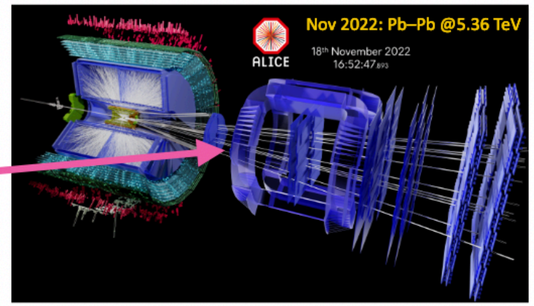
ALICE detector in run 3

Upgraded readout of time projection chamber (TPC)

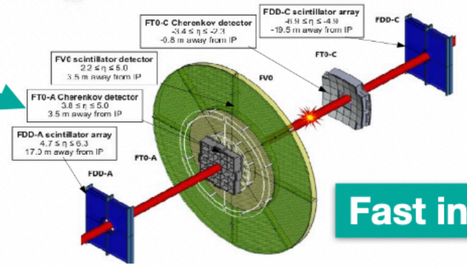


The 2nd generation inner tracking system (ITS2)





Muon forward tracker (MFT)

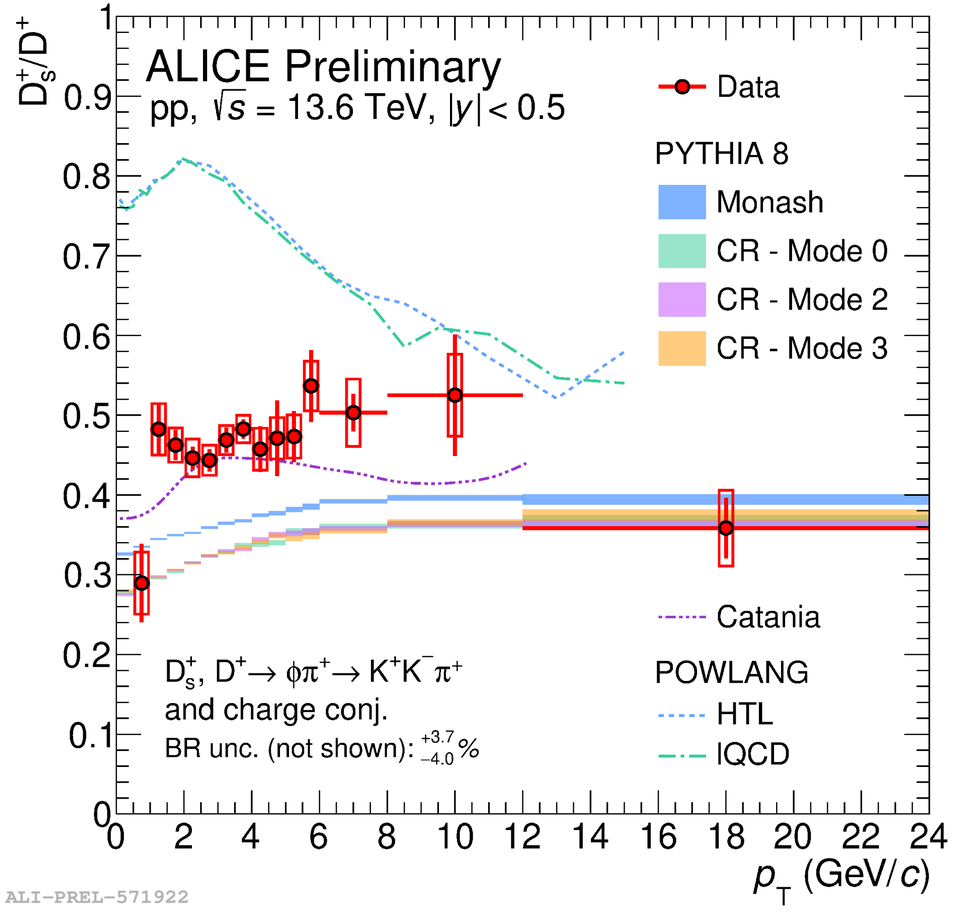


Fast integrated trigger (FIT)

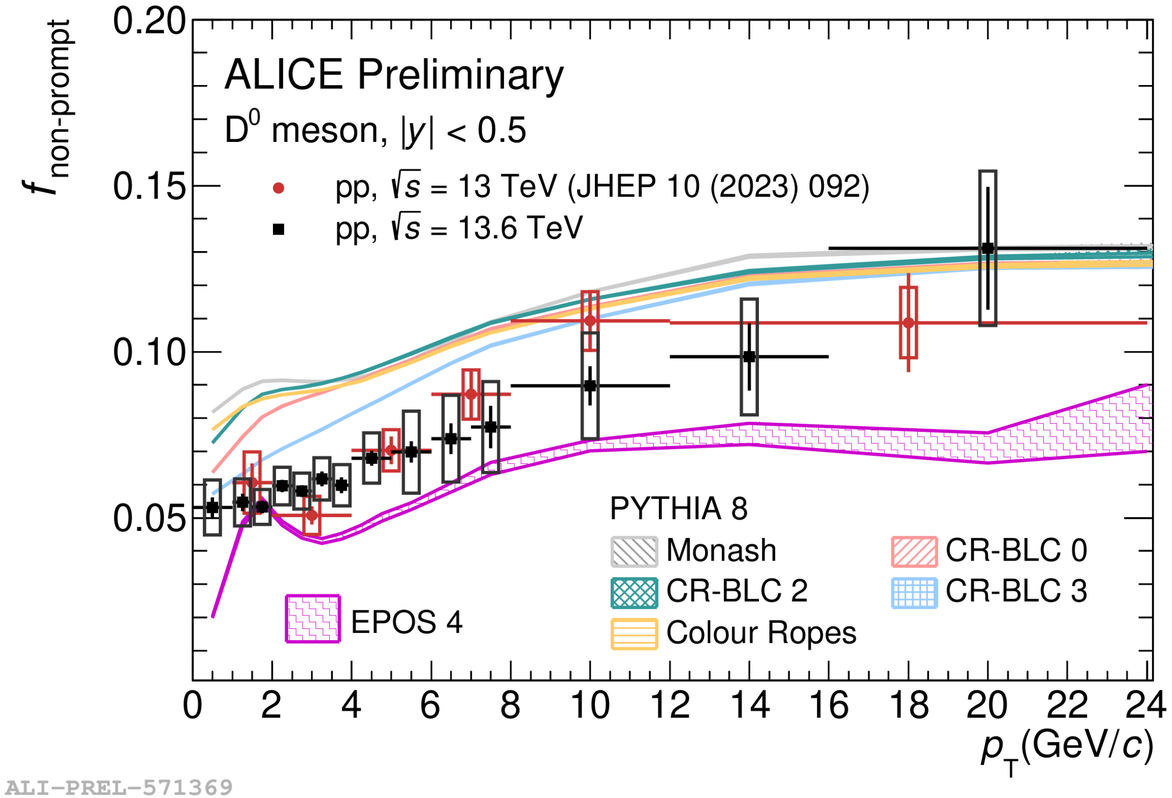
New observables in addition to precise measurements on HF sector

New results from run 3

D_s^+ and b→D^0 production :



ALI-PREL-571922

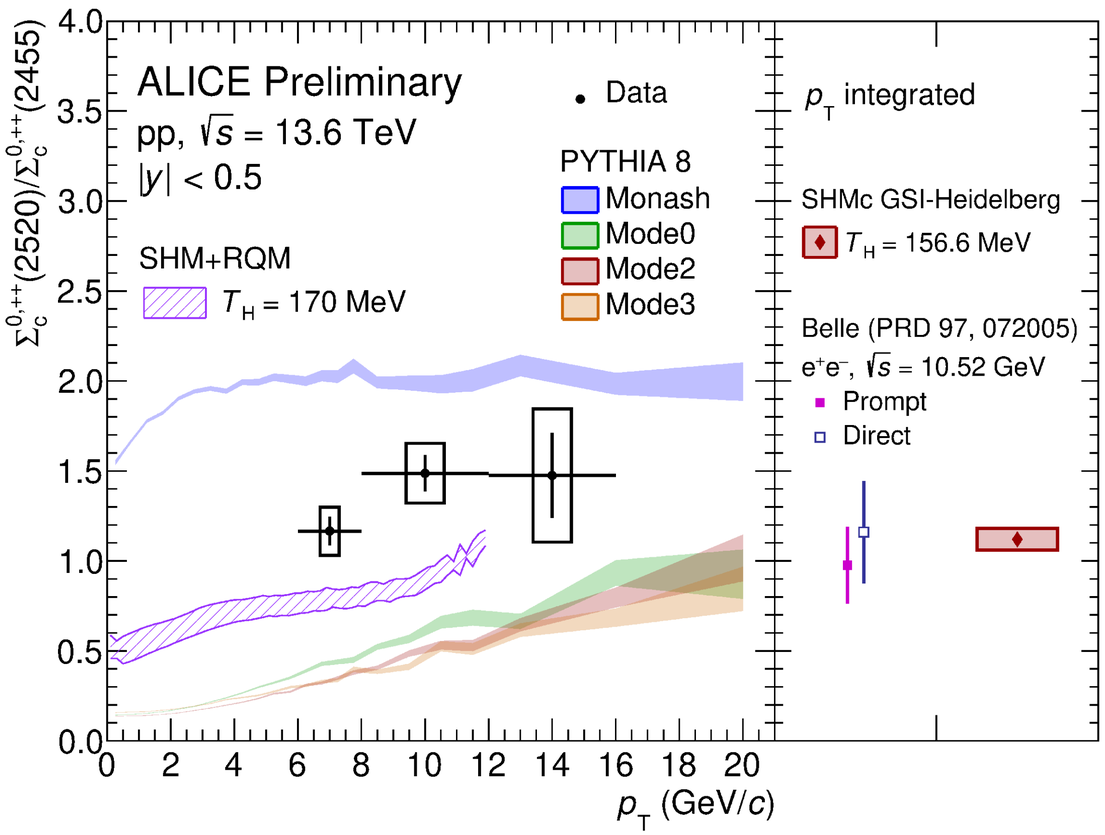


ALI-PREL-571369

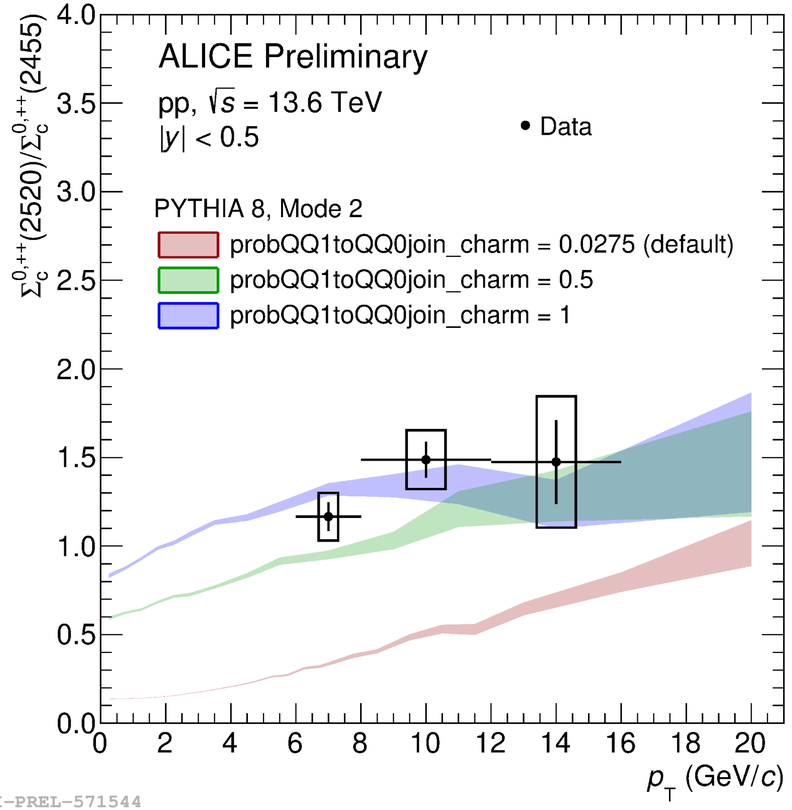
Measurements are extended to lower p_T and more granular w. r. t. run 2
→ Stronger constraints on the modelling of charm-quark hadronization

New results from run 3

$\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ **ratio :**



ALI-PREL-574270



ALI-PREL-571544

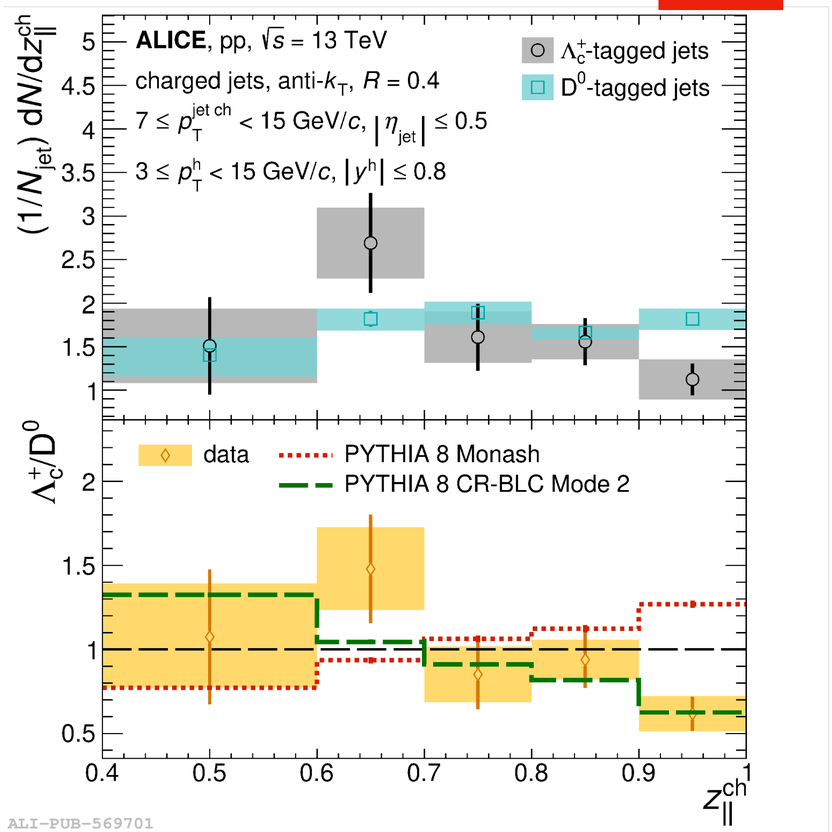
First $\Sigma_c^{0,++}(2520)$ production measurement at the LHC

- PYTHIA with neither Monash nor CR-BLC reproduces data
- Ratio sensitive to c-diquark spin-1 to spin-0 suppression factor

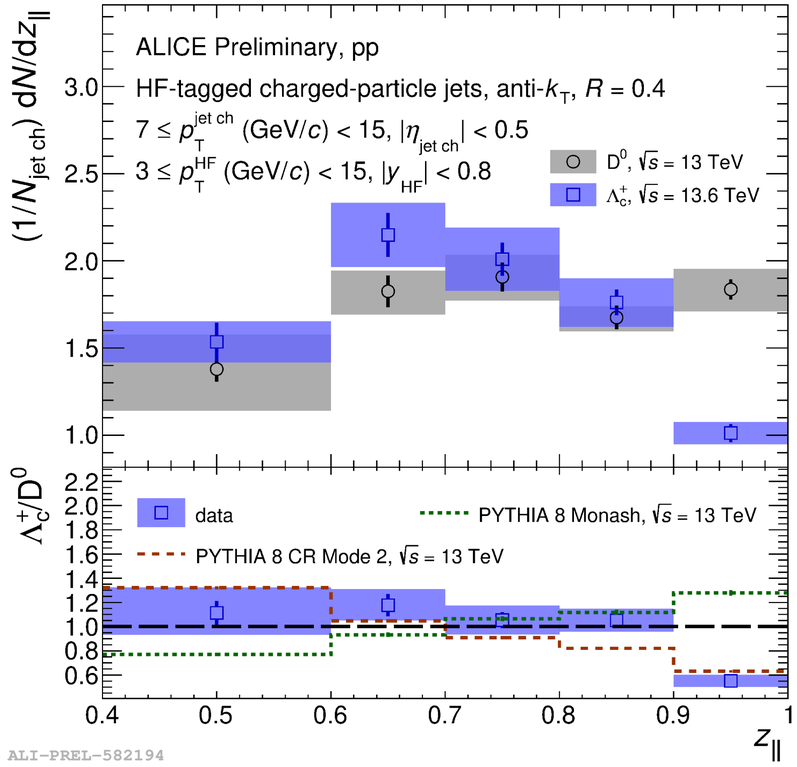
New results from run 3

Λ_c^+ fragmentation function:

Run 2



Run 3



Improved precision compared to Run 2

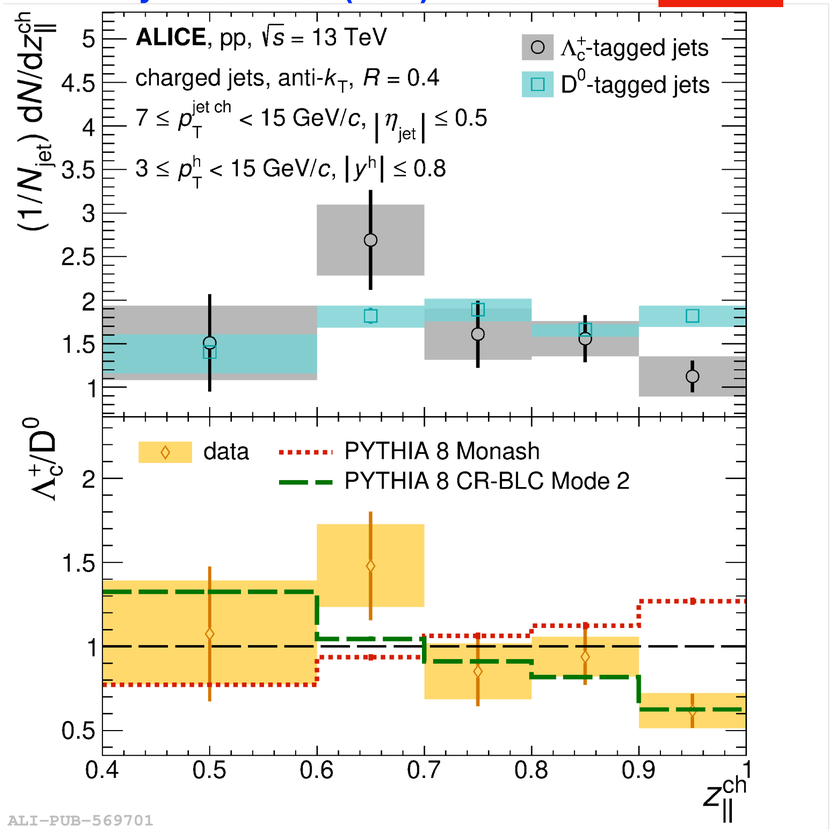
- Compared to PYTHIA simulations and to a measurement of D⁰ charged jets
- Fragmentation of charmed baryons is softer with respect to charmed mesons, as predicted by models including mechanisms of charmed-baryon production beyond leading-colour string fragmentation

New results from run 3

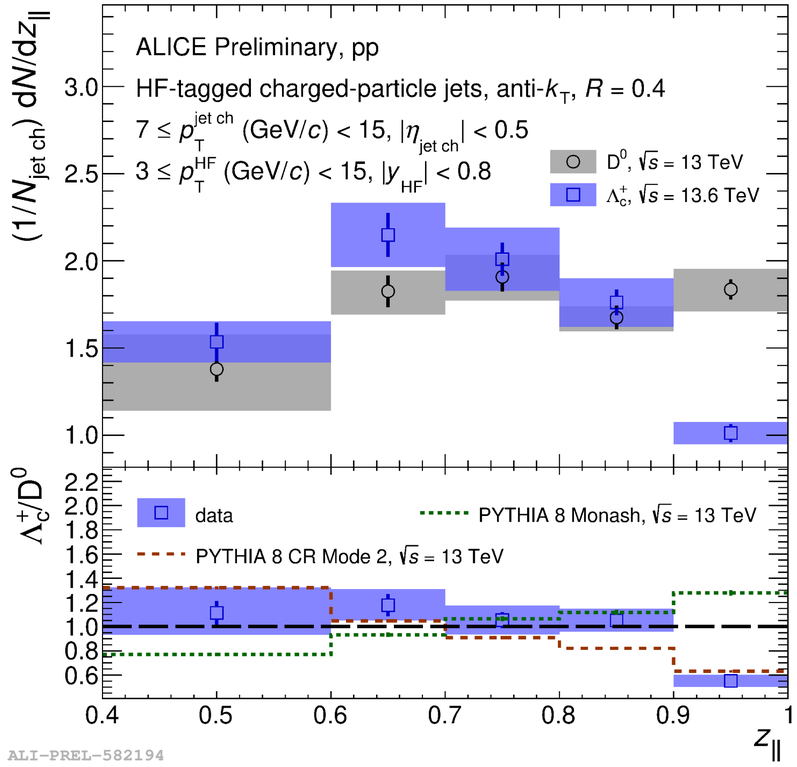
Λ_c^+ fragmentation function:

Phys. Rev. D109 (2024) 072005

Run 2



Run 3



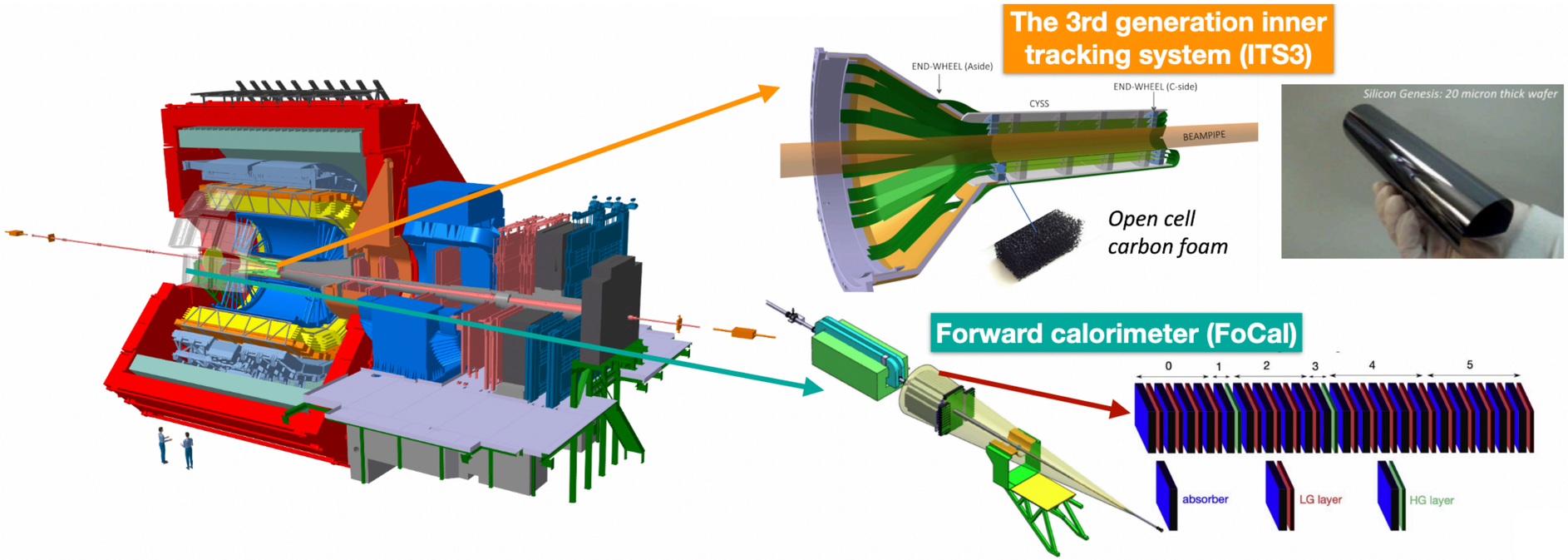
Improved precision compared to Run 2

- Compared to PYTHIA simulations and to a measurement of D⁰ charged jets
- Fragmentation of charmed baryons is softer with respect to charmed mesons, as predicted by models including mechanisms of charmed-baryon production beyond leading-colour string fragmentation

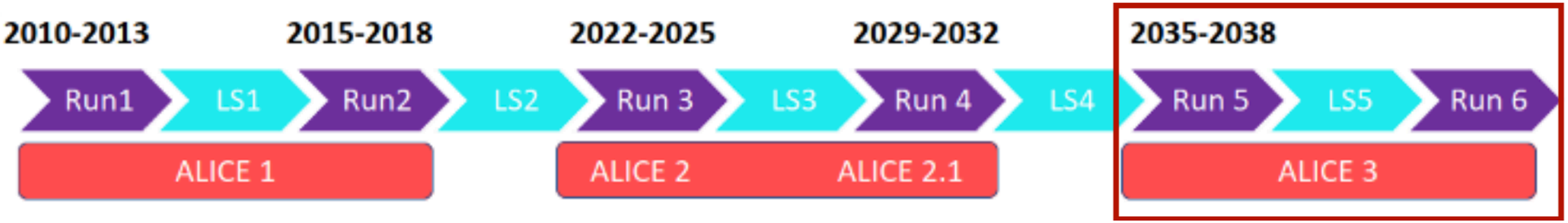
Outlook for Run 4 : Femtoscopy of the QCD

Technical Design reports:
[ITS3]
[FoCal]

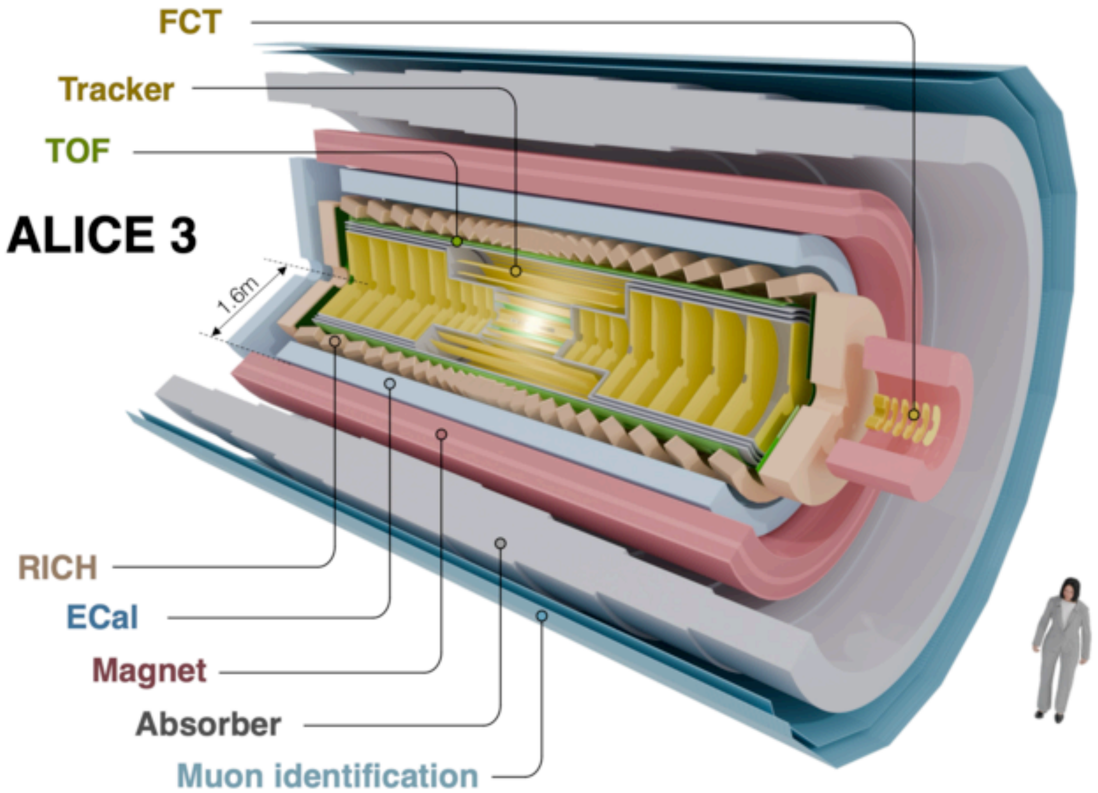
Main motivations:
Improve performance for open heavy-flavour and dielectron measurements



ALICE 3 : A next generation experiment



- Wide η range
- Excellent precision for secondary vertexing and PID performance
- high readout rate capabilities

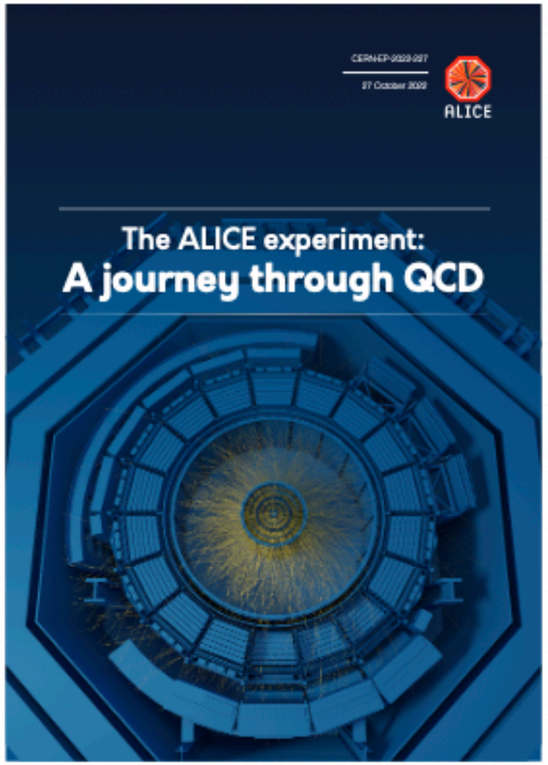


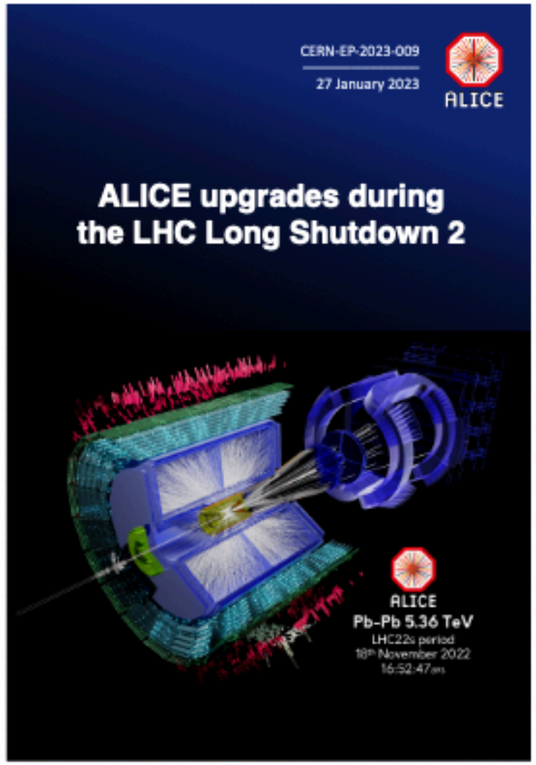
ALICE 3 LOI :
CERN-LHCC-2022-009

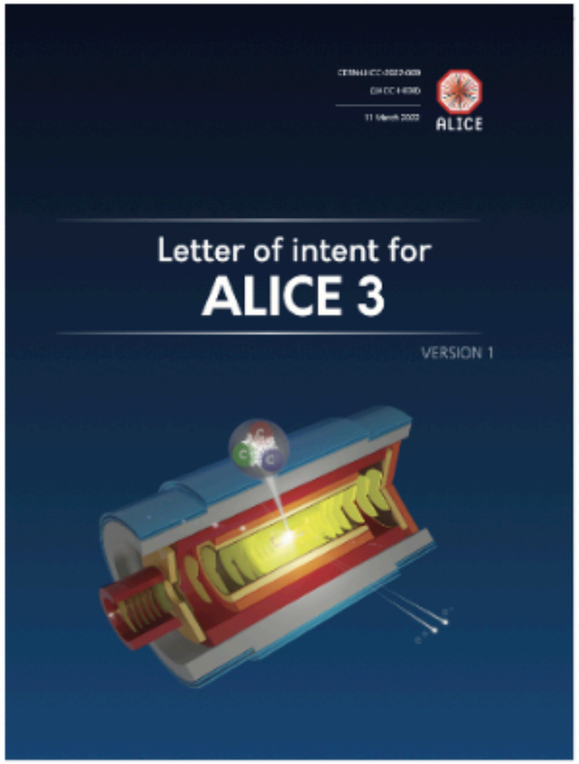
Physics motivation:
Measurements of rare charm and beauty hadrons (especially multicharm) and correlations to be measured precisely at ultra-low transverse momenta

ALICE

Find out more





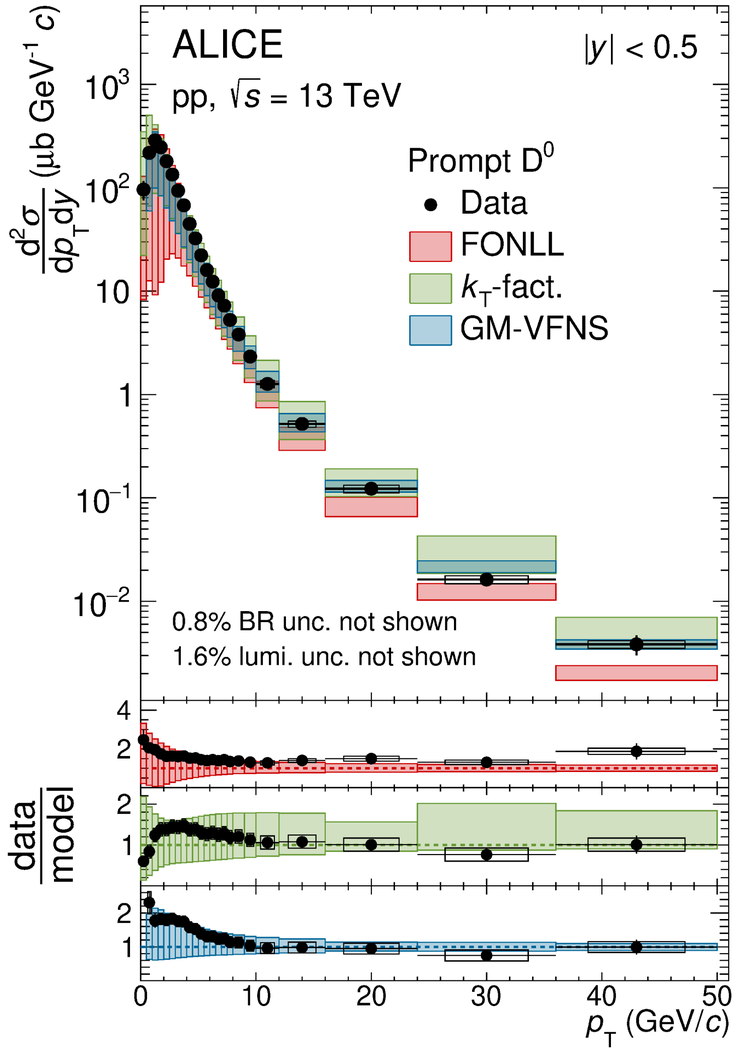


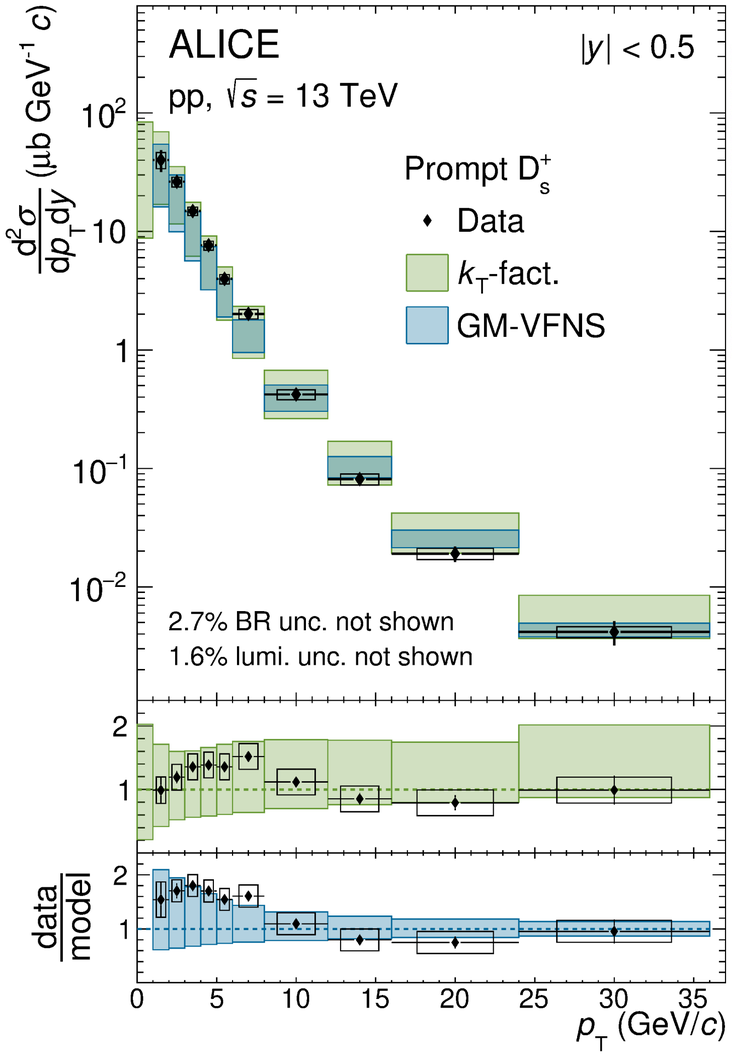
Thank you

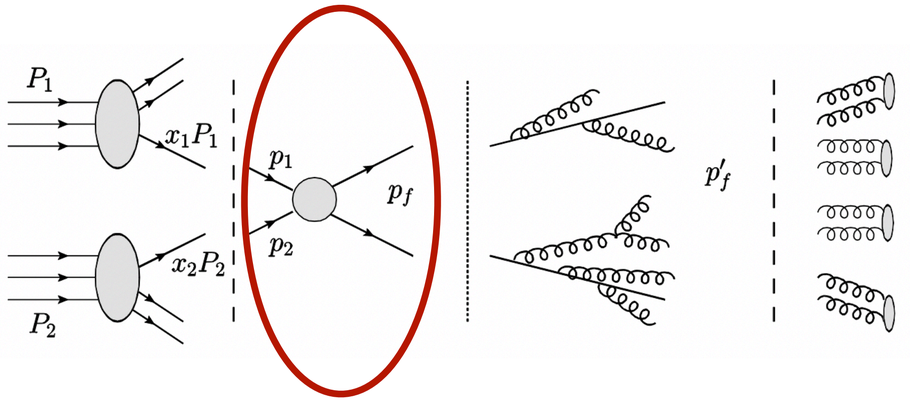
Back up

Cross-section measurement of D mesons

JHEP 12 (2023) 086







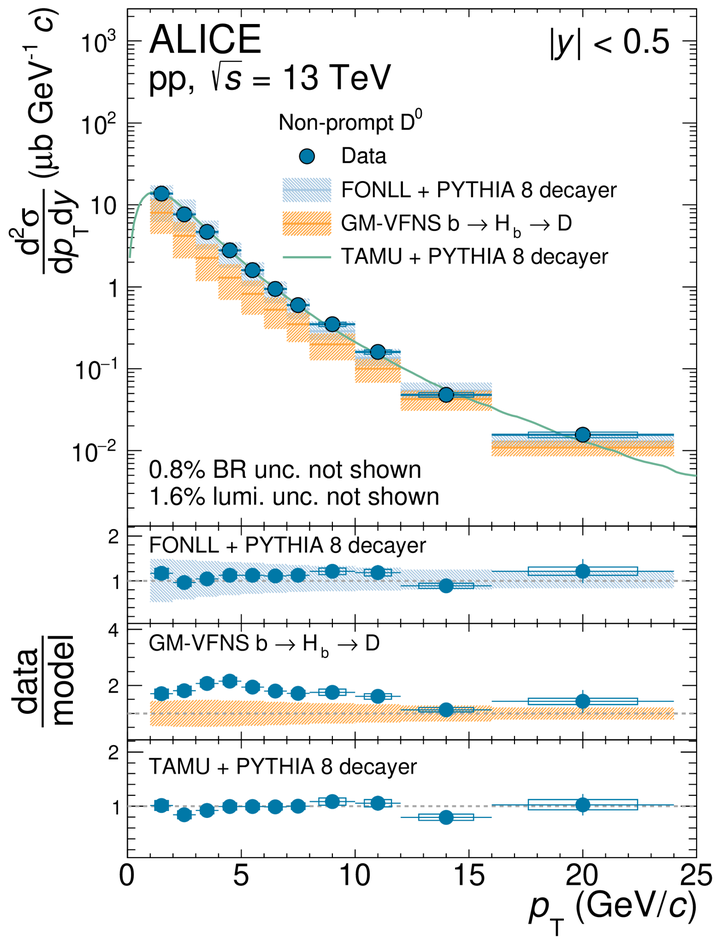
Prompt charm hadron :
hadrons from c-quark hadronization or from the decay of excited charm hadrons

- p_T-differential cross sections described by pQCD calculations (FONLL, kT-factorization, GM-VFNS) ➡ Good agreement within uncertainties

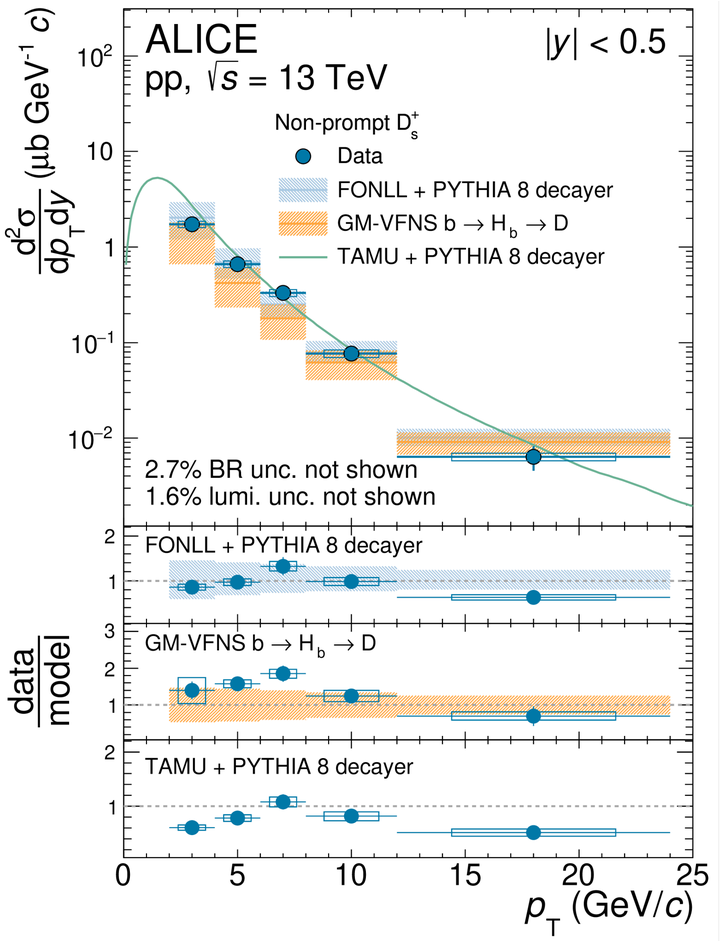
ALI-PUB-567836 ALI-PUB-567851

Measurement of beauty cross section

JHEP 10 (2024) 110



ALI-PUB-586555



ALI-PUB-586563

Non-prompt charm hadron : charm hadrons from beauty-hadron decays

PYTHIA 8 + FONLL

- Consistent with data within uncertainties

TAMU

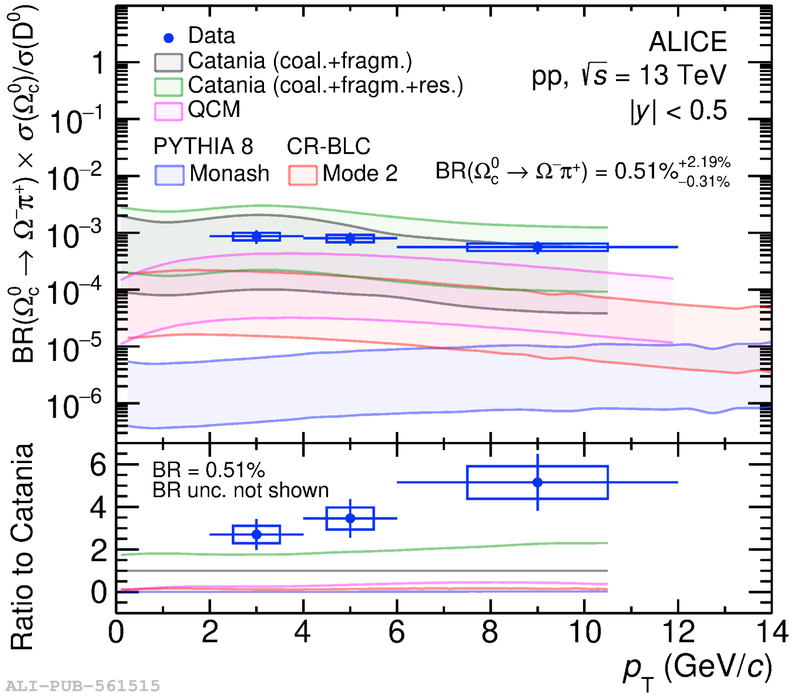
- Good agreement for D^0
- Tend to overestimate the D_s^+

GM-VFNS

- Underestimate the data at low p_T, whereas a better description at high p_T

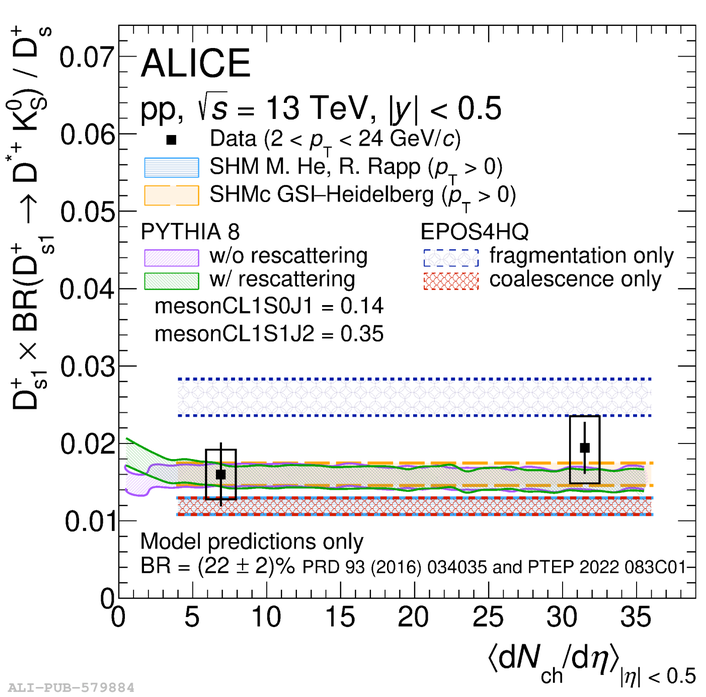
Heavier charm baryons : Ω_c^0 , $D_{s1}^+(1^+)(2536)^+$ and $D_{s2}^*(2^+)(2573)^+$

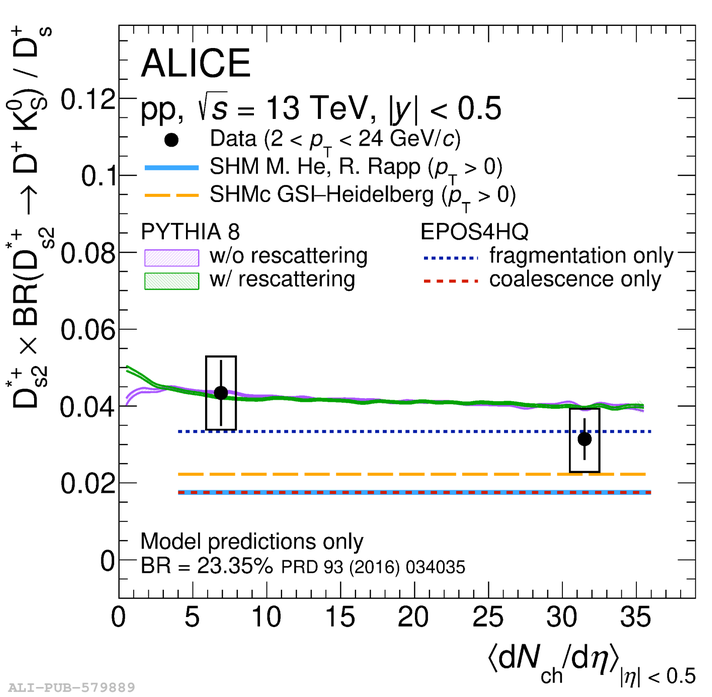
Phys. Lett. B 846 (2023) 137625



- Ω_c^0/D⁰ ratio shows no p_T dependence
- PYTHIA 8 Monash, PYTHIA 8 CR-BLC, quark-recombination model (QCM) underestimate the Ω_c^0/D⁰ ratio
- Catania closer to the measurement when additional resonances are considered

arXiv:2409.11938



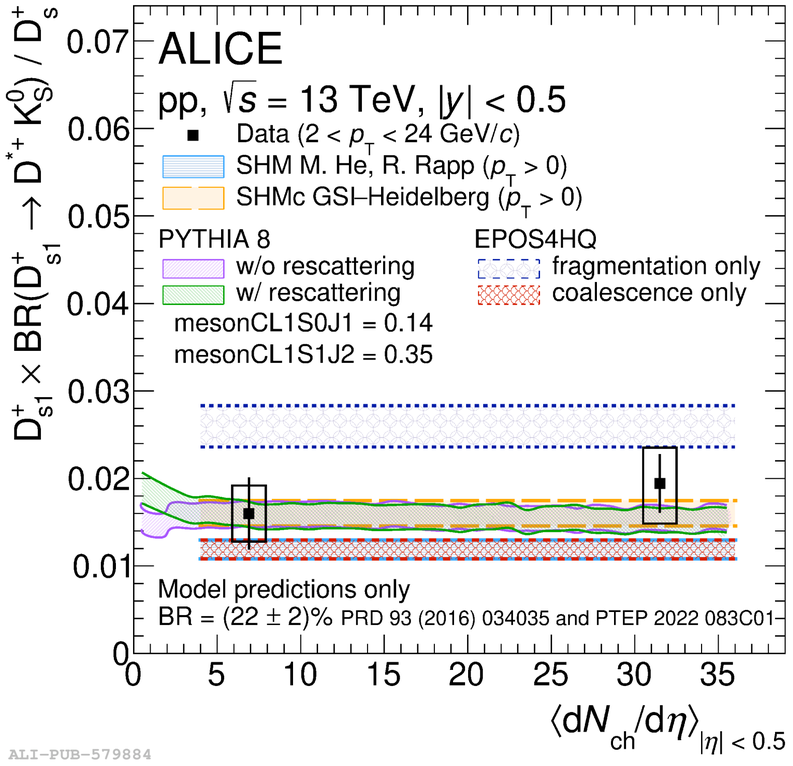


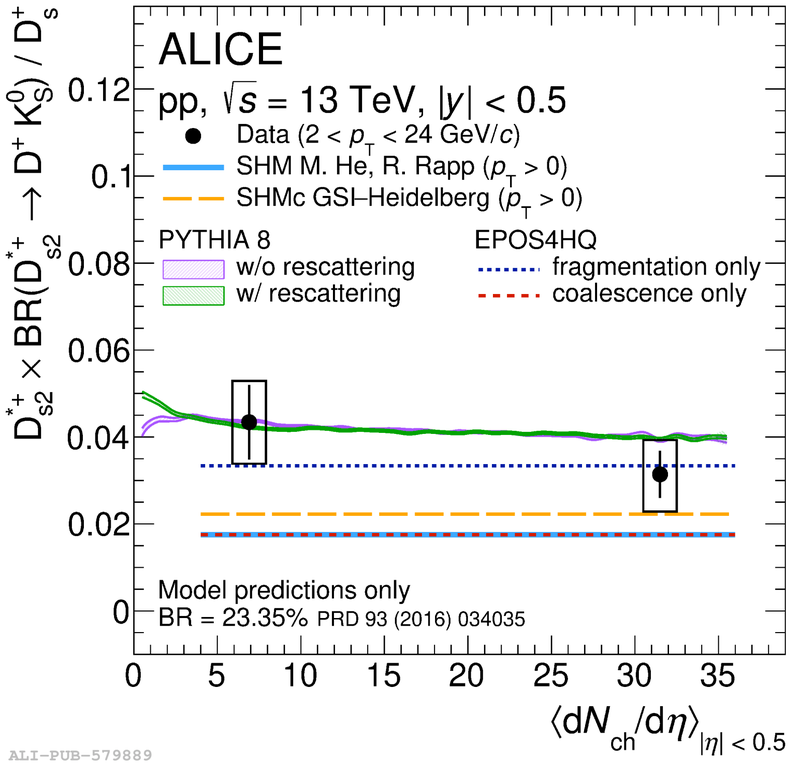
- First measurement of orbitally excited charm-strange mesons in pp collisions by ALICE
- Reproduced by SHM, models based on coalescence

Measurements of $D_{s1}(1^+)(2536)^+$ and $D^*_{s2}(2^+)(2573)^+$

First measurement of orbitally excited charm-strange mesons in pp collisions by ALICE

arXiv:2409.11938





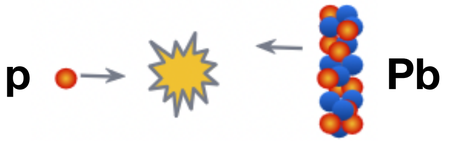
- **SHM and SHMc :**
- Measured ratios $D_{s1}(1^+)(2536)^+/D_s^+$ within 0.5 and 1.2σ at high and low multiplicity, respectively.
- They slightly underestimate the measured central values of the $D^*_{s2}(2^+)(2573)^+/D_s^+$ ratio by 2σ and 1σ at low and high multiplicity, respectively.

- **EPOS4HQ** : predicted ratios are systematically lower in the case of pure coalescence compared to pure fragmentation.

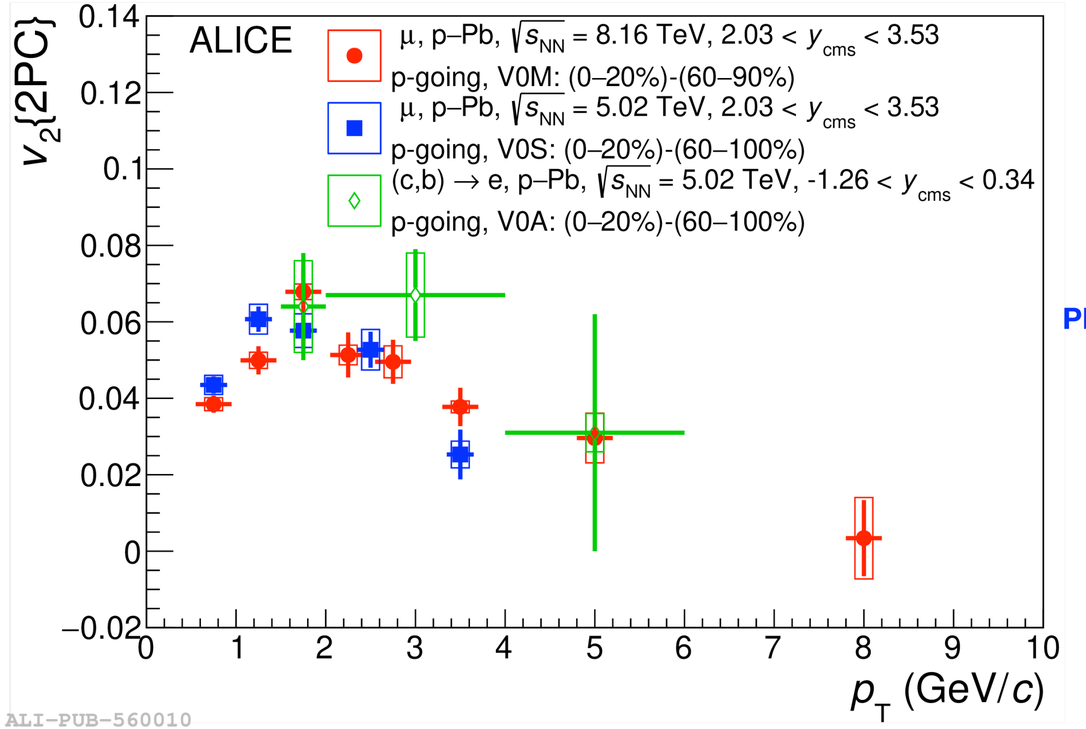
For $D^*_{s2}(2^+)(2573)^+/ D_s^+$, the data points suggest a possible decrease with increasing average charged-particle multiplicity :

- **PYTHIA8** simulations w/ and w/o rescattering
- might be related to the fact that the lifetime of the $D^*_{s2}(2^+)(2573)^+$ is longer than the expected duration of the hadronic phase in the collision
- the magnitude of hadronic interactions for D mesons with light hadrons is expected to be small in high-multiplicity pp collisions

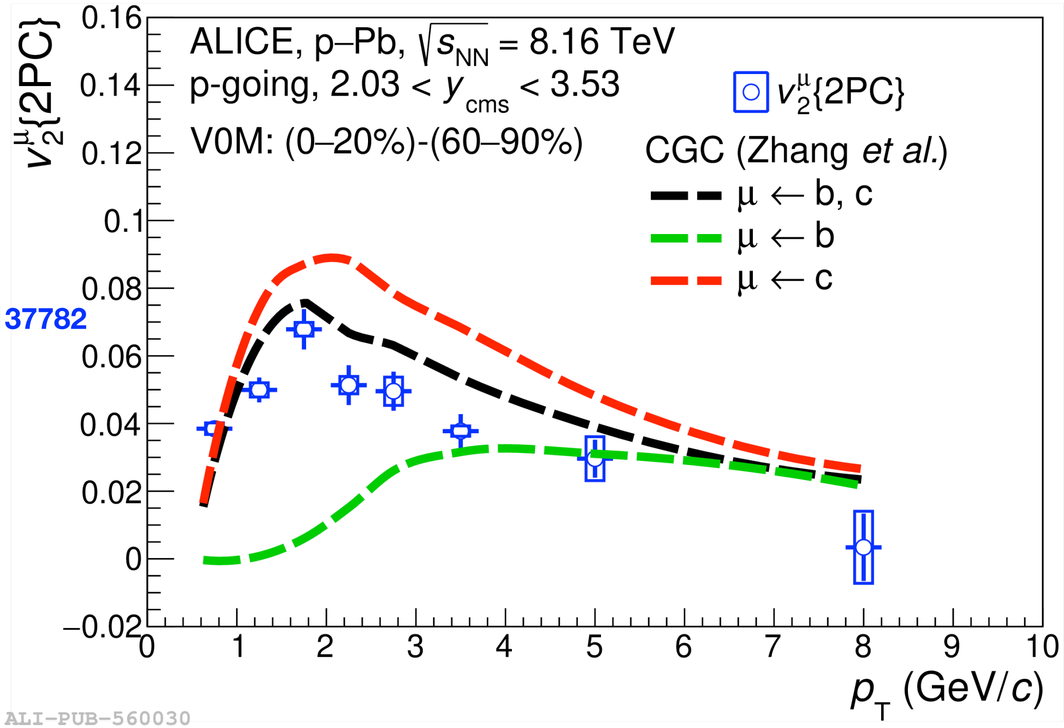
Azimuthal anisotropy in small system



v_2 of HF particles in high multiplicity p—Pb collisions.



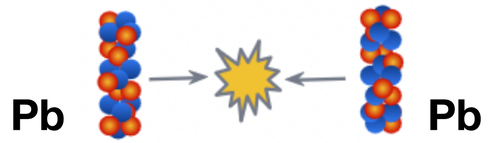
PLB 846 (2023) 137782



- v_2 of inclusive muons (dominated by HF decays at high p_T) at forward rapidity compared with c,b —> e at mid-rapidity.
- Good agreement within uncertainties.

- Data compared with predictions from CGC and AMPT models for c,b —>μ
  - AMPT: v_2 driven by the anisotropic parton escape mechanism
  - CGC: correlations between partons in the initial stages generate a v_2
- Both models describe data at high p_T

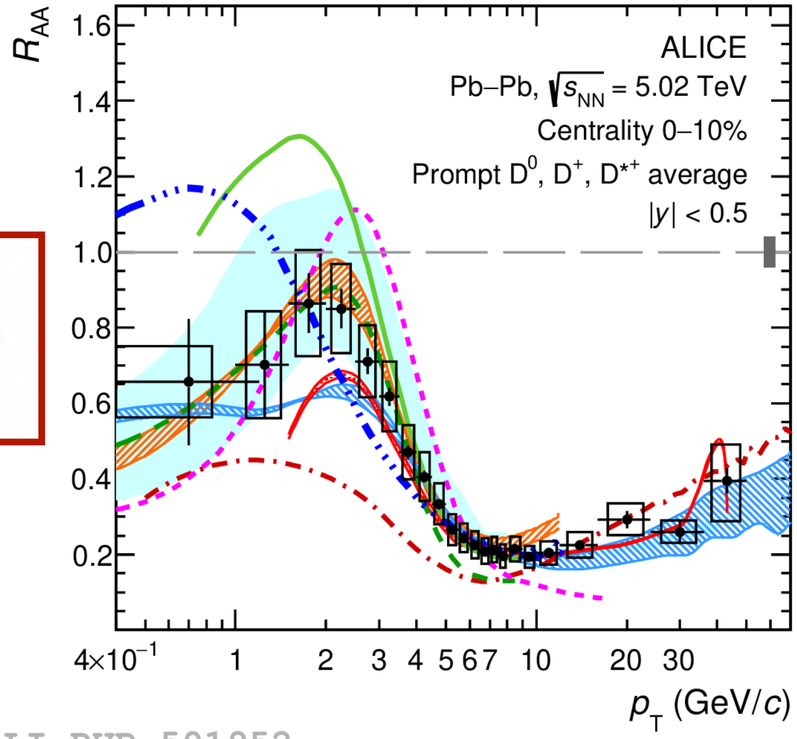
Charm quark in Pb-Pb collisions

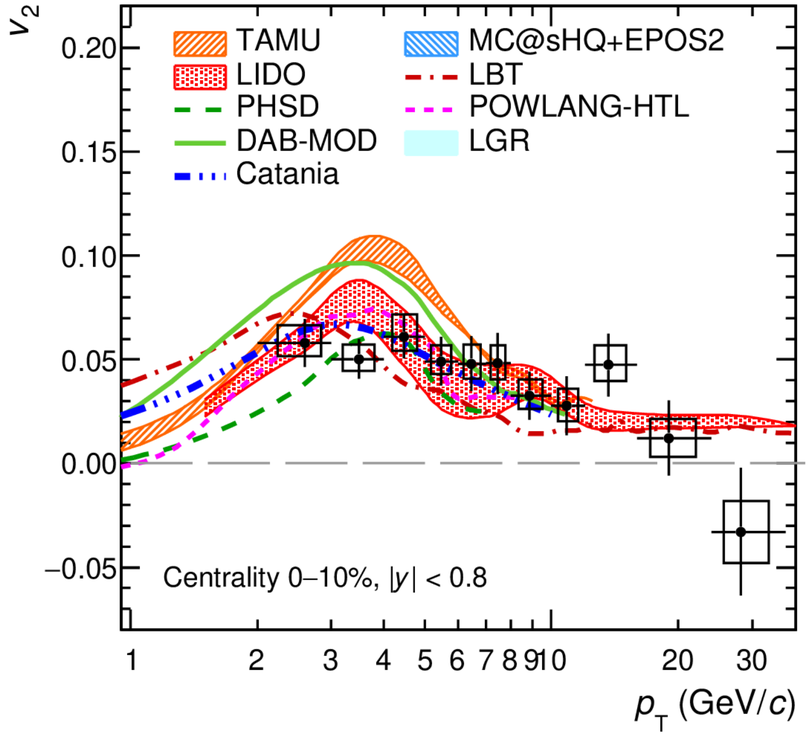


Charm quark interaction and energy loss in the QGP

JHEP 01 (2022) 174

$$R_{AA} = \frac{1}{< N_{coll} >} \frac{Y_{AA}}{Y_{pp}}$$



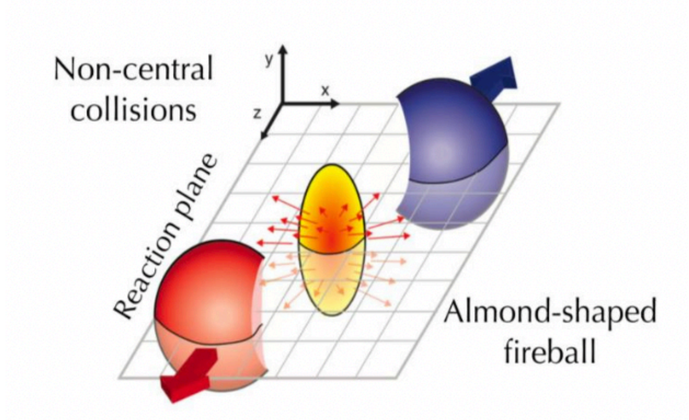


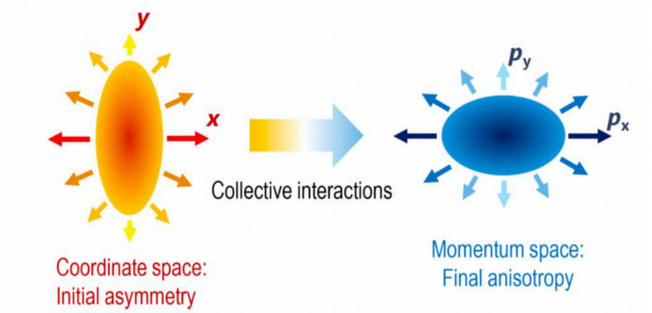
$$v_2 = < \cos[2(\phi - \Psi_2)] >$$

ALI-PUB-501952

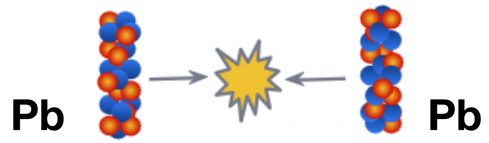
- Understanding interaction and energy loss of heavy quarks in the QGP over time —> Simultaneous comparison of D-meson R_{AA} and v_2
- Interplay of CNM effects, realistic evolution of the QGP, heavy-quark interaction (radiative and/or collisional) and hadronization via coalescence and/or fragmentation required to describe data.
- Models provide fair description of data —> still challenging for models to describe R_{AA} and v_2 simultaneously in the full p_T range.

Elliptic flow (v_2) of beauty quarks

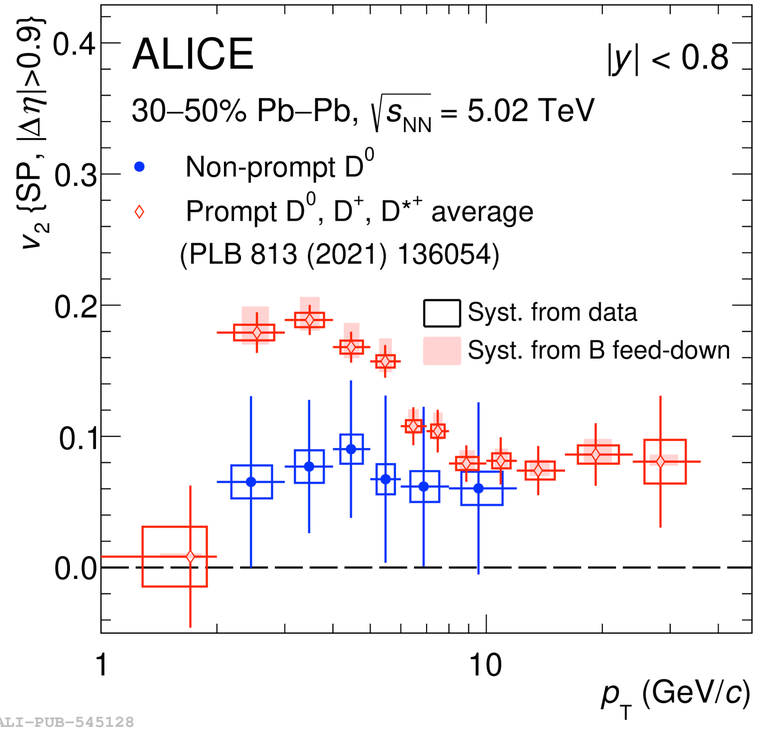


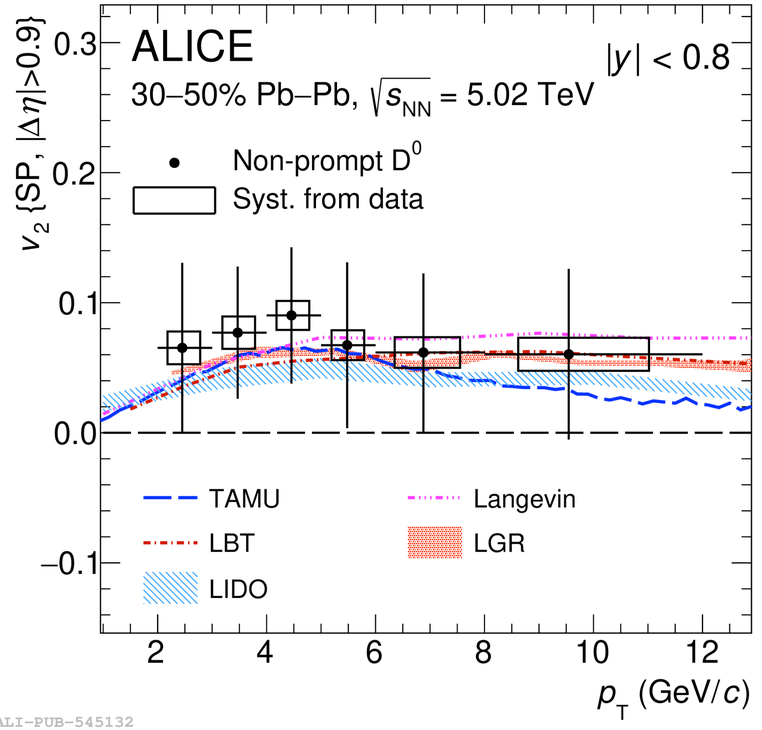


$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \text{ , } v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$



EPJC 83 (2023) 1123





- v_2(b->D⁰) > 0
- v_2(b->D⁰) < v_2(D) : Different degree of participation between charm and beauty quarks in the medium expansion

Theory models beauty quark transport in QGP → give reasonable description of data.

- All models, except TAMU (collisional only) include collisional interactions and radiative processes
- Hadronization via coalescence and fragmentation.