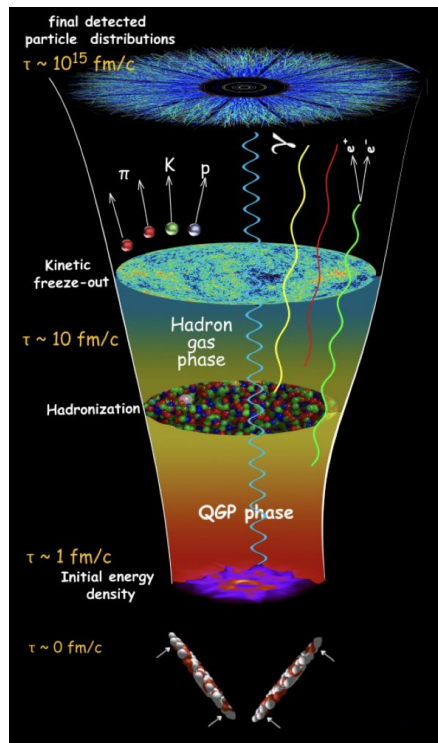
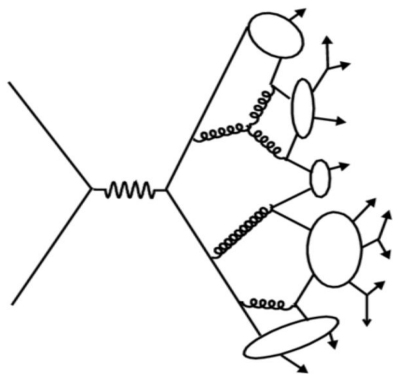


Heavy-quark hadronization at LHC: status and future perspectives

Andrea Dubla



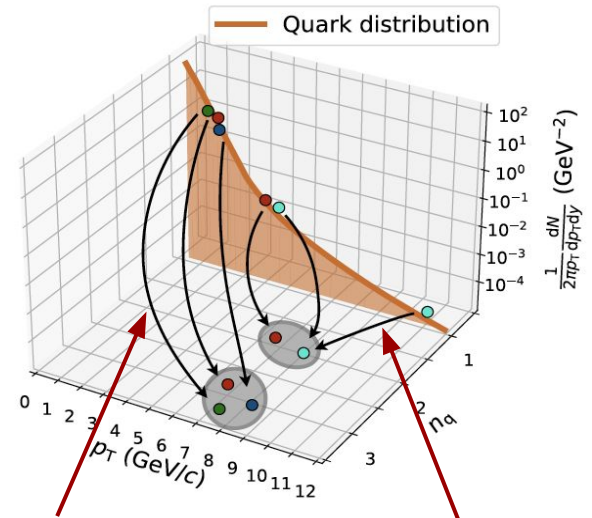
- **Hadronisation:** the mechanism by which quarks and gluons produced in hard partonic scattering processes form the hadrons
- **No first-principle description of hadron formation**
 - Non-perturbative problem, not calculable with QCD
 - Necessary to resort to models and make use of phenomenological parameters
- **Hadronisation of the QGP medium**
 - Transition from a deconfined medium composed of quarks, antiquarks and gluons to color-neutral hadronic matter

➤ Hadronisation from a QGP: heavy quarks might coalesce with light (di-) quarks from the system

- **Fragmentation functions** $D_q \rightarrow h(z, Q^2)$:
 - Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition*
 - z is the fraction of the parton momentum taken by the hadron h
 - Parameterized on data (e^+e^-) and assumed to be “**universal**”

- **Coalescence/recombination:**
 - Single parton description may not be valid anymore
 - No need to create $q\bar{q}$ pairs via splitting/string breaking
 - Partons that are “*close to each other in phase space*” (position and momentum) can **recombine** into hadrons

- **Coalescence vs. fragmentation:**
 - Competing mechanisms, dominant in different p_T regions
 - **Recombination depends on “environment”**, i.e. density and momentum distribution of surrounding (anti)quarks



Recombining quarks:

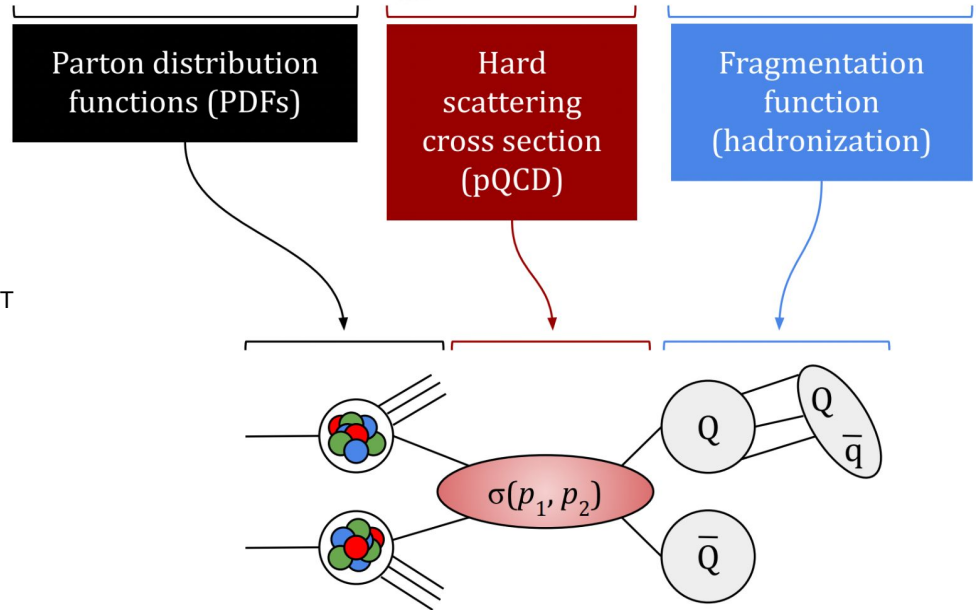
$$p_{\text{meson}} = p_{q1} + p_{q2}$$

$$p_{\text{baryon}} = p_{q1} + p_{q2} + p_{q3}$$

Fragmenting parton:

$$p_h = z \cdot p_q \text{ with } z < 1$$

$$\frac{d\sigma^{\text{H}_c}}{dp_T^{\text{H}_c}}(p_T; \mu_F, \mu_R) = \text{PDF}(x_1, \mu_F) \cdot \text{PDF}(x_2, \mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1, x_2, \mu_F, \mu_R) \otimes D_{c \rightarrow \text{H}_c}(z = p_{\text{H}_c}/p_c, \mu_F)$$



Hard scattering:

- large quark mass provides hard scale
- pQCD can calculate cross sections down to low p_T

PDF → from ep collisions

FF → from e^+e^- collisions

Hadron-to-hadron production ratios effective for probing hadronisation effects, PDFs and partonic cross sections fully cancel in the yield ratios

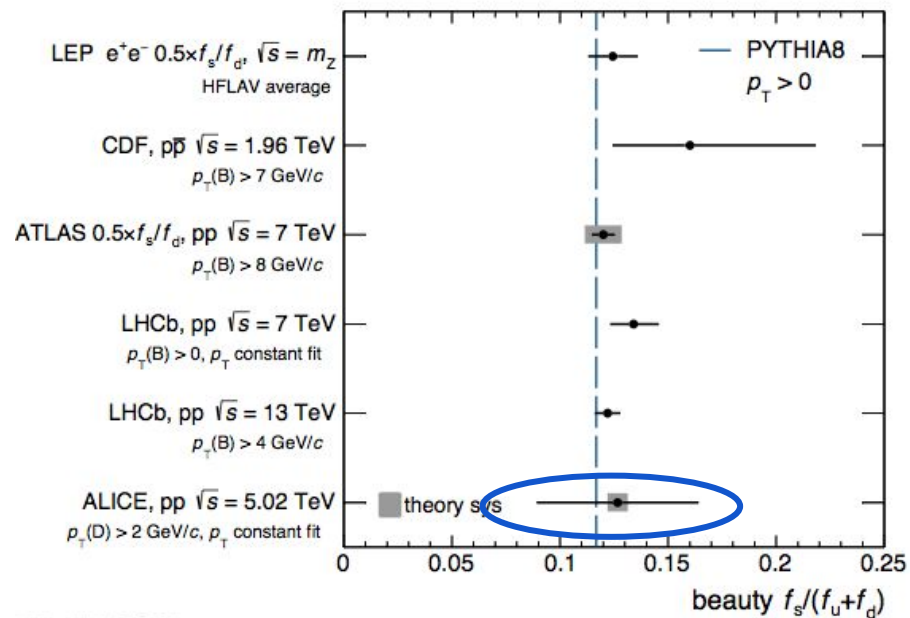
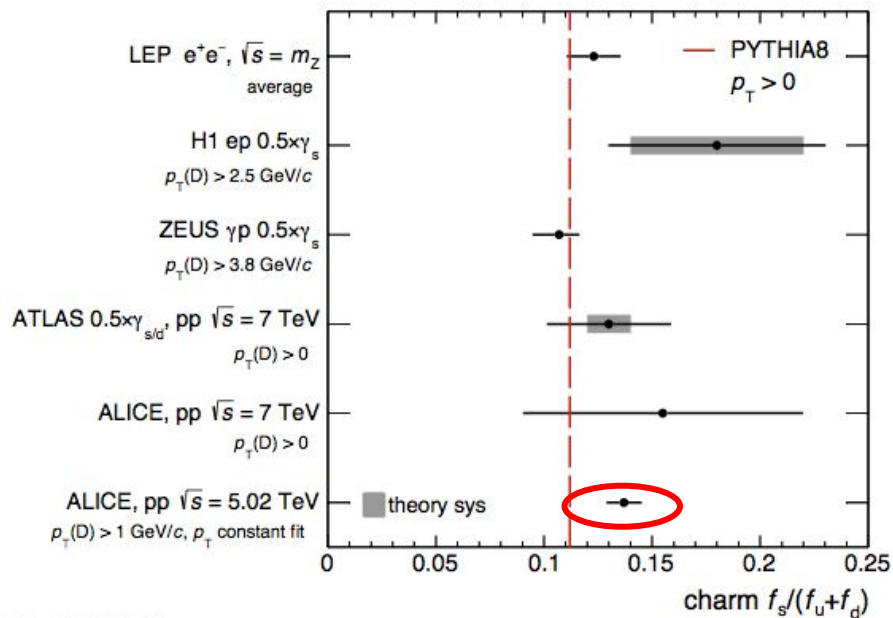
- Ratio fragmentation fraction (FF) to meson with and w/o strange quark content similar for charm and beauty
- **No significant dependence on energy and collision system**

JHEP 05 (2021) 220

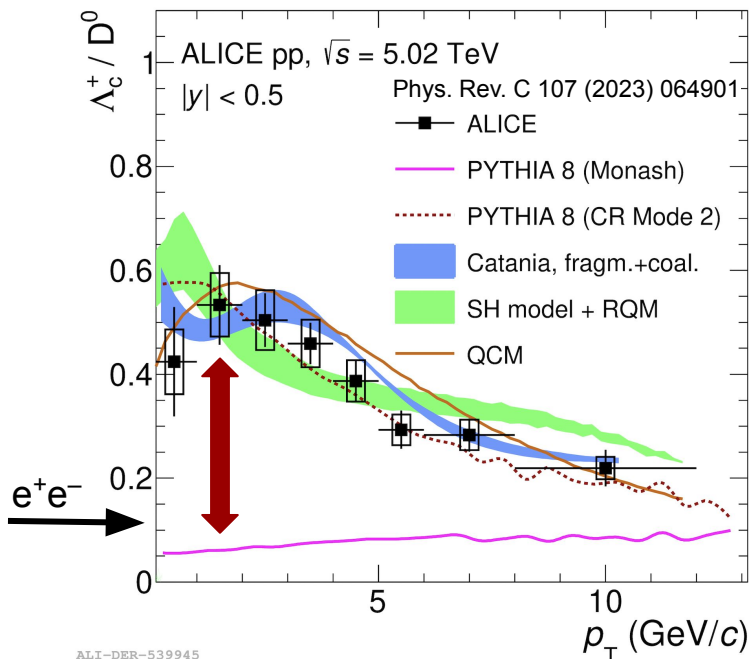
Charm

$$D_s^+ / (D^0 + D^+)$$

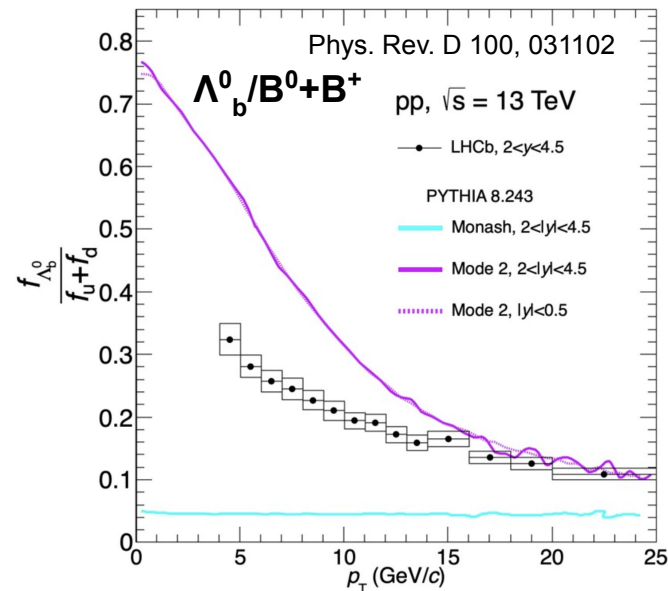
Beauty



Baryon/meson ratio in pp

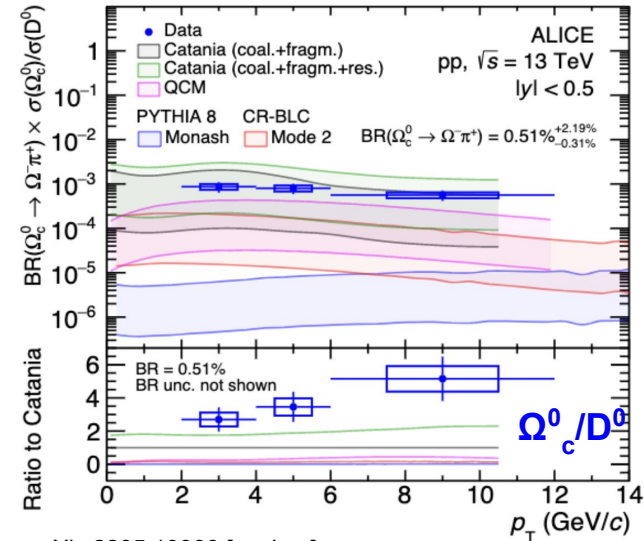
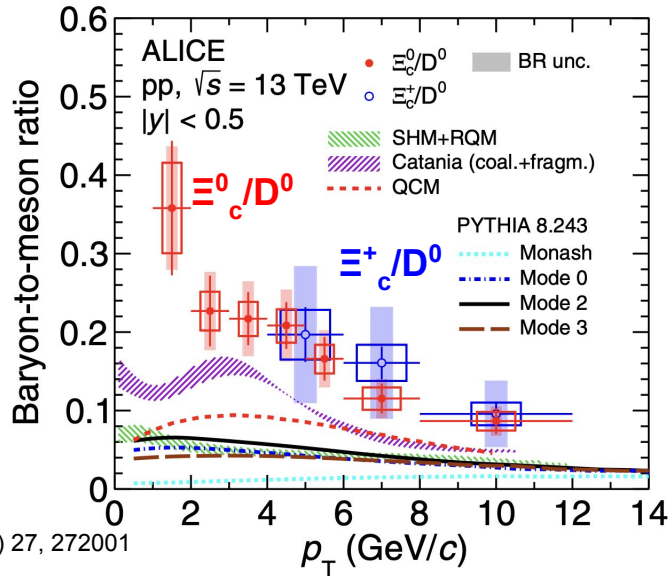


Similar observation in the beauty sector



- **Coalescence inspired models** enhance the baryon yield and better describe the data
- Additional **higher resonance states** not yet measured in experiment but predicted by RQM?
- Do models also describe measurements at **forward rapidity**?
 - Is there any obvious difference (parton density, charm density)?

A common trend for charm baryons



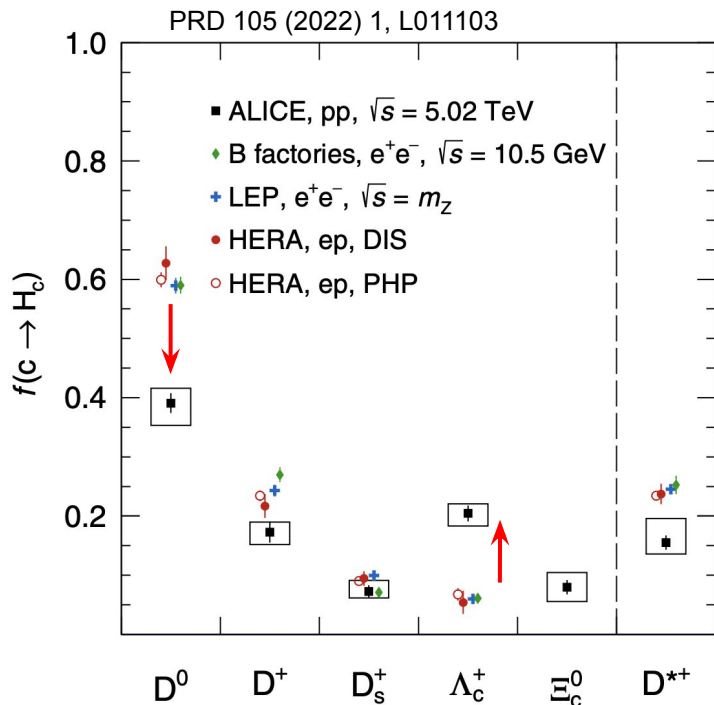
PRL 127 (2021) 27, 272001

arXiv:2205.13993 [nucl-ex]

➤ **In the strangeness sector the enhancement is even larger!**

- Additional challenges from strange-quark production
- Coalescence is the model that gets consistently closer to data

PYTHIA: JHEP 1508 (2015) 003
 SHM+RQM: PLB 795 117-121 (2019)
 Catania: PLB 821 (2021) 136622
 QCM: EPJC 78 no. 4, (2018) 344

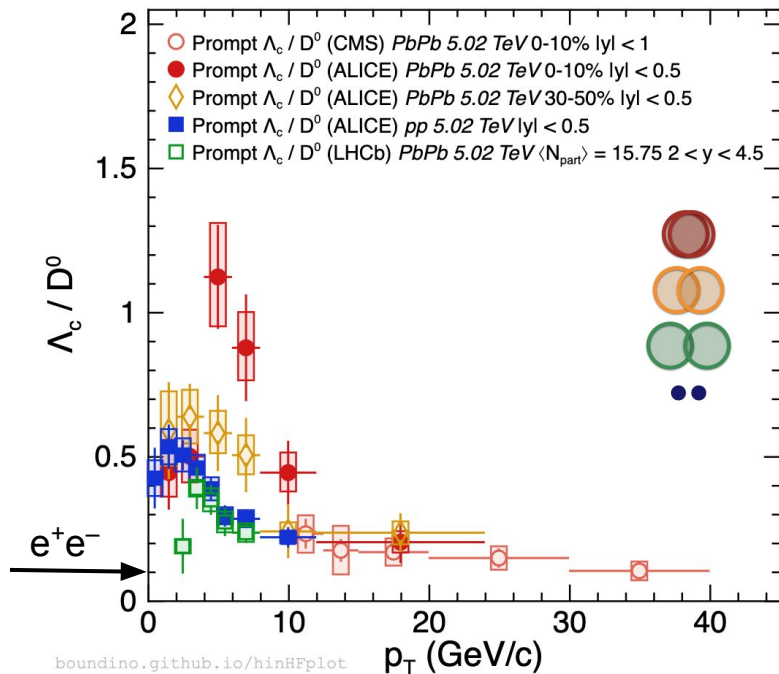


➤ Evidence of for different fragmentation fractions in pp collisions at LHC and e^+e^- (ep) collisions at lower \sqrt{s}

- Indication that parton-to-hadron fragmentation depends on the collision system
- Assumption of their universality not supported by the measured cross sections at the LHC

→ Independent fragmentation picture not valid in partonic-color-rich environment

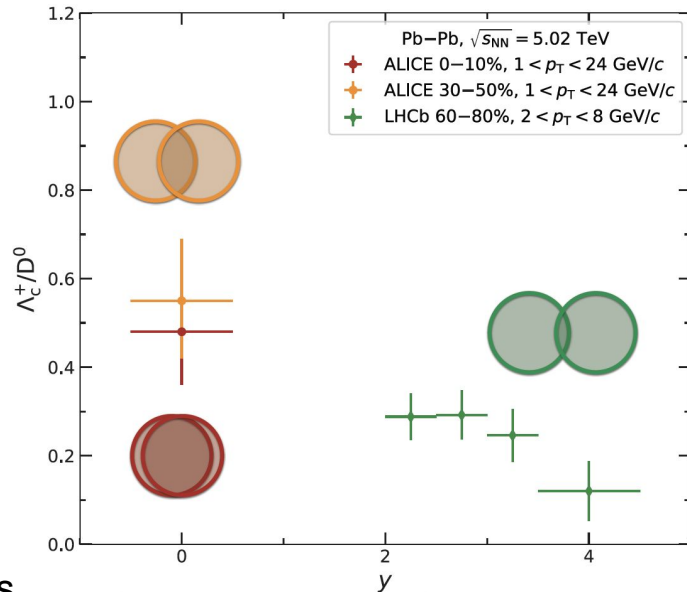
→ Break-down of universality of fragmentation functions



➤ Λ_c / D^0 in heavy-ion collision is higher at intermediate p_T wrt e^+e^- and pp

- Higher probability to hadronise via coalescence?
- Radial flow from medium expansion?
- An interplay of the two effect?

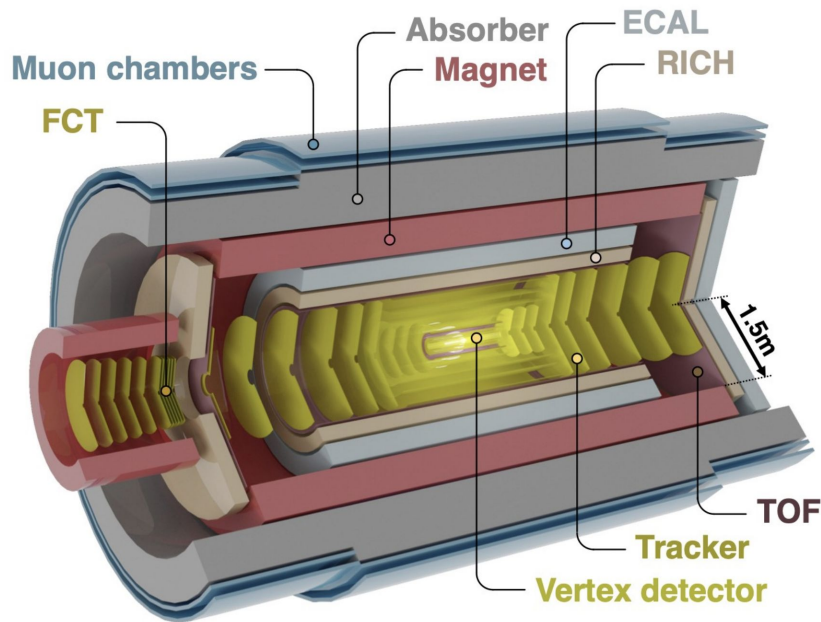
LHCb:
 JHEP 06 (2023) 132
 Phys. Rev. D 100, 031102
CMS:
 PLB 803 (2020) 135328
 arXiv:2307.11186 [nucl-ex]
ALICE:
 PLB 839 (2023) 137796
 PLB 839 (2023) 137796
 PRL 127 (2021) 202301



- Possible **rapidity dependence** need further investigation
- what do models (coalescence) predict?
- Other **baryons with strange** component are needed
- **Run 3 and Run 4** at the LHC will allow answering those questions

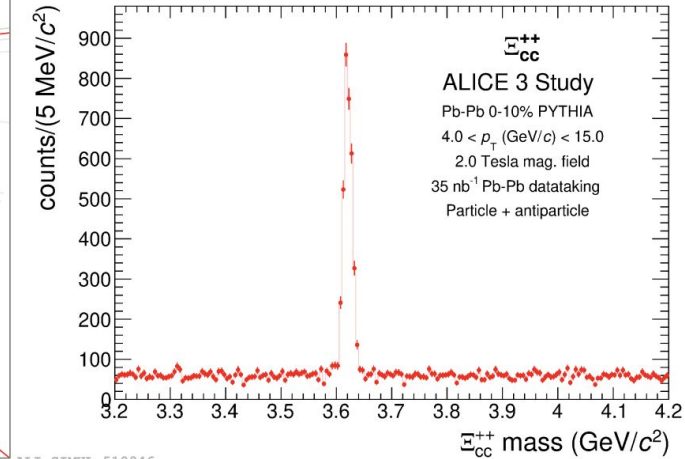
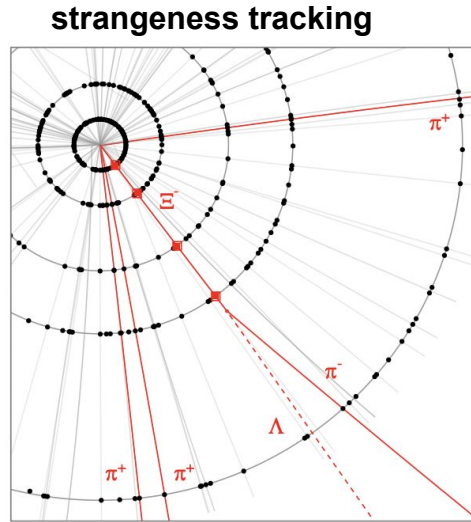
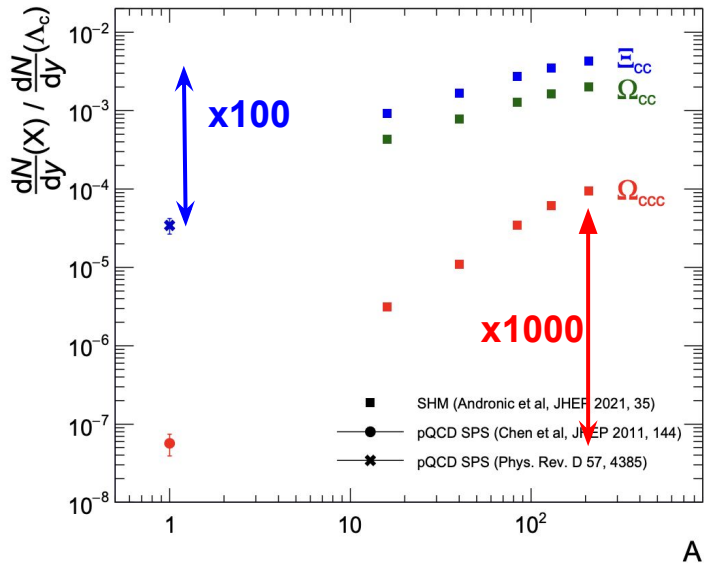
Main requirements:

- Increased readout rate, reduced data size for storage (online data reduction)
- Improved tracking and vertexing performance at low p_T for background suppression
- Preserve and enhance particle identification (PID) capabilities



- Compact and lightweight **all-silicon tracker**
- p_T resolution better than 1% @ 1 GeV/c
- **Retractable vertex detector** with excellent pointing resolution - About 3-4 μm @ 1 GeV/c
- **Large acceptance:** $-4 < \eta < 4$, $p_T > 0.02$ GeV/c
- **PID capabilities** via TOF, RICH, and ECAL
- **Continuous read-out and online processing**
- Large data sample to access rare signals

- Crucial new insight by measuring baryons containing multiple charm quarks (Ξ_{cc}^+ , Ξ_{cc}^{++} , Ω_{cc}^+ , Ω_{ccc}^{++})
- Yields of multi-charm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models - production in single hard scattering disfavored
- **Direct window on hadron formation from QGP and unique testing ground for charm deconfinement and thermalisation**

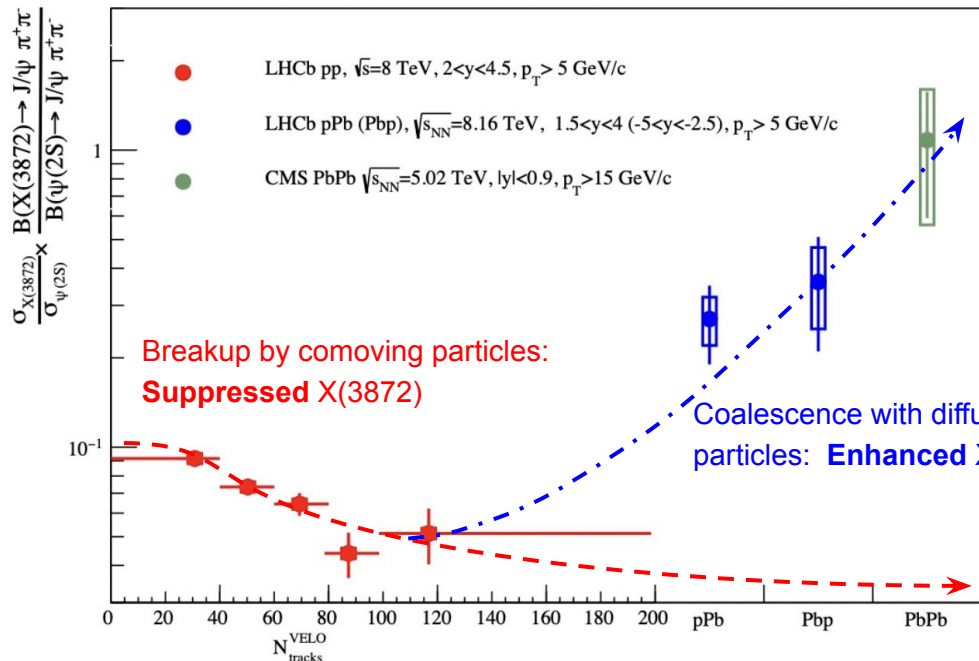




Another window on coalescence

➤ Relevance of coalescence in large systems?

- X(3872) → form from suppression to enhancement?
- Stress test with system size scan: $ep \rightarrow eA \rightarrow pp \rightarrow pO \rightarrow OO \rightarrow pA \rightarrow ArAr \rightarrow XeXe \rightarrow PbPb$



- Extension of measurements toward low p_T is crucial
- Centrality dependence

- Further studies will also shed light on the **internal structure** of these exotic objects H. Zhang et al., PRL 126(2021) 012301 and B. Wu et al., EPJA 57(2021) 122

- LHCb:
- PRL 126 (2021) 092001 (2021)
 - LHCb-CONF-2022-001
- CMS:
- Phys.Rev.Lett. 128 (2022) 3, 032001

Heavy flavours

- LHC data challenge the universality of fragmentation function
- Clear signs of coalescence in open charm measurements (and in J/Ψ - not shown today)
- **short term goal:** measurements of strange-charm baryons in HI collisions

Outlook:

- Beauty: need of precise measurements of hadrochemistry, p_T spectra for different hadrons
 - Accessible with precision with future large pp and Pb-Pb data samples
- Multi-charm hadron, B_c -meson, and exotica will be at reach with the future ALICE 3 detector
 - They can open a new window for further testing hadronization models in a rich partonic environment

Backup

Independent fragmentation

- heavy-flavour hadron production from hard-scattering processes (large Q^2):
 - Factorization of: PDFs, partonic cross section (pQCD), fragmentation function

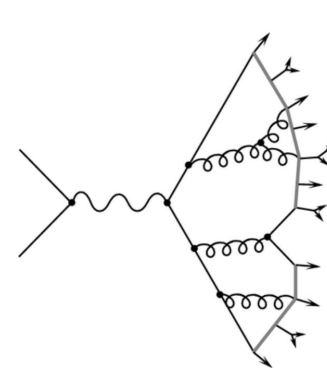
$$\sigma_{pp \rightarrow hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab \rightarrow q\bar{q}} \otimes D_{q \rightarrow h}(z, Q^2)$$

- **Fragmentation functions** $D_{q \rightarrow h}(z, Q^2)$:

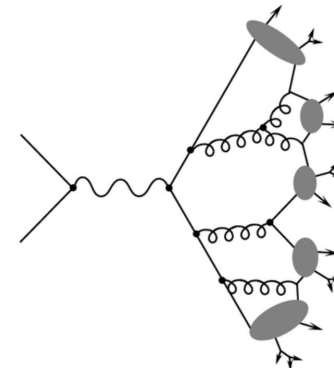
- Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition*
- z is the fraction of the parton momentum taken by the hadron h
- Parameterized on data (e^+e^-) and assumed to be “universal”

- In **event generators**: final stage of the parton shower interfaced to non-perturbative hadronisation models

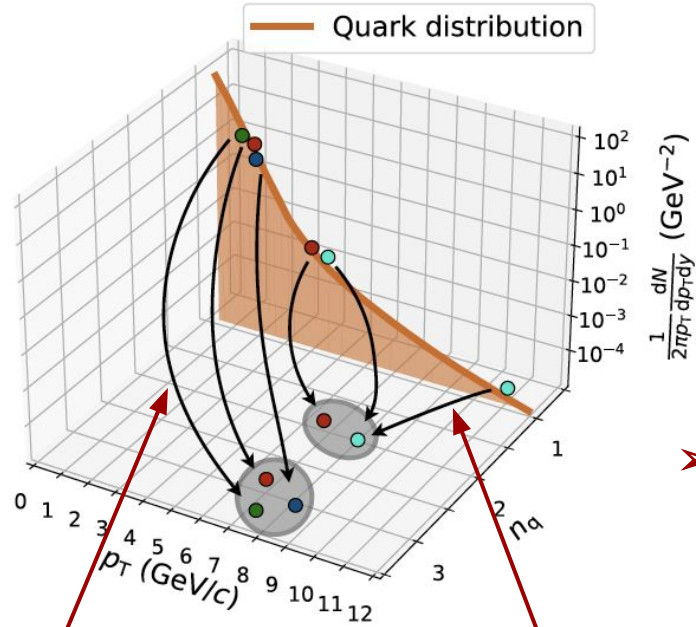
- (a) **String fragmentation** (e.g. Lund model in PYTHIA)
- (b) **Cluster decay** in HERWIG



(a) String hadronization



(b) Cluster hadronization



Recombining quarks:

$$p_{\text{meson}} = p_{q1} + p_{q2} \quad ;$$

$$p_{\text{baryon}} = p_{q1} + p_{q2} + p_{q3}$$

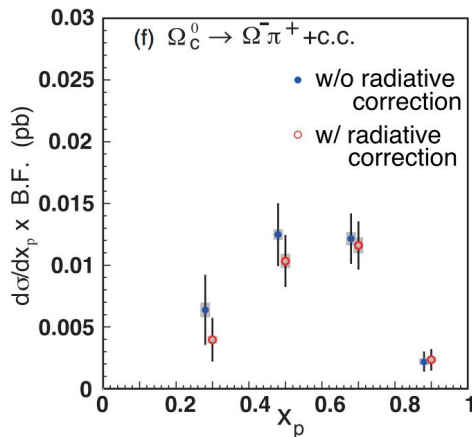
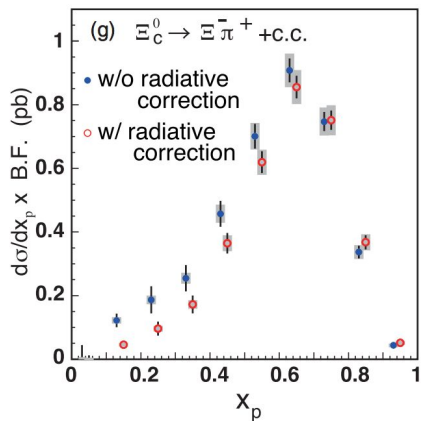
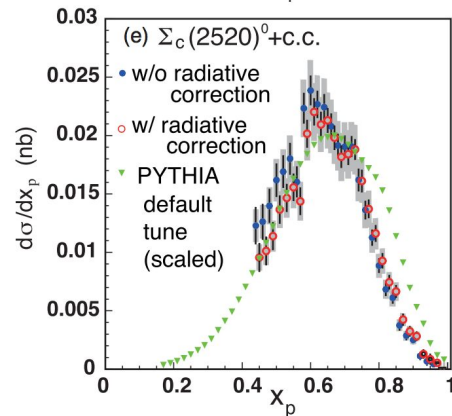
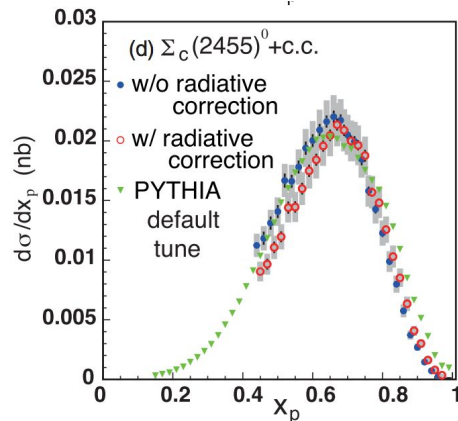
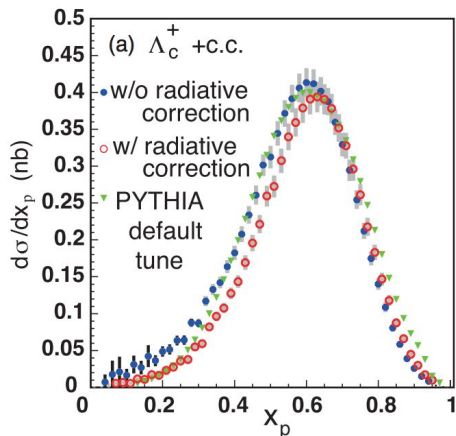
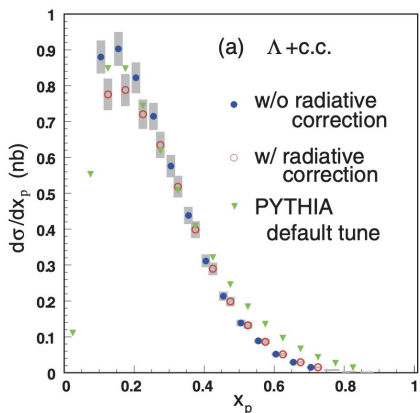
Fragmenting parton:

$$p_h = z \cdot p_q \quad \text{with } z < 1$$

- Single parton description may not be valid anymore
- No need to create qq pairs via splitting/string breaking
- Partons that are “close” to each other in phase space (position and momentum) can **recombine** into hadrons

➤ **Coalescence vs. fragmentation:**

- Competing mechanisms, dominant in different p_T regions
- **Recombination depends on “environment”**, i.e. density and momentum distribution of surrounding (anti)quarks
- Recombination naturally enhances baryon/meson ratios at intermediate p_T

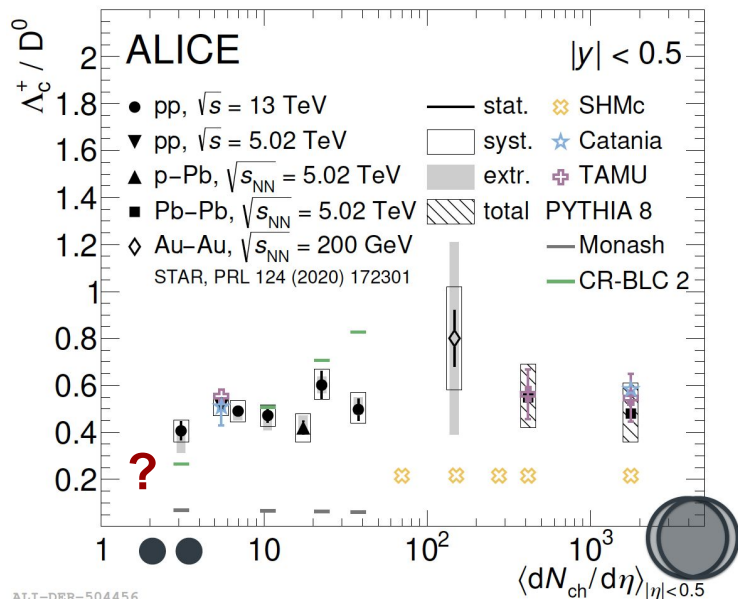
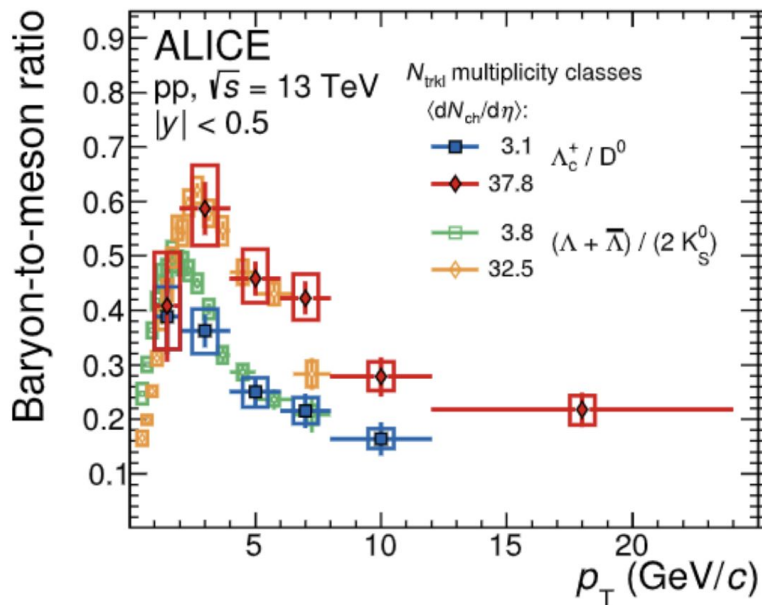


$$x_p = pc / \sqrt{s/4 - M^2 c^4}$$

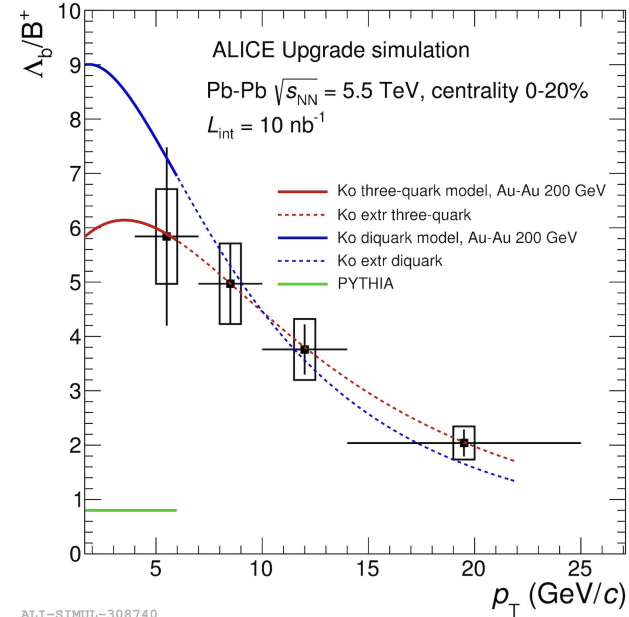
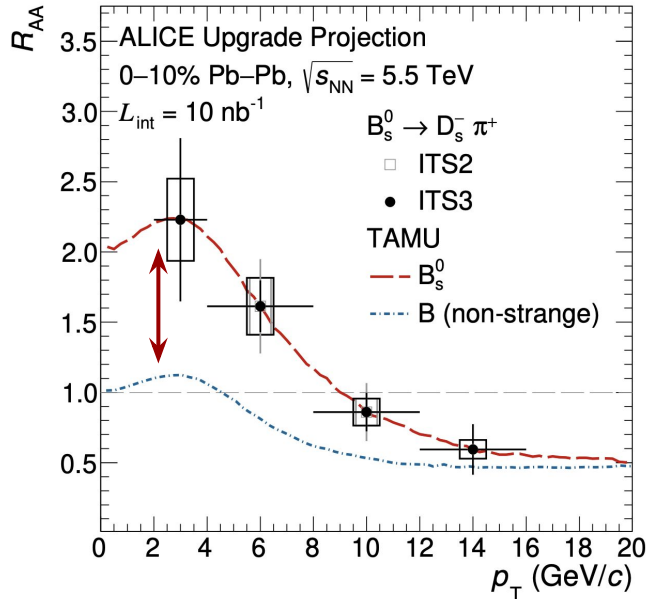
- Charm baryons vs PYTHIA in e^+e^-
- Standard PYTHIA describe the data

Mention here universality of FF

Baryon-to-meson ratio vs multiplicity



- Baryon/meson ratios in pp collisions: different p_T trend depending on multiplicity
 - Larger baryon production at intermediate p_T with increasing multiplicity
- No modification of p_T -integrated Λ_c/D^0 from pp to Pb-Pb
- **Towards very low multiplicity** - would it be possible to reach the e^+e^- limit?

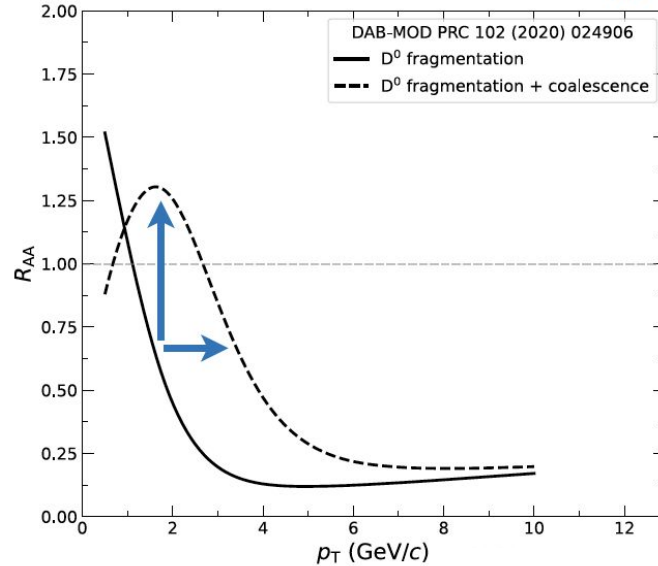


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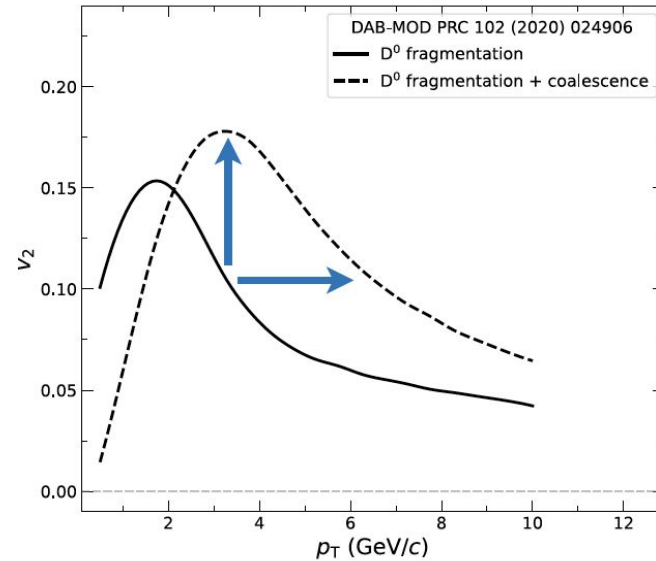
➤ **Full reconstruction of beauty hadrons will be at reach in Run 3-4**

- Expected enhancement in B^0 in Pb-Pb collisions will be quantifiable for the first time
- Reconstruction of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ (BR = $4.9 \cdot 10^{-3}$)
 - Will be affected by large uncertainties and limited to $p_T > 4-5$ GeV/c in Run 3 and Run 4

Nuclear modification factor

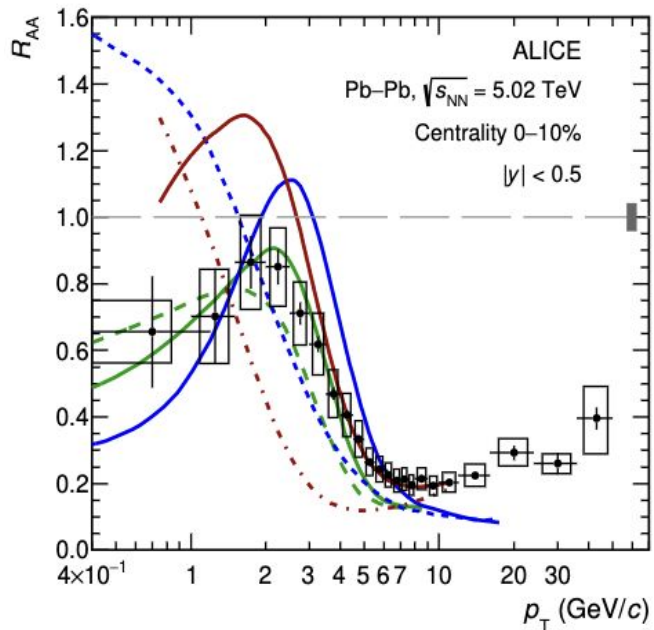


Elliptic flow

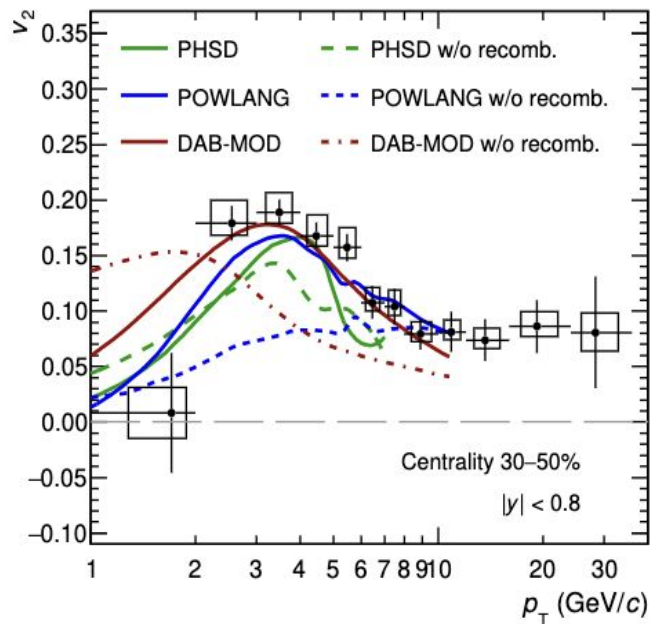


- **Coalescence** of heavy quarks with light quarks from the QGP affects **HF hadron momentum distributions**
 - HF hadrons pick-up the radial and elliptic flow of the light quark

Nuclear modification factor



Elliptic flow



- Coalescence component is crucial to describe the data at low/mid p_T

- B_c^+ production in heavy-ion collisions is an ideal probe to be sensitive both to dead cone effect and statistical recombination
 - CMS: used 2018 Pb-Pb data, but statistics need to be improved with future measurements

