Charm and beauty production and hadronization with the ALICE experiment

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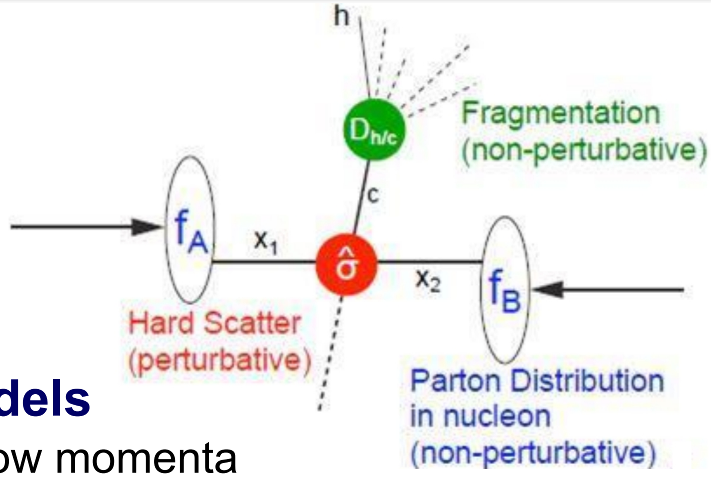
Production and fragmentation in pp collisions

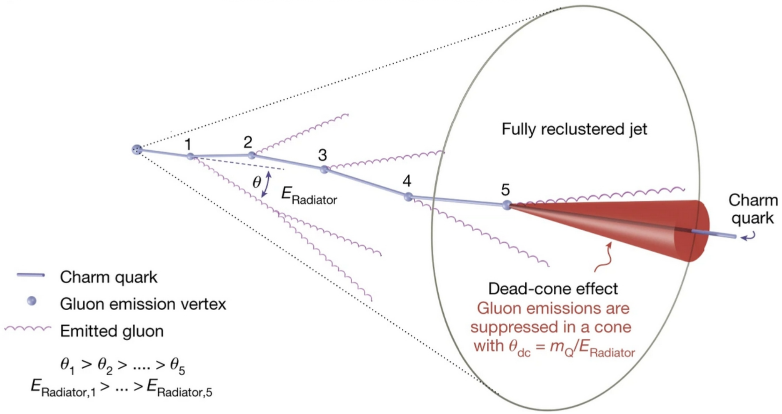
- **HF production: factorization approach**
  - Parton distribution function (PDF)
  - Hard scattering
  - Fragmentation

Feynman-*x*:
$x_i = p^A_{\|} / p^A_{\|,max}$
Q : momentum transfer

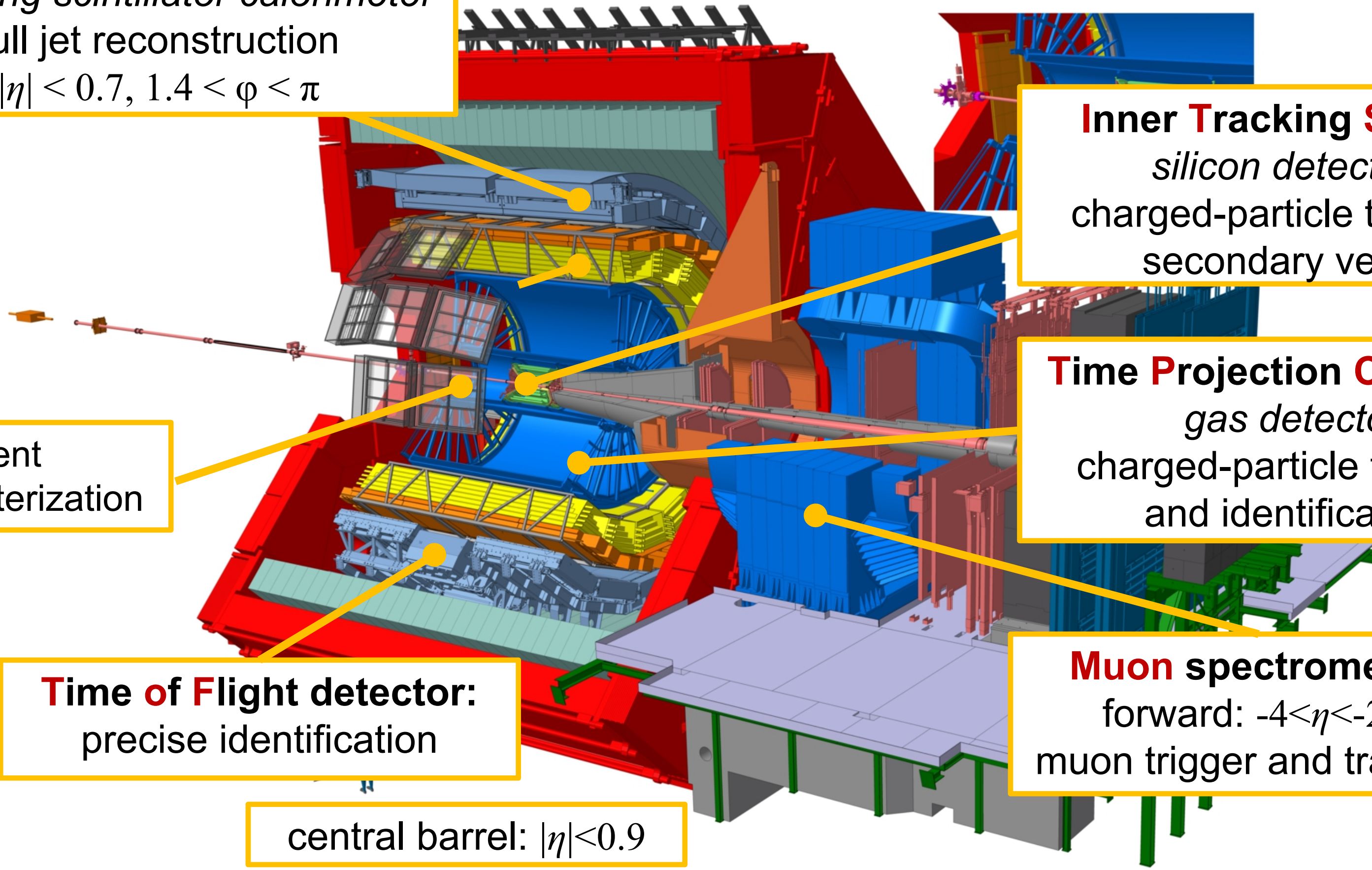
$$\sigma_{hh\to H} = f_a(x_1,Q^2) \otimes f_b(x_2,Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to H}(z_q,Q^2)$$



- **Production yields: primary tests of pQCD models**
  - Heavy quarks: $m_{c,b} >> \Lambda_{QCD}$ → Perturbative even at low momenta
  - color-charge effect: light jets are mostly gluons, HF from quarks
- **Jet substructure and correlations:**
  - Mass-dependence, dead-cone effect
  - Contribution of gluon splitting
- **Mesons and baryons**
  - Tests of fragmentation models
- **Multiplicity-dependence**
  - probe complex vacuum QCD effects



ALICE



ElectroMagnetic Calorimeter
sampling scintillator calorimeter
full jet reconstruction
$|\eta| < 0.7$, $1.4 < \varphi < \pi$

Inner Tracking System
silicon detectors
charged-particle tracking,
secondary vertex

Time Projection Chamber:
gas detector
charged-particle tracking
and identification

V0: event
characterization

Muon spectrometer:
forward: $-4<\eta<-2.5$
muon trigger and tracking

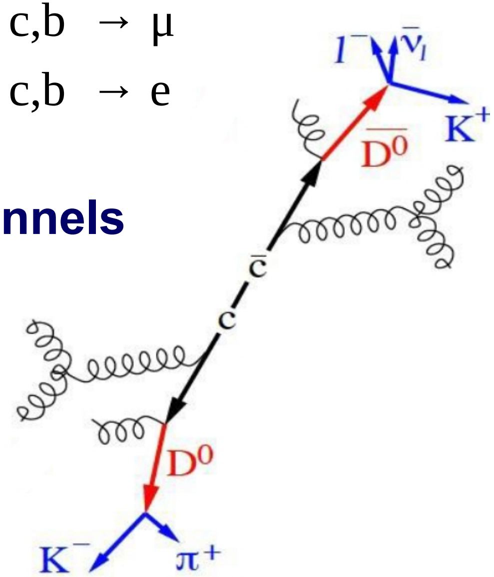
Time of Flight detector:
precise identification

central barrel: $|\eta|<0.9$

HF: reconstruction in the experiment

Semileptonic decays

- c,b → μ
- c,b → e

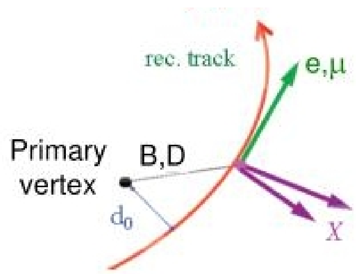


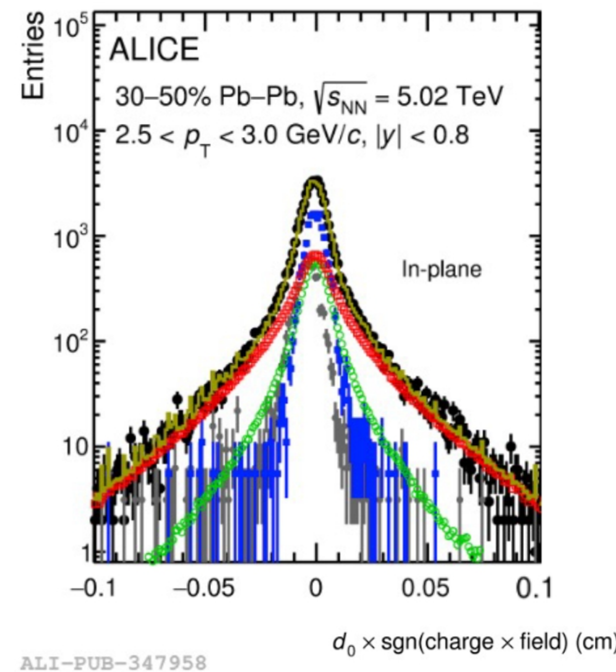
Hadronic decay channels

- $D^0 \rightarrow K^-\pi^+$
- $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+)\pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_S^+ \rightarrow \Phi(\rightarrow K^+ K^-)\pi^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\Lambda_c^+ \rightarrow pK^0_S(\rightarrow \pi^+\pi^-)$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
- $\Sigma_c^{0,++} \rightarrow \Lambda^+_c \pi^{+,-}$
- $\Omega_c^0 \rightarrow \Omega^-\pi^+$

Identification aided by secondary vertex resolution in the ITS

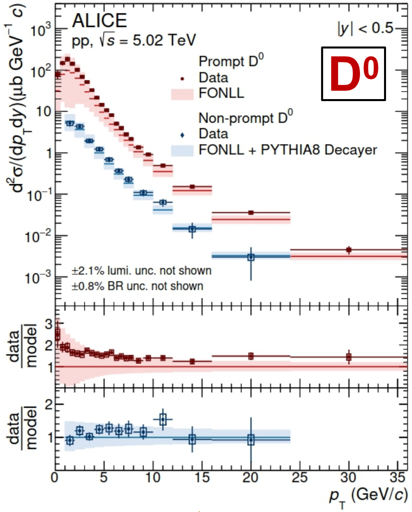
Lifetime of heavy flavor:	$c\tau$ (D) ~ 100-300 μm $c\tau$ (B) ~ 400-500 μm
Secondary vertex resolution:	< 100 μm

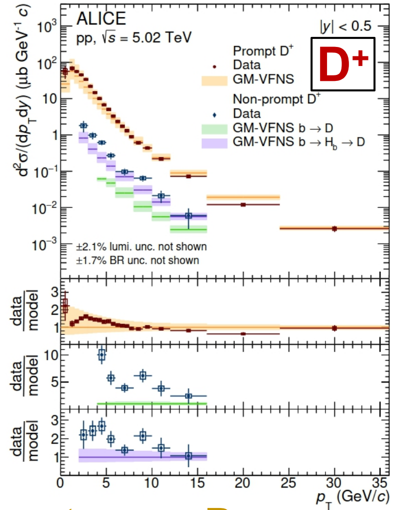




charm and beauty: precision measurements

prompt D, non-prompt D(<-B)

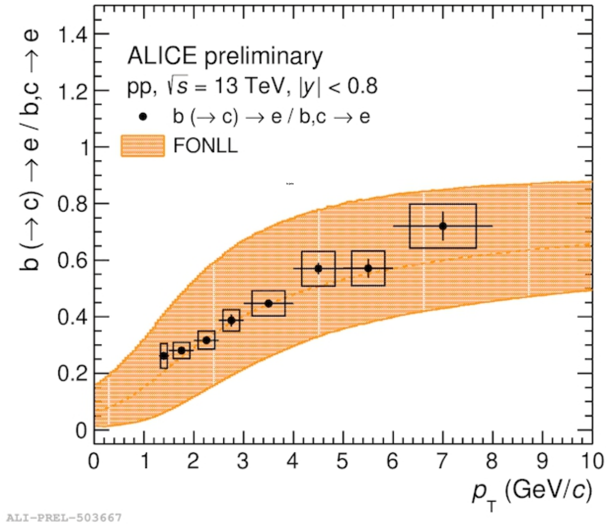




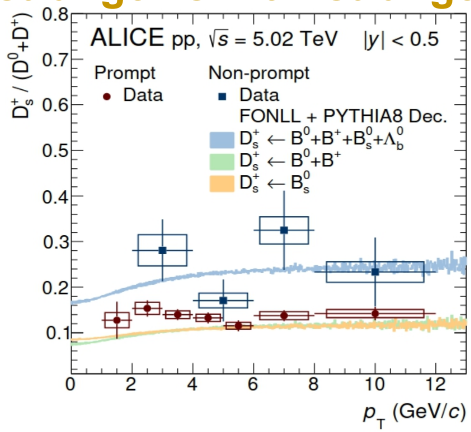
HEP 05 (2021) 220

FONLL: JHEP 05 (1998) 007
JHEP 03 (2001) 006,
GM-VFNS: JHEP 05 (2018) 196,
JHEP 12 (2017) 021

c, b decay electrons



strange vs. non-strange D

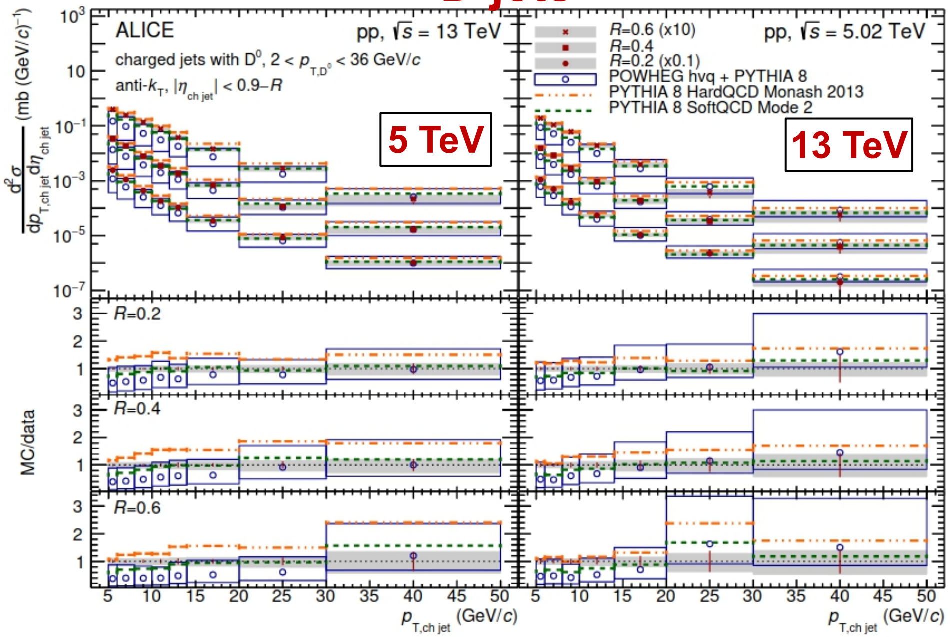


Detailed tests of pQCD models

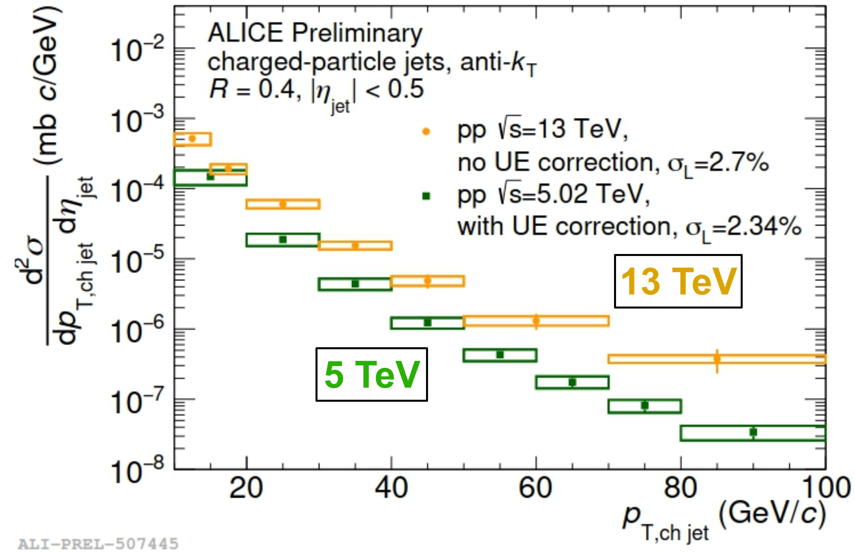
- $D^{0,+}$ down to low momenta ($p_T \approx 0$)
- D mesons generally well described by models based on factorization (GM-VFNS tends to underestimate non-prompt D)
- Beauty-fraction in electrons well described
- **Data provide strong constraints for models**

heavy-flavor tagged jets: proxy for the quark

D-jets CERN-EP-2022-070

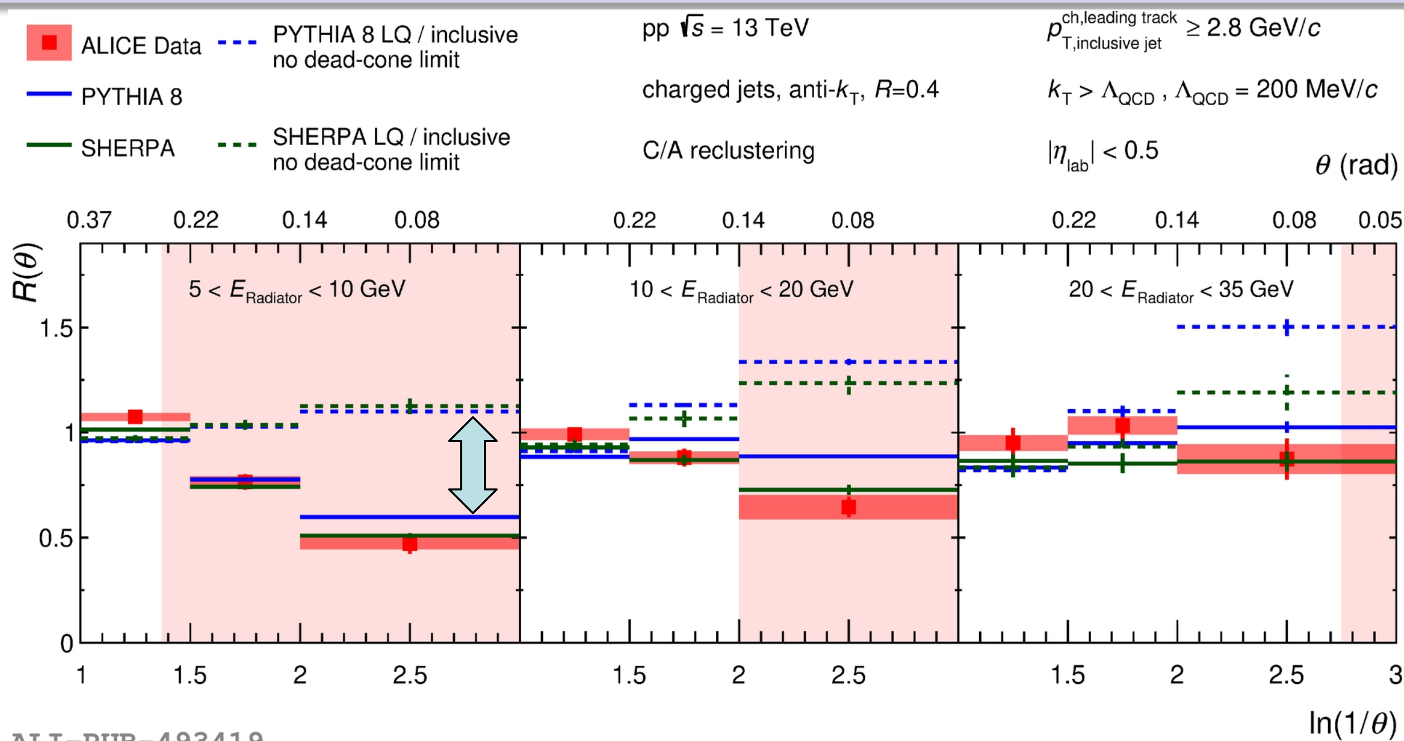


b-jets

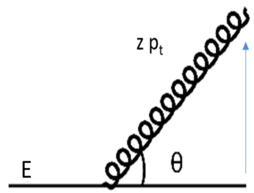


- **Heavy-flavor jets: direct proxy for the hard quark**
  - **D-jets** are jets tagged with the reconstruction of D^0 mesons
  - **b-jets** tagged based on the position of secondary vertex
- Hardening of the p_T-spectrum at higher collision energies
- Strongly restricts models **=>** **unique opportunity to study flavor-dependent jet properties**
- *Reference for nuclear modification*

HF fragmentation: dead cone in ALICE



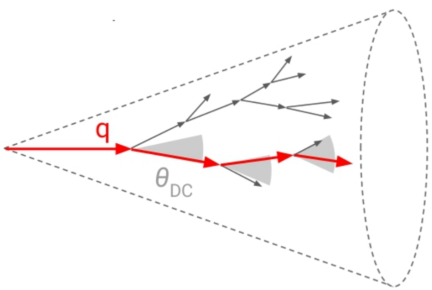
ALI-PUB-493419



$$\theta \approx \frac{k_T}{zp_t}$$

$$\theta < \theta_{DC} = \frac{m_q}{E_q}$$

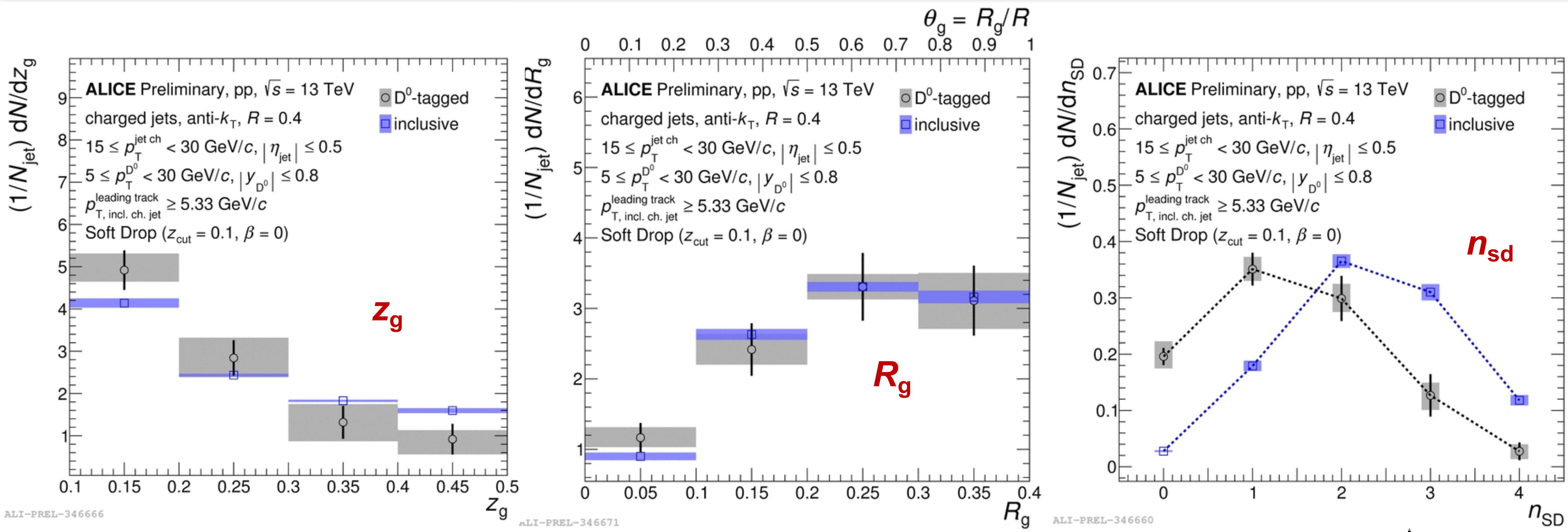
Nature 605 (2022) 440



- **D-tagged to inclusive ratios vs. ln(1/θ) at √s=13 TeV**
- Significant suppression of low-angle splittings in D-tagged jet

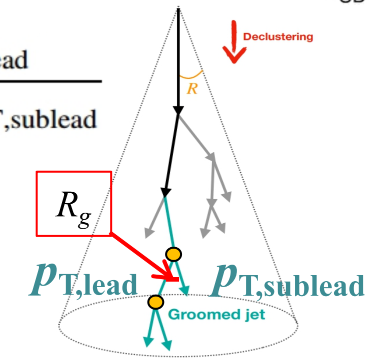
  ⇒ **First direct measurement of the dead cone** in hadronic collisions
- Effect decreases toward higher energy of the radiator (→ $\theta > m_q/E_q$)

c fragmentation: D-jet groomed substructure



ALICE-PUBLIC-2020-002

$$z_g = \frac{p_{T,\text{sublead}}}{p_{T,\text{lead}} + p_{T,\text{sublead}}}$$



- **D⁰-tagged charged-jet groomed substructure**
  pp $\sqrt{s}$ = 13 TeV, $z_{cut} = 0.1$, $\beta = 0$
- n_{SD} : charm jets typically have less hard splitting than light jets

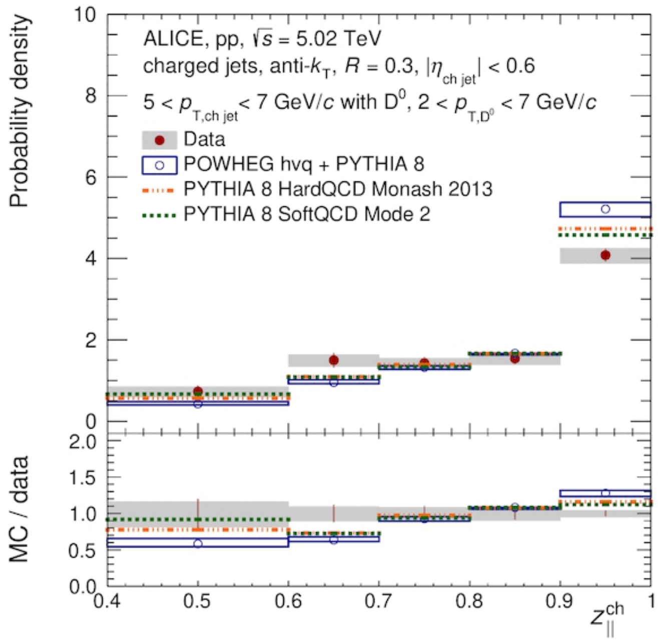
⇒ **Consistent with harder heavy-flavor fragmentation**
(mass and color charge effects)

charm fragmentation - D-jet $z_{||}$

- **Parallel momentum fraction, pp $\sqrt{s}$ = 13 TeV**
  - Characteristic to heavy-flavor fragmentation
- **D⁰-meson fragmentation** is softer at high p_T than at lower p_T
  - POWHEG+PYTHIA6 predicts a stronger change towards low p_T

$$z_{||}^{ch} = \frac{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{HF}}}{\boldsymbol{p}^{\text{jet ch}} \cdot \boldsymbol{p}^{\text{jet ch}}}$$

D⁰ in jets **$5 < p_T^{ch,jet} < 7$ GeV/c** **$15 < p_T^{ch,jet} < 50$ GeV/c**



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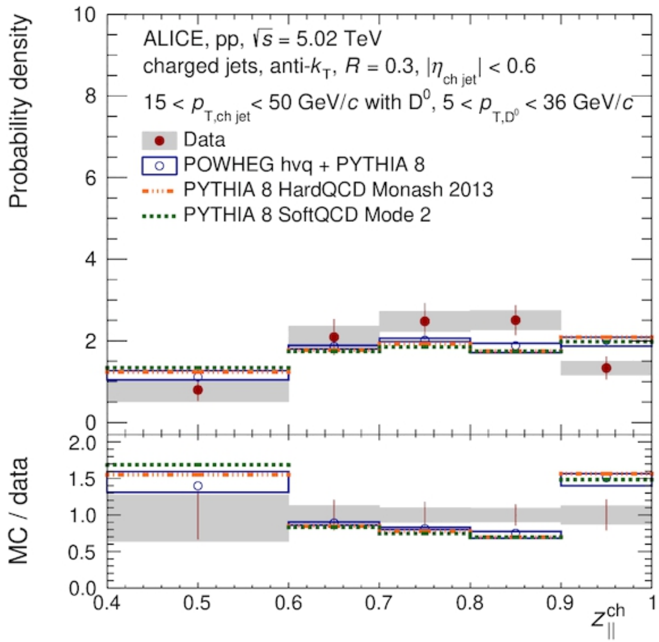
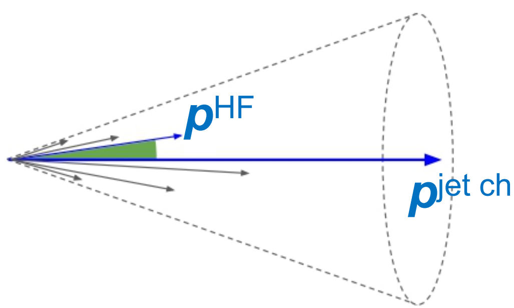


ALI-PUB-521264

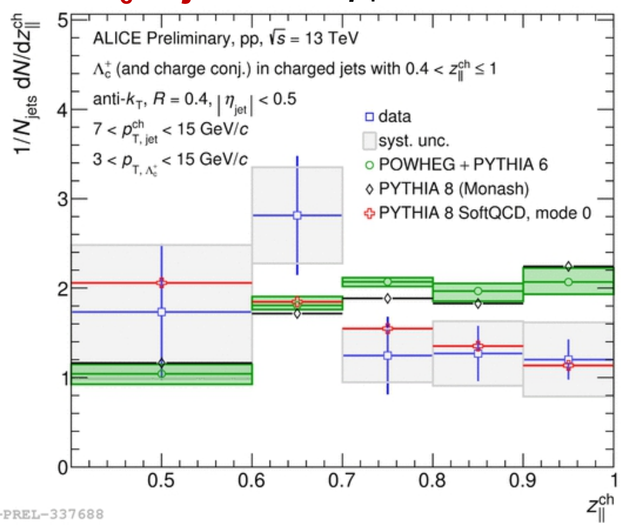


charm fragmentation - Λ_c-jet $z_{||}$ and r-shape

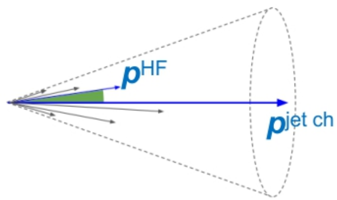
- **Parallel momentum fraction**
  - Baryon vs. meson fragmentation
  - **Λ_c fragmentation described the best with PYTHIA8 CR-BLC** (color junctions)
    Christiansen-Skands, HEP 1508 (2015) 003

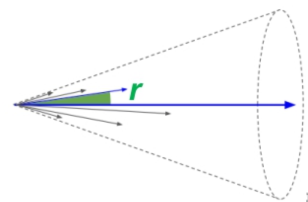
- **Radial angular distance distribution of a hadron from the jet axis**
  - Sensitive to hadronisation mechanisms
  - **Λ_c fragments closer to jet axis than D^0?**
  - Better described by Monash than CR-BLC

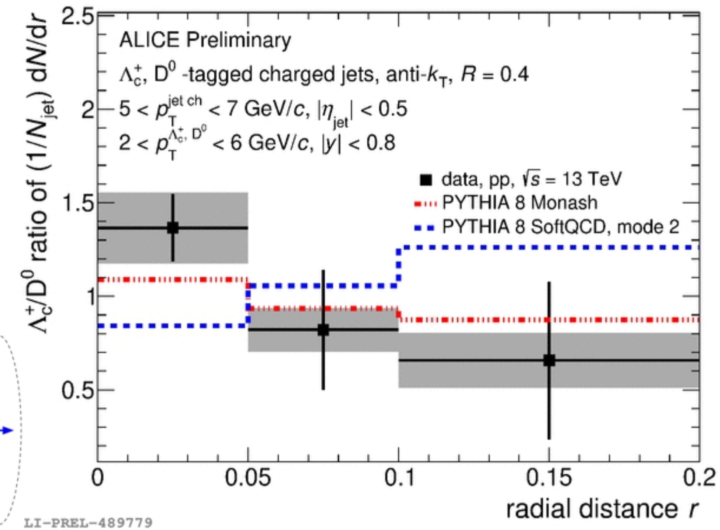
Λ_c in jets **$7 < p_T^{ch,jet} < 15$ GeV/c**



$$z_{||}^{ch} = \frac{\mathbf{p}^{\text{jet ch}} \cdot \mathbf{p}^{\text{HF}}}{\mathbf{p}^{\text{jet ch}} \cdot \mathbf{p}^{\text{jet ch}}}$$

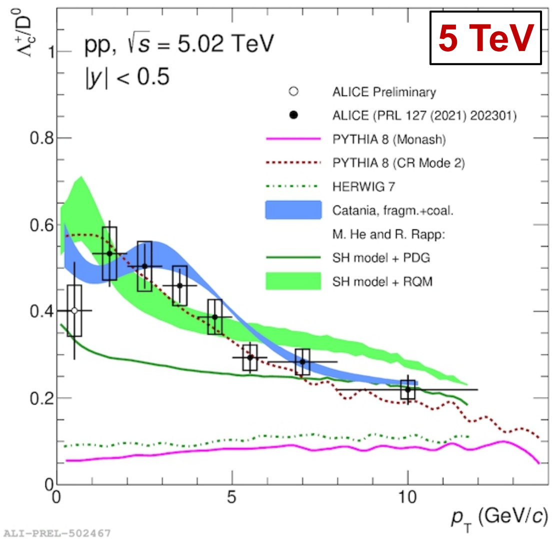


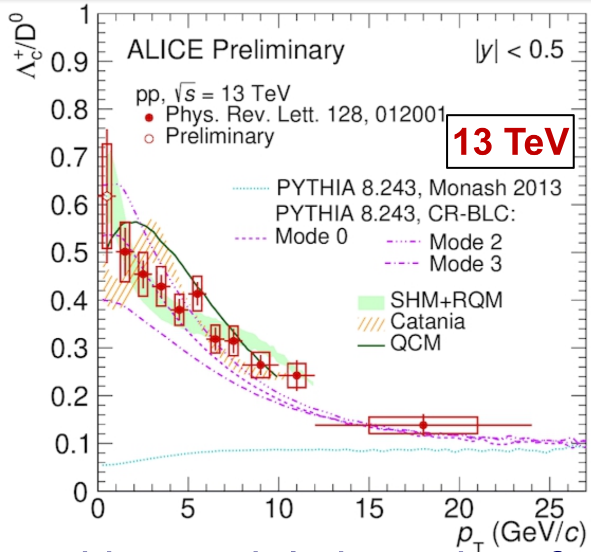




- **More statistics needed for decisive conclusions**

charm baryon fragmentation - Λ_c^+



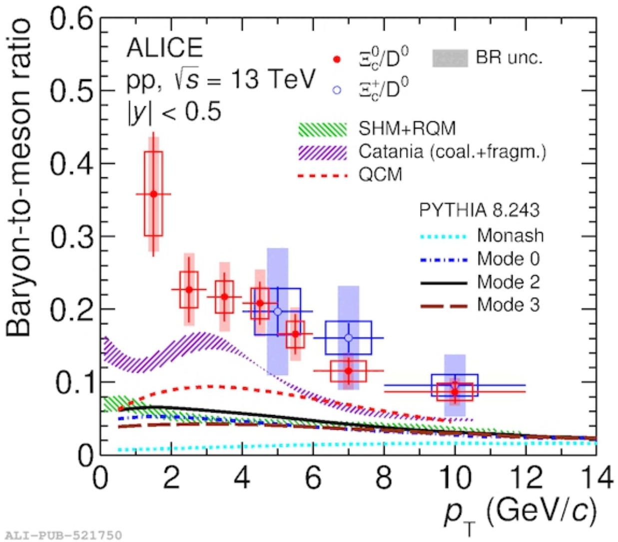


- **Charm baryon to meson ratios are specific probes of charm hadronization**
- New measurement down to $p_T \approx 0$

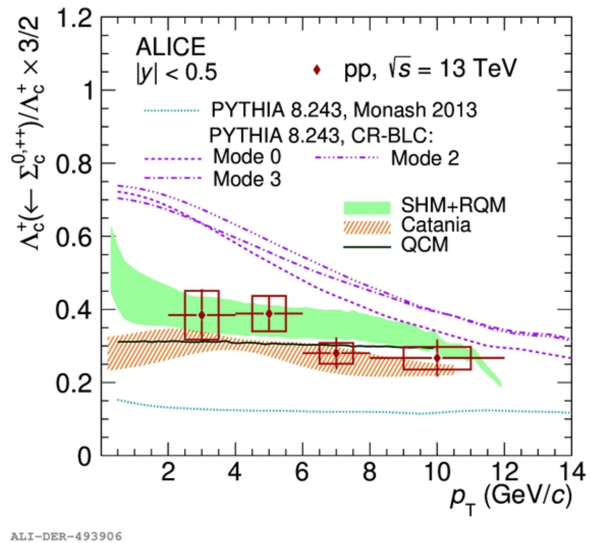
- Λ_c^+/D^0 ratios are underestimated by models based on factorization approach with fragmentation functions from ee collisions:
  Universality of heavy-flavor fragmentation broken
  - **PYTHIA 8 CR-BLC:** string formation beyond leading color approximation
    JHEP 1508 (2015) 003
  - **Catania**: fragmentation + coalescence of charm and light quarks
    PLB 821 (2021) 136622
  - **SH model + RQM:** feed-down from augmented set of charm-baryon states
    arXiv:1902.08889
  - **QCM:** coalescence model based on statistical weights + “equal quark-velocity”
    EPJ C 78 no. 4, (2018) 344

charm baryon fragmentation - Ξ_c, Σ_c, Ω_c

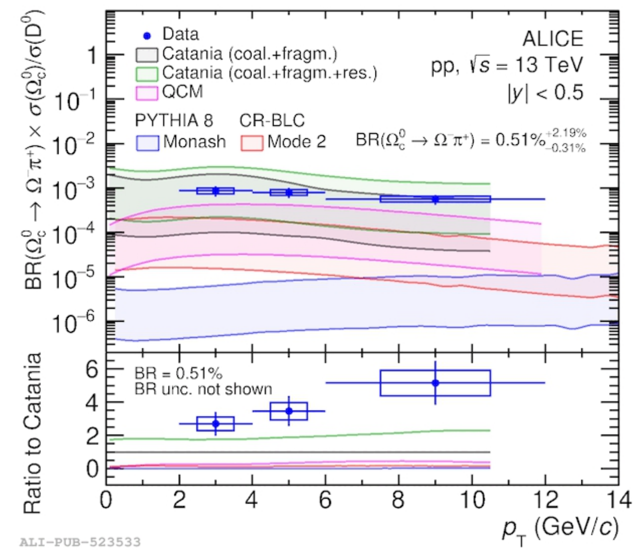
Phys. Rev. Lett. 128 (2022) 012001



JHEP 10 (2021) 159

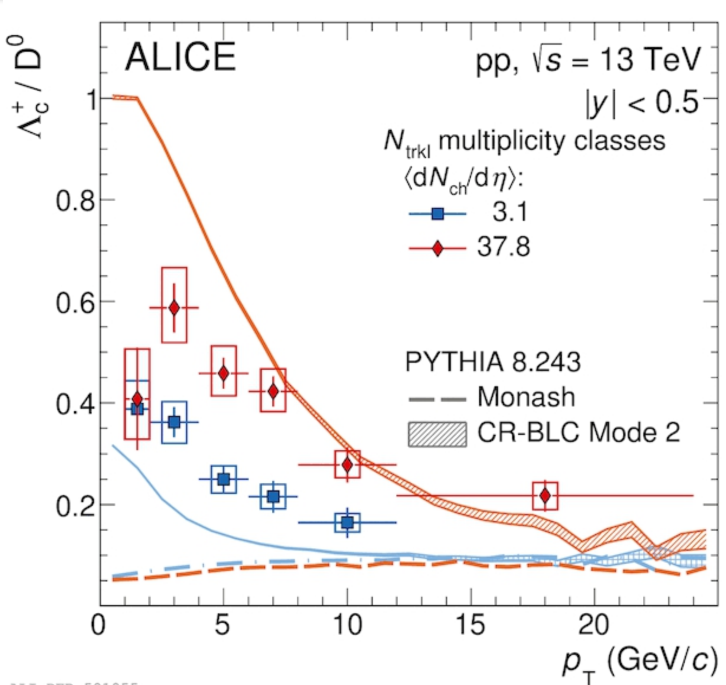


arXiv:2205.13993

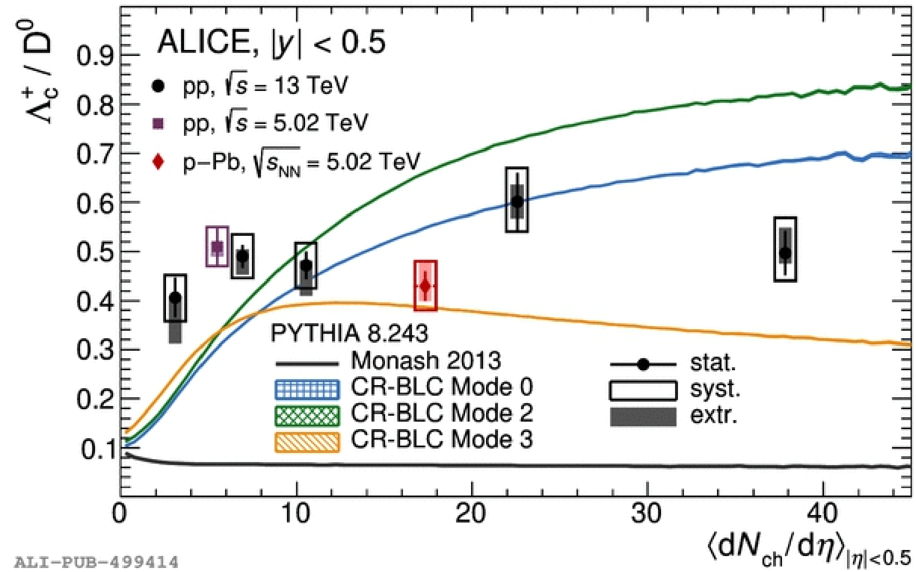


- Charm baryon to meson ratios are specific probes of charm hadronization
- Heavier charm states - still a challenge for models
  - $\Xi_c^{0,+}$: underestimated by models
  - $\Sigma_c^{0,++}$: differs from Λ_c^+ in isospin; yet it is an important contributor to Λ_c^+ via its decay. PYTHIA8-CR BLC overestimates this contribution by a factor 2
  - Ω_c^0 : best description by Catania (coalescence)

multiplicity-dependence of Λ_c^+ production



Phys.Lett.B/ 829 (2022) 137065

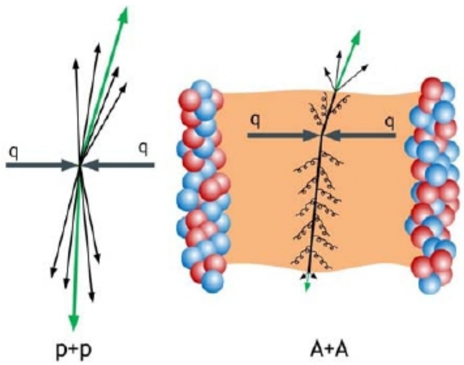


- ***Low-p_T* Λ_c^+/D^0 enhancement increases with multiplicity** (5.3σ for $1<p_T<12$ GeV/c)
  - Trend qualitatively described by PYTHIA8 CR-BLC
- ***p_T*-integrated Λ_c^+/D^0 enhancement does not depend on multiplicity**
  - regardless of energy, collision system

=> enhancement from different redistribution in p_T for mesons and baryons?

Toward larger systems

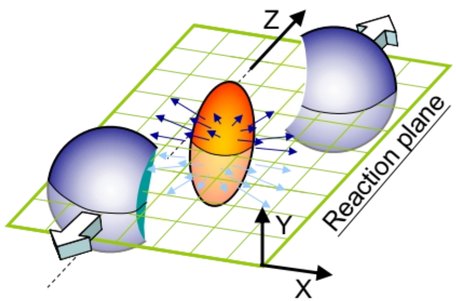
- **pA: Cold nuclear matter effects**
  - PDF modification: (anti)shadowing, gluon saturation
  - Energy loss in cold nuclear matter (CNM)
  - k_T-broadening
- **A-A: Probing the hot QCD medium**
  - Dead cone effect → expected mass ordering:
    $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow ?\ R_{AA}^{h} < R_{AA}^{D} < R_{AA}^{B}$
  - Color charge effect (HF is mostly quarks <=> gluon contribution
  - Change of fragmentation: Baryons, jets



- ***Nuclear modification:***
  collisional vs. radiative energy loss

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

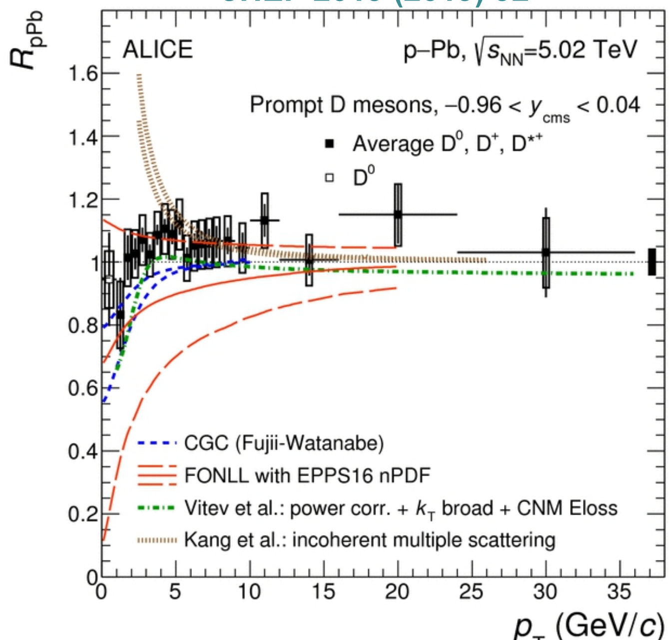
- ***Collectivity:***
  coalescence and thermalization of heavy flavor



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n(\varphi - \Psi_R)\right)\right) \qquad v_n = \langle \cos(n(\varphi - \Psi_R)) \rangle$$

heavy-flavor production in p-Pb: CNM

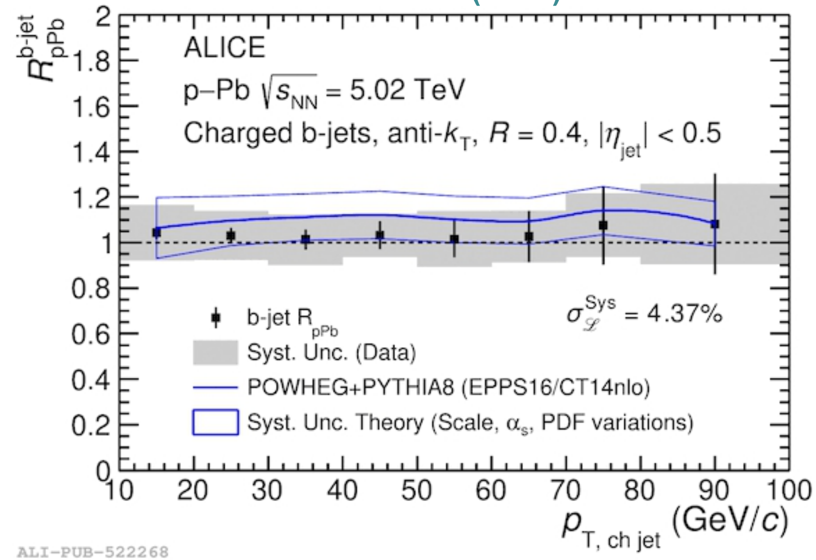
JHEP 2019 (2019) 92



D-mesons

down to $p_T \approx 0$

JHEP 01 (2022) 178



b-tagged jets

measured for the 1st time

for $10 < p_T < 100$ GeV/c

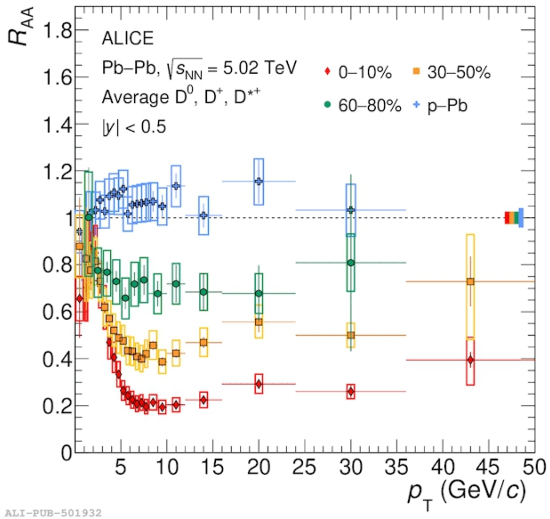
- R_{pPb} **consistent with unity** within uncertainties in the measured p_T range

=> No strong nuclear modification is present by the cold nuclear matter

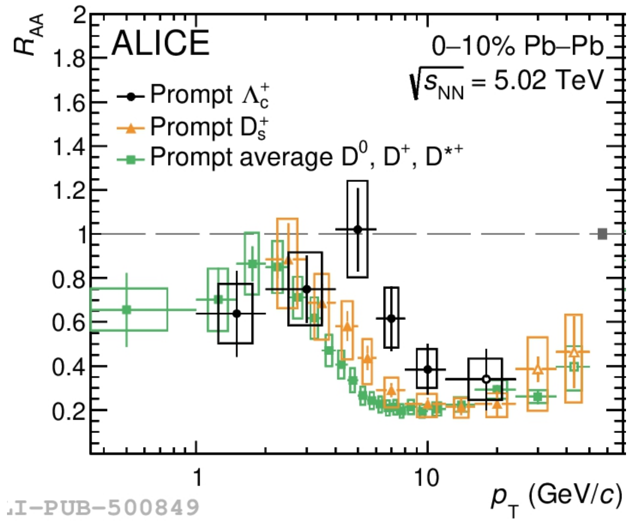
  - Strong constraints - valuable input for model development

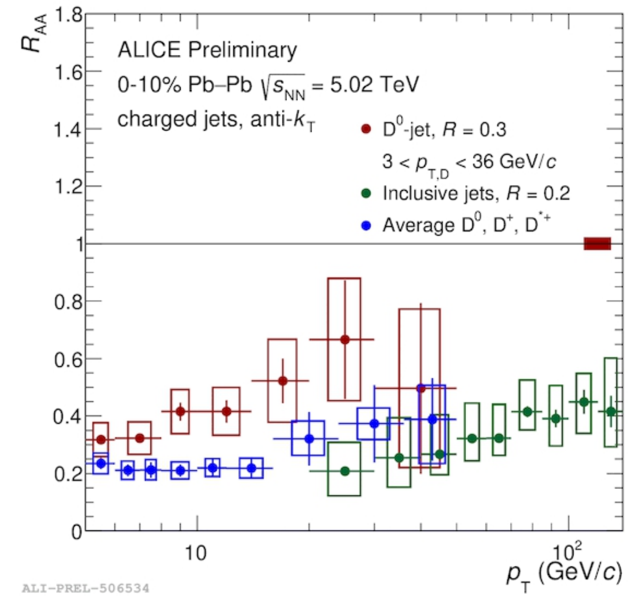
charm from the hot medium: R_{AA}

arXiv:2110.09420



arXiv:2112.08156



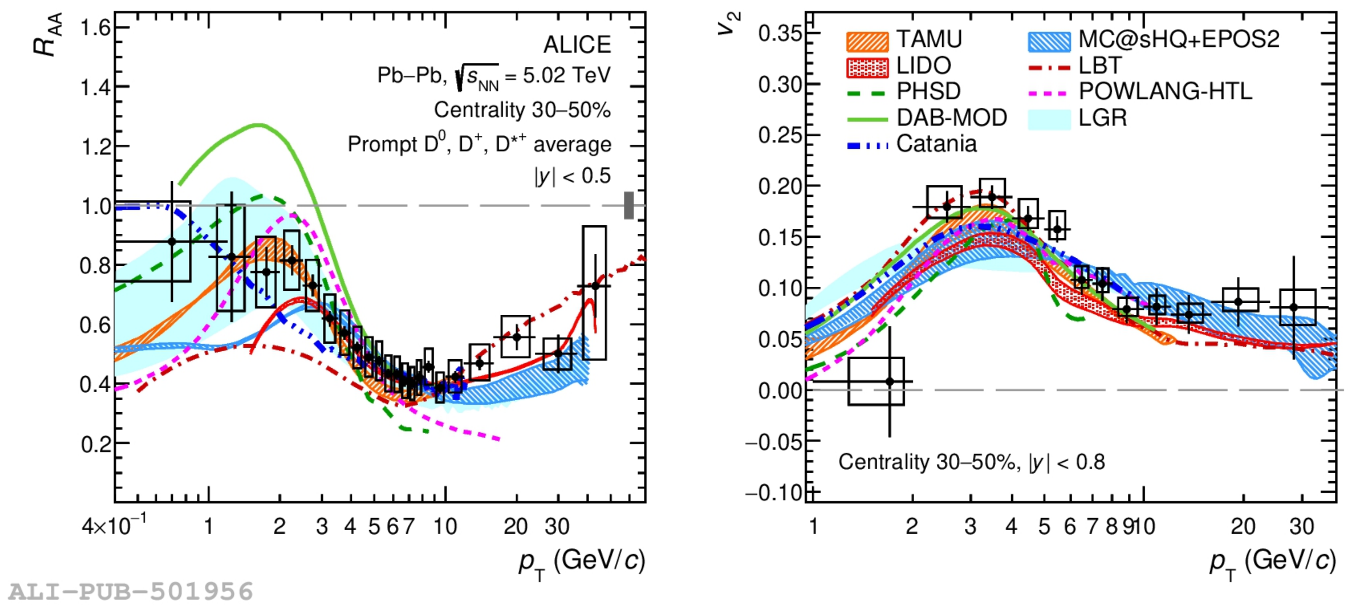


- **Non-strange D-mesons**
  Increasing suppression for more central collisions (toward larger system sizes and densities) at p_T>3 GeV/c

- **D_s and Λ_c**
  Hint of differences indicate modified hadronisation mechanisms

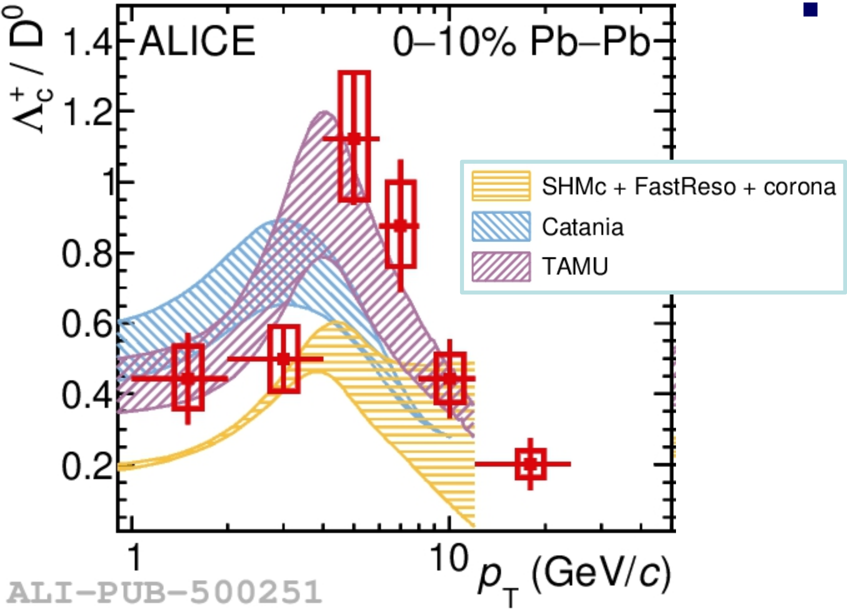
- **D_0 in jets:**
  Less suppressed than D^0 !
- Sensitivity to different energy loss of quarks and gluons (Casimir-factors)
- Possible sensitivity to mass effect (dead cone)

constrain models: charm R_{AA} and v_2



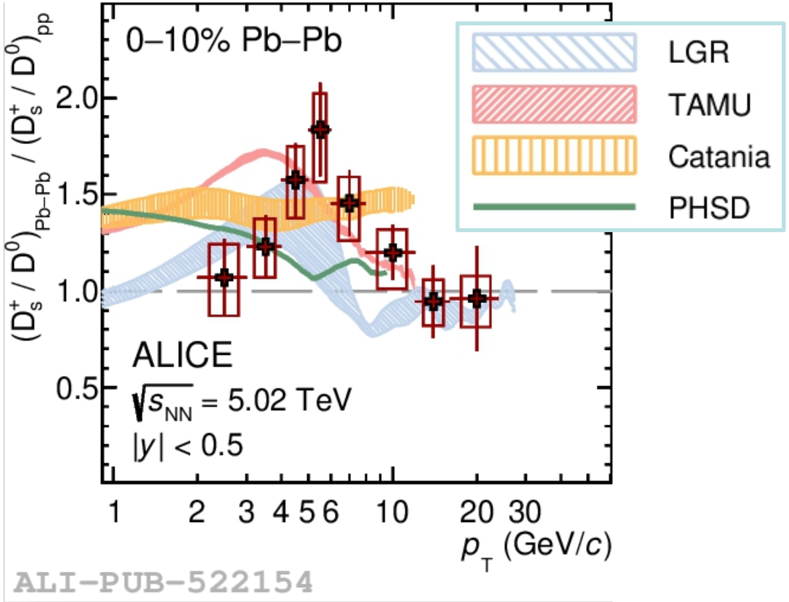
- Substantial collectivity observed for charm
- Most charm-quark transport models describe R_{AA} and v_2 simultaneously
  - Hadronisation via recombination is important at intermediate p_T (PHSD, POWLANG, DAB-MOD) **=> D meson picks up flow during recombination/coalescence**
  - Radiative energy loss plays a role at itermediate to high p_T (LIDO and LGR)

charm hadron ratios: probe hadronization

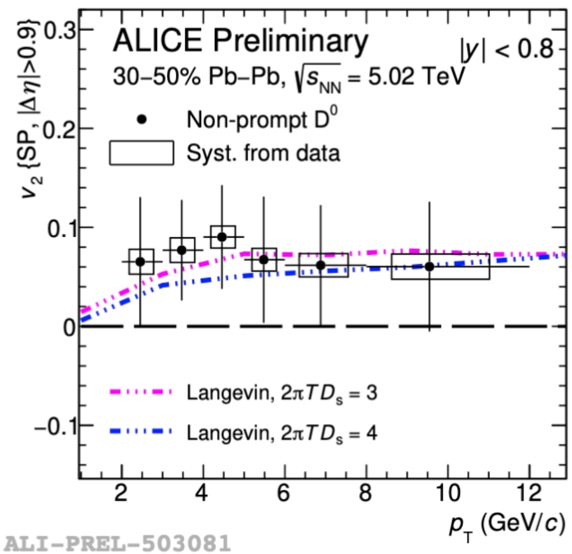


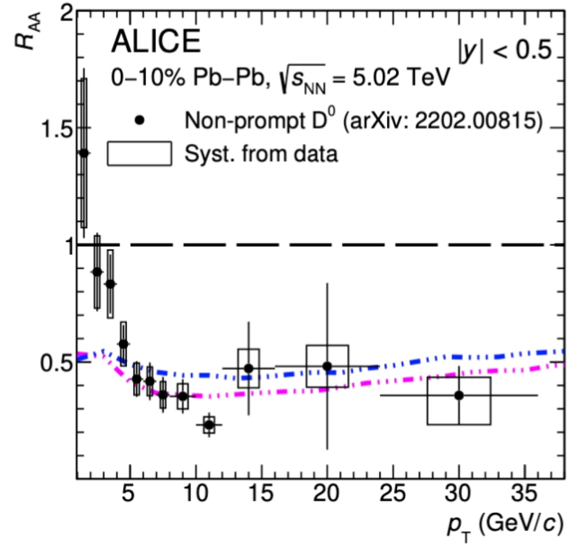
- **Λ_c^+/D^0 ratio**
  - A 3.7σ enhancement at 4<p_T<8 GeV/c
  - Similar to that seen in light barion-to-meson ratios
  - Data described by TAMU, Catania and SHMc qualitatively agree
  - **Interplay of radial flow and recombination**
  - Different p_T redistribution for mesons and baryons

- **strange - non-strange D double ratio**
  - A 2.3σ enhancement at 4<p_T<8 GeV/c
  - Described by models including **strangeness enhancement** with fragmentation and recombination



beauty transport in the medium: R_{AA} and v_2





- Non-prompt D^0 meson R_{AA} and v_2 simultaneously compared to different Langevin configurations
  - Both cases consistent with measurements

=> more precise data will provide important constraint to beauty spatial diffusion coefficient

Summary and outlook

Production and fragmentation of charm and beauty in pp collisions

- precision pQCD benchmark via heavy-flavour production
- tests of parton shower and fragmentation via jet substructure

  => first direct measurement of the QCD dead cone
- detailed studies of fragmentation with charmed mesons and baryons

  => fragmentation is not universal

Heavy-flavor production from small to large systems

- p-Pb collisions => CNM effects do not play a strong role for heavy flavor
- charm nuclear modification and flow of different charm hadrons

  => charm picks up collectivity via coalescence
- first low-p_T D-jet measurement in Pb-Pb: less suppression than for D mesons

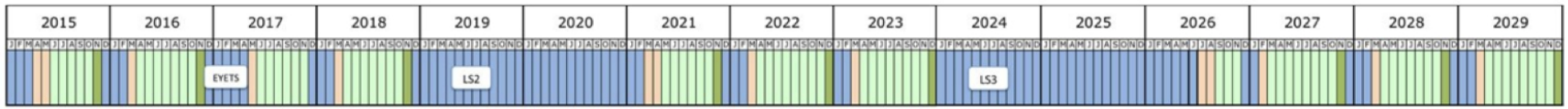
Upcoming Run3:

- 2 orders of magnitude more data with upgraded detector
- It will allow for unprecedented differential measurements

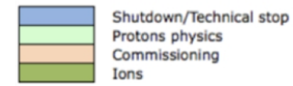
A golden possibility to study the charm-baryon and beauty sector

Thank you!

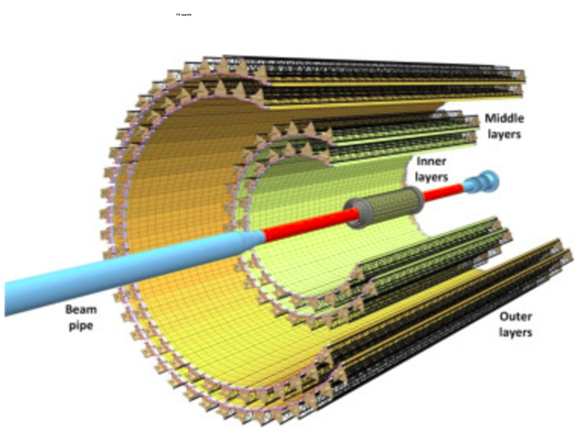
ALICE Upgrade for Run-3 and Run-4

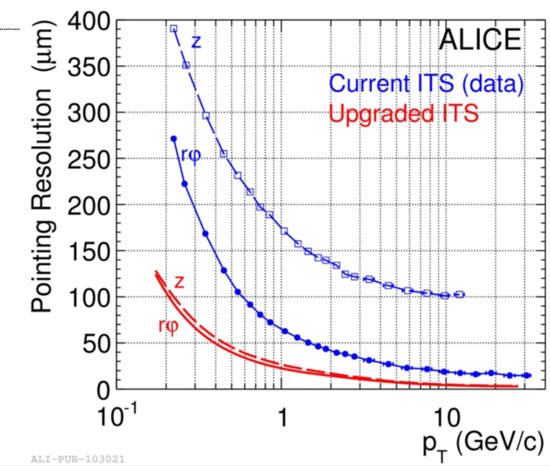


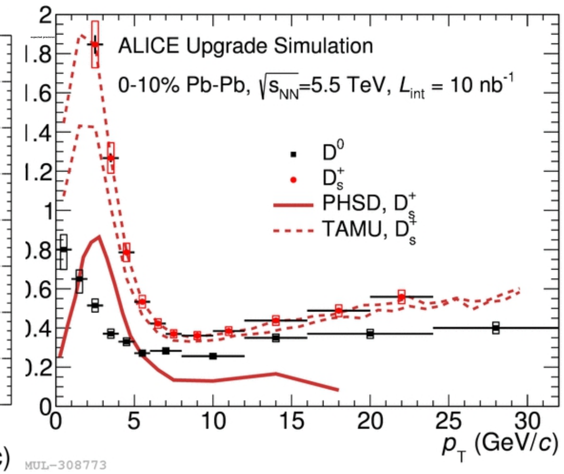
Run 2: $\mathcal{L}_{Pb-Pb} = 1.0\ nb^{-1}$ Run 3: $\mathcal{L}_{Pb-Pb} = 6.0\ nb^{-1}$ Run 4: $\mathcal{L}_{Pb-Pb} = 7.0\ nb^{-1}$



- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb^{-1} (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continuous readout

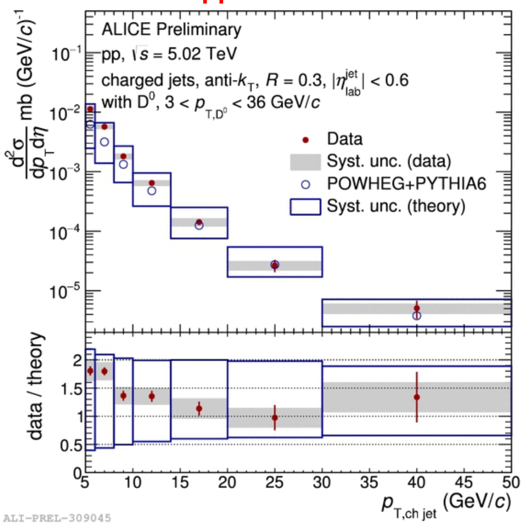




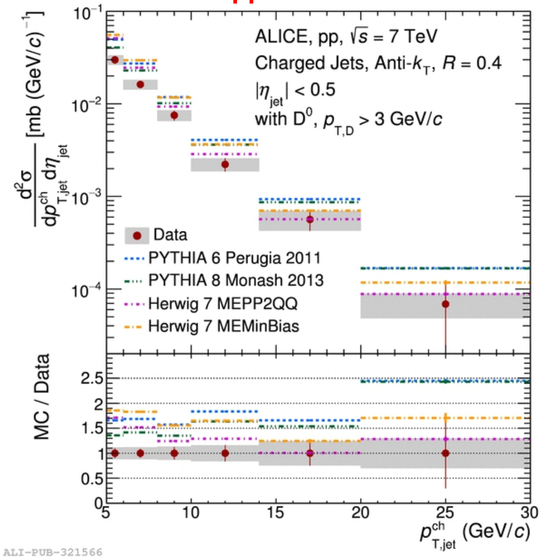


Charm production: D^0-jet cross sections

pp √s=5.02 TeV



pp √s=7 TeV



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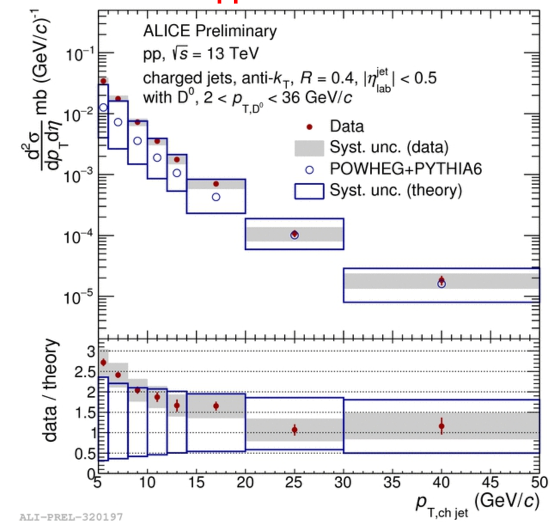
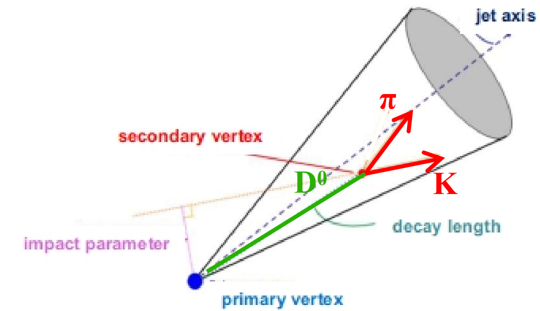
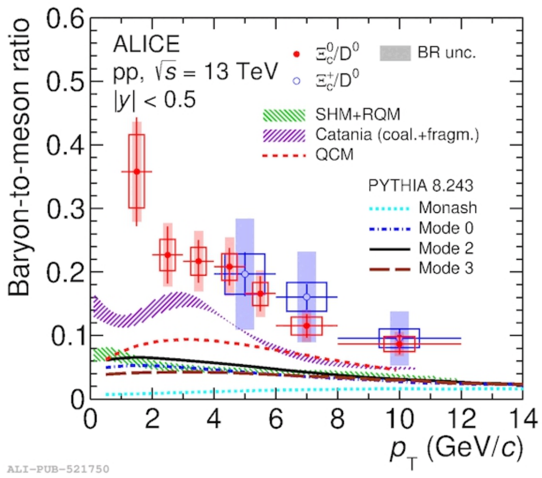
pp √s=13 TeV



- Analysis technique
  - Identify D^0 mesons via hadronic decays
  - Replace decay products with D^0 in jet
- Comparison with models
  - NLO POWHEG+PYTHIA (hvq) calculations consistent with data (only marginally at low-p_T)
  - Neither LO PYTHIA 6 and 8, nor NLO HERWIG 7 describe the cross-section



Charm baryons - Ξ_c, Σ_c



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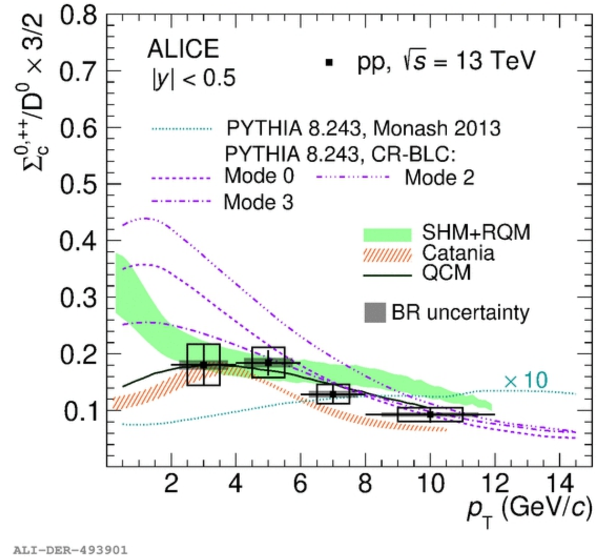
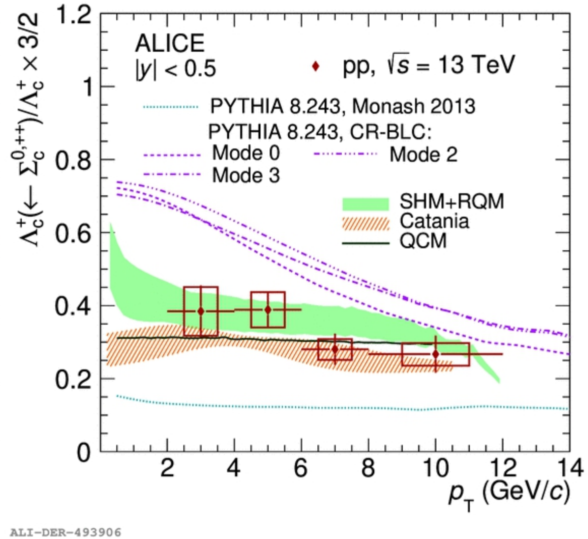
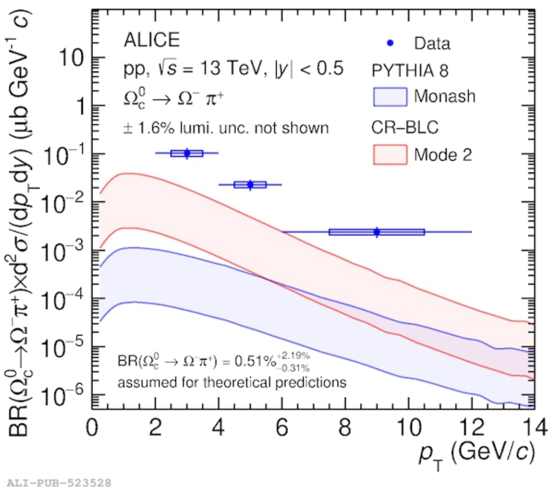
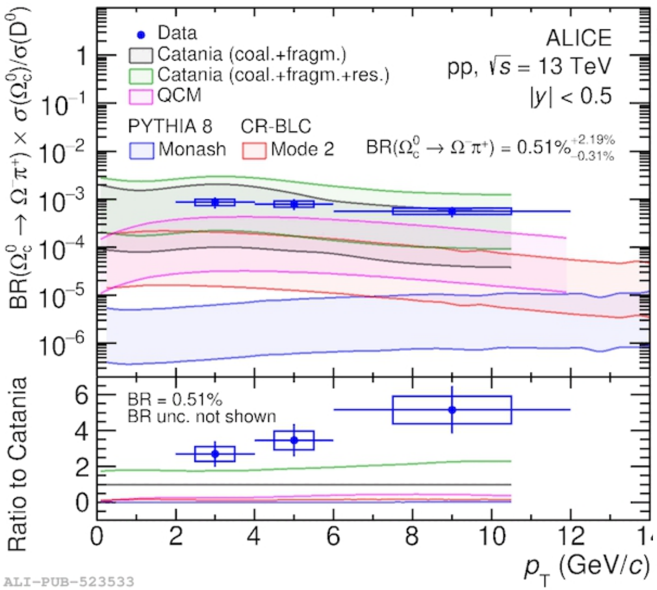


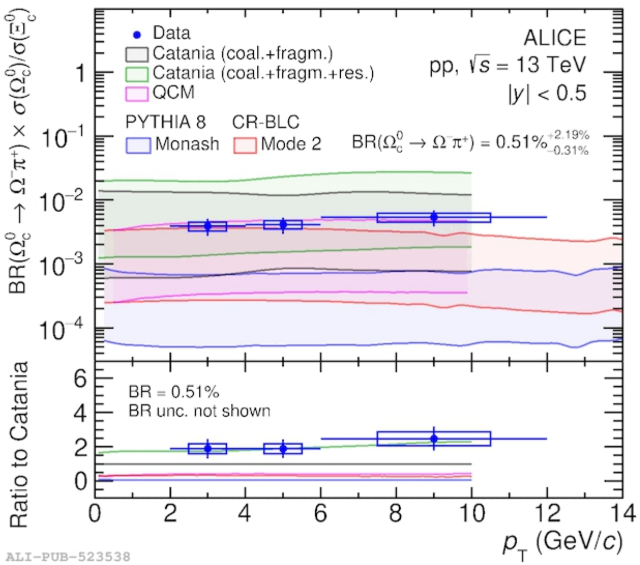


Charm baryon fragmentation - Ω_c^+

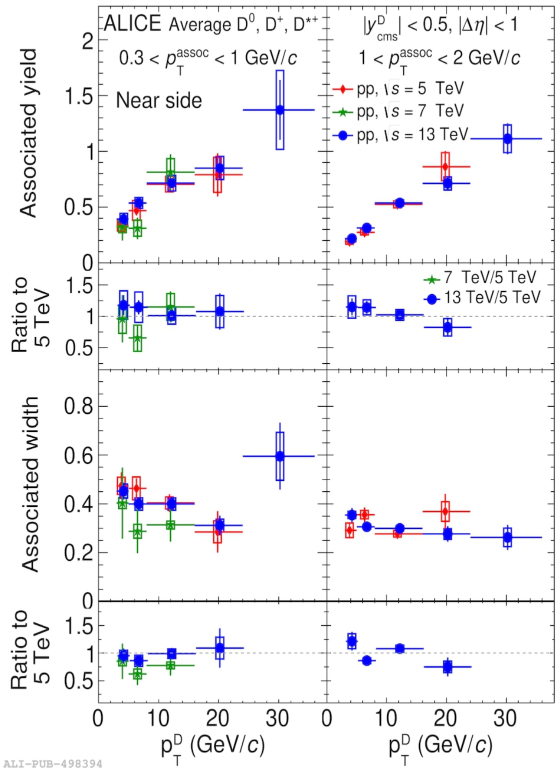
https://arxiv.org/abs/2205.13993



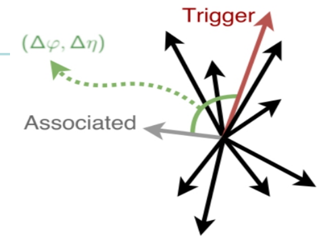




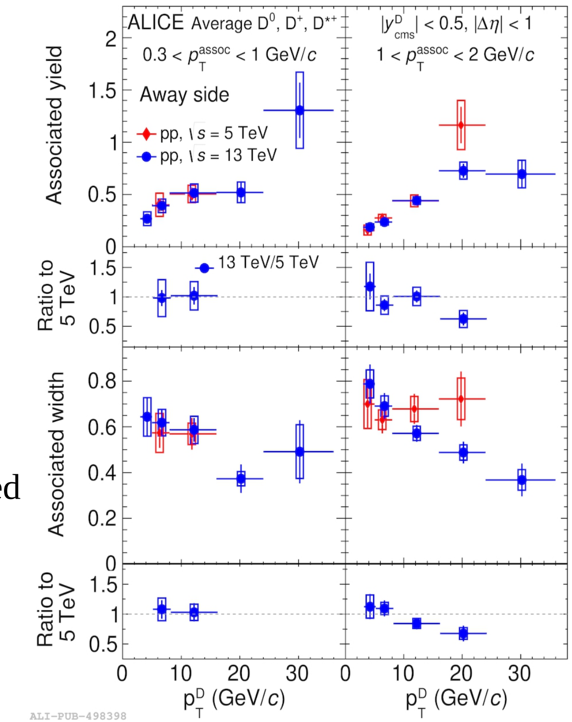
Fragmentation of HF: D meson-hadron azimuthal correlations



Main focus on **charm fragmentation** by studying features of near-side (NS) region.



- Away-side (AS) studies provide info on **production processes** and **hard-gluon radiations.**
- General features with increasing p_T^D
  - More energetic parton → more phase space for other fragmenting particles
  - Larger heavy-quark boost → increased peak collimation
- No sizable energy dependence within total uncertainties



Eur. Phys. J. C 80, 979 (2020)

c, b collectivity