Event-activity dependence of heavy-flavor production at the ALICE experiment

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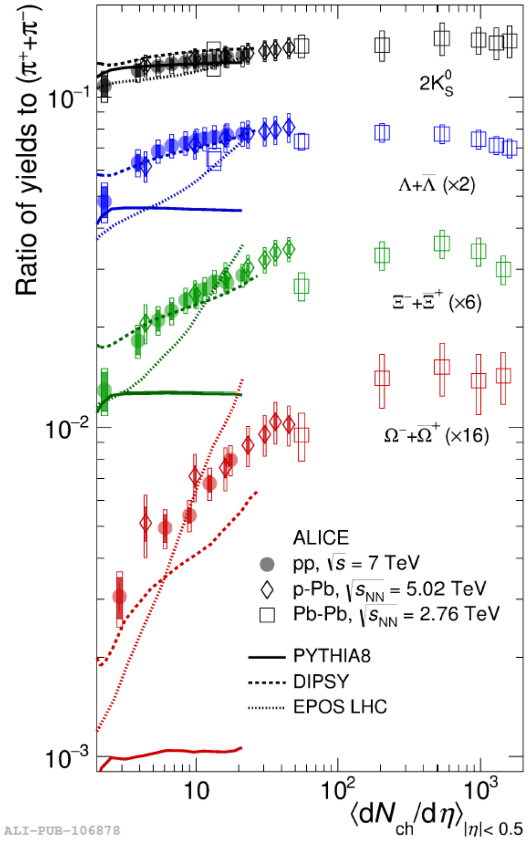
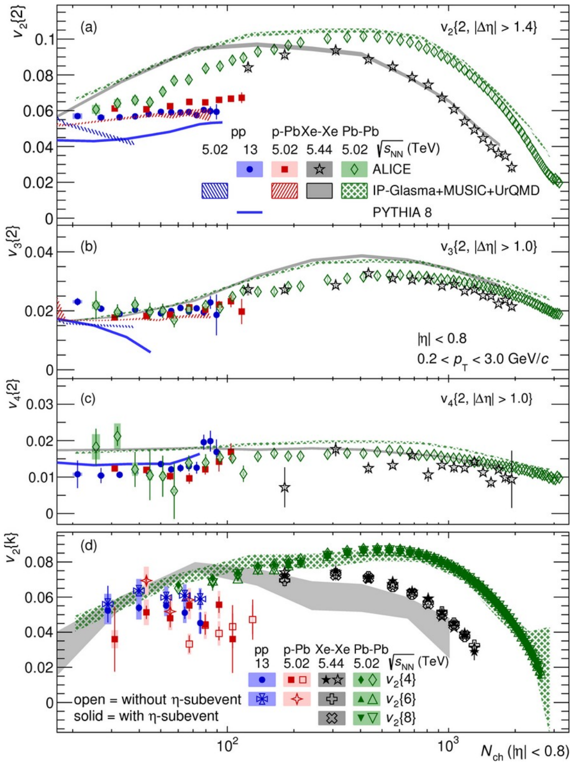
Small collision systems

- **High-multiplicity pp collisions:** similar signatures to those observed in heavy-ion collisions where the formation of a quark-gluon plasma (QGP) is expected:
- **Strangeness enhancement**
- Long-range multiparticle correlations, “**flow**”

Nature Phys. 13 (2017) 535



Phys. Rev. Lett. 123 (2019) 142301



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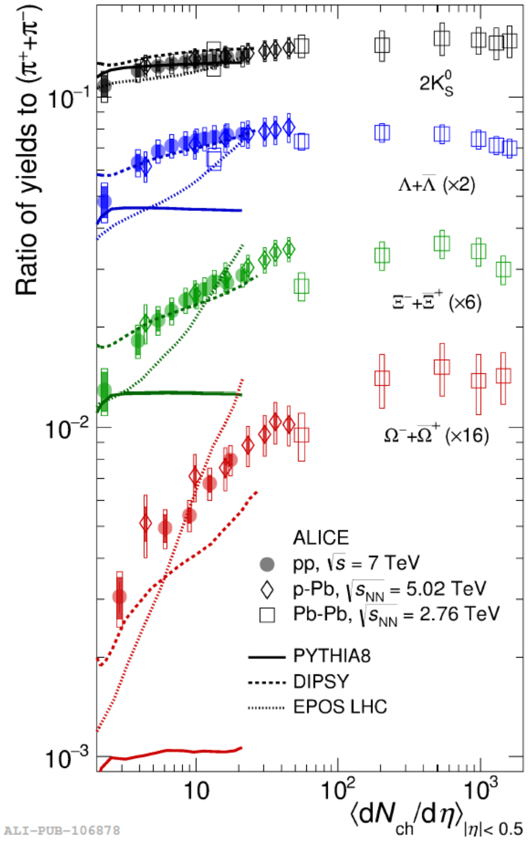
- **Strangeness enhancement**
- Long-range multiparticle correlations, “**flow**”
- **Is there a quark-gluon plasma in pp collisions?**
- Or are vacuum-QCD effects responsible for this behavior

Nature Phys. 13 (2017) 535



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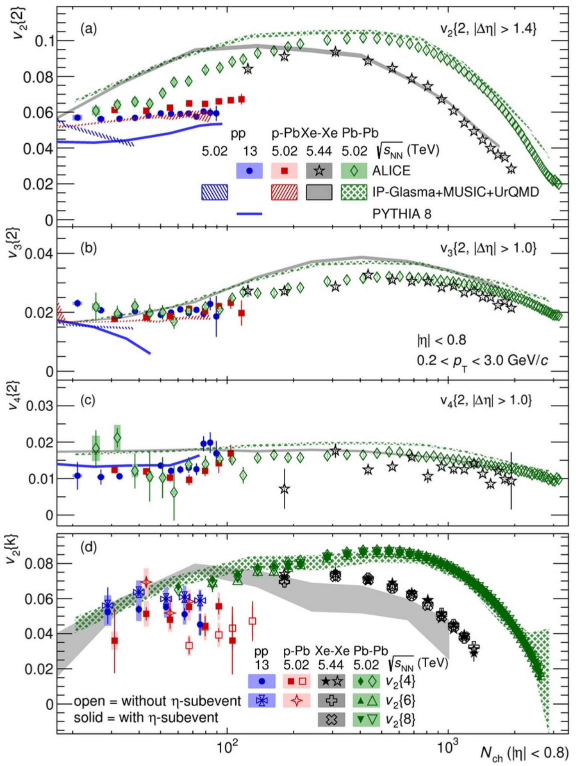
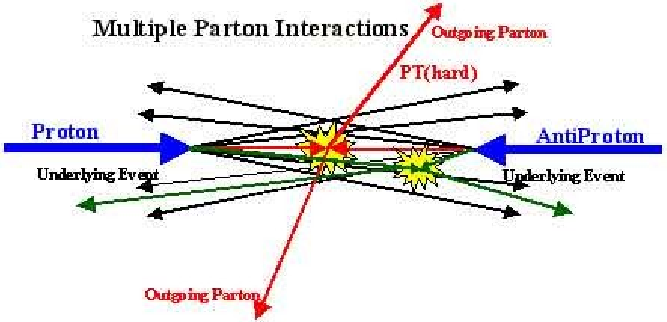


Heavy-flavor w.r.t. event activity

- **QGP-like effects may be generated by complex vacuum-QCD processes** such as multiple-parton interactions (MPI) with color reconnection (CR)



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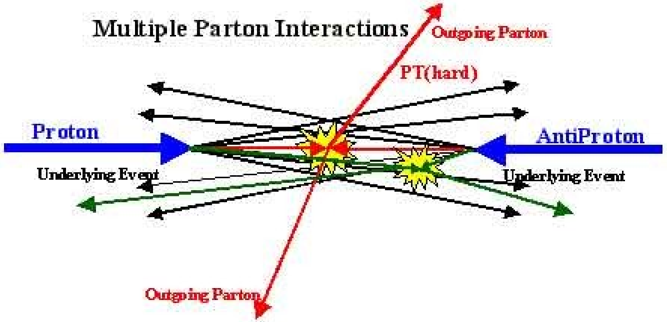
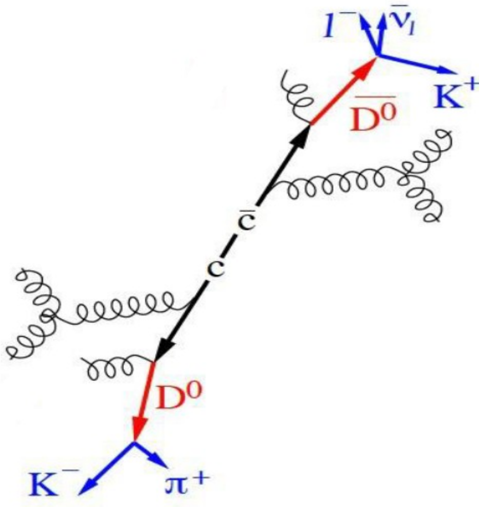
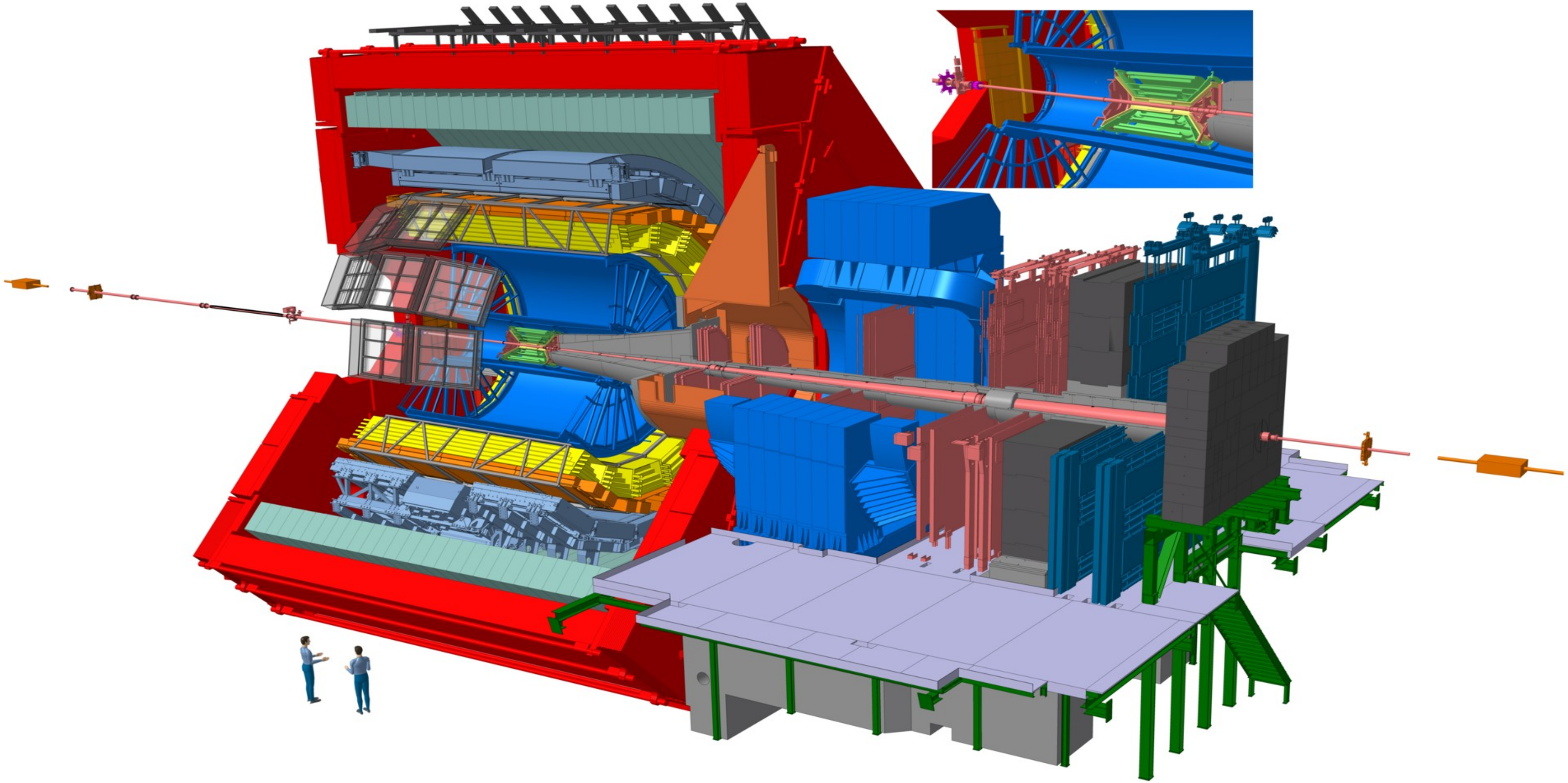




- **Heavy-flavor** quarks work as hard probes down to low p_T => **pQCD benchmark**
- Measuring the dependence of heavy-flavor production charged-hadron multiplicity and event activity allows for the investigation of:
  - Collective-like effects from small to large systems
  - Interplay between the hard and soft particle production
  - Role of multiparton interactions in heavy-quark production
  - Charm fragmentation across different collision systems

The ALICE experiment (Run-2)



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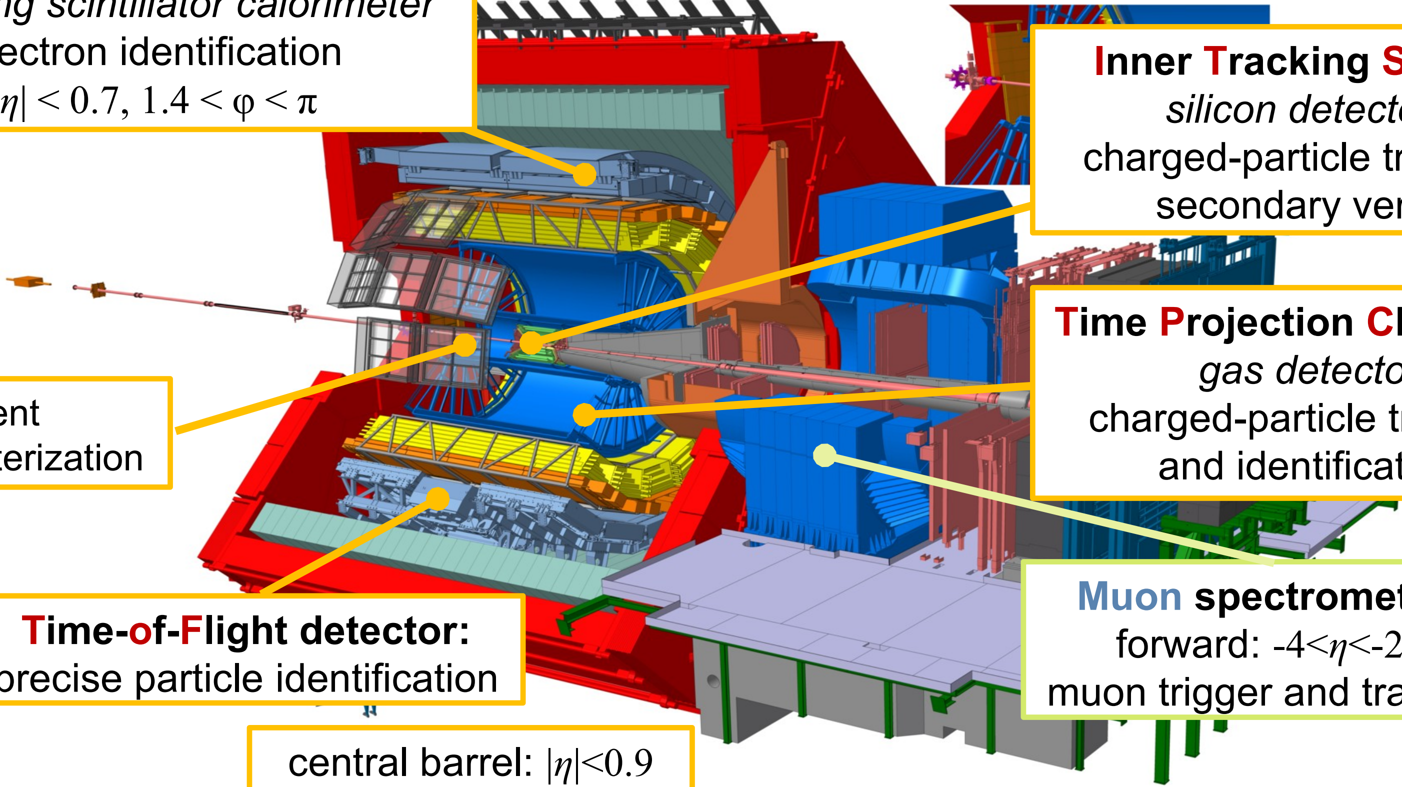


ElectroMagnetic Calorimeter
sampling scintillator calorimeter
electron identification
$|\eta| < 0.7,\ 1.4 < \varphi < \pi$

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

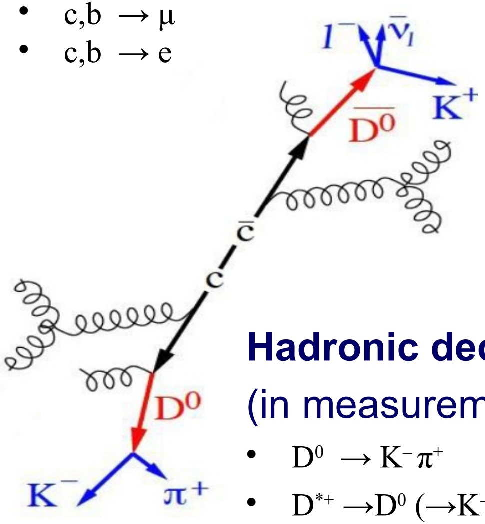
Time-of-Flight detector:
precise particle identification

central barrel: $|\eta|<0.9$

Reconstruction of heavy flavor decays

Semileptonic decays

- c,b $\rightarrow \mu$
- c,b $\rightarrow e$



Hadronic decays

(in measurements shown)

- $D^0 \rightarrow K^- \pi^+$
- $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+)\pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_S^+ \rightarrow \Phi(\rightarrow K^+ K^-)\pi^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\Lambda_c^+ \rightarrow p K^0_S(\rightarrow \pi^+\pi^-)$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$
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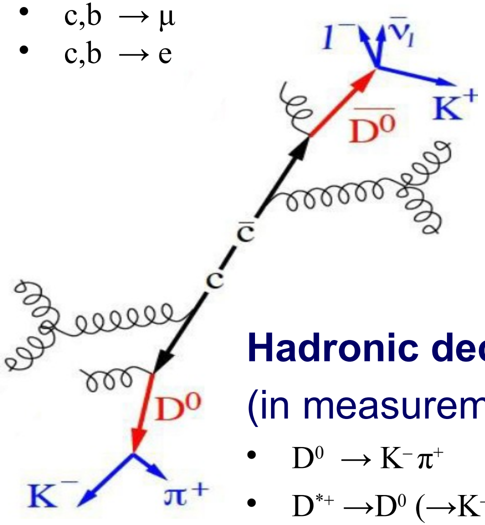

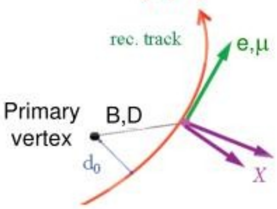

Identification

- PID of daughter hadrons
- Topological selection
- Secondary vertex in the ITS

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

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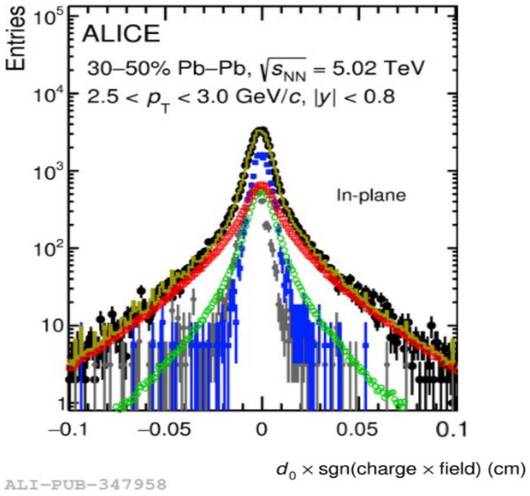

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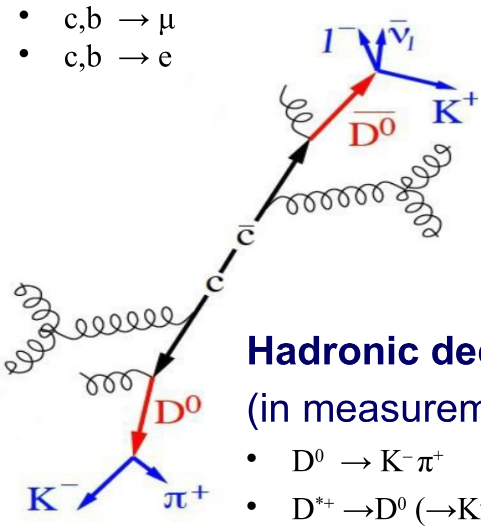

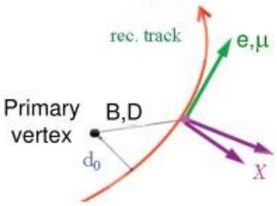

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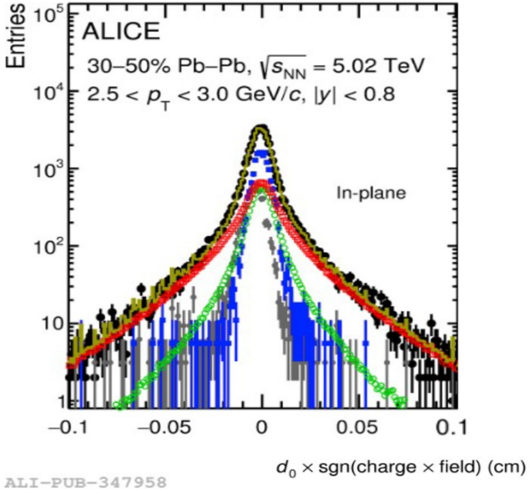
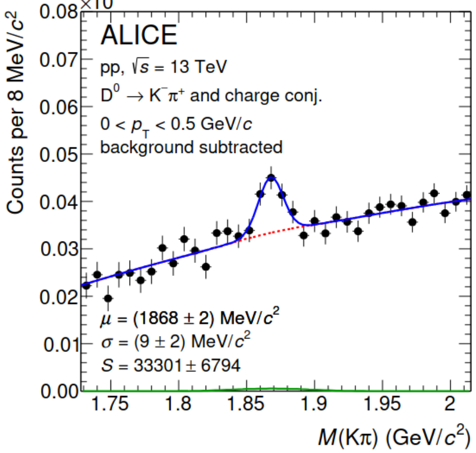


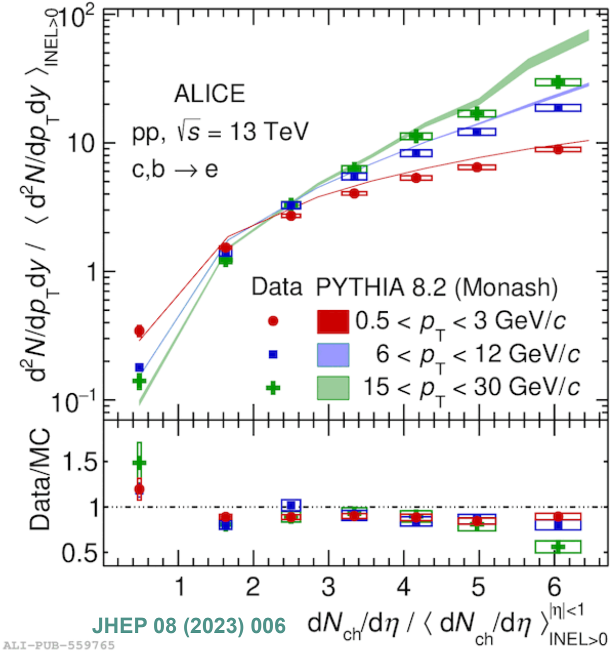
JHEP 12 (2023) 086



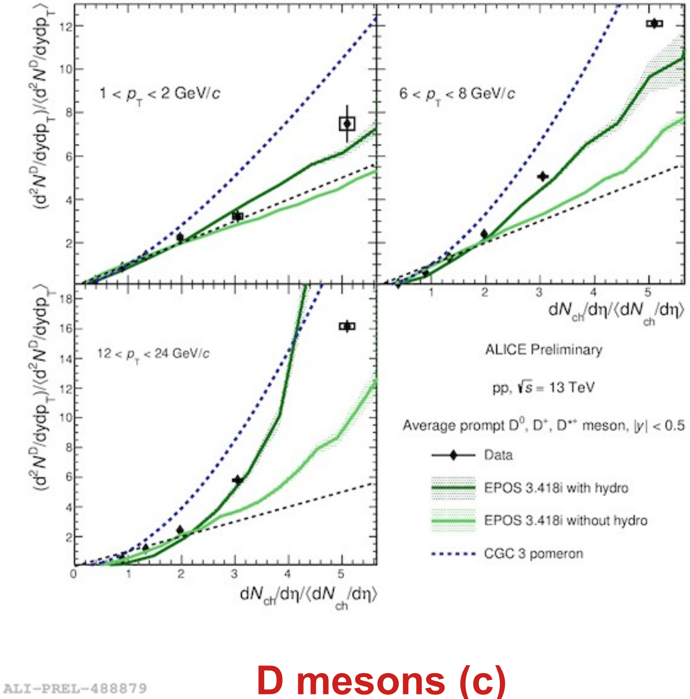
Peak extraction
(D^0 example)

Steeper-than-linear dependence of self-normalized yields on multiplicity at $\sqrt{s}$ = 13 TeV

- Strong constraints for models
- Sensitive to autocorrelation: good simultaneous description of jets and UE needed



HF electrons (c + b)



D mesons (c)

Heavy-flavor production vs. multiplicity

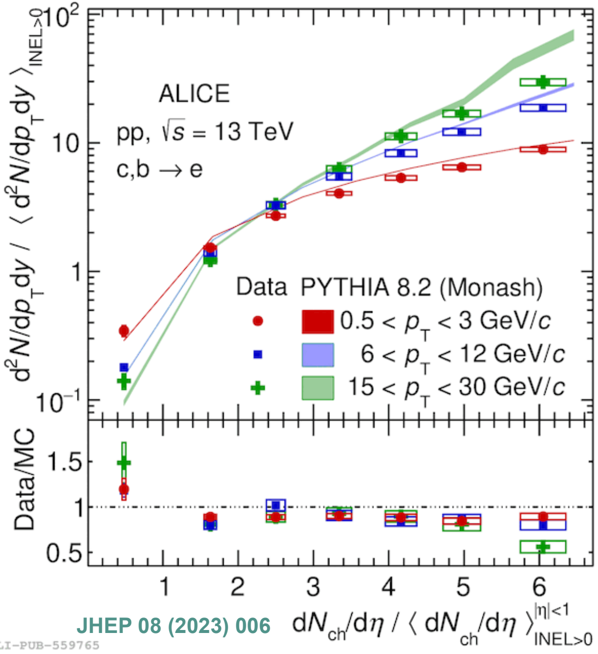
Steeper-than-linear dependence of self-normalized yields on multiplicity at $\sqrt{s}$ = 13 TeV

- Strong constraints for models
- Sensitive to autocorrelation: good simultaneous description of jets and UE needed

Performance of models:

- **PYTHIA 8 with MPI** (pQCD-based with PS and Lund fragmentation) adequately describes data
- **EPOS** parton model with hydrodynamic evolution captures trends

PYTHIA: Comput.Phys.Commun. 191 (2015) 159
EPOS: Nucl.Phys.B Proc.Suppl. 175 (2008) 81
CGC 3 pomeron: PRD 101 (2020) 094020



JHEP 08 (2023) 006

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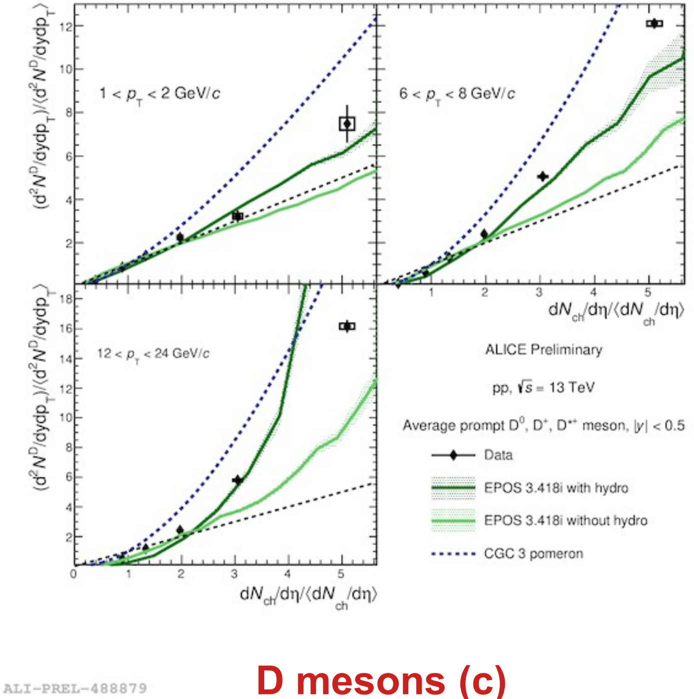


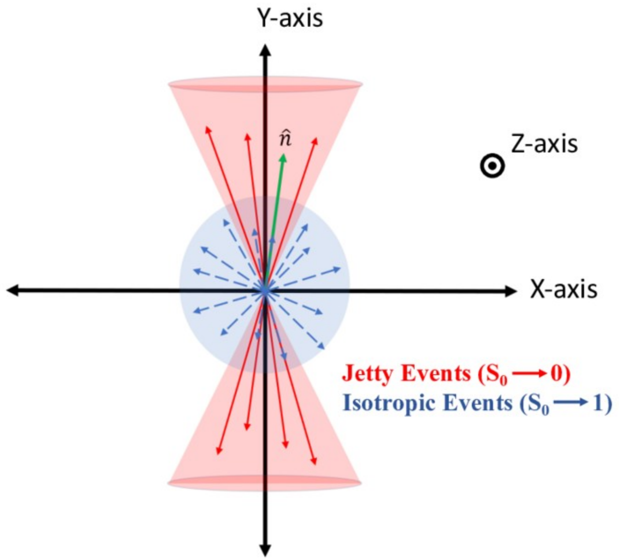
D mesons (c)

Transverse spherocity S_0

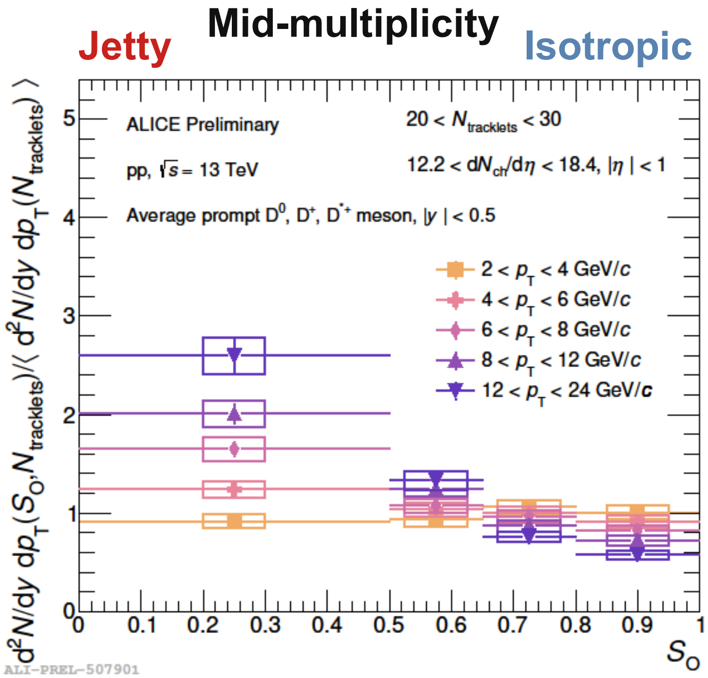
- Event-shape observable to express jettyness vs. isotropy

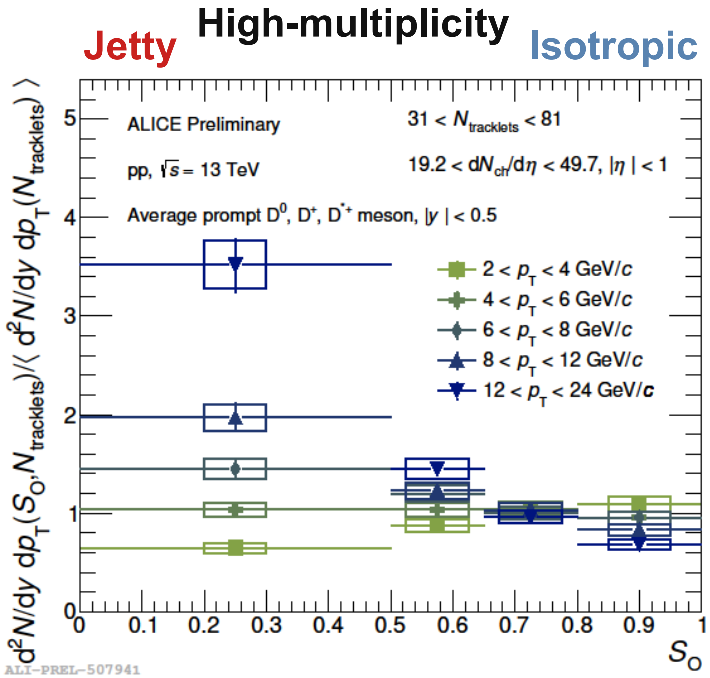
$$S_0 = \frac{\pi^2}{4}\left(\frac{\sum_i |\vec{p}_{\mathrm{Ti}} \times \hat{n}|}{\sum_i p_{\mathrm{Ti}}}\right)^2$$

- Sensitive to initial hard scatterings and underlying event
- **Jetty events** ($S_0 \to 0$) dominated by hard QCD processes
- **Isotropic events** ($S_0 \to 1$) dominated by soft QCD processes



D-meson self-normalized yields vs. S_0





- Hint of an enhanced D-meson production toward higher multiplicity in jetty events
- Effect of hard scatterings leading to average increase in charged-particle multiplicity

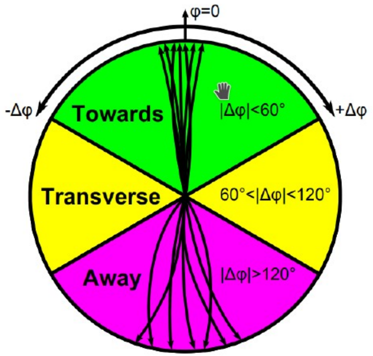
Transverse event activity R_T

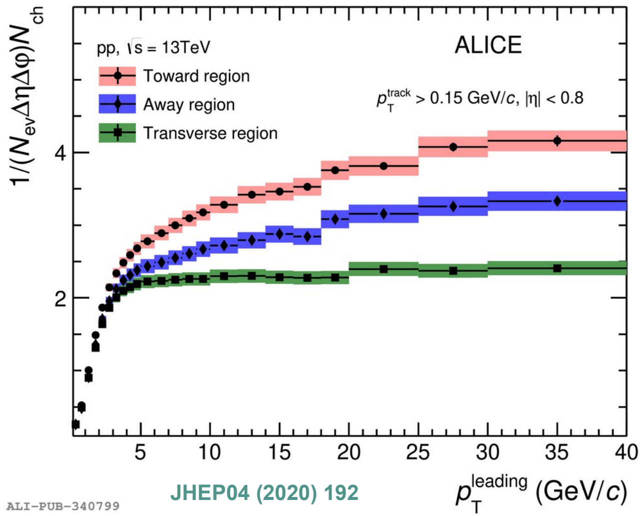
- Event-activity observable representing the underlying event (UE)

$$R_{\mathrm{T}} = \frac{N_{\mathrm{T}}^{\mathrm{ch}}}{\langle N_{\mathrm{T}}^{\mathrm{ch}} \rangle}$$

N_T^{ch} : event multiplicity in the transverse region

- High-p_T leading particle required
- **Toward** and **Away** regions typically contain the leading and subleading jet
- **Transverse** region is mostly independent of the hard scattering process for leading particle p_T >5 GeV/c, and mostly contains the UE
  - $R_T < 1$: low underlying-event activity
  - $R_T > 1$: high underlying-event activity
- In models with multiple-parton interactions (MPI), R_T is strongly correlated with the number of MPIs

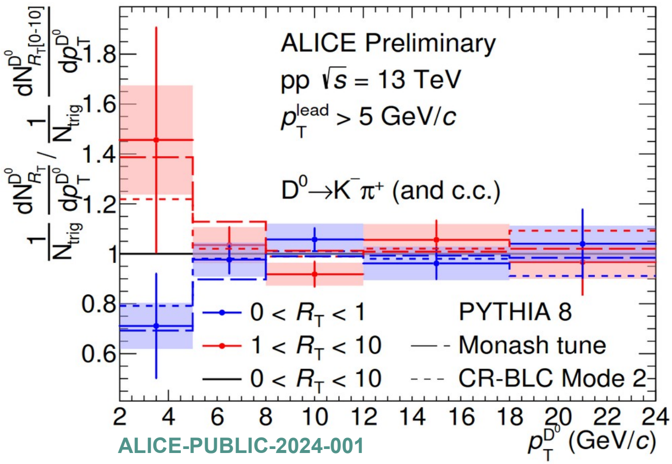




JHEP04 (2020) 192

D-meson production vs. R_T

- Statistics allowed measurement only in **Toward** region:
  - High p_T: D^0-meson production is independent of transverse activity – these hadrons are produced in connection to the leading process
  - Low p_T: a hint of transverse-activity dependence
  - PYTHIA 8 with Monash and CR-BLC mode 2 tunes describes the data within uncertainties



ALICE-PUBLIC-2024-001

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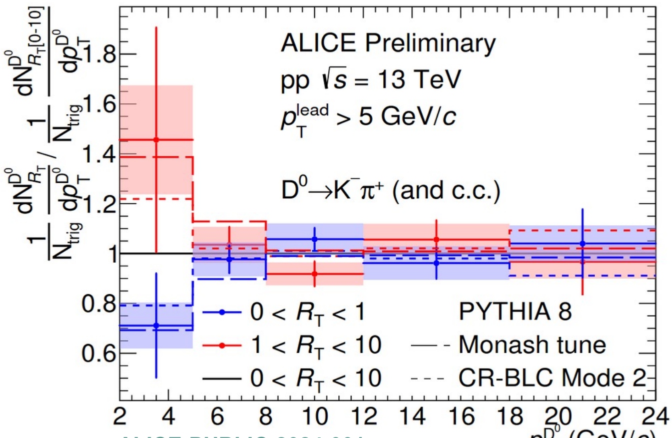
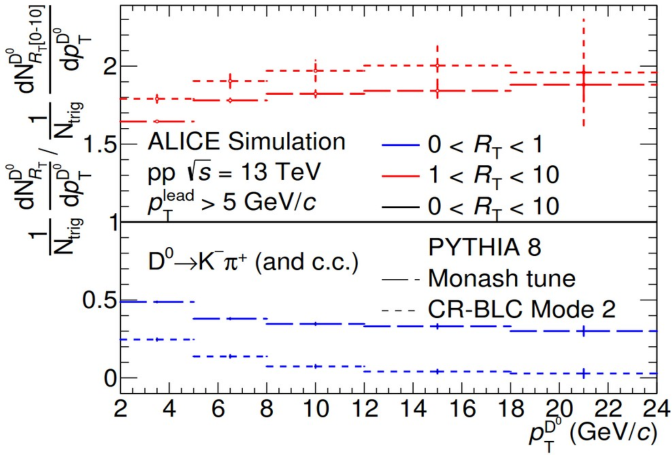
- **Transverse** region:
  - PYTHIA 8 with Monash and CR-BLC Mode 2 tunes suggests dependence on transverse activity at any p_T
  - Heavy-flavor production is strongly influenced by UE
- **The expected Run 3 luminosity will make it feasible to measure D-meson production in the transverse region**





Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003

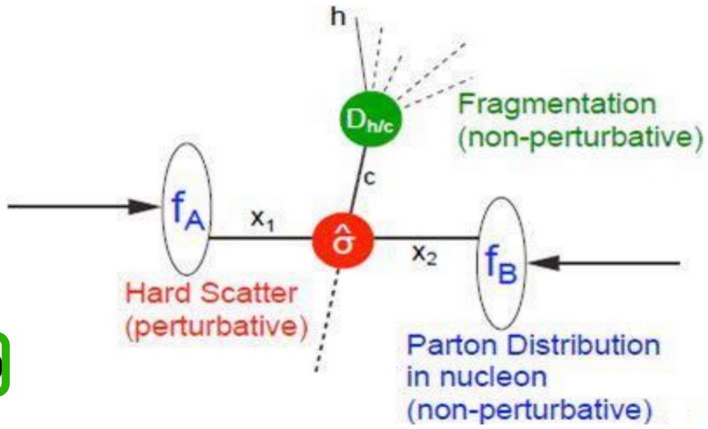
Heavy flavor fragmentation

- Production of heavy-flavor hadrons:
  - Parton distribution functions (PDF)
  - Hard scattering process
  - Fragmentation

- Factorization hypothesis: these 3 are independent!

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

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



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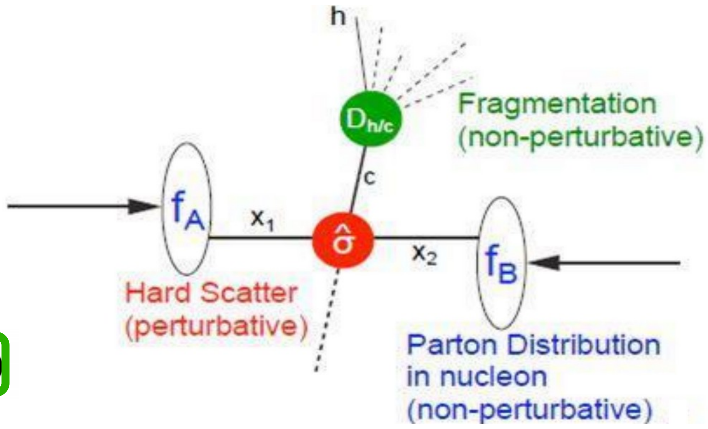

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Q : momentum transfer

- Traditional assumption: fragmentation is independent of collision systems

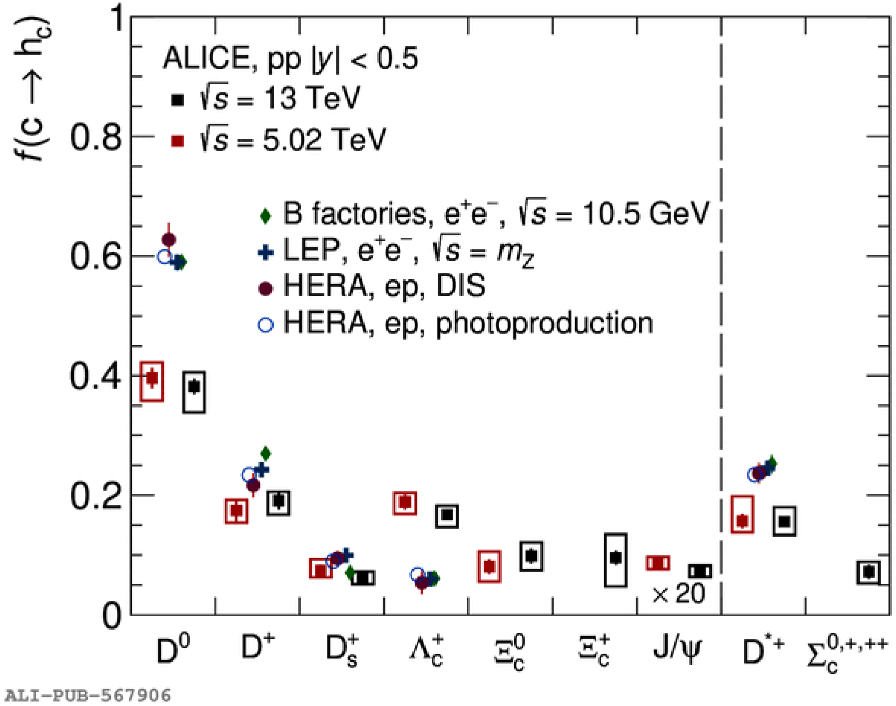
- In reality: several effects may influence it (MPI, quark-coalescence)
  - **Under-explored**! Baryon vs. meson? Strange vs. non-strange?

Charm-quark hadronization: HERA to LHC

Charm-quark fragmentation fractions into different hadrons $f(c \rightarrow h_c)$ from HERA ep, LEP e^+e^- and the LHC pp collisions

- Reduction of D mesons by about 1/3
- Enhancement of charmed baryons
- No significant discrepancy between different LHC energies

Fragmentation is not universal

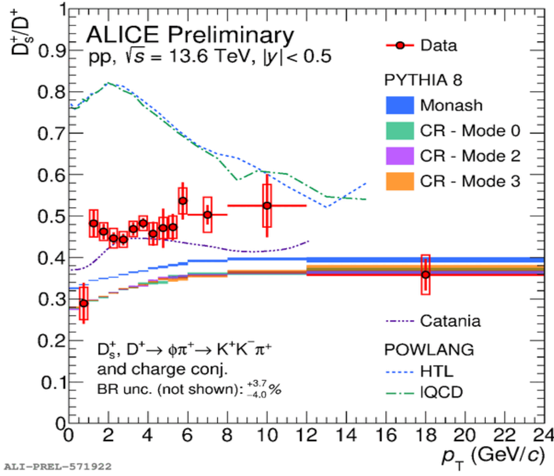


JHEP 12 (2023) 086

Comparison of heavy-flavor mesons

New Run-3 measurements in pp collisions at $\sqrt{s}$ = 13.6 TeV

- **Strange vs. non-strange charm:** D_s^+/D^+ ratio
  - No substantial p_T-dependence present
  - **Catania** (coalescence and thermalized fragmentation) describes data
  - **POWLANG** (QGP) overestimates data
  - **PYTHIA 8** underestimates measurement
    CR-BLC vs. Monash difference is minor



Monash: EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003
Color ropes: JHEP 03 (2015) 148
EPOS 4: PRC 108 (2023) 064903
Catania: EPJC 78 no. 4, (2018) 348
POWLANG: JHEP 03 (2016) 123

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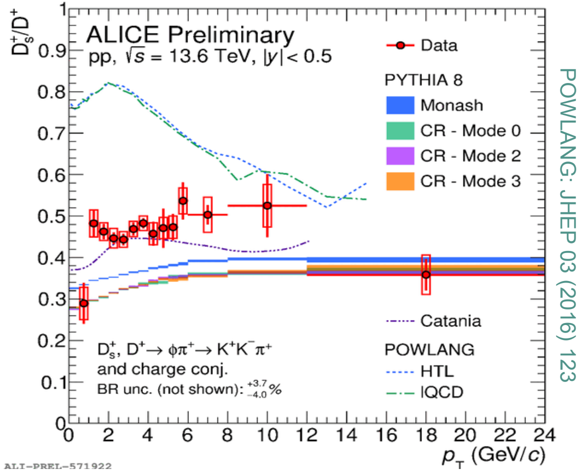
    CR-BLC vs. Monash difference is minor
- **Charm vs. beauty**: prompt to non-prompt D ratio
  - Trend in p_T captured by models
  - PYTHIA 8 tunes (MPI with CR) overestimate the ratio
  - EPOS (parton dynamics) underestimates it



ALI-PREL-571922

Monash: EPJC74 (2014) 8, 3024
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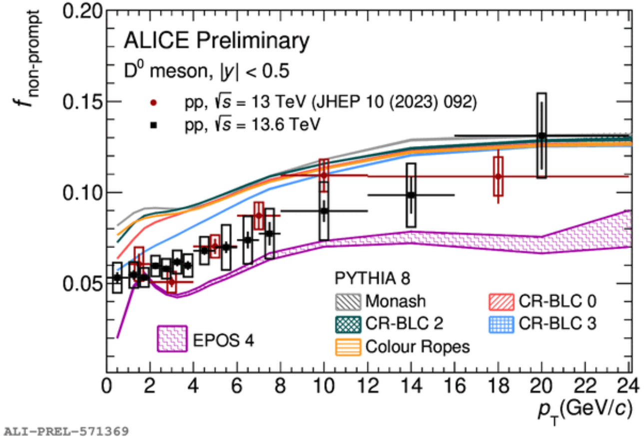
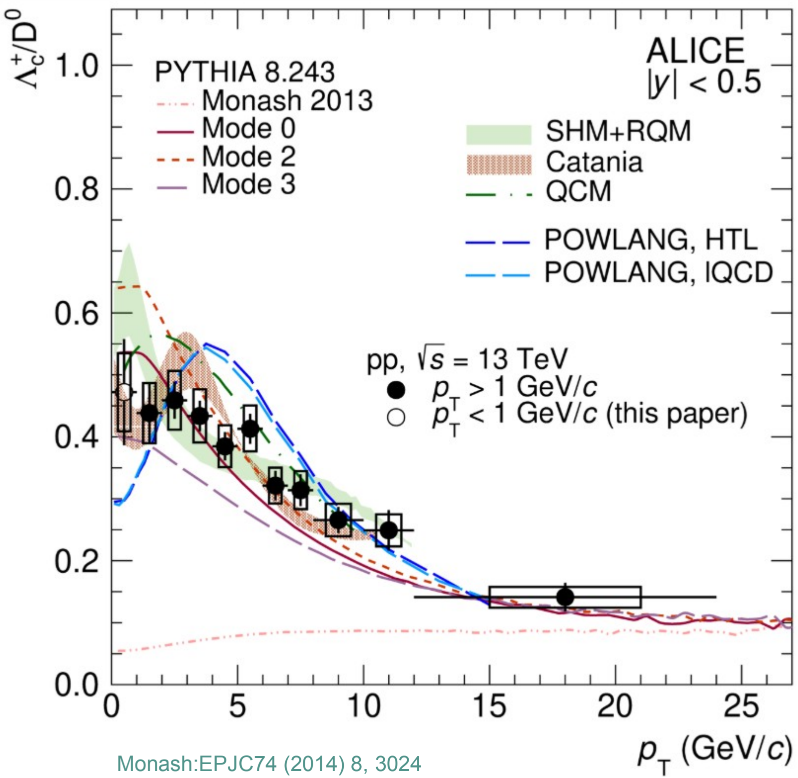


ALI-PREL-571369

Charmed-baryon enhancement

- **charm baryon vs. meson**
- Significant enhancement in **prompt Λ_c^+** to D^0 ratio at low to intermediate p_T vs. e^+e^- and e^-p collisions
  - PYTHIA 8 Monash tune (based on e^+e^- and e^-p fragmentation) fails to describe the trends
- Several proposed models reproduce the behavior
  - Color-reconnection with color string junctions (CR-BLC modes 0, 2, 3)
  - Statistical hadronization model with extra charm-baryon resonances (SHM+RQM)
  - Quark coalescence models (Catania and QCM)
  - POWLANG (assuming QGP-like medium)



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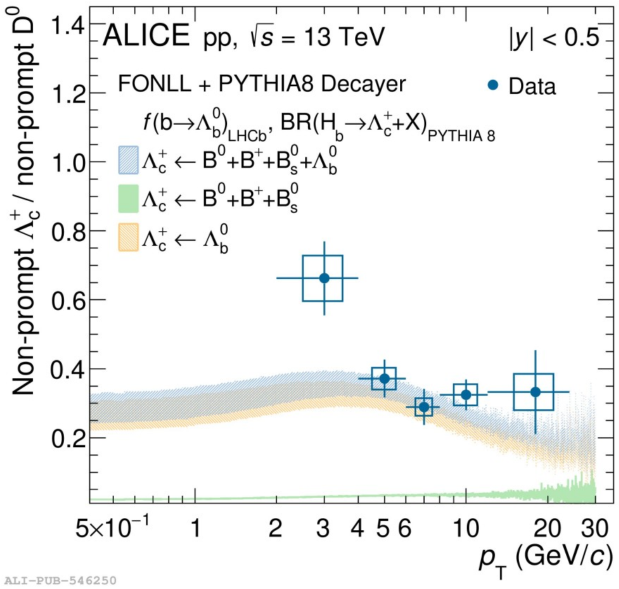
CR-BLC: JHEP 08 (2015) 003
SHM+RQM: PLB 795 (2019) 117
Catania: EPJC 78 no. 4, (2018) 348
POWLANG: JHEP 03 (2016) 123
EPOS4: PRC 108 (2023) 064903

Beauty hadrons

- Similar enhancement present for **non-prompt Λ_c^+** at low and intermediate p_T
- (most non-prompt Λ_c^+ comes from $\mathbf{\Lambda_b^0}$)
- **Both beauty and charm** baryons show an enhancement compared to mesons



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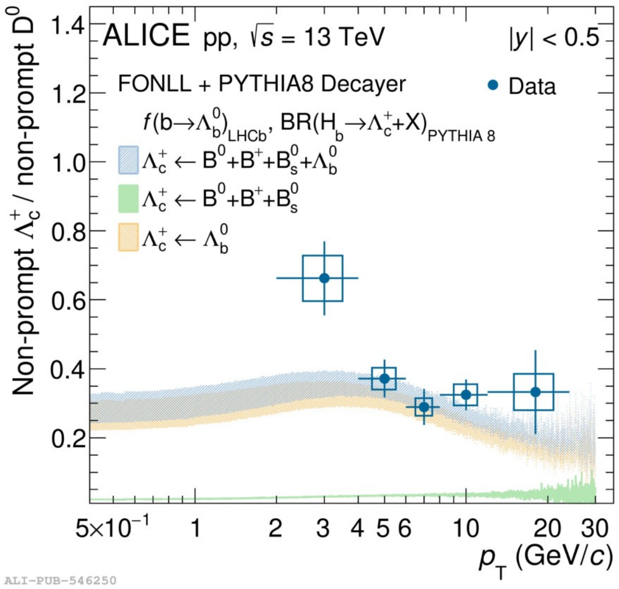
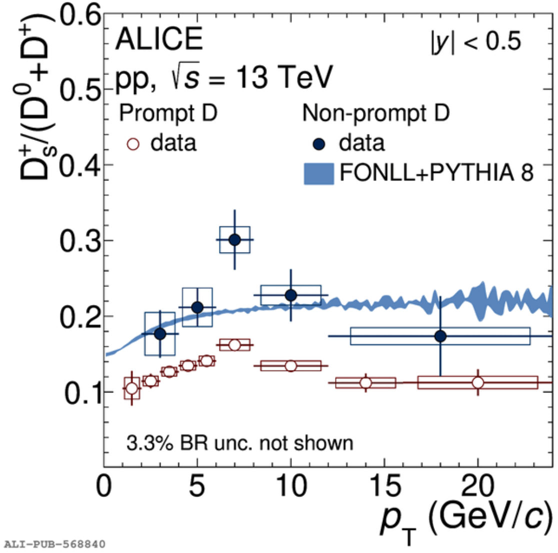




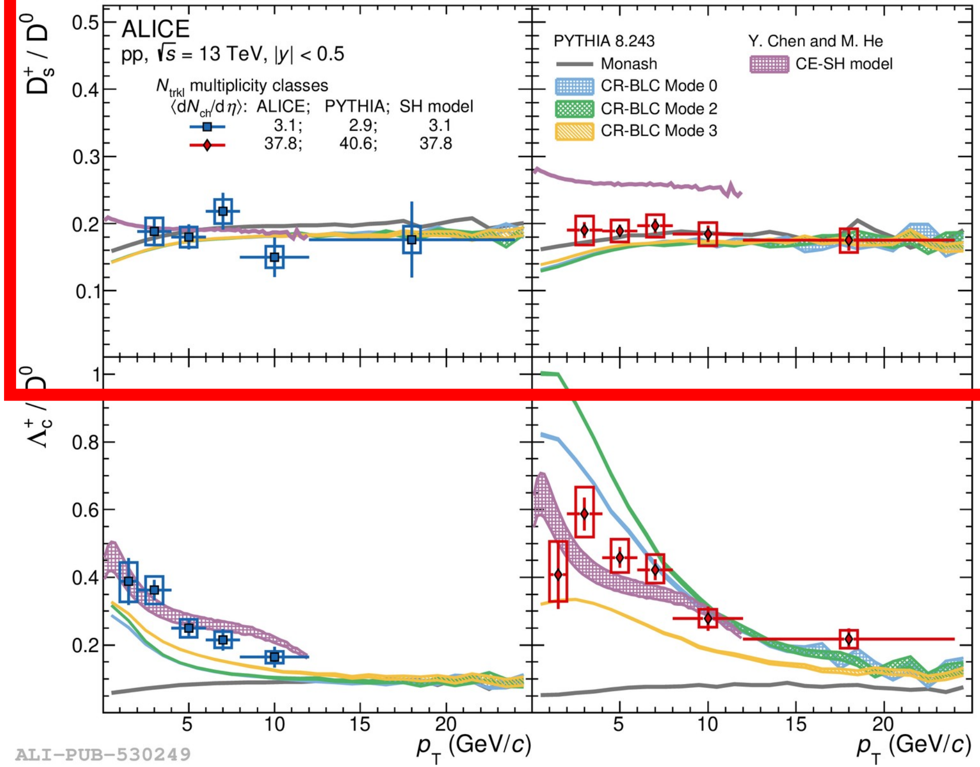
- **Non-prompt $D_s^+/(D^0+D^+)$** ratio, on the contrary, is well described by pQCD calculations with PYTHIA 8 decayer

FONLL: JHEP 9805 (1998) 007
PYTHIA: Comput.Phys.Commun. 191 (2015) 159

Charmed hadron yields vs. multiplicity

Charmed strange-to-nonstrange mesons

- Independent of p_T and multiplicity
- Described well by PYTHIA tunes
- CE-SH (canonical ensemble + statistical hadronization) model overestimates data at high multiplicities



Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003
CE-SH: PLB 815 (2021) 136144

PLB 829 (2022) 137065

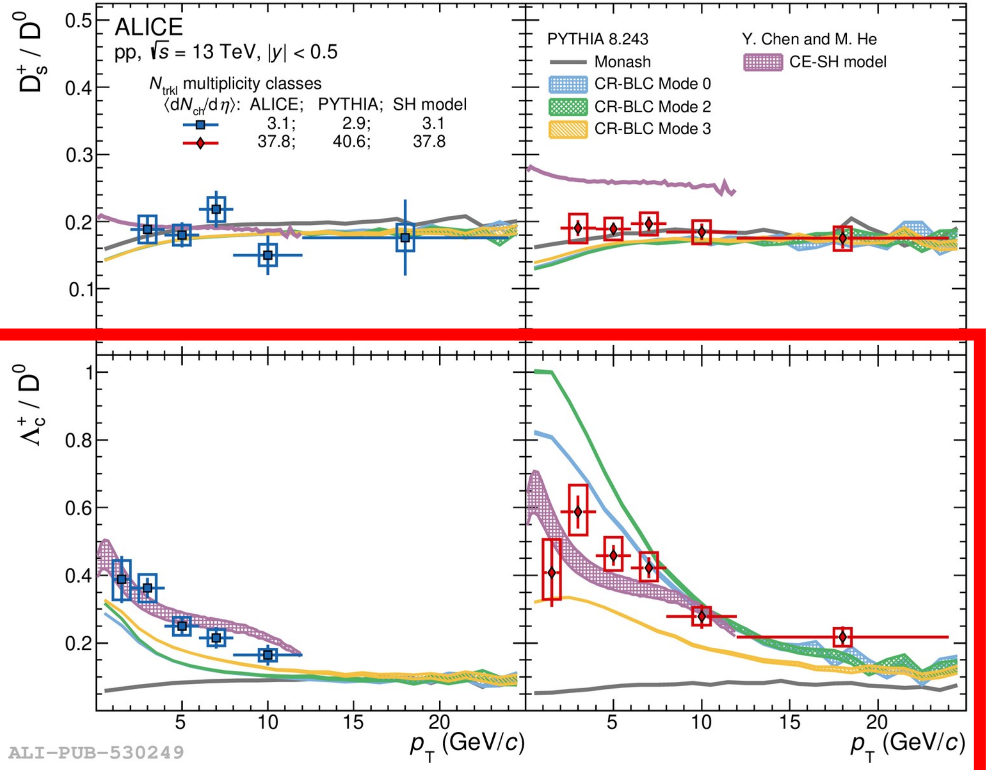
Charmed hadron yields vs. multiplicity

Charmed strange-to-nonstrange mesons

- Independent of p_T and multiplicity
- Described well by PYTHIA tunes
- CE-SH (canonical ensemble + statistical hadronization) model overestimates data at high multiplicities

Charmed baryon-to-meson ratio

- Significant dependence on multiplicity at low p_T (5.3σ difference)
- PYTHIA 8 with CR-BLC qualitatively describes the multiplicity dependence
- CE-SH model also describes the trends



Monash:EPJC74 (2014) 8, 3024
CR-BLC: JHEP 08 (2015) 003
CE-SH: PLB 815 (2021) 136144

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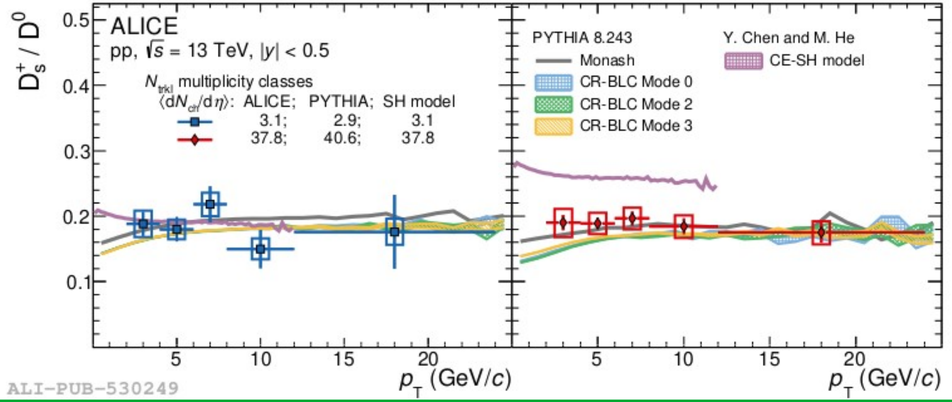
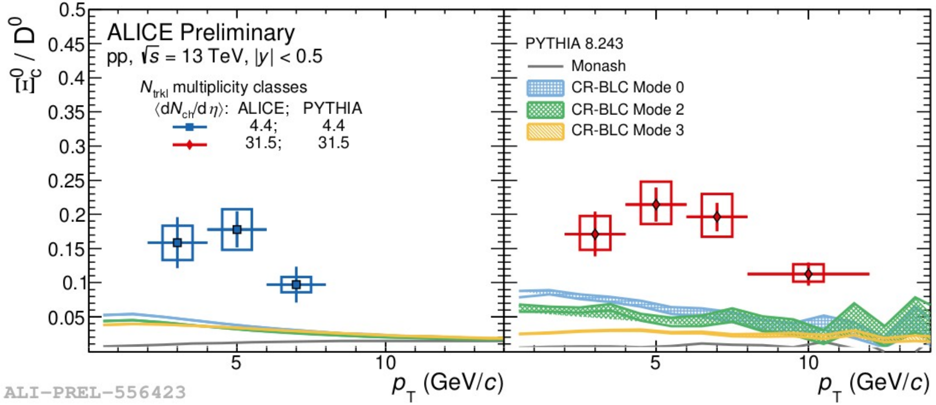


Charmed-strange baryon-to-meson ratio

- Hint of p_T-dependence
- no multiplicity dependence within uncertainties
- Significantly underestimated by PYTHIA CR-BLC at all multiplicities



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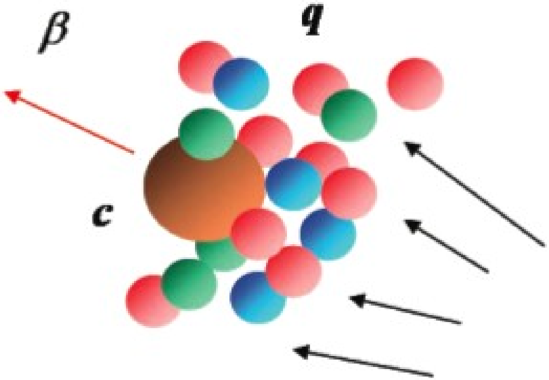
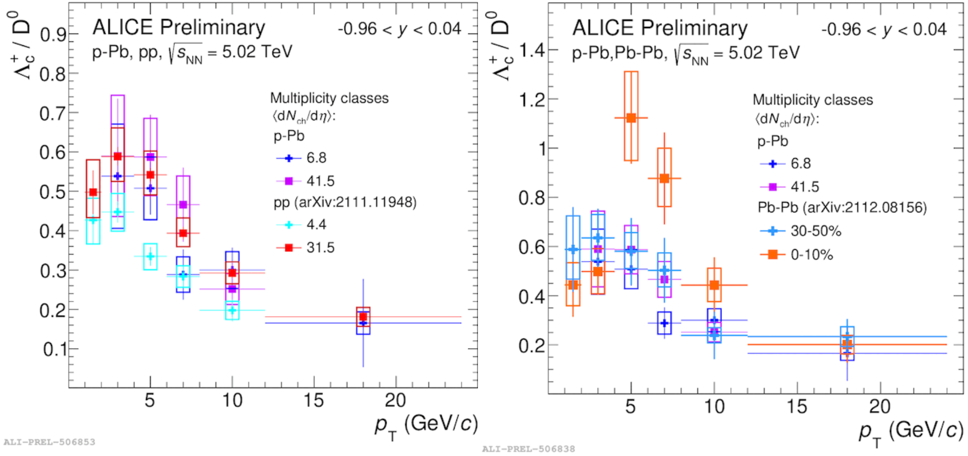
Toward larger systems

- **Large system: observed phenomena come from multiple sources**
  1) High-multiplicity vacuum-QCD effects
     - MPI with CR
  2) Hot nuclear effects
     - Collisional and radiative energy loss of heavy quark
     - Participation in hydrodynamical evolution
     - Thermalization
     - Coalescence
  3) Cold nuclear effects
     - Shadowing, etc.
- **Comparative measurements of baryons, strange and non-strange mesons in different collisions help clarify the picture**



Charm baryon-meson ratios in HI collisions



Multiplicity-dependence of the Λ_c^+/D^0 ratio

- Similar enhancement pattern to that in light baryon-to-meson ratios
- High-multiplicity pp, low- and high-mult p–Pb, and semicentral Pb–Pb are similar
- Strong separation for low-multiplicity pp: Threshold effect?
- **Radial-flow-like pattern in central Pb-Pb**

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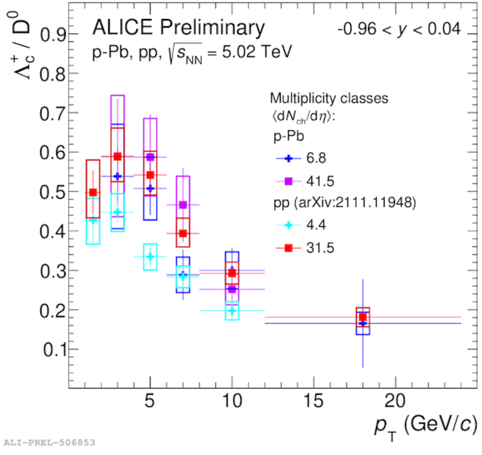

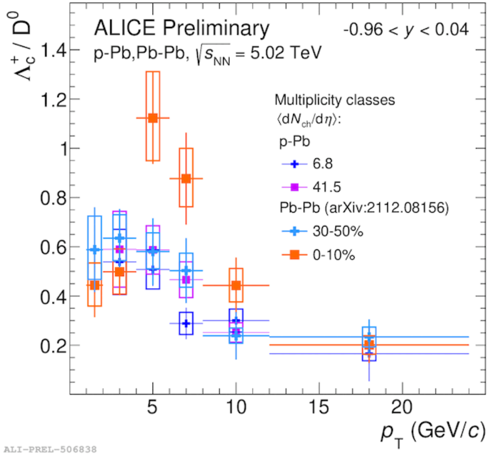

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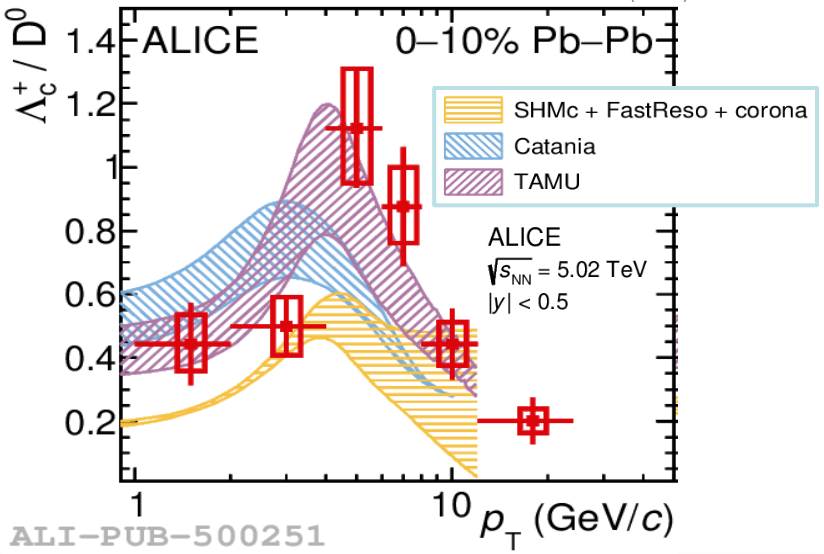
- **Radial-flow-like pattern in central Pb-Pb**

Λ_c^+/D^0 ratio in Pb-Pb collisions vs. models

- Data qualitatively described by TAMU and Catania, SHMc slightly underestimates it
- **Interplay of radial flow and recombination**
- Different p_T redistribution for mesons and baryons

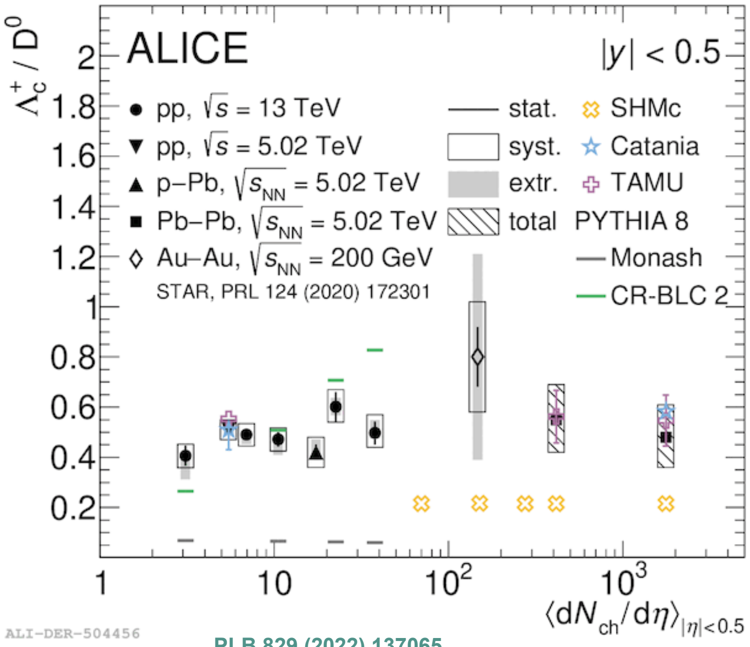
SHMc: JHEP 07 (2021) 03
Catania: EPJC 78 no. 4, (2018) 348
TAMU: PRL 110 (2013) 15



Charm hadron ratios vs. multiplicity

p_T-integrated Λ_c^+/D^0 ratios:

- Dependence on multiplicity, from low-p_T pp up to central Pb-Pb collisions
- Despite strong N_{ch}-dependent trends at mid-p_T, **no evidence of p_T-integrated N_{ch}-dependence**
- Significantly higher values than in e^+e^- and ep
- Collision-energy dependence is weak: STAR 200 GeV and ALICE 5.02 TeV consistent
- Model performance:
  - Increase predicted by PYTHIA 8 CR-BLC is not supported
  - SHMc (Pb–Pb): flat trend, but underestimates data
  - TAMU, Catania: similar for pp and Pb–Pb



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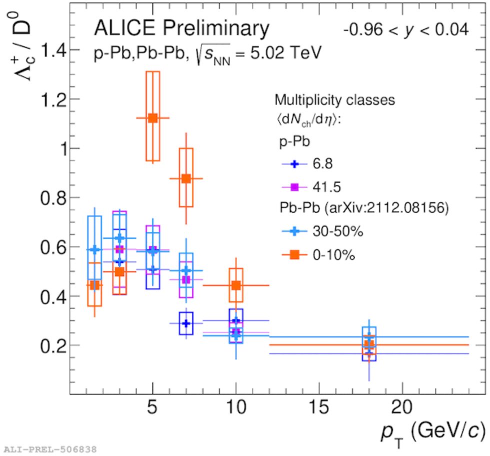
Summary and outlook

Event-activity-dependent heavy-flavor measurements:

- Opportunity to understand the complexity of pp collisions
  → **Fragmentation is not universal**
- Examine the interplay of hot and cold nuclear, and vacuum effects
  → **Large systems can still be described within the standard thermal equilibrium + hydrodynamical evolution picture**



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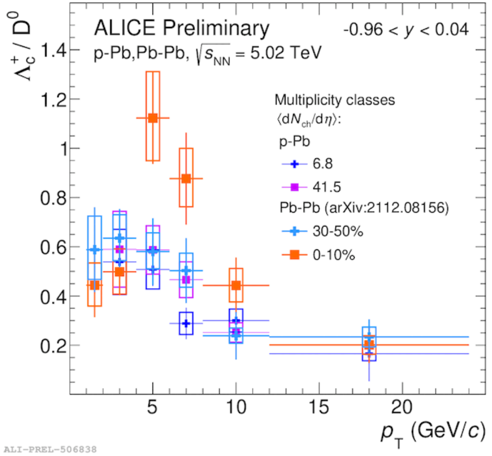
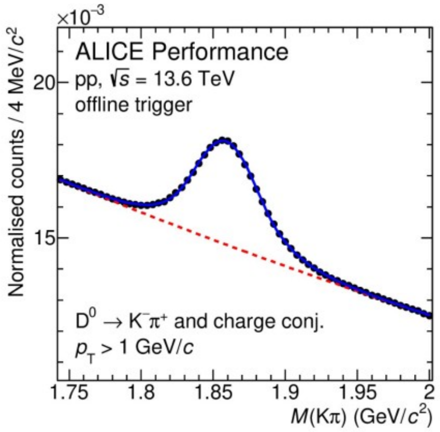




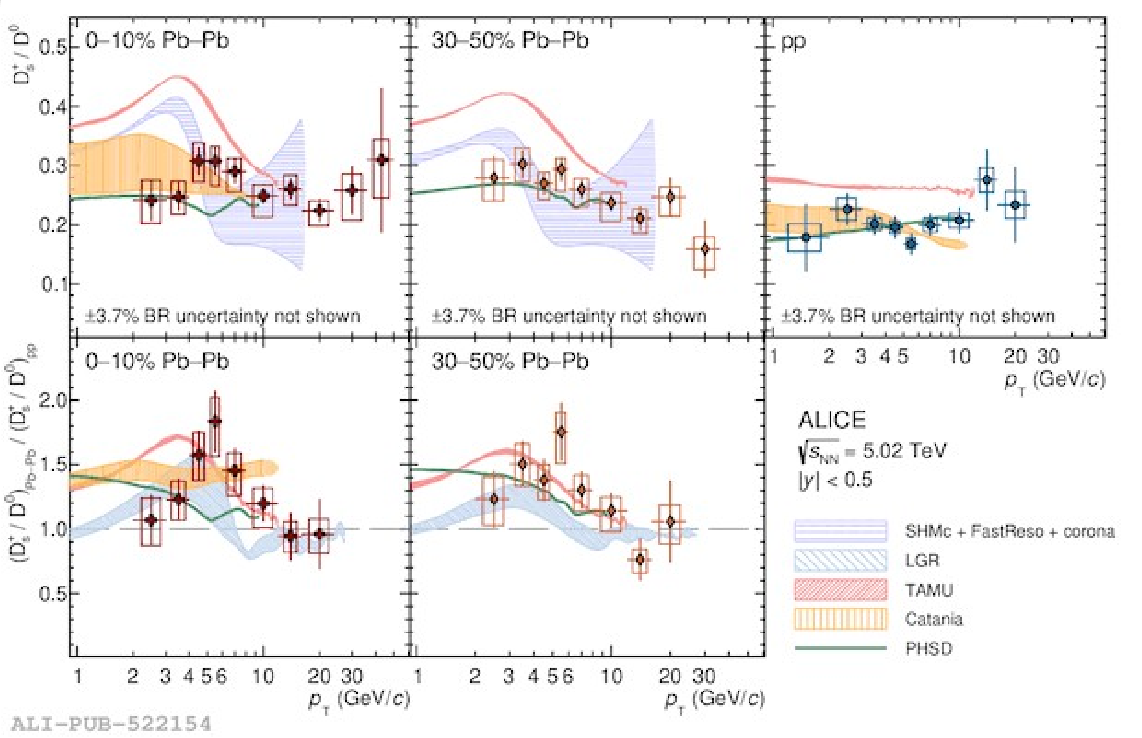
LHC Run-3 in progress:

- New ITS, GEM-based inner TPC
- Approximately 100x luminosity in pp
- Continuous readout system
- Precision and differential measurements
- Novel observables to disentangle possible sources of the observed effects

Stay tuned for new, precise Run 3 results!


Thank you!

Strangeness in Pb-Pb collisions



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

ALICE 3 – the detector concept

- **Compact silicon tracker** with a very low material budget
- Superconducting magnet system (Max field: B = 2 T)
- **Particle identification** in a wide range of momenta and $|\eta|<4$
- **Precise vertexing** capabilities and **great momentum resolution**
- Continuous readout, online data processing