Charm-hadron production, correlations and jets with ALICE

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Istituto Nazionale di Fisica Nucleare

ALICE

GDRI/COST workshop – Lisbon – 14/06/2018

PHYSICS MOTIVATIONS

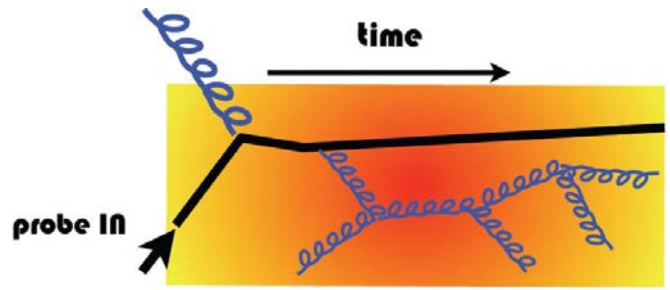
HEAVY-FLAVOUR PRODUCTION

Open heavy flavour in Pb-Pb collisions

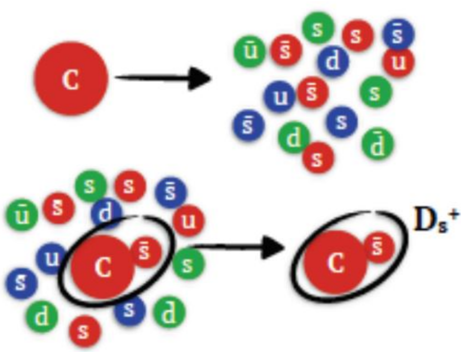
- Heavy quarks experience the full evolution of the hot and dense medium produced in ultra-relativistic heavy-ion collisions → Excellent probes of the QGP

In particular, heavy quarks are expected to:

- Lose less energy w.r.t light quarks and gluons due to different Casimir factor and dead-cone effect
  - ➢ Microscopic study of medium and characterisation of energy loss mechanisms



- Participate to some extent to the collective motion inside the medium
  - ➢ Provide information on medium transport properties ➡ ***F. Grosa's contribution***

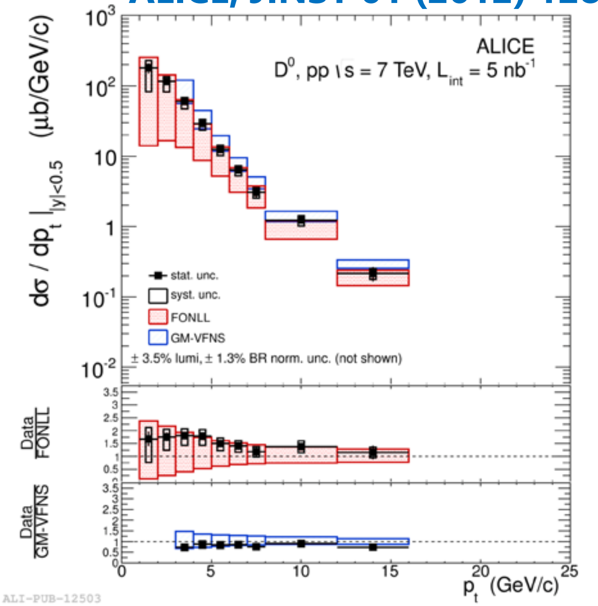


- At low p_T, possibly hadronise also via coalescence:
  - ➢ Modified momentum distribution of HF hadrons (radial flow «bump»)
  - ➢ Enhance v_2 of HF hadrons (light quark contribution)
  - ➢ Modify hadrochemistry, enhancing D_s^+, Λ_c^+ production

HEAVY-FLAVOUR PRODUCTION

Studies of heavy-flavour production important also in smaller systems

ALICE, JINST 01 (2012) 128



pp collisions

- Test and set constraints on production mechanisms
  - ➢ Production cross section can be treated perturbatively due to the large Q^2 involved
  - ➢ pQCD-based calculations describe reasonably well open charm and beauty production at the LHC
- Probe parton distribution function (especially for gluons) at low values of Bjorken x
- Reference for studies in p-Pb and Pb-Pb collisions

p-Pb collisions

- Heavy-flavour production and kinematic properties can be modified by:
  - ➢ Cold nuclear matter effects, like shadowing, gluon saturation/color glass condensate, Cronin effect, possible energy loss mechanisms
  - ➢ "Collective-like" effects (e.g. elliptic flow), resembling what observed in heavy-ion collisions, which is ascribed to the hydrodynamic expansion of the system

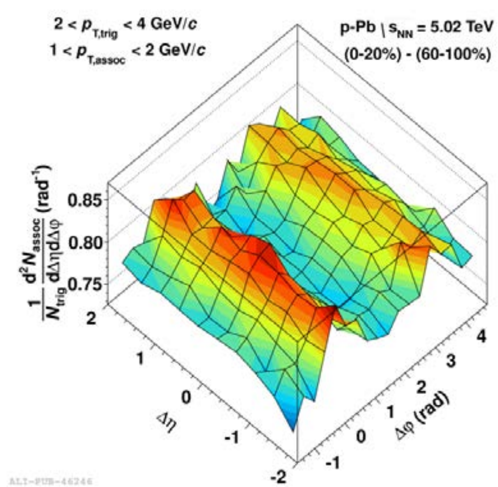
HEAVY-FLAVOUR CORRELATIONS

HF correlations: allow to gain further insight w.r.t. single-particle observables, by relating heavy-flavour particles to:

- The other tracks from the fragmentation of the same heavy quark
- The fragmentation particles from the other heavy quark in the event
- The underlying event (soft particle production)

pp collisions

- Investigate heavy-flavour quark fragmentation properties and characterize heavy-flavour jets
- Sensitivity to modeling of HQ production processes
- Reference for p-Pb and Pb-Pb results



ALICE, PLB 719 (2013) 29-41

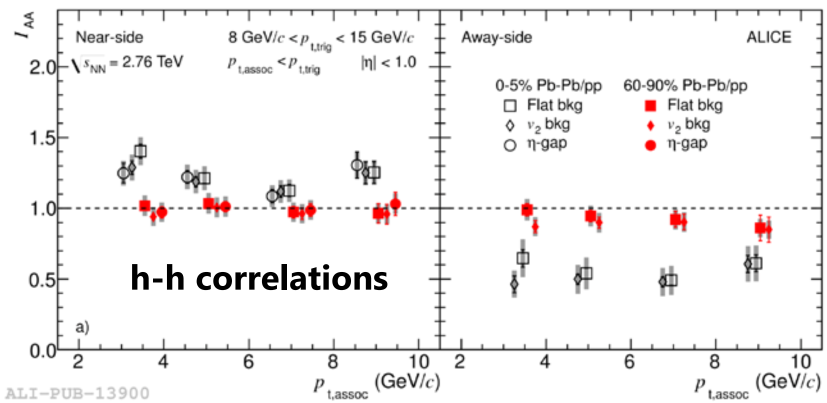
p-Pb collisions

- Investigate possible modifications of angular correlation pattern from cold nuclear matter effects
- Search for long-range ridge-like structures (double ridge), observed in di-hadron correlations, also in the heavy-flavour sector, possibly due to initial- (e.g. CGC) or final-state effects (e.g. hydrodynamics)

HEAVY-FLAVOUR CORRELATIONS

Pb-Pb collisions

- Probe the QGP effects on heavy quarks by studying how correlation distributions of heavy-flavour particles are modified w.r.t. vacuum



ALICE, PRL 108 (2012) 092301

- Add sensitivity to study contribution of radiative and collisional parton energy loss in QGP medium?

Pb-Pb @ 2.76 TeV
LO process only
→ Initial distribution: Δφ=π

For light flavour correlations:

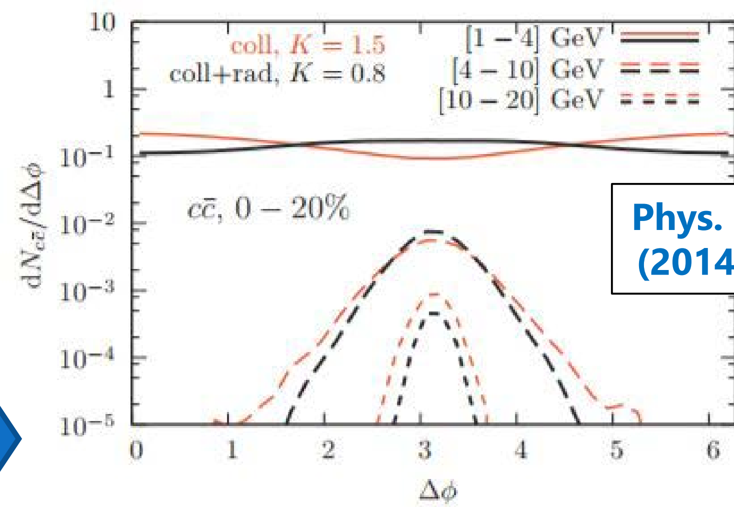
Away-side suppression at high p_T

- ➢ Path-length dependence of energy loss

Near-side peak enhancement: interplay of

- ➢ Modification to quark/gluon ratio
- ➢ Bias in partons p_T spectrum due to energy loss in medium
- ➢ Modified parton fragmentation

Note - Different fragmentation, energy loss in medium, kinematic bias between heavy and light quarks! I_{AA} not directly comparable!



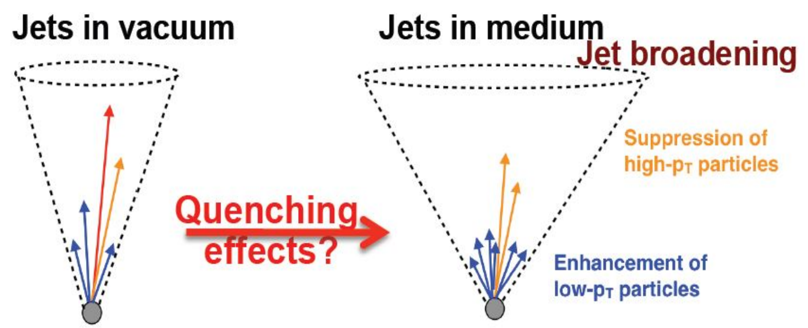
Phys. Rev. C 90 (2014) 024907

HEAVY-FLAVOUR JETS

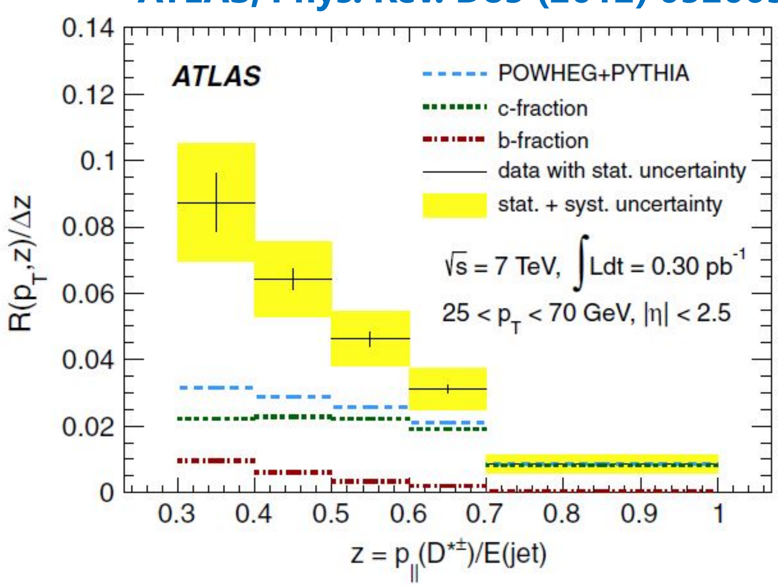
Complementary information w.r.t. correlations, seeing the parton fragments as a single object instead of as a particle ensemble

Tight connection with HF correlations also for some goals, with alternative approach:

- Spatial distribution of energy lost in the medium by heavy quarks → differences with respect to light flavour/gluon jets?



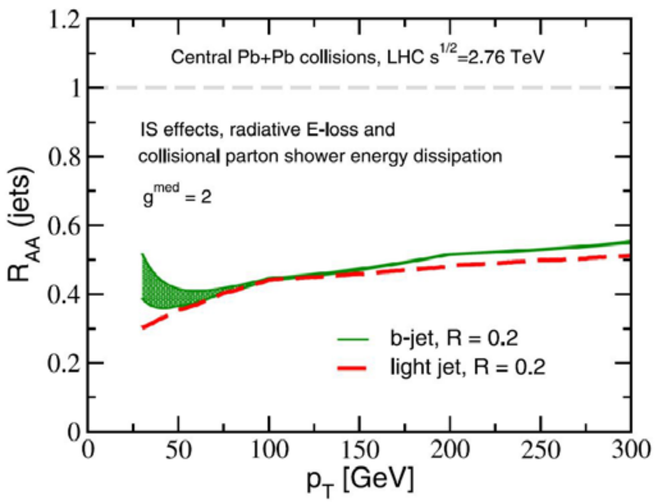
ATLAS, Phys. Rev. D85 (2012) 052005



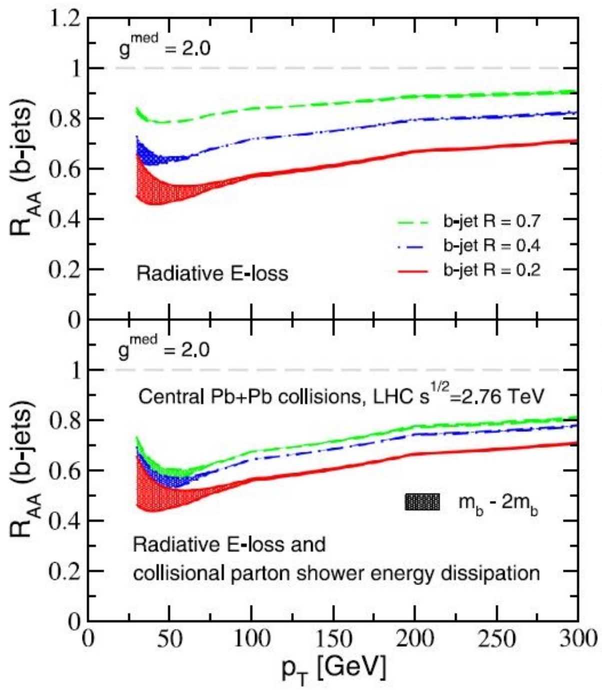
- Jets tagged by HF hadron (D-jets, b-jets, ...): study of jet momentum fraction taken by the particle and its modification in a QGP medium
- Studies important also in pp and p-Pb (reference for Pb-Pb measurements, impact of cold-nuclear-matter effects)

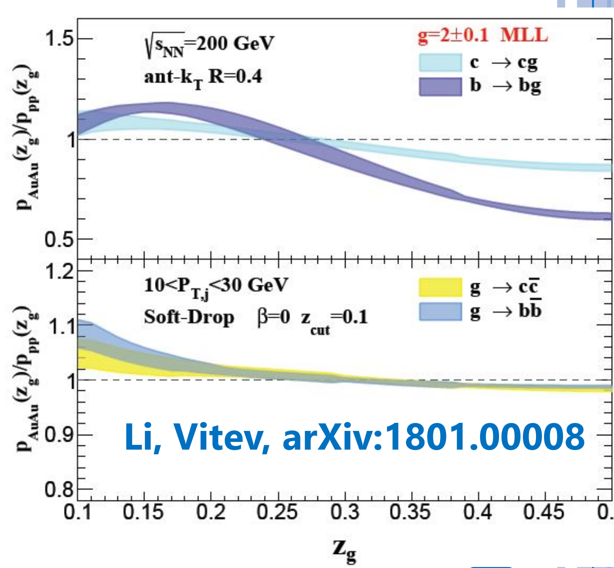
HEAVY-FLAVOUR JETS

- Comparison of b-jet R_{AA} with inclusive jet to investigate mass effect on medium-induced ΔE
  - ✓ Mass effects relevant for p_T < 75 GeV/c, dead-cone effect not negligible
  - ✓ Measurements vs opening radius *R* to characterize energy dissipation and possibly separate collisional and radiative energy loss
  - ✓ Energy loss in gluon splitting cases (high p_T): b-pair seen by medium as massive gluon?
  - ✓ Addressing the jet momentum sharing (via "soft drop declustering" technique) could probe the QGP-induced modifications of the heavy-flavour 1→2 jet splitting function



Vitev et al., PLB 726 (2013) 251



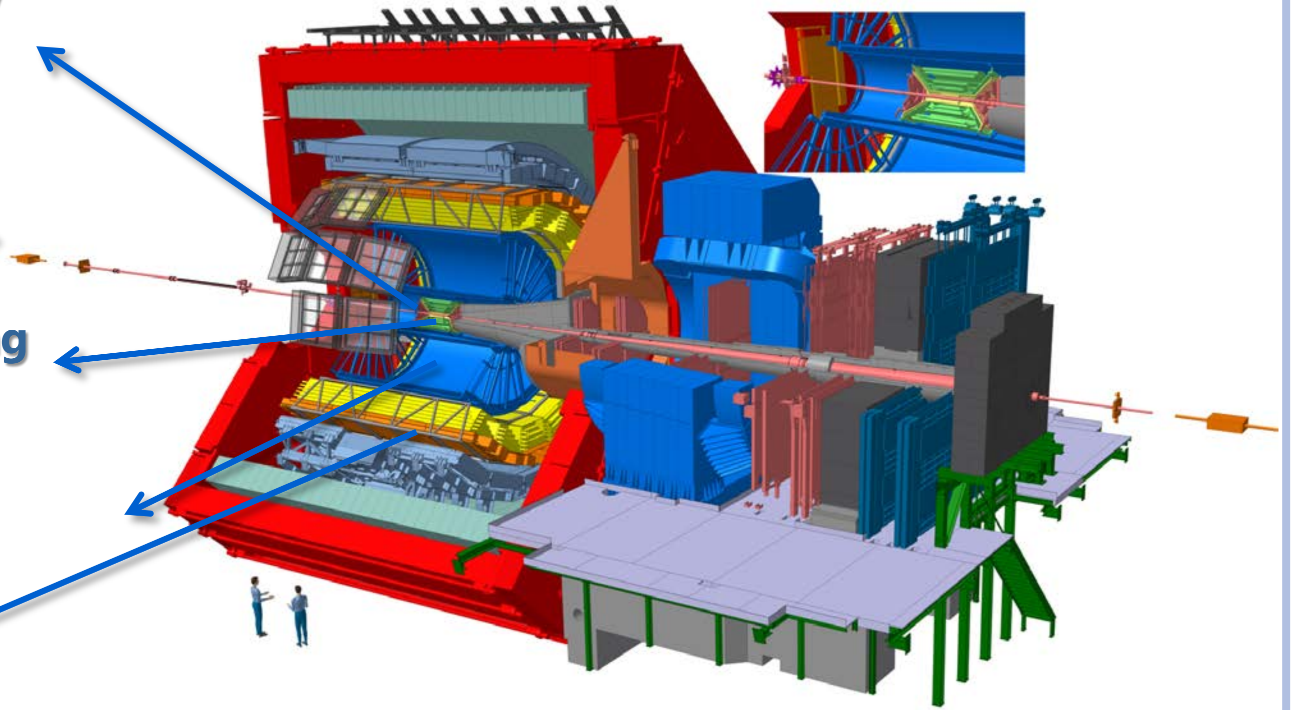


Li, Vitev, arXiv:1801.00008

D-meson production and modifications by nuclear matter effects

THE ALICE DETECTOR

ALICE central barrel coverage (ITS+TPD+TOF): $|\eta| < 0.9$

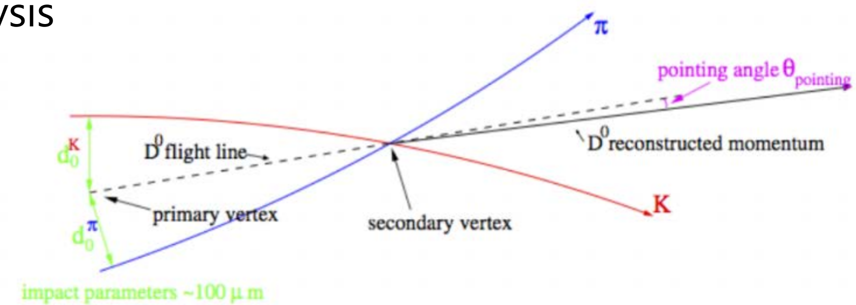


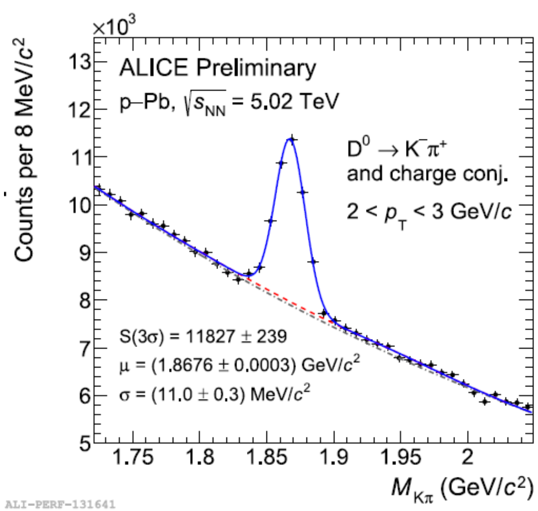
Data samples:

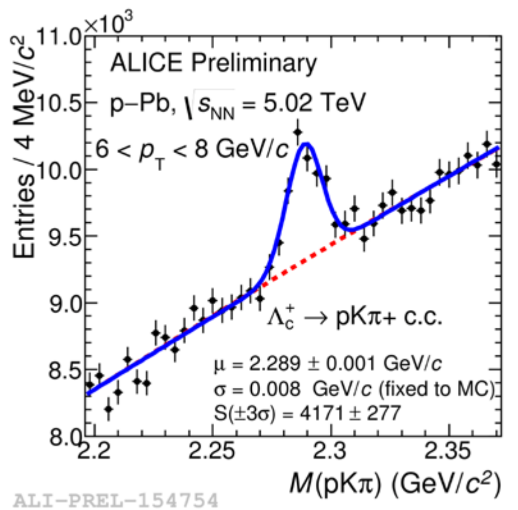
- **pp**: $L_{int} \approx 5$ nb^{-1} at $\sqrt{s}$ = 7 TeV (2010), $L_{int} \approx 8$ nb^{-1} at $\sqrt{s}$ = 13 TeV (2016), $L_{int} \approx 19$ nb^{-1} at $\sqrt{s}$ = 5 TeV (2017), MB events,
- **p-Pb**: $L_{int} \approx 300$ μb^{-1} at $\sqrt{s_{NN}}$ = 5.02 TeV (2016), MB events
- **Pb-Pb**: $L_{int} \approx 26$ μb^{-1} at $\sqrt{s_{NN}}$ = 5.02 TeV (2015), MB events

CHARMED HADRON RECONSTRUCTION

- Reconstruction and selection of charm-hadron candidates exploiting the displaced decay topologies + particle identification on daughter tracks (p/K/π)
  - Multivariate approach (BDT) also available for Λ_c^+ in p-Pb
- Signal extracted via an invariant-mass analysis
- Feed-down from beauty-hadron decays subtracted by means of FONLL calculations + assumptions on feed-down nuclear modification factor



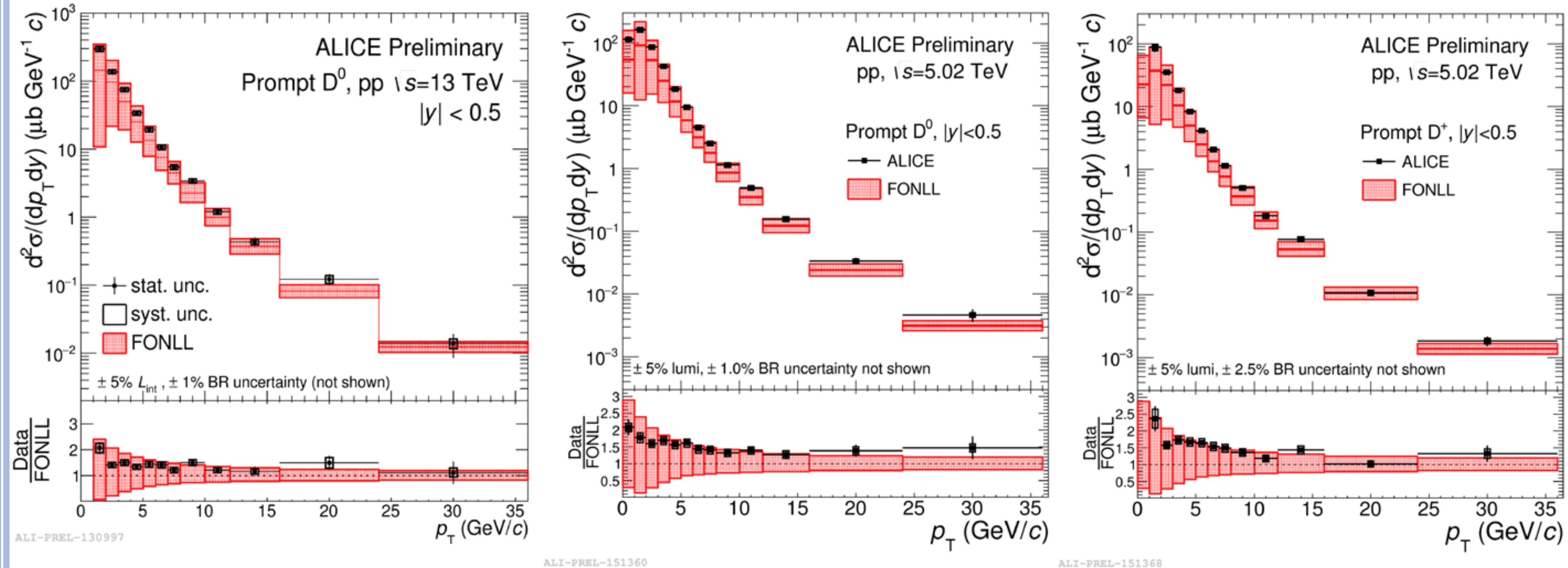




Charmed hadrons ($|y| < 0.5$)

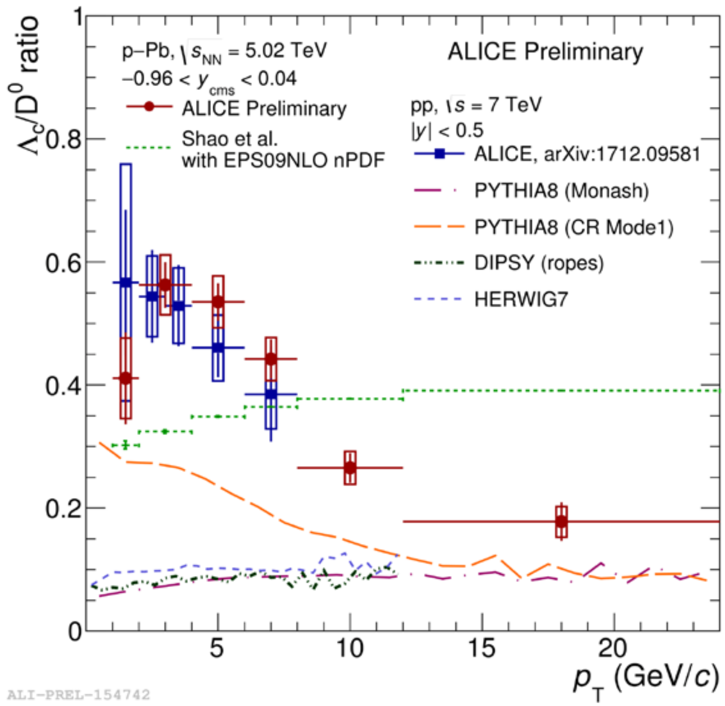
- ✓ $D^0 \to K^-\pi^+$
- ✓ $D^* \to D^0\pi^+ \to K^-\pi^+\pi^+$
- ✓ $D^+ \to K^-\pi^+\pi^+$
- ✓ $D^+_s \to \varphi\pi^+ \to K^-K^+\pi^+$
- ✓ $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda c \to pK^0_s$, $K^0_s \to \pi^+\pi^-$
- ✓ $\Lambda_c^+ \to e^+\Lambda\nu$, $\Lambda \to p\pi^-$
- ✓ $(\Xi_b \to)\ \Xi_c^0 \to e^+\Xi^-\nu e$, $\Xi^- \to \pi^-\Lambda$

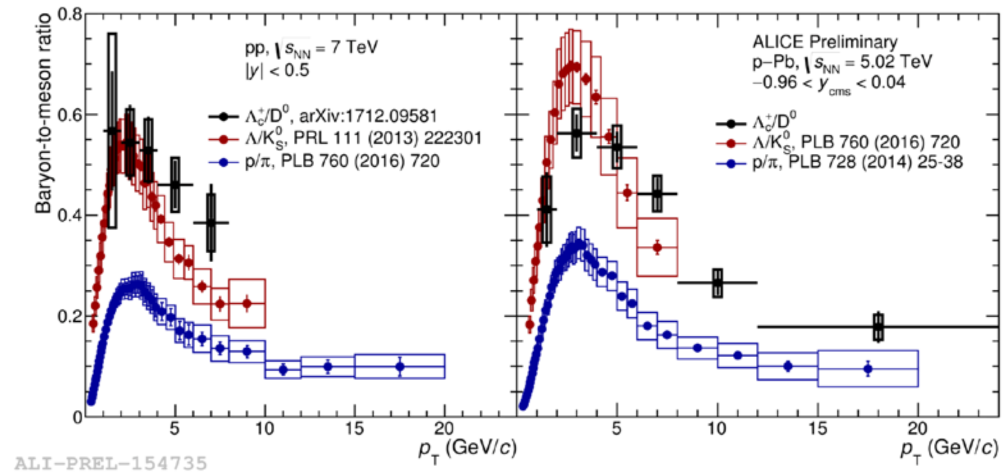
D MESONS IN pp COLLISIONS



- D-meson cross sections vs p_T measured for several energies ($\sqrt{s}$ = 2.76, 5.02, 7, 8, 13 TeV) → New results from pp@5 TeV
- Excellent constraints for charm production cross section over a wide p_T interval
  - ➢ D^0 cross section down to $p_T = 0$
- All measurements are consistent with pQCD calculations, data always on upper part of FONLL uncertainty band (much larger than data one)

CHARMED BARYONS IN pp AND p-Pb



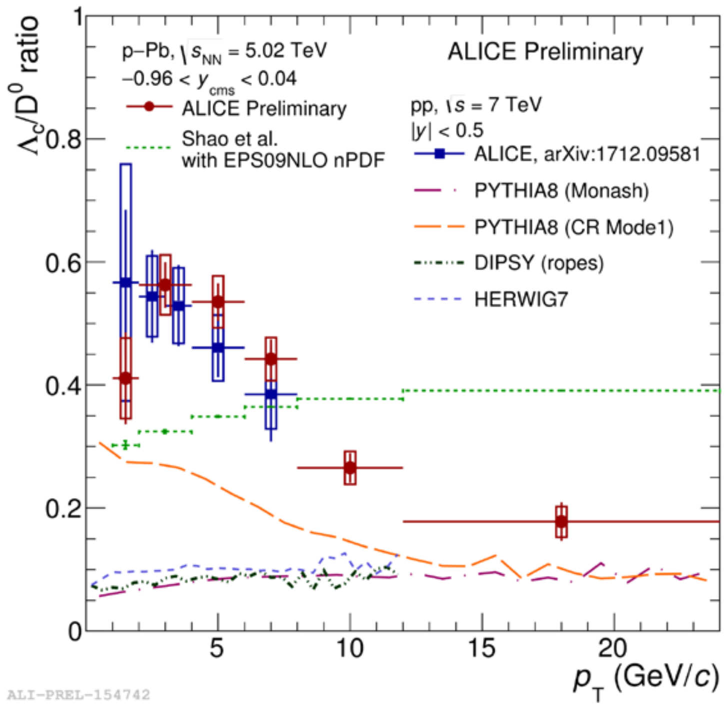


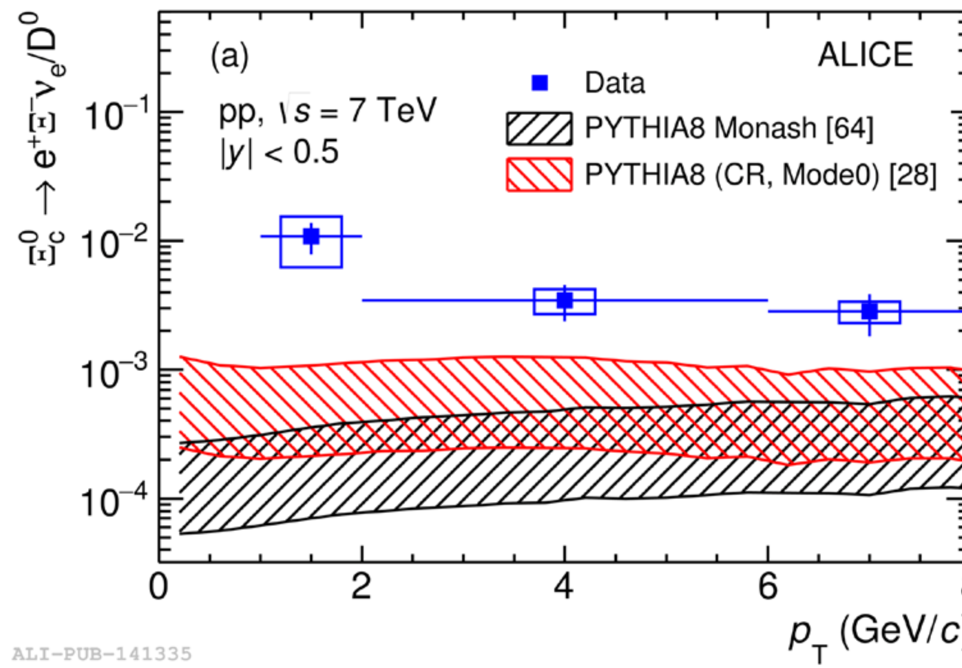
- Λ_c^+/D^0 ratios in pp and p-Pb collisions are compatible within uncertainties
  - p-Pb: decreasing values from p_T > 4 GeV/c, as for light flavor baryon-to-meson ratio
- First Ξ_c^0 production measurement at LHC
- Both Λ_c^+/D^0 and Ξ_c^0/D^0 ratios are **higher than MC expectation** (tuned on e^+e^-, e^-p data)
  - ➢ Enhanced color reconnection configuration of PYTHIA 8 is closer to data
  - ➢ Theory bands on Ξ_c^0 due to the uncertainty on the branching ratio $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$

CHARMED BARYONS IN pp AND p-Pb

ALICE

arXiv:1712.04242





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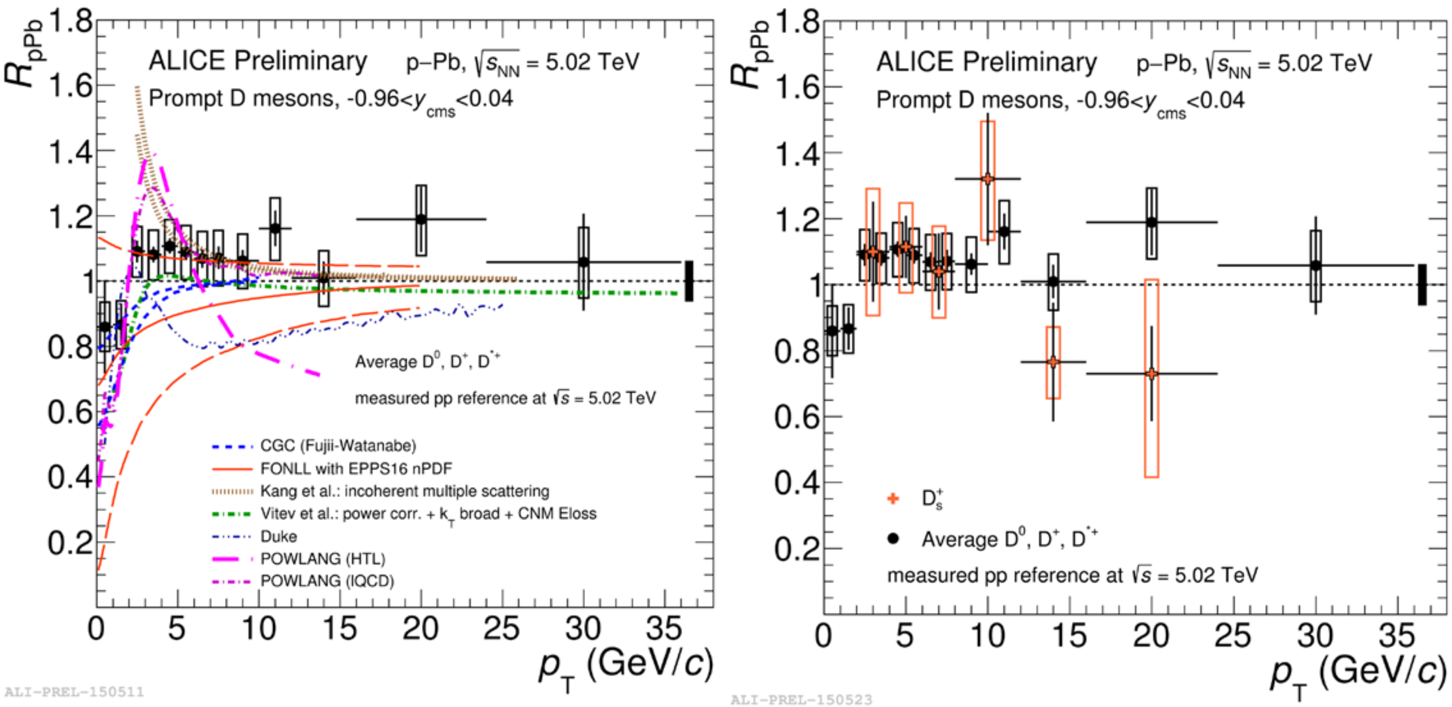
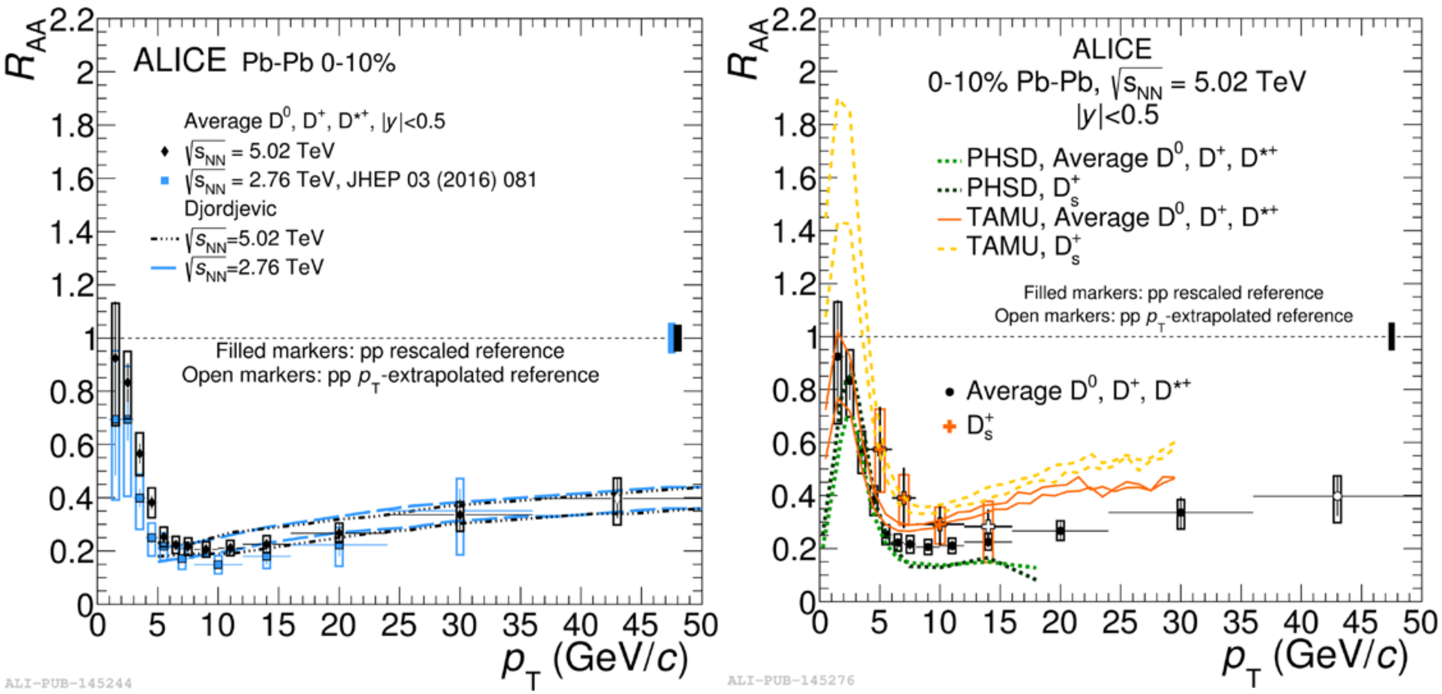
D-MESON R_{pPb}



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

- New preliminary results with better precision, due to reduction of uncertainties in the pp reference (2017 sample)
- Non-strange D meson R_{pPb} is **compatible with unity** within uncertainties
  - Described by models including cold nuclear-matter effects and, at low p_T, by those assuming QGP formation
- **No differences** in strange vs non-strange D-meson R_{pPb} within current uncertainties

D-MESON R_{AA} RESULTS



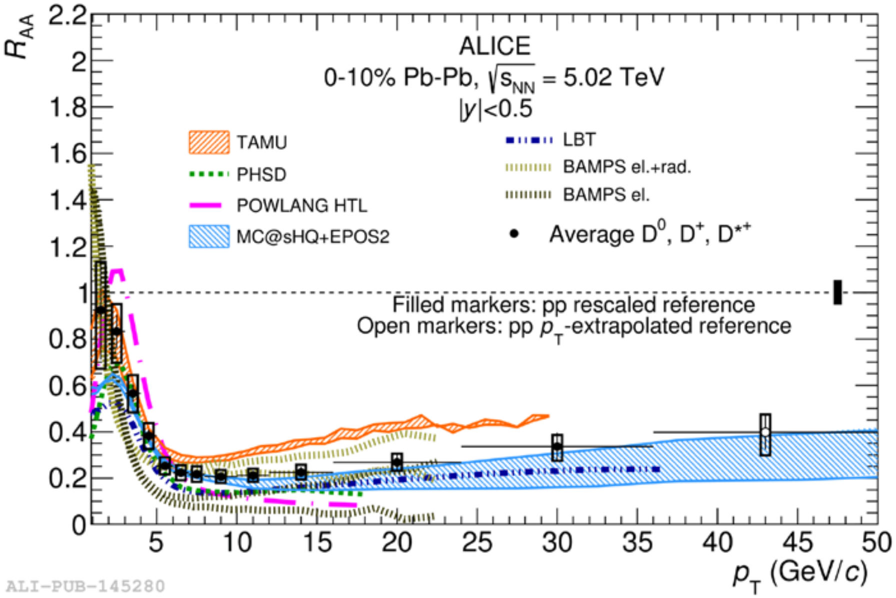
arXiv:1804.09083

$$R_{AA} = \frac{\frac{dN_{AA}}{dp_T}}{\langle T_{AA}\rangle \cdot \frac{d\sigma_{pp}}{dp_T}}$$

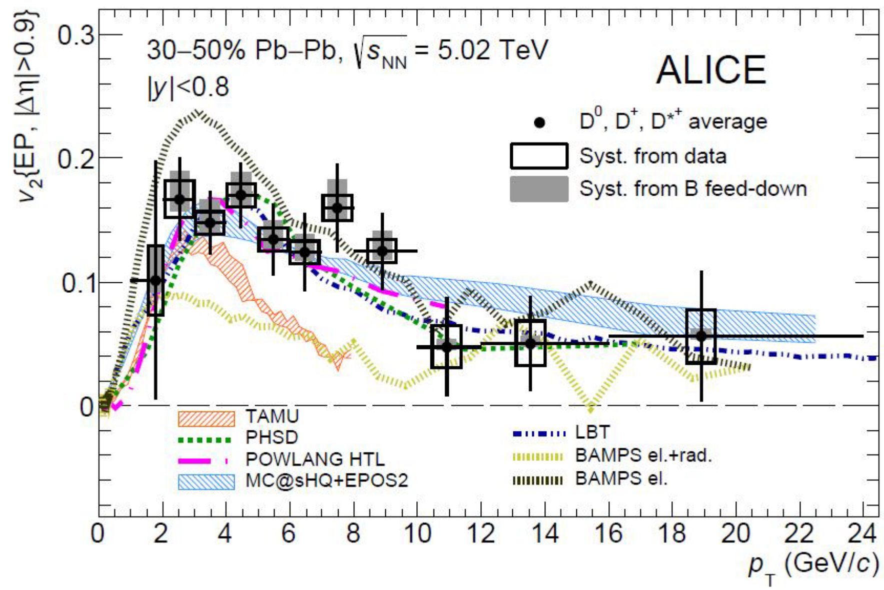
- **Strong D-meson suppression** in central Pb-Pb collisions (factor ≈5 at 6-10 GeV/c)
  - Similar suppression at 5.02 TeV and 2.76 TeV: expected by models as a counterbalance between denser medium and harder spectrum of charm quark
- **Hint for $R_{AA}(D_s^+)$ > R_{AA}(non-strange D)** in lower p_T range, predicted by models
  - Due to hadronisation via coalescence + strangeness enrichment?

D-MESON R_{AA} (AND v_2) VS MODELS

arXiv:1804.09083

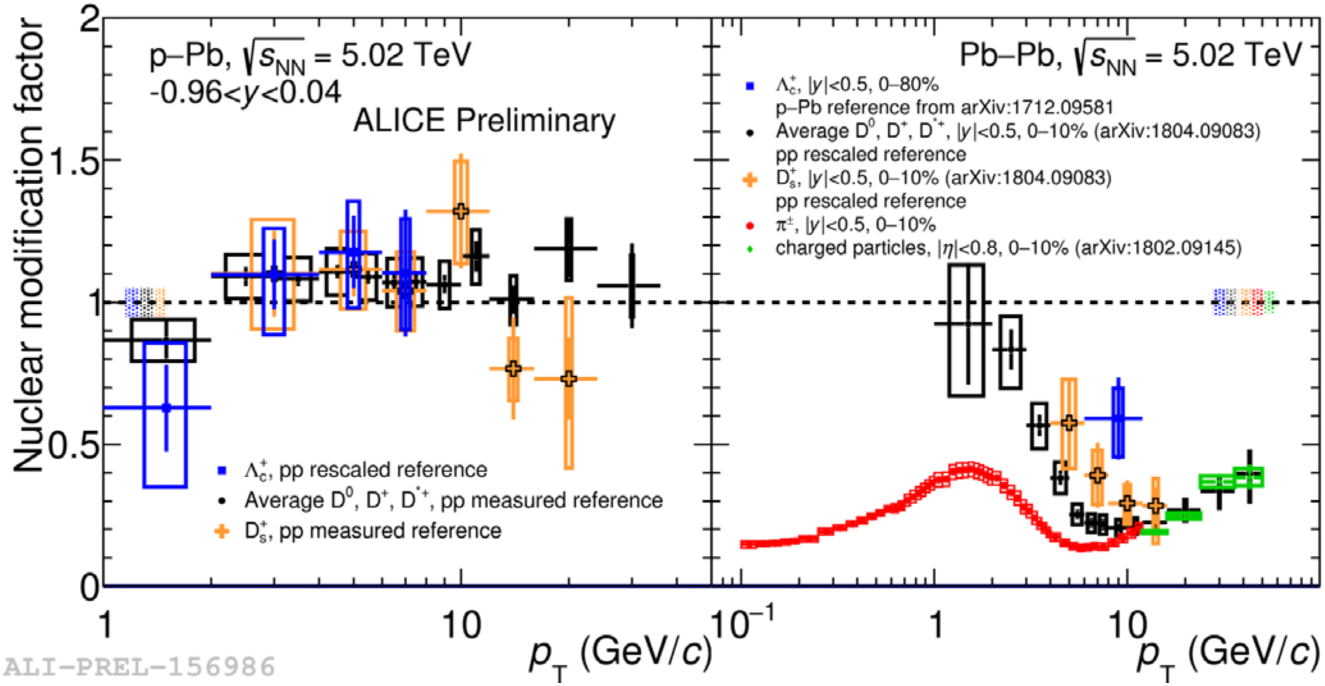


PRL 120, 102301 (2018)



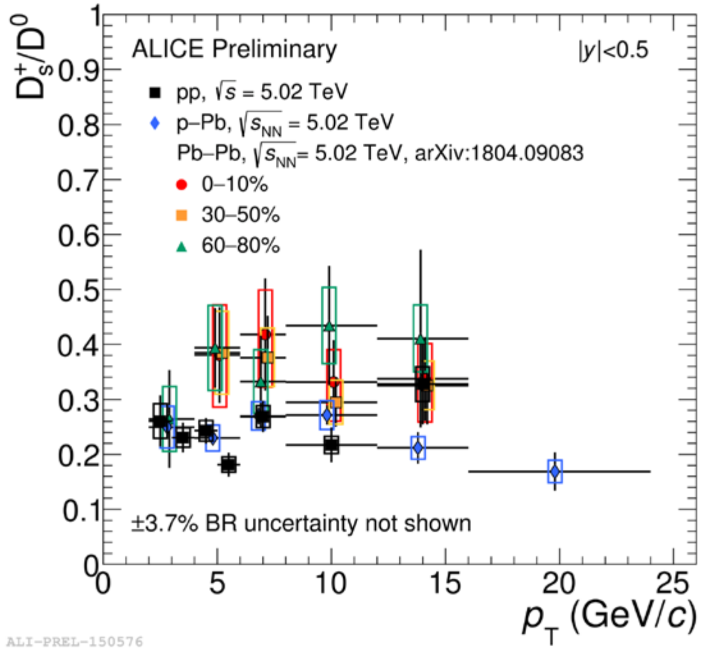
- Models with diffusion coefficient $2\pi D_s(T)$ in the range **1.5-7** at T_c with a corresponding thermalisation time **τ_{charm}~ 3-14 fm/*c*** describe better the v_2 values and p_T trend
- A simultaneous description of complementary observables (R_{AA} and v_2) over a wide p_T range is a challenging task: measurements allow us to set strong constraints to models
  - Models in which charm quarks pick up collective flow via **recombination** or **subsequent elastic collisions + radiative energy loss** in expanding medium better describe both v_2 and R_{AA} at low p_T

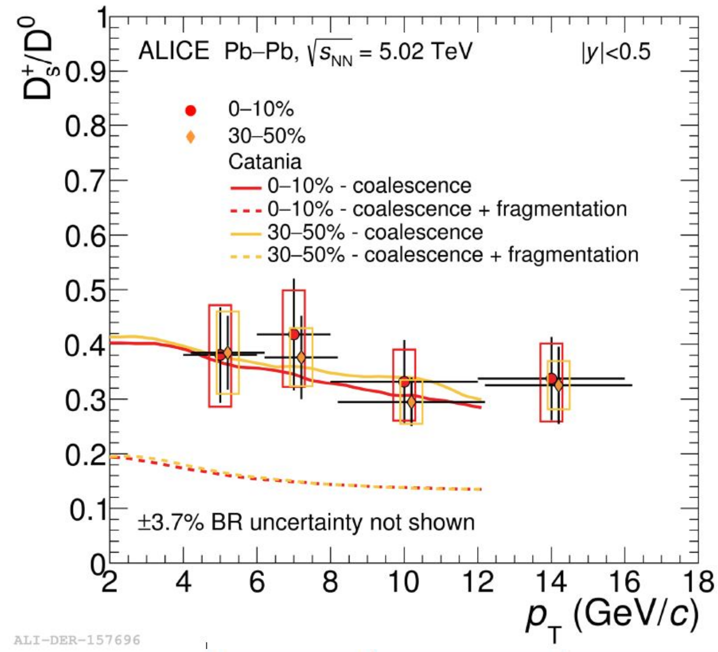
CHARM HADRONS R_{pPb} AND R_{AA}



- R_{pPb} of Λ_c^+, D_s^+ and non-strange D-mesons **all compatible with unity**
- Hint of **larger R_{AA} for Λ_c^+** in 0-80% than for D meson in 0-10%, expected by coalescence scenario
- Possible hierarchy for **$R_{AA}(\Lambda_c^+$, 0-80%)** > **$R_{AA}(D_s^+$, 0-10%)** > **$R_{AA}(D^{0,+,*+}$, 0-10%)**
  - ➢ From hadronisation via coalescence?
- At low p_T, **R_{AA}(non-strange D)** > **$R_{AA}(\pi)$.**
  - ➢ To be interpreted with care: different fragmentation functions, initial parton p_T spectrum, radial flow contribution, N_{coll} scaling violation at low p_T for charged pions, …

CHARM HADRON RATIOS





- Hint of **enhanced D_s^+ production** compared to non-strange D mesons in Pb-Pb collisions
  - No evidence of centrality dependence within uncertainties
- In Pb-Pb collisions, **Λ_c^+/D^0 ratio shows hint of enhancement** w.r.t. pp and p-Pb
  - Underestimated by model predictions

Models	System energy	Λ_c^+/D^0
Oh et al.	Au-Au (central) 200 GeV	~0.35 (p_T = 6 GeV/c)
Ghosh et al.	RHIC and LHC	0.15-0.2 (p_T = 9 GeV/c)
Das et al.	Pb-Pb (0-20%) 5.5 TeV	~0.2 (p_T = 9 GeV/c)
Plumari et al.	Pb-Pb (0-20%) 2.76 TeV	0.1-0.2 (p_T = 8 GeV/c)

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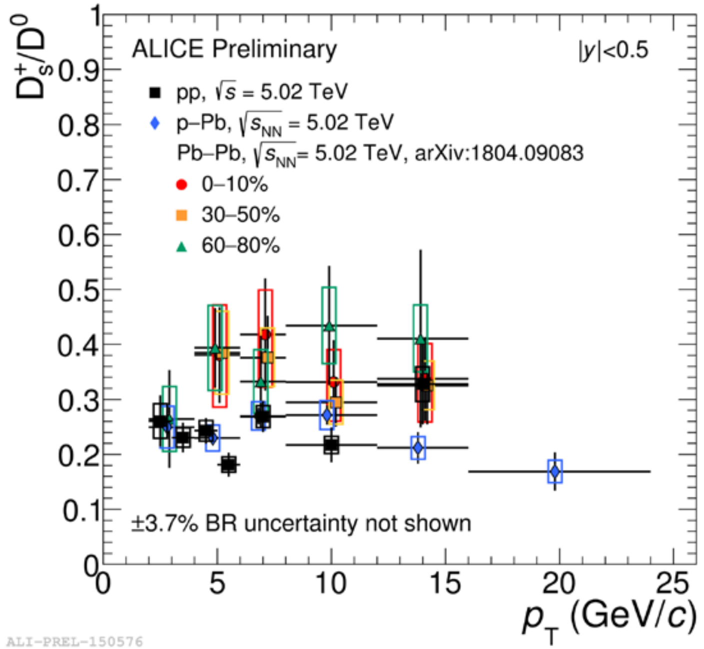

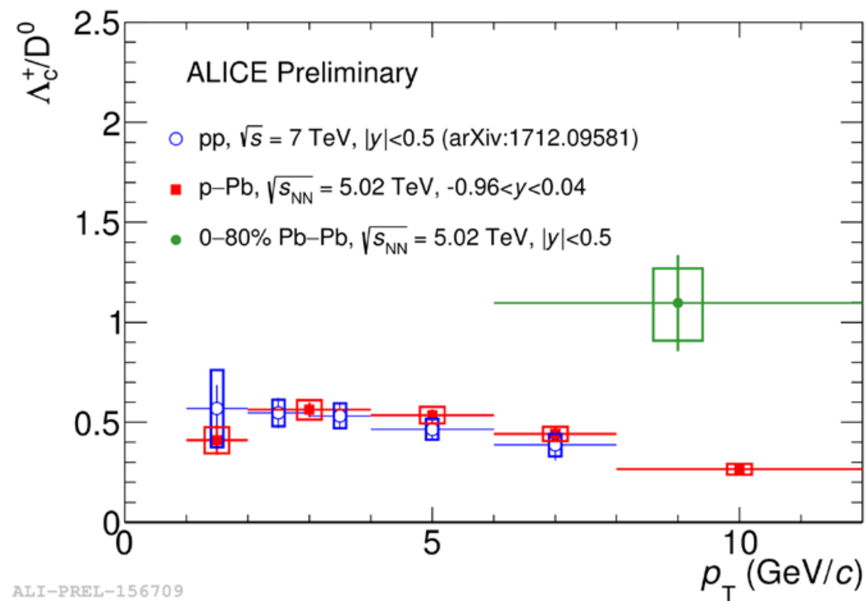

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D-meson – hadron azimuthal correlations

D-h CORRELATIONS: ANALYSIS STRATEGY

- Selected D mesons (including background) used as «**trigger**» particles for building (Δφ,Δη) angular correlations
- «**Associated**» particles correlated to D-mesons selected via kinematic (p_T > 0.3 GeV/c, |η| < 0.8) and track-quality cuts
- Background D-meson candidates removed exploiting sideband subtraction
- Correction for limited detector acceptance and for detector spatial inhomogeneities via **event mixing**
- Correction for inefficiencies in D-meson and associated track reconstruction
- Removal of B→D feed-down contribution and of contamination from secondary tracks
- Weighted average of D^0, D^+, D^{*+} Δφ correlations
- Fit to correlation distributions to extract quantitative observables (near- and away-side peak yields and widths, baseline height)

$$f(\Delta\phi) = c + \frac{Y_{NS}}{\sqrt{2\pi}\sigma_{NS}} e^{\frac{(\Delta\phi-\mu_{NS})^2}{2\sigma_{NS}^2}} + \frac{Y_{AS}}{\sqrt{2\pi}\sigma_{AS}} e^{\frac{(\Delta\phi-\mu_{AS})^2}{2\sigma_{AS}^2}}$$

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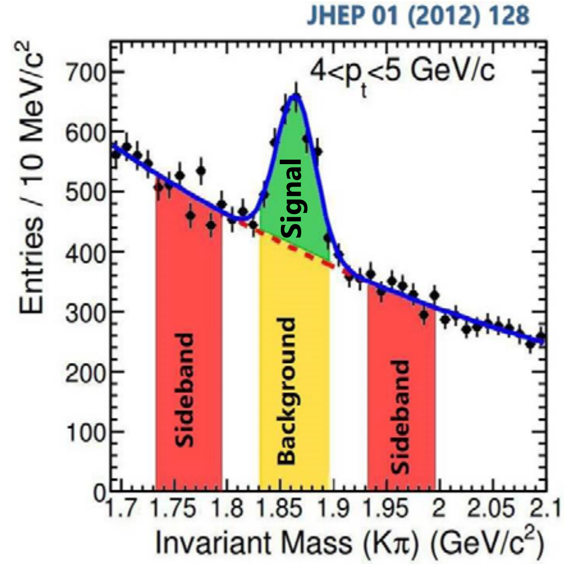
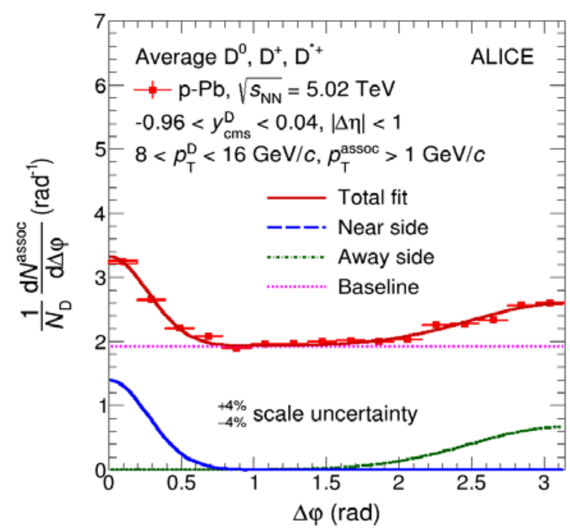
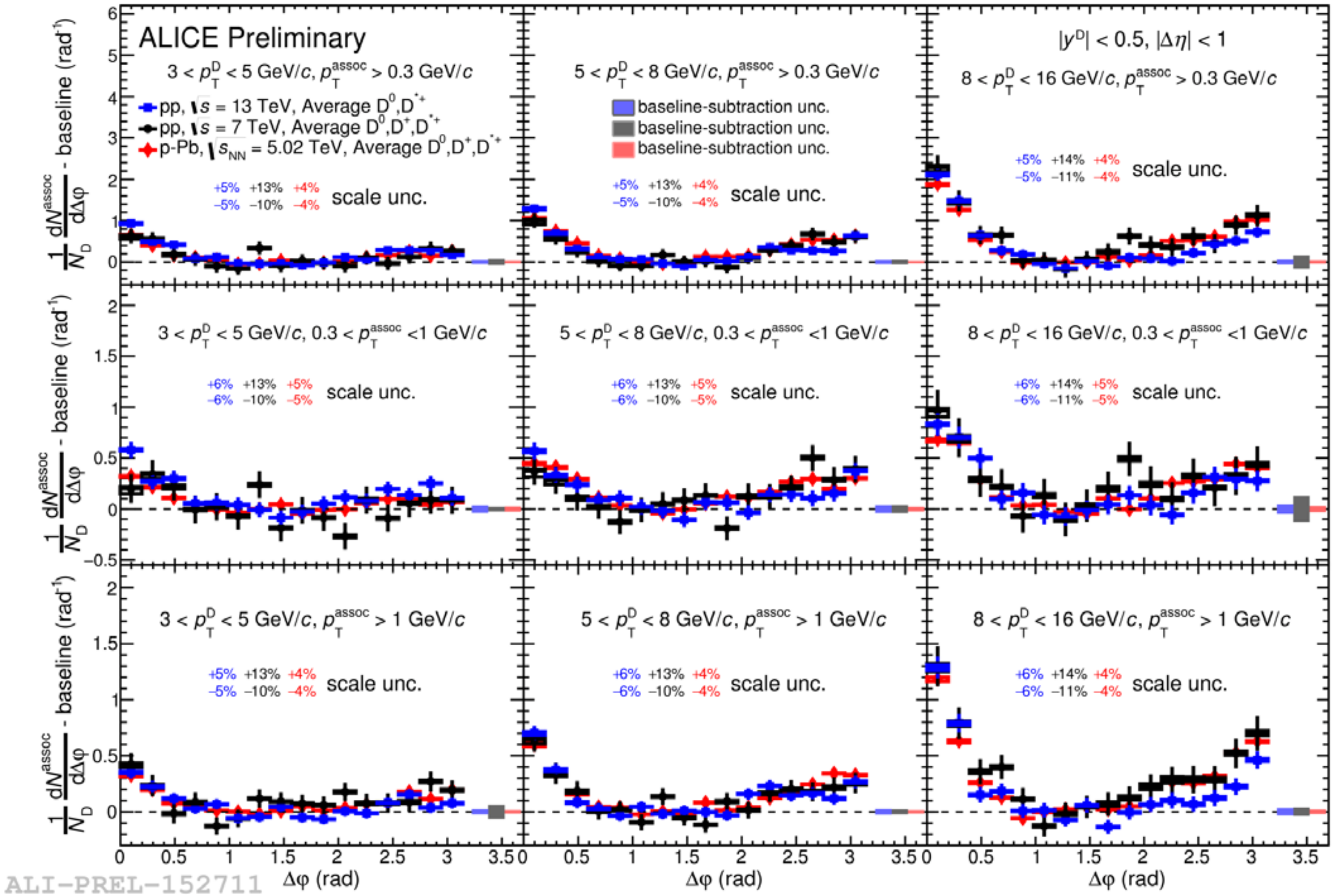




ALICE, EPJ C 77 (2017) 245

D-h CORRELATIONS: pp VS p-Pb



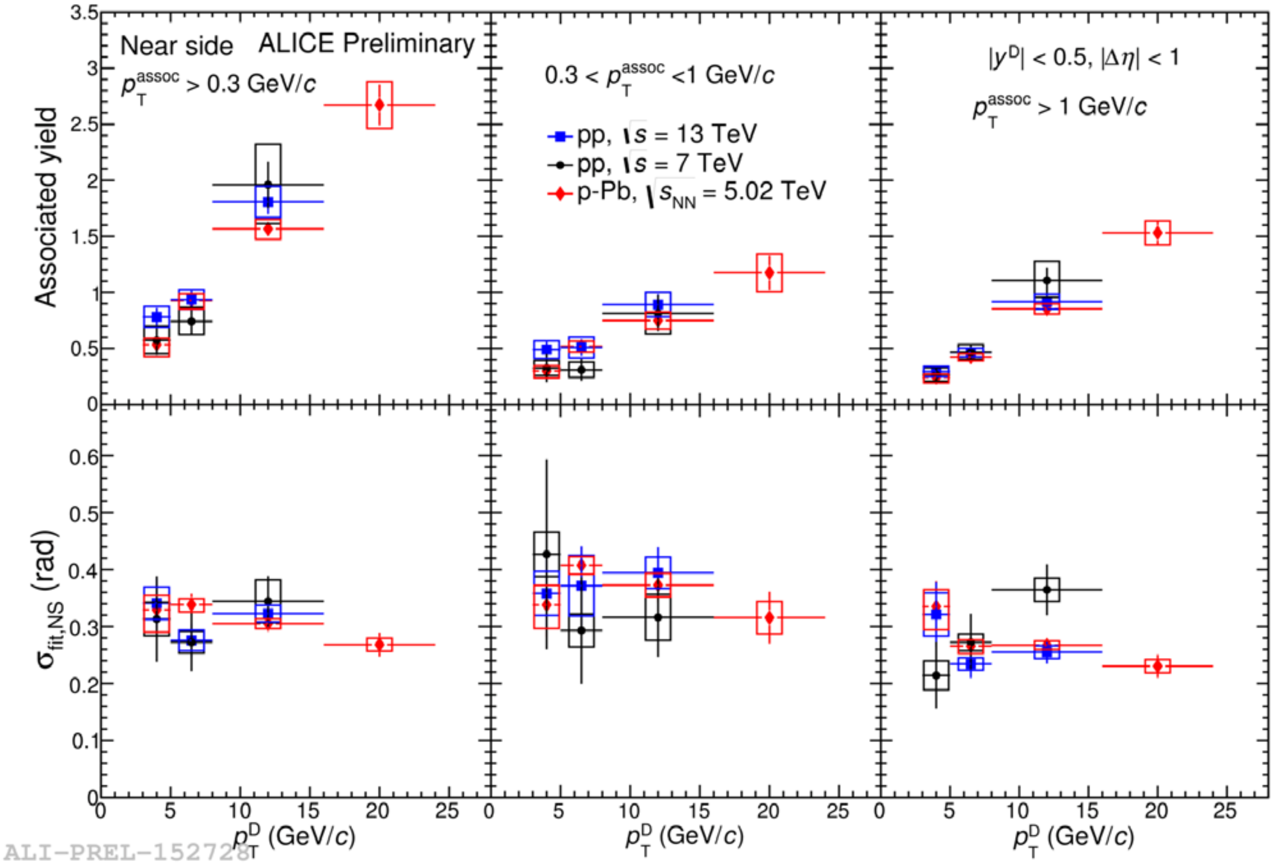
Comparison of D-h Δφ correlation distributions after baseline subtraction

***p*$_T$(D) ranges**
3-5, 5-8, 8-16 GeV/*c*

***p*$_T$(assoc) ranges**
>0.3, 0.3-1, >1 GeV/*c*

- Compatibility of correlation pattern and its p_T evolution for all kinematic ranges for pp collisions at $\sqrt{s}$ = 5, 13 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV

D-h CORRELATIONS: pp VS p-Pb



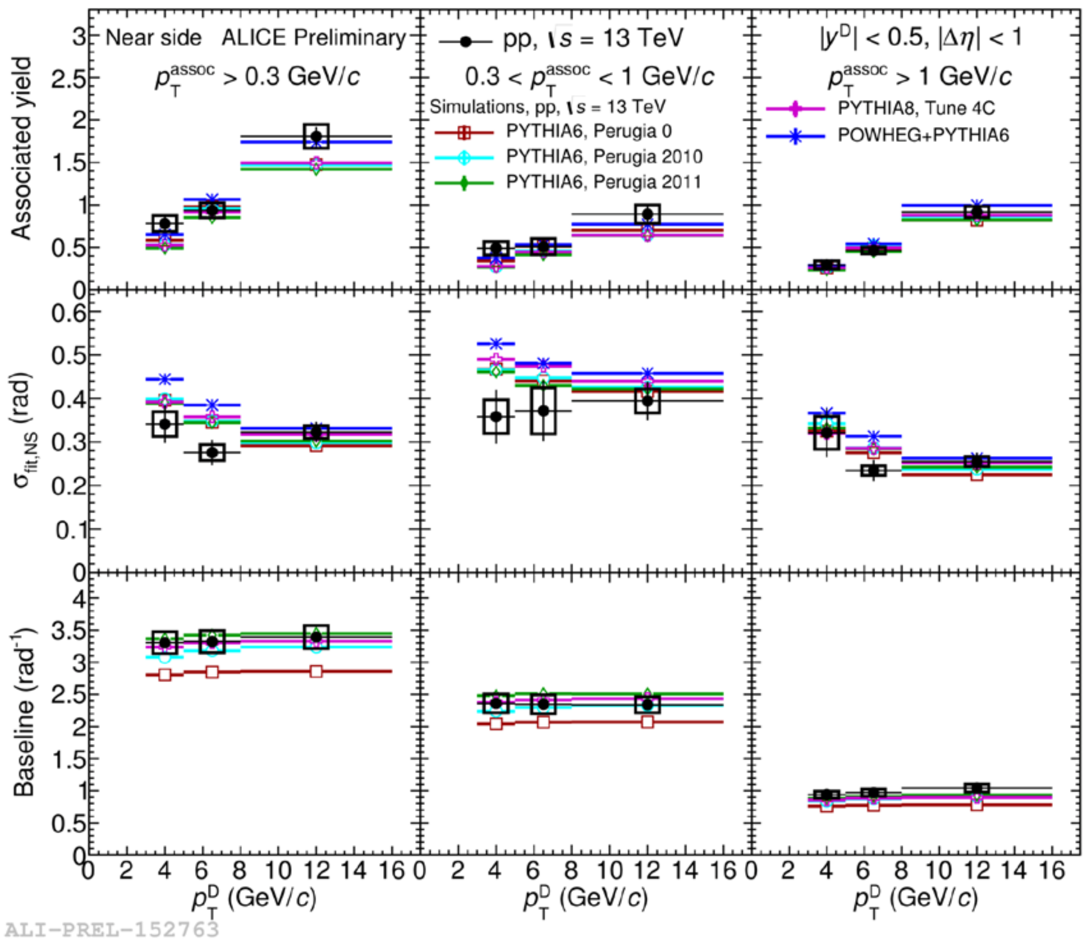
Comparison of near-side peak yield and width from fit to the correlation distributions

***p*$_T$(D) ranges**
3-5, 5-8, 8-16, 16-24 GeV/*c*

***p*$_T$(assoc) ranges**
>0.3, 0.3-1, >1 GeV/*c*

- Expected rising trend of yields vs p_T(D). Tendency of narrower peak with p_T(D)
- Similar near-side peak properties for the three systems
  - No evidence, within uncertainties, of modifications from possible cold-nuclear matter or medium-like effects

D-h CORRELATIONS: pp VS MODELS



Comparison of near-side peak yield and width from data and Monte Carlo predictions

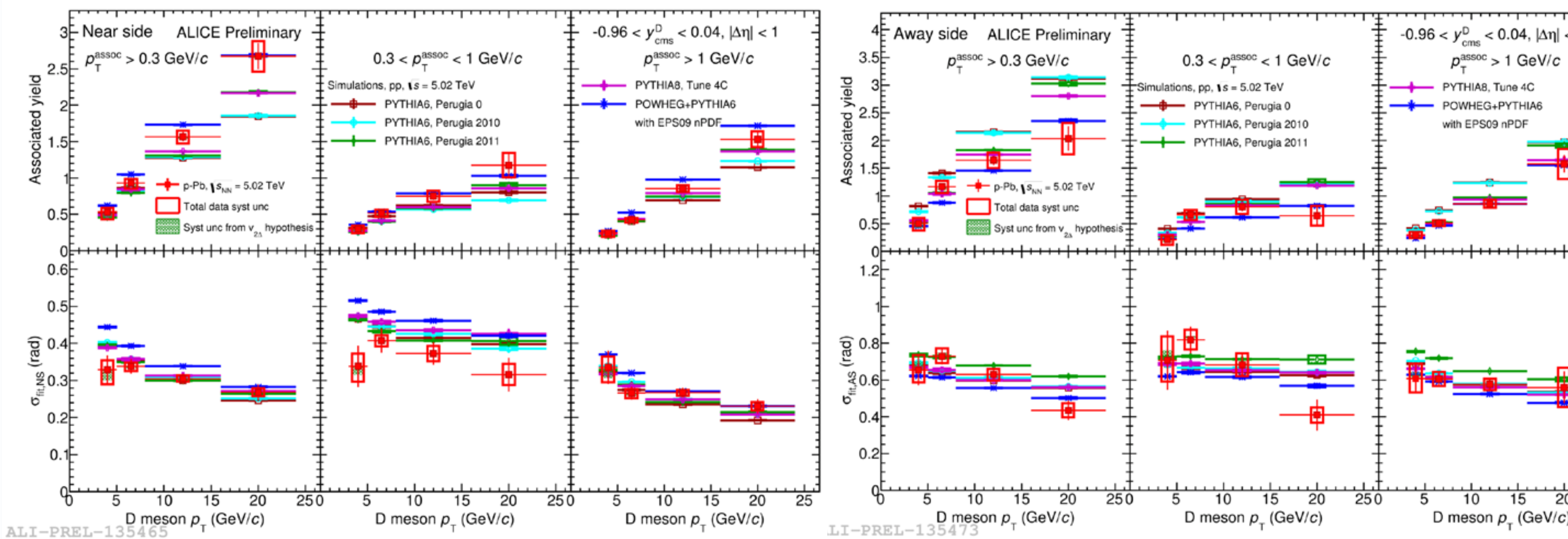
***p_T*(D) ranges**
3-5, 5-8, 8-16 GeV/*c*

***p_T*(assoc) ranges**
>0.3, 0.3-1, >1 GeV/*c*

- New results at 13 TeV confirm good description of data features by PYTHIA6,8, POWHEG predictions
  - Good observable to study the charm jet fragmentation modification in the QGP
- Analysis of the away-side ongoing with a x4 larger data sample

D-h CORRELATIONS: p-Pb VS MODELS

Comparison of near-side and away-side peak yields and widths to Monte Carlo predictions



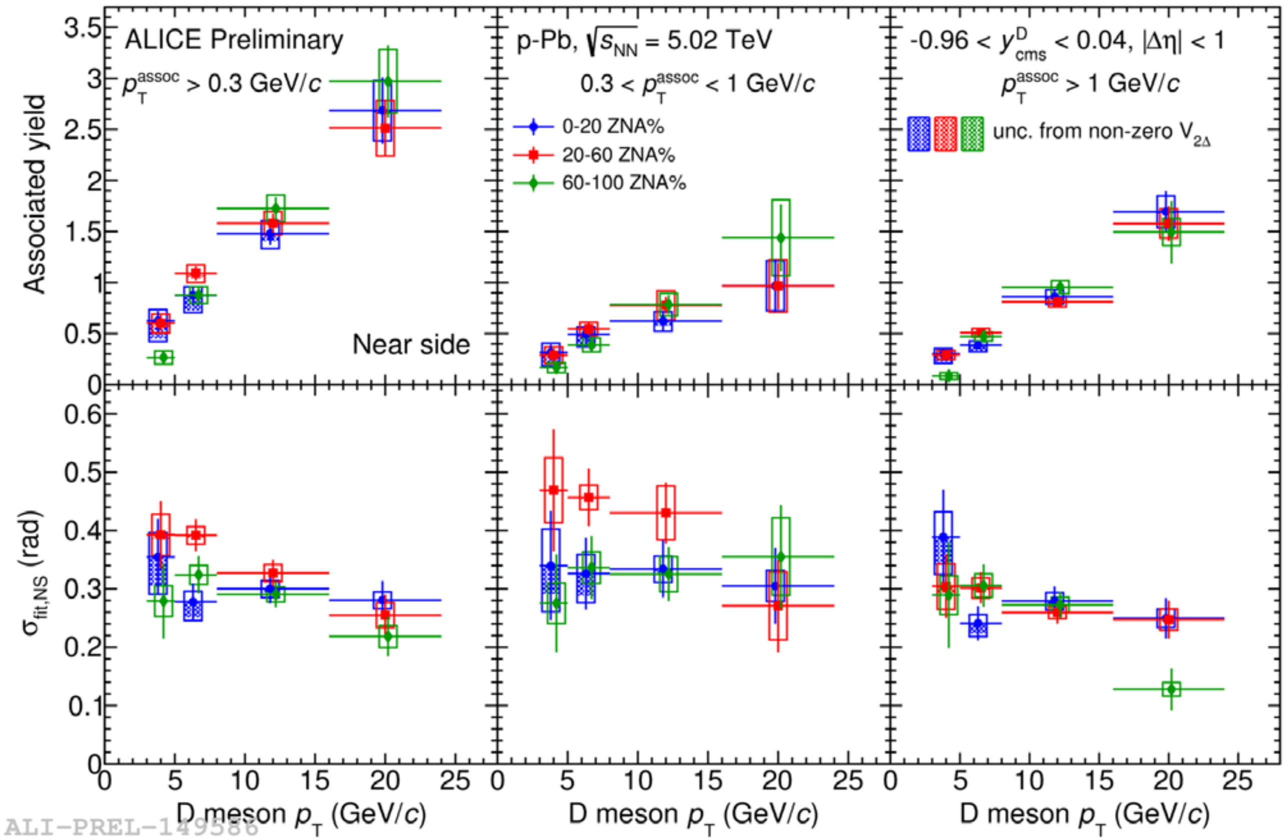
Near-side

- Best description of near-side yields given by POWHEG. Some tension with the other models at high p_T(D). POWHEG seems anyway to overpredict the peak widths.

Away-side

- Reversed hierarchy for predictions of yield and width w.r.t near-side peak. Observables sensitive to modelling production processes

D-h CORRELATIONS: p-Pb VS CENTRALITY



Comparison of near-side peak properties versus event centrality

p_T(D) ranges
3-5, 5-8, 8-16, 24 GeV/c

p_T(assoc) ranges
>0.3, 0.3-1, >1 GeV/c

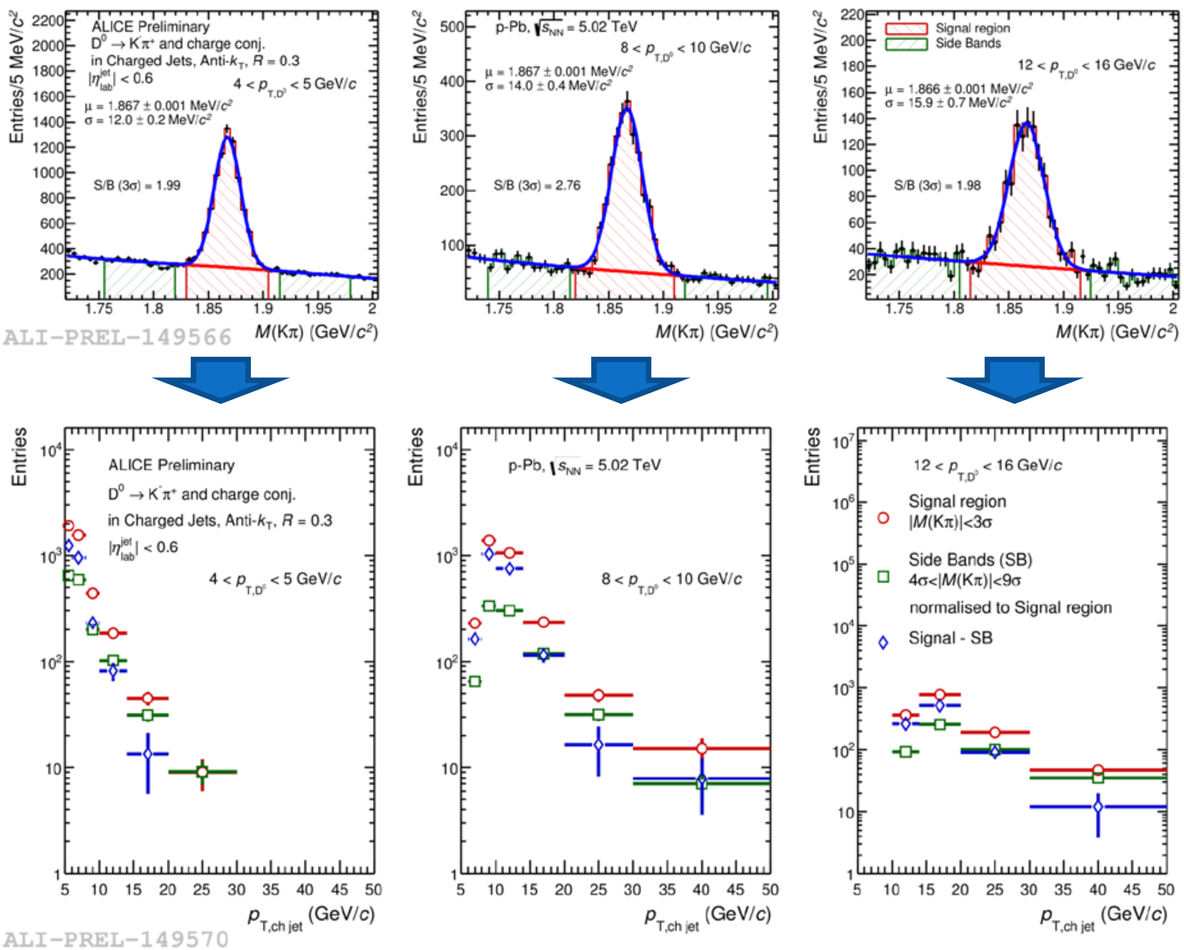
Centrality classes
0-20%, 20-60%, 60-100%
(ZNA estimator)

- Charm jet fragmentation **doesn't show modifications** as a function of centrality above the current uncertainties
  - Possible flow in central p-Pb events taken into account as systematic uncertainty
- No sensitivity to extract v_2 via HM – LM subtraction with available statistics

D-meson jets

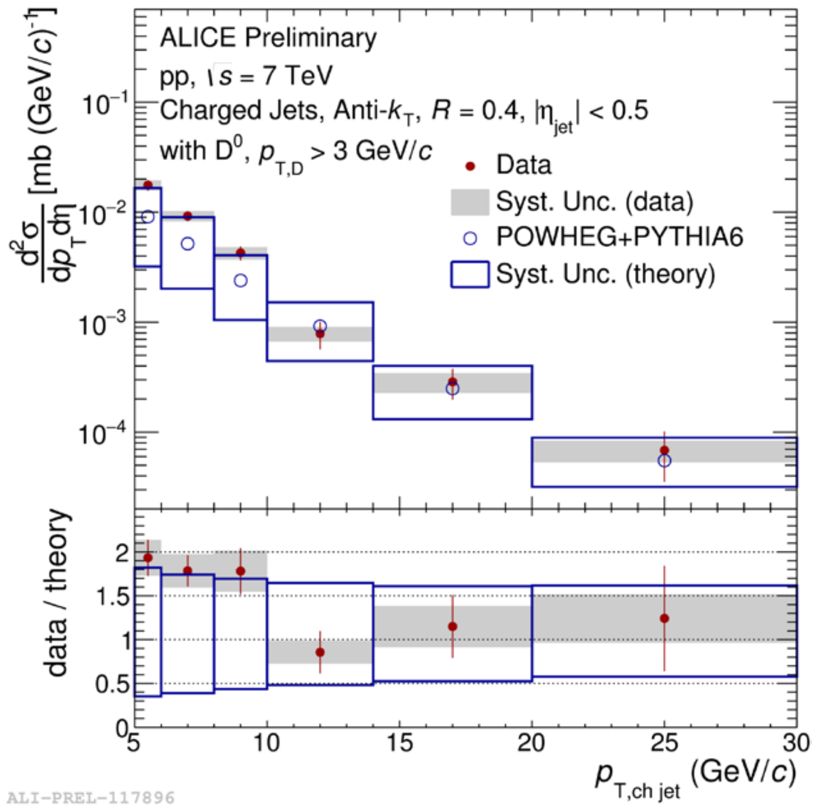
D-JETS: ANALYSIS STRATEGY

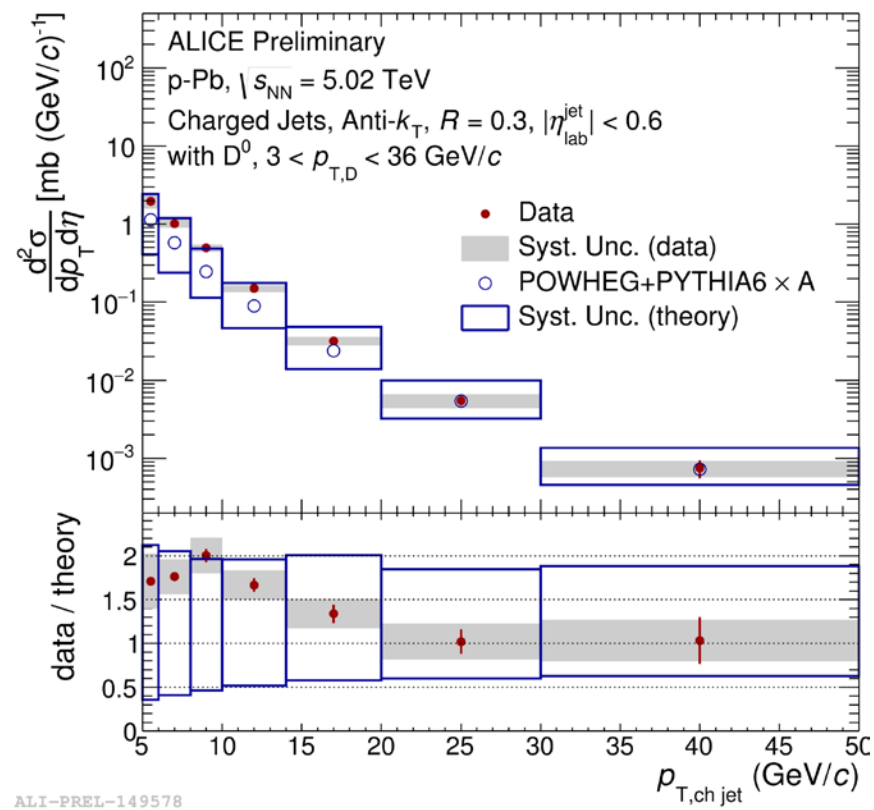
- Charged jets tagged by the presence of a reconstructed D-meson candidate inside the cone
  - Jet finder algorithm (Fastjet, anti-k_T) run for each D-meson candidate, after substituting the daughter tracks with the D-meson particle



- Invariant mass study to extract D-jet raw yield
  - Background spectrum from the sidebands
- Spectrum corrected for D-jet efficiency and for beauty feed-down, exploiting folded POWHEG+PYTHIA predictions
- Corrected D-jet spectrum unfolded for detector effects and background fluctuations (in p-Pb and Pb-Pb)

D-TAGGED JETS IN pp AND p-Pb COLLISIONS

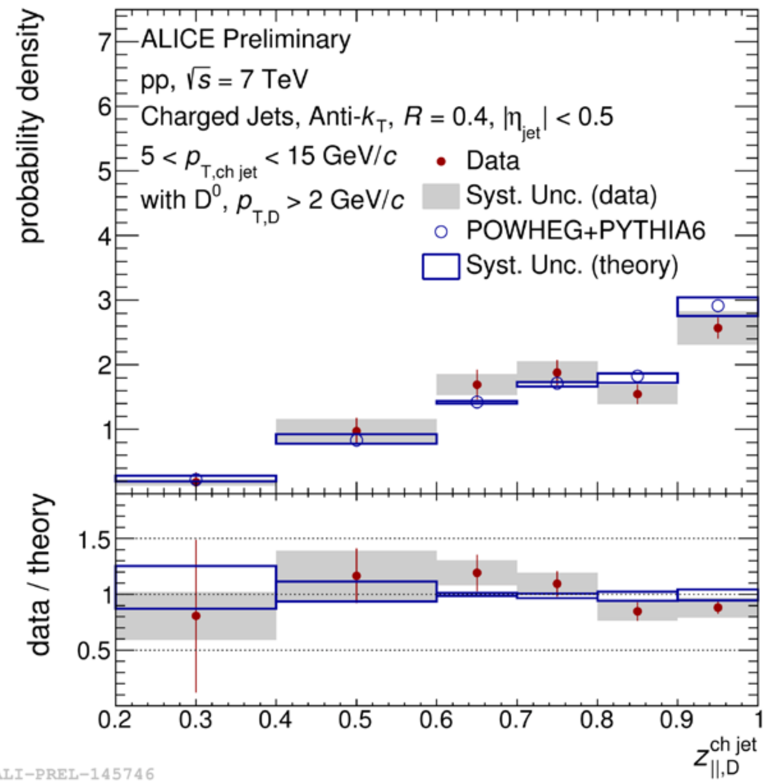




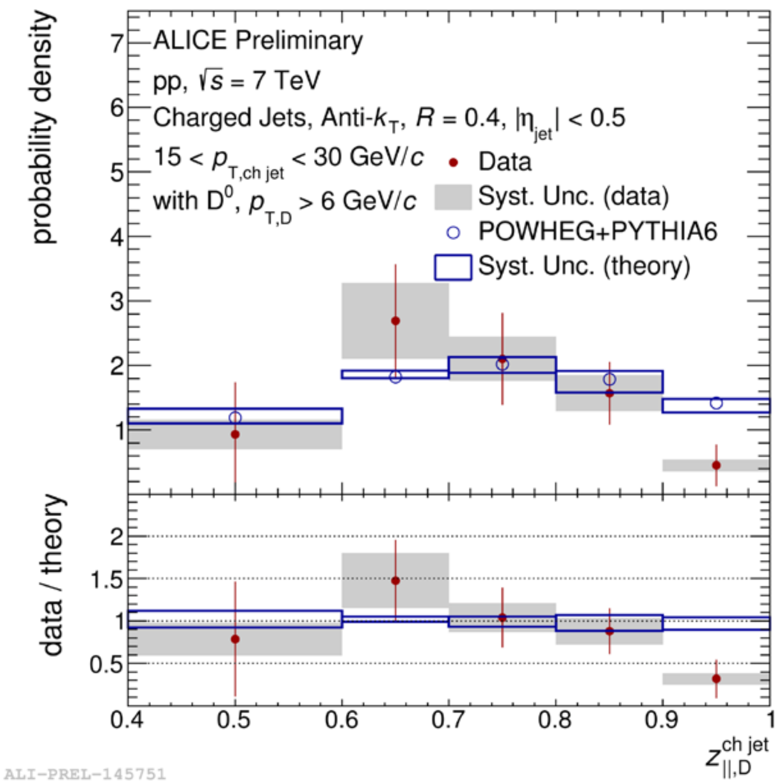
- ***p_T*-differential cross section** of charged jets with a reconstructed D^0 meson inside the jet cone in pp and p-Pb collisions
- POWHEG+PYTHIA predictions (NLO pQCD) **describe well** the measured cross section
  - Theory uncertainties larger than data ones

D-TAGGED JET $z_{||,D}$ IN pp COLLISIONS

5 < p_T(jet) < 15 GeV/c



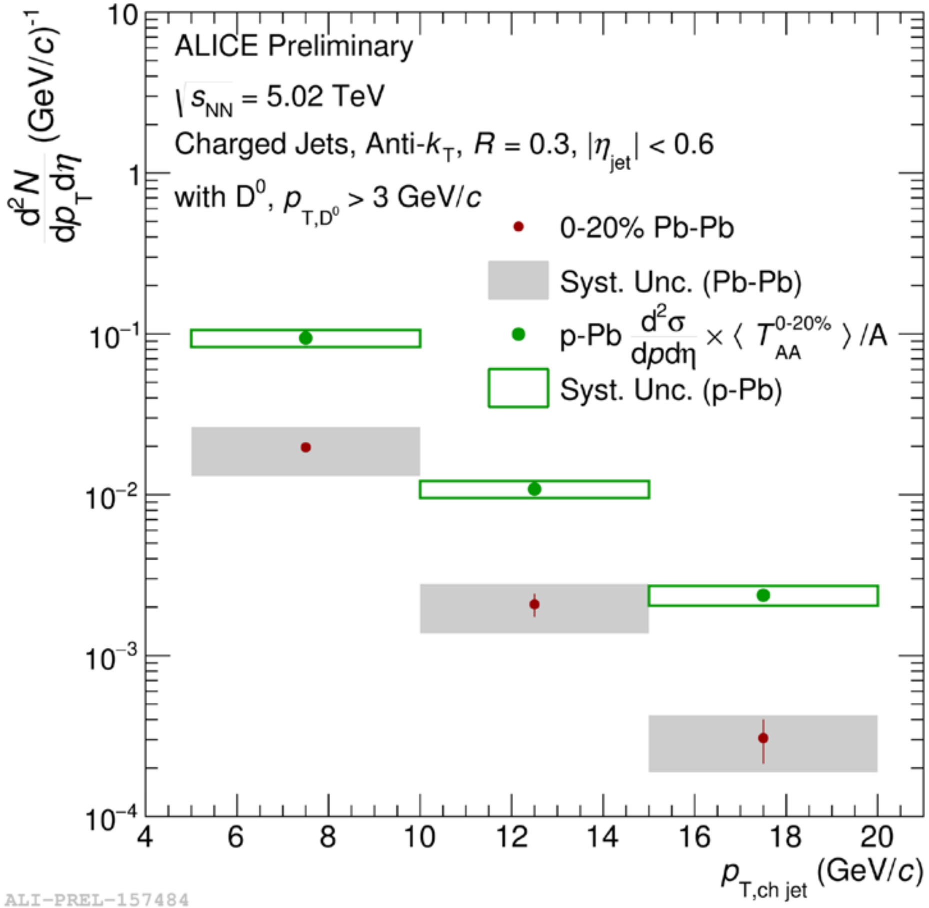
15 < p_T(jet) < 30 GeV/c



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

- **Charged-jet momentum fraction** carried by D^0 meson compared to PYTHIA+POWHEG predictions, for two p_T(jet) ranges in pp collisions
- Overall, good description of data. Hint of softer fragmentation at high p_T in data w.r.t. prediction? Uncertainties are anyway still too large to conclude

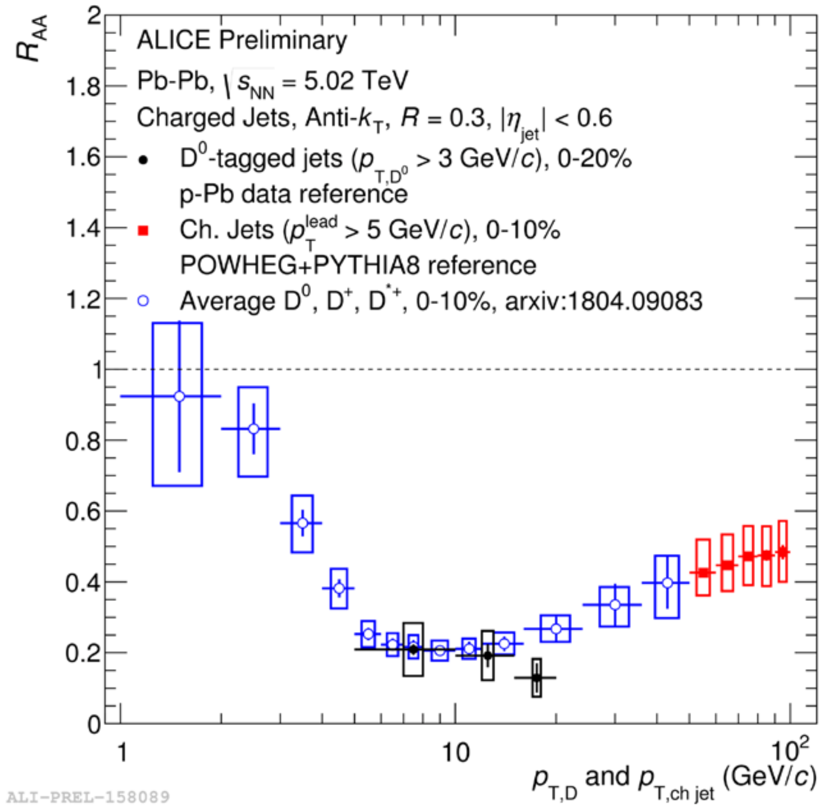
D-TAGGED JETS IN Pb-Pb COLLISIONS



- **5 < p_T(jet) < 20 GeV/c**
  - D^0 selected from p_T > 3 GeV/c
- Tagging of jet via identified particle allows to better address rejection of fake jets at low p_T
- Reference from D^0-jet cross section in p-Pb collisions at same energy
- **First measurement of D-meson tagged jets in heavy-ion collisions**

- Strong suppression of production cross section in 0-20% Pb-Pb collisions w.r.t. binary-scaled predictions from p-Pb collisions over the full p_T(jet) range
- Studies for extension of the addressed p_T range ongoing already with 2015 dataset

D-TAGGED JETS IN Pb-Pb COLLISIONS



- Reference from D^0-jet cross section in p-Pb collisions at same energy
- Improve precision, extended p_T reach and more differential observables (momentum fraction and jet shapes) with next Pb-Pb runs
- **Looking forward to compare data with model predictions!**

- Comparison with inclusive jets still difficult due to non-overlapping p_T ranges, but hint of lower R_{AA} for D-jets in 5 < p_T(jet) < 20 GeV/c than inclusive jets with p_T > 50 GeV/c
  - Can address different quark/gluon jet ratio and collisional/radiative energy loss fractions
- R_{AA} comparable with single D-meson measurement: jet R_{AA} dominated by leading particle energy loss? Or a coincidence? Yet not apple-to-apple comparison (jet vs. hadron pt scale)

CONCLUSIONS

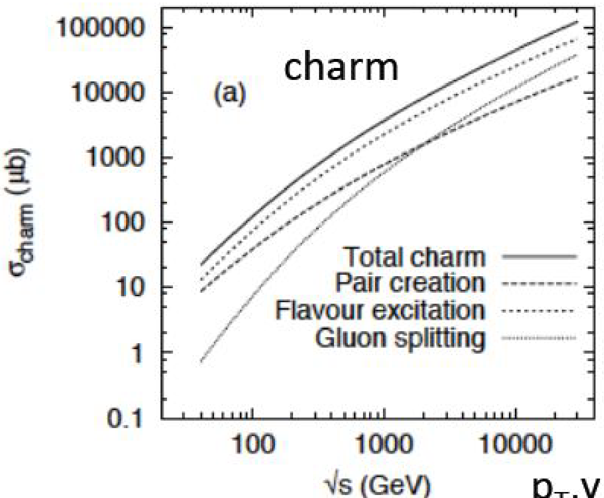
CONCLUSIONS

- **Charm-hadron production**
  - R_{pPb} of non-strange D-mesons, D_s^+ meson and Λ_c^+ all compatible with unity: no evident CNM effect on charm-hadron production at mid-rapidity. Other observables, not discussed here, point to non-negligible nuclear effects (see backup and A. Dubla's talk)
  - Strong suppression for all charm species, with hint of $R_{AA}(\Lambda_c^+) > R_{AA}(D_s^+) > R_{AA}(D^{0,+,*+})$ hierarchy: consistent with coalescence + strange enhancement picture (same conclusion from $D_s^+/D^{0,+}$ ratios)
- **D-meson – charged particle azimuthal correlations:**
  - Correlation distribution shapes and near-side peak observables compatible for pp@5 TeV, pp@13 TeV, p-Pb@5 TeV collisions, and well described by PYTHIA and POWHEG expectations
  - In p-Pb collisions, no centrality dependence observed for near-side peak (same-side jet fragmentation) with current uncertainties
- **D-meson tagged jets:**
  - p_T-differential cross section in pp and p-Pb collisions and jet momentum fraction in pp collisions well described by POWHEG+PYTHIA predictions, though with large uncertainties
  - First measurement of D-tagged jets in heavy-ion collisions: strong suppression observed in central Pb-Pb collisions for $5 < p_T(\text{jet}) < 20$ GeV/c
- **Higher precision on current observables and more differential measurement expected with 2018 Pb-Pb run and after the ALICE upgrade**
- **Looking forward for theoretical predictions!**

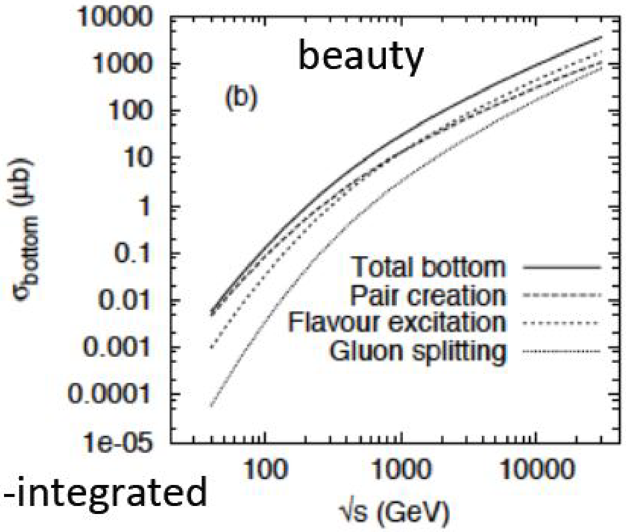
Backup Slides

HEAVY QUARK PRODUCTION

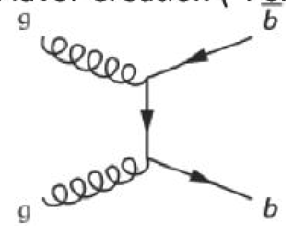
PYTHIA (E. Norrbin, T. Sjostrand, Eur.Phys.J.C17:137-161,2000)



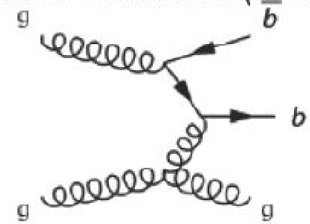
p_T,y -integrated



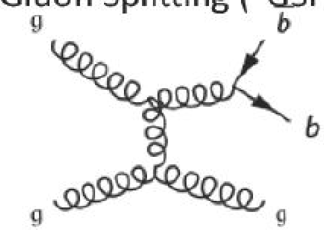
Flavor Creation (“FCR”)



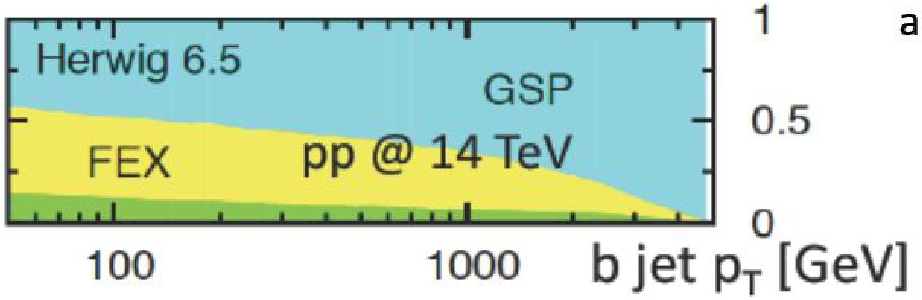
Flavor Excitation (“FEX”)



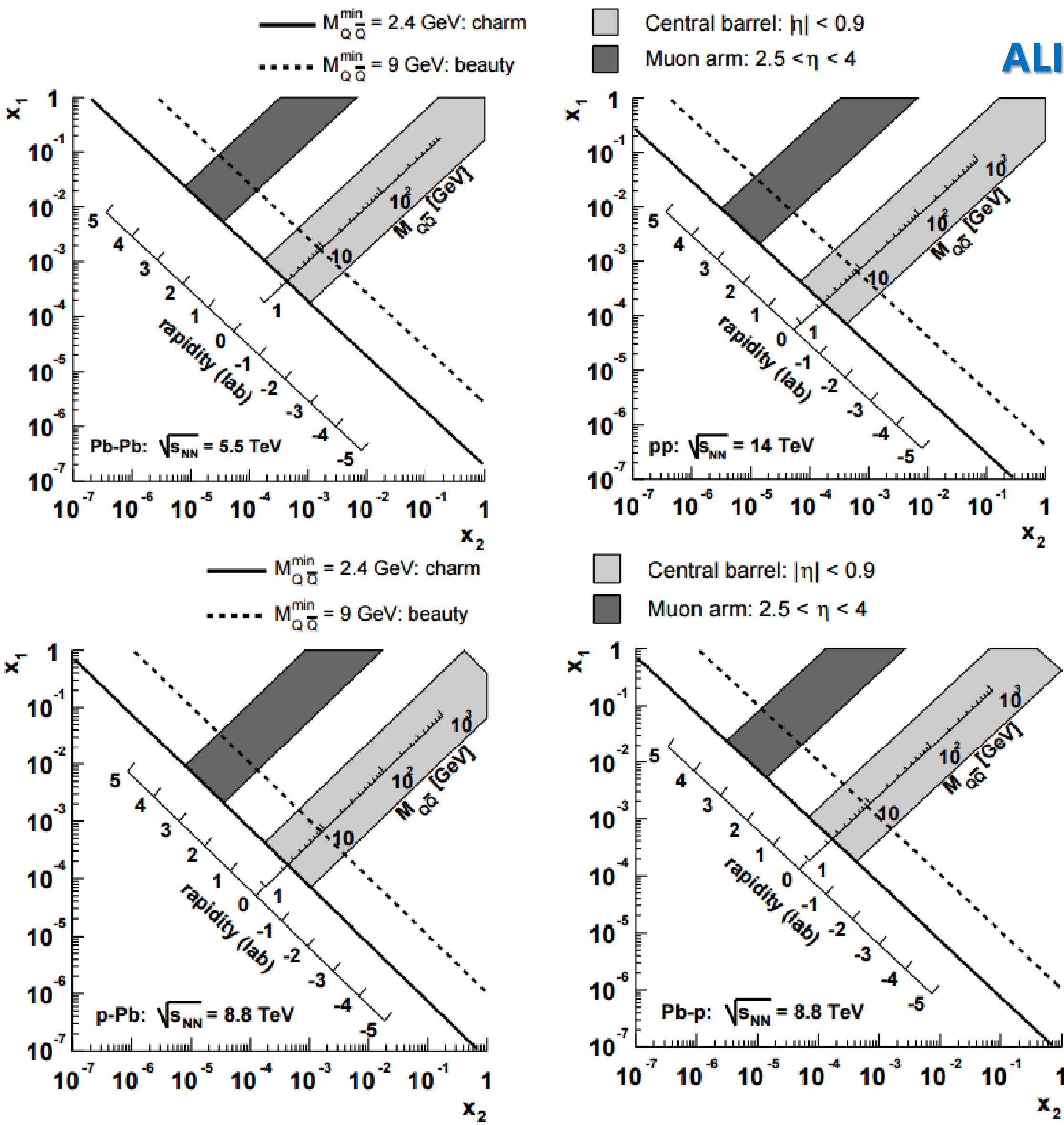
Gluon Splitting (“GSP”)



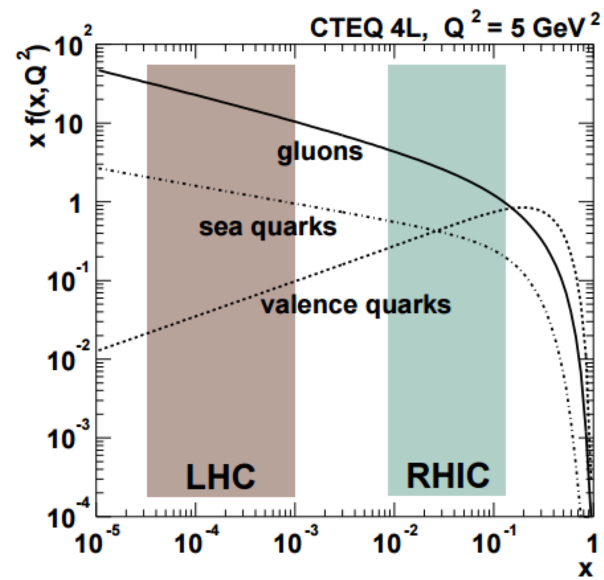
HERWIG 6.5 (A. Banfi, G. Salam, G. Zanderighi, JHEP 0707:026,2007, arXiv:0704.2999)



BJORKEN X REGIONS AT THE LHC AND PDF



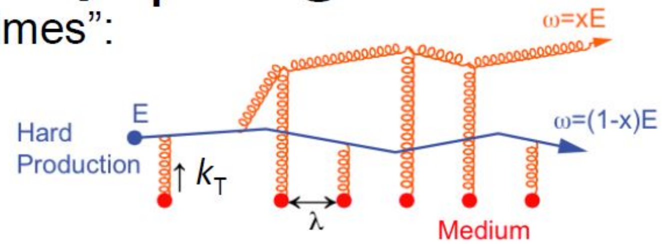
ALICE, J. Phys. G, 32 (2010) 1295



Parton Distribution Functions in CTEQ 4L parametrization, for $Q^2 = 5$ GeV^2

Models: low and high p_T regimes

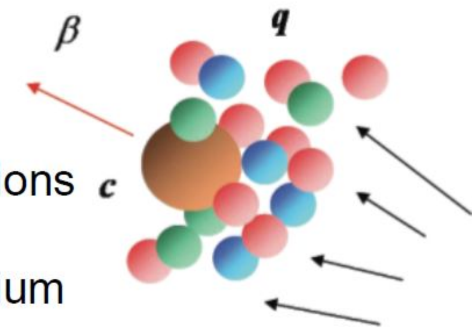
In a oversimplified scheme we can identify two "regimes":



High p_T:

- region **dominated by radiative energy loss**
- Quantum interferences in multiple scattering important (LPM effect)
- Relevant parameter: $\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$

pQCD-based models provide fair description



Low p_T:

- Region **dominated by "collisional" energy loss**
- Heavy quarks undergo many soft and incoherent elastic collisions **~Brownian motion**
- Goal: study how and if HQ reach the equilibrium with the medium
- Relevant parameter: **spatial diffusion coefficient, D_s**

Injecting a particle at x=0 and t=0, the mean squared position at time t is:

$$\langle x^2(t) \rangle = 6 D_s t$$

Strong coupling with the system → small D_s

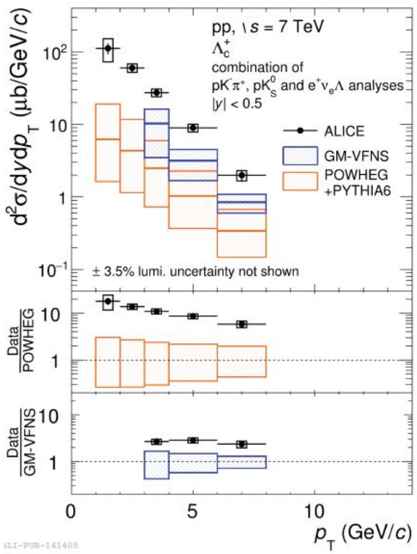
53

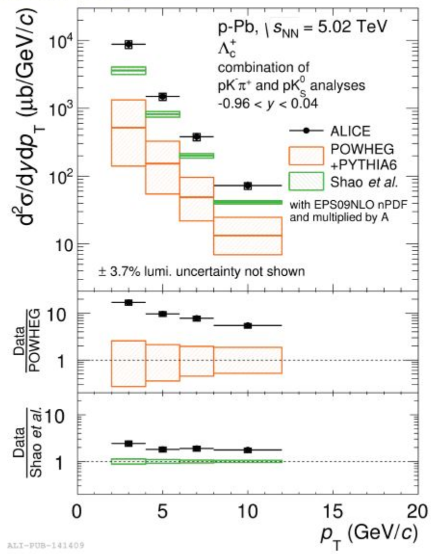
A. Rossi

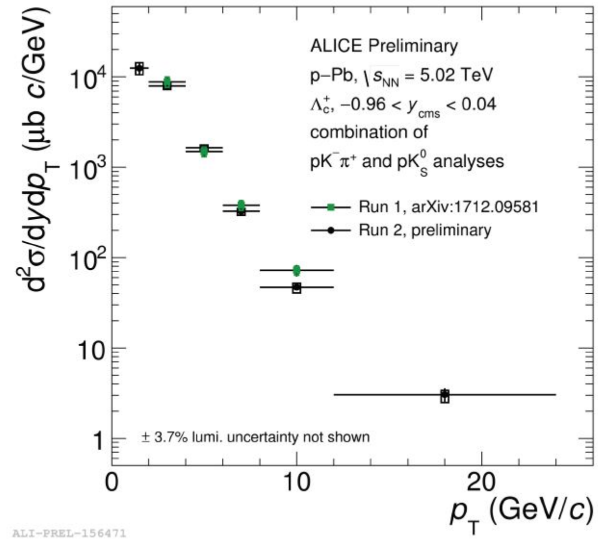
CHARM-HADRON – ADDITIONAL PLOTS

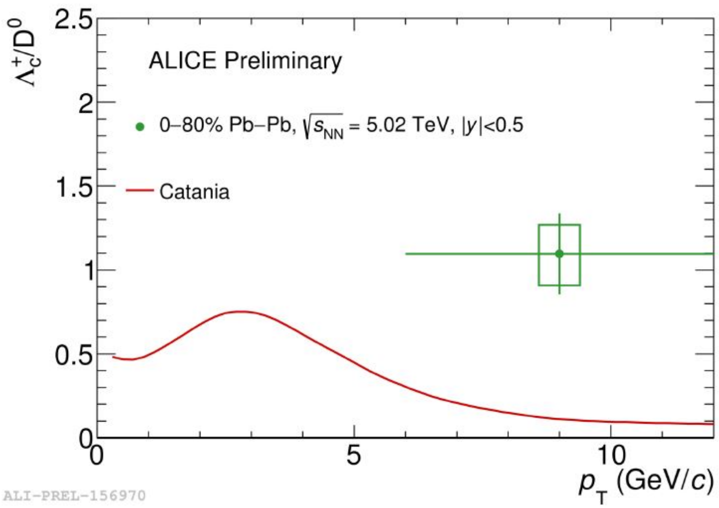
ALICE

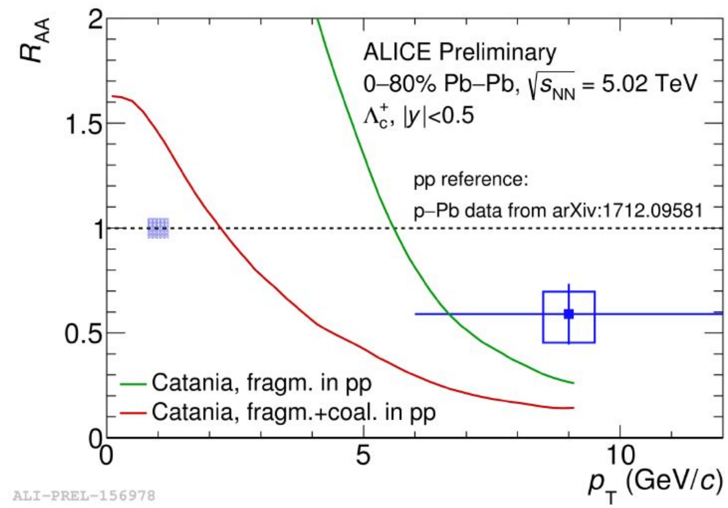
arXiv:1712.09581





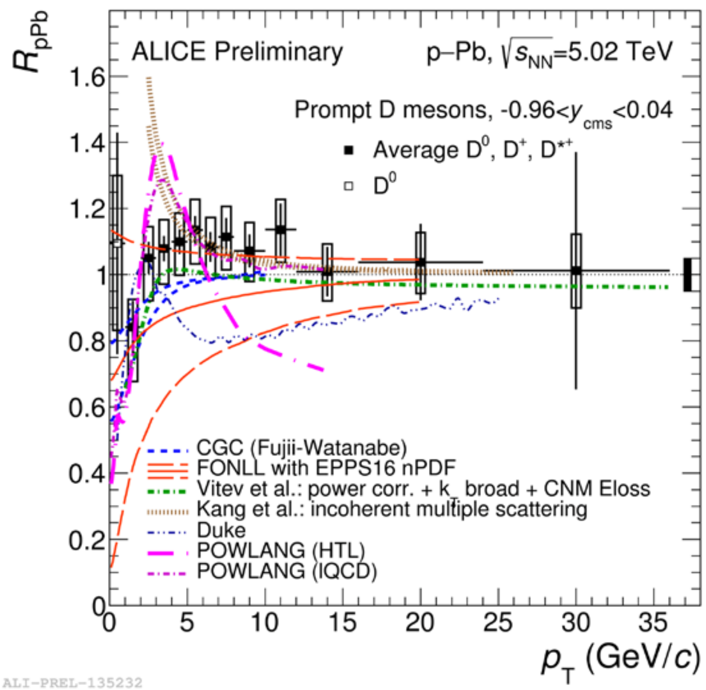


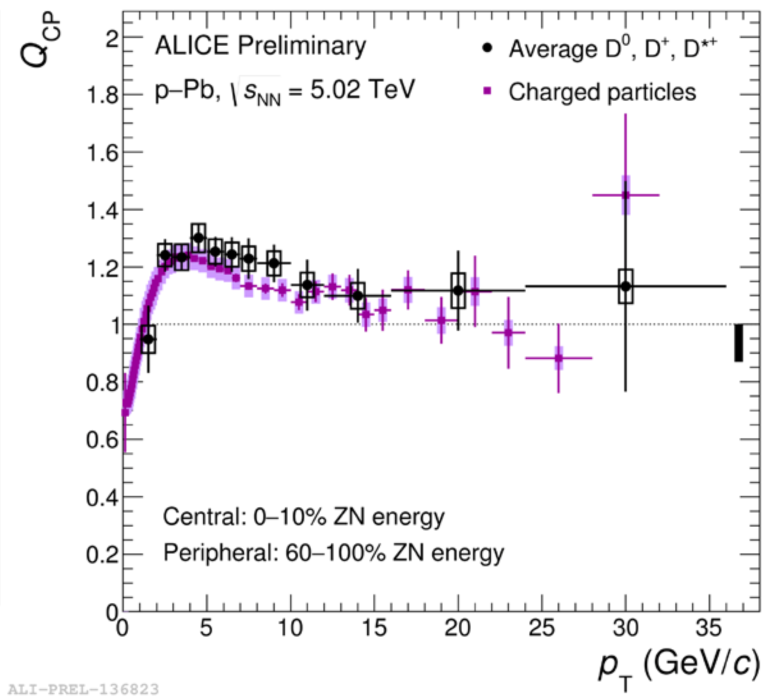




D-MESON R_{pPb} AND Q_{CP}

ALICE-PUBLIC-2017-008

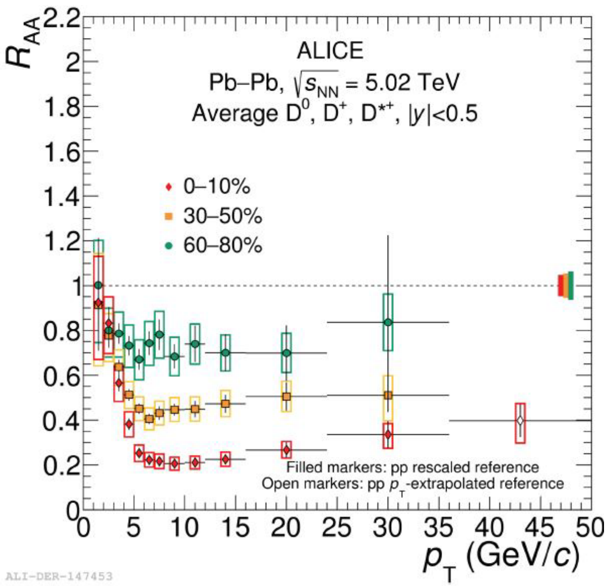


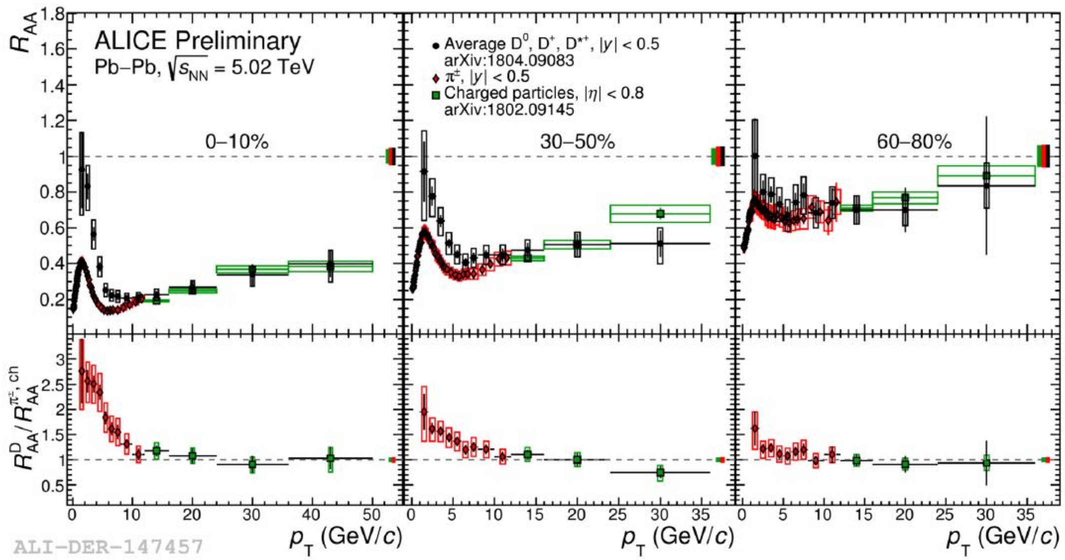


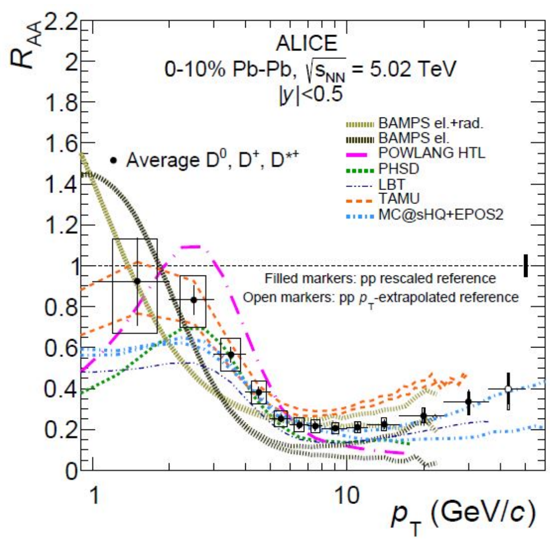
$$R_{\mathrm{pPb}} = \frac{\frac{\mathrm{d}\sigma_{\mathrm{pPb}}}{\mathrm{d}p_{\mathrm{T}}}}{A \cdot \frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}}}$$

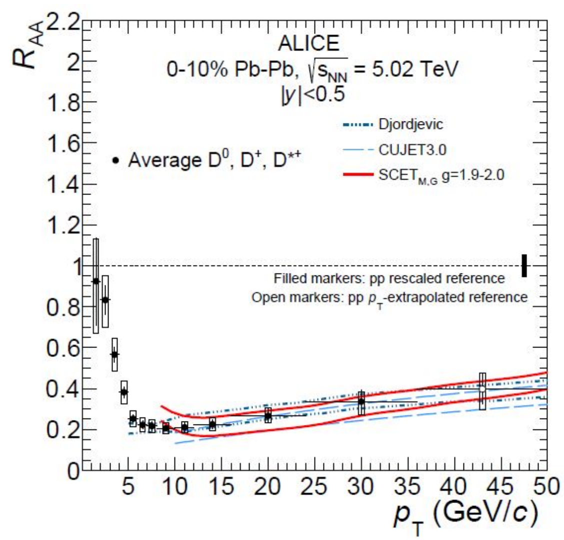
- Non-strange D meson R_{pPb} is **compatible with unity** within uncertainties
  - Described by models including cold nuclear-matter effects and, at low p_{T}, by those assuming QGP formation
- Better precision at low p_{T} needed to draw firmer conclusions
- Hint for D-meson "central-to-peripheral" ratio (Q_{CP}) > 1 with 1.5σ in $2 < p_{\mathrm{T}} < 8$ GeV/c
  - Need theory models for its interpretation

FURTHER D-MESON R_{AA} RESULTS









PROSPECT OF MODELS (PREDICTING R_{AA} & v_2)

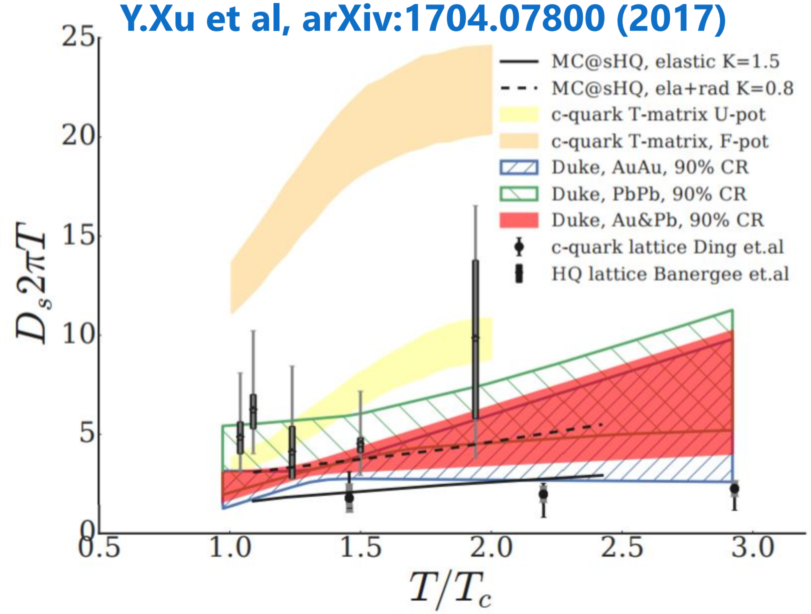
TRANSPORT MODELS	Collisional Energy loss	Radiative Energy loss	Coalescence	Hydro	nPDF
BAMPS + rad. J. Phys. G42 (2015) 115106	✓	✓	✗	✓	✗
LBT arXiv:1703.00822	✓	✓	✓	✓	✓
PHSD PRC 93 (2016) 034906	✓	✓	✓	✓	✓
POWLANG EPJC 75 (2015) 121	✓	✗	✓	✓	✓
TAMU Phys. Lett. B735 (2014) 445	✓	✗	✓	✓	✓
MC@sHQ+EPOS PRC 89 (2014) 014905	✓	✓	✓	✓	✓
pQCD Eloss MODELS	**Collisional Energy loss**	**Radiative Energy loss**	**Coalescence**	**Hydro**	**nPDF**
CUJET3.0 JHEP 02 (2016) 169	✓	✓	✗	✗	✗
Djordevic PRC 92 (2015) 024918	✓	✓	✗	✗	✓
SCET JHEP 03 (2017) 146	✓	✓	✗	✗	✓

D-MESON R_{AA} - MODELS

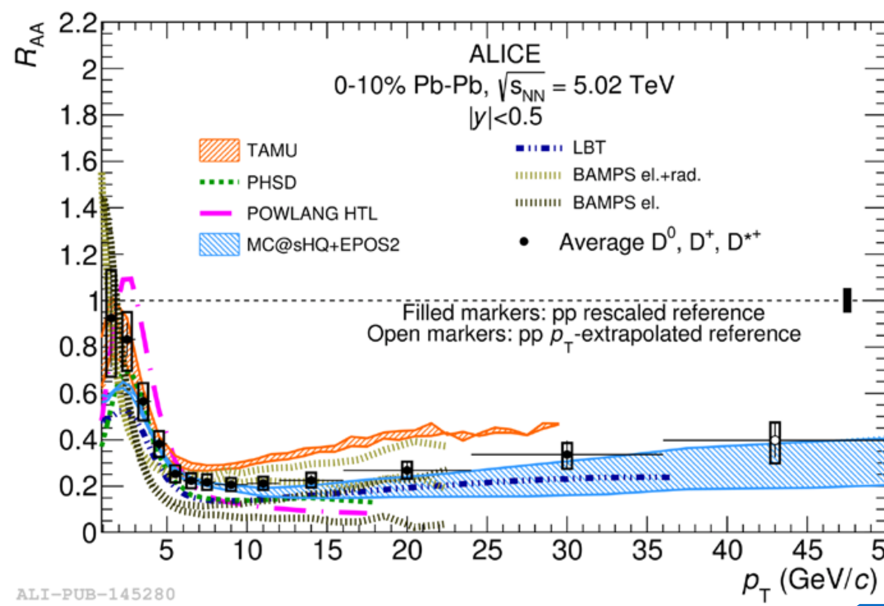
MC@sHQ+EPOS2: PR C89 (2014) 014905
Coll+Rad Eloss, recombination, EPOS-expansion
PHSD: PR C92 (2015) 1, 014910, PR C93 (2016) 3, 034906
Parton-Hadron-String Dynamics transport, coalescence
Xu, Cao, Bass: PR C88 (2013) 044907
Langevin with Coll+Rad Eloss, recombination+hydro
SCETM,G NLO: arXiv: 1610.02043
Soft Collinear Effective Theory, Bjorken expansion
Djorkevic: PR C92 (2015) 024918
Coll+Rad Eloss, recombination, finite-size hydro

POWLANG HTL: EPJ C71 (2011) 1666; JP G38 (2011) 124144
Langevin transport, Coll Eloss, recombination, hydrodynamics
AdS/CFT: JHEP 1411 (2014) 017; PR D91 (2015) 8, 085019;
Ads/CFT correspondence, Langevin Eloss + fluctuations, hydro
BAMPS: JP G 38 (2011) 124152; PL B 717 (2012) 430
Boltzmann transport, Coll. Eloss, expansion
TAMU: PL B735 (2014) 445-450
Transport, Coll. Eloss, resonant scatt. and coalescence+hydro

Y.Xu et al, arXiv:1704.07800 (2017)



Temperature dependence of the spatial diffusion coefficient Ds2πT

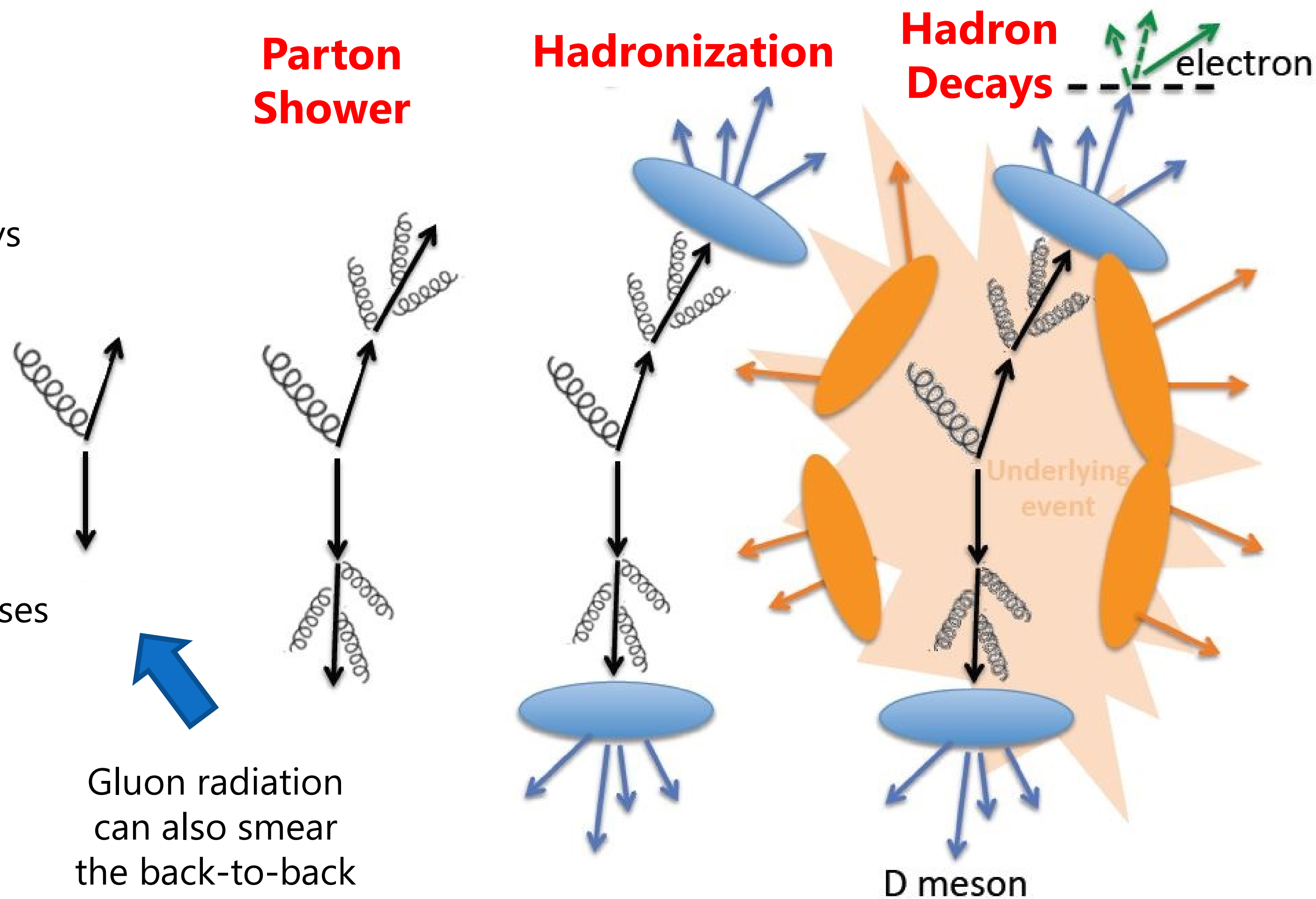


HF CORRELATIONS - INTRO

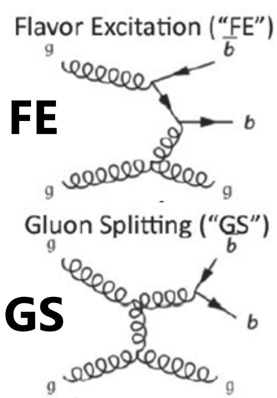
From heavy quark production to final state

Hard Scattering

N.B. heavy quark production not always back-to-back…



…due to NLO processes



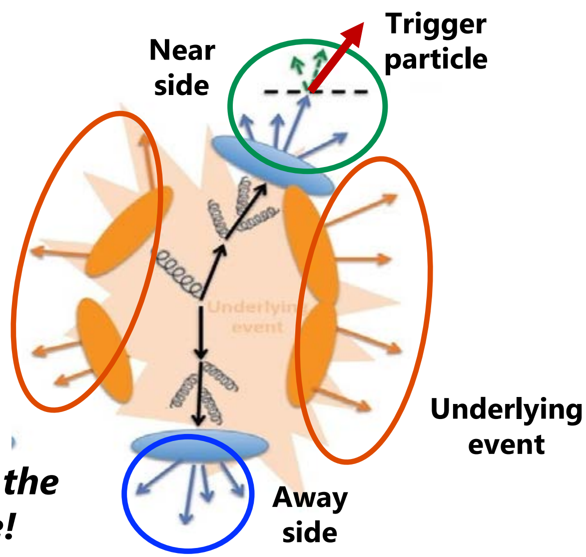
Gluon radiation can also smear the back-to-back structure of HF jets in final state

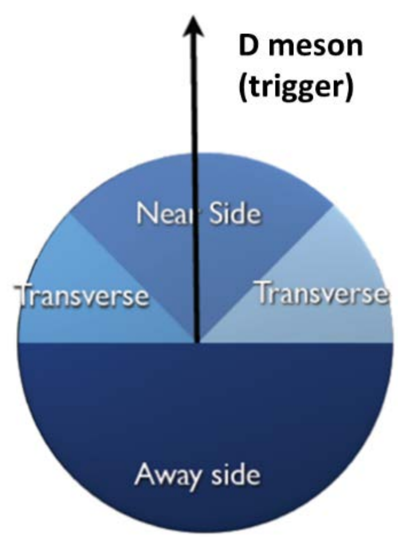
This in vacuum. In Pb-Pb, additional effects by the QGP medium!

THE IDEAL CASE…

- Select an heavy-flavour particle (*trigger particle*) and correlate it to other particles, specific or generic, in the event (*associated particles*)
  - i.e. «count» the number of associated particles vs $\Delta\varphi = \varphi_{trig} - \varphi_{assoc}$, $\Delta\eta = \eta_{trig} - \eta_{assoc}$
- Three main region can be identified in angular (azimuthal) correlation distributions.
- Ideal and simplest case: LO production (back-to-back), no gluon radiation from parton, negligible angular opening between HF quark and trigger particle. In this situation:
  - **Near-side region** (peak at $\Delta\varphi=0$) → tracks from the jet containing the trigger
  - **Away-side region** (peak at $\Delta\varphi=\pi$) → tracks from fragmentation of the other HF jet
  - Correlations to underlying event tracks (flat in $\Delta\varphi$), produces a **baseline** higher than 0

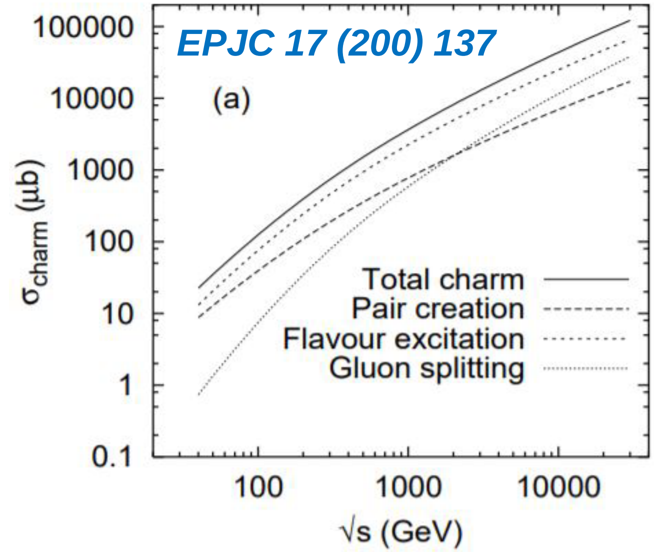
Already not the ideal case!

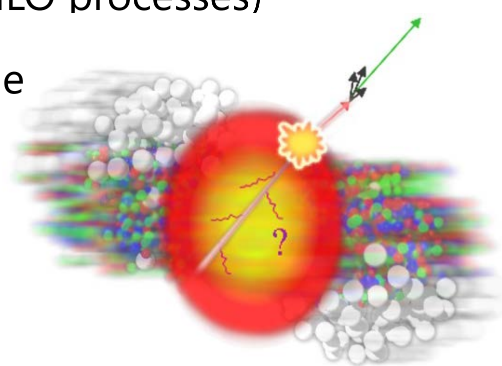


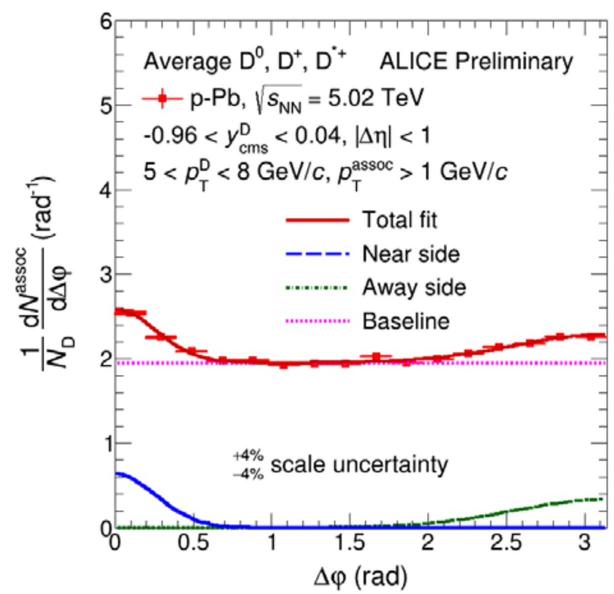


…AND THE REALITY

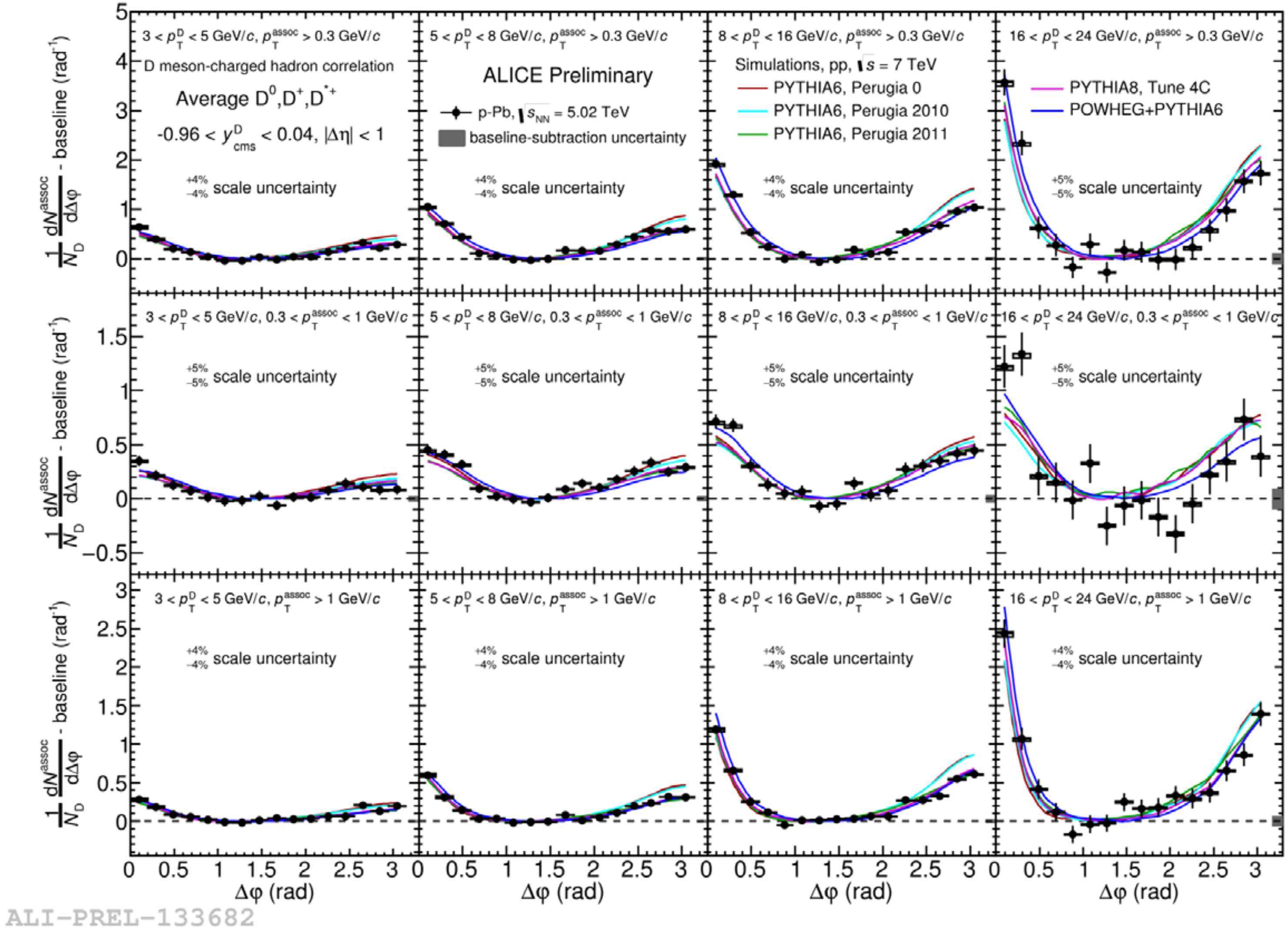
- Things are not so simple in reality! For example:
  - **NLO production processes** or **gluon radiation** from heavy quarks → broadening of away-side peak w.r.t. near-side (wider and lower AS peak)
  - **Gluon splitting process** → correlations with underlying event tracks have a **bump in the AS** (tracks from recoiling gluon). In addition, if the heavy quarks are collinear, near-side peak shape is altered
  - **Non-zero opening angle** between HF particles and heavy quarks smears the correlation peaks
  - Under the baseline also **correlations with HF tracks** are present (mainly from NLO processes)
  - **Partonic energy loss** in the medium can lead to **suppression of away side** (*surface bias*)







p-Pb VS MC PREDICTIONS – Δφ DISTRIBUTIONS

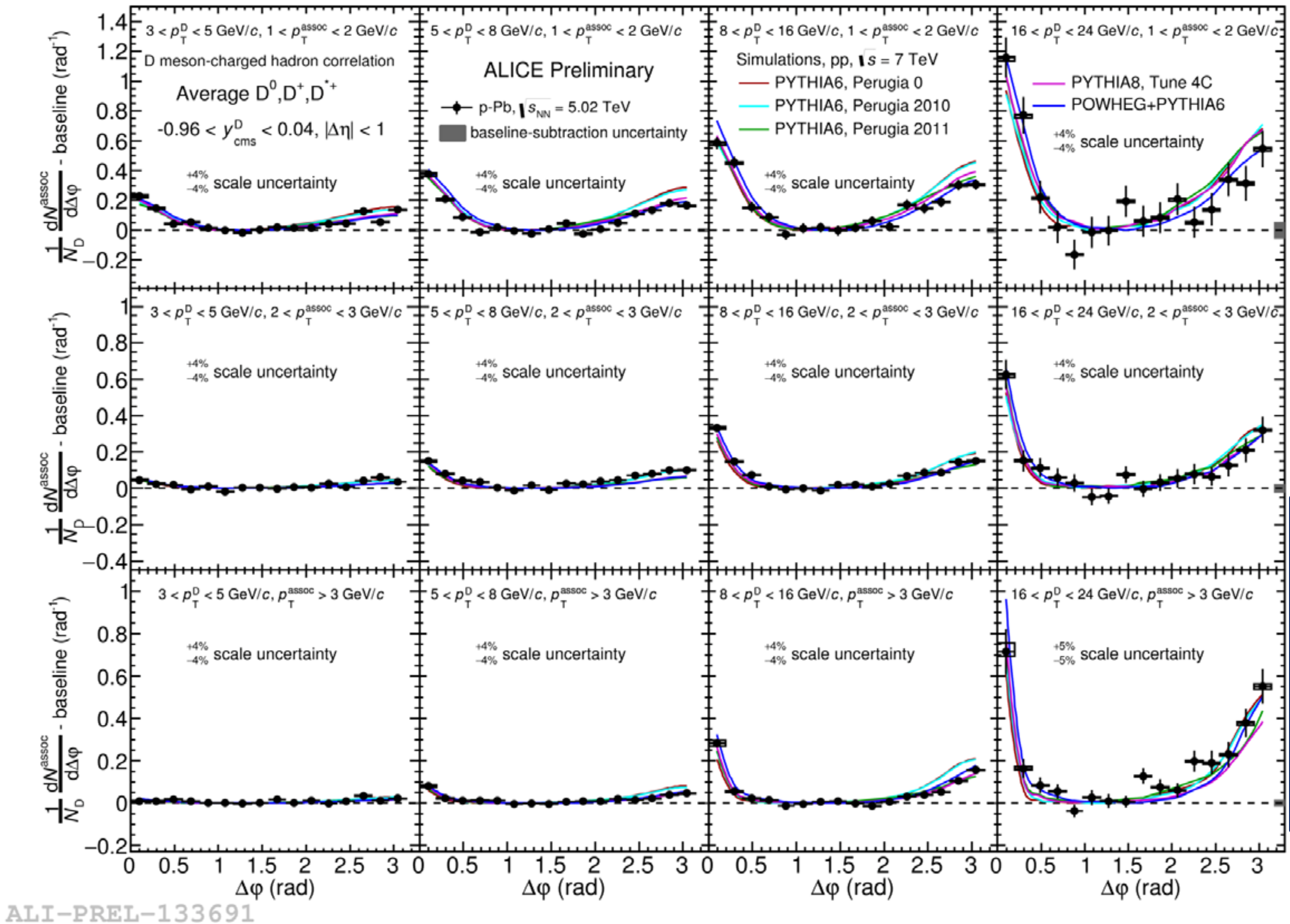


Lower p_T^{assoc} ranges:

- **>0.3** GeV/c
- **0.3-1** GeV/c
- **>1** GeV/c

- Correlation distributions and their p_T trend well described by PYTHIA6,8 & POWHEG

p-Pb VS MC PREDICTIONS – Δφ DISTRIBUTIONS



Higher p_T^{assoc} ranges:

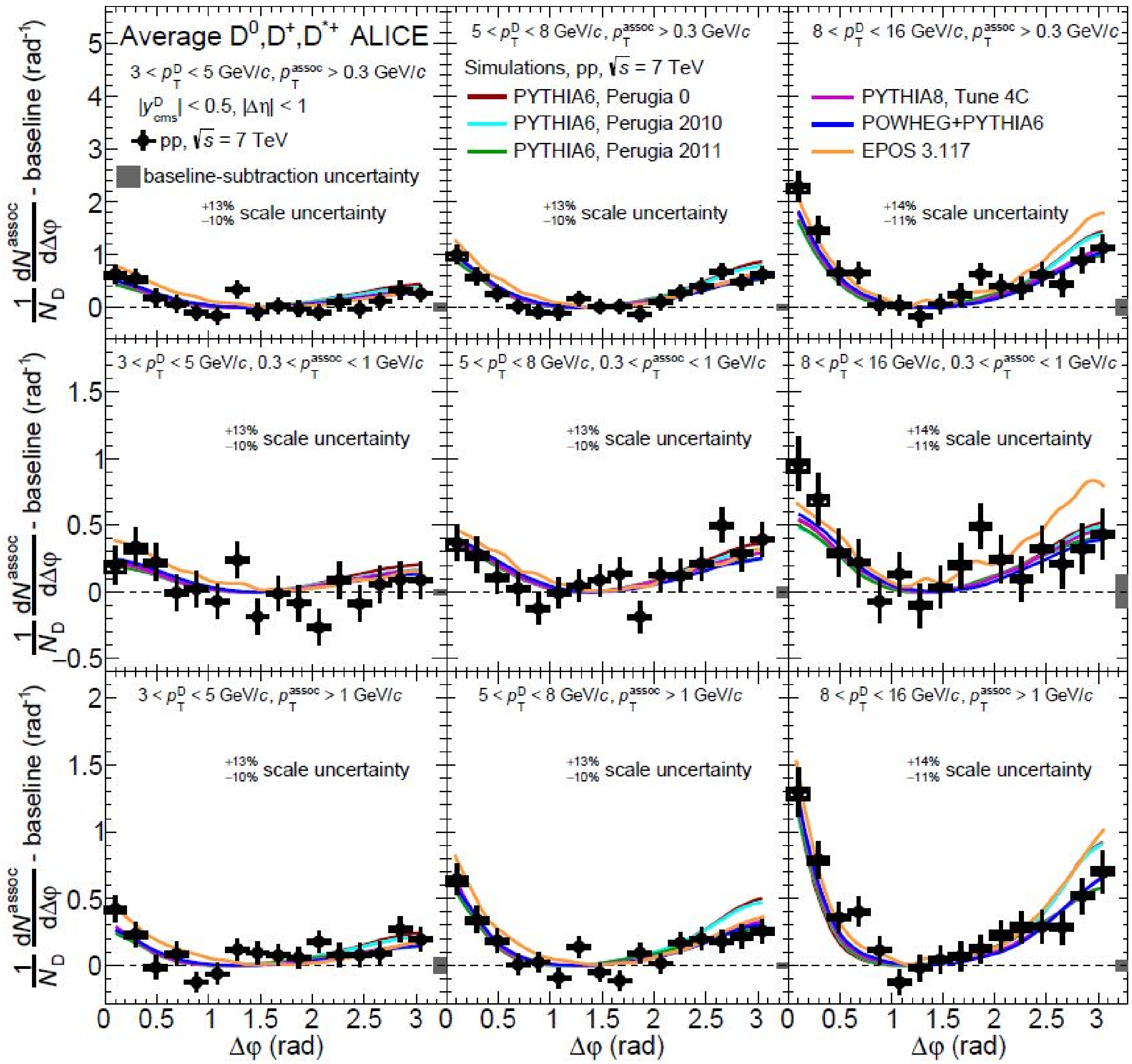
- **1-2** GeV/c
- **2-3** GeV/c
- **>3** GeV/c

(extension w.r.t. paper results)

Bottom-left panel: **$p_T^{assoc} \approx p_T^D$**
No NS peak is expected at LO due to high z of D mesons (but could arise from NLO processes)

- Correlation distributions and their p_T trend well described by PYTHIA6,8 & POWHEG

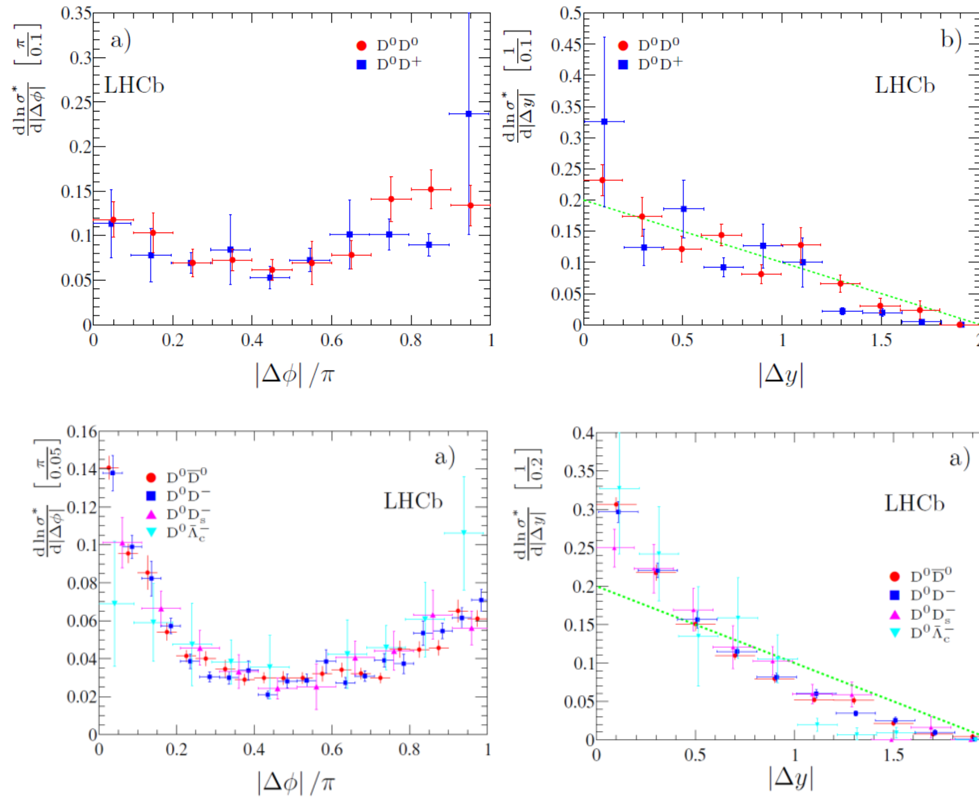
FURTHER PAPER RESULTS



PREVIOUS RESULTS ON HF CORRELATIONS (LHC ONLY)

Selection of LHCb measurements for DD (top row) and DDbar (bottom row) angular correlations in pp collisions at 7 TeV:

- DD are uncorrelated (independently produced)
- DDbar are mostly produced in the same hard scattering
  - ✓ NS and AS peaks are clearly visible

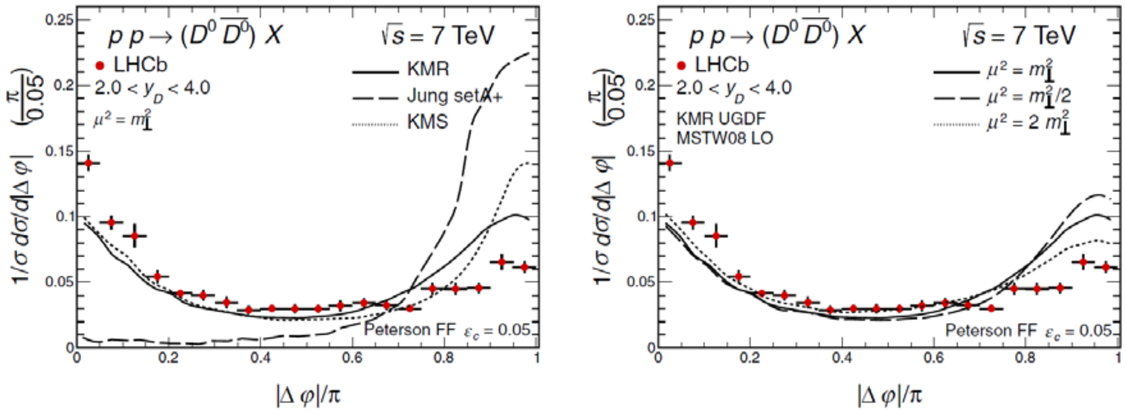


LHCb, JHEP 06 (2012) 141

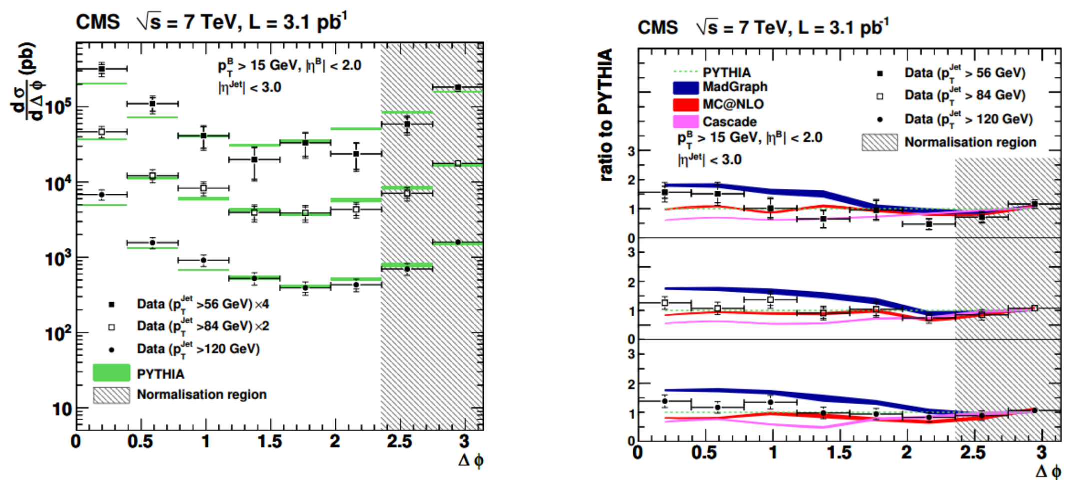
PREVIOUS RESULTS ON HF CORRELATIONS (LHC ONLY)

- LHCb measurements for D^0-D^0bar correlations compared with calculations from k_T-factorization approach, in pp collisions at 7 TeV

LHCb, JHEP 06 (2012) 141



- CMS measurements for B-Bbar production cross section as a function of $\Delta\varphi$, compared with predictions, in pp collisions at 7 TeV



CMS, JHEP 136 (2011) 1103

PYTHIA 6/8 - DETAILS

- Large set of hard parton processes, including heavy quark generation
- Hard scattering only at leading order (2$\rightarrow$2 processes)
  - Next-to-leading order processes mimicked in the parton shower
- p_T ordering for initial-state and final-state radiation
  - Change from virtuality ordering in previous versions
- Lung string model for hadronization
- Includes multi-parton-interactions (MPI)

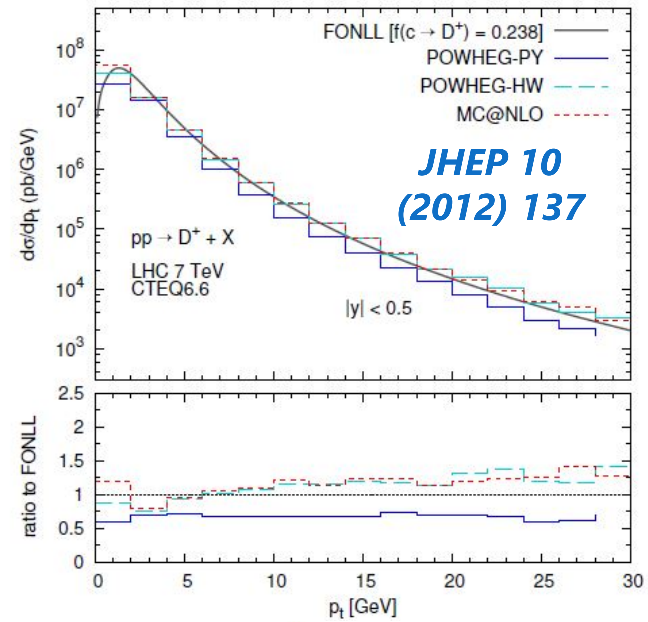
- **PYTHIA 6** Perugia tunes: differ from the previous ("S0") for improved initial- and final-state radiation models, underying event, color reconnection. CTEQ5L PDF set is used.
  - **Perugia 0**: first of the series
  - **Perugia 2010**: different amount of final-state radiation, modification of z fragmentation (hardening of spectra)
  - **Perugia 2011**: first tune to use LHC data

- **PYTHIA 8**: better treatment of MPI and color reconnection w.r.t. PYTHIA 6

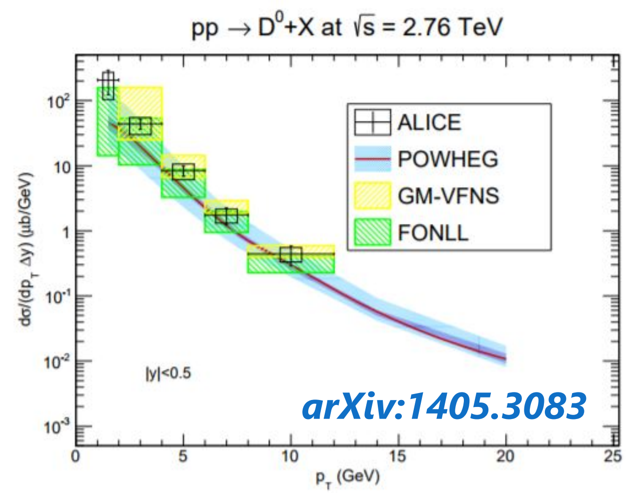
- Reference manuals: ***arXiv:hep-ph/0603175*** (v6.4), ***arXiv:1410.3012 [hep-ph]*** (v8.2)

POWHEG - DETAILS

- Hard processes provided at NLO level
- Replaces the harder part of parton shower (up to a cetrain Q^2 threshold) with its own, with NLO accuracy
- Softer part of the parton shower dealt by a subsequent shower Monte Carlo (i.e. PYTHIA or HERWIG)
  - ➢ Feeding done via Les Houches interface
  - ➢ Easy matching in case of pT-ordered parton showers (like PYTHIA), more tricky for angular-ordered ones (like HERWIG) – "double" showering must be avoided



- For open heavy flavour production, comparison with FONLL and GM-VFNS gives agreement within models uncertainties
- Non negligible dependence on the shower Monte Carlo (and even on its tune) is observed



arXiv:hep-ph/0709.2092

EPOS 3 - DETAILS

- Initial conditions based on Gribov–Regge theory
- pp (Pb-Pb) collision decomposed in simple interactions, called "parton ladders", composed of an hard scattering è ISR/FSR.
- The parton ladders decay producing quark-antiquark pairs, creating in this way fragments, identified with hadrons
- Multi-parton interactions are also accounted for
- Non-linear effects are included via a saturation scale
- Hydrodynamic behaviour can be switched on for the core of the collision
    - ➢ Already for pp collisions, the energy density is enough to justify this treatment

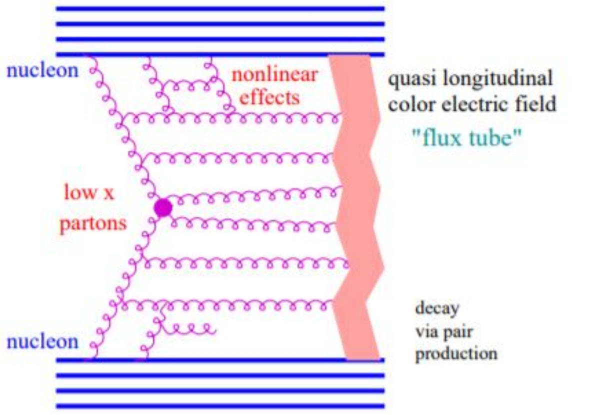
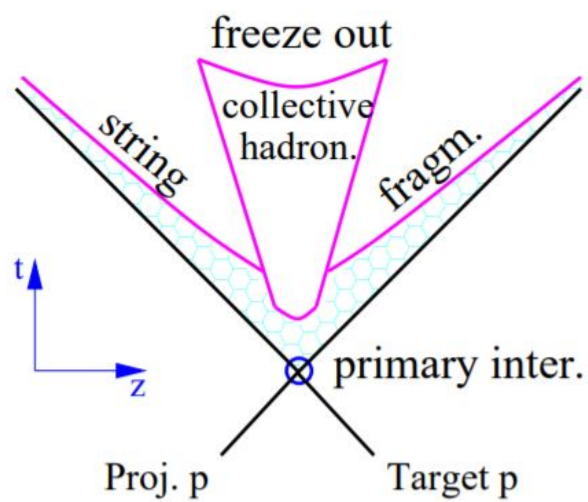


Figure 2. Elementary interaction in the EPOS model.



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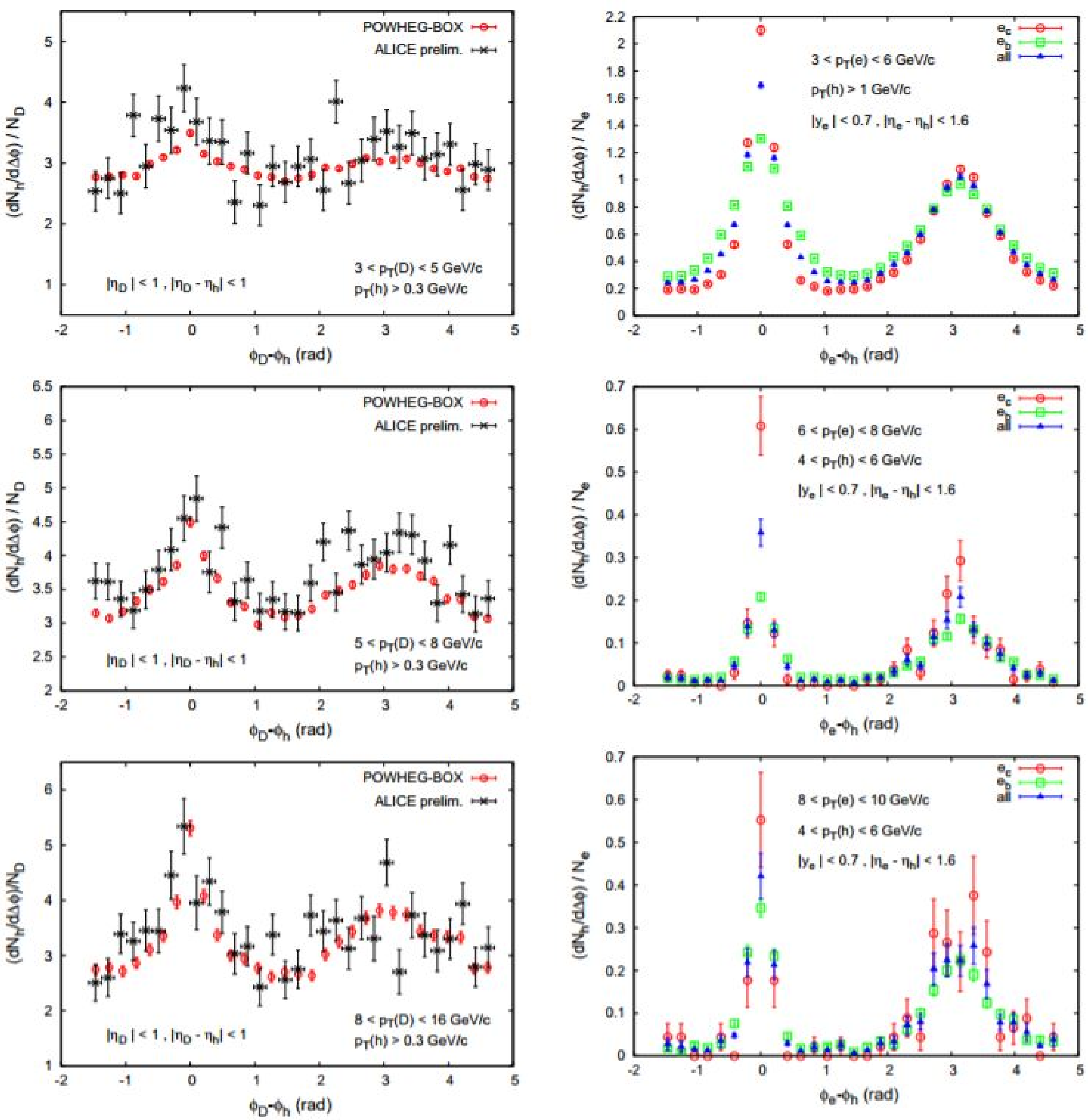
arXiv:hep-ph/0709.2092

POWLANG PREDICTIONS (D-h, e-h)



POWLANG: initial hard production of the QQ pairs and parton-shower stage through the POWHEG-BOX package + successive evolution in the plasma through the relativistic Langevin equation

Left: Azimuthal D–h correlations in pp collisions at √s = 7 TeV for various cuts compared to preliminary ALICE data

Right: Azimuthal e–h correlations in p–p collisions at √s = 7 TeV for various kinematical cuts accessible by ALICE