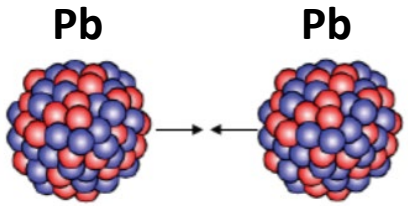
Measurements of heavy-flavour jets, correlations and elliptic flow in small systems with ALICE

Fabio Colamaria, for the ALICE Collaboration

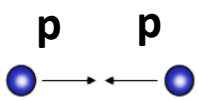
Initial Stages 2019 – NYC (US), 26/06/2019

MOTIVATIONS: HEAVY-FLAVOUR STUDY

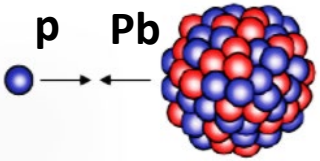
- Heavy quarks experience the full evolution of the hot and dense medium produced in ultra-relativistic heavy-ion collisions
  - Excellent probes of the **Quark-Gluon Plasma medium**



- Great interest for heavy-flavour studies also in **small systems** (pp, p-Pb):



  - Test and constrain pQCD calculations
  - Probe PDF for very small of Bjorken *x*
  - Reference for measurements in p-Pb and Pb-Pb



  - Investigate cold-nuclear-matter effects on heavy quarks (HQ)
  - Search for "collective-like" effects in heavy-flavour sector

- Larger pp and p-Pb data samples collected during LHC Run2 (2015-2018)
  - Allow for **more differential studies** w.r.t single particle analysis
  - Additional physics motivations

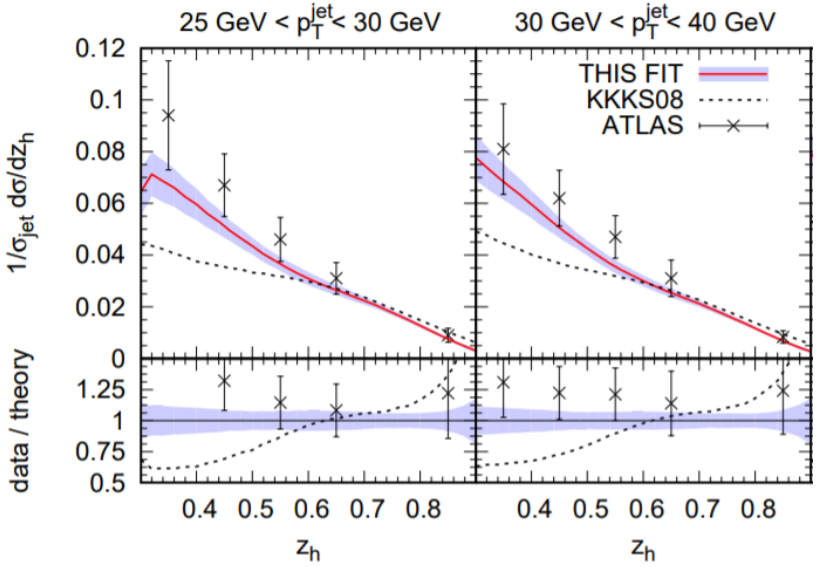
➡ **Heavy-flavour (HF) jets and correlations**

MOTIVATIONS: HF JETS AND CORRELATIONS

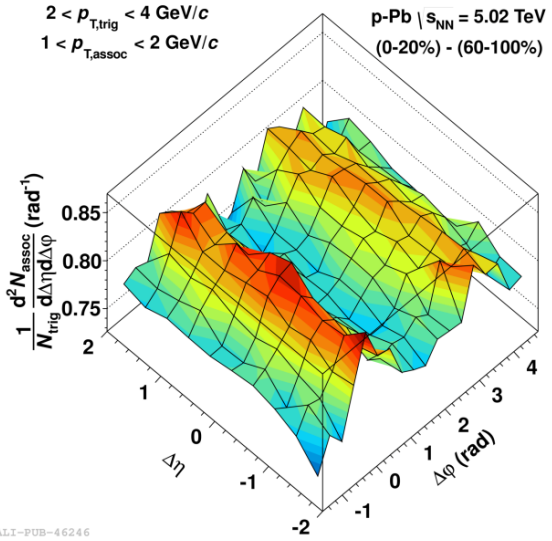
pp collisions

- Test pQCD predictions with more direct access to parton (recover a large fraction of its p_T)
- Investigate heavy-flavour quark fragmentation properties and characterize heavy-flavour jets
- Sensitivity to modelling of HQ production processes (→angular correlations)

Phys. Rev. D 96, 034028 (2017)



Phys. Lett. B 719 (2013) 29-41



p-Pb collisions

- Investigate possible modifications of heavy-quark fragmentation and hadronisation from cold-nuclear-matter effects
- Search for long-range ridge-like structures, possibly due to initial- (e.g. gluon saturation) or final-state effects (e.g. hydrodynamics)

THE ALICE DETECTOR

ALICE **central barrel** coverage (ITS+TPD+TOF): $|\eta| < 0.9$
ALICE **muon spectrometer** coverage: $-4 < \eta < -2.4$

EMCal: electron PID + trigger

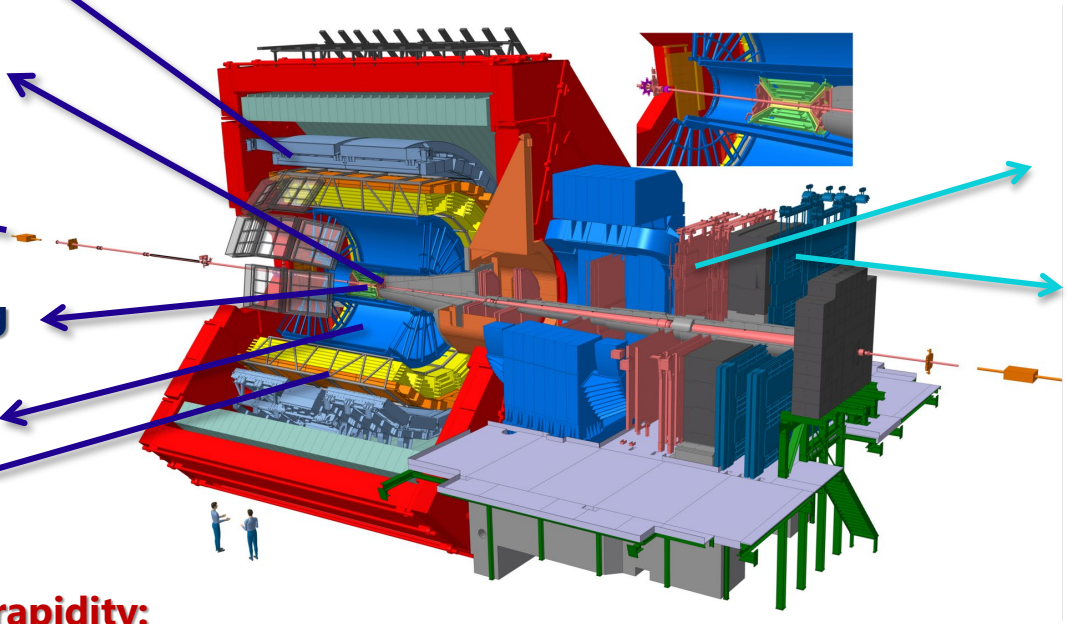
V0: trigger + centrality/multiplicity

ZDC: centrality estimation

ITS: tracking + vertexing

TPC: tracking + PID

TOF: PID



Muon Tracker

Muon Trigger

Heavy-flavour at central rapidity:

- Charmed hadrons from hadronic decay channels ($\mathbf{D^0}, \mathbf{D^+}, \mathbf{D^{*+}}, \mathbf{D_S^+}, \mathbf{\Lambda_c^+}, \mathbf{\Xi_c^0}$)
- Electrons from semileptonic decays ($\mathbf{b, c} \rightarrow \mathbf{e^{\pm}}X$)
- Non-prompt J/Psi from $\mathbf{B \rightarrow J/\Psi X \rightarrow e^+e^-X}$
- Non-prompt D-mesons $\mathbf{B \rightarrow D^0X \rightarrow K\pi X}$
- Jets with heavy-flavour content

Heavy-flavour at forward rapidity:

- Muons from semileptonic decays ($\mathbf{b, c} \rightarrow \boldsymbol{\mu^{\pm}}X$)

HEAVY-FLAVOUR JET RECONSTRUCTION

- Reconstruction of jets from charged-particle clustering
  - Charged tracks with $p_T > 0.15$ GeV/c
  - Fastjet with anti-kT; $|\eta^{jet}| < 0.9 - R$
  - Average jet background subtraction (in p-Pb)
- Heavy-flavour tagging by requesting the presence of a:

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- Subtraction of jets with combinatorial D via sideband subtraction
- D-meson reconstruction efficiency correction
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- Secondary-vertex tagging-efficiency correction
- Rejection of misidentified c-jets, LF-jets (purity correction)

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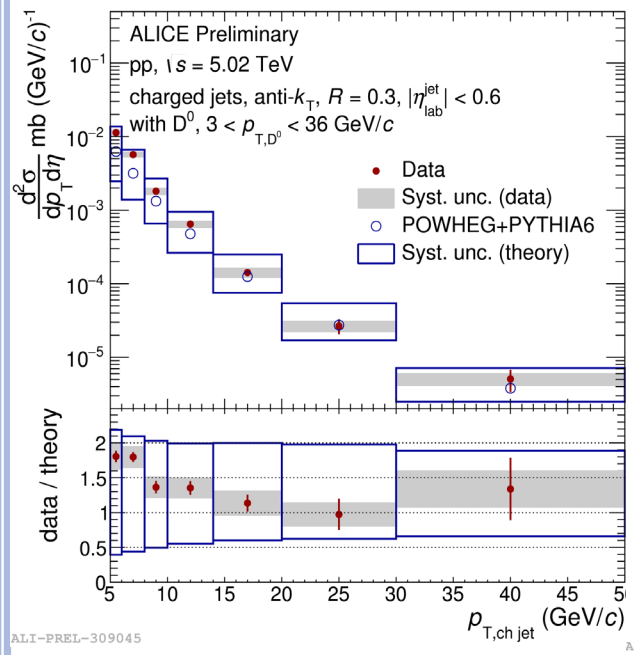
Unfolding of the jet spectrum to remove detector effects on the jet measured quantities + **normalisation**

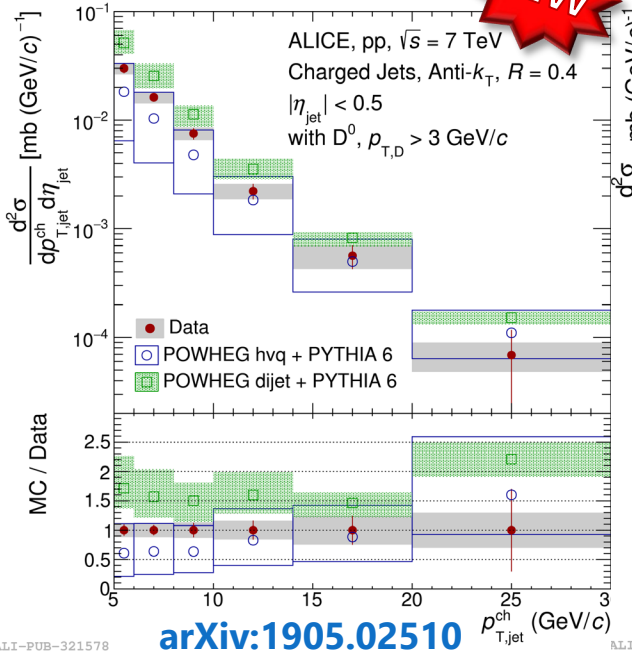
D-TAGGED JETS IN pp COLLISIONS

p_T-differential cross section of **D^0-meson tagged jets** in pp collisions at $\sqrt{s}$ = 5.02, 7, 13 TeV

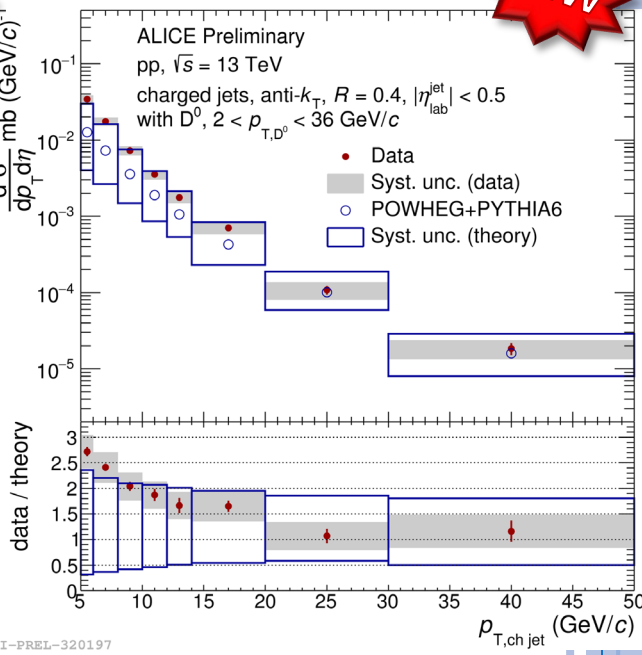
$\sqrt{s}$ = 5.02 TeV



$\sqrt{s}$ = 7 TeV NEW



$\sqrt{s}$ = 13 TeV NEW

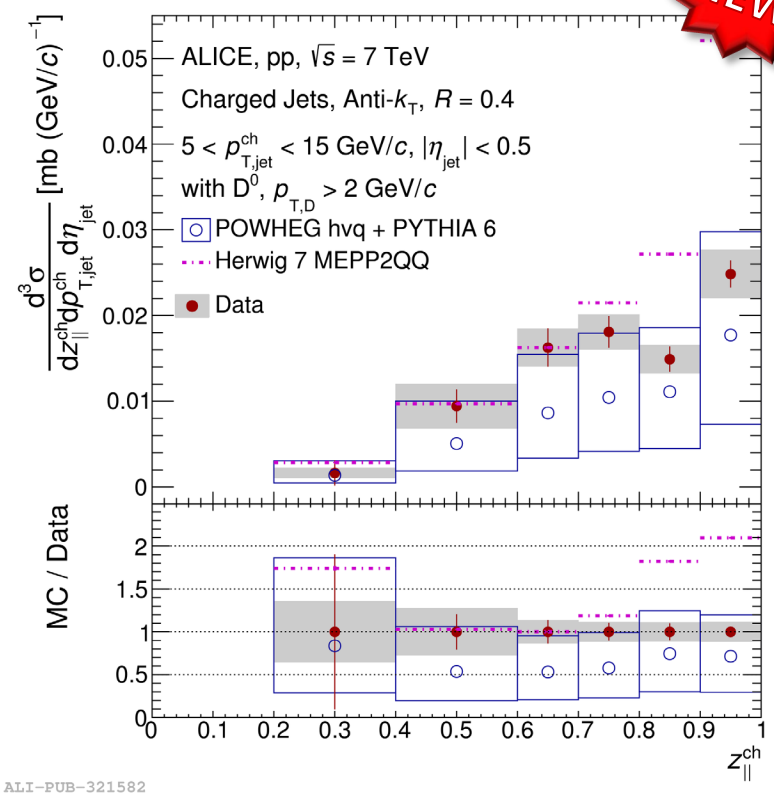


arXiv:1905.02510

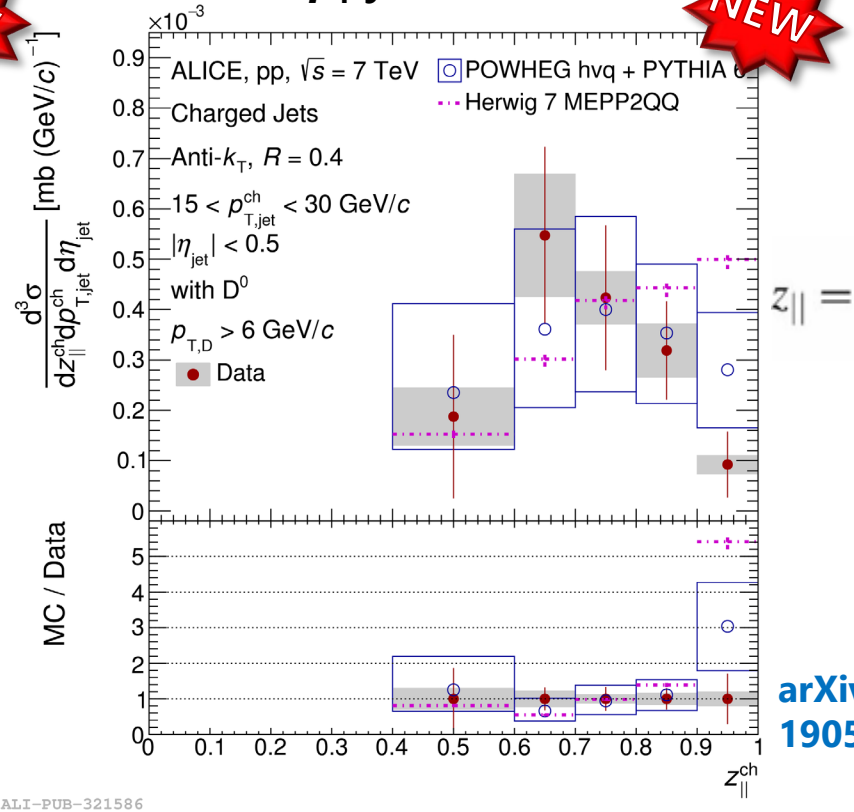
- Very low p_T reach: p_T(jet) > 5 GeV/c!
- POWHEG+PYTHIA predictions (NLO pQCD) **describe well** the measured cross section
  - Theory uncertainties larger than data ones
  - Note: minimum p_T(D) is lower (2 GeV/c) for $\sqrt{s}$ = 13 TeV results

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

5 < p_T(jet) < 15 GeV/c NEW



15 < p_T(jet) < 30 GeV/c NEW

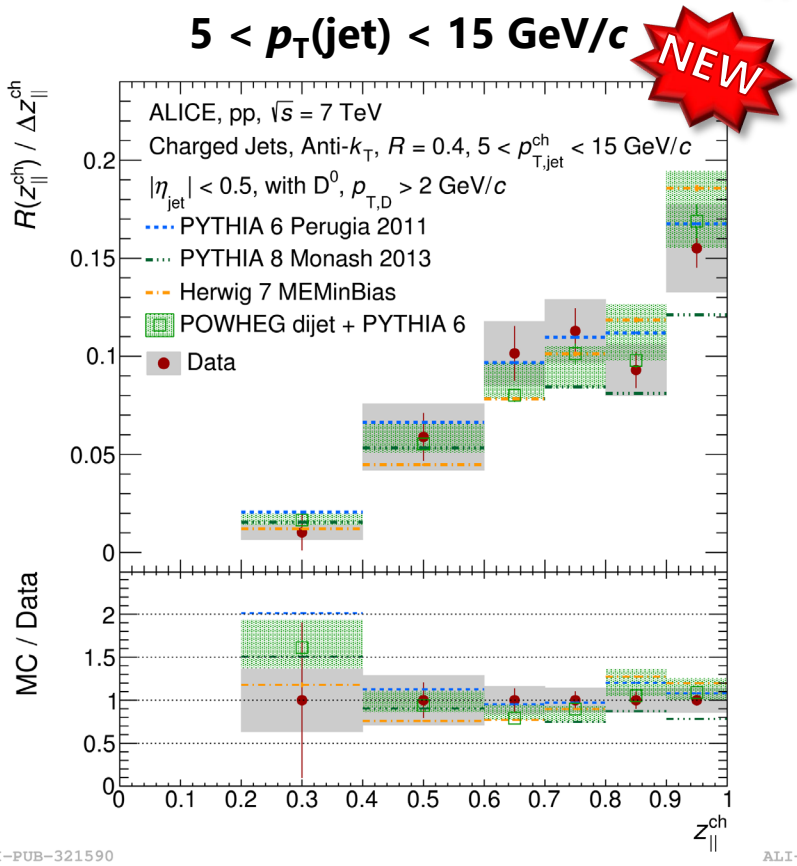


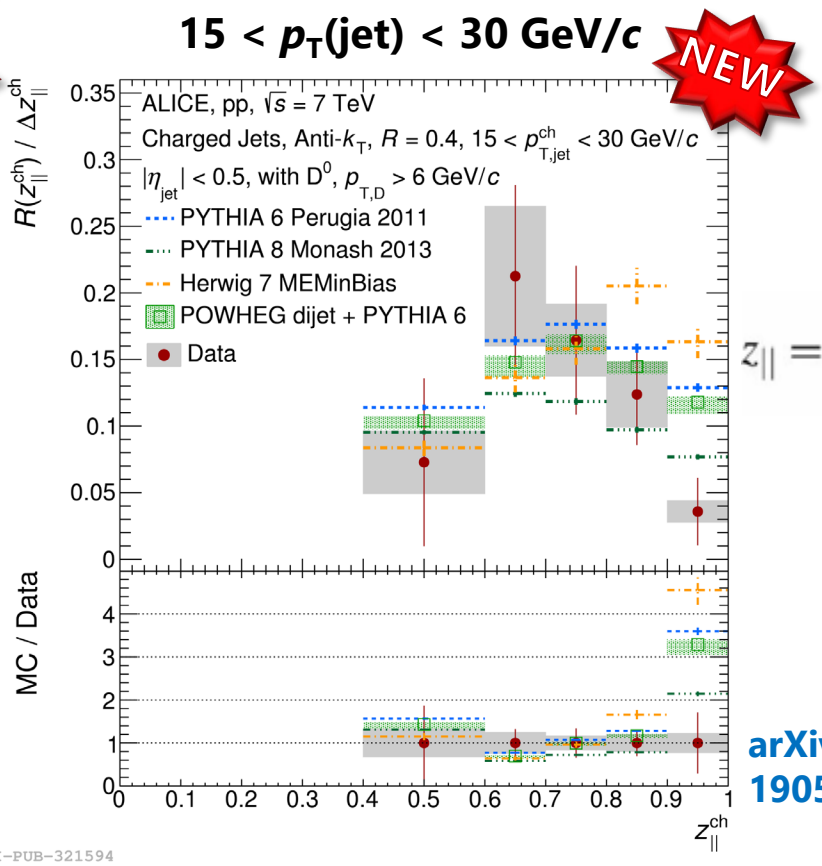
$$z_{||} = \frac{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{D}}}{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{ch\,jet}}}$$

arXiv: 1905.02510

- D^0-tagged jet cross section as a function of **jet parallel 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

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





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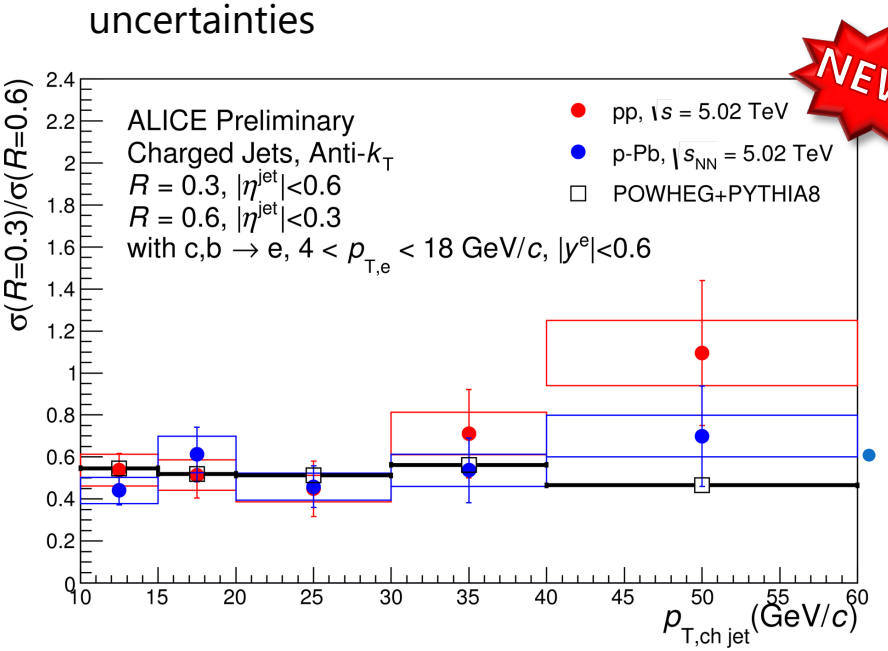
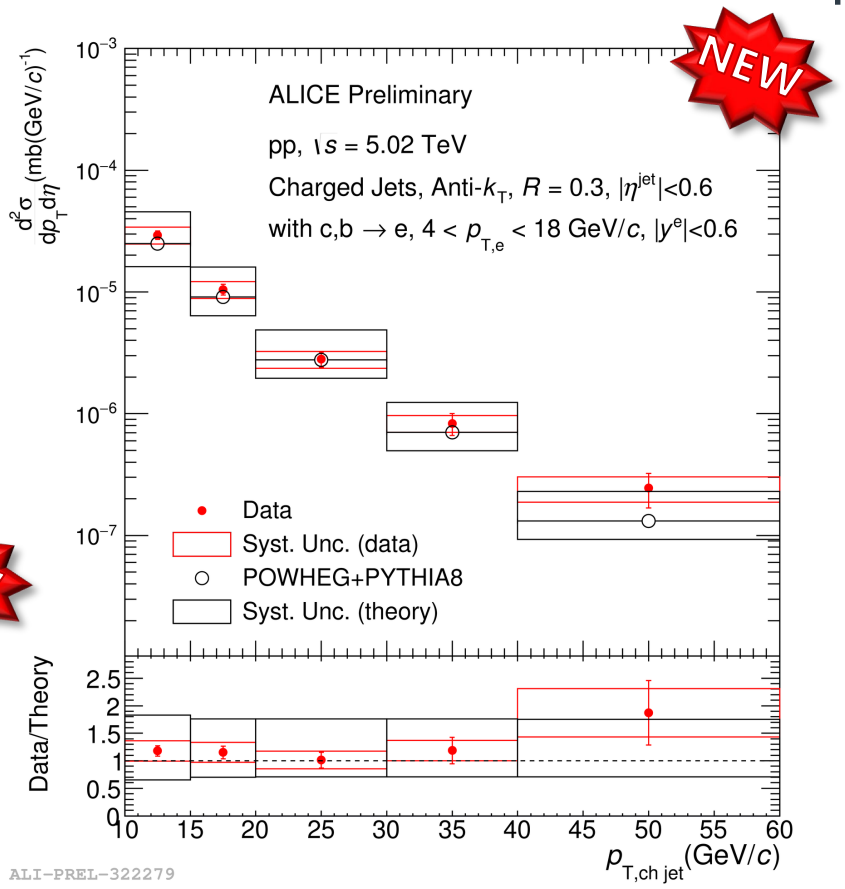
- Overall, good description of data. Hint of softer fragmentation at high p_T in data w.r.t. prediction
- Similar conclusions, for **rate to inclusive jets**, from LO models (Herwig, Pythia8, Pythia6)

HF ELECTRON JETS IN pp COLLISIONS

- p_T-differential cross section of HFe-tagged charged jets, in pp collisions at $\sqrt{s}$ = 5 TeV
  - For different jet cones R=0.3, 0.4, 0.6
  - Sensitive to beauty! (HFe dominated by beauty for p_T(e) > 5 GeV/c)
- POWHEG+PYTHIA8 predictions **in agreement** with measurement within uncertainties

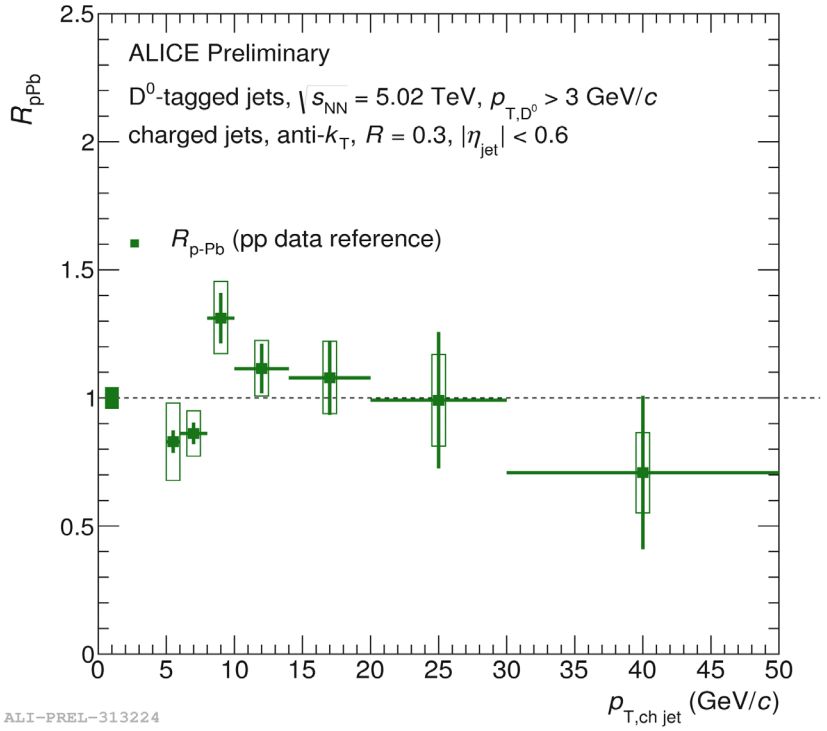




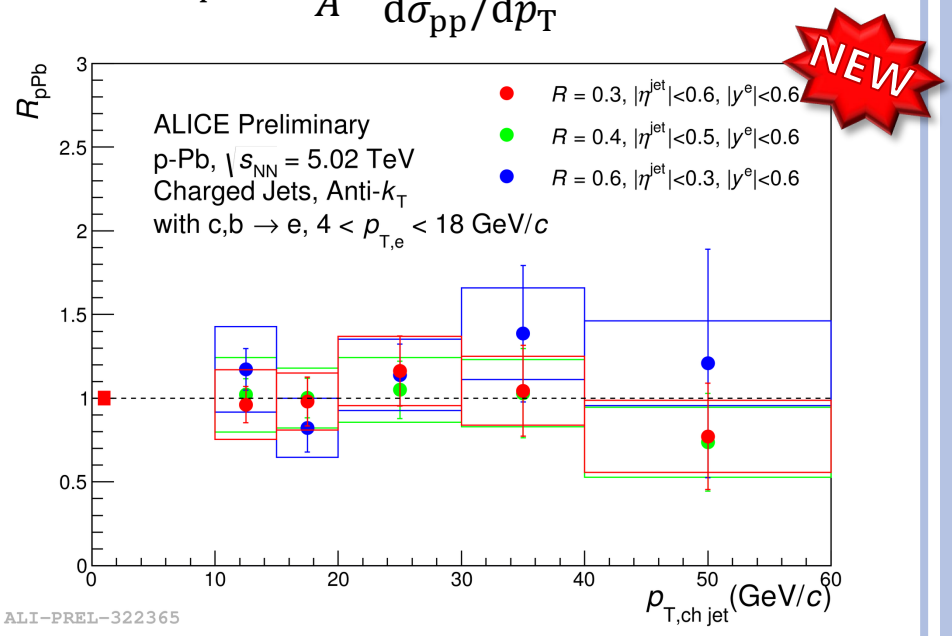
Ratio of cross section with **R=0.3** over **R=0.6** also **well described** by POWHEG+PYTHIA8 NLO calculations

R_{pPb} OF D-MESON AND HFe JETS

Nuclear modification factor of **D^0-tagged** and **HFe-tagged** charged jets:



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

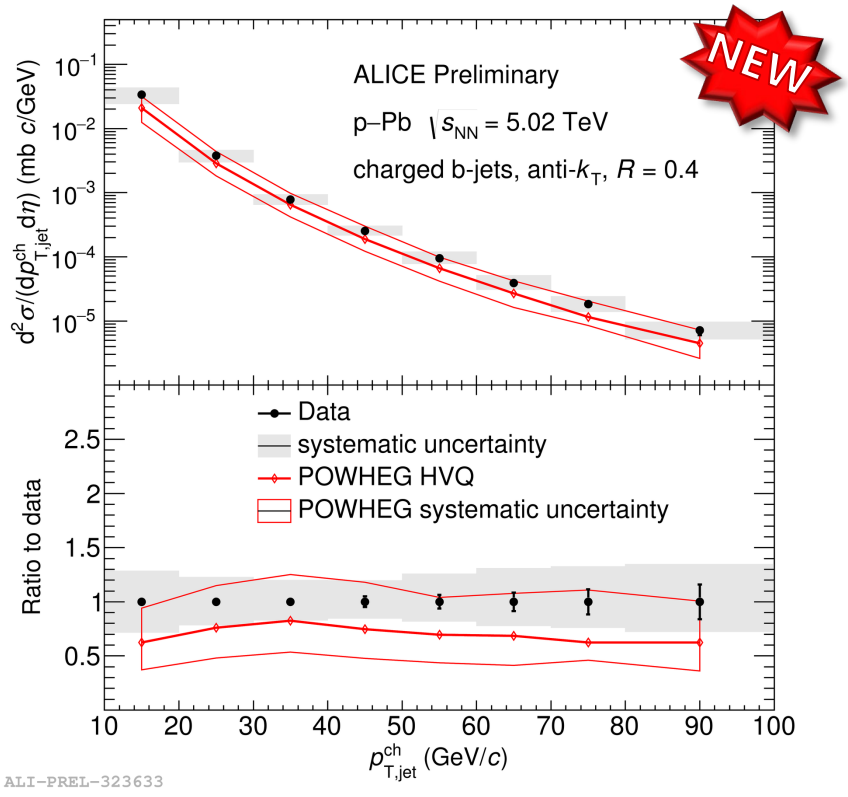


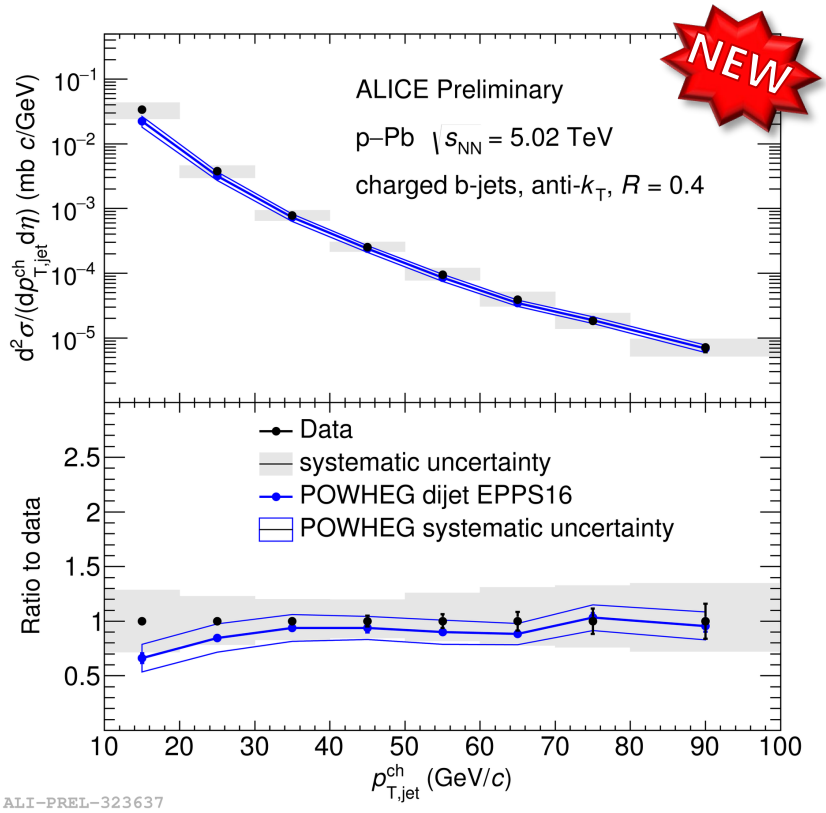
- R_{pPb} for both tagging particles are **consistent with unity** over the full p_{T} range
  - ➢ No evidence of strong cold-nuclear-matter effects on charm (and beauty) jet production
- Single-particle R_{pPb} measurement also consistent with one, hinting to no large modifications to the parton fragmentation from pp to p-Pb

→ See Mattia Faggin's talk on Tuesday at 15:20 (parallel nPDF/CNM)

b-TAGGED JETS IN p-Pb COLLISIONS

First ALICE measurement of **beauty jets** in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV





- Cross section **described within uncertainties** by POWHEG+PYTHIA NLO calculations with HVQ and dijet production process + nuclear PDF
- Very low p_{T} reach, $\boldsymbol{p_{\mathrm{T}}}$**(jet) > 10 GeV/**$\boldsymbol{c}$, complementing other existing measurements at the LHC at higher p_{T}

HF CORRELATION: ANALYSIS PROCEDURE

Reconstruction of **D mesons** via hadronic decays

Reconstruction of **HF electrons (HFe)**

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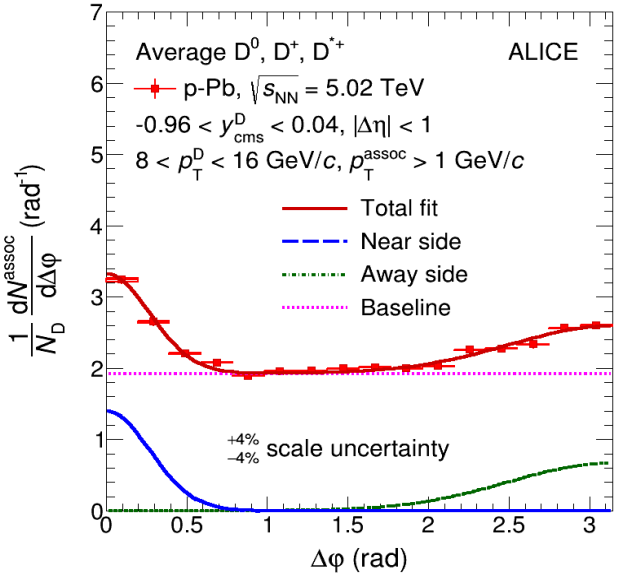

EPJ C 77 (2017) 245

- Average of D^0,D^+,D^{*+} distribution, fit, and extraction of peak yields and widths

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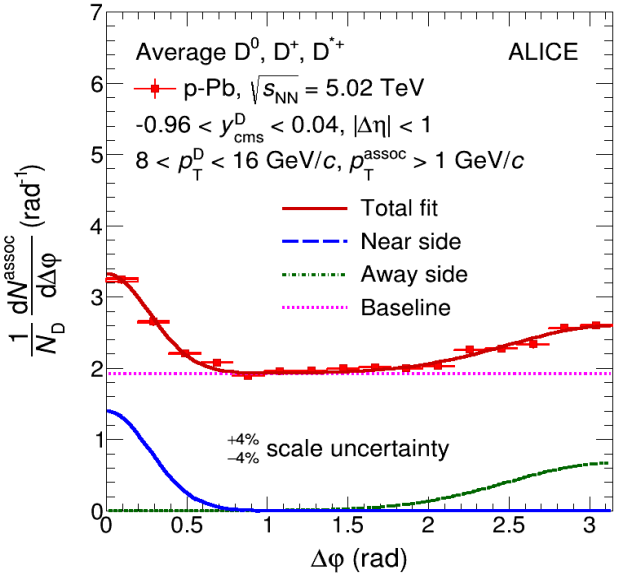
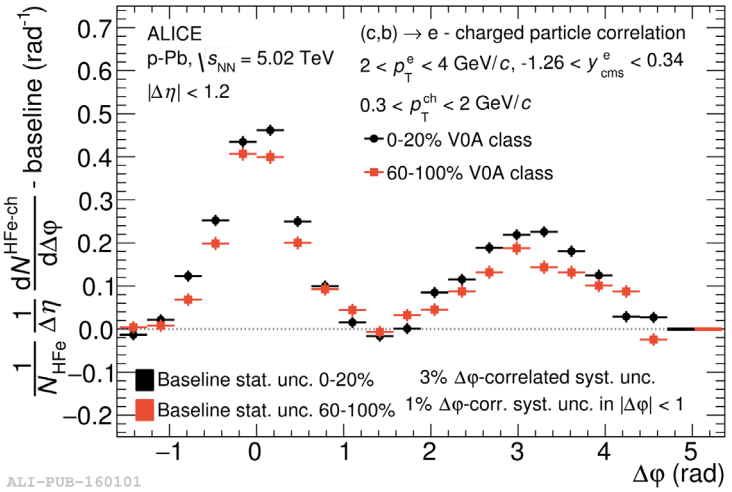


EPJ C 77 (2017) 245

- Average of D^0,D^+,D^{*+} distribution, fit, and extraction of peak yields and widths

- Subtraction of hadron contamination from *E/p* distribution in the EMCal
- Subtraction of non-HFe electron via invariant mass analysis

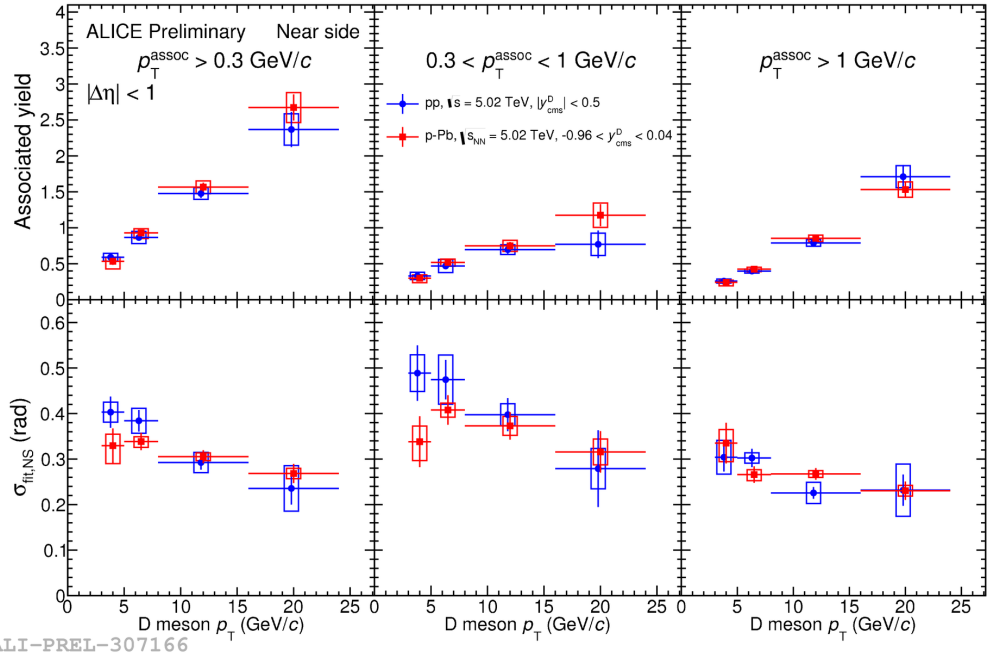


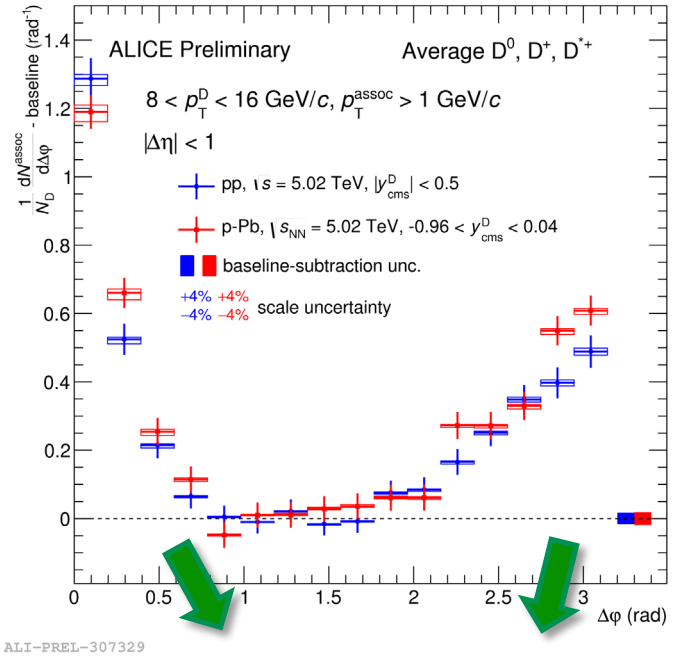
PRL 122, 072301 (2019)

D-h CORRELATIONS IN pp AND p-Pb

- Azimuthal correlation distributions of D mesons with charged particles in pp and p-Pb collisions
- **Similar correlation pattern** and in pp and p-Pb over a large kinematic range:
  - $3 < p_T(\mathrm{D}) < 24$ GeV/c
  - $0.3 < p_T(\mathrm{assoc}) < 3$ GeV/c

pp@5.02 TeV
p-Pb@5.02 TeV





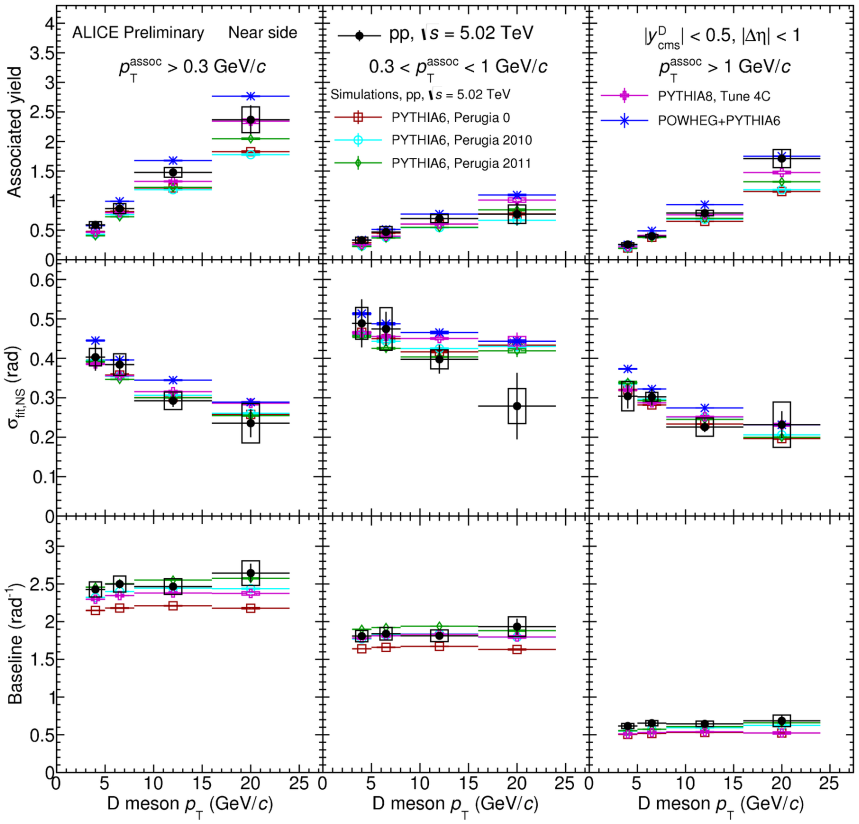
Near-side (NS) **Away-side (AS)**

- Near-side yields and widths **consistent between pp and p-Pb**
  - Same for away-side, not shown
  - No evidence of cold-nuclear-matter effects larger than uncertainties

D-h CORRELATIONS IN pp VS MODELS

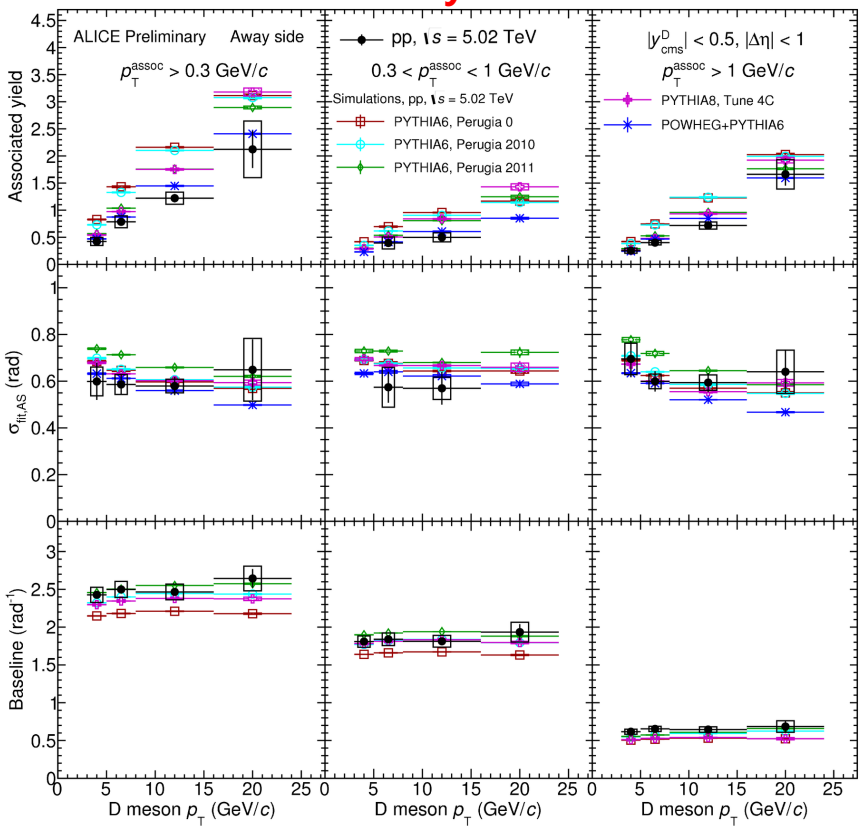
Comparison of near-side and away-side peak yields and widths to Monte Carlo predictions

Near-side



ALI-PREL-307362

Away-side

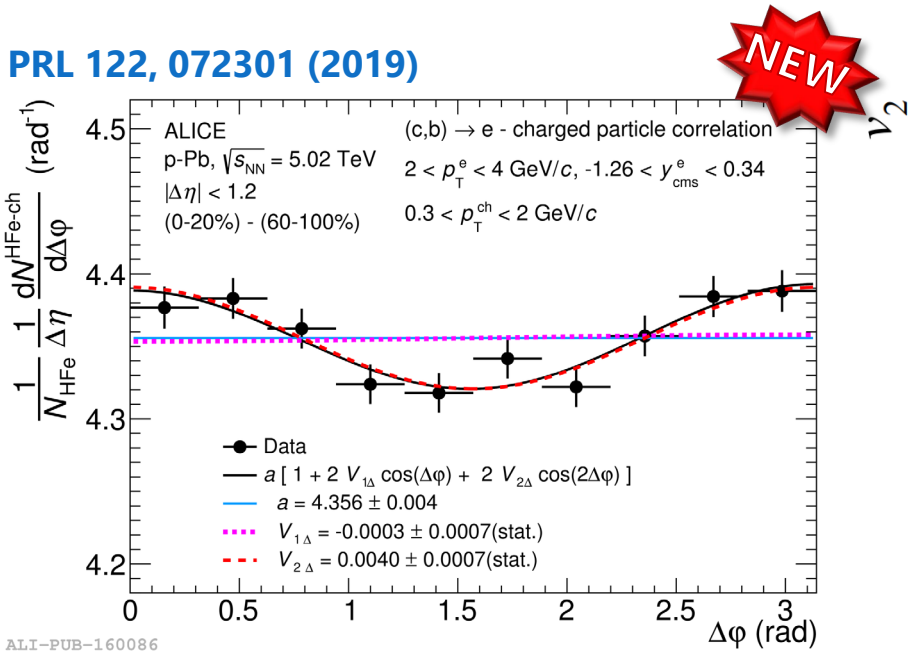


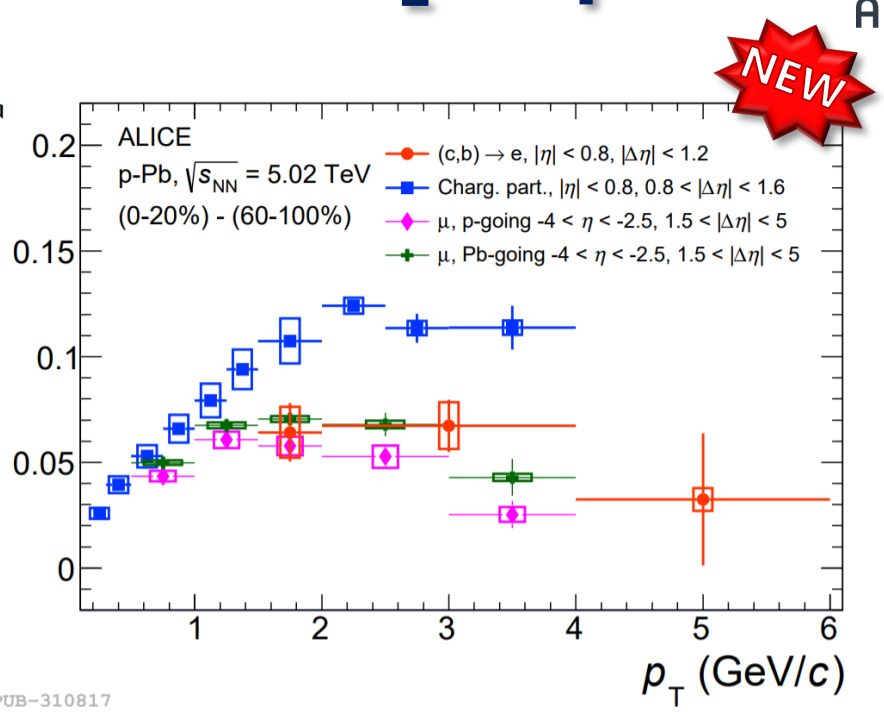
ALI-PREL-307380

- POWHEG+PYTHIA (NLO) predicts larger NS yields/widths and smaller AS yields/widths than models at LO
- NS peak not favouring a specific model; AS possibly better described by POWHEG+PYTHIA
- Observables sensitive to modelling of heavy-quark production processes and fragmentation

HEAVY-FLAVOUR ELECTRON v_2 IN p-Pb

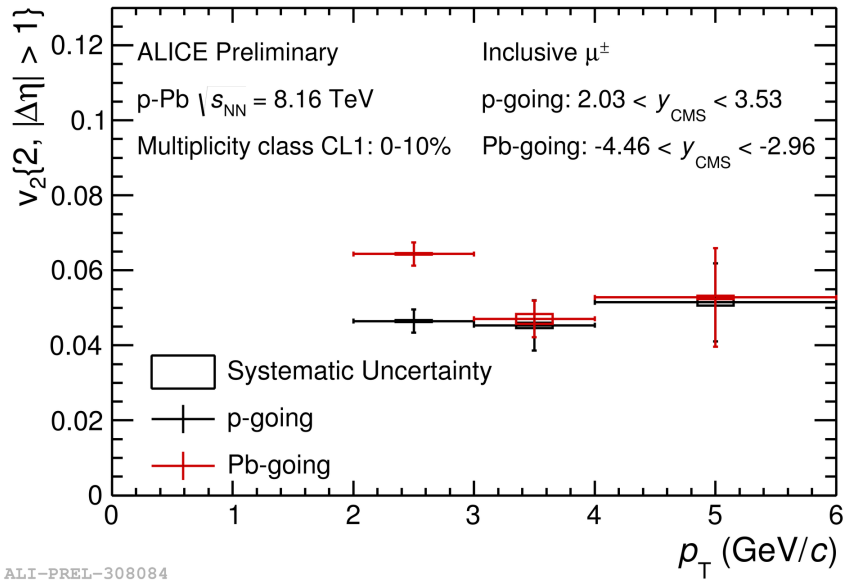
PRL 122, 072301 (2019)

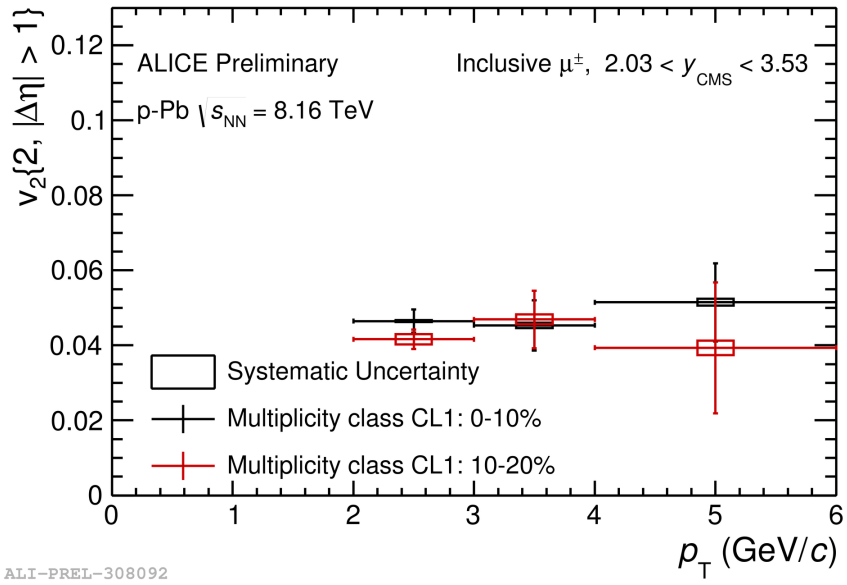




- Azimuthal correlations of heavy-flavour decay electrons with charged particles in HM (high multiplicity, 0-20%) and LM (low multiplicity, 60-100%) p-Pb collisions
- v_2 extracted from Fourier decomposition of HM – LM correlation distribution
- **Positive v_2** for heavy-flavour decay electrons (**5σ effect** for $1.5 < p_T^e < 4$ GeV/c)
  - Strength of v_2 lower than for charged particles (but different p_T ranges of original partons), and comparable with muons (but different rapidities)

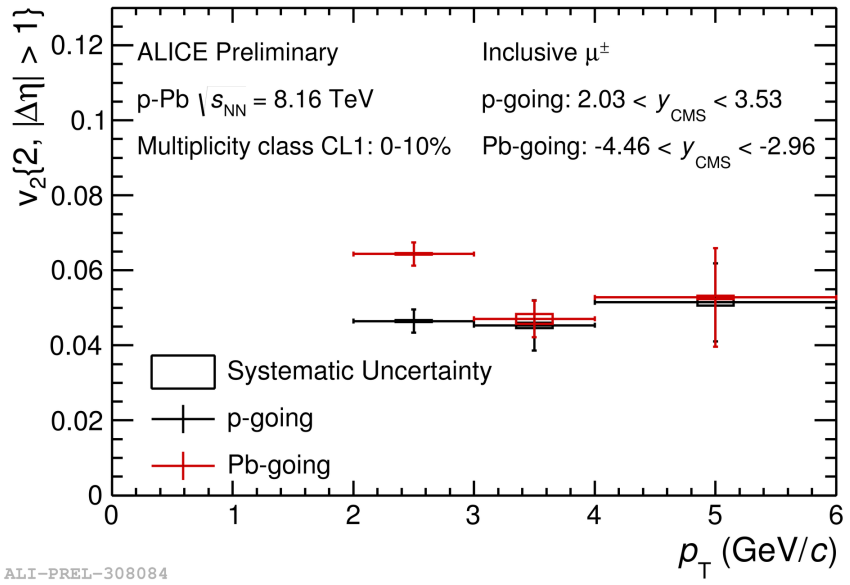
HEAVY-FLAVOUR MUON v_2 IN p-Pb

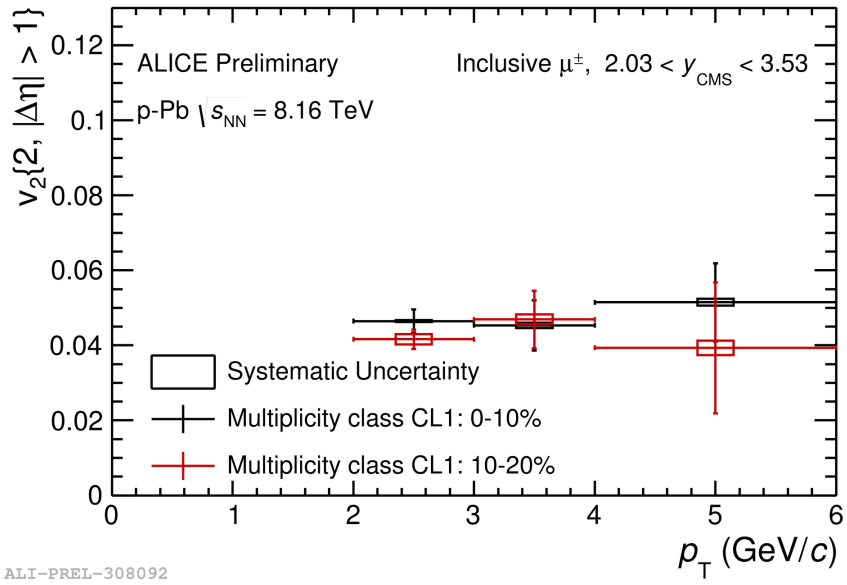




- Same values of muon v_2 in HM p-Pb obtained also via 2-particle cumulant method
- Muon sample dominated by heavy-flavour contribution above 2 GeV/c
- Compatibility of v_2 values at forward and backward rapidity

HEAVY-FLAVOUR MUON v_2 IN p-Pb





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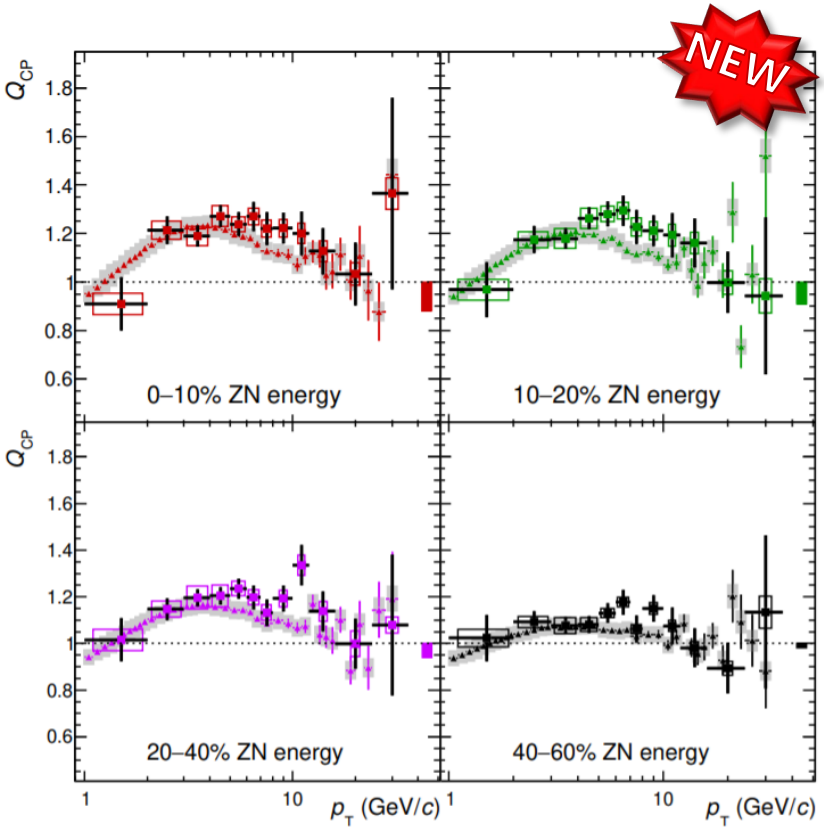
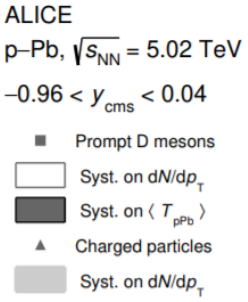
$v_2^{HFe,HF\mu} > 0$ in p-Pb: Initial-state (gluon saturation) or **final-state effect?**

If it's final, does it come from **collectivity** as for Pb-Pb?

Need model predictions to investigate further the origin!

D-MESONS Q_{CP} IN p-Pb COLLISIONS





Ratio of corrected yields in central p-Pb collisions over peripheral p-Pb collisions, $\boldsymbol{Q_{CP}}$:

$$Q_{\mathrm{CP}} = \frac{(\mathrm{d}^2N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{\mathrm{i}}_{\mathrm{p-Pb}}/\langle T_{\mathrm{pPb}}\rangle_{\mathrm{i}}}{(\mathrm{d}^2N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{60-100\%}_{\mathrm{p-Pb}}/\langle T_{\mathrm{pPb}}\rangle_{60-100\%}}$$

- Nicely complements elliptic flow measurements of heavy-flavour leptons in high-multiplicity p-Pb collisions

- Measurement of $\boldsymbol{Q_{CP} > 1}$ with ≈3σ significance for 20-40% class, for $3 < p_T(D) < 7$ GeV/c
  - Similar feature observed also for charged particle measurements
- **One possible origin**: **radial flow** induced by hydrodynamic evolution of the collisions
  - Models are needed for interpreting the results!

CONCLUSIONS

- p_T -differential cross section of **D-tagged**, **HFe-tagged and b-tagged charged jets** in small systems **described by POWHEG+PYTHIA** predictions within uncertainties
  - **Parallel D-jet momentum fraction** of D^0 in overall agreement with predictions, with hints of softening for data distribution w.r.t. models at high p_T
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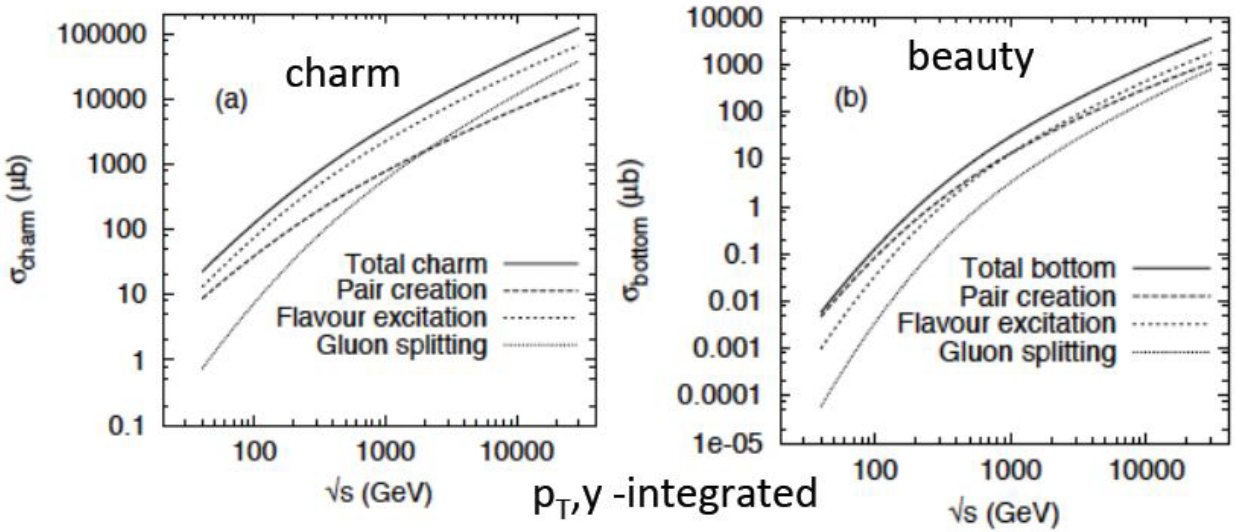
- **Positive elliptic flow** of **heavy-flavour hadron decay electrons** (at central rapidity) and **muons** (at forward/backward rapidity) in high multiplicity p-Pb collisions
  - Initial state or final state effect? Does it come from collectivity?
- Possible onset of collectivity in such conditions could be supported by $Q_{CP} > 1$ of **D mesons** at intermediate p_T

BACKUP SLIDES

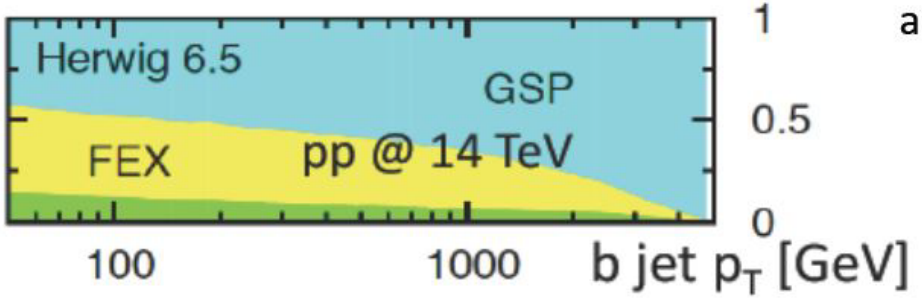
HEAVY QUARK PRODUCTION

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

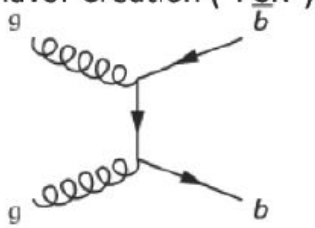


p_T,y -integrated

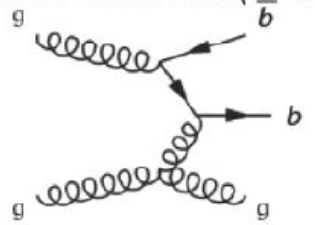
HERWIG 6.5 (A. Banfi, G. Salam, G. Zanderighi, JHEP 0707:026,2007, arXiv:0704.2999)



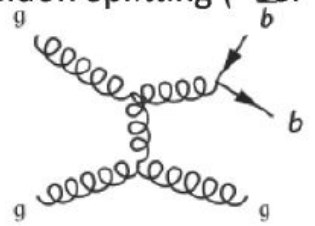
Flavor Creation ("FCR")



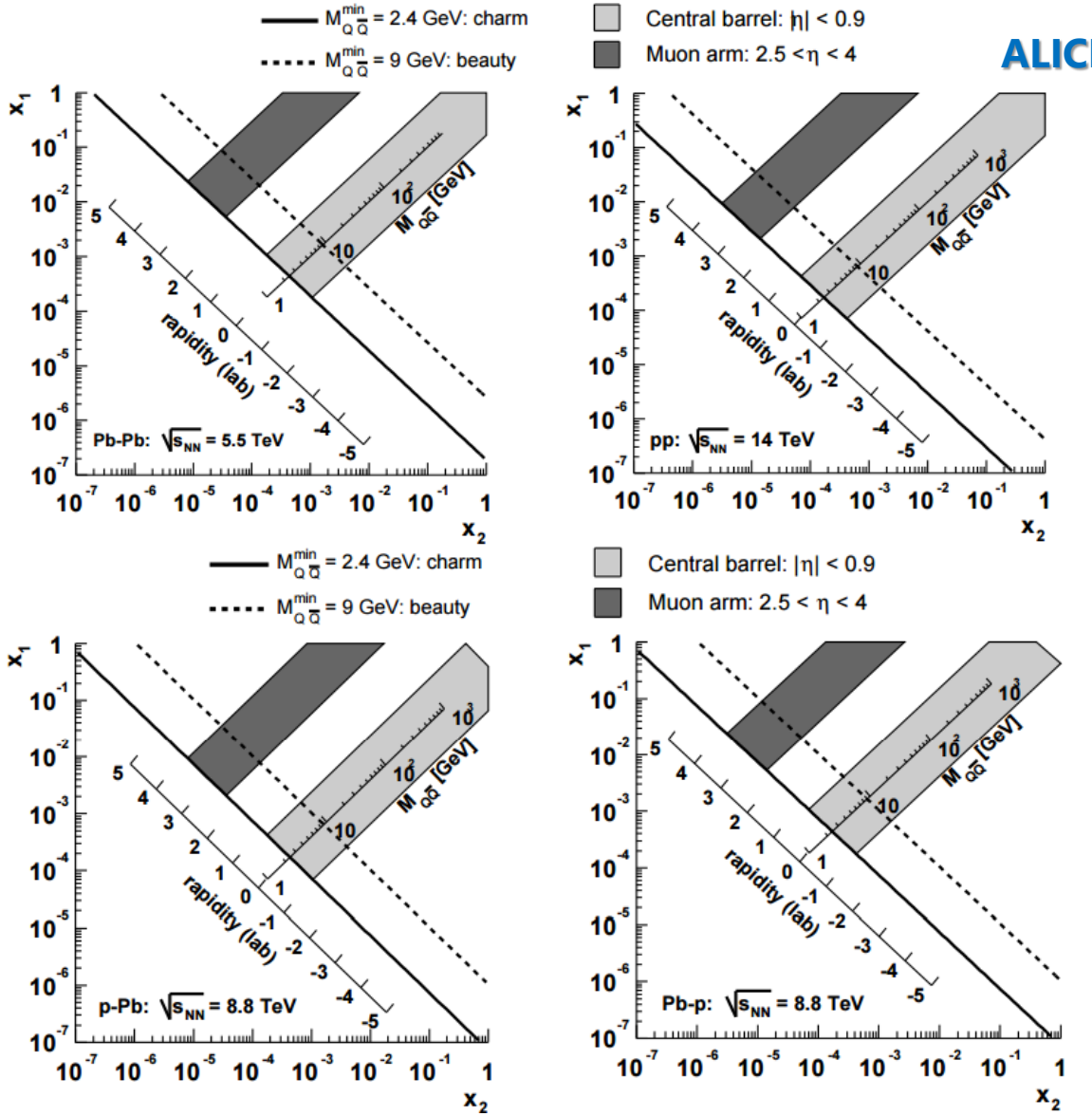
Flavor Excitation ("FEX")



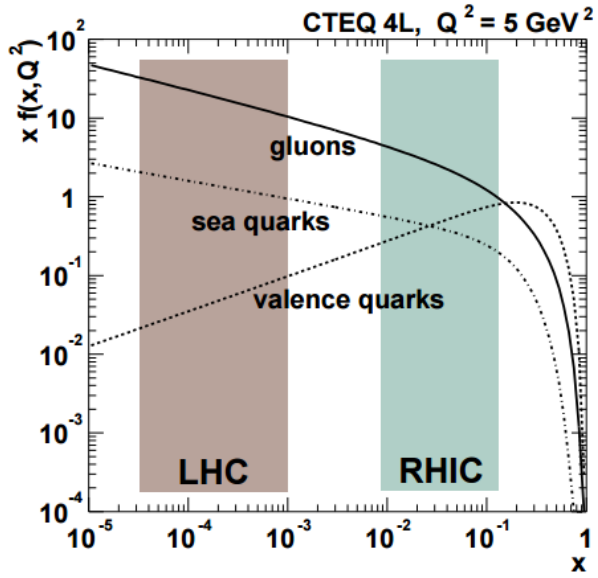
Gluon Splitting ("GSP")



BJORKEN X REGIONS AT THE LHC AND PDF



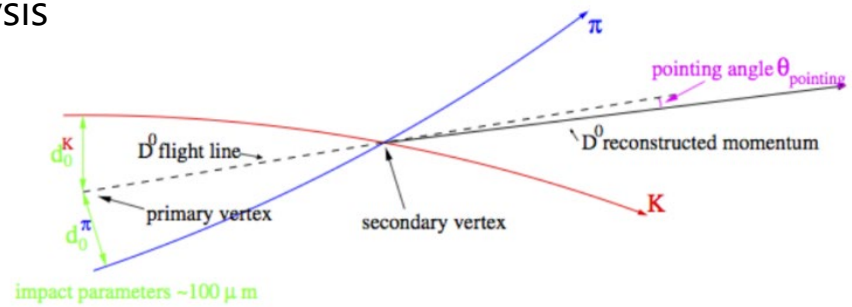
ALICE, J. Phys. G, 32 (2010) 1295

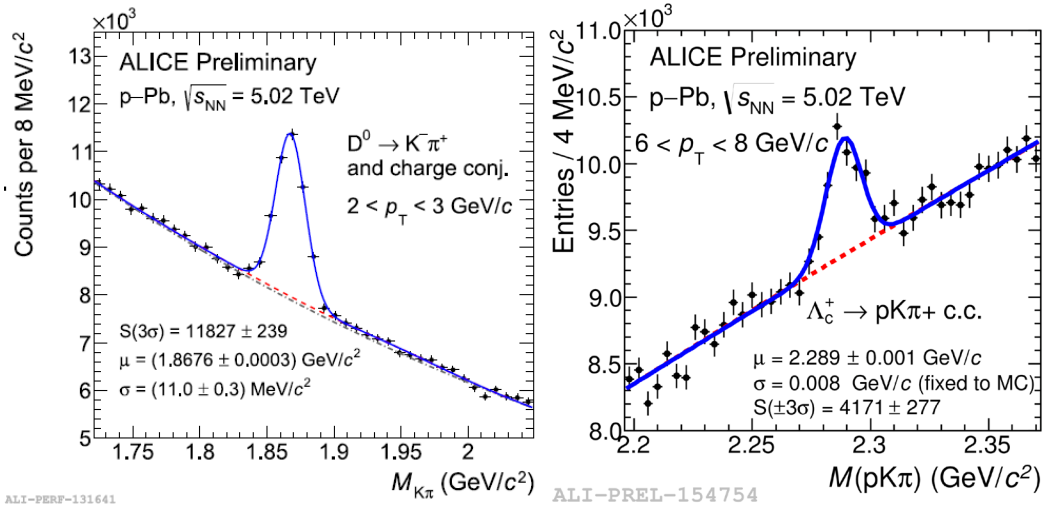


Parton Distribution Functions in CTEQ 4L parametrization, for Q^2 = 5 GeV^2

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

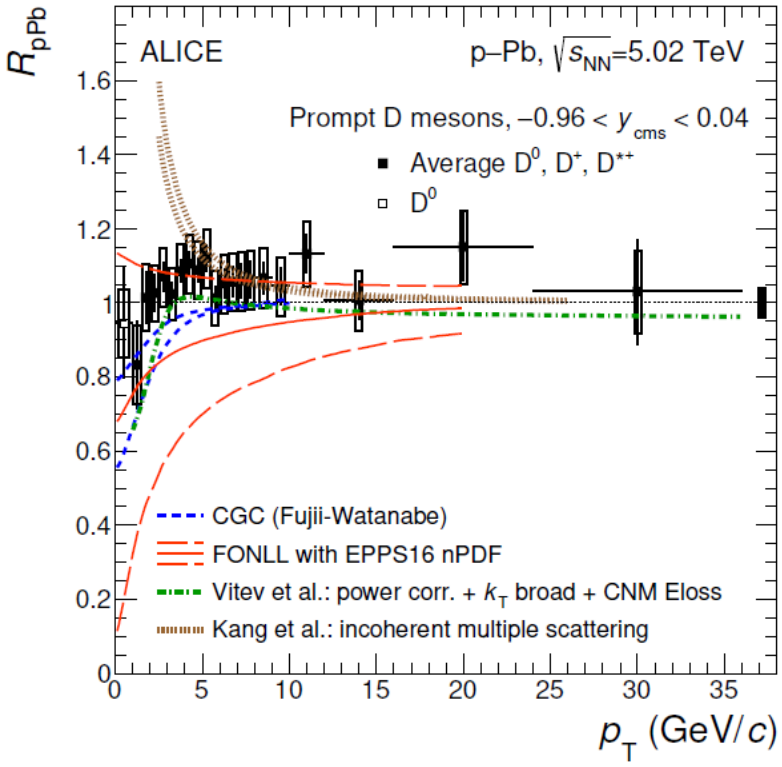


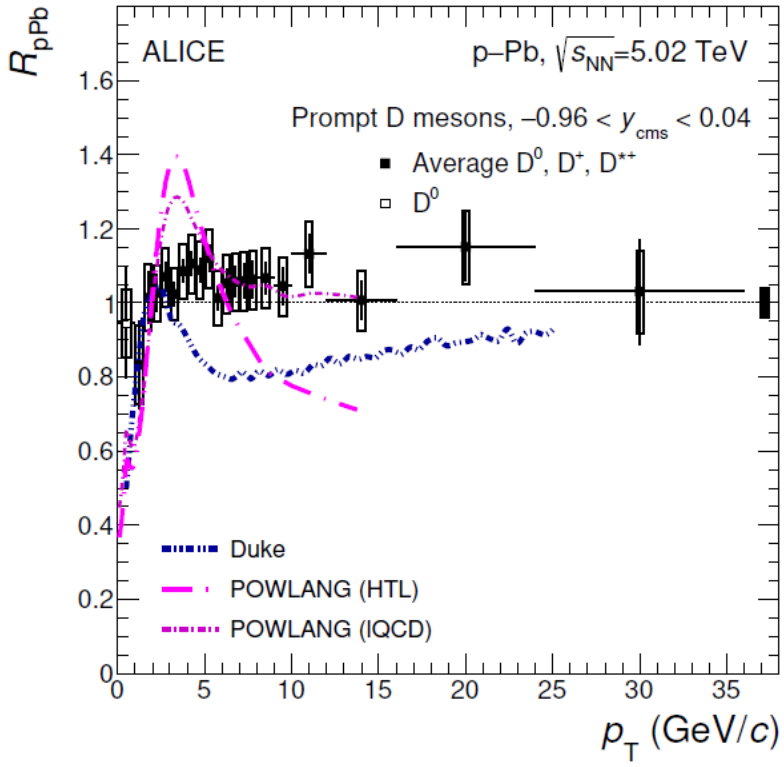


Charmed hadrons ($|y| < 0.5$)

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

D-MESON R_{pPb}

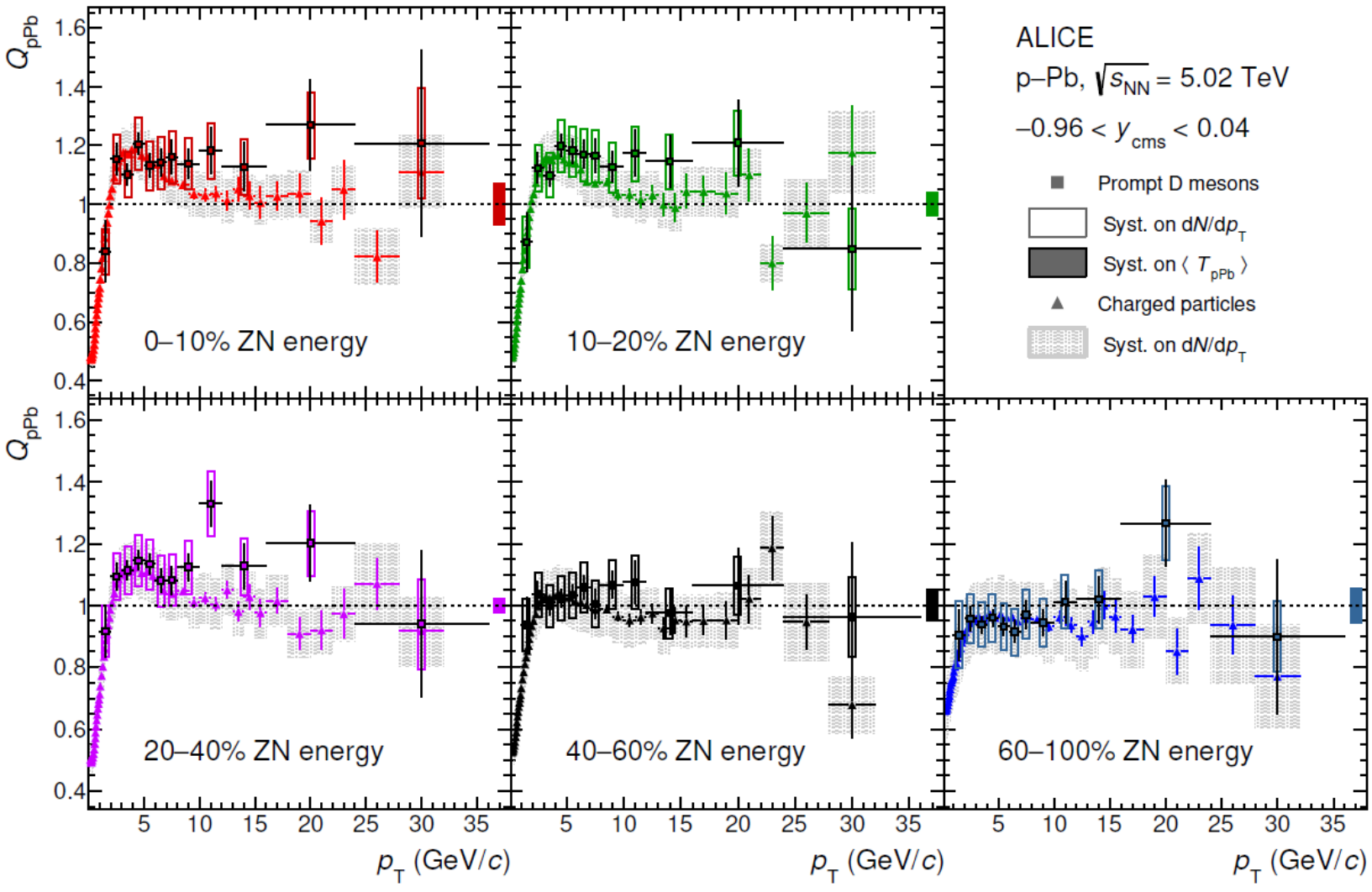




- New published results with better precision, due to reduction of uncertainties in the pp reference (2017 sample)
- Non-strange D meson R_{pPb} is **compatible with unity** within uncertainties
  - Described by models including cold nuclear-matter effects; models assuming QGP formation are more disfavoured

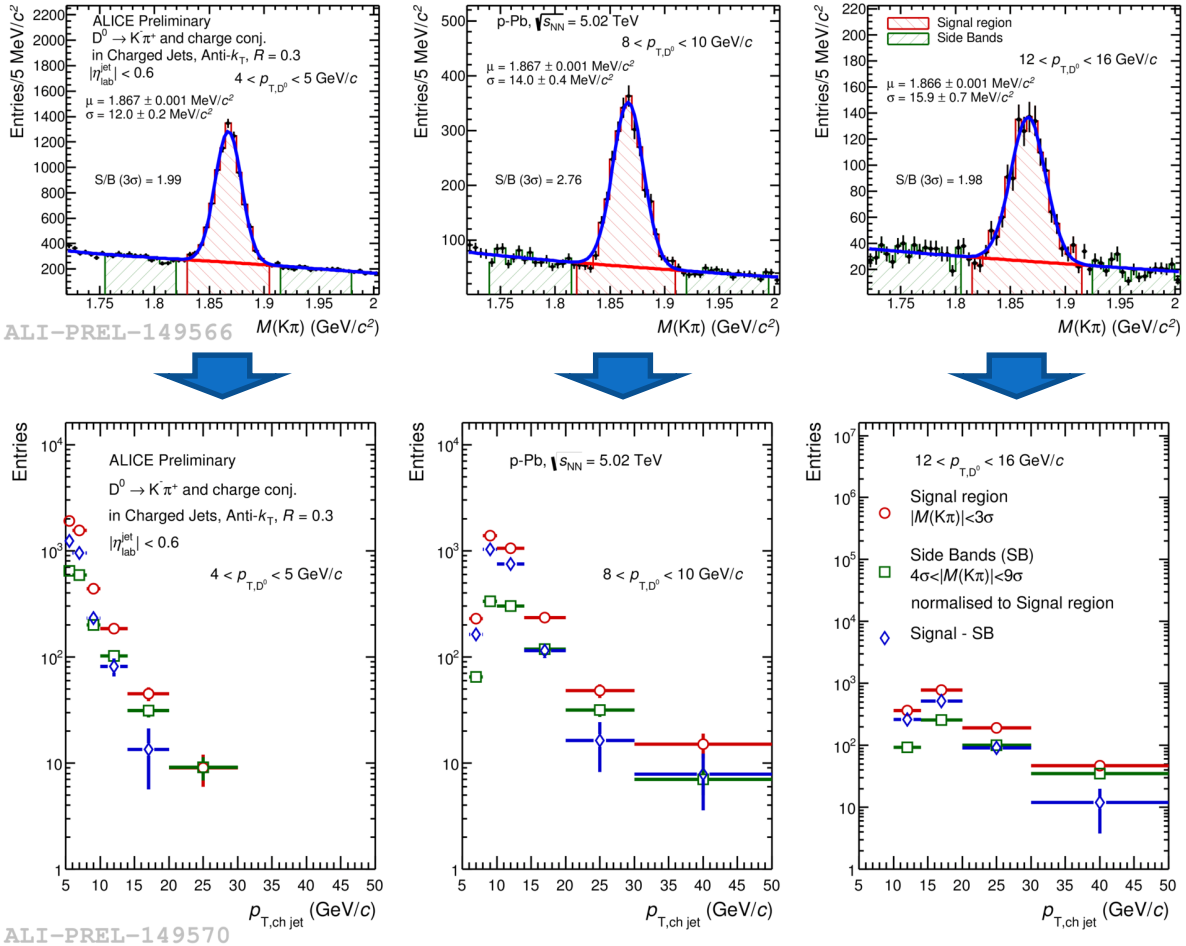
$$R_{\mathrm{pPb}} = \frac{\frac{\mathrm{d}\sigma_{\mathrm{pPb}}}{\mathrm{d}p_{\mathrm{T}}}}{A \cdot \frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}}}$$

D-MESON Q_{pPb}


ALICE
p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
–0.96 < y_{cms} < 0.04
Prompt D mesons
Syst. on dN/dp_T
Syst. on ⟨ T_{pPb} ⟩
Charged particles
Syst. on dN/dp_T
Q_{pPb}
0–10% ZN energy
10–20% ZN energy
20–40% ZN energy
40–60% ZN energy
60–100% ZN energy
p_T (GeV/c)

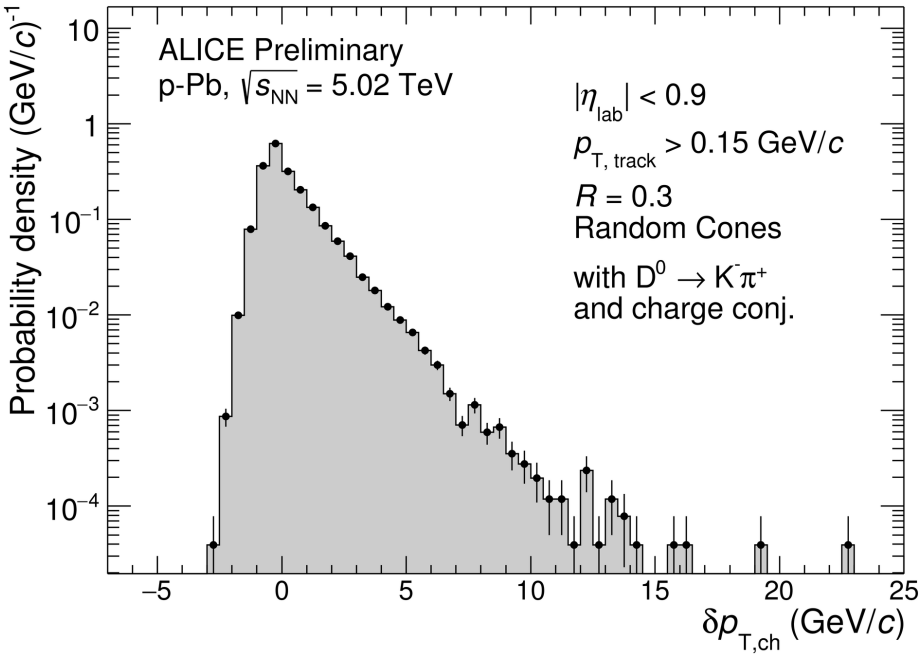
D-JETS: ANALYSIS STRATEGY

- 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

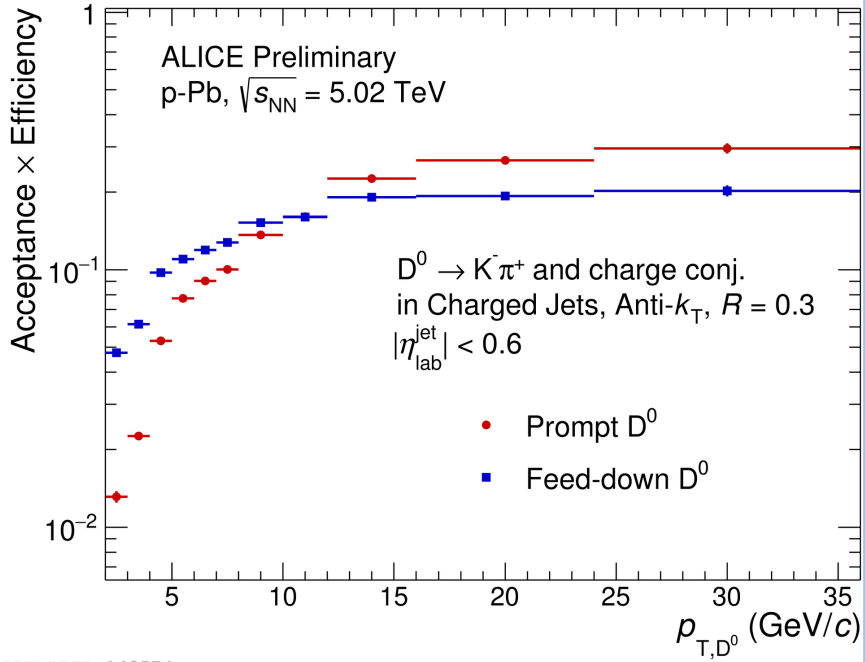


- Invariant mass study to extract D-jet raw yield
  - Background spectrum from the sidebands
- Spectrum corrected for D-jet efficiency and for beauty feed-down, exploiting folded POWHEG+PYTHIA predictions
- Corrected D-jet spectrum unfolded for detector effects and background fluctuations (in p-Pb and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

D-JETS – TECHNICAL PLOTS

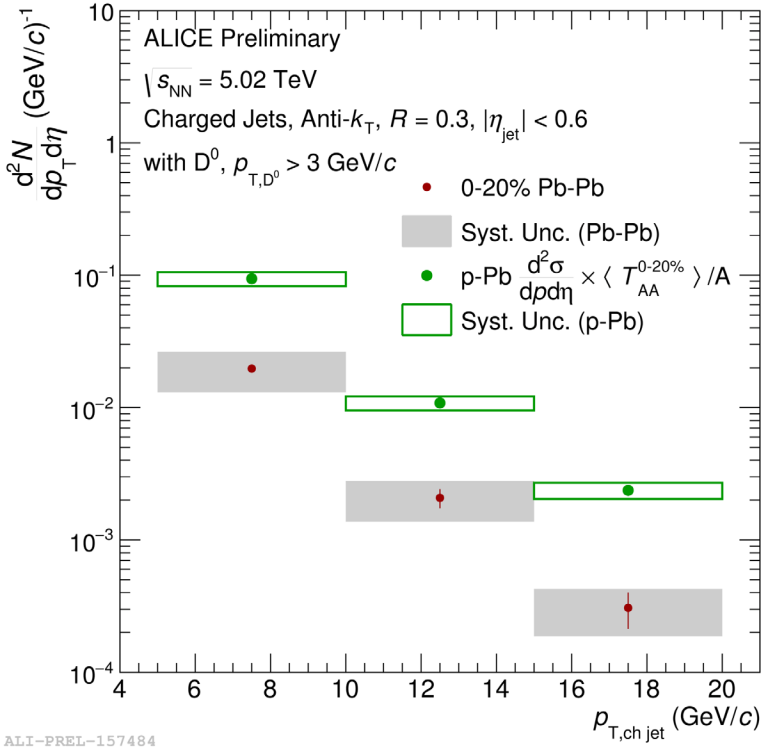


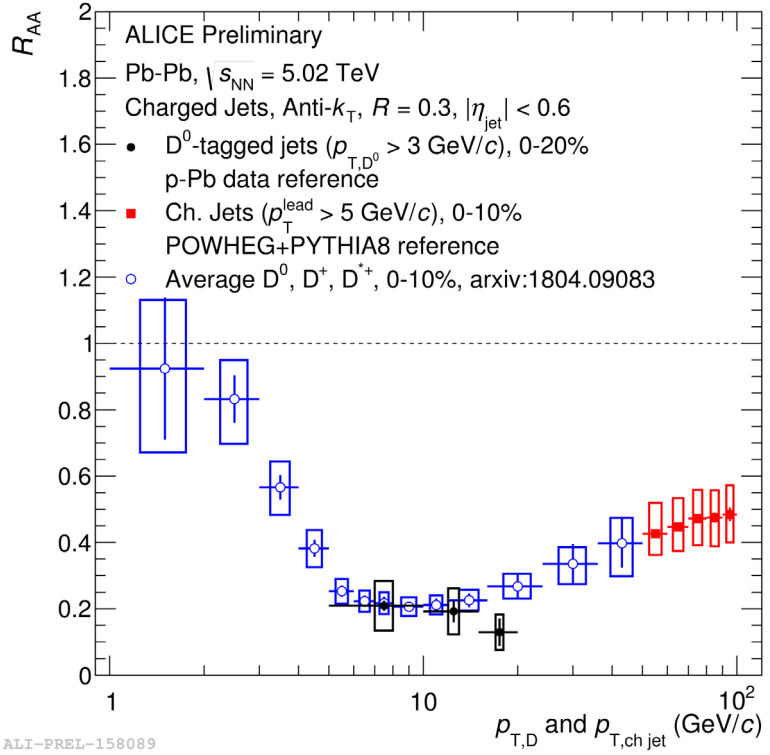
ALI-PREL-149558



ALI-PREL-149574

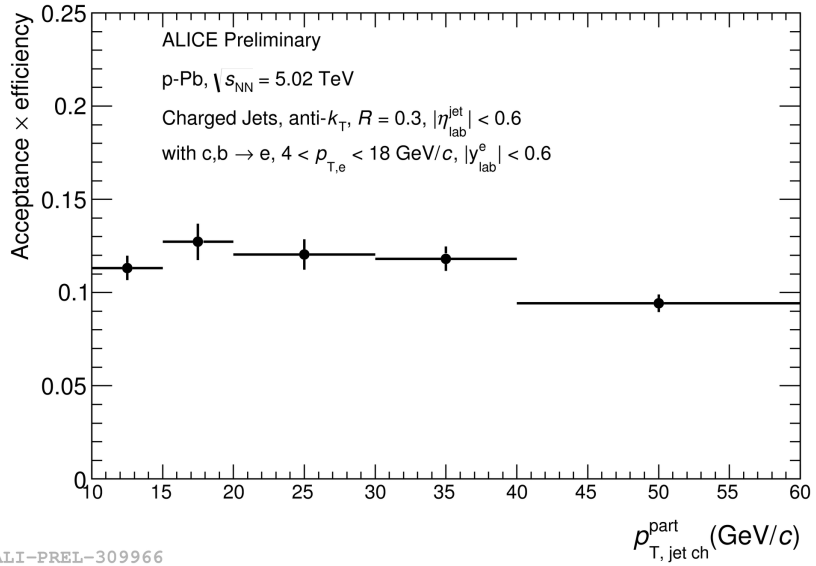
D-TAGGED JETS IN Pb-Pb COLLISIONS



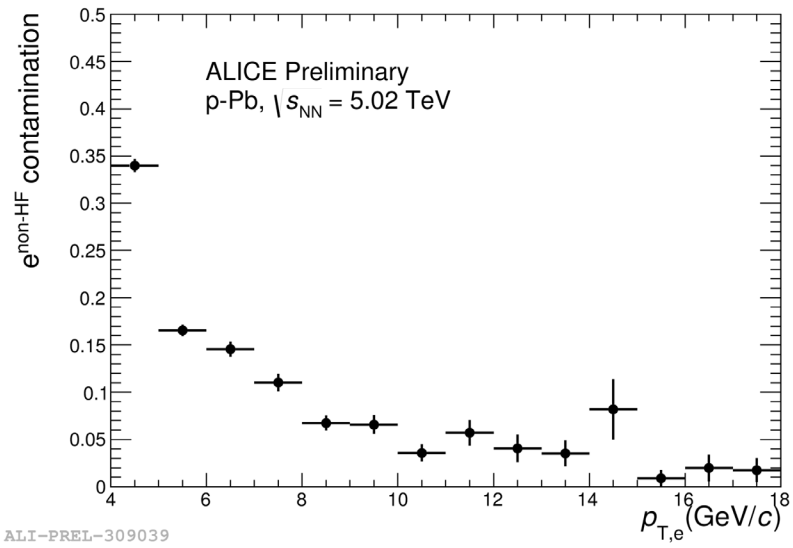


- Strong suppression of production cross section in 0-20% Pb-Pb collisions over full p_T(jet) range
- Comparison with inclusive jets difficult due to non-overlapping p_T ranges, but hint of lower R_{AA} for D jets in $5 < p_T(\text{jet}) < 20$ GeV/c than inclusive jets with $p_T > 50$ GeV/c
  - Can address 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 p_T scale)

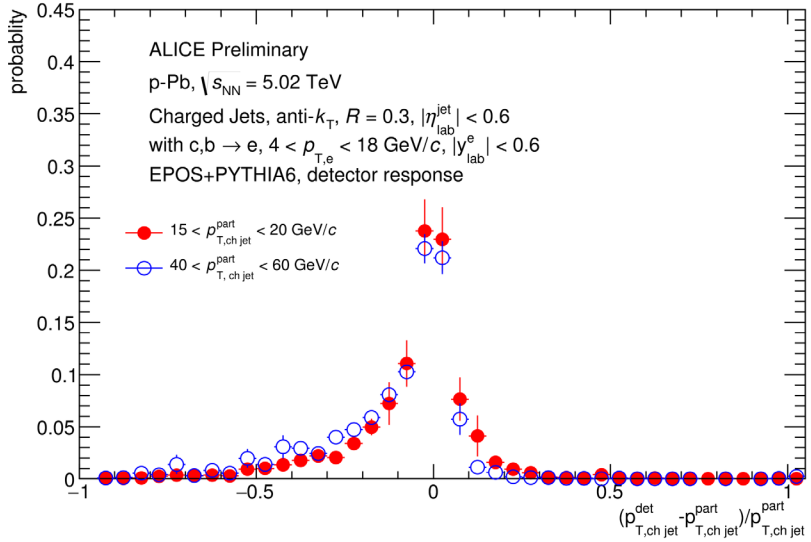
HFe-JETS – TECHNICAL PLOTS



ALI-PREL-309966

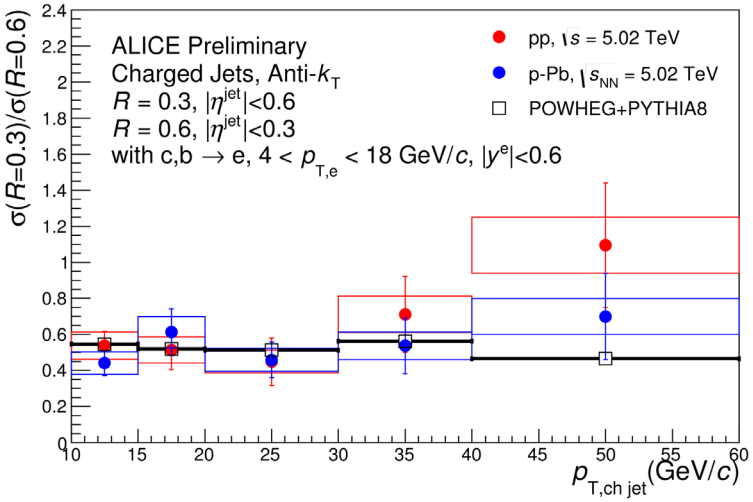


ALI-PREL-309039



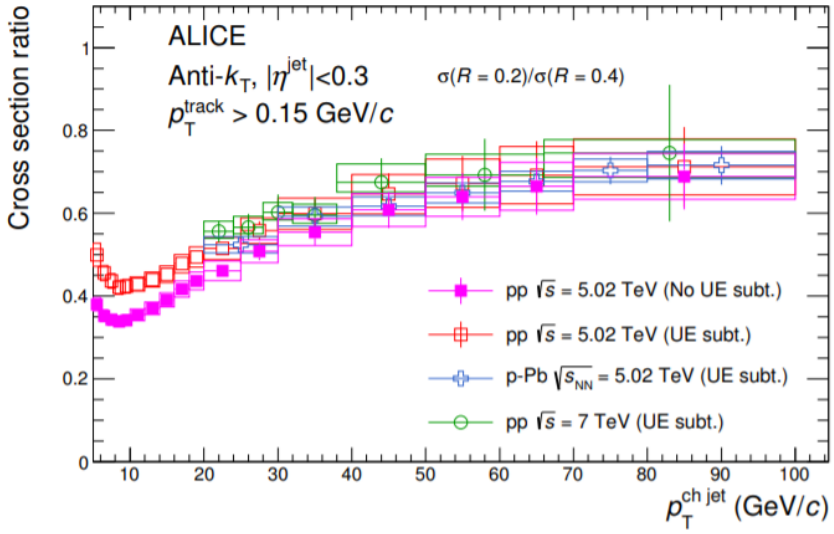
ALI-PREL-309060

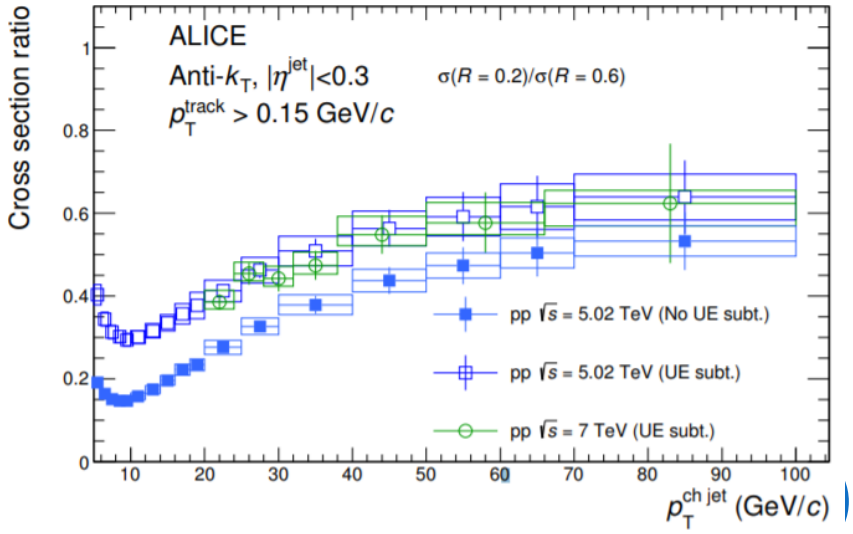
HFe-JET CROSS SECTION RATIO AT DIFFERENT R



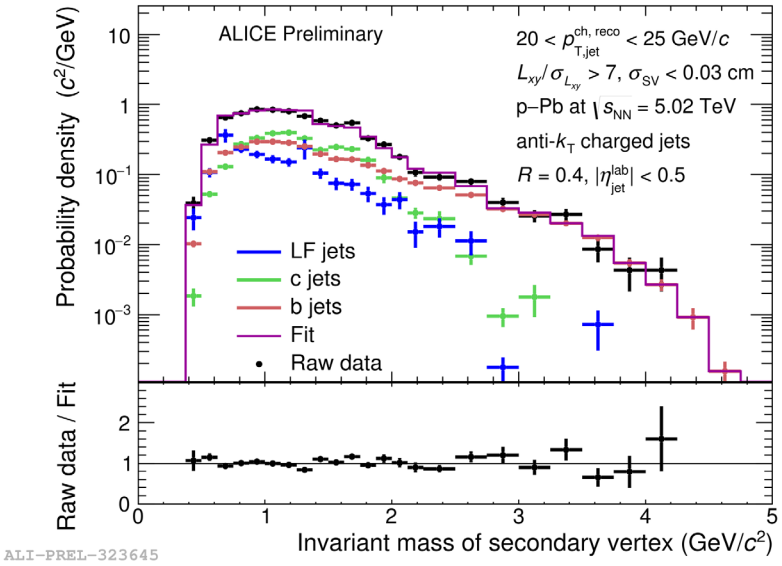
HFe-tagged jets

Charged jets

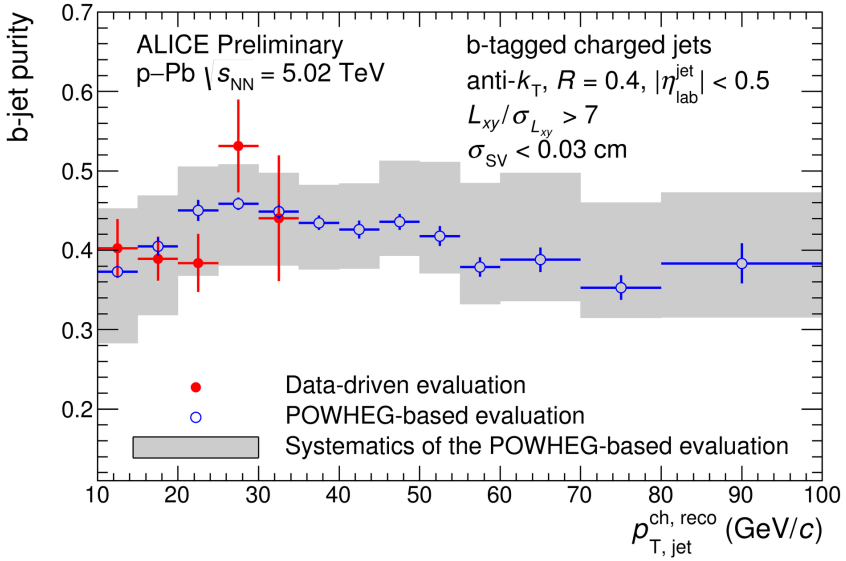




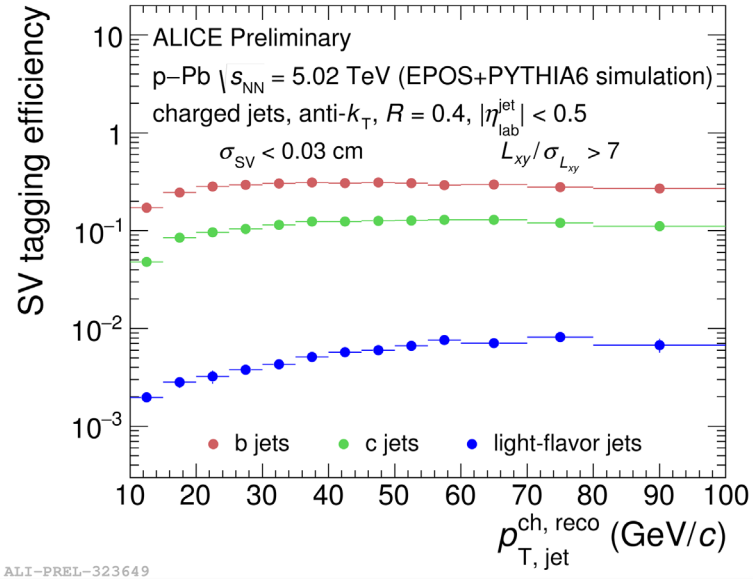
b-JETS – TECHNICAL PLOTS



ALI-PREL-323645



ALI-PREL-323641



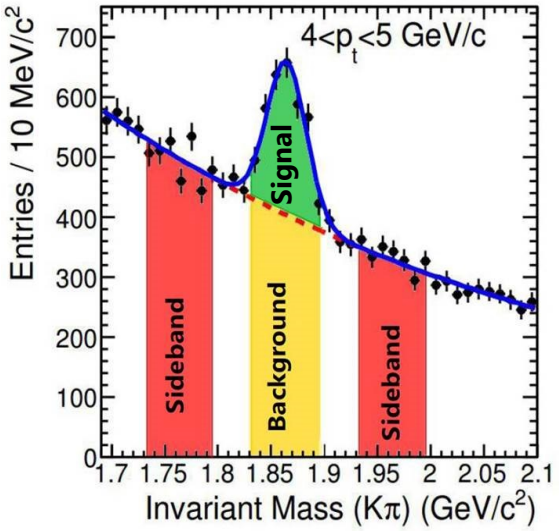
ALI-PREL-323649

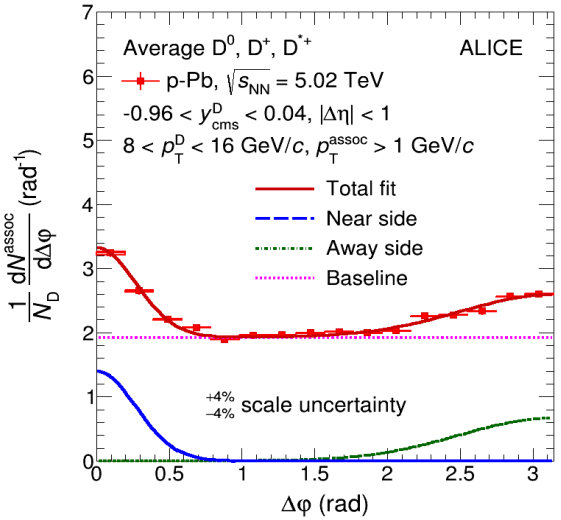
D-h CORRELATIONS: ANALYSIS STRATEGY

- 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)

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

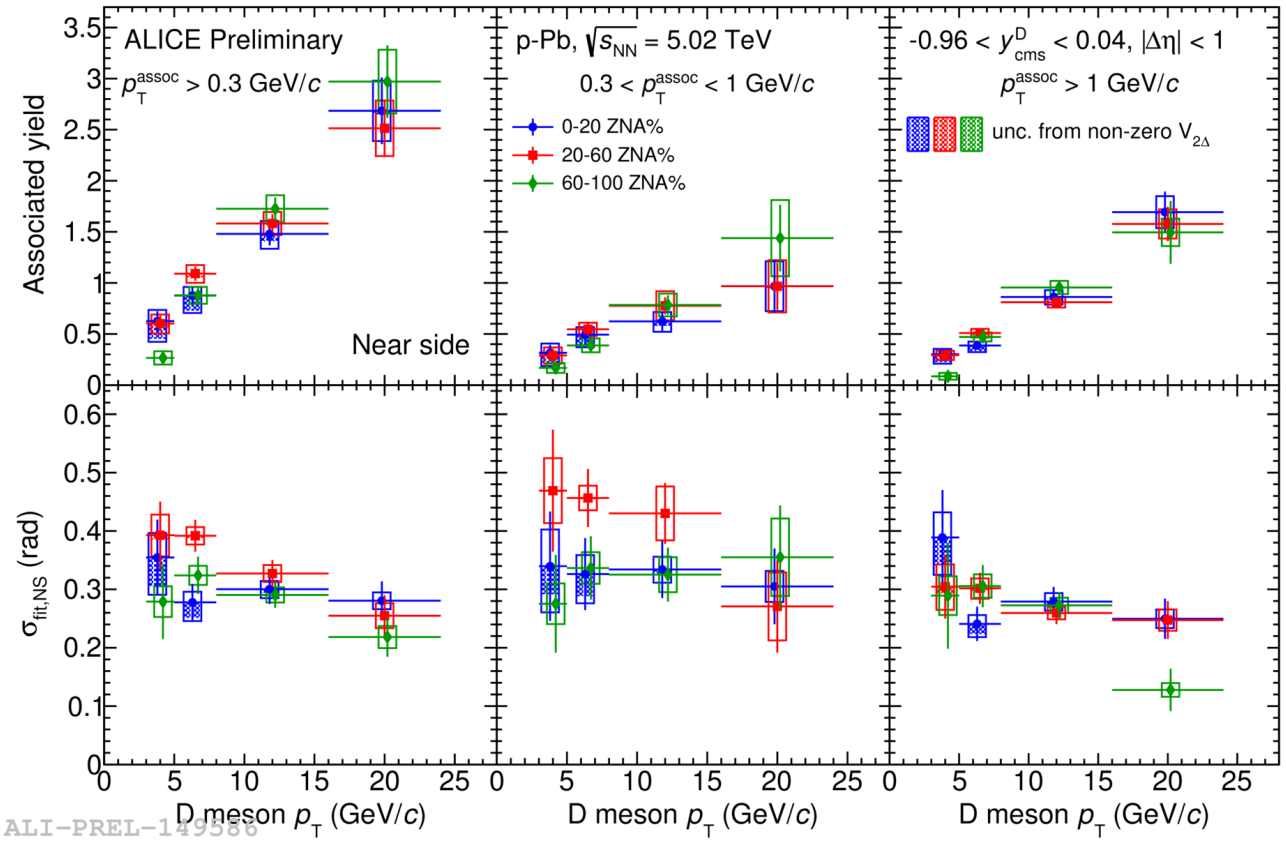
JHEP 01 (2012) 128





ALICE, EPJ C 77 (2017) 245

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

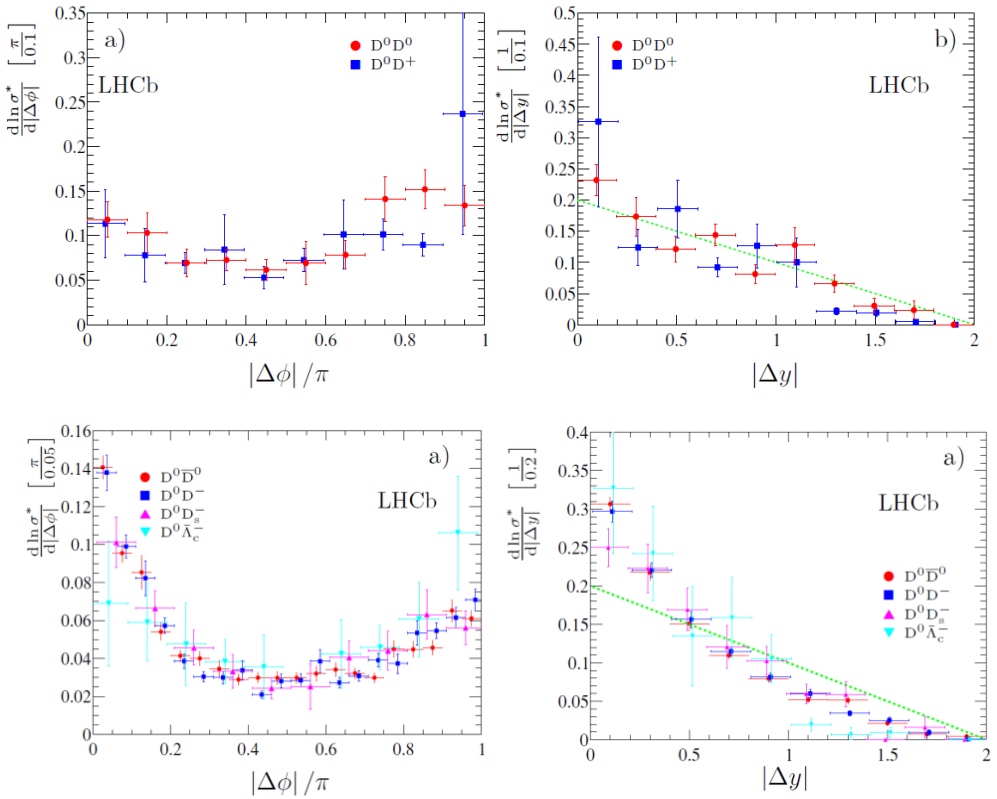
Centrality classes
0-20%, 20-60%, 60-100% (ZNA estimator)

- 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

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



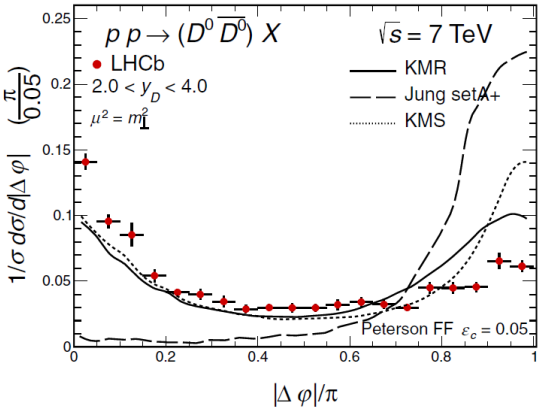
LHCb, JHEP 06 (2012) 141

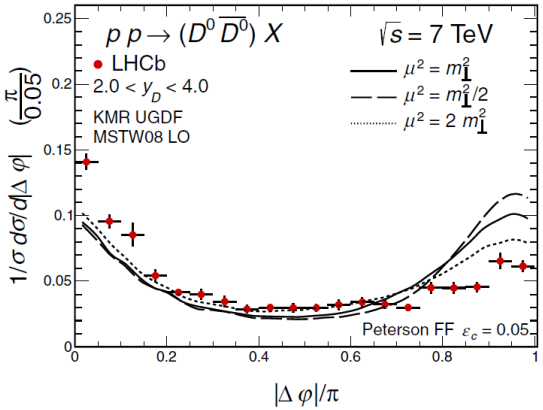
PREVIOUS RESULTS ON HF CORRELATIONS (LHC ONLY)

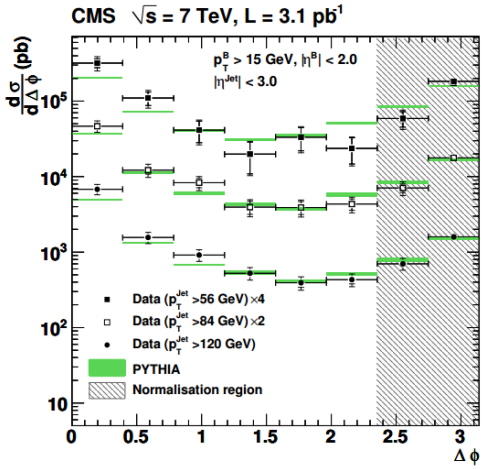
- LHCb measurements for D^0-D^0bar correlations compared with calculations from k_T-factorization approach, in pp collisions at 7 TeV

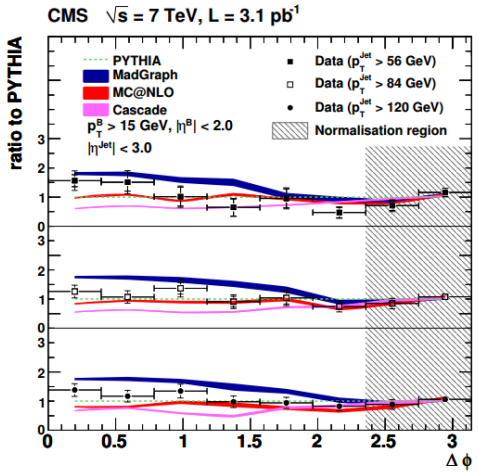
- CMS measurements for B-Bbar production cross section as a function of $\Delta\varphi$, compared with predictions, in pp collisions at 7 TeV

LHCb, JHEP 06 (2012) 141



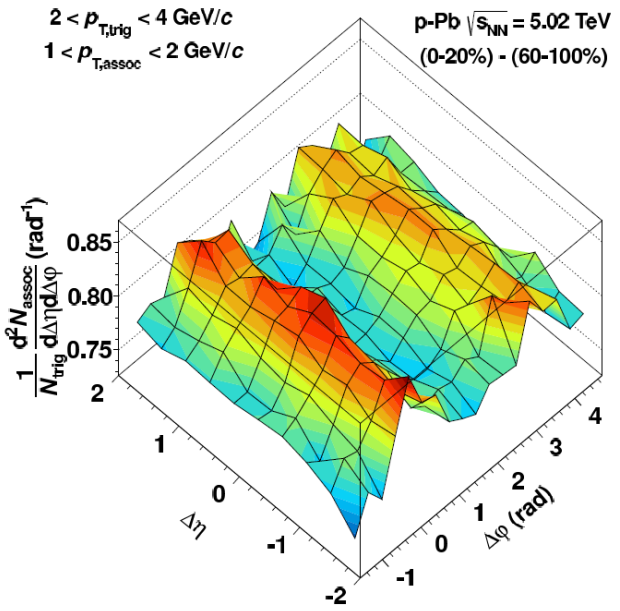


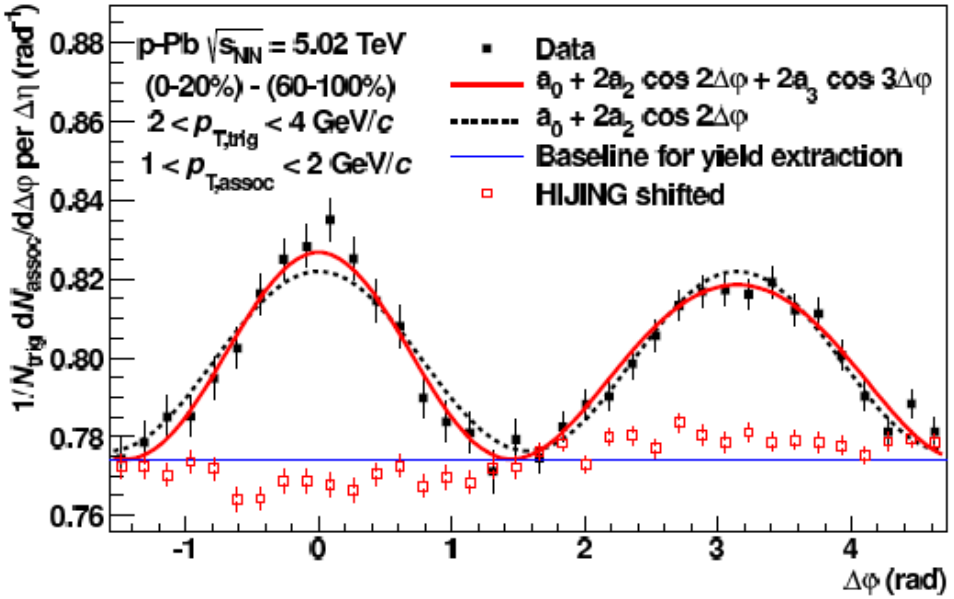


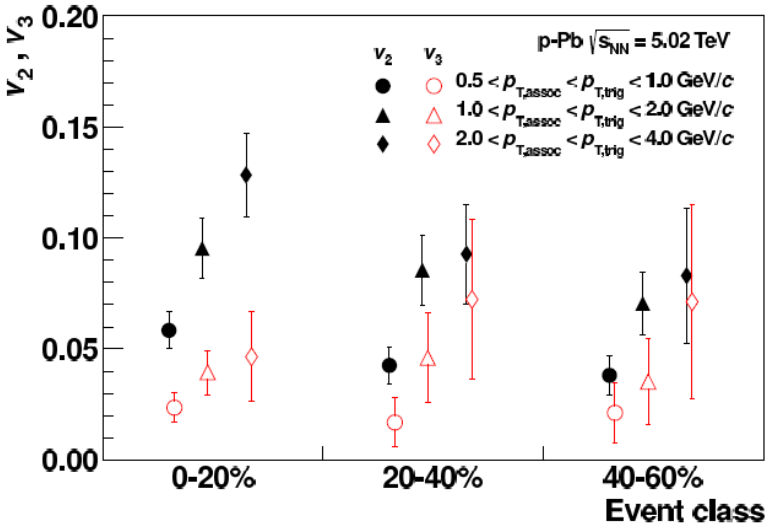


CMS, JHEP 136 (2011) 1103

OTHER pPb COLLECTIVE EFFECTS AT LHC

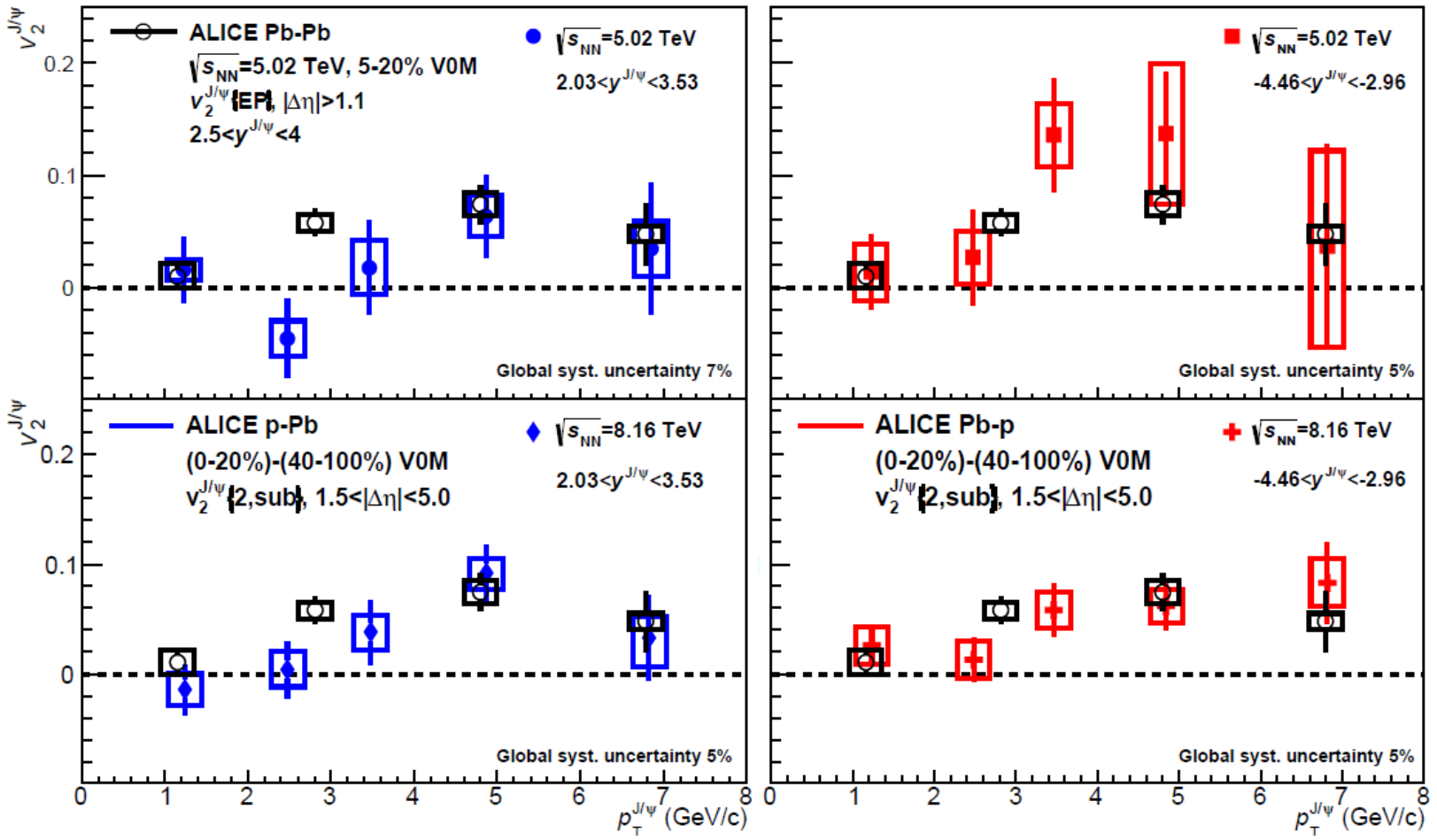






ALICE, charged particles

OTHER pPb COLLECTIVE EFFECTS AT LHC

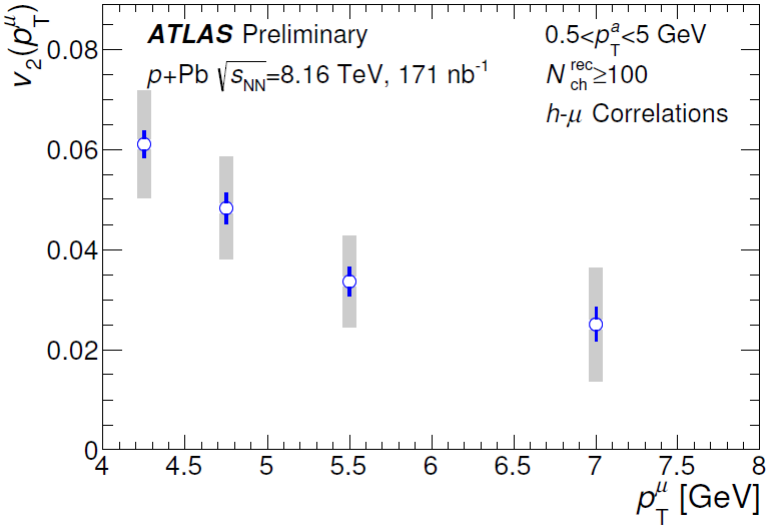


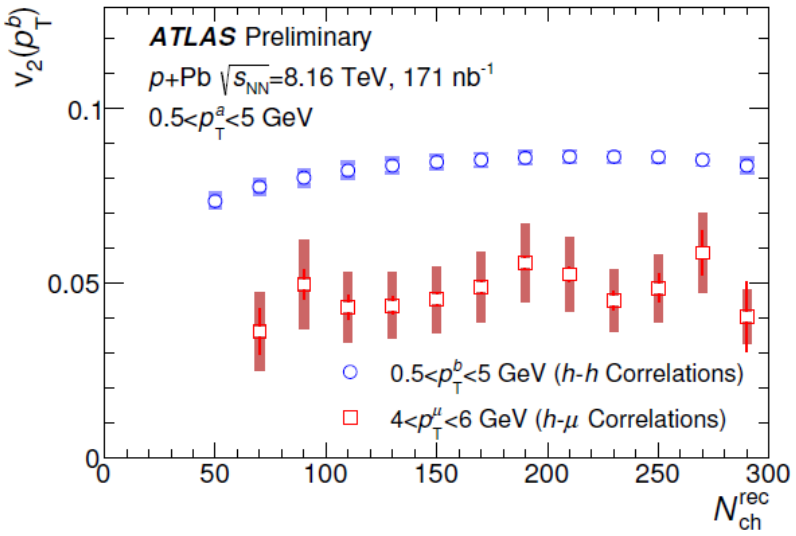
ALICE, Jpsi meson

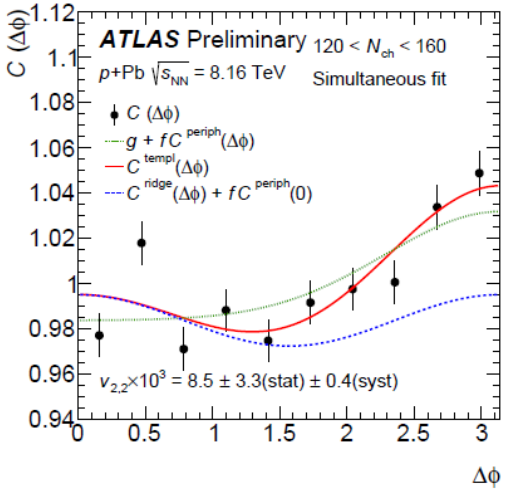
OTHER pPb COLLECTIVE EFFECTS AT LHC

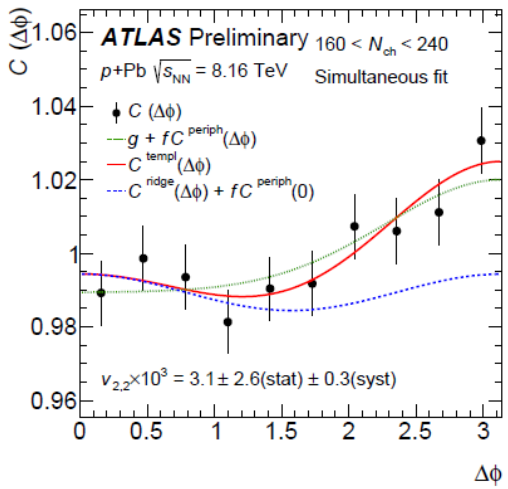
ALICE

ATLAS, HF muon





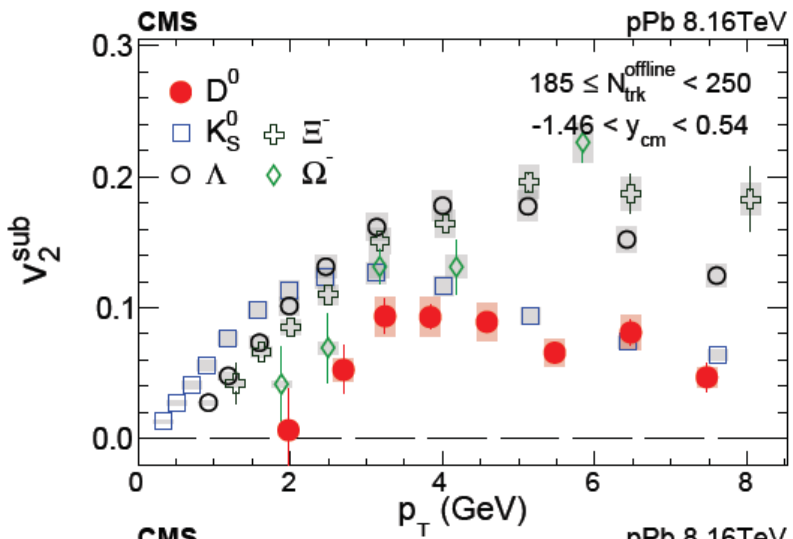


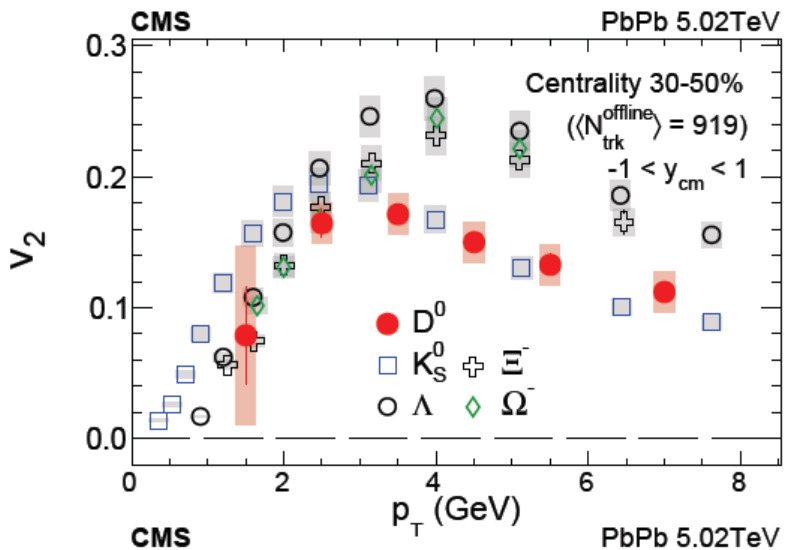


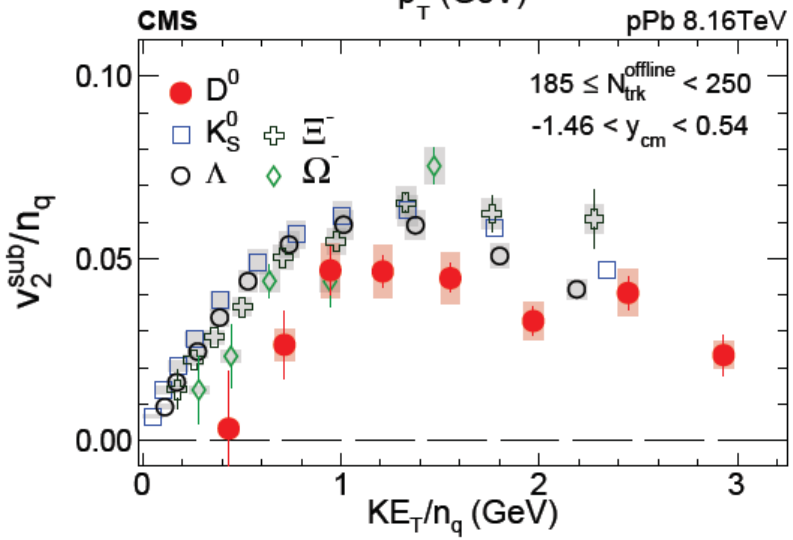
ATLAS, D*+ meson

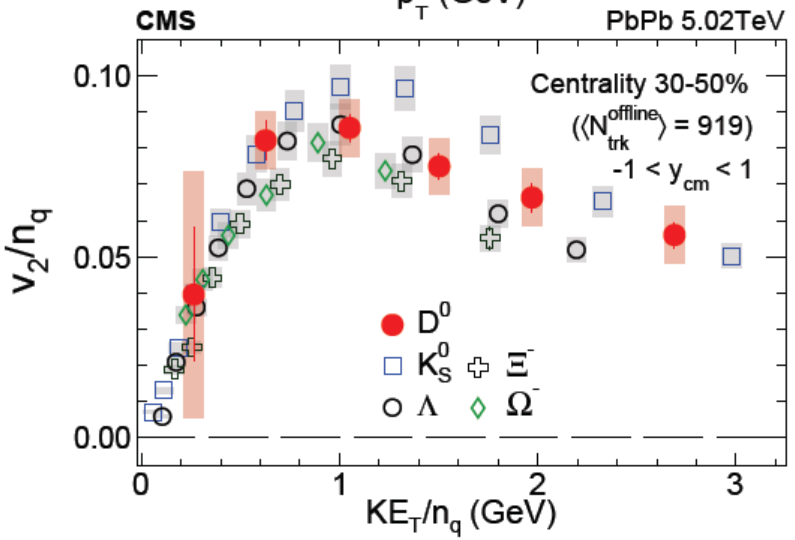
$$v_{2,2}(80 < N_{ch} < 120) = (15.4 \pm 8.5(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-3},$$
$$v_{2,2}(120 < N_{ch} < 160) = (8.5 \pm 3.3(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3},$$
$$v_{2,2}(160 < N_{ch} < 240) = (3.1 \pm 2.6(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-3}.$$

OTHER pPb COLLECTIVE EFFECTS AT LHC









CMS, D^0 meson