OVERVIEW OF HEAVY-FLAVOUR MEASUREMENTS WITH THE ALICE DETECTOR AT THE LHC

Fabio Colamaria
on behalf of the ALICE Collaboration

INFN
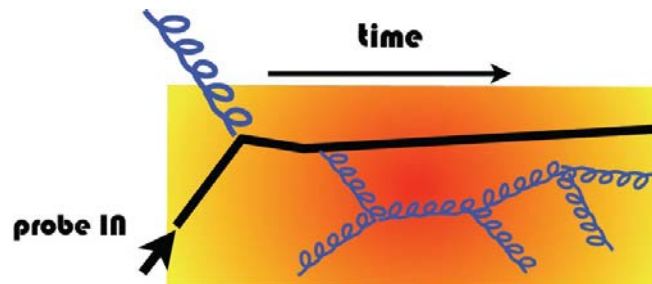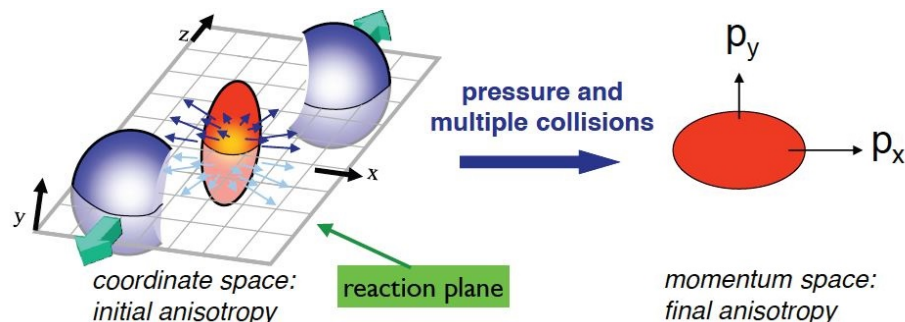Istituto Nazionale di Fisica Nucleare

ALICE

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Jets and Heavy Flavour Workshop – Santa Fe – 29/01/2018

PHYSICS MOTIVATIONS

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

- The modifications induced by the medium are translated to their final-state particles
 $\rightarrow$ Excellent probes of the QGP medium

In particular, heavy quarks are expected to:

- Participate to some extent to the collective motion inside the medium
  - ➢ Provide information on medium transport properties

- 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

coordinate space: initial anisotropy

reaction plane

momentum space: final anisotropy

pressure and multiple collisions

time

probe IN

2

PHYSICS MOTIVATIONS

Quarkonium in Pb-Pb collisions

- J/Ψ suppression in heavy-ion central collisions was one of the first signatures of QGP production (**T.Matsui, H.Satz, PLB178 (1986) 416**)

- With increasing energy density, two competing mechanisms:

  - ➢ **Statistical regeneration**: enhanced quarkonium production via (re)combination at hadronisation or during QGP ($c\bar{c}$ multiplicity increases with energy density)

  - ➢ **Sequential melting**: differences in the quarkonium binding energies induce a sequential melting of the various states for increasing medium temperature

- Interesting to probe suppression of higher charmonium states, as Ψ(2S) and beyond

- What about bottomonium states? Different radii, no expected regeneration, ...

3
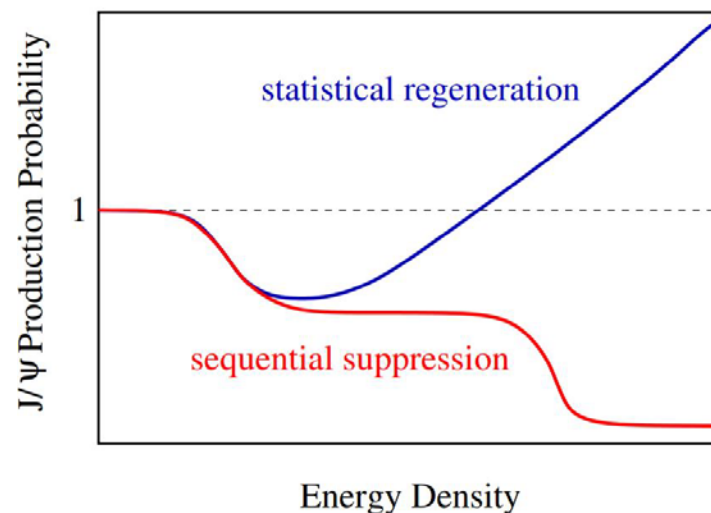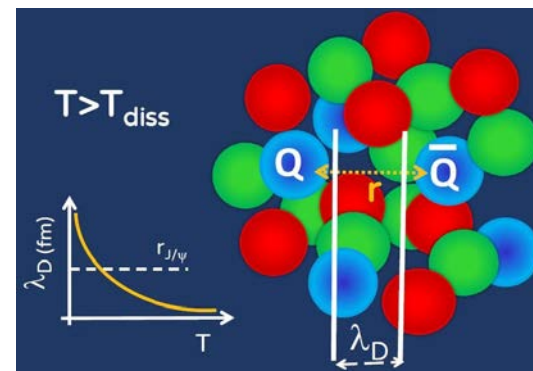
PHYSICS MOTIVATIONS

The study of heavy flavours in small systems is also of great interest

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
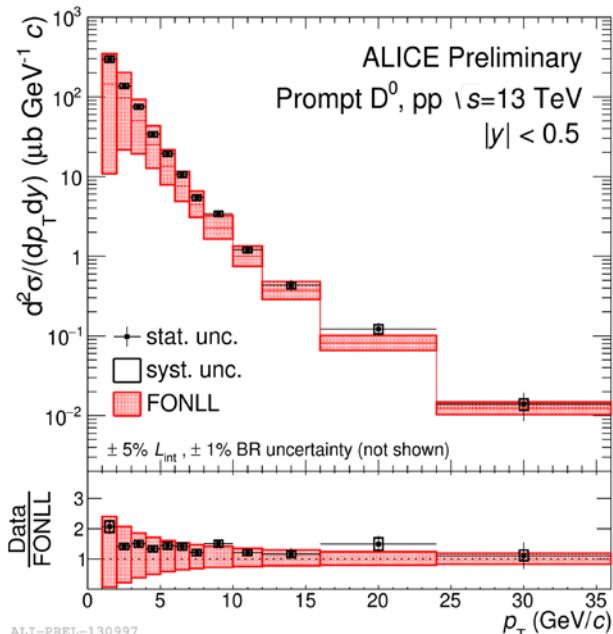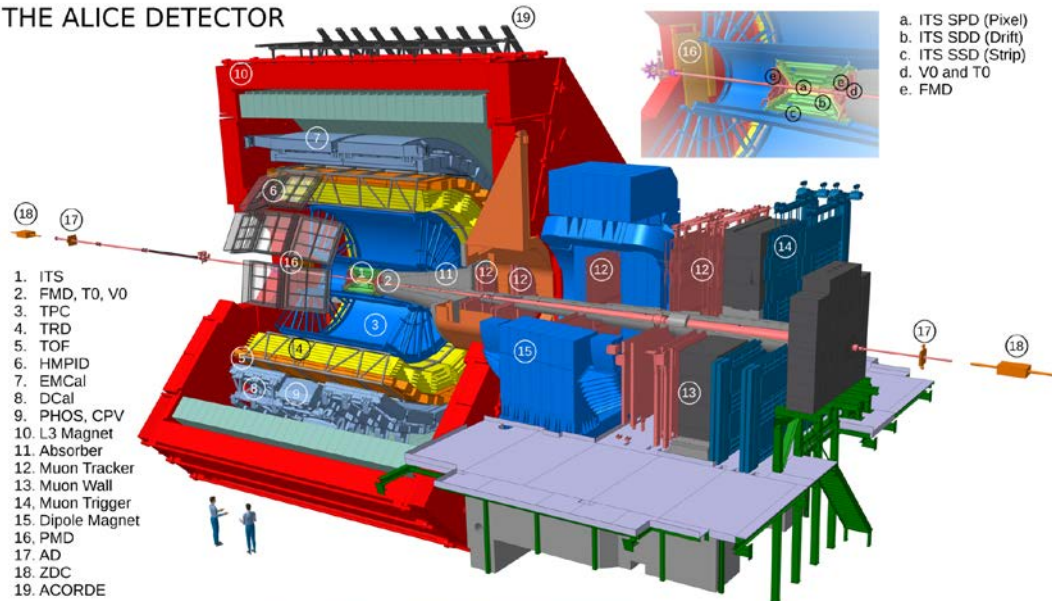

pp collisions

- Test and set constraints on production mechanisms

  ➢ pQCD-based calculation describe reasonably well open charm and beauty production at the LHC (see backup slides)

  ➢ NRQCD+FONLL, color octet, color singlet, color evaporation model for quarkonium

- Reference for studies in p-Pb and Pb-Pb collisions

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HEAVY-FLAVOUR RECONSTRUCTION WITH ALICE

THE ALICE DETECTOR

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

Open heavy flavour

Charmed hadrons ($|y| < 0.5$)

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

HF decay leptons
- c,b hadrons $\to$ eX ($|y| < 0.9$)
- c,b hadrons $\to$ μX ($2.5 < y < 4$)
- b $\to$ eX via impact parameter fit

Beauty-decay J/ψ ($|y| < 0.9$)
- b hadrons $\to$ J/ψ X, J/ψ $\to e^+e^-$

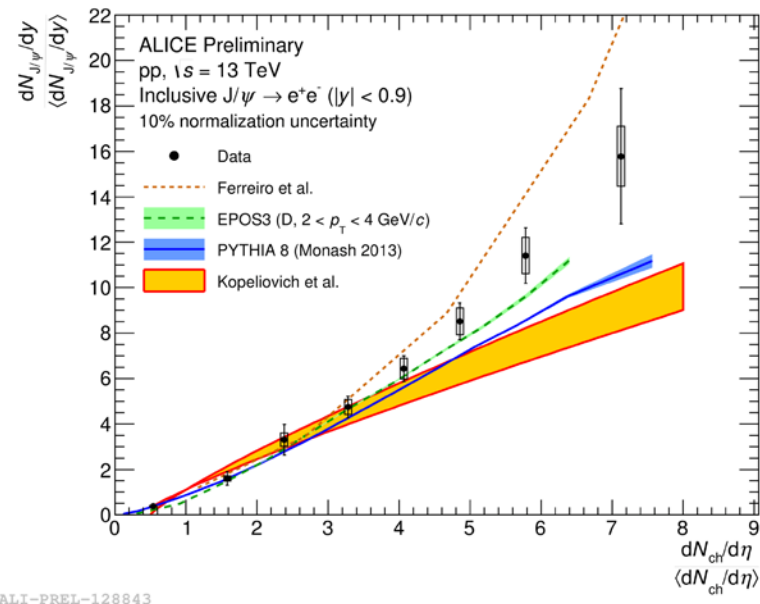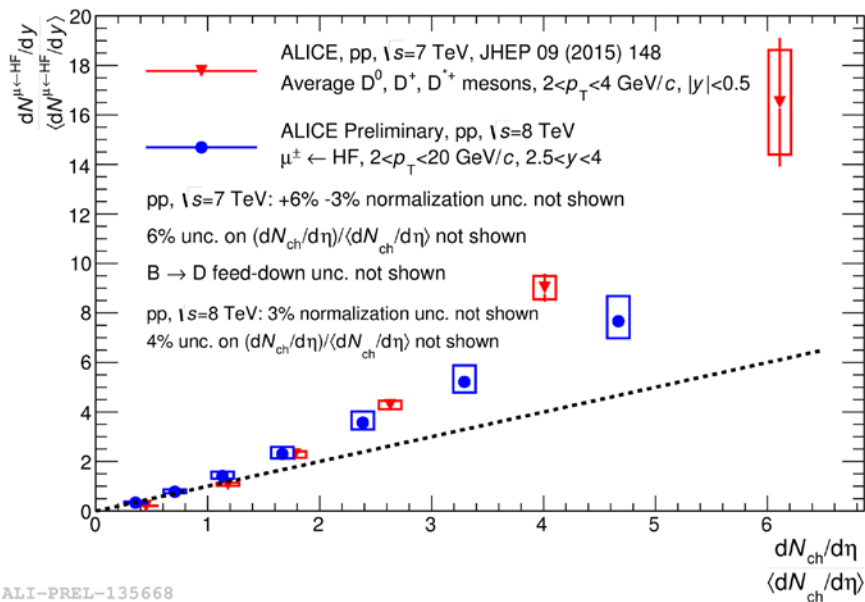**+ open heavy-flavour jets, correlations, production vs multiplicity/centrality**

Quarkonium

- **Central rapidity** ($|y| < 0.9$):
  - J/Ψ $\to e^+e^-$

- **Forward rapidity** ($2.5 < y < 4$):
  - J/Ψ $\to \mu^+\mu^-$
  - Ψ(2S) $\to \mu^+\mu^-$
  - Υ(1S), Υ(2S), Υ(3S) $\to \mu^+\mu^-$

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OPEN HEAVY-FLAVOUR RESULTS

HF PRODUCTION VS MULTIPLICITY

ALI-PREL-135668

ALI-PREL-128843

- Yield of D mesons ($|y|<0.5$), HF-decay muons ($2.5 < y < 4$) and J/Ψ ($|y| < 0.9$) show faster-than-linear increase with charged-particle multiplicity at central rapidity
  - Feature not related to hadronisation, but rather to production process

- **Observed a qualitative agreement with models assuming:**
  - Multi-parton interactions influencing HF production (PYTHIA8, EPOS3 w/ hydro)
  - Contributions of higher Fock-states (Kopeliovich et al.)
  - Soft-particle saturation (Ferreiro: percolation, PYTHIA8: color reconnection)

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CHARMED BARYONS IN pp AND p-Pb

ALI-PUB-141421
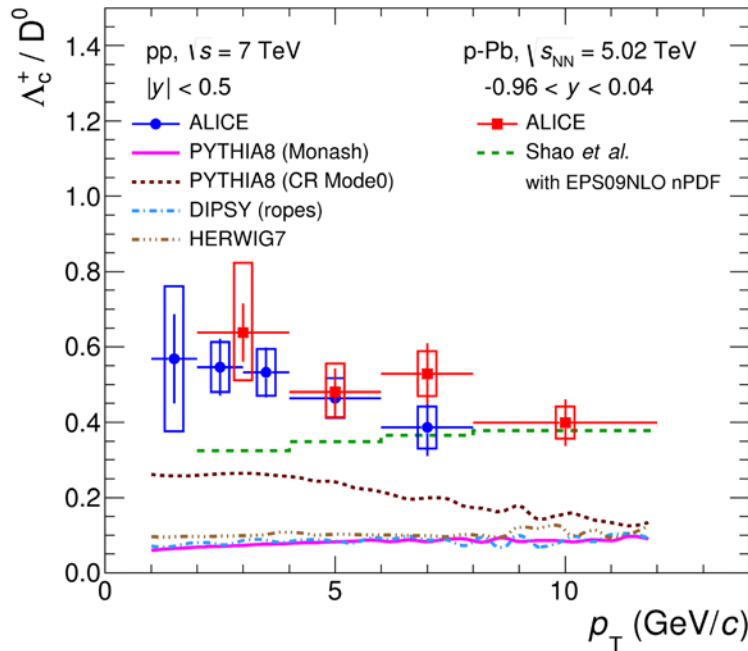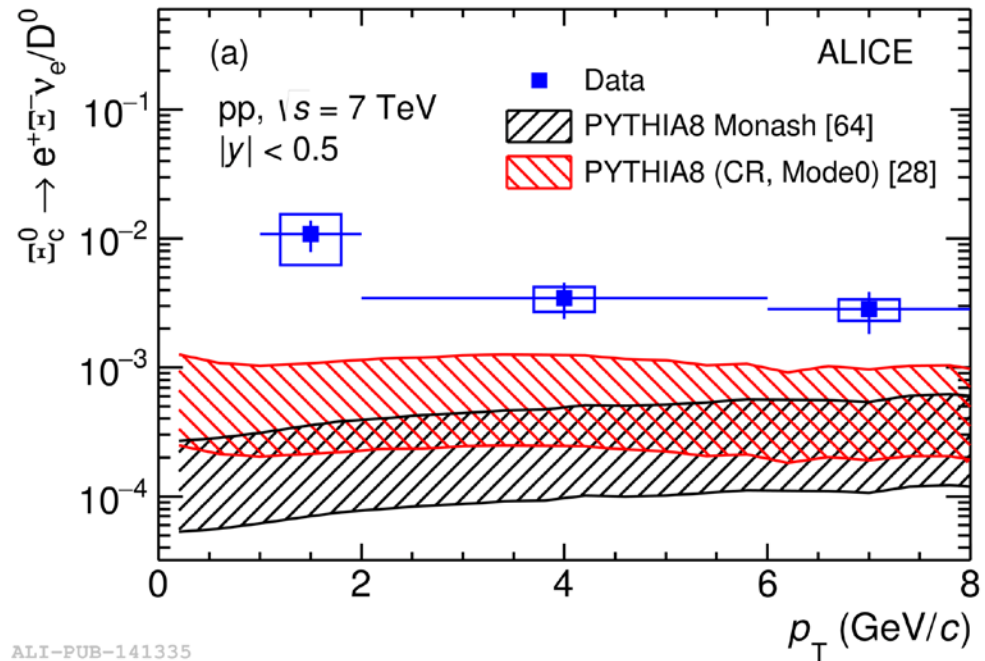
ALI-PUB-141335

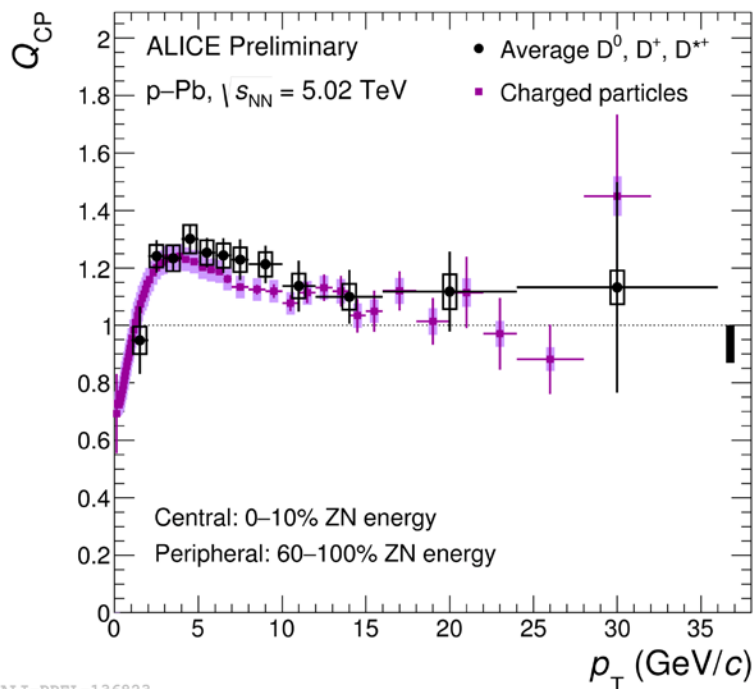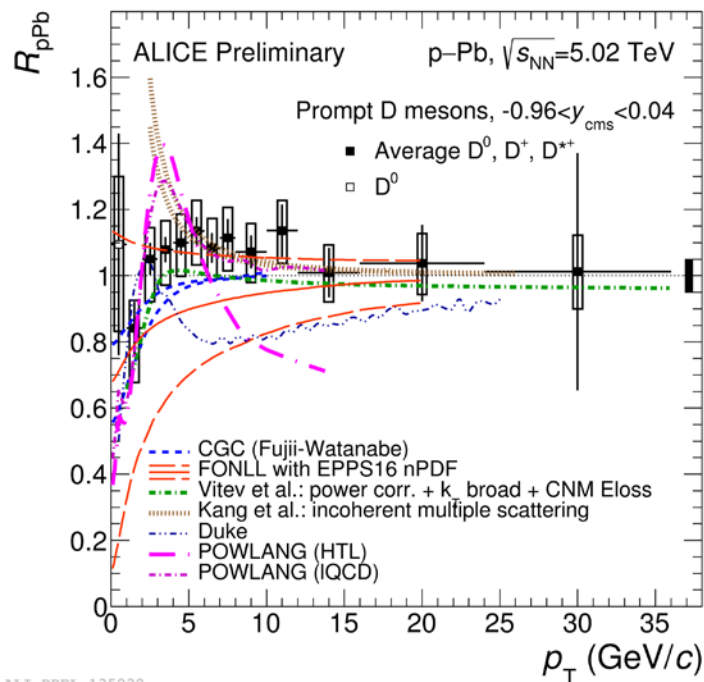- Λ_c^+/D^0 ratios in pp and p-Pb collisions are compatible within uncertainties
- **First Ξ_c^0 production measurement at LHC**
- Both Λ_c^+/D^0 and Ξ_c^0/D^0 ratios are **higher than expectation** from Monte Carlo
  - ➤ Enhanced color reconnection configuration of PYTHIA 8 is closer to data
  - ➤ Theory bands on Ξ_c^0 due to the uncertainty on the branching ratio $\Xi_c^0 \to e^+\Xi^-\nu_e$

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

$$R_{pPb} = \frac{\frac{d\sigma_{pPb}}{dp_T}}{A \cdot \frac{d\sigma_{pp}}{dp_T}}$$

ALI-PREL-135232   ALI-PREL-136823

- 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_T < 8 GeV/c
  - Need theory models for its interpretation

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HEAVY-FLAVOUR ELECTRON v_2 IN p-Pb
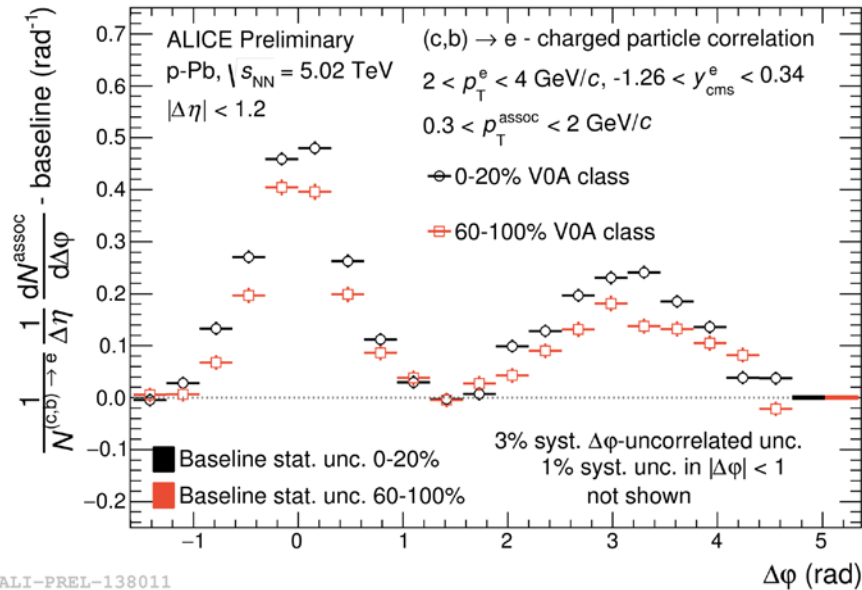
ALI-PREL-138011
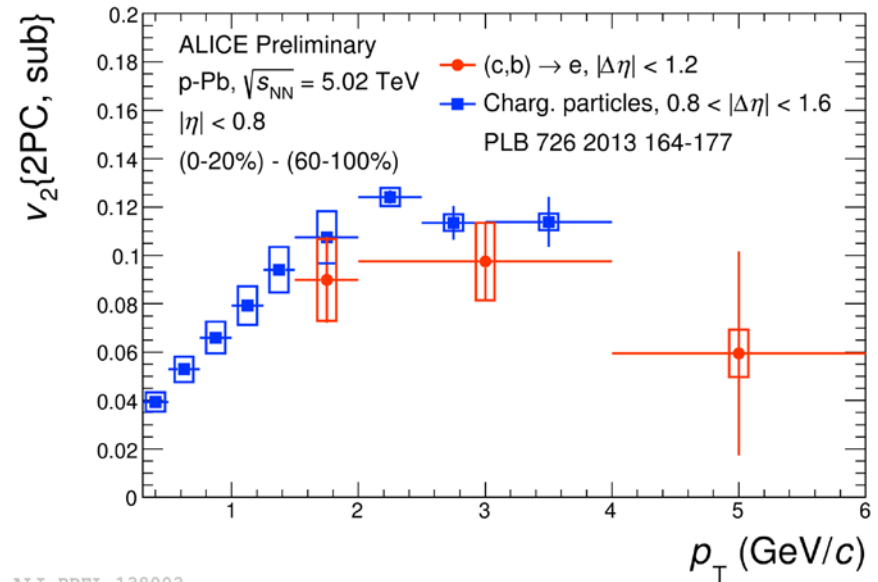
ALI-PREL-138003

- Azimuthal correlations of heavy-flavour decay electrons with charged particles in 0-20% p-Pb collisions
  - ➢ 60-100% multiplicity class addressed to subtract jet contribution
- **Positive v_2** for heavy-flavour decay electrons (**4.4σ effect** for $1.5 < p_T^e < 4$ GeV/c)
  - ➢ Strength of v_2 comparable with charged-particles measurement (though the p_T ranges of the original partons are not equivalent)
- Initial-state effects or final-state, collective effect?

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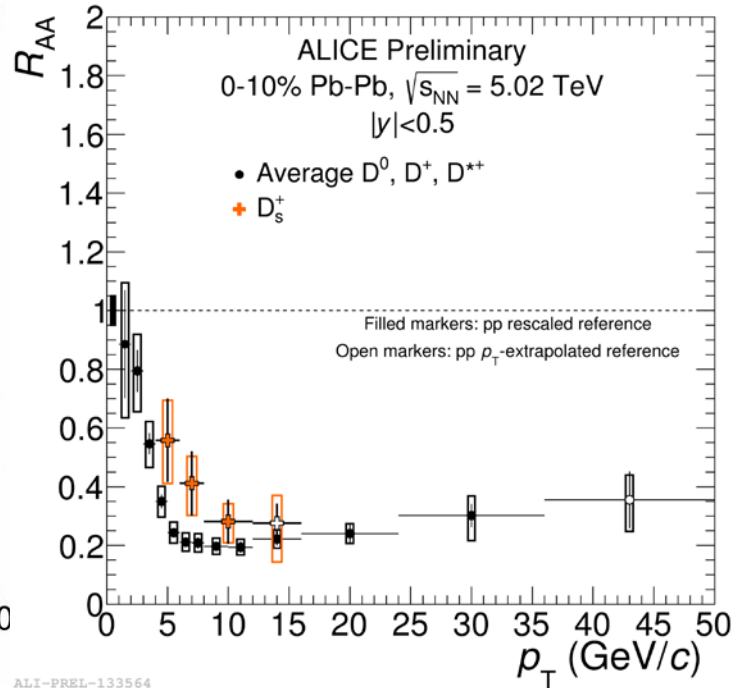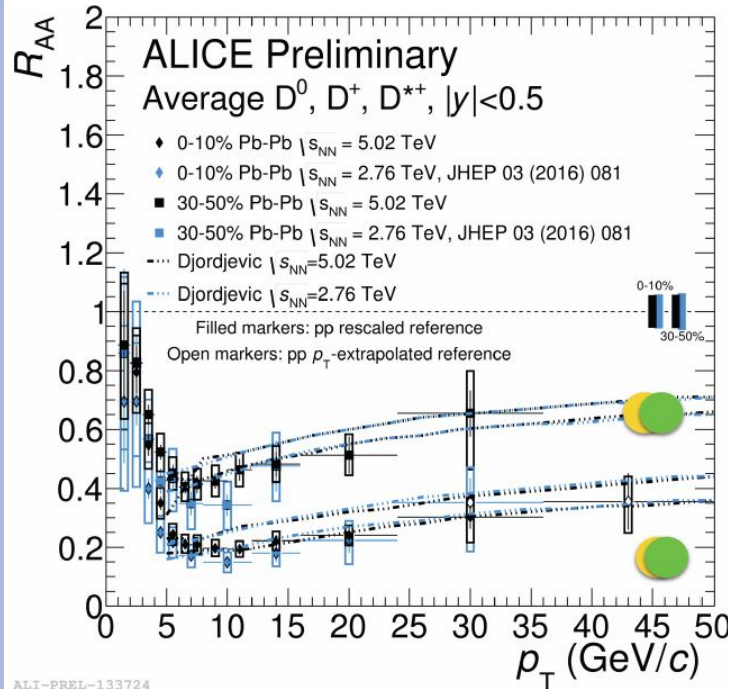
$$R_{AA} = \frac{\frac{dN_{AA}}{dp_T}}{\langle T_{AA} \rangle \cdot \frac{d\sigma_{pp}}{dp_T}}$$

- **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: predicted by models as a balancing effect between denser medium and harder charm quark spectrum
- Hint for $R_{AA}(D_s^+) > R_{AA}$(non-strange D) in lower p_T range
  - ➤ Due to hadronisation via coalescence in a strangeness-rich environment?

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D-MESON v_2 IN Pb-Pb

arXiv:1707.01005

ALI-PUB-132097

ALI-PUB-132093
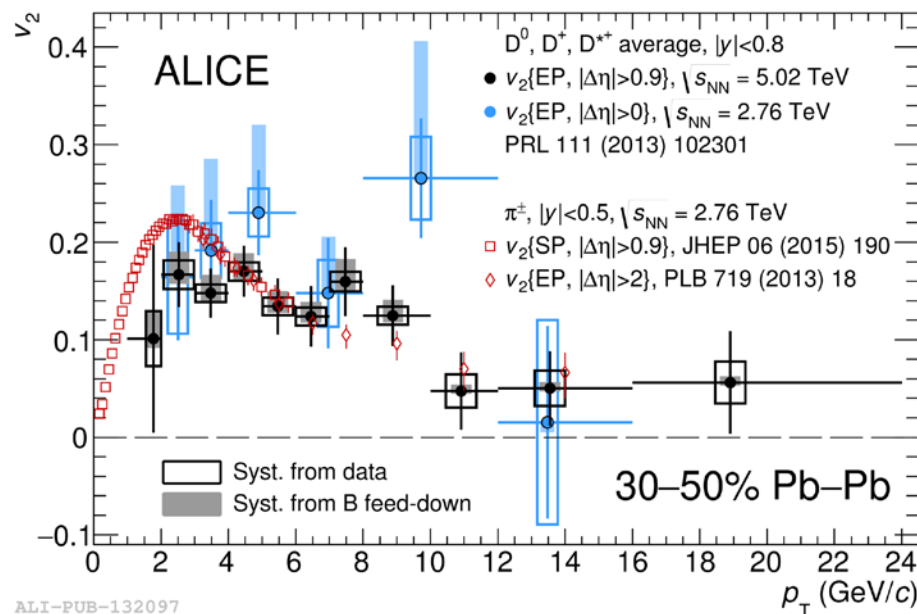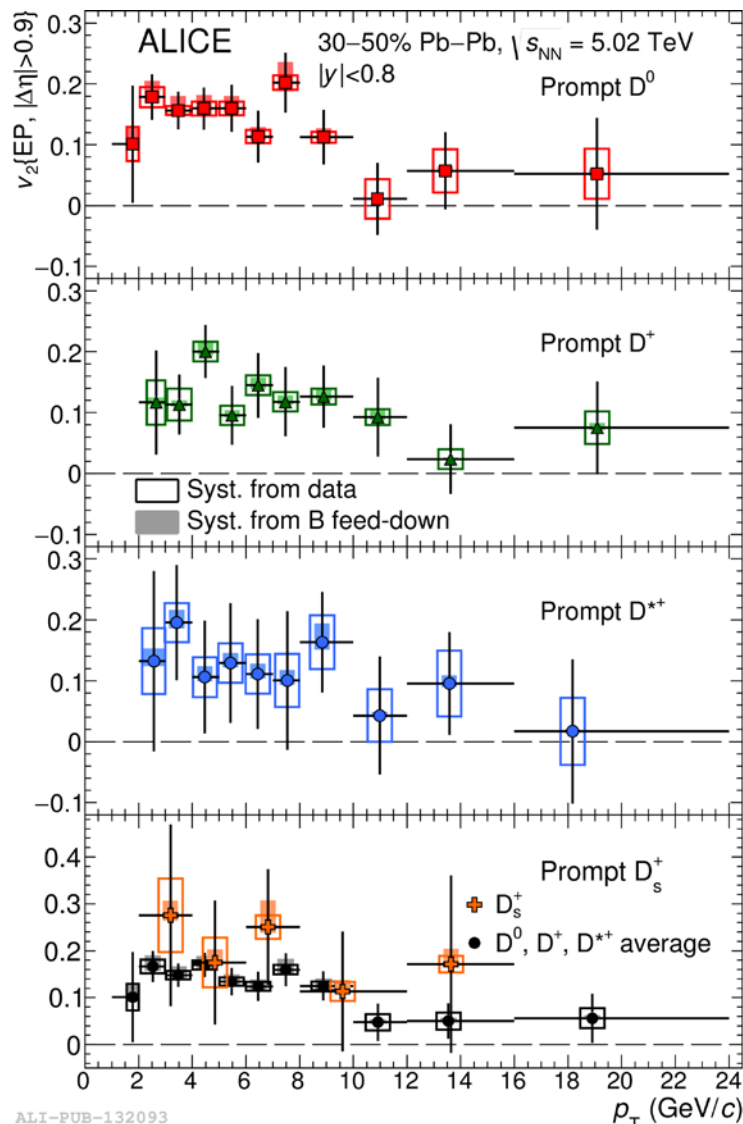
- **First measurement of D_s^+ v_2**, comparable with non-strange D-meson v_2
- **D-meson $v_2 > 0$**, and compatible with charged-pion v_2 within uncertainties (hint of difference for $p_T < 4$ GeV/c)
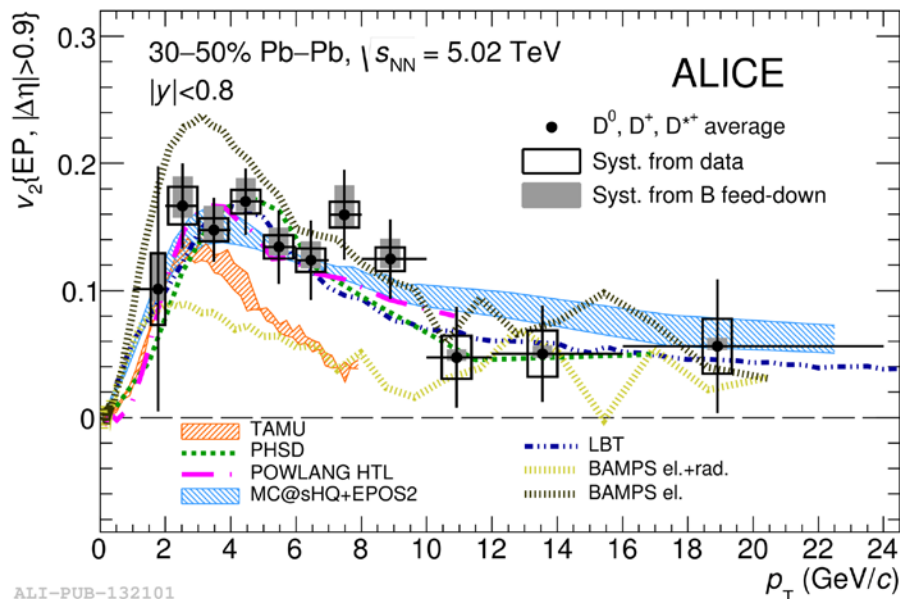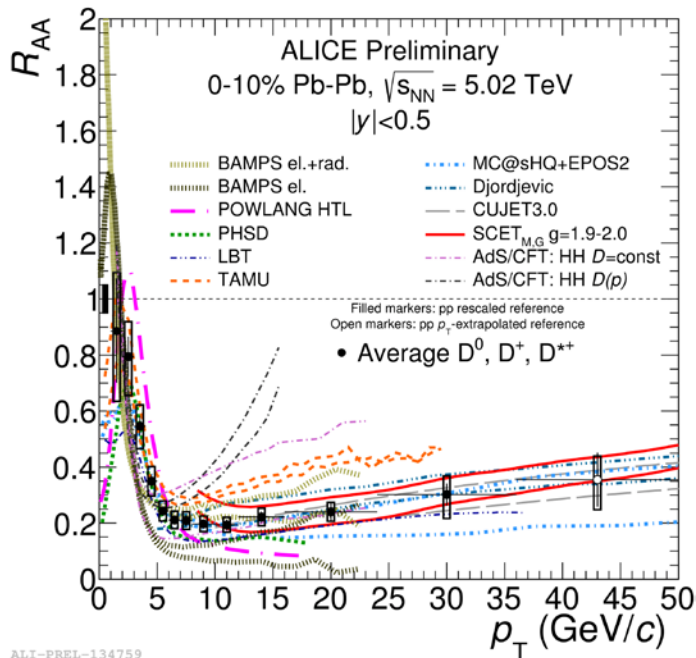
- Charm quarks participate to collective motion in the medium
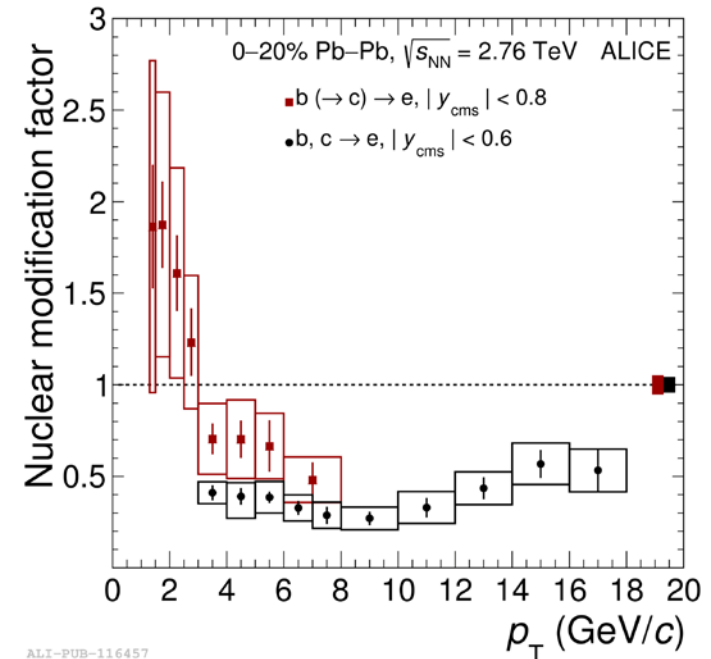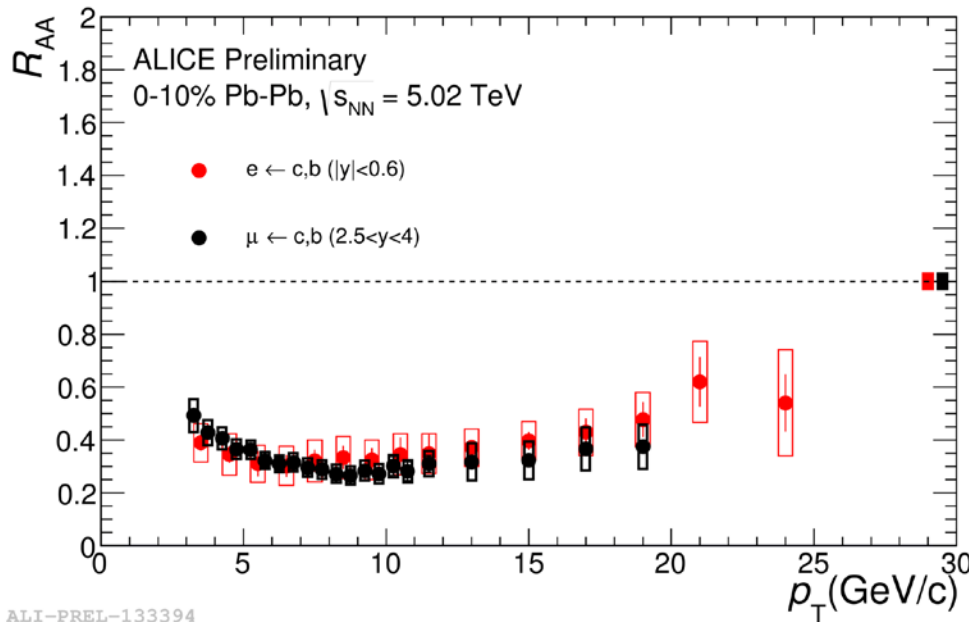
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D-MESON R_{AA} AND v_2 VS MODELS

- 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 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

  ➢ Wide variety of models available, including different effects (radiative, collisional energy loss, coalescence, realistic initial conditions and medium evolution).

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HF LEPTONS R_{AA} RESULTS

ALICE Preliminary
0-10% Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

$e \leftarrow c,b$ ($|y|<0.6$)

$\mu \leftarrow c,b$ ($2.5<y<4$)

ALI-PREL-133394

0–20% Pb–Pb, $\sqrt{s_{NN}}$ = 2.76 TeV   ALICE

$b (\rightarrow c) \rightarrow e$, $|y_{cms}| < 0.8$

$b, c \rightarrow e$, $|y_{cms}| < 0.6$

ALI-PUB-116457

- Strong (and similar) suppression of heavy-flavor decay leptons at central and forward rapidity in Pb-Pb collisions

- Beauty is the main component from p_T > 5 GeV/c

  ➢ Indication of **beauty suppression at high p_T**

- Hints of R_{AA} < 1 from 3 GeV/c also from beauty electrons, identified via the analysis of the electron impact parameter distribution
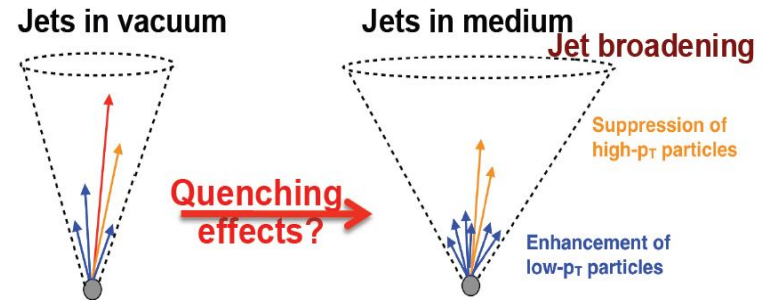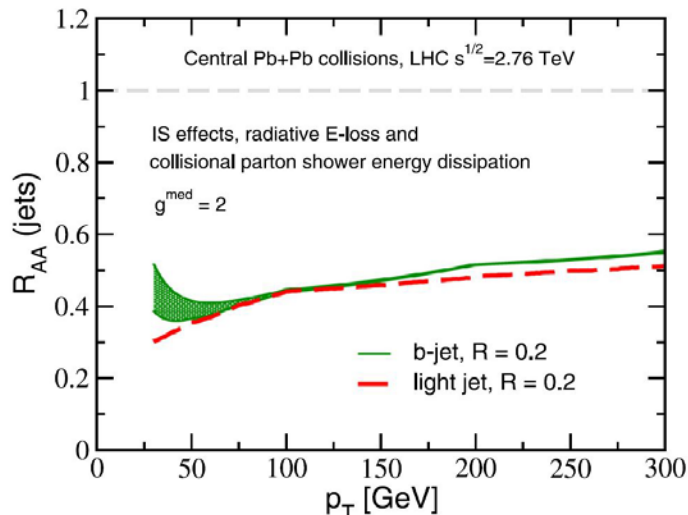
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ADDRESSING HF JETS

PHYSICS MOTIVATIONS – HF JETS

Heavy-flavour jets (with b, c content)

- Study modification of the heavy-quark fragmentation (via D-, B-tagged jets)

- Retrieve information on the energy lost in the medium by heavy quarks (via angular correlations)
  - Peak yields modifications (I_{AA}) to address jet quenching
 - Jet structure modification (particle multiplicity, opening angle, intra-jet p_T distribution)

Jets in vacuum   Jets in medium
Jet broadening
Quenching effects?
Suppression of high-p_T particles
Enhancement of low-p_T particles

Vitev et al., PLB 726 (2013) 251

Central Pb+Pb collisions, LHC $s^{1/2}$=2.76 TeV

IS effects, radiative E-loss and collisional parton shower energy dissipation

g^{med} = 2

R_{AA} (jets)

b-jet, R = 0.2
light jet, R = 0.2

p_T [GeV]

- Comparison of b- and inclusive-jet R_{AA} to probe mass effects on medium-induced energy loss
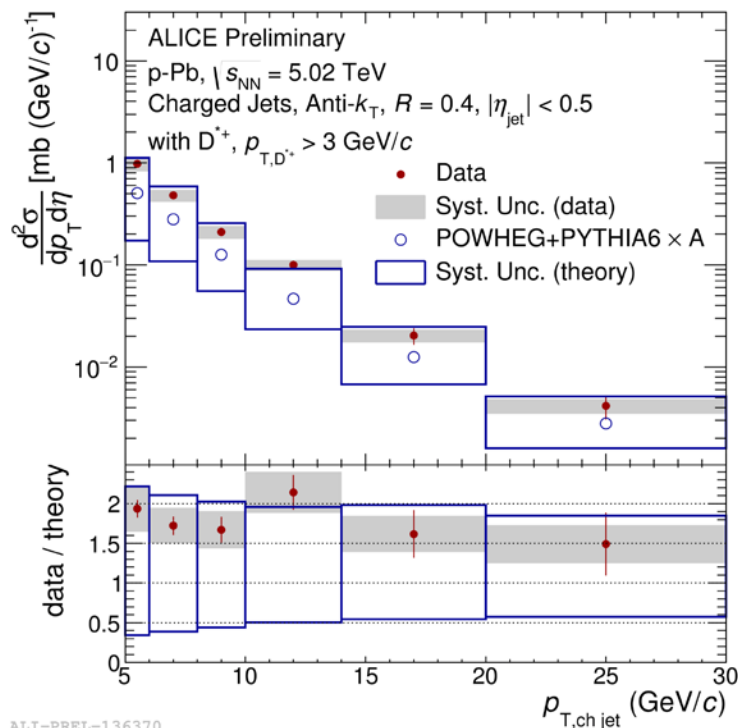
Model by Vitev et al.:
- ✓ Mass effects relevant for p_T<75 GeV/c, dead-cone effect enters in play
- ✓ Measurements vs opening radius R to characterise energy dissipation and quantify contribution of radiative and collisional energy loss

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# D-MESON JETS IN pp AND p-Pb
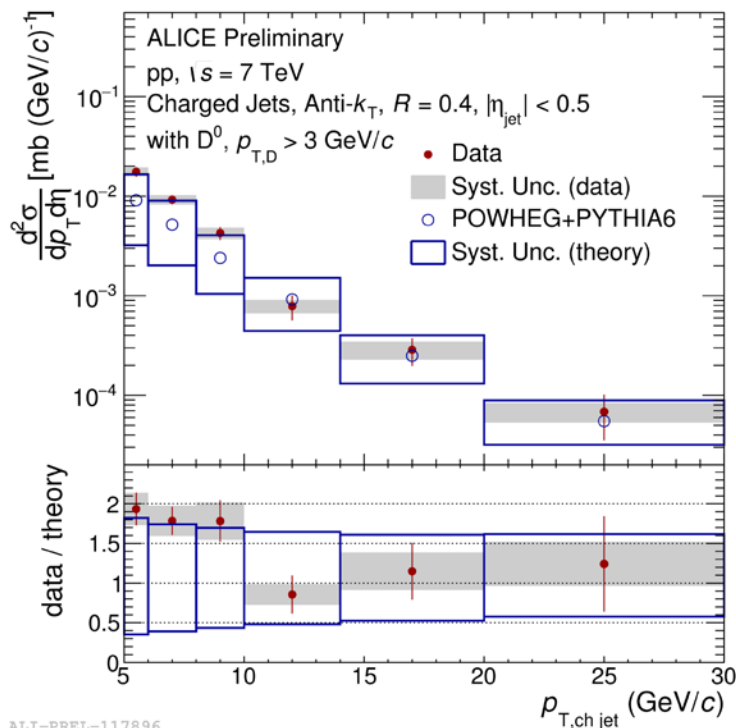
ALI-PREL-117896

ALI-PREL-136370

- D-jet spectrum measured from p_T = 5 GeV/c to 30 GeV/c; tagging via full reconstruction of D mesons via hadronic decay channels

- Data described by POWHEG+PYTHIA6 (Perugia 2011 tune) simulations within uncertainties (theory uncertainties are larger than data)

- Sensitivity to fragmentation function; evaluation of D-jet R_{pPb} currently ongoing

- **Closer access to parton kinematics, allows the study of charm-jet structure**

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HF ELECTRON CORRELATIONS IN Pb-Pb
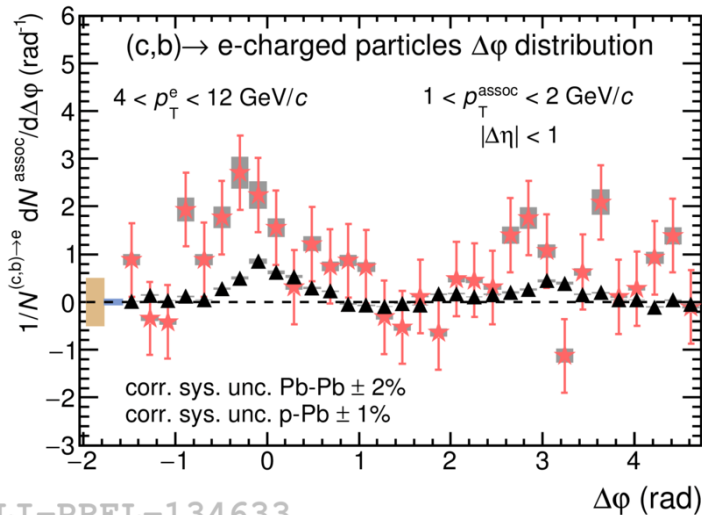
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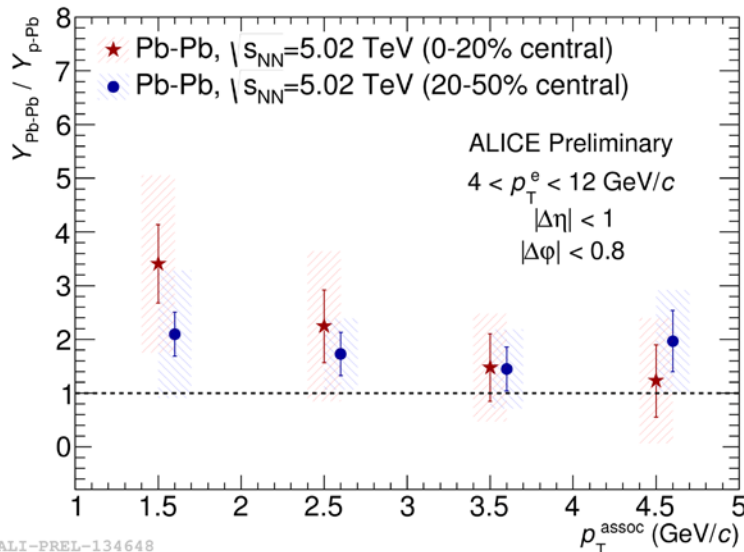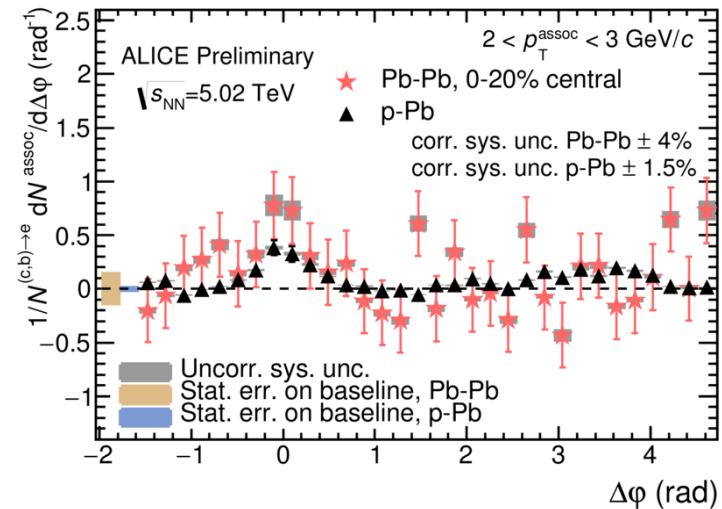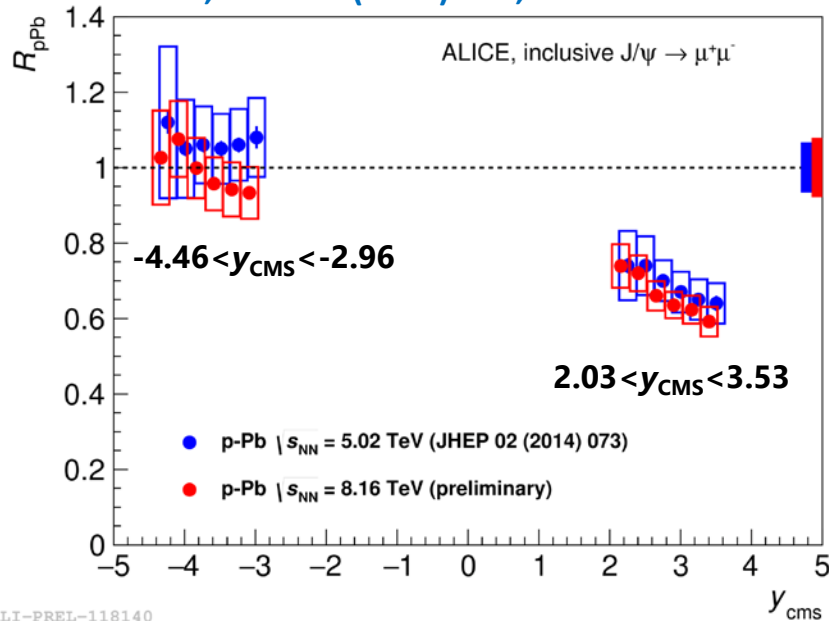

ALI-PREL-134648

- Near-side yields from integration of correlation distribution in $|\Delta\varphi|<1$

- At low p_T^{assoc}, **hints of a hierarchy appear** between central Pb-Pb, peripheral Pb-Pb and p-Pb, despite large uncertainties

- Similar feature observed in h-h (see backup), interesting to have predictions from models

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QUARKONIUM RESULTS

ALICE, JHEP 02 (2014) 073, ALICE-PUBLIC-2017-001

ALICE, inclusive J/ψ → μ⁺μ⁻

$-4.46 < y_{CMS} < -2.96$

$2.03 < y_{CMS} < 3.53$

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV (JHEP 02 (2014) 073)
p-Pb $\sqrt{s_{NN}}$ = 8.16 TeV (preliminary)

ALI-PREL-118140

ALICE Preliminary
Inclusive J/ψ → μ⁺μ⁻, p-Pb $\sqrt{s_{NN}}$ = 8.16 TeV

EPS09NLO + CEM (R. Vogt)
nCTEQ15 (J. Lansberg et al.)
CGC + NRQCD (R. Venugopalan et al.)
CGC + CEM (B. Ducloue et al.)
Energy loss (F. Arleo et al.)
Transport (hot + cold nuclear effects) (P. Zhuang et al.)
Comovers (E. Ferreiro)

ALI-PREL-122994

- Clear **J/Ψ suppression at forward-y**, R_{pPb} compatible with unity at backward-y

- Similar R_{pPb} at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV (despite slightly different Bjorken-x coverage)

- Models based on shadowing and/or energy loss describe well data (large uncertainties, especially from shadowing)

Pb
p
Backward

p
Pb
Forward

20
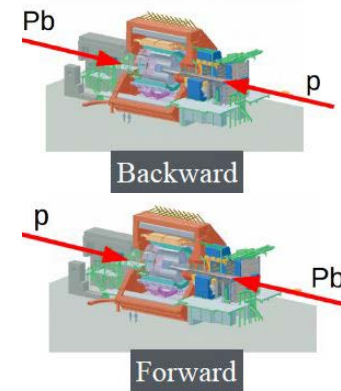
J/Ψ VS Ψ(2S) R_{pPb}

ALICE-PUBLIC-2017-001
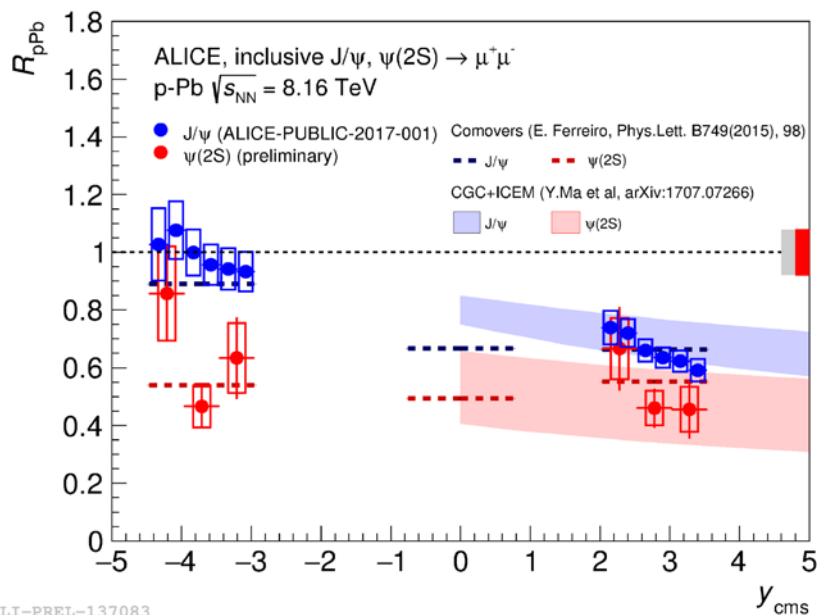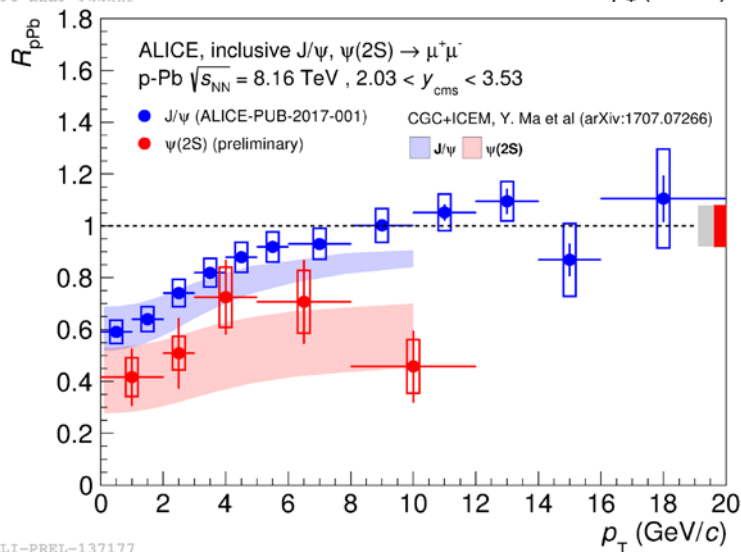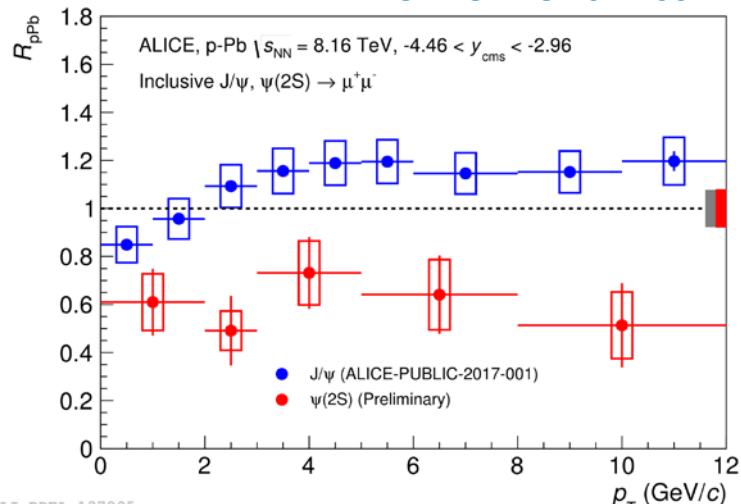

- **$R_{pPb}(J/\Psi) > R_{pPb}(\Psi(2S))$**, especially at backward-y
  - Stronger Ψ(2S) suppression unexpected, since at LHC energies formation time > crossing time
- Models including **final-state effects** are in fair agreement with data for both mesons
  - Ma and Venugopalan: soft color exchanges between hadronising $c\bar{c}$ pair and comovers
  - Ferreiro: "classical" comover models, break-up cross section tuned on low energy results

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BOTTOMONIUM PRODUCTION IN p-Pb
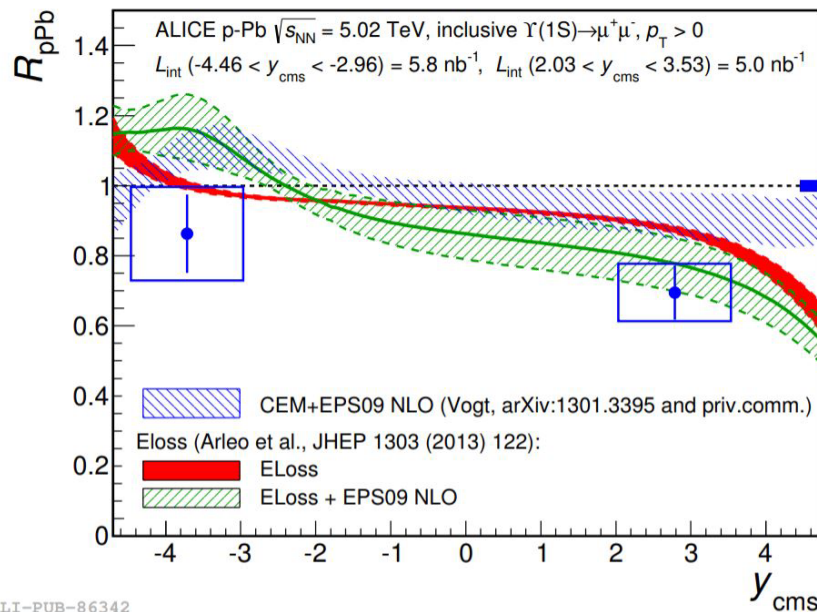
ALI-PUB-86342
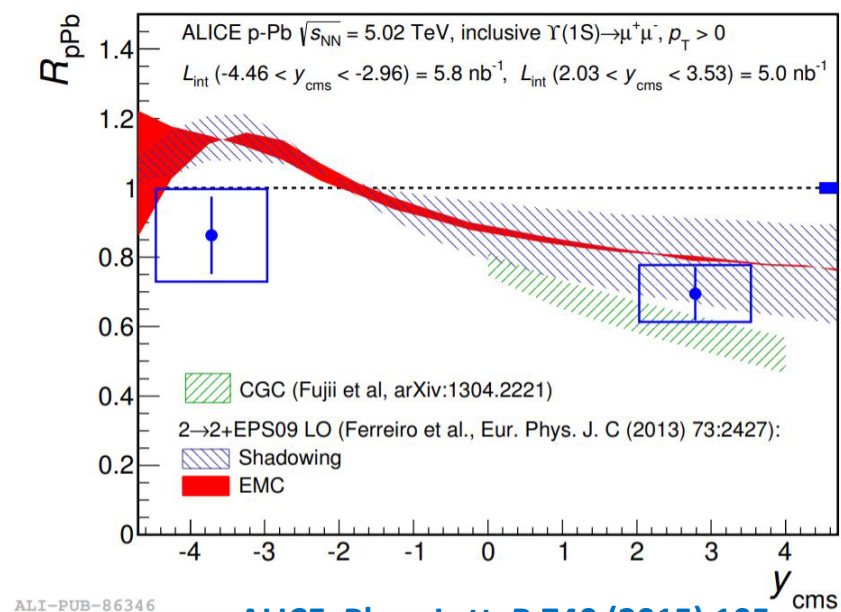
ALI-PUB-86346

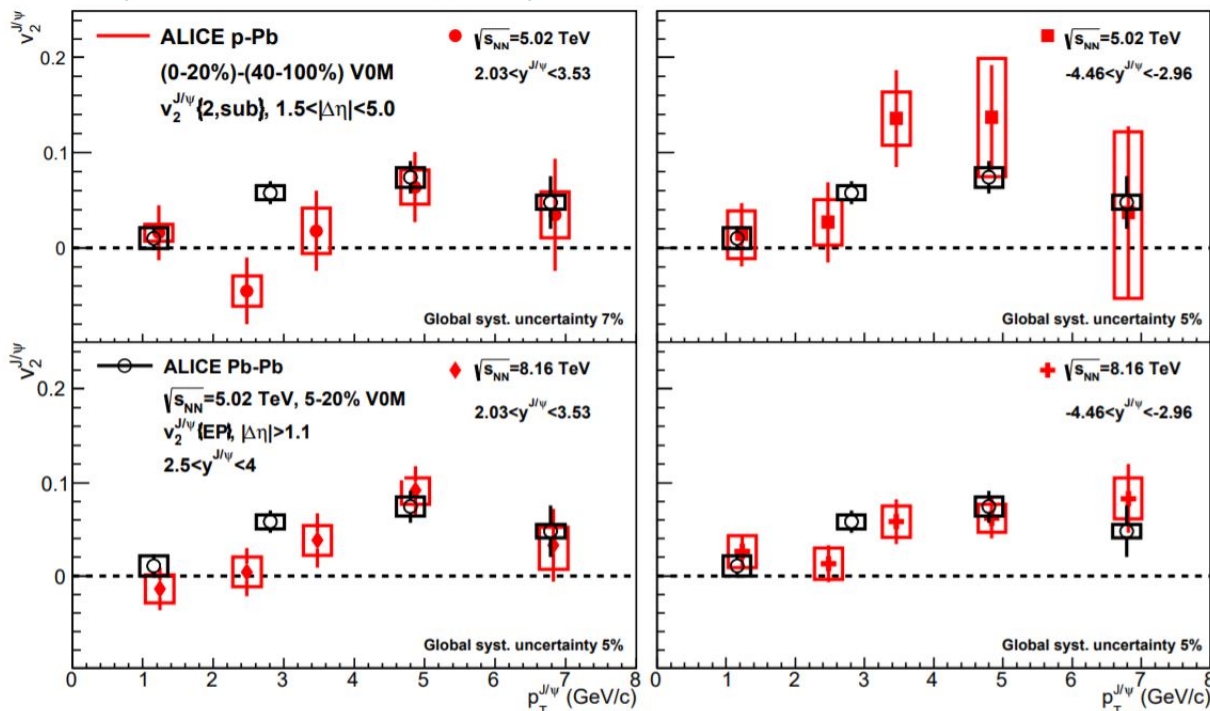**ALICE, Phys. Lett. B 740 (2015) 105**

ALI-PUB-90668

- Model predictions describe the measured R_{pPb} at forward-y and tend to underestimate the suppression at backward-y

- ALICE and LHCb results are compatible within (large) uncertainties

- ALICE Run2 results, with better precision, coming soon

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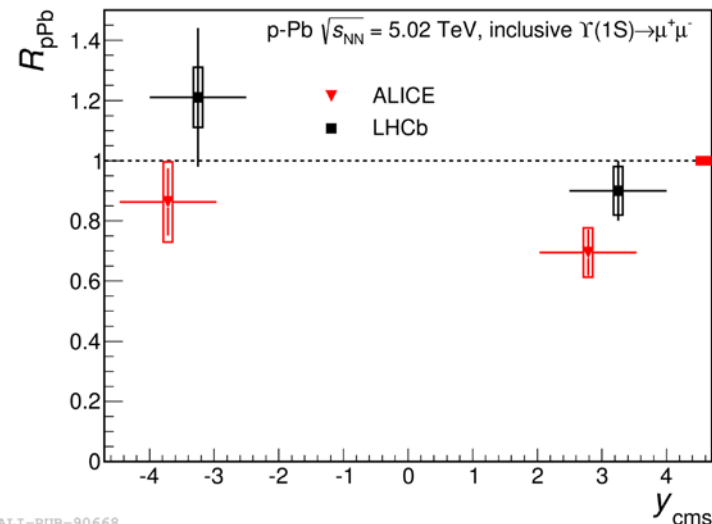
J/Ψ ELLIPTIC FLOW IN p-Pb

ALICE, arXiv:1709.06807 - ALICE, arXiv:1709.05260
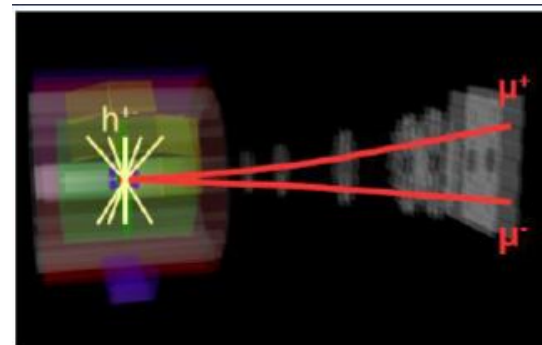
- Azimuthal correlations of forward/backward J/ψ and charged particles at mid-rapidity

- p_T < 3 GeV/c → v_2 compatible with 0 (as from expectation of no recombination)
- 3 < p_T < 6 GeV/c → Evidence of **positive v_2**
- Total significance (forward+backward, $\sqrt{s_{NN}}$ = 5.02 + $\sqrt{s_{NN}}$ = 8.16 TeV) about **5σ**
- Values comparable to the measurements in central Pb-Pb collisions
 - **Common mechanism** for the onset of J/ψ v_2 ?

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ALICE, PLB 766 (2017) 212
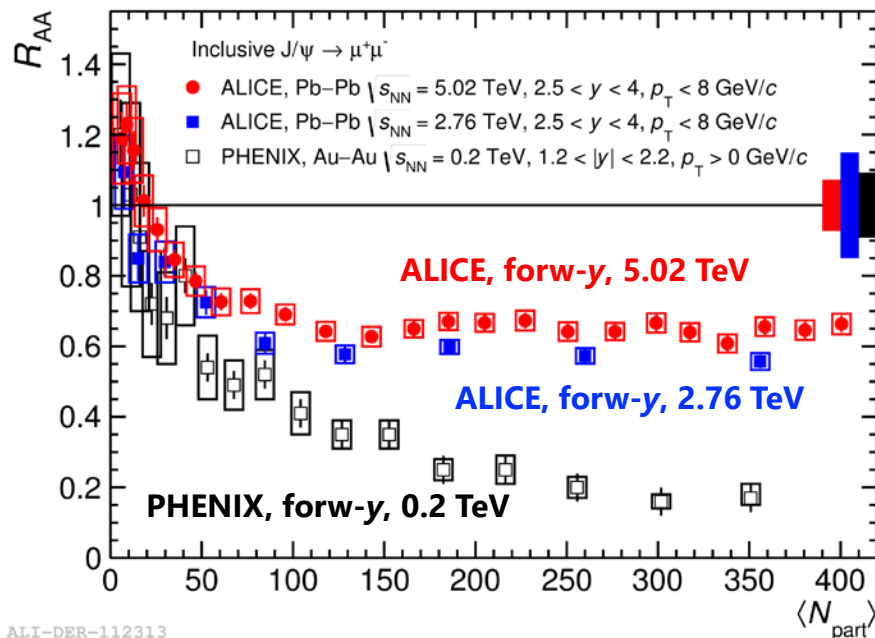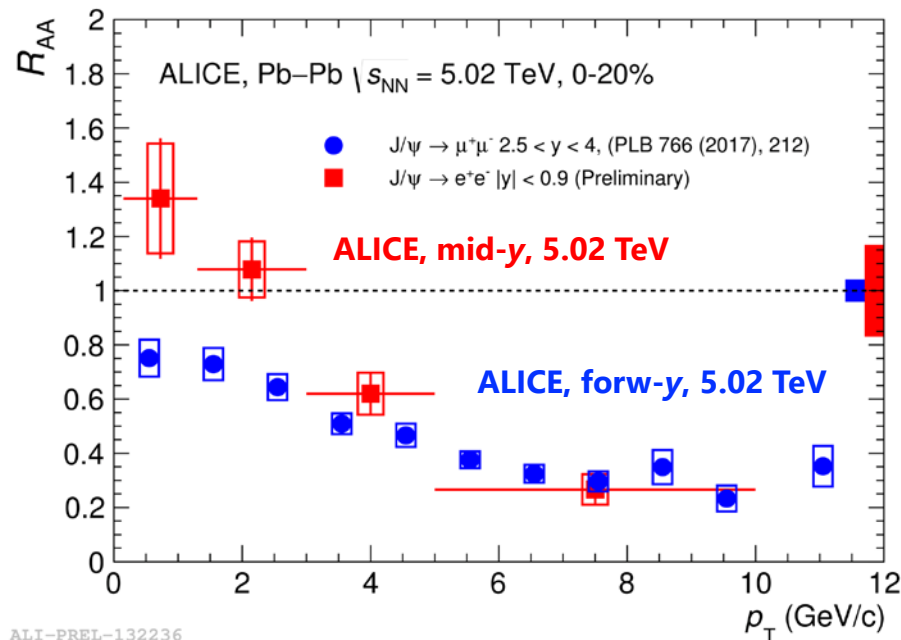
- J/Ψ suppression at $\sqrt{s_{NN}}$ = 5.02 TeV similar to that at $\sqrt{s_{NN}}$ = 2.76 TeV

- R_{AA} trend vs multiplicity flattens beyond $\langle N_{part} \rangle \sim 50$, differently from PHENIX results at lower energy → **substantial contribution from recombination**

- Increased suppression at low p_T for forward-y measurement with respect to mid-rapidity results

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J/Ψ NUCLEAR MODIFICATION FACTOR IN Pb-Pb
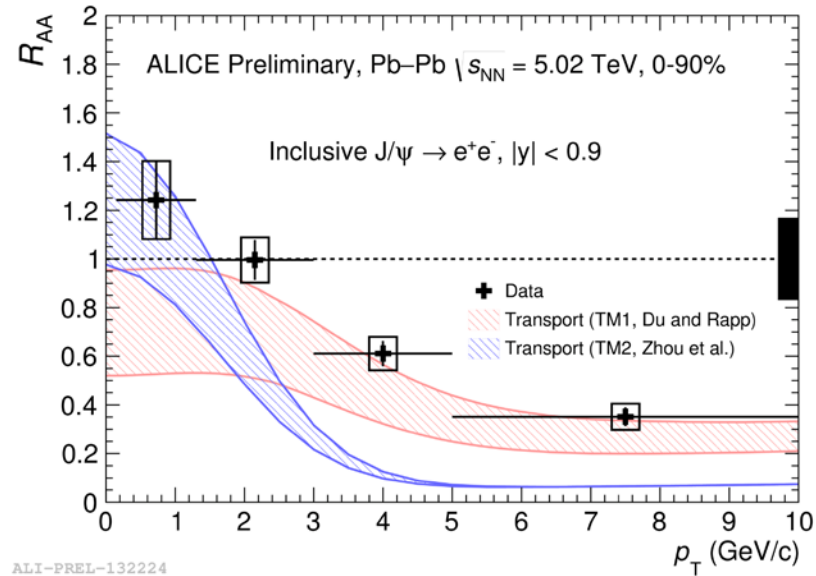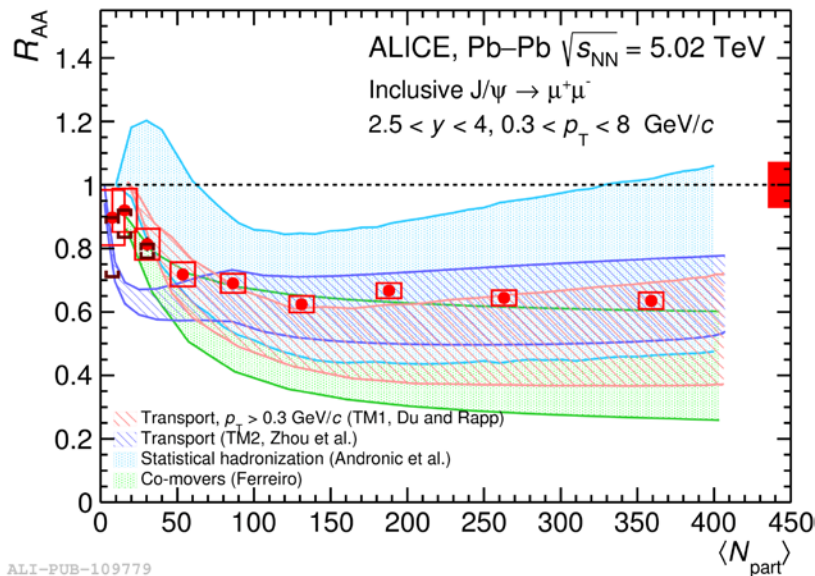
**Statistical hadronisation**: J/Ψ produced at chemical freeze-out according to their statistical weight

Transport models: Based on thermal rate equation with continuous J/Ψ dissociation and regeneration in QGP and hadronic phase

Comover model: J/Ψ dissociated via parton-hadron interactions + regeneration contribution

- All models describe the data fairly well (some tension with TM2 at mid-rapidity), but are affected by large uncertainties associated to charm cross section and shadowing

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J/Ψ ELLIPTIC FLOW IN Pb-Pb
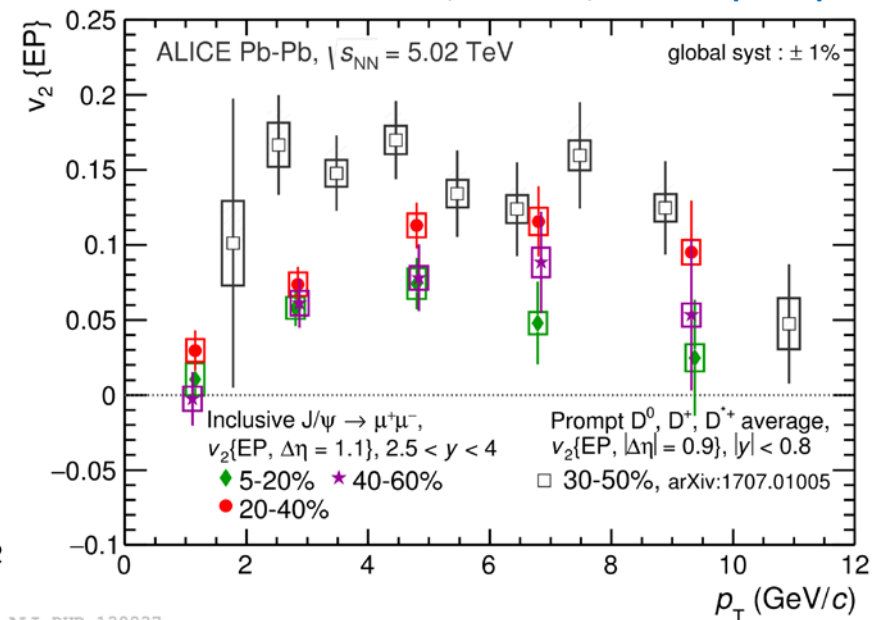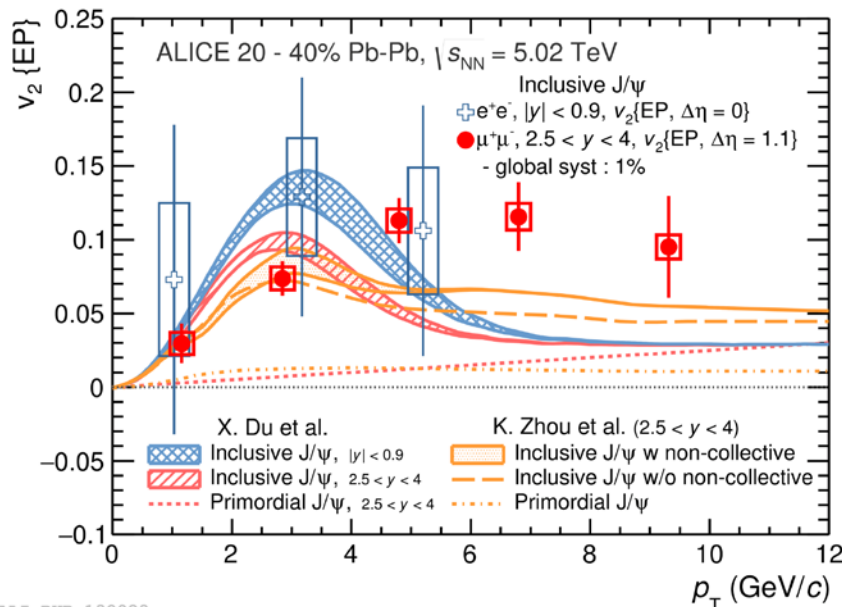
- **Positive v_2** signal observed for different centralities and p_T ranges
- Comparison with models:
  - Low-p_T v_2 fairly reproduced including a strong J/Ψ regeneration component
  - High-p_T v_2 underestimated (prompt J/Ψ from CMS also show positive v_2)
- Comparison with open charm gives **larger values for D-meson v_2 at low p_T** (but different kinematics)
  - Is J/Ψ and D-meson elliptic flow inherited from thermalized charm quarks?

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BOTTOMONIUM PRODUCTION IN Pb-Pb
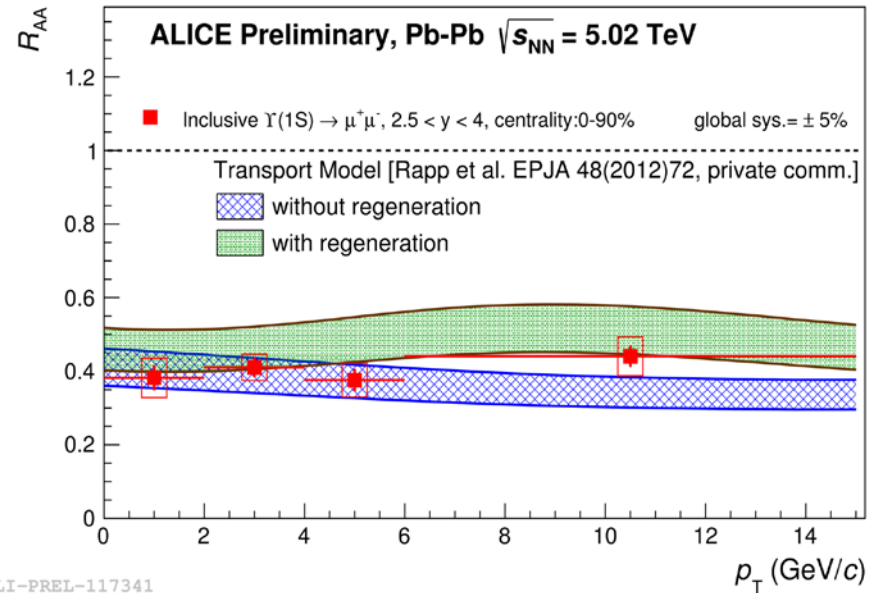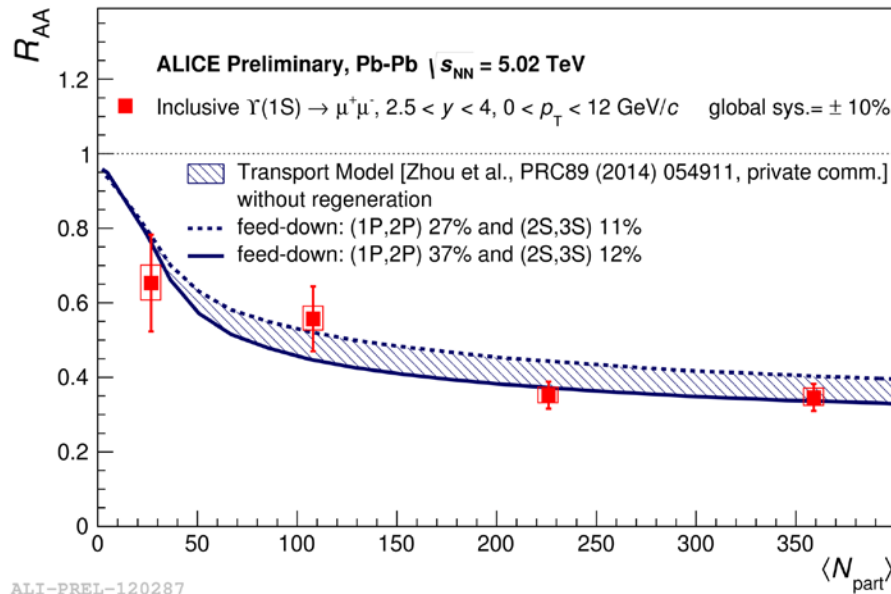
- **Strong Y(1S) suppression** in most central collisions
  - ➤ No transverse momentum dependence within uncertainties
- Transport and anisotropic hydrodynamical models qualitatively reproduce the data
  - ➤ No need of significant contribution from regeneration to describe data
- $R_{AA}(Y(2S))/R_{AA}(Y(1S))$ ratio: $0.26 \pm 0.12(stat) \pm 0.06(syst)$
 - ➤ Hint of **sequential Y suppression**

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PERSPECTIVES AFTER THE UPGRADE

With the ALICE upgrade (LS2), we move from observation to **precision era**:

➤ Striking improvement data precision on currently accessible observables

➤ Extension of p_T ranges (D and B mesons down to 0)

➤ New observables available: beauty mesons and baryons, higher Ψ and Y states, non-prompt J/Ψ and separation of muons from c and b at forward-y with Muon Forward Tracker, …

➤ Large boost for beauty physics and for more differential HF observables in all systems (heavy-flavour correlations and jets, studies vs multiplicity/centrality, …)
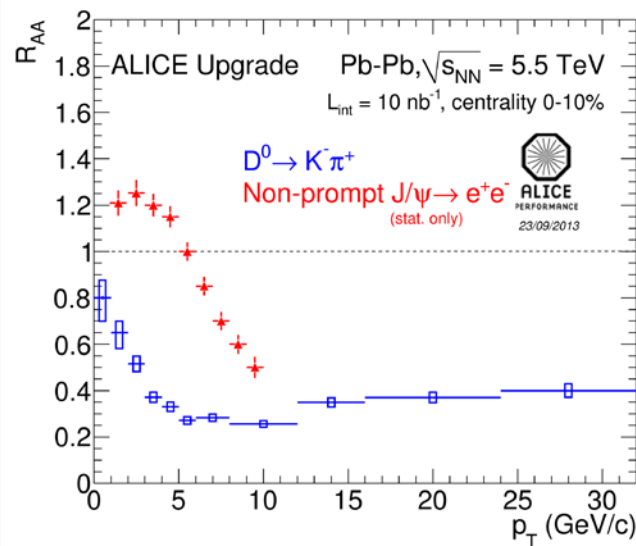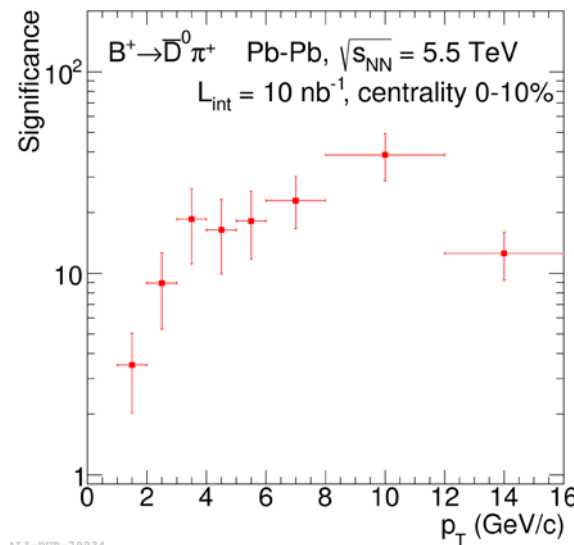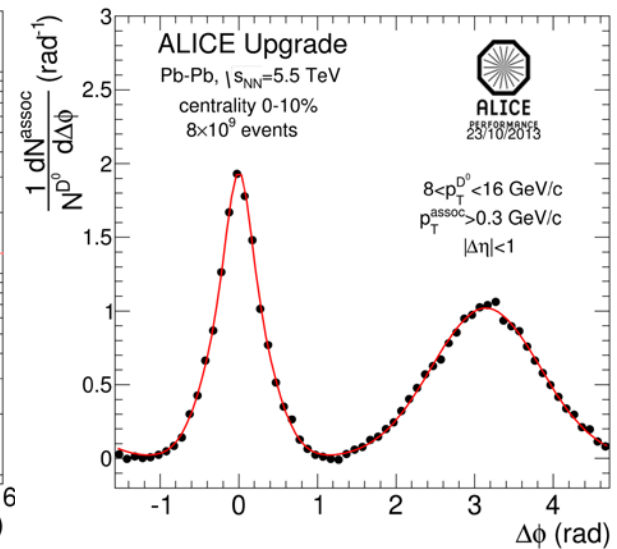
CONCLUSIONS

- ALICE produced a large set of interesting (and some surprising!) results in the heavy-flavour sector during Run1 and Run2

- **Open heavy-flavour**

  - Λ_c^+, Ξ_c^0 baryon production underestimated by models $\rightarrow$ Is charm hadronisation correctly understood?

  - D-meson R_{pPb} compatible with unity (small CNM/QGP effects), but hint for $Q_{CP} > 1$

  - Positive v_2 of HF decay electrons via e-h correlations $\rightarrow$ Collective effects in p-Pb?

  - Significant D-meson suppression, hint for $R_{AA}(D_s^+) > R_{AA}(D^0, D^+, D^{*+})$ $\rightarrow$ Hadronisation via coalescence?

  - Significant charm flow observed in Pb-Pb: hint for $v_2(D) < v_2(\pi^+)$ below 4 GeV/c

- **Quarkonium**

  - J/Ψ R_{pPb} can be described by cold nucler matter effects

  - Strong $\Psi(2S)$ suppression in p-Pb $\rightarrow$ Due to final-state effects?

  - Significant J/Ψ v_2 at intermediate p_T for both p-Pb and Pb-Pb $\rightarrow$ Common mechanism?

  - J/Ψ R_{AA} described by interplay of suppression and recombination mechanisms

  - Hint for sequential suppression of bottomonium states in Pb-Pb

- After the ALICE Upgrade, improved precision on current measurements and access to a new broad set of observables to characterise the QGP properties $\rightarrow$ Stay tuned!
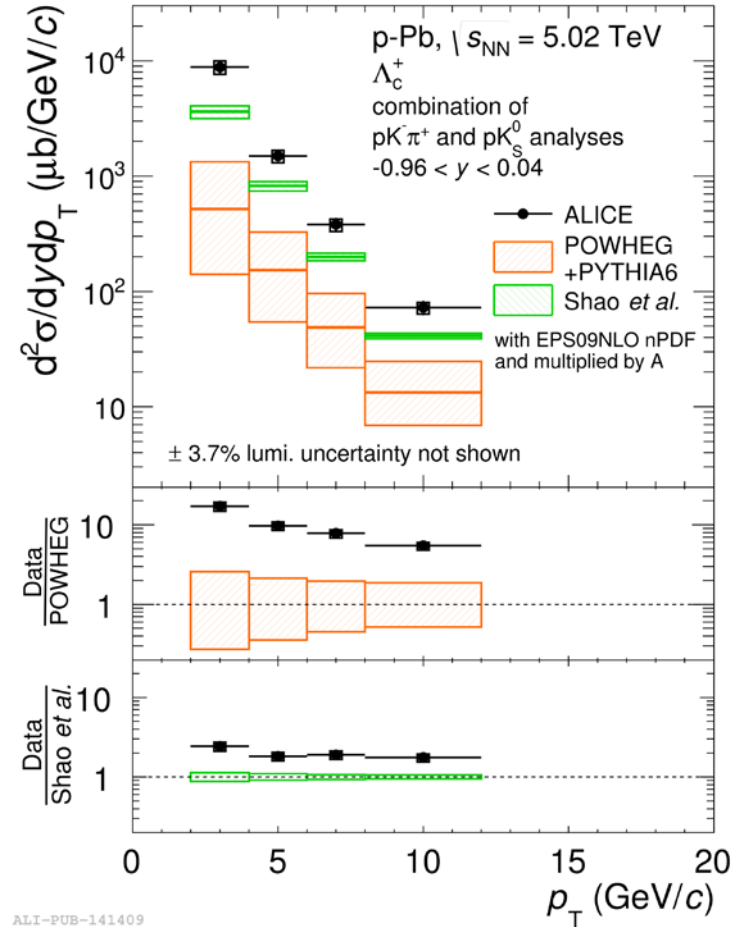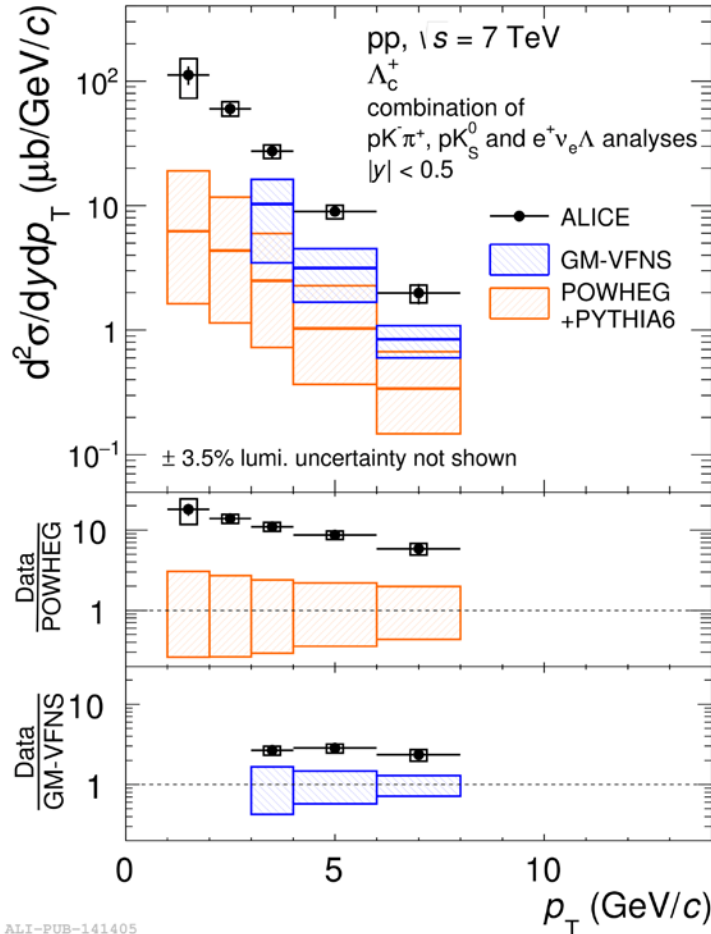
BACKUP SLIDES

CROSS SECTIONS IN pp COLLISIONS
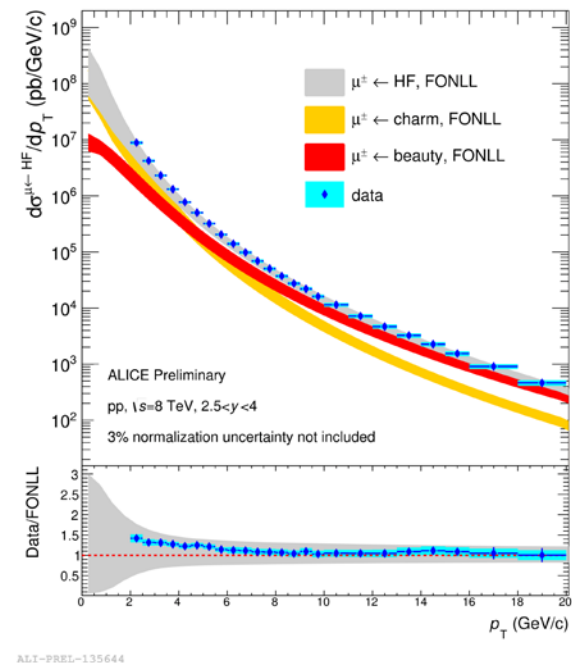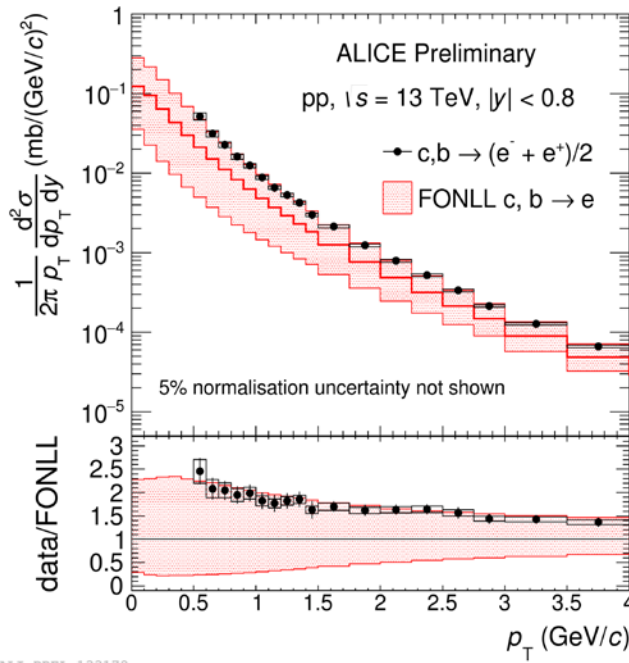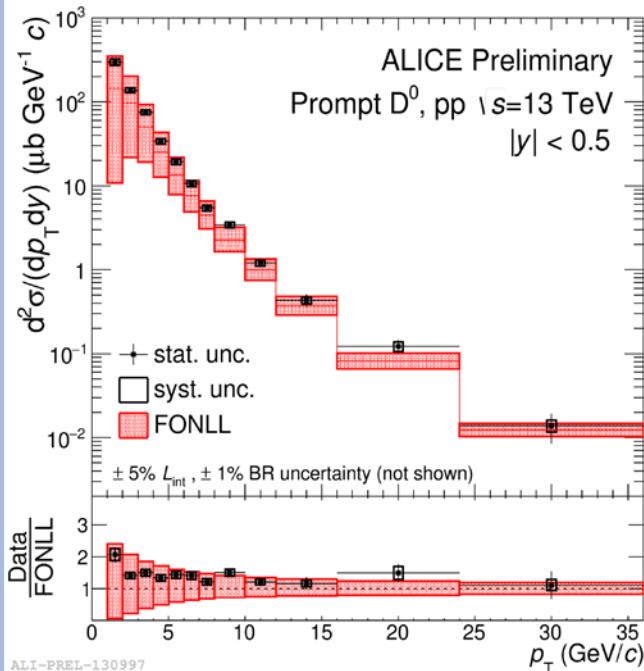
- D-meson and HF decay lepton cross sections vs p_T measured for several energies ($\sqrt{s}$ = 2.76, 5.02, 7, 8, 13 TeV)
  - D^0 cross section down to p_T = 0
- Excellent constrain for charm and beauty production over a wide rapidity interval
- All measurements are consistent with pQCD calculations

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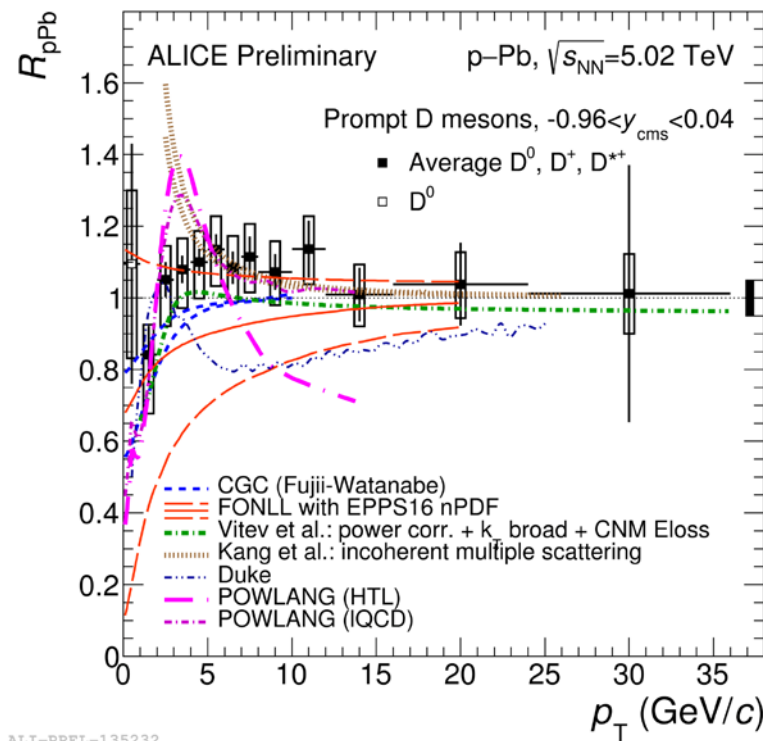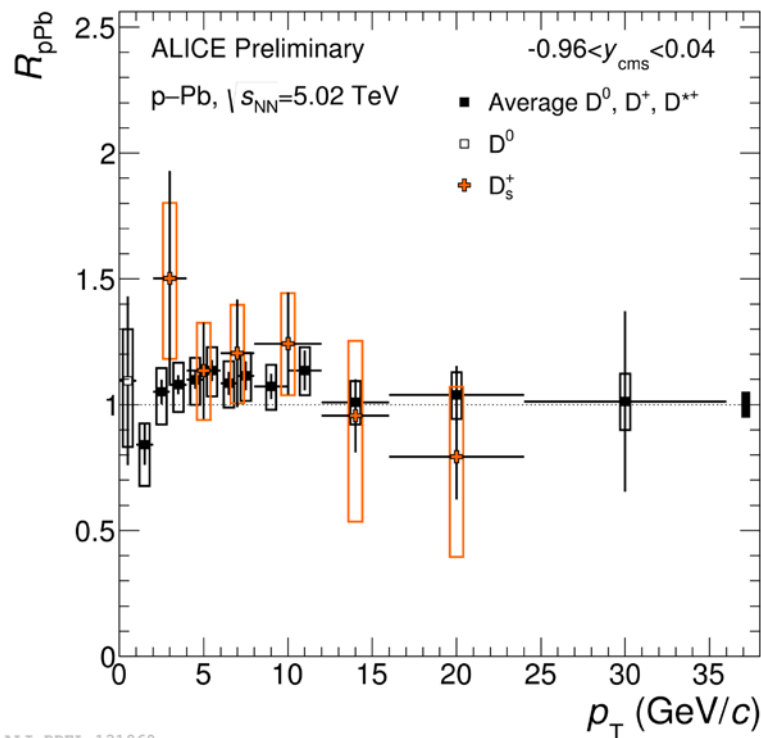
- Λc+ pT-differential cross section from pT > 1 (2) GeV/c in pp (p-Pb) collisions
- Λc+ production cross section **higher than pQCD calculations** in pp and p-Pb collisions: is charm hadronisation correctly described?

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D-MESON R_pPb

ALI-PREL-131960

ALI-PREL-135232

- Similar R_{pPb} trend for D_s^+ and non-strange D mesons
- Non-strange D meson R_{pPb} is **compatible with unity** within uncertainties
  - ➤ Described by models including Cold Nuclear-Matter effects, as well as by those predicting QGP formation (at least at low p_T)
- Better precision at low p_T needed to draw firmer conclusions

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Dₛ⁺/D⁺ RATIO IN ALL SYSTEMS
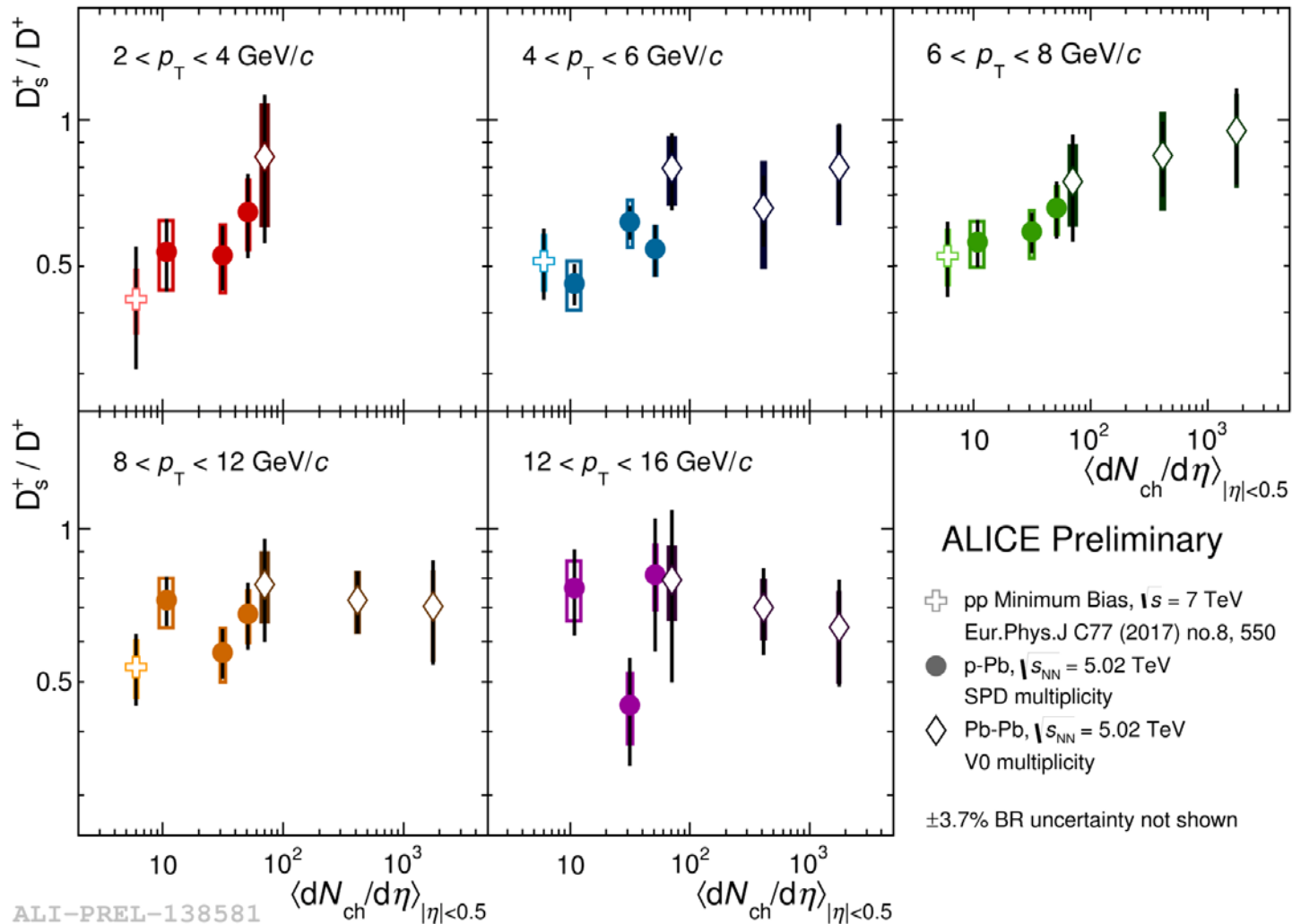
- Hints of larger Ds+/D+ ratios at larger multiplicity below 8 GeV/c

D-MESON Q_{pPb} VS CENTRALITY

ALI-PREL-136799

ALI-PREL-136823
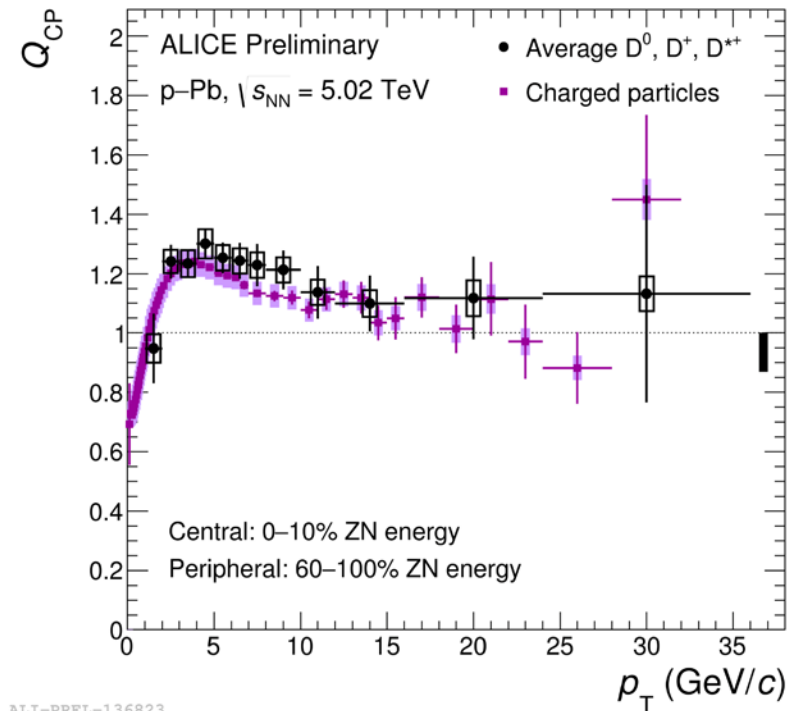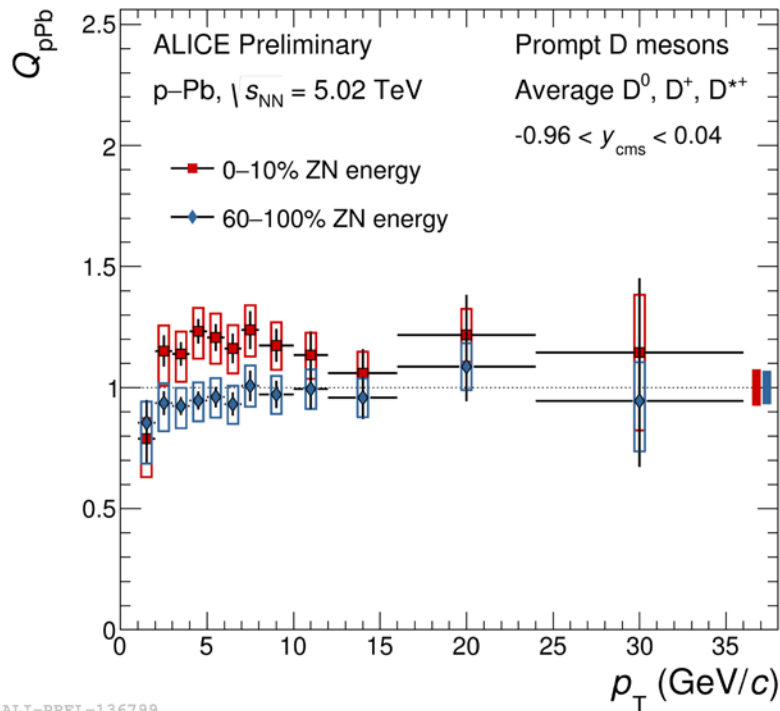
- D-meson Q_{pPb} in 0-10% and 60-100% compatible with unity and within each other
- Hint for D-meson "central-to-peripheral" ratio (Q_{CP}) >0 with 1.5σ in 2<pT<8 GeV/c
  - ➢ Need theory models for its interpretation
- Very similar values and trend w.r.t. charged pion QCP
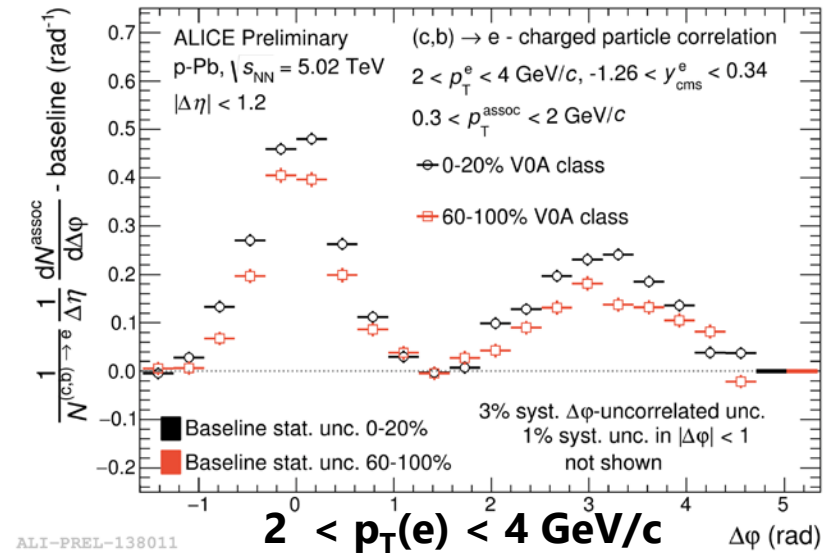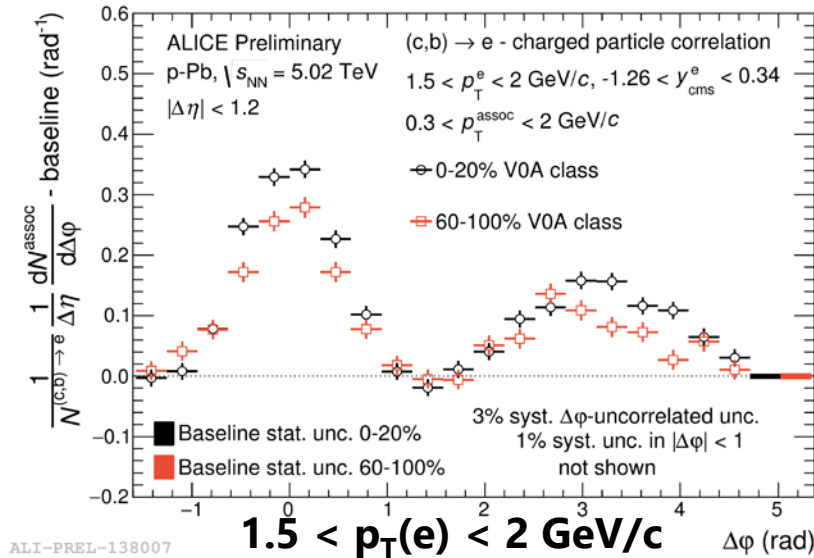 - ➢ Initial-state effect? Mass effect? Radial flow?

35
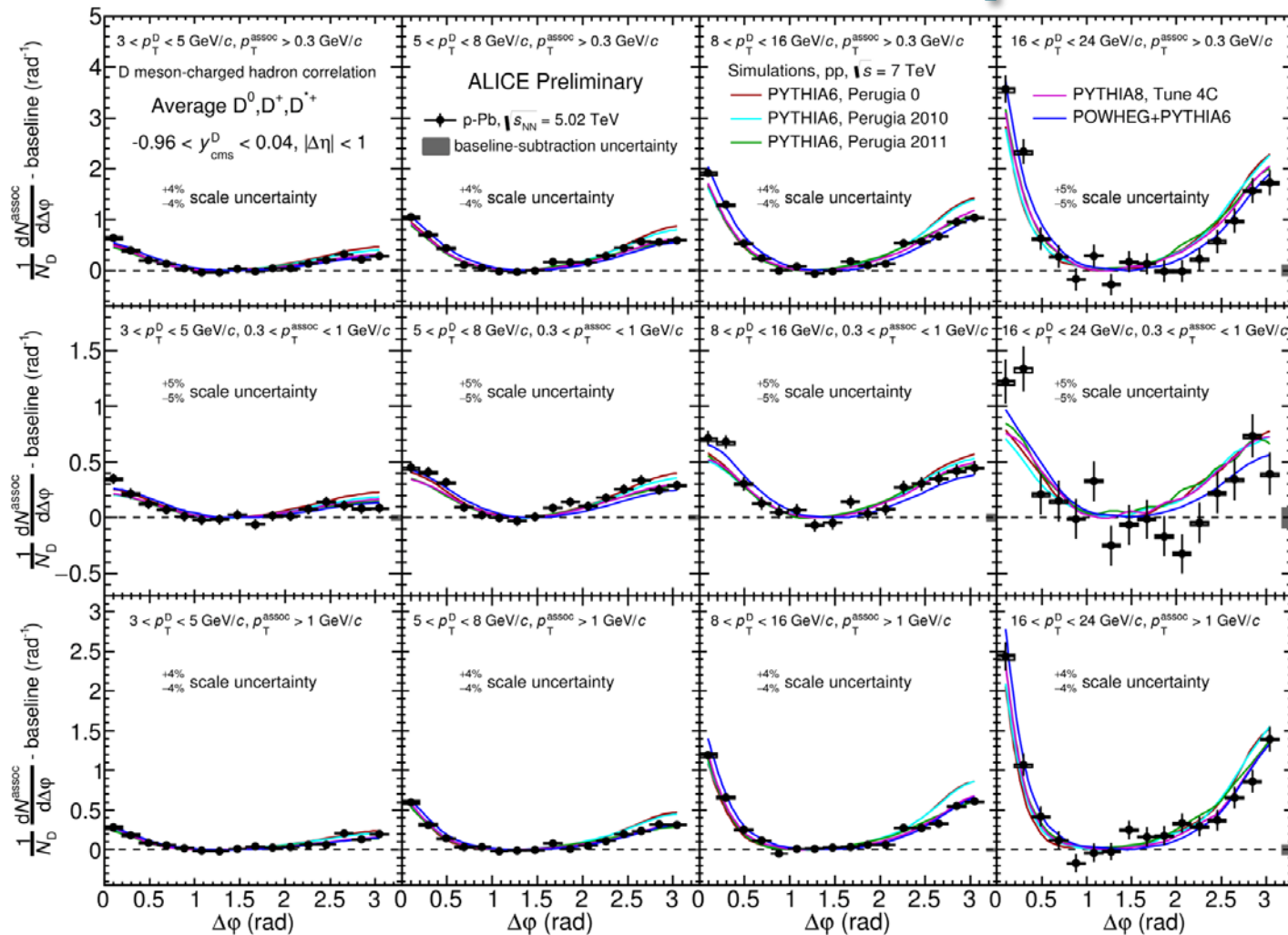
ALI-PREL-133682

- Correlation distributions and their p_T trend well described by PYTHIA6,8 & POWHEG
- p-Pb results in agreement with those measured in pp at 7 TeV

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e-h CORRELATIONS IN p-Pb (LOW p_T)

**1.5 < p_T(e) < 2 GeV/c**

2 < p_T(e) < 4 GeV/c

- HFe-h azimuthal correlation distributions in p-Pb, for different centralities (V0A estimator), for 1.5 < p_T(e) < 6 GeV/c and 0.3 < p_T(assoc) < 2 GeV/c

- 0-20% centrality class shows an enhancement around Δφ = 0,π w.r.t. 60-100, pointing toward elliptic flow modulation also for particles from HF quarks
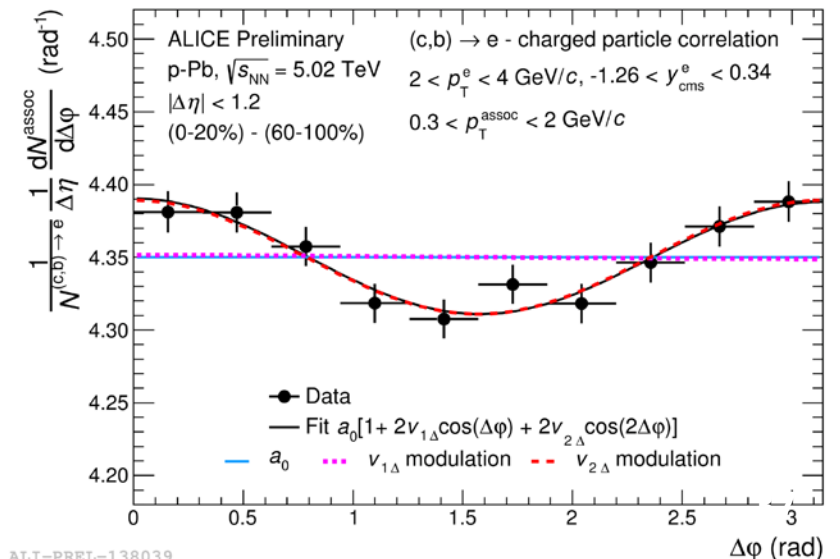
e-h CORRELATIONS IN p-Pb AND Pb-Pb (HIGH p_T)

- HFe-h distributions for p-Pb and Pb-Pb (0-20%) at 5.02 TeV, for $4 < p_T^e < 12$ GeV/c
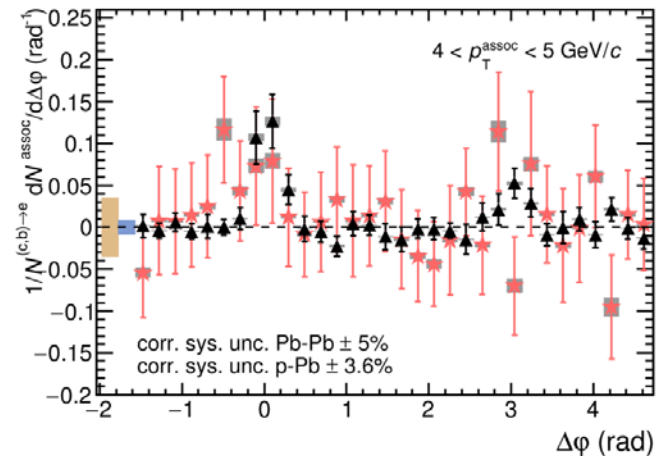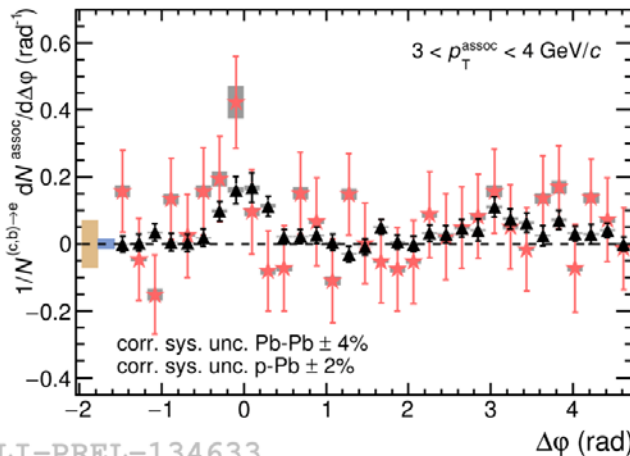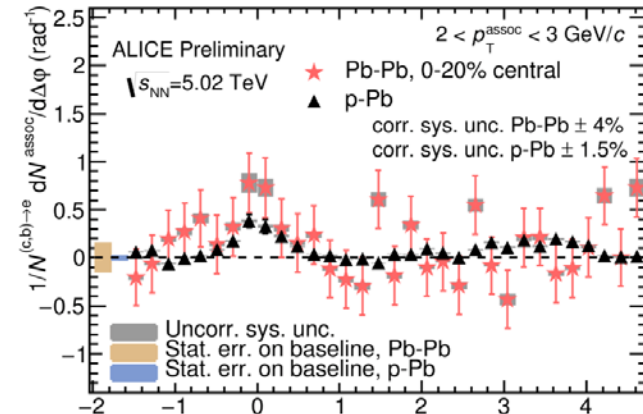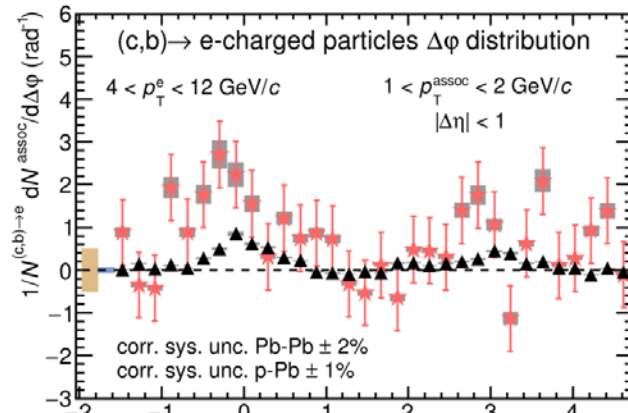
ALI-PREL-134633

- After baseline subtraction, hints of near-side enhancements at low p_T^{assoc}
- No sensitivity for away side studies with current statistics

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h-h CORRELATIONS in Pb-Pb (HIGH p_T)

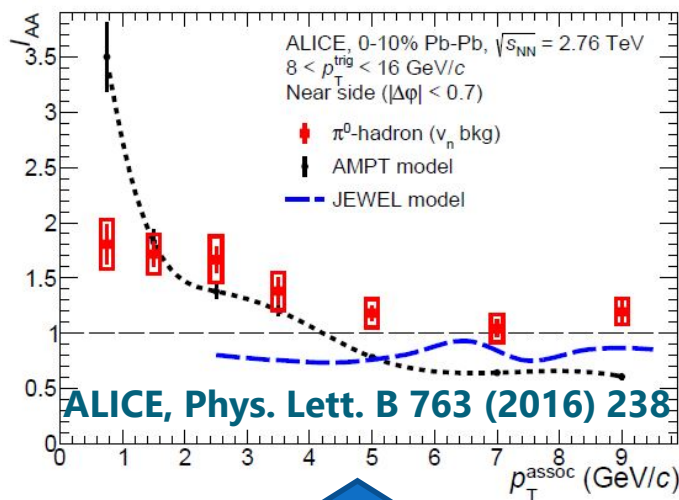**Parton energy loss and jet quenching via high p_T hadron-hadron correlations in Pb-Pb**

Away-side suppression at high p_T

➤ Large in-medium energy loss due to *surface bias*

Near-side peak enhancement, potential interplay of:

➤ Modification to quark/gluon ratio
➤ Bias in parton p_T spectrum due to energy loss
➤ Modified parton fragmentation

e-h in Pb-Pb
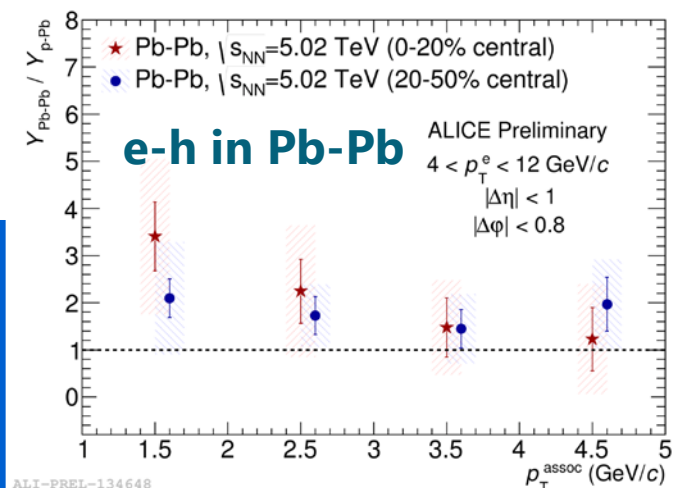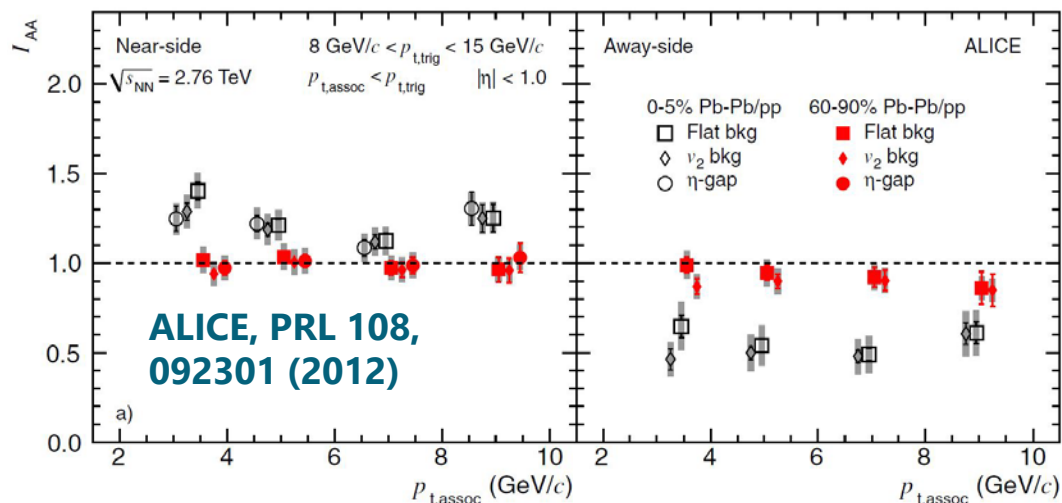
Similar results from in extended p_T range via π^0-hadron correlations
➤ Enhancement of low-p_T track in away-side peak → Redistribution of lost energy

ALICE, PRL 108, 092301 (2012)

ALICE, Phys. Lett. B 763 (2016) 238

D-MESON R_{AA}

ALI-PUB-129303   ALI-PUB-129313
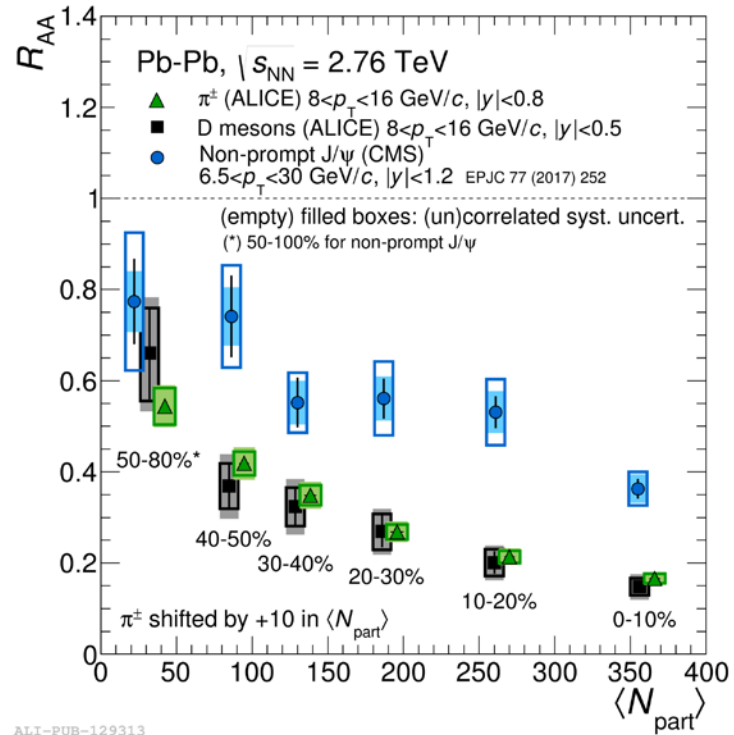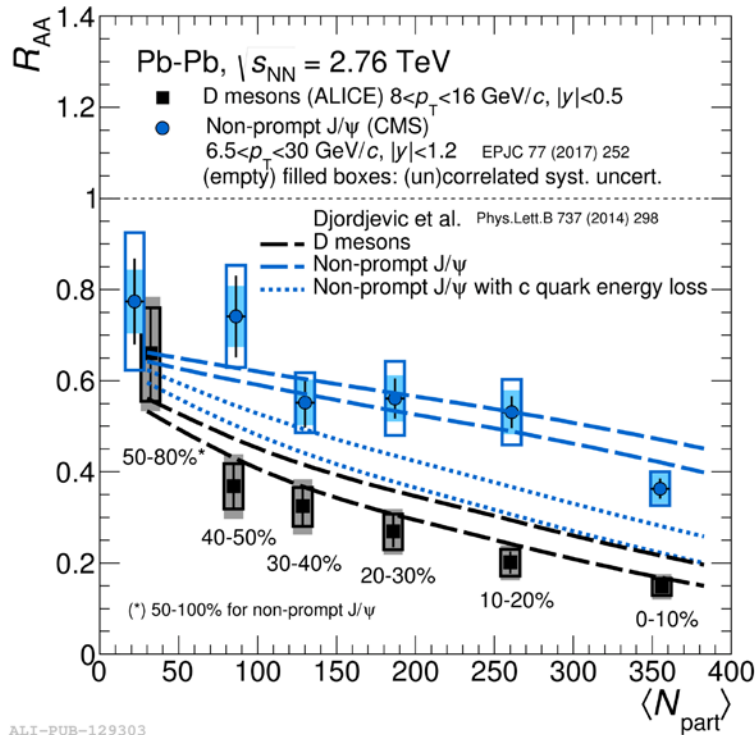
- Indication of $R_{AA}(B) > R_{AA}(D)$

  - ➤ Different suppression and centrality dependence expected from models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{uds} \geq \Delta E_c > \Delta E_b$)

- Similar D meson and pion R_{AA} expected from dead-cone/Casimir factor effects + different charm and gluon/light quark spectrum slope and fragmentation

M. Djordjevic, PRL112 (2014) 042302

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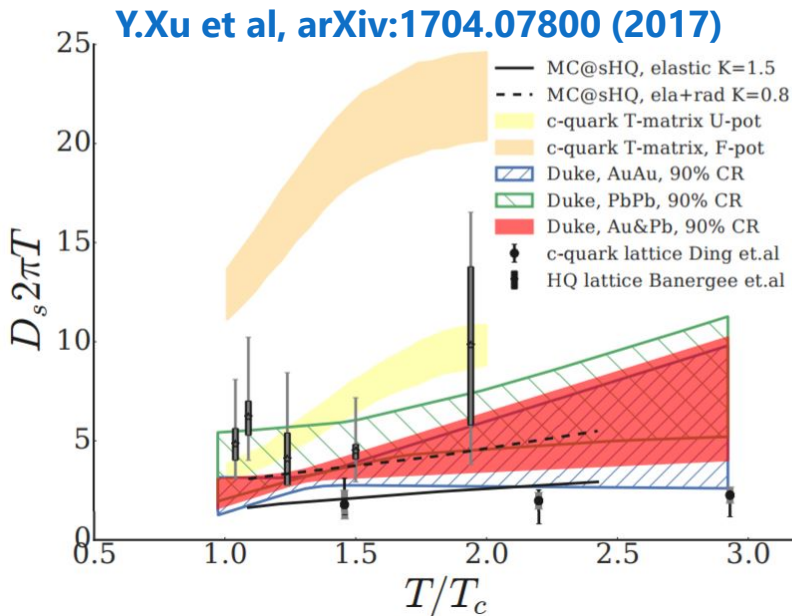**AdS/CFT:** JHEP 1411 (2014) 017; PR D91 (2015) 8, 085019;
Ads/CFT correspondence, Langevin Eloss + fluctuations, hydro
BAMPS: JP G 38 (2011) 124152; PL B 717 (2012) 430
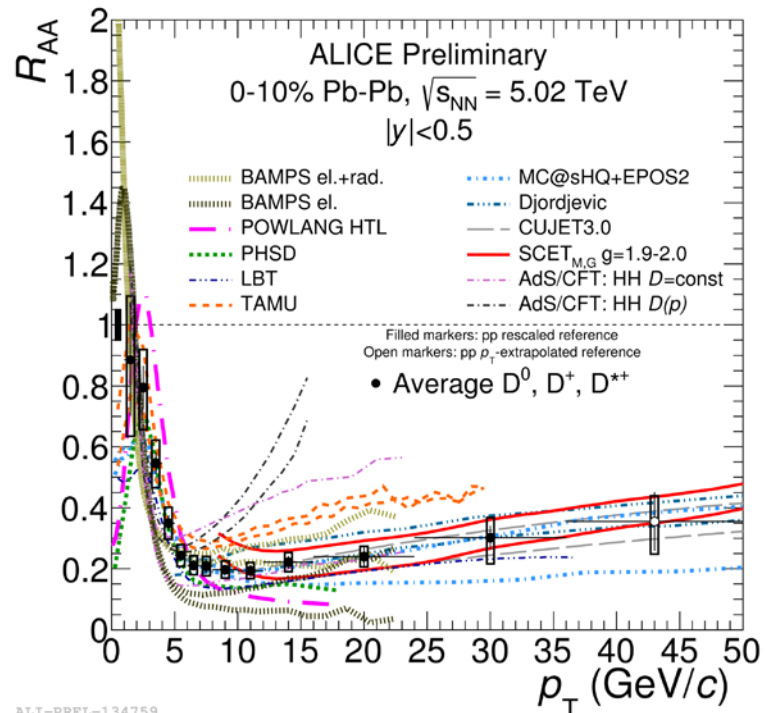Boltzmann transport, Coll. Eloss, expansion
TAMU: PL B735 (2014) 445-450
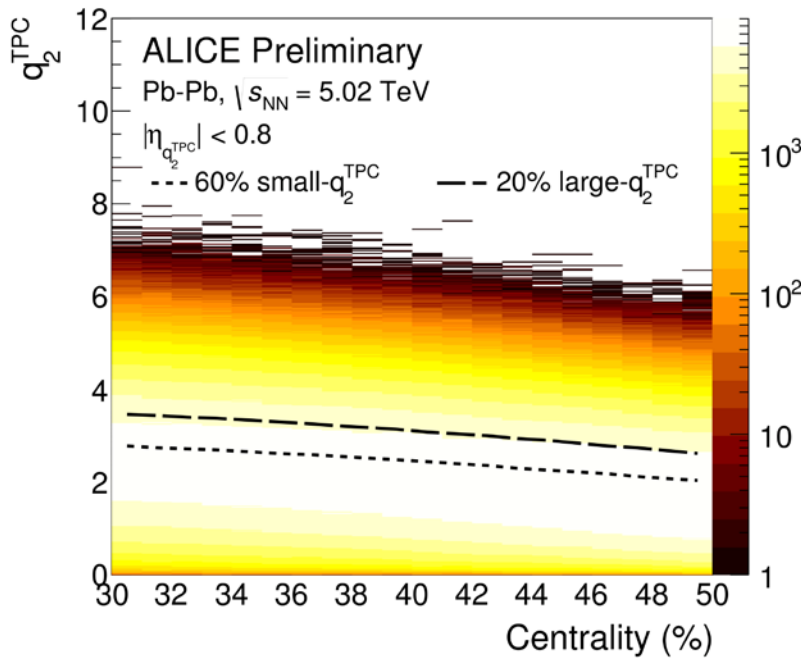Transport, Coll. Eloss, resonant scatt. and coalescence+hydro

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

Temperature dependence of the spatial
diffusion coefficient Ds2πT

EVENT SHAPE ENGINEERING

ALI-PREL-121008

ALI-PREL-121121

Event eccentricity quantified by q_2:

$$q_2 = \frac{|\vec{Q}_2|}{\sqrt{M}}, \quad Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i, \quad Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i$$

$$\langle q_2^2 \rangle \approx 1 + \langle M - 1 \rangle \langle v_2^2 - \delta_2 \rangle \quad \text{δ: non-flow effects}$$

Study the charm-quark coupling to the bulk by measuring v_2 at different q_2 values
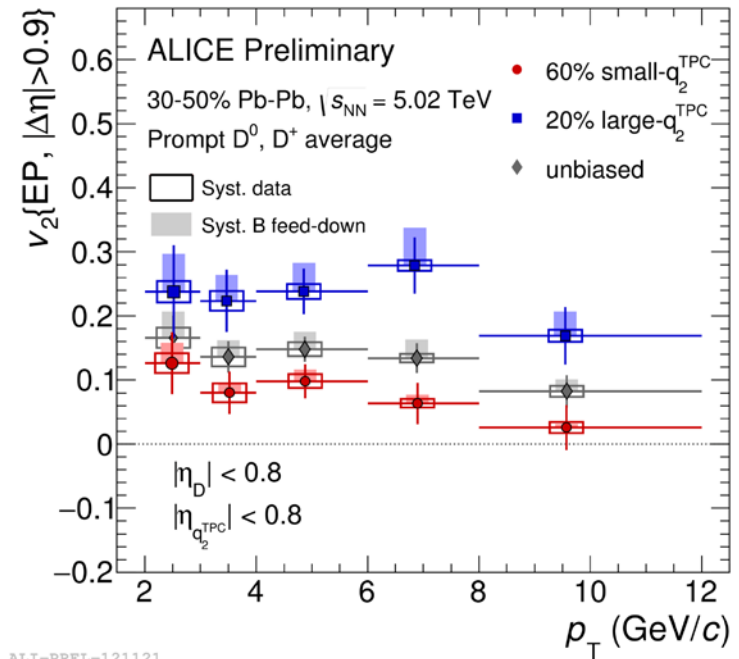
Significant separation of D-meson v_2 in events with large and small q_2 :

➢ Charm quarks sensitive to the light-hadron bulk collectivity and event-by-event initial condition fluctuations

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HEAVY FLAVOUR LEPTON v_2
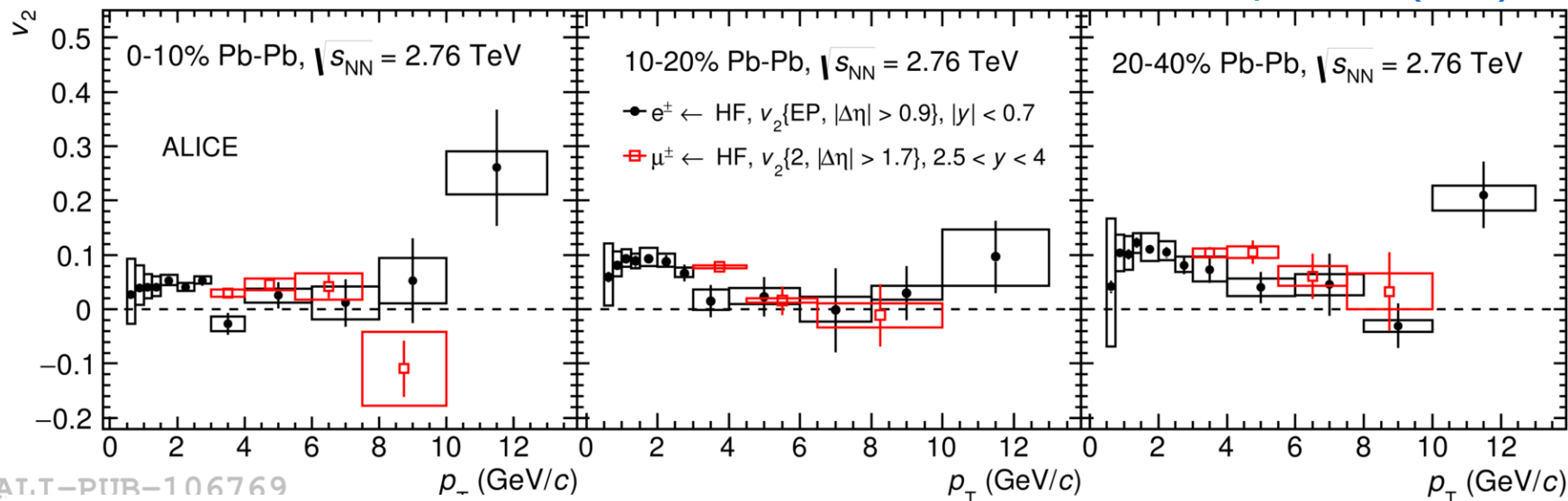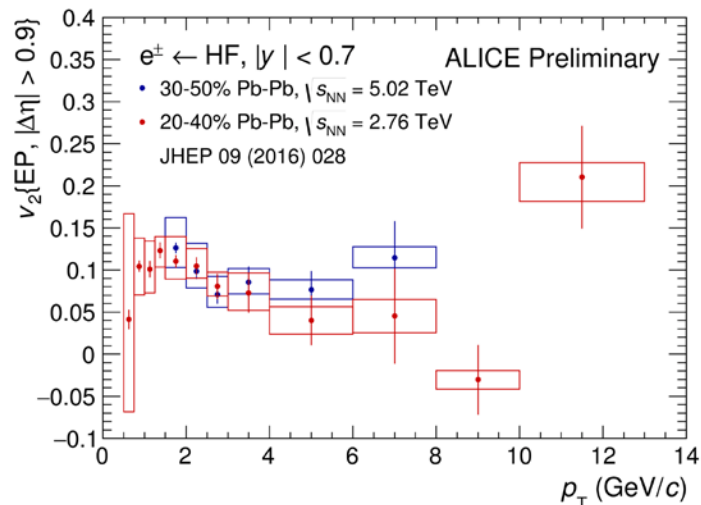
- Similar values of v_2 of heavy-flavour decay electrons (mid-rapidity) and muons (forward rapidity)

- Positive v_2 of HF electrons in semi-central 20-40% Pb-Pb collisions at 2.76 TeV.

- Expected increase of v_2 from central to semi-central collisions.

- Similar v_2 at $\sqrt{s_{NN}} = 2.76$ and 5 TeV

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J/Ψ PRODUCTION IN pp
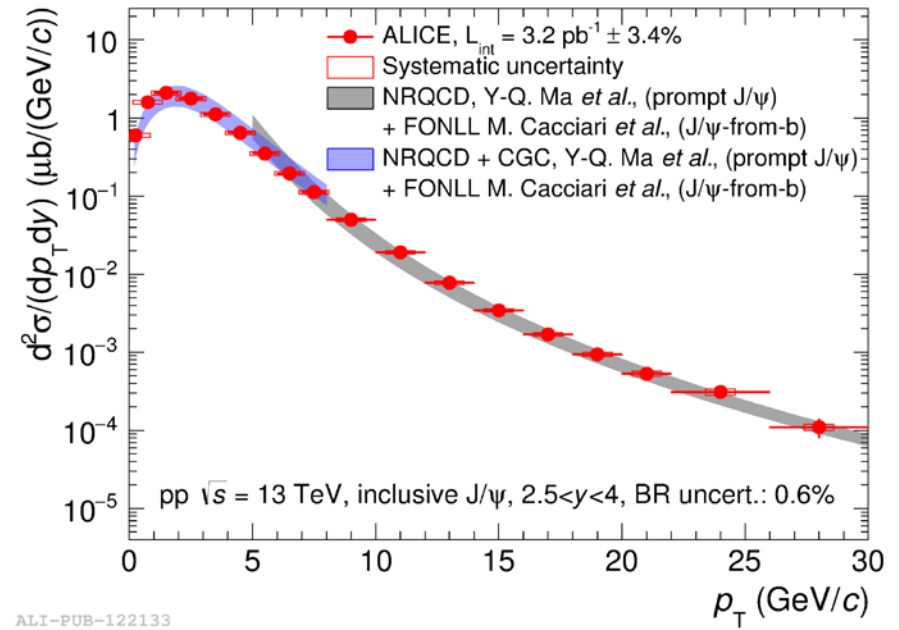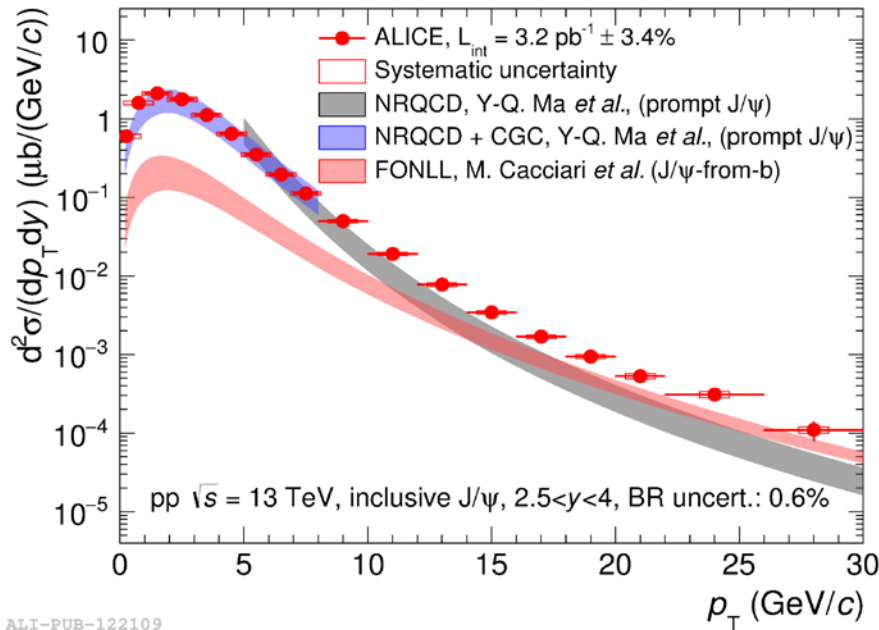
ALICE, EPJC 77 (2017) 392

- Constrain to production models + reference for Pb-Pb studies
- Good description of data by models
  - ➤ Low p_T: NRQCD coupled to a CGC description of the proton reproduces data (small contribution from non-prompt J/ψ)
  - ➤ High p_T: sizable contribution from non-prompt J/ψ from B-decays, taken into account via FONLL

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J/Ψ PRODUCTION VS MULTIPLICITY IN pp
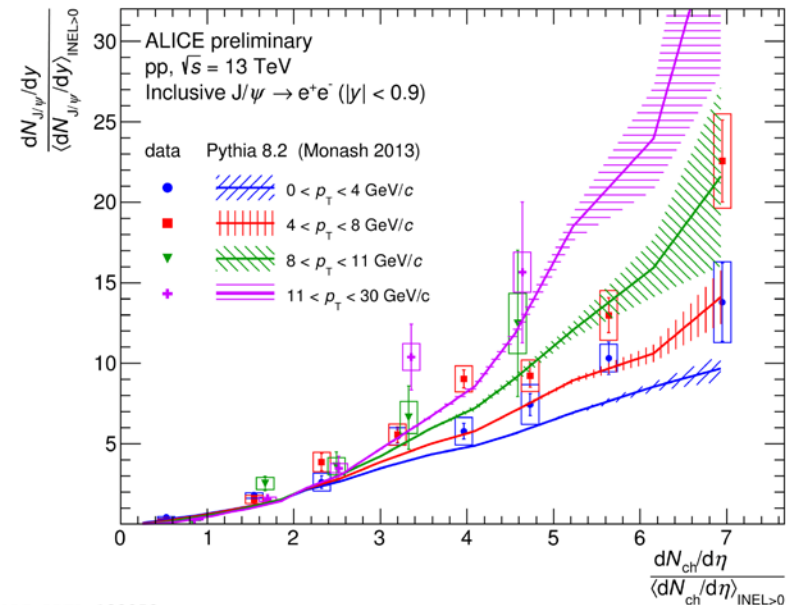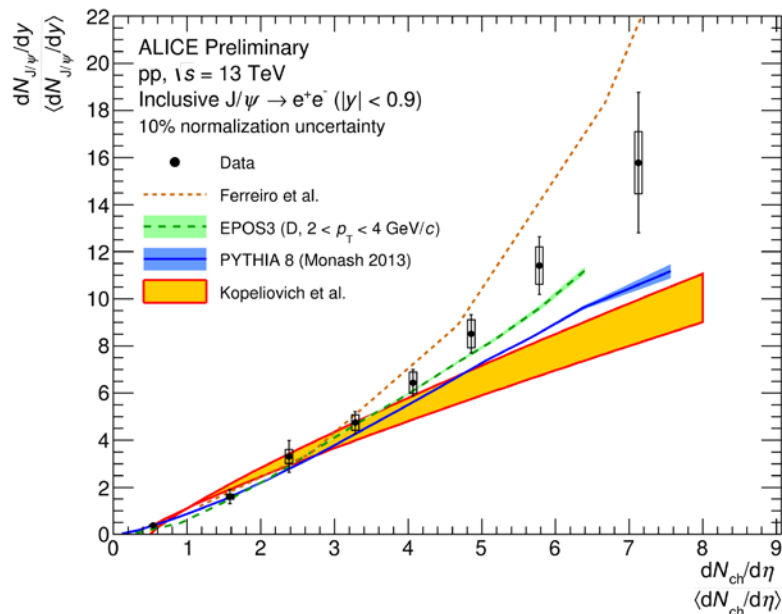
- **Observed a qualitative agreement with models assuming:**
  - ➢ Multi-parton effects in J/ψ production (PYTHIA8, EPOS3 w/ hydro)
  - ➢ Contributions of higher Fock-states (Kopeliovichet al.)
  - ➢ Soft particle saturation (Ferreiro: percolation, PYTHIA8: color reconnection)
- PYTHIA predicts a hierarchy of self-normalized yields with p_T at high multiplicity
  - ➢ Not possible to claim anything on this feature with current uncertainties

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BOTTOMONIUM PRODUCTION IN pp

- Simultaneous measurement of Y(1S), Y(2S) and Y(3S) states at forward rapidity

- Cross section for 2.5 < y < 4, p_T < 12 GeV/c

  - $\sigma_{Y(1S)}$ = 71 ± 6(stat) ± 7(syst) nb

  - $\sigma_{Y(2S)}$ = 26 ± 5(stat) ± 4(syst) nb

  - $\sigma_{Y(3S)}$ = 9 ± 4(stat) ± 1(syst) nb

- Results are in agreement with LHCb measurements within 1.2σ

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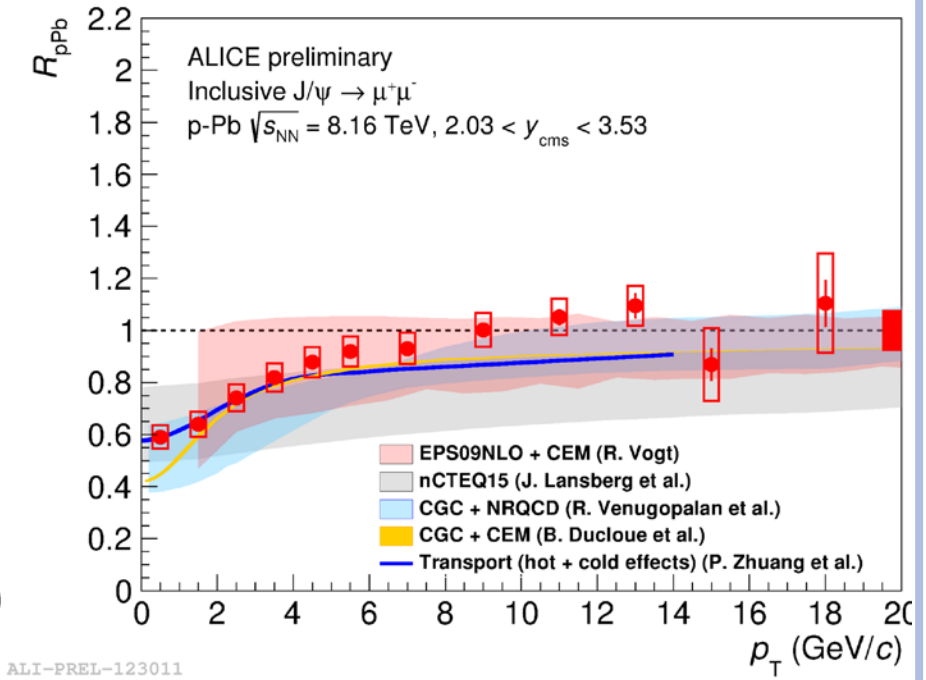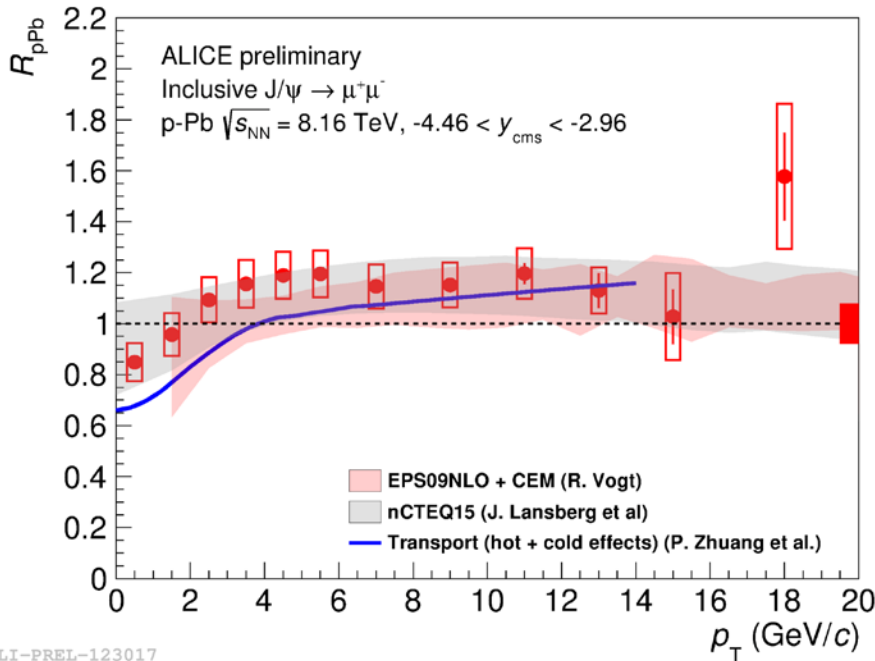
- Extended p_T coverage up to 20 GeV/c

- R_{pPb} increases with p_T at forward y, weaker momentum dependence at backward y

- Good description of the p_T trend be models, though theory uncertainties still prevent a more quantitative comparison

J/Ψ PRODUCTION VS MULTIPLICITY IN p-Pb

ALICE p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Inclusive J/ψ

- 2.03 < y_{cms} < 3.53, p-going direction
- -4.46 < y_{cms} < -2.96, Pb-going direction
- -1.37 < y_{cms} < 0.43

ALICE,arXiv:1704.00274

± 3.1 % normalisation unc. not shown
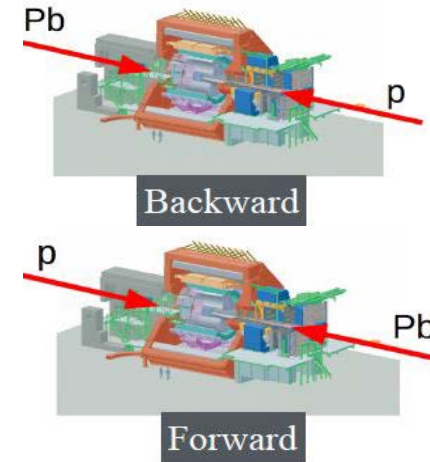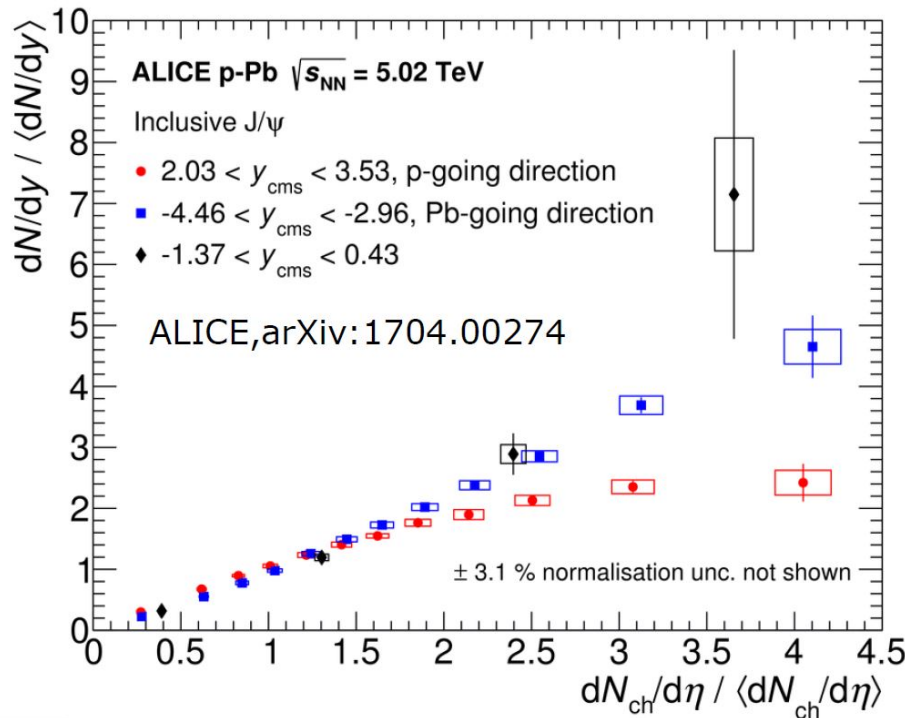
ALICE, PLB 776 (2018) 91-104

- Multiplicity dependent measurement (up to 1% most central events)
- Increase of the self-normalized J/ψ yield with charged particle multiplicity
  - ➤ Mid-y and backward-y: behaviour similar to pp
  - ➤ Forward-y direction: saturation at high multiplicities (Bjorken-x range in the domain of shadowing / saturation)

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J/Ψ NUCLEAR MODIFICATION FACTOR IN Pb-Pb
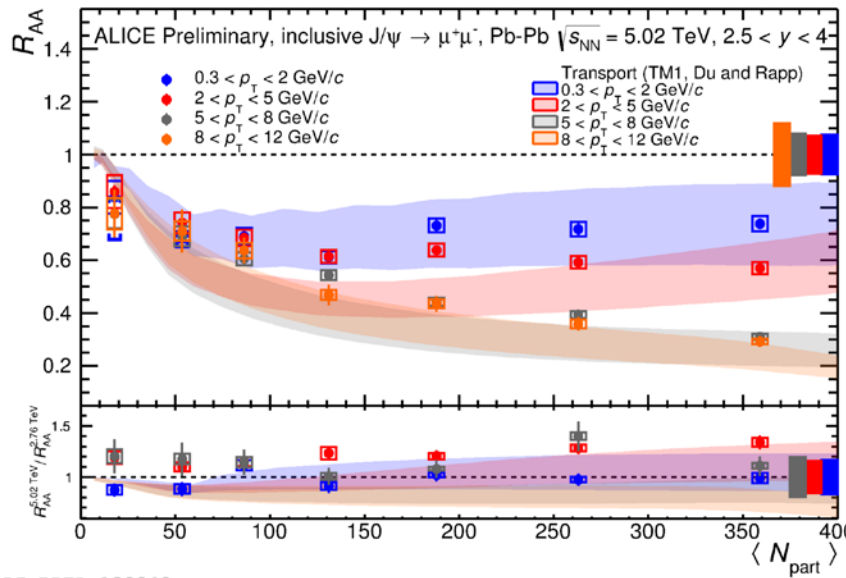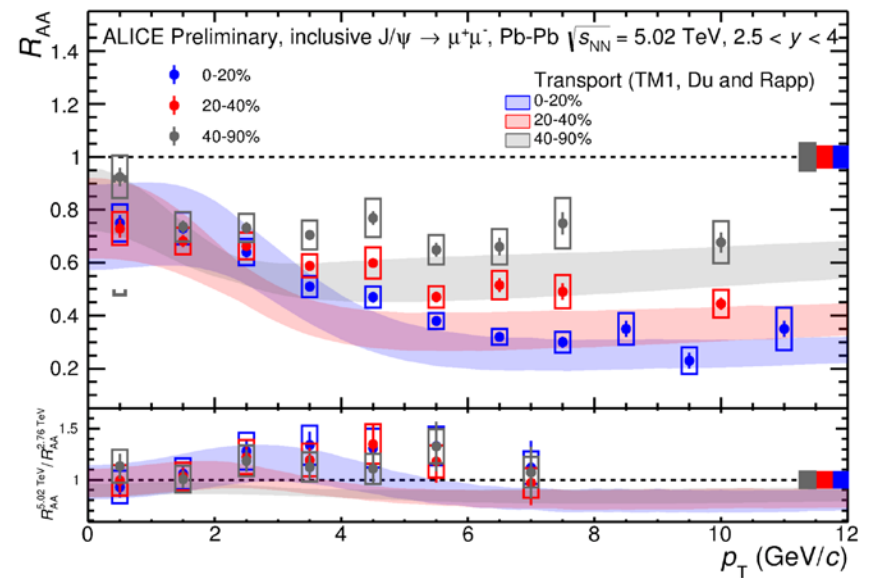
- R_{AA} vs p_T for different centrality bins (and viceversa) at $\sqrt{s_{NN}}$ = 5.02 TeV
- Striking features observed:
  - R_{AA} vs centrality flattish in $0 < p_T < 2$ GeV/c (large contribution from regeneration)
  - ~80% suppression for central events at $p_T \approx 10$ GeV/c
- Excellent precision opens up the way for disentangling among the models

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R_AA OF Ψ(2S)
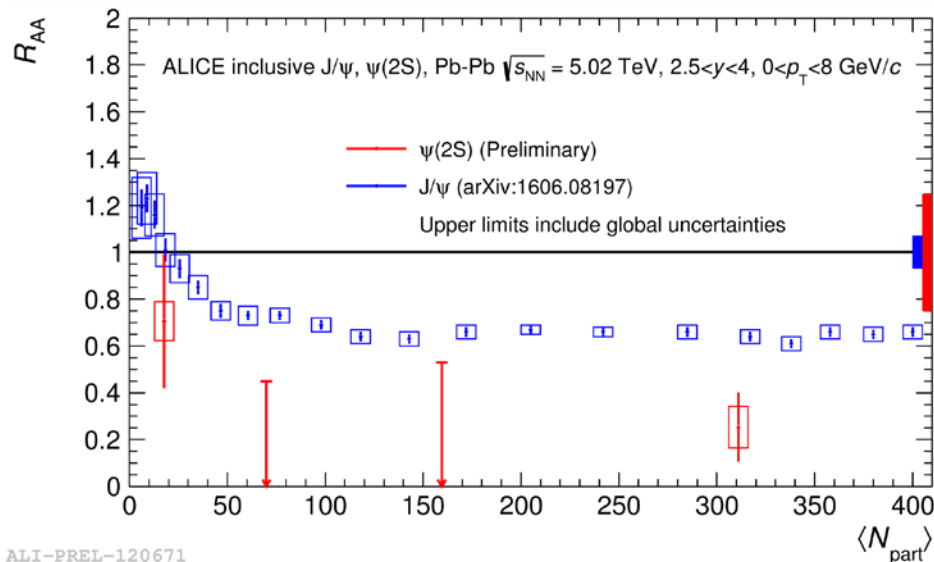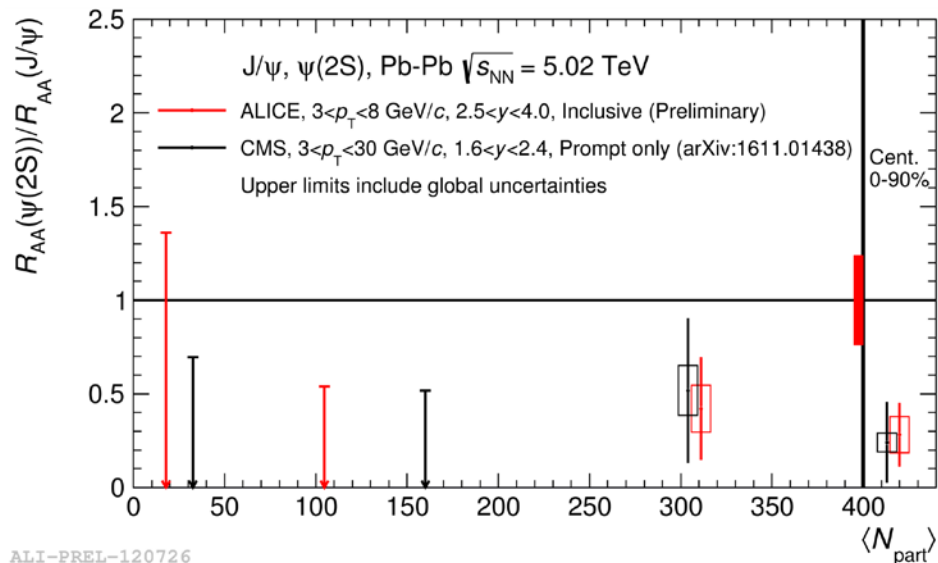
ALI-PREL-120671

ALI-PREL-120726

- Ψ(2S) measurement in Pb-Pb affected by large uncertainties (due to low S/B)

- Larger suppression than for the J/Ψ, both in central and semi-central collisions

- Good agreement with CMS results

PERSPECTIVES FOR b-JET STUDIES

Beauty jets
→ tracks
----- b hadron
------ impact parameter

b jet
secondary vertex
L_{xy}
light jet
d0
primary vertex
light jet
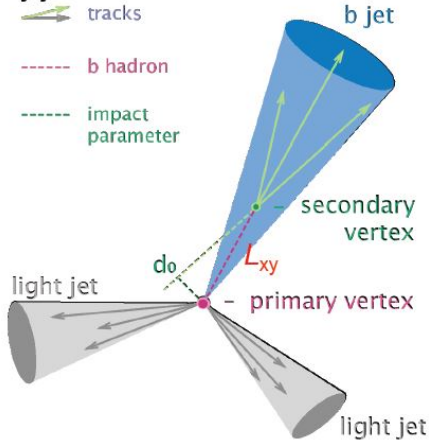
http://bartosik.pp.ua/hep_sketches/btagging

- Analysis ongoing in pp and p-Pb
- Expected first measurements in all systems with run 2 data
- Precise measurements in run 3
- Complementary to CMS if low-pT reach ~15-20 GeV/c

ALICE simulation
PYTHIA + HIJING, p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
3 track vertex, $p_{T, track}$ >1 GeV/c Anti-k_T, R=0.4
most displaced vertex in jet $p_{T, jet}^{gen}$ >20 GeV/c, |η_{jet}|<0.5

Jet flavour:
- beauty
- charm
- light quarks and gluons

ALI-SIMUL-95610
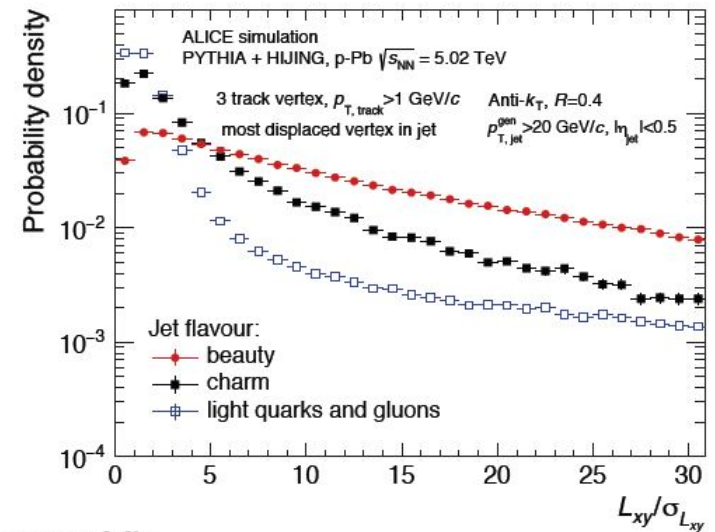
3 approaches:

- Single-track selection based on distance-to-closest approach (DCA)

- Secondary vertex reconstruction + rectangular selections to identify displaced topology

- Single track, secondary vertices, constituent, selection based on Machine-Learning based classification

$30 \leq p_{T, jet}^{gen} < 40$ GeV/c

Jet flavour
— charm (ML)
— udsg (ML)
■ charm (cut)
● udsg (cut)

ALICE Simulation
PYTHIA + HIJING, p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
FastJet, anti-k_T, R = 0.4, |η_{jet}| < 0.5

ALI-SIMUL-131081
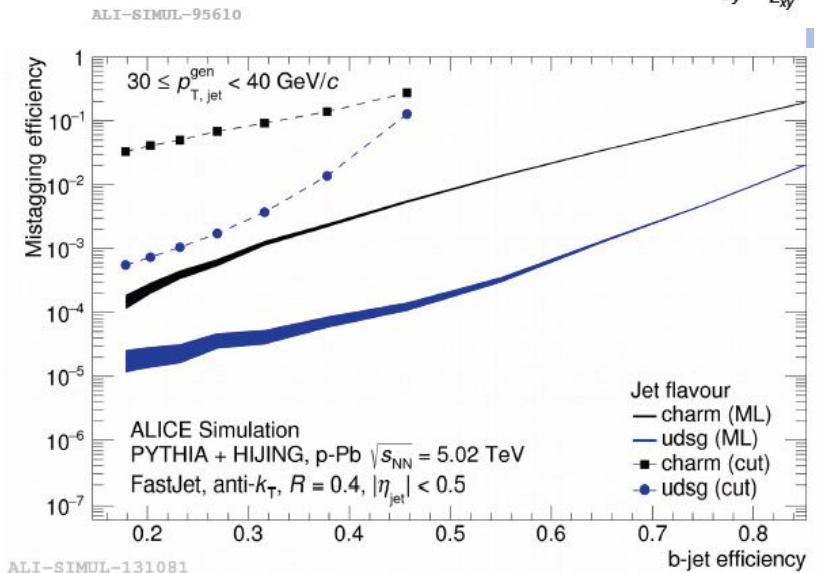
DATA SAMPLES

| Collision	$\sqrt{s_{NN}}$ (TeV)	Year	Trigger	L_{Int}	Results
pp	2.76	2011	Min.Bias	0.9 nb^{-1}	
pp	2.76	2011	Muon	19 nb^{-1}	
pp	5.02	2015	Min.Bias	2 nb^{-1}	
pp	5.02	2015	Muon	50 nb^{-1}(SL) ,100 nb^{-1}(SH)	
pp	7	2010	Min.Bias	5 nb^{-1}	
pp	7	2010	Muon	16.5 nb^{-1}	
pp	8	2012	Muon	2 nb^{-1}	
pp	13	2016	Min.Bias	3 nb^{-1}	
p-Pb	5.02	2013	Min.Bias	47 μb^{-1}	
p-Pb	5.02	2013	Muon	5 nb^{-1} (p-Pb), 5 nb^{-1} (Pb-p)	
p-Pb	5.02	2013	Electron	1.6 nb^{-1} (p-Pb), 1.1 nb^{-1} (Pb-p)	
p-Pb	5.02	2016	Min.Bias	292 μb^{-1}	
p-Pb	8.16	2016	Muon	~8 nb^{-1} (p-Pb), 9 nb^{-1} (Pb-p)	
Pb-Pb	2.76	2010	Min.Bias	2.7 μb^{-1}	
Pb-Pb	2.76	2011	Min.Bias + Cent.	21 μb^{-1}	
Pb-Pb	2.76	2011	Min.Bias + SemiCent.	6 μb^{-1}	
Pb-Pb	2.76	2011	Min.Bias + Periph.	2 μb^{-1}	
Pb-Pb	2.76	2011	Muon	70 μb^{-1}	
Pb-Pb	2.76	2011	Electron	~25 μb^{-1}	
Pb-Pb	5.02	2015	Min.Bias	13 μb^{-1}	
Pb-Pb	5.02	2015	Muon	225 μb^{-1}	

PHYSICS MOTIVATIONS – HF JETS

Heavy-flavour jets (with b, c content)

- Tight connection with HF correlations (some shared goals, alternate approach):
  - ✓ Spatial distribution of energy lost in the medium by heavy quarks
  - ✓ Modification of heavy-quark fragmentation (via D-,B-tagged jets)

- Study of di-jet imbalance useful also in the HF sector
  - ✓ Further motivation: address NLO contribution to heavy-quark production
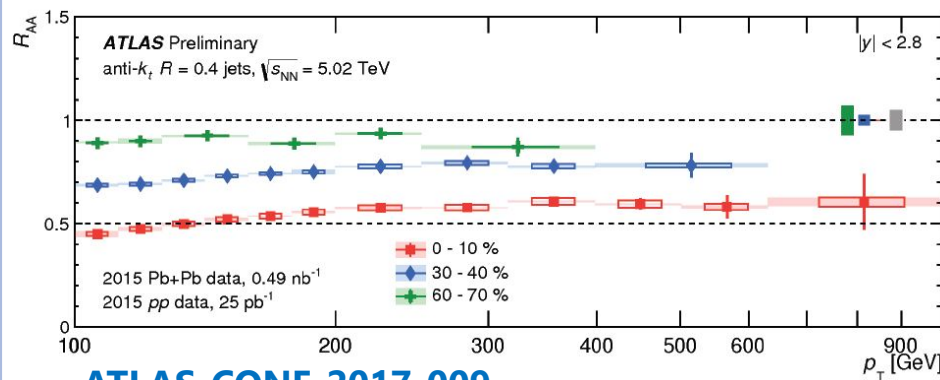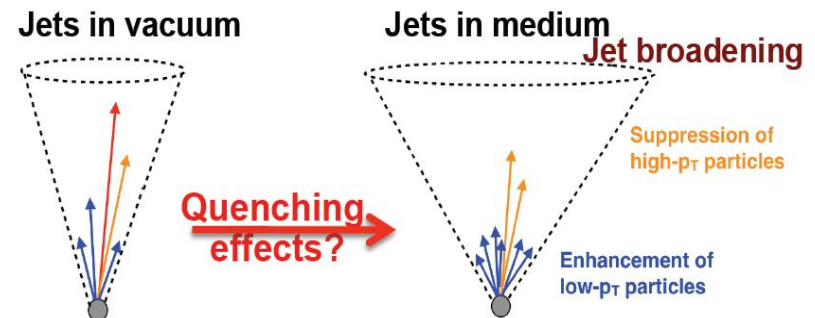

ATLAS-CONF-2017-009

- Comparison of b-jet R_{AA} with inclusive jet to investigate mass effect on medium-induced energy loss

PHYSICS MOTIVATIONS – HF JETS

Model by Vitev et al., radiative energy loss + collisional parton shower energy dissipation

- ✓ Mass effects relevant for $p_T<75$ GeV/c, dead-cone effect enters in play
- ✓ Measurements vs opening radius R to characterise energy dissipation and possibly separate collisional and radiative energy loss
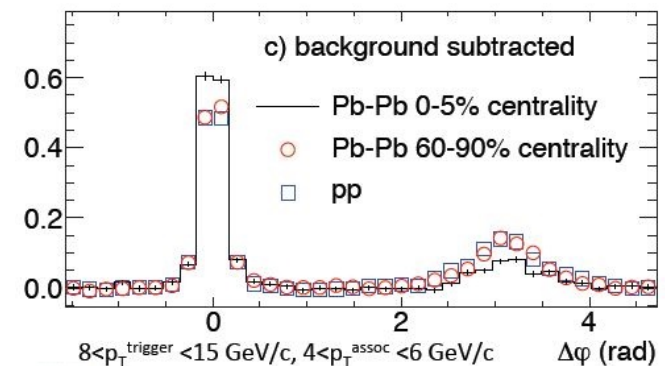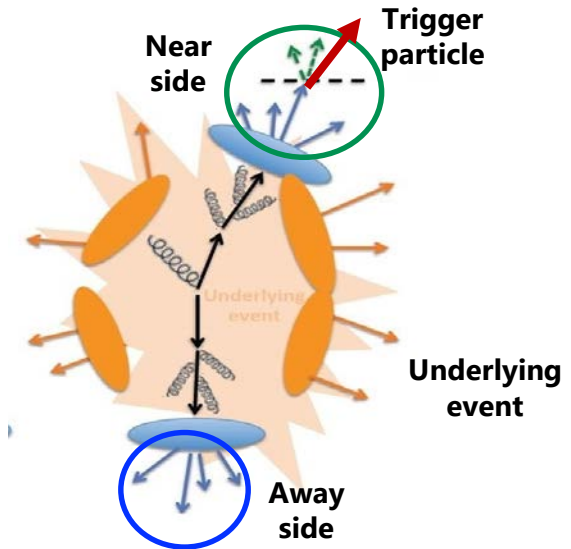- ✓ Energy loss in gluon splitting cases: b-pair seen by medium as massive gluon?

What about c-jets? Some studies by Cao et al. (**Phys. Rev. C 93 (2016) 024912**) but no quantitative predictions for charm jets

Vitev et al., PLB 726 (2013) 251
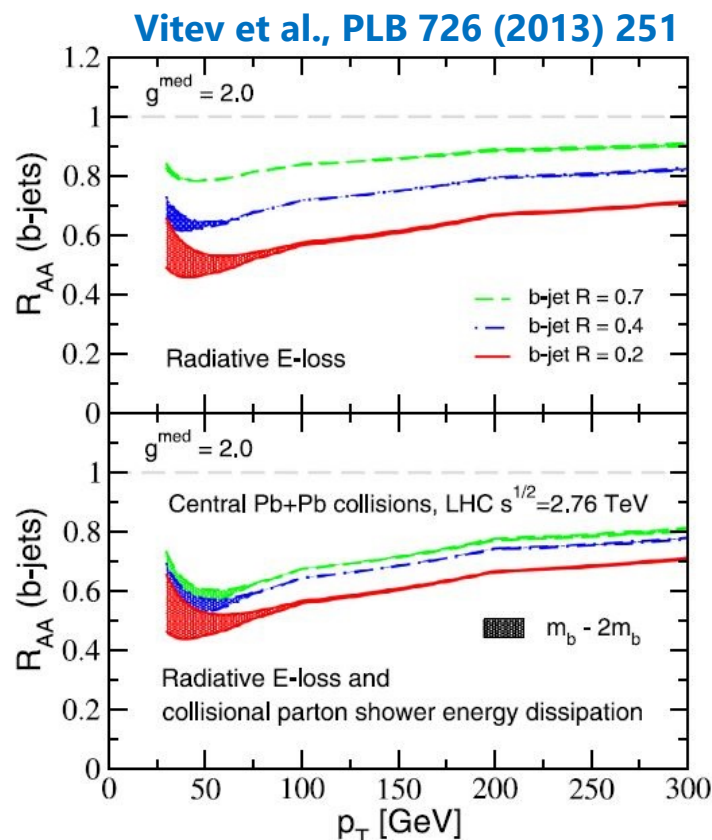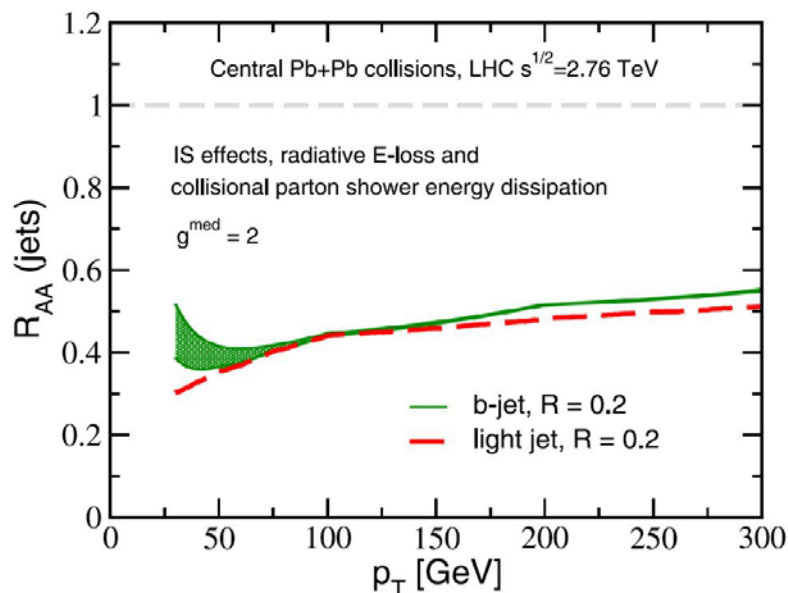
PHYSICS MOTIVATIONS – CORRELATIONS

Study of hard probes correlations in PbPb provide additional information w.r.t. single particle observables

- Probe QGP effects on hard partons via modifications of correlation pattern w.r.t. vacuum

  - ✓ Peak yields modifications (I_{AA}) to address jet quenching

  - ✓ Jet structure modification (particle multiplicity, opening angle, intra-jet p_T distribution)

- Investigate redistribution of parton energy loss (spatially and in momentum)

- Put constrain on models describing energy loss, in combination with single particle R_{AA}

- Study of collective effects – also in small systems! (not discussed here)

Near side — Trigger particle — Underlying event — Away side

c) background subtracted
— Pb-Pb 0-5% centrality
○ Pb-Pb 60-90% centrality
□ pp

$8 < p_T^{trigger} < 15$ GeV/c, $4 < p_T^{assoc} < 6$ GeV/c $\Delta\varphi$ (rad)
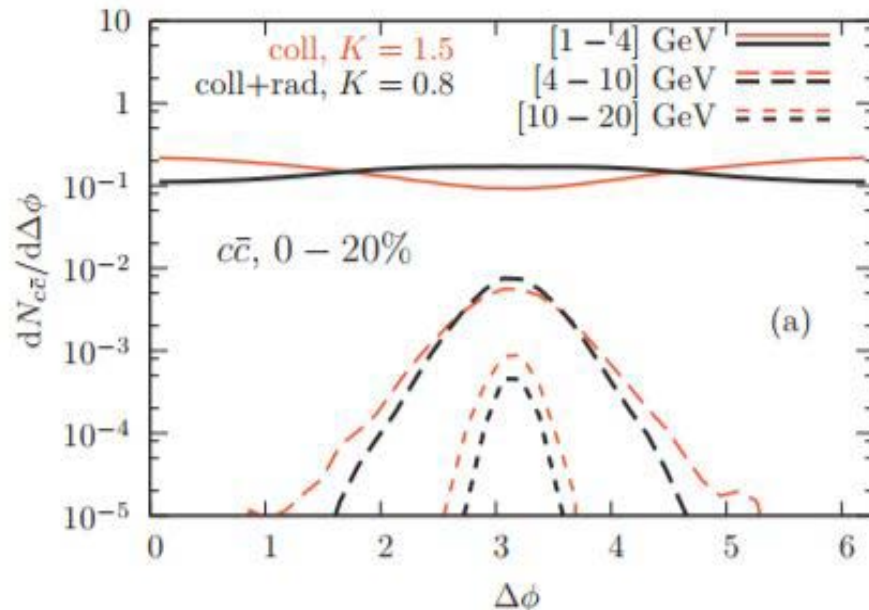
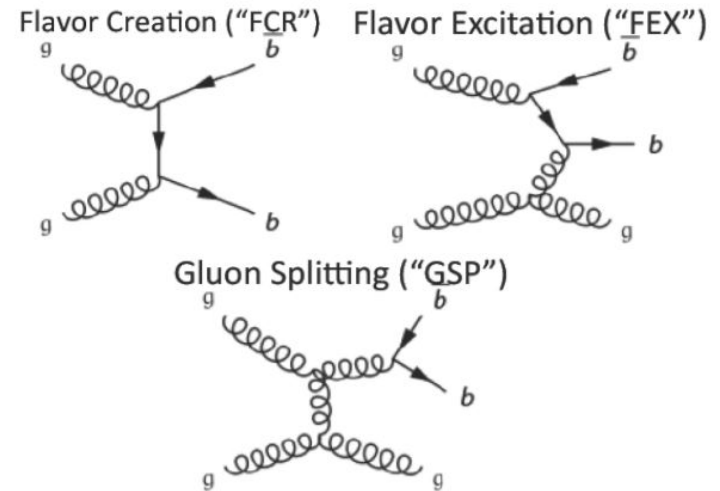**ALICE, PRL 108, 092301 (2012)**

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PHYSICS MOTIVATIONS – CORRELATIONS

In particular, for heavy-flavour correlations

- Disentangle radiative and collisional in-medium energy loss

Flavor Creation ("FCR")   Flavor Excitation ("FEX")

Gluon Splitting ("GSP")

M. Nahrgang et al., Phys. Rev. C 90 (2014) 024907

- Studies in small systems crucial not only as a reference for Pb-Pb:
  - ✓ HF quark production mechanisms
  - ✓ HF quark fragmentation into jets
  - ✓ Charm/beauty separation
  - ✓ Collective effects in high-multiplicity environment

CENTRALITY ESTIMATION IN p-Pb

- Looser correlation between N_{part} vs impact parameter, and multiplicity vs N_{part} in p-Pb collisions impairs centrality evaluation based on charged-particle multiplicity
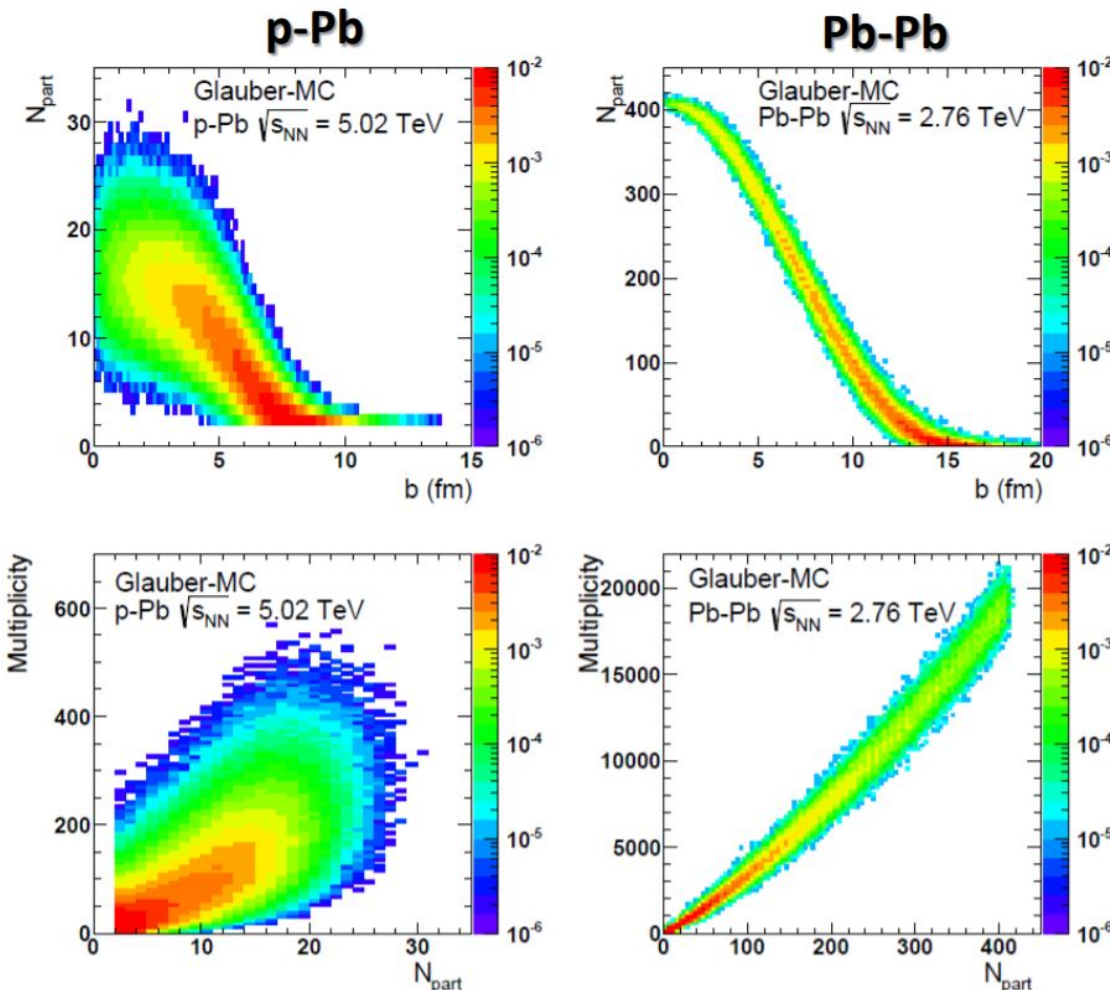
- Centrality selection based on the energy deposited by slow nucleons from the Pb nucleus remnant minimizes the biases on the centrality estimate

- Hybrid method used to derive T_{pPb} and N_{coll} for a given centrality class

ALICE, PRC 91 (2015) 064905

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