Heavy Flavour thermalisation

C.Cheshkov (IP2I Lyon)

HQ transport in QGP

- c,b produced in initial hard scatterings (no thermal production)
- Interaction with QGP constituents -> collective and energy-loss effects
- Due to large HQ mass -> “Brownian motion” inside QGP
  - incomplete thermalization
  - encoded in a single parameter - diffusion coefficient D_s
- Simultaneous measure of open-HF RAA and v_2 -> constrain D_s

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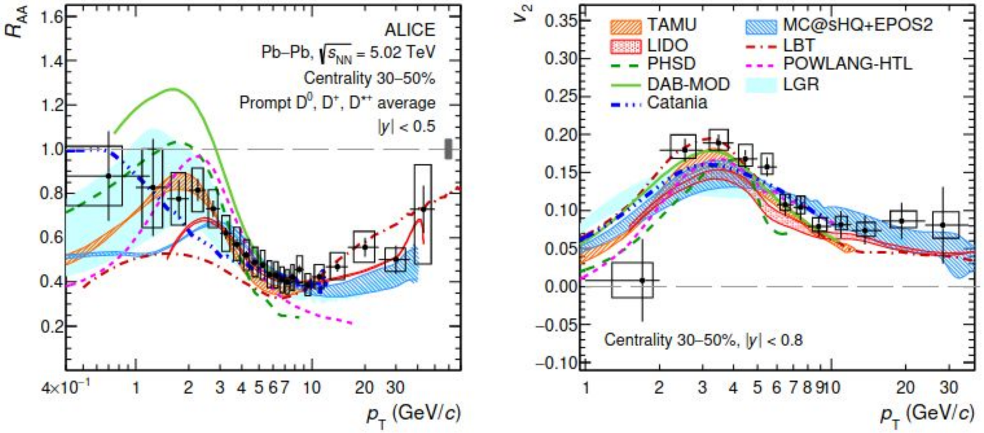

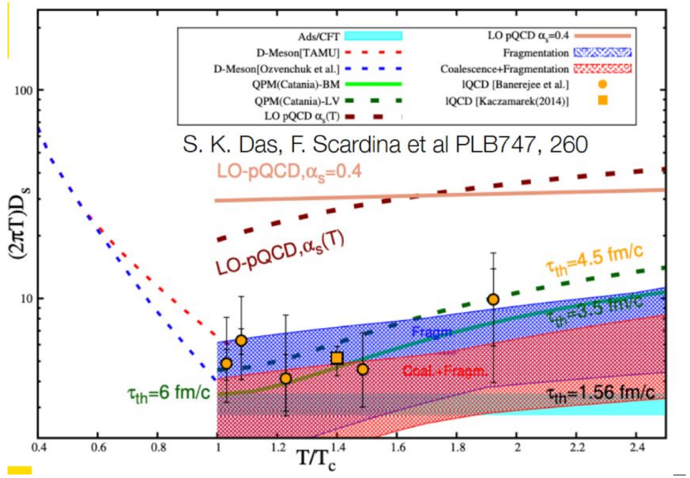

HQ transport in QGP

- Beauty relaxation time > QGP lifetime
  -> less thermalised -> more sensitive probe of HQ transport in QGP
- Better theory control in transport modelling
- Disentangle collisional and radiative energy-loss mechanisms (radiative energy loss suppressed due to dead-cone effect)
- Precise enough measurements of B-hadrons flow will probably not be in reach in Run 3&4

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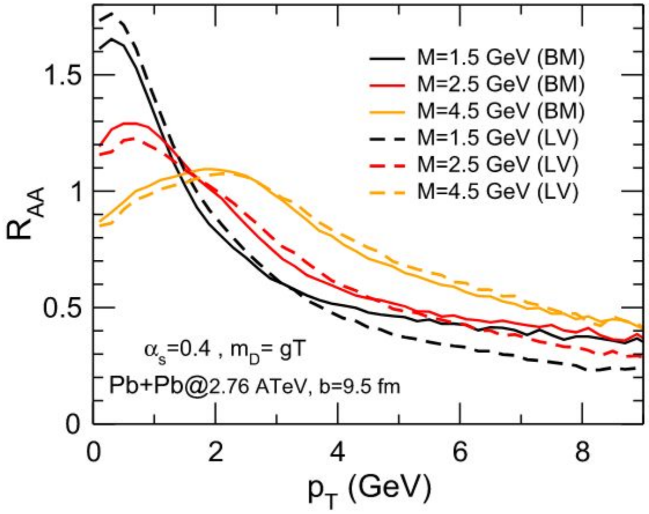
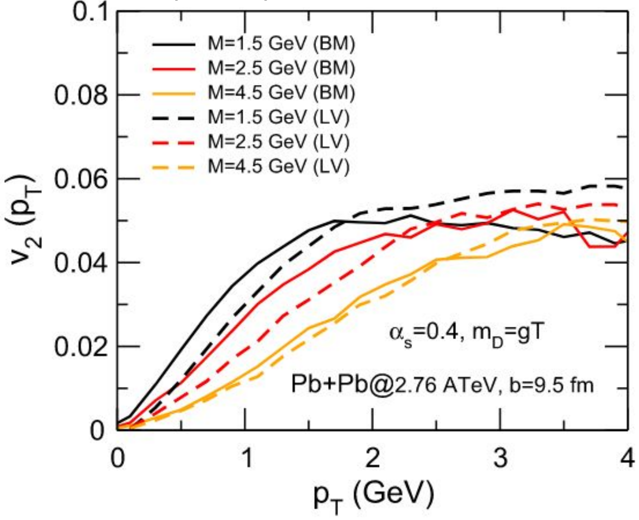
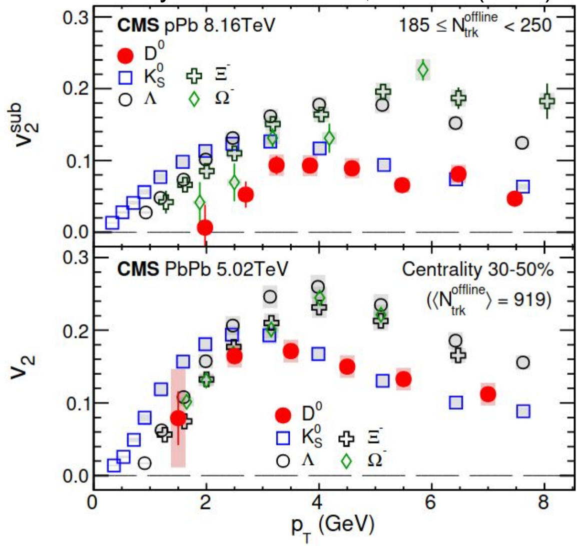




HQ transport in small collision systems

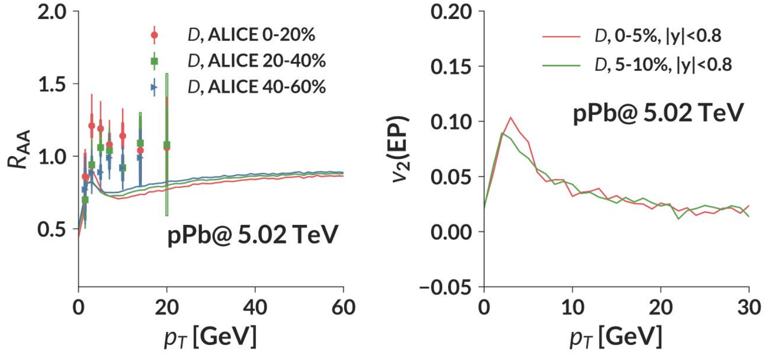
- Smaller and shorter-lived system -> charm farther away from equilibrium
- However:
  - Significant charm v_2 also in p-Pb (and pp), similar ratio wrt LF particles
  - No significant modification of spectra beyond possible mild shadowing effects at low p_T

Phys. Rev. Lett. 121, 082301 (2018)



D-meson R_{AA} & v_2 in p+Pb:

see talk



- Transport model tuned on Pb-Pb -> significant charm v_2 in p-Pb, but also sizeable modification of spectra

High-pT and (mini)jet v_2 and R_{pA} in p-Pb

- Sizeable positive v_2 of high-p_T hadrons and (mini)jets observed, while spectra shows no signs of medium-related modification
- Quenching models unavoidably introduce tight relation between $R_{A(p)A}$ and v_2/ε_2, and this in general the case in AA data
- Indication that this relation is ‘broken’ for hard probes in small collision systems

see link

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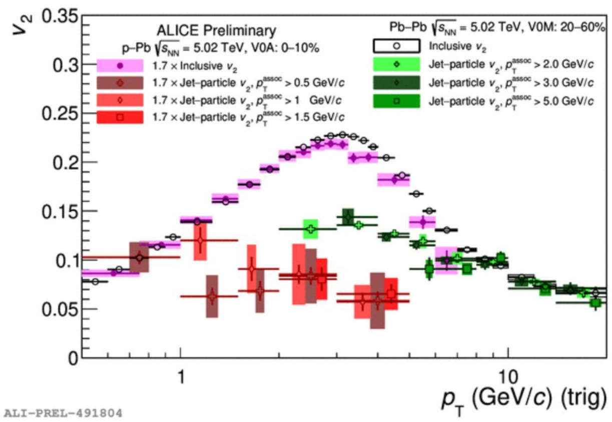
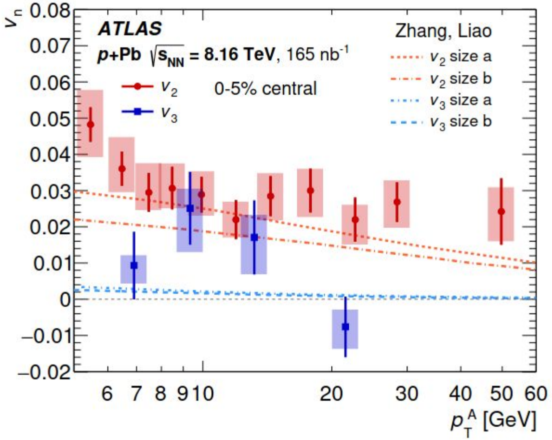
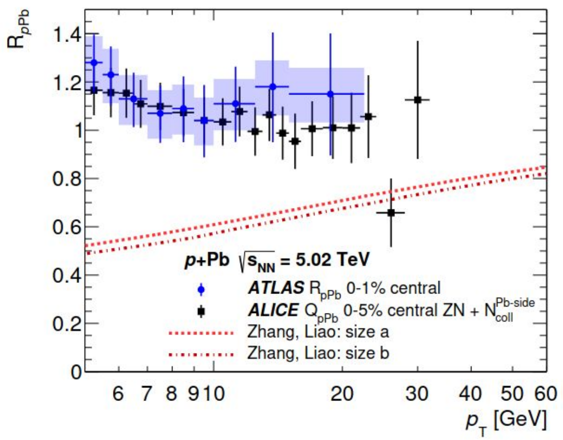
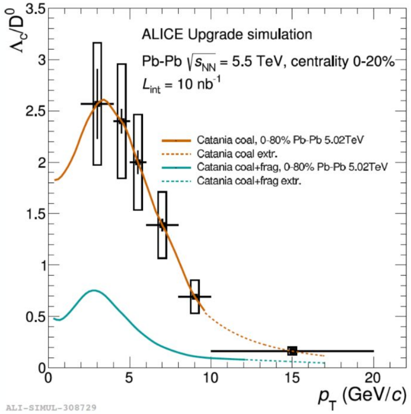


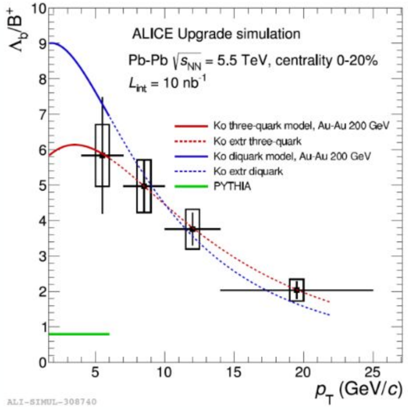


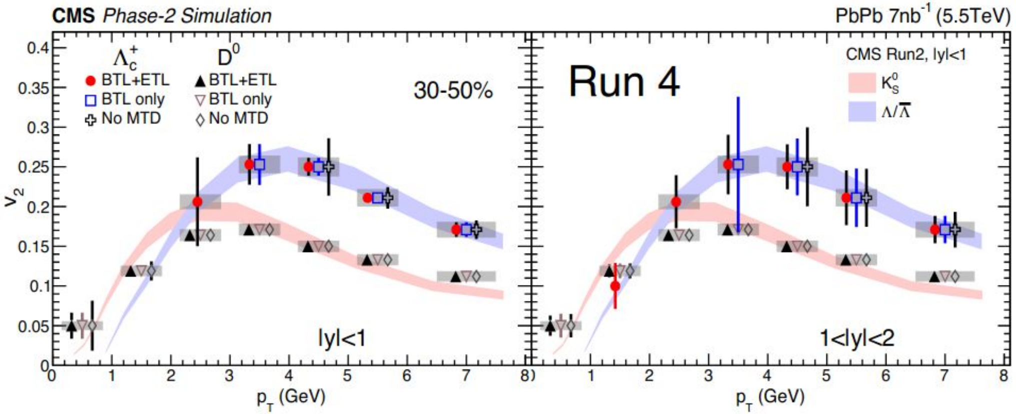


HF hadronisation

- In experiments, no direct access to HQ, but rather to final-state hadrons -> understand hadronisation (coalescence vs fragmentation) -> models
  - Λ_c/D^0, Λ_b/B^+, strange vs non-strange, …
  - At LHC, strong modification of fragmentation fractions wrt vacuum (e^+e^- collisions) and also function of multiplicity -> coalescence
- Another insight into hadronization from HF baryons v_2
  - Test NCQ (# of constituent quarks) scaling $v_2(\Lambda_c)/v_2(D^0) \approx 3/2$ as signature of coalescence as dominant mechanism

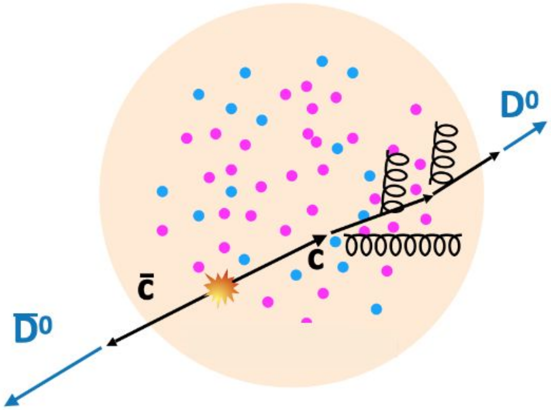


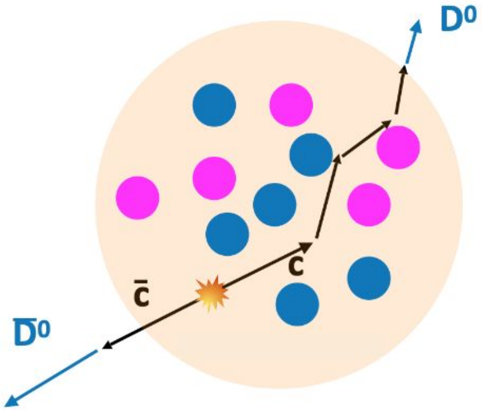


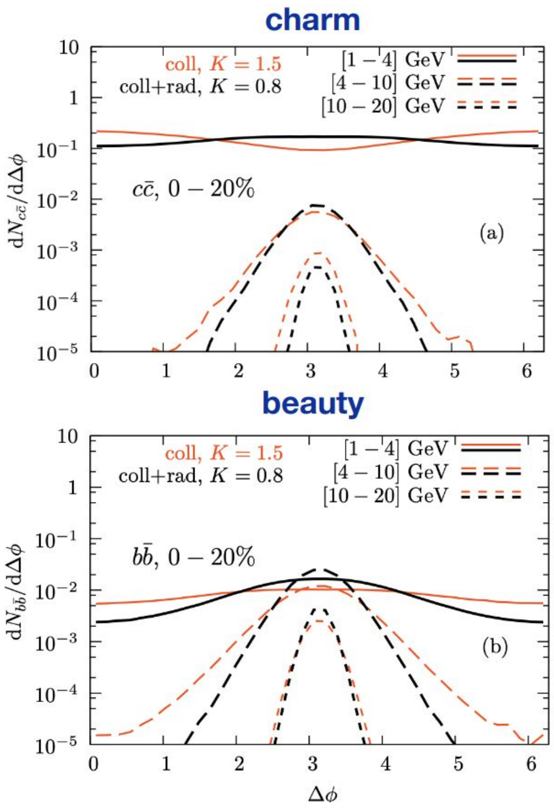


HQ correlations

- Azimuthal correlations of DD-bar, BB-bar as complementary observable
- Decorrelation at low p_T -> measure of momentum diffusion -> degree of thermalisation
- At intermediate and high p_T, sensitive to energy-loss mechanisms (collisional vs radiative)
- Most likely accessible experimentally only in Run 5+



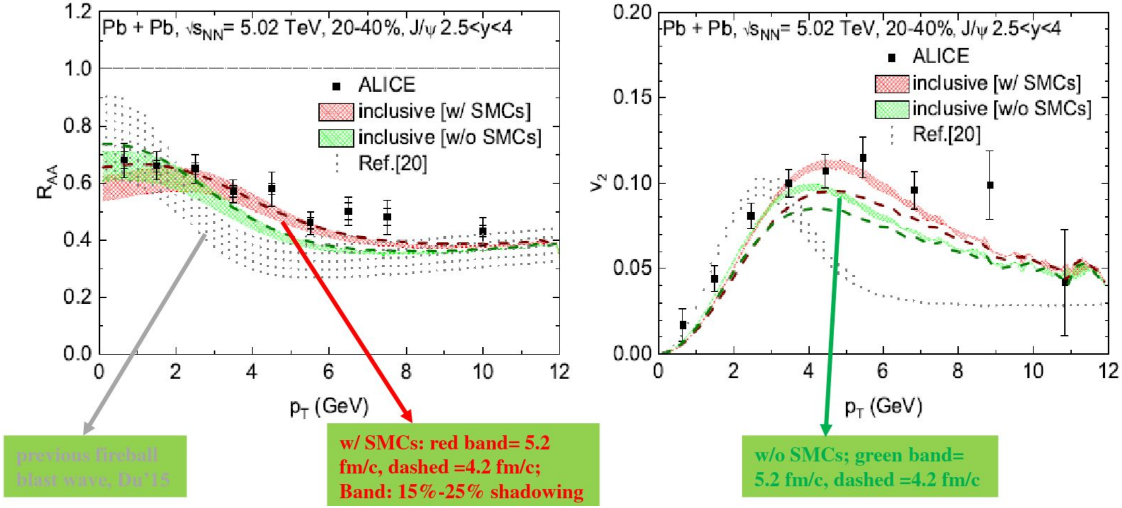




M Nahrgang et al, PRC 90, 024907

J/ψ in Pb-Pb

arXiv:2111.13528



- In the past, TAMU transport model underestimated v_2 (and R_{AA} to lesser extent) for p_T > 3 GeV/c
- Recent developments largely "cured" the problem:
  - "Calibrated" on open-HF data
  - Introduction of realistic space-dependent charm momentum distributions -> regeneration component extends up to higher p_T
  - Dissociation of primordial component reworked using e-by-e hydro and taking into account density/temperature anisotropy

- Υ data is important benchmark for the model
- So far Υ R_{AA} and Υ(1S) v_2 are measured
  - Υ(1S) v_2 ≈ 0, as expected given negligible regeneration component + dissociation at higher T at initial collision stages -> small anisotropy (dissociation distances << system size)

- J/ψ R_{AA} and v_n, Υ R_{AA} and Υ(1S) v_2 will be further measured with decent precision in Run 3&4
  - Υ(2S) v_2, which is expected to be more pronounced, would wait for Run 5+

Alternative simplified coalescence picture of J/ψ flow

- NCQ model:
  - $v_n^{J/\psi}(p_T^{J/\psi}) = 2v_n^c(p_T^{J/\psi}/2)$
  - $v_n^{\pi}(p_T^{\pi}) = 2v_n^q(p_T^{\pi}/2)$
- Then D-meson v_n can be obtained as:
  $v_n^D(p_T^D) = v_n^q(p_T^q) + v_n^c(p_T^c)$
- In coalescence picture, q and c have similar velocities
  -> $p_T^q/p_T^D \approx 0.2$
- Data disfavor this ratio, but works remarkably well (v_2 and v_3 in all centrality bins) with $p_T^q/p_T^D = 0.4$

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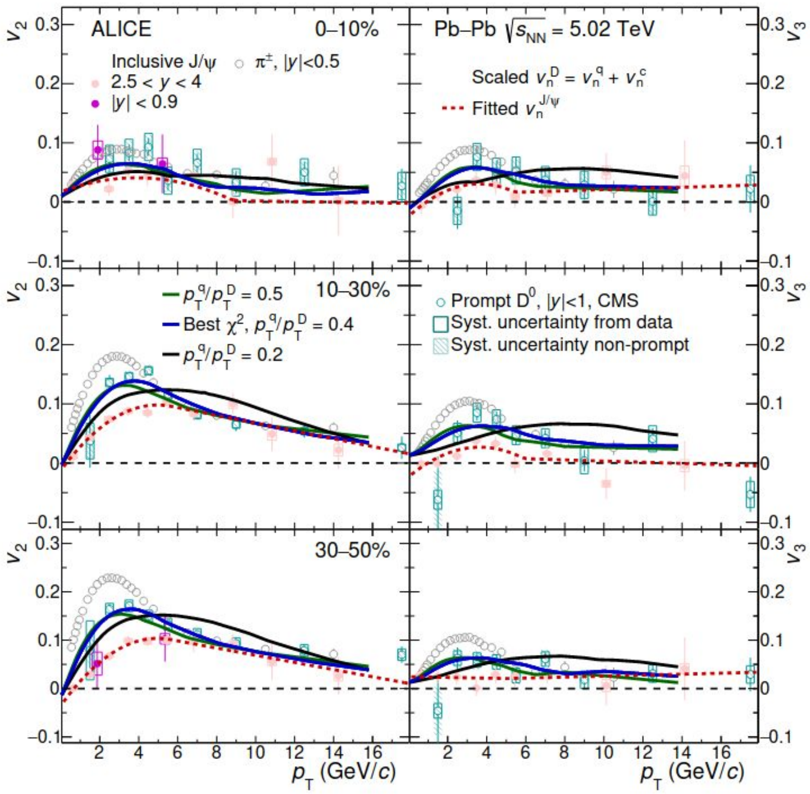
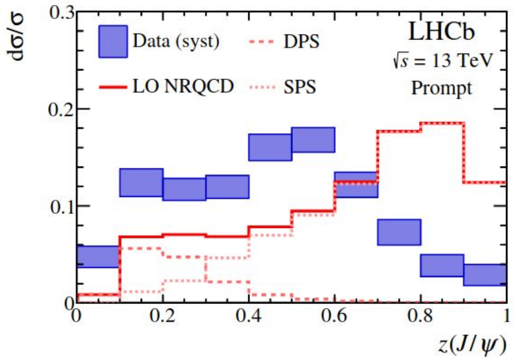


J/ψ-jet fragmentation in pp and Pb-Pb

- Much higher in-jet associated production wrt to initially expected from models
  - More recent NRQCD-based calcs agree well with data (PRL 119, 032002 (2017))

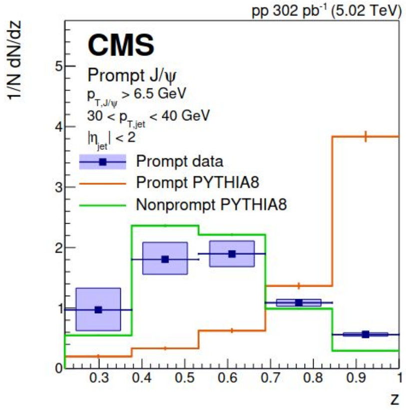
- Evidence for increasing trend of R_{AA} vs z, compatible with jet quenching scenario
  - Low z -> J/ψ created later in parton shower -> stronger quenching via multiple subsequent emissions
  - Connection to J/ψ R_{AA} and v_2 at high (and intermediate?) p_T, where J/ψ R_{AA} and v_2 follow the general trend of other particle species
  - Important to measure fragmentation down to lower p_T?
    - In experiment, this is not only a question of stat, but also how to deal with background in AA

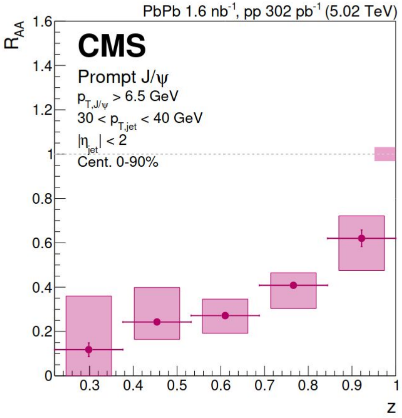
Phys. Rev. Lett. 118, 192001 (2017)



jet pT>20 GeV/c
2.5 < |eta| < 4

Phys. Lett. B 825 (2021) 136842





J/ψ v_2 in p-Pb

- Surprisingly, J/ψ also shows significant v_2 in p-Pb
- So far no clear explanation, expected negligible regeneration and dissociation in p-Pb
- CGC-based calcs agree fairly well with data, but:
  - In experiment, J/ψ v_2 measured using correlations with bulk particles, while in model v_2 arises from initial-state momentum correlations, which in general are uncorrelated with the initial-state spatial anisotropy which drives bulk flow (see backup)
  - Model predicts practically the same v_2 for Υ, which would be surprising given Pb-Pb results and should be measured (in Run5+)

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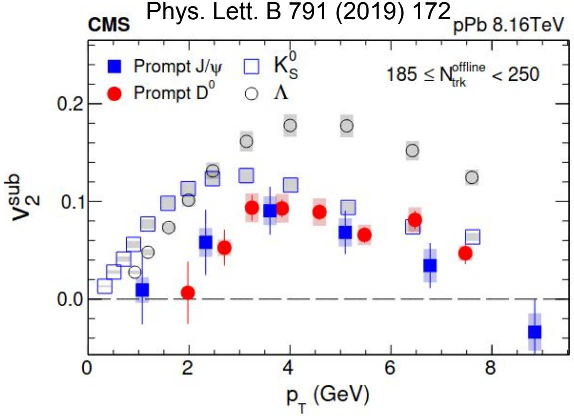
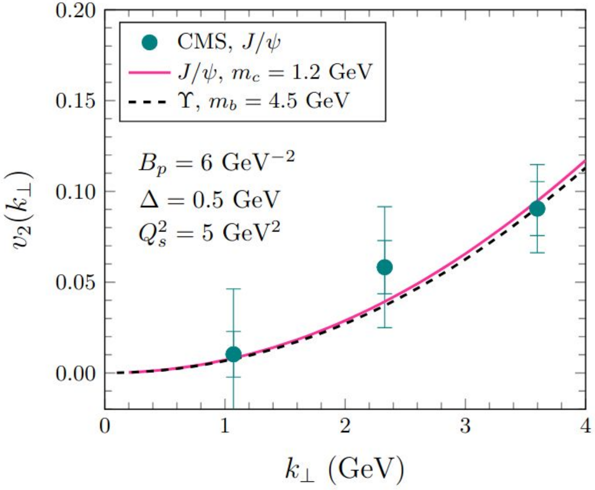
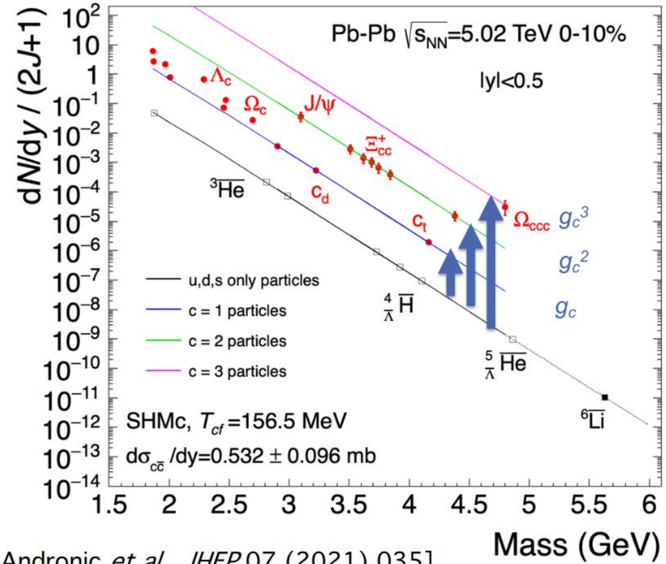




PRL 122 (2019) 17, 172302

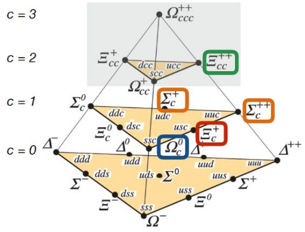
Multi-charm baryons

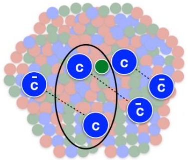
- Negligible production from single hard scattering
- Statistical Hadronisation Model (SHM) predicts drastic increase of production pp -> AA via recombination of uncorrelated and thermalized charm quarks
  - Charm fugacity g_c -> enhancement wrt LF in order to ‘match’ the increased charm production cross-section at LHC energies
- Interplay between degree of thermalisation and hadronisation can be studied further via measurements of various states

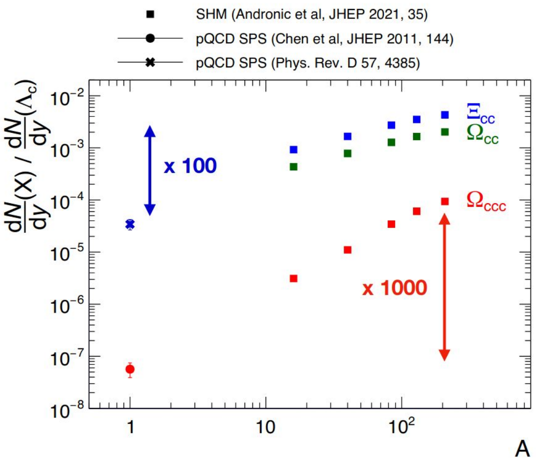


[A. Andronic *et al.*, *JHEP* 07 (2021) 035]

- Ultimate experimentally-accessible manifestation of deconfinement?
- Precise multi-charm baryon measurements possible in Run 5+

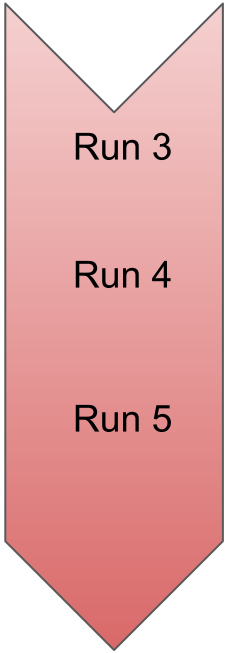




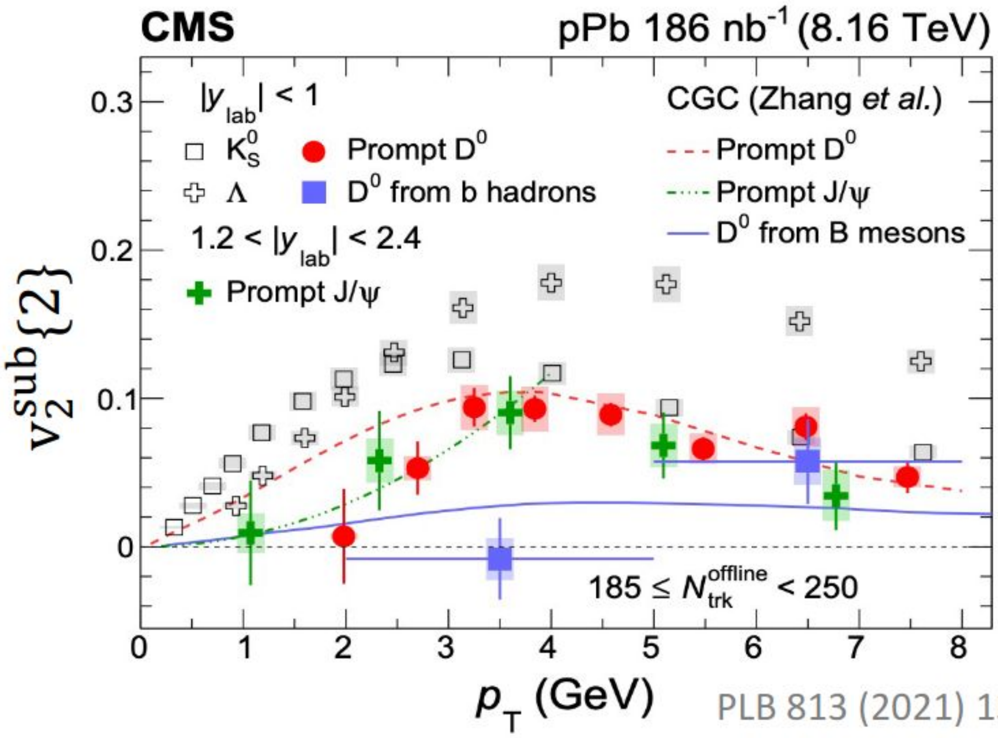


Sort of a summary

- Charm thermalisation and hadronisation via production and flow measurements
- J/ψ regeneration, Υ dissociation
- Beauty thermalisation and hadronisation via production and flow measurements
- Thermalisation and energy loss via DD-bar, BB-bar, γ-HF jet correlations
- Production of multi-charm baryons

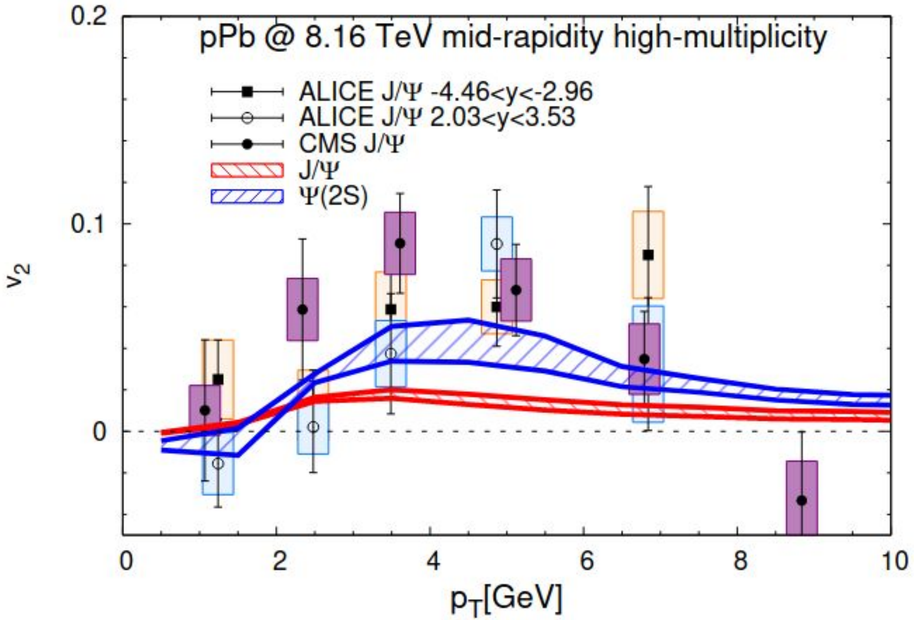


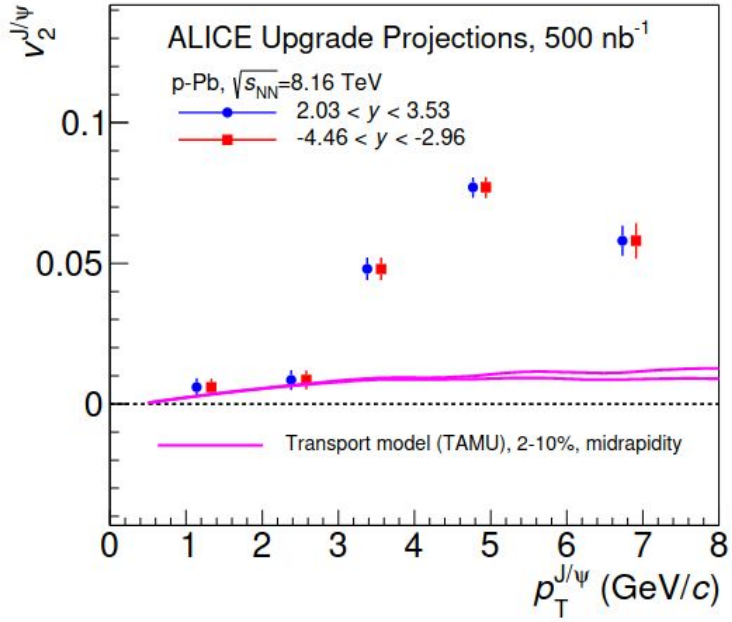
Backup



PLB 813 (2021) 136036

Progress in Particle and Nuclear Physics 122 (2022) 103906





Phys. Rev. Lett. 125, 192301 (2020)

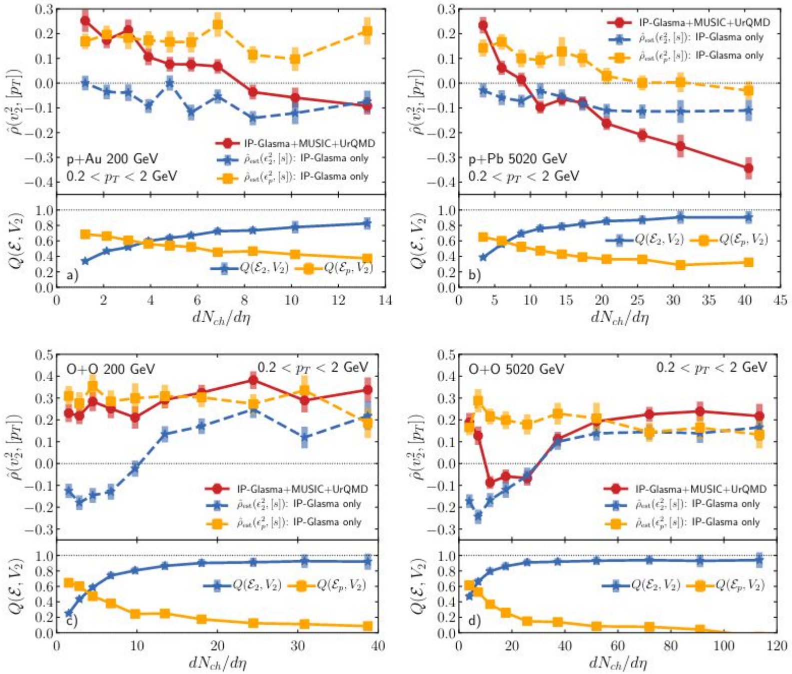


FIG. 2. The correlator $\hat{\rho}(v_2^2,[p_t])$ (circles) together with estimators based on the initial geometry ($\hat{\rho}_{est}(\varepsilon_2^2,[s])$, stars) and the initial momentum anisotropy ($\hat{\rho}_{est}(\varepsilon_p^2,[s])$, squares) in a) $\sqrt{s}$ = 200 GeV p+Au, b) $\sqrt{s}$ = 5.02 TeV p+Pb, c) $\sqrt{s}$ = 200 GeV, and d) $\sqrt{s}$ = 5.02 TeV O+O collisions. Lower panels show the Pearson coefficients between v_2 and the initial ellipticity (stars) and the initial momentum anisotropy (squares), respectively.

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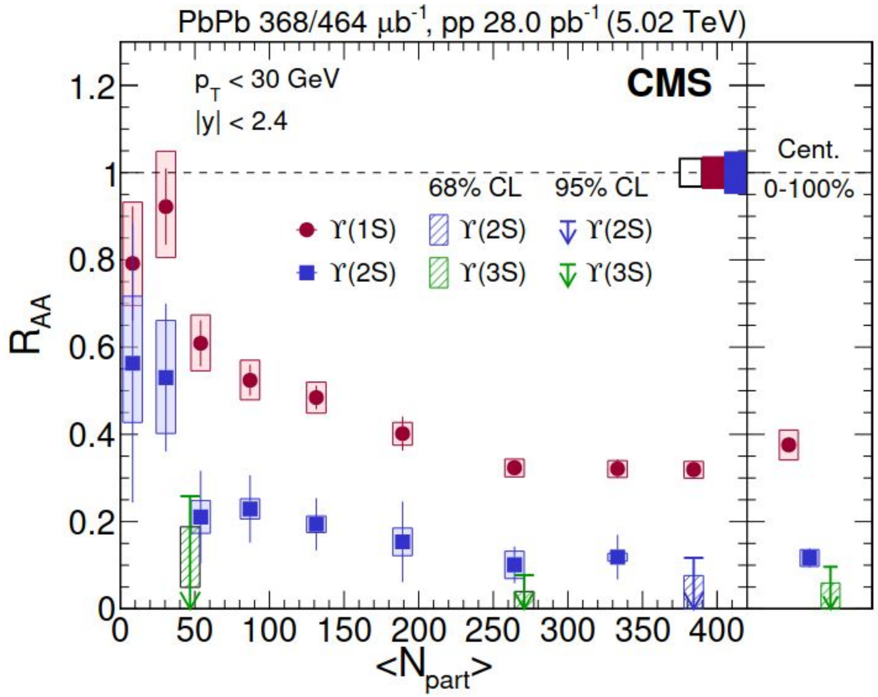

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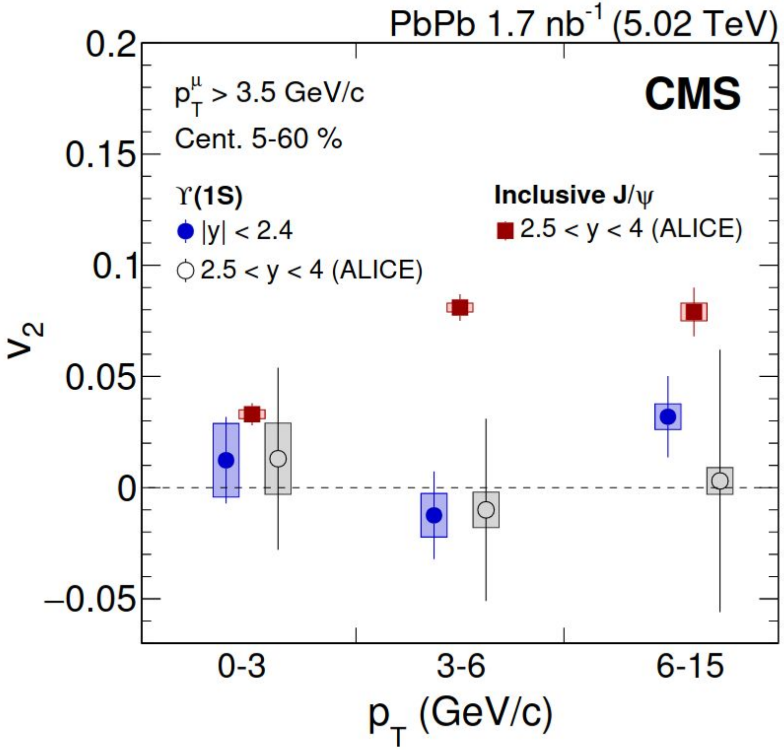
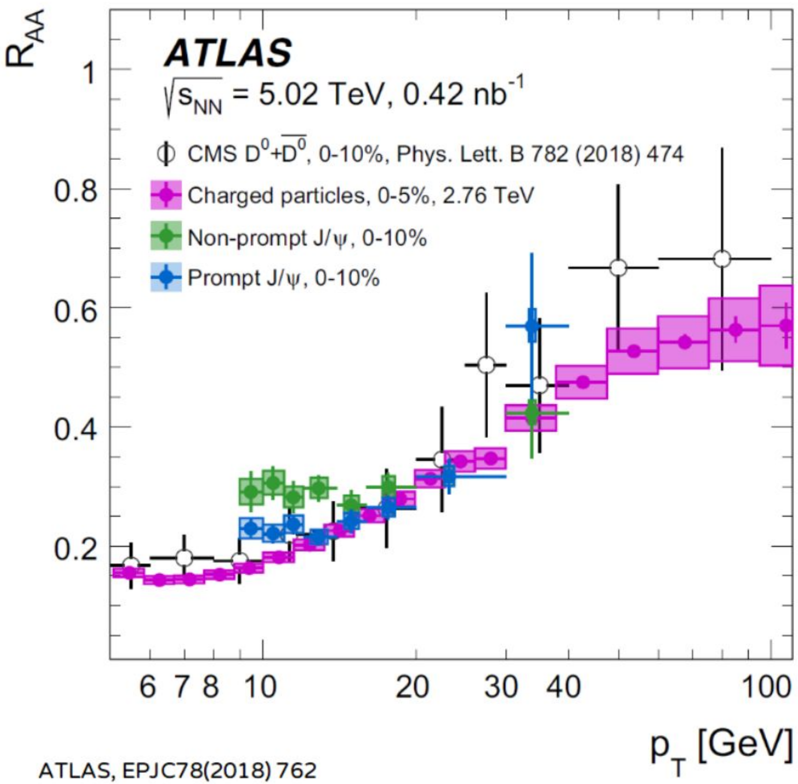
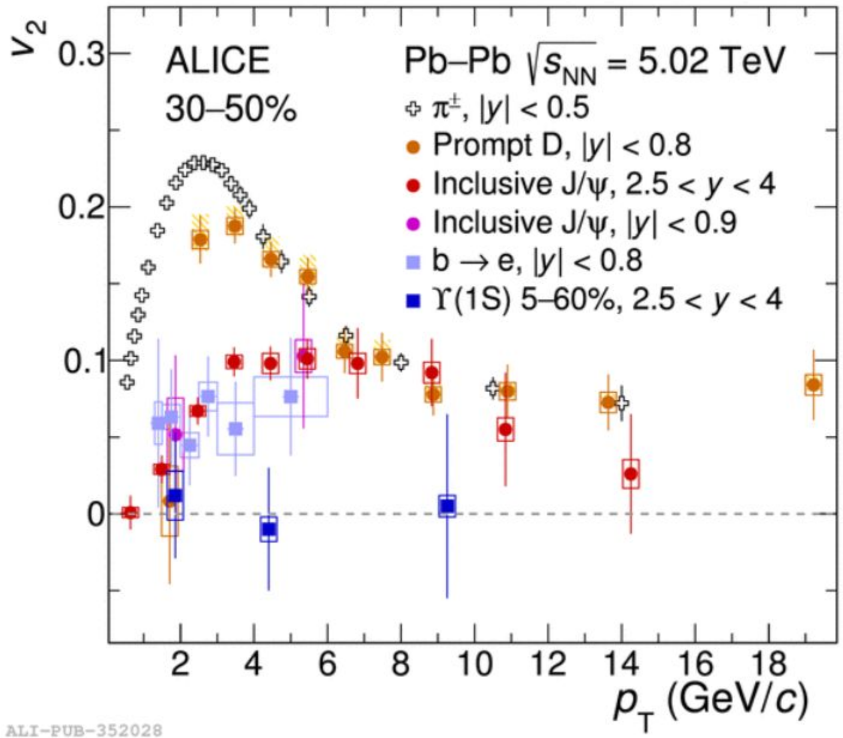
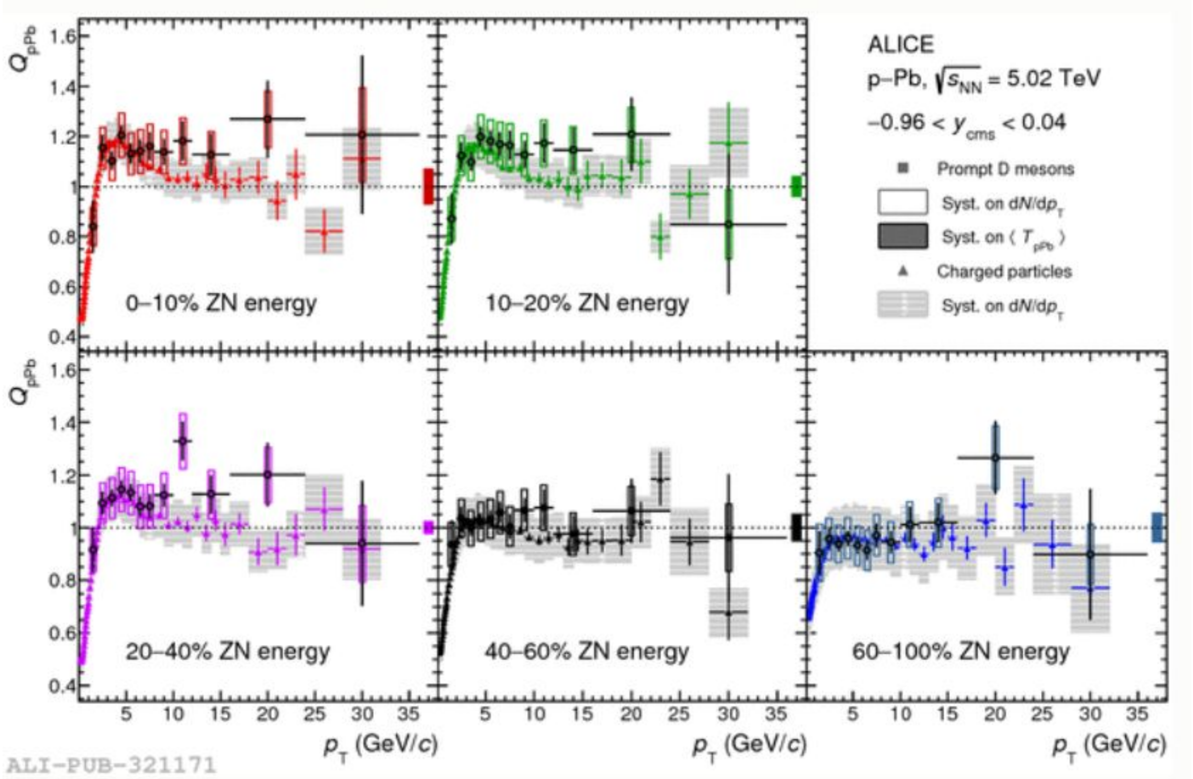




ATLAS, EPJC78(2018) 762





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)
ALI-PUB-321171

JHEP 1710 (2017) 090