Open heavy-flavour measurements in Pb–Pb collisions with ALICE at the LHC

Chiara Bianchin for the ALICE Collaboration

May 19, 2015

Outline

Heavy quarks as probes of the QGP
How we measure open heavy flavours in ALICE
Results
Future perspectives and conclusions

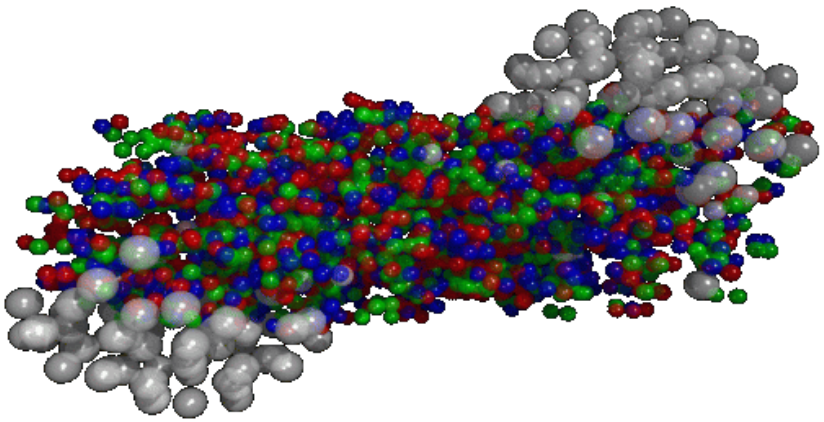
Related talks at this conference:

- Plenary Andrea Dainese (experiment)
- Plenary Marlene Nahrgang (theory)
- Parallel Sarah LaPointe, ALICE talk

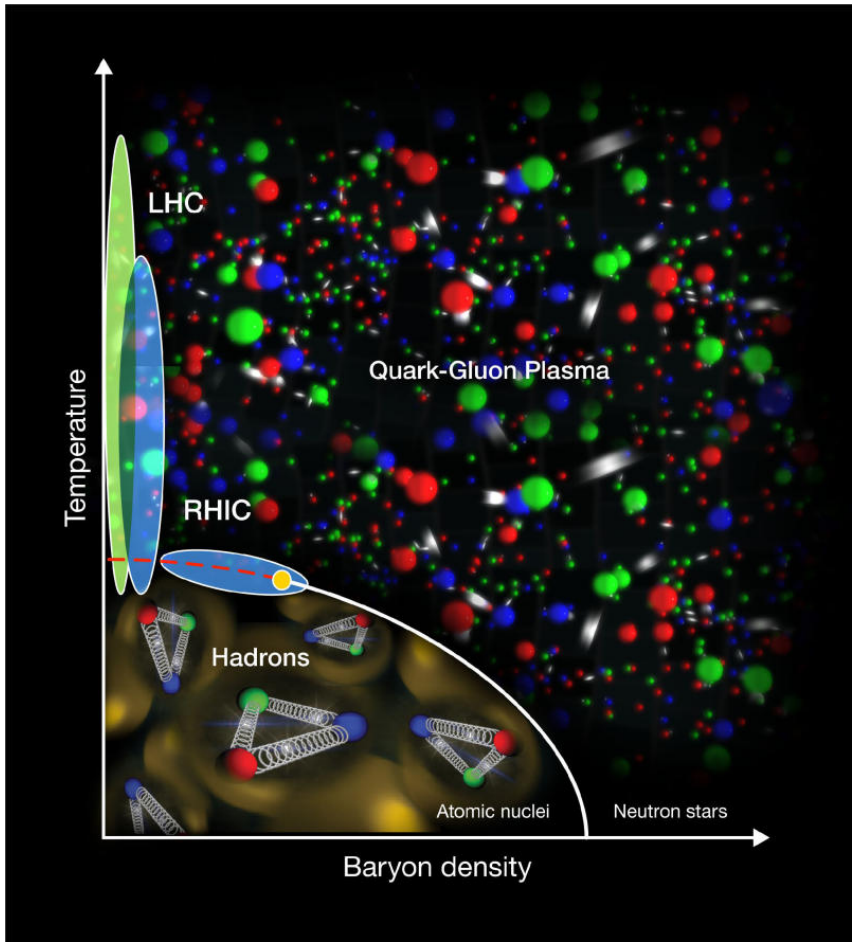
Section 1

Heavy quarks as probes of the QGP

Quark-Gluon Plasma (QGP) and heavy-ion collisions

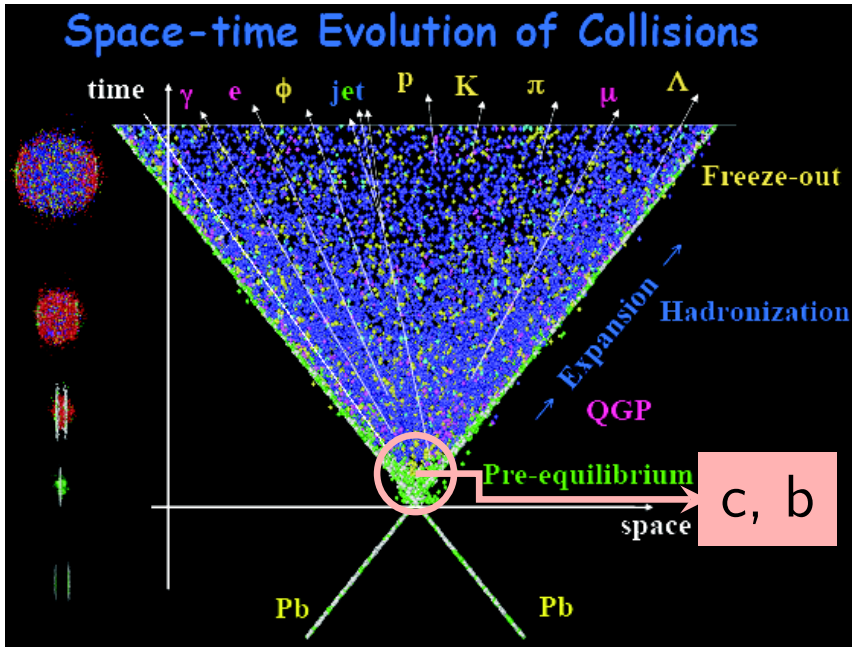


- Reproduce the state of matter of the early Universe colliding heavy ions at high energy
- Study the properties of the QGP and the phase transition between quark-gluon plasma and hadron gas



- At the LHC Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}$ (Run 1) (5 TeV Run 2)

Heavy flavours (HF) as probes of the QGP

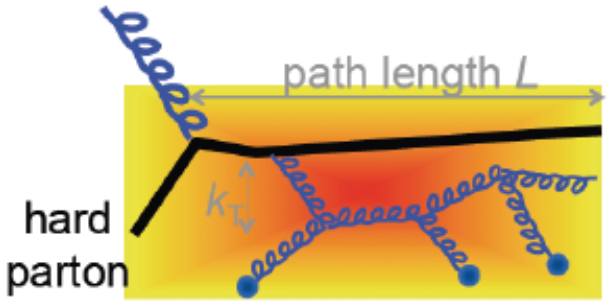


- Early formation time: $t_Q \sim \frac{1}{2m_Q}$
  - $t_c \simeq 0.1\ \mathrm{fm}/c$, $t_b \simeq 0.02\ \mathrm{fm}/c$
  - Much smaller than the QGP life time $t_{QGP} \sim 10\ \mathrm{fm}$!
- HF interact with the medium
- Measure open heavy-flavour production

Heavy flavours in the medium

HF travel through the medium

- Collisional + radiative energy loss
- Colour charge and mass dependence of energy loss:
  $\Delta E(\mathrm{g}) > \Delta E(\mathrm{q}) > \Delta E(\mathrm{c}) > \Delta E(\mathrm{b})$



Y.L. Dokshitzer, D.E. Kharzeev, Phys. Lett. B 519, 199 (2001).

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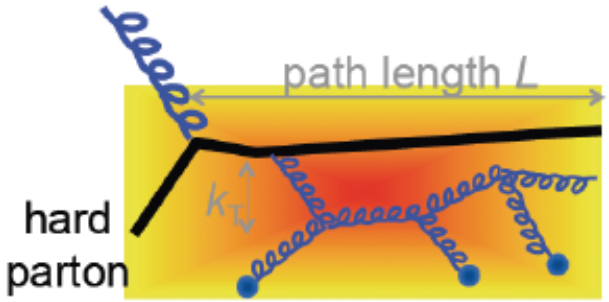
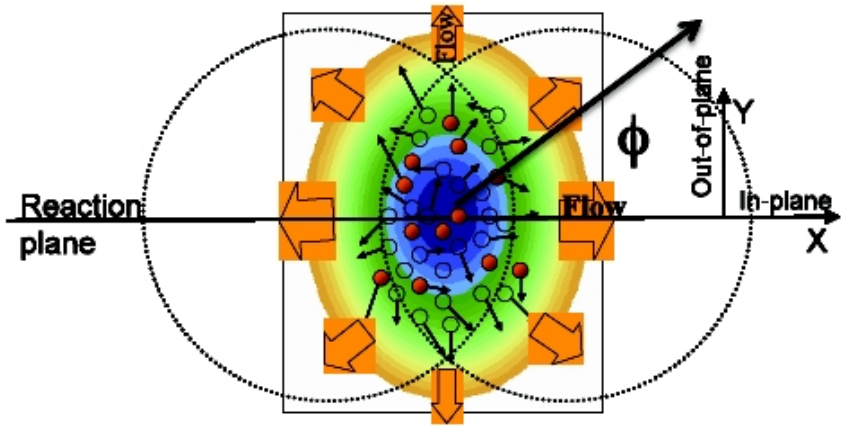


Y.L. Dokshitzer, D.E. Kharzeev, Phys. Lett. B 519, 199 (2001).

Collectivity in the QGP

- Initial spatial anisotropy converts into final momentum anisotropy via interaction among the partons
- Do heavy flavours take part in the collectivity?



HF in small systems (pp and p-Pb collisions)

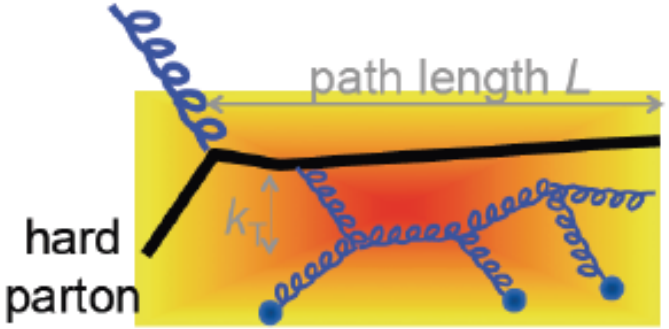
- pp: test pQCD-based predictions for production cross sections
- p-Pb: cold nuclear matter effects
  - Shadowing at LHC energies
  - Possible saturation regime
  - Partonic energy loss from initial and final state radiation
  - Investigate potential final state effects
- Control experiments for Pb–Pb measurements

Sarah LaPointe's talk

Nuclear modification factor

$$R_{\mathrm{AA}} \equiv \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}},$$

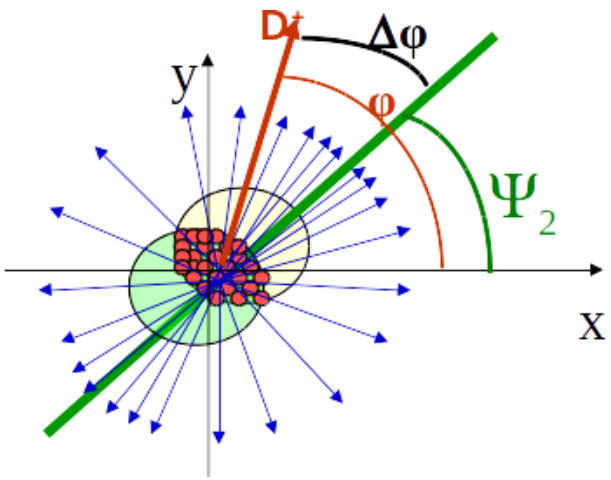
$$\langle T_{\mathrm{AA}} \rangle = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$



- R_{AA} quantifies the modification of the momentum distributions
  - Does also the relation $\underbrace{R_{\mathrm{AA}}(\mathrm{B})}_{\text{beauty}} > \underbrace{R_{\mathrm{AA}}(\mathrm{D})}_{\text{charm}} > \underbrace{R_{\mathrm{AA}}(\text{light hadrons})}_{\text{u, d, s}}$ hold?
    - Different shape of parton p_{T}-distributions
    - Different fragmentation functions
    - ...

Azimuthal anisotropy

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{\mathrm{N}_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos 2(\varphi - \Psi_{RP}) + \ldots\right)$$

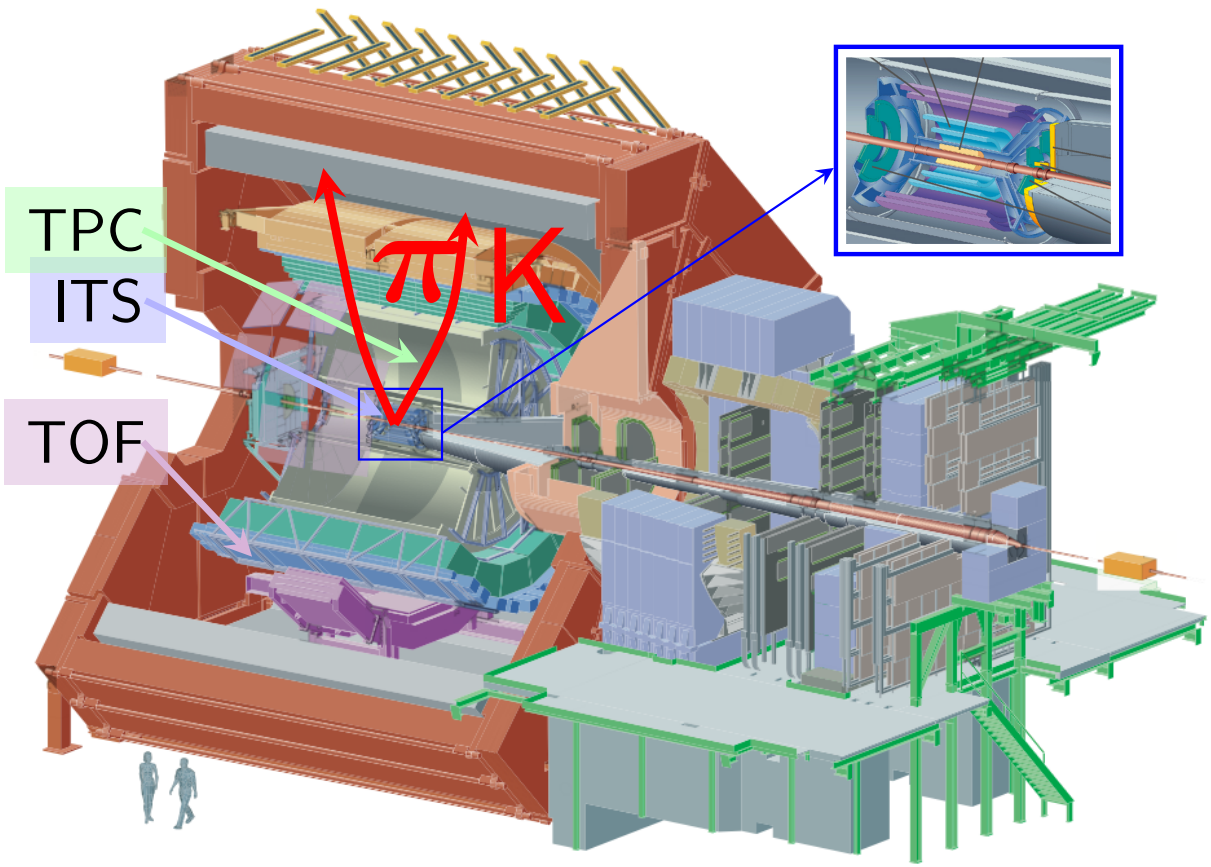


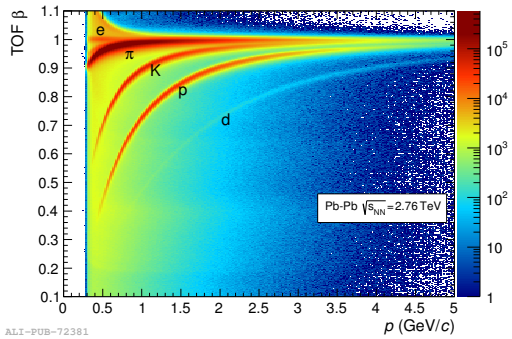
- The second Fourier coefficient, v_2 or elliptic flow, quantifies the anisotropy
- At low p_{T}: collective behaviour of the medium
- At high p_{T}: path-length dependence of energy loss

Section 2

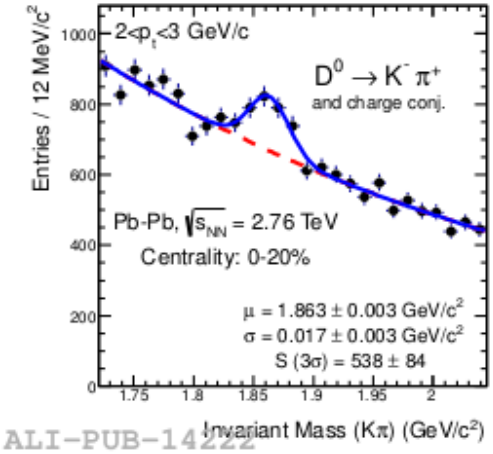
How we measure open heavy flavours in ALICE

A Large Ion Collider Experiment





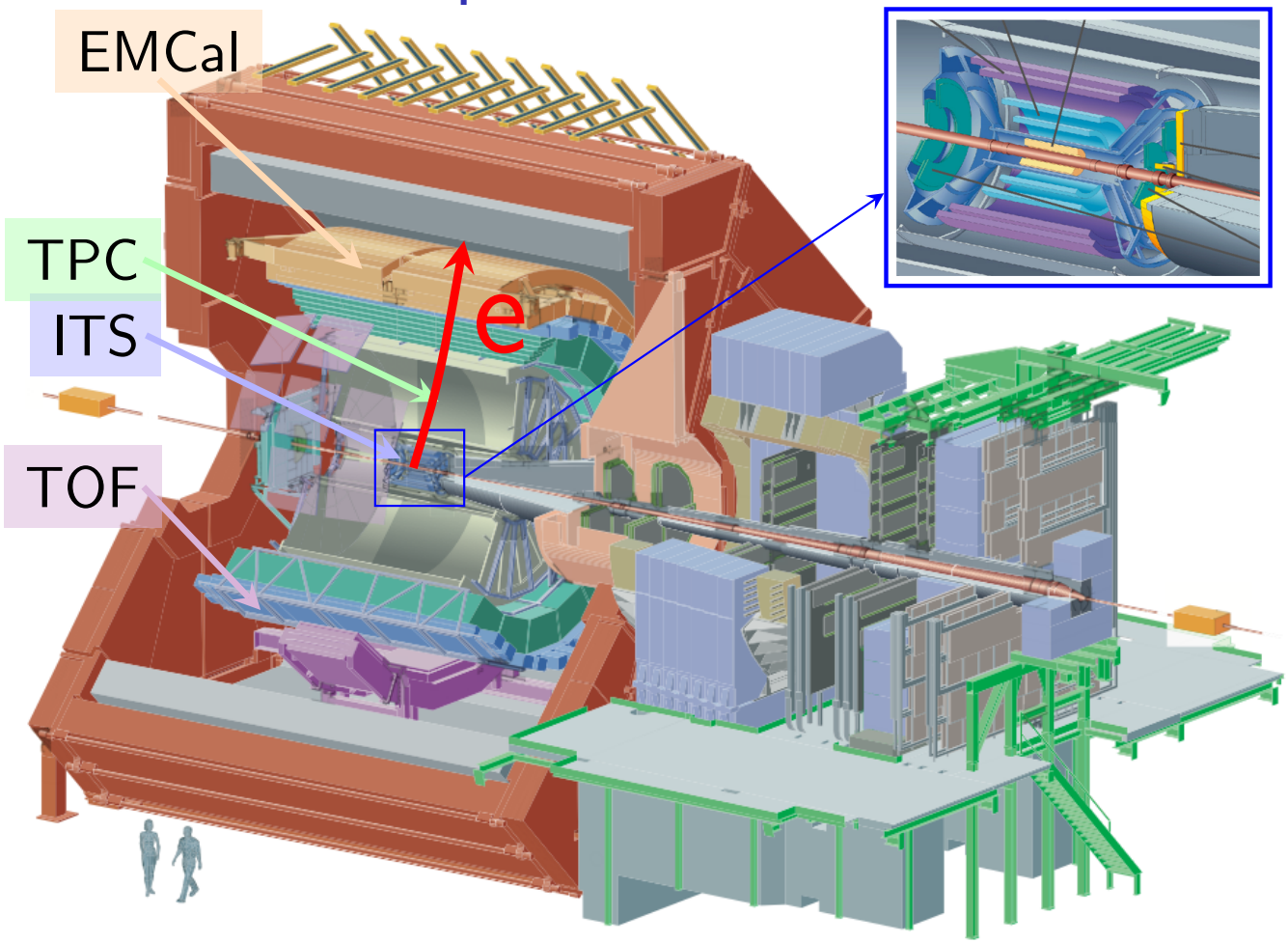
PID + Topological selection



- $D^0 \to K^-\pi^+$
- $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$

and charge conjugates

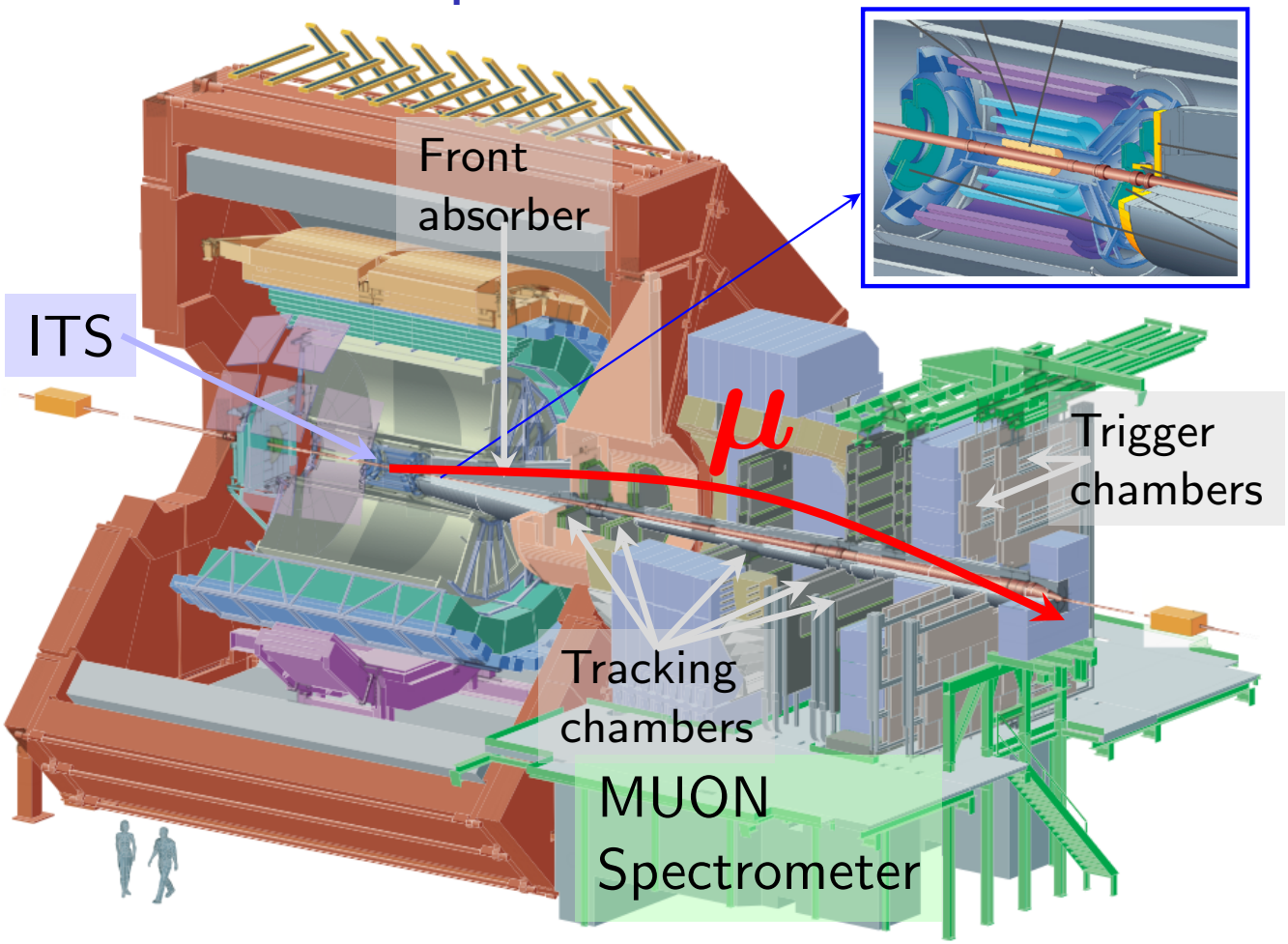
A Large Ion Collider Experiment



e ID:

- Use ITS+TOF+TPC in the low p_{T} region $p_{\mathrm{T}} \lesssim 3\ \mathrm{GeV}/c$
- Use TPC+EMCal in high p_{T} region $p_{\mathrm{T}} \gtrsim 2\ \mathrm{GeV}/c$ (up to $\sim 13\ \mathrm{GeV}/c$)

A Large Ion Collider Experiment



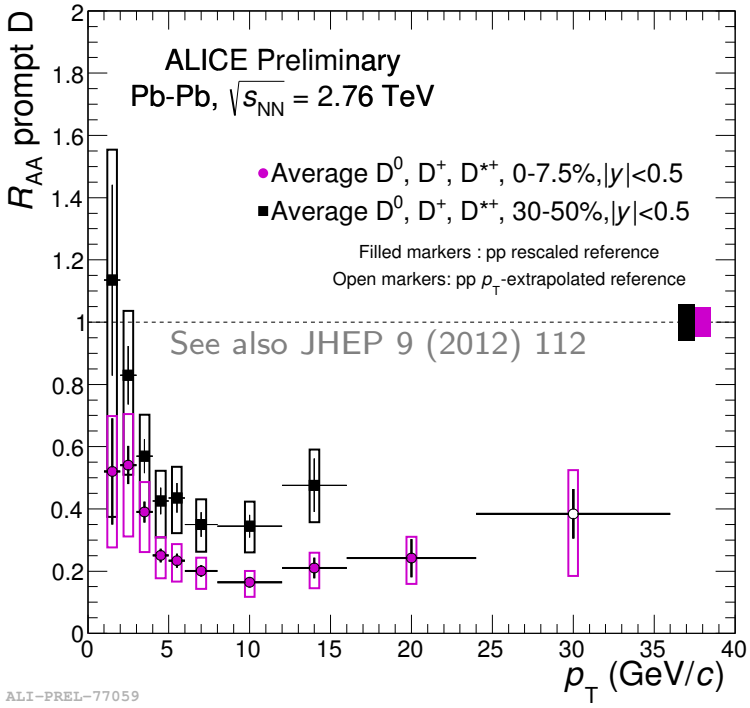
μ ID:

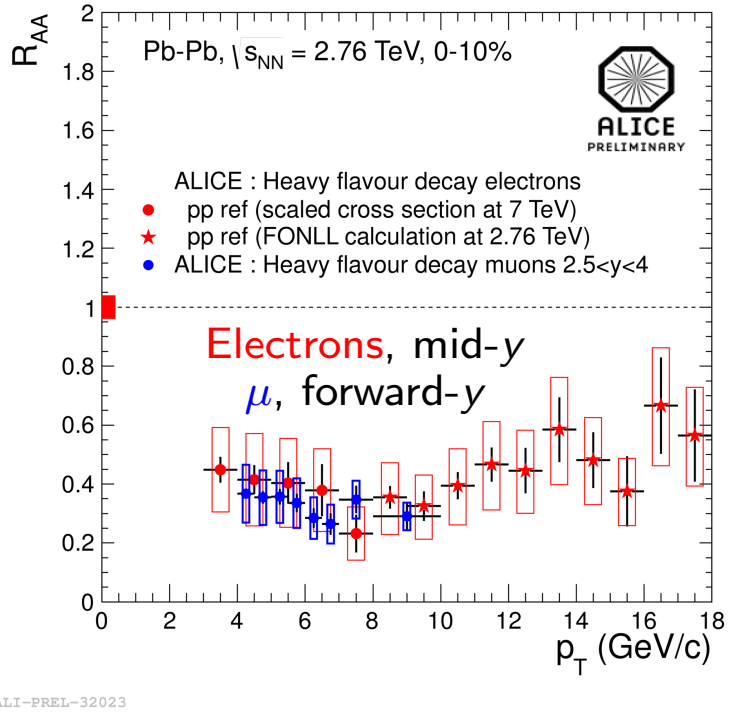
- At forward rapidity
- Hadron contamination reduced by the absorber, tracking chambers, and trigger chambers downstream an iron wall

Modification of HF-particle p_T distribution

Strong modification of open HF hadron p_T spectra in Pb–Pb collisions

Prompt D mesons (mid-y)

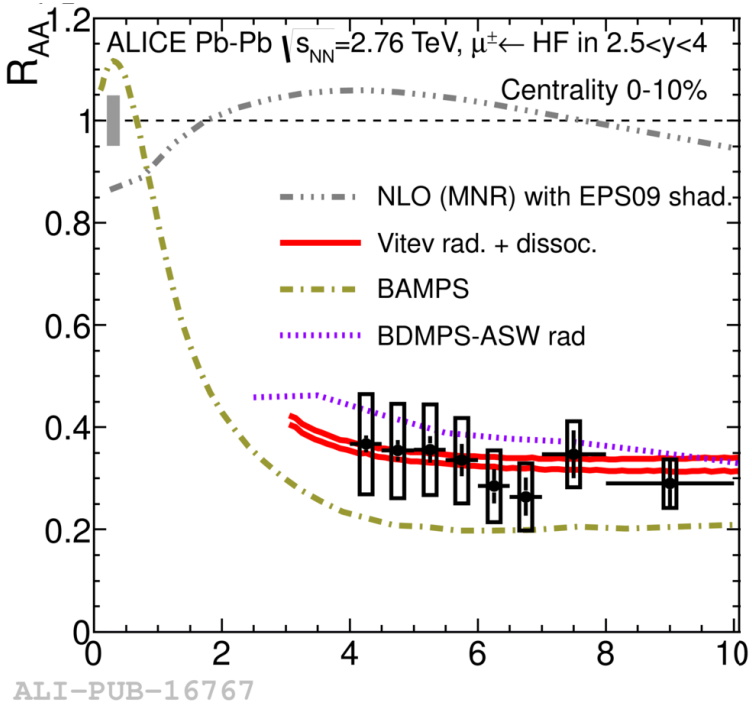




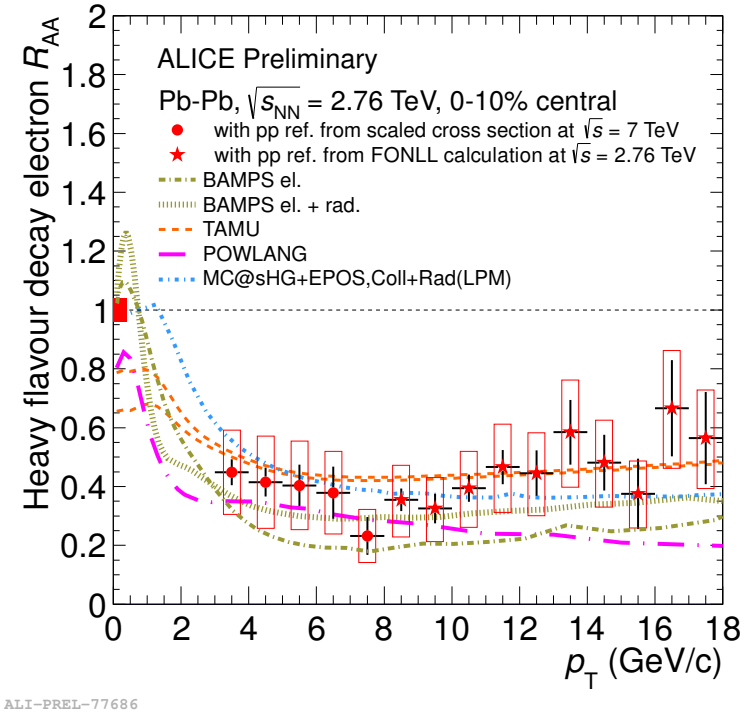
- D mesons more suppressed in central collisions
- Where does the energy lost end up?
  - Low-p_T measurement crucial to recover it

- Beauty contributes at high p_T
- mid $y \approx$ forward y

Comparison with models implementing energy loss



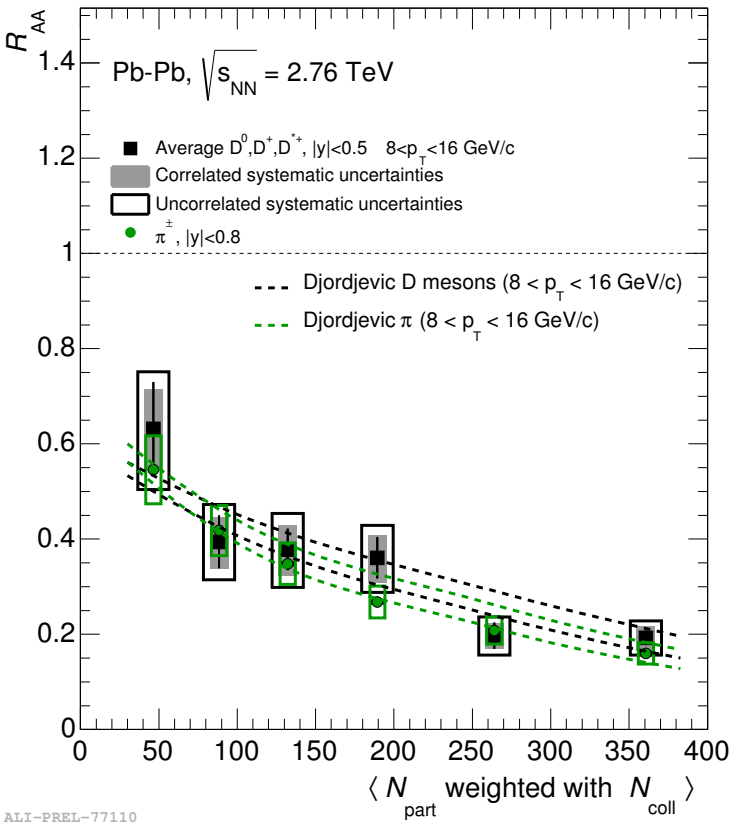
Phys. Rev. Lett. 109 (2012) 112301

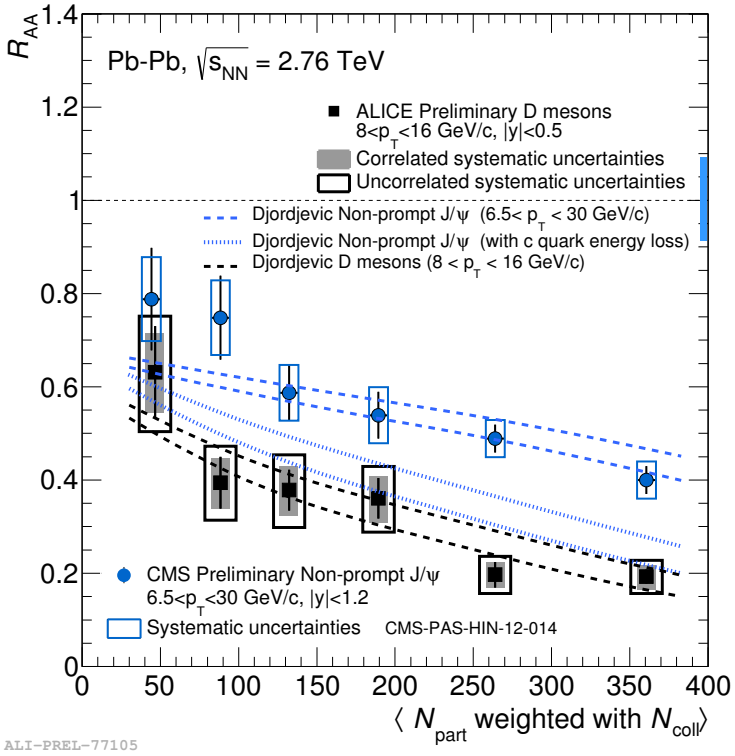


- Models compatible with data (HF via muon decay, forward rapidity)
- Shadowing doesn't explain the suppression (grey line)

- Several models reproduce the trend of the data (electrons at mid-y)
- Uncertainties too large to discriminate among various models

Mass and colour-charge dependence of energy loss



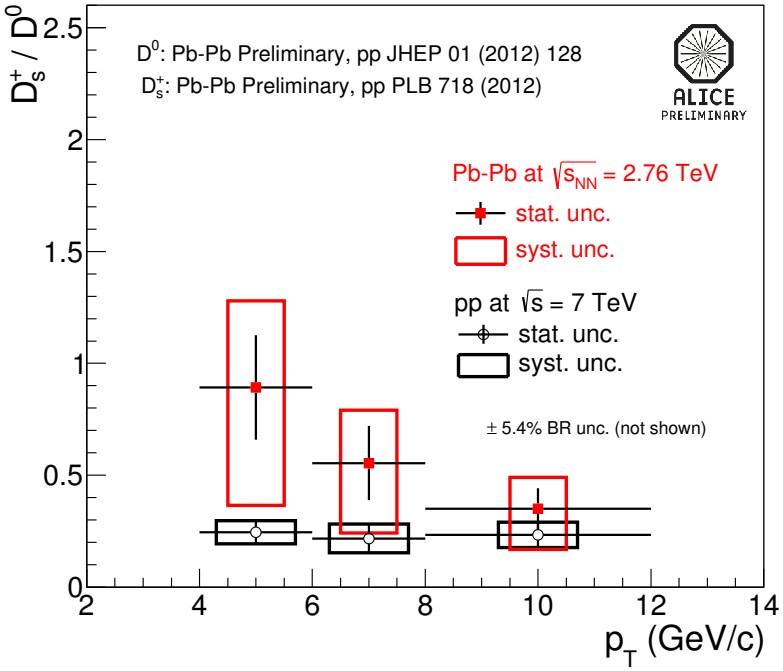


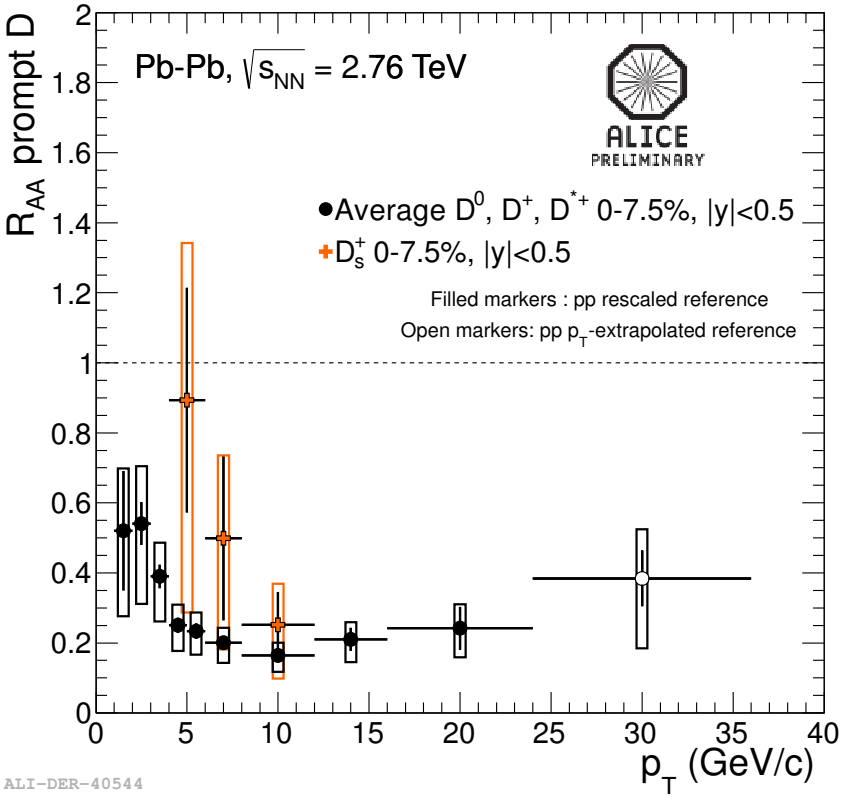
- Pion and D R_{AA} are similar
- e.g. Djordjevic reproduce the data
  - Combination of energy loss, p_T shape, and fragmentation

- $R_{AA}(J/\psi \leftarrow B) > R_{AA}(D)$
- The quark mass used in the model is crucial to reproduce the data

Strangeness enhancement

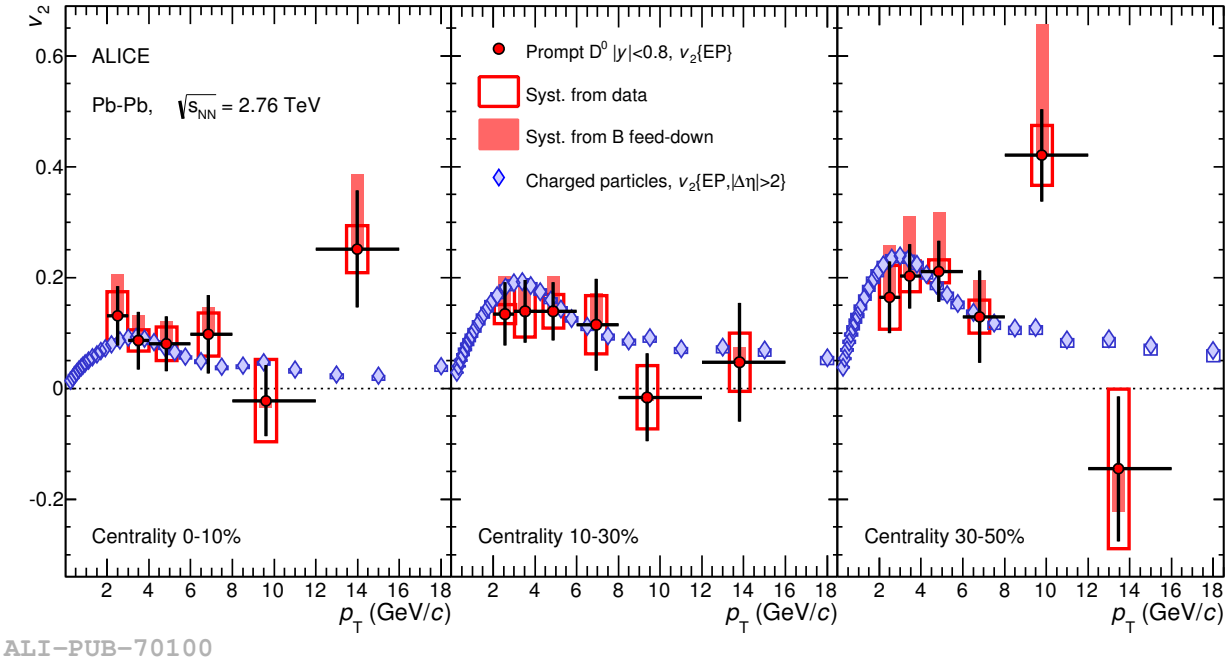
- Expected and observed in the light sector an enhancement of strange hadron production in the medium





- D_s compatible with average of D mesons within uncertainties
- Hint of enhancement at low p_T

Collectivity? Heavy-flavour hadron v_2

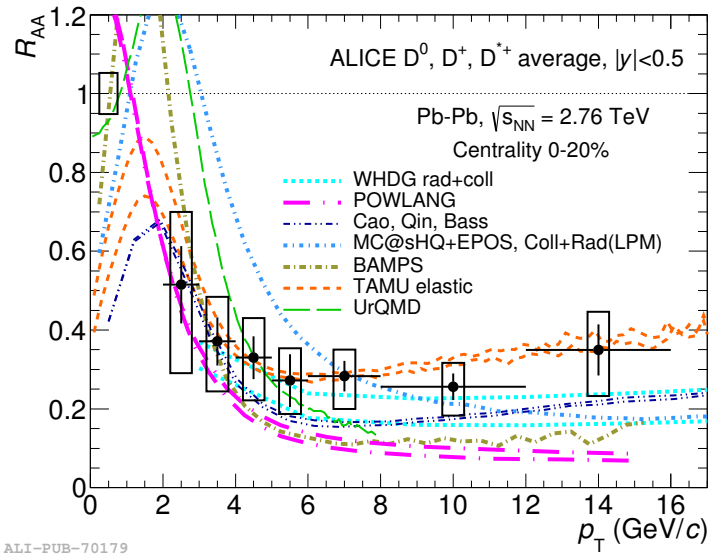


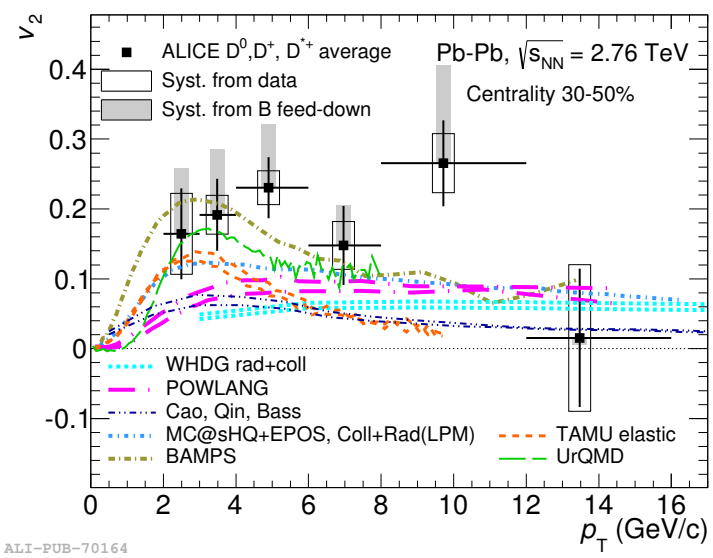
Phys. Rev. C 90 (2014) 034904,Phys. Rev. Lett. 111 (2013) 102301

Positive D mesons v_2 in $2 < p_T < 6$ GeV/c ($\sigma = 5.7$)

- Similar v_2 for D mesons and light hadrons
- At high p_T v_2 measures the path-length dependence of energy loss
- At low-p_T v_2 results indicate that charm participates in the collective expansion of the medium

Comparison with models

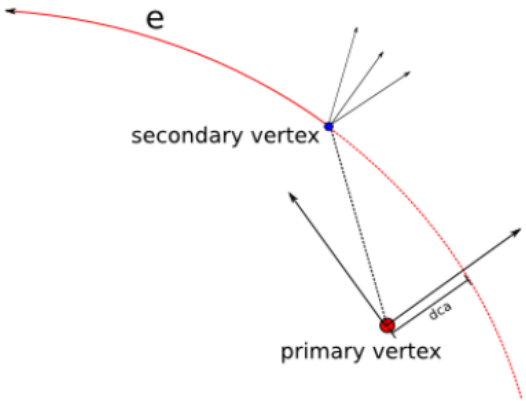


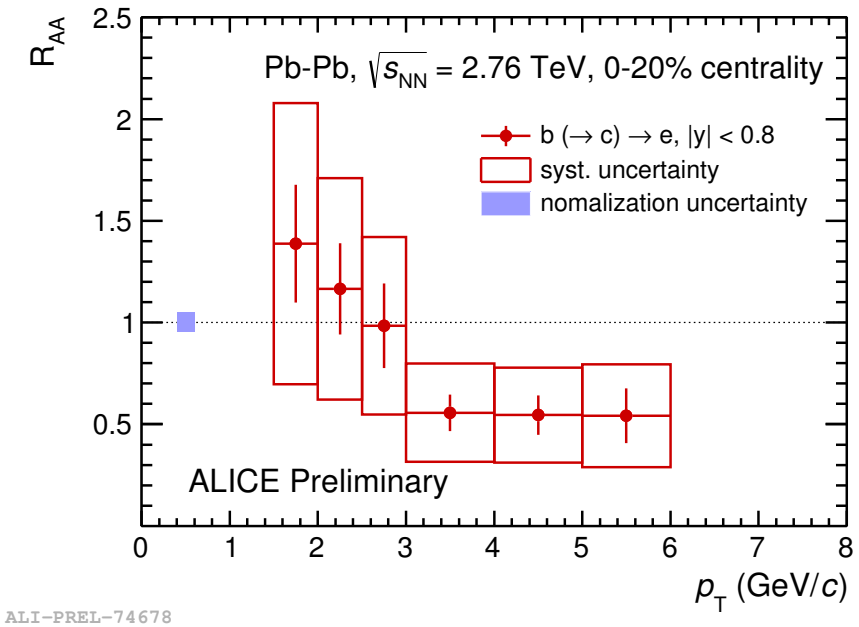


- Some models reproduce better R_{AA}, others v_2
- Data constrain them in the description of R_{AA} and v_2 simultaneously

BAMPS: J.Phys. G38 (2011) 124152; WHDG: J.Phys. G38 (2011) 124114; Aichelin et al.: Phys.Rev.C 79(2009)044906; POWLANG: Eur.Phys J. C 71 (2011) 1666 ; TAMU: arXiv:1204.4442 UrQMD: arXiv:1211.6912, J.Phys.Conf.Ser. 426 (2013) 012032; Cao, Quin, Bass: arXiv:1308.0617

Electrons from beauty-hadron decays





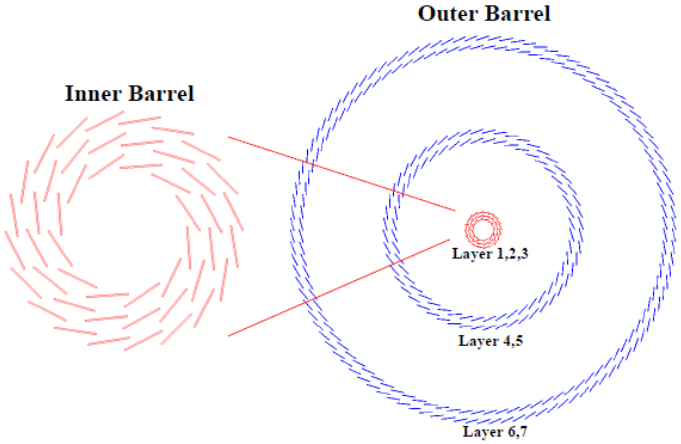
- Beauty-decay electron distribution obtained by exploiting the larger decay length of beauty hadrons with respect to other sources
- Hint of suppression of high-p_{T} beauty-hadron

- Displaced D^0 and direct reconstruction of B meson hadronic decays possible with the ALICE upgrade (Run 3)
- More direct access the beauty kinematics

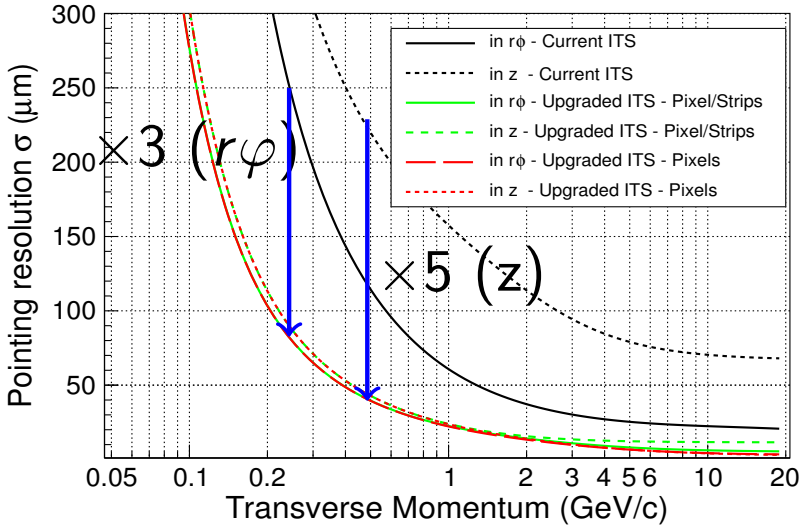
Future perspectives (Run 3)

New ITS, new TPC readout, Muon Forward Tracker (MFT), high-rate readout upgrade for all detectors

- Improve p_{T} reach and precision of the current measurements
  - Distinguish between models
- Study hadronization of heavy quarks, fragmentation and coalescence
  - Measure baryons
  - D-hadron correlations and jets
- Measure displaced D mesons
- Separate charm and beauty measurement at forward y with the MFT



ITS standalone d_0 resolution

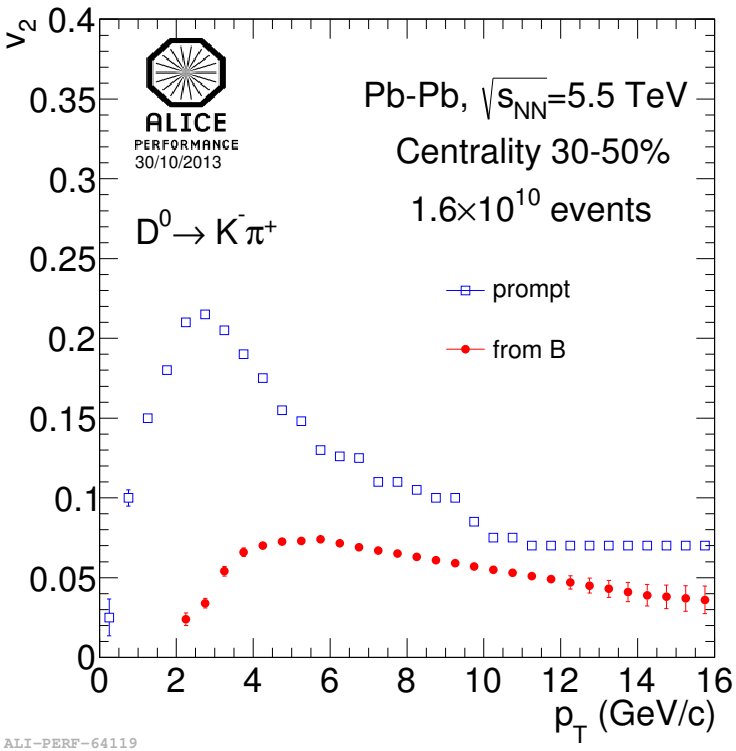


CDR, CERN-LHCC-2012-13 LoI, CERN-LHCC-2012-12

(Selected) performance studies for the upgrade

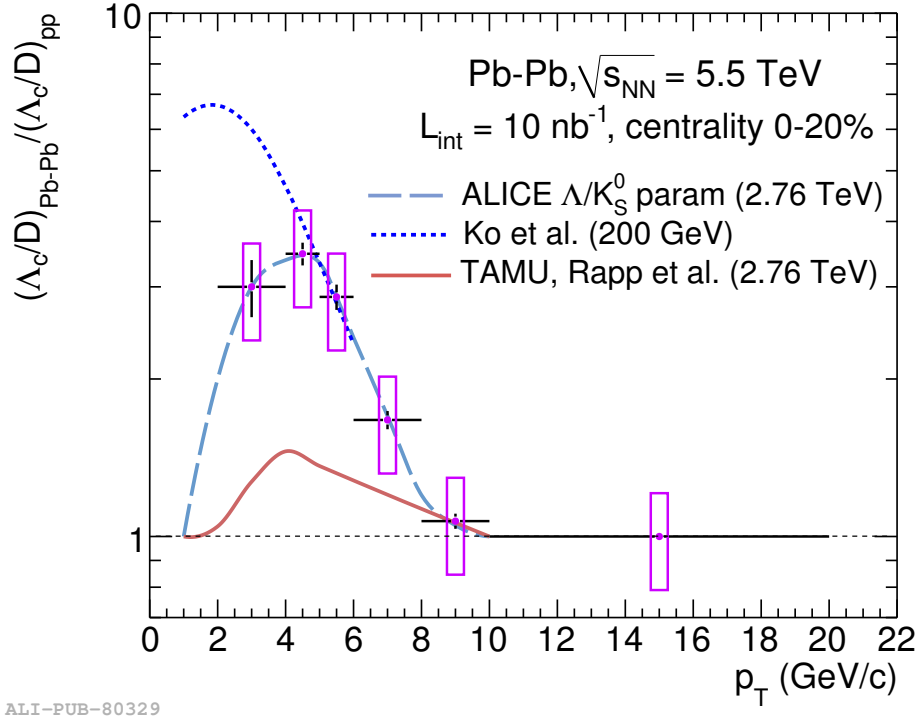
- Expected integrated luminosity: $10\ \mathrm{nb}^{-1}$ (corresponding to $\sim 8 \times 10^9$ events in 0-10% central) in Pb–Pb collisions

Prompt and secondary D meson v_2



CERN-LHCC-2012-12

Λ_c-over-D ratio

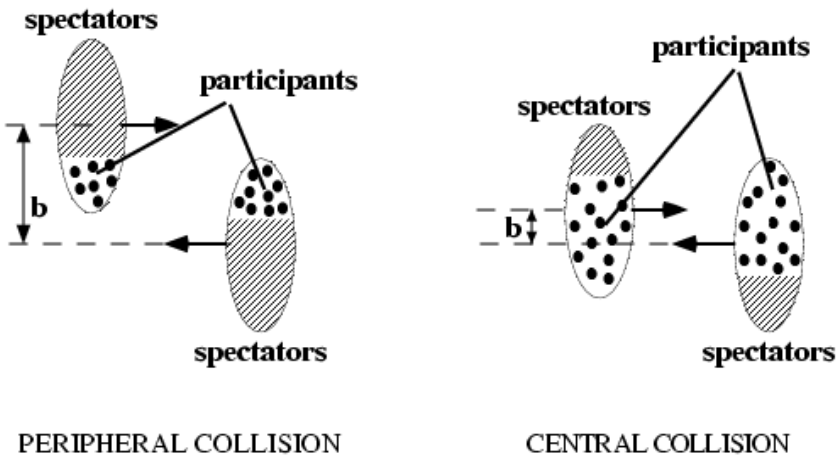


Conclusions and Outlook

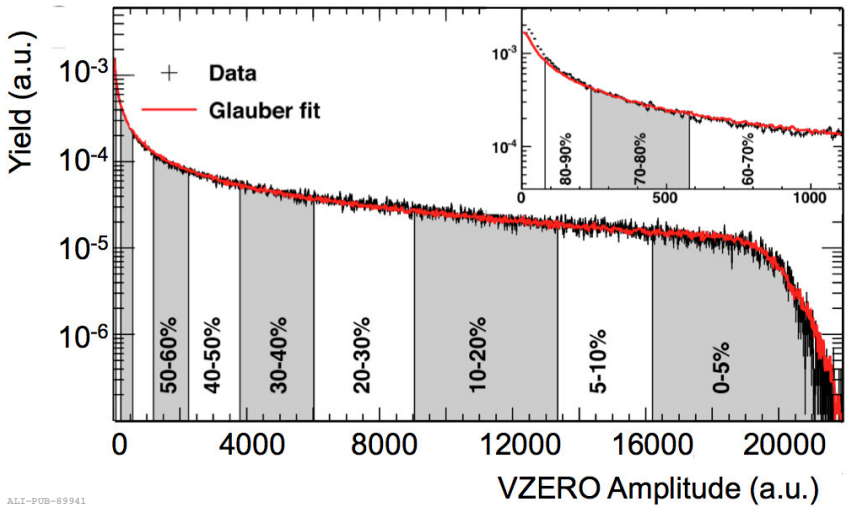
- Run1 measurements from ALICE provide important insight into the properties of the QGP matter
- Open heavy flavours probe the transport properties of the medium
- The R_{AA} of non-prompt J/ψ is larger than the R_{AA} of D mesons that is similar to the R_{AA} of π
- Charmed mesons positive v_2 indicates that charm quarks participate to the collective expansion
- With the ALICE upgrade, better impact parameter resolution and high rate capabilities will improve the current performance, new decay channels accessible

Extra slides

Collision centrality



Measurement

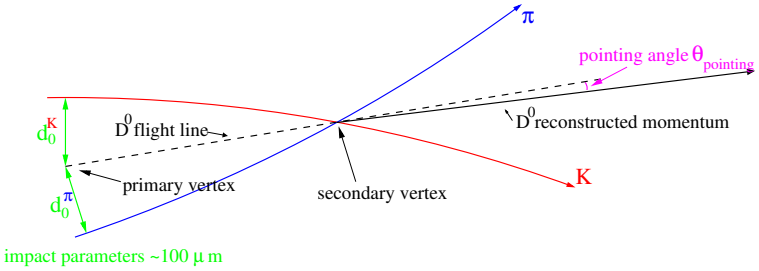


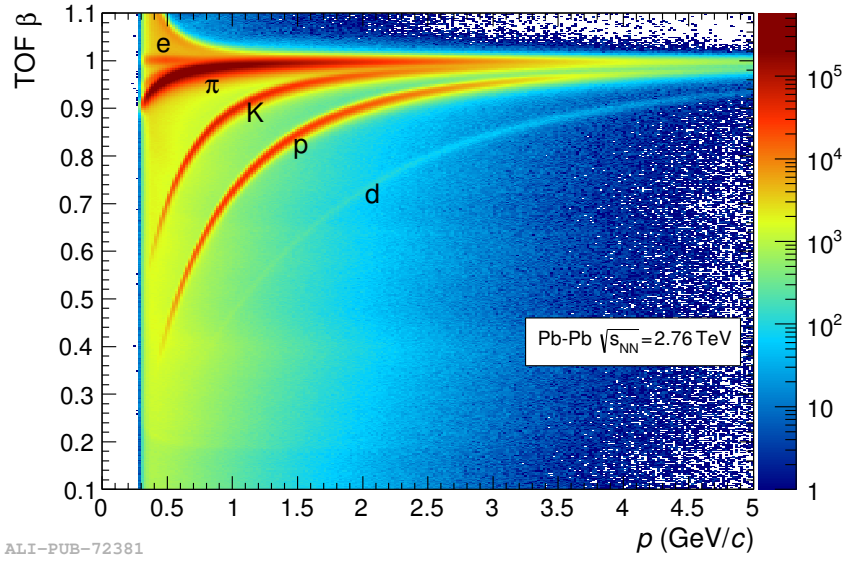
JINST 8 (2013) P10016

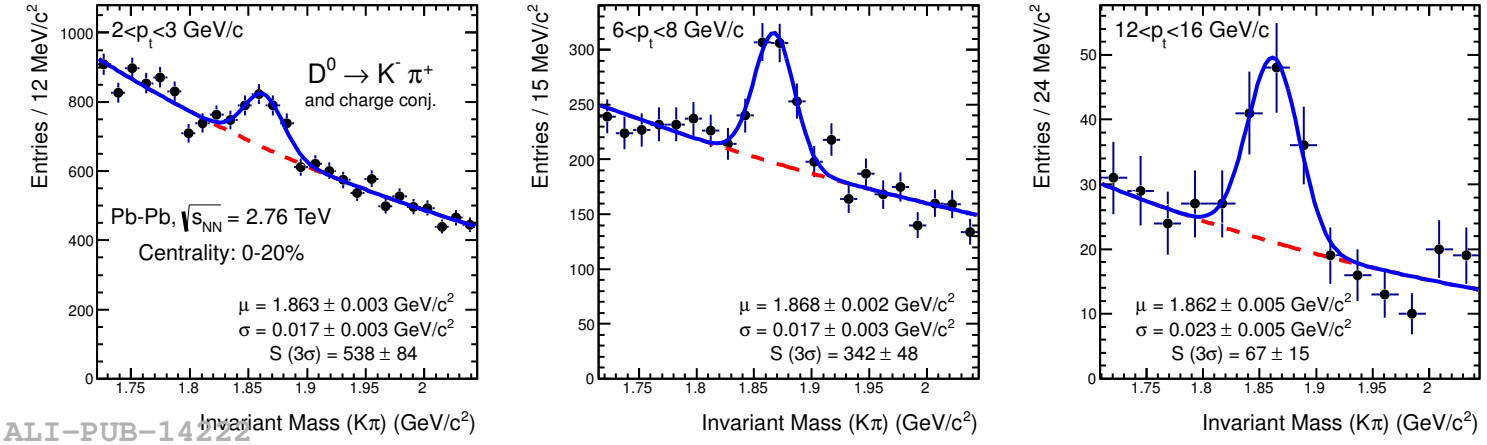
- Central collision: more nucleons participate $\rightsquigarrow$ higher particle multiplicity in the final state
- Multiplicity measured in the V0 scintillators ($2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$)
- Definition of centrality classes as percentage of total cross section
- A Glauber model reproduces the V0 amplitude distribution

D meson reconstruction strategy

- Particle Identification (TPC+TOF)
- Topological selection
- Invariant mass analysis, signal extraction via fit

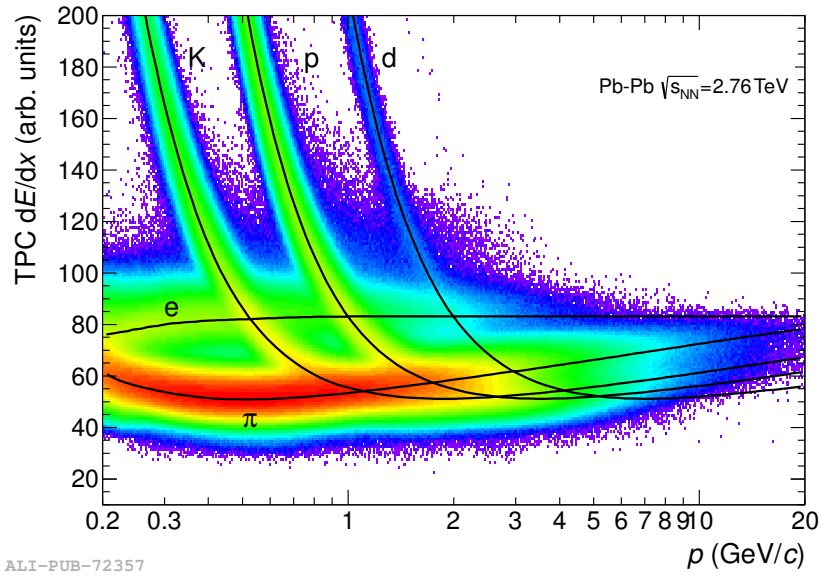






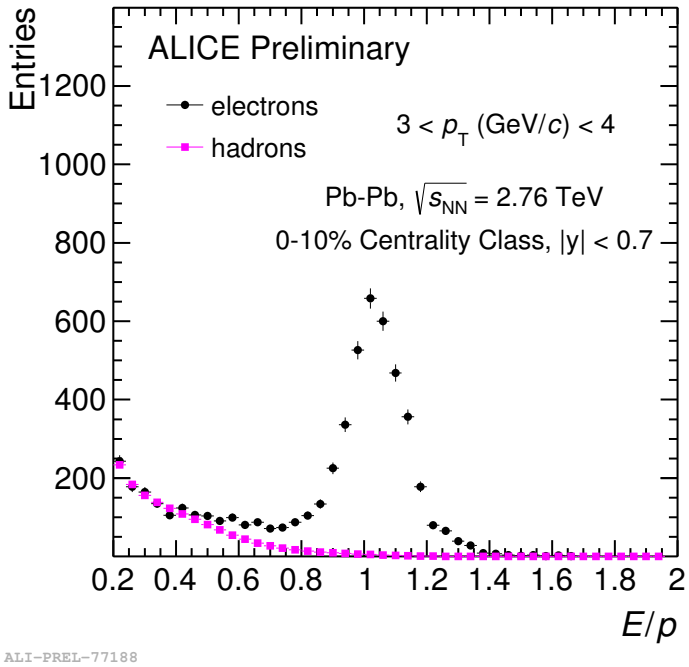
Electron selection strategy

ITS+TPC+TOF



- Electron selection:
  - TPC $-1 < n\sigma < 3$
  - TOF $-2 < n\sigma < 2$
  - ITS $-1 < n\sigma < 1$ for $p_{\mathrm{T}} < 1.5\ \mathrm{GeV}/c$

EMCal+TPC

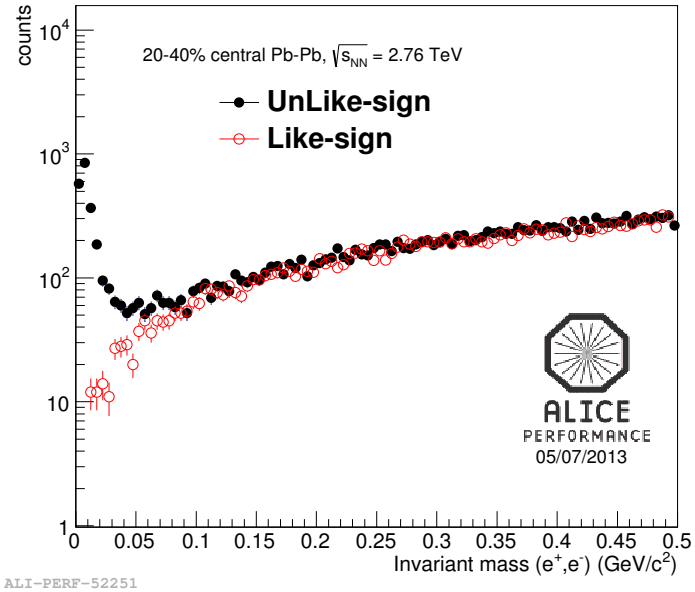


- EMCal $0.8 < E/p < 1.2$ and selection on the shower shape
- TPC $-1 < n\sigma < 3$

Electron background subtraction

Invariant mass method (photonic electrons)

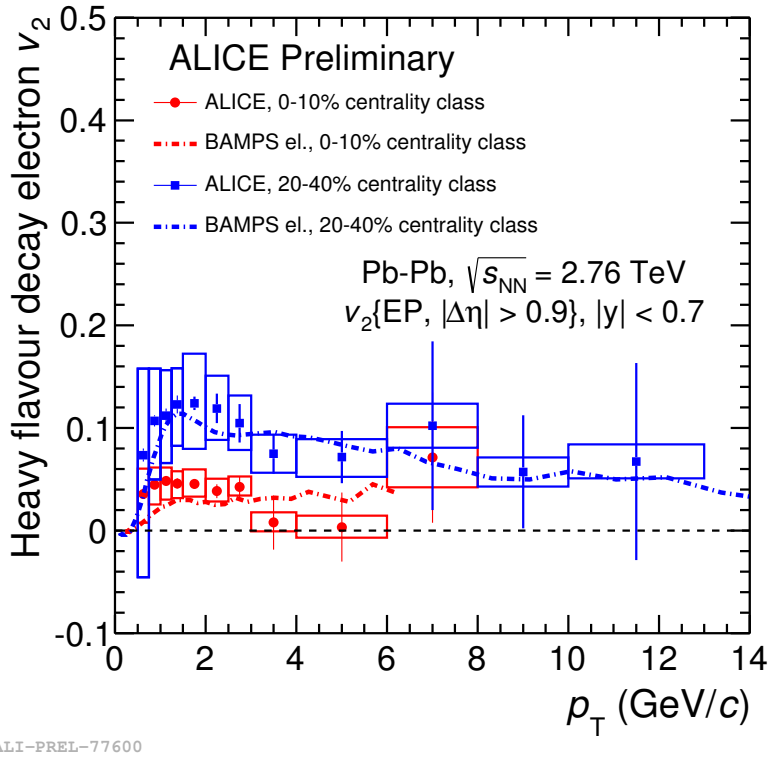
- π^0 Dalitz decays and γ conversions are the most abundant
- Each electron is paired with a unlike sign one. Their invariant mass define the photonic background, then statistically subtracted

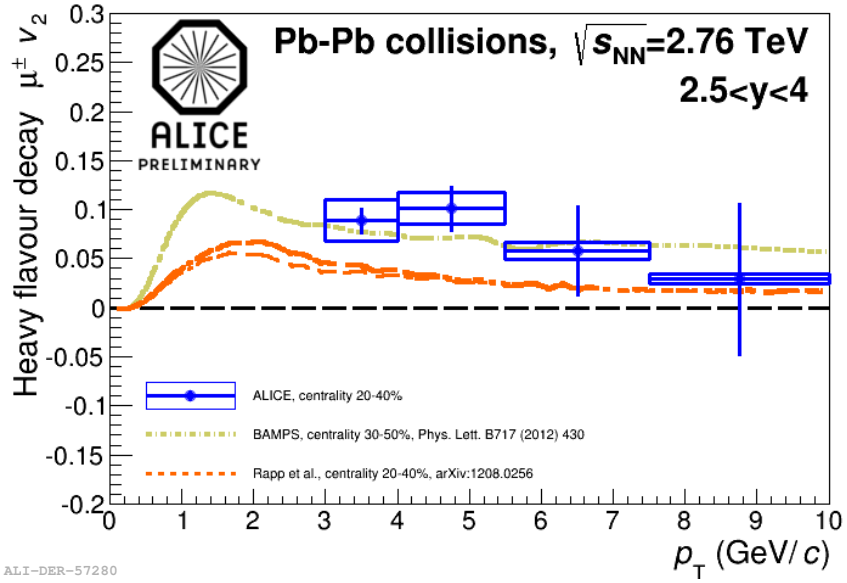


Cocktail method

- Cocktail of electrons originating from π^0 Dalitz decay, γ conversion, light mesons, and J/ψ measured by ALICE
- Subtract the cocktail from the inclusive electron distribution

v_2 of HF- electrons and muons





Single-muons from heavy-flavour decays

ALICE

Track selection

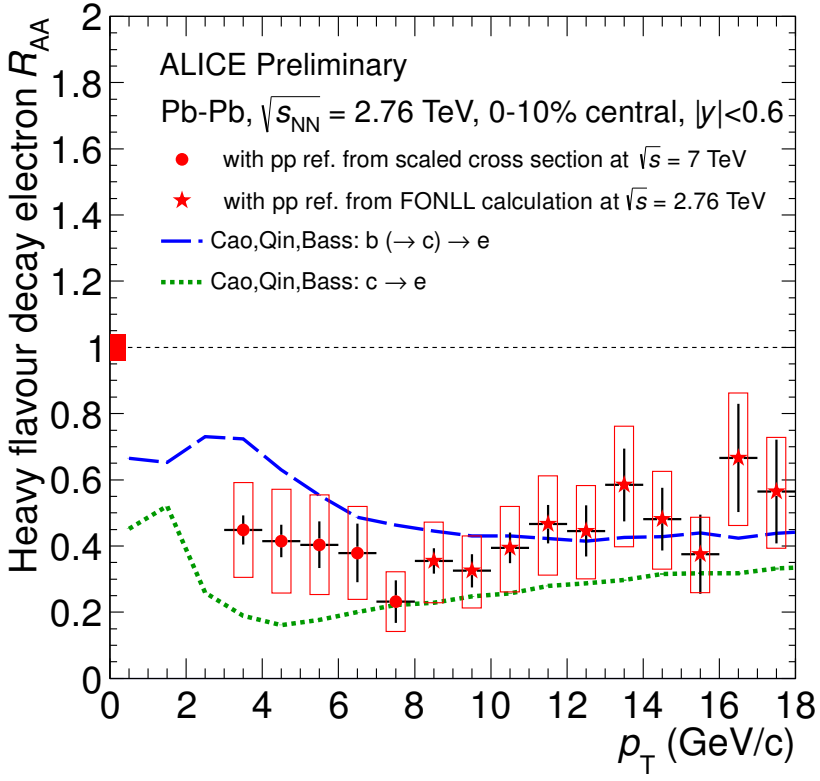
- Match the tracks with tracklets in the trigger chambers to reject punch-through hadrons
- Cut on distance of closest approach to reject beam-gas interactions

Background subtraction

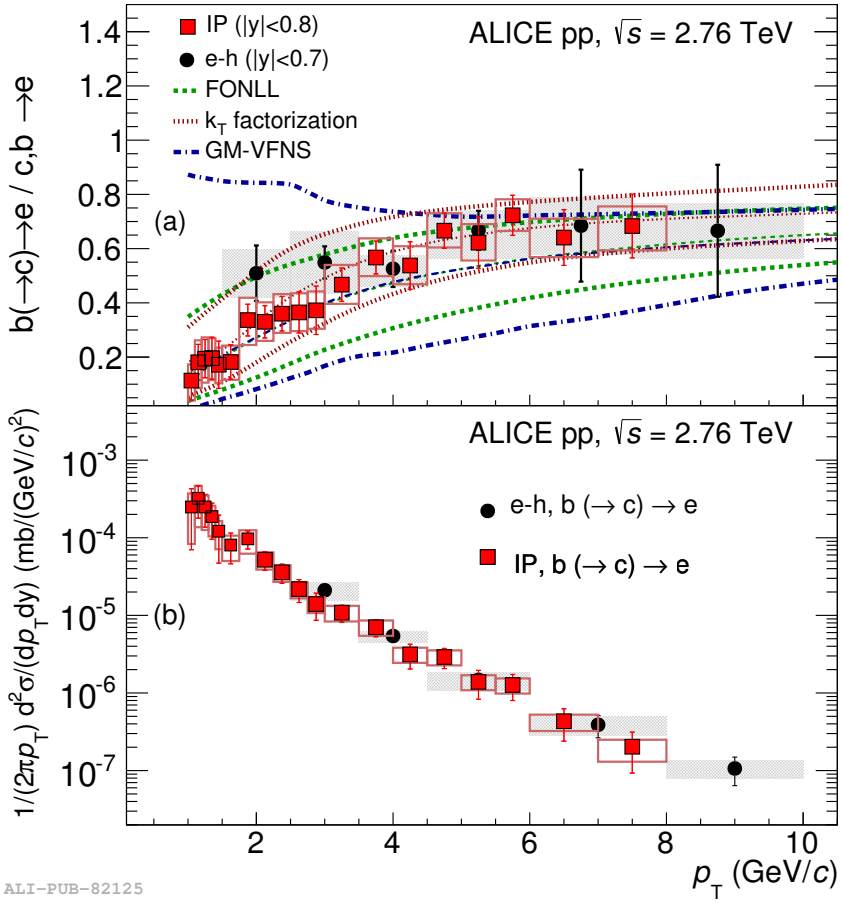
- Mainly μ from π and K decays
  - Less relevant for $p_{\mathrm{T}} \geq 4\ \mathrm{GeV}/c$
- Extrapolate to forward rapidity the K and π yields measured at mid-rapidity

Charm and beauty fraction of heavy-flavour electrons

R_{AA} compared to model expectation for beauty and charm



Beauty fraction in pp collisions

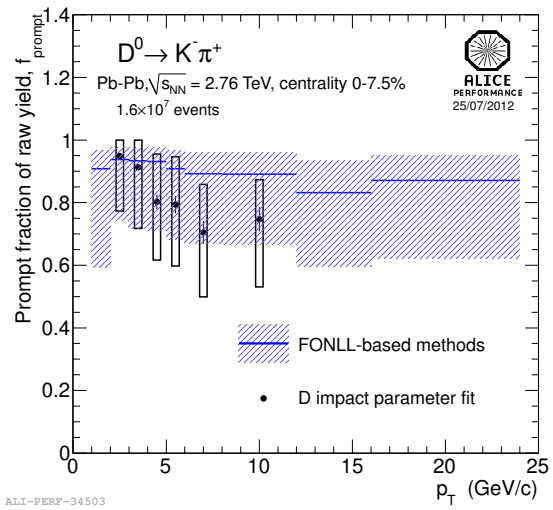


Feed-down from B mesons

- Subtraction of $\mathrm{D} \leftarrow \mathrm{B}$ meson R_{AA}
  - Secondary D mesons fraction estimated using FONLL beauty cross section scaled by the overlap function $\langle T_{\mathrm{AA}} \rangle$ and EvtGen for the decay
  - Hypothesis on the feed-down R_{AA} varied for the systematic uncertainty ($1/3 < R_{\mathrm{AA}}^{feed-down} / R_{\mathrm{AA}}^{prompt} < 3$)

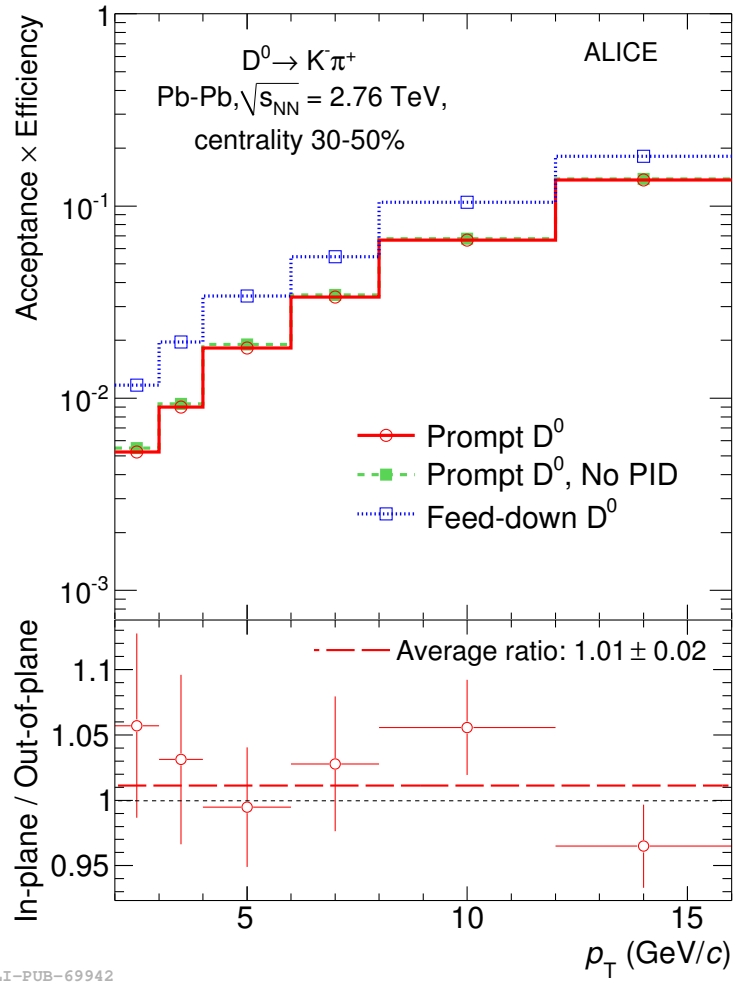
$$v_2^{prompt} = \frac{1}{f_{prompt}} v_2^{all} - \frac{1 - f_{prompt}}{f_{prompt}} v_2^{feed-down}$$

- Systematic uncertainty on R_{AA}
- Systematic uncertainty on v_2
  - Central value uses the assumption $v_2^{prompt} = v_2^{feed-down}$
  - Systematic uncertainty: span variation to $v_2^{feed-down} = 0$

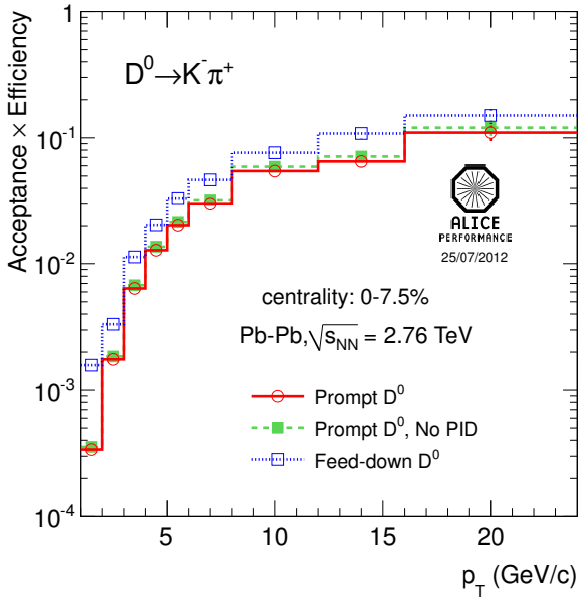


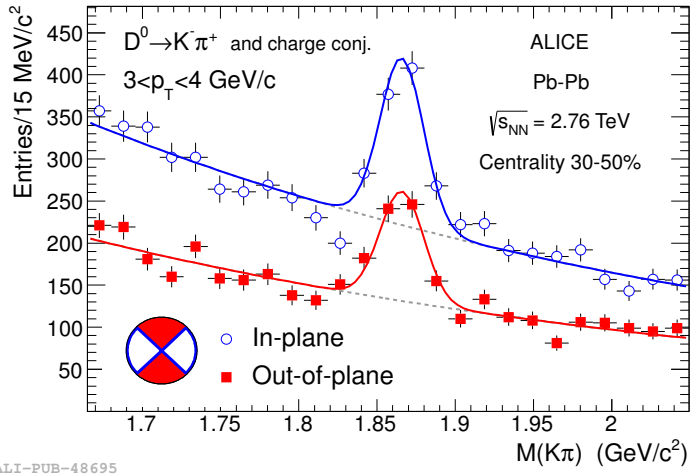
D meson reconstruction efficiency

30-50%



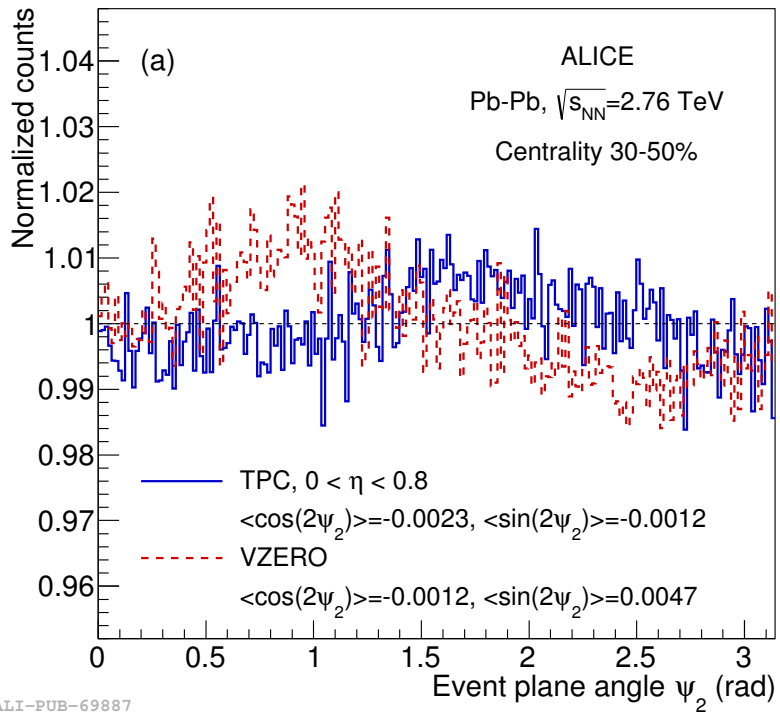
0-7.5%

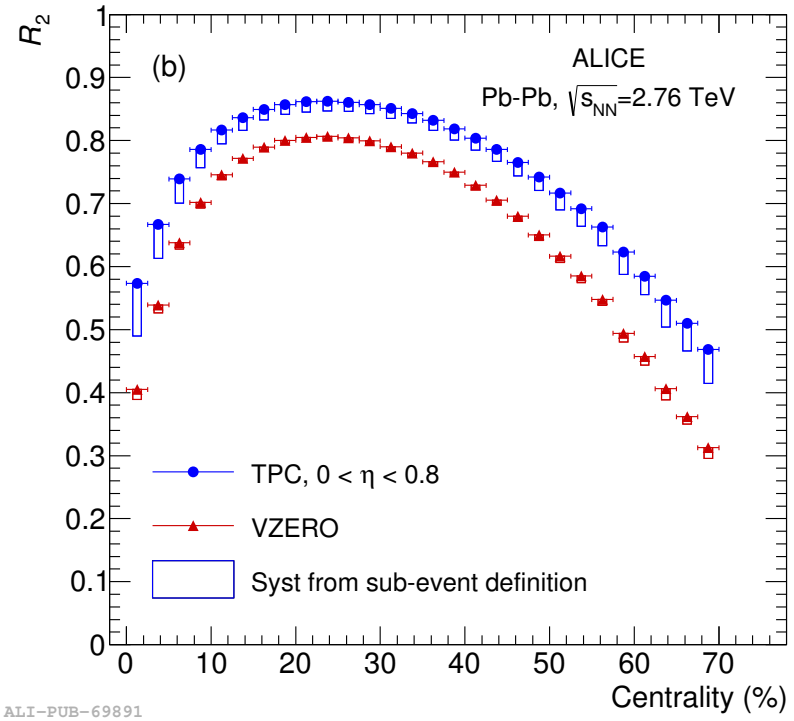




Event plane method

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$





The Scalar Product method

$$v_2 = \frac{\left\langle u \cdot \frac{Q}{M} \right\rangle}{\sqrt{\left\langle \frac{Q_a}{M_a} \cdot \frac{Q_b}{M_b} \right\rangle}} \quad (1)$$

C. Adler et al., Phys.Rev. C66, 034904 (2002)

- $Q = \sum_{j=1}^{M_{\mathrm{RP}}} \exp^{i2\varphi_j}$,
  - φ_j azimuth of j-th Reference Particle (RP)
- M_{RP} multiplicity
- $u = \exp^{i2\varphi}$
  - φ azimuth of D meson (Particle Of Interest, POI)
- a, b indicate two sub-events

- With a $\Delta\eta$ between POI and RF, non-flow correlations are reduced (not included in this analysis)