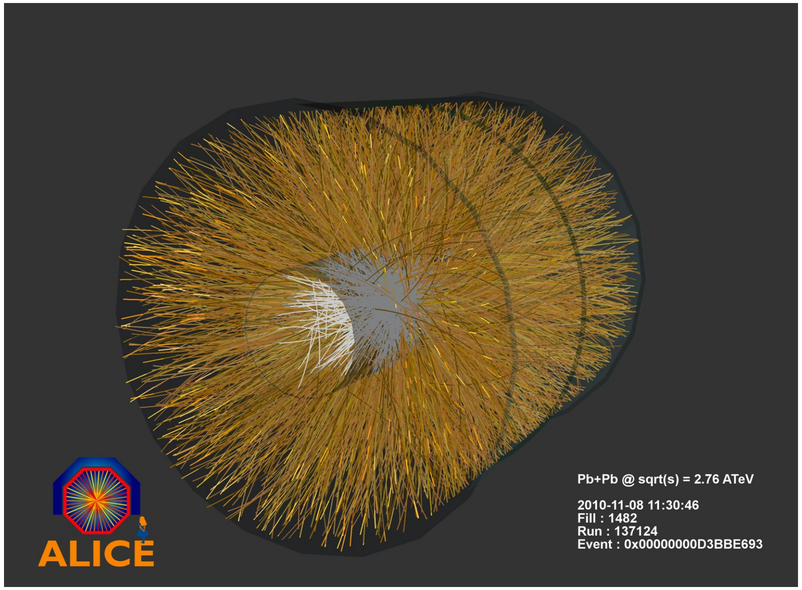
Istituto Nazionale
di Fisica Nucleare

Recent ALICE measurements on open heavy-flavour production in pp, p-Pb, and Pb-Pb collisions at the LHC

A. Rossi, Padova University & INFN

on behalf of the ALICE Collaboration



ALICE

Outline

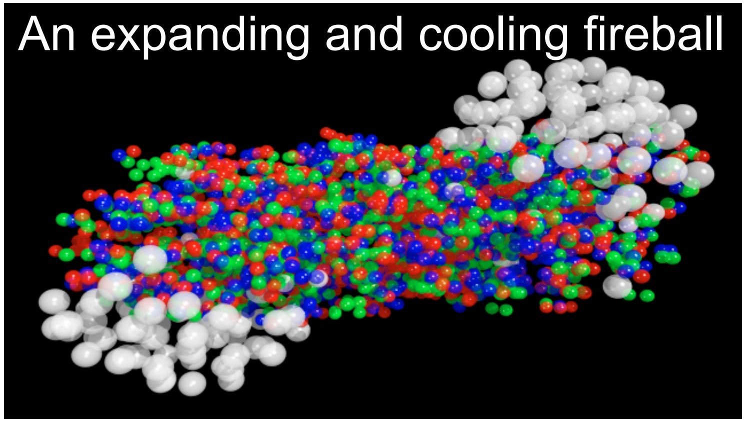
- Introduction and physics motivations

- Open heavy-flavour reconstruction with ALICE

- Main and most recent results
  - pp and p-Pb collisions:
    - as a reference for Pb-Pb collisions
    - more differential studies
  - Pb-Pb collisions

- Future plans

Hard probes for studying the QGP


An expanding and cooling fireball

Heavy-Ion Collisions produce a system of strongly-interacting matter

- Extended size
- High temperature, high pressure
- Local thermodynamical equilibrium

➜ Phase transition to a deconfined state:

Quark Gluon Plasma (QGP)

Thanks to several measurements performed at SPS, RHIC, and LHC (e.g. J/ψ suppression and regeneration) the existence of QGP is established.

⇩

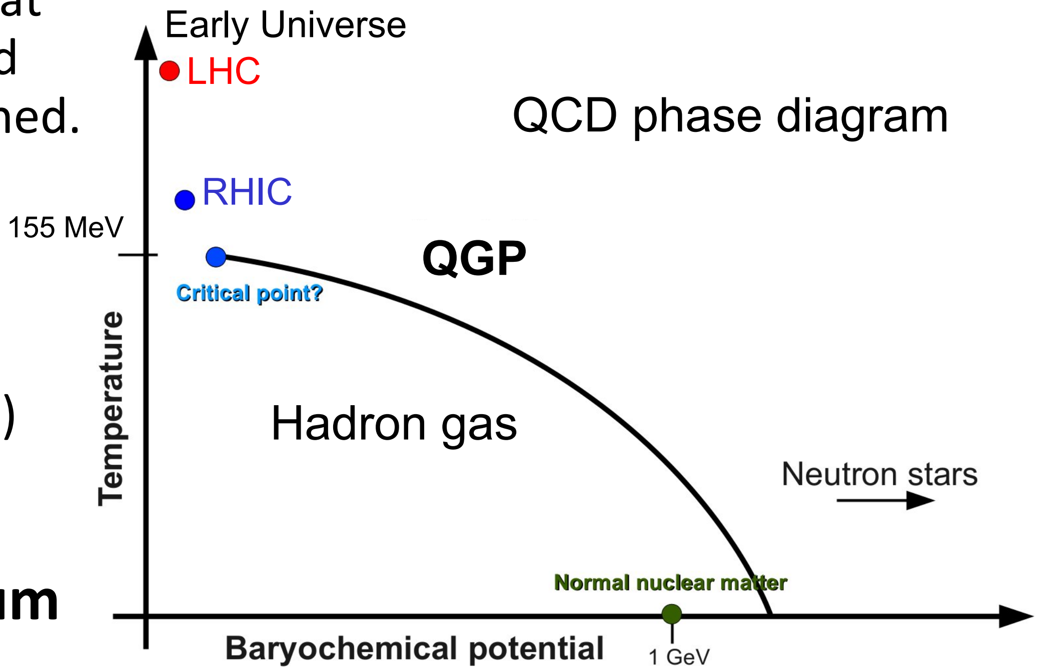
From "discovery phase" to detailed characterization of QGP properties

⇩

Hard probes (jets, heavy-quarks, quarkonia) → "resolve" medium constituents

⇩

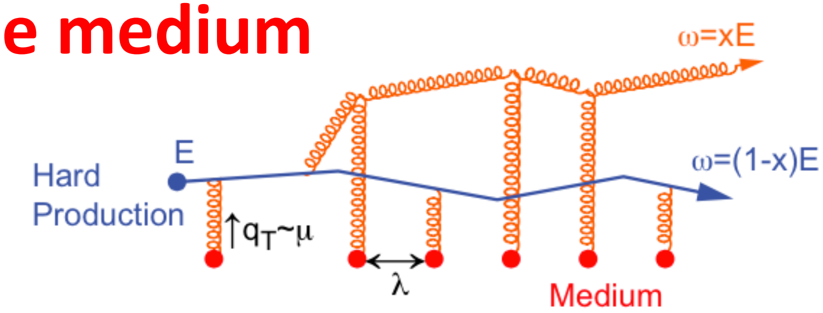
Microscopic description of the medium



QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

⇨ **“Calibrated probes” of the medium**



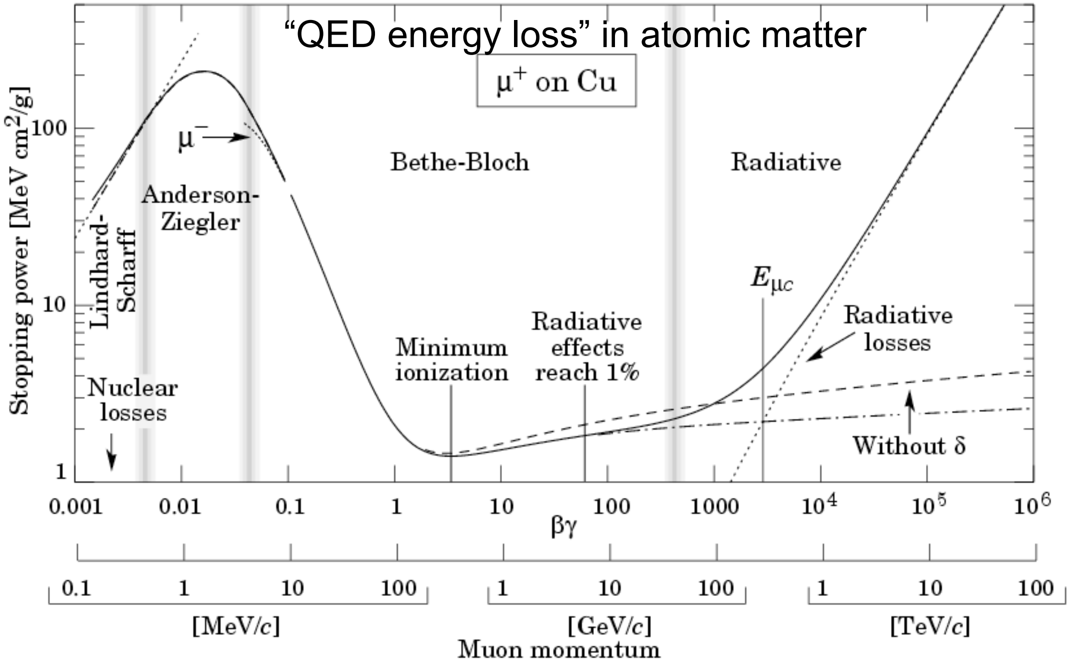
Study parton interaction with the medium

- **energy loss via radiative** (“gluon Bremsstrahlung”)
  collisional processes

~ Study QCD “Bethe-Block” curve
for partons in the QGP

⇩

Connection of “local” interactions with global medium properties



QGP tomography with heavy quarks

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at all p_T for charm and beauty (large masses >> Λ_{QCD})

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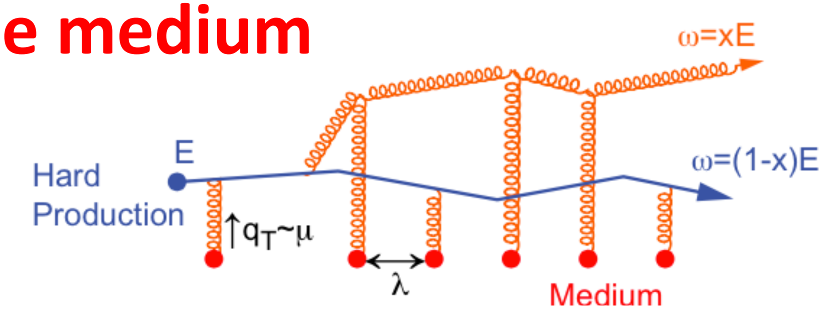
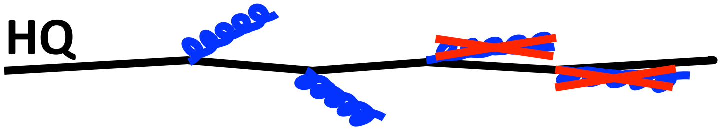
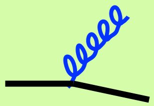


Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes
  - path length and medium density
  - **color charge** (Casimir factor)
  - **quark mass** (e.g. from dead-cone effect)



Gluonsstrahlung probability



$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

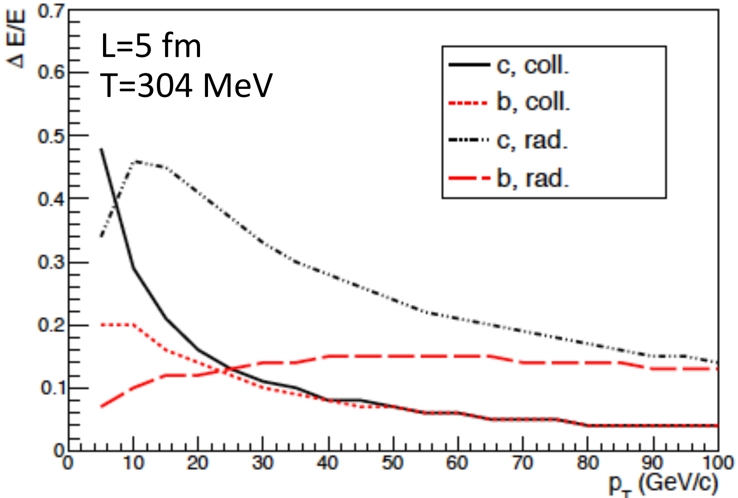


Figure from A. Andronic *et al.*, EPJC C76 (2016)
M. Djordjevic, Phys. Rev. C80 064909 (2009),
Phys. Rev. C74 064907 (2006).

QGP tomography with heavy quarks

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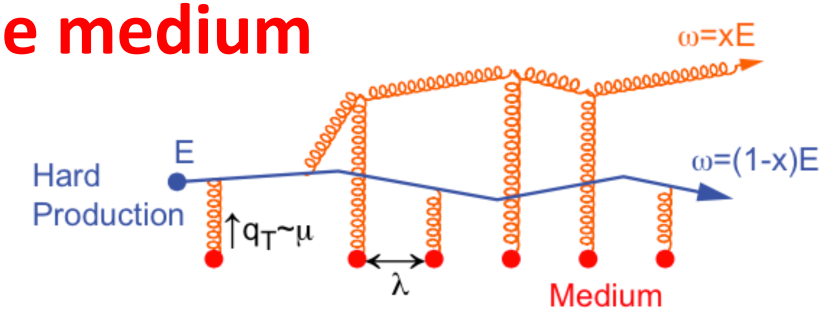

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$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

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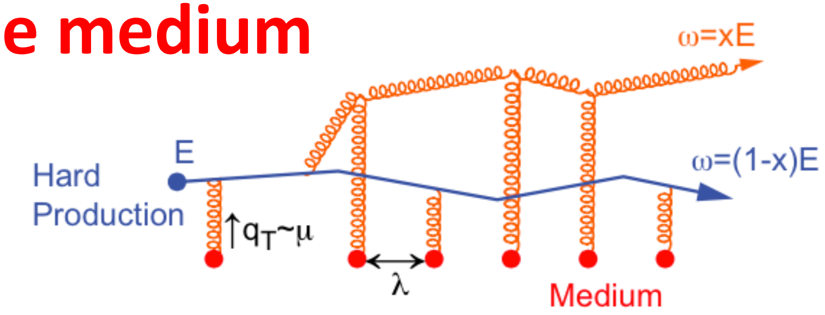

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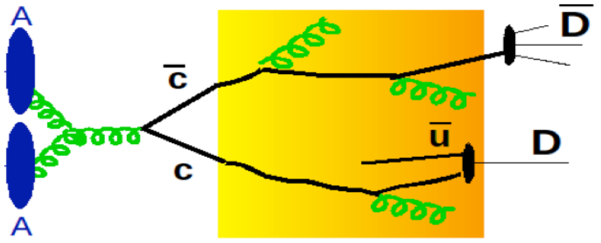
- medium **modification to HF hadron formation**
  - hadronization via quark coalescence



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"Calibrated probes" of the medium

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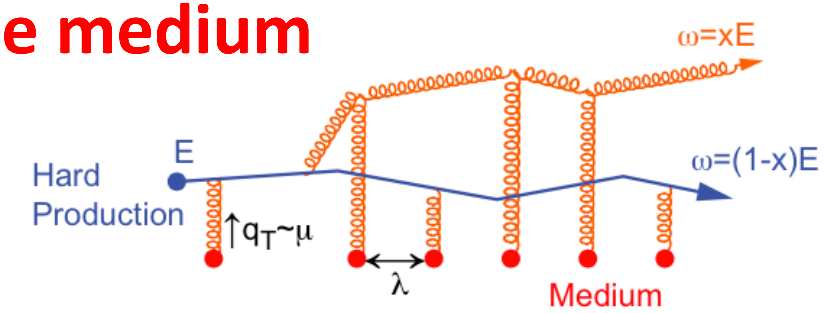

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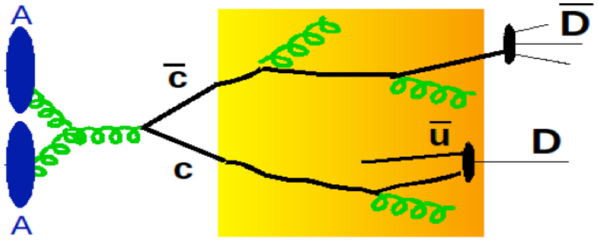


- participation in collective motion ➜ azimuthal anisotropy of produced particle

How can we measure medium effects?

Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a "geometrical" factor (from Glauber model)

Pb-Pb

$$R_{AA}(p_{\mathrm{T}}) = \frac{dN_{AA}/dp_{\mathrm{T}}}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_{\mathrm{T}}}$$

Nuclear overlap function, encodes collision geometry

pp

If $R_{AA}=1$ → no nuclear effects
If $R_{AA}\neq1$ → nuclear effects

Trivial but important caveat:

(simplistic scheme)

What we want to probe

$$\frac{dN_{AA}}{dp_T} = \begin{matrix}\text{"vacuum"}\\ \text{parton spectra}\end{matrix} \otimes \begin{matrix}\text{initial-state}\\ \text{effects}\end{matrix} \otimes \boxed{\begin{matrix}\text{parton interaction}\\ \text{with the medium}\end{matrix} \otimes \begin{matrix}\text{(modified?)}\\ \text{hadronization}\end{matrix} \otimes \begin{matrix}\text{hadronic}\\ \text{phase}\end{matrix}} \left(\otimes \begin{matrix}\text{decay}\\ \text{e.g. for leptons}\end{matrix}\right)$$

Measured spectra in AA collisions result from a convolution of many pieces

→interpretation of the results requires comparison with models

→must measure observables with different sensitivity to the various ingredients

pp and p-Pb collisions

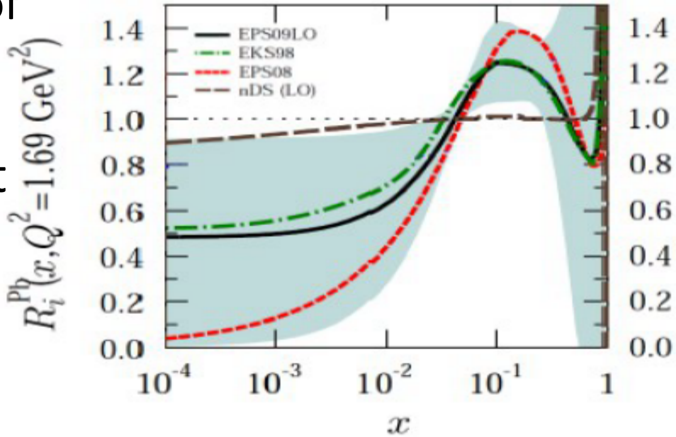
pp collisions

p_T-differential cross sections → Test predictions based on pQCD calculations
→ Reference for Pb-Pb collisions

p-Pb collisions

Measure effects, not due to QGP formation, that can modify the yield of hard probes in nuclear collisions:

- Nuclear modification of the PDFs
  - shadowing at low Bjorken-*x* is the dominant effect at LHC energies
  - gluon saturation?
    H.Fujii and K.Watanabe, Nucl.Phys.A915(2013) 1



K. J. Eskola et al: JHEP04(2009)065

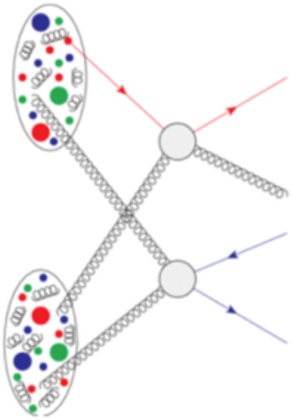
- k_T-broadening
  Due to multiple collisions of the parton before the hard scattering
- energy loss in cold nuclear matter

Other final-state effects? (e.g. from system collectivity/hydro)

pp and p-Pb collisions, more differential measurements

HF production vs. multiplicity in pp and p-Pb collisions

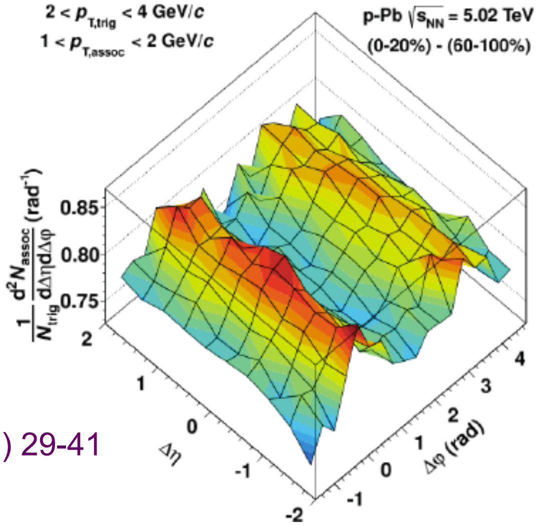
- Interplay between hard and soft processes in particle production
- Study the role of multi-parton interactions (MPI) in the heavy-flavour sector
- Investigate a possible centrality dependent of the modification of the p_T spectra in p-Pb w.r.t. pp collisions



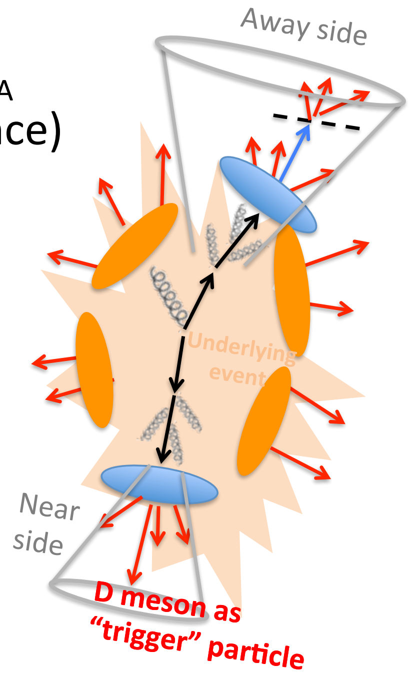
Azimuthal correlation of D meson with charged particles in pp and p-Pb collisions

- Sensitive to charm quark fragmentation properties → address charm jet properties
- Modification of angular correlations in p-Pb w.r.t. pp collisions?
  - may arise from both initial and final-state effects
- Reference for future Pb-Pb measurements → complementary information to R_{AA} and v_2 measurements to study in-medium energy loss (e.g. path-length dependence)

Hadron-hadron correlations: "double-ridge" in high-multiplicity p-Pb collisions

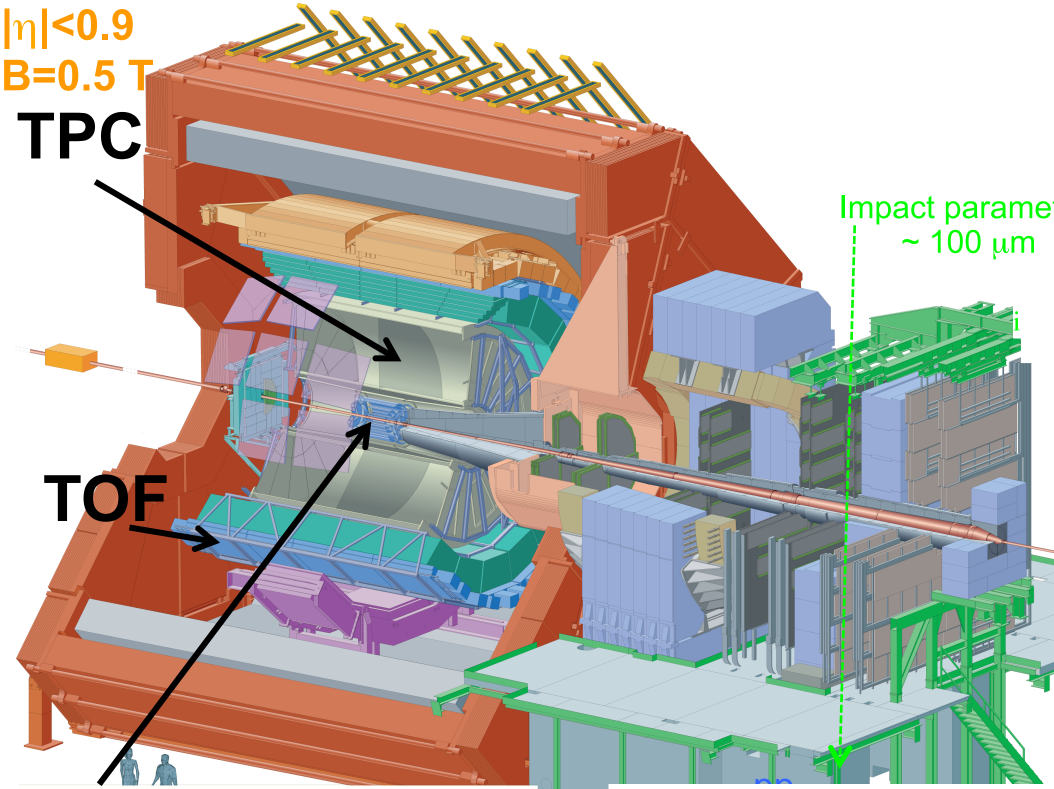


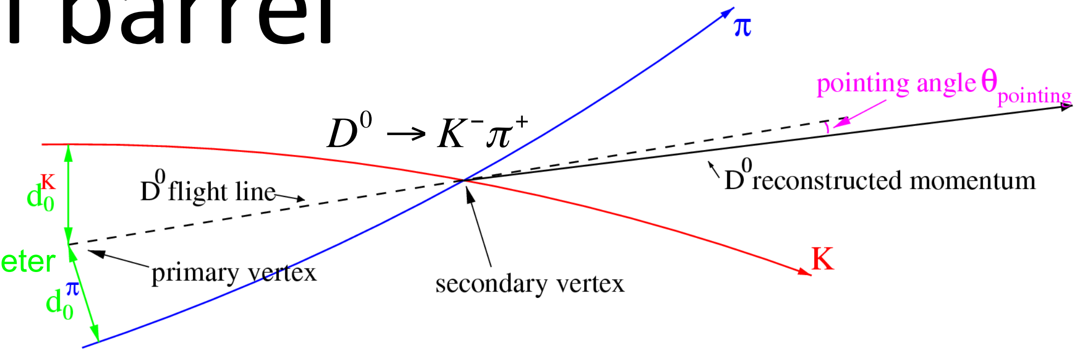
ALICE, PLB719 (2013) 29-41



Heavy-flavour reconstruction in ALICE central barrel

CENTRAL BARREL
$|\eta|<0.9$
B=0.5 T



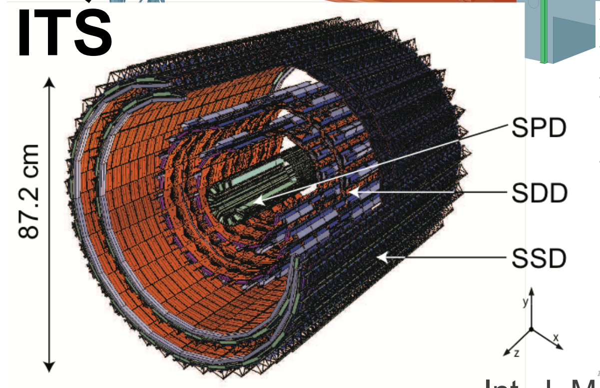


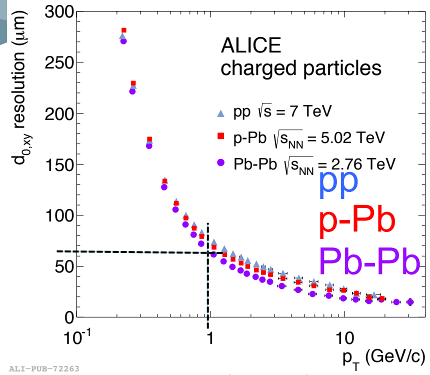
Charmed mesons and baryons:

Invariant mass analysis of reconstructed hadronic decays

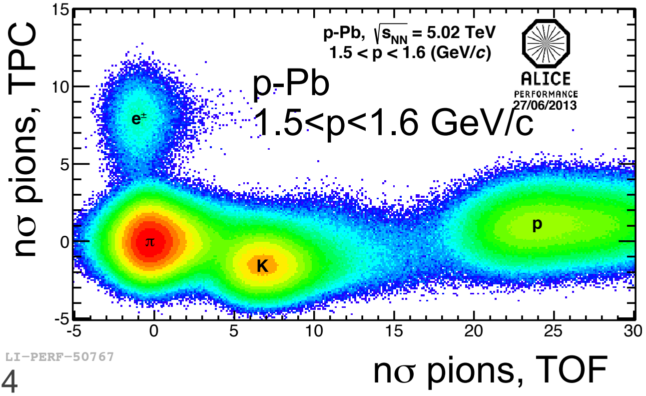
$D^0 \rightarrow K^-\pi^+$ $\quad$ $D^{*+} \rightarrow D^0\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$ $\quad$ $D^+_s \rightarrow \phi\pi^+$, $\phi \rightarrow K^-K^+$

Displaced secondary vertices (→ ITS)
+ PID (π/K/p separation with TOF+TPC)

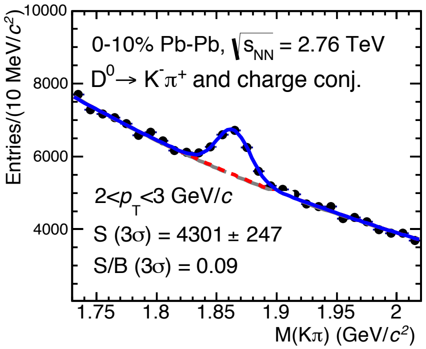




Int. J. Mod. Phys. A 29 (2014) 1430044



nσ pions, TOF



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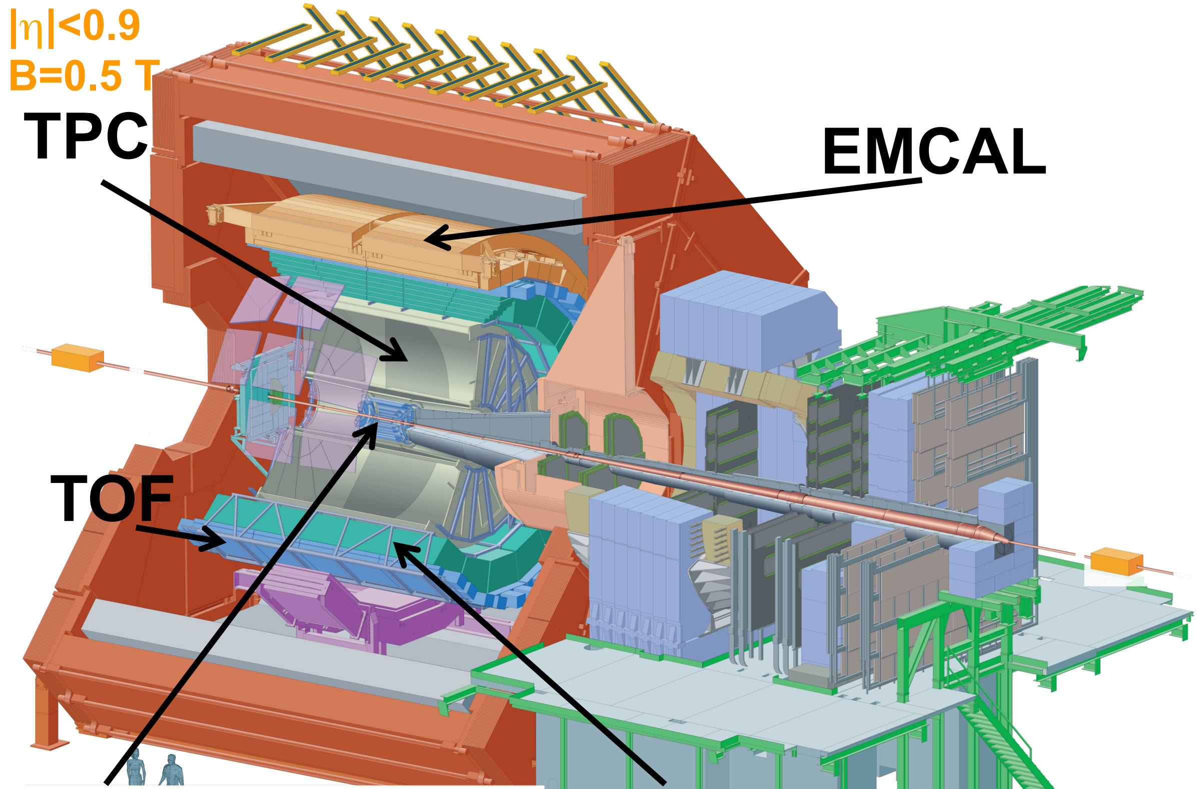

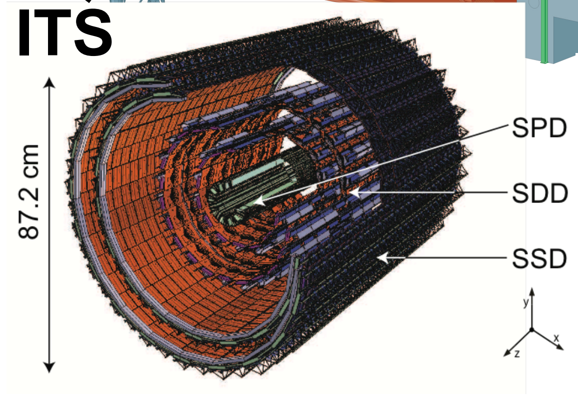

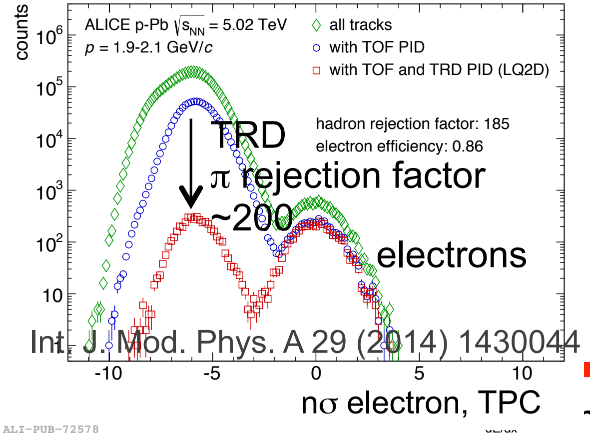

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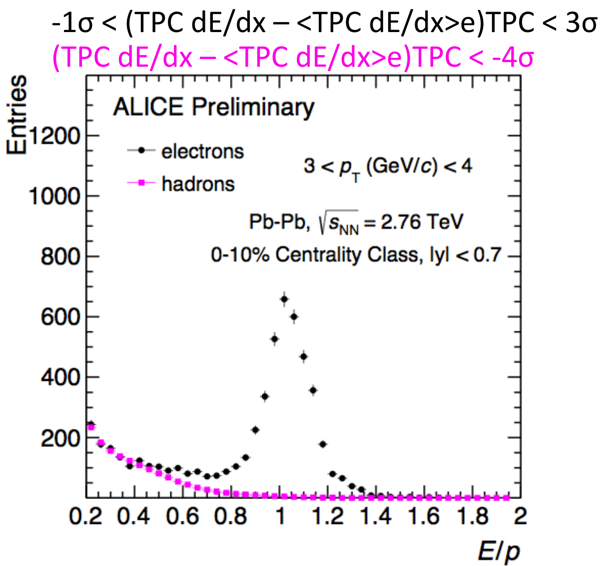


Electrons from semi-leptonic heavy-flavour hadron decays

D,B, Λ_c,..→ e X

Electron identification:

Low p_T: TPC, TOF, ITS

Intermediate-high p_T: TPC, TRD, EMCAL

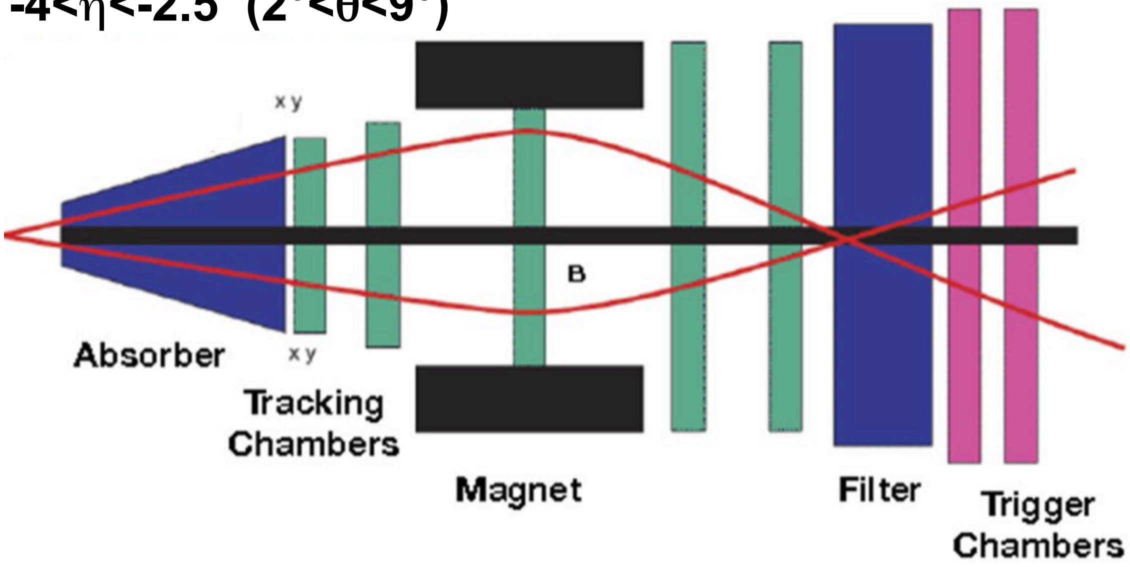
Non-HF decay electron subtraction

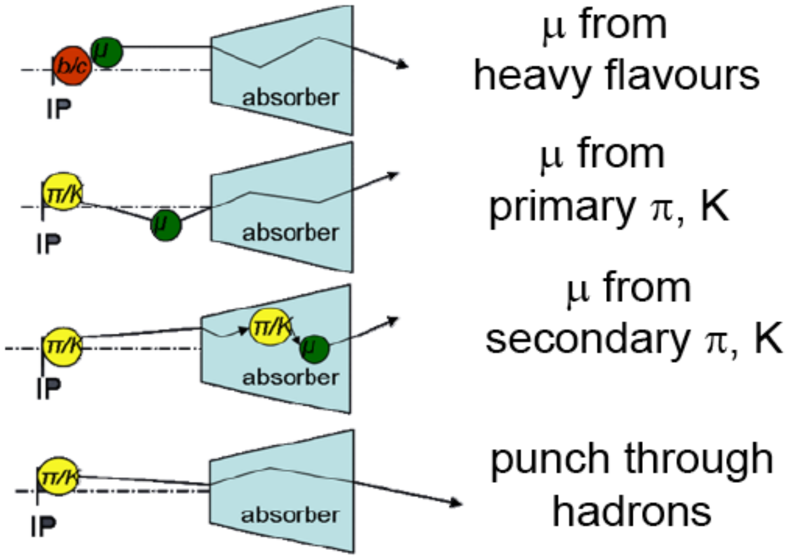
- data-tuned cocktail
- conversion + Dalitz with e^+e^- invariant mass analysis

Beauty/charm decay electron separation with impact parameter cut / fit

Heavy-flavour reconstruction in ALICE **forward muon** spectrometer

MUON SPECTROMETER
$-4<\eta<-2.5$ ($2°<\theta<9°$)





Muons from semi-leptonic heavy-flavour hadron decays

D,B, Λ_c,..→ μ X

Muon track selection

- Acceptance/geometrical cuts
- Tracks matched with trigger
- Pointing to the collision point

Heavy-flavour decay muon signal counting

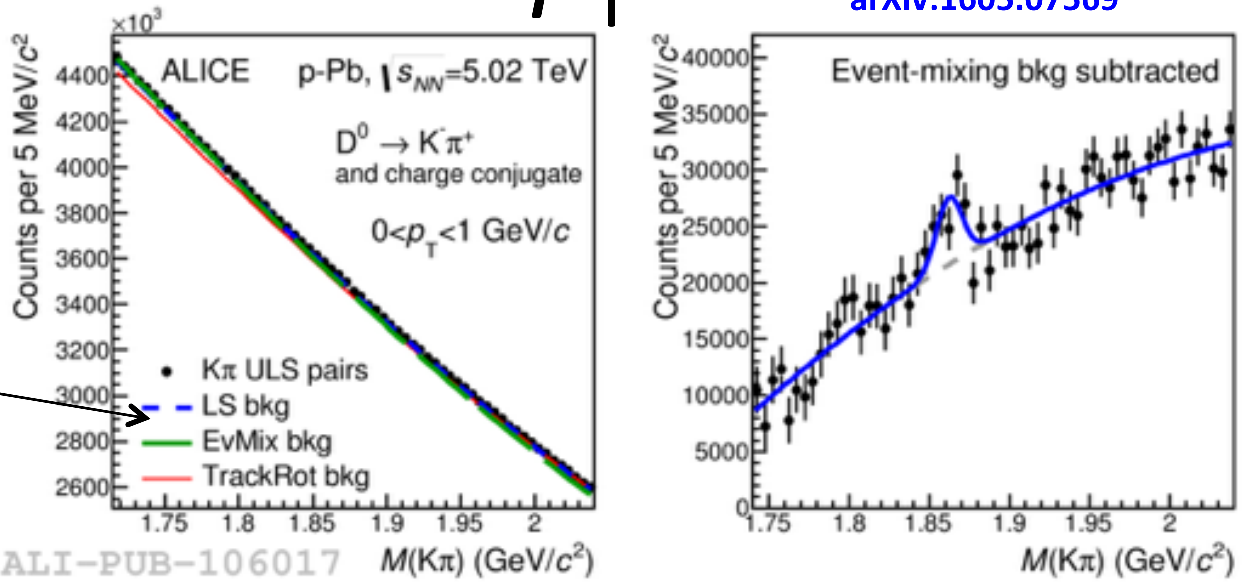
- After subtraction of muons from primary π,K decays via simulations with data-tuned π,K abundances
- Background of μ from W/Z/γ* decay subtracted with templates obtained from Monte Carlo simulations (POWHEG)

pp and p-Pb collisions

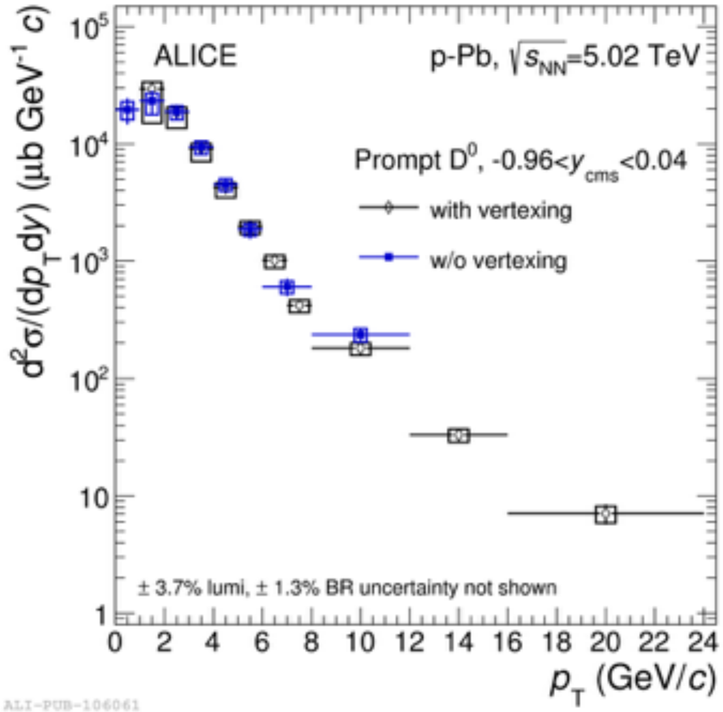
D mesons down to p_T=0

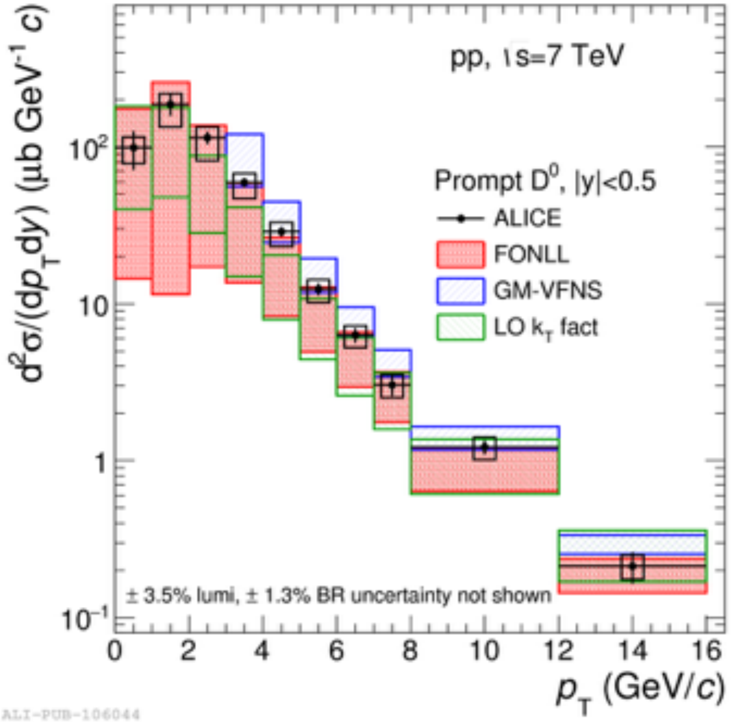
arXiv:1605.07569

- Effectiveness of standard analysis based on decay vertex reconstruction reduces for p_T<2 GeV/c (no boost)
- Alternative approach based on PID only
- Careful background subtraction with 4 different approaches



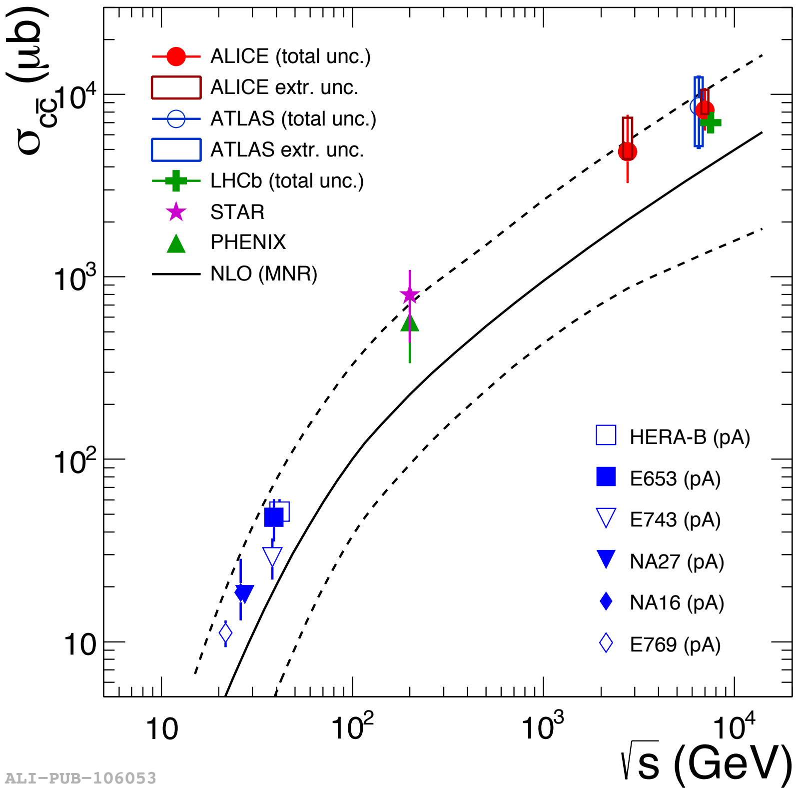
- Compatible results w/ and w/o vertex reconstruction for p_T>1 GeV/c
- Better performance w/o vertex reconstruction for p_T<2 GeV/c
- pQCD-based theoretical calculations reproduce the data
- Data much more precise than theoretical calculations





Total charm cross section

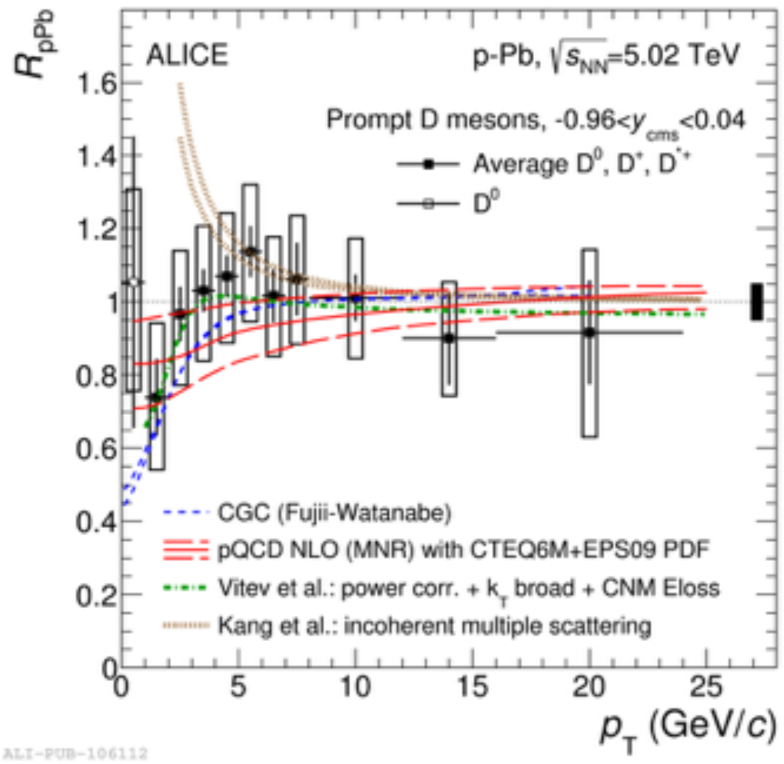
arXiv:1605.07569

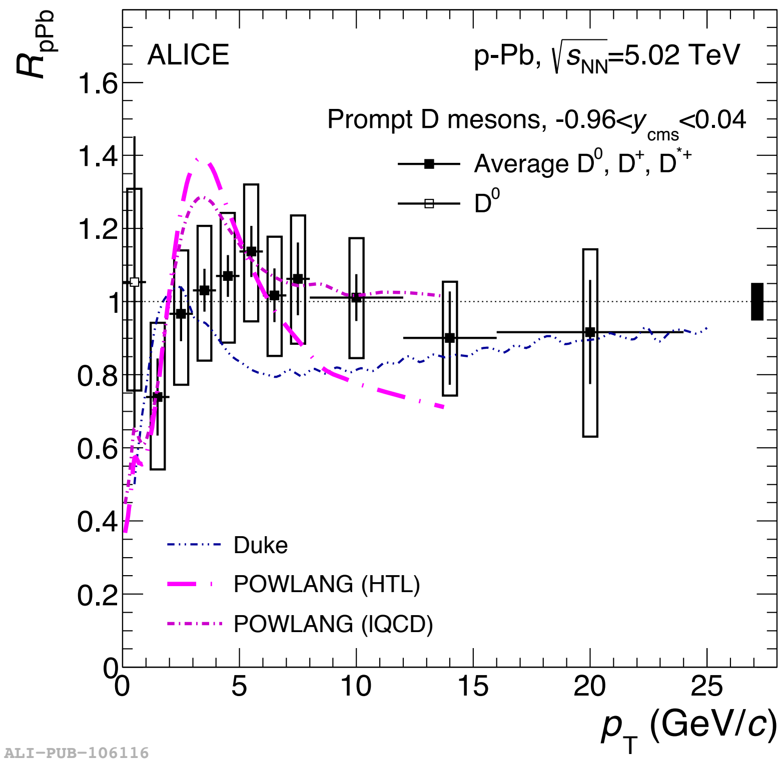


Factor ~2 reduction on systematic uncertainty

D-meson R_{pPb}

arXiv:1605.07569

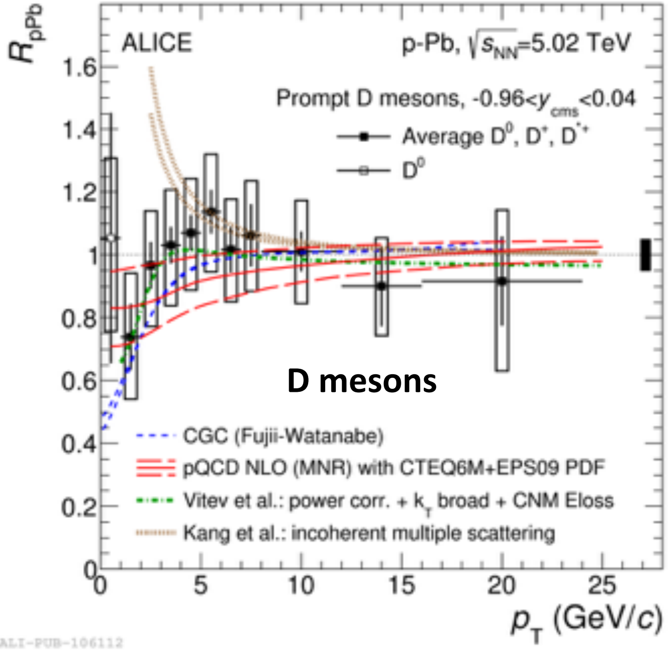




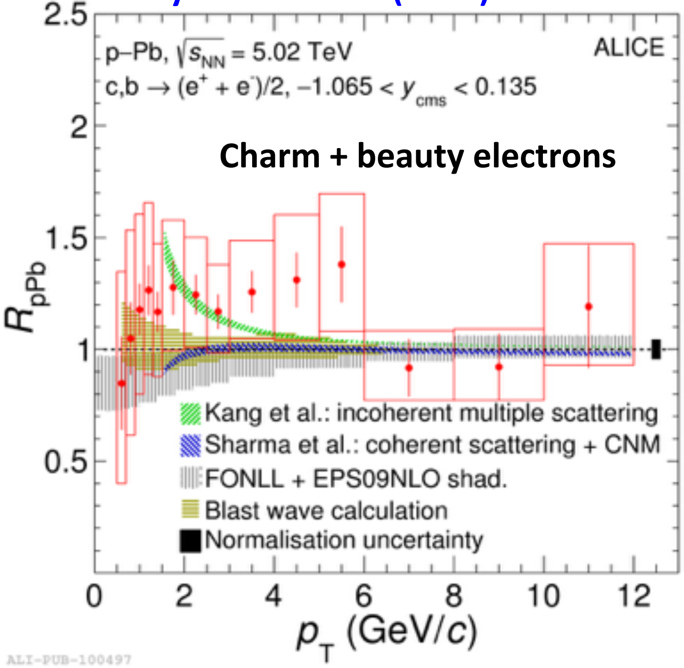
- **D-meson R_{pPb} compatible with unity within uncertainties**
- Data are described by models including initial-state and cold nuclear matter effects (left panel), as well as by models assuming the formation of a small-size QGP in p-Pb collisions (right panel)
- Need larger samples of both p-Pb and pp collisions @5 TeV for constraining models at low p_{T} where predictions differentiate.

D-meson, charm and beauty electron R_{pPb}

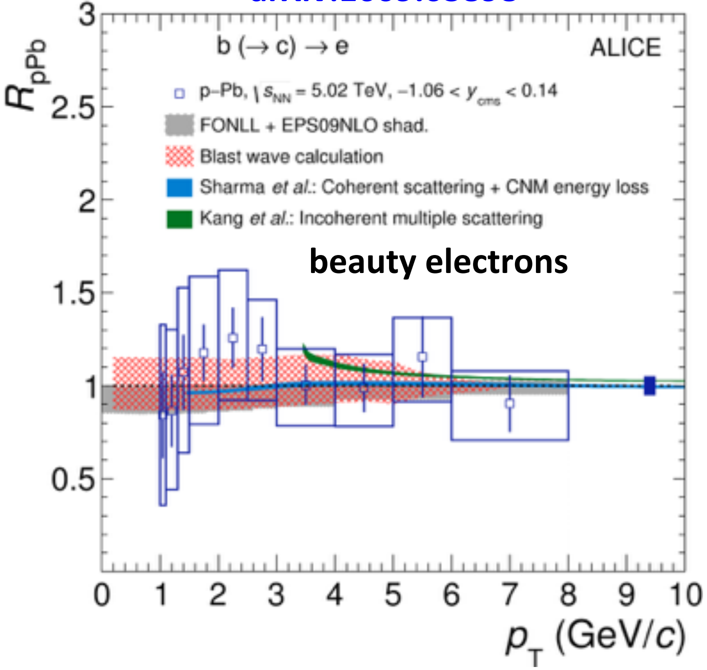
arXiv:1605.07569



Phys. Lett. B 754 (2016) 81-93



arXiv:1609.03898



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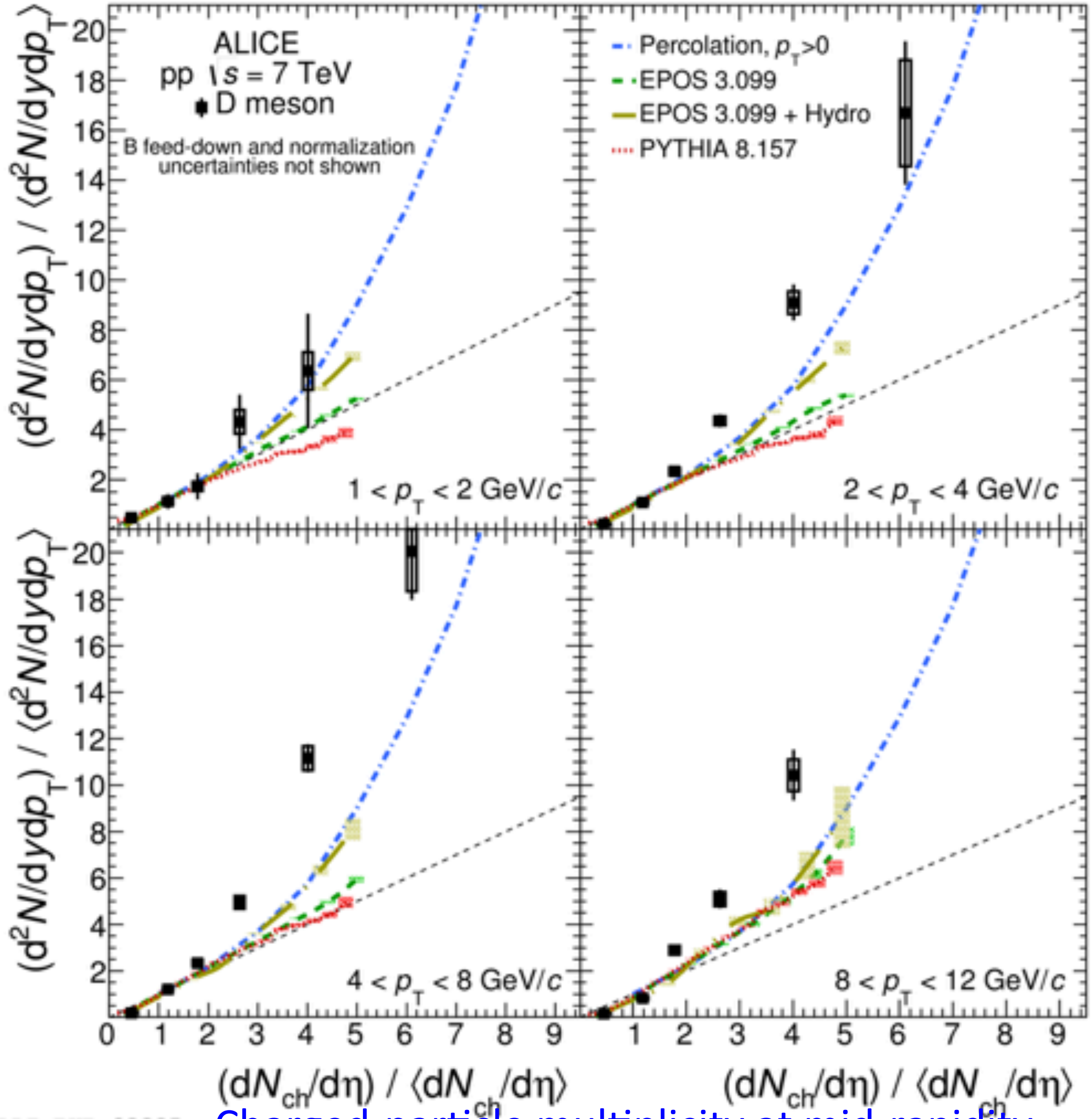
pp and p-Pb collisions:
more differential measurements

D-meson yields vs. multiplicity: comparison with models (pp)



Charged-particle multiplicity at mid-rapidity

JHEP 09 (2015) 148

Percolation (Ferreiro, Pajares, PRC 86 (2012) 034903

Particle production via exchange of colour sources between projectile and target (close to MPI scenario)

- Faster than linear increase

EPOS 3.099 (Werner et al., PRC 89 (2014) 064903)

Gribov-Regge multiple-scattering formalism
Saturation scale to model non-linear effects
Number of MPI directly related to multiplicity → slightly faster than linear
With hydrodynamical evolution applied to the core of the collision → faster than linear increase

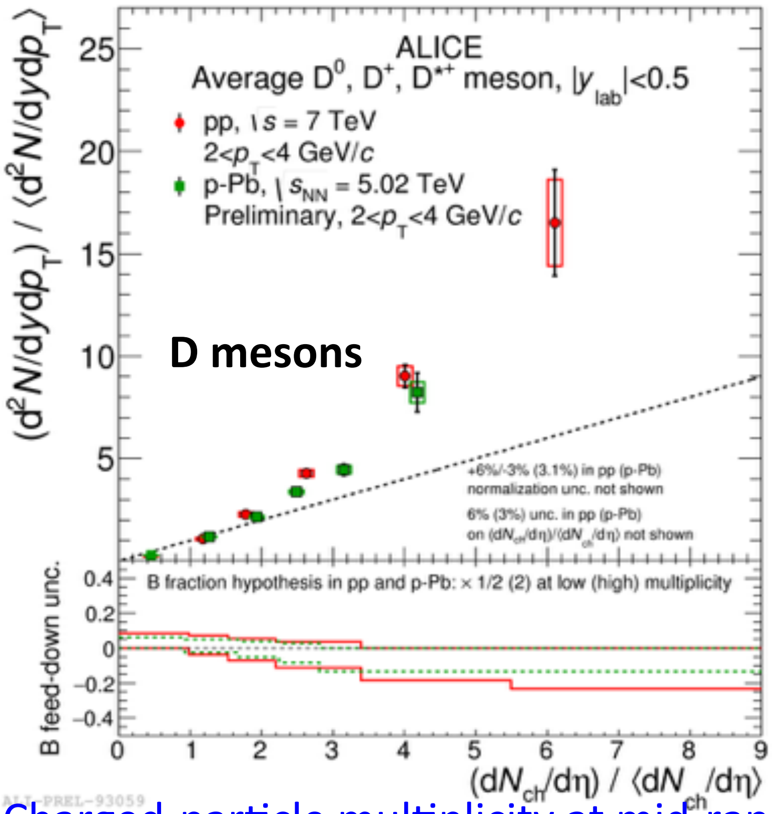
PYTHIA 8 (Sjostrand et al., Comput. Phys. Commun. 178 (2008) 852)

Soft-QCD tune
Colour reconnection
MPI

- Linear increase

D-meson yields vs. multiplicity in pp and p-Pb collisions

JHEP 09 (2015) 148
JHEP 08 (2016) 1



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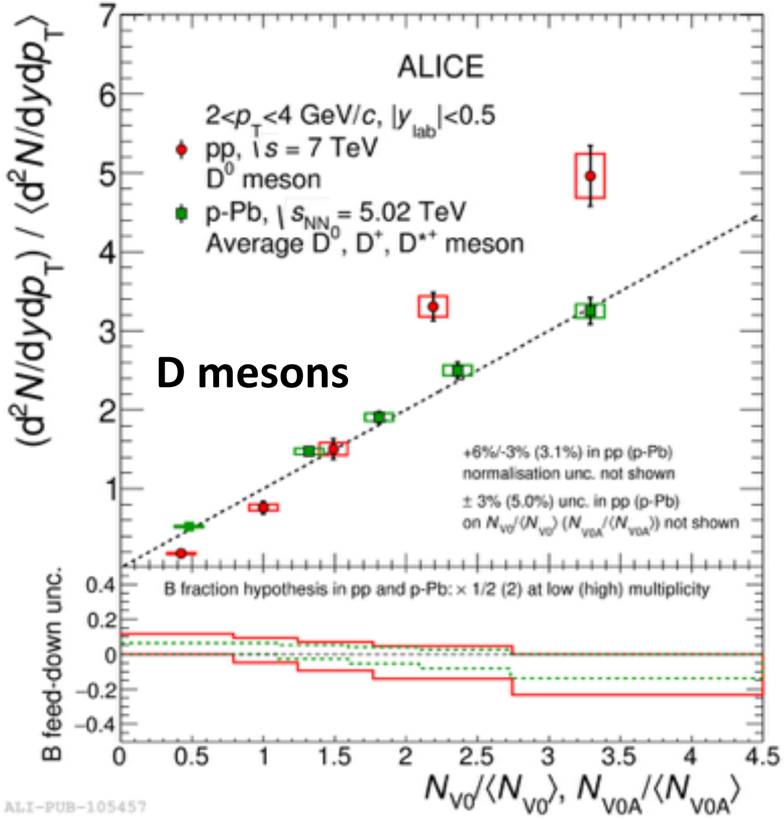
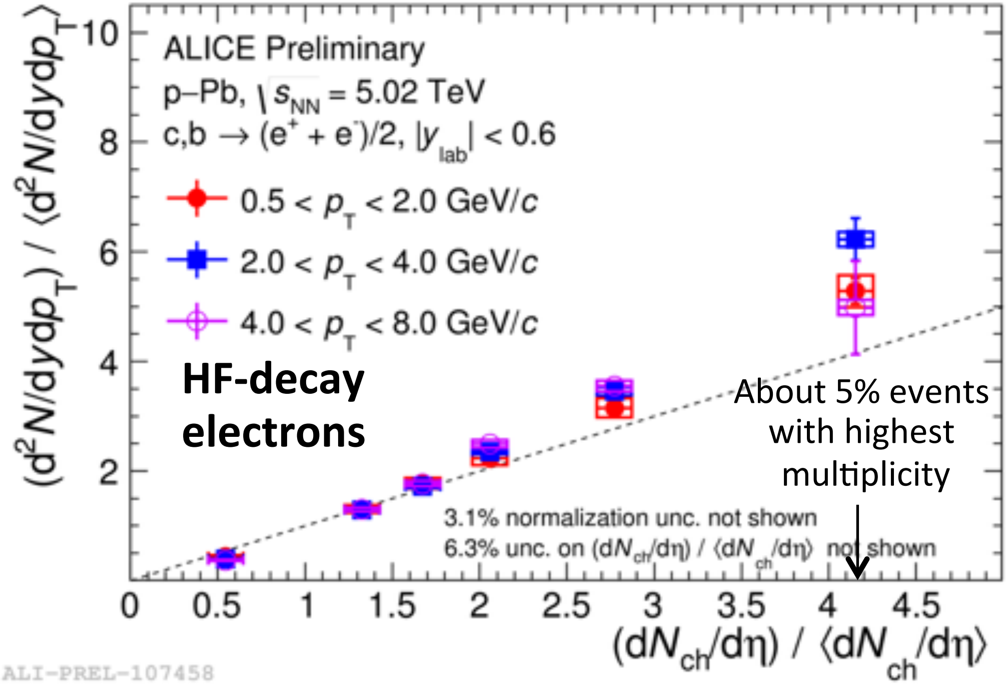


Charged-particle multiplicity at backward rapidity (Pb direction)

p-Pb: interplay of collision geometry (N_{coll}>1) and MPI, difficult to disentangle the two contributions
With event activity estimated at mid-rapidity (same region of D mesons): similar faster-than-linear increase in pp and p-Pb collisions
With event activity estimated at backward rapidity ($|\Delta\eta|>1.9$): faster increase in pp than in p-Pb

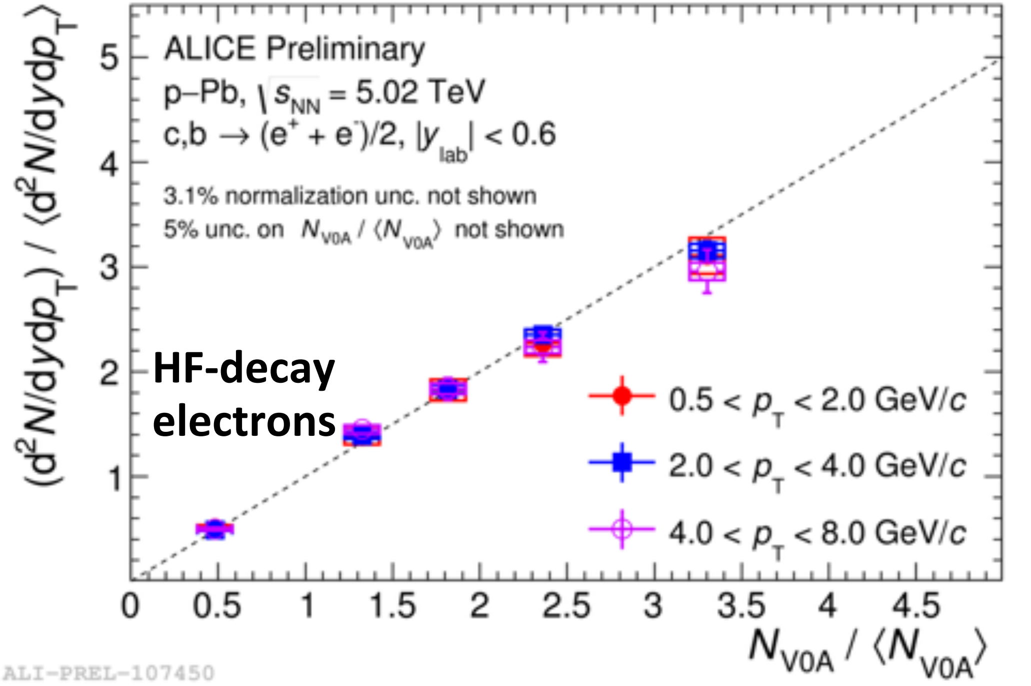
Heavy-flavour hadron decay electron yields vs. multiplicity in p-Pb collisions



HF-decay electrons

About 5% events with highest multiplicity

Charged-particle multiplicity at mid-rapidity



HF-decay electrons

Charged-particle multiplicity at backward rapidity (Pb direction)

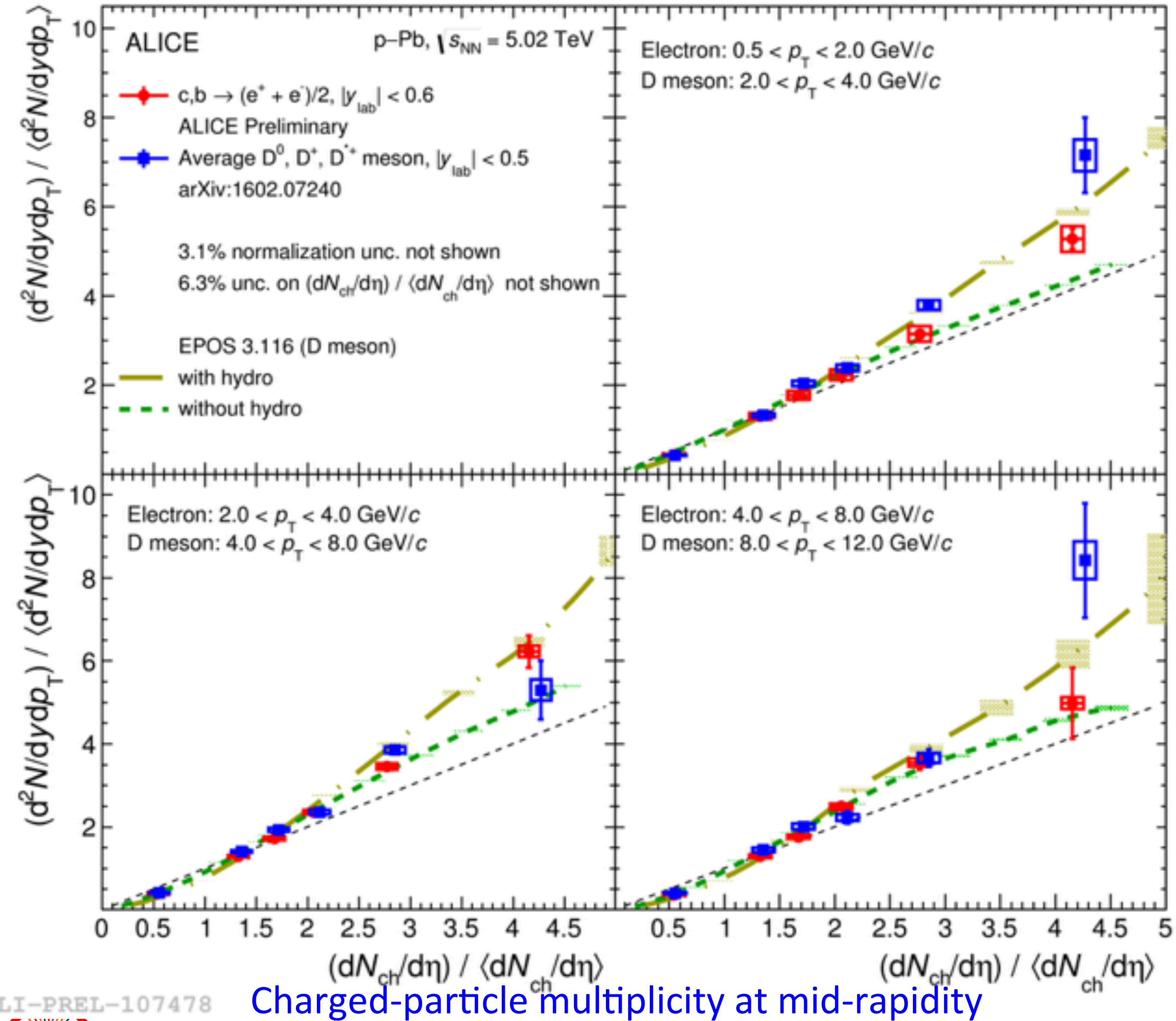
p-Pb: interplay of collision geometry (N_{coll}>1) and MPI, difficult to disentangle the two contributions

With event activity estimated at mid-rapidity (same region than HF-decay electrons): faster-than-linear increase

With event activity estimated at backward rapidity ($|\Delta\eta|$>1.9): ~ linear increase

No change for p_T>4 GeV/c where b→e^- contribution becomes larger than 50%

D-meson and HF-decay yields vs. multiplicity: comparison with models (p-Pb)



Charged-particle multiplicity at mid-rapidity

Momentum ranges compared are chosen to better match the electron parent-hadron momentum with the D-meson momentum range.

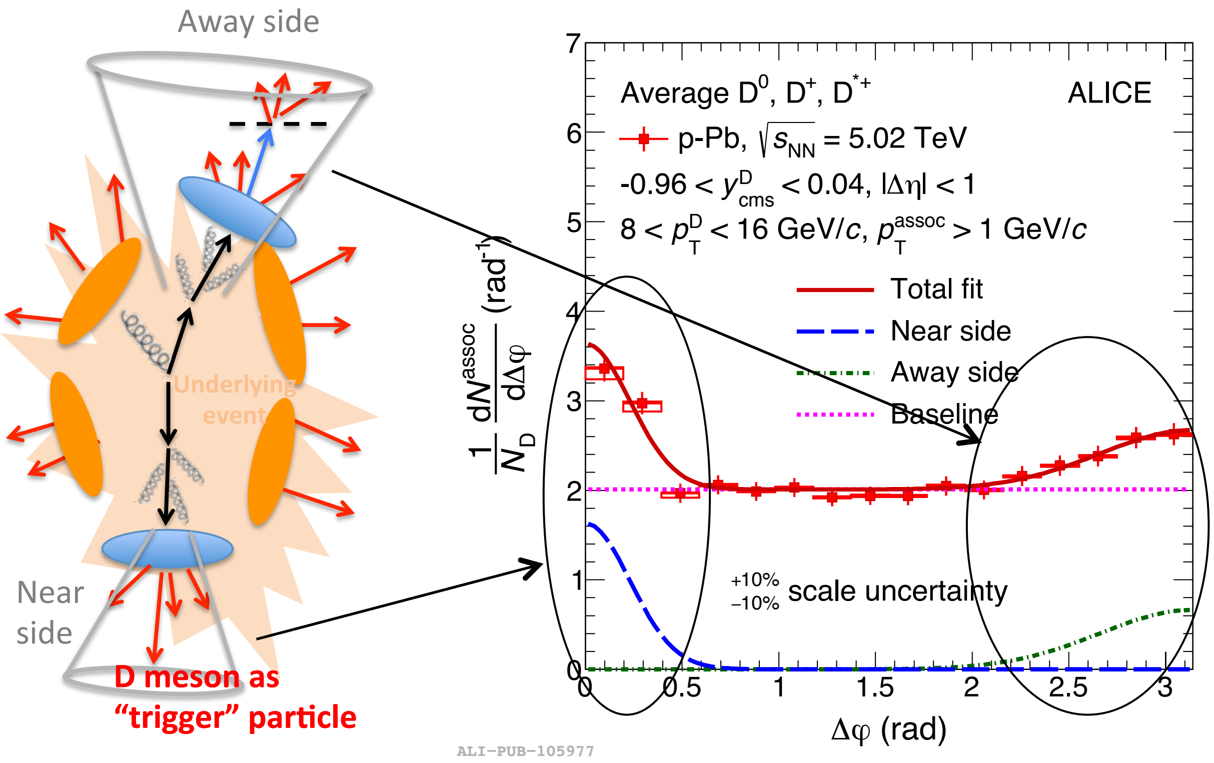
D meson and HF-decay electrons self-normalized yields compatible within uncertainties

EPOS 3.116

(Werner et al., PRC 89 (2014) 064903)

- Calculation for D mesons
- Initial conditions and hydrodynamical evolution
- Hint that D mesons are better reproduced by simulation with hydro

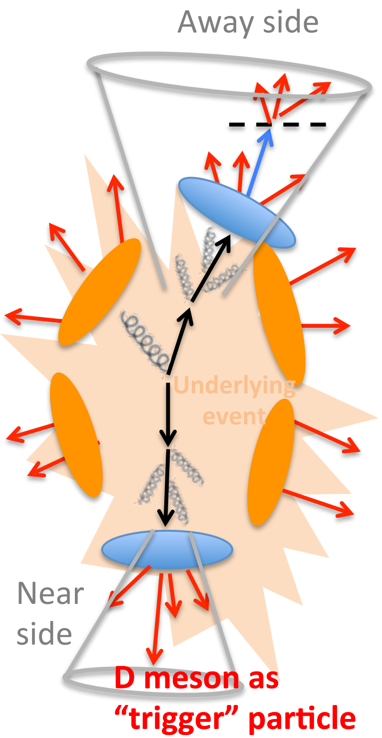
Azimuthal correlations of D mesons with charged particles



arXiv:1605:06963

Near-side peak properties (width, "associated yield") → address charm jet properties

Azimuthal correlations of D mesons with charged particles: pp vs. p-Pb

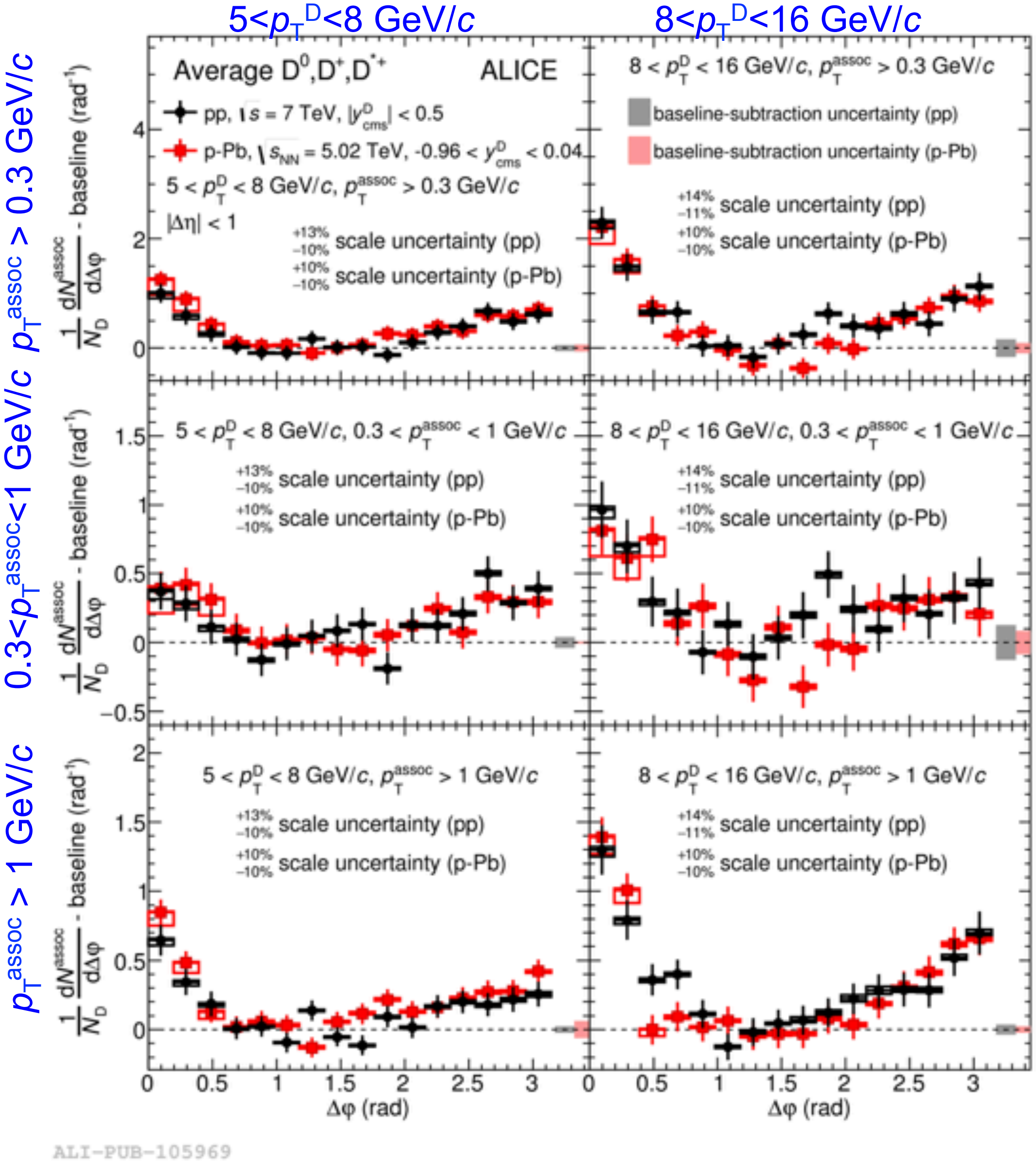


Away side

Underlying event

Near side

D meson as "trigger" particle

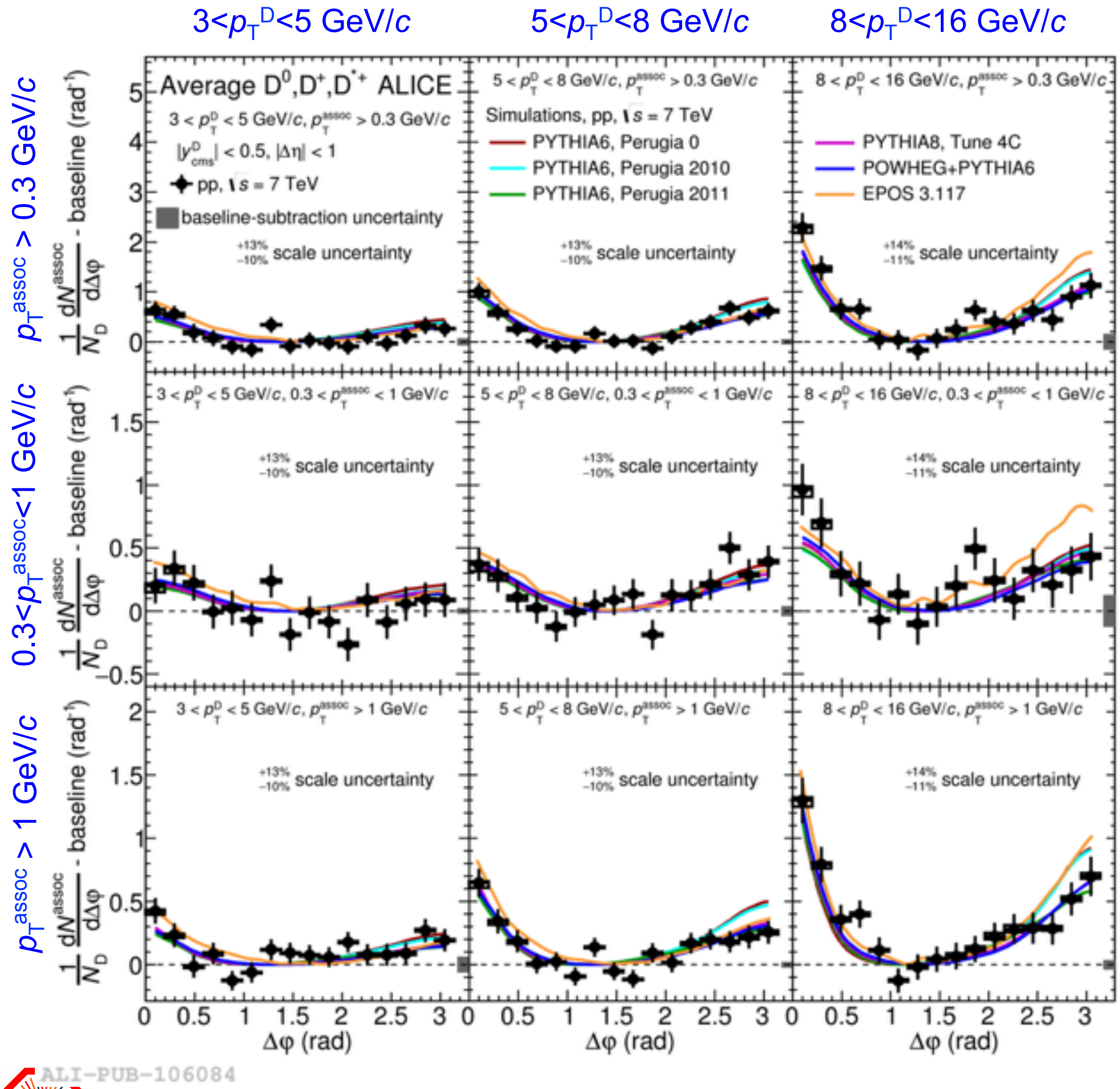


pp and p-Pb results compatible within uncertainties after the subtraction of the baseline

arXiv:1605:06963

Comparison to models

arXiv:1605:06963



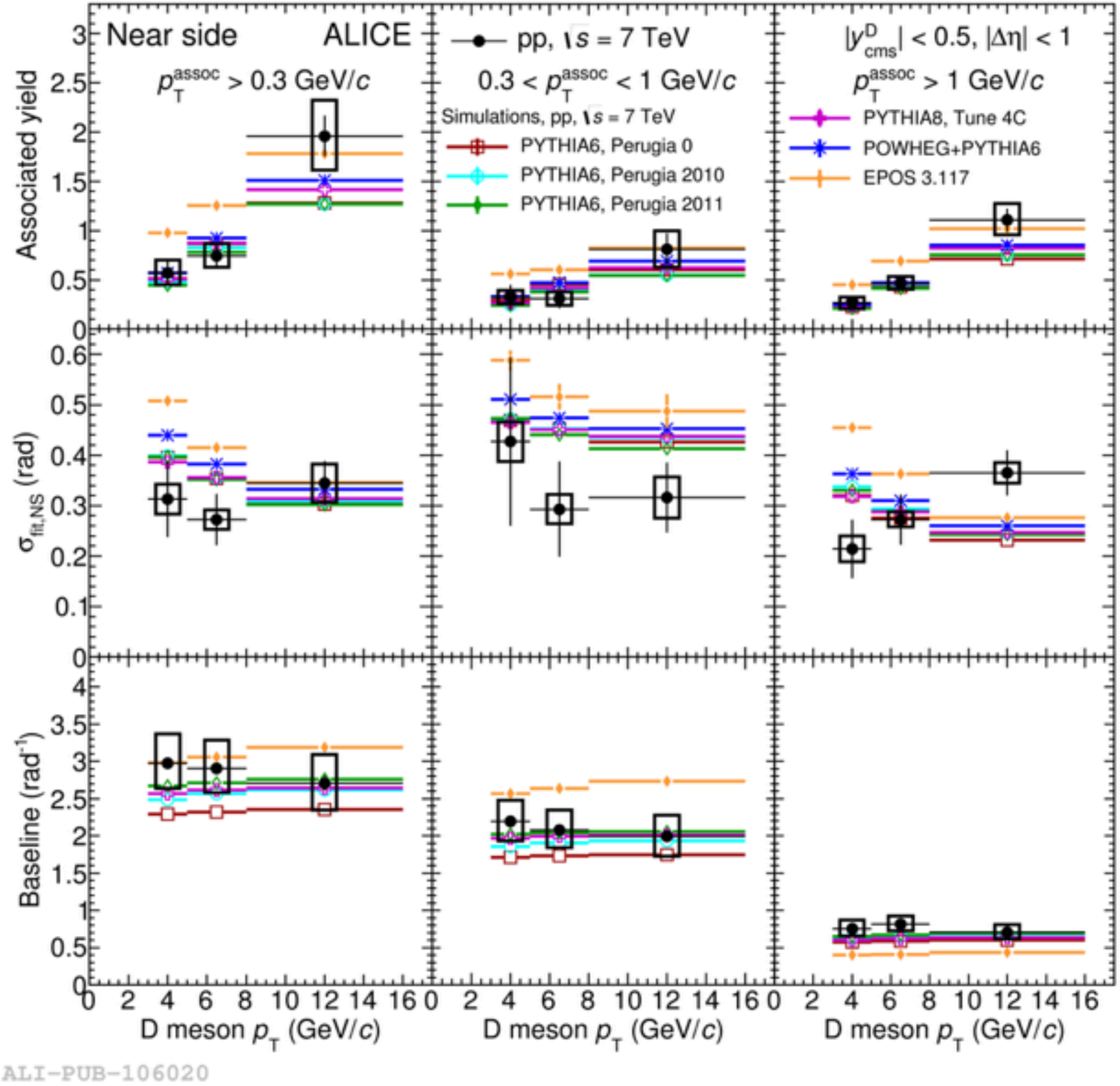
Baseline-subtracted correlation distributions in pp collisions reproduced within uncertainties by

- PYTHIA 6, PYTHIA 8
- POWHEG+PYTHIA
- EPOS 3.117

Comparison to models

arXiv:1605:06963

$p_T^{assoc} > 0.3$ GeV/*c* $0.3 < p_T^{assoc} < 1$ GeV/*c* $p_T^{assoc} > 1$ GeV/*c*

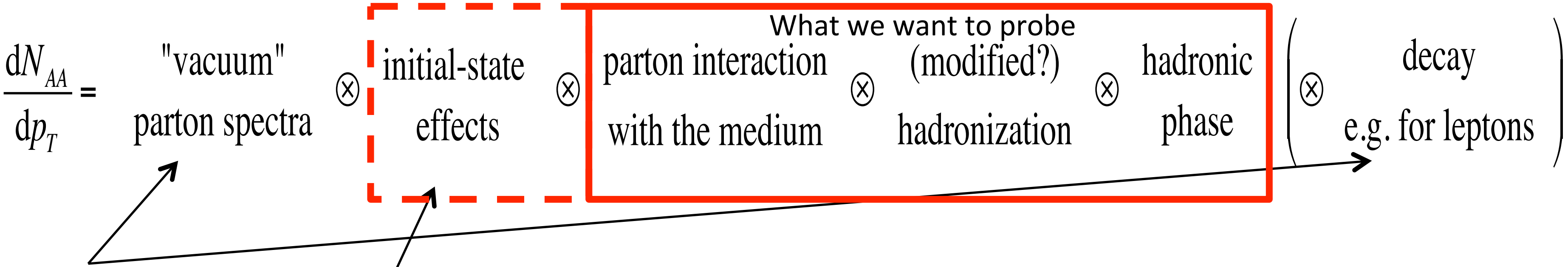


Near-side associated yield, width and baseline described within uncertainty by

- PYTHIA 6 , PYTHIA 8
- POWHEG+PYTHIA
- EPOS 3.117

Pb-Pb collisions

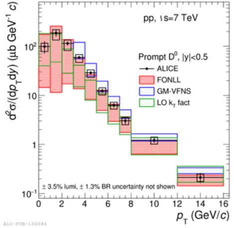
A rather long shopping list



What we want to probe

$$\frac{dN_{AA}}{dp_T} = \begin{matrix}\text{"vacuum"}\\ \text{parton spectra}\end{matrix} \otimes \begin{matrix}\text{initial-state}\\ \text{effects}\end{matrix} \otimes \begin{matrix}\text{parton interaction}\\ \text{with the medium}\end{matrix} \otimes \begin{matrix}\text{(modified?)}\\ \text{hadronization}\end{matrix} \otimes \begin{matrix}\text{hadronic}\\ \text{phase}\end{matrix} \left(\otimes \begin{matrix}\text{decay}\\ \text{e.g. for leptons}\end{matrix} \right)$$

pp collisions

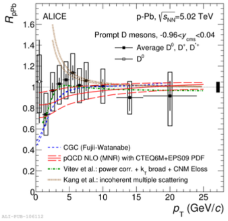


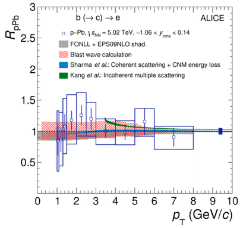
Charm and beauty lose energy

Via radiative and collisional processes

- quark mass (e.g. from dead-cone effect)
- color charge (Casimir factor)
- path length and medium density

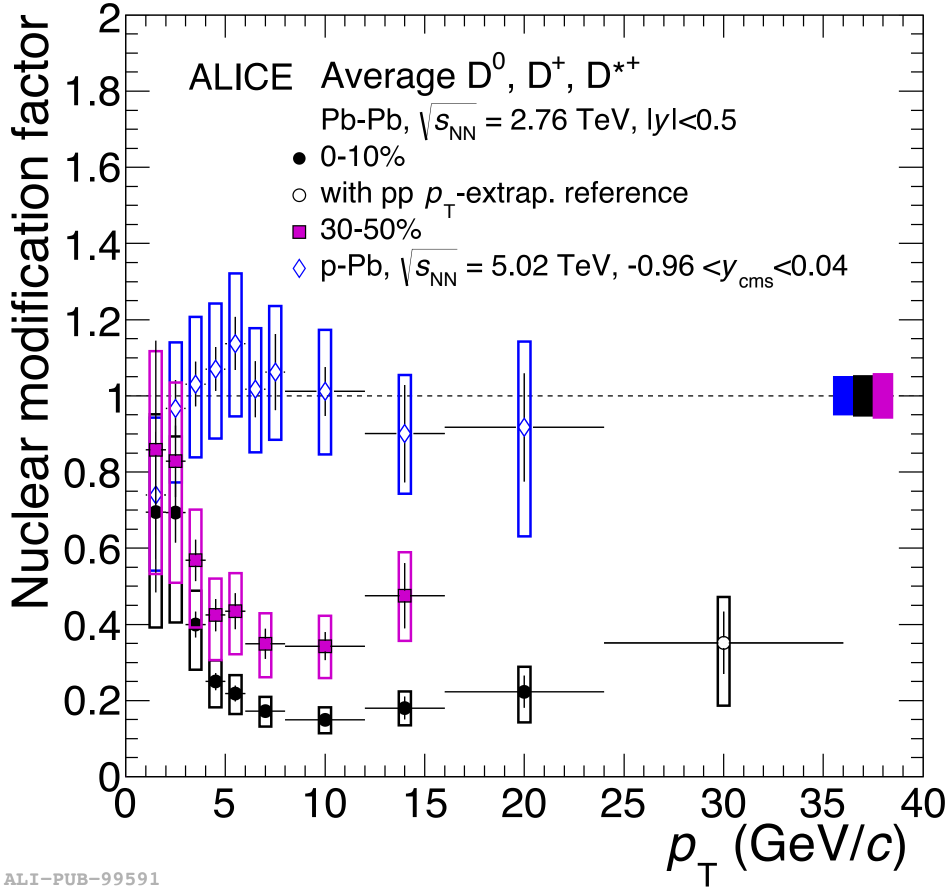
Constrain models with measurements from p-Pb collisions





Hadronization via coalescence with medium quarks?

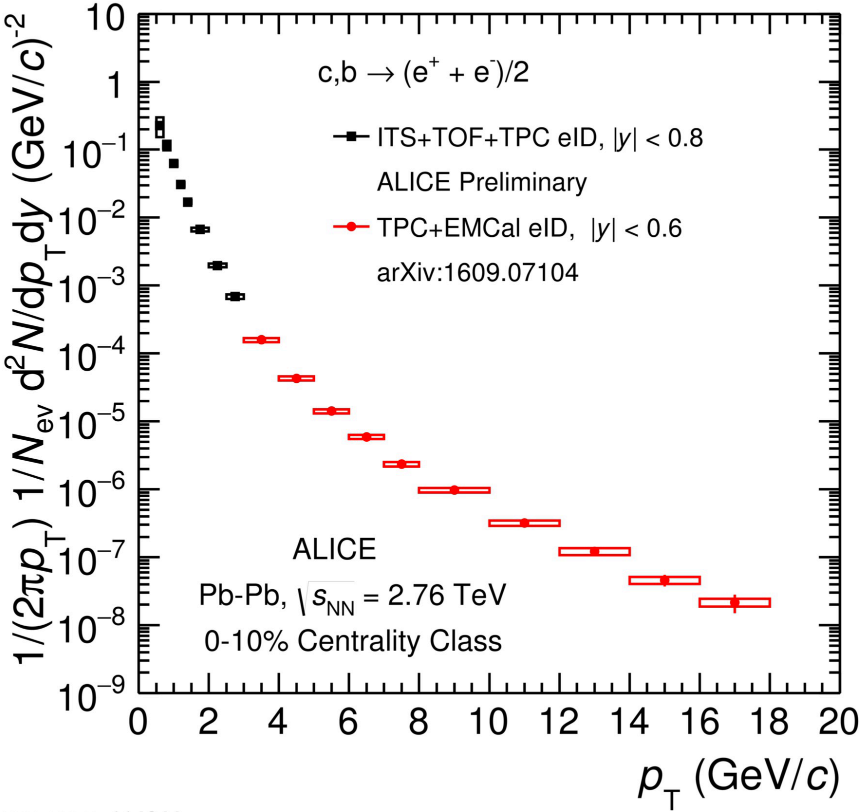
D-meson suppression at $\sqrt{s_{NN}}$=2.76 TeV



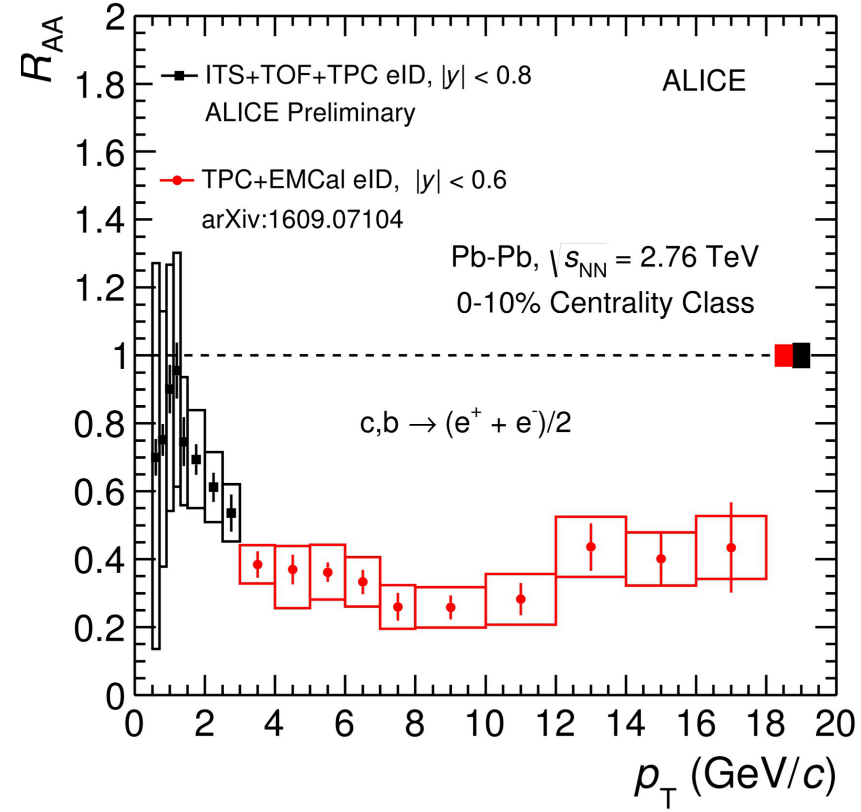
JHEP1603 (2016) 081

D meson production suppressed up to a factor ~6 (p_T~10 GeV/c) in central Pb-Pb collisions
Comparison with R_{pPb}~1 → **final-state effect due to in-medium charm-quark energy loss**

Heavy-Flavour decay electron R_{AA}



ALI-PREL-114344



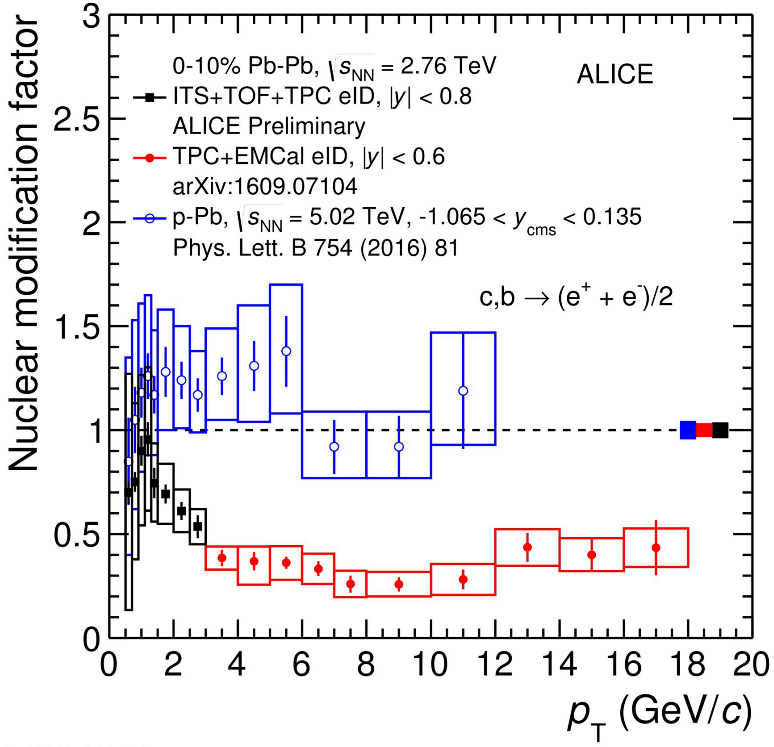
ALI-PREL-114357

New R_{AA} measurements at $\sqrt{s_{NN}}$=2.76 TeV

- final result for p_T>3 GeV/c with TPC+EMCAL (large beauty contribution) **arXiv:1609.07104**
- New measurement for **0.5<p_T<3 GeV/c: crucial interval in all systems for testing binary scaling** of the total $c\bar{c}$ cross section.
    - Systematic uncertainty dominated by the reference at the same collision energy (Phys. Rev. D 91 (2015) 012001)
    - R_{AA} rising towards low p_T in the range 1<p_T<3 GeV/c

Heavy-Flavour decay electron R_{AA} vs. R_{pPb}

arXiv:1609.07104
Phys. Lett. B 754 (2016) 81-93

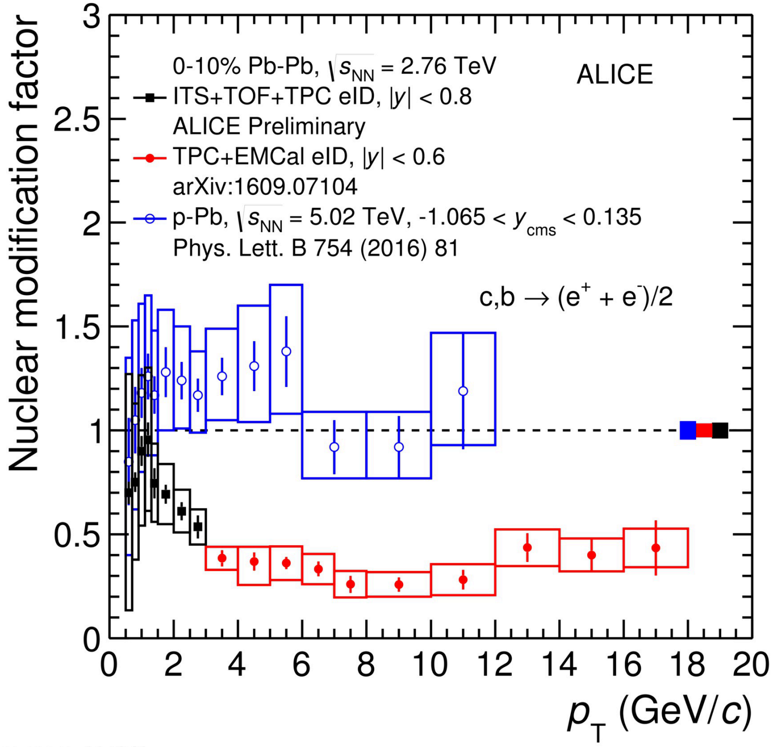


ALI-PREL-114361

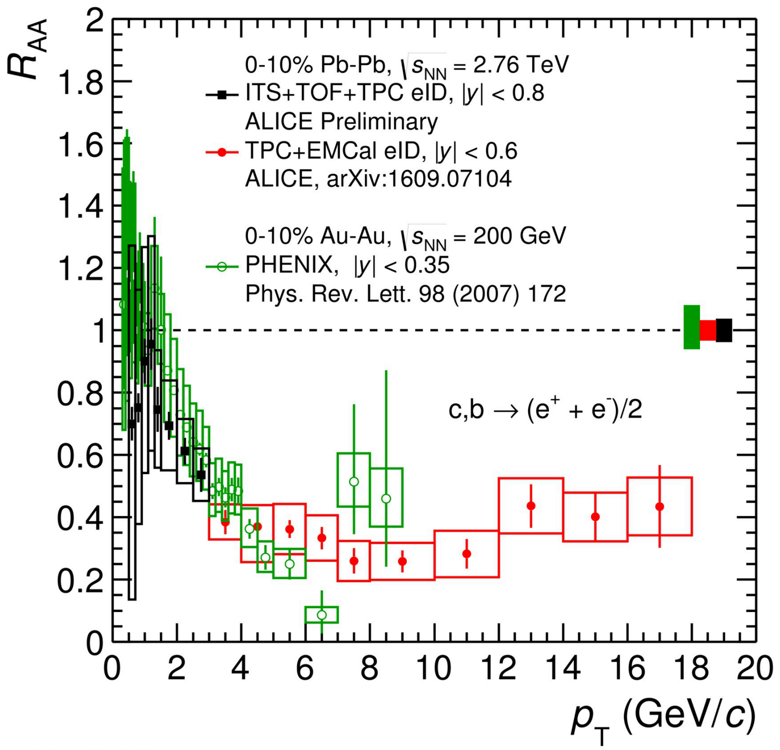
- Comparison of R_{pPb} and R_{AA} at intermediate-high p_T → suppression observed in Pb-Pb is a final-state effect due to charm and beauty in-medium energy loss.
- Beauty component >50% from p_T>5 GeV/c in pp → **beauty suppression at high p_T**

Heavy-Flavour decay electron R_{AA} vs. R_{pPb}

arXiv:1609.07104
Phys. Lett. B 754 (2016) 81-93



ALI-PREL-114361

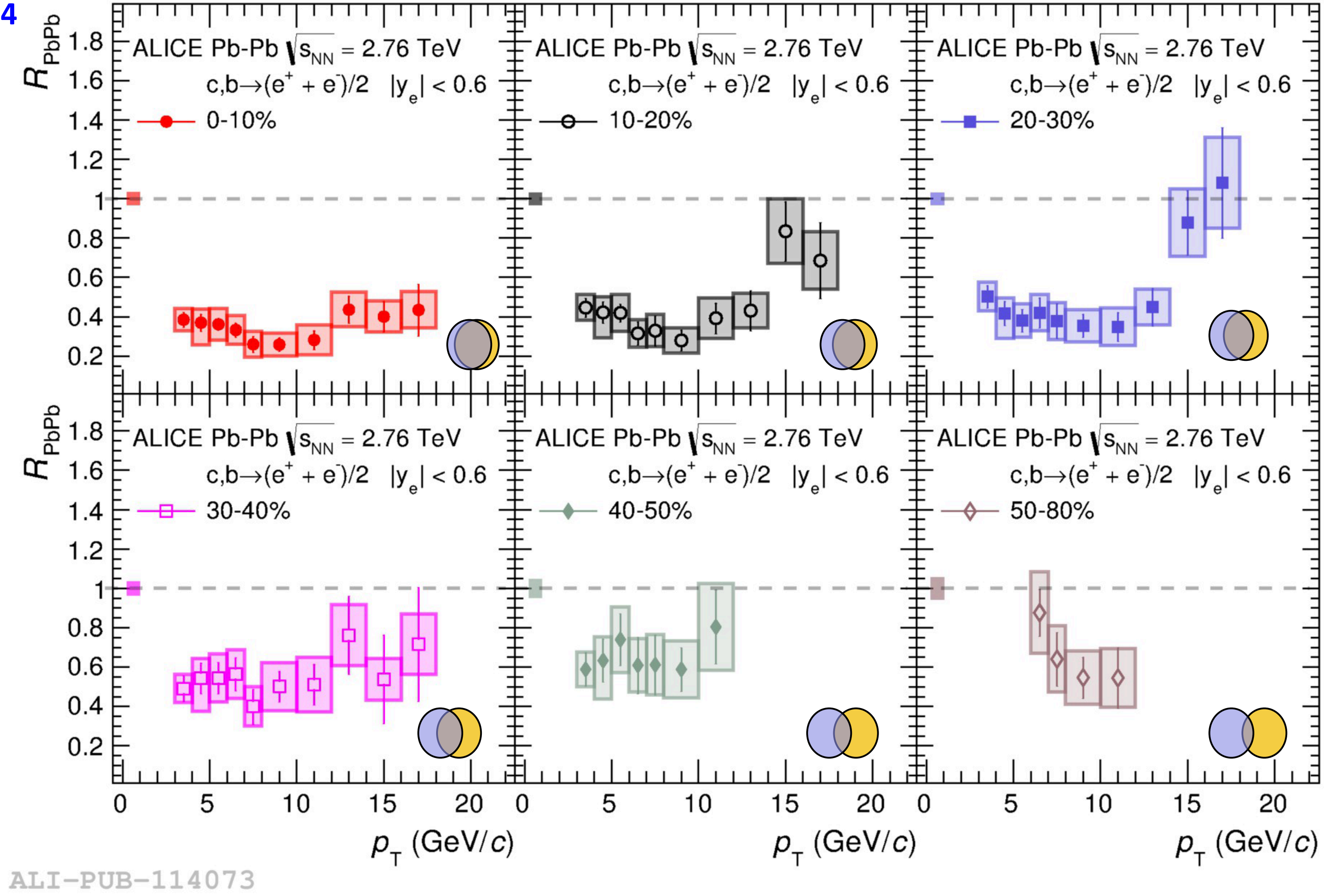


ALI-PREL-114340

- Comparison of R_{pPb} and R_{AA} at intermediate-high p_{T} → suppression observed in Pb-Pb is a final-state effect due to charm and beauty in-medium energy loss.
- Beauty component >50% from p_{T}>5 GeV/c in pp → **beauty suppression at high p_{T}**
- At low p_{T}: values and trend compatible with PHENIX R_{AA} in Au-Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV
  - N.b. Does not imply same energy loss! (different initial spectra, initial-state effects, charm and beauty fraction)

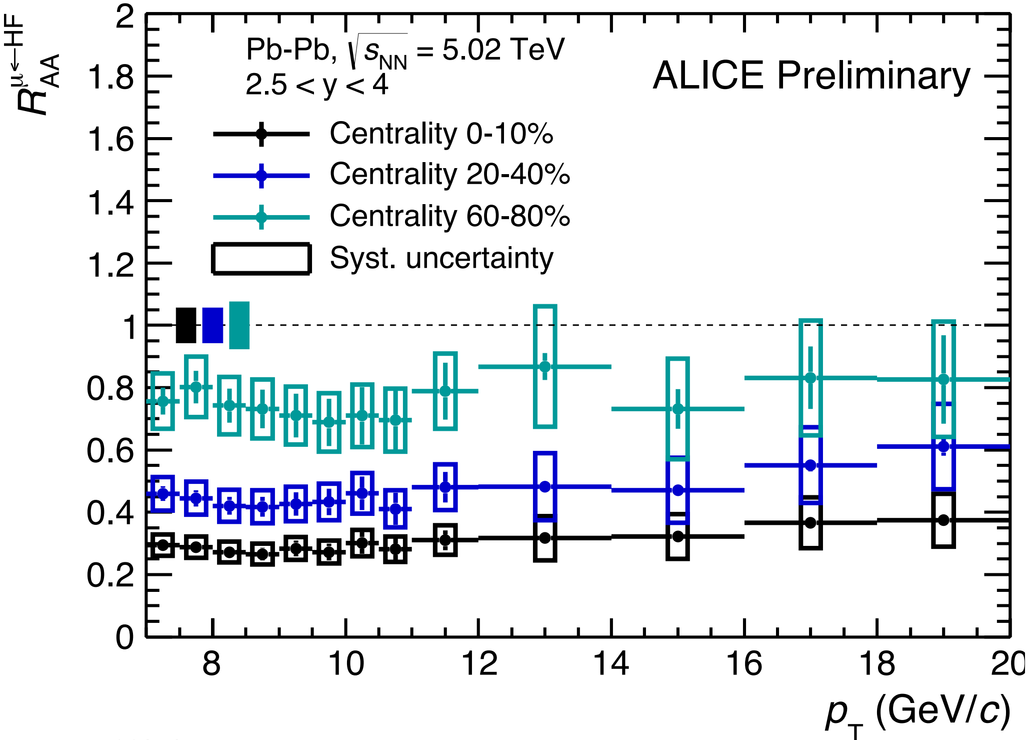
Heavy-Flavour decay electron R_{AA}

arXiv:1609.07104

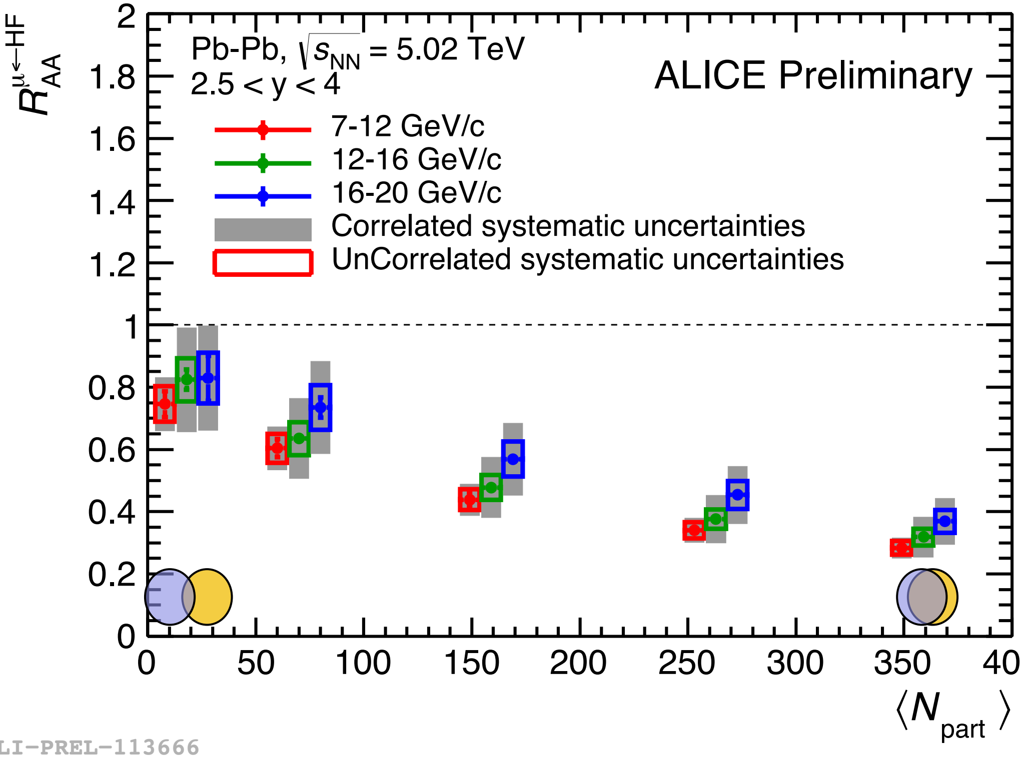


R_{AA} vs. centrality: stronger suppression at intermediate p_T in central than peripheral collisions

Heavy-Flavour decay muon R_{AA} at $\sqrt{s_{NN}}$=5.02 TeV



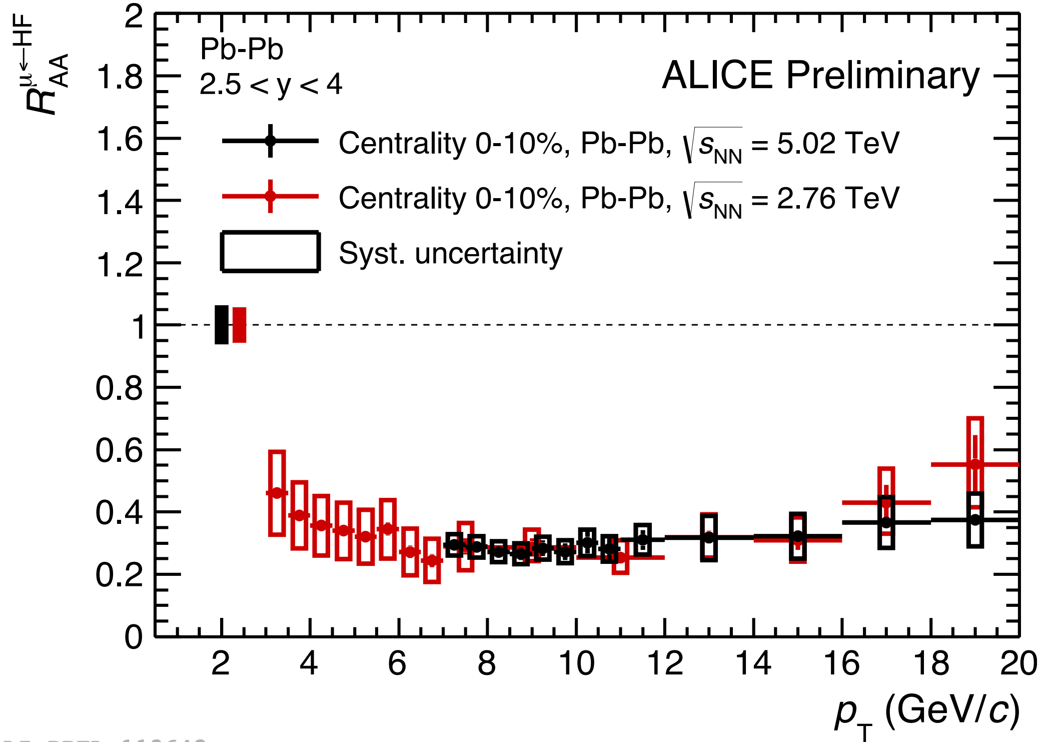
ALI−PREL−113634



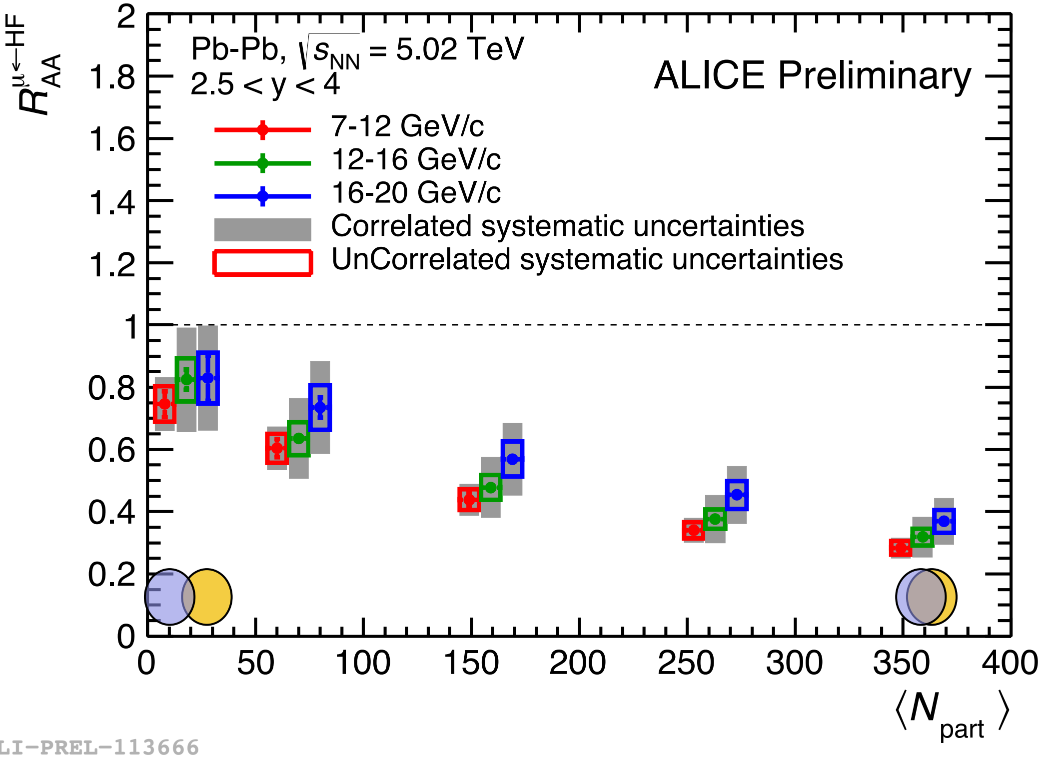
LI−PREL−113666

- Strong suppression (R_{AA}~0.3-0.4 in 7<p_T<12 GeV/c) in central collisions
- Beauty component >50% from p_T>5 GeV/c in pp → **beauty suppression at high p_T**
- R_{AA} increases towards peripheral centralities

Heavy-Flavour decay muon R_{AA} at $\sqrt{s_{NN}}$=5.02 TeV



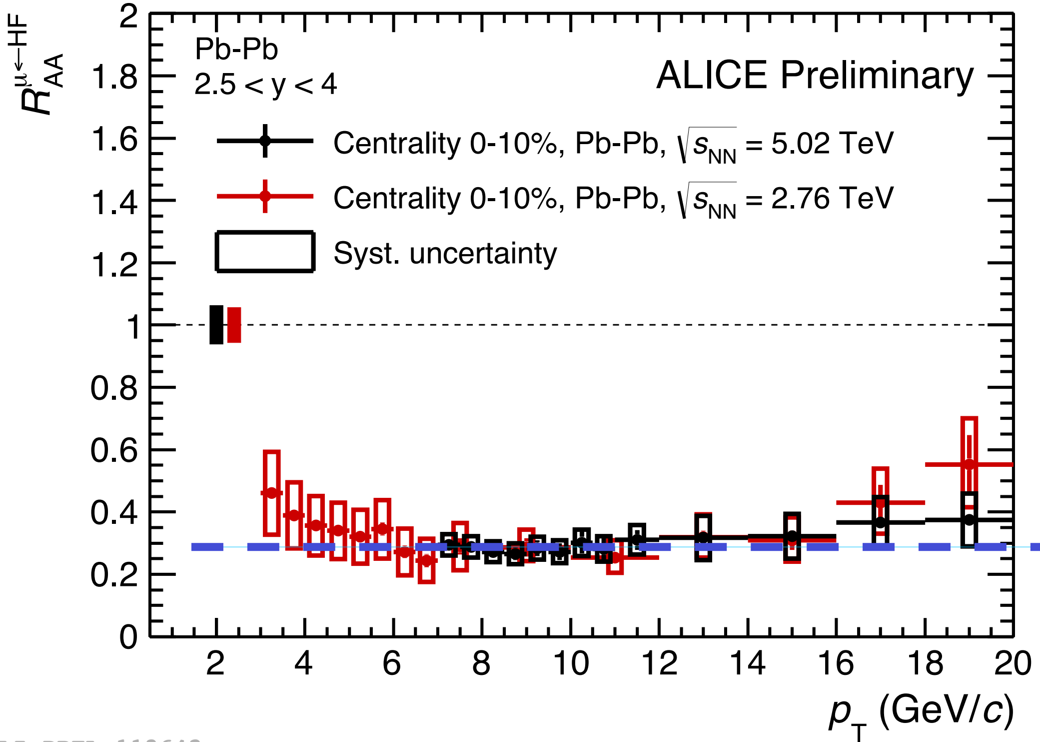
ALI−PREL−113642



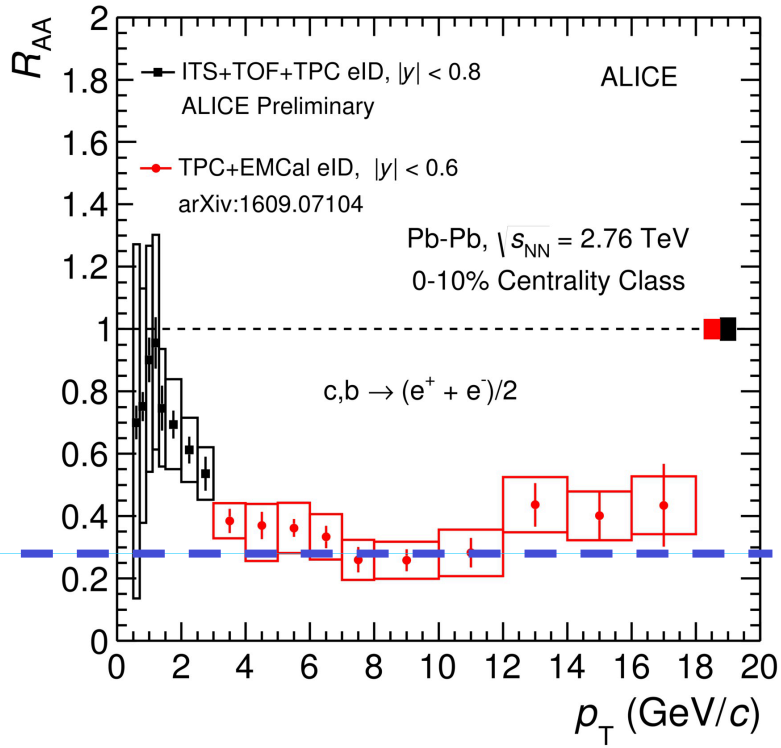
LI−PREL−113666

- Strong suppression (R_{AA}~0.3-0.4 in 7<p_T<12 GeV/c) in central collisions
- Beauty component >50% from p_T>5 GeV/c in pp → **beauty suppression at high p_T**
- R_{AA} increases towards peripheral centralities
- **Very similar R_{AA} at $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$=5.02 TeV** (n.b. does not imply same energy loss for charm and beauty at the two collision energies: slightly stronger energy loss at 5.02 TeV from slightly higher energy density may be compensated by harder spectra + possible variation of charm and beauty fractions)

Heavy-Flavour decay muon R_{AA} at $\sqrt{s_{NN}}$=5.02 TeV



ALI-PREL-113642



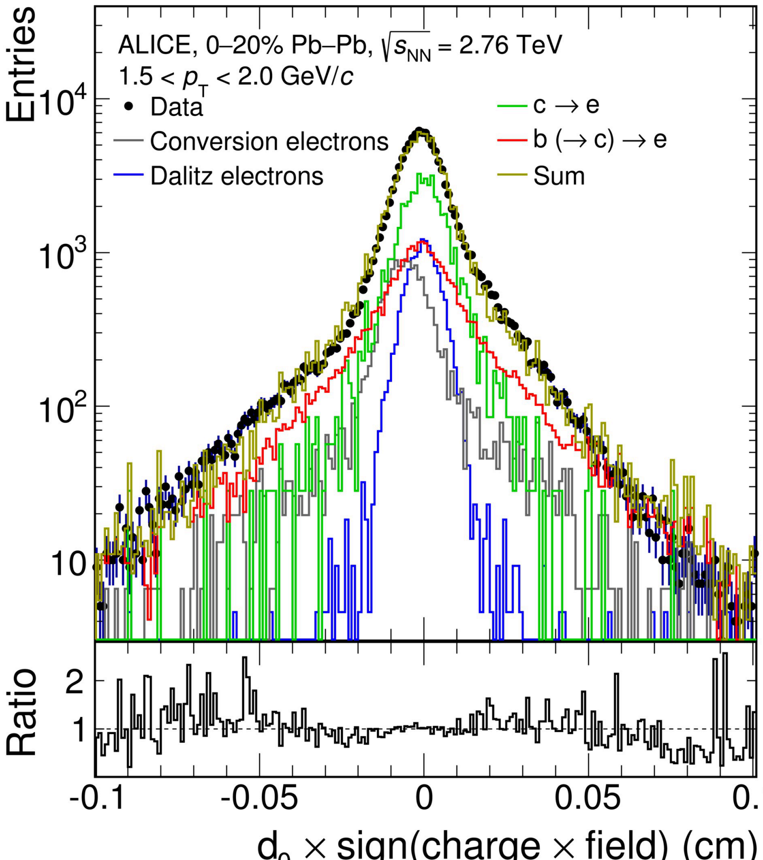
ALI-PREL-114357

Compatible R_{AA} for HF-decay electrons with $|y|<0.6$ and HF-decay muons with $2.5<y<4$

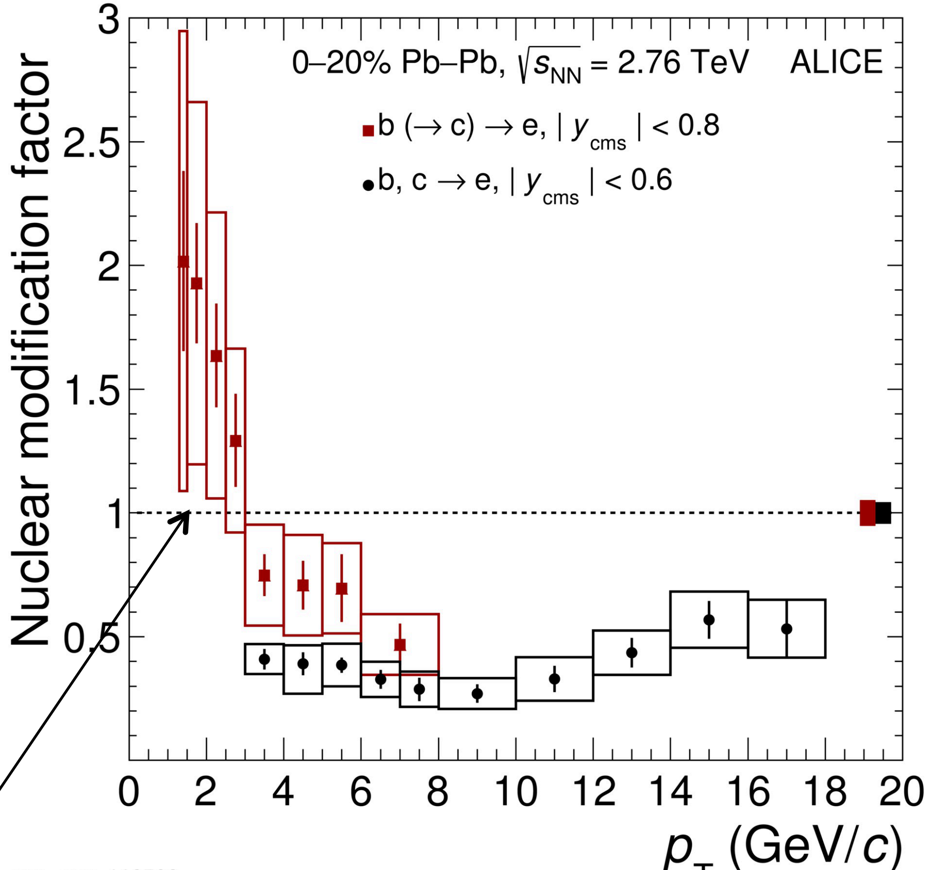
→ **beauty suppression at intermediate-high p_T at mid- and forward rapidity**

Beauty-decay electron R_{PbPb}

arXiv:1609.03898



ALI-PUB-112436

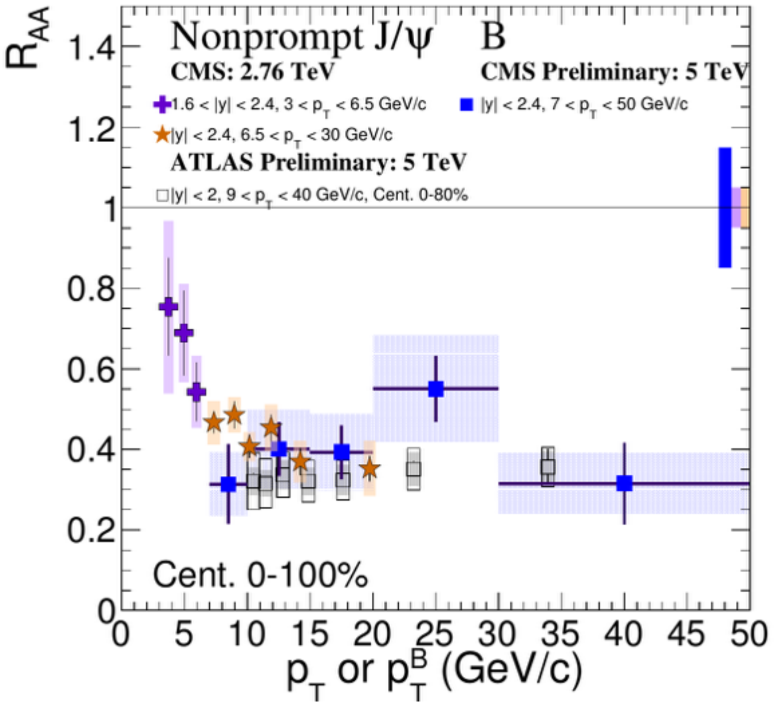


ALI-PUB-112709

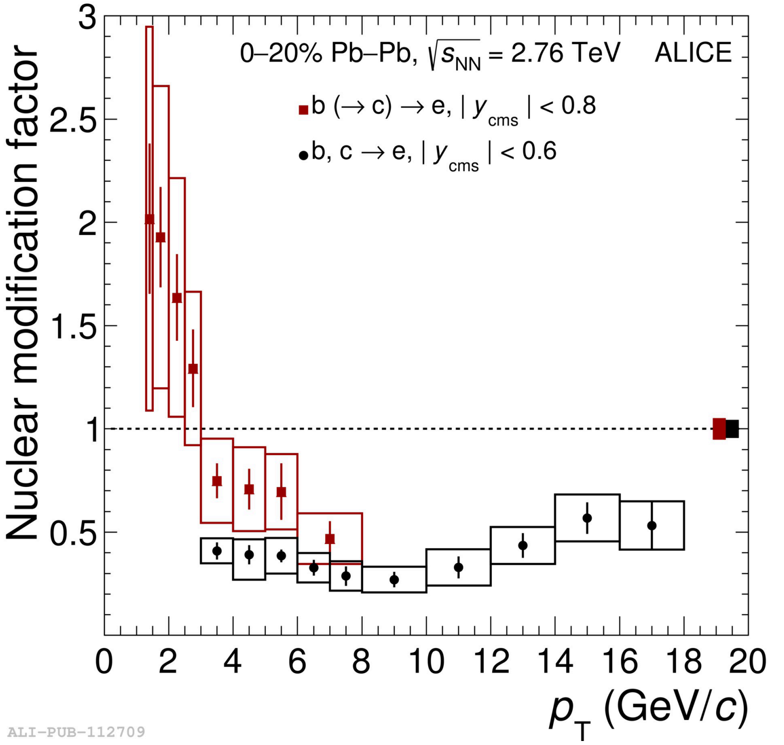
First measurement of beauty-decay electron R_{AA}

- Indication for **R_{AA}<1 for p_{T}>3 GeV/*c***
- Result consistent with the picture of mass-dependent radiative and collisional energy loss

Beauty suppression at LHC



arXiv:1609.03898

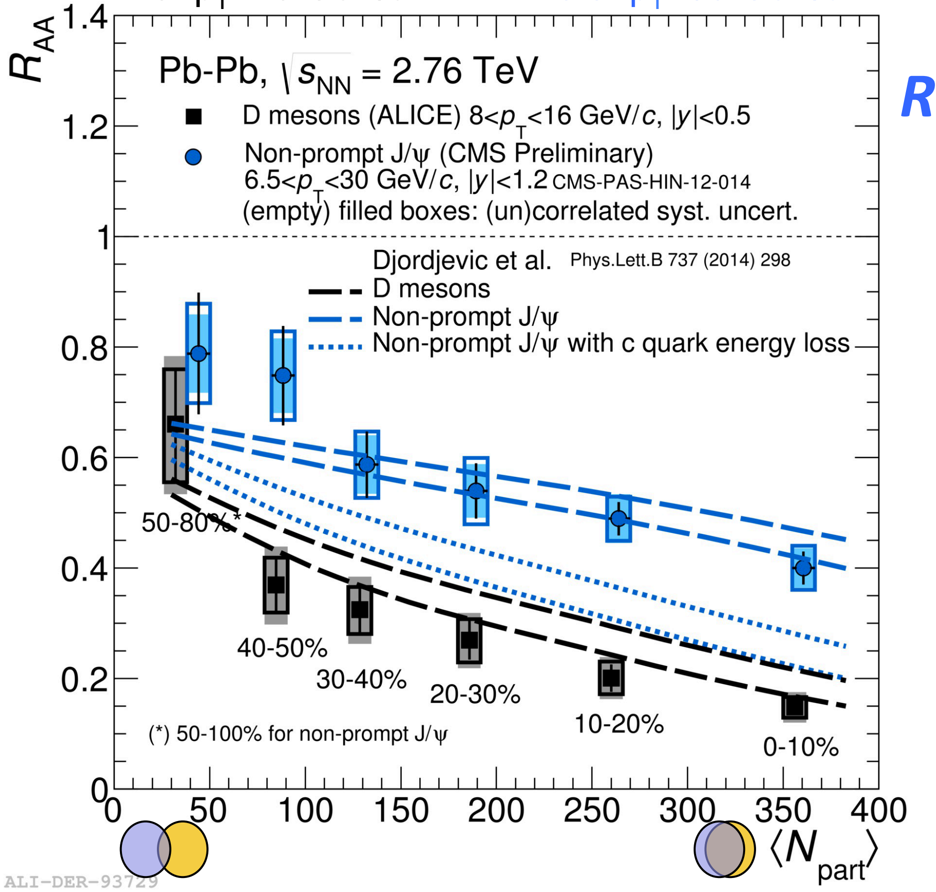


Several measurements at the LHC confirm beauty suppression at intermediate/high p_T:
B mesons (CMS), J/ψ from B (CMS, ATLAS, ALICE in backup), beauty-electrons (ALICE), high-p_T electrons (ALICE) and muons (ALICE,ATLAS)

ALICE, JHEP 1511 (2015) 205
CMS-PAS-HIN-12-014
CMS-PAS-HIN-15-005

Charm vs. beauty

ALICE, D mesons vs. **CMS, J/ψ from B**
8<p_T<16 GeV/*c* 6.5<p_T<30 GeV/*c*



R_{AA} (J/ψ from B) > **R_{AA}(D)** in central collisions

p_T interval tuned to have p_T(D)~p_T(B):
~70% of J/ψ from B mesons with 8<p_T<16 GeV/*c*
(median ~11 GeV/*c* vs. ~10 for D mesons)

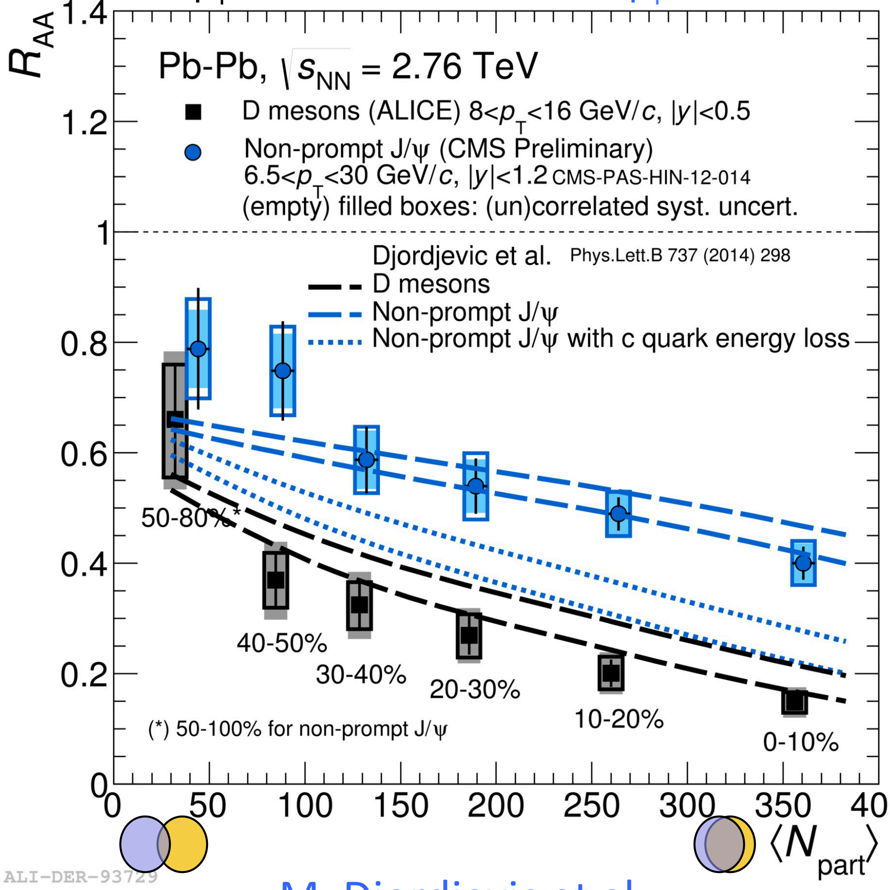
⇩

Indication of R_{AA} (B) > R_{AA}(D)

ALICE, JHEP 1511 (2015) 205
CMS-PAS-HIN-12-014
CMS-PAS-HIN-15-005

Charm vs. beauty

ALICE, D mesons vs. **CMS, J/ψ from B**
$8<p_T<16$ GeV/*c* — $6.5<p_T<30$ GeV/*c*



M. Djordjevic et al.
(Phys. Lett. B 737 (2014) 298; priv. comm.)

Radiative (DGLV formalism) + collisional energy loss, dynamical scattering centres in the medium

R_{AA} (J/ψ from B) > **R_{AA}(D)** in central collisions

p_T interval tuned to have p_T(D)~p_T(B):
~70% of J/ψ from B mesons with $8<p_T<16$ GeV/*c*
(median ~11 GeV/*c* vs. ~10 for D mesons)

⇩

Indication of R_{AA} (B) > R_{AA}(D)

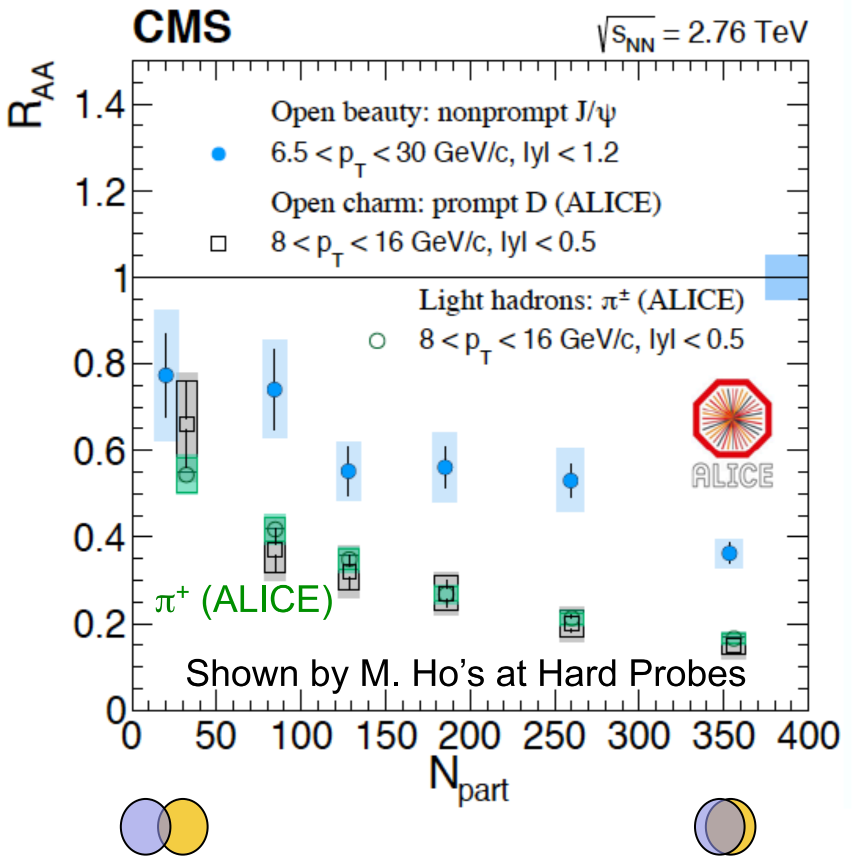
The different suppression and the centrality dependence are **described by models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b$)**

Comparison to other models (WHDG, MC@HQs +EPOS2, BAMPS, TAMU, Vitev et al.) shown in extra slides

ALICE, JHEP 1511 (2015) 205
CMS-PAS-HIN-12-014
CMS-PAS-HIN-15-005

Charm vs. beauty

ALICE, D mesons vs. **CMS, J/ψ from B**
$8<p_T<16$ GeV/*c* $6.5<p_T<30$ GeV/*c*



M. Djordjevic et al.
(Phys. Lett. B 737 (2014) 298; priv. comm.)
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~70% of J/ψ from B mesons with $8<p_T<16$ GeV/*c*
(median ~11 GeV/*c* vs. ~10 for D mesons)

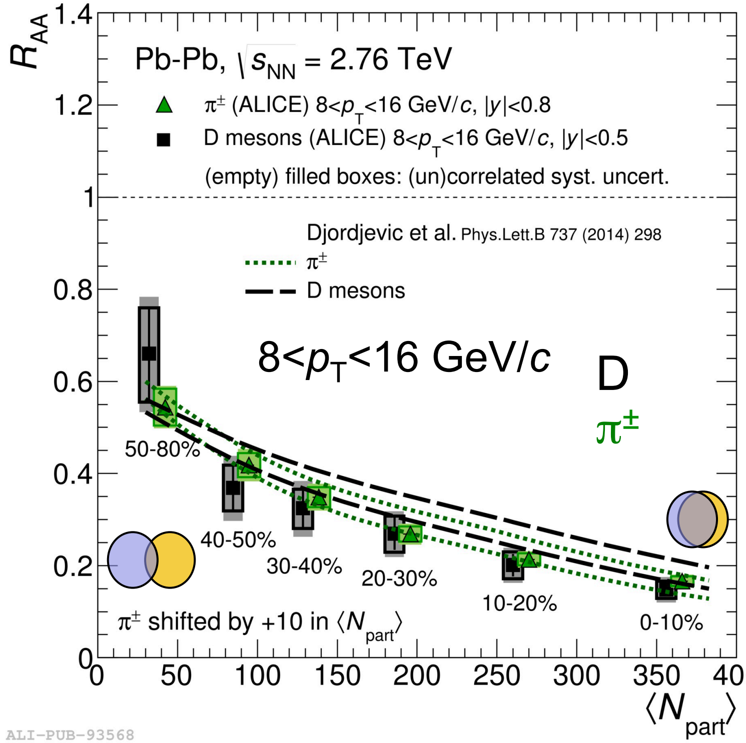
⇩

Indication of R_{AA} (B) > R_{AA}(D)

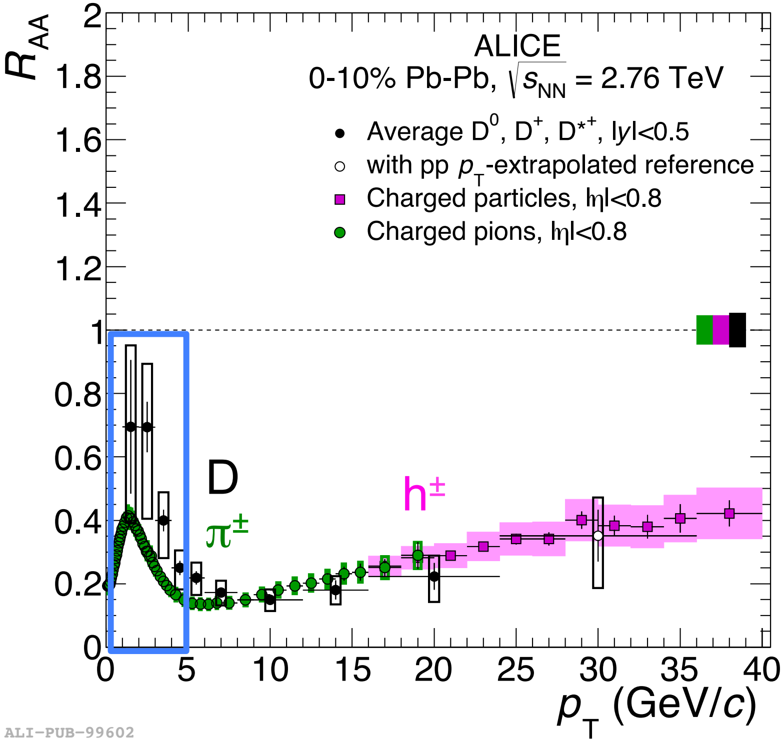
The different suppression and the centrality dependence are **described by models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b$)**

Same conclusion with final CMS results

Charm vs. light quarks/gluons



ALI-PUB-93568



ALI-PUB-99602

D-meson and pion R_{AA} compatible within uncertainties

Described by models (e.g. **M. Djordjevic, PRL112 (2014) 042302, see extra slides**) including:

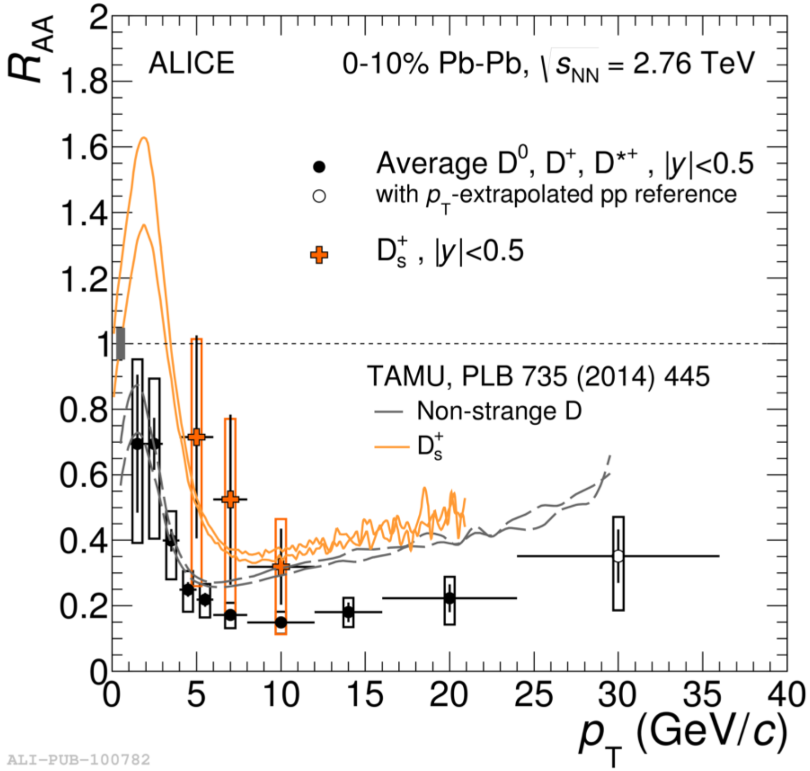
- Mass and colour charge dependent energy loss
- Different p_T spectra of charm quarks, light quarks and gluons
- Different fragmentation functions (harder for charm than light quarks and gluons)

What about low p_T (<5 GeV/c)?

- More data needed to study the (small?) effect of charm quark mass at low p_T
- N.B. for p_T<2 GeV/c not all pions come from hard scattering (yield does not scale with N_{coll})!

D_s vs. non-strange D mesons

ALICE, JHEP1603 (2016) 081
ALICE, JHEP1603 (2016) 082

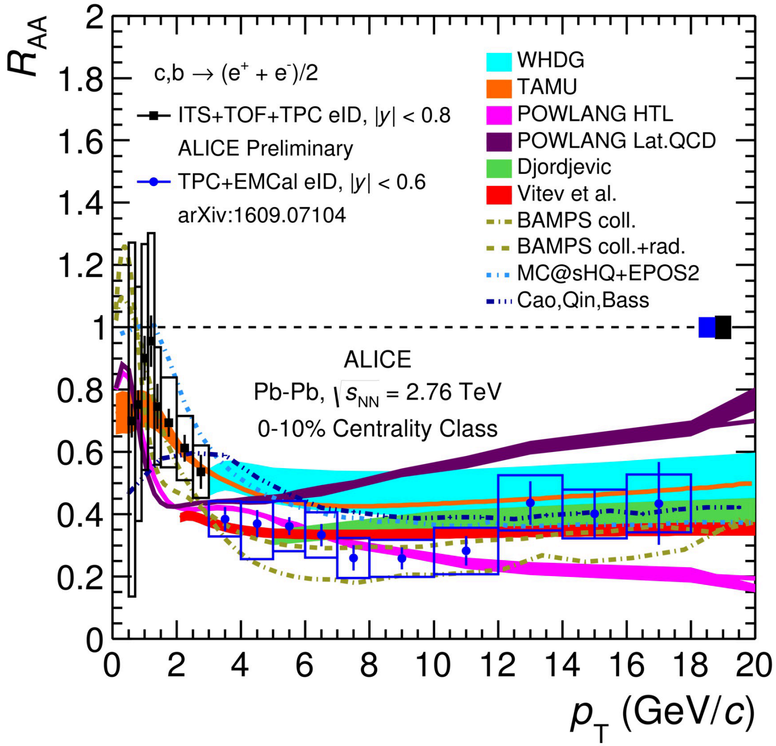


- D_s in Pb-Pb: similar suppression than non-strange D mesons in 8-12 GeV/c
- **$R_{AA}(D_s)$ >$R_{AA}(D^0,D^+,D^{*+})$ at low p_T? More statistics needed**
  - Important for constraining quark coalescence models

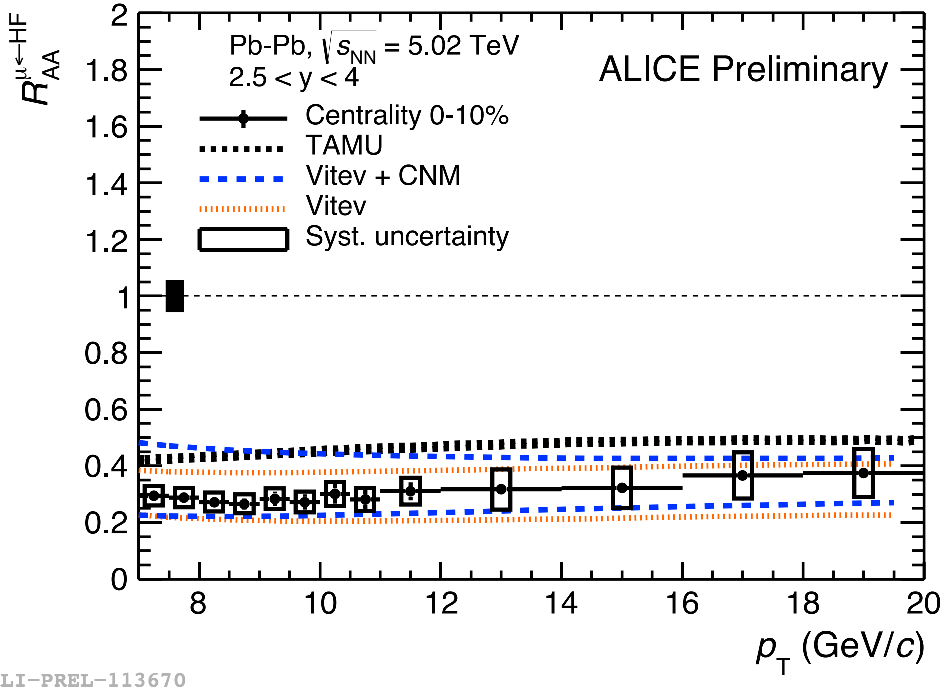
Kuznetsova, Rafelski, EPJ C 51 (2007) 113
He, Fries, Rapp, PLB 735 (2014) 445

Key measurement for run 2 and run 3.

HF-decay leptons: comparison to models



ALI-PREL-114353



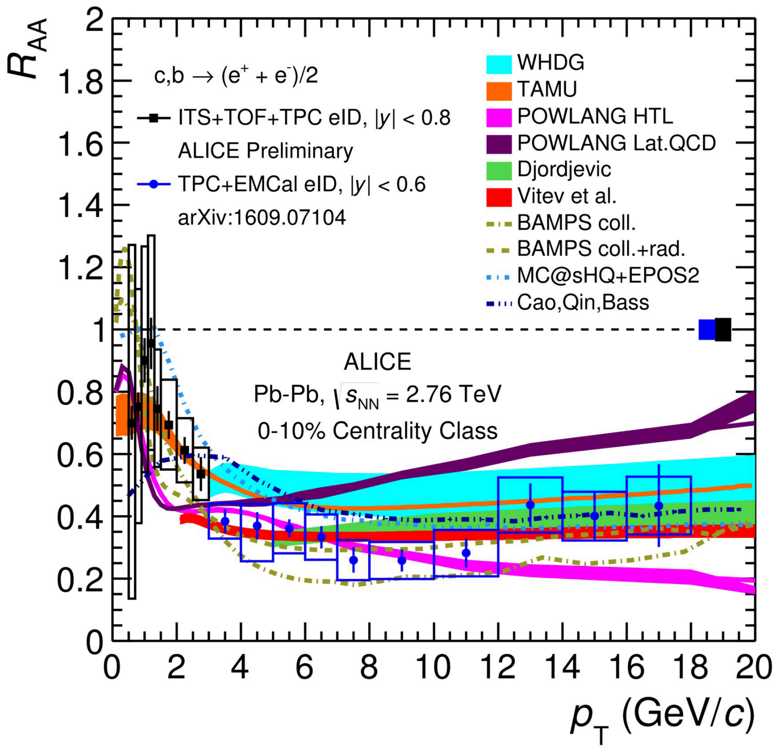
ALI-PREL-113670

Model references in backup

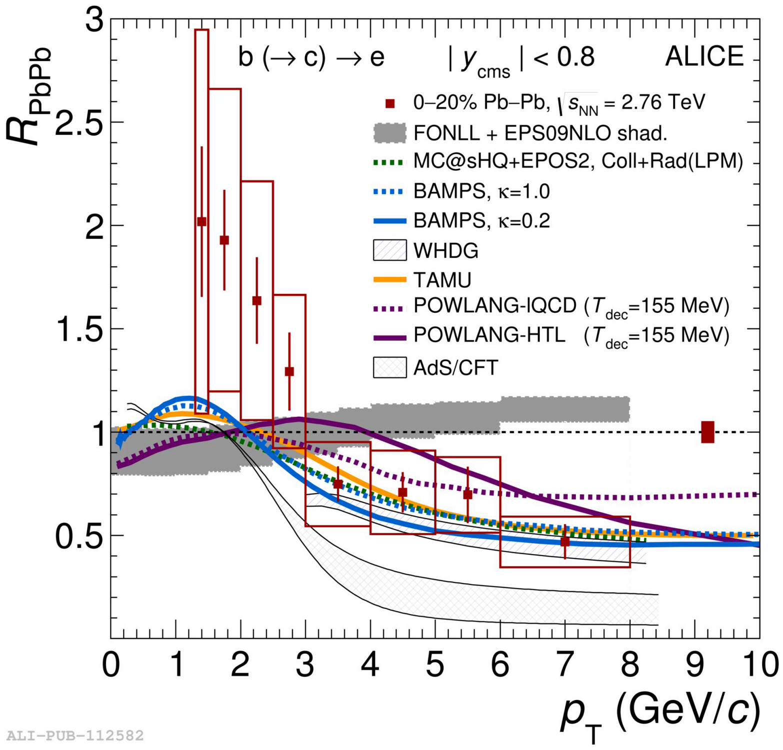
The data are described within uncertainties by models

- including charm and beauty radiative and/or collisional energy loss
- not expecting a significant difference from $\sqrt{s_{NN}}$=2.76 TeV $\sqrt{s}$=5 TeV
- not expecting a significant dependence of R_{AA} from rapidity

HF-decay leptons: comparison to models



ALI-PREL-114353



ALI-PUB-112582

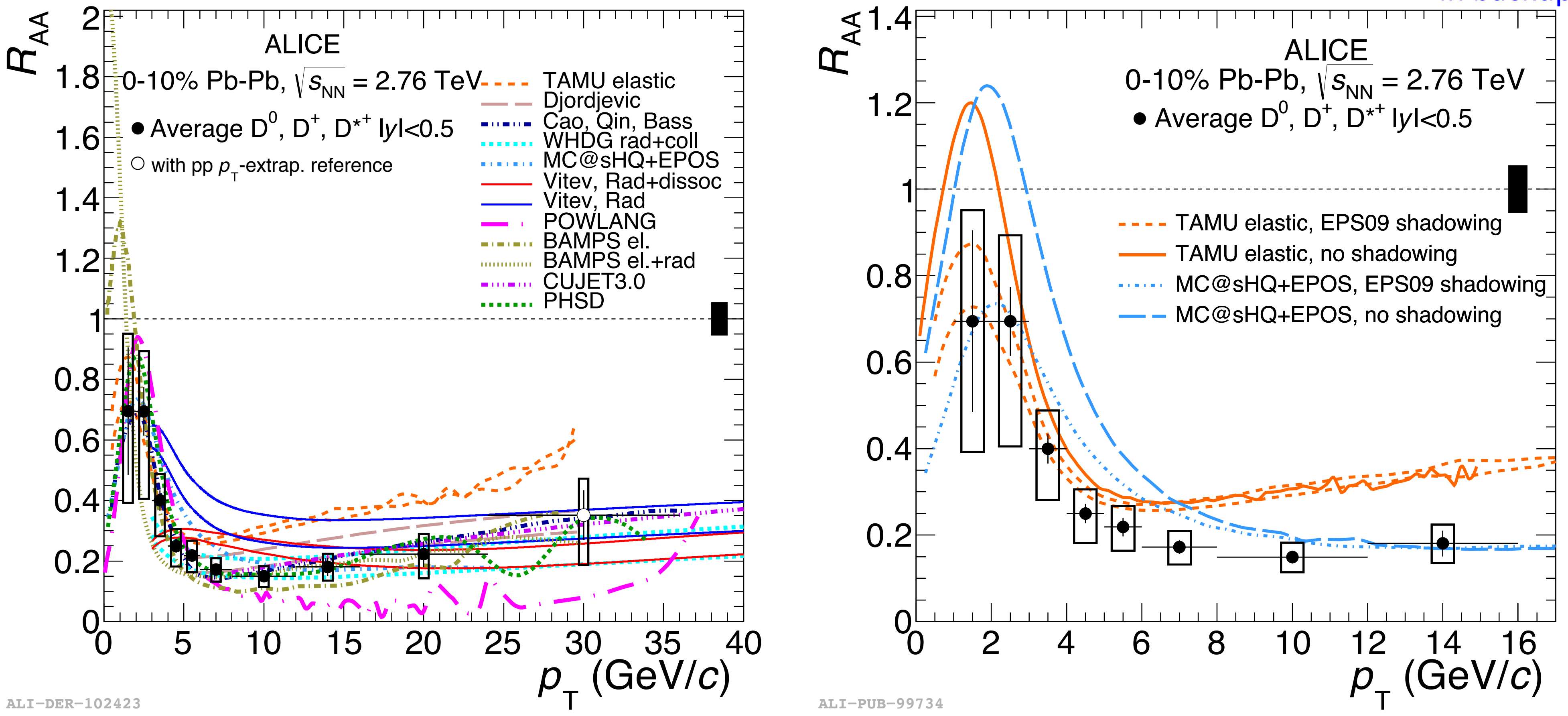
Model references in backup

The data are described within uncertainties by models

- including charm and beauty radiative and/or collisional energy loss
- not expecting a significant difference from $\sqrt{s_{NN}}$=2.76 TeV $\sqrt{s}$=5 TeV
- not expecting a significant dependence of R_{AA} from rapidity
- predicting quark-mass dependent energy loss (n.b. do not simply compare the curves!).

D mesons, further comparison with models

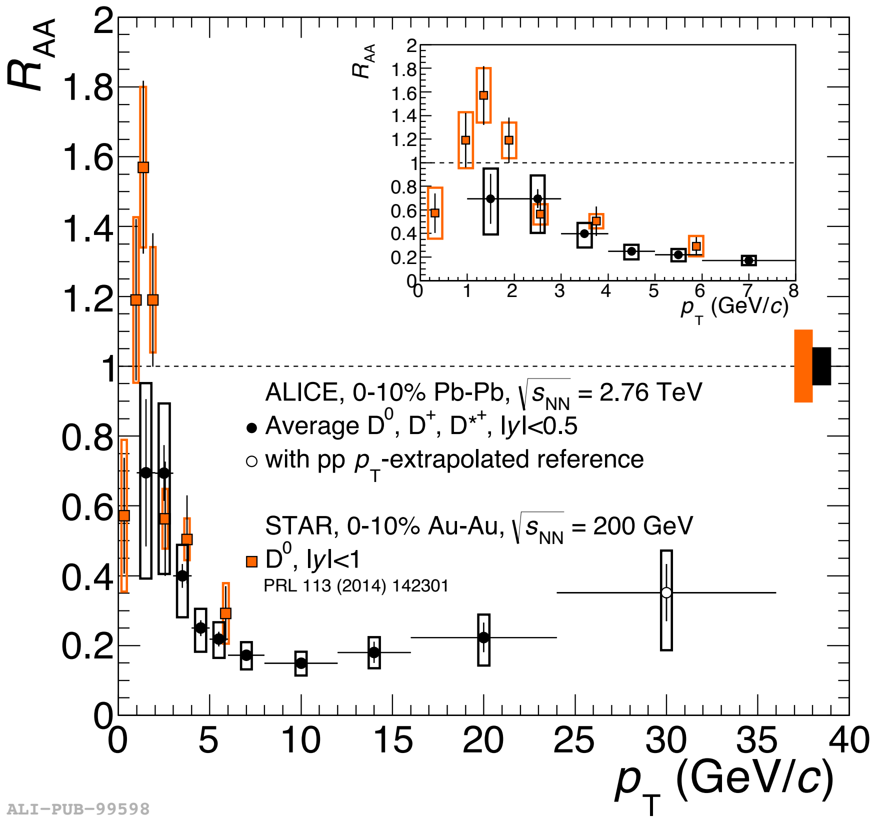
Model references in backup

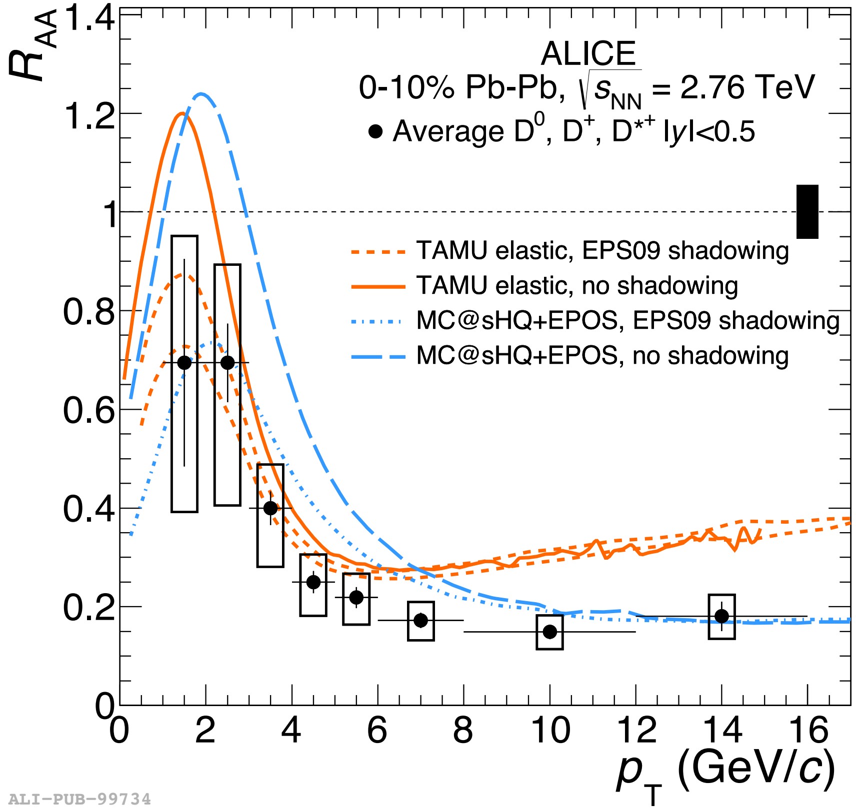


- Several models describe the data within uncertainties
  - TAMU elastic (no radiative energy loss) overestimate R_{AA} at high p_T (as expected)
- Inclusion of shadowing improves agreement between models and data

D-meson R_{AA} at LHC and RHIC

Model references in backup





Different trend w.r.t. STAR D_0 R_{AA} for p_T<2 GeV/*c*?

Several ingredients to be considered: stronger shadowing and less steep pp spectrum at the LHC, different effect of the radial flow on the R_{AA}, different impact of coalescence at the two energies.

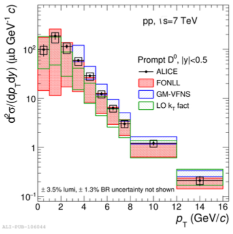
Some models (e.g. TAMU at low p_T, Phys. Lett. B 735 (2014) 445) can describe both measurements

A rather long shopping list

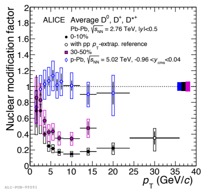
What we want to probe

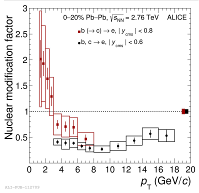
$$\frac{dN_{AA}}{dp_T} = \begin{matrix}\text{"vacuum"}\\ \text{parton spectra}\end{matrix} \otimes \begin{matrix}\text{initial-state}\\ \text{effects}\end{matrix} \otimes \boxed{\begin{matrix}\text{parton interaction}\\ \text{with the medium}\end{matrix} \otimes \begin{matrix}\text{(modified?)}\\ \text{hadronization}\end{matrix} \otimes \begin{matrix}\text{hadronic}\\ \text{phase}\end{matrix}} \left(\otimes \begin{matrix}\text{decay}\\ \text{e.g. for leptons}\end{matrix} \right)$$

pp collisions

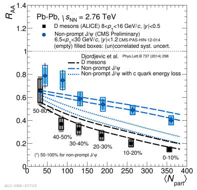


Charm and beauty lose energy

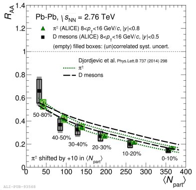




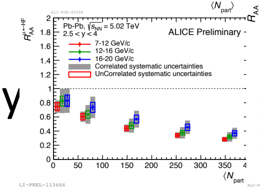
Via radiative and collisional processes

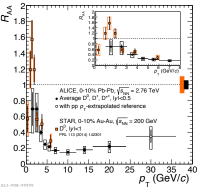


- quark mass (e.g. from dead-cone effect)



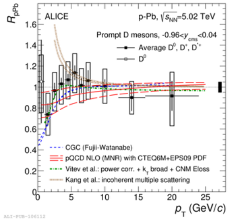
- color charge (Casimir factor)

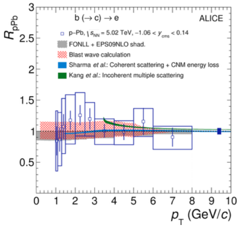




- path length and medium density

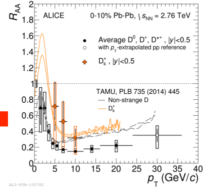
Constrain models with measurements from p-Pb collisions





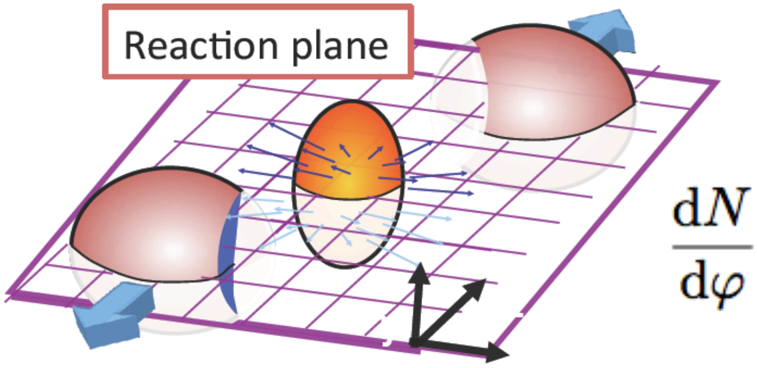
Collective motion → Azimuthal anisotropy

Hadronization via coalescence?



Elliptic flow (azimuthal anisotropy)

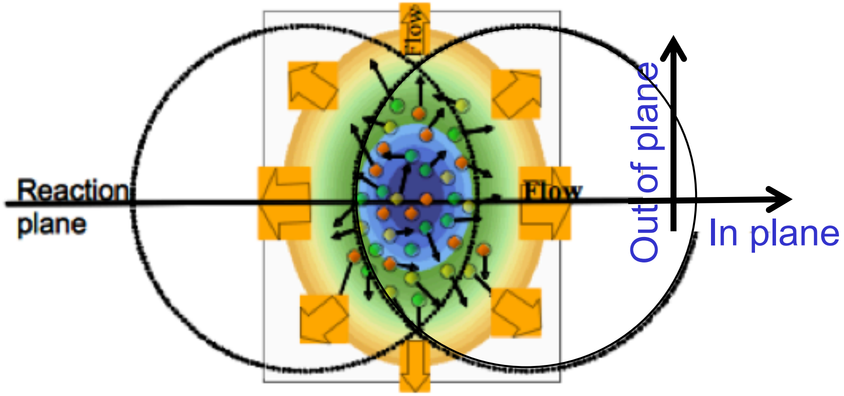
Study azimuthal distribution of produced particles w.r.t. the reaction plane (Ψ_{RP})



Initial spatial anisotropy $\rightarrow$ momentum anisotropy

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

$$v_n = \langle \cos(n[\varphi - \psi_n]) \rangle$$



$v_2>0$ → **Thermalization/collective motion** (at low p_T)

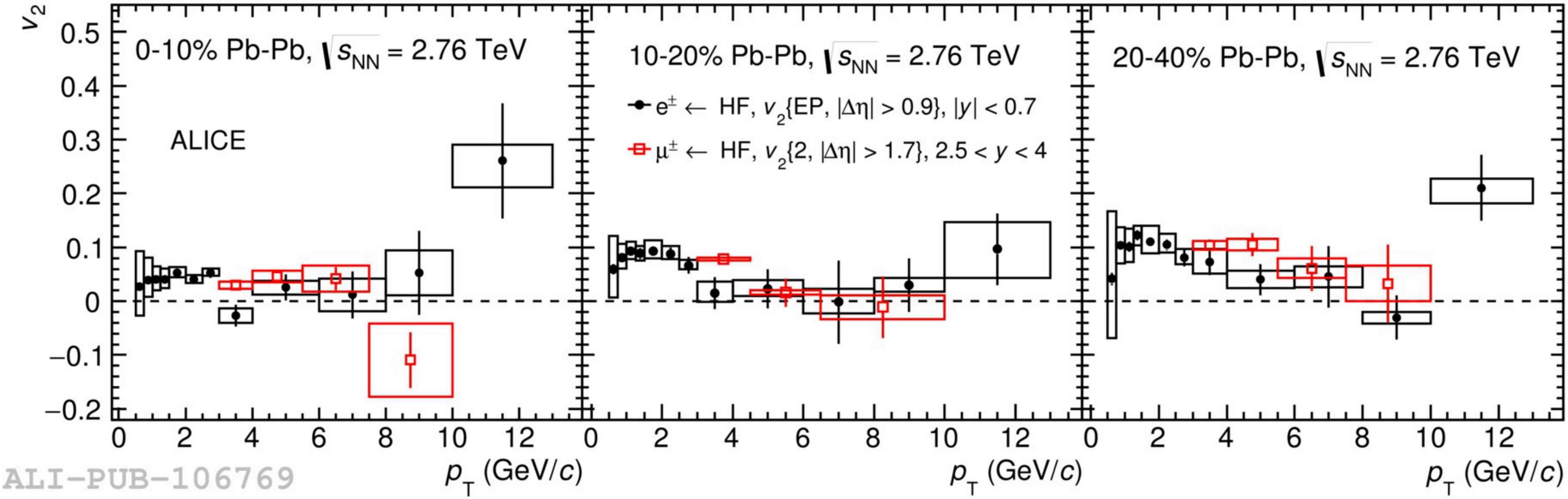
$v_2>0$ → **Path length dependence of energy loss** (at high p_T)

v_2+ R_{AA}: complementary information → improve sensitivity to relative contribution of collisional and radiative energy losses and to coalescence

Heavy-flavour decay leptons v_2

HF-decay muons
$2.5<y<4$
PLB 753, (2016) 41

HF-decay electrons
$|y|<0.7$
arXiv:1606.00321



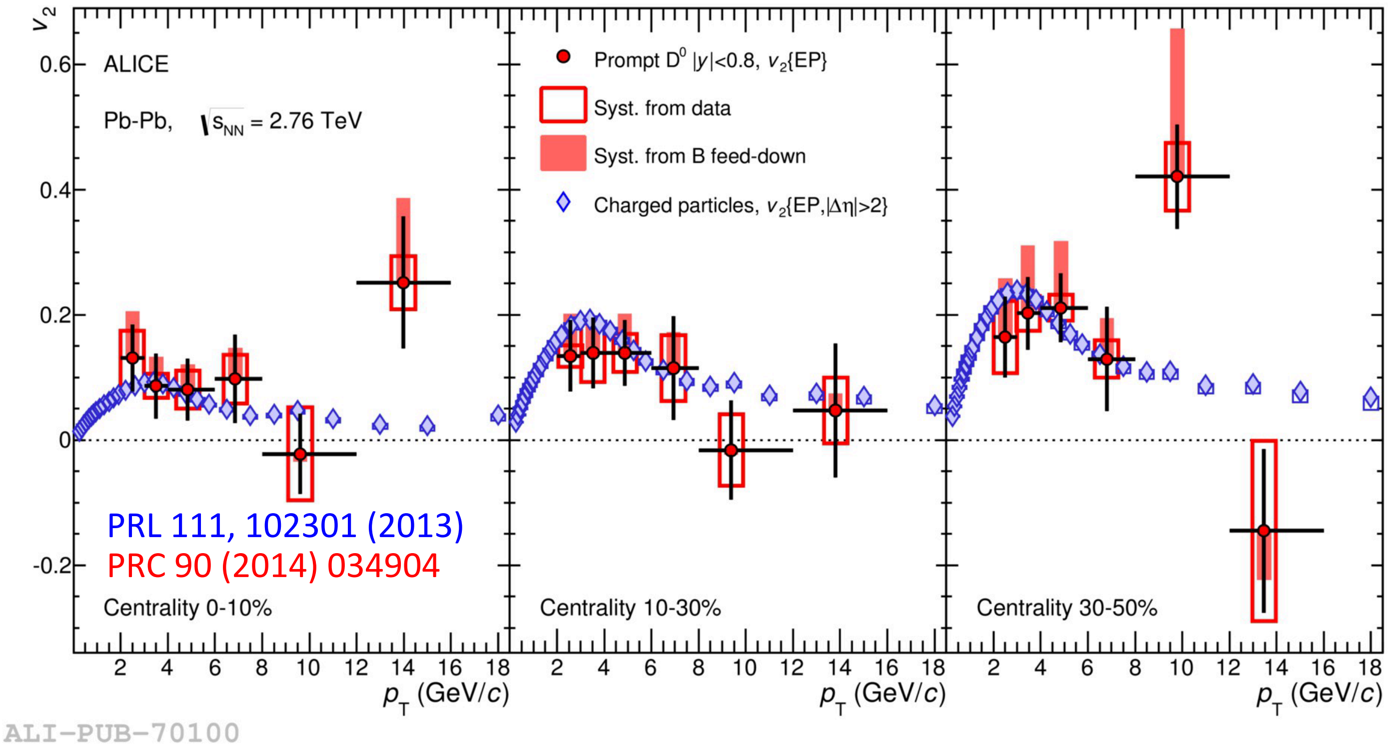
Positive v_2 observed (5.9 σ for heavy-flavour decay electrons in $2<p_T<2.5$ GeV/c).

Similar v_2 for heavy-flavour decay muons at forward rapidity and heavy-flavour decay electrons at mid-rapidity.

Hint of increase of v_2 from centrai to semi-central collisions.

D-meson elliptic flow at $\sqrt{s_{NN}}$=2.76 TeV

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



PRL 111, 102301 (2013)

PRC 90 (2014) 034904

Positive D-meson v_2 (5σ effect in 2<p_T<6 GeV/c in30-50% centrality).

Hint for an increase from central to semi-central collisions.

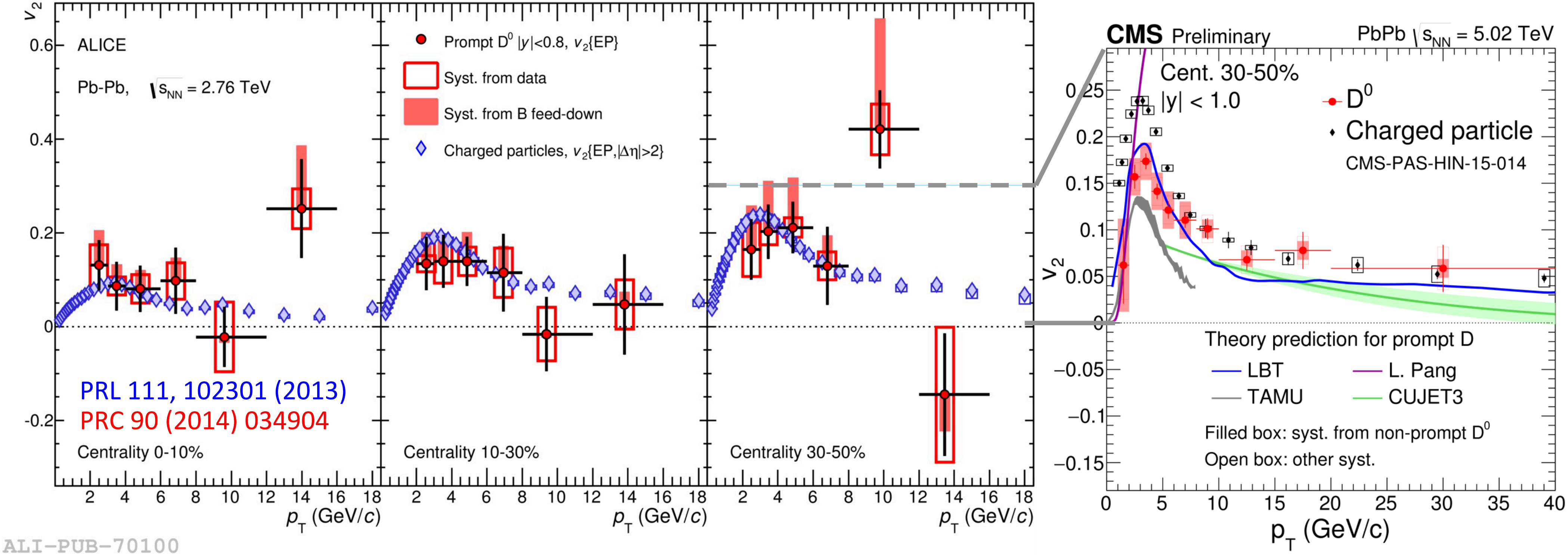
Similar to charged particle v_2

→ Suggest that charm is influenced by the collective motion of the system.

Comparison with D^0-meson v_2 at $\sqrt{s_{NN}}$=5.02 TeV by CMS

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

Shown at Hard Probes



PRL 111, 102301 (2013)

PRC 90 (2014) 034904

ALI−PUB−70100

Positive D-meson v_2 (5σ effect in $2<p_T<6$ GeV/*c* in30-50% centrality)

Hint for an increase from central to semi-central collisions.

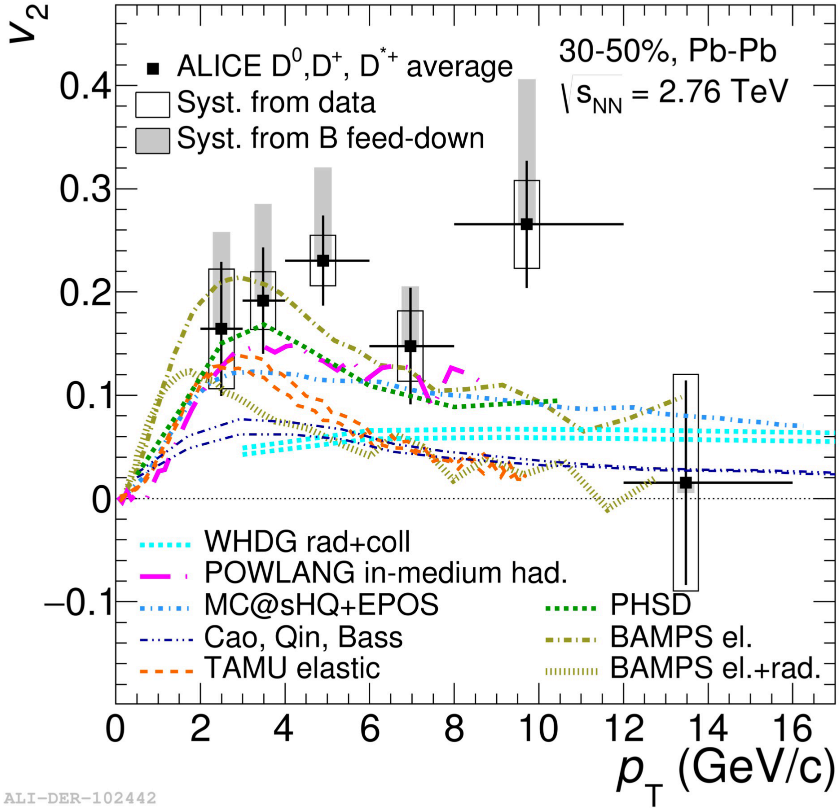
Similar to charged particle v_2

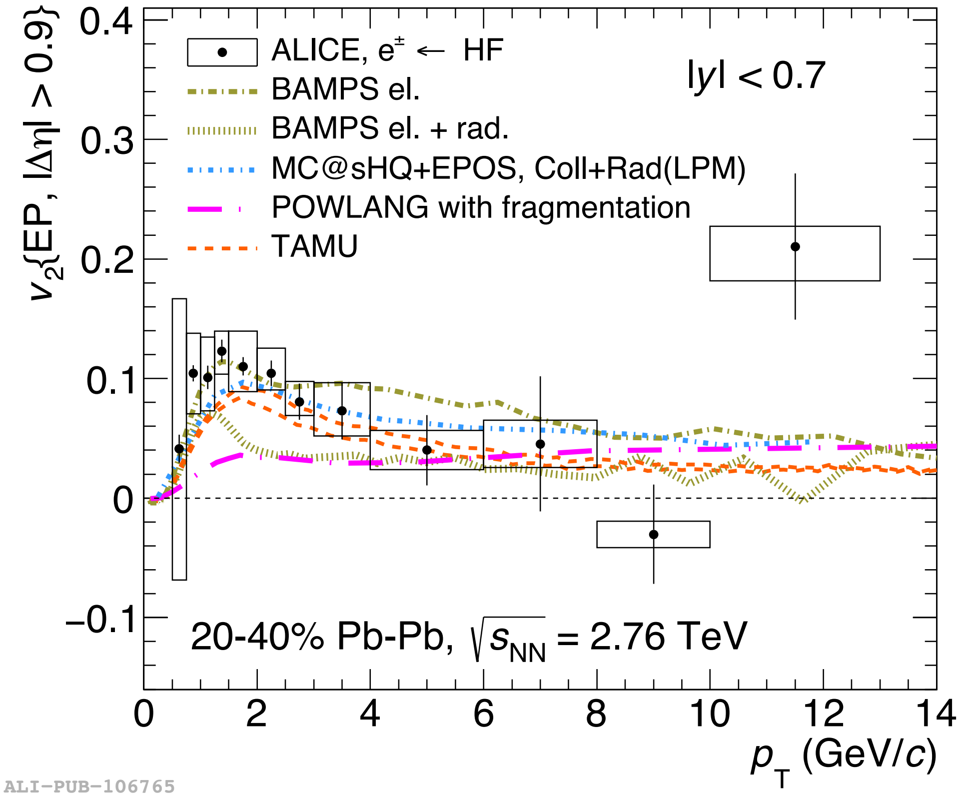
→ Suggest that charm is influenced by the collective motion of the system.

→ confirmed by CMS result at 5 TeV

v_2: comparison with models

Model references in backup

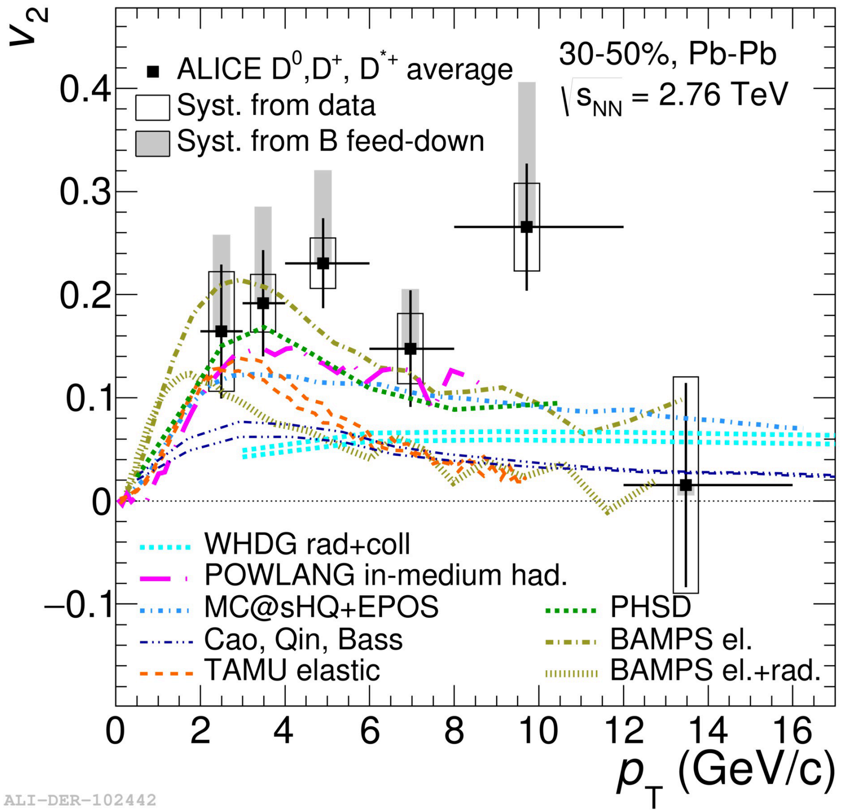


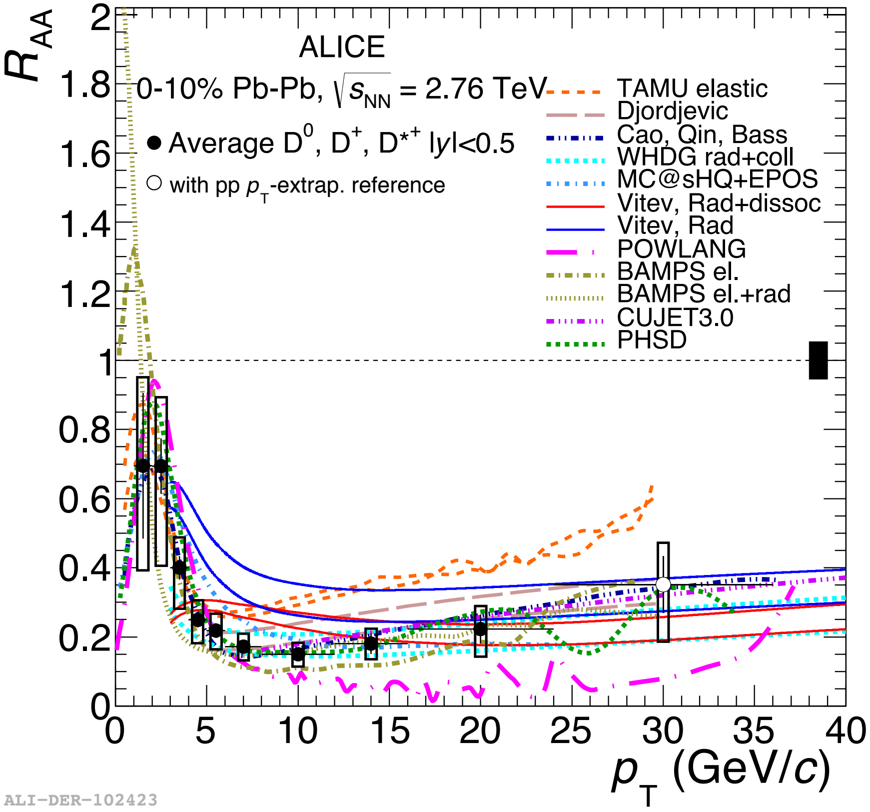


- v_2 at low p_T better described by models including mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion of the medium (collisional energy loss, recombination)
- Highlight importance that models include a realistic description of the medium evolution and of initial conditions

v_2 and R_{AA}: comparison with models

Model references in backup



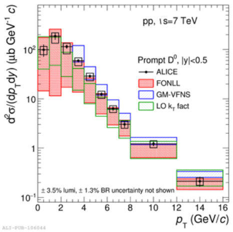


- v_2 at low p_T better described by models including mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion of the medium (collisional energy loss, recombination)
- Highlight importance that models include a realistic description of the medium evolution and of initial conditions
- v_2 and R_{AA} measurements over a wide p_T range can set stringent constraints to model

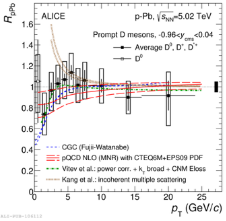
A rather long shopping list

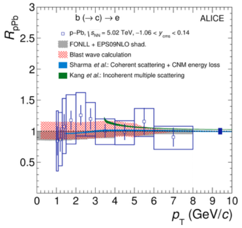
$$\frac{dN_{AA}}{dp_T} = \begin{array}{c}\text{"vacuum"}\\ \text{parton spectra}\end{array} \otimes \begin{array}{c}\text{initial-state}\\ \text{effects}\end{array} \otimes \overset{\text{What we want to probe}}{\boxed{\begin{array}{c}\text{parton interaction}\\ \text{with the medium}\end{array} \otimes \begin{array}{c}\text{(modified?)}\\ \text{hadronization}\end{array} \otimes \begin{array}{c}\text{hadronic}\\ \text{phase}\end{array}}} \left(\otimes \begin{array}{c}\text{decay}\\ \text{e.g. for leptons}\end{array} \right)$$

pp collisions

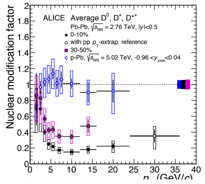
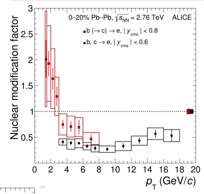


Constrain models with measurements from p-Pb collisions

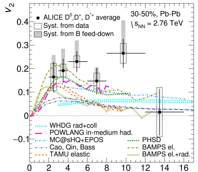
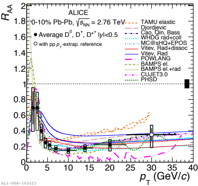




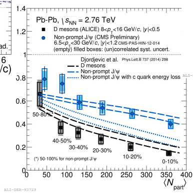
Charm and beauty lose energy

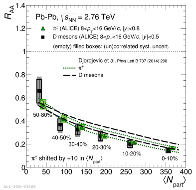
Via radiative and collisional processes

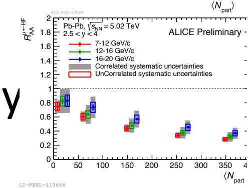
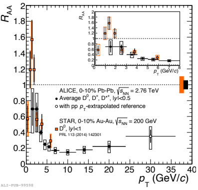
- quark mass (e.g. from dead-cone effect)



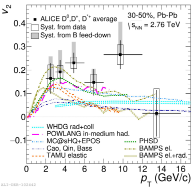
- color charge (Casimir factor)



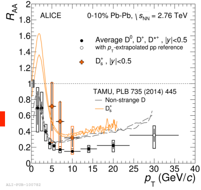
- path length and medium density

Collective motion → Azimuthal anisotropy



Hadronization via coalescence?



Plans for run 2 and beyond

Goals for ongoing run-2

- New R_{AA} and v_2 measurements in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV
  - non-strange D mesons and D_s
  - HF-decay leptons
- First D-meson measurement down to p_T=0?
- with improved precision especially at low p_T

- Improve precision of R_{pPb} measurement down to p_T=0

require large reference sample (~1G events) of min. bias pp collisions at the same energy

- Improve precision of multiplicity-differential studies in pp and p-Pb collisions

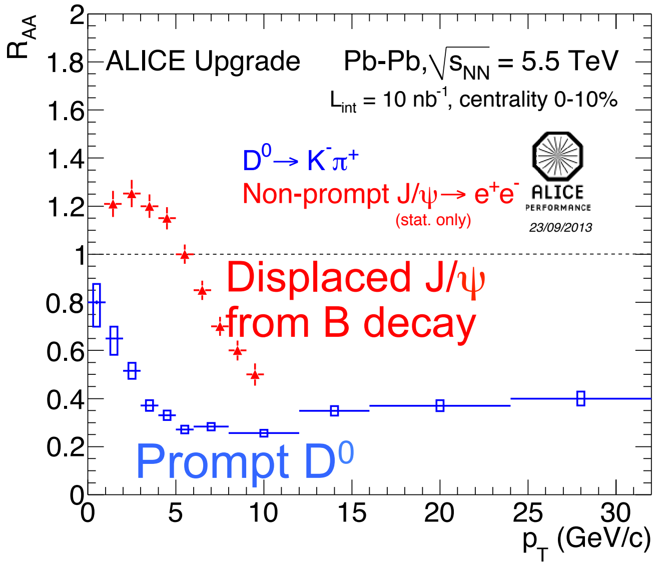
- New measurements of azimuthal correlations in Pb-Pb collisions and small systems also as a function of the multiplicity
  - D mesons with charged particles
  - HF-decay electrons with charged particles

Long-shutdown 2 → Detector upgrade

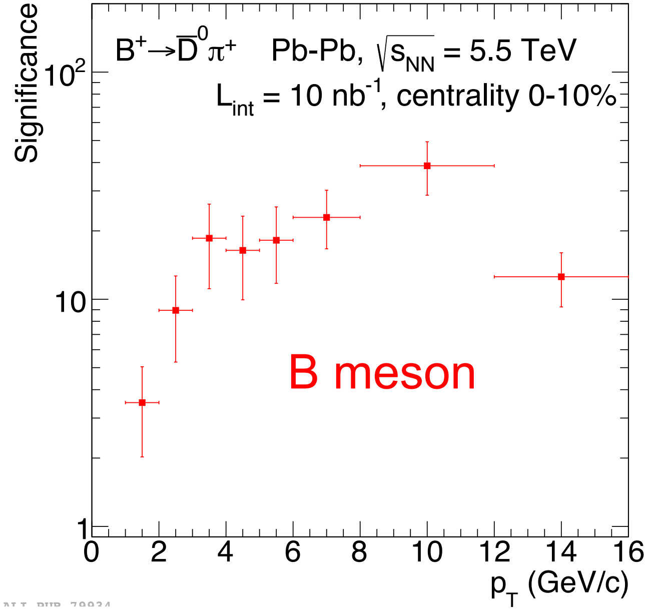
- new ITS, addition of MFT → improve spatial resolution at impact point at mid- and forward rapidity
- new readout for several subdetectors
  - "continuous readout" at high rate (50 kHz) → collect 10nb^{-1} Pb-Pb collision (x100 more for min. bias events w.r.t. run 1 and 2)

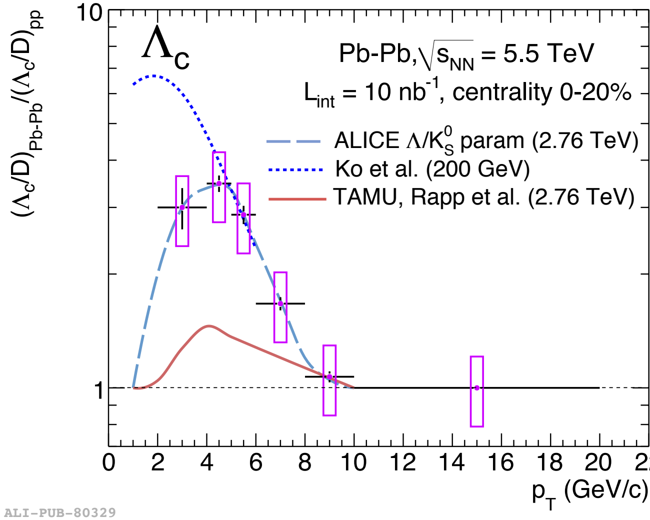
→ tremendous improvement for reconstructing charm and beauty signals (including D_s, Λ_c, non-prompt J/ψ at mid and forward rapidity, B meson, Λ_b) down to very low p_T

Examples of performance on HF signals after ALICE upgrade



ALI-PERF-59950





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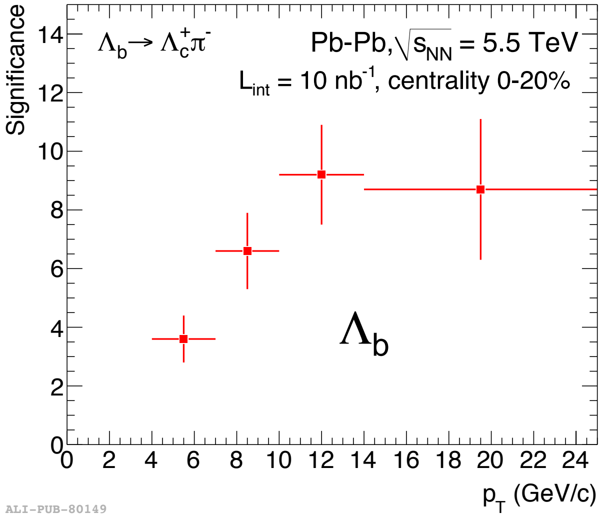

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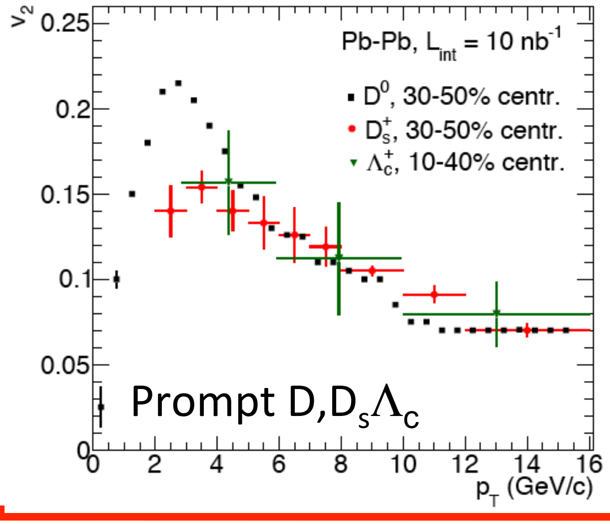
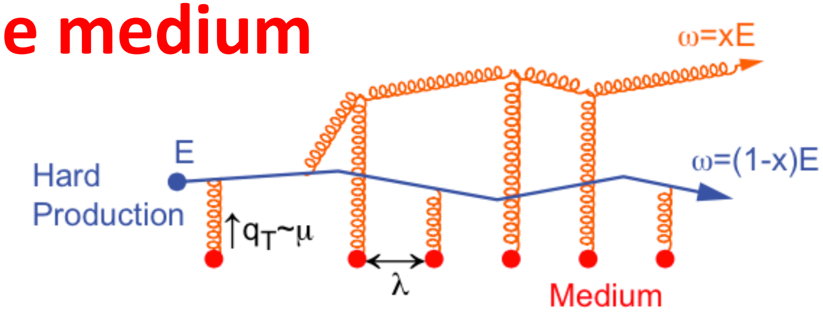


Extra

QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

⇨ **"Calibrated probes" of the medium**



Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes

~ Study QCD "Bethe-Block" curve for partons in the QGP

⇩

Connection of "local" interactions with global medium properties

e.g. in BDMPS-Z formalism*, at intermediate energies

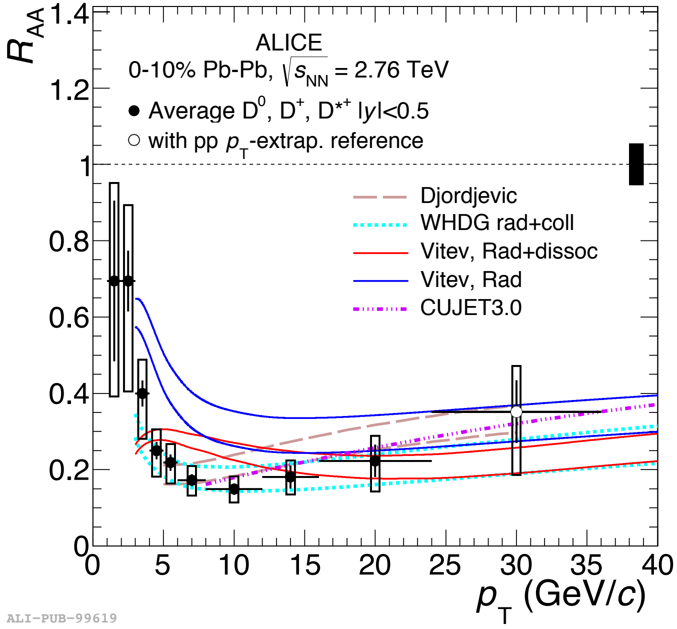
$$\langle \Delta E \rangle^{\text{rad}} \propto \alpha_s C_R \hat{q} L^2$$

$$\hat{q} = \frac{\mu^2}{\lambda} = \mu^2 \rho \sigma$$

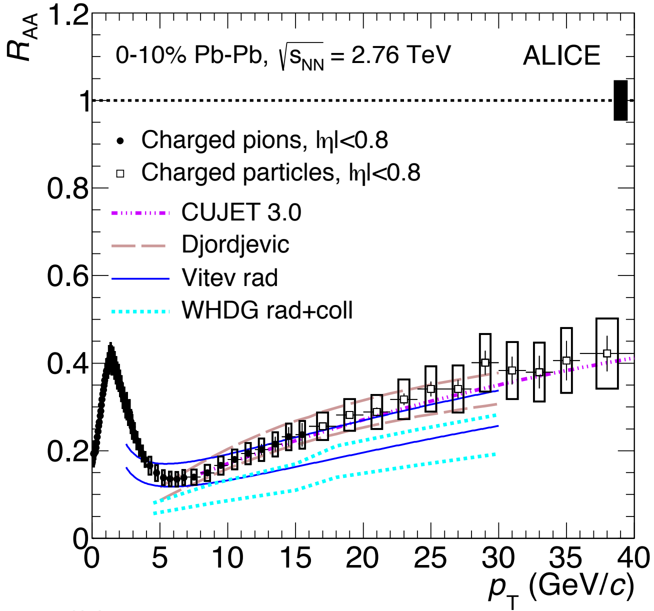
Transport coefficient(s)

*Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.

Charm vs. light quarks/gluons



ALI-PUB-99619



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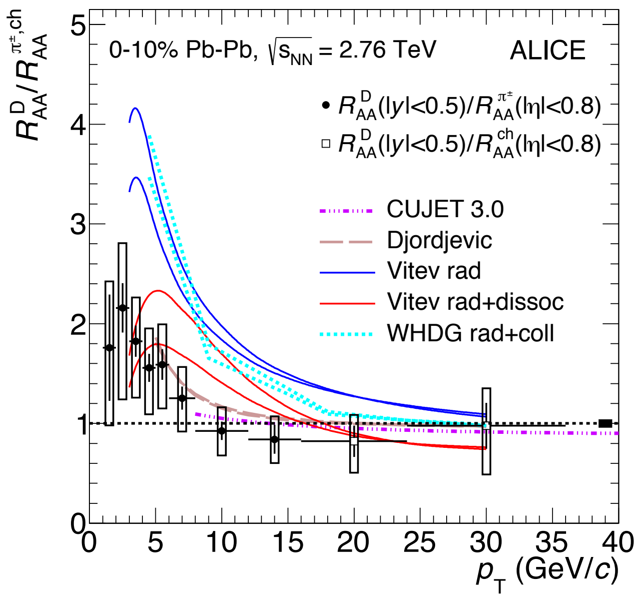


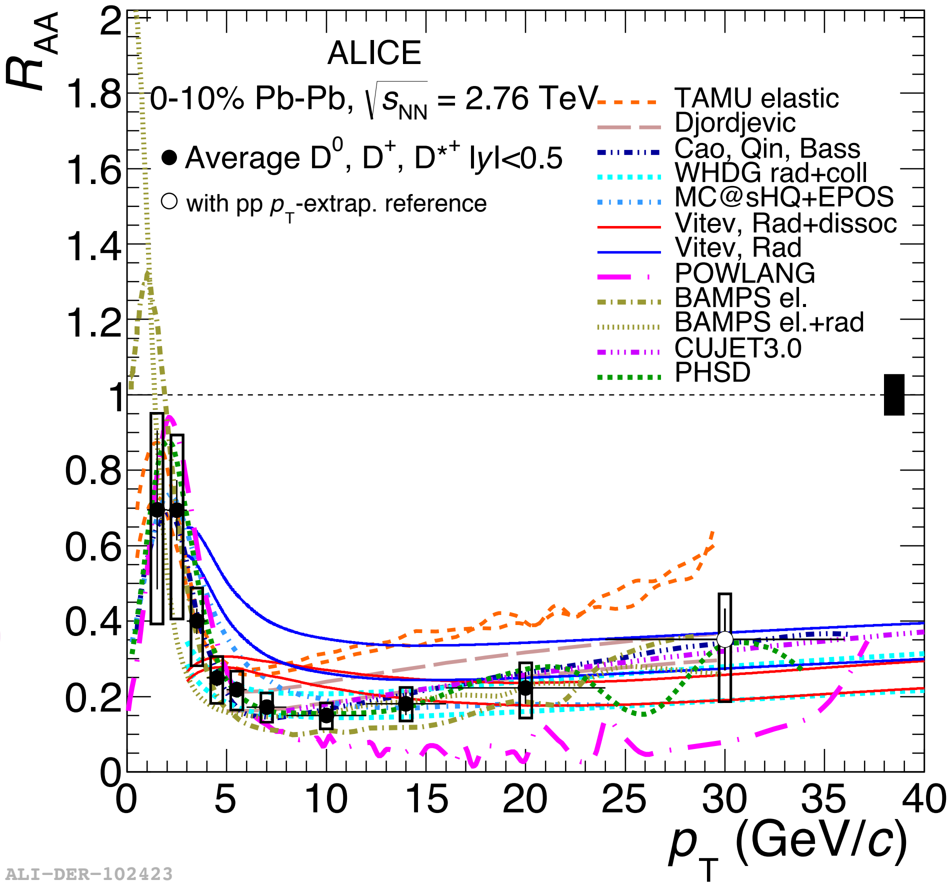
ALI-PUB-99713

Not trivial to describe both D meson and pion/charged-particle R_{AA} within the same model

- in the ratio of R_{AA} predictions, uncertainties on the medium density/temperature cancel
- the model by Djordjevic and CUJET 3.0 do it over the whole momentum range they cover
- the version of Vitev model with radiative-only energy loss does not describe the data

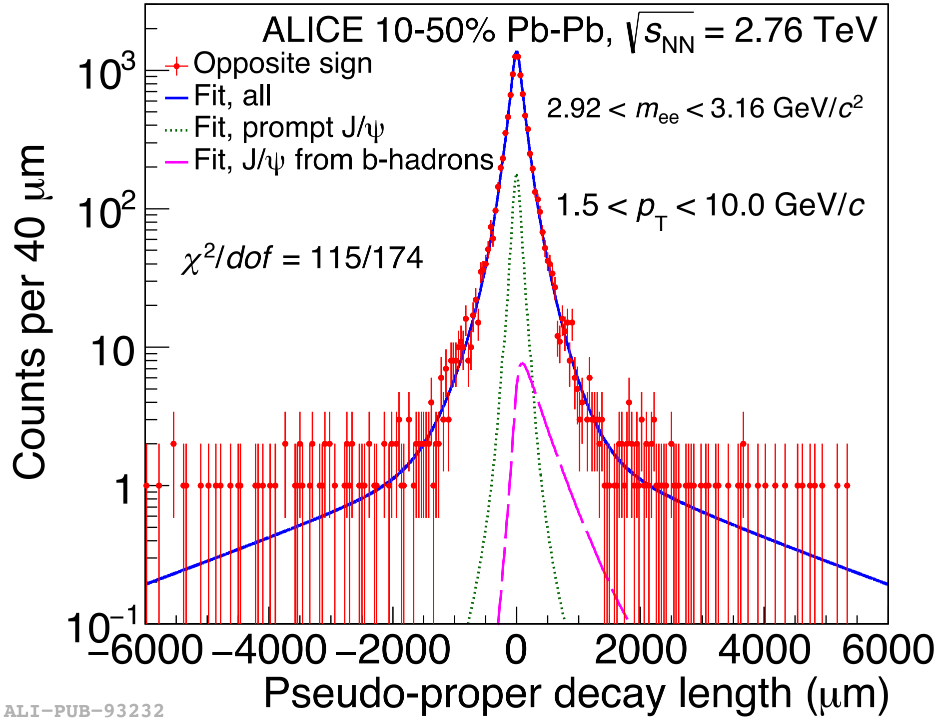
Model references

- POWLANG: EPJ C 75 (2015) 121;
- TAMU: arXiv:1401.3817;
- MC@HQ+EPOS: PRC 89 (2014) 014905;
- WHDG: Nucl. Phys. A 872 (2011) 256;
- BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph];
- Cao,Quin, Bass: PRC 88 (2013);
- Vitev:: PRC 80 (2009) 054902;
- Djordjevic: PRL 737 (2014) 298
- CUJET 3.0: Chin. Phys. Lett. 32 no. 9, (2015) arXiv:1411.3673 [hep-ph].
- PHSD: arXiv:1512.00891

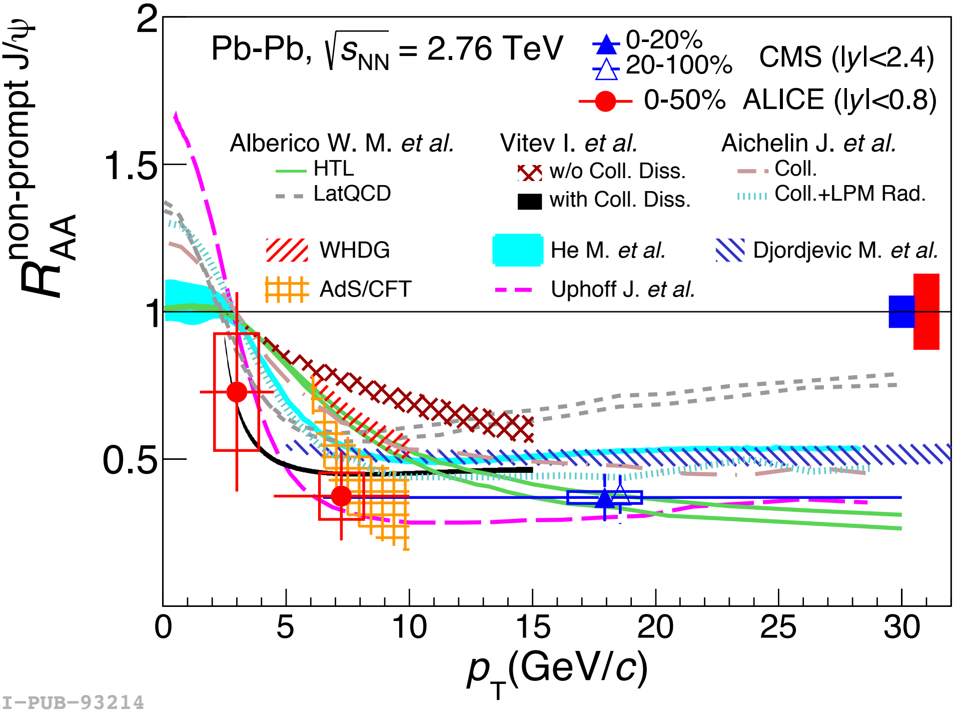


ALICE non-prompt J/ψ

JHEP 07 (2015) 051



ALI−PUB−93232

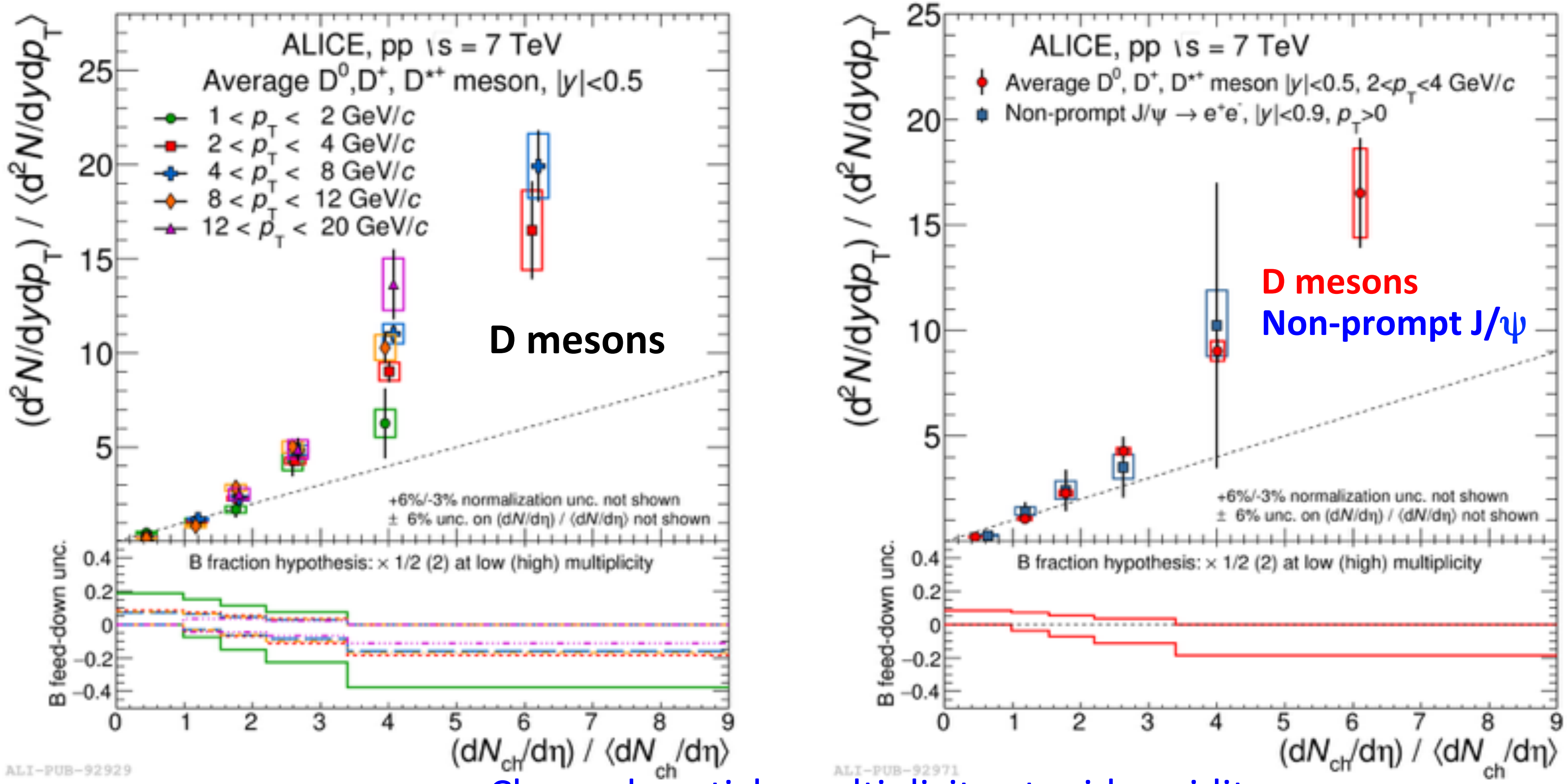


ALI−PUB−93214

Charm and beauty yields vs. multiplicity in pp collisions

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle}=\frac{Y^{mult}/(\epsilon^{mult}\times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot}\times N^{tot}_{event}/\epsilon^{trigger})}$$

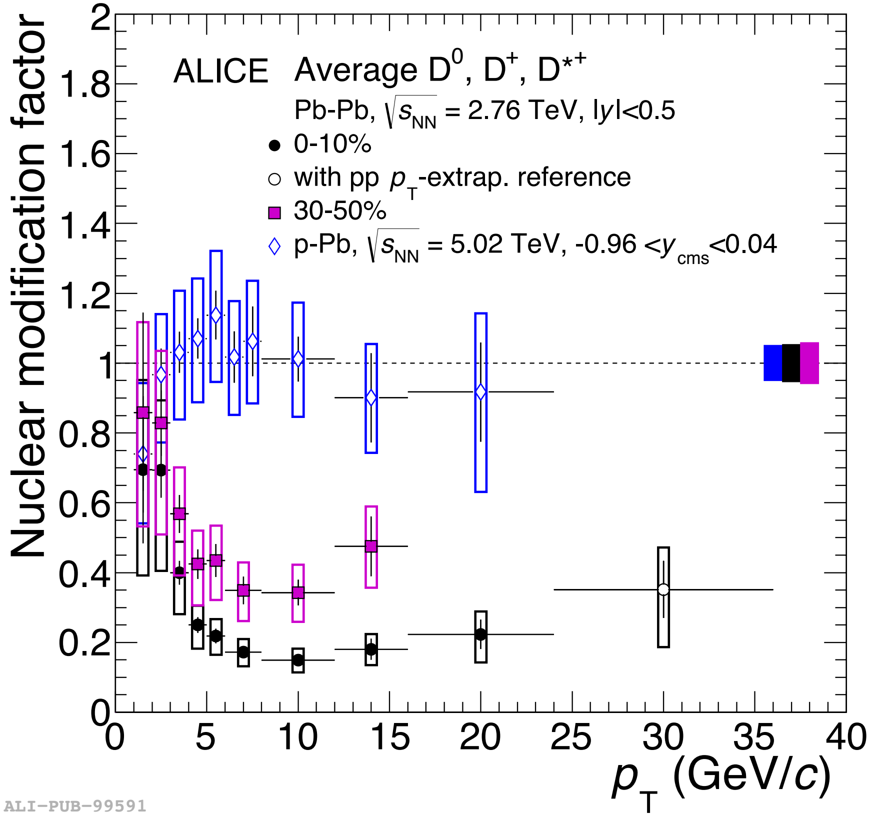
JHEP 09 (2015) 148

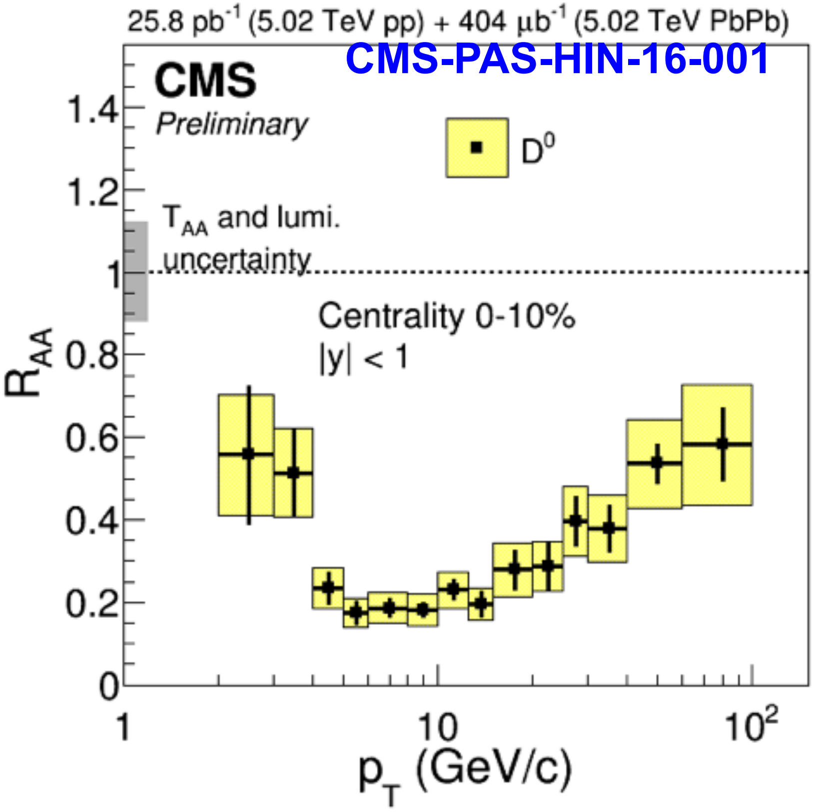


Charged-particle multiplicity at mid-rapidity

- Faster-than-linear increase of self-normalized D-meson yields as a function of the charged particle multiplicity at mid-rapidity
- No evidence for a p_T dependence within uncertainties
- Similar increase for D mesons and non-prompt J/ψ

CMS D meson R_{AA}

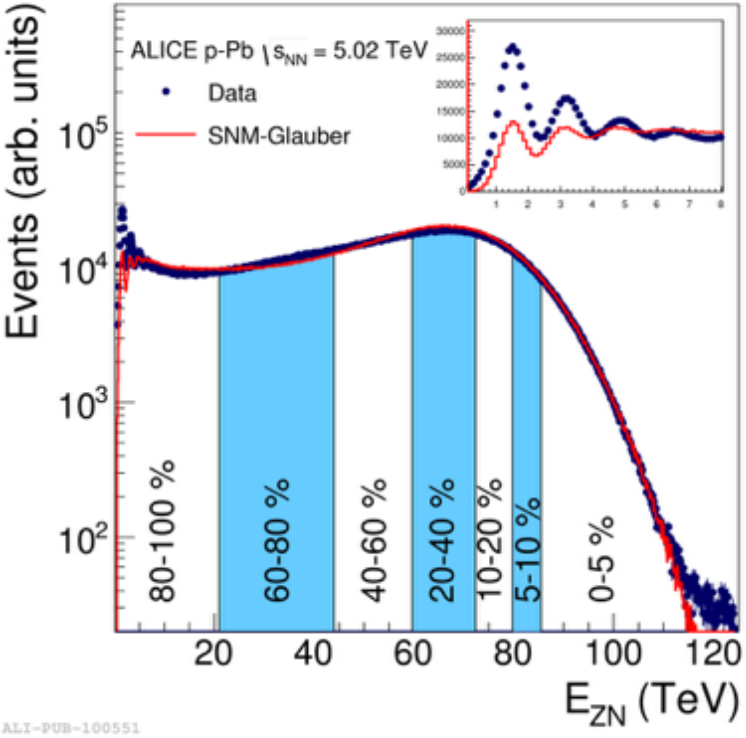




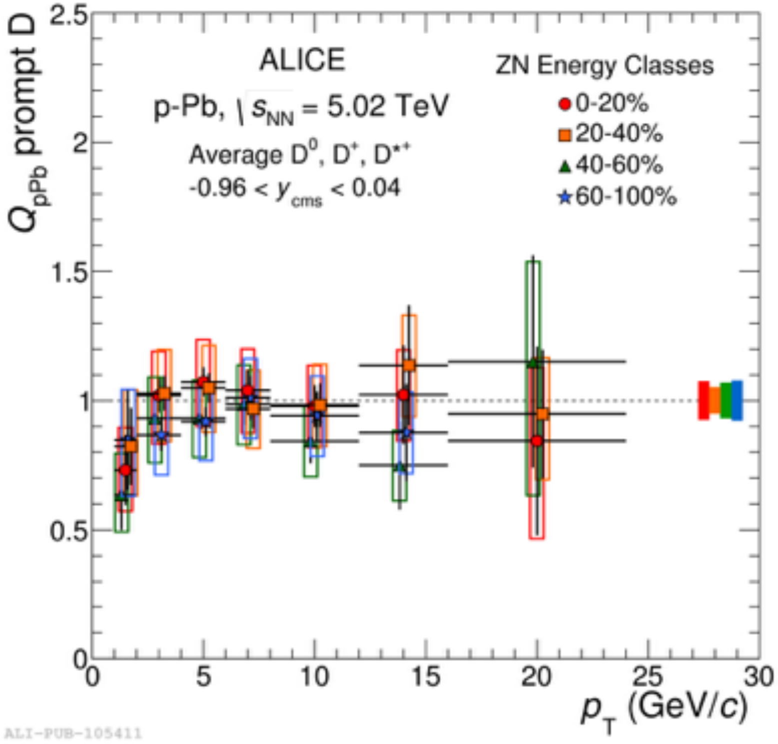
Compatible D-meson R_{AA} at 2.76 at 5.02 TeV

Centrality dependent D-meson R_{pPb}

Centrality estimated on the basis of the energy deposited in the neutron ZDC in the Pb-going direction

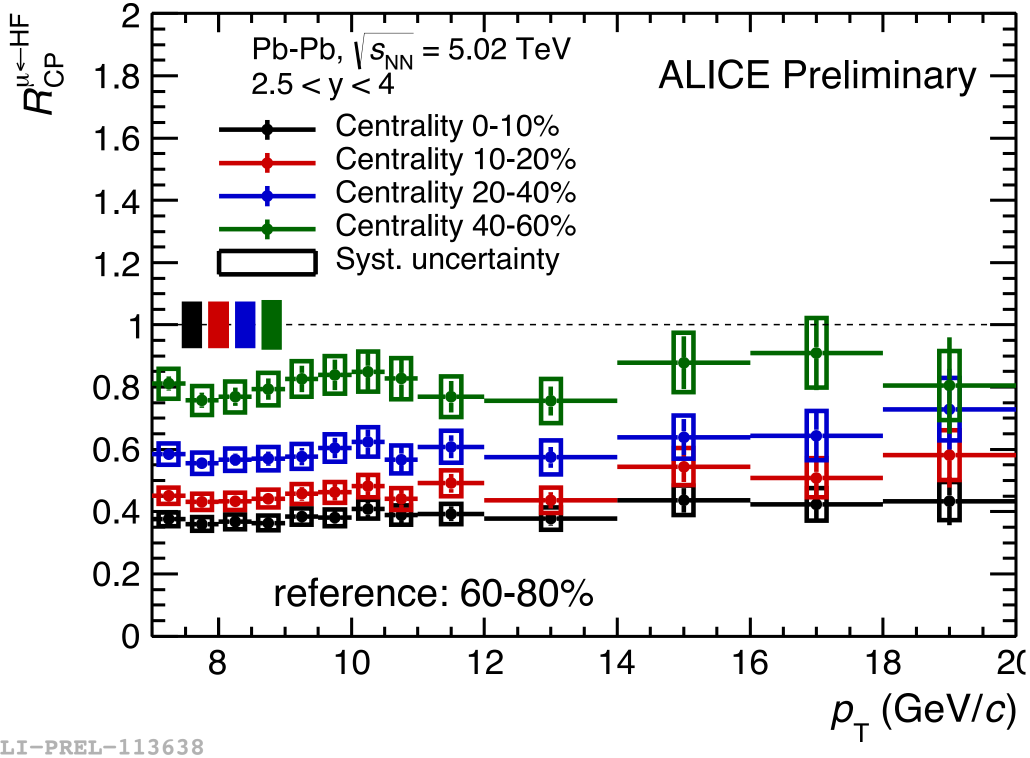


JHEP 08 (2016) 1

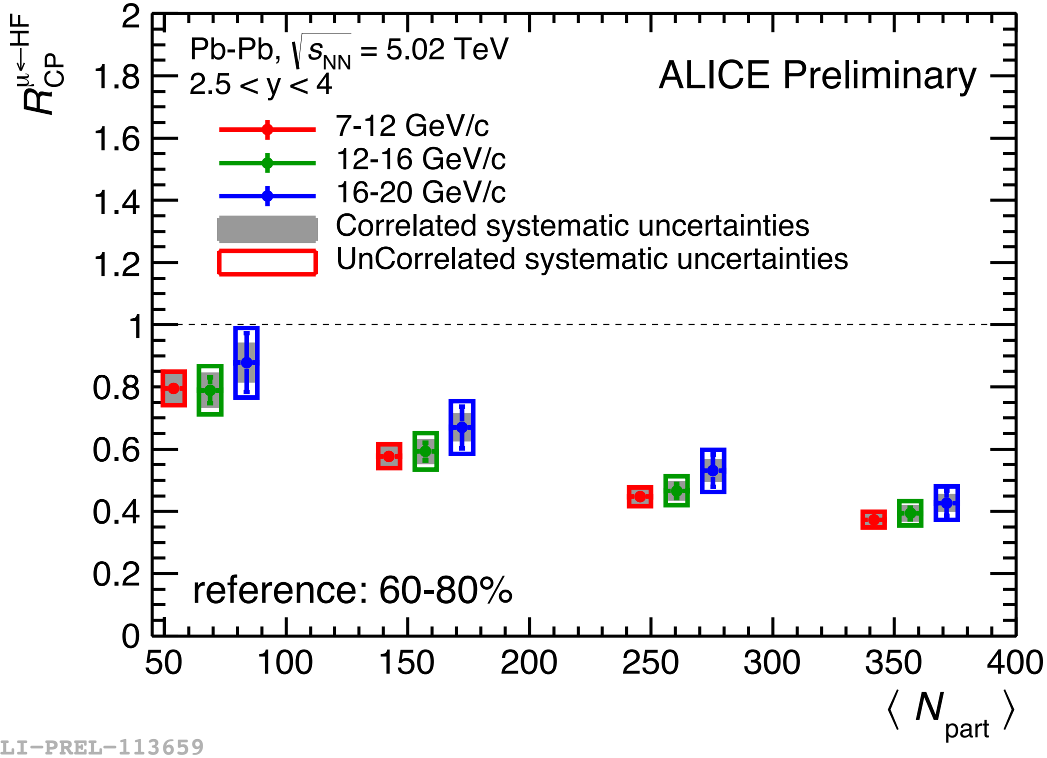


No centrality dependence observed within uncertainties

HF-decay muon R_{CP}



ALI-PREL-113638



ALI-PREL-113659

Physics goals with ALICE upgrade

Main physics topics, exploiting LHC & ALICE specific potentials:

Precise measurement of heavy-flavour hadron production (spectrum, elliptic flow) in a wide momentum range, down to very low p_T

- Charm/beauty quark interaction with the QGP medium (in-medium energy loss)
- Study degree of charm thermalization and possible hadronization via coalescence
- Detect possible charm thermal production

J/ψ, ψ' states down to zero p_T in wide rapidity range

- Charmonium dissociation and regeneration pattern as a probe of colour deconfinement

Measurement of low-mass and low-p_T di-leptons (from ρ,ω,.. decay, in-medium $q\bar{q} \rightarrow l^+l^-$, direct photons) → **electromagnetic radiation from QGP**

- Medium temperature(s)
- Space-time evolution and equation of state of the QGP
- Chiral-symmetry restoration → modification of ρ spectral function

… and more:

Jet quenching and fragmentation: PID of jet particle content, heavy flavour tagging

Heavy nuclear states ($^{3}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{He}$)

ALICE upgrade strategy

Physics Goal

High precision measurements of rare signals at low p_T which cannot be selected with a dedicated trigger (very low signal/background)

Requirements

Large event samples on tape
→ Target of **$L_{int} \geq 10\ nb^{-1}$ Pb-Pb minimum bias data** + pp and p-A data
→ Factor 100 gain in statistics for minimum bias trigger over the current programme

Improve spatial precision on track and vertex position

Strategy

Upgrade ALICE readout (for several detectors) and **online systems**

- → Read out all Pb-Pb interactions at maximum rate of 50 kHz (set by LHC luminosity target for Pb-Pb, $\mathcal{L}=6\times10^{27}cm^{-2}s^{-1}$) with a minimum bias trigger
- → Data reconstruction performed online

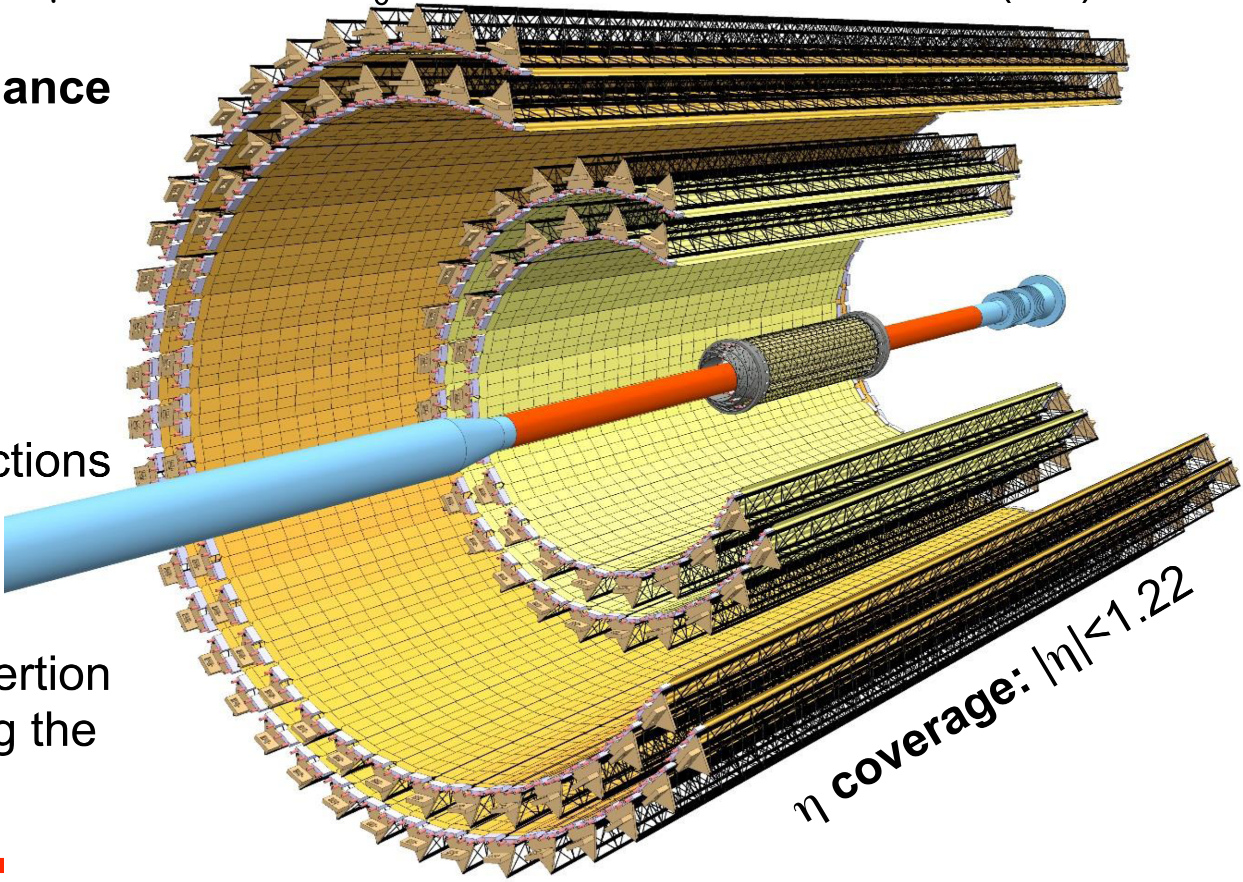
New silicon trackers: new Inner Tracking System (ITS, at mid-rapidity) and Muon Forward Tracker (MFT, at forward rapidity)

⊕ Forward trigger detectors upgrade (Fast Interaction Trigger) and a possible new forward calorimeter

New ITS

Design requirements:

1. **Improve impact parameter resolution by a factor ~3 (5) in rφ (z)**
   - ➜ Reduce pixel size (currently 50 μm x 425 μm)
     - Monolithic Active Pixel Sensors (MAPS) with size ~ 29 μm x 27 μm
   - ➜ Go closer to the interaction point:
     - ➜ new smaller beam pipe: 2.9 cm → 1.9 cm
     - ➜ first layer with smaller radius (2.2 cm, currently 3.9 cm)
   - ➜ Reduce material thickness: 50 μm silicon, X/X_0 from current ~1.13% to ~0.3(0.8)% per layer
2. **High standalone tracking performance** (efficiency, spatial and momentum resolutions)
   - ➜ Increase granularity
   - ➜ Add 1 layer (from 6 to 7)
3. **Faster (x50) readout**: Pb-Pb interactions up to 100 kHz
4. **Maintenance:** allow for removal/insertion of faulty detector components during the annual winter shutdown

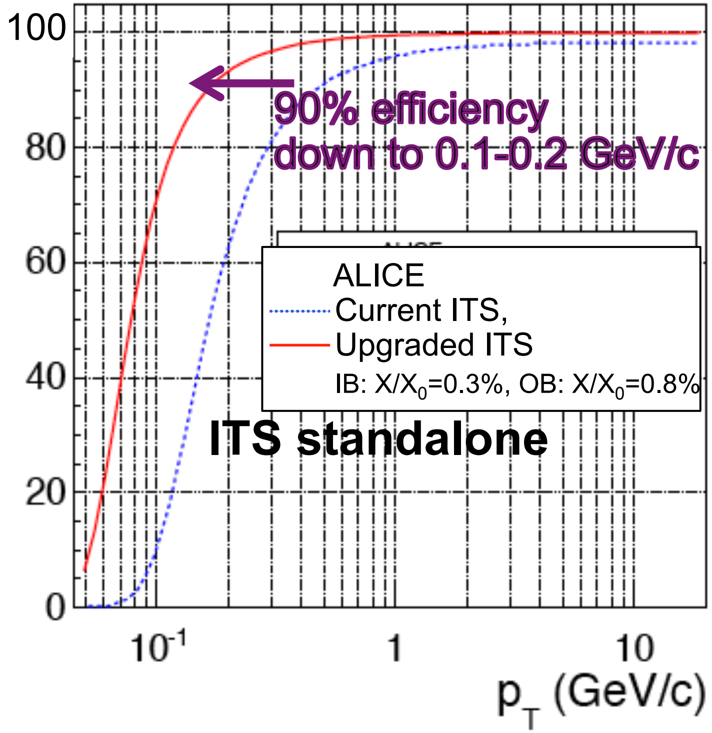


η coverage: |η|<1.22

New ITS: performance

Studies done with simulations with realistic and complete detector geometry and material budget description.

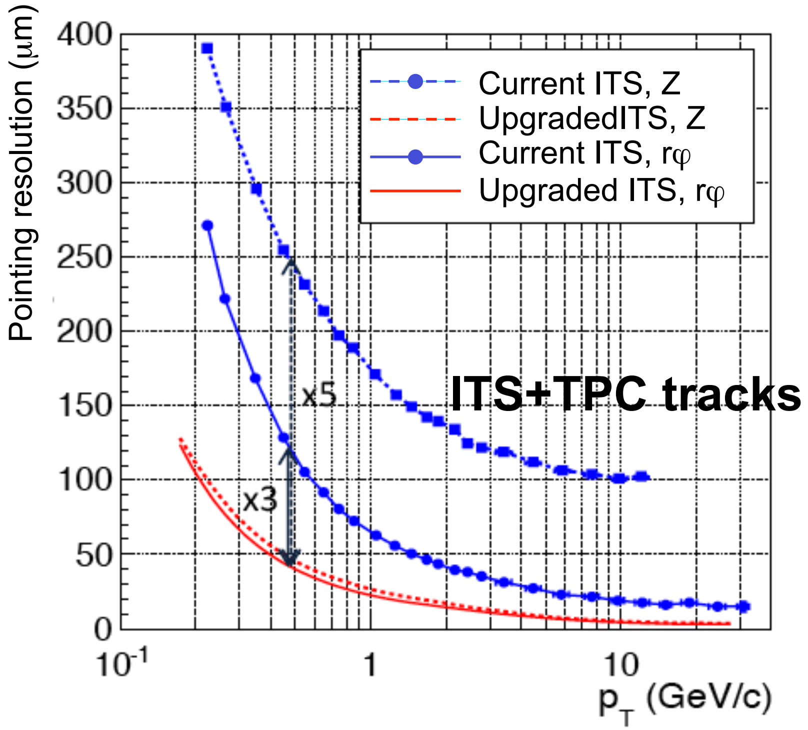
Track reconstruction efficiency



90% efficiency down to 0.1-0.2 GeV/c

ITS standalone

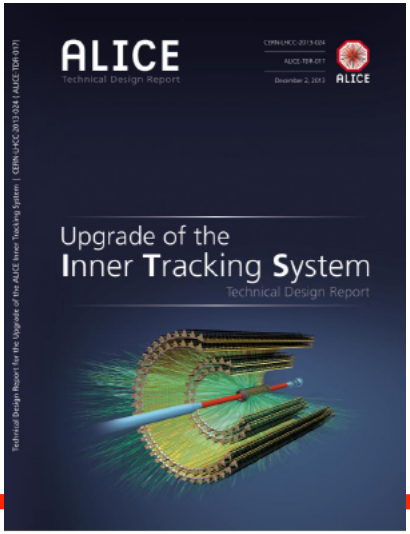
Track spatial resolution at the primary vertex



ITS+TPC tracks

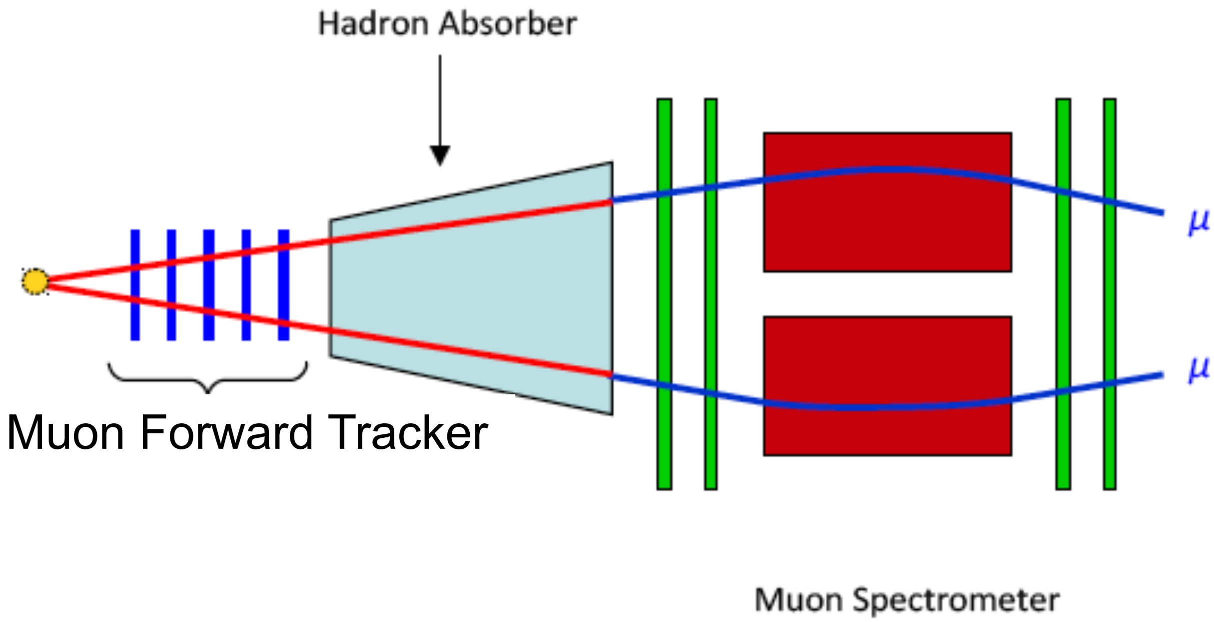
Find more in ALICE ITS TDR:

CERN-LHCC-2013-024 ; ALICE-TDR-017


ALICE
Technical Design Report

Upgrade of the
Inner Tracking System
Technical Design Report

Muon Forward Tracker



Complementing muon spectrometer
at forward rapidity

Muon tracks are extrapolated and matched to the MFT clusters before the absorber

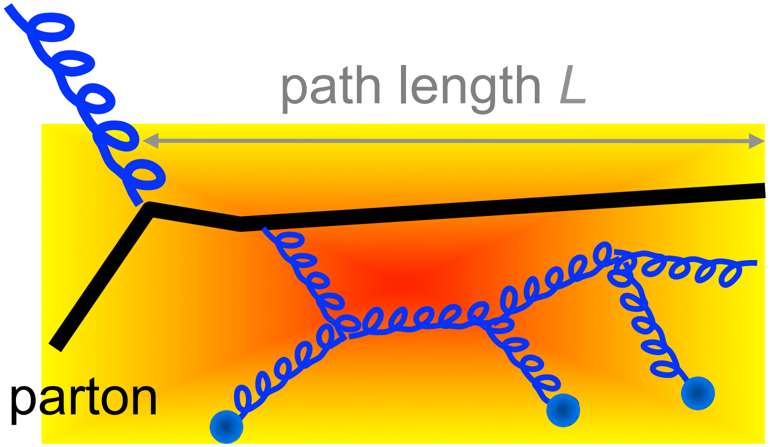
High pointing accuracy

Separation of charm and beauty signals (single μ, J/ψ)

Heavy-flavour energy loss

Verify and quantify over a wide momentum range:

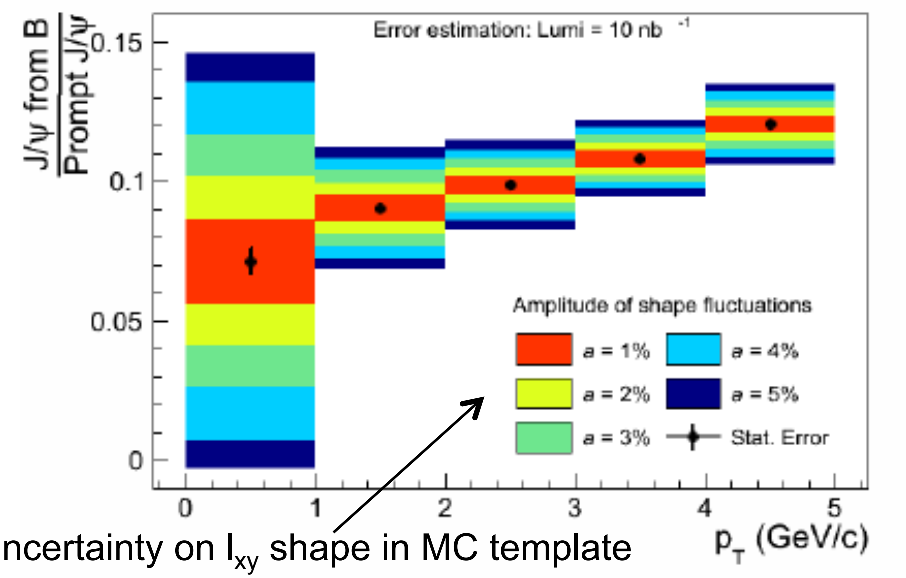
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



Current status:

- **Charm vs. light:** precise D meson measurements needed at low p_T
- **Charm vs. beauty energy loss**:
  - More precise measurements needed at high p_T
  - Lack of information on beauty at low p_T

With upgrade: access to beauty at low p_T via:



Uncertainty on l_{xy} shape in MC template

Displaced HF μ and $J/\psi \rightarrow \mu^+\mu^-$
At forward rapidity with MFT