

(Open) Charm measurement in ALICE at the LHC

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on behalf of the ALICE Collaboration



Outline

Physics motivations for heavy-flavour measurements with ALICE at the LHC

Open charm measurement with ALICE detector

Selection of main and most recent results:

- pp collisions
- p-Pb collisions (if time)
- Pb-Pb collisions (focus of this talk)

Prospects with detector upgrade

Heavy-flavour with ALICE: main goals

pp collisions

Reference for p-Pb and Pb-Pb collisions.

Characterise heavy-flavour production and set constraints to theoretical calculations.

p-Pb collisions

Study cold nuclear matter effects (shadowing, gluon saturation, k_T -broadening, energy loss in CNM in the initial and final state).

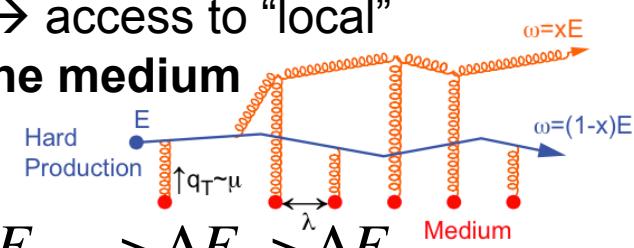
Address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions.

Pb-Pb collisions

Study heavy quark interactions with the QGP constituents → access to “local” interactions, crucial to achieve a **microscopic picture of the medium**

Heavy-quark energy loss:

- radiative + collisional processes
- mass and Casimir factor dependence $\rightarrow \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- hadronisation via coalescence \rightarrow enhanced D_s and charmed-baryon yields



Heavy-quark azimuthal anisotropy

→ participation to system collective motion and possible thermalisation (at low p_T)

→ path length dependence of energy loss (at high p_T)

Heavy-flavour with ALICE: main goals

pp collisions

Reference for p-Pb and

from M. Gazdzicki's talk

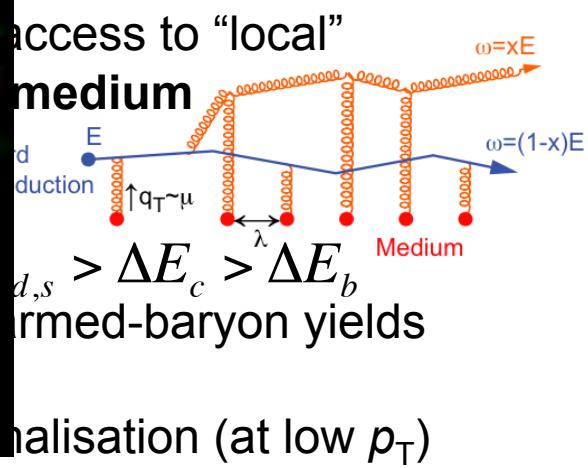
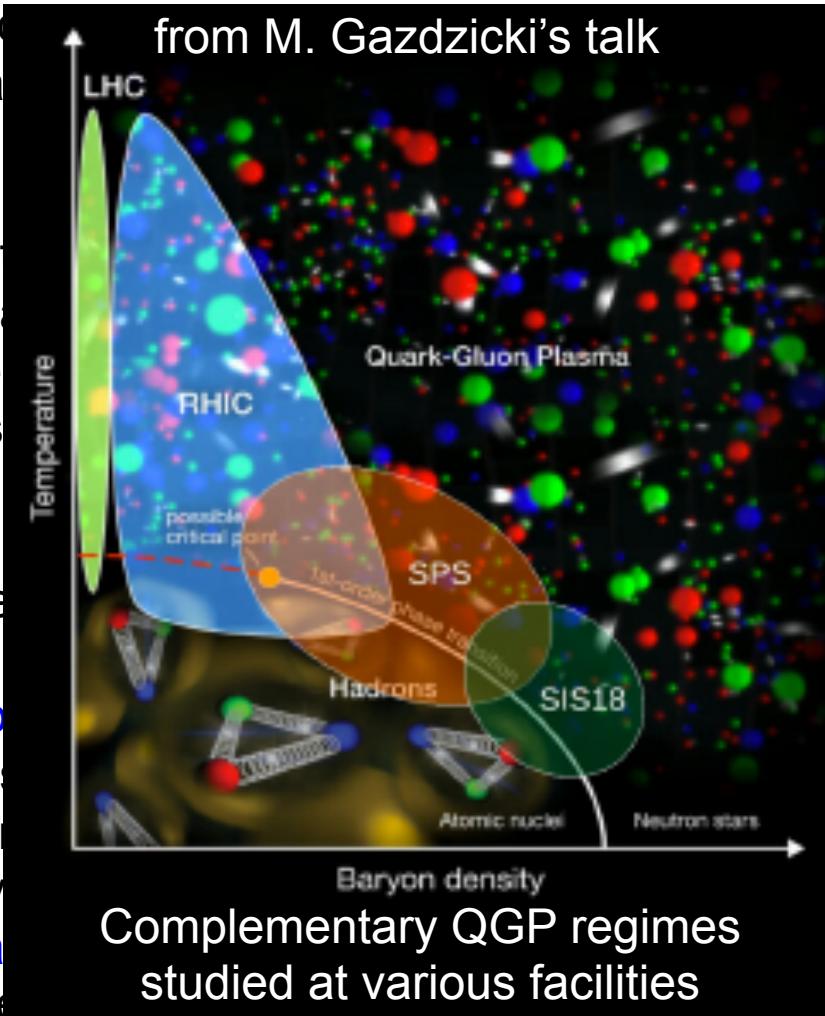
Characterise heavy-flav-

neoretical calculations.

p-Pb collisions

Study cold nuclear matter loss in CNM in the initialisation, k_T -broadening, energy

Address possible collective (possible) formation of a QGP in p-Pb collisions



Pb-Pb collisions

Study heavy quark interactions, crucial to

Heavy-quark energy loss

- radiative + collisional
- mass and Casimir effects
- hadronisation via gluons

Heavy-quark azimuthal correlation

→ participation to system

→ path length dependence of energy loss (at high p_T)

normalisation (at low p_T)

Main observables in nuclear collisions

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

$$R_{AA}(p_T) = \frac{dN_{AA} / dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp} / dp_T}$$

Pb-Pb

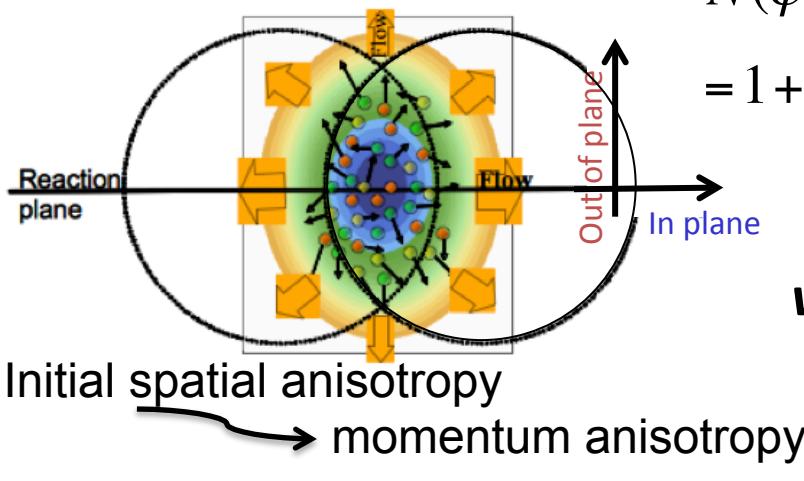
PP

Nuclear overlap function,
encodes collision geometry

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

Elliptic flow (v_2): study azimuthal distribution of produced particles w.r.t. the reaction plane (Ψ_{RP})

$$N(\varphi) \propto 1 + 2 \sum v_n \cos(n(\varphi - \psi_{RP}))$$
$$= 1 + 2v_1 \cos(\varphi - \psi_{RP}) + 2v_2 \cos(2(\varphi - \psi_{RP})) + \dots$$



$v_2 > 0$

Thermalization/collective motion
(at low p_T)

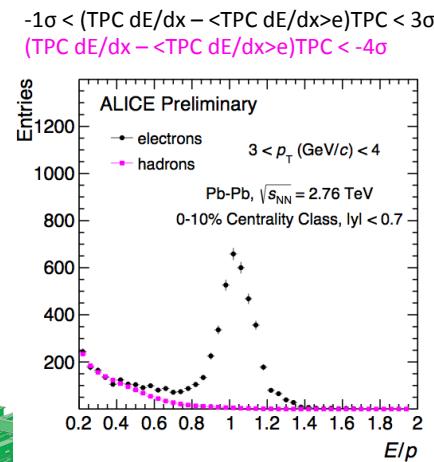
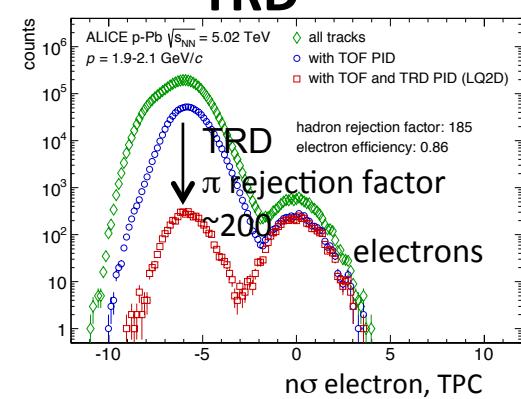
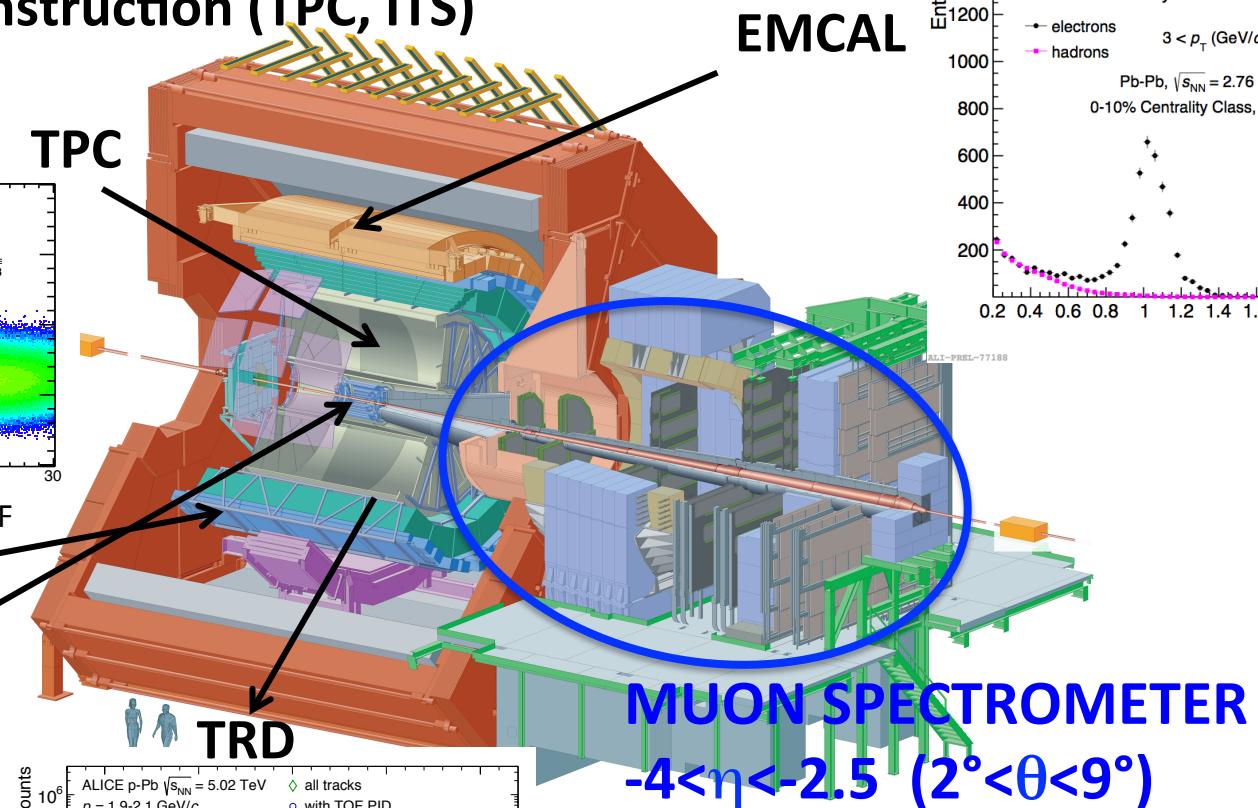
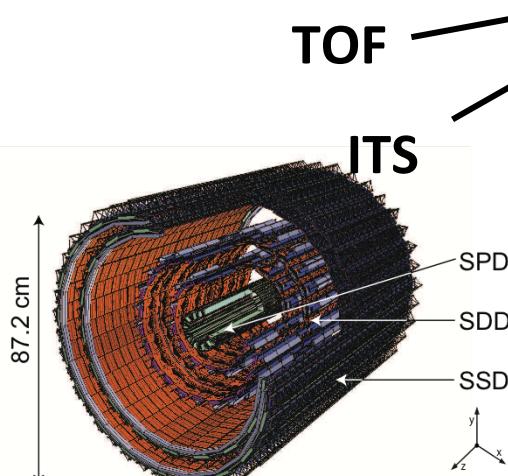
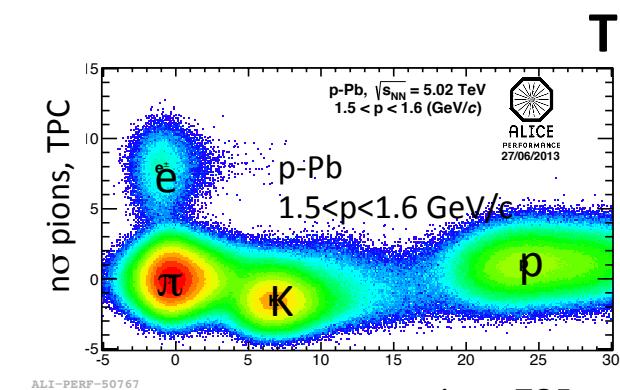
Path length dependence of energy loss
(at high p_T)

The ALICE detector

Central barrel ($|\eta| < 0.9$, $B = 0.5$ T)

Track and vertex reconstruction (TPC, ITS)

Particle Identification



Heavy-flavour reconstruction with ALICE

Heavy-flavour hadron decay leptons:

- Electrons at mid rapidity ($|y|<0.9$)
 - electron identification with TPC, TOF, ITS, TRD, EMCAL
 - Non-HF electrons (mainly gamma-conversion and π^0, η Dalitz decay) removed
 - 1) statistically with data-tuned cocktail
 - 2) by finding the “partner” with e^+e^- invariant mass technique
- Muons at forward rapidity ($-4<\eta <-2.5$) with muon spectrometer:
 - Tracks matched with trigger
 - Subtraction of muons from primary π, K decays via simulations with data-tuned π, K abundances

Charmed hadron reconstruction ($|y|<0.9$)

Invariant mass analysis of reconstructed hadronic decays

$$D^0 \rightarrow K^-\pi^+, D^{*+} \rightarrow D^0\pi^+, D^+ \rightarrow K^-\pi^+\pi^+, D_s^+ \rightarrow \phi\pi^+, \phi \rightarrow K^-\bar{K}^+$$

$$\Lambda_c^+ \rightarrow pK^-\pi^+, \Lambda_c^+ \rightarrow pK_s^0$$

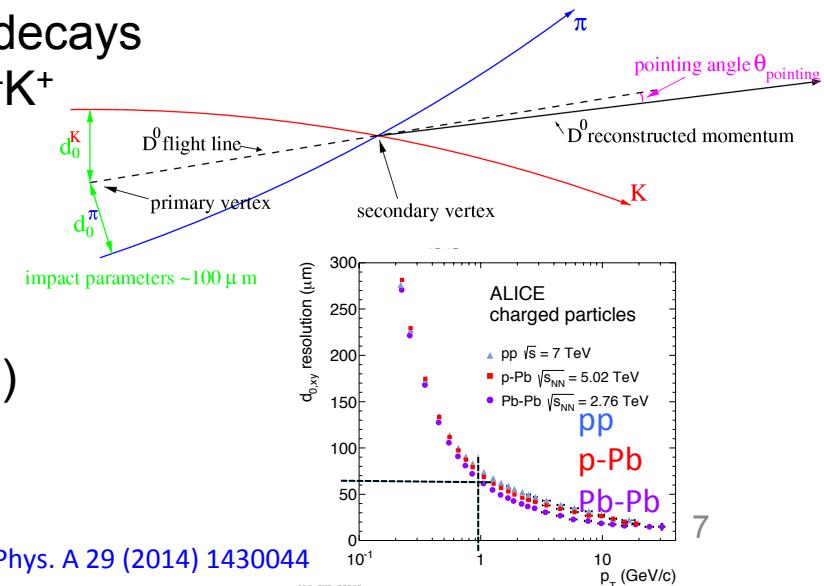
Displaced secondary vertices (\rightarrow ITS)

+ PID (p/K/ π separation with TOF+TPC)

... and semi-leptonic decays (no decay vertex reco)

$$\Lambda_c^+ \rightarrow e^+\Lambda\nu, \Lambda \rightarrow p\pi^-$$

$$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e, \Xi^- \rightarrow \pi^-\Lambda$$



More details on D^0 reconstruction

2 techniques

-- “Standard” with decay vertex reconstruction:

topological selection to reject background

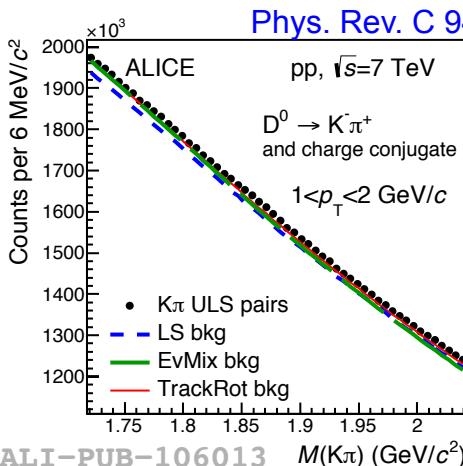
→ higher S/B, lower selection efficiency (see backup)

-- (D^0 only) Analysis w/o vertex reconstruction:

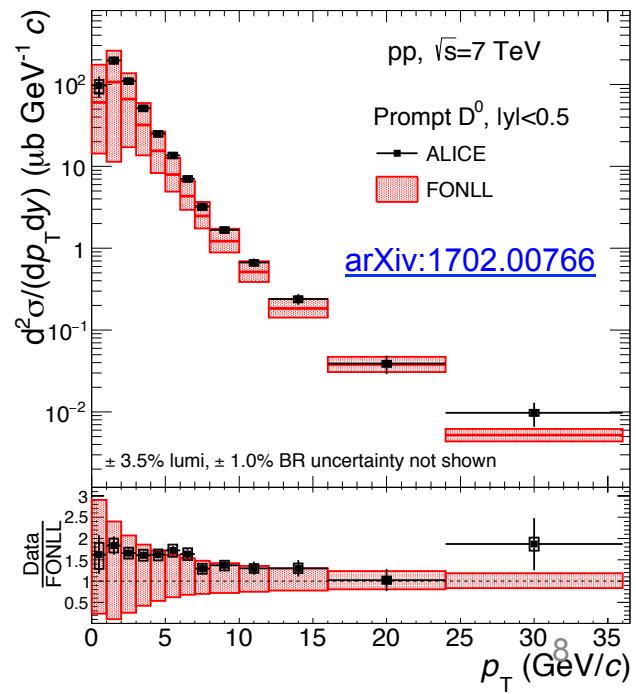
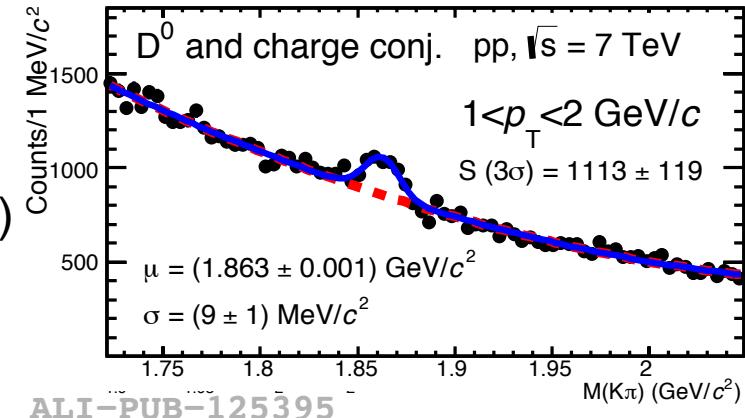
yield extraction with background invariant mass distribution estimated with several techniques

(event mixing, track rotation, like-sign, direct fit),

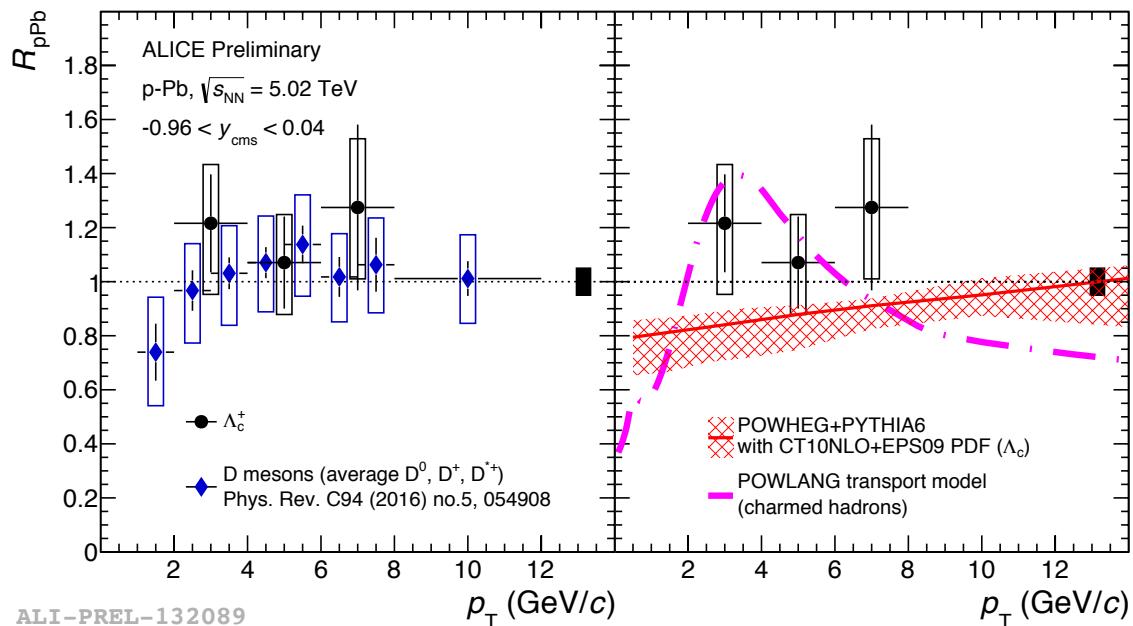
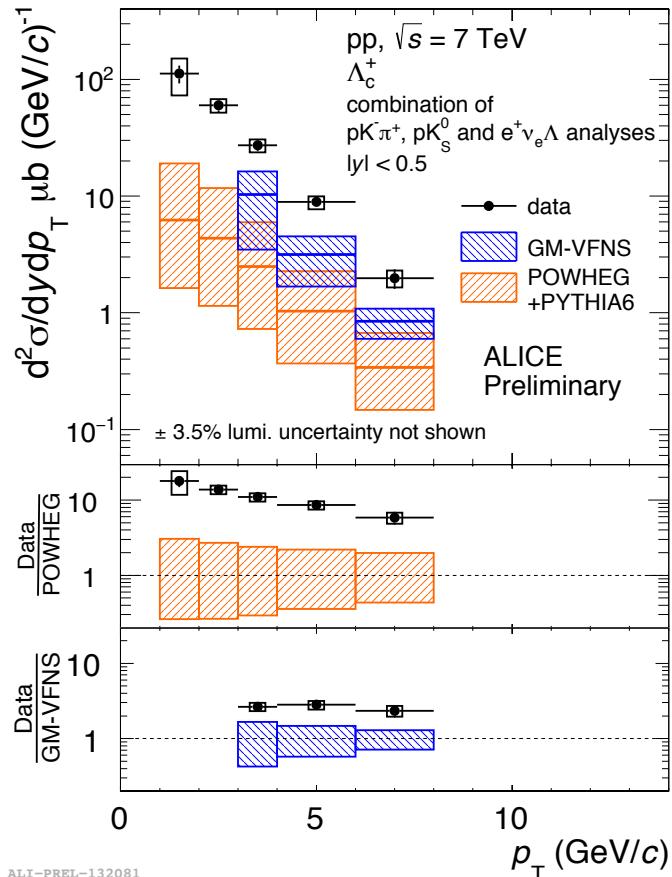
better precision for $p_T < 1$ GeV/c (short decay length)



→ D^0 cross section measured down to $p_T=0$
 (so far in pp at $\sqrt{s}=7$ TeV and p-Pb at $\sqrt{s_{NN}}=5$ TeV)



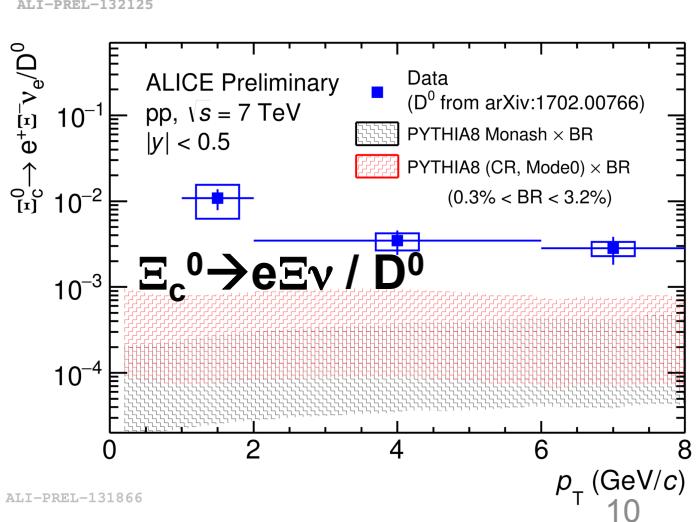
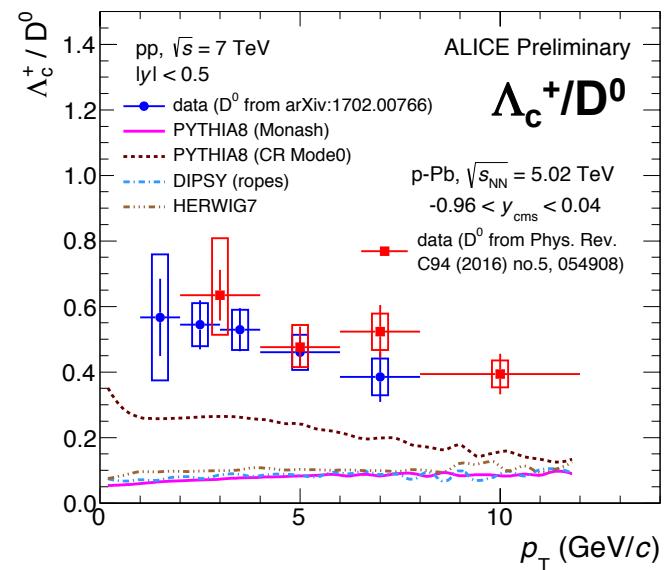
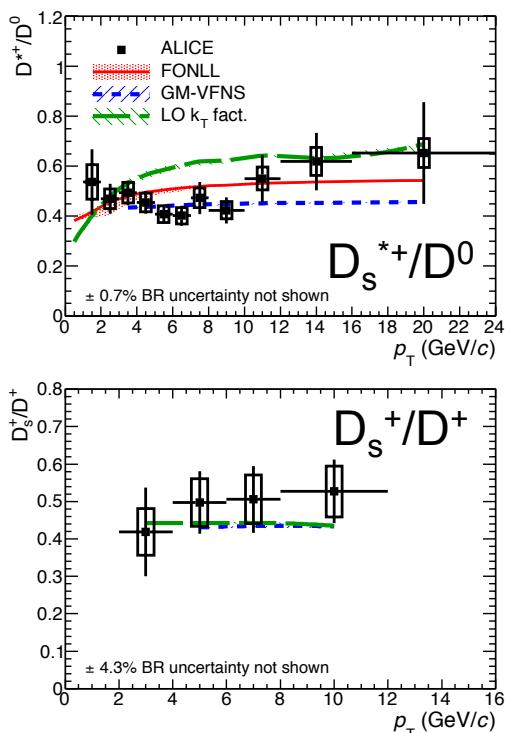
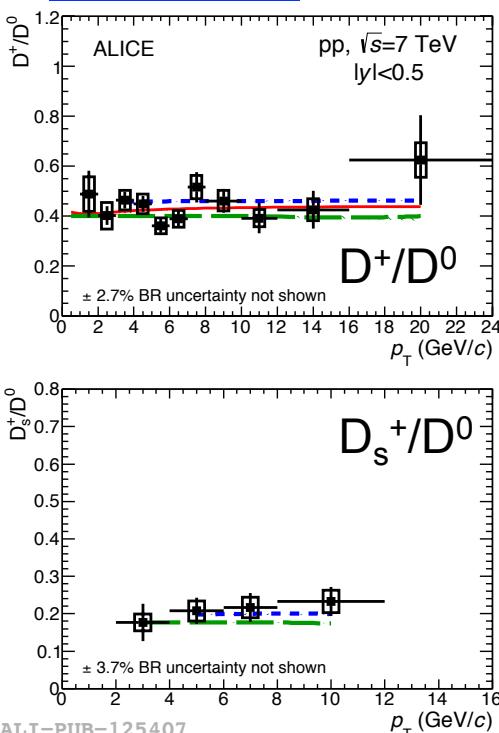
Charmed baryons in pp and p-Pb



- Λ_c production cross section higher than theoretical expectations
- R_{pPb} compatible with unity, with pQCD+nPDF, as well as with a model assuming QGP formation in p-Pb

Charm-particle species ratios (pp)

[arXiv:1702.00766](https://arxiv.org/abs/1702.00766)

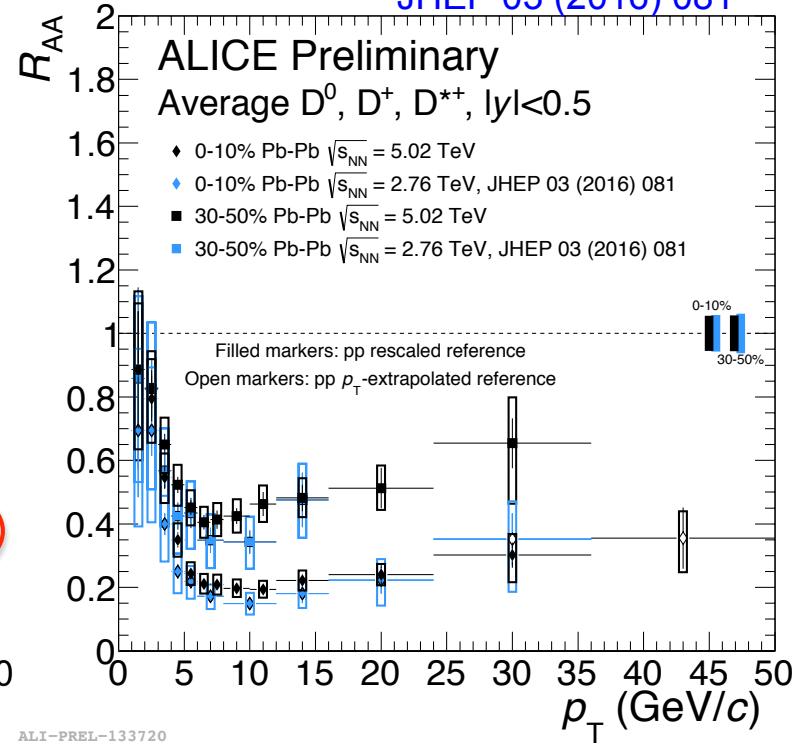
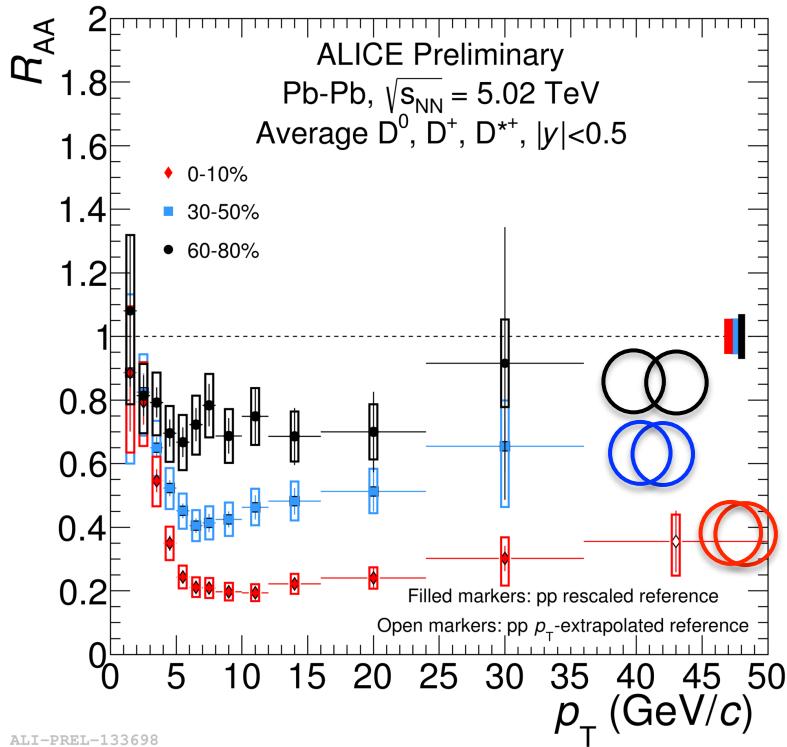


- D-meson species relative abundances as expected from theory, including D_s /non-strange D.
 - Λ_c/D^0 and Ξ_c^0/D^0 higher than theoretical expectations (large uncertainties)
 - **Is charm hadronisation understood?**
 - Need to reduce experimental uncertainties to provide more precise input to models

Pb-Pb results

Non-strange-D-meson R_{AA}

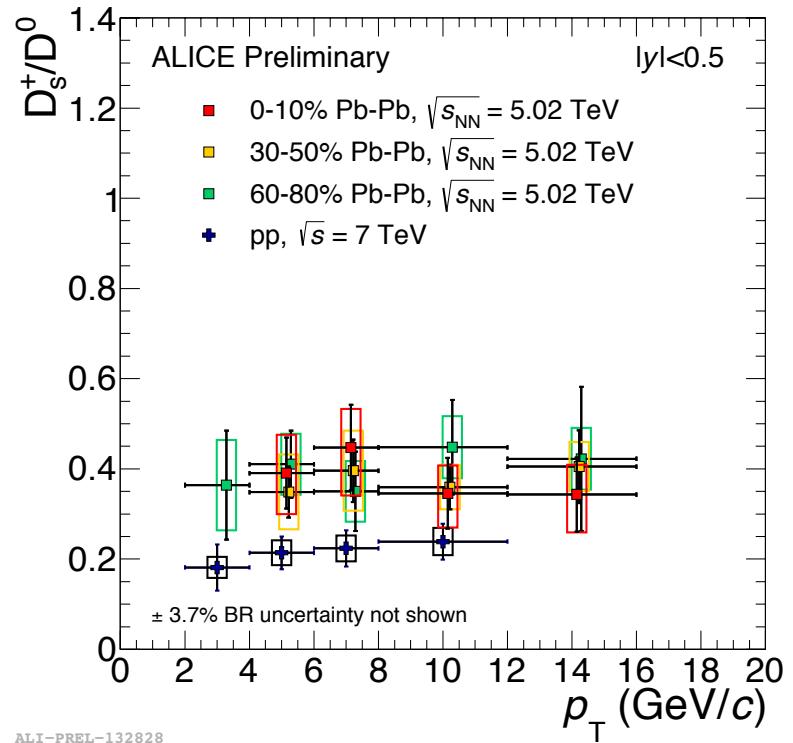
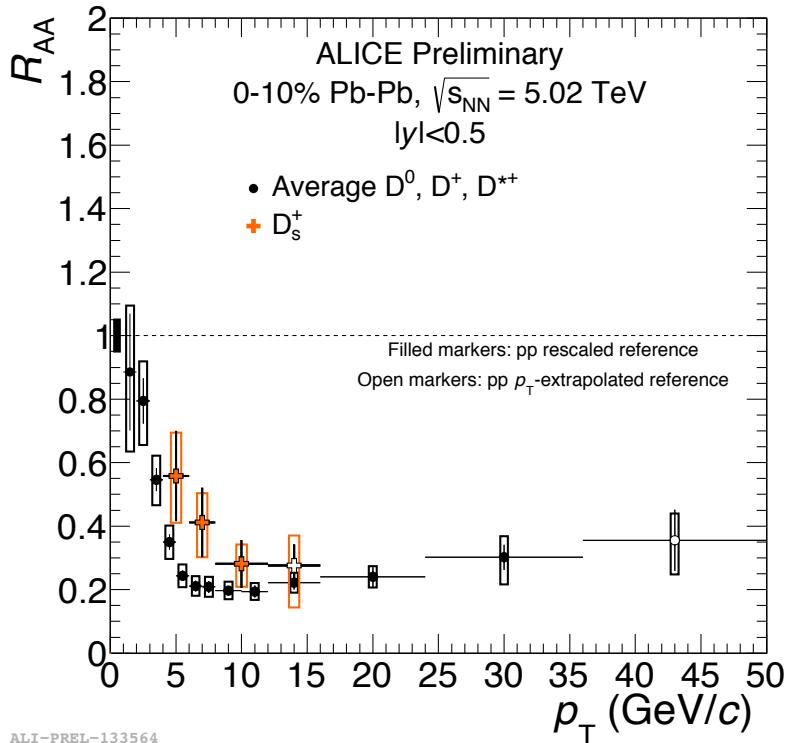
ALICE-PUBLIC-2017-003
JHEP 03 (2016) 081



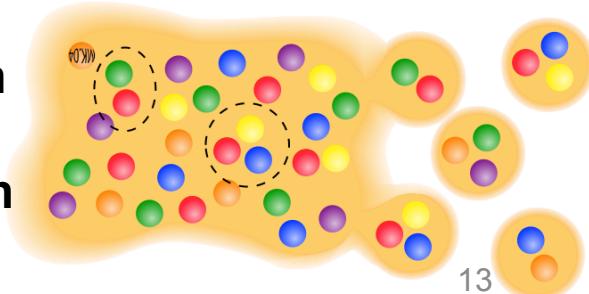
- Strong suppression of high- p_T D-meson production in central Pb-Pb collisions.
- Suppression increasing with centrality.
- Similar R_{AA} at 2.76 TeV and 5 TeV
 - Improved precision and high- p_T reach with run-2 data

D_s^+ -meson R_{AA}

ALICE-PUBLIC-2017-003

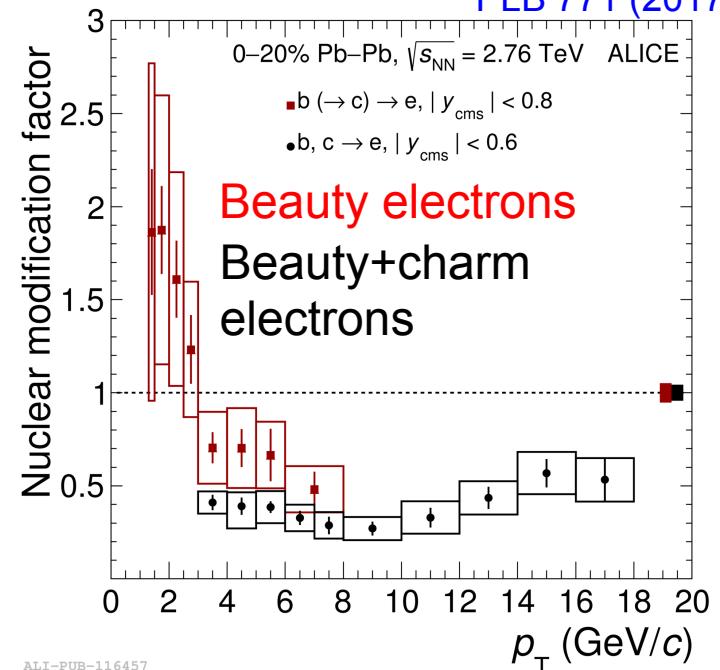
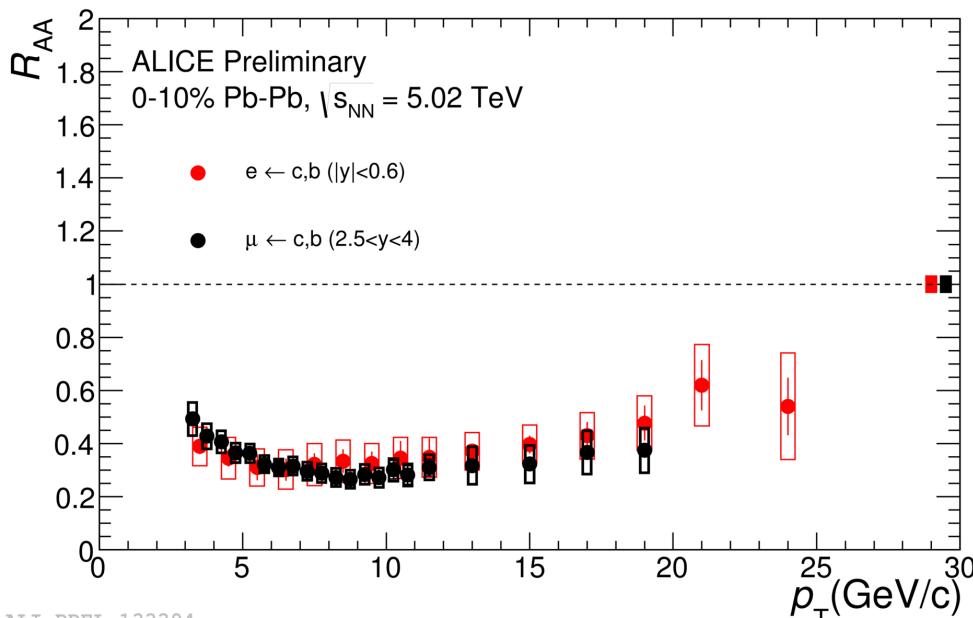


- Hint for $R_{AA}(D_s^+) > R_{AA}$ (non-strange D) at low p_T .
 - Hint for higher D_s /non-strange D meson ratio in Pb-Pb than pp collisions, w/o evident centrality dependence
- Hadronisation via coalescence in a strangeness-rich environment?



Heavy-flavour decay leptons

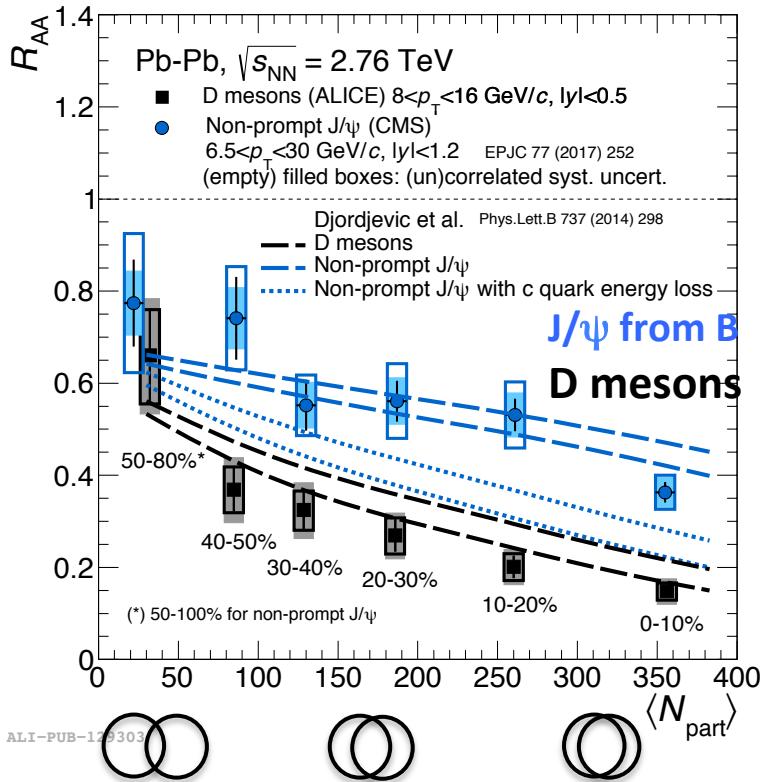
JHEP 07 (2017) 052
 PLB 771 (2017) 467-481



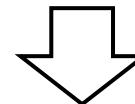
- Strong suppression of heavy-flavour decay electrons [muons] at central [forward] rapidity in 0-10% Pb-Pb collisions. Similar results at central and forward rapidity.
- Beauty components dominates from $p_T > 5$ GeV/c \rightarrow indication of beauty suppression.
- Beauty-electron R_{AA} measured directly with impact parameter fit (at 2.76 TeV): indication of suppression for $p_T > 3$ GeV/c.
- Hint of $R_{AA}(\text{beauty electrons}) > R_{AA}(\text{HF electrons})$: consistent with expectation of smaller energy loss for beauty quarks.

Open charm and beauty

ALICE, JHEP 1511 (2015) 205, JHEP 1706 (2017) 032
 CMS, EPJ C 77 (2017) 252



$R_{AA}(J/\psi \text{ from } B) > R_{AA}(D)$ in central collisions



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

The different suppression and the centrality dependence as expected from **models with quark-mass dependent energy loss**

$$(\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b)$$

Expected from dead cone effect:

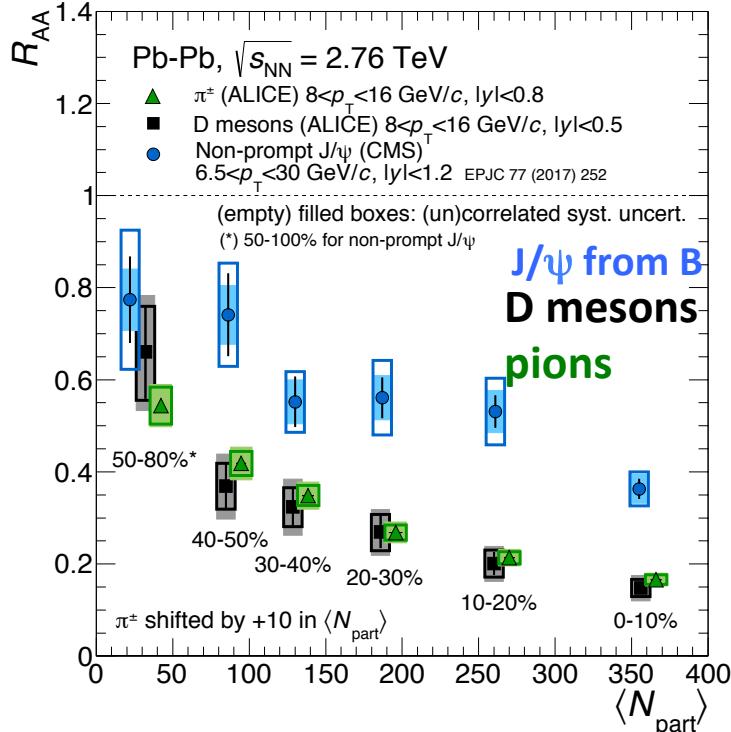


$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

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

Open charm and beauty

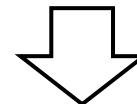
ALICE, JHEP 1511 (2015) 205, JHEP 1706 (2017) 032
 CMS, EPJ C 77 (2017) 252



Similar D meson and pion R_{AA}

Expected from small charm-quark mass
 + differences between charm and
 gluon/LF spectra slope and
 fragmentation

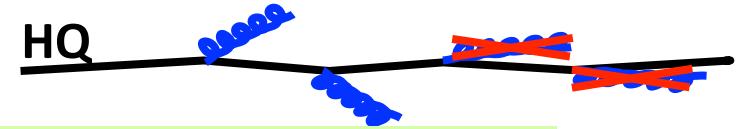
$R_{AA}(\text{J}/\psi \text{ from B}) > R_{AA}(\text{D})$ in central collisions



Indication of $R_{AA}(\text{B}) > R_{AA}(\text{D})$

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

Expected from dead cone effect:



Gluonsstrahlung probability

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

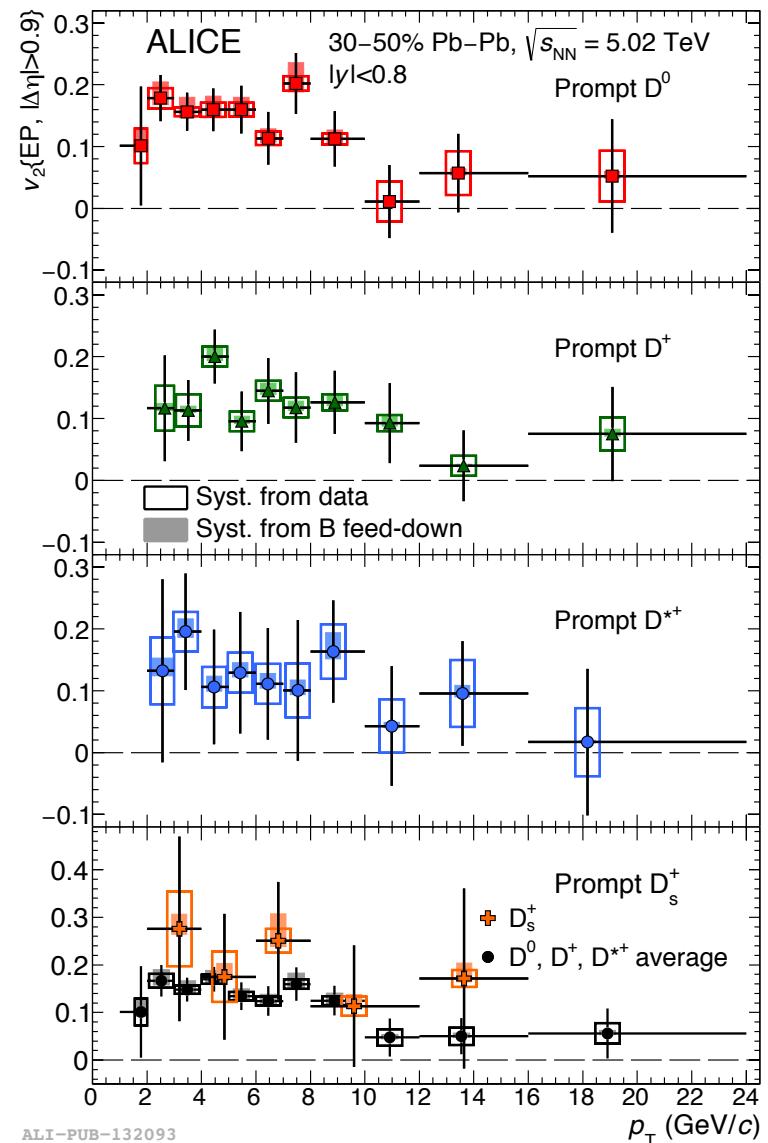
Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
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D-meson v_2

Compatible v_2 of D^0, D^+, D^{*+} .

D-meson average v_2 significantly larger than 0 up to $10 \text{ GeV}/c \rightarrow$ charm quarks sensitive to medium collective motion.

First measurement of $D_s^- v_2$: compatible with non-strange D-meson v_2 within uncertainties.



D-meson v_2

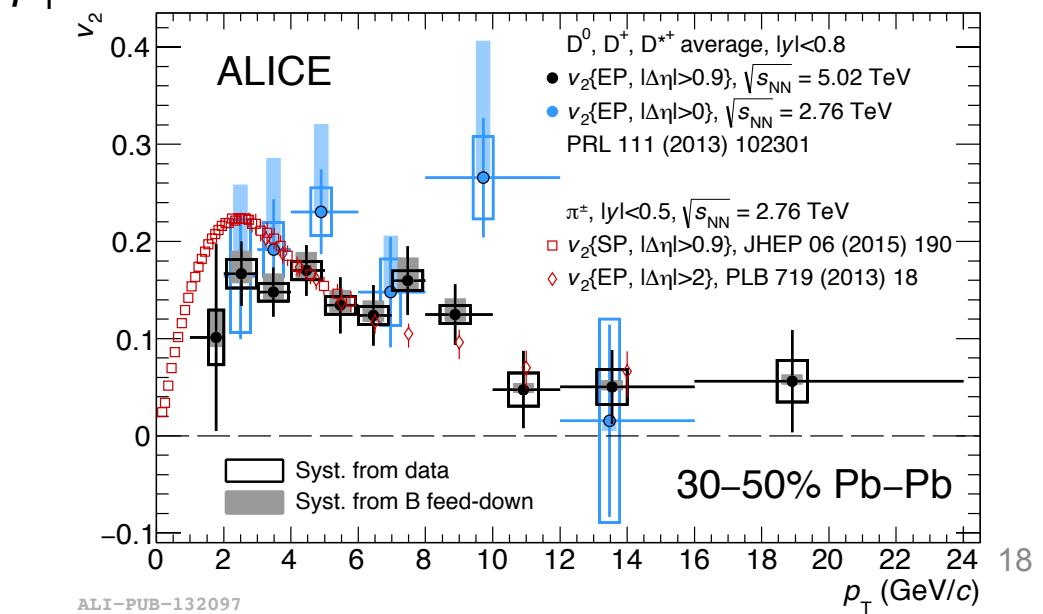
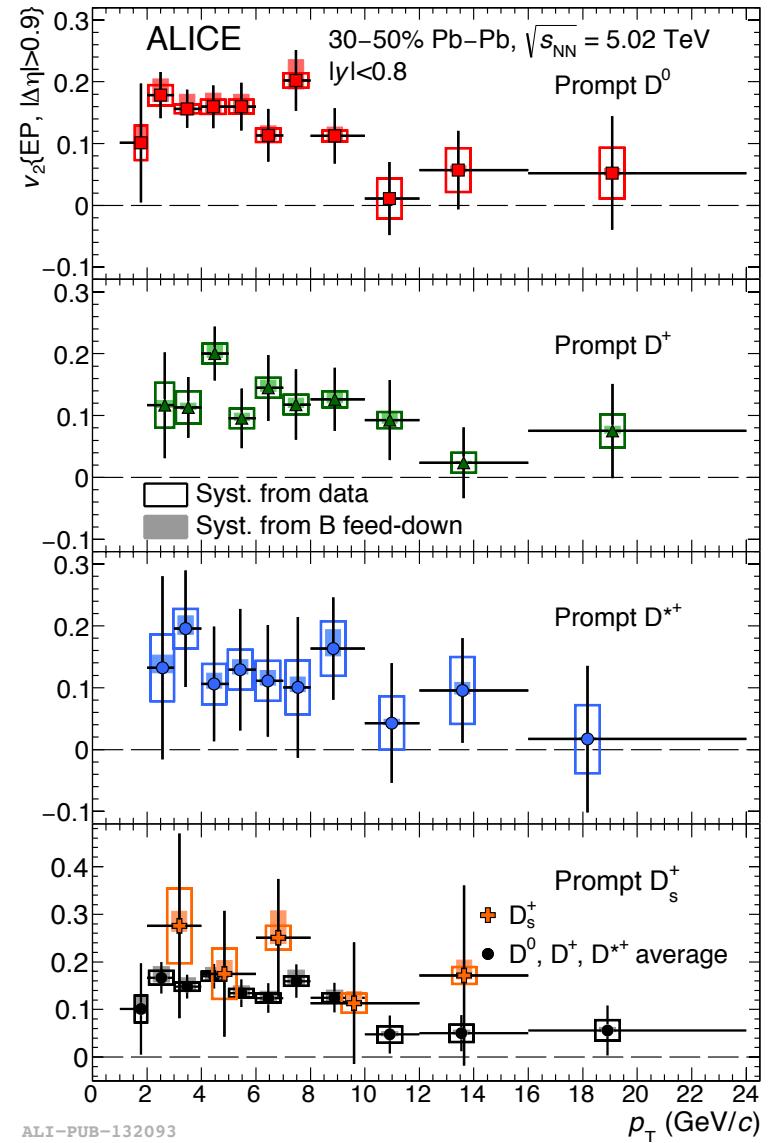
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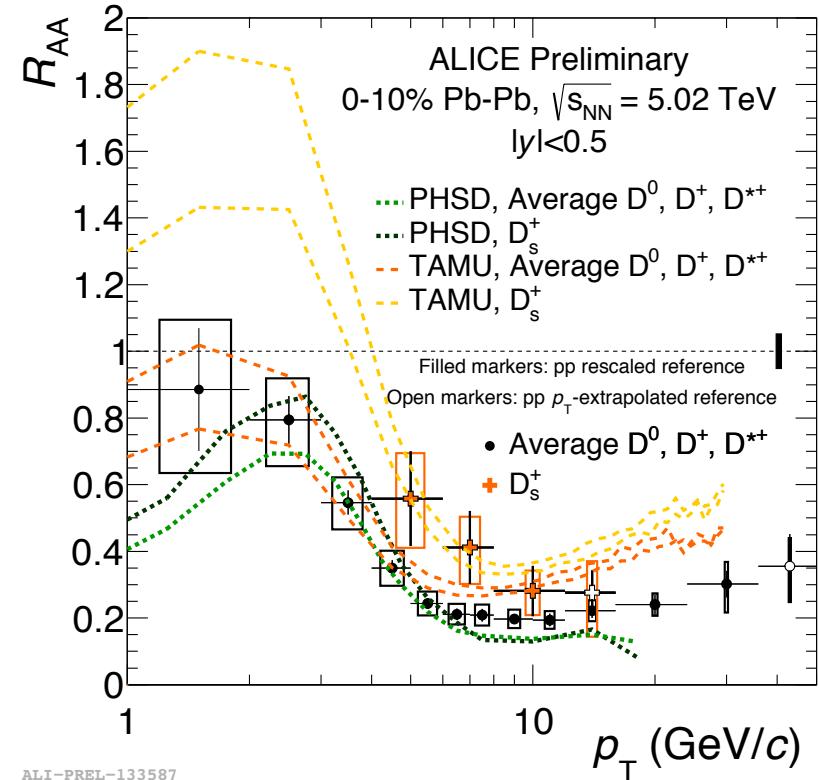
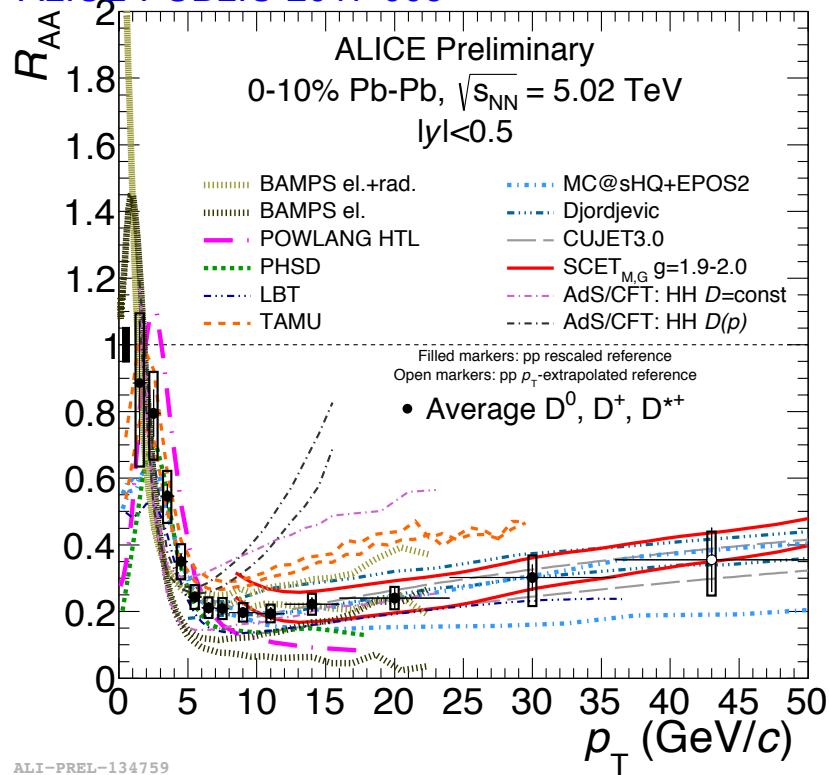
Similar v_2 at $\sqrt{s_{NN}}=2.76$ and 5 TeV .

D meson and charged pion v_2 compatible within uncertainties: hint for smaller v_2 of D mesons for $p_T < 4 \text{ GeV}/c$.



Comparison to models

ALICE-PUBLIC-2017-003



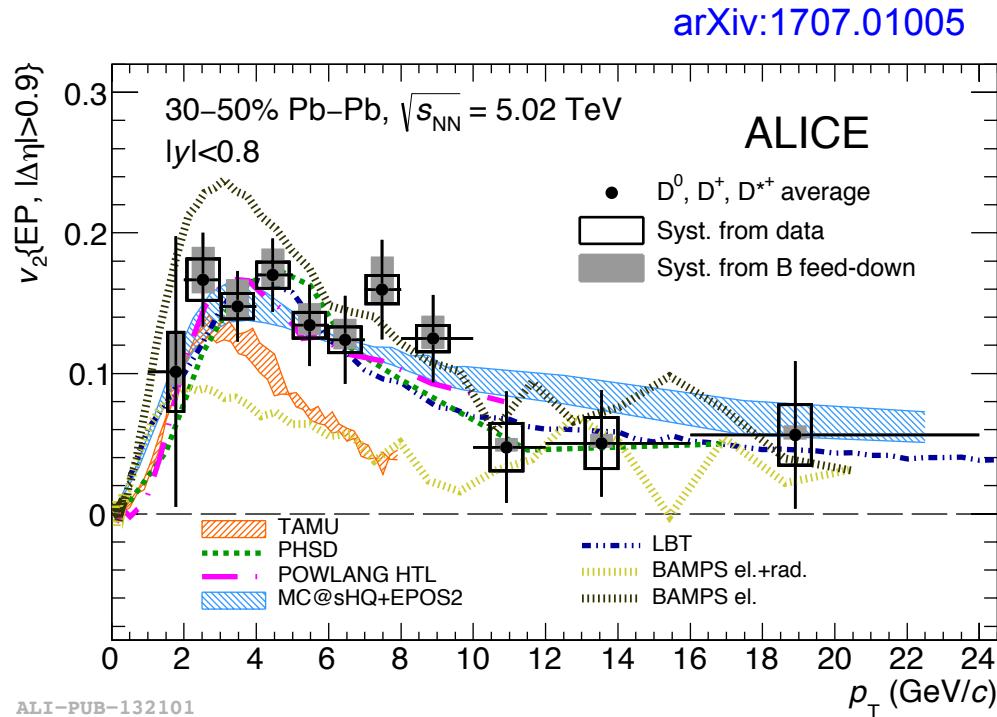
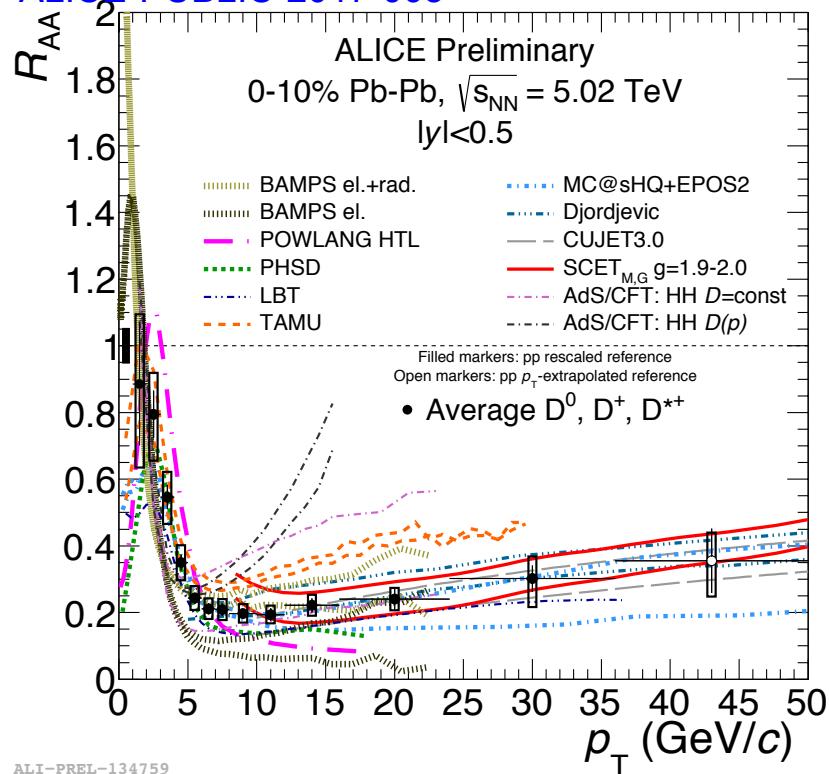
- Important inputs to models differing for the inclusion of various effects (radiative, collisional energy loss, coalescence, realistic initial conditions and medium evolution).

BAMPS: JPG 42, 115106 (2015)
POWLANG: EPJC 75, 121 (2015)
PHSD: PRC 92, 014910 (2015)
LBT: arXiv 1703.00822
TAMU: PLB 735, 445-450 (2014)

MC@sHQ+EPOS: PRC 89, 014905 (2014)
Djordjevic: PRC 92, 024918 (2015)
CUJET: JHEP 02, 169 (2016)
SCET: JHEP 03, 146 (2017)
Ads/CFT: JHEP 1411, 017 (2014)

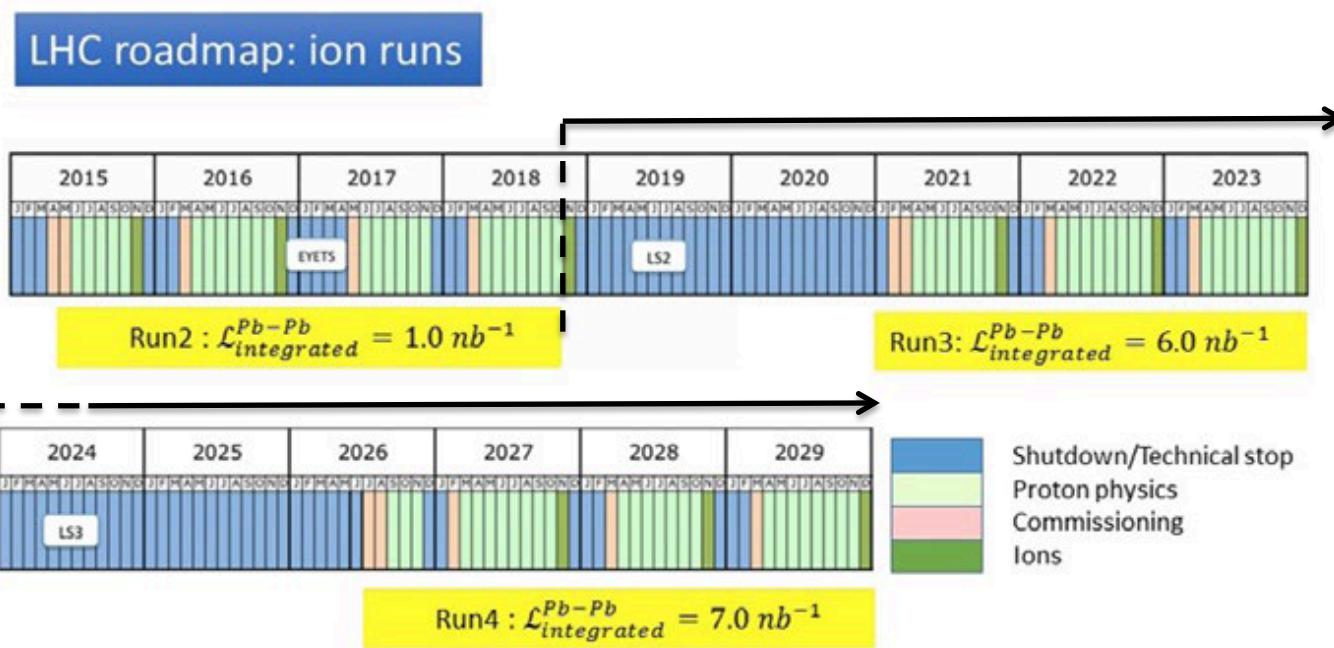
Comparison to models

ALICE-PUBLIC-2017-003



- Important inputs to models differing for the inclusion of various effects (radiative, collisional energy loss, coalescence, realistic initial conditions and medium evolution).
- Models able to reproduce v_2 favour diffusion coefficient $2\pi TD_s(T)$ in the range 1.5-7 at T_c with a corresponding thermalisation time $\tau_{\text{charm}} = 3-14$ fm/c.
- Powerful constraints by considering complementary observables (R_{AA} and v_2 of non-strange D and D_s^+) over wide p_T ranges and in different centrality classes.**

Prospects with detector upgrade



Main physics goals for heavy-flavour with ALICE upgraded detector

Convolution of many effects (radiative and collisional energy loss, coalescence, CNM) → Very rich physics but many degrees of freedom in models

→ Extraction of physical information (e.g. transport and diffusion coefficients) require precise data and “dedicated” observables measured over a wide momentum range

Energy loss: precise quantification of mass and Casimir-factor dependence measure (constrain) transport coefficients

Need to measure charm and beauty R_{AA} and v_2 with very good precision.

After run-2: lack of precision on charm at low p_T , lack of information on beauty at low p_T

Open charm down to $p_T=0$ needed also as reference for quarkonia

Hadronisation via coalescence: need precise measurement of D_s , Λ_c , (Ξ_c) R_{AA} and v_2 in fine p_T intervals at low p_T .

... for beauty as well (Λ_b)

Many of the signals are rare and with very low S/B

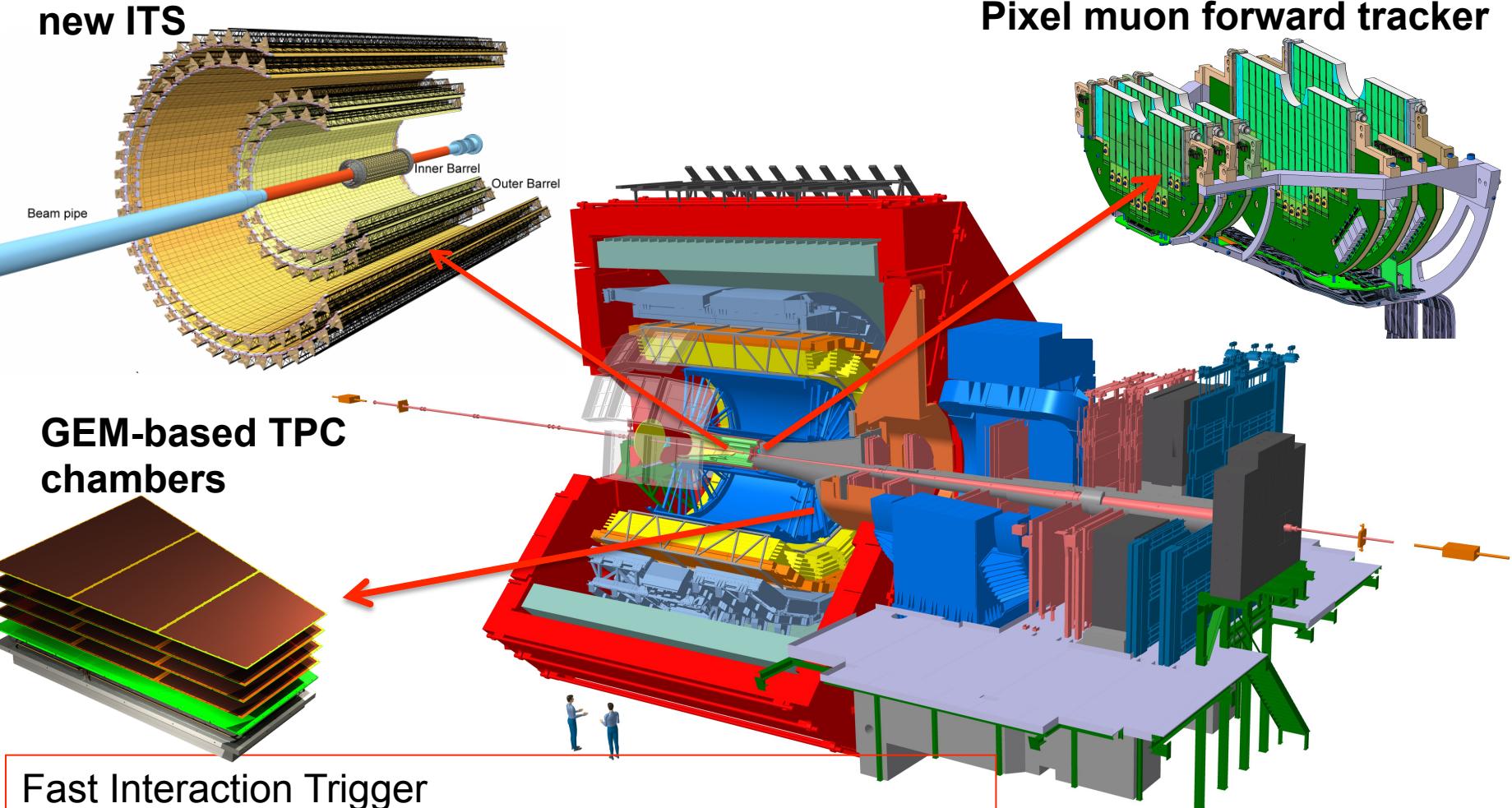
- Need large min. bias data samples
- trigger selection not efficient
- readout all events at 50 kHz

Λ_c or D at low p_T : decay vertices displaced by few tens of microns

- Need to improve track spatial precision to increase S/B

Forward rapidity: need to add capability of separating charm and beauty muons and J/ ψ

ALICE after Run-2

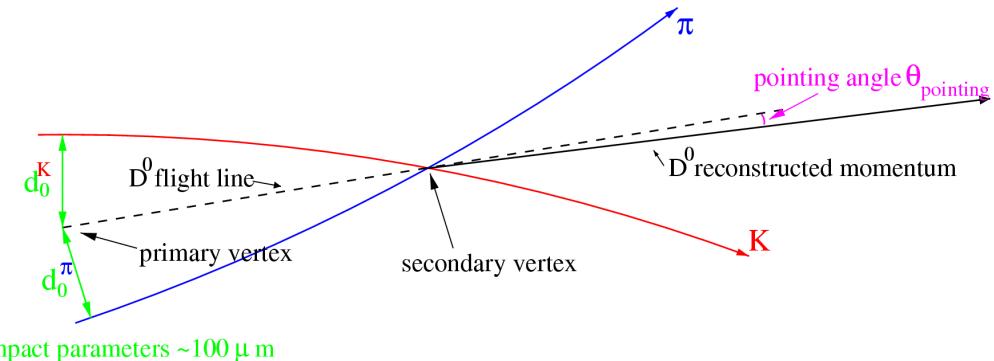


Fast Interaction Trigger
New Online-Offline system
Readout upgrade of other detectors
Goal: collect 10 nb^{-1} of min. bias Pb-Pb collisions
x100 gain w.r.t. run 1+2 for min. bias

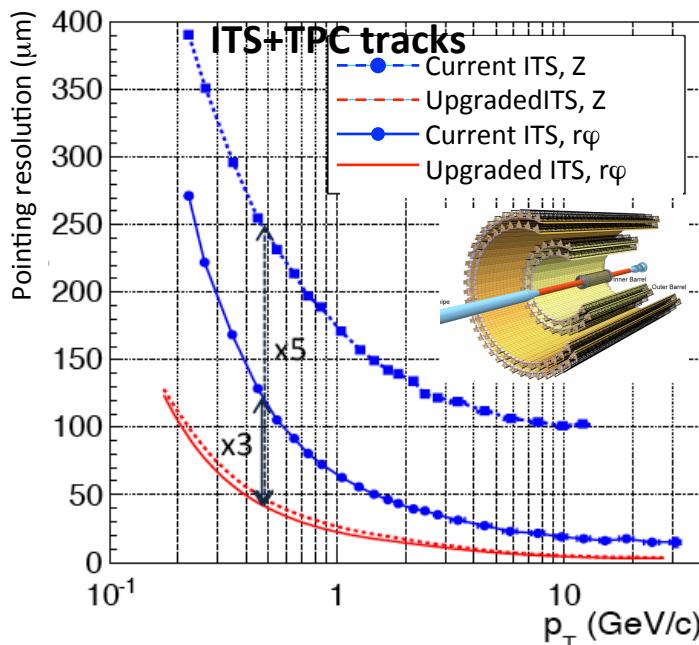
All projects moving
into production
phase this year

Detector performance, examples

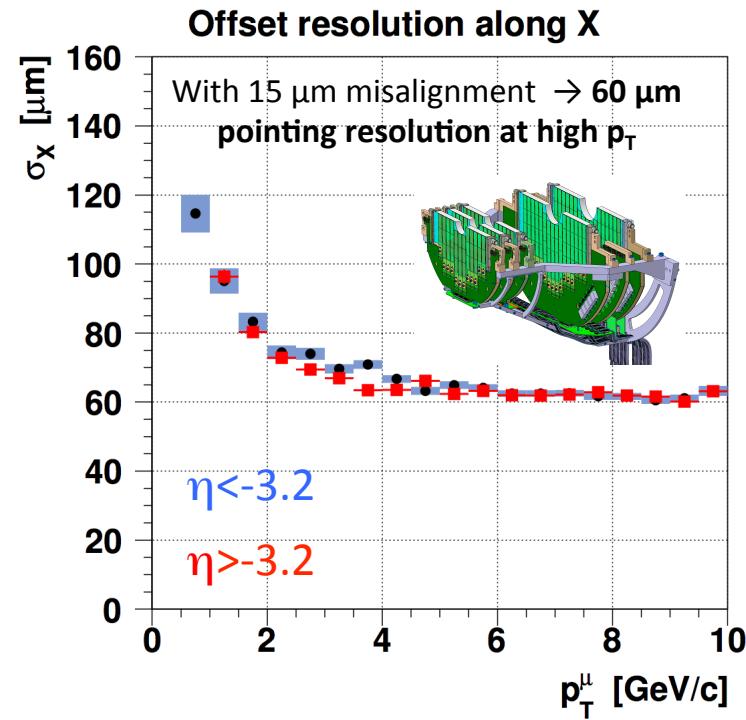
$\sigma_{\tau} (D^0) \sim 123 \mu m$
 $\sigma_{\tau} (\Lambda_c^+) \sim 60 \mu m$
 $\sigma_{\tau} (B, \Lambda_b) \sim 400-500 \mu m$



Track spatial resolution at the primary vertex

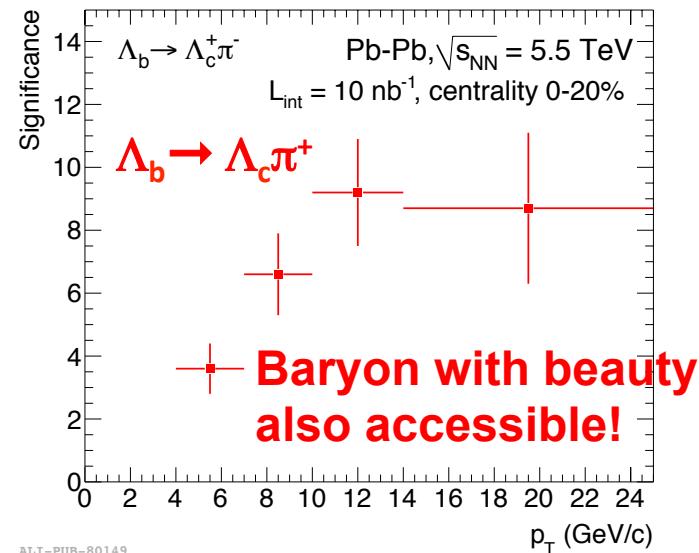
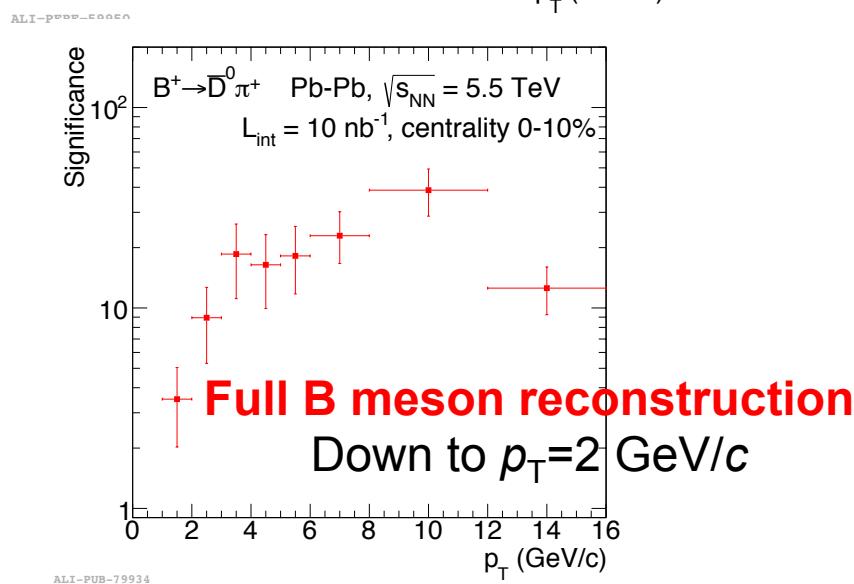
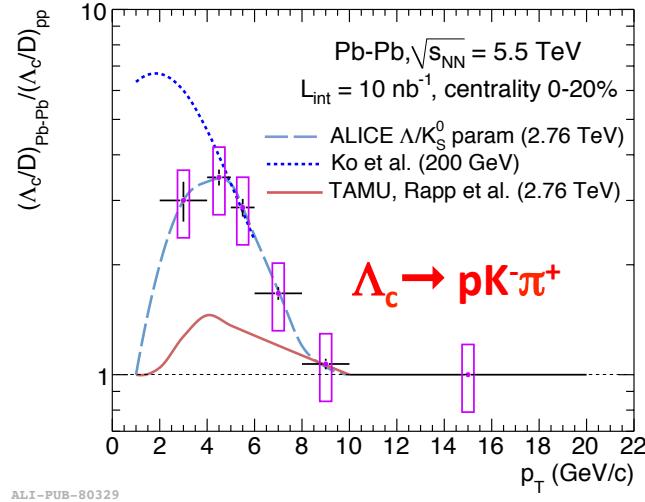
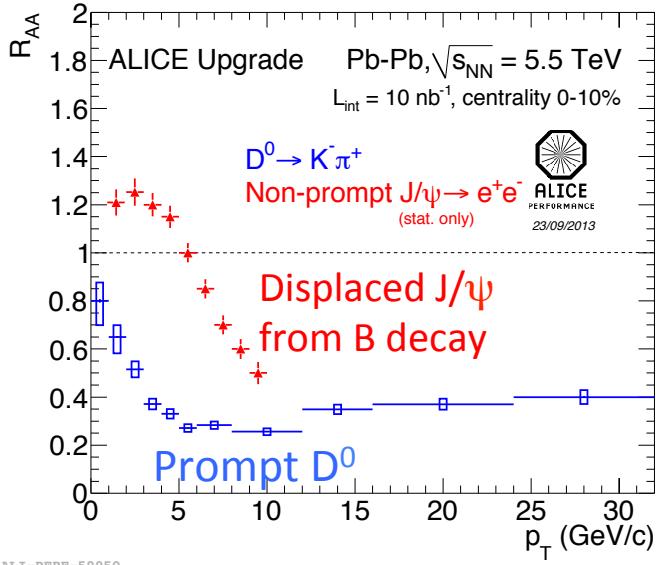


CERN-LHCC-2013-024 ; ALICE-TDR-017



Performance examples for HF signals

Access to charm and beauty down to very low p_T



Conclusion

Proton-proton

D-meson production in proton-proton collisions described by pQCD over a wide momentum range (down to $p_T=0$): theoretical uncertainties much larger than data ones.

Λ_c^+, Ξ_c^0 - baryon production underestimated by models: did we understand charm hadronisation?

Proton-Pb

D-meson $R_{p\text{Pb}}$ compatible with unity \rightarrow “small” effects from CNM (or QGP in p-Pb)

- Crucial to improve precision at low p_T \rightarrow new pp reference (2017), upgrade

Pb-Pb

Significant D-meson suppression \rightarrow charm energy loss

Indication for $R_{AA}(D) < R_{AA}(B)$ \rightarrow mass-dependent energy loss

Hint for $R_{AA}(D_s^+) > R_{AA}$ (non-strange D)

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

Improved precision from run-2 data allows to set important constraints for models describing charm

R_{AA} and v_2 .

Upgrade goals (after LS2)

Detector upgrade \rightarrow improve data precision, extend the p_T range, new observables, in particular D meson down to $p_T=0$, B mesons, heavy-flavour baryons in Pb-Pb.

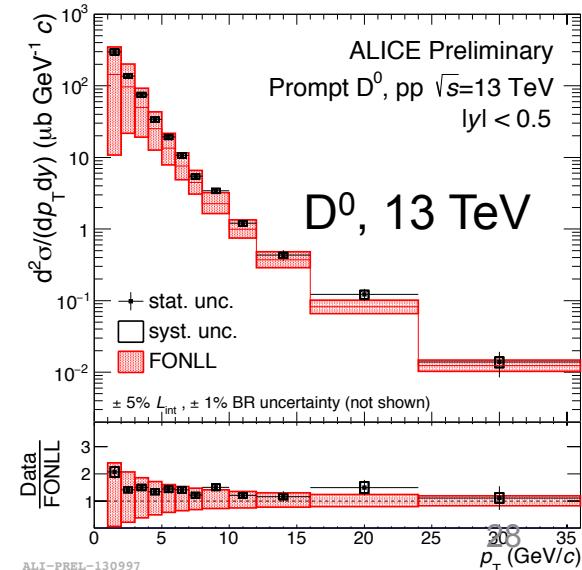
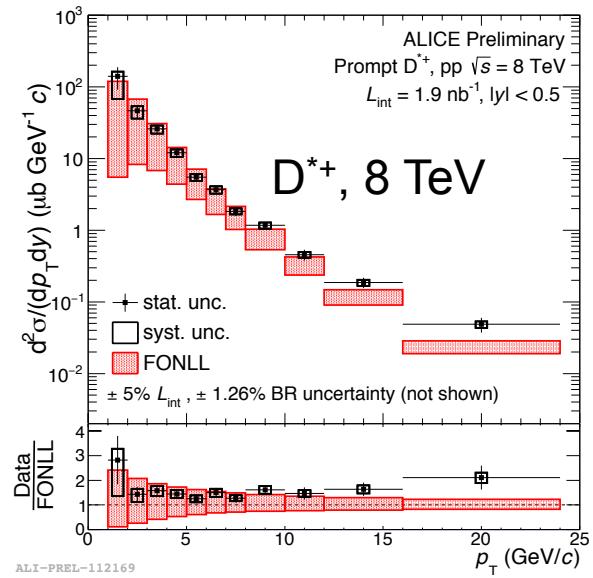
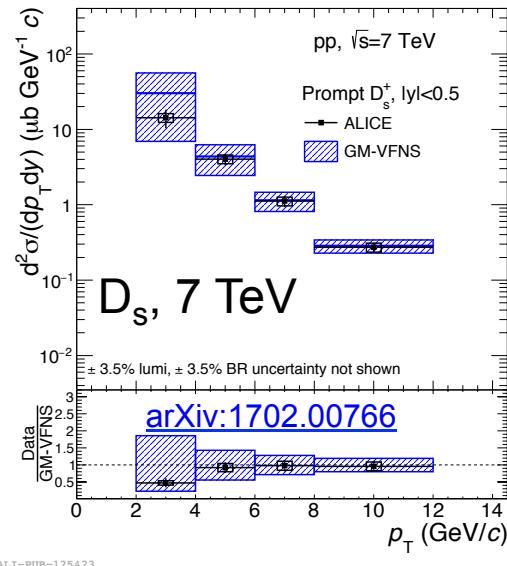
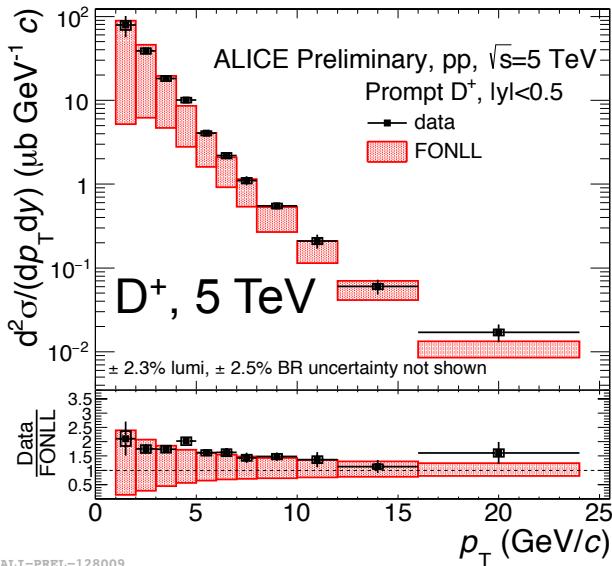
\rightarrow Deeper understanding of heavy-quark interaction with the QGP constituents

\rightarrow Allow for determination of transport coefficients and diffusion coefficients

... and tremendous boost for HF jets, HF correlations, event-shape-engineering, studies as a function of event multiplicities in small systems, ...

Extra

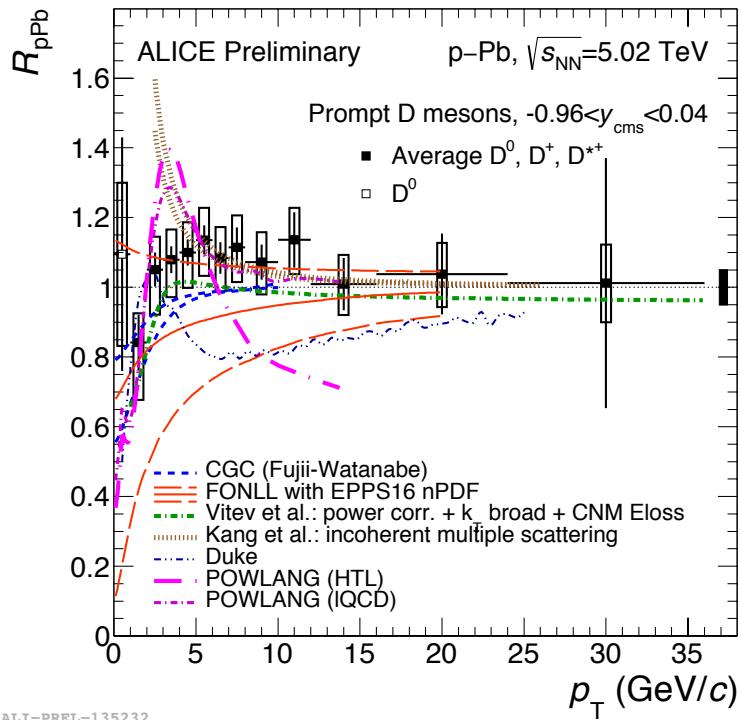
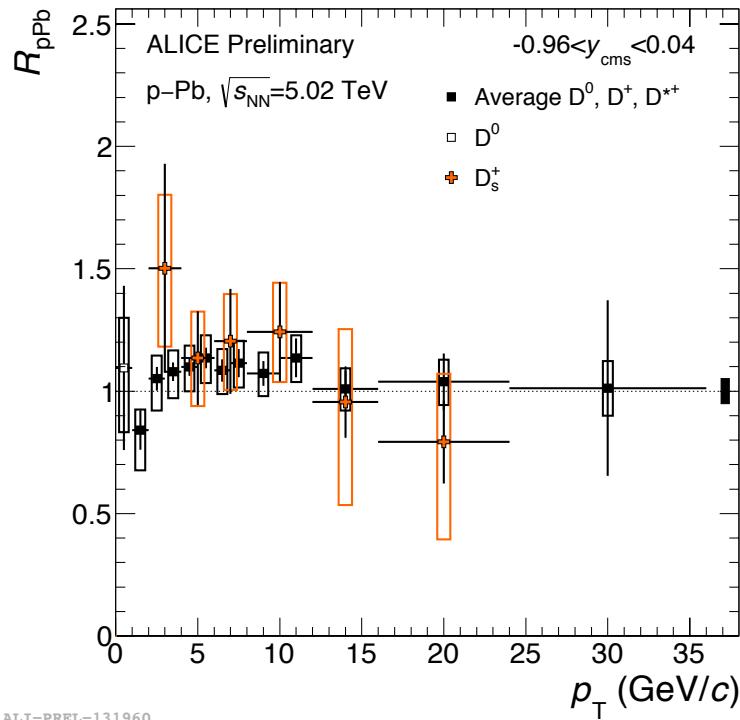
Recent results in pp collisions



- D^0, D^+, D^{*+}, D_s meson cross section measured at several collision energies
- Down to $p_T=0$ for D^0 at 7 TeV
- pQCD calculations describe the data
- Data uncertainties much lower than theoretical ones

Recent highlights from p-Pb

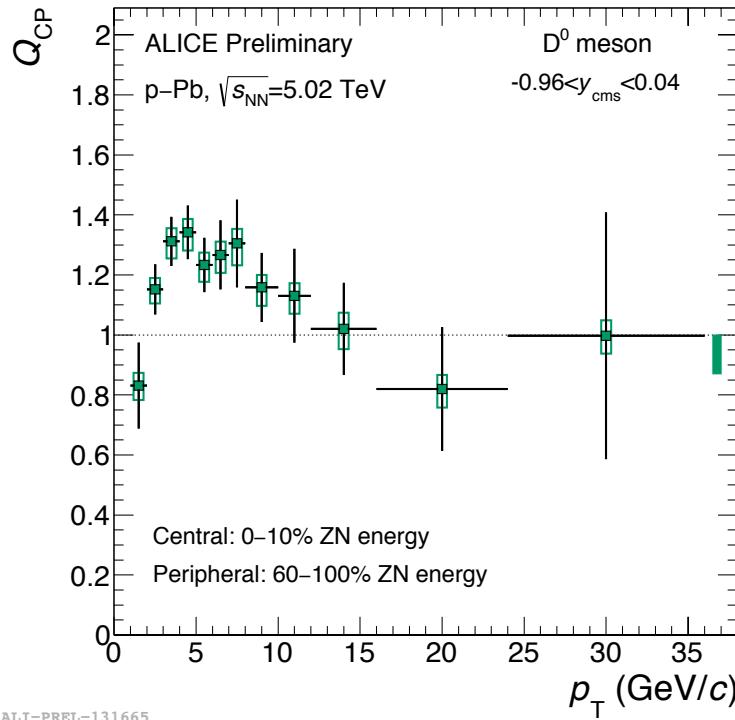
ALICE-PUBLIC-2017-008



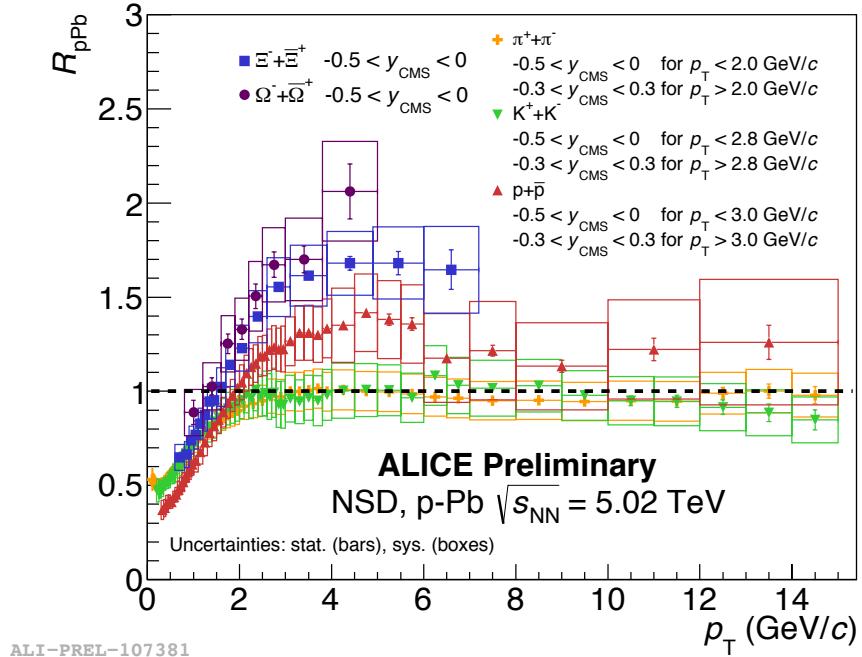
- Non-strange D meson and D_s^+ R_{pPb} compatible with unity.
 - Described by models including Cold Nuclear-Matter effects.
 - Described by models including formation of QGP in p-Pb, though data disfavour suppression $>10\text{-}15\%$ at high p_T .
- Need to improve precision for more conclusive statements.

Recent highlights from p-Pb

ALICE-PUBLIC-2017-008



ALI-PREL-131665



- Hint for “Central-to-peripheral” ratio (Q_{CP}) larger than unity (1.7σ in $3 < p_T < 8$ GeV/c).
- Similar “bumpy” trend observed for proton and strange-baryon R_{pPb}
Initial-state effect? Mass effect? Radial flow?
... early to say, need comparison with theoretical calculations

ALICE data-taking in Run-2

System	Year	\sqrt{s}_{NN} (TeV)	L_{int}
pp	2015-2016	13	$\sim 14 \text{ pb}^{-1}$
pp	2015 (~ 4 days)	5.02	$\sim 100 \text{ nb}^{-1}$
p-Pb	2016	5.02	$\sim 3 \text{ nb}^{-1}$
p-Pb	2016	8.16	$\sim 20 \text{ nb}^{-1}$
Pb-p	2016	8.16	$\sim 20 \text{ nb}^{-1}$
Pb-Pb	2015	5.02	$\sim 0.4 \text{ nb}^{-1}$

- Goals for 2017-18:
 - Pb-Pb: reach 1/nb target
 - pp 13 TeV: reach 40/pb target
 - High statistics pp 5 TeV sample

ALICE upgrade: New ITS

Design requirements:

1. Improve impact parameter resolution by a factor ~3 (5) in $r\varphi$ (z)

- Reduce pixel size (currently 50 μm x 425 μm)
 - monolithic (MAPS) with size $\sim 29 \mu\text{m} \times 27 \mu\text{m}$
- Go closer to 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 $\sim 1.13\%$ to $\sim 0.3(0.8)\%$ per layer

2. High standalone tracking performance

(efficiency, spatial and momentum resolutions)

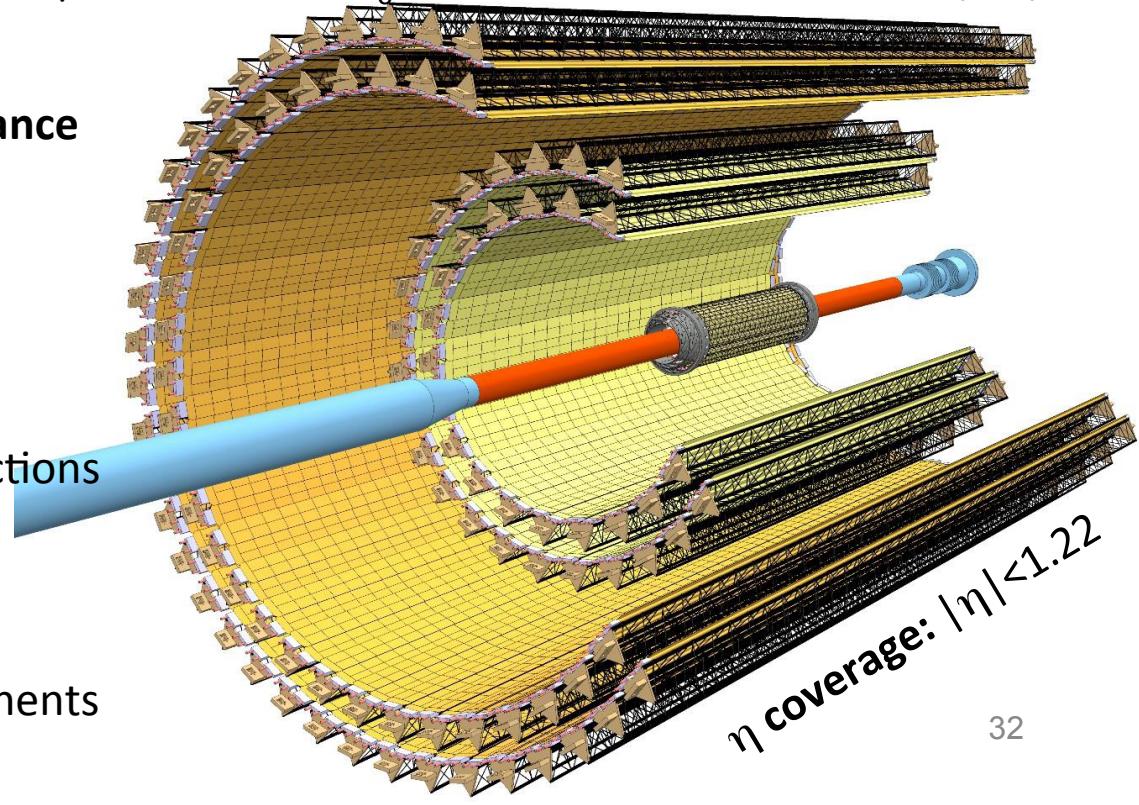
- Increase granularity
- Add 1 layer (from 6 to 7)

3. Faster (x50) readout: Pb-Pb interactions

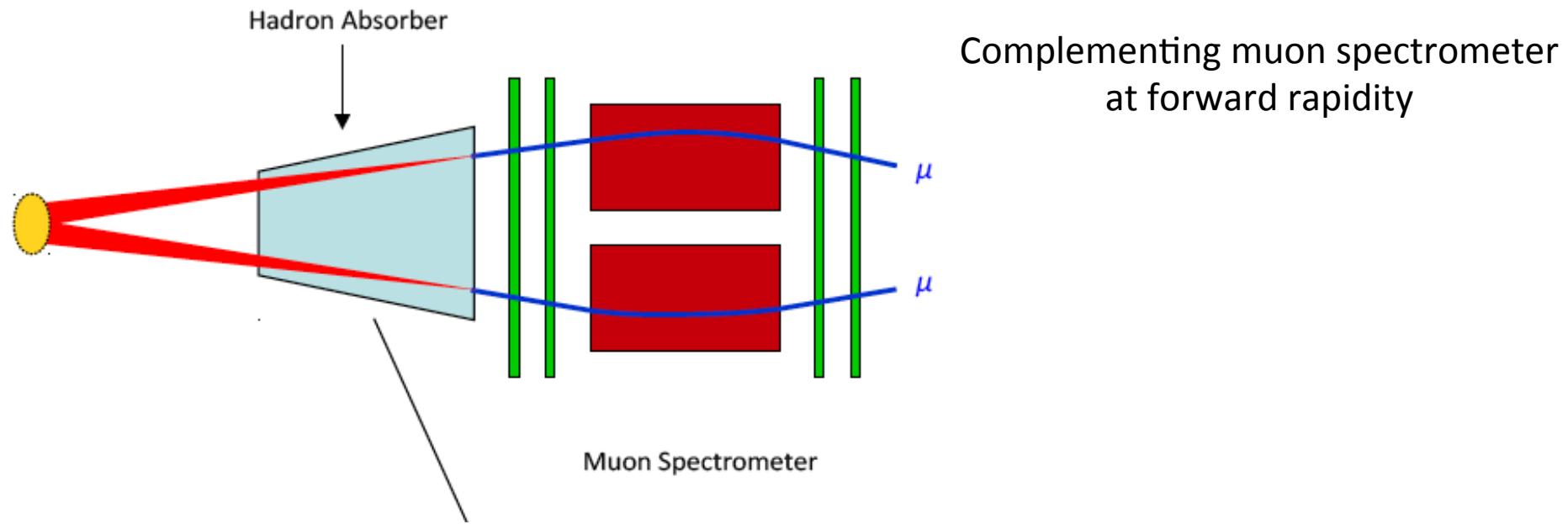
up to 100 kHz

4. Maintenance: allow for removal/

insertion of faulty detector components during annual winter shutdown



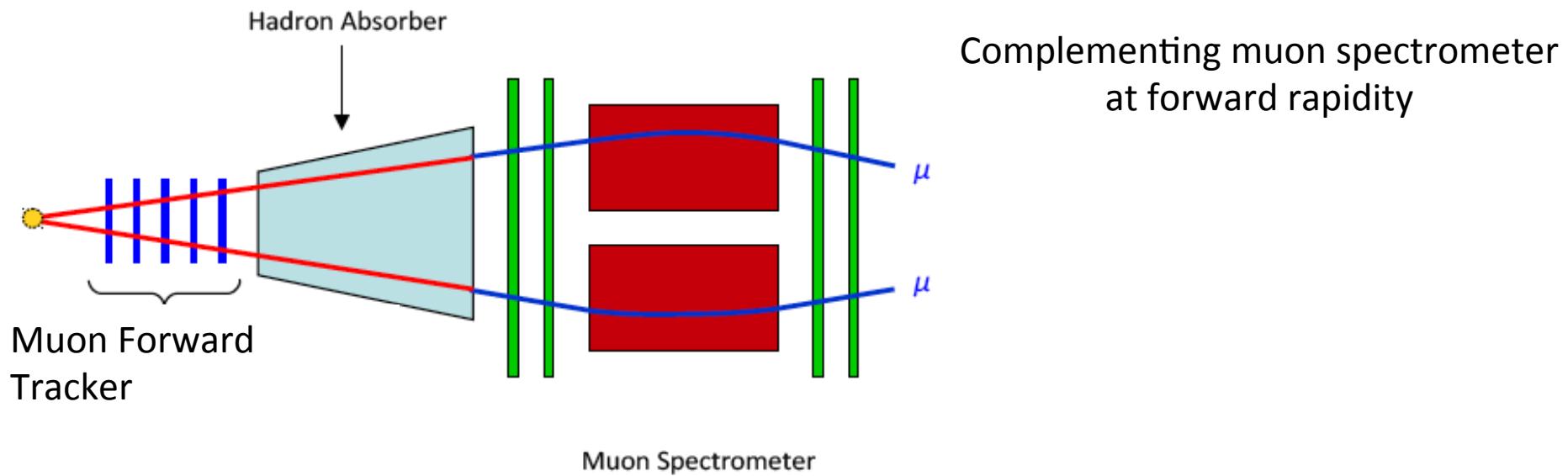
Muon Forward Tracker



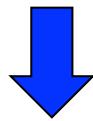
Extrapolating back to the vertex region degrades the information on the kinematics and trajectory

- Cannot separate prompt and displaced muons

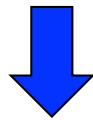
Muon Forward Tracker



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



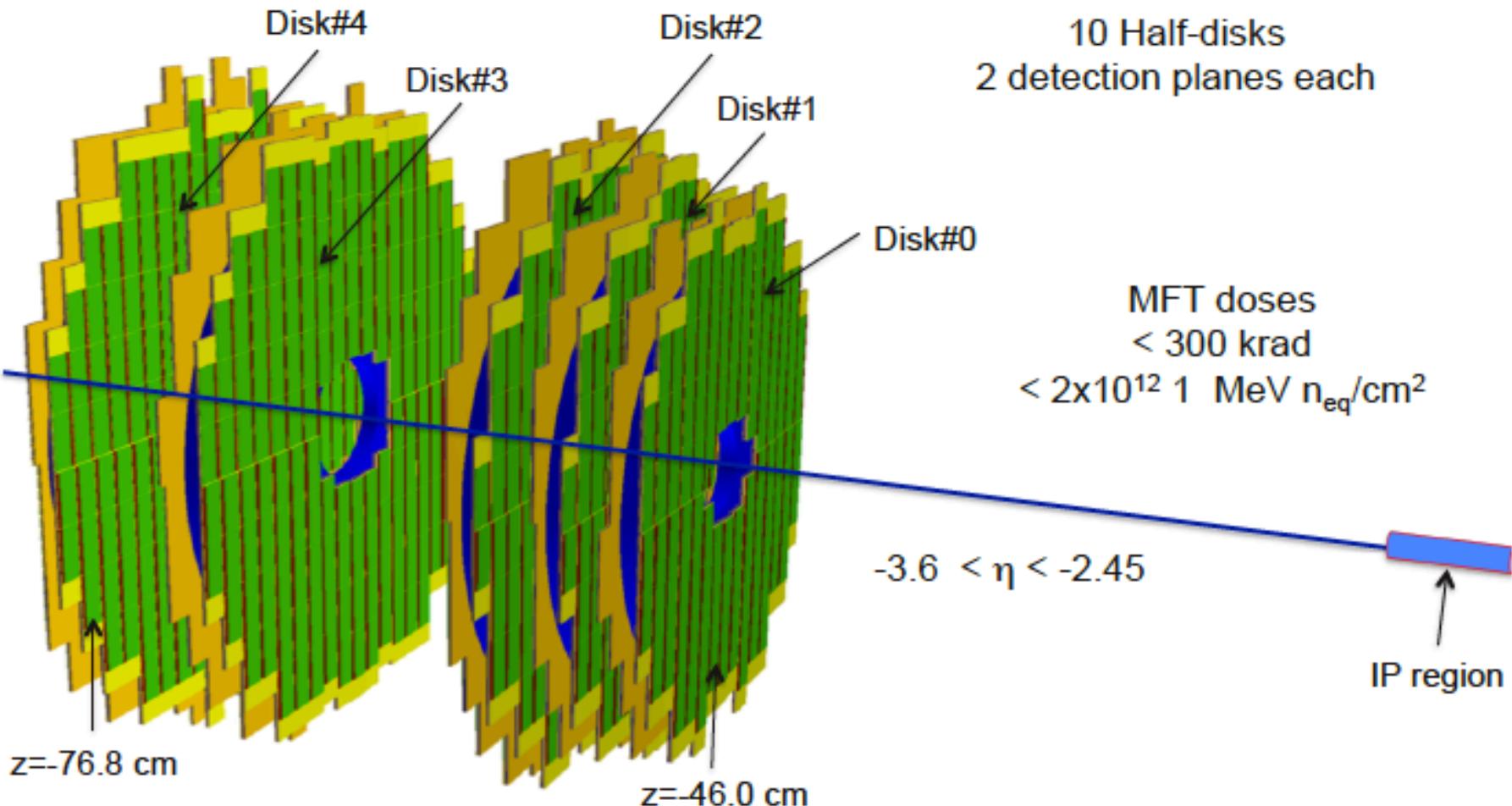
High pointing accuracy



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

Muon Forward Tracker

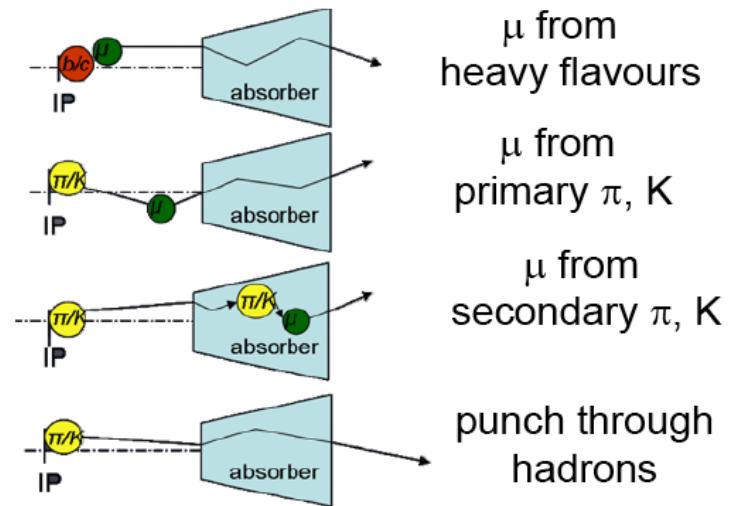
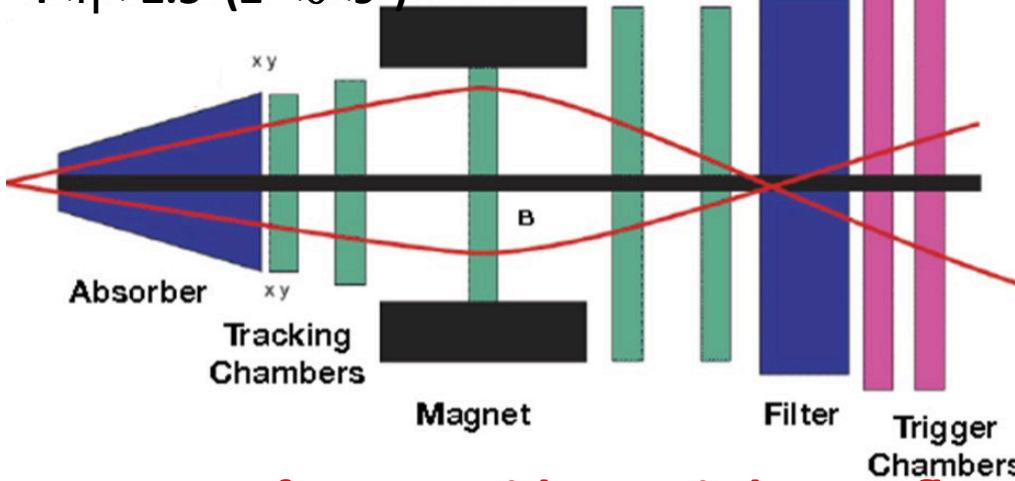
920 silicon pixel sensors (0.4 m^2) on 280 ladders of 2 to 5 sensors each.



Heavy-flavour reconstruction in ALICE forward muon spectrometer

MUON SPECTROMETER

$-4 < \eta < -2.5$ ($2^\circ < \theta < 9^\circ$)



Muons from semi-leptonic heavy-flavour hadron decays $D, B, \Lambda_c, \dots \rightarrow \mu X$

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 $W/Z/\gamma^*$ decay subtracted with templates obtained from Monte Carlo simulations (POWHEG)

QGP tomography with heavy quarks

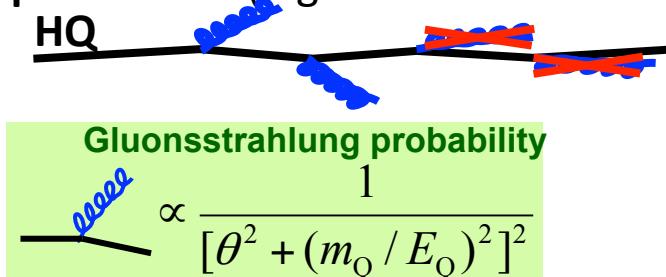
- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium
- Hard fragmentation → measured meson properties closer to parton ones



“Calibrated probes” of the medium

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)



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

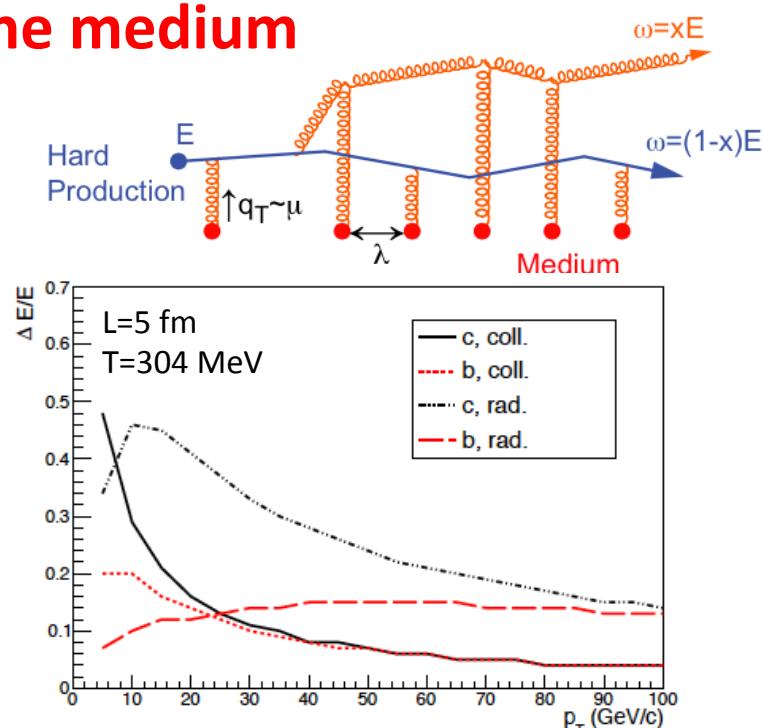


Figure from A. Andronic *et al.*, EPJC C76 (2016)
M. Djordjevic, Phys. Rev. C80 064909 (2009), Phys. Rev. C74 064907 (2006).

QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2 ← at all p_T for charm and beauty (large masses $\gg \Lambda_{\text{QCD}}$)
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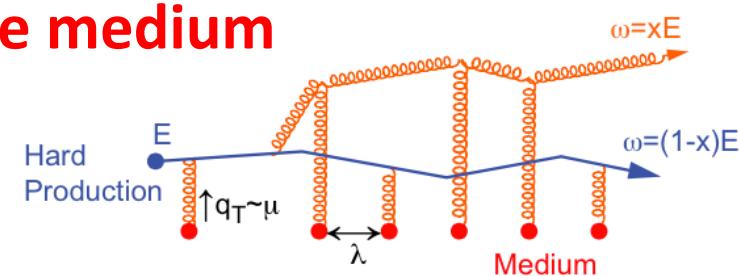


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$$\left. \right\} \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



QGP tomography with heavy quarks

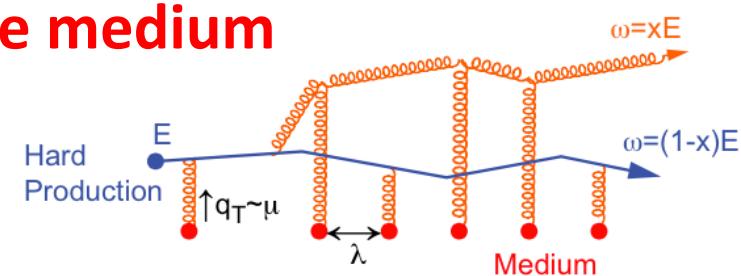
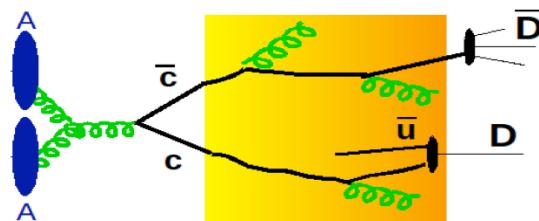
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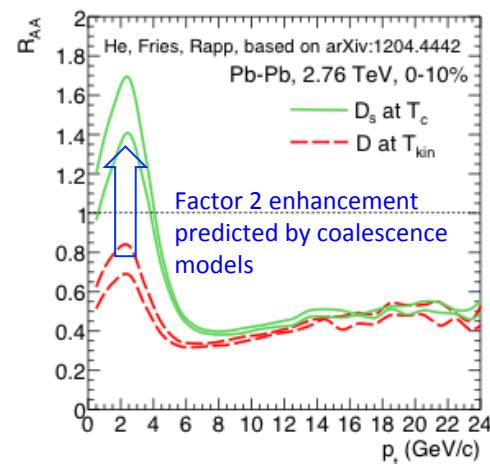
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- **medium modification to HF hadron formation**
 - hadronization via quark coalescence



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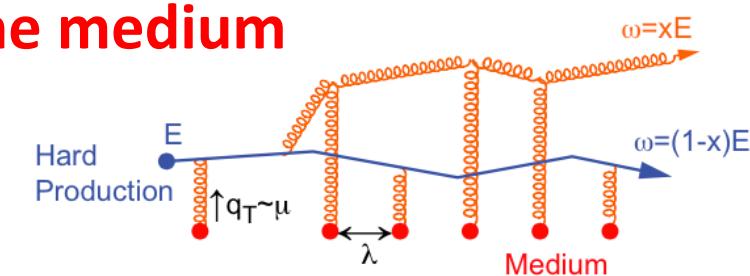
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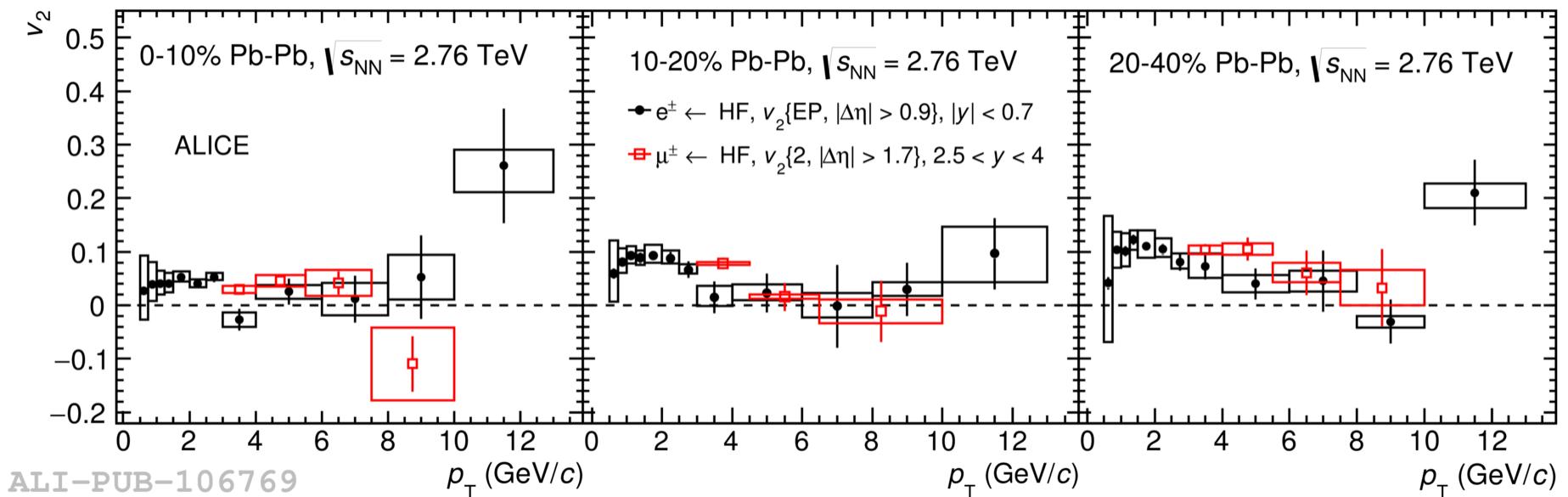
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- **medium modification to HF hadron formation**
 - hadronization via quark coalescence

- participation in collective motion → azimuthal anisotropy of produced particle



Heavy-flavour lepton v_2

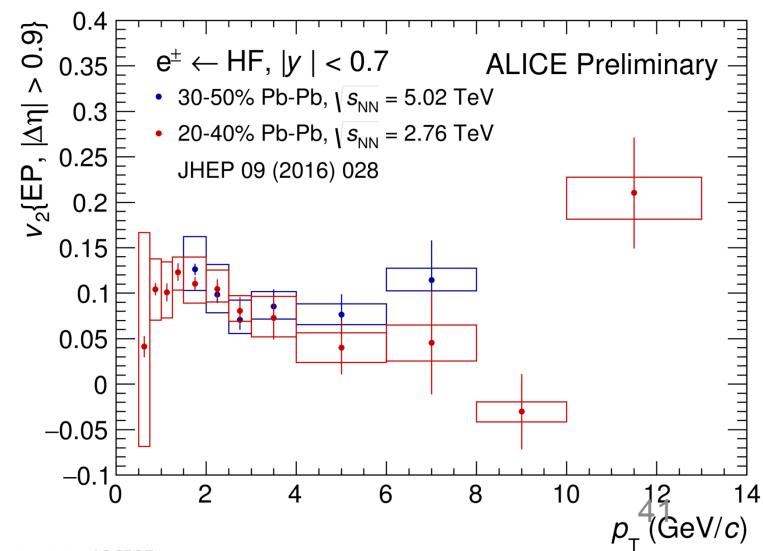


Positive v_2 of HF electrons in semi-central 20-40% Pb-Pb collisions at 2.76 TeV.

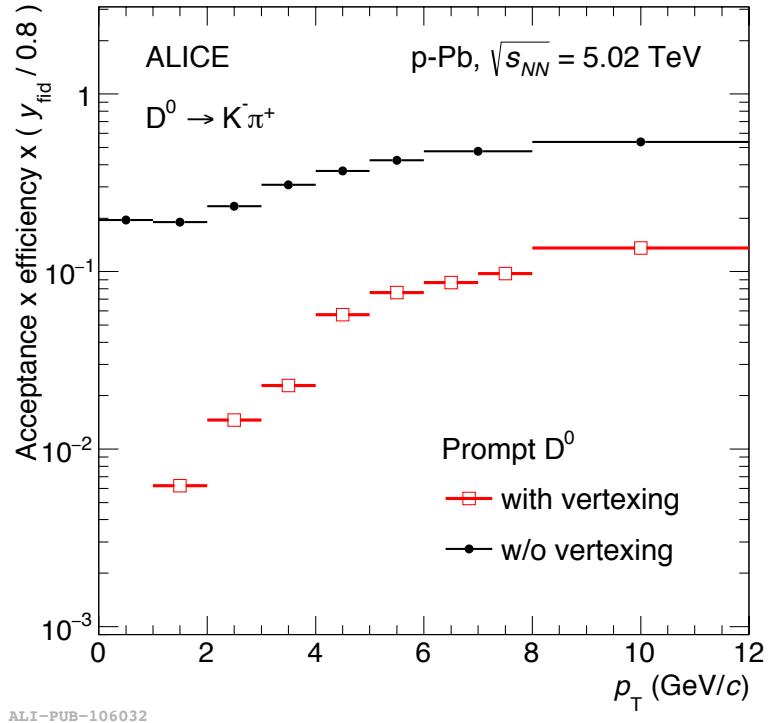
v_2 tends to increase from central to semi-central collisions.

Similar v_2 at mid-rapidity [electrons] and forward rapidity [muons].

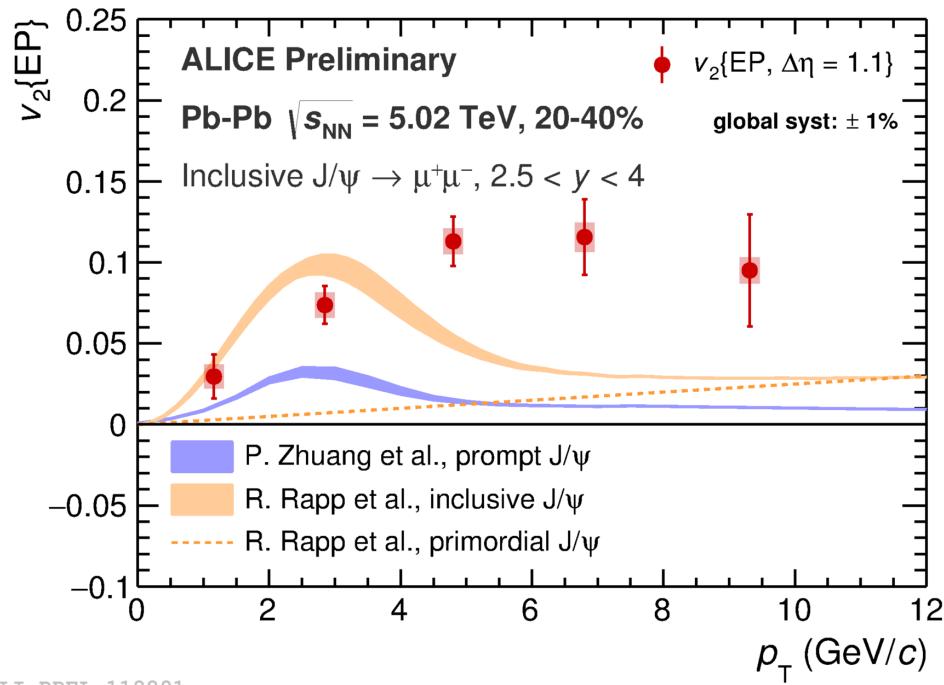
Similar v_2 at $\sqrt{s_{NN}}=2.76$ and 5 TeV



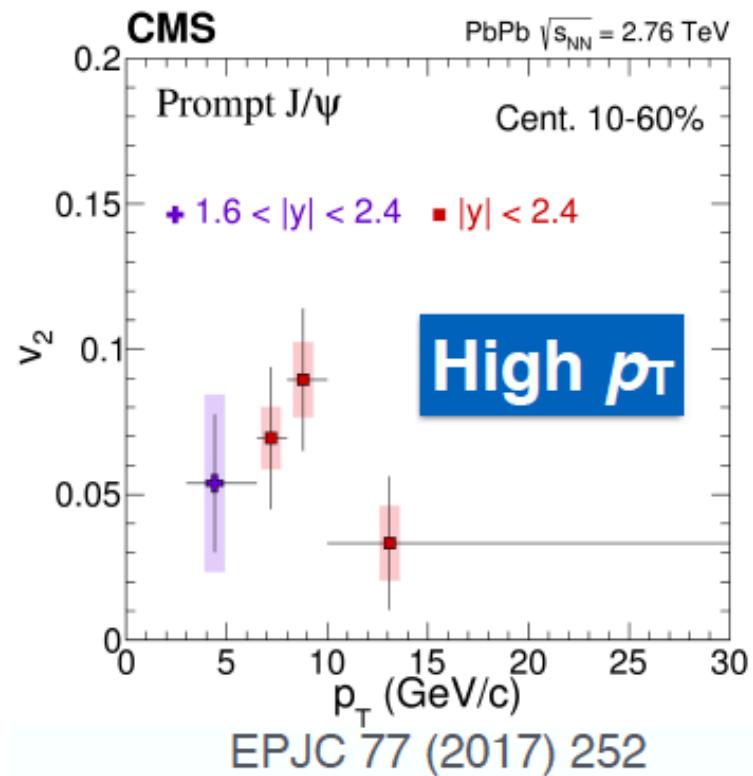
D-meson reconstruction



J/ ψ elliptic flow

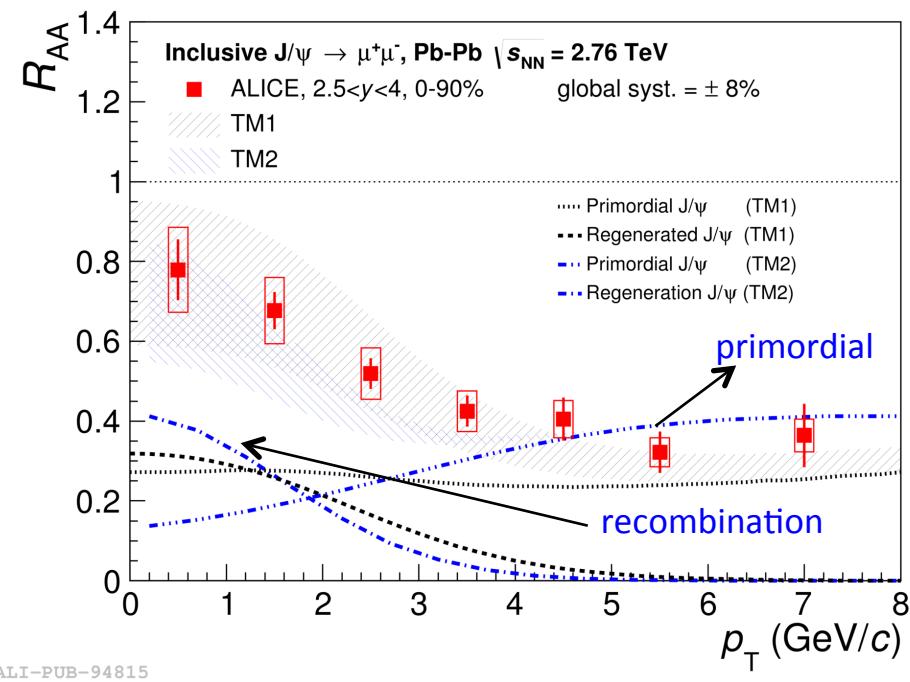
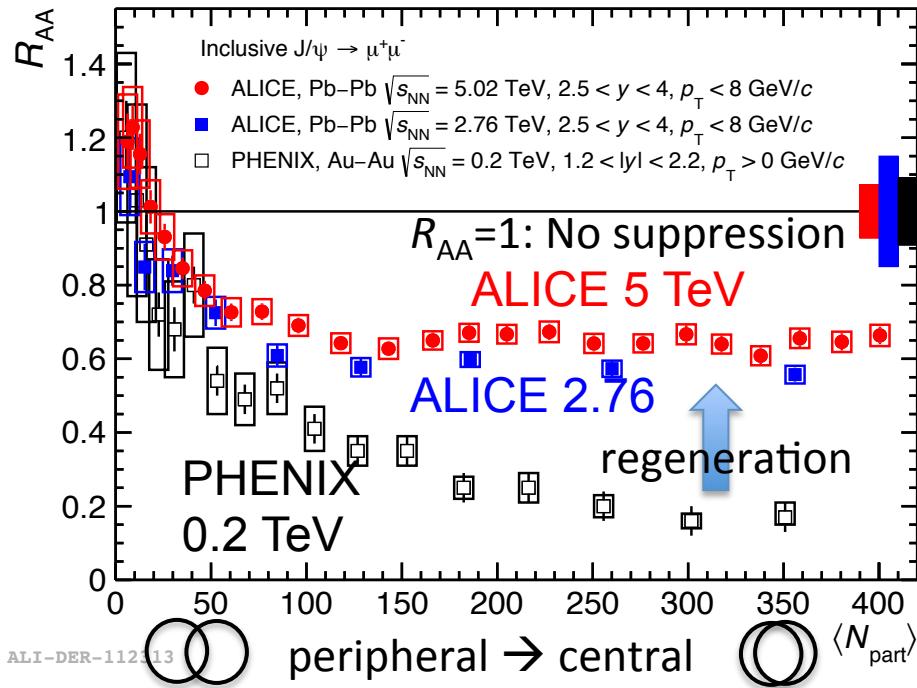


ALI-PREL-118891



Positive J/ ψ elliptic flow
Expected for J/ ψ from recombination
Remains high at high $p_T \rightarrow$ not expected from models

J/ ψ suppression: LHC vs. RHIC



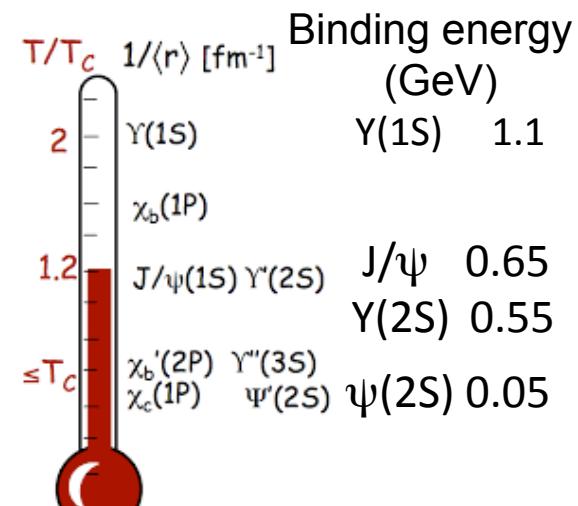
- J/ψ suppression stronger in central events than peripheral
- Smaller suppression at LHC than RHIC
- Analysis vs. transverse momentum: suppression stronger at higher momentum. In agreement with models expecting about 50% contribution of J/ψ from recombination at low p_T .

“Twice a signature of QGP”

Quarkonia: sequential suppression

Indication that $\psi(2S)$ is more suppressed than J/ψ

$\Upsilon(2S) \sim 4$ times more suppressed than $\Upsilon(1S)$



A. Mocsy, Eur.Phys.J. C61 (2009)

