Heavy-flavour production in heavy-ion collisions with ALICE at the LHC

Róbert Vértesi
for the ALICE collaboration
Wigner RCP, Budapest
vertesi.robert@wigner.mta.hu

Hungarian Academy of Sciences
Wigner Research Centre for Physics

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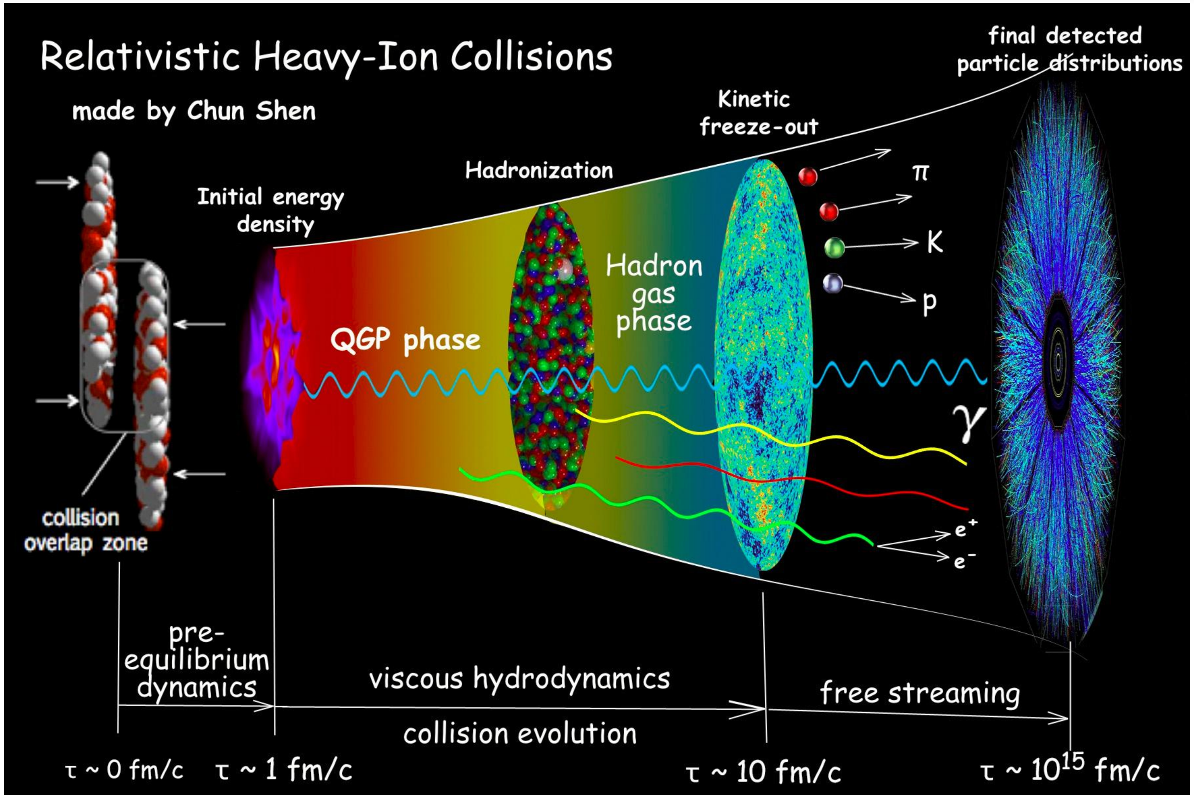
and the János Bolyai scholarship of the Hungarian Academy of Sciences

The Quark-Gluon Plasma



Heavy-ion collisions are hot and dense enough to deconfine quarks!

- Theory expectations: gas-like material where quarks roam freely
- Experimental findings: a nearly perfect fluid of quarks! → **sQGP**
  - strongly coupled
  - extremely low viscosity

Heavy-flavour (HF) probes

- Heavy quarks are produced early

  $\tau_{c,b} \sim \frac{1}{2} m_{c,b} \sim 0.1$ fm $<< \tau_{QGP} \sim 5\text{-}10$ fm

  Rapp, Hees, ISBN:978-981-4293-28-0

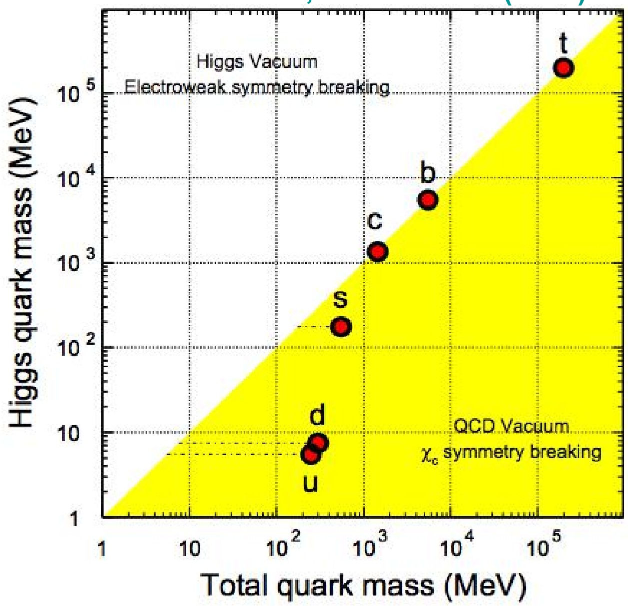
- Heavy quarks are (almost) conserved

  $m >> \Lambda$ ($m_c \sim 1.5$ GeV, $m_b \sim 5$ GeV)

  - No flavour changing
  - Negligible thermal production

  → Very little production or destruction in the sQGP

X. Zhu et al, PLB 647 366 (2007)



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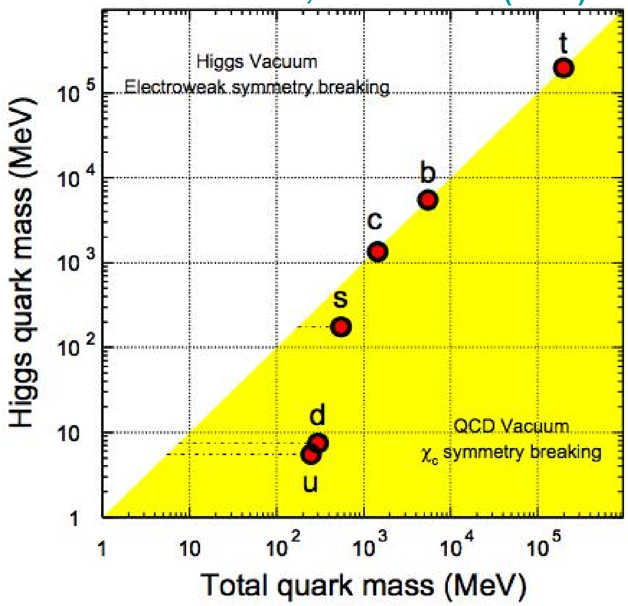
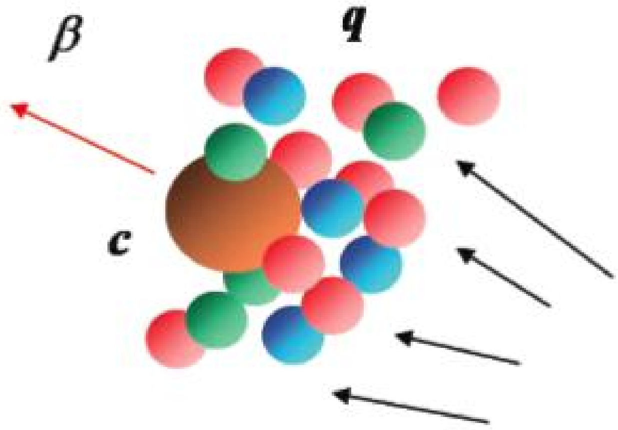


- Transport through the whole system
  - **Heavy quark kinematics in the sQGP**
  - Access to **transport properties** of the system
  - ...observables down to **low momenta**
  - **Hadronization** (fragmentation, coalescence)
  - **Heavy vs. light? Charm vs. bottom?**



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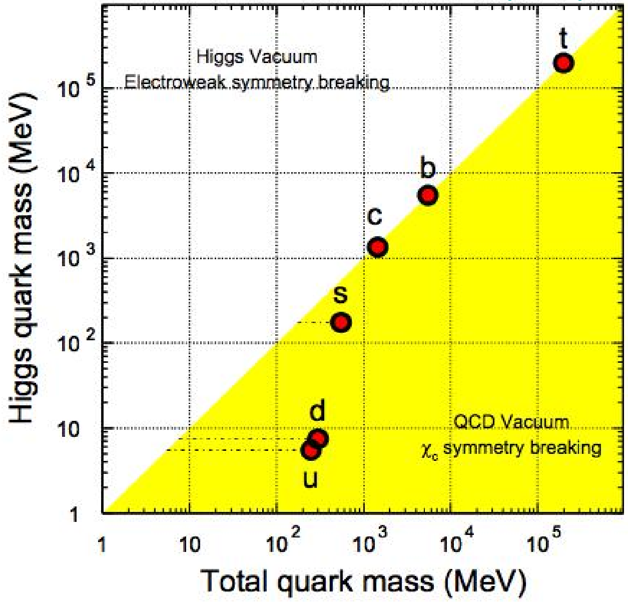

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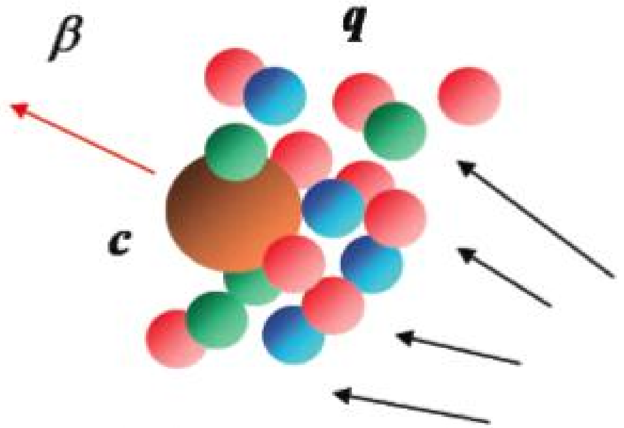
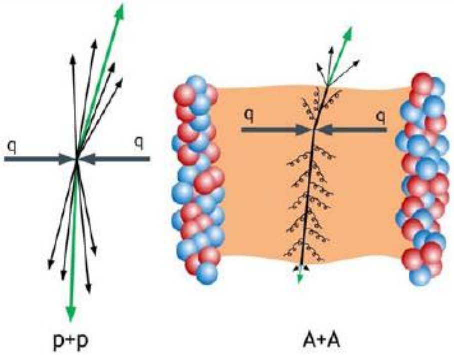


Penetrating probes down to low momenta!

Nuclear modification

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$



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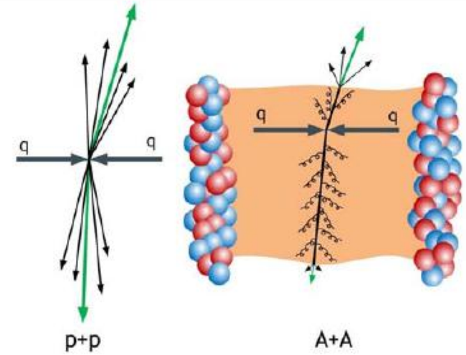
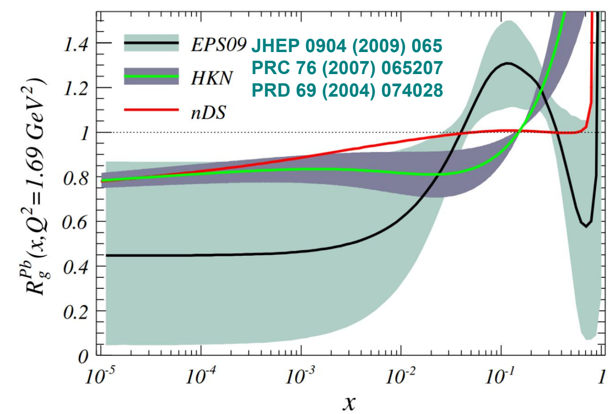


- **pp** collisions: reference system

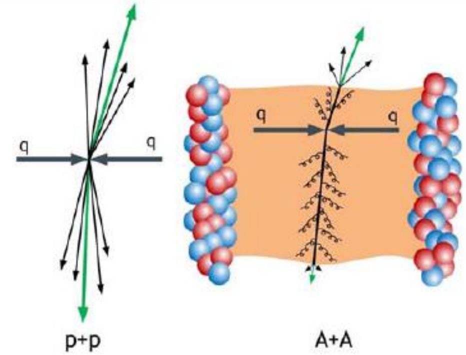
  → Luuk Vermunt (this section)

- **p-A collisions**: Understand cold nuclear matter (CNM) effects
  - PDF modification: (anti)shadowing, gluon saturation
  - Energy loss in CNM, $k_{\rm T}$-broadening
  - *Hot effects may exist also in p-A collisions!*



Nuclear modification

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



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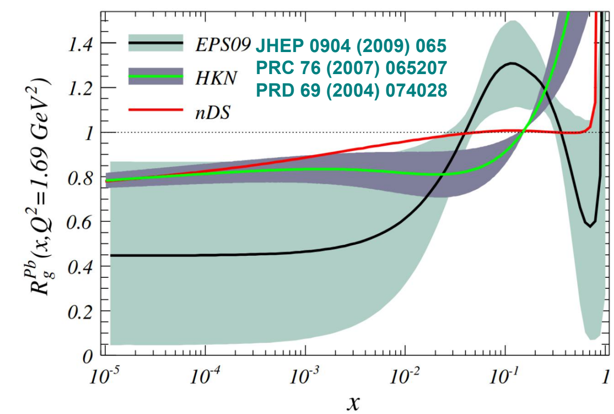
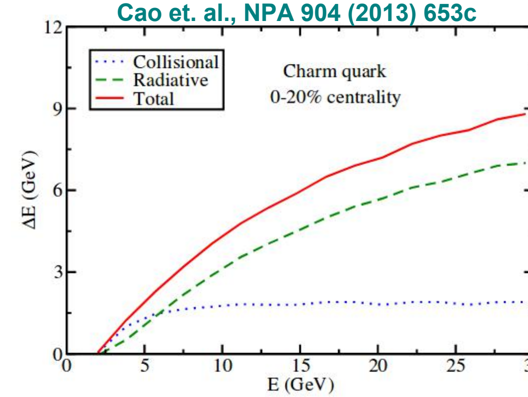


- **A-A collisions**: Energy loss due to hot medium effects (on top of CNM)
  - **Collisional energy loss** (Langevin-like evolution)
  - **Energy loss via gluon radiation**
  - Dead cone effect → expected mass ordering:

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow \textbf{?}\ R_{AA}^{h} < R_{AA}^{D} < R_{AA}^{B}$$

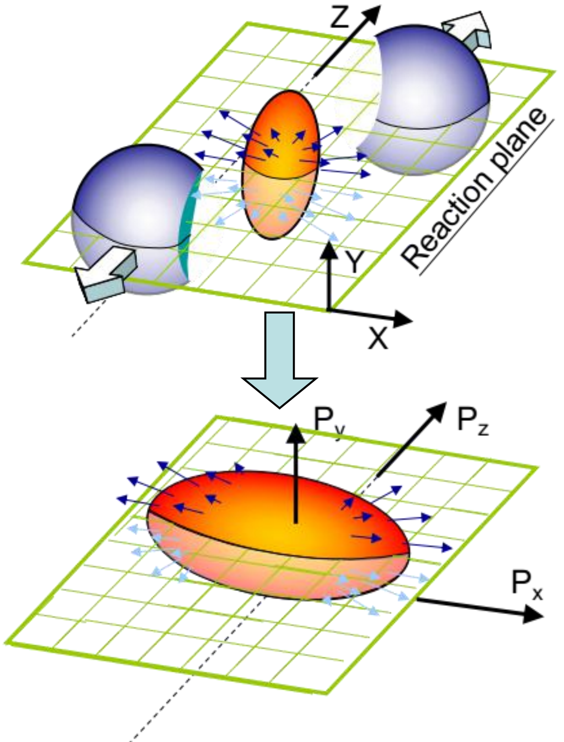
  - Color charge effect (HF is mostly quarks, while in light-flavour there is a large contribution from gluons)

Cao et. al., NPA 904 (2013) 653c



Participation in collectivity

- Spatial anisotropy in the collision region...
  - Pressure difference
    $R_x < R_y ==> P_x > P_y$
- ... converts to momentum anisotropy
  - Parametrization: Fourier-coefficients
    $$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n(\varphi - \Psi_R)\right)\right)$$
    $$v_n = \langle\cos(n(\varphi - \Psi_R))\rangle$$
  - **Anisotropy parameter v_2: "elliptic flow"**



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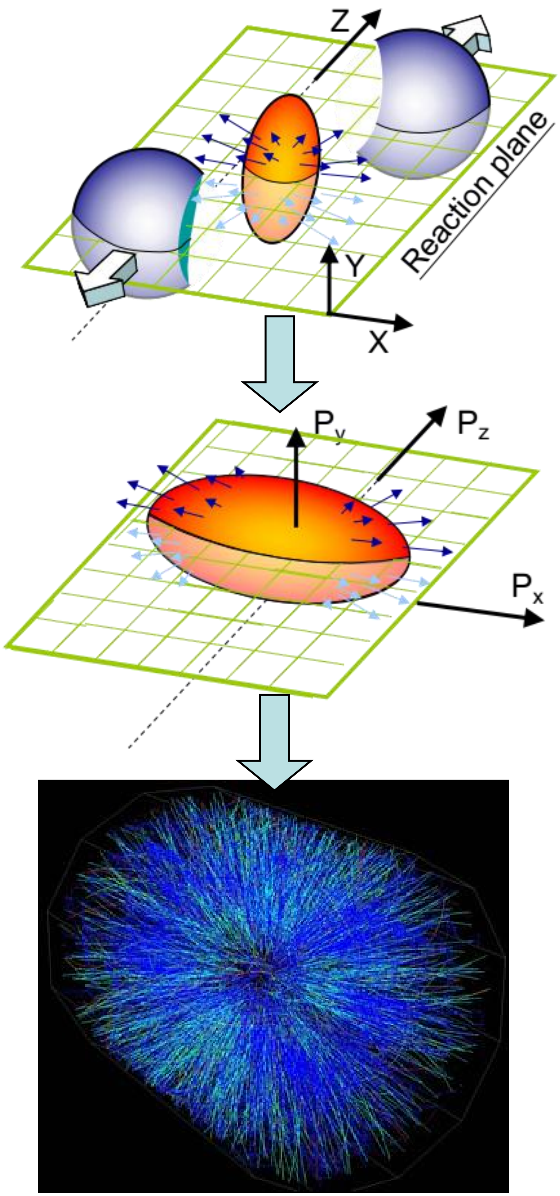
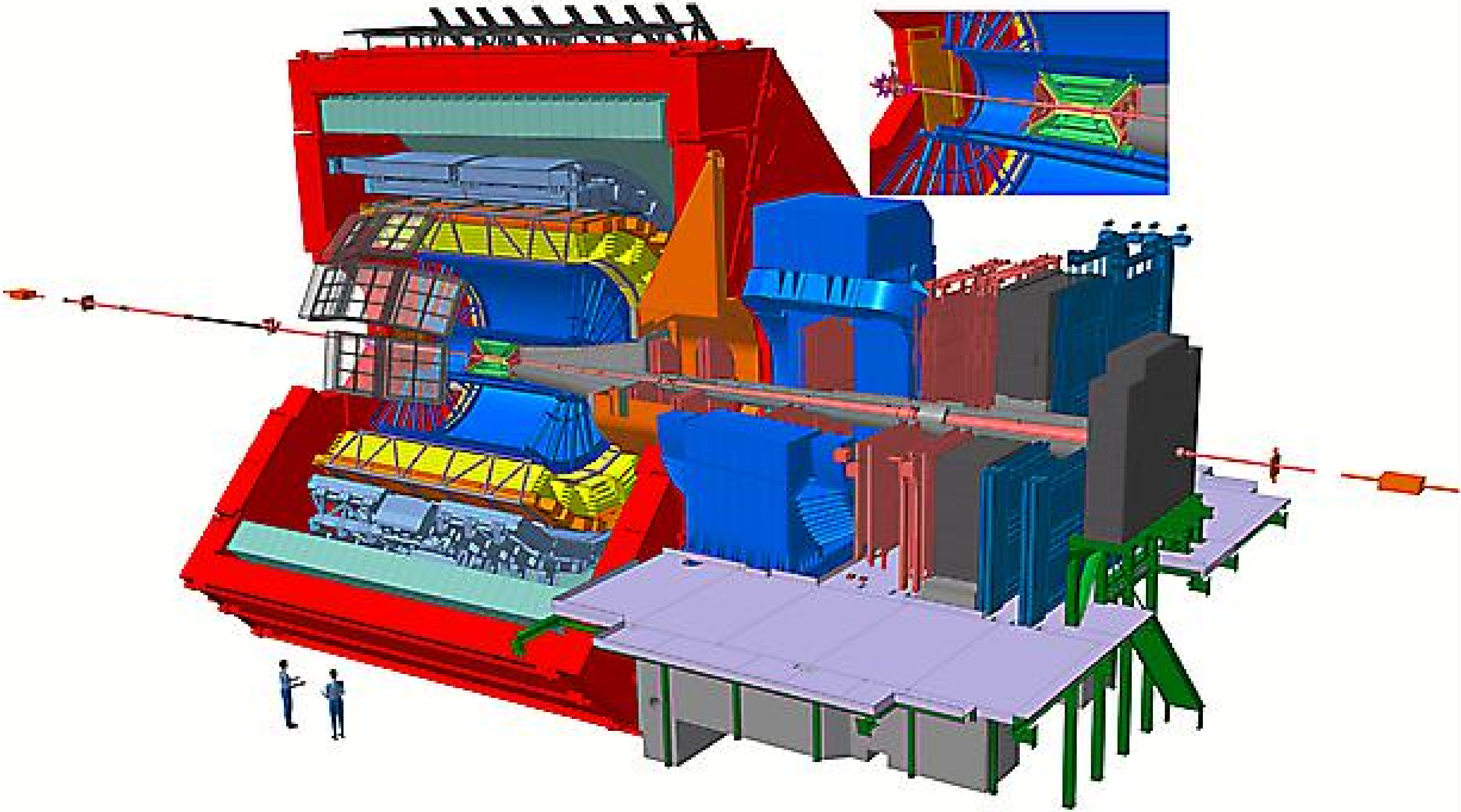
    $$v_n = \langle \cos(n(\varphi - \Psi_R)) \rangle$$
  - **Anisotropy parameter v_2: "elliptic flow"**
- **strongly coupled medium => substantial v_n**
  $\lambda \ll \bar{R}$
  - Does heavy flavour flow?
  - In what stage does it pick up flow?
    - Does it thermalize with the medium?
    - Do heavy quarks coalesce with flowing light quarks?

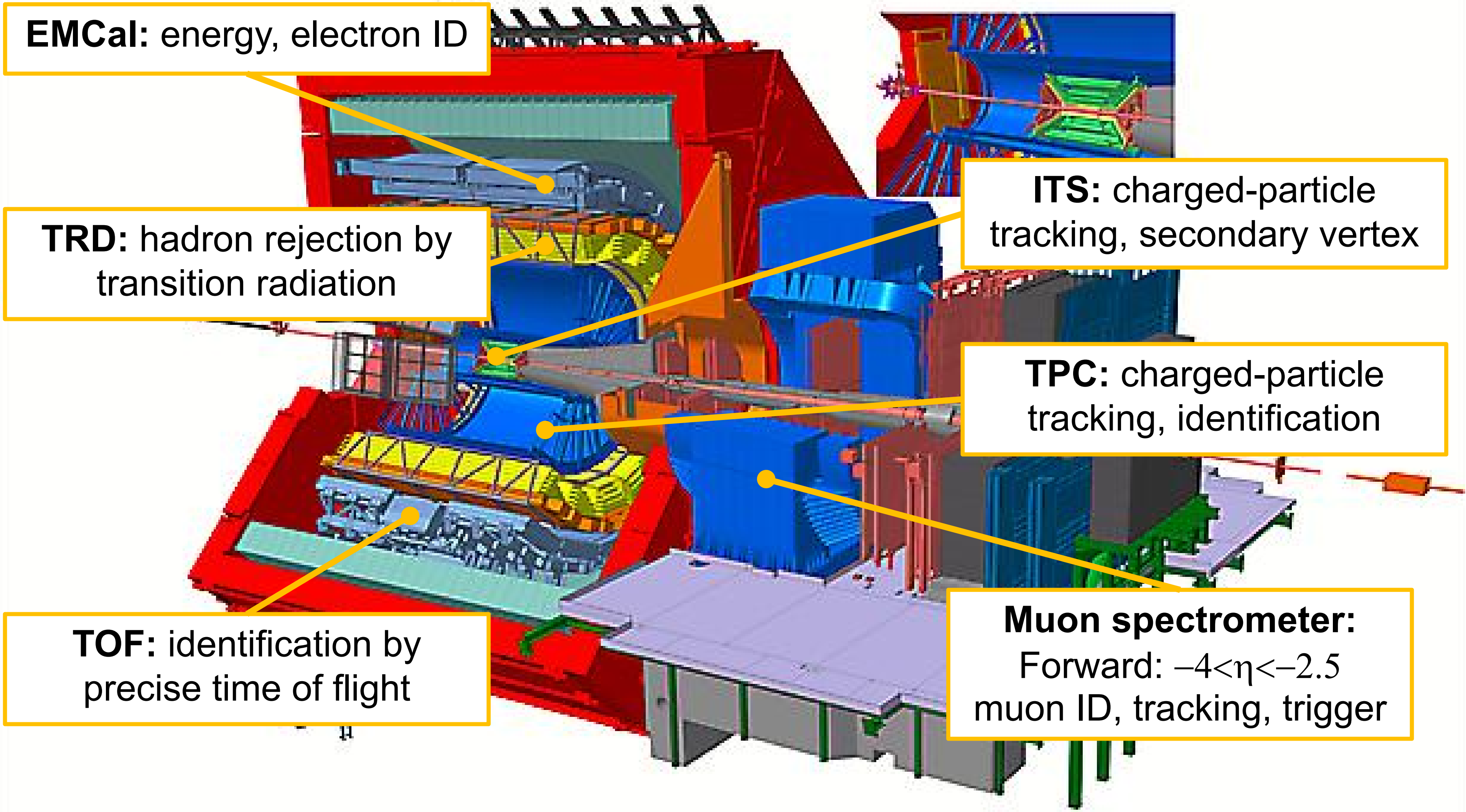


ALICE



- A dedicated heavy-ion experiment at the LHC, excellent PID

ALICE



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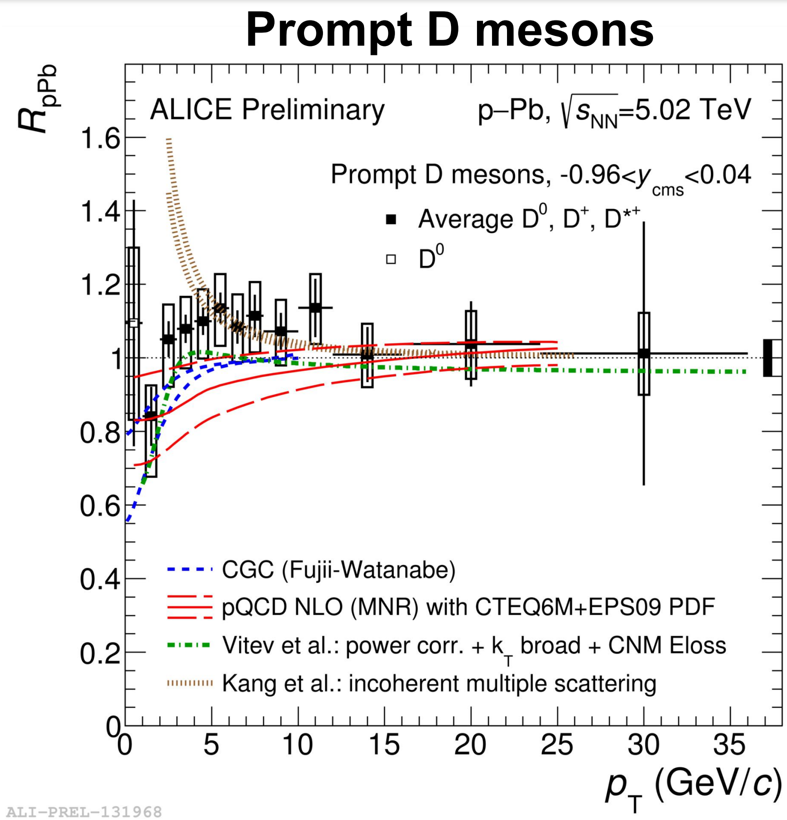
CNM effects in p-Pb collisions?

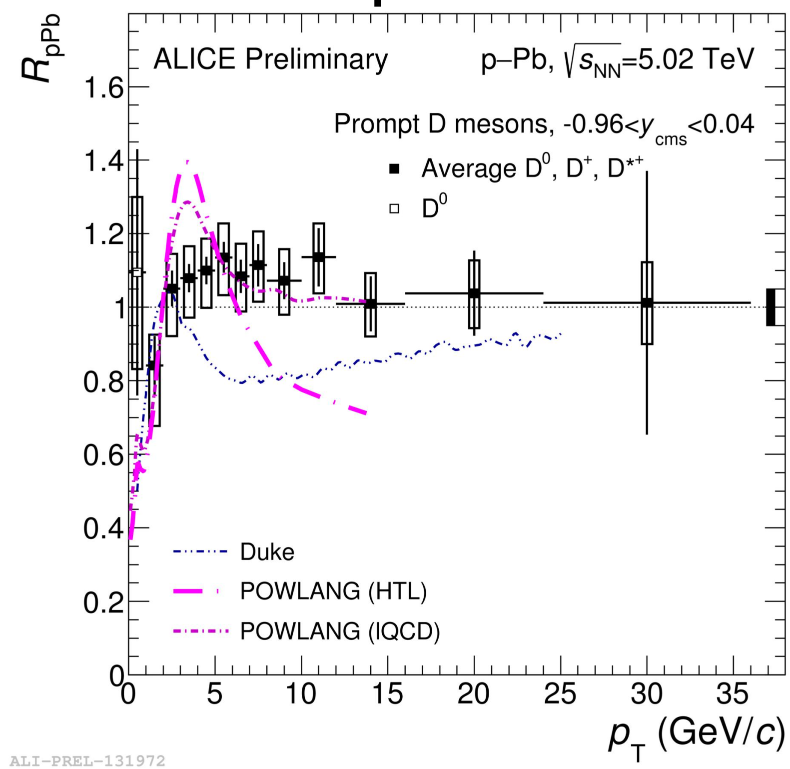


Models:
CGC, arXiv:1308.1258
MNR: NPB 373 (1992) 295
Vitev, PRC 75 (2007) 064906
Kang, PLB 740, 23 (2015)

- **D-meson production in p-Pb collisions -** *New, more precise Run-II data*
  - **No modification w.r.t. pp collisions within uncertainties**
  - No indication of CNM effects from intermediate to high p_T
  - Data described by several models containing CNM effects

Hot effects in p-Pb collisions?

Prompt D mesons



Models:
Duke, NPPP 276 (2016) 225
Powlang, JHEP 03 (2016) 123

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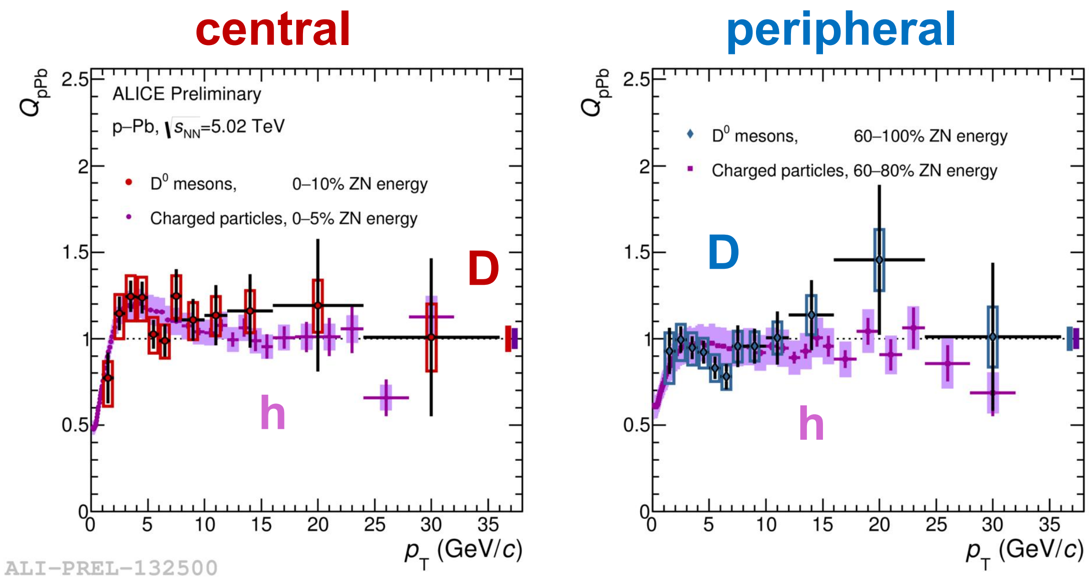
  - **No modification w.r.t. pp collisions within uncertainties**
  - No indication of CNM effects from intermediate to high p_T
  - Data described by several models containing CNM effects
- A model including small-volume QGP formation also describes data

p-Pb: modification vs. centrality



Centrality-dependent nuclear modification factor

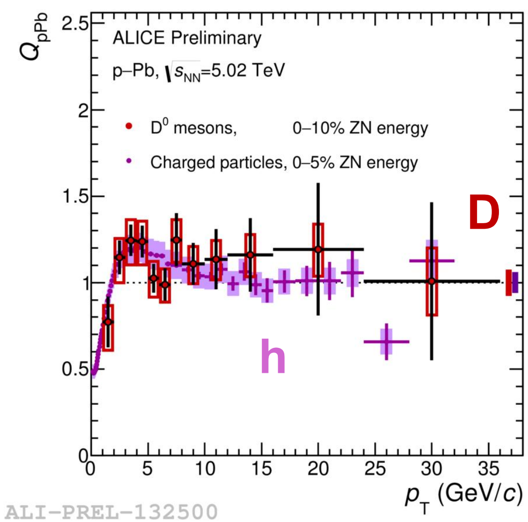
$$Q_{\mathrm{pPb}} = \frac{(\mathrm{d}N^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})^{\mathrm{cent}}_{\mathrm{pPb}}}{\langle T_{\mathrm{pPb}}\rangle \times (\mathrm{d}\sigma^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})_{\mathrm{pp}}}$$

- $\langle T_{pPb} \rangle$: nuclear overlap from the Glauber model in a given centrality class
- Multiplicity estimation using the Zero-degree neutron detectors

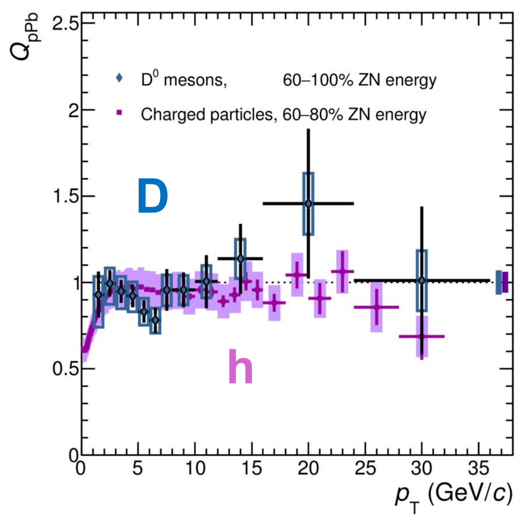
- D-meson Q_{pPb} consistent with unity - both central and peripheral
  - Also consistent with that of charged hadrons - both central and peripheral

p-Pb: modification vs. centrality

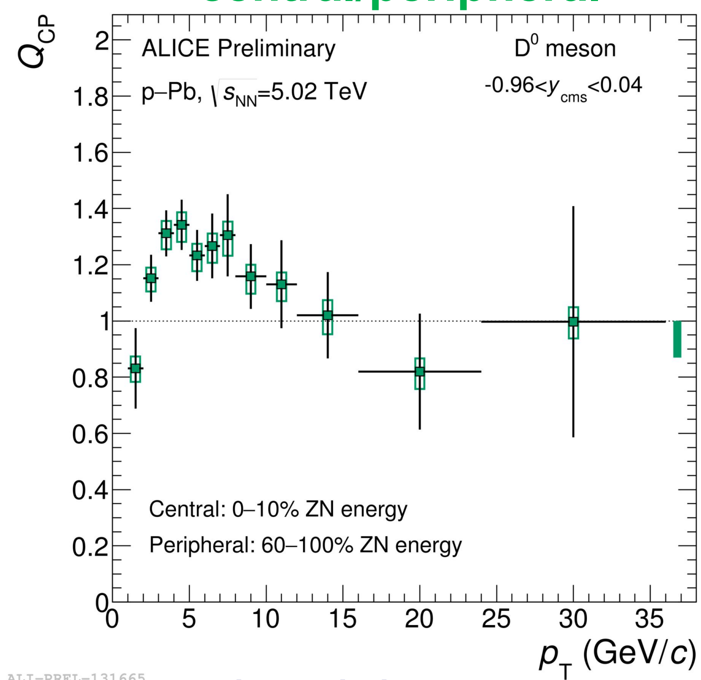
central



peripheral

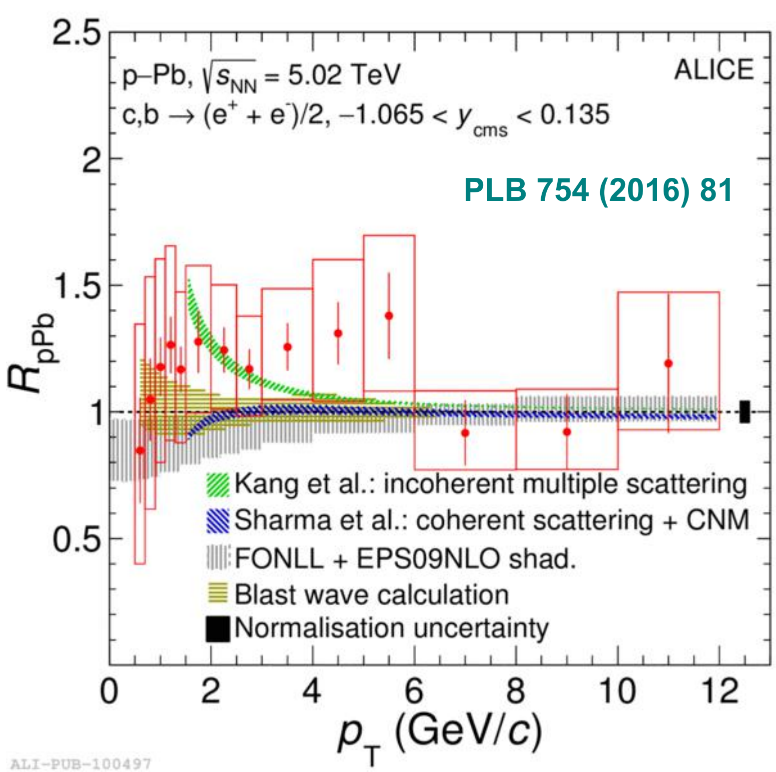


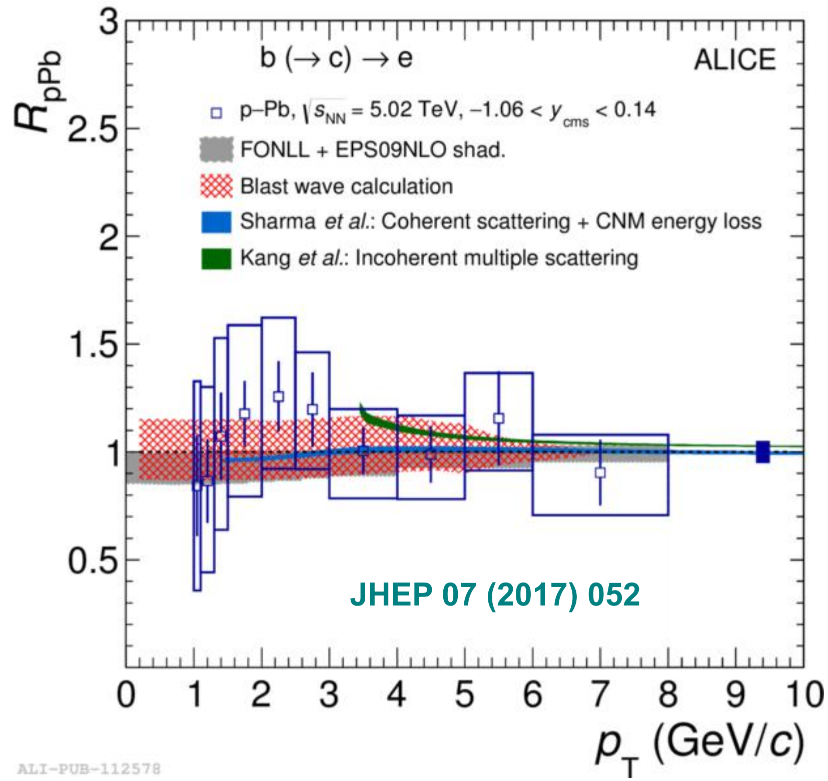
central/peripheral



- D-meson Q_{pPb} consistent with unity - both central and peripheral
  - Also consistent with that of charged hadrons - both central and peripheral
- However, significant difference between central and peripheral data (Q_{CP})
  - Possible collectivity in small systems (radial flow)
  - Initial and final state effects may also play a role (eg. multiple scatterings)
  - *Note: Care should be taken with the interpretation because of biases in centrality class definition and the choice of multiplicity estimator. ZN is the least biased.*

CNM effects - Charm and Beauty



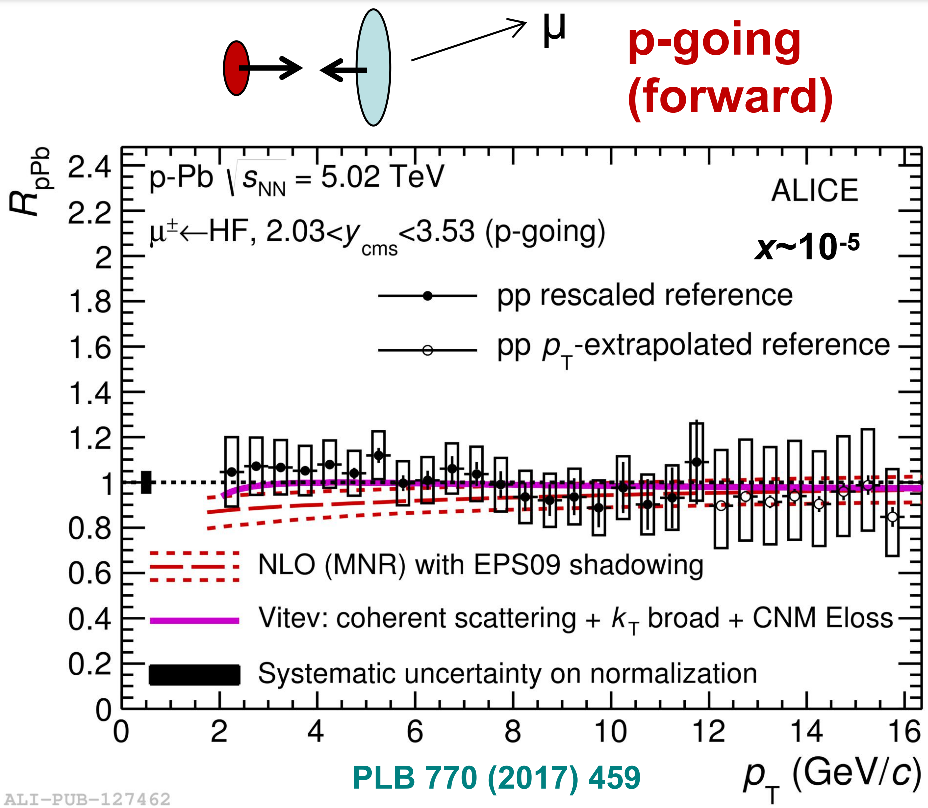


Models: FONLL+EPS09, JHEP 10 (2012) 137; JHEP 04 (2009) 065
Blast wave, PLB 731 (2014) 51
Sharma, PRC 80 (2009) 054902
Kang, PLB 740 (2015) 23

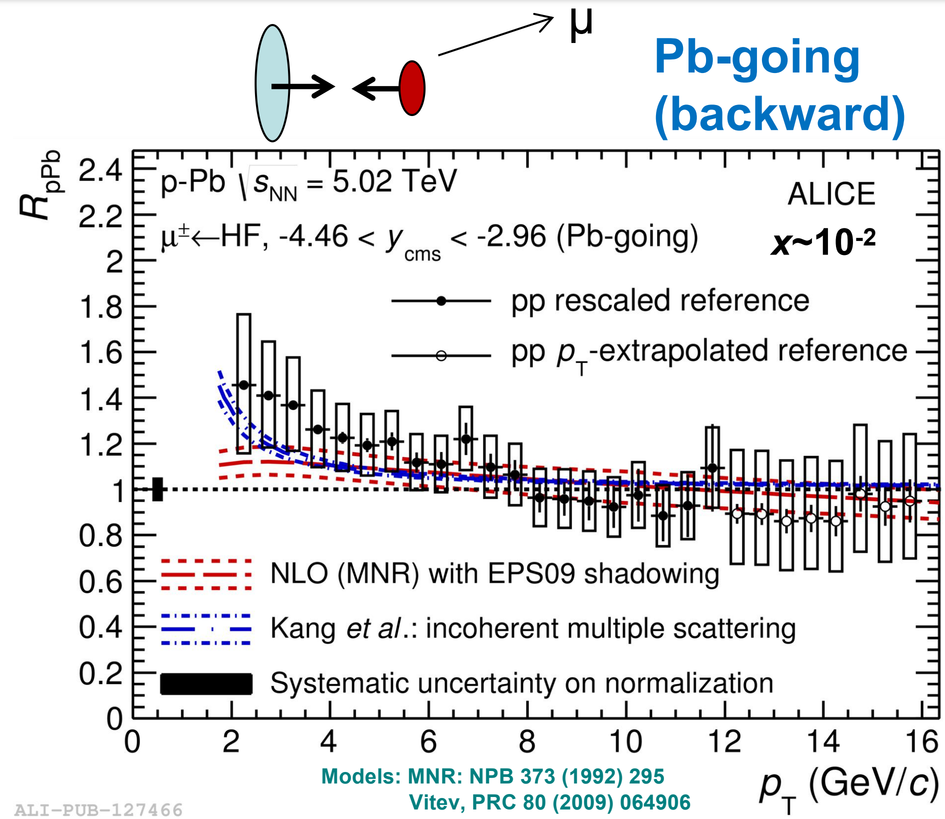
- **HF decay electrons (charm+beauty)** and **separated beauty electrons** both consistent with no modification in p-Pb coll. in the whole p_T range
- Several models describe the data within uncertainties

  → increased precision from Run 2 will be essential

CNM effects - Forward, backward



PLB 770 (2017) 459

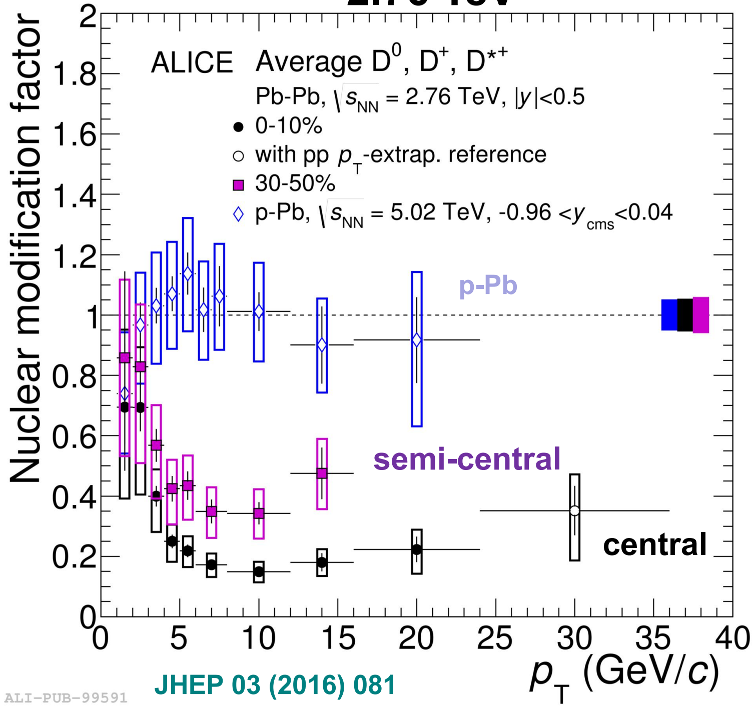


Models: MNR: NPB 373 (1992) 295
Vitev, PRC 80 (2009) 064906
Kang, PLB 740 (2015) 23

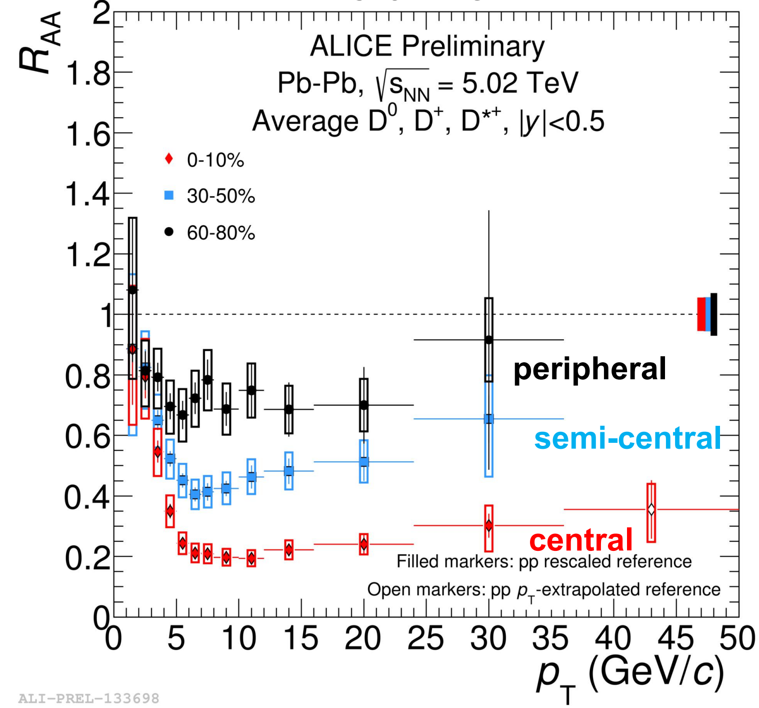
- Heavy-flavour decay muons probe the nPDFs at different *x* values
- Forward production is consistent with no nuclear modification
- **Hint of an enhancement of HF muons at backward rapidity at low p_T**
- Measurements described by models within uncertainties

Pb-Pb: Suppression of D mesons

2.76 TeV



5.02 TeV



- **Strong supression at high p_T in central Pb-Pb collisions**
  - R_{AA}≈0.2 at p_T≈5 GeV/c, similar in $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$=5.02 TeV

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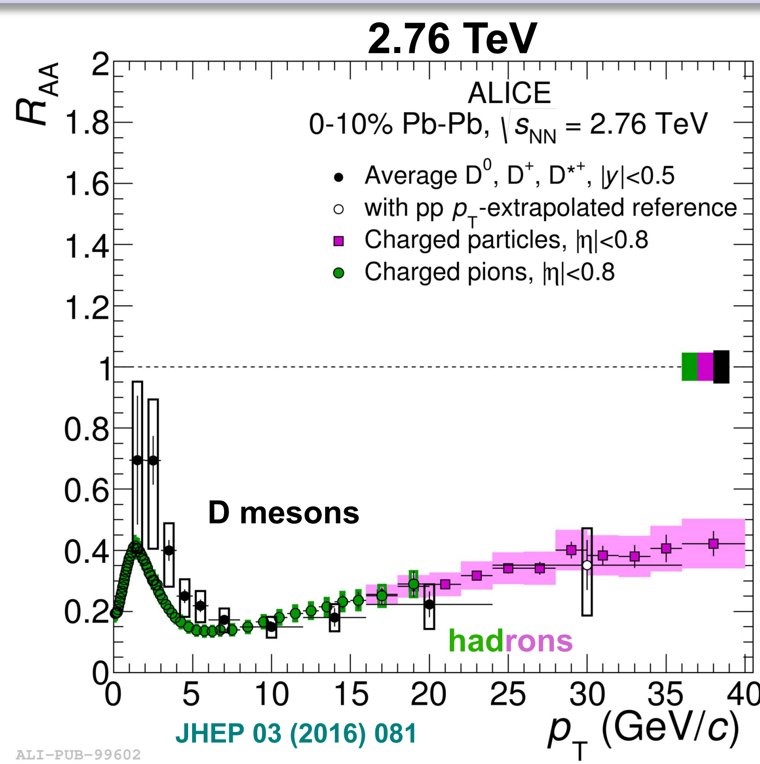

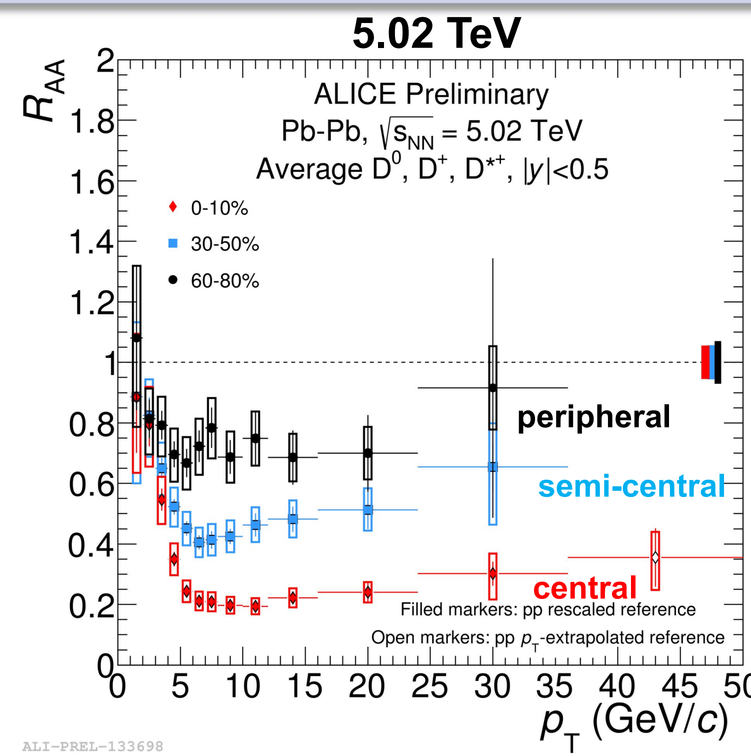

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- Very similar to light hadron suppression
  - **Mass ordering?** Expected $\Delta E_q > \Delta E_c$ but observed $R_{AA}^{h} \approx R_{AA}^{D}$

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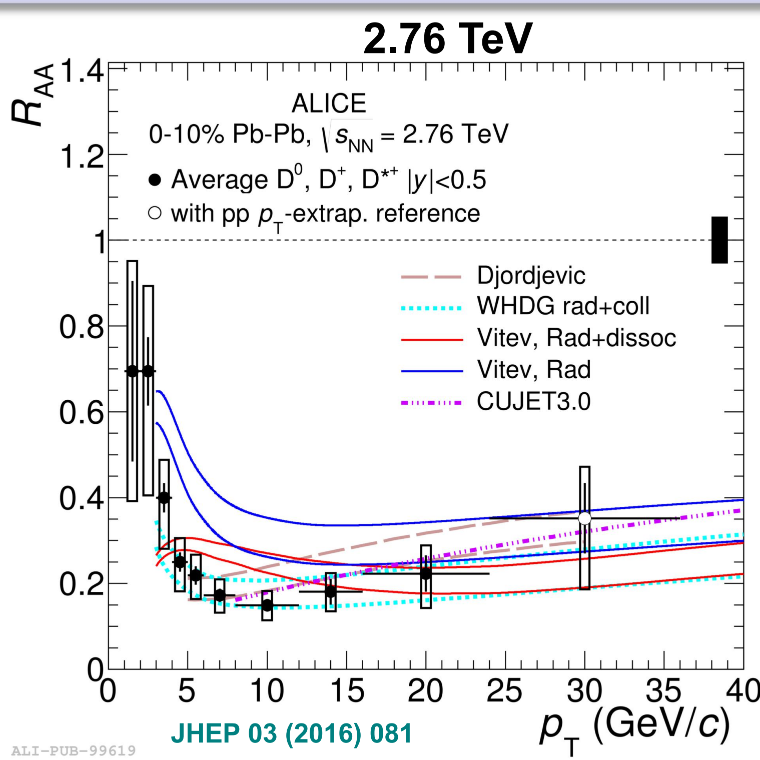
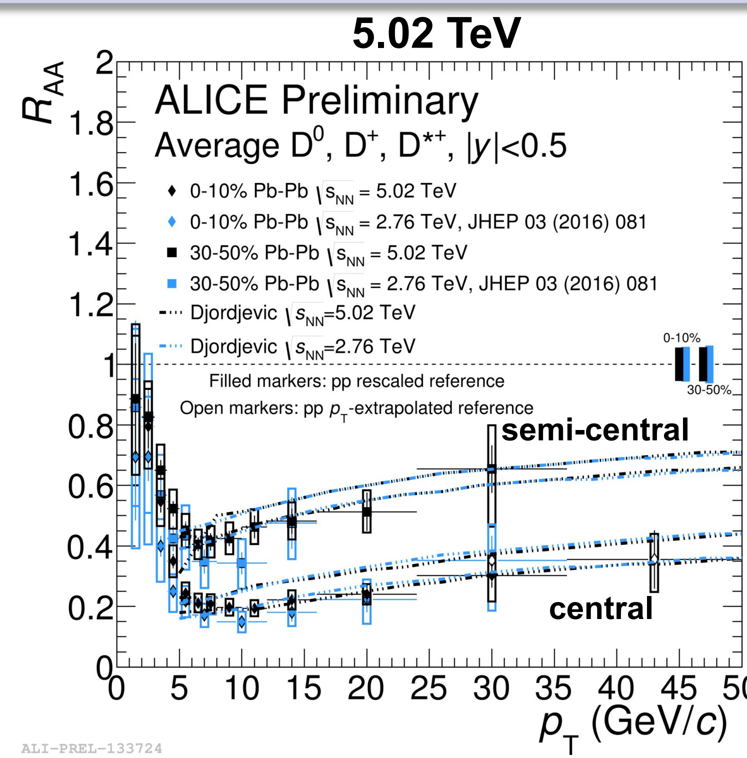


JHEP 03 (2016) 081



Models: Djordjevic, PLB 737 (2014) 298
WHDG, NPA 784 (2007) 426
Vitev, PRC 80 (2009) 054902
CUJET, Chin.Phys.Lett. 32 (2015) 092501

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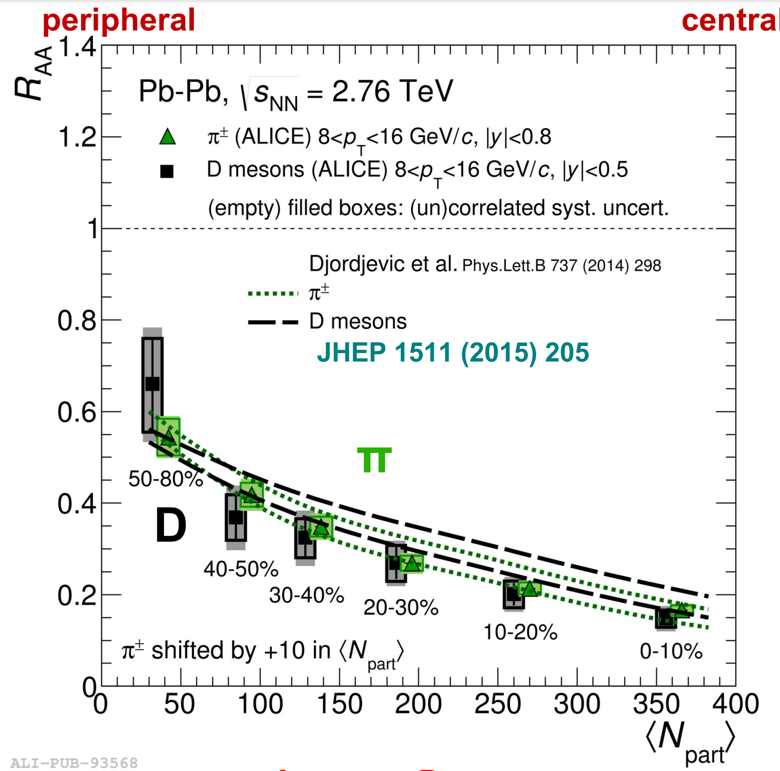
- Very similar to light hadron suppression
  - **Mass ordering?** Expected $\Delta E_q > \Delta E_c$ but observed $R_{AA}^h \approx R_{AA}^D$
- Several pQCD-based models able to reproduce the suppression
  - Different color charge effects, p_T spectrum shapes, fragmentation

Flavour/mass dependence - hadrons



$R_{AA}^{h} \approx R_{AA}^{D}$

- **D-meson** suppression at high p_T consistent with **pions**

  Understanding: different fragmentation, p_T-spectrum shape, color charge effects level out expected ordering

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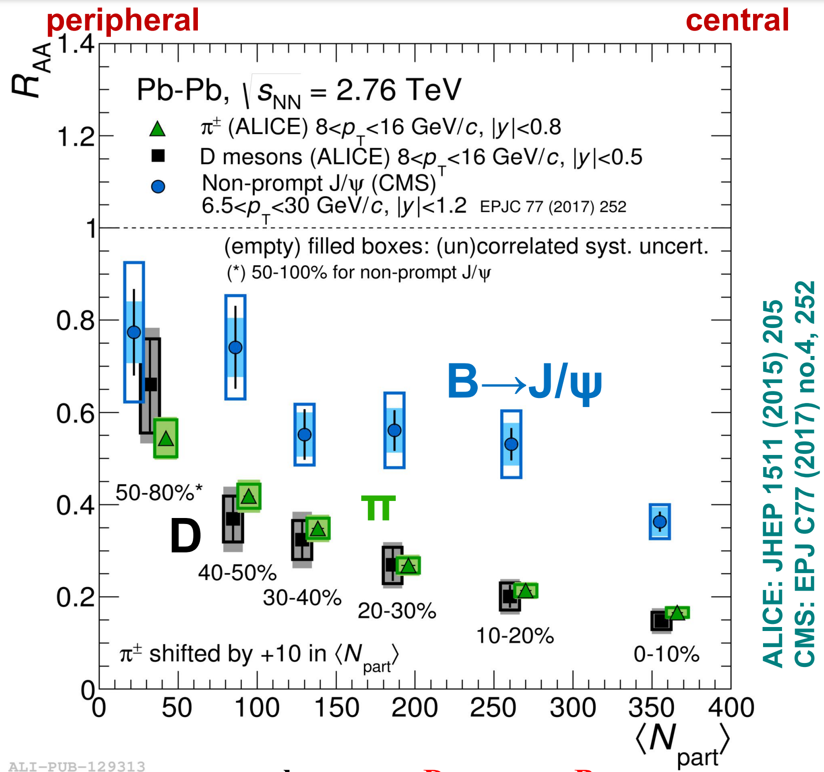

$$R_{AA}^{h} \approx R_{AA}^{D} < R_{AA}^{B}$$

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- **B→J/ψ** suppression at high p_T is weaker *(note the |y| range)*

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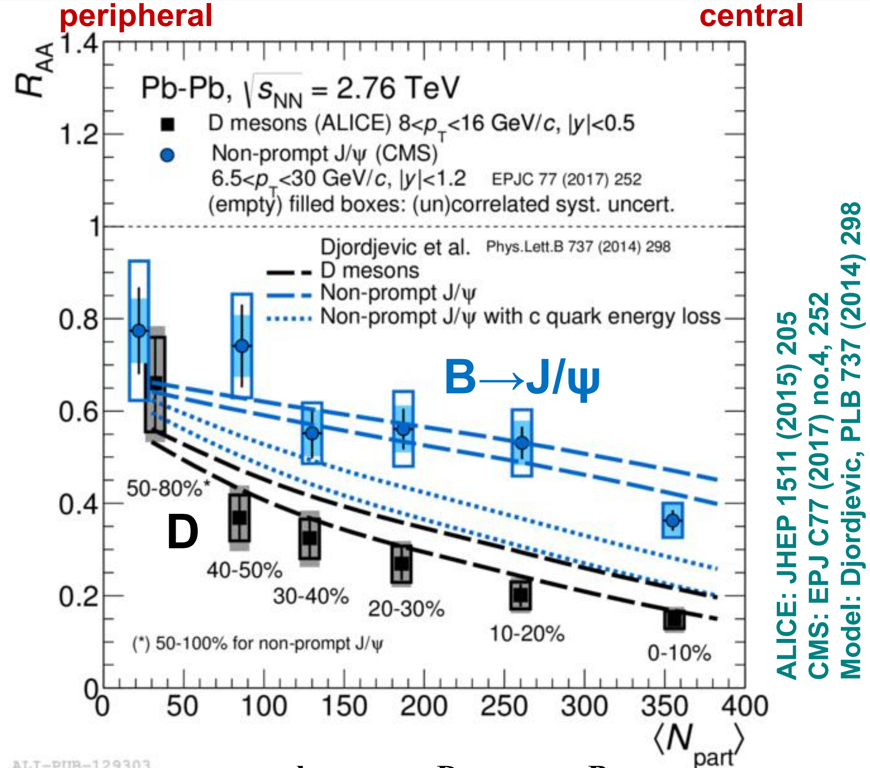

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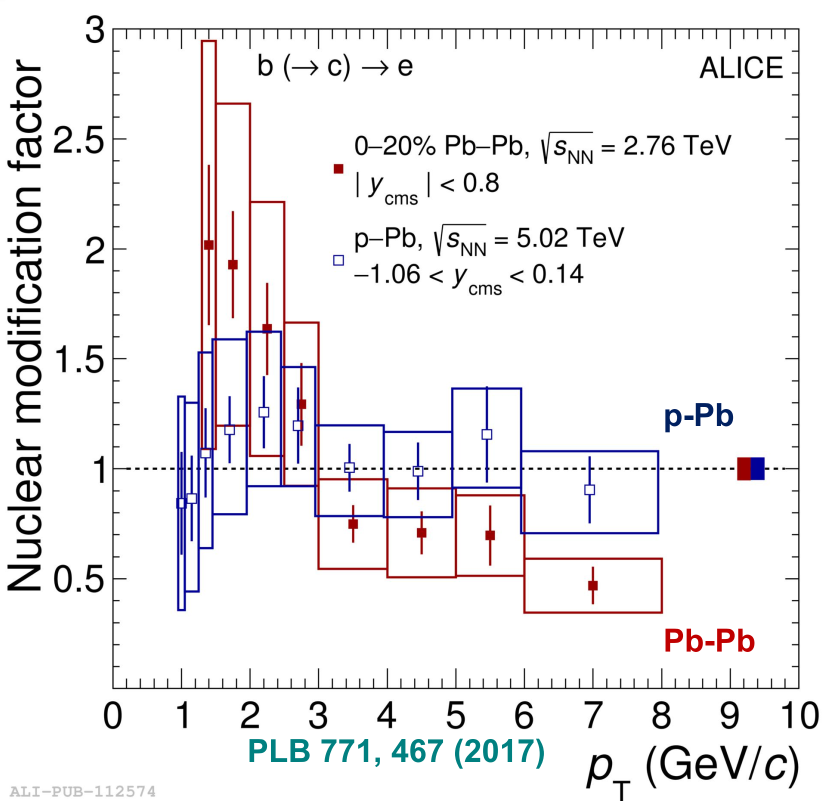
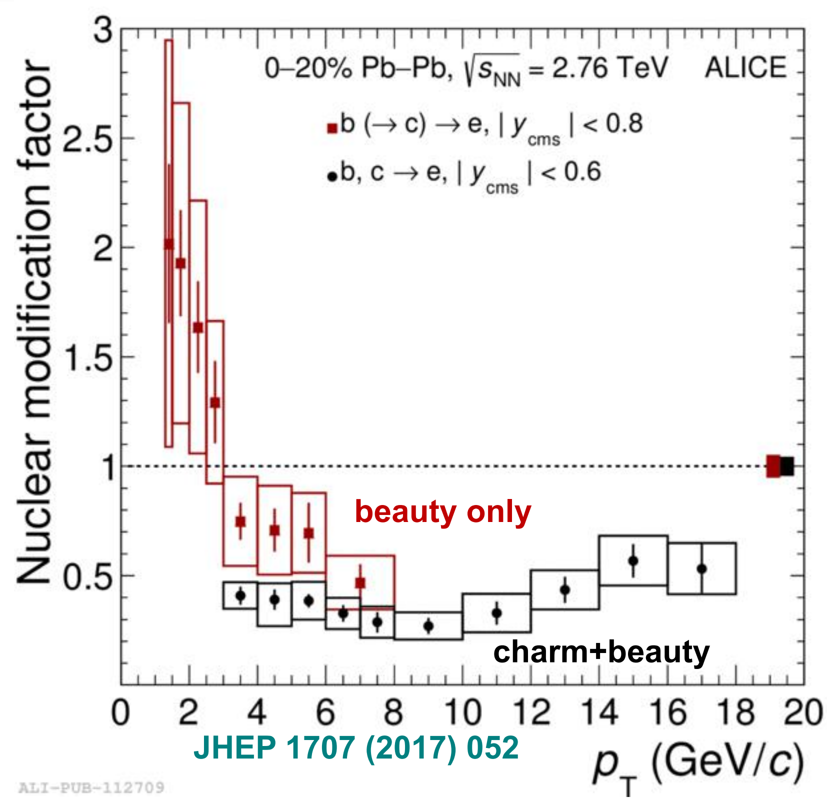
  Model understanding: different parton masses cause different energy loss in similar kinematic range

Charm and Beauty - HF electrons



PLB 771, 467 (2017)



JHEP 1707 (2017) 052

- Significant (c,b)→e suppression in Pb-Pb collisions from medium to high p_T
  - Reminder: Results in p-Pb collisions are consistent with unity
- Separated beauty-decay electrons hint a weaker b-quark suppression

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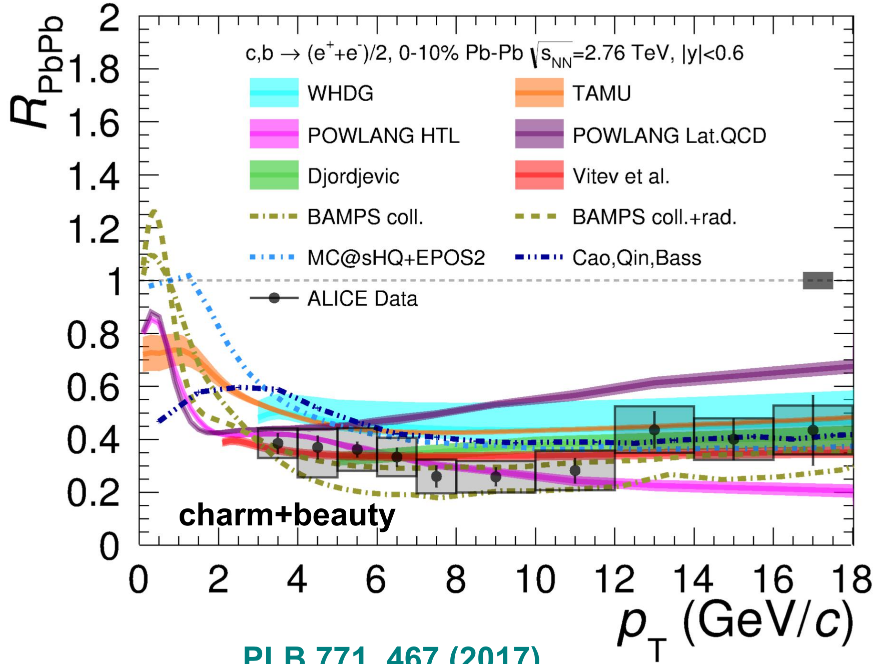

PLB 771, 467 (2017)

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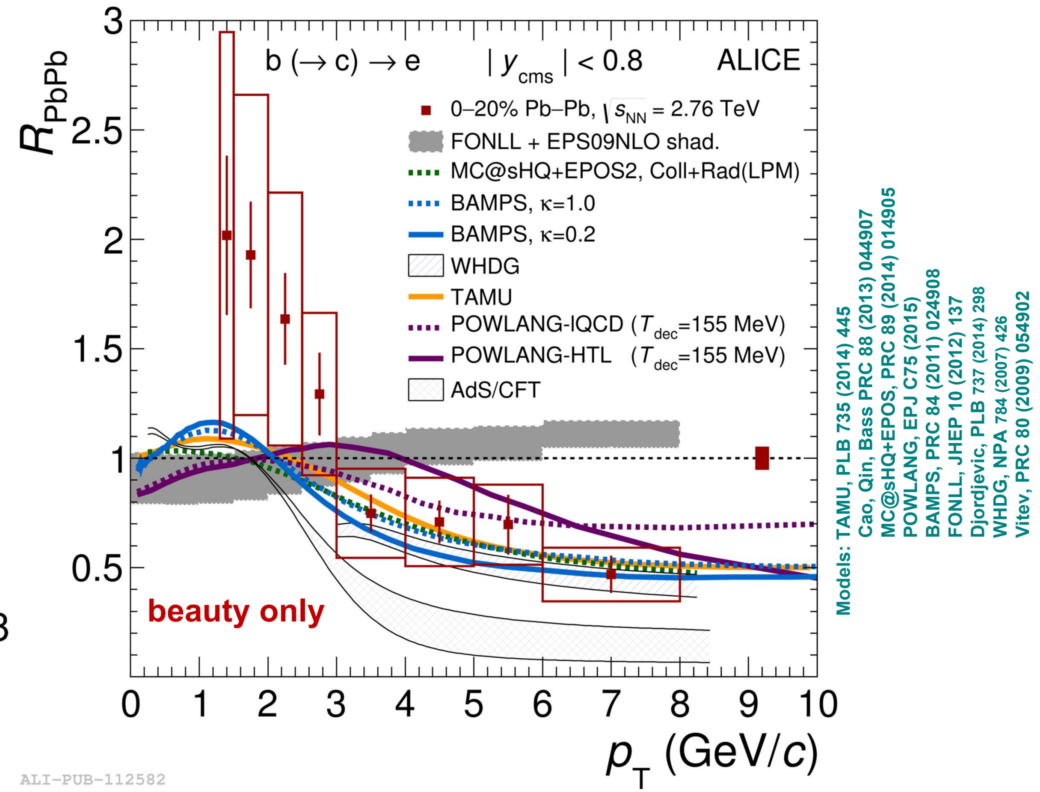

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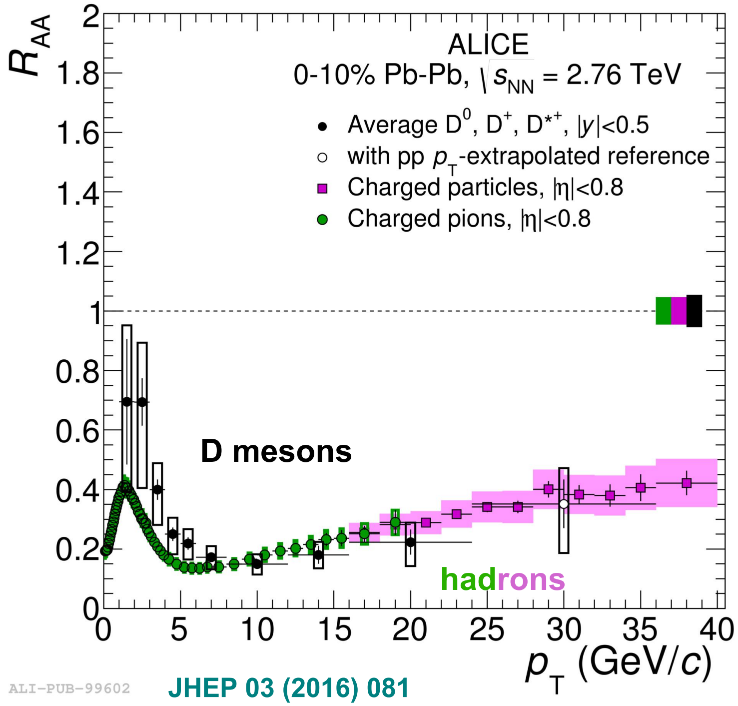
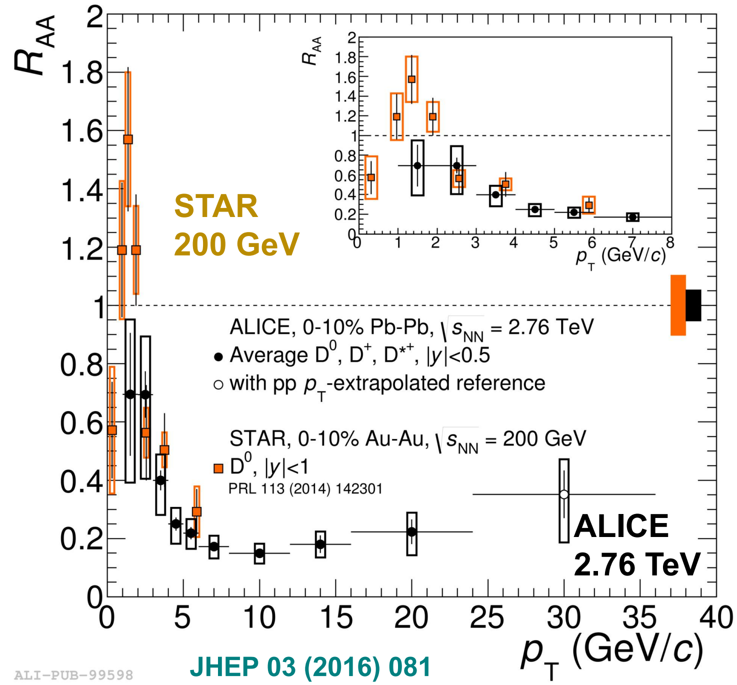
  - Reminder: Results in p-Pb collisions are consistent with unity
- Separated beauty-decay electrons hint a weaker b-quark suppression
- Models describe both (c,b)→e and b(→c)→e within uncertainties
  - Difference understood by quark mass dependent energy loss

Low-p_T modification - coalescence?



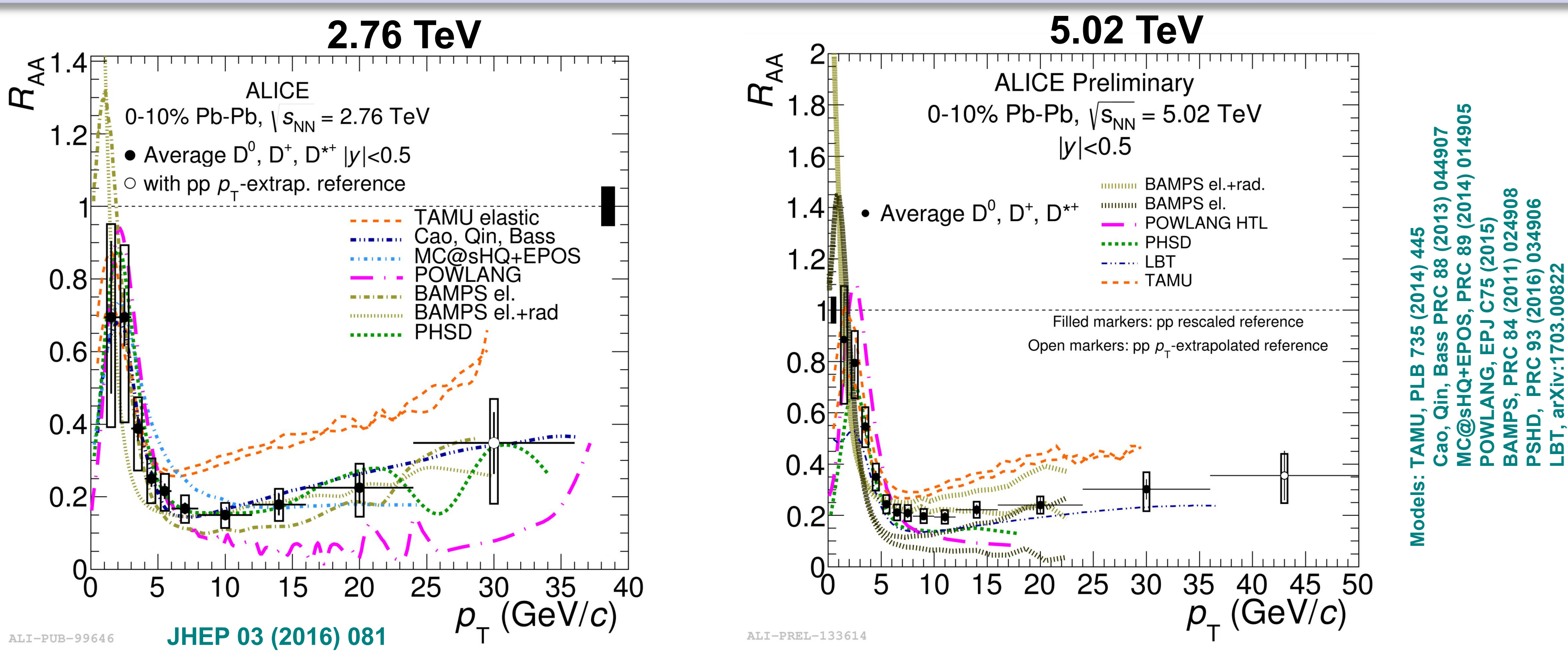


- **D-meson R_{AA} at low p_T**: hint of less suppression than for light flavour

  Note: Trend is not as strong as at RHIC

  (also less shadowing, steeper pp spectrum, different radial flow at RHIC!)

Low-p_T modification - coalescence?



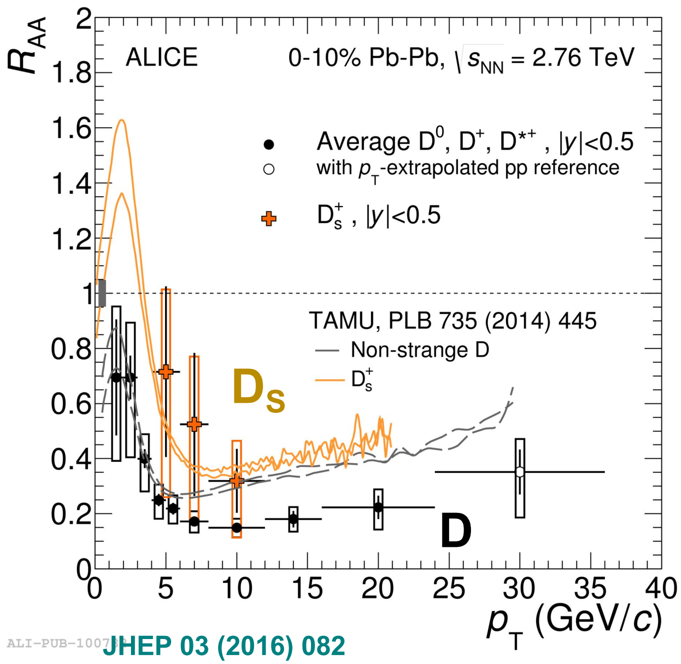
- **D-meson R_{AA} at low p_T**: hint of less suppression than for light flavour

  Note: Trend is not as strong as at RHIC
  (also less shadowing, steeper pp spectrum, different radial flow at RHIC!)
- Present at $\sqrt{s_{NN}}$=2.76 as well as $\sqrt{s_{NN}}$=5.02 TeV
- Transport model calculations → **charm-light quark coalescence?**

  Model ingredients: hydro or Glauber initial conditions, different fragmentation etc.

D_S mesons in Pb-Pb collisions

2.76 TeV



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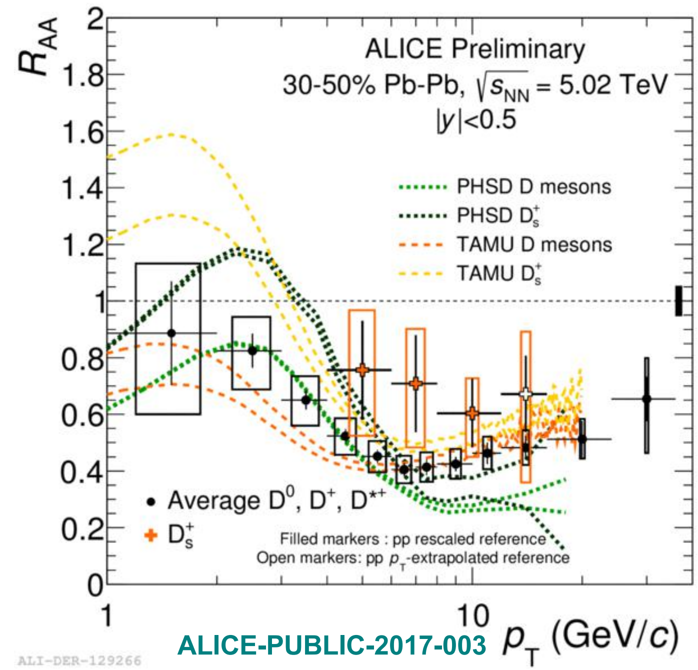
5.02 TeV



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Models: TAMU, PLB 735 (2014) 445
PHSD, EPJ 68 (2009) 3

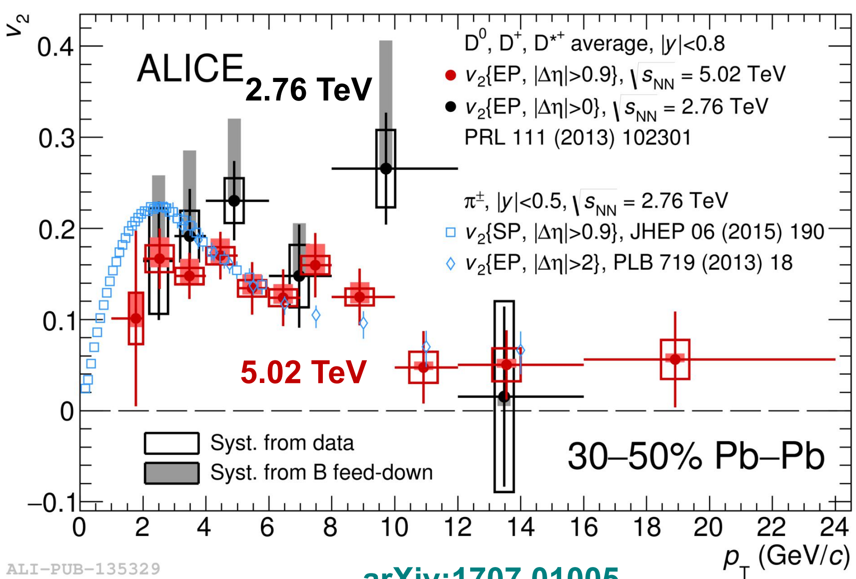
- Indication of less D_S-meson suppression than that of D mesons
  - Both in $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$=5.02 TeV central Pb-Pb data
- Expected if recombination significantly contributes to charm-quark hadronisation in the sQGP

...but...

- *Uncertainties too large to draw a firm conclusion*

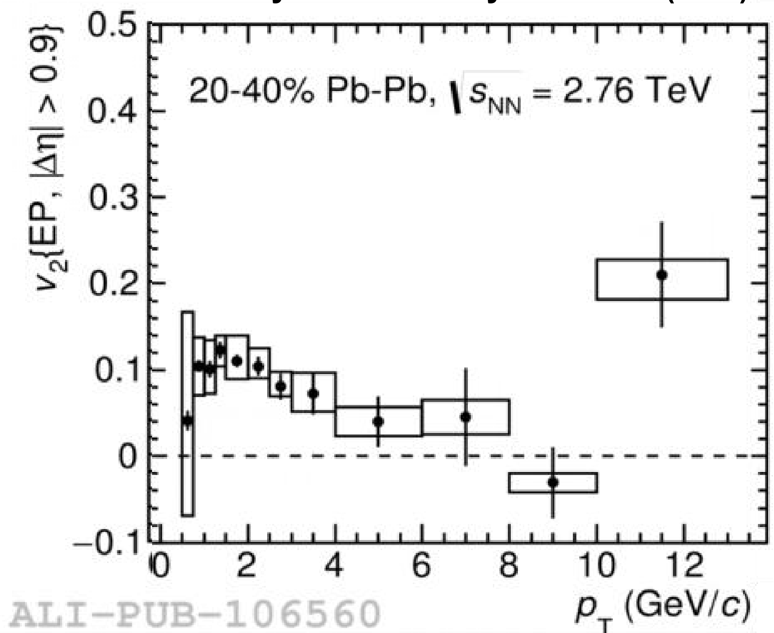
Azimuthal anisotropy

D mesons



arXiv:1707.01005

Heavy flavour decay electrons (HFE)



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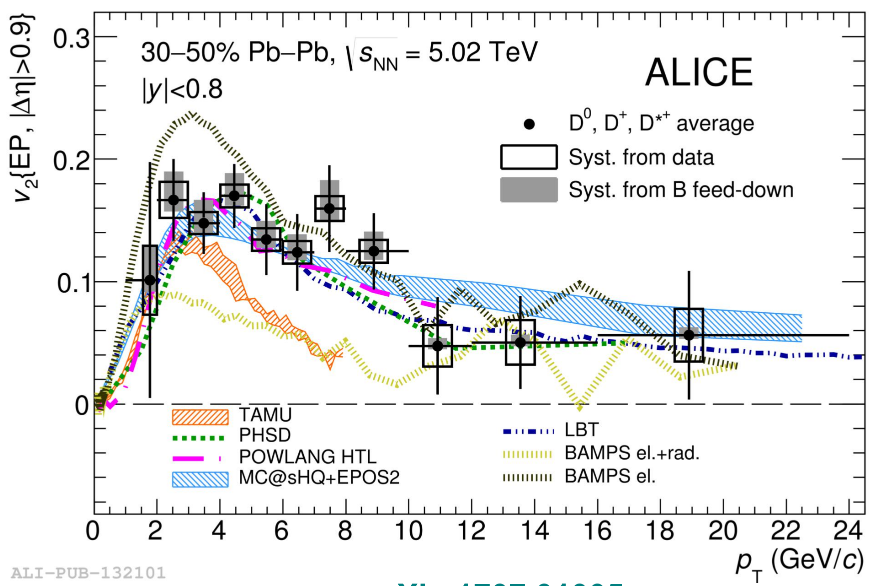
- A significant v_2 of HF is observed at the LHC: both D and HFE
  - **D-meson v_2** is qualitatively similar to **light meson (π±) v_2** at $\sqrt{s_{NN}}$=5.02 TeV
  - **D-meson v_2 at $\sqrt{s_{NN}}$=2.76 TeV** and **$\sqrt{s_{NN}}$=5.02 TeV** agree within uncertainties

Azimuthal anisotropy

D mesons



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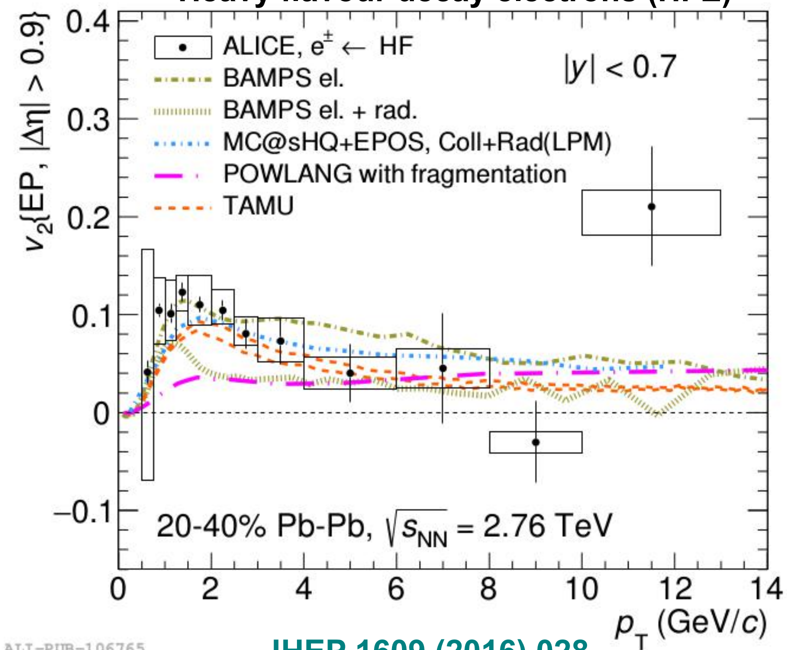

JHEP 1609 (2016) 028

Models: TAMU, PLB 735 (2014) 445
MC@sHQ+EPOS, PRC 89 (2014) 014905
POWLANG, EPJ C75 (2015)
BAMPS, PRC 84 (2011) 024908
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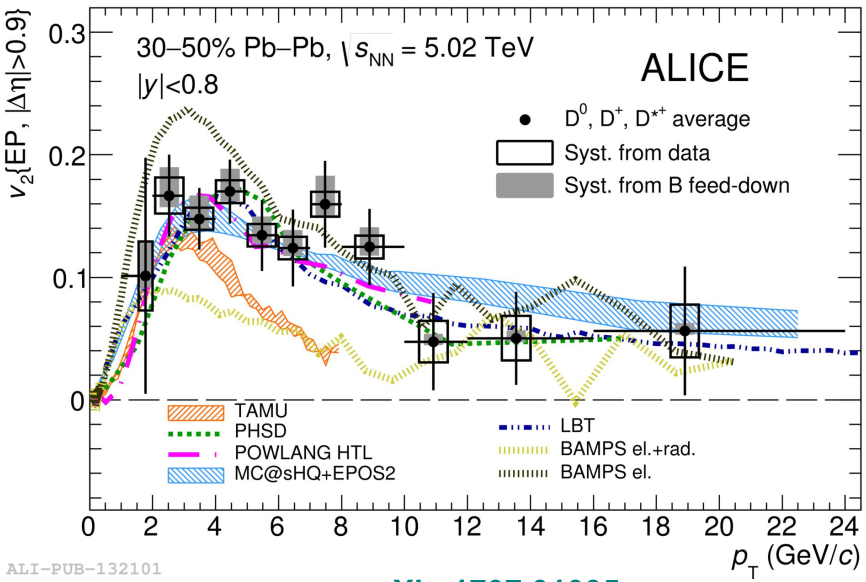
Azimuthal anisotropy

D mesons



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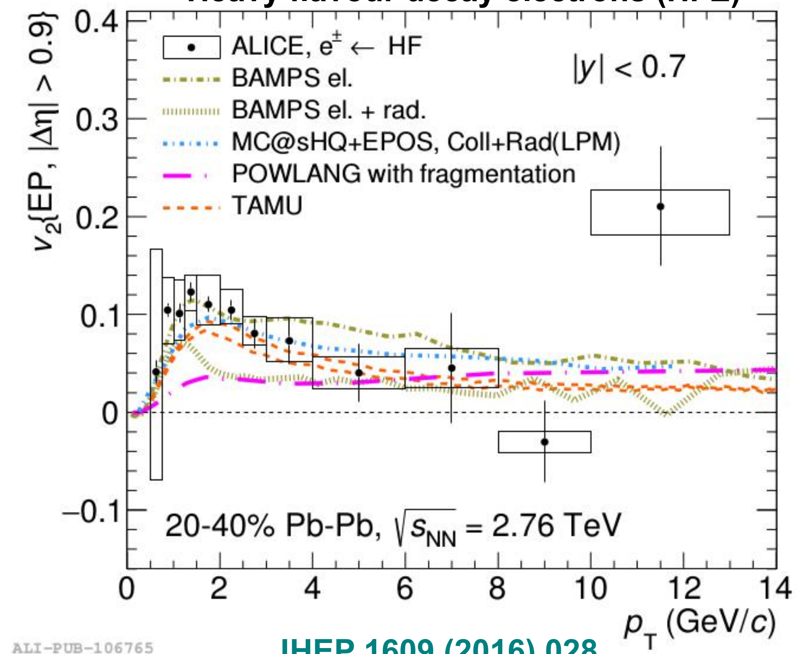

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R_{AA} and v_2 together provide strong constraints on models

Summary

Nuclear modification in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

- No significant nuclear modification is observed at mid-rapidity
- But: D-meson Q_{CP} is significantly above unity at low p_T
- Indication of nuclear modification of HF muons in the backward direction
- Whether matter in p-Pb collisons is entirely cold still remains a question

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Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$=5.02 TeV

- *Energy loss*
  - **High-p_T suppression does not show ordering**: $R_{AA}^{\pi} \approx R_{AA}^{D}$
  - Ordering in central collisions at low-p_T (HFE): $R_{AA}^{b\to e} > R_{AA}^{c,b\to e}$
  - Ordering at intermediate p_T (hadrons): $R_{AA}^{B} > R_{AA}^{D}$
- *Collectivity and coalescence*
  - R_{AA} at low p_T: **coalescence of charm and the flowing medium**
  - Coalescence picture supported by higher D_S-meson R_{AA}
  - Substantial flow of heavy flavour (D and HFE)

  - *v_2 and R_{AA} together: strong constraints on models*

Outlook

LHC in the Run-II era: a real heavy-flavour factory!

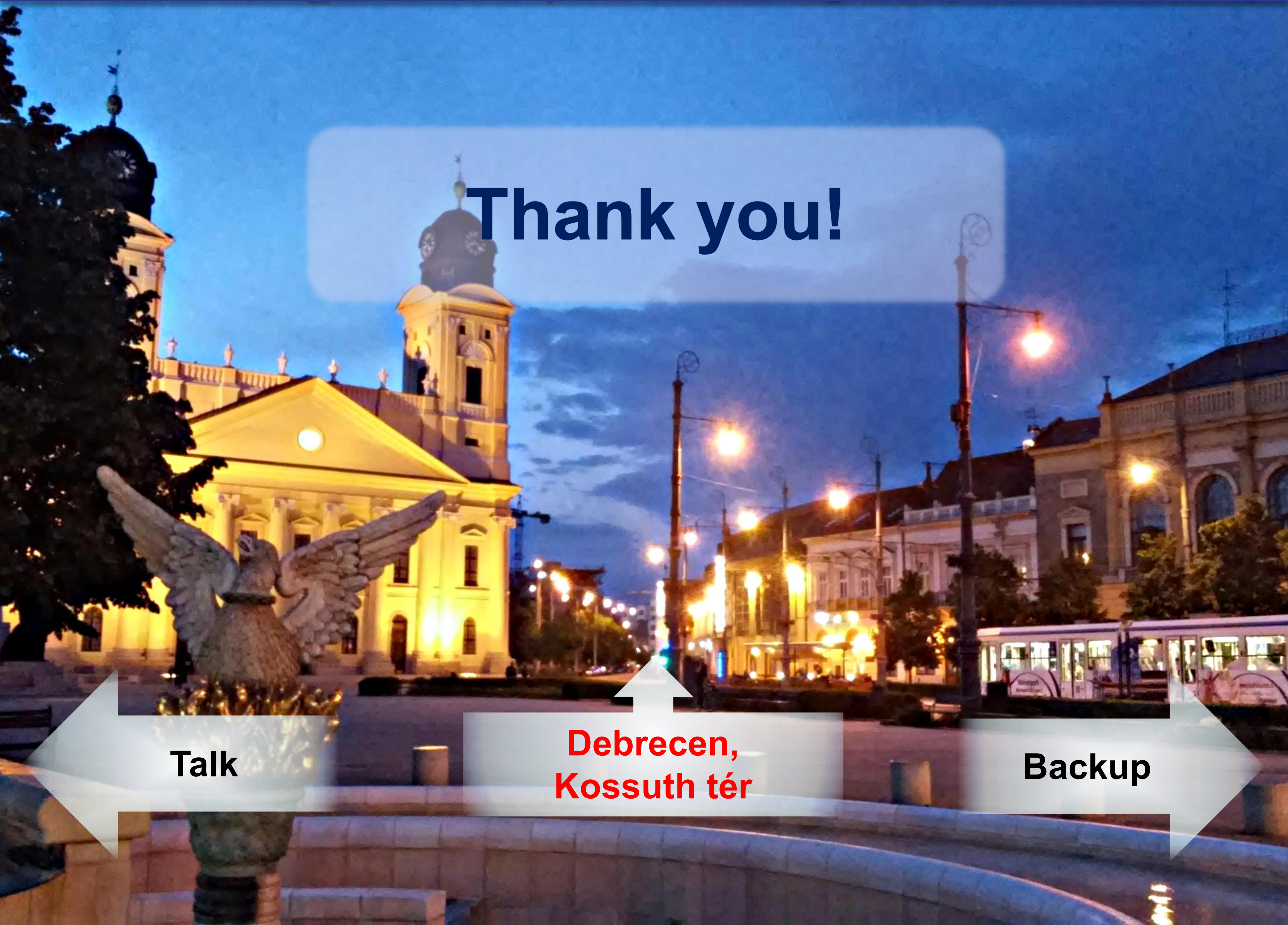
- **First final results already out**
- p-Pb collisions at $\sqrt{s}$=5.02 TeV (already 6x luminosity), 8.16 TeV
- Pb-Pb collisions at $\sqrt{s}$=5.02 TeV

- Higher precision: greater model selectivity
  - Smaller uncertainities, measurements down to p_T=0
  - Λ_c : coalescence and hadronization on the HF sector
- New measurements:
  - Full b-tagged jets and D in jets: insight to HF fragmentation
  - Understanding colour charge / mass effects

Future upgrades: precision beauty measurements

- Detector upgrades: ITS, TPC, readout, Muon Forward Tracker
- Goal: ~100x statistics gain w.r.t. Run-I + Run-II

Thank you!



Talk

Debrecen,
Kossuth tér

Backup

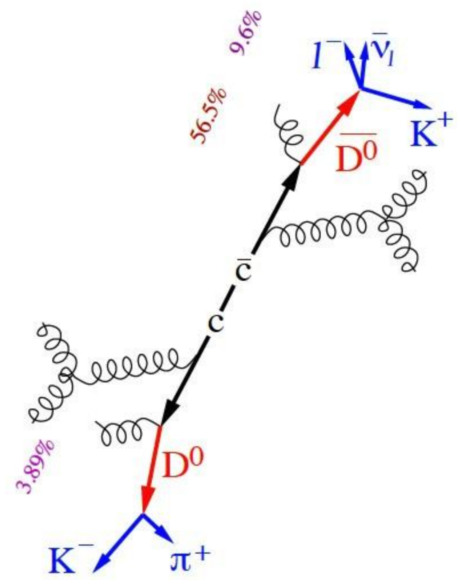
Physics reach after LS2 (2019-20)

Observable	Current, $0.1\,\mathrm{nb}^{-1}$ p_T^{min} (GeV/c)	Current, $0.1\,\mathrm{nb}^{-1}$ statistical uncertainty	Upgrade, $10\,\mathrm{nb}^{-1}$ p_T^{min} (GeV/c)	Upgrade, $10\,\mathrm{nb}^{-1}$ statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
D_s meson R_{AA}	4	15 %	< 2	3 %
D meson from B R_{AA}	3	30 %	2	1 %
J/ψ from B R_{AA}	1.5	15 % (p_T-int.)	1	5 %
B^+ yield	not accessible		3	10 %
Λ_c R_{AA}	not accessible		2	15 %
Λ_c/D^0 ratio	not accessible		2	15 %
Λ_b yield	not accessible		7	20 %
D meson v_2 ($v_2 = 0.2$)	1	10 %	0	0.2 %
D_s meson v_2 ($v_2 = 0.2$)	not accessible		< 2	8 %
D from B v_2 ($v_2 = 0.05$)	not accessible		2	8 %
J/ψ from B v_2 ($v_2 = 0.05$)	not accessible		1	60 %
Λ_c v_2 ($v_2 = 0.15$)	not accessible		3	20 %
Dielectrons				
Temperature (intermediate mass)	not accessible			10 %
Elliptic flow ($v_2 = 0.1$) [4]	not accessible			10 %
Low-mass spectral function [4]	not accessible		0.3	20 %
Hypernuclei				
${}^3_\Lambda$H yield	2	18 %	2	1.7 %

ALICE ITS upgrade TDR

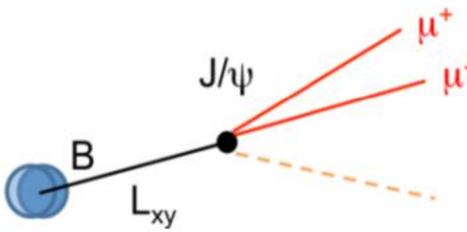
Experimental access to open HF

- Indirect semi-leptonic decays
  - higher branching ratio, easier trigger
  - a mixture of *c*, *b* contributions
  - → *b* can be isolated via displaced electrons

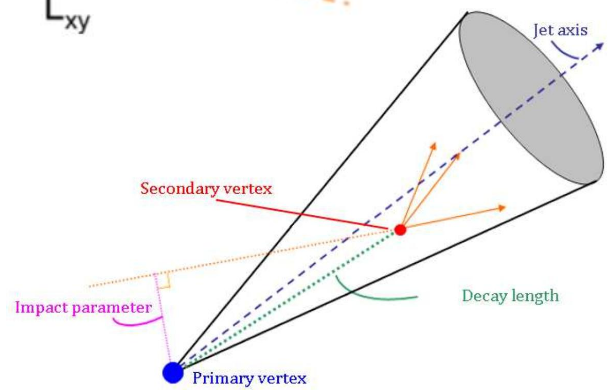


- Direct reconstruction of hadronic decays
  - Access to kinematics
  - High background (→ secondary vertex)

- Non-prompt J/ψ reconstruction
  - Selective to decays of B
  - Secondary vertex reconstuction needed



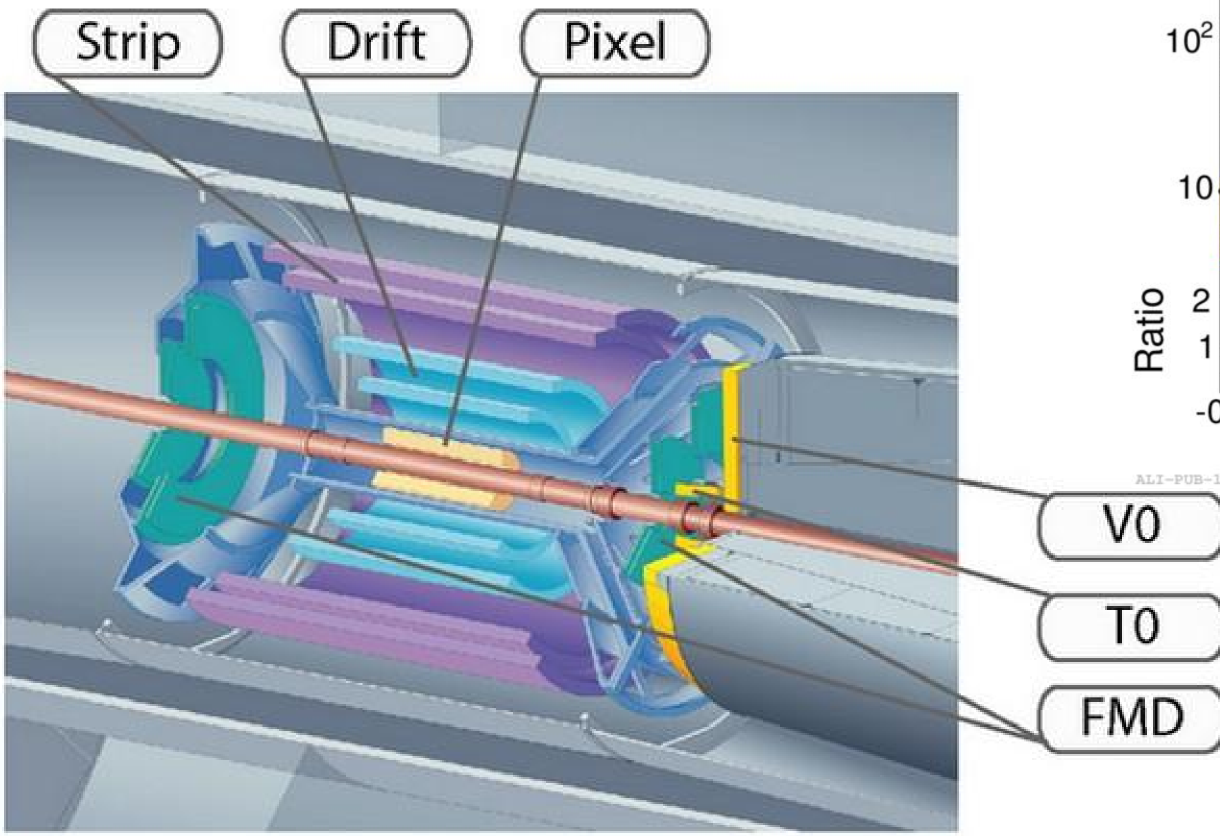
- Full jet reconstruction: D in jets, b-tagging
  - Insight to fragmentation properties
  - Tag via secondary vertex or impact parameter

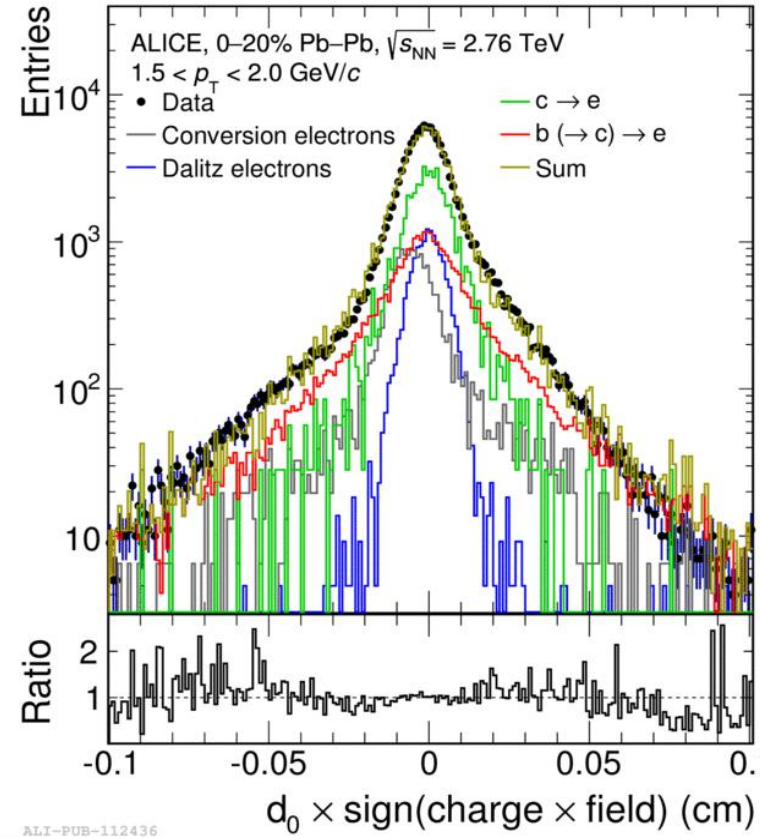


ITS

- Semiconducting technology
- Resolves secondary vertex

heavy quark lifetimes: $c\tau(D) \sim 100\text{-}300\ \mu m$
$c\tau(B) \sim 400\text{-}500\ \mu m$
Secondary vertex resolution: $\sim 100\ \mu m$





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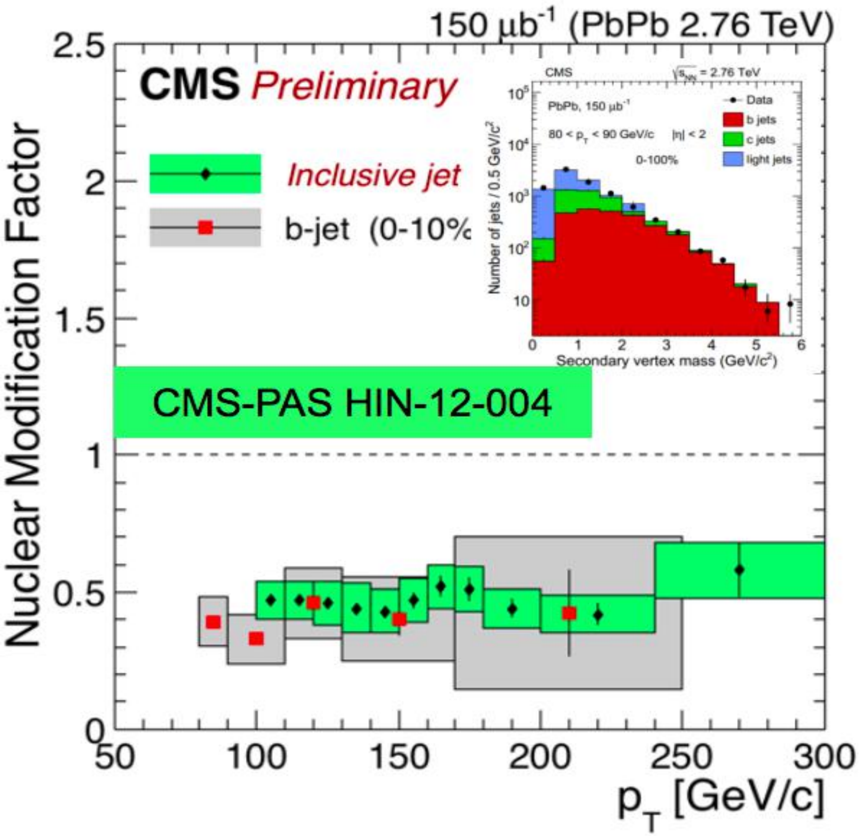
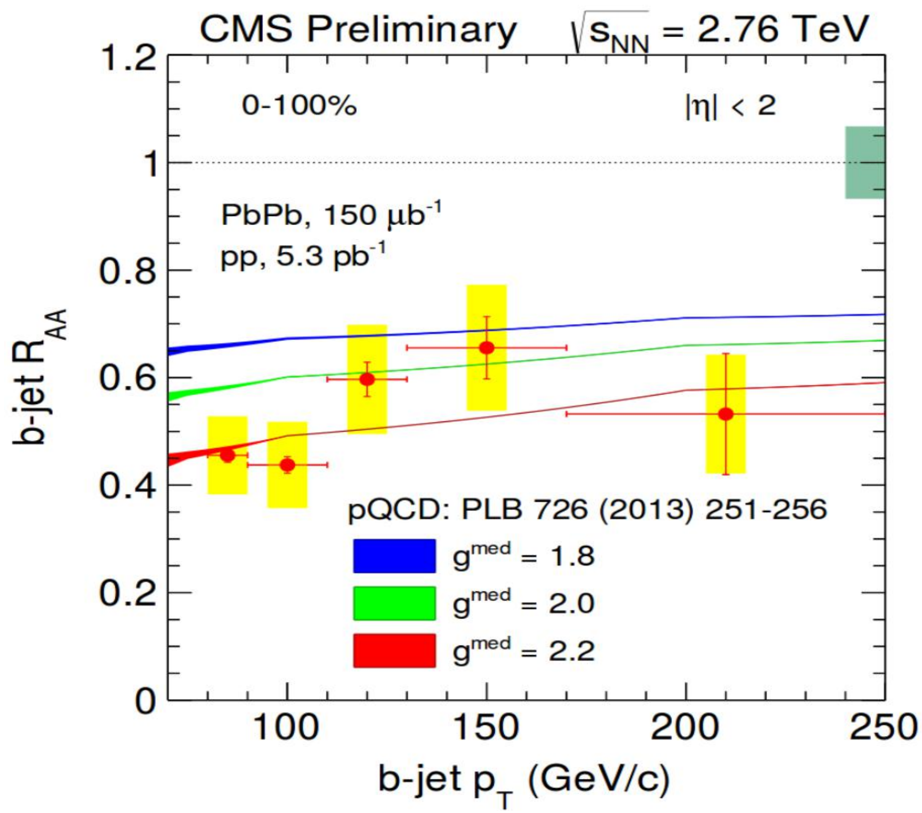
Distribution of electron track DCA (distance of closest approach to primary vertex).

MC template fitting allows for statistical separation of charm and beauty contributions.

Full B-jet reconstruction (CMS)



R_{AA}(b-jet) ~ R_{AA}(h-jets)

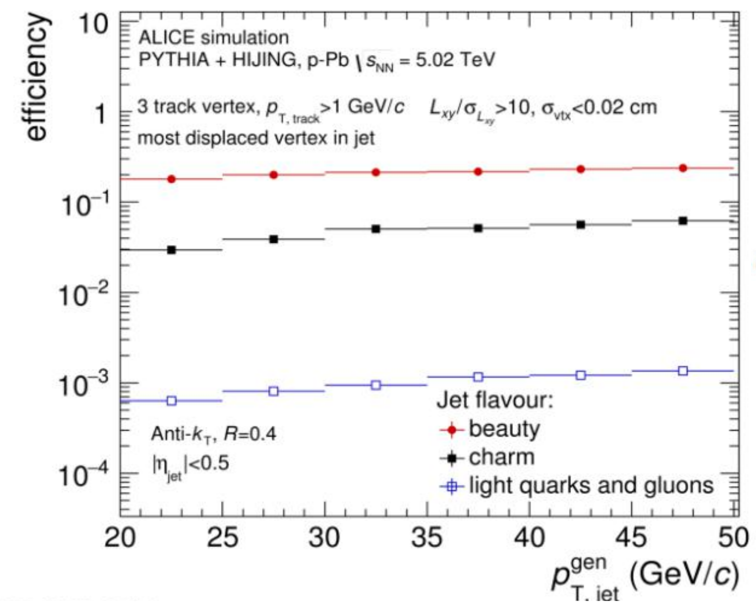


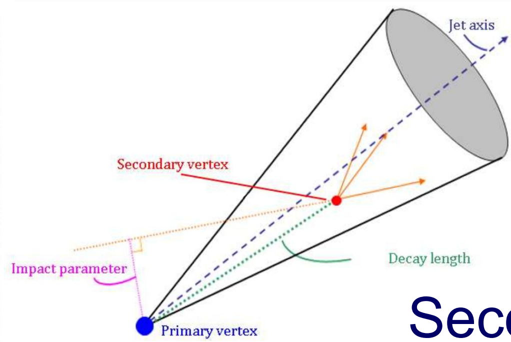
Huang-Bo-Vitev, PLB 726, 251 (2013)

- Very high p_T: similar inclusive and b-jet suppression
- Colour charge effects? Contribution of gluon splitting?

→ Future precise measurements towards lower p_T

b-jet tagging performance





Secondary vertex method

- L_{xy} : projection of decay length on the (x,y) plane
- L_{xy}/σ_{Lxy} : significance of L_{xy}
- σ_{vtx} : secondary vertex dispersion