Heavy-flavour measurements
with the ALICE experiment at the LHC

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Heavy-flavour (HF) probes

- Heavy quarks are produced early

$$\tau_{c,b} \sim \tfrac{1}{2}\, m_{c,b} \sim 0.1\ \mathrm{fm} \ll \tau_{QGP} \sim 5\text{-}10\ \mathrm{fm}$$

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

- Heavy quarks are (almost) conserved

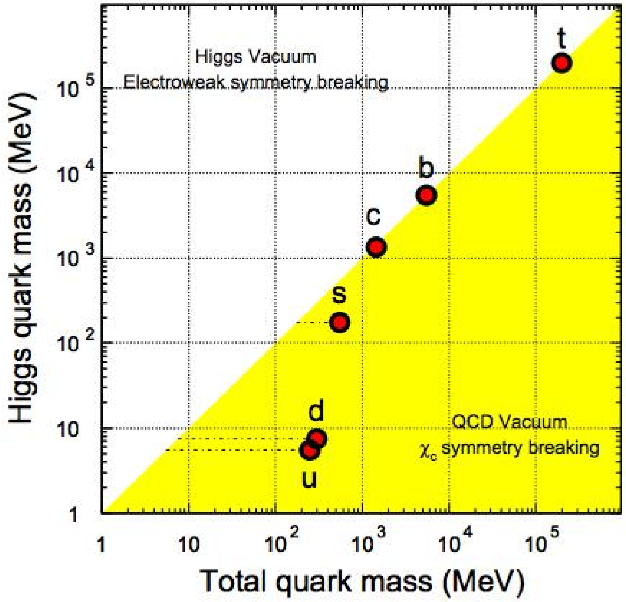
$$m \gg \Lambda\ (m_c\sim 1.5\ \mathrm{GeV},\ m_b\sim 5\ \mathrm{GeV})$$

  - No flavour changing
  - Negligible thermal production

→ Very little production or destruction in the sQGP

Collins, Soper, Sterman, NPB 263 (1986) 37.

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



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  - **Heavy quark kinematics in the sQGP**
  - Access to **transport properties** of the system
  - ...exits the medium also at **low momenta**
  - **Hadronization** (fragmentation, coalescence)
  - **Heavy vs. light? Charm vs. bottom?**

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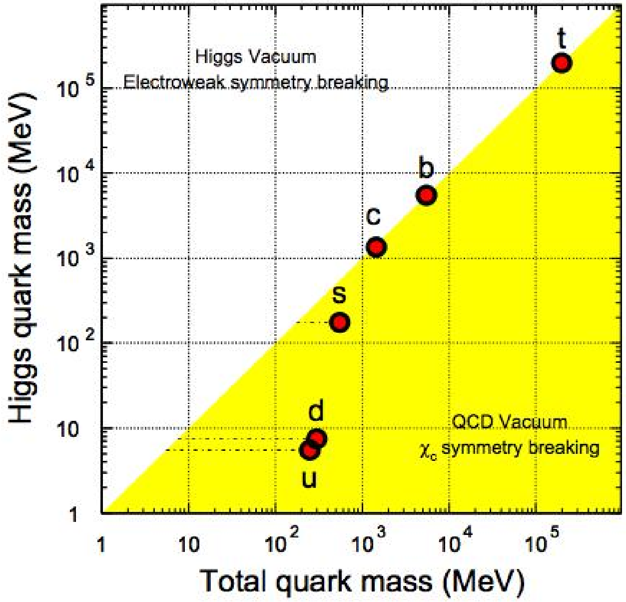

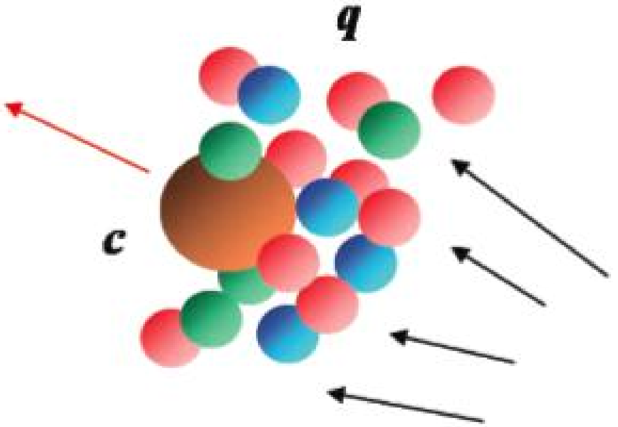

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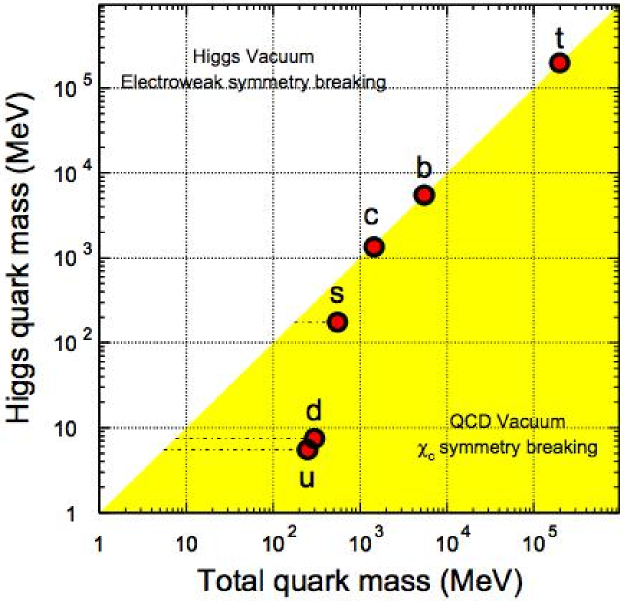

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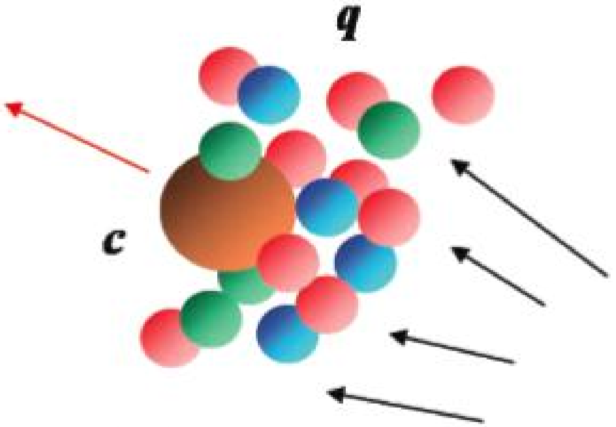
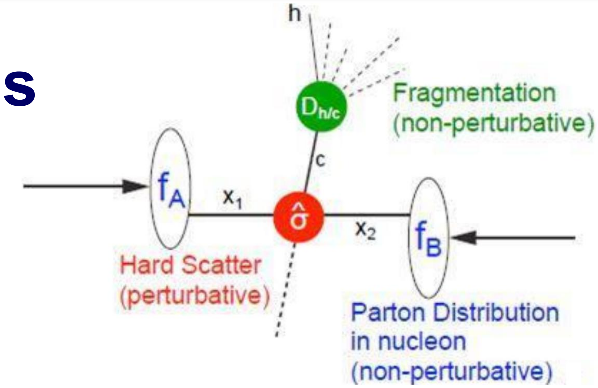


Penetrating probes down to low momenta!

Heavy flavour in small systems

Production cross sections in pp collisions

- Primary (vacuum) pQCD benchmark



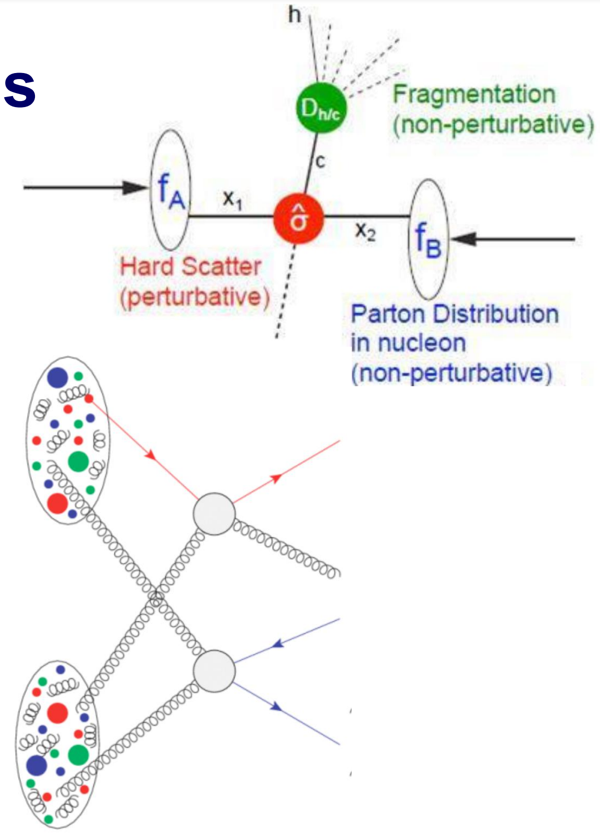
Heavy flavour in small systems

Production cross sections in pp collisions

- **Primary (vacuum) pQCD benchmark**

HF production vs. event activity

- Interplay between hard and soft processes
- Link between initial and final state
- Origin of observed universality?
- Multiple parton interactions (MPI)?
- Role of collective effects in small collision systems with high multiplicity?



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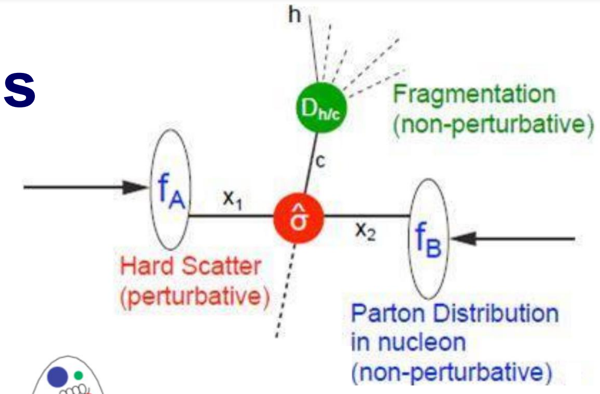

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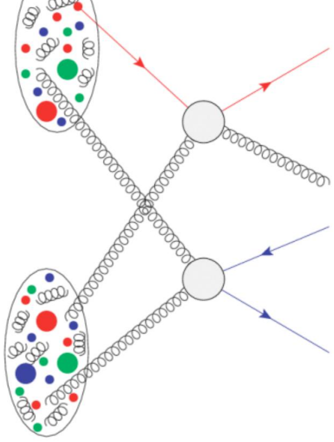
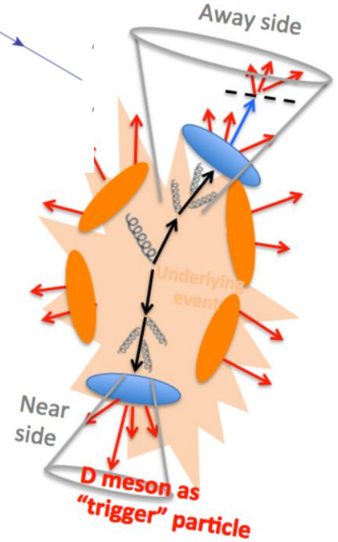


Jet and correlation observables

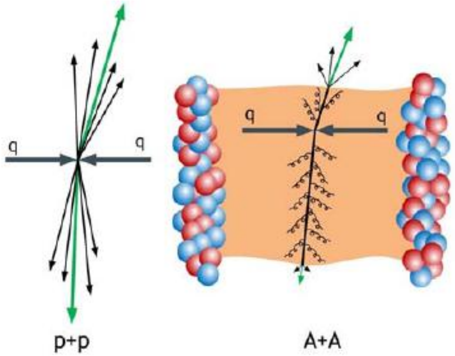
- Fragmentation of charm vs. light quarks
- Properties of jets with charm content
- Contribution of gluon splitting to HF yields



Heavy ions: Nuclear modification

- **pp** collisions: reference system

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



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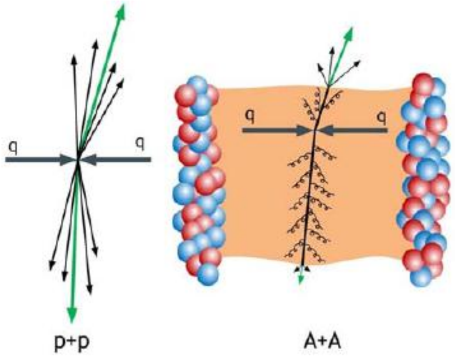
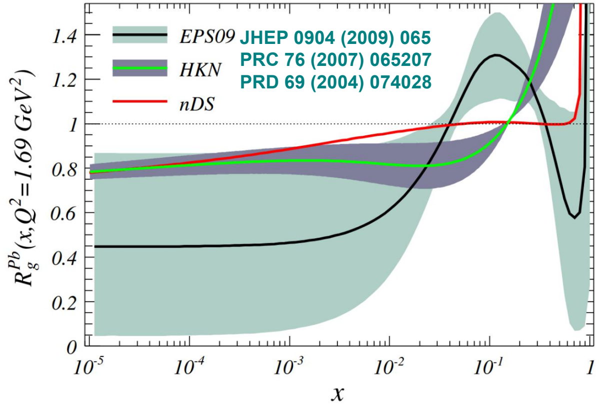
- **pA collisions**: Understand cold nuclear matter (CNM) effects
  - PDF modification: (anti)shadowing, gluon saturation
  - Energy loss in CNM, k_{T}-broadening
  - *Understand the origin of collective-like effects*





JHEP 0904 (2009) 065
PRC 76 (2007) 065207
PRD 69 (2004) 074028

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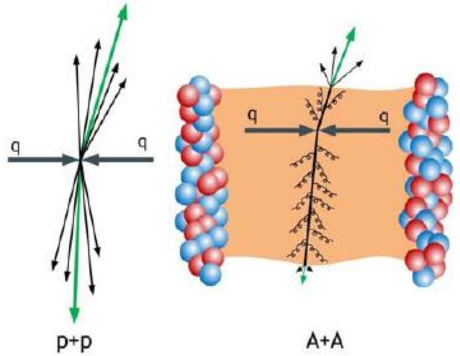

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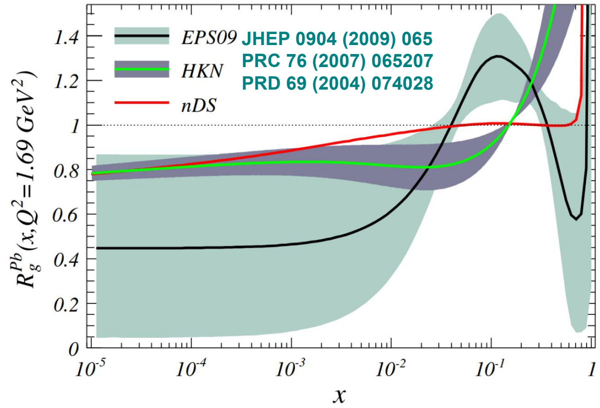


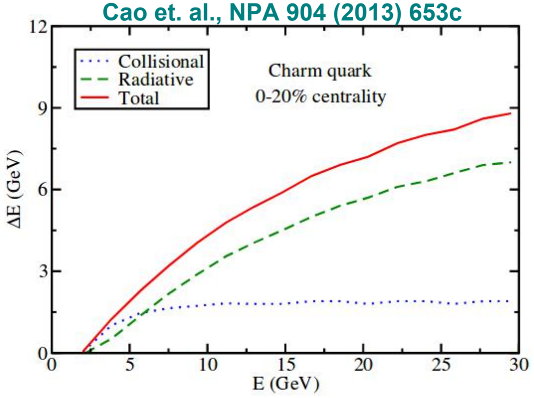
JHEP 0904 (2009) 065
PRC 76 (2007) 065207
PRD 69 (2004) 074028

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

$$\Delta E_{\mathrm{g}} > \Delta E_{\mathrm{q}} > \Delta E_{\mathrm{c}} > \Delta E_{\mathrm{b}} \rightarrow ?\ R_{\mathrm{AA}}{}^{\mathrm{h}} < R_{\mathrm{AA}}{}^{\mathrm{D}} < R_{\mathrm{AA}}{}^{\mathrm{B}}$$

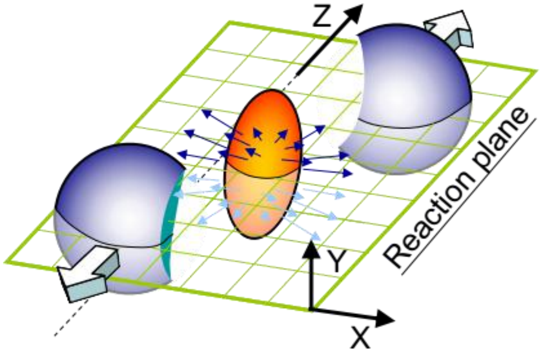
  - Color charge effect (HF is mostly quarks <=> large contribution from gluons in light flavour)

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



Heavy ions: Collectivity

- Spatial anisotropy in the collision region...
  - Pressure difference
    $R_x < R_y ==> P_x > P_y$



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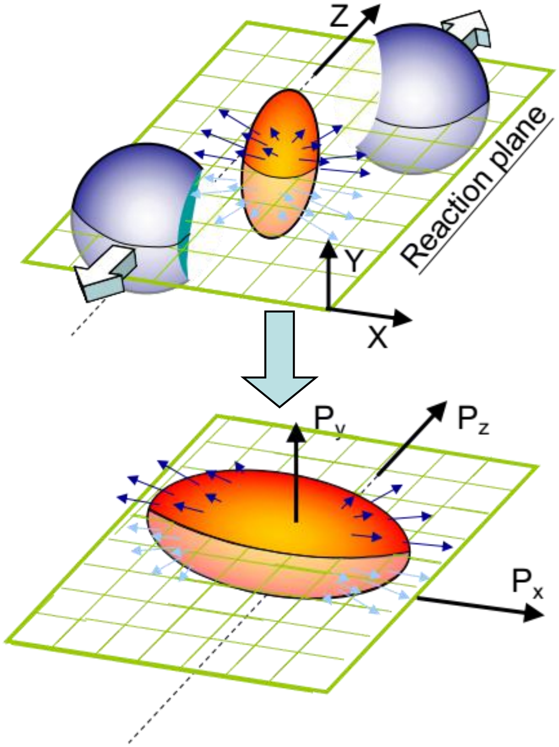
    $R_x < R_y \Longrightarrow P_x > P_y$
- ... converts to momentum anisotropy
  - Parametrization: Fourier-coefficients
    $$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n(\varphi - \Psi_R)\right)\right)$$
    $$v_n = \langle\cos(n(\varphi - \Psi_R))\rangle$$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



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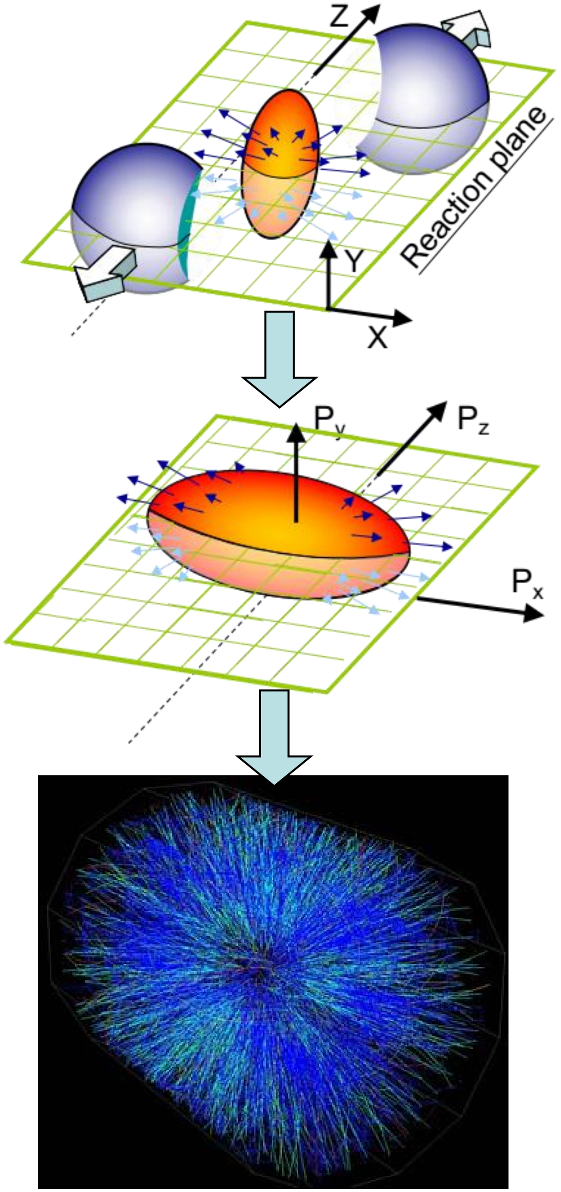
  - **Anisotropy parameter v_2: "elliptic flow"**
- **strongly coupled medium => substantial v_n**

$$\lambda \ll \bar{R}$$

λ : mean free path
$\bar{R}$: characteristic size of particle source

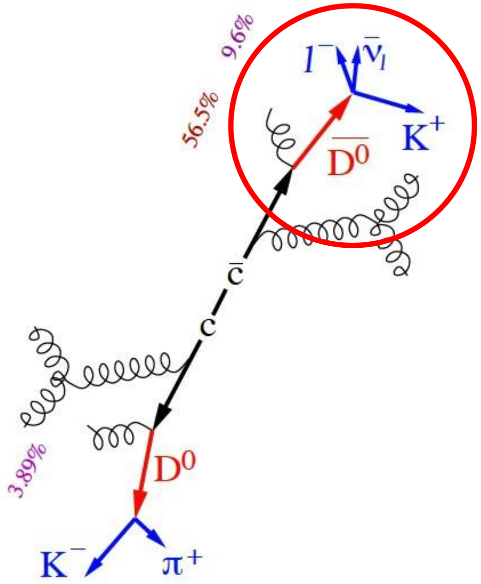
  - Does heavy flavour flow?
  - In what stage does it pick up flow?
    - Does it thermalize with the medium?
    - Do heavy quarks coalesce with flowing light quarks?



Experimental access to open HF

- Semi-leptonic decays
  - relatively high branching ratio, easy trigger
  - a mixture of c, b quark contributions

  → b can be isolated via displaced electrons



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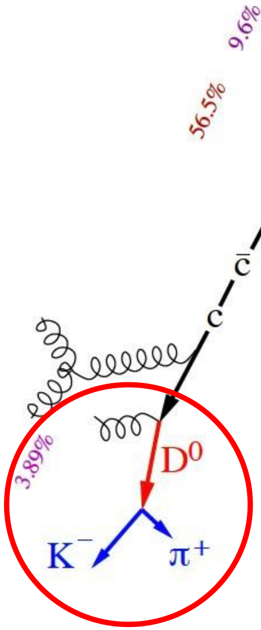

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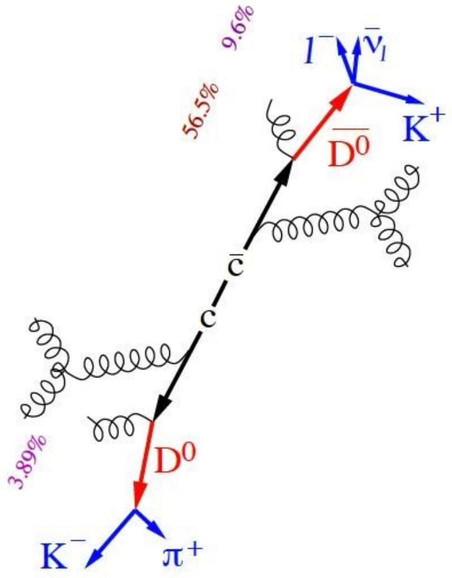

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  - Insight to fragmentation properties
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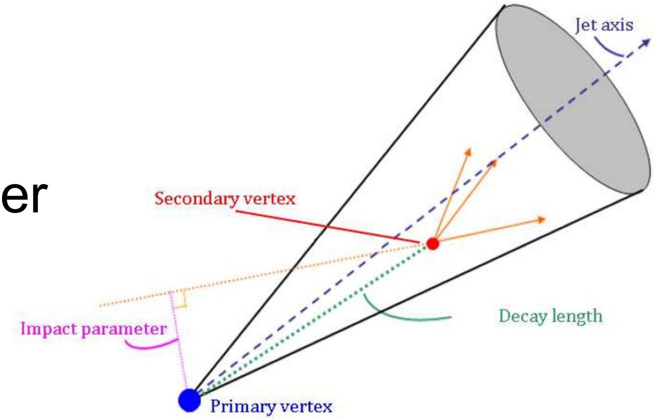

- Other methods:
  - Correlations, Non-prompt J/ψ, ...

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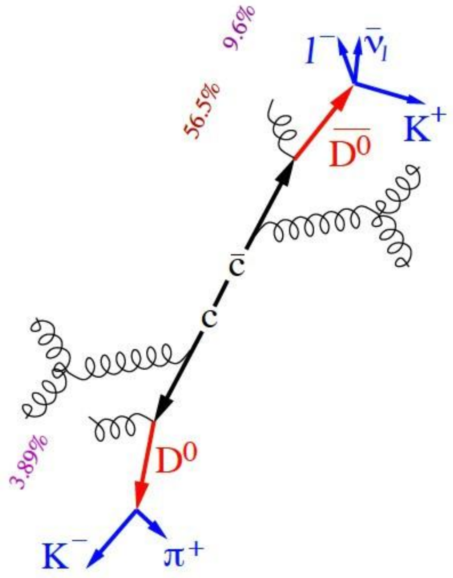

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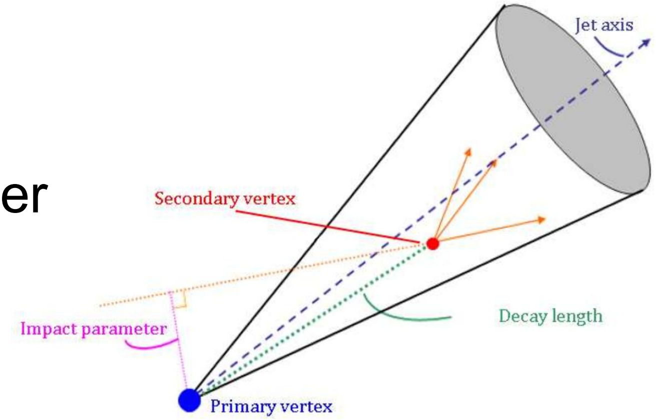
→ b-jets: Artem Isakov (this session)



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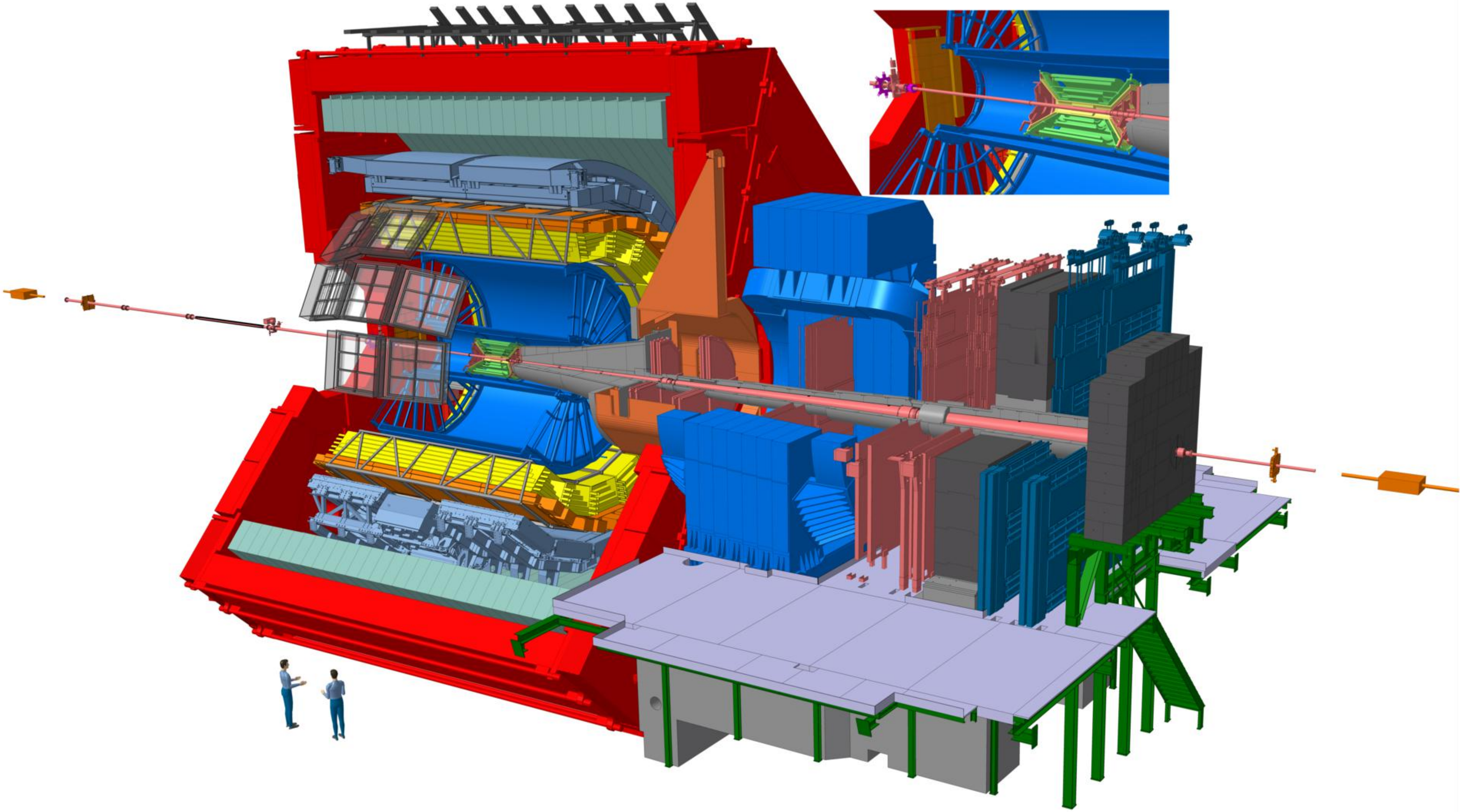
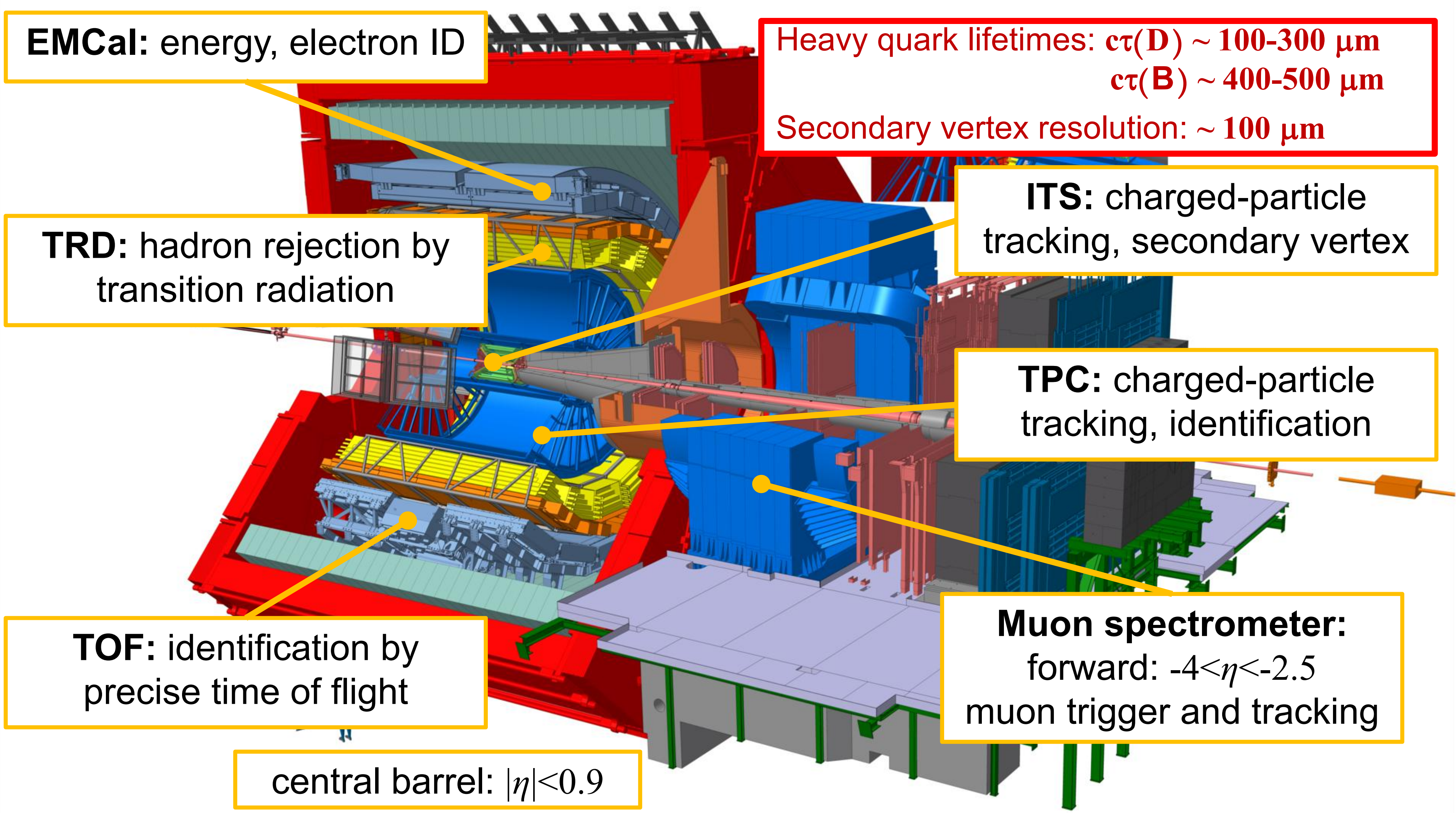
ALICE



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

ALICE



EMCal: energy, electron ID

TRD: hadron rejection by transition radiation

TOF: identification by precise time of flight

central barrel: $|\eta|<0.9$

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

Secondary vertex resolution: $\sim 100\ \mu m$

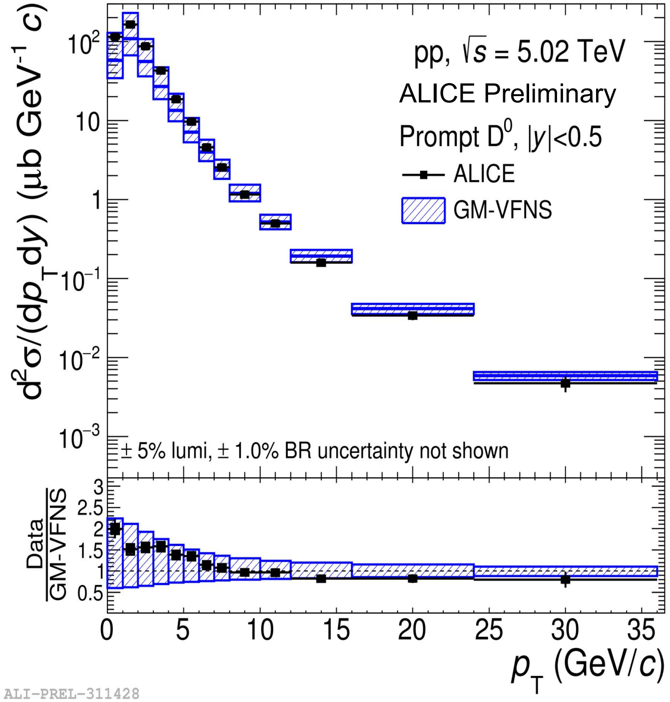
ITS: charged-particle tracking, secondary vertex

TPC: charged-particle tracking, identification

Muon spectrometer:
forward: $-4<\eta<-2.5$
muon trigger and tracking

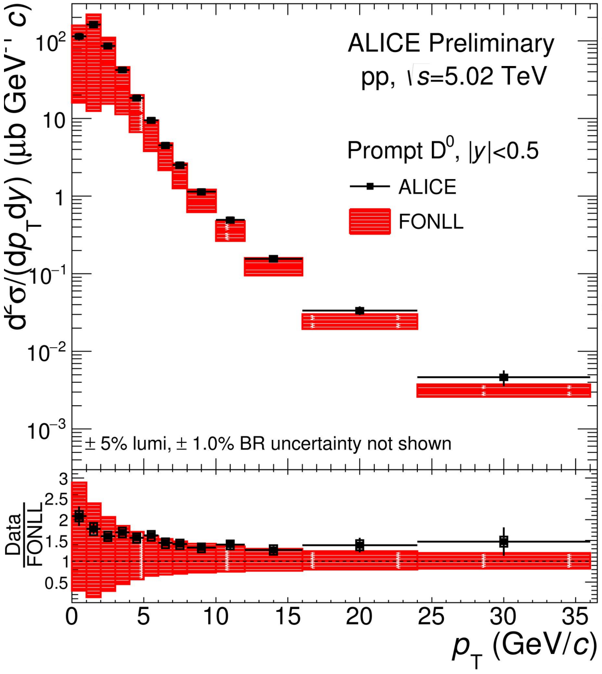
A dedicated heavy-ion experiment at the LHC, excellent PID

Charm mesons in QCD vacuum: D^0



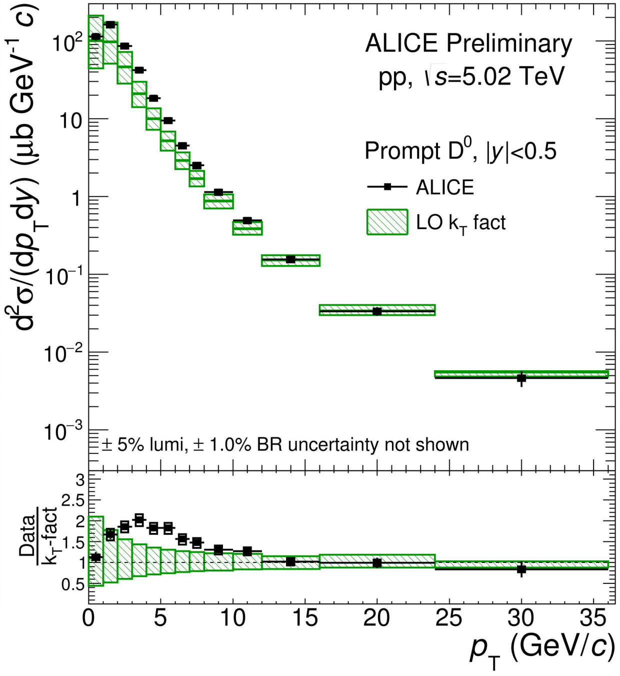
ALI-PREL-311428

GM-VFNS: EPJ C72 (2012) 2082



-PREL-151360

FONLL: JHEP 1210 (2012) 137



LI-PREL-311432

LO k_T-fact.: PRD 87 (2013) 094022

Recent high-precision measurements in pp at √s=5.02 TeV:

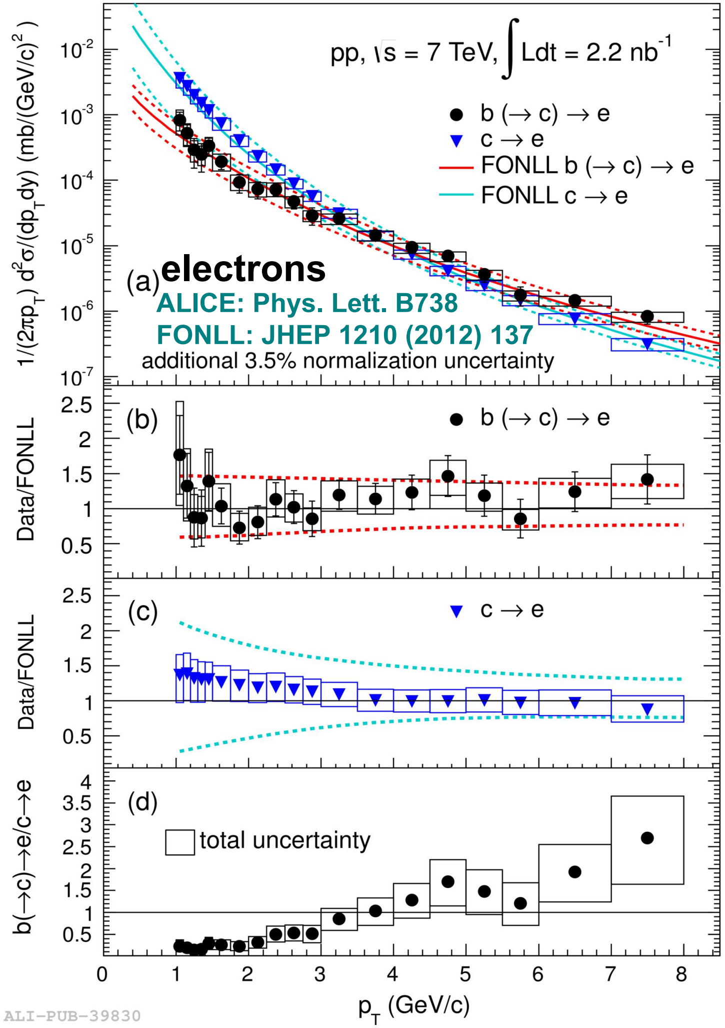
Reference for heavier systems (p-Pb and Pb-Pb)

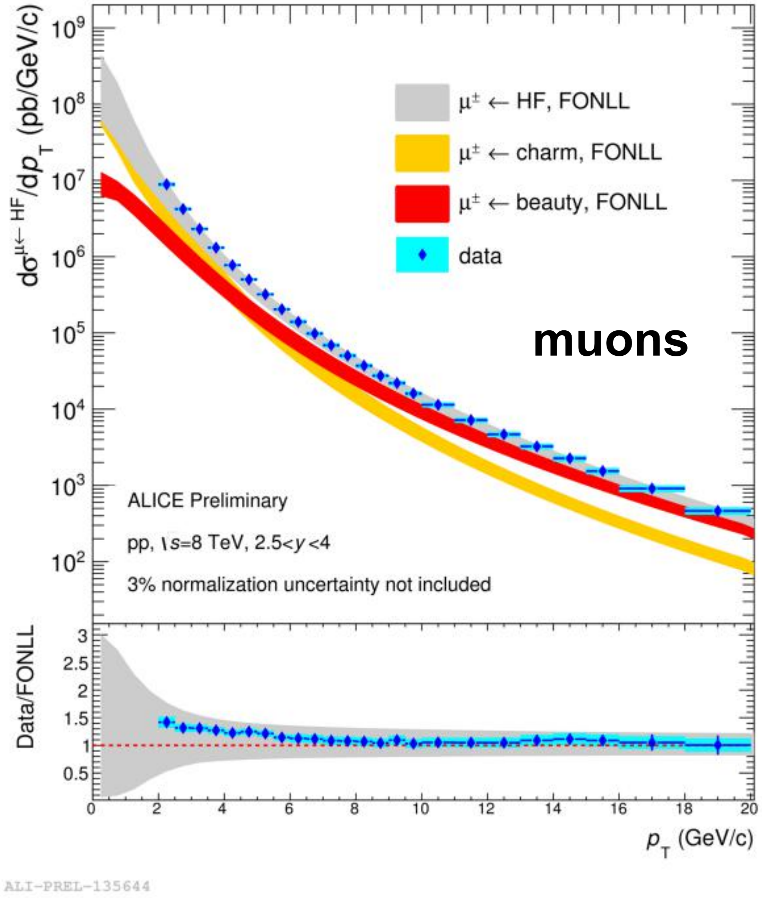
- D^0 at very low p_T (<1 GeV/c): PID only,
  no vertex reconstruction or topological cuts

Detailed test of pQCD model predictions

- Provide strong constraints for models

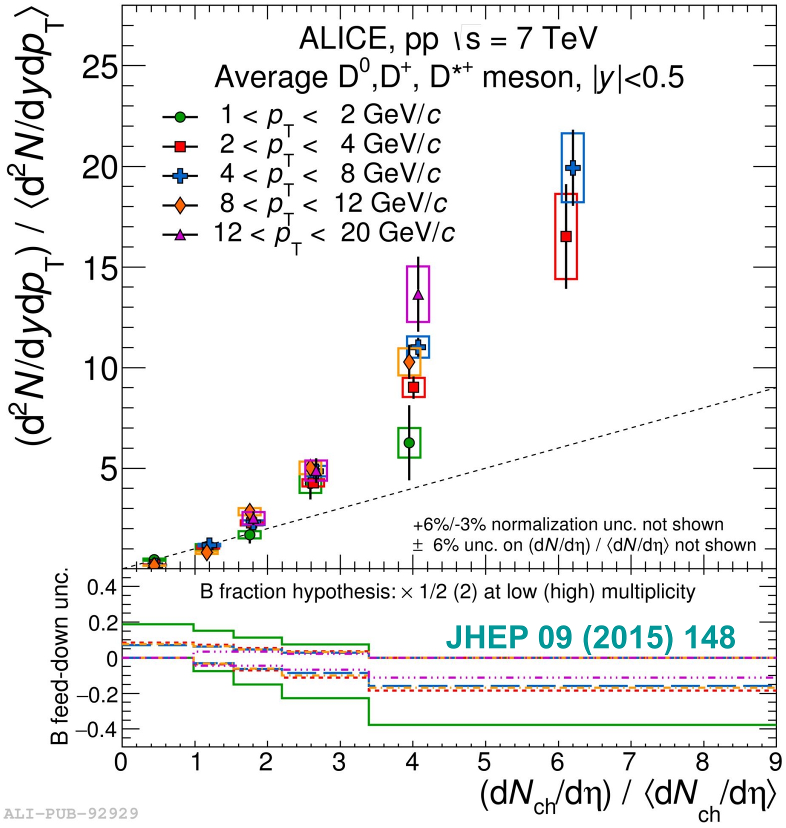
HF electrons and muons



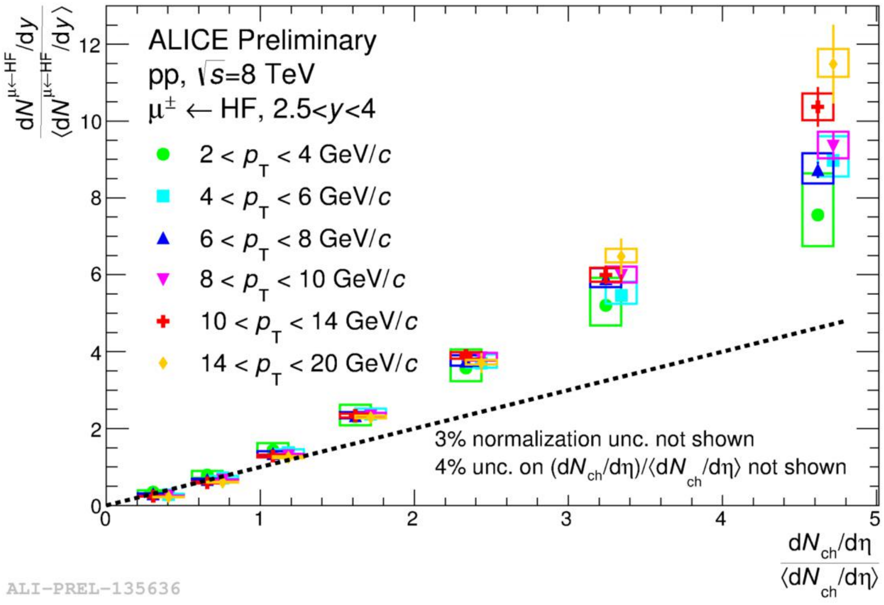


- FONLL pQCD describes both **beauty** and **charm** electrons
- Agreement for **electrons** at mid-rapidity and **muons** at 2.5<y<4

D-meson yields vs. multiplicity (pp)

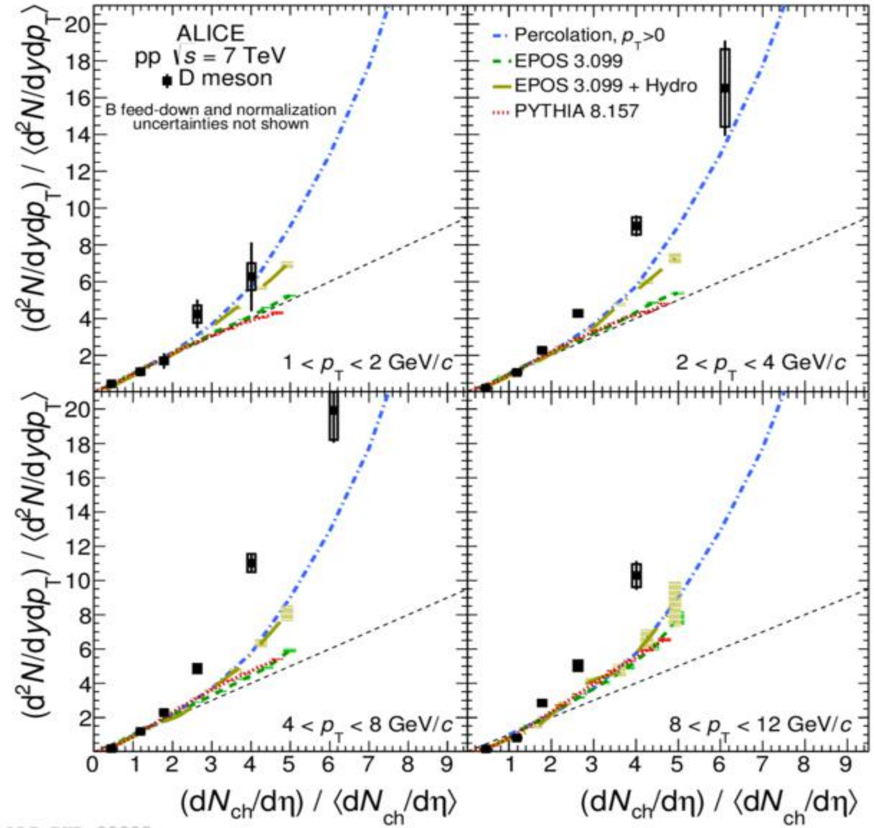


JHEP 09 (2015) 148



- Production vs. multiplicity of **D mesons** and **muons** steeper than linear

Yields vs. multiplicity: models (pp)

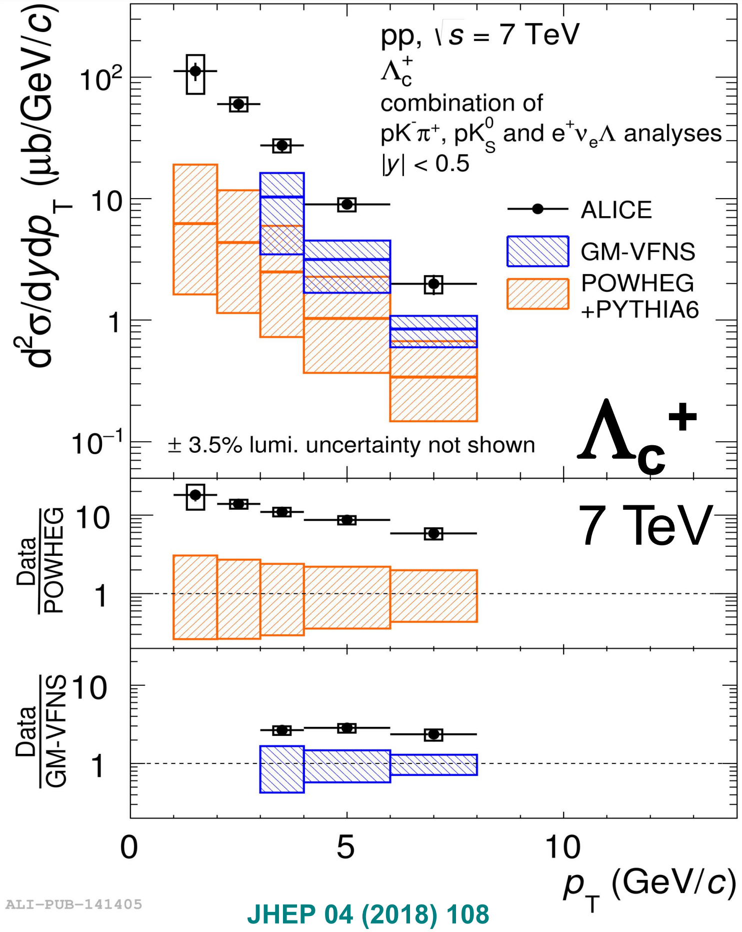


JHEP 09 (2015) 148

- **Percolation model** - **PRC 86 (2012) 034903**
  - Target-projectile color exchange (scenario similar to MPI)
  - Steeper-than-linear increase
- **EPOS 3.099+Hydro** - **PRC 89 (2014) 064903**
  - Gribov-Regge formalism
  - MPI linked to multiplicity
  - Steeper-than-linear increase with hydro
- **PYTHIA8** - **Comp.Phys.Commun. 178 (2008) 852**
  - SoftQCD with color reconnections
  - MPI
  - initial and final state gluon radiation
  - linear increase

- Production of D mesons increases steeper than linear with multiplicity
- **Some models with multiple parton interactions (MPI) also expect stronger-than-linear increase**

Charmed baryon production: Λ_c^+, Ξ_c

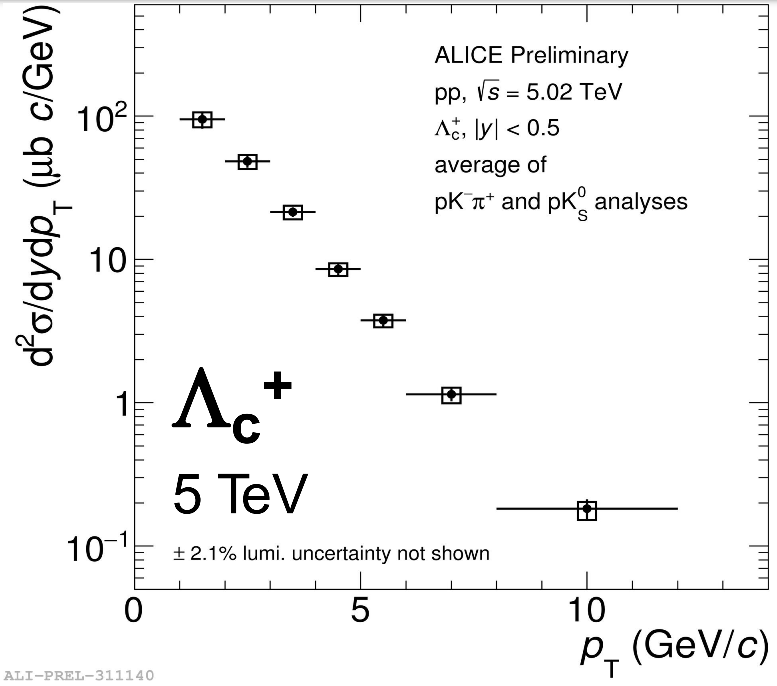


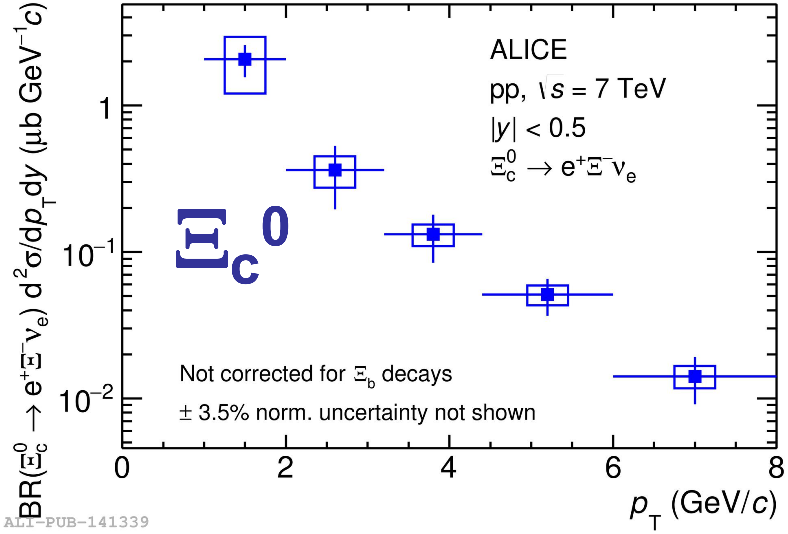
GM-VFNS: EPJ C41 (2005) 199, EPJ C72 (2012) 2082

POWHEG: JHEP 06 (2010) 043

PYTHIA8: JHEP 05 (2006) 026

JHEP 04 (2018) 108

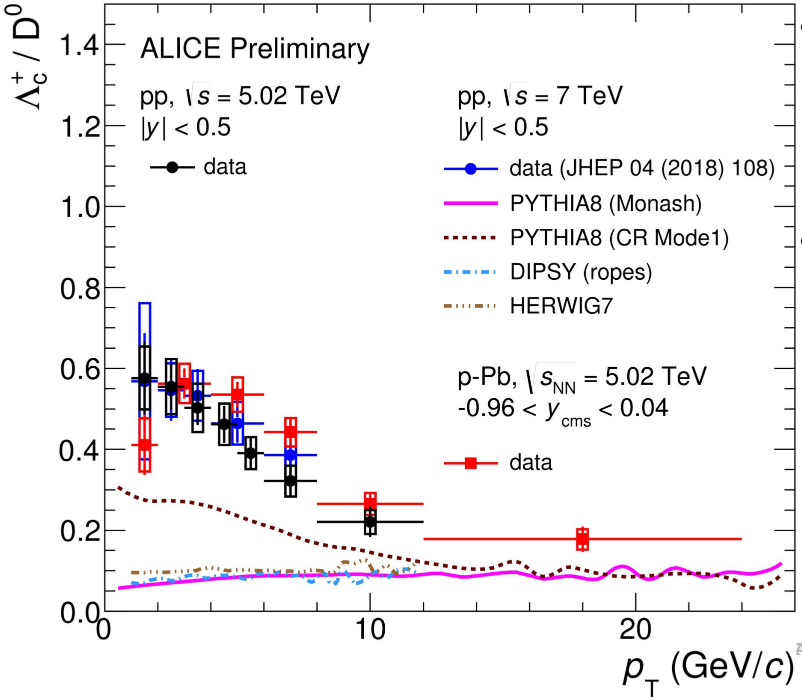




- First Ξ_c measurement at the LHC
- Recent high-precision Λ_c^+ measurement
  - Production of Λ_c^+ underestimated by theory

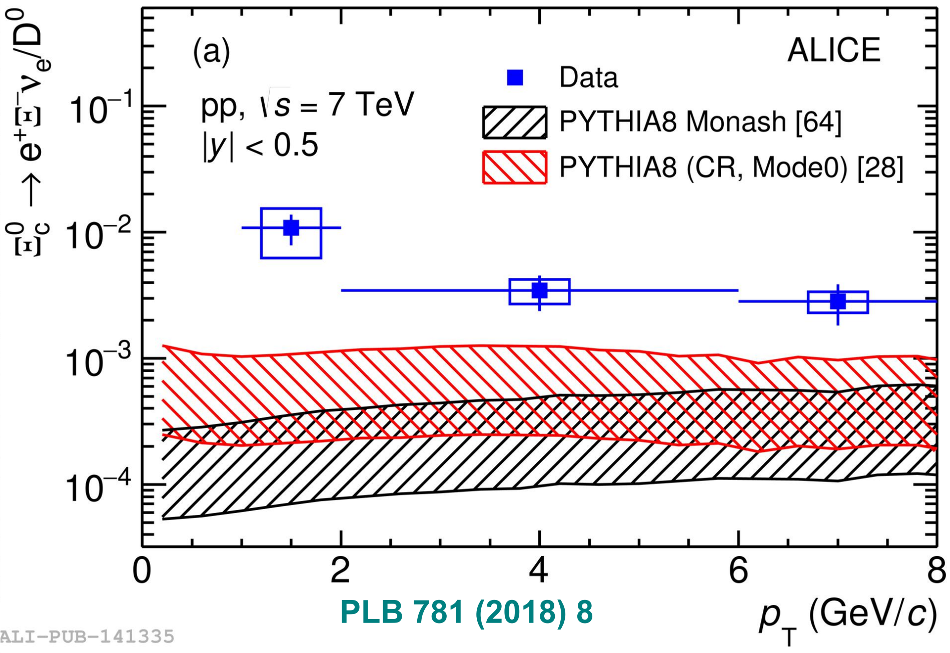
Baryon-to-meson ratio: Λ_c^+/D^0, Ξ_c^0/D^0

Λ_c^0/D



ALI-PREL-311152

Ξ_c^0/D



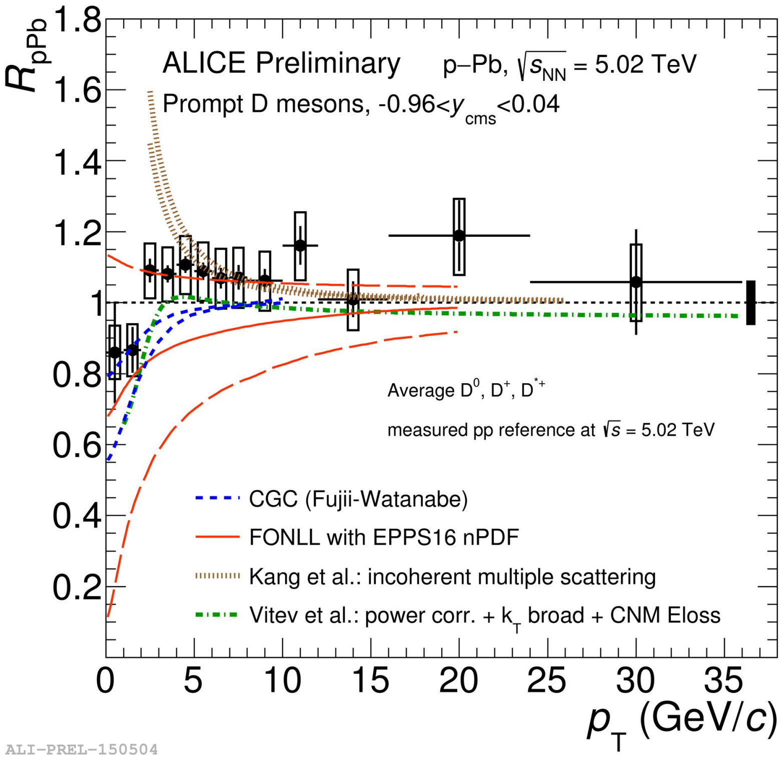
ALI-PUB-141335

PLB 781 (2018) 8

PYTHIA8: JHEP 05 (2006) 026
DIPSY: JHEP 1503 (2015) 148
HERWIG7: EPJ C76 (2016) no.4 196

- Ξ_c^0/D^0 as well as Λ_c^+/D^0 is underestimated by models
  - Similarly to Λ_c^+ cross section
  - Several model classes ==> lack of basic understanding
- Detailed measurement of charm barions provide valuable input for theoretical understanding of HF fragmentation

CNM effects in p-Pb collisions?

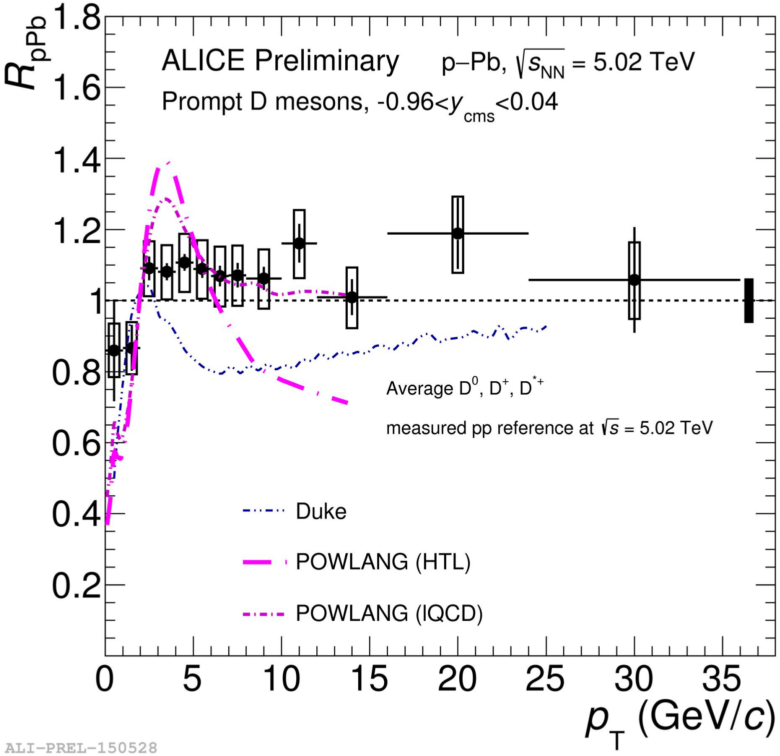


New reference:
√s=5.02 TeV pp data
-> smaller systematics

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**
  - **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?



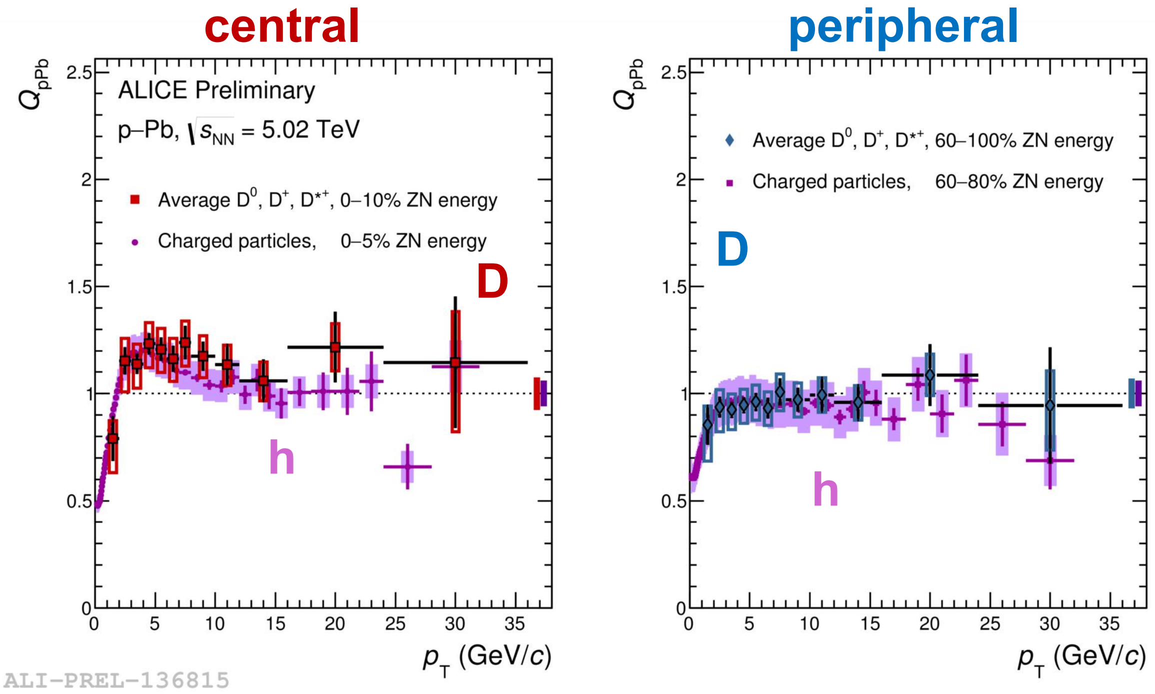
ALI-PREL-150528

New reference:
√s=5.02 TeV pp data
-> smaller systematics

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

- **D-meson production in p-Pb collisions**
  - **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



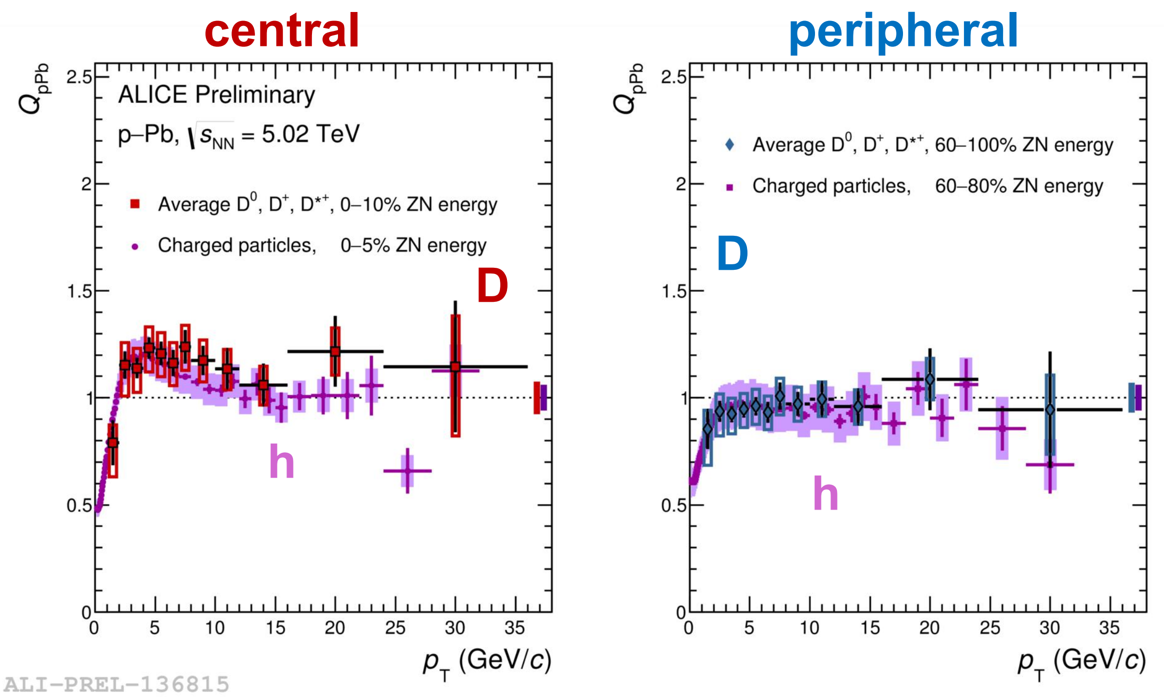
Centrality-dependent nuclear modification factor

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

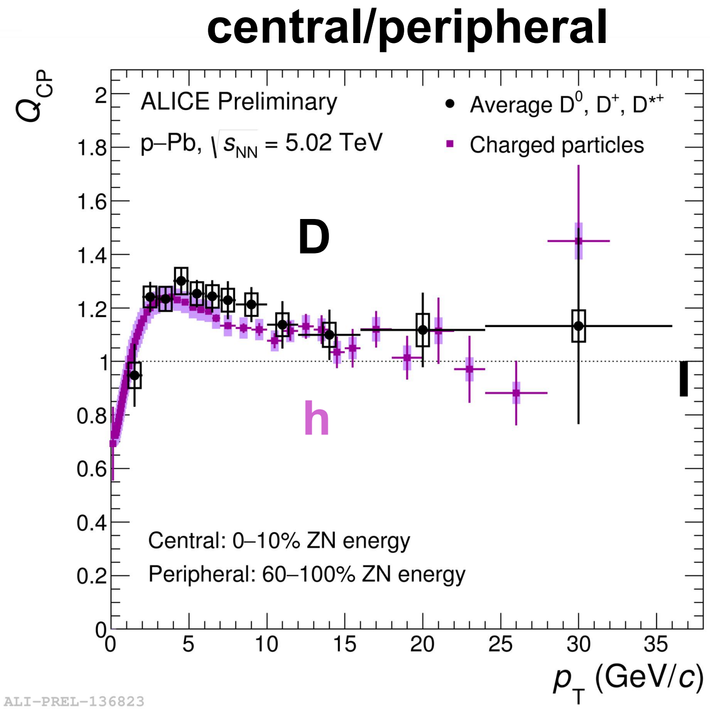
- $<T_{pPb}>$: nuclear overlap from the Glauber model in a given centrality class
- Multiplicity estimation using the Zero-degree neutron detectors

- 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



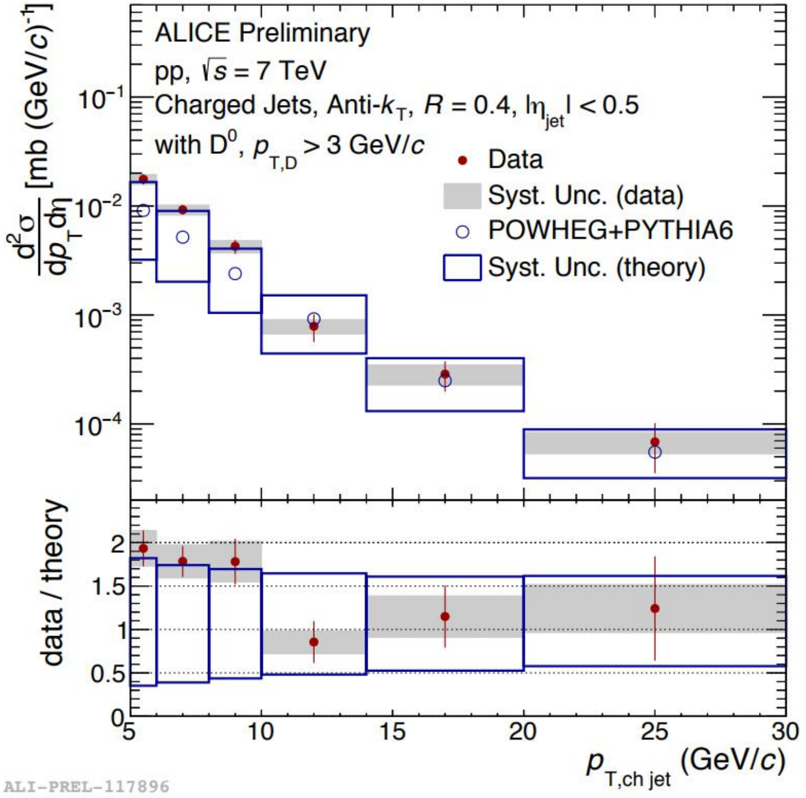
ALI-PREL-136815

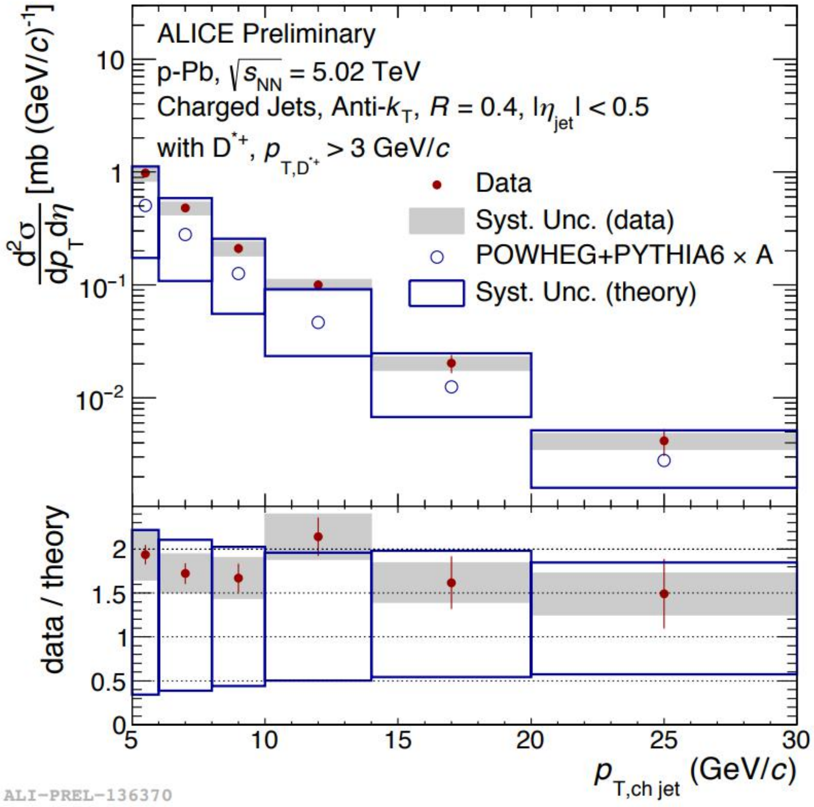


ALI-PREL-136823

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

Charm jets in pp and p-Pb collisions



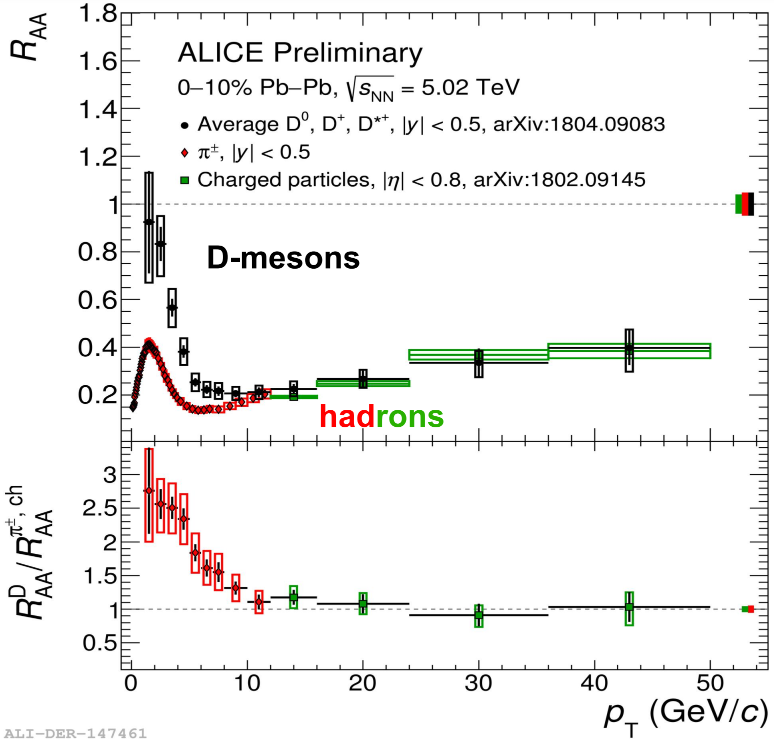


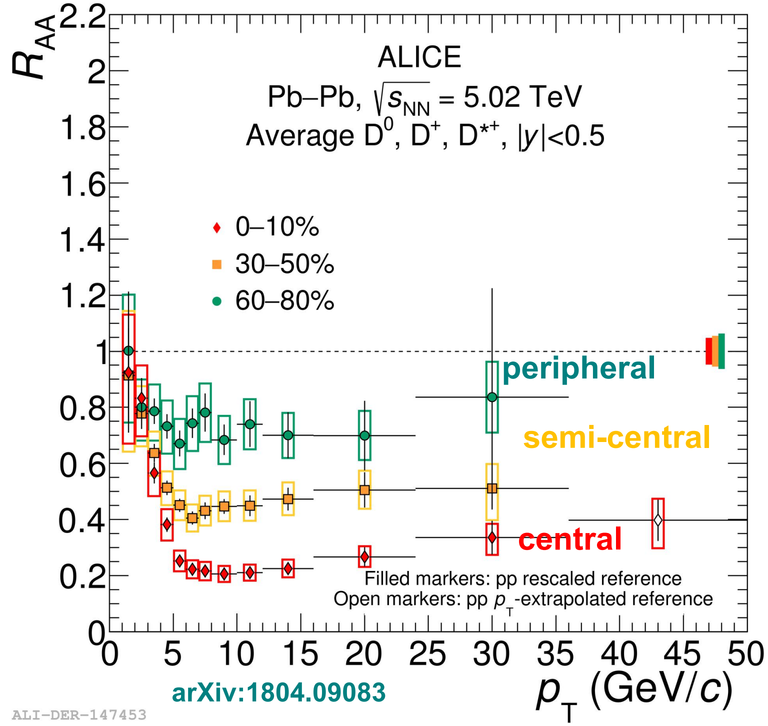
- New D-jet measurements down to p_T^{jet} = 5 GeV/c
- POWHEG+PYTHIA6 (Perugia11) describes data within uncertainties
- Data provides strong constraints on theory!

==> **Unique oportunity to study charm jet properties**

Baseline for future Pb-Pb measurement (jet modification)

Pb-Pb: Suppression of D mesons

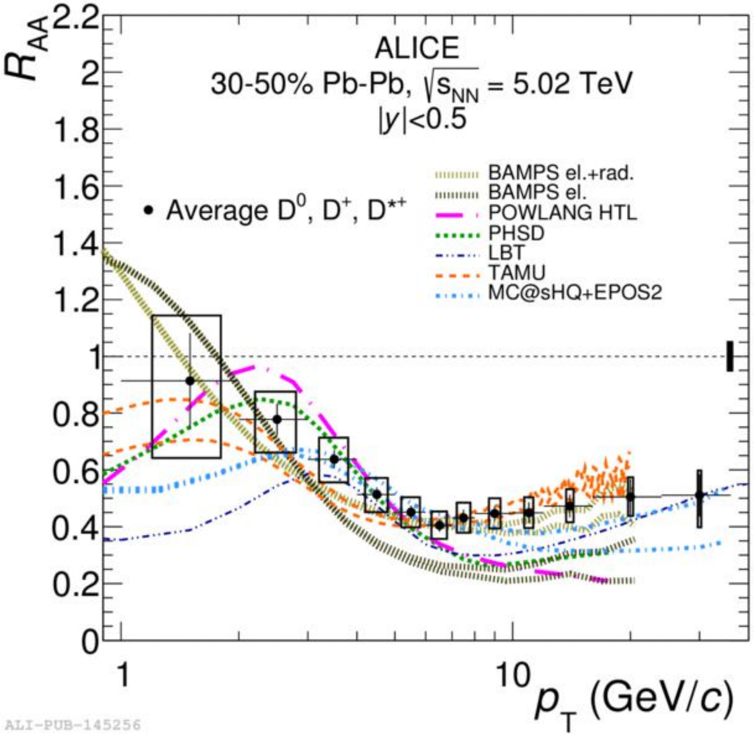




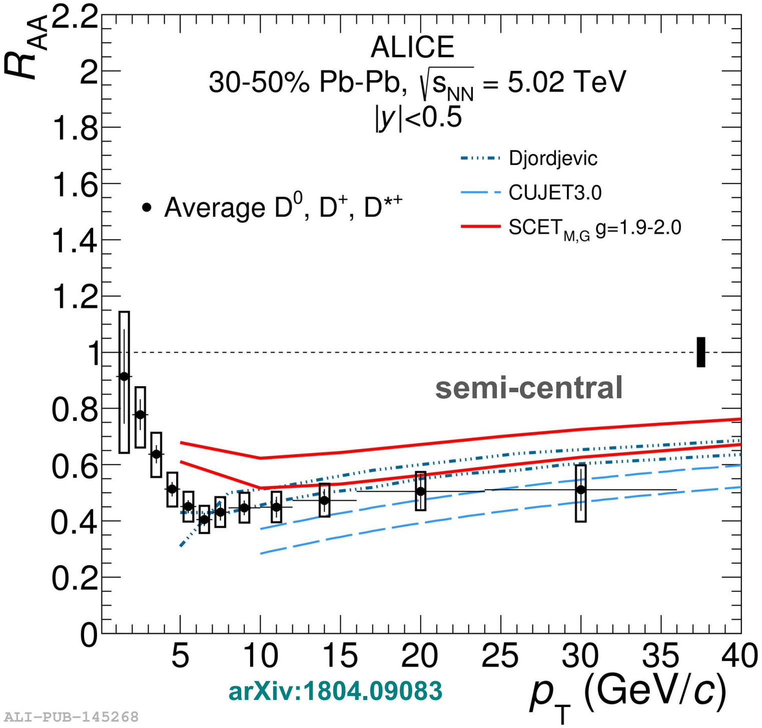
- ***High-p_T***: Suppression pattern similar to light flavour
  - **Mass ordering?** Expected $\Delta E_q > \Delta E_c$ but observed $R_{AA}^h \approx R_{AA}^D$

- ***Low-p_T***: Charm suppression is significantly weaker than light flavor
  - **Coalescence of light and charm quarks?**

Pb-Pb: Suppression of D mesons



5.02 TeV



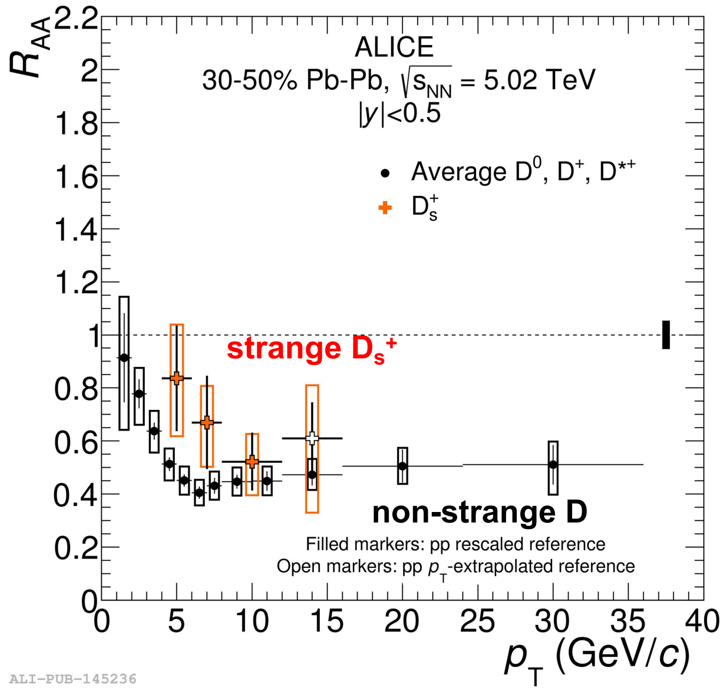
arXiv:1804.09083

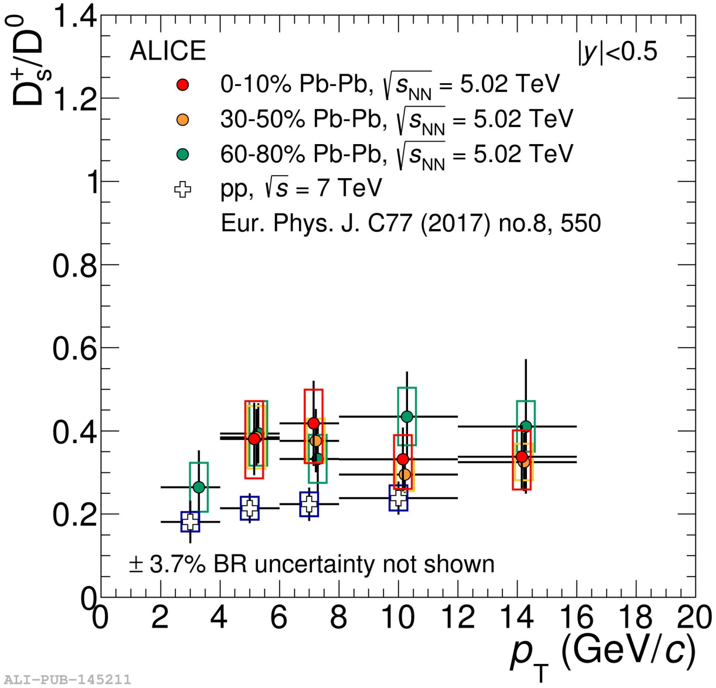
Models: Djordjevic, PLB 737 (2014) 298
WHDG, NPA 784 (2007) 426
Vitev, PRC 80 (2009) 054902
SCET, JHEP 03 (2017) 146
CUJET, Chin.Phys.Lett. 32 (2015) 092501

- ***High-p_T***: Suppression pattern similar to light flavour
  - **Mass ordering?** Expected $\Delta E_q > \Delta E_c$ but observed $R_{AA}^h \approx R_{AA}^D$
  - Still: several pQCD-based models with different components reproduce it
- ***Low-p_T***: Charm suppression is significantly weaker than light flavor
  - **Coalescence of light and charm quarks?**
  - Several transport models give good description, low discrimination power

Coalescence of strange and charm

arXiv:1804.09083

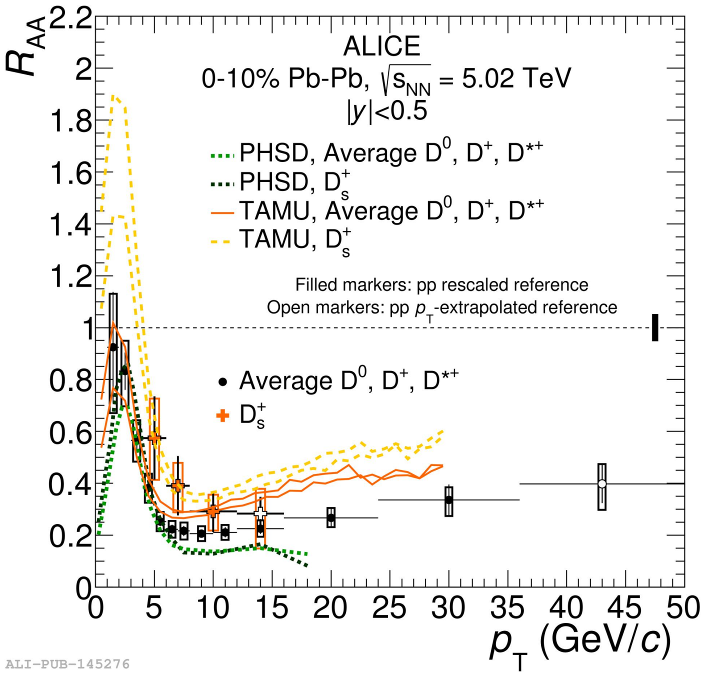


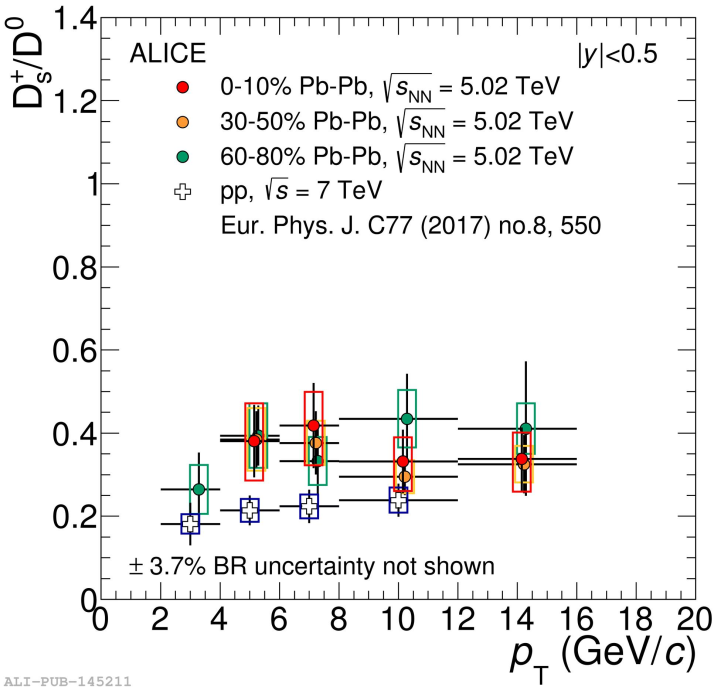


- Strangeness enhancement expected to show up in coalescence
- Hint of a weaker D_S suppression than for non-strange D mesons
    - No evidence of centrality-dependence

Coalescence of strange and charm

arXiv:1804.09083

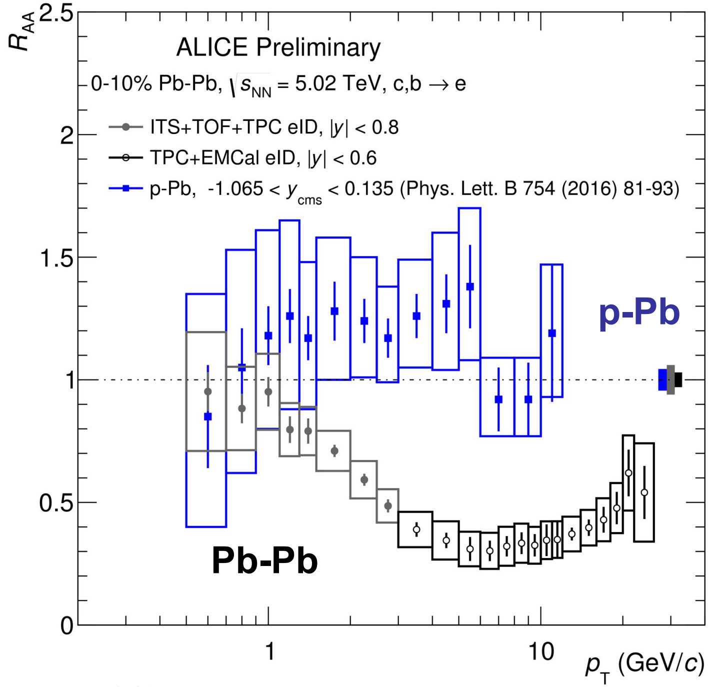




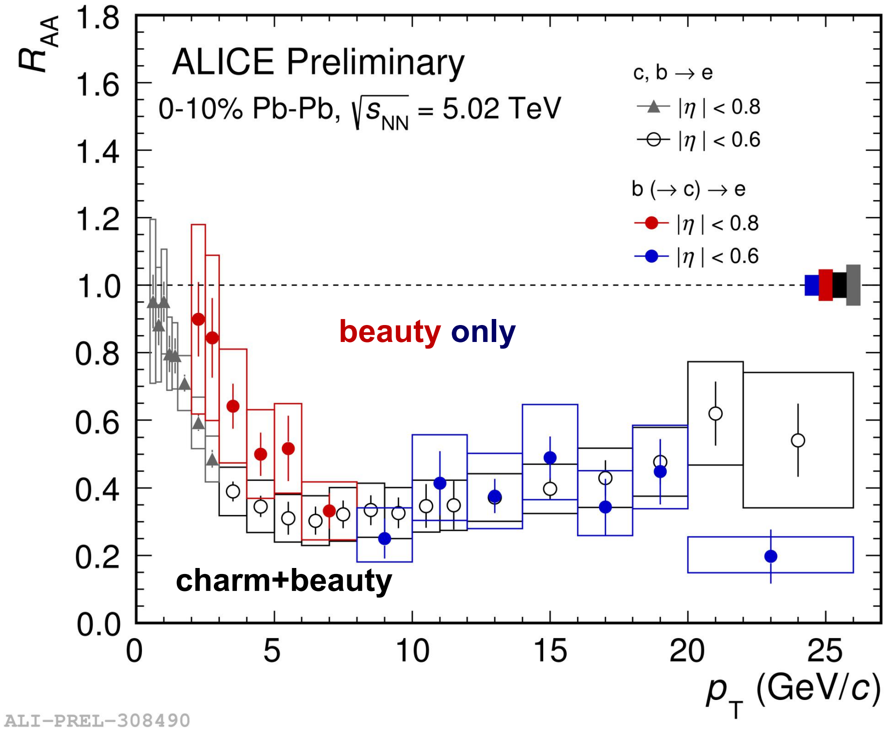
Models
TAMU, PLB 735 (2014) 445
PHSD, PRC 93 no. 3, (2016) 034906

- Strangeness enhancement expected to show up in coalescence
- Hint of a weaker D_S suppression than for non-strange D mesons
  - No evidence of centrality-dependence
- Consistent with a strangeness-enhancement scenario with coalescence

Charm and Beauty - HF electrons



ALI-PREL-149521



ALI-PREL-308490

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

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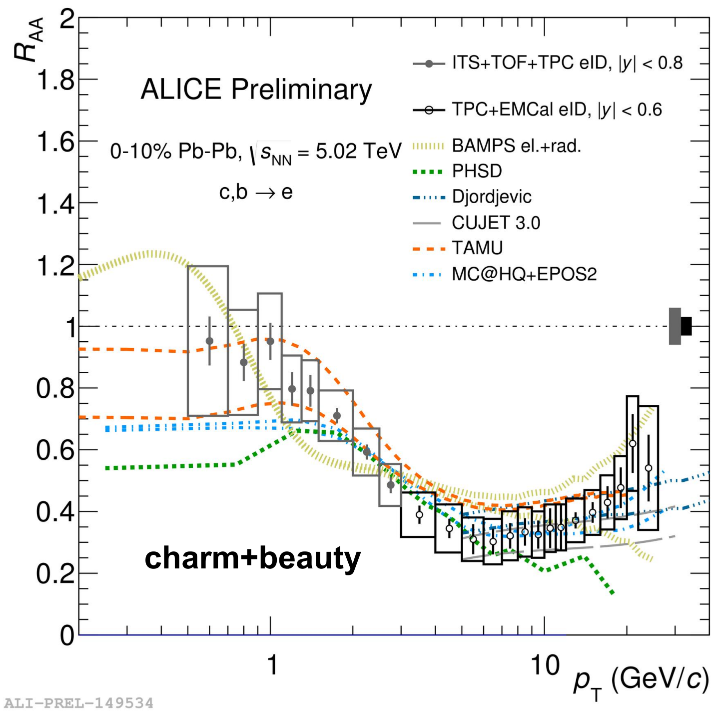
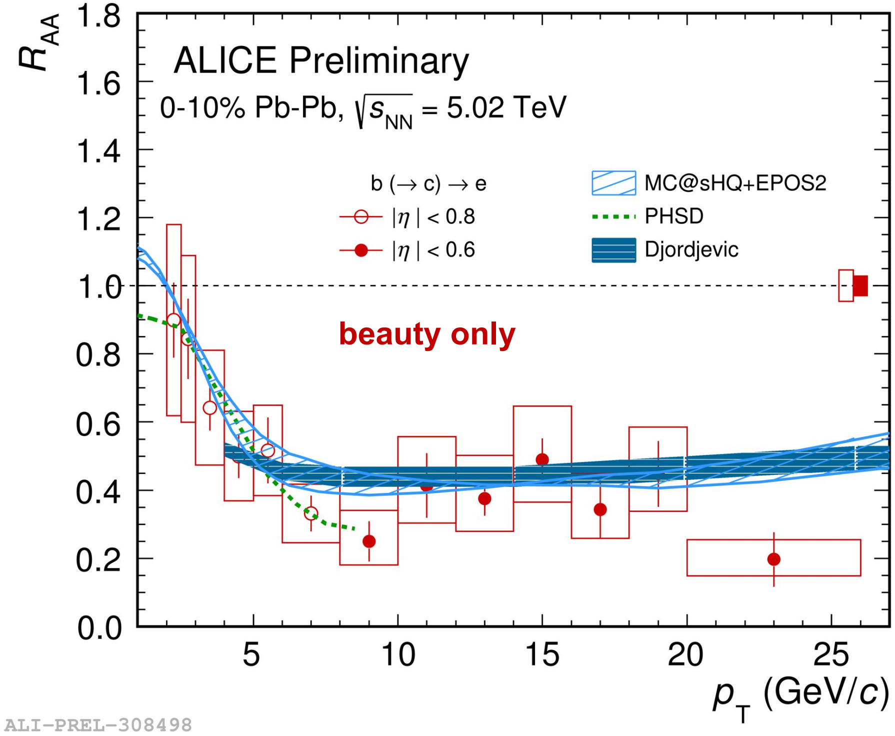
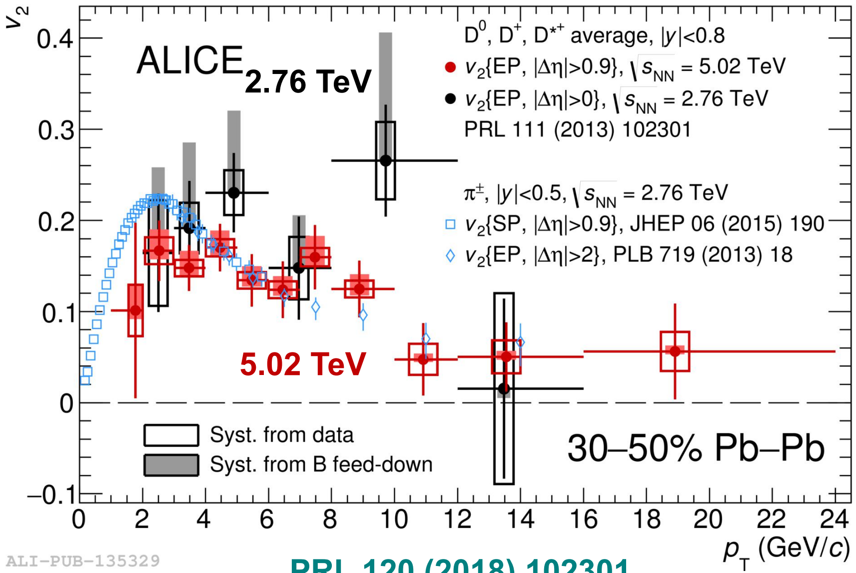




- Significant (c,b)→e suppression in Pb-Pb collisions from medium to high p_T
    - Note: Results in p-Pb collisions are consistent with unity
- Separated beauty-decay electrons hint a weaker b-quark suppression
- Models describe both (c,b)→e and b(→c)→e within uncertainties
    - Difference understood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

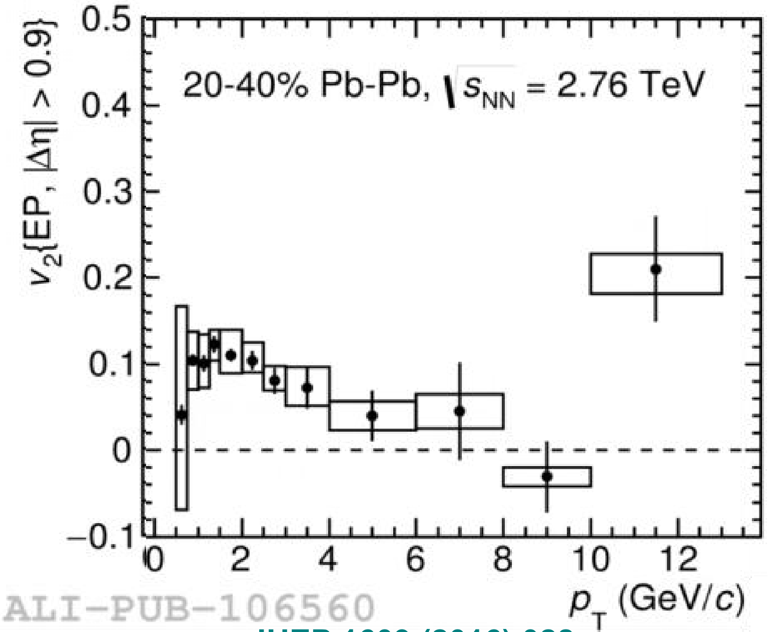
Azimuthal anisotropy

D mesons



PRL 120 (2018) 102301

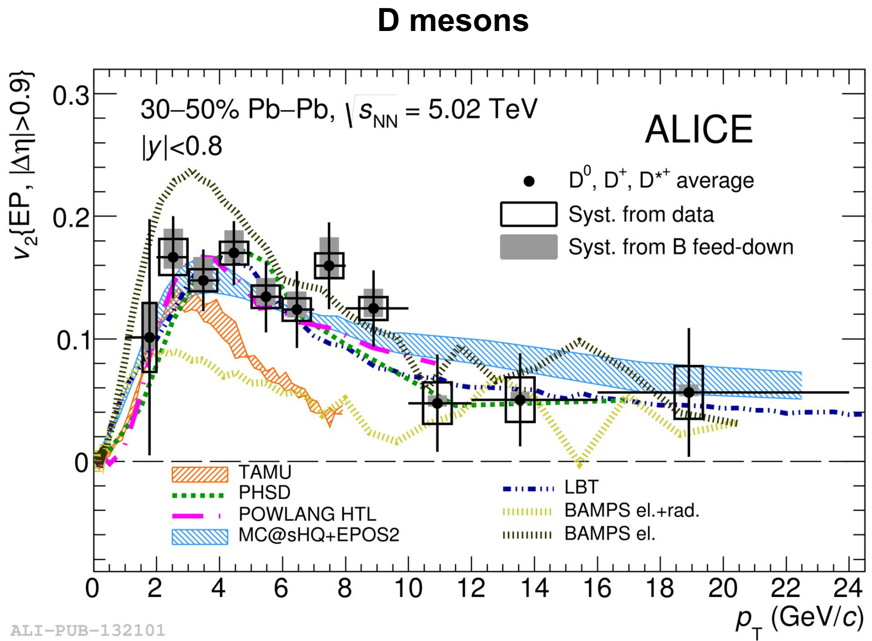
Heavy flavour decay electrons (HFE)



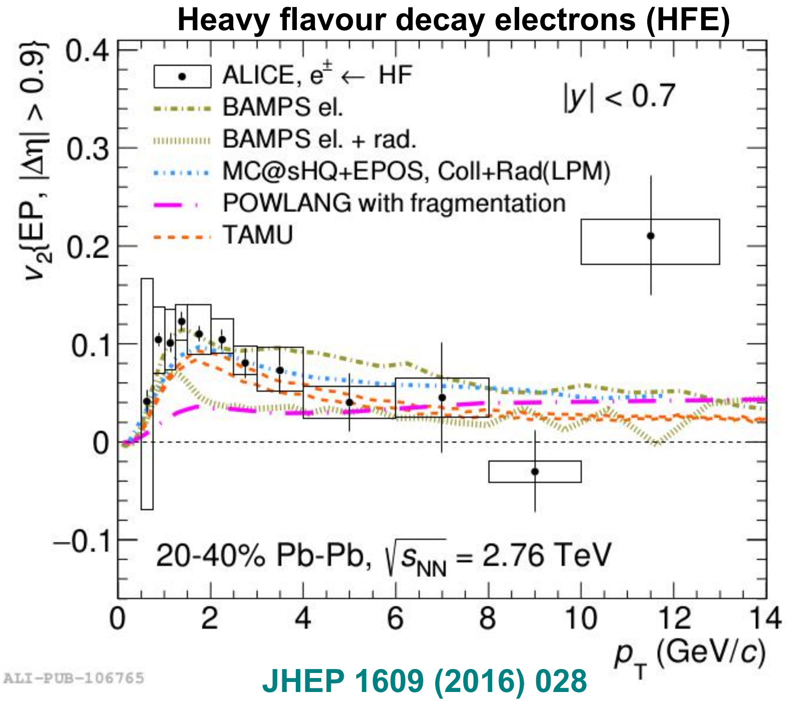
JHEP 1609 (2016) 028

- 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: models


D mesons

PRL 120 (2018) 102301


Heavy flavour decay electrons (HFE)

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
PSHD, PRC 93 (2016) 034906
LBT, arXiv:1703.00822

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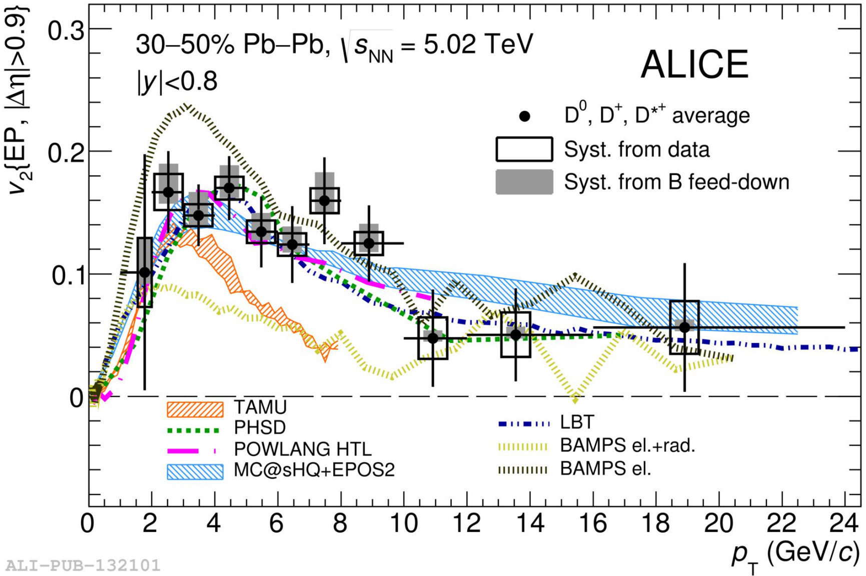
- Several models describe azimuthal anisothropy

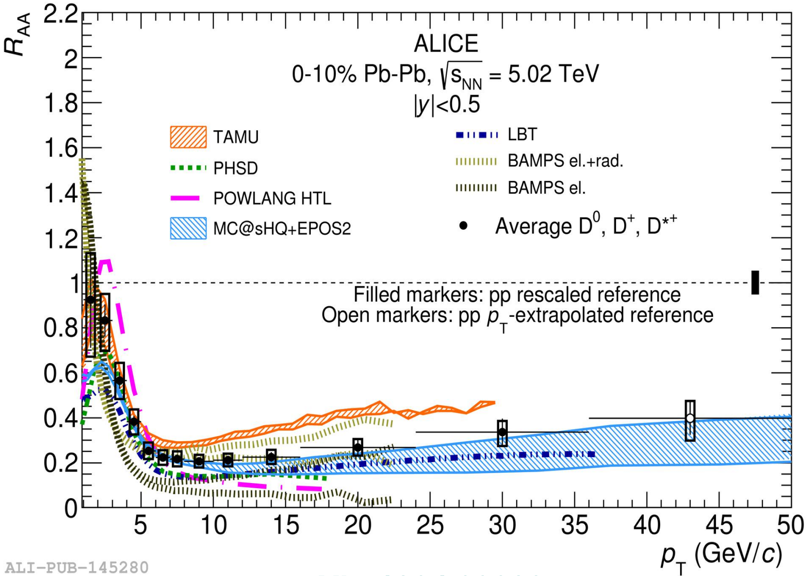
Azimuthal anisotropy vs. R_{AA}

D-meson v_2



PRL 120 (2018) 102301

D-meson R_{AA}



arXiv:1804.09083

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- Models in which charm picks up flow via recombination or collisional energy loss do better in reproducing R_{AA} and v_2 simultaneously

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

Summary

QCD vacuum: pp collisions at √*s*=7 TeV and √*s*=8 TeV

- *D-mesons, HF leptons (also full D-jets):*
  - Spectra adequately described by pQCD models
  - Steeper-than-linear increase of production with multiplicity: *MPI*
- *Charmed baryons:* models unable to describe measurements
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  - High-p_T suppression does not show ordering: $R_{AA}^{\pi} \approx R_{AA}^{D}$
  - Ordering at lower p_T-ranges : $R_{AA}^{b\to e} > R_{AA}^{b,c\to e}$
- ***Collectivity and coalescence:***
  - R_{AA} at low p_T hints coalescence with the flowing medium
  - Significant azimuthal anisothropy → *v_2 & R_{AA} constrain models*

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Run-3 upgrade: ~100x stats; precision beauty measurements

Thank you!

and enjoy Budapest

Outlook

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

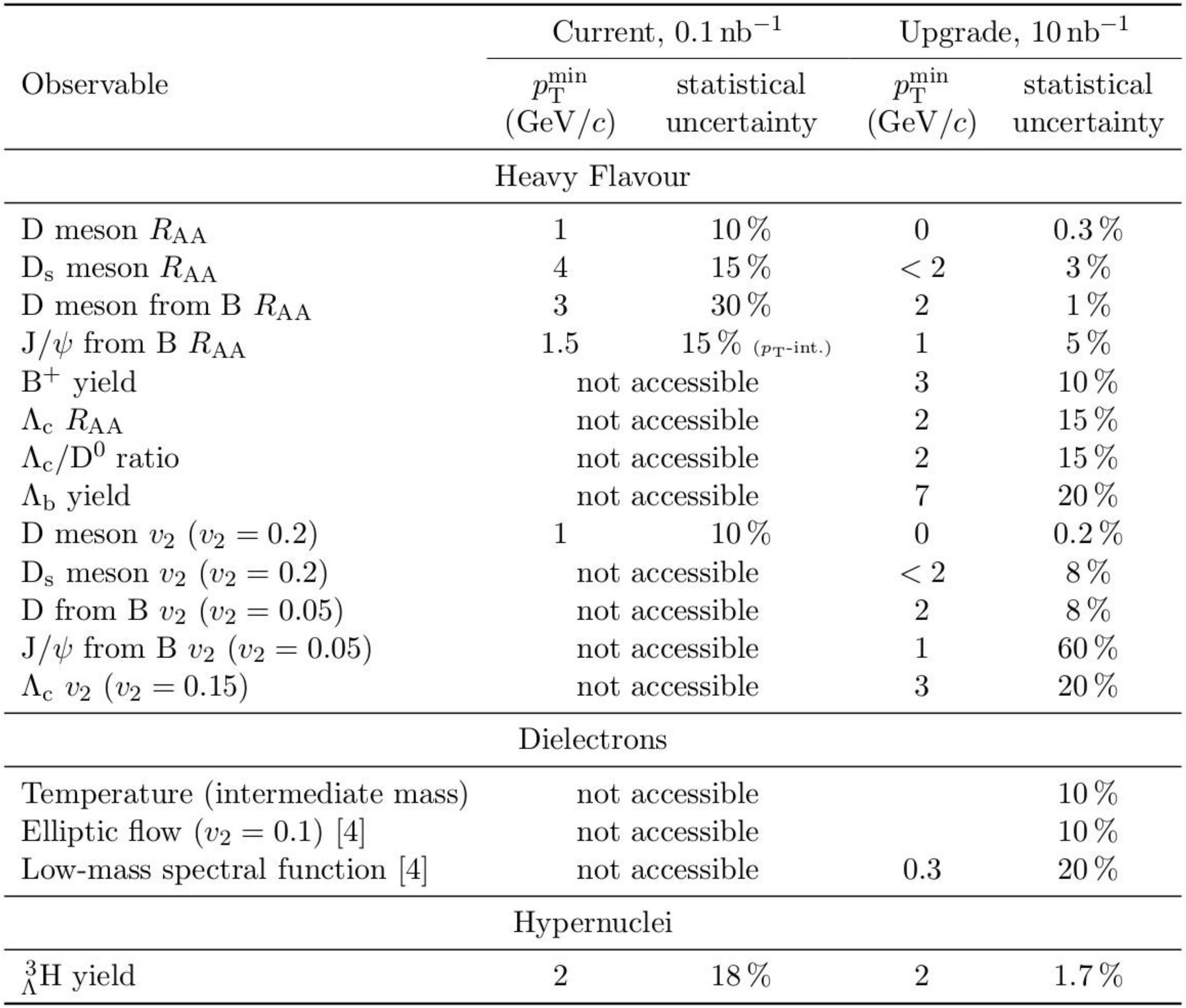
- **More and more final results already out**
- p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV and $\sqrt{s_{NN}}$=8.16 TeV
- Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

- 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: insight to HF fragmentation
  - Understanding colour charge / mass effects

Future upgrades: precision beauty measurements

- Detector upgrades: ITS, TPC, MFT, readout, O^2
- Goal: ~100x statistics gain w.r.t. Run-I + Run-II

Physics reach after LS2 (2019-20)



Observable	Current, $0.1\,\mathrm{nb}^{-1}$ $p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	Current, $0.1\,\mathrm{nb}^{-1}$ statistical uncertainty	Upgrade, $10\,\mathrm{nb}^{-1}$ $p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	Upgrade, $10\,\mathrm{nb}^{-1}$ statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
$\mathrm{D_s}$ 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 %
$\mathrm{B^+}$ yield	not accessible		3	10 %
Λ_{c} R_{AA}	not accessible		2	15 %
$\Lambda_{\mathrm{c}}/\mathrm{D}^0$ 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 %
$\mathrm{D_s}$ 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				
${}^{3}_{\Lambda}\mathrm{H}$ yield	2	18 %	2	1.7 %

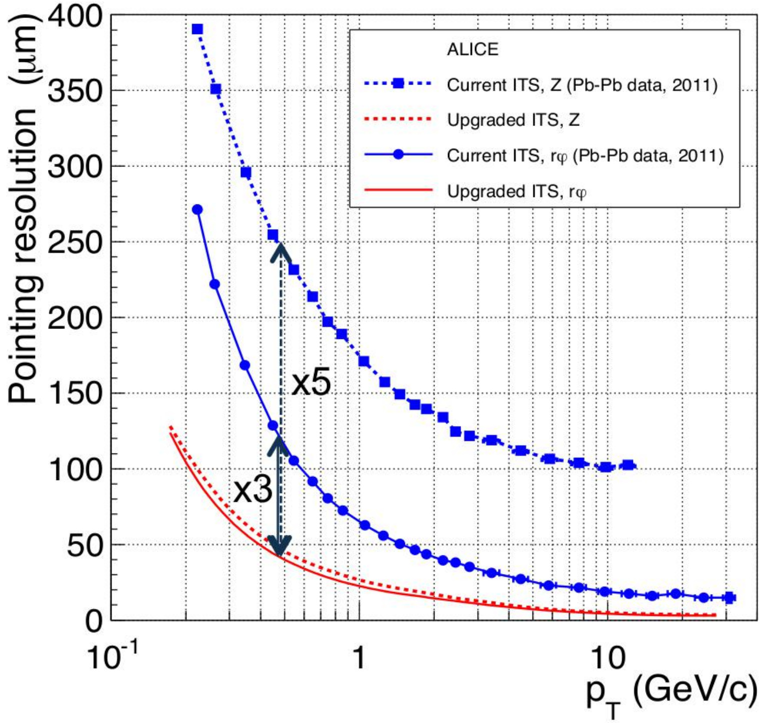
ALICE ITS upgrade TDR

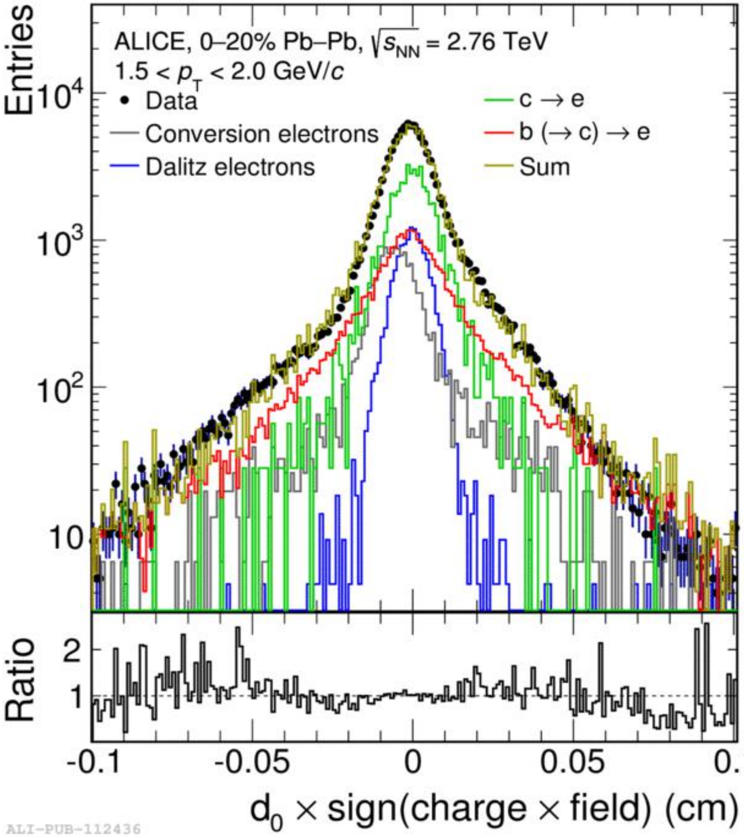
ITS performance

- Semiconducting technology
- Resolves secondary vertex

heavy quark lifetimes: **ct(D) ~ 100-300 mm**
ct(B) ~ 400-500 mm

Secondary vertex resolution: ~ **100 mm**





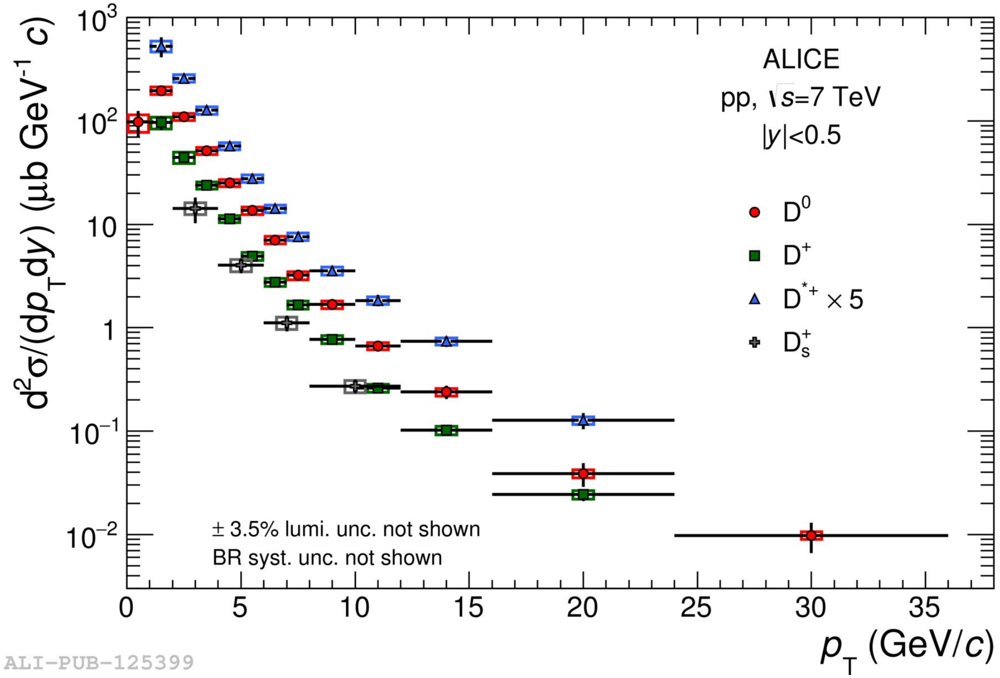
JHEP 07 (2017) 052

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

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

p_T spectrum of D mesons

Eur.Phys.J. C77 (2017) 550

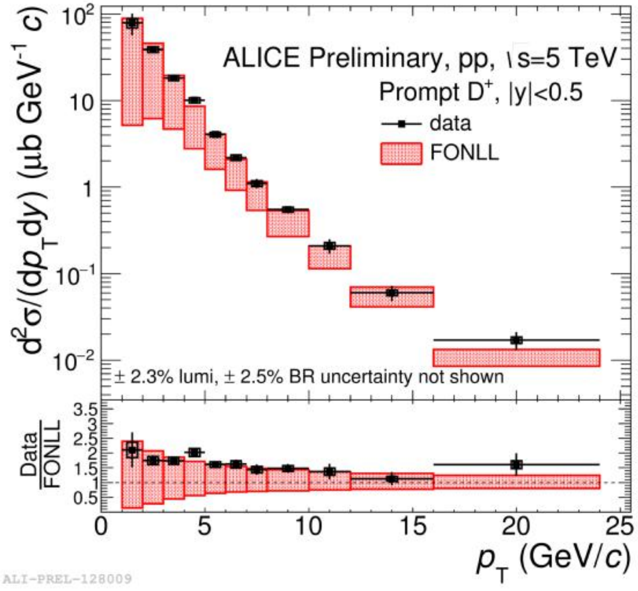


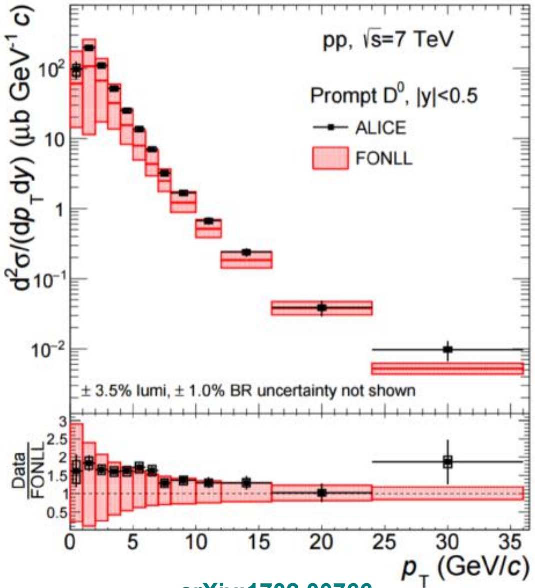
$D^0 \to K^-\pi^+$	BR ~ 3.9%
$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$	BR ~ 2.6%
$D^+ \to K^-\pi^+\pi^+$	BR ~ 9.5%
$D_S^+ \to \Phi(\to K^+K^-)\pi^+$	BR ~ 2.3%

Recent high-precision measurements in pp at √s=7 GeV:
Reference for heavier systems (p-Pb and Pb-Pb)

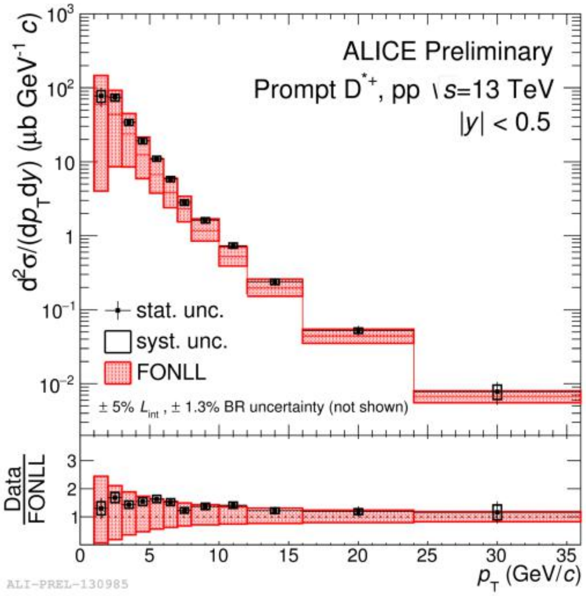
- D^0 at very low p_T (<1 GeV/c): PID only,
  no vertex reconstruction or topological cuts

D mesons at different energies (pp)



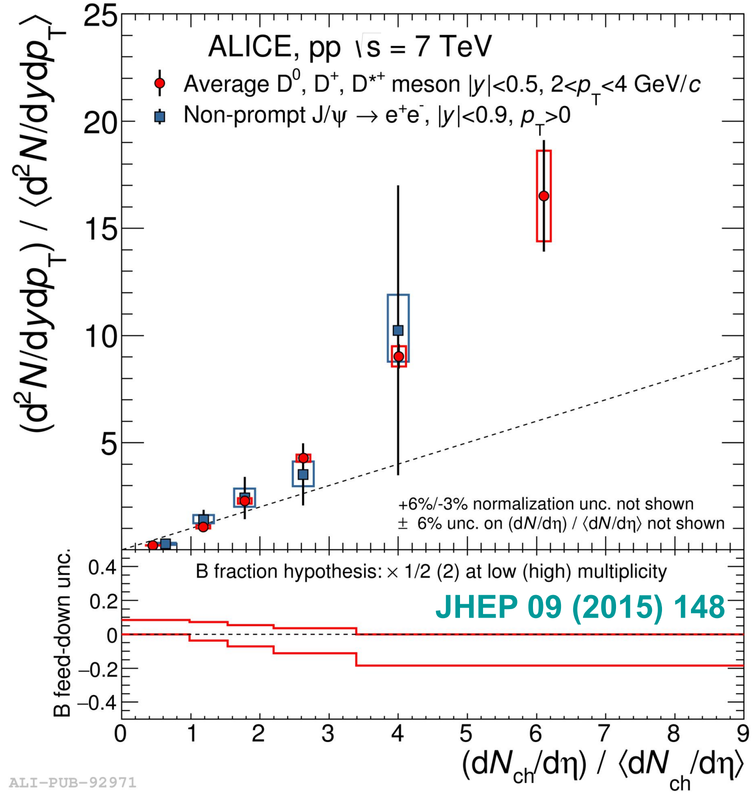


arXiv:1702.00766

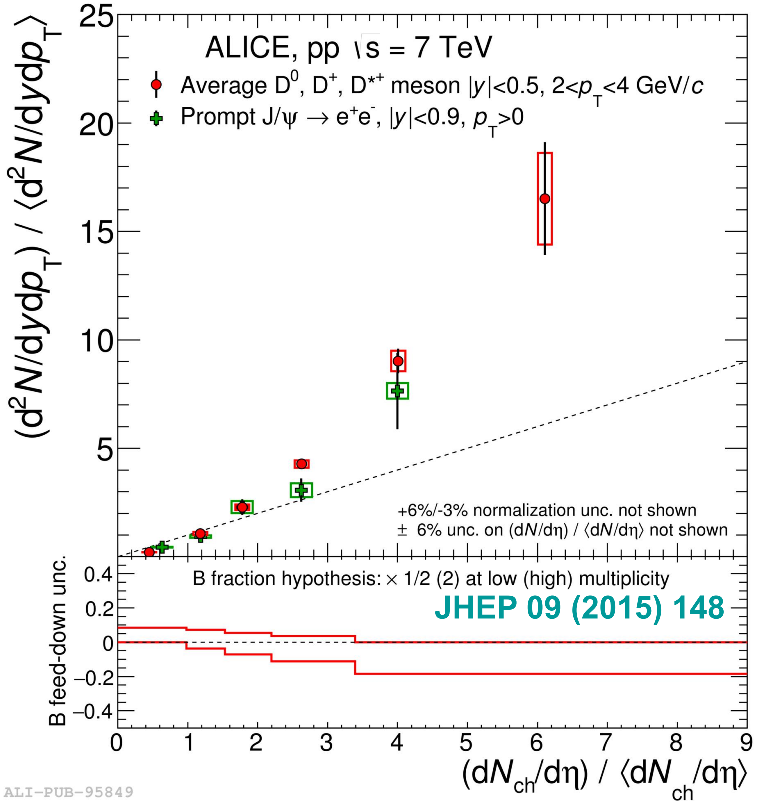


- D-meson production cross section
- Down to p_T =0 for D^0 at 7 TeV
- pQCD calculations describe the data within uncertainties
- data uncertainties much lower than theoretical one

D-meson yields vs. multiplicity (pp)



ALI-PUB-92971



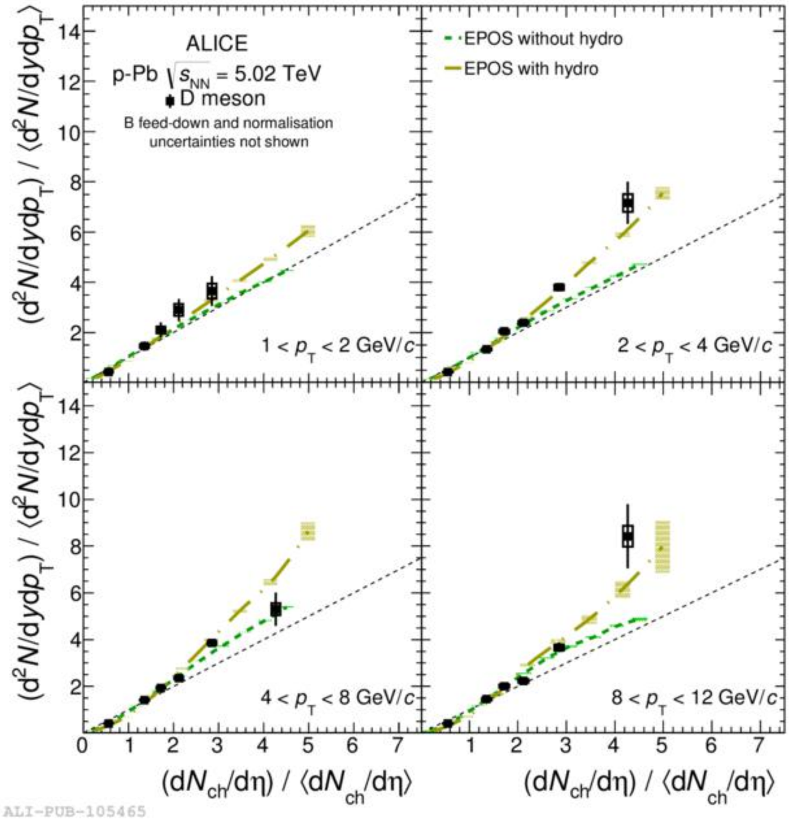
ALI-PUB-95849

- Production vs. multiplicity of **D mesons** and muons steeper than linear
- Same trend for **non-prompt (B→)J/Ψ** as well as **prompt J/Ψ** yields

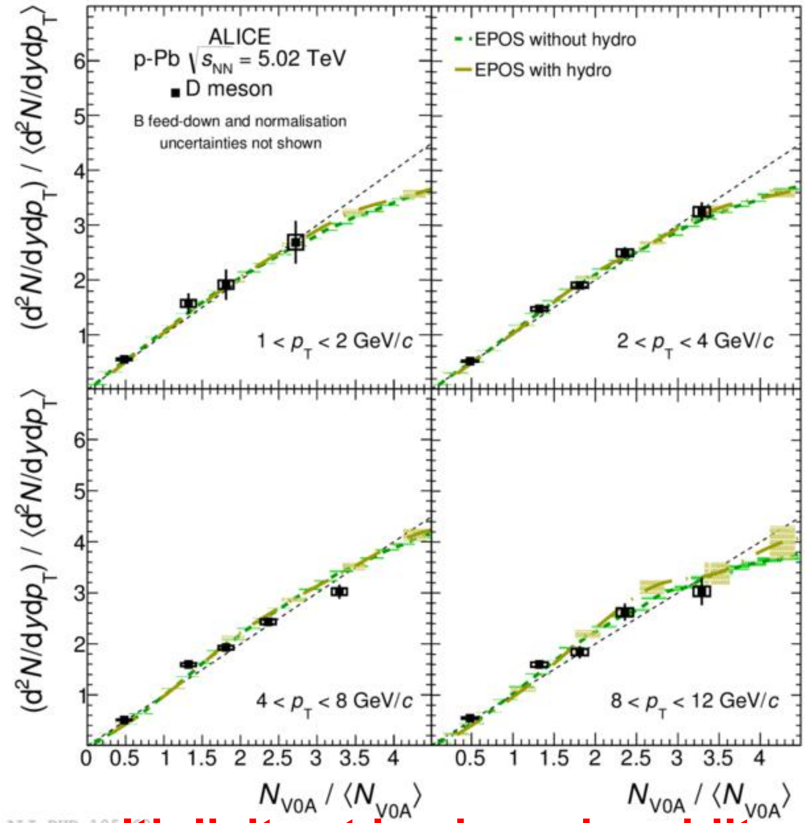
→ No strong flavour dependence

→ Enhancement is likely to be related to $c\bar{c}$, $b\bar{b}$ production processes, is not strongly influenced by hadronisation

Yields vs. multiplicity in p-Pb: models



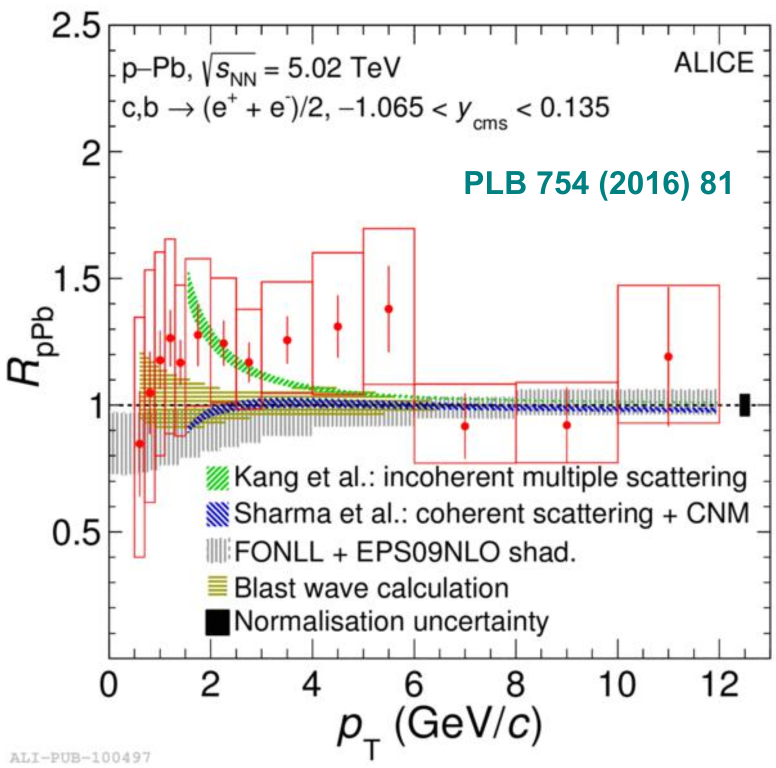
multiplicity at mid-rapidity



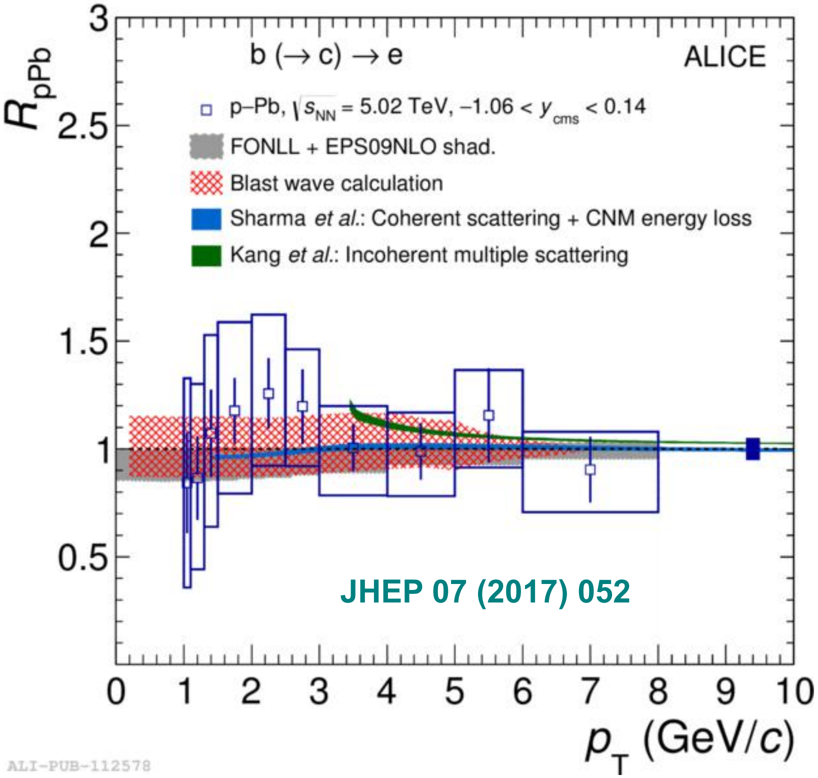
multiplicity at backward rapidity (Pb-going): test auto-correlations

- Multiplicity at mid-rapidity: similar enhancement in p-Pb and pp collisions
- Multiplicity at backward rapidity: linear-like, less rapid increase in p-Pb coll.
- **EPOS with hydro** evolution: qualitatively good description in both cases

CNM effects - Charm and Beauty



PLB 754 (2016) 81



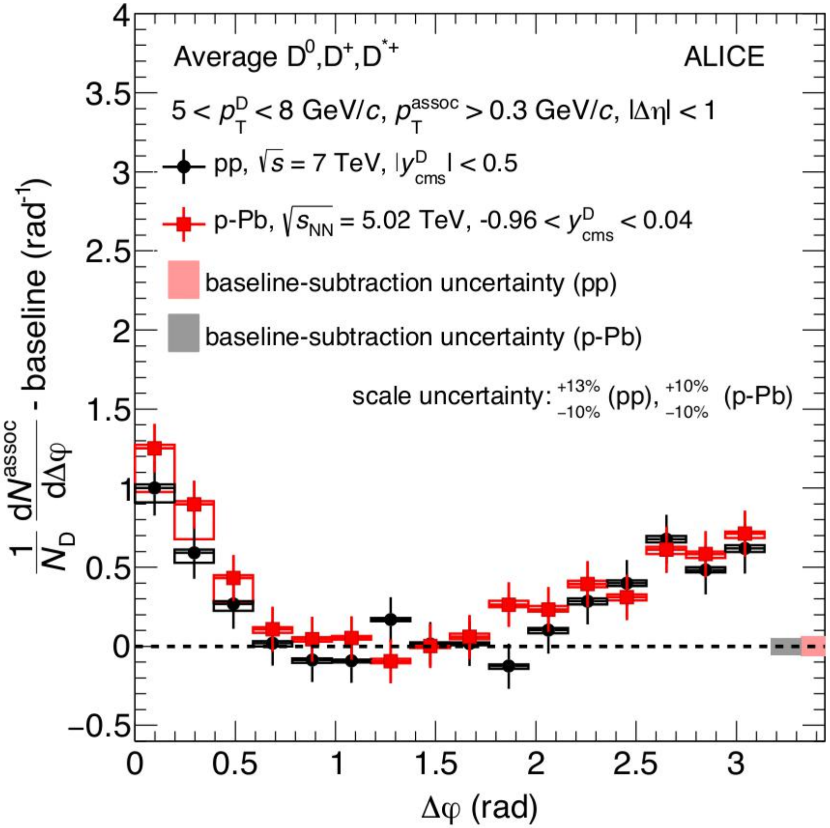
JHEP 07 (2017) 052

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

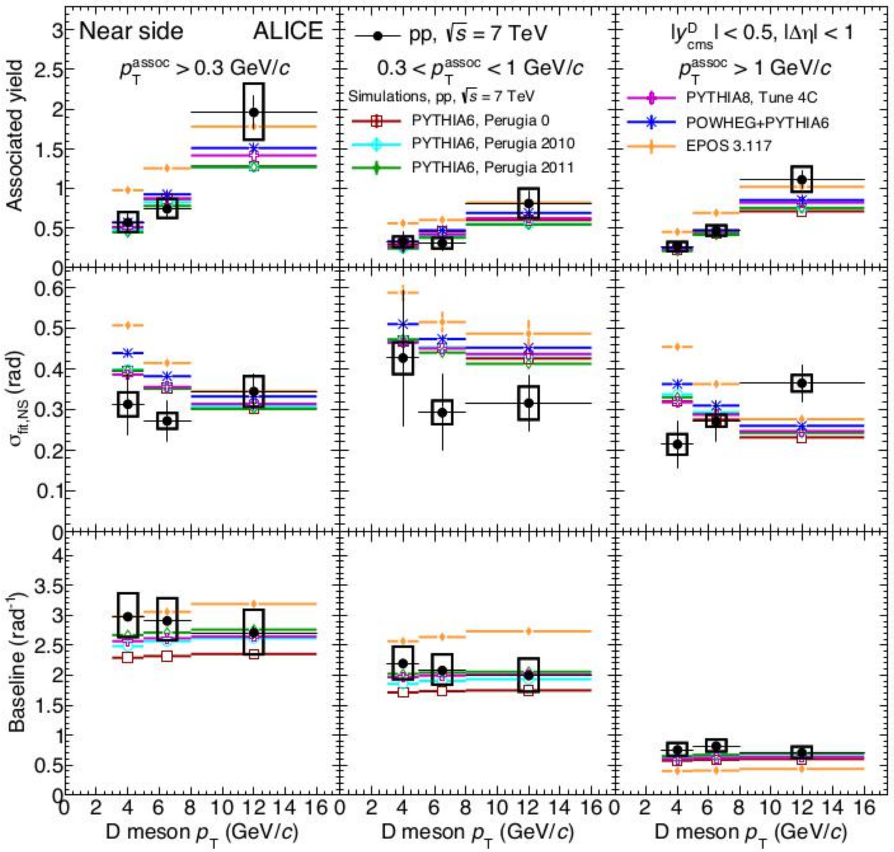
- **HF decay electrons (charm+beauty)** and **separated beauty electrons** both consistent with no modification in p-Pb coll. in the whole p_T range
- Several models describe the data within uncertainties

→ increased precision from Run 2 will be essential

D-h azimuthal correlations



ALI-DER-106234

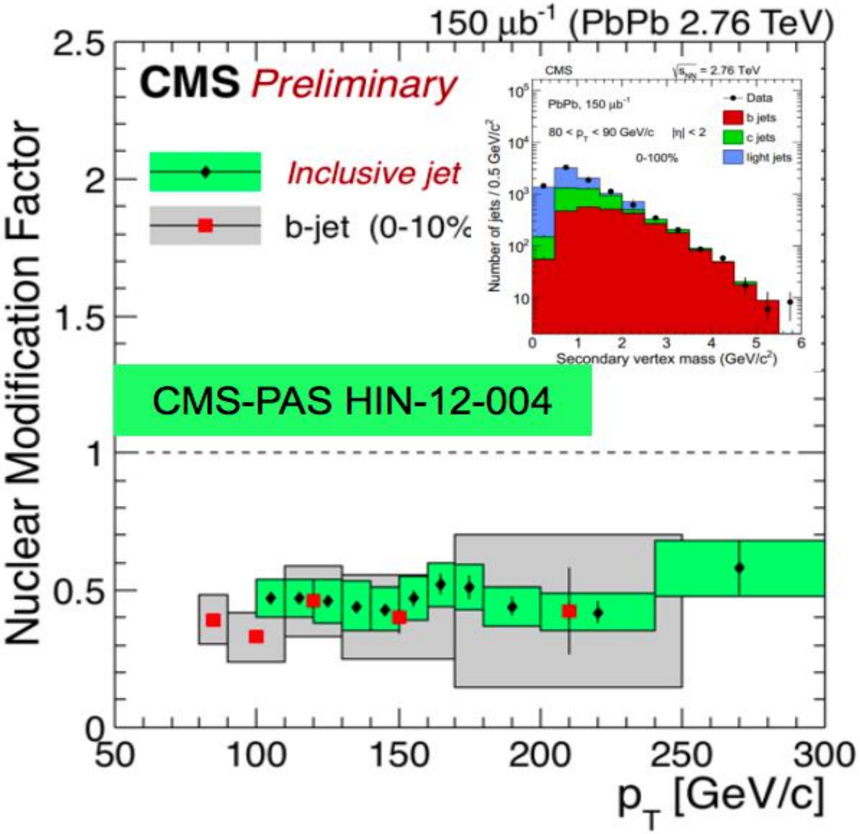


ALI-PUB-106020

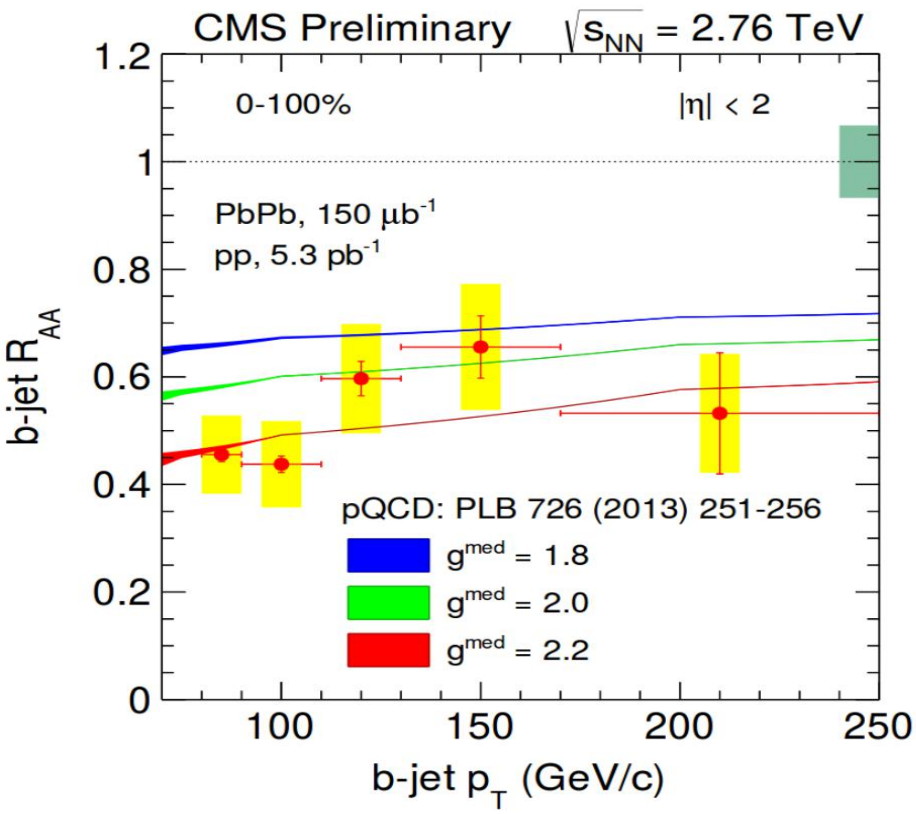
Charged hadron - D-meson correlations in azimuthal angle

- No significant difference between correlations in **p-Pb** and **pp** collisions after baseline subtraction
- Near side peak fit parameters (yield, width, baseline) typically described by simulations (PYTHIA8, POWHEG+PY6, EPOS3.117) within uncertainties

Full B-jet reconstruction (CMS)



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

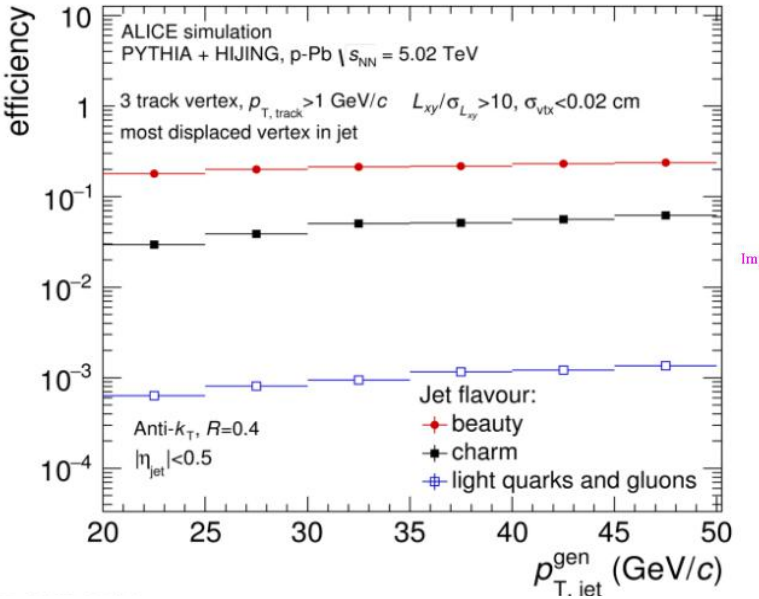


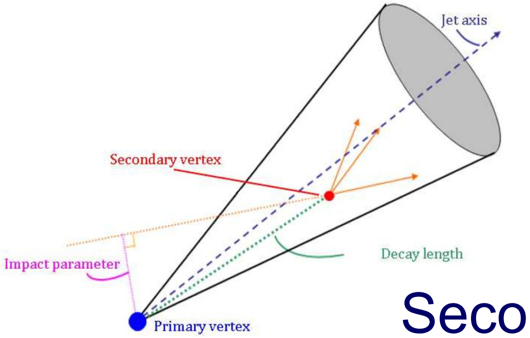
Huang-Bo-Vitev, PLB 726, 251 (2013)

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

→ Future precise measurements towards lower p_T

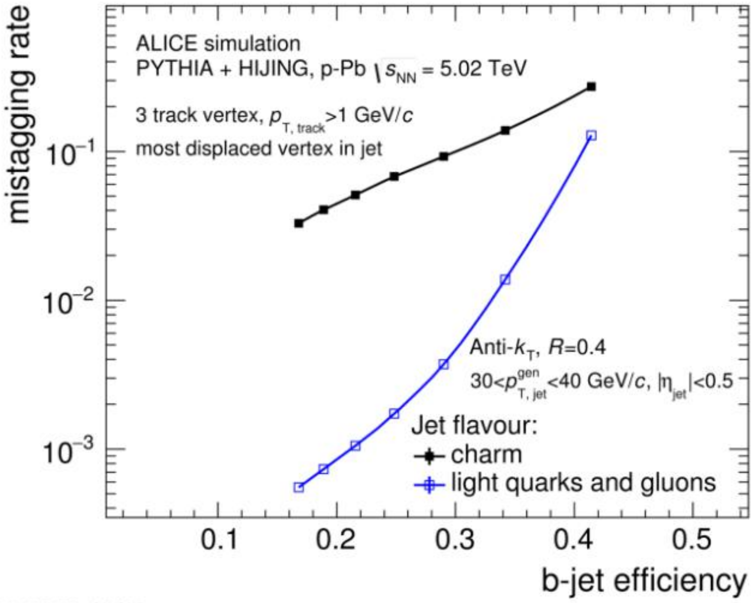
b-jet tagging performance

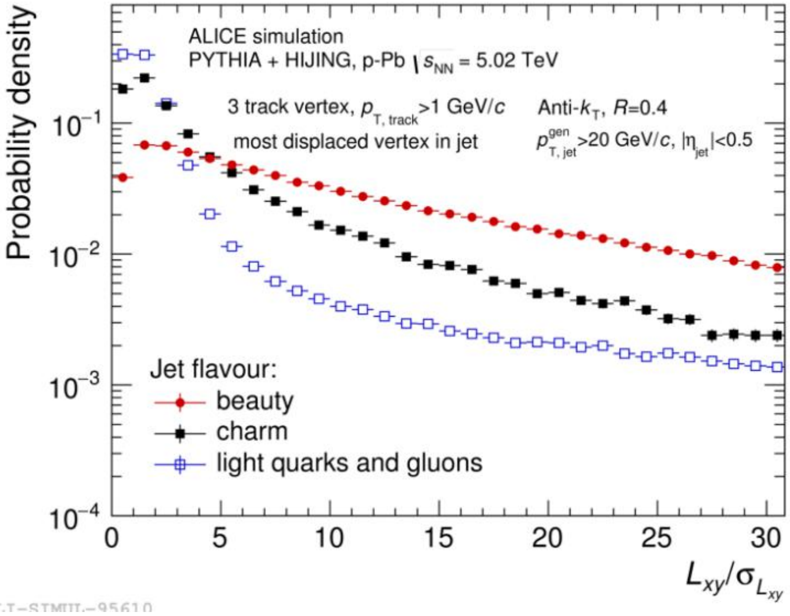




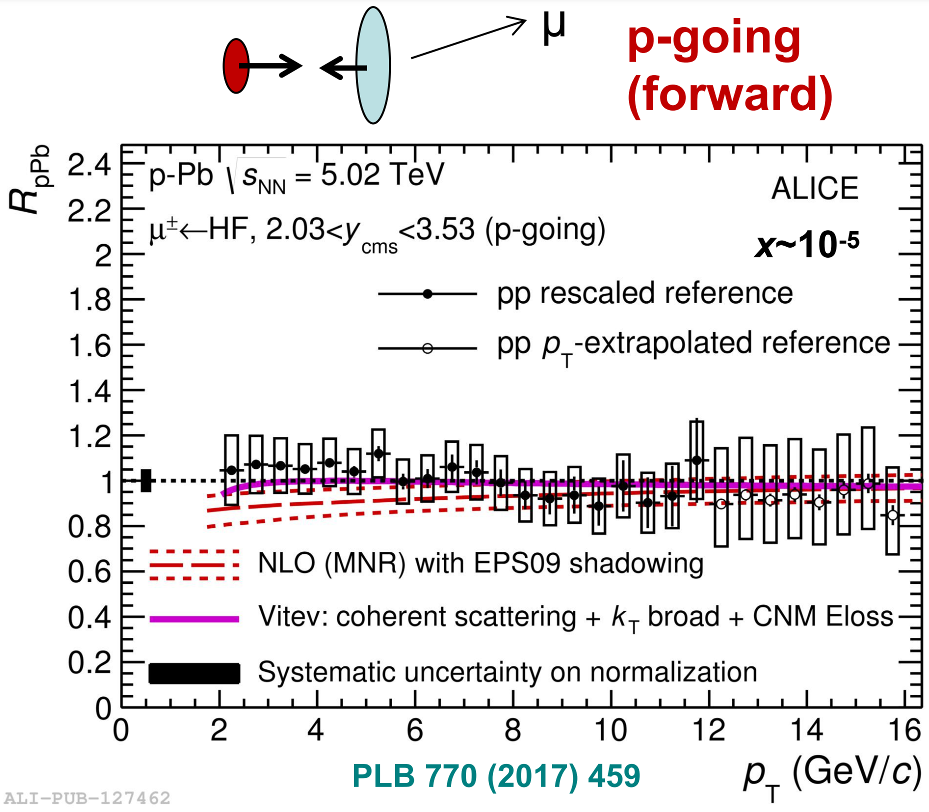
Secondary vertex method

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

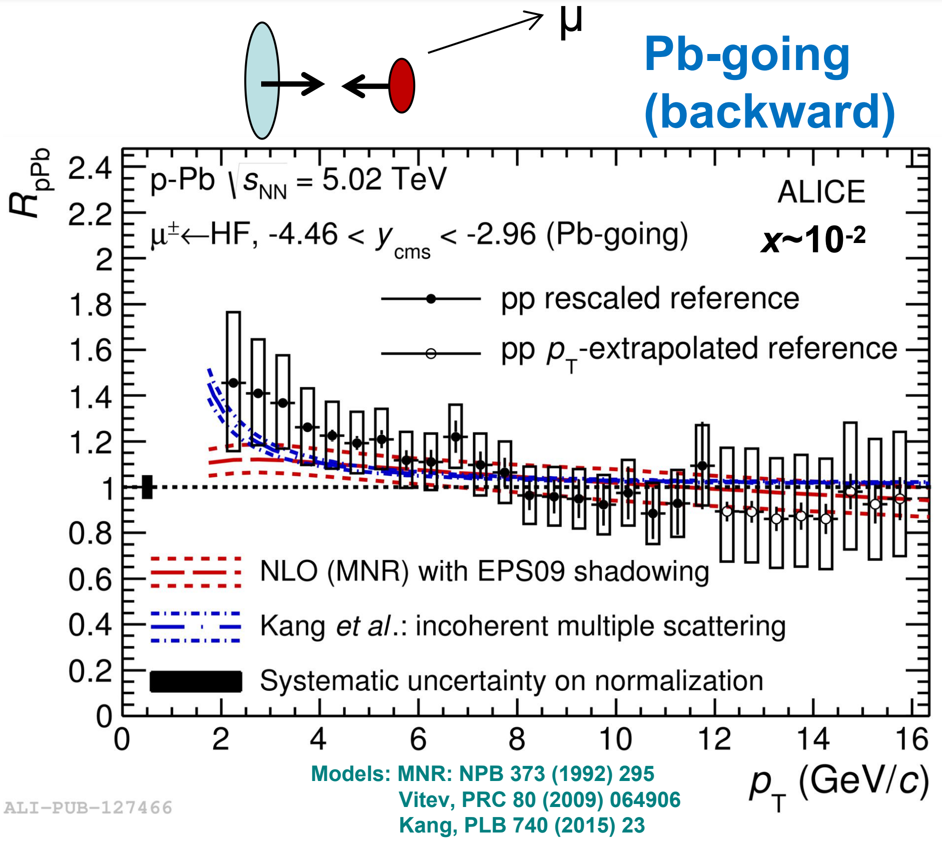




CNM effects - Forward, backward



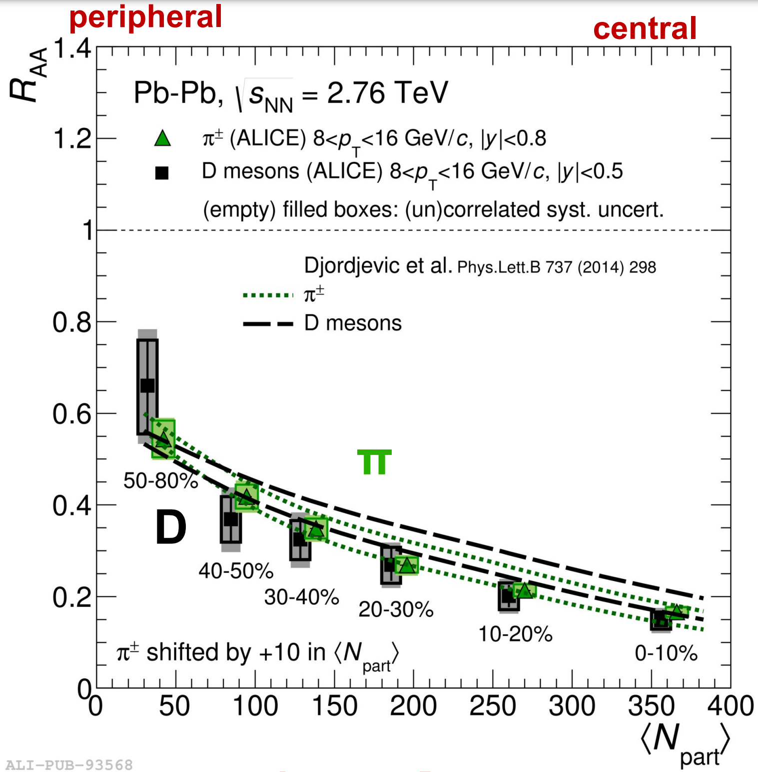
PLB 770 (2017) 459



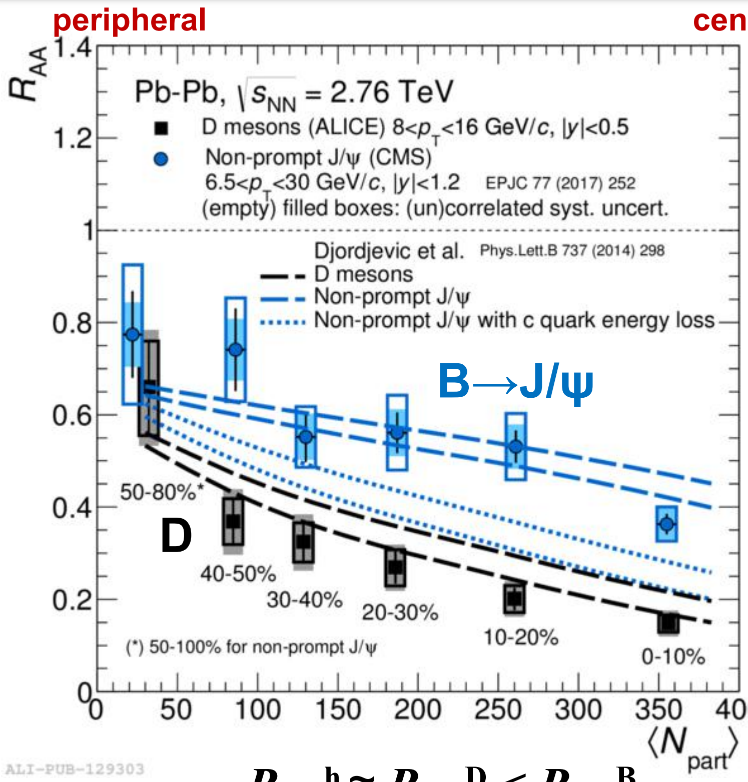
Models: MNR: NPB 373 (1992) 295
Vitev, PRC 80 (2009) 064906
Kang, PLB 740 (2015) 23

- 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

Flavour/mass dependence - hadrons



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



ALICE: JHEP 1511 (2015) 205
CMS: EPJ C77 (2017) no.4, 252
Model: Djordjevic, PLB 737 (2014) 298

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

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

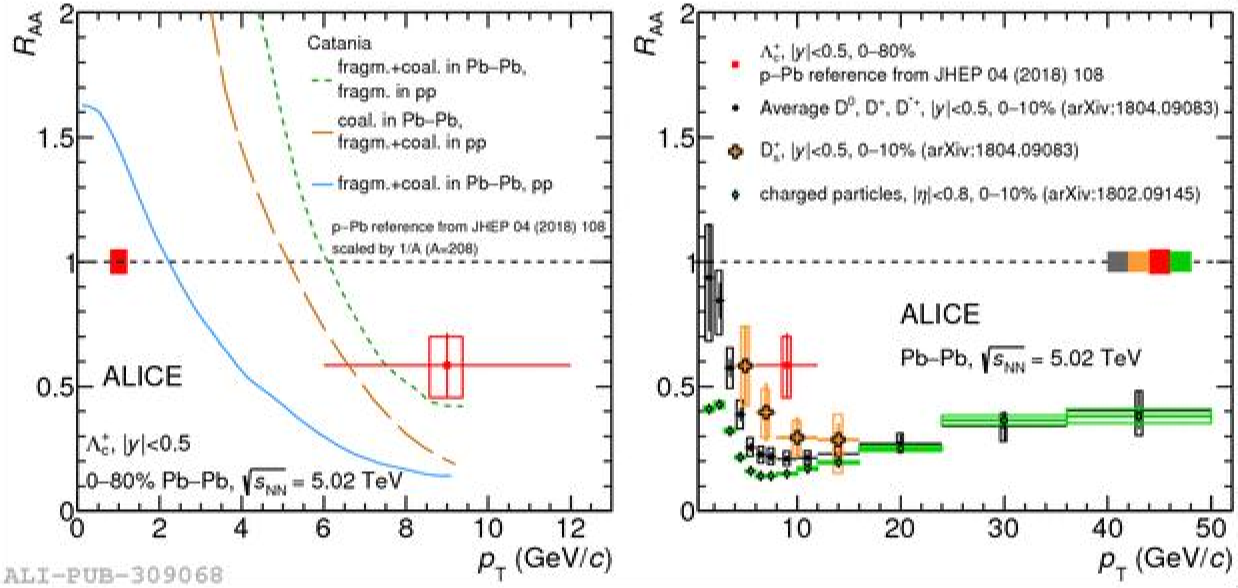
  Understanding: different fragmentation, p_T-spectrum shape, color charge effects level out expected ordering

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

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

Λ_c in Pb-Pb: R_{AA} and Λ_c^+/D^0

R_{AA}



Λ_c^+/D^0