Heavy-flavour measurements with the ALICE experiment at the LHC

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for the ALICE collaboration

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Heavy-flavour (HF) probes

- Heavy quarks are produced early

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

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

- Heavy quarks are (almost) conserved

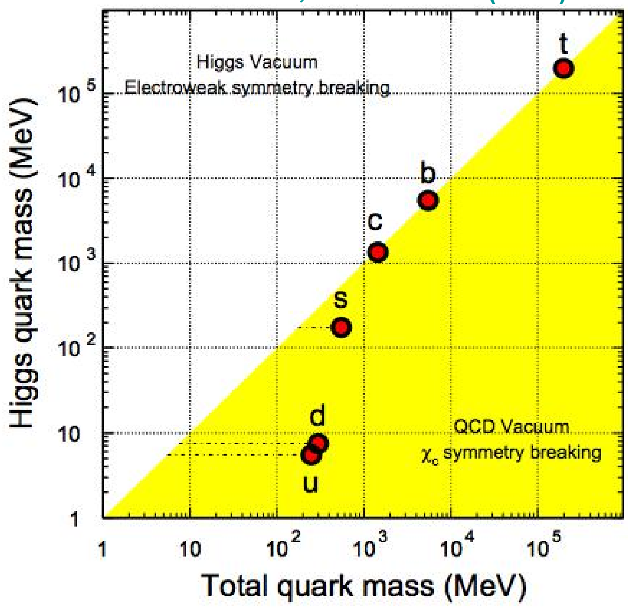
  $m \gg T_{QGP}$ ($m_c \sim 1.5$ GeV, $m_b \sim 5$ GeV)

  - No flavour changing
  - Negligible thermal production

  → Very little production or destruction in the sQGP

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

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



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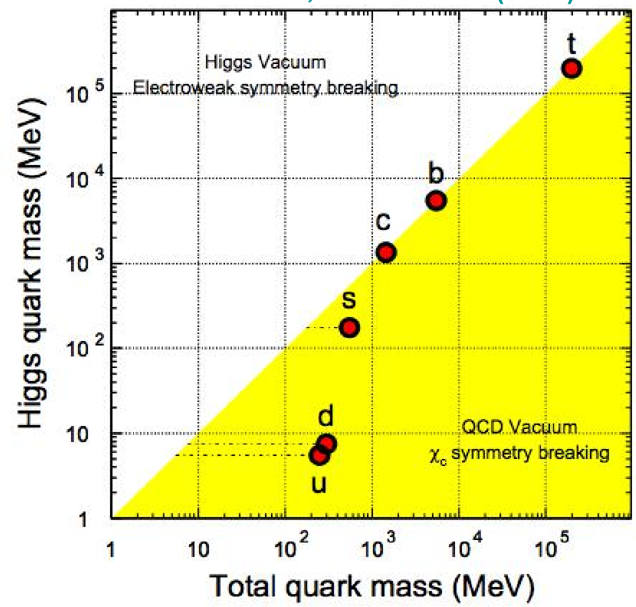
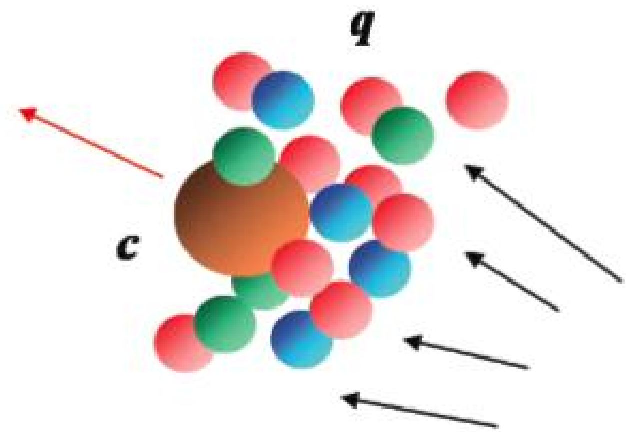


- Transport through the whole system
  - **Heavy quark kinematics in the sQGP**
  - Access to **transport properties** of the system
  - ...exits the medium also at **low momenta**
  - **Hadronization** (fragmentation, coalescence)
  - **Heavy vs. light? Charm vs. bottom?**



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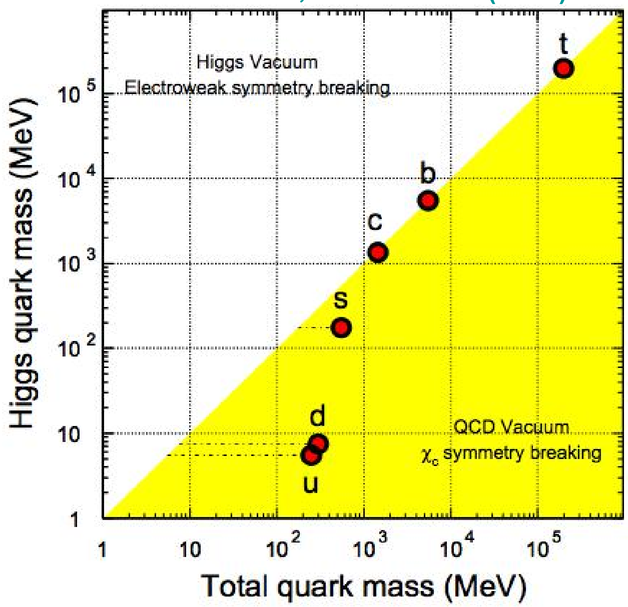

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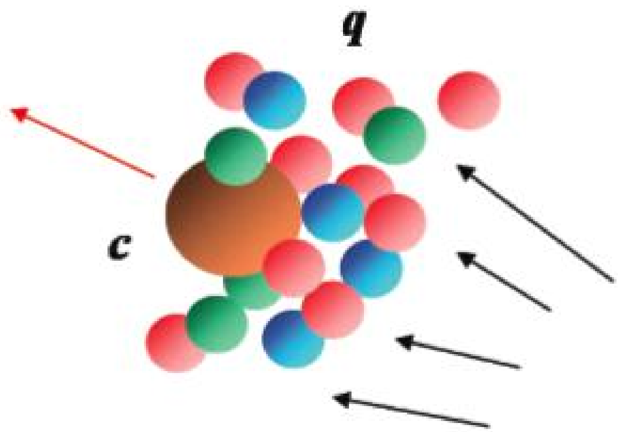
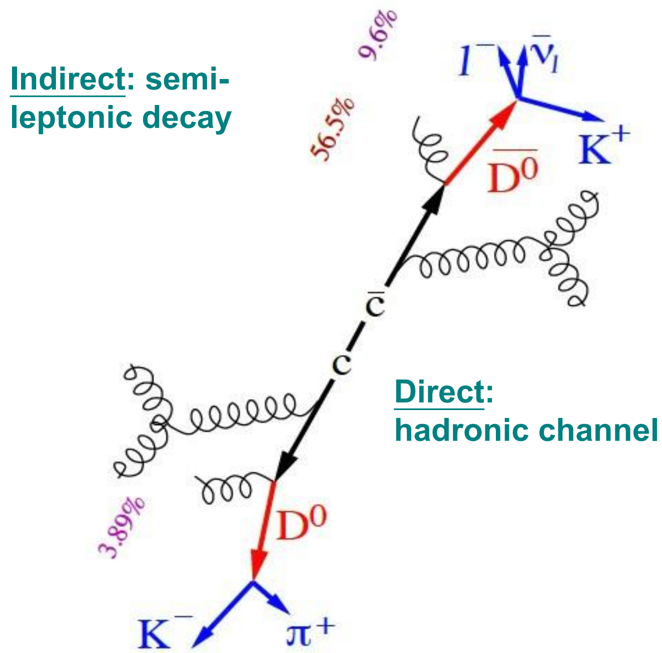


Penetrating probes down to low momenta!

Experimental access to open HF

- Heavy quarks (c,b) hadronize into mesons (D,B) or baryons (Λ_c ...)
- These hadrons later decay weakly into light mesons
- Experimental access:

  identification of decay products



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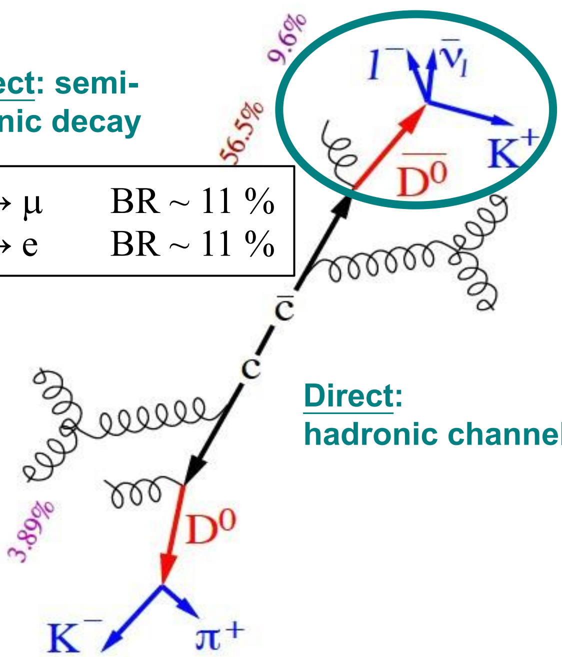
Indirect: semi-leptonic decay

c,b → μ	BR ~ 11 %
c,b → e	BR ~ 11 %



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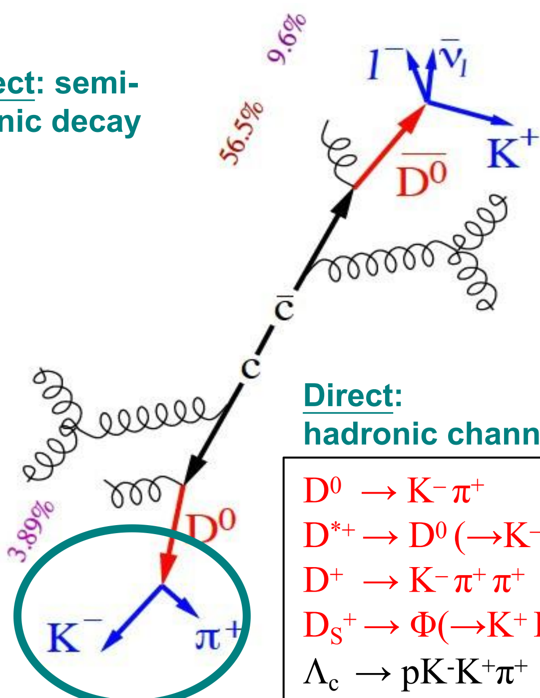

Direct: hadronic channel

$D^0 \rightarrow K^- \pi^+$	BR ~ 3.9%
$D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+)\pi^+$	BR ~ 2.6%
$D^+ \rightarrow K^- \pi^+ \pi^+$	BR ~ 9.5%
$D_S^+ \rightarrow \Phi(\rightarrow K^+ K^-)\pi^+$	BR ~ 2.3%
$\Lambda_c \rightarrow pK^- K^+ \pi^+$	BR ~ 6.2%
$\rightarrow pK_s^0$	BR ~ 1.6%

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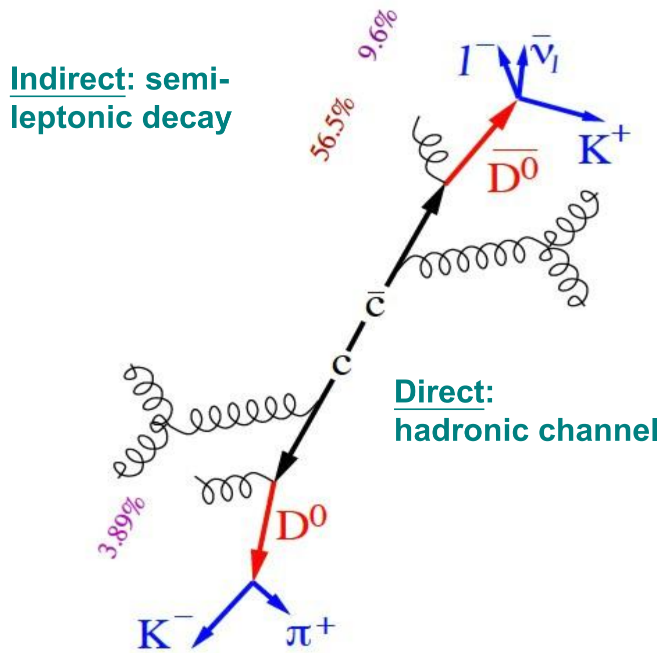
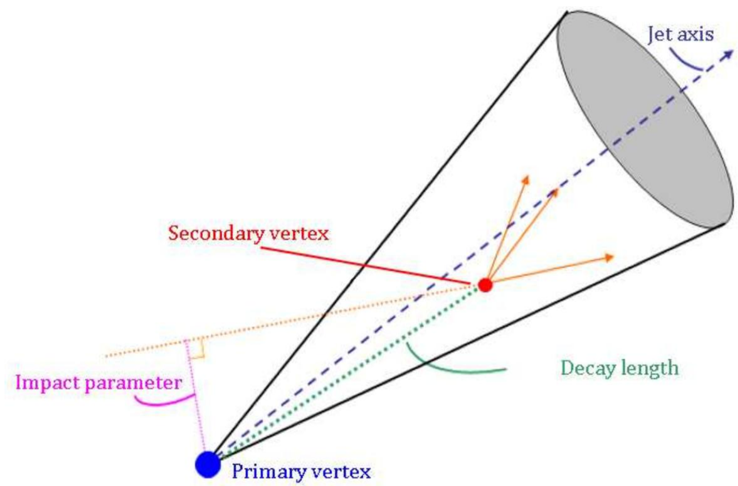
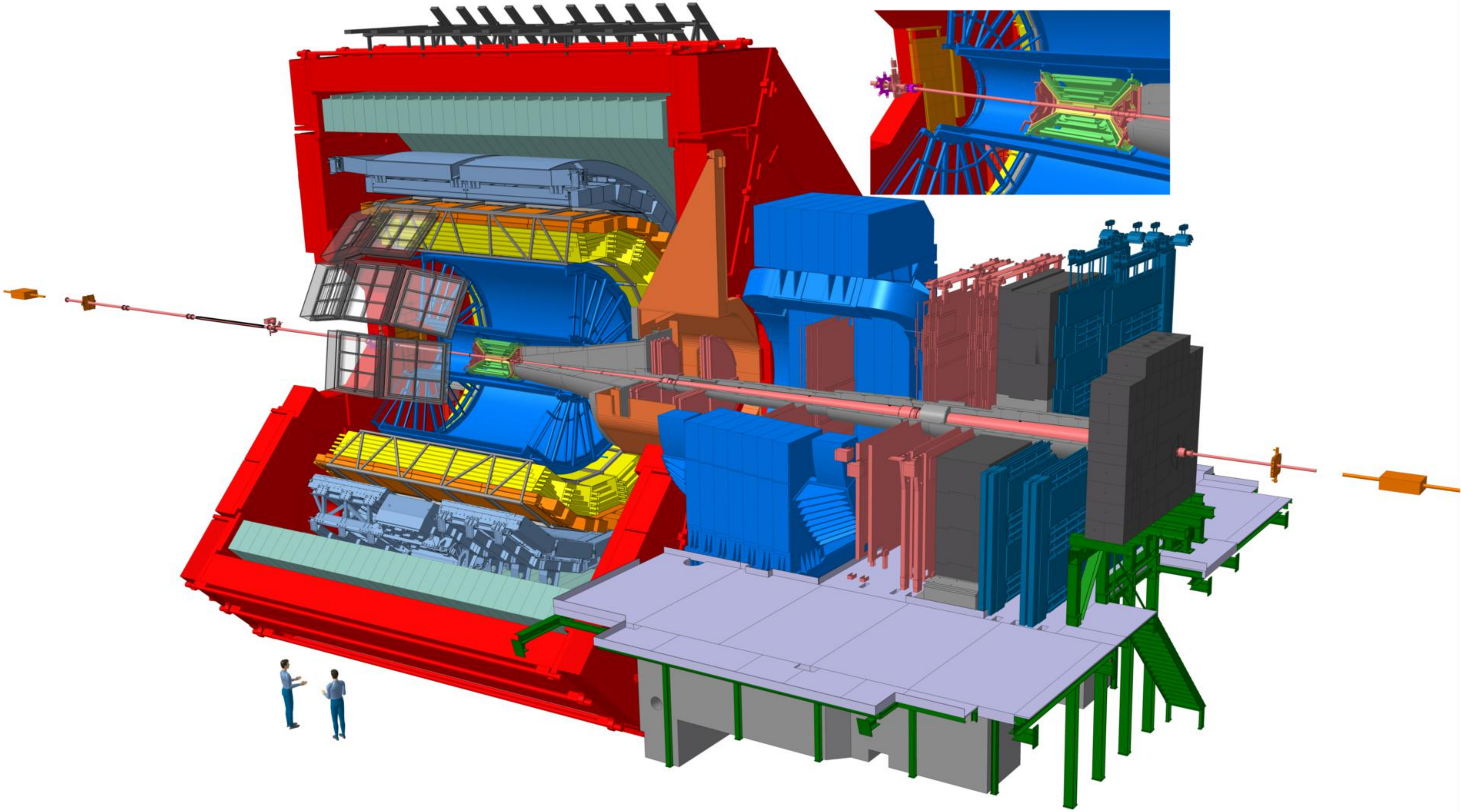


finding the location of the decay
(secondary vertex)



Lifetime of heavy quarks $c\tau(D) \sim 100\text{-}300\ \mu m$
$c\tau(B) \sim 400\text{-}500\ \mu m$
Secondary vertex resolution $<100\ \mu m$

ALICE



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

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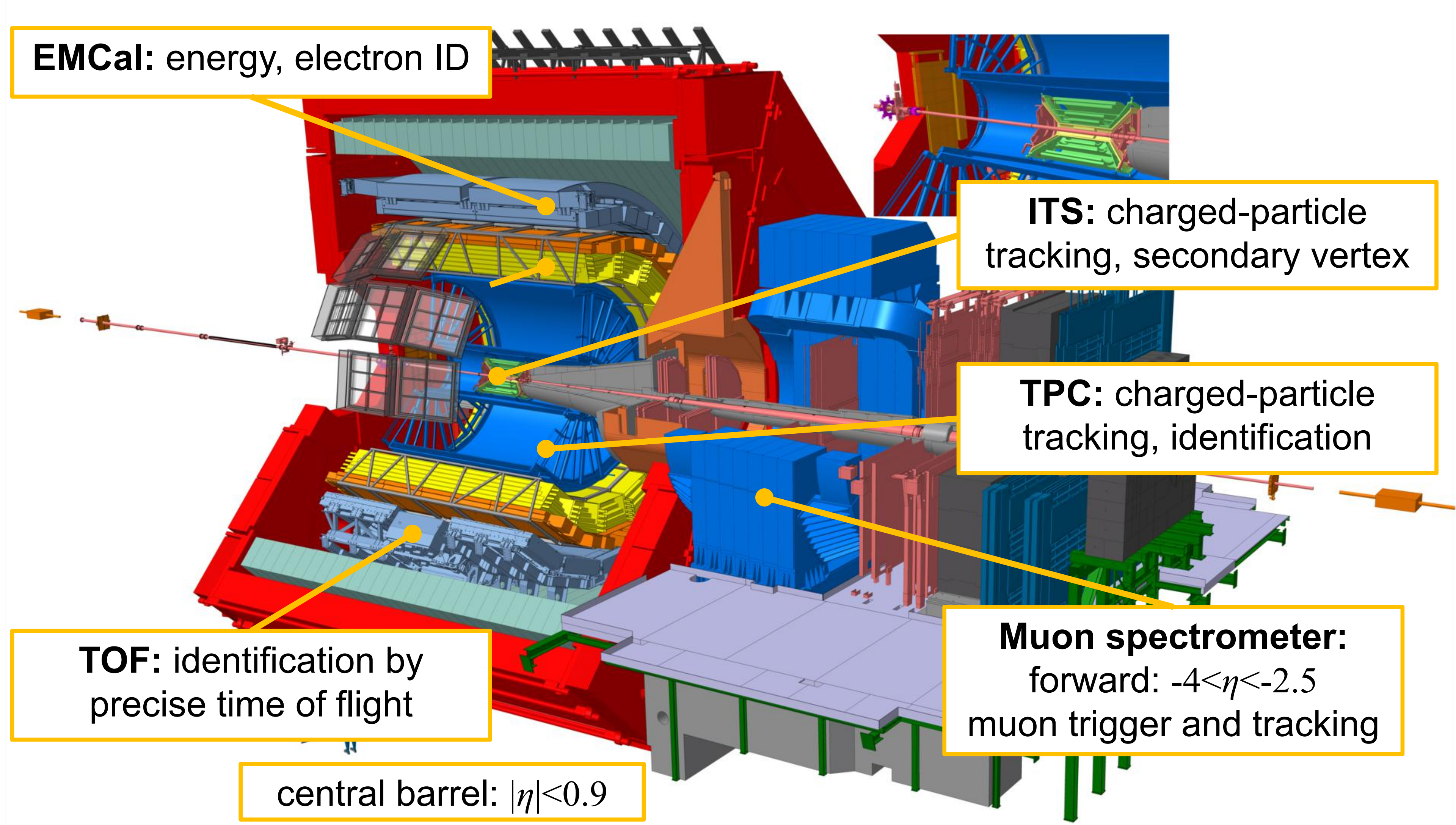

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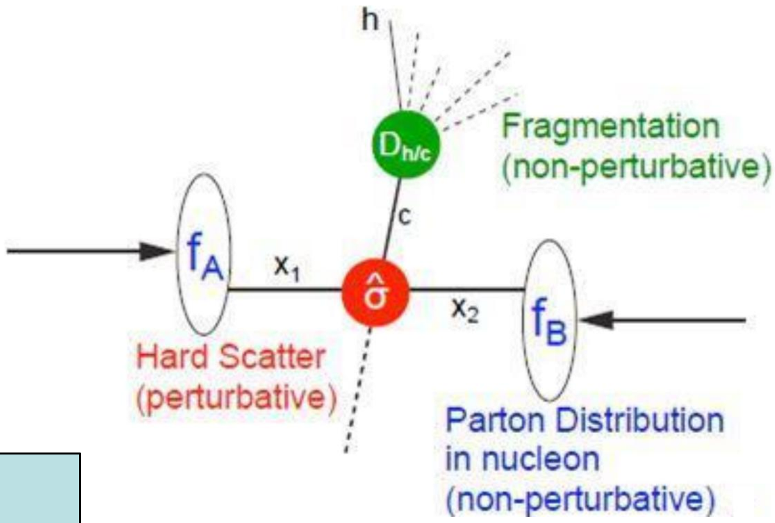
Heavy quarks in pp collisions

- **Yields:**
  Primary tests of pQCD models
  - Heavy quarks: $m_{c,b} >> \Lambda_{QCD}$
    → Perturbative even at low momenta
  - Factorization:
    - Parton distribution function (PDF)
    - Hard scattering
    - Fragmentation



Feynman-*x*:
$x_i = p^A_{||} / p^A_{||,max}$
Q : momentum transfer

$$\sigma_{hh \to H} = f_a(x_1, Q^2) \otimes f_b(x_2, Q^2) \otimes \sigma_{ab \to q\bar{q}} \otimes D_{q \to H}(z_q, Q^2)$$

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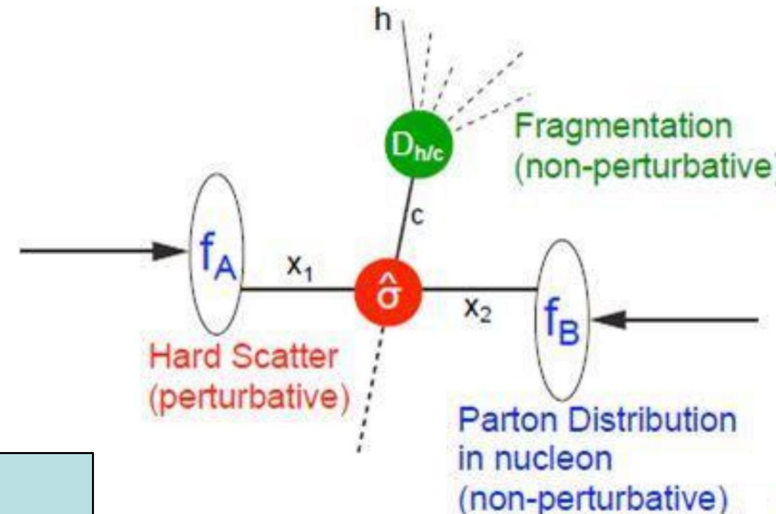

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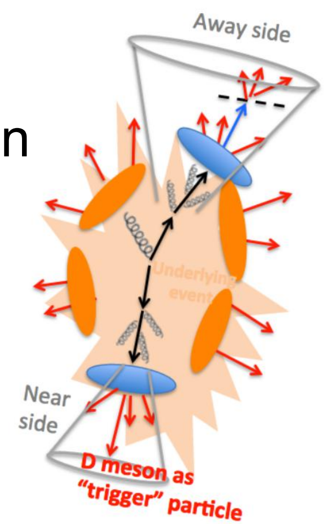
  - Light and heavy: mass and color-dependent fragmentation
  - Contribution of gluon splitting
- **Mesons and baryons**
  - Tests of fragmentation models



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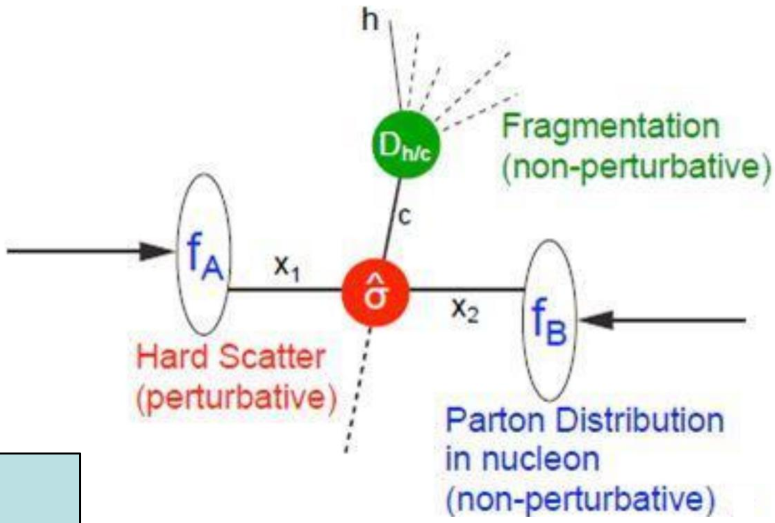

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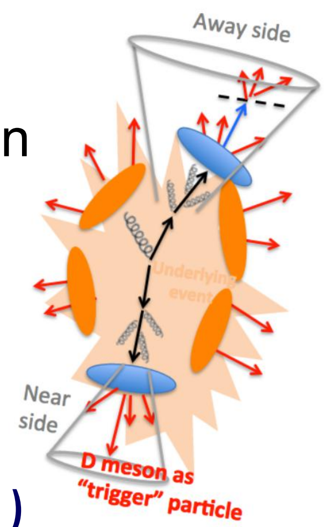
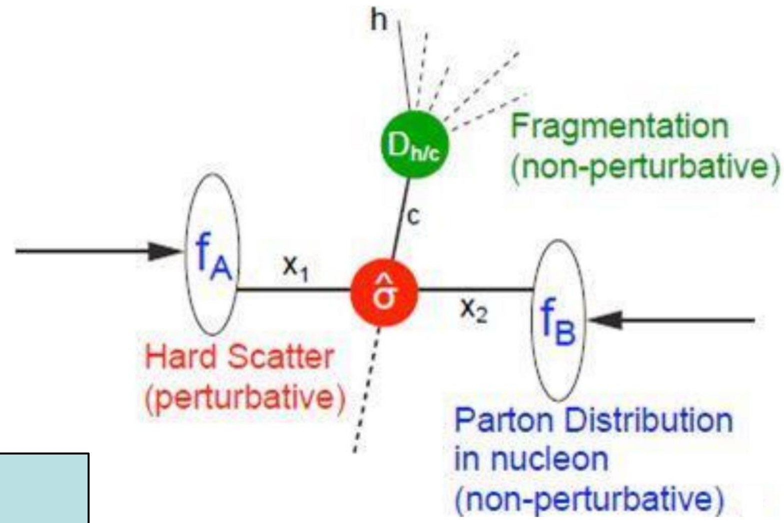


- ***Reference for p–A and A–A collisions*** *(eg. R_{pA}, R_{AA})*

Heavy quarks in pp collisions



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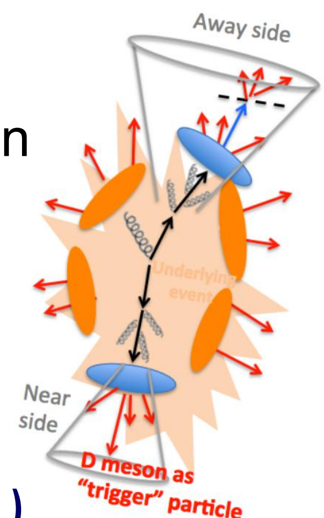
Eszter Frajna
Wednesday 14:55



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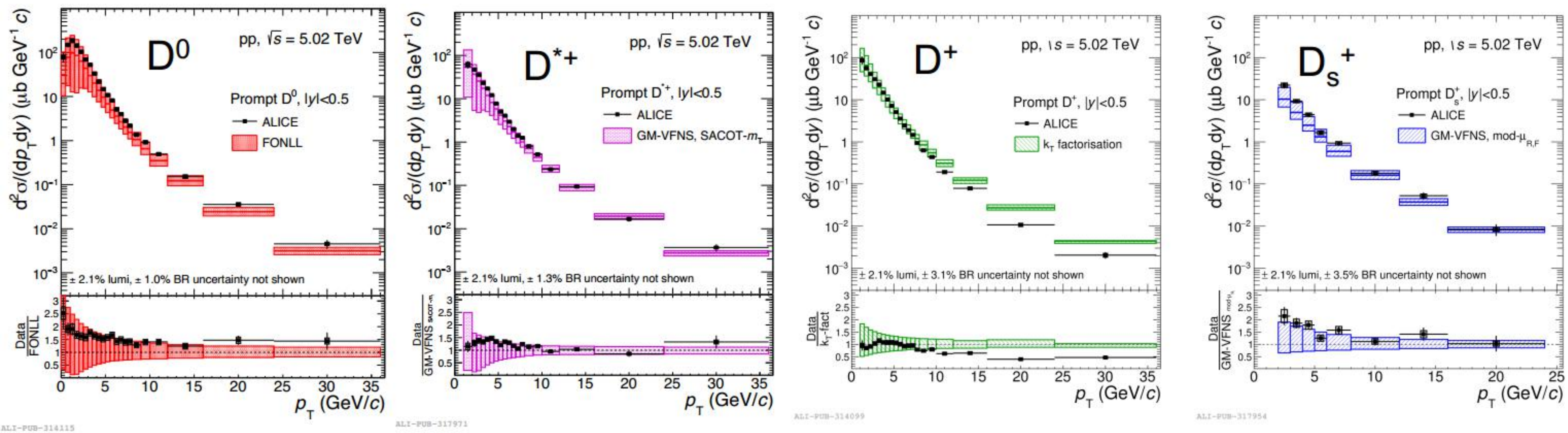
- ***Reference for p–A and A–A collisions*** (eg. R_{pA}, R_{AA})

D (charmed) mesons in QCD vacuum

Eur.Phys.J. C79 (2019) no.5, 388



FONLL: JHEP 10 (2012) 137

GM-VFNS SACOT-m_T: JHEP 05 (2018)

kT-factorization: PRD 98, no. 1 (2018)

GM-VFNS mod μR,F: JHEP 12 (2017); NPB925 (2017)

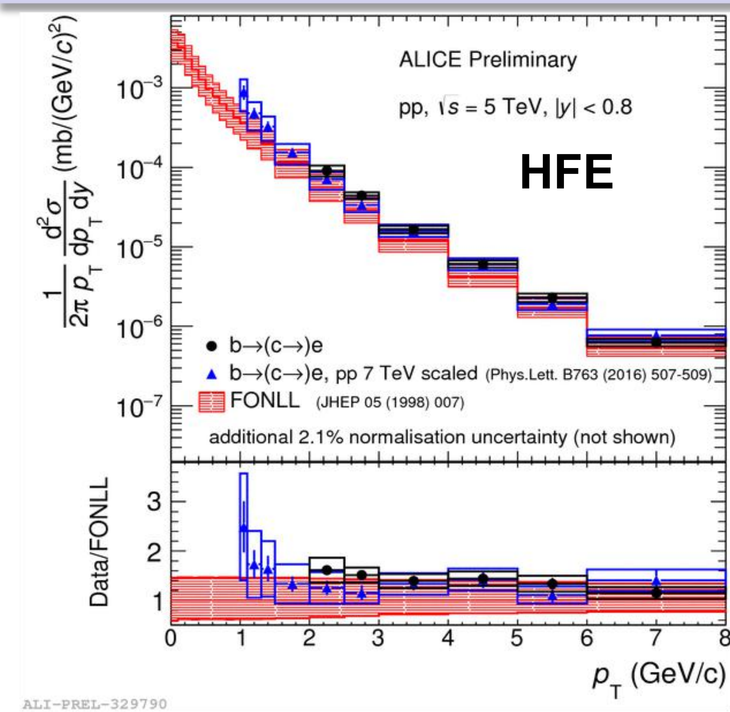
$\sqrt{s}$=5.02 TeV pp: new, high-precision D^0, D^{*+}, D^+, D_s^+ measurements

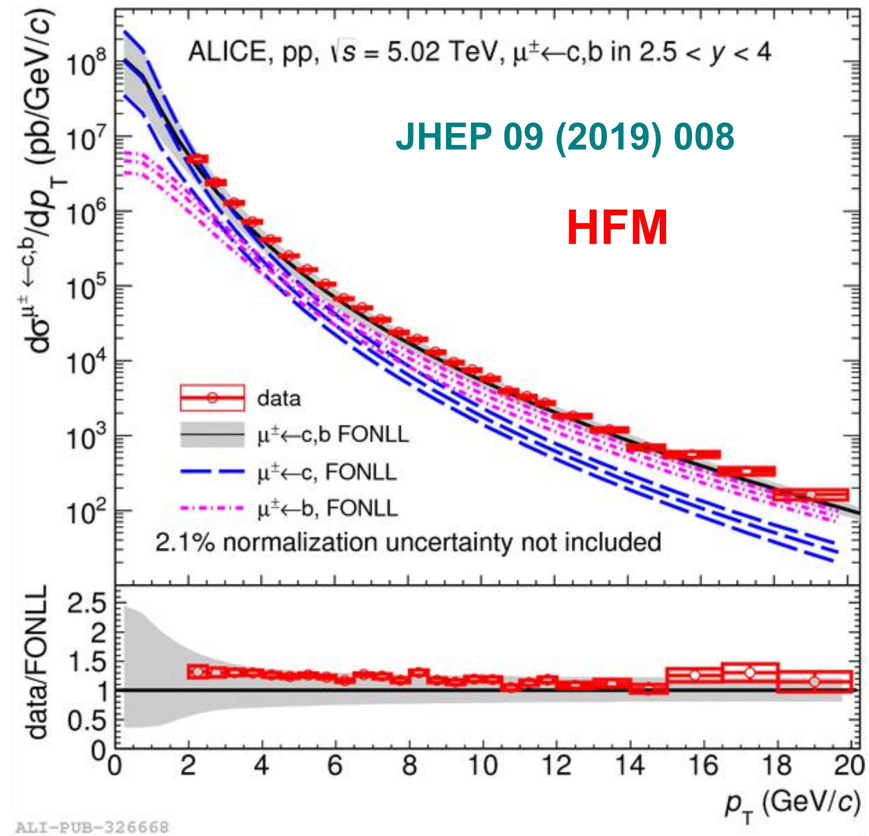
- D^0 down to low momenta (p_T>0): no topological cuts, only PID
- **New reference for heavy-ion systems** (p–Pb and Pb–Pb)

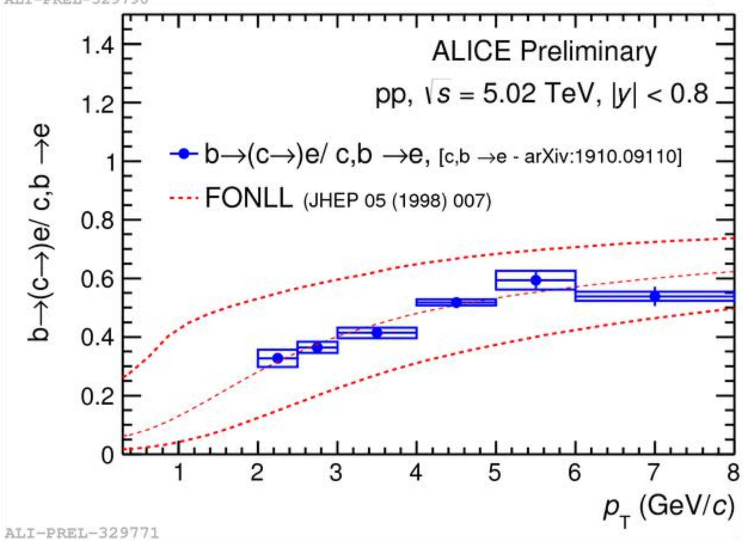
A detailed test of pQCD models

- Data well described by models based on factorization
- Data provide strong constraints for models

HF decay electrons and muons



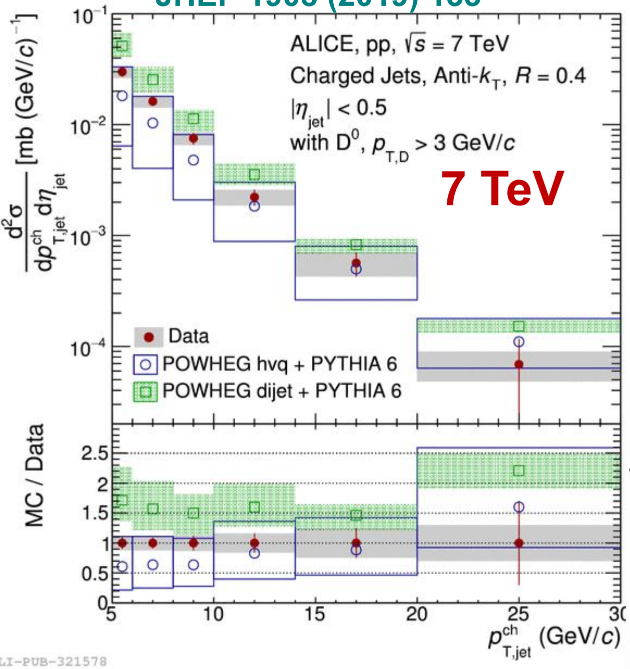


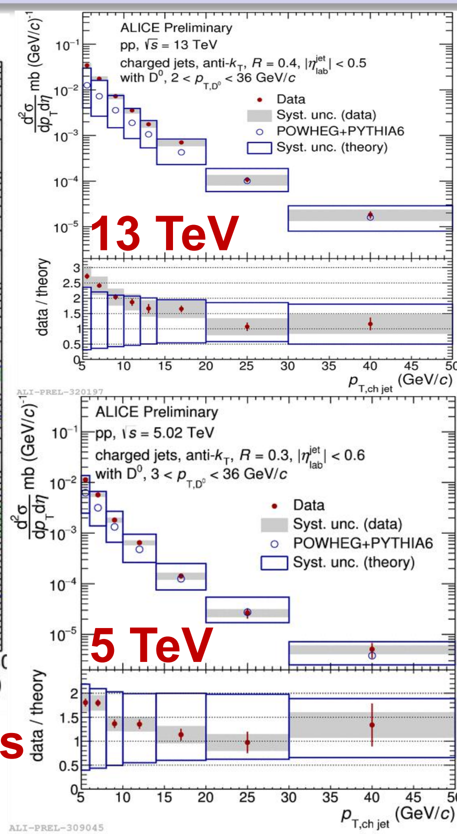


- FONLL pQCD describes **beauty electrons** and **beauty/charm** ratio
- Agreement for **electrons** at mid-rapidity and **muons** at $2.5<y<4$

D-tagged and b-tagged jets

JHEP 1908 (2019) 133





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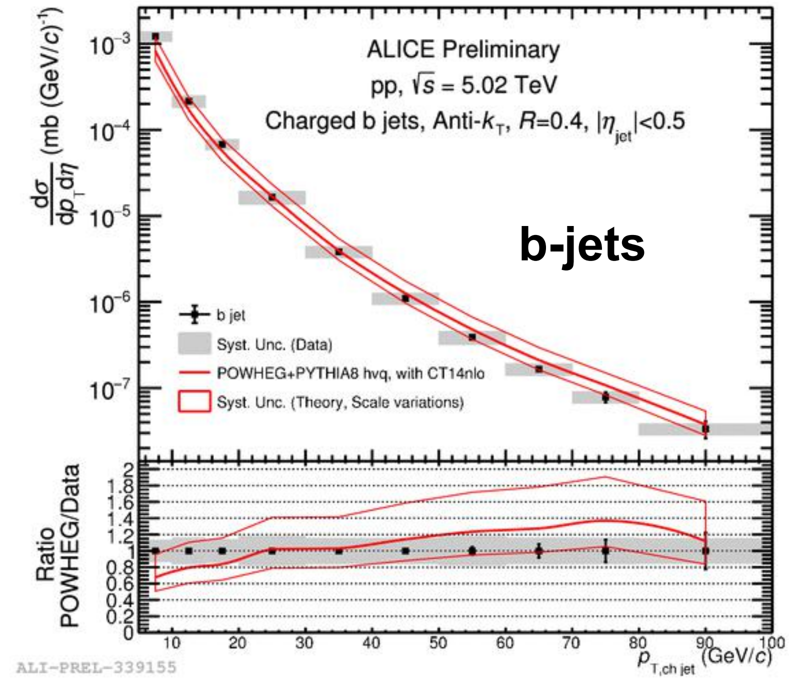
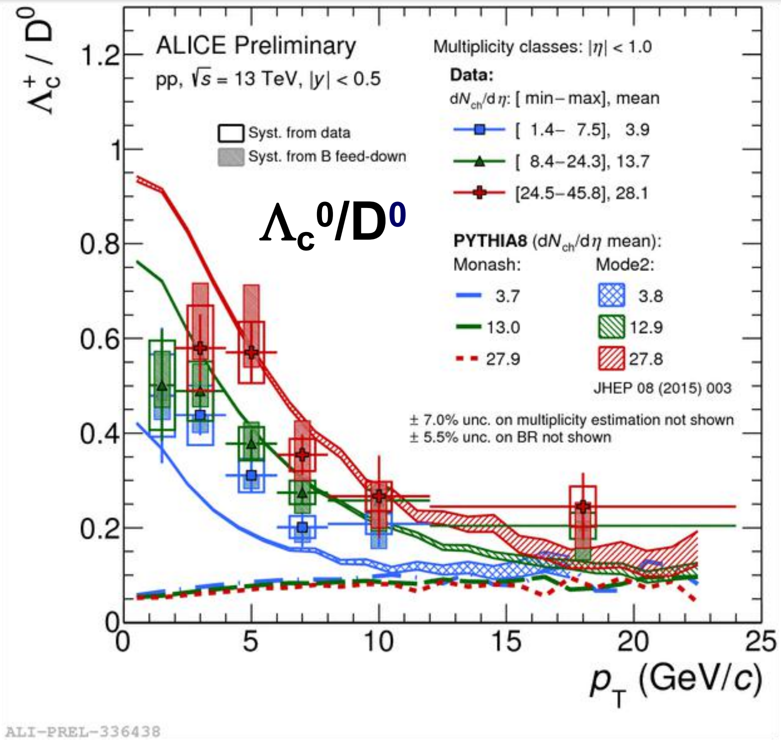
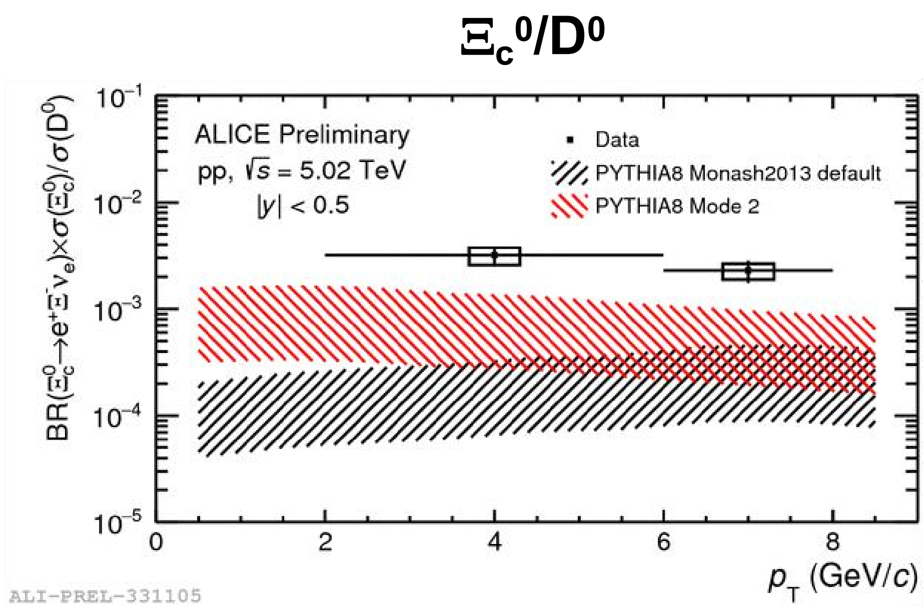


- **D-jets** are jets tagged with the reconstruction of D^0 mesons at 5, 7 and 13 TeV
- **b-jets** tagged based on impact parameter
- POWHEG(HVQ)+PYTHIA6(Perugia11) describes both adequately
- Strongly restricts models
  => unique opportunity to study flavor-dependent jet properties
  Reference for nuclear modification

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

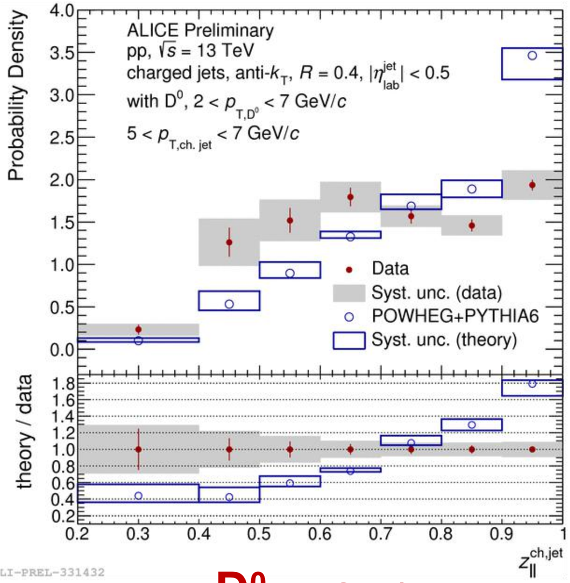




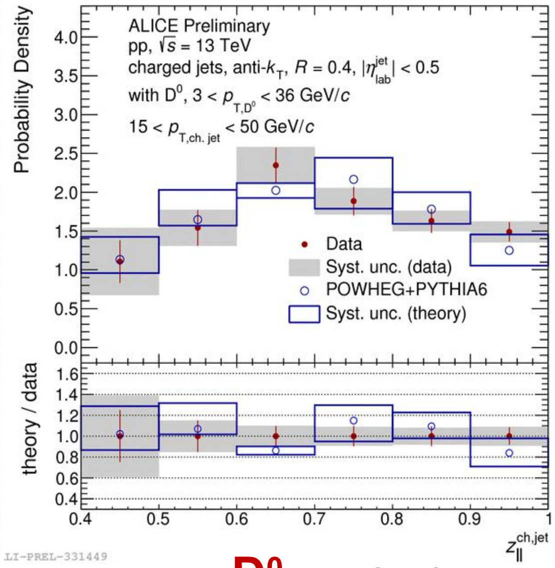
PYTHIA8: JHEP 05 (2006) 026
DIPSY: JHEP 1503 (2015) 148
HERWIG7: EPJ C76 (2016) no.4 196

- Ξ_c^0/D^0 as well as Λ_c^+/D^0 are underestimated by models based on ee collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation?
    Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon states?
    He, Rapp, 1902.08889
- Detailed measurement of charm baryons provide valuable input for theoretical understanding of HF fragmentation

Charm fragmentation



D^0 2-7 GeV/c



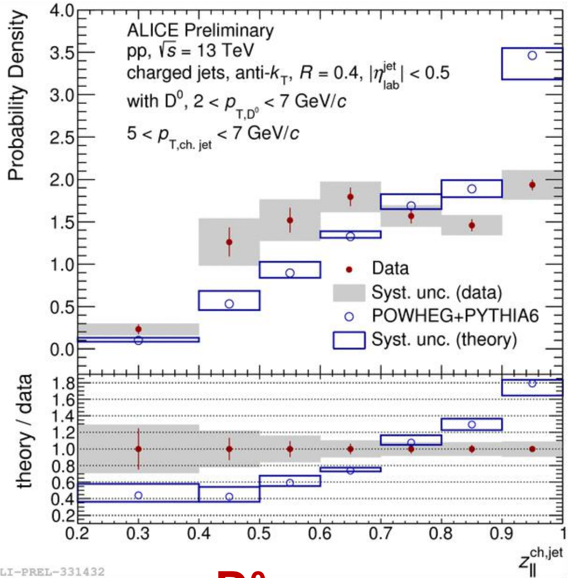
D^0 3-36 GeV/c

- **Fragmentation of D mesons**

$$z_{||}^{ch} = \frac{\vec{p}_D \cdot \vec{p}_{ch\ jet}}{\vec{p}_{ch\ jet} \cdot \vec{p}_{ch\ jet}}$$

  - Comparison to model POWHEG hvq CT10NLO + PYTHIA6
  - Softer fragmentation in data for low p_T
  - Model consistent with data at higher p_T

Charm fragmentation



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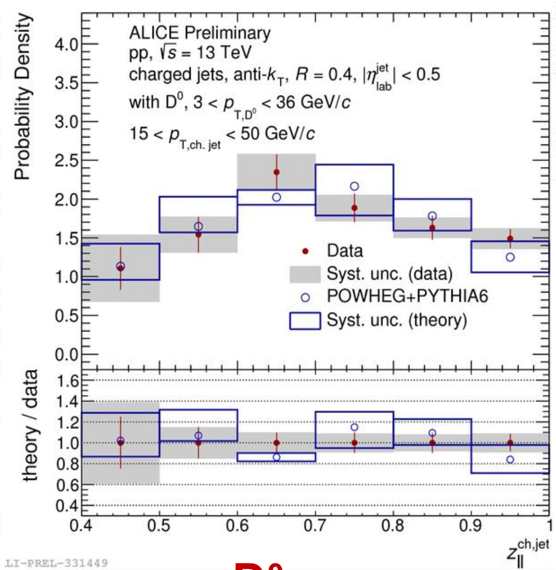

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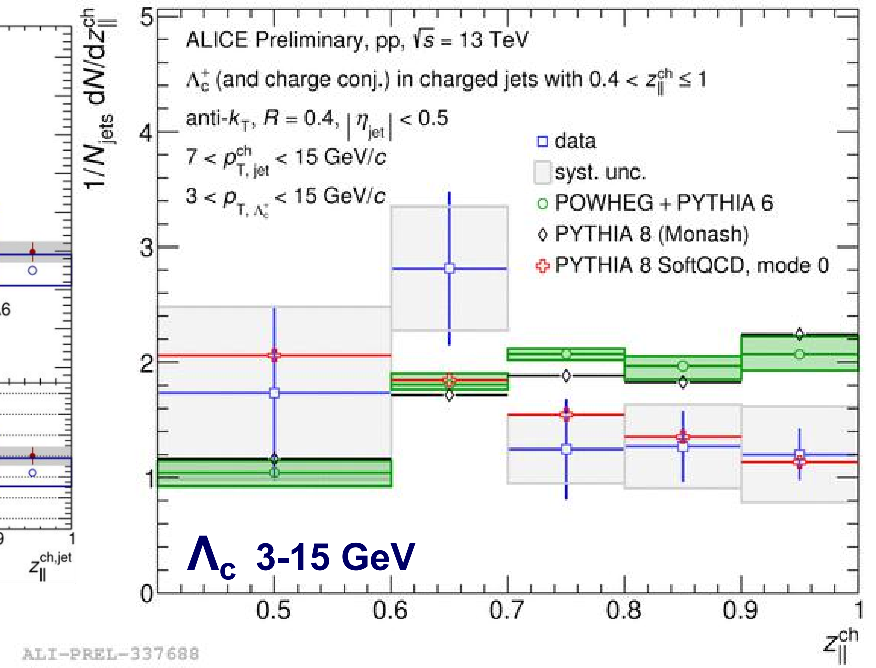

$$z_{\parallel}^{\mathrm{ch}} = \frac{\vec{p}_{\mathrm{D}} \cdot \vec{p}_{\mathrm{ch\,jet}}}{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{ch\,jet}}}$$

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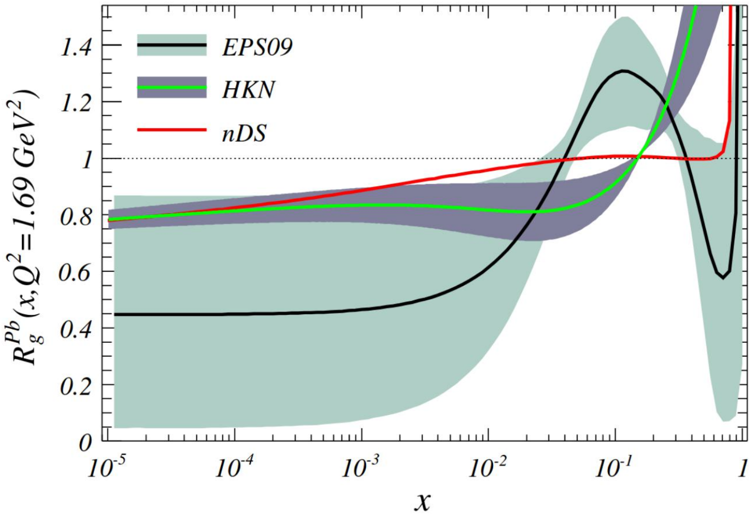
  - Softer fragmentation in data for low p_{T}
  - Model consistent with data at higher p_{T}
- **Λ_c-tagged jets at 13 TeV** - first measurement at the LHC
  - Exciting prospects for high luminosity LHC run
  - Comparison to models seems to favor PYTHIA with softer settings

p-Pb collisions: CNM effects?

- Nuclear modification
  - PDF modification: (anti)shadowing, gluon saturation
  - Energy loss in cold nuclear matter (CNM)
  - k_T-broadening

  Baseline for hot nuclear effects



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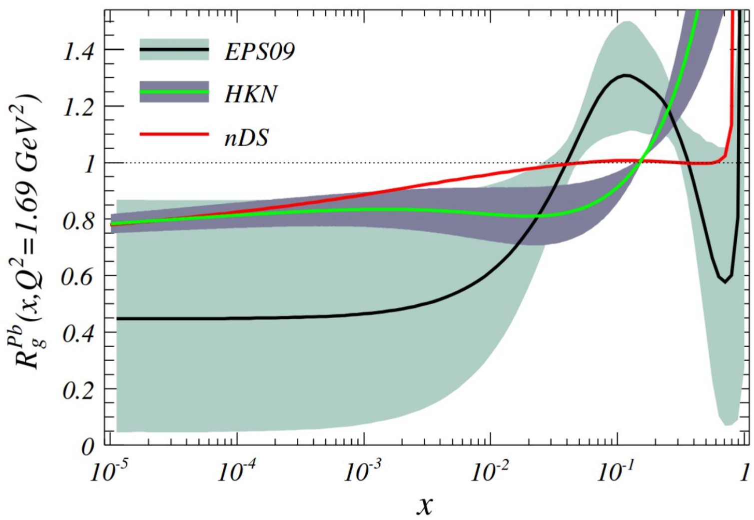
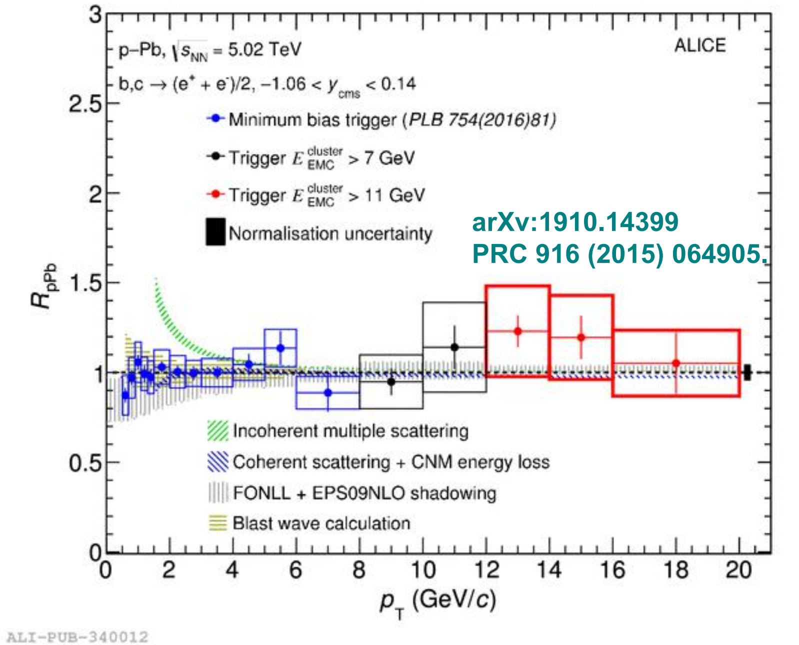
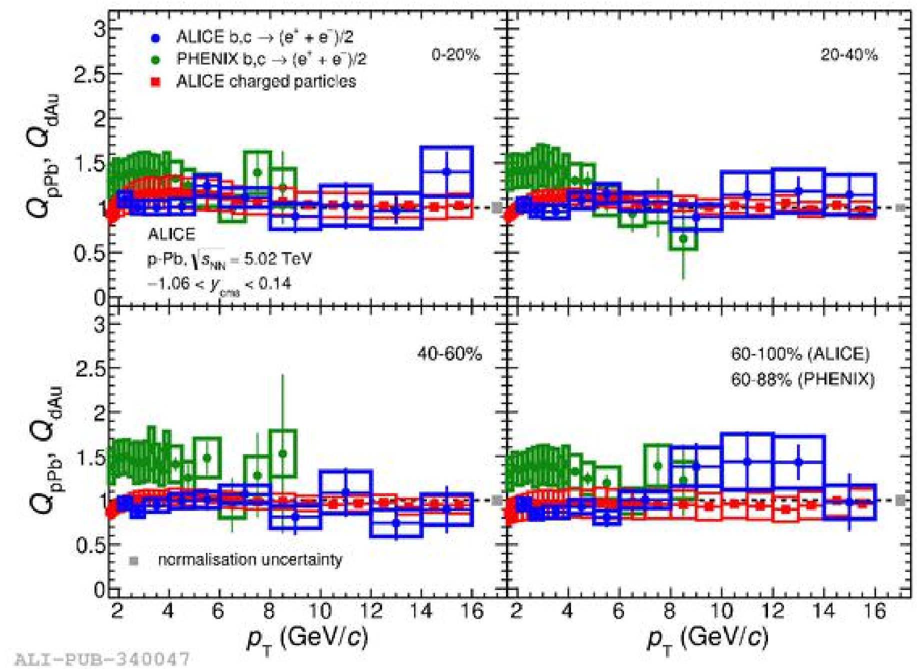


- Multiplicity-dependence?
  - *Any hot droplets?*
- Origin of collectivity in small systems?
  - Disentangle initial and final state effects

HFE in p-Pb collisions



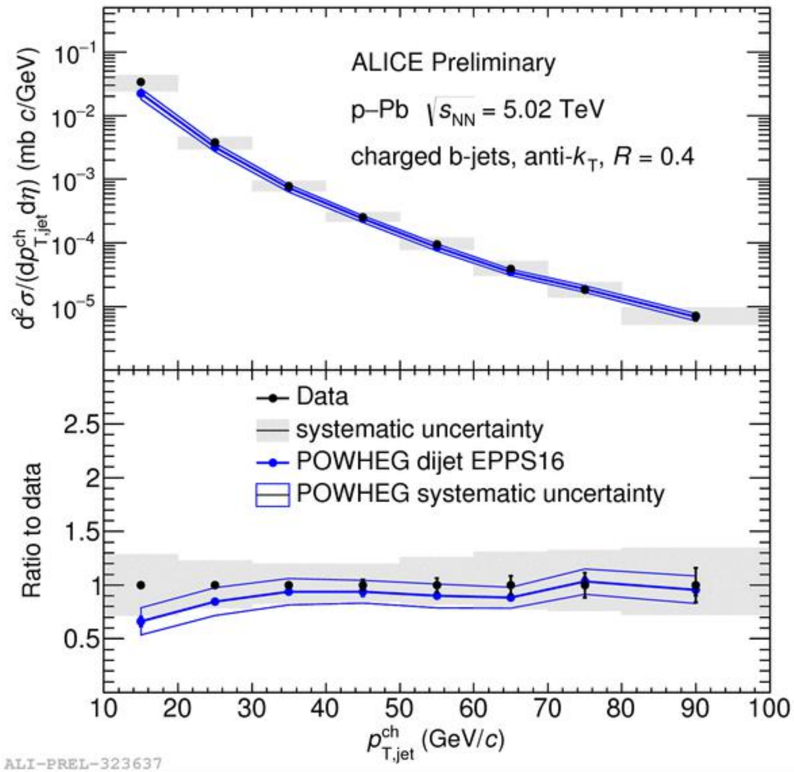
arXv:1910.14399
PRC 916 (2015) 064905

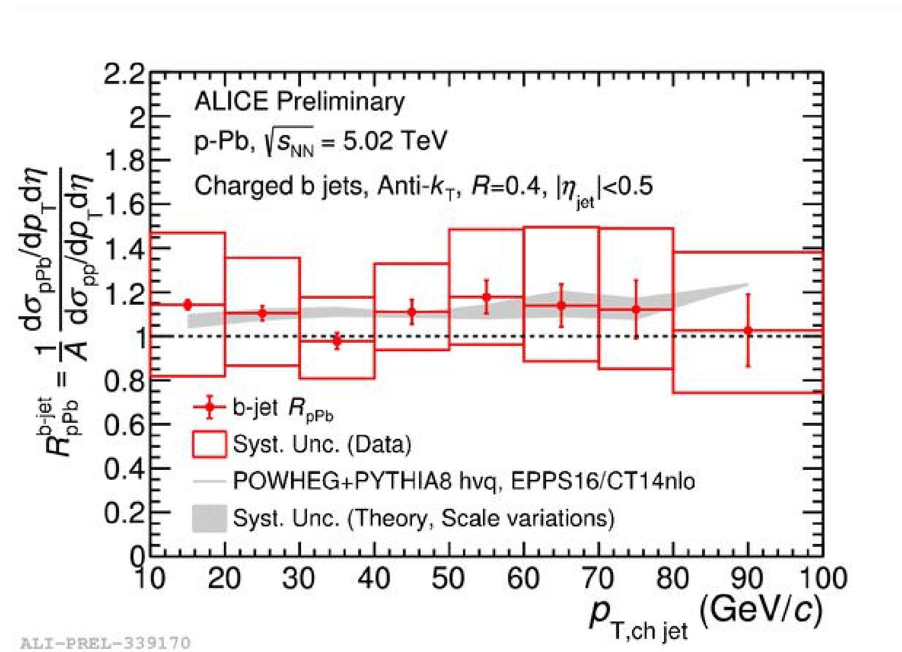


PHENIX: PRL109 24 (2012) 242301
Kang et al:PLB 740(2015)23
Sharma et al: PRC 80(2009) 054902
FONLL: JHEP 9805(1998)007

- **HFE production in p-Pb collisions:**
  No modification w.r.t. pp collisions within uncertainties
- **Q_{pPb} consistent with unity at all centralities**
  - More radial flow in PHENIX d–Au than at the LHC ?

b-tagged jets

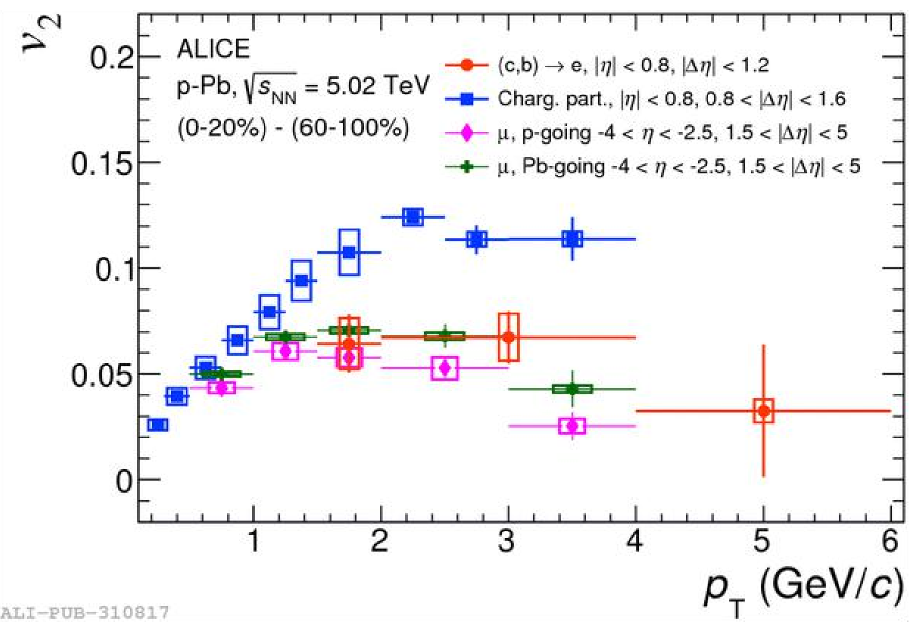


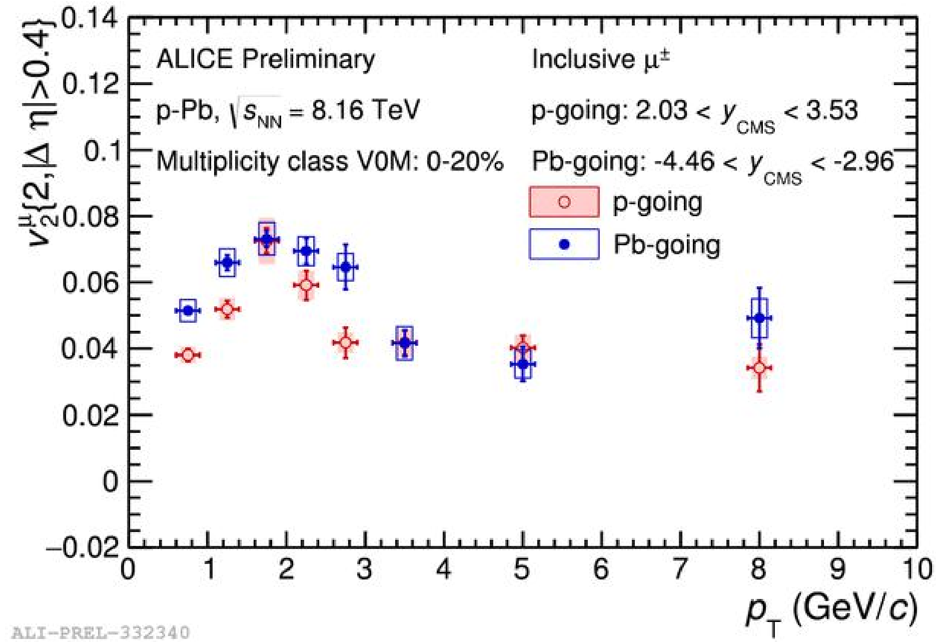


- **b-tagged jet cross section and R_{pPb}** measured for $10 < p_T < 100$ GeV/c
  - Tagging based on reconstructed secondary vertex
- Data is well described by POWHEG simulatons within uncertainties
- **R_{pPb} consistent with unity** within uncertainties in the measured p_T range

Asymuthal anisotropy in p-Pb

PRL 122, 072301



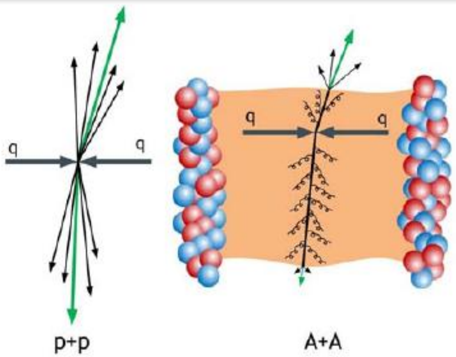


- **Collectivity of HFE and HFM in small systems**
  c,b→e at mid-rapidity, c,b→μ forward/backward
  - Values of e and μ v_2 comparable with each other within uncertainties
  - Low-p_T: comparable to charged hadrons
  - Mid-p_T: about half the charged hadron v_2
  - Tendency of smaller p-going than Pb-going v_2

Heavy ions: hot nuclear effects

- ***Nuclear modification***

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



  - **Collisional energy loss**
  - **Energy loss via gluon radiation**
  - Dead cone effect → expected mass ordering:

    $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \rightarrow ?\ R_{AA}^{h} < R_{AA}^{D} < R_{AA}^{B}$
  - Color charge effect (HF is mostly quarks <=> gluon contribution in LF)
  - **Change of fragmentation: Baryons, jets**

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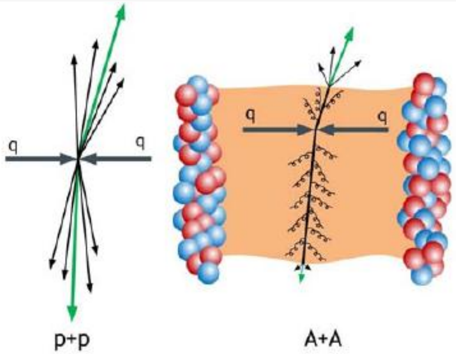

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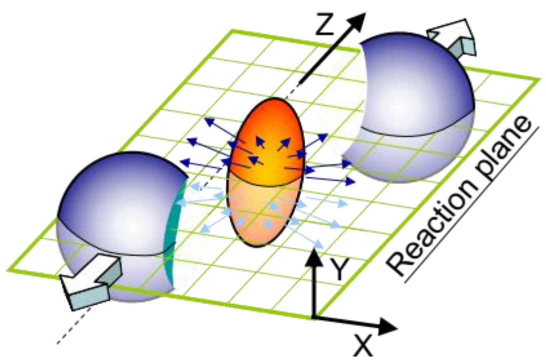
  - **Change of fragmentation: Baryons, jets**

- ***Collectivity:*** **strongly coupled medium => substantial v_n**

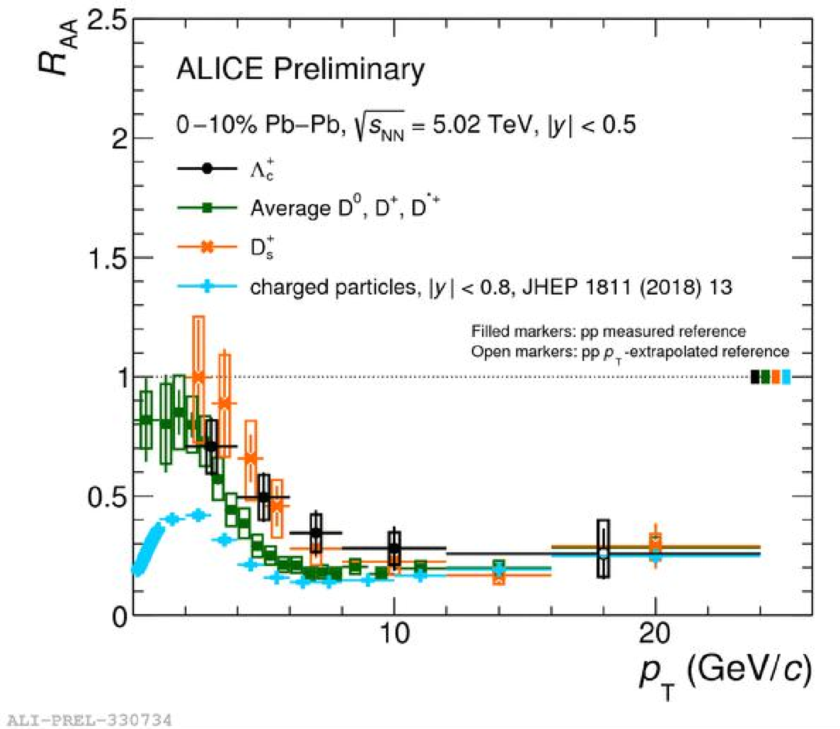
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n(\varphi - \Psi_R)\right)\right)$$

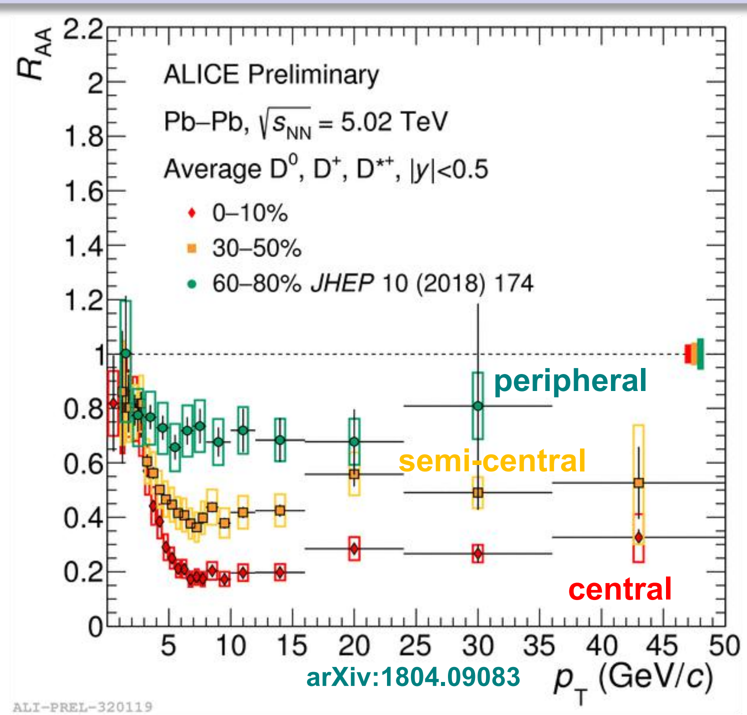
$$v_n = \langle \cos(n(\varphi - \Psi_R)) \rangle$$



  - 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?

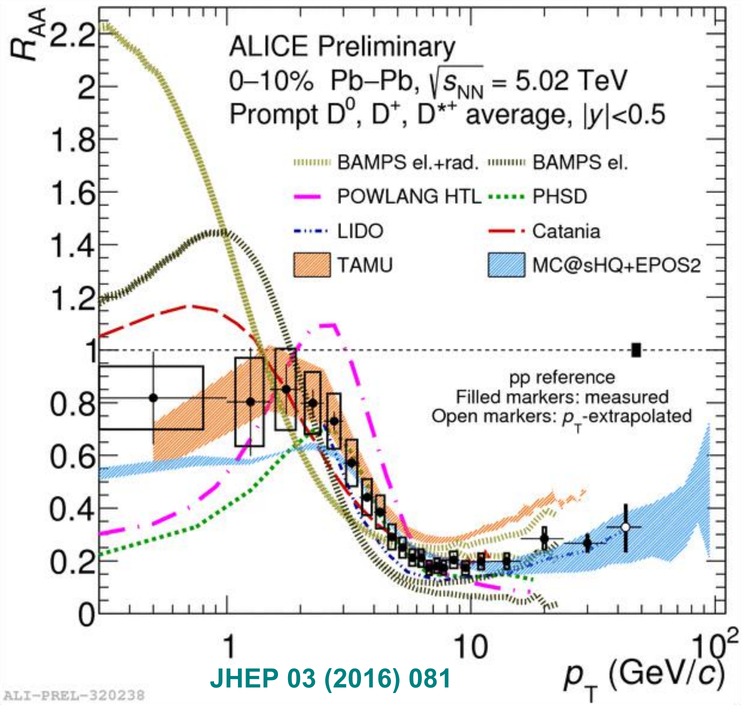
Pb-Pb: Suppression of charm

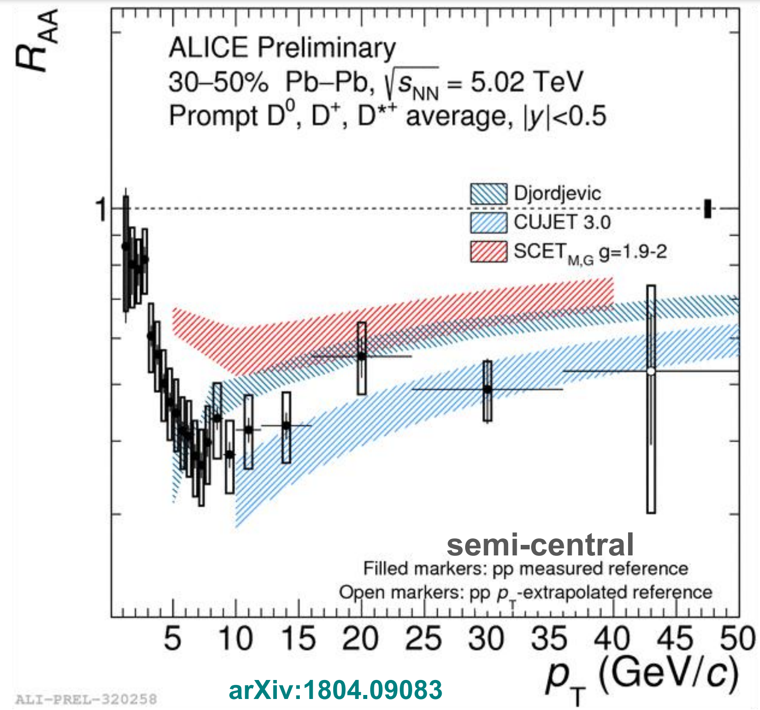




- D^0 measurements down to p_T~0
- ***High-p_T***: Suppression pattern similar to light flavor
  - **Mass ordering?** Expected $\Delta E_q > \Delta E_c$ but observe $R_{AA}^h \approx R_{AA}^D$
- ***Low-p_T***: Charm suppression is significantly weaker than light flavor
  - **Coalescence of light and charm quarks?**

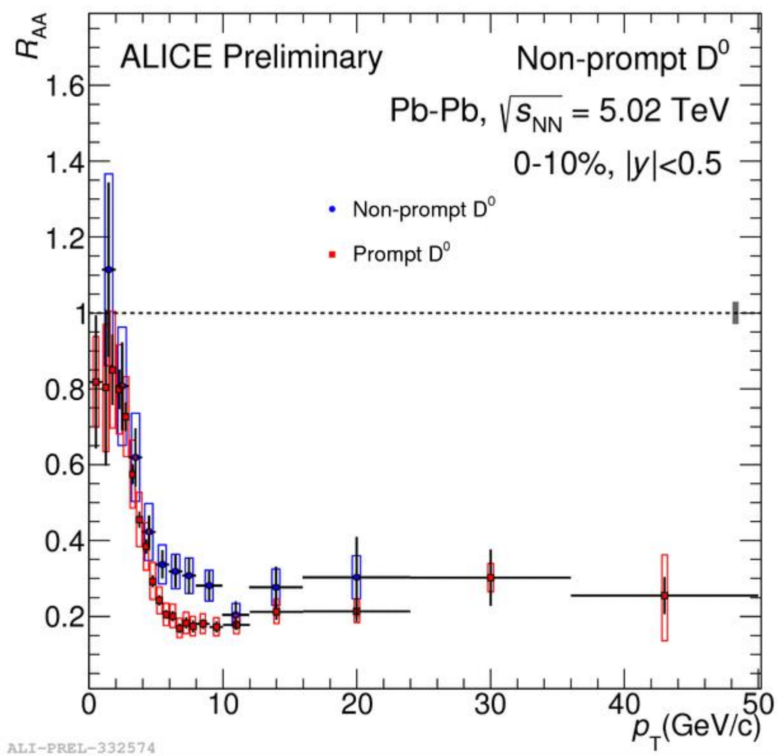
Pb-Pb: Suppression of D mesons





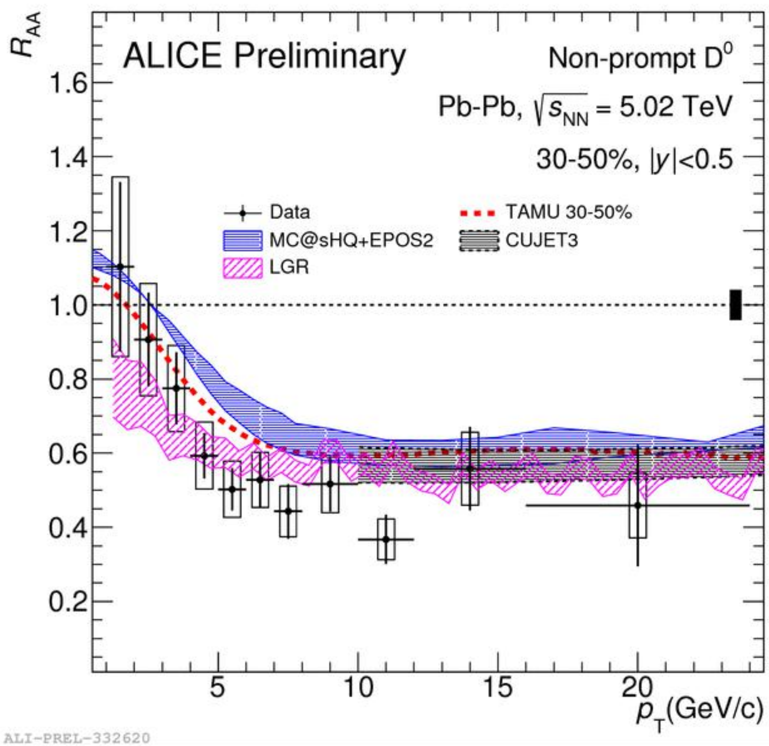
- D^0 measurements down to p_T~0
- ***High-p_T***: Suppression pattern similar to light flavor
  - **Mass ordering?** Expected $\Delta E_q > \Delta E_c$ but observe $R_{AA}{}^h \approx R_{AA}{}^D$
  - Different fragmentation, p_T-slopes, color charge effects level out ordering
- ***Low-p_T***: Charm suppression is significantly weaker than light flavor
  - **Coalescence of light and charm quarks?**
  - **Several models give good description, low discrimination power**

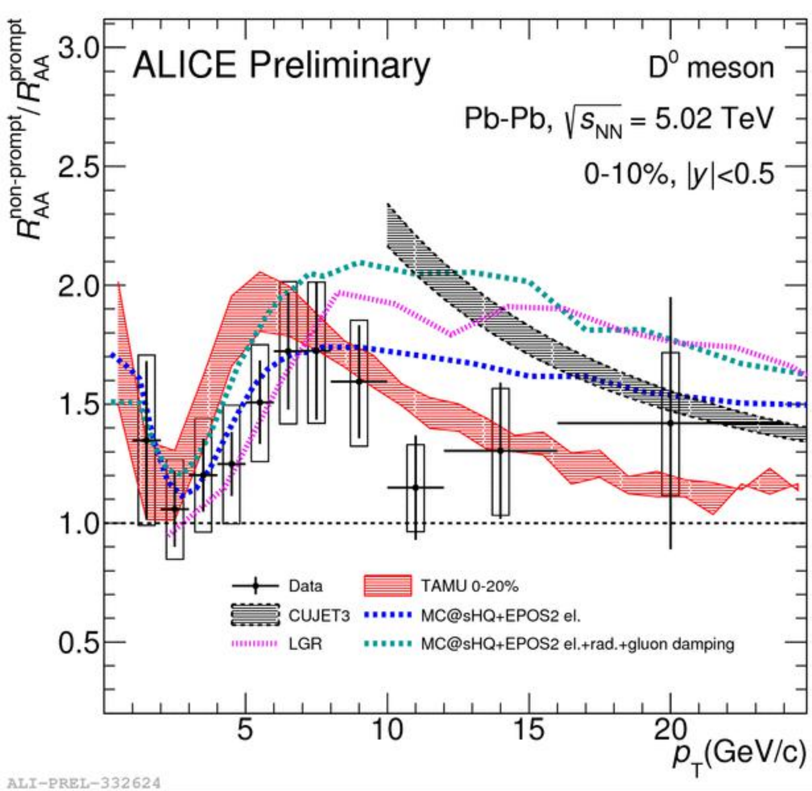
Prompt and non-prompt D mesons



- Non-prompt D mesons: access to beauty suppression in Pb–Pb collisions
    - Intermediate p_T: non-prompt D^0 is less suppressed than prompt D^0

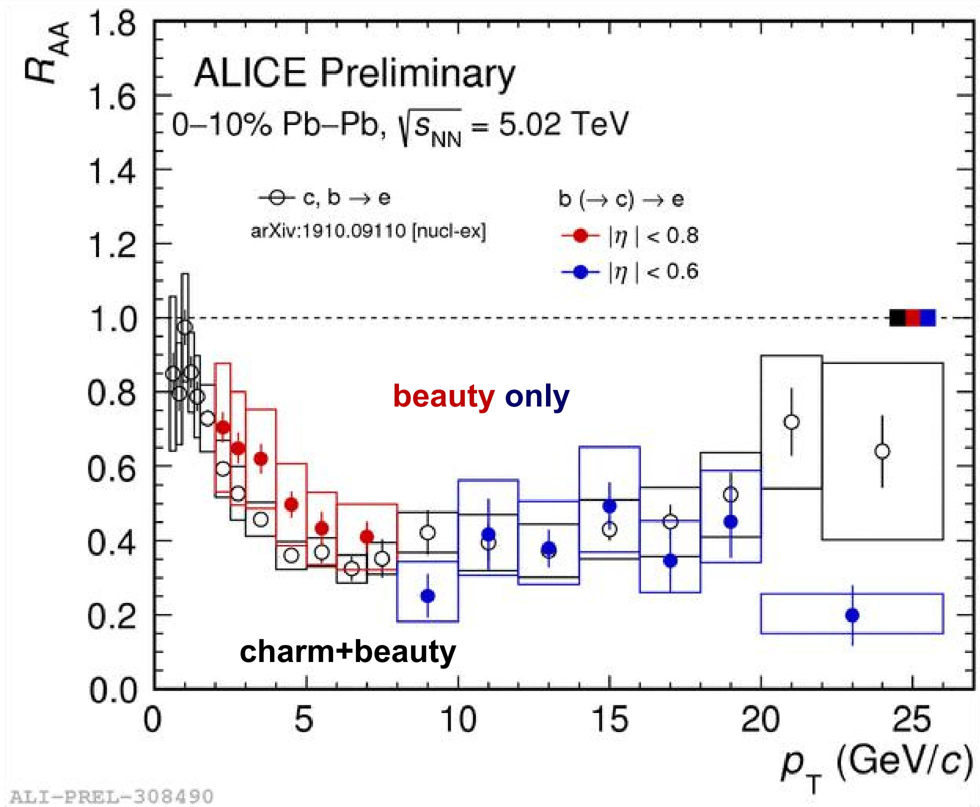
Prompt and non-prompt D mesons





- Non-prompt D mesons: access to beauty suppression in Pb–Pb collisions
  - Intermediate p_T: non-prompt D^0 is less suppressed than prompt D^0
- Calculations including flavour-dependent energy loss describe it
  - Ratio helps cancel some of the model and data uncertainties

Charm and Beauty: HF decay electrons



- 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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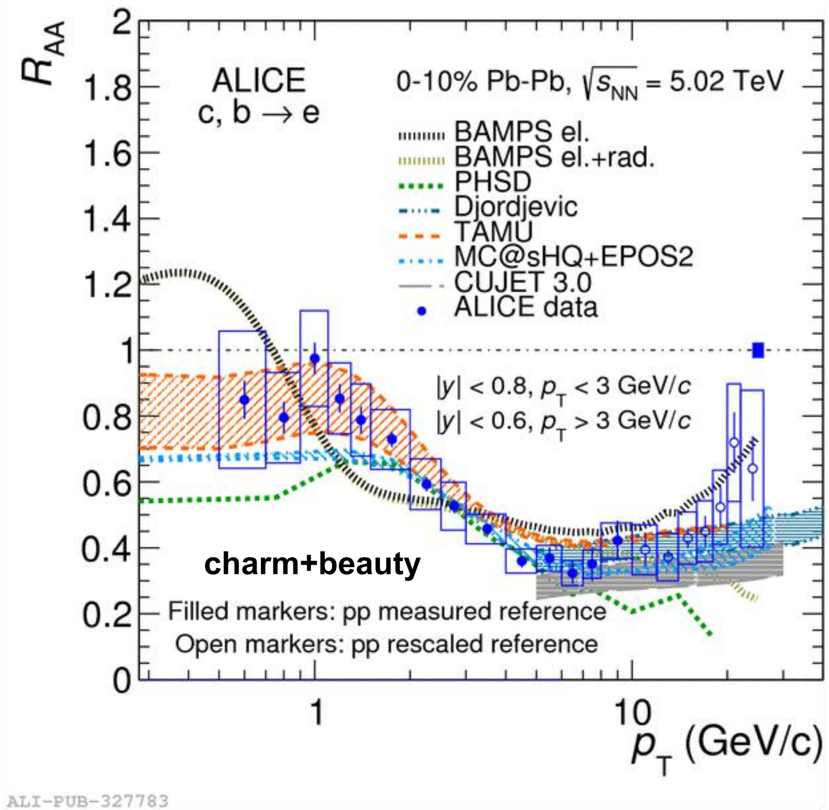
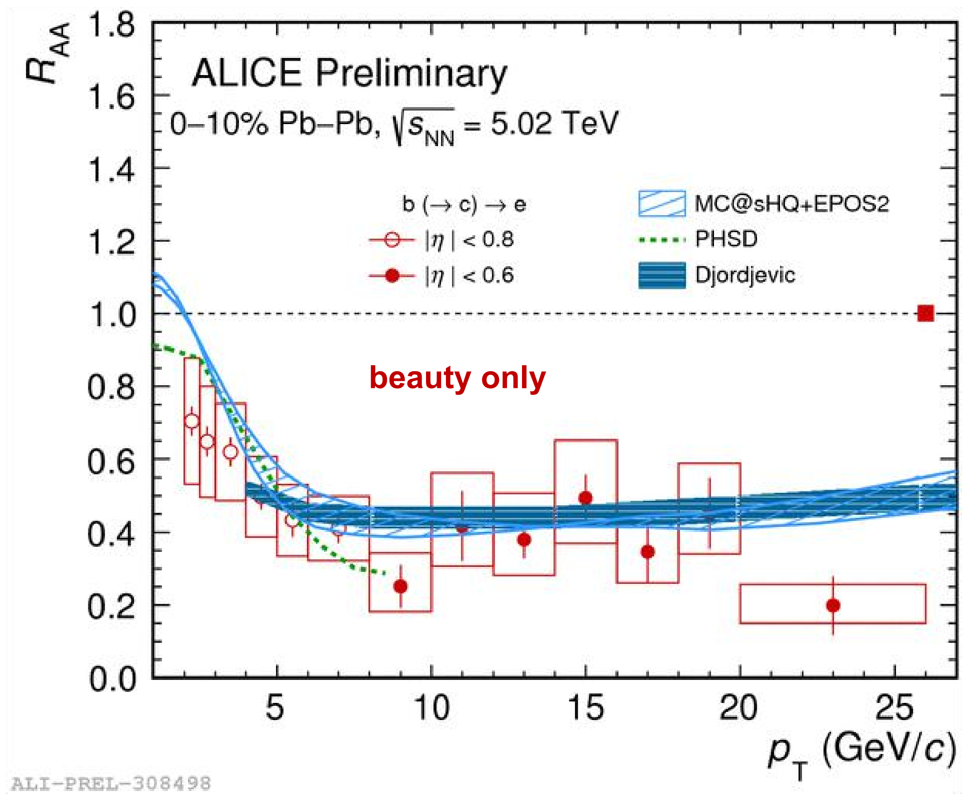
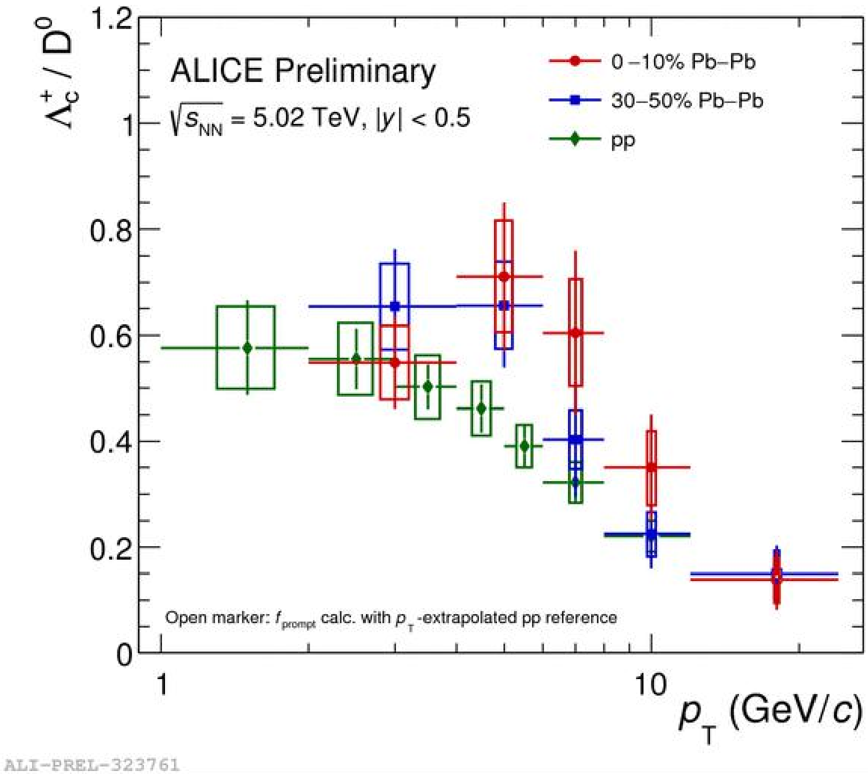
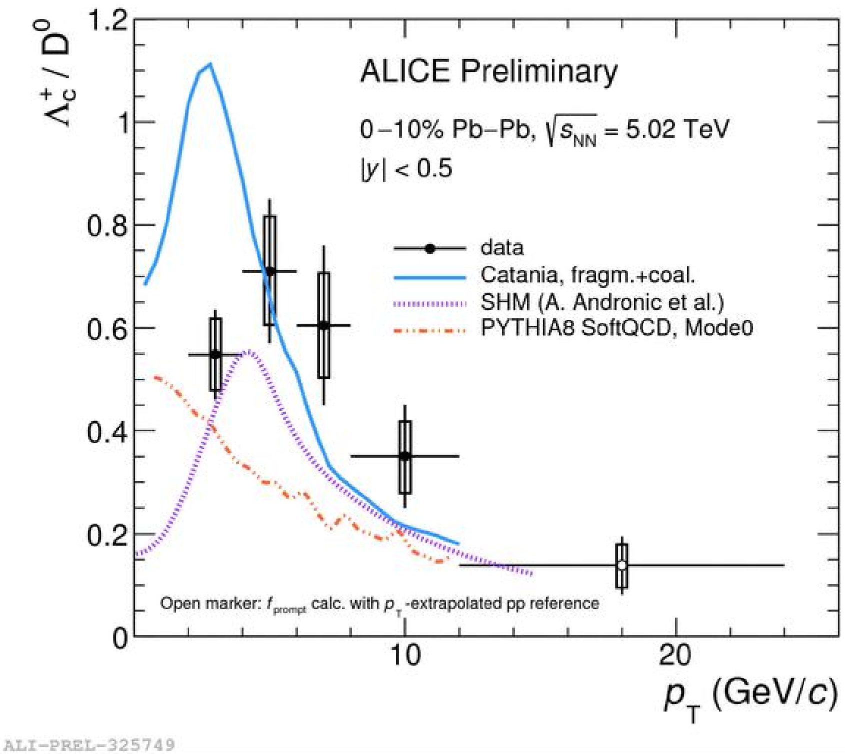




- Significant (c,b)→e suppression in Pb–Pb collisions from medium to high p_T
  - Note: Results in p–Pb collisions are consistent with unity
- Separated beauty-decay electrons hint a weaker b-quark suppression
- Models describe both (c,b)→e and b(→c)→e within uncertainties
  - Difference understood by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

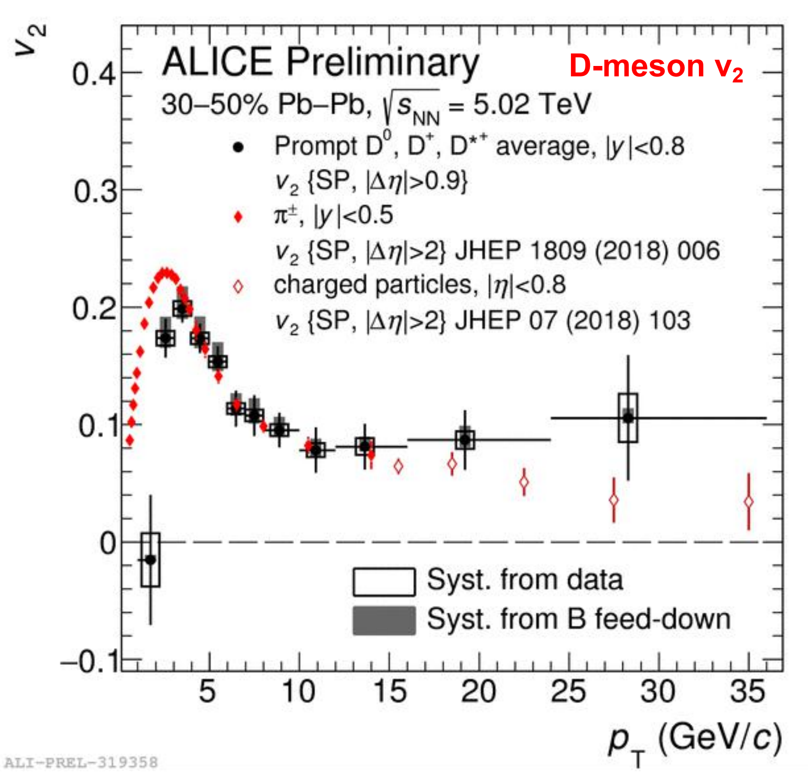
Production of Λ_c in Pb-Pb collisions

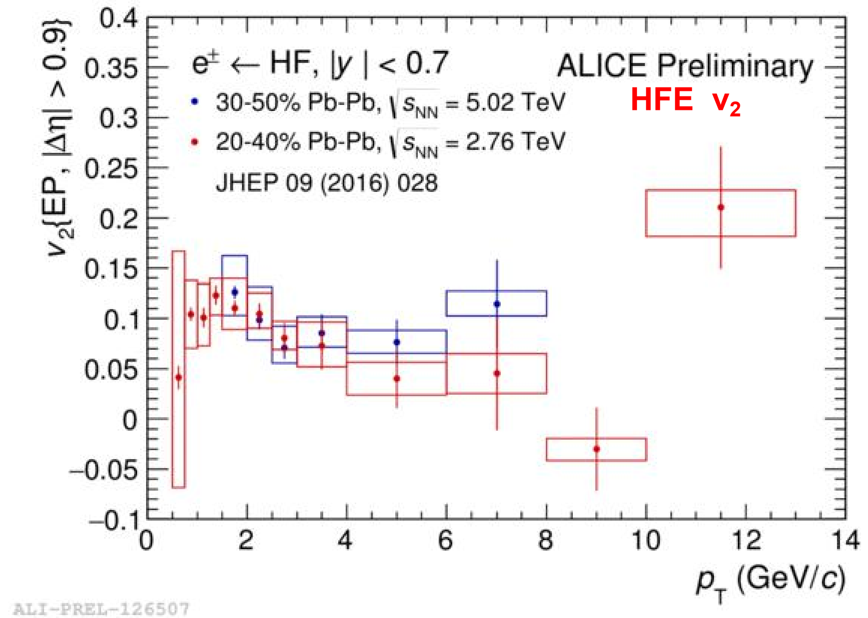




- Charged baryon/meson ratio Λ_c/D_0
  - mid-p_T: tendency of moderate increase from pp to central Pb–Pb collisions
  - Models include recombination follow the same trend as data
- Hint of baryon to meson enhancement

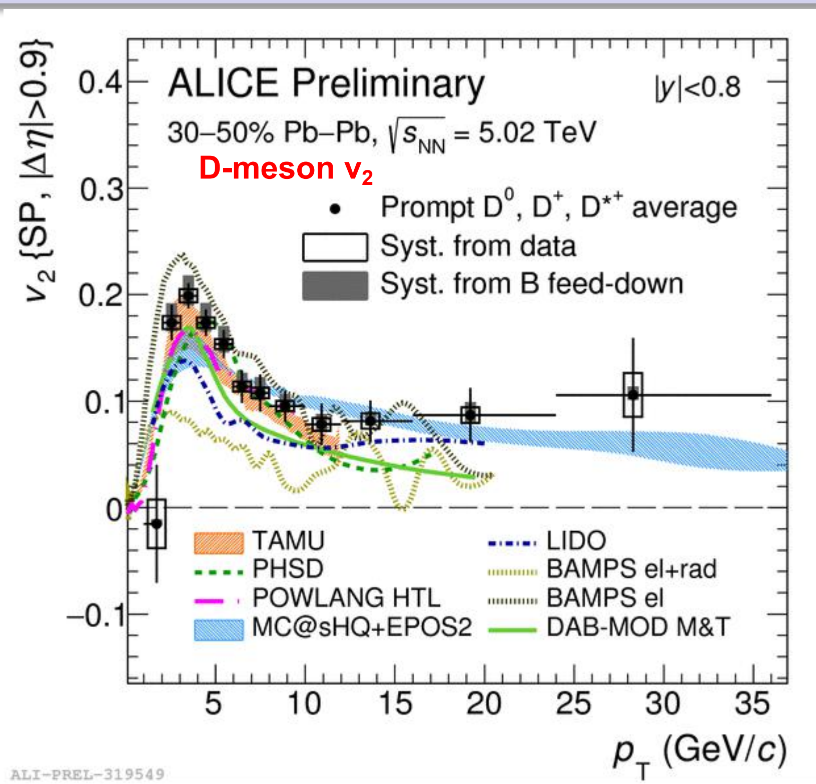
Heavy-flavor azimuthal anisotropy

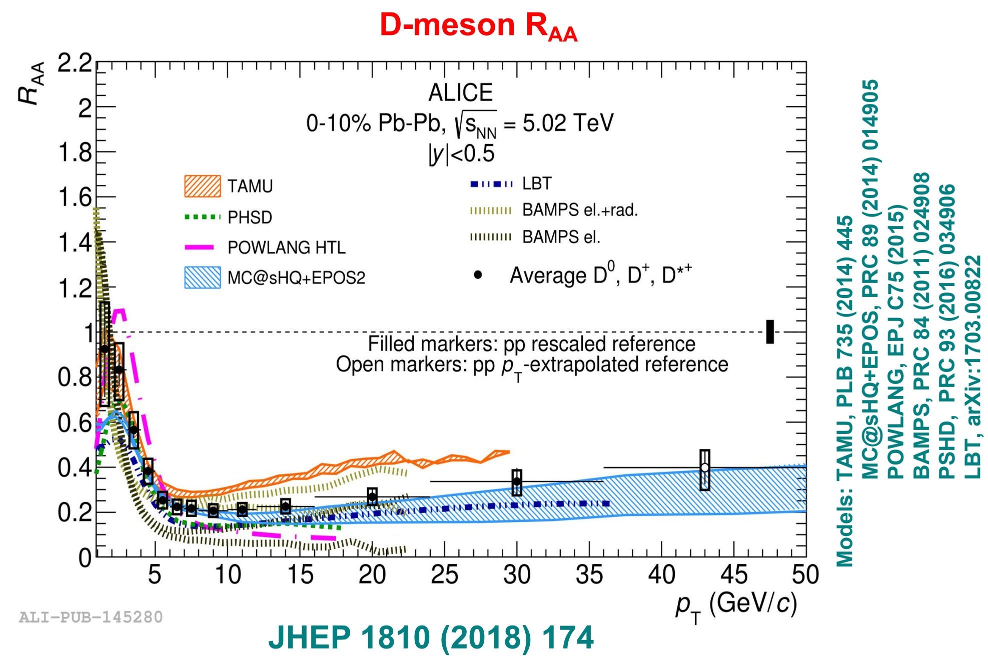




- **D mesons flow**: A significant v_2 of D mesons is observed at the LHC
  - **D-meson v_2** is qualitatively similar to **charged partice v_2** at $\sqrt{s_{NN}}$=5.02 TeV
- **Heavy-flavor decay electrons flow:** Significant v_2 observed at the LHC
  - HFE v_2 at $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$=5.02 TeV agree within uncertainties

Azimuthal anisotropy of D: and R_{AA}

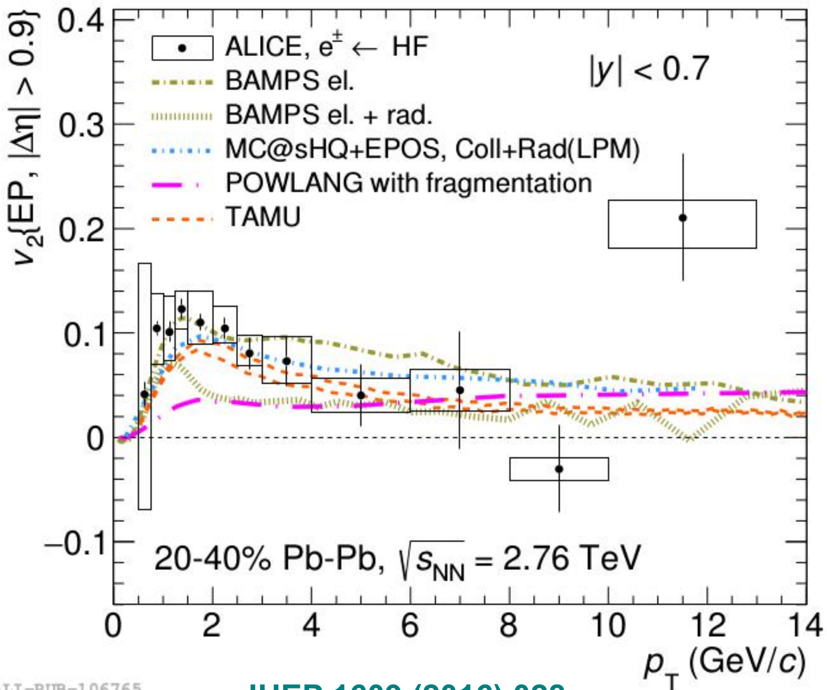




- **D mesons flow**: A significant v_2 of D mesons is observed at the LHC
  - D-meson v_2 is qualitatively similar to charged particle v_2 at $\sqrt{s_{NN}}=5.02$ TeV
- Models in which charm picks up **flow via recombination or collisional energy loss** do better in reproducing R_{AA} and v_2 simultaneously

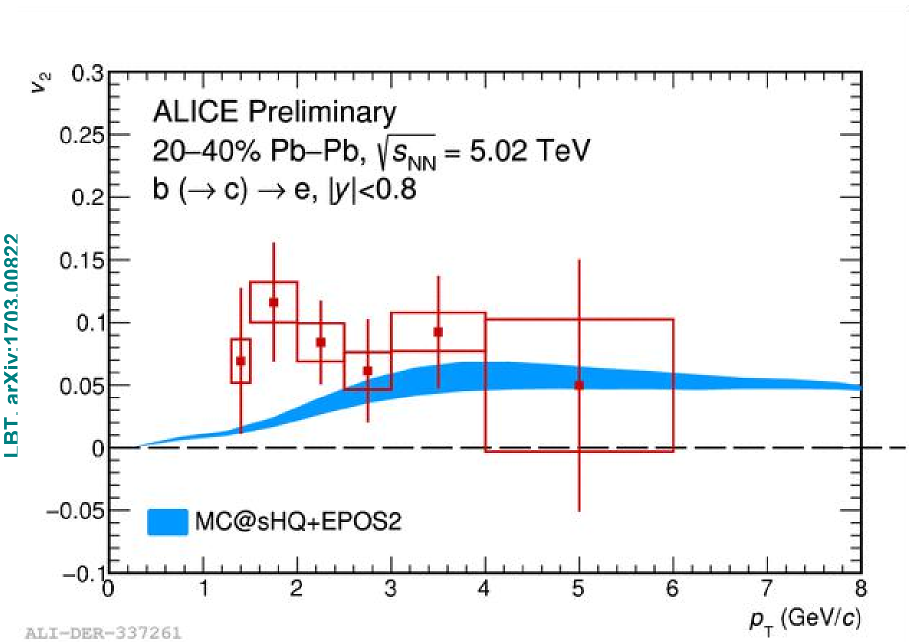
R_{AA} and v_2 together provide strong constraints on models

Azimuthal anisotropy of HFE: c vs. b



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



- **HFE: significant v_2 of both the charm and beauty contributions**
  - Several models describe **HFE** v_2 (charm and beauty contributions)
  - **Separated beauty-decay electron contribution** to the v_2 qualitatively similar

Summary

QCD vacuum: pp collisions at $\sqrt{s}$=5.02, 7, 8 and 13 TeV

- *D-meson, HFE, HFM spectra* adequately described by pQCD models
- *HF-tagged jets:* information about fragmentation, model development
- *Charmed baryons:* Unexpected enhancement, recent model explanation

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  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 $\rightarrow$ *v_2 & R_{AA} constrain models*
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Run-3 upgrade: ~100x stats; precision beauty measurements

Thank you!

and enjoy Budapest

Physics reach after LS2 (2019-20)

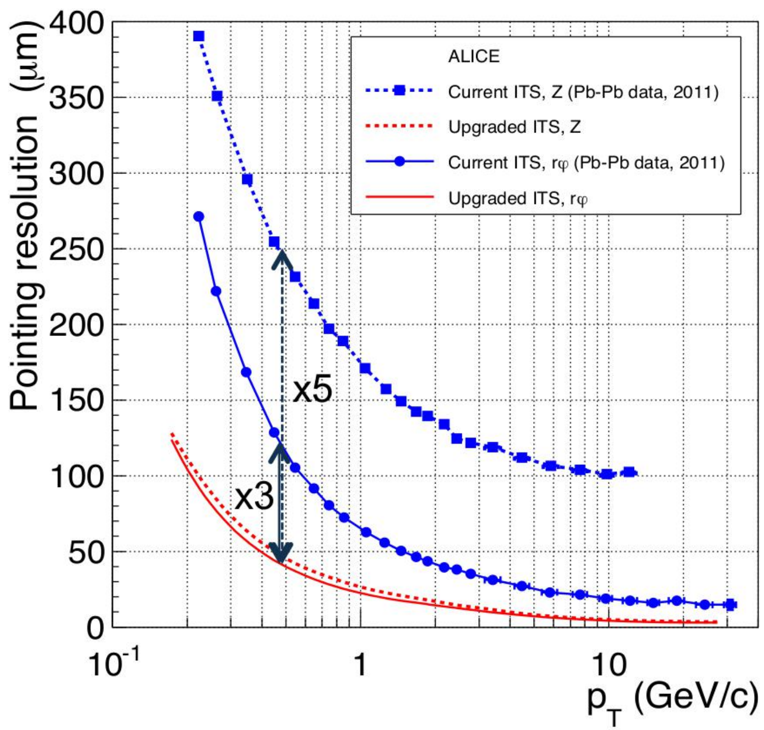
Observable	Current, $0.1\,\mathrm{nb}^{-1}$ p_T^{min} (GeV/c)	Current, $0.1\,\mathrm{nb}^{-1}$ statistical uncertainty	Upgrade, $10\,\mathrm{nb}^{-1}$ p_T^{min} (GeV/c)	Upgrade, $10\,\mathrm{nb}^{-1}$ statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
D_s meson R_{AA}	4	15 %	< 2	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 %

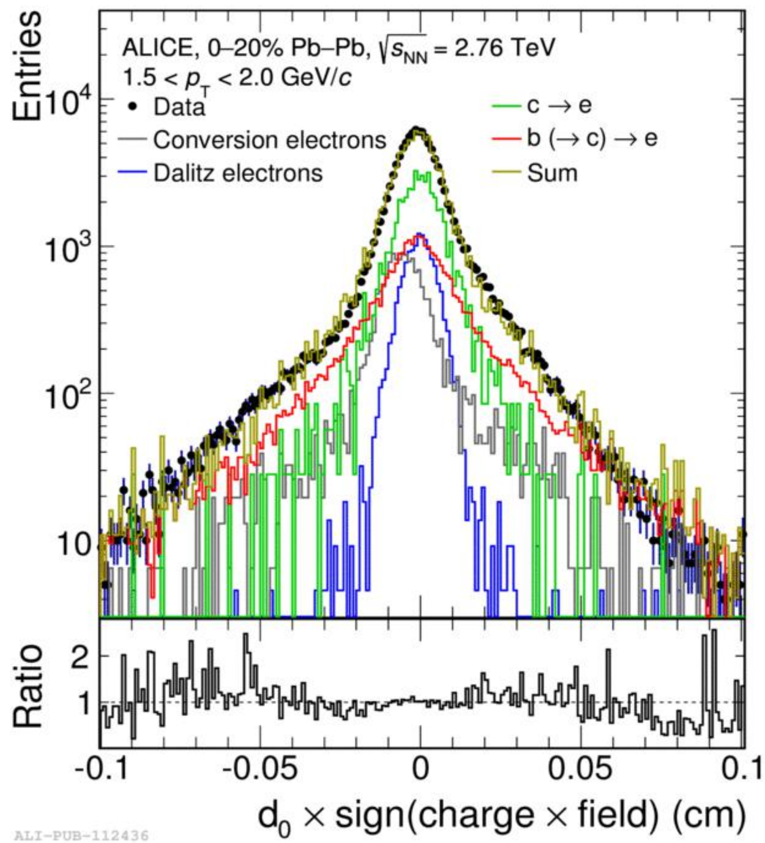
ALICE ITS upgrade TDR

ITS performance

- 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: $\sim 100\ \mu m$



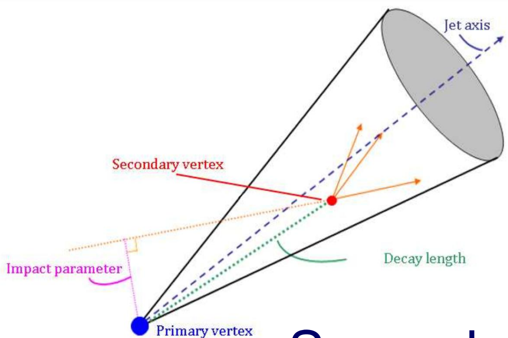


JHEP 07 (2017) 052

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

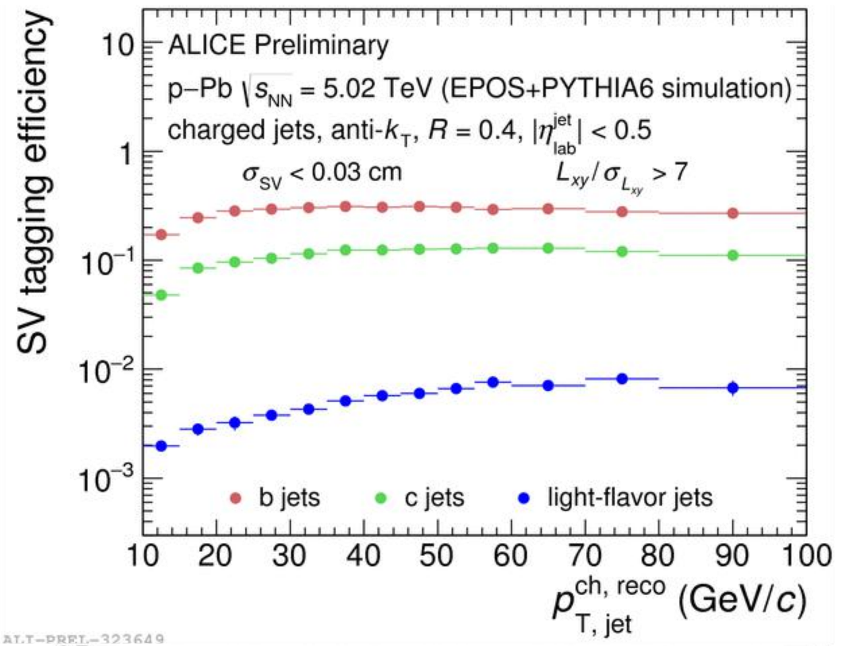
MC template fitting allows for statistical separation of charm and beauty contributions.

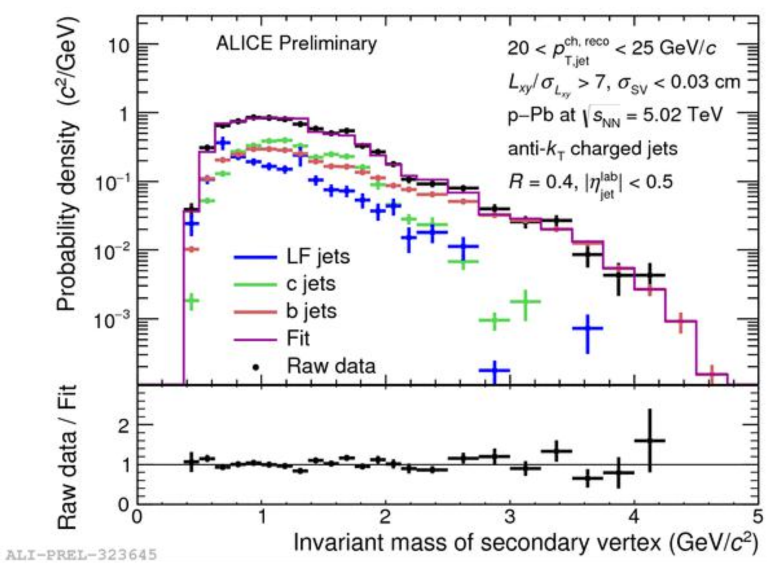
b-jet tagging performance

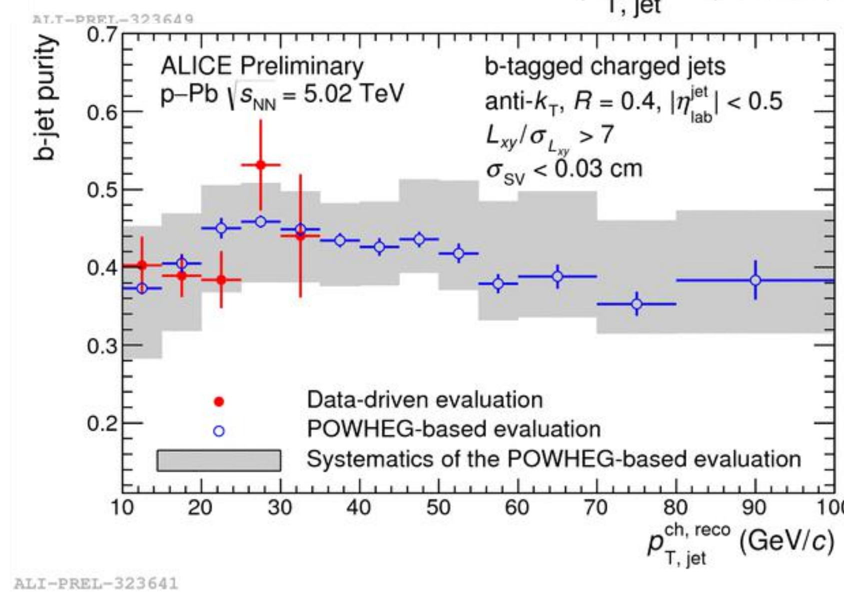


Secondary vertex method

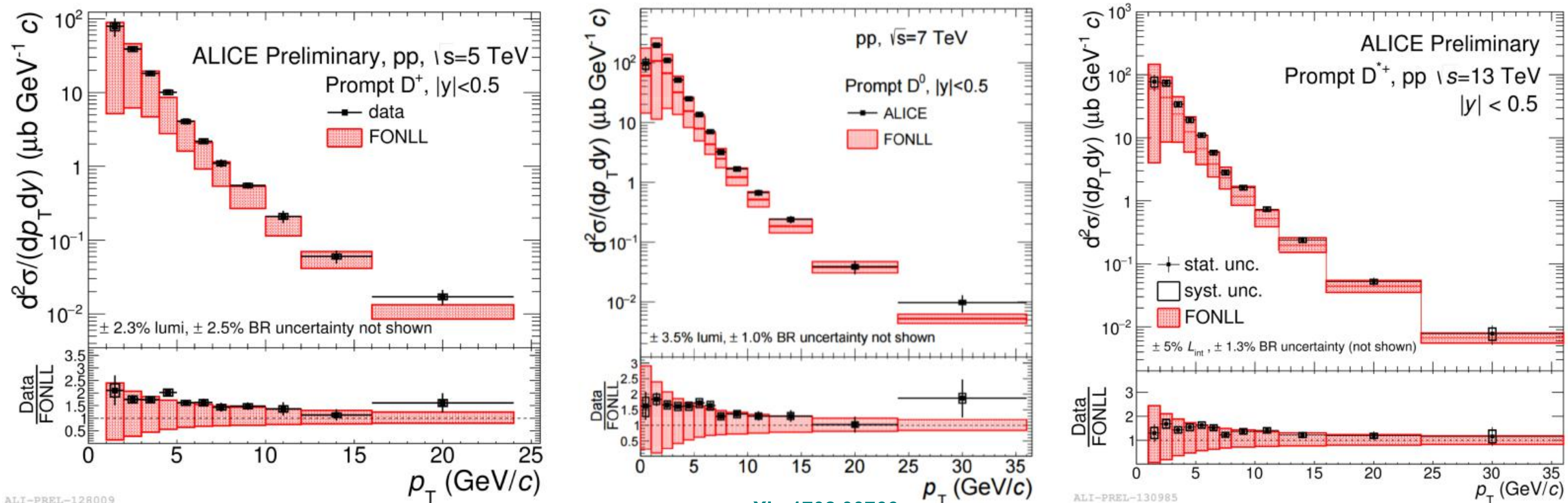
- L_{xy} : projection of decay length on the (x,y) plane
- L_{xy}/σ_{Lxy} : significance of L_{xy}
- σ_{vtx} : secondary vertex dispersion







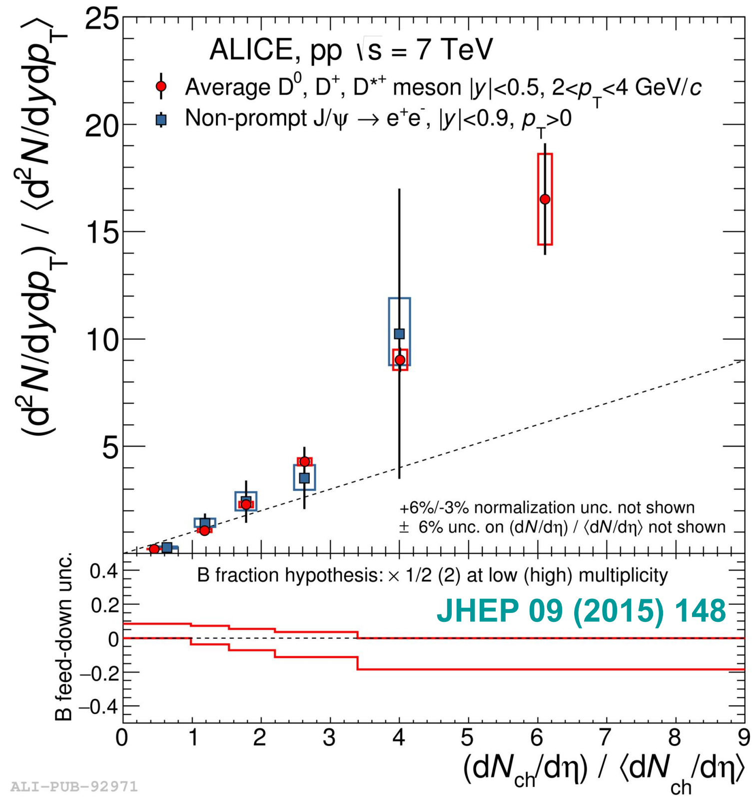
D mesons at different energies (pp)

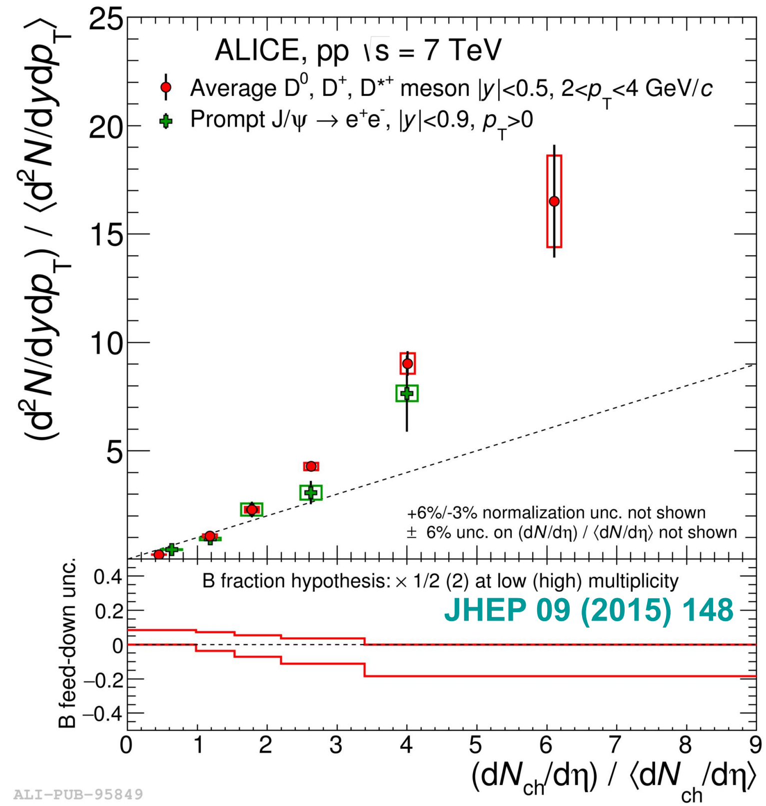


arXiv:1702.00766

- 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)



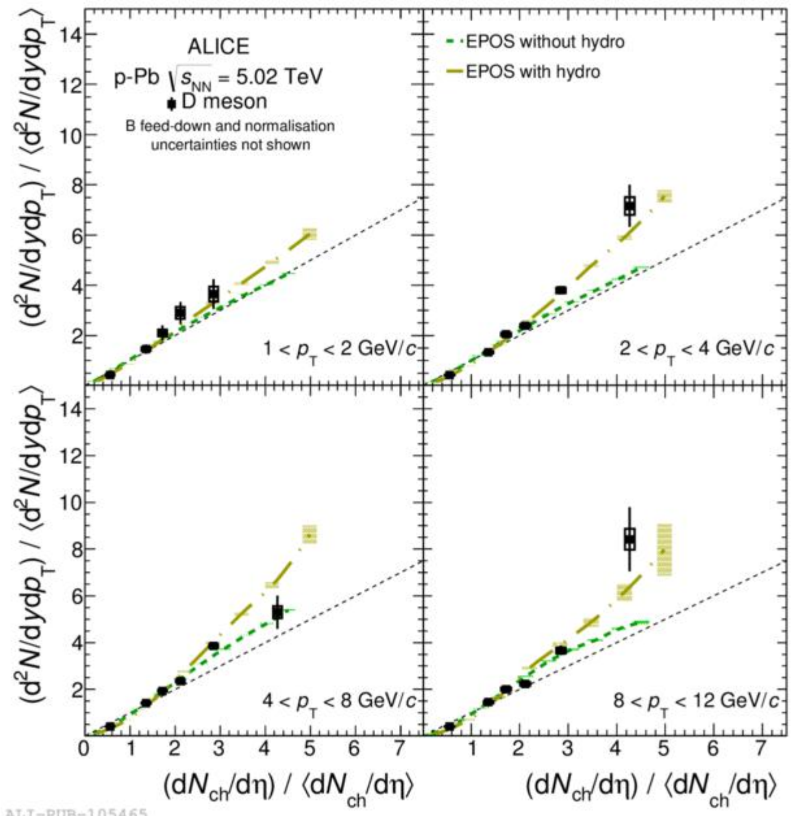


- Production vs. multiplicity of **D mesons** and muons steeper than linear
- Same trend for **non-prompt (B→)J/Ψ** as well as **prompt J/Ψ** yields

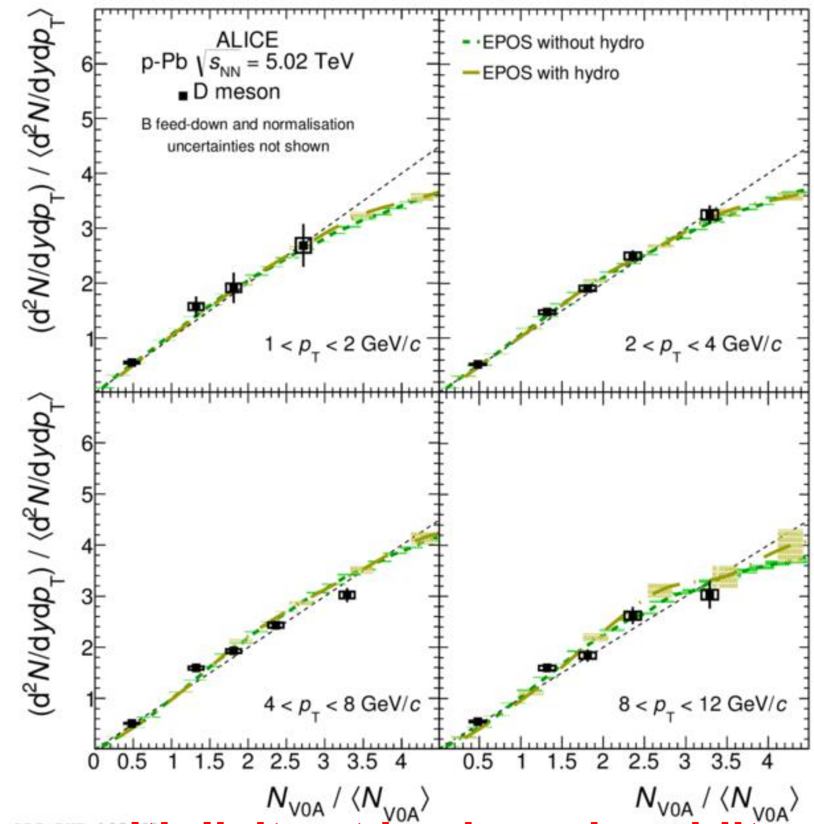
  → No strong flavour dependence

  → 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



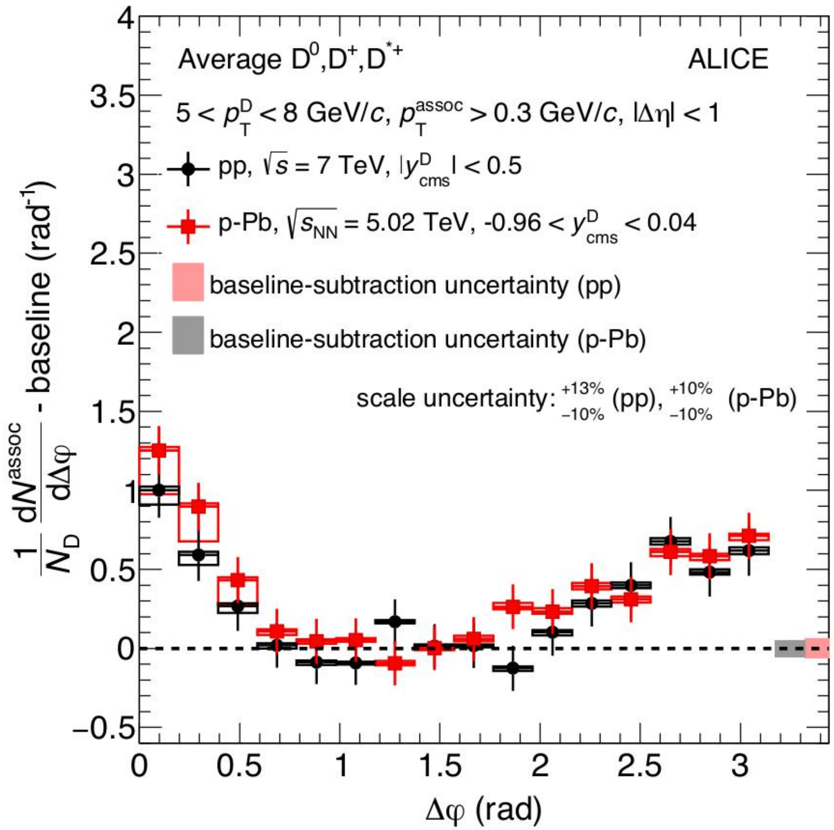
multiplicity at mid-rapidity



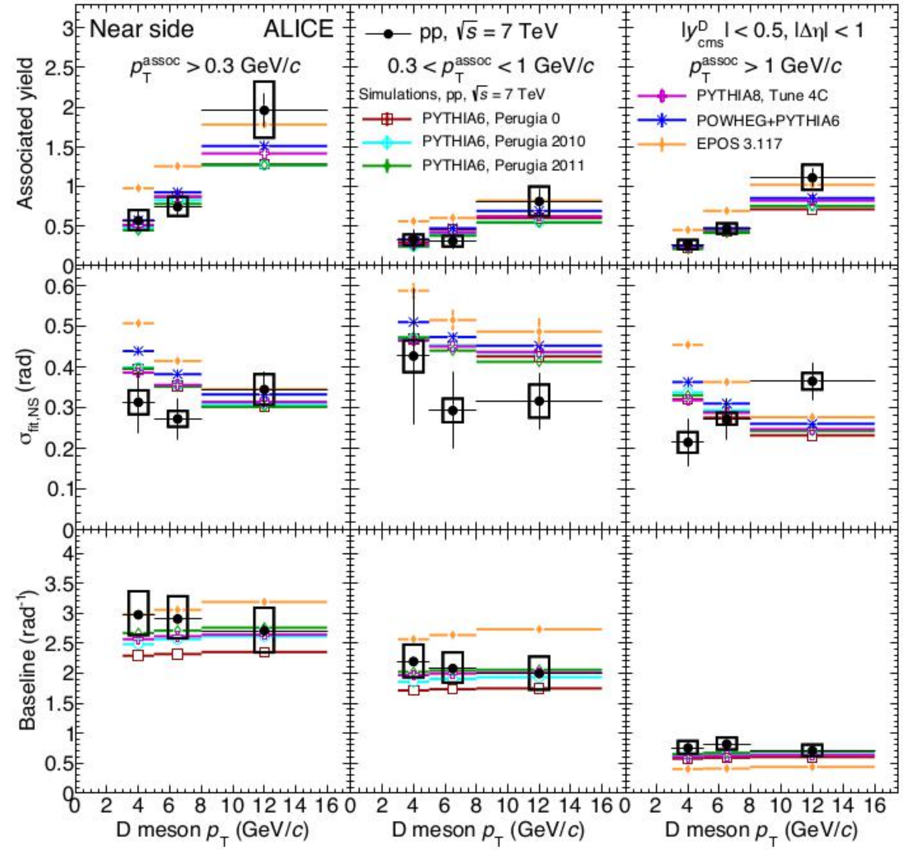
multiplicity at backward rapidity (Pb-going): test auto-correlations

- 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

D-h azimuthal correlations



ALI-DER-106234

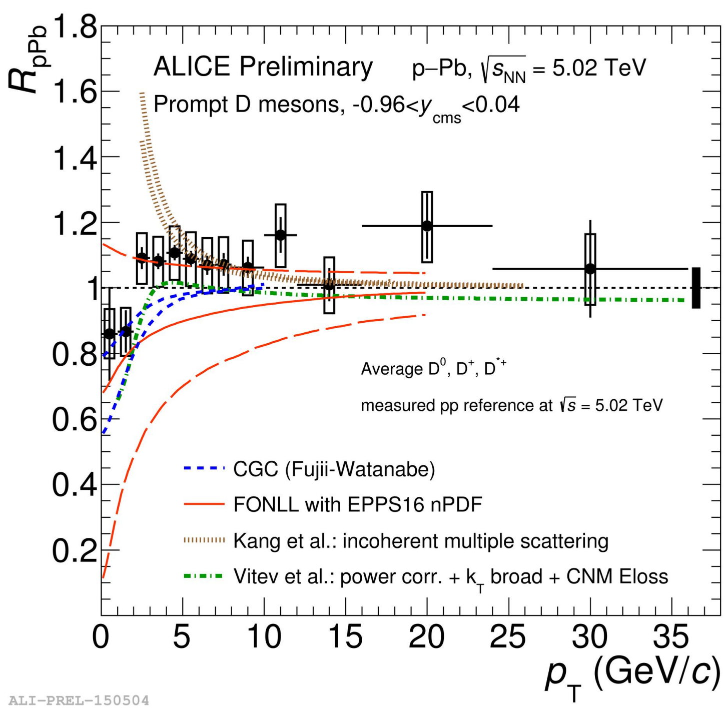


ALI-PUB-106020

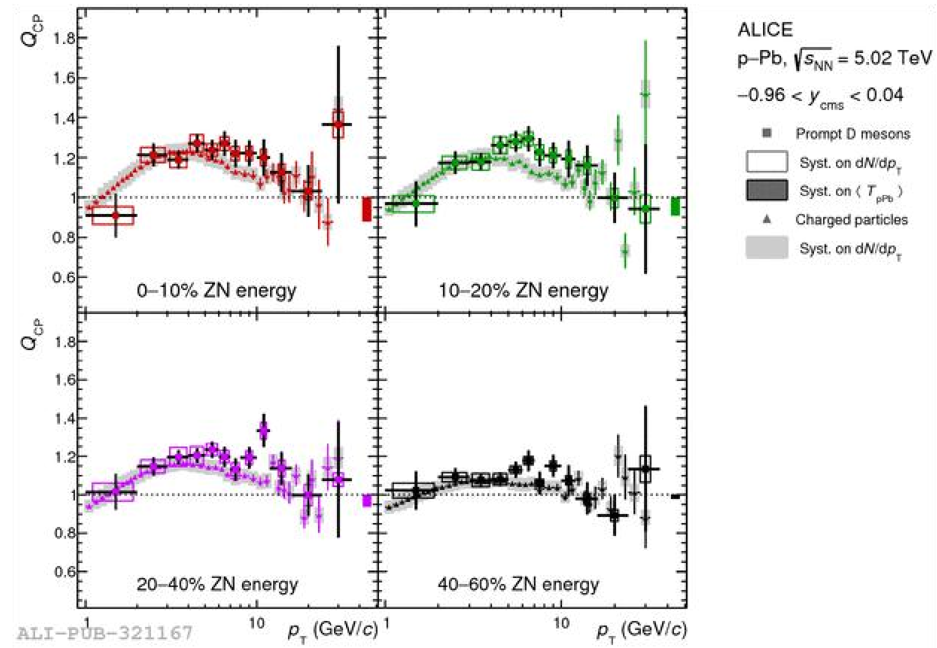
Charged hadron — D-meson correlations in azimuthal angle

- 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

CNM effects in p-Pb collisions?

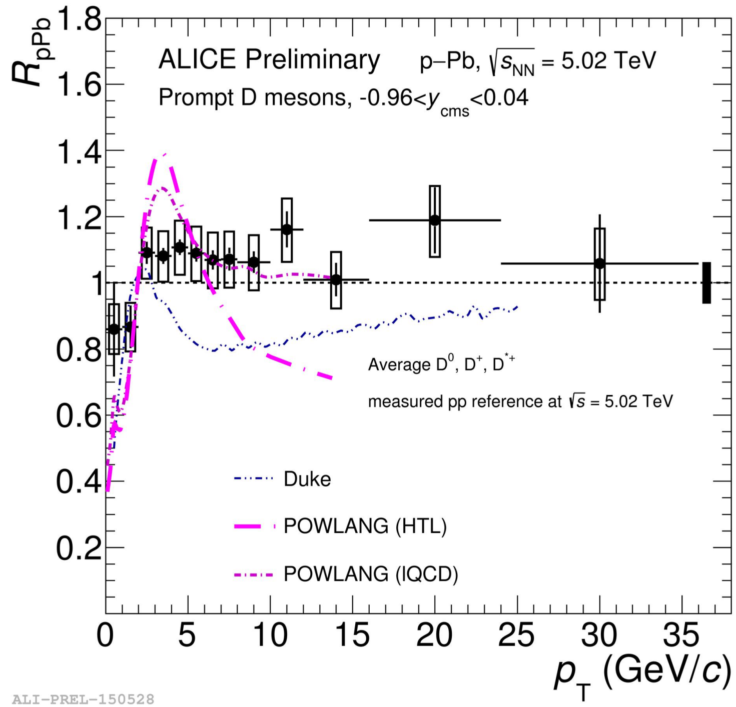


Models:
CGC, arXiv:1308.1258
MNR: NPB 373 (1992) 295
Vitev, PRC 75 (2007) 064906
Kang, PLB 740, 23 (2015)

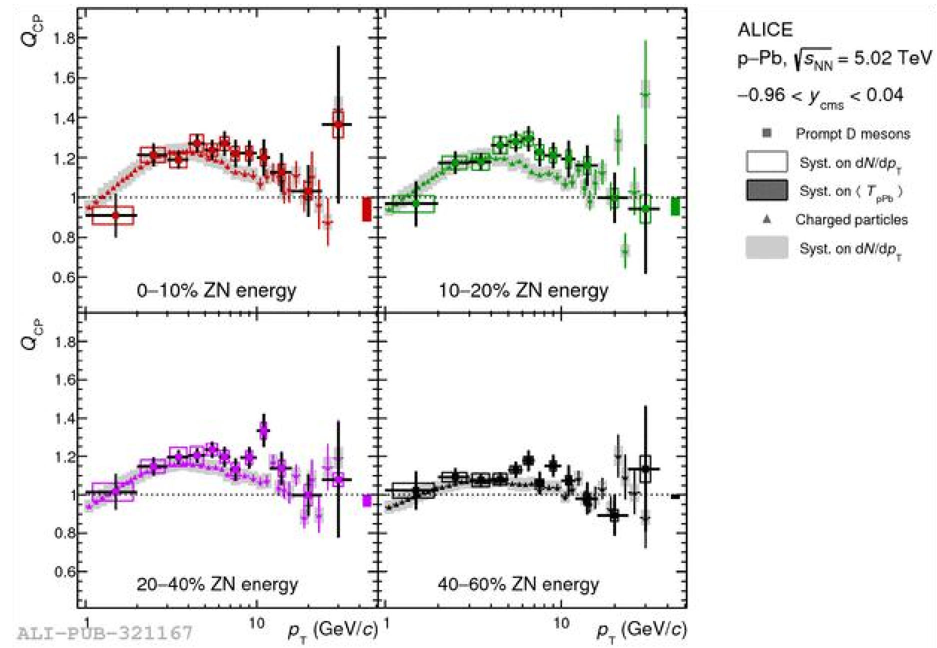


- **D-meson production in p-Pb collisions:**
  No modification w.r.t. pp collisions within uncertainties
  - No indication of CNM effects from intermediate to high p_T
  - Data described by several models containing CNM effects
- Hint of Q_{CP} > 1 for central collisions (1.5σ at 3<pT< 8 GeV/c)
  - similar to light hadrons
  - Radial flow? Initial or final-state effect?

Hot effects in p-Pb collisions?



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



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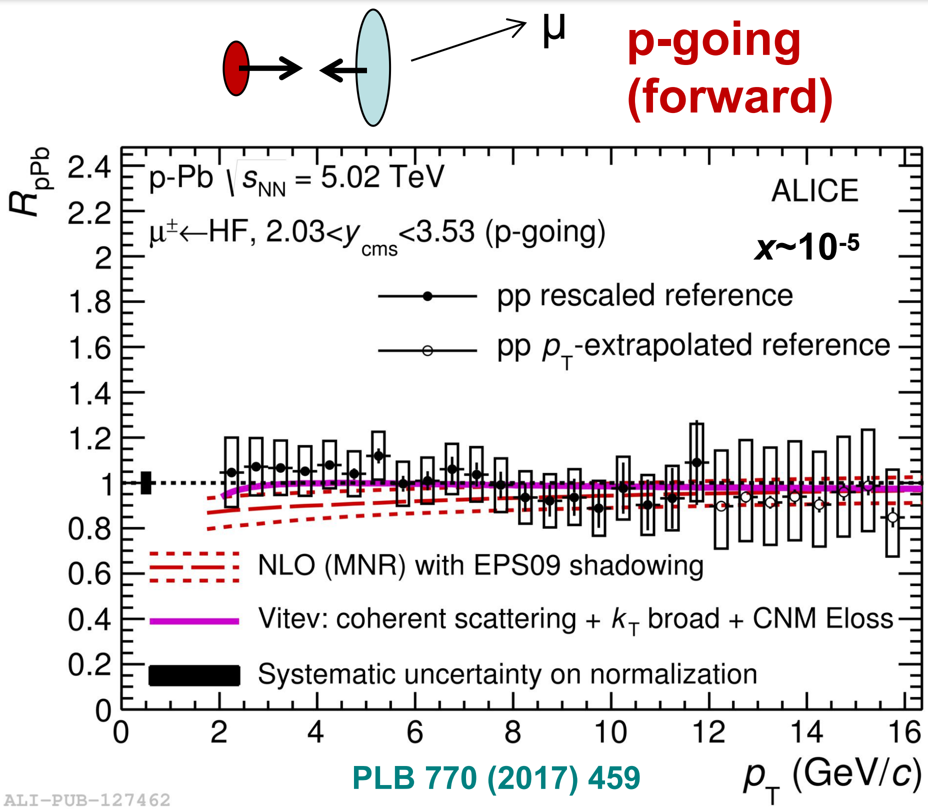
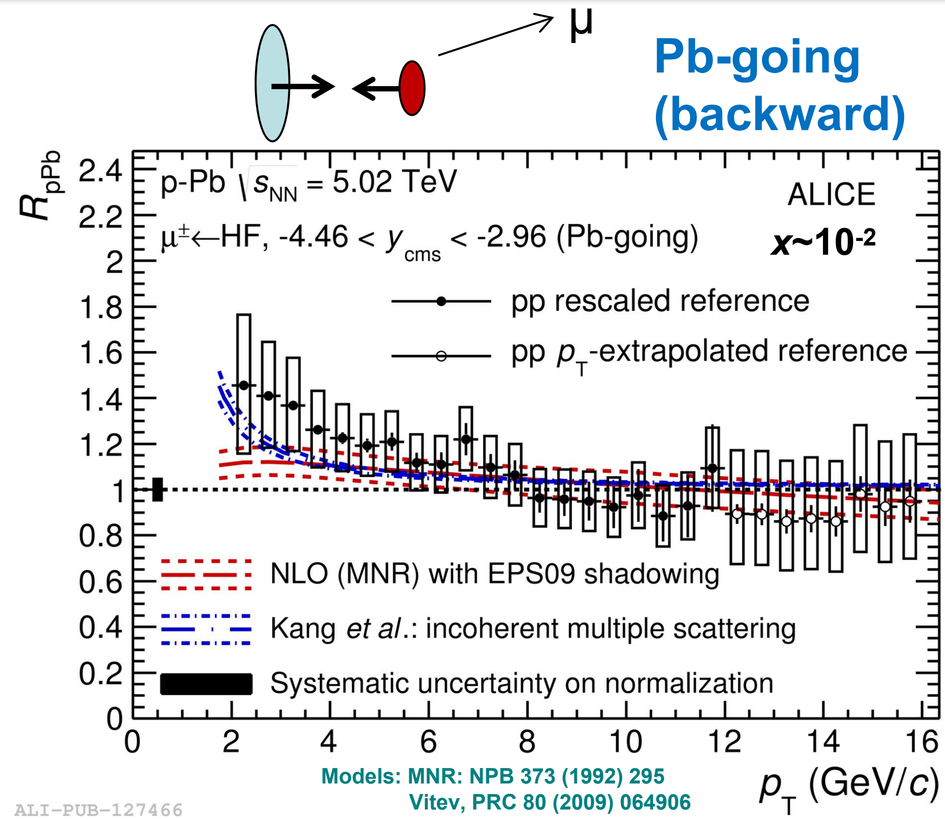
  No modification w.r.t. pp collisions within uncertainties
  - No indication of CNM effects from intermediate to high p_T
  - Data described by several models containing CNM effects
- **A model including small-volume QGP formation also describes data** (but not favored by)

CNM effects - Forward, backward



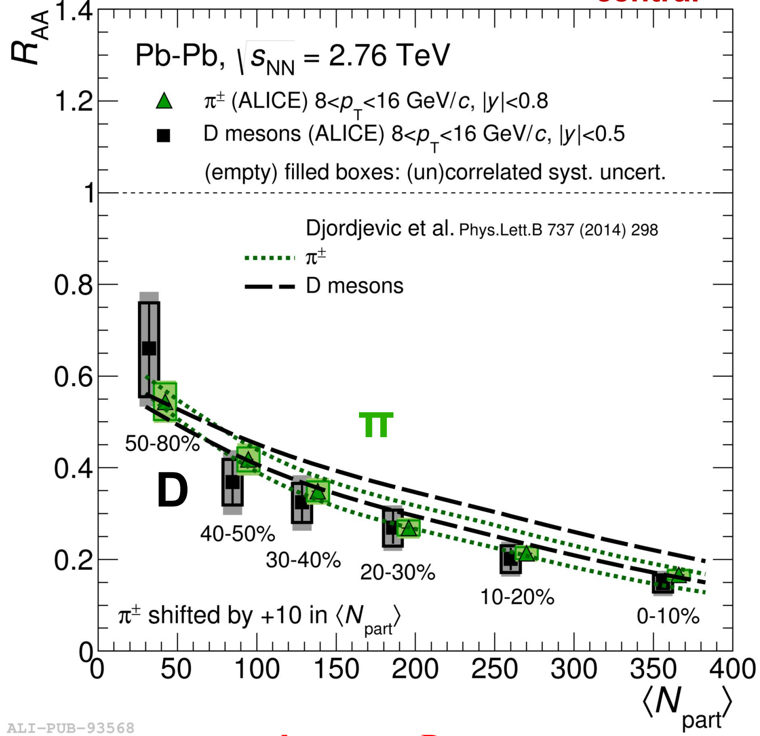
PLB 770 (2017) 459



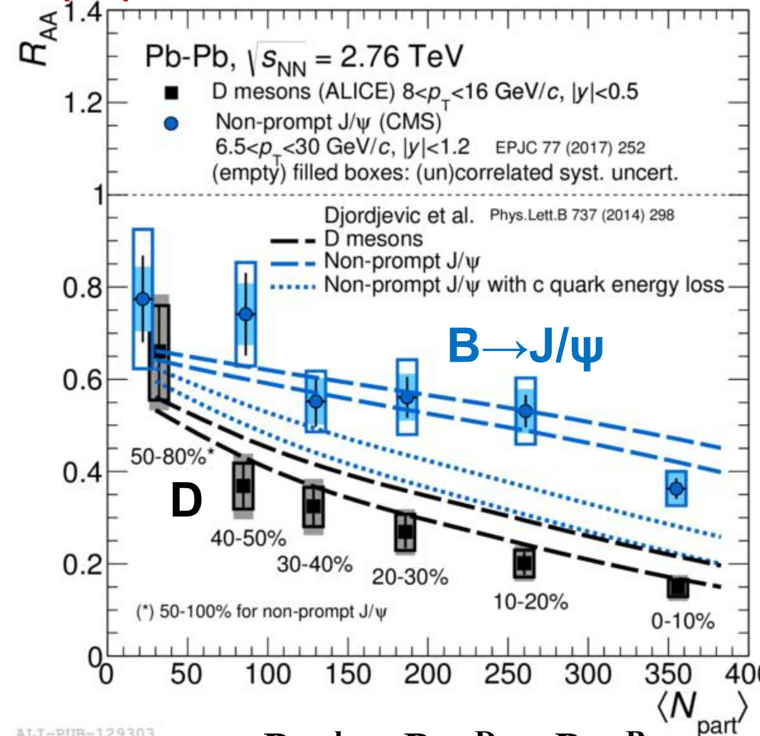
Models: MNR: NPB 373 (1992) 295
Vitev, PRC 80 (2009) 064906
Kang, PLB 740 (2015) 23

- 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



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



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

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

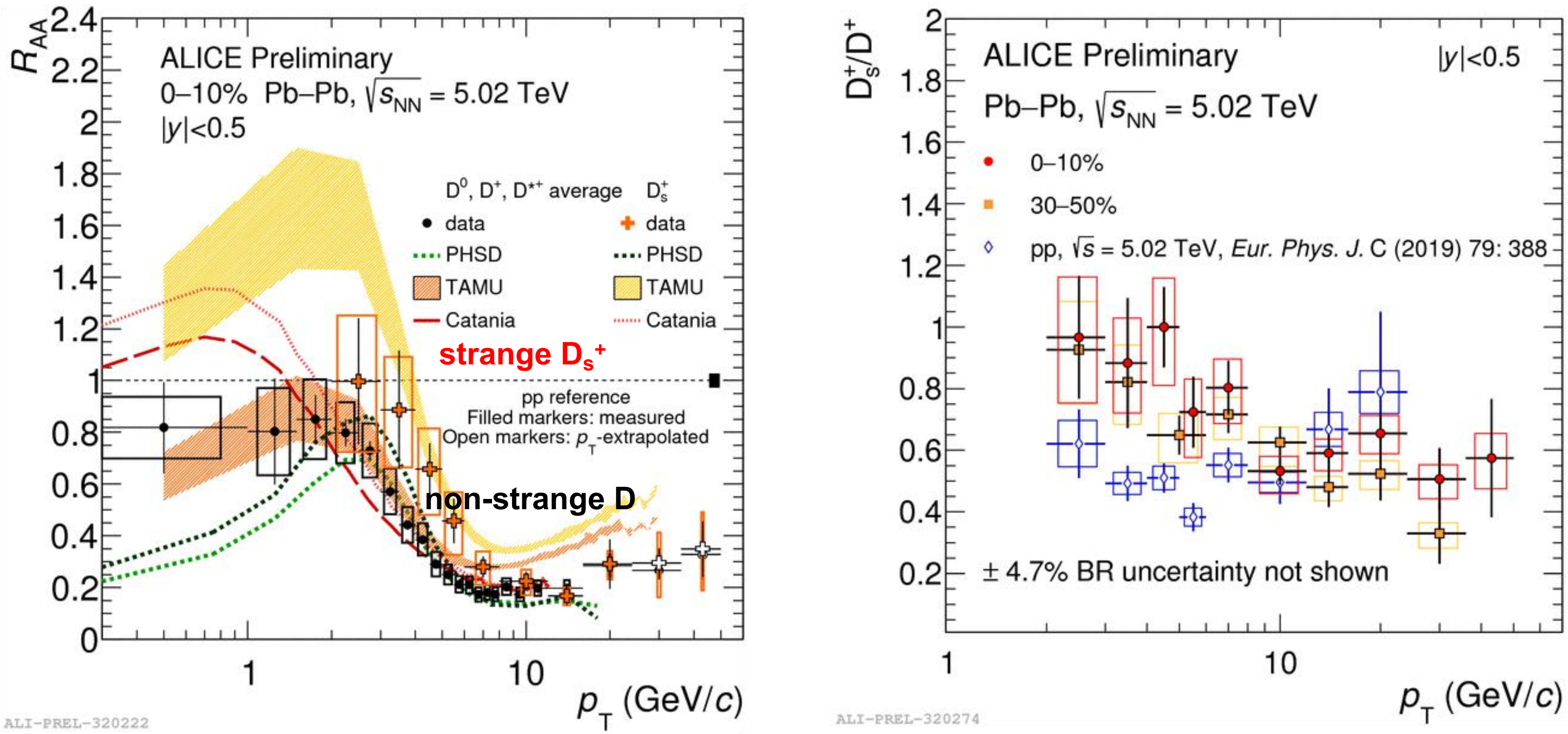
- **D-meson** suppression at high p_T consistent with **pions**

  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

Coalescence of strange and charm



- 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