Heavy-flavour measurements with the ALICE experiment at the LHC

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Heavy-flavour (HF) probes

- Heavy quarks are produced early

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

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

- Heavy quarks are (almost) conserved

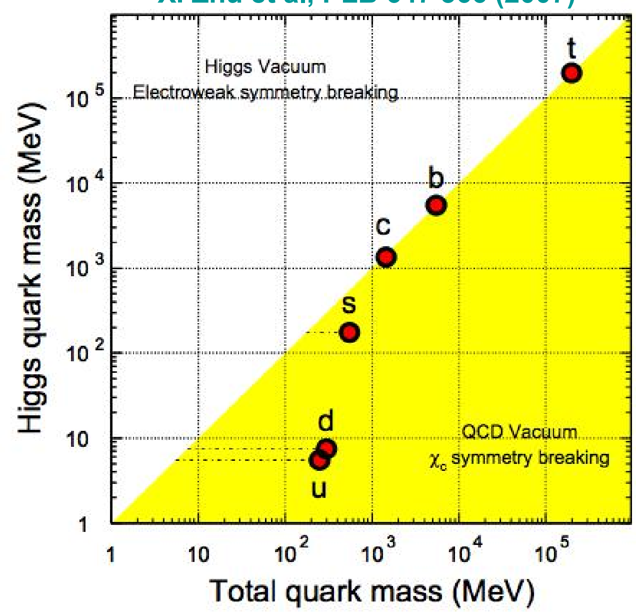
  $m \gg T_{QGP}$ (m_c~1.5 GeV, m_b~5 GeV)

  - 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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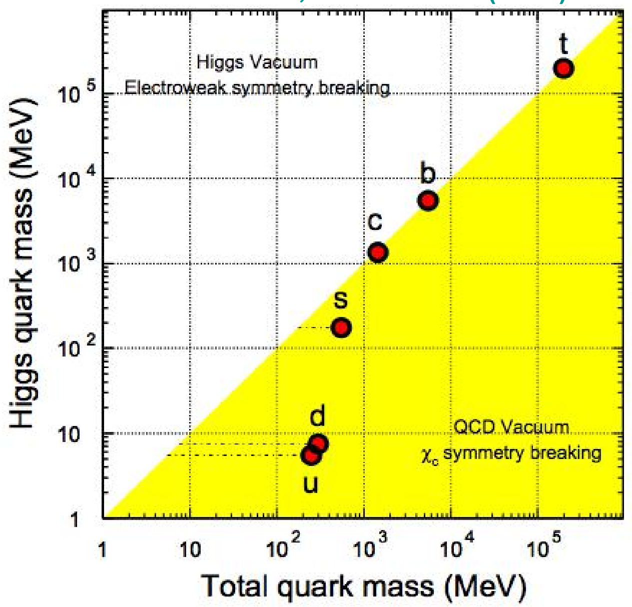
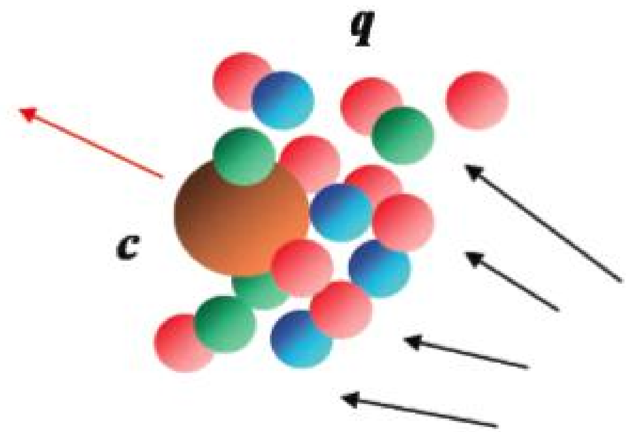


- Transport through the whole system
  - **Heavy quark kinematics in the sQGP**
  - Access to **transport properties** of the system
  - ...exits the medium also at **low momenta**
  - **Hadronization** (fragmentation, coalescence)
  - **Heavy vs. light? Charm vs. bottom?**



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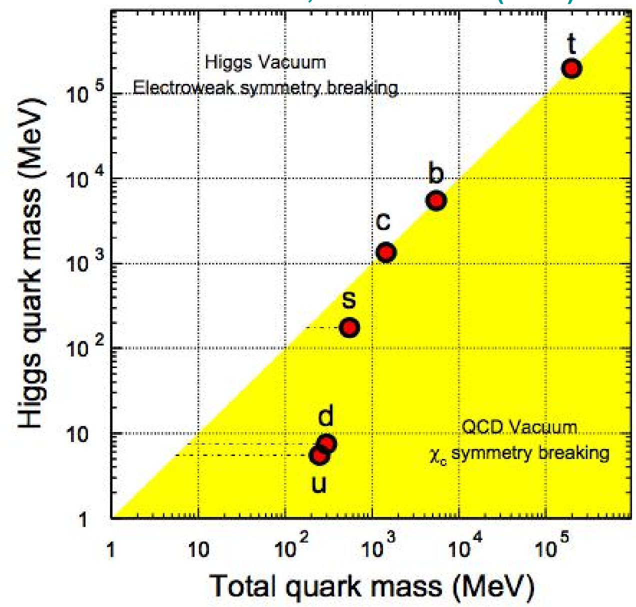

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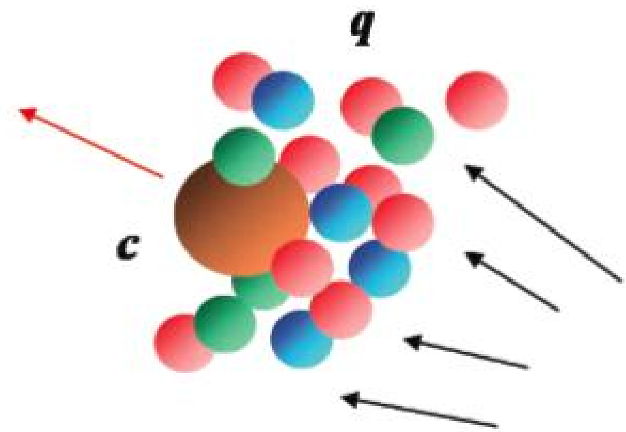


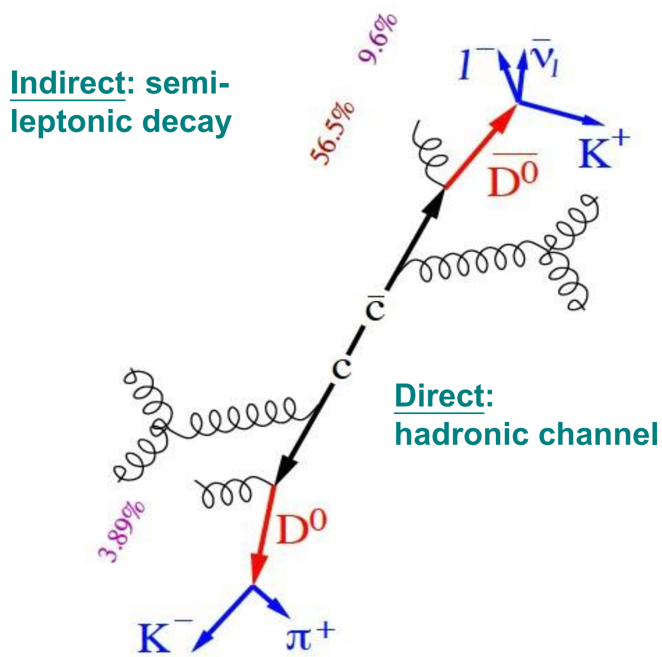
Penetrating probes down to low momenta!

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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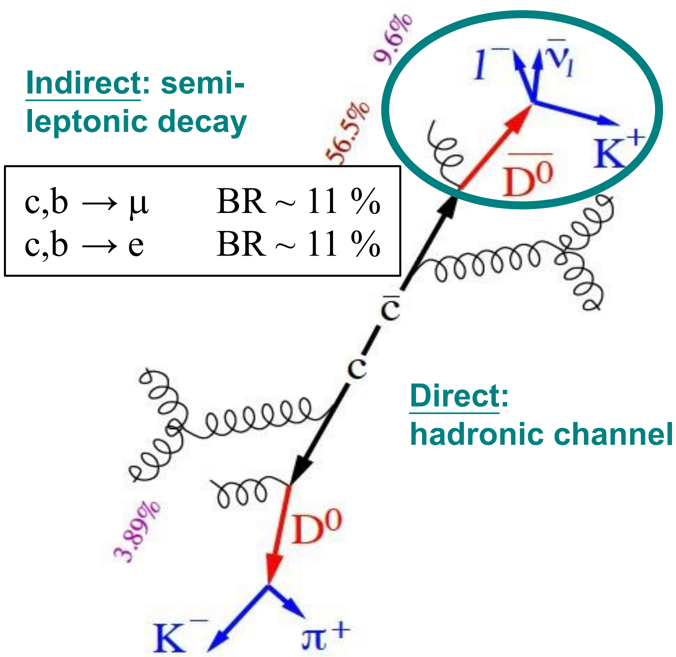

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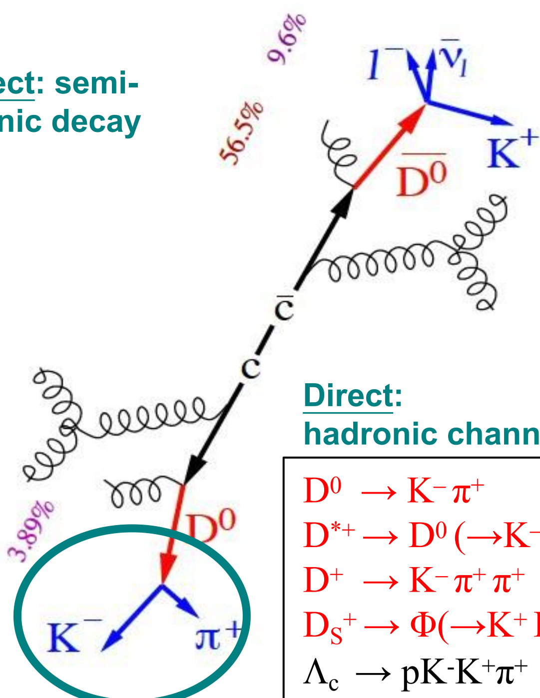
Indirect: semi-leptonic decay



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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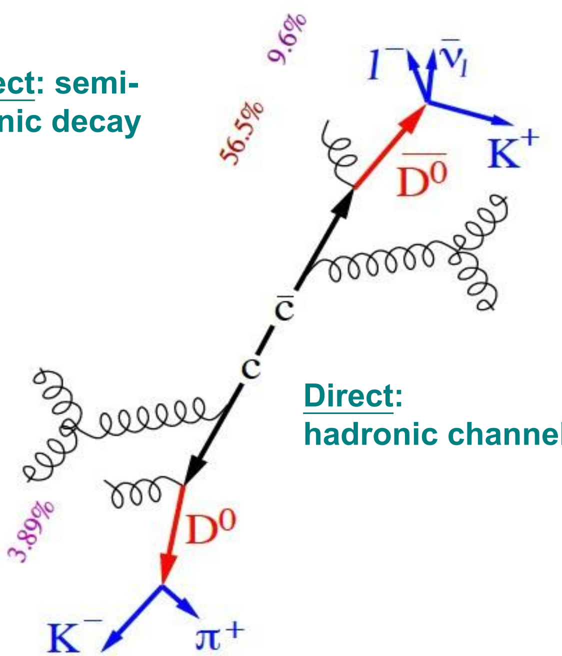
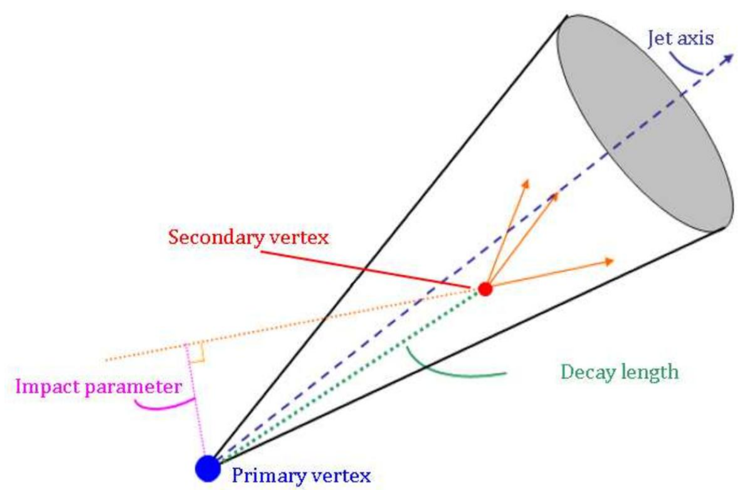


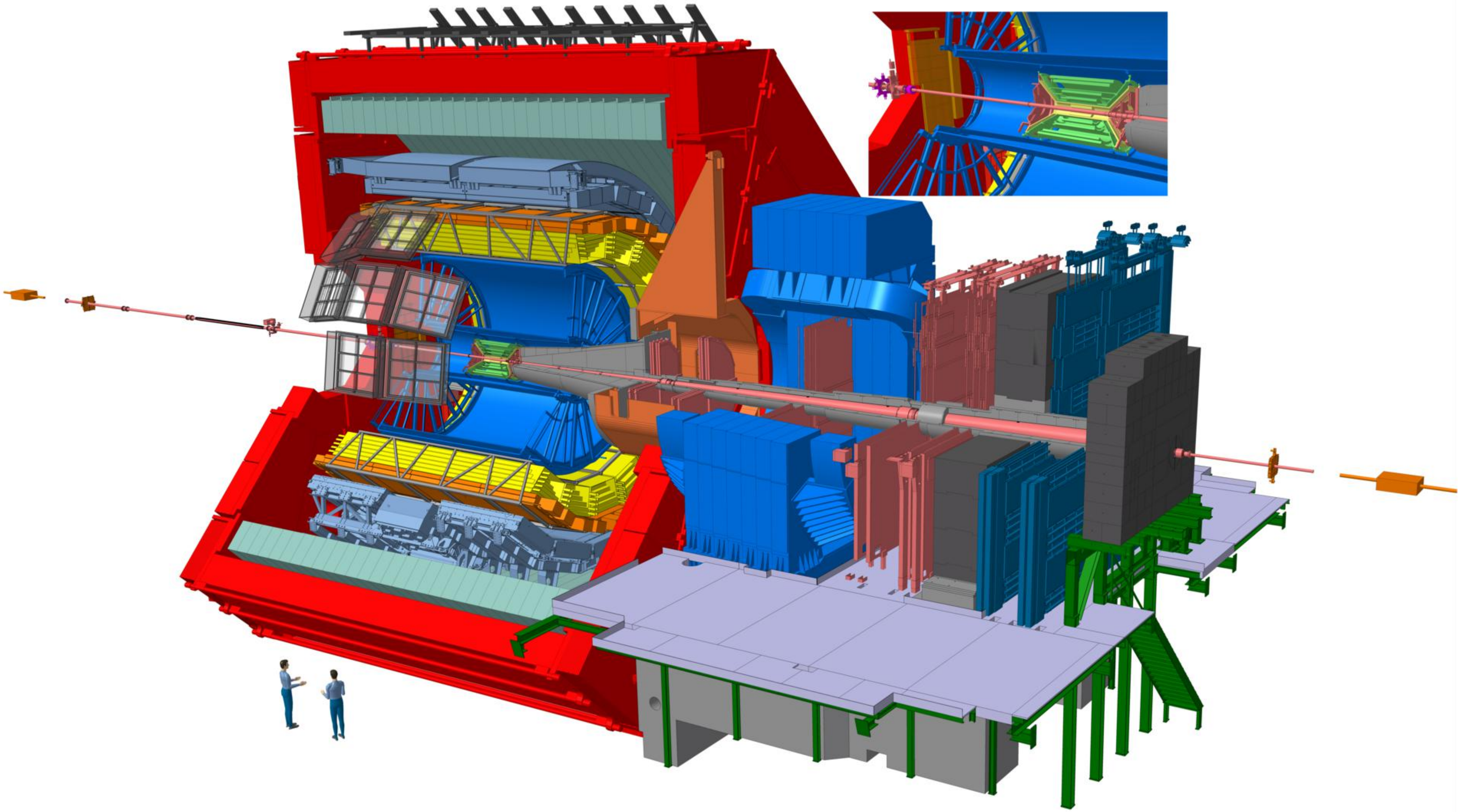
Direct: hadronic channel

finding the location of the decay
(secondary vertex)



Lifetime of heavy quarks	$c\tau(D) \sim$ 100-300 mm
	$c\tau(B) \sim$ 400-500 mm
Secondary vertex resolution <100 mm	

ALICE



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

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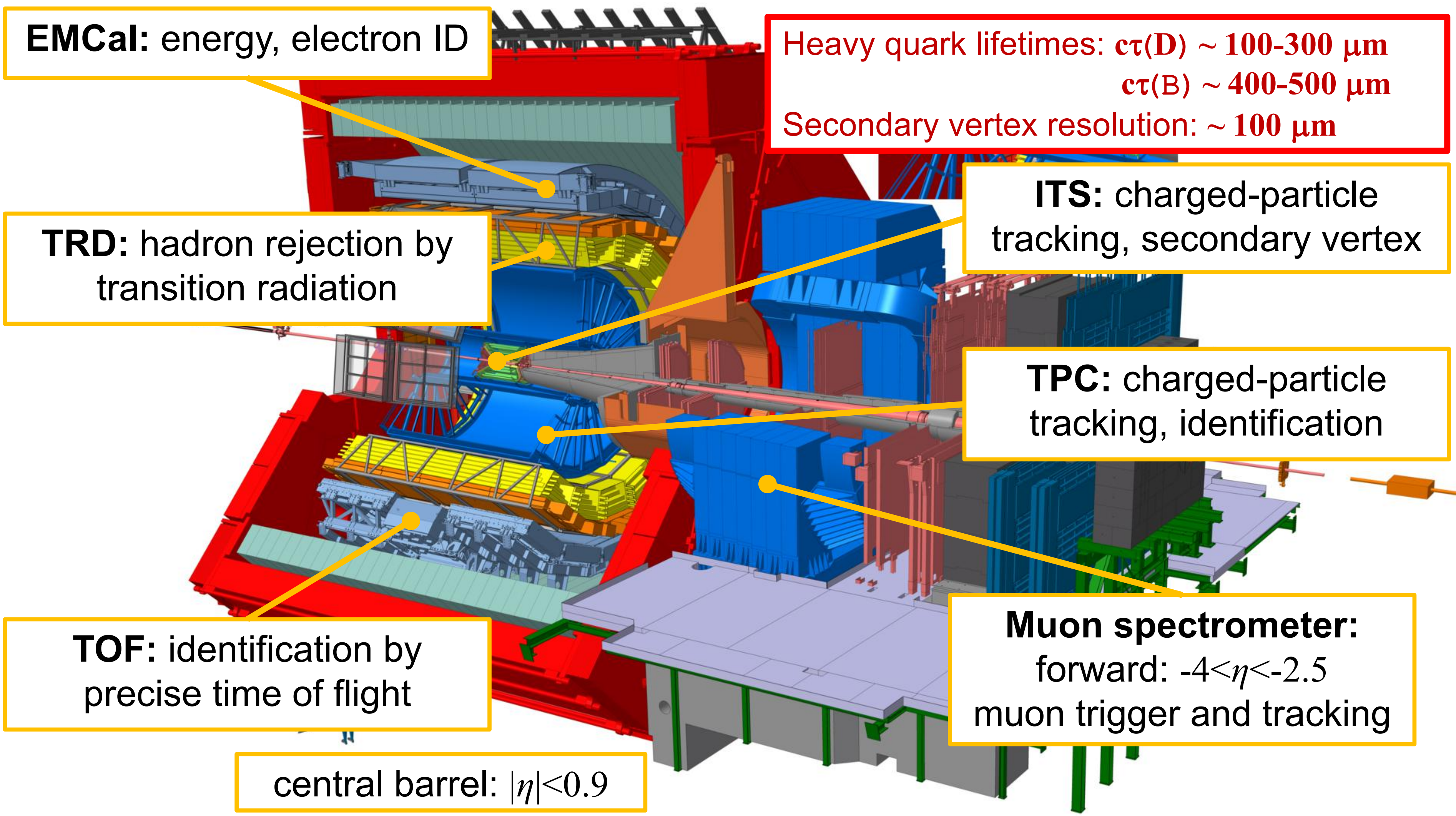

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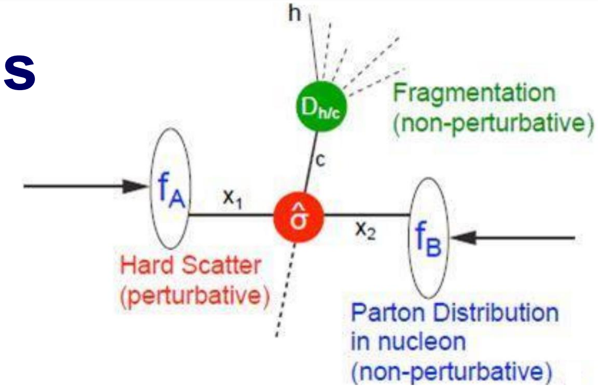
Heavy flavour in small systems

Production cross sections in pp collisions

- Primary (vacuum) pQCD benchmark



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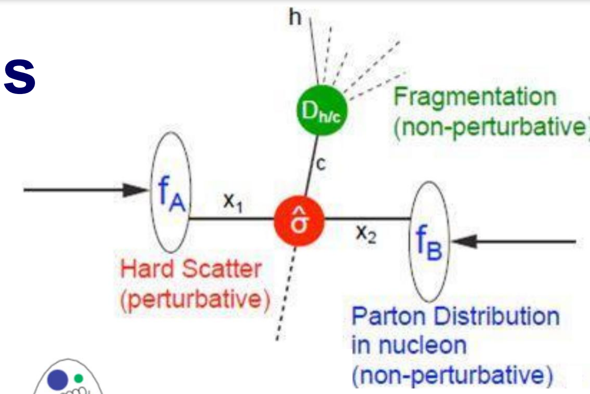
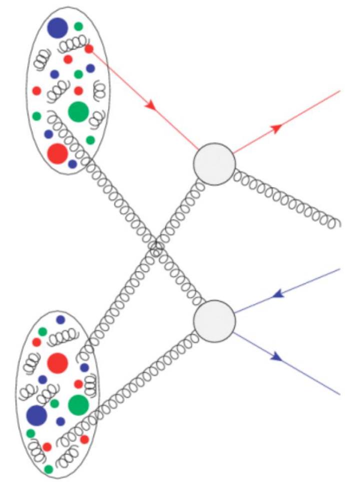


Production cross sections in pp collisions

- **Primary (vacuum) pQCD benchmark**

HF production vs. event activity

- Interplay between hard and soft processes
- Link between initial and final state
- **Role of collective effects** in small collision systems with high multiplicity? MPI?



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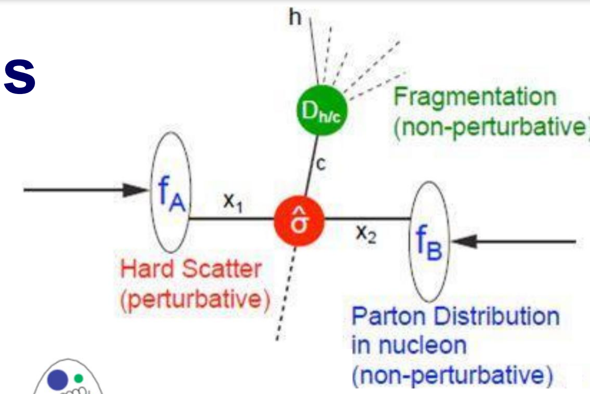

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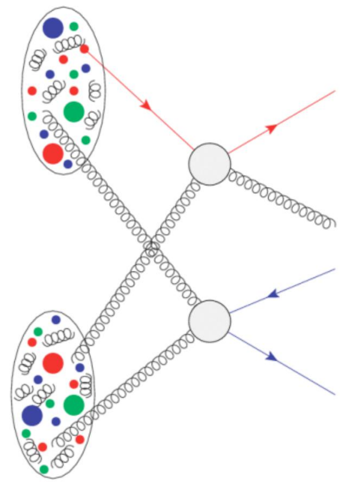
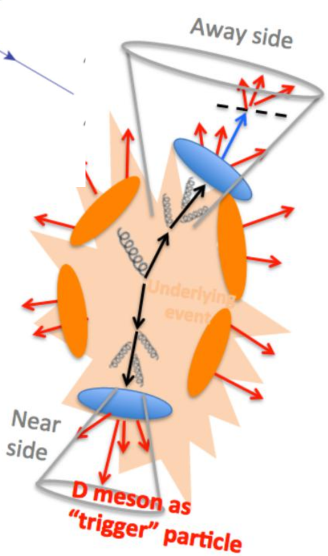


Jet and correlation observables

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



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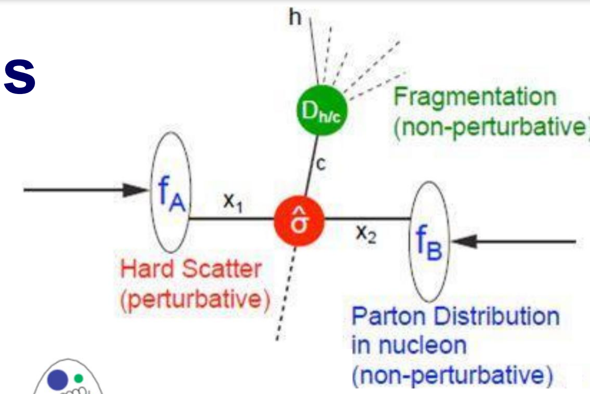
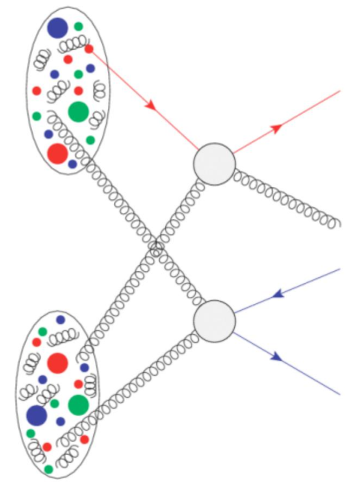
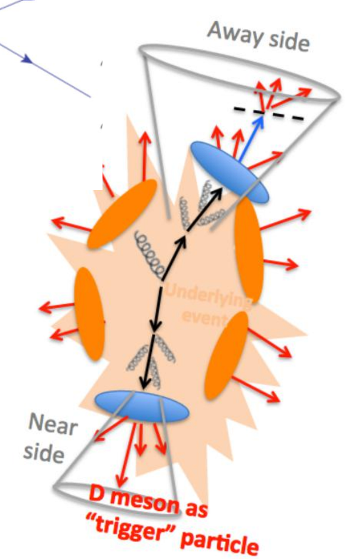
Mesons and baryons

- **Tests of fragmentation models**

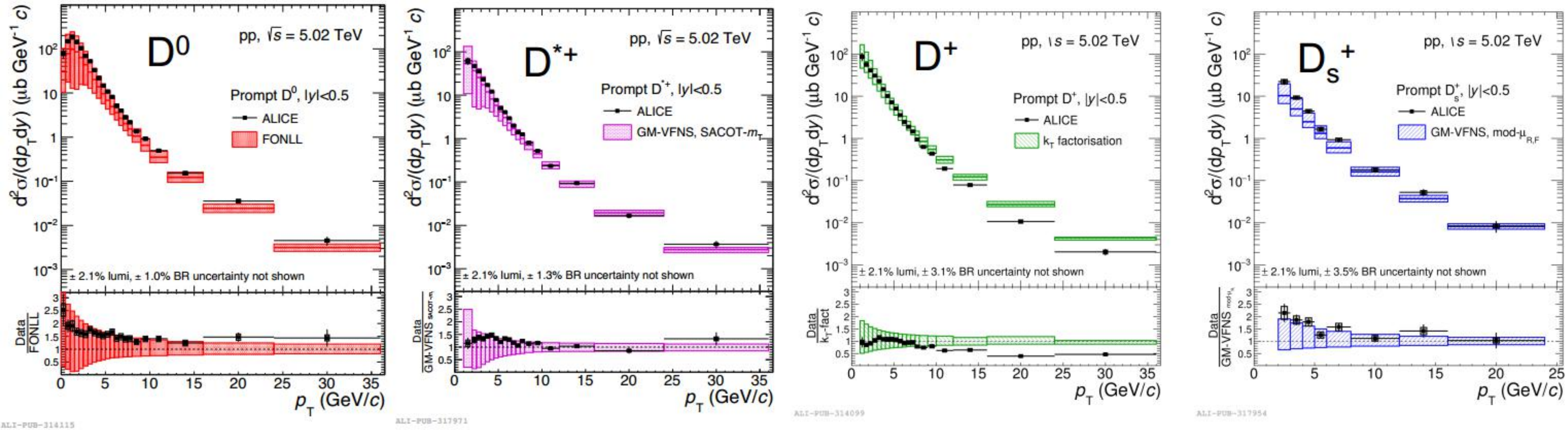






D (charmed) mesons in QCD vacuum

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)

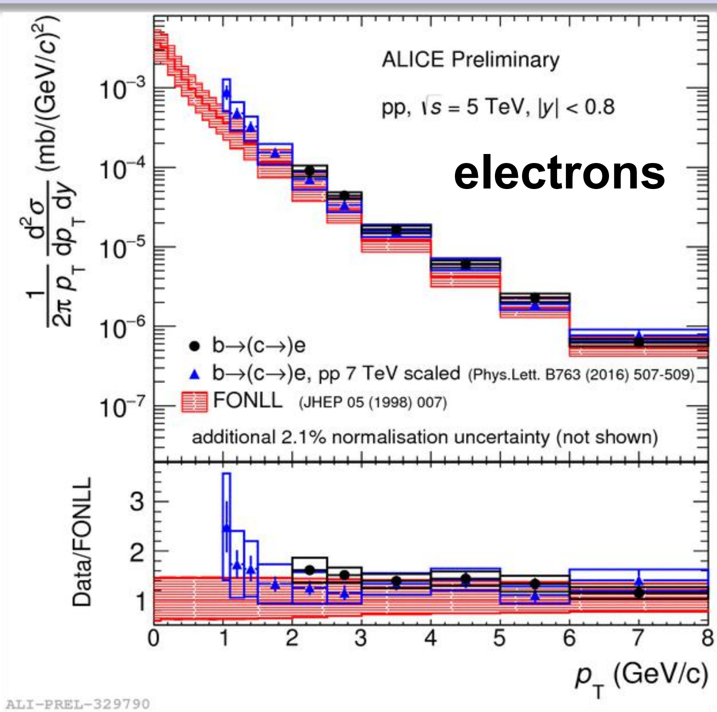
$\sqrt{s}$=5.02 TeV pp: new, high-precision D^0, D^{*+}, D^+, D_s^+ measurements

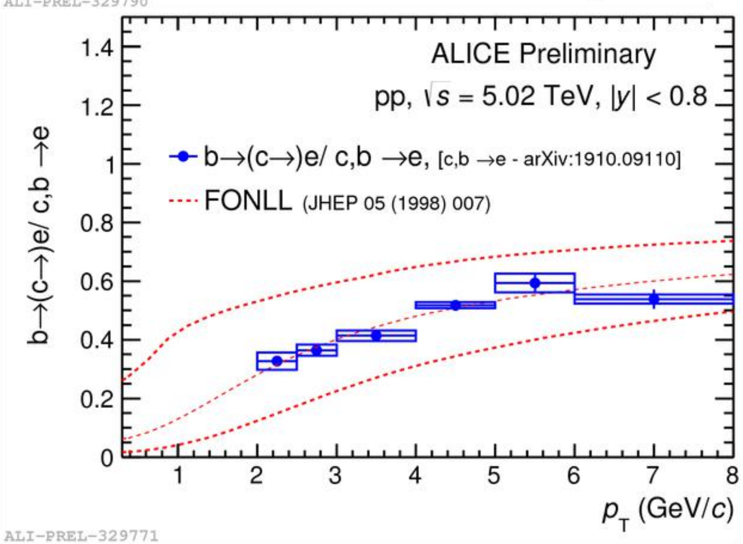
- D^0 down to low momenta (p_T>0 GeV/c): no topological cuts, only PID
- **New reference for heavy-ion systems** (p-Pb and Pb-Pb)

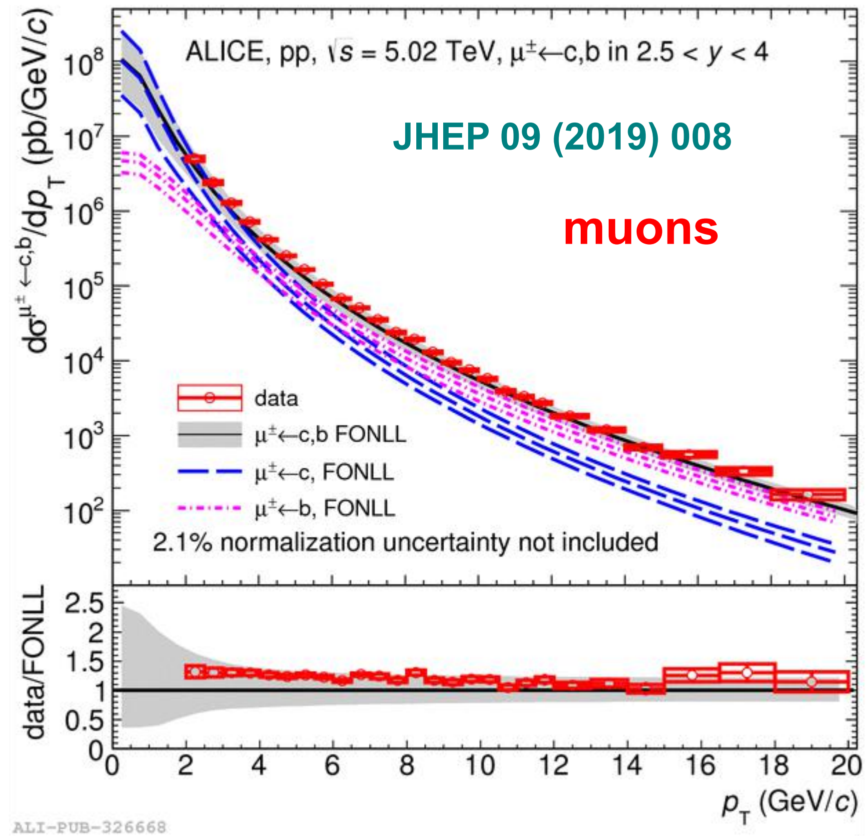
A detailed test of pQCD models

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

HF electrons and muons



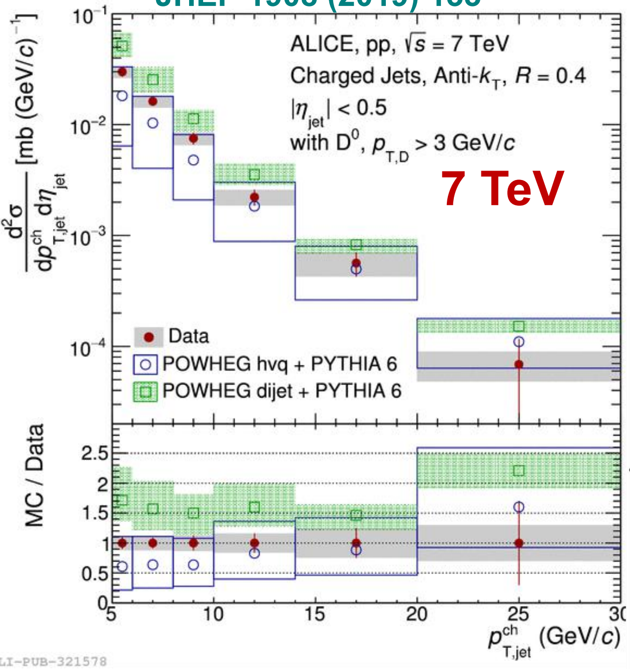


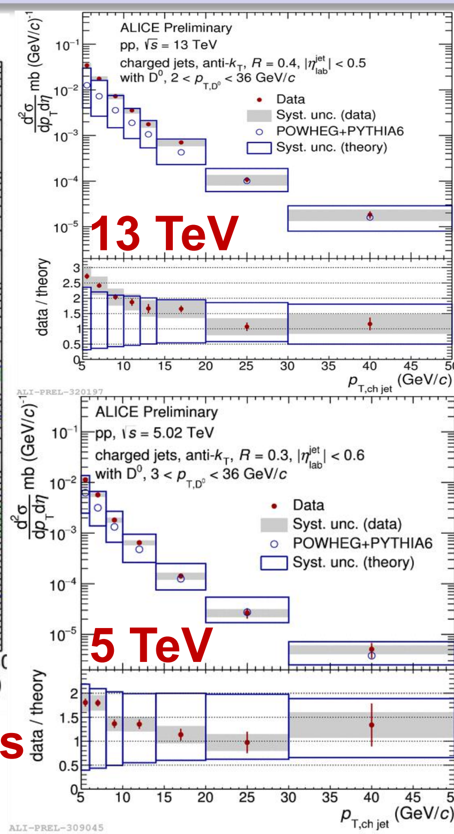


- FONLL pQCD describes **beauty electrons** and **beauty/charm** ratio
- Agreement for **electrons** at mid-rapidity and **muons** at $2.5<y<4$

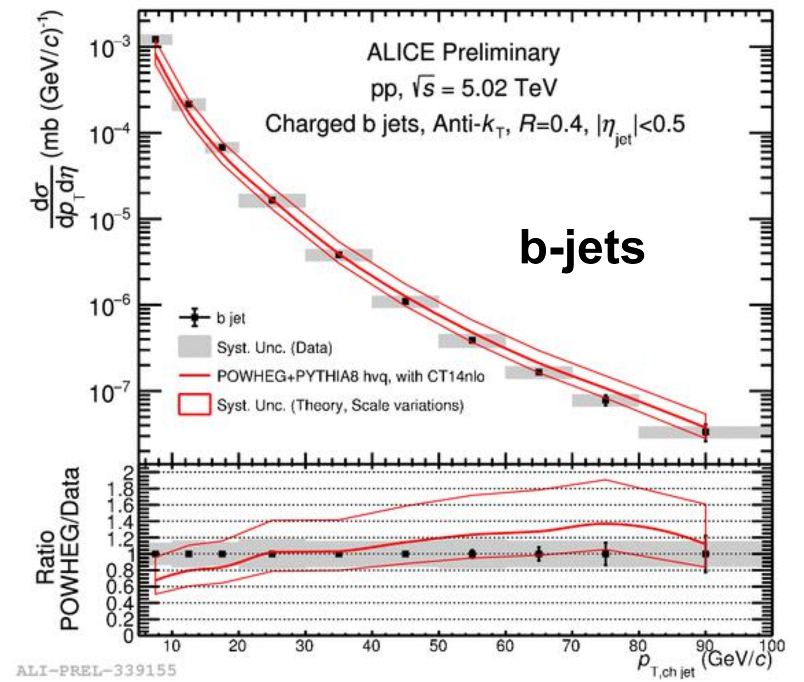
D-tagged and b-tagged jets

JHEP 1908 (2019) 133



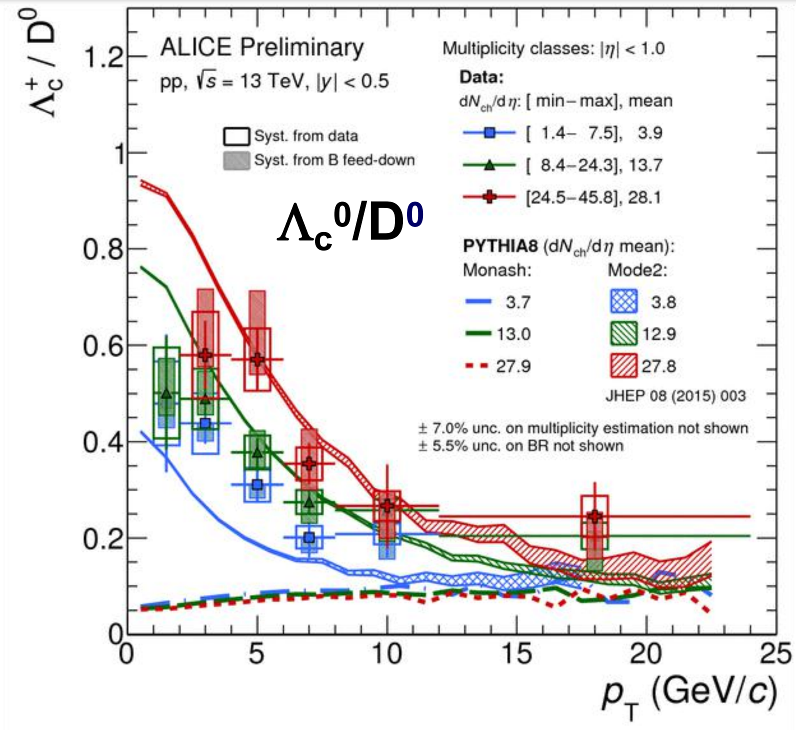


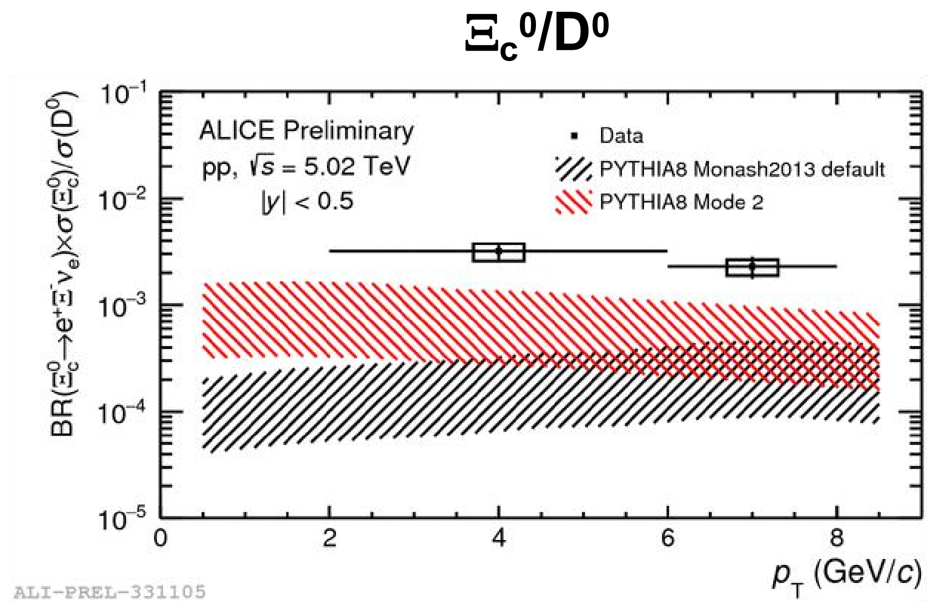
D-tagged jets



- **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



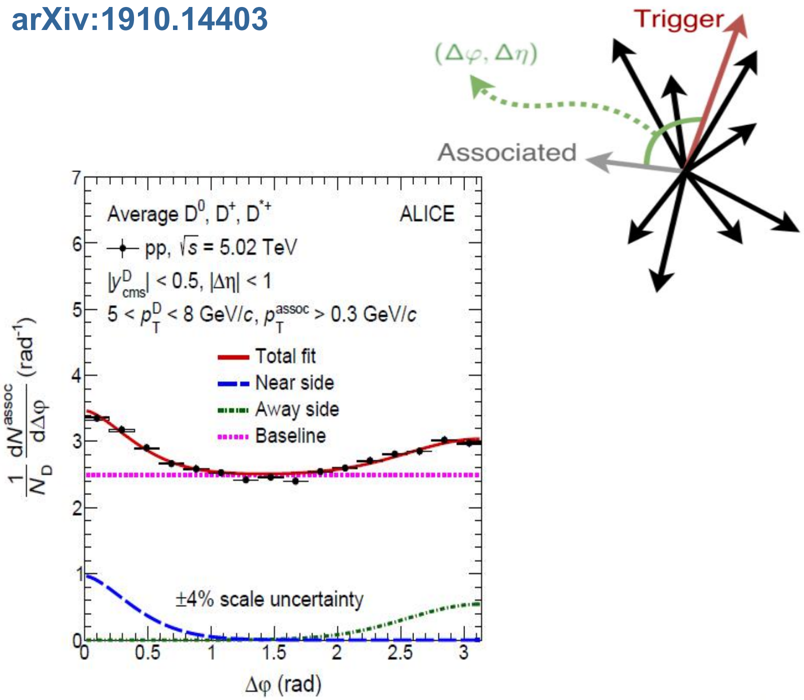


PYTHIA8: JHEP 05 (2006) 026
DIPSY: JHEP 1503 (2015) 148
HERWIG7: EPJ C76 (2016) no.4 196

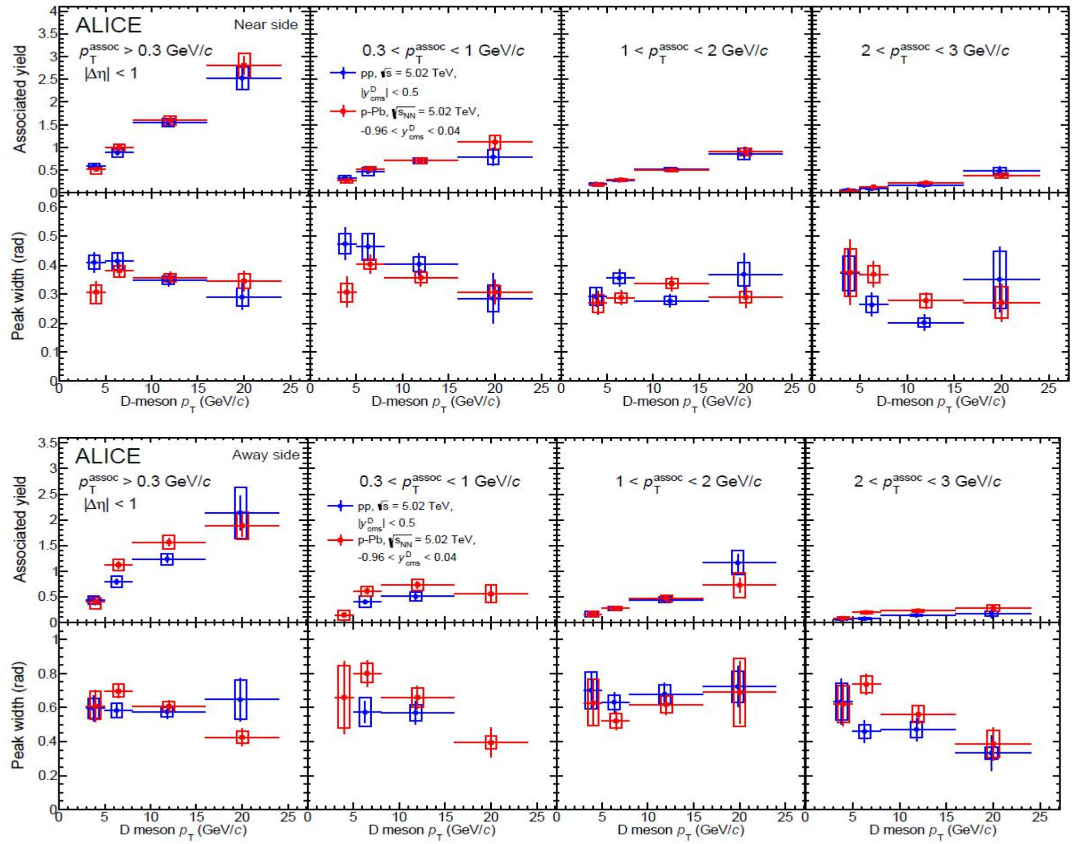
- Ξ_c^0/D^0 as well as Λ_c^+/D^0 are underestimated by models based on ee collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation?
    Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon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

D-h angular correlations

arXiv:1910.14403

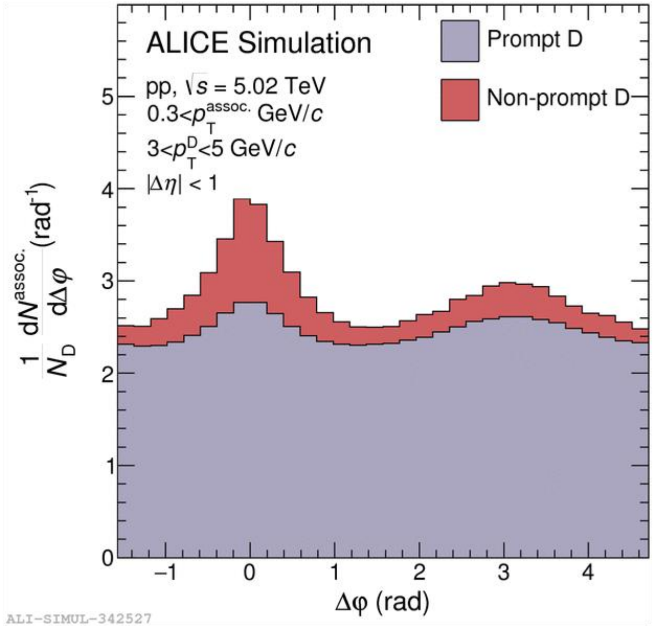


$$f(\Delta\varphi) = b + \frac{Y_{NS}\cdot\beta}{2\alpha\Gamma(1/\beta)}\cdot e^{-\left(\frac{\Delta\varphi}{\alpha}\right)^{\beta}} + \frac{Y_{AS}}{\sqrt{2\pi}\sigma_{AS}}\cdot e^{\frac{(\Delta\varphi-\pi)^2}{2\sigma_{AS}^2}}$$

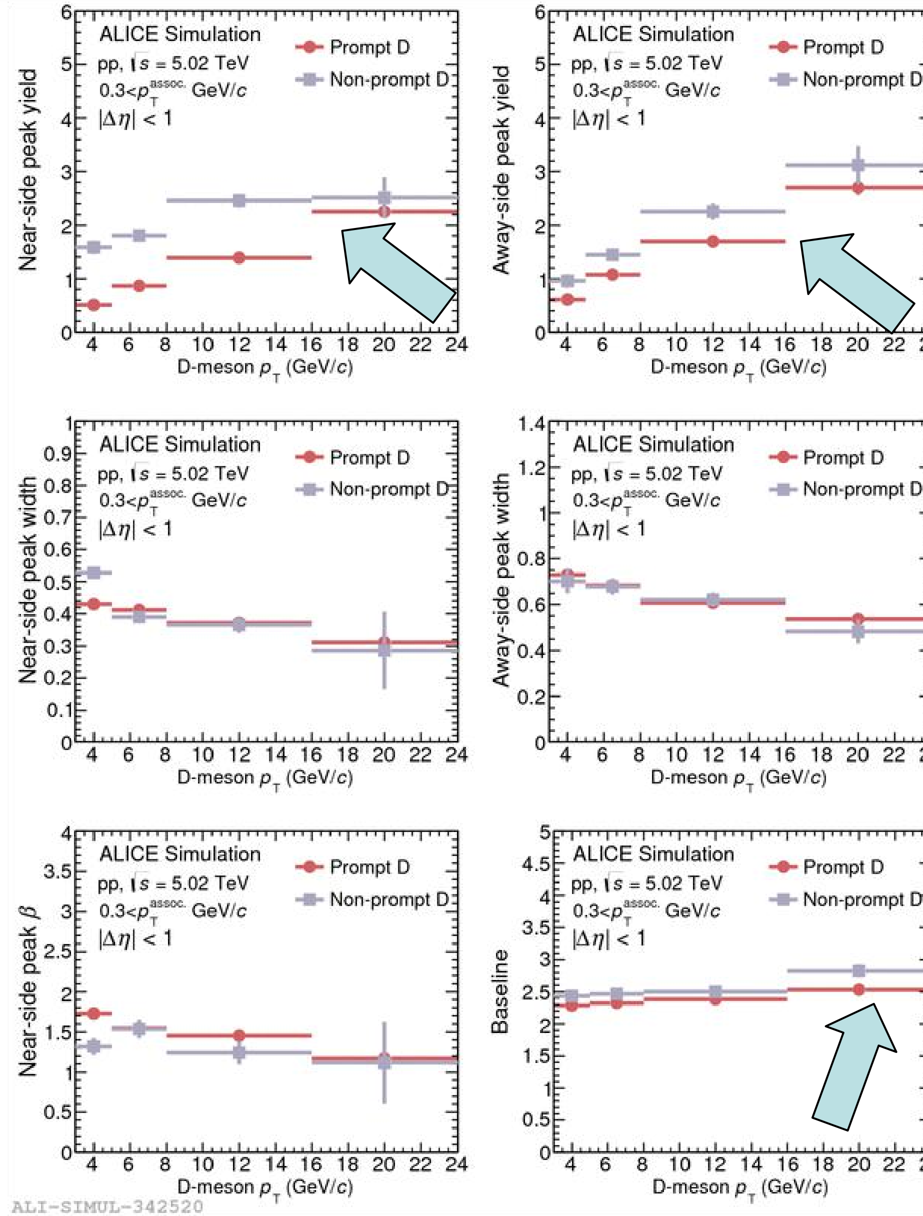


- Near-side peak narrowing with increasing p_T^D
- Away-side yields increase with p_T^D value
- No significant difference between D-h correlation parameters in pp and p-Pb systems

D-h in PYTHIA: prompt/non-prompt D



E Frajna (ALICE), https://indi.to/tHf8p



- Higher per-trigger yields and baseline for non-prompt D mesons

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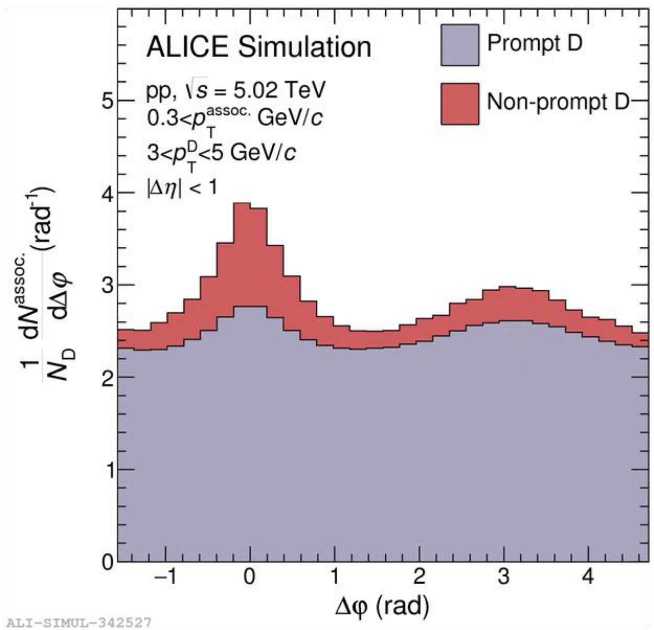

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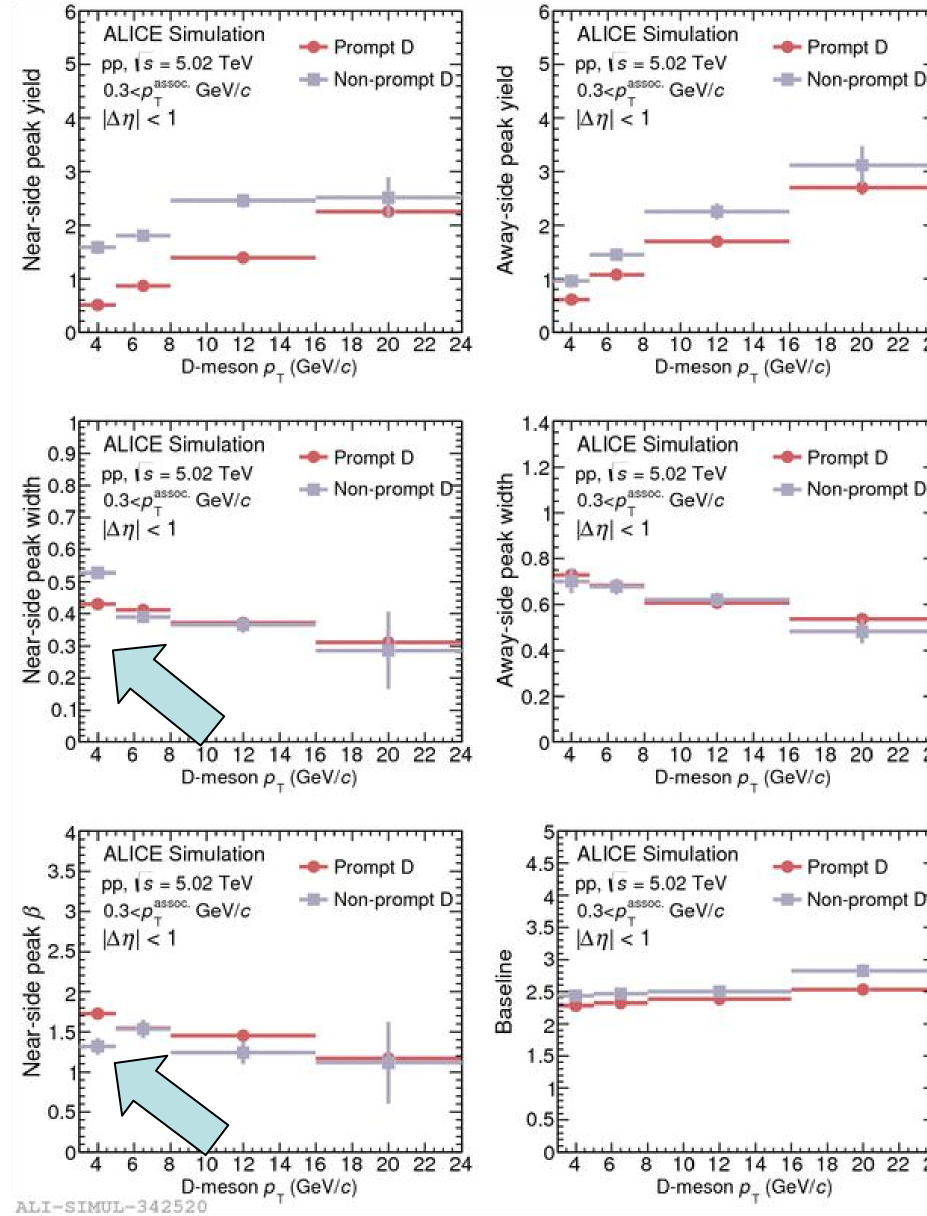

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- **Shapes: significantly different** at the near side at low p_T.

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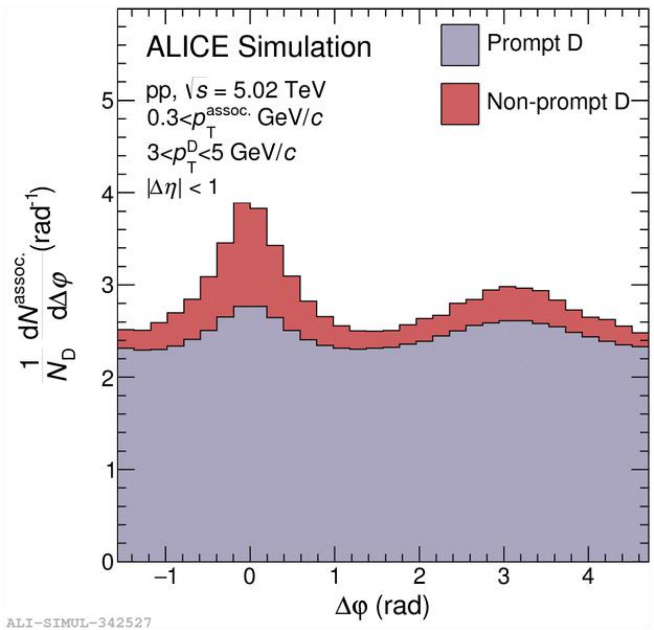

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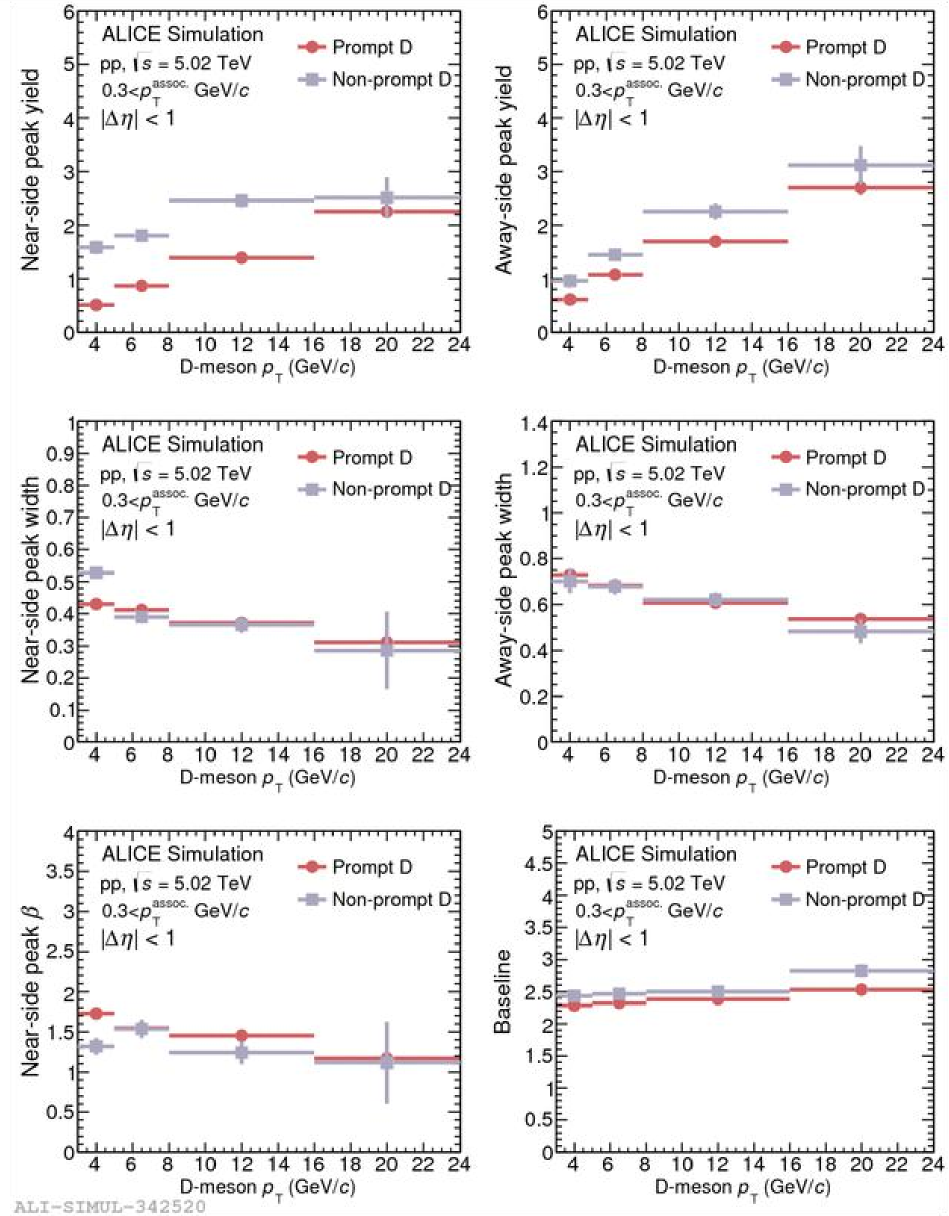

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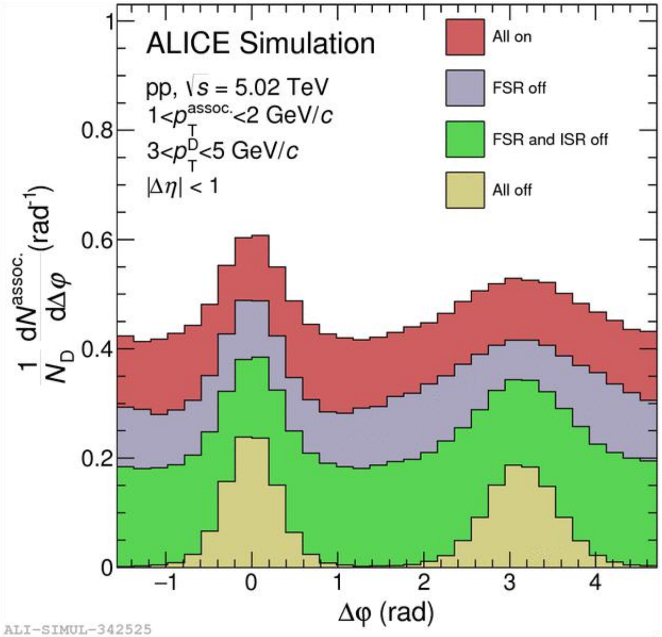
- **Shapes: significantly different** at the near side at low p_T.
- **A possibility to statistically separate b and c contributions**

E Frajna, R V, Universe 2019 5 (5) 118

D-h in PYTHIA: partonic processes



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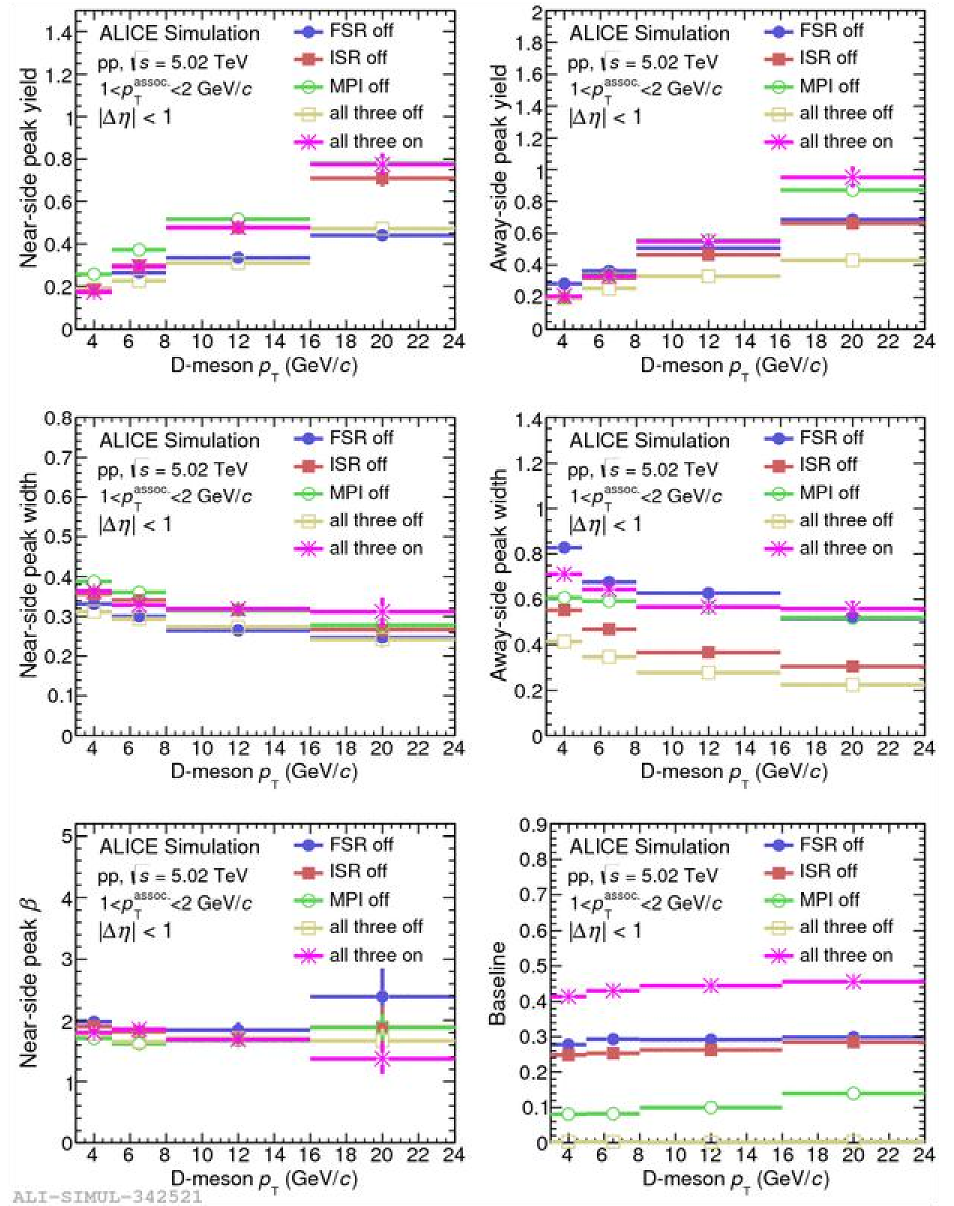
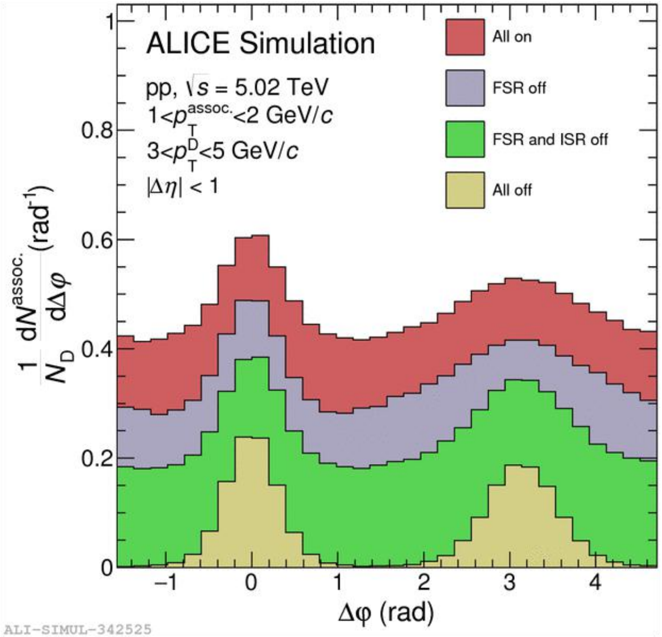


Partonic processes in PYTHIA 8

- Initial-state radiation
- Final-state radiation
- Multiple-parton interactions

D-h in PYTHIA: partonic processes



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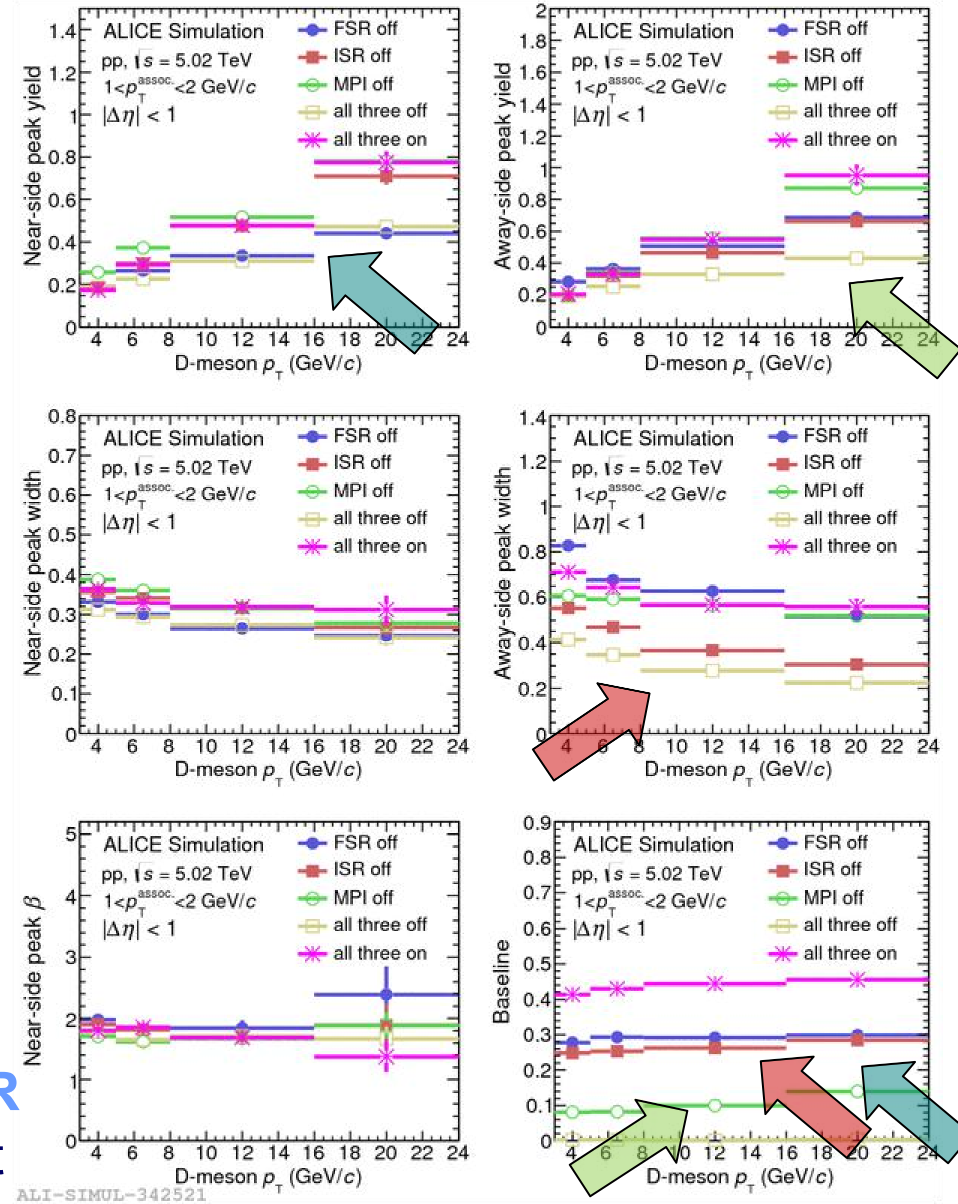
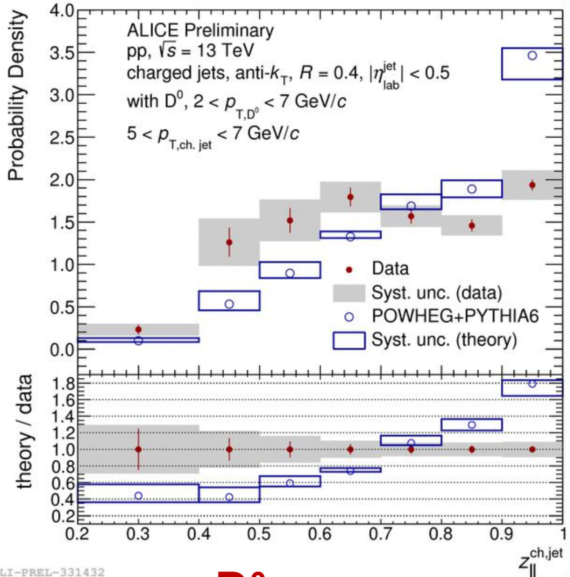
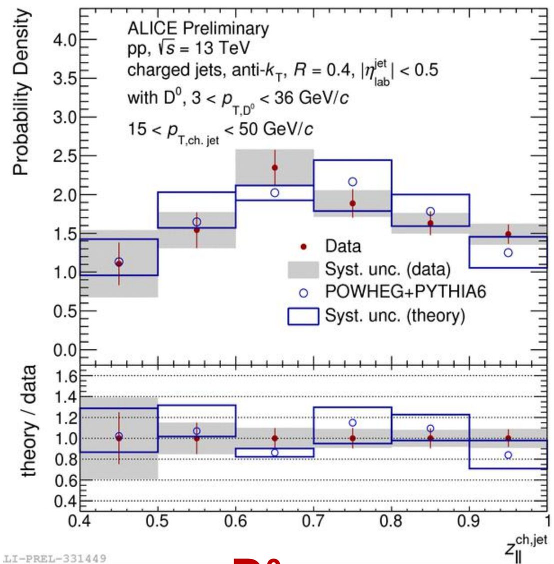


- **Near-side yield**: significant **FSR** contribution (at higher $p_T^{trigger}$).
- **Away-side yield**: **MPI** contribution
- **Away-side width**: increased by parton-level effects - mainly **ISR**
- **Baseline**: contributions of **ISR**, **FSR** and **MPI** effects to underlying event

Charm fragmentation



D^0 2-7 GeV/c



D^0 3-36 GeV/c

- **Fragmentation of D mesons**

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

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

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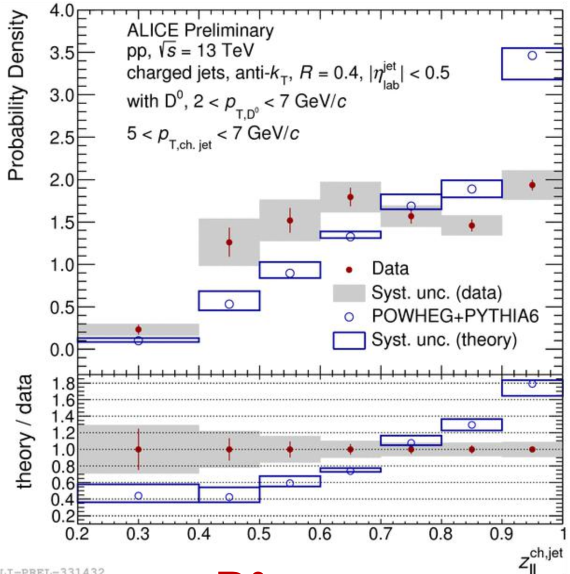

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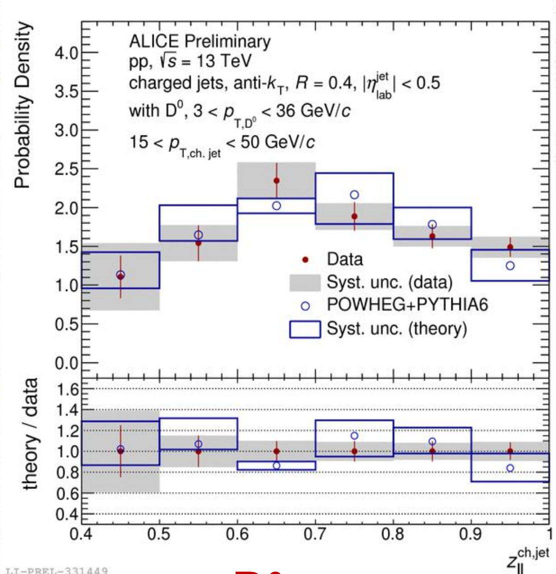

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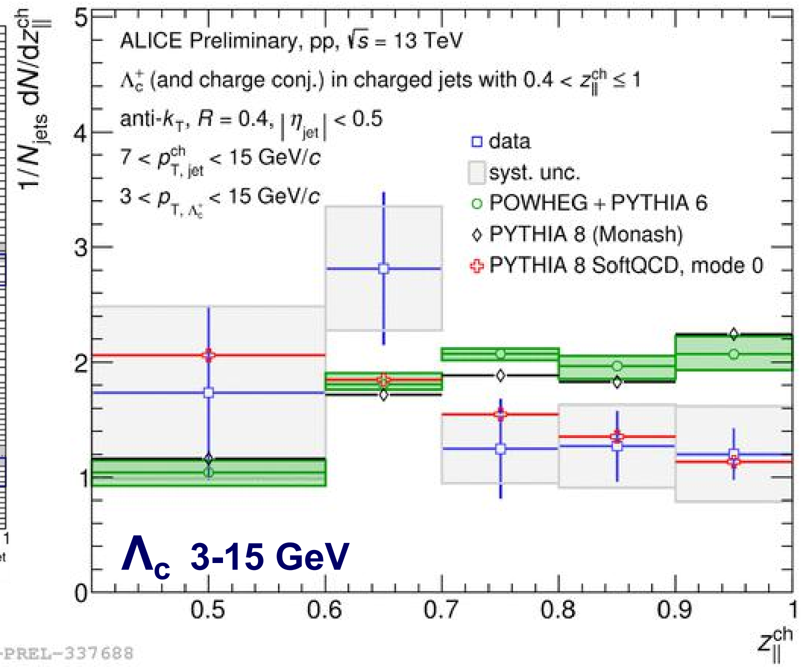

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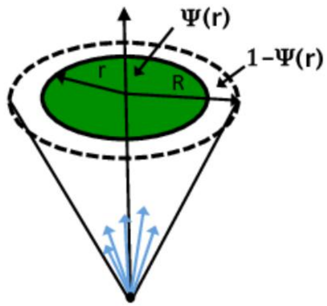
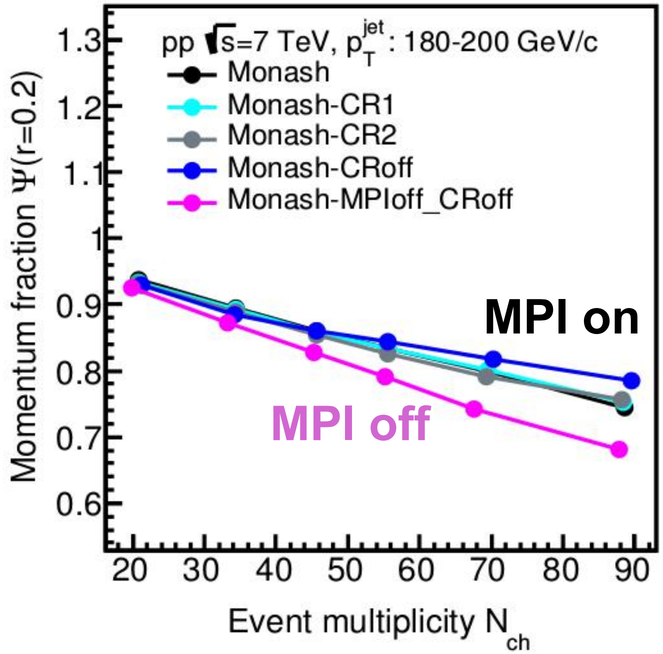
  - Softer fragmentation in data for low p_T
  - Model consistent with data at higher p_T
- **Λ_c-tagged jets at 13 TeV** - first measurement at the LHC
  - Exciting prospects for high luminosity LHC run
  - Comparison to models seems to favor PYTHIA with softer settings

Jet structure vs. multiplicity



Z Varga, RV, GG Barnaföldi, Adv.High Energy Phys. 2019 (2019) 6731362



- PYTHIA8, HIJING++
- **Radial structure of light-flavor jets** $\psi(N_{ch})$
  - Significantly influenced by **multiple-parton interactions**

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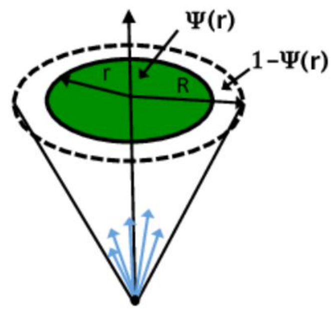

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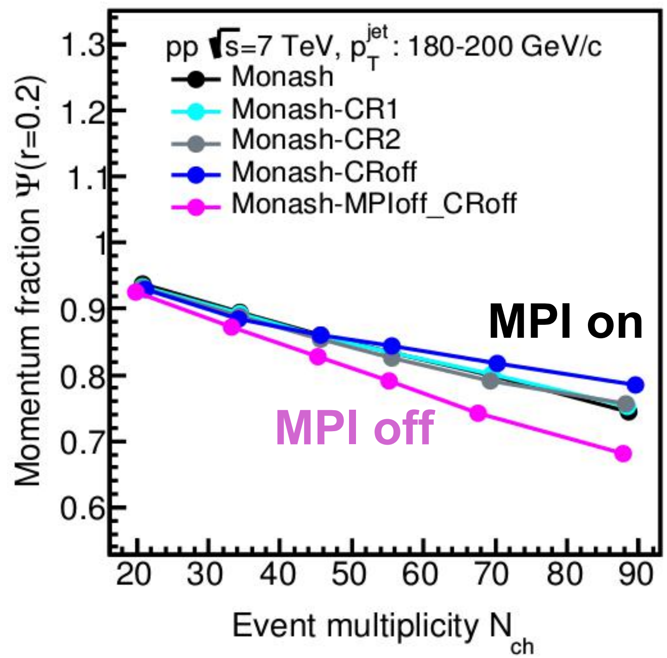
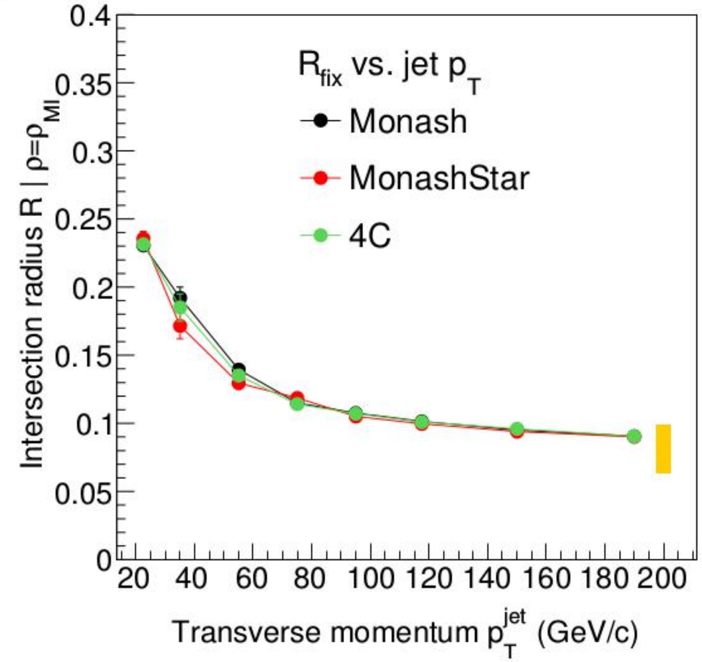
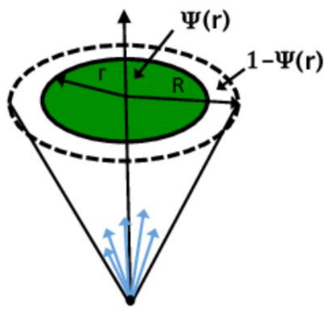


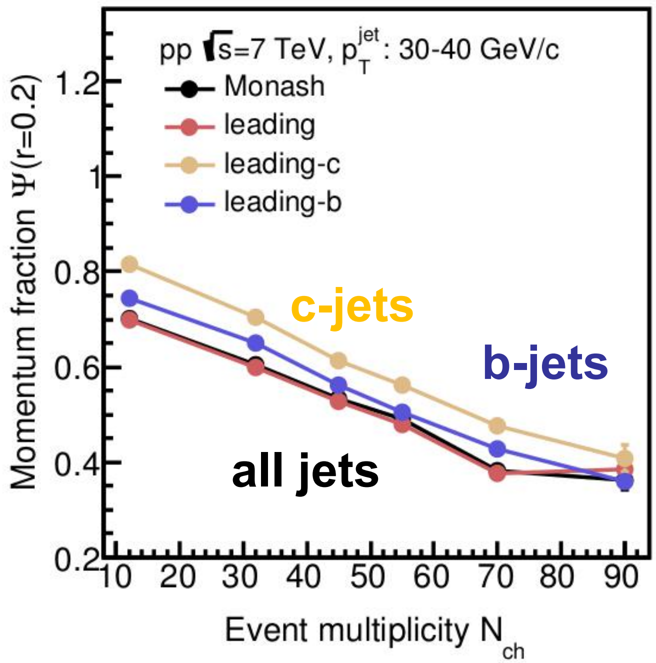


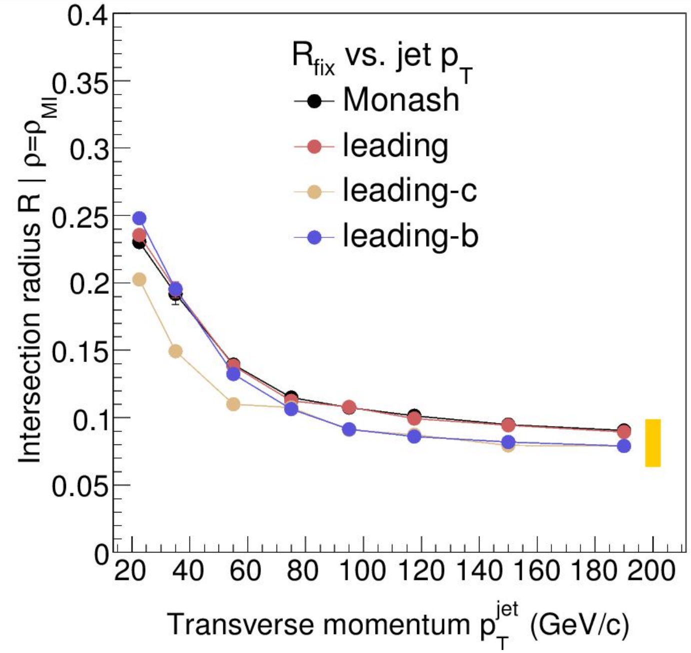
- PYTHIA8, HIJING++
- **Radial structure of light-flavor jets** $\psi(N_{ch})$
  - Significantly influenced by **multiple-parton interactions**
- **Multiplicity-scaled jet size measure** $R_{\mathrm{fix}}(p_{\mathrm{T}})$
  - **Does not depend on any physical settings for LF** (generator, tune, CR/MPI, jet algorithm etc.)

Jet structure vs. multiplicity



Z Varga, RV, GG Barnaföldi, Universe 5 (2019) no.5, 132





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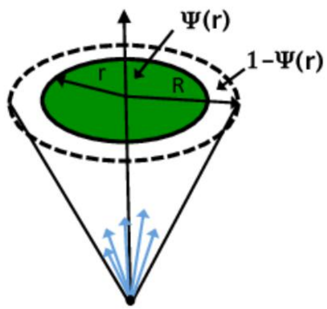
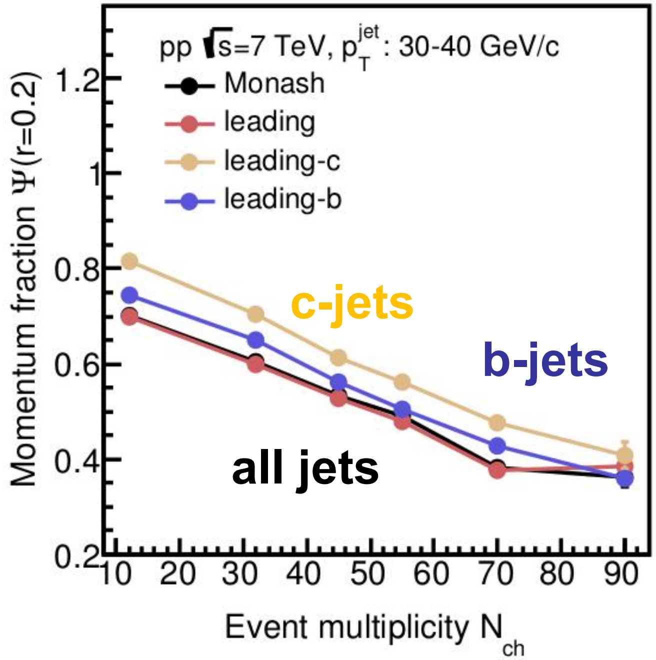
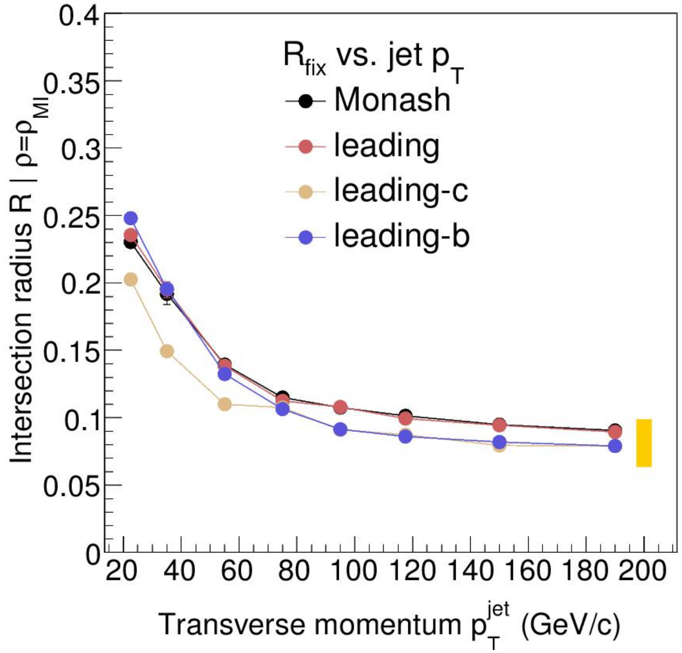
  - **Integral structures splitting** for the three flavors (lf,c,b)
- **Multiplicity-scaled jet size measure** $R_{fix}(p_T)$
  - Strong dependence of the split on momentum
- **Heavy flavor jet structures sensitive to fragmentation**

Jet structure vs. multiplicity



Z Varga, RV, GG Barnaföldi, Universe 5 (2019) no.5, 132





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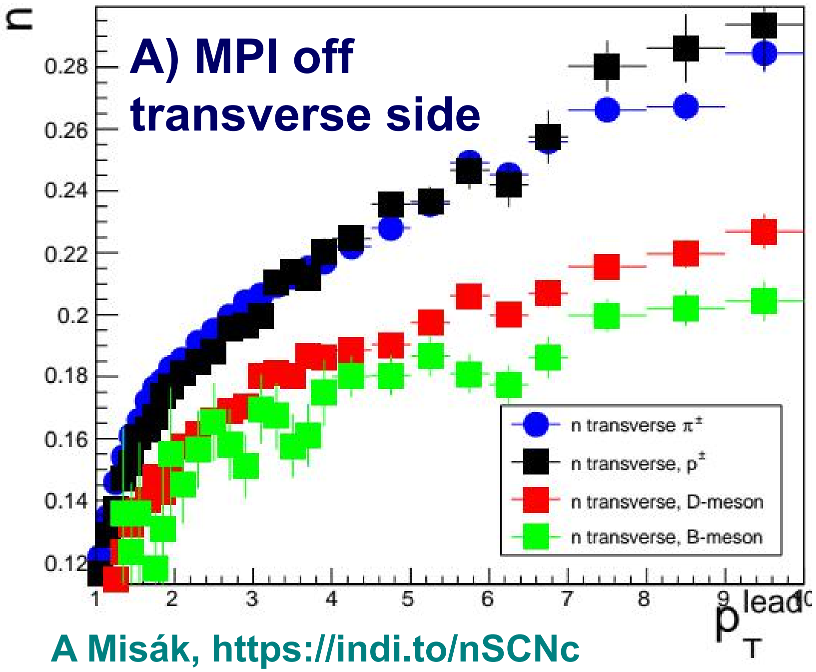
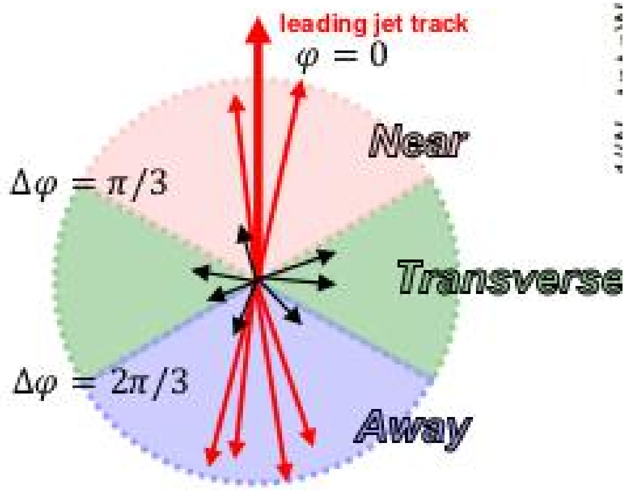
Flavor-inclusive analysis underway in ALICE 13 TeV pp

Underlying event w/ identified triggers



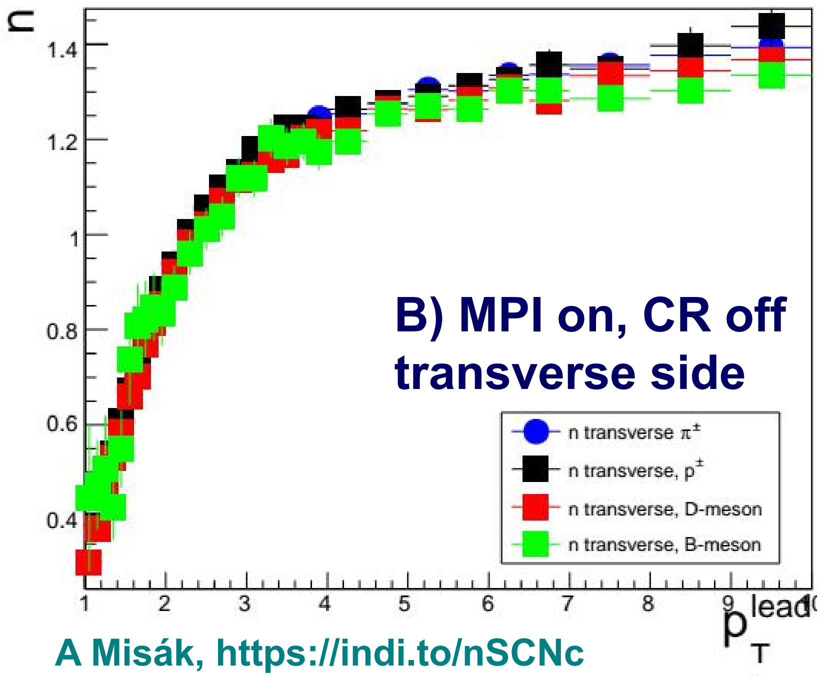
A Misák, https://indi.to/nSCNc



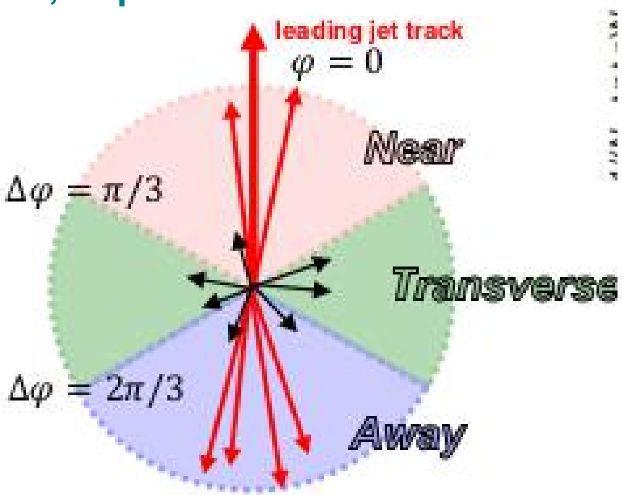
- PYTHIA8 simulations, 7 TeV pp
- Identify a trigger: π, p, D or B
- Examine particle production in underlying event (transverse side)

A. **No MPI case**
   - particle production clearly ordered by flavor of trigger

Underlying event w/ identified triggers



A Misák, https://indi.to/nSCNc



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   - Agrees with traditional assumption: **UE does not depend on leading hard process**

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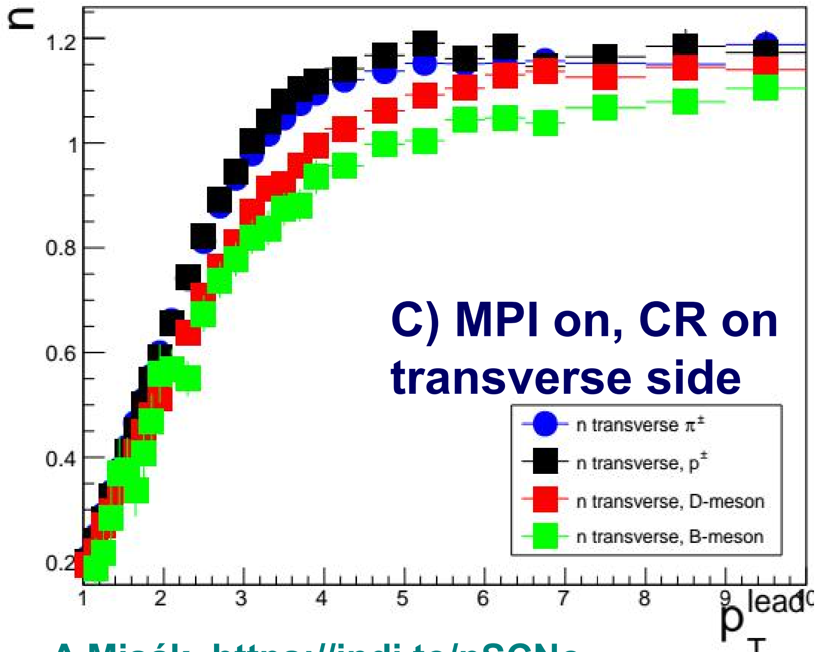
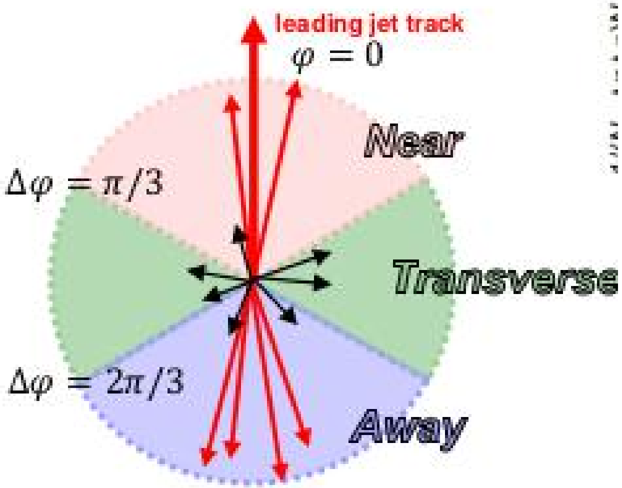


A Misák, https://indi.to/nSCNc



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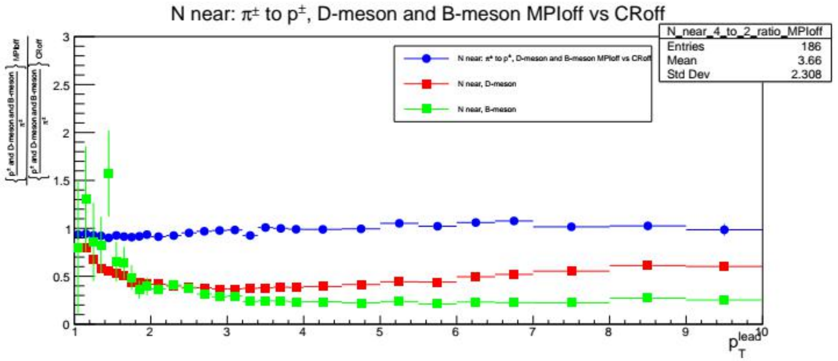
C. Physical case (both MPI & CR)
- **Flavor-dependence (re)introduced by color reconnection**
- Similar effect seen in LF & strange

Ortiz, Valencia, Palomo, PRD 99 (2019), 034027

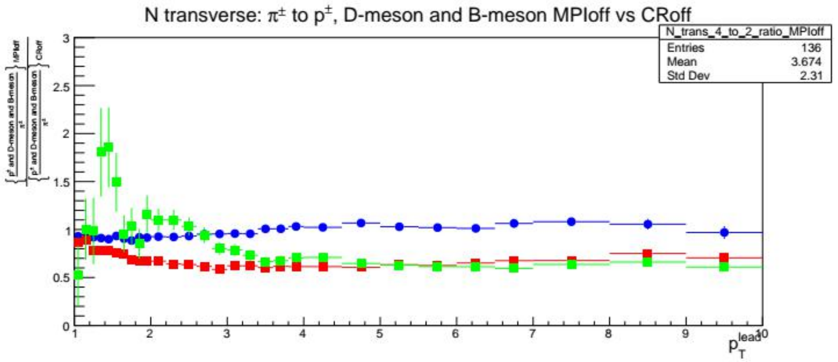
HF fragmentation and underlying event

effect of MPI

A Misák, https://indi.to/nSCNc



near side

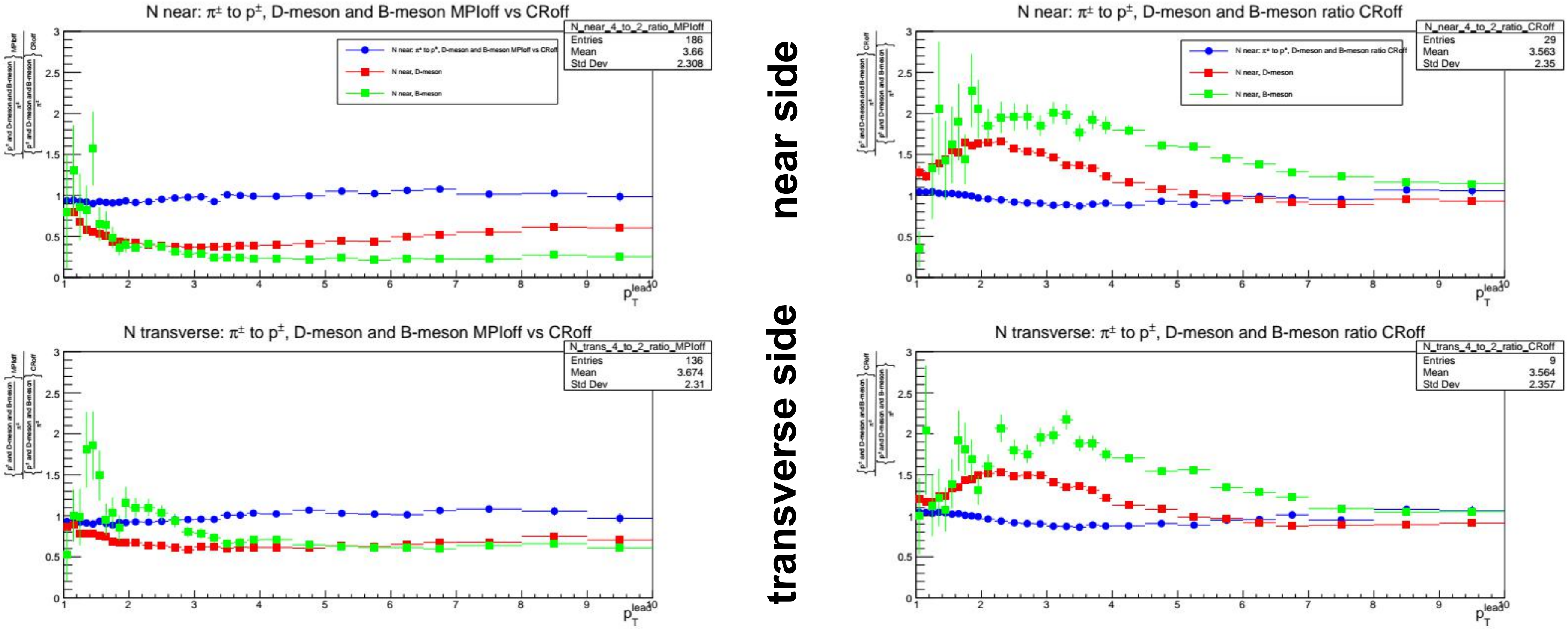


transverse side

- Relative effect of **multiple-parton interactions**
  - Near side: flavor-dependent radiation/fragmentation
  - **Transverse side:** LF and HF separated
    sensitive to color charge effects (quark vs gluon jets)

HF fragmentation and underlying event

effect of MPI A Misák, https://indi.to/nSCNc **effect of CR**

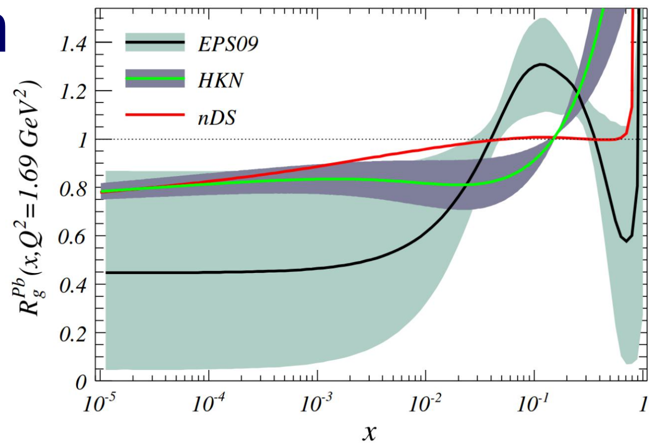


- Relative effect of **multiple-parton interactions**
  - Near side: flavor-dependent radiation/fragmentation
  - **Transverse side:** LF and HF separated
    sensitive to color charge effects (quark vs gluon jets)
- **Color reconnection: same relative effect in jets and the UE**

p-Pb collisions: CNM effects?

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

Baseline for hot nuclear effects



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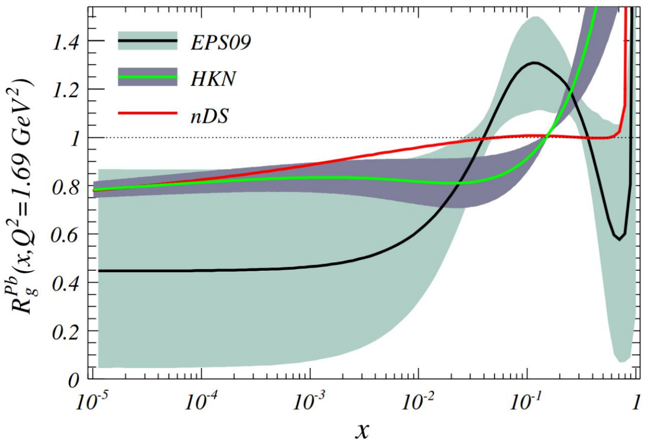
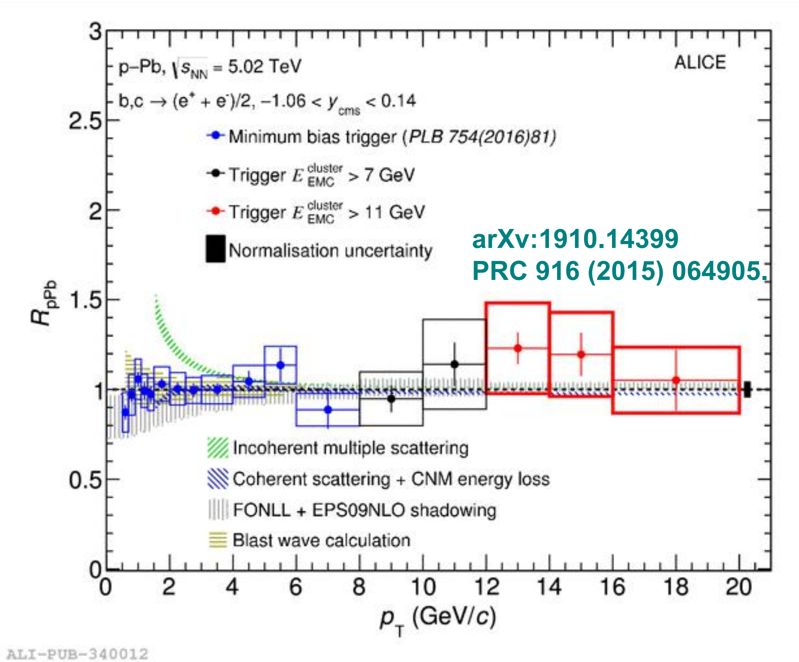
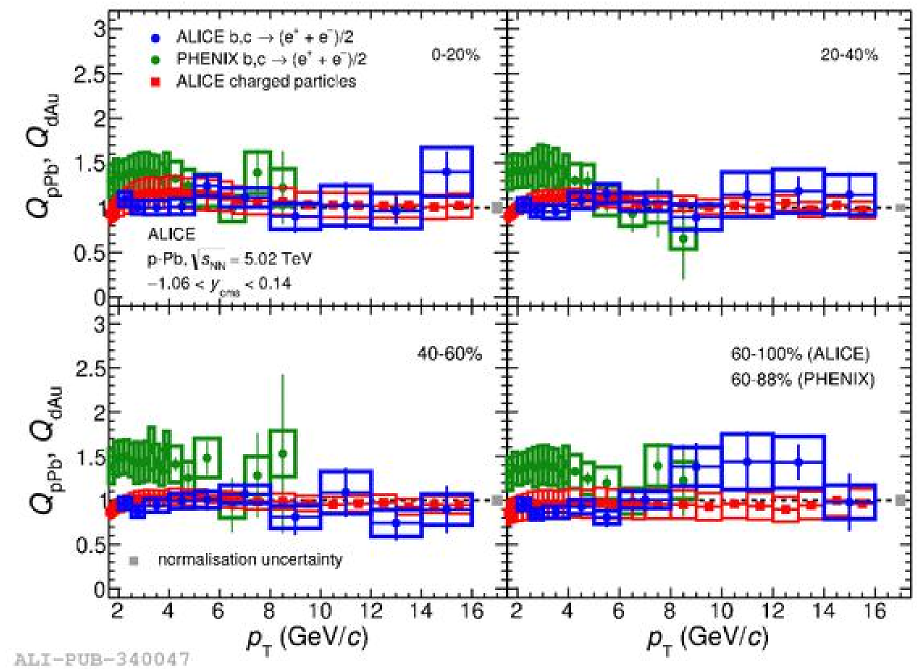


- Multiplicity-dependence?
  - *Any hot droplets?*
- Origin of collectivity in small systems?
  - Disentangle initial and final state effects

HFE in p-Pb collisions



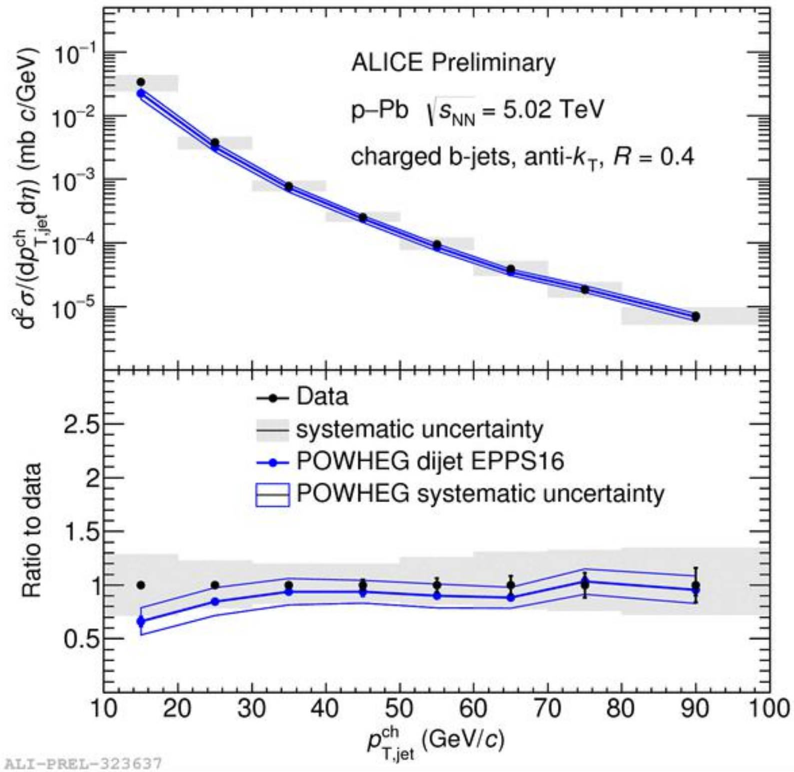
arXv:1910.14399
PRC 916 (2015) 064905

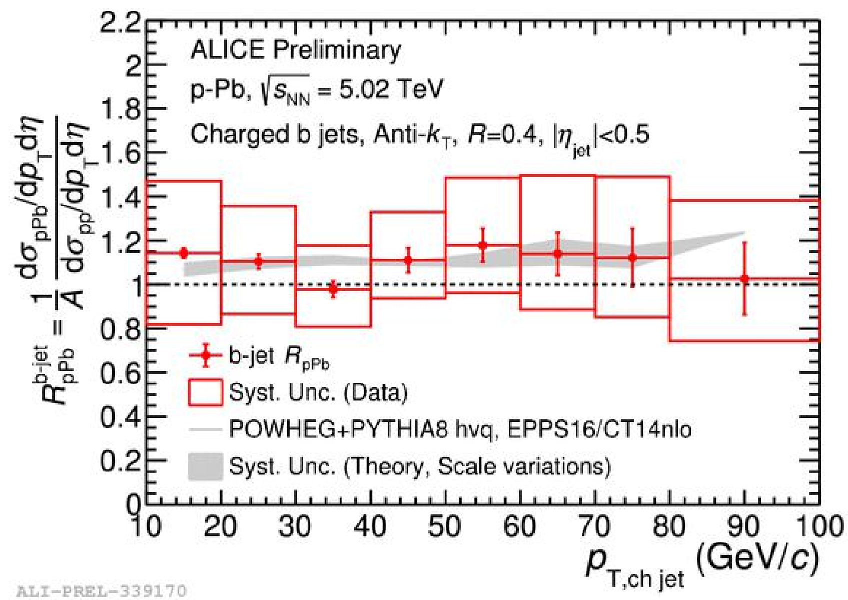


PHENIX: PRL109 24 (2012) 242301
Kang et al:PLB 740(2015)23
Sharma et al: PRC 80(2009) 054902
FONLL: JHEP 9805(1998)007

- **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



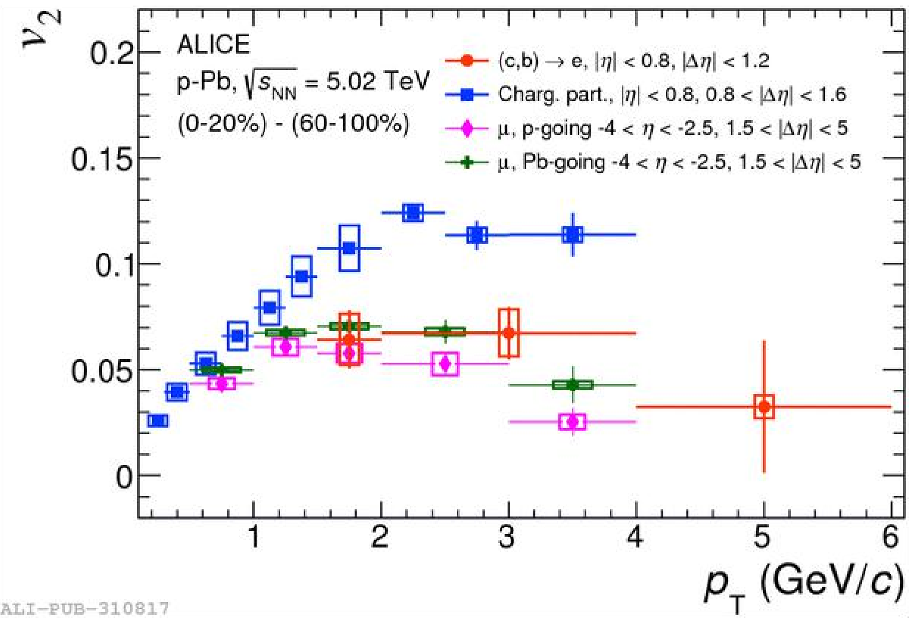


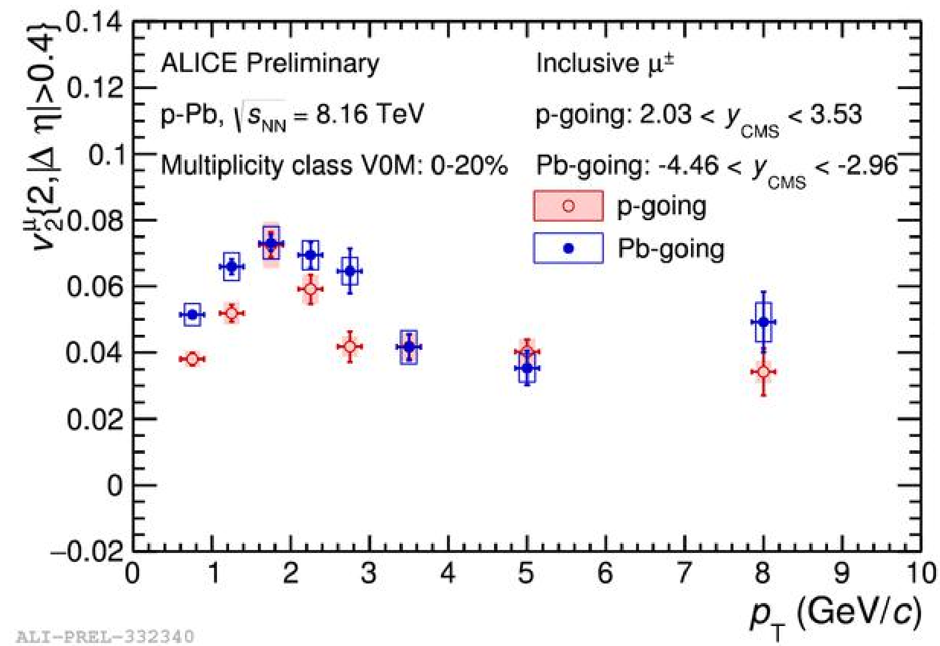
R V (ALICE), arXiv:1910.01981

- **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



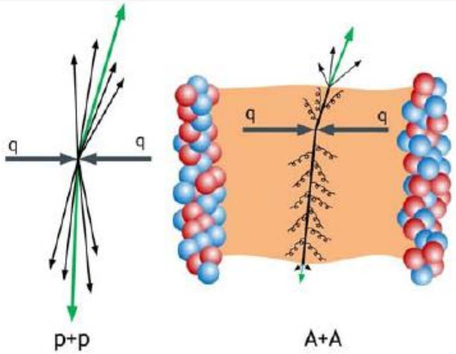


- **Collectivity of HFE and HFM in small systems**
  c,b→e at mid-rapidity, c,b→μ forward/backward
  - Values of e and μ v_2 comparable with each other within uncertainties
  - Low-p_T: comparable to charged hadrons
  - Mid-p_T: about half the charged hadron v_2
  - Tendency of smaller p-going than Pb-going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

Heavy ions: hot nuclear effects

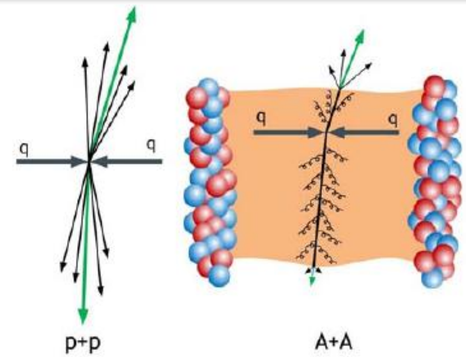
- ***Nuclear modification***

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



  - **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**

Heavy ions: hot nuclear effects



- ***Nuclear modification***

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

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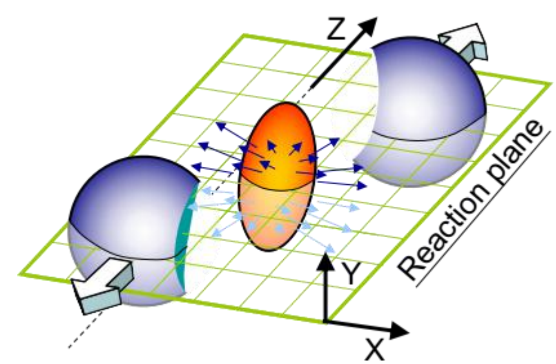
  - Color charge effect (HF is mostly quarks <=> gluon contribution in LF)
  - **Change of fragmentation: Baryons, jets**

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

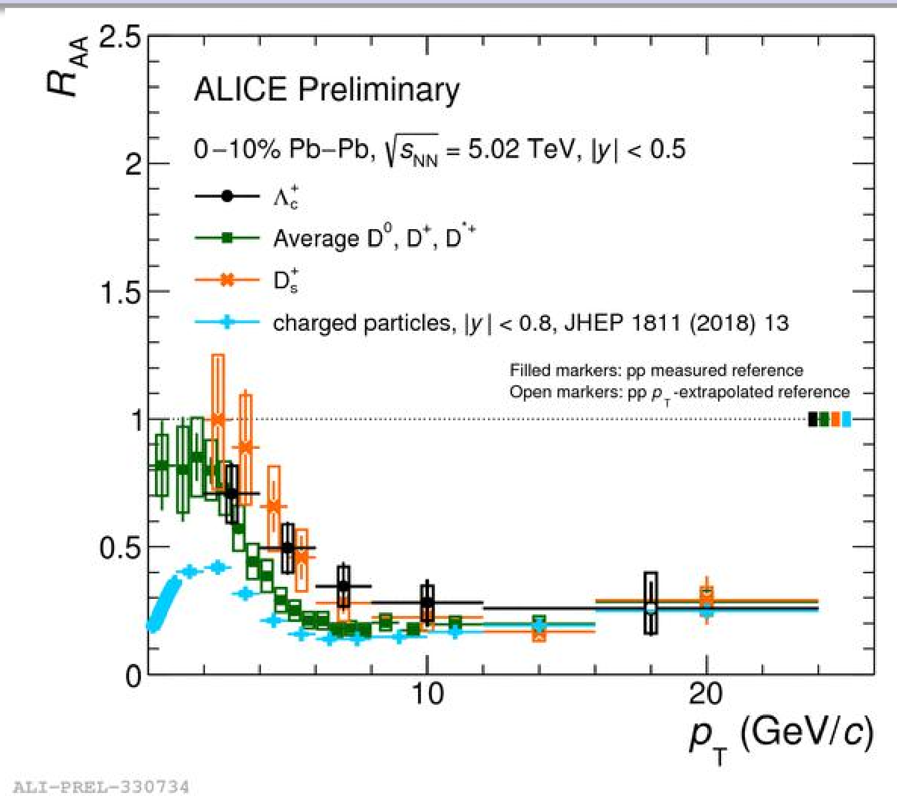
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n(\varphi - \Psi_R)\right)\right)$$

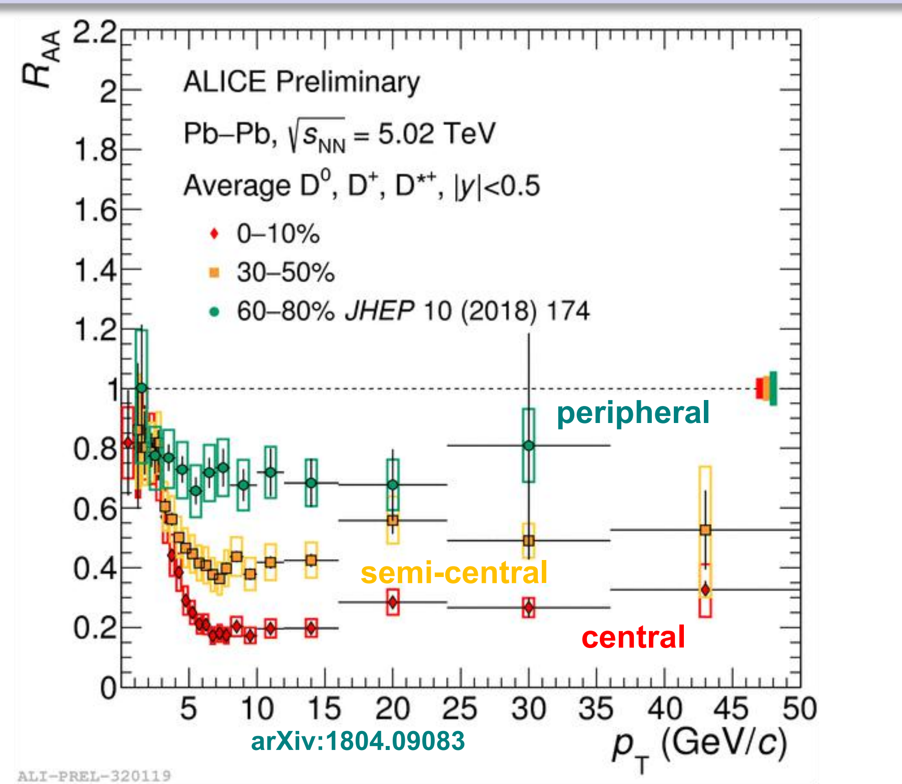
$$v_n = \langle \cos(n(\varphi - \Psi_R)) \rangle$$

  - 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?



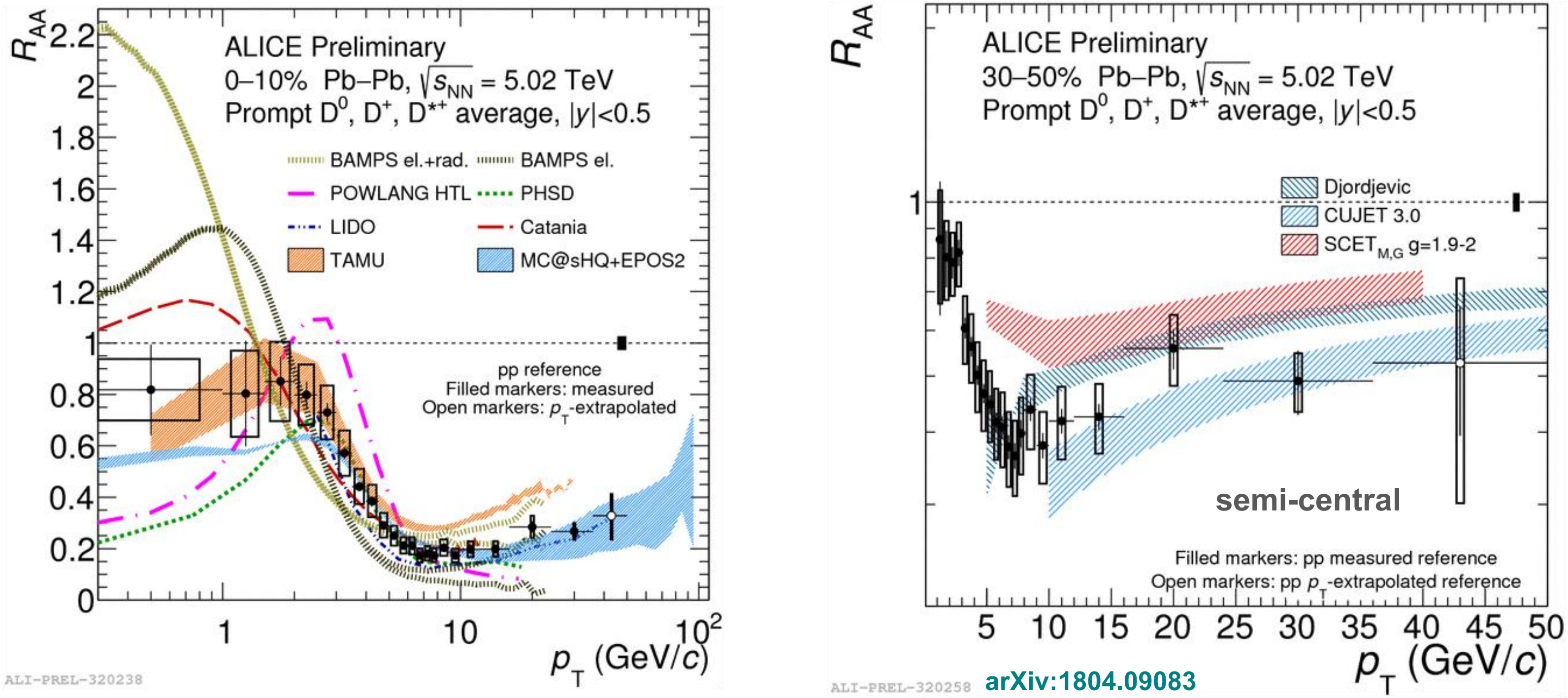
Pb-Pb: Suppression of charm





- 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 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



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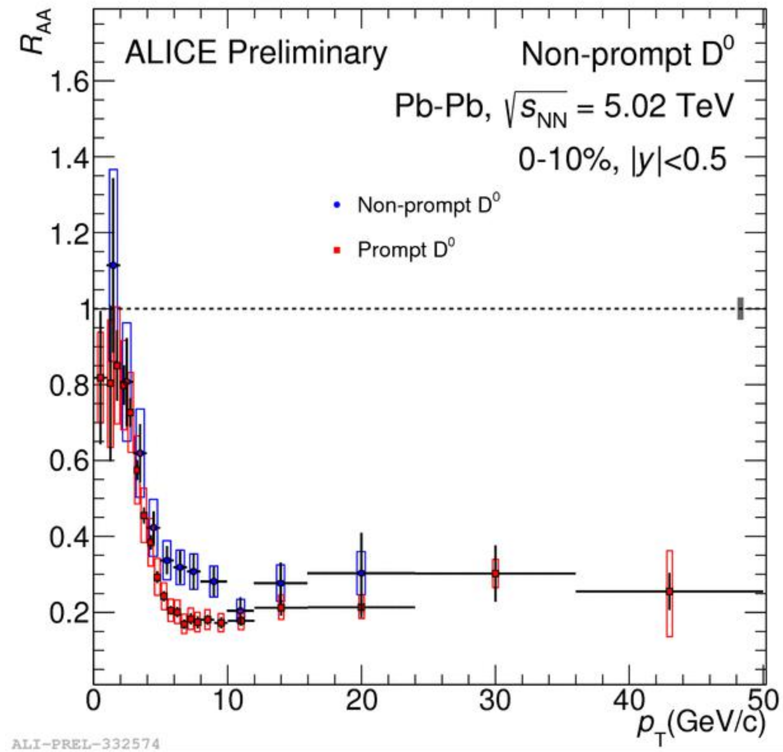
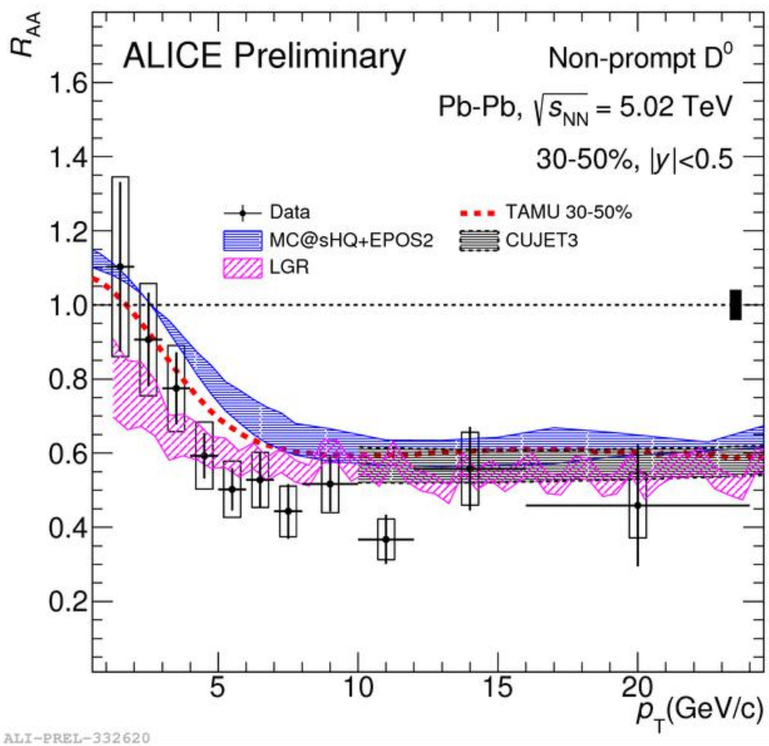
- ***Low-p_T***: Charm suppression is significantly weaker than light flavor
  - **Coalescence of light and charm quarks?**
  - **Several models give good description, low discrimination power**

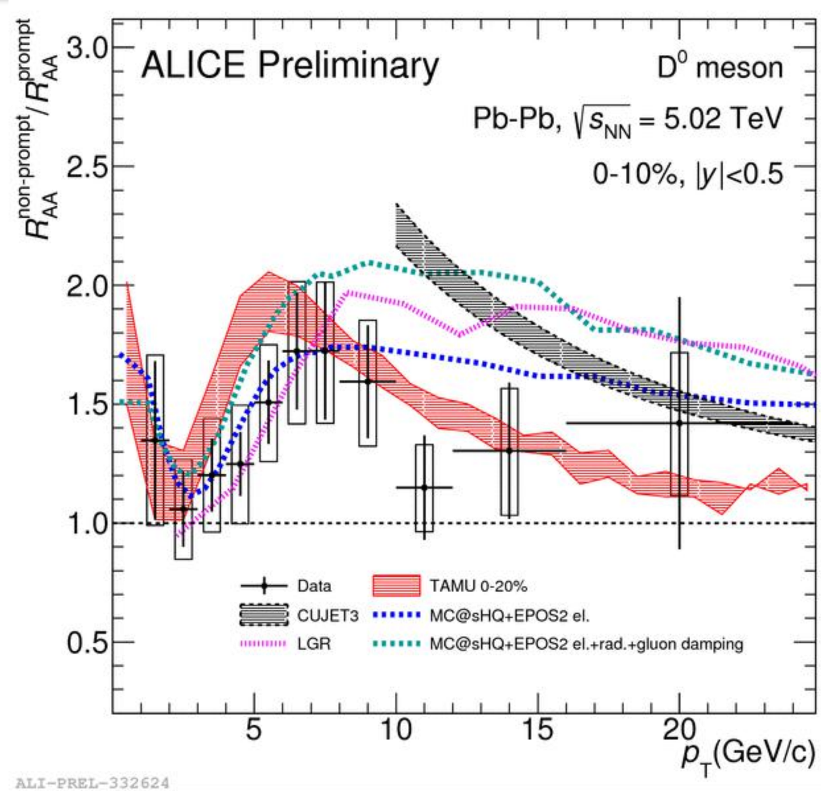
Prompt and non-prompt D mesons



- 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

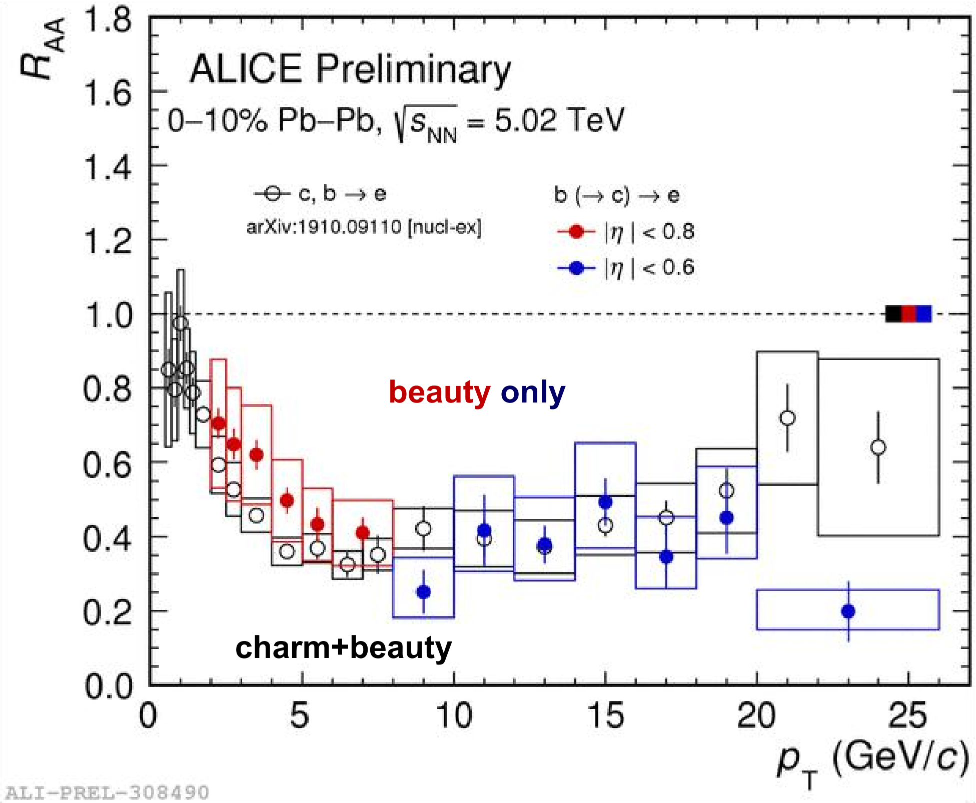
Prompt and non-prompt D mesons





- 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 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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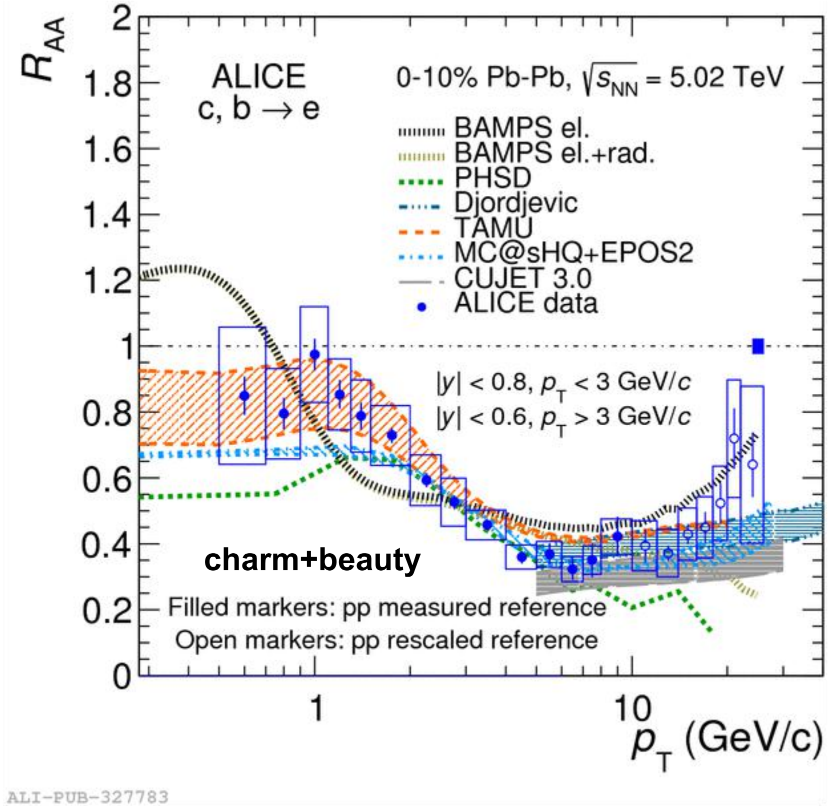
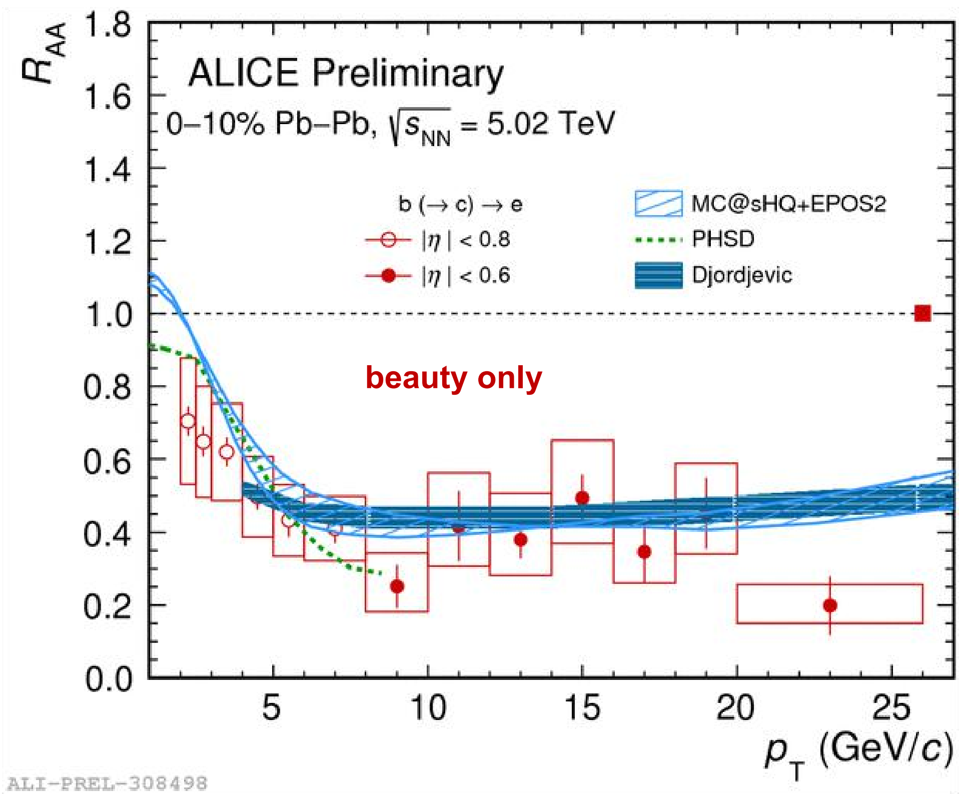
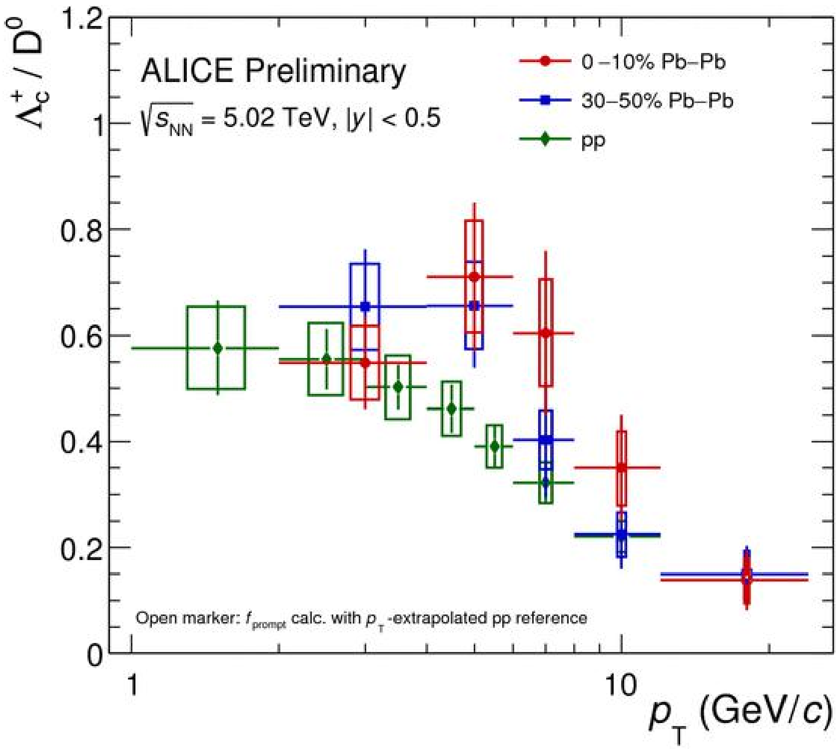


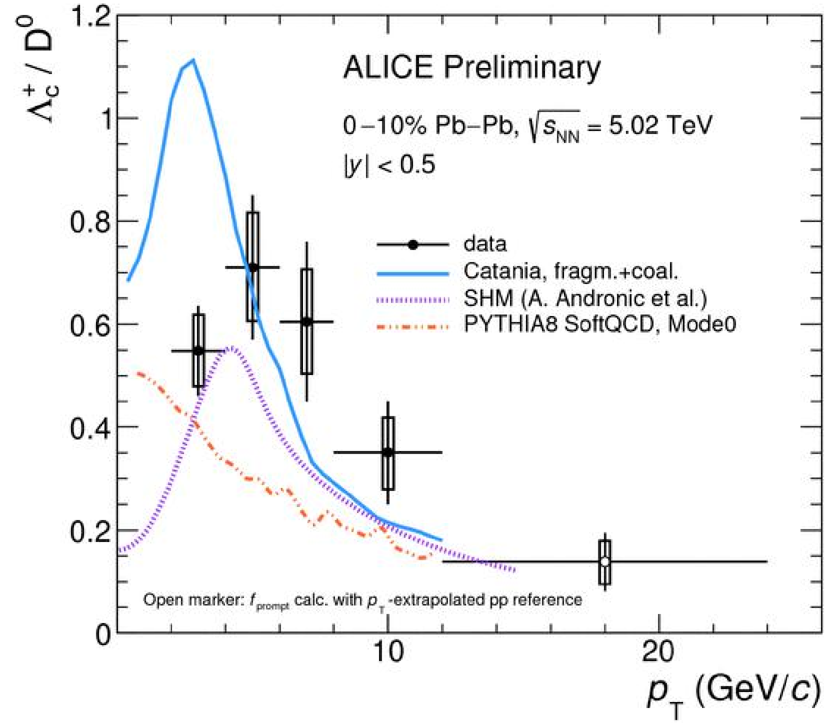


- Significant (c,b)→e suppression in Pb-Pb collisions from medium to high p_T
  - Note: Results in p-Pb collisions are consistent with unity
- Separated beauty-decay electrons hint a weaker b-quark suppression
- Models describe both (c,b)→e and b(→c)→e within uncertainties
  - Difference understood by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

Production of Λ_c in Pb-Pb collisions



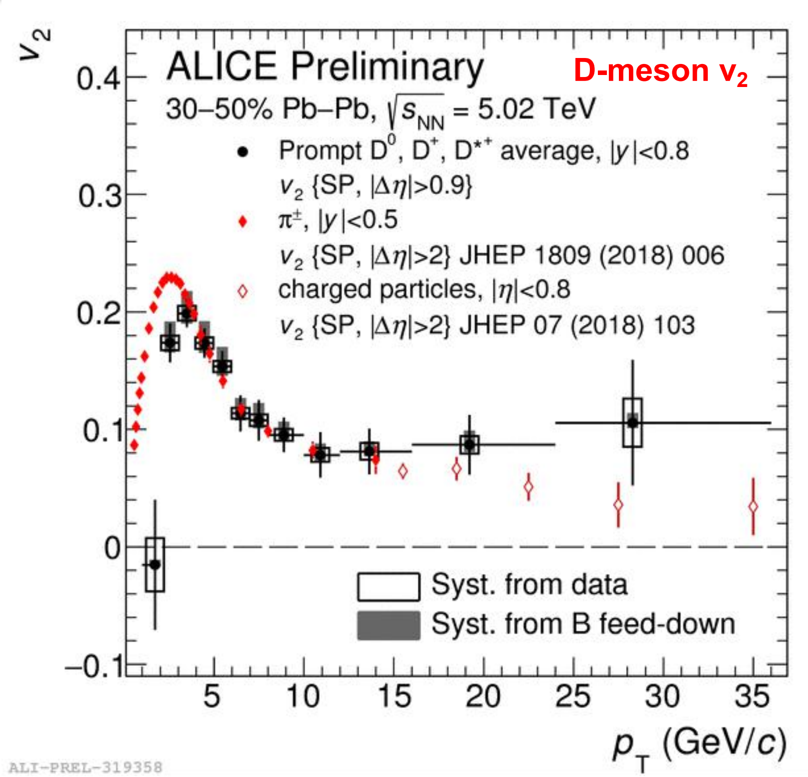
ALI-PREL-323761

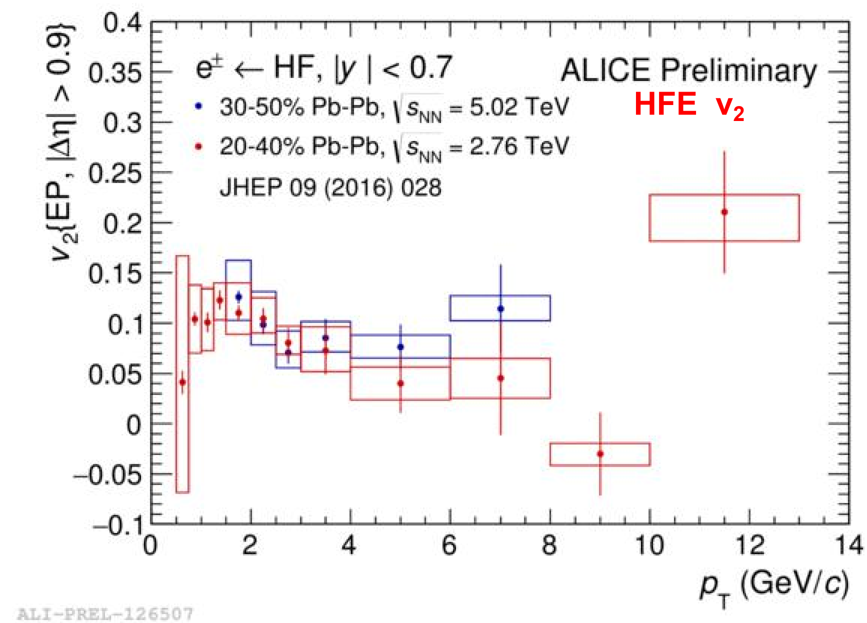


ALI-PREL-325749

- 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

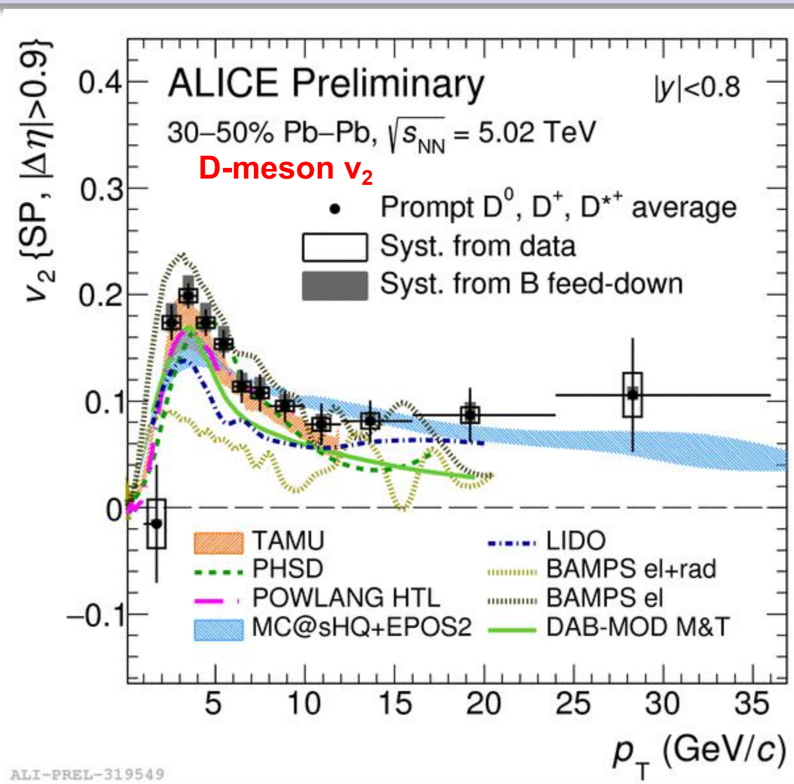
Heavy-flavor azimuthal anisotropy

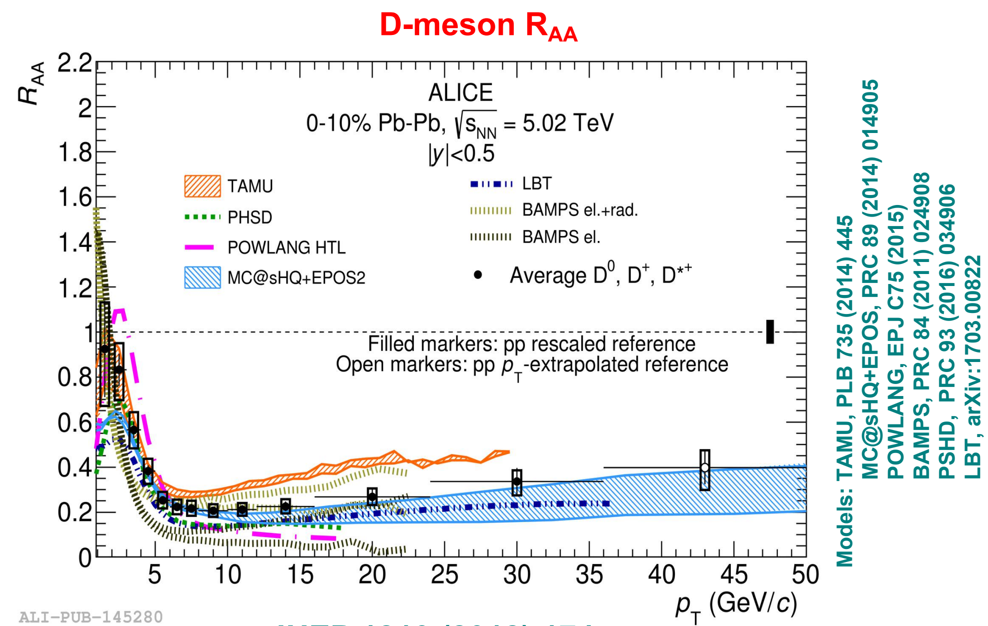




- **D mesons flow**: A significant v_2 of D mesons is observed at the LHC
  - **D-meson v_2** is qualitatively similar to **charged partice v_2** at $\sqrt{s_{NN}}=5.02$ TeV
- **Heavy-flavor electrons flow:** A significant v_2 observed at the LHC
  - HFE v_2 at $\sqrt{s_{NN}}=2.76$ **TeV** and $\sqrt{s_{NN}}=5.02$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

Azimuthal anisotropy of D: and R_{AA}





JHEP 1810 (2018) 174

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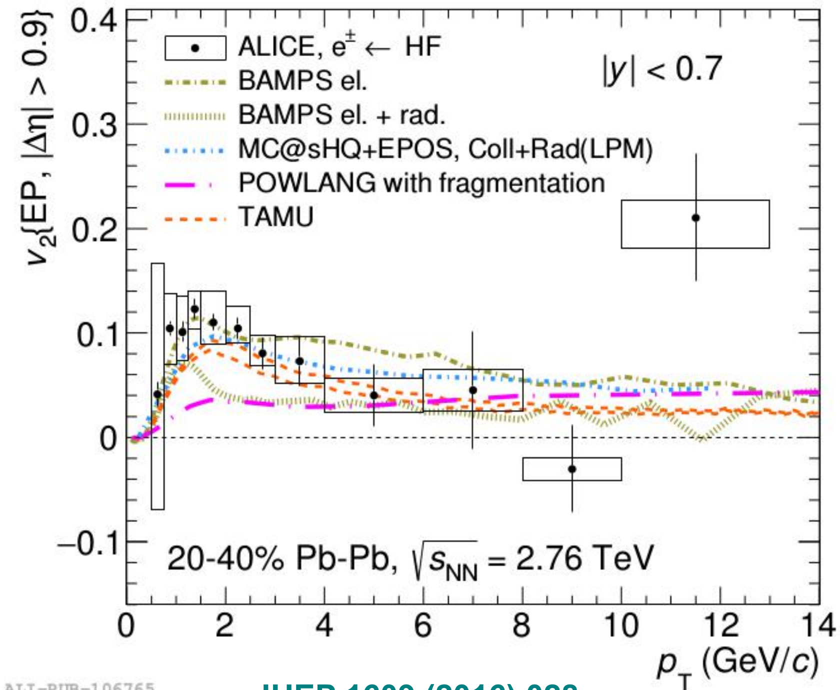
  - D-meson v_2 is qualitatively similar to charged particle v_2 at $\sqrt{s_{NN}}$=5.02 TeV
- Models in which charm picks up **flow via recombination or collisional energy loss** do better in reproducing R_{AA} and v_2 simultaneously

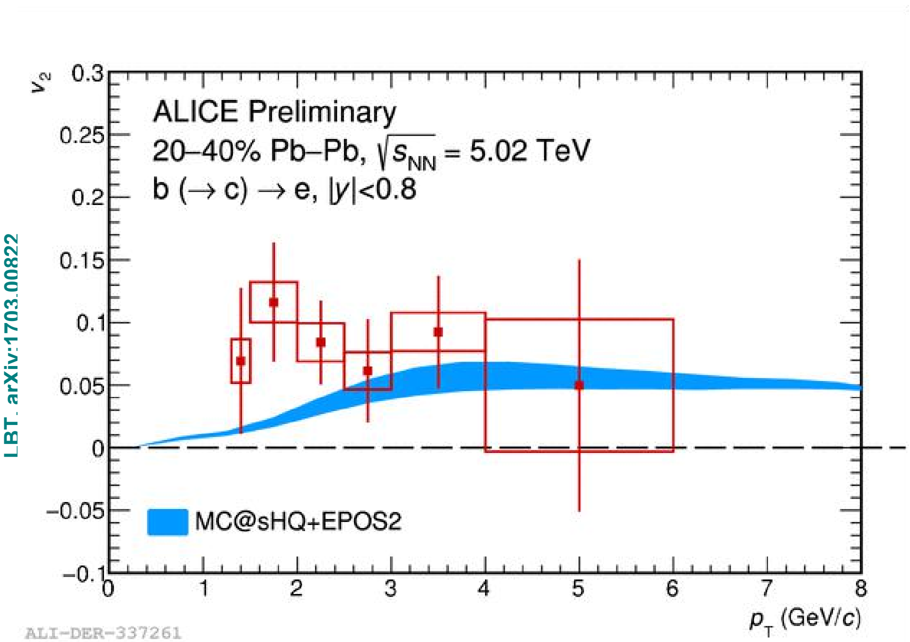
R_{AA} and v_2 together provide strong constraints on models

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

- ***Nuclear modification by cold nuclear matter***
  - R_{AA} consistent with unity at mid-rapidity for D mesons, HFE, b-jets
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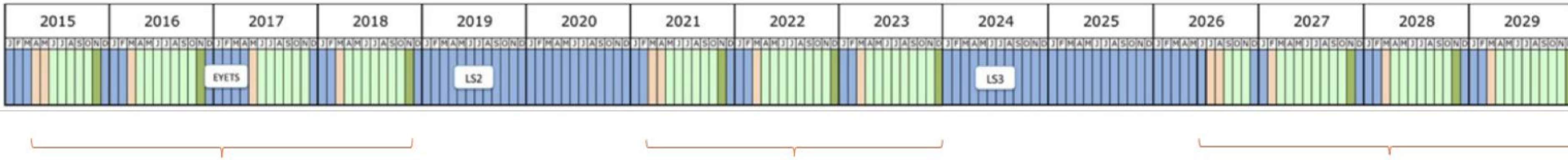
Medium effects in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

- ***Energy loss:*** No ordering in high-p_T suppression: $R_{AA}^{\pi} \approx R_{AA}$
  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*
- **Λ_c** : HF Barion over meson enhancement hinted by data

ALICE Upgrade for Run-3 and Run-4



Run 2: $\mathcal{L}_{Pb\text{-}Pb} = 1.0\ nb^{-1}$ Run 3: $\mathcal{L}_{Pb\text{-}Pb} = 6.0\ nb^{-1}$ Run 4: $\mathcal{L}_{Pb\text{-}Pb} = 7.0\ nb^{-1}$

Shutdown/Technical stop
Protons physics
Commissioning
Ions

- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb-1 (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continouos readout

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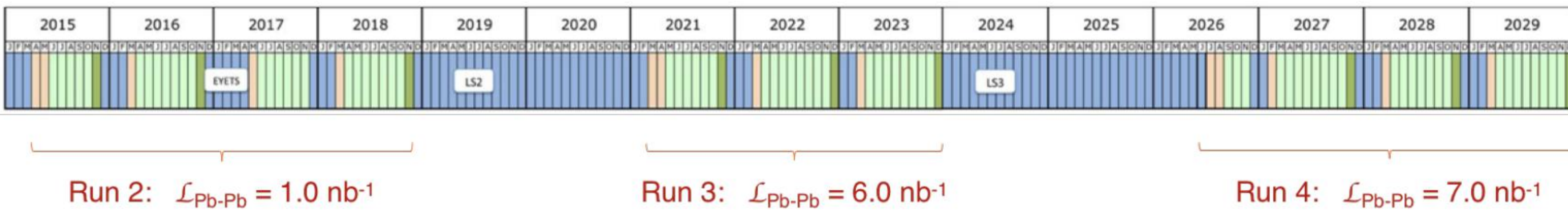

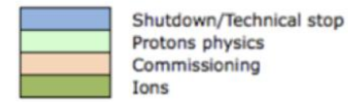

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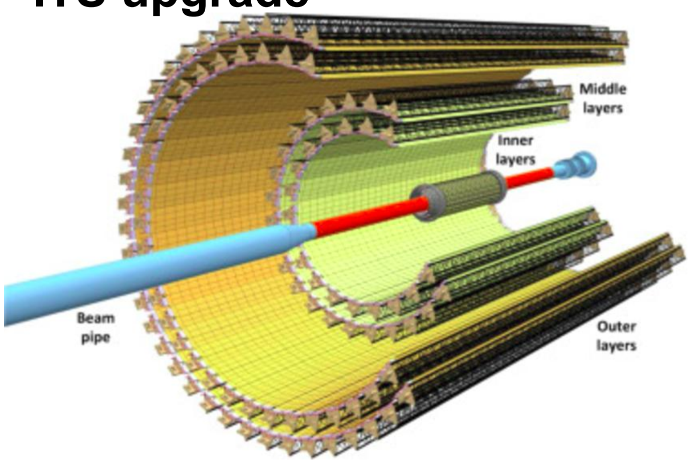
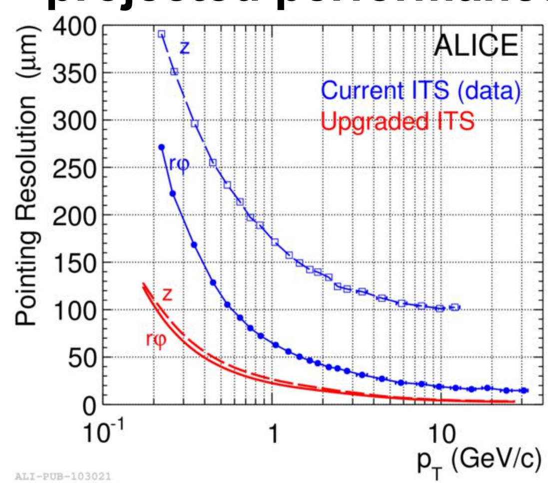
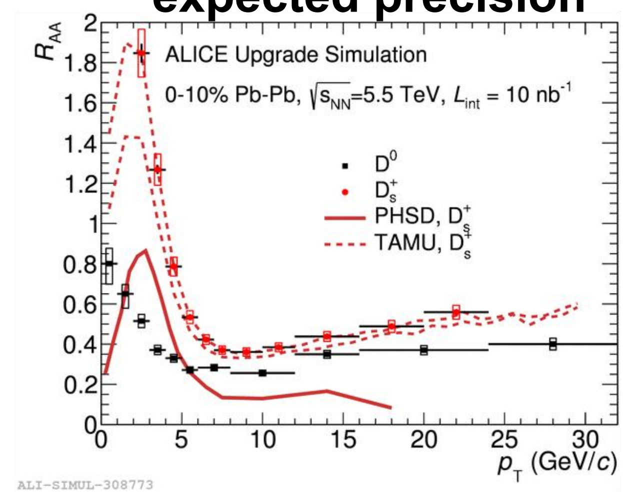
ITS upgrade



projected performance



expected precision



Thank you!

Physics reach after LS2 (2019-20)

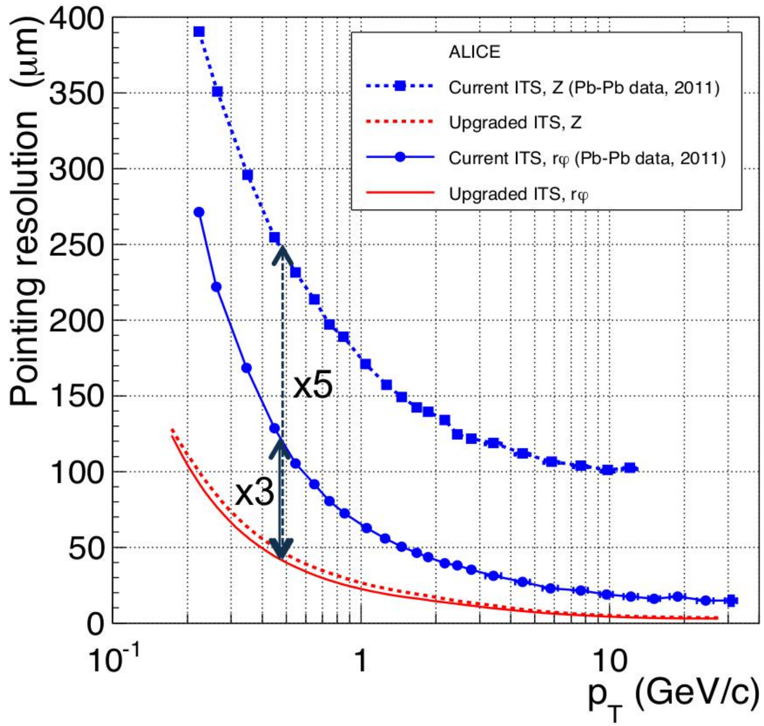
Observable	Current, $0.1\,\mathrm{nb}^{-1}$ p_T^{min} (GeV/c)	Current, $0.1\,\mathrm{nb}^{-1}$ statistical uncertainty	Upgrade, $10\,\mathrm{nb}^{-1}$ p_T^{min} (GeV/c)	Upgrade, $10\,\mathrm{nb}^{-1}$ statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
D_s meson R_{AA}	4	15 %	< 2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

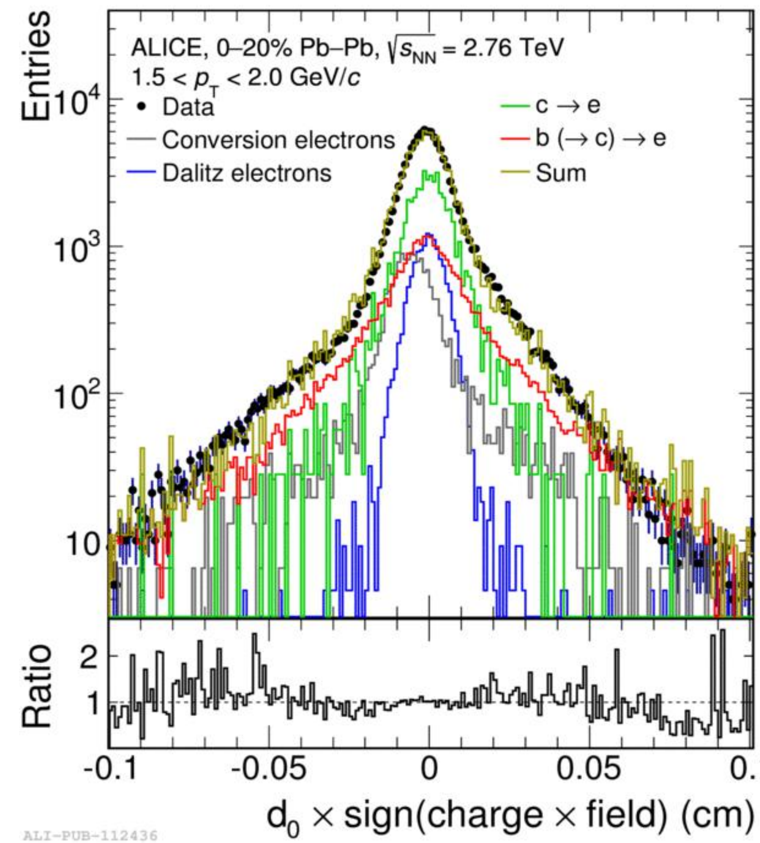
ALICE ITS upgrade TDR

ITS performance

- Semiconducting technology
- Resolves secondary vertex

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





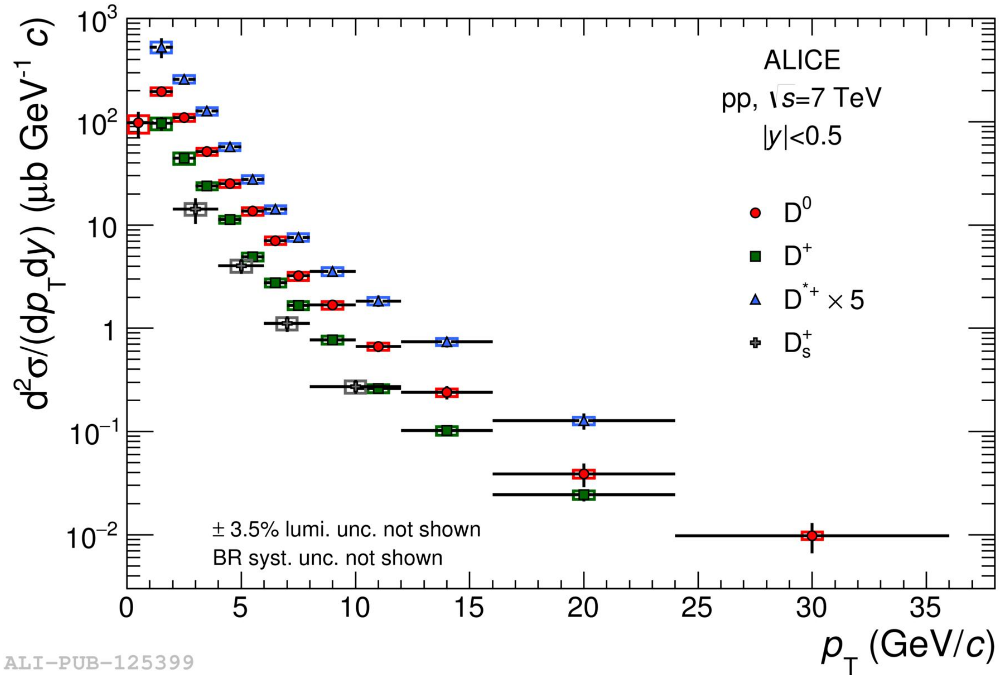
JHEP 07 (2017) 052

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

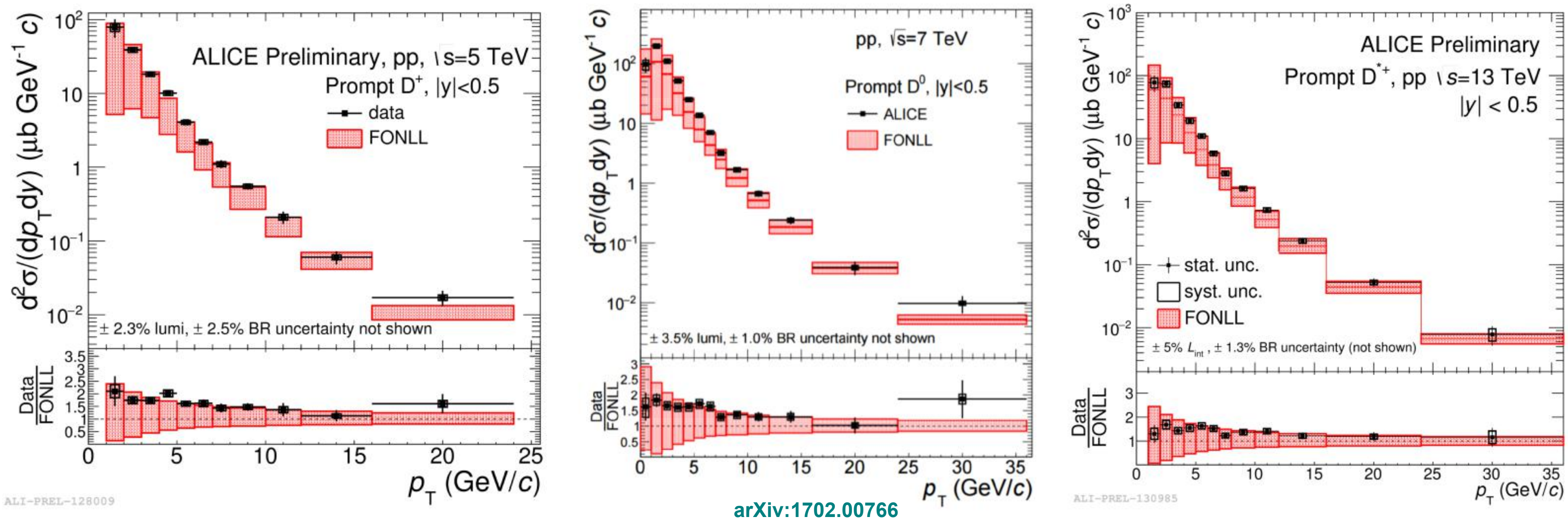


$D^0 \rightarrow K^- \pi^+$	BR ~ 3.9%
$D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+)\pi^+$	BR ~ 2.6%
$D^+ \rightarrow K^- \pi^+ \pi^+$	BR ~ 9.5%
$D_S^+ \rightarrow \Phi(\rightarrow K^+ K^-)\pi^+$	BR ~ 2.3%

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

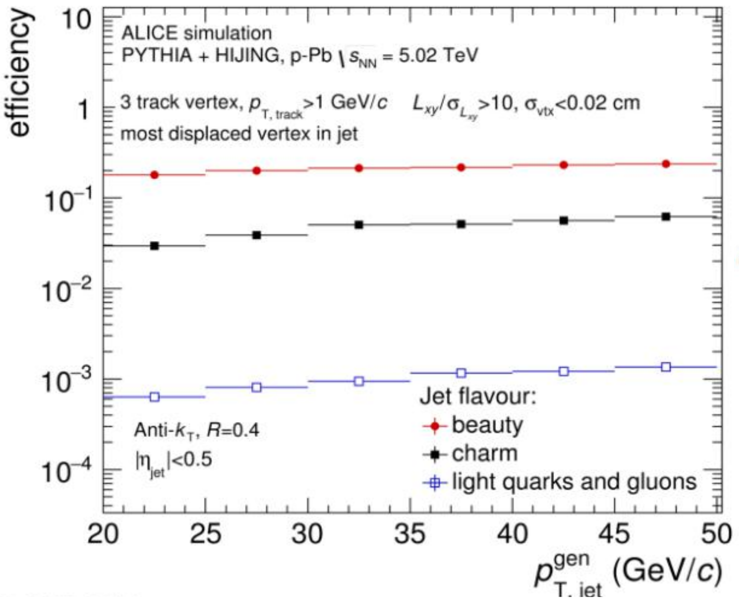
- D^0 at very low p_T (<1 GeV/c): PID only, no vertex reconstruction or topological cuts

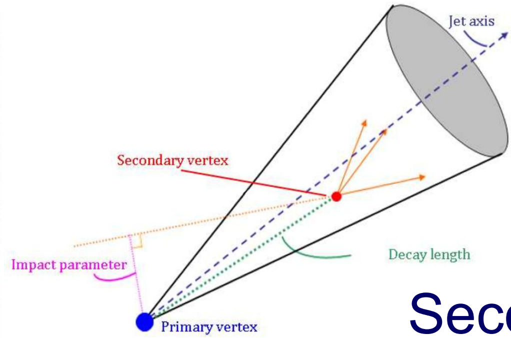
D mesons at different energies (pp)



- 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

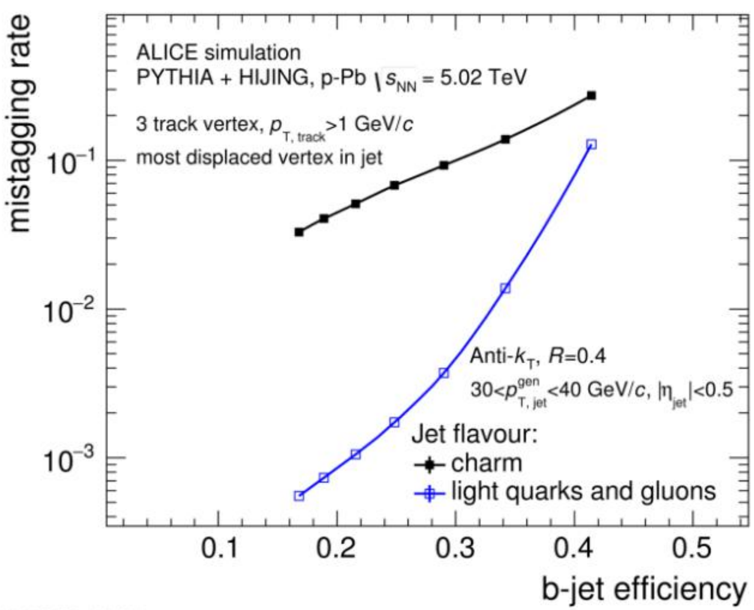
b-jet tagging performance

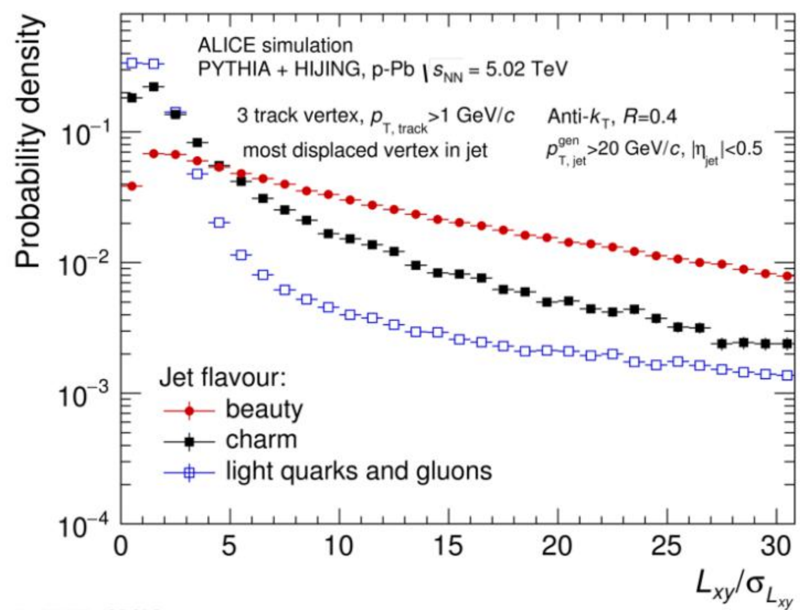




Secondary vertex method

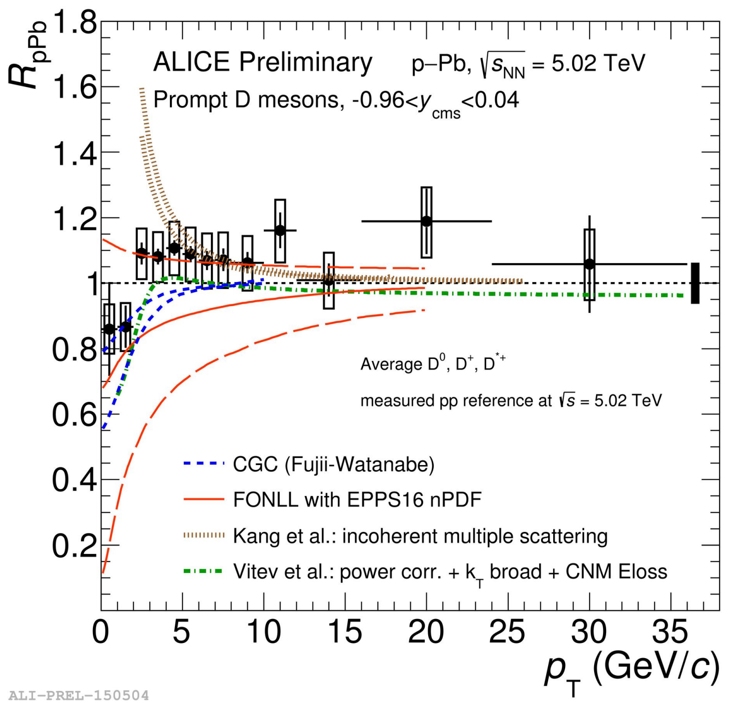
- L_{xy} : projection of decay length on the (x,y) plane
- L_{xy}/σ_{Lxy} : significance of L_{xy}
- σ_{vtx} : secondary vertex dispersion



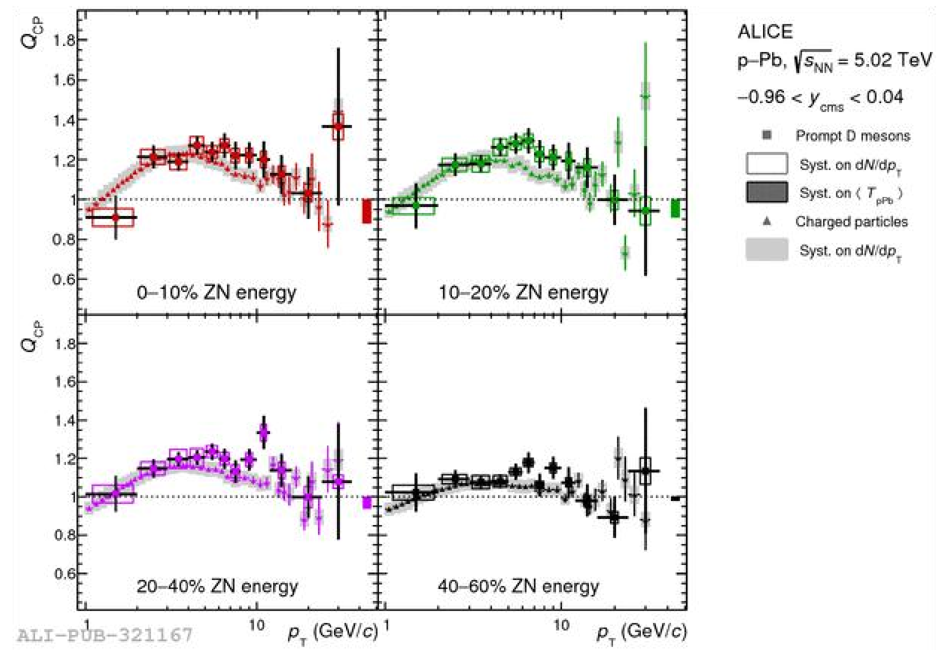


ALI-SIMUL-95610

CNM effects in p-Pb collisions?

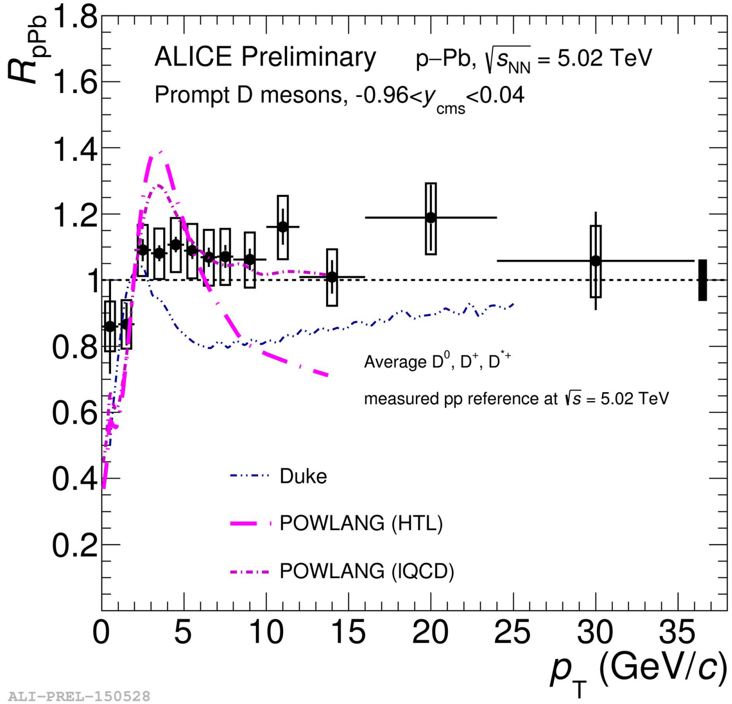


Models:
CGC, arXiv:1308.1258
MNR: NPB 373 (1992) 295
Vitev, PRC 75 (2007) 064906
Kang, PLB 740, 23 (2015)

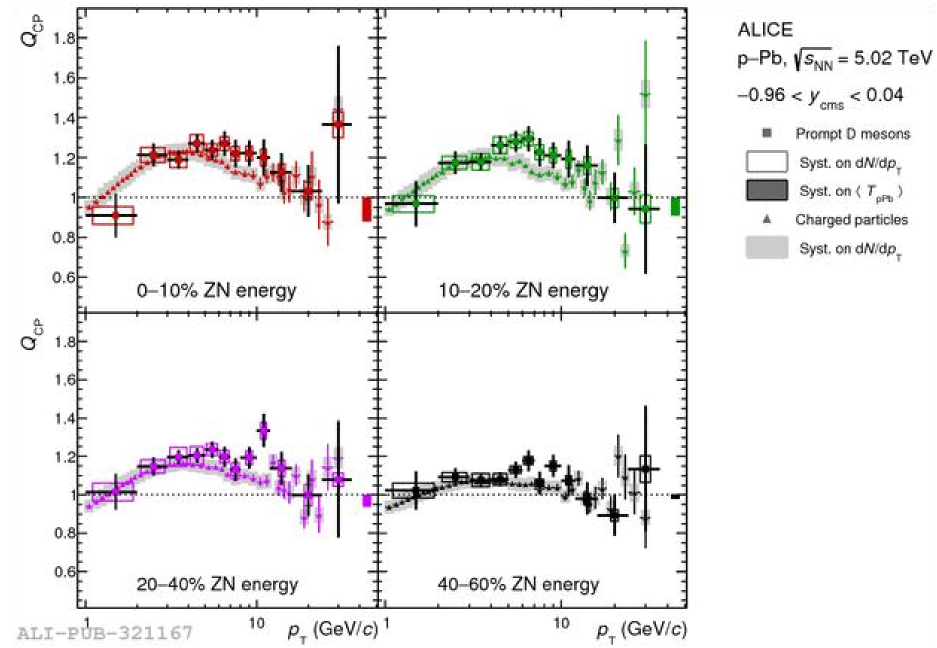


- **D-meson production in p-Pb collisions:**
  No modification w.r.t. pp collisions within uncertainties
  - No indication of CNM effects from intermediate to high p_T
  - Data described by several models containing CNM effects
- Hint of Q_{CP} > 1 for central collisions (1.5σ at 3<pT< 8 GeV/c)
  - similar 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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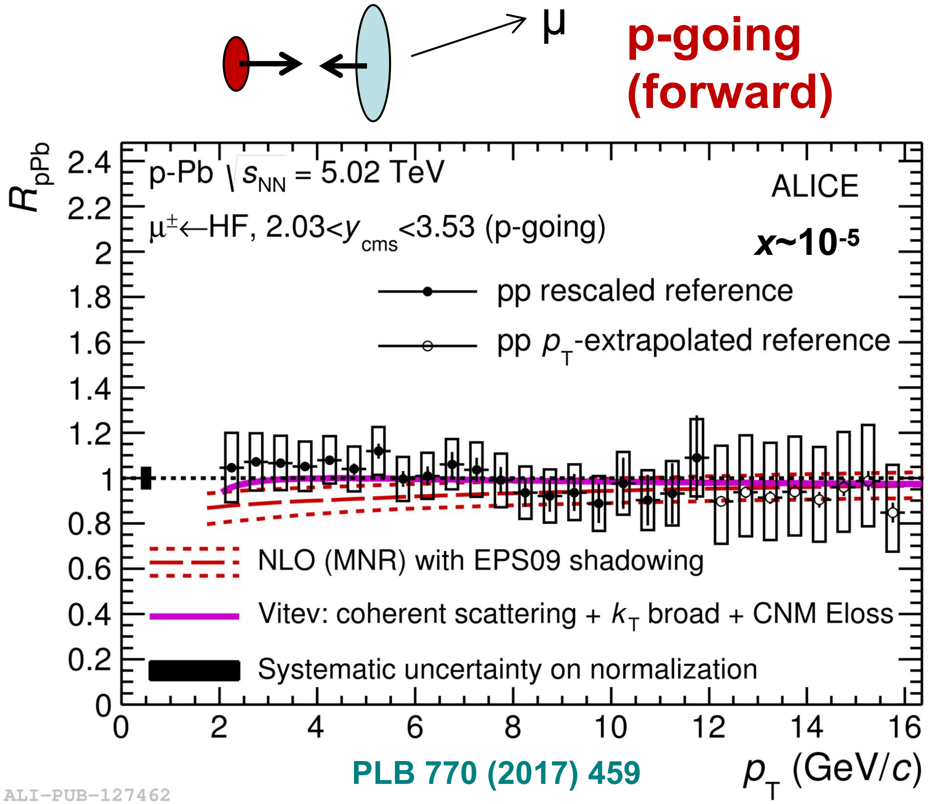
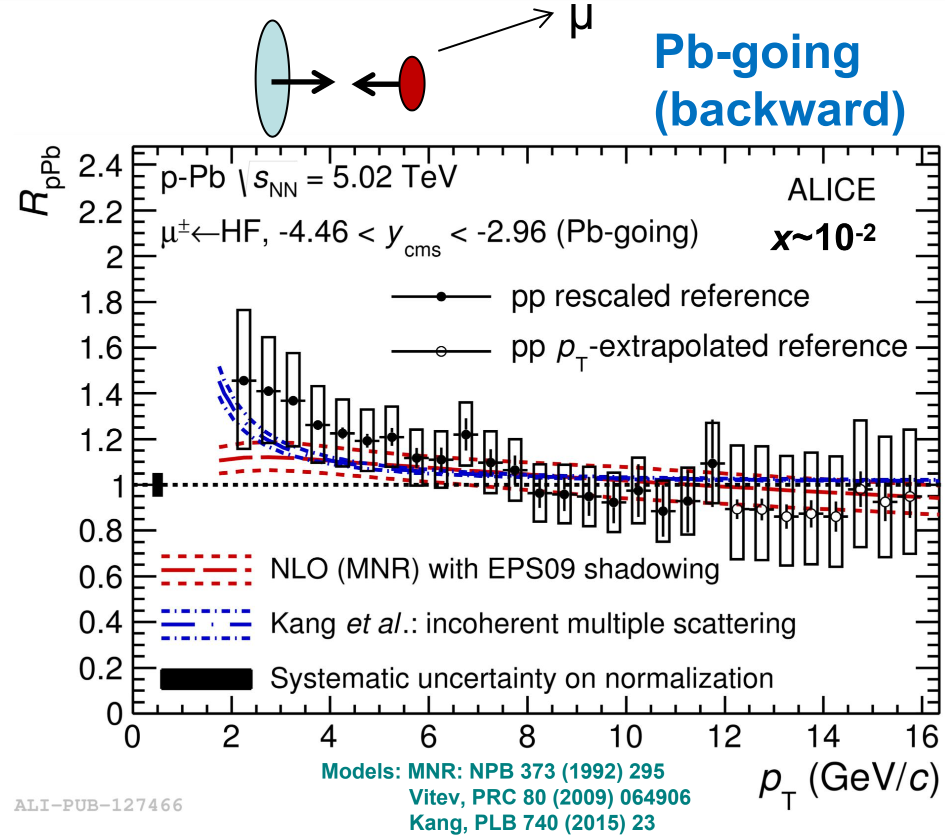
  No modification w.r.t. pp collisions within uncertainties
  - No indication of CNM effects from intermediate to high p_T
  - Data described by several models containing CNM effects
- **A model including small-volume QGP formation also describes data** (but not favored by)

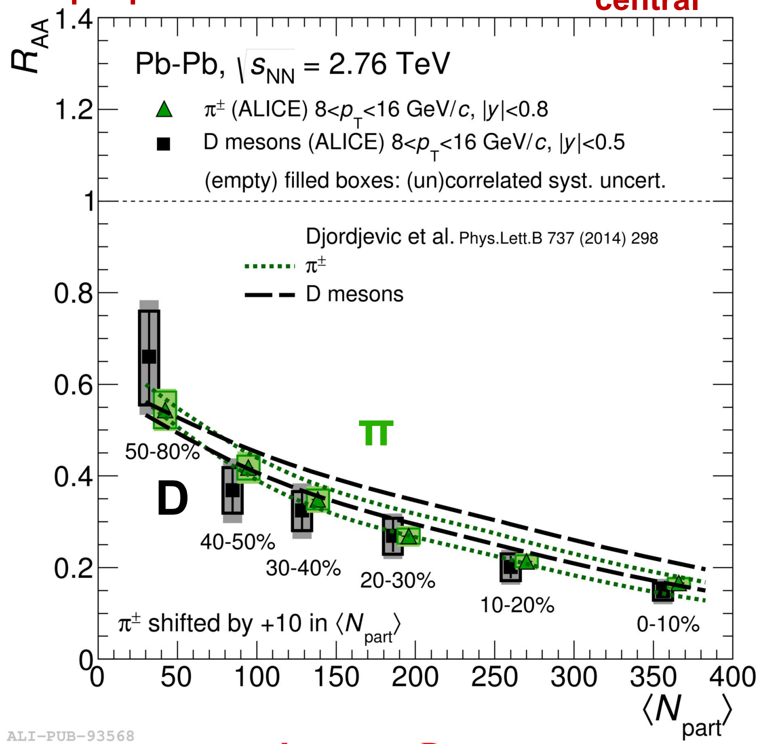
CNM effects - Forward, backward



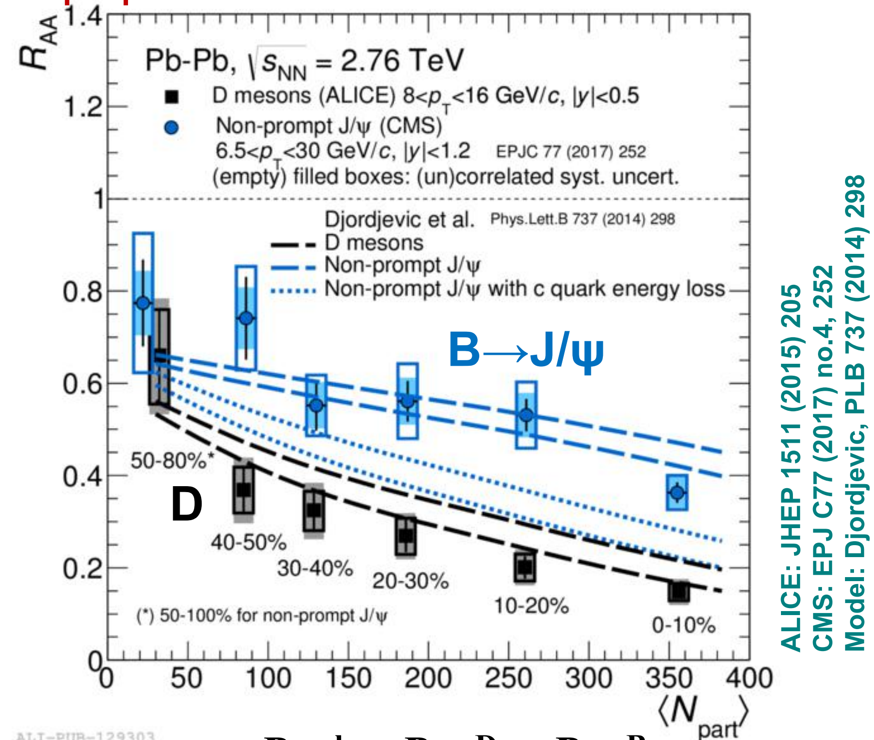


- Heavy-flavour decay muons probe the nPDFs at different *x* values
- Forward production is consistent with no nuclear modification
- **Hint of an enhancement of HF muons at backward rapidity at low p_T**
- Measurements described by models within uncertainties

Flavour/mass dependence - hadrons



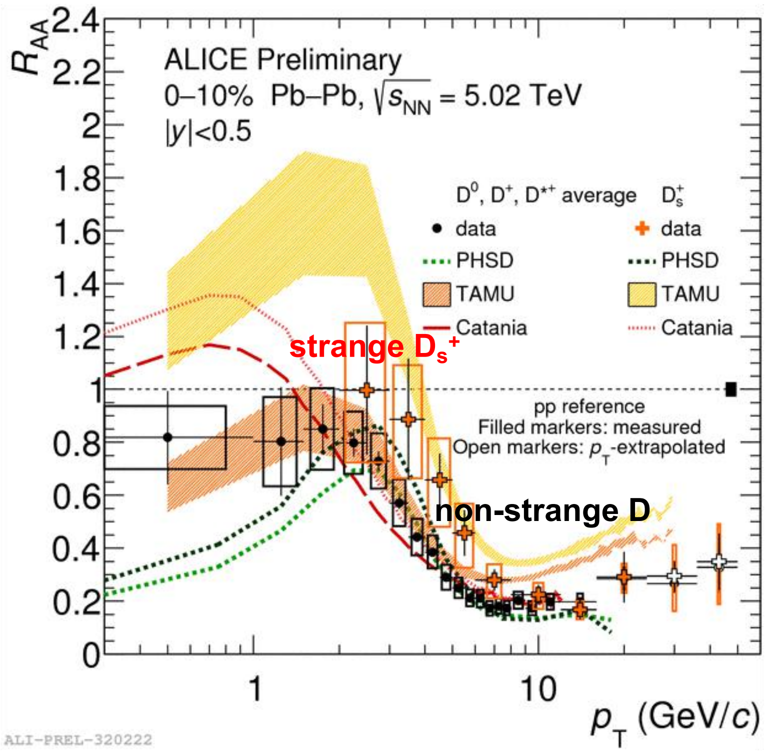
$R_{AA}^{h} \approx R_{AA}^{D}$

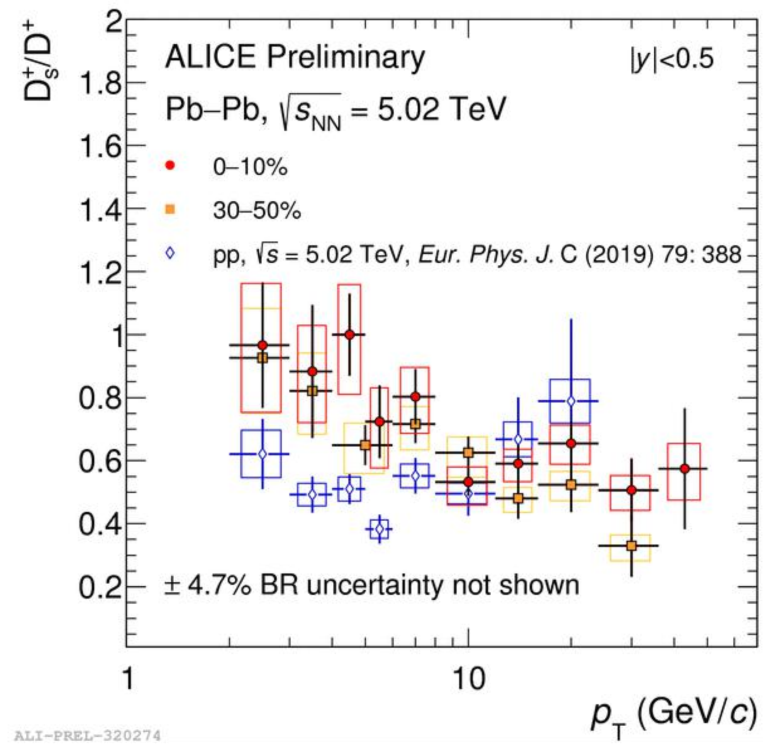


$R_{AA}^{h} \approx R_{AA}^{D} < R_{AA}^{B}$

- **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

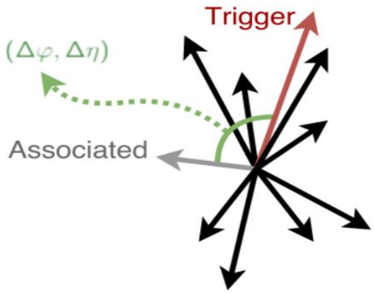
Coalescence of strange and charm



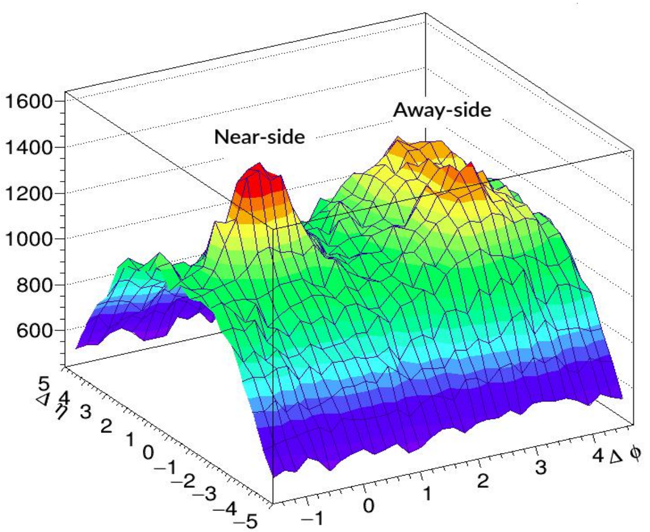


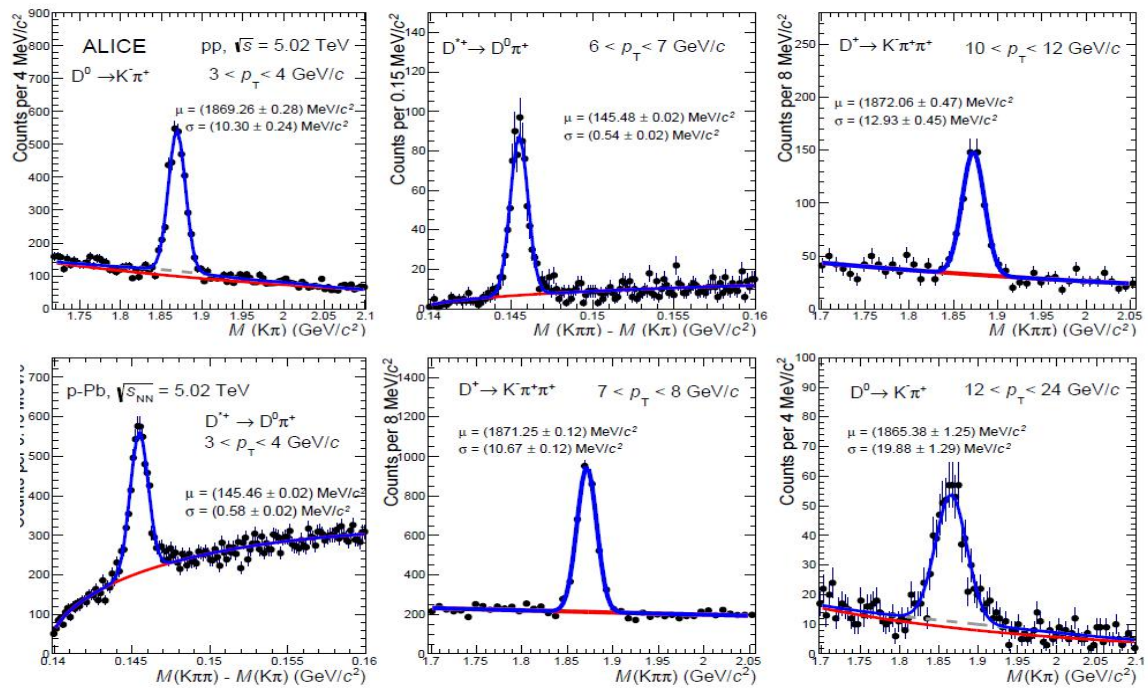
- Strangeness enhancement expected to show up in coalescence
- Hint of a weaker D_S suppression than for non-strange D mesons
  - No evidence of centrality-dependence
- Consistent with a strangeness-enhancement scenario with coalescence

D-h correlations - reconstruction



$$\frac{1}{N_{trigger}}\frac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta}$$





arXiv:1910.14403

$$\bar{c}_{inclusive}(\Delta\varphi,\Delta\eta) = \frac{p_{prim}(\Delta\varphi)}{S_{peak}}\left(\left.\frac{C(\Delta\varphi,\Delta\eta)}{ME(\Delta\varphi,\Delta\eta)}\right|_{peaks} - \frac{B_{peak}}{B_{sidebands}}\left.\frac{C(\Delta\varphi,\Delta\eta)}{ME(\Delta\varphi,\Delta\eta)}\right|_{sidebands}\right)$$

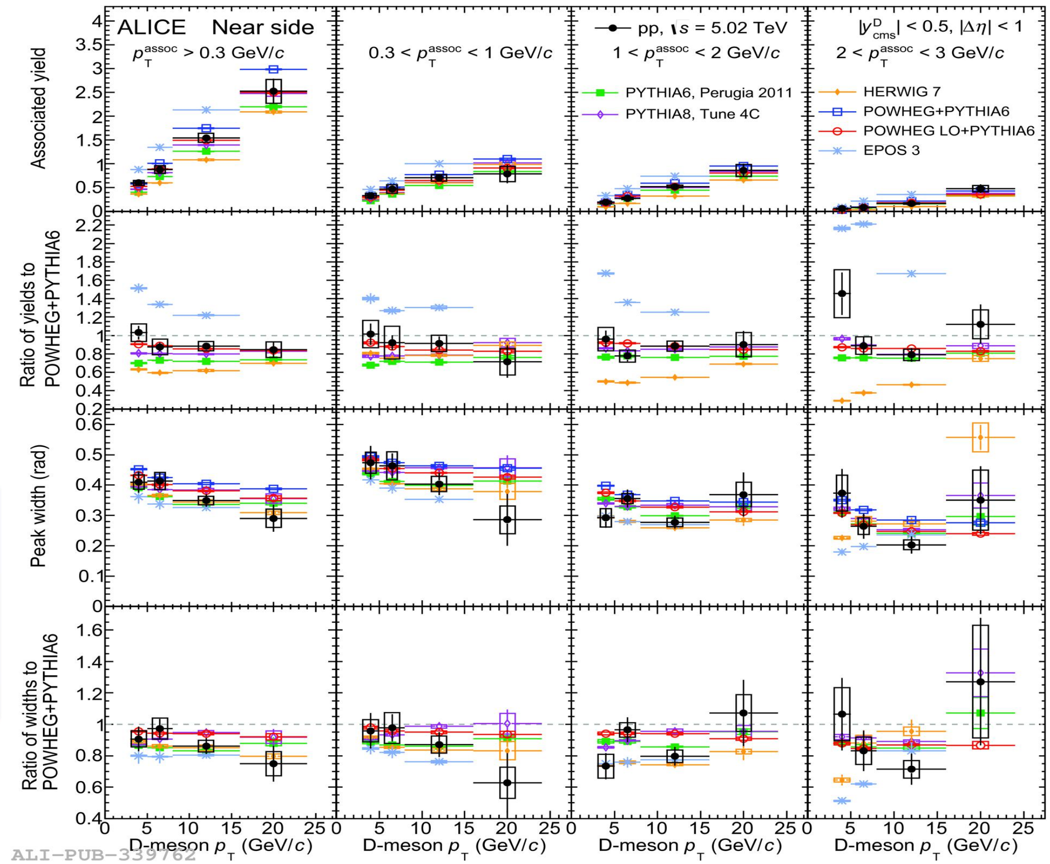
E Frajna (ALICE), https://indico.cern.ch/event/867085/contributions/3656153

Comparsion to Monte Carlo simulations (near-side)

PYTHIA6: LO generator with initial and final state parton shower, Lund string fragmentation.
PYTHIA8: also includes multiple-parton interactions and improved colour reconnection description.
HERWIG 7: NLO including heavy flavor, cluster hadronisation model, the showering ordering is different from PYTHIA (angular ordering with respect to p_T ordering).
POWHEG+PYTHIA: NLO calculation of hard processes, followed by Lund fragmentation.
POWHEG LO+PYTHIA: hard process stopped at the LO level, Lund fragmentation.
EPOS3: 3D+1 viscous hydrodynamical evolution starting from flux tube initial conditions, which are generated in the Gribov-Regge multiple scattering framework.

Near-side and away-side: sensitivity to fragmentation and parton shower

- Best description by POWHEG+PYTHIA6, POWHEG LO +PYTHIA6 and PYTHIA8 & Yields typically underestimated by HERWIG & NLO models predict slightly broader peaks & EPOS3 typically overpredicts the yields



arXiv:1910.14403

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Comparsion to Monte Carlo simulations (away-side)

PYTHIA6: LO generator with initial and final state parton shower, Lund string fragmentation.
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HERWIG 7: NLO including heavy flavor, cluster hadronisation model, the showering ordering is different from PYTHIA (angular ordering with respect to p_T ordering).
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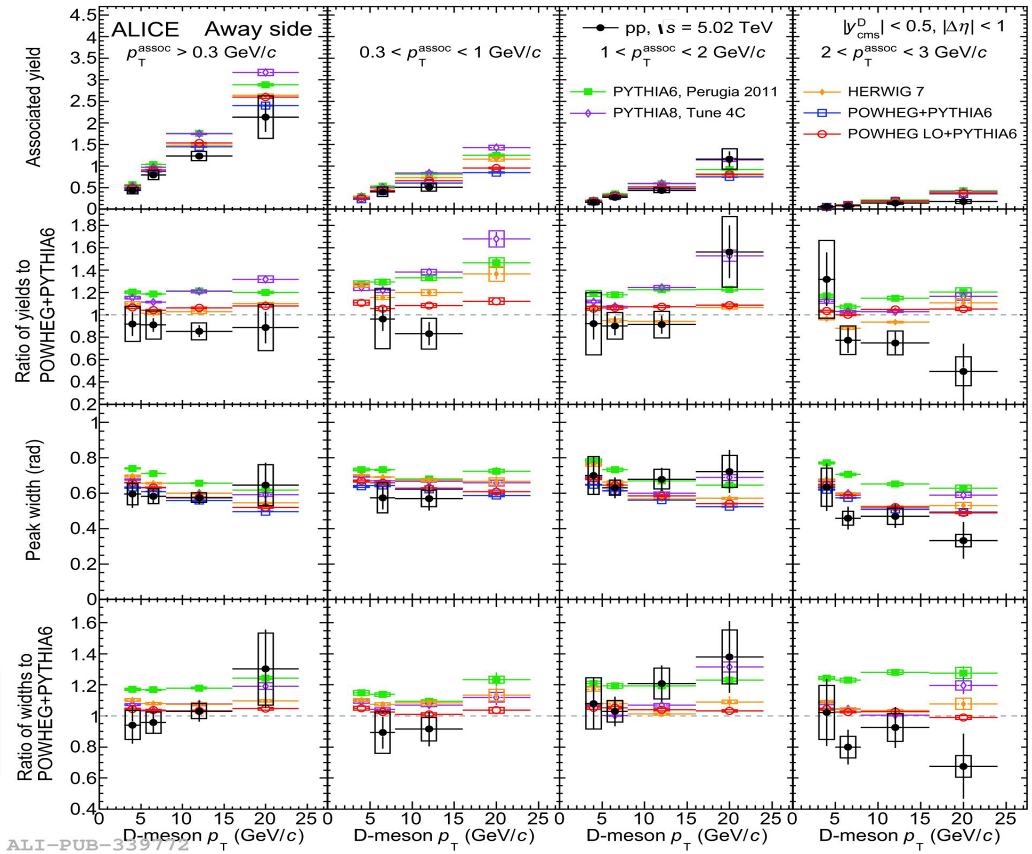
- PYTHIA6 (Perugia11) overpredicts both the yields and widths & PYTHIA8 (4C) overpredicts low-p_T yields and widths



arXiv:1910.14403

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Comparsion to Monte Carlo simulations (baseline)

PYTHIA6: LO generator with initial and final state parton shower, Lund string fragmentation.
PYTHIA8: also includes multiple-parton interactions and improved colour reconnection description.
HERWIG 7: NLO including heavy flavor, cluster hadronisation model, the showering ordering is different from PYTHIA (angular ordering with respect to p_T ordering).
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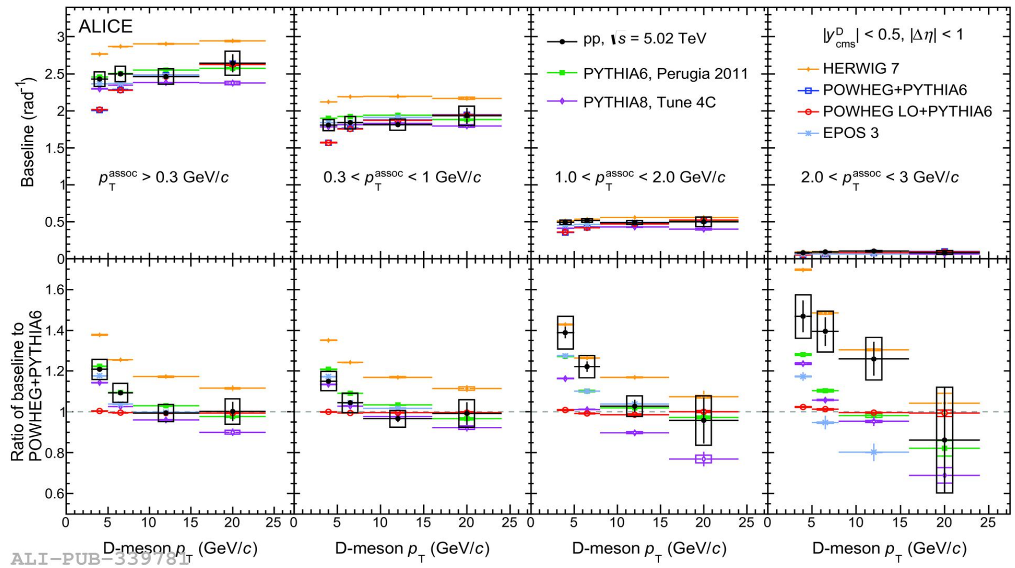
- PYTHIA6 (Perugia11) overpredicts both the yields and widths & PYTHIA8 (4C) overpredicts low-p_T yields and

Baseline: Sensitive to the underlying event

- p_T^{assoc}<1 GeV: best description by PYTHIA
- p_T^{assoc}>1 GeV: best description by HERWIG
- POWHEG NLO and LO are the same in all ranges (not trivial since influence expected from NLO charm contributions)



arXiv:1910.14403

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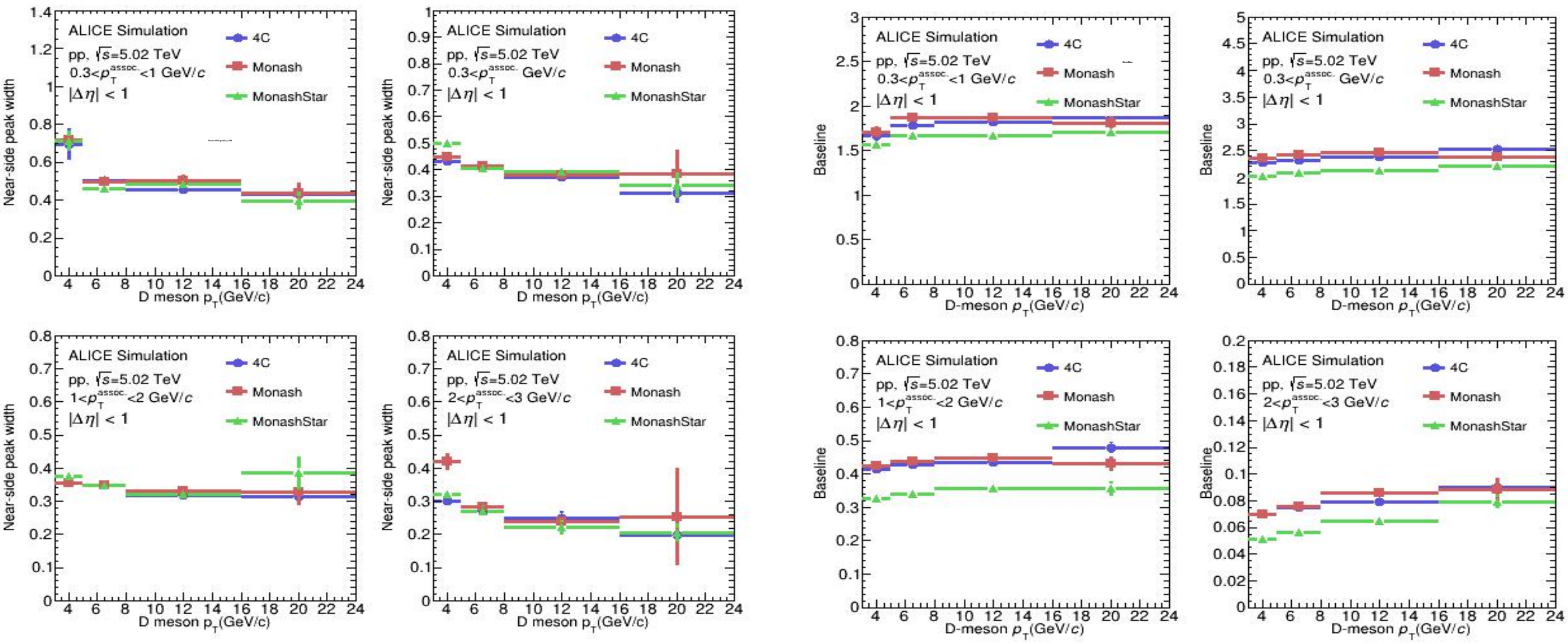
https://indico.cern.ch/event/867085/contributions/3656153

CORRELATIONS USING PYTHIA 8 - different tunes



- Near side peaks are similarly predicted
- Significantly lower baseline for MonashStar (~20% at max)
- Different underlying events

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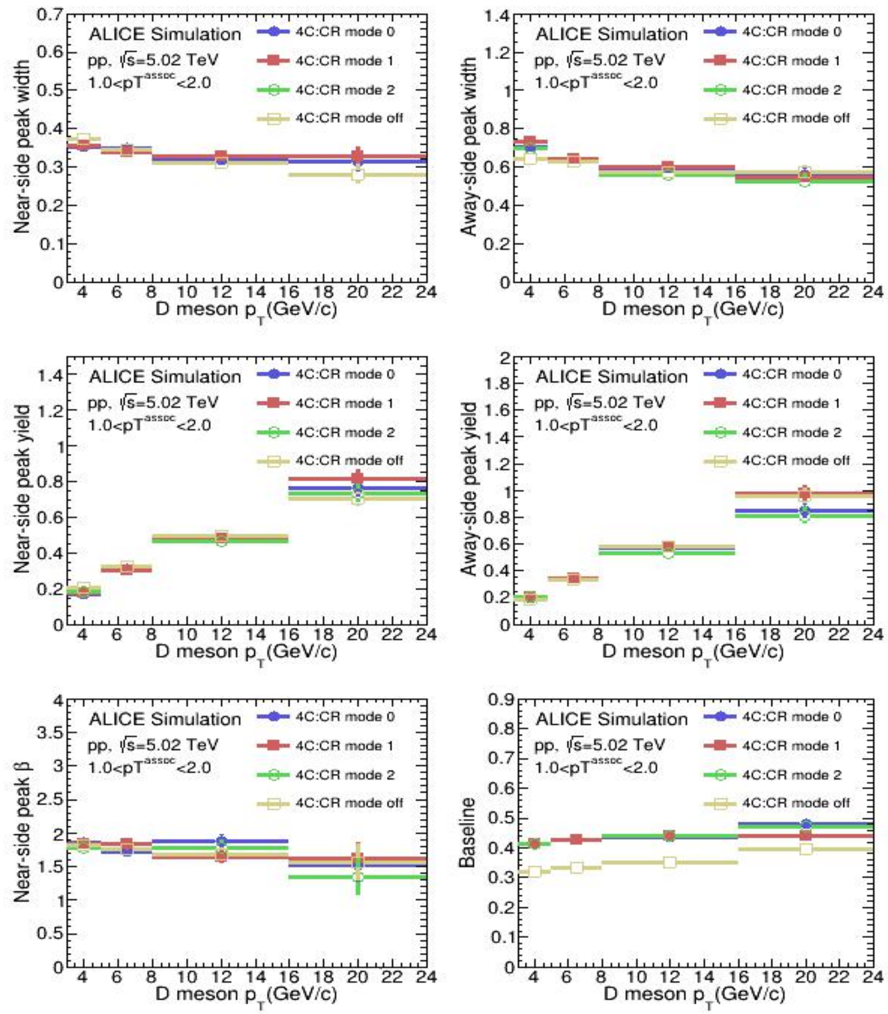
Different colour reconnection modes

- Mode 0 : The MPI-based original Pythia 8 scheme.
- Mode 1 : The new QCD based scheme.
- Mode 2 : The new gluon-move model.
- Reconnection off.

A tendency for a narrowing of the near-side and away-side peak with increasing p_T^D.

An increasing trend of the near-side and away-side yield with increasing p_T^D.

Baseline: Other parameters than CR off are mostly the same => difference only in underlying event.



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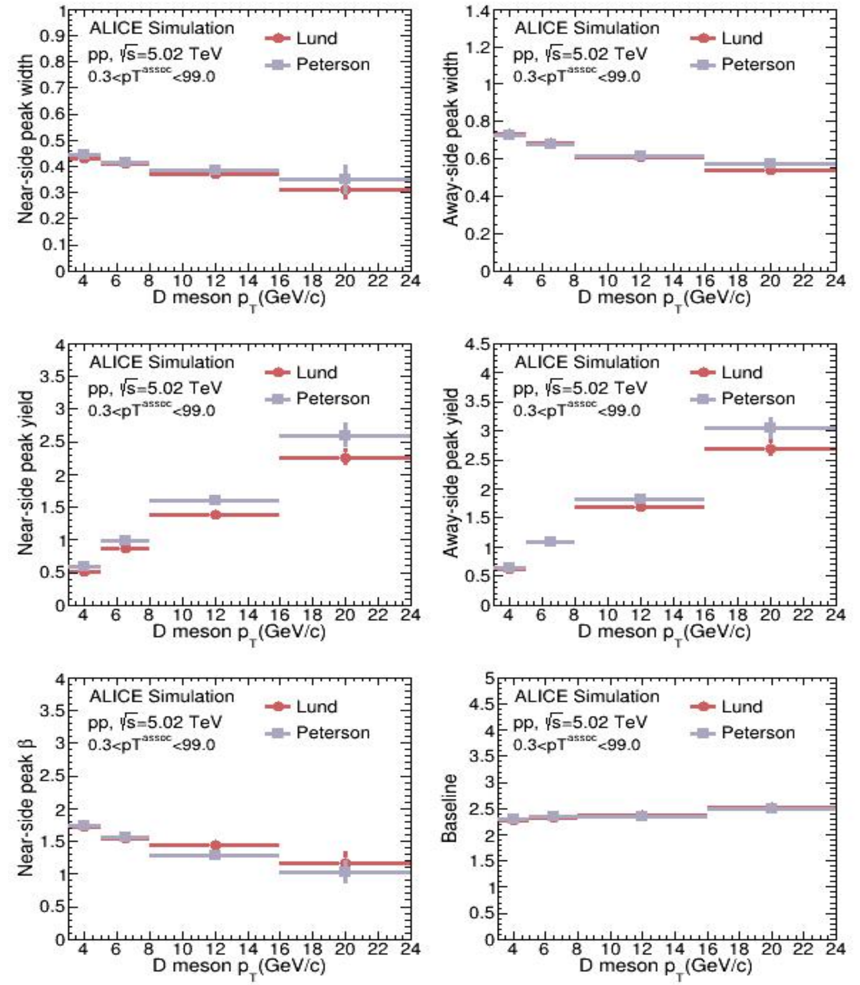
HF fragmentation: Lund vs. Peterson model

Peterson formula is a fragmentation function for heavy quarks. We use this instead of the Lund formula. For fits to experimental data, better agreement can be obtained.

$$f(z) = \frac{1}{z(1-\frac{1}{z}-\frac{\epsilon}{1-z})^2}$$

Hint of different trends, but **no significant difference between the two models.**



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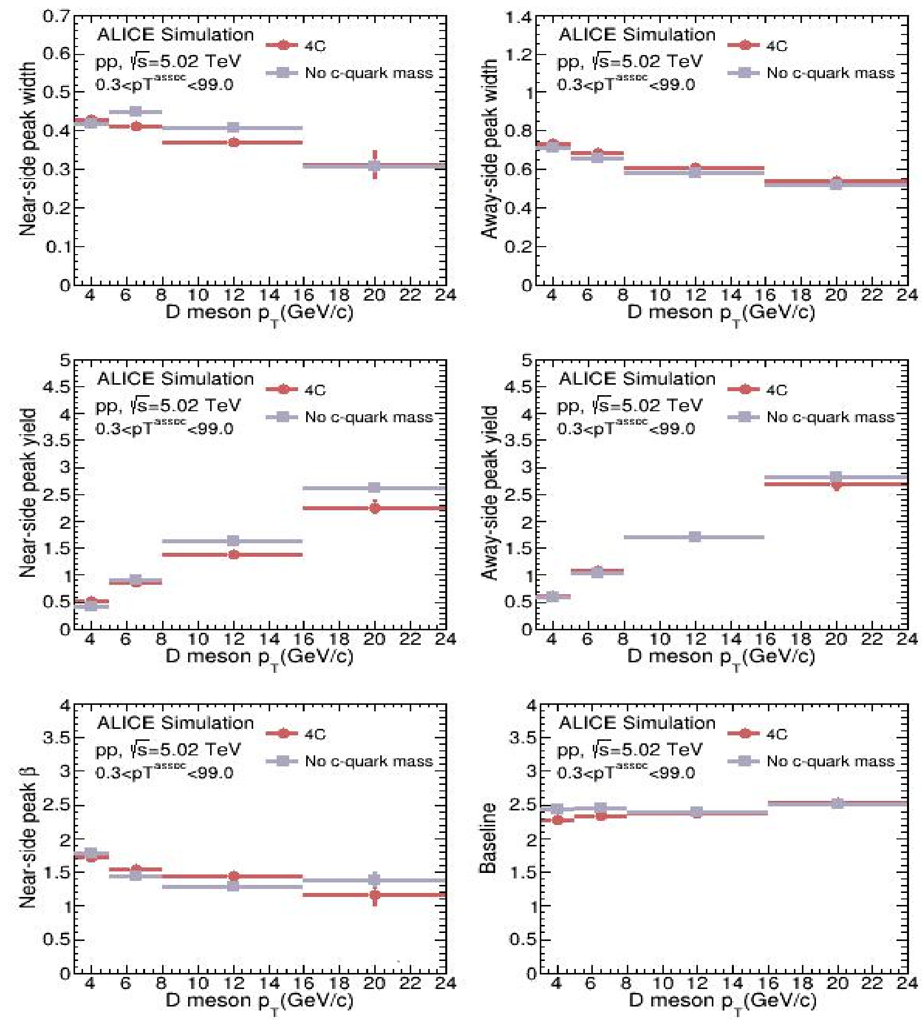
No c-quark mass

Disable the charm quark mass in order to sort the mass cone effect and the color charge effect.

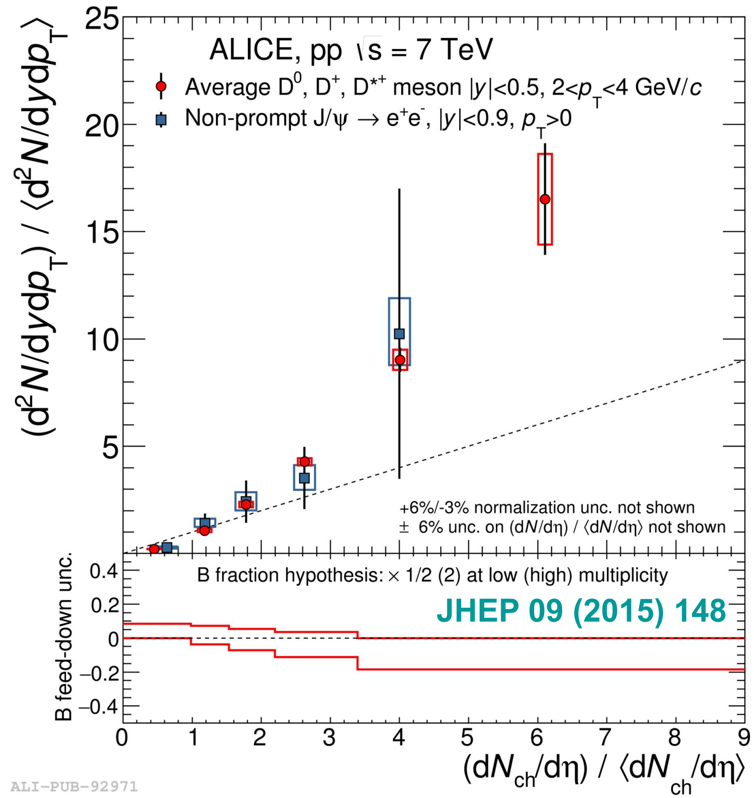
Slight differences at near-side width and yield.

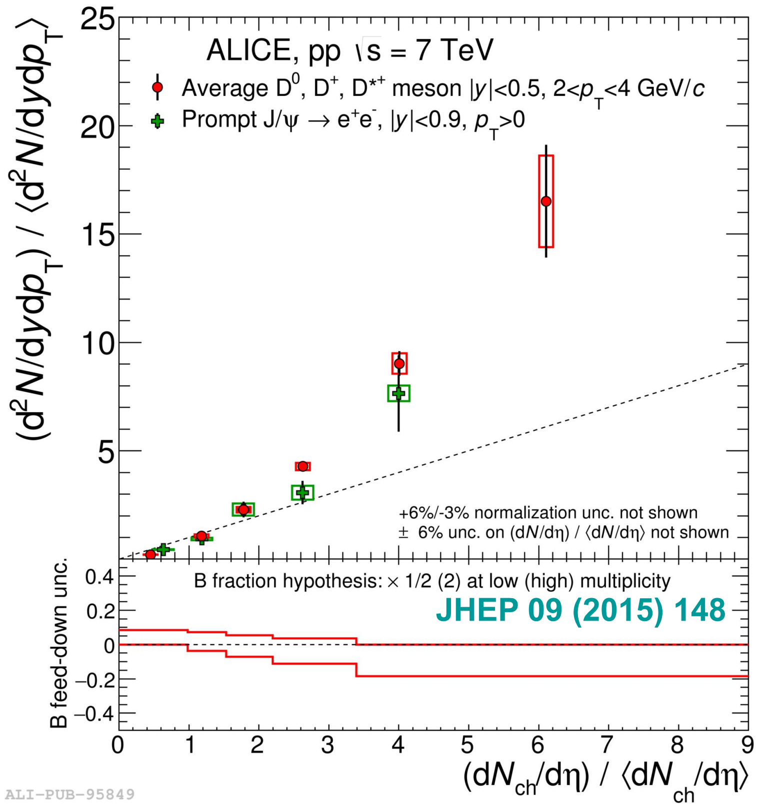
Baseline: Slight difference in underlying event at low p_T.



E Frajna (ALICE), https://indico.cern.ch/event/867085/contributions/3656153

D-meson yields vs. multiplicity (pp)



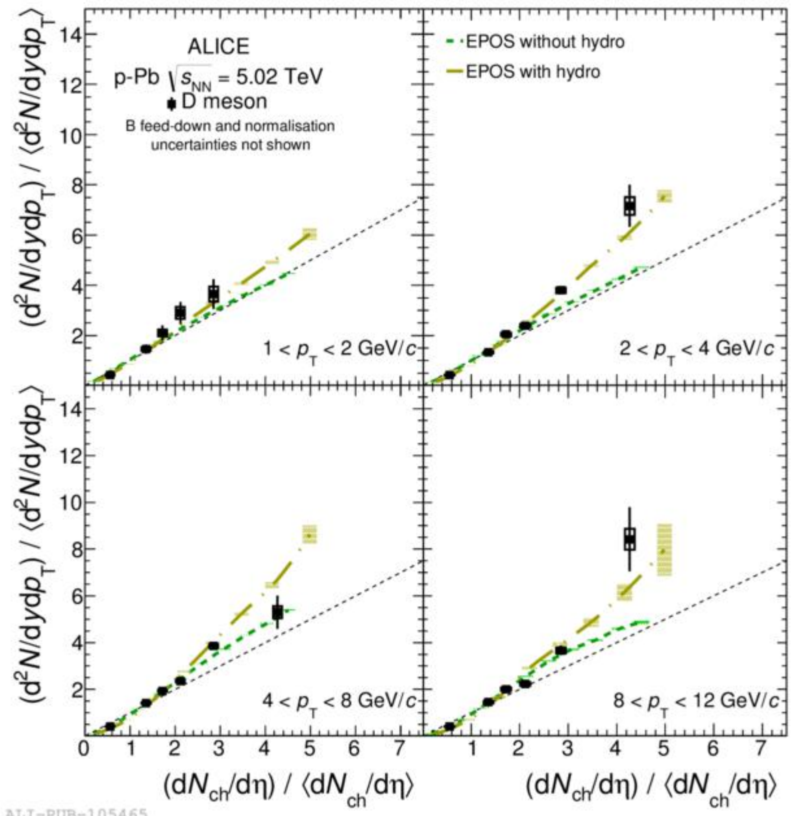


- Production vs. multiplicity of **D mesons** and muons steeper than linear
- Same trend for **non-prompt (B→)J/Ψ** as well as **prompt J/Ψ** yields

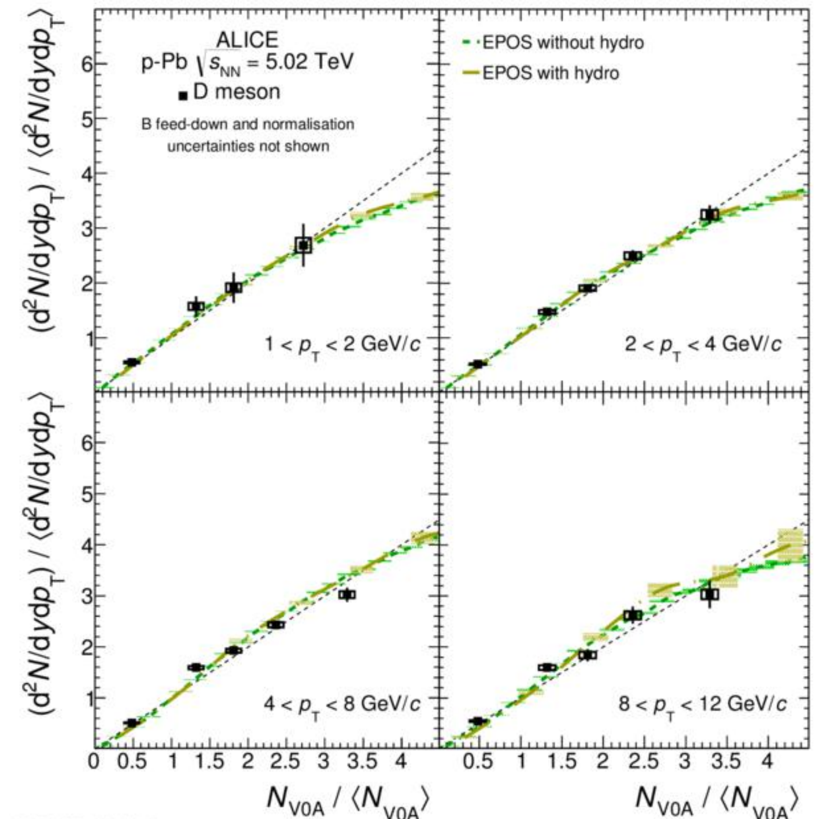
→ No strong flavour dependence

→ 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