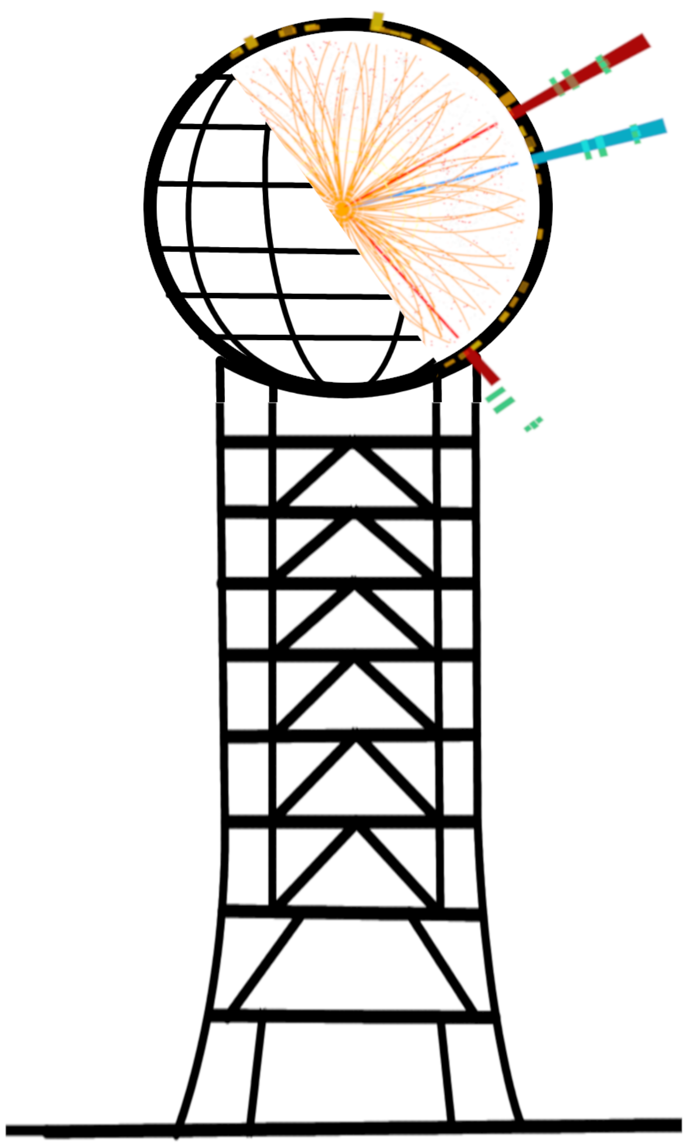
Probing Quark Gluon Plasma with open heavy-flavor



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19-22 March 2019
University of Tennessee at Knoxville

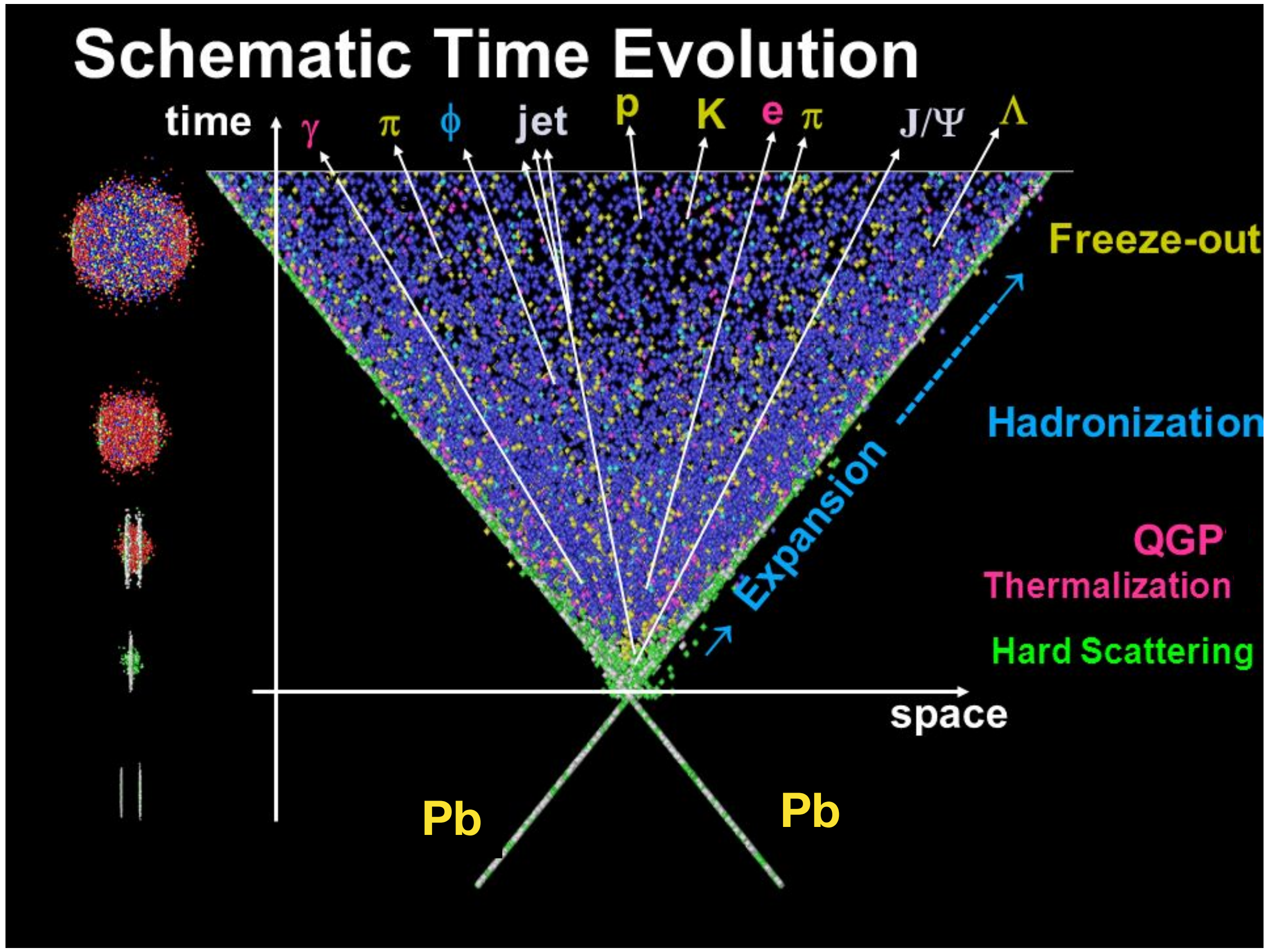
The University of Texas at Austin

Introduction

Heavy quarks (charm and beauty): excellent probes of QGP

A-A collisions:

- Produced in hard scattering processes in the initial stages of the collisions with high Q^2 values.
  - Calculable with pQCD.
  - Numbers are conserved in the full evolution of the medium.
- Traverse the QCD medium undergoing elastic (collisional) and inelastic collisions (radiational)
  - Sensitive to transport properties of the medium
- Study hadronization mechanism.



p-A and d-A collisions:

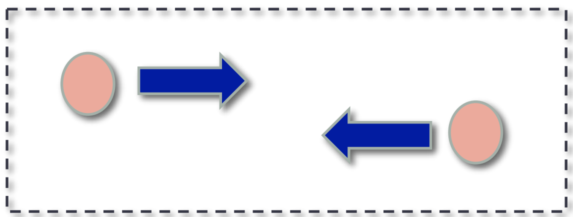
- Address cold nuclear matter (CNM) effects in the initial and final stages of the collisions.
- Study multiplicity dependent effects.

pp collisions:

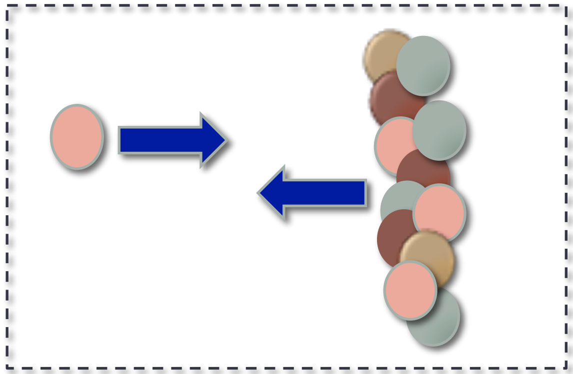
- Test pQCD calculations

pp and p-A measurements

pp

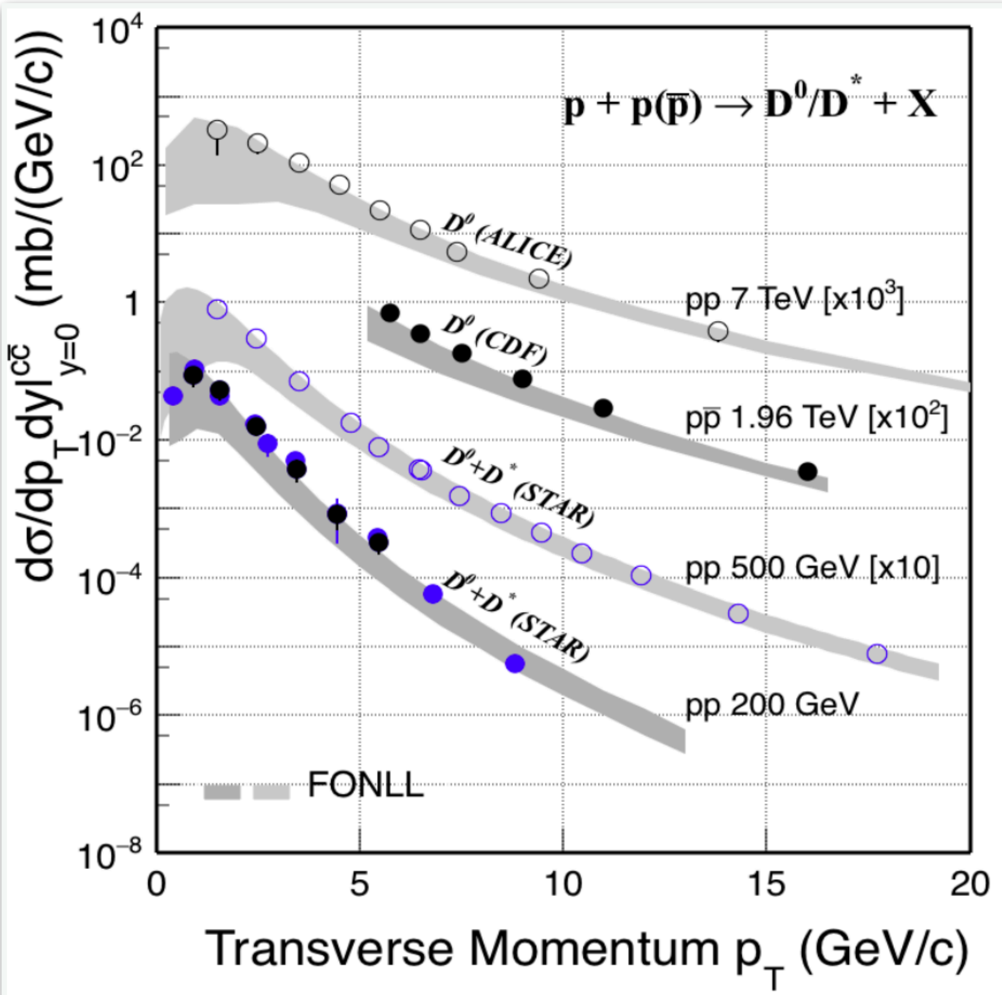


p-A/d-A



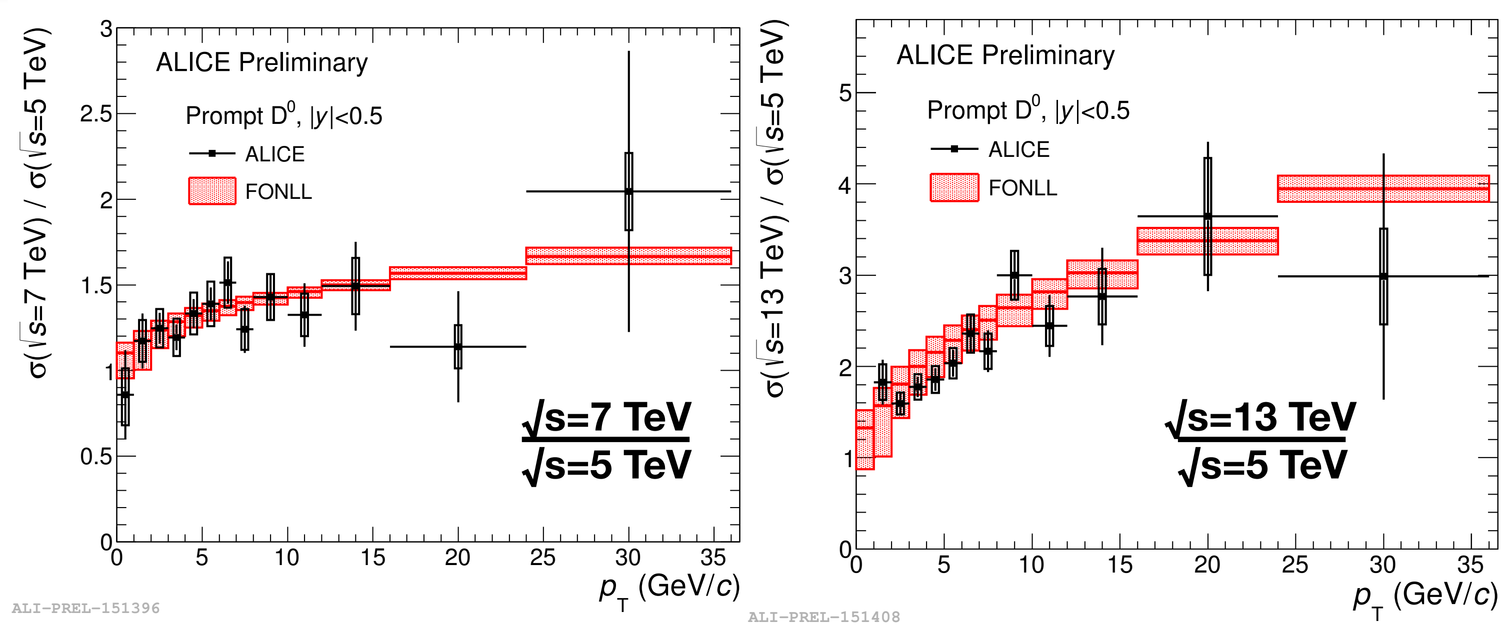
- ✓ Test pQCD calculations
- ✓ Study cold matter effects
- ✓ Multiplicity dependent heavy-flavor production
- ✓ Baryon production
- ✓ Jet production and kinematics

Heavy-flavor in pp collisions



- **p_T and y differential measurements of D and B mesons.**
  - ❖ Consistent with pQCD calculations within uncertainties at RHIC and LHC.

D mesons



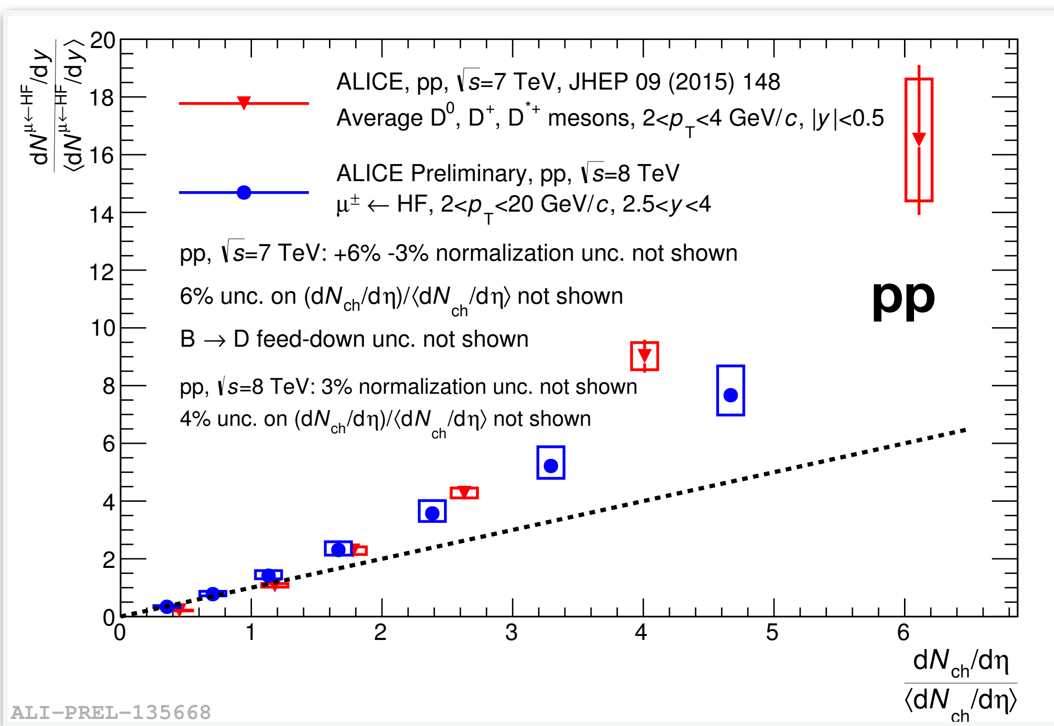
- Ratios of cross-sections at different energies - some of the uncertainties cancel in pQCD model calculation.
  - Stringent constraints to the evolution cross-section with energy.

Multiplicity dependent HF yield

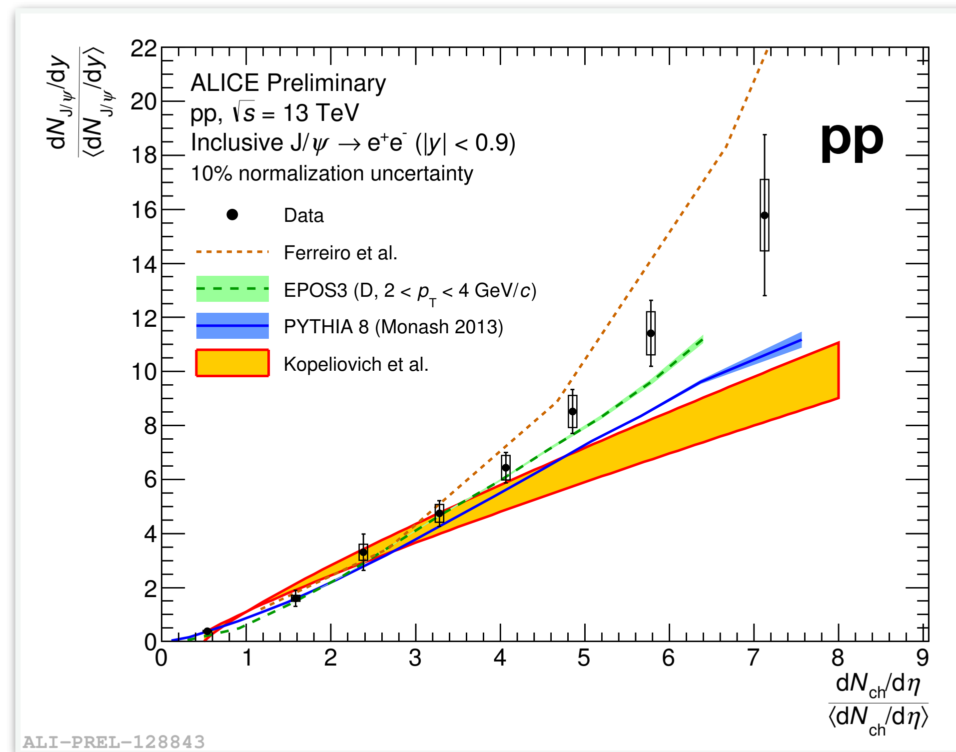
Differential measurements to study particle production as a function of charged-particle multiplicity

- Insight into processes in the collisions at the partonic level, such as Muti-Parton Interactions.
- Interplay between hard and soft mechanisms of particle production

D mesons (|y|<0.5)
c,b->μ (2.5<y<4)



J/ψ (|y|<0.9)



- Yield of **D mesons**, **HF-decay muons,** **J/Ψ** show faster than linear increase w.r.t charged-particle multiplicity in pp collisions

  —> **behavior most likely related to production processes and not influenced by hadronisation**

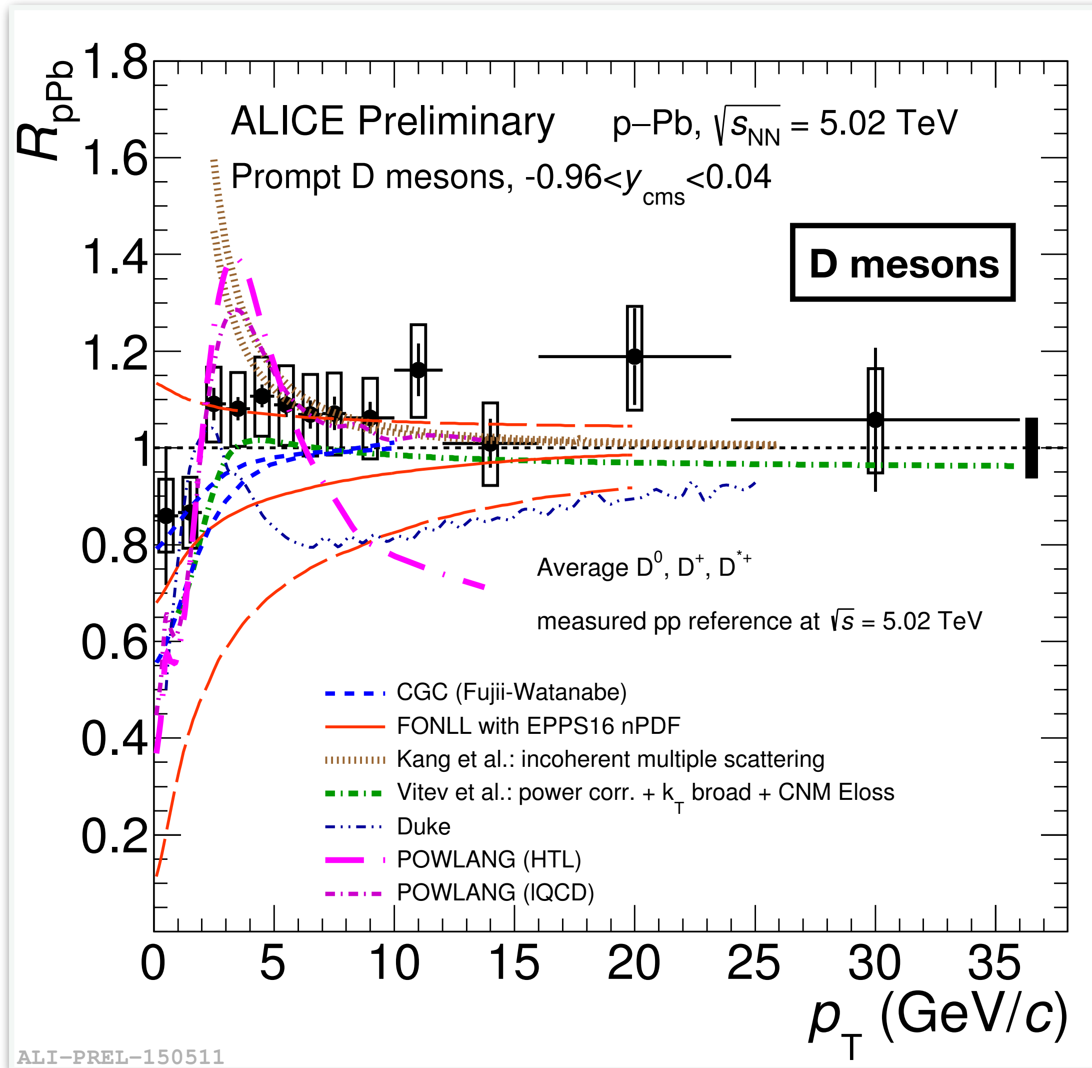
- Qualitative agreement of J/Ψ measurement with models with different assumptions on production mechanisms
  - Multi-parton effects - PYTHIA8, EPOS3
  - Soft particle saturation - Ferreiro (percolation), PYTHIA8 (color reconnection)
  - Higher Fock states - Kopeliovich et.al

Ferreiro: PRC86(2012) 034903
EPS3: Phys.Rept 350 (2001) 93
PYTHIA8: Comput.Phys.Commun. 178(208)852
Kopeliovich PRD 88 (2013) 116002

Heavy-flavor in p-A collisions

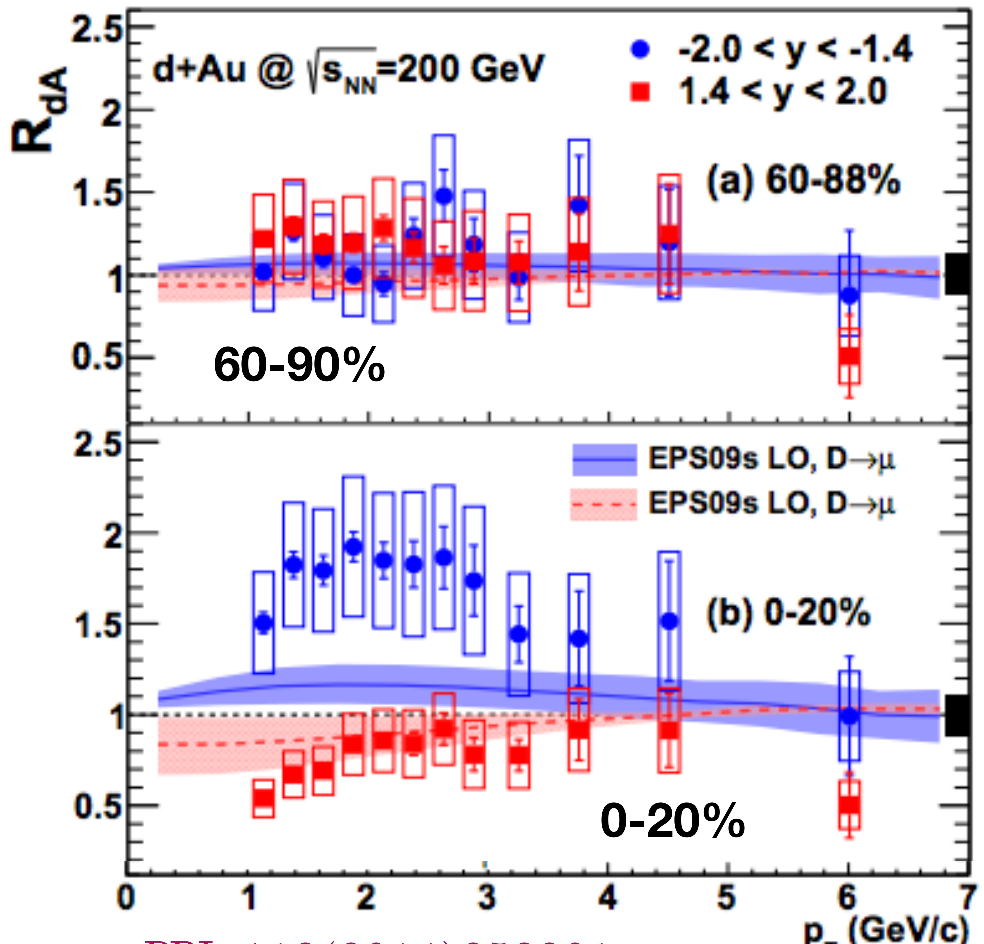
R_{pPb} of D mesons (Average of D^0, D^+, D^{*+}) at central rapidity

$$R_{pPb} = \frac{d\sigma_{pPb}/dp_T}{A \times d\sigma_{pp}/dp_T}$$



- R_{pPb} of D mesons consistent with unity
- **Cold nuclear matter effects small —> no large modification of the yields in the measured p_T range**
- Data described well by several models
  - initial-state effects (nPFDs, k_T broadening, CNM energy loss, nuclear shadowing and coherent multiple scattering, incoherent multiple scatterings)
  - final-state effects (transport models assuming QGP formation in p-Pb collisions —> though suppression of >15% at high p_T disfavored by data.

Centrality dependent HF production



PRL 112(2014)252301

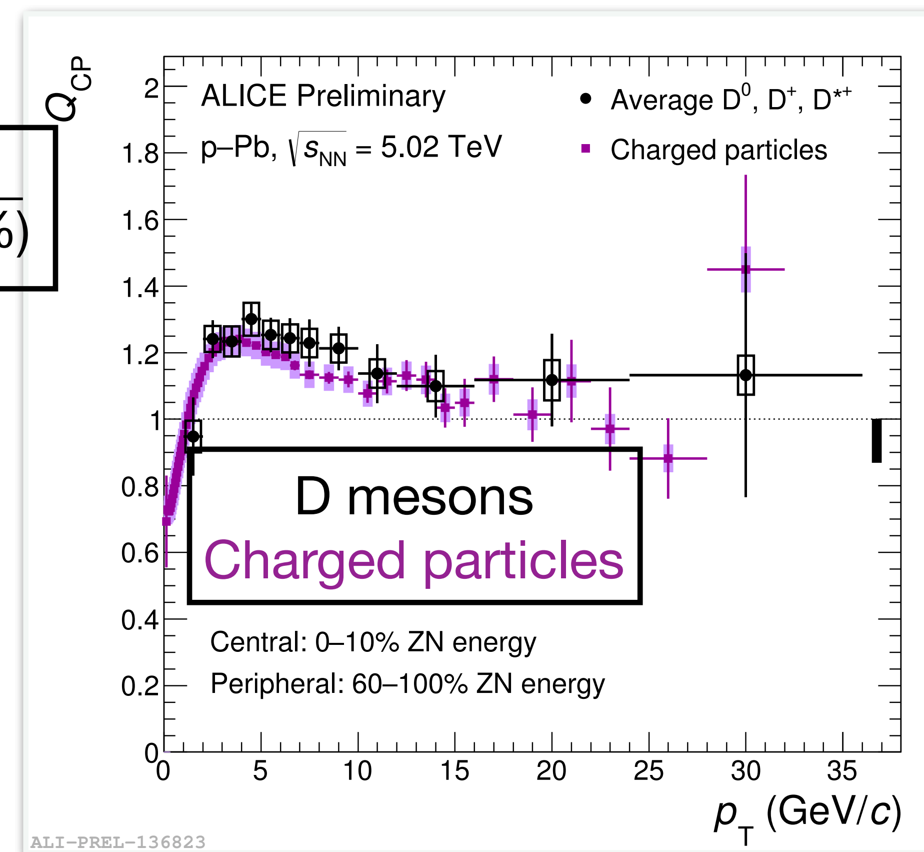
c,b -> μ
-0.2 < y < -1.4
1.4 < y < 2.0

$$R_{pPb} = \frac{d\sigma_{pPb}/dp_T}{A \times d\sigma_{pp}/dp_T}$$

RHIC (d-Au):

- **Enhancement of μ yield** at low p_T at **mid- and backward- rapidities** in **central collisions**, while no modification in peripheral collisions.
  - ❖ Models with CNM effects does not reproduce data.
- At forward rapidity: small suppression observed at low p_T and consistent with models which include gluon shadowing and parton energy loss in CNM.

$$Q_{cp} -> \frac{\text{central (0-10\%)}}{\text{peripheral (60-100\%)}}$$



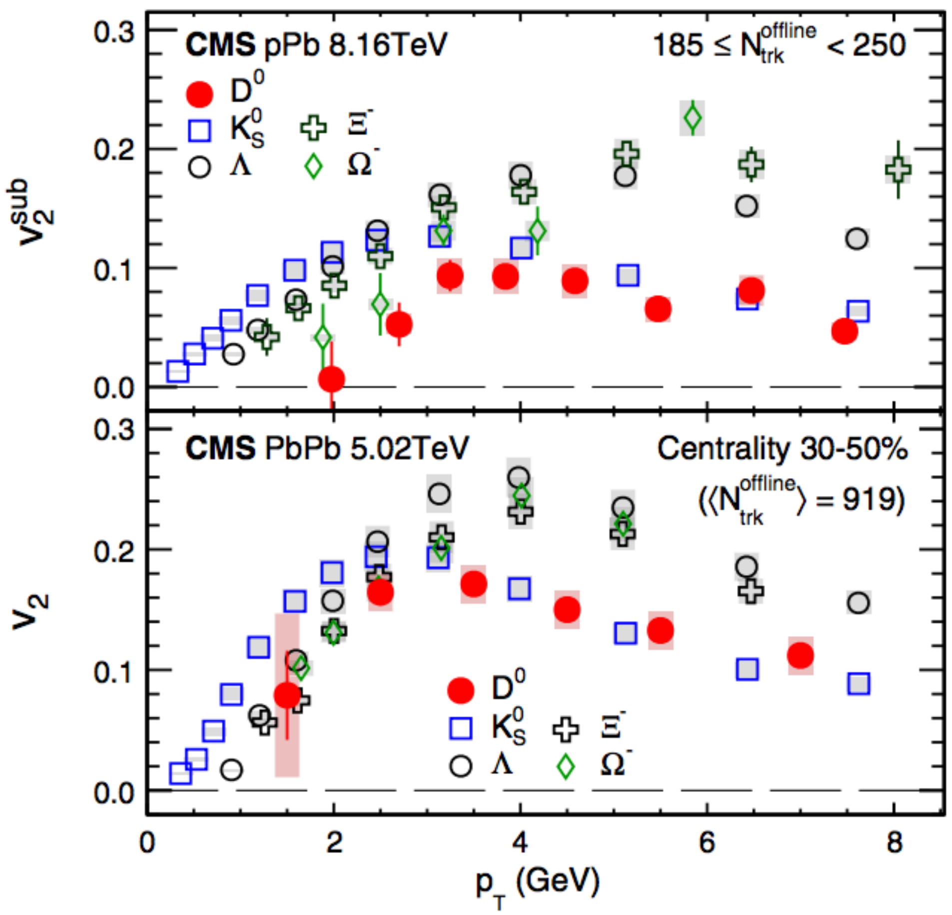
LHC (p-Pb):

- **Enhancement of D meson yield** at low p_T in central w.r.t. peripheral p-Pb collisions at **mid-rapidity.**
  - ❖ Similar enhancement for charged particles.
- **Initial or final state effects playing a role here?**

Need model calculations for interpretation

Azimuthal anisotropy in small systems

- **v_2 of D^0 measured in high-multiplicity p-Pb collisions at 8.16 TeV.**
- Comparison of v_2 vs p_T with K_s^0, Λ, Ξ^- : shows similar mass ordering as in semi-central Pb-Pb collisions



PRL 121(2018)082301

Azimuthal anisotropy in small systems

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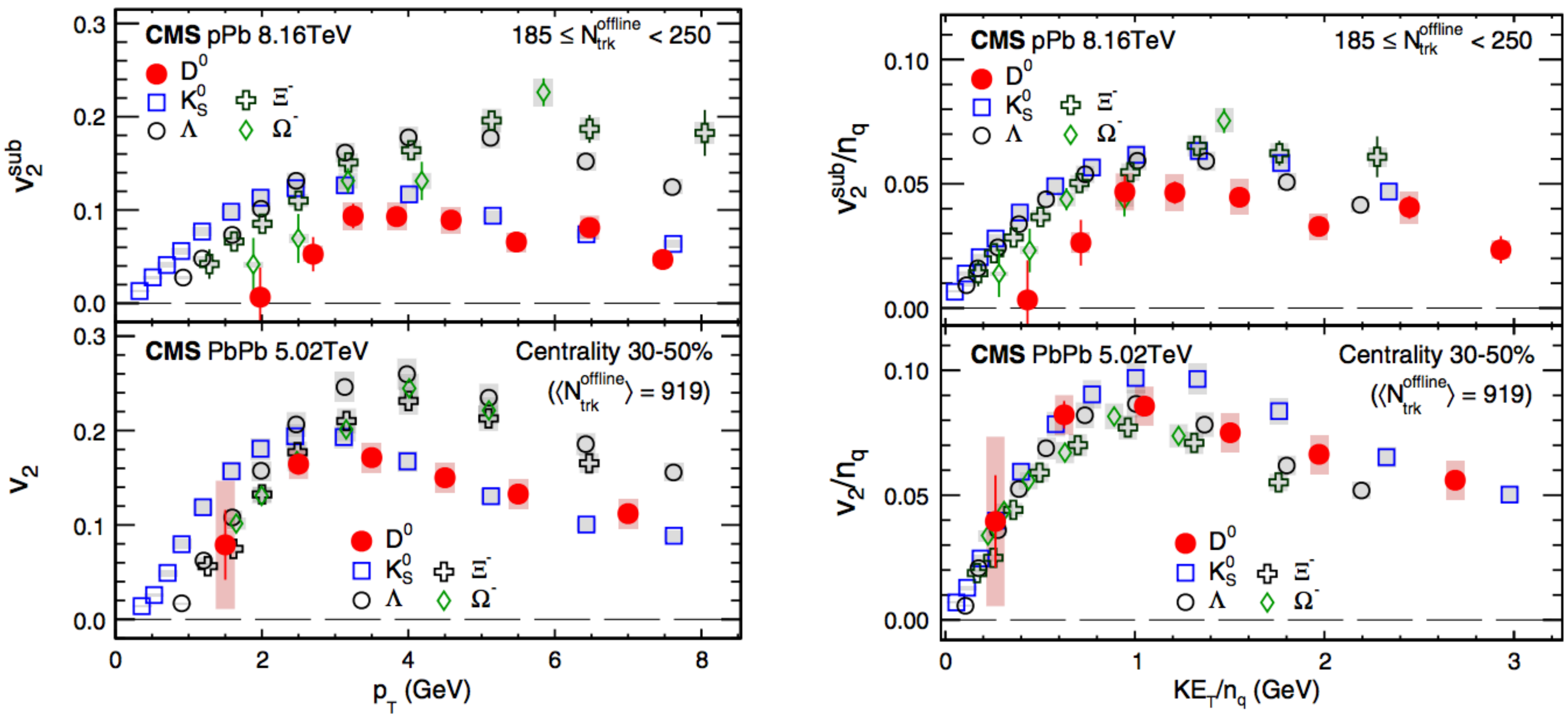


PRL 121(2018)082301

v_2/n_q vs KE_T/n_q in p-Pb and Pb-Pb collisions:

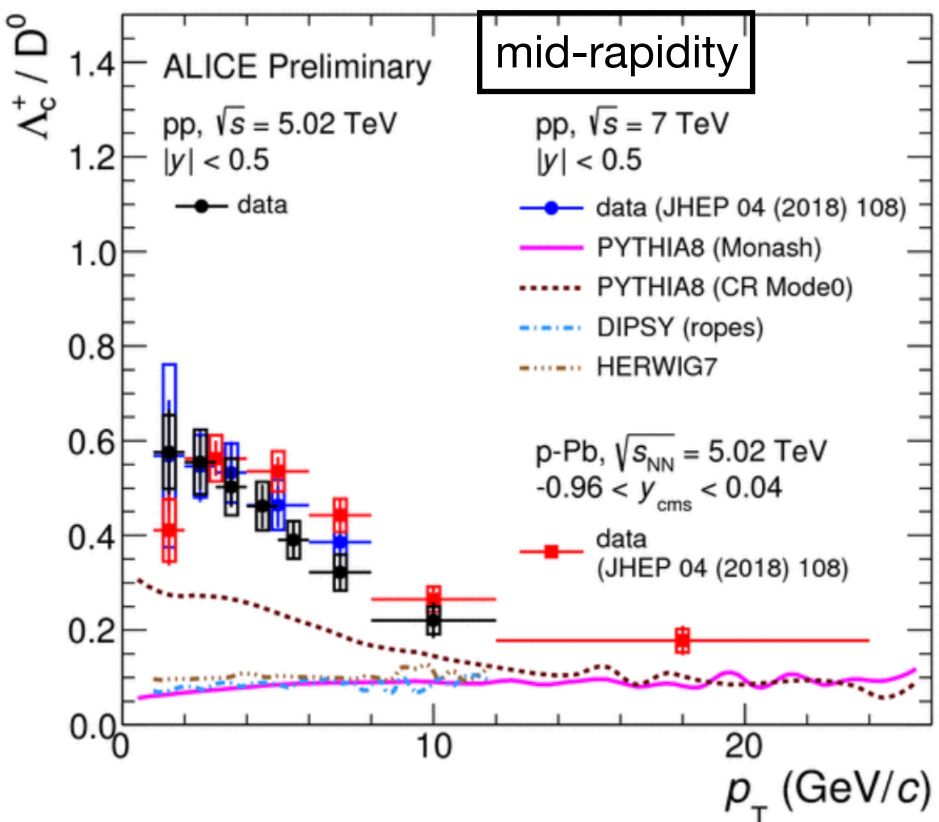
- low KE_T/n_q: Universal trend for non-charm particles, while charm has lower values unlike in Pb-Pb.
- Large KE_T/n_q: trend qualitatively different in p-Pb and Pb-Pb collisions for all particles.

Different/multiple (initial/final) effects playing a role in small and large systems?

Heavy-flavour measurements provide constraints in understanding the underlying effects.

Investigating baryon production mechanisms with Λ^+_c

Measurement of Λ_c^+/D^0 in p-Pb collisions vs p_T at backward-, mid-, forward rapidities



pp $\sqrt{s}$ = 5 TeV
pp $\sqrt{s}$ = 7 TeV
p-Pb $\sqrt{s_{NN}}$ 5.02 TeV

Mid-rapidity:

- pp and p-Pb consistent with each other.
- Models (PYTHIA8, DIPSY, HERWIG) underestimate the data.
  - ❖ PYTHIA8 with enhanced color reconnection closer to data

Baryon production

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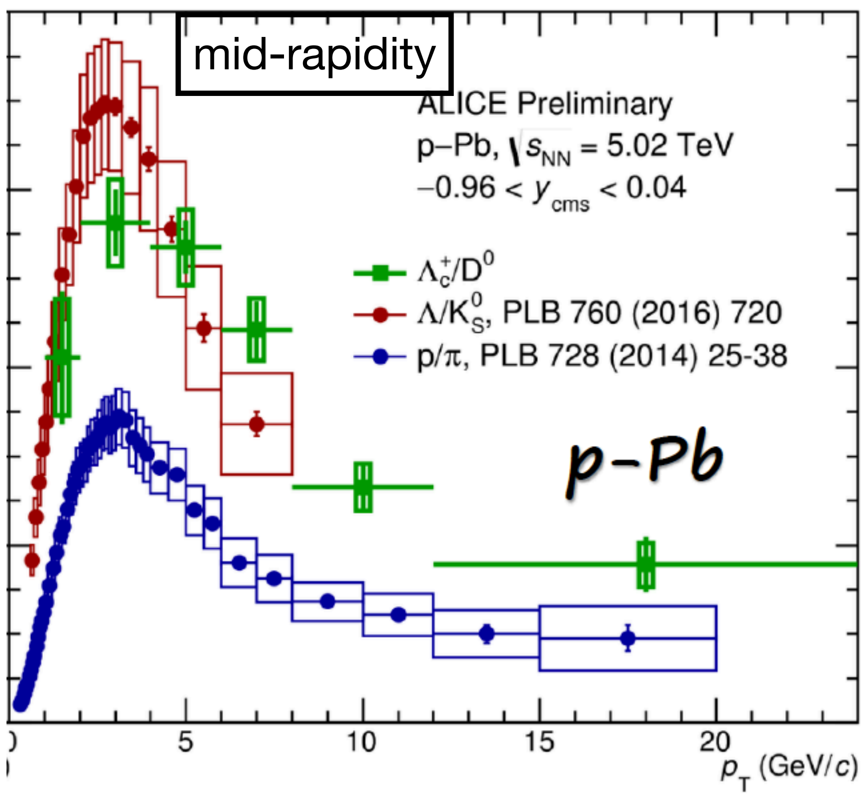
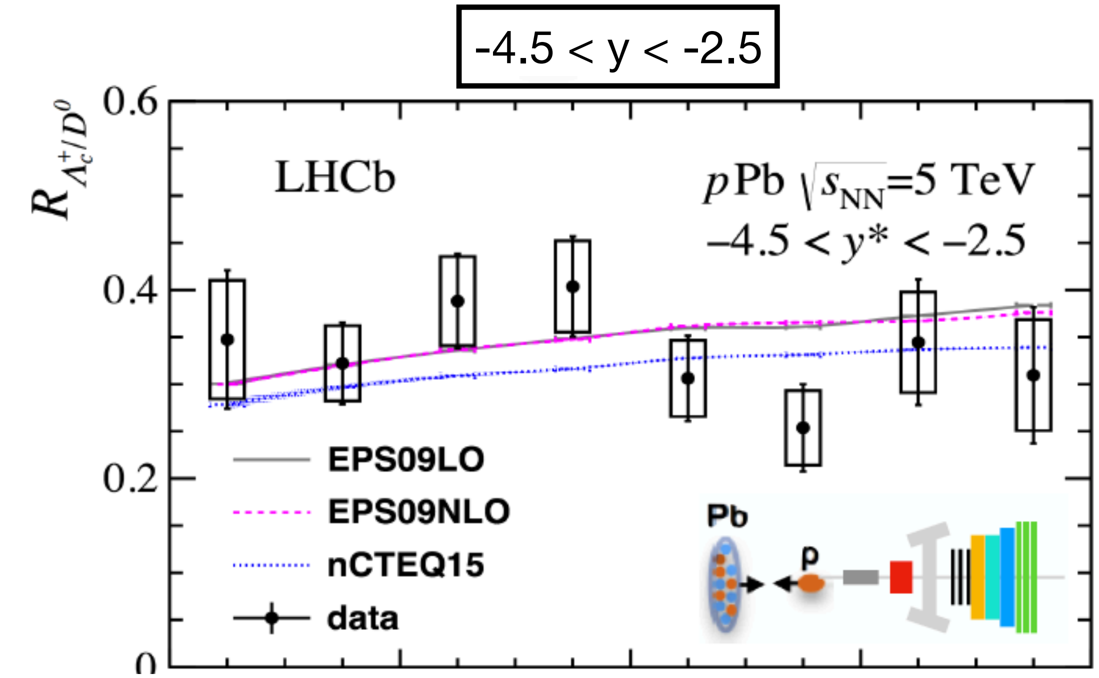
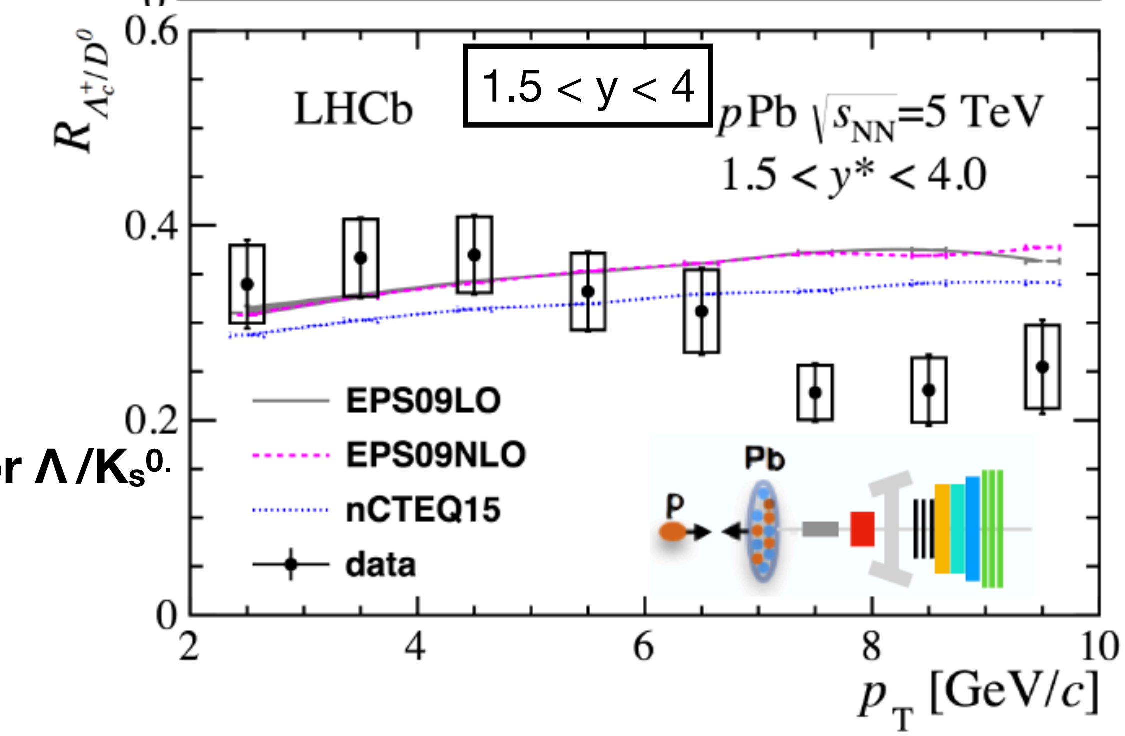






Mid-rapidity:

- pp and p-Pb consistent with each other.
- **Models (PYTHIA, DIPSY, HERWIG) underestimate the data.**
  - PYTHIA8 with enhanced color reconnection closer to data
- Decreasing trend for p_T > 4 GeV/c —> **similar in light flavor sector Λ/K^0_s.**

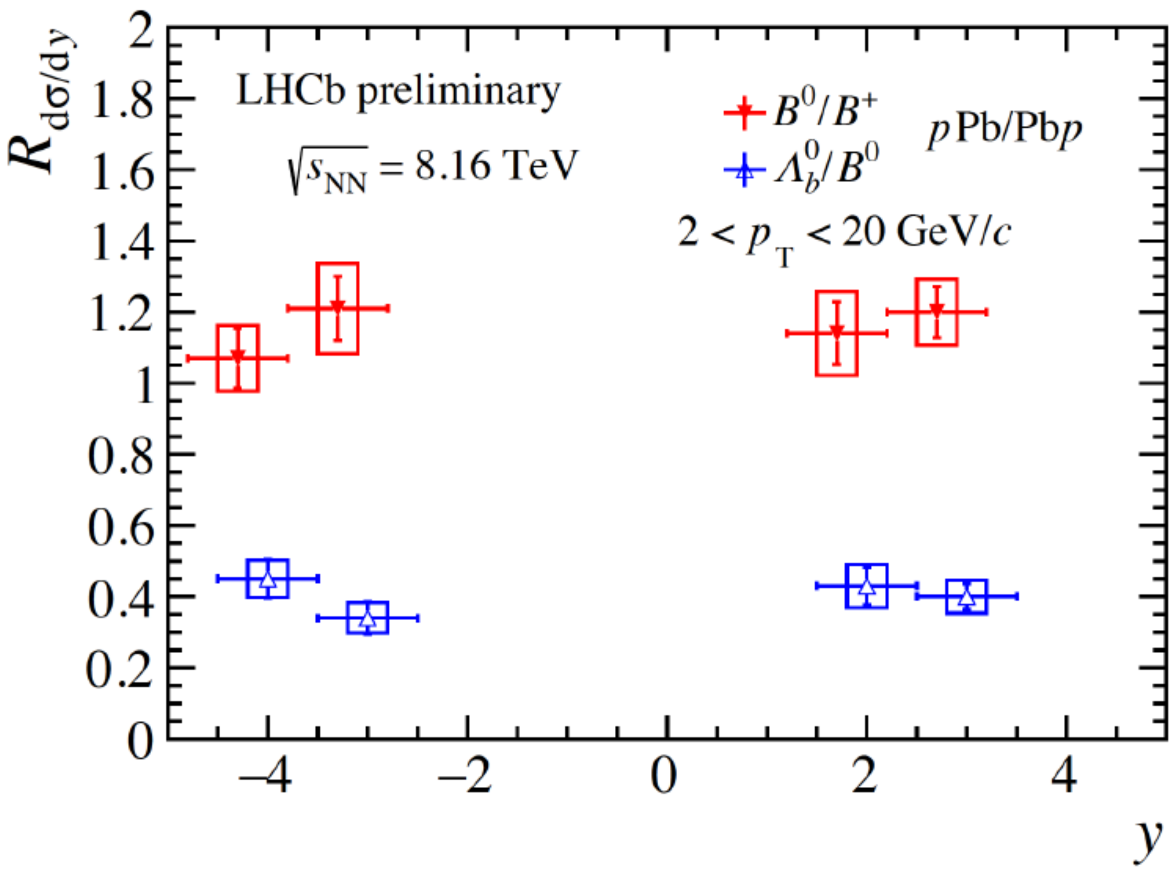
Forward and Backward rapidities:

- Similar values for both rapidities. Also consistent with pp
- Decreasing trend at high p_T.
- **Consistent with nPDF models.**

Beauty production

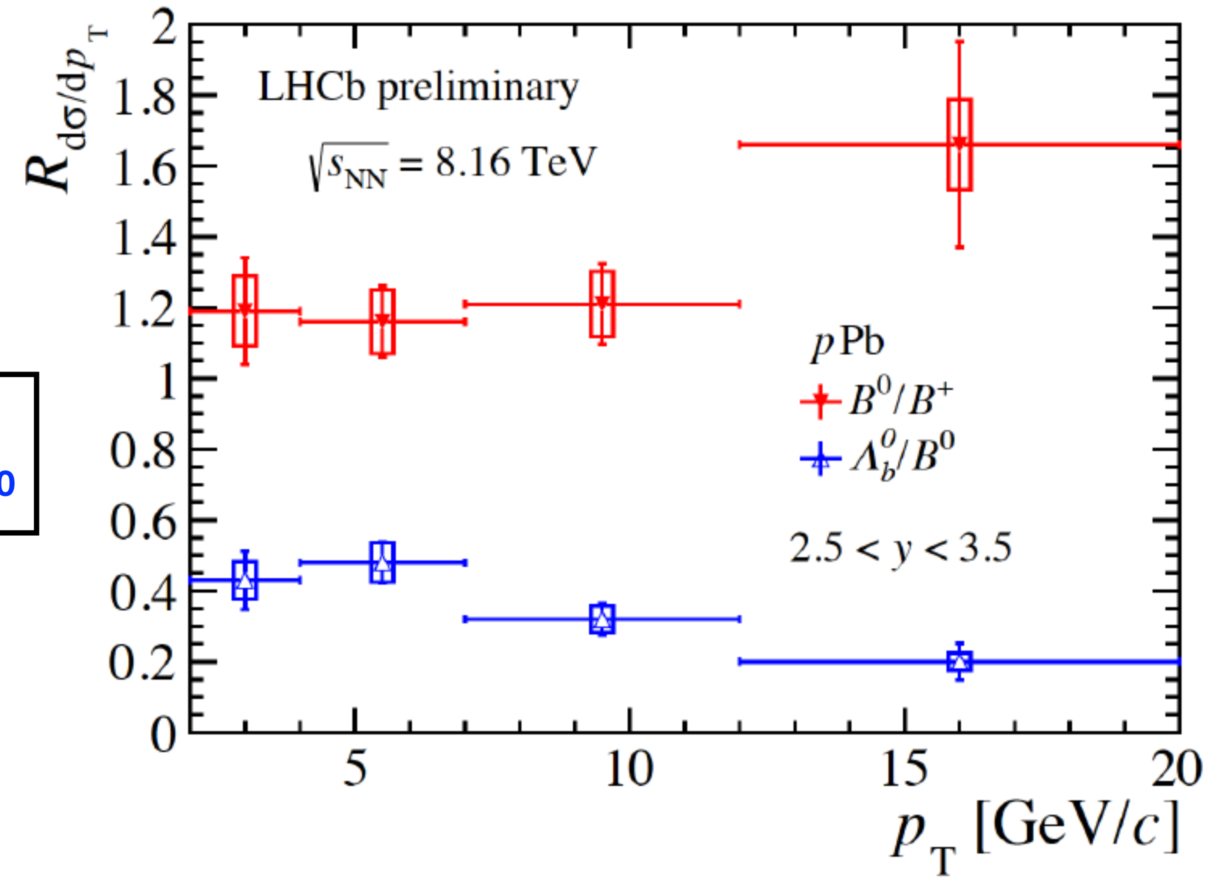
Beauty production and hadronization studied using B^+, B^0, Λ_b^0

Ratio vs rapidity, $2 < p_T < 20$ GeV/c



B+/B0
Λb0 /B0

Ratio vs p_T, $2.5 < y < 3.5$



B^+/B^0:

- Independent of rapidity and p_T and consistent with unity within uncertainty.

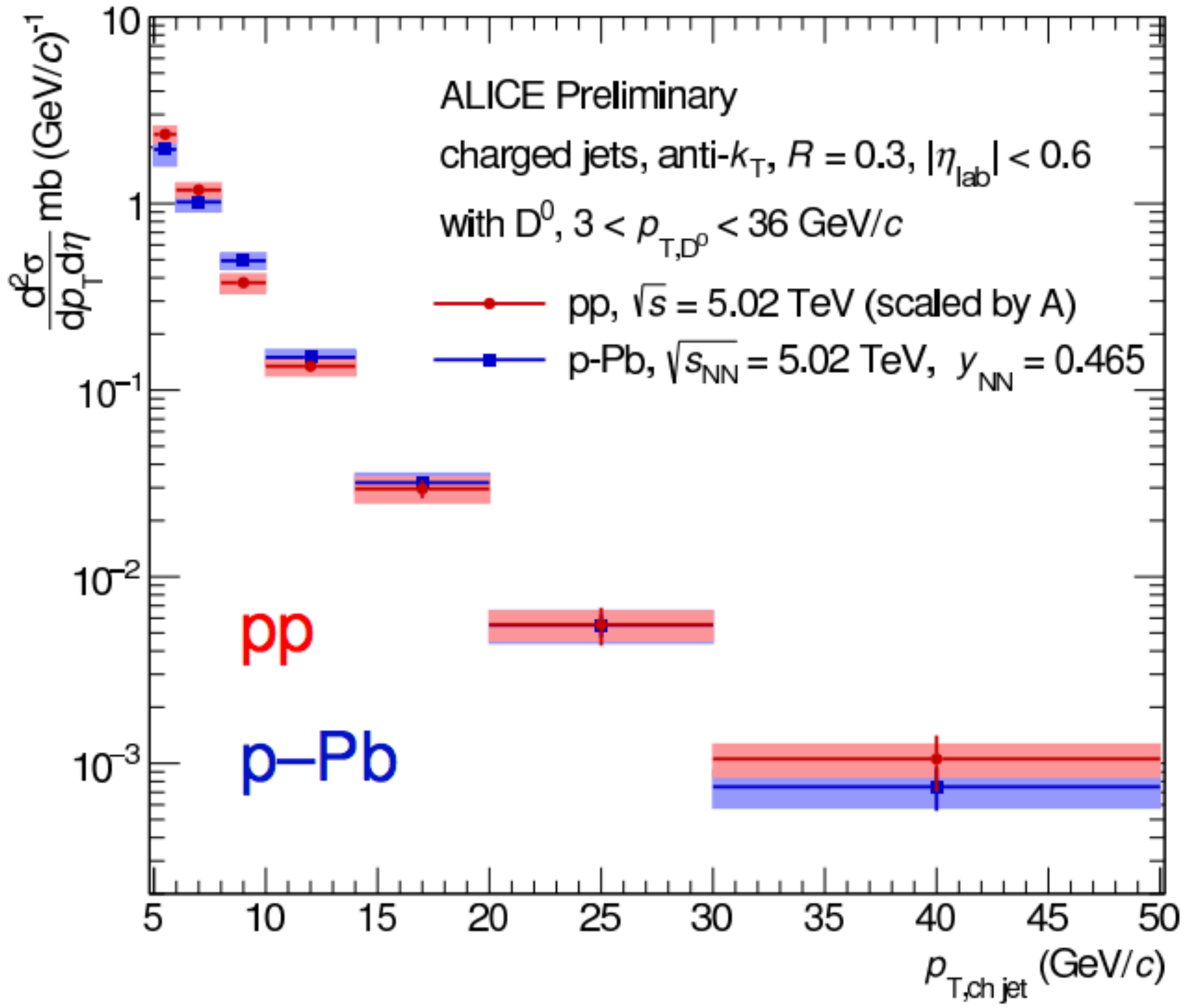
Λ_b^0/B^0:

- Independent of rapidity
- Decreasing trend with p_T
- Similar to measurements in pp

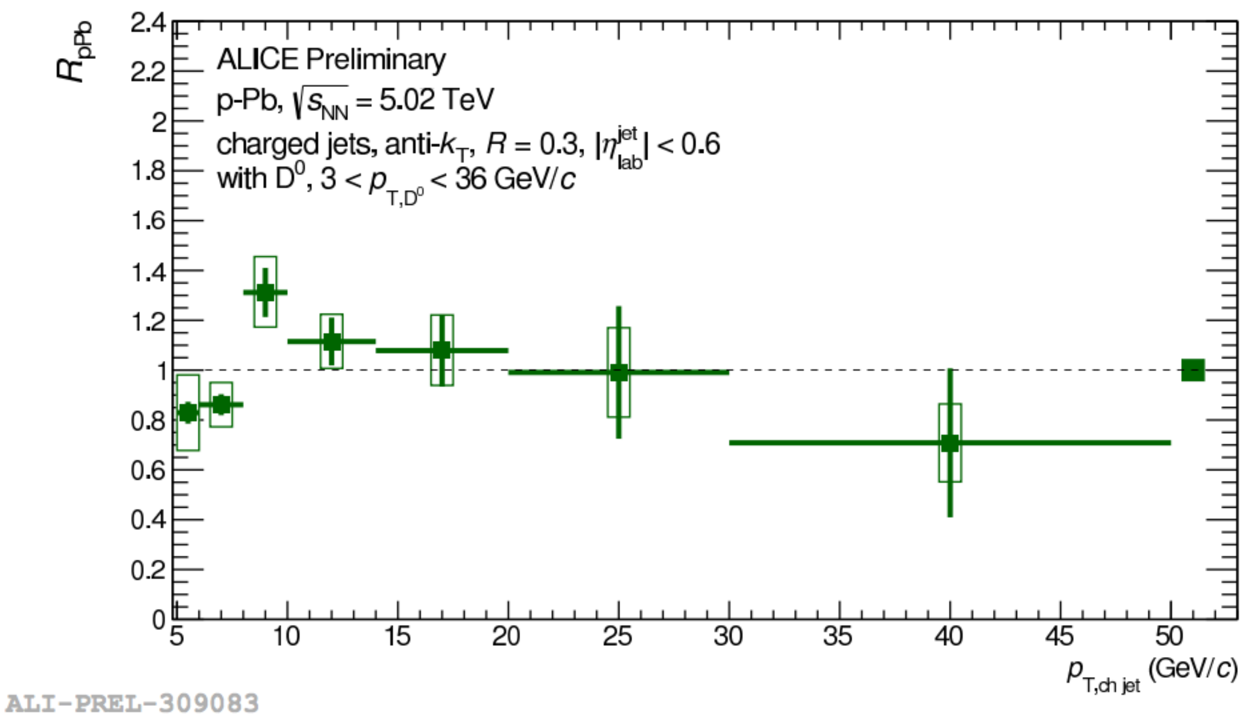
Heavy-flavour tagged jets

Study heavy-flavour jet production and modification due to cold nuclear matter effects

Jets with D^0, $3 < p_T^{D0} < 36$ GeV/c



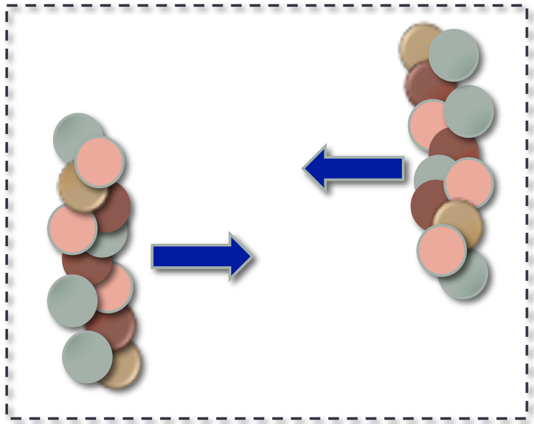
R_{pPb} of jets with D^0, $3 < p_T^{D0} < 36$ GeV/c



R_{pPb} consistent with unity

- Measured for $5 < p_T^{ch,jet} < 50$ GeV/c in pp and p-Pb
- **pp measurement in good agreement with NLO pQCD POWHEG+PYTHIA calculations**

A-A measurements

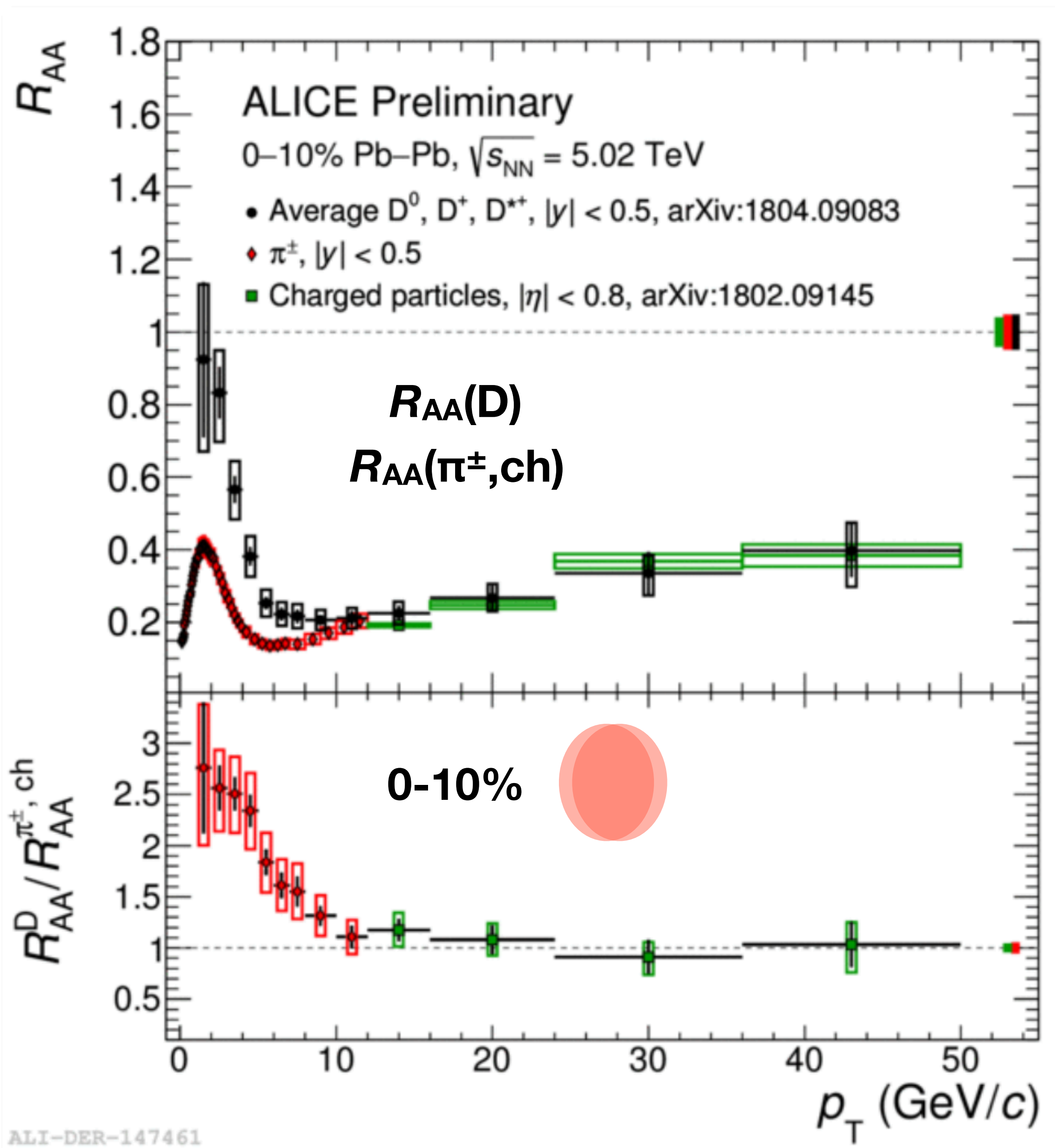


- ✓ Mass and flavor dependent interaction and energy loss
- ✓ Hadronization and baryon production mechanisms
- ✓ Jet production, fragmentation and kinematics

D meson production

R_{AA} of D mesons at central rapidity

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{Pb-Pb}/dp_T}{d\sigma_{pp}/dp_T}$$



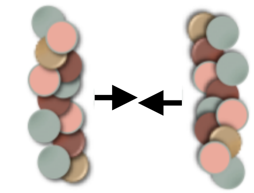
Average of D^0, D$^+$, D^{*+}

$\pi^\pm$

Charged particles

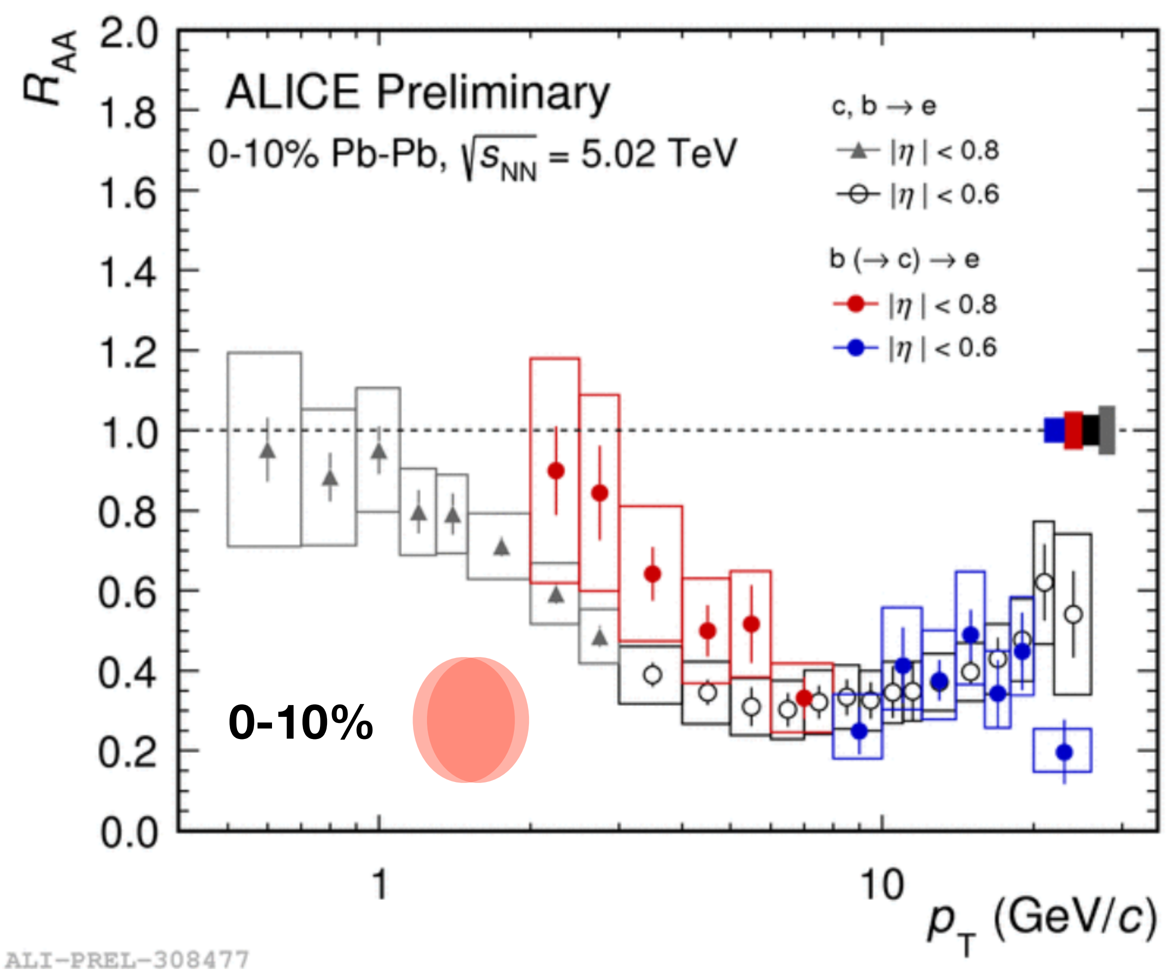
- Comparison with $\pi^\pm$ and charged particles:
  - **High p_T: R_{AA}(D) ~ $R_{AA}(\pi^\pm$,ch)** for p_T > 10 GeV/c
  - **Low p_T: R_{AA}(D) > $R_{AA}(\pi^\pm$,ch)**
- Mass dependent energy loss??
- **Interpretation not straight forward at low p_T:**
  - Pion yield largely comes from soft processes for p_T < 3 GeV/c: does not scale with N_{coll}.
  - Different fragmentation and initial spectra shapes for light and heavy quarks and gluons.
  - Different effects from shadowing, coalescence and radial flow.

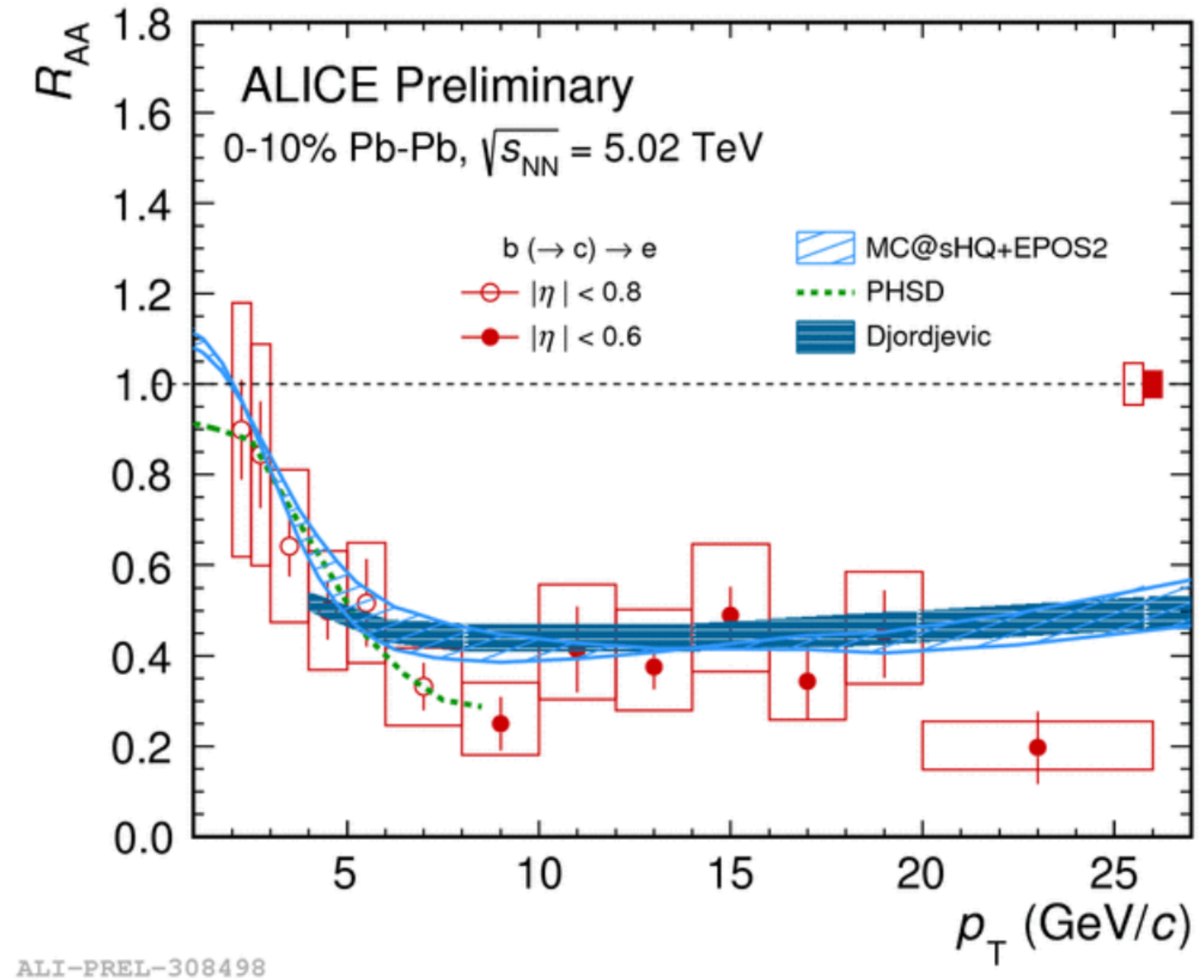
Beauty production



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{Pb-Pb}/dp_T}{d\sigma_{pp}/dp_T}$$

R_{AA} of electrons from beauty-hadron decays





Hint of **R_{AA} (b->e)** **> R_{AA}(b,c->e)** for 2 < p_T < 6 GeV/c

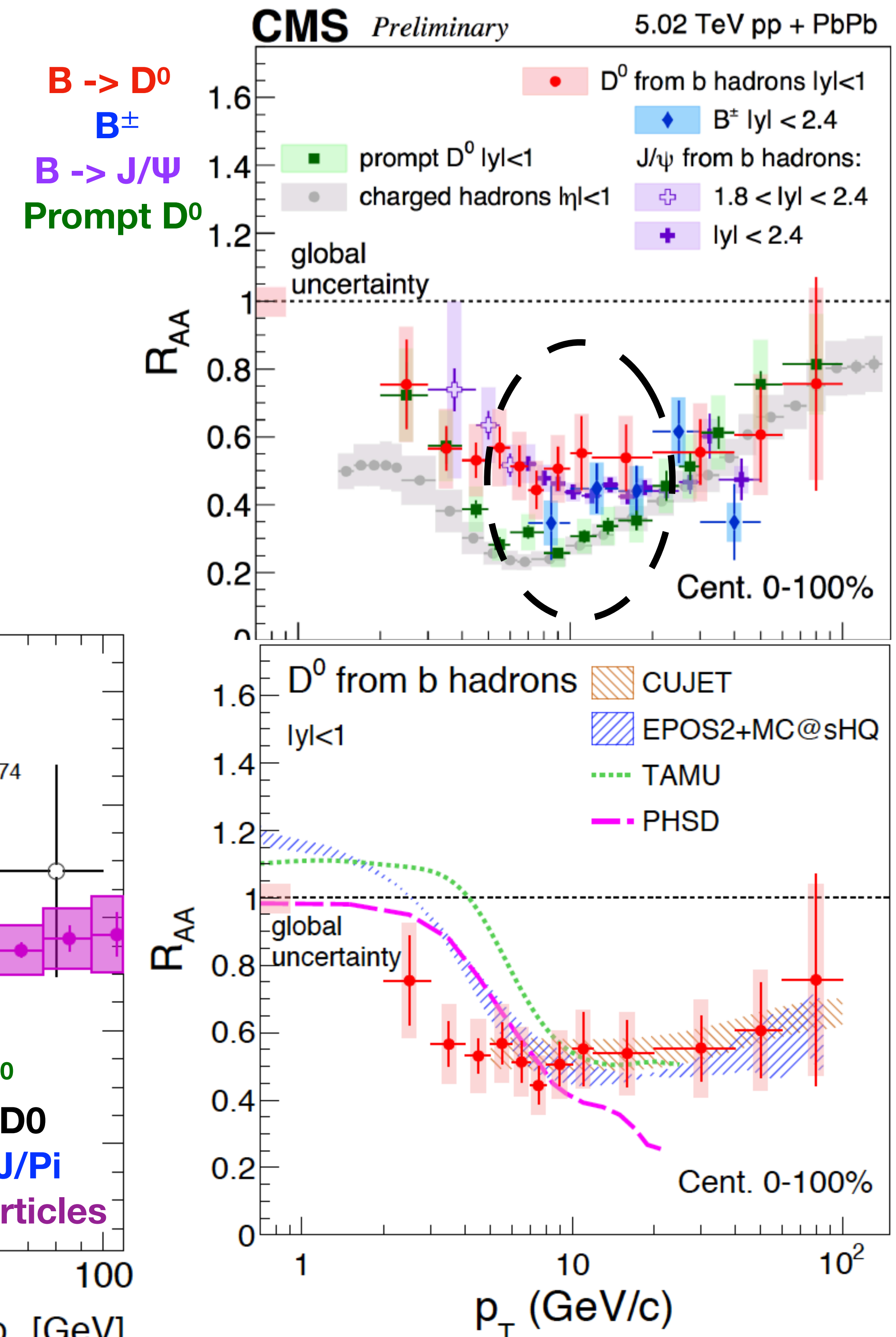
- Consistent with model predictions from MC@HQ+EPOS2, PHSD, Djordjevic with collisional and radiative energy loss

Beauty production

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{Pb-Pb}/dp_T}{d\sigma_{pp}/dp_T}$$

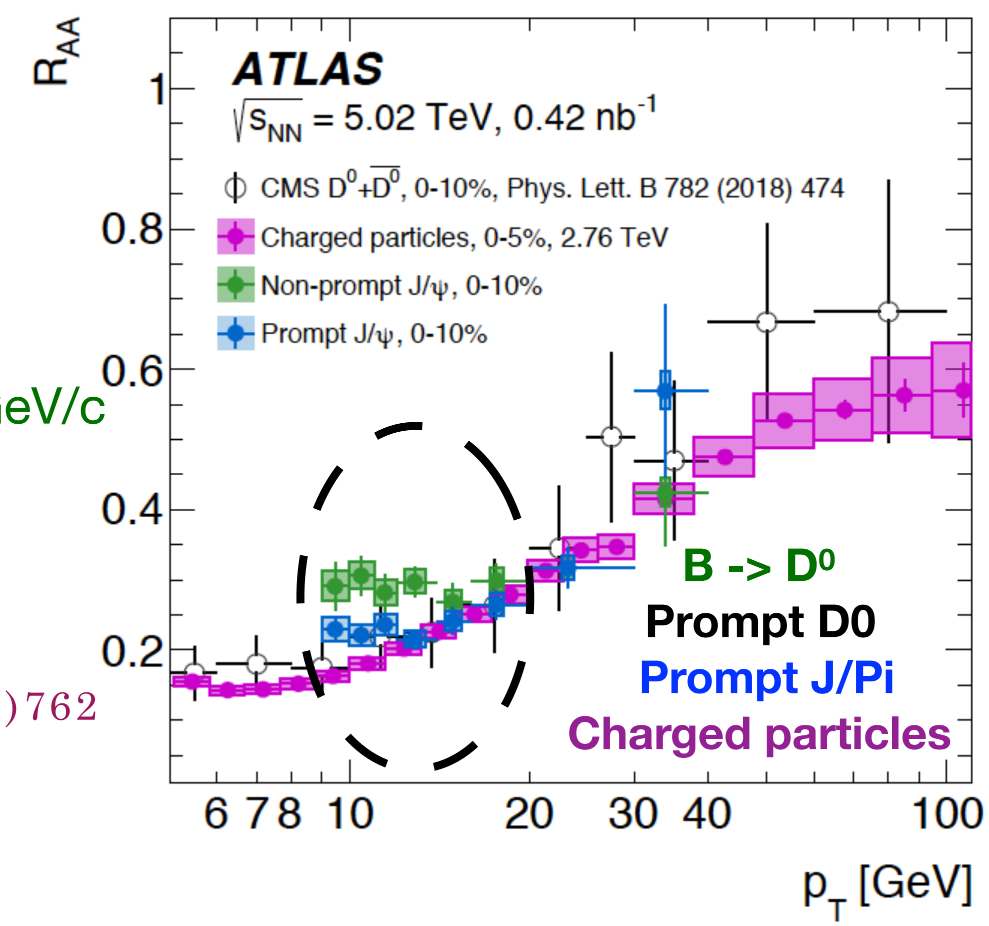
0-100% Pb-Pb:

- R_{AA} of B^+, non-prompt D^0, non-prompt J/Ψ, compatible within uncertainties.
- Show **hint of $R_{AA}(B) > R_{AA}(D)$** upto ~ 10-15 GeV/c
- Models (CUJET, MC@HQ+EPOS2) with collisional and radiative energy loss describe R_{AA} of non-prompt D^0 at high p_T.



0-10% Pb-Pb:

Similar picture of possible $R_{AA}(B) > R_{AA}(D)$ upto ~ 10 GeV/c

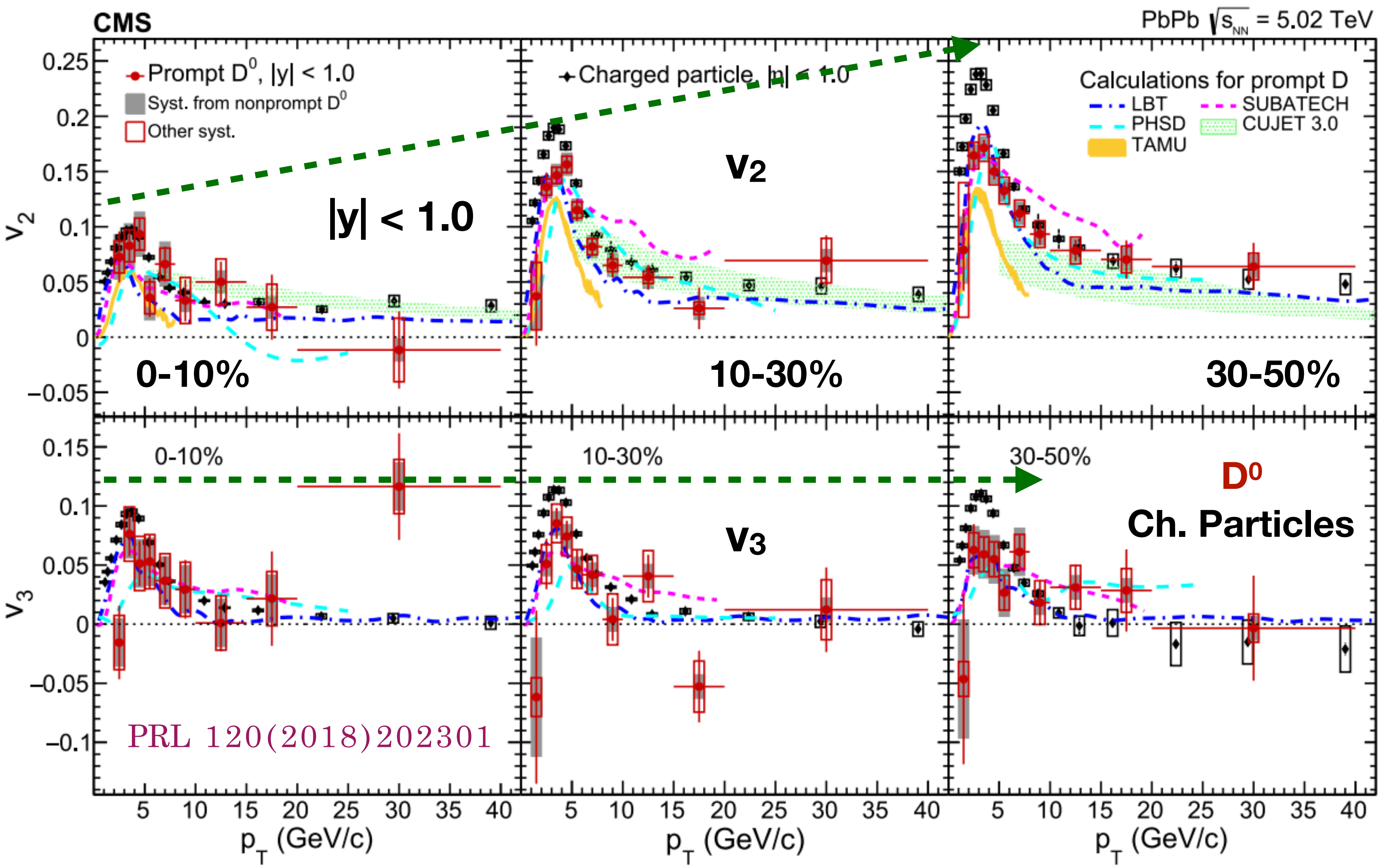


EPJC 78(2018)762

D meson v_3

Azimuthal anisotropy coefficients v_2 and v_3 of D^0 meson measured at central rapidity at LHC

v_n measurement allows to quantify charm interaction strength at low p_T and constraint its path length dependent energy loss at high p_T.

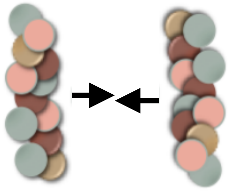


- v_2 and v_3 follows the same trend.
  - ❖ low pT: increasing with p_T to a significant positive value
  - ❖ High p_T: decreases
- $v_n(D)$ exhibit same p_T dependence as Ch. particles.
  - ❖ $v_n(D)$ < v_n(Ch.P) for 10-50% for p_T < 6 GeV/c.
  - ❖ $v_n(D)$ ~ v_n(Ch.P) for p_T > 6 GeV/c
- **v2 increases with decreasing centrality.**
- **v3 ~ centrality independent.**

- LBT, SUBATECH, CUJET include collisional and radiative energy loss -> described the data qualitatively well.
- LBT, SUBATECH, PHSD, with initial-state fluctuations, predict v_3.
  - ❖ LBT and SUBATECH in reasonable agreement with data, PHSD under predict v_3.

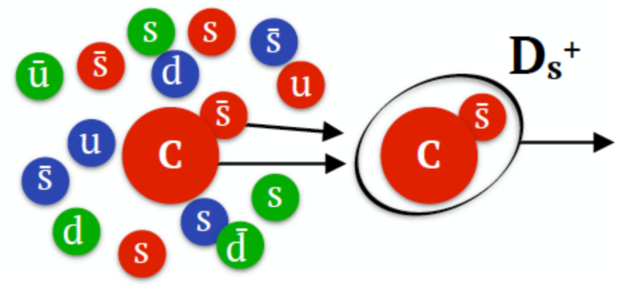
Charm quarks acquire significant elliptic and triangular flow via interaction with medium.

Heavy-flavour hadronization

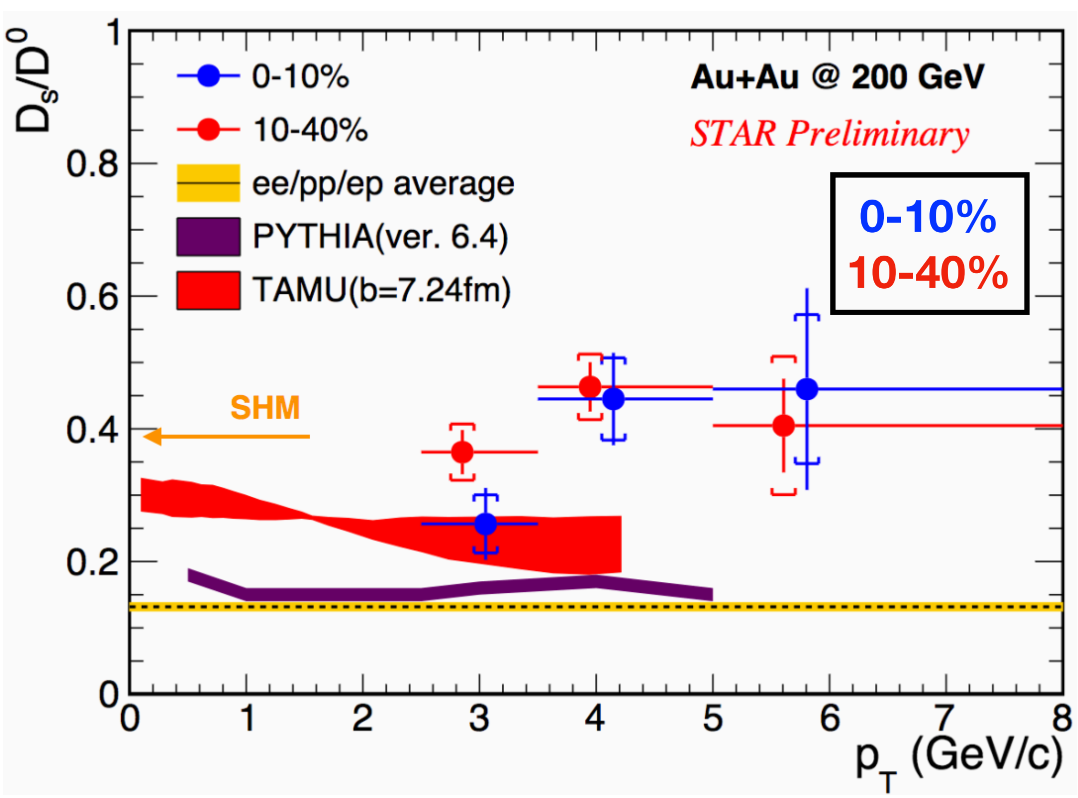


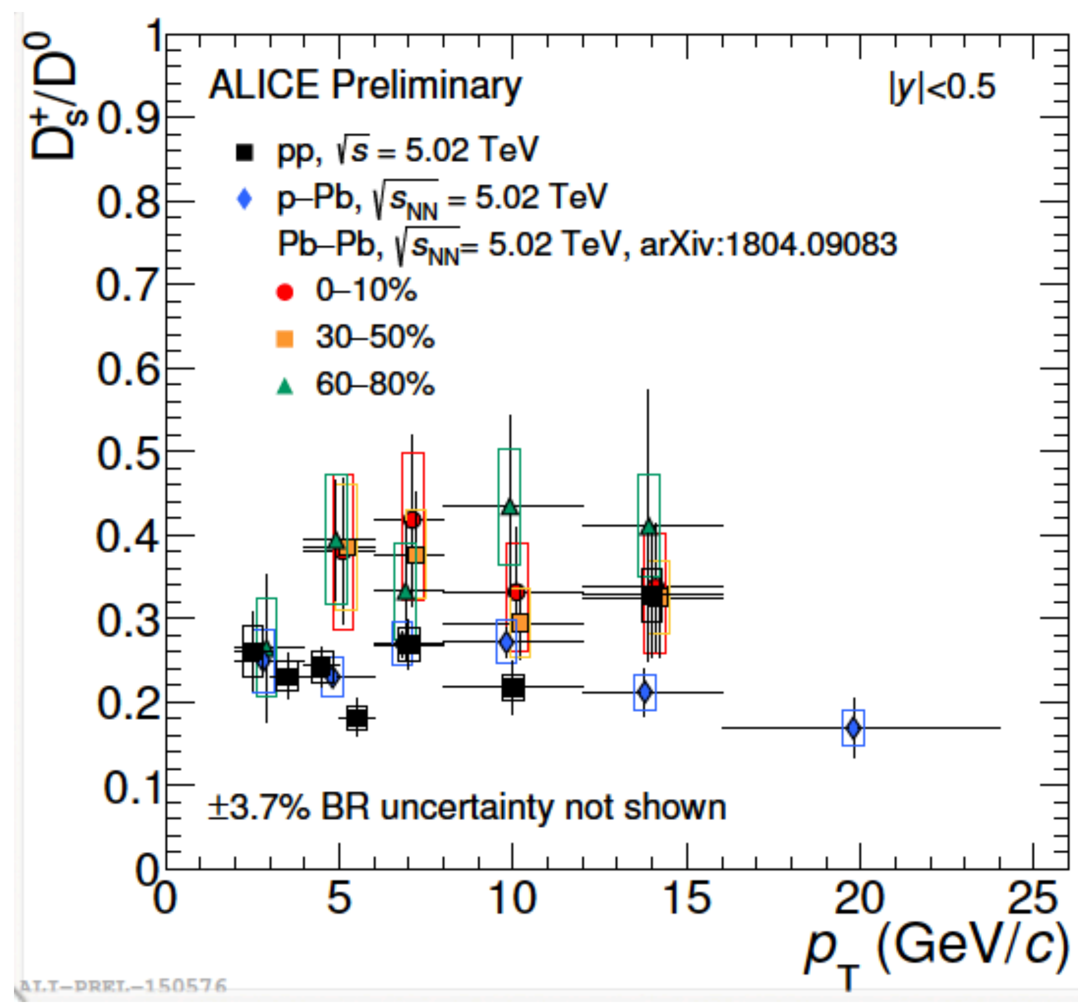
Studying heavy-flavour hadronization mechanism

- QGP rich in strange quarks -> expected enhancement of $\mathbf{D^+_s}$ over $\mathbf{D^0}$ yield if hadronization via coalescence.



- @RHIC: D_s/D^0 ~ 0.4 in Au-Au
- @LHC: D_s/D^0 ~ 0.4 in Pb-Pb while ~ 0.25 in pp —> **hint of enhancement**





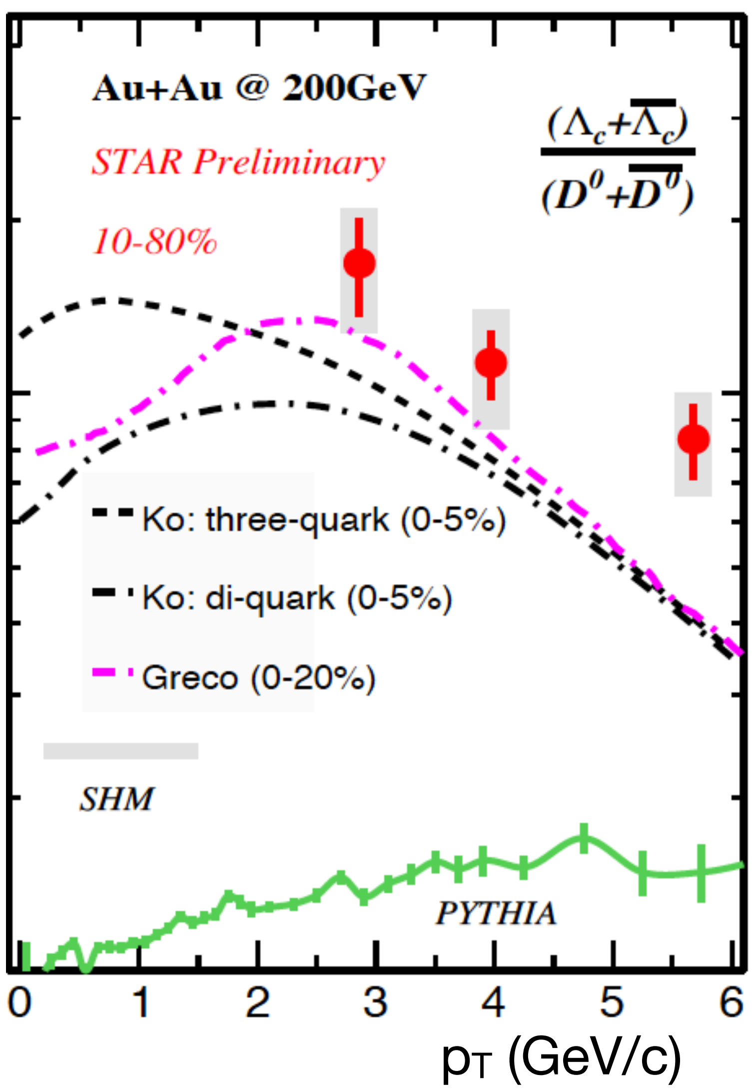
0-10% Pb-Pb
pp
p-Pb

Baryon production

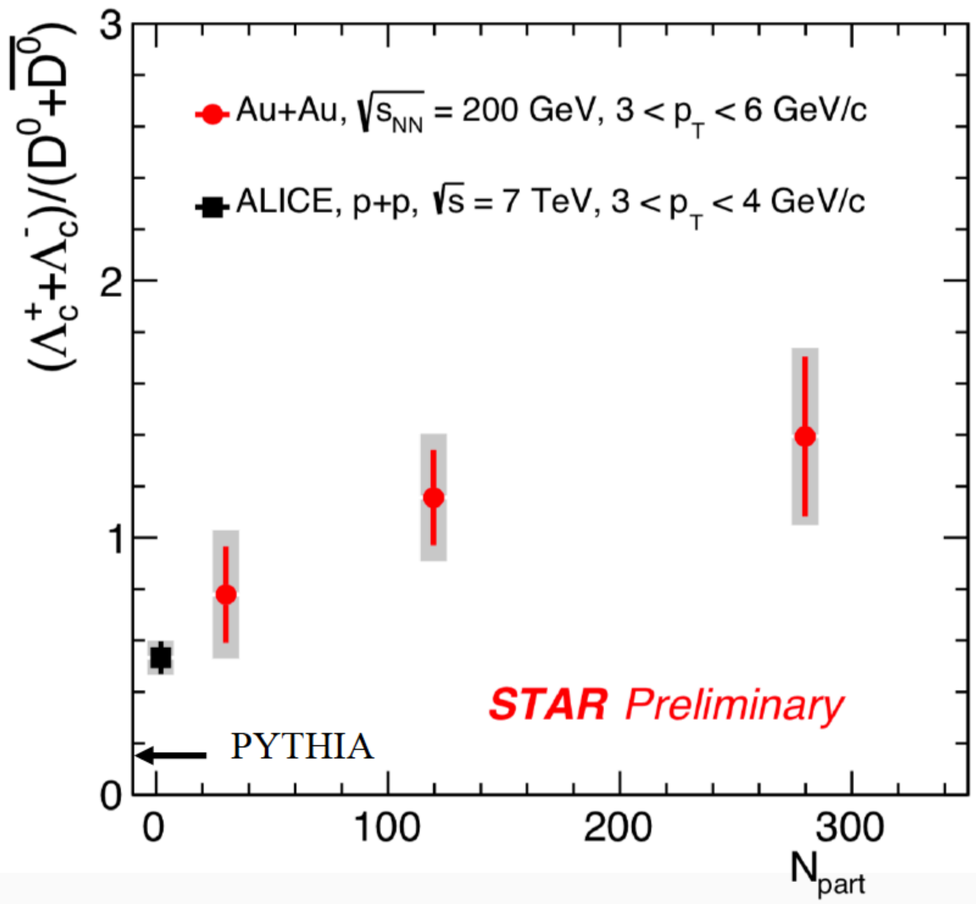
Investigating baryon production mechanisms in A-A with Λ^+_c

- Expected **enhancement of baryon over meson yield** in if **hadronization via coalescence**.
- Λ^+_c/D^0 measured at RHIC and LHC.

Λ^+_c/D^0 vs p_T, 10-80% Au-Au



Λ^+_c/D^0 vs N_{part}, 3< p_T < 6 GeV/c



- **Significant enhancement observed w.r.t PYTHIA.**
- Models including hadronization via coalescence closer to data.
- Λ^+_c/D^0 ratio comparable to baryon-to-meson ratio in light flavour sector

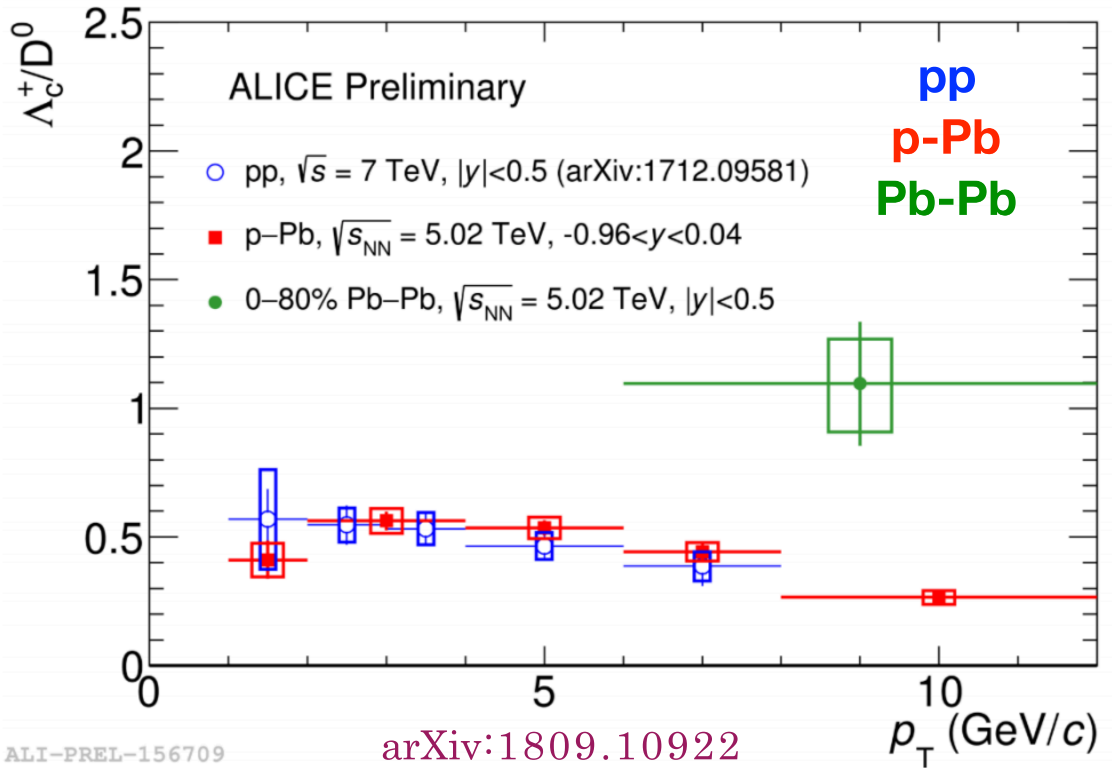
- **Λ^+_c/D^0 ratio increases with centrality.**
- Value at peripheral Au-Au close to pp.

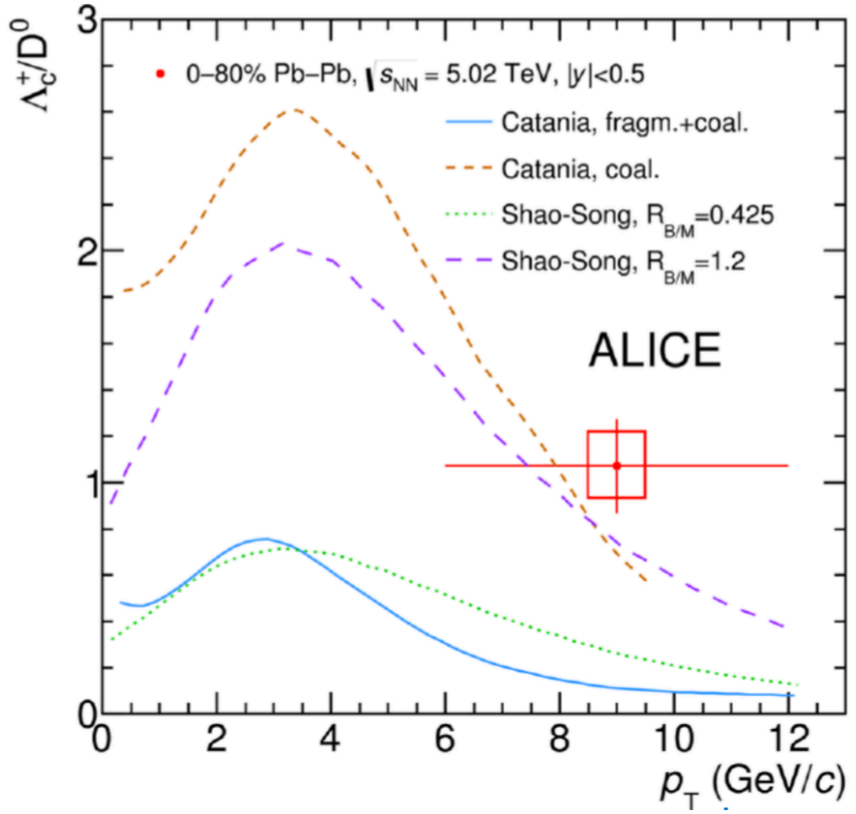
Baryon production

Investigating baryon production mechanisms in A-A with Λ^+_c

- Expected **enhancement of baryon over meson yield** in if **hadronization via coalescence**.
- Λ^+_c/D^0 measured at RHIC and LHC.

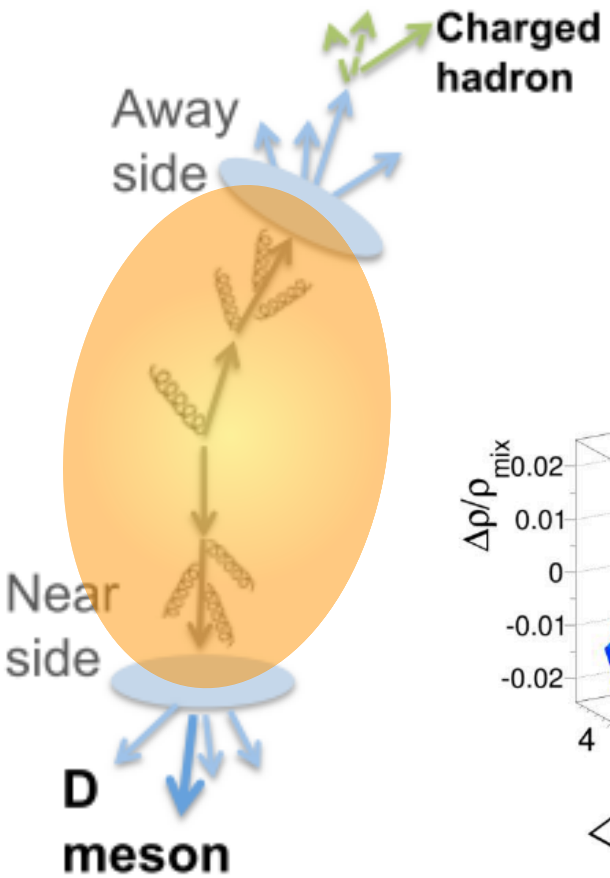
Λ^+_c/D^0 vs p_T, 0-80% Pb-Pb





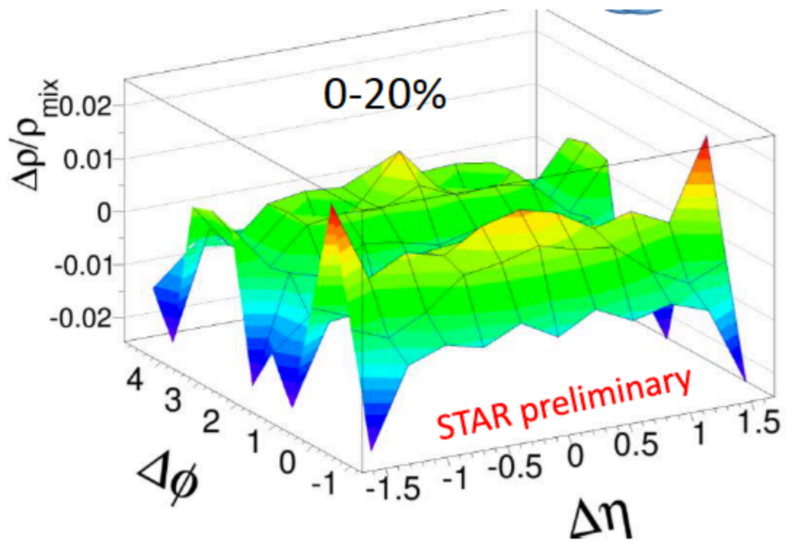
- **Λ^+_c/D^0 in Pb-Pb collisions higher than in pp and p-Pb collisions**
- **Λ^+_c/D^0 in Pb-Pb collisions higher than in pp and p-Pb collisions** -> model calculations with coalescence close to data.

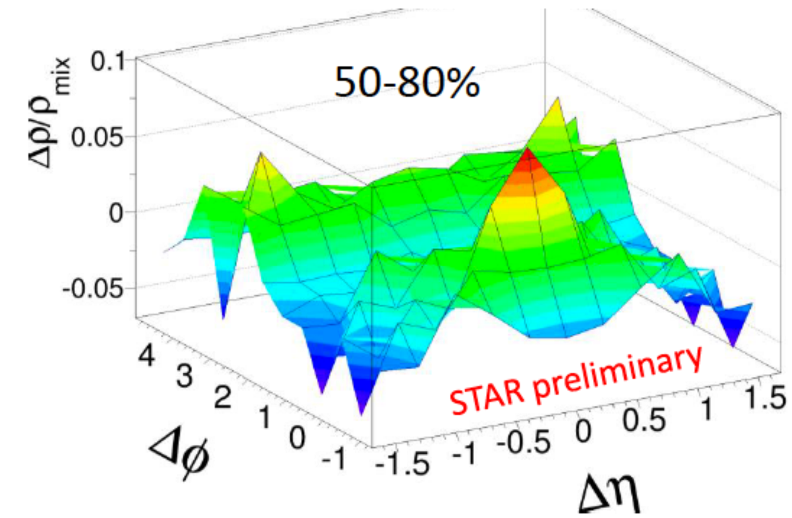
Δη, Δφ correlations of D-meson



Study heavy-flavour jet structure using 2-D angular correlations in Δη, Δϕ

- Measurement of Δη, Δϕ correlation for D^0 and charged particle in **0-20%, 20-50% and 50-80% Au-Au collisions** at $\sqrt{s_{NN}}$ = 200 GeV/c

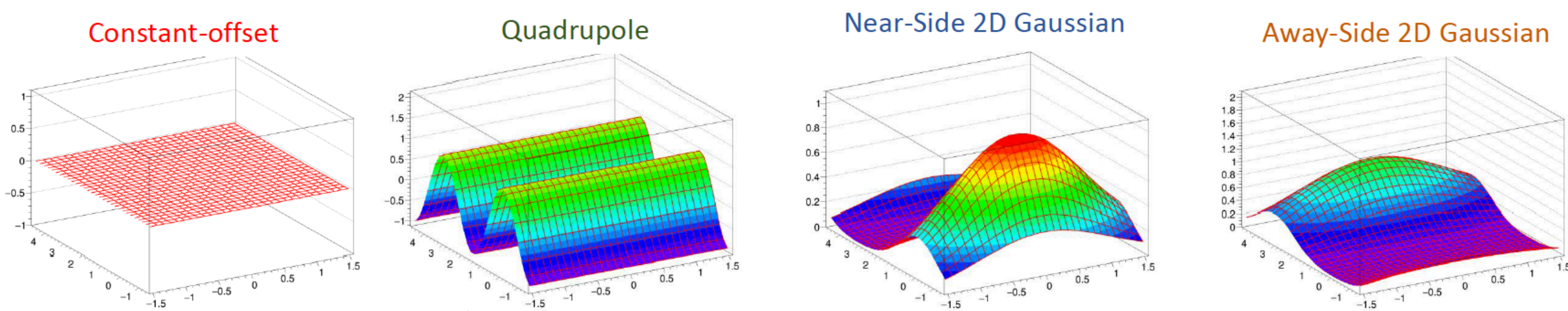




Trigger:
$2 < p_T^{D0} < 10$ GeV/c

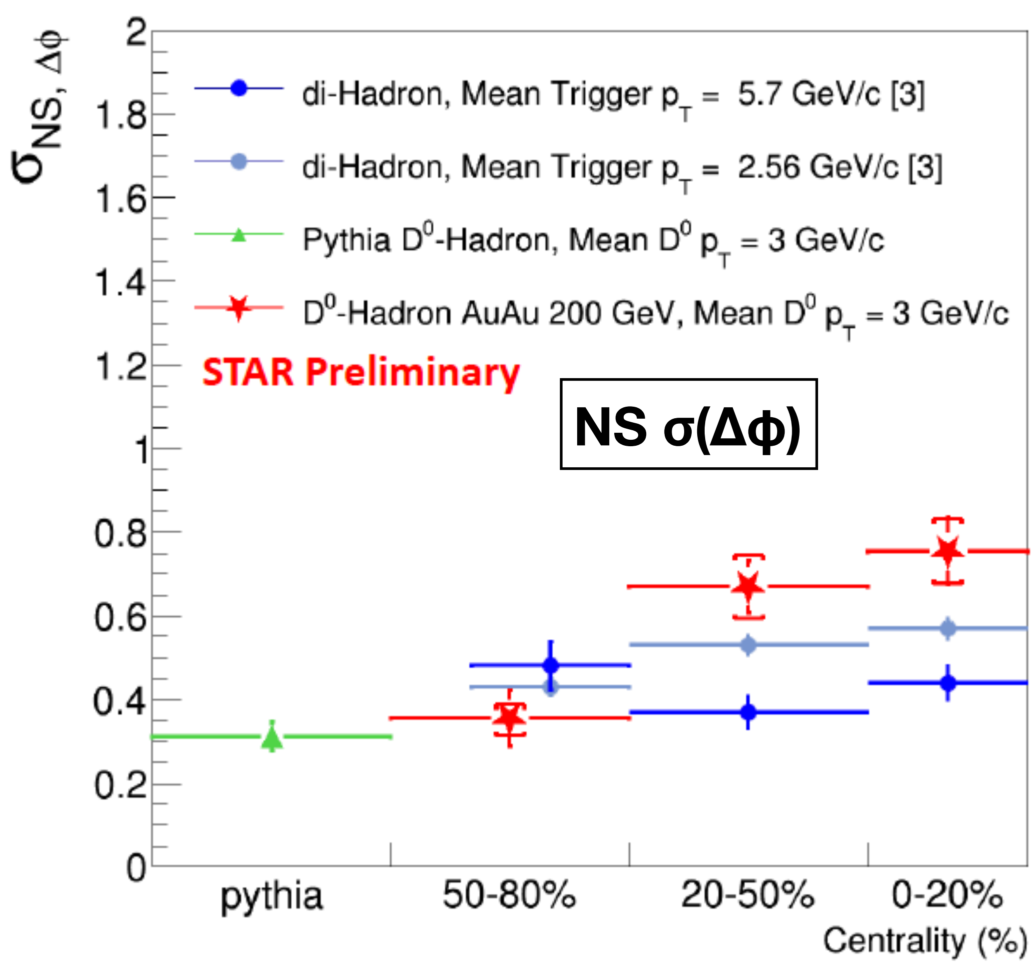
Associated:
$p_T^{ch} > 0.15$ GeV/c

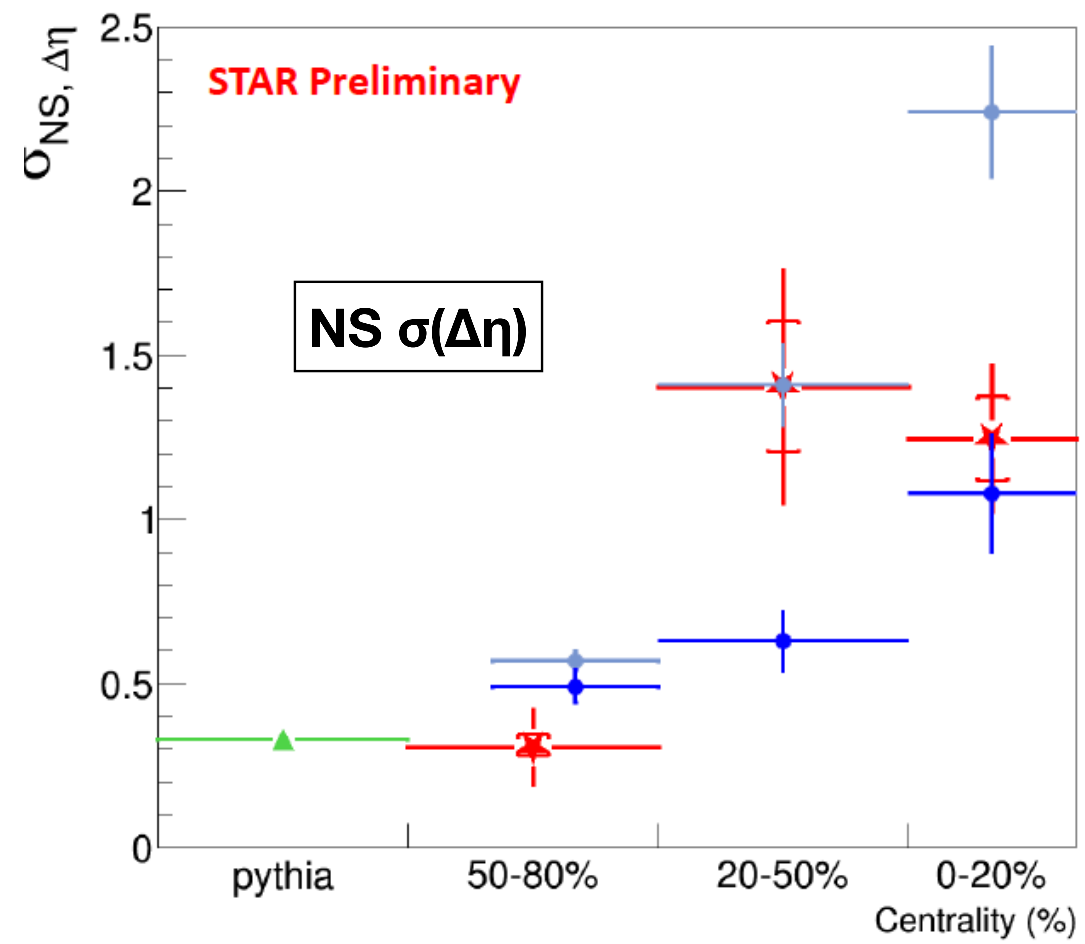
2D correlation structure fit with a const + v_2 term + near-side Gaus + away-side Gaus



$\Delta\eta$, $\Delta\varphi$ correlations of D-meson

- Extract near-side width along $\Delta\eta$ and $\Delta\phi$ vs centrality.
- Data compared with Pythia and light flavour correlations.
- Width in 50-80% Au-Au consistent with Pythia.
- **Trend of broadening of near-side width in $\Delta\eta$ and $\Delta\phi$ from peripheral to central collisions —> trend of larger broadening in $\Delta\eta$ than in $\Delta\phi$.**



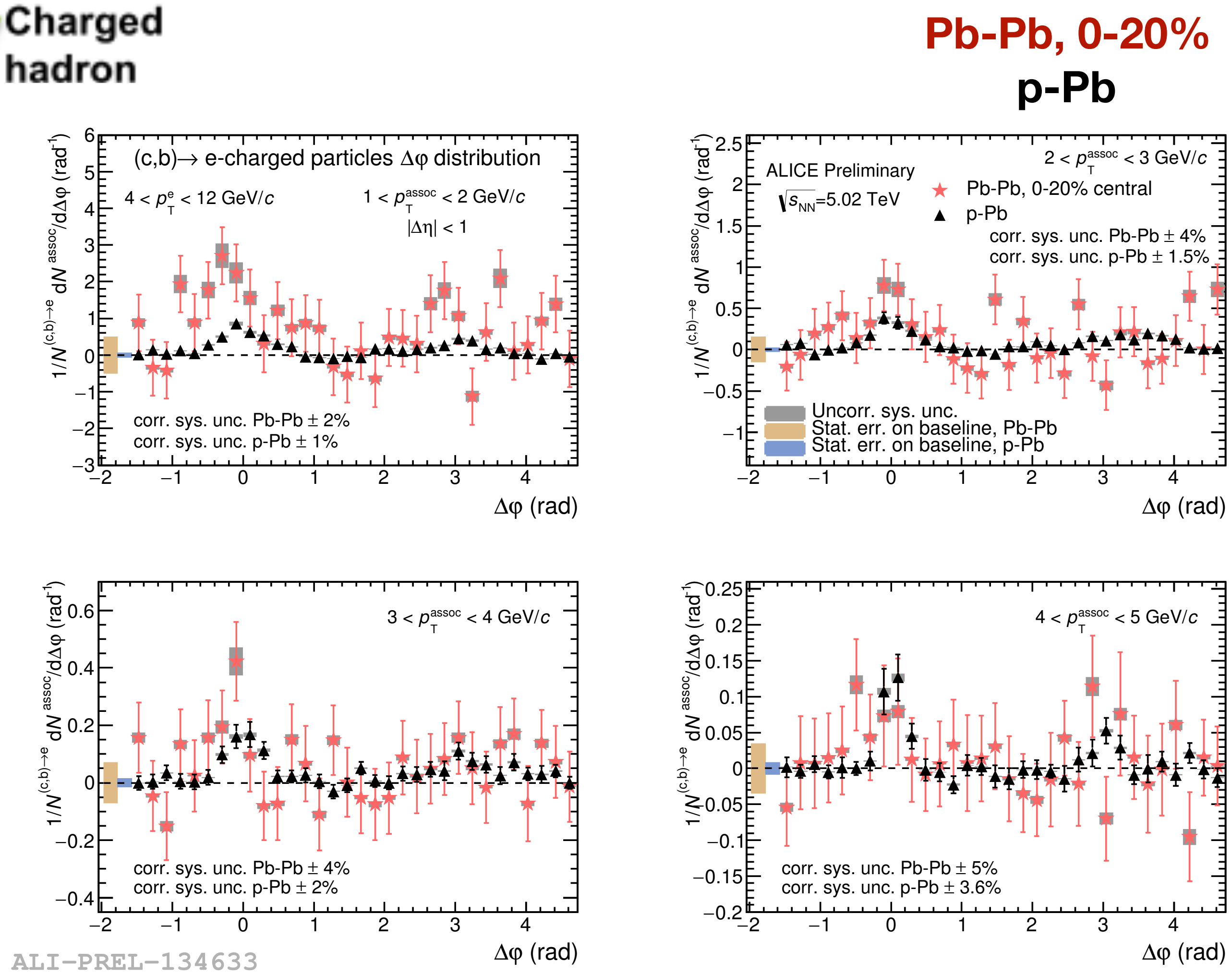


Trigger:
$2 < p_T^{D0} < 10$ GeV/c

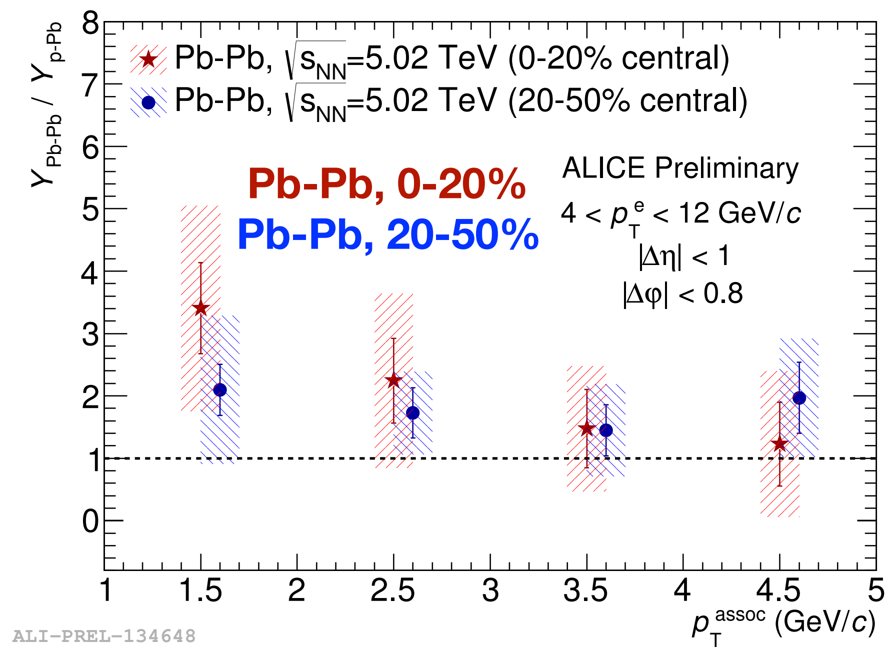
Associated:
$p_T^{ch} > 0.15$ GeV/c

Δφ correlations of HF-decay electrons and charged particles

Study possible modification of fragmentation and hadronization of heavy quarks.



- Δφ correlations of c,b -> e and charged particles.
- Trigger electron - 4 < p_T^e < 12 GeV/c, different associated p_T bins.
- Near-side yields in **0-20% and 20-50% Pb-Pb collisions** compared to **p-Pb collisions** at $\sqrt{s_{NN}}$ = 5.02 TeV



- Y(Pb-Pb)/Y(p-Pb) in 0-20% and 20-50% Pb-Pb collisions.
  - **Hint of enhancement of yield in central Pb-Pb collisions at low associated p_T.**
  - **Ratio ~ 1 at high p_T.**
- More precise measurement expected with the next Pb-Pb run.

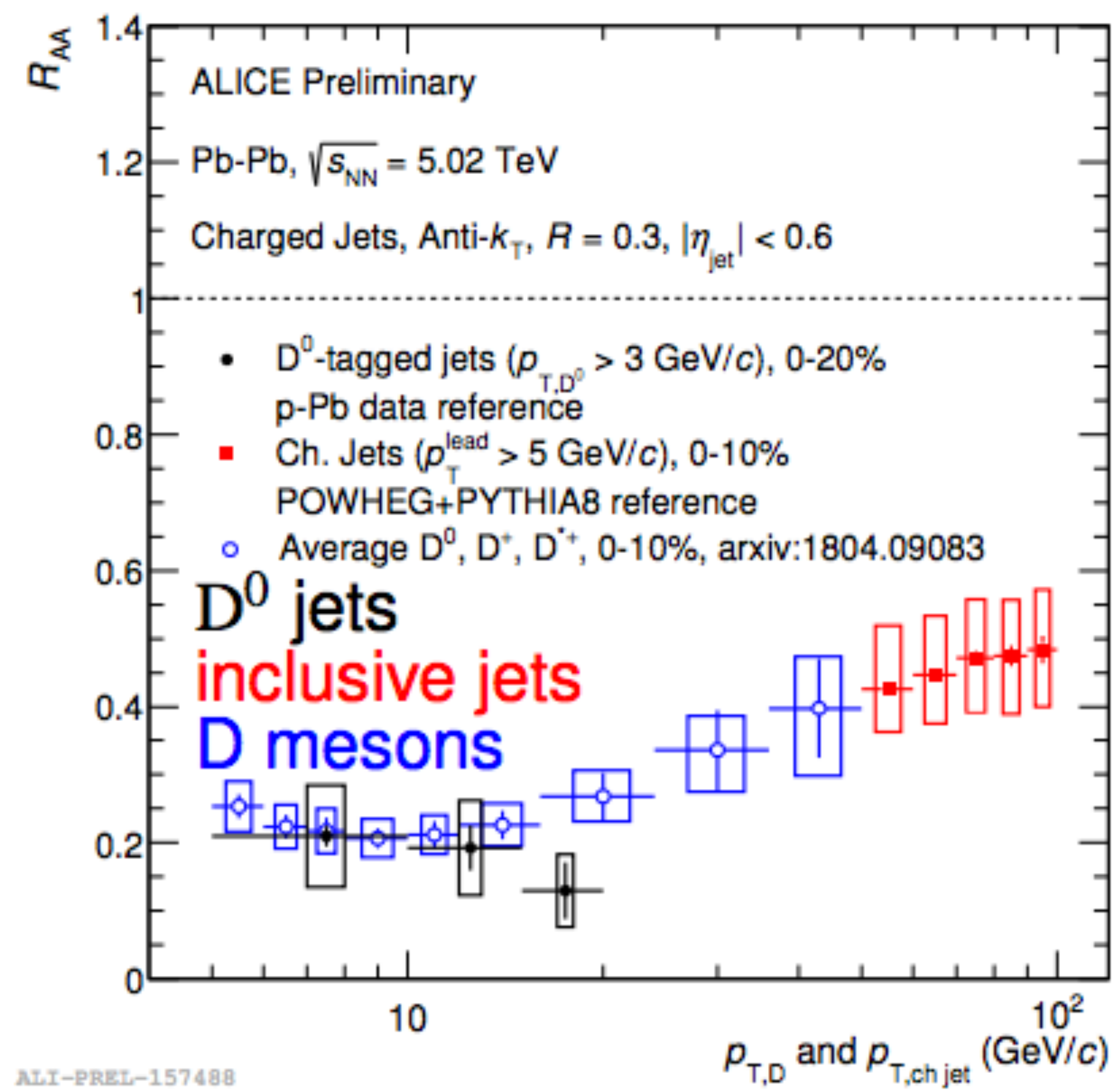
Heavy-flavour tagged jets

Study in-medium color/mass dependent energy loss and modification of internal jet sub-structure with heavy-flavour jet
-> access to initial heavy quark energy profile

D^0 in jets with $p_T^{D0} > 3$ GeV/c measured in Pb-Pb collisions.

Jets measured for $5 < p_T^{Jet} < 20$ GeV/c

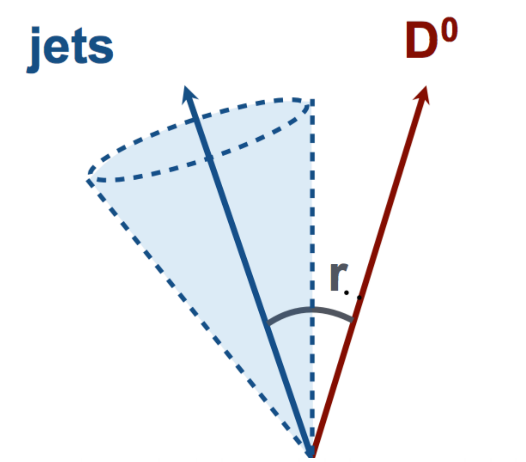
R_{AA} of D^0 jets compared with D^0 —> similar suppression.



Heavy-flavour tagged jets

Study the modification of jet fragmentation and modification of jet radial profile

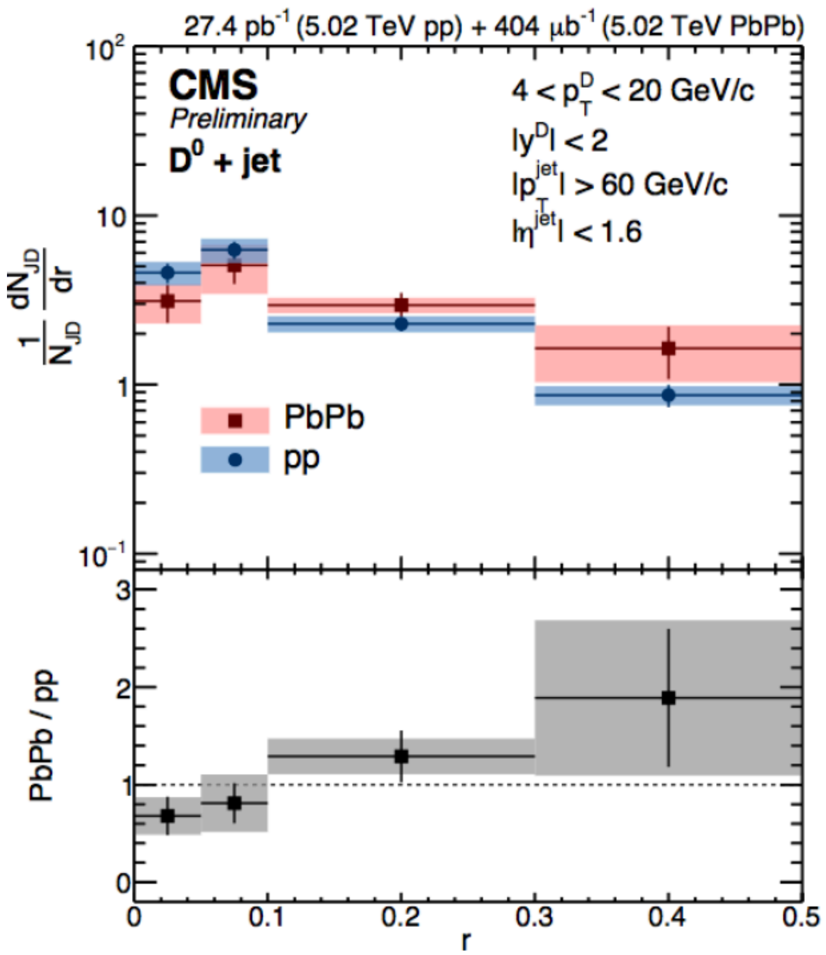
- Measure radial distribution of D^0 in jets -> angular distribution of D^0 w.r.t jet axis



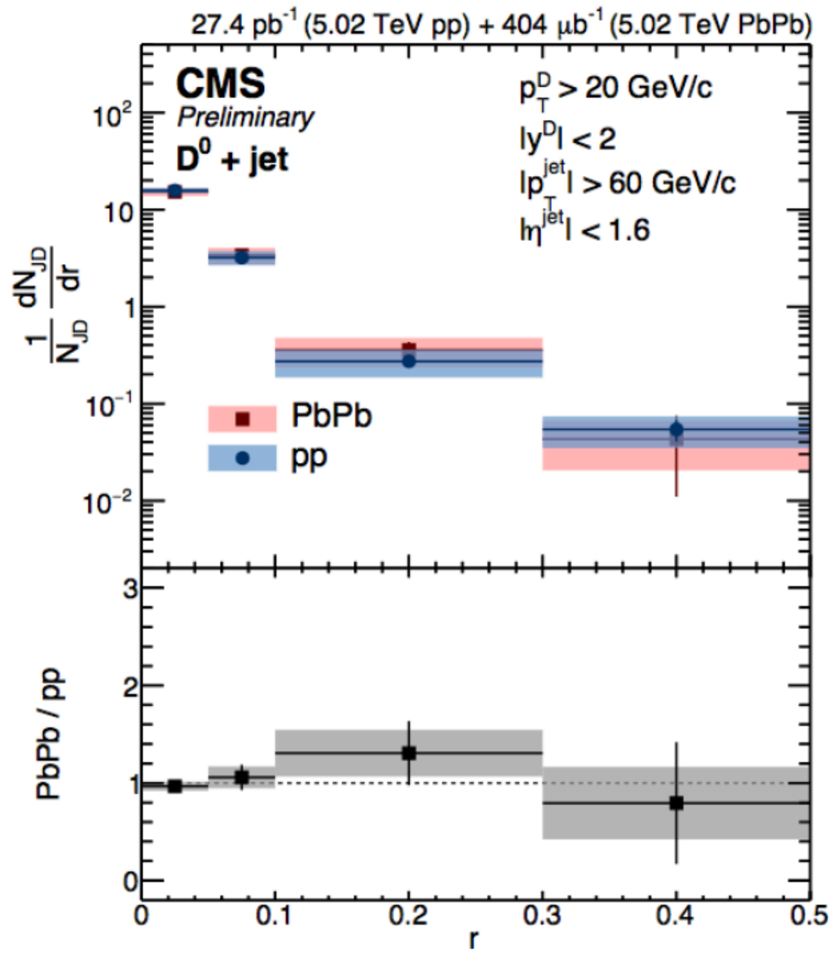
$$r = \sqrt{\Delta\phi_{JD}^2 + \Delta\eta_{JD}^2}$$

$$\frac{1}{N_{JD}}\frac{dN_{JD}}{dr} = \frac{1}{N_{JD}\Delta r}\frac{N_{JD}|_{\Delta r}}{\alpha \times \epsilon}$$

$4 < p_T^{D0} < 20$ GeV/c



$p_T^{D0} > 20$ GeV/c



R = 0.3
$p_T^{Jet} > 60$ GeV/c

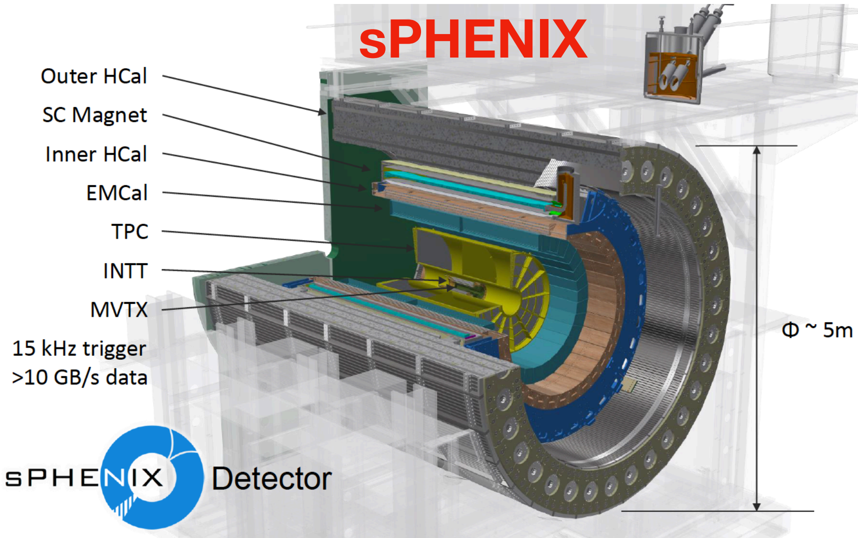
Radial distribution:

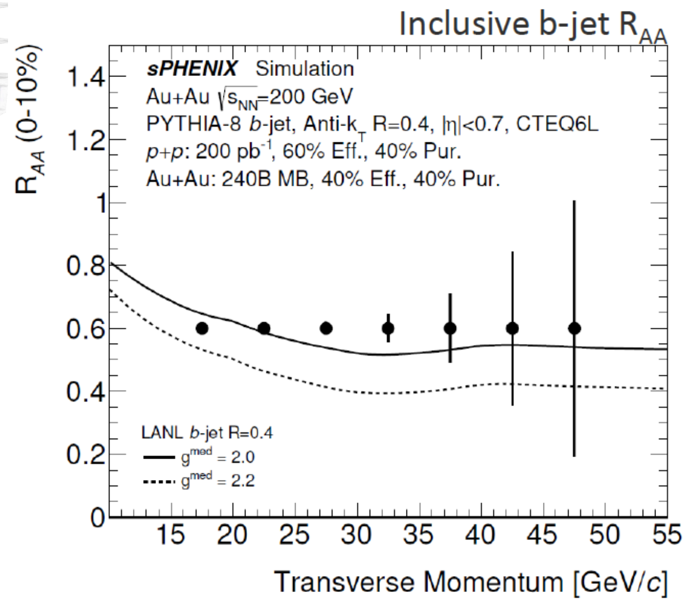
- Low p_T D^0: max at $0.05 < r < 0.1$
- High p_T D^0: closer to jet-axis

Ratio of Pb-Pb to pp:

- **Low p_T D^0: increasing trend with r —> could indicate D^0 further away from jet-axis in Pb-Pb compared to pp.**
- High p_T D^0: ratio consistent with unity.

Looking forward for heavy-flavour physics





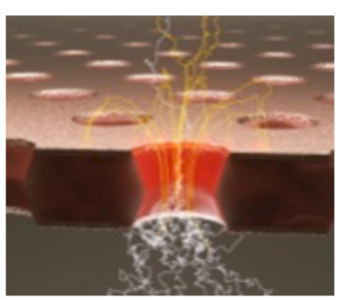
RHIC:

sPHENIX: extensive heavy-flavor physics capabilities including measurements of b-jets and full B meson reconstruction.

LHC:

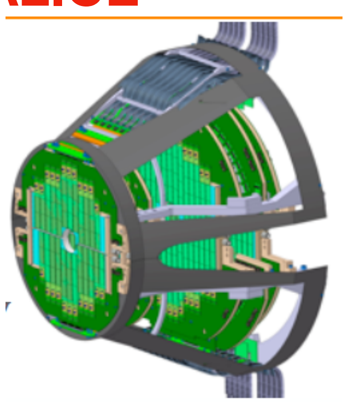
ALICE: New ITS, MFT, TPC readout chambers and fast interaction trigger among other planned upgrades —> high precision measurements including beauty hadrons possible.

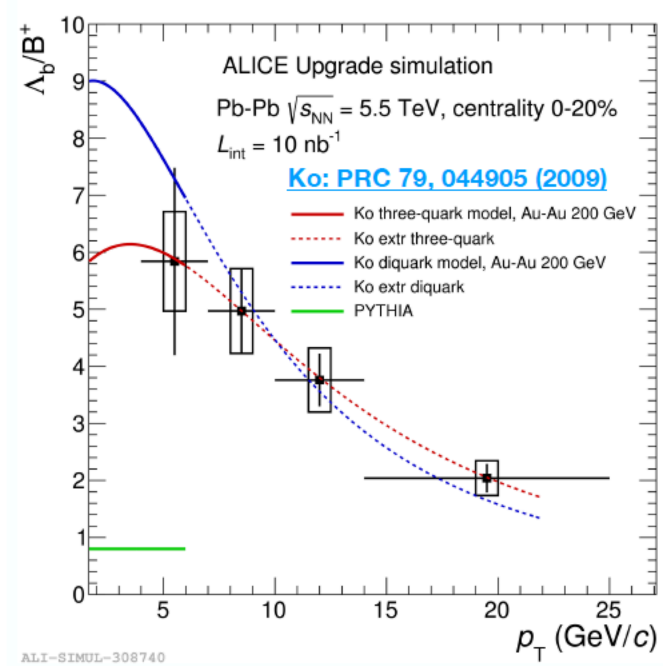
J.Phys. G41 (2014) 087002.



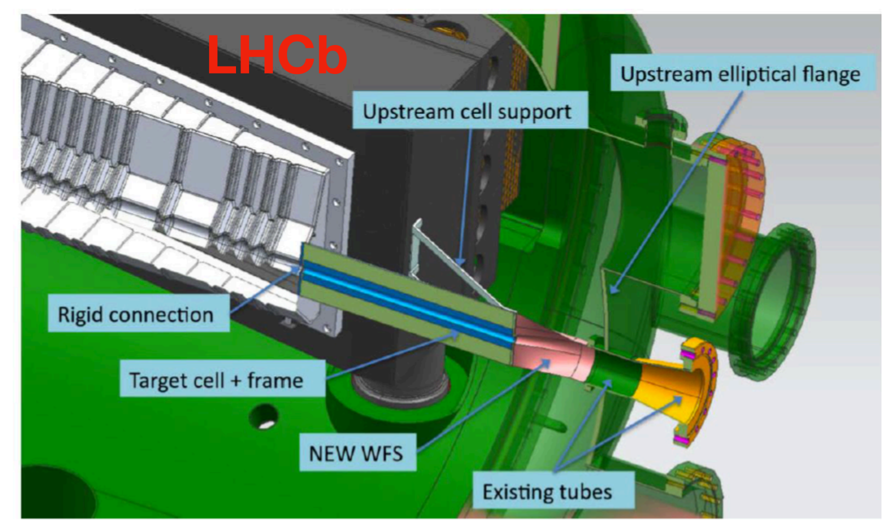
CERN-LHCC-2013-020

ALICE





LHCb: SMOG upgrade to extend fixed target collision capabilities —> high precision charm measurements at different $\sqrt{s_{NN}}$.



Summary & Conclusions

Heavy quarks are excellent probes to investigate pp, pA and AA collisions

Small systems:

- Heavy-flavor production measurements in **minimum bias collisions** —> described by **pQCD calculations with cold nuclear matter effects**.
- Measurement in **high multiplicity** events —> indicate **need for better understanding** of initial and final state effects.
- Charm and beauty baryon measurements used to investigate hadronization mechanisms.

A-A collisions:

- Good precision of D meson R_{AA} and v_2 -> **extending to measure B mesons** to study mass and flavor dependent interaction with the medium.
- Heavy-flavour baryons and strange-HF mesons used to study hadronization mechanisms -> **recombination/coalescence is important**.
- Studying the modification of jet-fragmentation and structure using heavy-flavour tagged jets and correlations.
- Upgrades to LHC experiments and new sPHENIX detector at RHIC -> new and more differential heavy-flavor measurement in future.

Back-up

Models: p-Pb

arXiv:1506.03981

Table 8: Summary of the various models of CNM approaches discussed in the text and compared to data in Section 3.3. The main physical processes and ingredients used in each calculation are listed.

Acronym	*Production mechanism*	*Medium effects*	*Main parameters*	*Ref.*
		Open heavy flavour		
pQCD+EPS09 LO	pQCD LO	nPDF	4+1 EPS09 LO sets	[368]
SAT	pQCD LO+CGC	Saturation	$Q^2_{s,p}(x_0)$, $Q^2_{s,A}(x_0)$	[378]
ELOSS	pQCD LO	E. loss, power cor., broa.	ϵ_a, ξ_d, μ^2, λ	[391]
		Quarkonia		
EXT+EKS98LO+ABS	generic 2 → 2 LO	nPDF and absorption	EKS98 LO, $\sigma_{\rm abs}$	[374, 375]
EXT+EPS09 LO	generic 2 → 2 LO	nPDF	4+1 EPS09 LO sets	[376, 377]
CEM+EPS09 NLO	CEM NLO	nPDF	30+1 EPS09 NLO sets	[363]
SAT	CEM LO+CGC	Saturation	$Q^2_{s,p}(x_0)$, $Q^2_{s,A}(x_0)$	[379]
ELOSS	NRQCD LO	E. loss, power cor.	ϵ_a, ξ_d, μ^2, λ	[83]
COH.ELOSS	pp data	Coherent E. loss	$\hat{q}$	[395, 396]
KPS	dipole model	Dipole absorption	$\sigma_{c\bar{c}}$	[385, 386]

Models: Pb-Pb

arXiv:1506.03981

Table 11: Comparative overview of the models for heavy-quark energy loss or transport in the medium described in the previous sections.

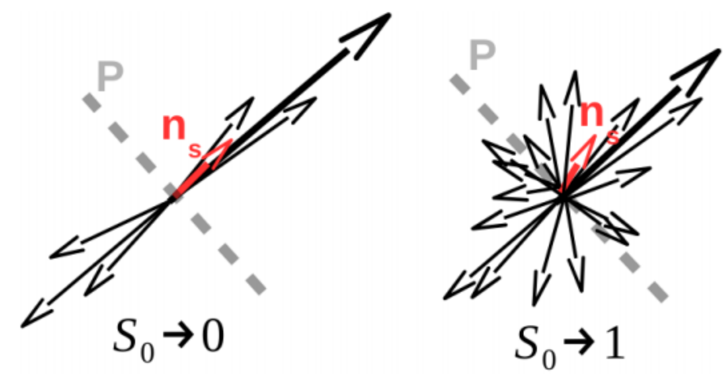
Model	*Heavy-quark production*	*Medium modelling*	*Quark–medium interactions*	*Heavy-quark hadronisation*	*Tuning of medium-coupling (or density) parameter(s)*
Djordjevic *et al.* [511–515]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss finite magnetic mass	fragmentation	Medium temperature fixed separately at RHIC and LHC
WHDG [459, 519]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
Vitev et al. [422, 460]	non-zero-mass VFNS no PDF shadowing	Glauber model nuclear overlap ideal fl. dyn. 1+1d Bjorken expansion	radiative energy loss in-medium meson dissociation	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
AdS/CFT (HG) [624, 625]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	AdS/CFT drag	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
POWLANG [507–509, 585, 586]	POWHEG (NLO) EPS09 (NLO) PDF shadowing	2+1d expansion with viscous fl. dyn. evolution	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume pQCD (or l-QCD *U* potential)
MC@$_s$HQ+EPOS2 [528–530]	FONLL EPS09 (LO) PDF shadowing	3+1d expansion (EPOS model)	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at LHC, slightly adapted for RHIC
BAMPS [537–540]	MC@NLO no PDF shadowing	3+1d expansion parton cascade	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
TAMU [491, 565, 606]	FONLL EPS09 (NLO) PDF shadowing	2+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss diffusion in hadronic phase	fragmentation recombination	assume l-QCD *U* potential
UrQMD [608–610]	PYTHIA no PDF shadowing	3+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume l-QCD *U* potential
Duke [587, 628]	PYTHIA EPS09 (LO) PDF shadowing	2+1d expansion viscous fl. dyn.	transport with Langevin eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at RHIC and LHC (same value)

HF production vs spherocity

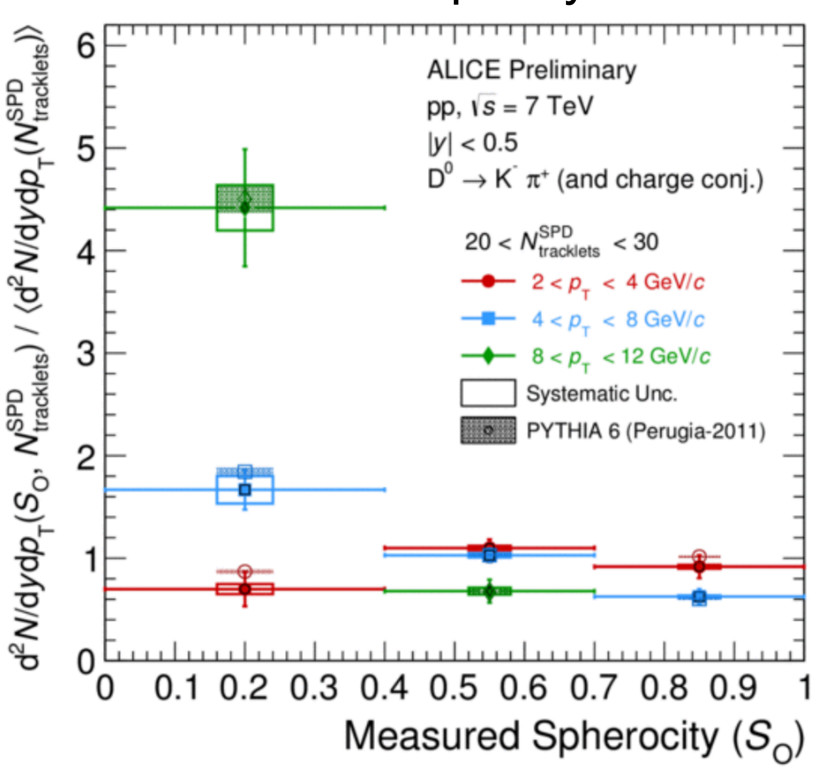
Definition of spherocity of an event:

$$S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{T_i} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2$$

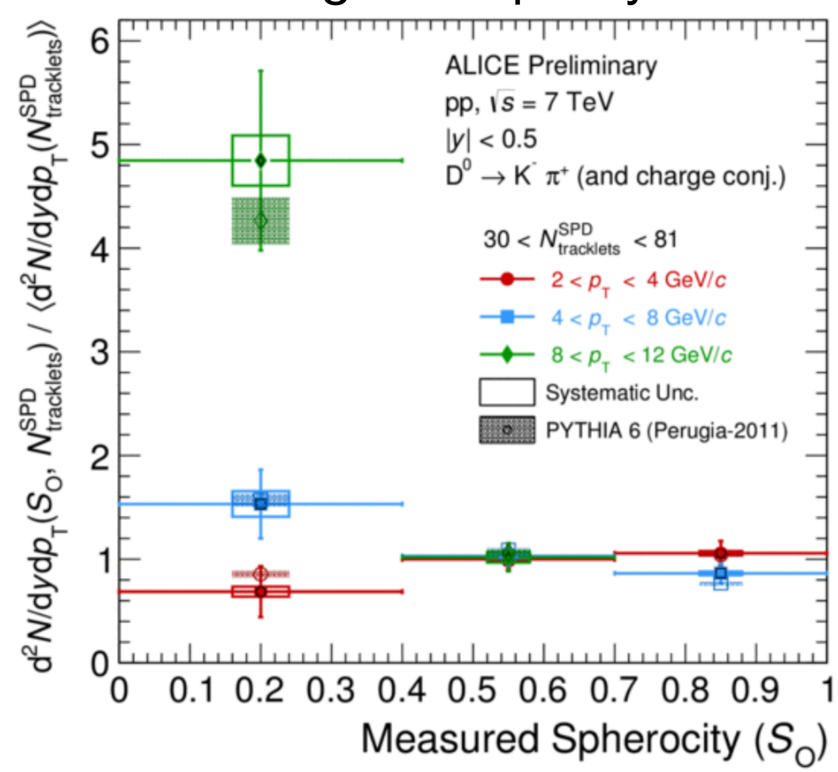
$$S_0 = \begin{cases} 0 \text{ "jetty" limit (hard events)} \\ 1 \text{ "isotropic" limit (soft events)} \end{cases}$$



Low multiplicity



High multiplicity

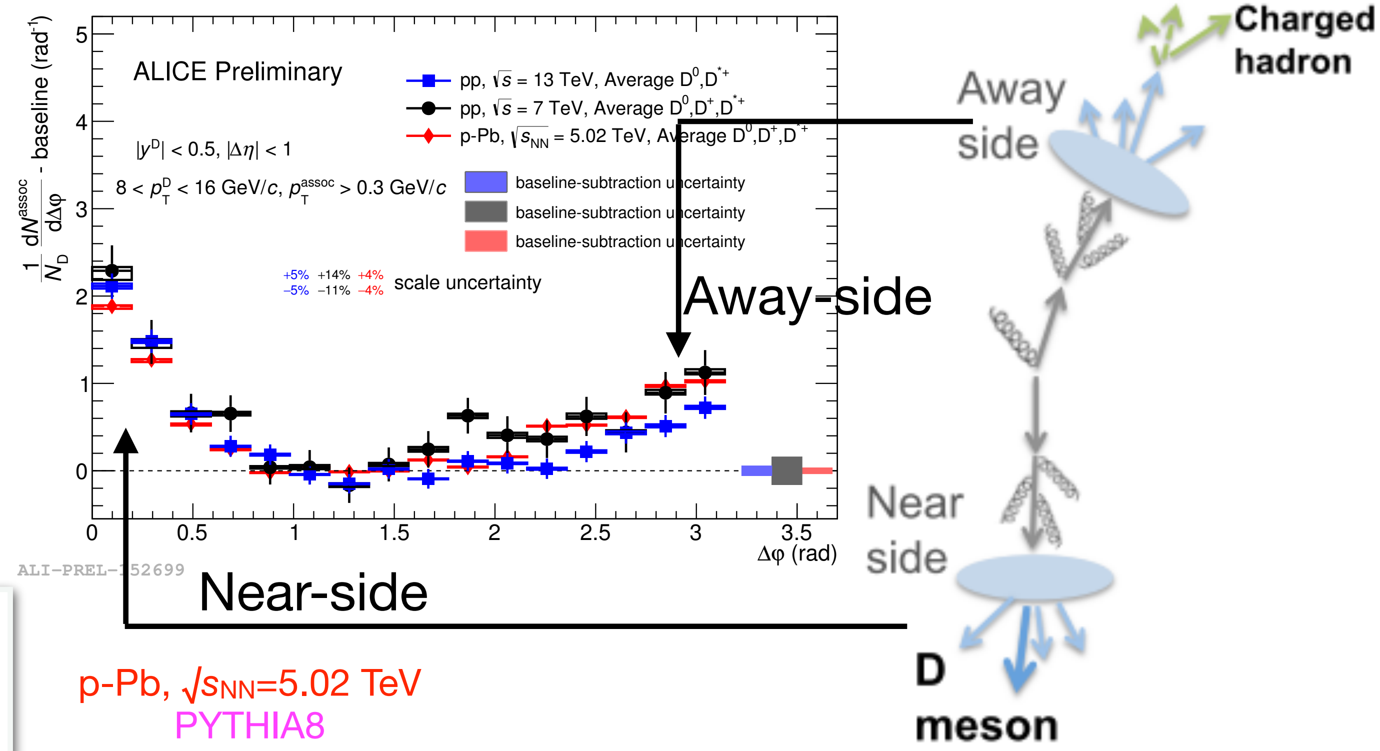


- D meson production vs spherocity independent of multiplicity.
- Low pT D meson: similar rate of production in all spherocity.
- High pT D meson: Higher rate of production in low spherocity or more jetty-like events.

Δφ correlations of D-meson

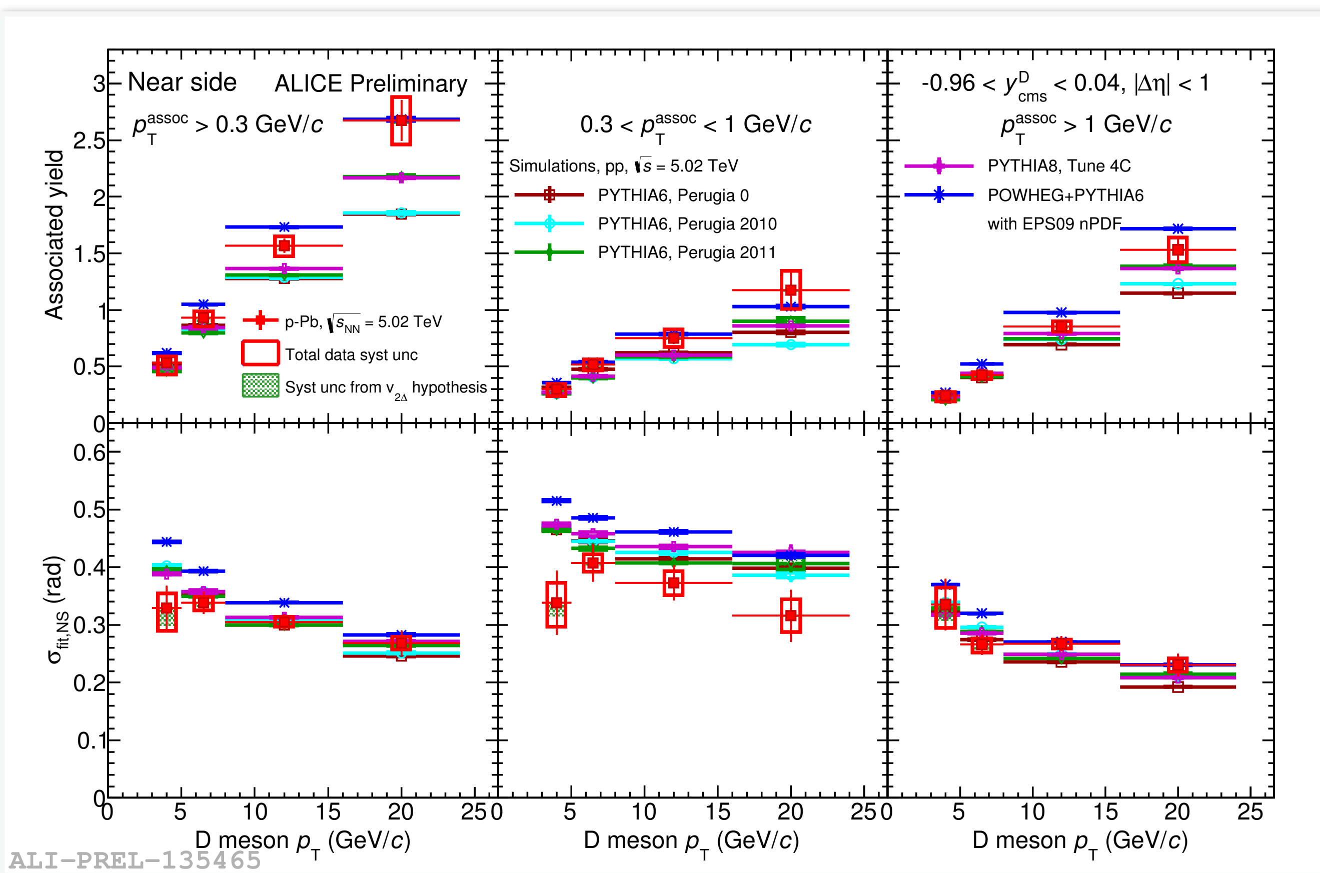
Further study heavy-flavour production mechanisms and fragmentation

- Azimuthal correlations of **D** (Average of D^0, D^+, D^{*+}) mesons with **charged particles** in pp and p-Pb collisions.
- Near-side peak properties, **yields and width extracted** with two Gaussian + baseline fit.



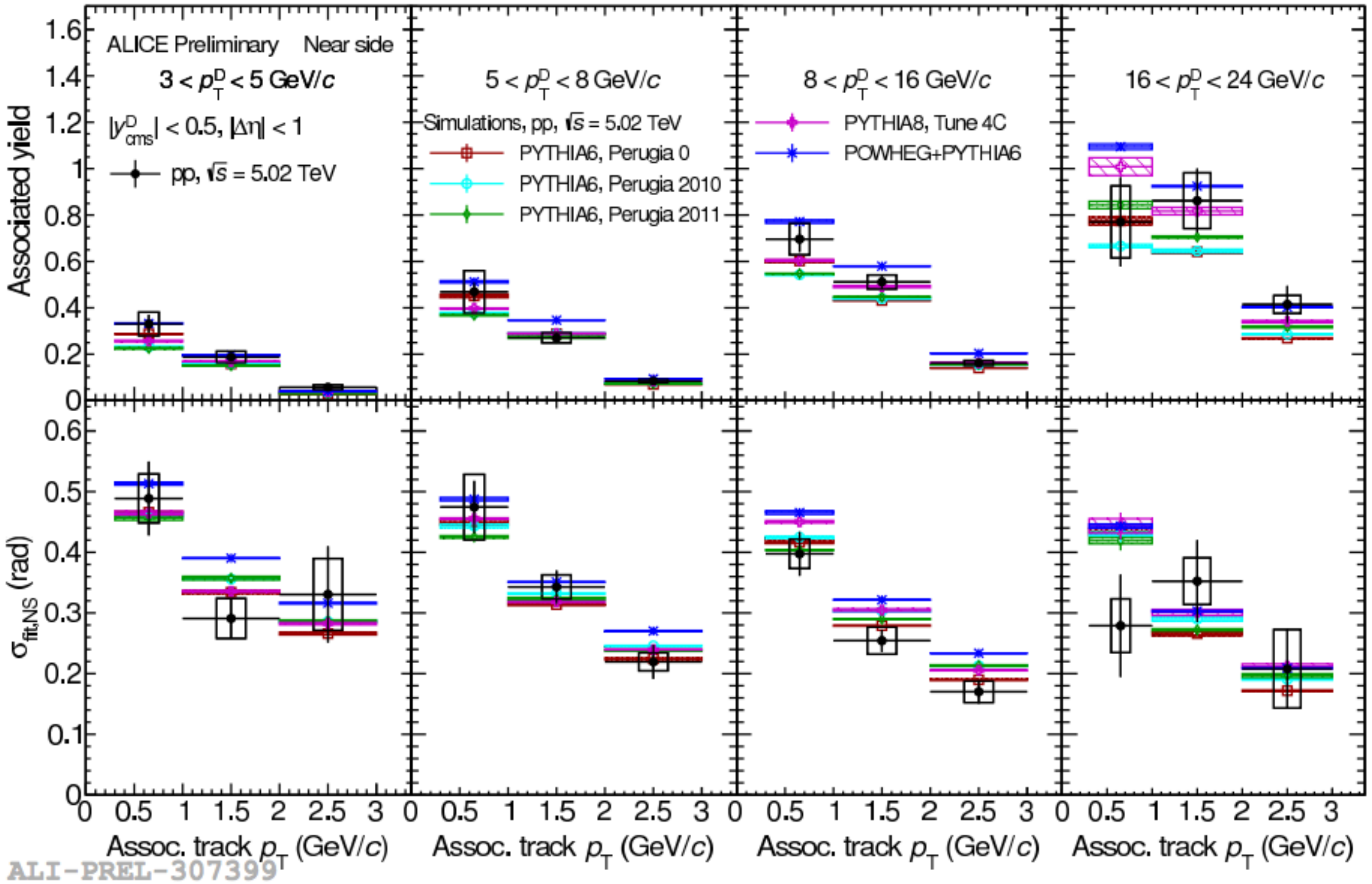
p-Pb, $\sqrt{s_{NN}}$=5.02 TeV
PYTHIA8
POWHEG+PYTHIA6

PYTHIA6, Perugia0
PYTHIA6, Perugia 2010
PYTHIA6, Perugia 2011



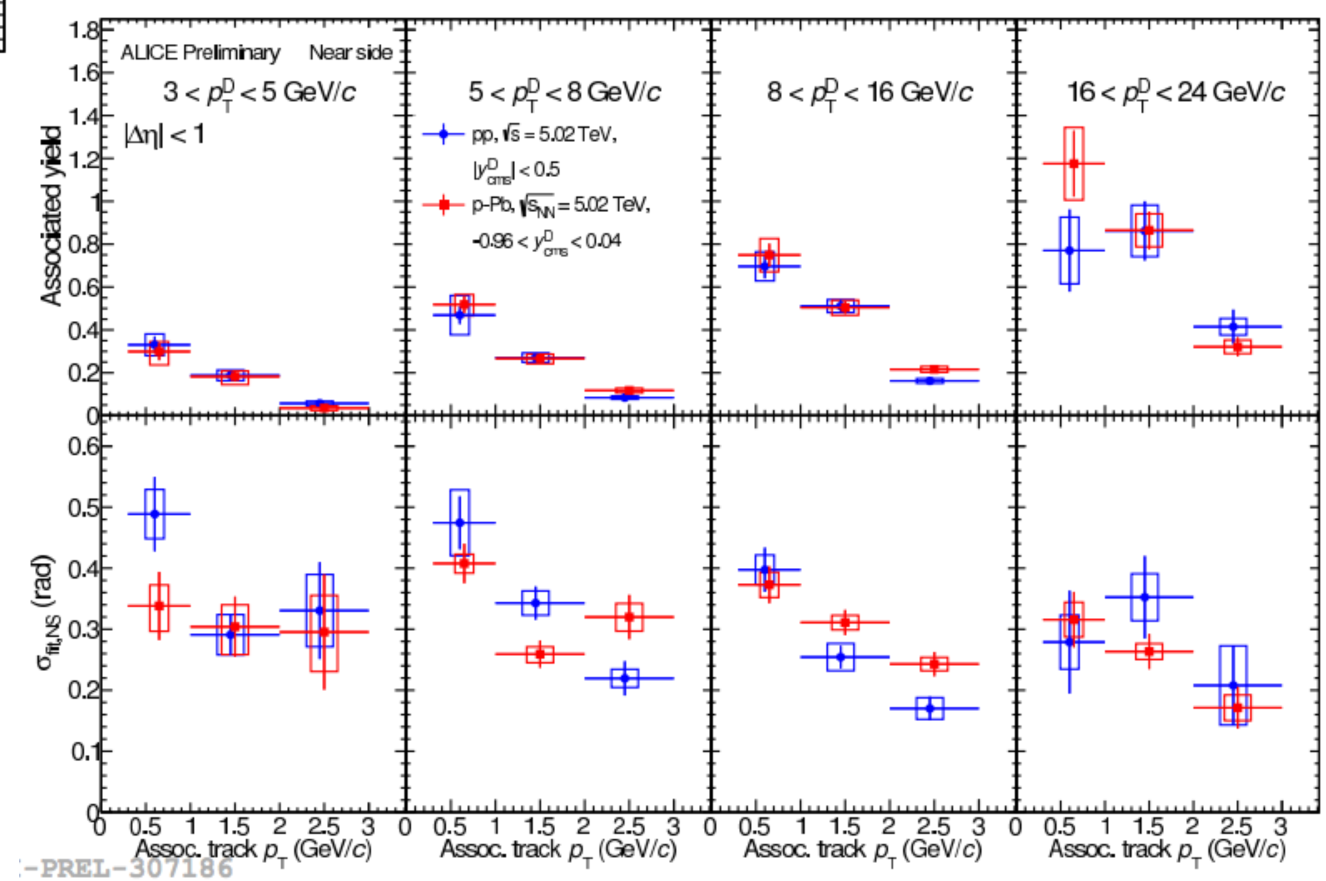
- Similar near-side peak properties in different energies and collision systems.
- Comparison to PYTHIA and PYTHIA+POWHEG expectations —> describe the correlation function and near-side peak properties reasonably well.

Δφ correlations of D-meson, pp



- Near-side yield and width in pp compared to different MC predictions.

pp Data
PYTHIA6, Perugia 0
PYTHIA6, Perugia 2010
PYTHIA6, Perugia 2011
PYTHIA8, Tune 4C
POWHEG+PYTHIA6

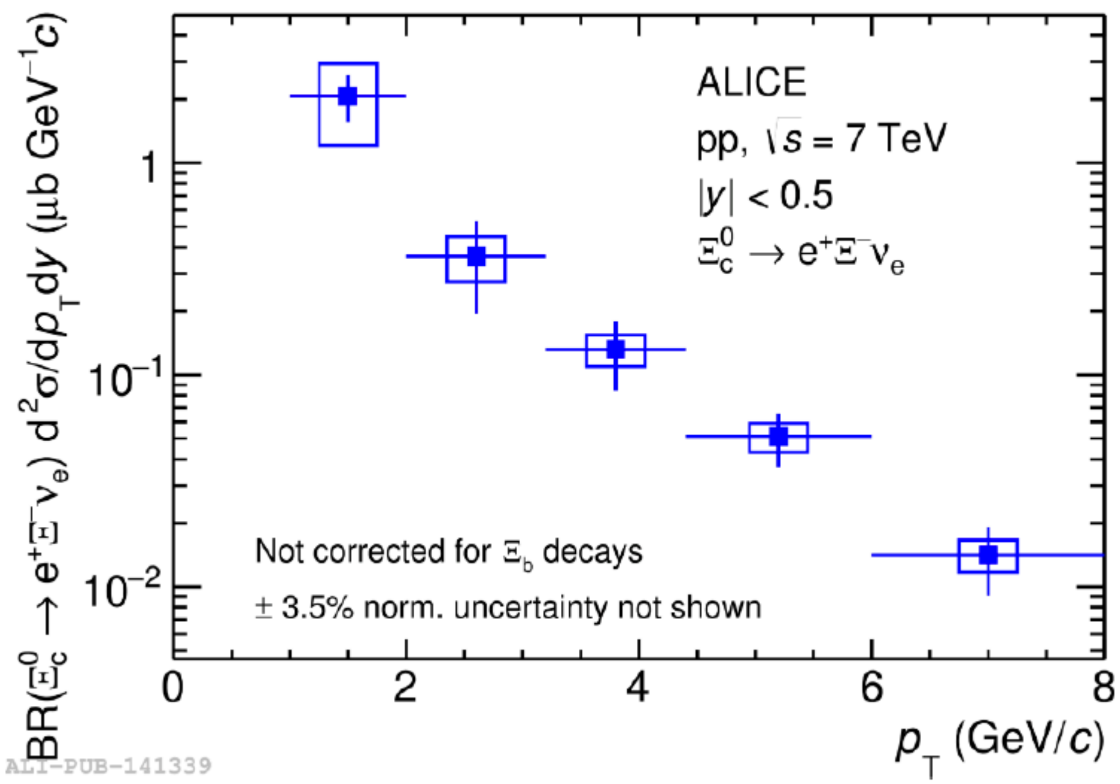


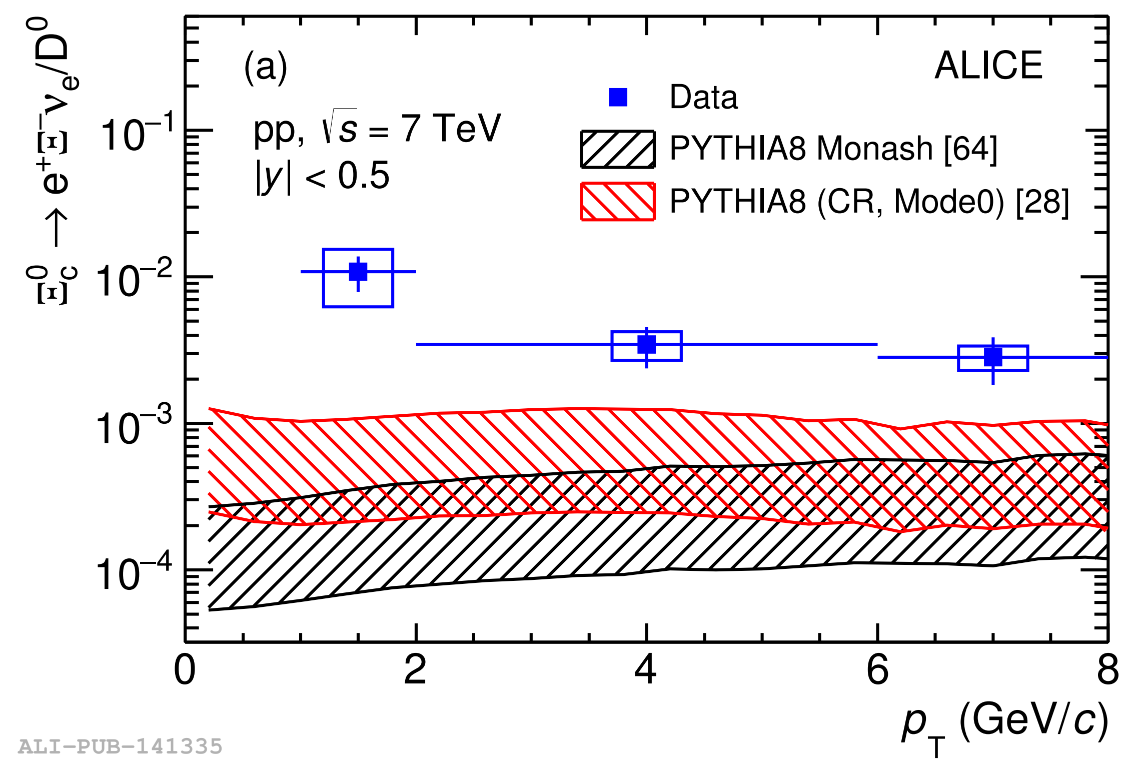
- Near-side yield and width in pp and p-Pb collisions

pp
p-Pb

Ξ^0_c in pp collisions

Investigating charm hadronisation mechanisms with Ξ^0_c.

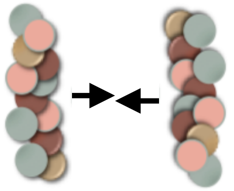




PLB 78 (2018) 8-19

- **First Ξ^0_c x BR measurement at the LHC** using $\Xi^0_c \rightarrow e^+\Xi^-\nu_e$ decay channel
  - **Baryon-to-meson ratio Ξ^0_c/D^0 larger than model predictions.**
    - BR not measured —> estimated to be 0.83% - 4.2%

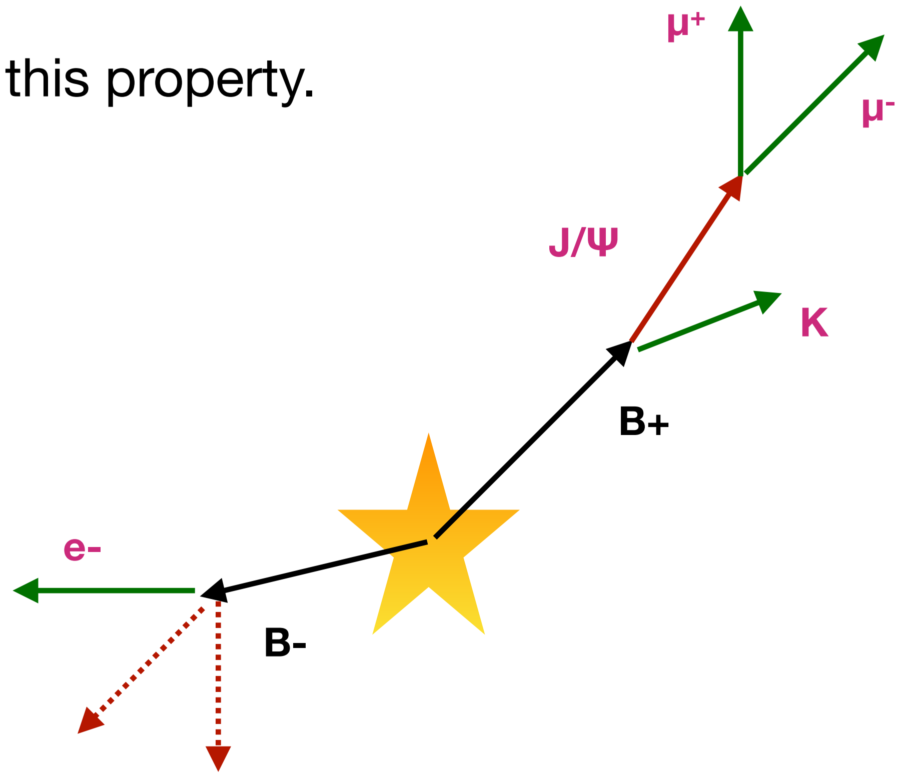
Beauty production



Study mass dependent energy loss with B mesons.

- B mesons have longer decay length than D mesons -> exploit this property.
- Decay channels used:
  - B -> l + X
  - B -> **J/Ψ** + X
  - B -> **D** + X

Pros: high statistics and higher efficiency
Cons: No full B information, affected by decay kinematics



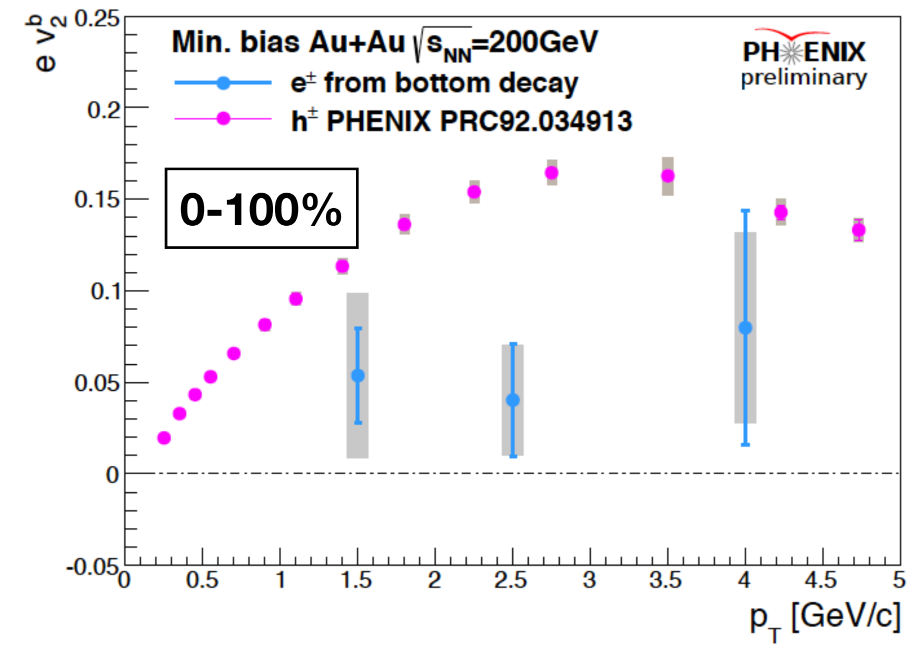
- B+ -> **J/Ψ + K** (BR ~ 0.06%)

Pros: Get original B kinematics
Cons: Low statistics and high combinatorial background

B meson v_2

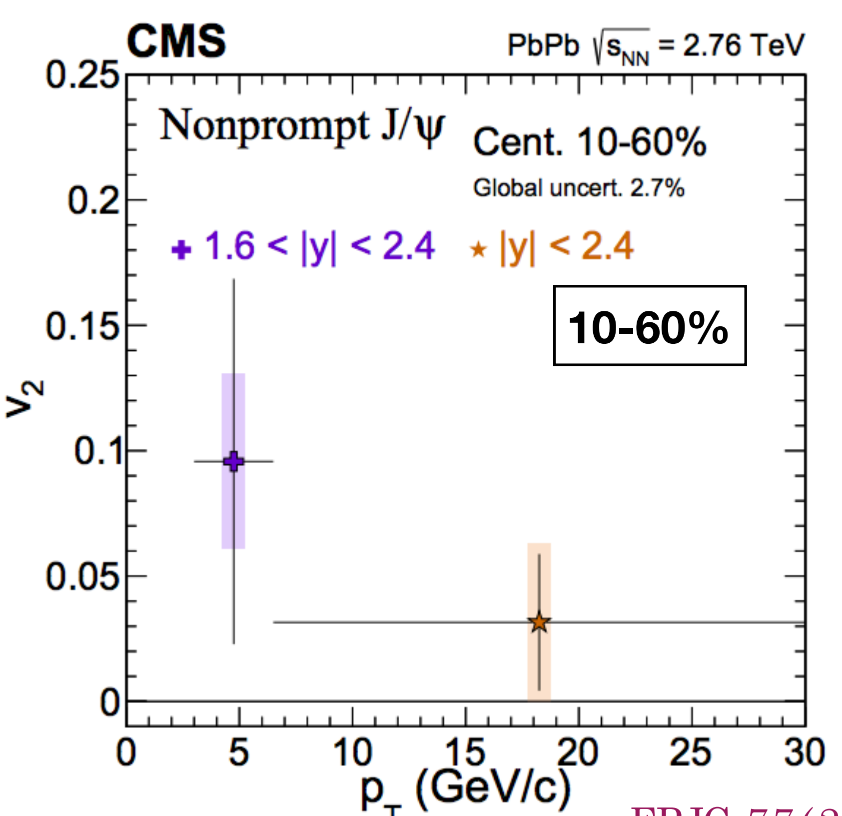
We know that charm flows, what about beauty?

RHIC:
- v_2 of b->e measured in 0-100% Au-Au -> consistent with zero within large uncertainties.

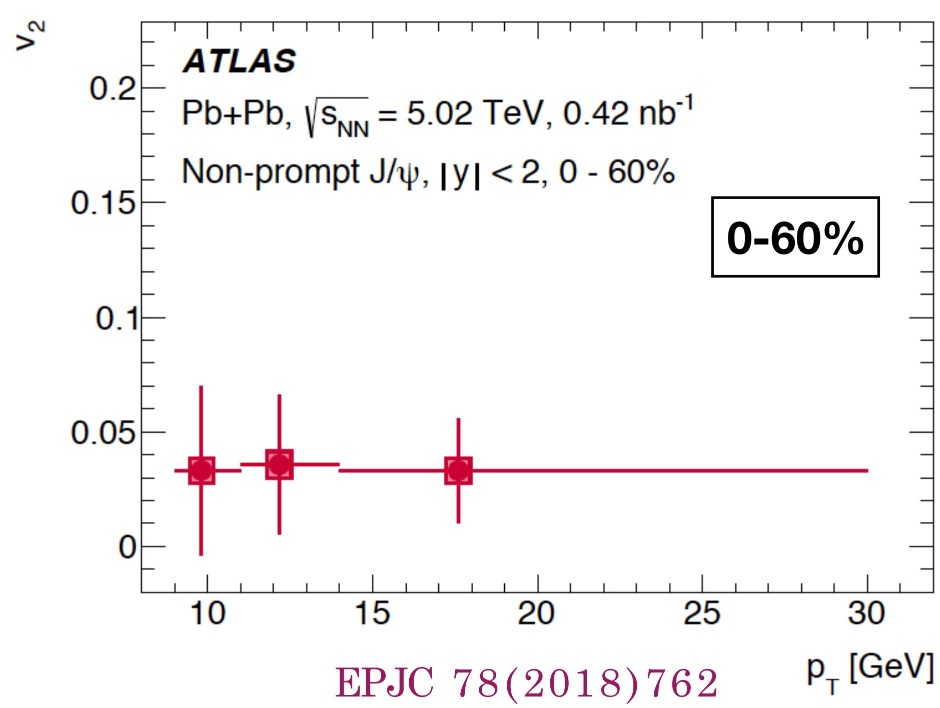


LHC:
- v_2 of B->J/Ψ measured:
  - ❖ Measurement consistent with zero with large uncertainties.
  - ❖ No strong centrality dependence for p_T > 9 GeV/c

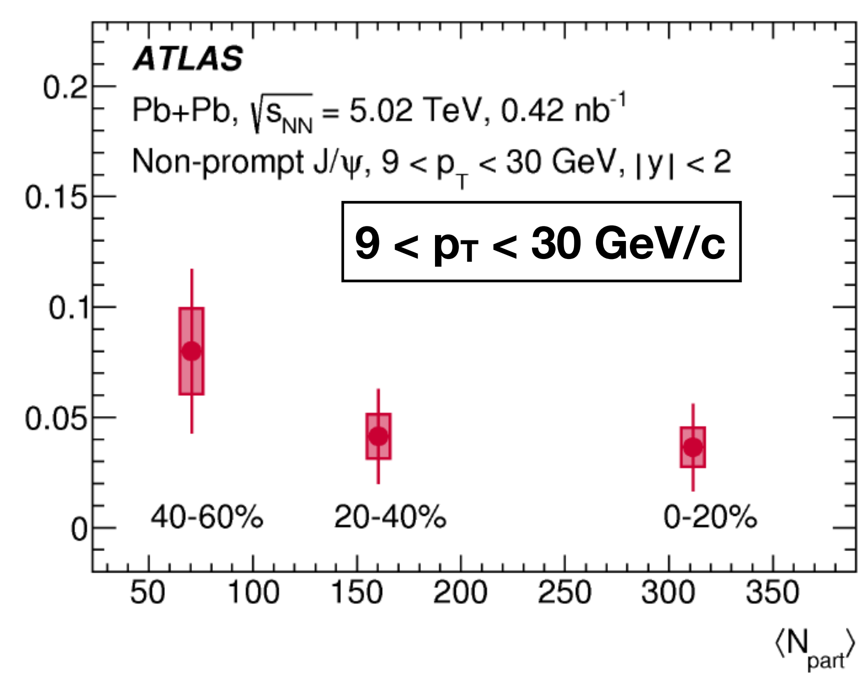
Promising measurements with higher statistics



EPJC 77(2017)252



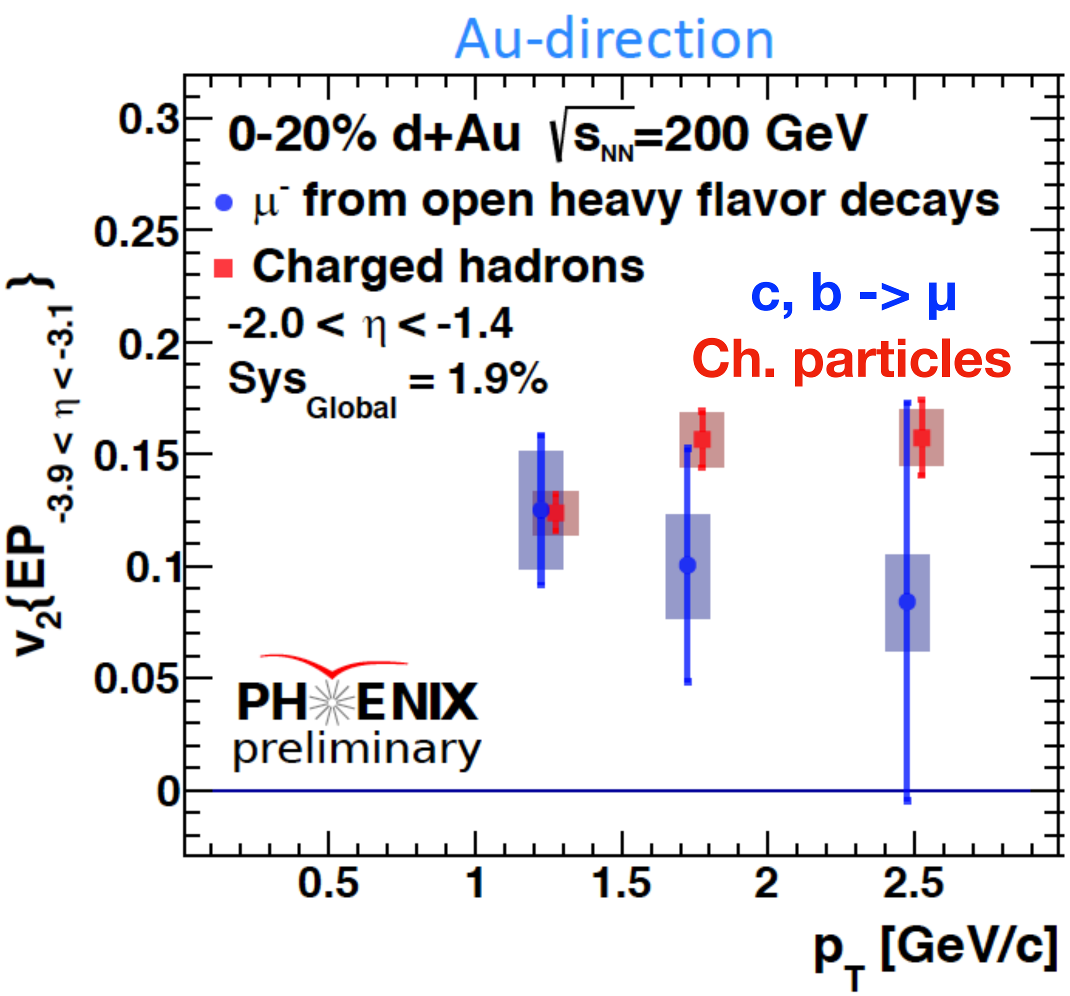
EPJC 78(2018)762



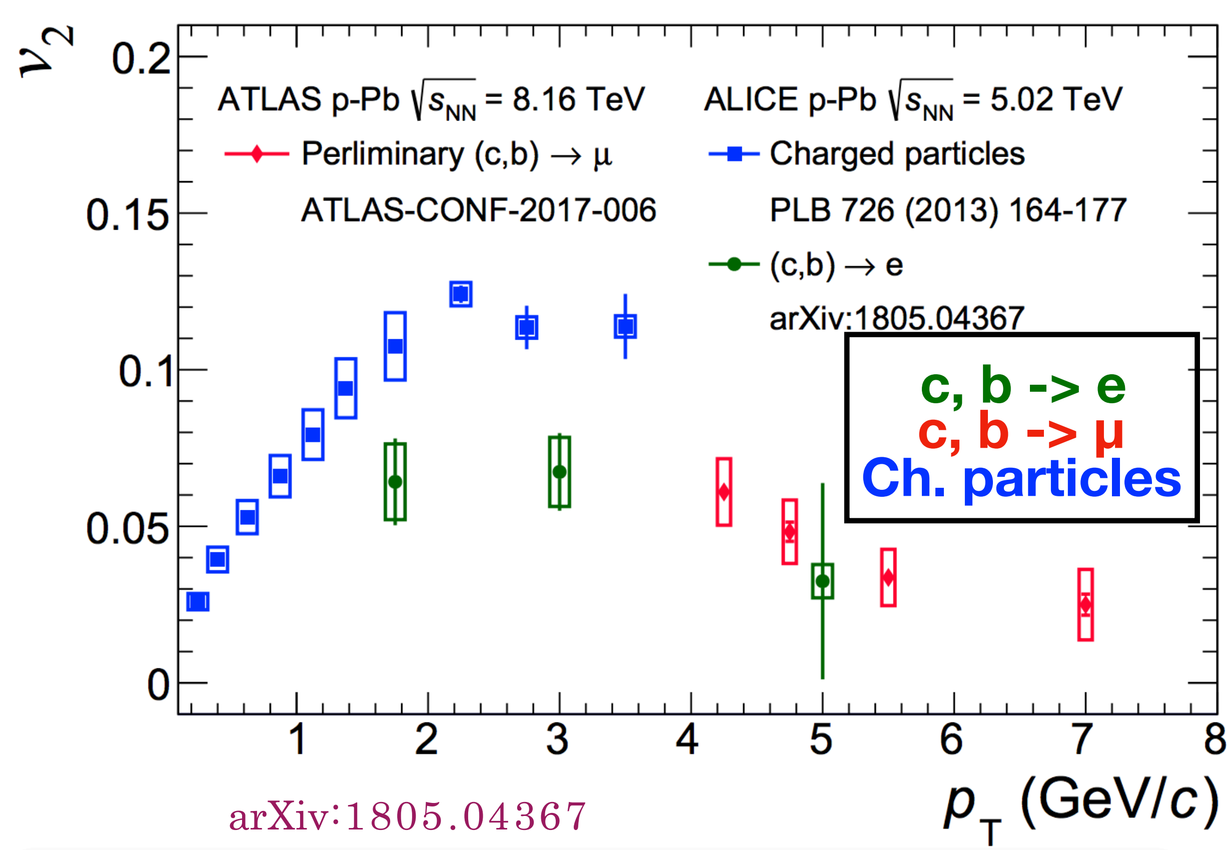
Azimuthal anisotropy in small systems

Azimuthal anisotropy, v_2, of heavy-flavour particles measured in high multiplicity events in small systems both at RHIC (d-Au) and at LHC (pp, p-Pb)

0-20% d-Au collisions

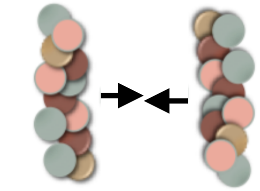


0-20% p-Pb collisions



- **Non-zero v_2 measured for c,b -> leptons.**
- HF leptons have v_2 lower than charged particles.

Heavy-flavour hadronization

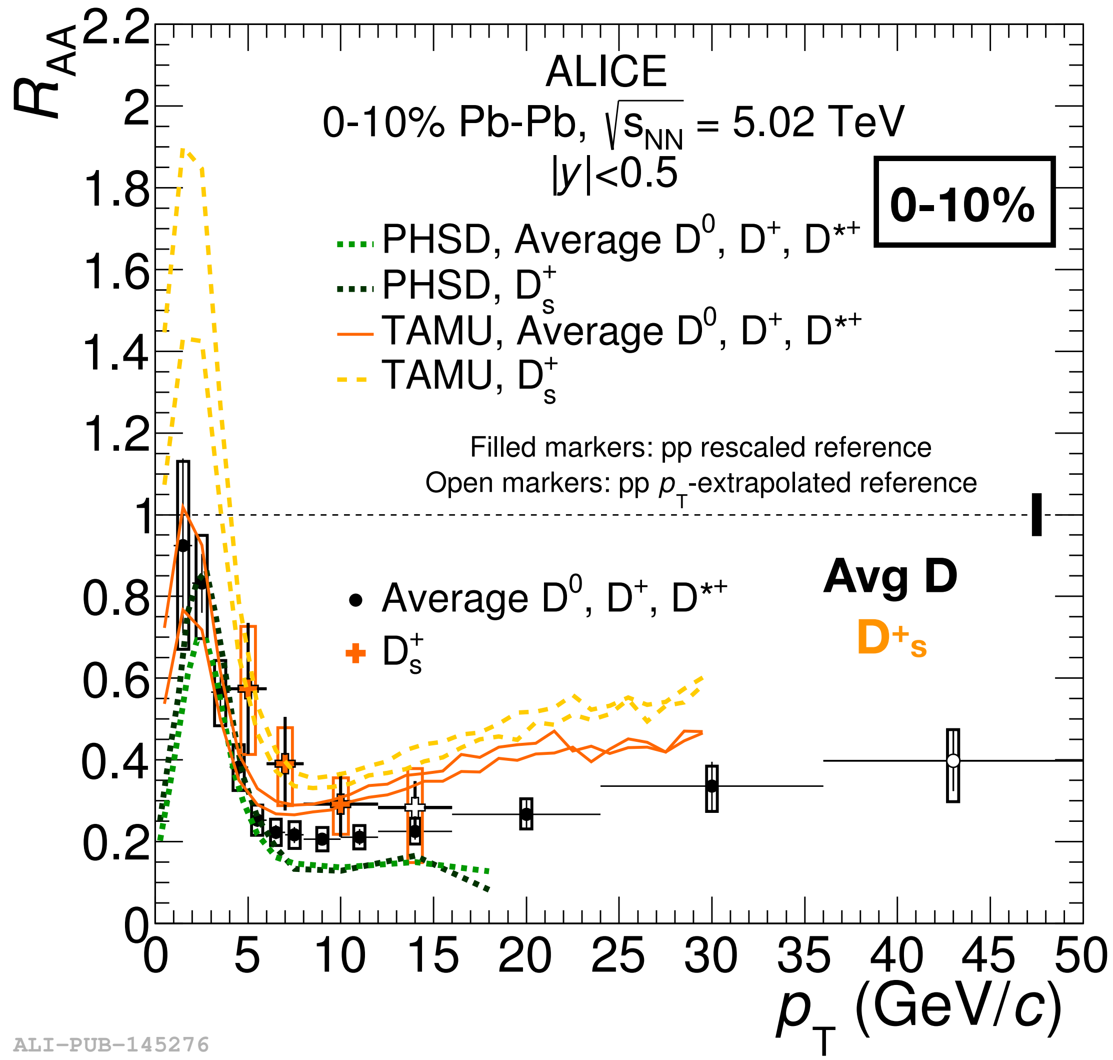


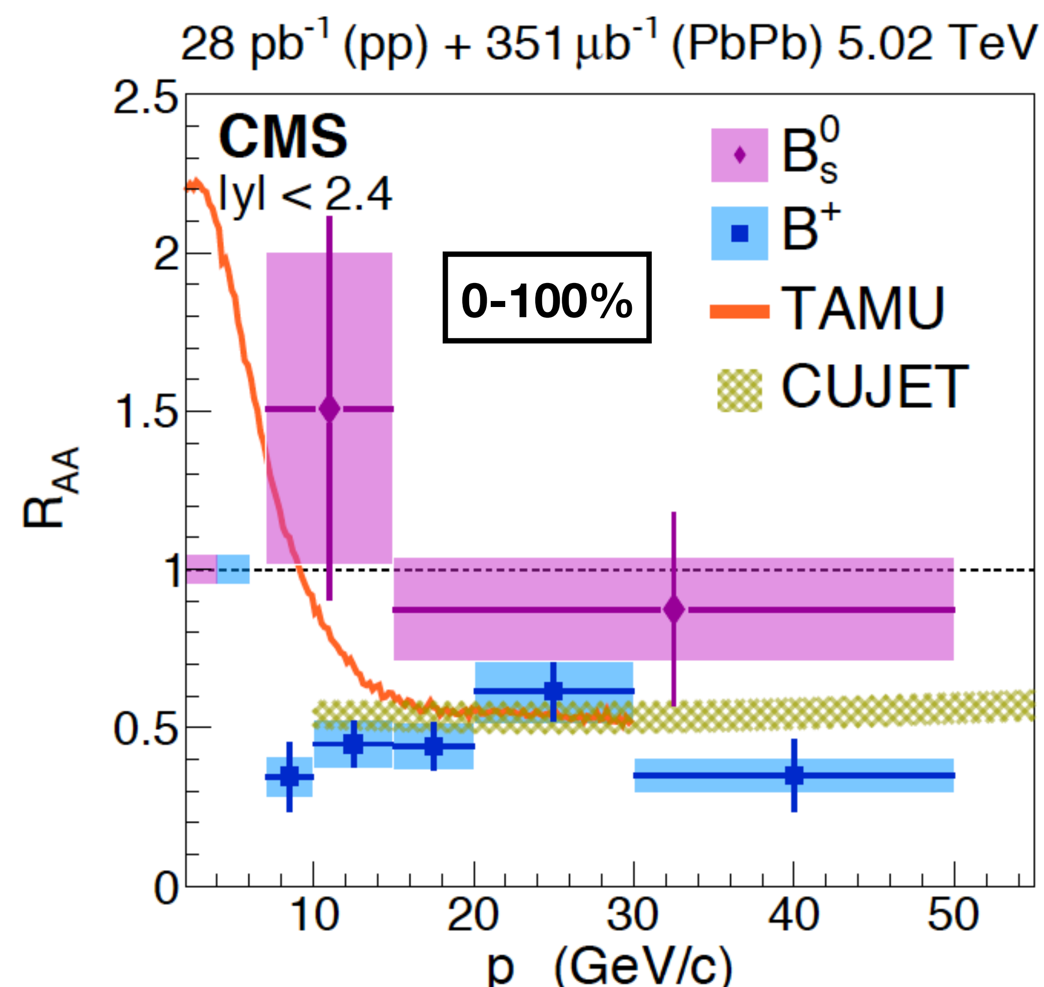
Precise D^{+}_{s}/D measurement to constraint models

Further insight on the pT dependence of coalescence could be obtained with B mesons

- R_{AA} of B^{0}_{s} > B^{+} ?

Promising measurement with higher statistics

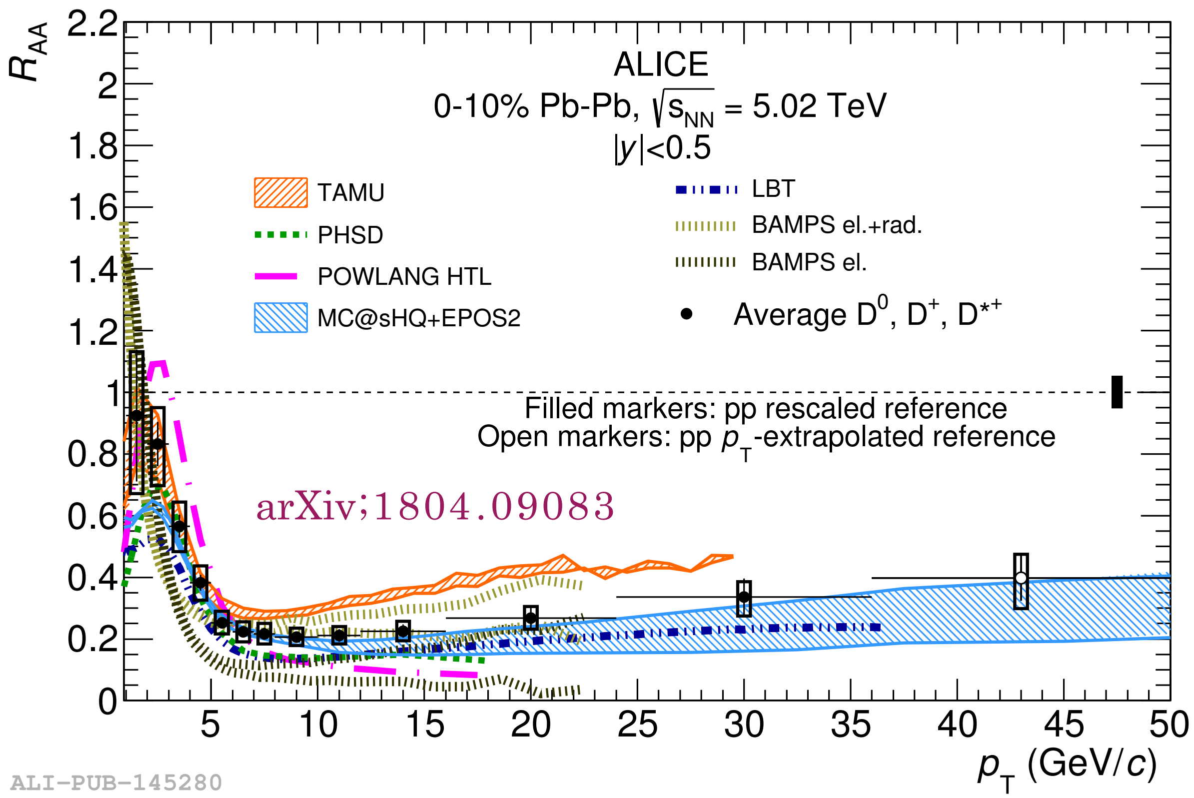


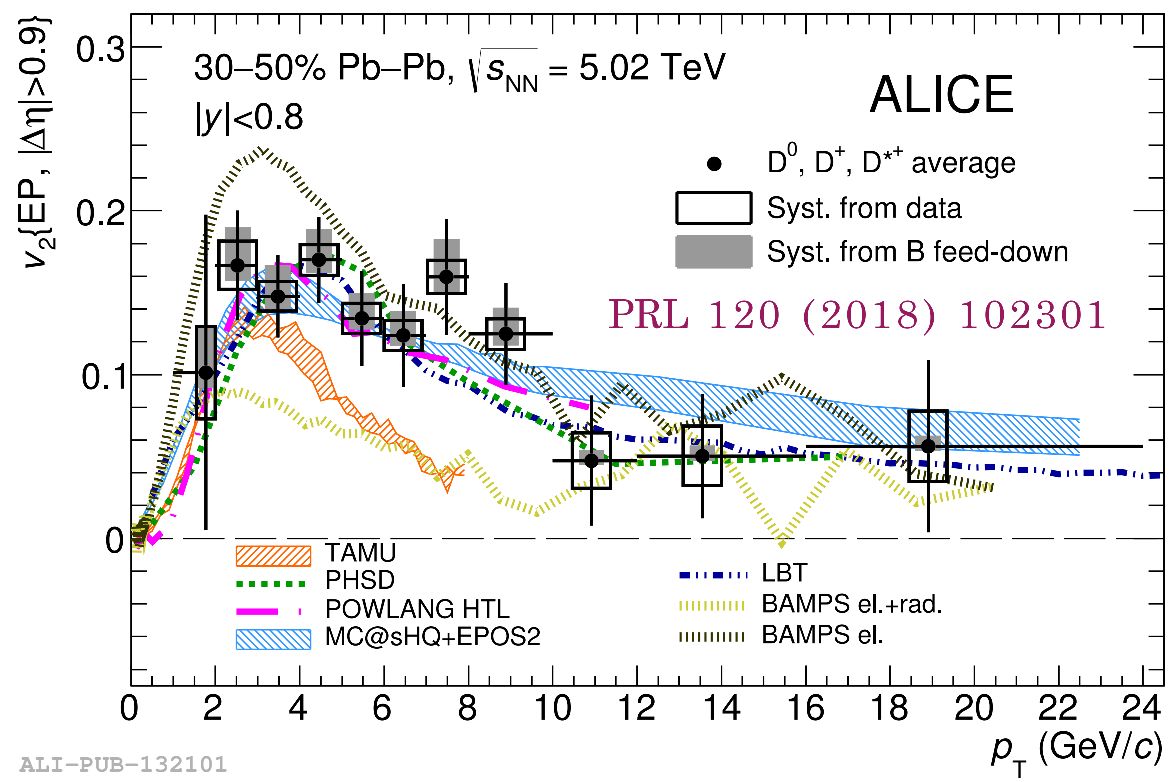


What do we know?

Comparison with models

- Initial heavy-quark production and its modification in nuclei
- Medium and its expansion
- Various quark-medium interaction mechanisms
- Hadronisation processes





- Qualitative description of data by
  - Models that include hydrodynamic expansion of QGP with collisional and radiative energy loss.
  - Models that include hadronisation via quark recombination in addition to independent fragmentation.
- **Models provide fair description of data in some p_T regions**

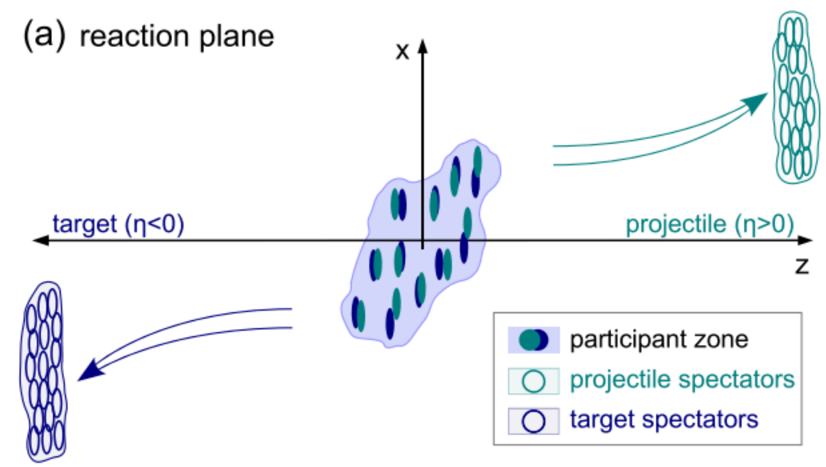
—> challenging to provide simultaneous description in the full p_T range

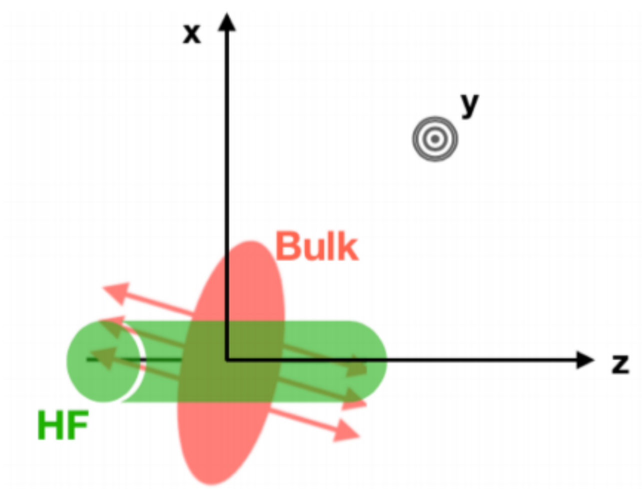
Directed flow (v_1)

- The initial tilt on the produced medium -> expected to give a **charge independent v_1**.
    - ❖ Heavy quarks produced early, symmetric in rapidity —> expected to experience the tilt more than light quarks.

$v_1(y)^{HQ} > v_1(y)^{LQ}$?

- Strong magnetic field produced by charged spectator nucleons in non-central A-A collisions.





PRL 112(2014)252301

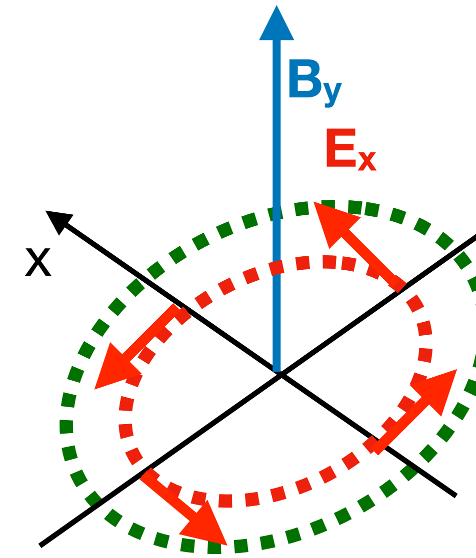
Directed flow (v_1)

- The initial tilt on the produced medium -> expected to give a **charge independent v_1**.
  - Heavy quarks produced early, symmetric in rapidity —> expected to experience the tilt more than light quarks.

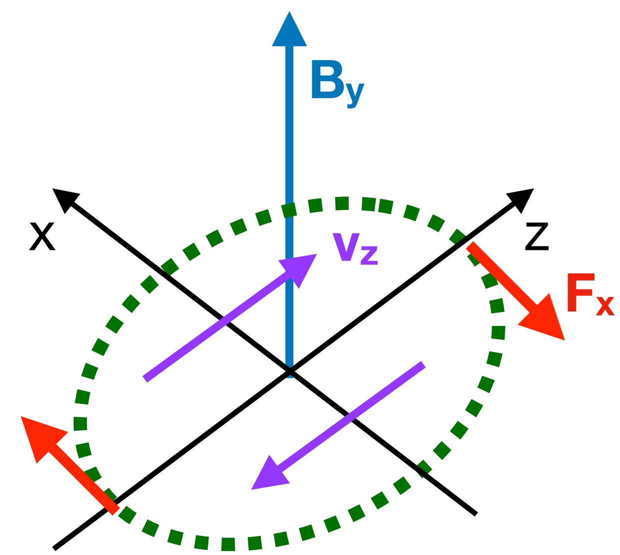
    $v_1(y)^{HQ} > v_1(y)^{LQ}$?
- Strong magnetic field produced by charged spectator nucleons in non-central A-A collisions.
- As spectators fly away -> B decreases in time.
  - **Faraday's law**: creates electric current in the medium.
- Expanding medium with longitudinal velocity ***v*** parallel to beam direction
  - **Hall effect**: Lorentz force on the moving charges.
- **Net current -> from Faraday + Hall effect**
  - Results in **charge dependent directed v_1**.
- Heavy quarks dynamics could be affected by the magnetic field and could retain these effects.
  - Good probe to study the early time EM fields.

$v_1(D) - v_1(\overline{D})$?

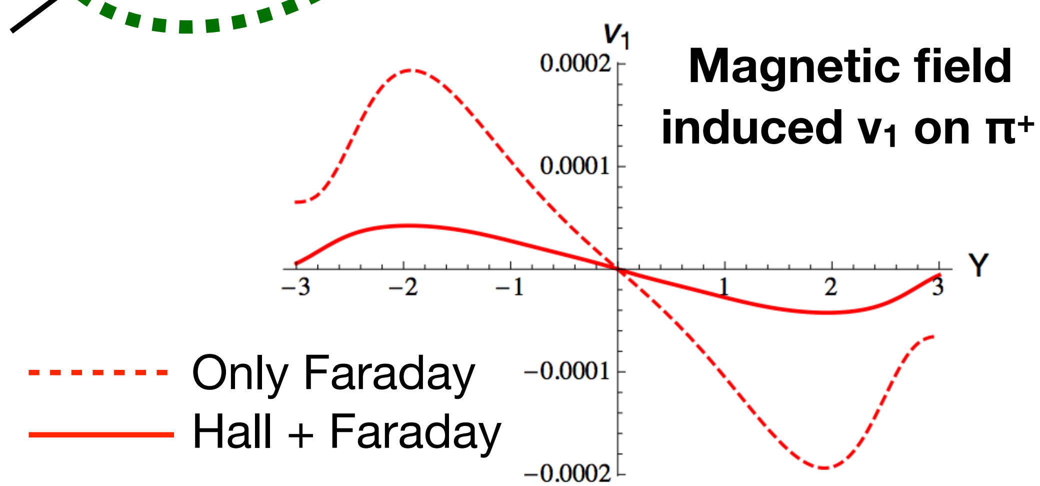
arXiv:1608.02231
PRL 120 (2018) 192301



$$\Delta \times E = -\delta B/\delta t$$



$$F = q\, v \times B$$



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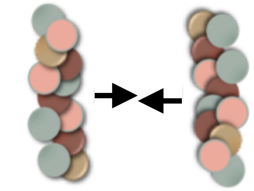
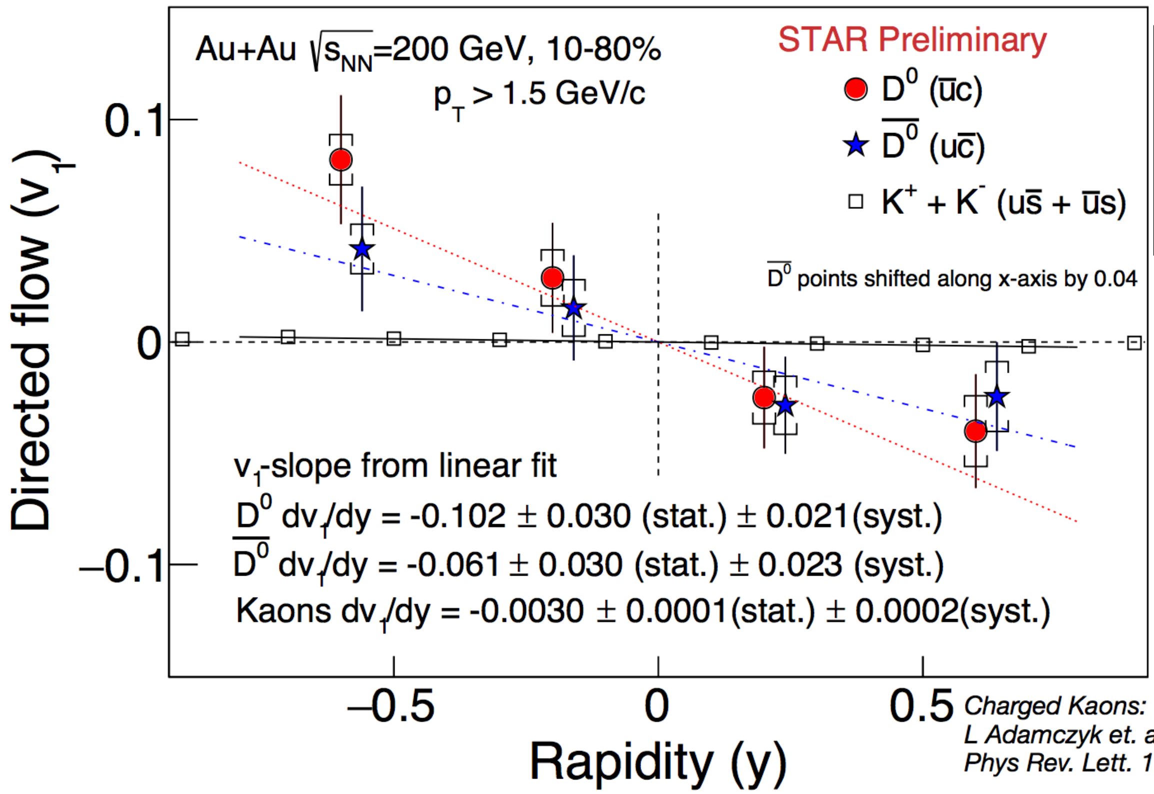
Directed flow (v_1), RHIC



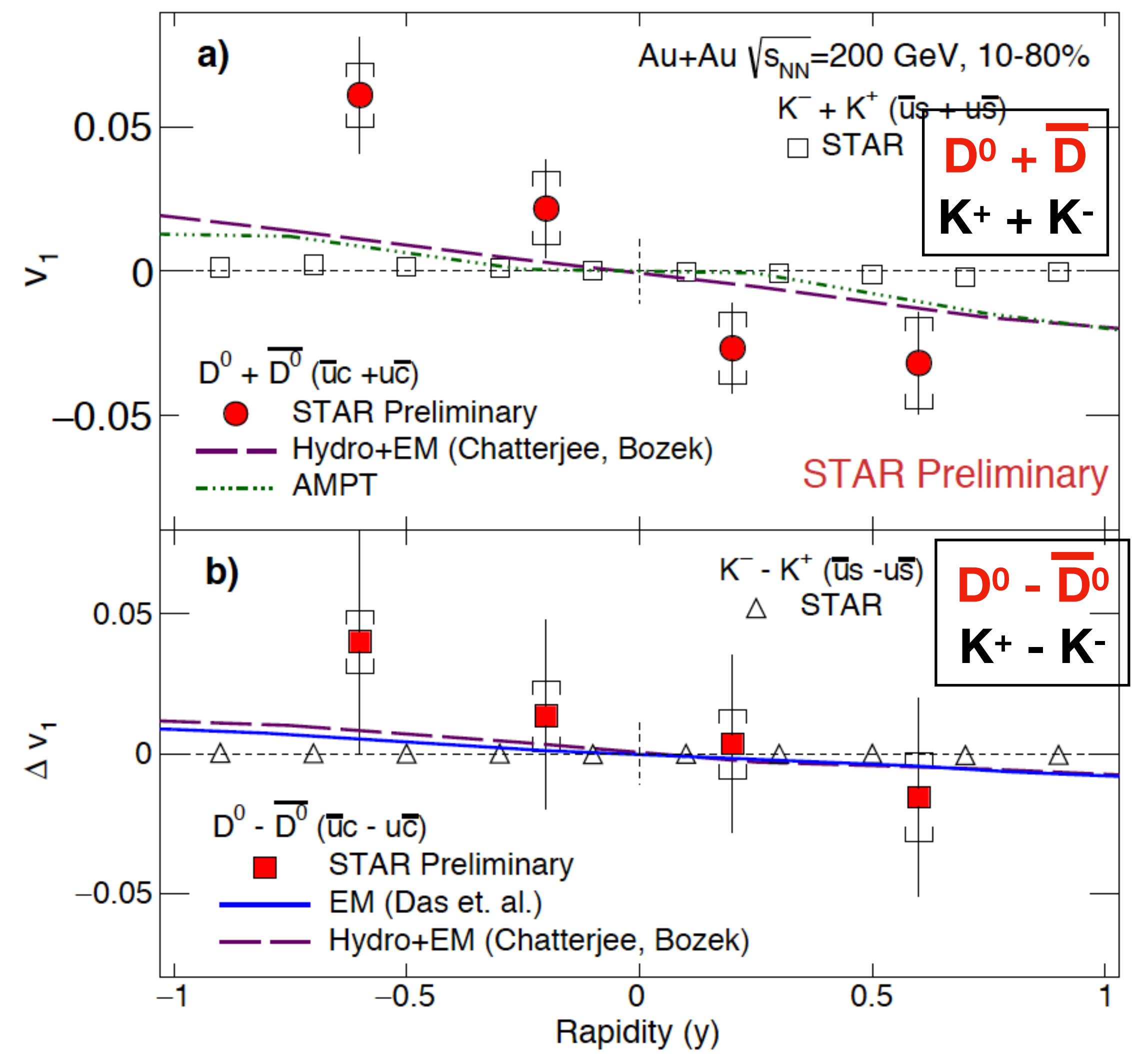


Charged Kaons: L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 120, 62301 (2018)

$K^+ + K^-$
D^0
$\overline{D^0}$

p_T^{D0} > 1.5 GeV/c

- v_1-odd measured for D^0 and $\overline{D^0}$ —> **non zero value.**
- $v_1(D^0)$ and $v_1(\overline{D^0})$ show negative slope at mid-rapidity.
- **Slope of $v_1(D^0)$ > $v_1(K)$**



- Comparing **$v_1(D^0)$ + $v_1(\overline{D^0})$** and **$v_1(D^0)$ - $v_1(\overline{D^0})$** with models with Hydro+EM
  - ❖ Qualitative agreement with model -> gives same sign of the slope
  - ❖ Low precision in data to confirm EM field induced charge-dependent v_1.

Directed flow (v_1), LHC

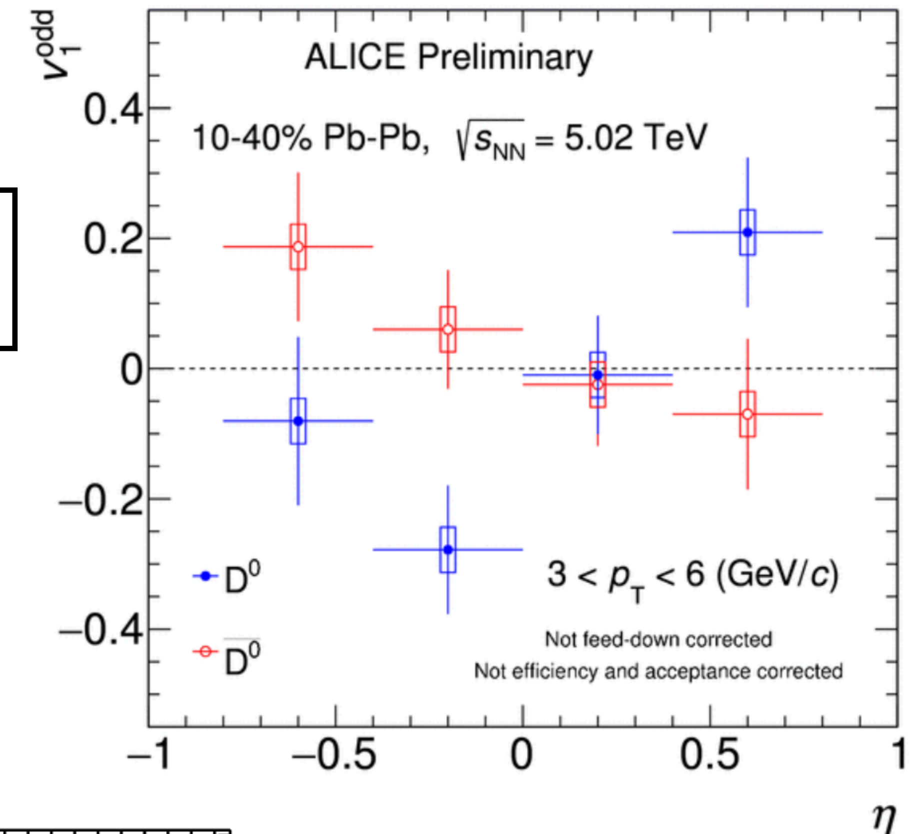
$3 < p_T^{D0} < 6$ GeV/c

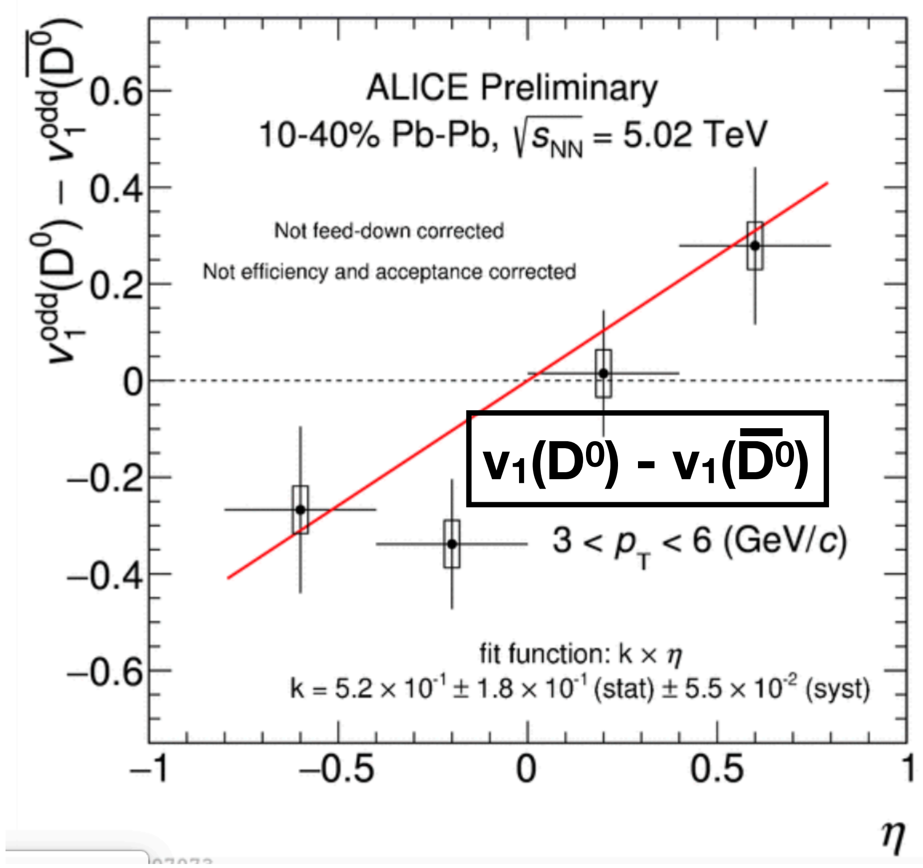
- v_1-odd measured for D^0 and $\overline{D^0}$ —> opposite trend vs η for D^0 and $\overline{D^0}$, but with large uncertainty.
- **$v_1(D^0)$ - $v_1(\overline{D^0})$**
  - ❖ Non-zero value observed.
  - ❖ Three orders of magnitude higher than $v_1(h^+)$ - $v_1(h^-)$.

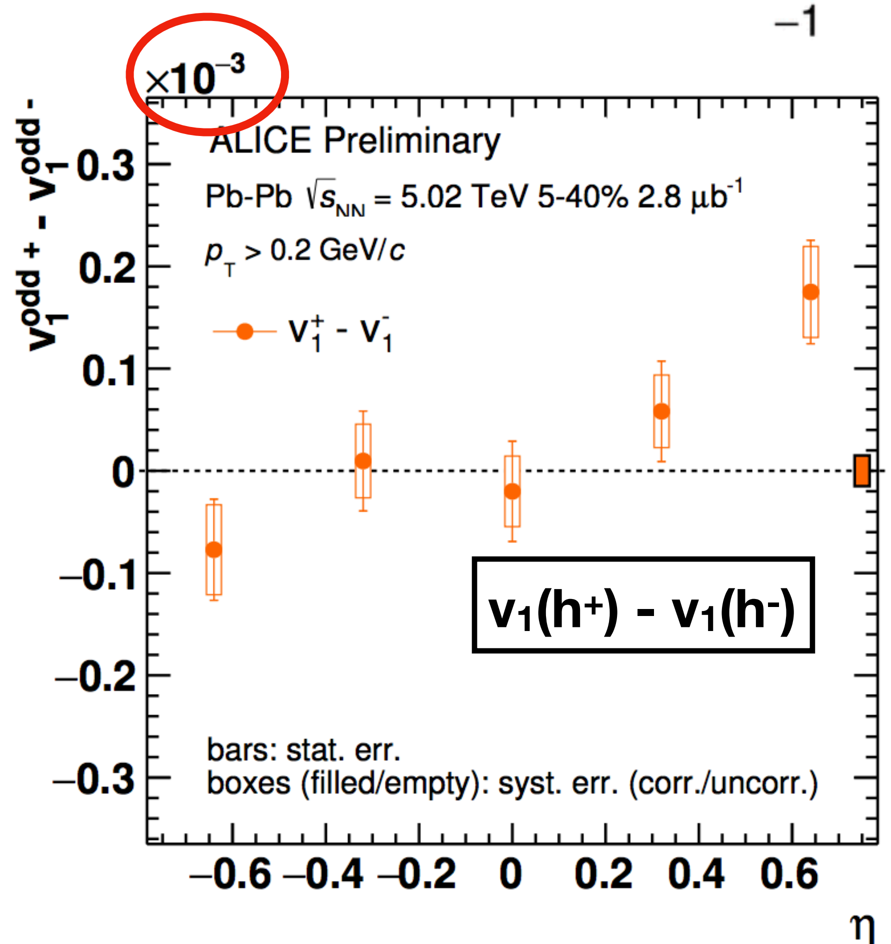
$v_1(D^0)$ - $v_1(\overline{D^0})$ at RHIC and LHC shows opposite slope

-> model comparison required.

$\overline{D^0}$
D^0







Directed flow (v_1), Charged particles