Heavy-flavor hadron production in heavy-ion collisions

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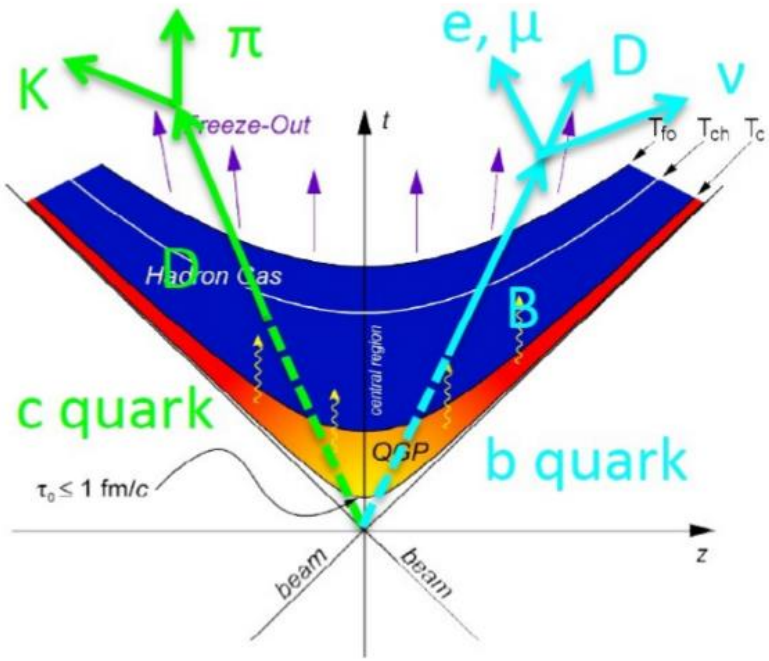
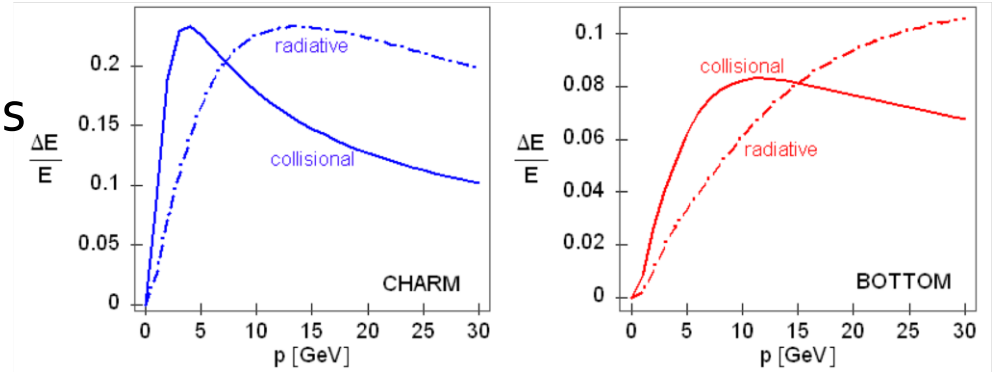
Heavy quarks in heavy-ion collisions

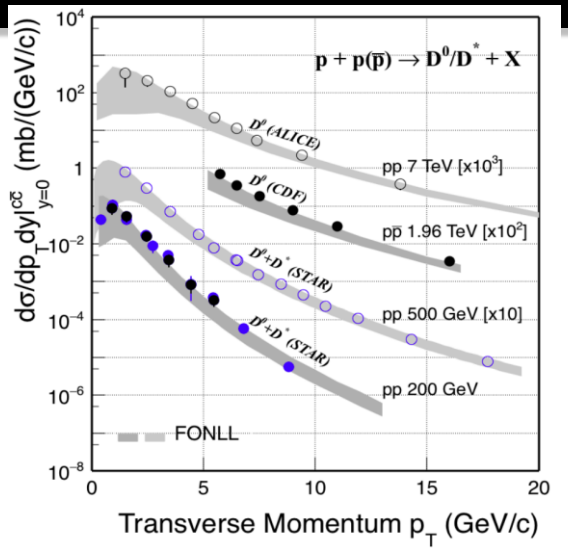
- Heavy quarks: m c/b >> Λ_{QCD}
  - Produced early through hard scatterings
  - Allow first principle QCD calculations
  - Experience the whole evolution of the system
- Interact with the medium differently from light quarks.
  - Good probe of medium properties, transport parameters
  - Collisional vs radiative energy loss.
  - Expected mass hierarchy of energy loss: $\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$
- Sensitive to hadronization process in the QGP
  - Fragmentation vs coalescence

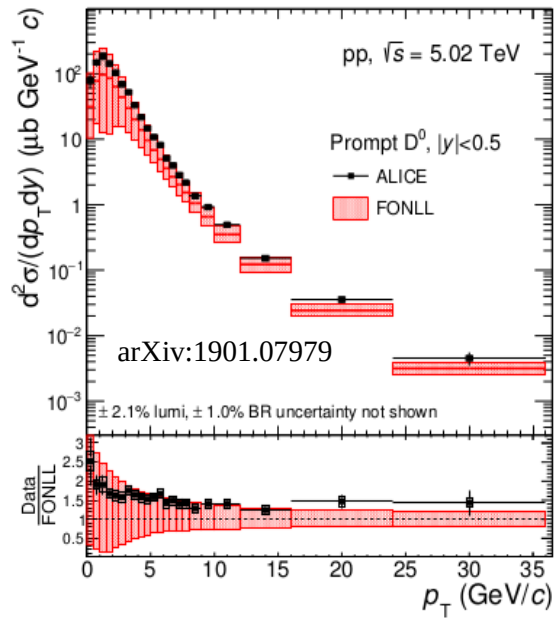


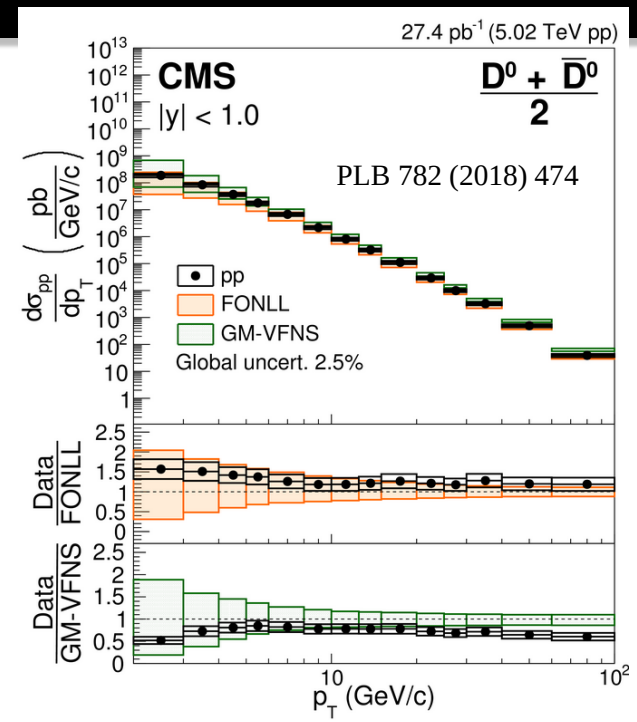


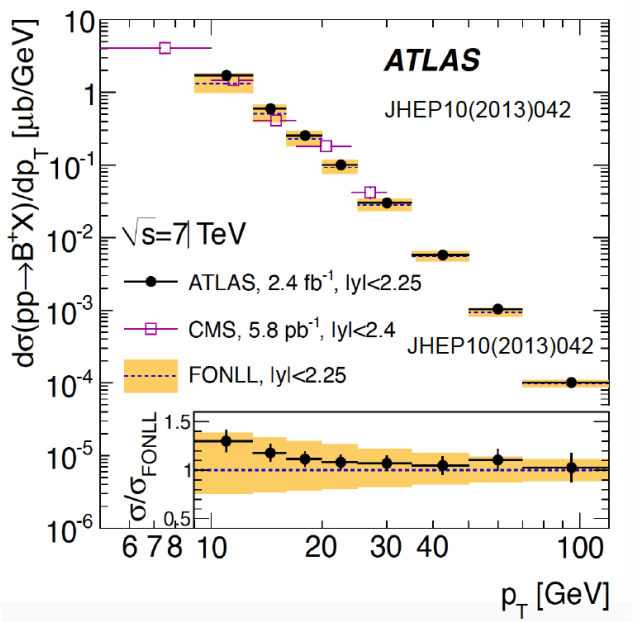
M. Djordjevic, PRC74 (2006) 064907

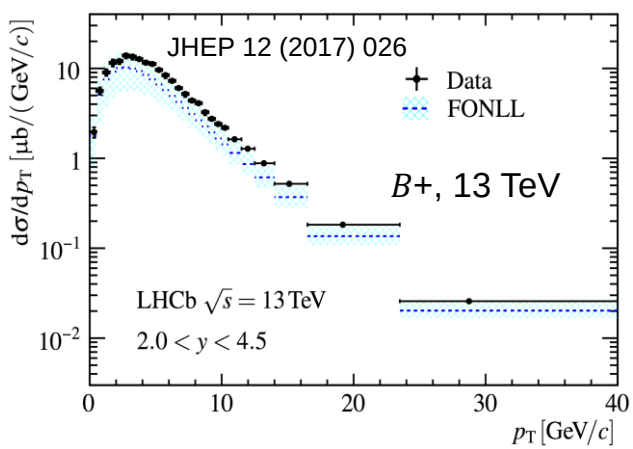
Heavy flavor in p+p

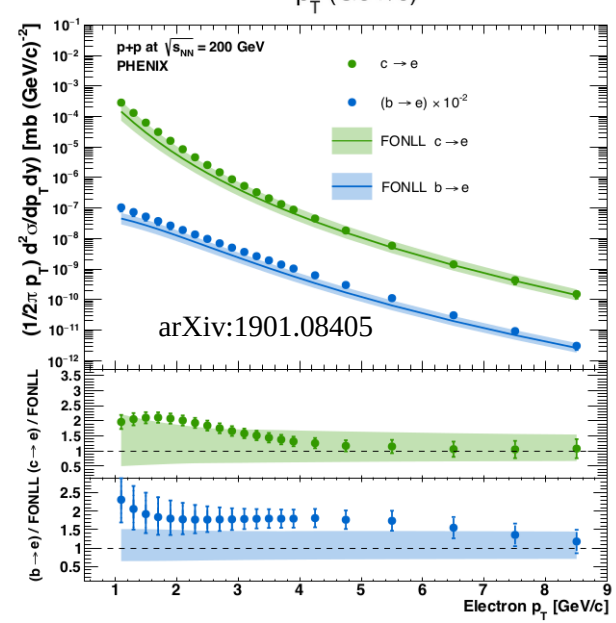












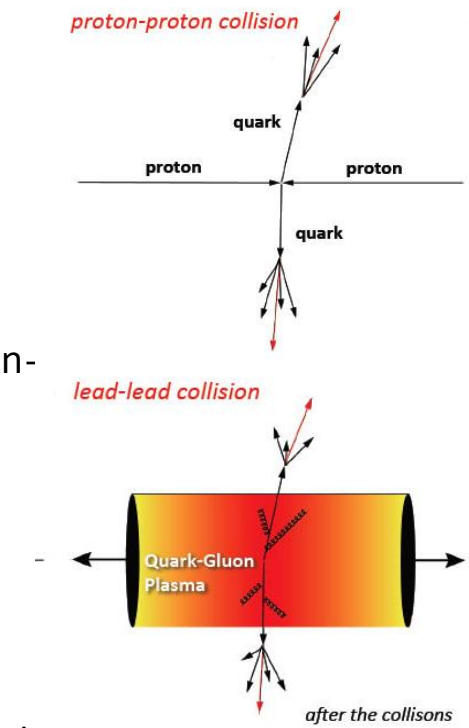
- Precision measurements, described by FONLL/NRQCD calculations
  - Larger uncertainties on the theory side

Common experimental observables

- Nuclear modification factor

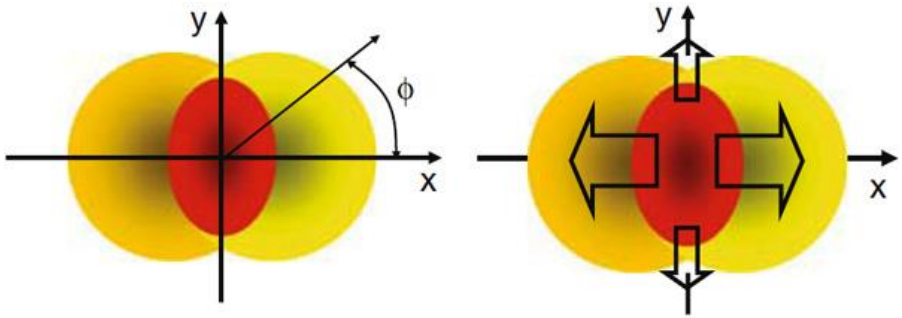
$$R_{AA}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2\sigma_{pp}/dp_T dy} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}} \begin{cases} R_{AA} > 1 \text{ (enhancement)} \\ R_{AA} = 1 \text{ (no medium effect)} \\ R_{AA} < 1 \text{ (suppression)} \end{cases}$$

  - Hard probes production expected to scale with number of binary nucleon-nucleon collision
  - Modified production due to presence of nuclear matter (hot or cold)



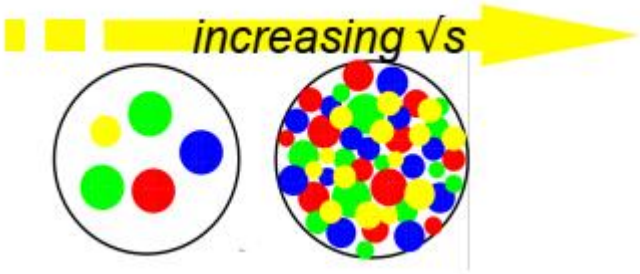
- Azimuthal anisotropy: v_n
  - Initial special asymmetry + interactions (pressure) =>final momentum anisotropy
  - Probe of thermalization and collectivity at low p_T
  - Path-length dependence of energy loss at high p_T

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

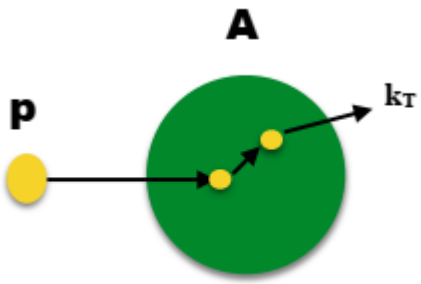


HF in small systems: p(d)-A

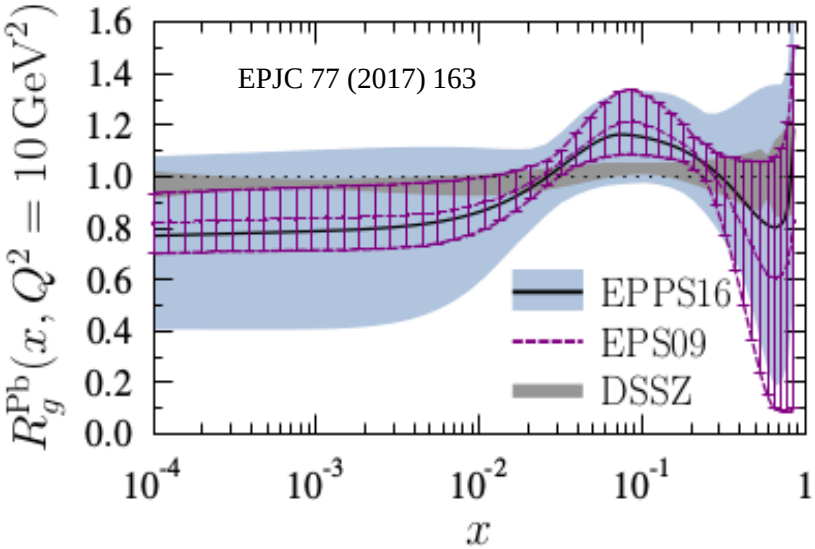
Probe "calibration" for A-A collisions



- Cold nuclear matter effects on heavy fla production
  - Initial state:
    Modification of nuclear PDF
    gluon saturation,
    Multiple scattering, initial parton energy loss
  - Final state effects
    Comover interactions



- Onset of collective behavior?
  - QGP?
  - Elliptic flow
  - Hadronization of heavy-flavors



D meson production in p-Pb

mid-rapidity

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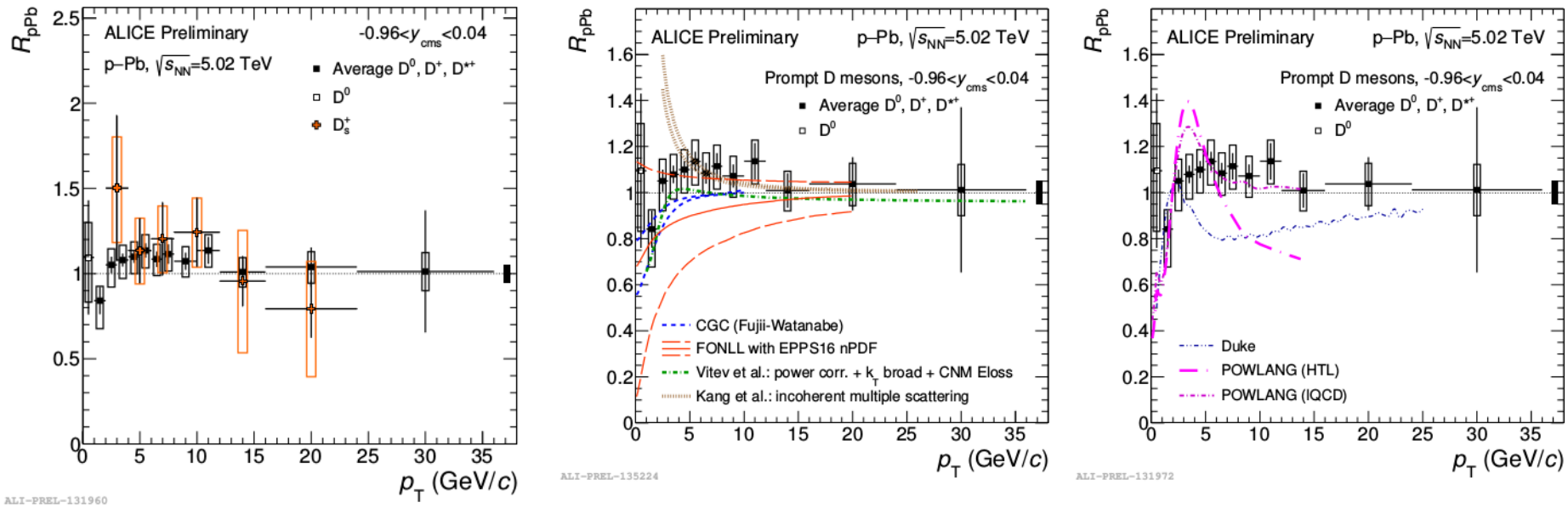


- At mid-rapidity
  - R_{pA}=1 at high-p_T within uncertainties
  - Described by modes including cold nuclear-matter effects
  - Transport models with QGP are disfavored

D meson production in p-A

Rapidity and p_T dependence - accessing CNM effects

Backward rapidity:

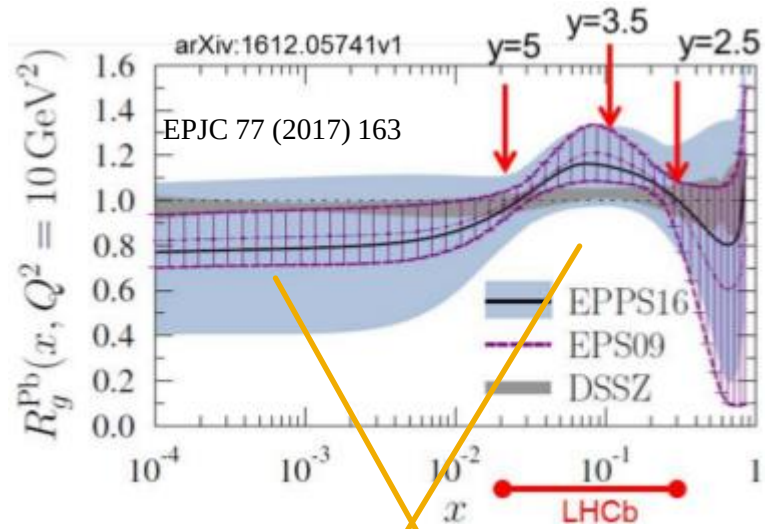
- R_{pPb} consistent with unity

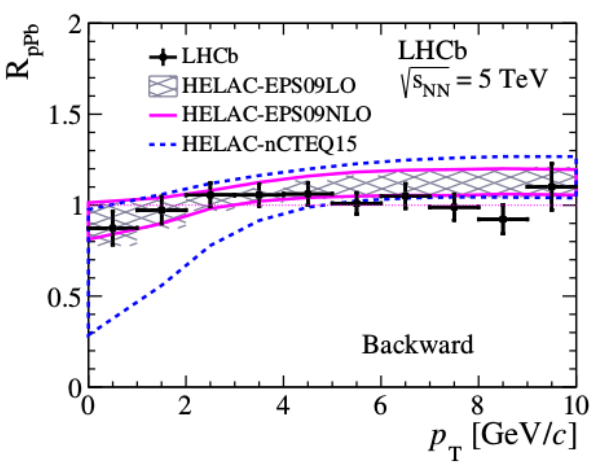
Forward rapidity:

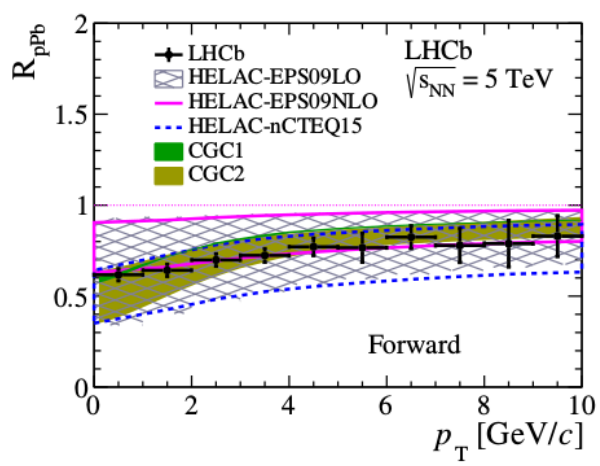
- R_{pPb}<1, exploring shadowing region
- Precise measurements - additional constrain on gluon nPDF at low-x

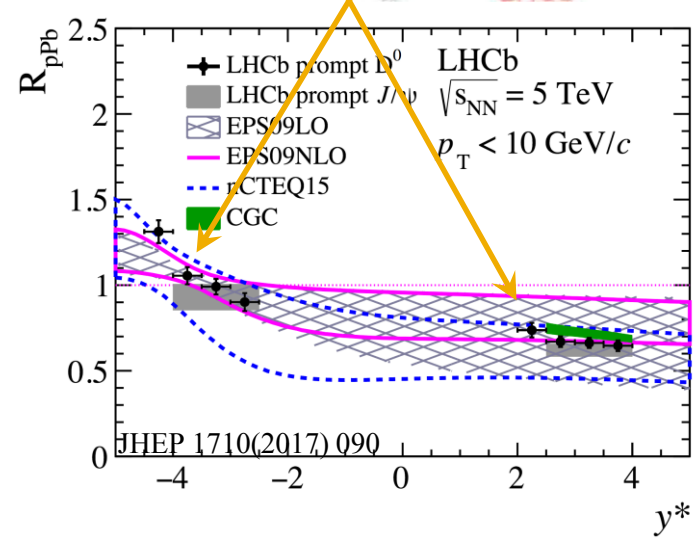
Important baseline for A-A collisions.

- Data start to constrain the gluon nPDF









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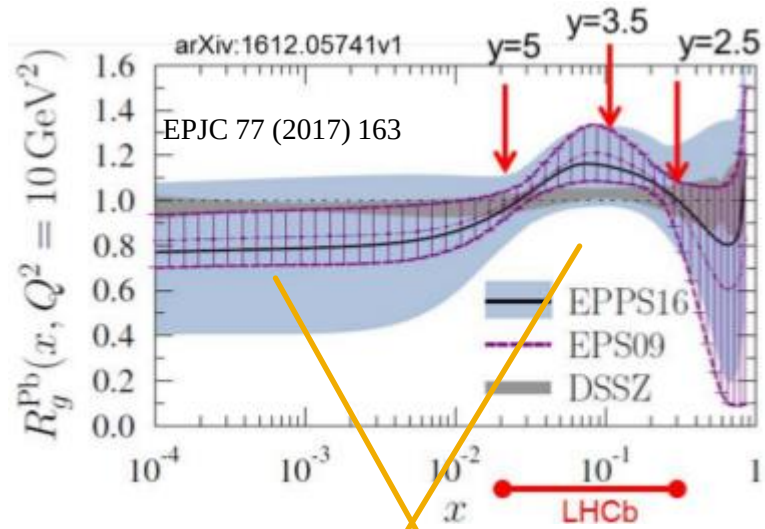

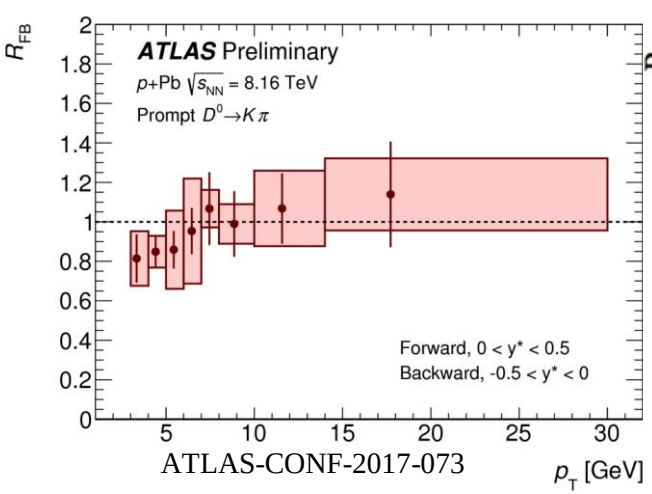

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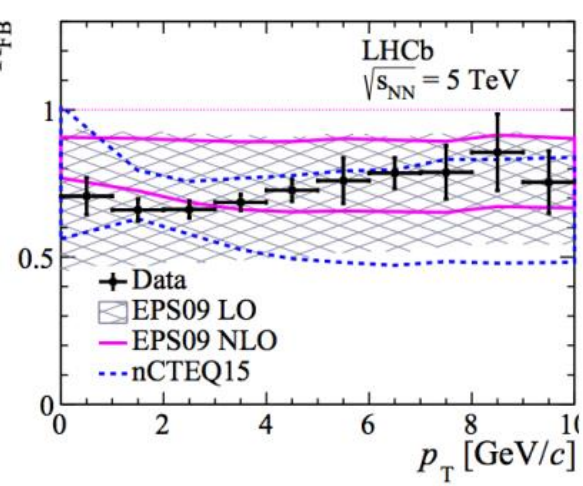
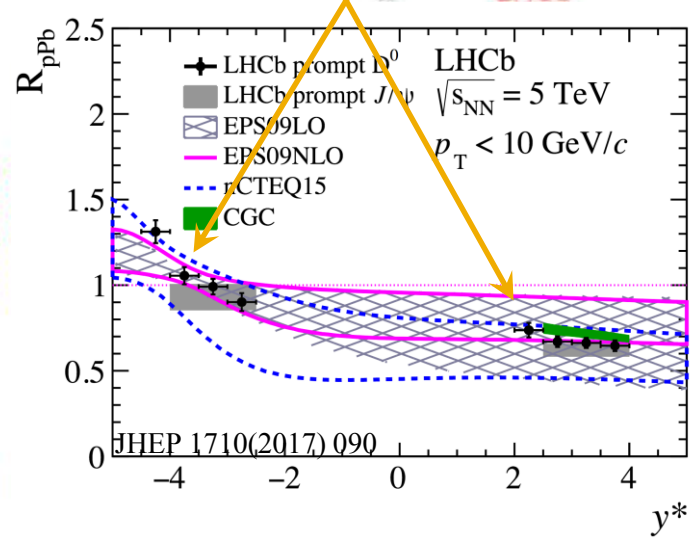
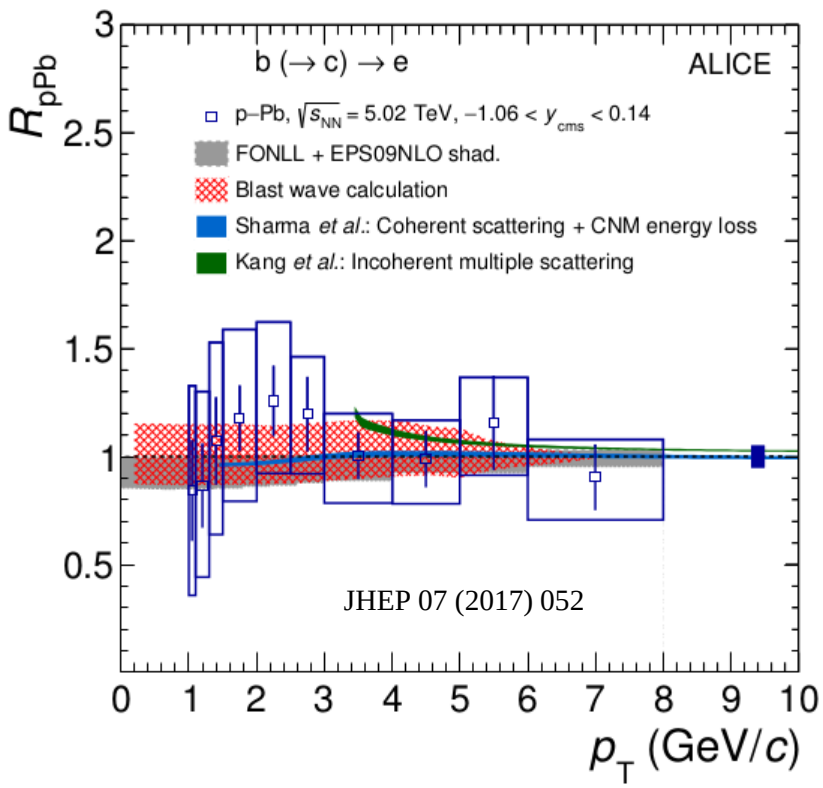
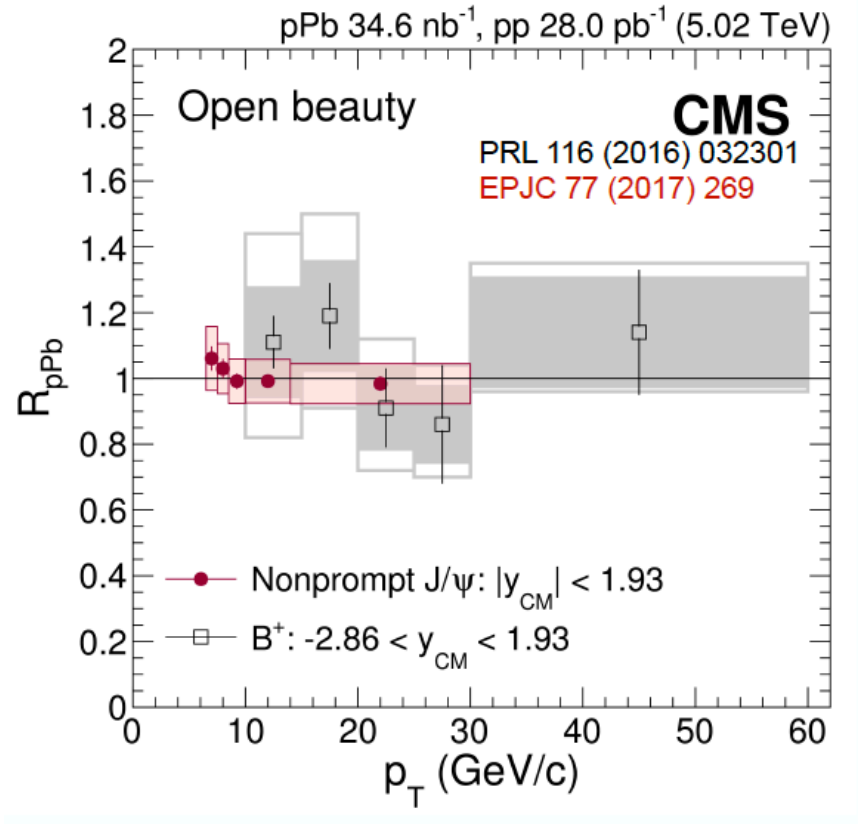




Beauty production in p-Pb





- At mid-rapidity R_{pPb} consistent with unity within the uncertainties
  - no modification of production
  - described by theoretical calculations with CNM effects

Beauty production in p-Pb

Direct reconstruction of B^+, B^0, Λ_b^0 at LHCb

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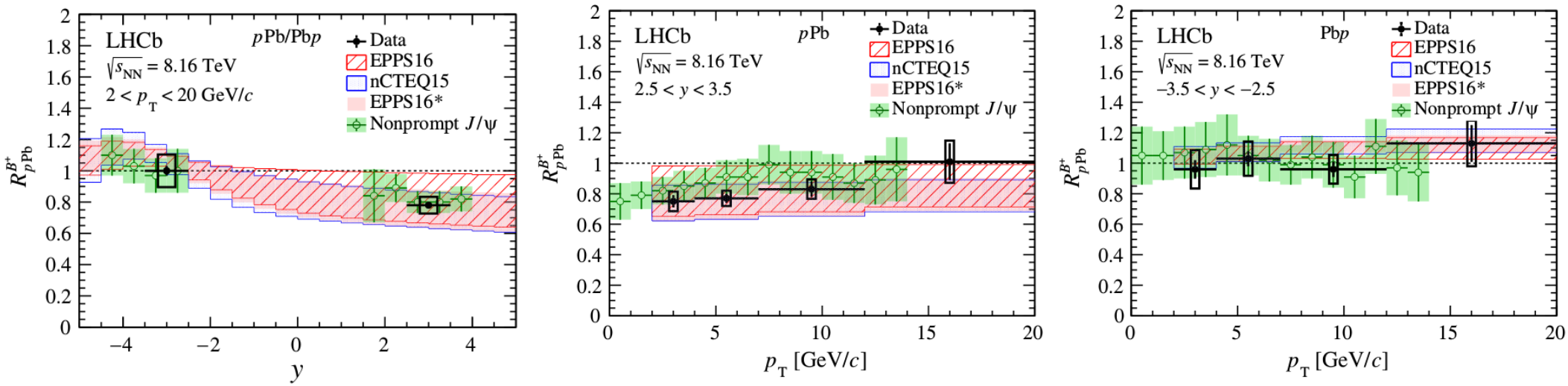
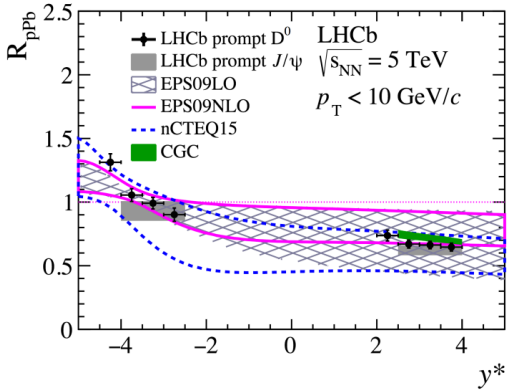
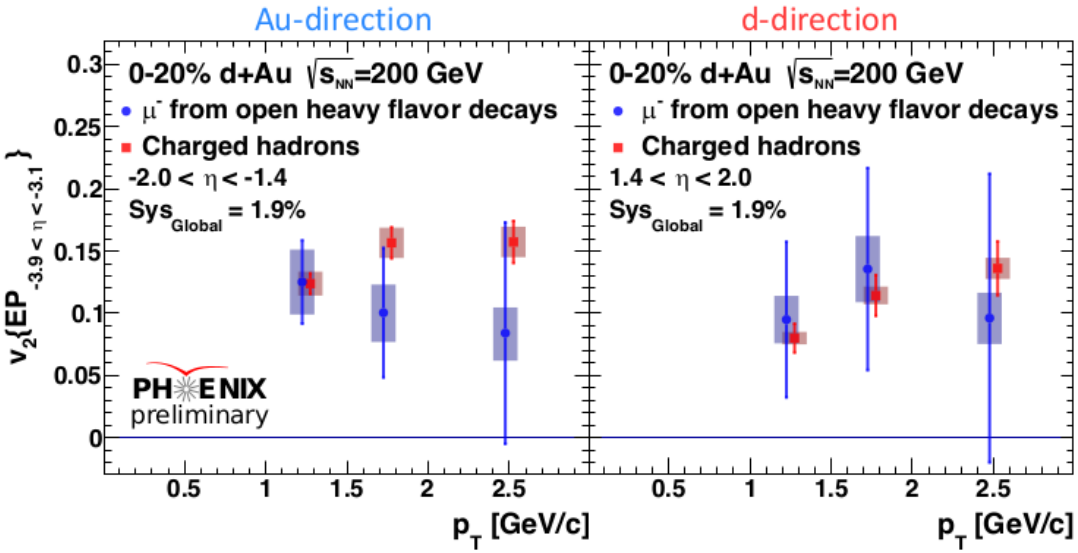


- Backward rapidity RpPb~1
- Significant suppression at forward rapidity at low-p_T ~ 25%
  - Similar trend as for prompt D^0 mesons.
  - Consistent with B->J/Ψ results and calculations using nPDF.



Collectivity in p-A?

0-20% d+Au collisions



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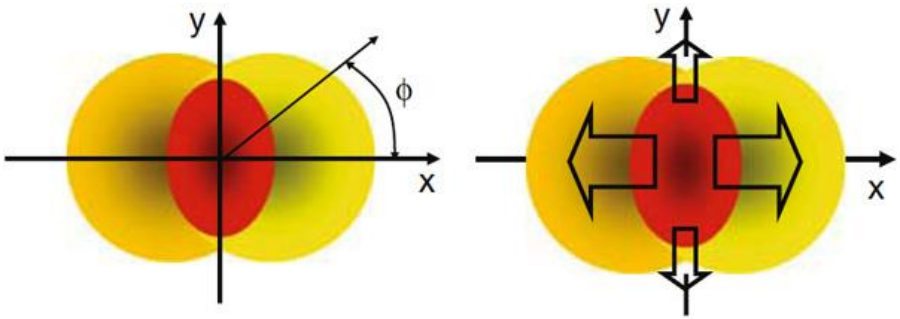
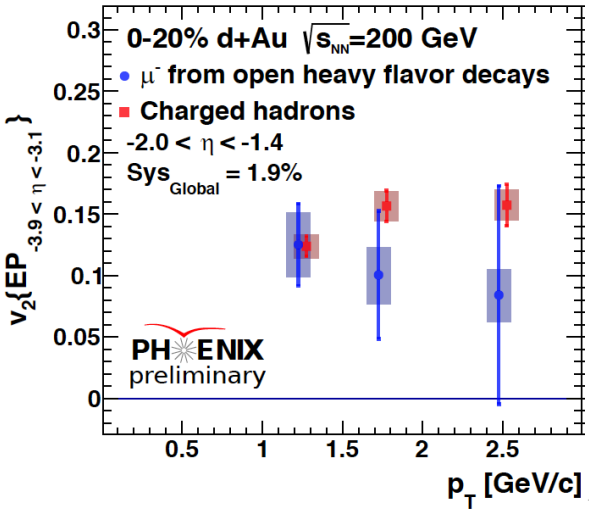


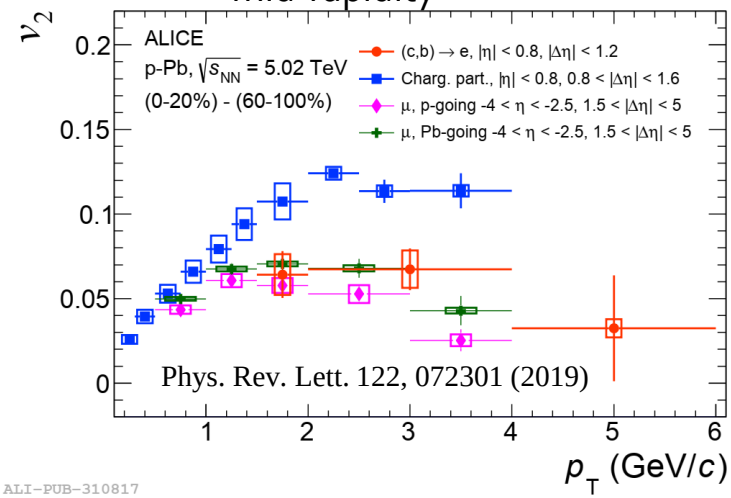
- First measurement of v2(c,b -> μ ±) at RHIC
  - HF flows in central dAu collisions

Collectivity in p-A?

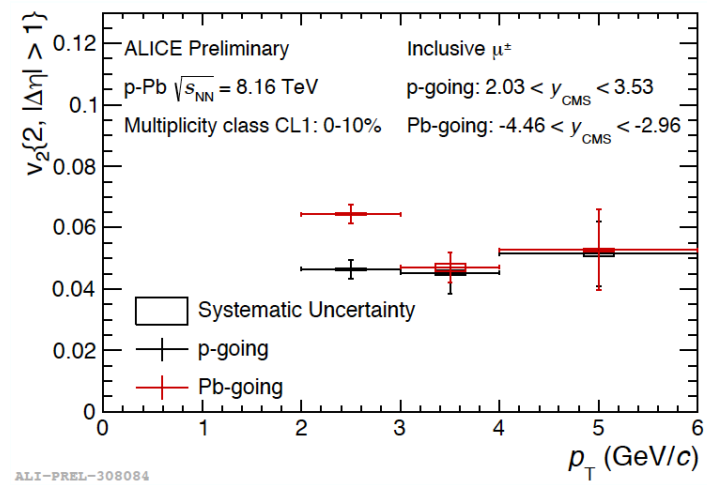
0-20% d+Au collisions
Au-direction



0-20% p+Pb collisions
mid-rapidity



0-10% p+Pb collisions
Forward/backward rapidity



- First measurement of v2(c,b -> μ ±) at RHIC
  - HF flows in central dAu collisions
- Clear signature of HF flow at LHC
  - HF leptons have v2 lower than charged particles

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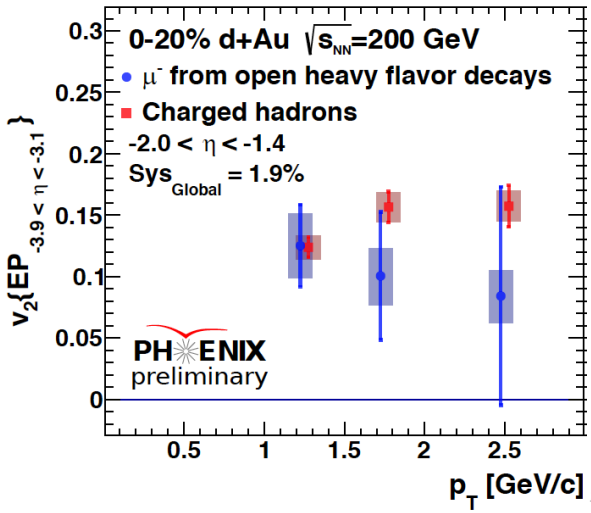

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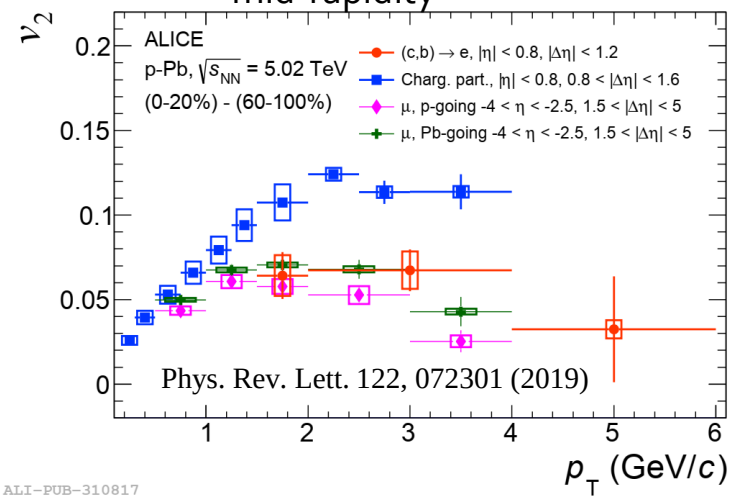

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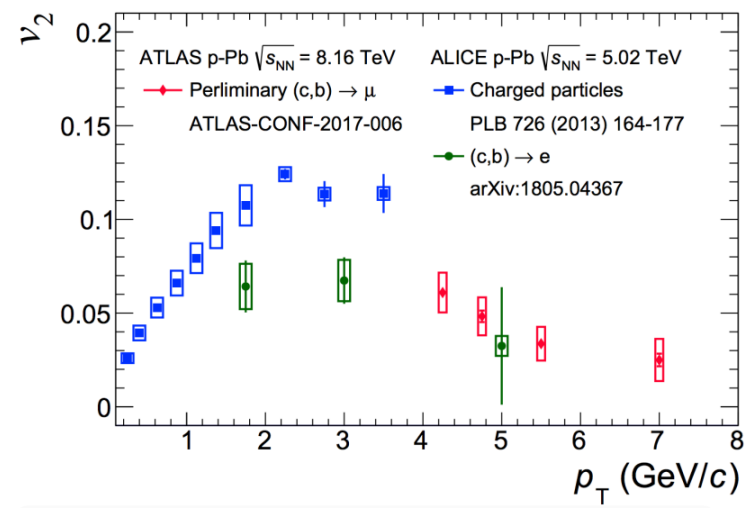
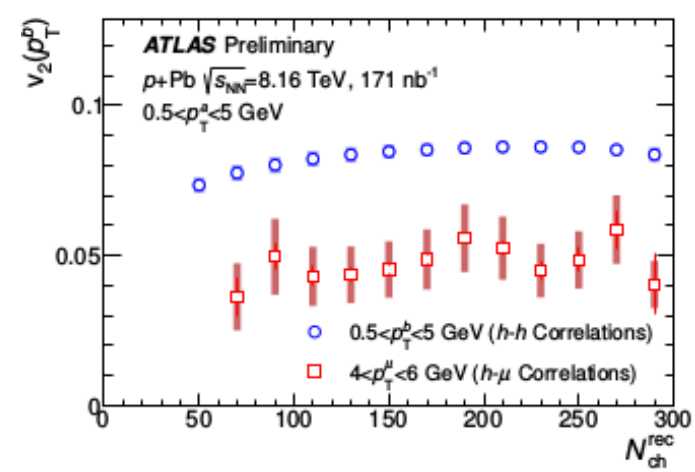


- First measurement of v2(c,b -> μ ±) at RHIC
  - HF flows in central dAu collisions
- Clear signature of HF flow at LHC
  - HF leptons have v2 lower than charged particles
- ATLAS h- μ correlations:
  - no clear multiplicity dependence



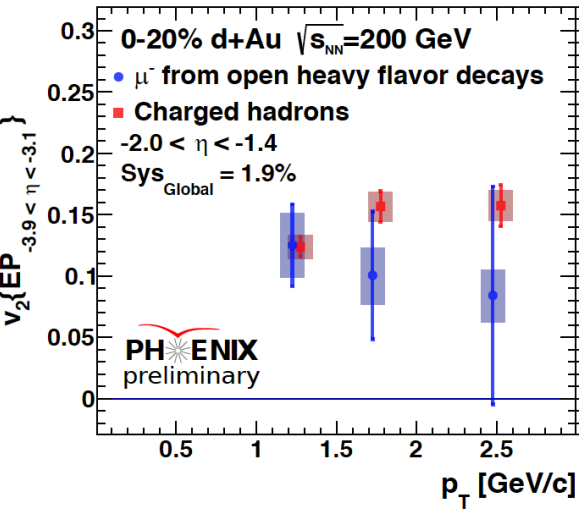
Significant v2 for c,b -> leptons observed in small systems for high multiplicity collisions at RHIC as well as at LHC

Collectivity in p-A?

- **Significant v2 for c,b -> leptons and D mesons** observed in small systems for high multiplicity collisions at RHIC as well as at LHC

0-20% d+Au collisions

Au-direction



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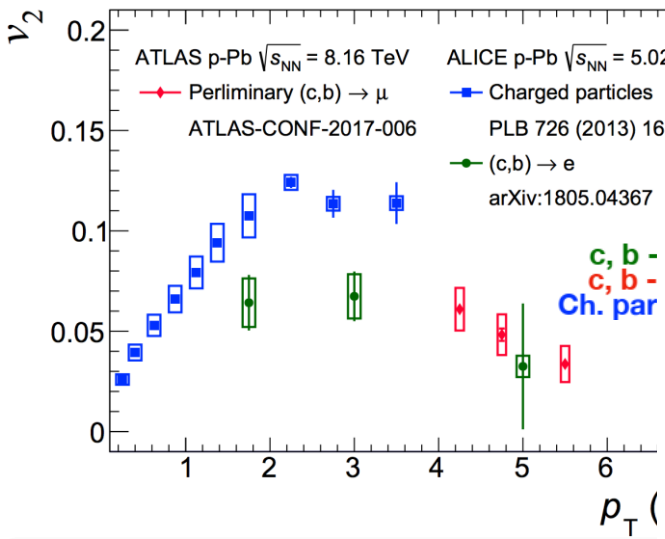
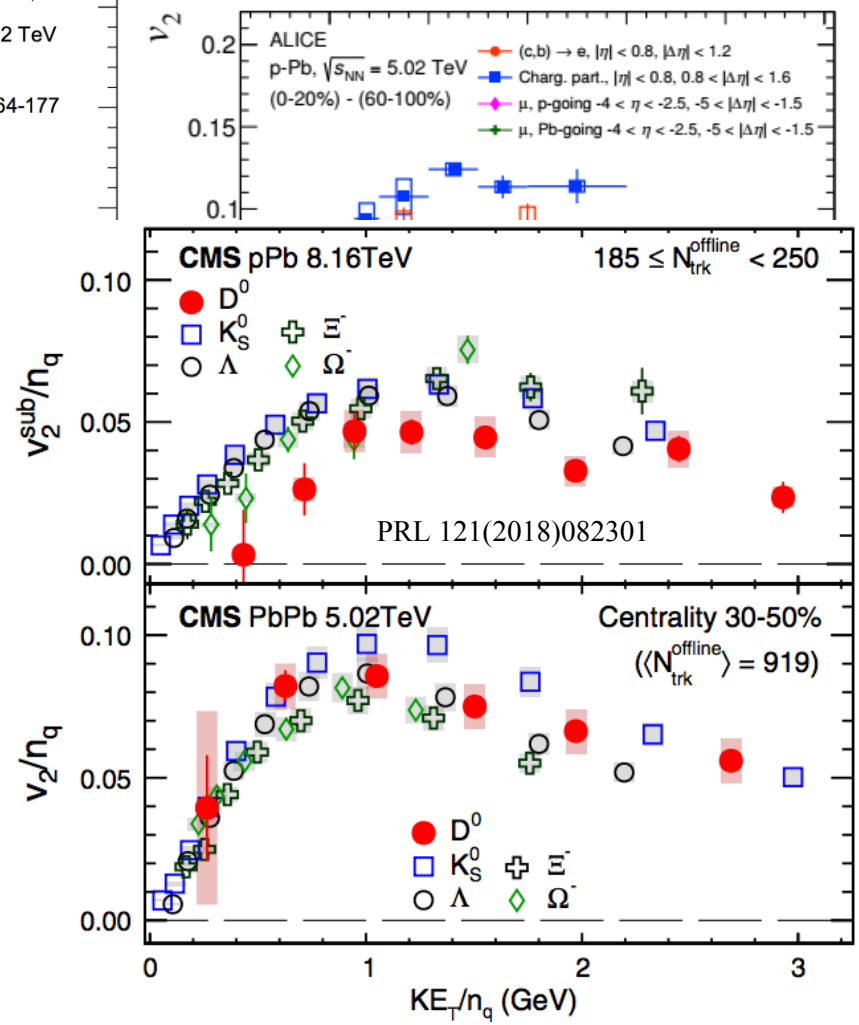


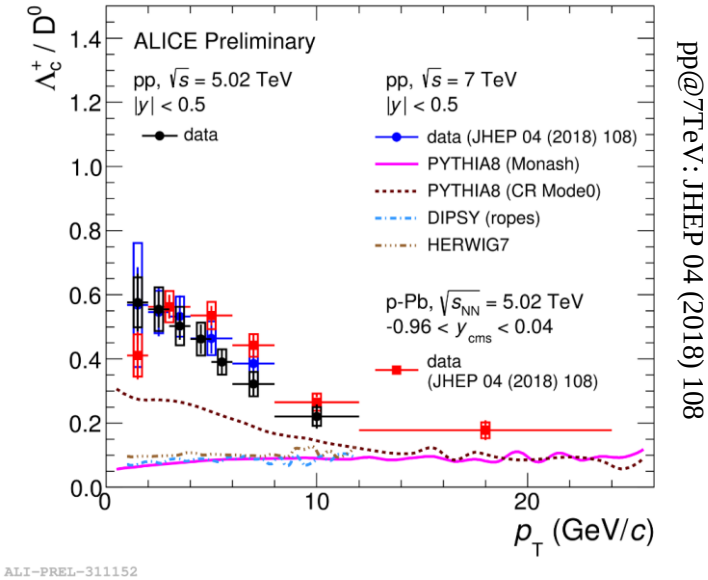


- D° flow at LHC
  - Significant v2 up to high-p_T
  - NCQ scaled v2 has different trend and is weaker compared to Pb+Pb
- Different (initial/final) effects contributing to v2 in small and large systems?
  - QGP in p+Pb?

Charm hadronization in pPb

- Study baryon production mechanism – CNM baseline for A+A collisions

mid-rapidity



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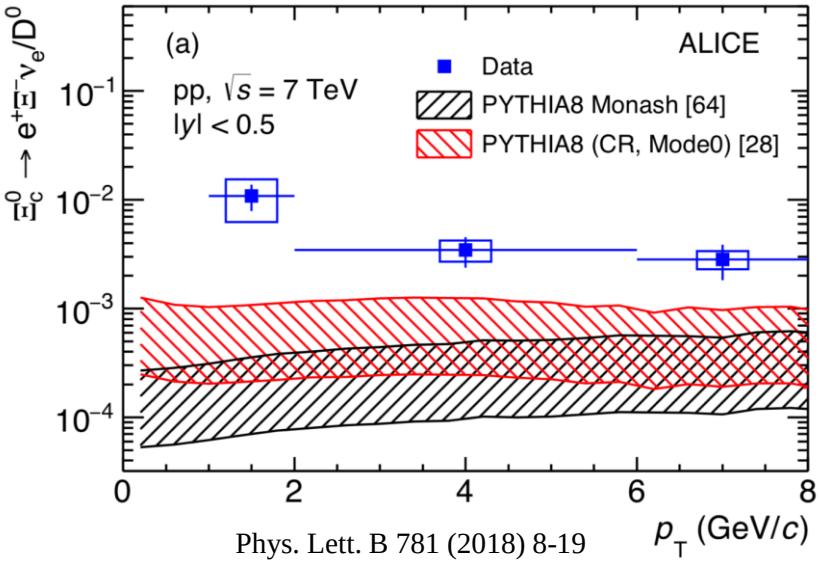

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- Λc/D° (and Ξc/D°) at mid-rapidity
  - Higher then expectation from e+e-
  - Consistent between p+p and p+Pb
  - Underestimated by models

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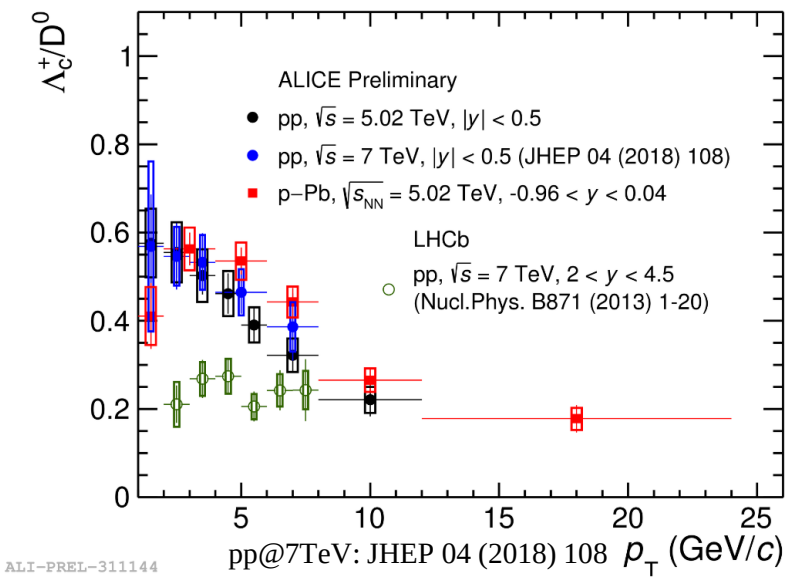

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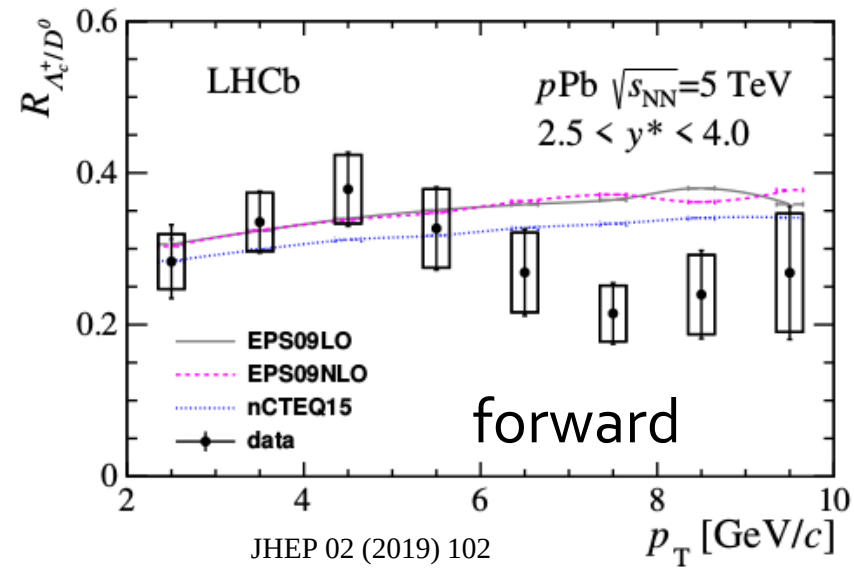

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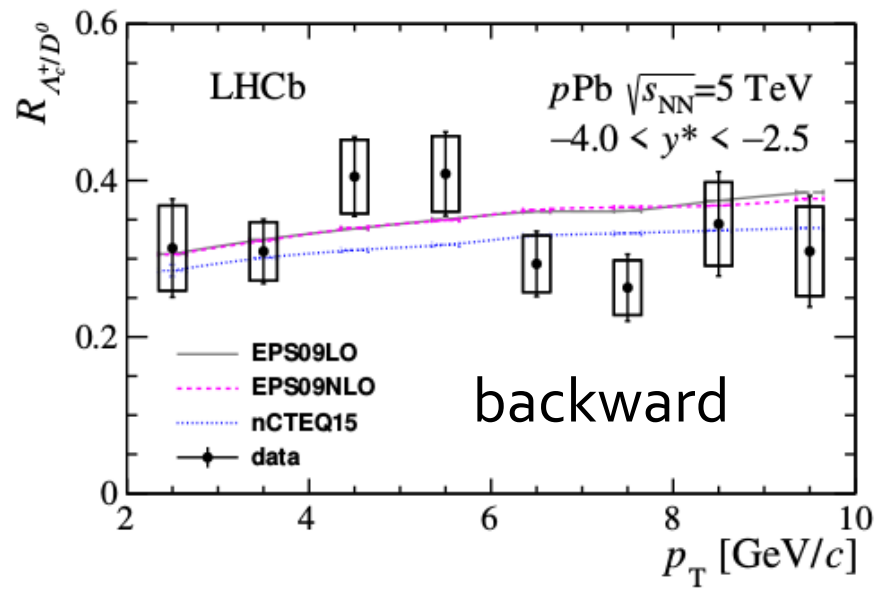
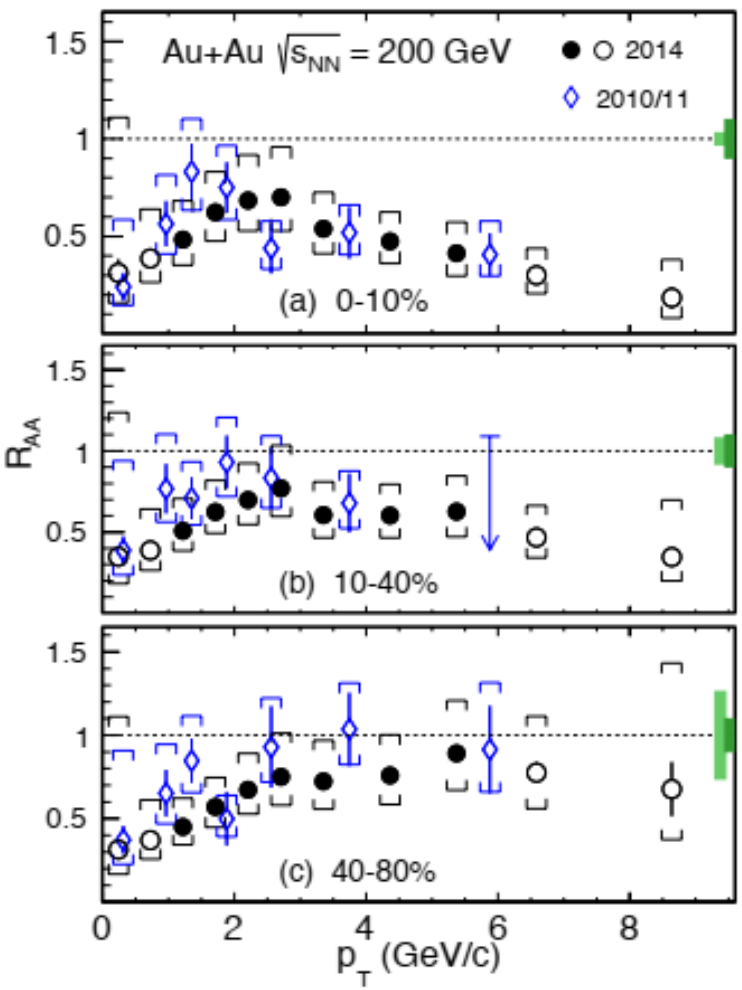
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238



- Λc/D° (and Ξc/D°) at mid-rapidity
  - Higher then expectation from e+e-
  - Consistent between p+p and p+Pb
  - Underestimated by models
- Forward/backward rapidity
  - Slightly lower compared to mid-rapidity
  - Hint of decrease with-p_T
  - consistent with nPDF models

Heavy flavour in A+A collisions

RHIC: D-meson suppression



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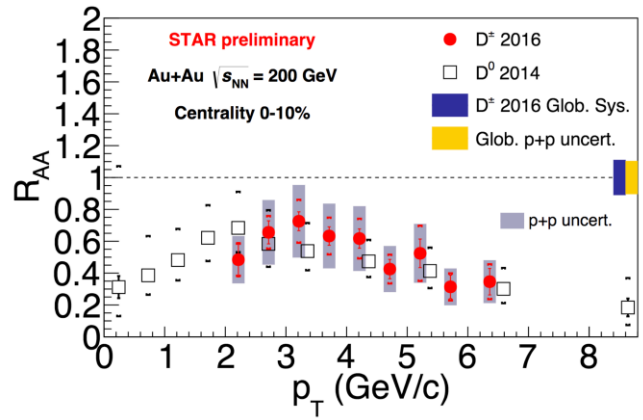
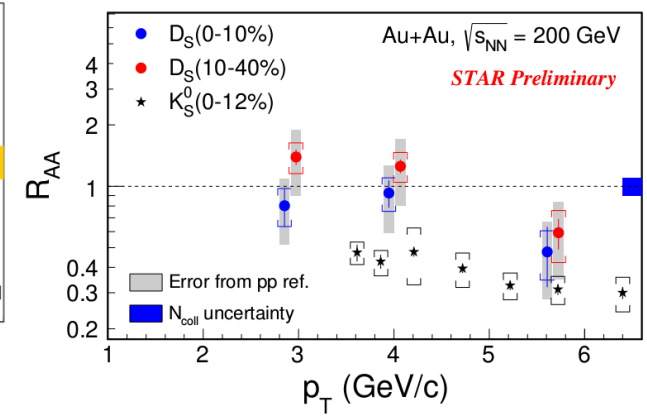
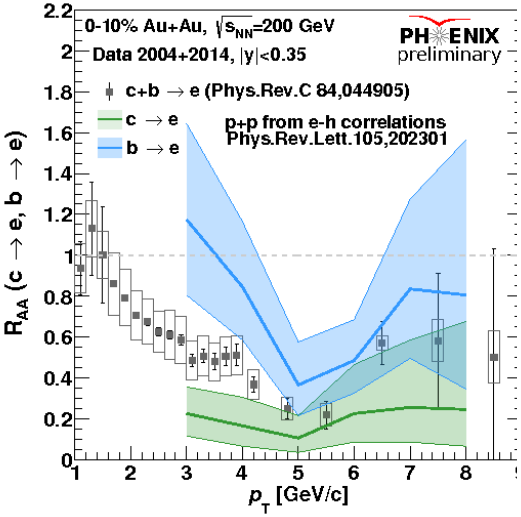


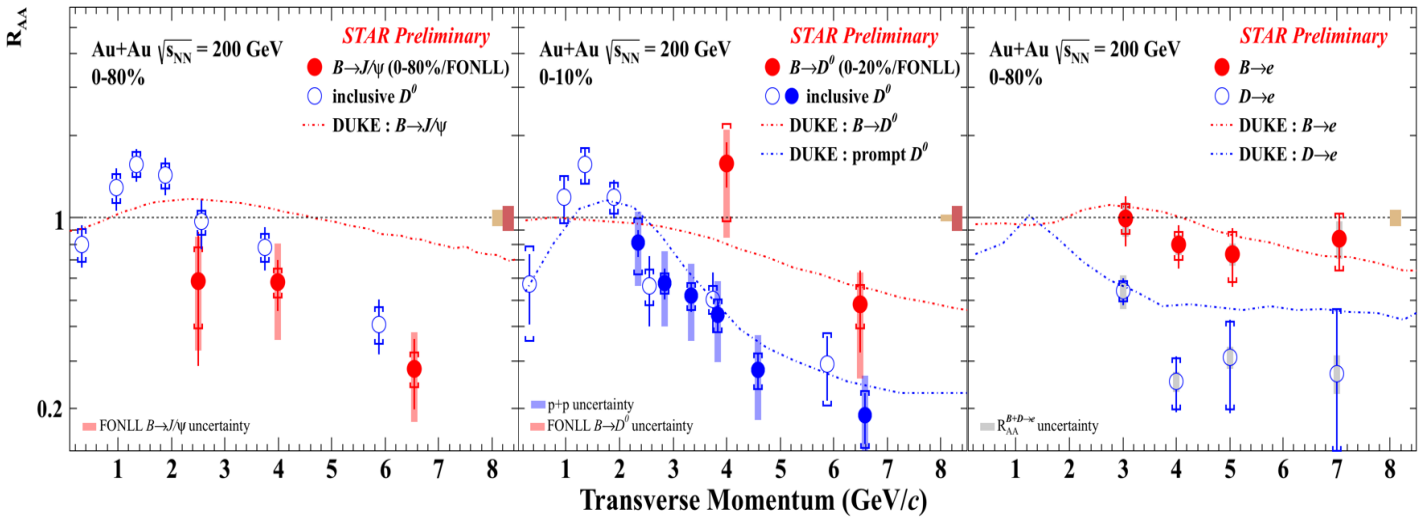


R_{AA} of directly reconstructed of D^0 mesons at STAR:

- Suppression at high p_T - increases towards more central collisions
  - significant energy loss in QGP
- Suppression at low p_T – no strong dependence on centrality
  - Interplay p_T shapes, radial flow, recombination
  - CNM effects?
- Less than unity for all p_T in 0-10% central collisions
- Similar suppression observed for charged D mesons

RHIC: Bottom suppression



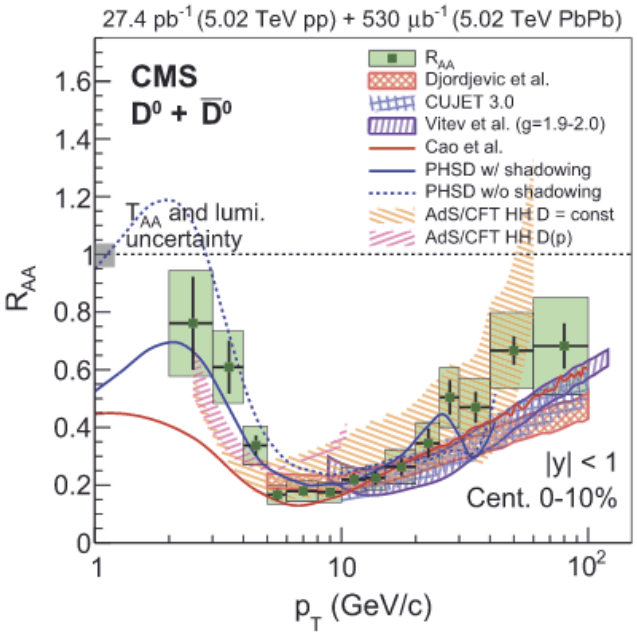


Phys. Rev. Lett. 113 (2014) 142301
Phys. Nucl. Phys. A 956, 473–476 (2016)
DUKE: Phys. Rev. C 92, 024907

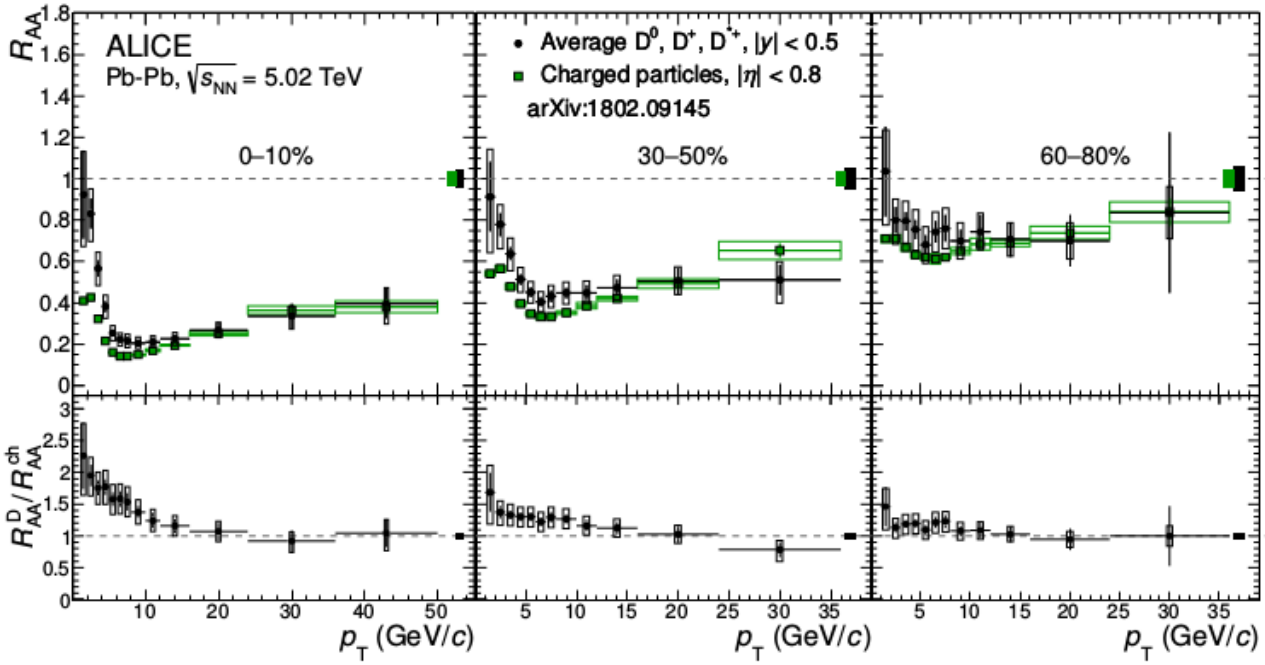
- PHENIX - non-photonic electrons (NPE)
  - smaller R_{AA}(b->e) and R_{AA} (c->e) v at low p_T in central Au-Au collisions
- STAR bottom measurements through non-prompt D, J/psi, NPE
  - Suppression observed in B->J/ψ and D^o
  - B->e is less suppressed than D->e (2σ effect)
- Consistent with mass-hierarchy of energy loss

Charm suppression at LHC

Phys. Lett. B 782 (2018) 474



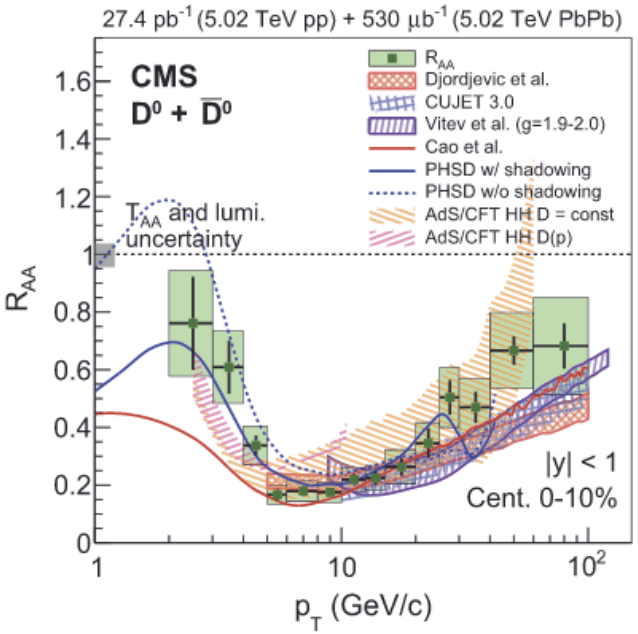
JHEP10(2018)174



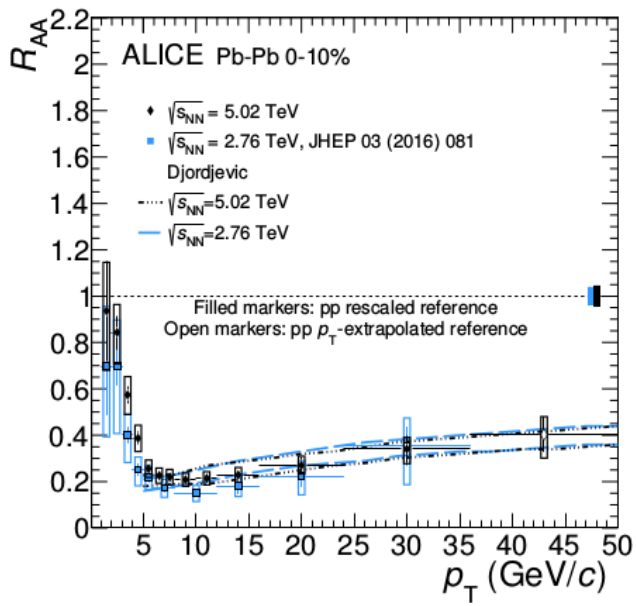
- Significant charm suppression in Pb+Pb up to p_T of 50 GeV
  - Hint of smaller suppression at low-p_T compared to light-flavor

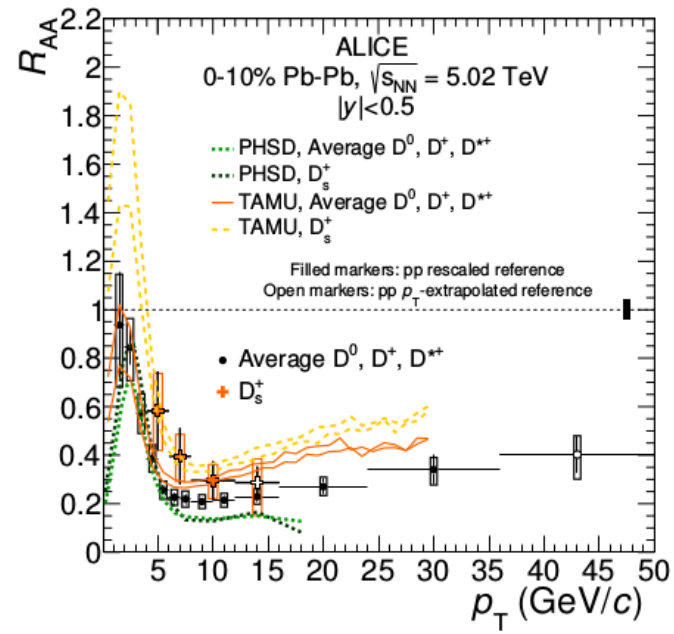
Charm suppression at LHC

Phys. Lett. B 782 (2018) 474



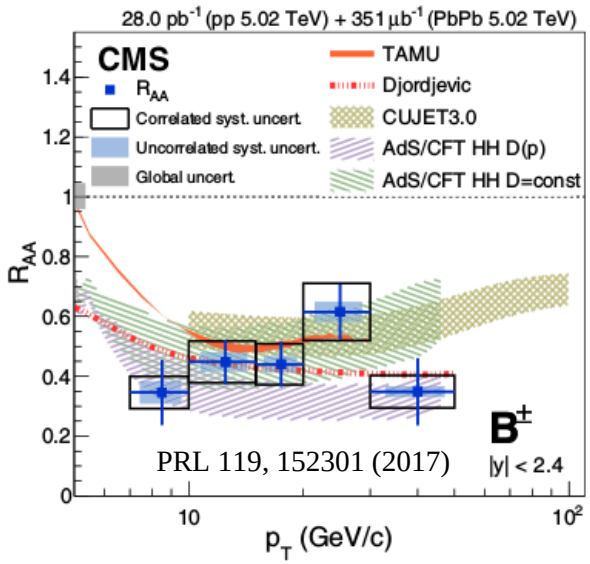
JHEP10(2018)174

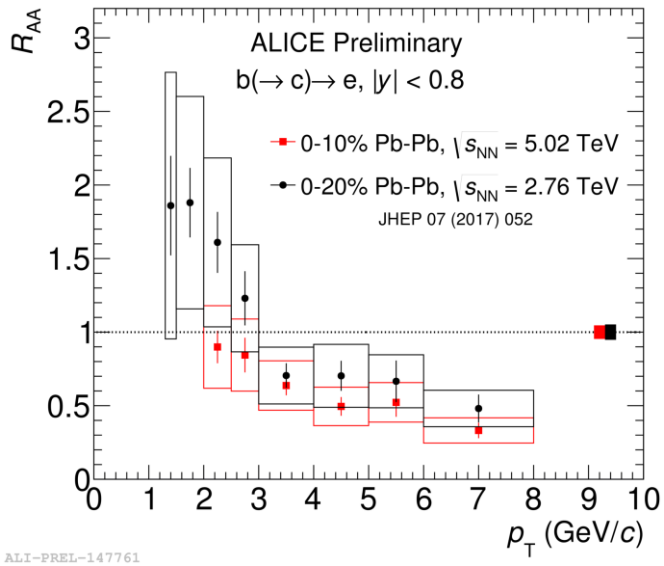


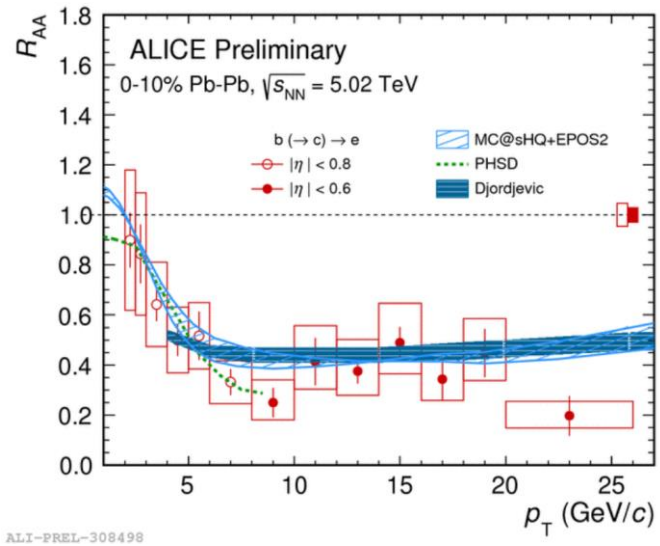


- Significant charm suppression in Pb+Pb up to p_T of 50 GeV
  - Similar suppression at 2.76 and 5.02 TeV
  - Decreasing at higher p_T in agreement with models
- Precise results putting constraints on theoretical calculations
  - High-p_T : need to include radiative energy loss to describe the data
  - Low-p_T : non negligible collisional energy loss (charm transport)
  - Shadowing improves description at low p_T

Beauty suppression at LHC







R_{AA} (B)

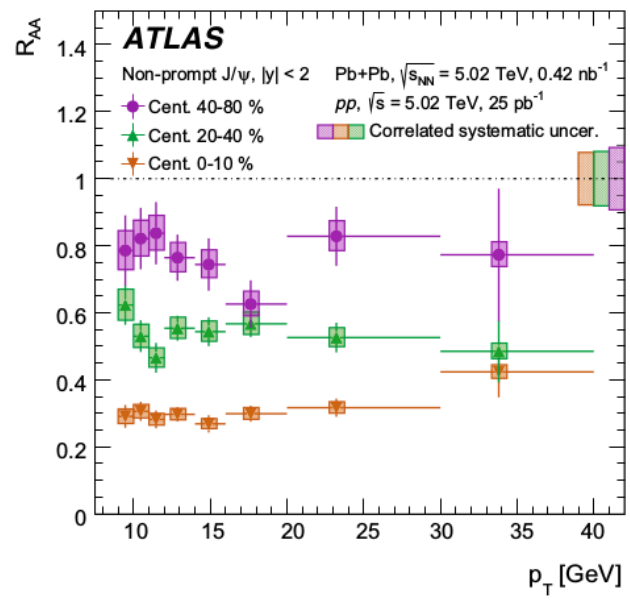
- Strong suppression (R_{AA}~0.4) in 0-100% Pb-Pb collision for p_T > 7 GeV/c

R_{AA} (b->e)

- New results at 5.02 TeV compatible with those at 2.76 TeV
- Extending the measurements to lower p_T (< 7 GeV/c)
- Observed suppression described by models with mass-dependent energy loss

Non-prompt J/psi

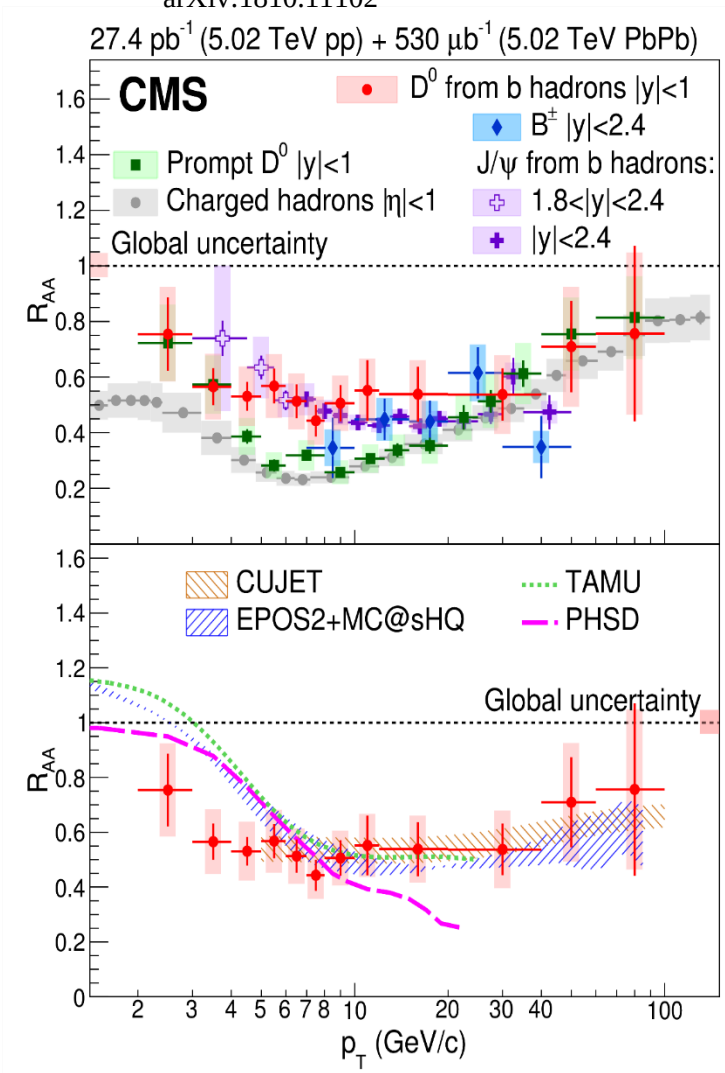
- Good agreement between ATLAS and CMS (EPJC. 78 (2018) 509)
- Flat suppression up to high p_T

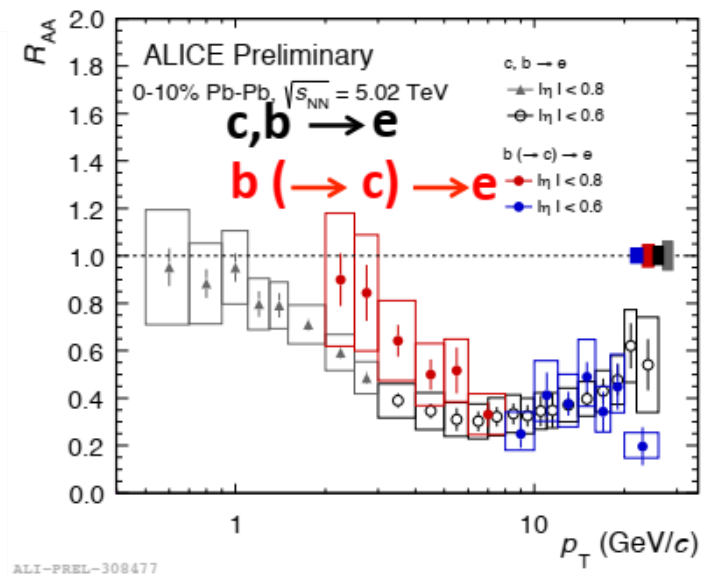


EPJC 78 (2018) 762

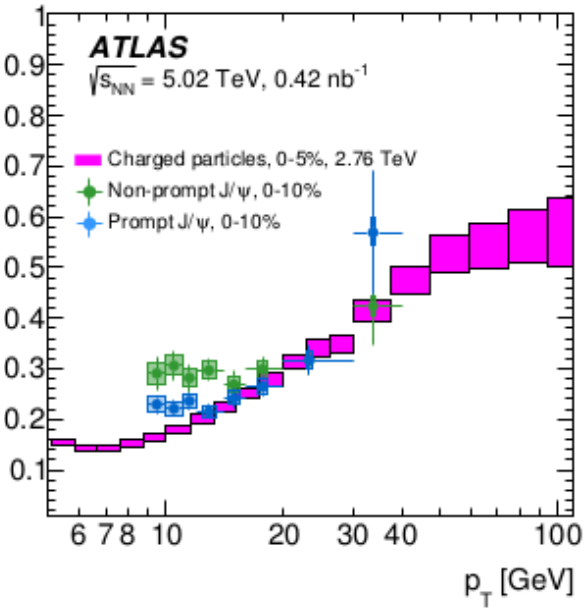
HF energy loss hierarchy?

PLB 782 (2018) 474
PRL. 119, 152301 (2017)
arXiv:1810.11102





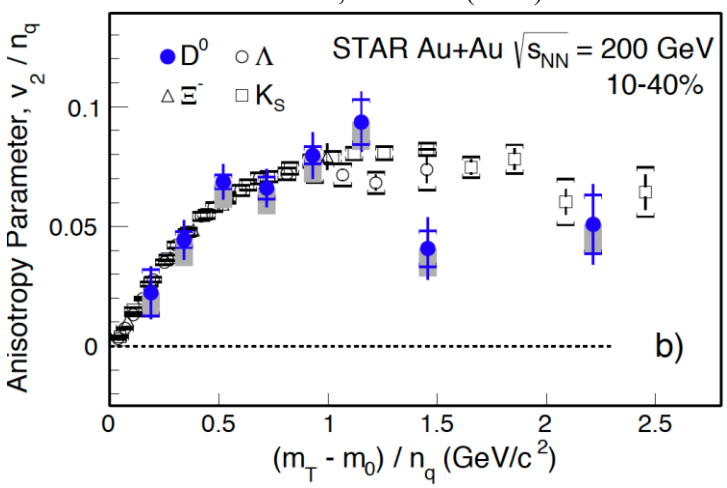
EPJC 78(2018)762



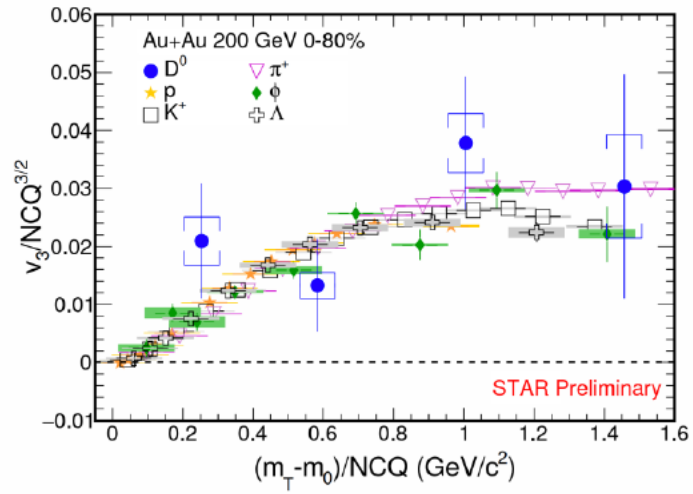
- Compatible results from beauty R_{AA} measurements at LHC
- Compatible with mass-hierarchy of energy loss
  - Hint of R_{AA} (B→J/ψ) > R_{AA}(D) for p_T < 10 GeV/c
  - Hint of less suppression for b→e than c→e at the same electron p_T
  - disappearance of the ordering at high p_T
- No significance difference between R_{AA} of light and heavy particles for p_T > 20 GeV/c

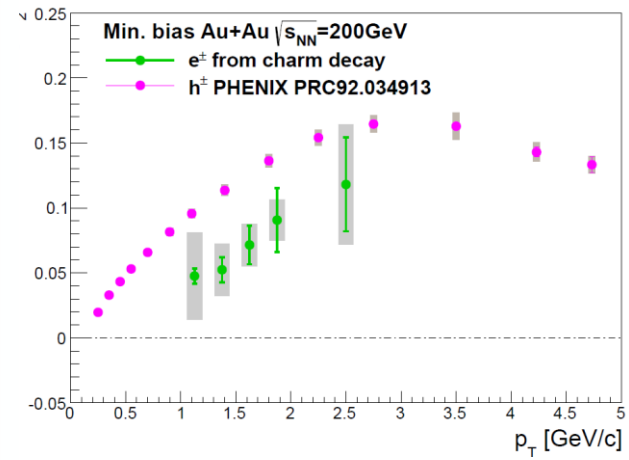
HF collectivity at RHIC

D0 v2: STAR, PRL 118 (2017) 212301



Λ, Ξ-, Ks: STAR, PRC 77 (2008) 054901



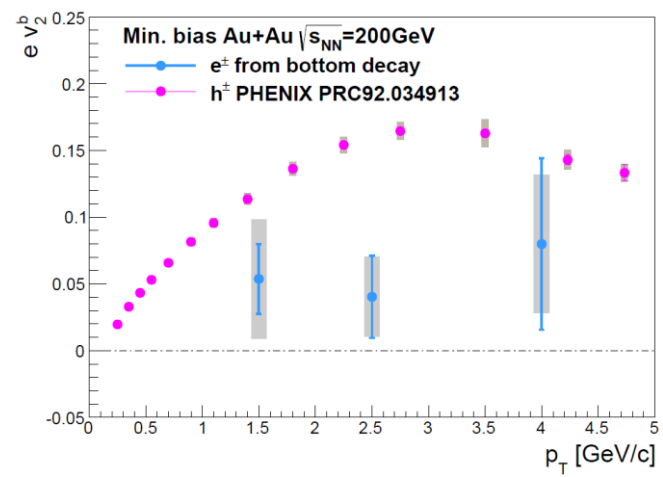


STAR D^0 meson v2 and v_3

- follow (m_T - mo) NCQ scaling as light flavor hadron

PHENIX heavy-flavor electrons

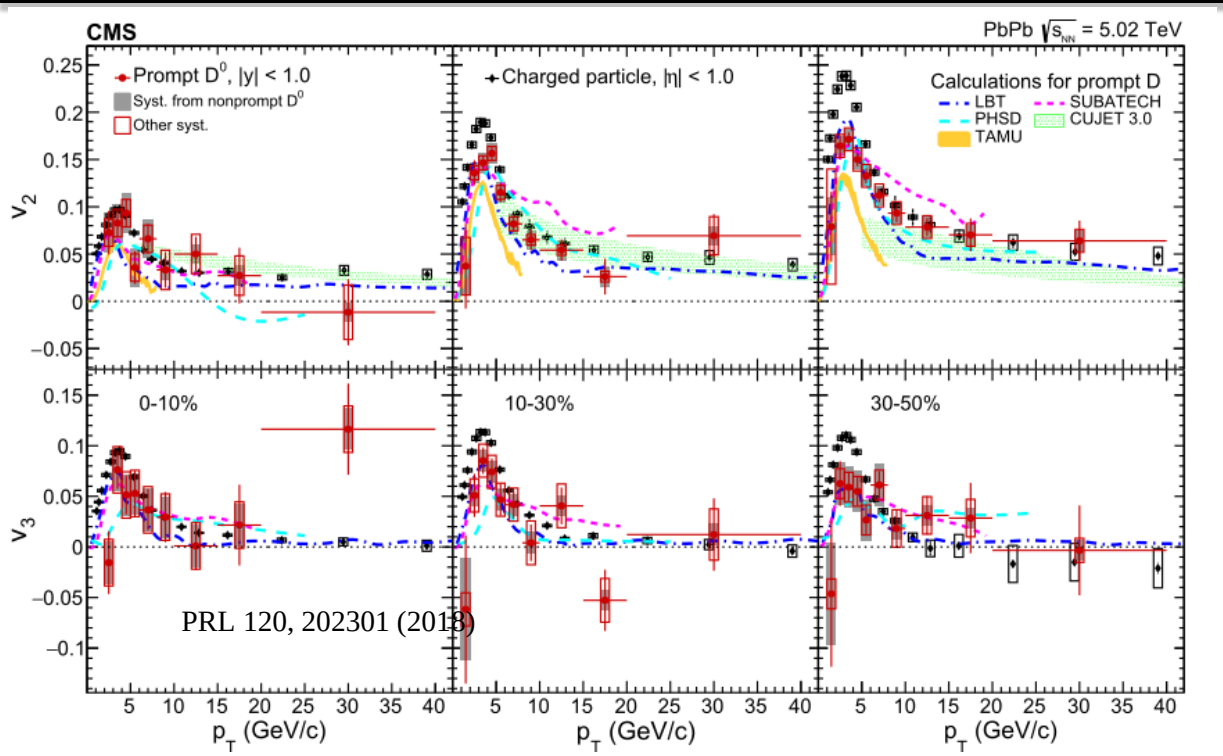
- v2(c ⟶ e) is positive and smaller than charged hadron v2
- v2(b ⟶ e) consistent with zero within large uncertainty
  - Likely smaller than v2(c⟶e)



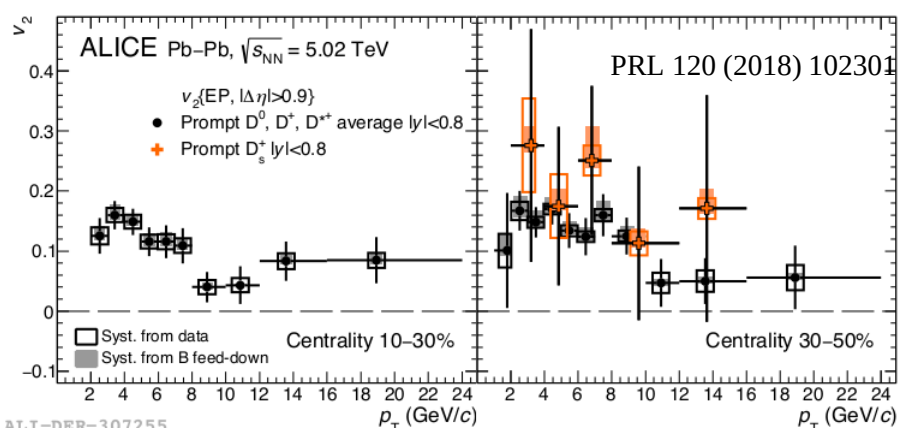
Evidence of charm is flowing with the medium

- Local equilibrium with the medium ?

Charm flow at LHC



PRL 120, 202301 (2018)



PRL 120 (2018) 102301

Non-zero $D^0 v_2$

- Good agreement between ALICE and CMS
- D^0 v2 < light-flavor particle v2
- First results from ALICE on D_S v2
  - compatible with D^0

First observations of $v_3 > 0$ for charm at LHC

- D^0 v_3 < light-flavor particle v_3
  - with large errors
- Models including charm re-scattering qualitatively describe data

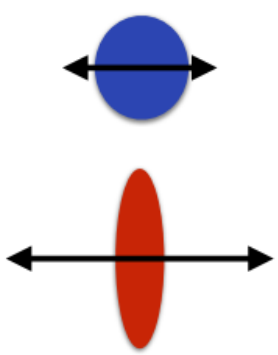
Significant flow of charm from interaction with medium

HF v2 with event-shape-engineering

- Study coupling of flow of charm and light quarks and it's fluctuation
- Event selection based on centrality and reduced flow vector q_2 (proxy to initial eccentricity)

$$q_2 = |\vec{Q}_2| / \sqrt{M}$$

$$\vec{Q}_2 = \sum_{j=1}^{M} e^{i2\varphi_j}$$

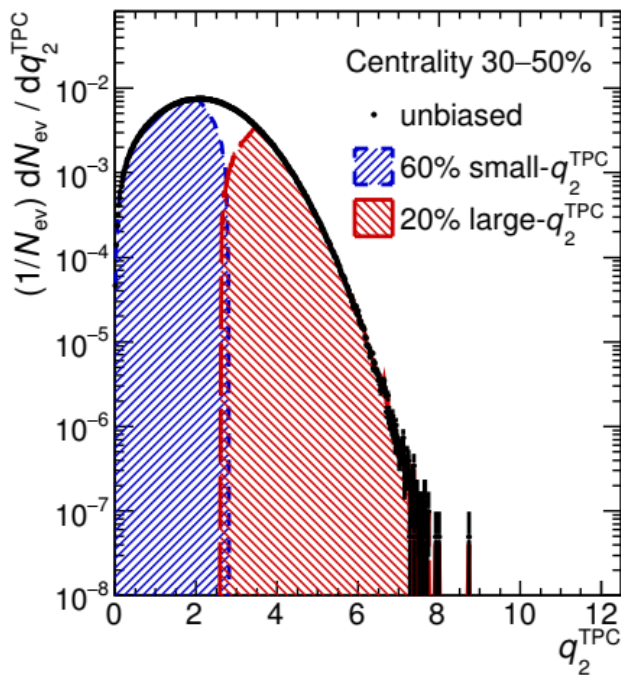


60% smallest q_2^{TPC}

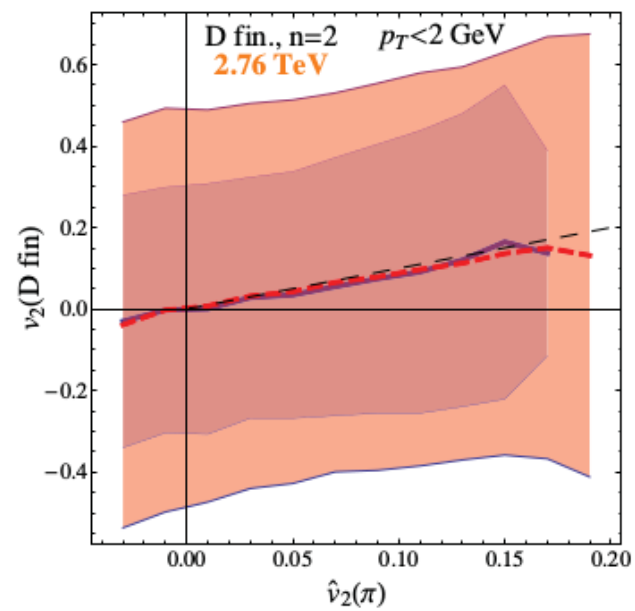
$\langle v_2 \rangle_{\text{small}-q_2} < \langle v_2 \rangle_{\text{unb}}$

20% largest q_2^{TPC}

$\langle v_2 \rangle_{\text{large}-q_2} > \langle v_2 \rangle_{\text{unb}}$

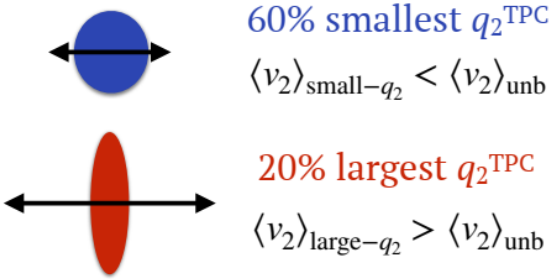


EPOSHQ: EPJ WoC 171, 18004 (2018)

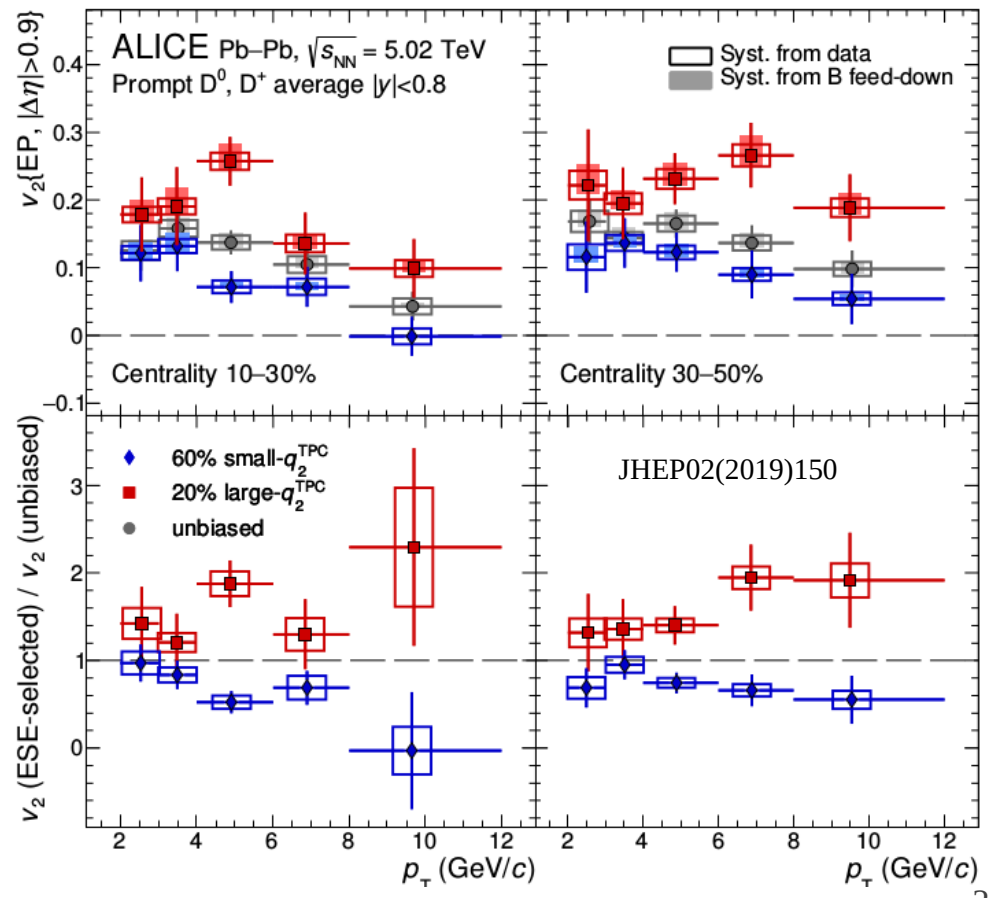


HF v2 with event-shape-engineering

- Study coupling of flow of charm and light quarks and it's fluctuation
- Event selection based on multiplicity and reduced flow vector q_2 (proxy to initial eccentricity)



- positive correlation between the D-meson and the light-hadron *v*2
- Similar effect in the 10-30% and 30-50% centrality classes within uncertainties
  - *v*2 (large-*q*2) > *v*2 (unbiased) of about 40%
  - *v*2 (small-*q*2) < *v*2 (unbiased) of about 25%



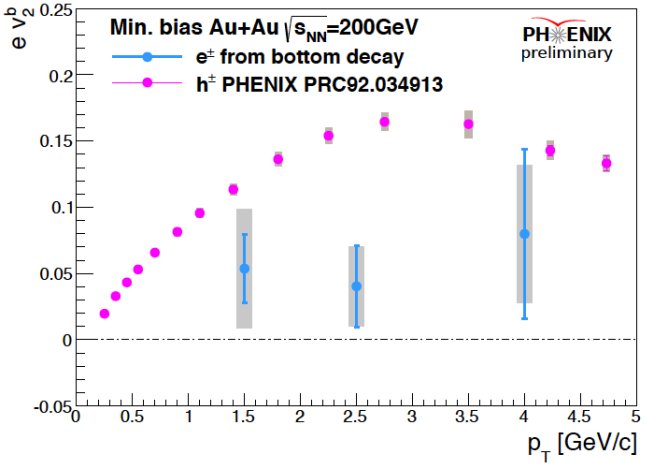
Does b-quark flow?

RHIC: v2 of b->e

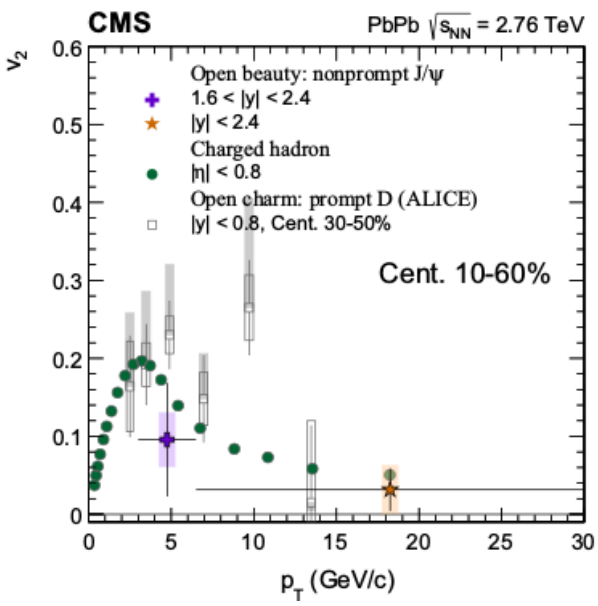
- measured in 0-100% Au-Au -> consistent with zero within large uncertainties.

LHC: v2 of B->J/Ψ

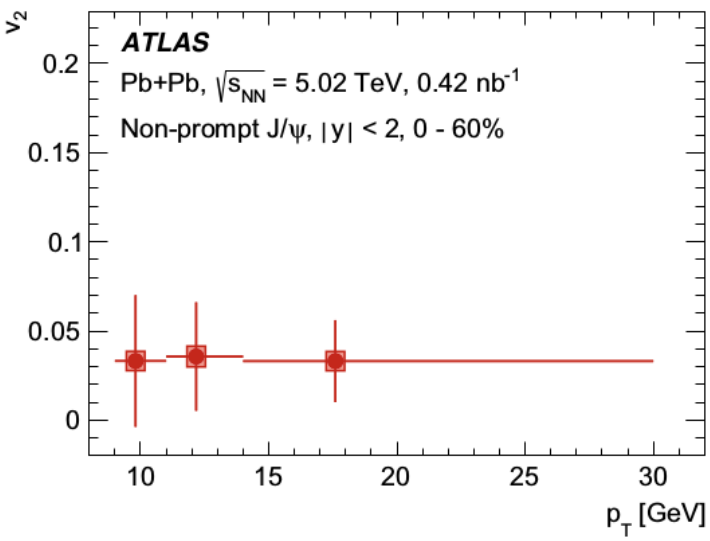
- Measurement consistent with zero with large uncertainties.
- No strong centrality dependence for $p_T > 9$ GeV/c

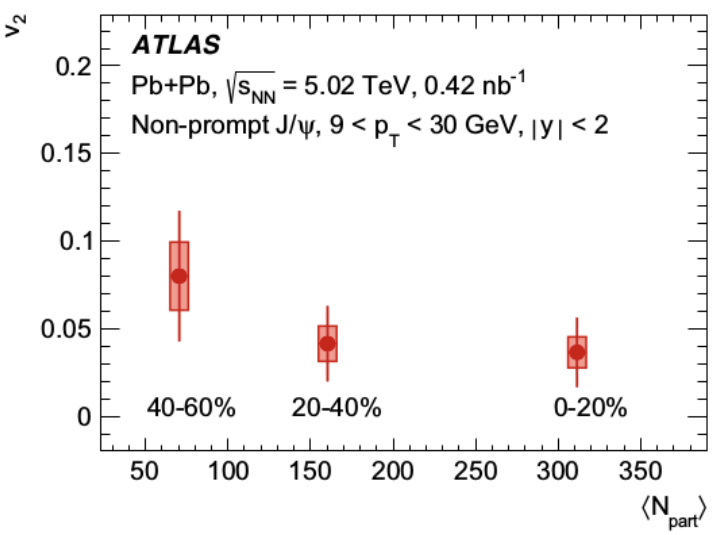


Needs higher precision



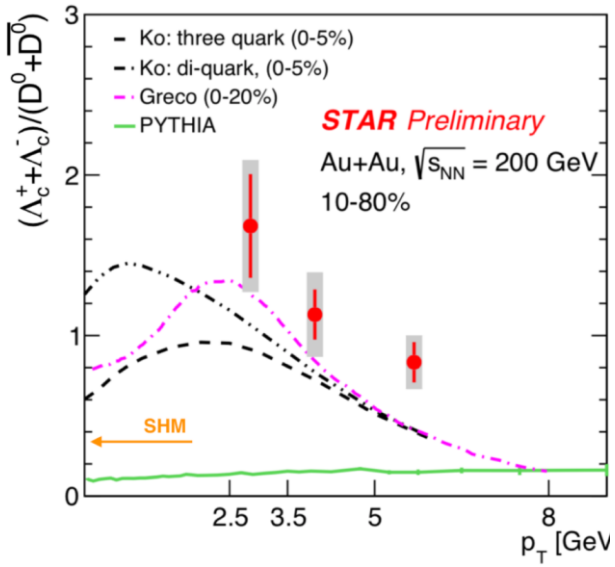
EPJC 77(2017)252

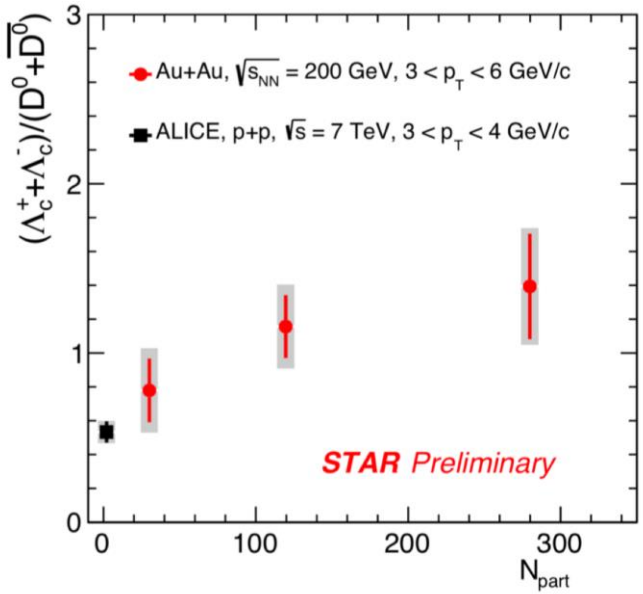


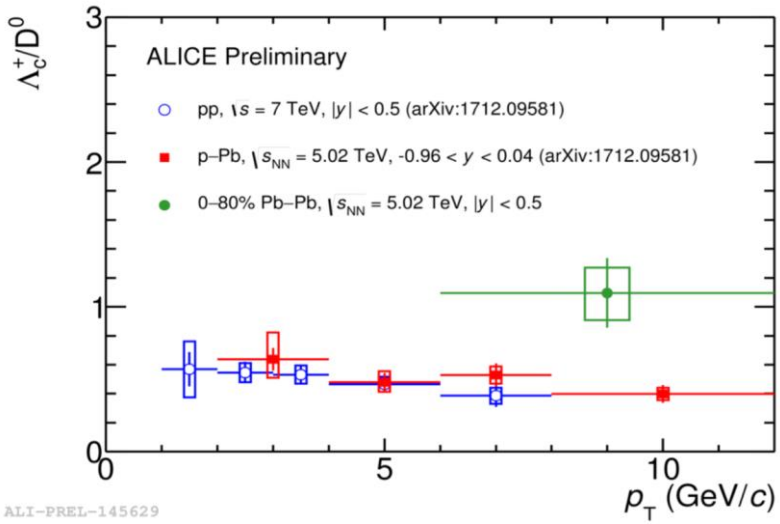


Eur. Phys. J. C 78 (2018) 784

Hadronization - Λc





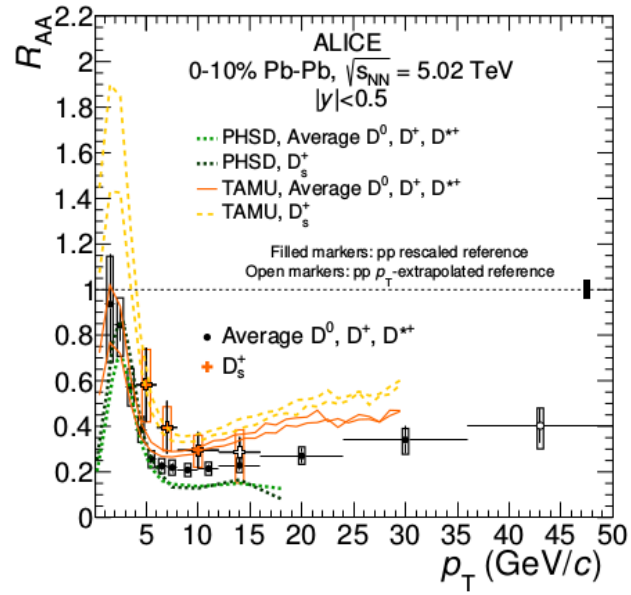


Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905

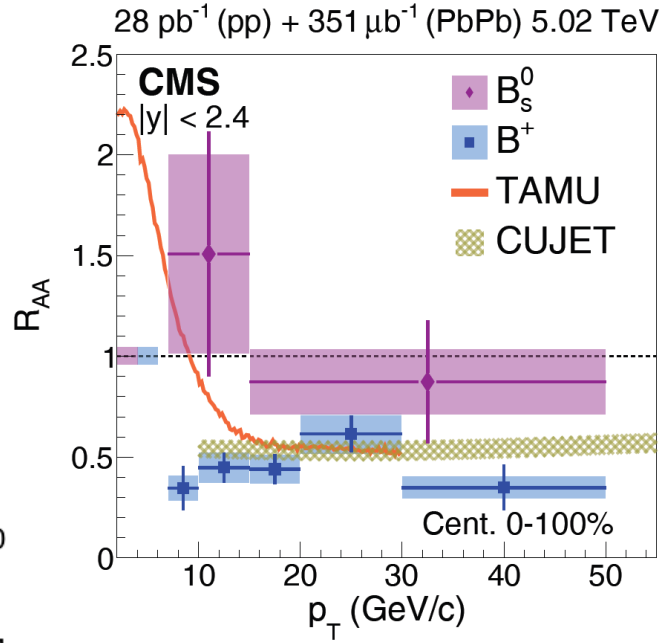
- Measurements for *Λc* as functions of p_T and centrality (Npart)
- Strong enhancement - increases toward low p_T, increases from peripheral to central
- Similar Λc/D at RHIC and LHC (different p_T ranges)
- **Enhancement larger than models based on fragmentation + recombination**

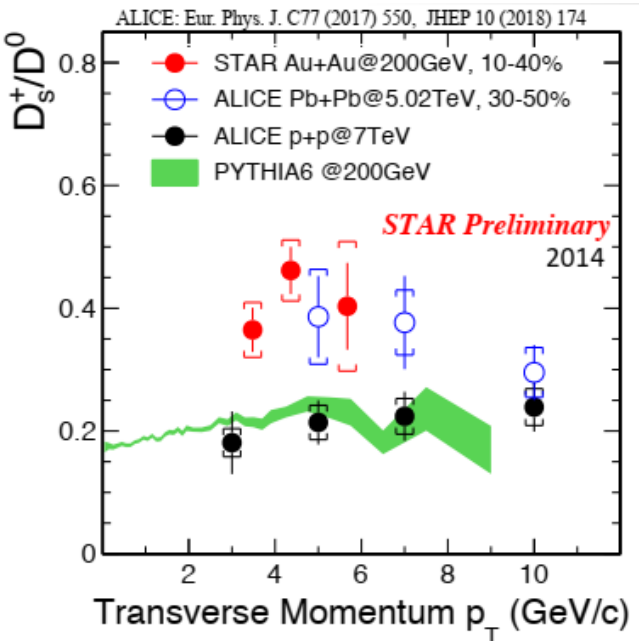
Hadronization – Ds, Bs

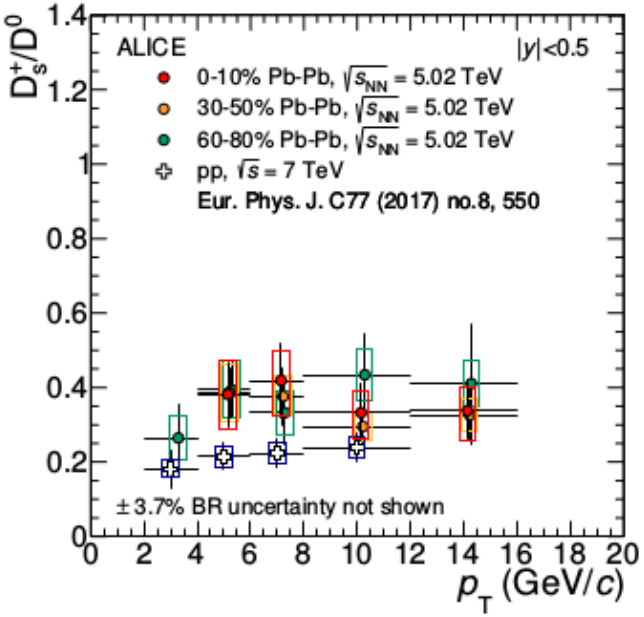
JHEP10(2018)174



PRL 119, 152301 (2017)







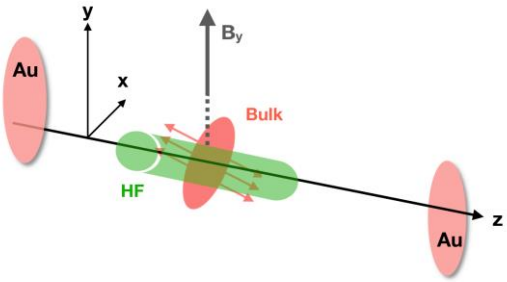
- Less suppression of Ds+ wr.t. non-strange D at intermediate p_T
- First Bs measurement in Pb-Pb - hint of enhancement of Bs/B+
- Consistent with coalescence + strangeness enhancement
  - Described by transport models

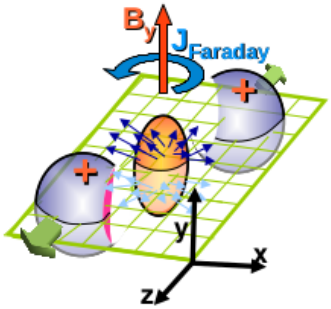
Do directed flow (v1)

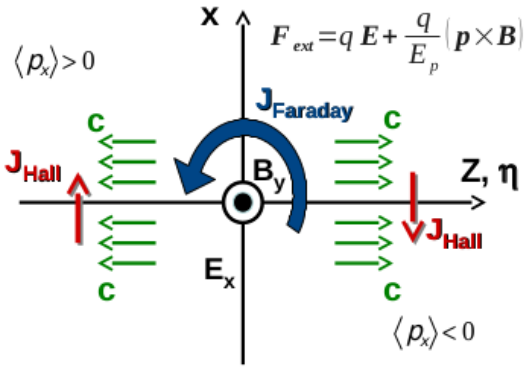
Interplay of two main sources for v_1:

- Initial tilt of fireball + drag
  - Independent of charges
  - Predict large v_1 slope for HQ

Chatterjee, Bozek, arXiv: 1804.04893

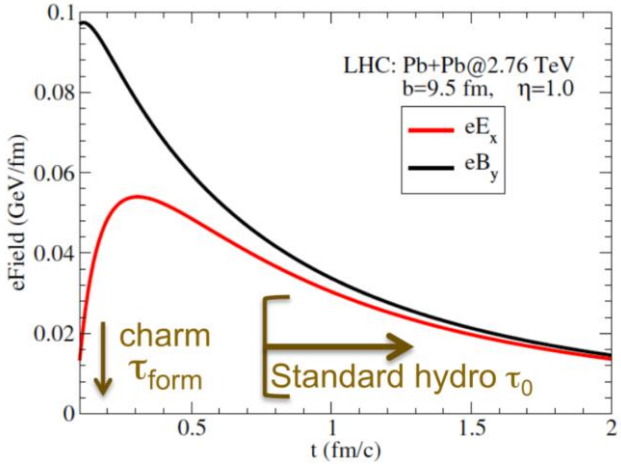




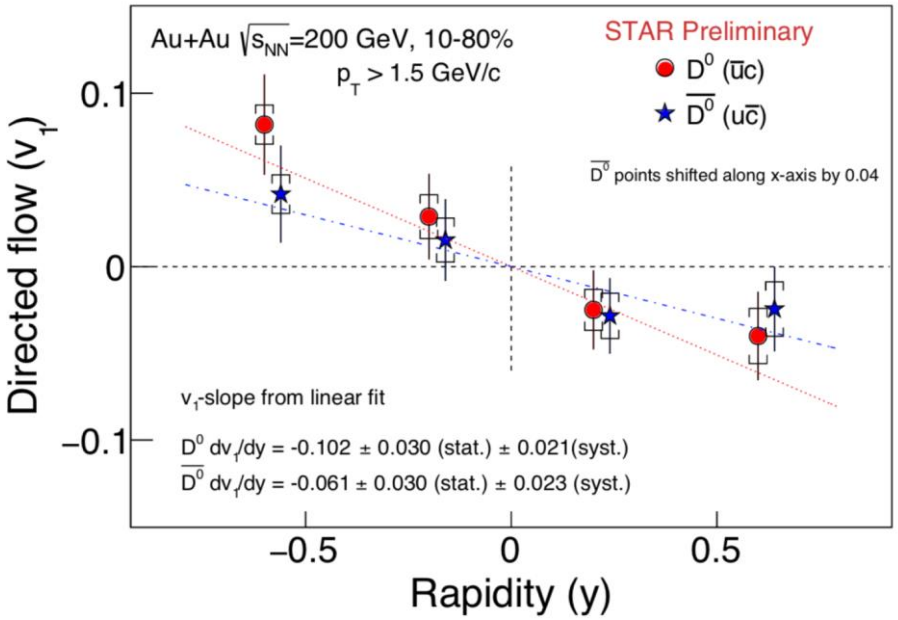


- Initial strong magnetic field
  - Charge-dependent v_1
  - Larger effect for HQ due to their early production
  - Interplay of Faraday and Hall effect

Das, Greco et al., Phys.Lett. B768 (2017) 260



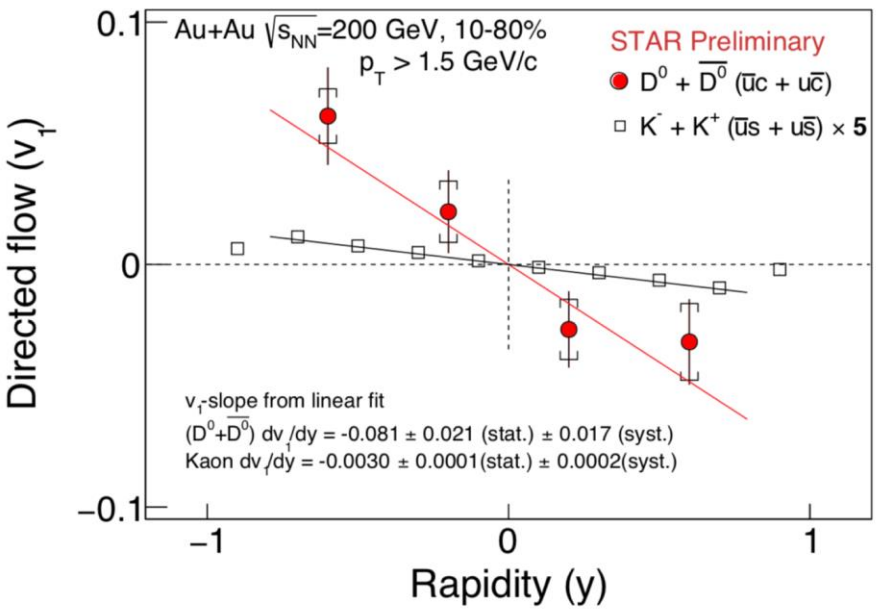
D° directed flow at RHIC

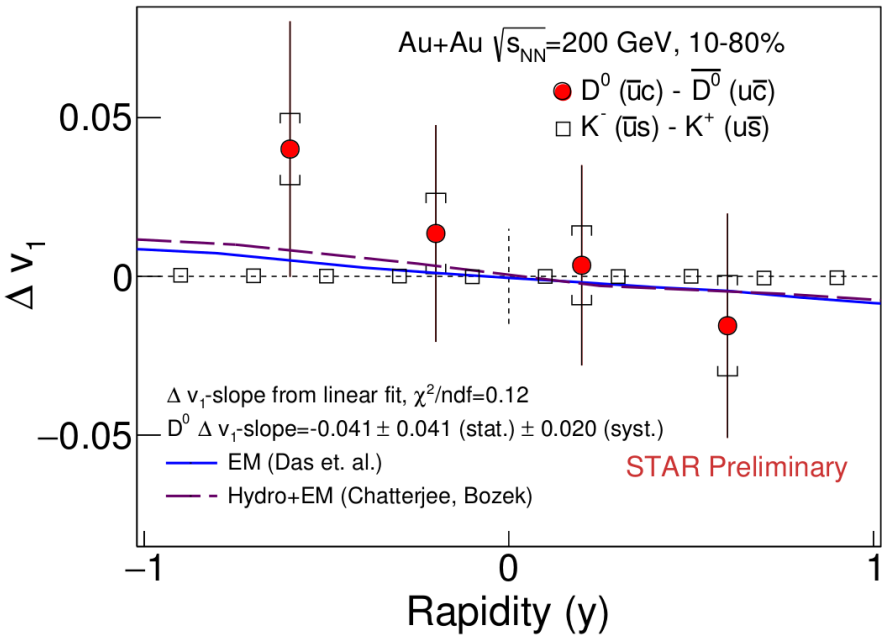


First observation of non-zero D° v1

- negative slope measured for both particles
  - much larger than for the kaons

D° directed flow at RHIC

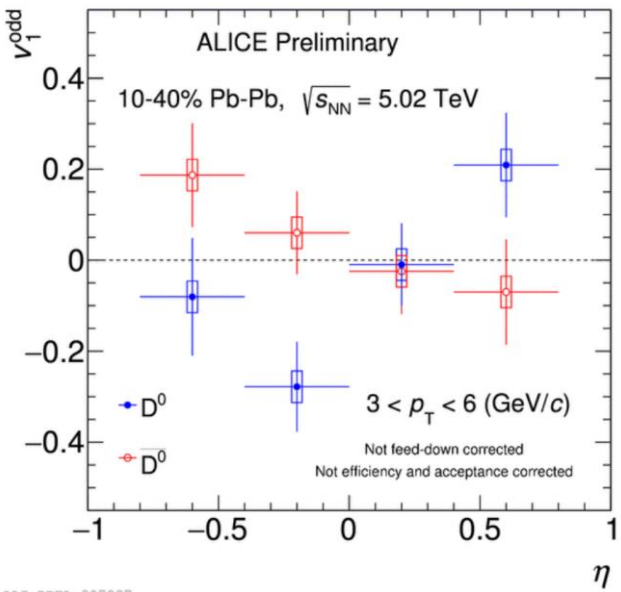


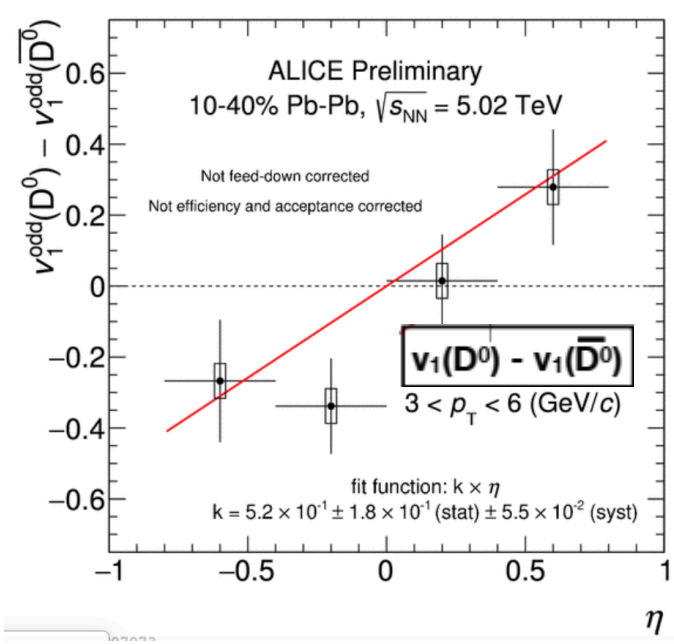


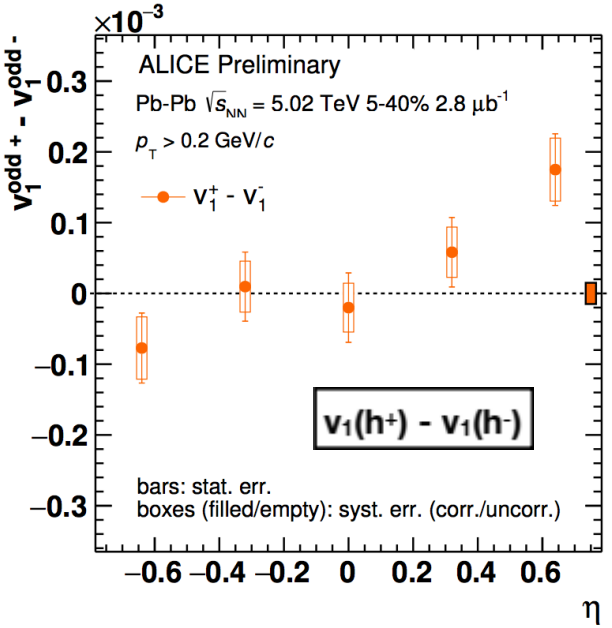
First observation of non-zero D° v1

- negative slope measured for both particles
  - much larger than for the kaons
- Data can be used to probe initial longitudinal distribution of matter
- Current precision is not sufficient to draw conclusion on magnetic field induced charge separation

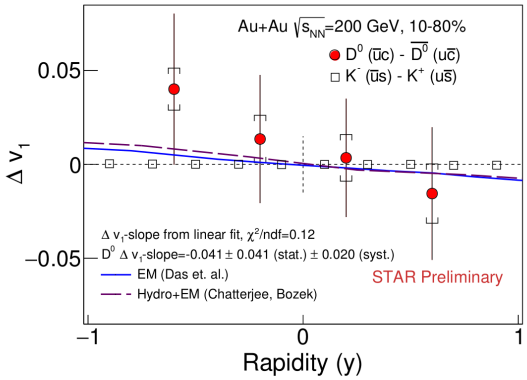
D⁰ directed flow at LHC







- **Opposite slopes for D⁰ and D⁰ albeit large uncertainty**
- **v1(D⁰) - v1(anti-D⁰)**
  - Non-zero value observed.
  - Three orders of magnitude higher than v1(h+) - v1(h-).
- **v1(D⁰) - v1(anti-D⁰): hint of opposite slope at RHIC and LHC**
  - Sensitive to the interplay of competing effects
  - model comparison required.



Open heavy-flavor summary

p+p

- Entering high-precision era of measurements
- pQCD describes production heavy-flavor => good probe

p+A

- Small modification of production due to cold nuclear matter effects
  - Good baseline for A+A studies
- Non-zero flow observed in high multiplicity events
  - How to reconcile with almost no energy loss?
  - Models needed

A+A

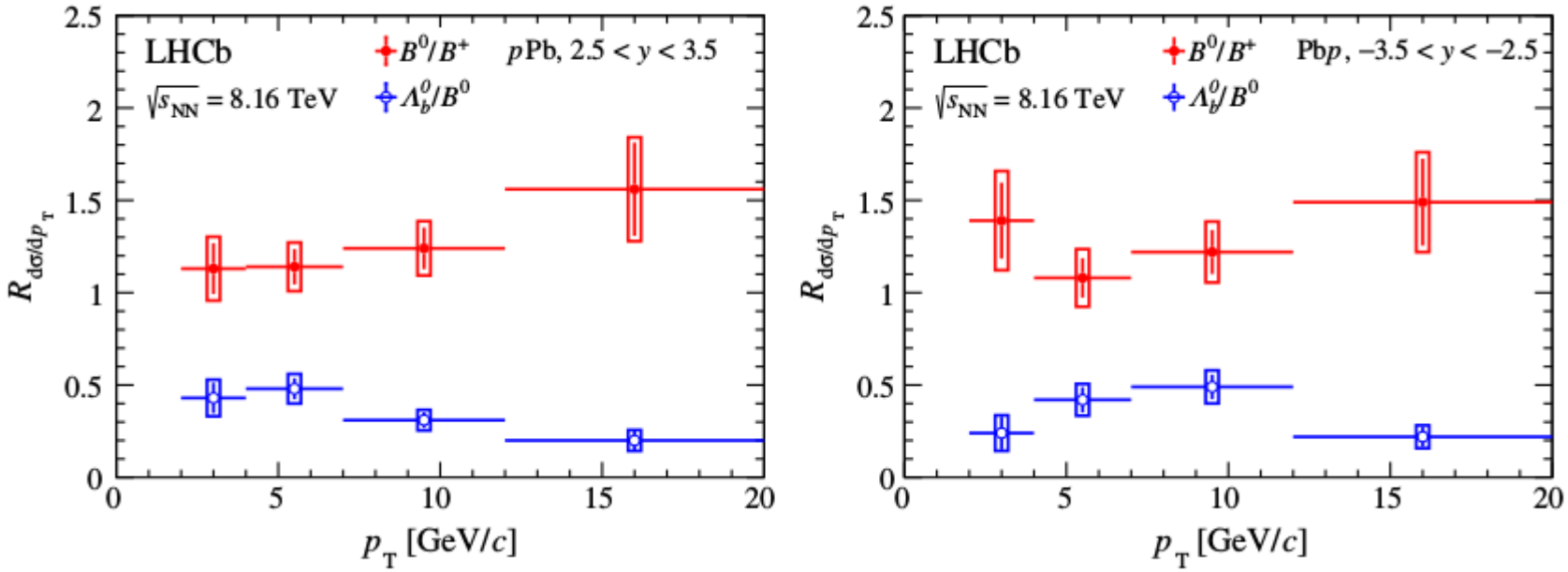
- Significant suppression of both charm and bottom at high-p_T
  - strong interactions between heavy quarks and the medium
- Bottom seems suppressed more
  - Consistent with mass hierarchy of the energy loss
  - Better precision needed
- Large flow of charm quarks
  - suggesting charm quark thermalization with the medium
- Enhancement of Λ^+_c / D^0 and D^+_s / D^0 ratios
  - Hadronization of charm quarks via coalescence
- Large non-zero D^0 v_1
  - Probe of early time EM fields

Backups

Beauty hadronization in p+Pb

B^+/B^o and Λ_b^o/B^o used to study b-quark hadronization

Phys. Rev. D 99, 052011 (2019)



B^+/B^o :

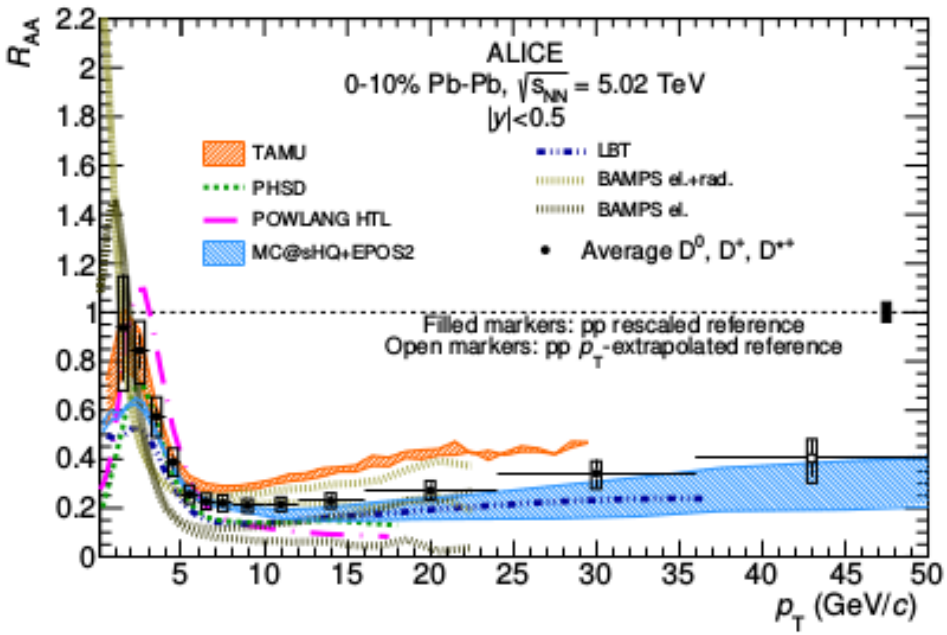
- Independent of rapidity and p_T and consistent with unity within uncertainty.

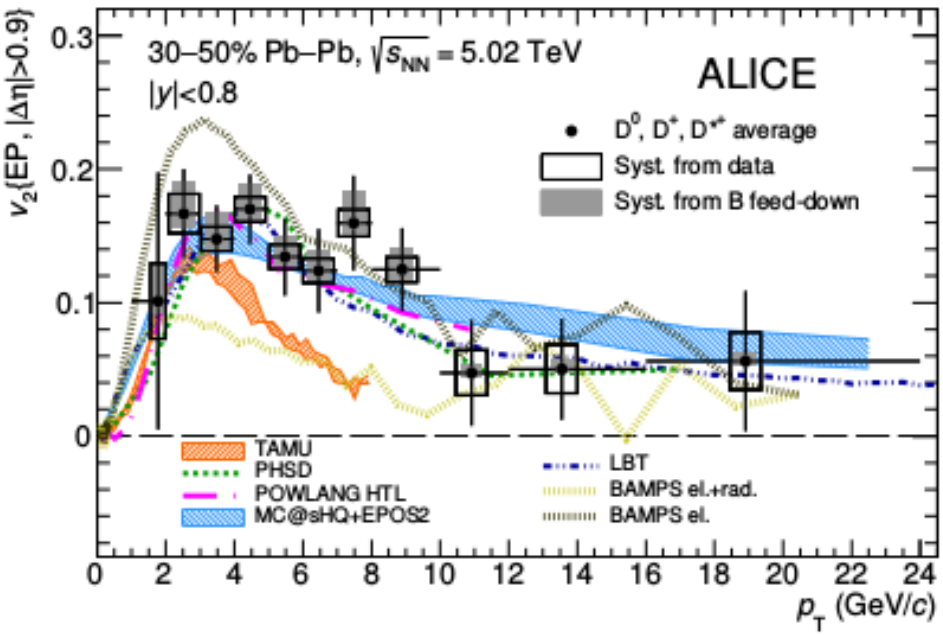
Λ_b^o/B^o :

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

Comparison to models

JHEP10(2018)174





- Simultaneous description of RAA and v2 and it's centrality dependence is able to put constraints on models
- Final goal - extract transport properties
- More differential probes are needed