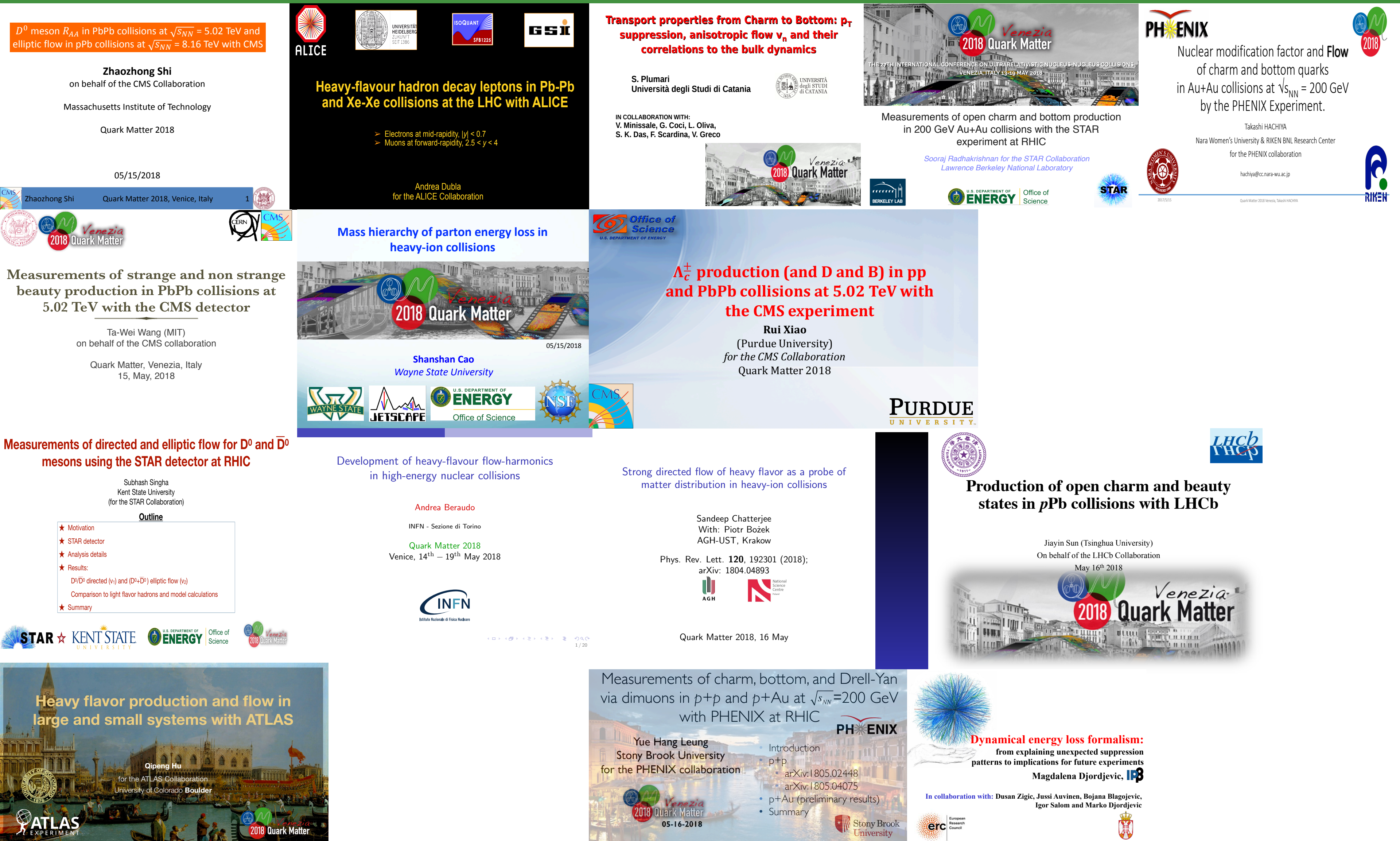
Hottest results of open heavy flavor measurements
(focused to nuclear modification factors)

Hyunchul Kim (Chonnam National University)

HIM 2018-05, May 25th – 26th
Chuncheon, Republic of Korea

Scenes of "open heavy flavor movie" in Venice



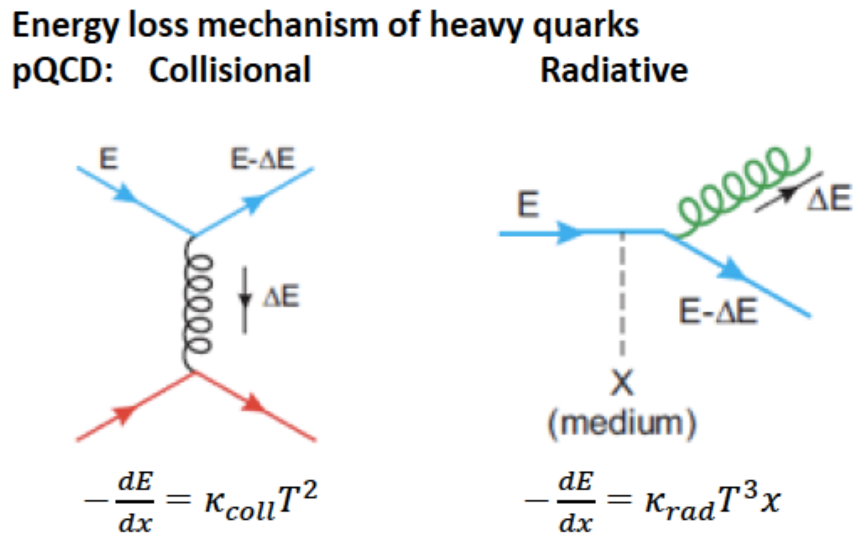
17 parallel talks + posters (Really Hot!)

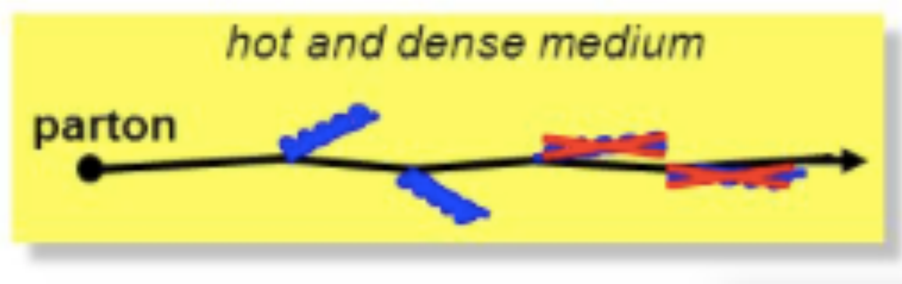
Motivation of heavy flavor

- **Heavy quark is produced in the early stage of the collisions, can used as the probe to investigate the hot and dense matter**
  - light quarks : can be produced in the medium also
  - Electroweak bosons : cannot interact with colored partons in the medium
- **With combined light quark, we can check the mass or flavor dependence**

Energy loss mechanism

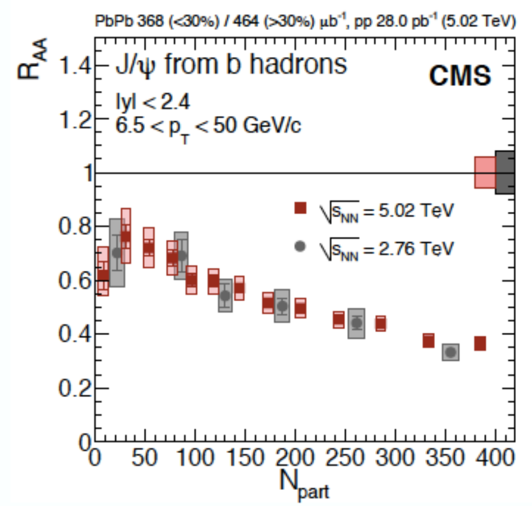
- Kinematics: "Dead cone effect" : gluon radiation is suppressed at angles < quark mass/energy
- E_{loss} in light quarks > E_{loss} in heavy quarks
- Suppression of induced radiation at low p_T and the disappearance of this effect at high p_T

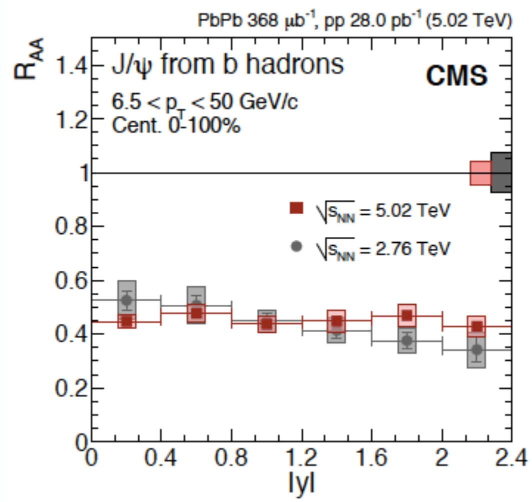




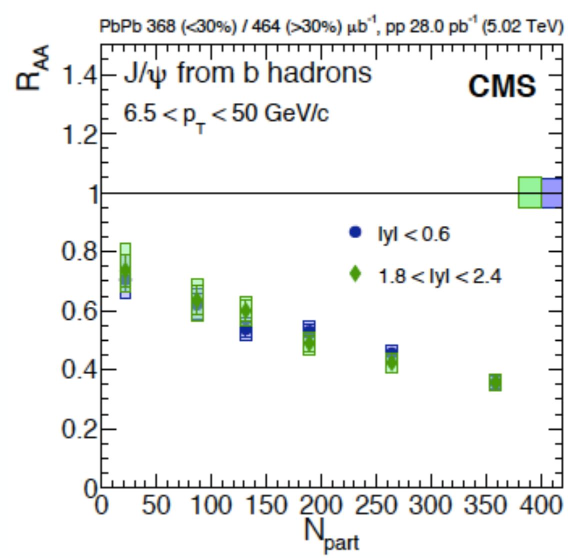
Nuclear modification factors (R_{pA} or R_{AA})

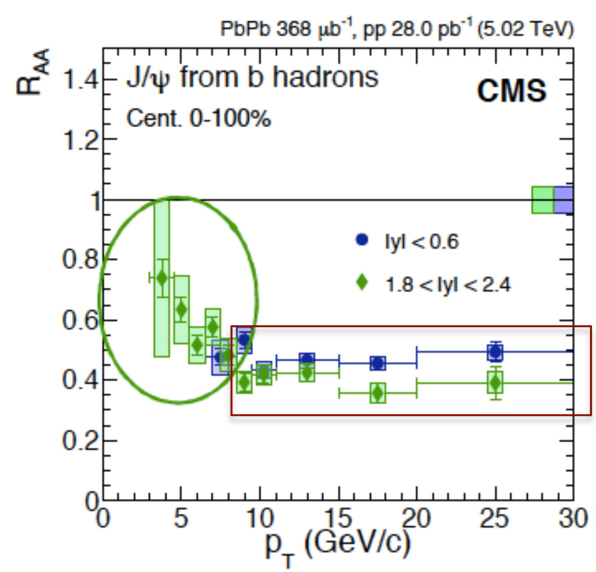
inclusive B meson

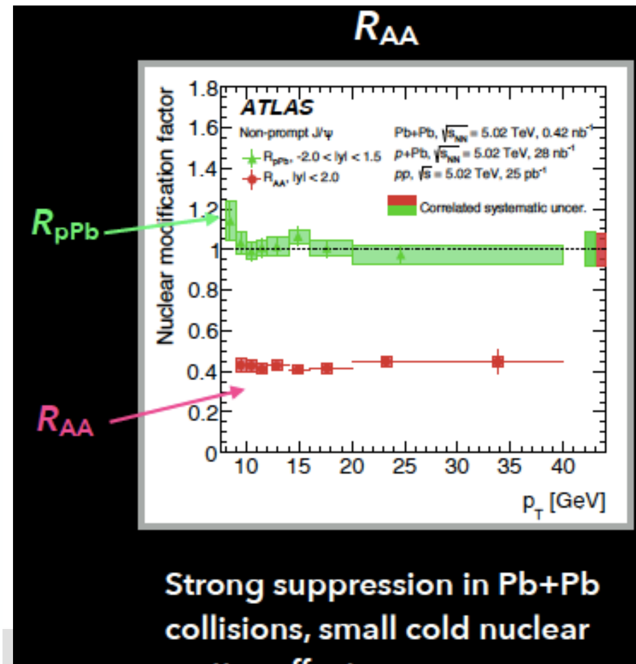




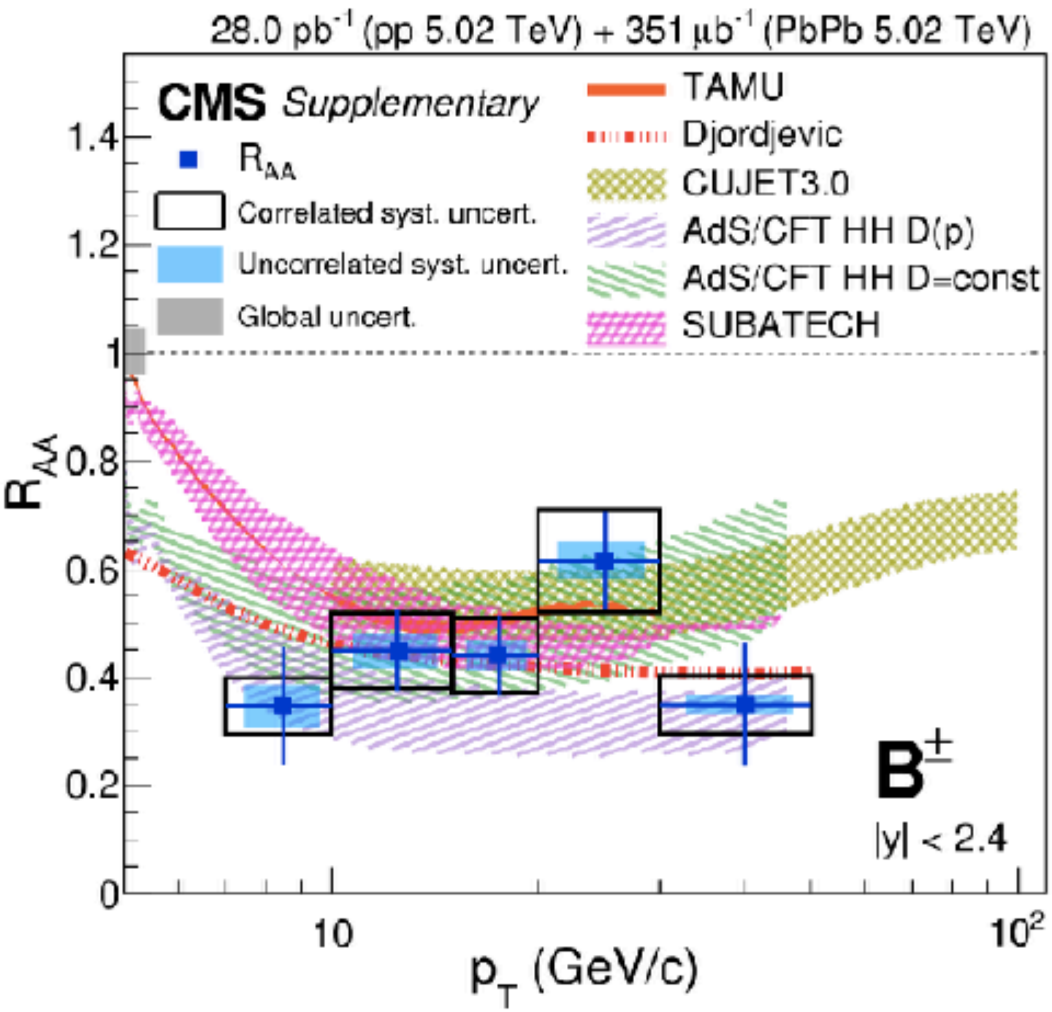
- No significant energy dependence
- no y-dependence at 5 TeV, and the results are compatible with the 2.76 TeV
- Measurement down to p_T<3 GeV at forward rapidity







B+ meson



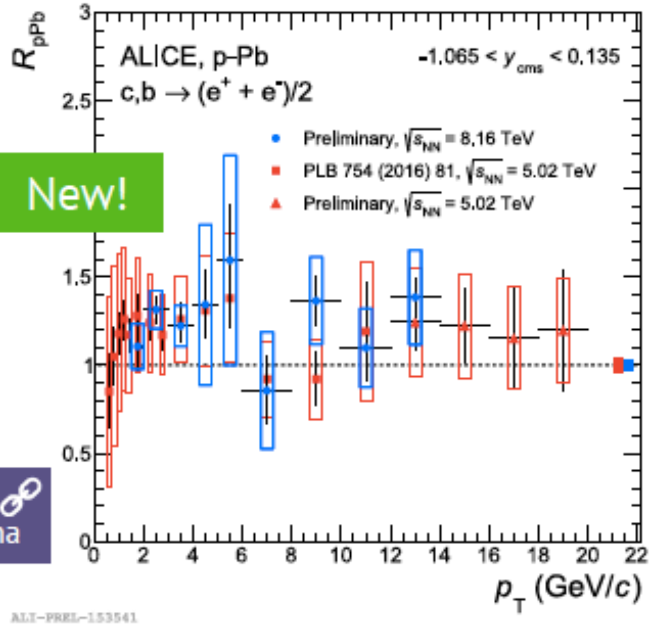
- First exclusively reconstructed in heavy-ion collisions
- Suppression of B+ meson production in PbPb collisions
- B+ meson R_{AA} ~ 0.3 to 0.6 with no obvious trend within uncertainty
- Compatible with theory prediction within uncertainty for p_T 10-50 GeV/c
- Necessity for high p_T measurement : distinguishing pQCD vs AdS/CFT base models

B->D R_{pPb}

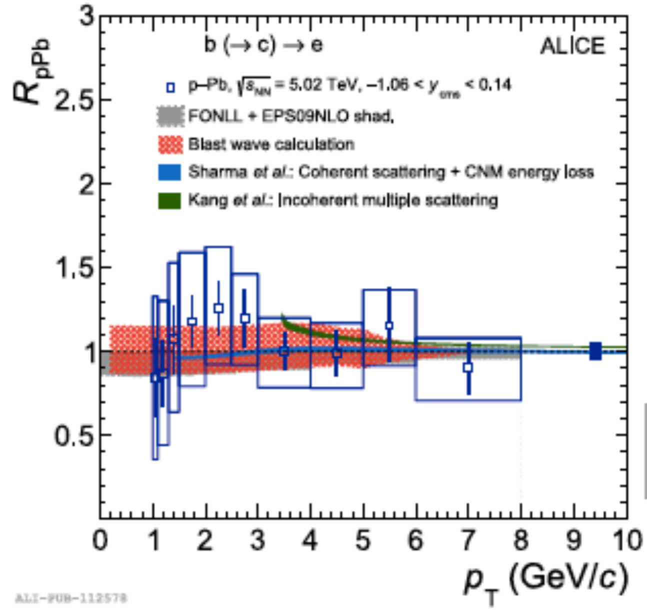
HF electron R_{pPb} at 5.02 and 8.16 TeV

ALICE

New!



Poster: D. Kawana



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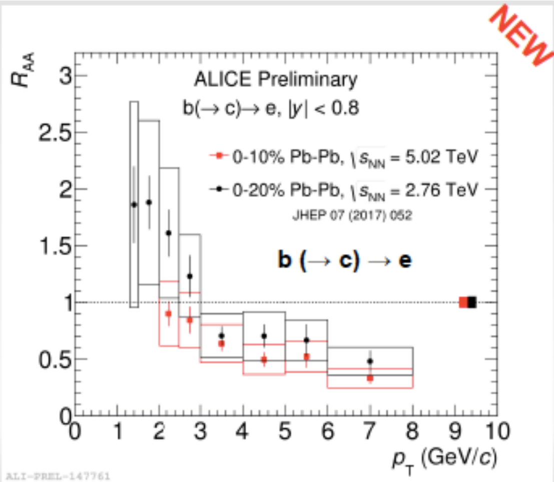
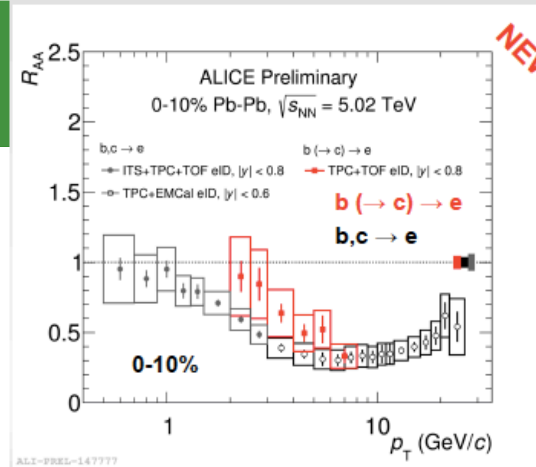
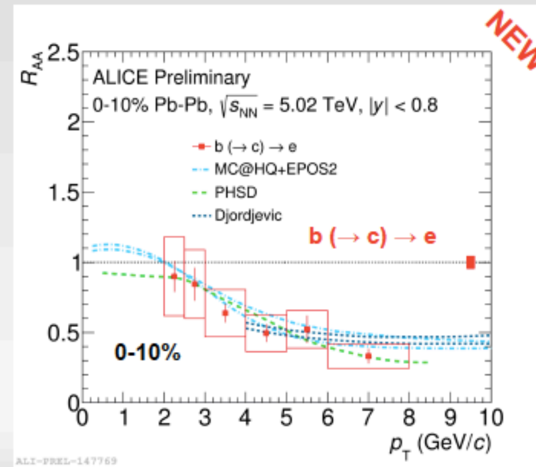
Model Ref.: check backup

- R_{pPb} is compatible with unity in all the p_T intervals
- No energy dependence within uncertainties

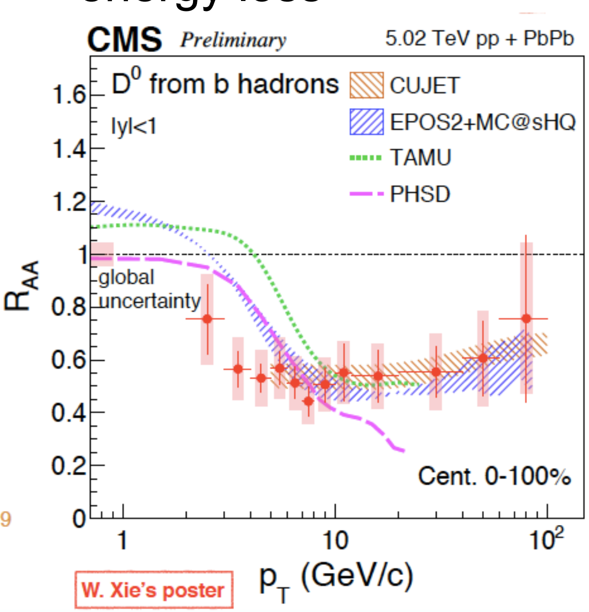
- Beauty and beauty+charm electron results are compatible within uncertainties
- Models describe well the R_{pPb}







- 2.76 TeV(0-20% centrality) -> 5.02 TeV(0-10% centrality), energy independent
- hint of a smaller suppression for beauty than charm+beauty decay electrons at the same electron pT
- large contribution to the systematic uncertainties from the rescaled pp cross section
- agreement within the uncertainties with models implementing mass-dependent energy loss

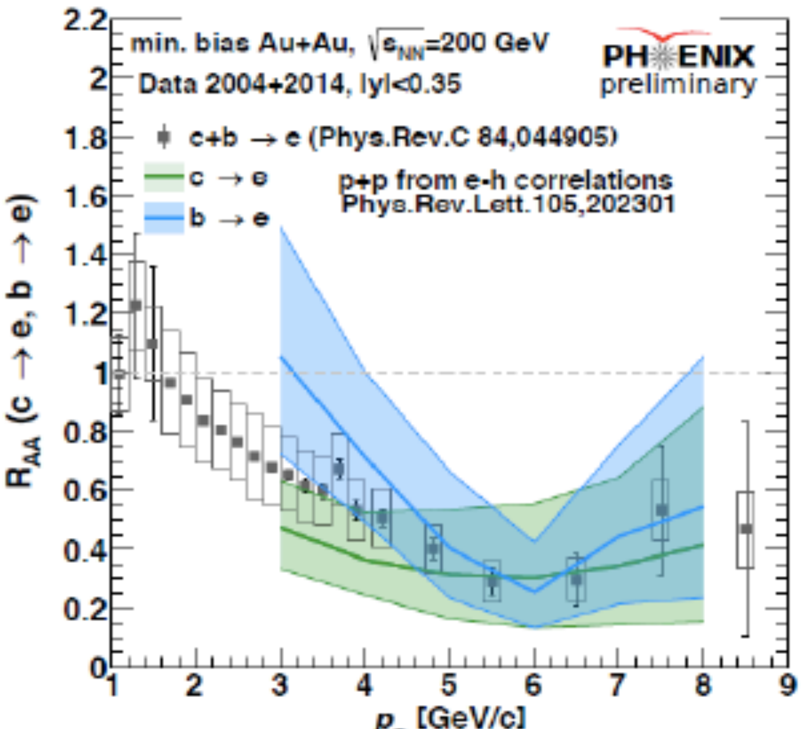


- suppression of non-prompt D production in PbPb collisions
- Compatible with theory prediction that includes both collisional and radiative energy loss (CUJET)
- The model including only collisional energy loss (PHSD), seems to predict a difference behavior compared with other models and data at high-pT

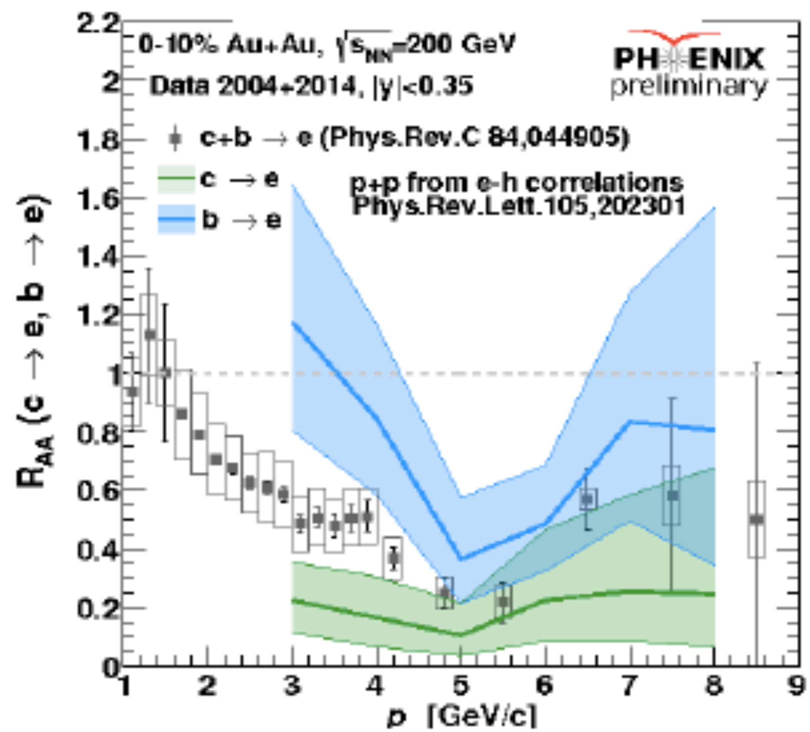
B->D R_{AA} in RHIC

$R_{AA}(b \to e)$ & $R_{AA}(c \to e)$ in Au+Au 200GeV

Min. Bias in Run2014



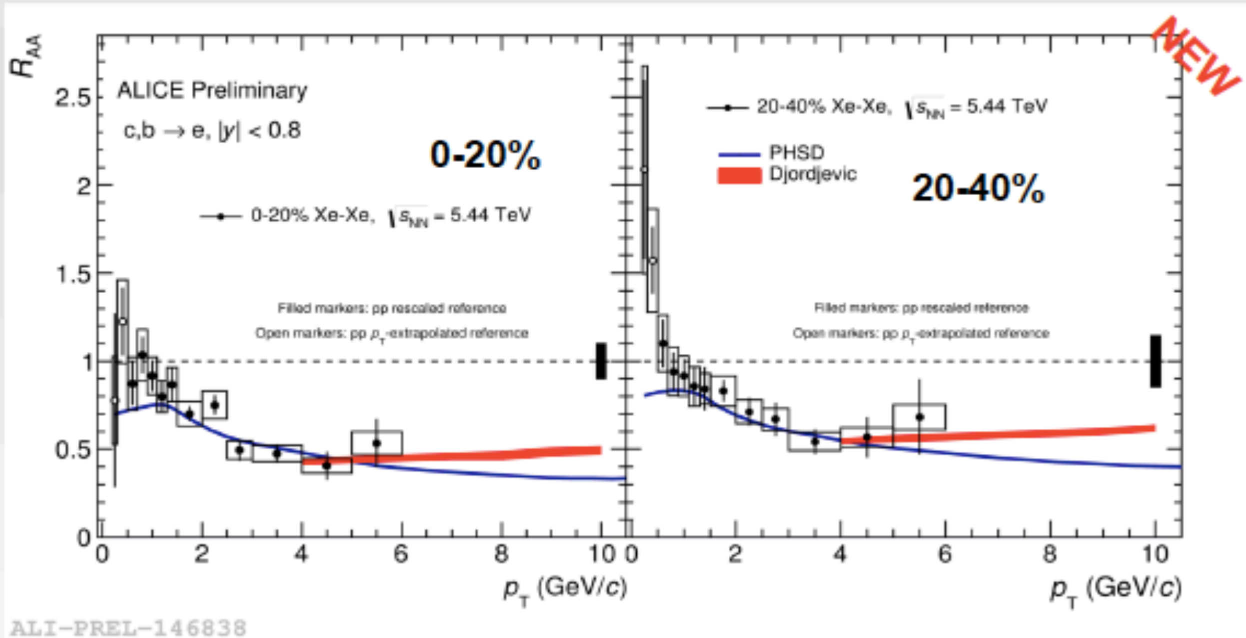
0-10% in Run2014



- In 0-10%, bottom and charm are more clearly separated
- Charm is more suppressed than MB
- Bottom is similar

Bonus! – in XeXe

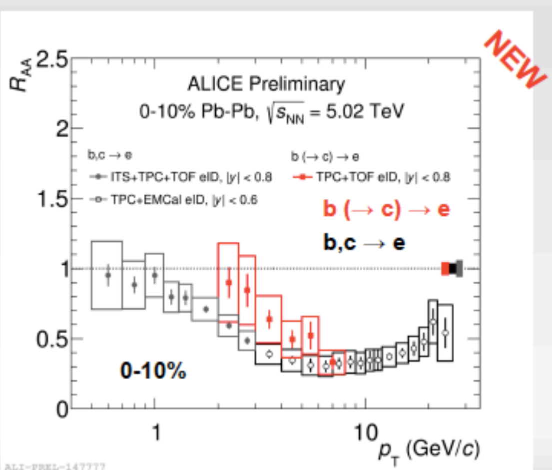
– **New R_{AA}** measured down to **p_T = 0.2 GeV/*c*** thanks to the low B field used in ALICE during the Xe-Xe data taking!



– Possible future measurement of total charm cross section in heavy-ion collisions

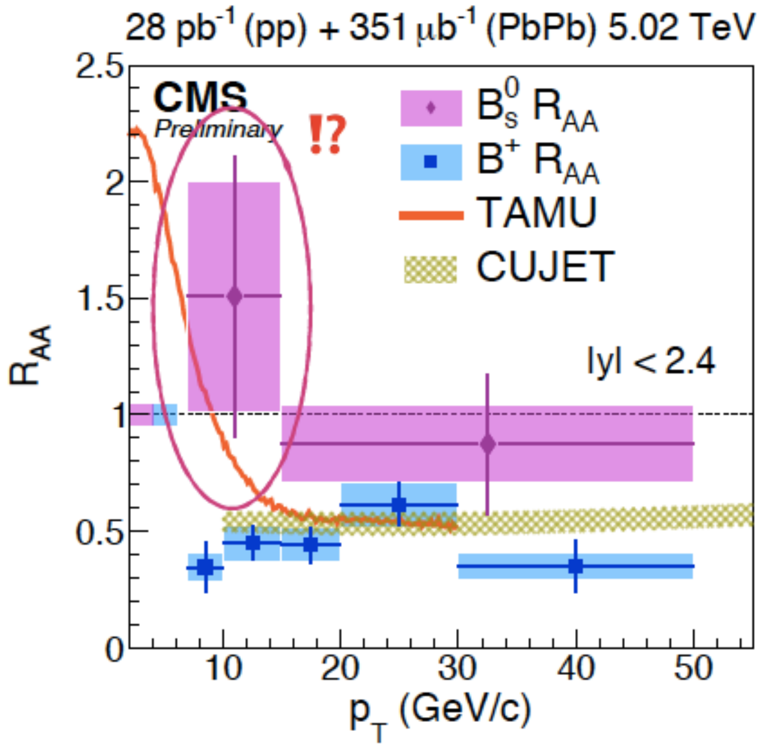
– Data are reproduced by model calculations

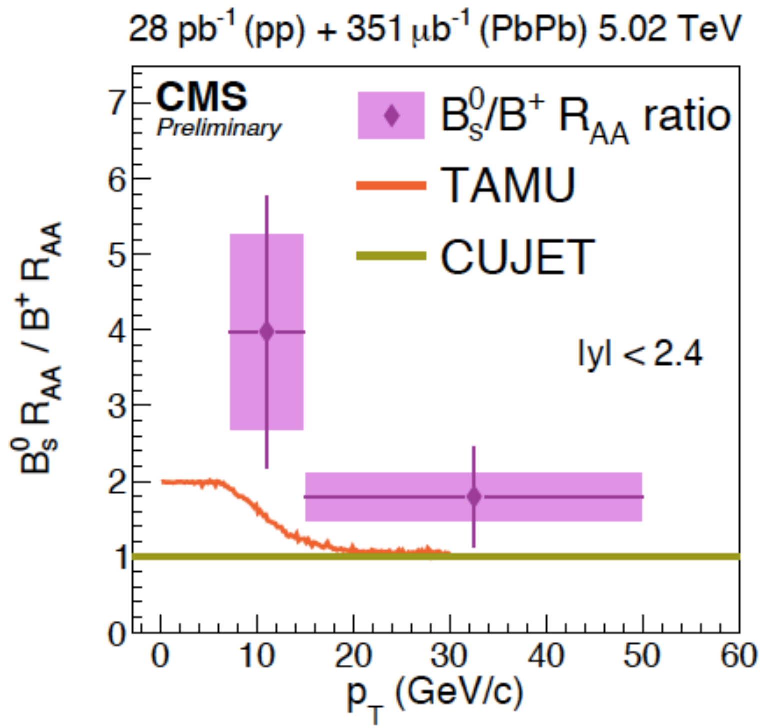
15



- R_{AA} ~ 0.5 in same p_T range between two systems?

Strangeness in B meson

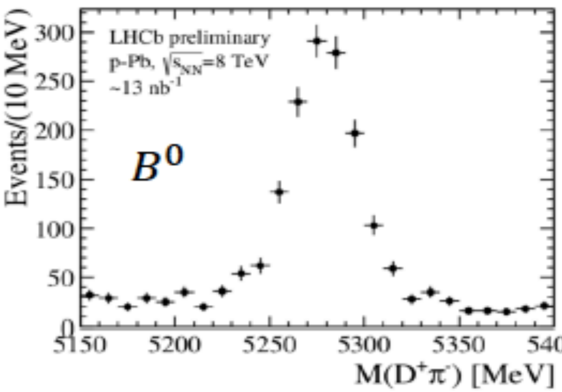


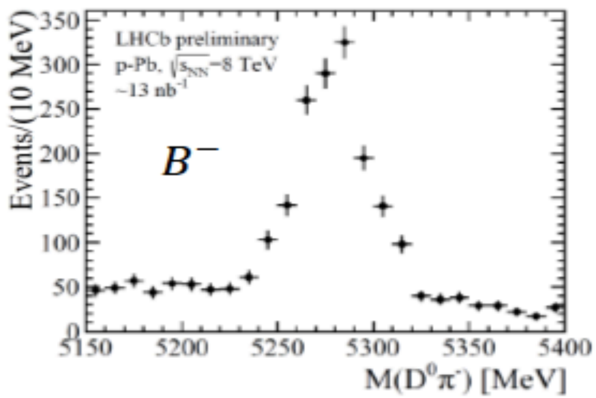


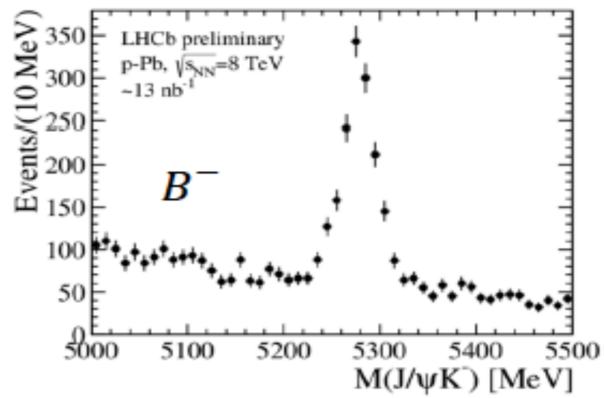
- First reconstructed in heavy-ion collisions
- Indication of less suppression of B_s comparing to B^+
- Ratio -> correlated uncertainties are cancelled

Preview from LHCb

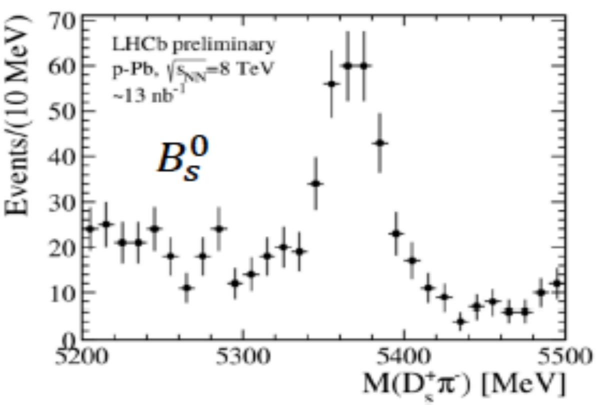
Open beauty measurements in pPb 8 TeV

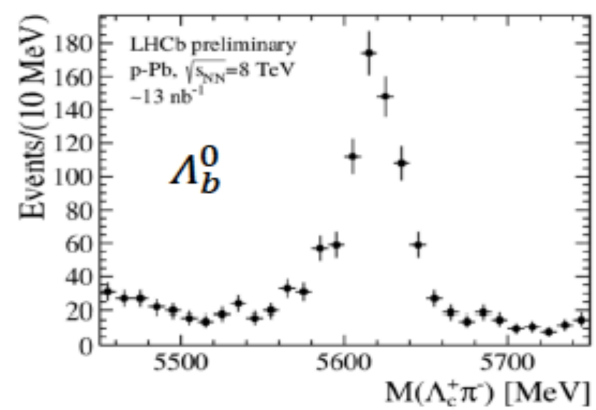




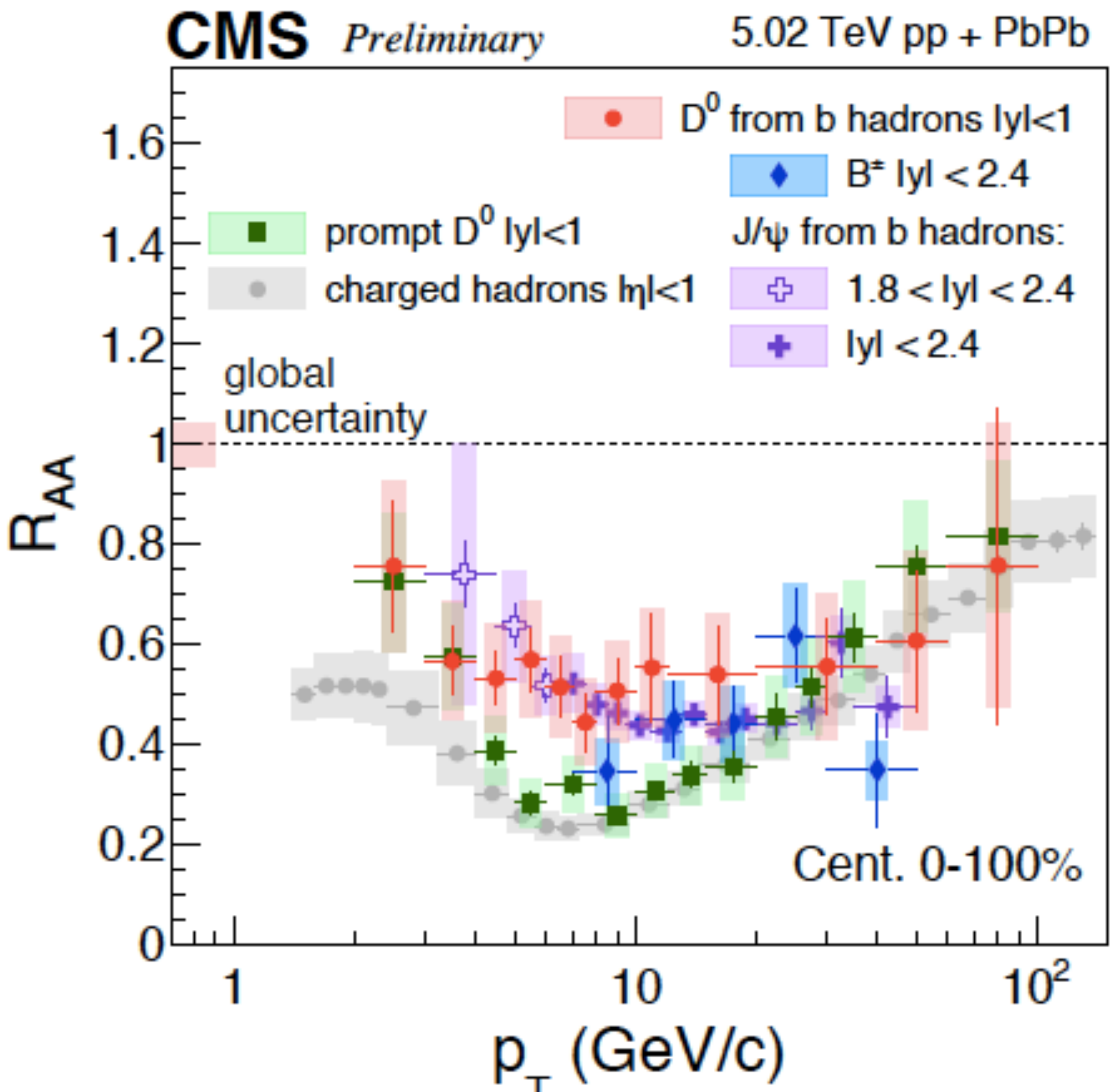


- Upcoming results on fully reconstructed b hadrons:
  - B^+, Λ_b^0 cross-sections in pPb
  - R_{FB} for B^+, Λ_b^0
  - baryon-meson ratio $R_{\Lambda_b^0/B^+}$
  - $R_{p\mathrm{Pb}}$ for B^+, Λ_b^0





Zoo with heavy flavors



- Compatible results from three beauty RAA measurements (non-prompt D, B+, and non-prompt J/ψ)
- Beauty seems to separate from charm and light flavor at ~ 20 GeV
- RAA between prompt D, charged particle, B+, non-prompt J/ψ and nonprompt D merging above ~ 20 GeV

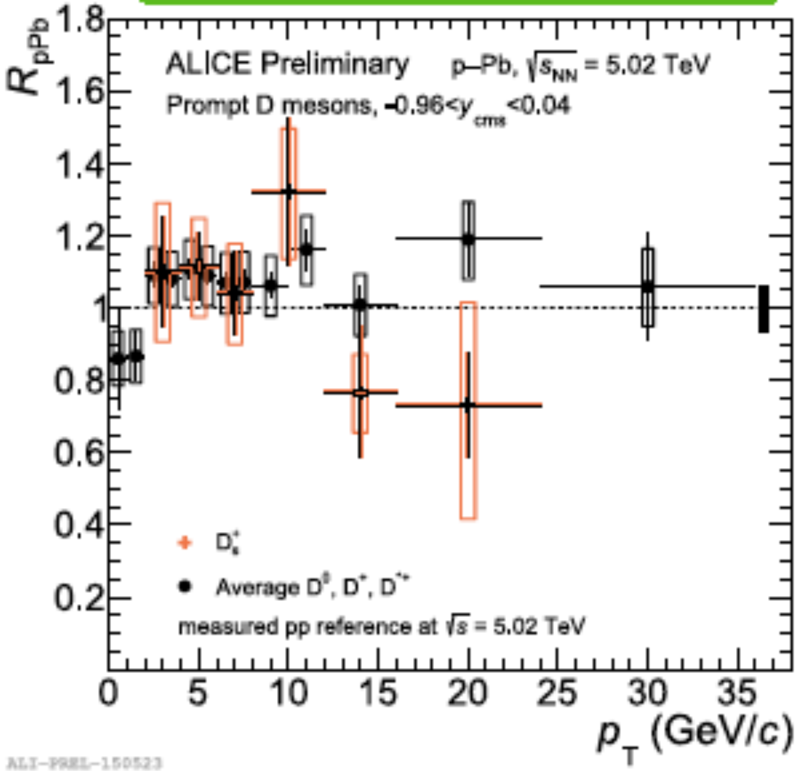
B meson (Hyunchul's summary)

- In pPb, nuclear modification factor shows unity within uncertainties
- In PbPb, we can see the suppression, independent of energy, rapidity
- Get hint of strangeness enhancement
- At high p_T, models only with collisional energy loss can't describe data well
- No significant system size dependence?
- Bottom is less suppress than Charm

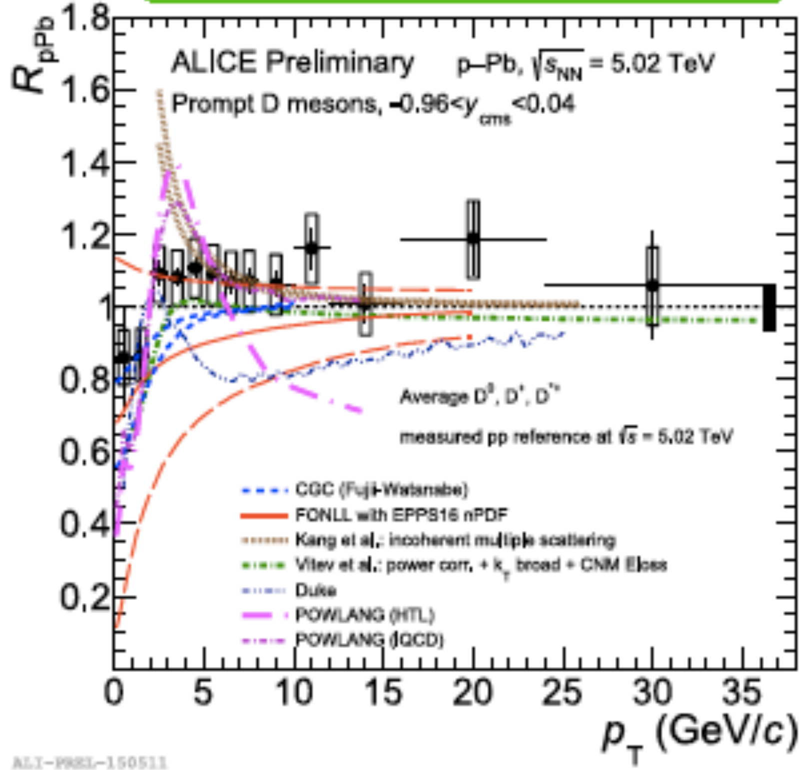
- LHCb will prepare exclusive B meson measurement in 8.16 TeV pPb

Prompt D meson R_{pA}

New pp reference at 5.02 TeV!



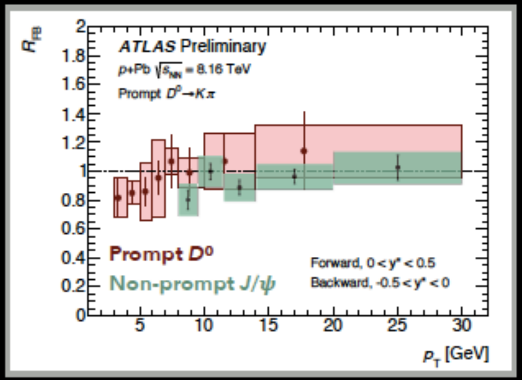
New pp reference at 5.02 TeV!



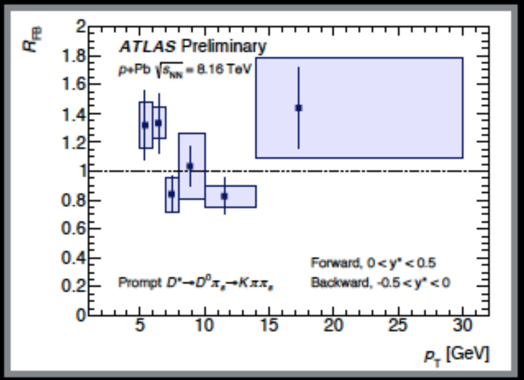
- D^+_s R_{pPb} compatible with D-meson R_{pPb}
- Both compatible with unity
- More stringent constraints to models at low *p*T

D^0 R_{pA}, R_{FB}

Prompt *D*⁰



Prompt *D**



- Forward: 0 < y* < 0.5, Backward: -0.5 < y* < 0
- No obvious modification in forward wrt. backward for prompt *D*
- Prompt *D* ~ Non-prompt J/ψ

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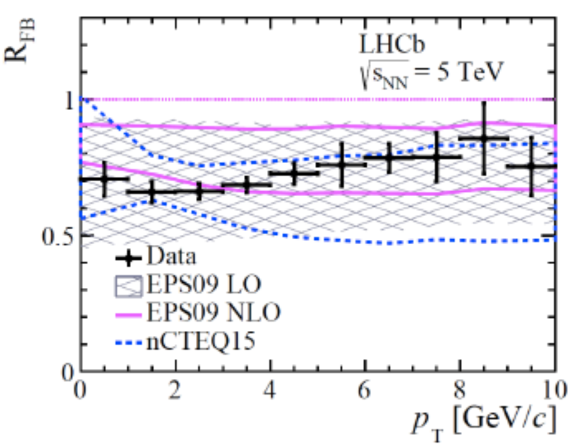
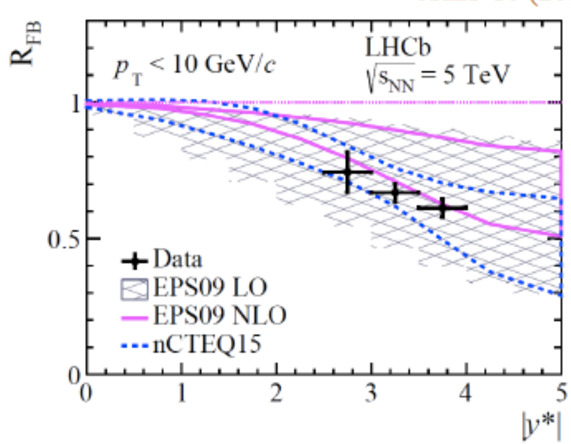




Eur. Phys. J. C77 (2017) 1

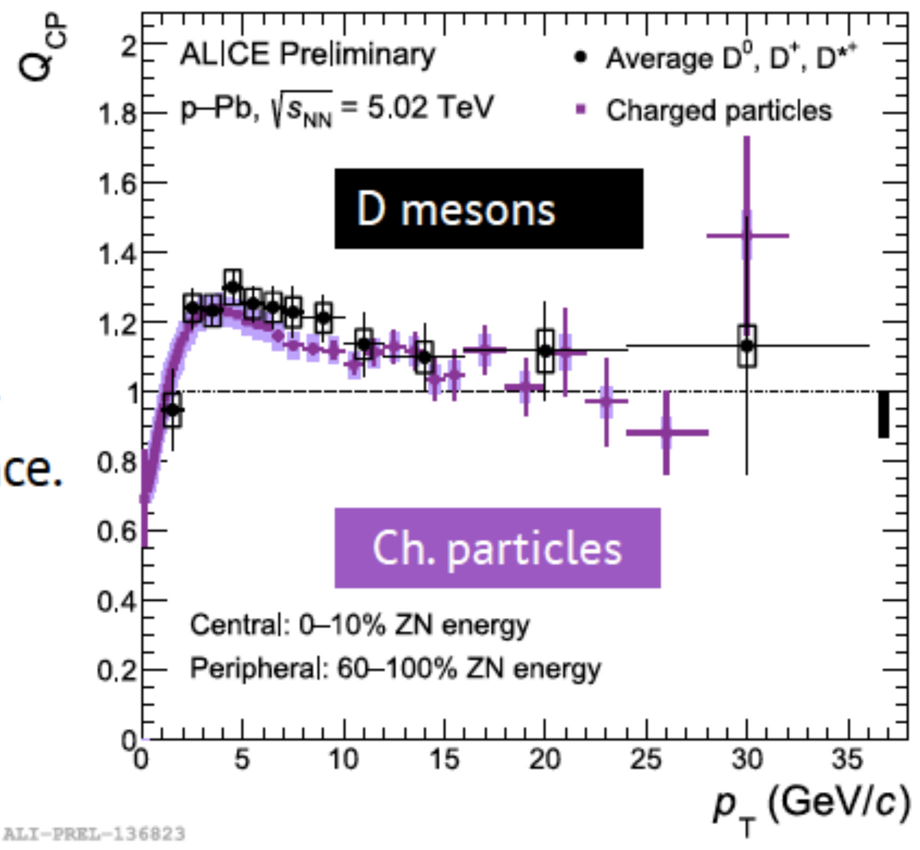
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238

D-meson production central/peri.

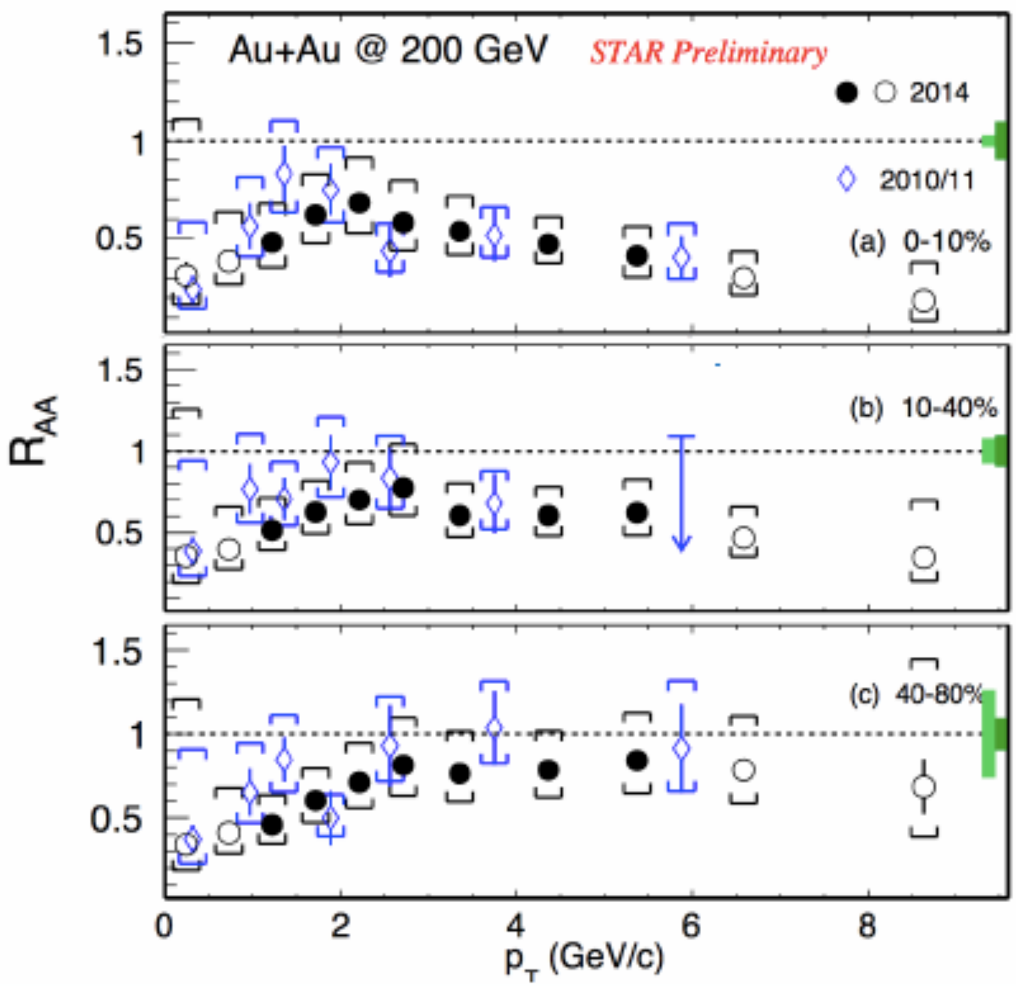
$$Q_{cp} = \frac{\dfrac{d^2N^{central}_{pPb}/dp_T}{\langle T^{central}_{pPb}\rangle}}{\dfrac{d^2N^{peri}_{pPb}/dp_T}{\langle T^{peri}_{pPb}\rangle}}$$

- Hint of $Q_{CP} > 1$ in $3 < p_T < 8$ GeV/c for D mesons with 1.5σ significance. Initial- or final-state effect?
- D-meson Q_{CP} similar to charged particles

Posters:
C. Bedda
C. Terrevoli



D^0 R_{AA} - RHIC



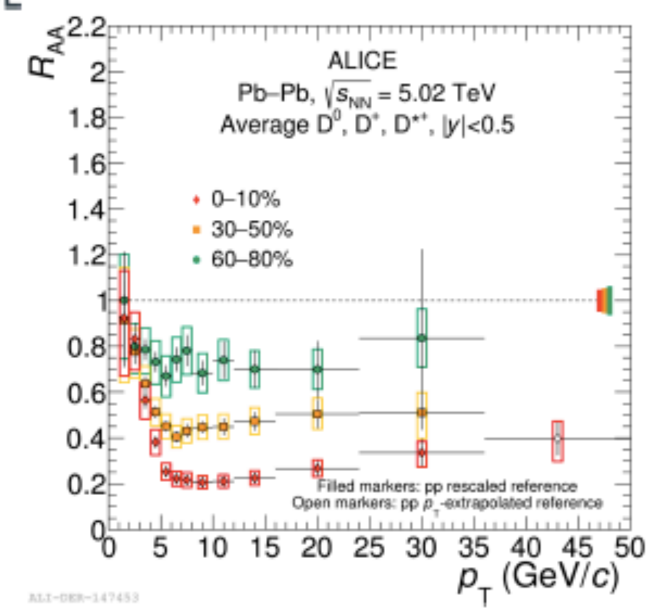
- R_{AA} in central events < 1 at all p_T
- Suppression at high p_T increases with centrality

ALICE, D meson R_{AA}

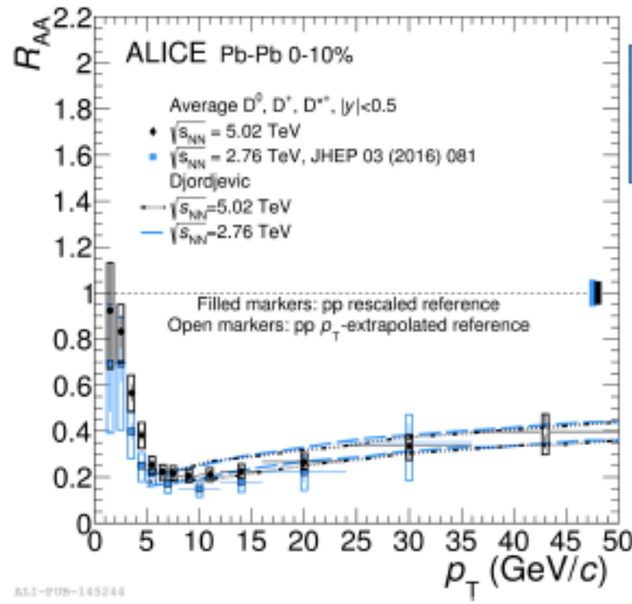
Poster ID: 45 by F.Grosa

[1] Djordjevic, Phys. Rev. C92 (2015) 024918

D meson R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



60-80%
30-50%
0-10%



Improved precision in Run-2 with respect to Run-1 measurements

Submitted!

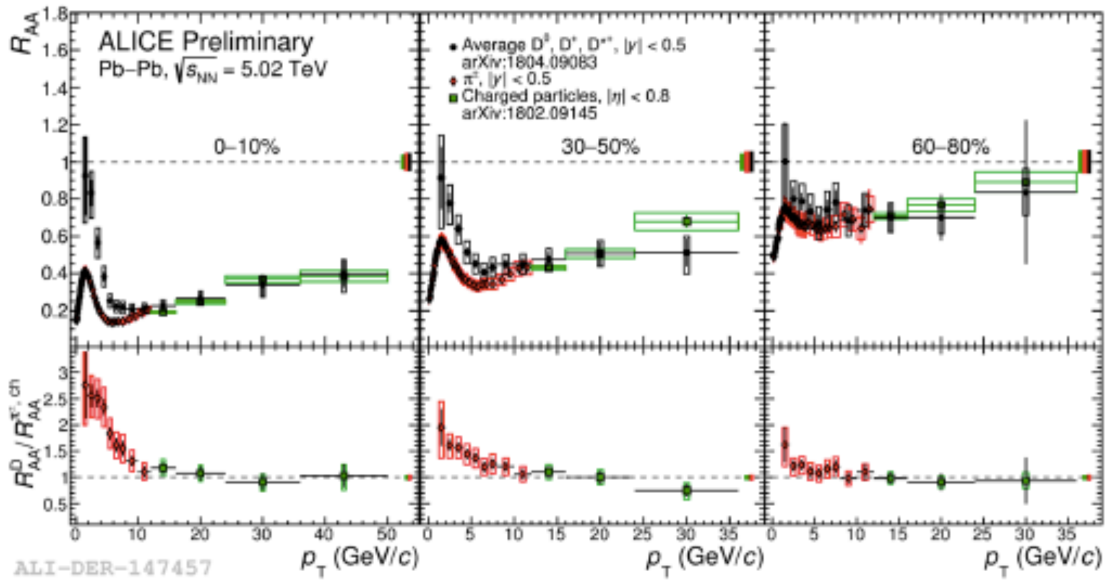
0-10%

arXiv:1804.09083

- **Strong suppression** of non-strange D meson in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, increasing with centrality
- Similar suppression between $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV
  - ➢ Described by model [1] at two energies -> **harder spectra and denser medium counterbalance**

ALICE, D meson R_{AA}

D-meson and charged-particle R_{AA} comparison



Submitted!

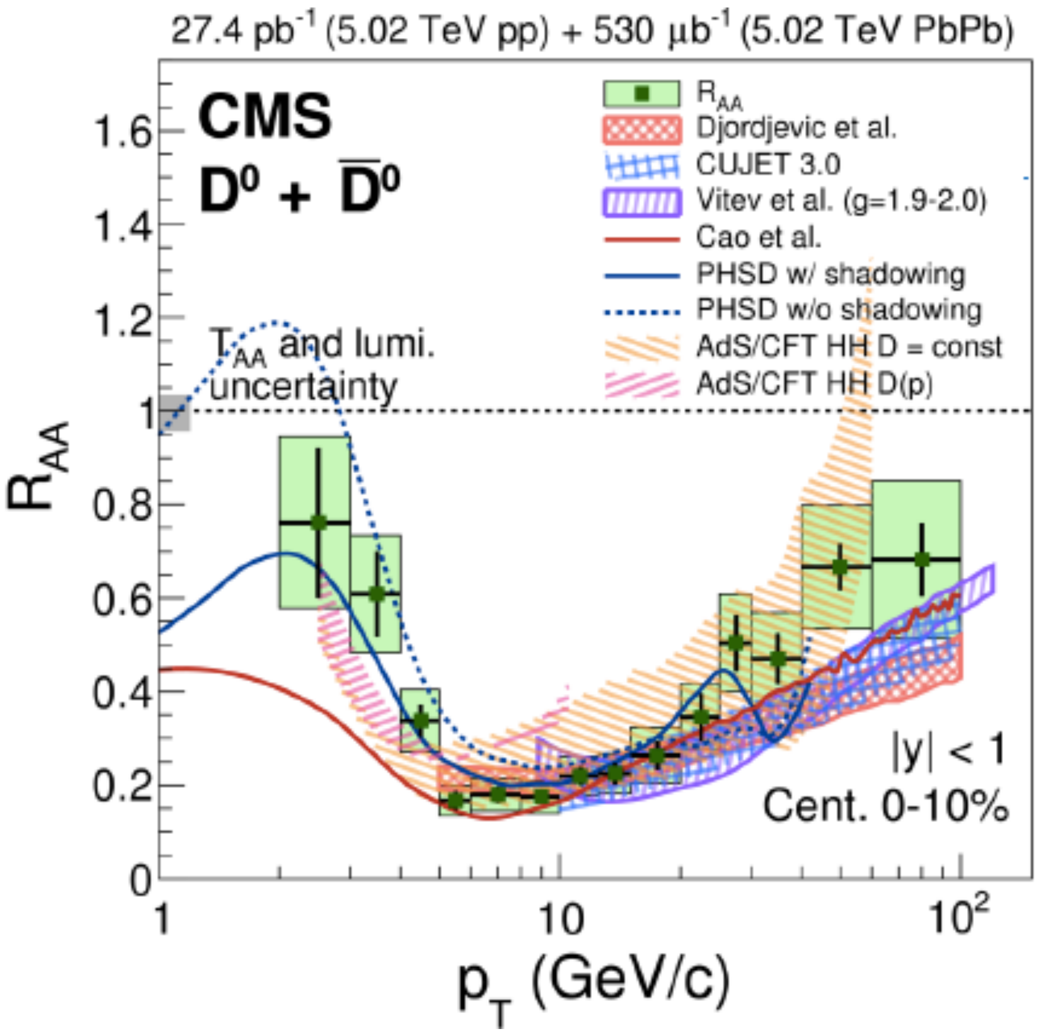
$\pi^{\pm}$ ALICE preliminary

Charged-particle: arXiv:1802.09145

arXiv:1804.09083

- Similar D-meson, $\pi^{\pm}$ and charged-particle R_{AA} result for $p_T > 10$ GeV/c in 0-10% and 30-50%, compatible results in 60-80% for $p_T > 1$ GeV/c
- D-meson R_{AA} larger than that of charged pions at low p_T for 0-10% and 30-50% centrality classes
  - Not straightforward interpretation: N_{part} vs N_{coll} scaling at low p_T, different fragmentation and initial spectra shapes, possible mass and Casimir factor effects, different impact of coalescence and radial flow

CMS, D^0 meson R_{AA}



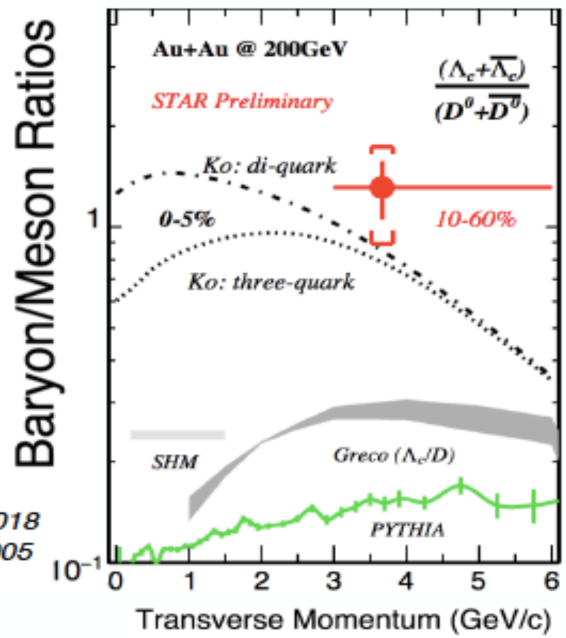
- Seen increasing trends, going to higher p_T
- Charm quarks lose a significant fraction of energy in the QGP medium
- RAA minimal near pT ~ 10 GeV/c and then increases
- at high pT, both pQCD and Ads/CFT predictions reasonably agree with data
- at low pT, PHSD with shadowing describes our data better

Λ_c (udc, 2.29 GeV/c)

Λ_c and Heavy Flavor Hadronization

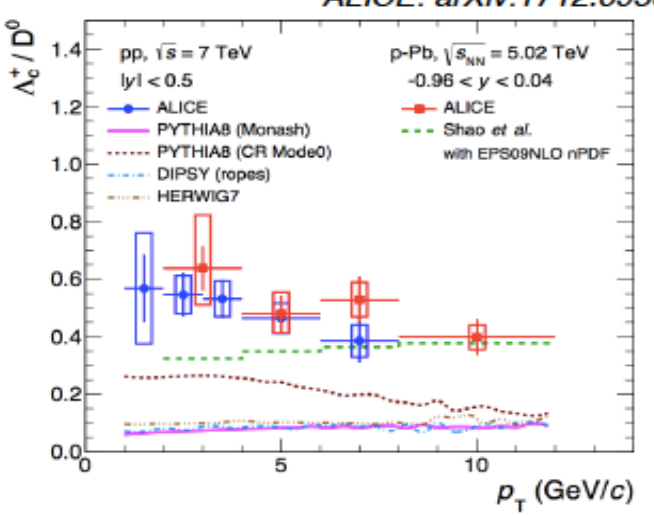
- Strong enhancement of Λ_c/D^0 ratio seen in Au+Au collisions by STAR
  - Enhancement predicted from coalescence hadronization
- An enhancement relative to PYTHIA also seen in p+p and p+Pb collisions at LHC

STAR: QM17



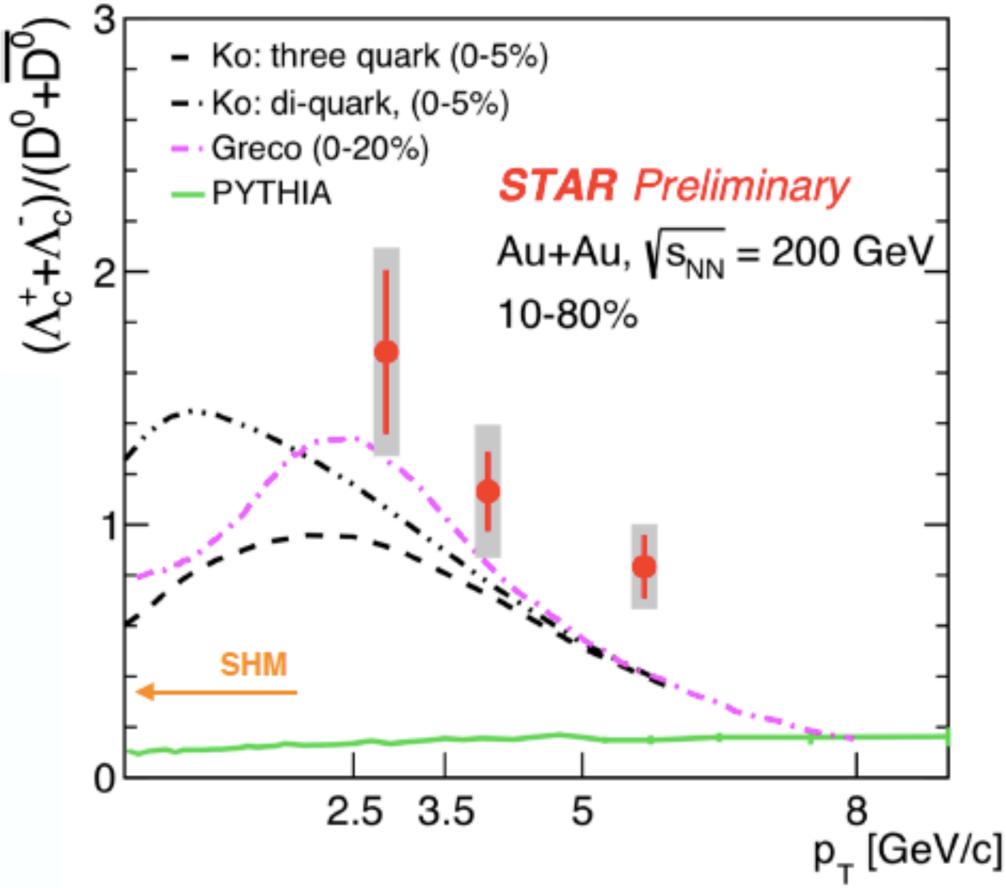
Ko: PRC 79 (2009) 044905
Greco: PRD 90 (2014) 054018
SHM: PRC 79 (2009) 044905

ALICE: arXiv:1712.09581



- How does Λ_c production change from peripheral to central A+A collisions?
- What is the p_T dependence of Λ_c production in A+A collisions?

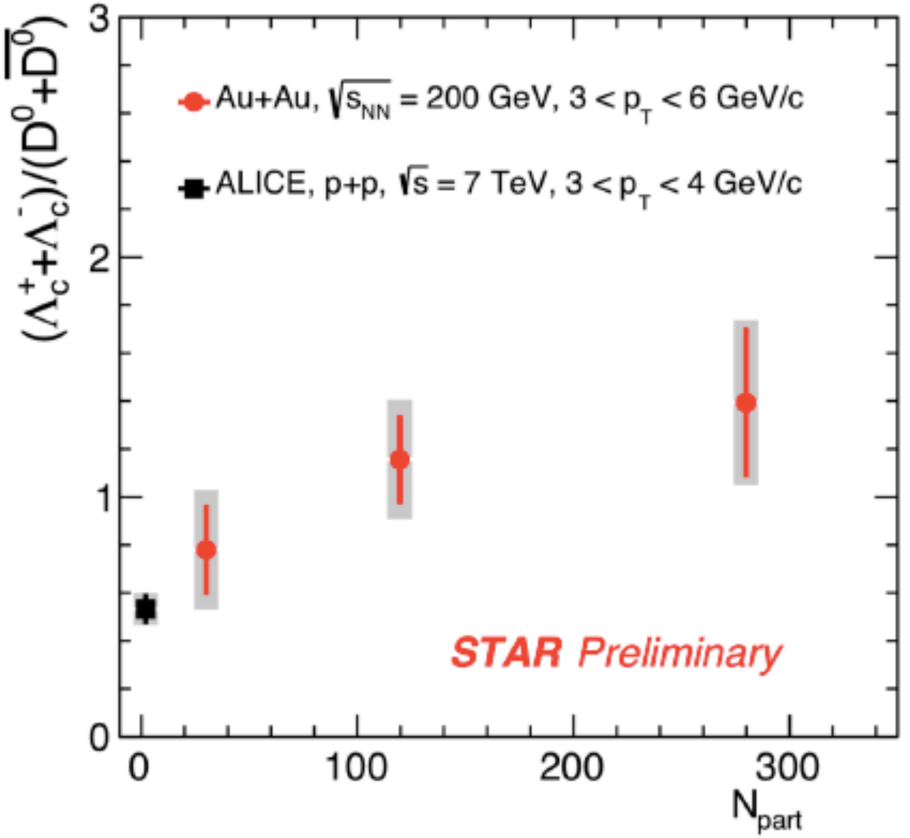
p_T Dependence of Λ_c/D^0 Ratio



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

- Strong enhancement of Λ_c production compared to PYTHIA calculations
- Enhancement increases towards low p_T
- Coalescence model predictions are closer to data, but the observed enhancement is larger than that predicted by models, particularly at higher p_T
- Ratio not described by Statistical Hadronization Models

Centrality Dependence of Λ_c Production

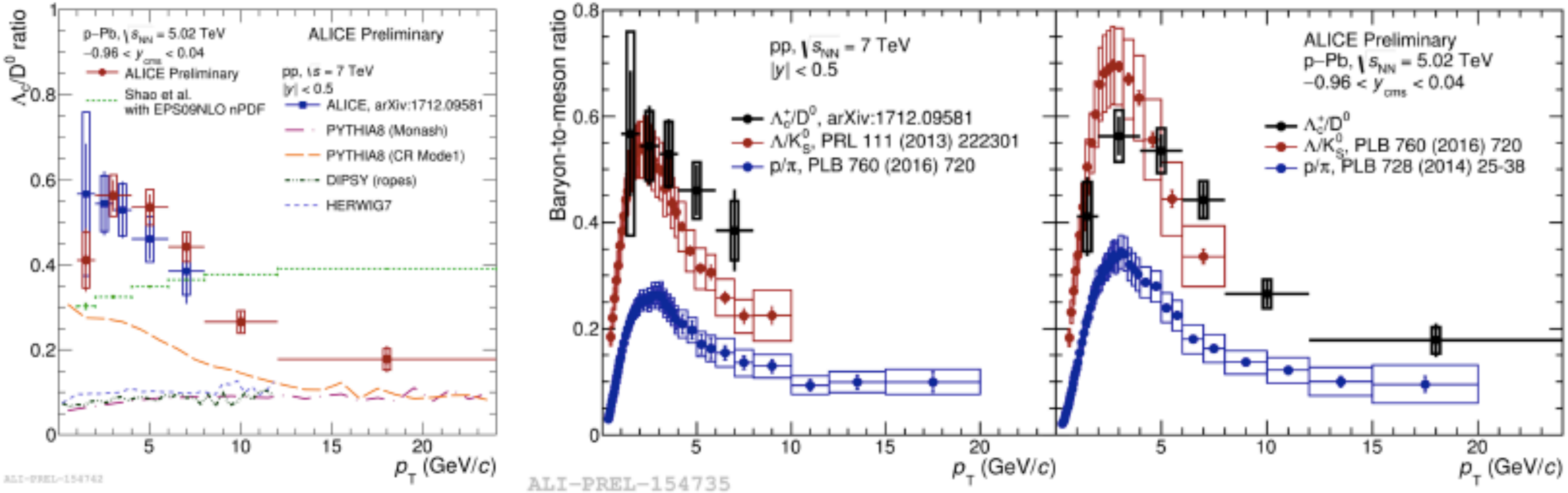


ALICE: arXiv:1712.09581

- First measurement of centrality dependence of Λ_c production in heavy-ion collisions
- Λ_c/D^0 ratio increases from peripheral to central, indicative of hot medium effects
- Ratio for peripheral Au+Au consistent with p+p values at 7 TeV

Λ_c^+/D^0 ratio in pp and p-Pb

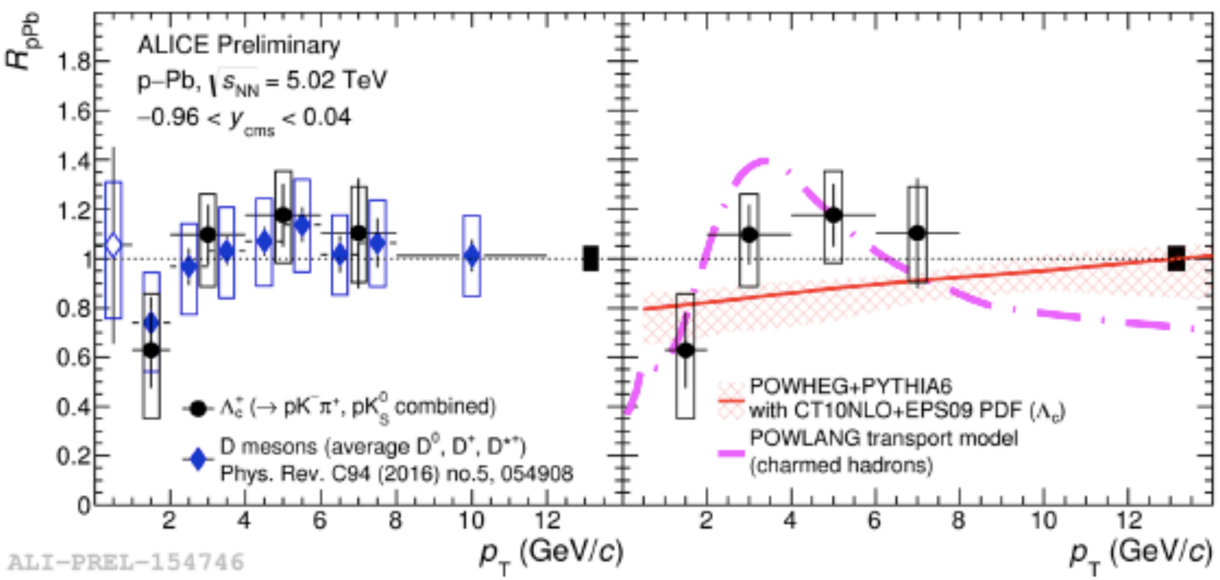
New!



- Λ_c^+/D^0 compatible within uncertainties in pp and p-Pb collisions
- Λ_c^+/D^0 ratio **higher than expectation** from MC (PYTHIA8 with enhanced colour reconnection closer to data)
- New, more precise, preliminary result in p-Pb collisions shows decreasing values from p_T = 4 GeV/c. Trend similar to baryon-to-meson ratio in the light-flavour sector

$\Lambda_c^+ \; R_{\mathrm{pPb}}$

POWHEG+PYTHIA6 with CT10NLO+EPS09 PDF: JHEP 09 (2007) 126, Phys. Rev. D82 (2010) 074024, JHEP 04 (2009) 065
POWLANG: JHEP 03 (2016) 123



$$R_{\mathrm{pA}} = \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

New!

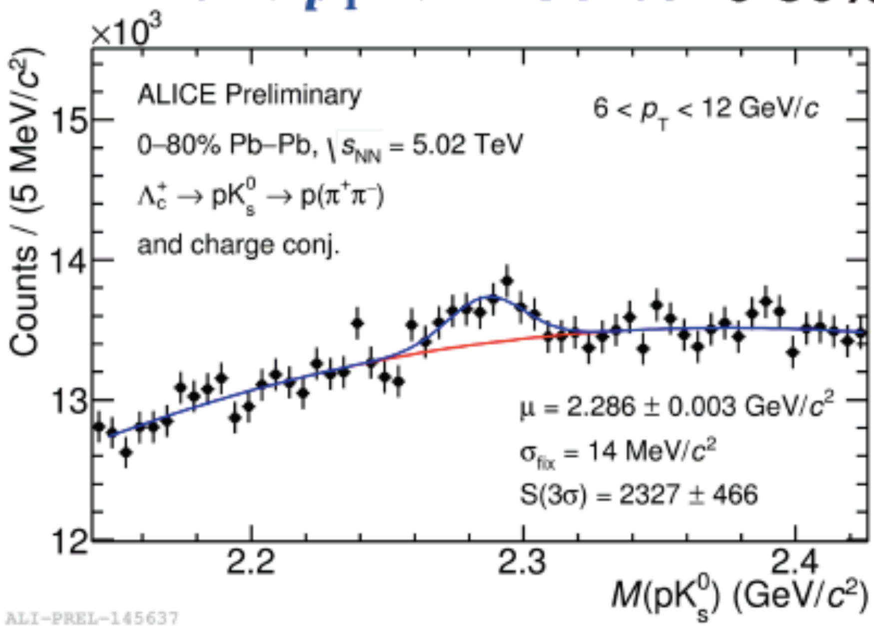
- R_{pPb} of Λ_c^+ consistent with unity, D-meson R_{pPb} and models within uncertainties:
  - **CNM effects**: POWHEG+PYTHIA with CT10NLO+EPS09 PDF
  - **Hot medium effects**: POWLANG with ‘small-size’ QGP formation, collisional energy loss

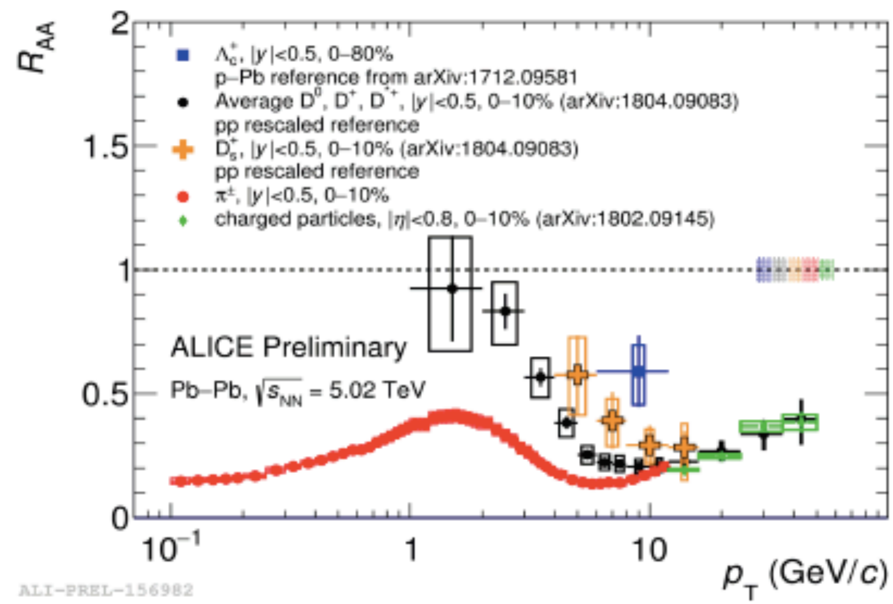
Poster ID: 132 by Y.Watanabe

Λ_c^+ invariant mass and R_{AA} in Pb-Pb

$6 < p_T < 12$ GeV/c 0-80%

New!





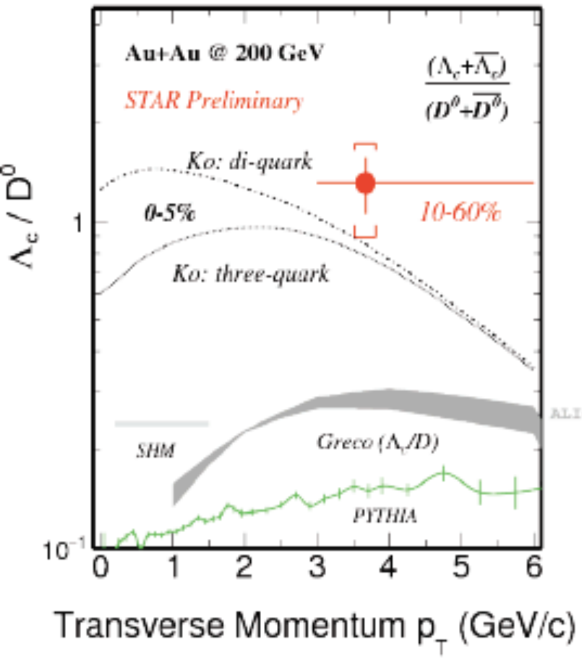
- Hint of larger R_{AA} for Λ_c^+ at 0-80% than D meson at 0-10%
  - Hierarchy Λ_c^+ R_{AA} > D_s^+ R_{AA} > non-strange D-meson R_{AA} > pion R_{AA}?

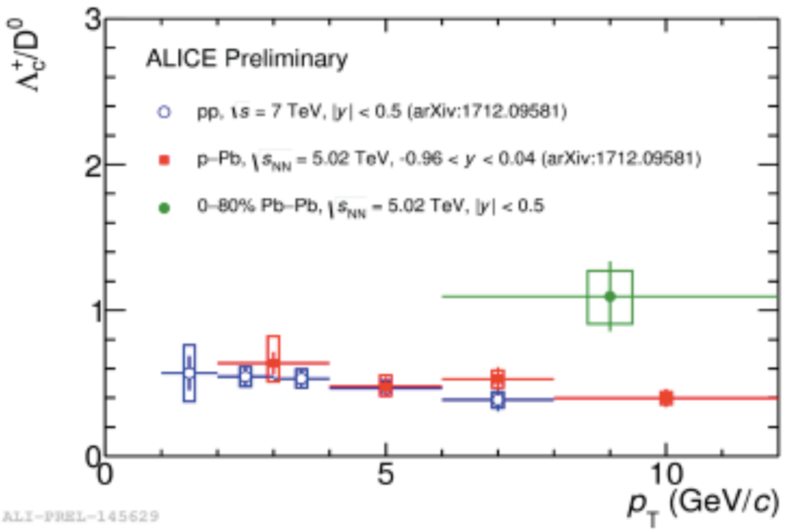
Baryon Meson

Strangeness

Λ_c^+/D^0 ratio in Pb-Pb

Oh et al.: Phys.Rev. C79(2009) 044905
Ghosh et al: Phys.Rev. D90 no.5, (2014) 054018
Das et al: Phys.Rev. D94 no.11, (2016) 114039
Plumari et al: Eur.Phys.J.C (2018) 78:348
STAR Preliminary: Nucl. Phys. A967, 928 (2017), 1704.04353





New!

Models	System energy	Λ_c^+/D^0
Oh et al.	Au-Au (central) 200 GeV	~0.35 (p_T = 6 GeV/c)
Ghosh et al.	RHIC and LHC	0.15-0.2 (p_T = 9 GeV/c)
Das et al.	Pb-Pb (0-20%) 5.5 TeV	~0.2 (p_T = 9 GeV/c)
Plumari et al.	Pb-Pb (0-20%) 2.76 TeV	0.1-0.2 (p_T = 8 GeV/c)

- Λ_c^+/D^0 ratio measured in Pb-Pb, hint of enhancement w.r.t pp and p-Pb
- Models tend to **underestimate** the data
- Similar value than that measured by STAR at low p_T in Au-Au @ 200 GeV

Λ_c^+/D^0 ratio in Pb-Pb

Oh et al.: Phys.Rev. C79(2009) 044905
Ghosh et al: Phys.Rev. D90 no. 5, (2014) 054018
Das et al: Phys.Rev. D94 no. 11, (2016) 114039
Plumari et al: Eur.Phys.J.C (2018) 78:348
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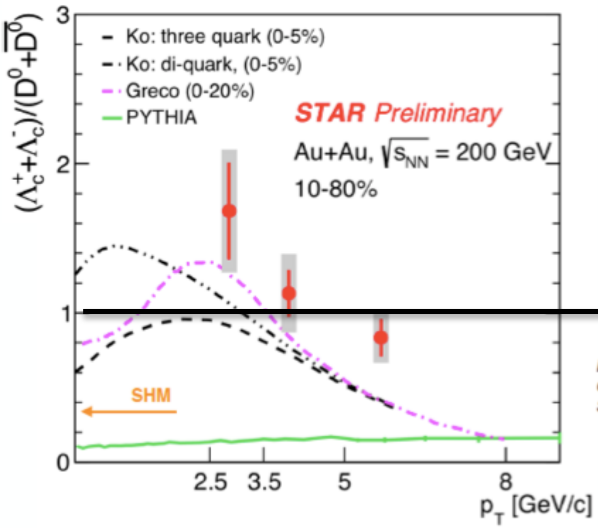

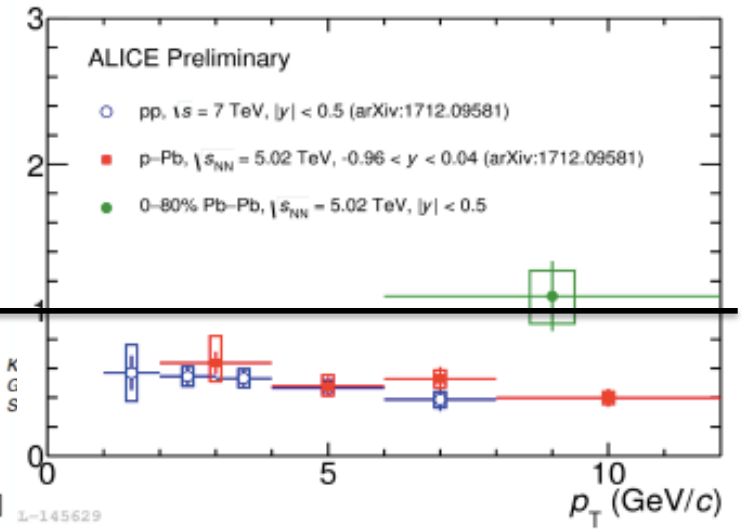

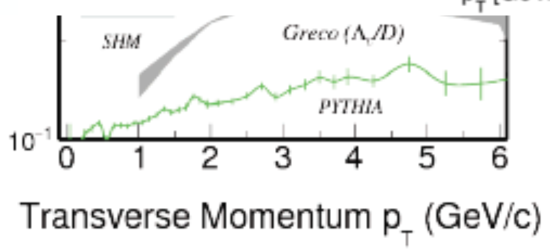

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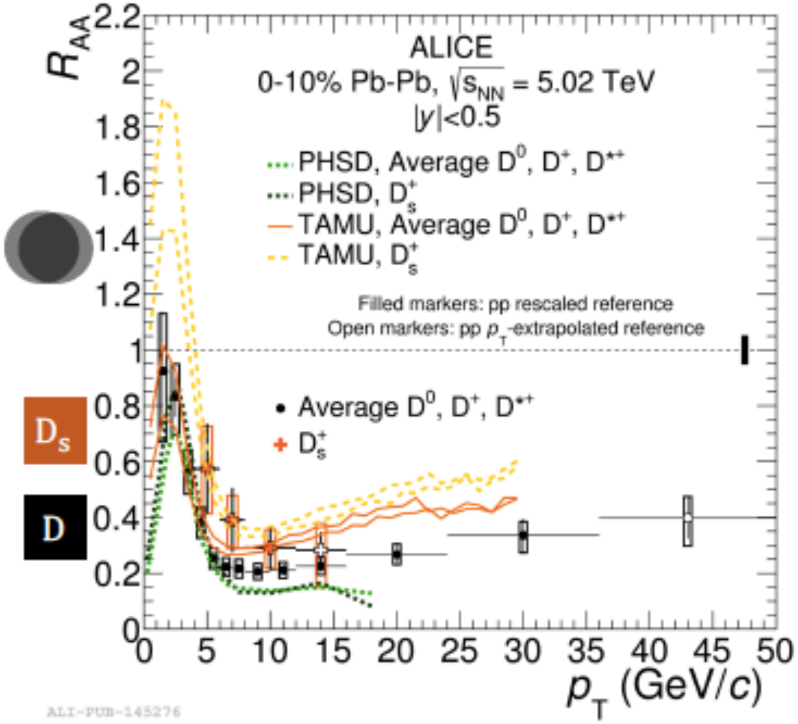
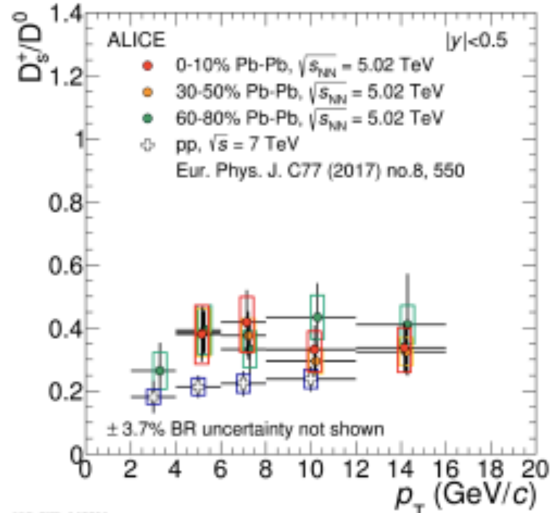
consistent STAR and ALICE?

strange and non-strange D-meson R_{AA}

PHSD: Phys. Rev. C93 no. 3, (2016) 034906
TAMU: Phys.Lett. B735 (2014) 445–450
Catania: Eur.Phys.J.C (2018) 78:348



arXiv:1804.09083



Submitted!

- Hint of **enhanced** D_s production in comparison to non-strange D mesons in Pb-Pb collisions. Expected from models
  - ➢ **Effect of coalescence + strangeness enhancement?**

PHSD: Phys. Rev. C93 no. 3, (2016) 034906
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ALICE

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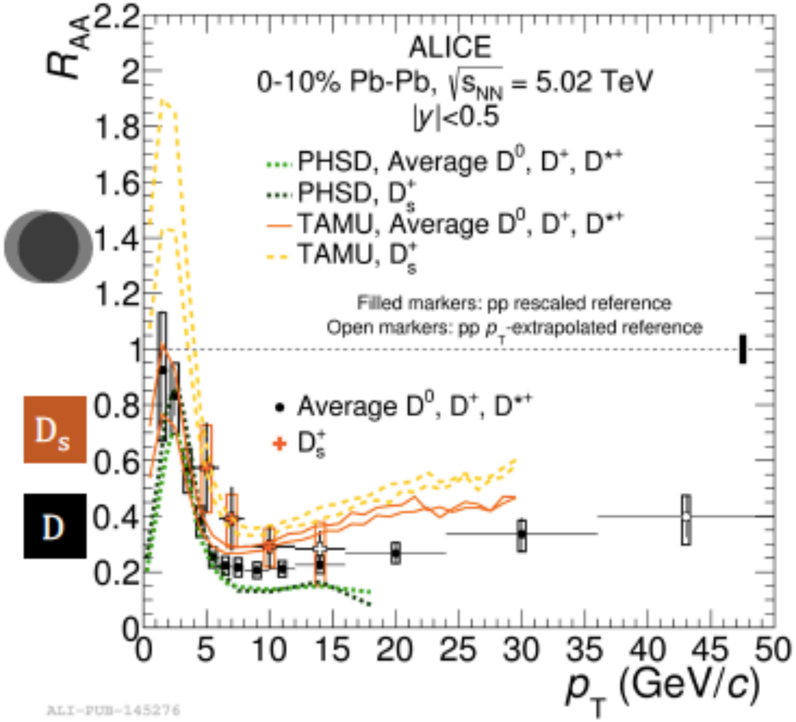
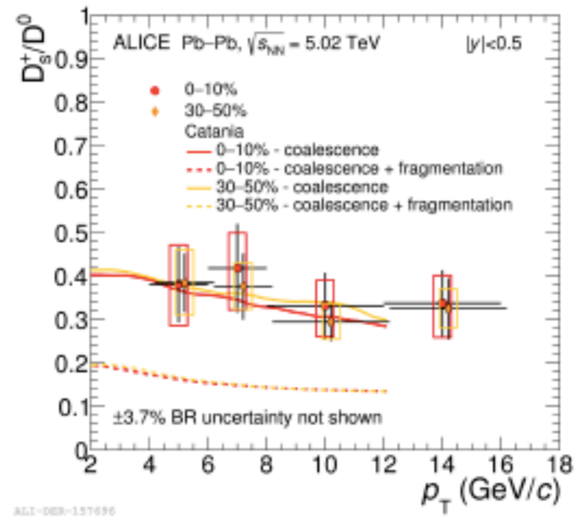


arXiv:1804.09083



Submitted!

- Hint of **enhanced** D_s production in comparison to non-strange D mesons in Pb-Pb collisions. Expected from models
  - ➢ **Effect of coalescence + strangeness enhancement?**
- D_s/D^0: no evidence for centrality dependence within uncertainties
  - ➢ Negligible centrality-dependence expected by pure-coalescence scenario

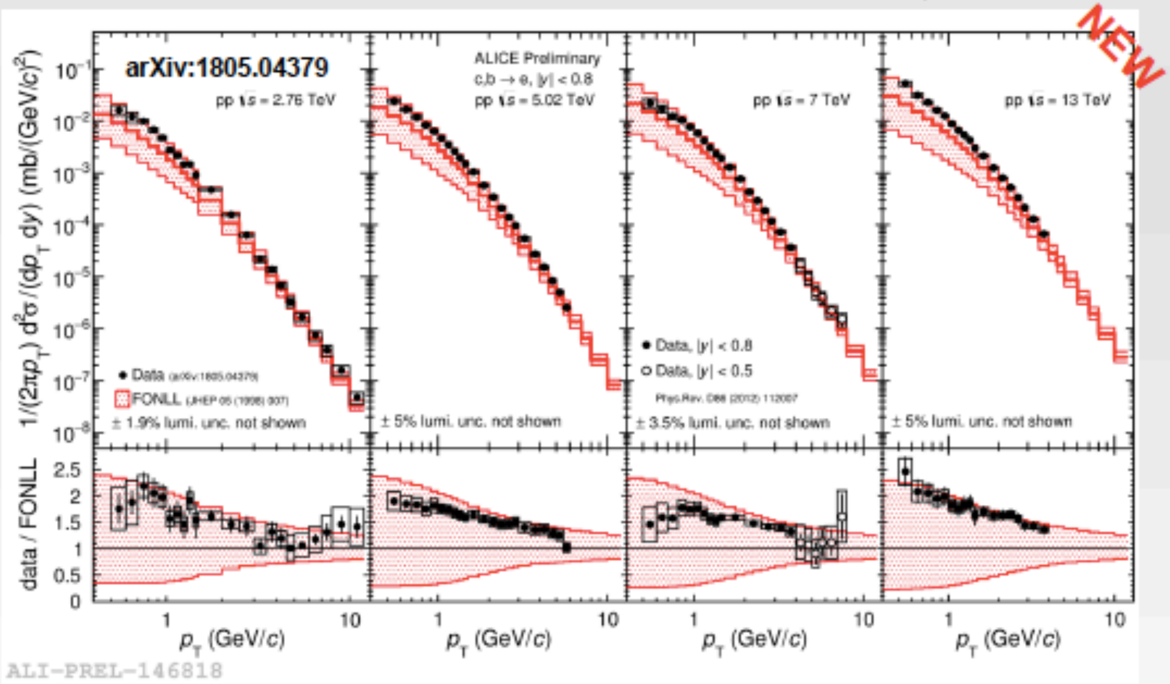
D meson (Hyunchul's summary)

- Non-strange D meson is strongly suppressed in PbPb, increasing with centrality, no significant energy dependence
- Strangeness is enhanced, independent of centrality
- Baryon/meson ratio shows centrality and p_T dependency, energy independence, and larger than expected in PYTHIA

Heavy-flavour decay electrons in pp collisions

ALICE

2.76 TeV → 5.02 TeV → 7 TeV → 13 TeV



– Testing the **centre-of-mass energy dependence** down to **p_T = 0.5 GeV/c**

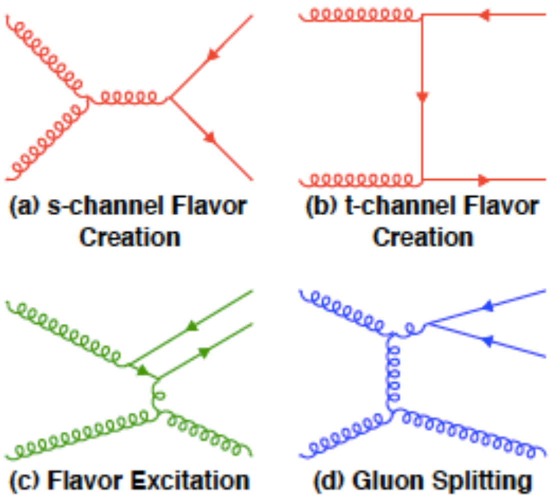
→ Large range of collision energy analysed, data consistently at the upper edge of FONLL calculation at all energies

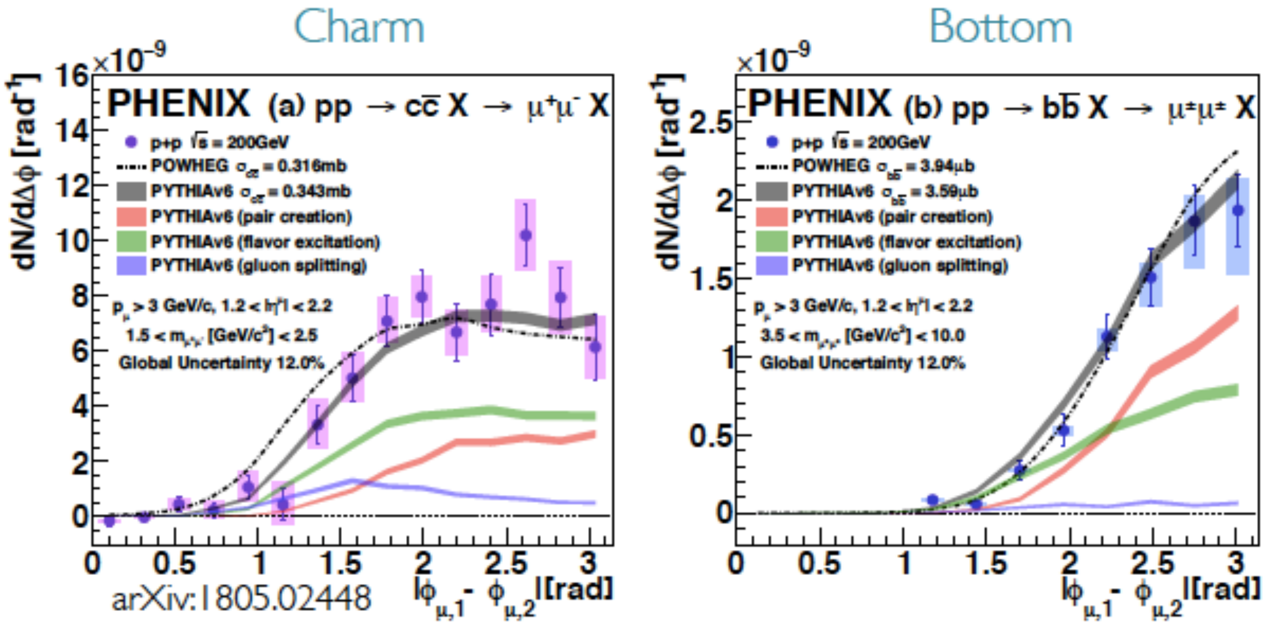
→ Large **reduction of systematic uncertainty** in the measurements w.r.t. previous publications!

5

Charm and bottom azimuthal correlations

- Extract charm and bottom in separate kinematic regions
- Charm and bottom dimuon $\Delta\phi$ compared to PYTHIA Tune A and POWHEG
  - Theoretical curves normalized with cross-sections from fitting technique



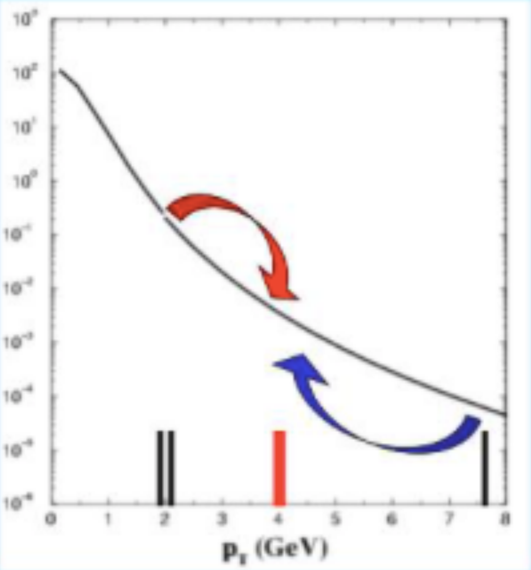


arXiv:1805.02448


Fine

Download

Coalescence vs. Fragmentation



Fragmentation:

- Leading parton $p_T \longrightarrow p_h = z\, p_T$ according to a probability $D_h(z)$
- $z < 1$, energy needed to create quarks from vacuum

Coalescence:

- partons are already there
- $p_h = n\, p_T$, $n = 2, 3$

\$ to be close in phase space \$

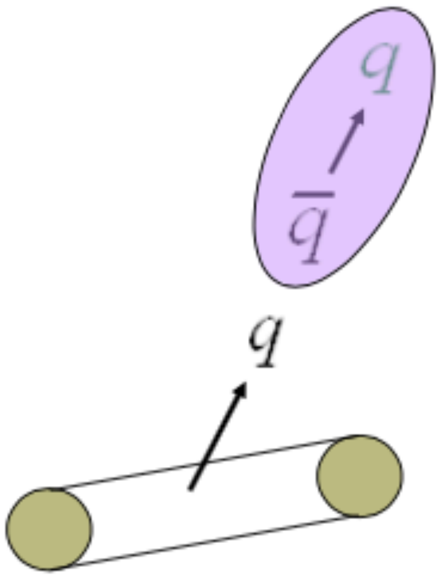
Even if eventually *Fragm.* takes over ...

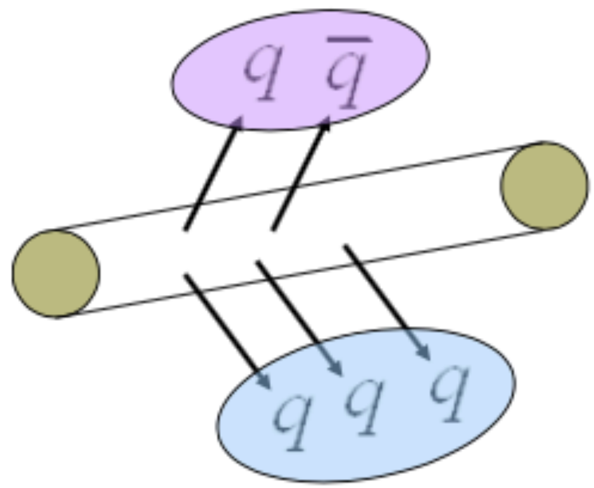
$$\begin{cases} C(p_T) \propto \left(\dfrac{p_T}{2}\right)^{-\alpha}\left(\dfrac{p_T}{2}\right)^{-\alpha} \\ F(p_T) \propto \left(\dfrac{p_T}{z}\right)^{-\alpha} \end{cases}$$

$$\frac{C}{F} \propto \left(\frac{4}{\langle z \rangle}\right)^{\alpha} (p_T)^{-\alpha}$$

Quark recombination ?

S. Voloshin, QM2002





Recombination

$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

$$p_M \approx 2p_Q \qquad p_B \approx 3p_Q$$

Fragmentation

$$\frac{\text{Baryon}}{\text{Meson}} \ll 1$$

Recombination+Fragmentation Model

R.J. Fries, C. Nonaka, B. Mueller & S.A. Bass, PRL 90 202303 (2003) ; PRC68, 044902 (2003)

basic assumptions:

- at low p_t, the quarks and antiquark spectrum is thermal and they recombine into hadrons locally "at an instant":

$$q\bar{q} \rightarrow M \qquad qqq \rightarrow B$$

  - features of the parton spectrum are shifted to higher p_t in the hadron spectrum
- at high p_t, the parton spectrum is given by a pQCD power law, partons suffer jet energy loss and hadrons are formed via fragmentation of quarks and gluons