



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

D^0 meson R_{AA} in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and elliptic flow in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with CMS

Zhaozhong Shi
on behalf of the CMS Collaboration
Massachusetts Institute of Technology
Quark Matter 2018

05/15/2018

Zhaozhong Shi Quark Matter 2018, Venice, Italy

ALICE

Heavy-flavour hadron decay leptons in Pb-Pb and Xe-Xe collisions at the LHC with ALICE

Andrea Dubla
for the ALICE Collaboration

- Electrons at mid-rapidity, $|y| < 0.7$
- Muons at forward-rapidity, $2.5 < y < 4$

Transport properties from Charm to Bottom: p_T suppression, anisotropic flow v_n and their correlations to the bulk dynamics

S. Plumari
Università degli Studi di Catania

IN COLLABORATION WITH:
V. Minissale, G. Coci, L. Oliva,
S. K. Das, F. Scardina, V. Greco

2018 Quark Matter

Measurements of open charm and bottom production in 200 GeV Au+Au collisions with the STAR experiment at RHIC

Sooraj Radhakrishnan for the STAR Collaboration
Lawrence Berkeley National Laboratory

PHENIX

Nuclear modification factor and Flow of charm and bottom quarks in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX Experiment.

Takashi HACHIMA
Nara Women's University & RIKEN BNL Research Center for the PHENIX collaboration

Measurements of strange and non strange beauty production in PbPb collisions at 5.02 TeV with the CMS detector

Ta-Wei Wang (MIT)
on behalf of the CMS collaboration
Quark Matter, Venezia, Italy
15, May, 2018

Mass hierarchy of parton energy loss in heavy-ion collisions

Shanshan Cao
Wayne State University

Λ_c^+ production (and D and B) in pp and PbPb collisions at 5.02 TeV with the CMS experiment

Rui Xiao
(Purdue University)
for the CMS Collaboration
Quark Matter 2018

Office of Science
U.S. DEPARTMENT OF ENERGY

PHENIX

Measurements of directed and elliptic flow for D^0 and \bar{D}^0 mesons using the STAR detector at RHIC

Subhash Singha
Kent State University
(for the STAR Collaboration)

Outline

- Motivation
- STAR detector
- Analysis details
- Results:
 - D^0/\bar{D}^0 directed (v_1) and ($D^0+\bar{D}^0$) elliptic flow (v_2)
 - Comparison to light flavor hadrons and model calculations
- Summary

Development of heavy-flavour flow-harmonics in high-energy nuclear collisions

Andrea Beraudo
INFN - Sezione di Torino
Quark Matter 2018
Venice, 14th – 19th May 2018

Strong directed flow of heavy flavor as a probe of matter distribution in heavy-ion collisions

Sandeep Chatterjee
With: Piotr Bozek
AGH-UST, Krakow
Quark Matter 2018

Phys. Rev. Lett. **120**, 192301 (2018);
arXiv: 1804.04893

Production of open charm and beauty states in pPb collisions with LHCb

Jiayin Sun (Tsinghua University)
On behalf of the LHCb Collaboration
May 16th 2018

LHCb

Heavy flavor production and flow in large and small systems with ATLAS

Cipeng Hu
for the ATLAS Collaboration
University of Colorado Boulder

Measurements of charm, bottom, and Drell-Yan via dimuons in p+p and p+Au at $\sqrt{s_{NN}}=200$ GeV with PHENIX at RHIC

Yue Hang Leung
Stony Brook University
for the PHENIX collaboration

- Introduction
- p+p
- arXiv:1805.02448
- arXiv:1805.04075
- p+Au (preliminary results)
- Summary

PHENIX

Dynamical energy loss formalism: from explaining unexpected suppression patterns to implications for future experiments

Magdalena Djordjevic, IPB

In collaboration with: Dusan Zigic, Jussi Auvinen, Bojana Blagojevic, Igor Salom and Marko Djordjevic

ATLAS

17 parallel talks + posters (Really Hot!)



Motivation of heavy flavor

- **Heavy quark is produced in the early stage of the collisions, can be 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

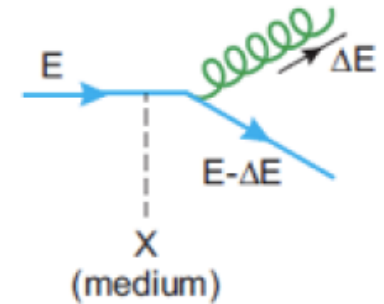
Energy loss mechanism of heavy quarks

pQCD: Collisional

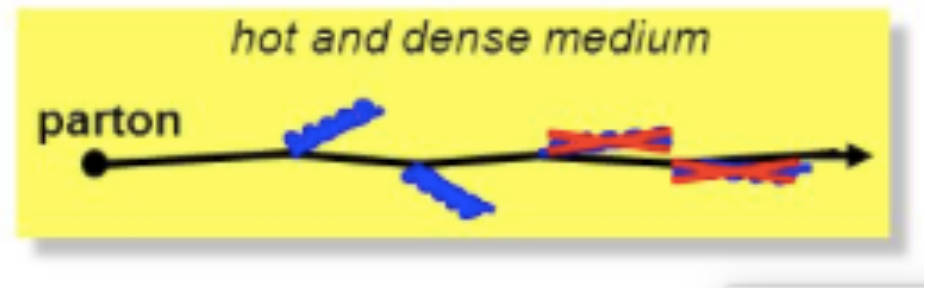
Radiative



$$-\frac{dE}{dx} = \kappa_{\text{coll}} T^2$$

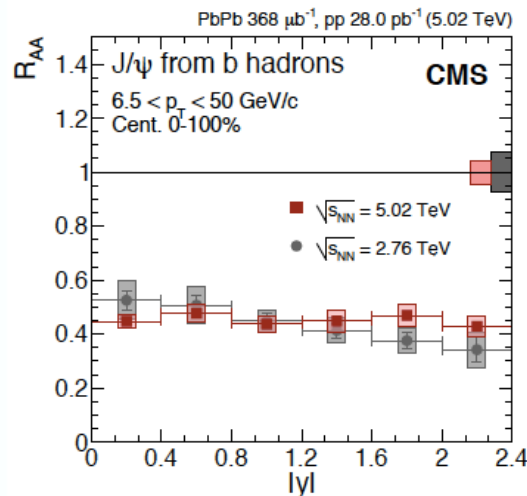
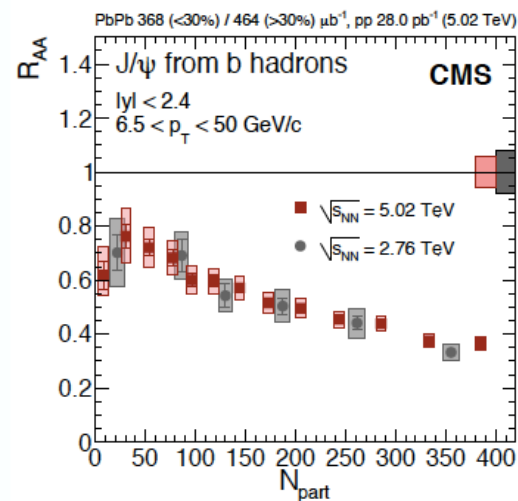


$$-\frac{dE}{dx} = \kappa_{\text{rad}} T^3 \chi$$

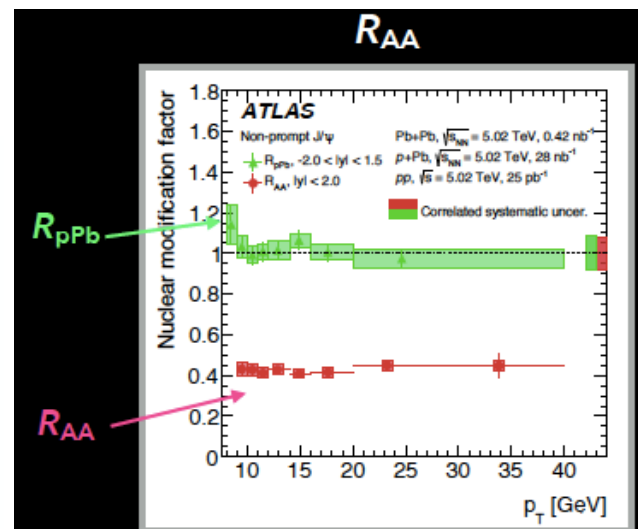
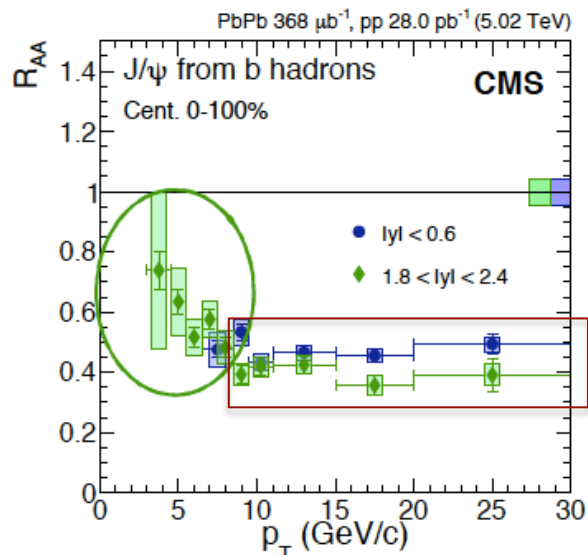
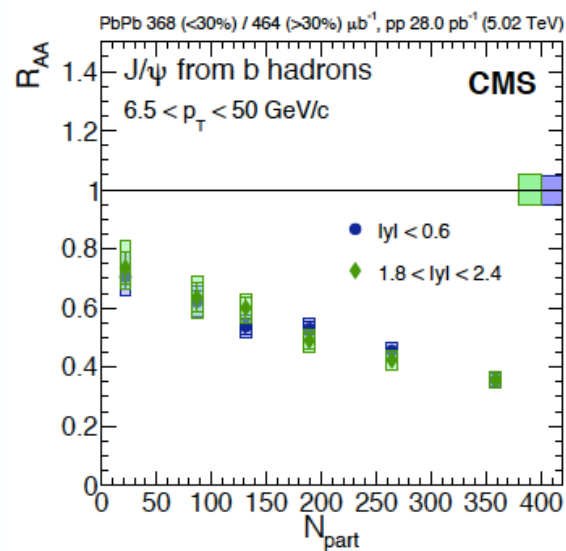


Nuclear modification factors (R_{pA} or R_{AA})

inclusive B meson

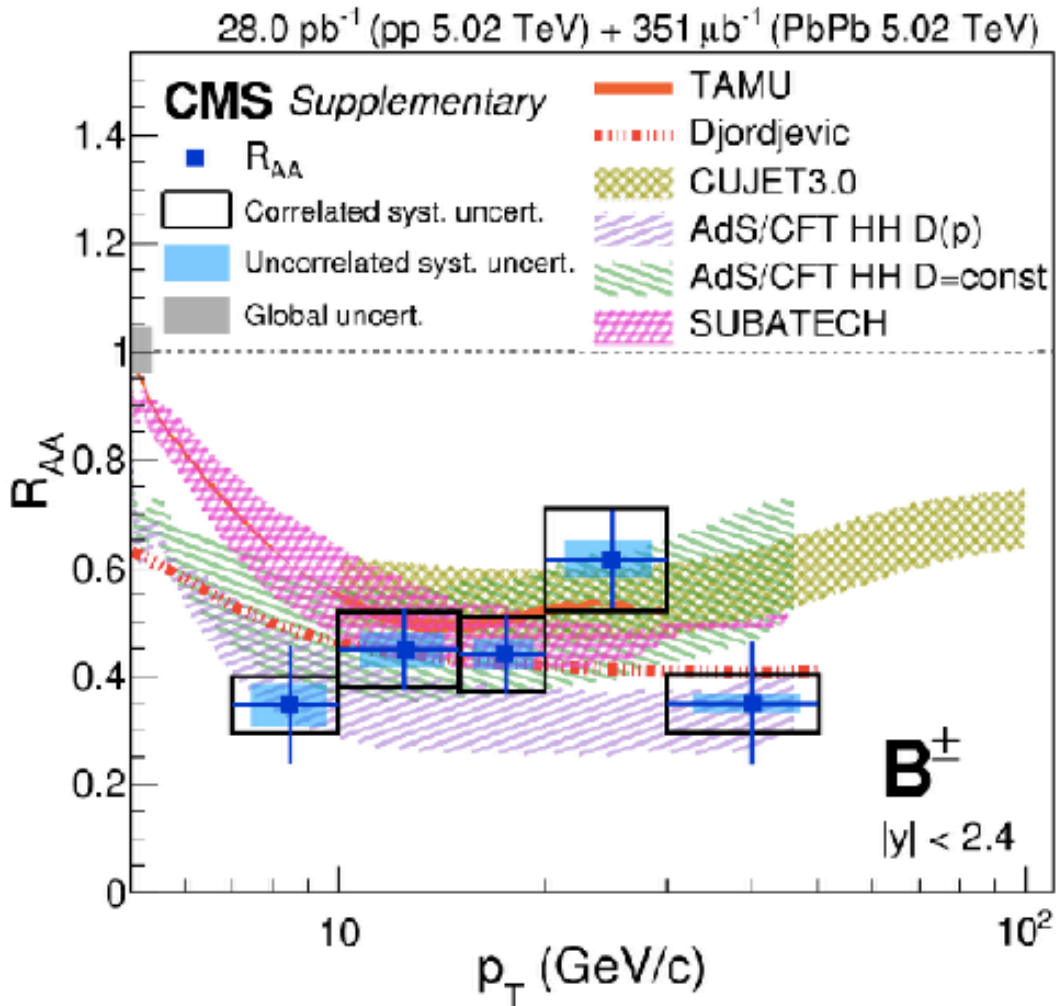


- No significant energy dependence
- no y-dependence at 5 TeV, and the results are compatible with the 2.76 TeV
- Measurement down to $p_T < 3$ GeV at forward rapidity



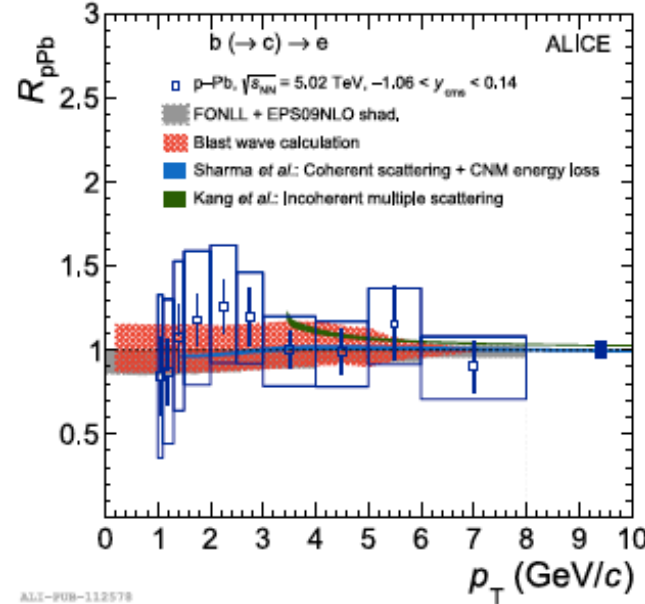
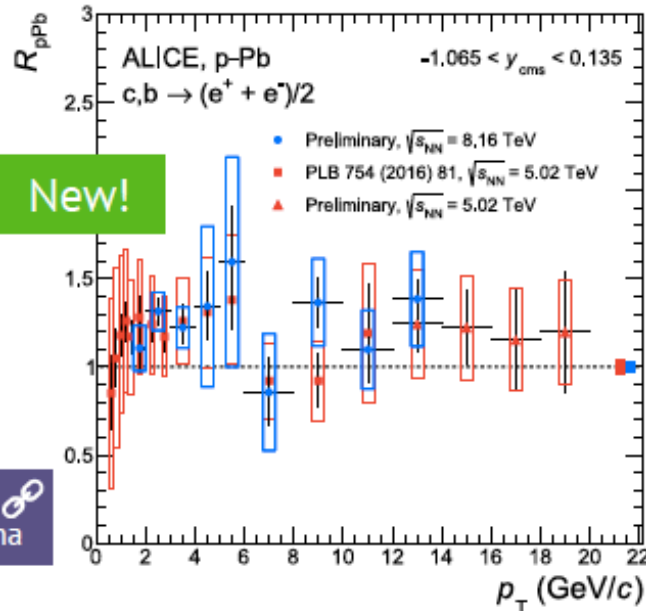
Strong suppression in Pb+Pb collisions, small cold nuclear matter effects

B+ meson



- First exclusively reconstructed in heavy-ion collisions
- Suppression of B+ meson production in PbPb collisions
- B+ meson $R_{AA} \sim 0.3$ 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

HF electron R_{pPb} at 5.02 and 8.16 TeV



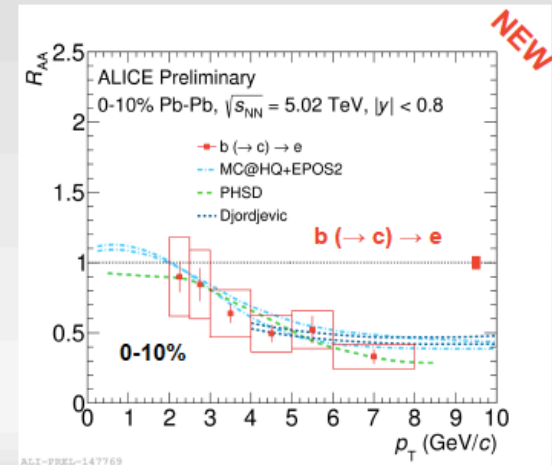
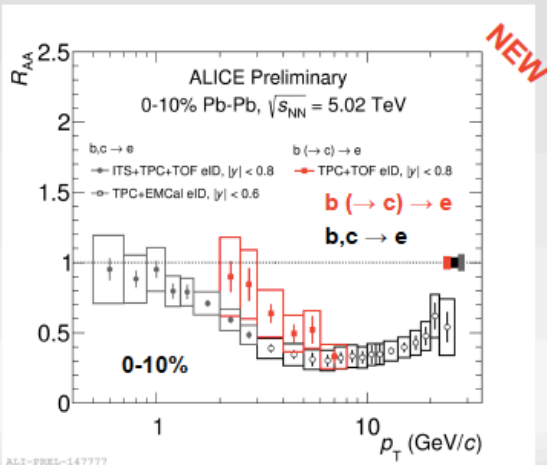
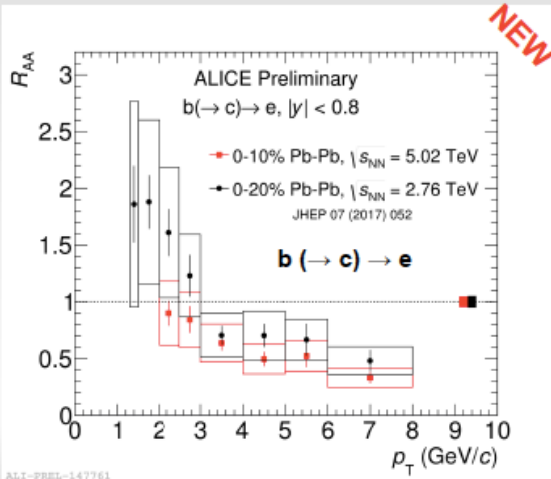
JHEP 07
(2017) 052

Model Ref.:
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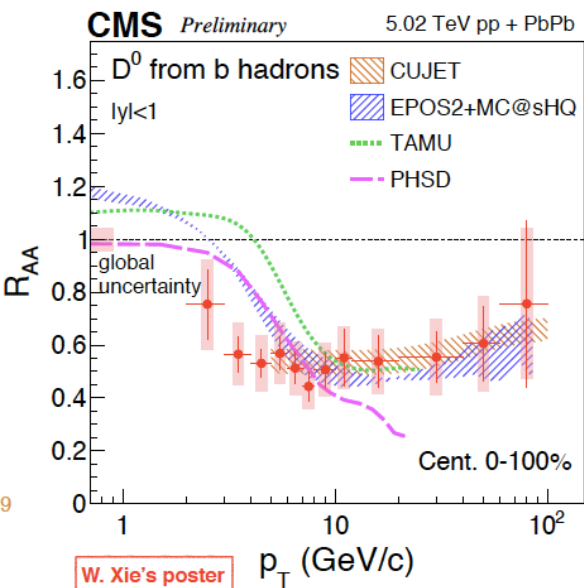
Poster:
D. Kawana

- 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}



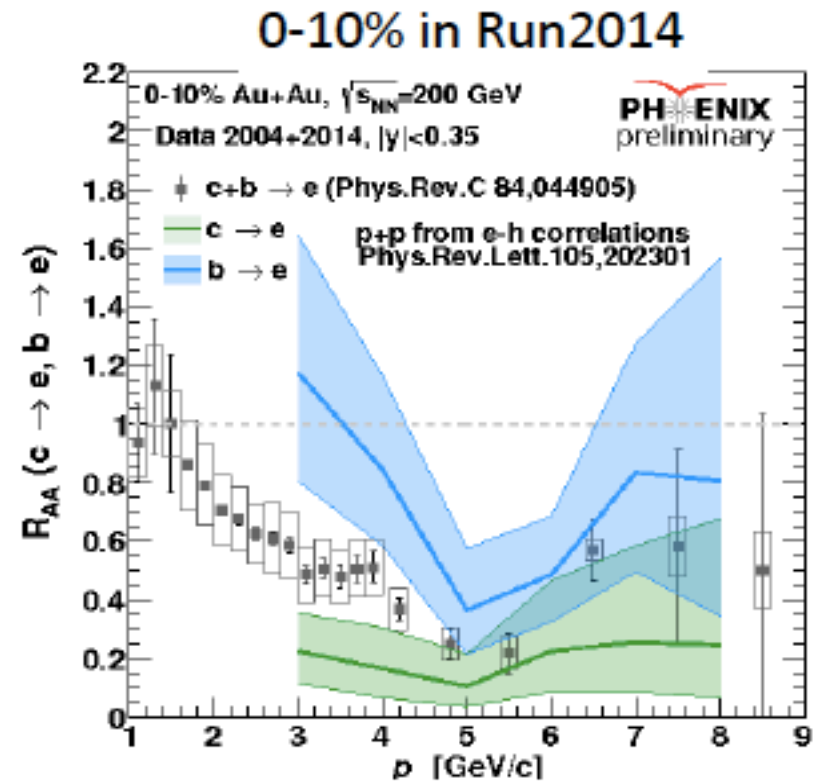
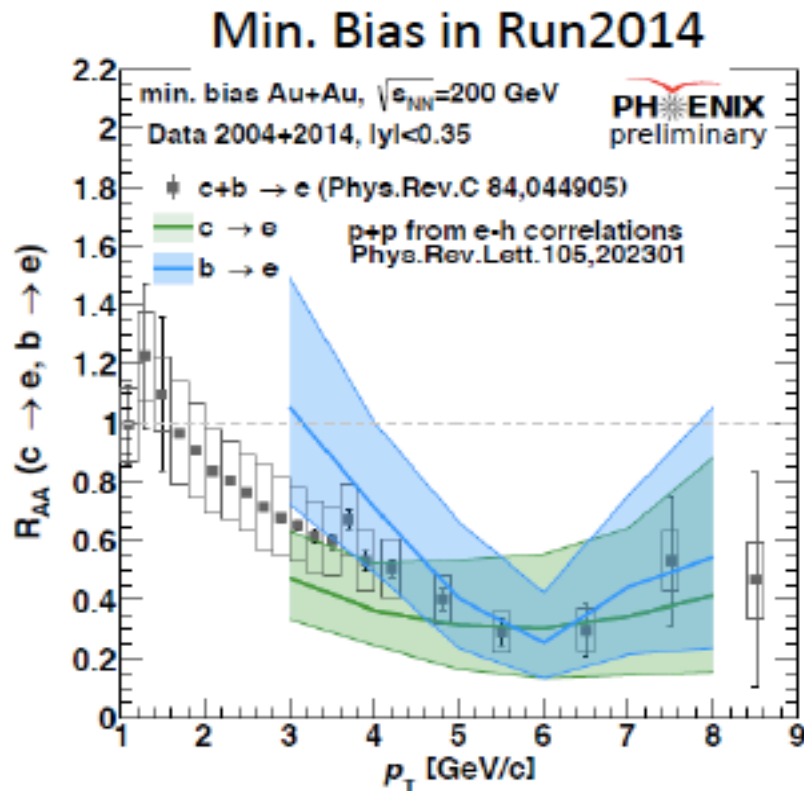
- 2.76 TeV(0-20% centrality) → 5.02 TeV(0-10% centrality), energy independent
- hint of a smaller suppression for beauty than charm+beauty decay electrons at the same electron p_T
- large contribution to the systematic uncertainties from the rescaled pp cross section
- agreement within the uncertainties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

B → D R_{AA} in RHIC

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

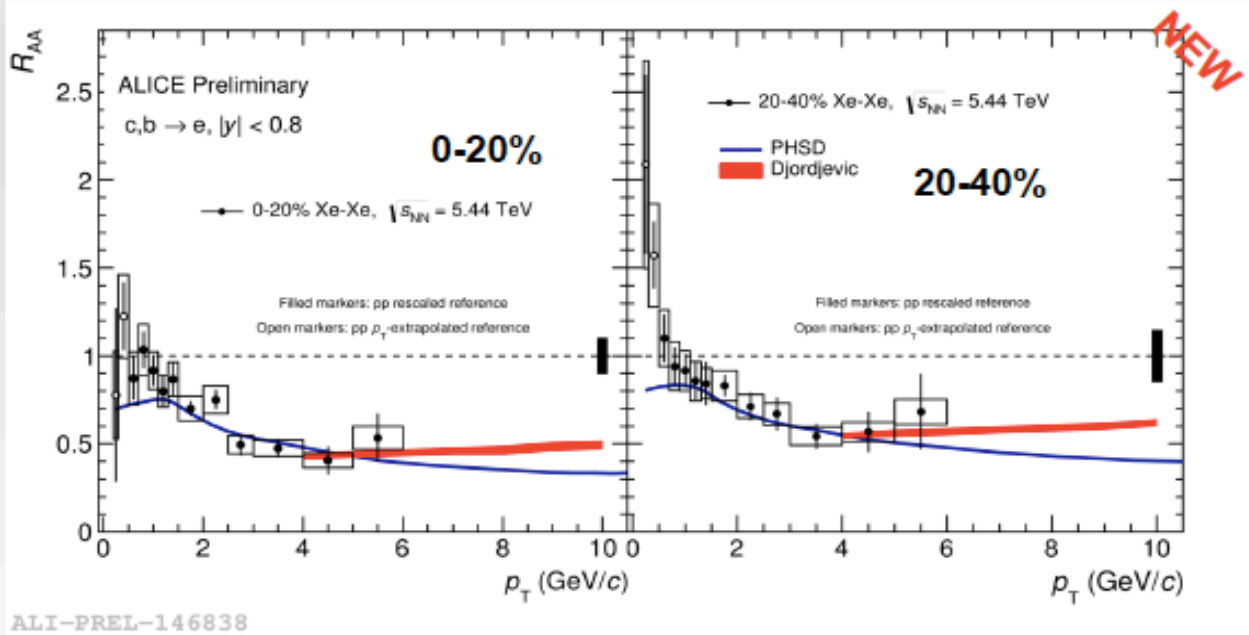


- In 0-10%, bottom and charm are more clearly separated
- Charm is **more suppressed** than MB
- Bottom is similar

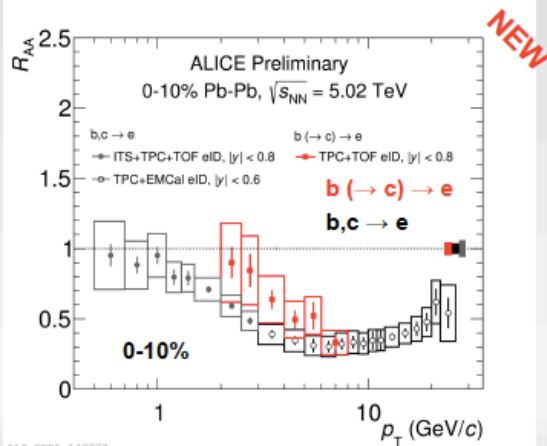
2017/5/15

Bonus! – in XeXe

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



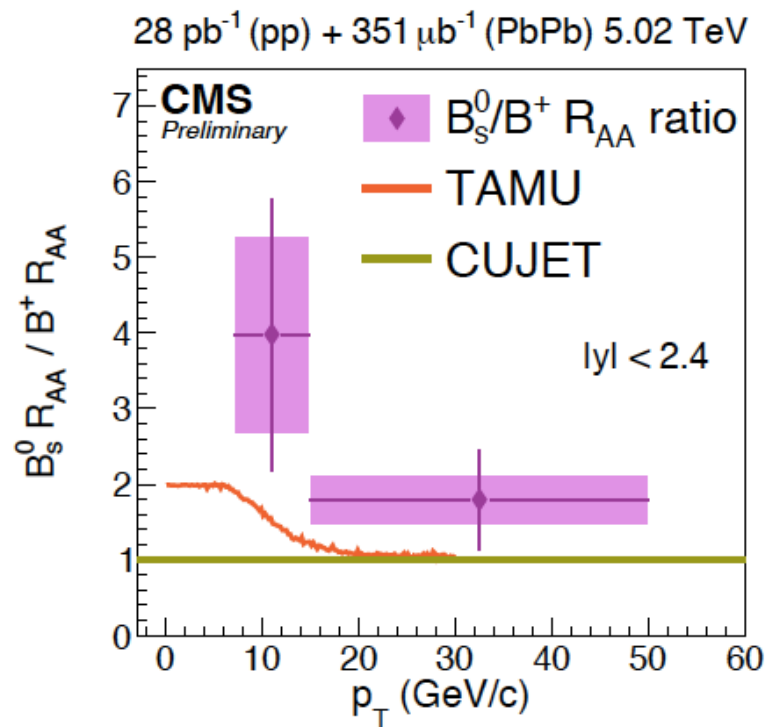
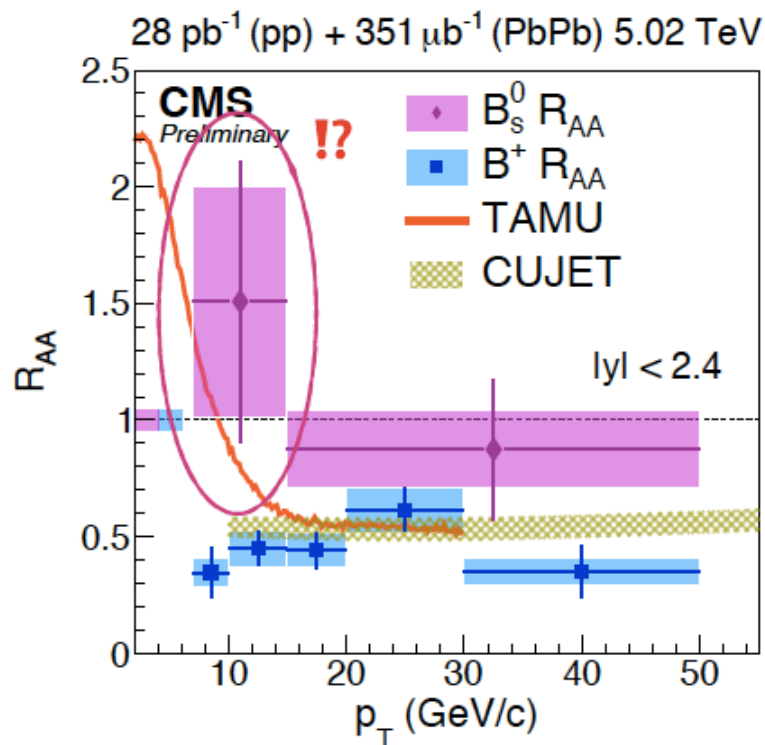
- Possible future measurement of total charm cross section in heavy-ion collisions
- Data are reproduced by model calculations



- $R_{AA} \sim 0.5$ in same p_T range between two systems?

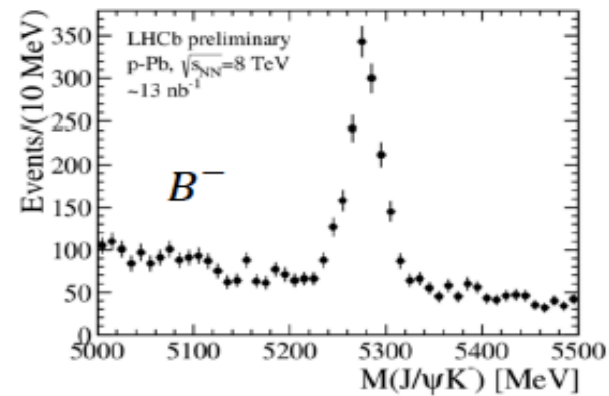
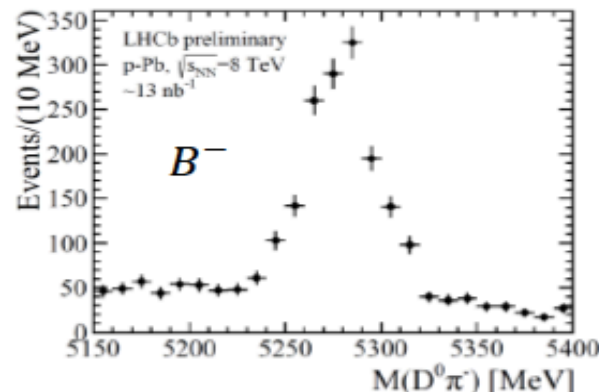
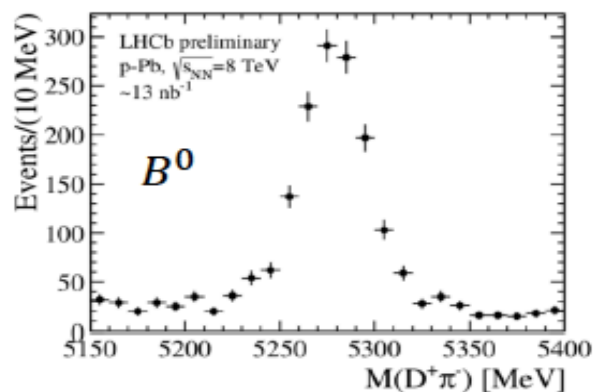


Strangeness in B meson

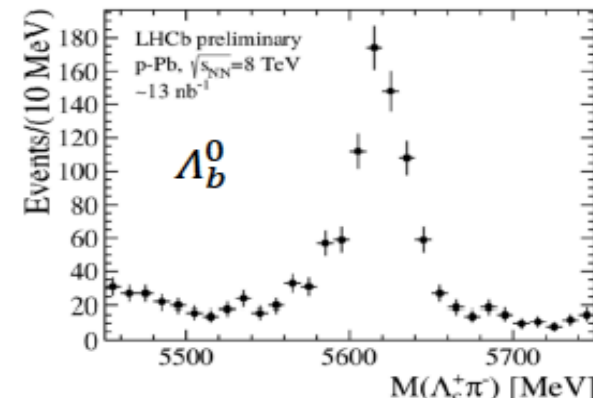
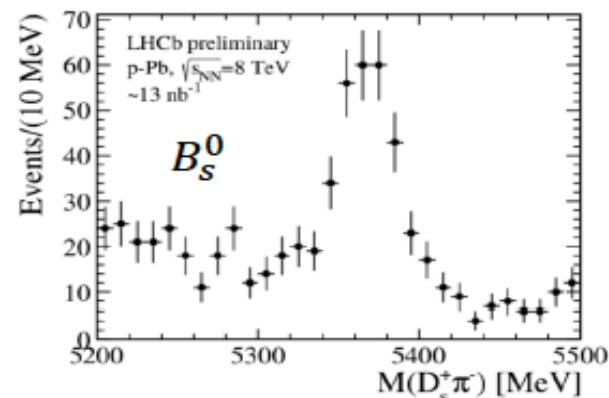


- First reconstructed in heavy-ion collisions
- Indication of less suppression of B_s comparing to B⁺
- Ratio -> correlated uncertainties are cancelled

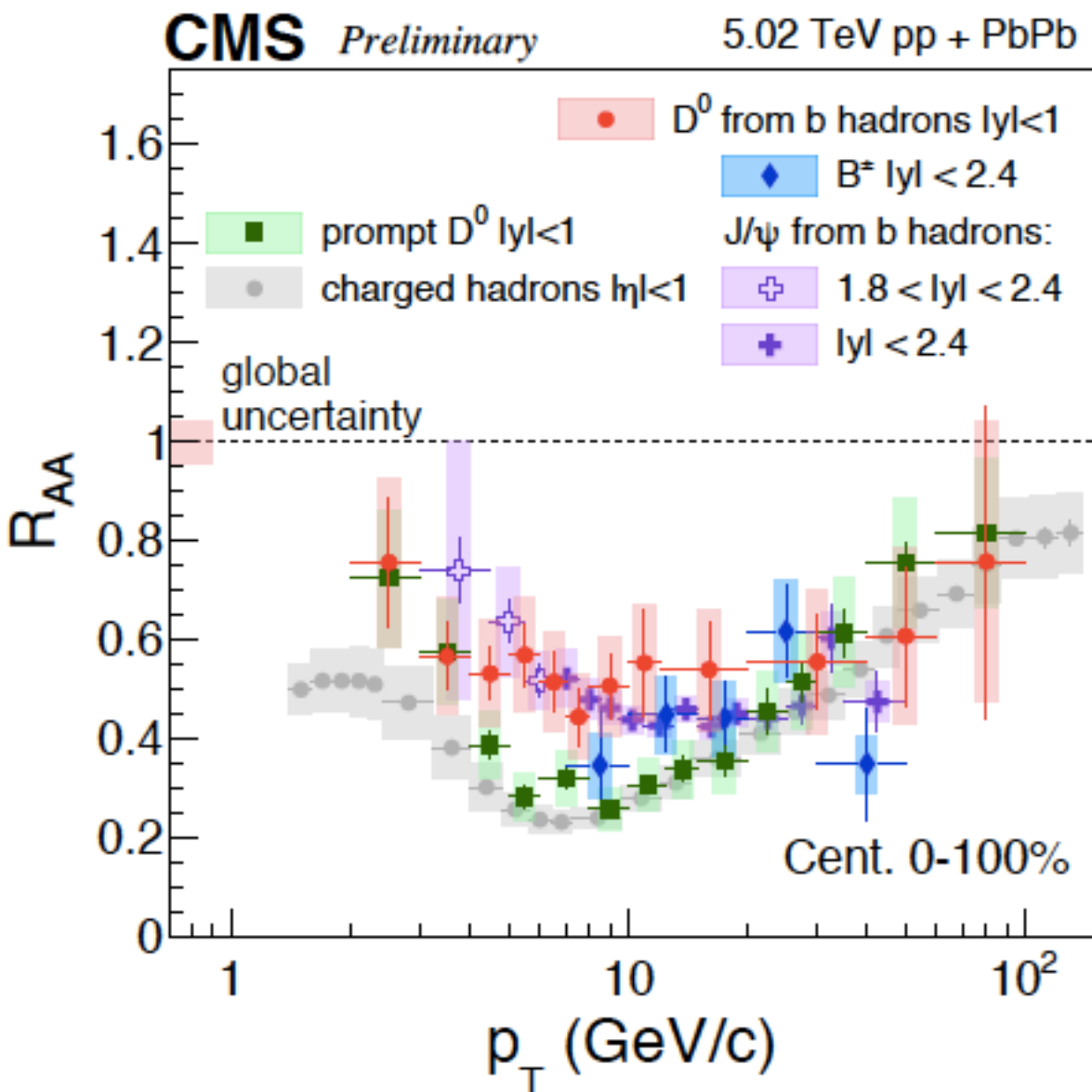
Open beauty measurements in $p\text{Pb}$ 8 TeV



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



Zoo with heavy flavors



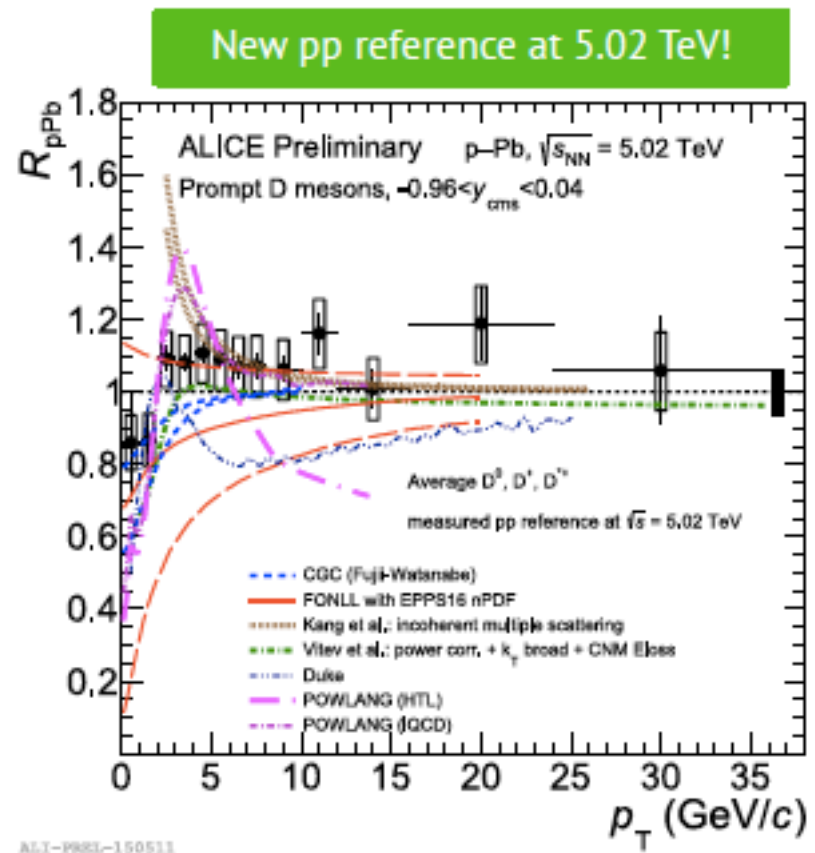
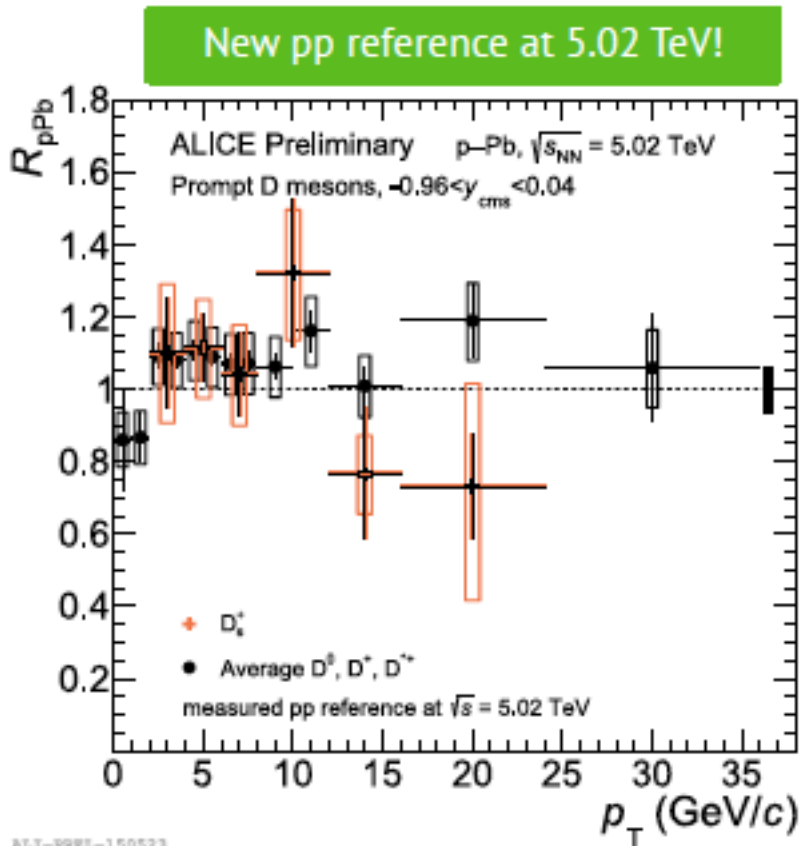
- Compatible results from three beauty RAA measurements (non-prompt D, B+, and non-prompt J/ψ)
- Beauty seems to separate from charm and light flavor at ~ 20 GeV
- RAA between prompt D, charged particle, B+, non-prompt J/ψ and nonprompt D merging above ~ 20 GeV

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

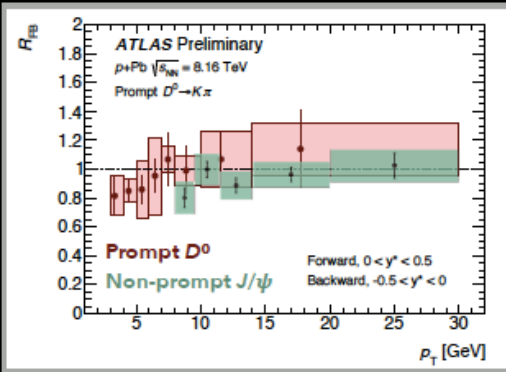
Prompt D meson R_{pA}



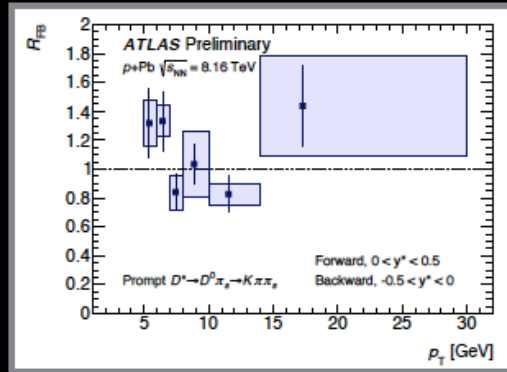
- D_s^+ R_{pPb} compatible with D-meson R_{pPb}
- Both compatible with unity
- More stringent constraints to models at low p_T

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

Prompt D^0

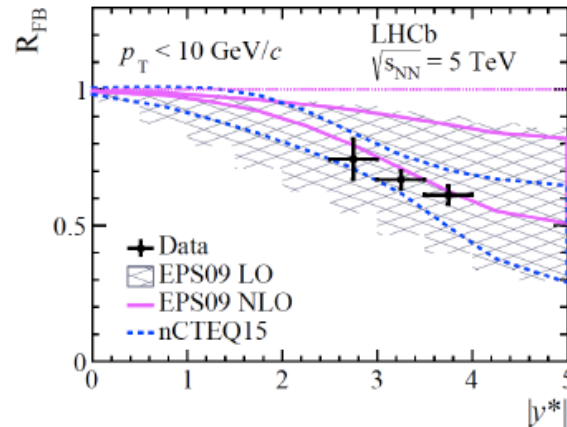
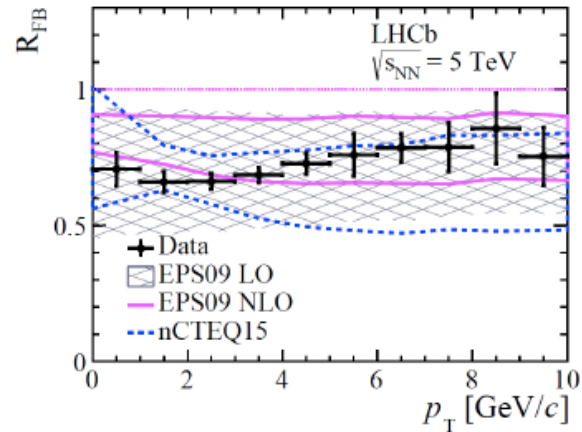


Prompt D^*



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

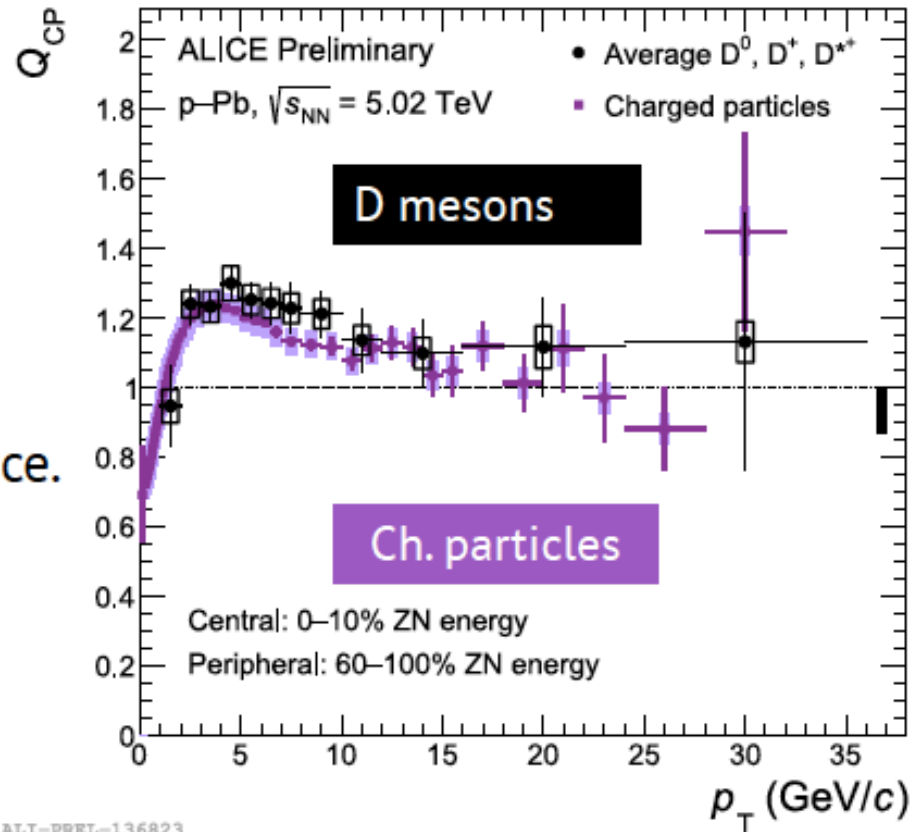
JHEP 10 (2017) 090





D-meson production central/peri.

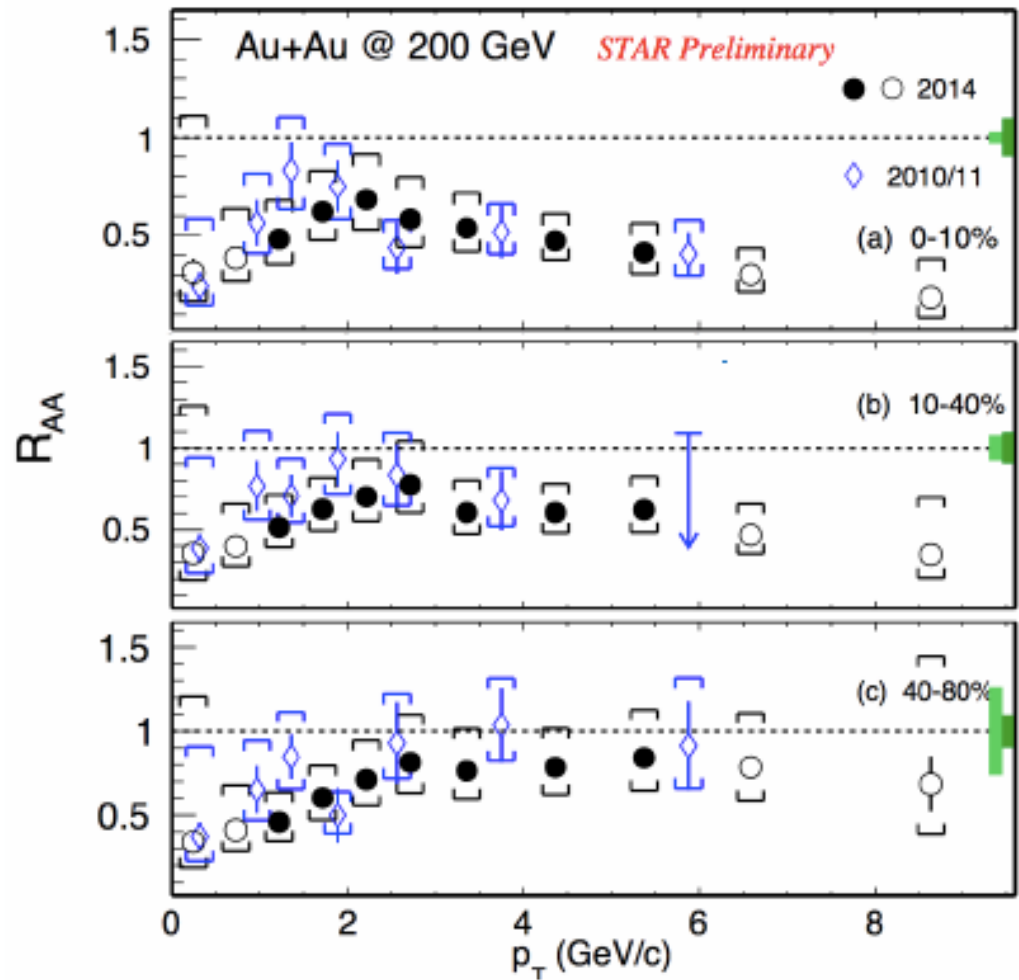
$$Q_{CP} = \frac{\frac{d^2 N_{pPb}^{central}}{dp_T}}{\langle T_{pPb}^{central} \rangle} \bigg/ \frac{\frac{d^2 N_{pPb}^{peri}}{dp_T}}{\langle T_{pPb}^{peri} \rangle}$$

- 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

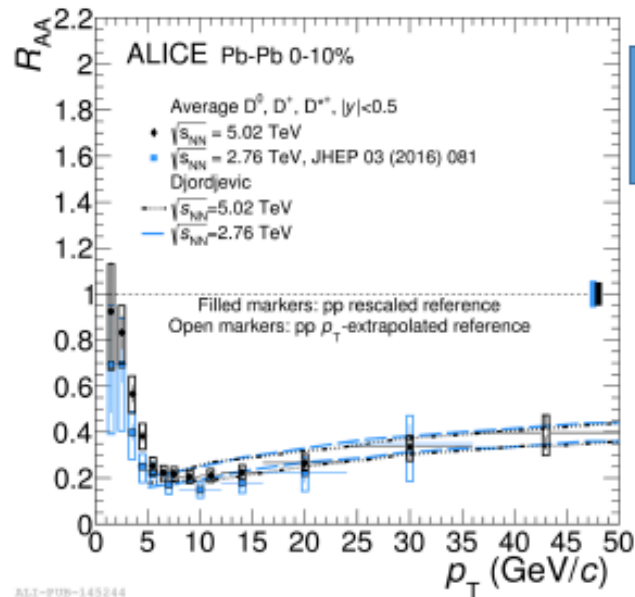
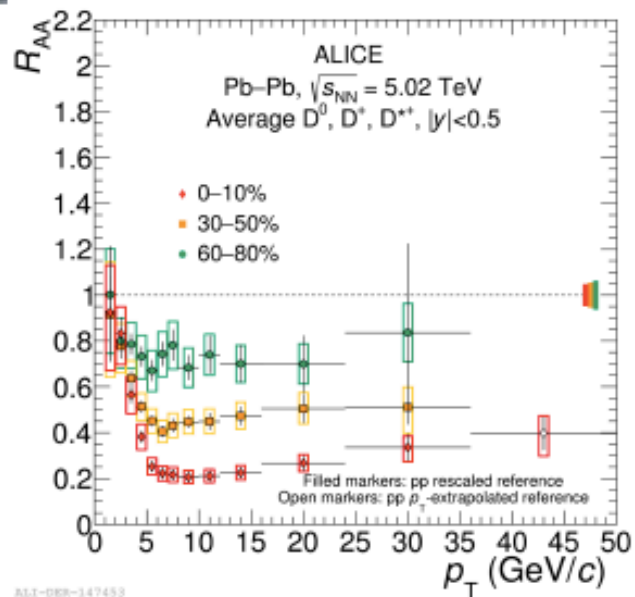
ALICE, D meson R_{AA}



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



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

Submitted!

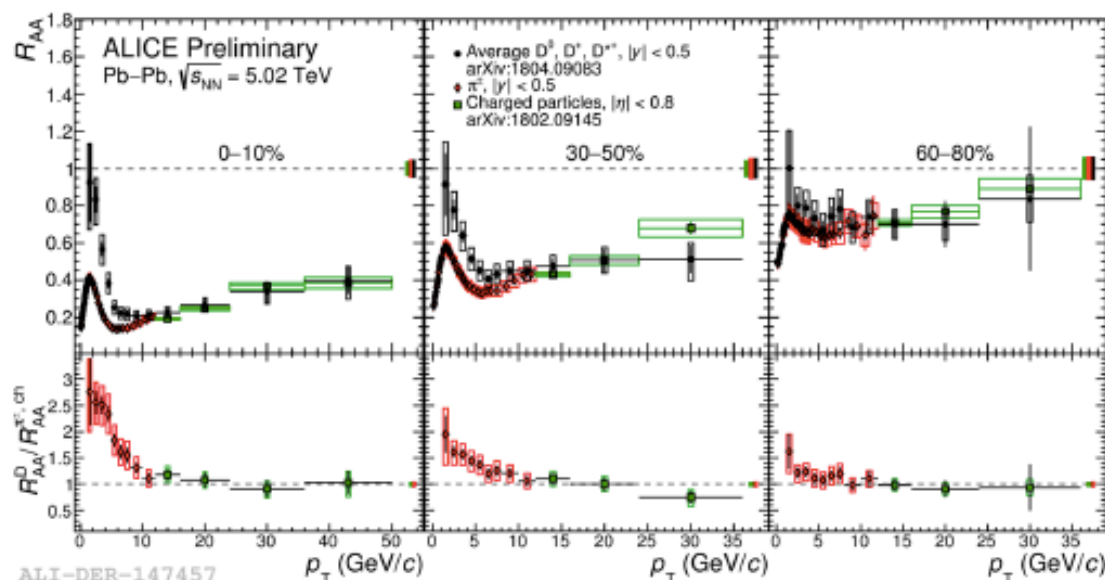
arXiv:1804.09083

- **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 and charged-particle R_{AA} comparison



Submitted!

π^\pm ALICE preliminary

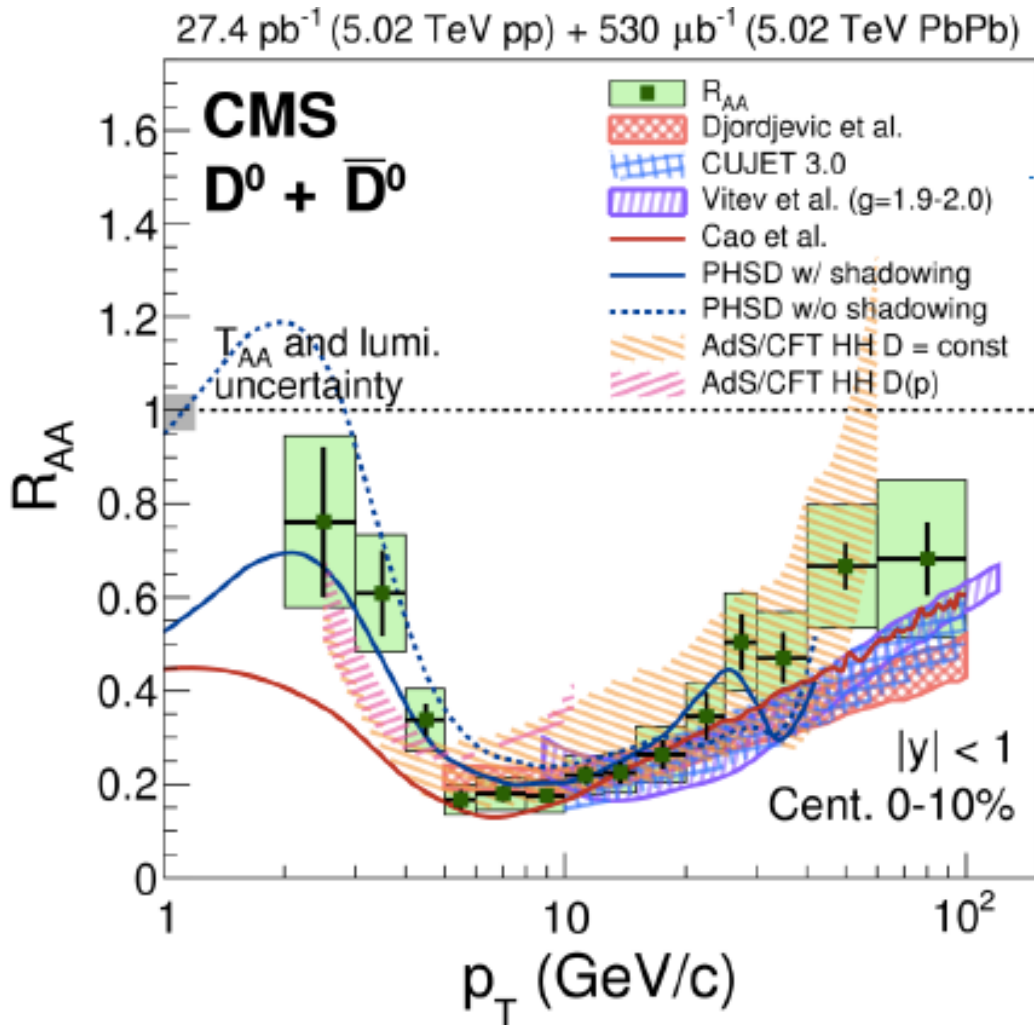
Charged-particle: arXiv:1802.09145

arXiv:1804.09083

- Similar D-meson, π^\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}

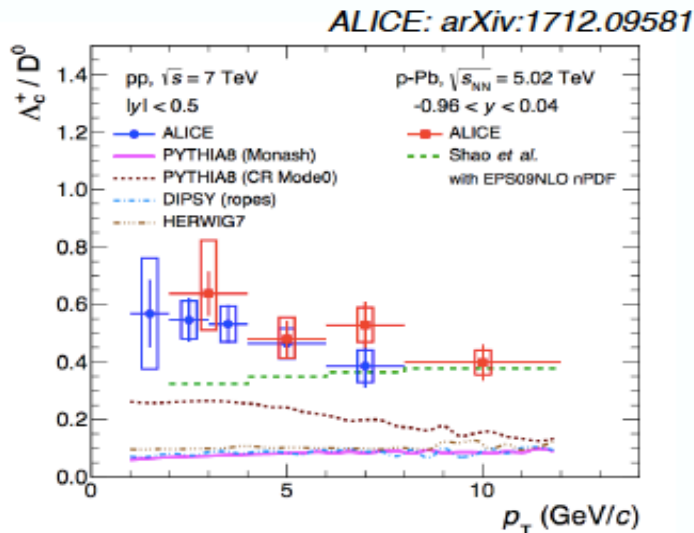


- Seen increasing trends, going to higher p_T
- Charm quarks lose a significant fraction of energy in the QGP medium
- R_{AA} minimal near $p_T \sim 10$ GeV/c and then increases
- at high p_T , both pQCD and AdS/CFT predictions reasonably agree with data
- at low p_T , PHSD with shadowing describes our data better

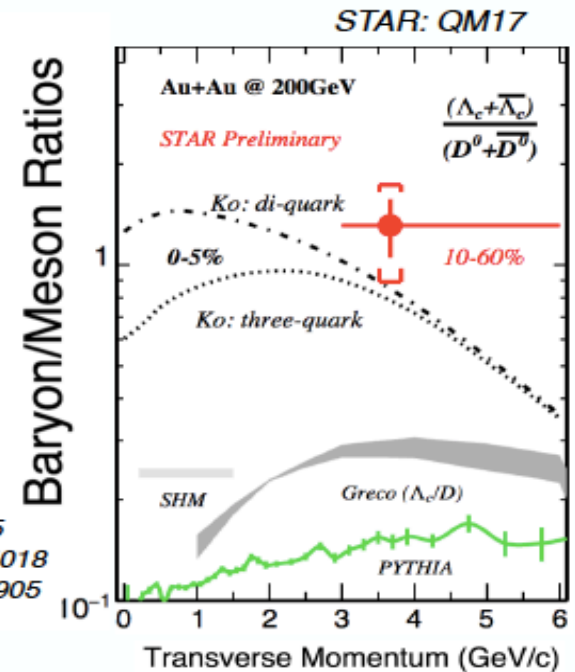
Λ_c (udc, 2.29 GeV/c)

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

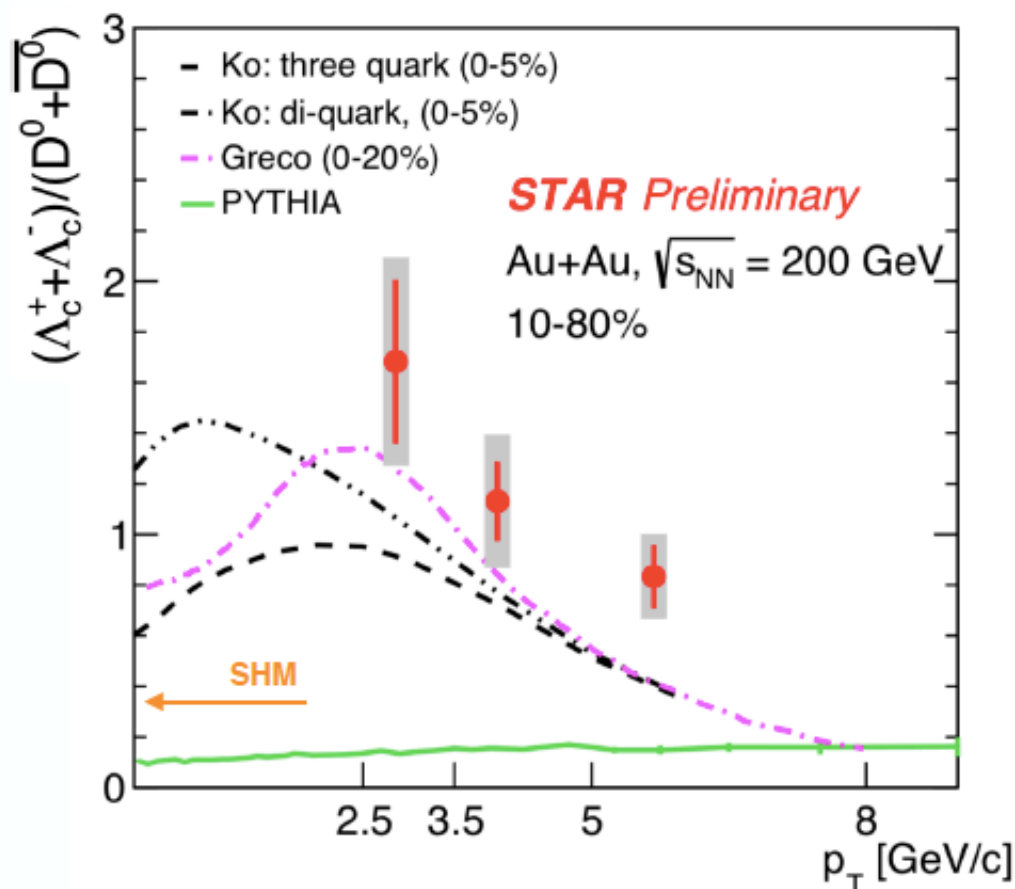


Ko: PRC 79 (2009) 044905
Greco: PRD 90 (2014) 054018
SHM: PRC 79 (2009) 044905



- 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?

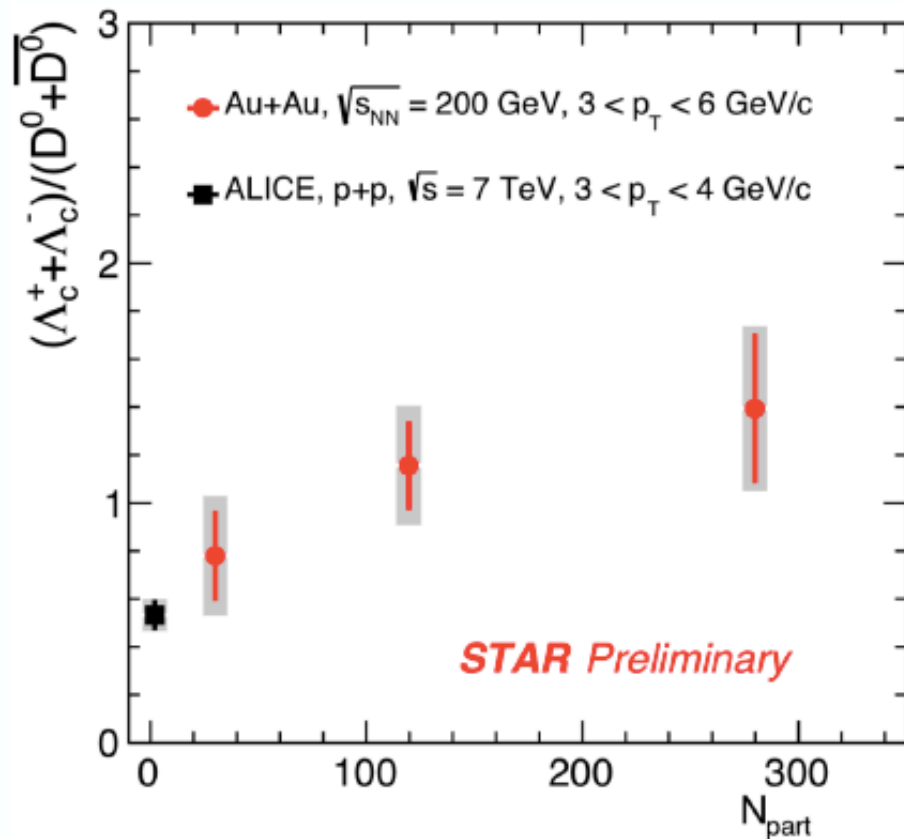
p_T Dependence of Λ_c/D^0 Ratio



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

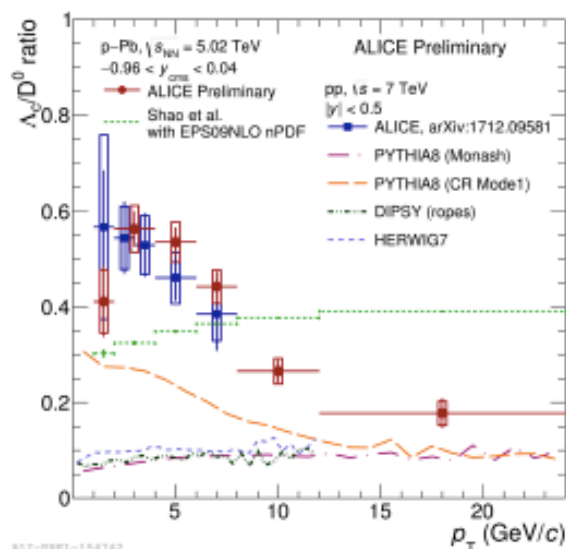
Centrality Dependence of Λ_c Production



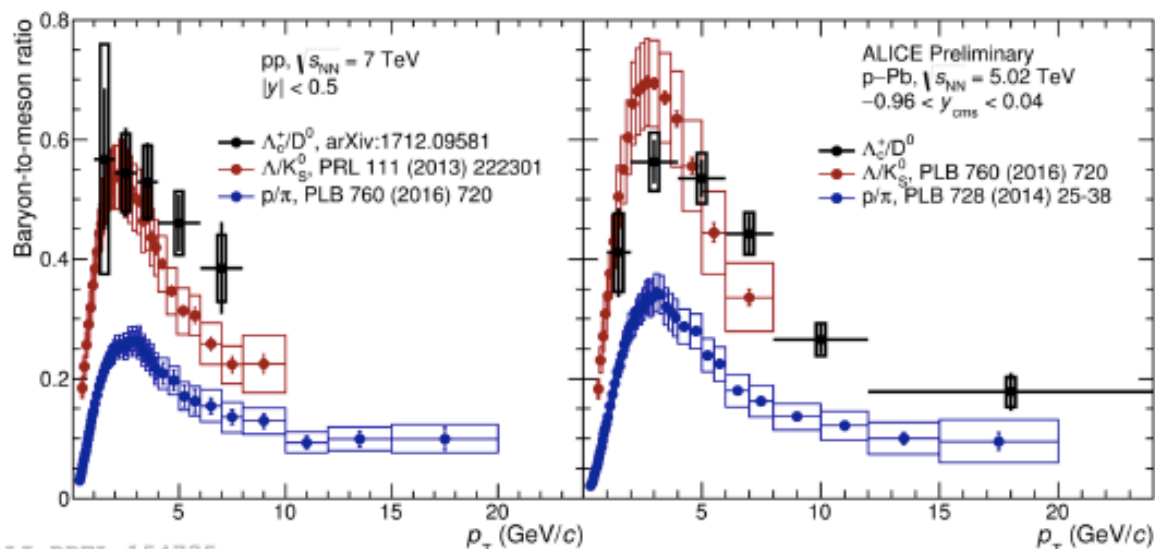
ALICE: arXiv:1712.09581

- 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





ALICE-PREL-154742



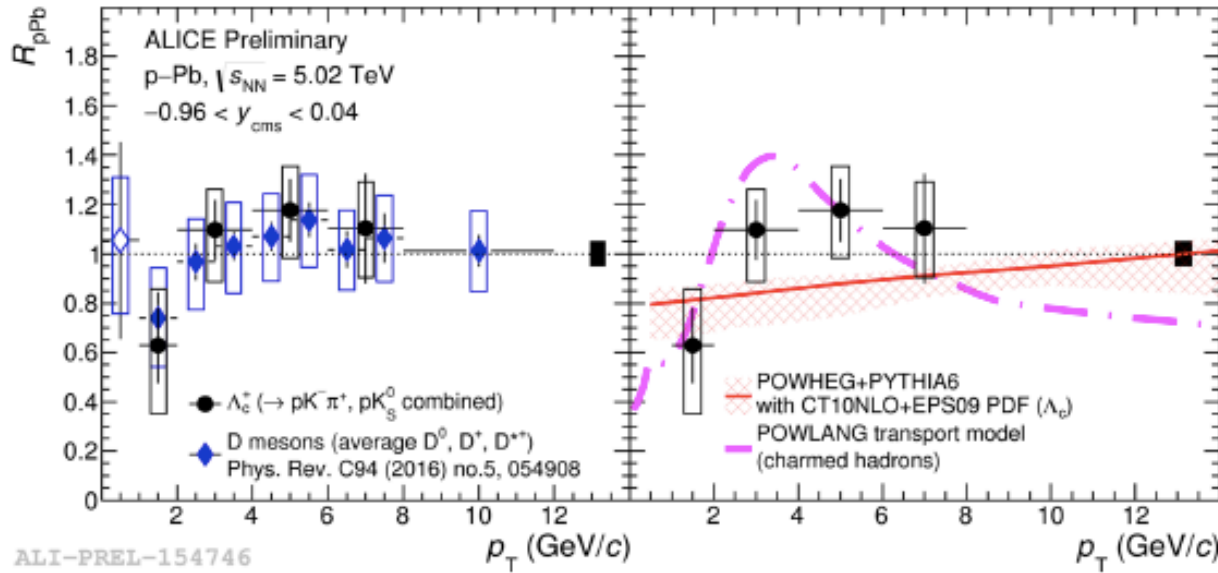
ALI-PREL-154735

- 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



Λ_c^+ R_{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



$$R_{pA} = \frac{1}{A} \frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T}$$

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

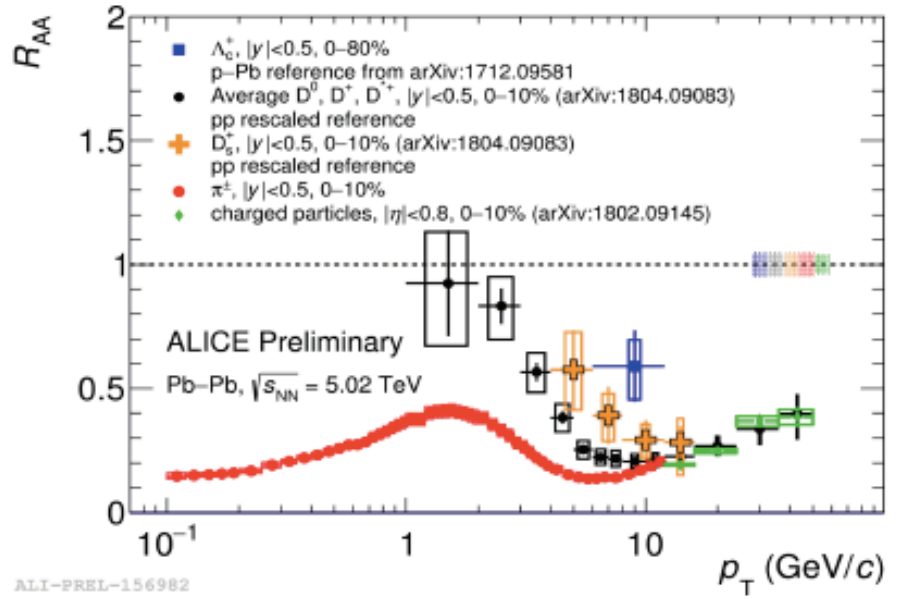
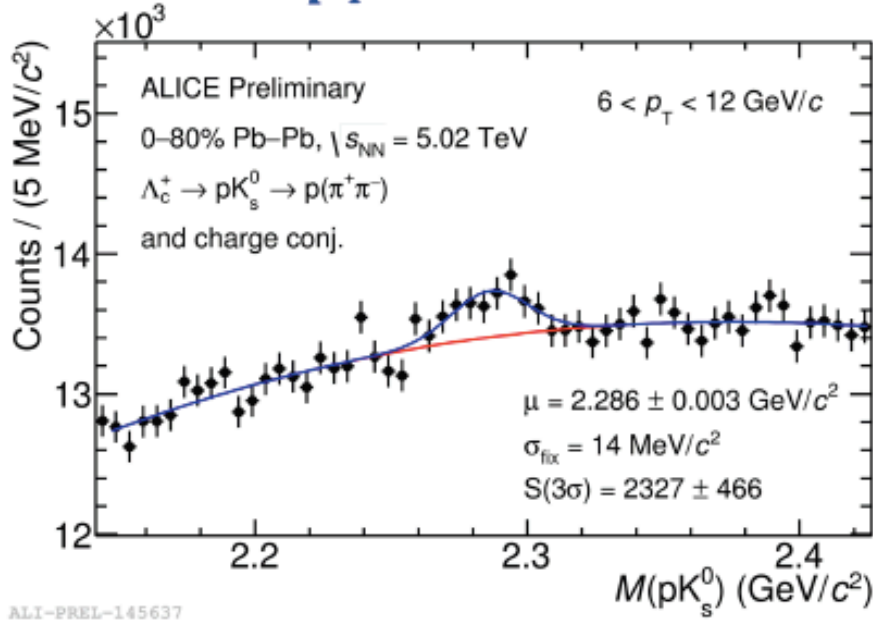


Poster ID: 132 by Y.Watanabe



Λ_c^+ invariant mass and R_{AA} in Pb-Pb $6 < p_T < 12 \text{ GeV}/c$ 0-80%

New!



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

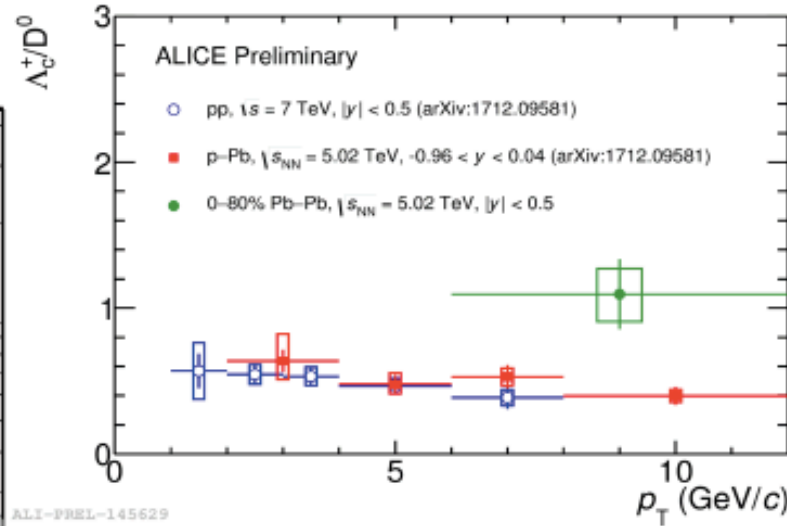
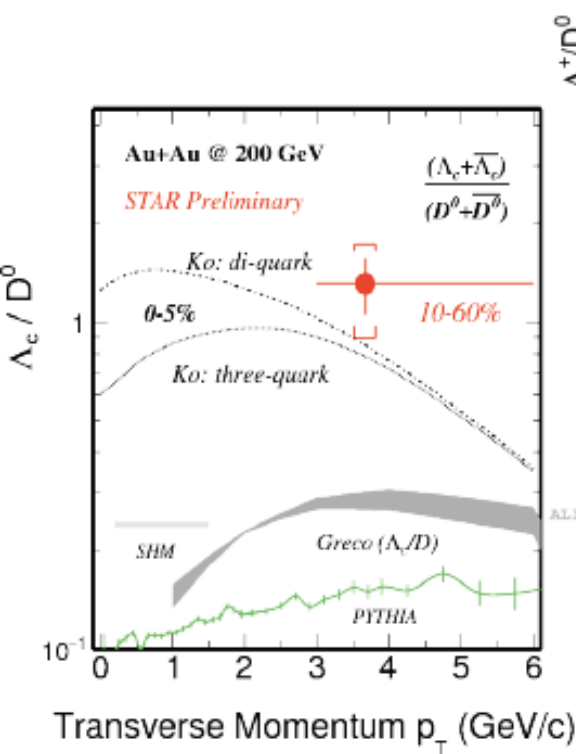
Baryon Meson
Strangeness



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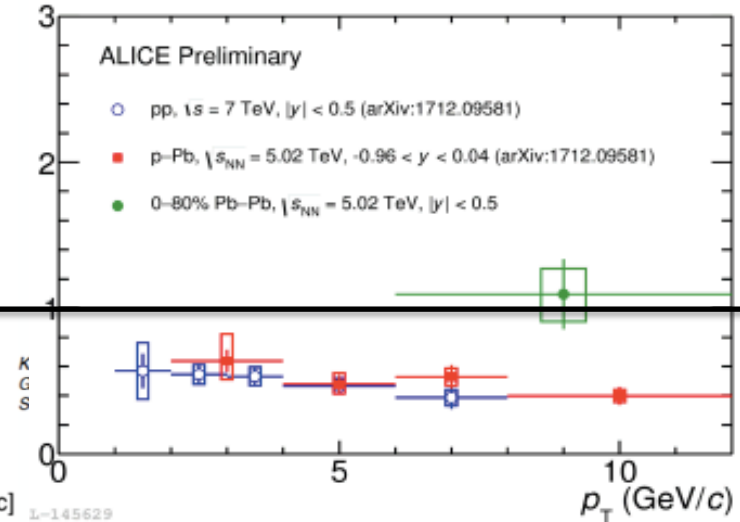
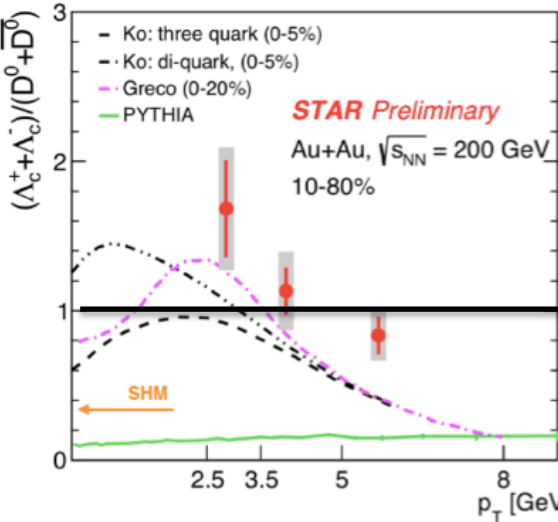
- Λ_c^+/D^0 ratio measured in Pb-Pb, hint of enhancement w.r.t pp and p-Pb
- Models tend to **underestimate** the data
- Similar value than that measured by STAR at low p_T in Au-Au @ 200 GeV



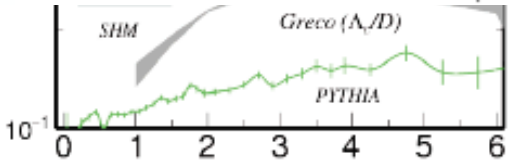
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Transverse Momentum p_T (GeV/c)

- 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

consistent STAR and ALICE?





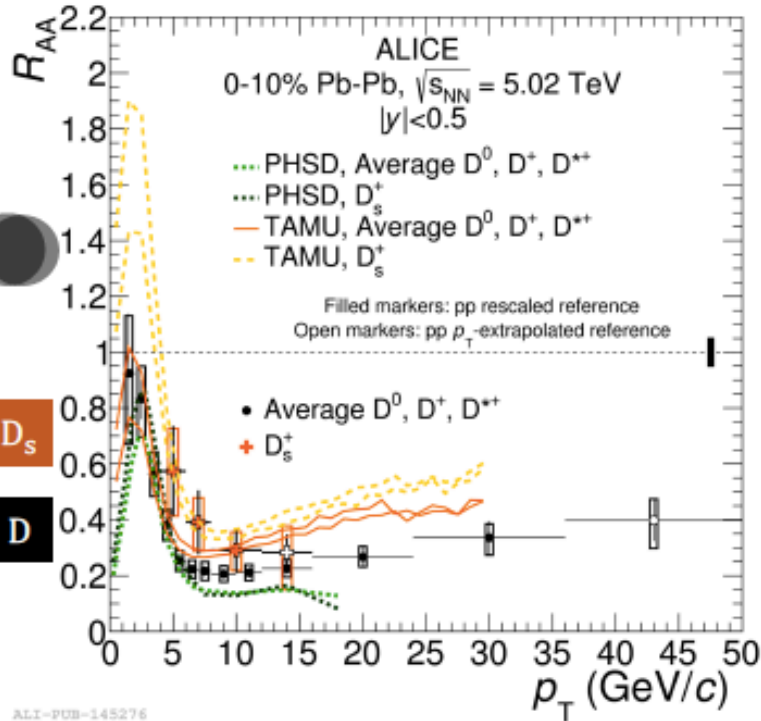
ALICE

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

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

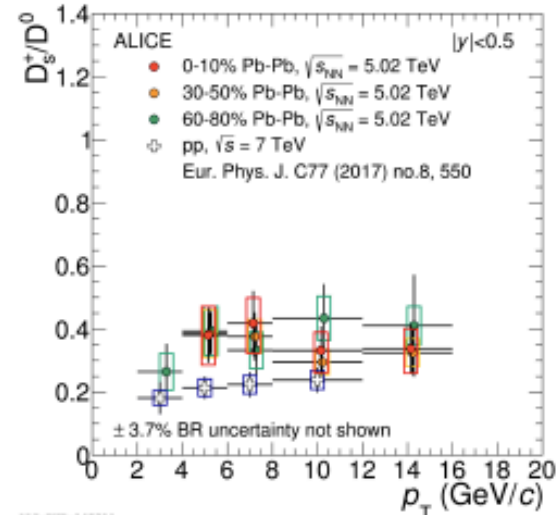
TAMU: Phys.Lett. B735 (2014) 445-450

Catania: Eur.Phys.J.C (2018) 78:348



ALI-PUB-145276

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?**



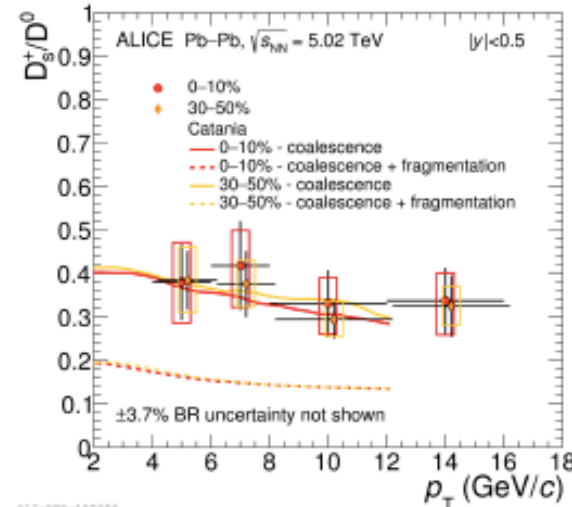
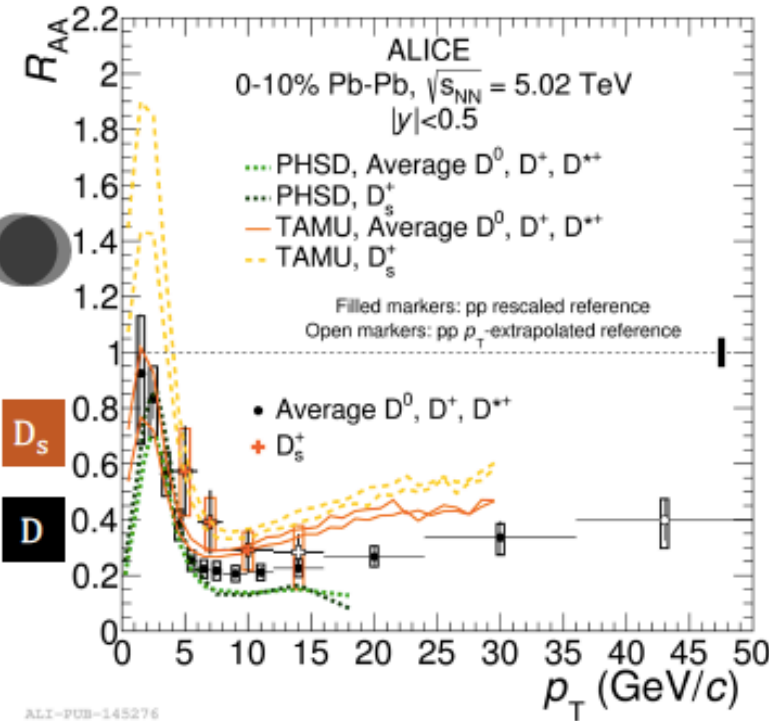
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Submitted!

- 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

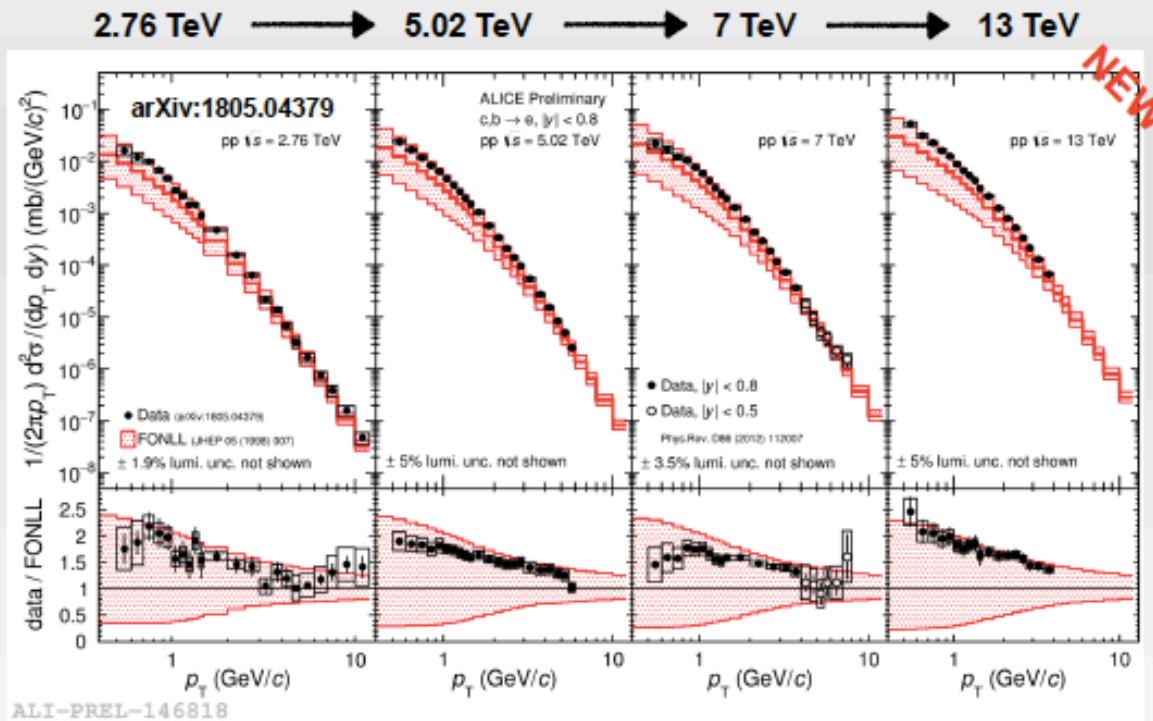
ALI-PUB-145276

arXiv:1804.09083

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

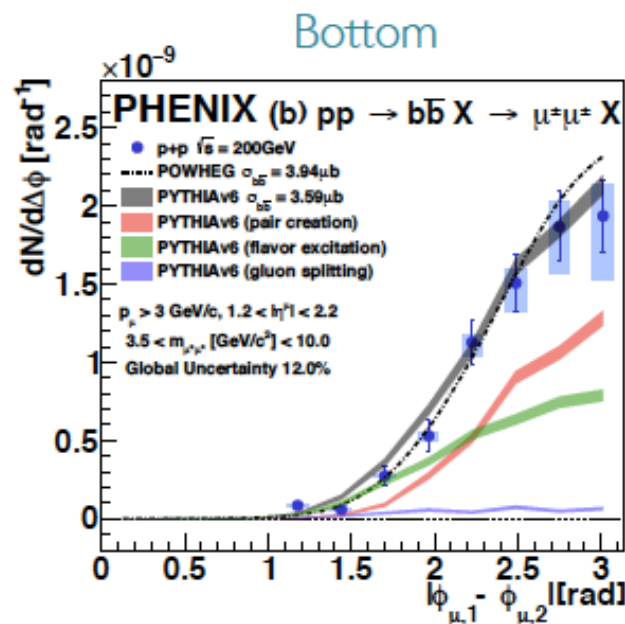
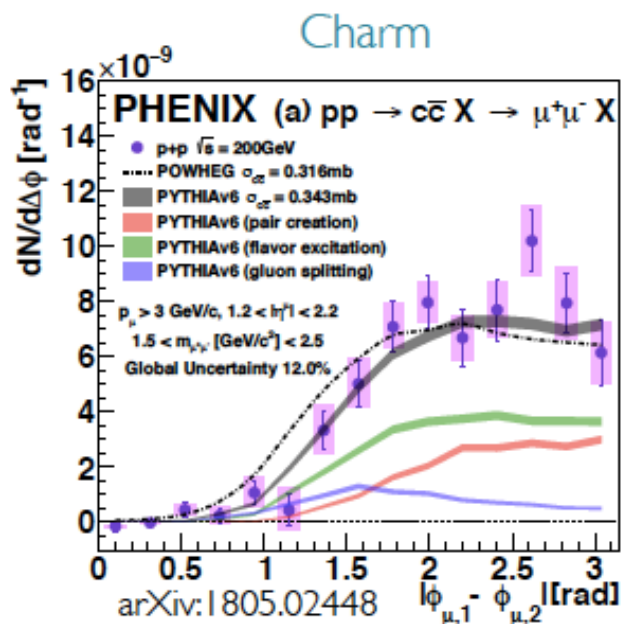
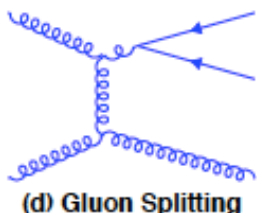
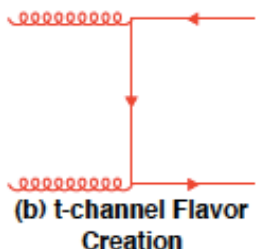
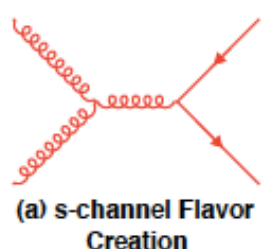


– Testing the **centre-of-mass energy dependence** down to $p_T = 0.5$ GeV/c

- 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!

Charm and bottom azimuthal correlations

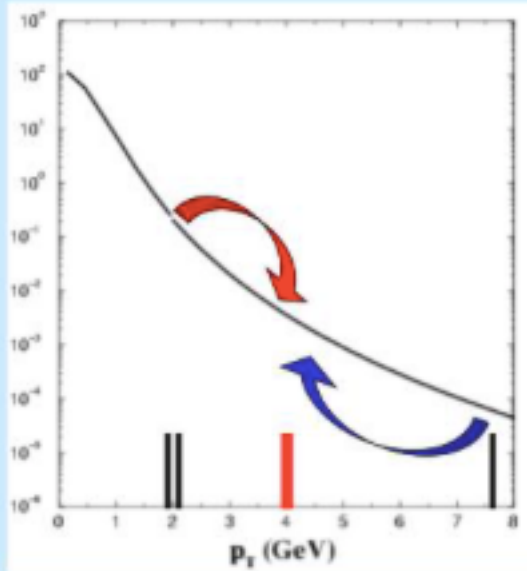
- Extract charm and bottom in separate kinematic regions
- Charm and bottom dimuon $\Delta\phi$ compared to PYTHIA Tune A and POWHEG
 - Theoretical curves normalized with cross-sections from fitting technique





Fine

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 \$

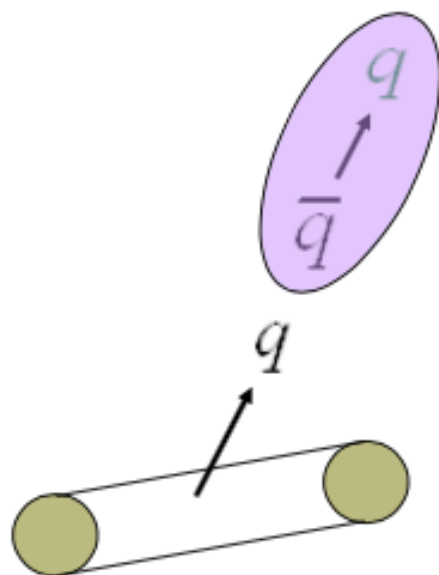
Even if eventually *Fragm.* takes over ...

$$\begin{cases} C(p_T) \propto \left(\frac{p_T}{2}\right)^{-\alpha} \left(\frac{p_T}{2}\right)^{-\alpha} \\ F(p_T) \propto \left(\frac{p_T}{z}\right)^{-\alpha} \end{cases} \quad \frac{C}{F} \propto \left(\frac{4}{\langle z \rangle}\right)^\alpha (p_T)^{-\alpha}$$



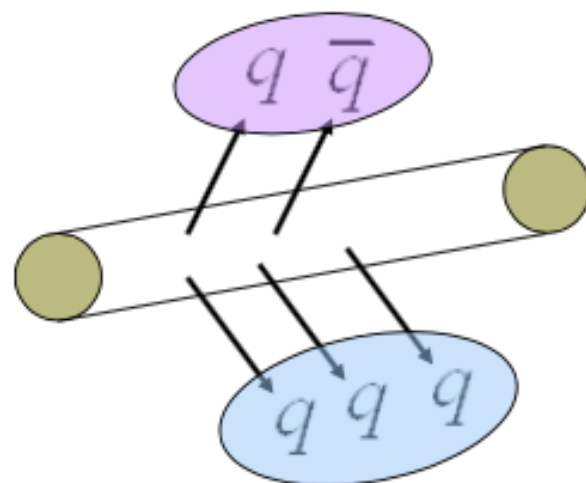
Quark recombination ?

S. Voloshin, QM2002



Fragmentation

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



Recombination

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

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

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":



- 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