# Recent Heavy Flavor Production in Heavy-Ion Collisions

—— **Mainly selected experiment results with China contributions**

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# Outline

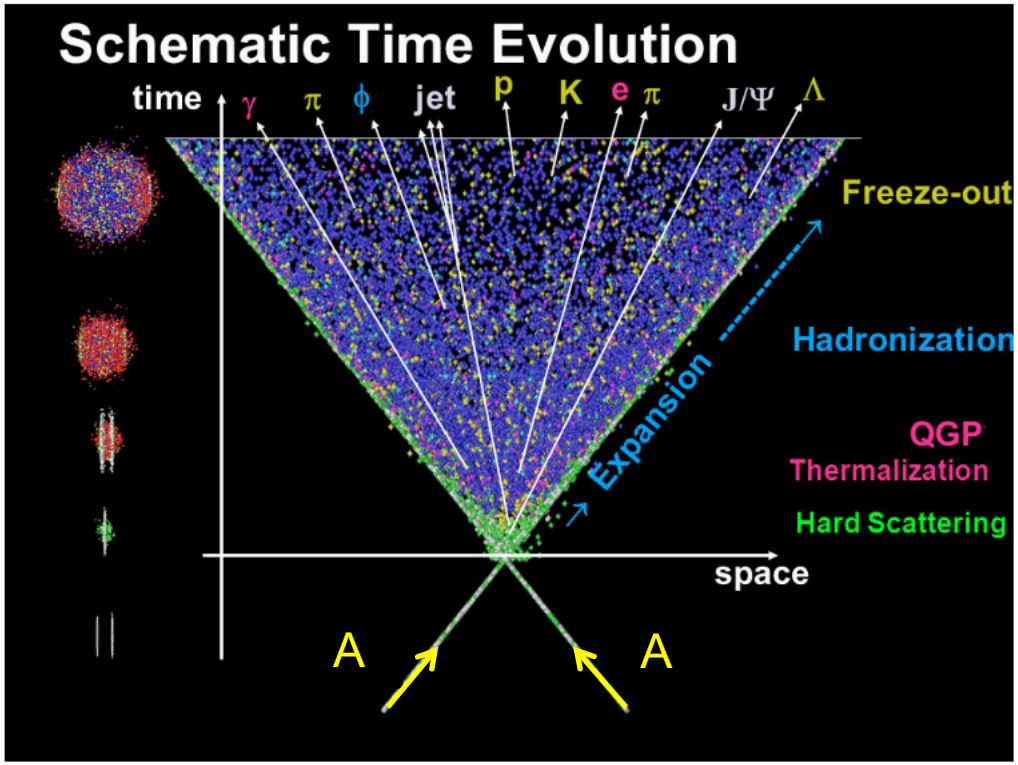
- Introductions
- RHIC and LHC experiment facilities
- Experiment results
  - Charm/beauty production, NMF
  - Charm hadronization
  - Charm flow
- Summary

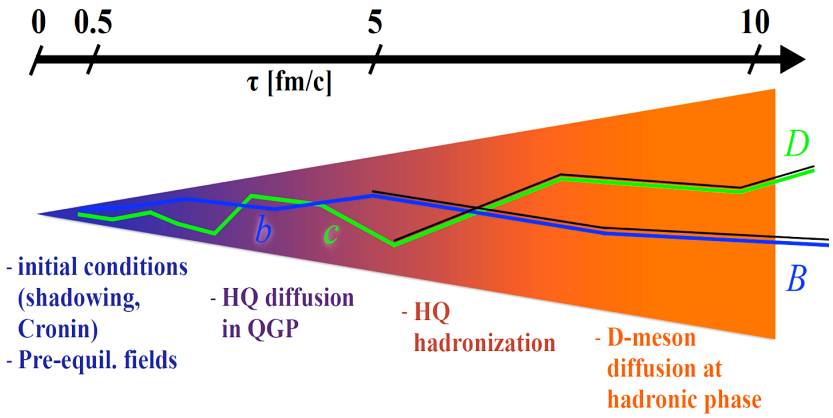
# Why are heavy quarks important?

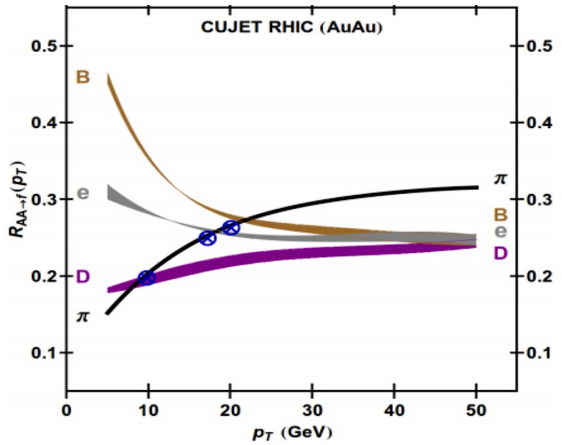
**Heavy quarks (charm and beauty): excellent probes of QGP**

**Hot-dense system (A-A collisions)**

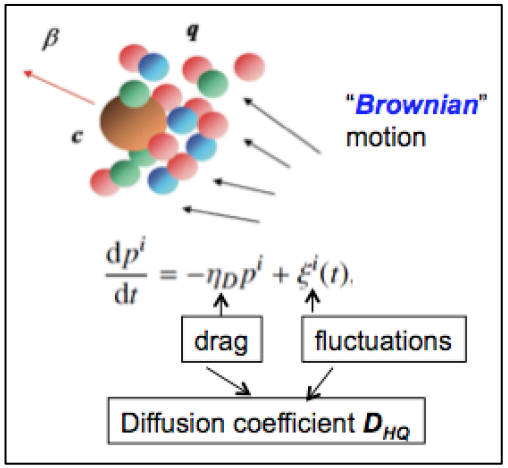
- Produced early in the history of HIC.
  - calculable by pQCD.
  - numbers are conserved.
- Experience most of the stages of the system evolution.
  - sensitive to properties of the medium.
  - HQ energy loss $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- HQ hadronization mechanism.



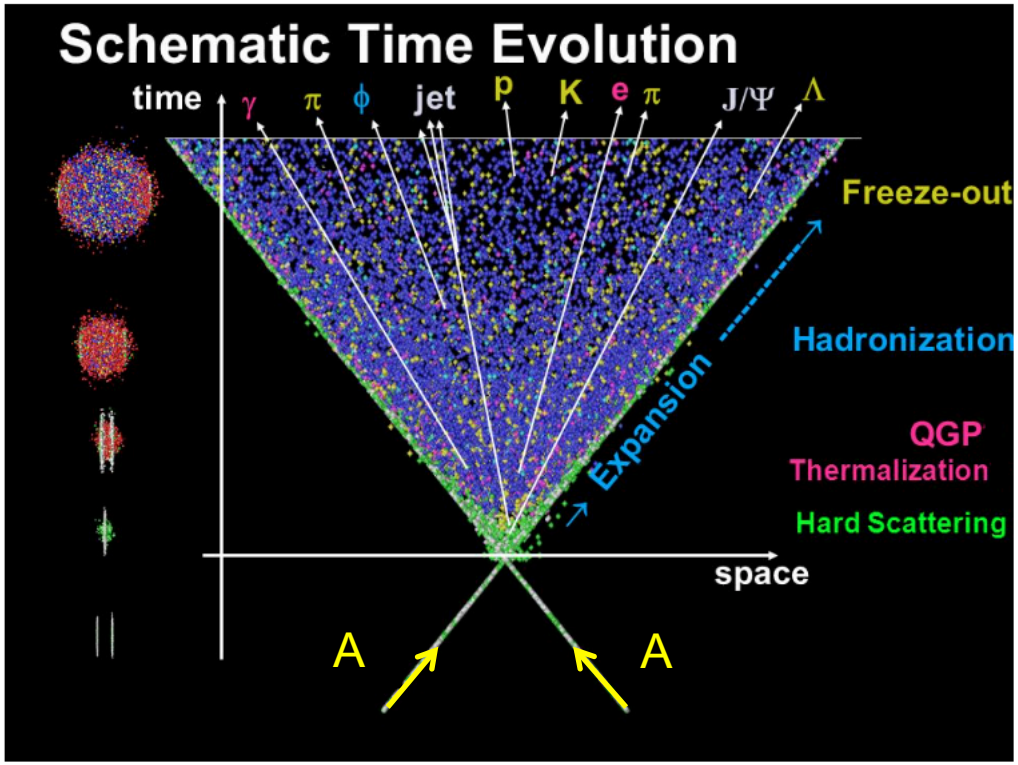




PRL 108 (2012) 022301



# Why are heavy quarks important?

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

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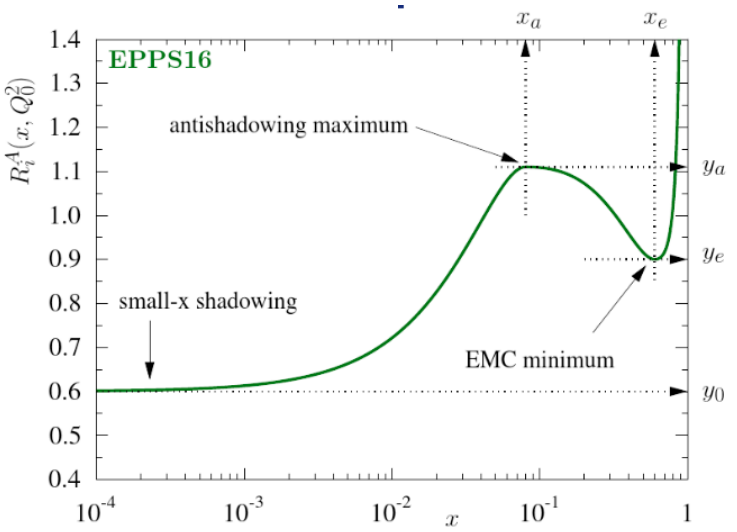
- HQ hadronization mechanism.

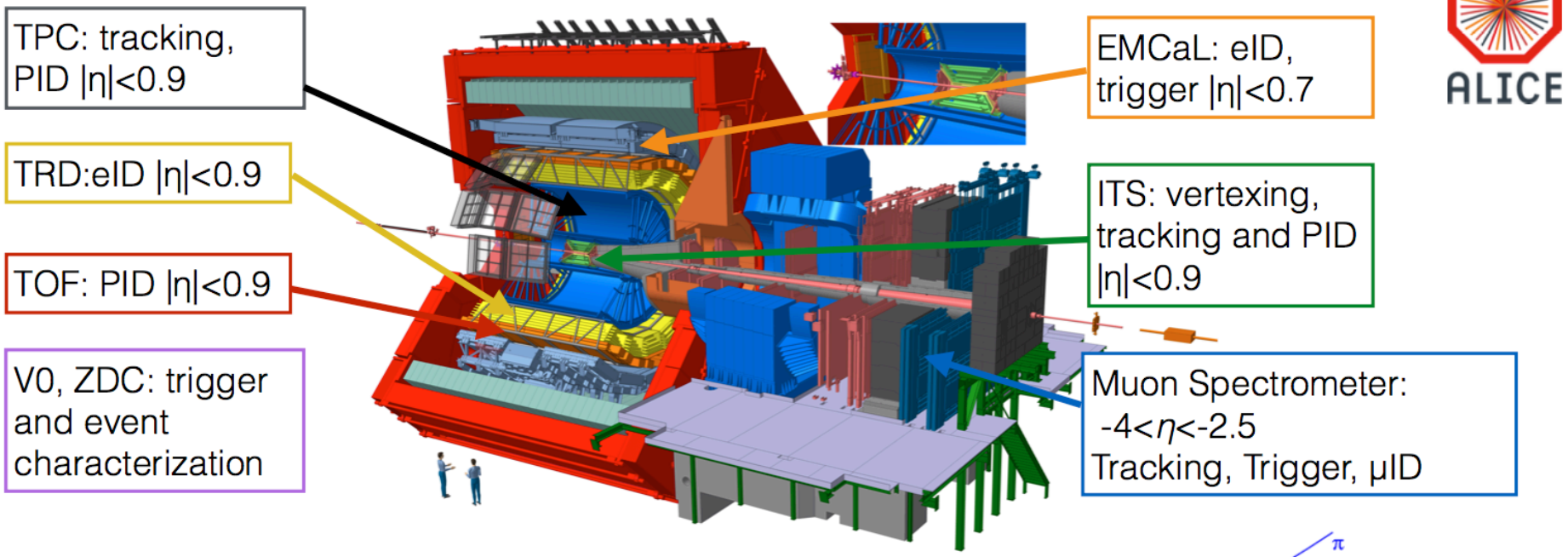
**Small system (p-A、d-A collisions)**

- Cold nuclear matter (CNM) effects in the initial and final stages of the collisions.

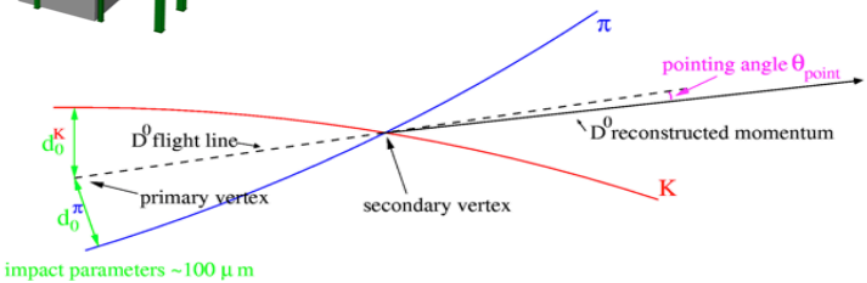



Quarkonium (Z. Liu、Y. Ding and X. Zhu's talk on Fri)

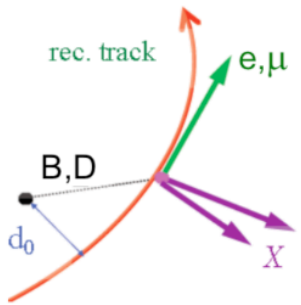
# Experiment facilities for HQ (ALICE)




Fully reconstructed **D mesons and $\Lambda_c$** hadronic decays:
**ITS**, **TPC**, **TOF**
$D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\pi^+$, $D_s^+ \rightarrow \Phi\pi^+ \rightarrow K^-K^+\pi^+$,
$\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow pK^0_s$




Partially reconstructed **semi-leptonic decays**
Muons: **Forward Muon Spectrometer.** D, B → μ± + X
Electrons: **ITS**, **TPC**, **TOF**, **EMCAL**, **TRD**. D, B → e± + X



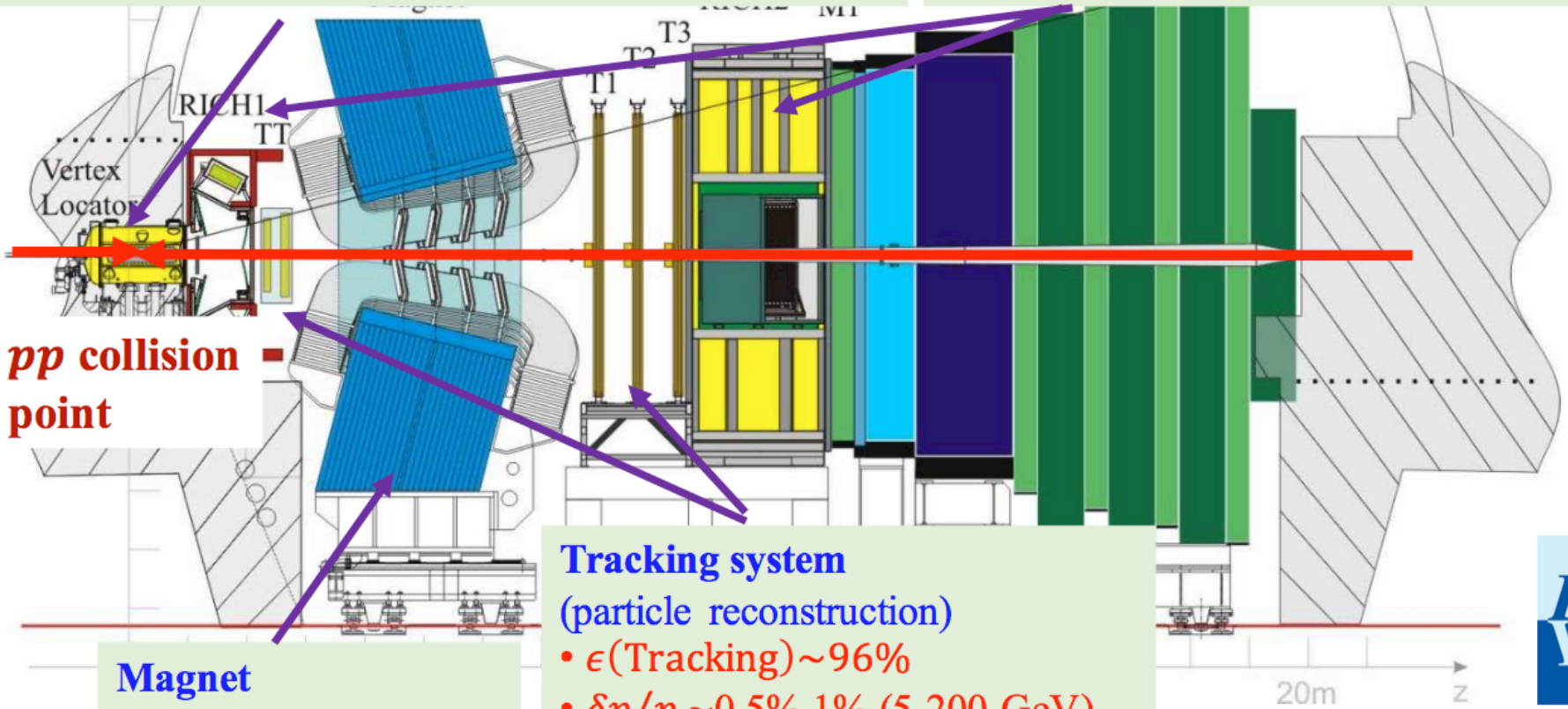
# Experiment facilities for HQ (LHCb)

## Precision measurements in $b, c$ flavor sectors

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

$\tau(H_b)$~1.5 ps, $\tau(H_c)$~0.1 – 1 ps
**Vertex Locator** (vertex reconstruction)
- Impact parameter resolution: $(15 + 29/p_T)\mu$m
- Time resolution: 45 fs, resolving HF decay vertex

Decays: $b \to c \to s$ ($K^{\pm}$);
Baryon → proton
**RICH detectors** ($K/\pi/p$ separation)
- $\epsilon(K \to K)$~95% for $r(\pi \to K)$~5%

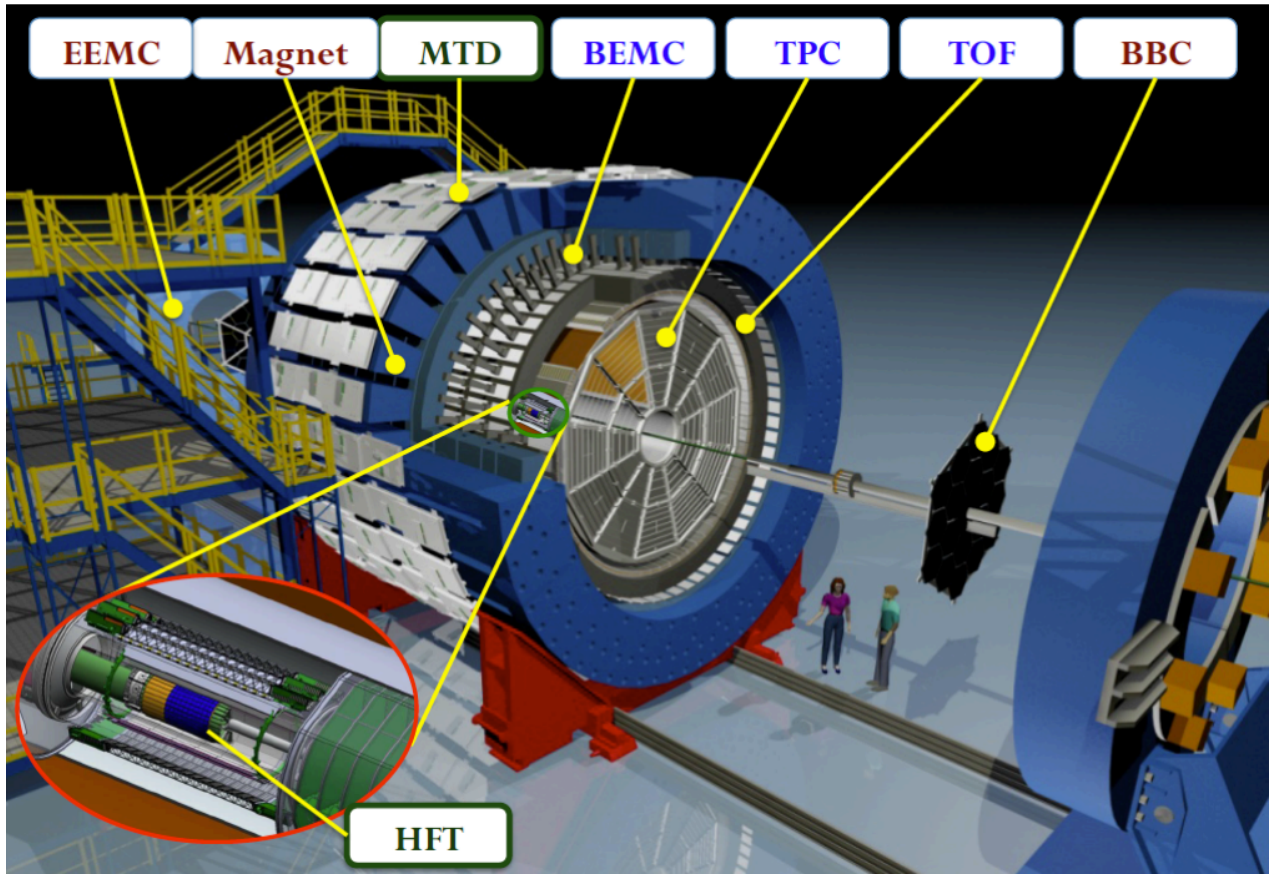


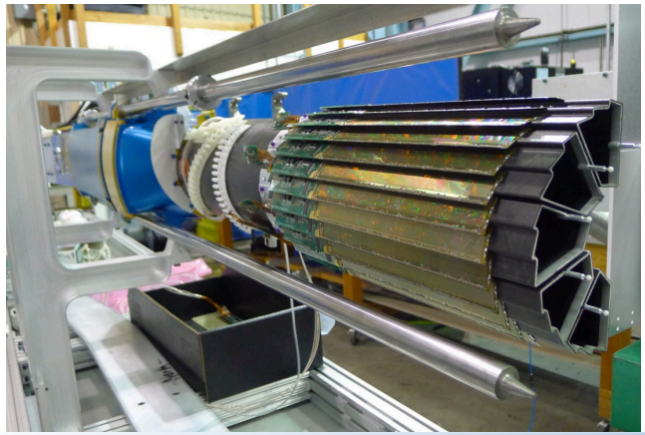

**Tracking system**
(particle reconstruction)
- $\epsilon$(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

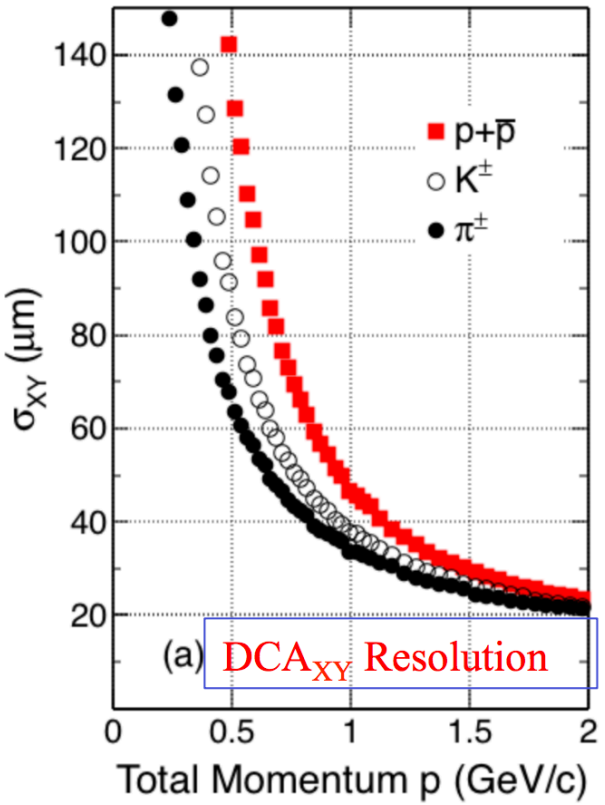
**Magnet**
Bending power: 4 Tm

Courtesy of Y.X. Zhang

# Experiment facilities for HQ (STAR)






Large acceptance: $|\eta| < 1$, $0 < \phi < 2\pi$

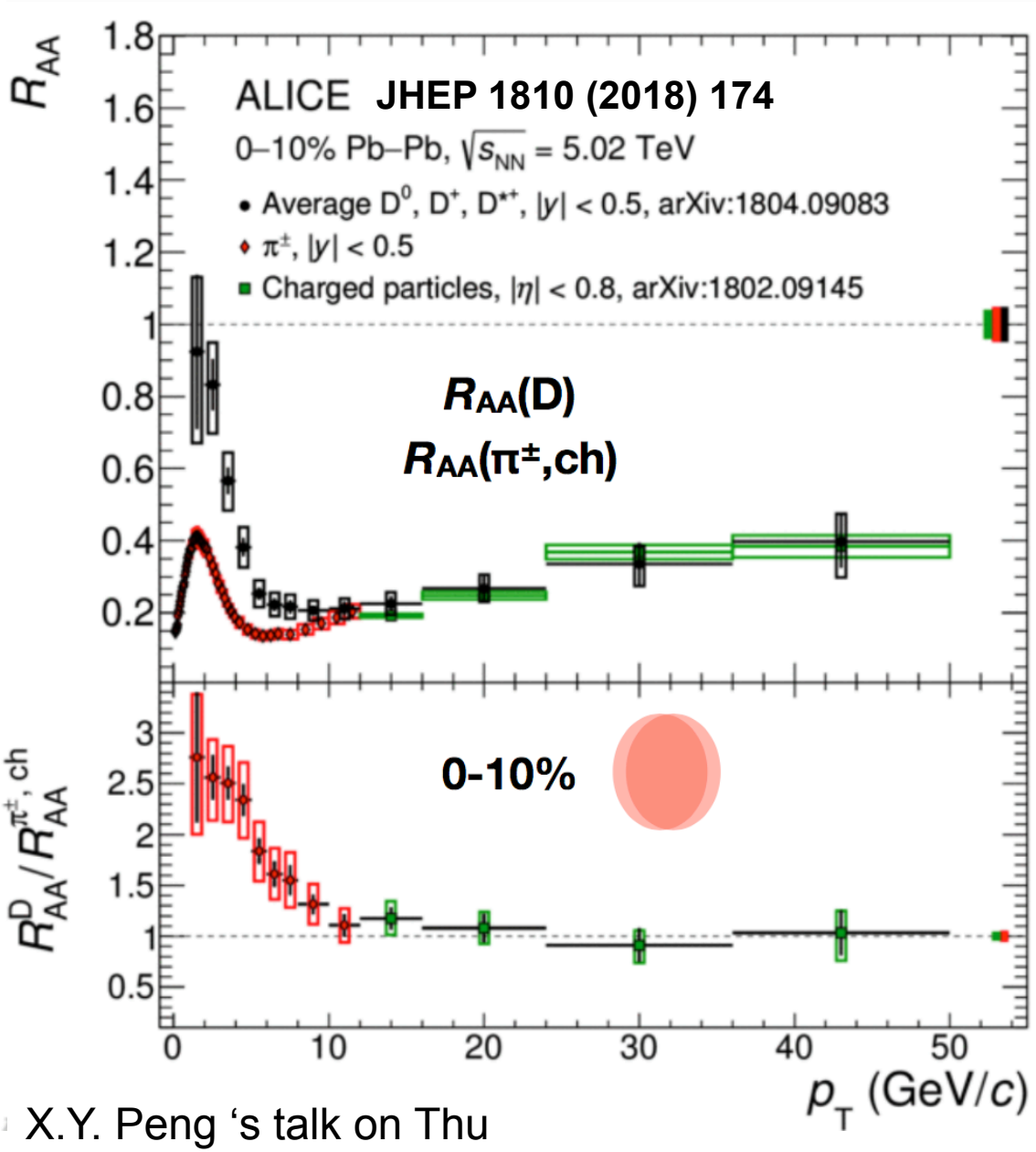
TPC + TOF + Ecal + HFT

Tracking, PID, trigger …

Heavy Flavor Tracker

– track pointing resolution ~50 μm @ $p_T$ ~0.8 GeV/c

# D-meson production in Pb-Pb at ALICE




X.Y. Peng 's talk on Thu

Nuclear modification factor:

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

- High $p_T$ @ $p_T$ > 10 GeV/c: $R_{AA}$(D) ~ $R_{AA}$ (π, h).
- Low $p_T$ @ $p_T$ < 10 GeV/c: $R_{AA}$(D) > $R_{AA}$ (π, h).
  - Mass dependent energy loss?
  - Charm redistributes in hadronization?
  - Radial flow?
  - CNM effects?
  - Is charm number really conserved at such high energy?

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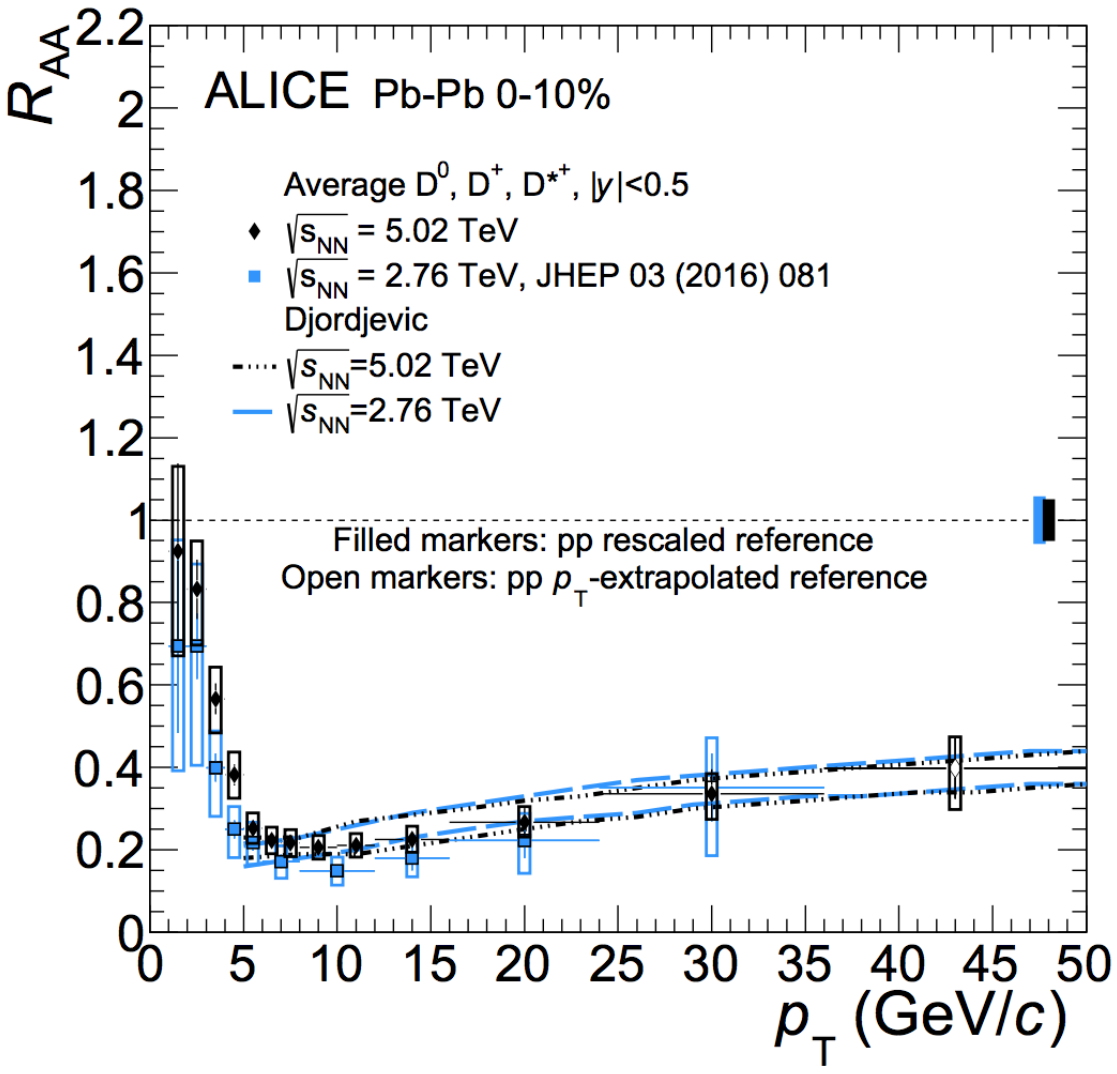
X.Y. Peng 's talk on Thu




**ALICE, JHEP 1810 (2018) 174**

[1] Djordjevic, PRC92 (2015) 024918

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- Consistent with model[1] calculations for both energies @ $p_T$ > 5 GeV/c.
- Similar suppression for both energies => harder spectra and denser medium counterbalance.

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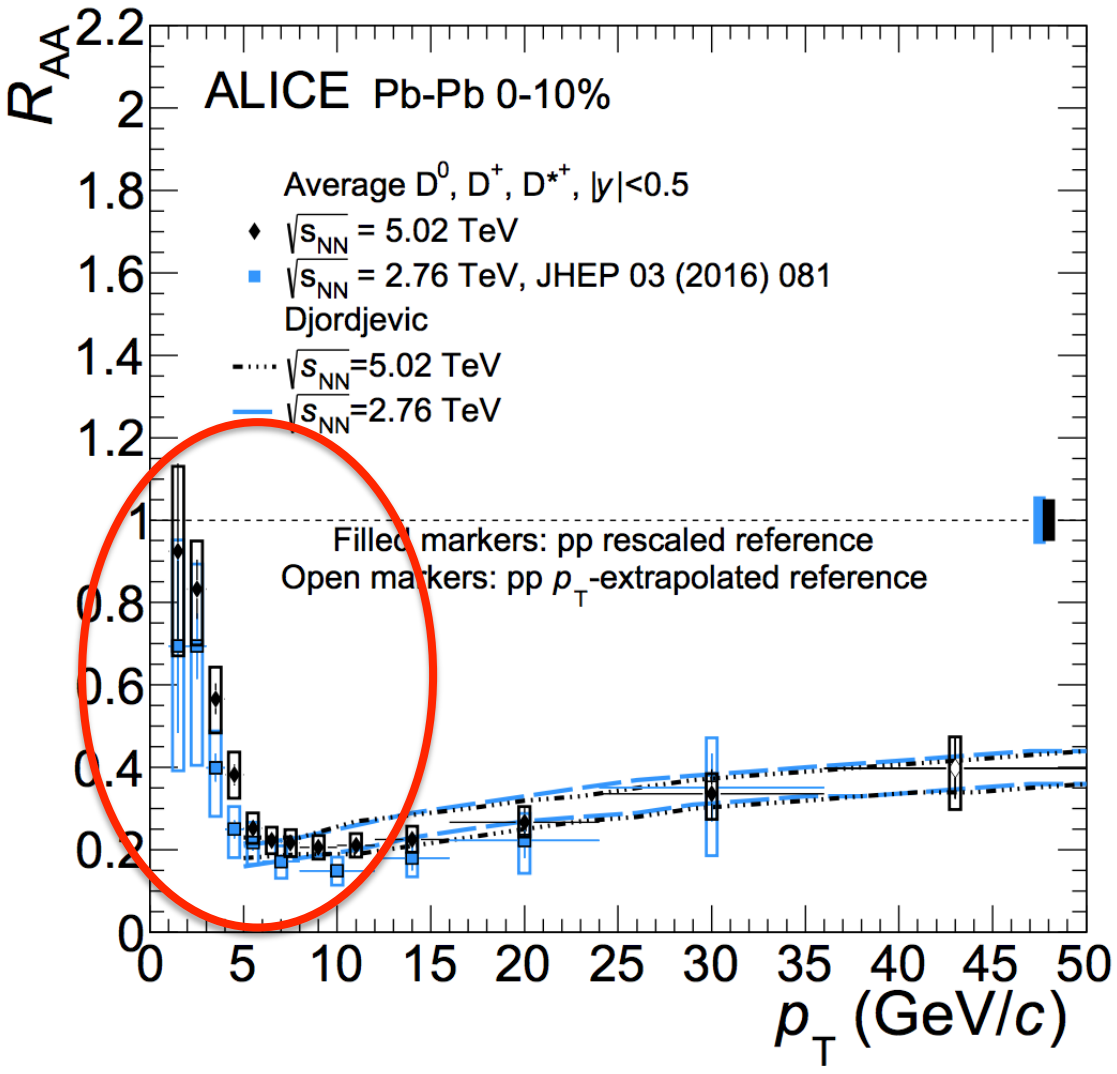


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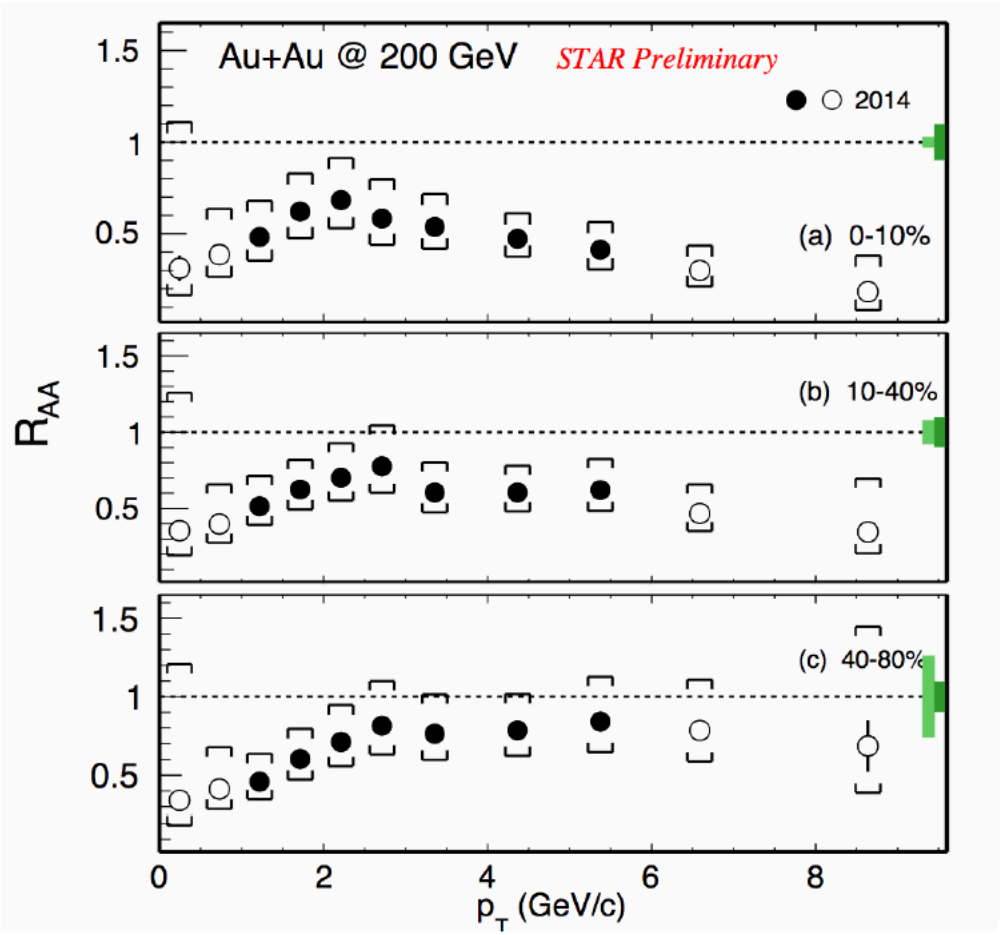
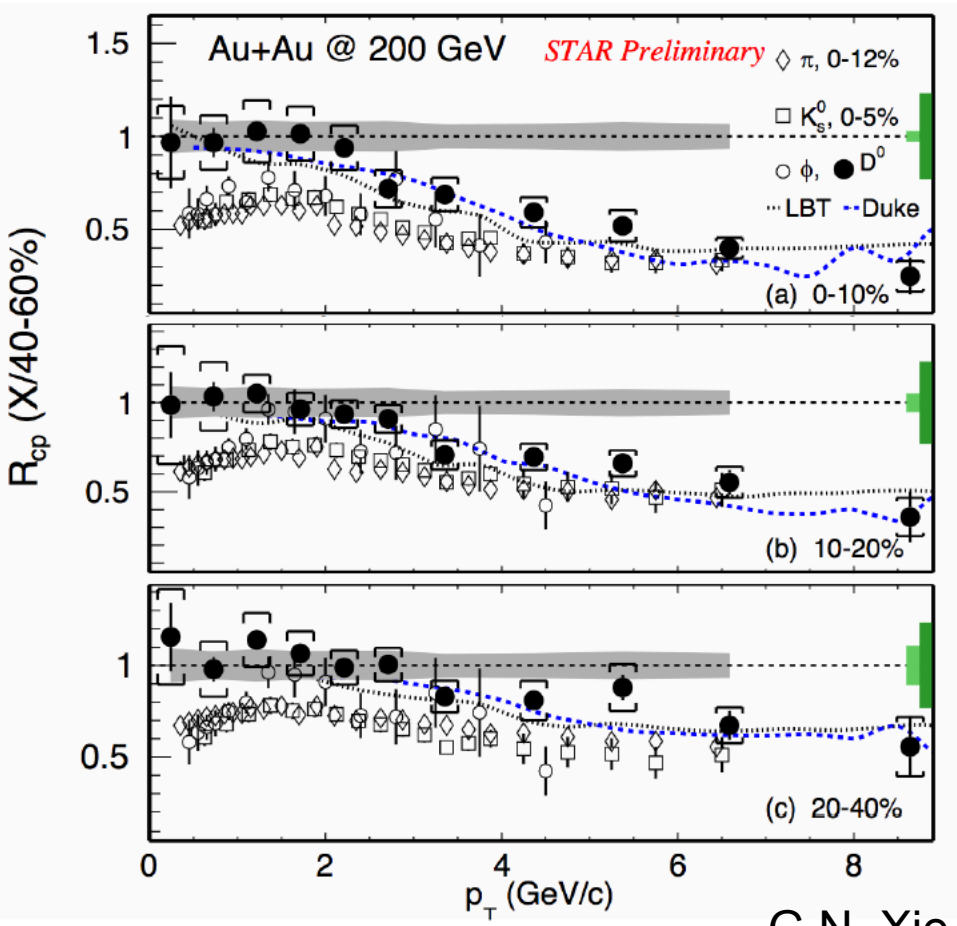
- Consistent with model[1] calculations for both energies @ $p_T$ > 5 GeV/c.
- Similar suppression for both energies => harder spectra and denser medium counterbalance.
- Low $p_T$, larger radial flow or more thermal charm hadronization in 5.02 TeV?
- Need more data.

# D-meson production in Au+Au at STAR



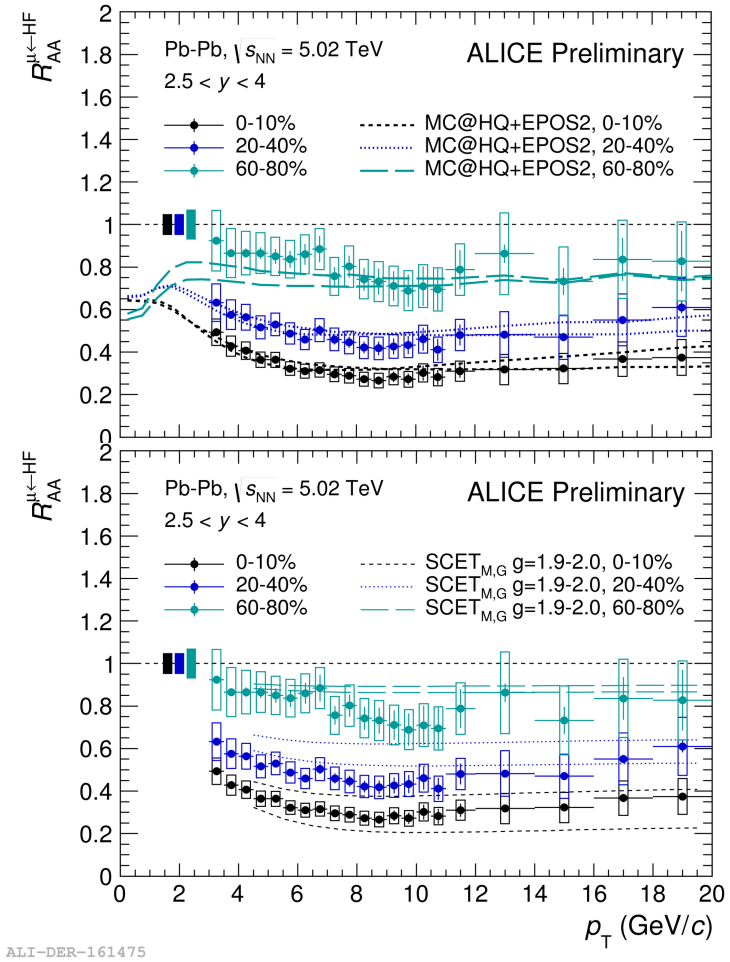




G.N. Xie HP18

- Low $p_T$ suppression may due to charm redistributions in medium and/or CNM.
- Both $R_{AA}$ and $R_{CP}$ show significant suppression at high $p_T$ in central collisions and consistent with light hadrons at $p_T > 6$ GeV/c. Similar as ALICE result.
- Transport models with charm quark energy loss can describe the data.

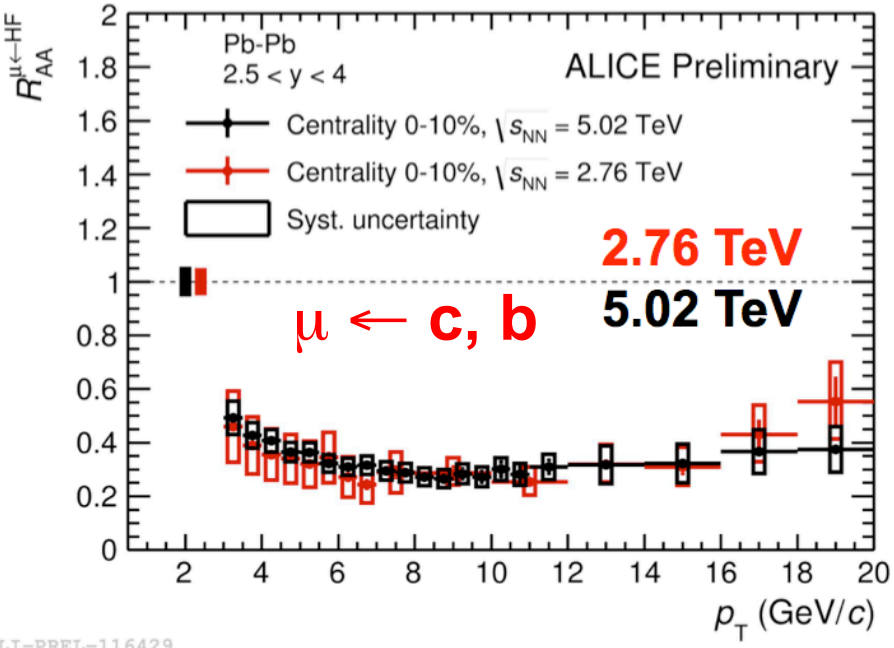
# Inclusive muon production at ALICE

$\mu \leftarrow$ c, b



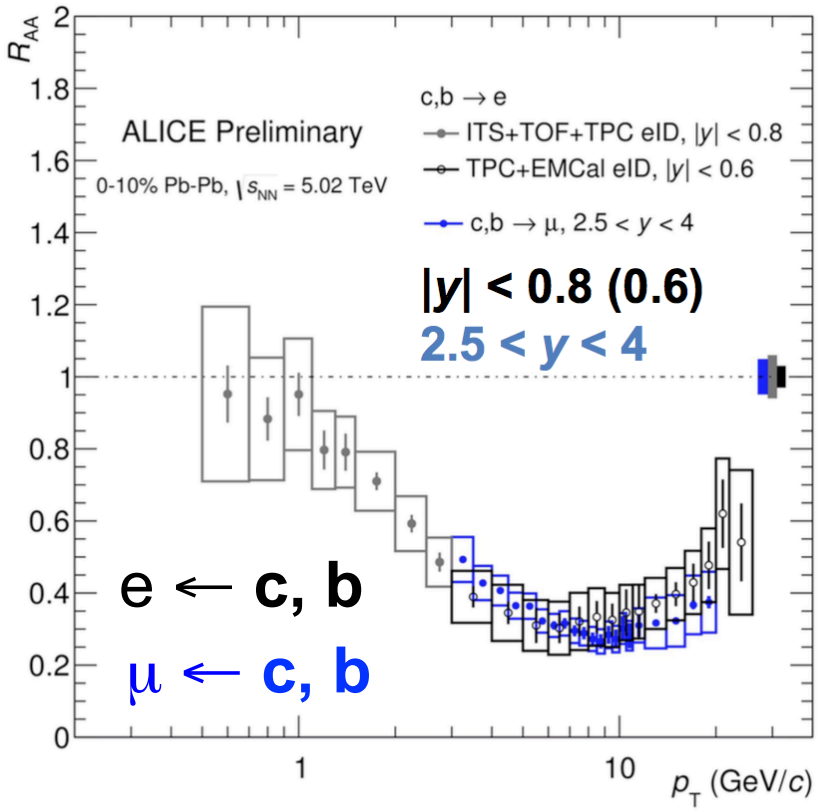

MC@sHQ: Phys.Rev. C89, (2014) 014905;
SCET: Phys. Rev. C 80 (2009) 054902;
POWLANG: EPJ C73 (2013) 2481;
TAMU: PLB735 (2014) 445–450.

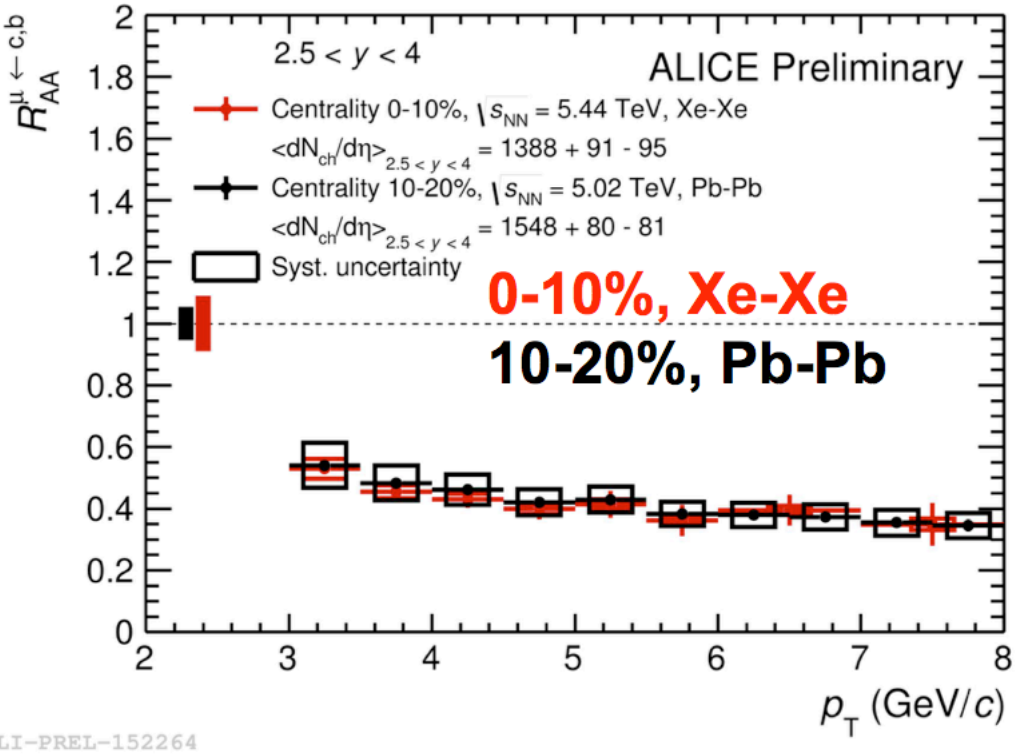
Z.M. Zhang 's talk on Thu




- Increasing suppression for more central collisions.
- High $p_T$, beauty contribution dominant, indication of beauty energy loss.
- Similar suppression at 5.02 TeV and at 2.76 TeV. Harder spectra and denser medium counterbalance.
- New constraints on models.

# Inclusive muon production at ALICE

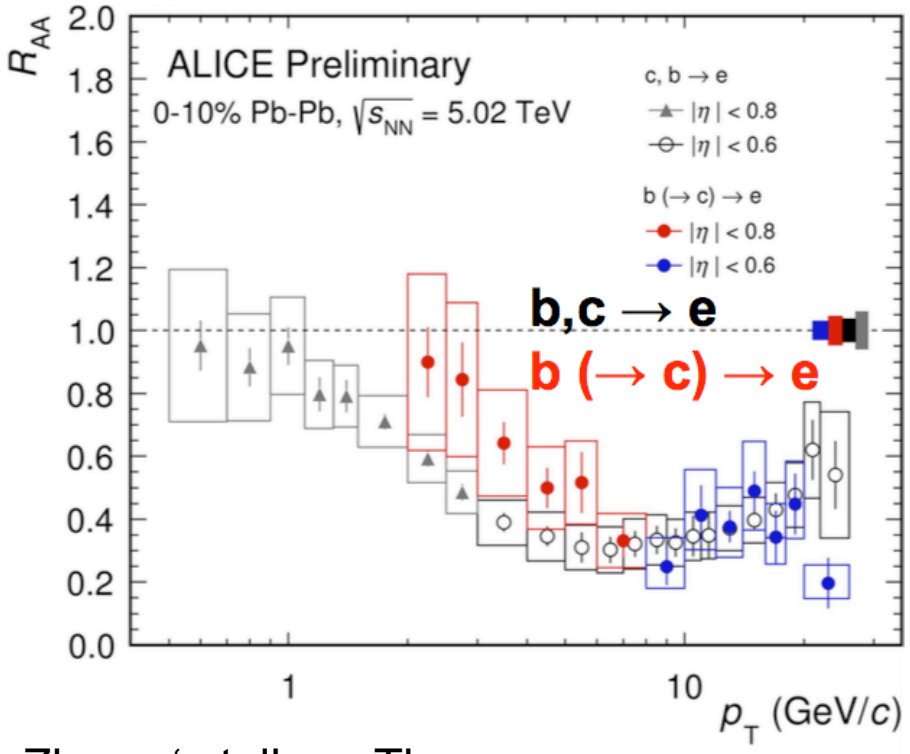


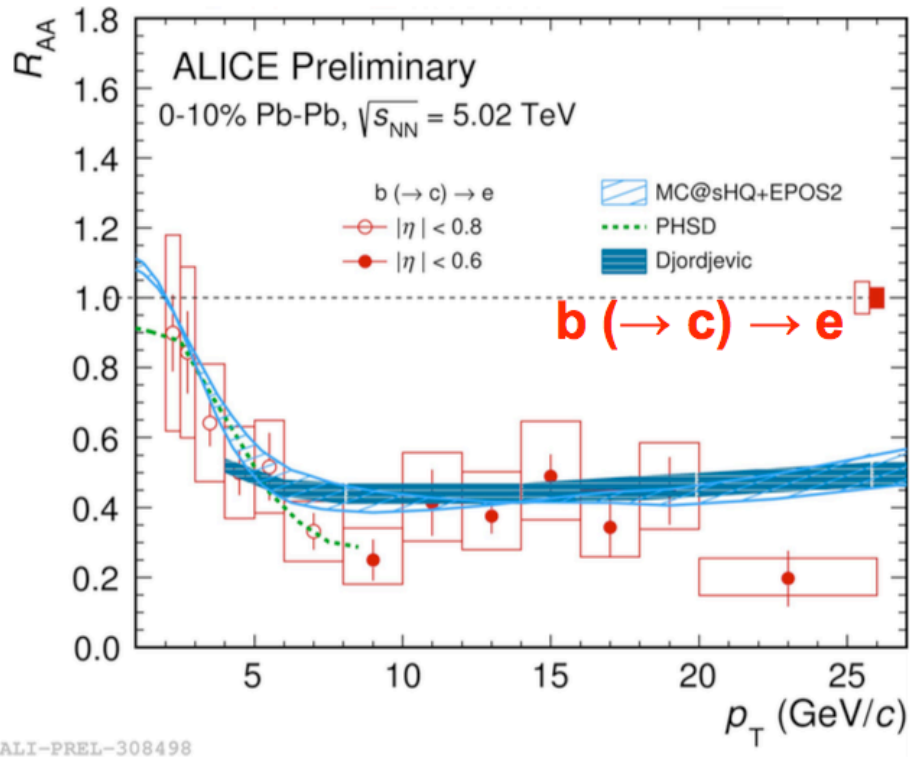




Z.M. Zhang ‘s talk on Thu

- Consistent with previous published inclusive electron in mid-rapidity.
- Similar results observed in 0-10% Xe-Xe and 10-20% Pb-Pb collisions at similar <dN/d$\eta$> => possible interplay of geometry and path-length dependence.

# Bottom production in Pb-Pb at ALICE

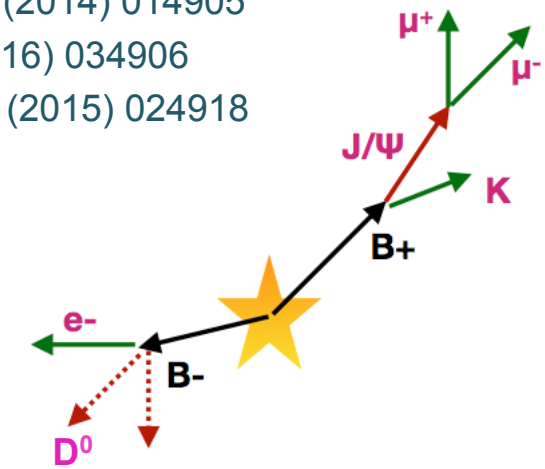


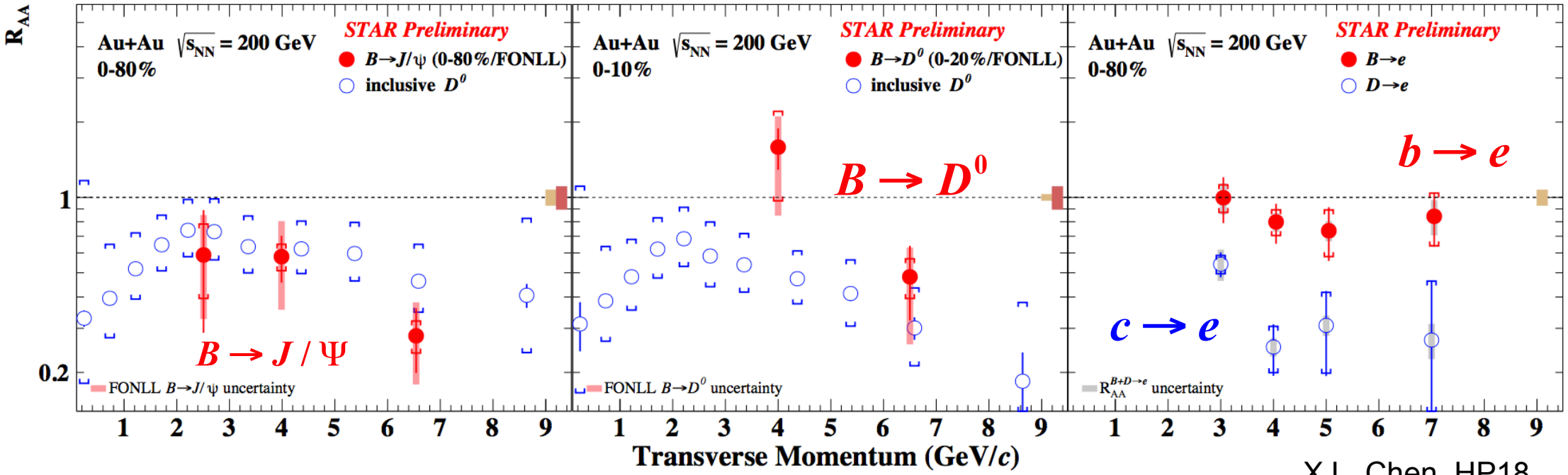

Z.M. Zhang 's talk on Thu

MC@sHQ: Phys.Rev. C89 (2014) 014905
PHSD: Phys. Rev. C93 (2016) 034906
Djordjevic: Phys. Rev. C92 (2015) 024918

- Hint of a smaller suppression for beauty-decay electron for $p_T$ < 6 GeV/c.
- Data are reproduced by models within uncertainties, implementing mass-dependent energy loss.



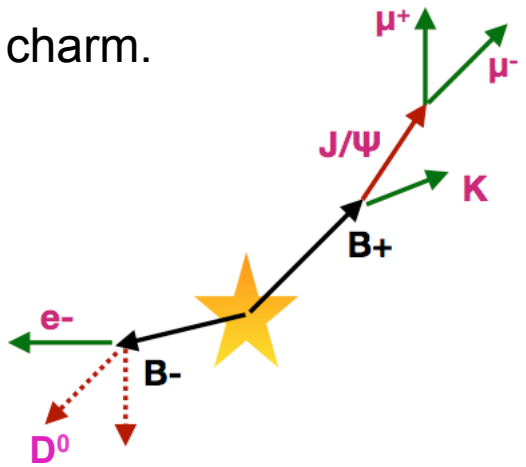
# Bottom measurement in Au+Au at STAR




X.L. Chen, HP18

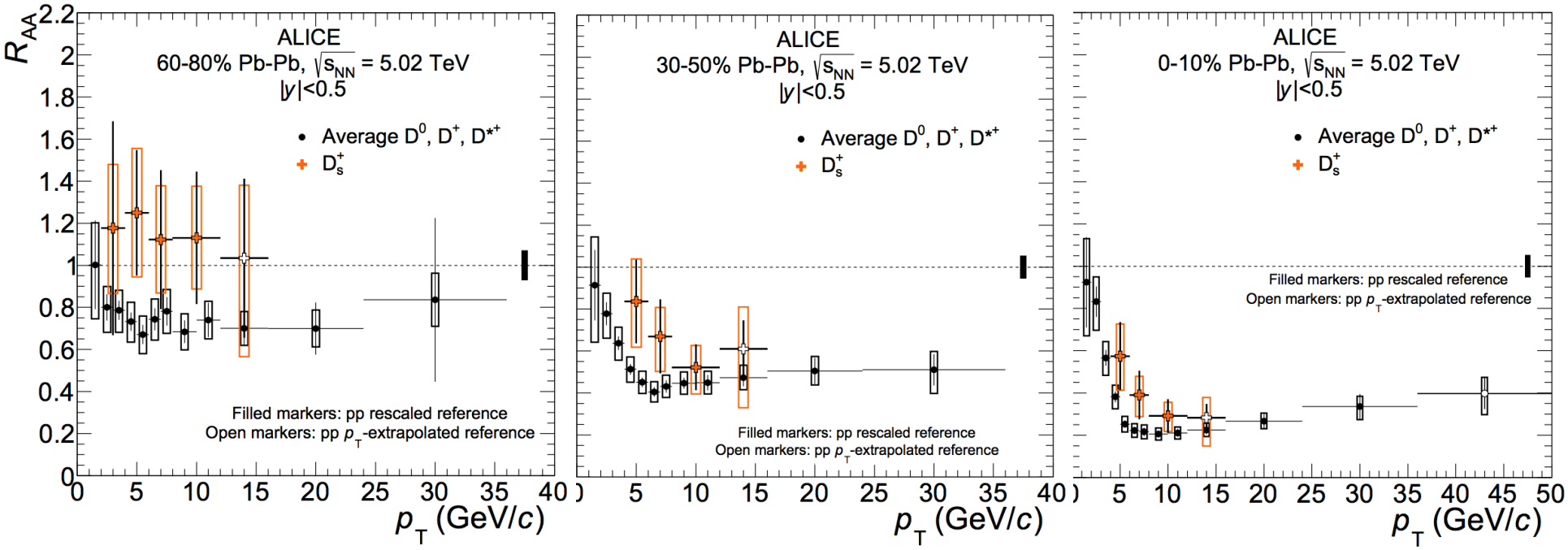
- B -> l + X
- B -> J/Ψ + X
- B -> D + X

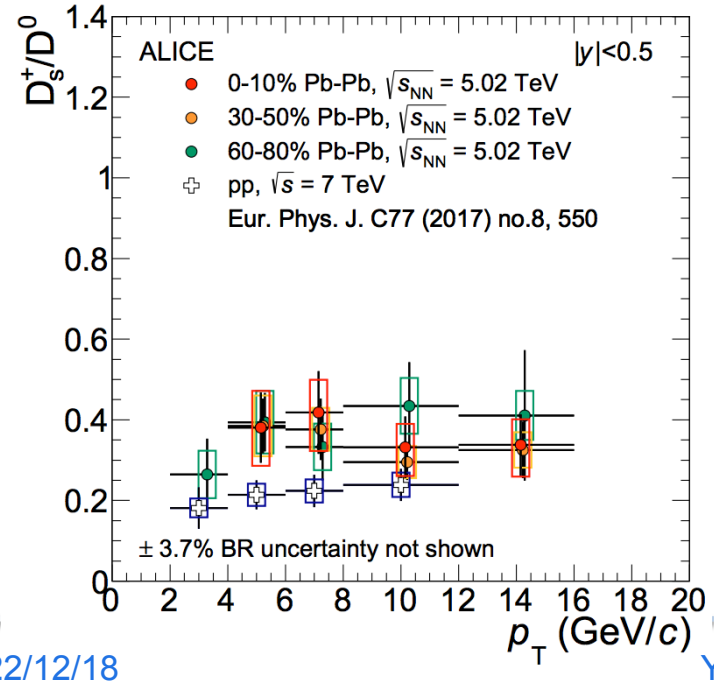
Very challenging via hadronic reconstruction of B-meson.
Benefit with x3 longer life time of beauty than that of charm.




- Strong suppression for B->$J/\Psi$ and B->$D^0$ at high $p_T$ => High $p_T$ beauty interacts with QGP and loses energy.
- Less suppression for b->e than c->e (~2$\sigma$), consistent with $\Delta E_c > \Delta E_b$ (low $p_T$).

# Strangeness enhancement in charm sector

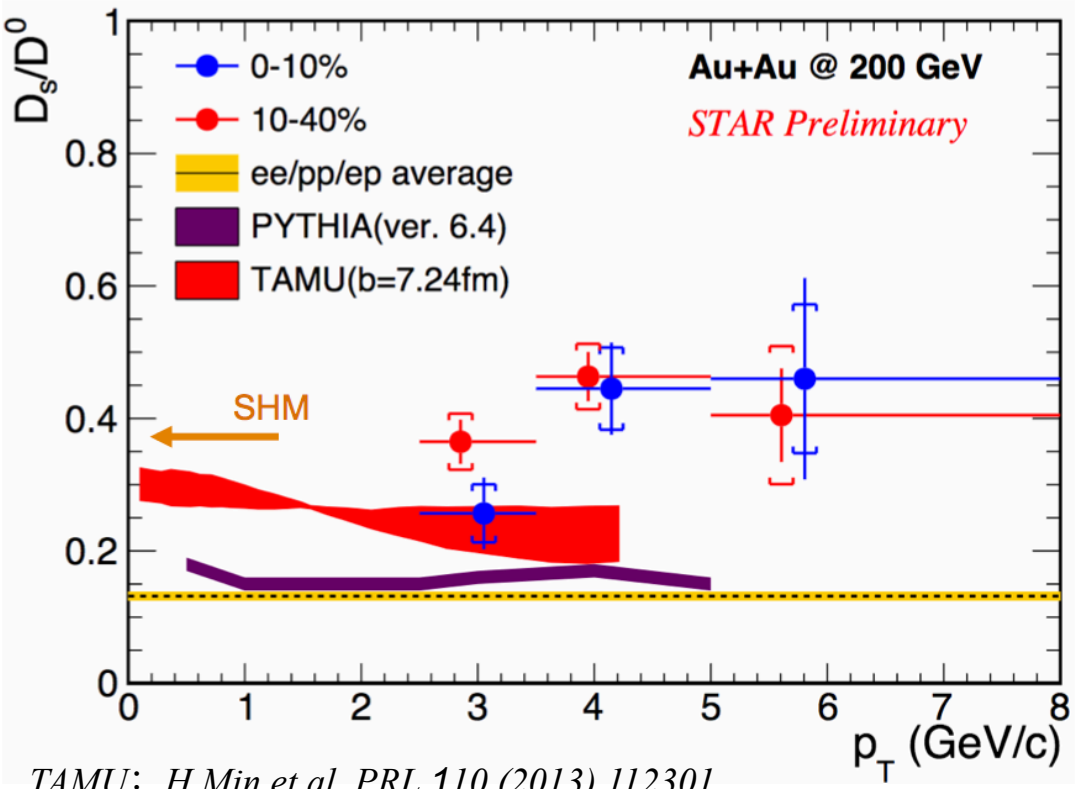


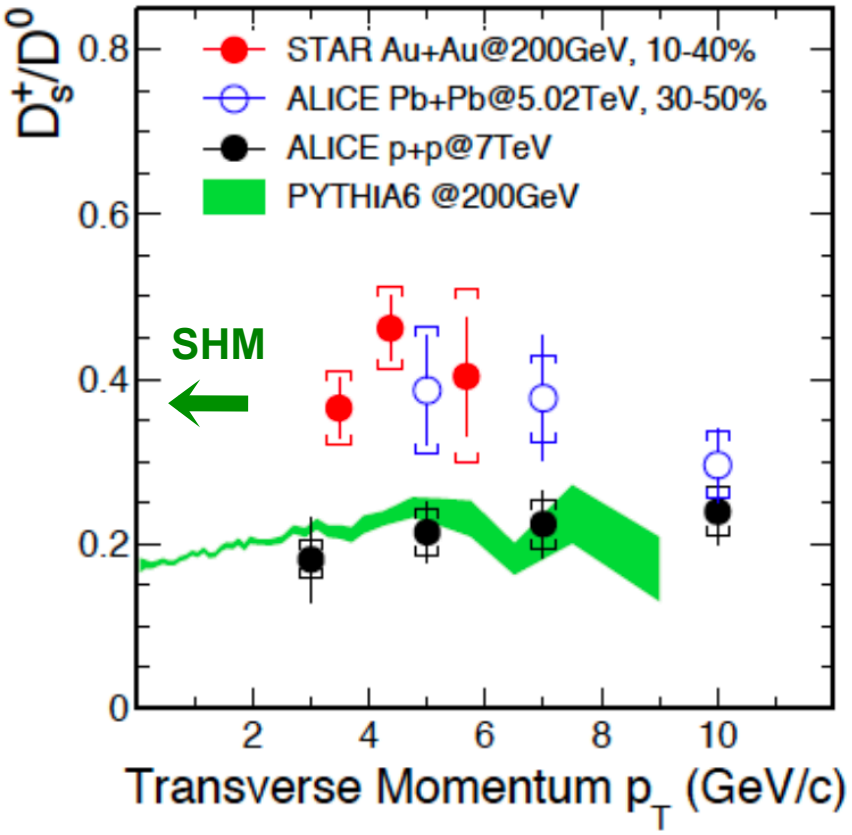

**ALICE, JHEP 1810 (2018) 174**

- Increasing suppression for more central collisions.
- $D_s$ systematically larger than average D-mesons.
- $D_s/D^0$ ratio in Pb-Pb is significantly enhanced compared to that in pp.
- Weak centrality dependence for $D_s/D^0$ ratios.

# Strangeness enhancement in charm sector

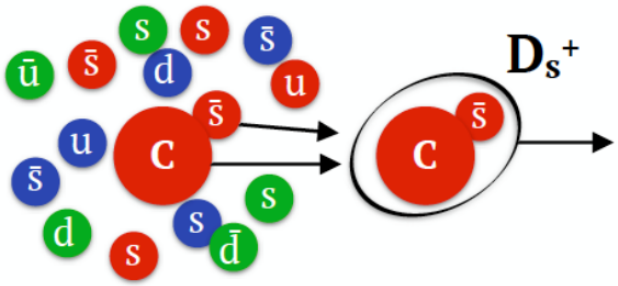



*TAMU: H.Min et al. PRL 110 (2013) 112301.*
*SHM: A. Andronic et al. PLB 571 (2003) 36.*

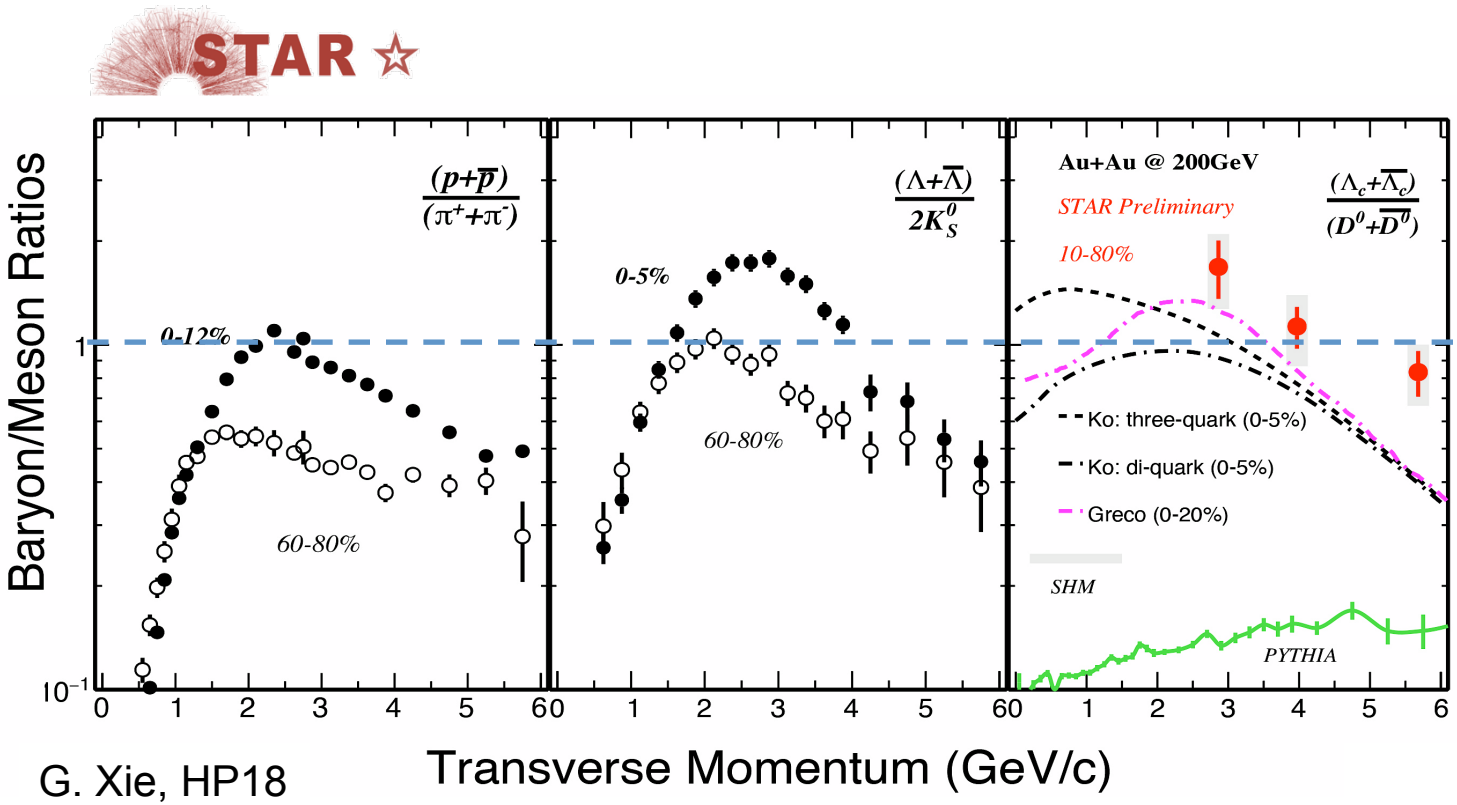


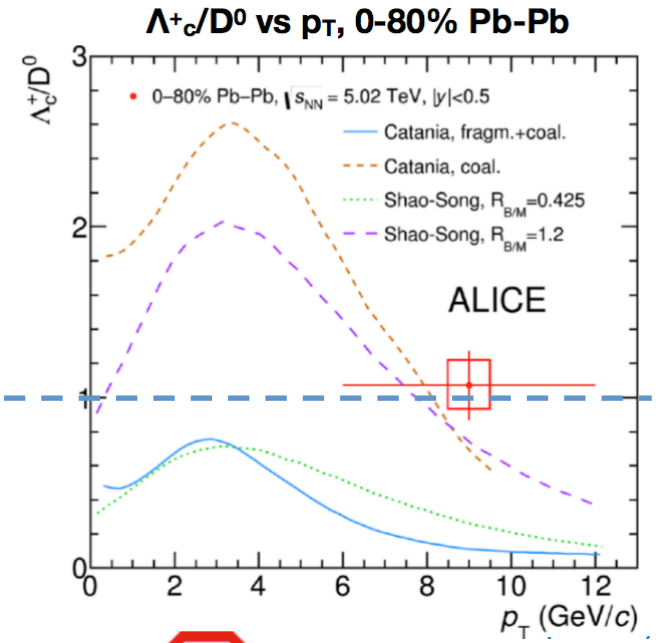

Significant $D_s/D^0$ enhancement in mid-central Au+Au and Pb+Pb collisions w.r.t fragmentation baseline or p+p measurement

- Charm coalescence hadronization
- Strangeness enhancement
- SHM predicts $D_s/D^0$ ratio ~ 0.35-0.40 (central)



# Baryon over meson ratio in charm sector




ALICE

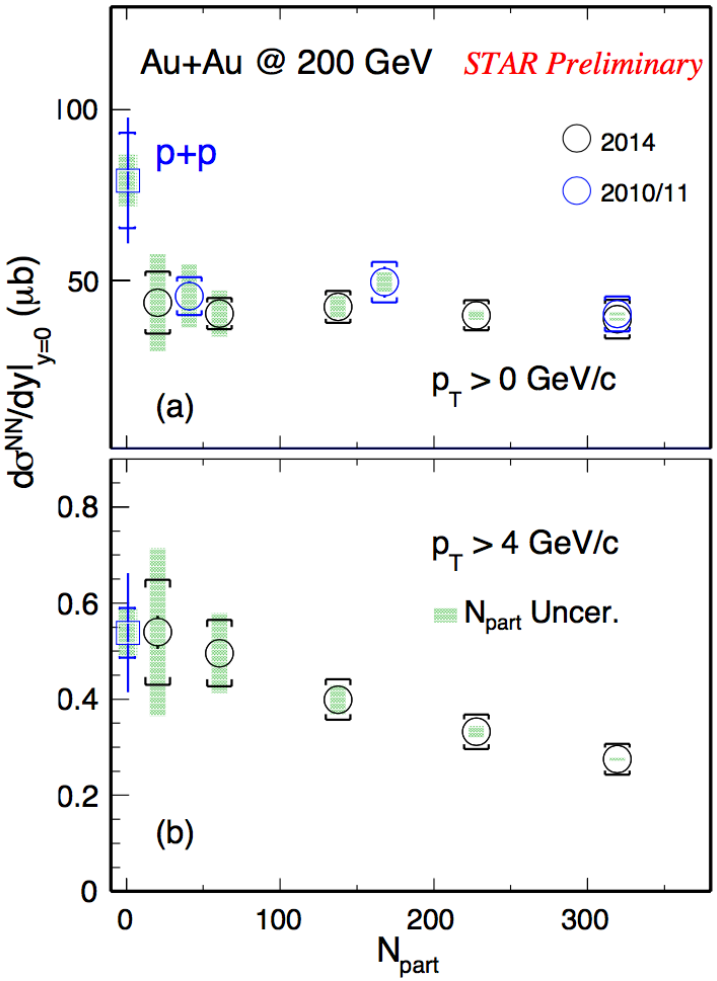
arXiv:1809.10922

G. Xie, HP18

*Ko model : PRC 79 (2009) 044905; Greco model : EPJC 78 (2018) 348)*

- Significant enhancement in $\Lambda_c/D^0$ compared to PYTHIA/fragmentation baseline.
- Similar enhancement observed at 200 GeV Au+Au and 5.02 TeV Pb-Pb (diff. $p_T$).
- The $\Lambda_c/D^0$ ratio is compatible with light flavor baryon-to-meson ratios.
- Consistent with coalescence + thermalized charm quarks, higher at high $p_T$.

# $D^0$ and total charm cross sections in Au+Au 200 GeV




| Charm Hadron | | Cross Section dσ/dy (μb) |
|---|---|---|
| AuAu 200 GeV (10-40%) | $D^0$ | 41 ± 1 ± 5 |
| | $D^+$ | 18 ± 1 ± 3 |
| | $D_s^+$ | 15 ± 1 ± 5 |
| | $\Lambda_c^+$ | 78 ± 13 ± 28 * |
| | **Total** | **152 ± 13 ± 29** |
| pp 200 GeV | **Total** | **130 ± 30 ± 26** |

*** derived using $\Lambda_c^+ / D^0$ ratio in 10-80%**

X. Chen, G. Xie

- $p_T$ integrated $D^0$ cross section is nearly independent with centrality and smaller than in p+p collisions. But for $p_T$ > 4 GeV/c, it decreases towards central collisions.
- Total charm cross section in Au+Au collisions is consistent with p+p value within uncertainties, but redistributed among different charm hadron species.

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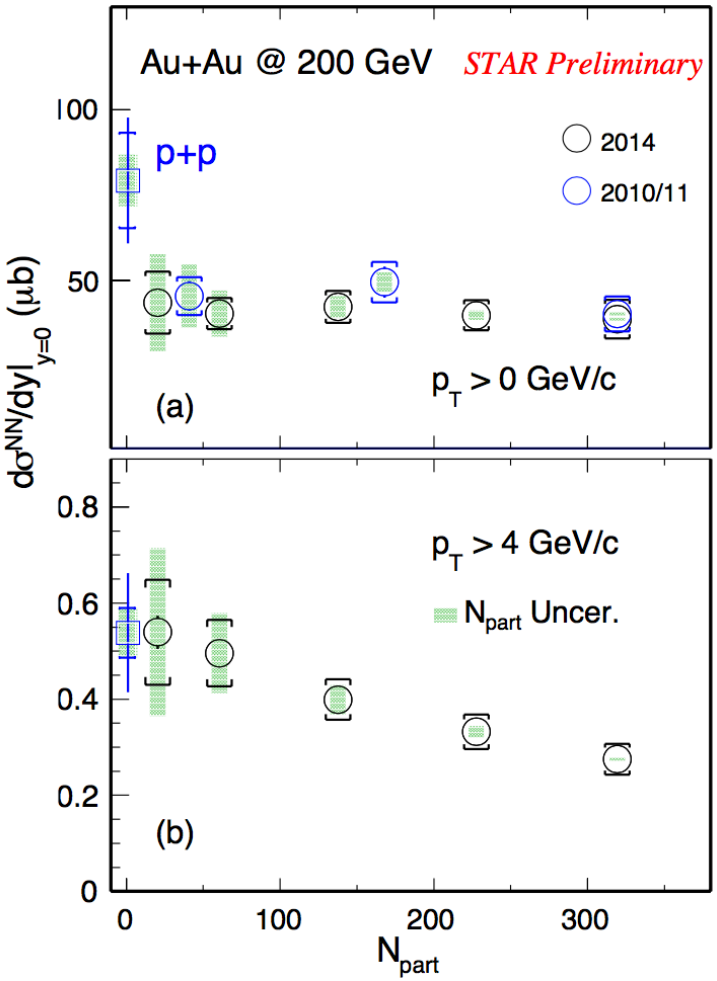


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Charm numbers are still conserved at RHIC!

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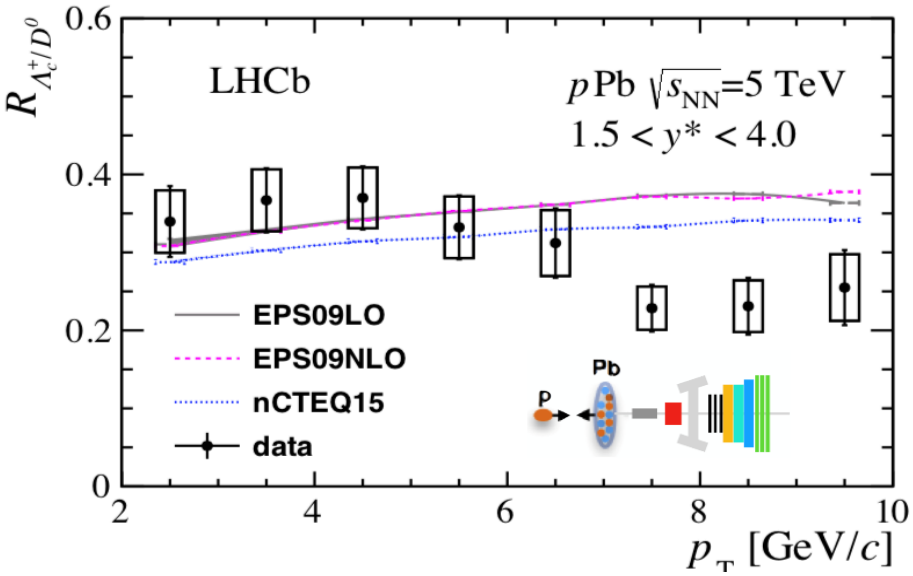
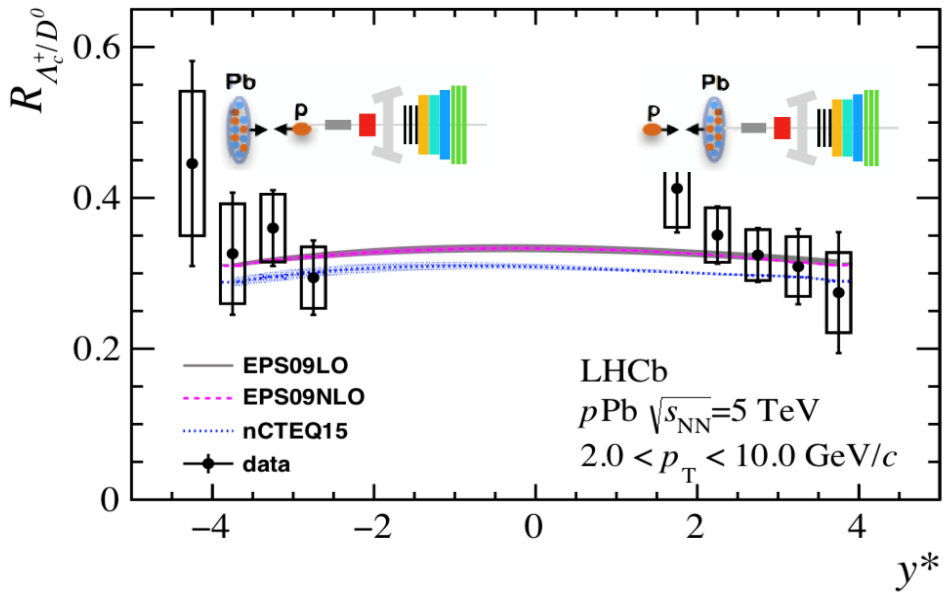
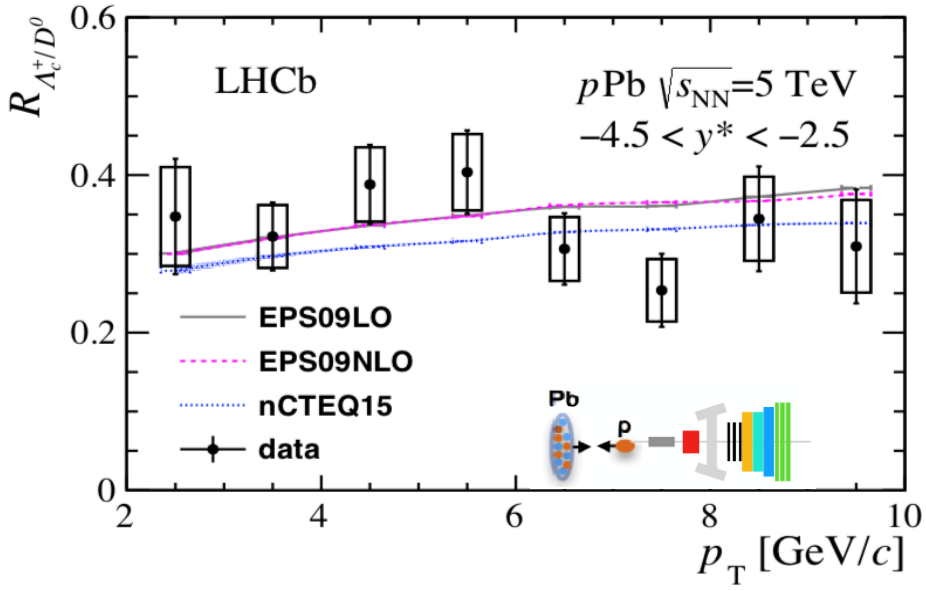
# $\Lambda_c$ production in p-Pb at LHCb

$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*, p_T)}{\sigma_{D^0}(y^*, p_T)}$$

- Sensitive to charm hadronization mechanism
- Consistent with model calculations for pp cross sections.



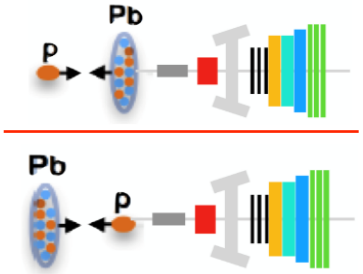




J. Sun and X. Zhu's talks

arXiv: 1809.01404, submitted to JHEP

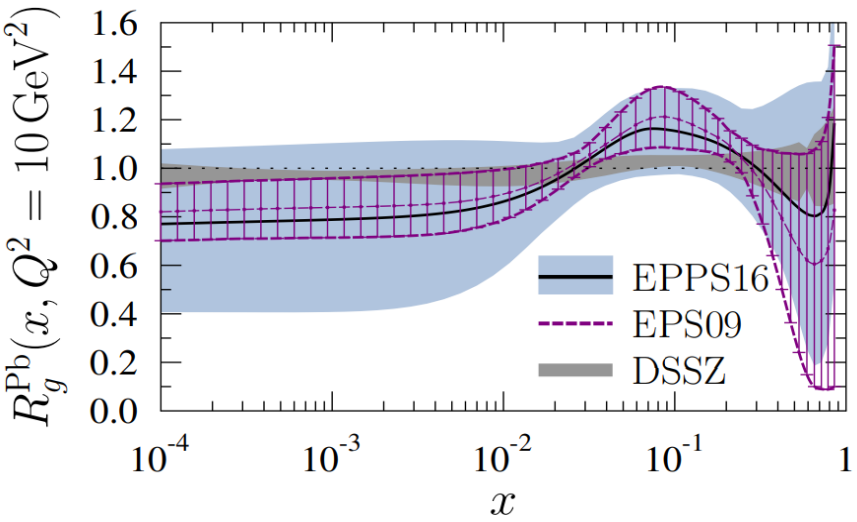
# $\Lambda_c$ production in p-Pb at LHCb

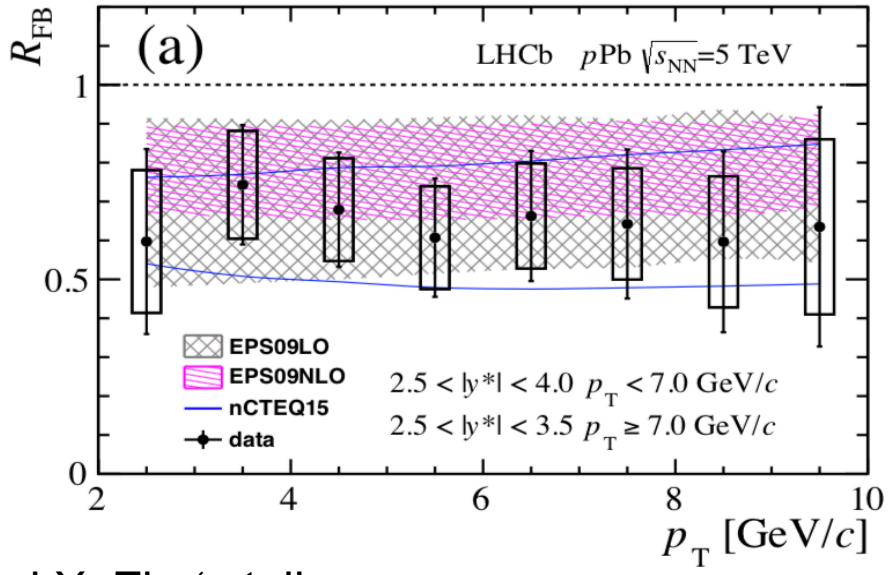
$$R_{FB} = \frac{\sigma(+|y^*|, p_T)}{\sigma(-|y^*|, p_T)}$$

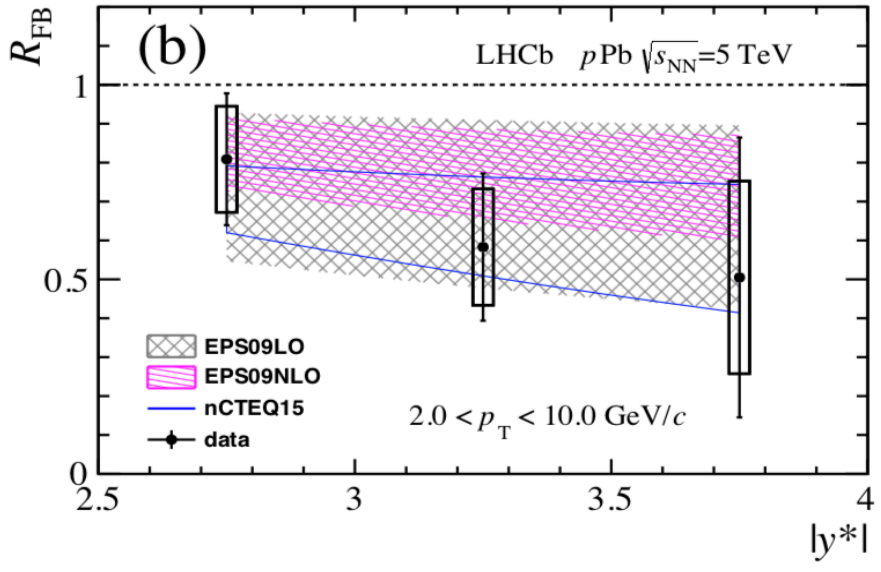



- Yield ratio between forward and backward suppressed.
- Consistent with nPDF calculations.
- B feed-down subtracted.

EPJ C10 (2017) 1140

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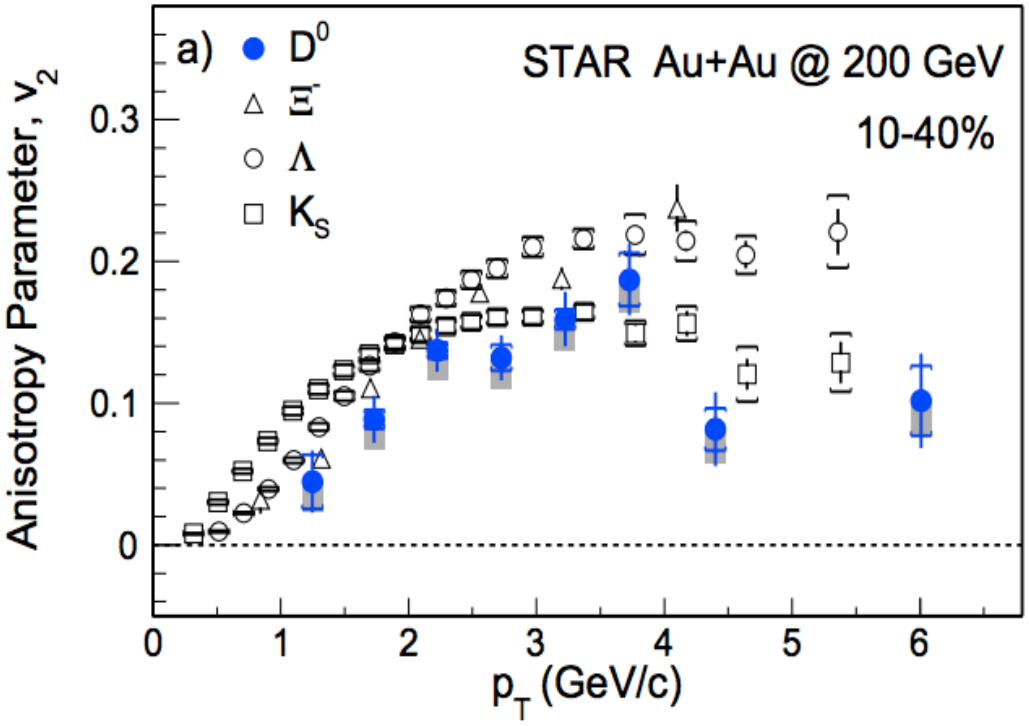
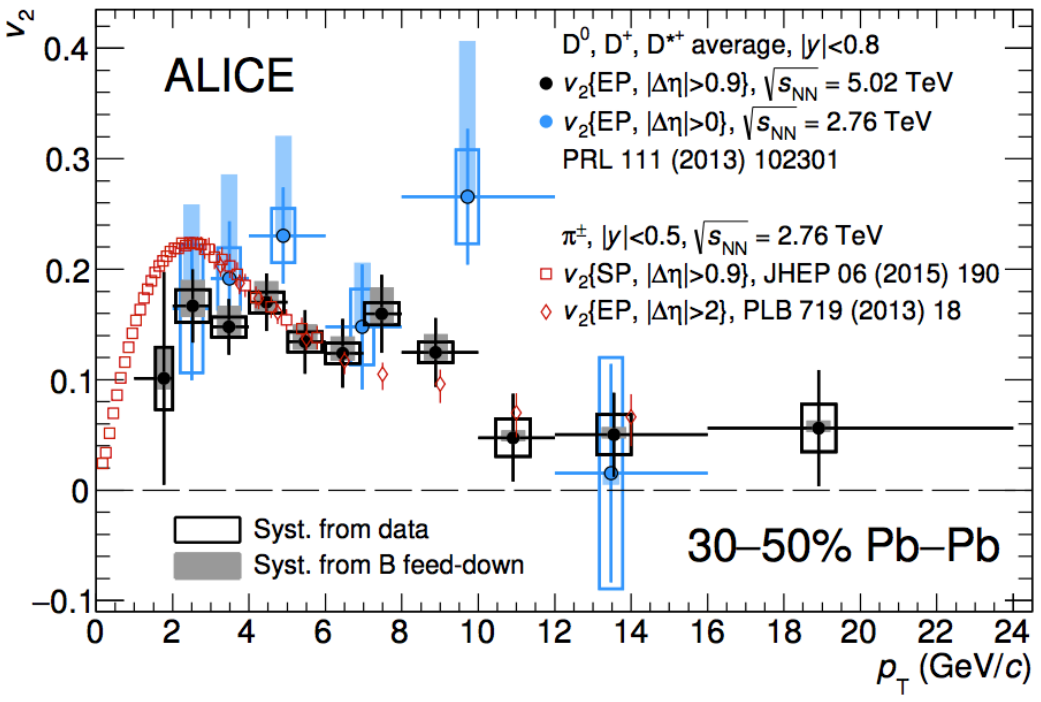
# D-meson elliptic flow



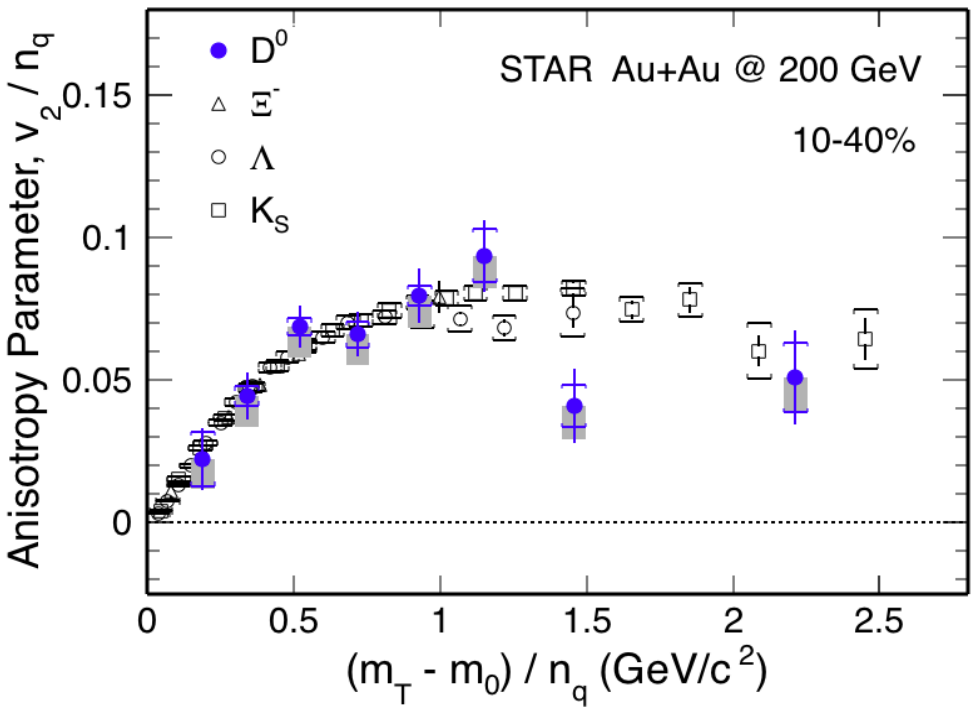

*STAR, PRL 118 (2017) 212301*

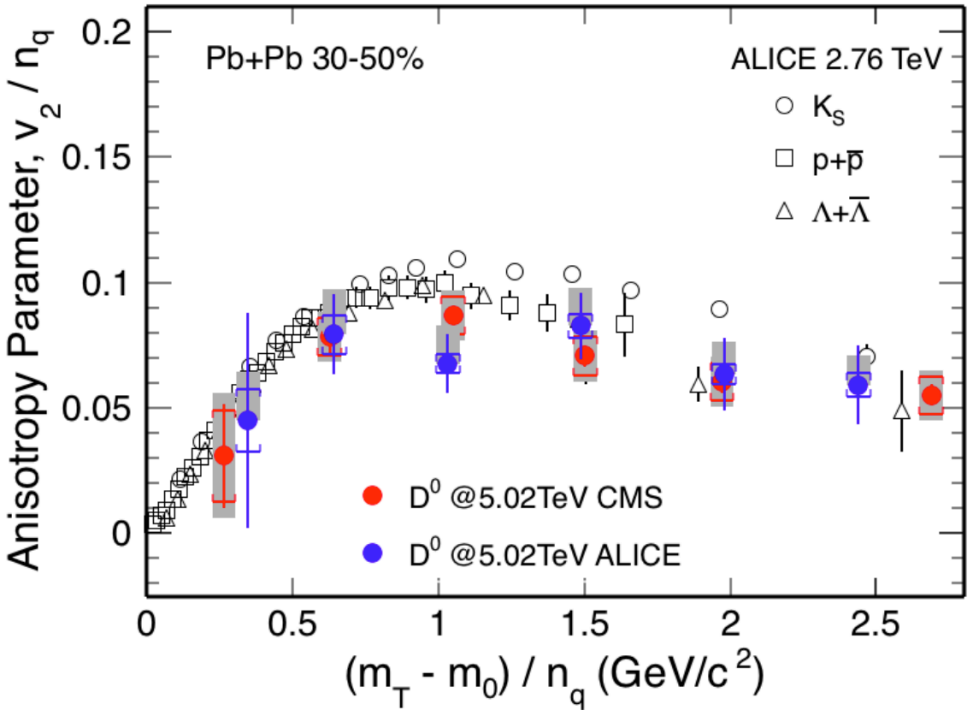



*ALICE, PRL 120 (2018) 102301*

- Strong D-meson elliptic flow observed in both STAR and ALICE.
- Mass ordering at $p_T$ < ~3 (4) GeV/c for STAR (ALICE) => hydrodynamic
- No clear collision energy dependence.

# D-meson elliptic flow

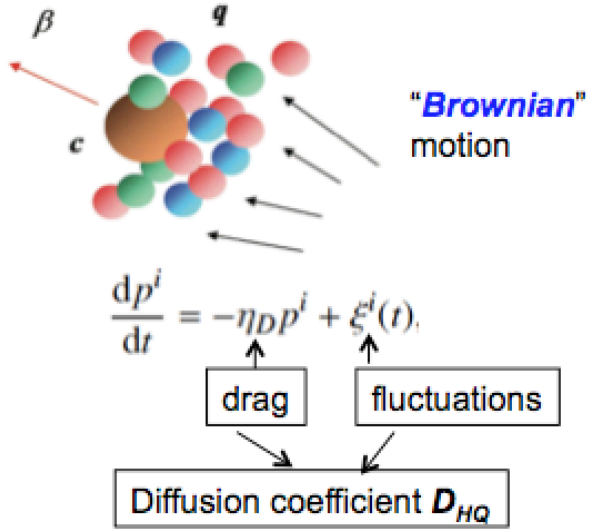



$v_2$(D) follows the ($m_T$-$m_0$) NCQ scaling as light hadrons within uncertainties for both RHIC and LHC .

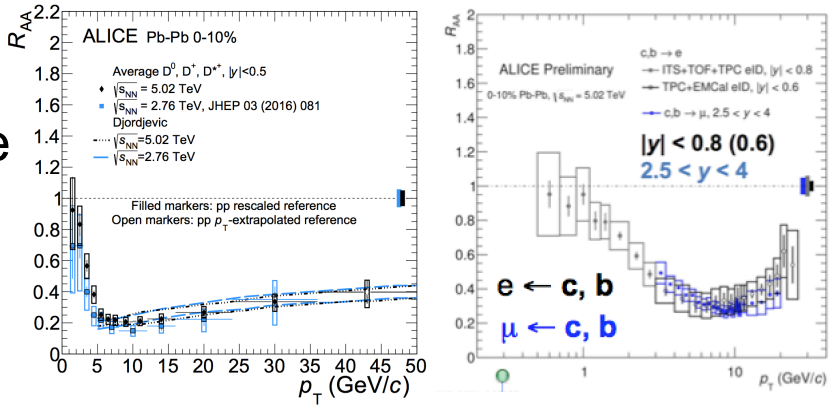
***Evidence of charm following the medium collectivity***

- suggest charm quarks may have achieved thermalization

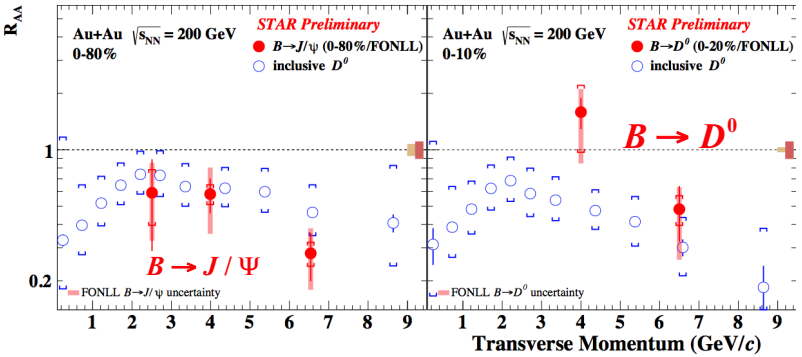


# Summary I: HF NMR and e-loss

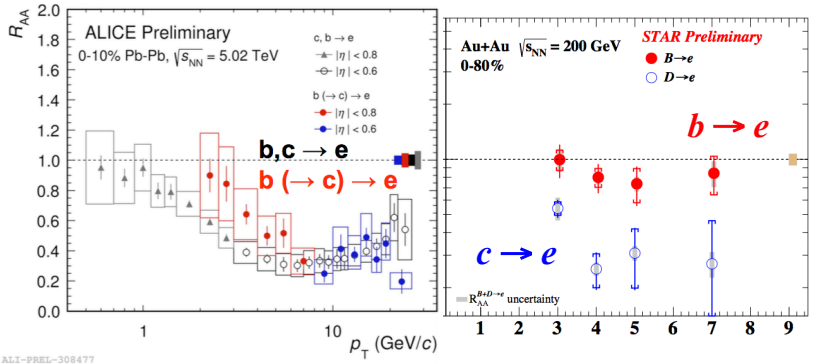
- D-meson at RHIC and LHC and inclusive μ at LHC are strongly suppressed in central A-A collisions => charm strongly coupled with medium and loses energy.




- High $p_T$ c,b->μ at LHC, high $p_T$ B->$D^0$ and B->J/Ψ at RHIC indicate beauty energy loss at high $p_T$.

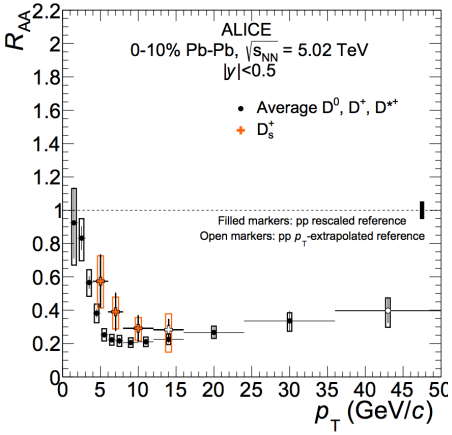


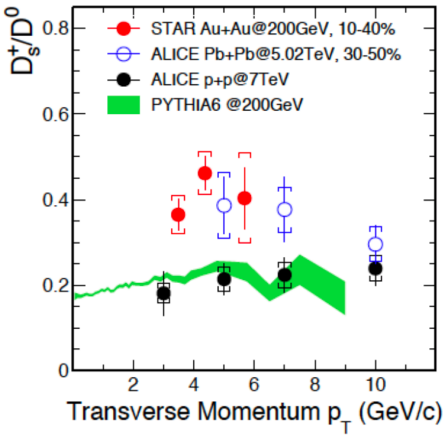

- b(->c)->e at RHIC/LHC and low $p_T$ B->$D^0$, b->e at RHIC show less energy loss of beauty at low $p_T$ => consistent with mass dependent energy loss picture.



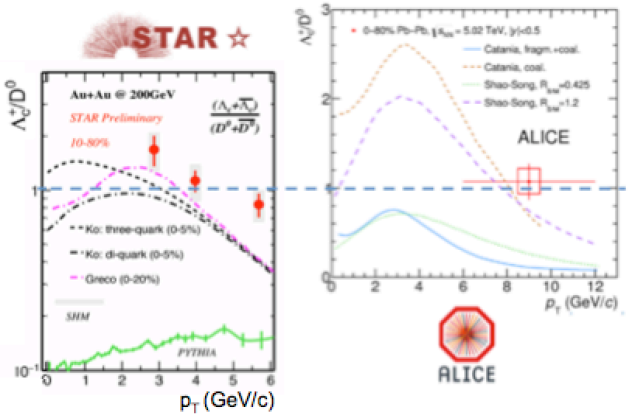
# Summary II: charm hadronization

- $D_s/D^0$ ratio is enhanced in both Au+Au and Pb-Pb collisions w.r.t pp and no clear centrality and collision energy dependence.

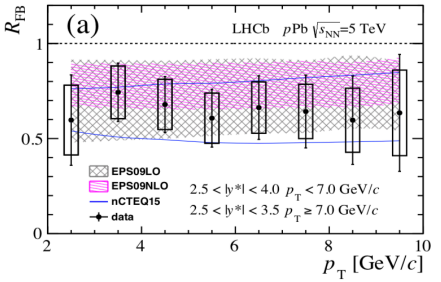


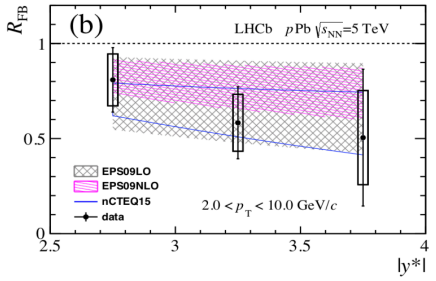




- $\Lambda_c/D^0$ ratio is enhanced in both Au+Au and Pb-Pb collisions w.r.t pp and p-Pb collisions and no clear collision energy dependence.




- $\Lambda_c$ $R_{FB}$ in p-Pb at LHC consistent with models with nPDFs with (anti-)shadowing effects.

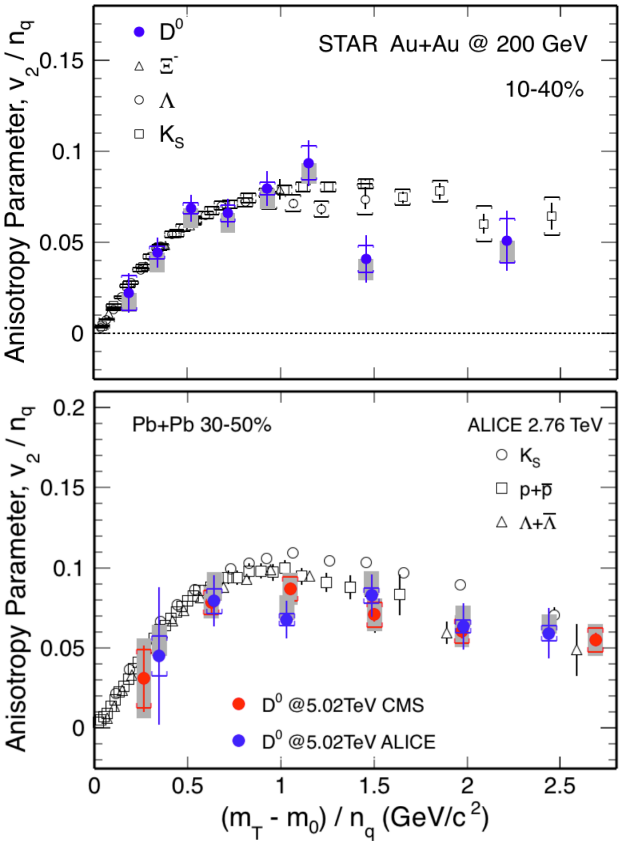



- Charm number conserved but redistributed in Au+Au collisions. Pb-Pb at LHC?

# Summary III: charm flow

- Strong D-meson $v_2$ observed at Au+Au and Pb-Pb collisions and no clear collision energy dependence.
- D-meson $v_2$ follows NCQ scaling and consistent with light flavor hadrons.

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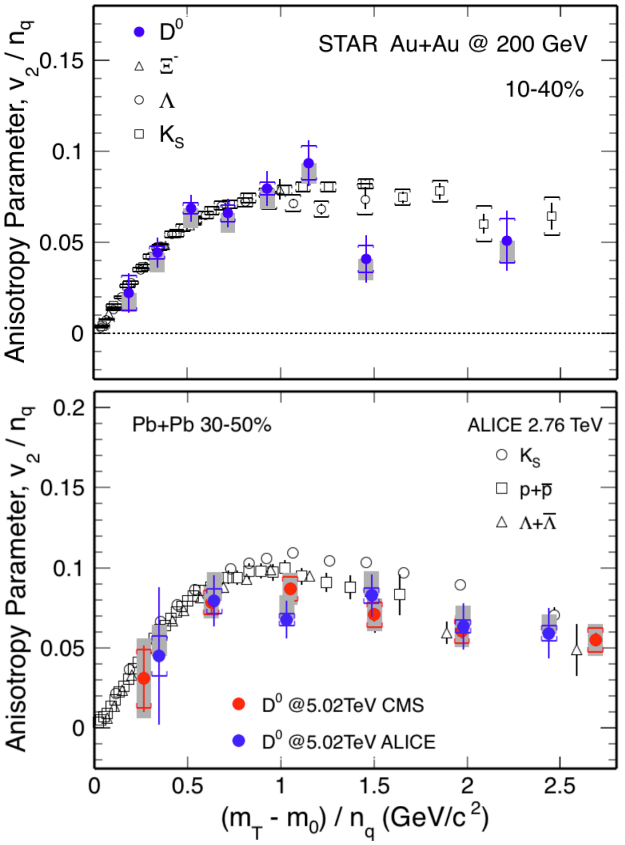


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*Thank you for your attention!*