Open Heavy Flavor Results from RHIC and the LHC

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SECOND CONFERENCE ON HEAVY ION COLLISIONS IN THE LHC ERA AND BEYOND

Why Study Heavy Quarks?

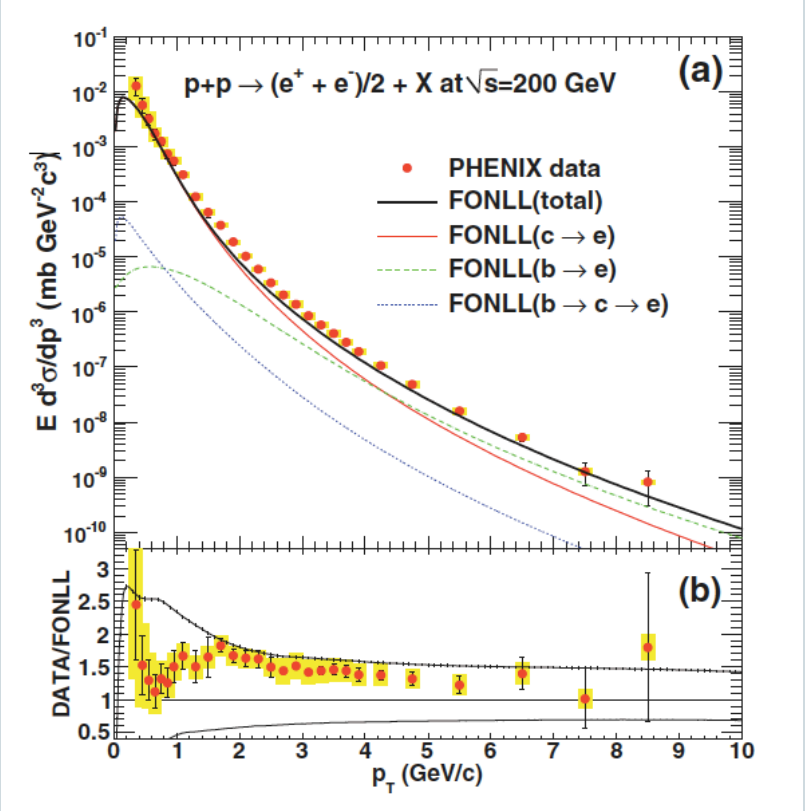
- Charm ($m_c \sim 1.5$ GeV) & Bottom ($m_b \sim 5$ GeV)

- $m_{c,b} >> \Lambda_{QCD}$
  - Large mass → short formation time
  - Medium doesn't change flavor, but can modify phase-space distribution
  - Difficult to destroy or create in medium

- Experience full evolution of medium
  - Describe medium and interaction
  - Measure intrinsic transport properties

The Role of Heavy Quarks: p+p collisions

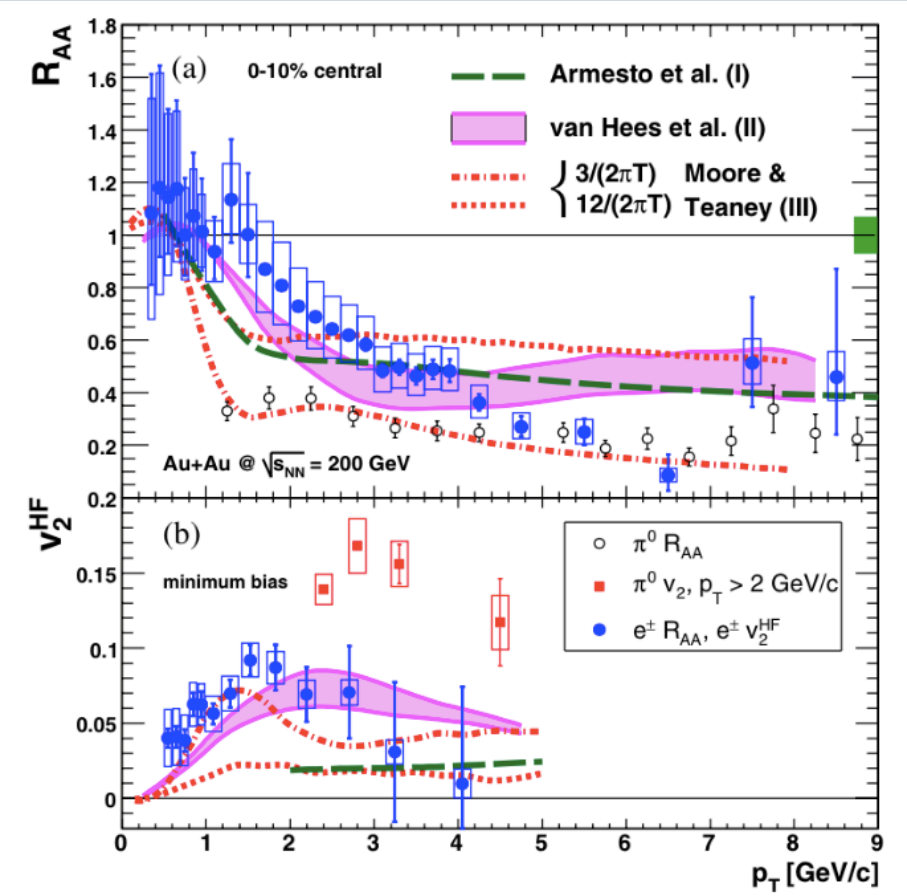
- Test pQCD predictions
  - Results in good agreement w/FONLL predictions
- Baseline for p(d)+A and A+A collisions



PRC 84(2011)084905

The Role of Heavy Quarks: A+A collisions

- Energy loss in the medium
- "Dead cone" effect
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Collectivity
  - Heavy quarks flow
  - Thermalization



Nuclear modification factor

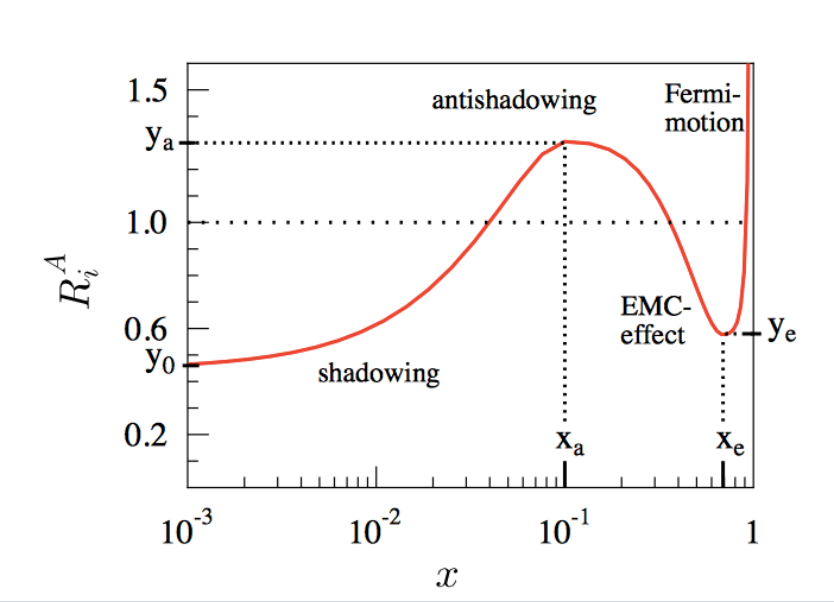
$$R_{AA} = \frac{dN_{AA}}{\langle N_{coll} \rangle \times dN_{pp}}$$

PRC 84, 044905 (2011)

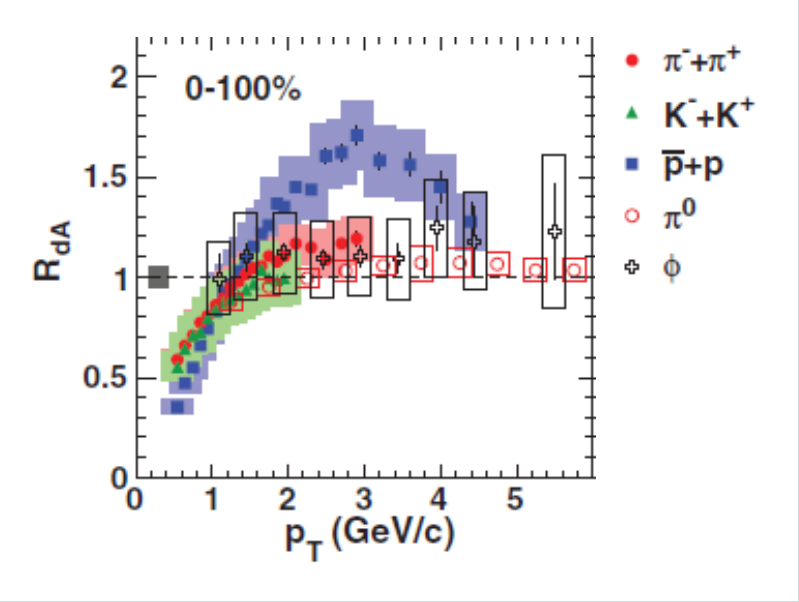
The Role of Heavy Quarks: p(d)+A collisions

- Another baseline system?
- Cold nuclear matter effects?

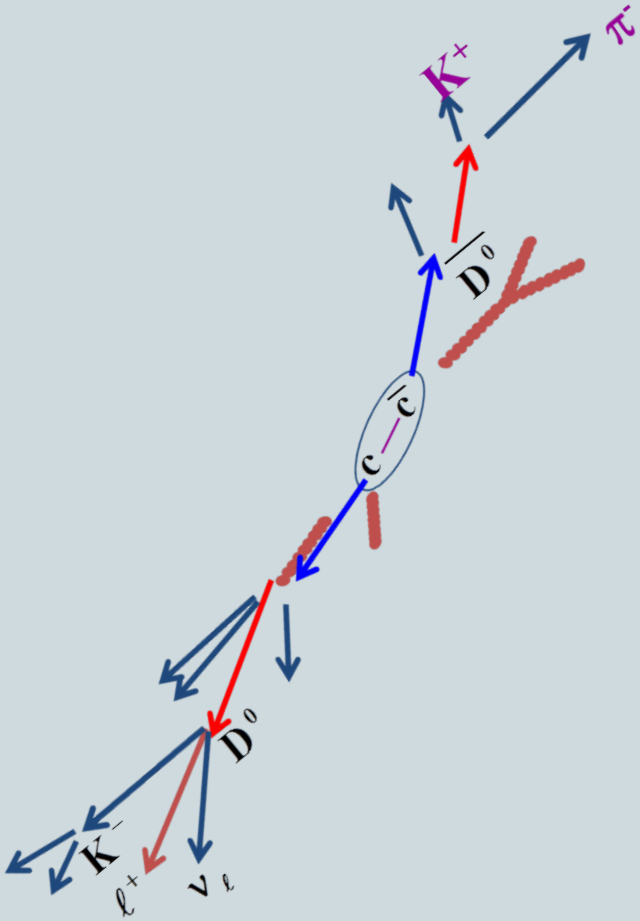
Modification to the nPDF



p_T broadening

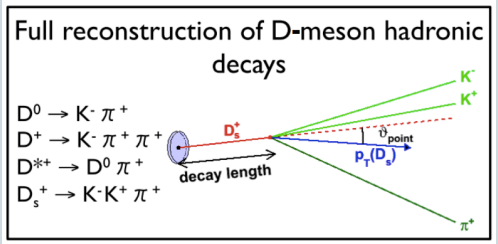


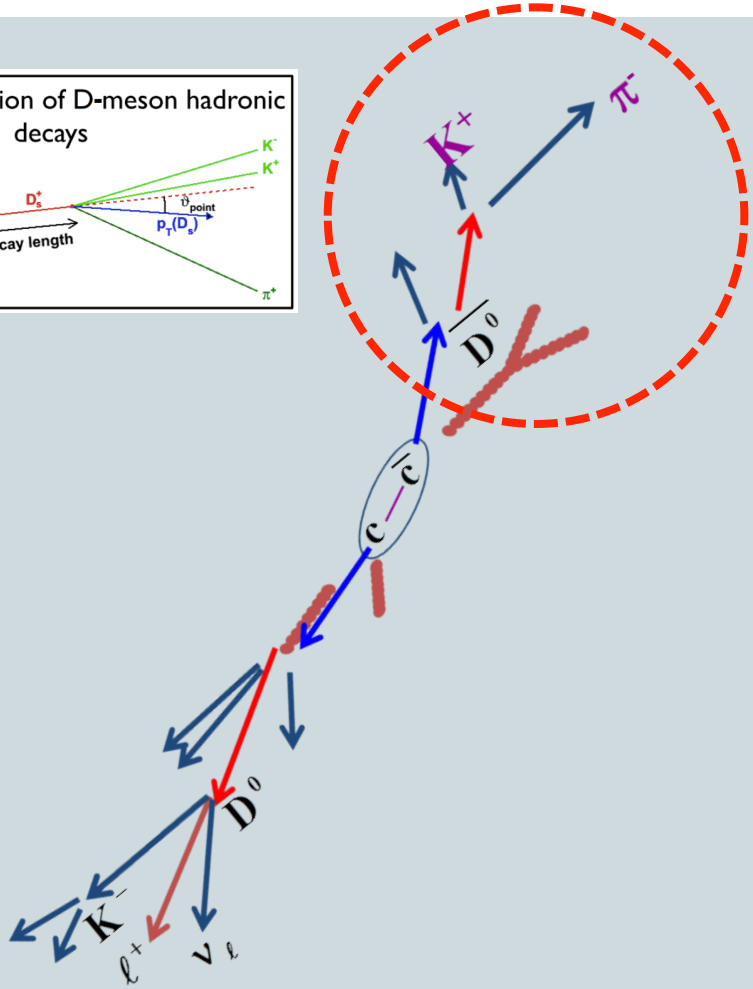
Measuring Heavy Flavor



Measuring Heavy Flavor

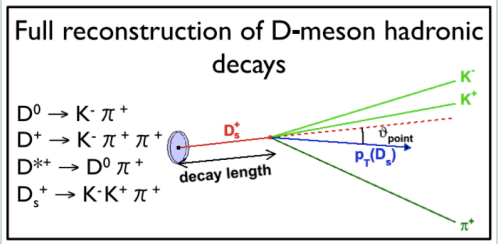
- Direct
  - Full hadron kinematics
  - Hard to trigger
  - Large combinatorial background



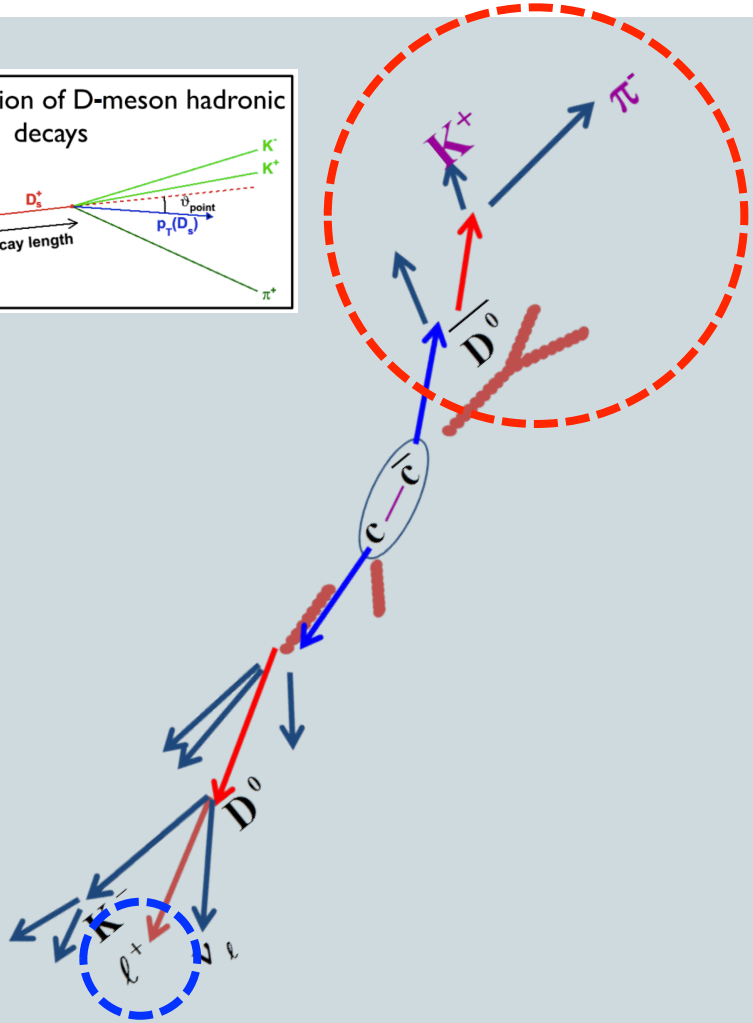


Measuring Heavy Flavor

- Direct
  - Full hadron kinematics
  - Hard to trigger
  - Large combinatorial background



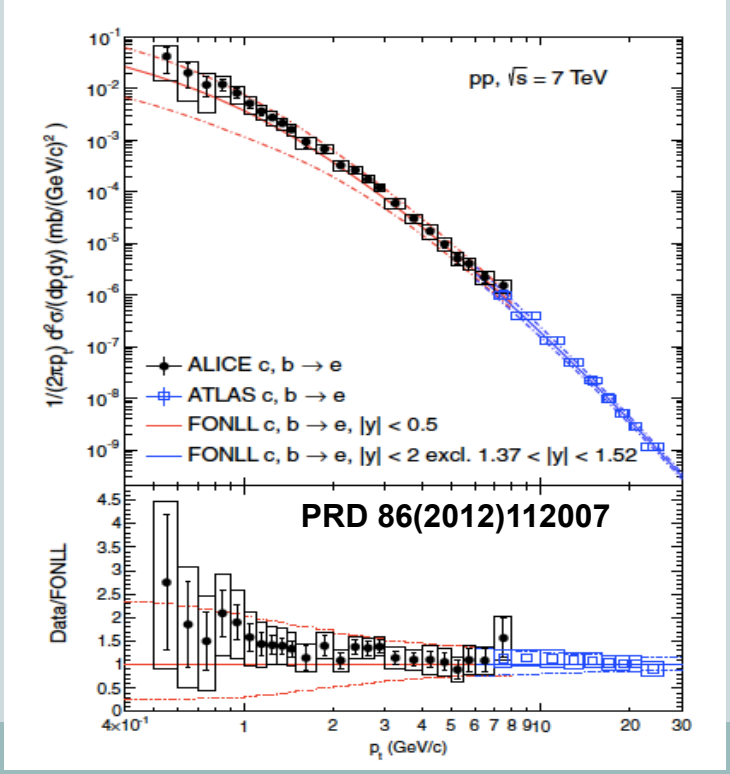
- Indirect
  - Kinematic smearing
  - Easy to trigger – high statistics
  - Lots of background sources
  - Branching ratios ~10%

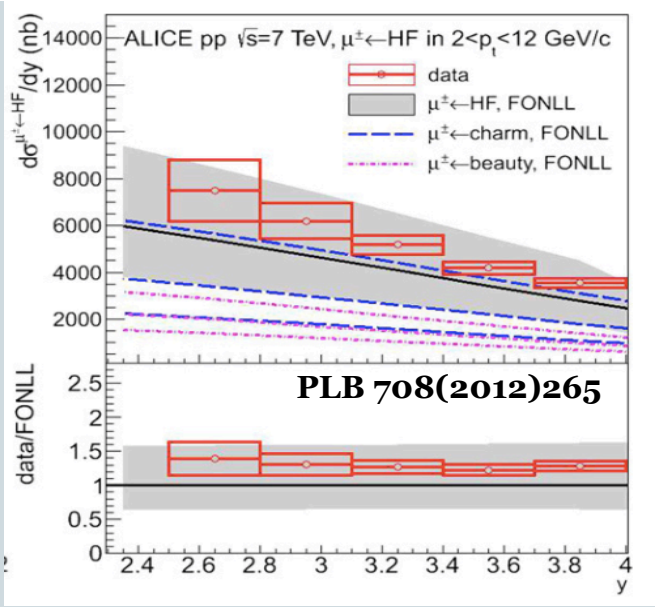


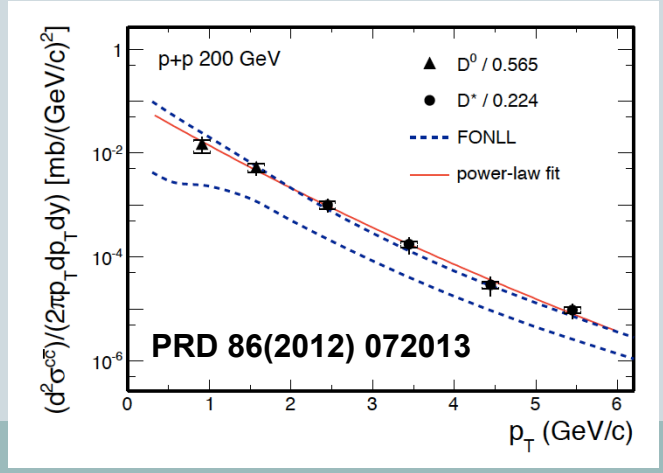
p+p collisions

Charm in p+p

- Data consistent with pQCD FONLL calculations
  - Multiple √s energies, experiments, rapidities

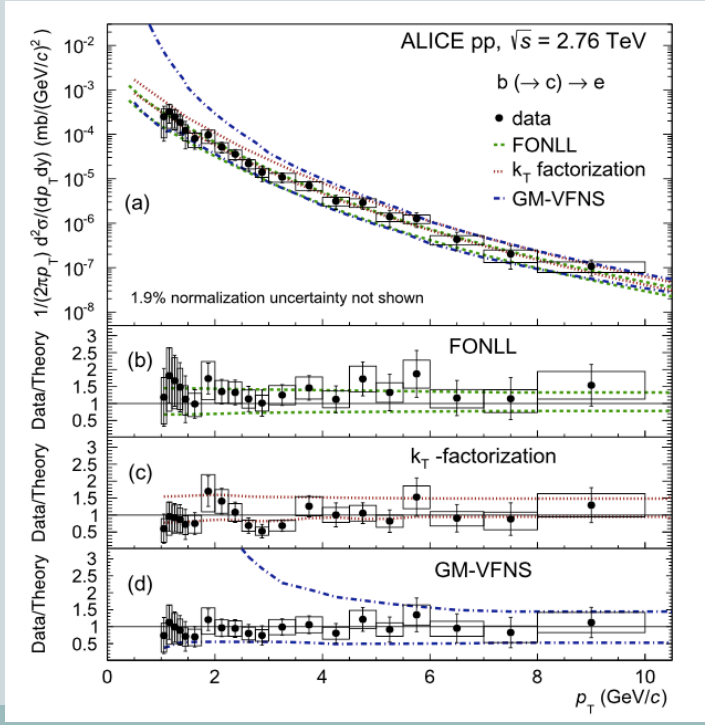






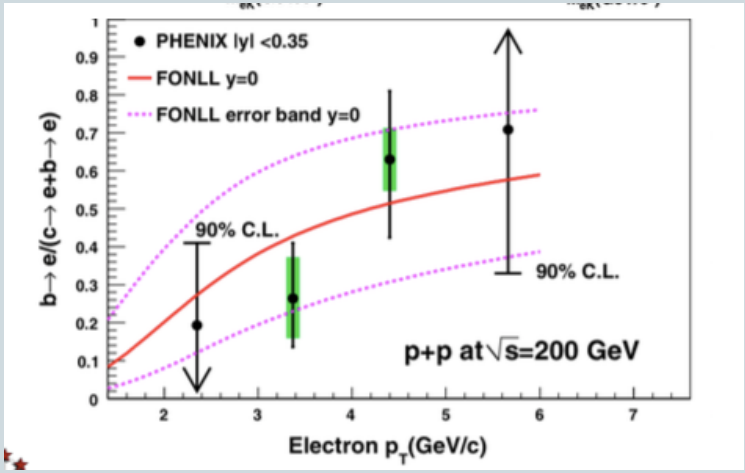
Bottom in p+p

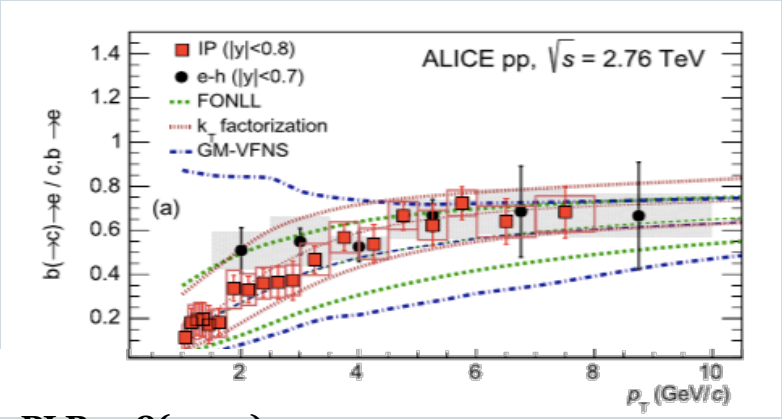
- Data consistent with pQCD FONLL calculations
  - Multiple √s energies, experiments, rapidities



PLB 708(2012)265

PRL 103(2009)082002

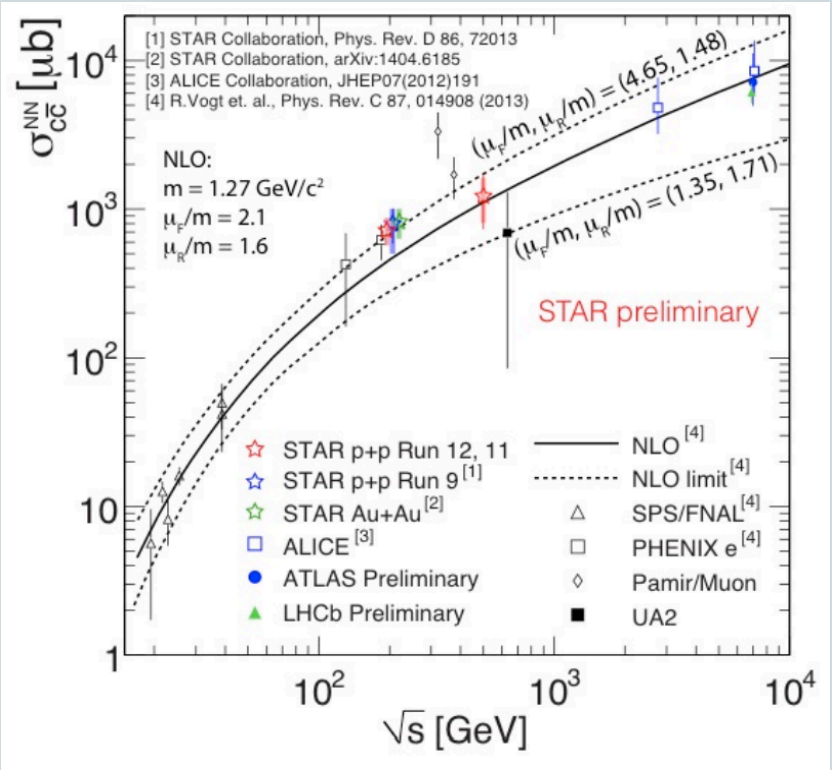


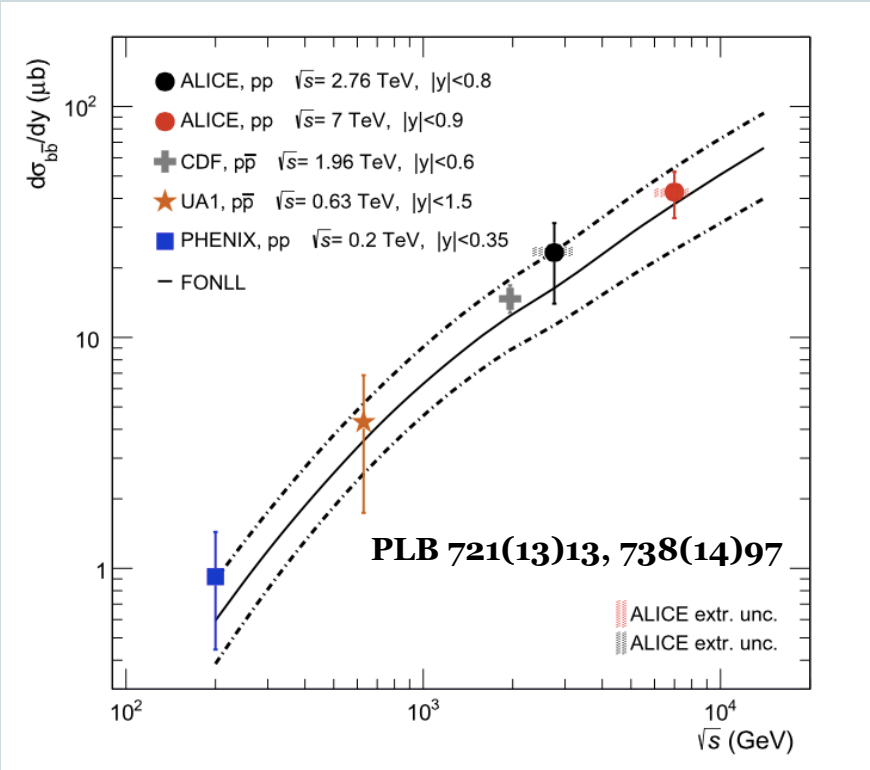


PLB 738(2014)97

Total Cross Sections

- Data consistent with pQCD FONLL calculations



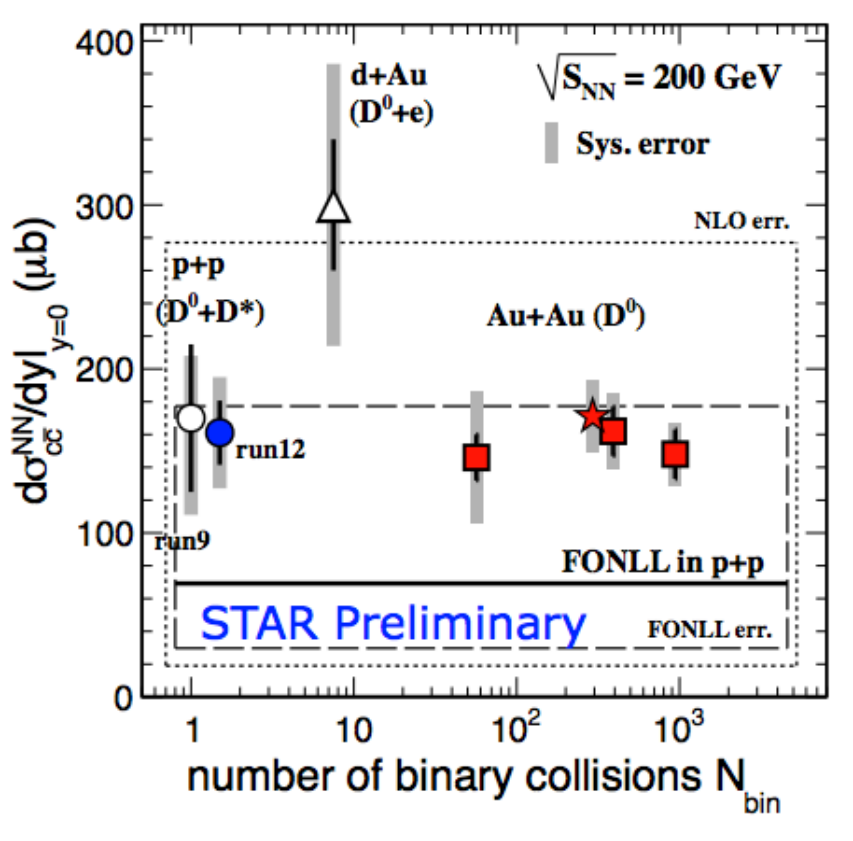


Charm **Bottom**

A+A collisions

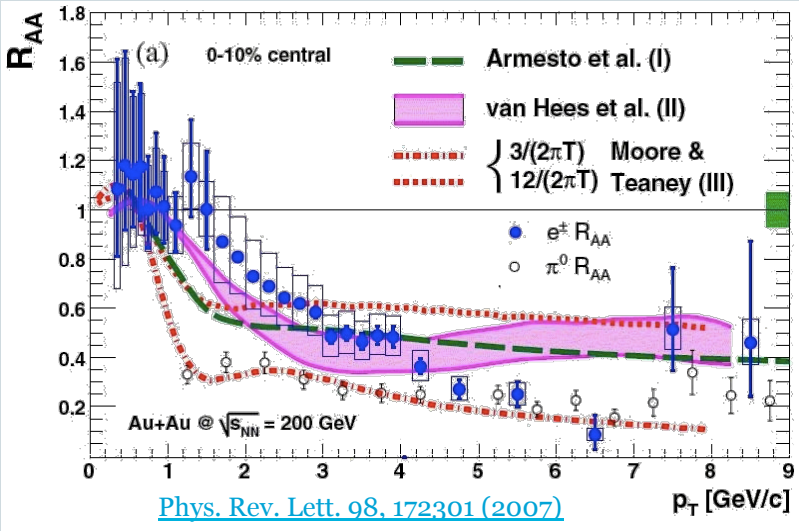
Heavy Flavor in A+A

- Total charm cross section (RHIC mid-rapidity) scales with number of binary collisions

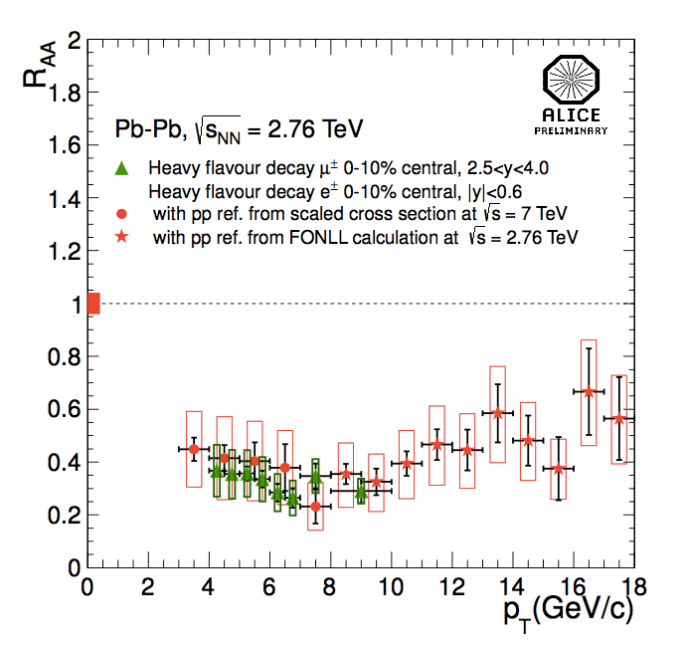


Heavy flavor leptons in A+A

- Significant energy loss in the medium
  - $R_{AA} < 1$ for $p_T > 2$GeV/c
  - $R_{AA}(HF) \sim R_{AA}(LF)$



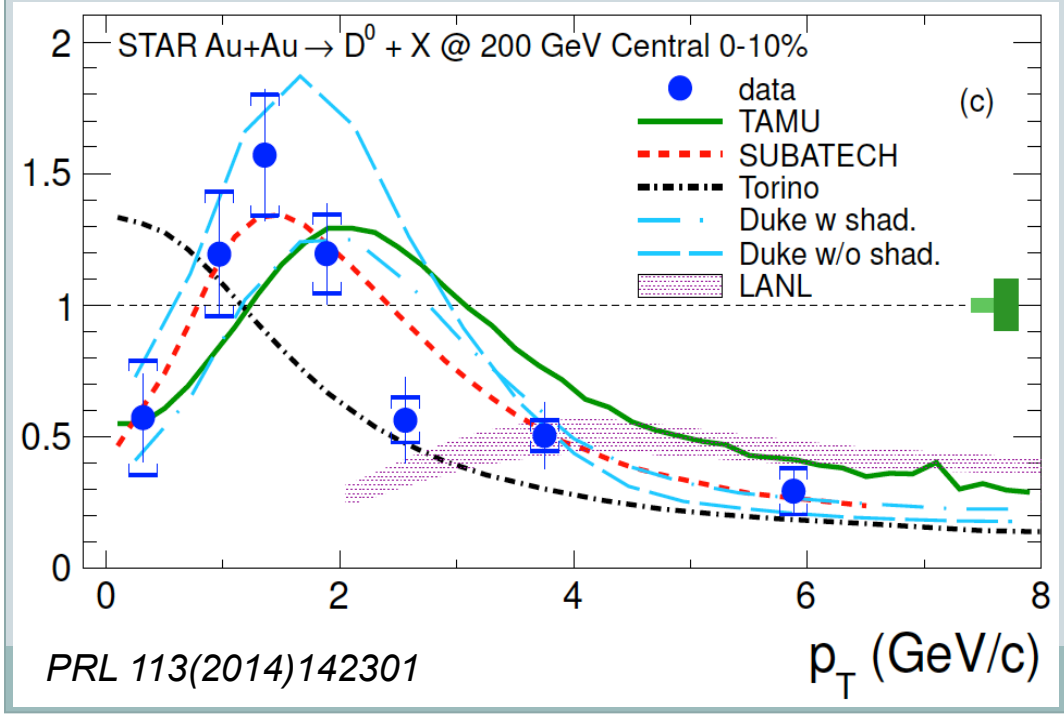
Phys. Rev. Lett. 98, 172301 (2007)



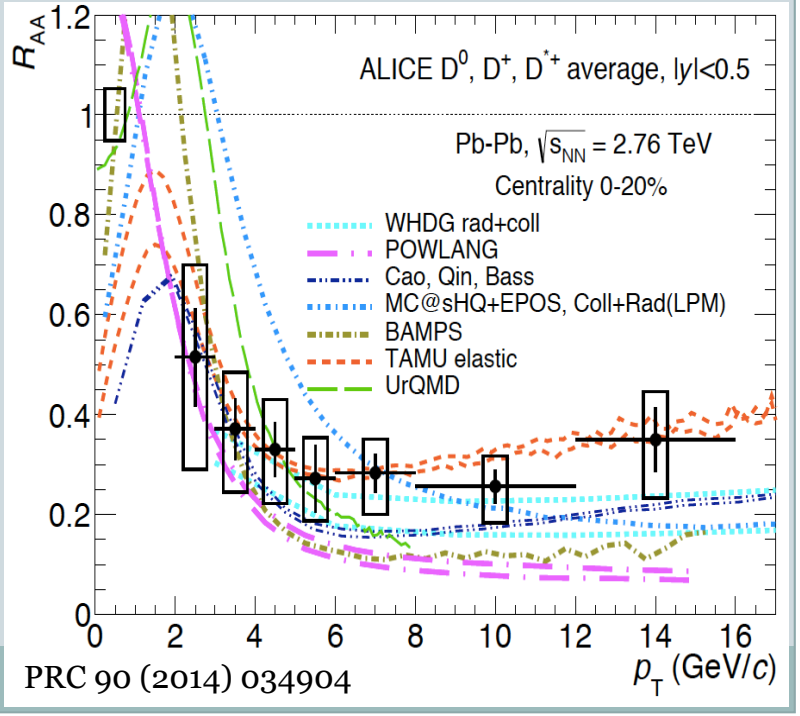
- $R_{AA}(e) \sim R_{AA}(\mu)$
  - No rapidity dependence

Charm modification

- High p_T: $R_{AA}(D) \sim R_{AA}(e)$
- Low p_T at RHIC: Enhancement



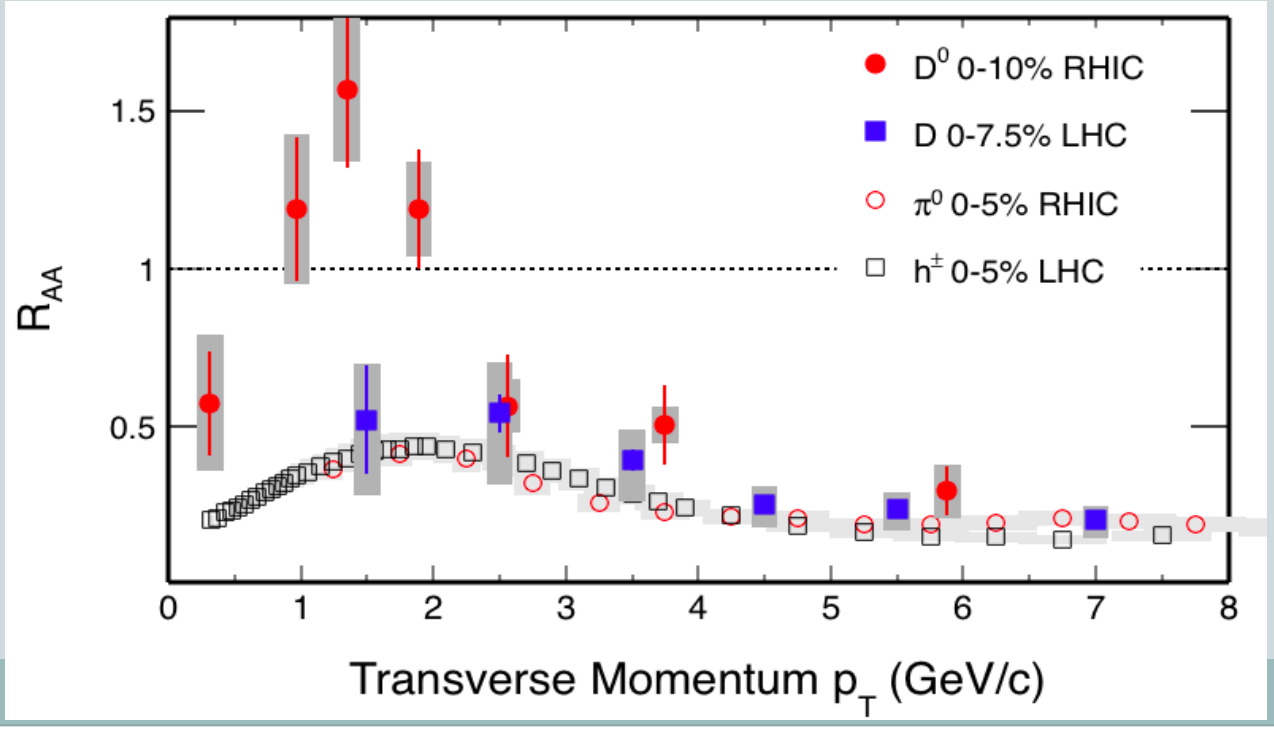
PRL 113(2014)142301



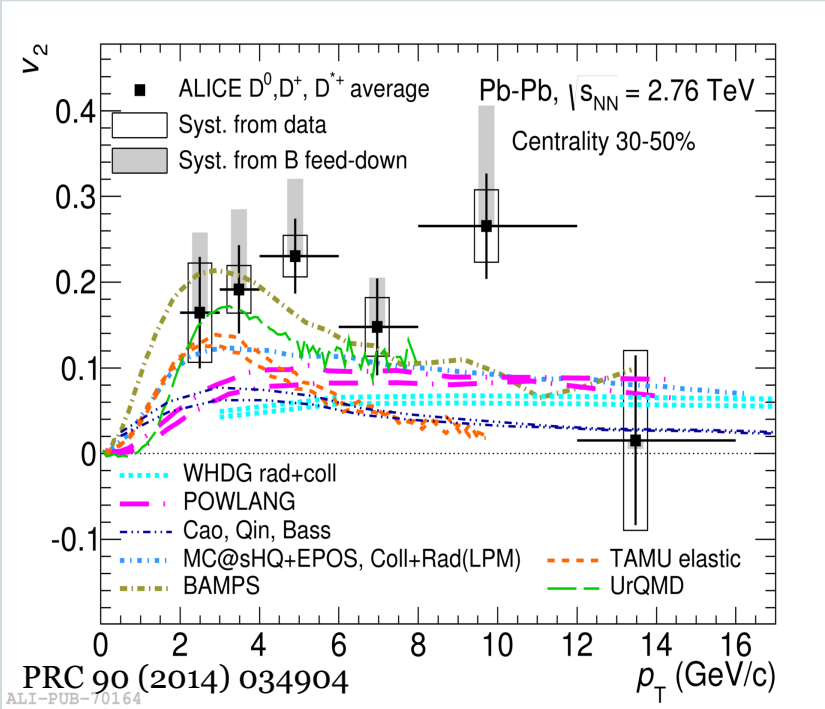
PRC 90 (2014) 034904

Charm modification

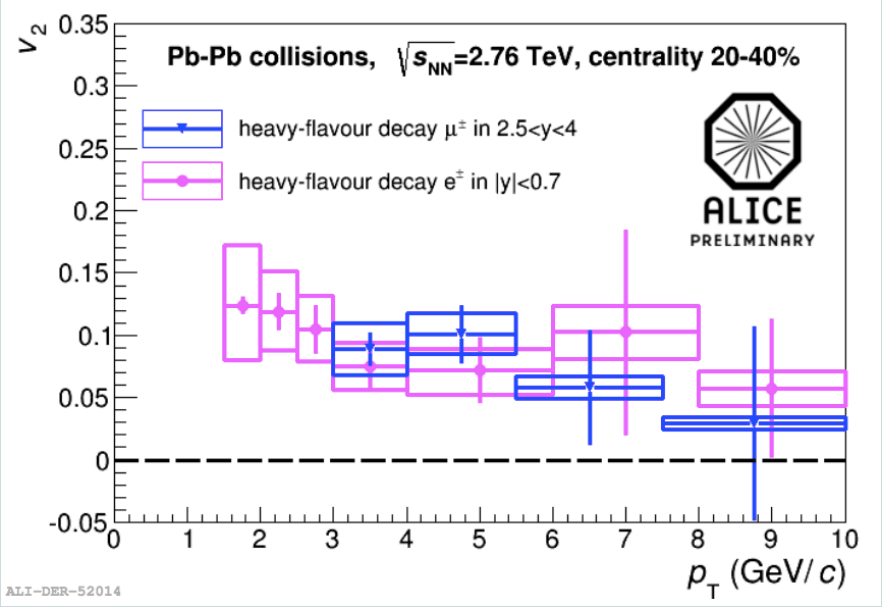
- High p_T: Similar suppression at RHIC & LHC
- Low p_T: CNM?
  - Probing different x-regions (~10^{-3} LHC & 10^{-2} RHIC)
  - Charm flow?



Charm Flows?



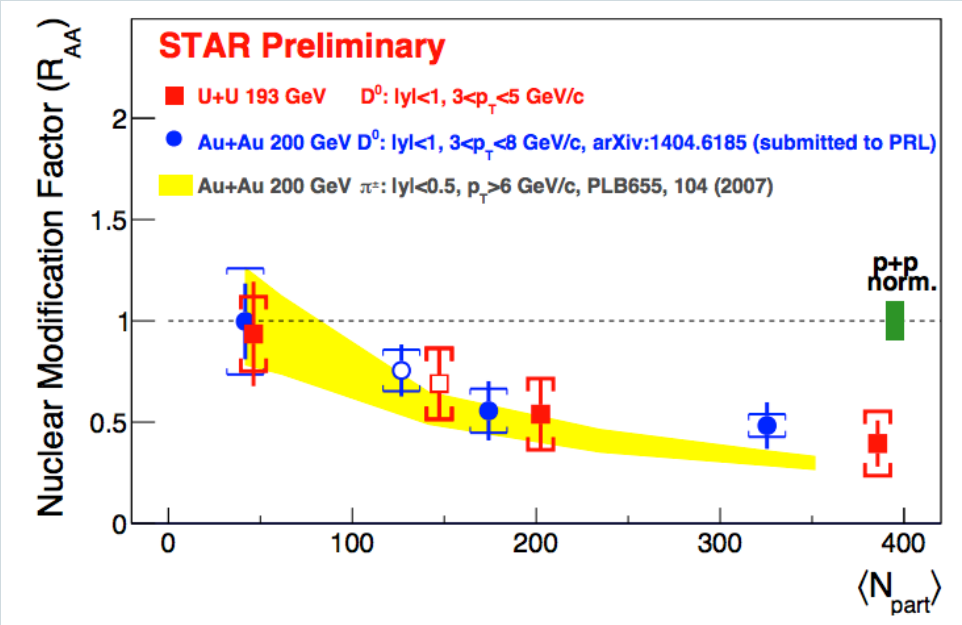
PRC 90 (2014) 034904



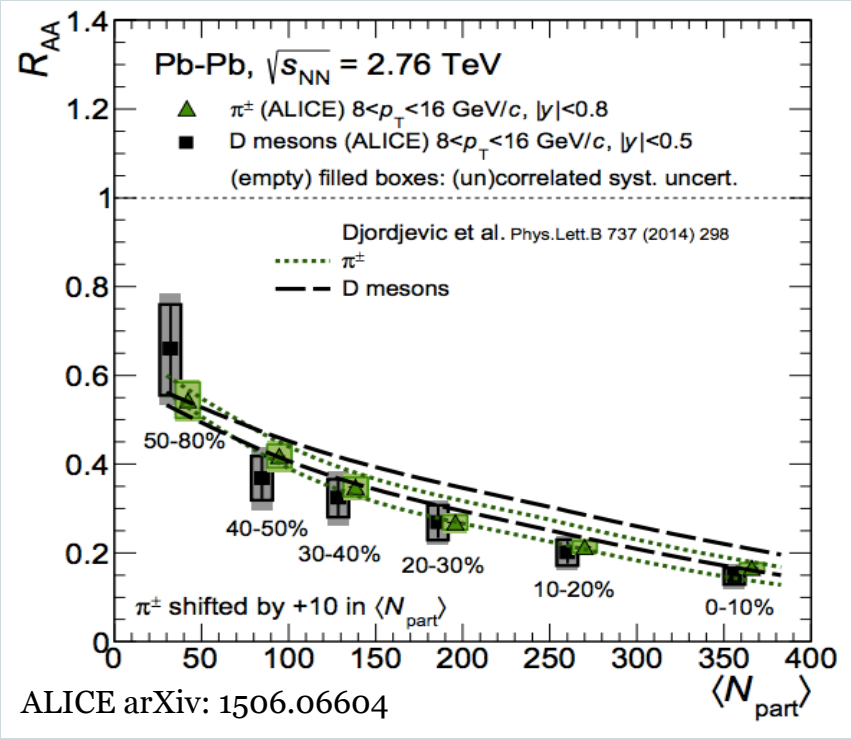
- Possibly with the medium
- Need better precision data at low p_T

Suppression across systems

RHIC



LHC

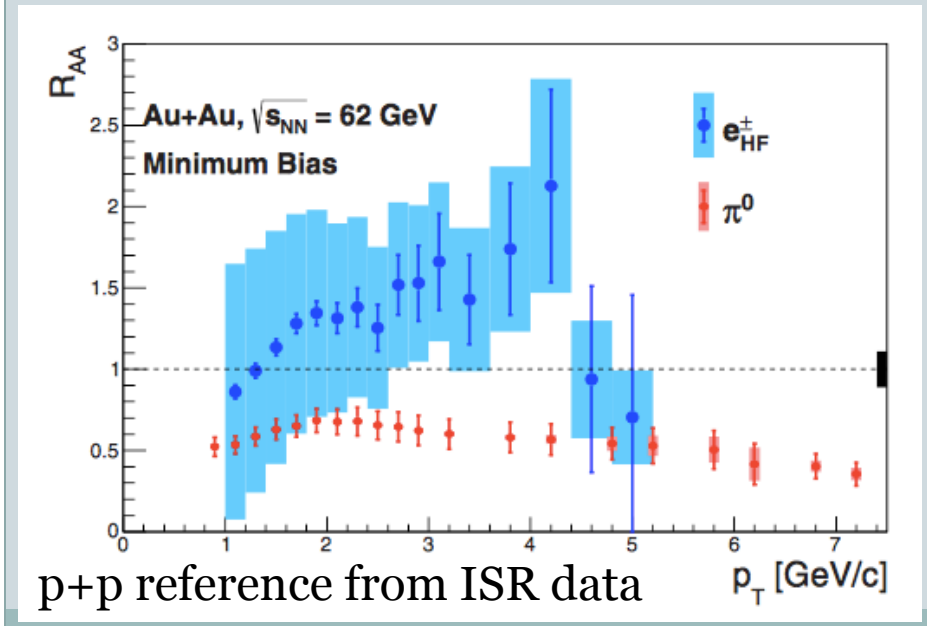


ALICE arXiv: 1506.06604

- $R_{AA}(HF) \sim R_{AA}(LF)$
- $R_{AuAu} \sim R_{UU}$ for similar N_{part}
- Several models consistent with the data
  - Should also describe v_2 and correlations

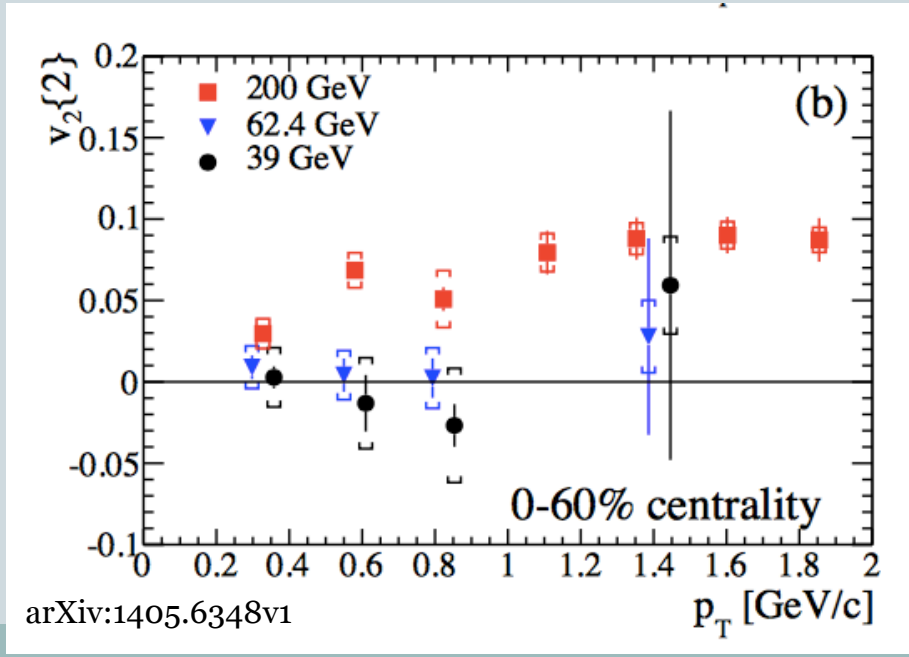
Dependence on collision energy

- No suppression at high p_T observed
  - π^0 still suppressed
- v_2(62.4/39 GeV) < v_2(200 GeV)
  - Reduced/no strong interaction with the medium?



p+p reference from ISR data

PRC 91, 044907 (2015)

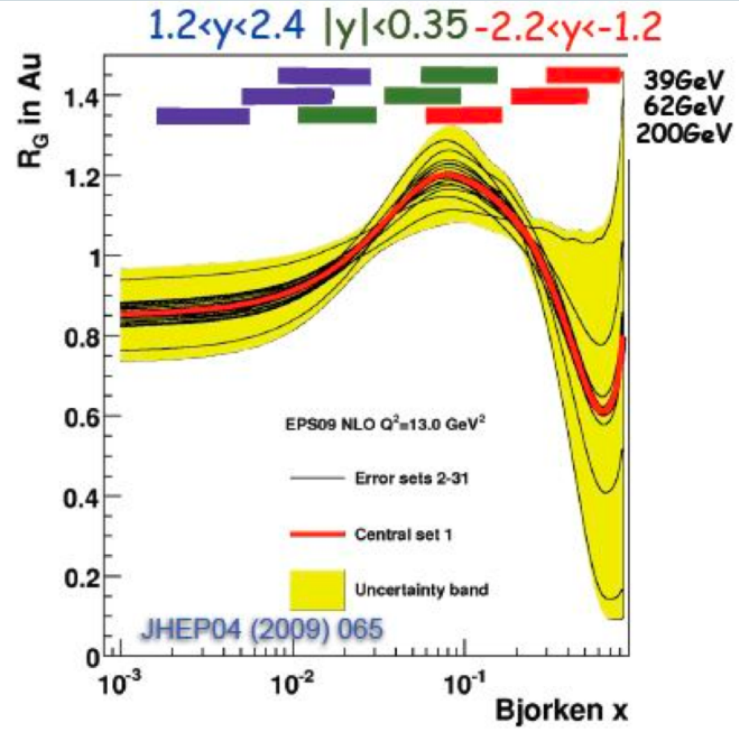


arXiv:1405.6348v1

p(d)+A collisions

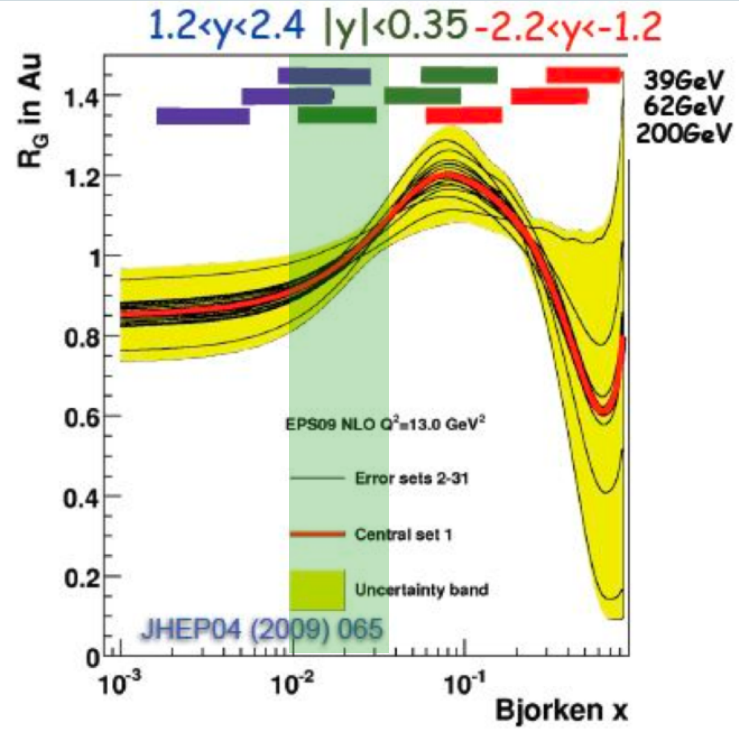
What about the other "small" systems? p(d)+A

- RHIC



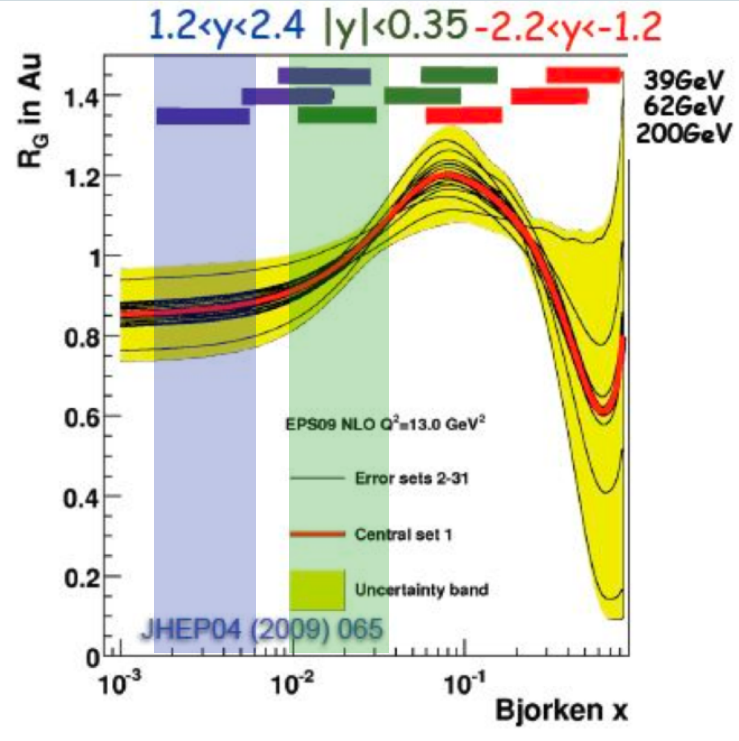
What about the other "small" systems? p(d)+A

- RHIC
  - Mid-rapidity
    - No modification



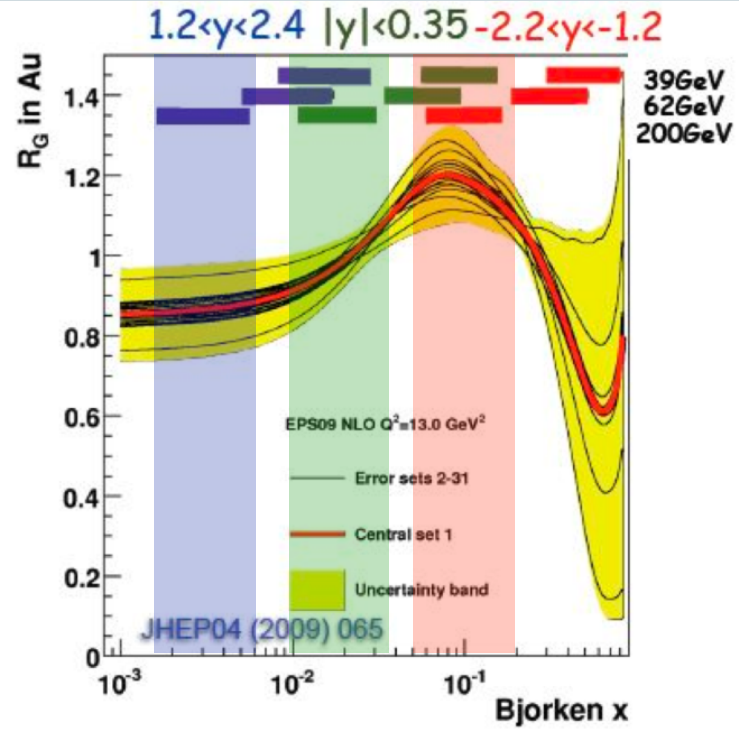
What about the other "small" systems? p(d)+A

- RHIC
  - Mid-rapidity
    - No modification
  - Forward rapidity
    - Shadowing



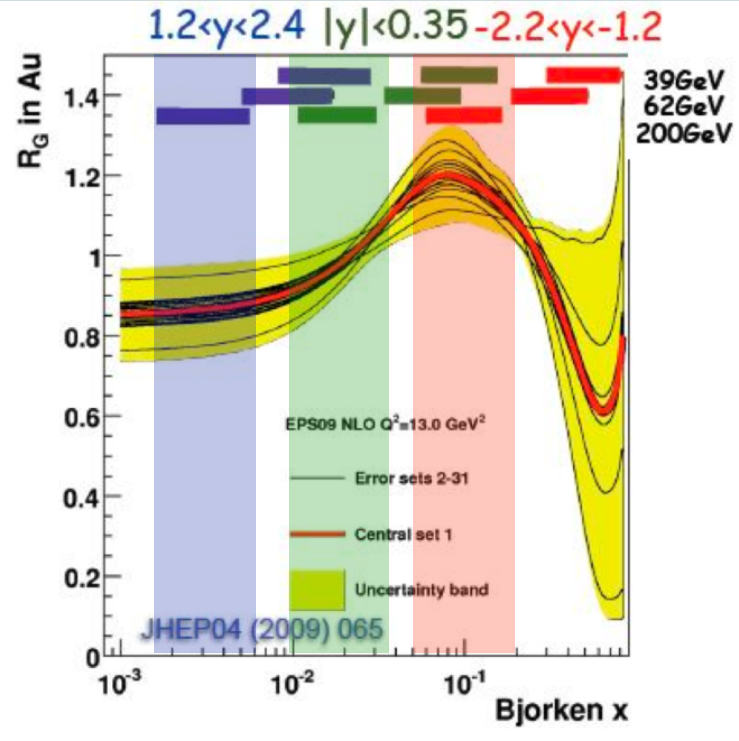
What about the other "small" systems? p(d)+A

- RHIC
  - Mid-rapidity
    - No modification
  - Forward rapidity
    - Shadowing
  - Backward rapidity
    - Anti-shadowing



What about the other "small" systems? p(d)+A

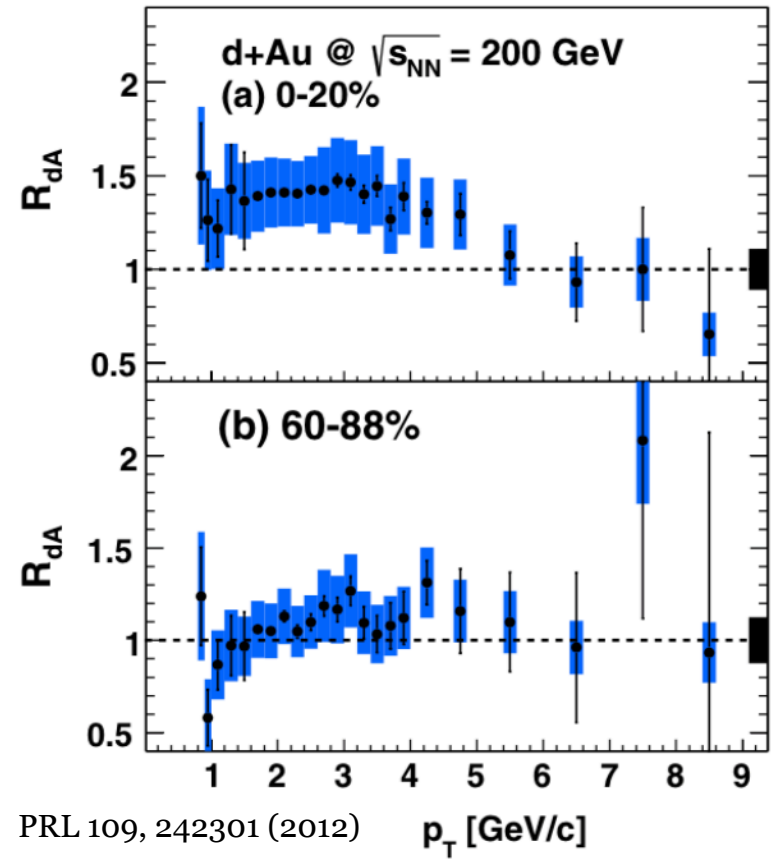
- RHIC
  - Mid-rapidity
    - No modification
  - Forward rapidity
    - Shadowing
  - Backward rapidity
    - Anti-shadowing
- LHC
  - Mid-rapidity: low-x



RHIC mid-rapidity d+Au

- Peripheral $R_{dA} \sim 1$
- Central $R_{dA} > 1$

- CNM effects?
  - Cronin?
  - p_T broadening?



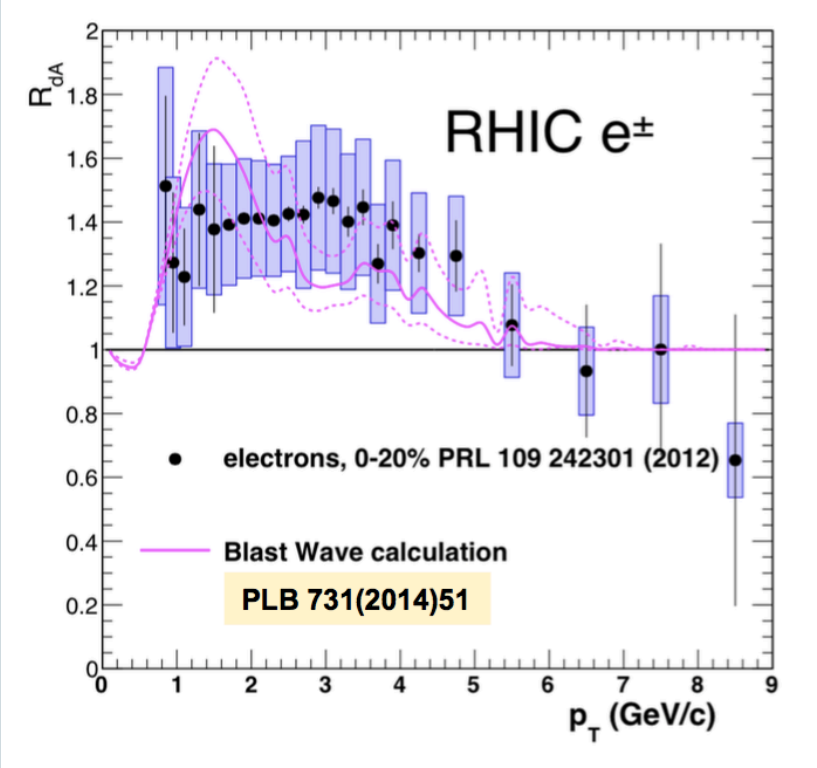
PRL 109, 242301 (2012)

RHIC mid-rapidity d+Au

- Peripheral $R_{dA} \sim 1$
- Central $R_{dA} > 1$

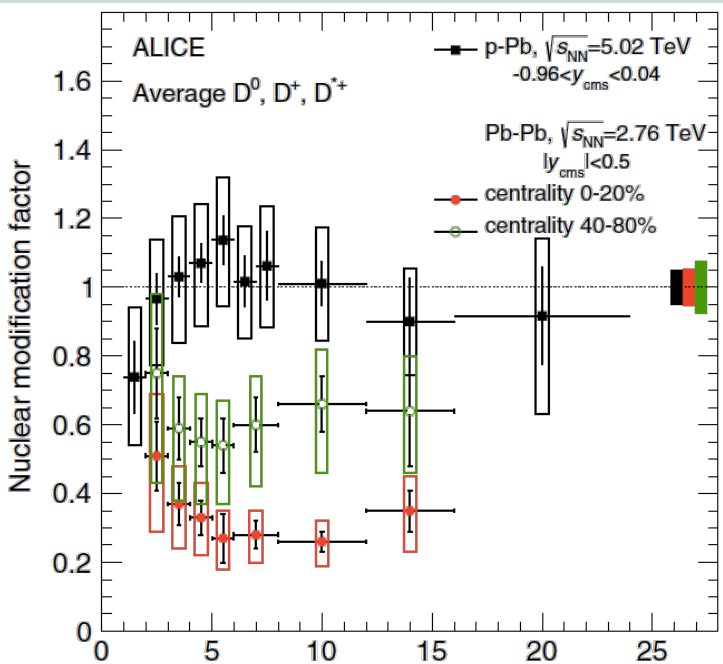
- CNM effects?
  - Cronin?
  - p_T broadening?

- Or a small drop of HNM?

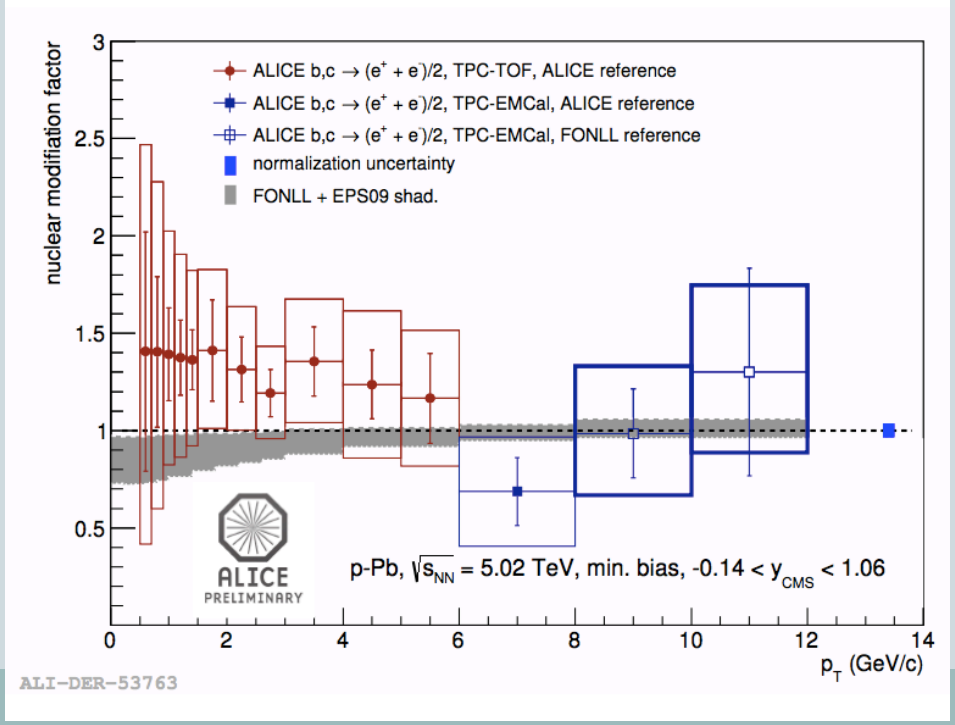


LHC heavy flavor in p+Pb

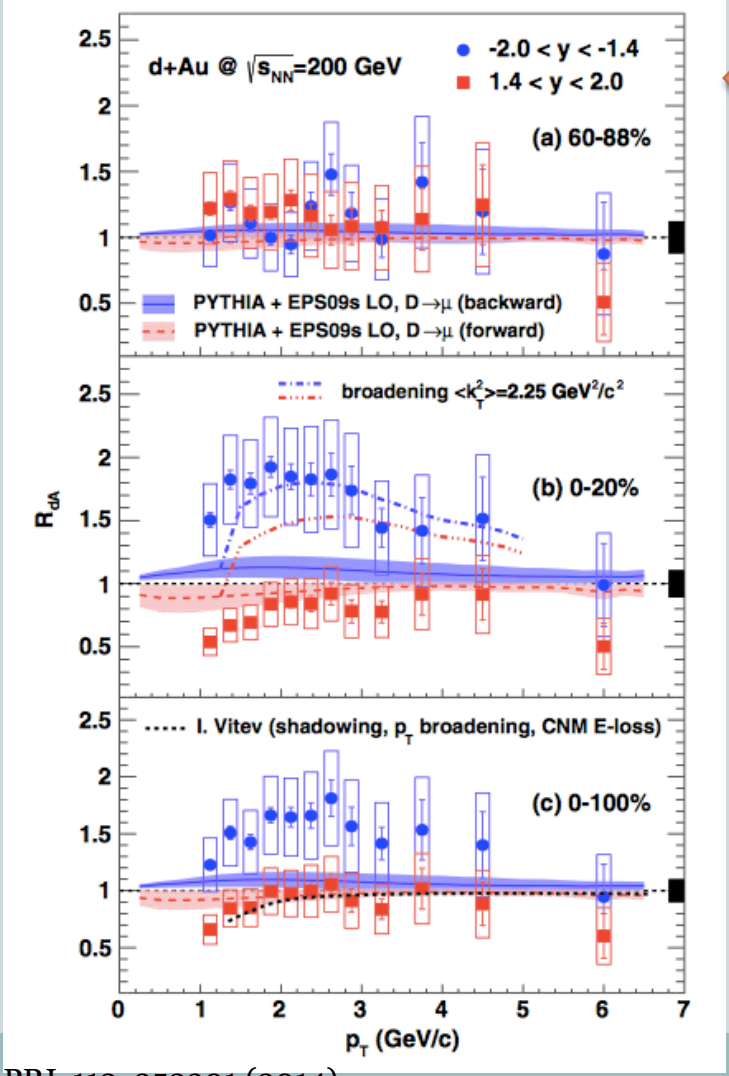
- R_{pPb} consistent w/1
  - Systematically higher
- $R_{pPb} \sim R_{dAu}$
- Pb+Pb suppression mainly a final state effect



PRL 113, 232301 (2014)



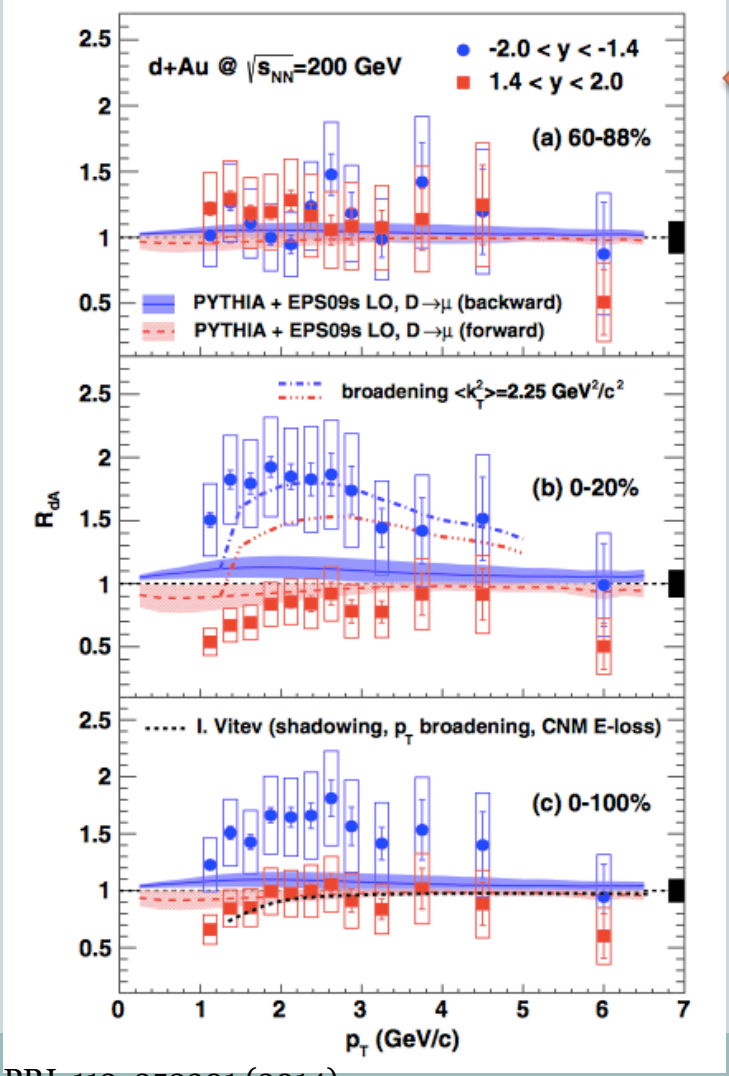
Forward Rapidities: RHIC d+Au



- Peripheral
  - R_{dA} ~ 1 for all rapidities

PRL 112, 252301 (2014)

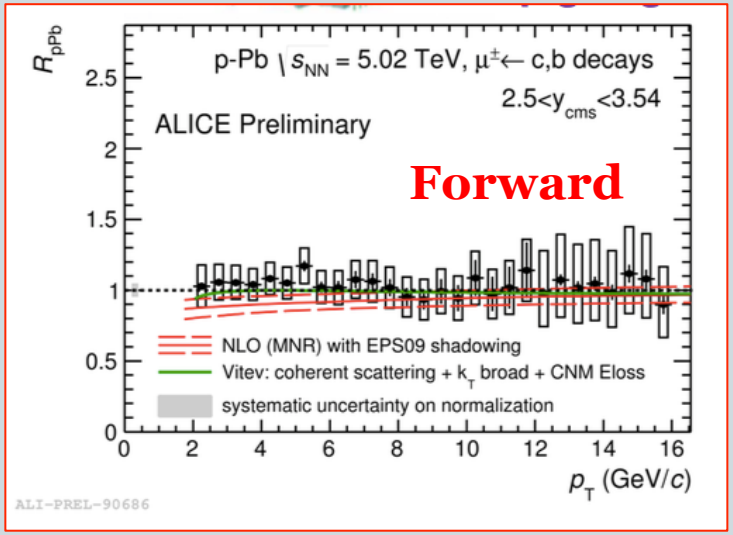
Forward Rapidities: RHIC d+Au



PRL 112, 252301 (2014)

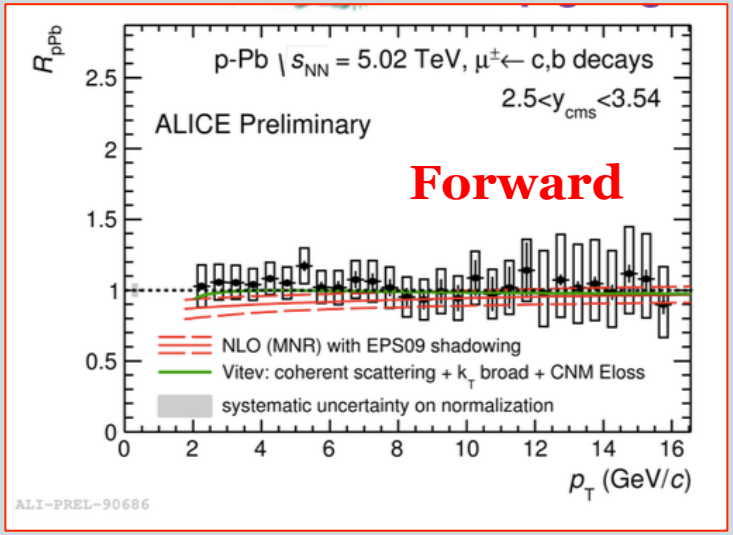
- Peripheral
  - R_{dA} ~ 1 for all rapidities
- Central
  - Forward: $R_{dA} < 1$
    - Consistent with pQCD +shadowing
  - Backward: $R_{dA} > 1$
    - Consistent with additional k_T broadening
  - Backward & Forward not described simultaneously

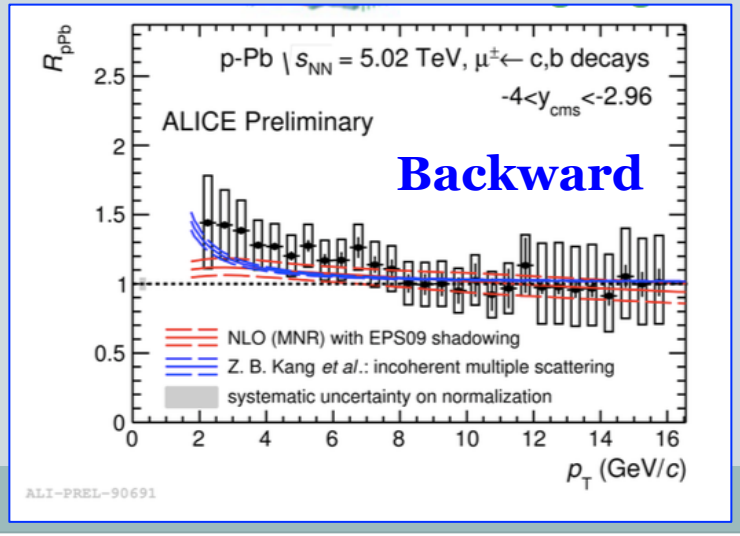
Forward Rapidities: LHC p+Pb



- Forward: $R_{pPb} \sim 1$
  - No modification

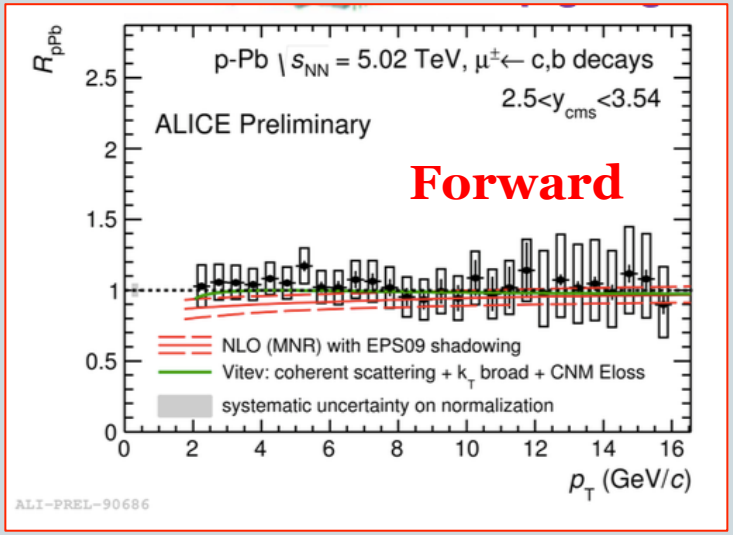
Forward Rapidities: LHC p+Pb

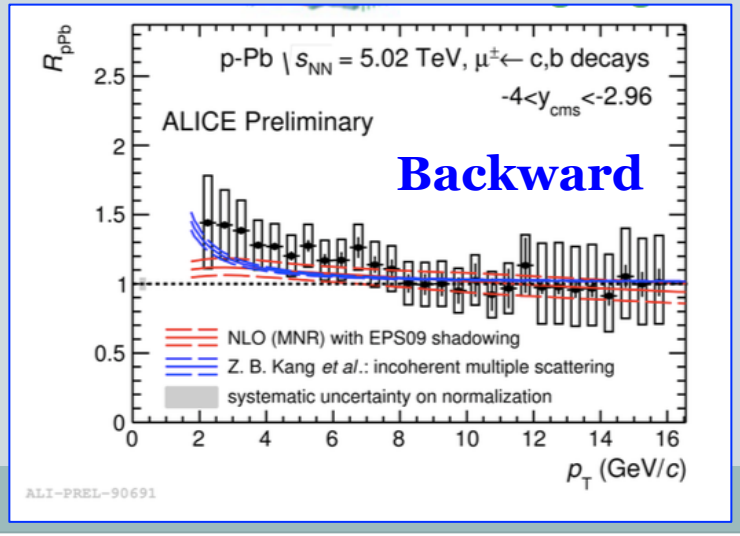




- Forward: $R_{pPb} \sim 1$
  - No modification
- Backward: R_{pPb} slightly larger than 1 at low p_T

Forward Rapidities: LHC p+Pb

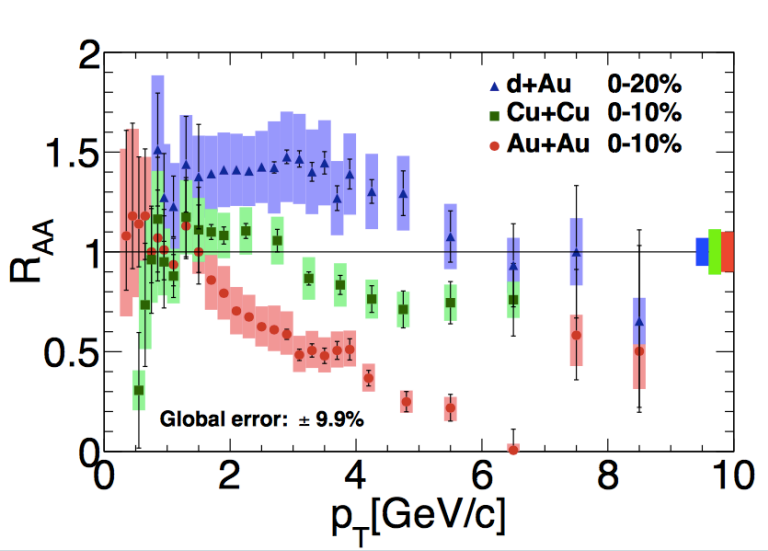




- Forward: $R_{pPb} \sim 1$
  - No modification
- Backward: R_{pPb} slightly larger than 1 at low p_T
- Consistent with RHIC results
- Consistent with pQCD models that include CNM effects

System Size Dependence

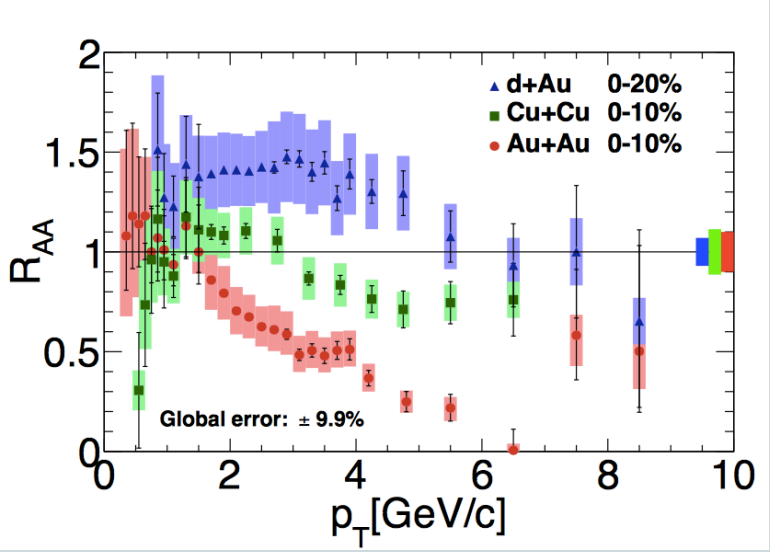
PRC 90 (2014) 034903



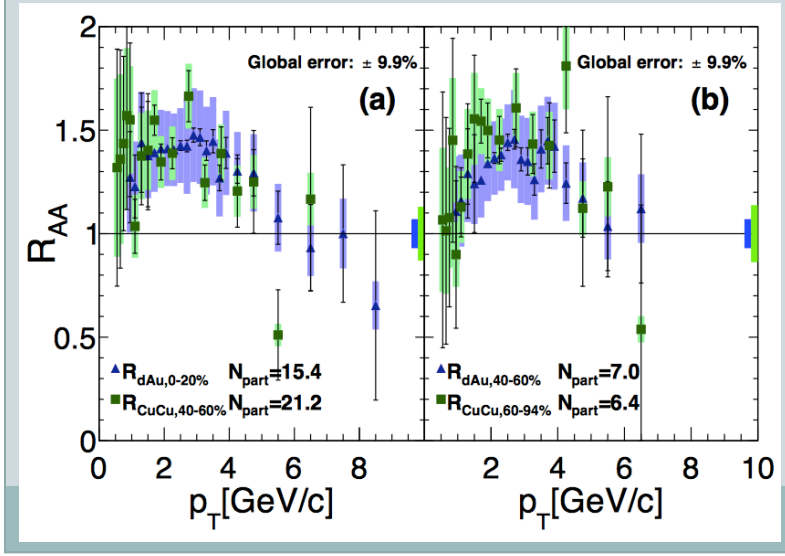
- Suppression
  - Central Cu+Cu & Au+Au
- Enhancement
  - Central d+Au & Peripheral Cu+Cu

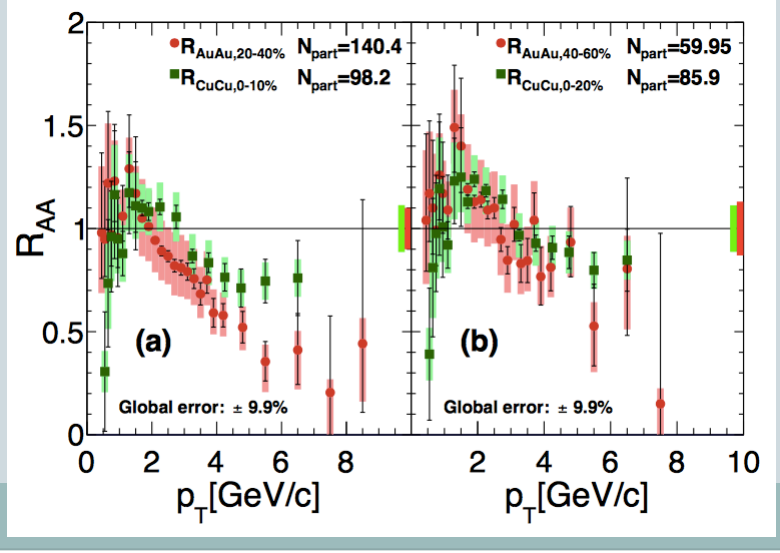
System Size Dependence

PRC 90 (2014) 034903



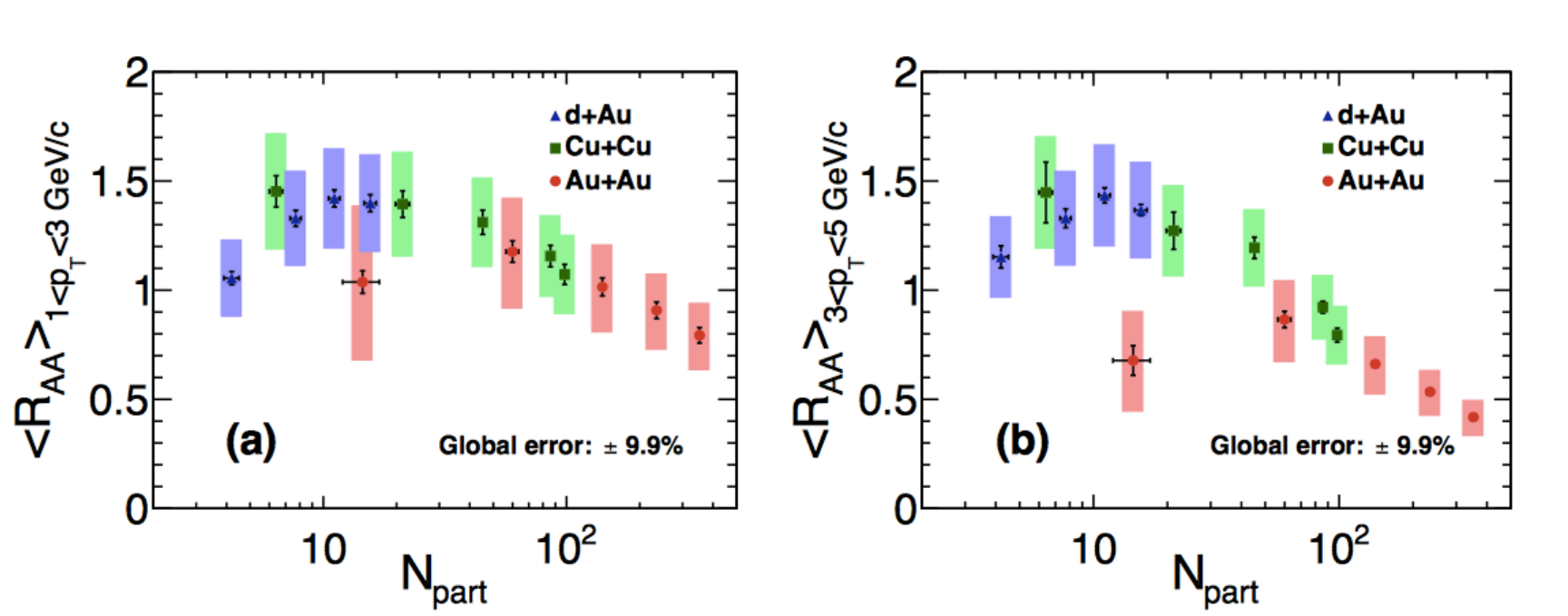
- Suppression
  - Central Cu+Cu & Au+Au
- Enhancement
  - Central d+Au & Peripheral Cu+Cu
- Same trend for similar N_{part}





System Size Dependence

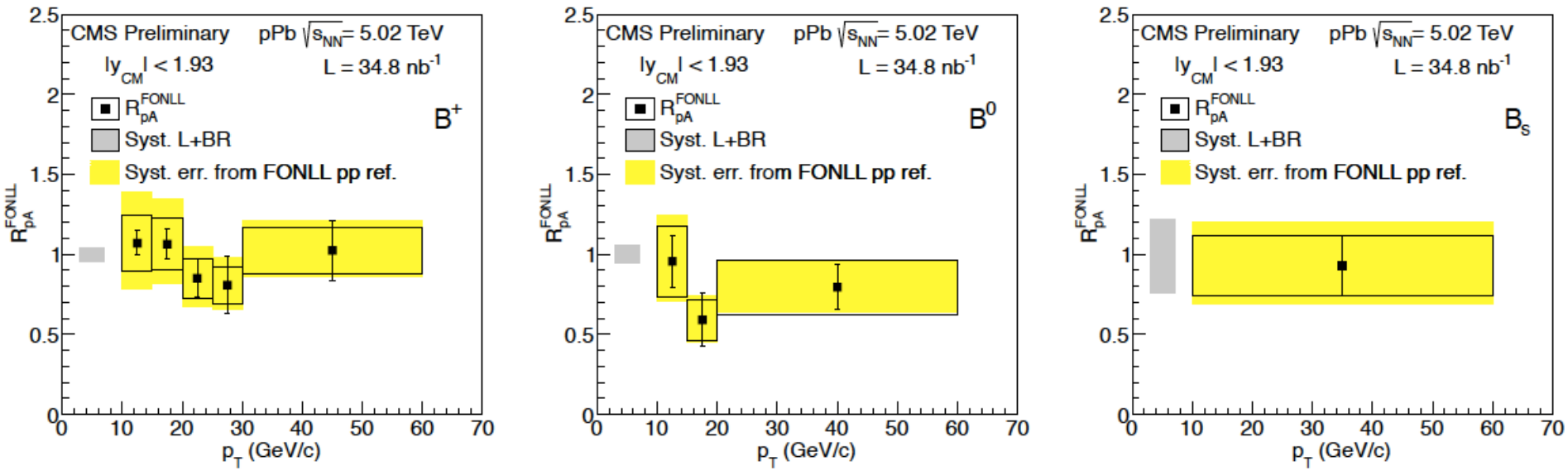
PRC 90 (2014) 034903



- Smooth trend from enhancement (central d+Au, peripheral Cu+Cu) to suppression (central Cu+Cu and Au+Au)

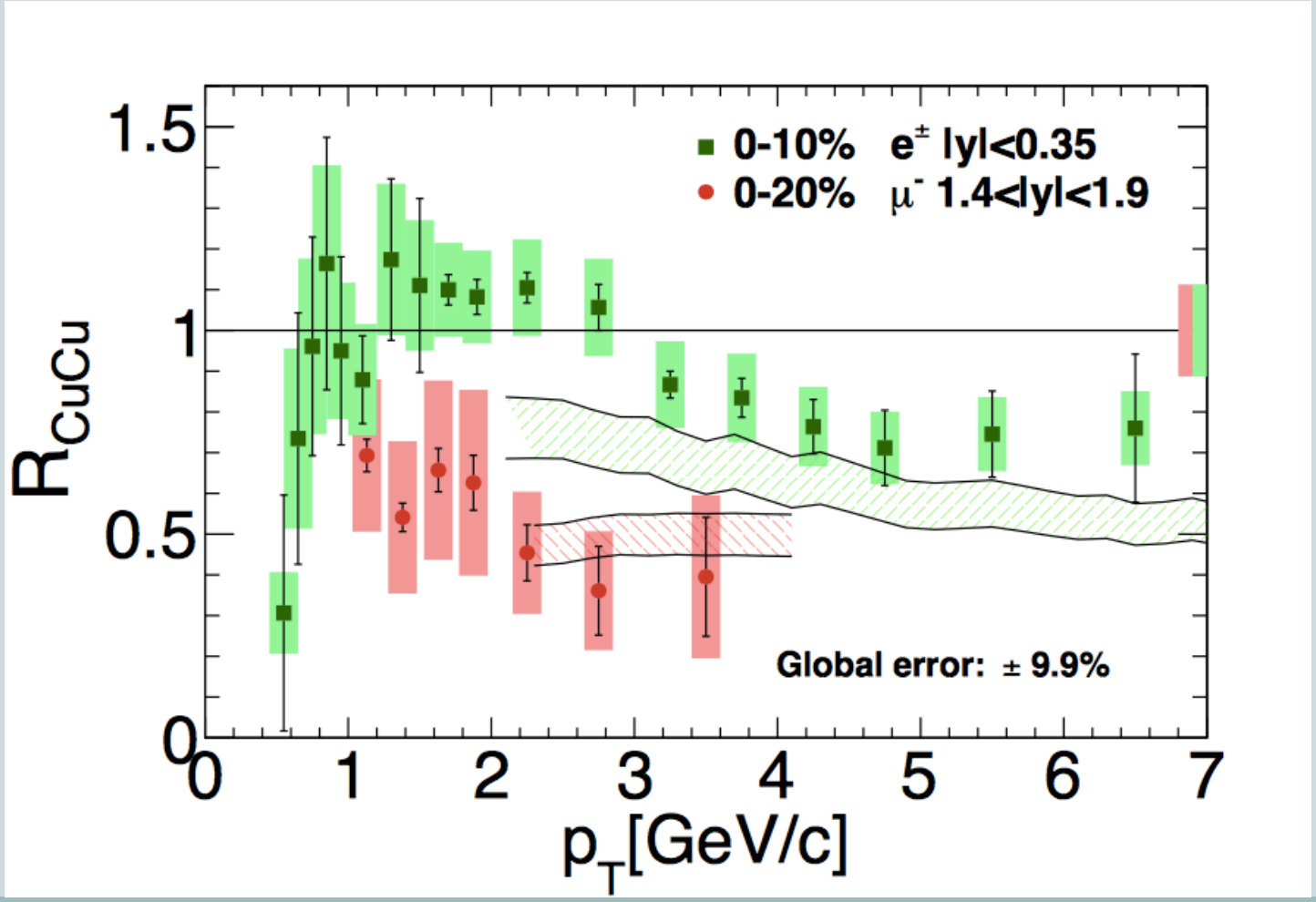
B mesons in p+Pb

- p+p reference from FONLL
- $R_{pPb} \sim 1$
- Pb+Pb suppression not coming from CNM effect



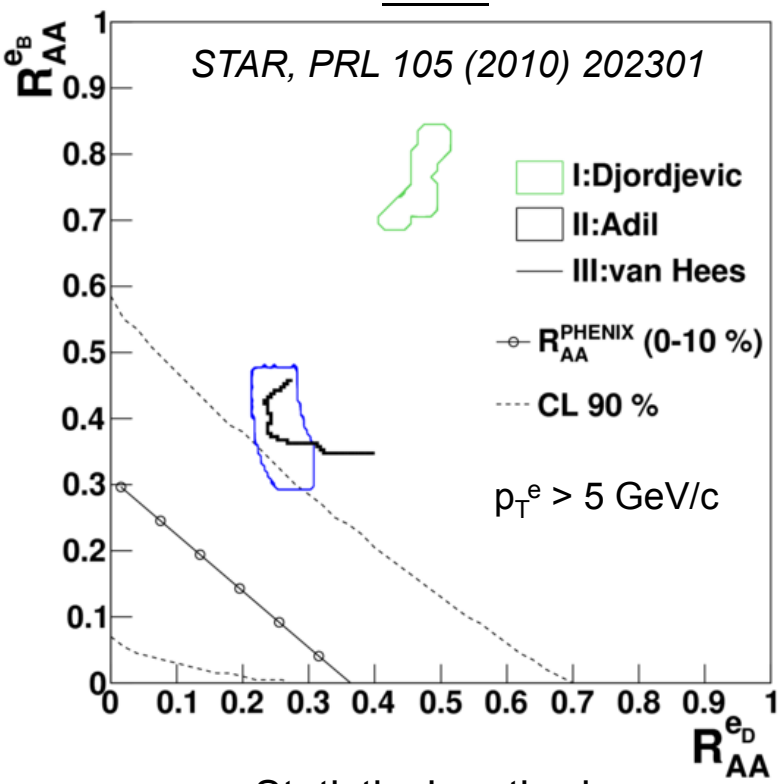
Summary

- Open heavy flavor (direct & indirect) give us insight into the medium produced in heavy-ion collisions
  - Energy loss in the medium
    - $R_{AA}(HF) \sim R_{AA}(LF)$
  - Charm quark flow
- p(d)+A
  - Evidence for CNM at RHIC (enhancement in mid & backward rapidities, suppression at forward rapidity)
  - No modification at mid-rapidity at LHC
    - Consistent with A+A suppression coming from HNM
- Where do we go from here?
  - Better precision, statistics, extended p_T range,
    - LHC Run II and RHIC Run 14 & 15
    - Upgrades at both the LHC & RHIC


0-10% e± |y|<0.35
0-20% μ- 1.4<|y|<1.9
Global error: ± 9.9%
R_CuCu
p_T [GeV/c]
0
0.5
1
1.5
0
1
2
3
4
5
6
7

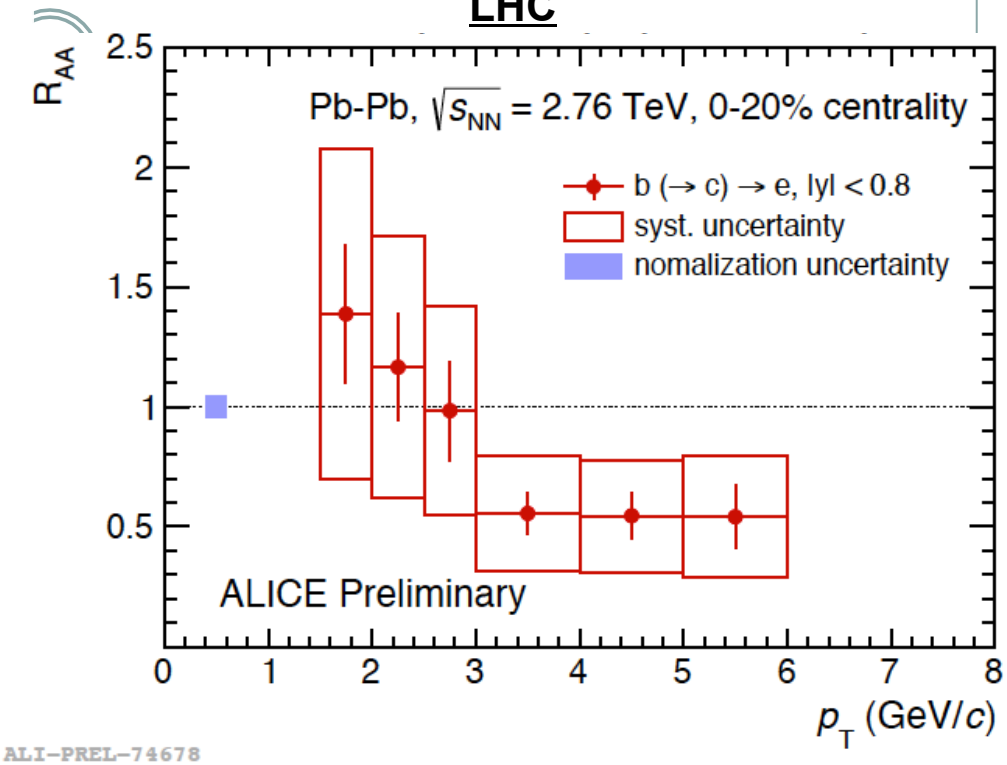
Bottom Suppression in Heavy Ion Collisions

RHIC



Statistical method

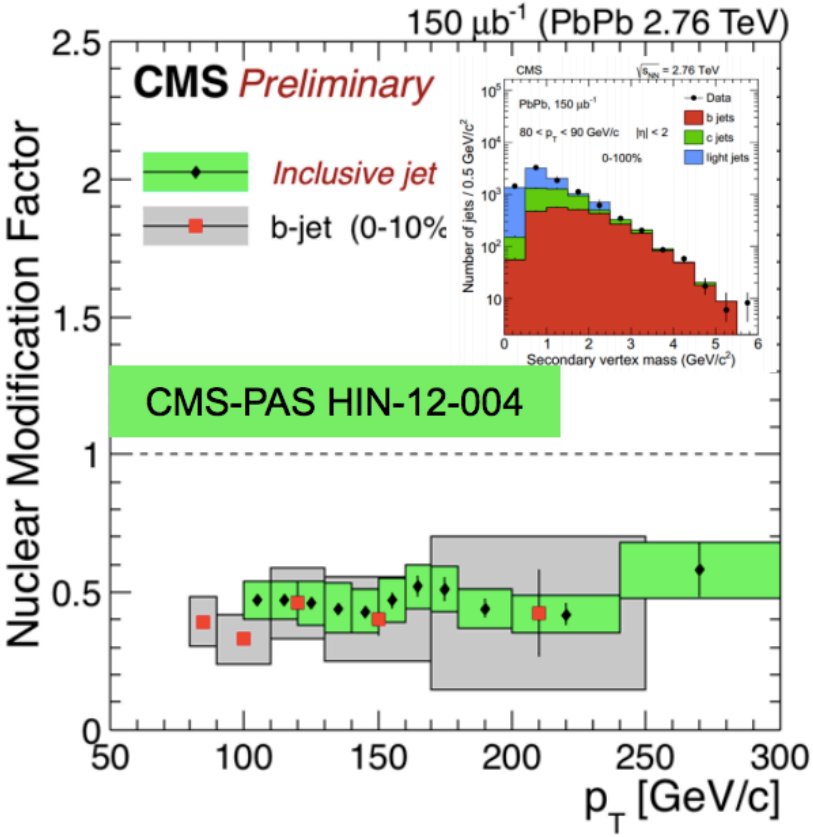
LHC

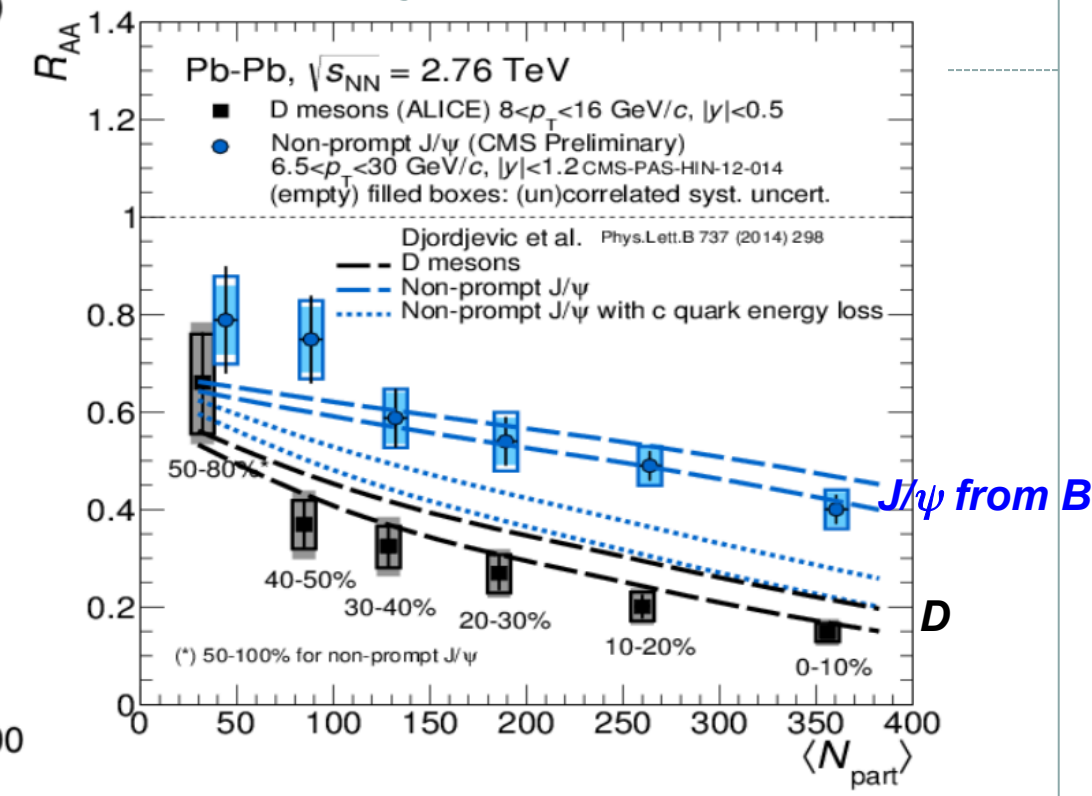


Impact parameter method

High p_T -> Flavor dependence of R_{AA} – "dead-cone" in pQCD
- $R_{AA}(e_D)$ vs. $R_{AA}(e_B)$ indicates bottom suppression in central A+A at RHIC/LHC
- Need precision measurement on both $R_{AA}(D)$ and $R_{AA}(B)$

Bottom Suppression in Heavy Ion Collisions





ALICE JHEP 09 (2012) 112, CMS-PAS-HIN-12-014, ALICE arXiv: 1506.06604

R_{AA} of b-jets at p_T>80 GeV/c comparable to that of light jets
caveat: sizable gluon splitting contribution

Suppression hierarchy between $R_{AA}(J/\psi^B)$ and $R_{AA}(D)$
– consistent with pQCD calculations