Measurements of Open Heavy Flavor Production at RHIC/LHC

RHIC&AGS Annual Users' Meeting 2017, BNL

Zhenyu Ye
University of Illinois at Chicago
Central China Normal University

- Introduction
- Recent progresses from experiments
- Summary and outlook

UIC The University of Illinois at Chicago

華中師範大學 HuaZhong Normal University

Office of Science U.S. DEPARTMENT OF ENERGY

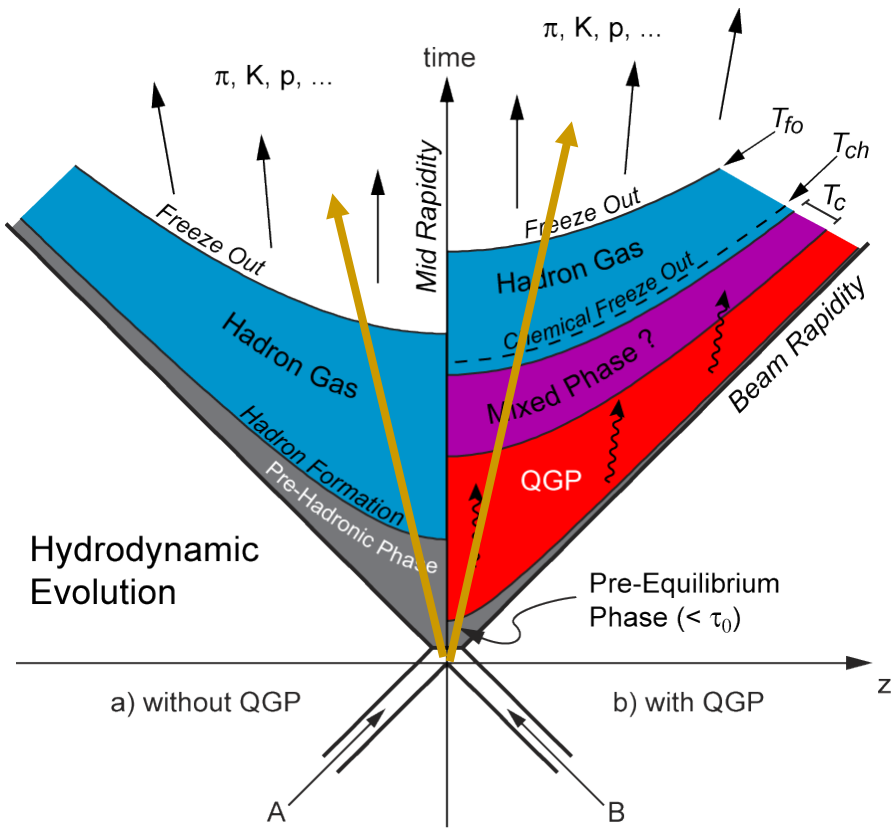
Why Heavy Quarks

- **Produced mostly at the early stage (<0.1 fm/c in rest frame) and experience the whole QGP evolution, carrying info before freeze out.**
- **Charm and bottom quarks with different masses (~1.3 vs 4.2 GeV/c^2) unique probes to study parton energy loss and QGP properties.**
- **Access to strongly coupled regime (low p_T) to confront lattice QCD and Ads/CFT calculations, and weakly coupled regime to test pQCD**

Soft processes:
π, K, p, …

EM probe: γ, γ^*

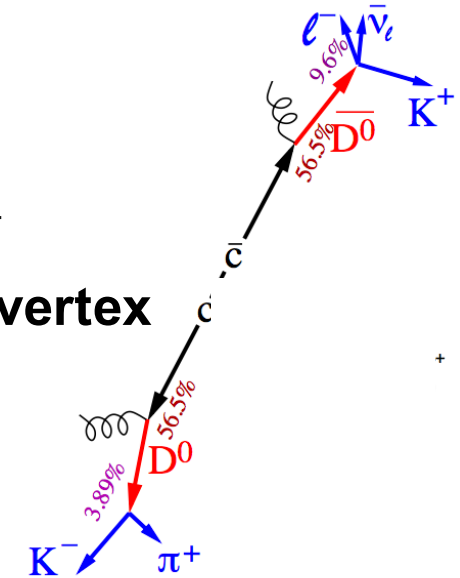
Hard probe:
c, b, high p_T jet



Zhenyu Ye

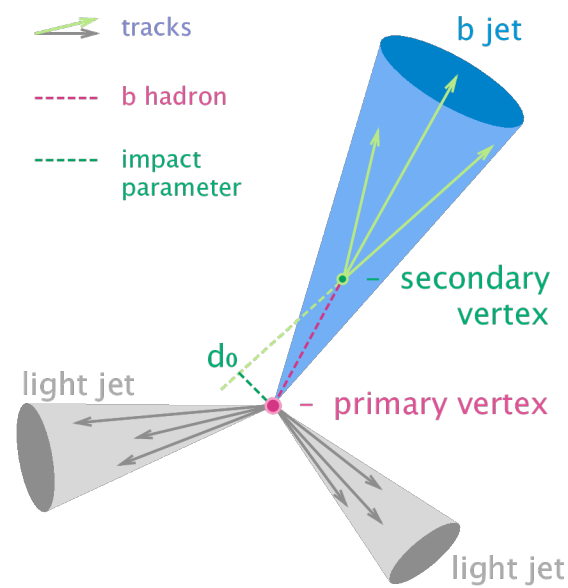
How to Study Them

- **Finding HF particles**
  - **Decay daughters:** $D^0 \to e^+X$, $B^0 \to J/\psi X$
  - **Reconstructed hadrons:** $D^0 \to \pi^+K^-$, $B^+ \to J/\psi K^+$
  - **Fully reconstructed jets: HF tagging through 2nd vertex**



	D^0	$D^\pm$	D_S	Λ_c	B^0	$B^\pm$	B_S
$c\tau$ (μm)	123	312	150	60	491	456	450
% in p+p	56%	24%	10%	10%	40%	40%	10%

- **Experimental observables**
  - **Yield as a function of p_T, y, n_{ch}, …**
  - **Nuclear modification factors: R_{CP}, R_{AA}, R_{pA}**
  - **Azimuthal anisotropy: v_n**
  - **Correlations:** $B-\bar{B}$, $D-\bar{D}$, $D-h$, e$-h$, …
  - **…**



Zhenyu Ye

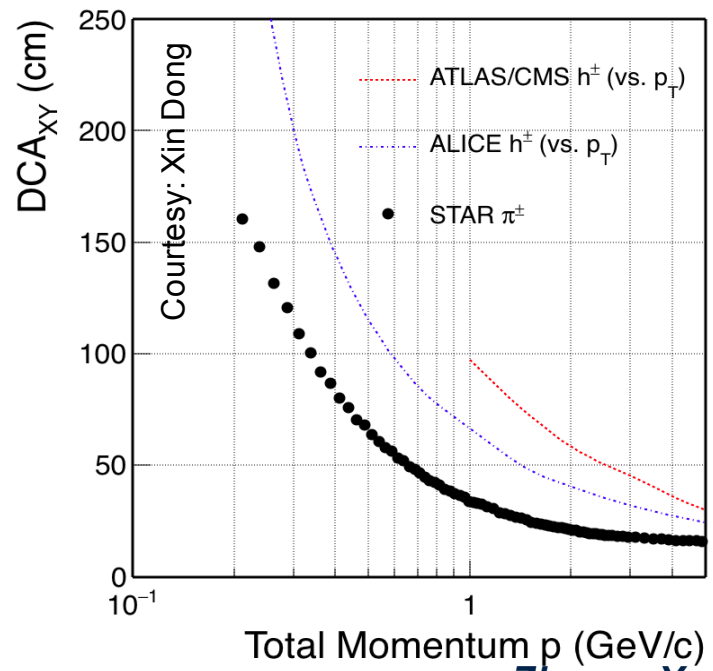
Challenges

- **Small production cross-section & large background: Silicon vertex detector with good resolution and low material is crucial**

	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
pixel det. type	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	MAPS
pixel size (μm)	50x425	50x400	100x150	200x200	50x425	20x20
L1 radius (cm)	3.9	5.1	4.4	N/A	2.5	2.8
L1 thickness	$1\%X_0$	$1\%X_0$	$1\%X_0$	$1\%X_0$	$1\%X_0$	$0.4\%X_0$

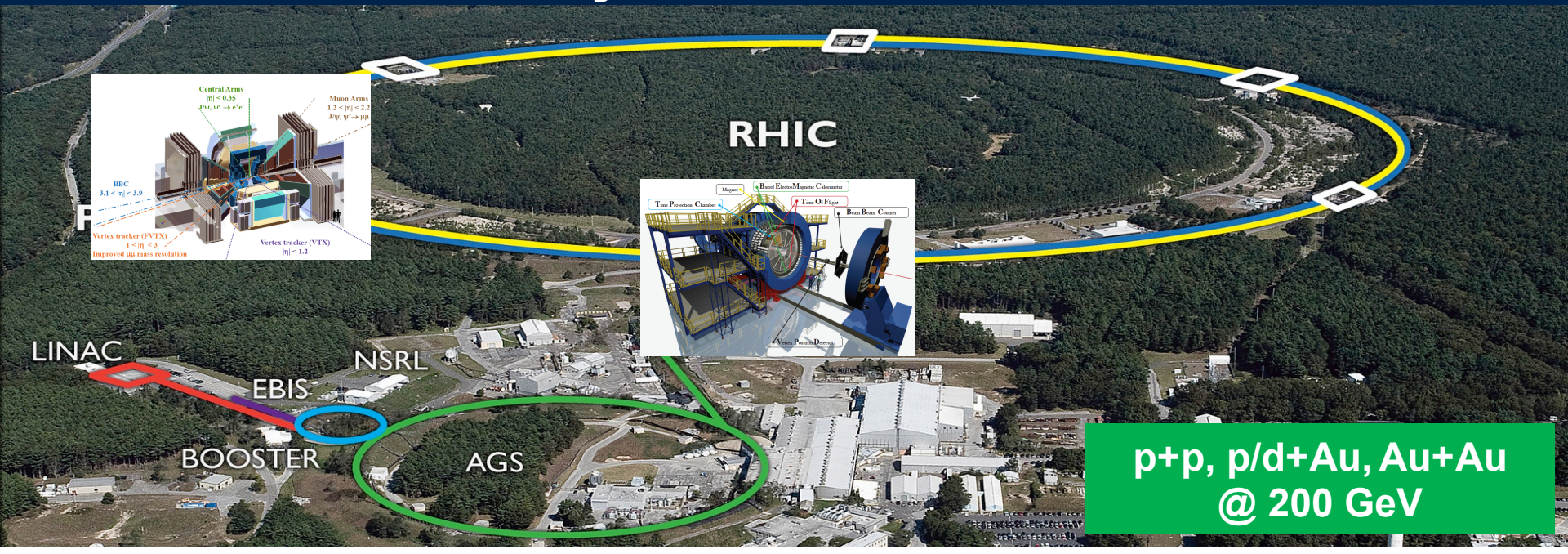
- **Lack of efficient trigger for hadronic channels. Large acceptance, high DAQ rate, and particle ID are helpful.**

- **Cold nuclear matter effects**
  - **nuclear PDFs**
  - **multiple scattering with nucleus**



Zhenyu Ye

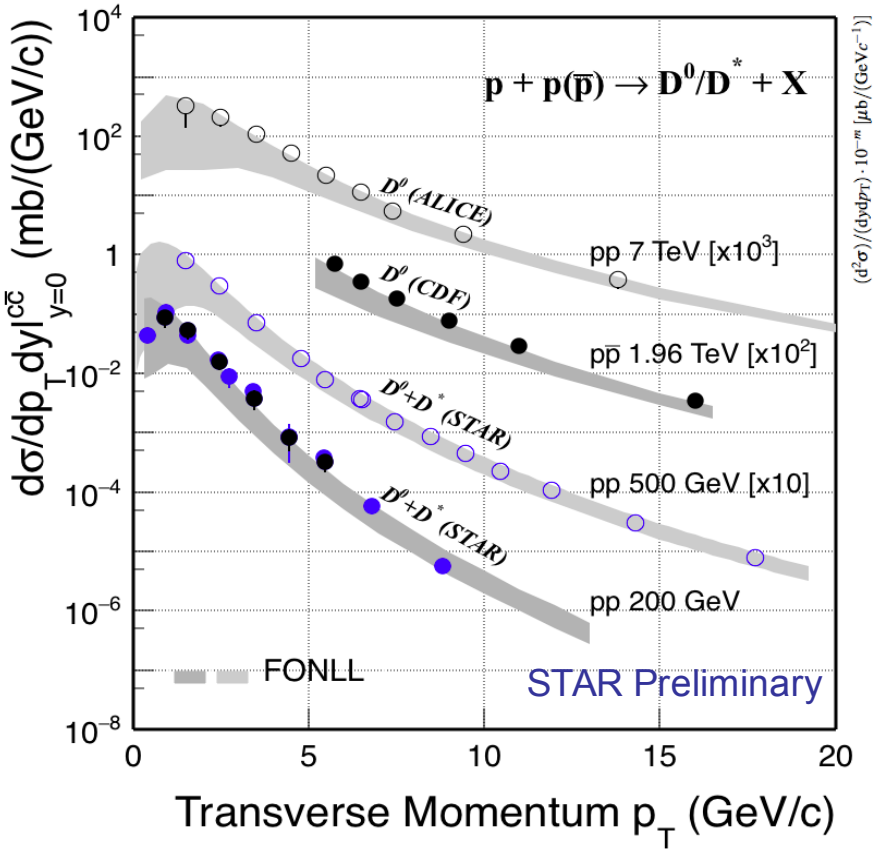
Heavy-Ion Colliders

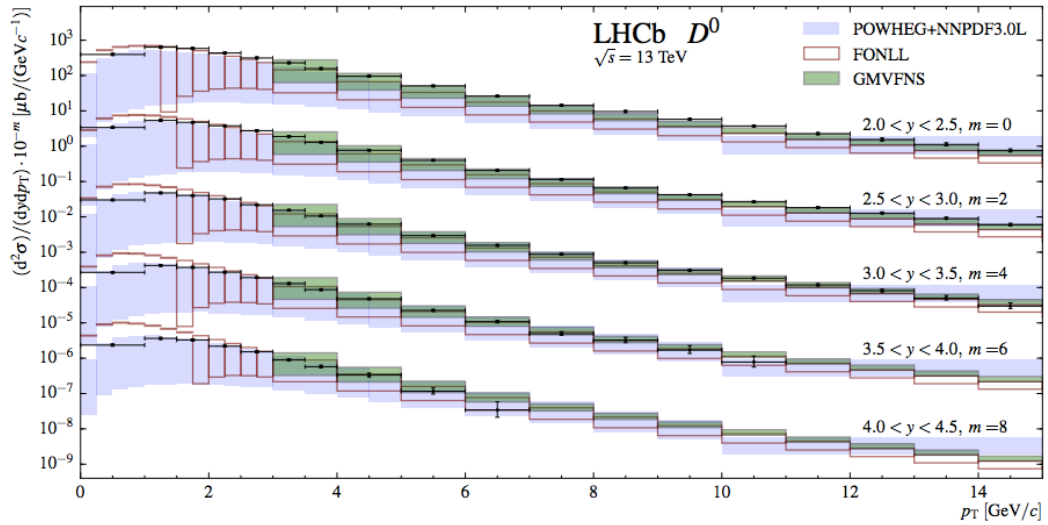


p+p, p/d+Au, Au+Au @ 200 GeV

p+p, p+Pb, Pb+Pb @ 2.76, 5.02 TeV

Charm Production in p+p collisions

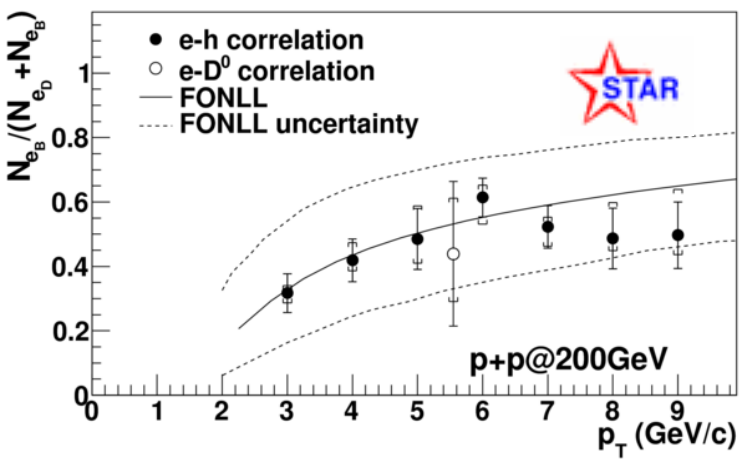


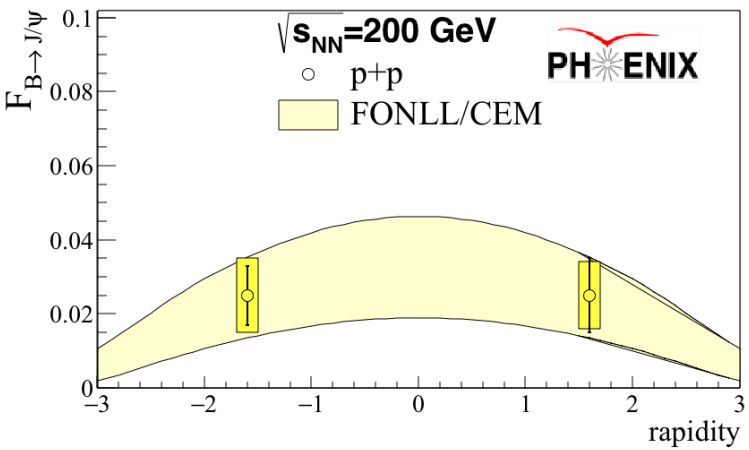


STAR, PRD 86 (2012) 072013, QM14
CDF, PRL 91 (2003) 241804
ALICE, JHEP 01(2012) 128, arXiv: 1702.00766
LHCb, JHEP 03 (2016) 159, 09 (2016) 013

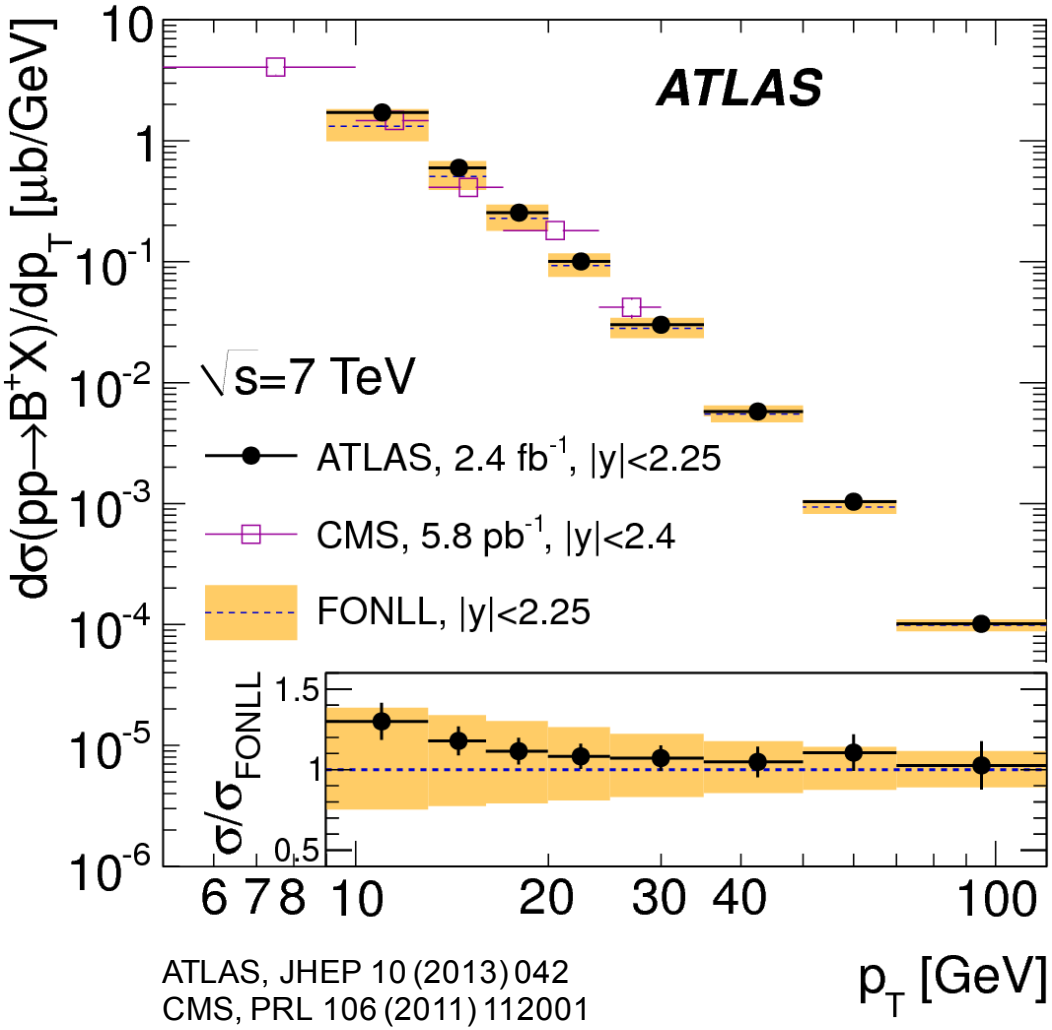
- Charm production cross-sections in p+p collisions described by pQCD calculations with large theoretical uncertainty
- FONLL underestimates the data, while GM-VFNS does a better job

Bottom Production in p+p collisions





STAR, PRL 105 (2010) 202301
PHENIX, arXiv:1702.01085

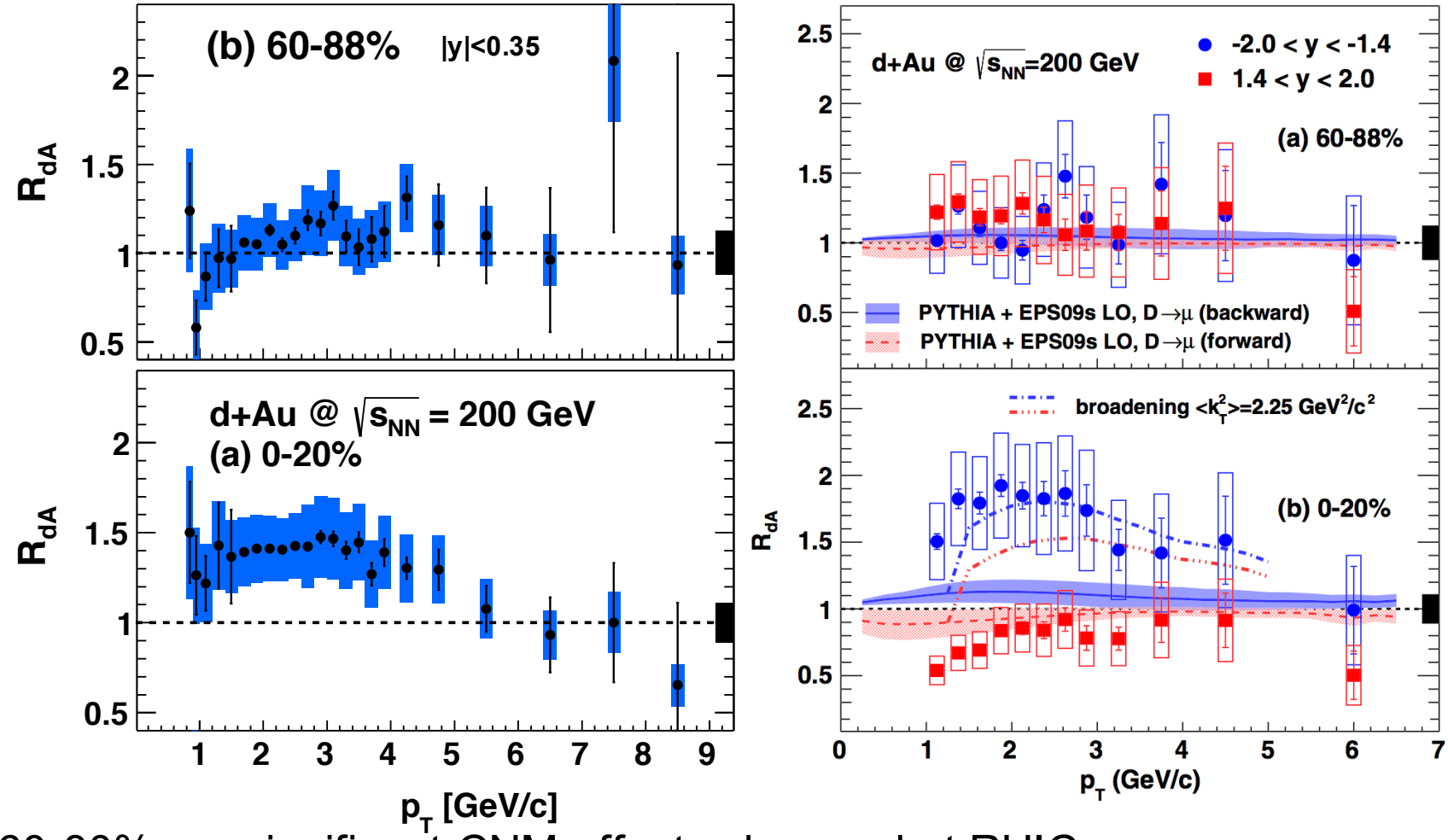


ATLAS, JHEP 10 (2013) 042
CMS, PRL 106 (2011) 112001

- Data and FONLL in better agreement for bottom production

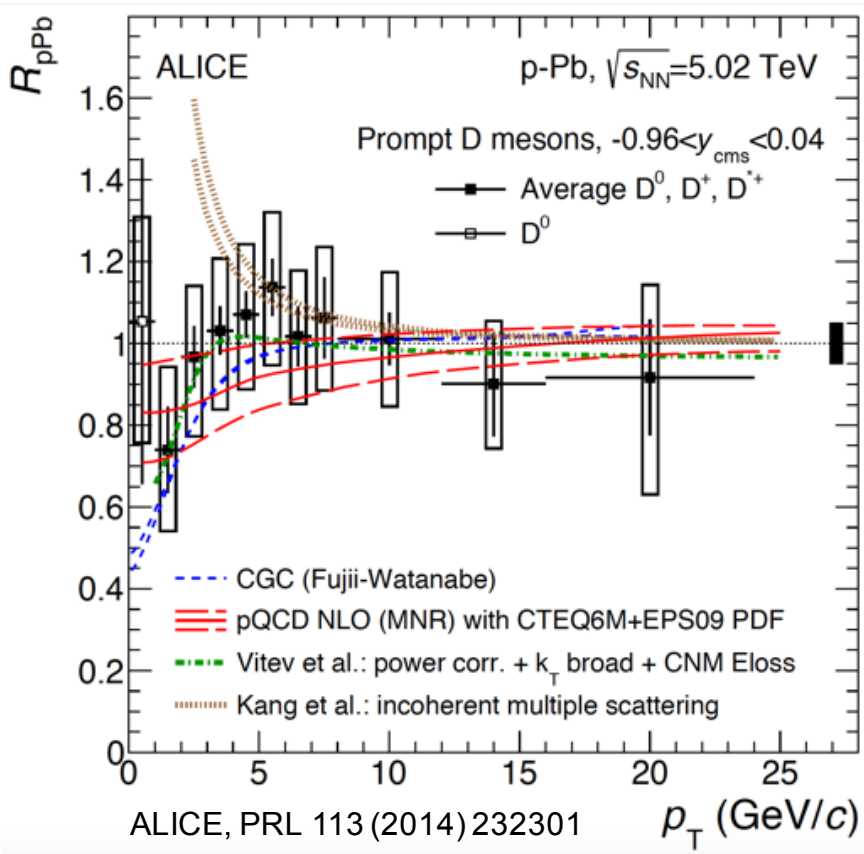
e/μ^{HF} in d+Au collisions at RHIC

PHENIX: PRL109 (2012) 242301, 112 (2014) 252301

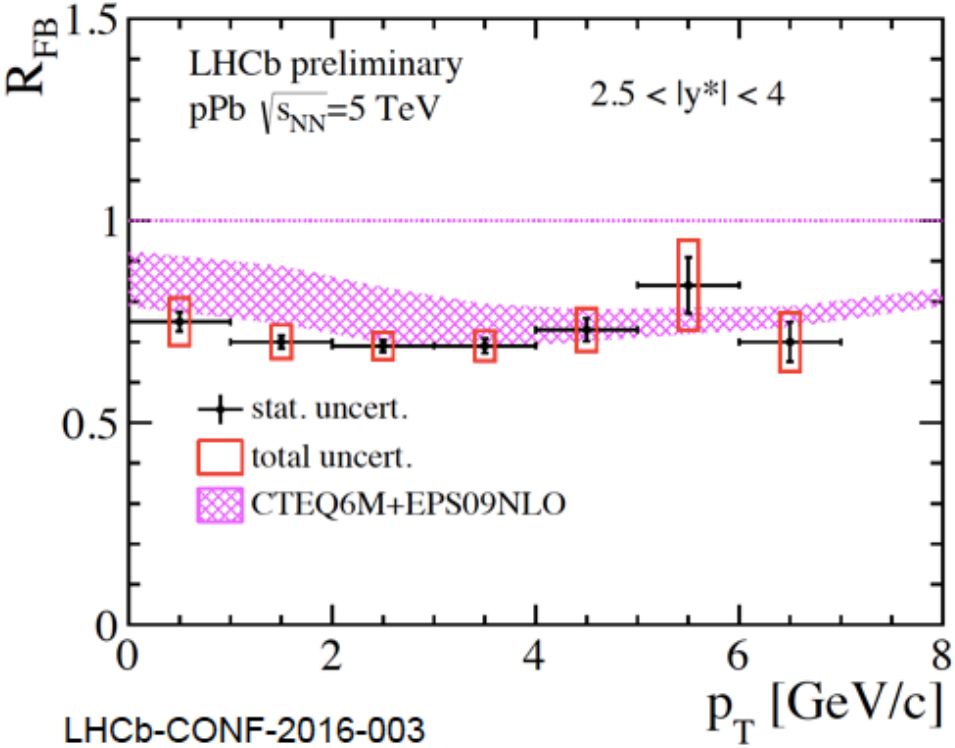


- 60-80%: no significant CNM effects observed at RHIC
- 0-20%: R_{dA}<1 at forward (d-going) and R_{dA}>1 at mid-rapidity and backward – nPDFs alone do not describe the data

Charm in p+Pb collisions at LHC



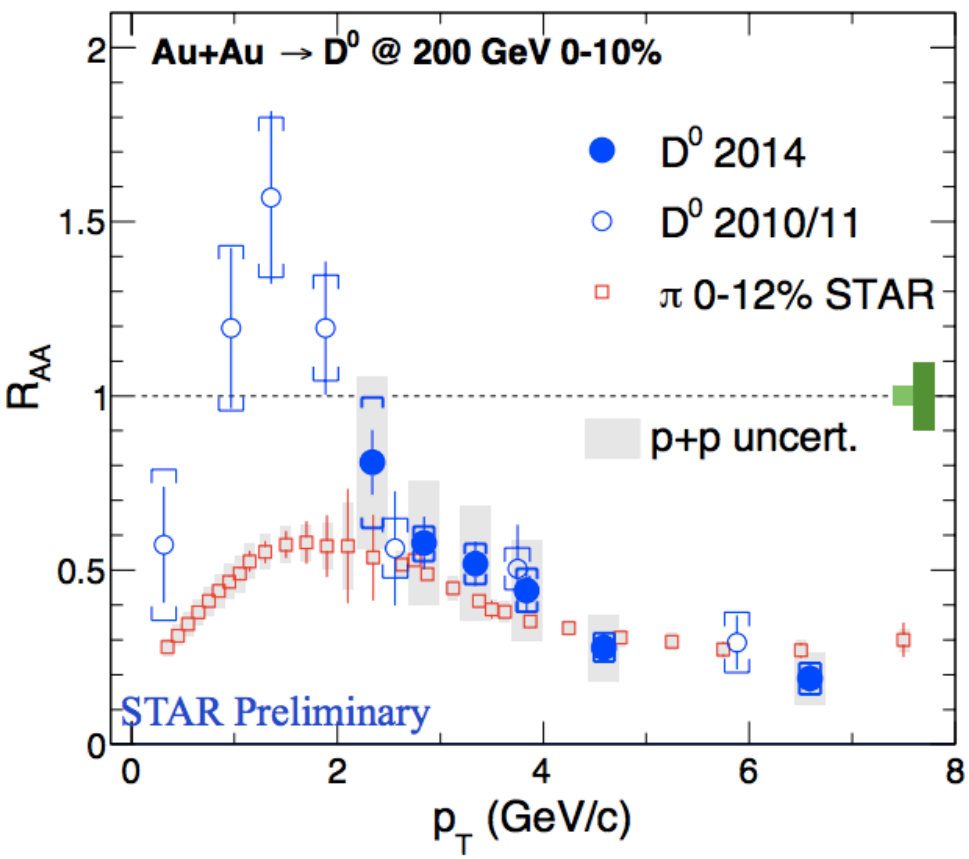
ALICE, PRL 113 (2014) 232301

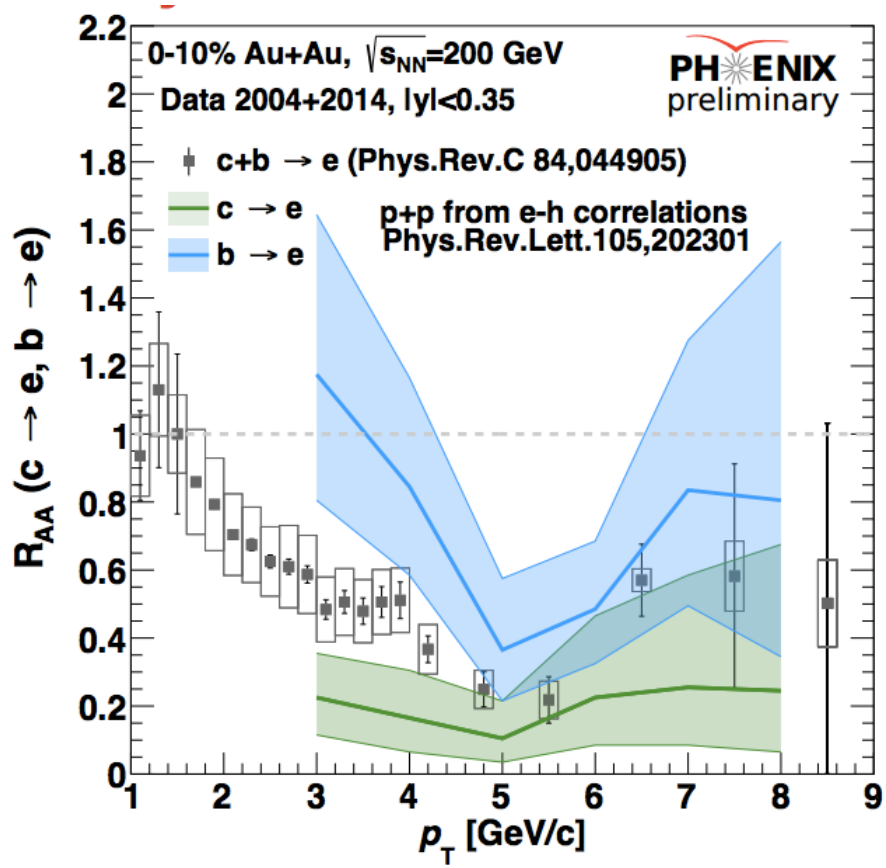


LHCb-CONF-2016-003

- No significant CNM effects (<20%) observed at mid-rapidity in MB collisions
- R_{pPb}<1 at forward rapidity (p-going) and R_{pPb}>1 at backward rapidity (Pb)
  R_{FB} ~ 0.8 described by nPDFs

Charm R_{AA} at RHIC

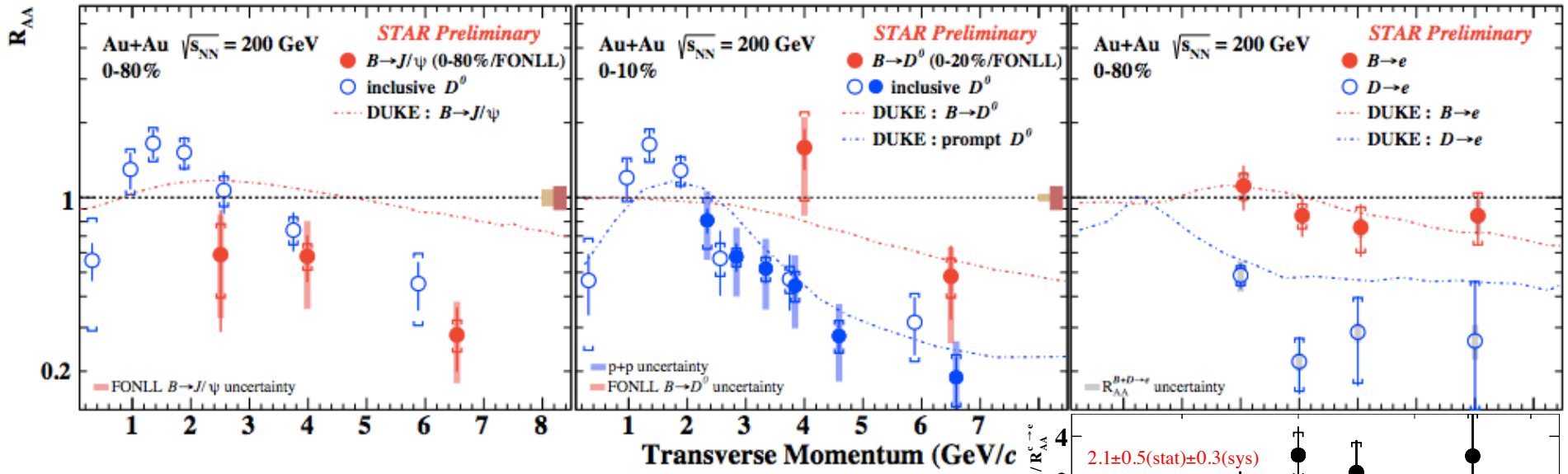


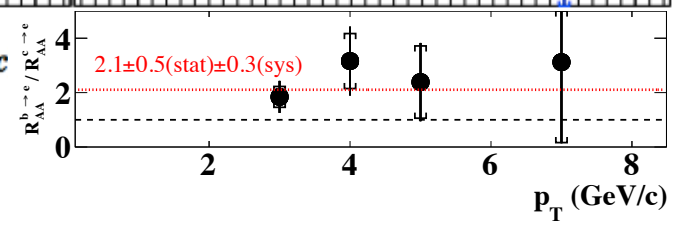


STAR D^0 2010/2011: PRL 113 (2014) 142301
STAR π 0-12%: PLB 655 (2007) 104

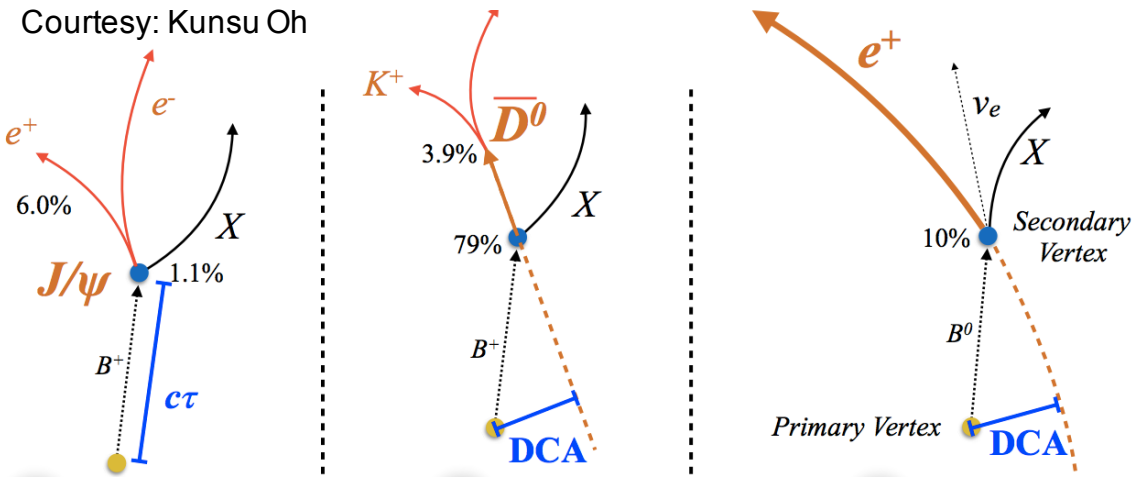
- D^0 and e^D R_{AA} <1 for p_T > 3 GeV/c – significant ΔE_c
- Indication of e^B R_{AA} > e^D R_{AA} – consistent with $\Delta E_b < \Delta E_c$

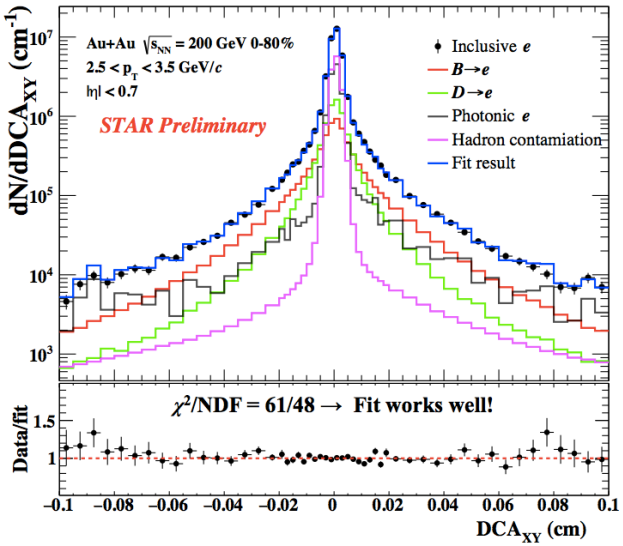
Bottom R_{AA} at RHIC





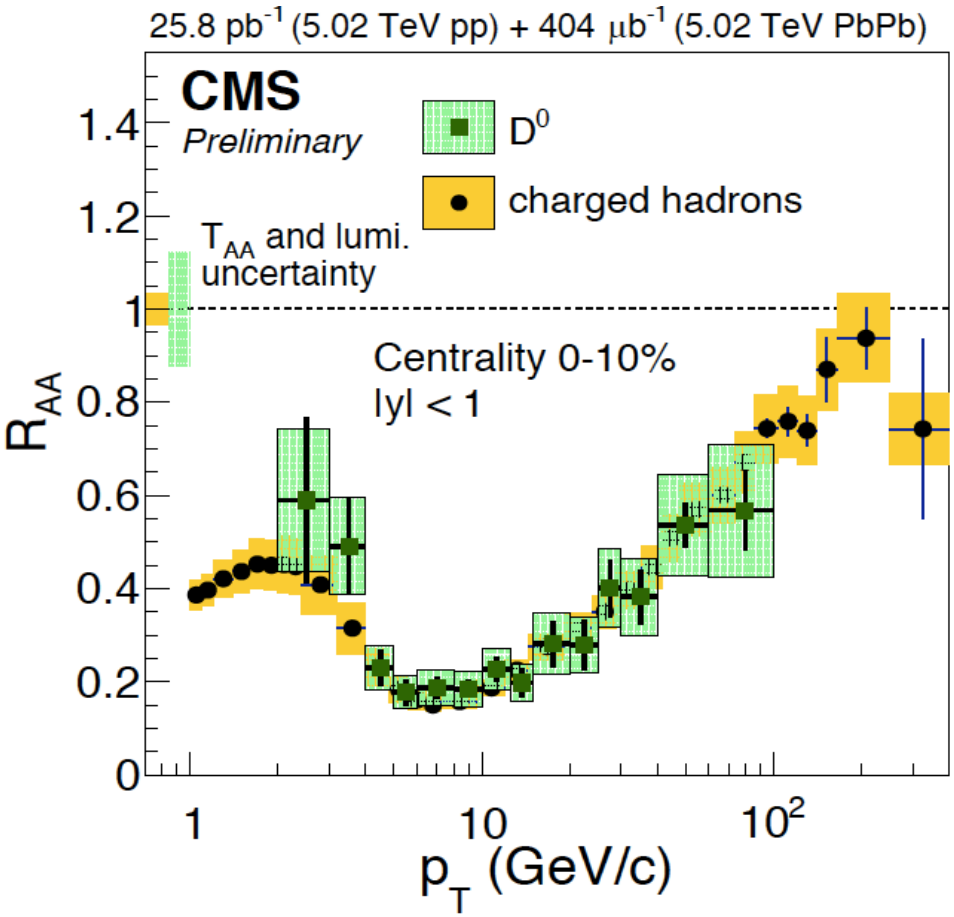
Courtesy: Kunsu Oh

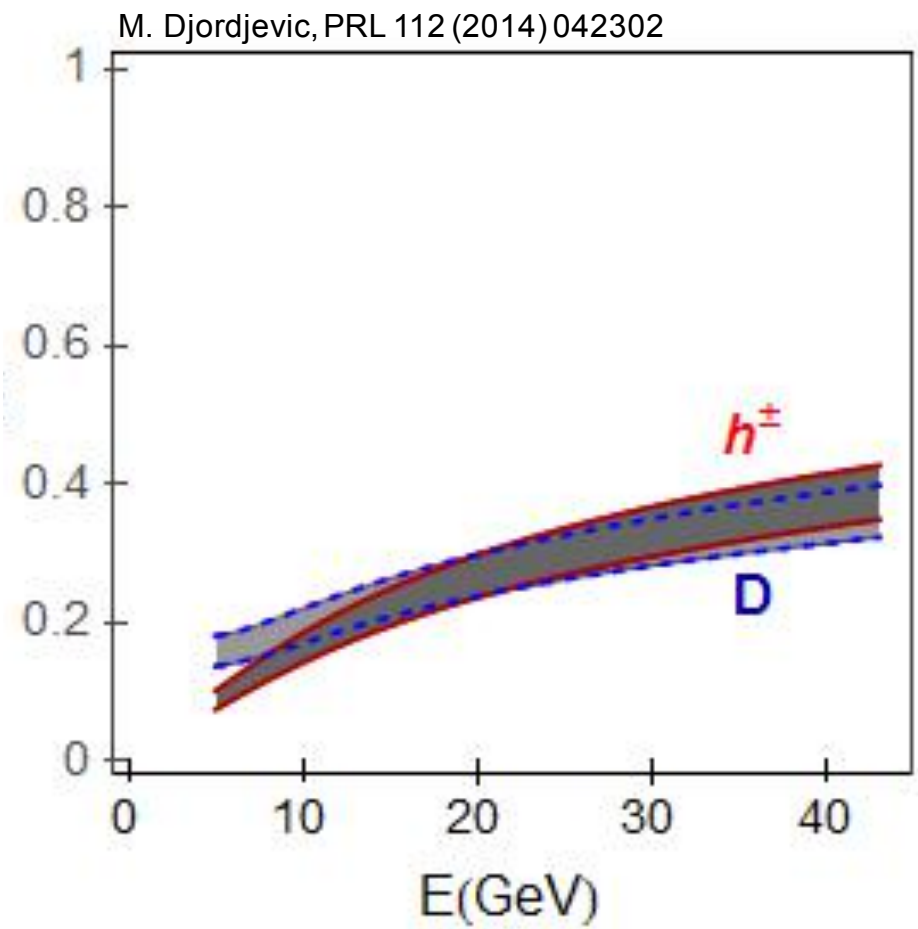




- B-decayed J/ψ and D^0 R_{AA}<1 for p_T > 5 GeV/c – significant ΔE_b
- e^B R_{AA} > e^D R_{AA} (2σ) – consistent with $\Delta E_b < \Delta E_c$

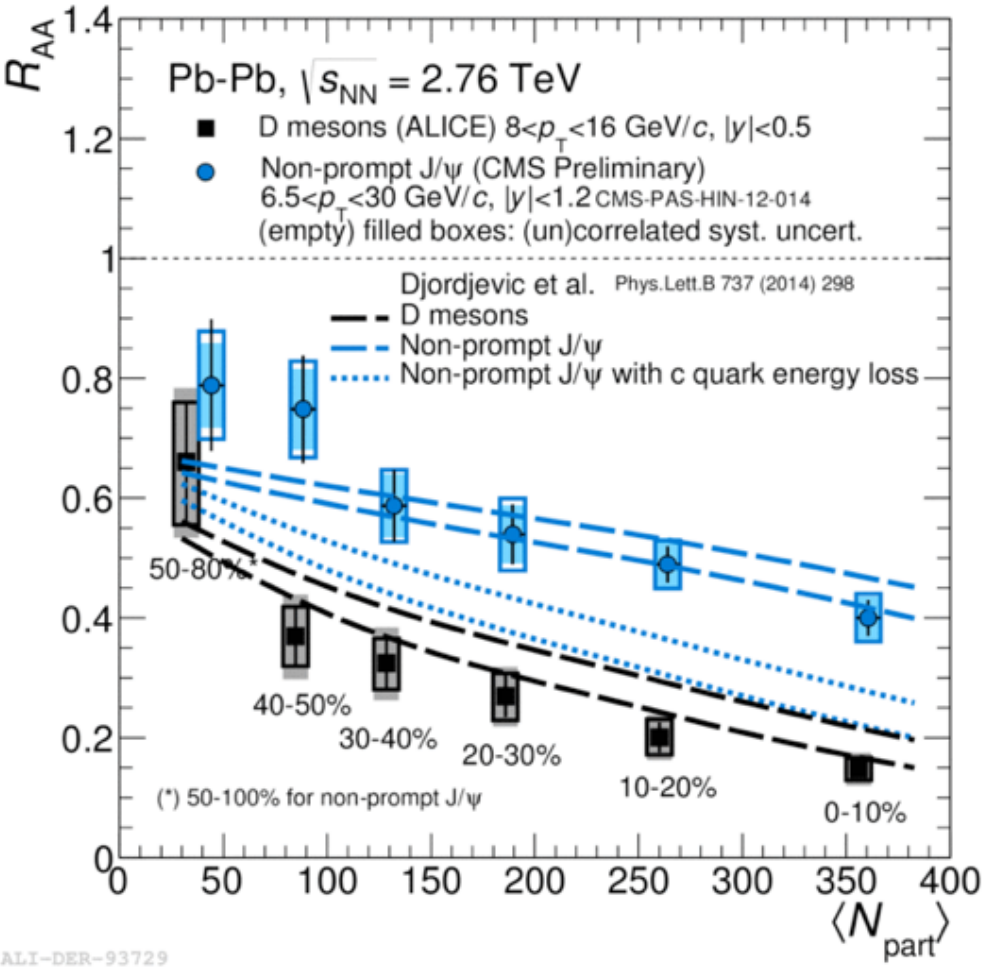
Charm R_{AA} at the LHC

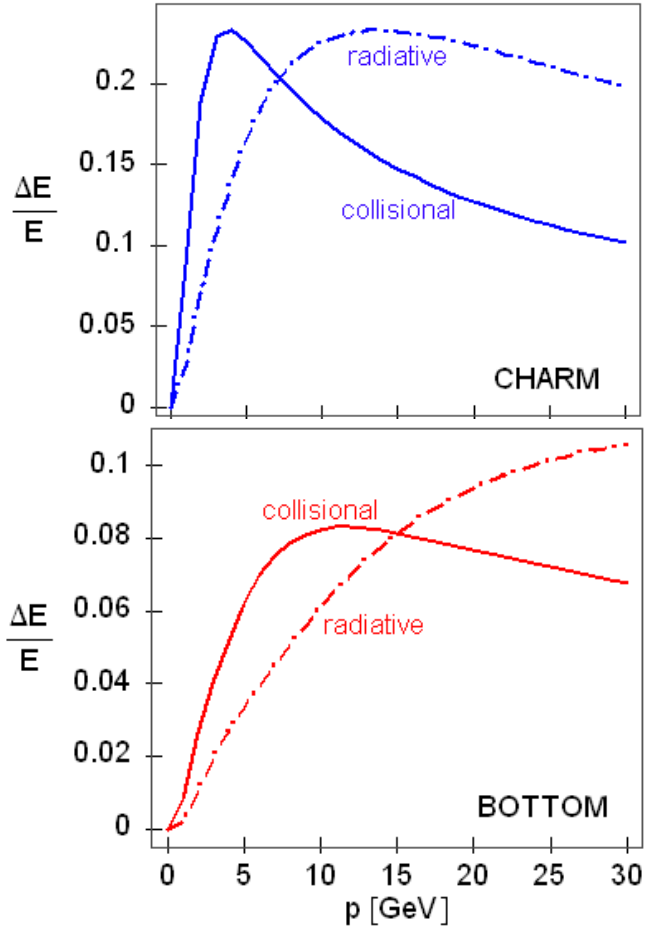




- D^0 and charged hadron (from both quarks and gluons) R_{AA} compatible – can be explainable by theoretical calculations with flavor-dependent energy loss, spectrum shape and fragmentation

Bottom R_{AA} at the LHC

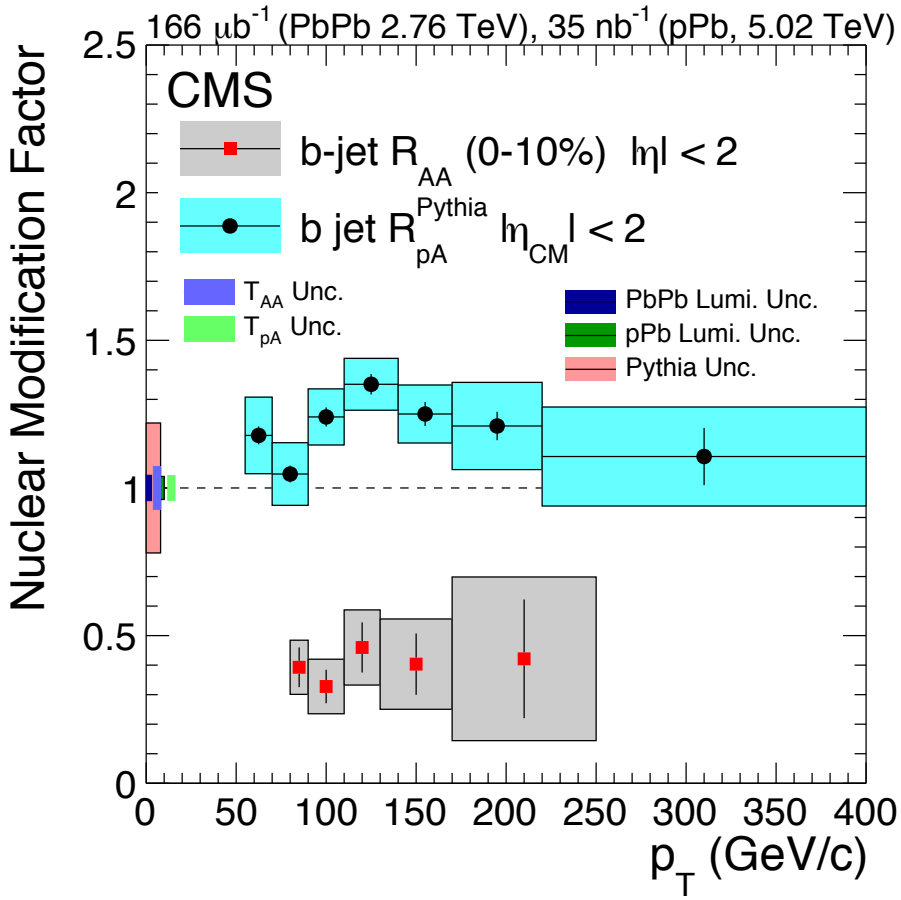


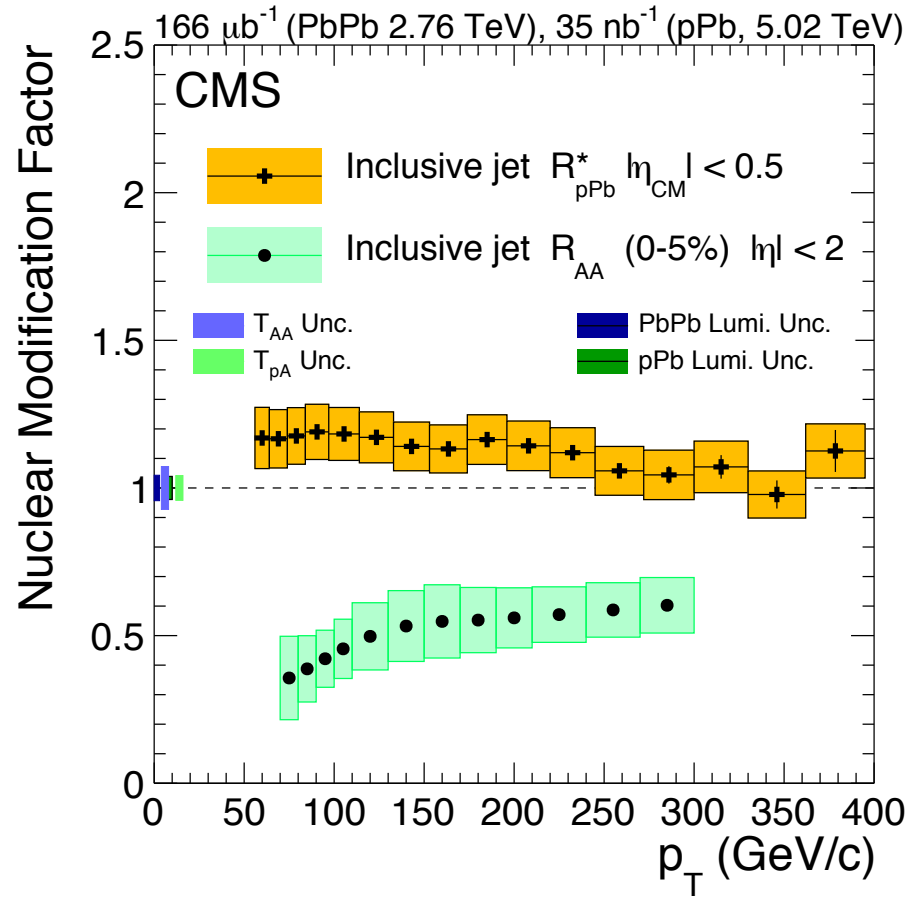


- D^0 and charged hadron (from both quarks and gluons) R_{AA} compatible – explainable by flavor-dependent energy loss, spectrum and fragmentation
- Non-prompt J/ψ R_{AA} at |y|<1.2 significantly larger than prompt D at |y|<0.5 – consistent with $\Delta E_b < \Delta E_c$

Zhenyu Ye

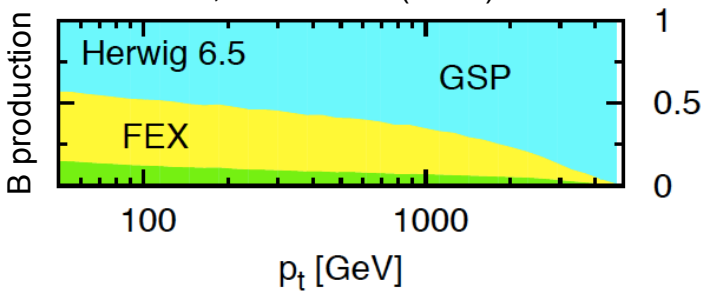
B-tagged Jets at the LHC





CMS: PRL 113 (2014) 132301, PLB 754 (2016) 59, EPJC 76 (2016) 372, arXiv:1609.05383

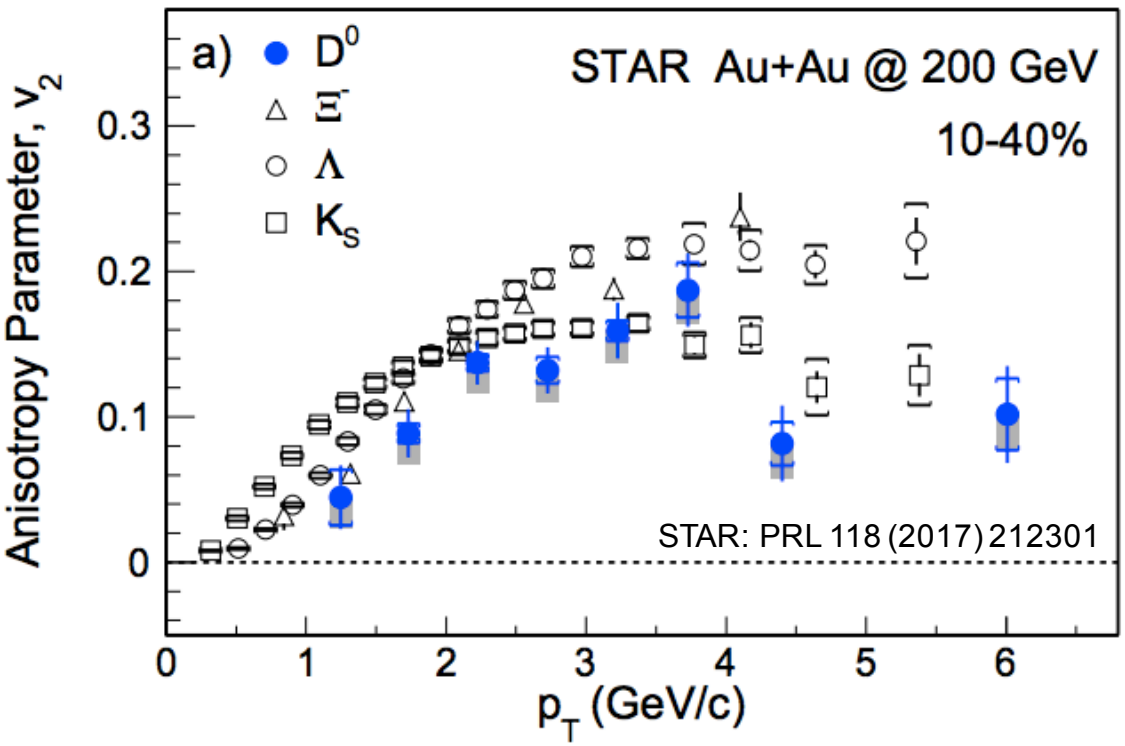
Banfi et al., JHEP 0707 (2007) 026

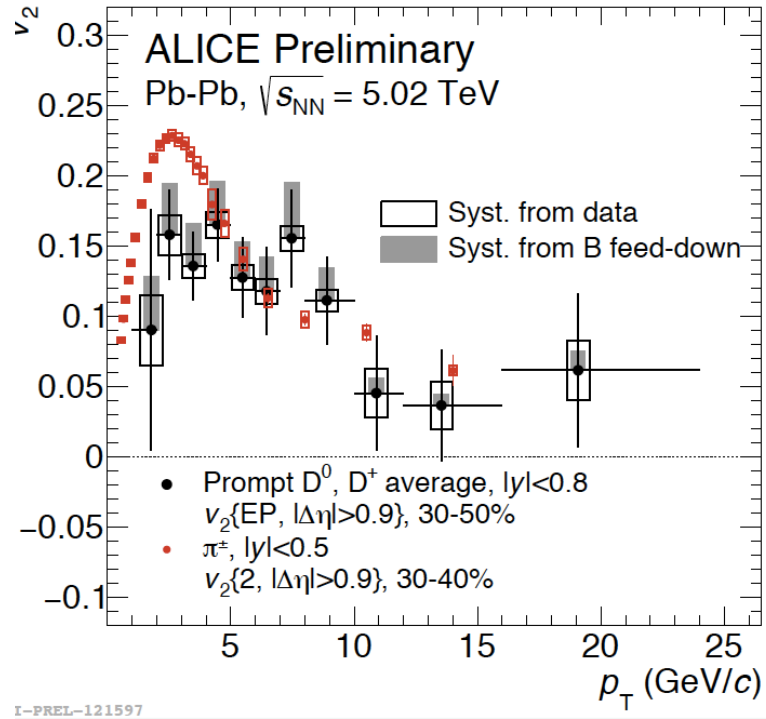


- B-tagged and inclusive jet R_{pPb}, R_{PbPb} compatible
  - >50% B-tagged jets from gluon splitting
  - inclusive jets include quark + gluon jets

Zhenyu Ye

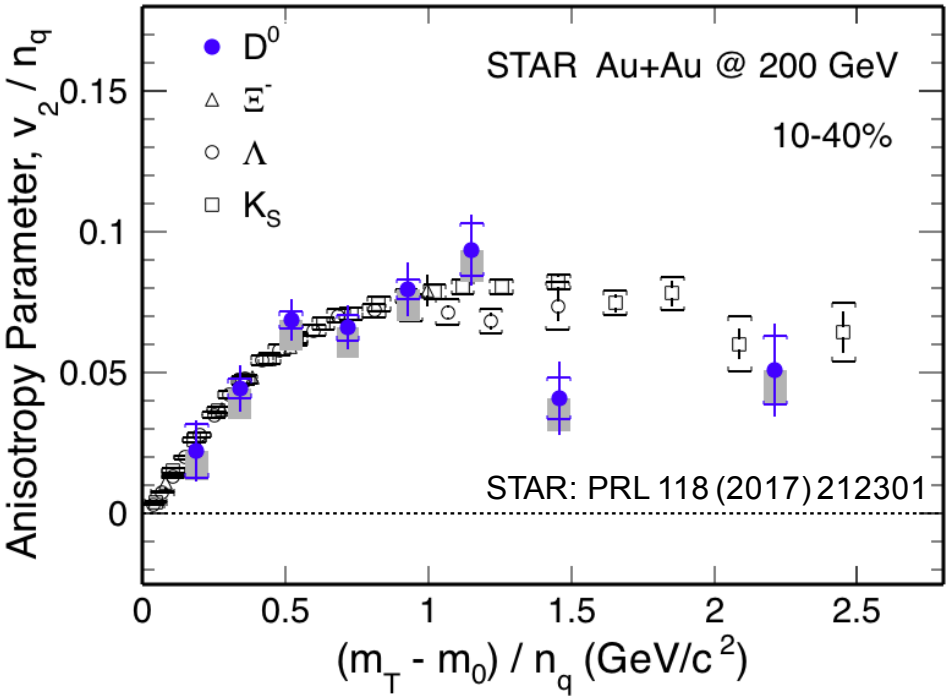
Charm Azimuthal Anisotropy

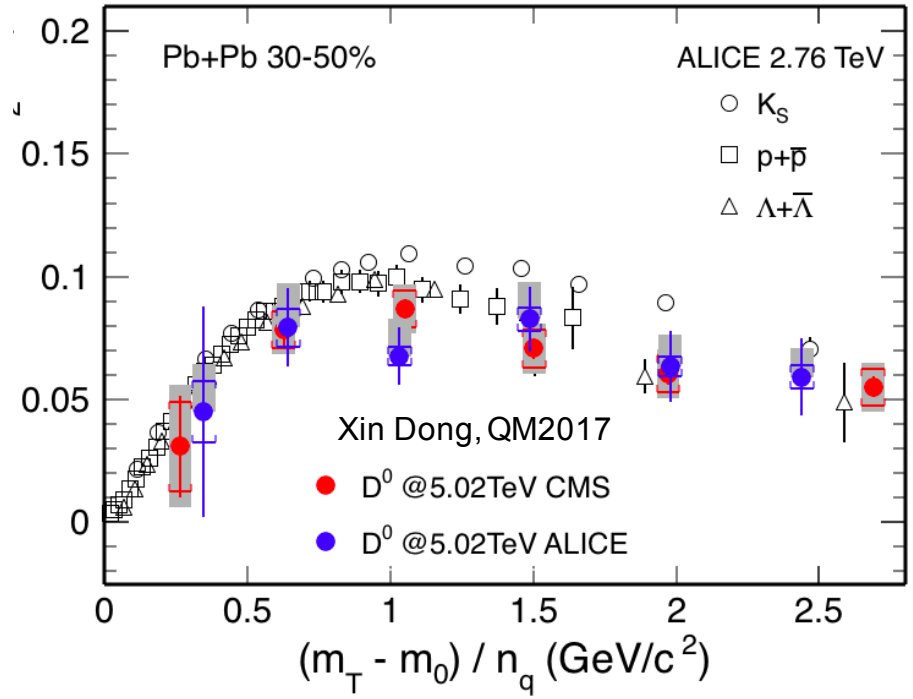




- Significant D^0 v_2 – mass ordering at low p_T

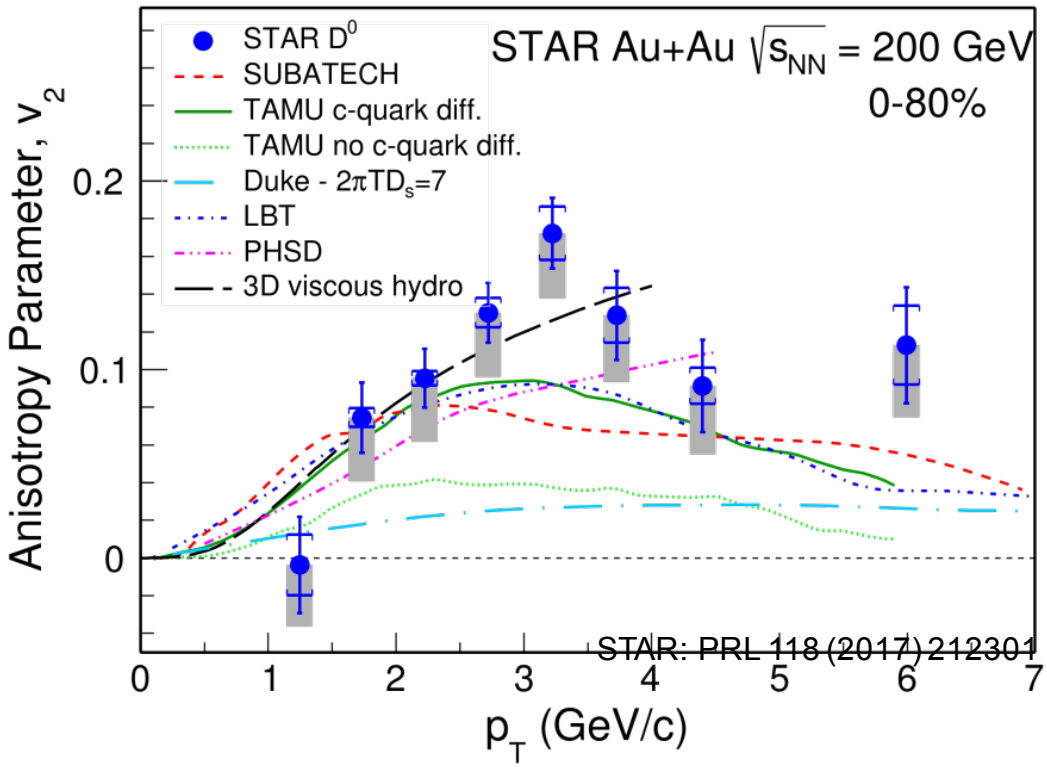
Charm Azimuthal Anisotropy

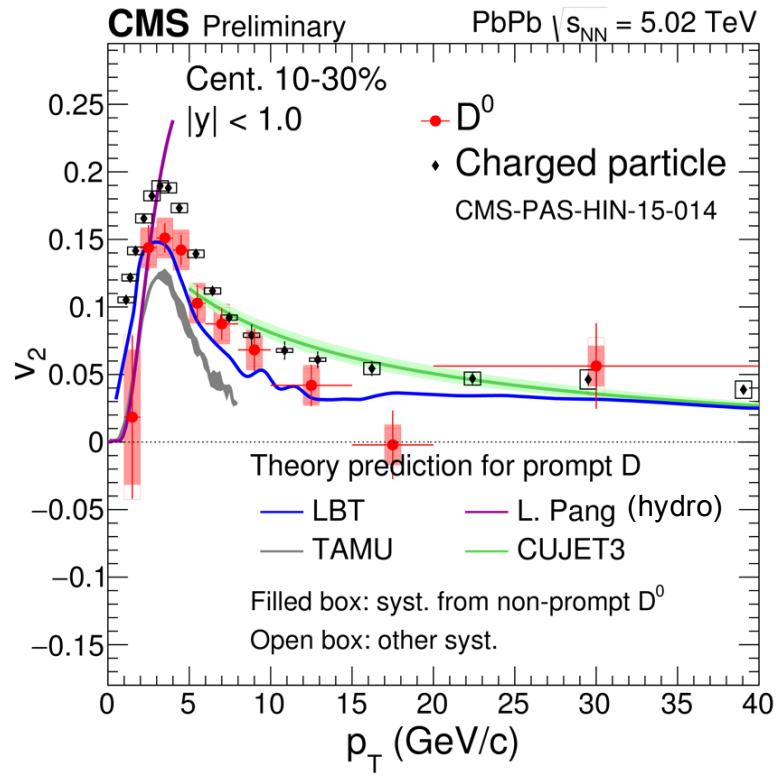




- Significant D^0 v_2 – mass ordering at low p_T
- Low p_T D^0 v_2 follows NCQ scaling – charm quark flows

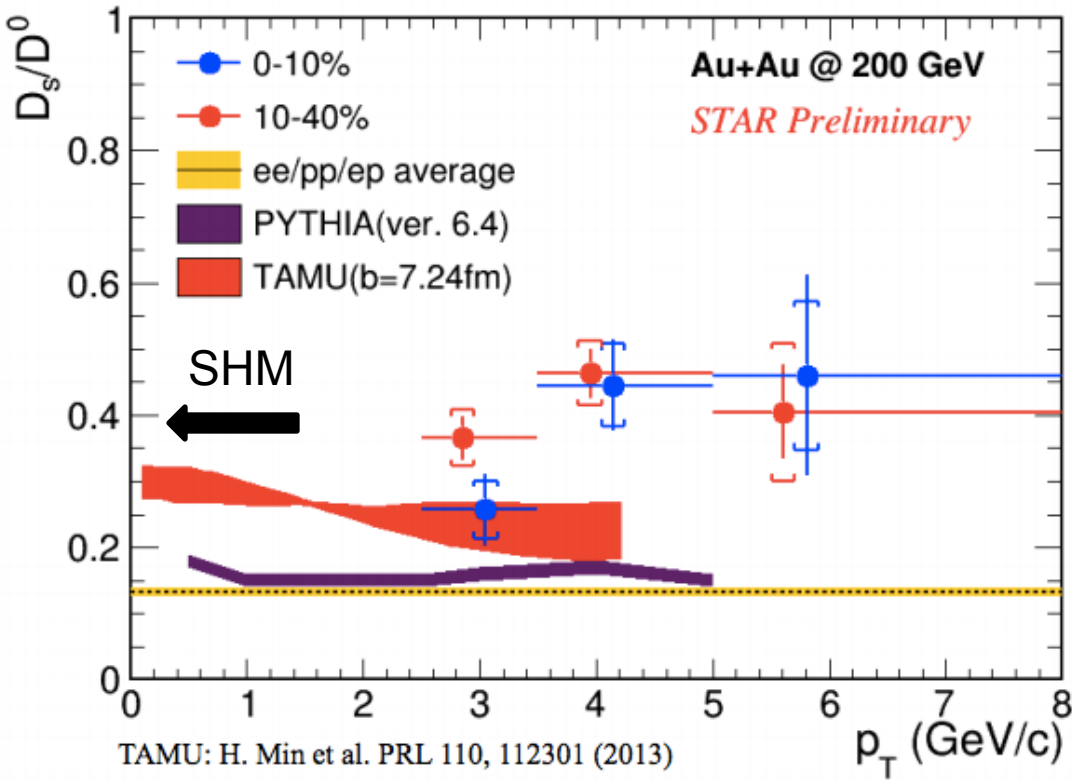
Charm Azimuthal Anisotropy

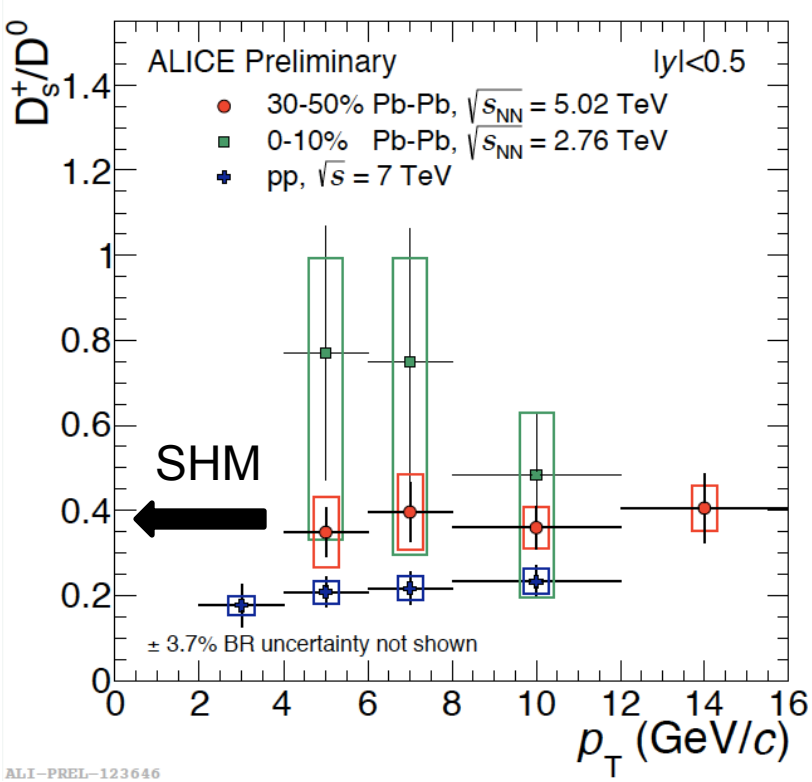




- Significant D^0 v_2 – mass ordering at low p_T
- Low p_T D^0 v_2 follows NCQ scaling – charm quark flows
- Low p_T D^0 v_2 described by 3D hydro – charm quark thermalization
- High p_T D^0 v_2 describe by LBT/CUJET – path length dependent E-loss

Charm Quark Hadronization – D_s/D^0



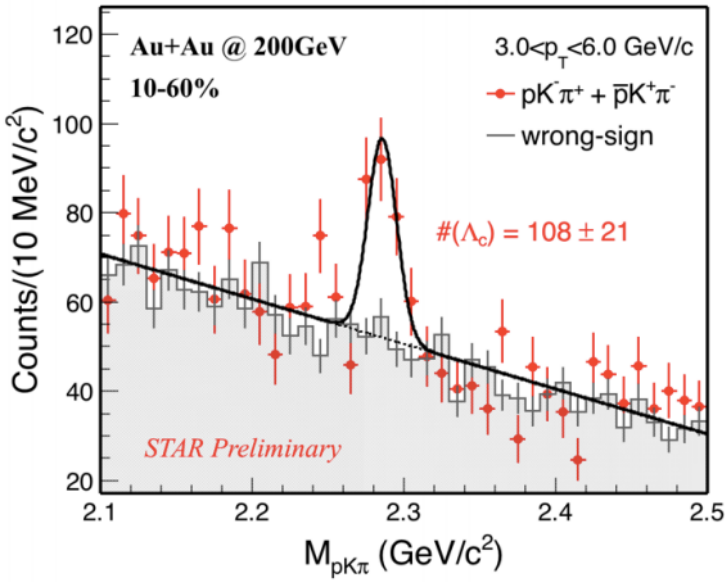


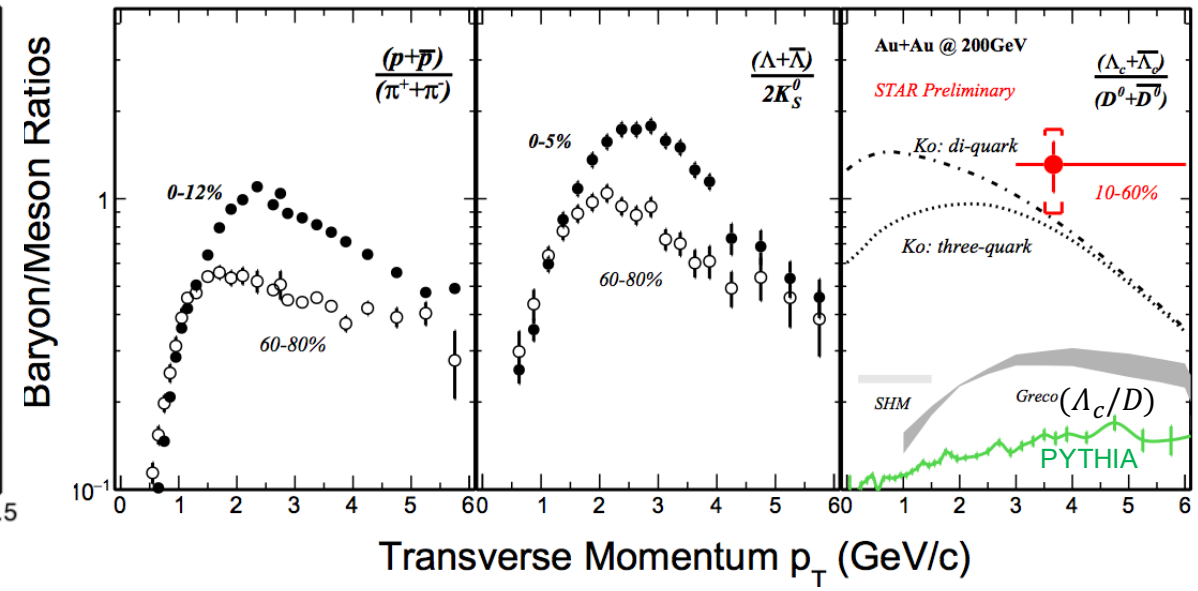
D_s/D^0 ratio in Au+Au 200 GeV, Pb+Pb 2.76 and 5.02 TeV collisions significantly larger than that in p+p – charm quark coalescence

- higher than TAMU prediction
- consistent with SHM prediction (0.35-0.4)

Zhenyu Ye

Charm Quark Hadronization - Λ_c/D^0



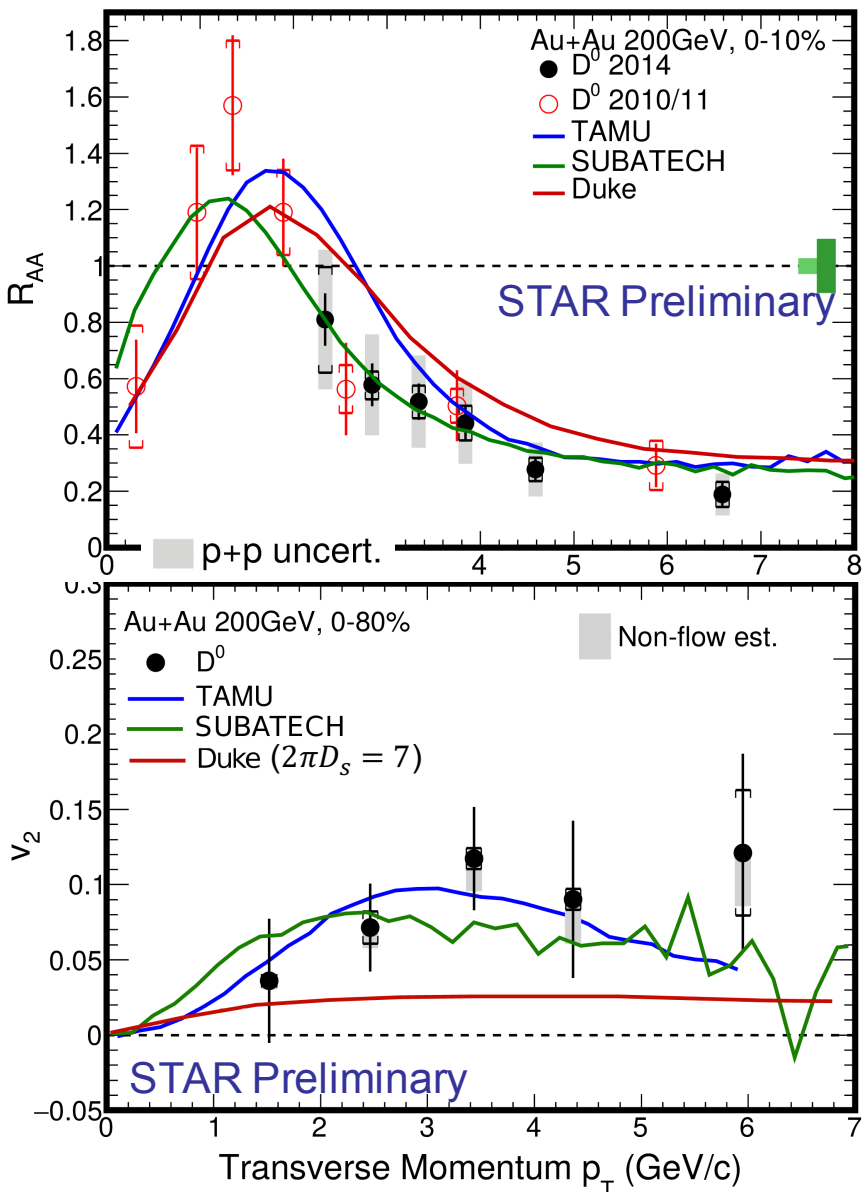


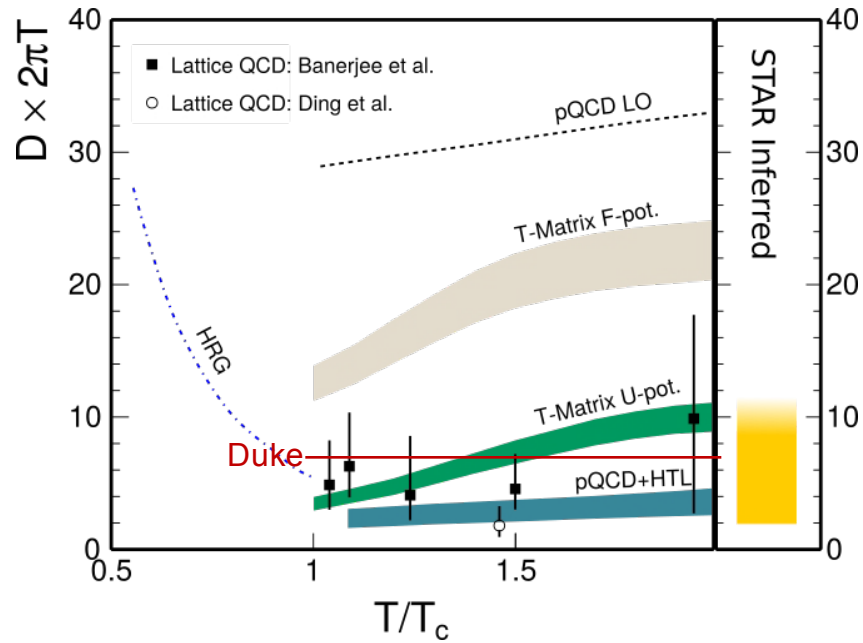
Ko: PRL 100 222301 (2008), PRC 79 (2009) 044905
Greco: PRD 90 054018 (2014)

Λ_c/D^0 ratio in Au+Au 200 GeV collisions significantly larger than in p+p – charm quark coalescence

- Similar level as p/π and Λ/K ratios
- Consistent with Ko predictions with thermalized charm quark coalescence

Towards Extracting QGP Properties





Models with charm diffusion coefficient of 2-12 describe D^0 R_{AA} and v_2 results. Lattice calculations are consistent with values inferred from data.

STAR D^0 2010/11: PRL 113 (2014) 142301
Theory curves: latest calculations from private communications
DUKE: PRC 92 (2015) 024907
A.Andronic arXiv:1506.03981(2015)

Zhenyu Ye

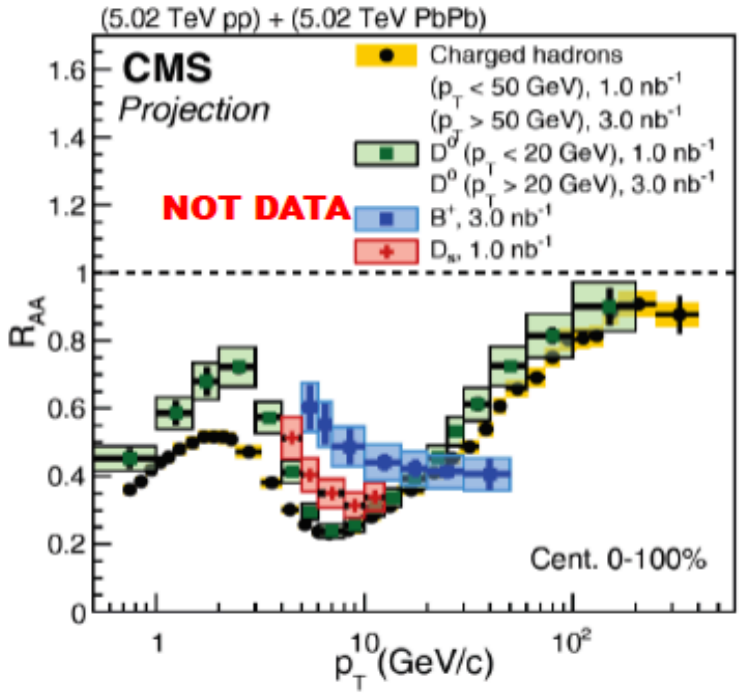
Summary and Outlook

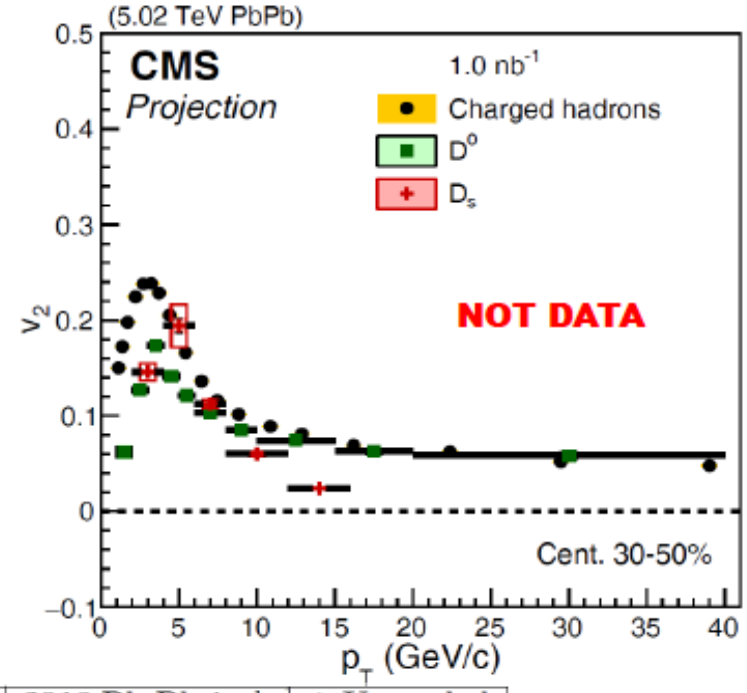
- **Mass hierarchy of parton energy loss $\Delta E_b < \Delta E_c$**
  - ✓ **supported by R_{AA} measurements at intermediate p_T**
  - **no evidence at high p_T yet**
- **Heavy quark thermalization with the QGP medium**
  - ✓ **supported by low p_T v_2 measurements for charm quarks**
  - **no precise experimental result for bottom quarks yet**
- **Heavy quark hadronization**
  - ✓ **charm quark coalescence supported by D_s/D^0 and Λ_c/D^0**
  - **no experimental result for bottom quarks yet**

- **Future directions – with upgrades at RHIC/LHC**
  - **Extend the measurements to lower (LHC) and higher p_T (RHIC)**
  - **Improve the precision on bottom measurements**
  - **HF correlations: $D-\bar{D}$, $D-h$, $J/\psi-h$ …**
  - **Extracting QGP properties (together with theoretic friends)**

Zhenyu Ye

Projected Performance in 2018 – Run III



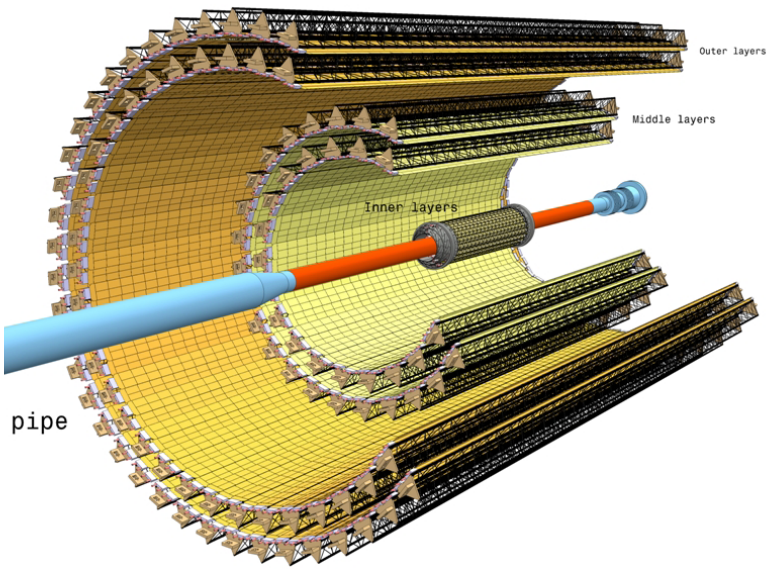


	Current 0.04 nb^{-1} + Present System		2018 Pb-Pb 1 nb^{-1} + Upgraded System	
Observables	p_T min	Statistical Uncertainty	p_T min	Statistical Uncertainty
$D^0 R_{AA}$	2	15%	0.5 - 1	10%
$D_s R_{AA}$	~ 4	20%	< 4	4%
$\Lambda_c R_{AA}$	10	$> 20\%$	< 10	4%
$B \to D R_{AA}$	6	20%	2	10%
$B^+(D^0\pi) R_{AA}$	Not accessible		~ 4	
Low p_T c and b jets	Not accessible		~ 30	
$D^0 v_2$ ($= 0.06$)	1	80%	0.5 - 1	18%
$D_s v_2$	Not accessible		~ 4	
$B \to D v_2$	Not accessible		~ 2	
$\Lambda_c v_2$	Not accessible		~ 6	

From Yen-Jie Lee HF workshop yesterday

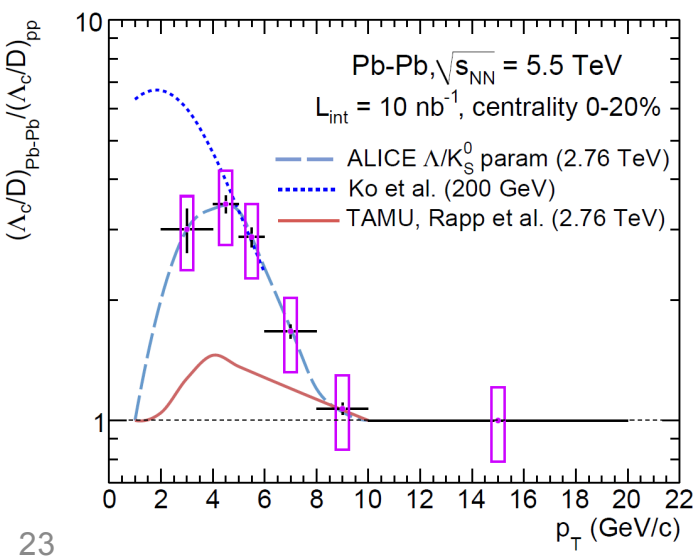
(Yen-Jie's gestimation)

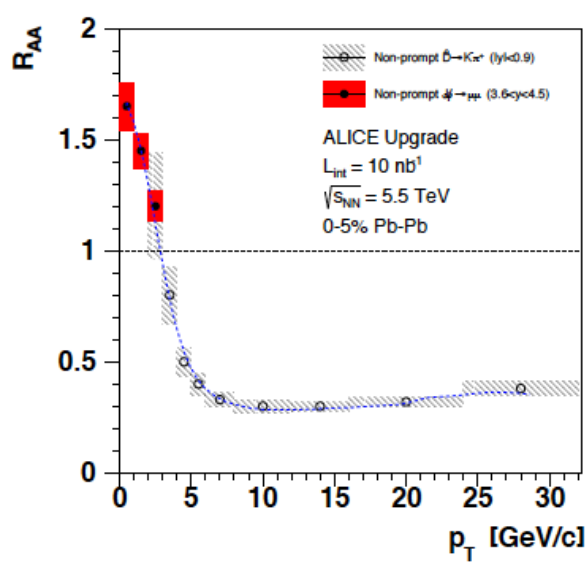
ALICE Upgraded ITS (2021-2023)

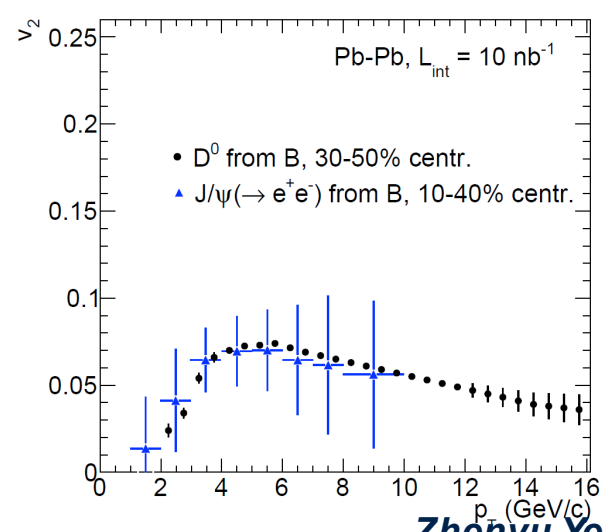


Improve impact parameter resolution by a factor of ~3

- Smaller beam pipe (R = 1.9 cm)
- Inner layer as close as possible (R = 2.2 cm)
- Thinner beam pipe (ΔR = 800 μm)
- Less material budget: thin sensors, 7 layers of monolithic pixel detectors (goal: 0.3% X_0 for inner layers, 0.8% X_0 for outer layers)
- Smaller pixel size: ≈ 28×28 μm² for the inner layers

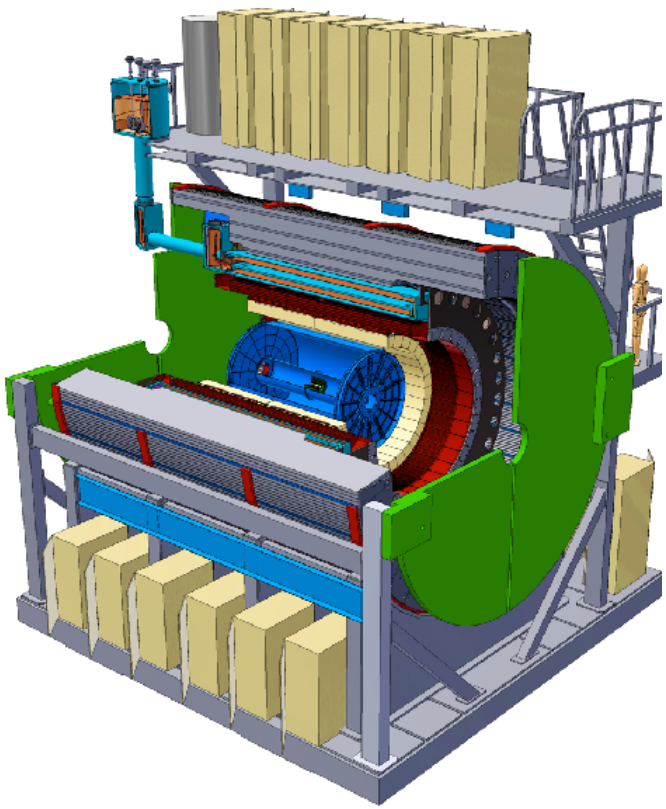


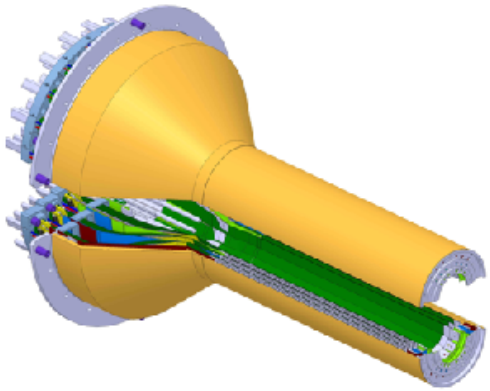


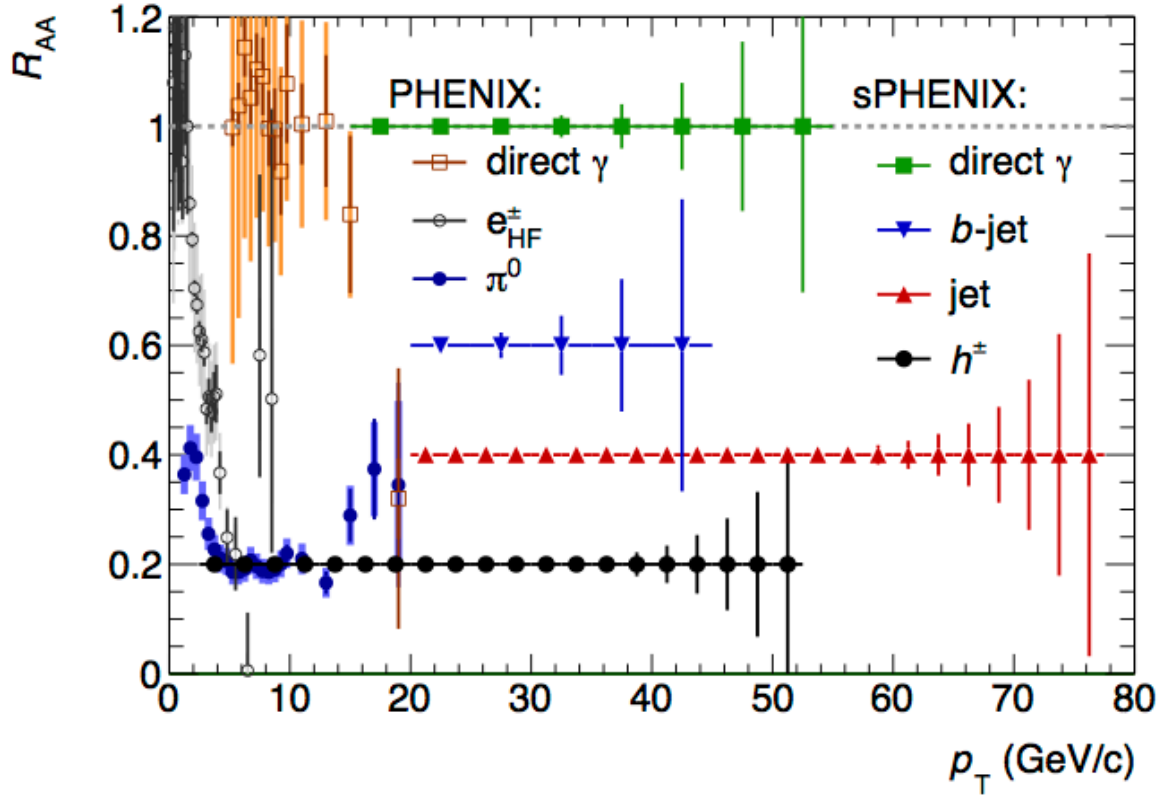


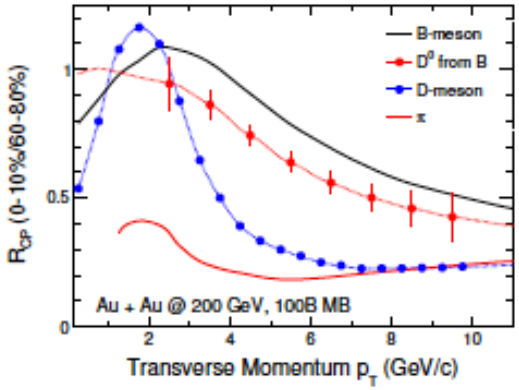
Zhenyu Ye

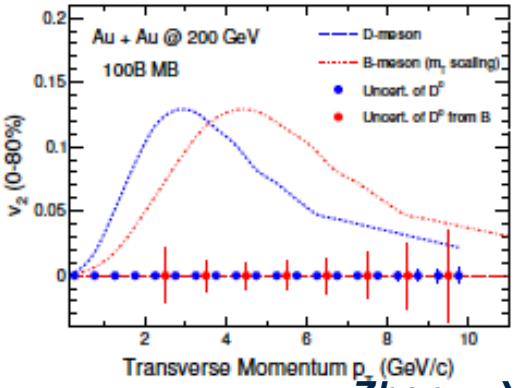
sPHENIX MVTX (2022-2026)







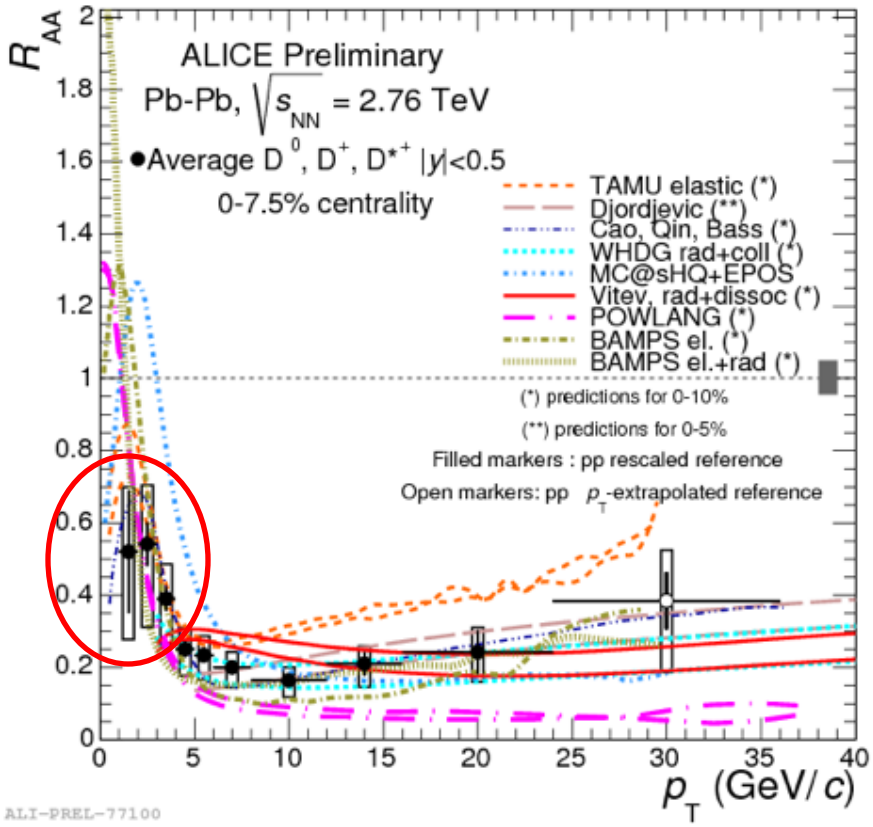


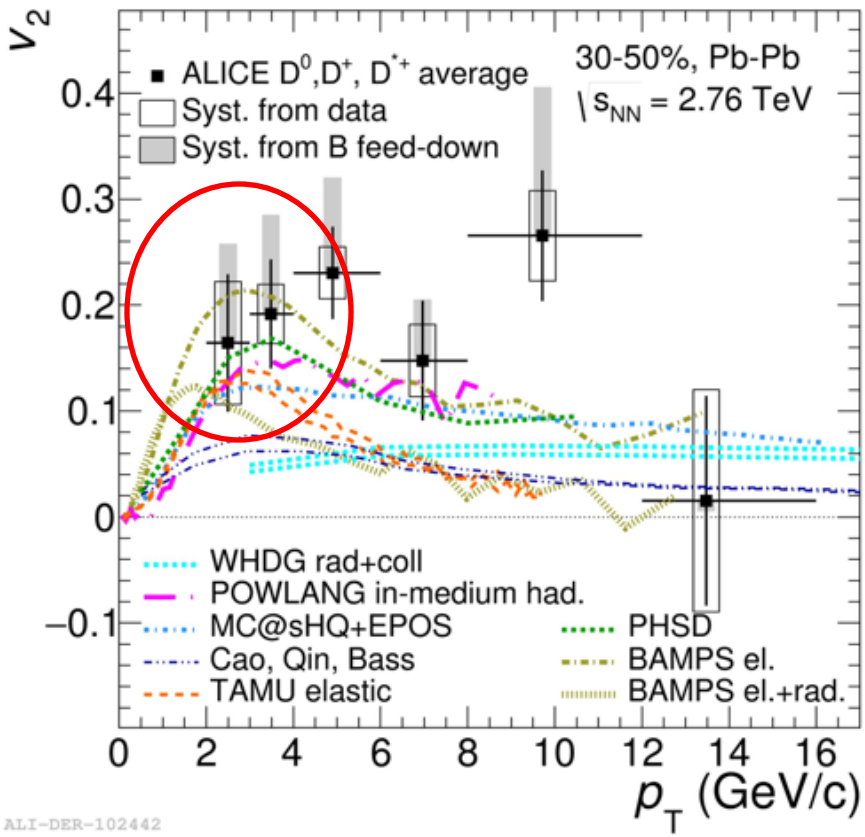


Zhenyu Ye

Backup

Open Charm in A+A collisions at LHC



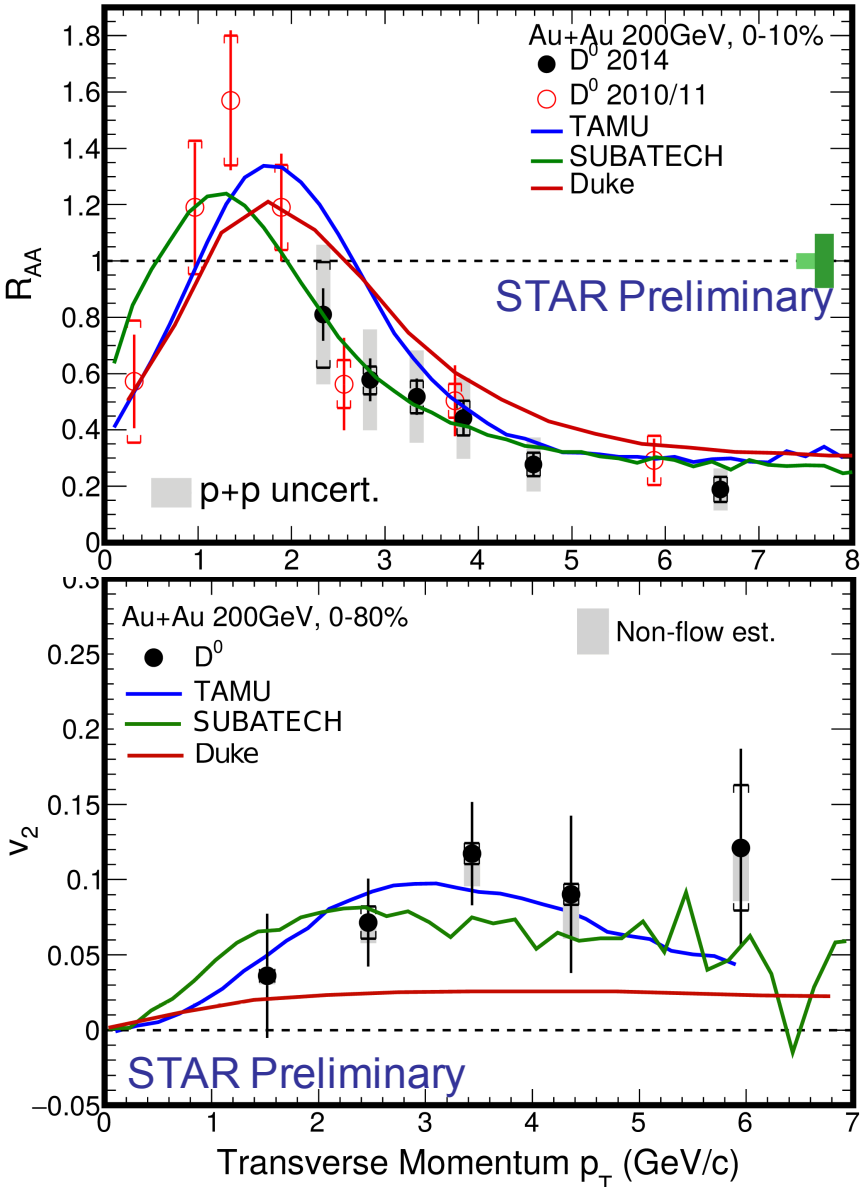


D^0 R_{AA} and v_2 can discriminate among different models:

- hints at low p_T that collisional energy loss is non negligible
- shadowing improve description of the R_{AA} data at low p_T

Zhenyu Ye

Open Charm in A+A collisions at RHIC



TAMU: non-perturb. T-matrix
$(2\pi T)D = 3\text{-}11$

SUBATECH: perturb.+resummation
$(2\pi T)D = 2\text{-}4$

DUKE: Langevin simulation with input parameter tuned to the LHC data
$(2\pi T)D = 7$

	$D \times 2\pi T$	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

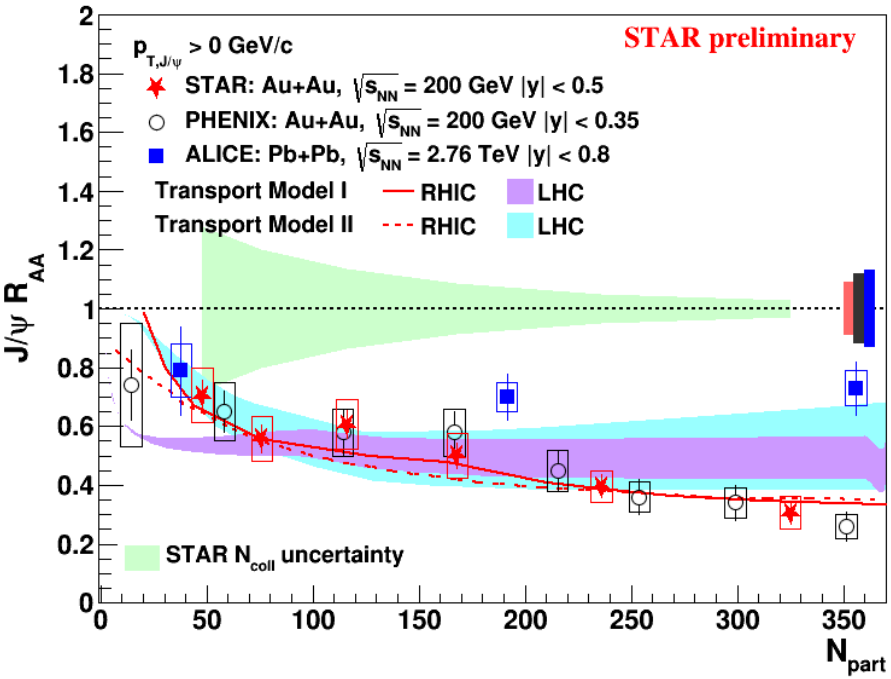
STAR D^0 2010/11: PRL 113 (2014) 142301
Theory curves: latest calculations from private communications
DUKE: PRC 92 (2015) 024907
A.Andronic arXiv:1506.03981(2015)

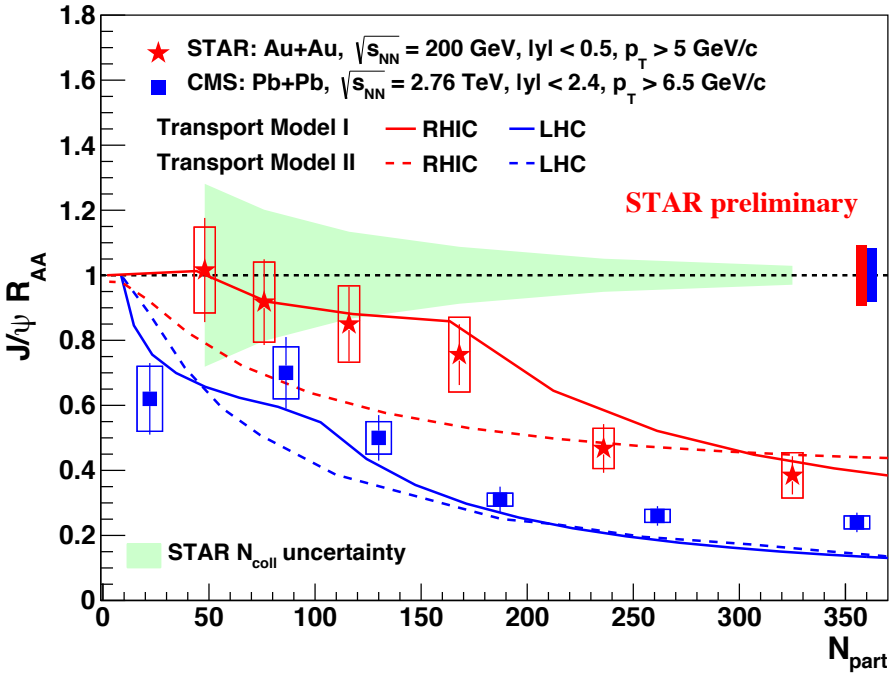
Zhenyu Ye

J/ψ in A+A collisions

ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

Transport model:
Model I at RHIC: PLB 678 (2009) 72
Model I at LHC: PRC 89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114

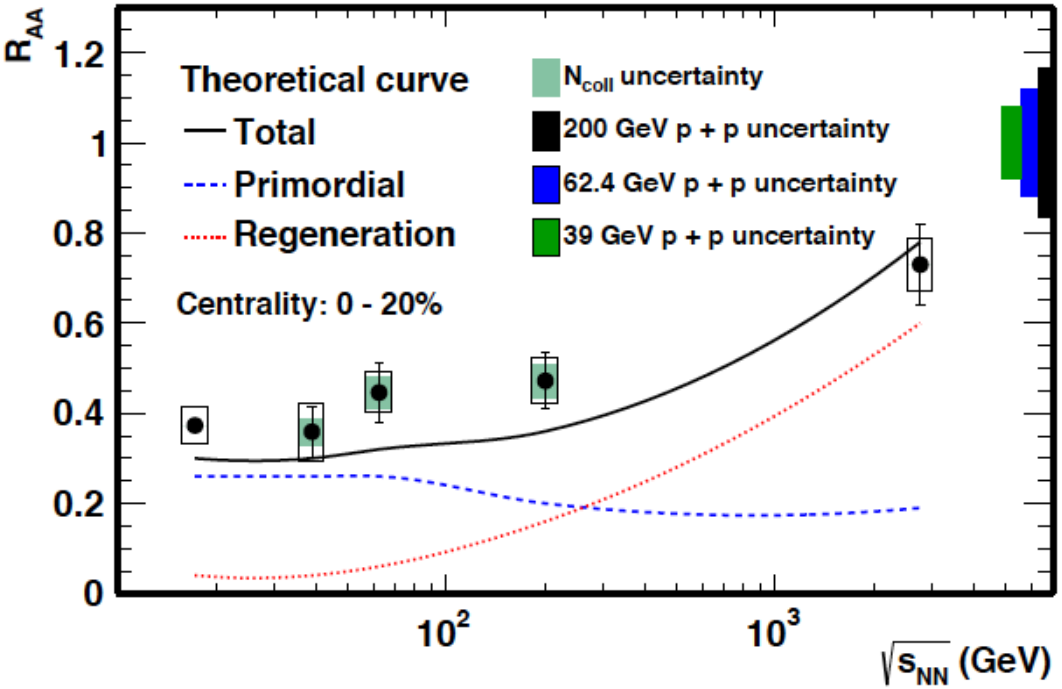


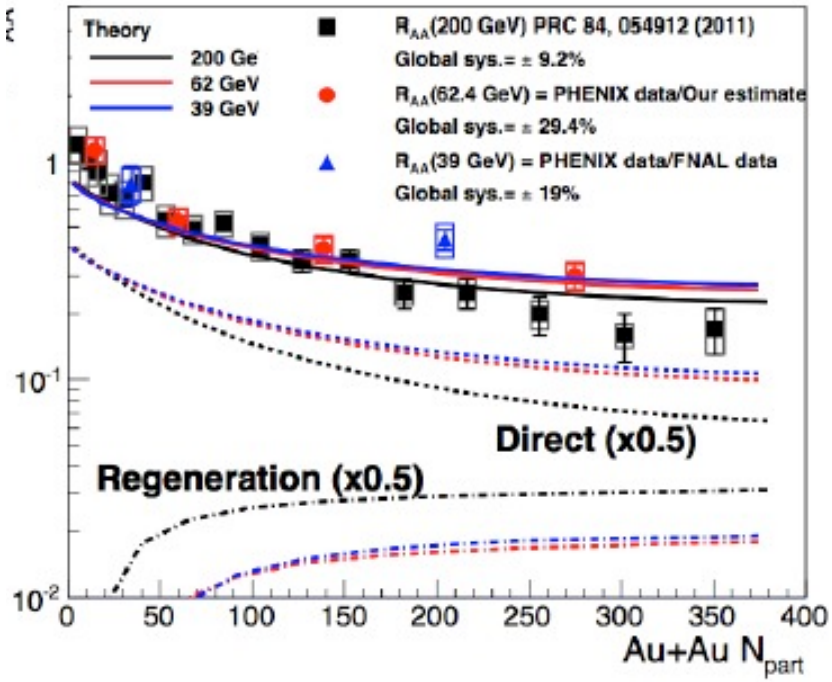


- J/ψ R_{AA} for p_T>0 GeV/c: RHIC is smaller than LHC -> more recombination at LHC
- J/ψ R_{AA} for p_T>5 GeV/c: LHC is smaller than RHIC -> stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe data

Zhenyu Ye

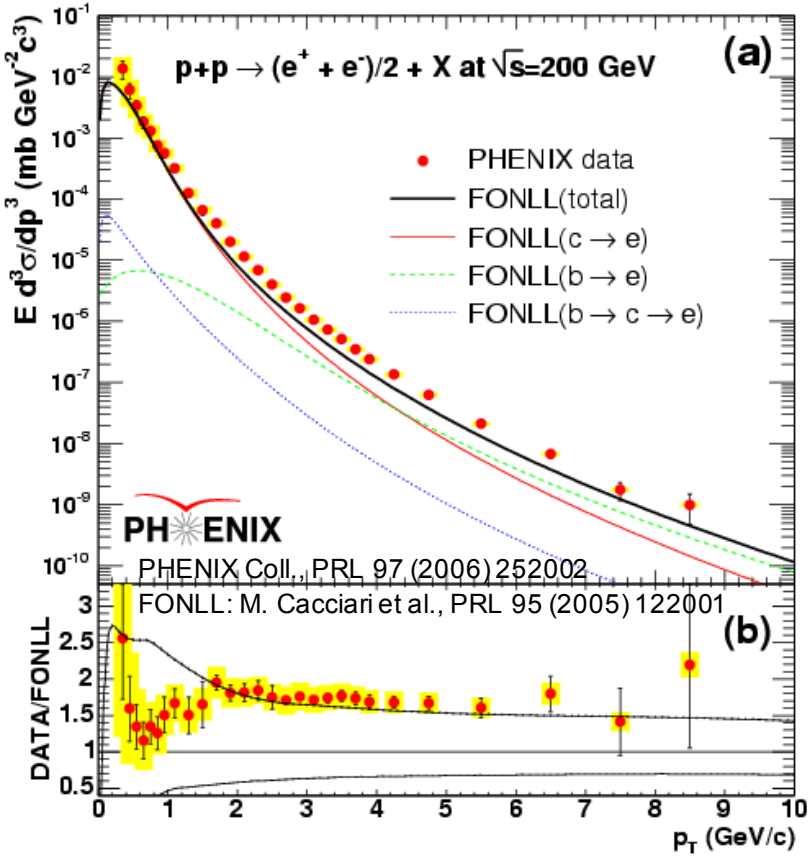
J/ψ in A+A collisions

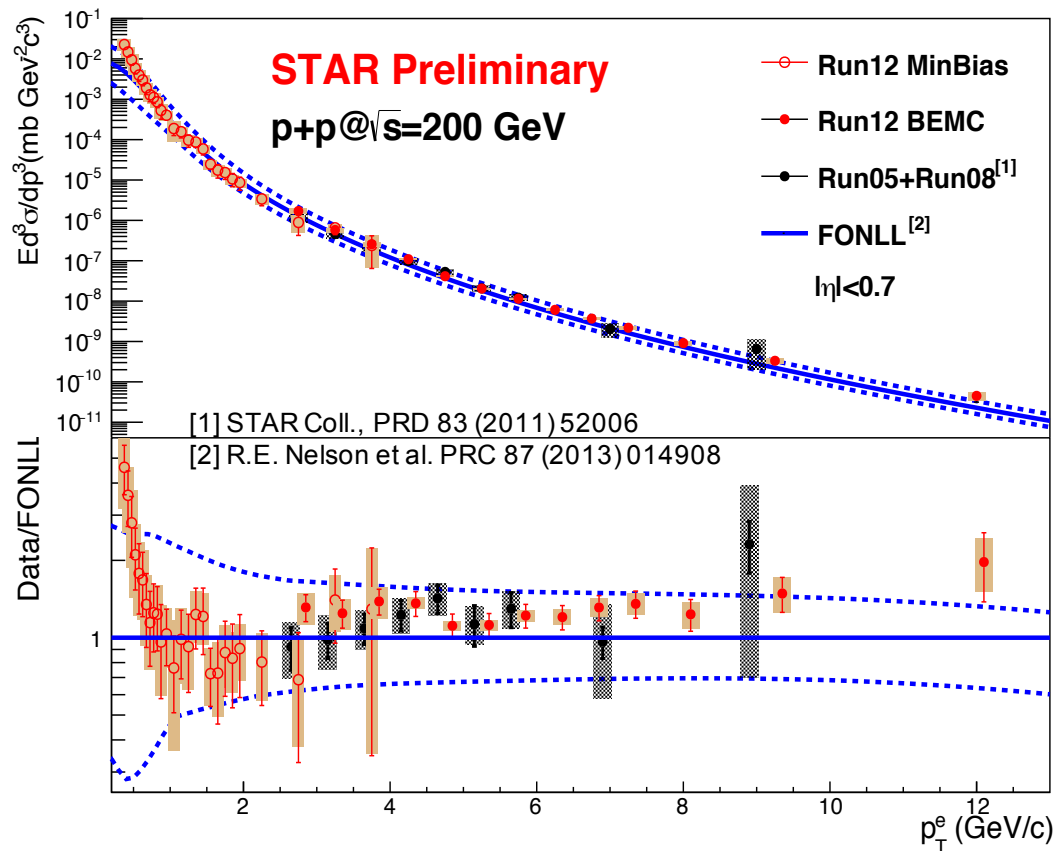




- Collision energy and centrality dependence of J/ψ R_{AA} can be described fairly well by calculations including both color-screening and regeneration effects

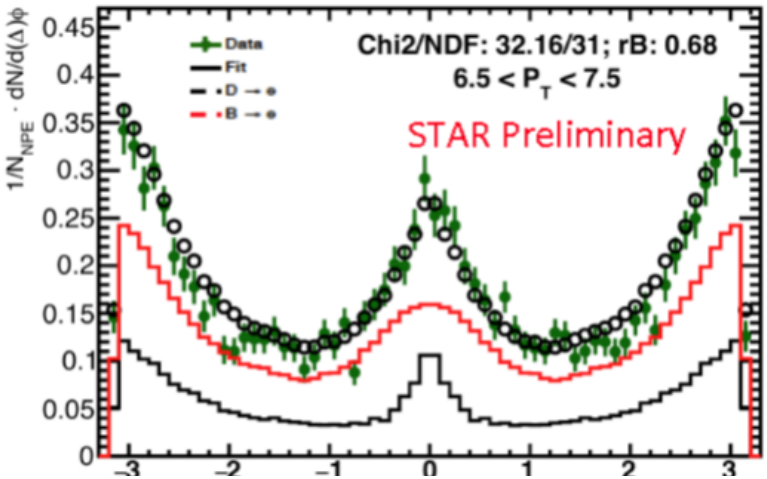
Open HF in p+p – e^{HF}

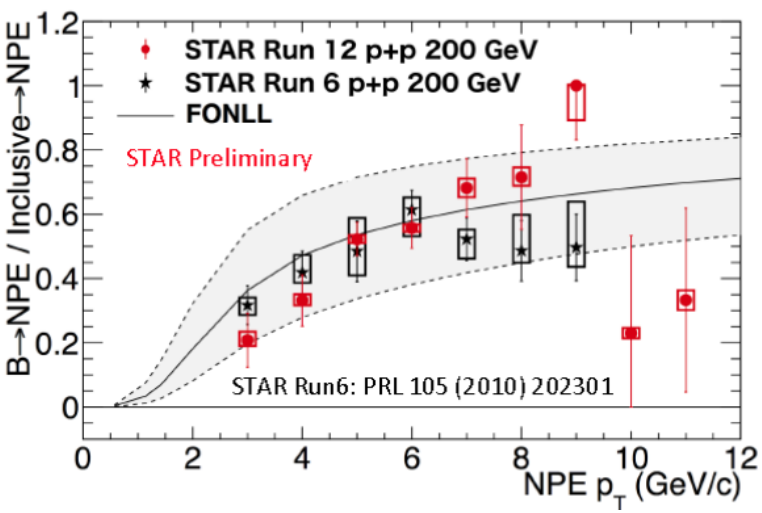


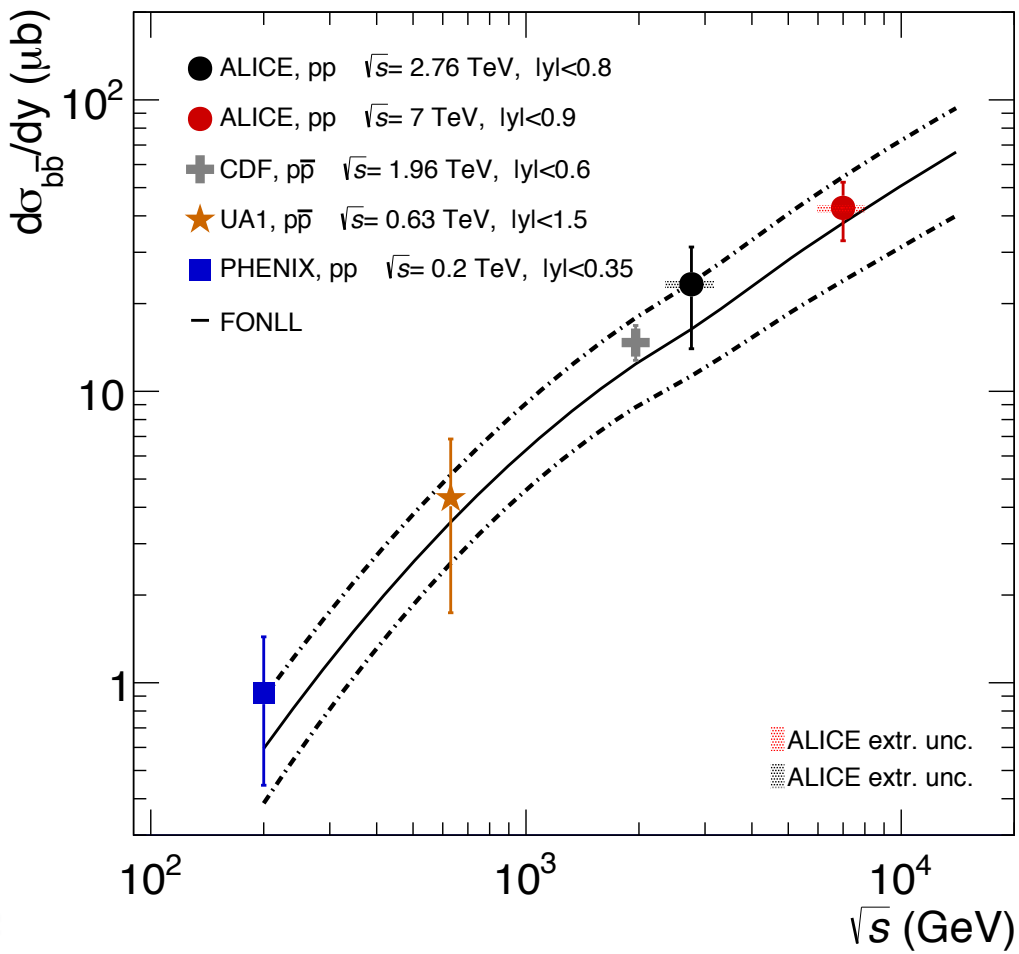


- Production of electrons from open HF decays (e^{HF}) in p+p collisions at RHIC described by pQCD calculations within large theoretical uncertainty

Open HF in p+p – B→ e^{HF}

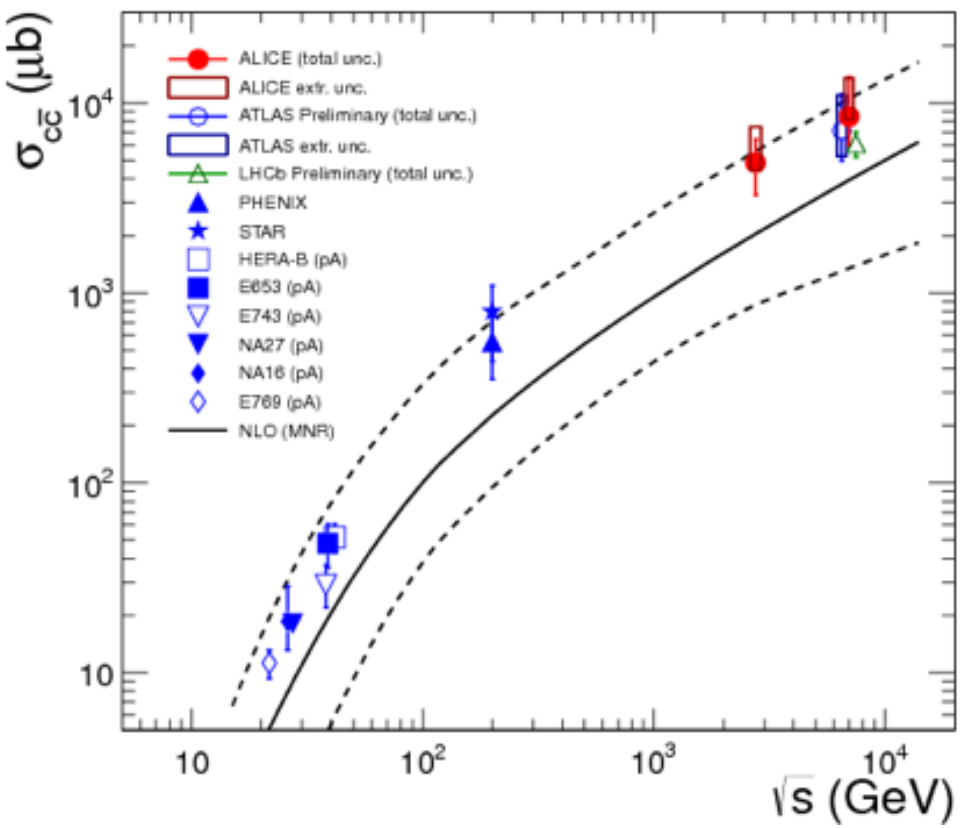


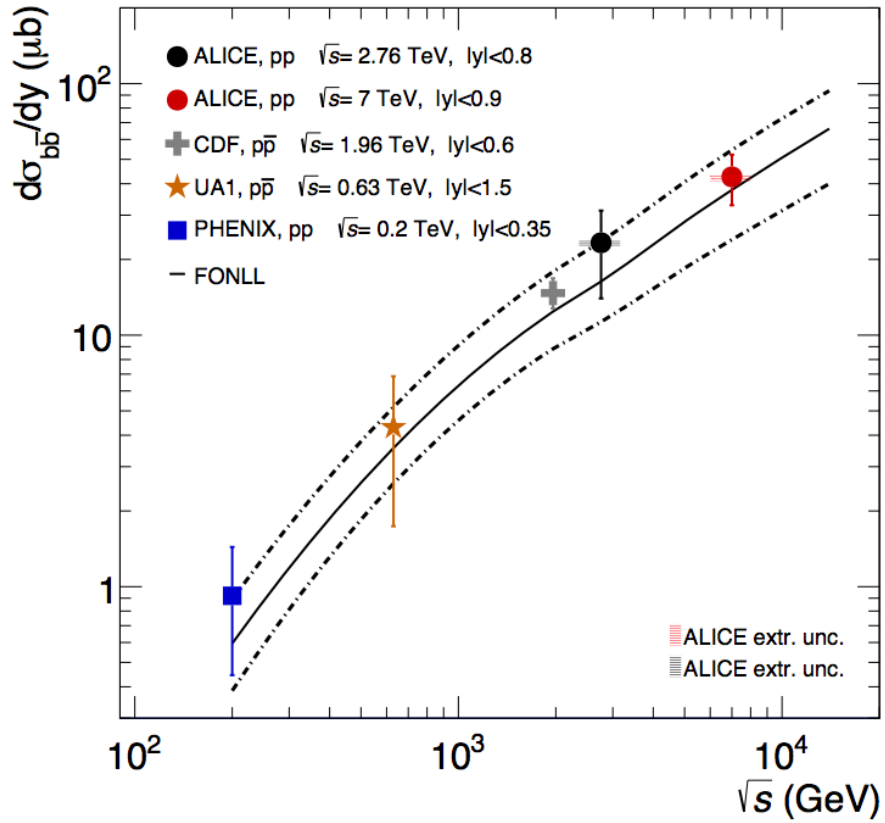




- Indirect measurement of B → e described by pQCD calculations

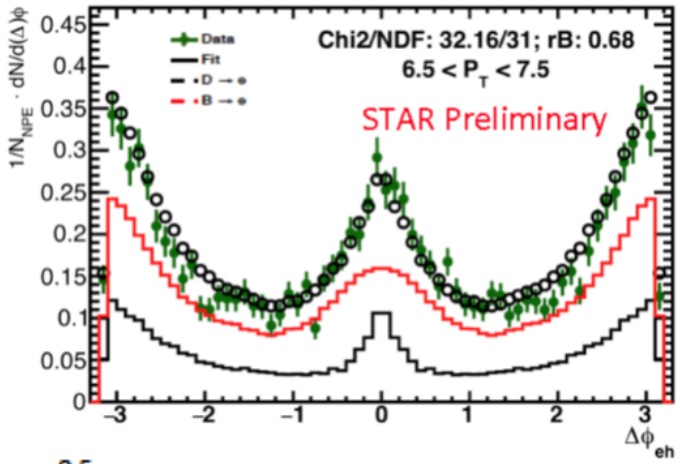
Open HF in p+p collisions

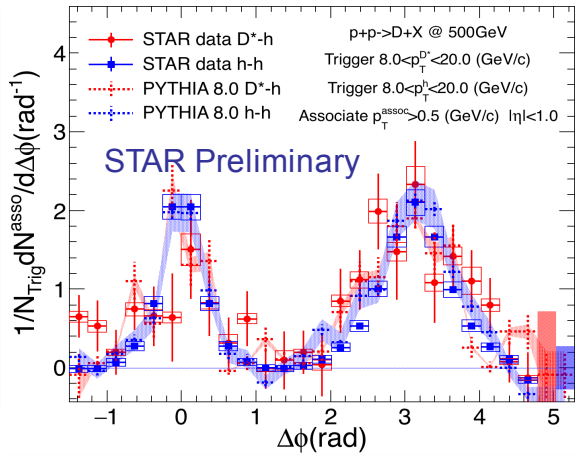


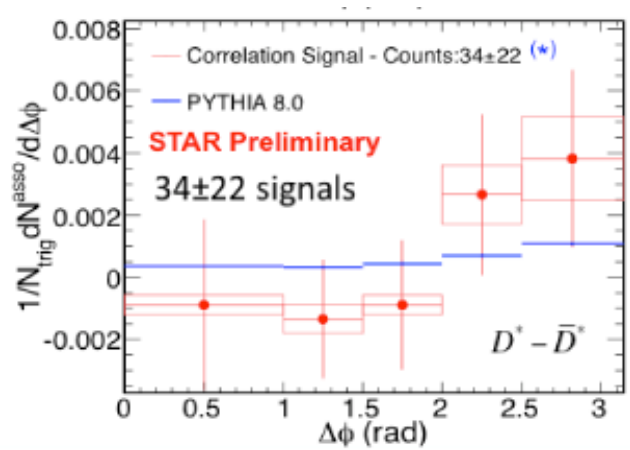


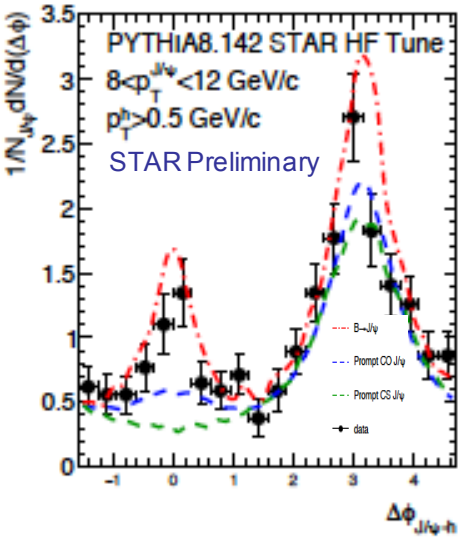
- Charm and Bottom production in p+p collisions are described by pQCD calculations but within large theoretical uncertainty

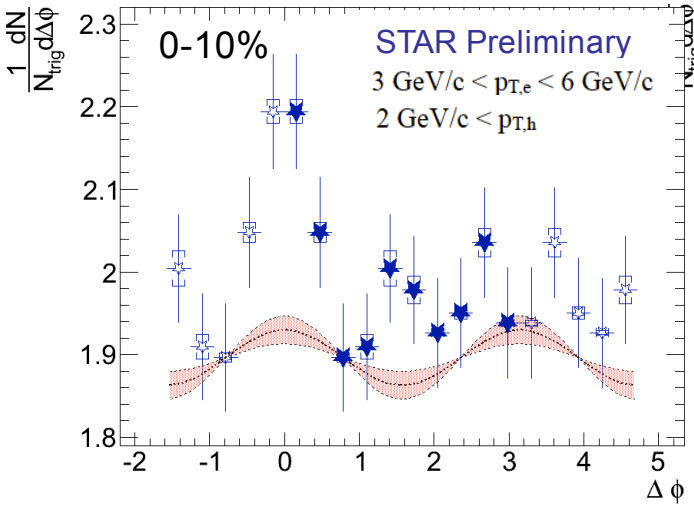
Open HF correlations

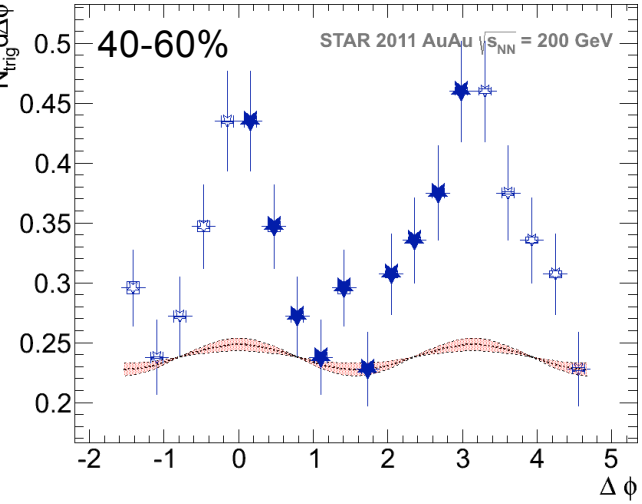






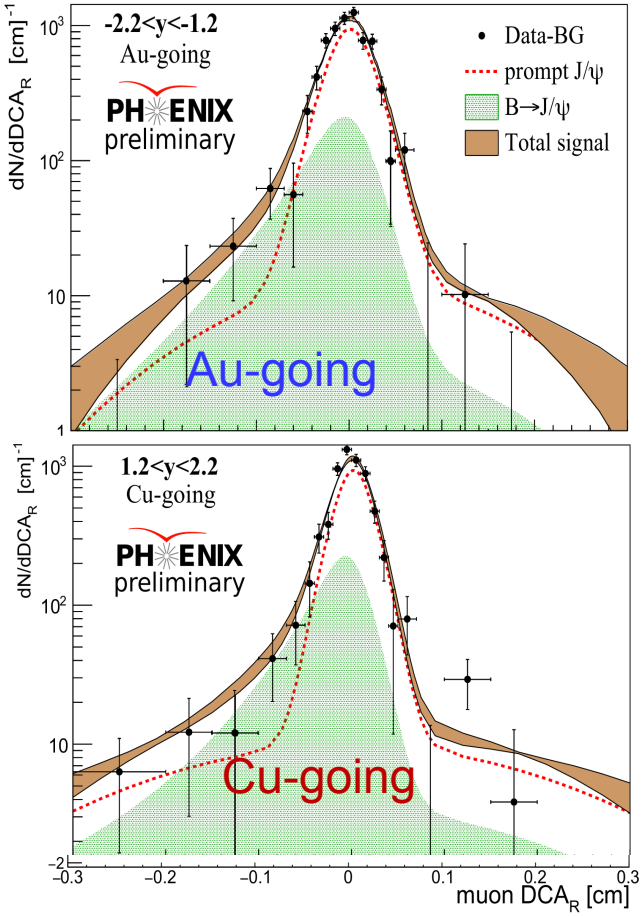


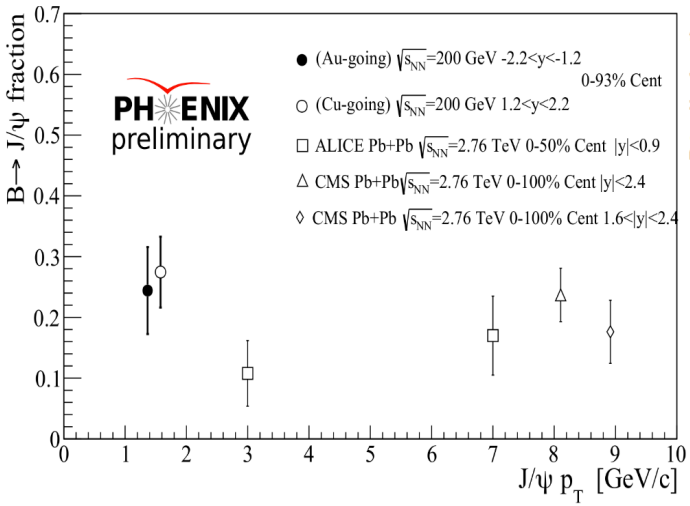


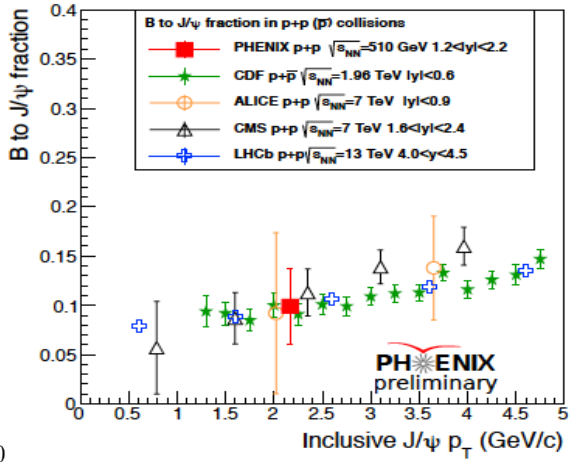


- e^{HF}/D-h in p+p described by PYTHIA8, large uncertainty for $D - \bar{D}$
- Away side suppression e^{HF}-h in 0-10% Au+Au collisions relative to 40-60%

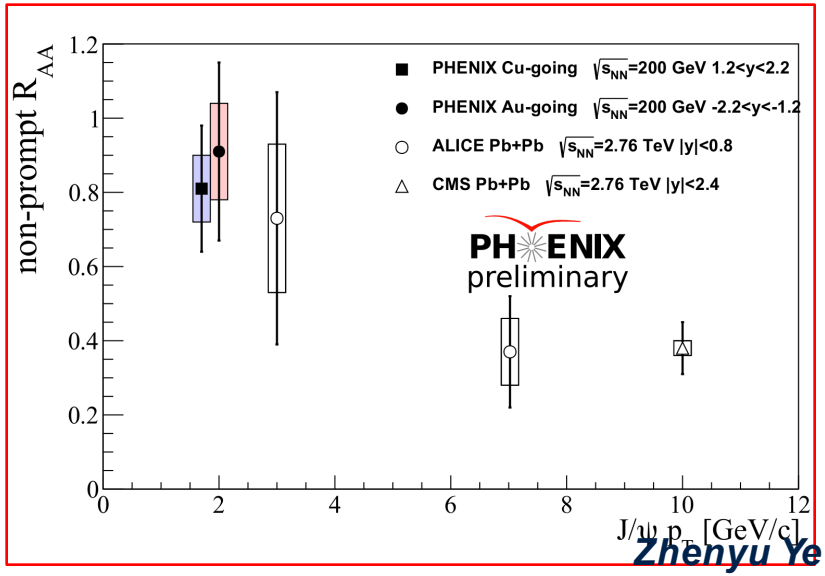
Open HF in Cu+Au – B→J/ψ







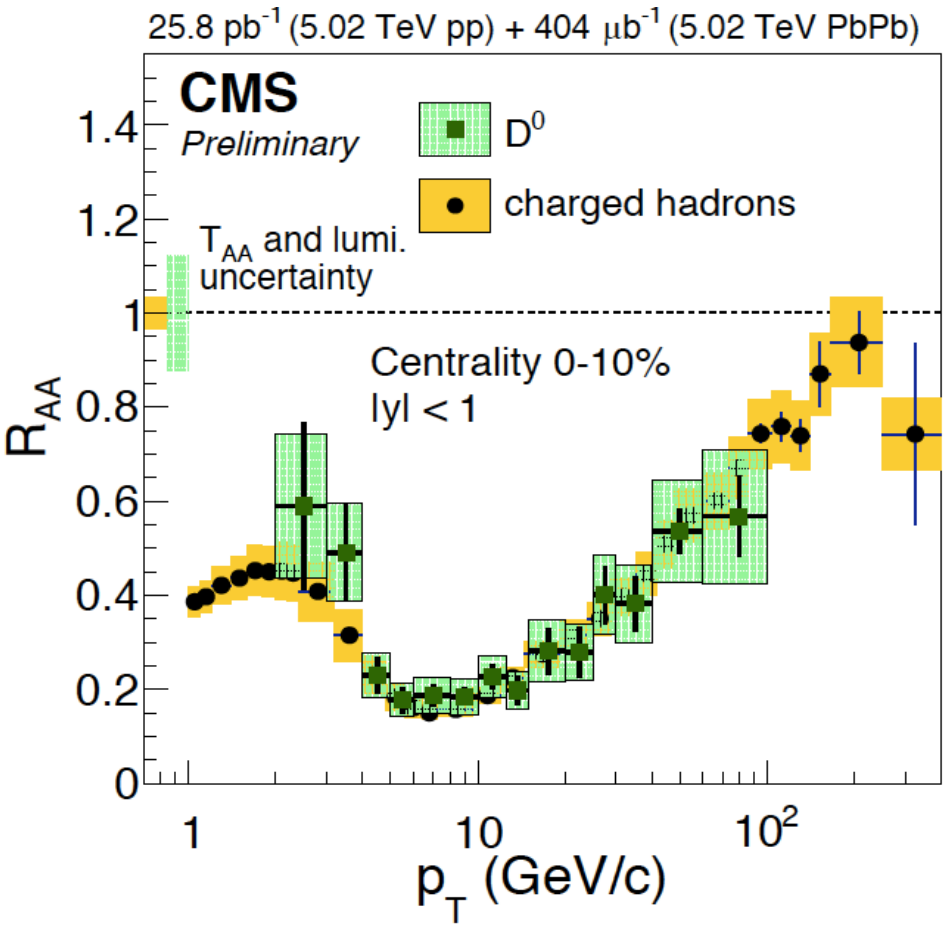
$$R_{CuAu}^{B\to J/\psi} = \frac{F_{B\to J/\psi}^{CuAu}}{F_{B\to J/\psi}^{pp} = 0.1} R_{CuAu}^{inc.J/\psi}$$

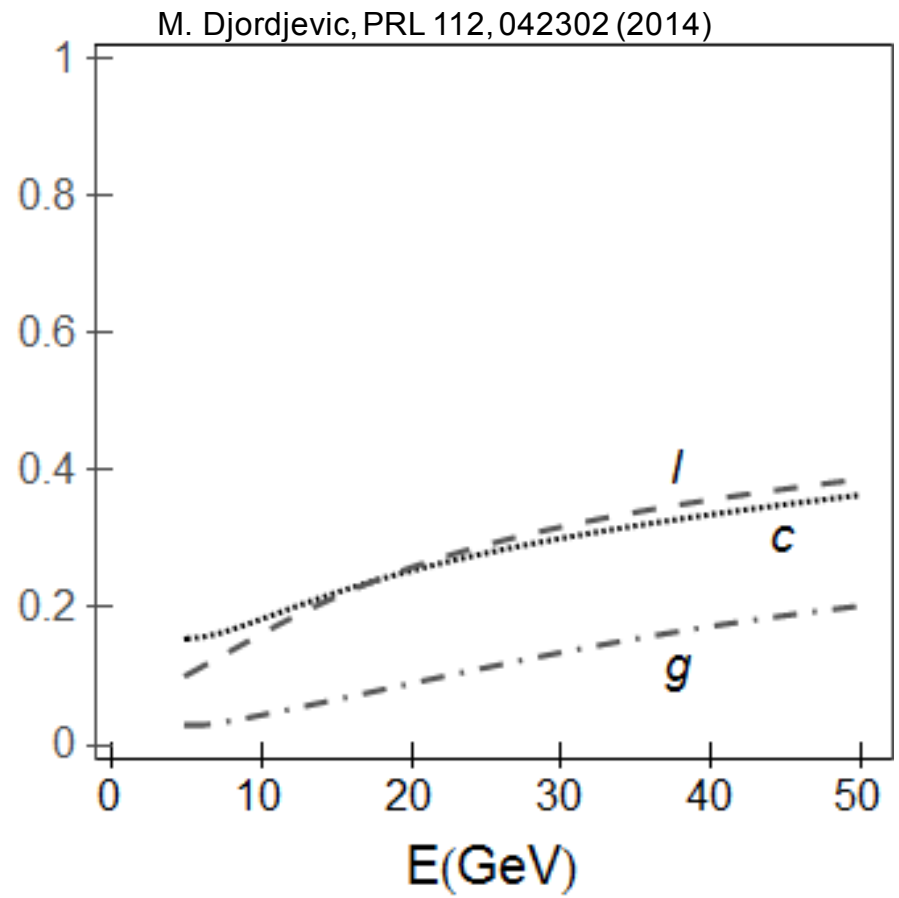


- Hint of larger B→J/ψ fraction in Cu+Au collisions than p+p collisions at 200 GeV
- R_{CuAu} calculated **assuming** B→J/ψ fraction=0.1 in p+p collisions at 200 GeV

Zhenyu Ye

Charm R_{AA} in A+A collisions at LHC

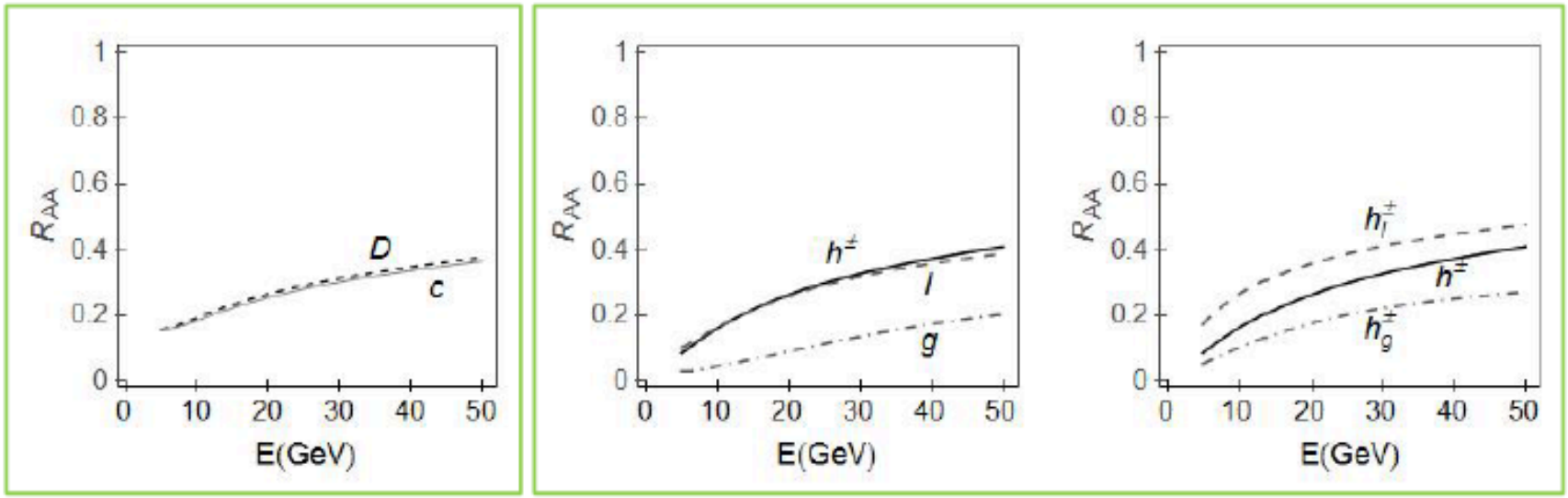




- D^0 R_{AA}<1 for p_T>3 GeV/c - charm quark energy loss
- D^0 and light hadron R_{AA} are consistent for p_T>4 GeV/c, $\Delta E_c < \Delta E_l < \Delta E_g$?

Zhenyu Ye

Charm R_{AA} in A+A collisions at LHC



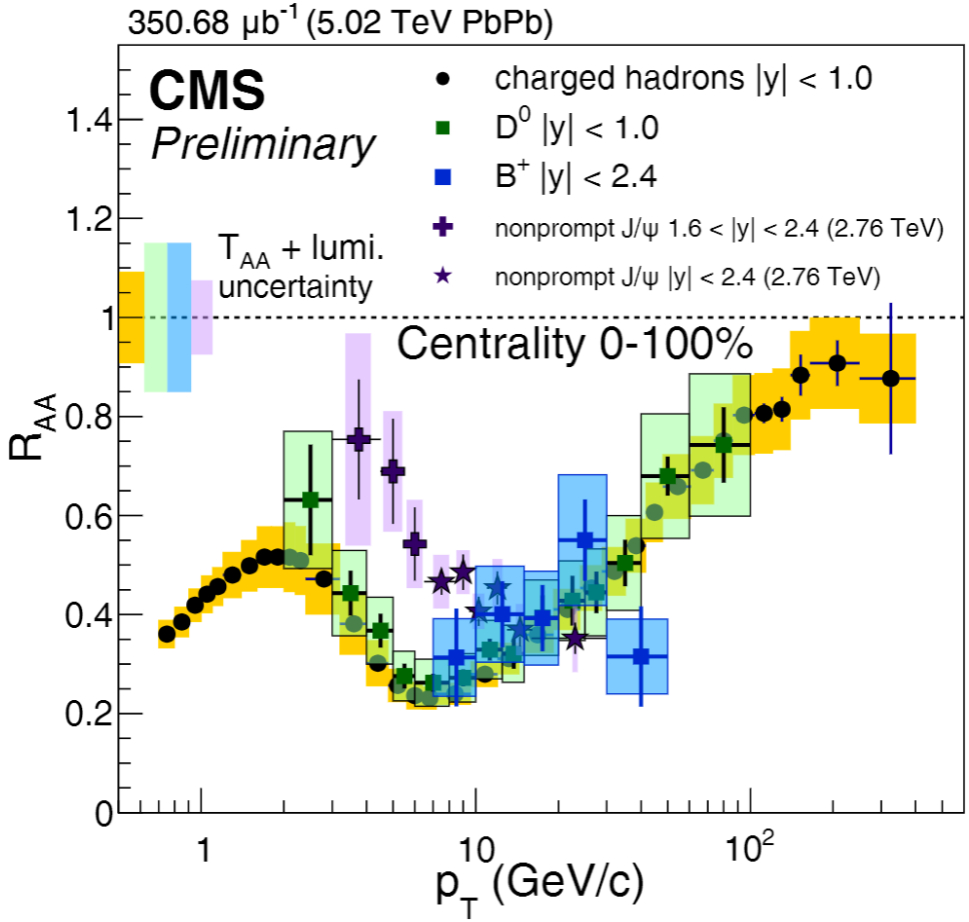
D meson is a genuine probe of bare charm quark suppression

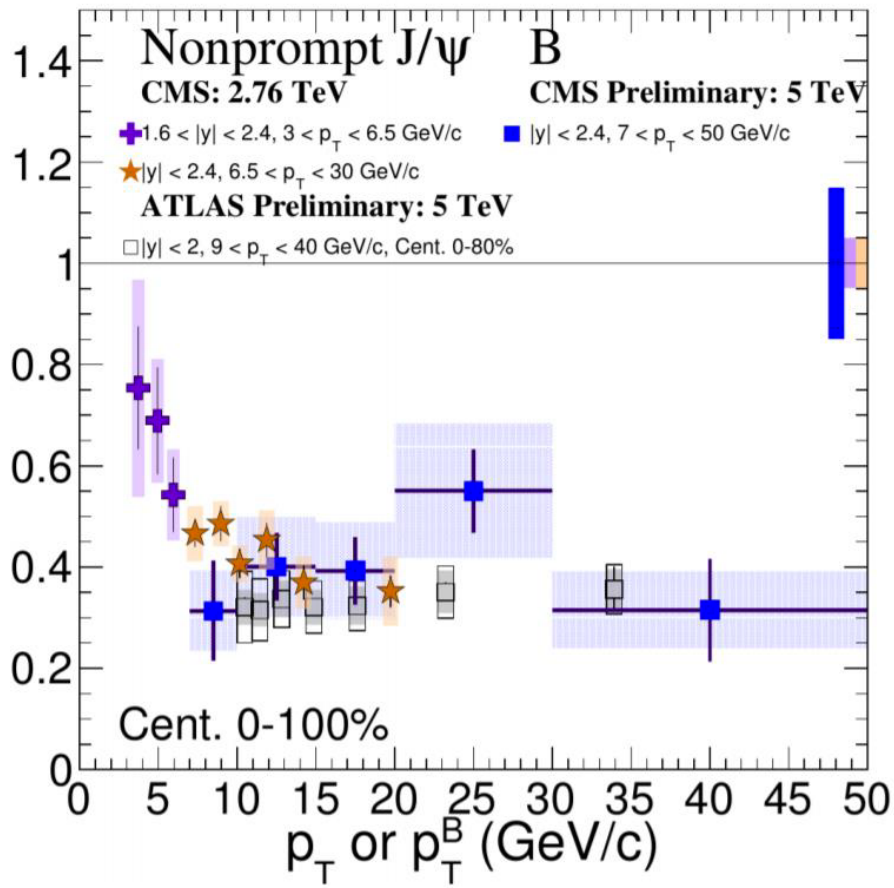
Distortion by fragmentation

Charged hadron R_{AA} = (bare) light quark R_{AA}

M.D., PRL 112, 042302 (2014)

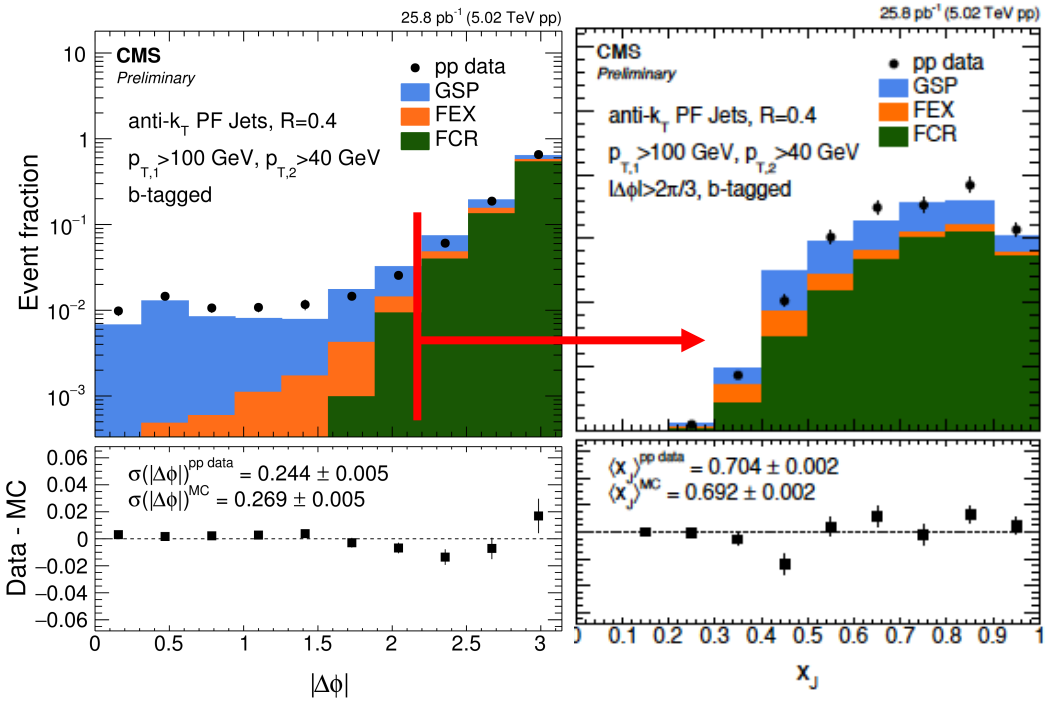
Open Bottom in A+A collisions at LHC

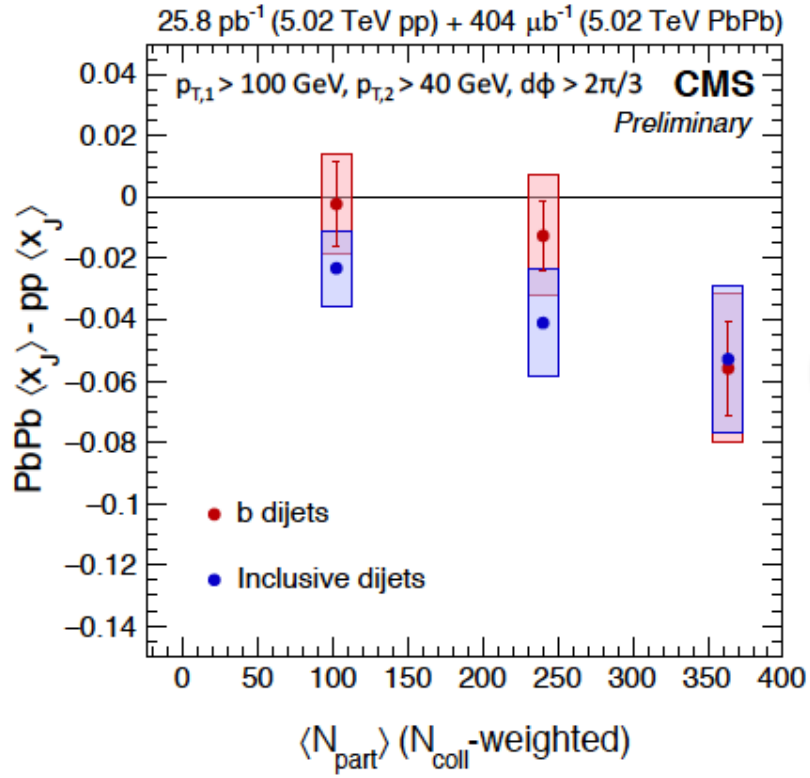


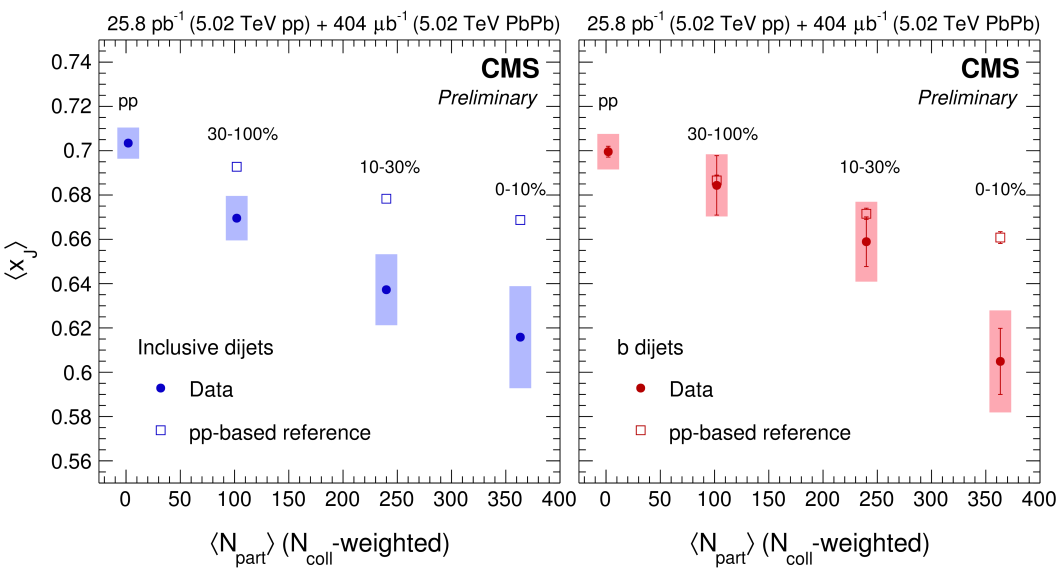


Zhenyu Ye

B-tagged Jets at the LHC







$$x_J = p_{T,2}/p_{T,1}$$

- $\langle x_J \rangle$ modification for back-to-back B-tagged and inclusive di-jets still compatible
  - <20% B-tagged jets from GSP
  - Inclusive jets ~ light/2 + gluon/2

Zhenyu Ye