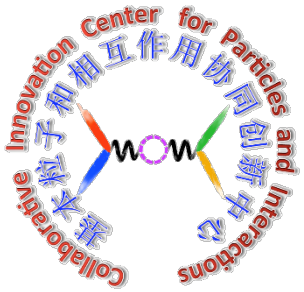
Workshop on STAR Forward Tracking Detector Upgrade and Related Physics
May 7-8, 2019, Shandong University, Qingdao, China

Recent STAR Heavy Flavor Results and Opportunities with STAR Forward Upgrade

Zebo Tang （唐泽波）

State Key Lab. of Particle Detection & Electronics

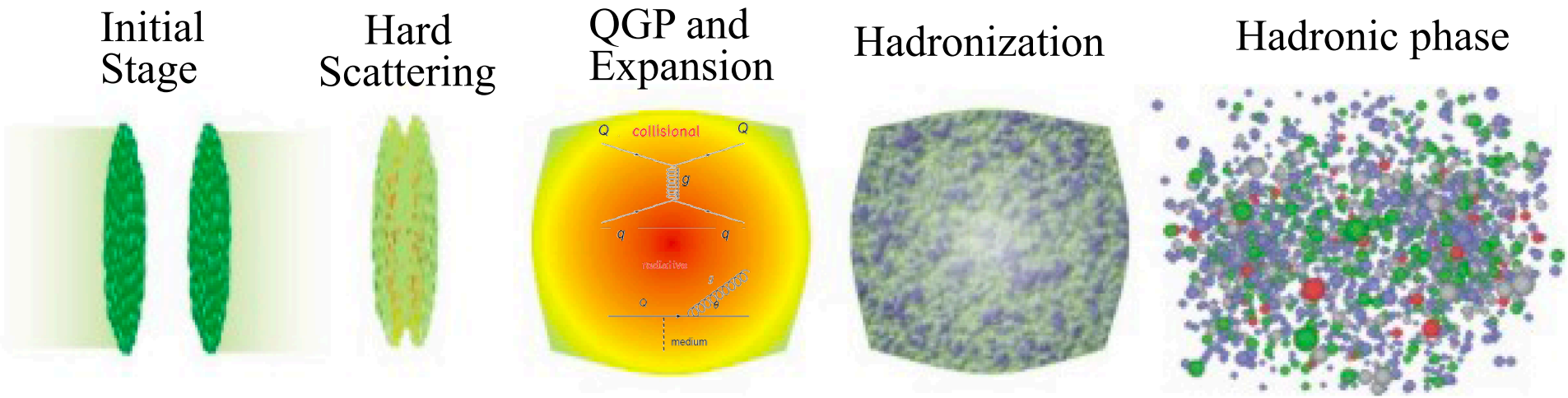
University of Science and Technology of China (USTC)



Outline

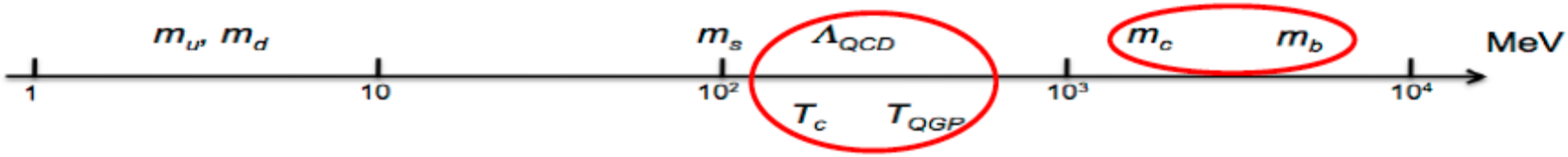
- Open heavy flavor results from STAR HFT
- Quarkonium results from STAR MTD
- Heavy flavor physics with STAR forward upgrades

Why Heavy Flavor?



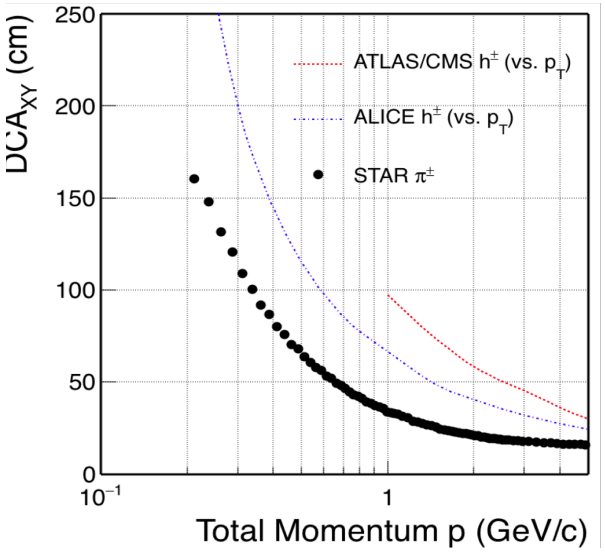
"Heavy" flavor: Penetrating probe of QGP

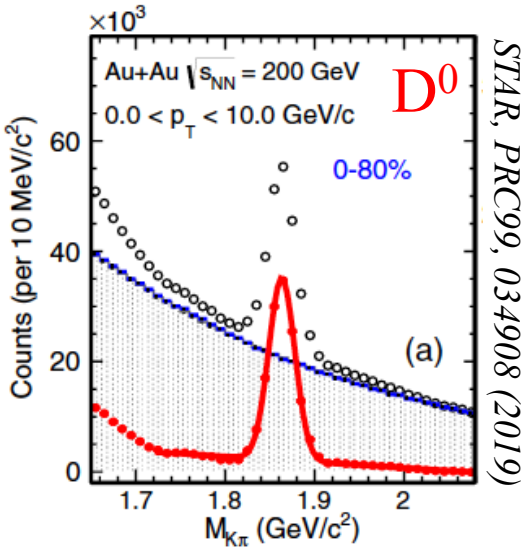
- Dominantly produced at early stage (hard scattering, gluon)
- Calibrated probe calculable in pQCD

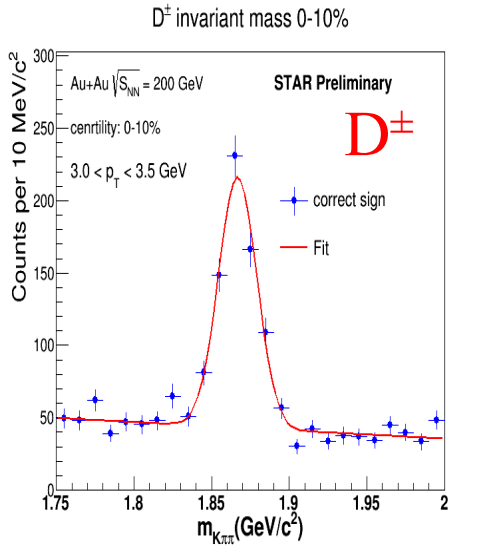


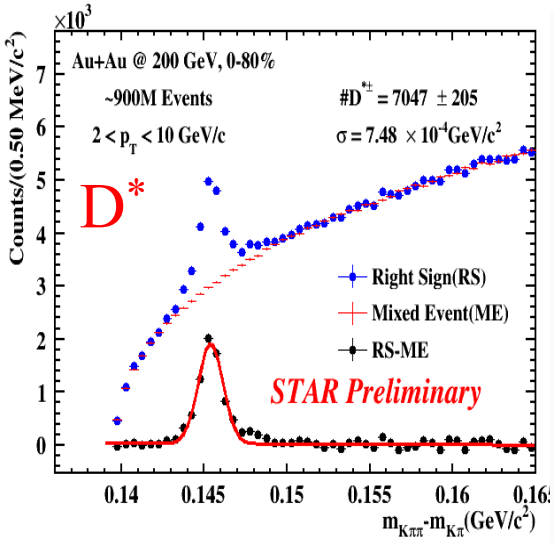
Quarkonium: Deconfinement in QGP (melting and regeneration)

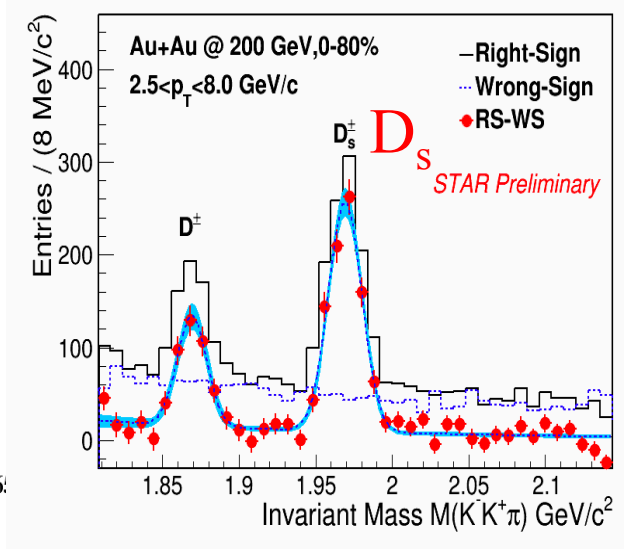
Heavy Flavor Hadron Signals with HFT

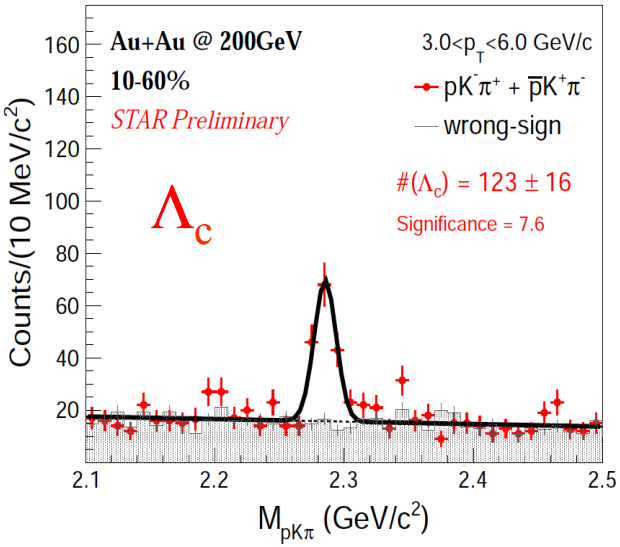






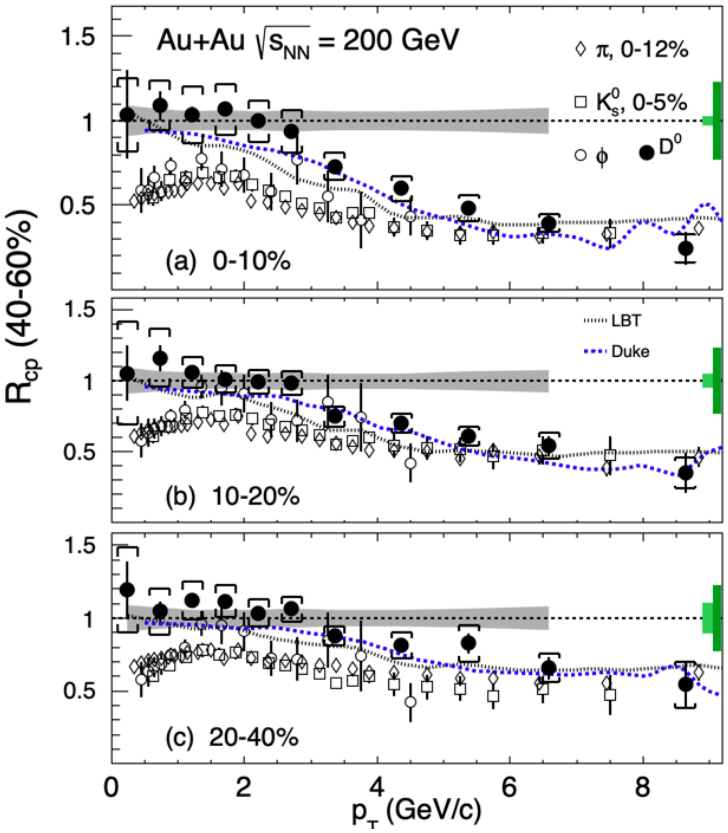


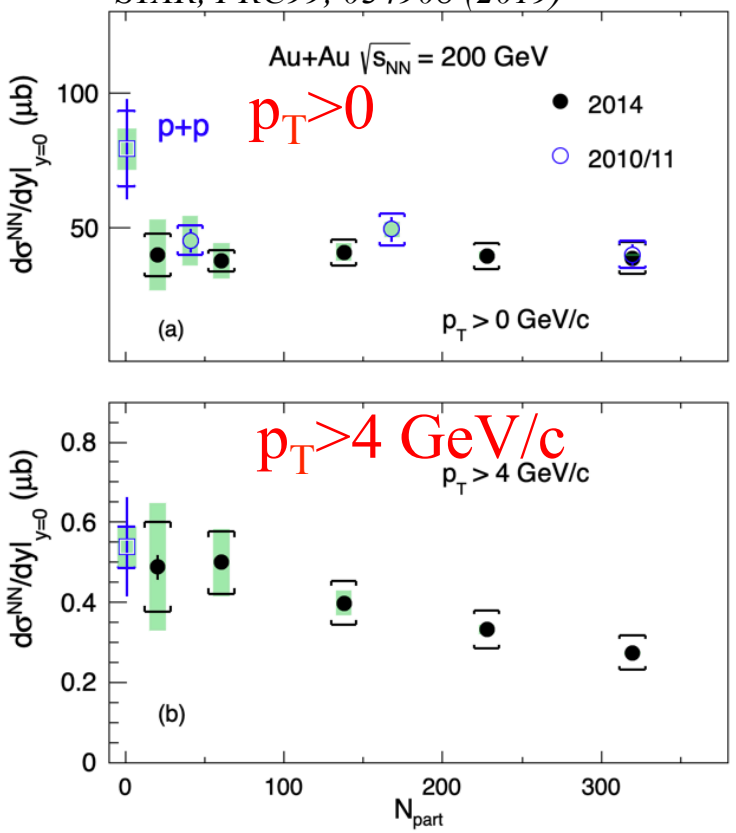




D^0 Suppression in Au+Au@200 GeV

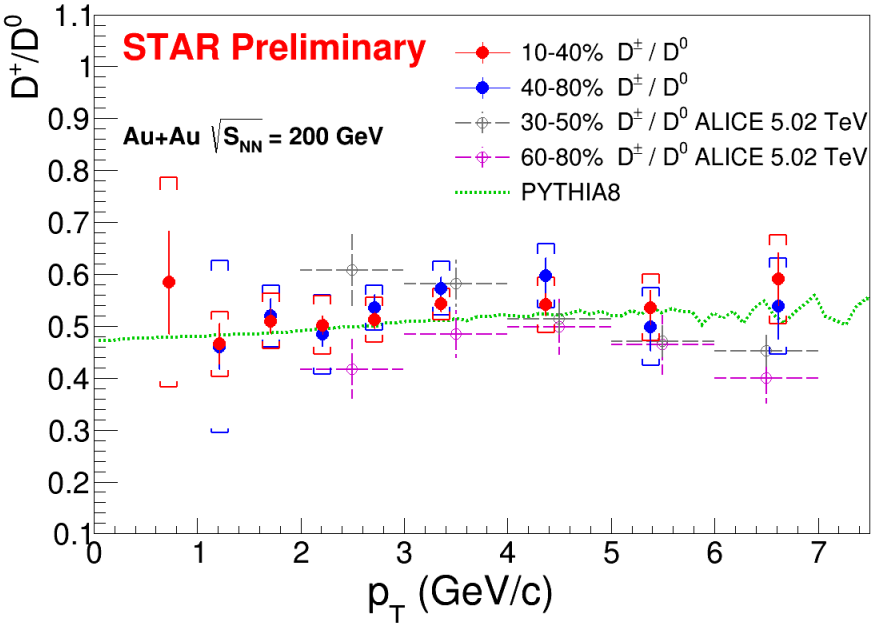
STAR, PRC99, 034908 (2019)

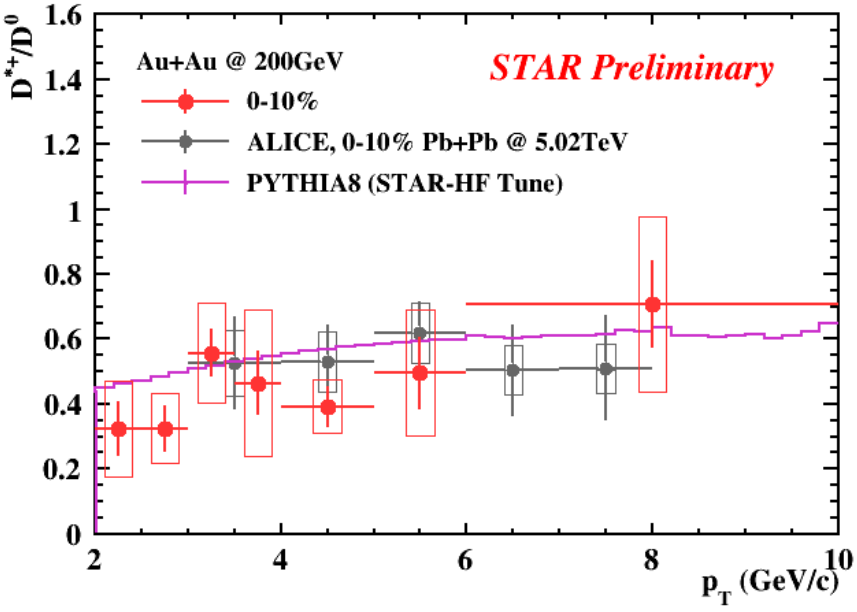




- Clear suppression at high p_T
  - Comparable to light flavor
  - Clear centrality dependence
- $d\sigma/dy$ at mid-y lower than p+p
  - Cold Nuclear Matter effects?
  - Charm redistribution?

$D^{\pm}$ and D^{*} Production in Au+Au

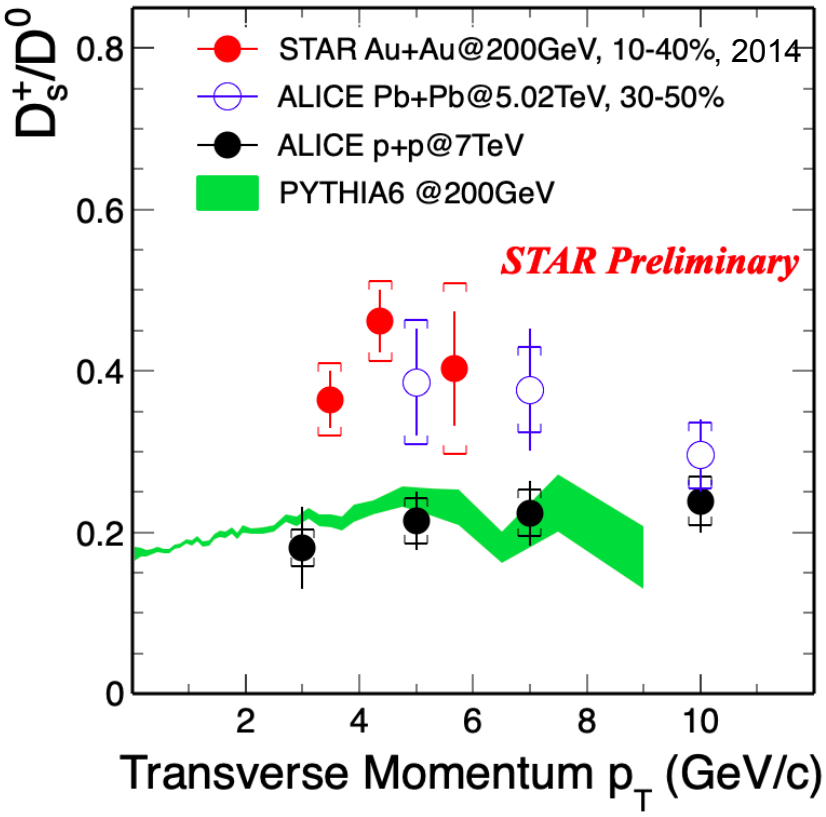




- $D^{\pm}/D^0$ and D^{*}/D^0 yield ratio in Au+Au @ 200GeV consistent with Pb+Pb @ 5.02 TeV and PYTHIA (p+p@200 GeV)
- $D^{\pm}$, D^{*} and D^0 have same suppression in heavy-ion collisions

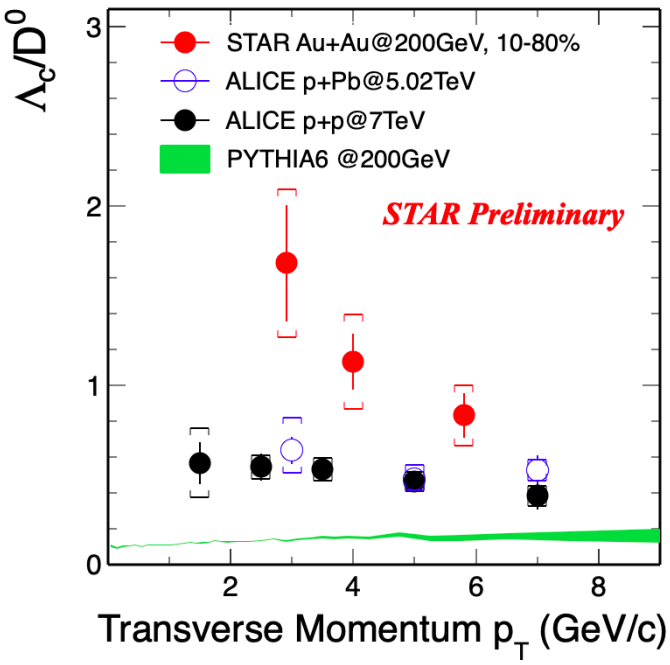
D_s Enhancement

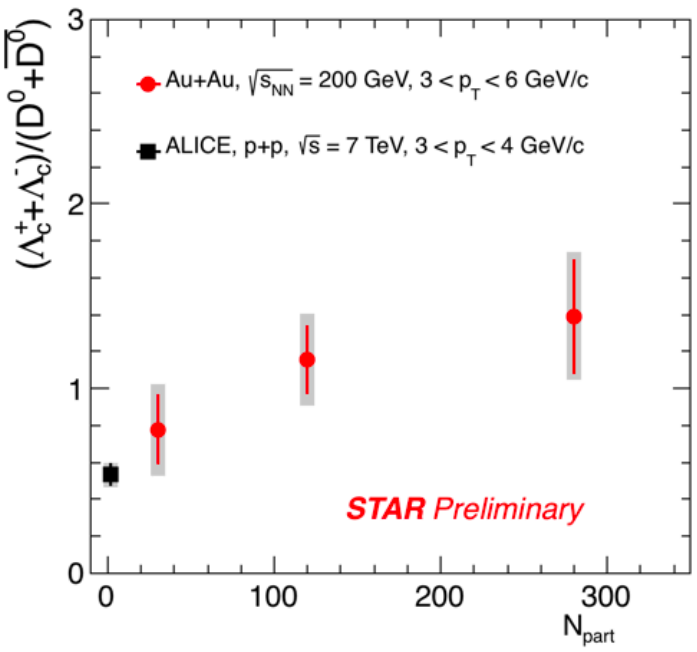
ALICE: EPJC, 550 (2017), JHEP 10, 174 (2018)



- D_s/D^0 significantly higher in heavy-ion than in p+p
- Strangeness enhancement + coalescence

Λ_c Enhancement





- Λ_c/D^0 @STAR significantly higher in heavy-ion than PYTHIA and in p+p/Pb @ALICE
- Increase towards central collisions
- Consistent with coalescence picture

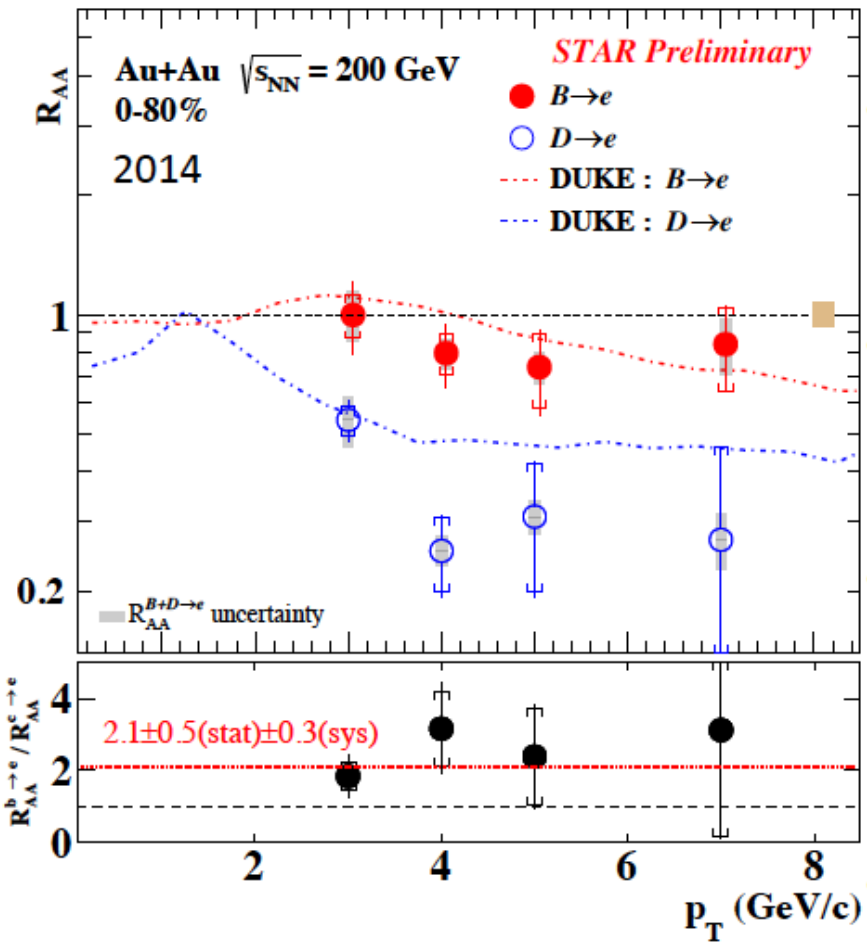
Charm Cross Section in Au+Au

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
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%**

- Charm quark cross section per binary collision in Au+Au consistent with p+p – Charm conservation
- Charm quark distribution among hadron species different between Au+Au and p+p – Charm redistribution

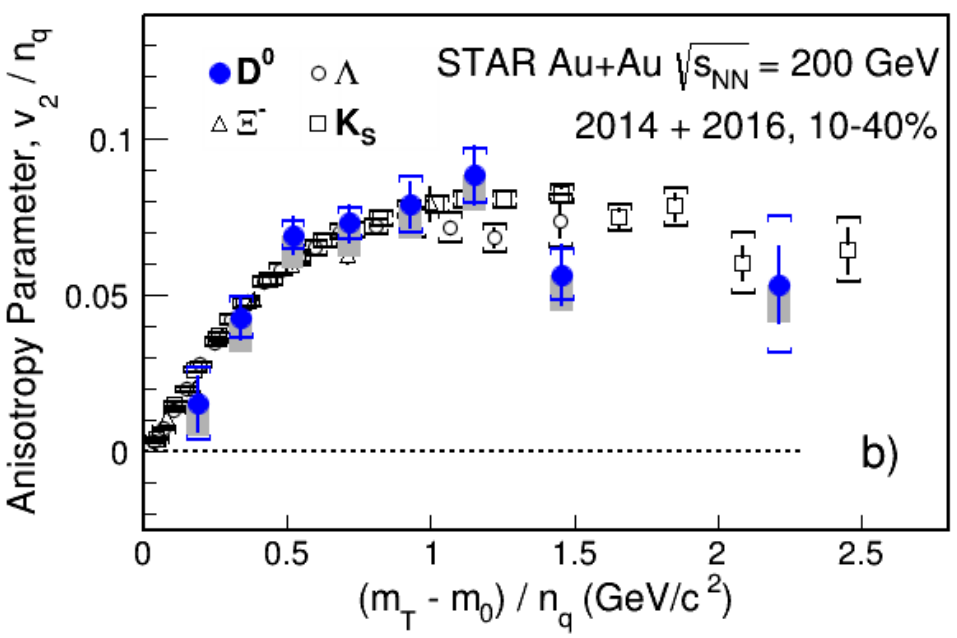
Bottom Quark Suppression

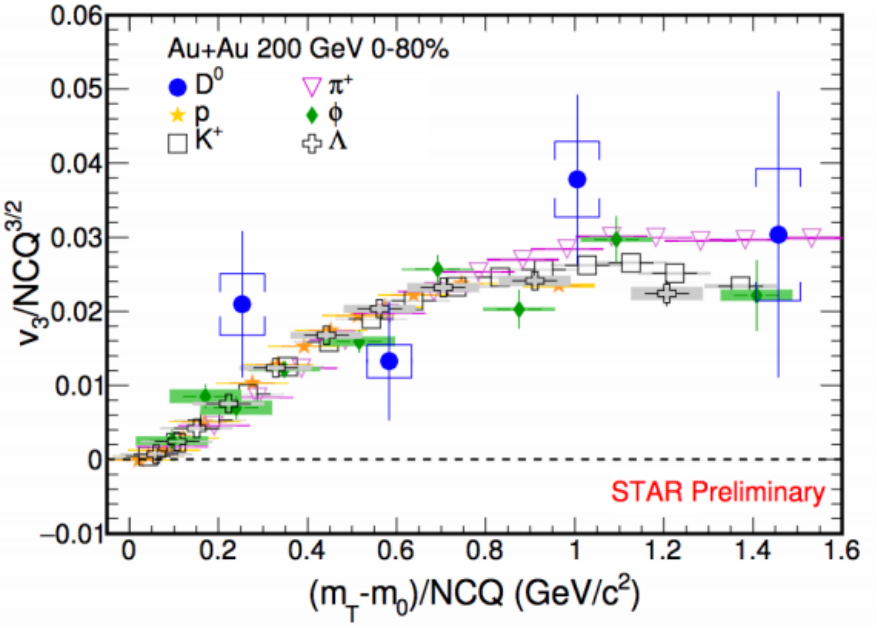


- Stronger suppression of e←B than e←D
- Described by theoretical calculations
- Consistent with mass hierarchy of parton energy loss

D^0 v_2 and v_3 in Au+Au

2014: STAR, PRL118, 212301 (2017)

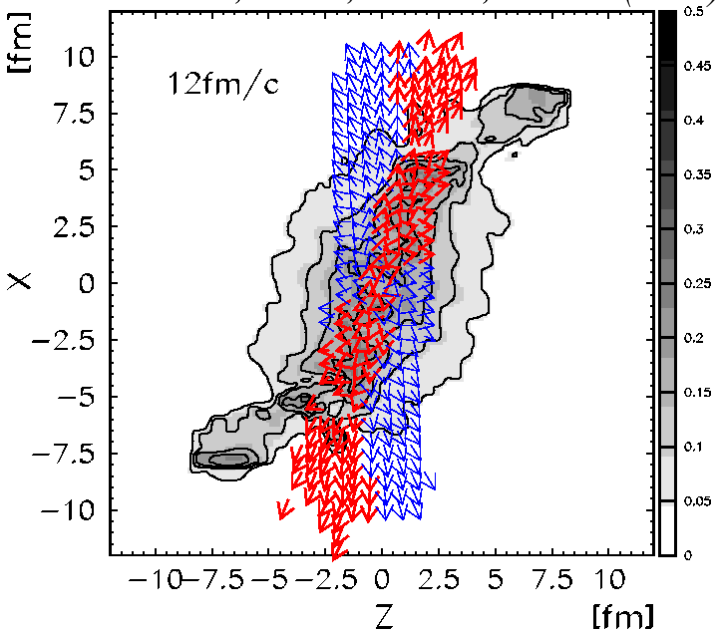


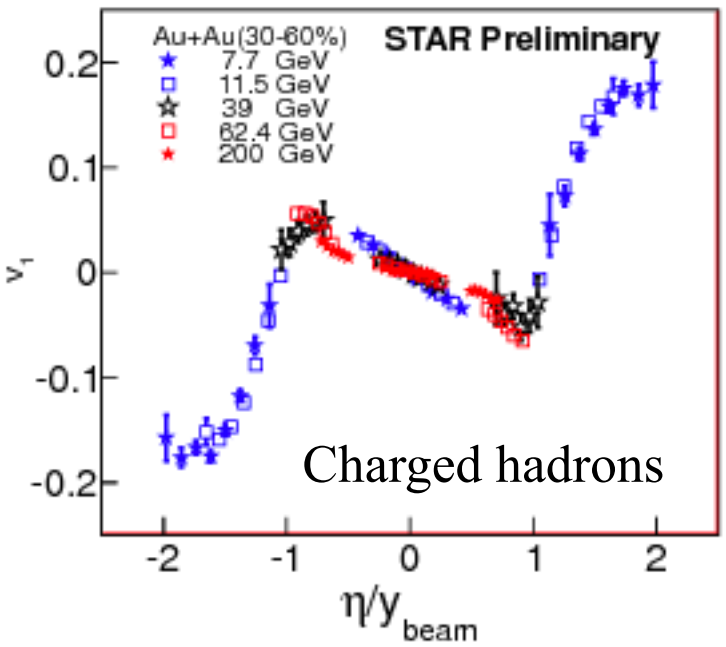


- Both v_2 and v_3 follow NCQ-scaling with light flavors
- Suggest charm quarks flow with the QGP
- Helps to constraint charm quark diffusion coefficient

Heavy Quark v_1 in Heavy-Ion Collisions

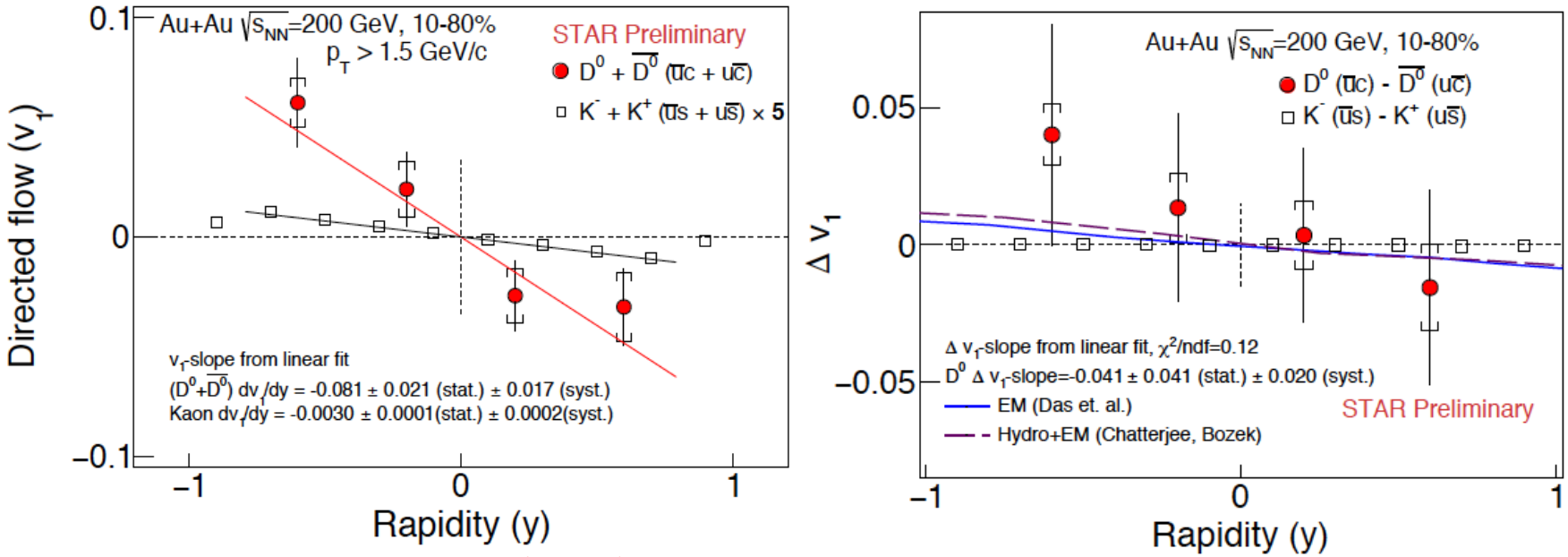
Brachmann, et. al. , PRC 61, 024909 (2000)





- Flow vs. anti-flow in non-central heavy-ion collisions
- Heavy quark produced according to binary collision density profile, which is symmetric in rapidity
- Large anti-flow induced by drag by the tilted bulk
- In addition, EM field induces opposite v_1 for charm and anti-charm

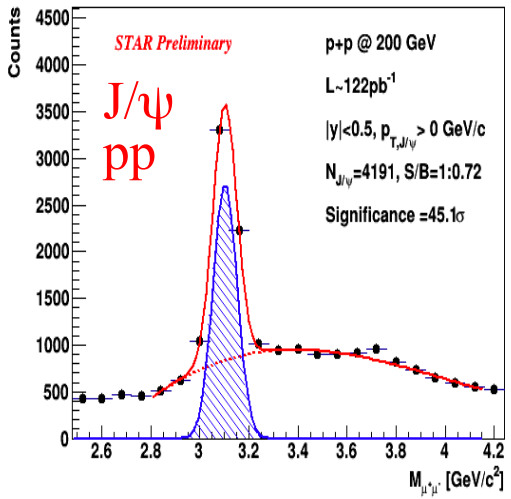
D^0 v_1 in Au+Au

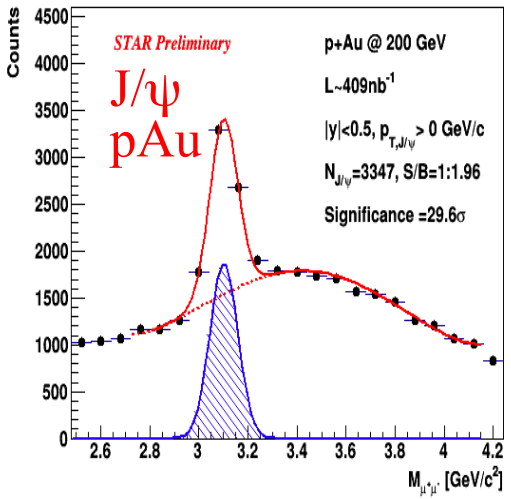


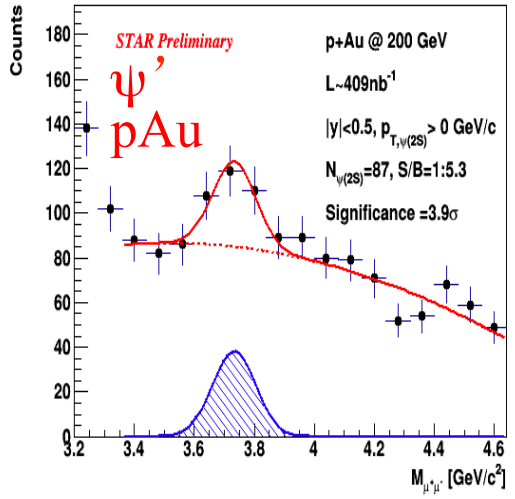
STAR, arXiv:1905.02052, submitted to PRL

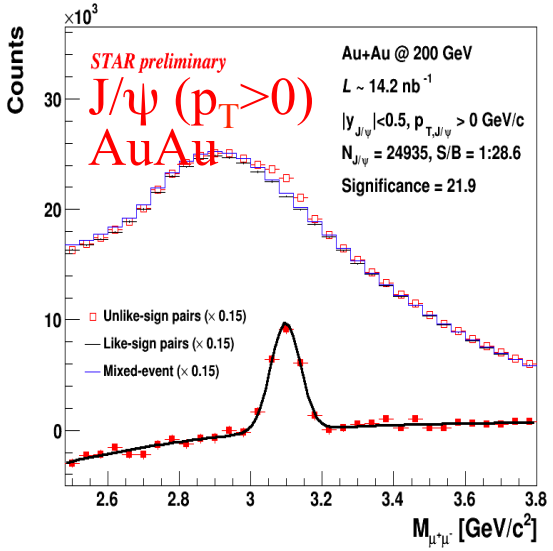
- v_1 of D^0 is about 20 times larger than that of the kaons (~3σ)
- Sensitive to both the initial titled source and heavy quark transport properties
- Current precision does not allow draw firm conclusion on EM effect

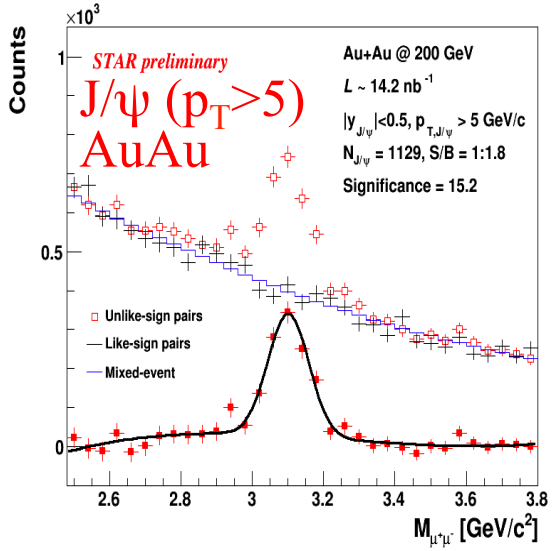
Quarkonium Signals with MTD

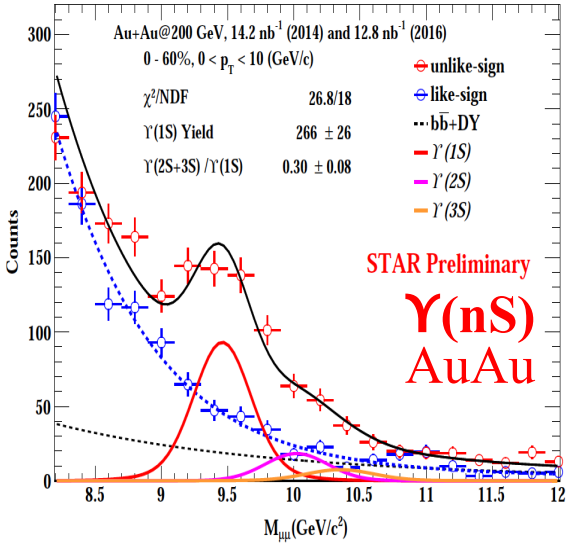




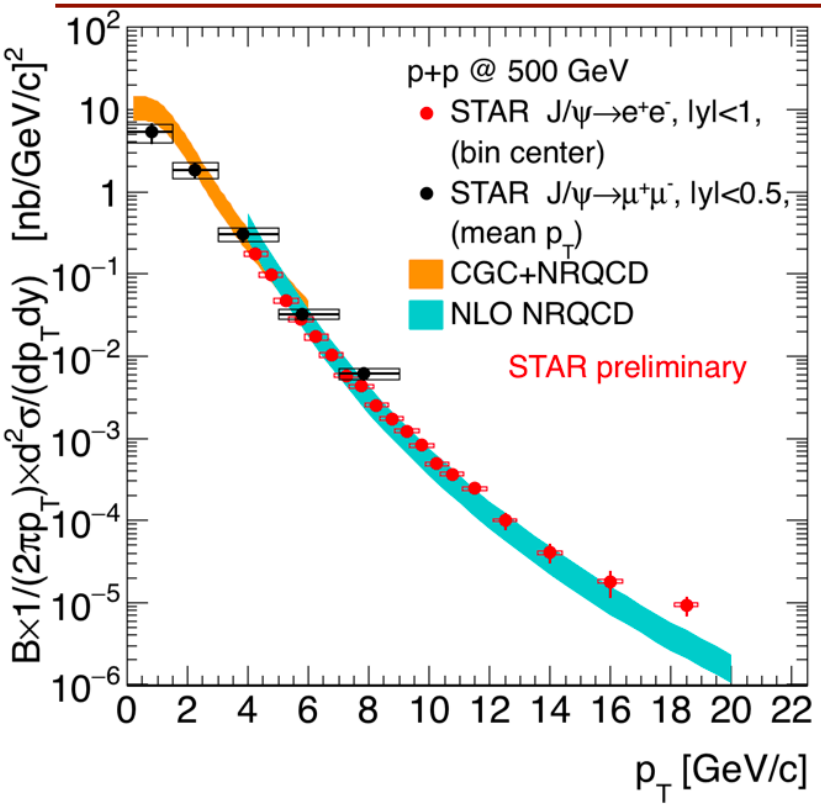


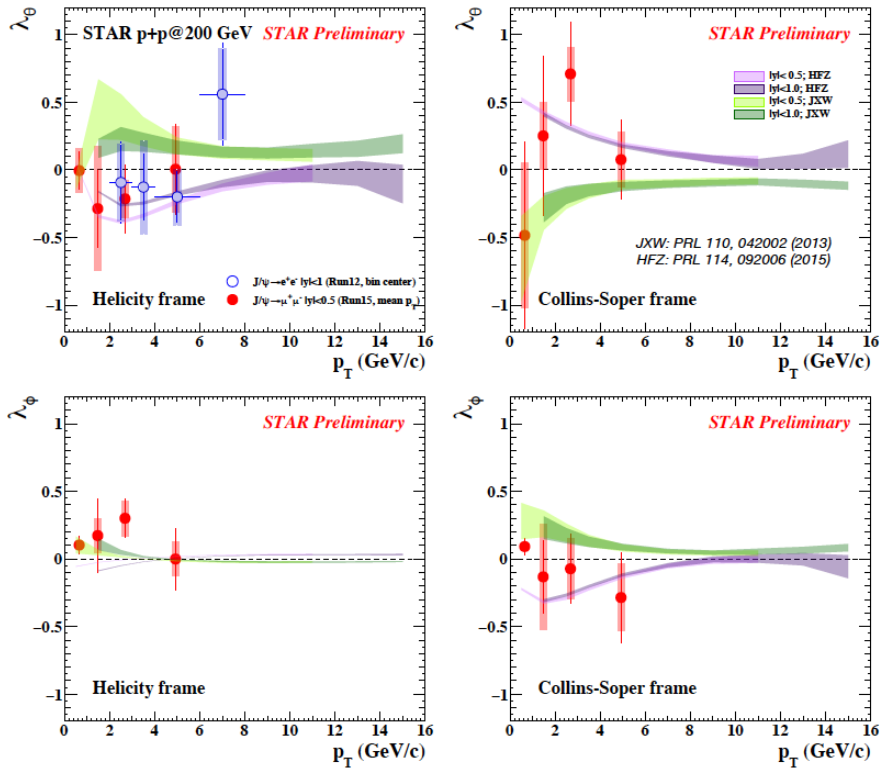






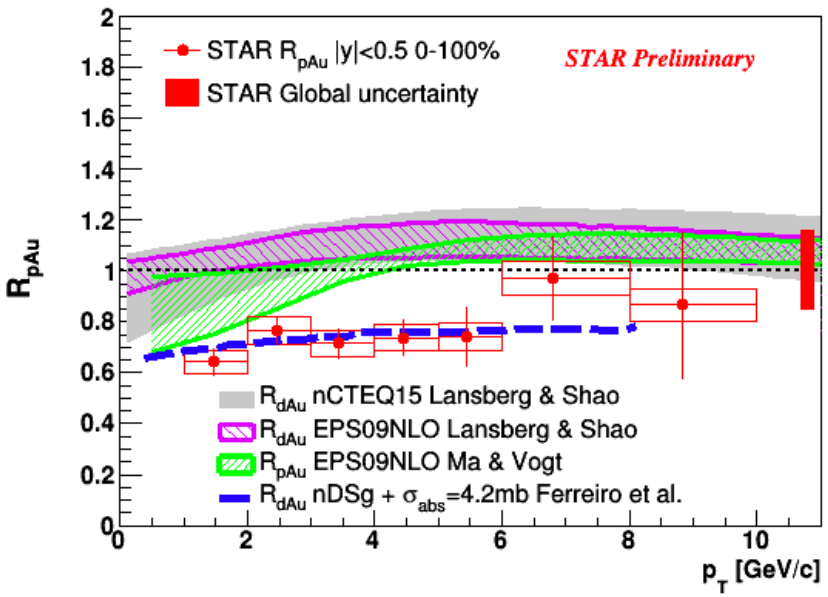
J/ψ Production in p+p

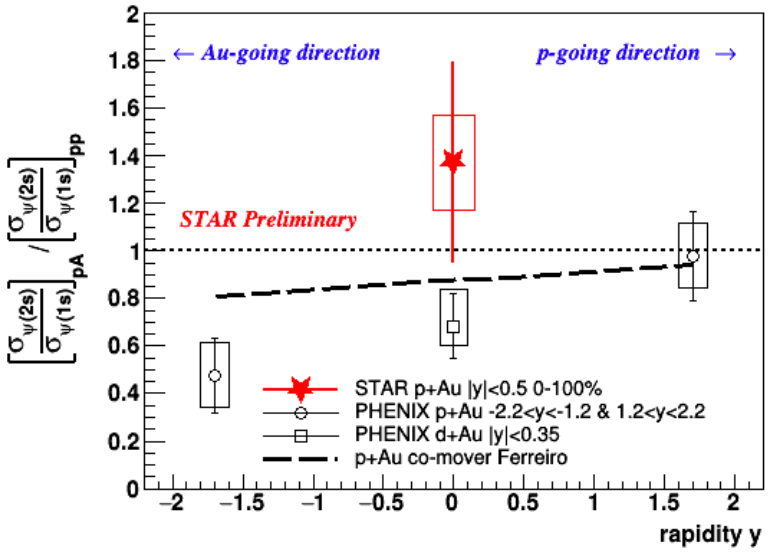




- Large p_T coverage by combining di-electron and di-muon
- p_T spectra described by CGC+NRQCD at low-p_T and NLO NRQCD at high p_T
- Polarization measurements can constraint theoretical calculations

Charmonium Production in p+Au



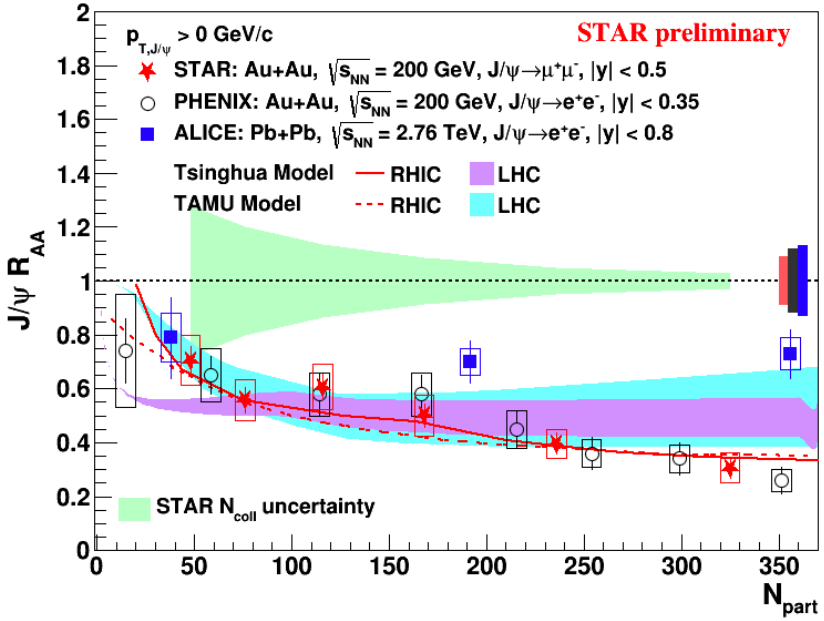


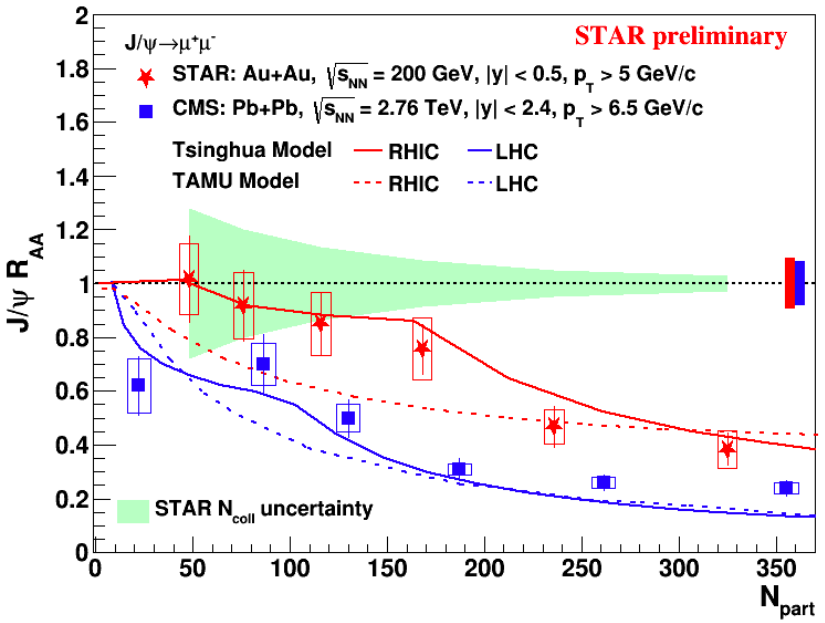
EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg & Shao, EPJC77, 1 (2017)
Comp. Phys. Comm. 198, 238 (2016) , Comp. Phys. Comm. 184, 2562(2013)
Ferreriro et al., Few Body Syst. 53, 27(2012)

PHENIX p+Au, PRC95 (2017) 034904
PHENIX d+Au, PRL111 (2013) 202301
Co-mover calculation, Ferreiro, private comm.

- Models with only nPDF describe the data, but additional nuclear absorption is favored
- First ψ(2S) to J/ψ double ratio measurement from STAR ~ unity

J/ψ Suppression in Au+Au





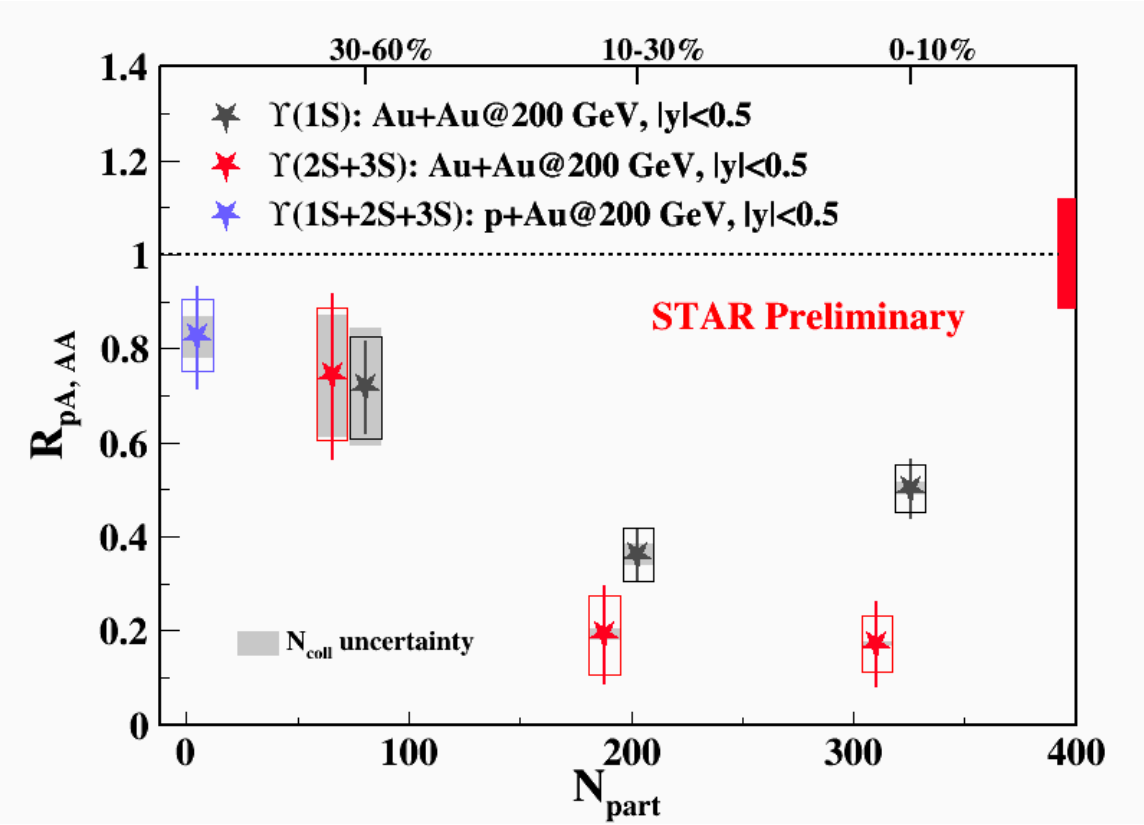
- Low-p_T: Significant suppression in central, stronger than LHC

  Regeneration at LHC on top of QGP melting and CNM

- High-p_T: Significant suppression in central, less than LHC

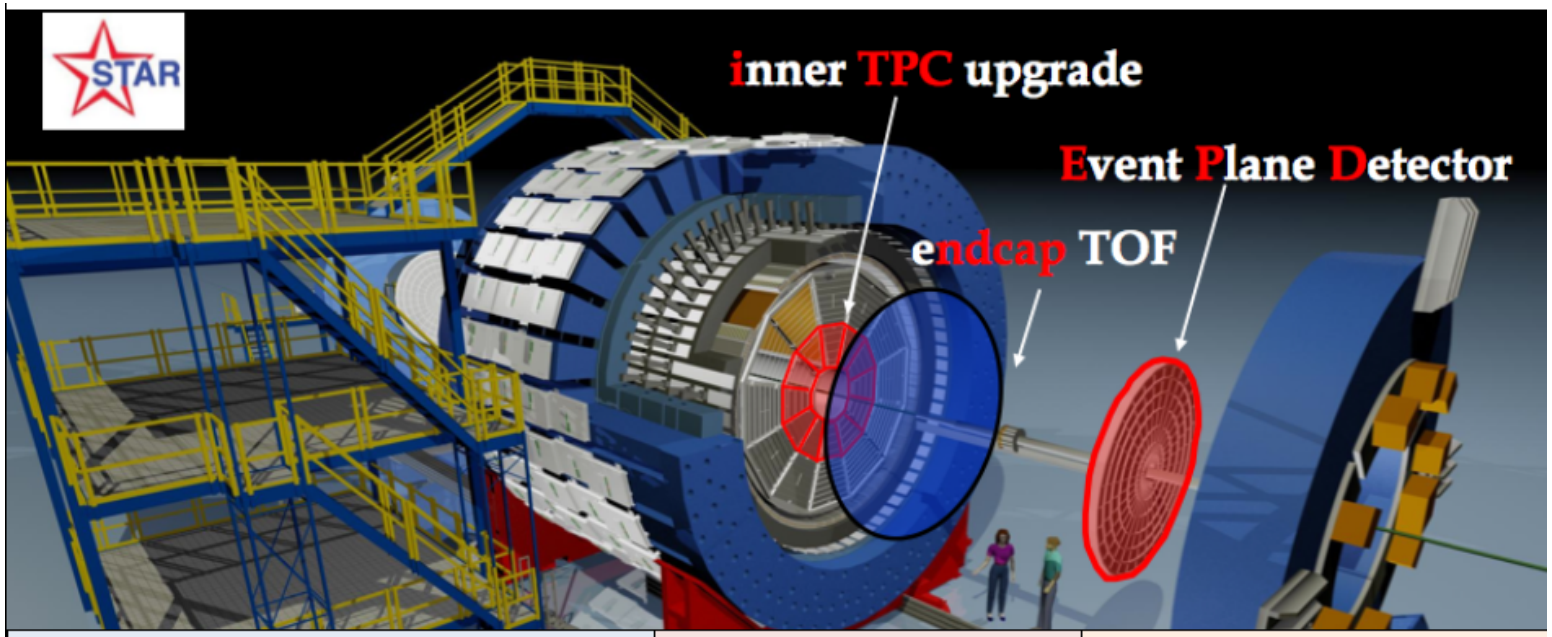
  QGP Melting

Upsilon Suppression in Au+Au



- Significant suppression of Upsilon(1S) in central collisions
- Stronger suppression of excited states than ground state
  - Consistent with sequential suppression

STAR Forward Upgrade (Phase I)



iTPC Upgrade:

- Rebuilds inner sectors of the TPC
- Continuous Coverage
- Extends η coverage from 1.0 to 1.5
- Improves dE/dx
- Lowers p_T cut-in from 125 to 60 MeV/c

EndCap TOF Upgrade:

- PID at η = 0.9 to 1.5
- Allows higher energy range of Fixed-Target program
- Provided by CBM-FAIR

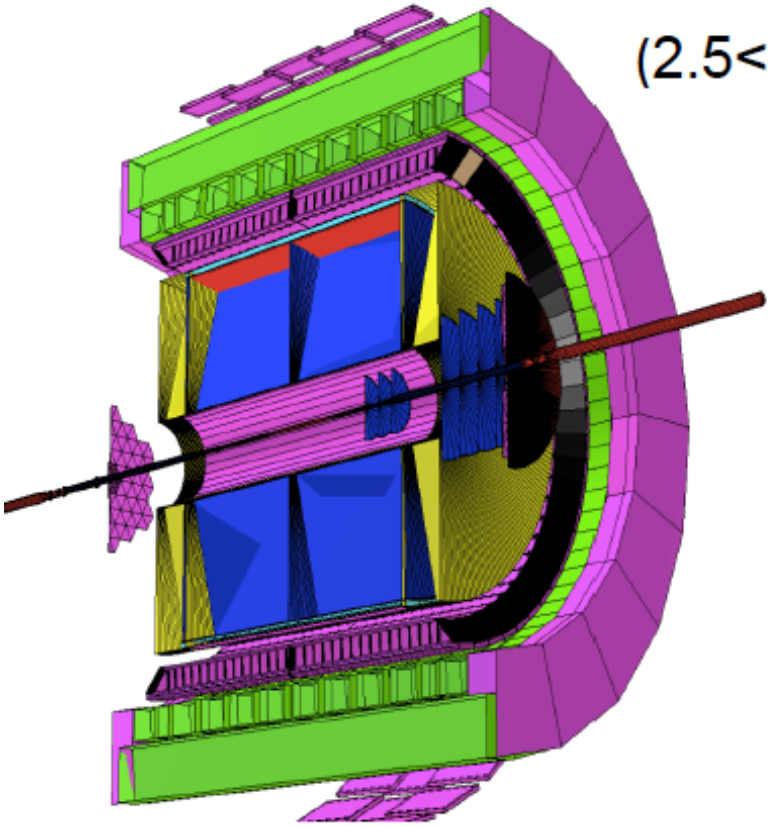
EPD Upgrade:

- Allows a better and independent reaction plane measurement critical to BES physics
- Improves trigger
- Reduces background

STAR Forward Upgrade (Phase II)

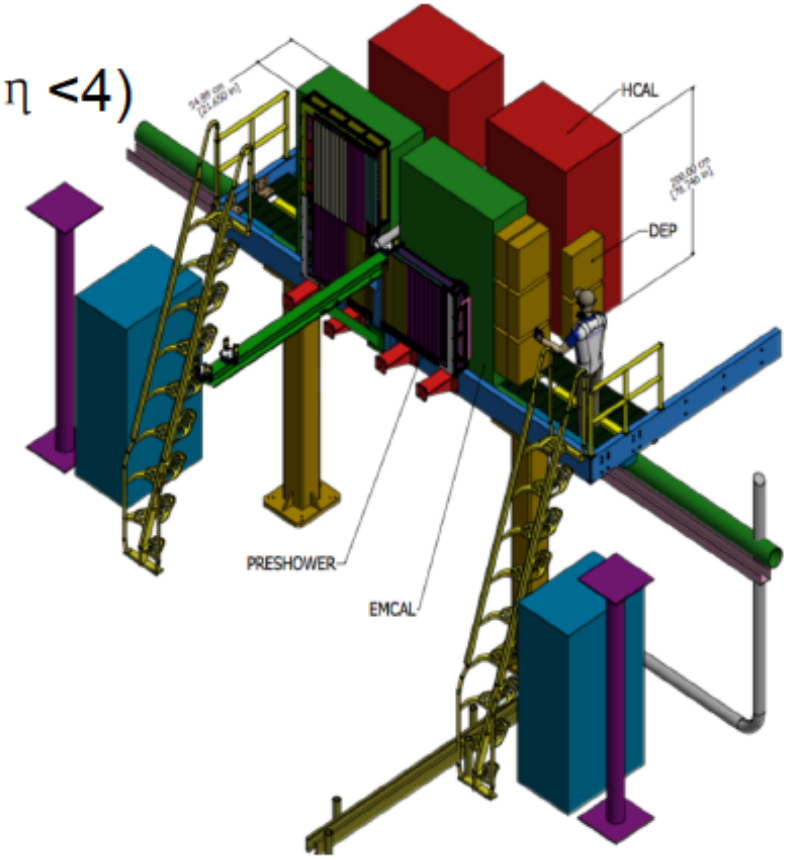
Forward Tracking System

(2.5< η <4)



Silicon + sTGC

Forward Calorimeter System



EM Cal + HCal

Electron with STAR Forward Upgrades

iTPC: 1.0<|η|<1.5

eTOF: -1.5<η<-0.9

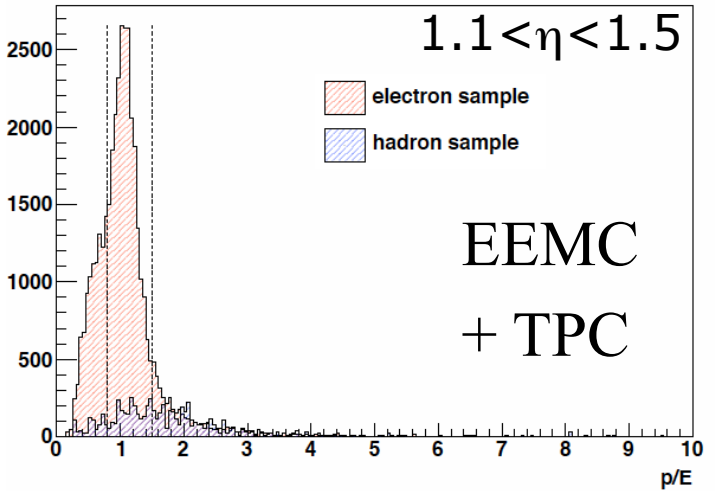
EEMC: 1<η<2

EPD: 2<|η|<5

FTS: 2.5<η<4.0

FCS: 2.5<η<4.0

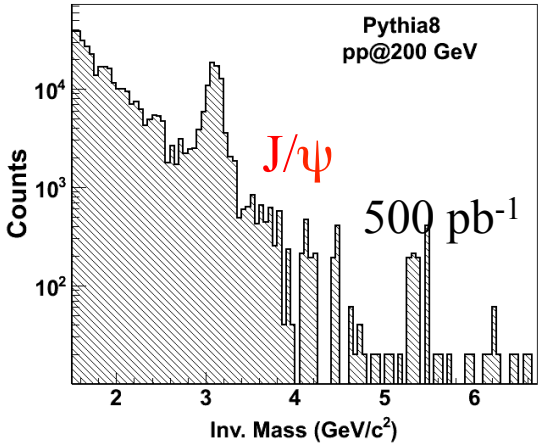
Naresh Subba, PhD Thesis, Kent State U. (2010)

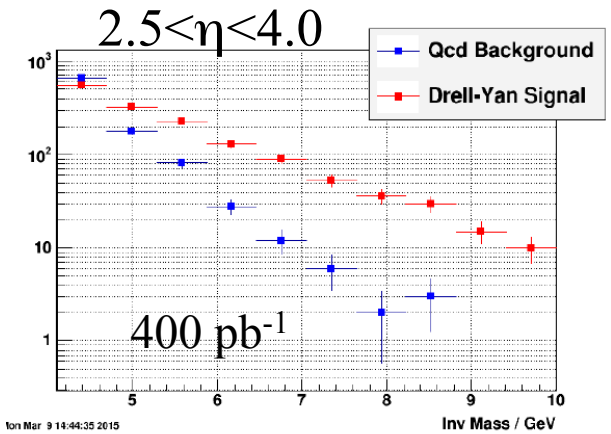


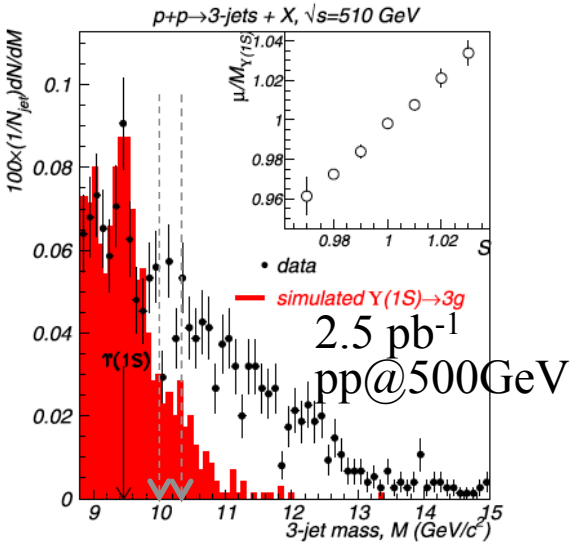
- Electron capability at two forward pseudo-rapidity regions
  1.0<~|η|<~1.5 and 2.5<η<4.0
- For di-electron, (pseudo-)rapidity could be even between if two legs in different pseudo-rapidity window.

Heavy Flavor Opportunities at Forward

- Open heavy flavor
  - Electron from heavy flavor decay
    $1.0<|\eta|<1.5$ and $2.5<\eta<4.0$
  - Possible D-meson reconstruction (simulation needed)
- Quarkonium
  - Reconstruct via di-electron channel
    $1.0<|\eta|<1.5$ and $2.5<\eta<4.0$ and between
  - Upsilon→ggg? (B.R. ~80% for 1S)
  - Radiative decay of quarkonium?

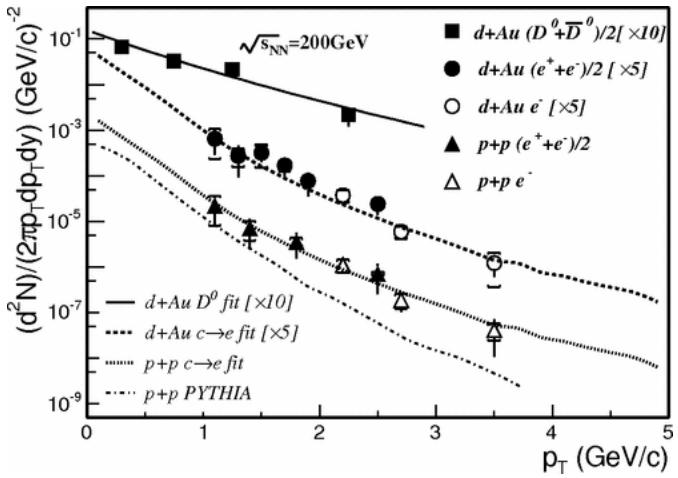


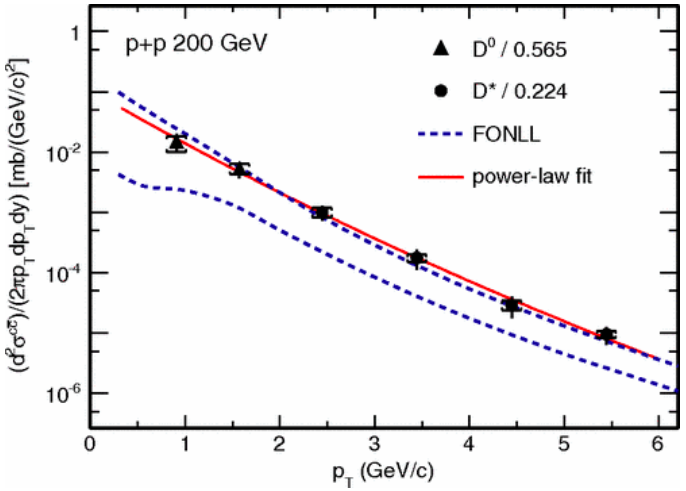




Open Heavy Flavor Production in p+p

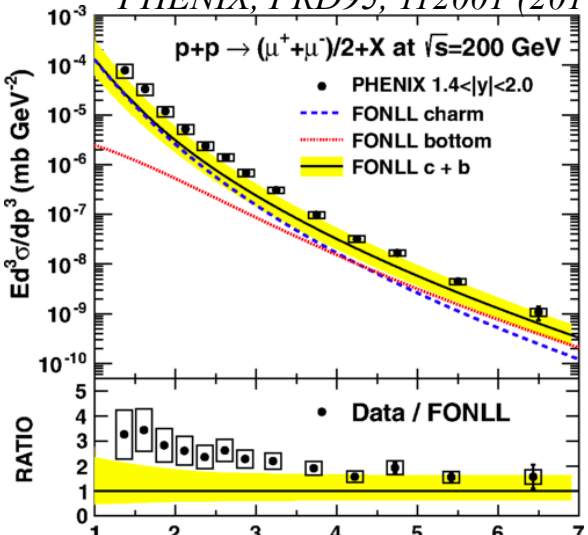
STAR, PRL94, 062301 (2005)

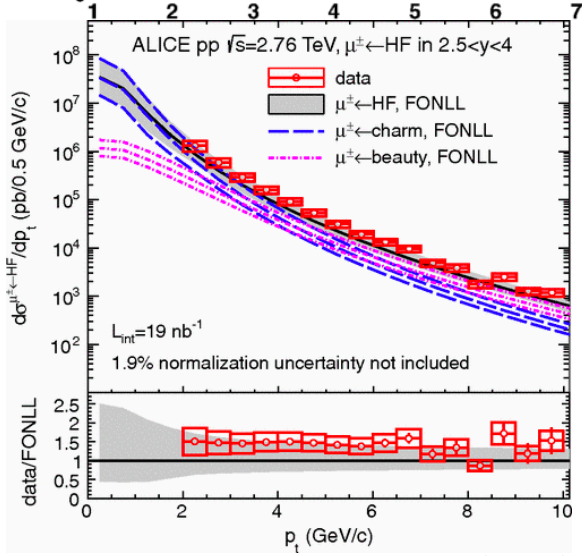




STAR, PRD86, 072013 (2015)

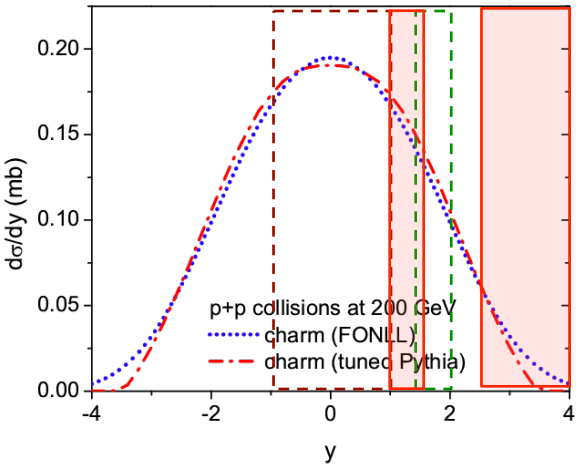
PHENIX, PRD95, 112001 (2017)





ALICE, PRL109, 112301 (2012)

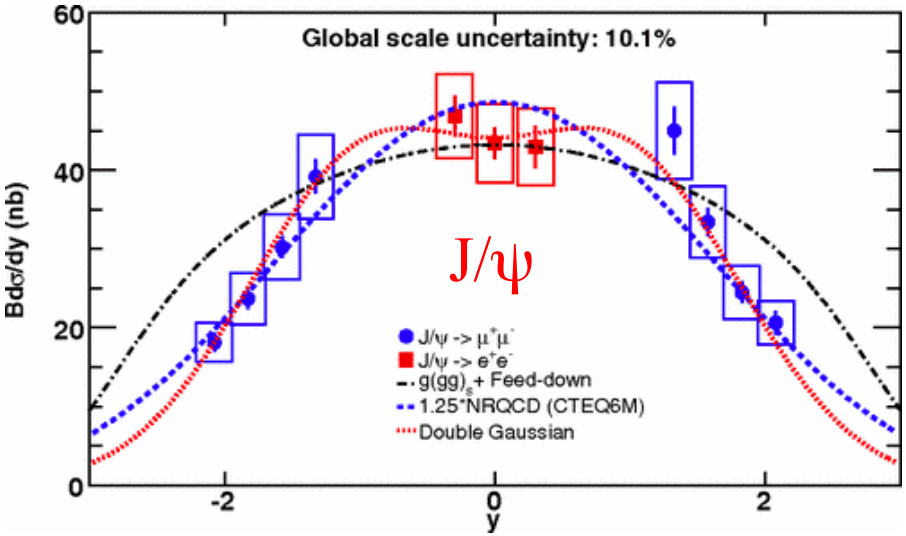
T. Song et. al., PRC92, 014910 (2015)

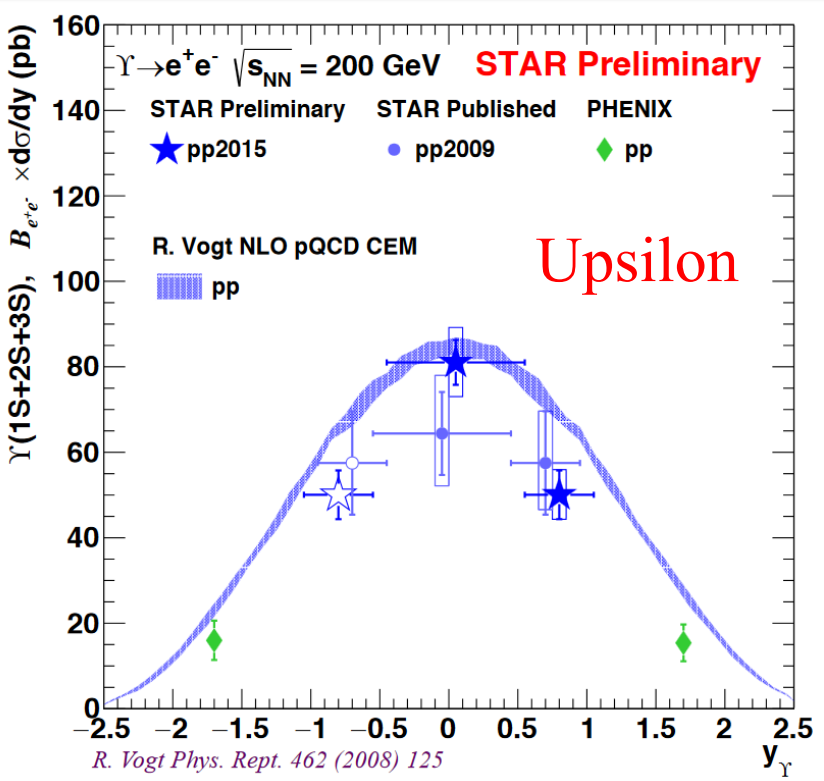


- Understanding of HF production mechanism and gluon PDF
- Important input of many models

Quarkonium production in p+p

PHENIX: PRL98, 232002 (2007)
NRQCD: F. Cooper, PRL93, 171801 (2004)
pQCD: V. Khoze, EPJC39, 163 (2005)



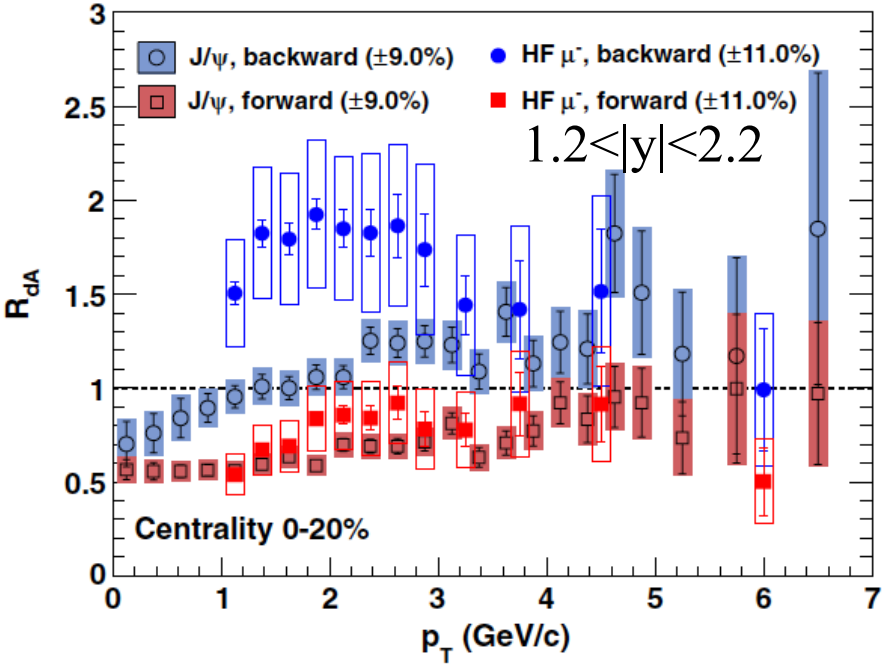


- Rapidity distribution of quarkonia are not well understood
- Test the production mechanism of the simplest QCD systems

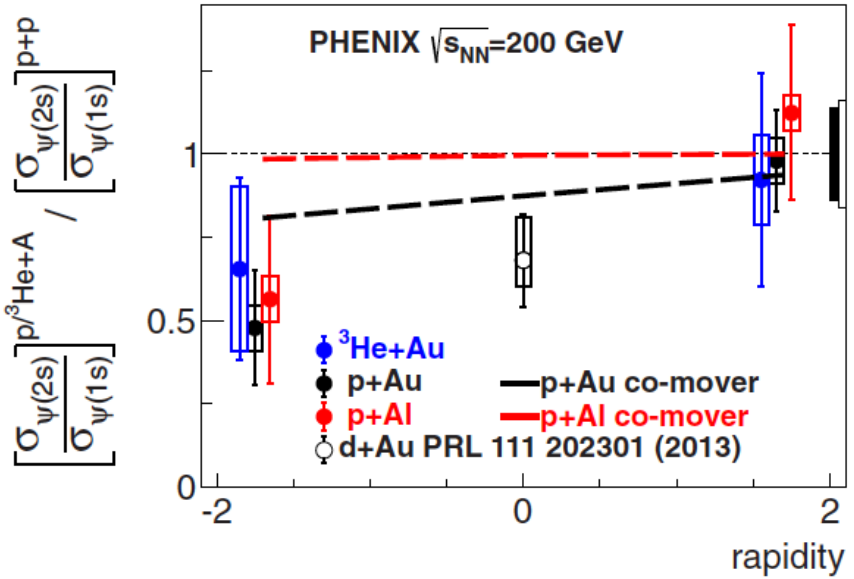
CNM Effects in p+A

- Gluon nPDF at small- and large-x (Very large uncertainty)
- Gluon saturation and energy loss
- Absorption of quarkonium
- Essential reference for heavy-ion collisions
- Important physics itself

PHENIX, PRL112, 252301 (2014)

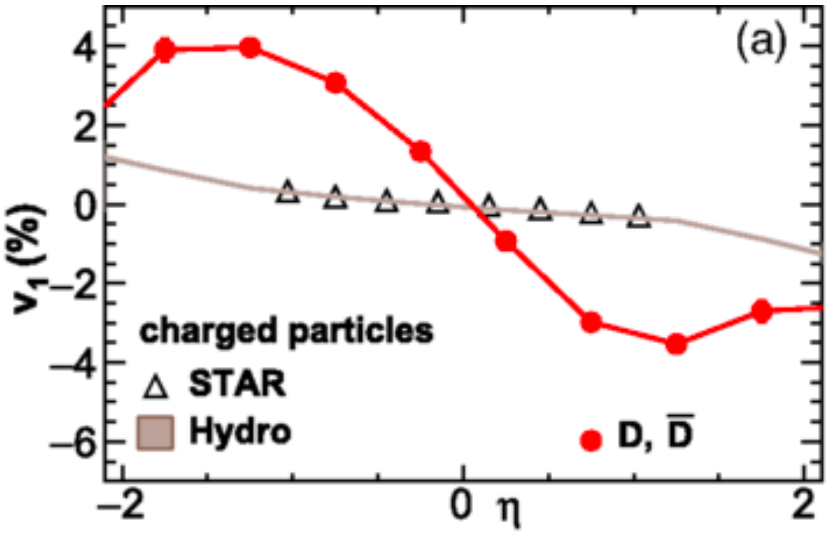


PHENIX, PRC95, 034904 (2017)
PHENIX, PRL111, 202301 (2013)

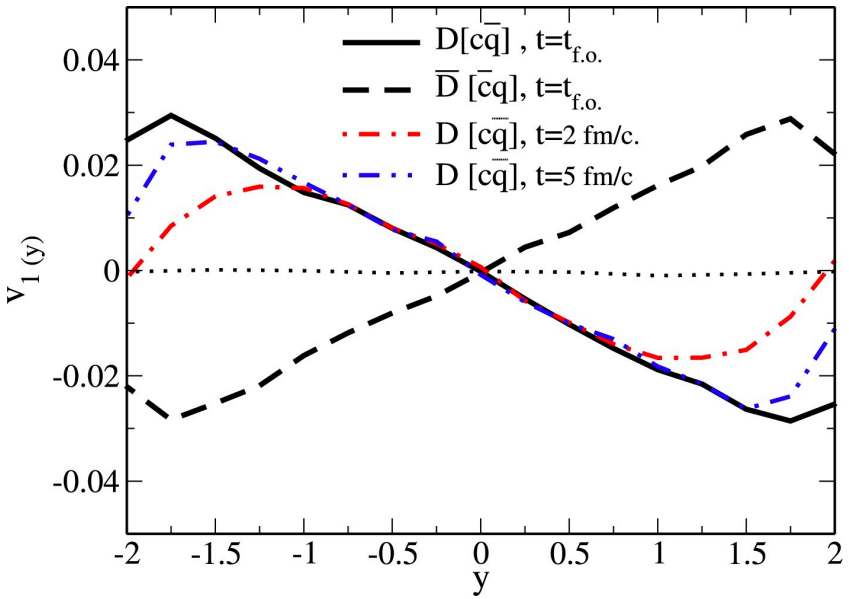


HF Directed Flow in A+A

S. Chatterjee et. al., PRL120, 192301 (2018)



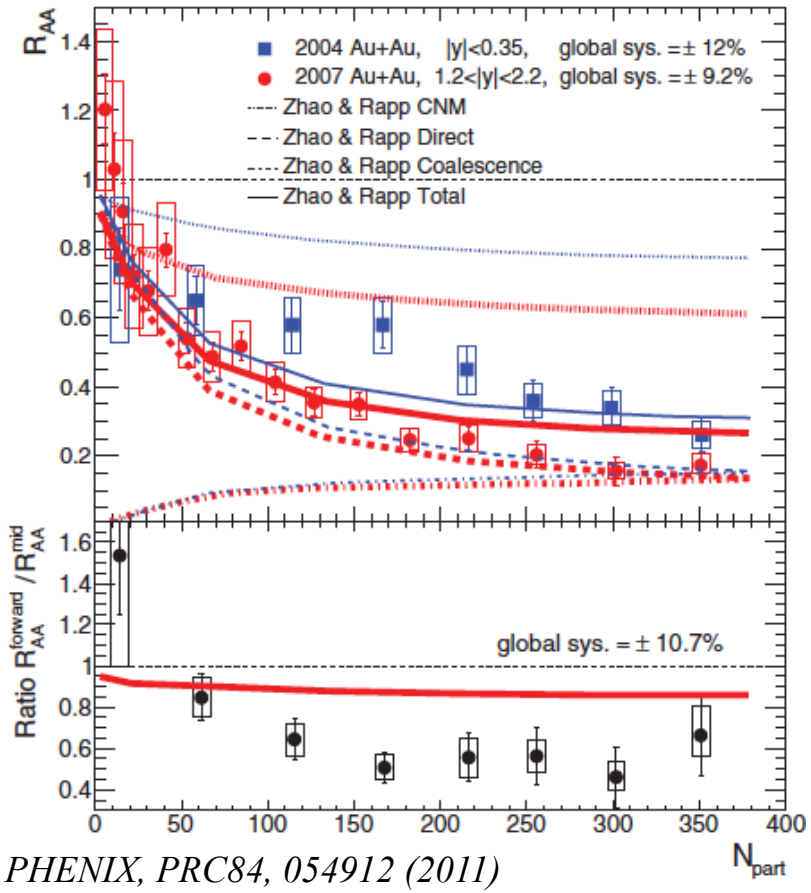
S. Das et. al., PLB768, 260 (2017)



- D v_1 sensitive to initial tilted source, heavy quark transport properties and EM field effect
- Forward upgrades enlarge the pseudo-rapidity coverage of electron from heavy flavor decay

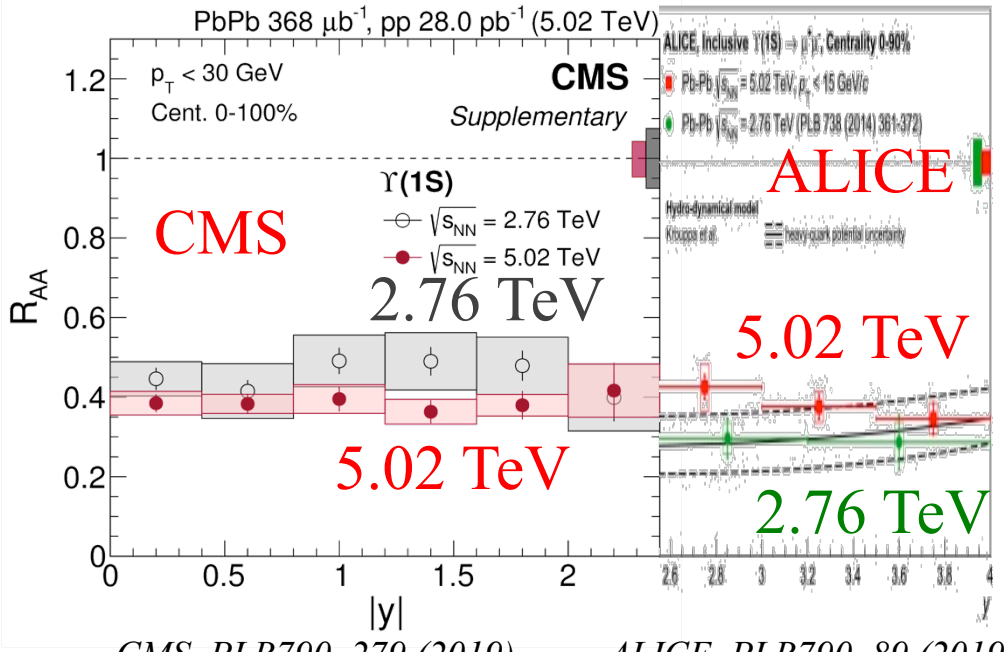
Quarkonium Suppression in A+A

J/ψ at RHIC



PHENIX, PRC84, 054912 (2011)

Upsilon(1S) @ LHC



CMS, PLB790. 279 (2019) *ALICE, PLB790, 89 (2019)*

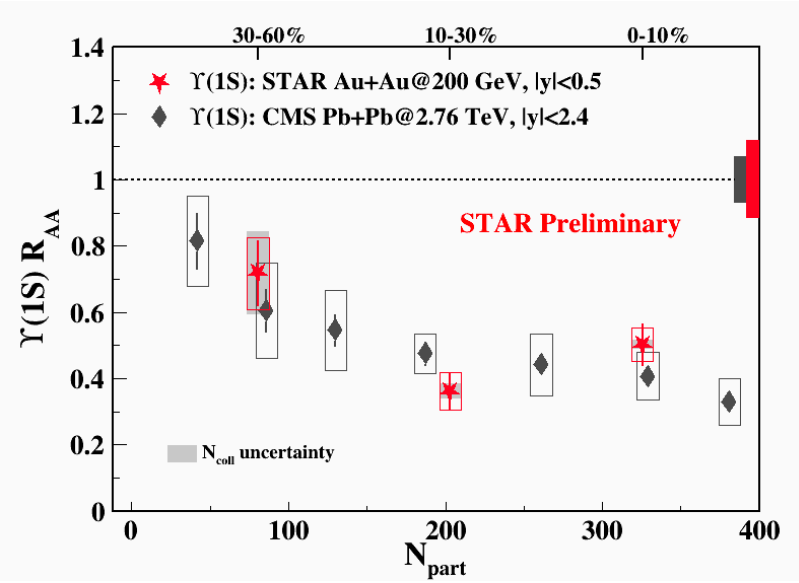
Rapidity dependence of J/ψ and Upsilon suppression to be understood

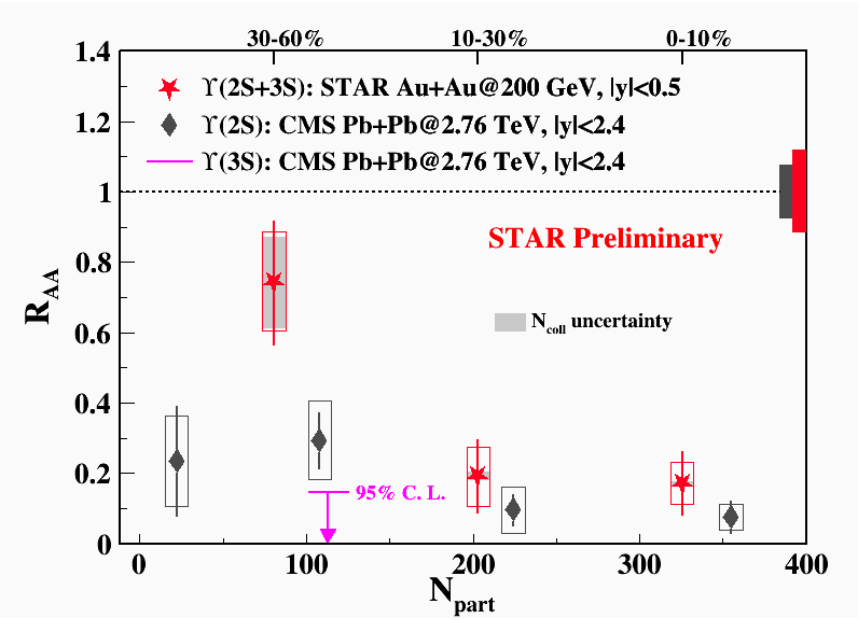
Summary

- STAR HFT enabled important studies on open heavy flavor physics
- STAR MTD enabled important studies on quarkonium production
- STAR forward upgrades (iTPC, eTOF, EPD, FTS, FCS) provides great (and unique) opportunities for heavy flavor physics

Thanks!

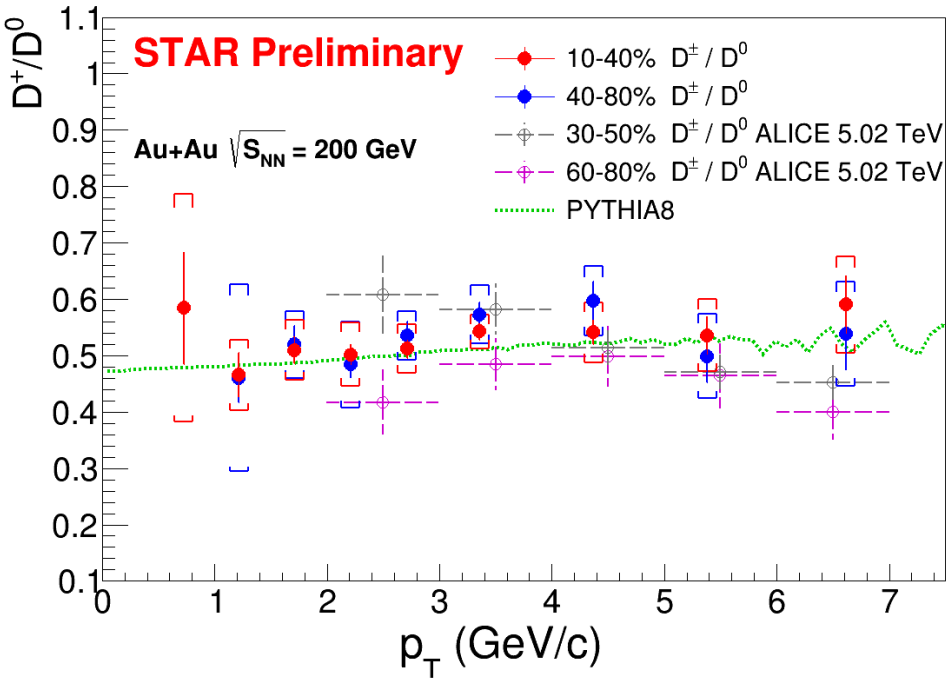
Compare to LHC





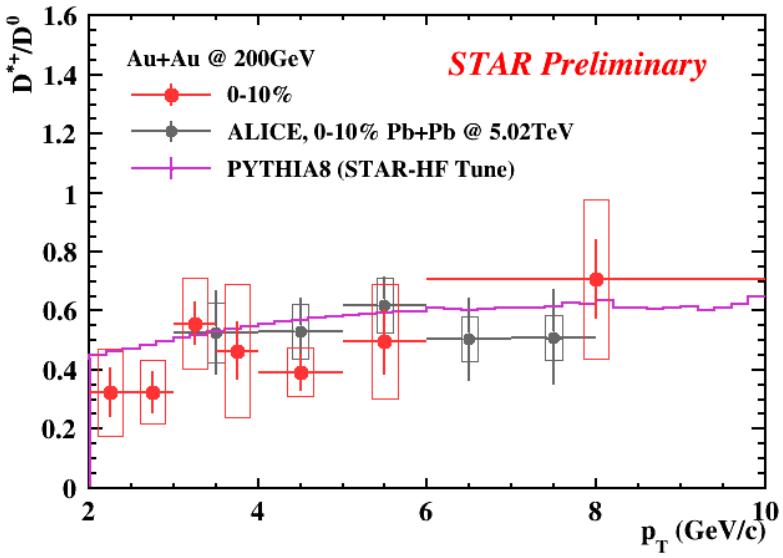
$D^{\pm}$ Suppression

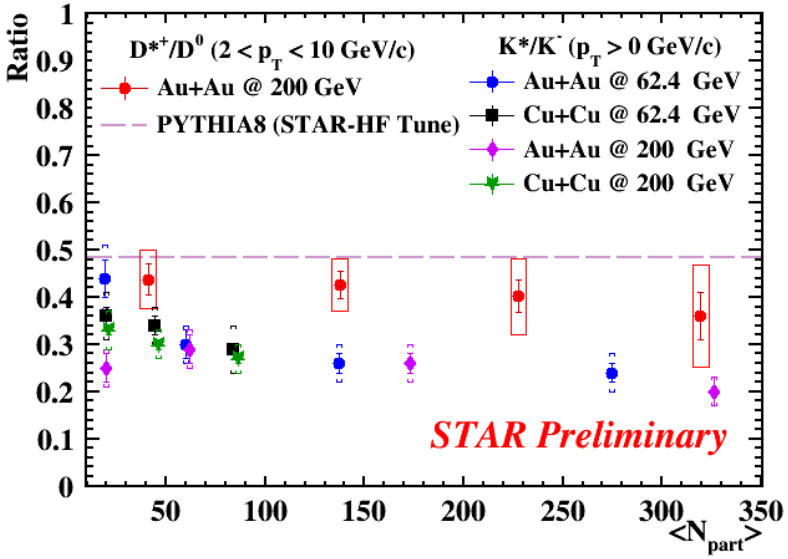
Particle symbol	Quark content	Rest mass (MeV/c^2)	Decay channel	Proper decay length (μm)
D^0	$c\bar{u}$	1864.84 ± 0.17	$K^- \pi^+$ 3.89%	~120
D^+	$c\bar{d}$	1869.62 ± 0.20	$K^- \pi^+ \pi^+$ 8.98%	~312



- $D^{\pm}/D^0$ yield ratio in Au+Au @ 200GeV is consistent with Pb+Pb @ 5.02 TeV and PYTHIA (p+p@200 GeV)
- $D^{\pm}$ and D^0 have the same suppression in heavy-ion collisions

D* Production





- D^{*+}/D^0 yield ratio in Au+Au @ 200GeV is consistent with Pb+Pb @ 5.02 TeV and PYTHIA (p+p@200 GeV)
- Ratio of the integral yields shows no strong centrality dependence
- No significant modification of D* spectral function