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Open and Hidden Heavy Flavor Production with RHIC-STAR

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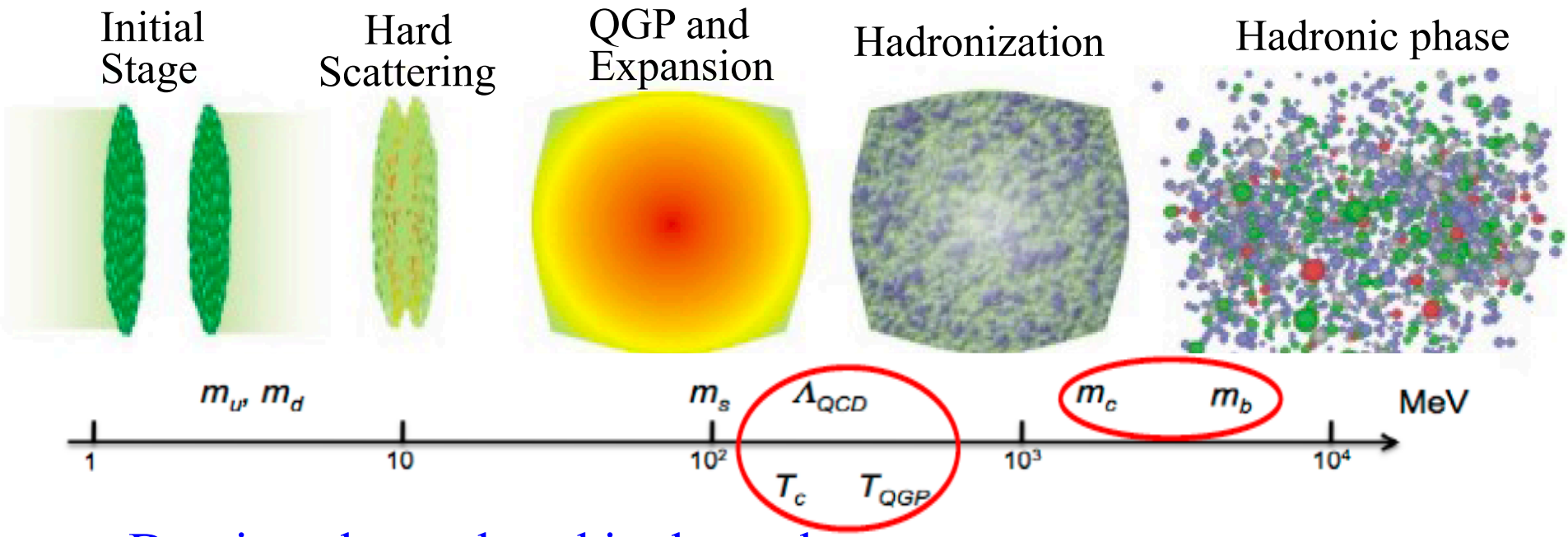
Heavy Flavor: Penetrating probe of QGP



- Dominantly produced in the early stage
  Experience the whole evolution of QGP
- Produced in hard scatterings
  Calibrate probe calculable in pQCD
- Strongly interact with the hot, dense medium
  Probes the properties of QGP

Outline

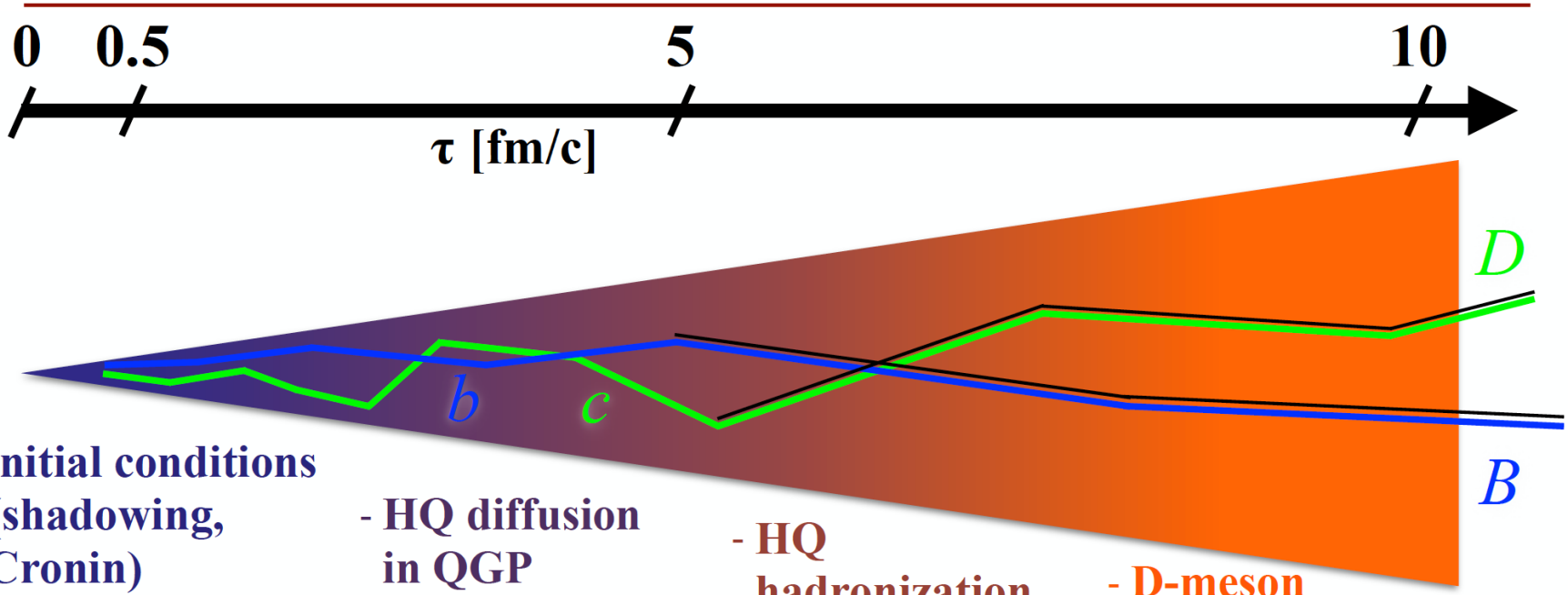
- Open heavy flavor production
  - D^0, $D^{\pm}$, $D^{*\pm}$ production
  - D_s production
  - Λ_c production

- *Hidden heavy flavor production*

  Please see

  - 查王妹：Very-low-p_T J/ψ production in HHIC S3, 10/10, 14:30
  - 王鹏飞：Upsilon in Au+Au collisions at 200 GeV S3, 10/10, 11:50
  - 杨　钱：J/ψ in p+p collisions at 500/510 GeV S3, 10/10, 11:30

Open Heavy Flavor

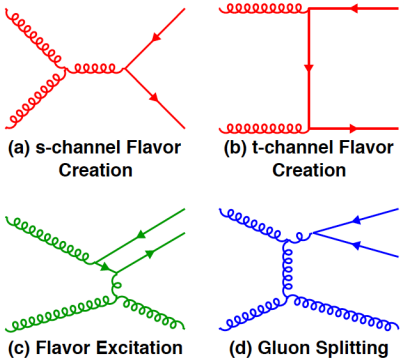


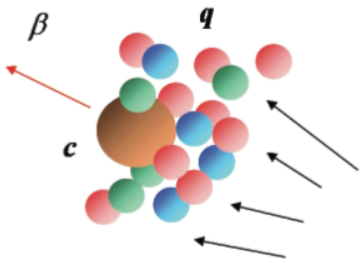
- initial conditions (shadowing, Cronin)
- Pre-equil. fields

- HQ diffusion in QGP

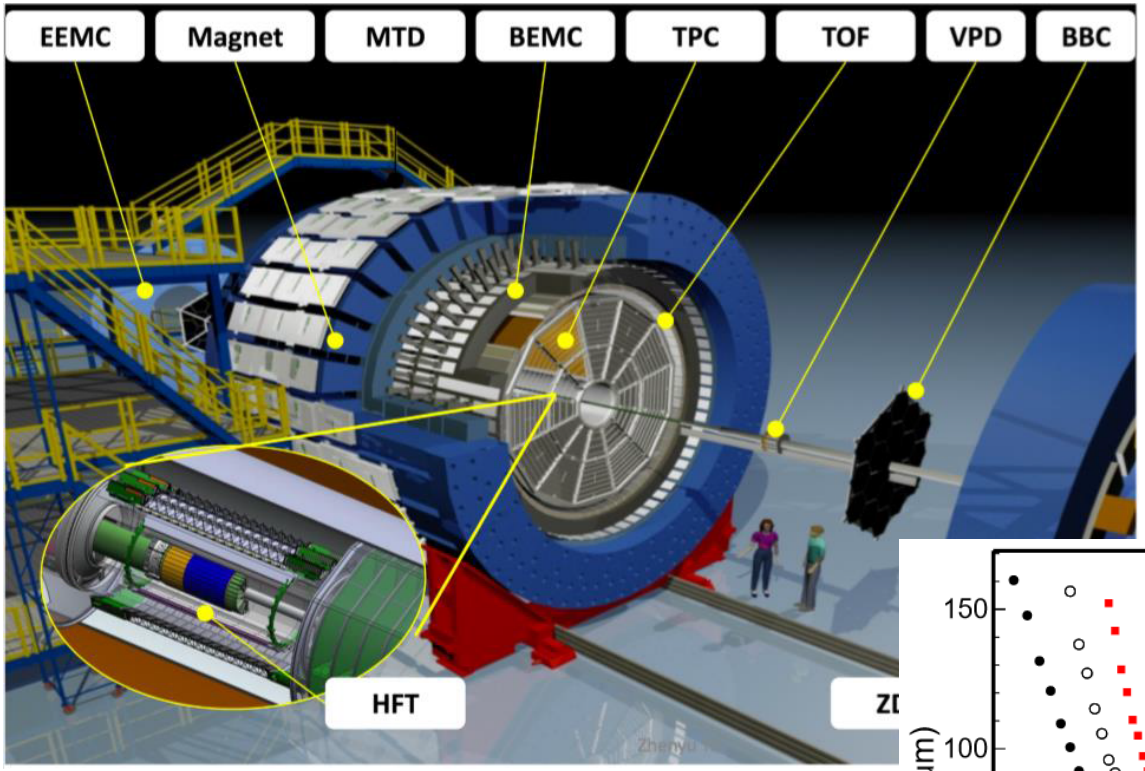
- HQ hadronization

- D-meson diffusion at hadronic phase





STAR Detector



TPC: tracking and dE/dx

TOF: time-of-flight

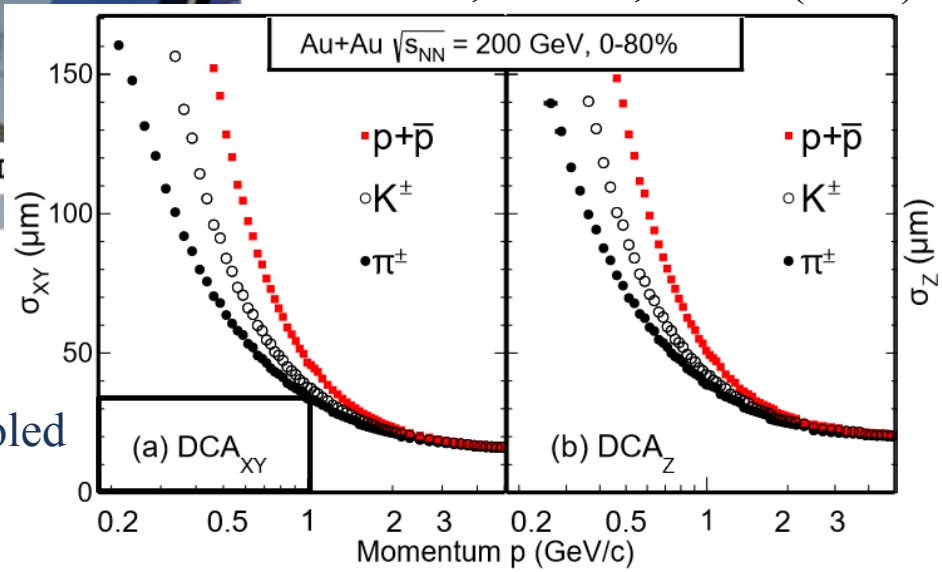
HFT: displaced vertex

Crucial for open heavy flavor reconstruction

HFT: (2014-2016)

- PIXEL detector: r ~2.8 & 8 cm,
  MAPS, 20.7x20.7 μm^2
  0.5% X0 (2014) 0.4% X0 (2016) , air-cooled
- Intermediate Silicon Tracker: r ~14 cm
- Silicon Strip Detector: r ~22 cm

STAR, PRC99, 34908 (2019)

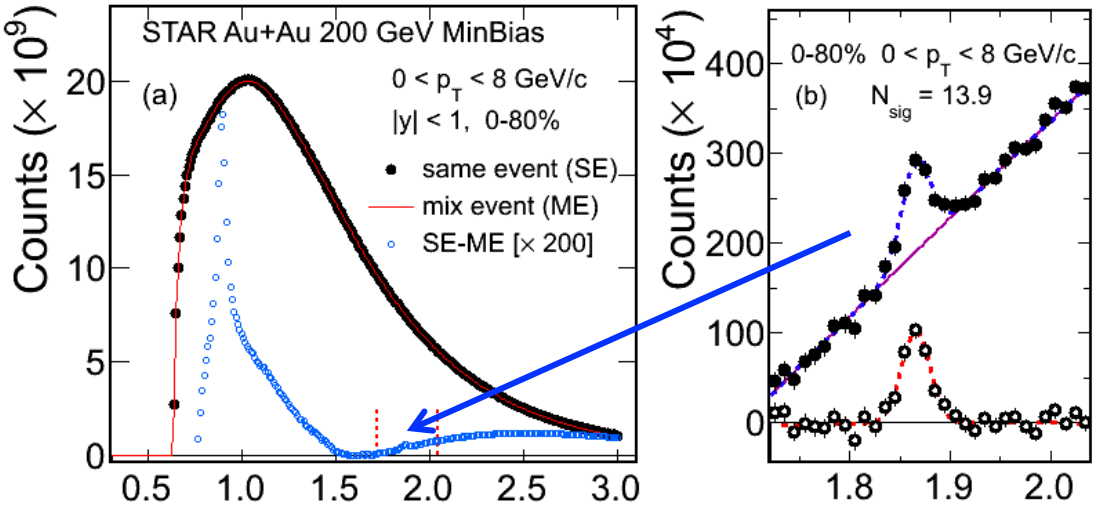


D^0 signals in Au+Au w/o and w/ HFT

2010+2011

820M events

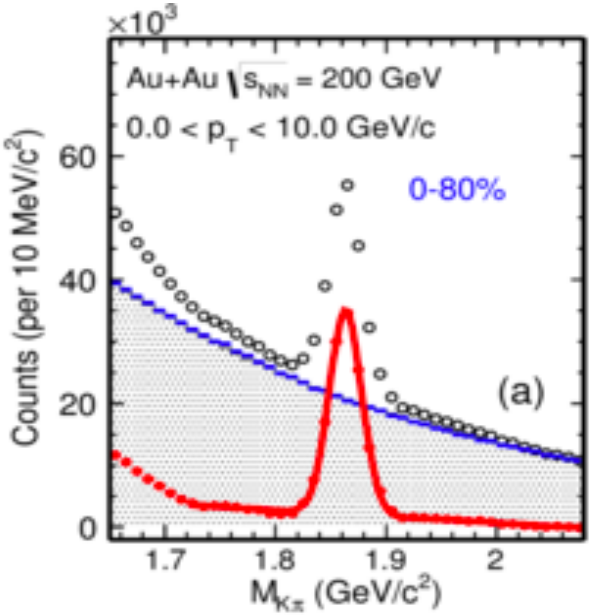
w/o HFT



2014

900M events

w/ HFT



$D^0 \rightarrow K\pi$

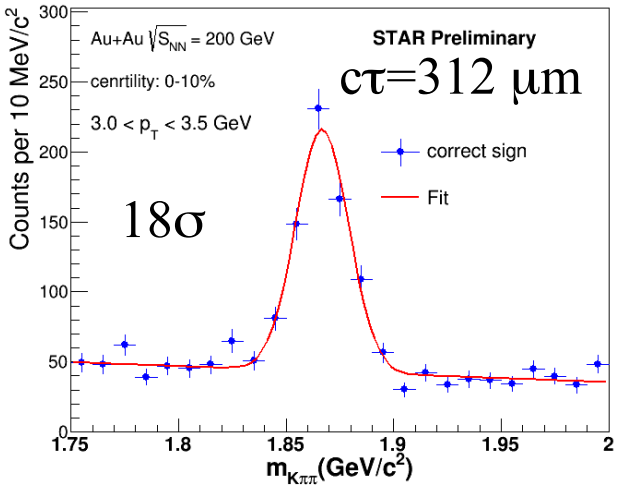
$B.R. = 3.89\%$

$c\tau = 123\mu m$

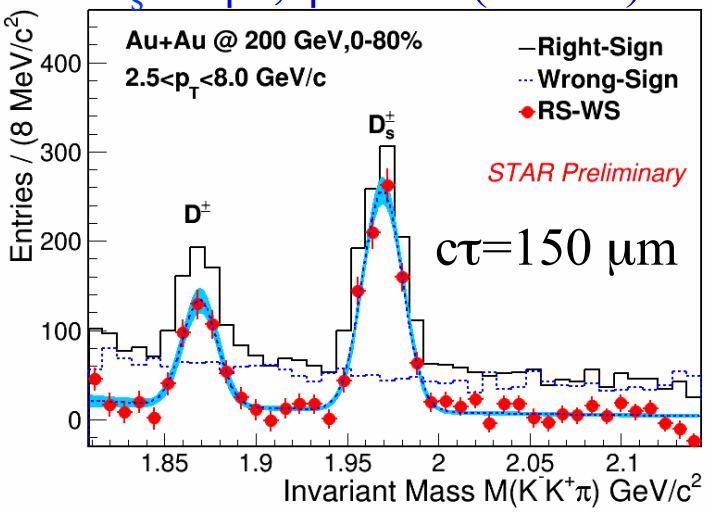
Significance improved by >15 thanks to HFT

Other open charm signals in Au+Au

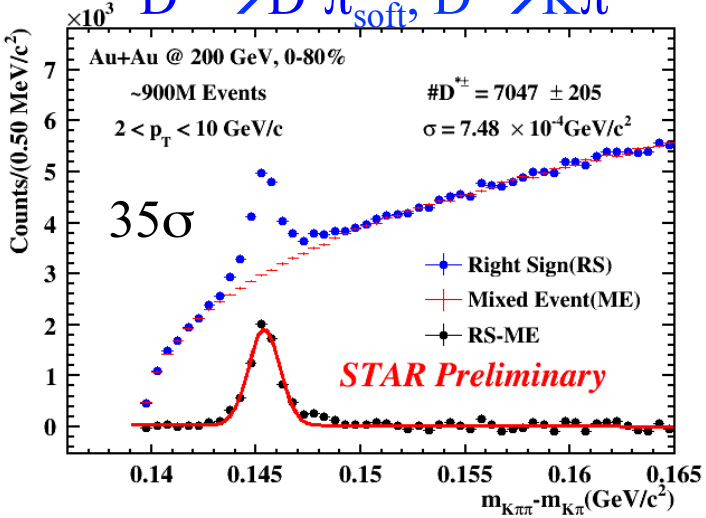
$D^{\pm} \rightarrow K\pi\pi$ (~8.98%)



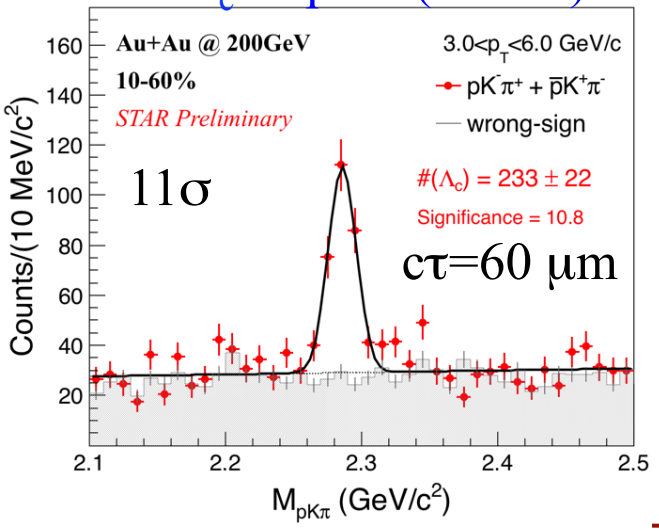
$D_s^{\pm} \rightarrow \phi\pi$, $\phi \rightarrow KK$ (2.27%)



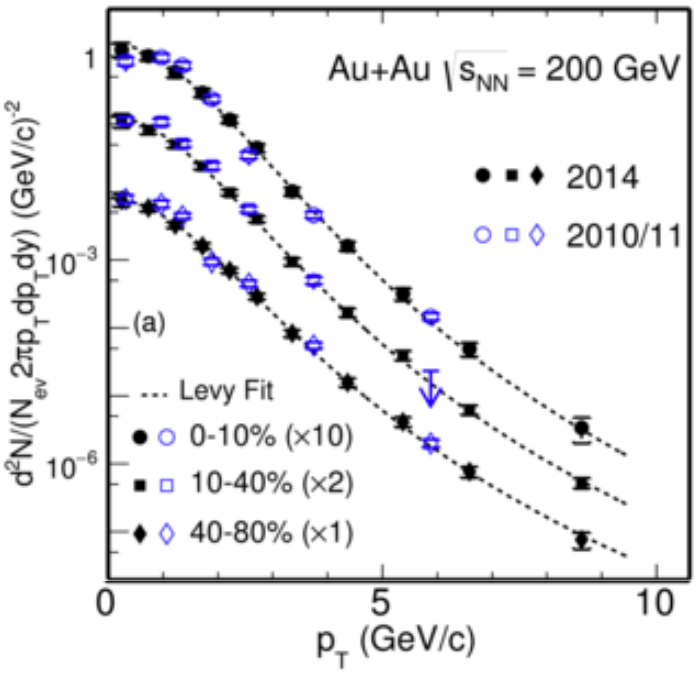
$D^{*\pm} \rightarrow D^0\pi_{soft}$, $D^0 \rightarrow K\pi$

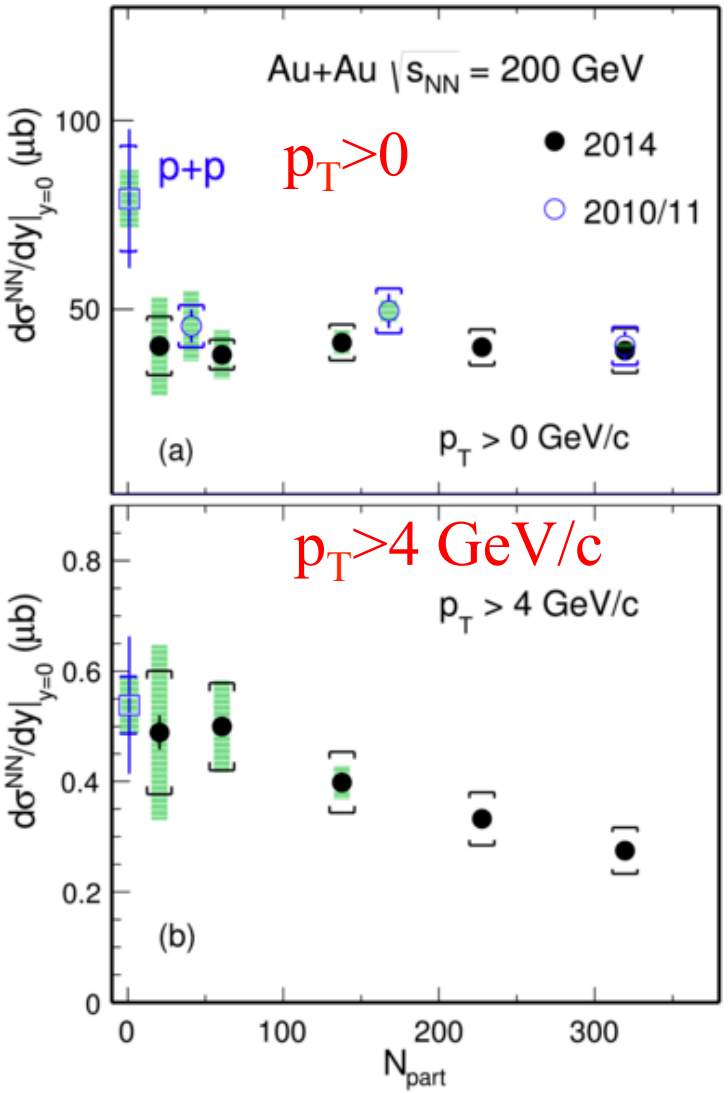


$\Lambda_c^{\pm} \rightarrow pK\pi$ (6.35%)



D^0 cross section in Au+Au @ 200 GeV

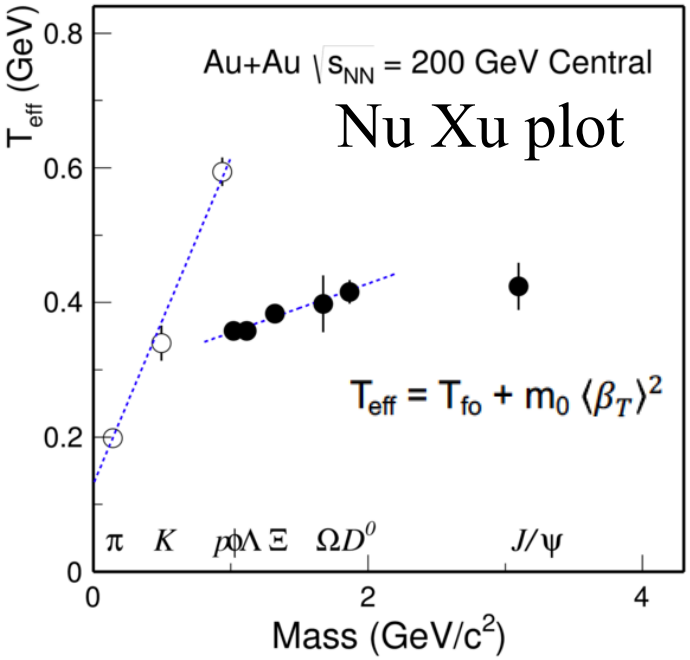


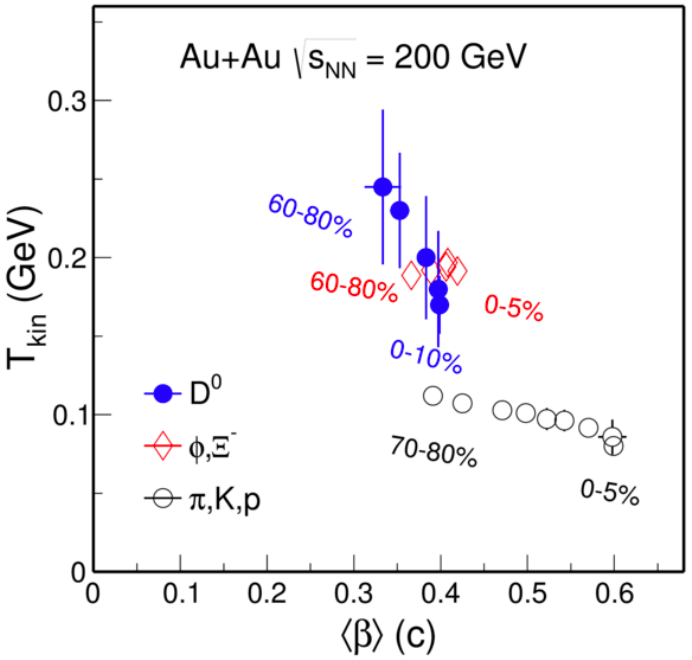


Low-p_T: independent with centrality and lower than in p+p

High-p_T: decrease towards central collisions

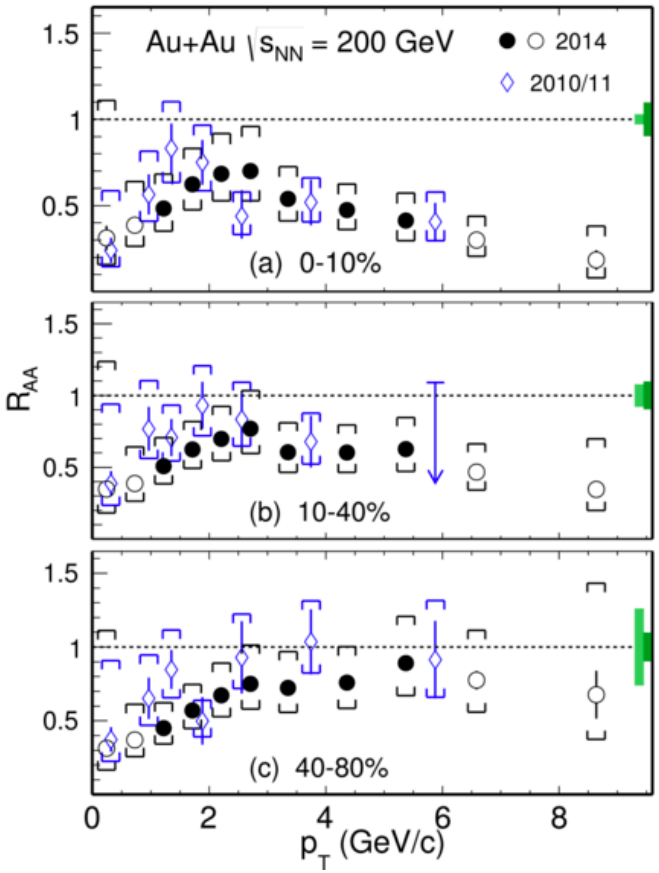
D^0 radial flow

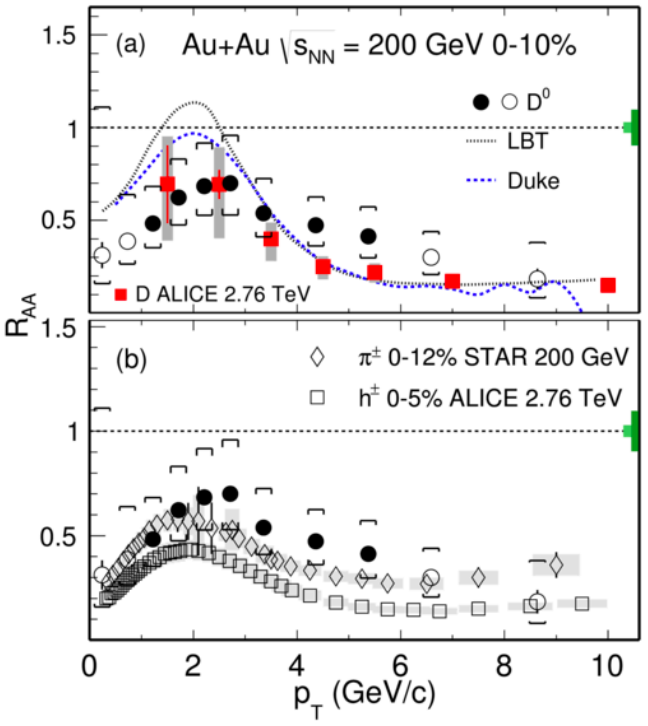




- Follows the same trends of multi-strange hadrons
- Deviates from the trends of light-flavor hadrons

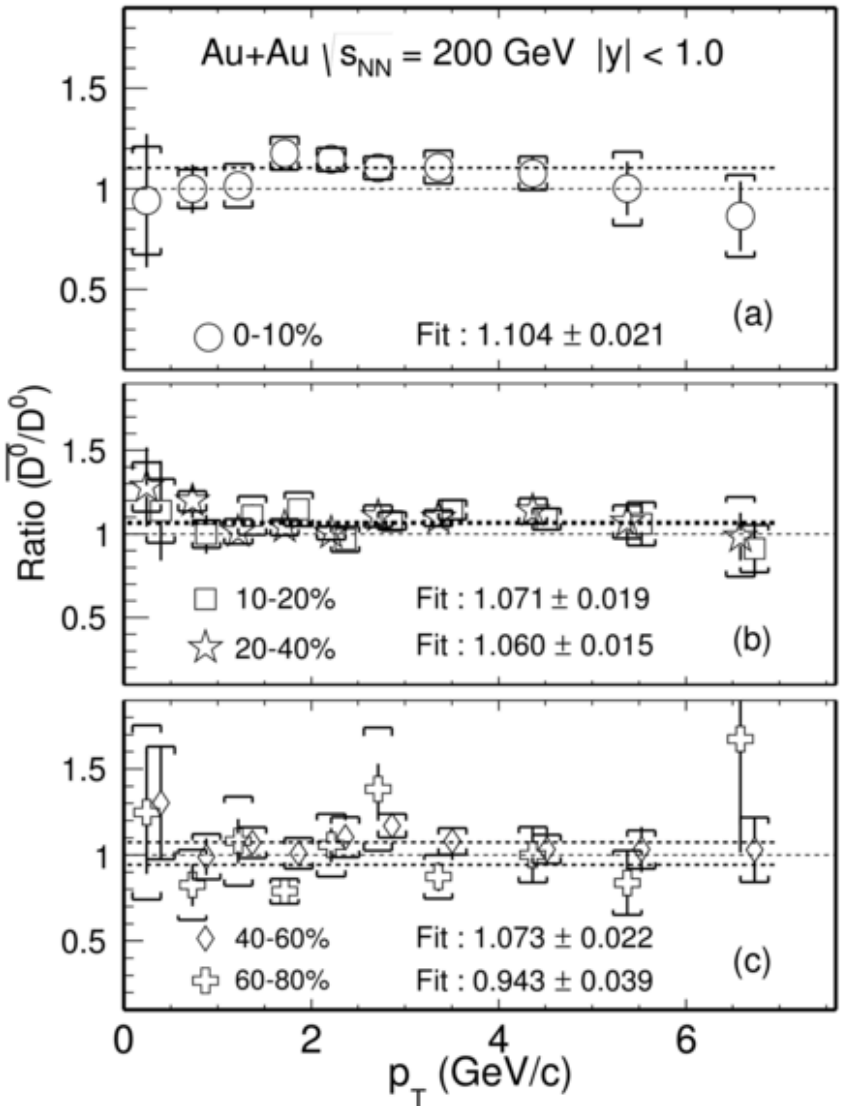
D^0 suppression





- Suppression for all p_T in 0-10% central collisions
- More suppression in central than in peripheral collisions
- Similar suppression as D0@LHC and π@RHIC

$\overline{D}^0/D^0$

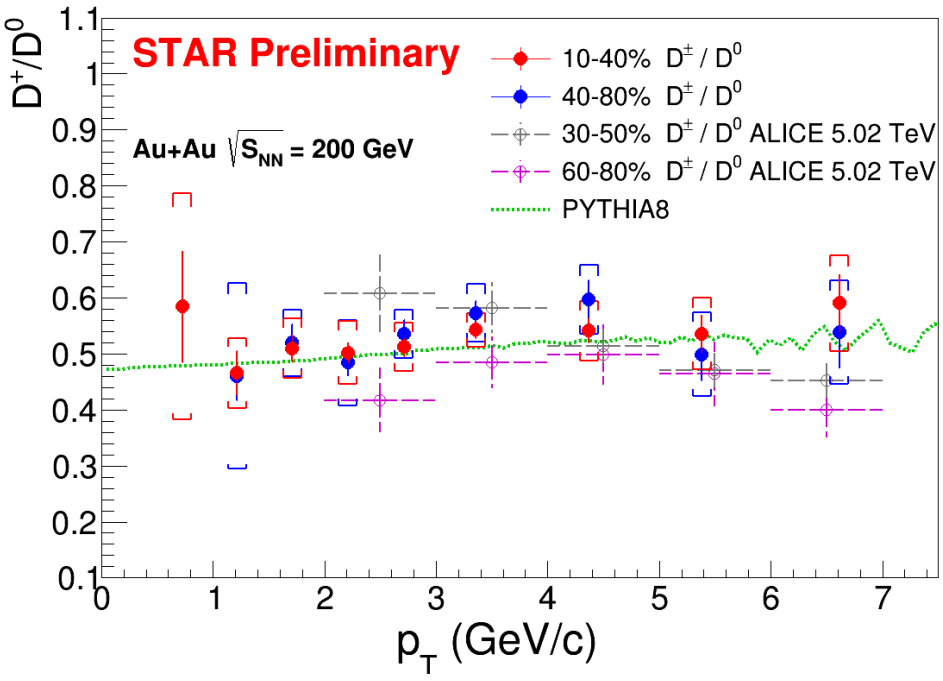


More $\overline{D}^0$ ($\bar{c}u$) than D^0 ($c\bar{u}$), especially in central collisions

Centrality	$\overline{D}^0/D^0$
0–10%	1.104 ± 0.021
10–20%	1.071 ± 0.019
20–40%	1.060 ± 0.015
40–60%	1.073 ± 0.022
60–80%	0.943 ± 0.039

Possibly due to finite baryon density

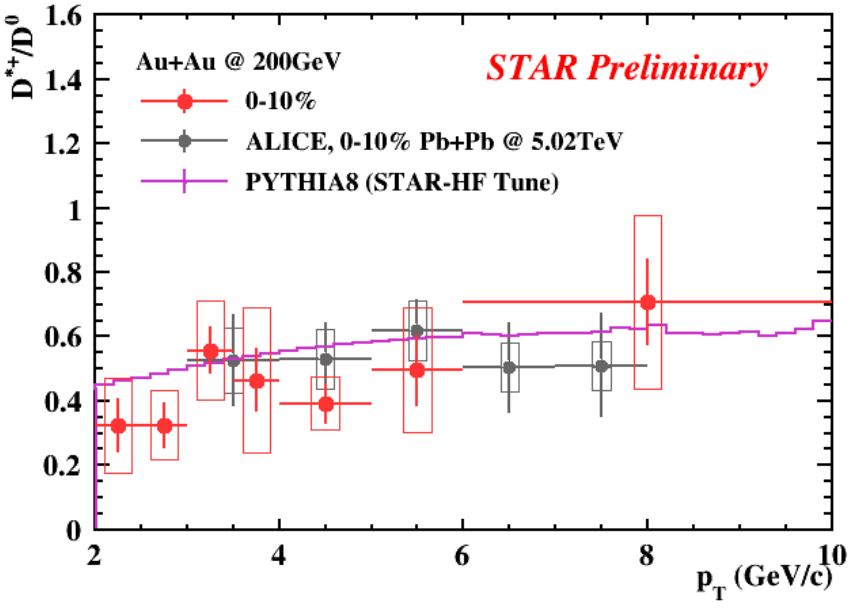
$D^{\pm}/D^{0}$

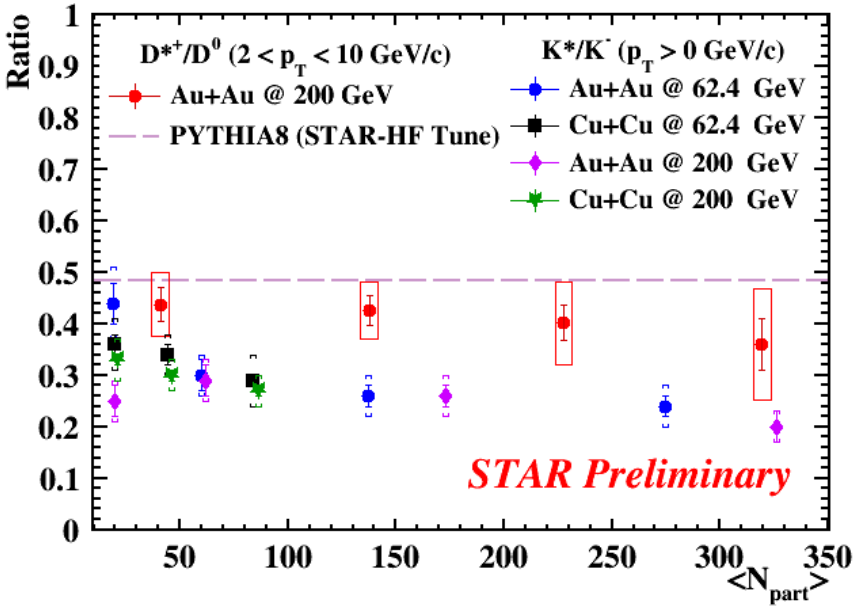


- Consistent with the ratio @ LHC Pb+Pb and PYTHIA

$D^{\pm}/D^{0}$ has similar suppression in heavy-ion collisions

$D^{*\pm}/D^0$

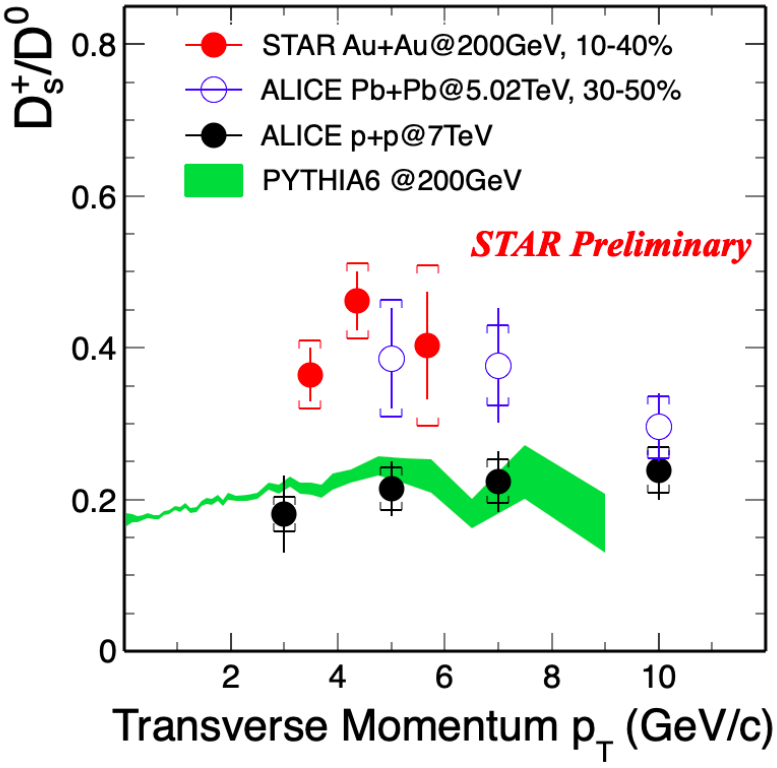




- $D^{*\pm}/D^0$ consistent with the ratio @ LHC Pb+Pb and PYTHIA
- $D^{*\pm}/D^0$ show no centrality dependence, different from K*/K

No significant modification of D* spectral function in Au+Au

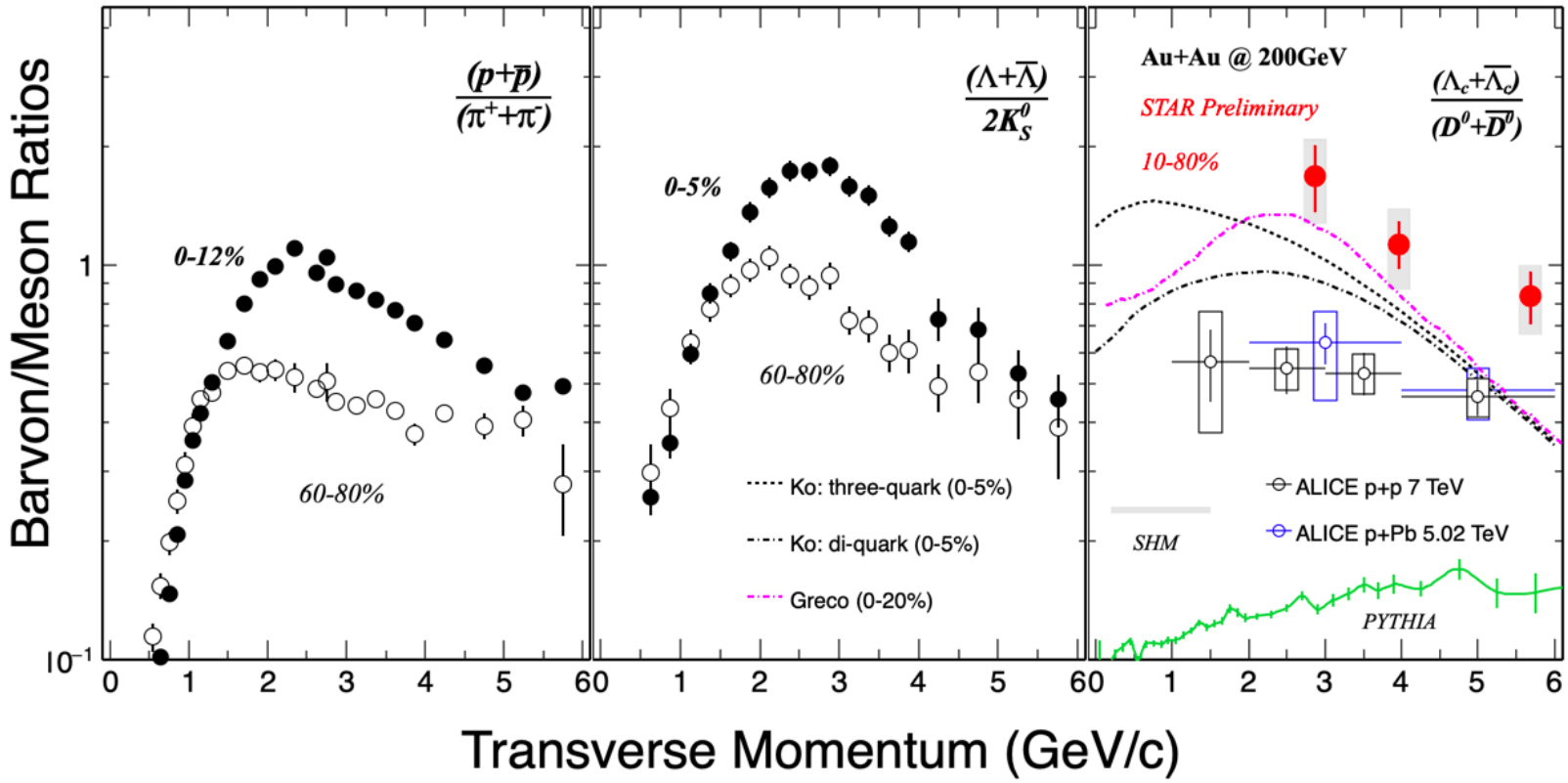
D_s/D^0



- Significant enhancement compare to PYTHIA and ALICE p+p
- Similar enhancement between RHIC and LHC

Strangeness enhancement + coalescence hardonization

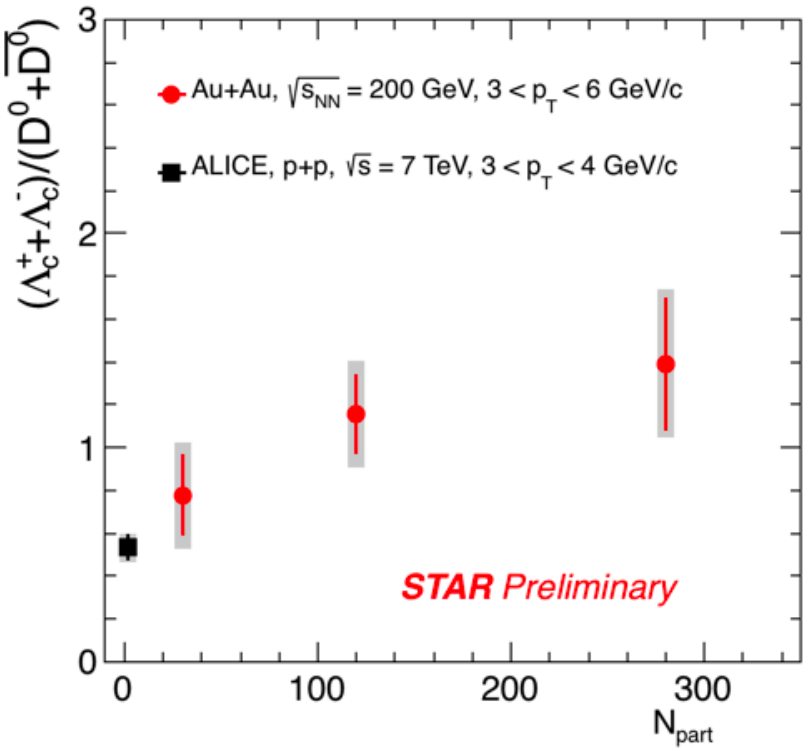
Λ_c/D^0



- Significant enhancement compare to PYTHIA and ALICE pp/pPb
- Comparable to light-flavor baryon-to-meson ratios

Consistent with charm quark hadronization via coalescence

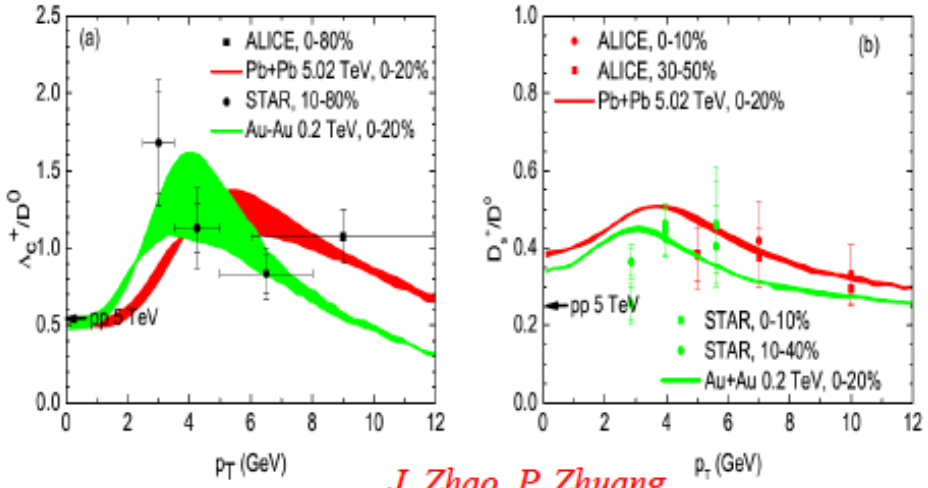
Centrality dependence



- Increase from peripheral to central collisions
- Ratio for peripheral Au+Au comparable with LHC p+p

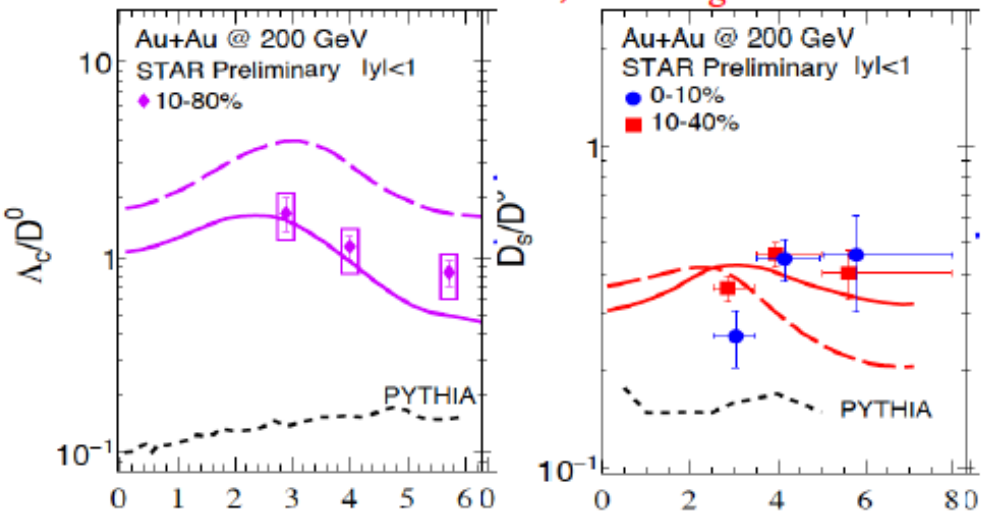
Compare to recent model predictions

M.He, R. Rapp

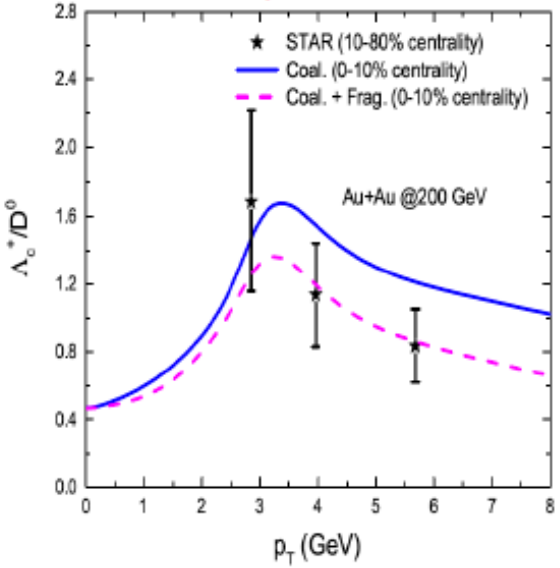


M. He and R. Rapp arXiv:1905.09216
K. Sun, C. M. Ko, etc. arXiv:1905.09774
J. Zhao, P. Zhuang, etc arXiv:1805.10858

J. Zhao, P. Zhuang



K. Sun, C. M. Ko



Charm quark 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

Summary

- Charm quark lose energy in the hot, dense medium

  D-mesons R_{AA}

- Charm quark diffusion in the hot, dense medium

  D-mesons radial flow and

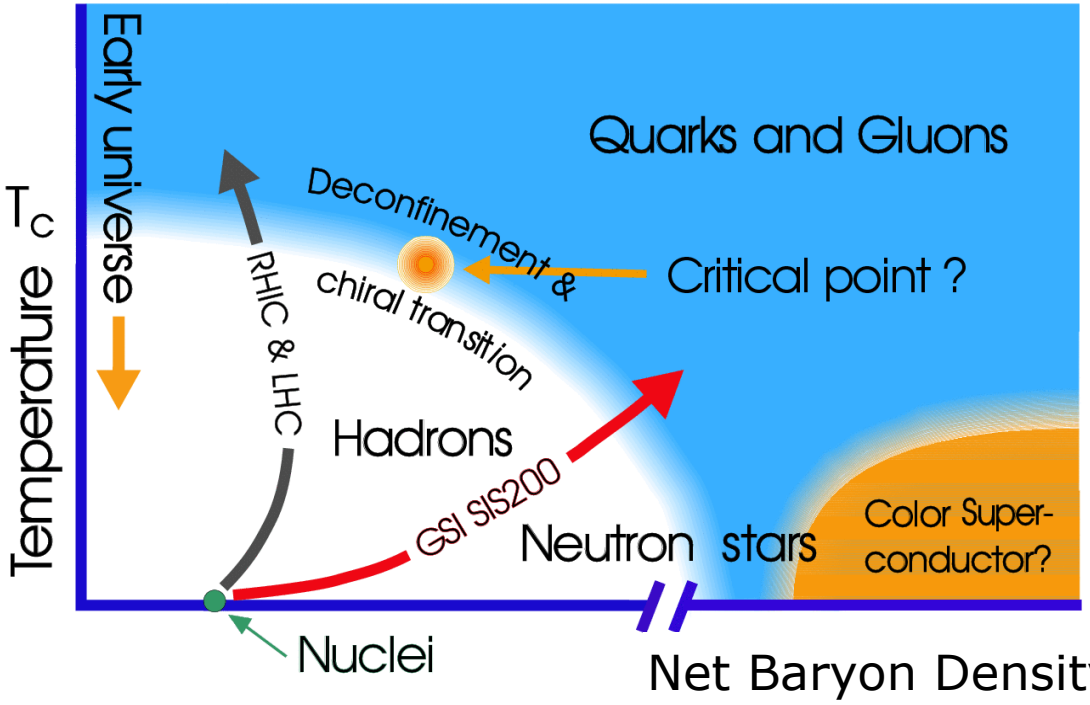
  v_2, v_3 (not shown)

- Charm quark hadronization via quark coalescence

  D_s/D^0 ratio

  Λ_c/D^0 ratio

Quark gluon plasma (QGP)

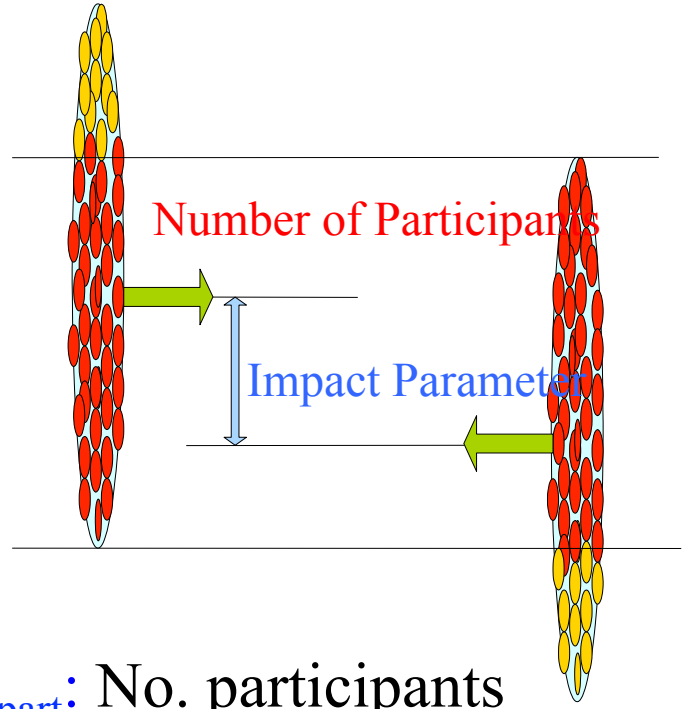


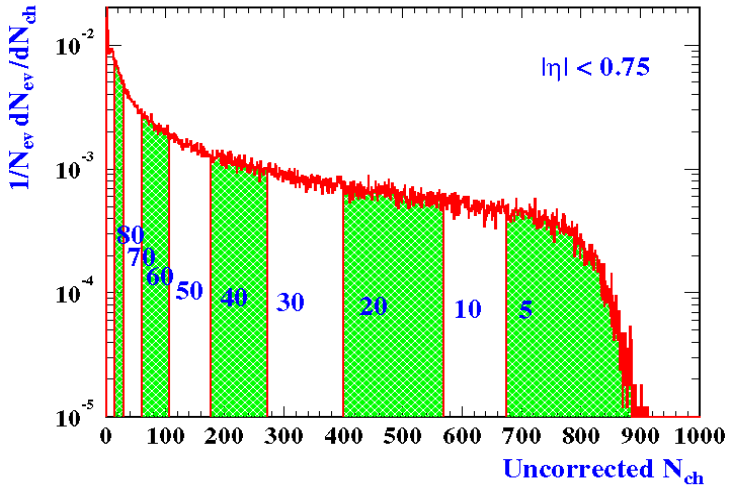
Quark gluon plasma (QGP):

- Many-body system with partonic degree of freedom
- Emergent properties
- The Universe was in this form ~μs after Big Bang

- Lattice QCD predicts phase transition at high temperature/density
- It was proposed to search for and study the properties of QGP via collisions of heavy ions at high energy
- Operating accelerators: RHIC@BNL, LHC@CERN…

Collisions geometry





N_{part}: No. participants

N_{coll}: No. binary nucleon-nucleon collisions

Central collisions:

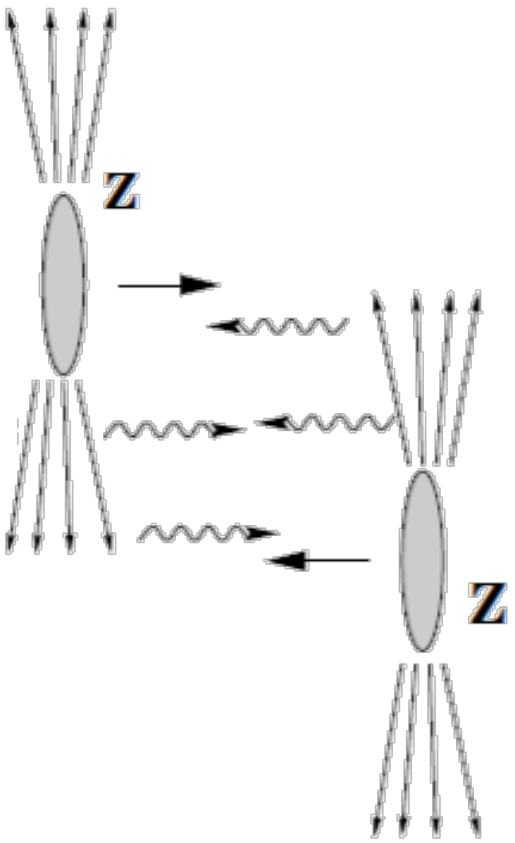
- Small impact parameter
- Large N_{part} and N_{coll}
- Large multiplicity

Centrality determined according to the measured (charged) multiplicity

Electromagnetic field in heavy-ion collisions

- Strong EM field accompanies the nuclei in relativistic heavy-ion collisions

  $B \sim \gamma Zeb/R^3 \sim O(10^{14}\ Tesla)$ @RHIC

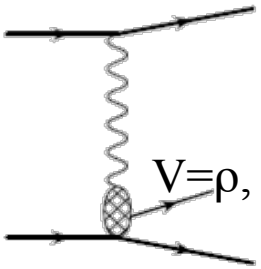


- The Lorentz contracted EM field can be expressed in terms of equivalent photon flux *E. Fermi, Z. Phys. 29, 315 (1924)*

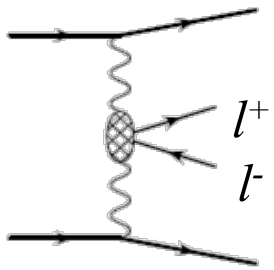
- The quasi-real photons can initiate γA or γγ collisions in relativistic heavy-ion collisions

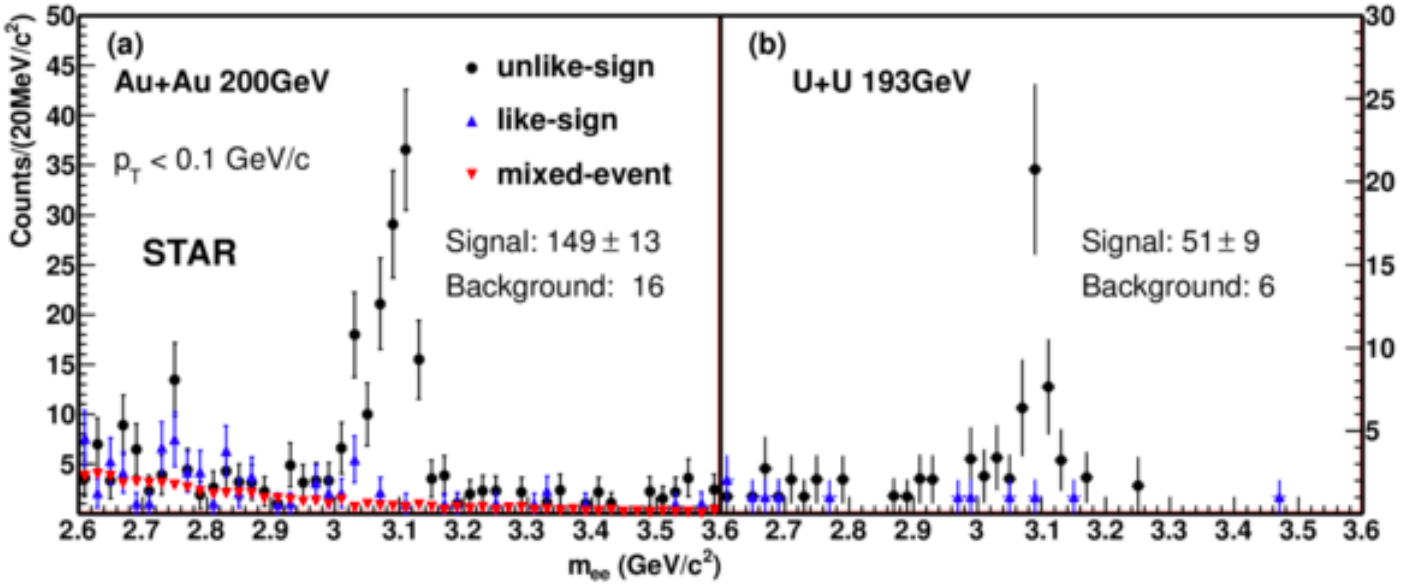
Clear J/ψ signals at very low p_T

γA



γγ

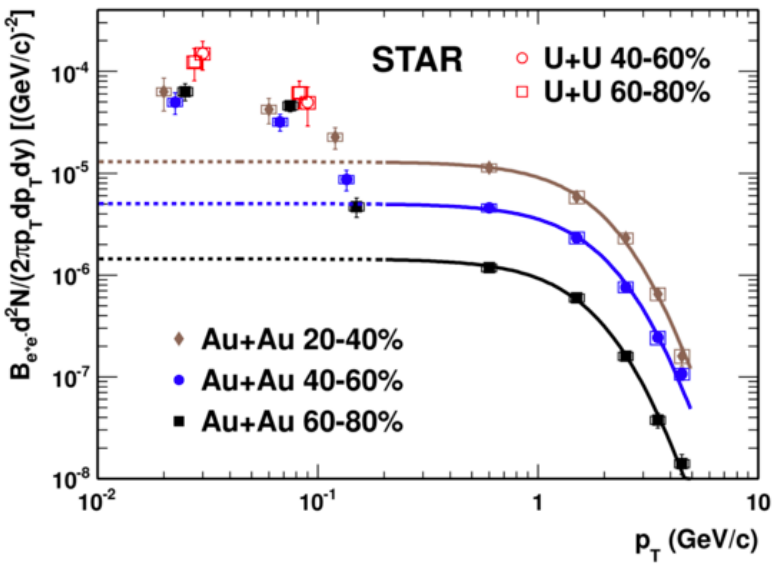


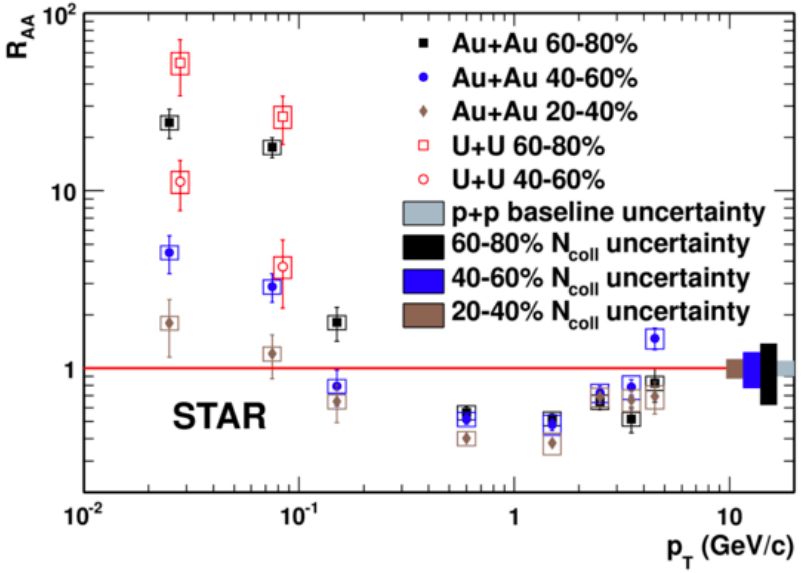


STAR, PRL121, 132301 (2018)

STAR, PRL123, 132302 (2019)

Very-low-p_T J/ψ enhancement at STAR



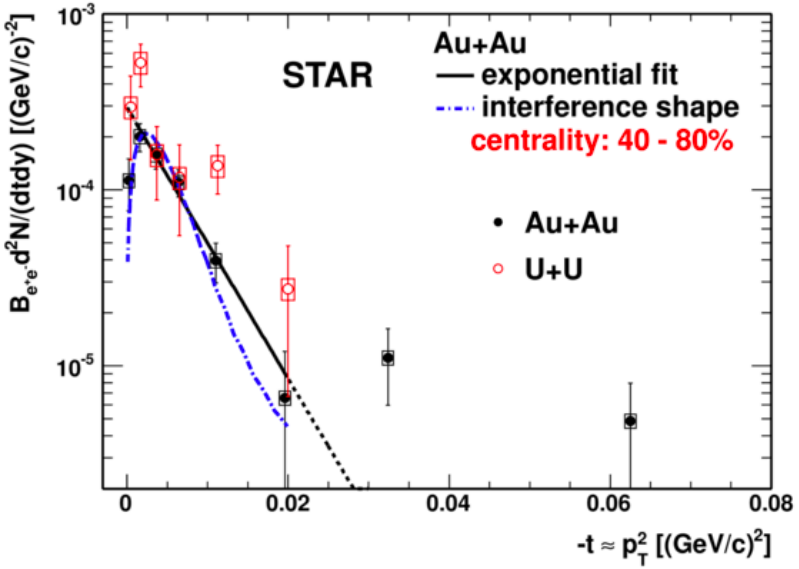


Fit fun. (empirical): $\dfrac{a}{\left(1+b^2 p_T^2\right)^n}$

Significant enhancement of J/ψ yield at p_T<0.1 GeV/c in (semi-)peripheral Au+Au and U+U collisions, $R_{AA} \sim 40$

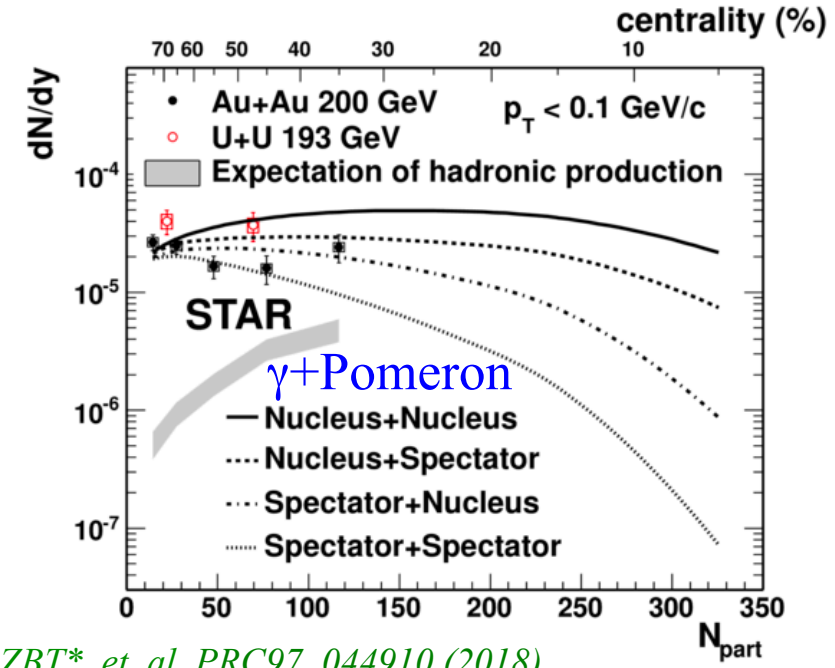
Confirm ALICE observation (PRL116, 222301 (2016))

Momentum transfer squared distribution

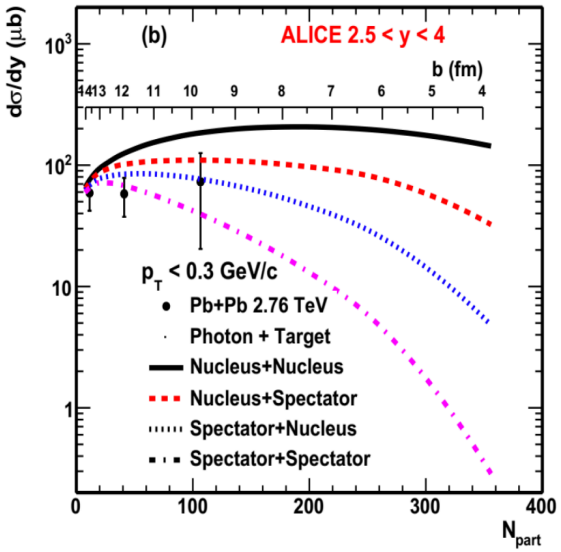


- First -t distribution of J/ψ production at low p_T in non-UPC
- Slope = 177 ± 22 $(GeV/c)^{-2}$ consistent with expected from coherent photoproduction for an Au nucleus (199 $(GeV/c)^{-2}$)
- The drop at the lowest bin may be an indication of interference $\chi^2/ndf = 4.8/4$

Centrality dependence of yield



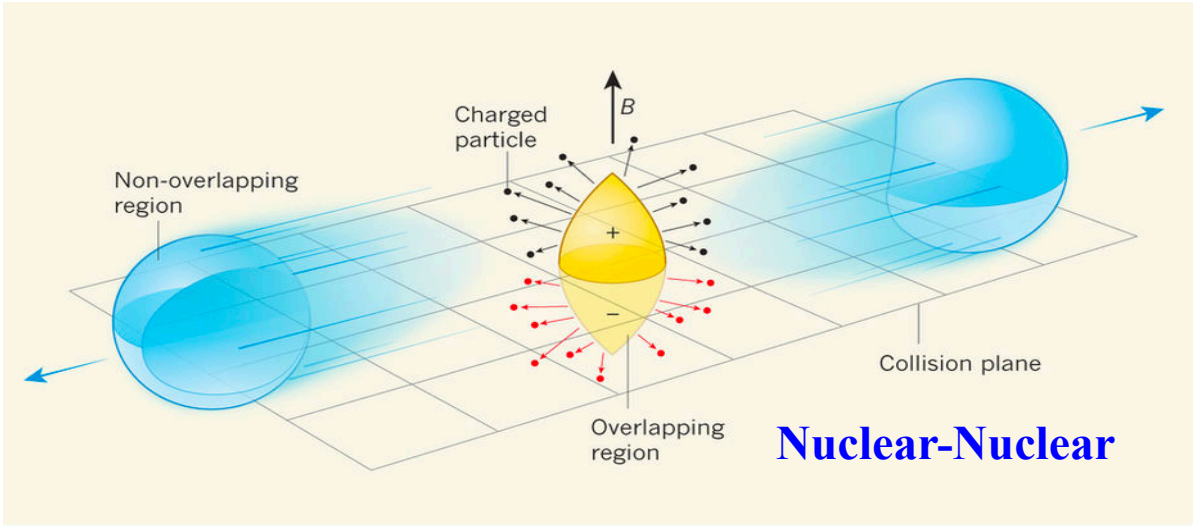
ALICE, PRL116, 222301 (2016)

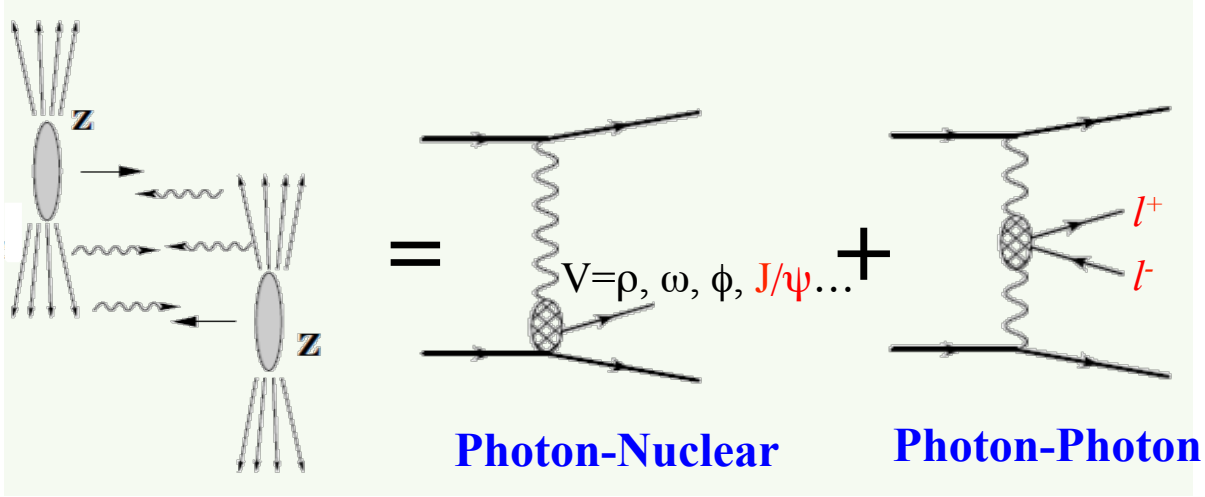


W. Zha, …, ZBT, et. al, PRC97, 044910 (2018)*
W. Zha, L. Ruan, ZBT*, Z. Xu, S. Yang, PRC99, 061901 (R) (2019)*
W. Zha, L. Ruan, ZBT*, Z. Xu, S. Yang, PLB789, 238-242 (2019)*
Z. Cao, …, W. Zha, CPC43, 064103 (2019)*

- No significant centrality dependence for very-low-p_T J/ψ
- Model calculations with all scenarios describe data at b~2R
  - "Nucleus+Spectator" and "Spectator+Nucleus" are favored

Coherent photoproducts in QGP

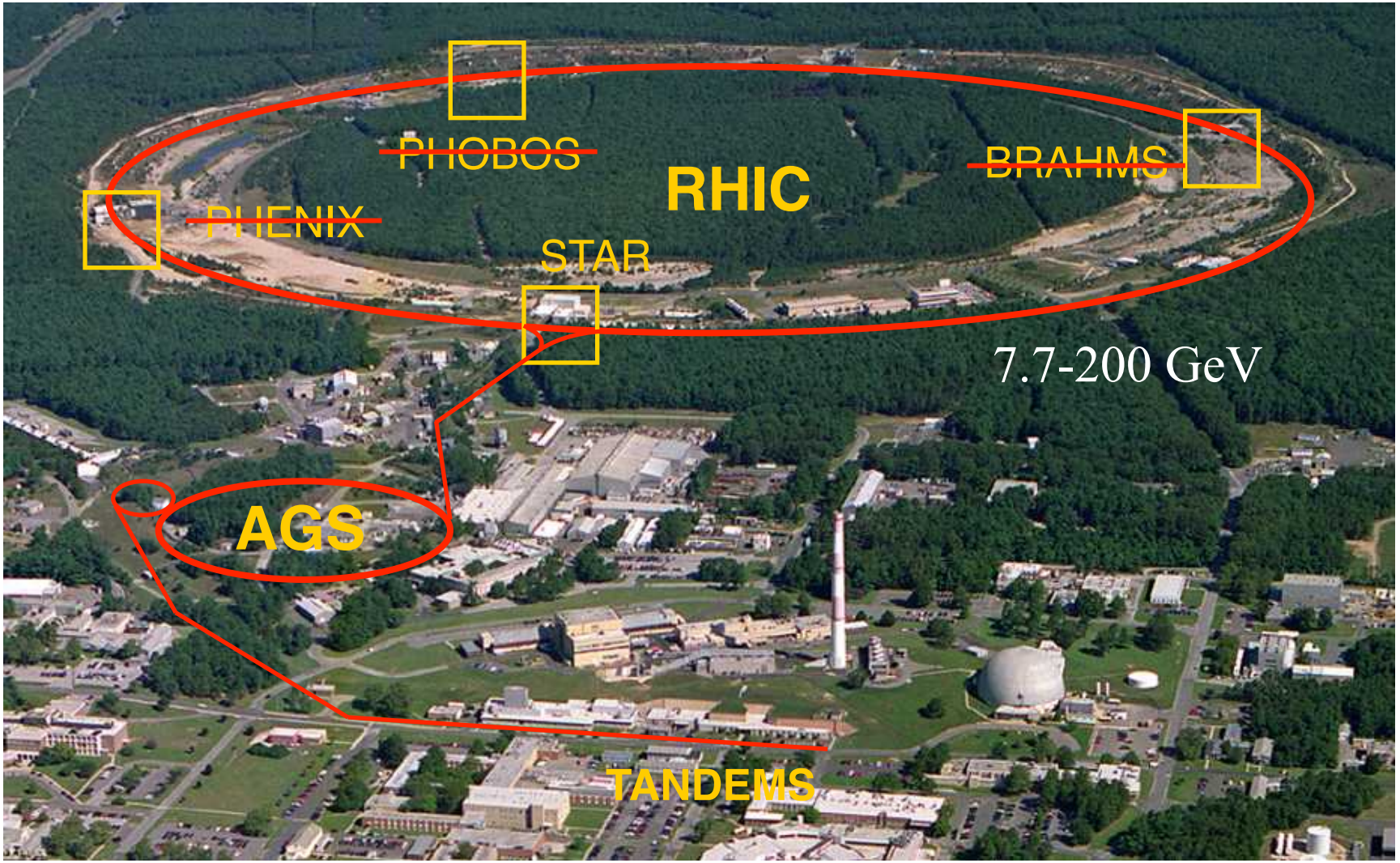




Novel probe of QGP

- Deconfinement
- EM field
- …

Relativistic Heavy Ion Collider @BNL



Large Hadron Collider @CERN