Excited QCD
Kopaonik, Serbia, 2018

Overview of heavy flavor results at STAR

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EUROPEAN UNION
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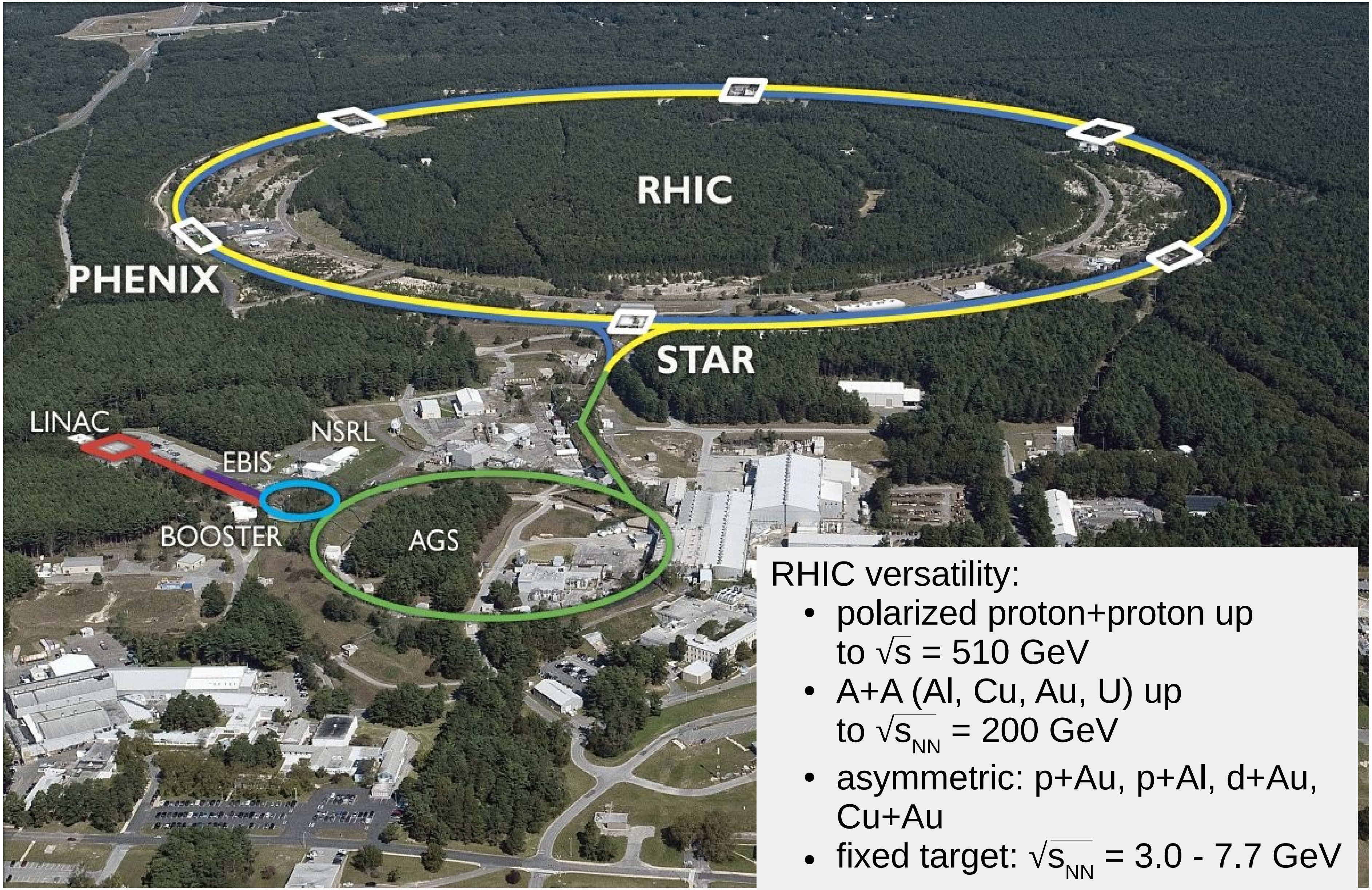
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Outline

- STAR experiment at RHIC
- Open heavy flavor measurements
- Quarkonium measurements
- Summary

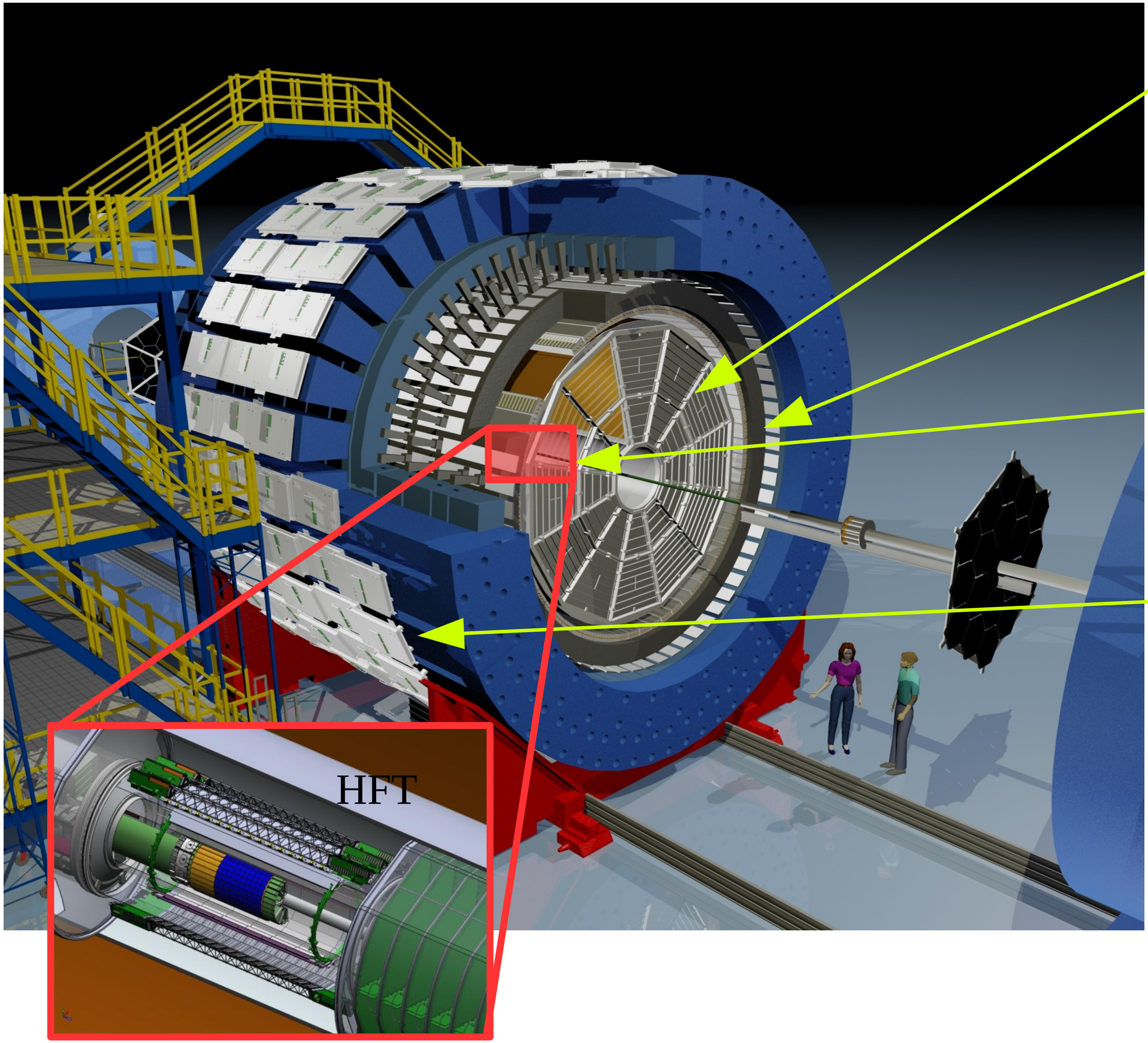
RHIC



RHIC versatility:

- polarized proton+proton up to $\sqrt{s}$ = 510 GeV
- A+A (Al, Cu, Au, U) up to $\sqrt{s_{NN}}$ = 200 GeV
- asymmetric: p+Au, p+Al, d+Au, Cu+Au
- fixed target: $\sqrt{s_{NN}}$ = 3.0 - 7.7 GeV

The Solenoidal Tracker At RHIC (STAR) detector



Time Projection Chamber (TPC):
- tracking
- particle identification via dE/dx

Time Of Flight (TOF):
- particle identification via $1/\beta$

Heavy Flavor Tracker (HFT, 2014-2016):
- tracking
- secondary vertex reconstruction

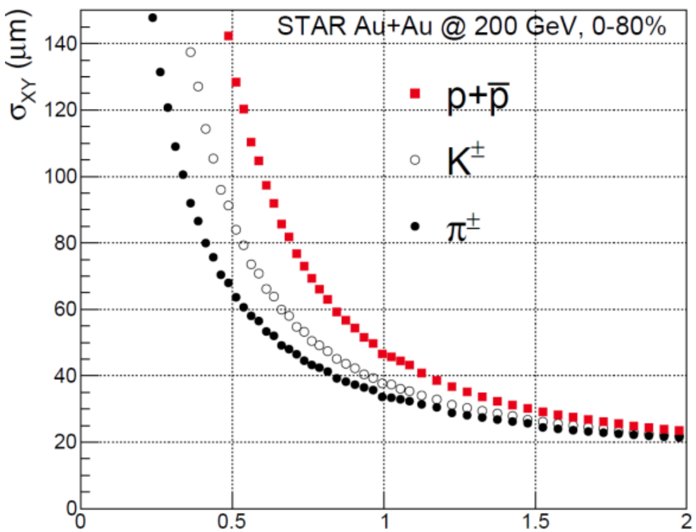
Muon Telescope Detector (MTD):
- triggering
- muon identification

TPC/TOF/HFT: full azimuthal coverage at mid-rapidity ($|\eta|<1$)

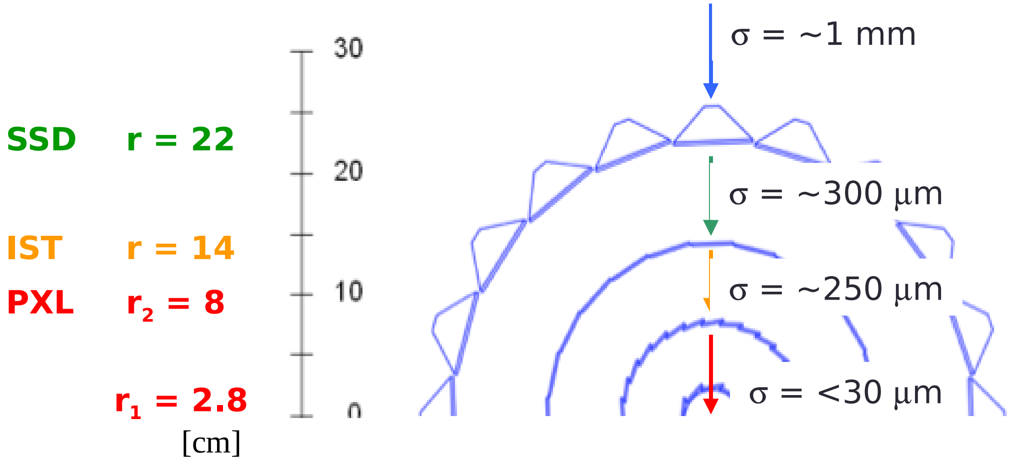
Heavy Flavor Tracker

Heavy Flavor Tracker (HFT):

- SSD – Silicon Strip Detector
- IST – Intermediate Silicon Tracker
- PXL – Pixel Detector (MAPS, 356M pixels of silicon, 20x20 μm^2, 0.4% X_0, air-cooled)



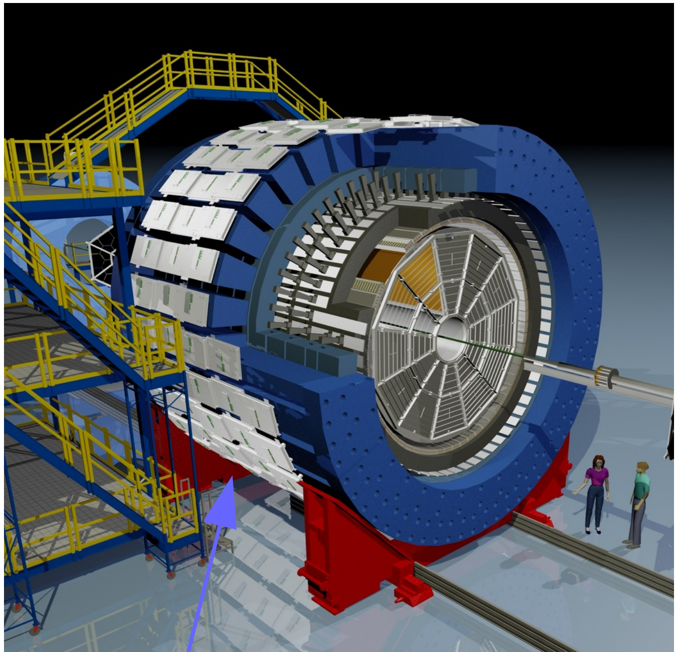
PRL 118 (2017) 212301

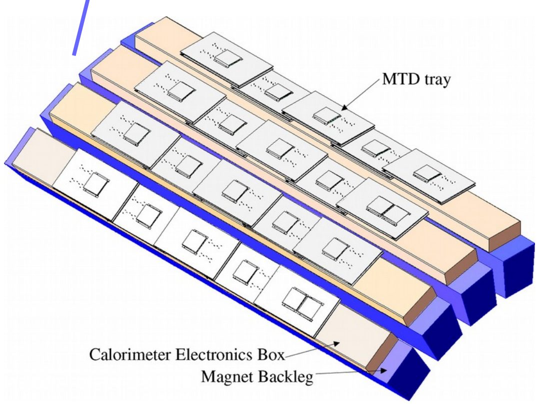


Track pointing resolution ~ 50 μm for Kaons with p = 750 MeV/c

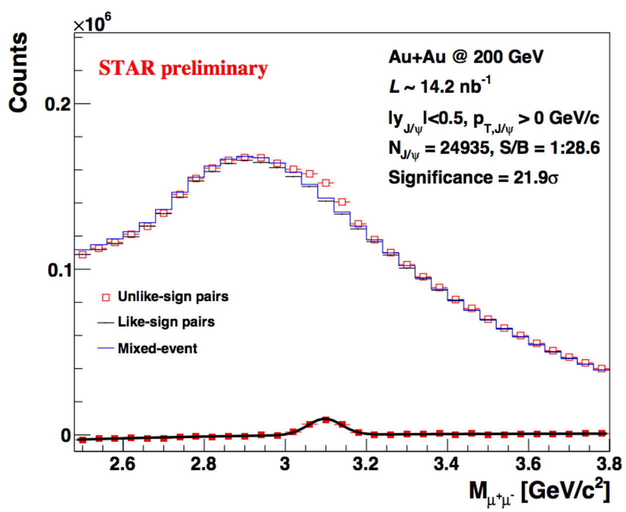
Λ_c: $c\tau$ = 60 μm

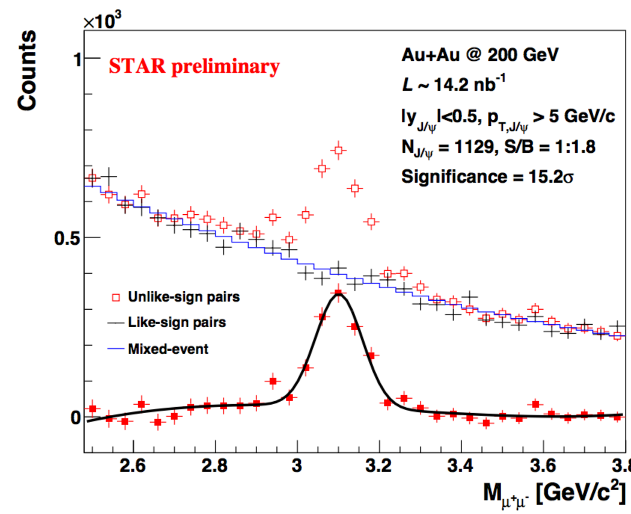
Muon Telescope Detector





- Designed for muon triggering and identification ($p_T \gtrsim 1.2$ GeV/c) with precise timing $\sigma \sim 100$ ps
- Multi-gap resistive plate chambers (MRPC), similar technology as used for Time of Flight (TOF) detector
- Placed behind magnet, which is used as a hadron absorber (~ 5 λ_I)
- Geometrical acceptance: ~45% in azimuth within $|\eta| < 0.5$



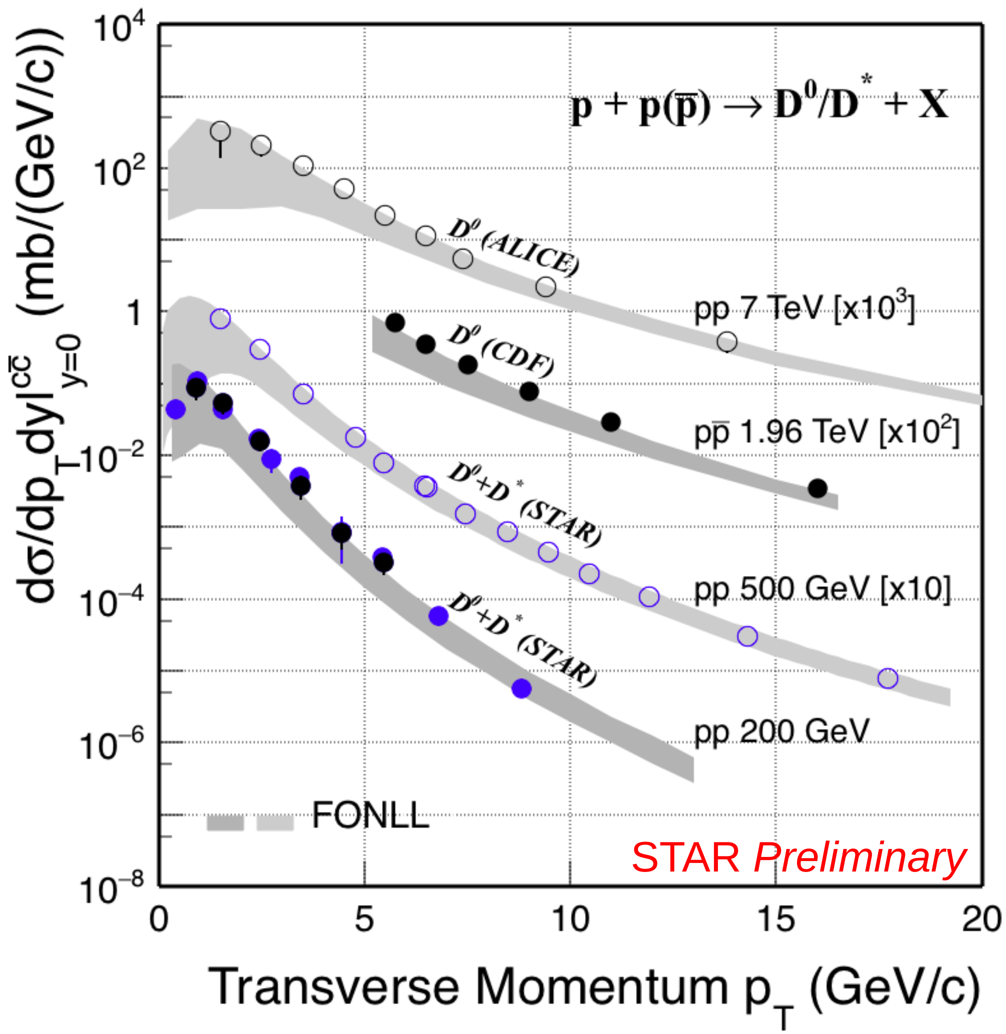


Open heavy flavor in the QGP

Heavy quarks (c, b)

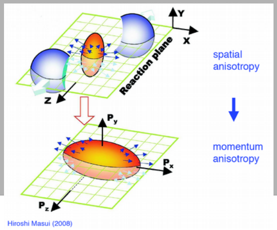
$\mathbf{m_b > m_c >> T_{QGP}, \Lambda_{QCD}}$

- Produced early in initial hard scatterings → experiencing the entire evolution of the hot nuclear matter → used as a probe to study properties of the QGP medium
- Charm production rates are well described by pQCD in p+p collisions
- Flavor dependence of parton energy loss is sensitive to the medium properties
- Compare yields of different charm hadrons to study the hadronization process



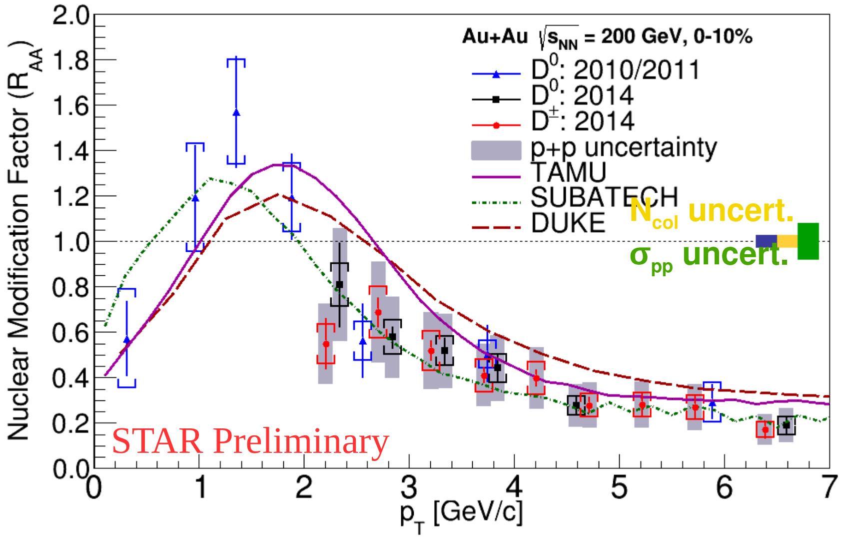
STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

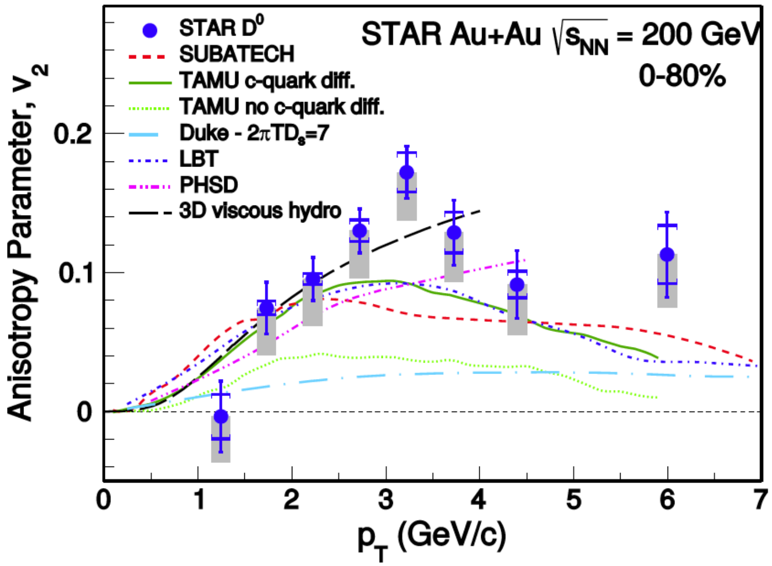
D^0 R_{AA} and elliptic flow



$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}$$

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\psi_r))\right)$$



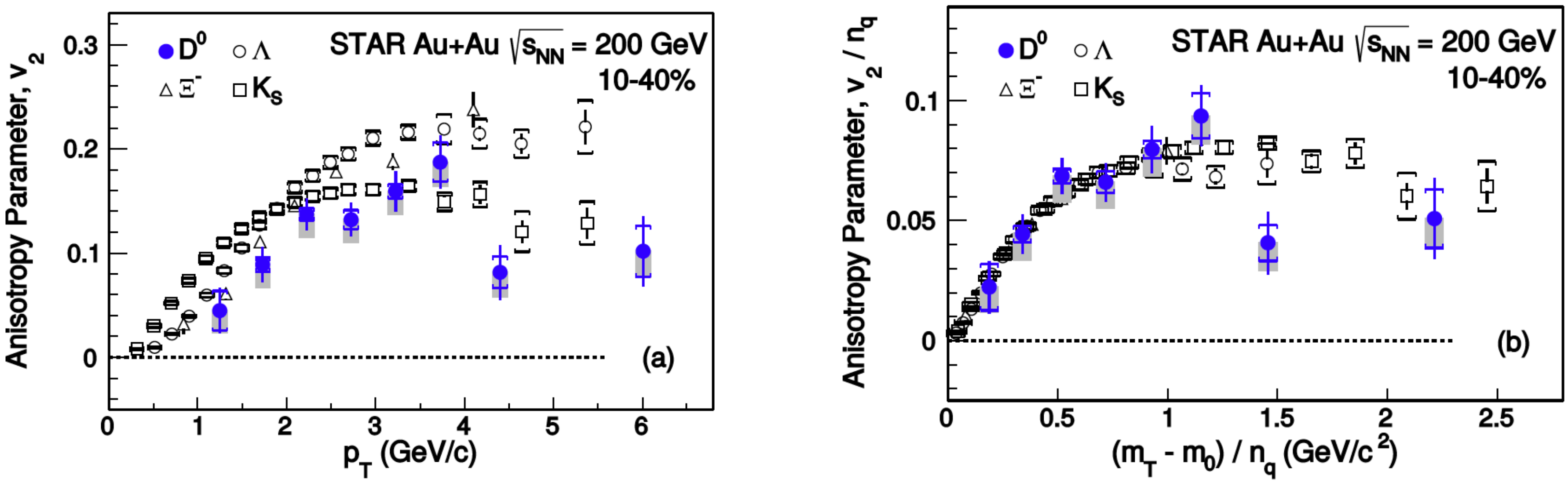


- Significant yield suppression in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for p_T > 2.5 GeV/c → strong charm-medium interaction
- R_{AA} of D^0 and $D^{\pm}$ are consistent

- D^0 azimuthal anisotropy significantly above zero for p_T > 1.5 GeV/c → charm quark flows with the medium
- Models with strong charm-medium interactions describe qualitatively the data
- D_s – charm quark spatial diffusion coefficient in the medium
- $(2\pi T)D_s$ = 2 -12 for T_c – $2T_c$

STAR D^0:2010/2011 PRL 113 (2014) 142301; v_2: PRL 118, 212301 (2017)
TAMU: Eur. Phys. J. C (2016) 76: 107 & private comm.;
SUBATECH: PRC 91(2015) 054902 & private comm.;Duke: PRC 92(2015) 024907 & private comm.; PHSD: PRC 90, 051901 (2014), PRC 92, 014910 (2015);
LBT: Phys. Rev. C 94, 014909 (2016); 3D viscous hydro: PRC 86, 024911 (2012), PRD 91, 074027 (2015) & private comm.

Comparison to light flavors

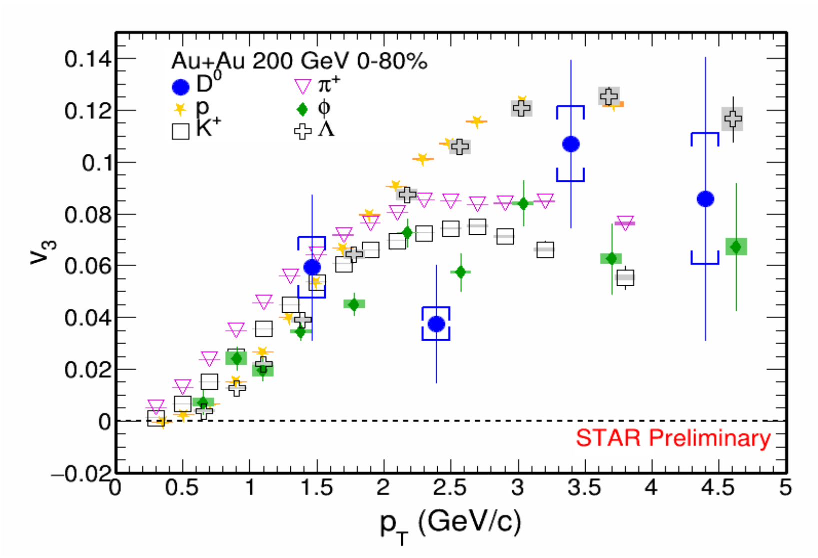


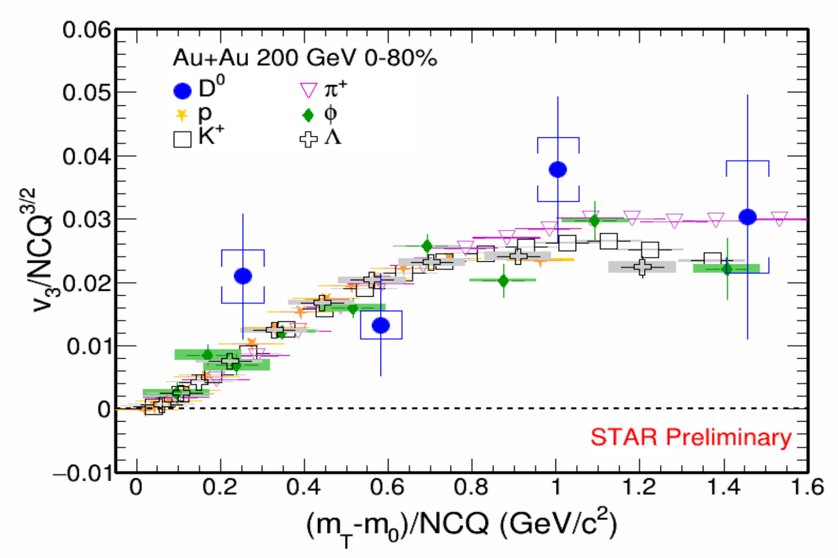
PRC 77 (2008) 54901, PRL 116 (2016) 62301, PRL 118 (2017) 212301

- Mass ordering is observed below 2 GeV/c
- D^0 v_2 exhibits same NCQ (number of constituent quarks) scaling as light hadrons

  → charm quarks may have acquired similar flow as light quarks

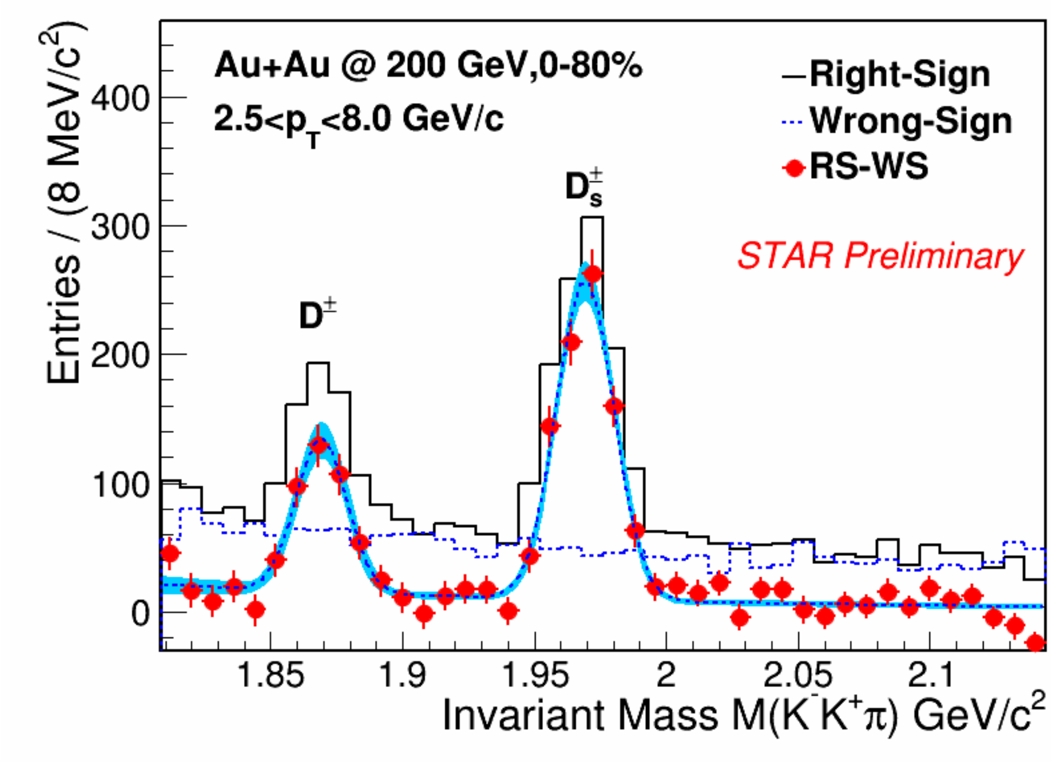
D^0 triangular flow

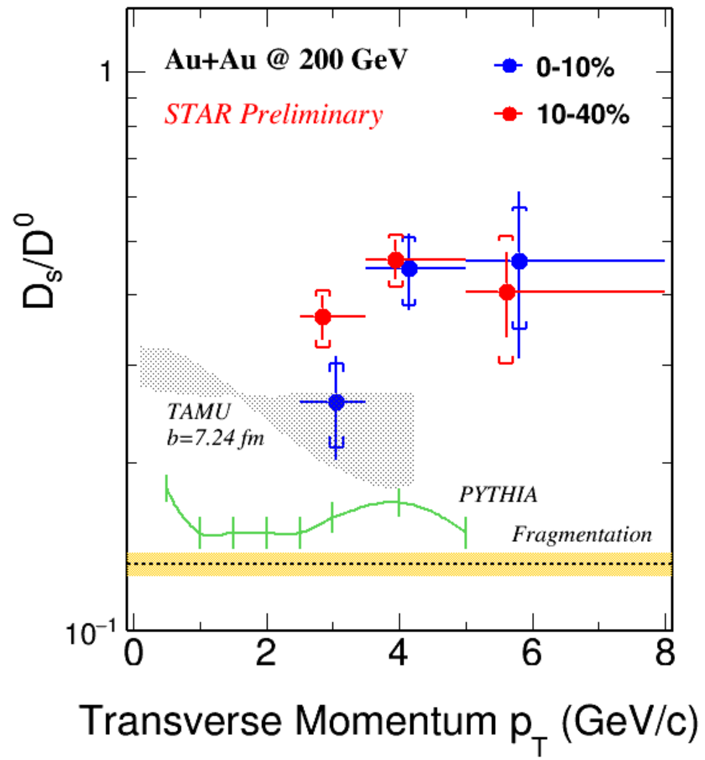




- First D^0 v_3 measurement at RHIC
- Non-zero D^0 v_3
  → importance of initial fluctuations
- Non-zero D^0 v_2 and v_3
  → strong collective behaviour
- D^0 v_3 also follows the NCQ scaling within errors
- Need more statistics for solid conclusion (add data from 2016)

D_s / D^0– study of charm hadronization mechanism



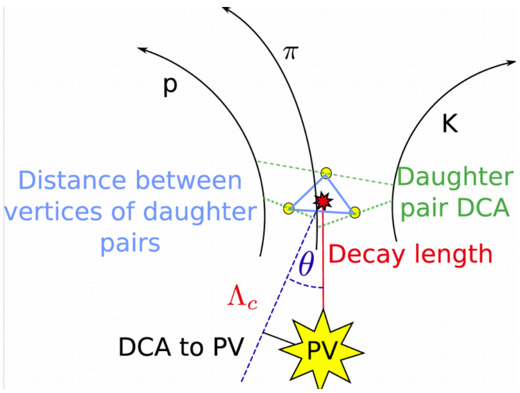


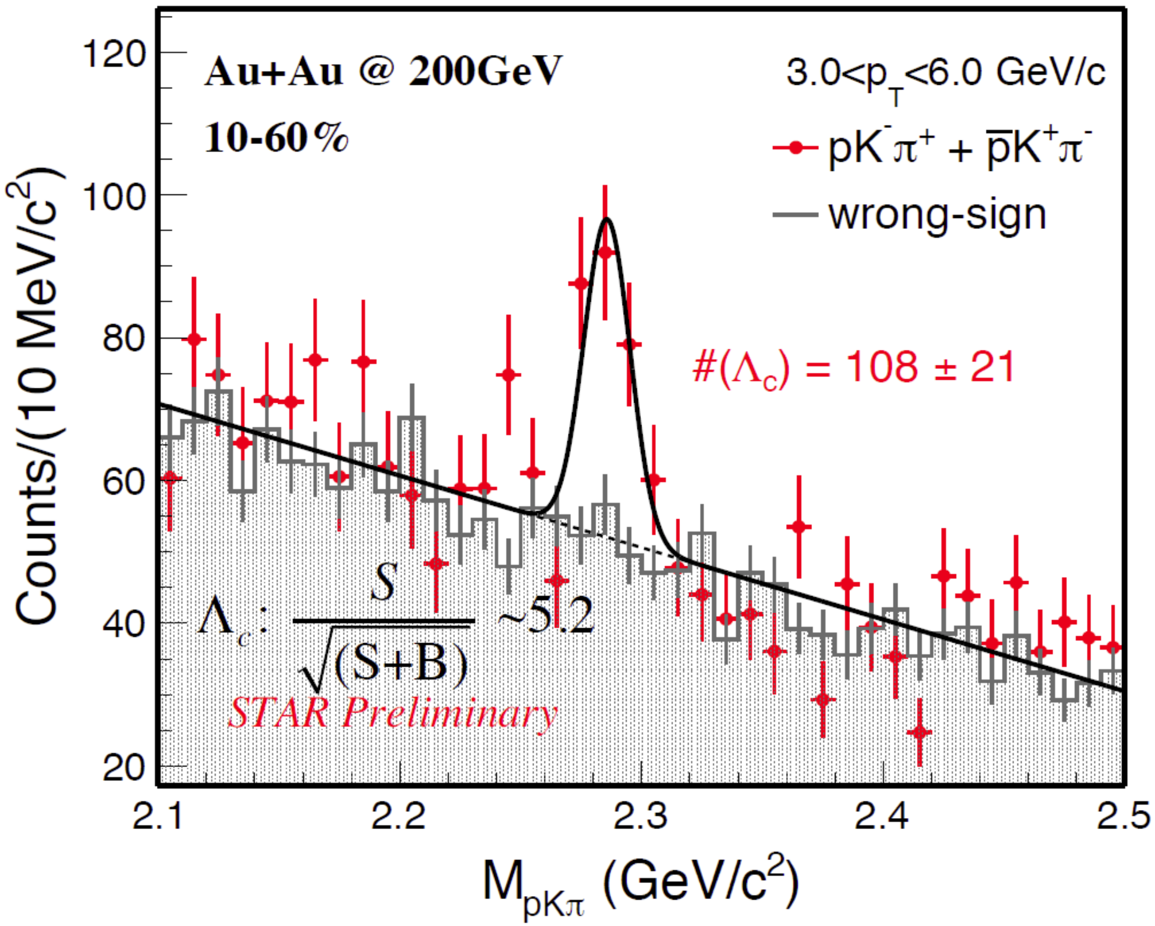
TAMU: PRL 110 (2013) 112301
H1 Collaboration, Eur.Phys.J.C38(2005)447
ZEUS Collaboration, Eur.Phys.J.C44(2005)351

- Strong enhancement of the D_s/D^0 ratio compared to fragmentation ratio measured at HERA and PYTHIA version 6.4
- Enhancement in 10–40% centrality seems stronger than the TAMU model calculation with charm quark coalescence

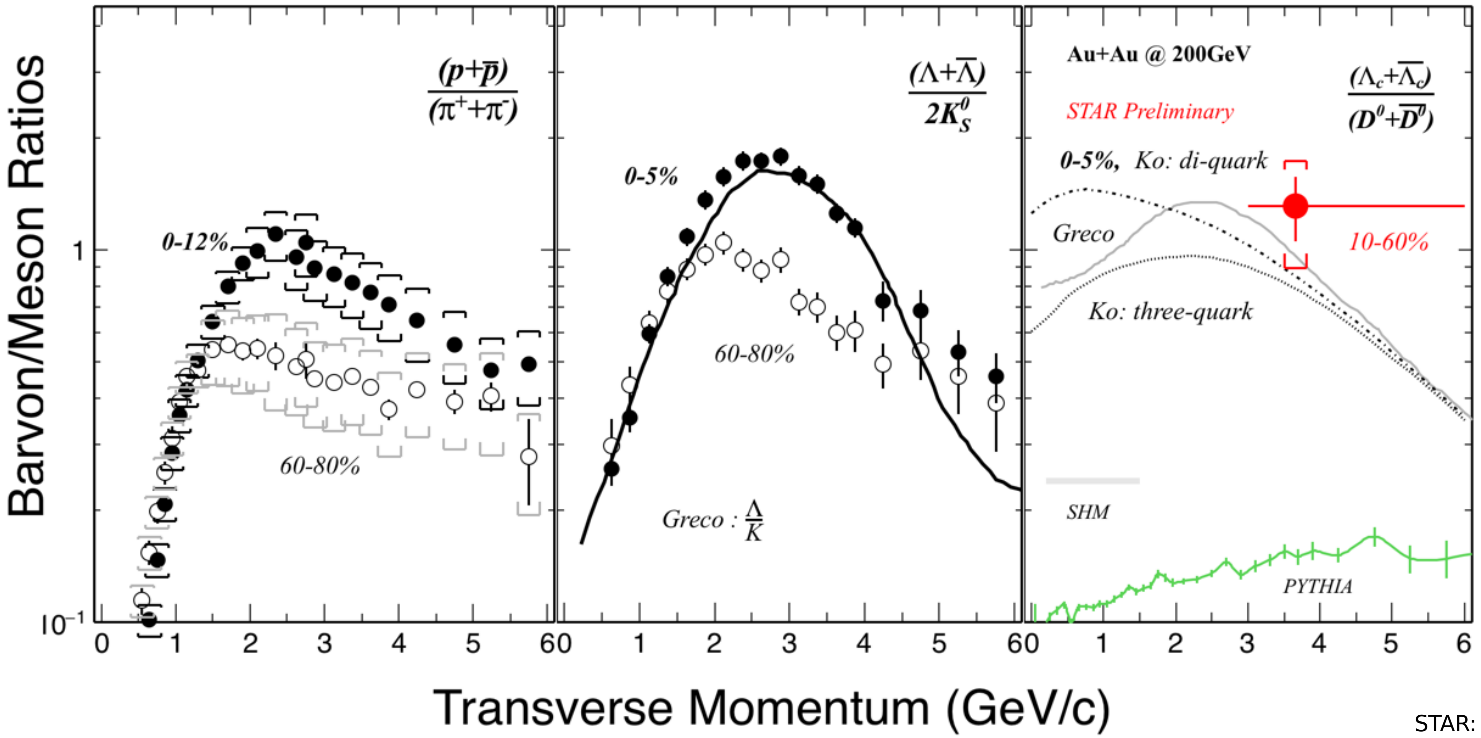
Λ_c reconstruction

- First measurement of charmed baryons in high-energy heavy-ion collisions
- $c\tau = 60\ \mu m$
- B.R. = 6.35%
- $\Lambda_c^{\pm} \rightarrow p^{\pm}K^{\mp}\pi^{\pm}$





Λ_c / D^0



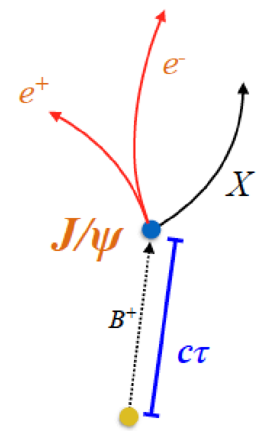
STAR: PRL 108 (2012) 072301
SHM: PRC 79 (2009) 044905
Ko: PRL 100 (2008) 222301
Greco: arXiv:1712.00730

- Clear enhancement of Λ_c / D^0 observed compared to PYTHIA:
  - STAR: 1.3 ± 0.3 (stat.) ± 0.4 (sys.)
  - PYTHIA: 0.1 - 0.15
- Compatible with baryon-to-meson ratios observed for light hadrons
- Ko's model (0-5%) can describe the data with both di-quark + 1 quark, and three-quark scenarios
- Grecos's model is consistent with data
- SHM prediction is lower than the data

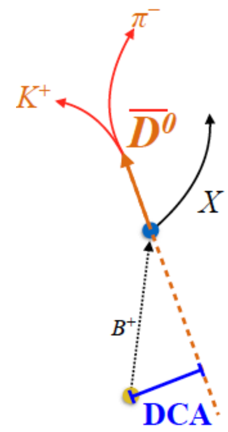
B production measurement

Separate measurements of c and b energy losses in the medium.

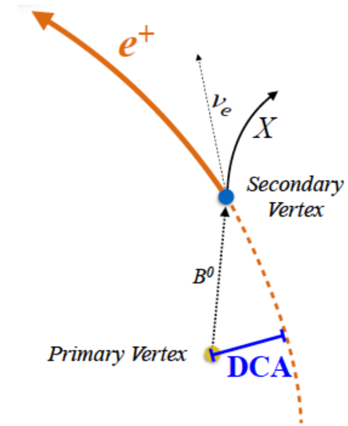
B → J/ψ

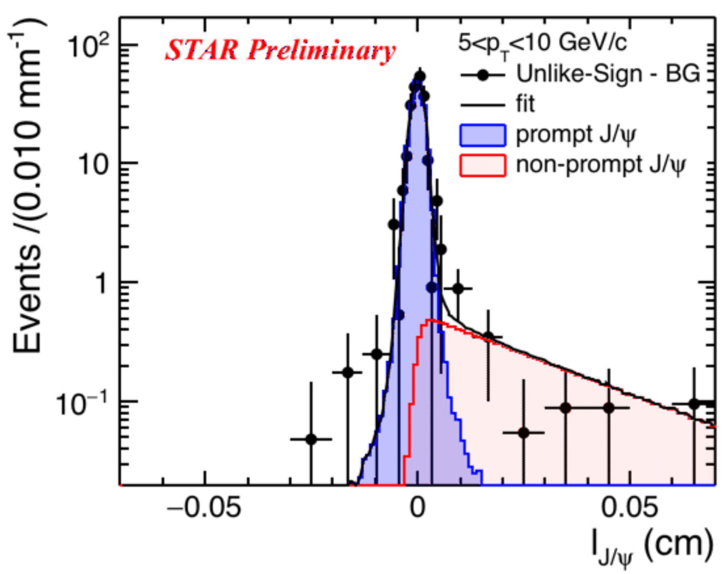


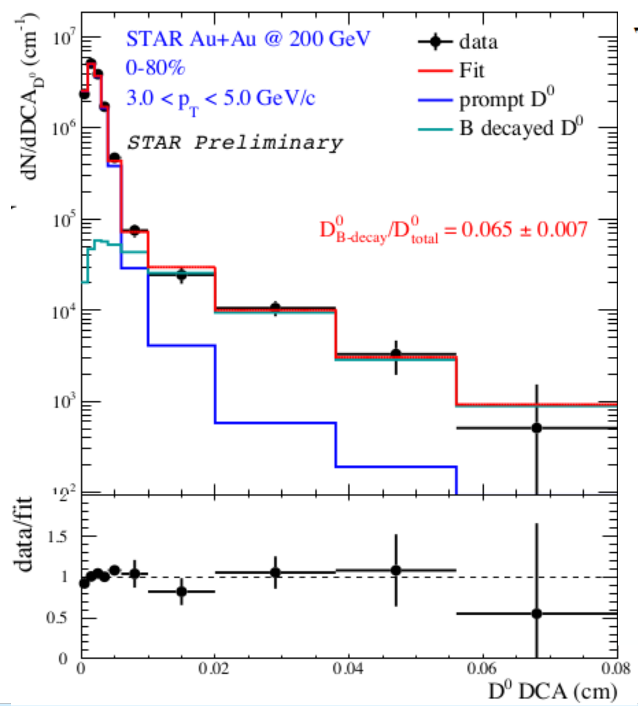
B → D⁰

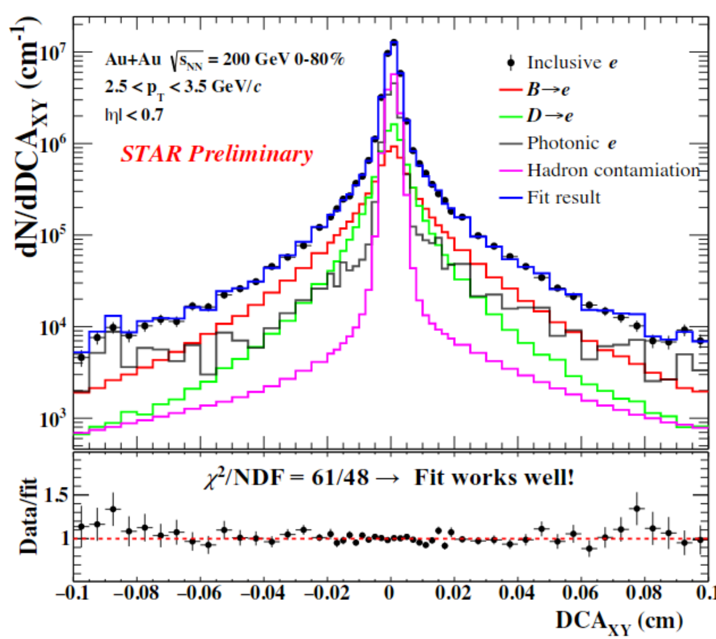


B/D → e

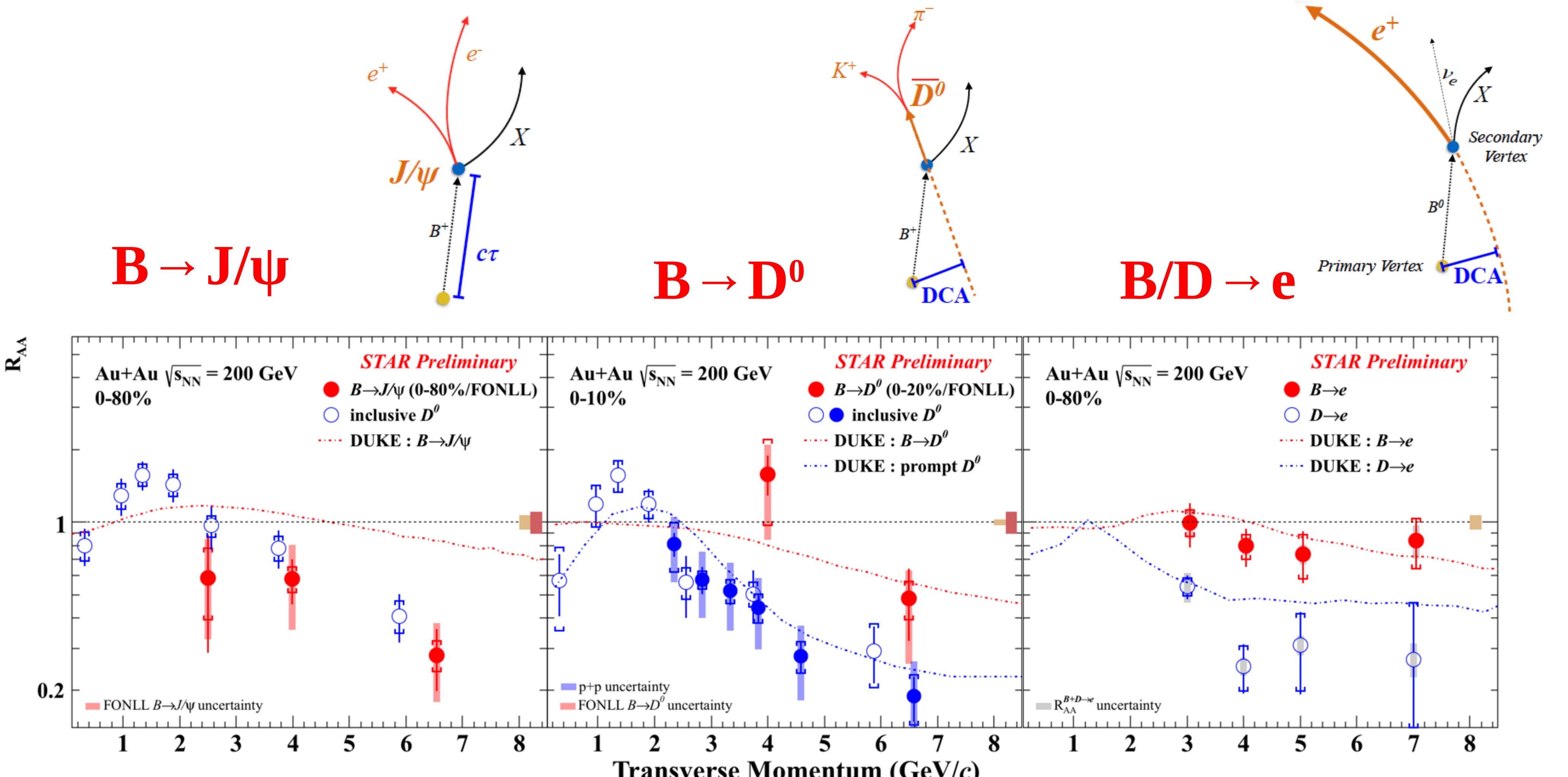








B-decay daughter R_{AA}



Duke: PRC 92(2015) 024907 & private comm.

- Suppression observed in B → J/ψ and D^0 at hight p_T
- B → e is less suppressed than D → e (2σ effect) → consistent with mass hierarchy of parton energy loss ($\Delta E_c > \Delta E_b$)

Quarkonia in the QGP

- Quarkonia dissociation in the medium due to color screening

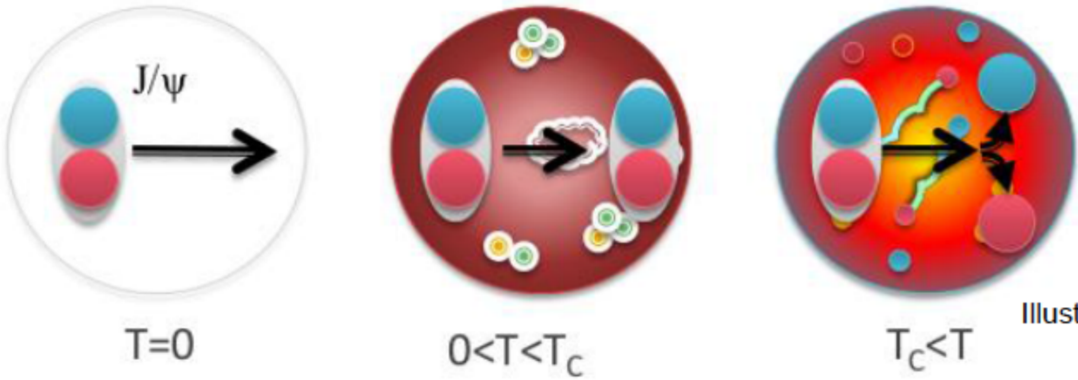


Illustration: A.Rothkopf

- Charmonia: J/ψ, ψ', χ_C
- Bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B

- Sequential melting: different states dissociate at different temperatures – QGP thermometer

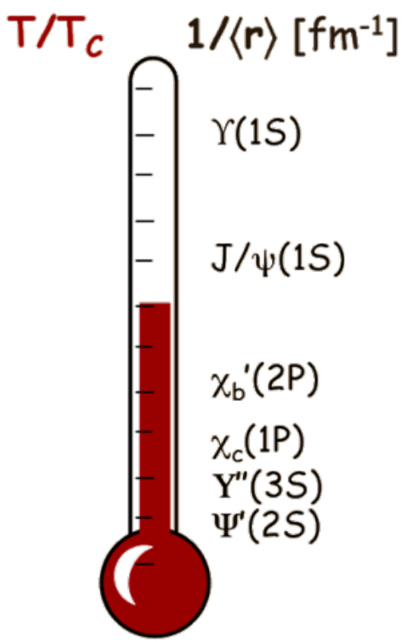
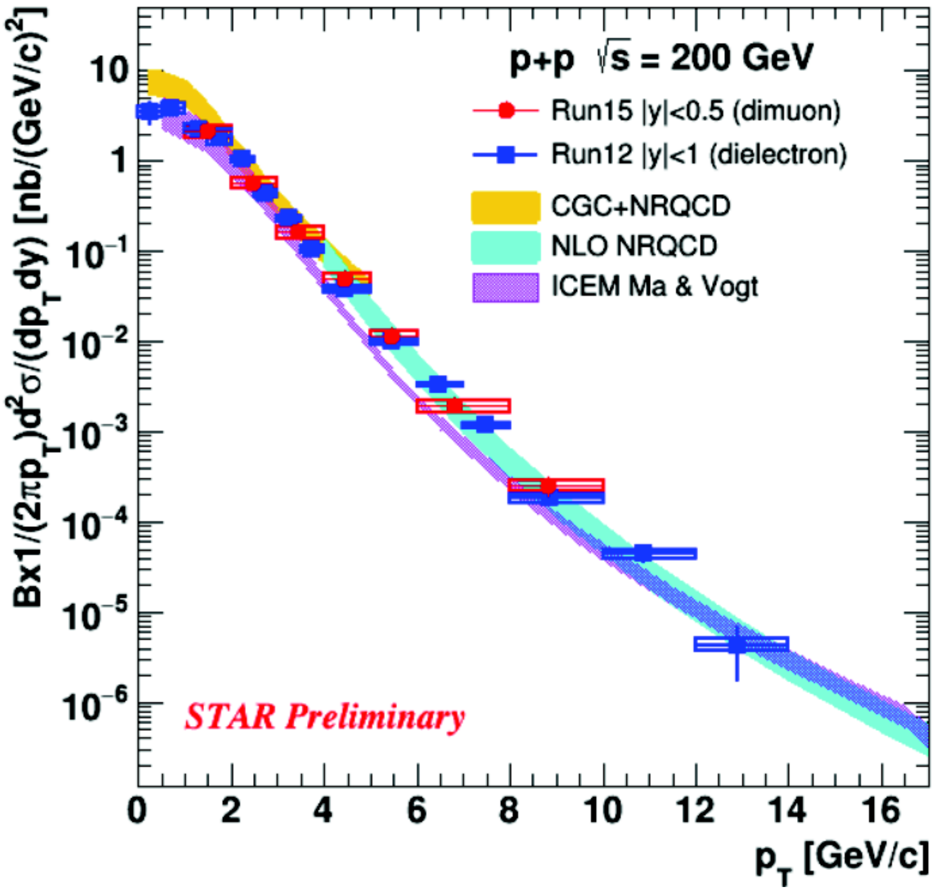
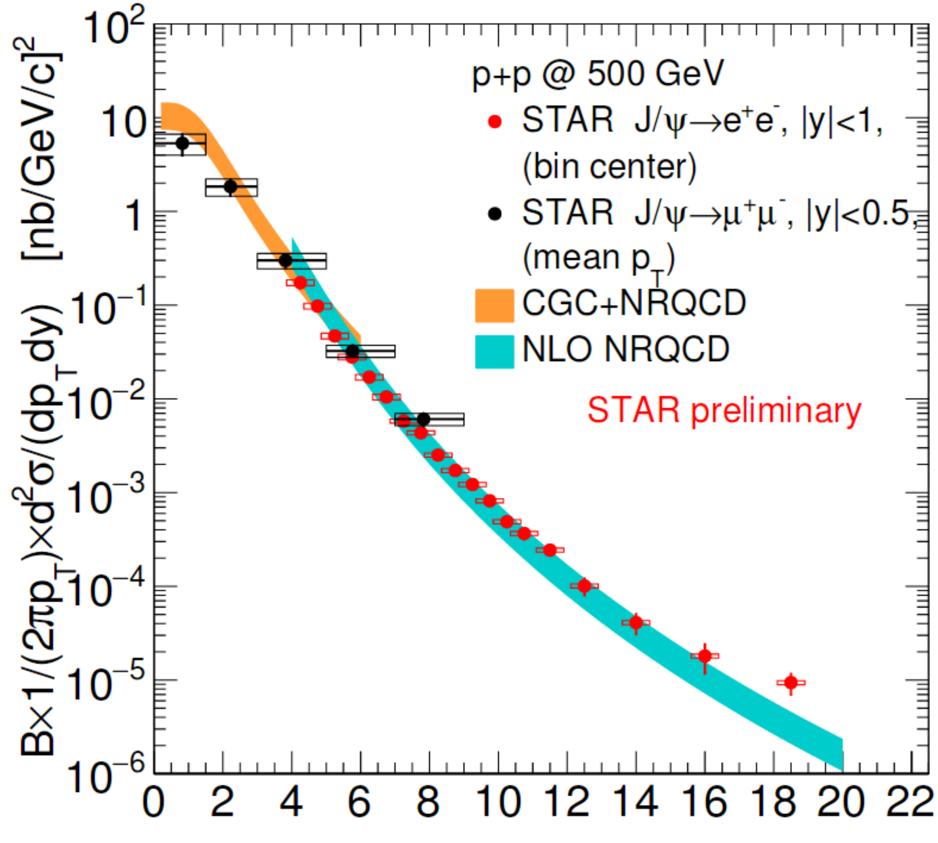


Illustration: A. Mocsy, EPJC61 (2009) 705

- Interpretation of J/ψ suppression is complicated
  - Hot medium effects
    - Dissociation
    - Regeneration from thermalized quarks
  - Cold nuclear matter effects
  - Feed-down from excited charmonium states and B-hadrons

J/ψ in p+p

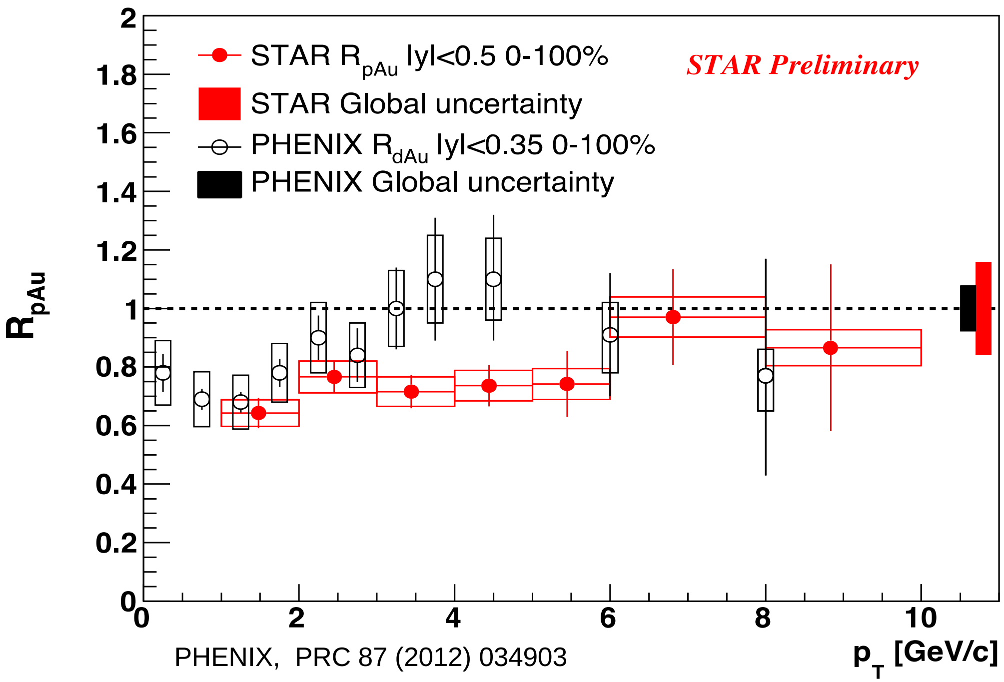


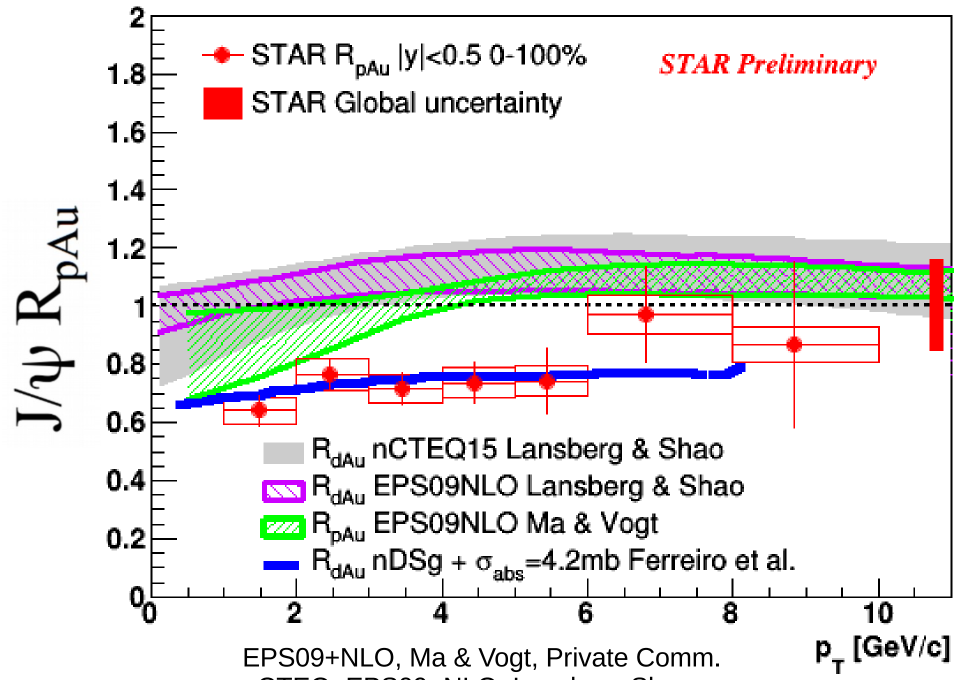


NLO NRQCD: Ma et al., PRL106 (2011) 042002
CGC+NRQCD: Ma, Venugopalan, PRL113 (2014) 192301
ICEM, Ma & Vogt, PRD 94 (2016) 114029

- Precise J/ψ production cross-section measured over wide p_T range in 200 and 500 GeV p+p collisions
- CGC+NRQCD & NLO NRQCD (prompt) are consistent with data above 1 GeV/c
- Improved CEM model (direct) describes 200 GeV data well at low p_T

J/ψ R_{pAu}

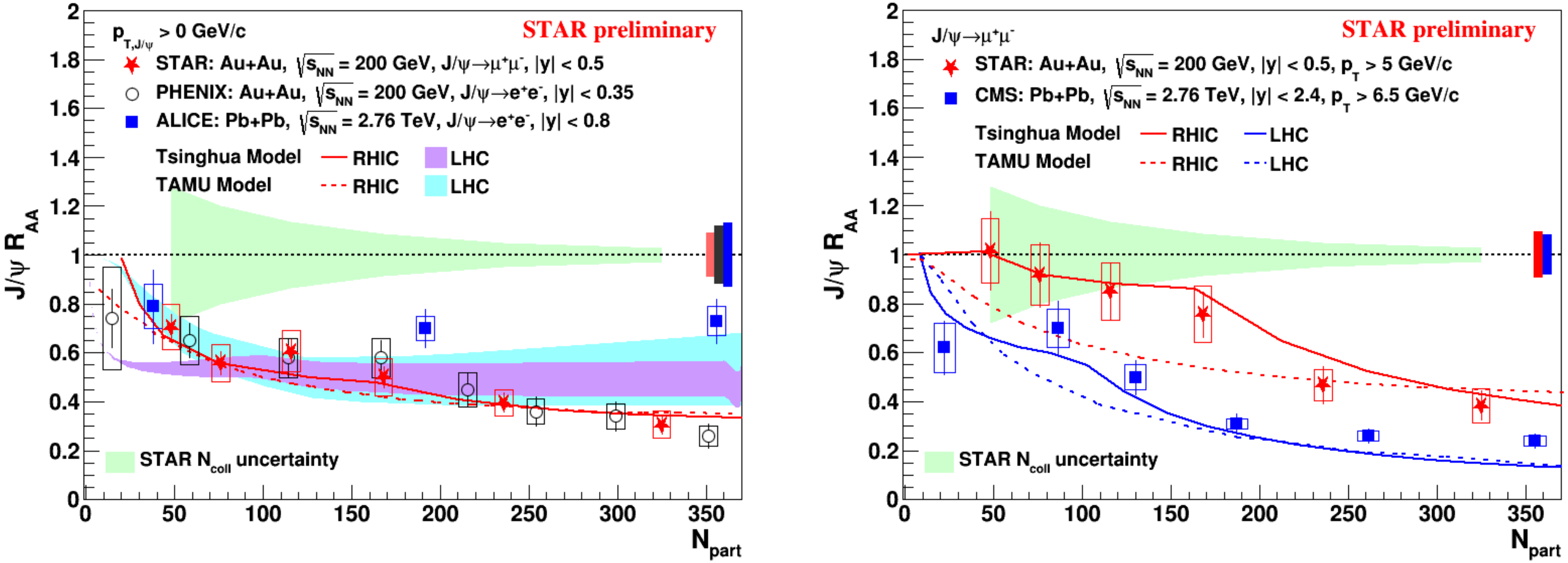




EPS09+NLO, Ma & Vogt, Private Comm.
nCTEQ, EPS09+NLO, Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570
Ferreiro et al., Few Body Syst. 53 (2012) 27

- First J/ψ R_{pAu} measurement at RHIC
- R_{pAu} is consistent with unity at high p_T and is less than unity at low p_T
- R_{pAu} is consistent with R_{dAu} within uncertainties
  - Bit of tension at p_T 3.5 – 5 GeV/c with a significance of 1.4σ
  - Suggest similar CNM effects in these collision systems
- R_{pAu} favors additional nuclear absorption effect on top of nPDF effects

J/ψ R_{AA} vs. centrality

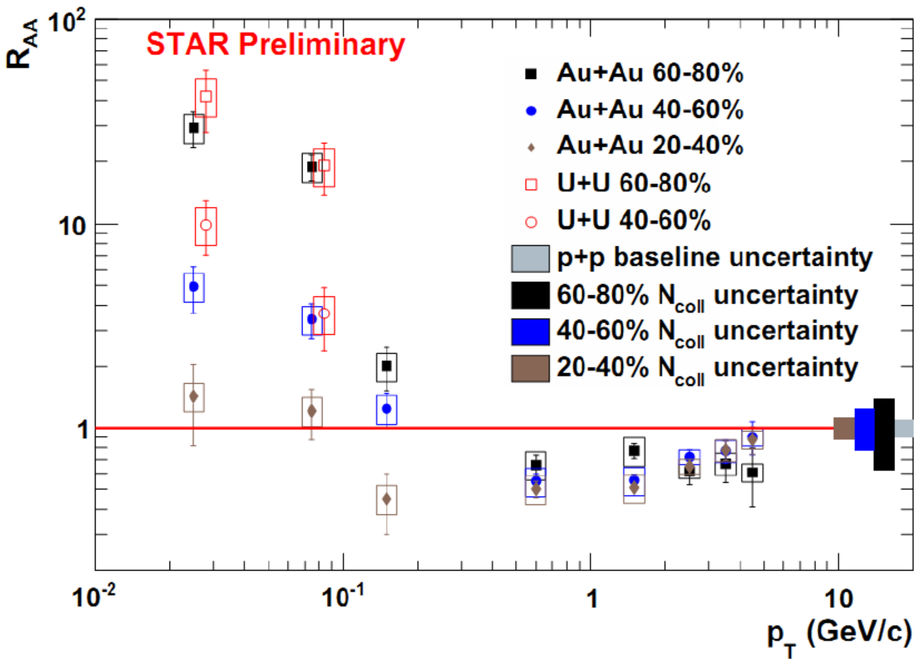


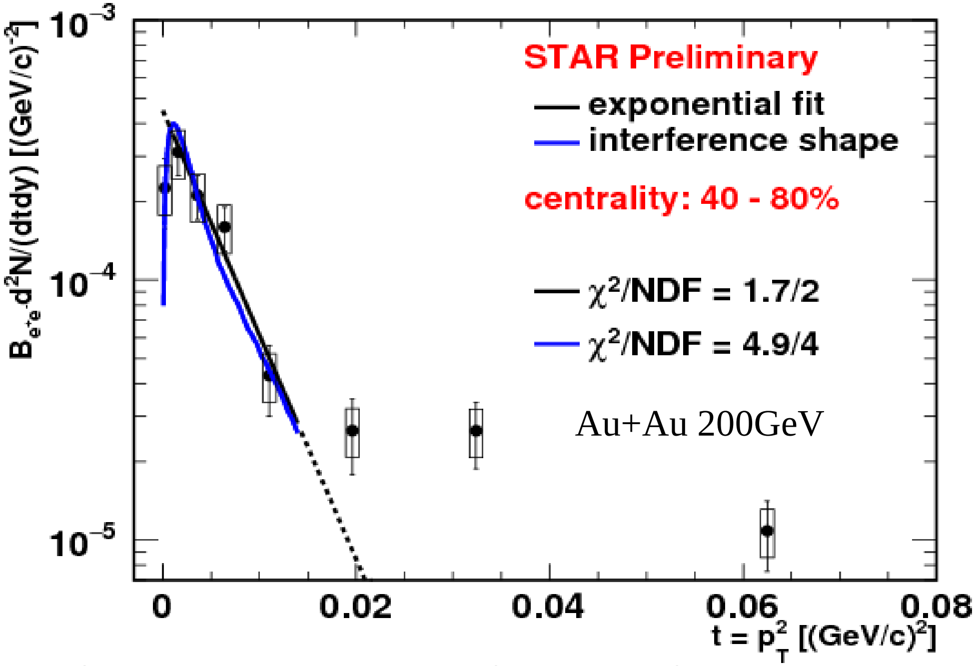
- J/ψ R_{AA} for p_T > 0 GeV/c: smaller at RHIC than LHC → more recombination at LHC
- J/ψ R_{AA} for p_T > 5 GeV/c: larger at RHIC than LHC → stronger dissociation at LHC
- Transport models with both regeneration and dissociation can qualitatively describe the data

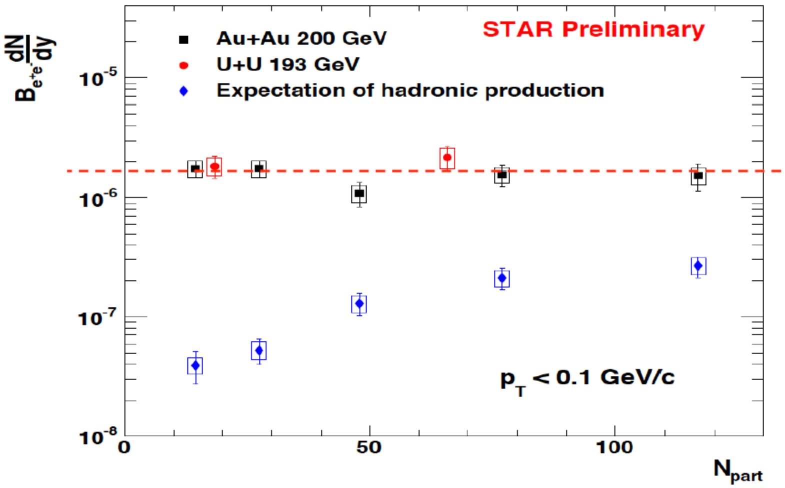
ALICE: PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

Transport models:
Model I at RHIC: PLB 678 (2009) 27
Model I at LHC: PRC89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114

J/ψ at very low p_T

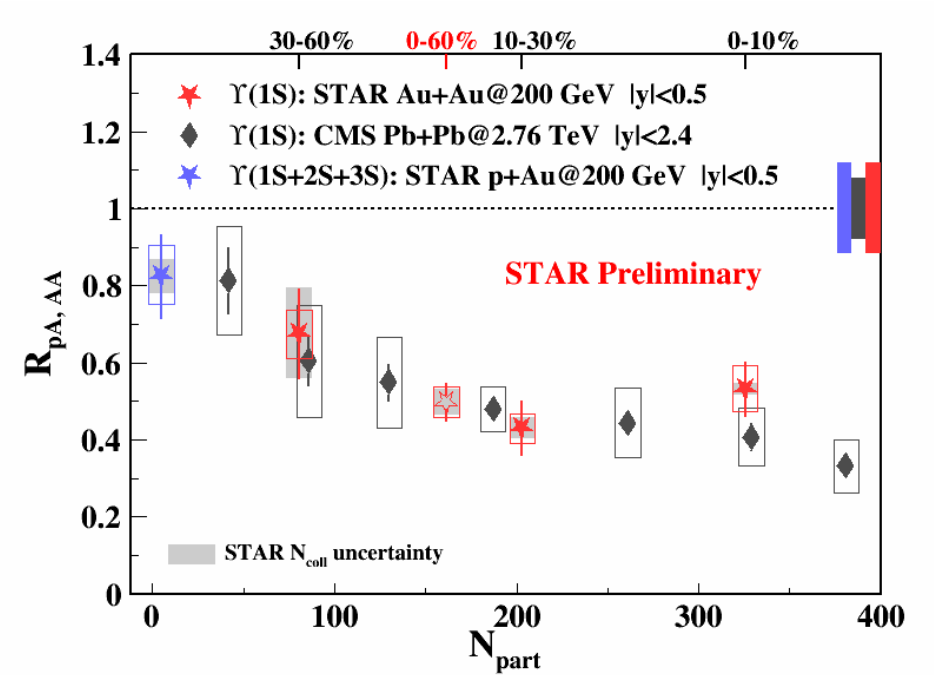


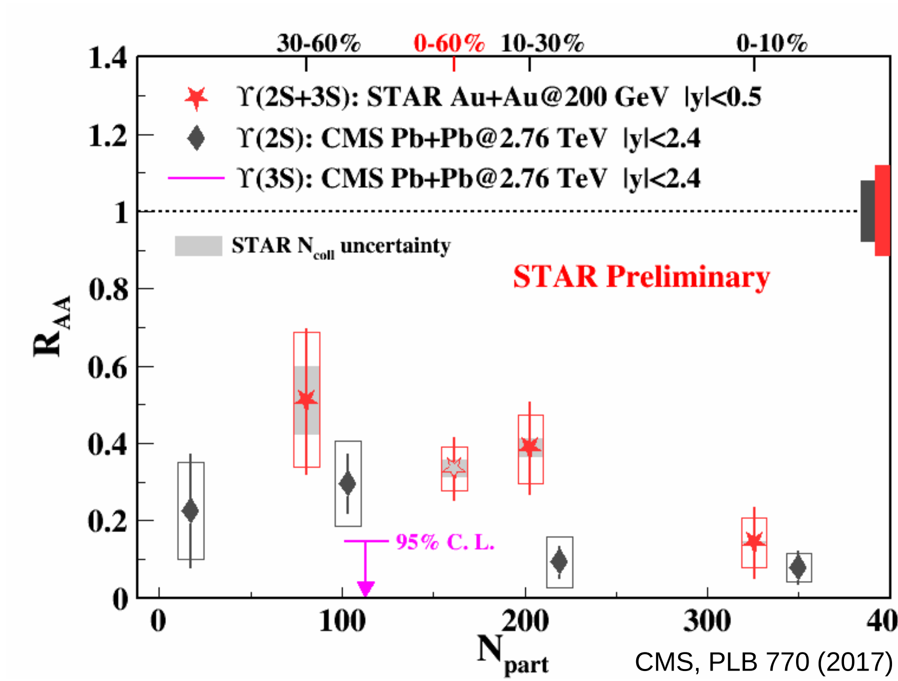




- Significant enhancement of J/ψ R_{AA} for p_T < 0.2 GeV/c
  - results between Au+Au and U+U are consistent
- No obvious centrality dependence in the production yield
- Slope of the t-distribution is similar to that of ρ meson measured in UPC
- Production mechanism: coherent photon-nucleus interaction?

ϒ R_{AA} vs. centrality





CMS, PLB 770 (2017) 357

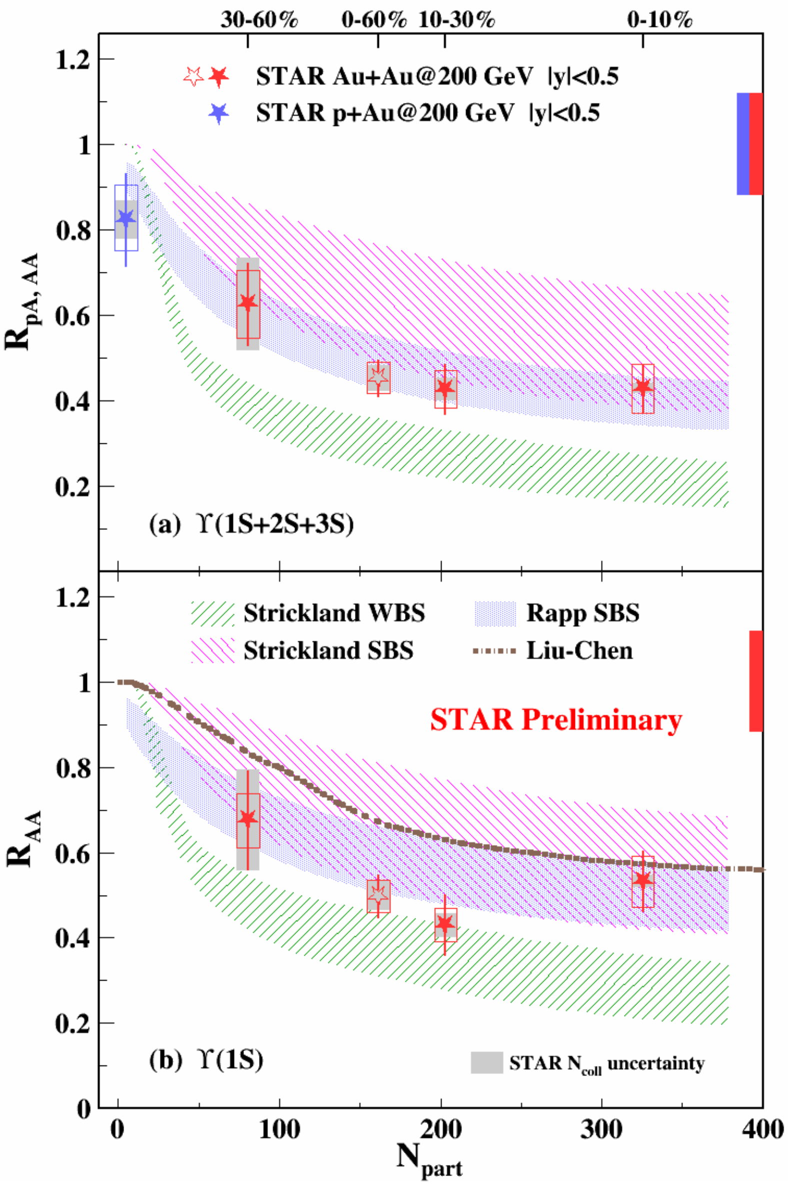
- ϒ(1S+2S+3S) R_{pA}:
  - indication of CNM effects
- ϒ(1S) R_{AuAu} :
  - suppression in central collisions
  - similar suppression as CMS measurements
- ϒ(2S+3S) R_{AuAu} :
  - larger suppression in central collisions than ϒ(1S) → **sequential melting**
  - indication for less suppression than at the LHC in semi-central collisions

STAR ϒ R_{AA} vs. models

- SBS (Strongly Binding Scenario):
  fast dissociation - potential based on internal energy
- WBS (Weakly Binding Scenario):
  slow dissociation - potential based on free energy

- Strickland, Bazov : *NPA 879 (2012) 25*
  - ➔ No CNM, no regeneration
- Liu, Chen, Xu, Zhang : *PLB 697 (2011) 32*
  - ➔ No CNM
  - ➔ Dissociation only for excited states: suppression of ground state due to feed-down
- Emerick, Zhao, Rapp : *EPJ A48 (2012) 72*
  - ➔ Includes CNM
  - ➔ SBS case

Data seem to favor SBS models



Summary

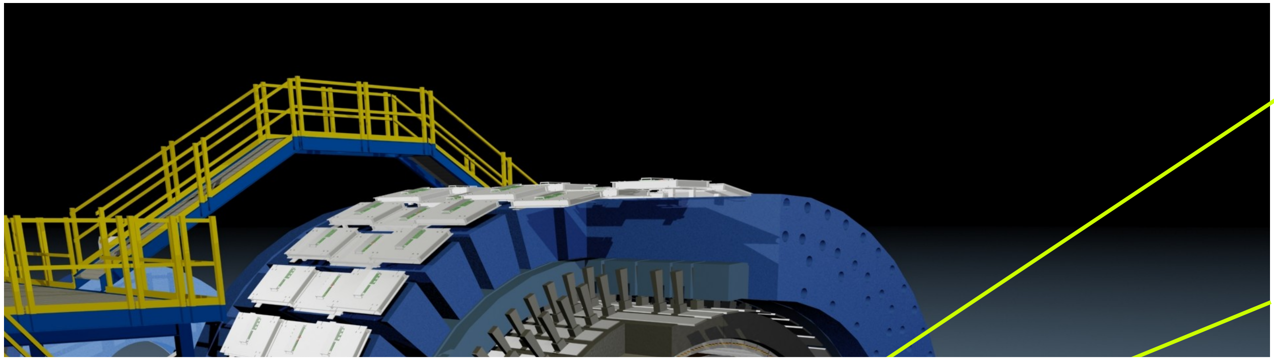
- Successful data taking with MTD and HFT in Au+Au collisions

- Open heavy flavor measurements:
  - Measurements of D^0 R_{AA} and anisotropic flow indicate:
    - charm quarks interact strongly with the QGP medium
    - charm quarks flow with the medium
  - Enhanced D_s/D^0 and Λ_c/D^0 ratios suggest that charm quarks also participate in coalescence hadronization.
  - B production measured via J/ψ, D^0 and electron decay channels in 200 GeV Au+Au collisions:
    - B → e is less suppressed than D → e (2σ effect) → consistent with mass hierarchy of parton energy loss ($\Delta E_c > \Delta E_b$)
    - Suppression of B→J/Ψ and B→ D^0 in high p_T region

- Quarkonium measurements:
  - J/ψ R_{pAu}:
    - ~ R_{dAu}: suggests similar CNM effects between p+Au and d+Au collisions
    - favors additional nuclear absorption effect on top of nPDF effect
  - J/ψ R_{AA}:
    - high p_T is strongly suppressed at RHIC → strong evidence for QGP formation
    - excess at very low p_T - consistent with coherent photon-nucleus interaction
  - ϒ R_{AA}:
    - stronger suppression of ϒ(2S+3S) than ϒ(1S) → sequential melting
    - data seem to favor models with Strongly Binding Scenario

Backup

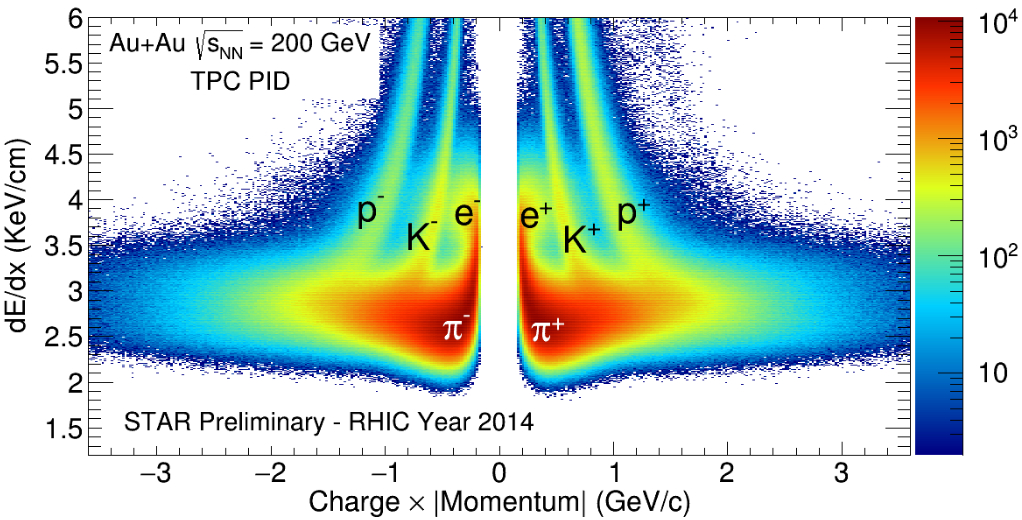
The Solenoidal Tracker At RHIC (STAR) detector

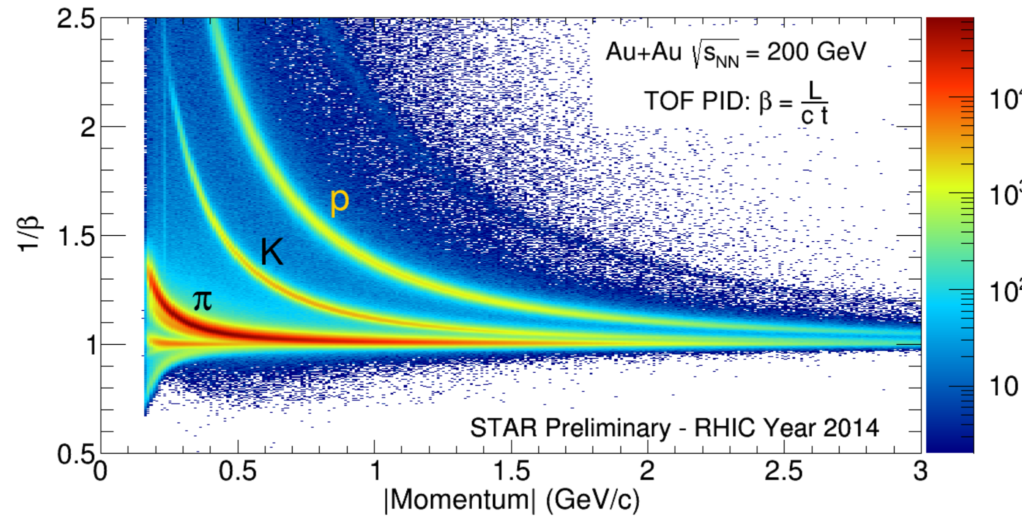


Time Projection Chamber (TPC):
- tracking
- particle identification via dE/dx

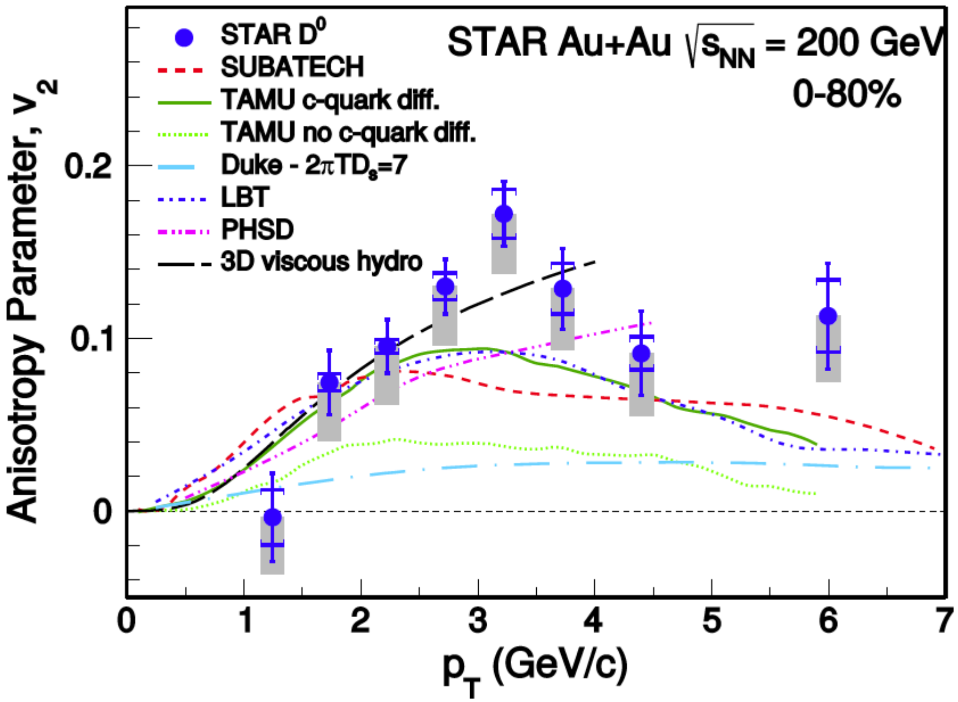
Time Of Flight (TOF):
- particle identification via 1/β

Excellent identification of long-lived hadrons and electrons in TPC and TOF





D^0 eliptic flow data vs. models



STAR: PRL 118, 212301 (2017)
TAMU: Eur. Phys. J. C (2016) 76: 107 & private comm.;
SUBATECH: PRC 91(2015) 054902 & private comm.;
Duke: PRC 92(2015) 024907 & private comm.;
PHSD: PRC 90, 051901 (2014), PRC 92, 014910 (2015);
LBT: Phys. Rev. C 94, 014909 (2016);
3D viscous hydro: PRC 86, 024911 (2012), PRD 91, 074027 (2015) & private comm.

3D viscous hydro and dynamic models are consistent with data.

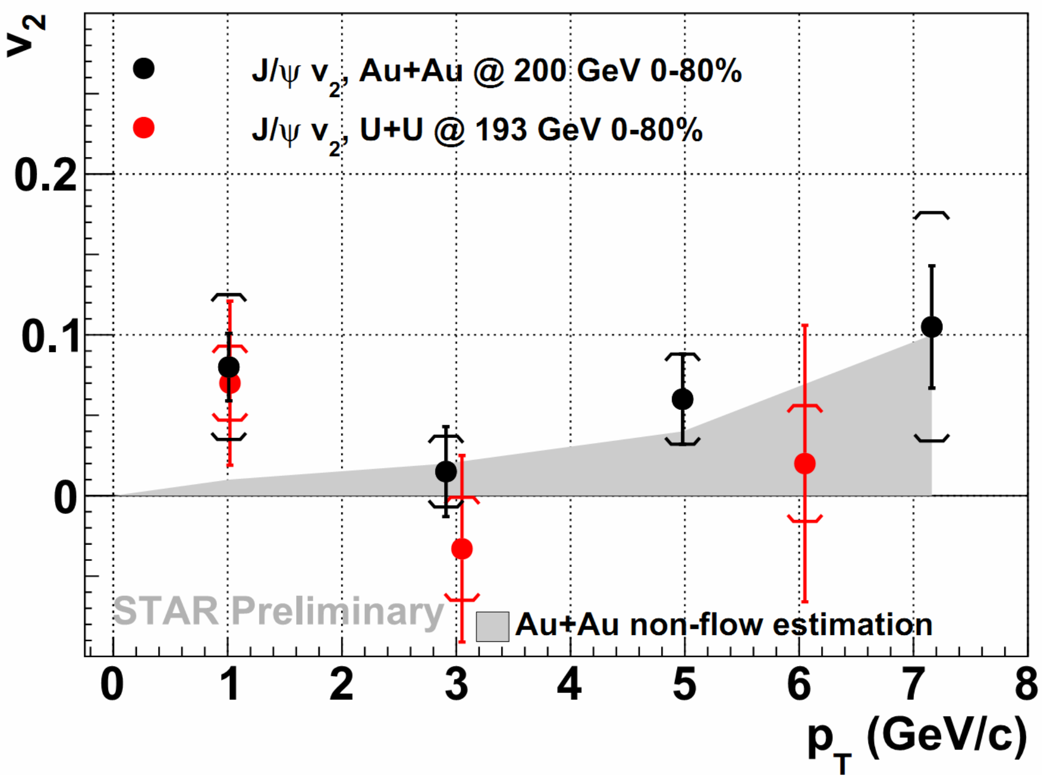
- **3D viscous hydro**dynamic model tuned to light hadrons: charm quarks have achieved thermal equilibrium
- D_s – charm quark spatial diffusion coefficient coefficient in the medium

- **TAMU**: non-perturbative T-Matrix approach: $(2\pi T)D_s$ = 2 - ~10
- **SUBATECH**: pQCD + Hard Thermal Loops for resummation: $(2\pi T)D_s$ = 2 – 4
- **DUKE**: Langevin simulation with transport properties tuned to LHC data: $(2\pi T)D_s$ = 7
- **PHSD**: Parton-Hadron-String Dynamics, a transport model $(2\pi T)D_s$ = 5 - 12
- **LBT**: A Linearized Boltzmann Transport model - Jet transport model extended to heavy quarks $(2\pi T)D_s$ = 3 – 6

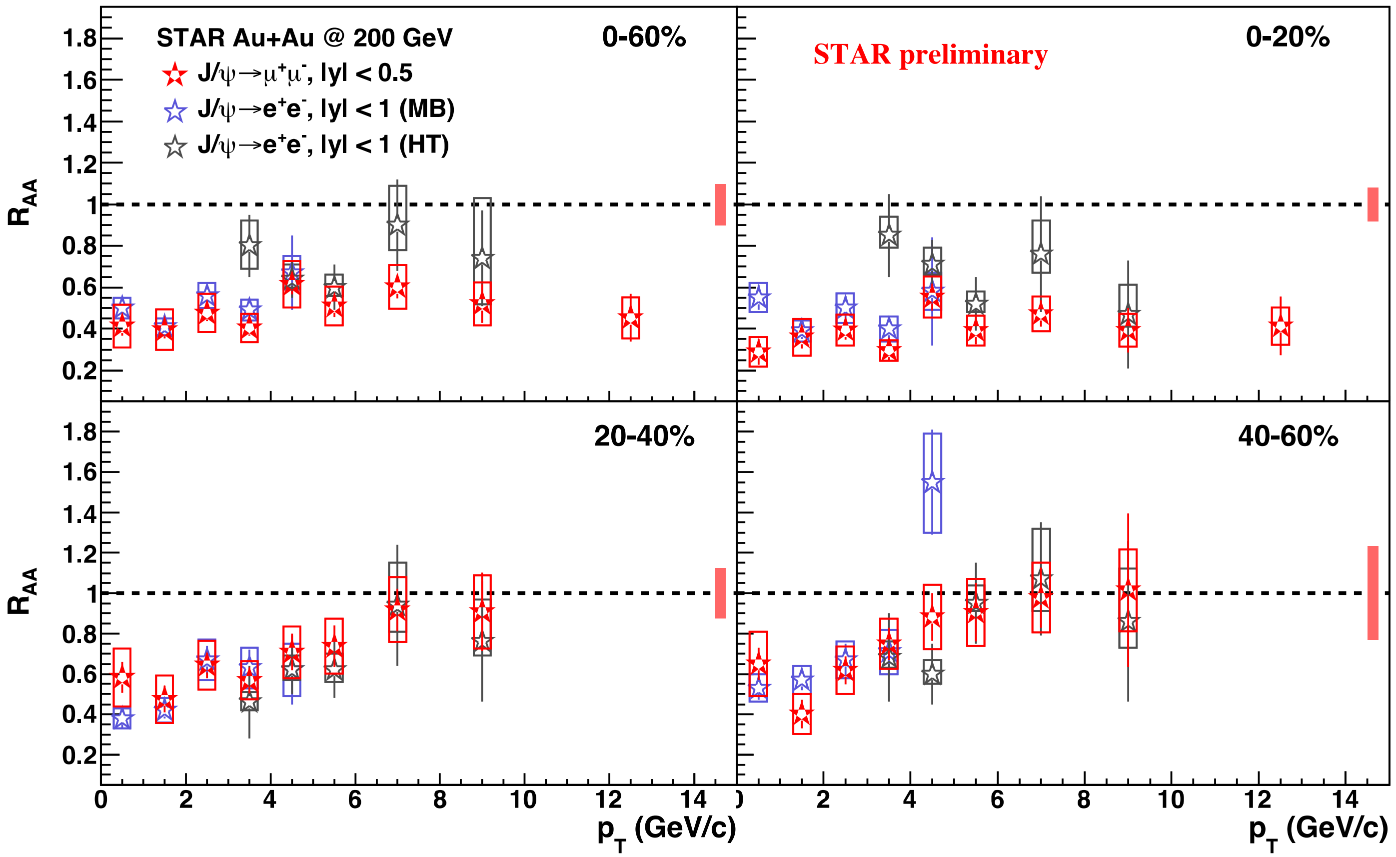
Together: $(2\pi T)$Ds = 2 -12 for T_c - $2T_c$

J/ψ v_2

- Two main production mechanism of J/ψ:
  - Primordial: little or zero v_2
  - Regenerated: inherit v_2 from the constituent charm quarks
- J/ψ v_2 from 200 GeV Au+Au and from 193 GeV U+U collisions are consistent with zero within uncertainties for p_T above 2 GeV/c.
  - Disfavor the scenario that the regeneration is the dominant contribution in this kinematic range



J/ψ R_{AA} in Au+Au collisons



- Consistent with di-electron channel results over entire p_T for all centralities
- Distinct rising R_{AA} with p_T for 20-40% and 40-60% centrality bins

Di-electron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)