Heavy Flavor Production at RHIC with the STAR Experiment

Strangeness in Quark Matter 2016, UC Berkeley, June 27-July 1, 2016

Zhenyu Ye[1,2] (for the STAR collaboration)

1. University of Illinois at Chicago
2. Central China Normal University

UIC The University of Illinois at Chicago

Office of Science U.S. DEPARTMENT OF ENERGY

華中師範大學 HuaZhong Normal University

Outline

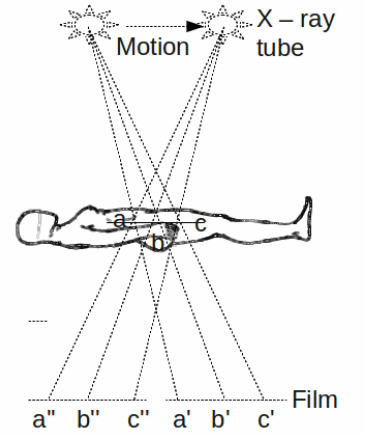
- Open Heavy Flavor Measurements
  - D mesons in Au+Au collisions with the HFT
  - HF-decayed electrons in p+p, Au+Au and U+U collisions
  - Separate D/B-decayed electrons in p+p collisions
- Quarkonium Measurements
  - J/ψ production in p+p collisions
  - J/ψ R_{AA} and Υ in Au+Au collisions with the MTD
  - J/ψ yield vs event activity in p+p collisions
  - Very low p_T J/ψ in peripheral Au+Au and U+U collisions
- Summary and Outlook

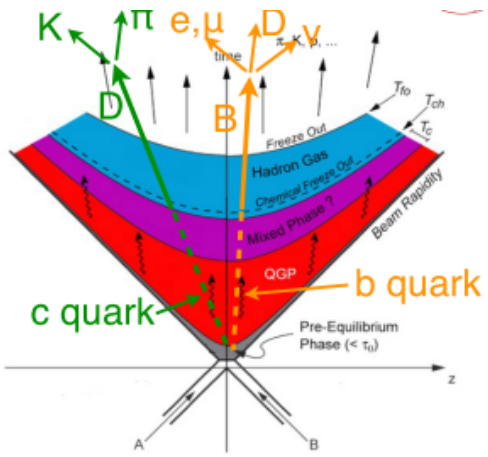
HFT: Heavy Flavor Tracker **MTD: Muon Telescope Detector**

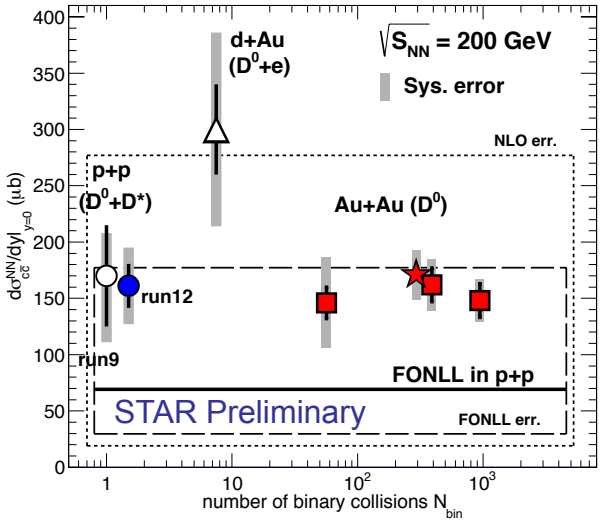
Open Heavy Flavor Production

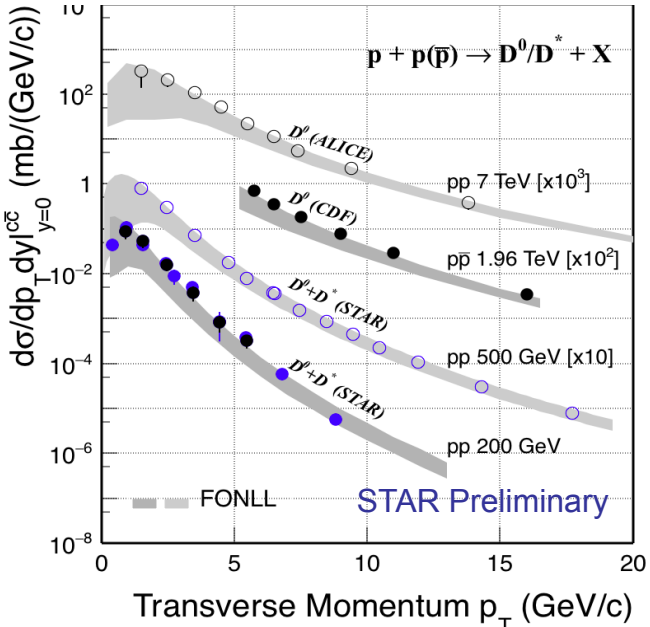
Heavy Quark Tomography

- Produced mostly from initial hard scatterings at RHIC, calculable by pQCD – calibrated probes to study QGP properties
- Compare light, charm, bottom to disentangle different parton energy loss mechanisms
- Compare yields of different open charm hadrons (D^0, D_s, Λ_c) to study hadronization









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

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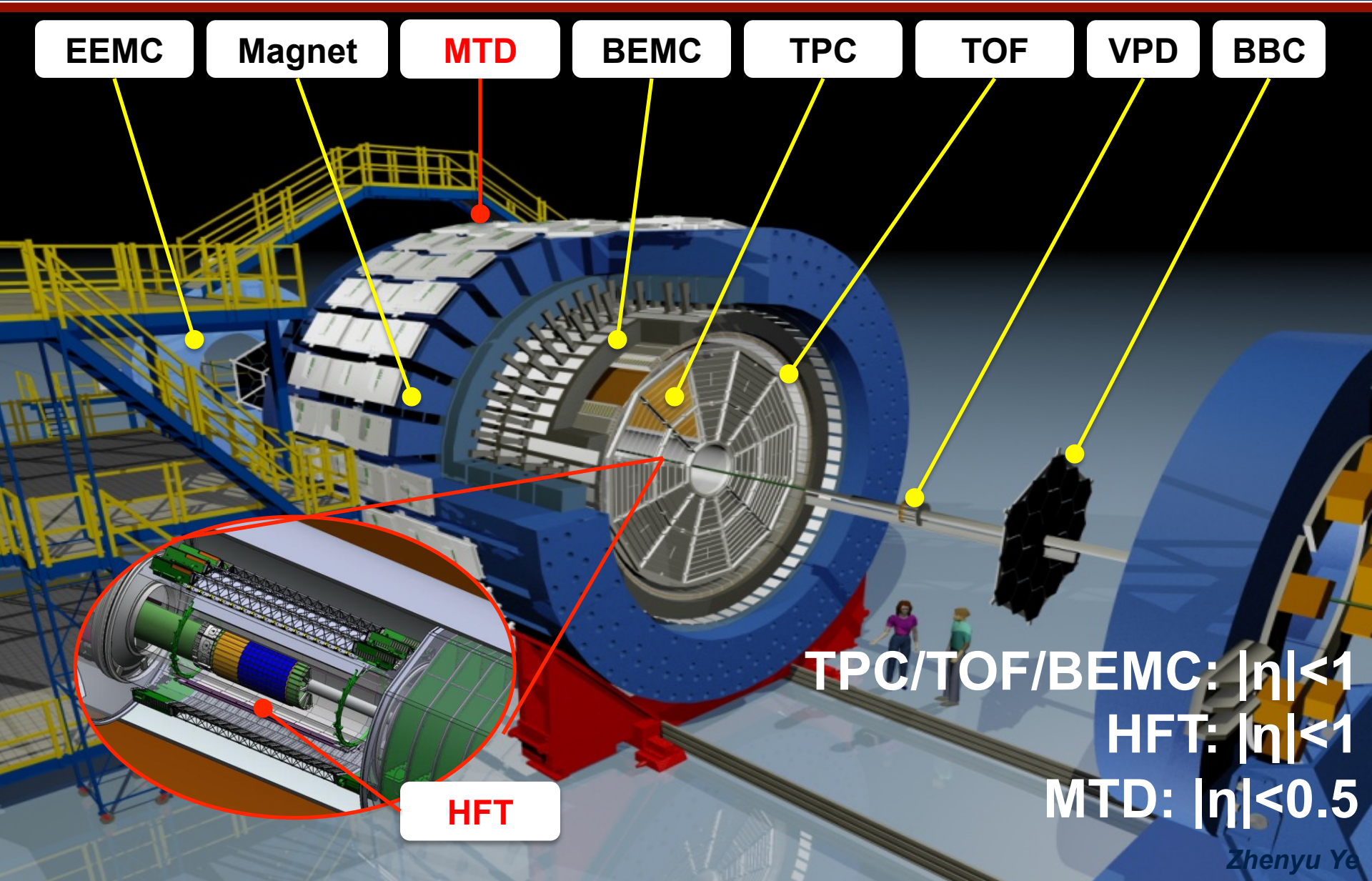
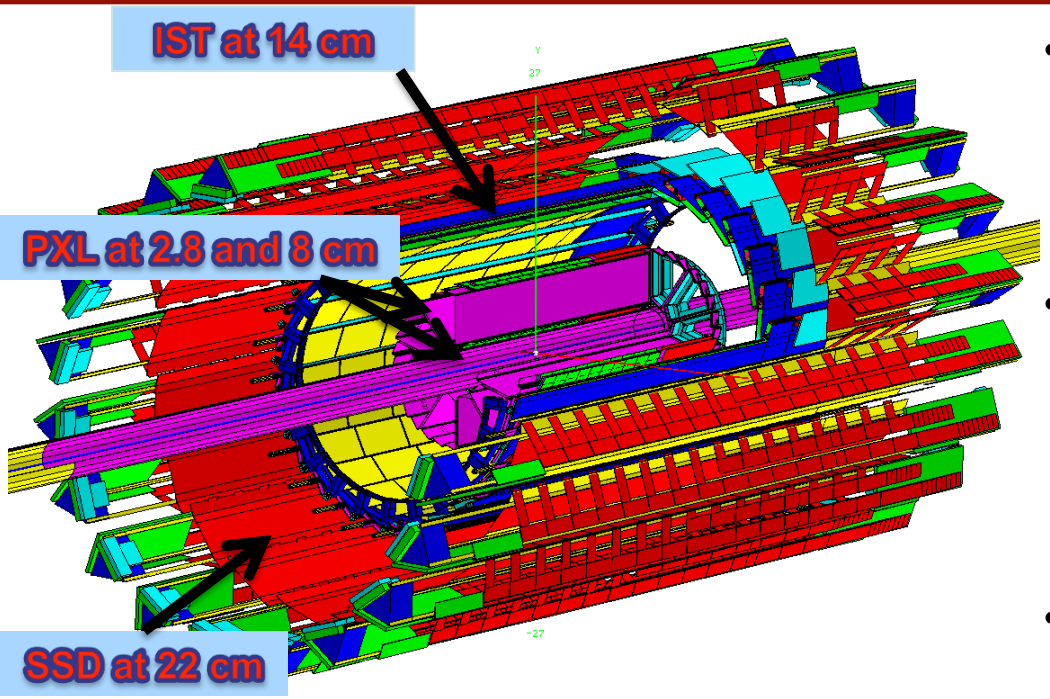
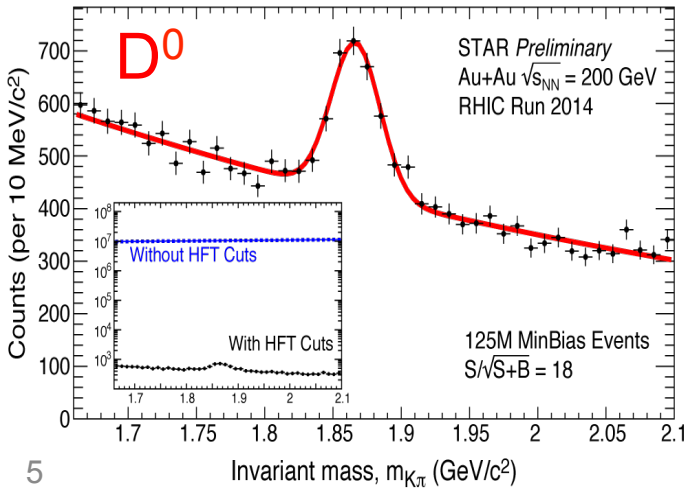
STAR Experiment at RHIC

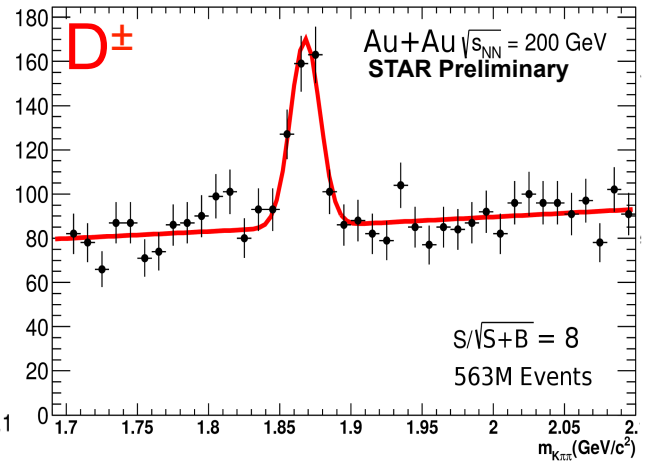


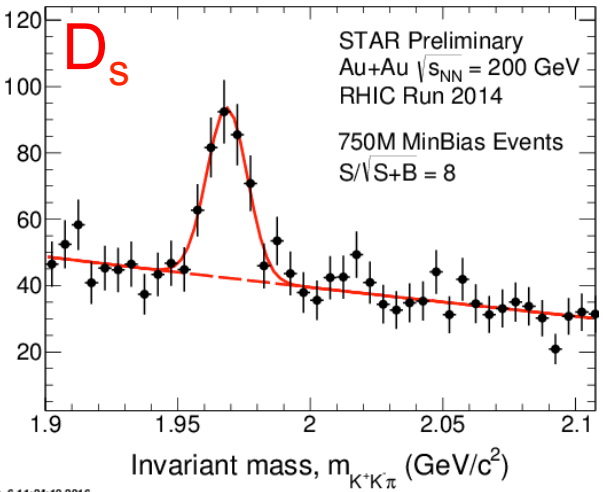
STAR Heavy Flavor Tracker



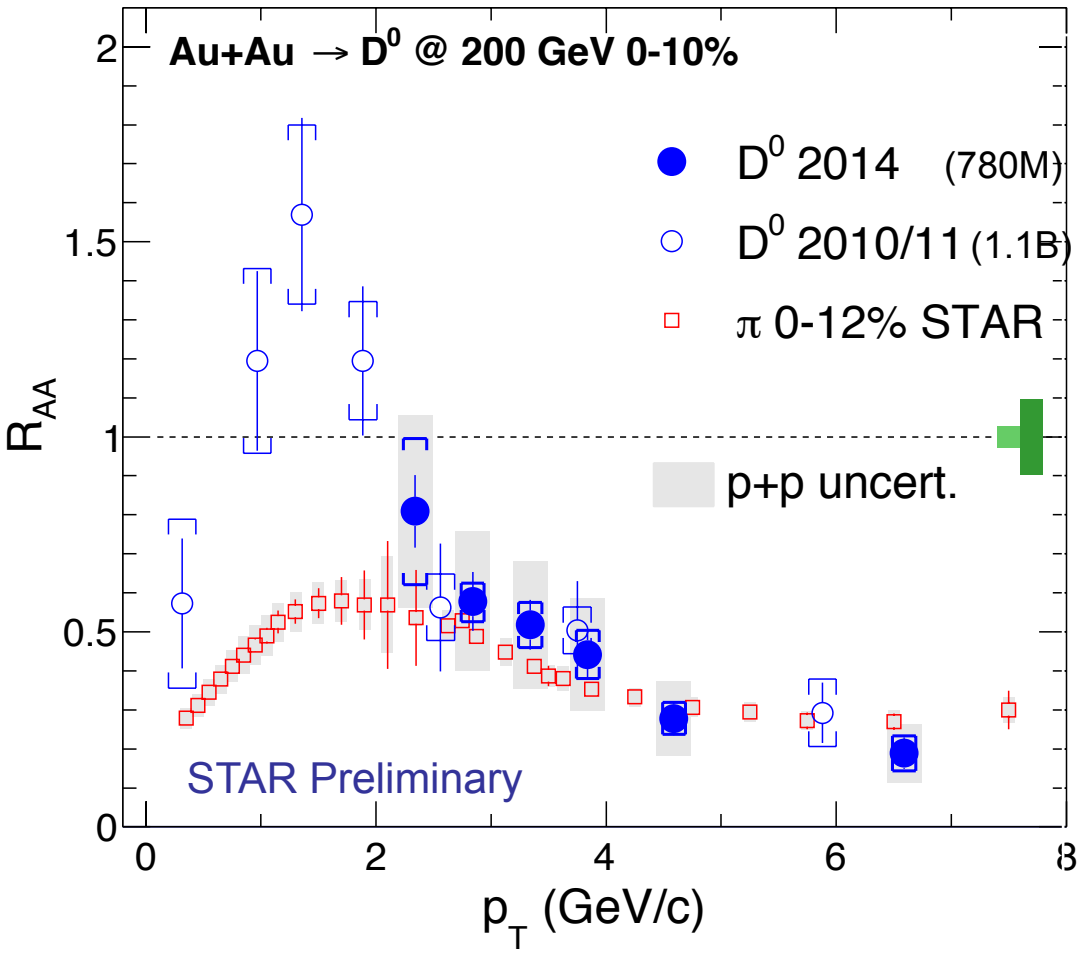
- First application of Monolithic Active Pixel Sensor technology in collider experiments. DCA resolution <50 μm for p_T=750 MeV/c Kaon
- Recorded about 3.2B Minimum Bias 200 GeV Au+Au events for D^0, $D^{\pm}$, D_s, Λ_c, and 1 nb^{-1} high p_T electron and dimuon samples for D/B➔e and B➔ J/ψ studies in 2014 and 2016.
- Results presented today are from 780M MB events in 2014.







Results from the HFT – D^0 R_{AA}



$$R_{AA} = \frac{dN_{AA}/dy}{N_{binary} \cdot dN_{pp}/dy}$$

- $R_{AA}(D)>1$ for p_T~1.5 GeV/c

  Charm coalescence with a radially flowing bulk medium

- High p_T: significant suppression in central Au+Au collisions.

  Strong charm-medium interaction

- $R_{AA}(D) \sim R_{AA}(\pi)$ at $p_T>4$ GeV/c

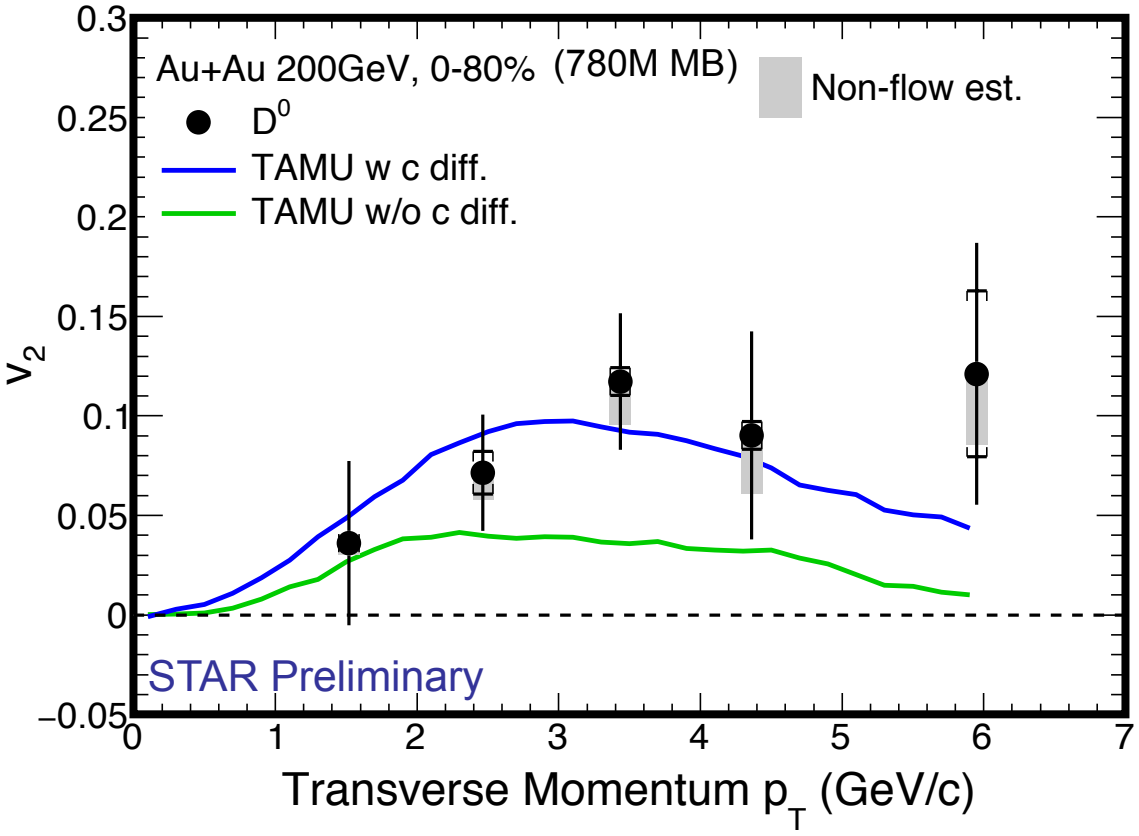
  Similar suppression for light partons and charm quarks at high p_T

- Low p_T R_{AA} study with HFT data in progress

STAR D^0 2010/11: PRL 113 (2014) 142301
STAR π 0-12%: PLB 655 (2007) 104

Results from the HFT – D^0 v_2

M. Lomnitz June 30



$$\frac{dN}{d\phi} = N_0\left[1+\sum_n 2v_n\cos n\phi\right]$$

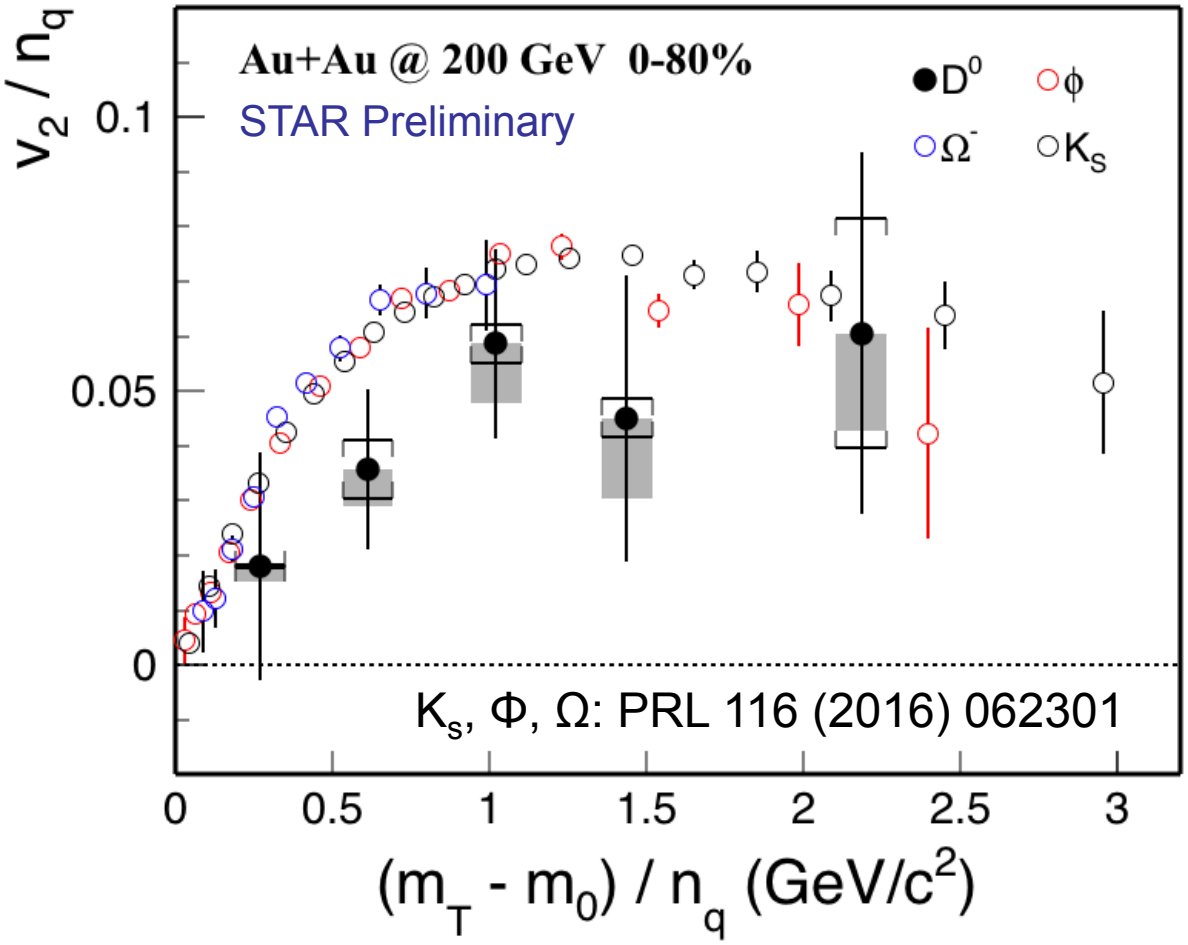
- Non-zero v_2 for p_T>2 GeV/c

Favors charm quark diffusion

Theory curves: latest calculations from private communications
TAMU: PRC 86 (2012) 014903, PRL 110 (2013) 112301

Results from the HFT – D^0 v_2

M. Lomnitz June 30



$$m_T = \sqrt{p_T^2 + m_0^2}$$

- Non-zero v_2 for p_T>2 GeV/c

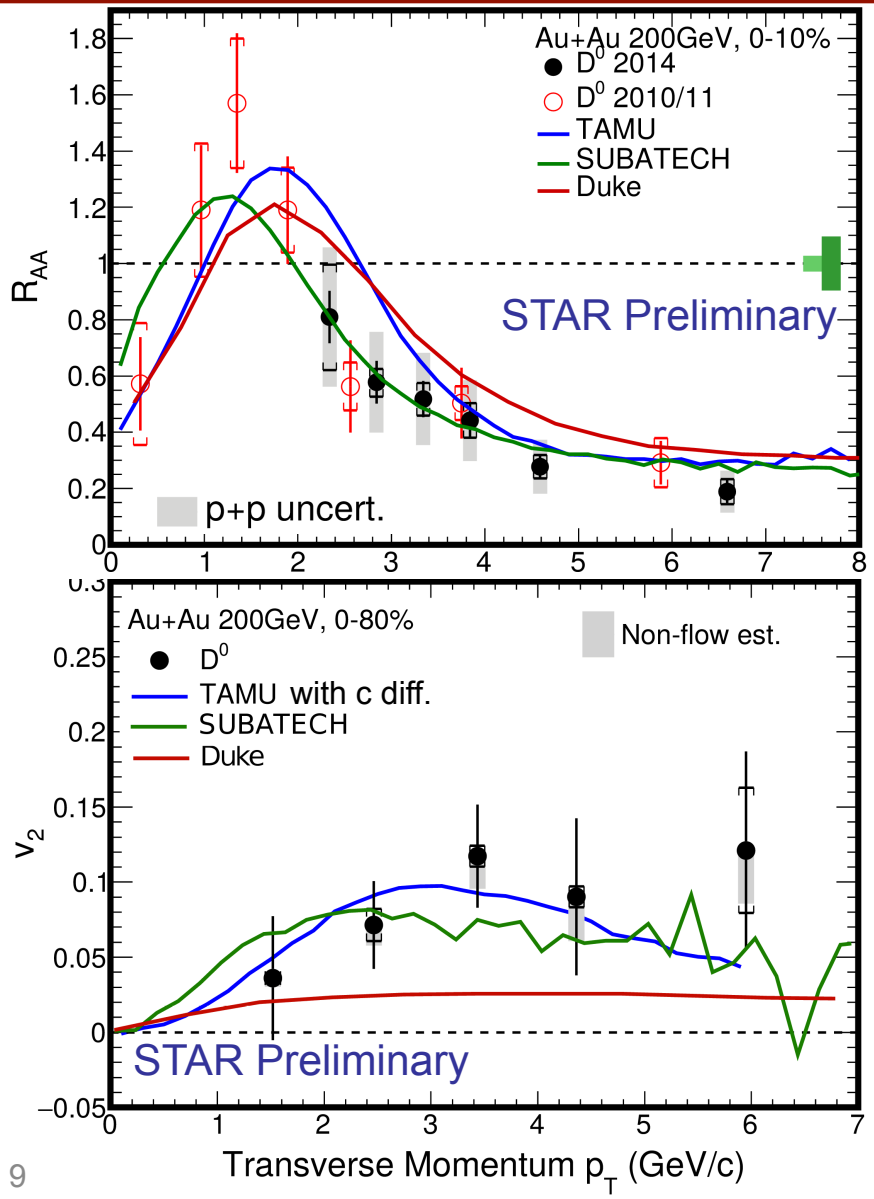
Favors charm quark diffusion

- Lower than light hadron v_2

Indication that charm quarks are not fully thermalized with the medium?

- Need D^0 v_2 with improved precision in narrower centrality bins

Comparison with Theory



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

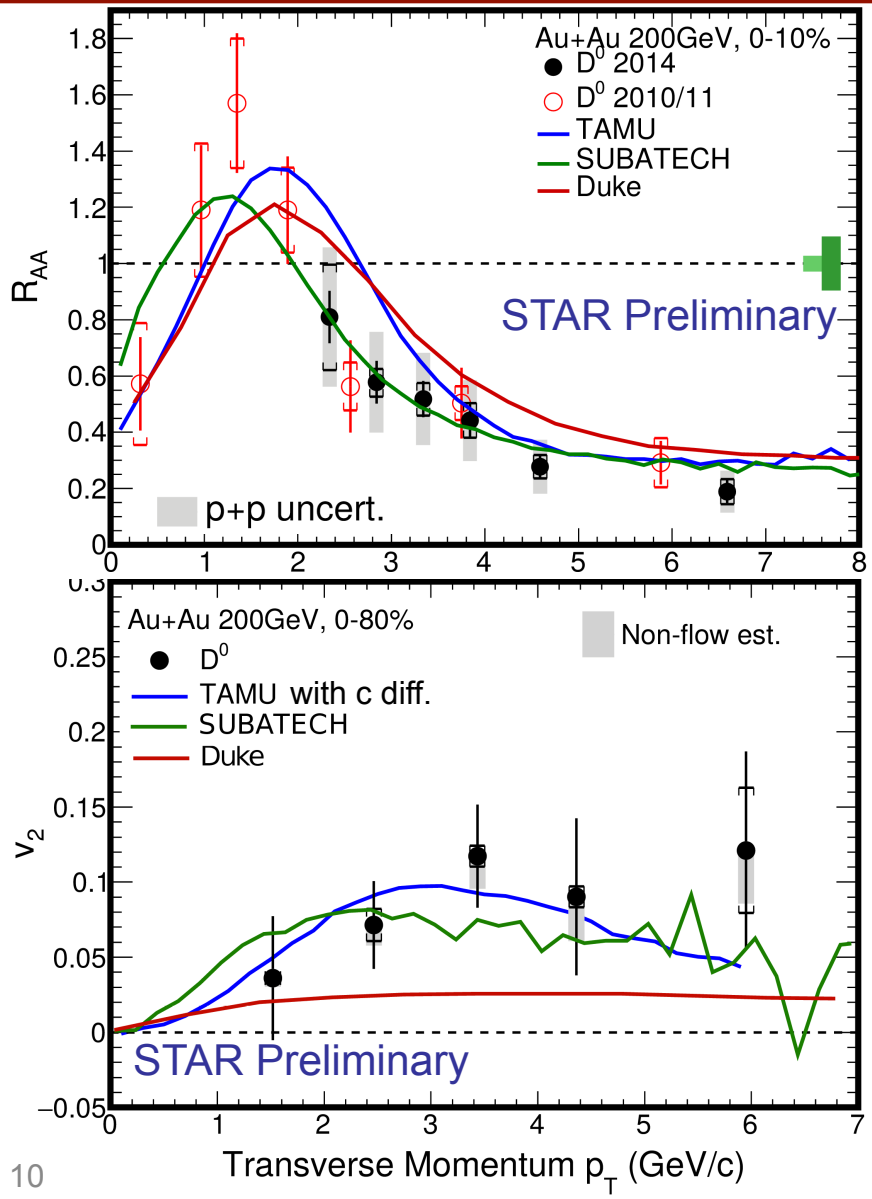
SUBATECH: perturb.+resummation
$(2\pi T)D = 2\text{-}4$

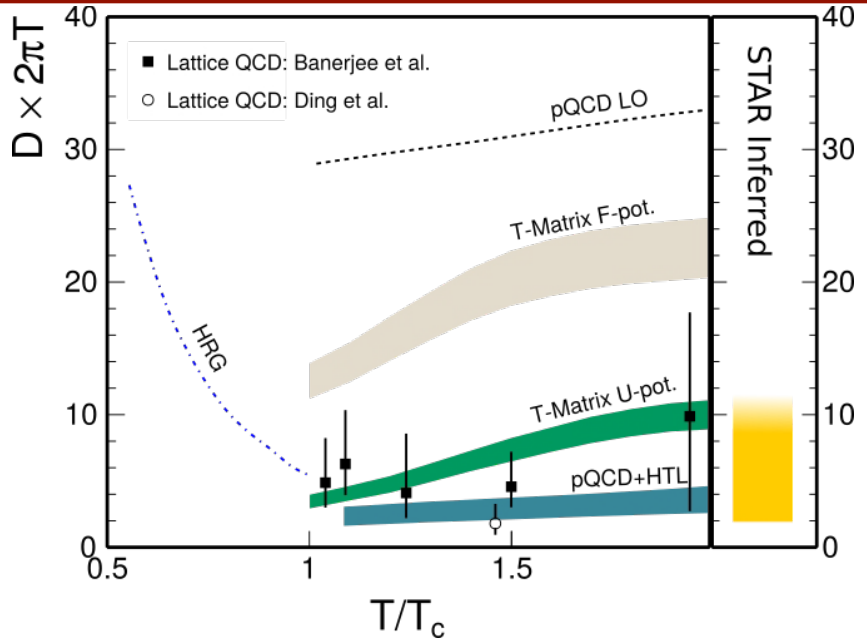
DUKE: Langevin simulation with input parameter tuned to the LHC data
$(2\pi T)D = 7$

	D × 2πT	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)

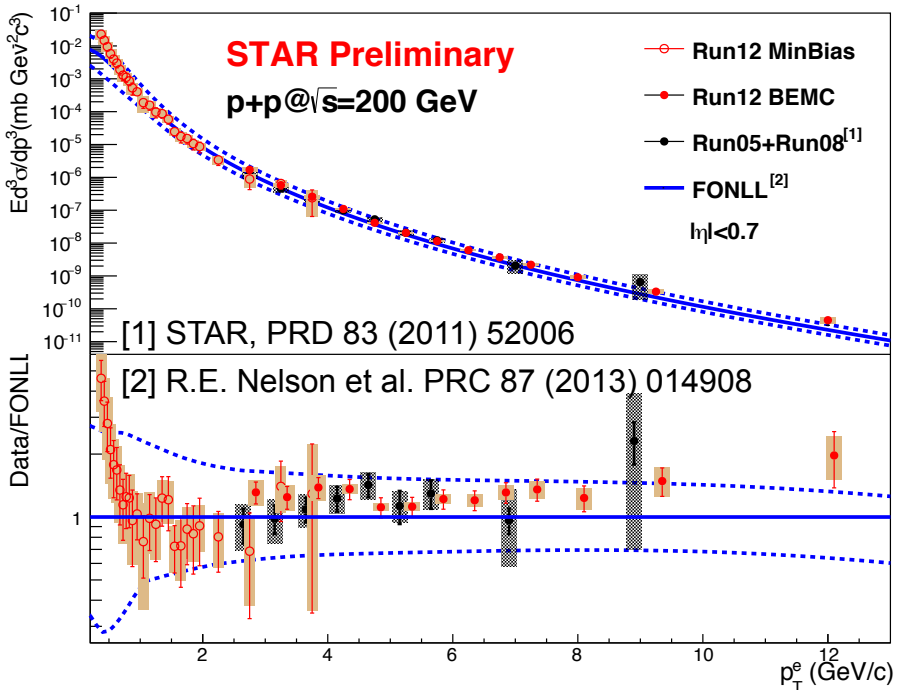
Comparison with Theory

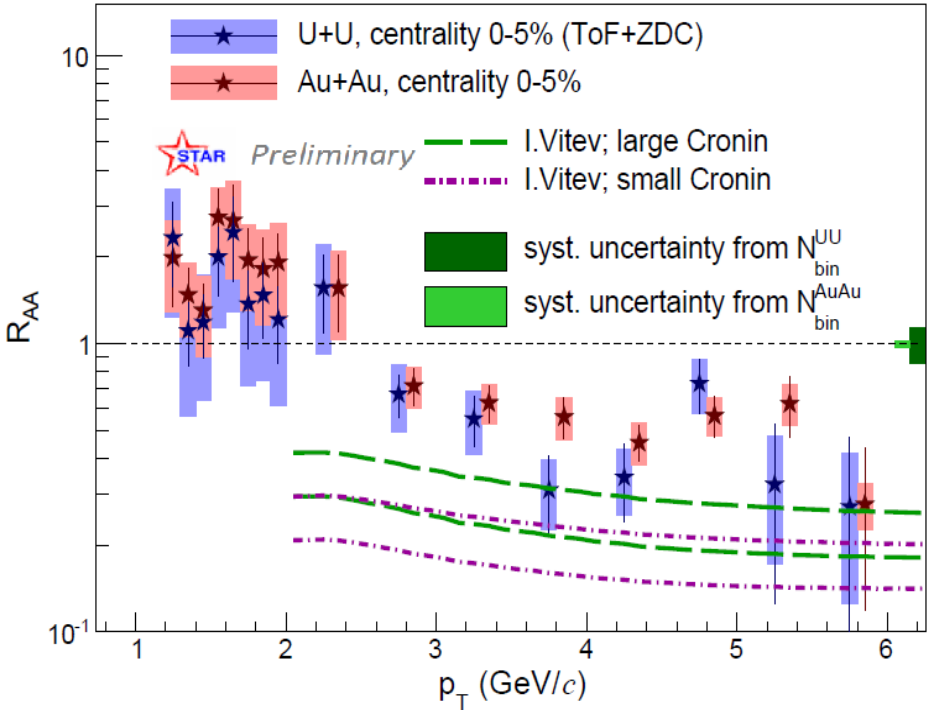




Models with charm diffusion coefficient of 2-11 describe STAR D^0 R_{AA} and v_2 results. Lattice calculations are consistent with these values inferred from data.

Electrons from Heavy Flavor Decay



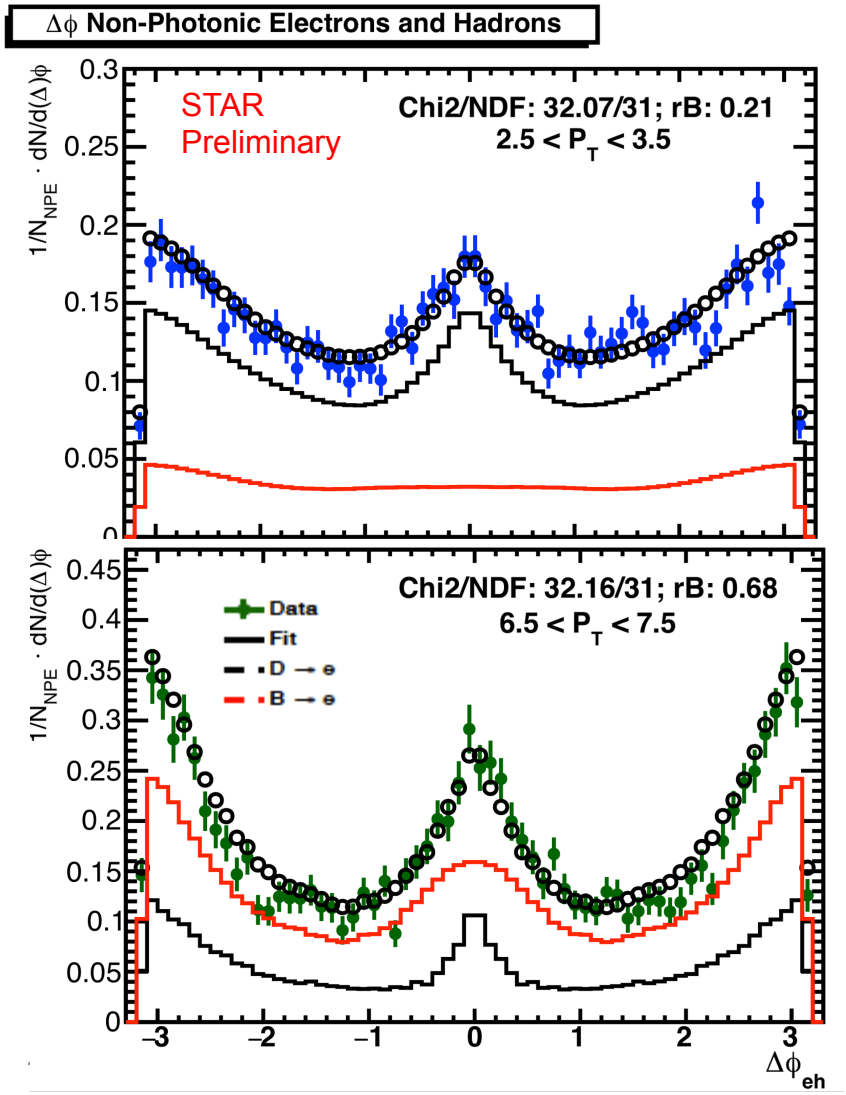


U+U and Au+Au use the same improved p+p reference from 2012 data

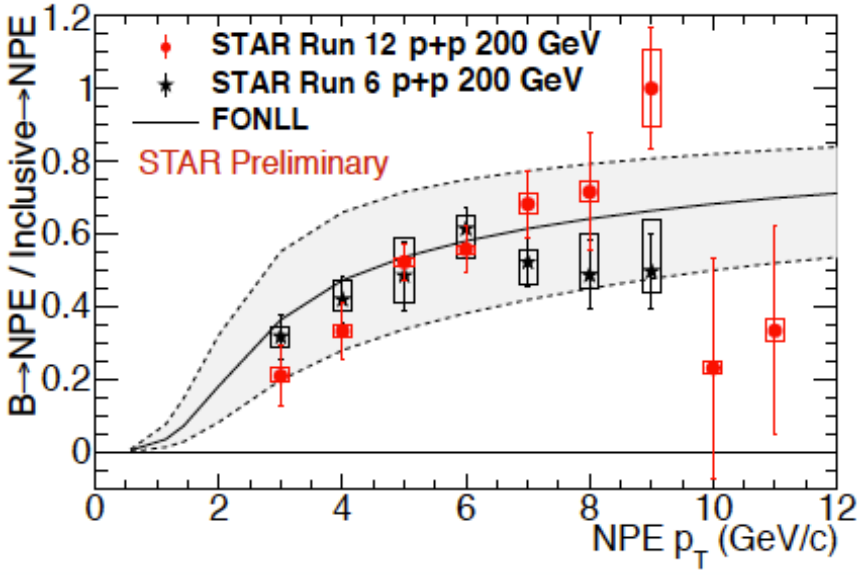
NPE R_{AA} in the 0-5% most central 200 GeV Au+Au and 193 GeV U+U collisions are consistent within uncertainties.

Separate D and B-decayed Electrons

W. Li June 30



STAR Run6: PRL 105 (2010) 202301



- B➔e contributions in p+p 200GeV obtained from e-h correlations; consistent with FONLL calculation
- Studies with the HFT in p+p and Au +Au 200 GeV collisions underway

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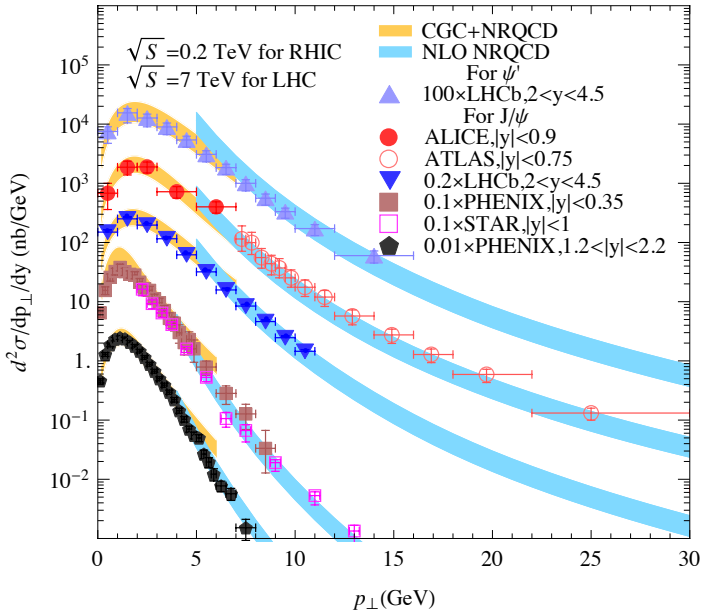
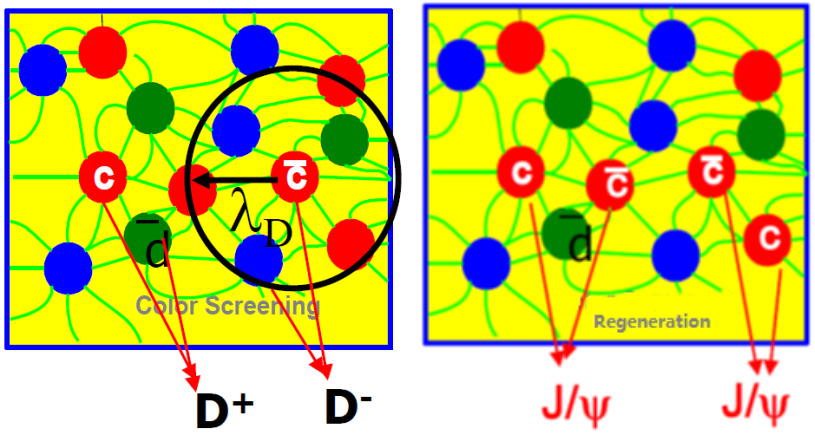
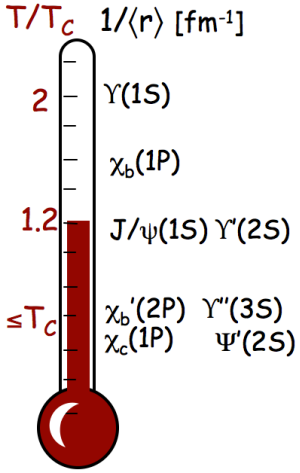
Quarkonium Production

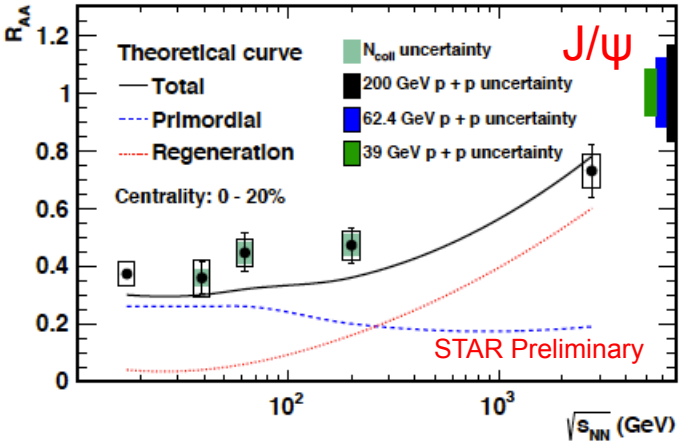
Quarkonium Thermometer

- Production mechanism in hadron collisions not fully understood – CEM, CSM, NRQCD
- Compare AA with pp: dissociation due to color screening, regeneration from uncorrelated heavy quarks, CNM effects
- Compare different quarkonium states: sequential melting – QGP thermometer



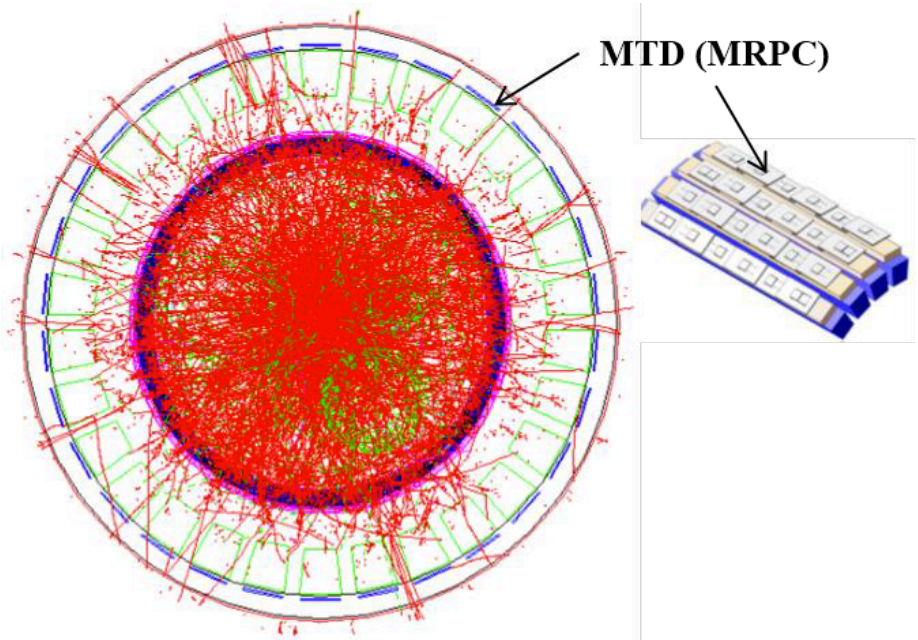




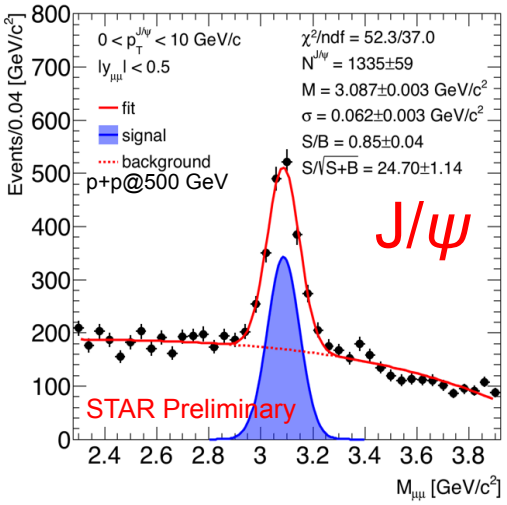


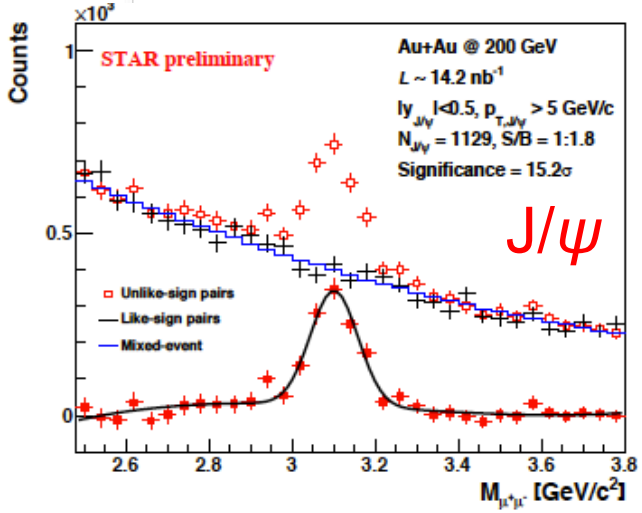
Y.Q. Ma, R. Venugopalan, PRL 113 (2014) 192301
X.Zhao, R.Rapp: PRC 82 (2010) 064905, NA50 PLB 477 (2000) 28, ALICE PLB 734 (2014) 314
A. Mocsy, EPJC 61 (2009) 705

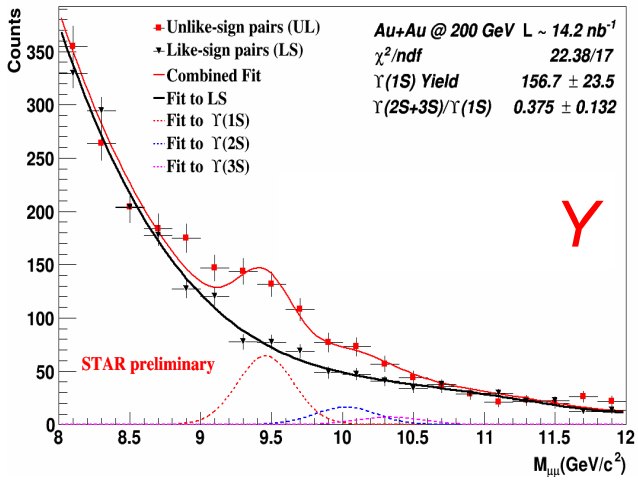
STAR Muon Telescope Detector



- Precise timing info (~100ps) for p_T>1.2 GeV/c; muon online triggering and offline identification
- Recorded 28 pb^{-1}, 120 pb^{-1}, 400 nb^{-1} and 22 nb^{-1} dimuon-triggered 500 GeV p+p, 200 GeV p+p, p+Au and Au+Au data for J/ψ and Υ studies
- Results presented today are based on 28 pb^{-1} p+p 500 GeV (63% MTD) and 14.2 nb^{-1} Au+Au 200 GeV data.







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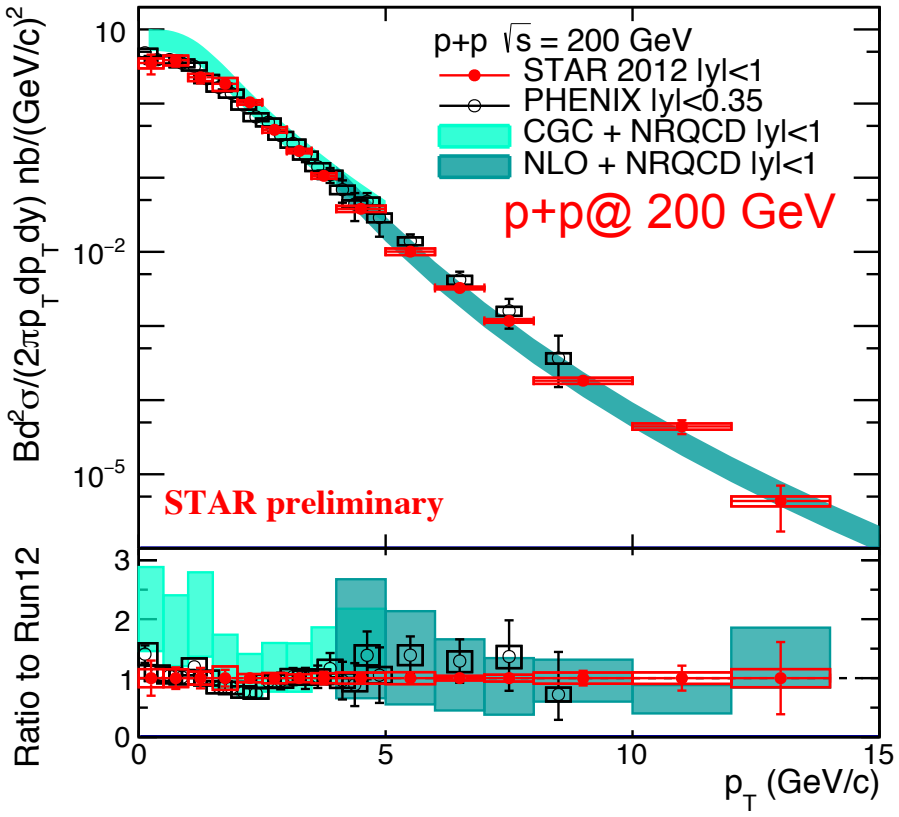
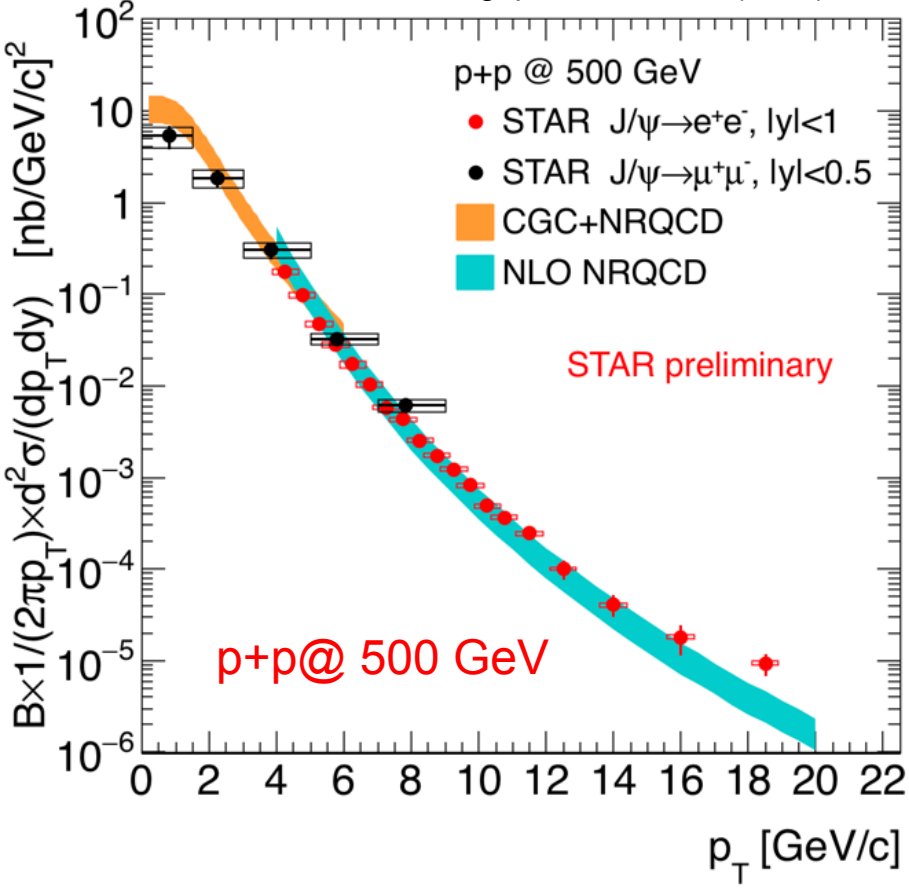
J/ψ Production in p+p 200/500 GeV

T. Todoroki June 28

PHENIX: PRD82 (2010) 012001
NLO NRQCD: Ma et al., PRL106 (2011) 042002
CGC+NRQCD: Ma, Venugopalan, PRL**113** (2014) 192301





- J/ψ production cross-section measured over wide p_T range in p+p 200 and 500 GeV;
- 200 GeV results consistent with PHENIX but with better precision for p_T>2 GeV/c
- NRQCD describes data fairly well; small tension at p_T<1 GeV/c with CGC+NRQCD

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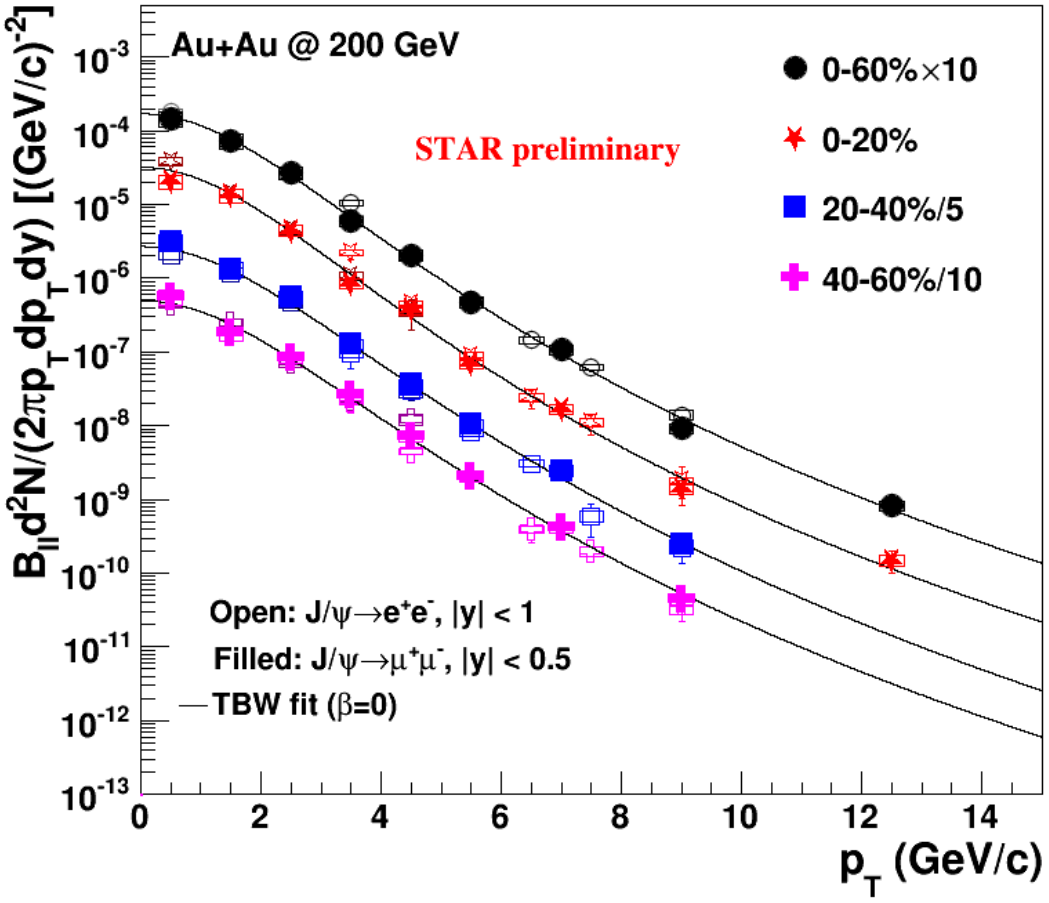
J/ψ R_{AA} in Au+Au 200 GeV

T. Todoroki June 28

STAR dielectron:
PLB 722 (2013) 55
PRC 90 (2014) 024906



- First J/ψ results from the dimuon channel at mid-rapidity in Au+Au collisions at RHIC
- Results are consistent with STAR published di-electron results

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J/ψ R_{AA} in Au+Au 200 GeV

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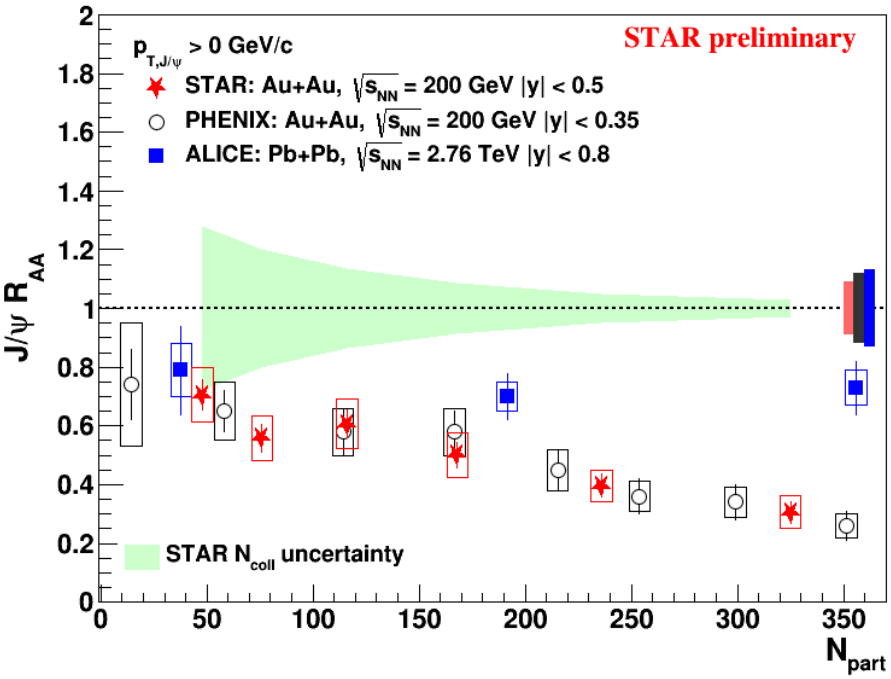
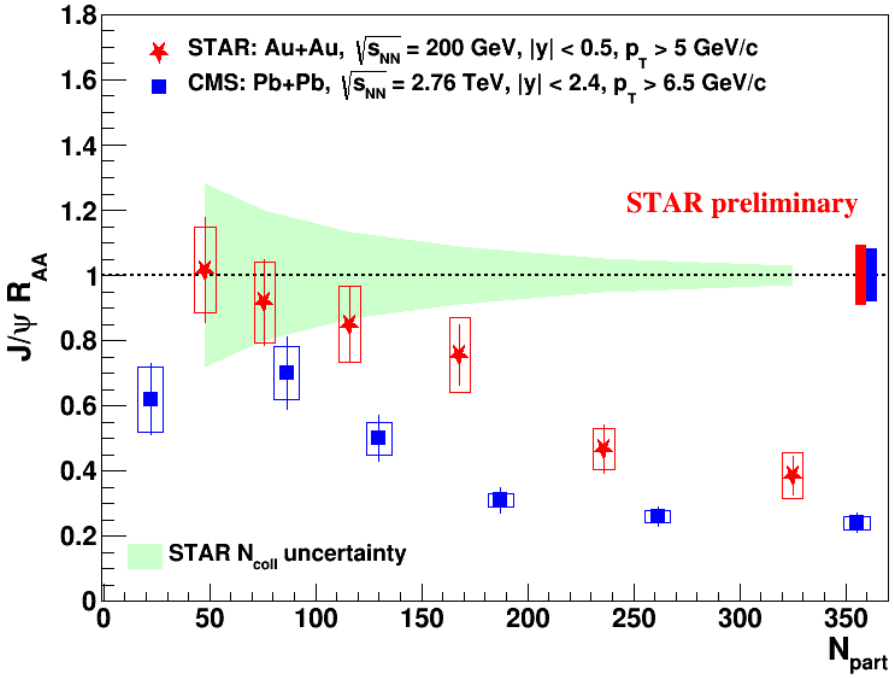
ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301





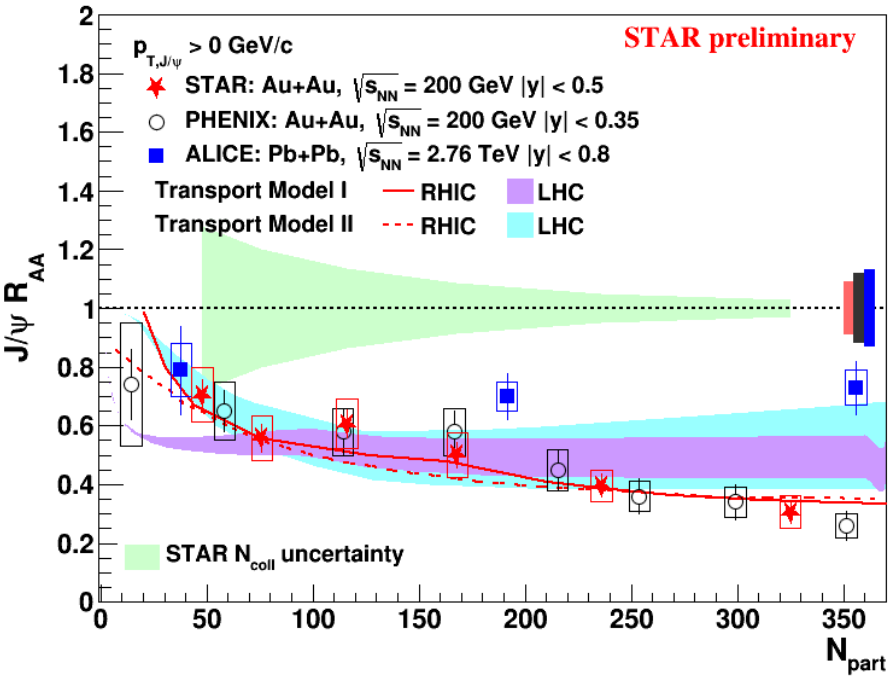
- J/ψ R_{AA} for p_T>0 GeV/c: RHIC is smaller than LHC -> more recombination at LHC
- J/ψ R_{AA} for p_T>5 GeV/c: LHC is smaller than RHIC -> stronger dissociation at LHC

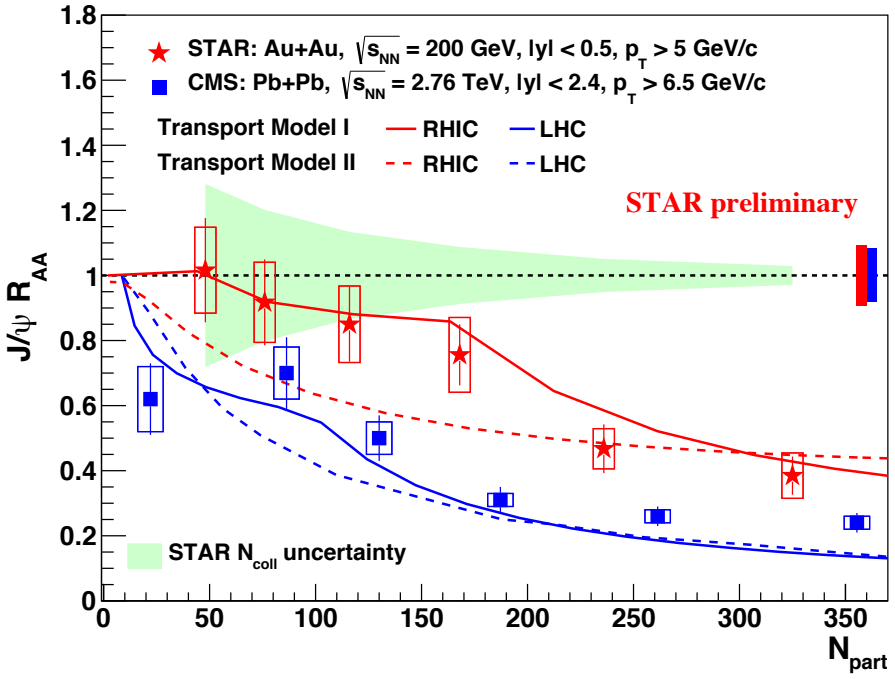
J/ψ R_{AA} in Au+Au 200 GeV

T. Todoroki June 28

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

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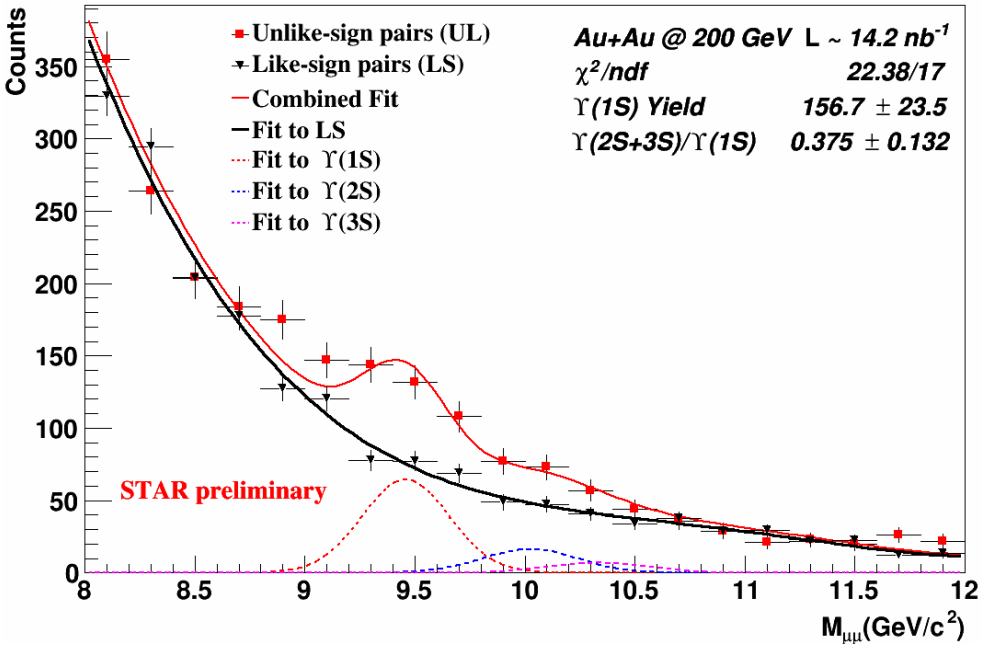
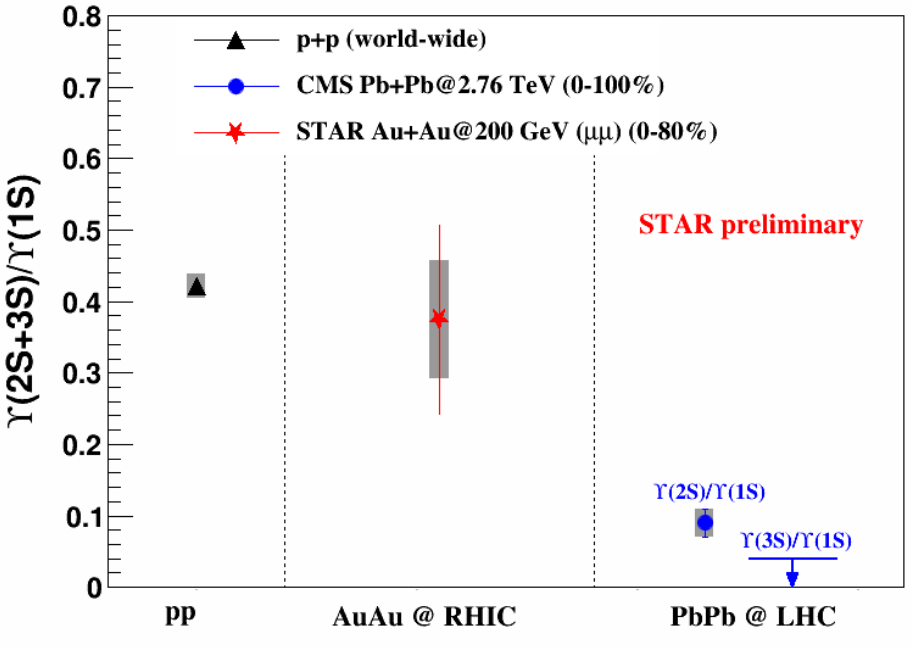
Υ Production in Au+Au 200 GeV

T. Todoroki June 28

CMS : PRL 109 (2012) 222301 JHEP 04 (2014) 103





- Signs of Y(2S+3S) from the di-muon channel
  - Challenging for di-electron channel due to Bremsstrahlung
- Hint of less melting of Y(2S+3S) at RHIC than at LHC ?

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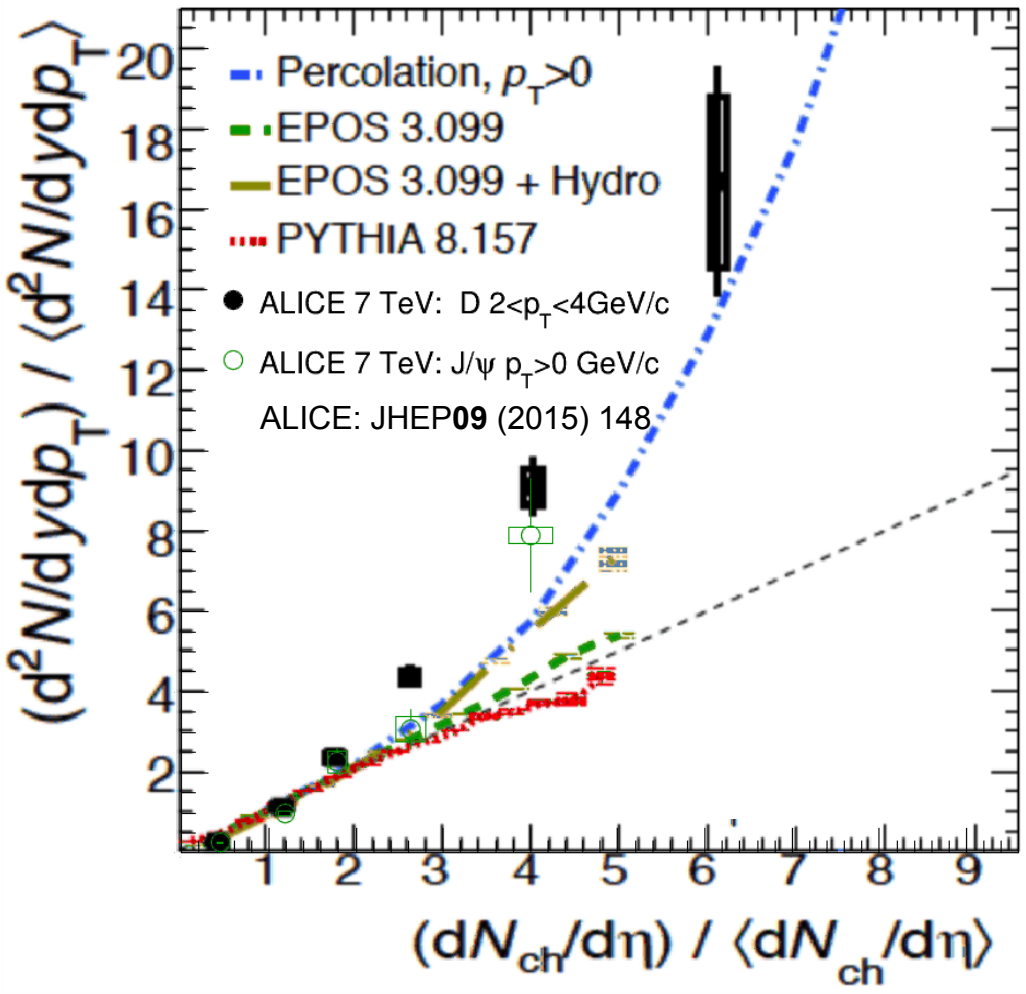
J/ψ Yield vs Event Activity (N_{ch})



Faster-than-linear rise of open charm and J/ψ production vs N_{ch} in p+p @ 7 TeV

- **Percolation model**: exchange color sources in collisions. High energy density suppresses soft processes more than hard processes
  N_{hard} rise faster than N_{ch} at LHC
- **EPOS3**: Gribov-Regge multiple parton scattering for initial conditions,
  $$N_{hard} \propto N_{ch} \propto N_{MPI}$$
- **EPOS3+Hydro**: energy density in 7 TeV p+p is high enough to apply hydrodynamic evolution to the core of the collisions.
  N_{hard} rise faster than N_{ch} at LHC
- **PYTHIA8**: including Multiple-Parton-Interaction`
  $$N_{hard} \propto N_{ch} \propto N_{MPI}$$

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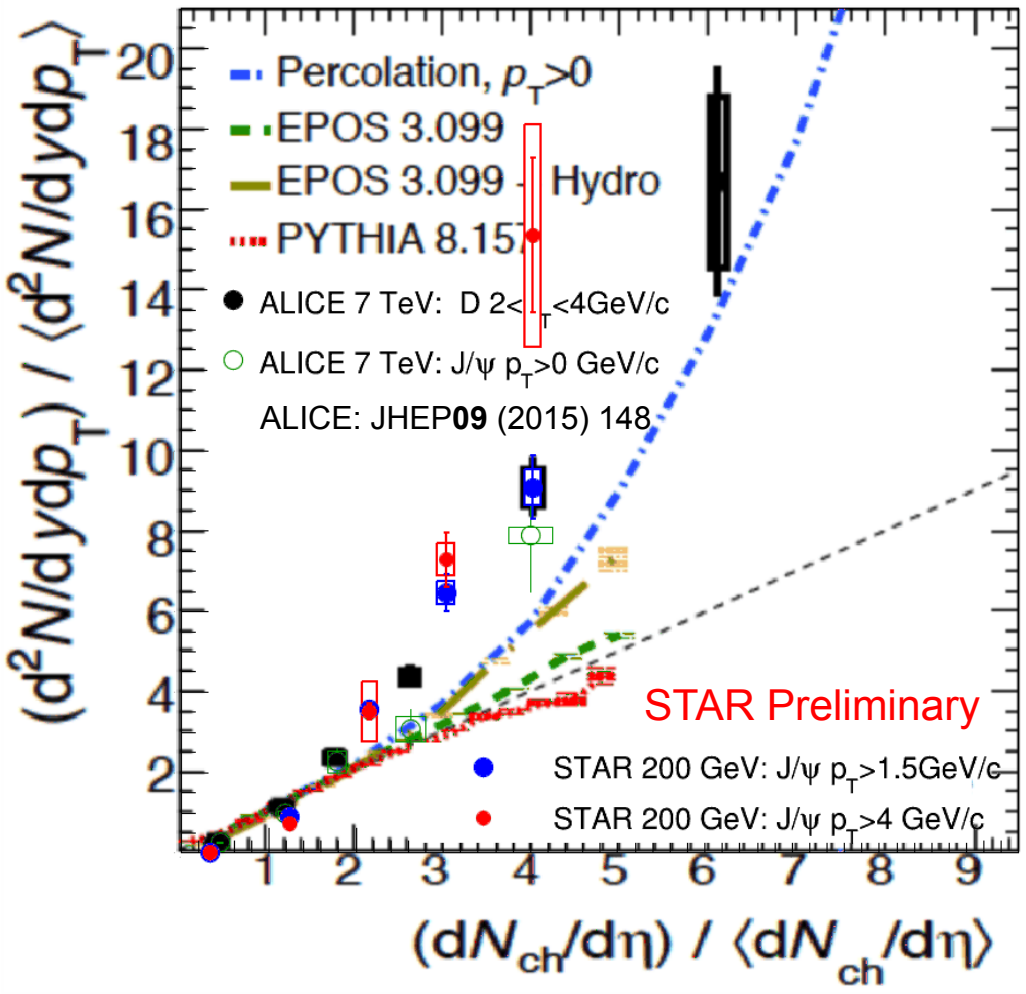
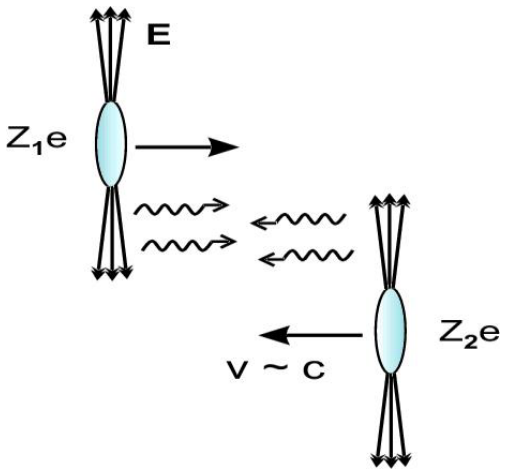
J/ψ Yield vs Event Activity (N_{ch})

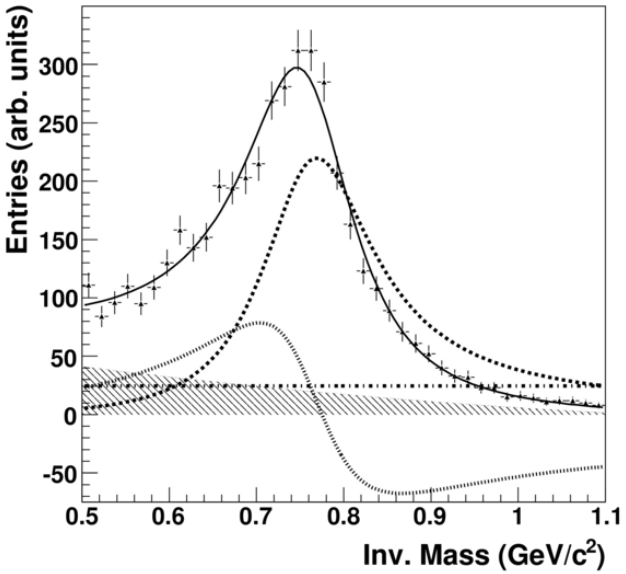


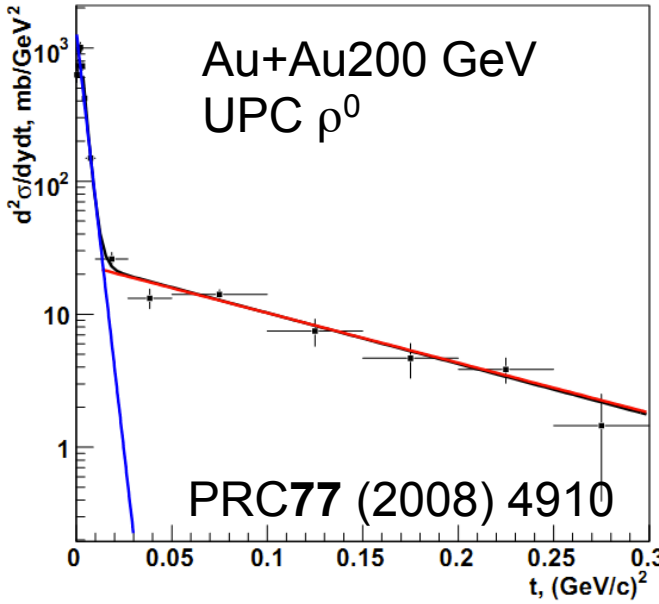
- **Percolation model**: exchange color sources in collisions. High energy density suppresses soft processes more than hard processes
  N_{hard} rise faster than N_{ch} at LHC
  Small collisional energy dependence
  N_{hard} rise faster than N_{ch} at RHIC
- **EPOS3+Hydro**: energy density in 7 TeV p+p is high enough to apply hydrodynamic evolution to the core of the collisions
  N_{hard} rise faster than N_{ch} at LHC
  Expect strong dependence on collision energy:
  $\langle dN_{ch}/d\eta \rangle$ ~ 3 at 200 GeV
  ~ 6 at 7 TeV
  N_{hard} rise linearly as N_{ch} at RHIC?

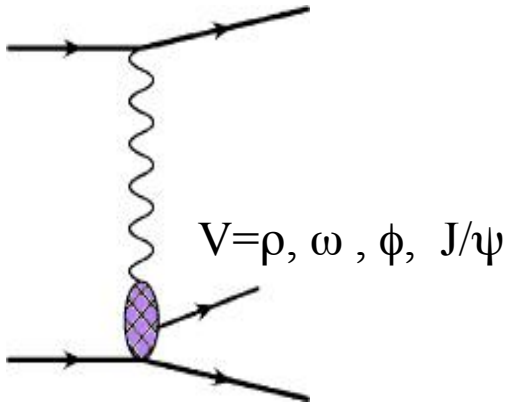
Stronger-than-linear rise following the same trend at 200 GeV and 7 TeV, probably not a hot medium effect but something more fundamental

ρ Meson Photoproduction in UPC









Photon-nucleus interactions

- Coherent and incoherent photoproduction of ρ mesons observed in Ultra-Peripheral Collisions (UPC)

J/ψ Photoproduction in Peripheral Collision?

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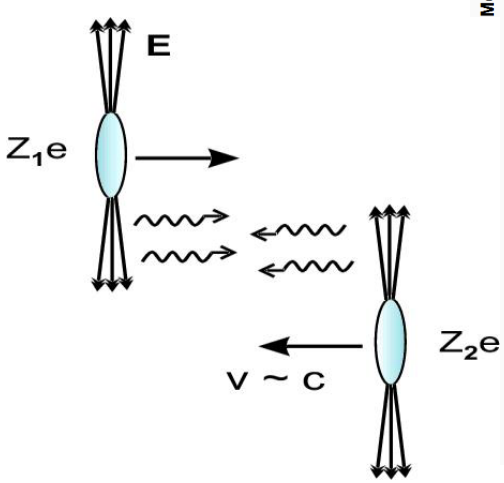

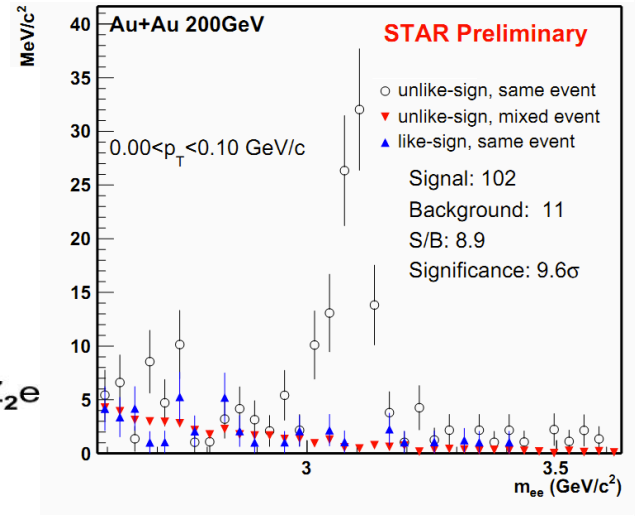

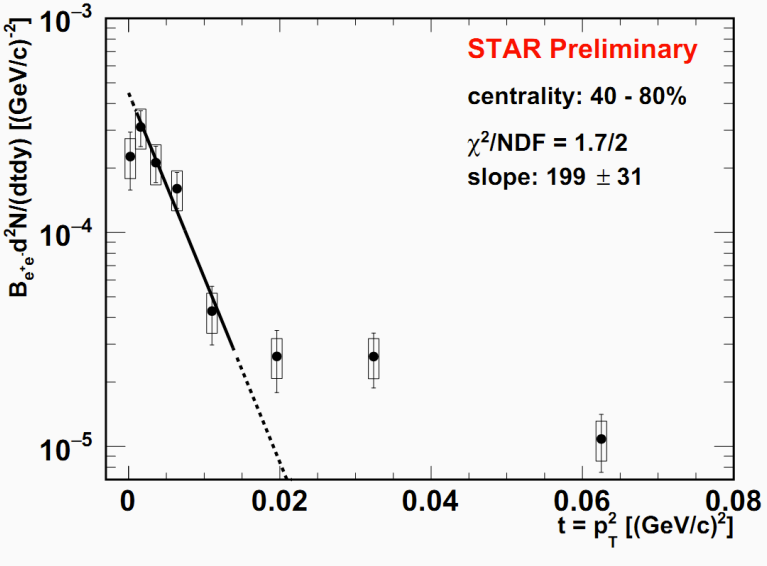

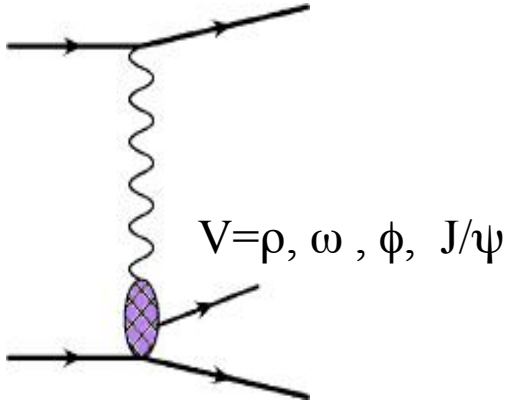

Photon-nucleus interactions

- Coherent and incoherent photoproduction of ρ mesons observed in Ultra-Peripheral Collisions (UPC)
- Observe excess of very low p_T J/ψ in peripheral collisions with features consistent with coherent photoproduction
  - Similar slope as UPC: 199 ±31(GeV/c)$^{-2}$
    UPC in STARLIGHT: 196 (GeV/c)$^{-2}$

J/ψ Photoproduction in Peripheral Collision?

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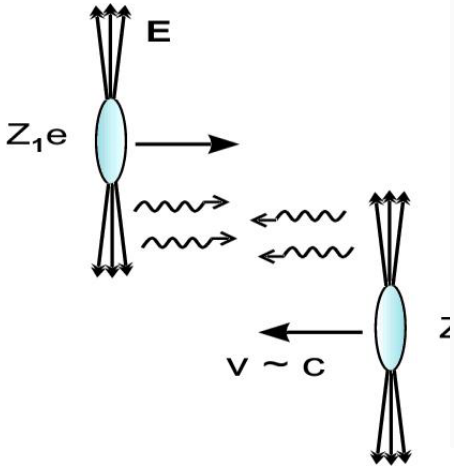

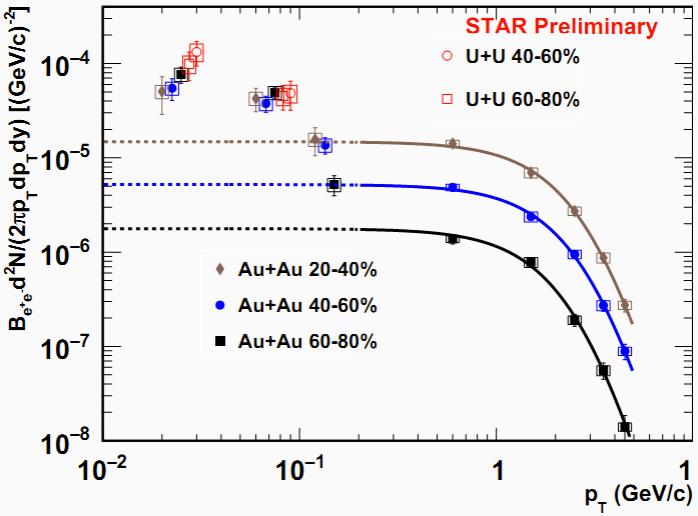

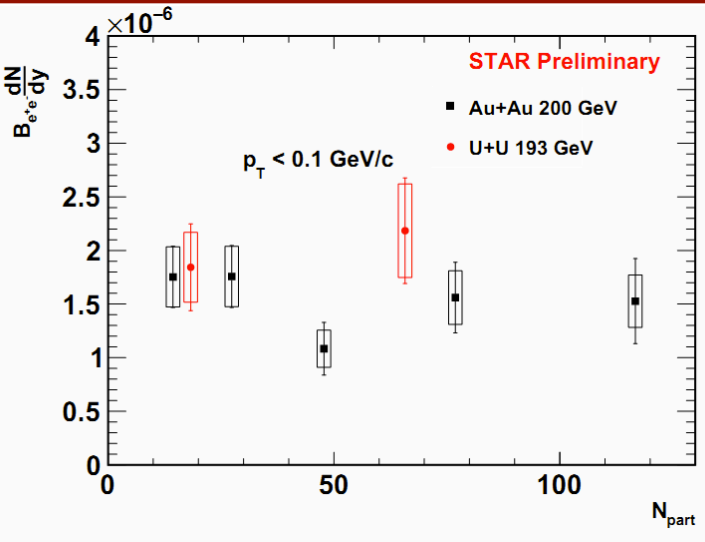

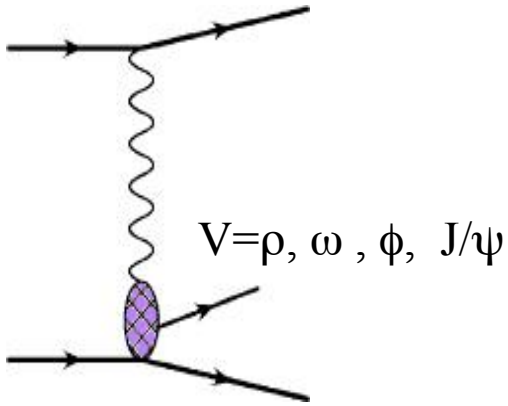

Photon-nucleus interactions

- Coherent and incoherent photoproduction of ρ mesons observed in Ultra-Peripheral Collisions (UPC)
- Observe excess of very low p_T J/ψ in peripheral collisions with features consistent with coherent photoproduction
  - Similar slope as UPC: 199 ±31(GeV/c)$^{-2}$
    UPC in STARLIGHT: 196 (GeV/c)$^{-2}$
  - Production cross-section independent of centrality

A challenge for theory but a new opportunity for QGP studies?

Zhenyu Ye

Summary and Outlook

- First results from the HFT and MTD
  - D^0 R_{AA} and v_2 in Au+Au collisions: favor model calculation with charm quark diffusion, diffusion coefficient inferred from data consistent with Lattice QCD
  - HF-decayed electron production: p+p cross-section described by FONLL, R_{AA} in 0-5% 200 GeV Au+Au collisions consistent with 193 GeV U+U collisions
  - J/ψ R_{AA} in Au+Au collisions: larger (smaller) R_{AA} at low (high) pT than LHC because of stronger recombination (dissociation) at LHC
  - Y in Au+Au collisions: hint for less Y(2S+3S) suppression at RHIC than LHC
  - J/ψ yield vs event activity in p+p collisions: faster-than-linear trend also observed at 200 GeV similar to 7 TeV, probably not a hot medium effect
  - Very low p_T J/ψ enhancement in peripheral Au+Au and U+U collisions: independent of centrality, consistent with coherent photoproduction
  - Not shown: D^0 v_3 (M.Lomnitz), D_s R_{AA} (Z.Long), J/ψ v_2 (T.Todoroki)
- More exciting results are expected
  - Factor of 2-4 in D^0 significance with new PXL offline reconstruction software
  - Factor of 2 (4) Au+Au data recorded on tape for the MTD (HFT)
  - p+p and p+Au data recorded on tape for precise p+p and CNM studies

List of STAR HF Talks at SQM2016

- Zhou, Long June 28, 14:00 Joseph Wood Krutch Theatre
  $D_s^{\pm}$ meson production in Au+Au collisions at $\sqrt{sNN}$=200 GeV in STAR
- Zha, Wangmei June 28 16:20 Room 104
  Excess of J/ψ yield at very low p_T in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV and U+U at $\sqrt{s_{NN}}$= 193 GeV with STAR
- Todoroki, Takahito June 28 17:40 Room 104
  Quarkonium measurements via the di-muon decay channel in p+p and Au +Au collisions with the STAR experiment
- Lomnitz, Michael June 30 09:20 Room 102
  Measurement of D^0 elliptic and triangular flow in Au+Au collisions at $\sqrt{sNN}$=200 GeV at RHIC
- Li, Wei June 30 11:20 Room 104
  Measurement of Bottom contribution to the non-photopic electron production in p+p collisions at sqrt(s)=500 GeV at STAR