Experimental Highlights: Heavy Quark Physics in Heavy-Ion Collisions at RHIC

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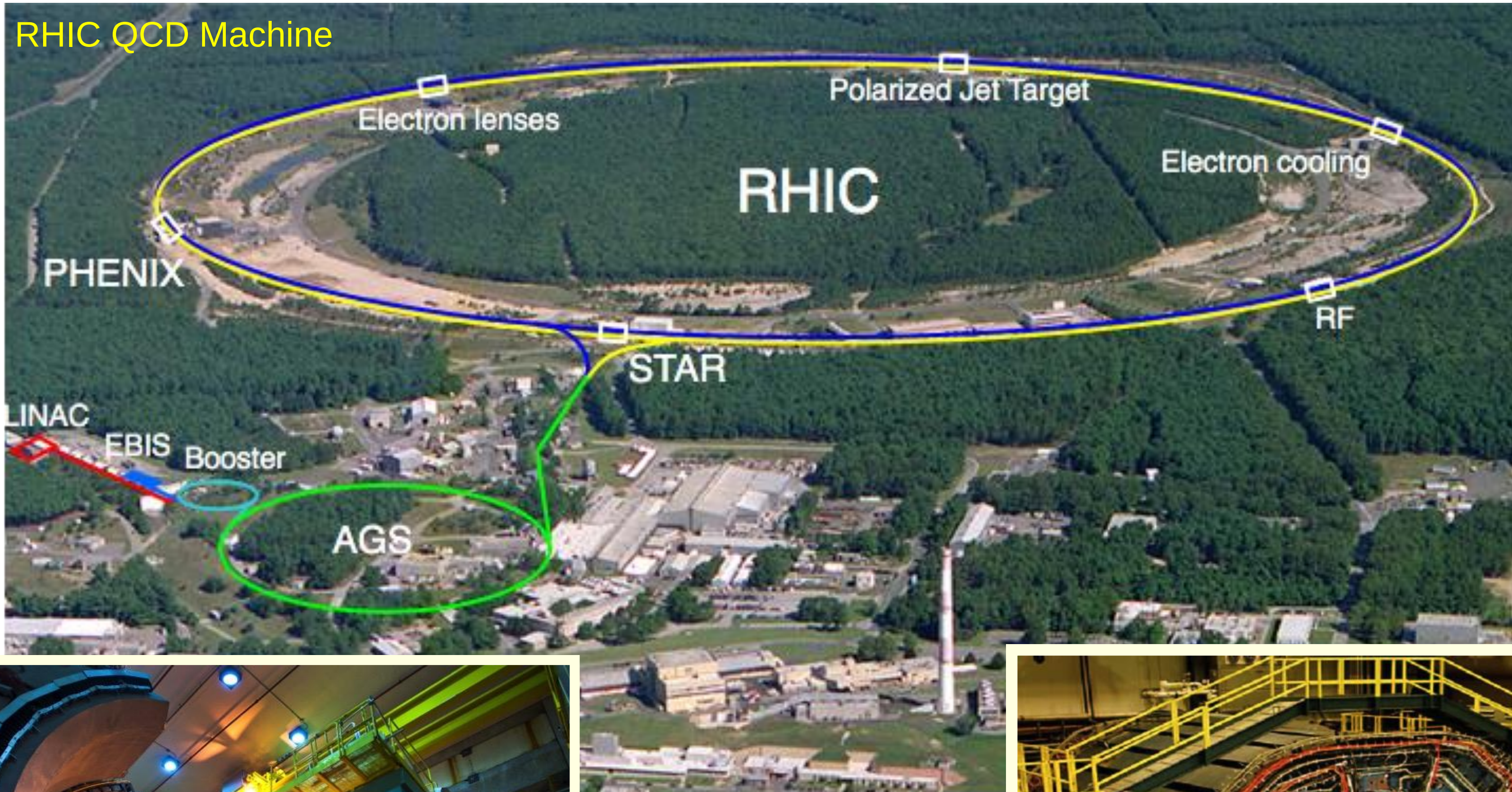
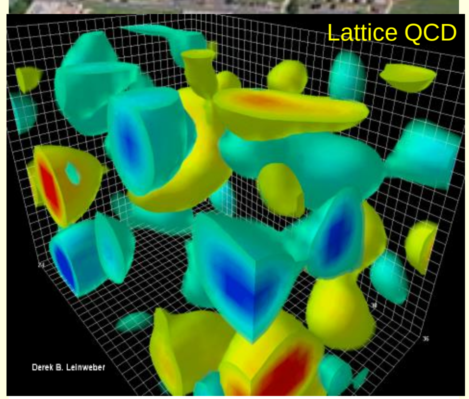
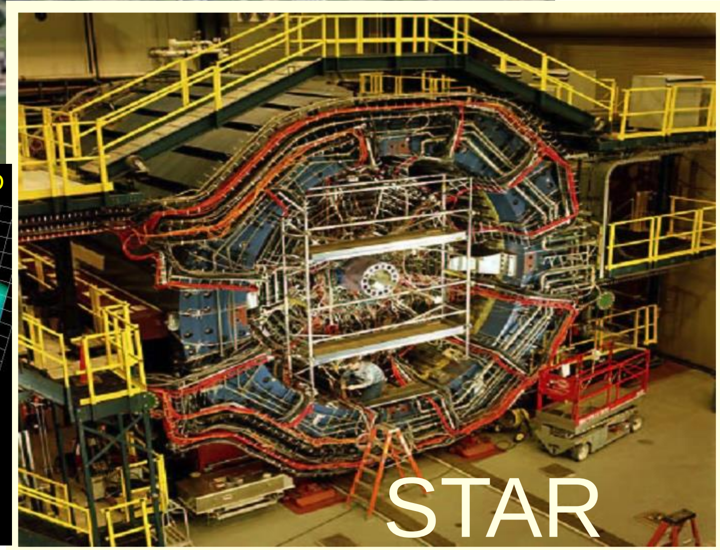
XIIth Quark Confinement and the Hadron Spectrum
Thessaloniki, Greece
August 29th to September 3rd, 2016

The RHIC Facility Today





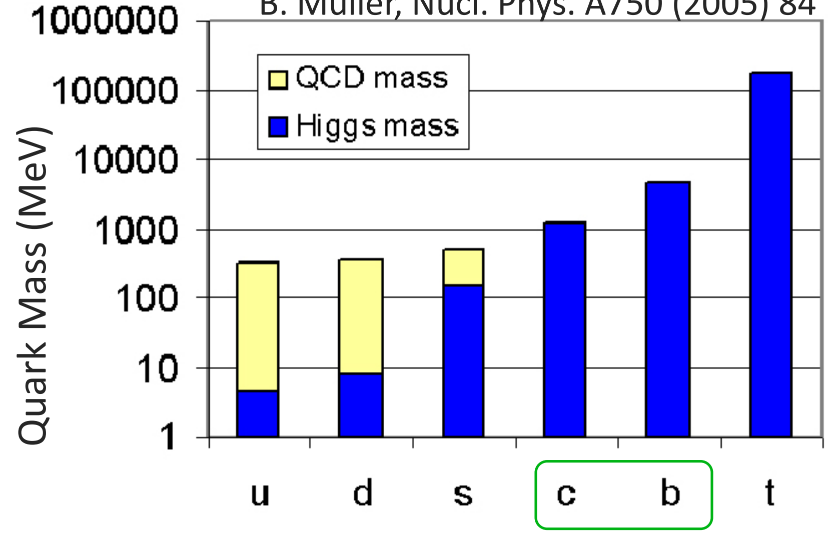


Heavy Flavor: Ideal Probe of QCD Matter

Theoretical motivation

- Symmetry breaking
  - **- Higgs mass:** electroweak symmetry breaking
    → current quark mass
  - **- QCD mass:** chiral symmetry breaking
    → constituent quark mass
- Charm and beauty quark masses are not affected by QCD vacuum
  → ideal probes to study QGP

B. Muller, Nucl. Phys. A750 (2005) 84

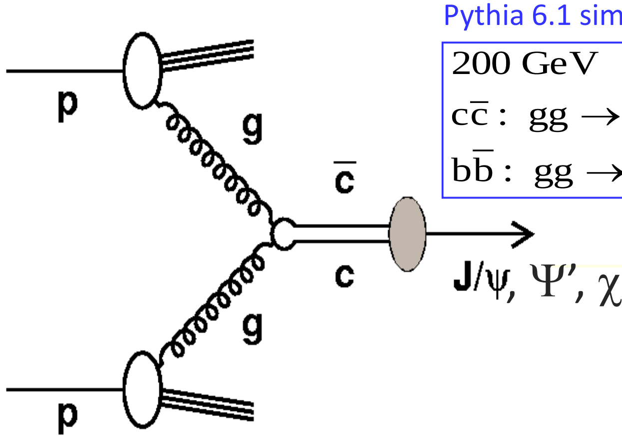


- Heavy quarks ($c\bar{c}$, $b\bar{b}$)
  - Bound states (J/ψ, Υ)

State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.36	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
Radius (fm)	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

- Due to their mass ($m_Q >> T_{cri}$, Λ_{QCD})
  → higher penetrating power
- Gluon fusion dominates
  → sensitive to initial state gluon distribution

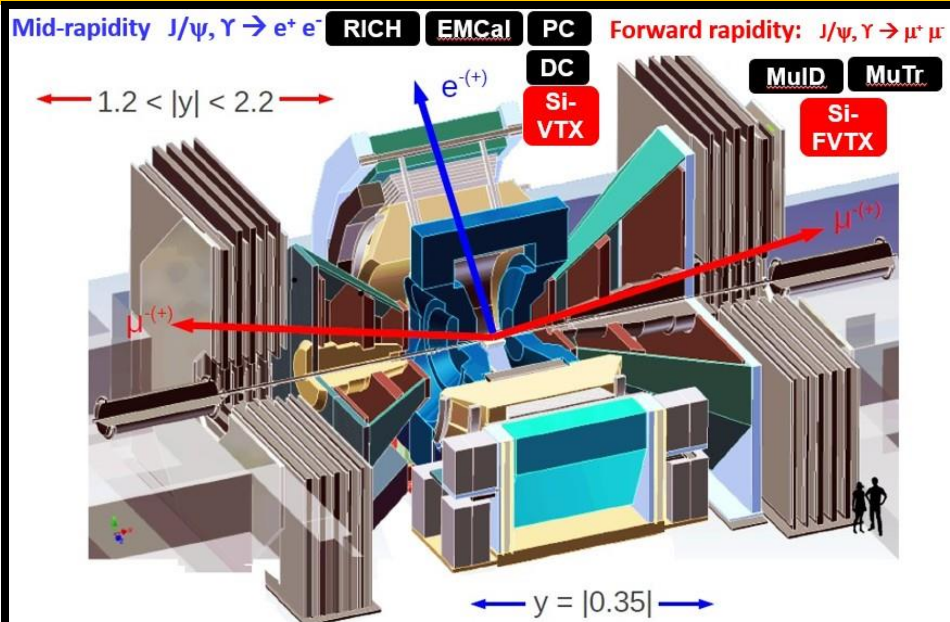
M. Gyulassy and Z. Lin, Phys. Rev. C51 (1995) 2177

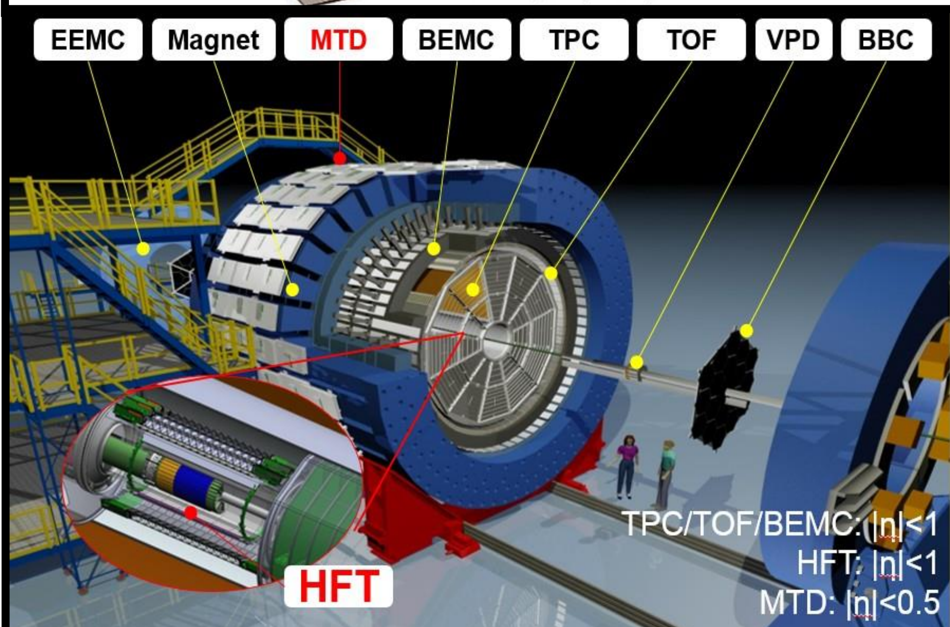


Pythia 6.1 simulation (LO)

200 GeV
$c\bar{c}$: $gg \to c\bar{c}$ 95%
$b\bar{b}$: $gg \to b\bar{b}$ 85%

Measuring Heavy Flavor in PHENIX and STAR





PHENIX Detector

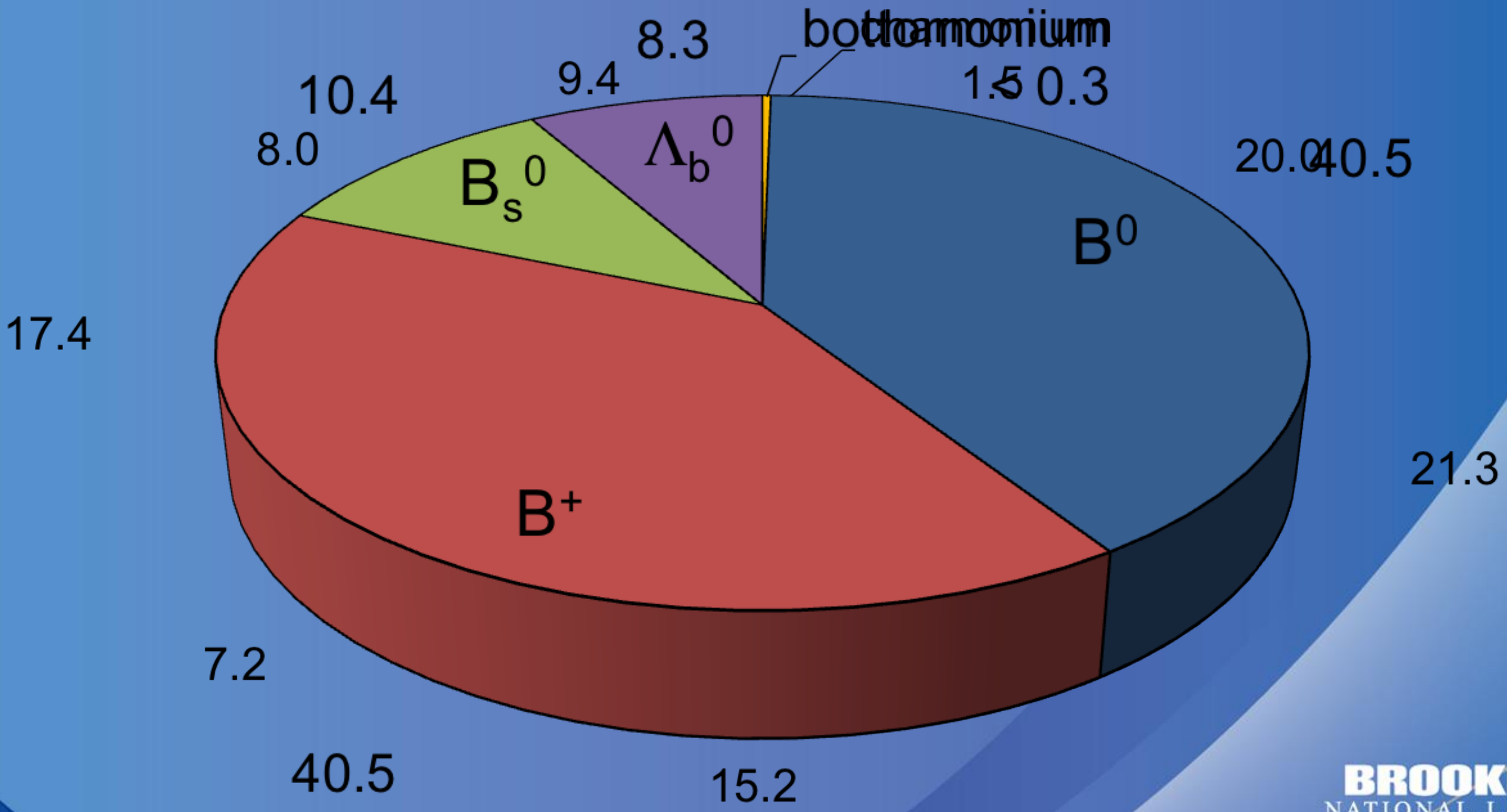
- **SiVTX**: Silicon Vertex Tracker : $|\eta| < 1.2$
  Central Arms:
  - Υ, J/ψ, ψ' $\rightarrow e^+ e^-$
  - D $\rightarrow$ X+e
  - $\rho,\omega,\varphi \rightarrow$ e+e- ,$K^+ K^-$
- **FVTX**: Forward Silicon Tracker: $1.2 < |\eta| < 2.2$
  Muon Arms:
  - Υ, $J/\psi \rightarrow \mu^+ \mu^-$
  - $D \rightarrow X + \mu$
  - $\rho,\omega,\varphi \rightarrow \mu+\mu$ -

STAR Detector

- **HFT**: Heavy FlavorTracker : $|\eta| < 1.2$
  - $D^0 \rightarrow K\pi$, $D^\pm \rightarrow K\pi\pi$ or , $D_s \rightarrow K^+ K^- \pi$
- **MTD**: Muon Telescope Detector: $|\eta| < 0.5$
  - Υ, $J/\psi \rightarrow \mu^+ \mu^-$

Where does all the heavy flavor go?

Courtesy of Kai Schweda (SQM2016)



Open Heavy Flavor

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Motivation for Open Heavy Flavor Measurements

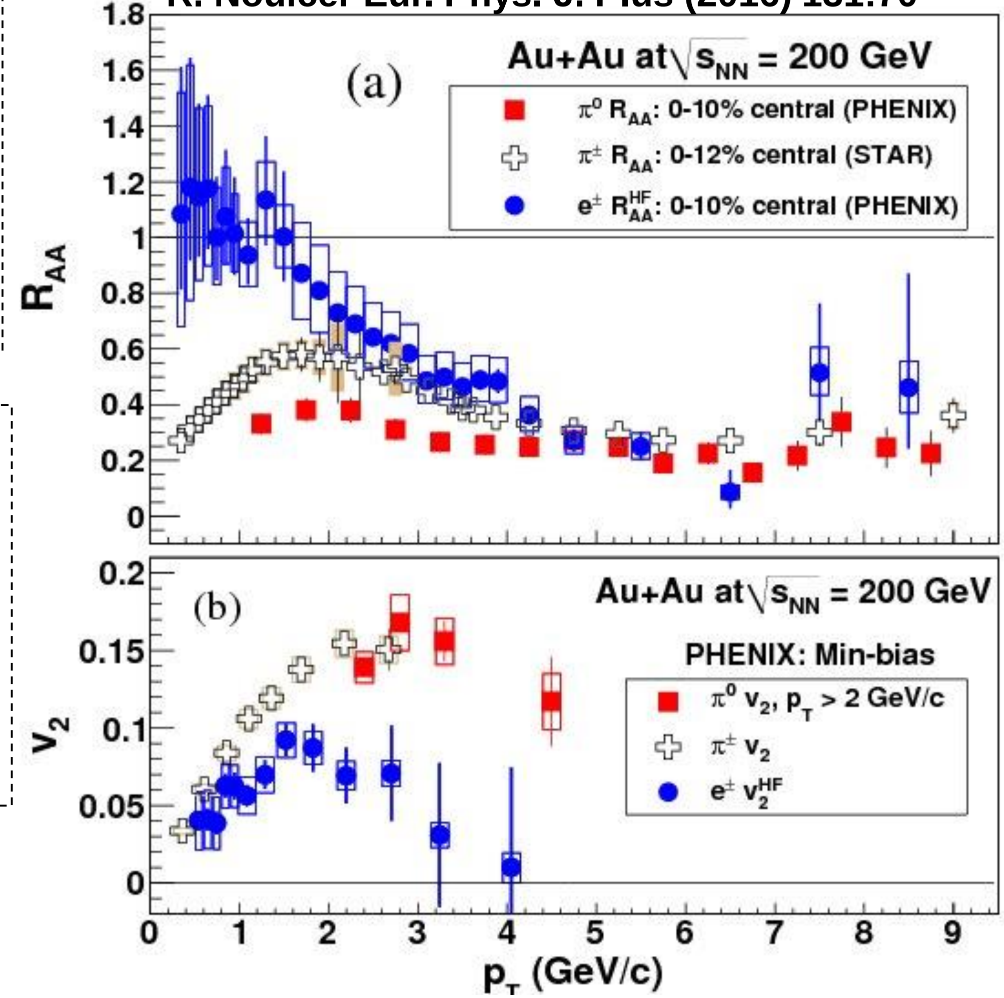
- Heavy quarks suppressed the same as light quarks, and they flow, but less.
- Collective behavior is apparent in e^{HF}; but it is lower than v_2 of π^0 for p_T > 2 GeV/c.

- This contradicts models that assumed only inelastic (radiative) in-medium energy loss, which predicted that R_{AA}(HQ) > R_{AA}(light quark) due to "dead cone effect".

✧ **Separating D and B meson contributions key for establishing mass hierarchy in understanding energy loss.**

Nuclear modification factor

R. Nouicer Eur. Phys. J. Plus (2016) 131:70

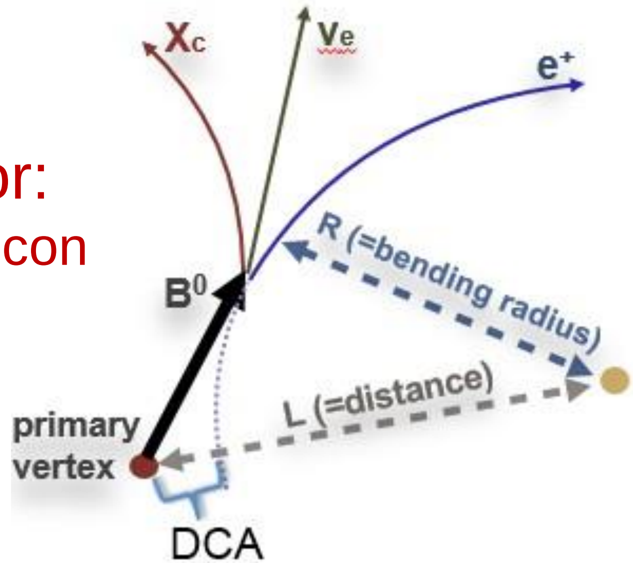


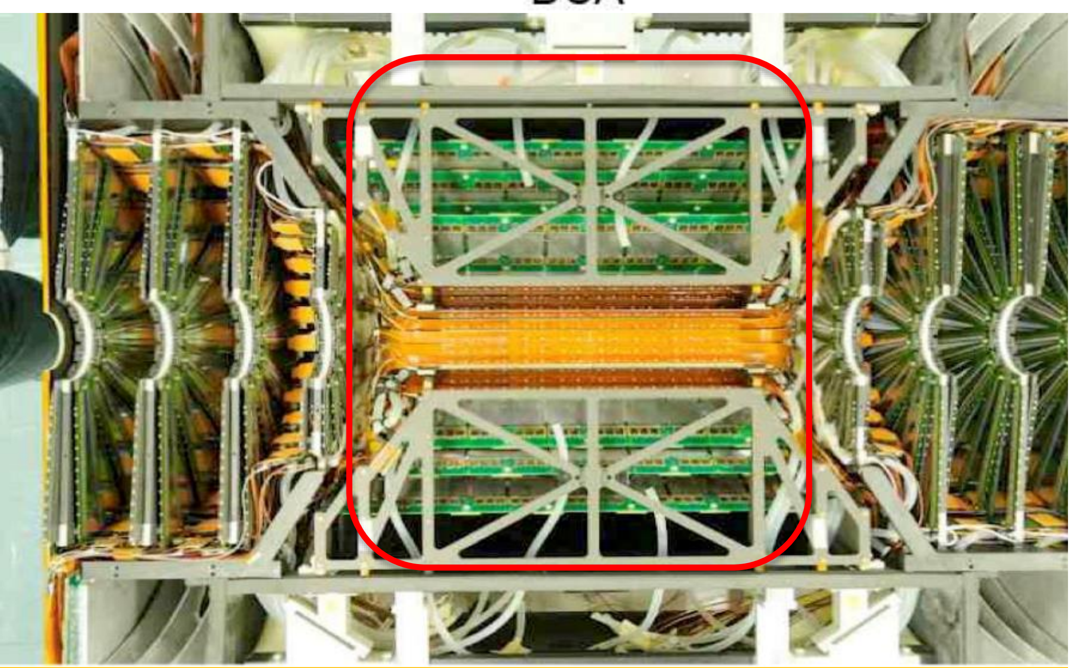
PHENIX Central Heavy Flavor Tracker (VTX)

NEW!

VTX detector:

4 barrels of silicon





DCA_T Distributions: b/c separation

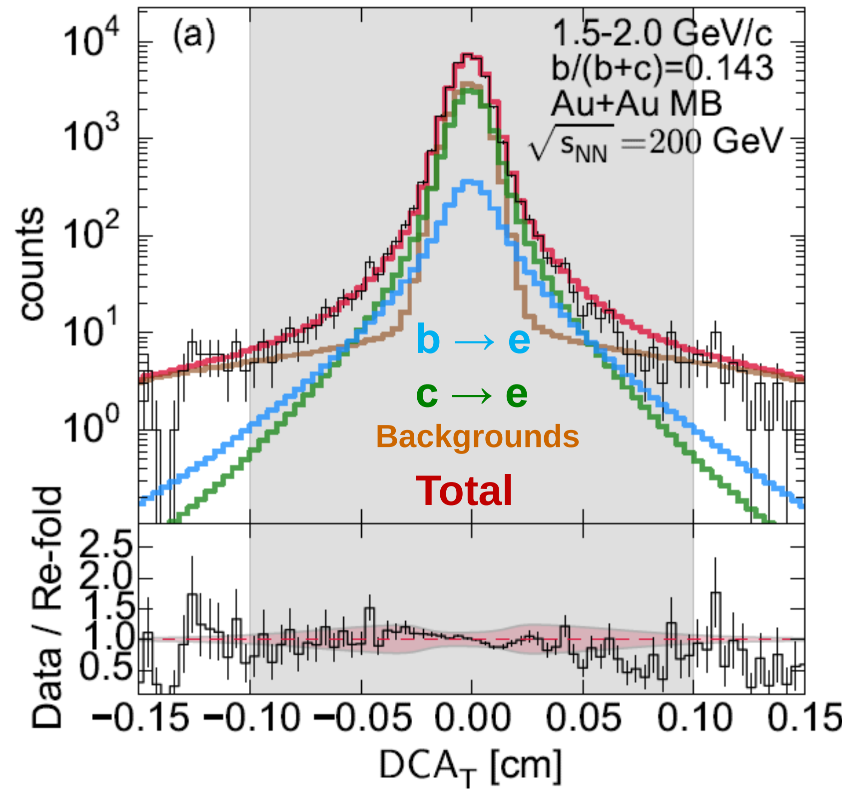
- VTX: $|\eta| < 1.2$
  - Au+Au 200 GeV: DCA_T resolution ~ 60 μm

Life time ($c\tau$)

D^0 : 123 μm

B^0 : 464 μm

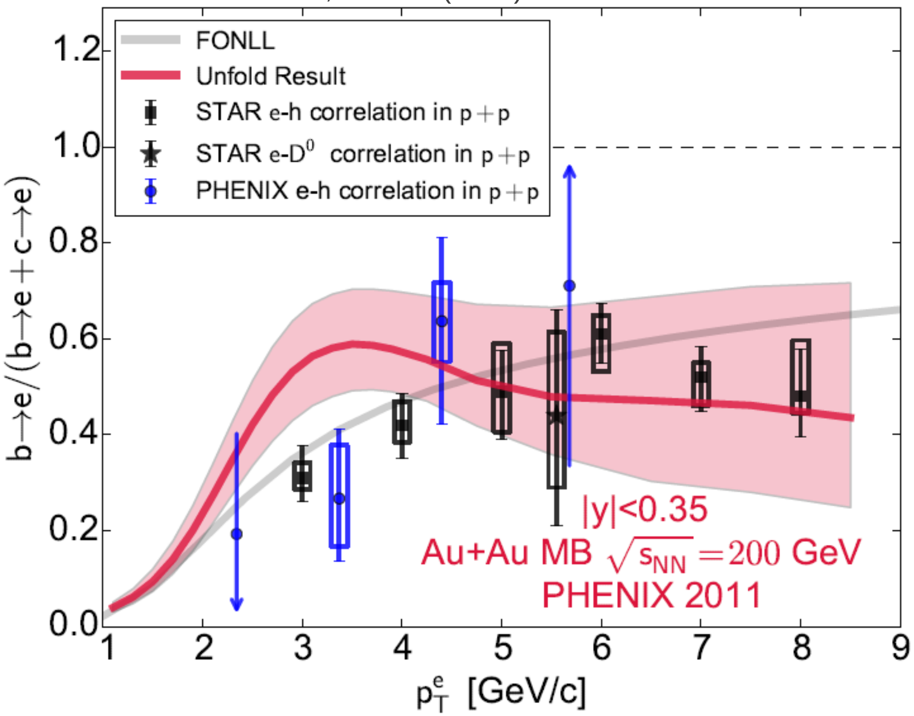
PHENIX: PRC **93**, 034904 (2016)

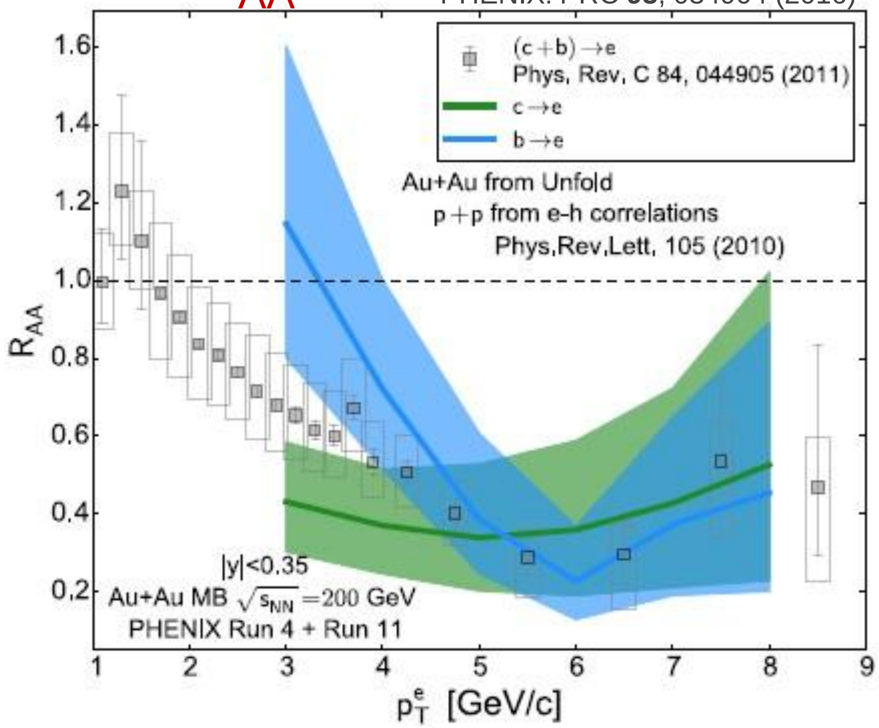


Open Heavy Flavor with VTX in PHENIX

First Results from PHENIX VTX: b/c separation

Bottom and Charm R_{AA}





$$R_{AA}^{c\to e} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R_{AA}^{HF}$$

$$R_{AA}^{b\to e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF},$$

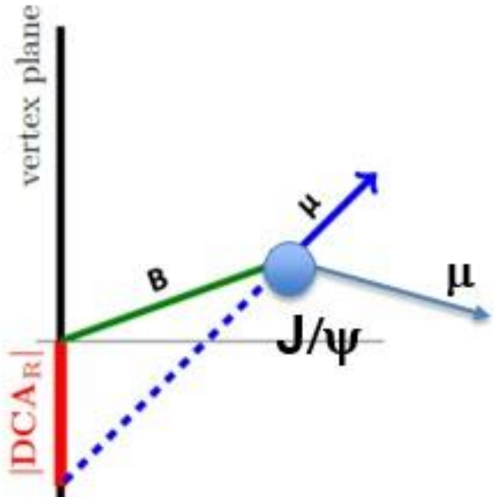
We see that around p_T < 4 GeV the electrons from bottom experience much less suppression than electrons from charm.

Stay Tuned:

- 2014 data set x10 better statistics than 2011
  - Decrease uncertainties
  - Increase p_T reach
  - Centrality separation
- Good 2015 p+p and p+Au data sets

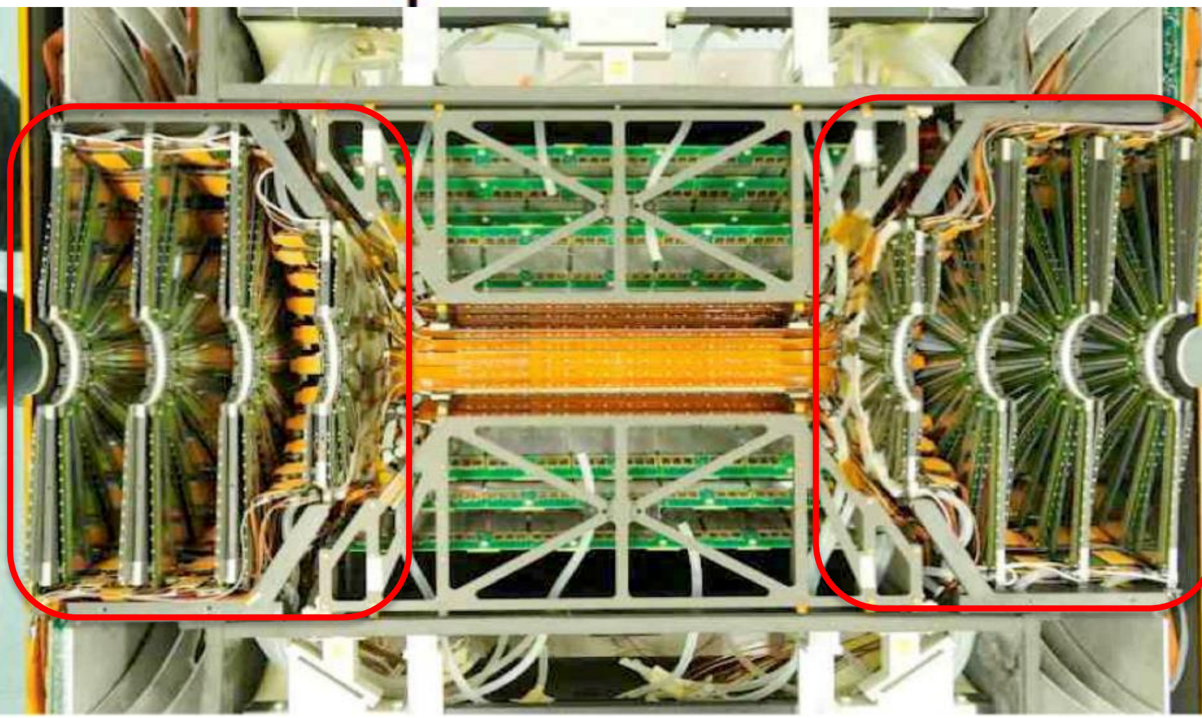
PHENIX Forward Heavy Flavor Tracker (FVTX)

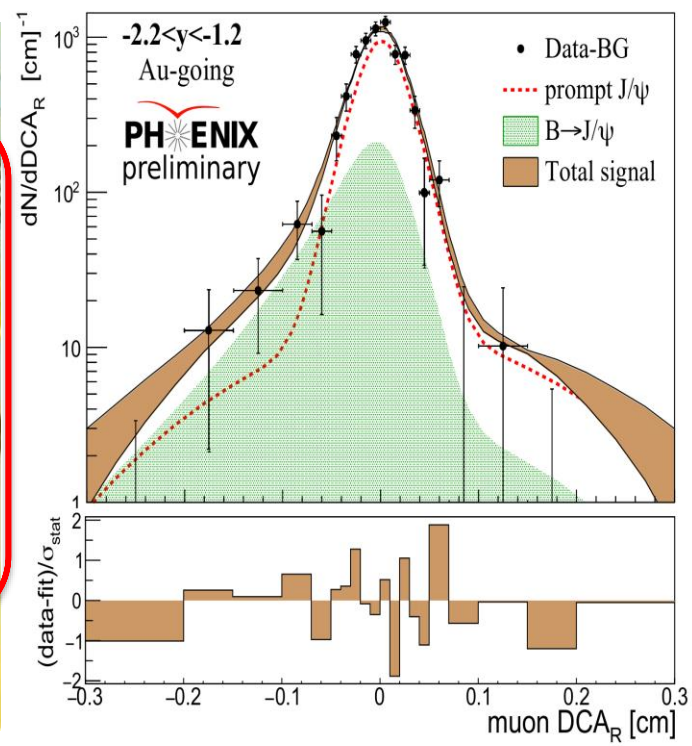
FVTX detector:



DCA_R Distributions

- FVTX:
- Forward rapidity - 1.2 < |η| < 2.2
- Improved muon momentum resolution & precise tracking

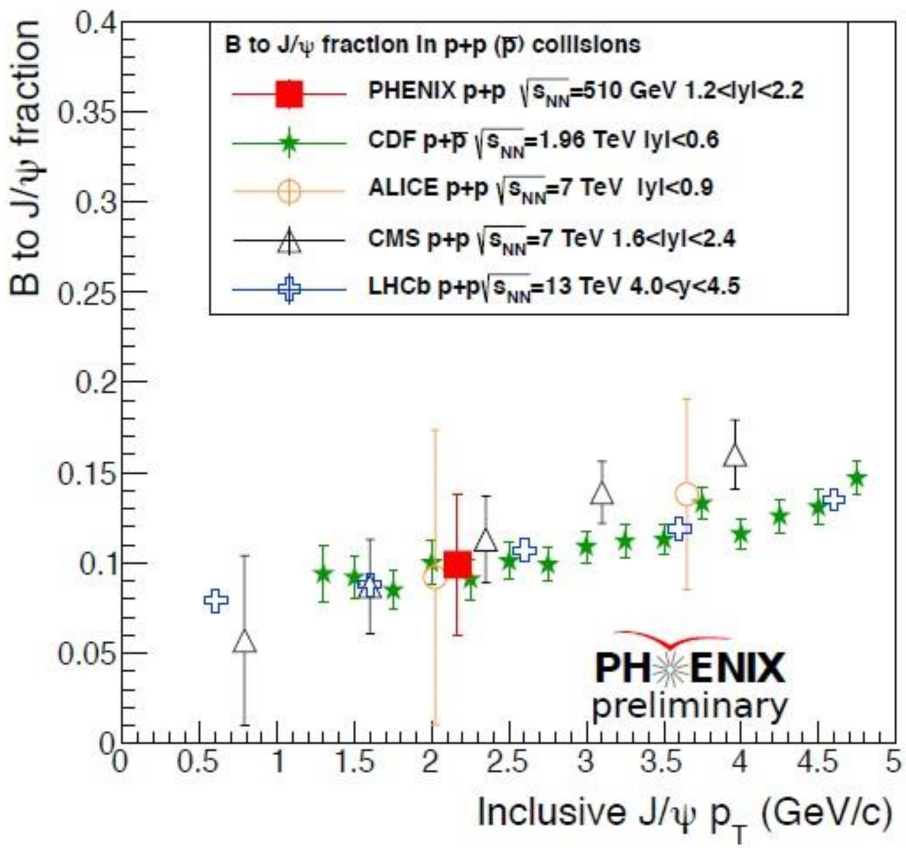


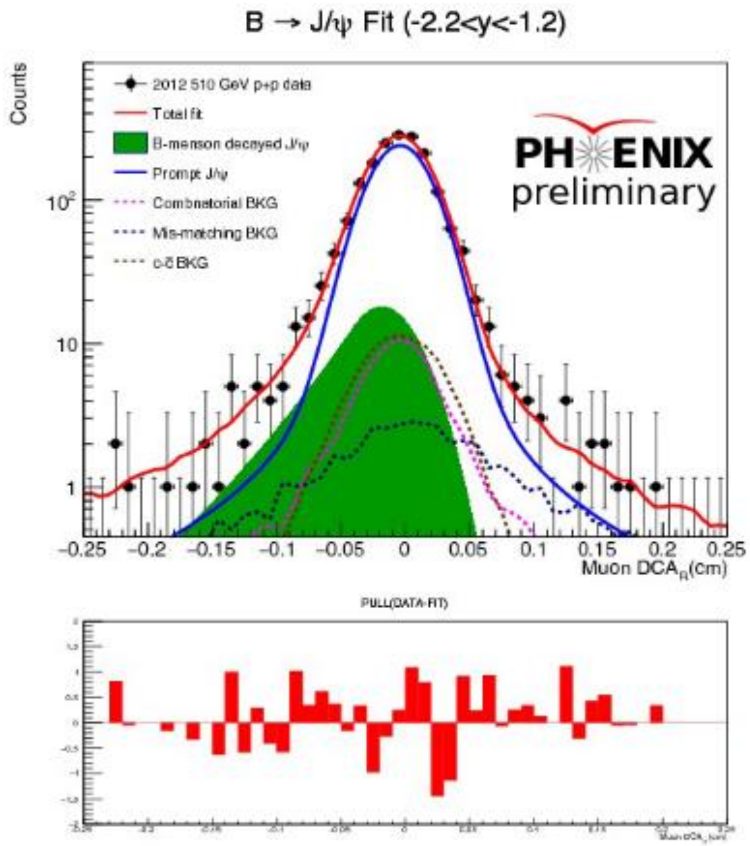


NEW!

Results from FVTX: B-meson →J/ψ in p+p 510 GeV

PHENIX: p+p at 510 GeV compared to word data





The fraction of B-mesons in J/ψ yields is of around 10%, in accordance with world data.

Open Heavy Flavor with FVTX in PHENIX

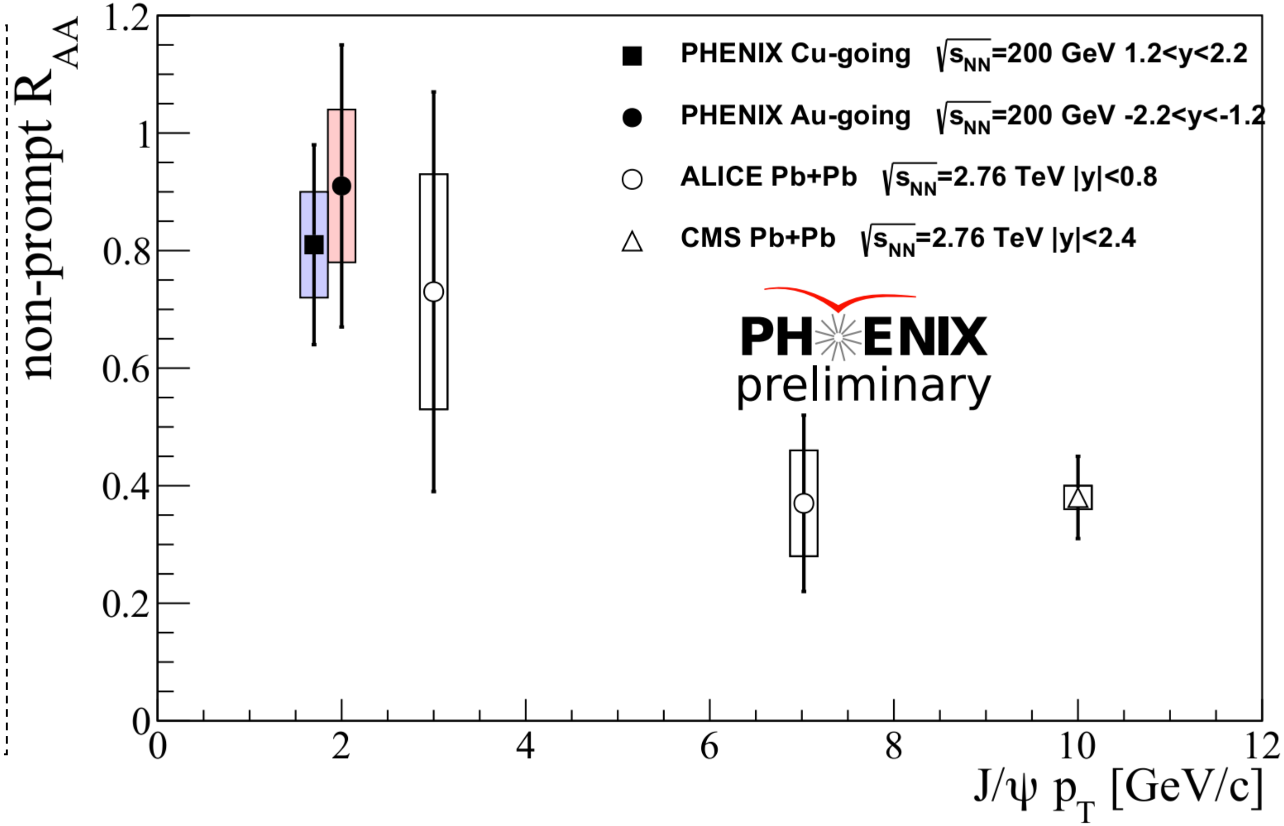
NEW!

Results from FVTX: B-meson →J/ψ in Cu+Au at 200 GeV

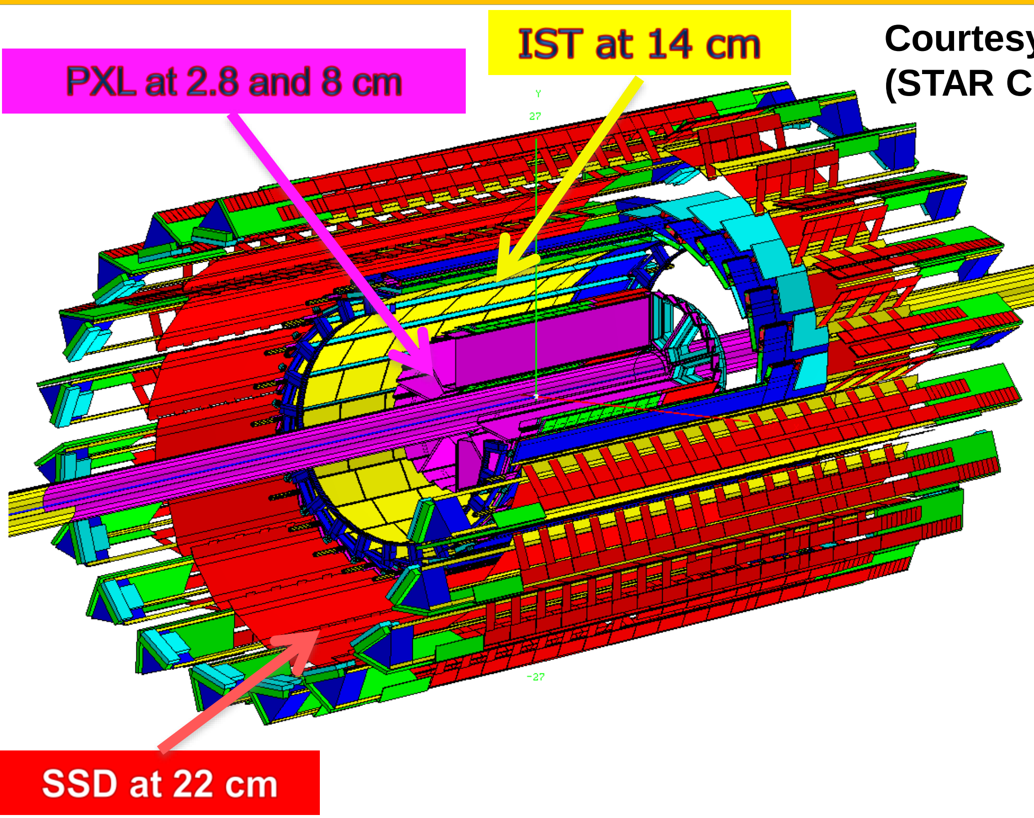
Nuclear Modification factor Cu+Au at 200 GeV: R_{AA} (B->J/ψ)

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

- The B →J/ψ fraction measured in the Cu+Au collisions at PHENIX is much larger than the LHC results.
- Assuming the fraction is 0.1 in 200 GeV p+p collisions, the R_{CuAu} defined as is less suppressed
- PHENIX and LHC R_{AA} follow the same trend.

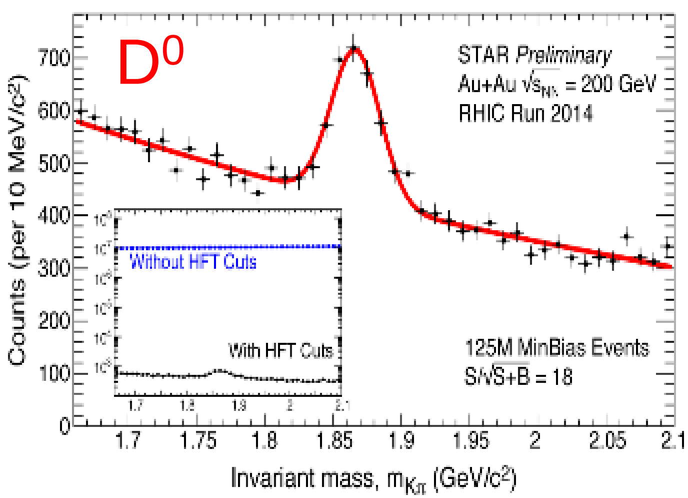


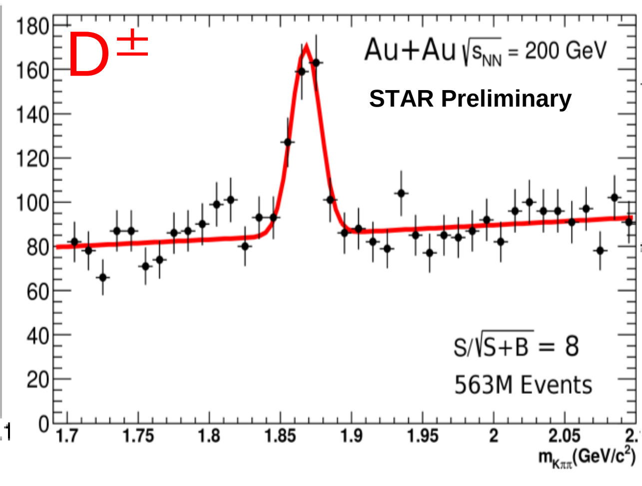
STAR Heavy Flavor Tracker (HFT)

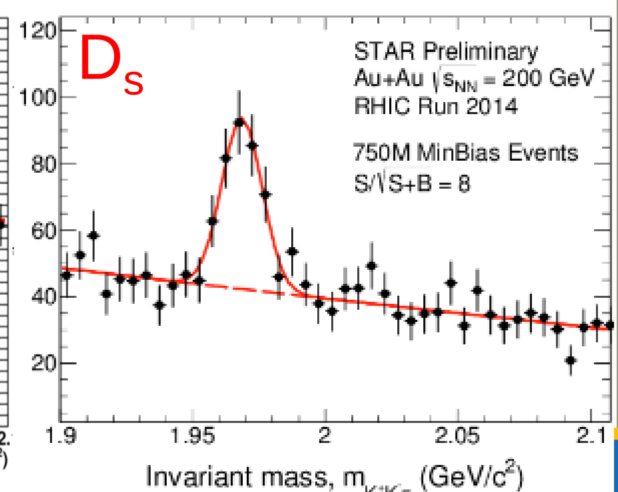


Courtesy of Zhenyu Ye (STAR Collaboration)

- First application of Monolithic Active Pixel Sensor technology in collider experiments. DCA resolution <50 μm for p_T= 750 MeV/c Kaon.
- Recorded about 3B Minimum Bias 200 GeV Au+Au events for D^0, $D^{\pm}$, D_s
- Results presented today are based on partial 2014 MB data.







Open Heavy Flavor with HFT in STAR: D^0 R_{AA} and v_2

NEW!

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

  Charm coalescence

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

  Strong charm-medium interaction

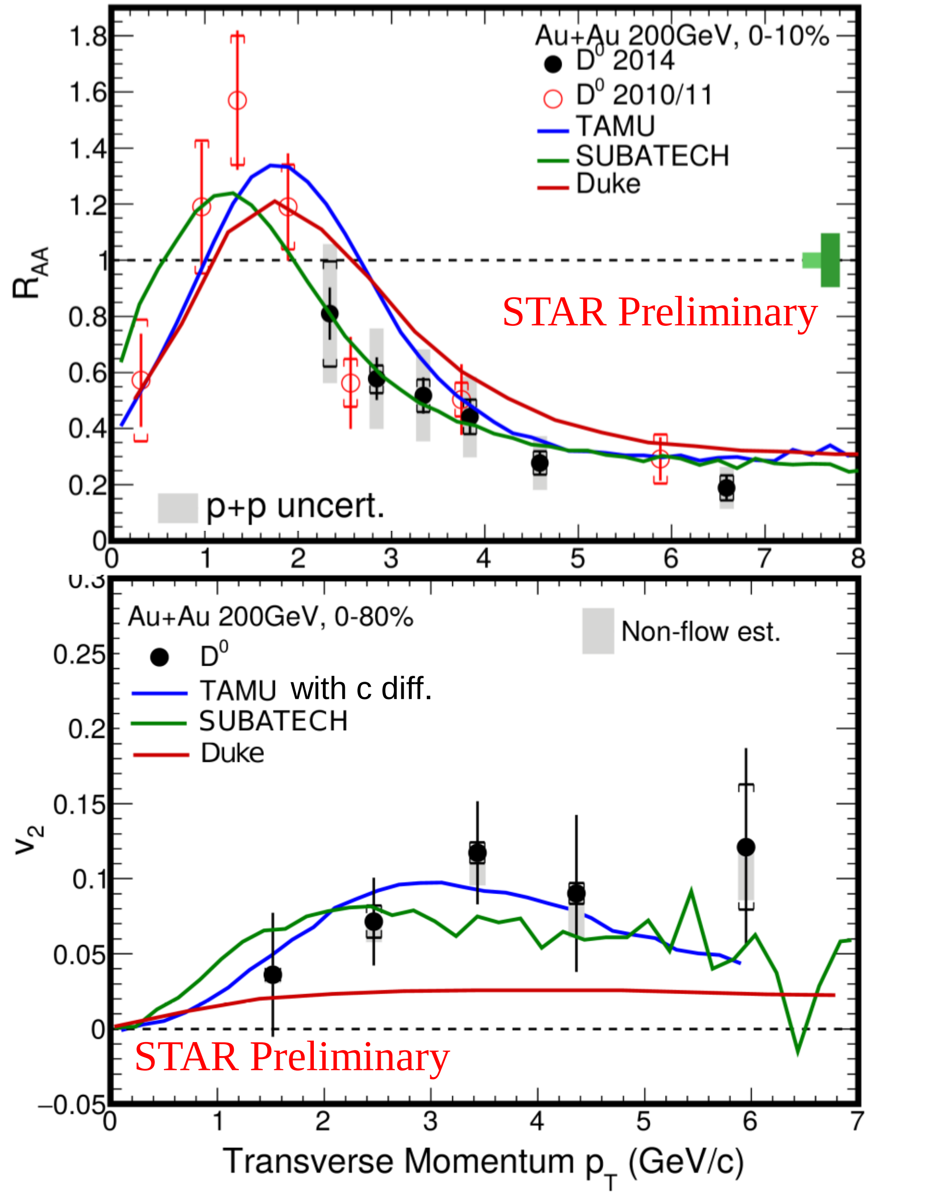
- R_{AA}(D) ~ $R_{AA}(\pi)$ at p_T>4 GeV/c

  Similar suppression for light partons and charm quarks at high p_T

Significant v_2 for D's at RHIC

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

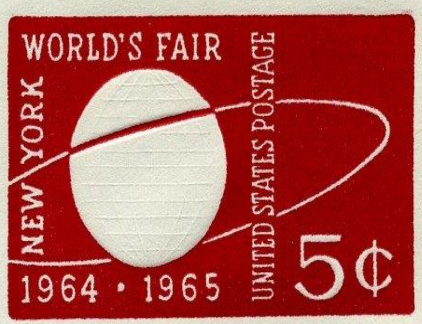
  Favors charm quark diffusion

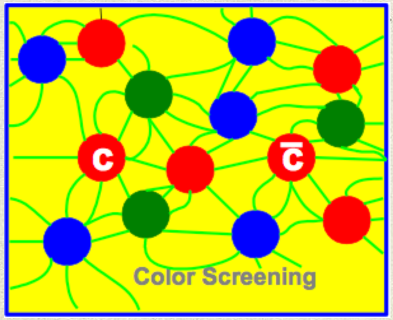


We received a letter with title: “J/ψ Suppression by Quark-Gluon Plasma Formation”
By: T. Matsui (MIT, LNS) , H. Satz (Bielefeld U. & Brookhaven)
Published in: Phys. Lett. B178 (1986) 416 that:

Quarkonia!

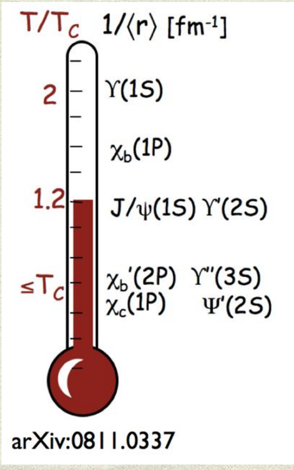
- Color screening in dense medium can cause disassociation of the bound state
- Should see sequential melting of the different states
- Use quarkonia as a medium thermometer!





… Turns out it’s not that simple!

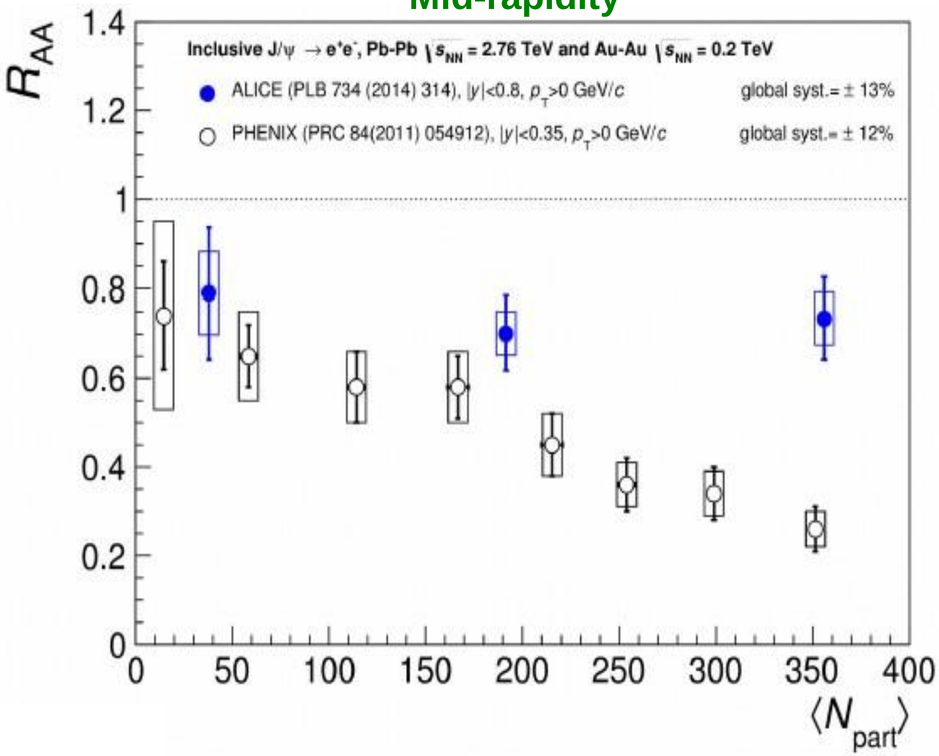
- Many effects which modify the yield other than disassociation!
  - Regeneration
  - Nuclear shadowing
  - CNM energy loss
  - Nuclear breakup
  - Breakup with co-moving hadrons



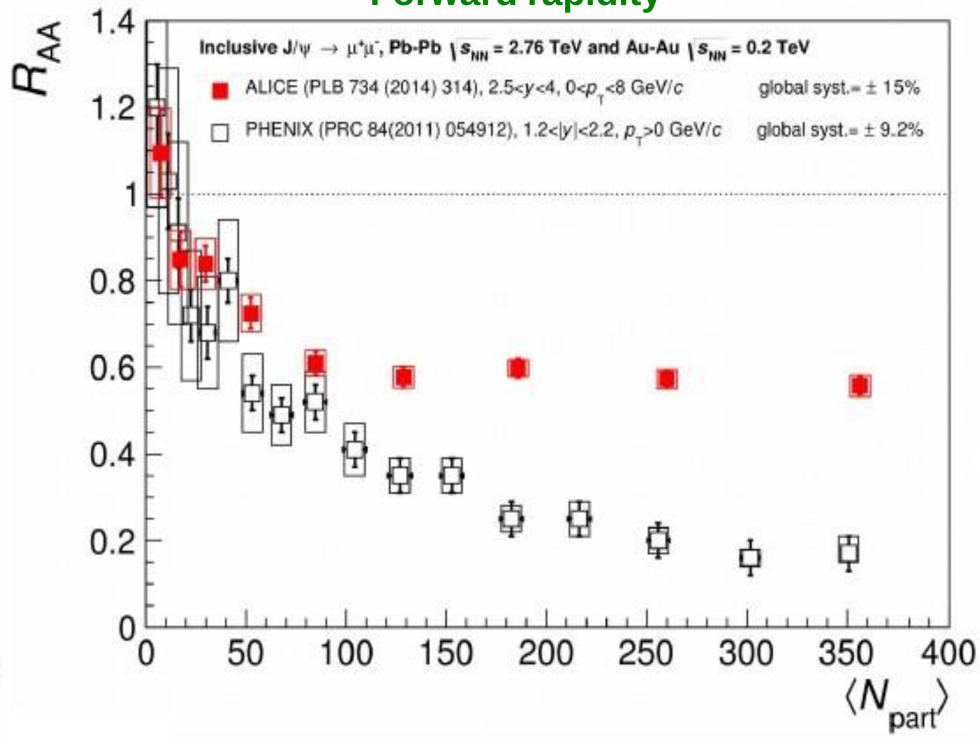
Motivation for Quarkonia Measurements

Centrality dependence of the J/ψ inclusive R_{AA} studied by PHENIX and ALICE at both central and forward rapidities.

Mid-rapidity



Forward rapidity

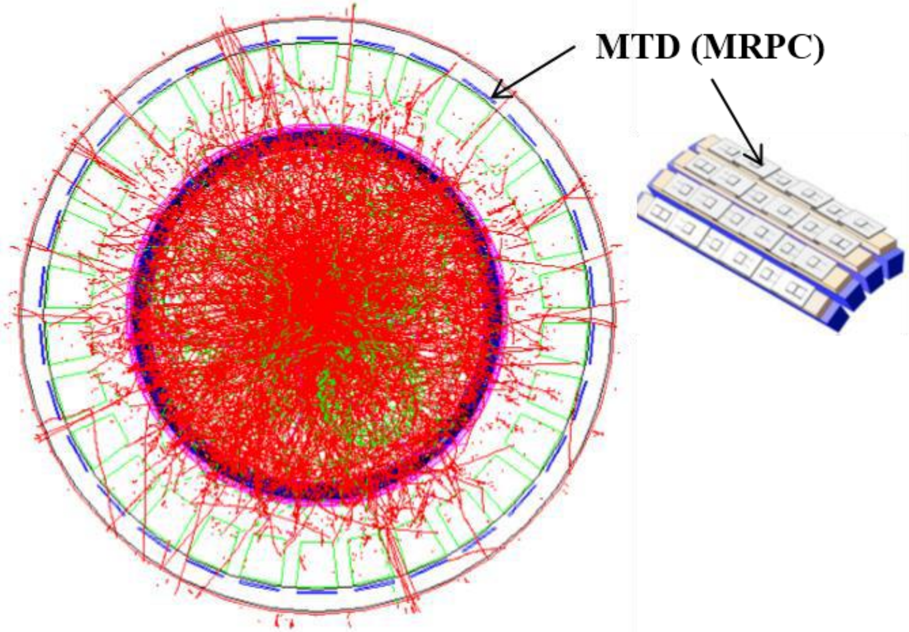


ALICE results show weaker centrality dependence and smaller suppression for central events, may suggest a (re)combination scenario.

STAR Muon Telescope Detector (MTD)

NEW!

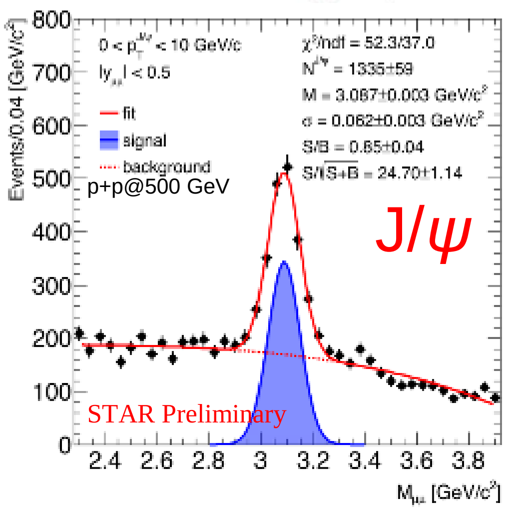
Courtesy of Zhenyu Ye
(STAR Collaboration)

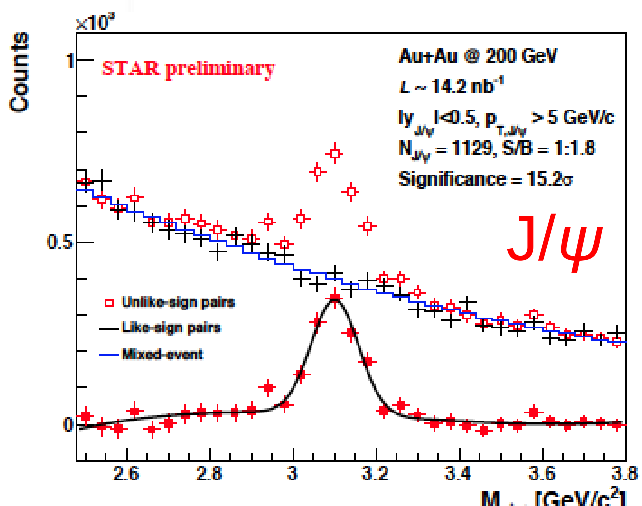


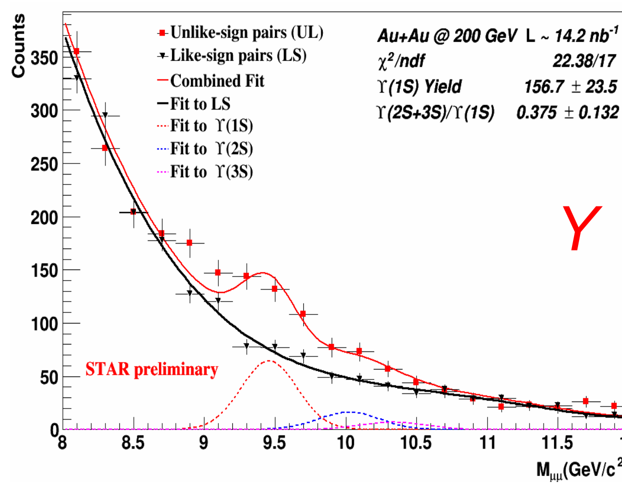
- Precise timing info (~100 ps) for $p_T > 1.2$ GeV/c; muon online triggering and offline identification.

- 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.





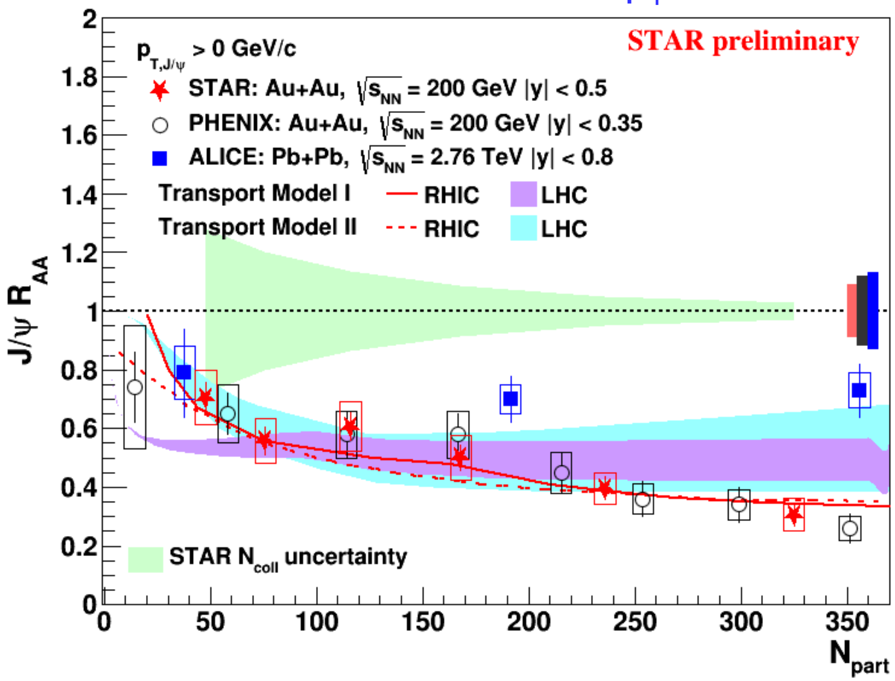


STAR: J/ψ R_{AA} in Au+Au at 200 GeV

NEW!

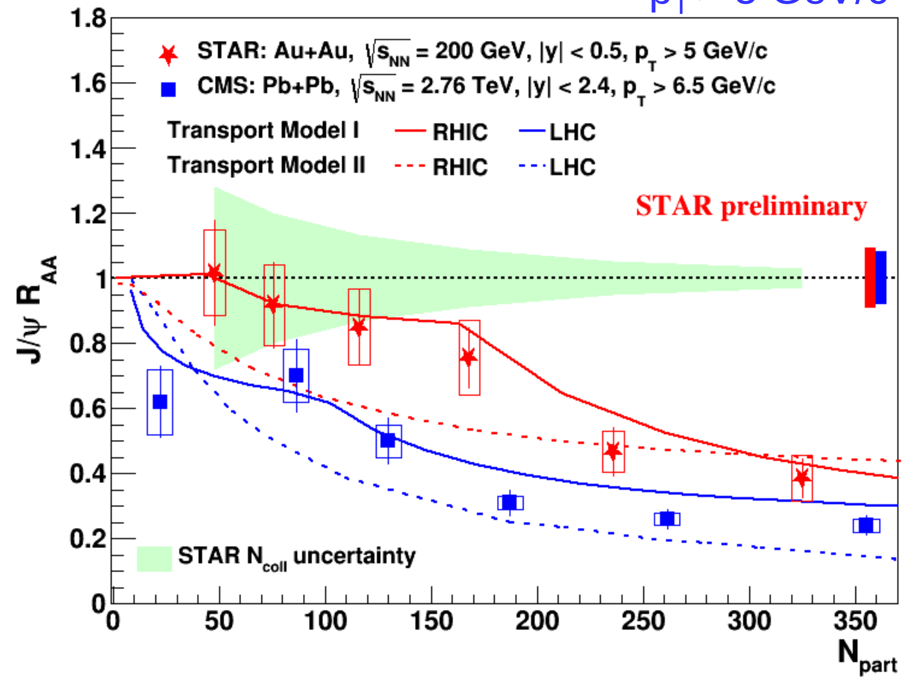
ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

$p_T > 0$ GeV/c



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

$p_T > 5$ GeV/c

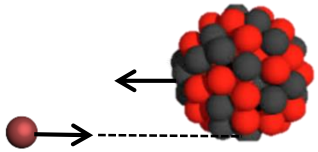


- J/ψ R_{AA} for p_T>0 GeV/c: RHIC is smaller than LHC -> more recombination at LHC
- J/ψ R_{AA} for p_T>5 GeV/c: LHC is smaller than RHIC -> stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe data

PHENIX: Suppression of ψ' in Central d+Au Collisions

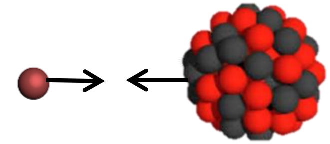
NEW!

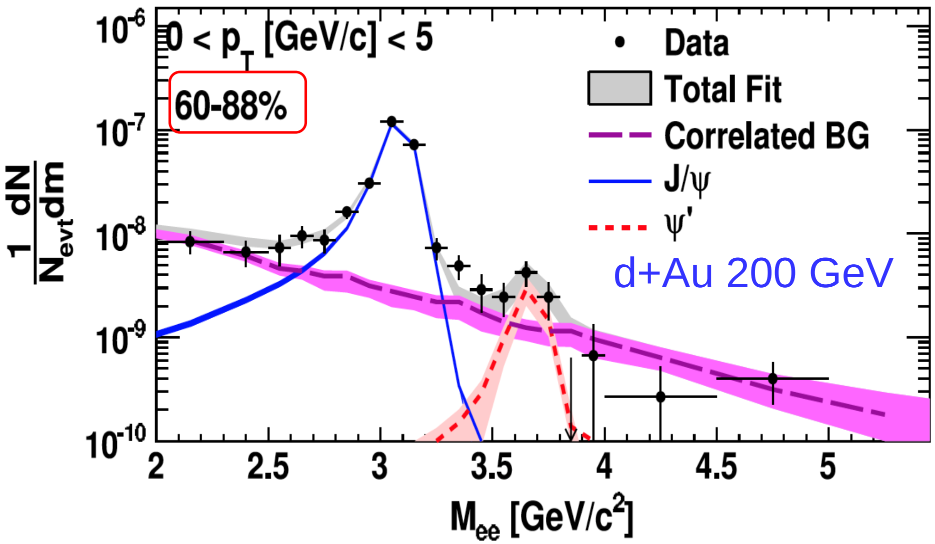
PHEN IX: PRL 111, 202301

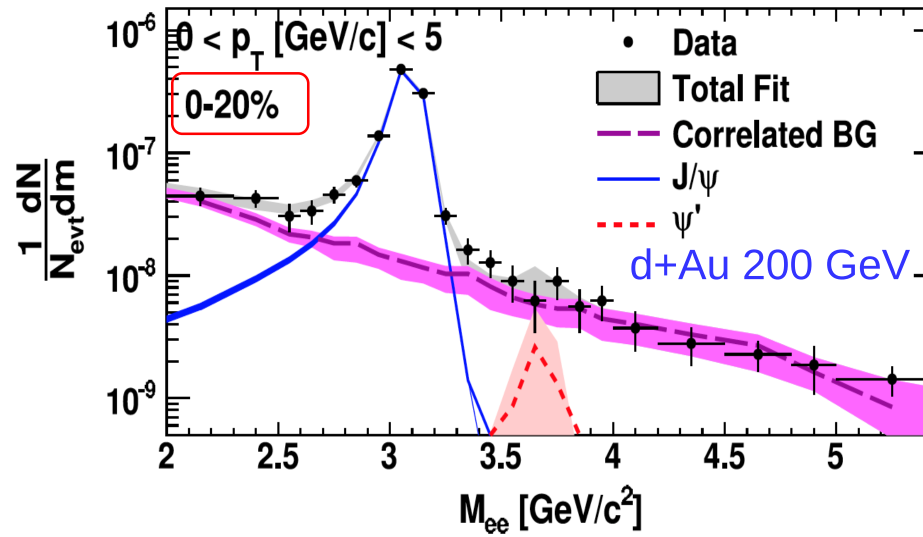


peripheral
60—88%
N_{coll} ~ 3

central
0—20%
N_{coll} ~ 15



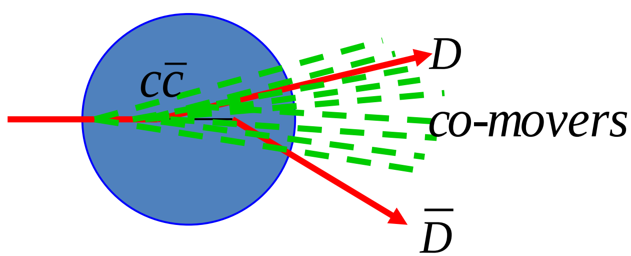


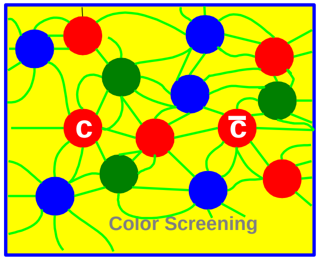


Breakup of quarkonia due to interaction with nuclear matters

1) Large suppression of the weakly bounded state ψ'

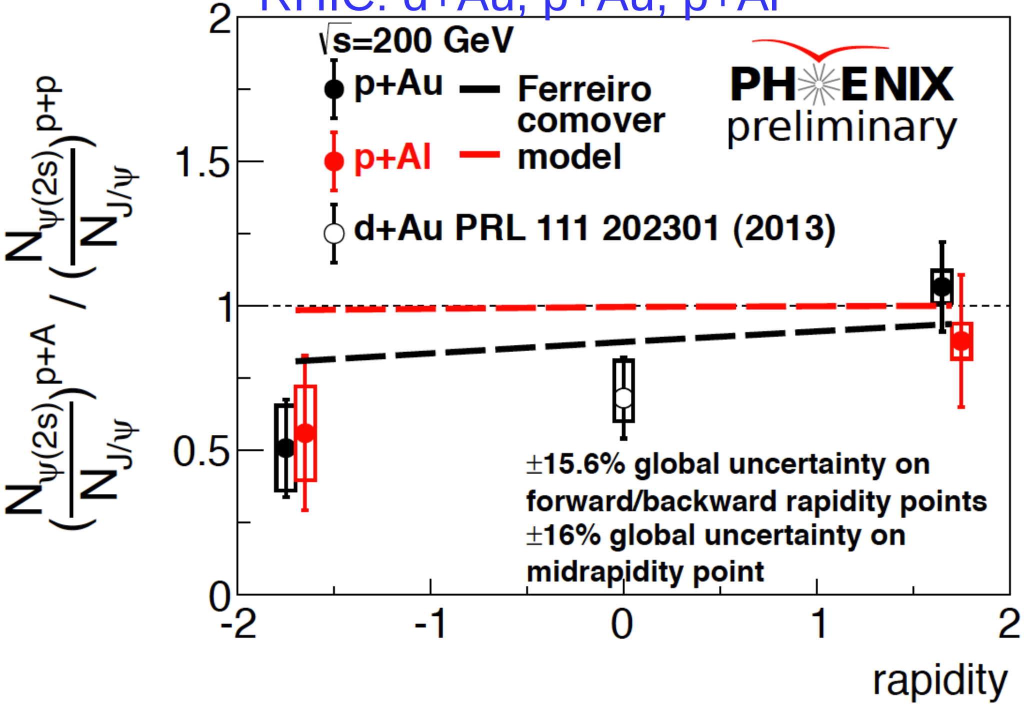
2) Interaction with nucleus? comovers? or medium?



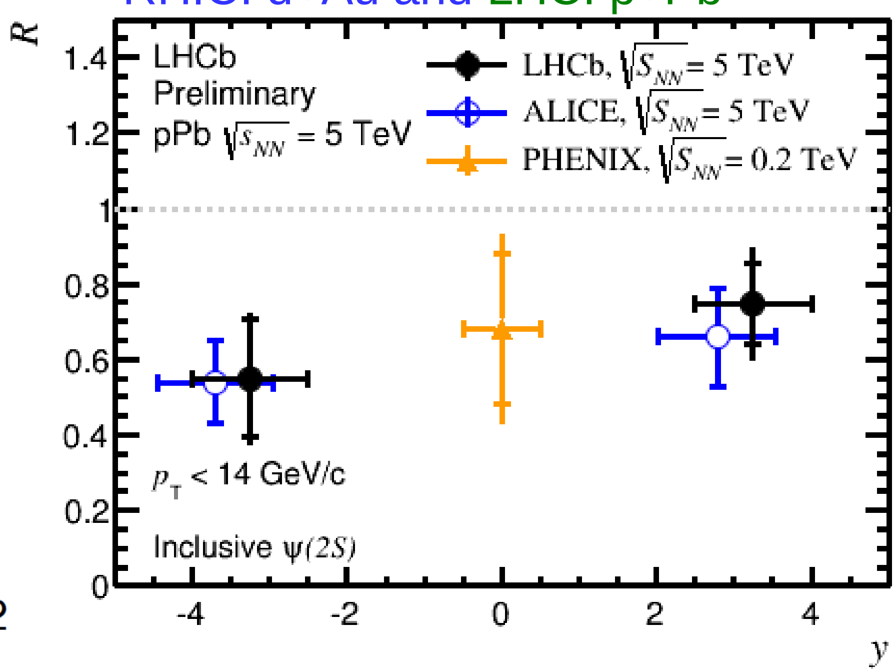


ψ' broken up in small systems: p+Al, p+Au and d+Au

RHIC: d+Au, p+Au, p+Al



RHIC: d+Au and LHC: p+Pb



- Comover dissociation model agree qualitatively with data
- Comparison with the QGP model work in progress.

- Similar relative suppression of ψ' at backward rapidity, but larger relative suppression of ψ' at forward rapidity at LHC

Summary

- ✧ **Without Doubt RHIC is Amazing QCD Machine**
  - ✧ Many Species, Many Energies, and High Luminosity and Stability

- ➢ **Open Heavy Flavor**

  - ✧ **Au+Au at 200 GeV**
    - Electrons from bottom similarly suppressed to those from charm for p_T > 4 GeV/c
    - Similar suppression of D mesons and light hadrons (at high-p_T > 4 GeV/c)
  - ✧ **Cu+Au at 200 GeV**
    - B-mesons → J/ψ at forward-rapidity are less suppressed than prompt J/ψ

- ➢ **Quarkonia**

  - ✧ **Small Systems p+Al, p+Au and d+Au**
    - ψ' has larger suppression than J/ψ at mid and backward rapidity
      - comover dissociation model agree qualitatively with data

- ➢ **Stay Tuned …!**
  - ✧ **More statistic:** decrease uncertainties, increase p_T reach, centrality separation
    → more surprises…