Open Heavy Flavor and Quarkonia Results at RHIC

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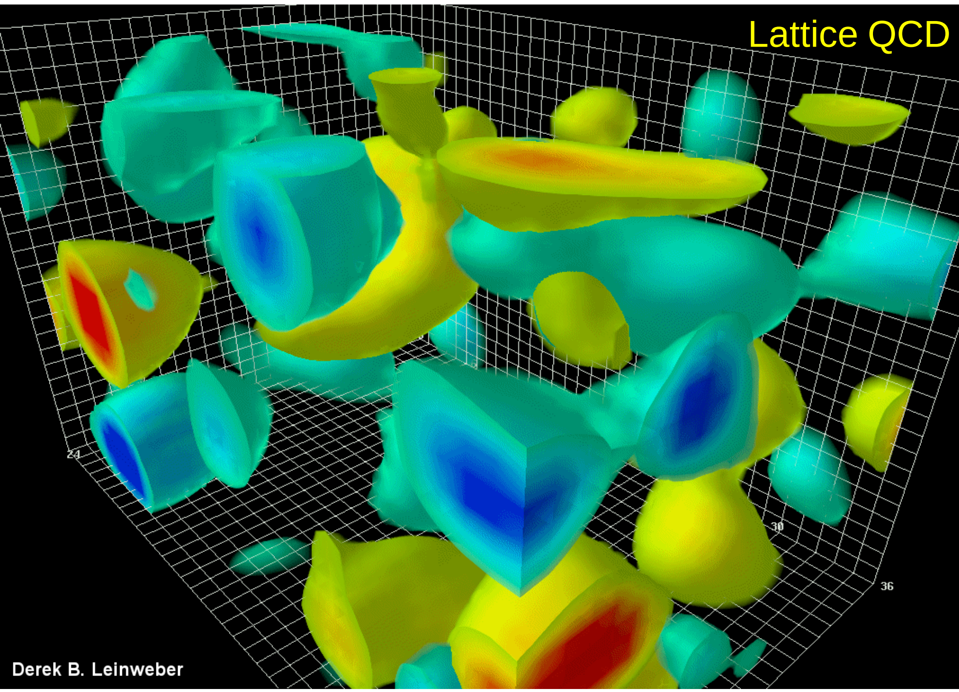
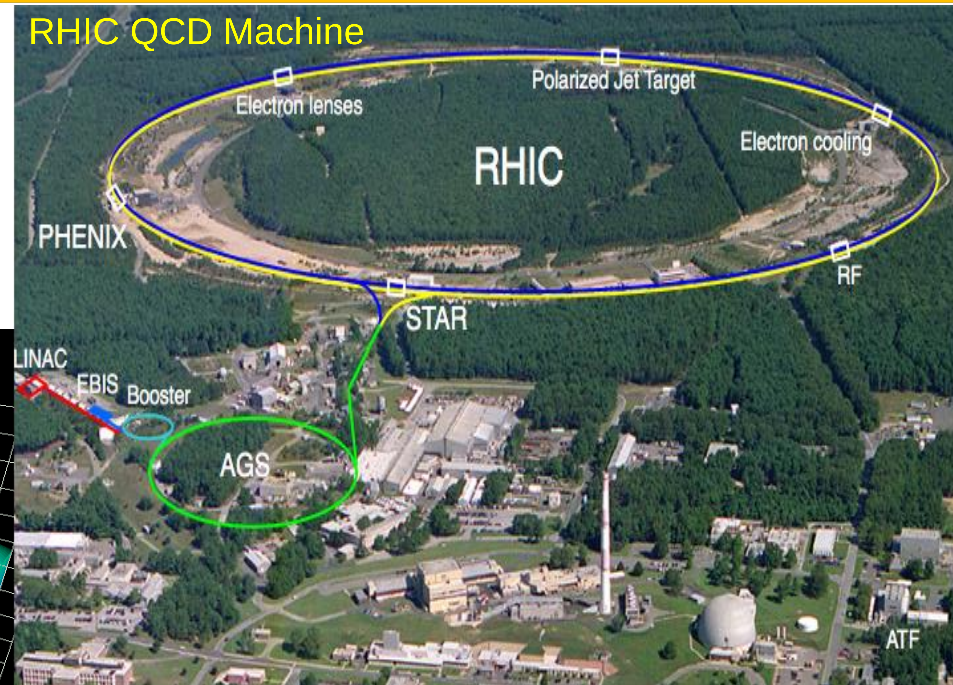
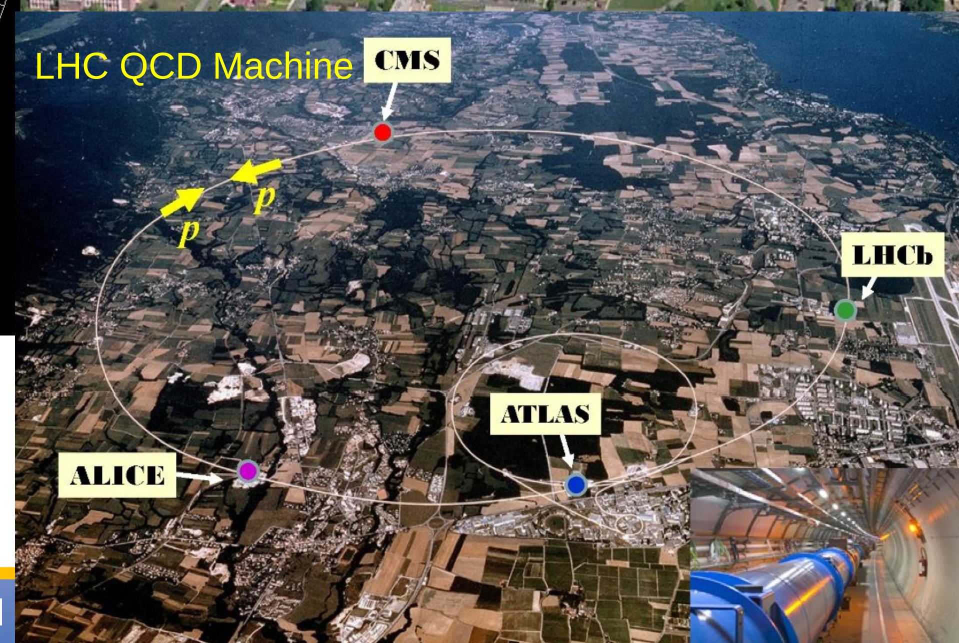
RHIC Amazing QCD Machine: Many Species and Many Energies!





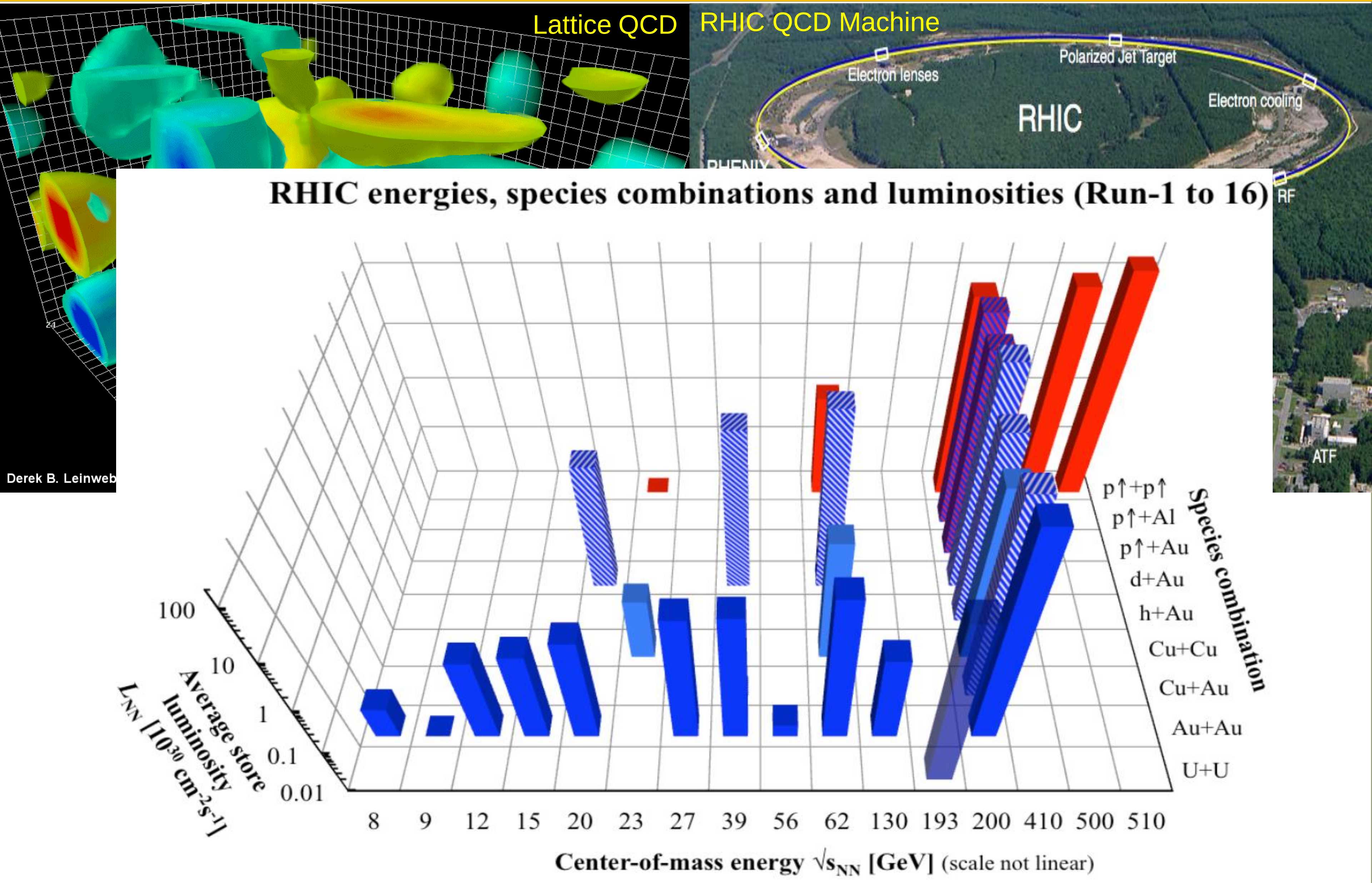


RHIC Amazing QCD Machine: Many Species and Many Energies!

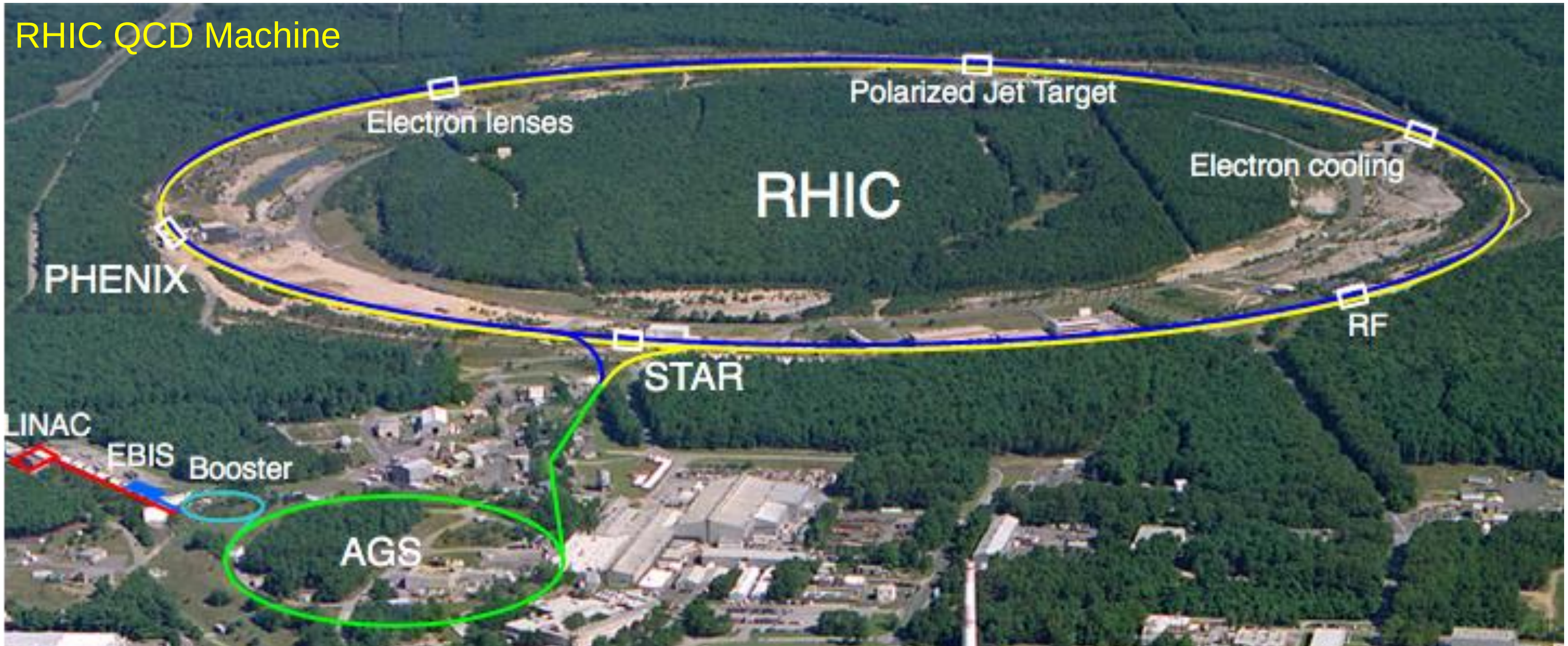
Run	Species	Total particle energy [GeV/nucleon]	total delivered Luminosity [μb^{-1}]
I (2000)	Au+Au	56	< 0.001
	Au+Au	130	20
II (2001/2002)	Au+Au	200	25.8
	Au+Au	19.6	0.4
	p+p	200	1.4x10^{-6}
III (2003)	d+Au	200	73x10^{-3}
	p+p	200	5.5x10^{-6}
IV(2004)	Au+Au	200	3.53x10^{-3}
	Au+Au	62.4	67
	p+p	200	7.1x10^{-6}
V (2005)	Cu+Cu	200	42.1x10^{-3}
	Cu+Cu	62.4	1.5x10^{-3}
	Cu+Cu	22.4	0.02x10^{-3}
	p+p	200	29.5x10^{-6}
	p+p	410	0.1x10^{-6}
VI (2006)	p+p	200	88.6x10^{-6}
	p+p	62.4	1.05x10^{-6}
VII (2007)	Au+Au	200	7.25x10^{-3}
	Au+Au	9.2	Small
VIII (2008)	d+Au	200	437x10^{-3}
	p+p	200	38.4x10^{-6}
	Au+Au	9.6	Small

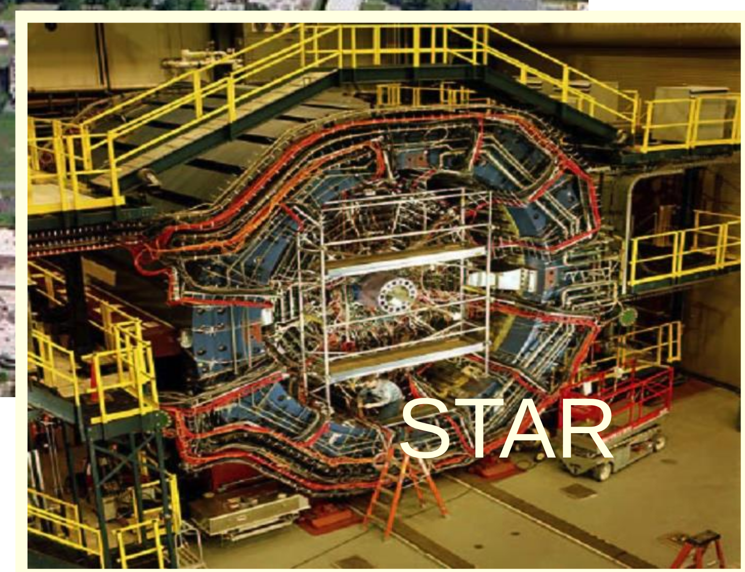
Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity [μb^{-1}]
IX (2009)	p+p	500	110x10^{-6}
	+p	200	114x10^{-6}
X (2010)	Au+Au	200	10.3x10^{-3}
	Au+Au	62.4	544
	Au+Au	39	206
	Au+Au	7.7	4.23
	Au+Au	11.5	7.8
XI (2011)	p+p	500	166x10^{-6}
	Au+Au	19.6	33.2
	Au+Au	200	9.79x10^{-3}
	Au+Au	27	63.1
XII (2012)	p+p	200	74x10^{-6}
	p+p	510	283x10^{-6}
	U+U	193	736
	Cu+Au	200	27x10^{-3}
XIII (2013)	p+p	510	1.04x10^{-9}
XIV (2014)	Au+Au	14.6	44.2
	Au+Au	200	43.9x10^{-3}
	^{3}He+Au	200	134x10^{-3}
XV (2015)	p+p	200	282x10^{-6}
	p+Au	200	1.27x10^{-6}
	p+Al	200	3.97x10^{-6}
XVI (2016)	Au+Au	200	46.1x10^{-3}
	d+Au	200	46.1x10^{-3}
	d+Au	62.4	44.0x10^{-3}
	d+Au	19.6	7.2x10^{-3}
	d+Au	39	---
	Au+Au	200	7:50 AM 06/27/2016

RHIC Amazing QCD Machine: Many Species and Many Energies!



The RHIC Facility Today





Heavy Flavor: Ideal Probe of QCD Matter

We study QCD matter (Hot vs Cold) through heavy flavor production:

1) Open Heavy Flavor 2) Quarkonia

Recipe on how to study hot and cold QCDM

System Size/ Collision Asymmetry

Change the relative contributions of **Cold** and **Hot** nuclear matter effects

Centrality

Suppression vs path length

Collision Energy

Change system energy density

Momentum

Hard collision dynamics

Rapidity

Probes different gluon (anti)shadowing

Heavy/Light

Mass ordering of suppression

Particle Species

Break-up, Temperature?

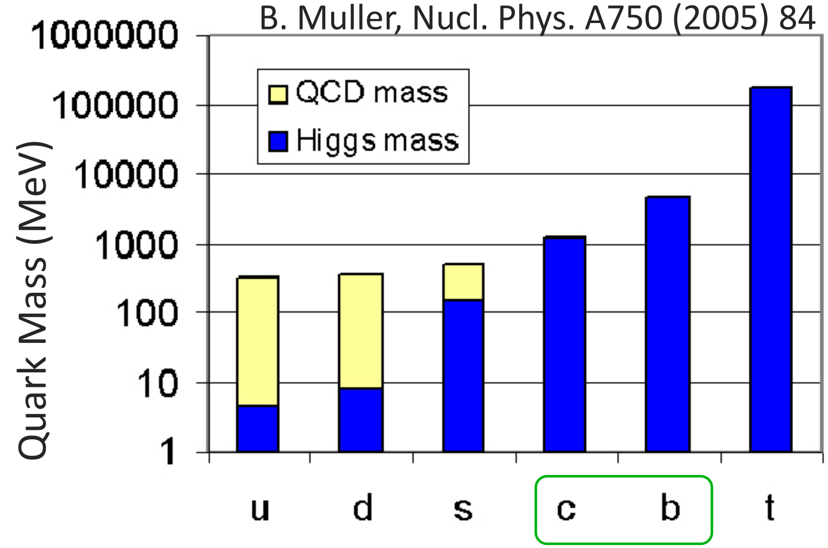
Each parameter probes different admixtures of nuclear modification

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

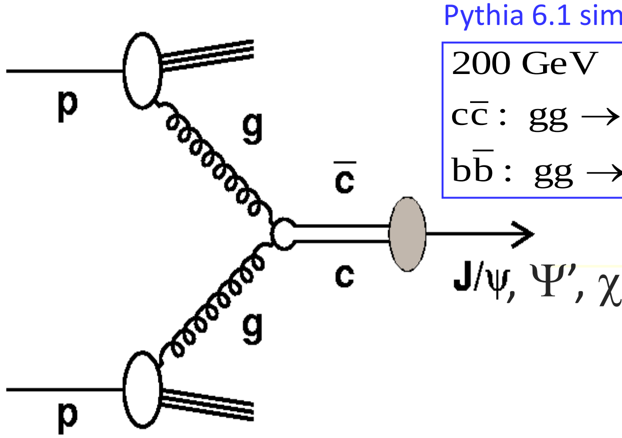


- ❖ Heavy quarks ($c\bar{c}$, $b\bar{b}$)
  - Bound states (J/ψ, Υ)

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



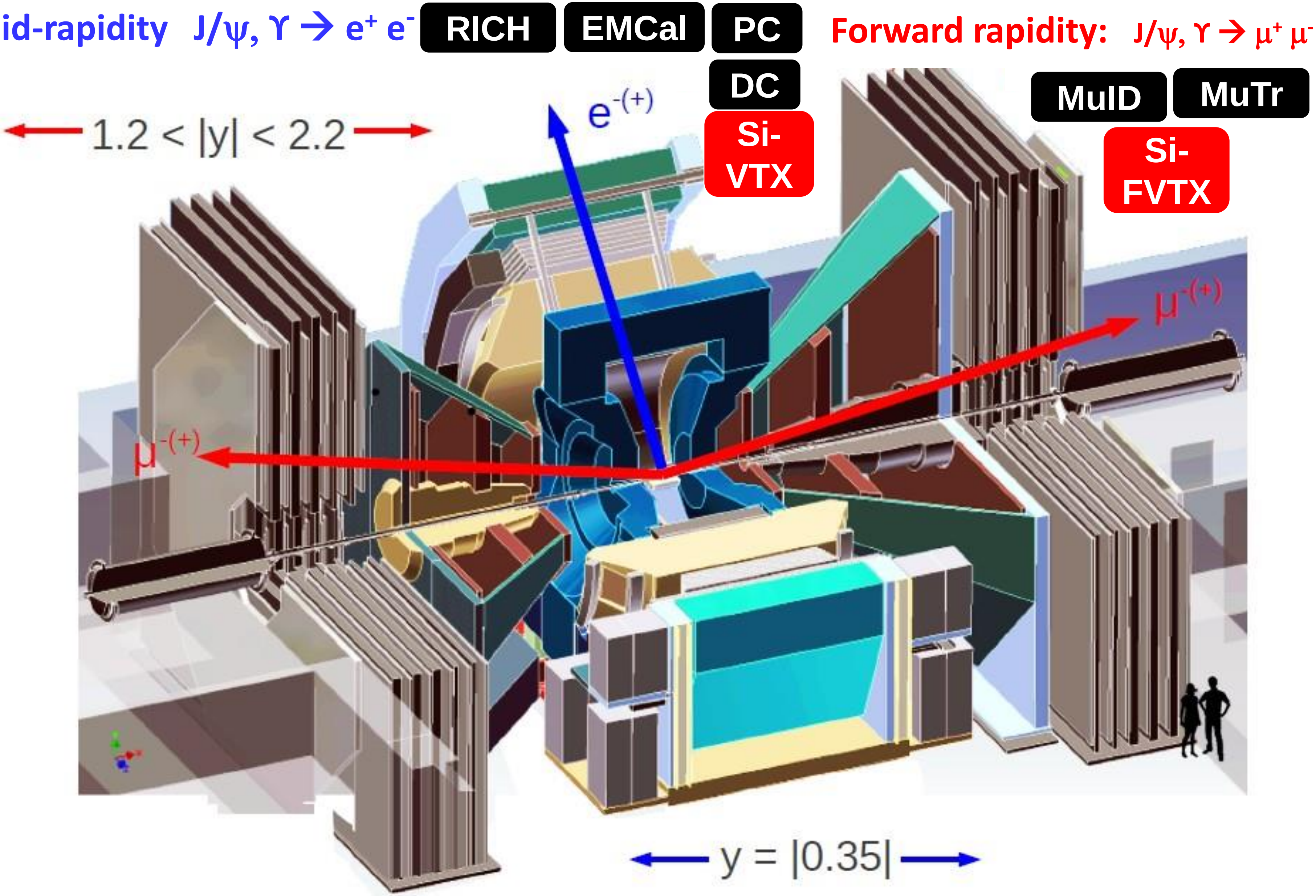
Pythia 6.1 simulation (LO)

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

Mid-rapidity $J/\psi, \Upsilon \rightarrow e^+ e^-$

Forward rapidity: $J/\psi, \Upsilon \rightarrow \mu^+ \mu^-$

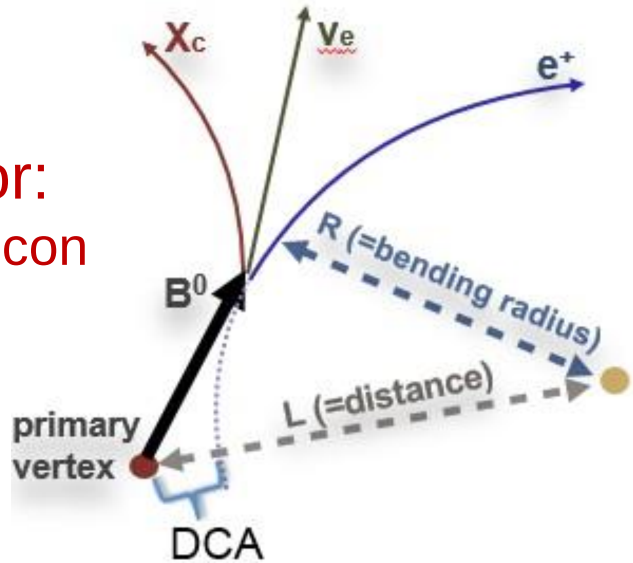


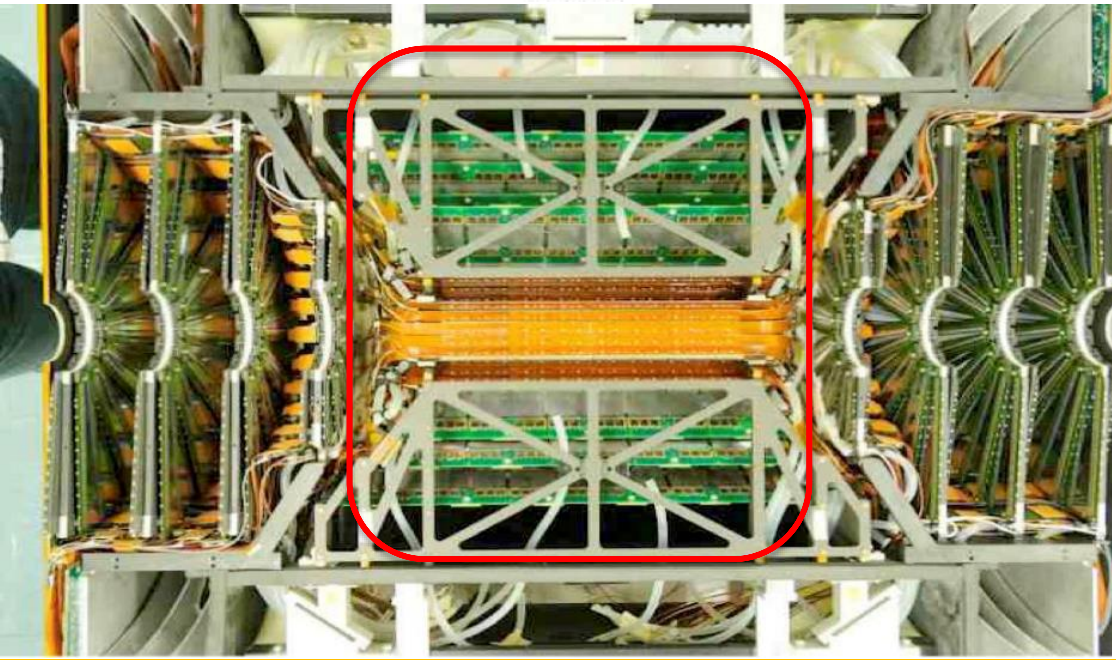
PHENIX Central Heavy Flavor Tracker (VTX)

NEW!

VTX detector:

4 barrels of silicon





DCA_T Distributions: b/c separation

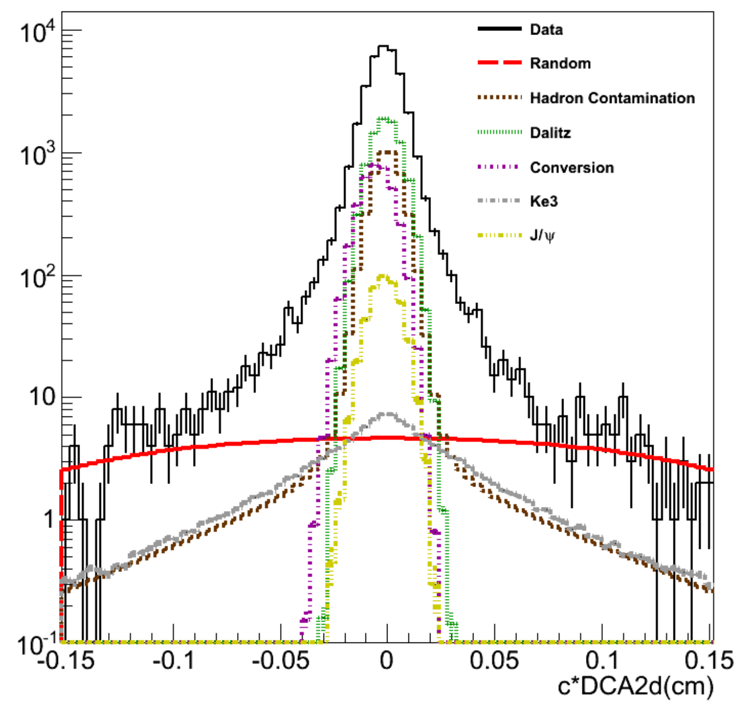
- VTX: $|\eta| < 1.2$
  - Au+Au 200 GeV: DCA_T resolution ~ 60 μm

Life time (cτ)

D^0 : 123 μm

B^0 : 464 μm

$1.50 < p_T < 2.00$



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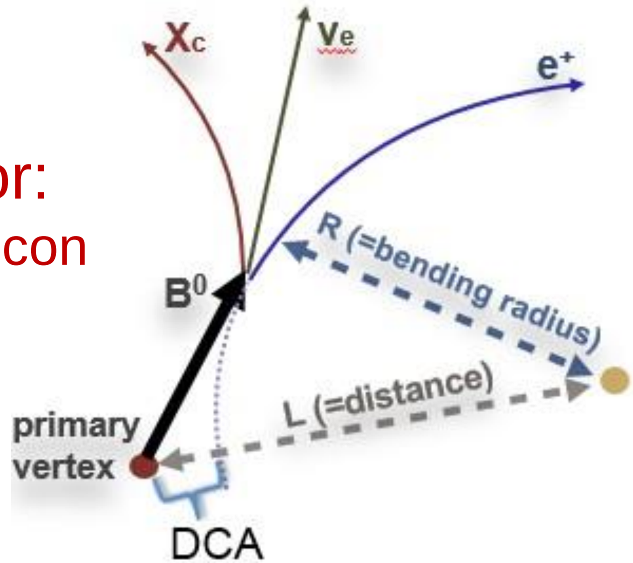
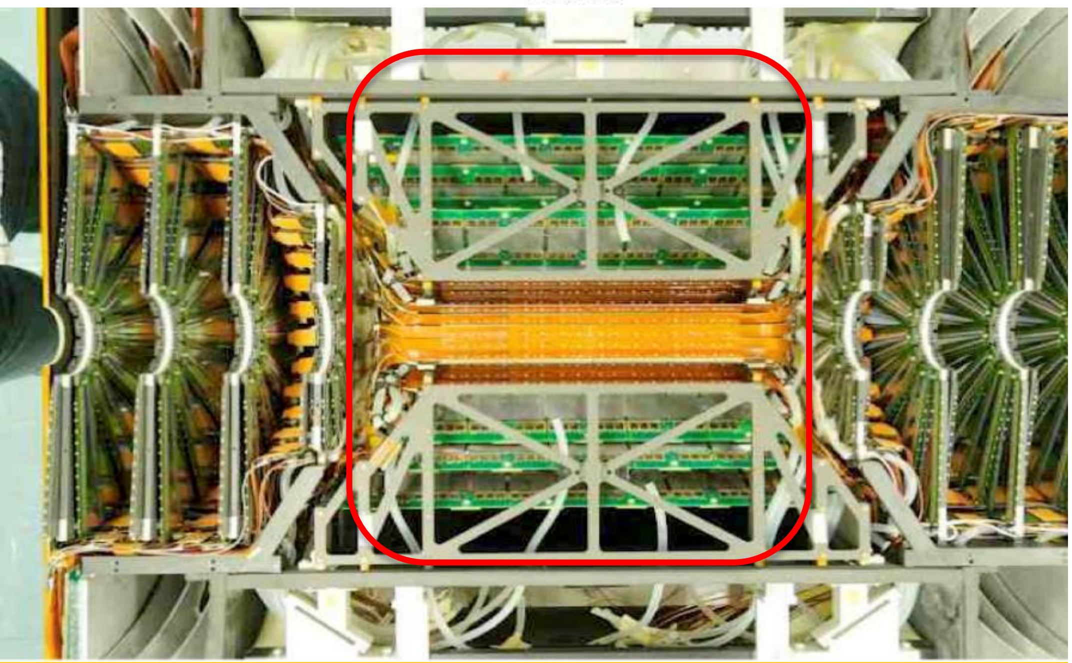




DCA$_T$ Distributions: b/c separation

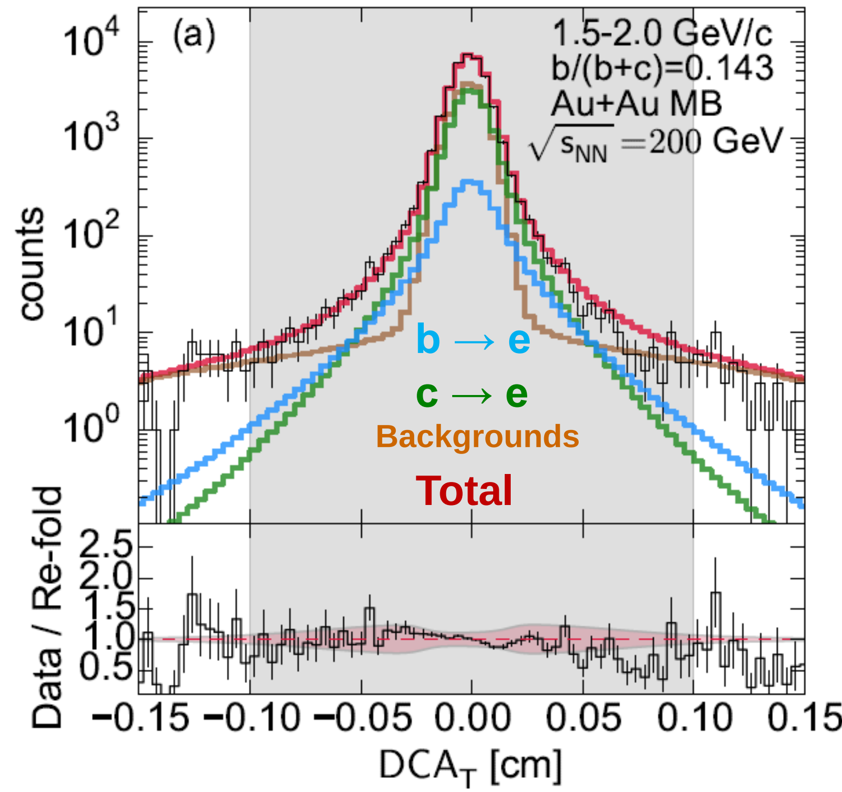
- VTX: |η | <1.2
  - Au+Au 200 GeV: DCA$_T$ resolution ~ 60 μm

Life time (cτ)

D^0 : 123 μm

B^0 : 464 μm

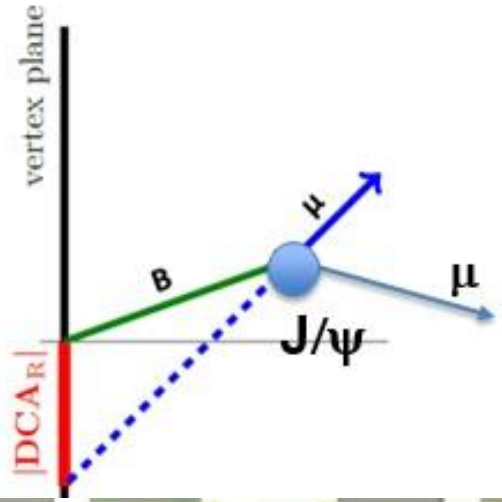
PHENIX: PRC **93**, 034904 (2016)



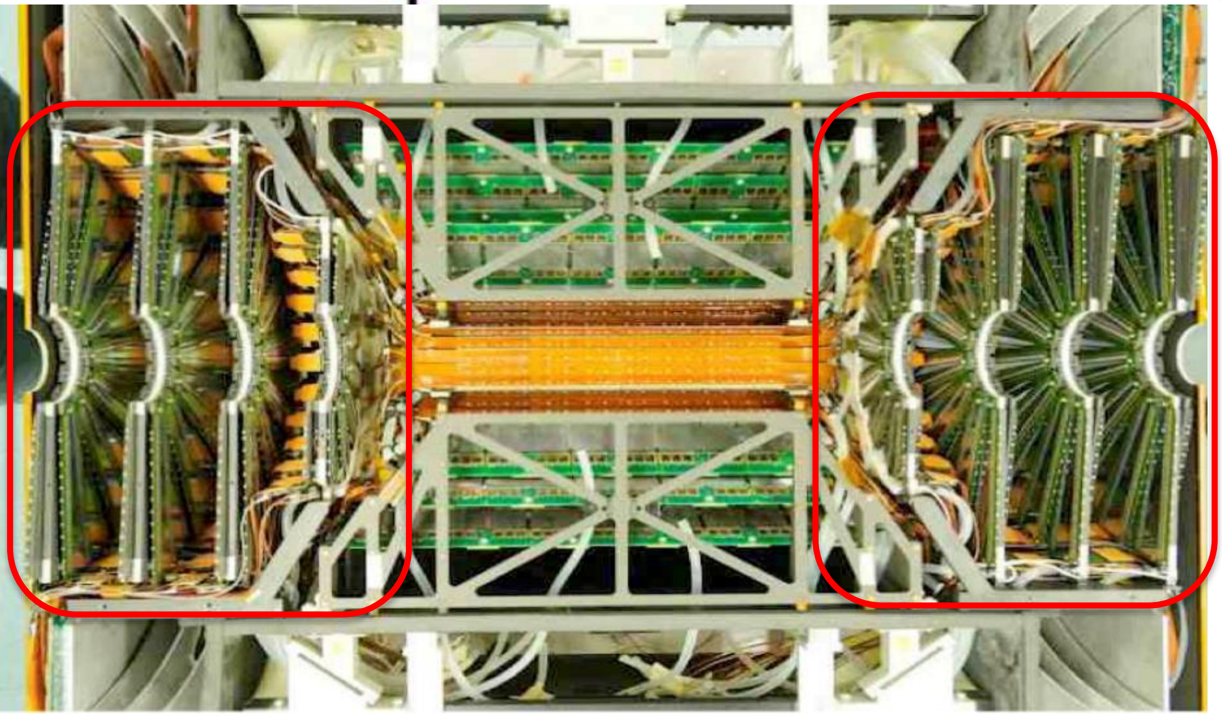
NEW!

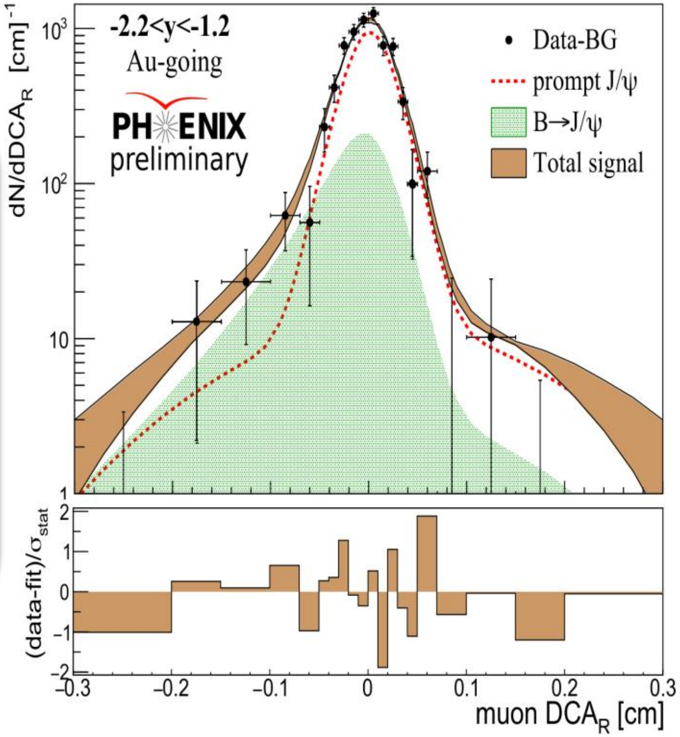
DCA_R Distributions: b/c separation

FVTX detector:

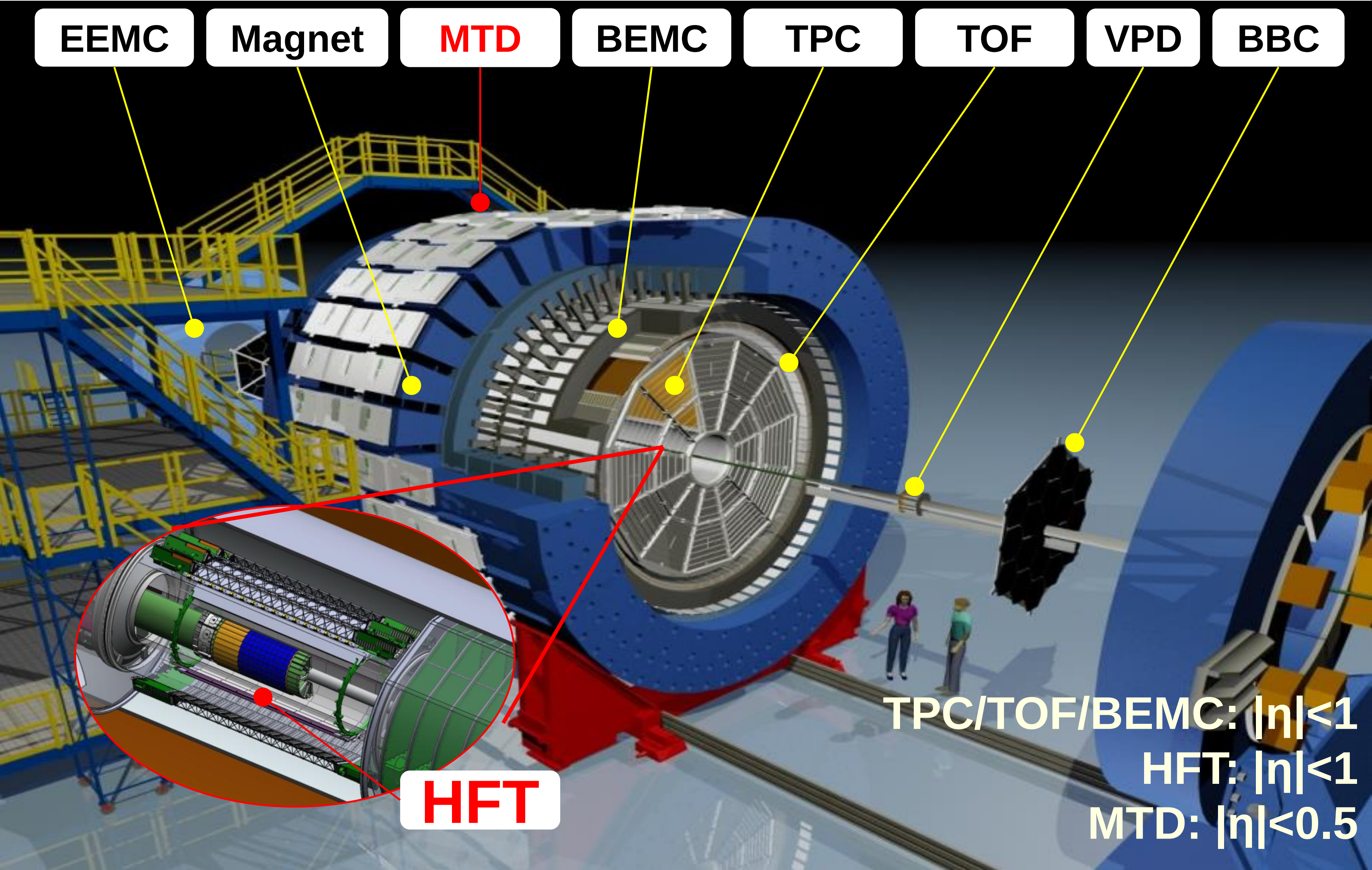


- FVTX:
- Forward rapidity - $1.2 < |\eta| < 2.2$
- Improved muon momentum resolution & precise tracking





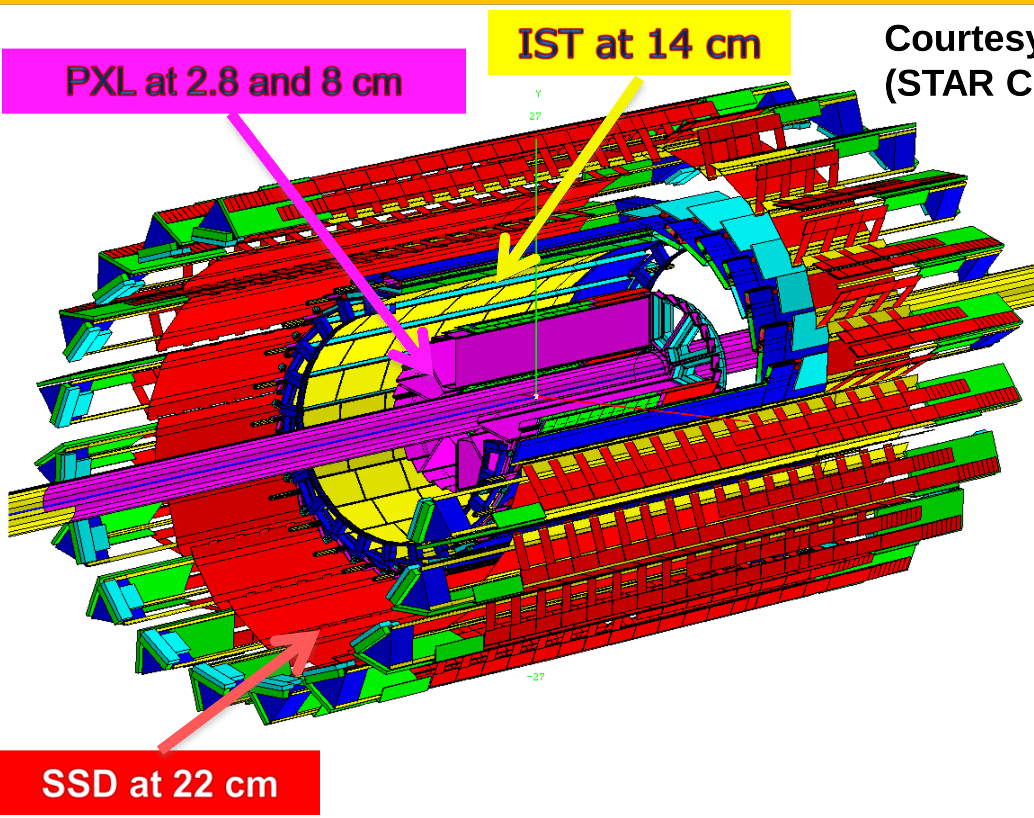
Measuring Heavy Flavor in STAR



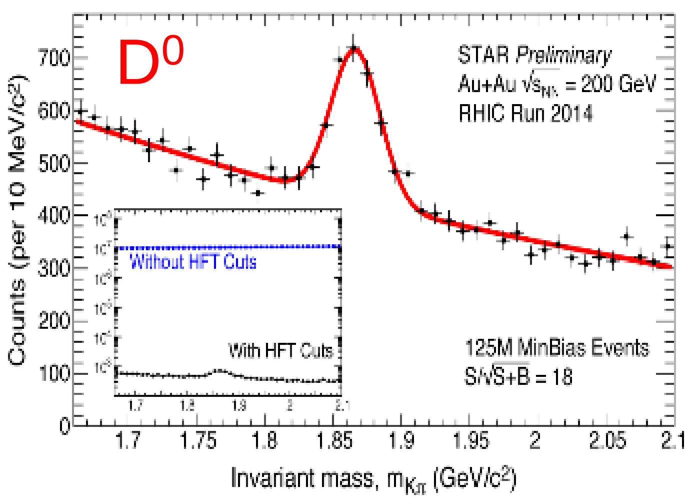
STAR Heavy Flavor Tracker (HFT)

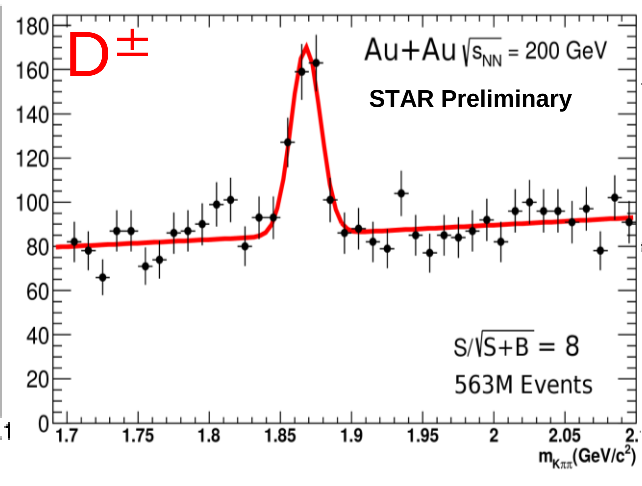
NEW!

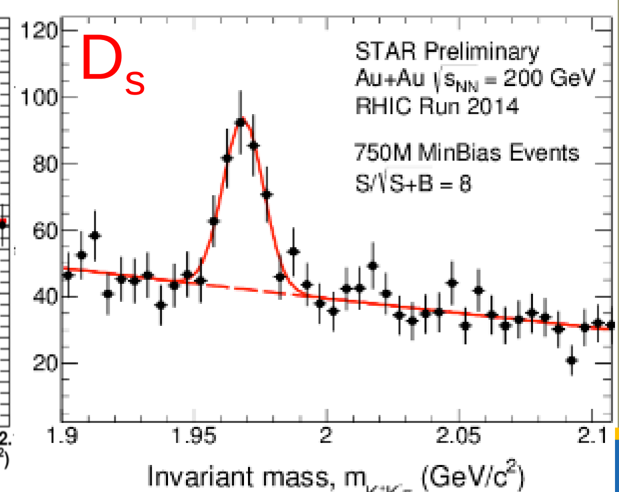
Courtesy of Zhenyu Ye (STAR Collaboration)



- 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.

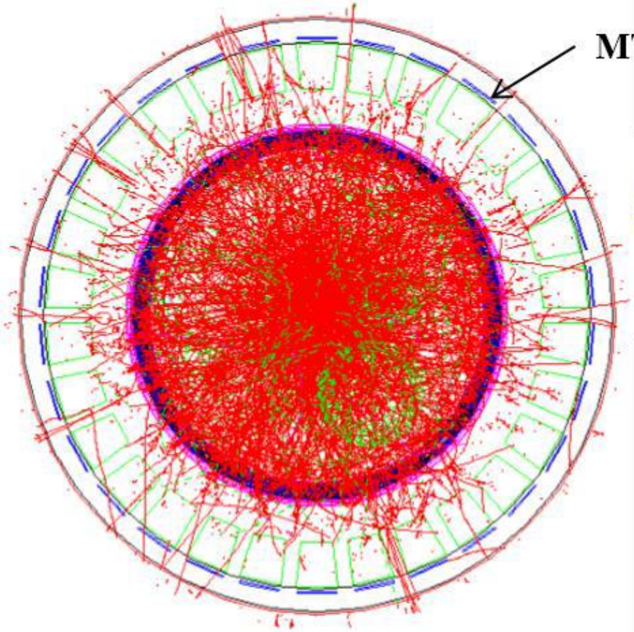




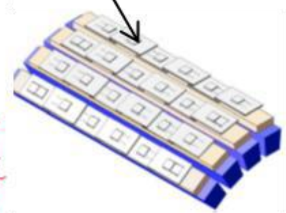


STAR Muon Telescope Detector (MTD)

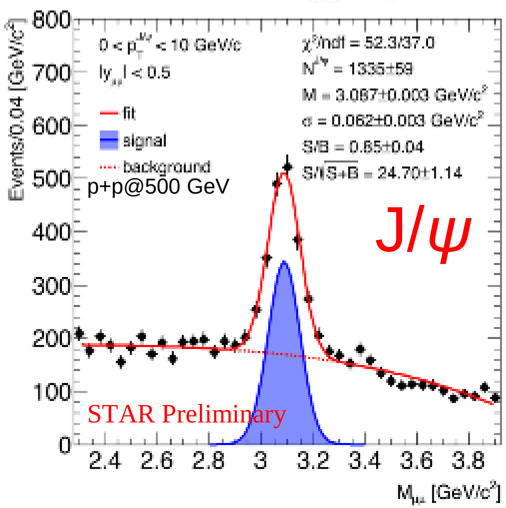
Courtesy of Zhenyu Ye
(STAR Collaboration)

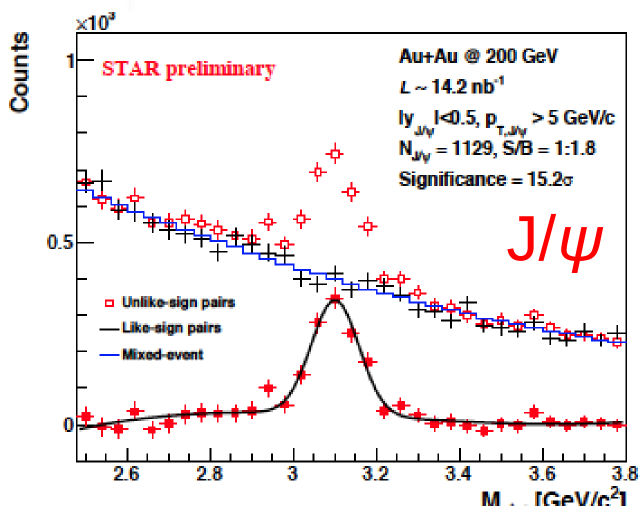


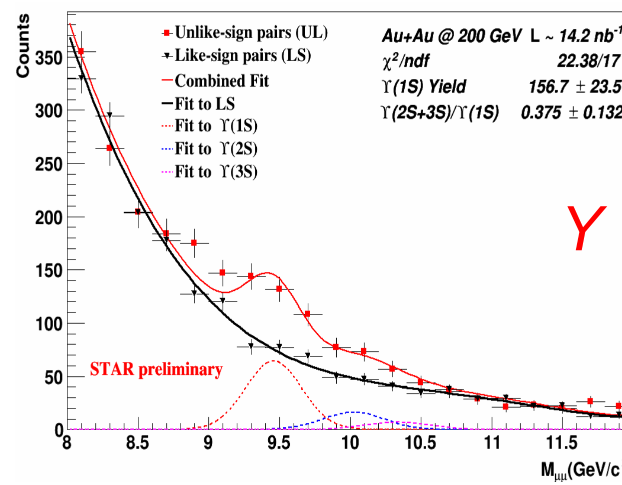
MTD (MRPC)



- 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.

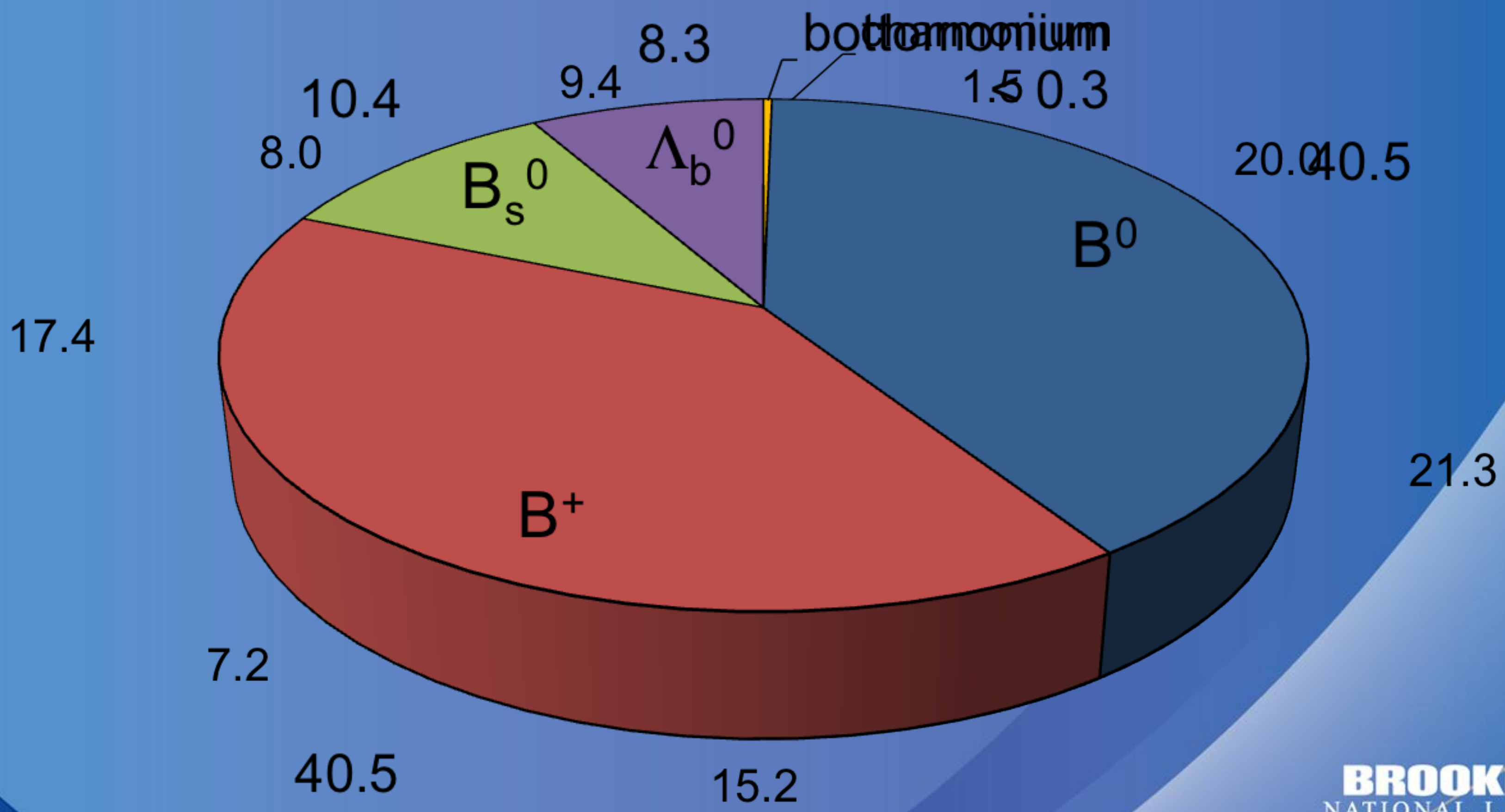






Where does all the heavy flavor go?

Courtesy of Kai Schweda (SQM2016)



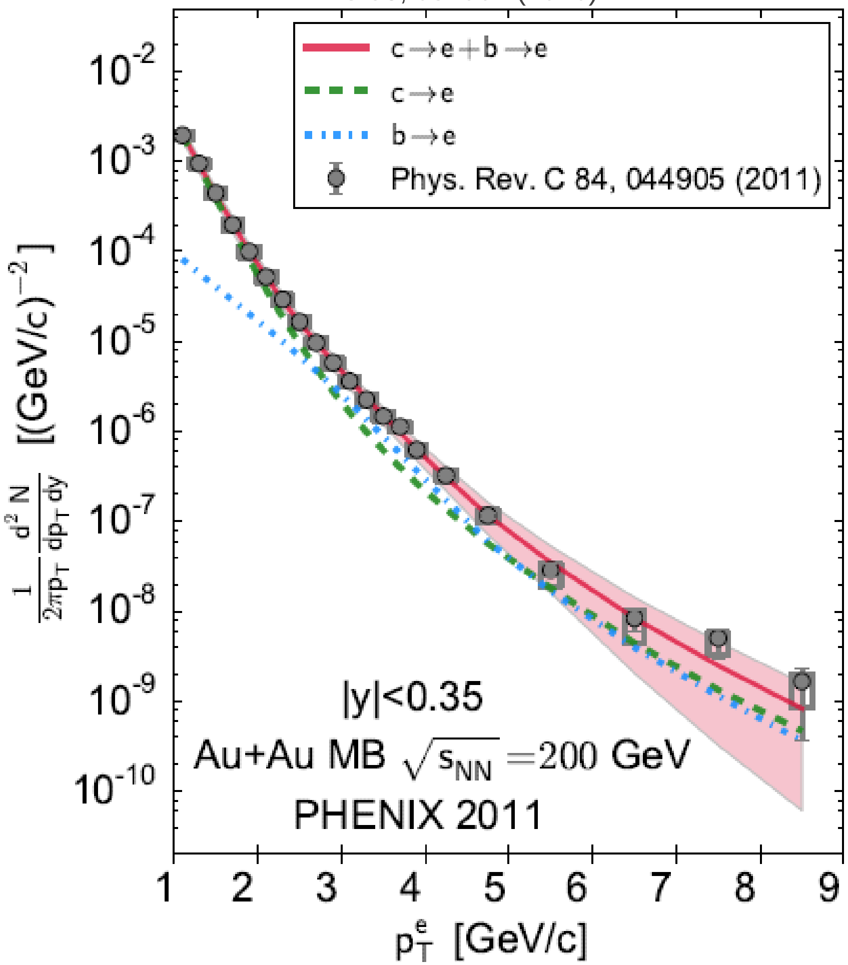
Open Heavy Flavor

NEW!

Results from PHENIX VTX: b/c separation

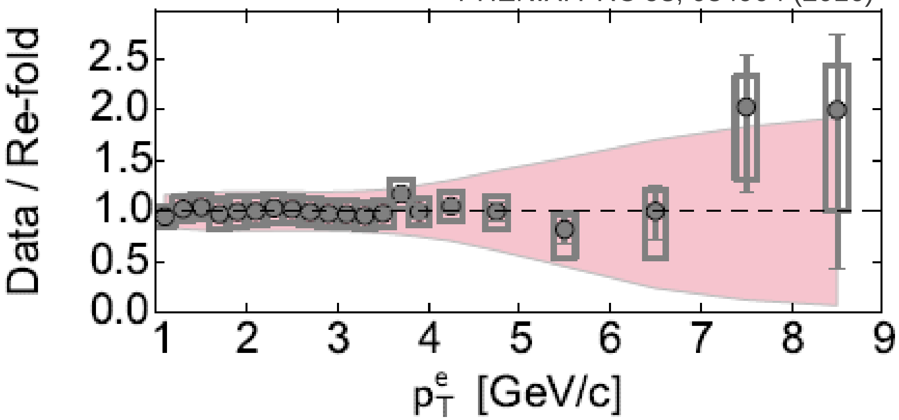
Invariant yield compared to previous published results

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



The unfolding results are consistent with the previous published inclusive heavy flavor electron invariant yields.

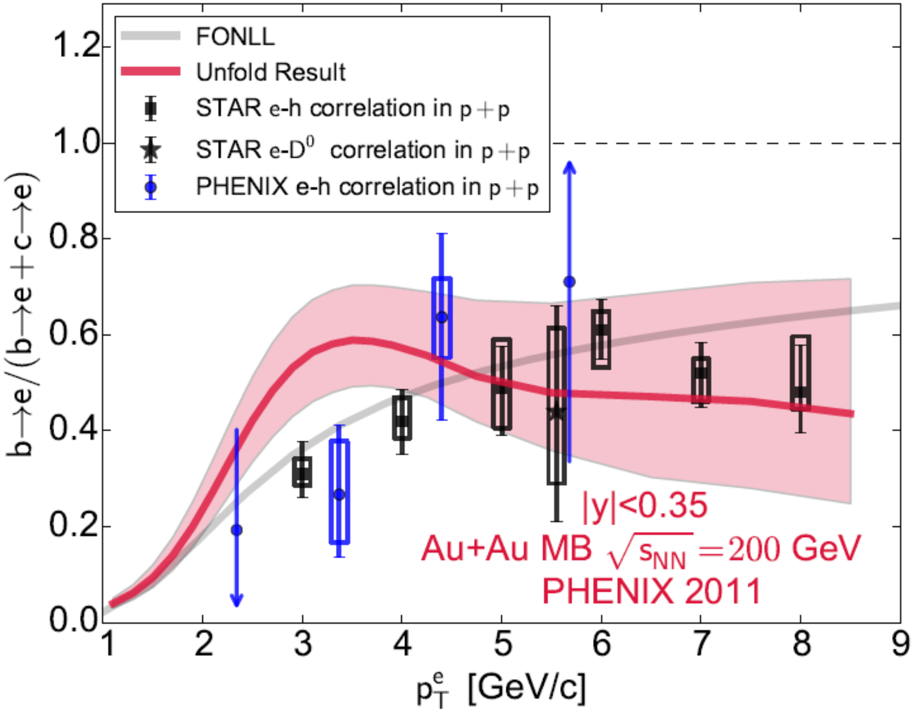
PHENIX: PRC **93**, 034904 (2016)



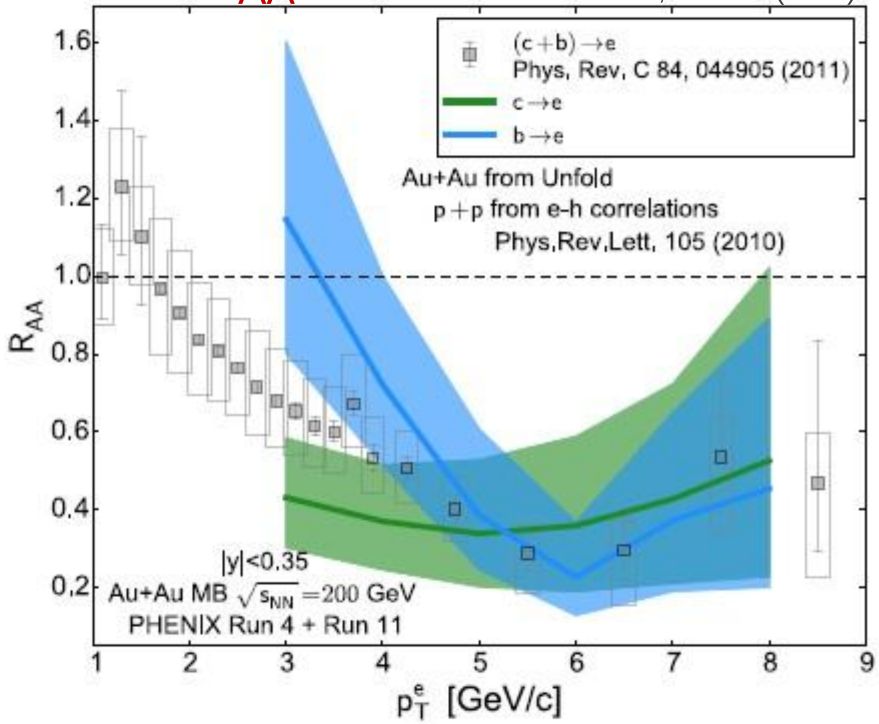
First Results from PHENIX VTX: b/c separation

Bottom and Charm R_{AA}

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



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



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

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

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

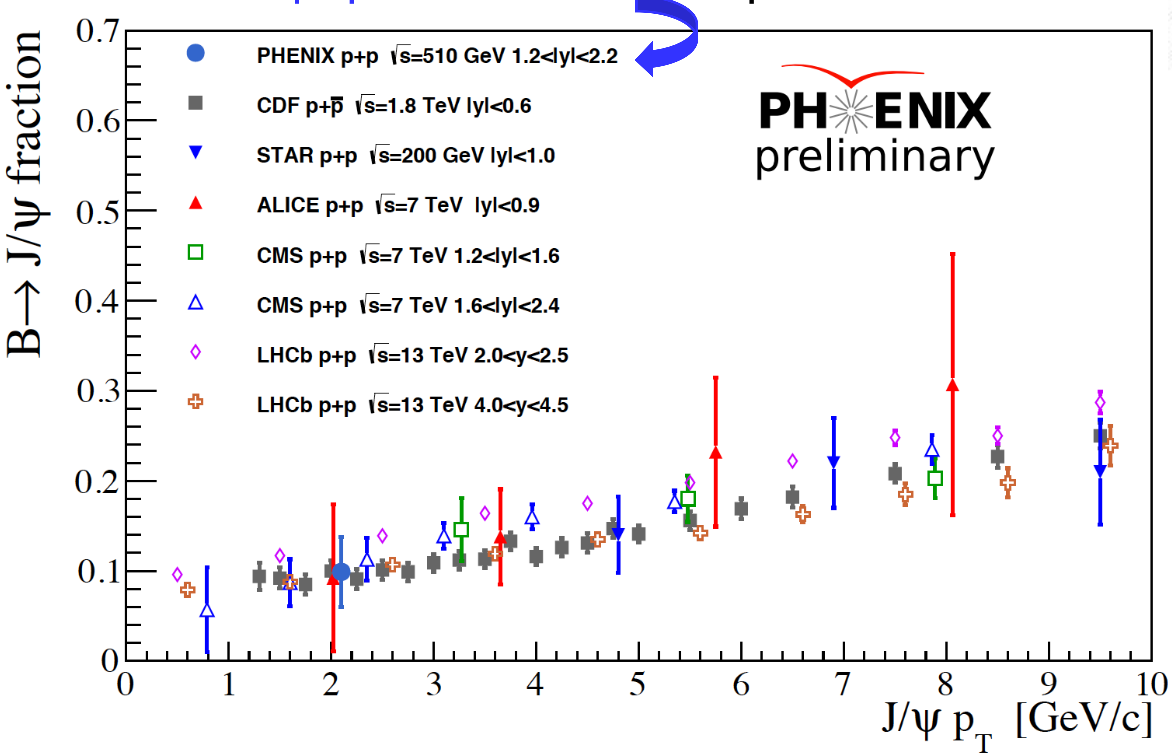
Stay Tuned:
- 2014 data set x10 better statistics than 2011
  - Decrease uncertainties
  - Increase p_T reach
  - Centrality separation
- Good 2015 p+p and p+Au data sets

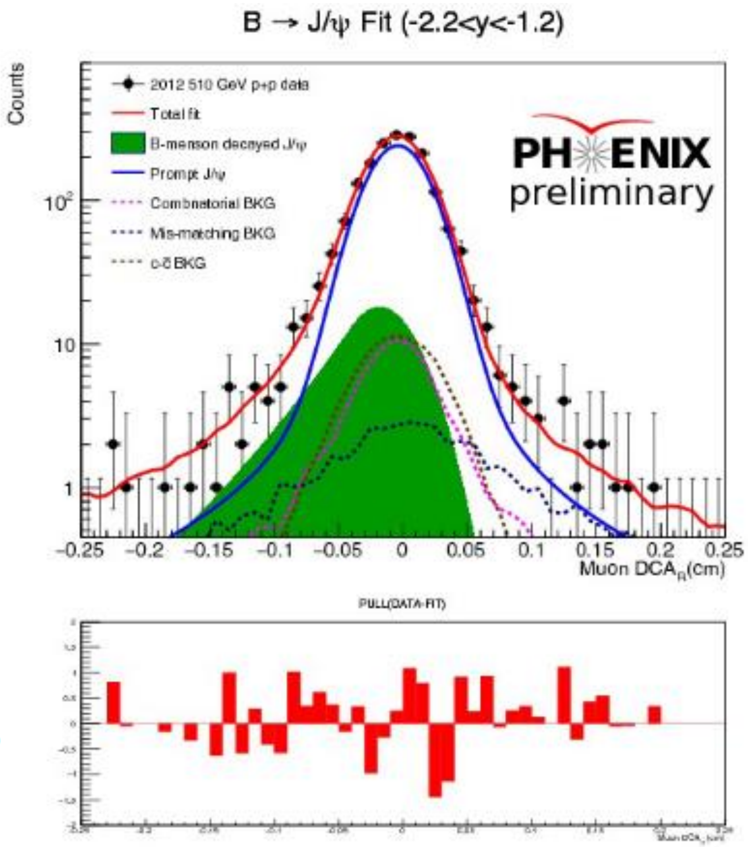
Open Heavy Flavor with FVTX in PHENIX

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

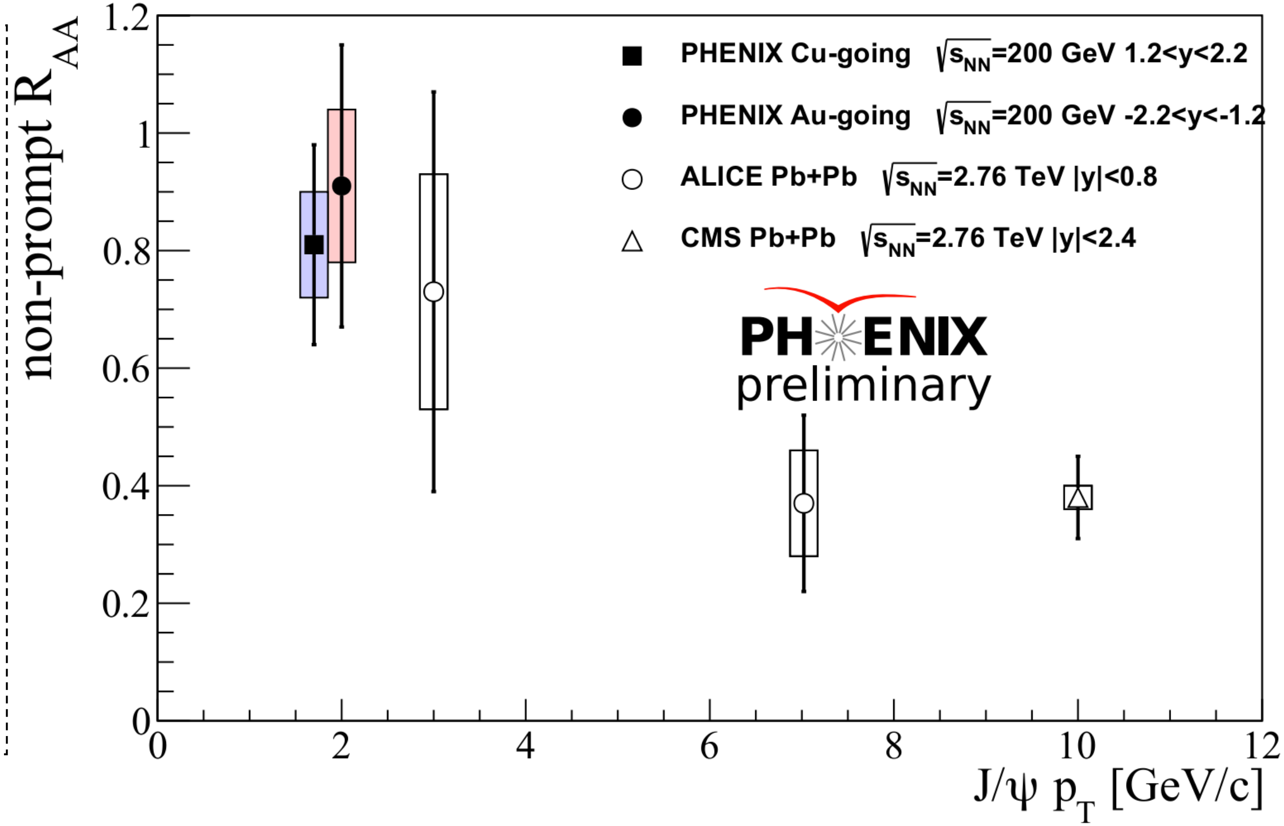
NEW!

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.



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

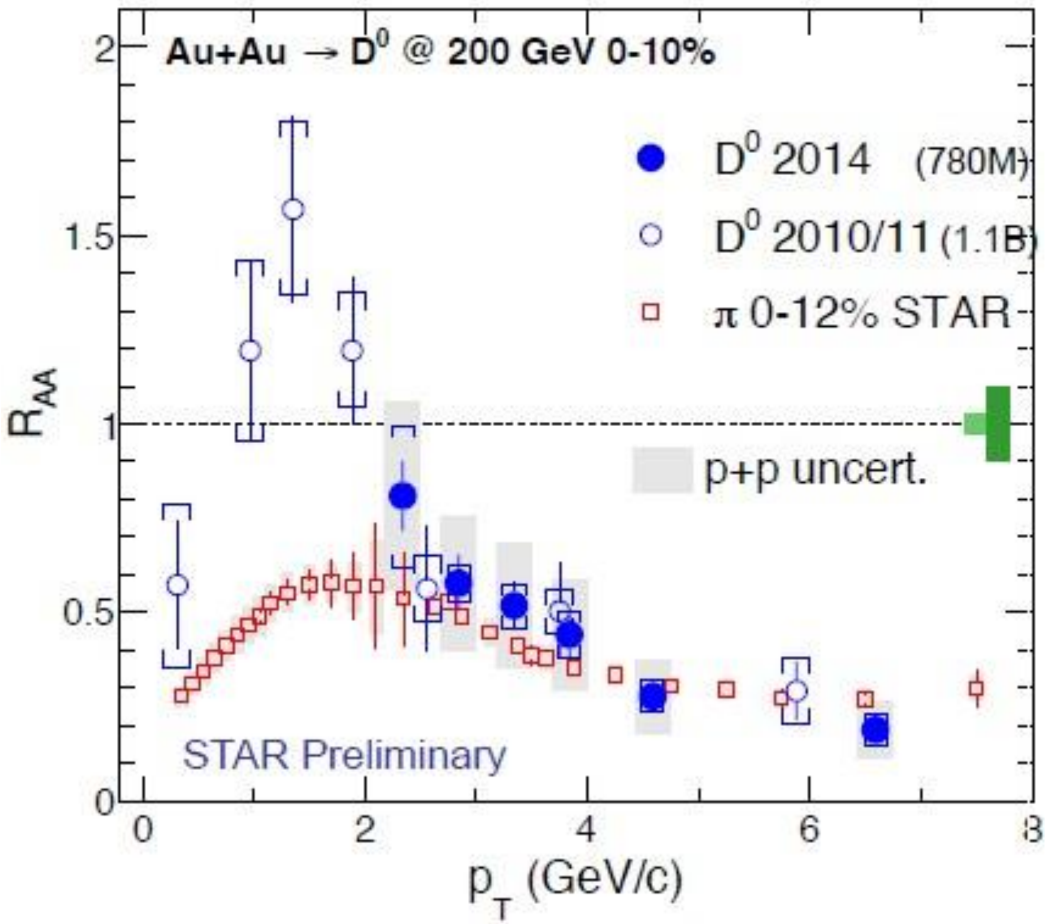
  Charm coalescence

- 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



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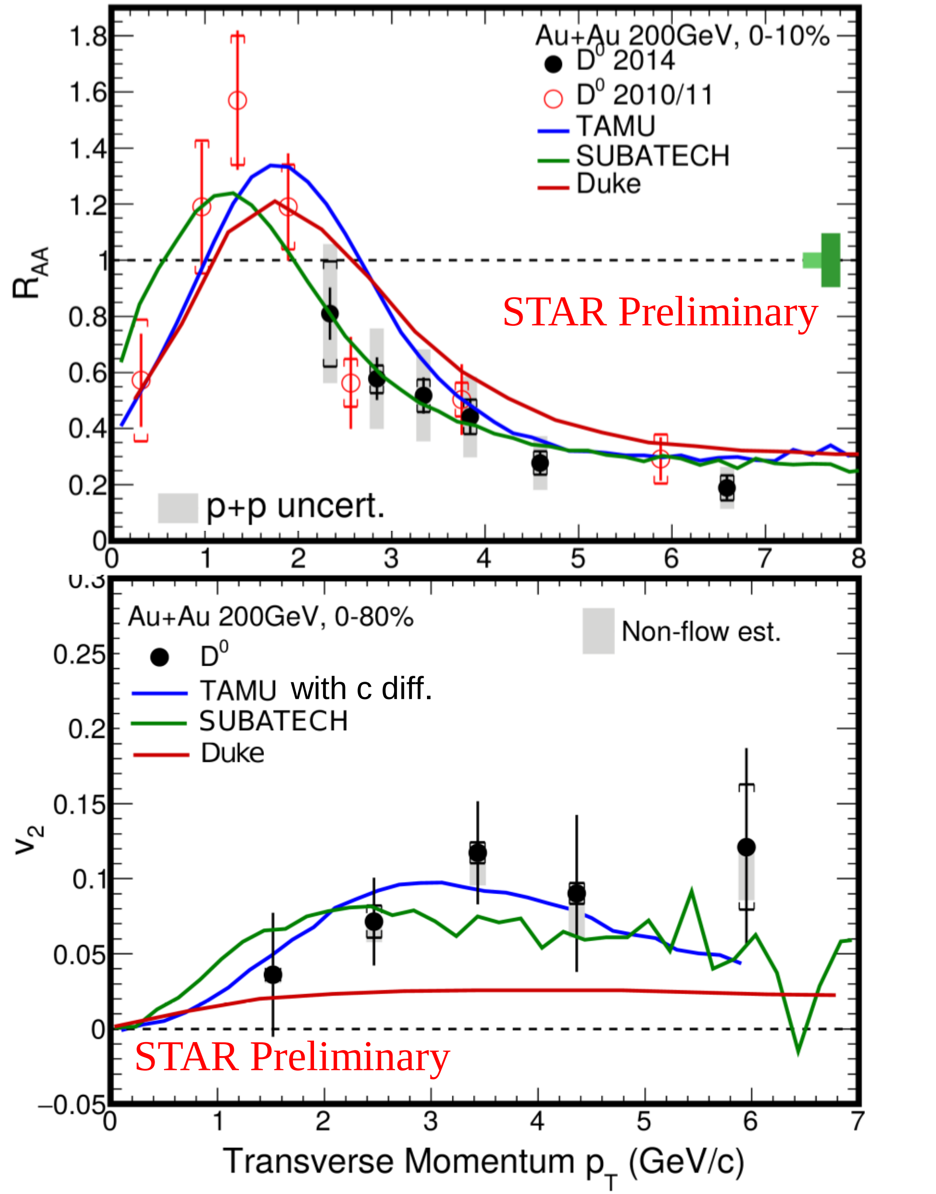
  Similar suppression for light partons and charm quarks at high p_T

Significant v_2 for D's at RHIC

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

  Favors charm quark diffusion

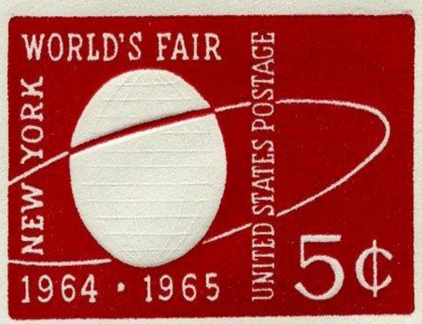


Quarkonia Production

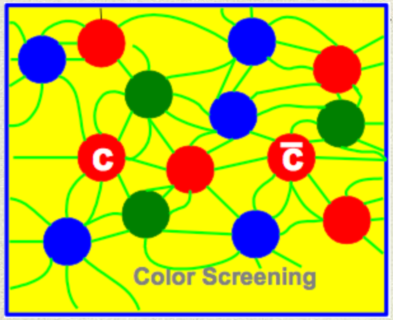
We received a letter (Phys. Lett. B178 (1986) 416) that:

Quarkonia!

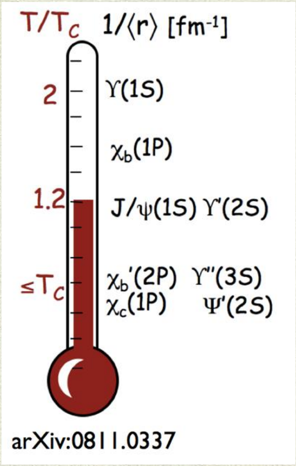
- Color screening in dense medium can cause disassociation of the bound state
- Should see sequential melting of the different states
- Use quarkonia as a medium thermometer!



… 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

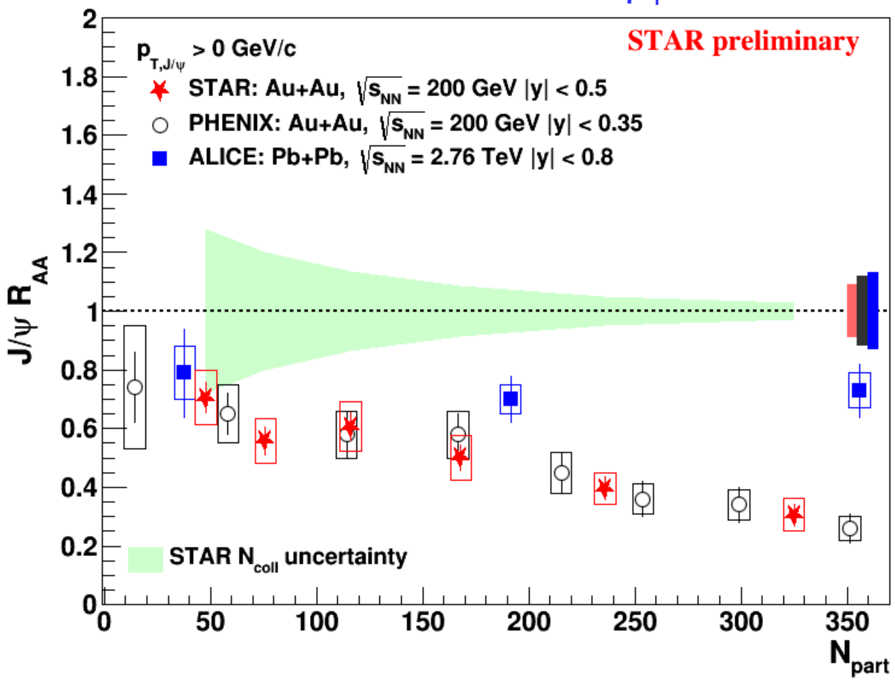


STAR: J/ψ R_{AA} in Au+Au at 200 GeV

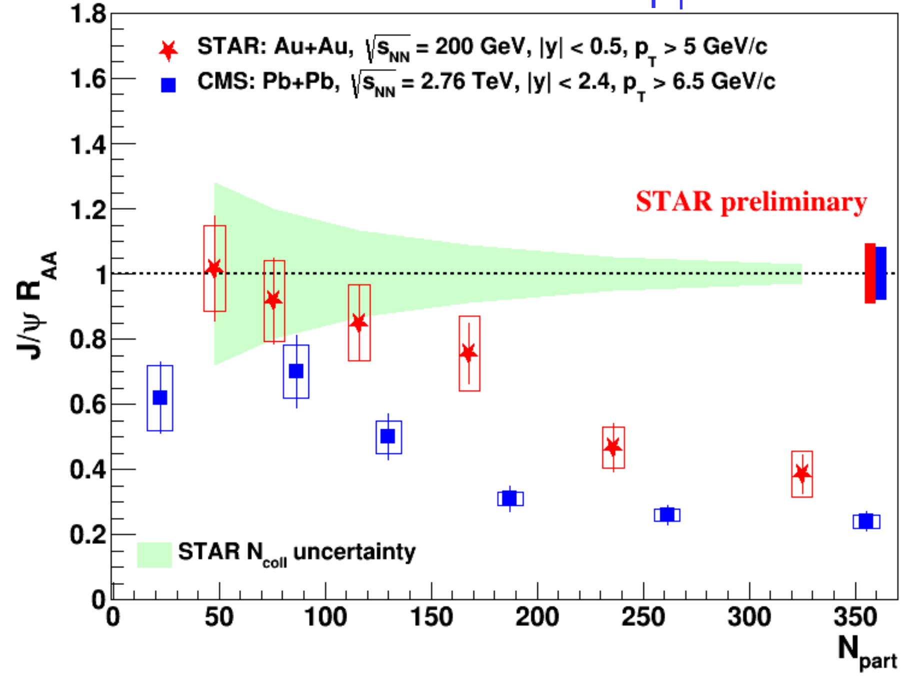
NEW!

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

p_T > 0 GeV/c



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

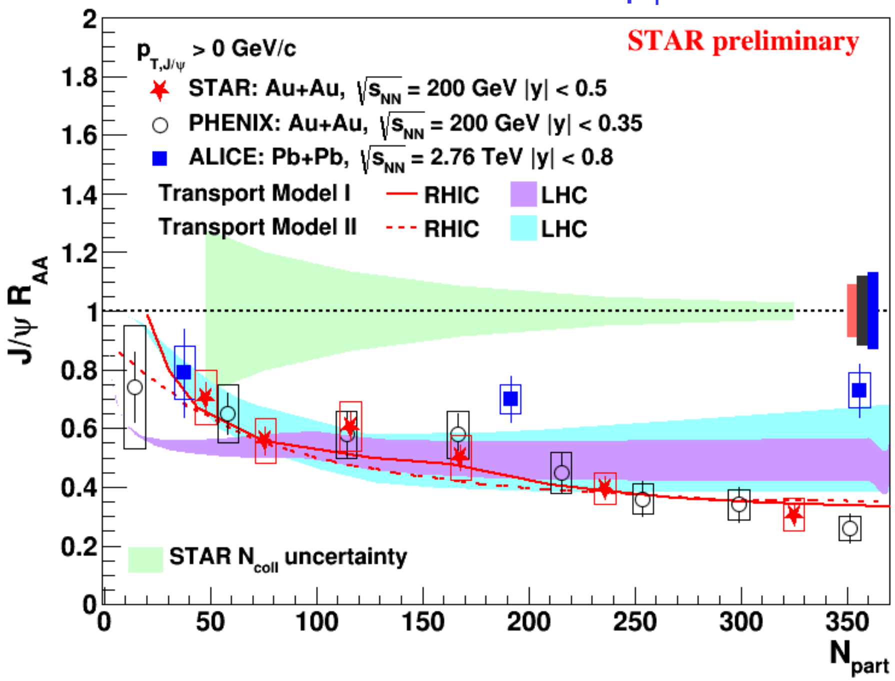
STAR: J/ψ R_{AA} in Au+Au at 200 GeV

NEW!

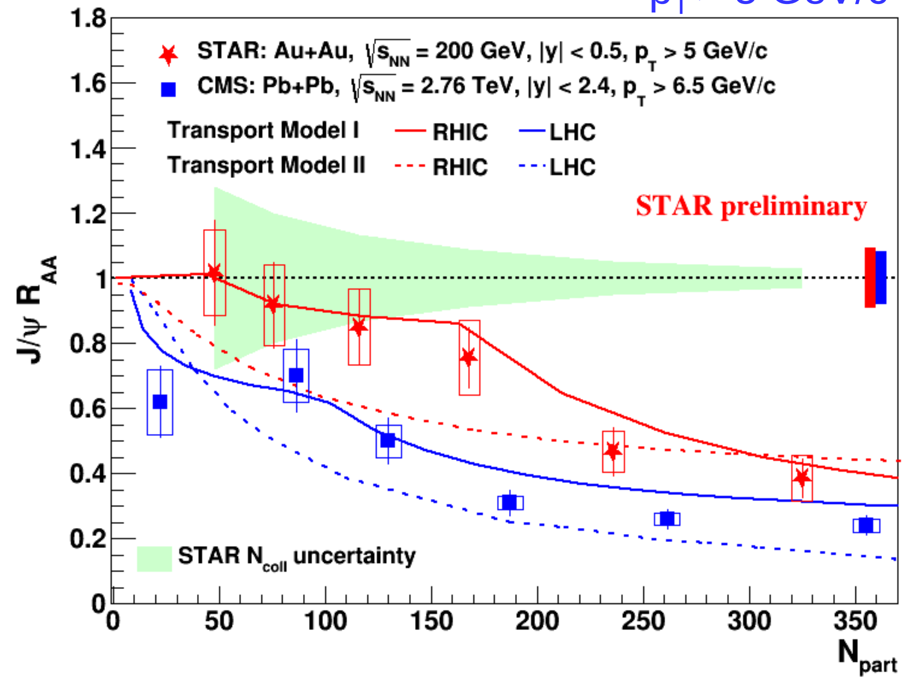
ALICE : PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

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 > 0 GeV/c



p_T > 5 GeV/c

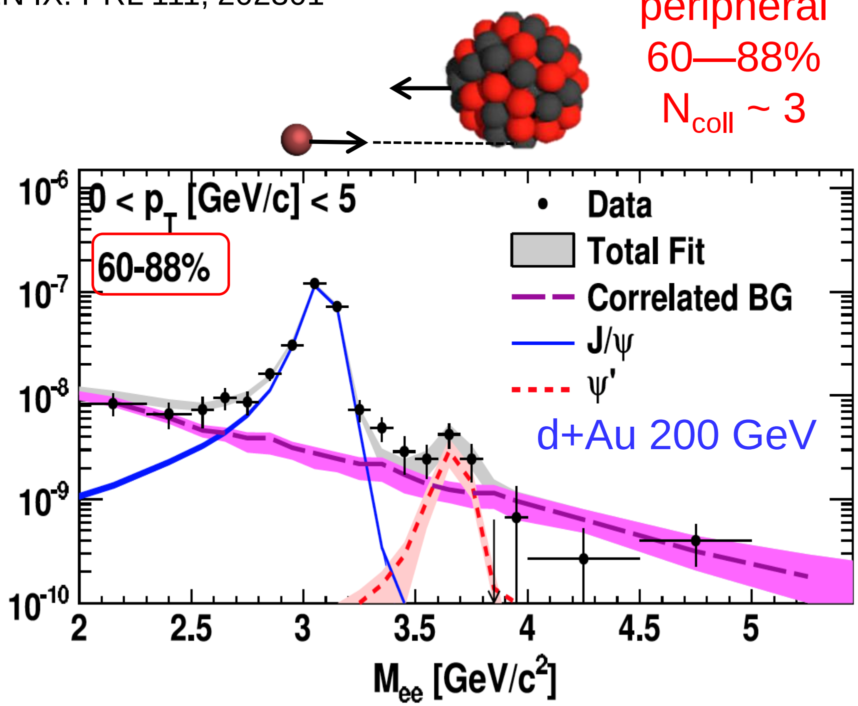


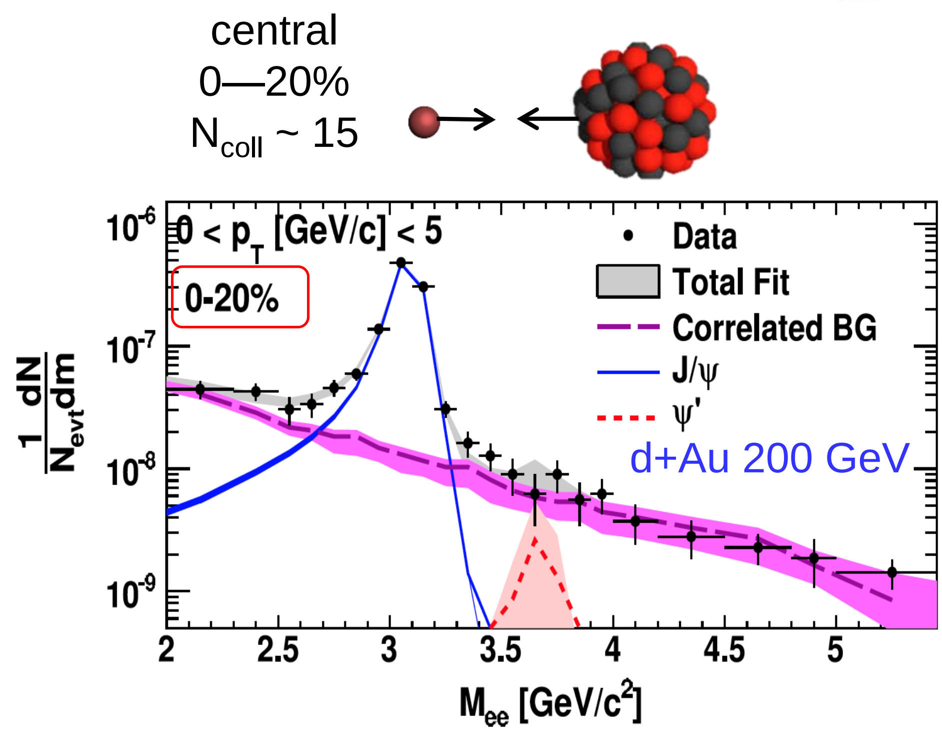
- J/ψ R_{AA} for p_T>0 GeV/c: RHIC is smaller than LHC -> more recombination at LHC
- J/ψ R_{AA} for p_T>5 GeV/c: LHC is smaller than RHIC -> stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe data

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

NEW!

PHEN IX: PRL 111, 202301

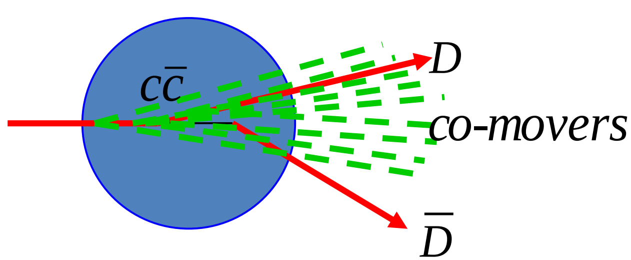


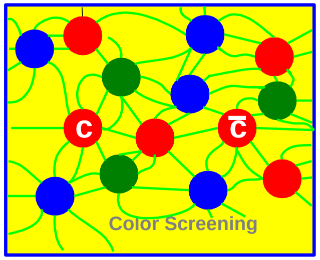


Breakup of quarkonia due to interaction with nuclear matters

1) Large suppression of the weakly bounded state ψ'

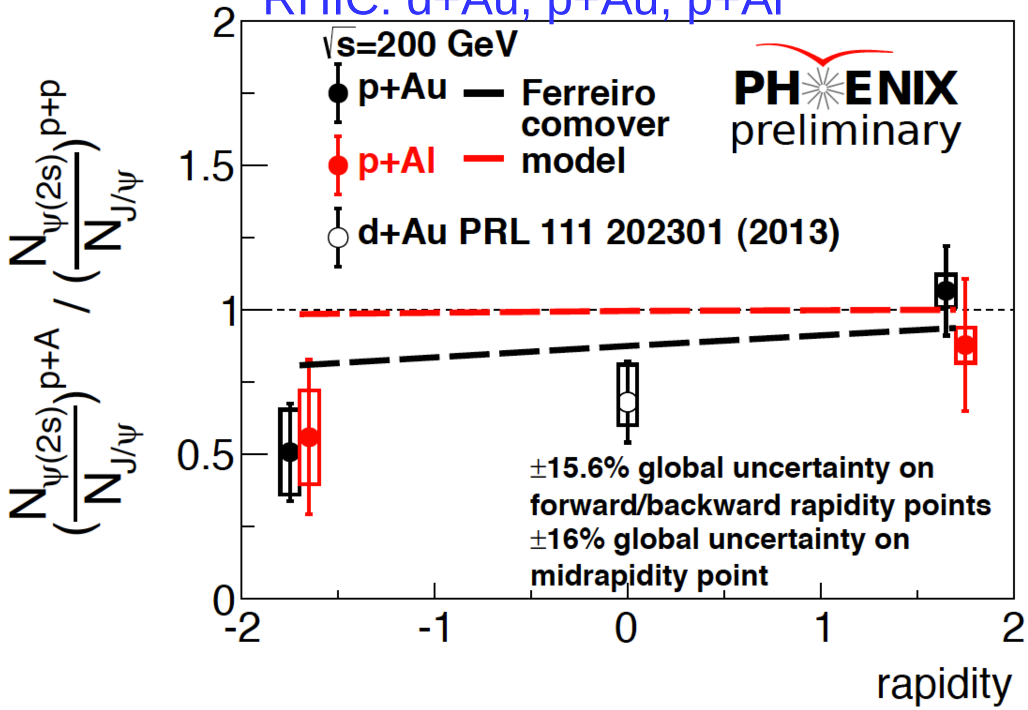
2) Interaction with nucleus? comovers? or medium?



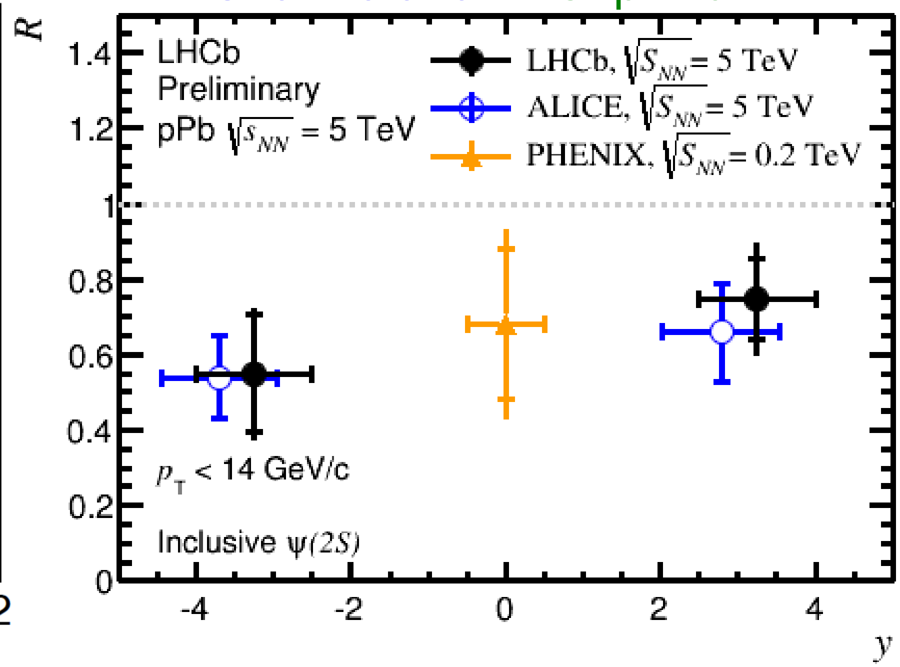


ψ' broken up in small systems: p+Al, p+Au and d+Au

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



RHIC: d+Au and LHC: p+Pb



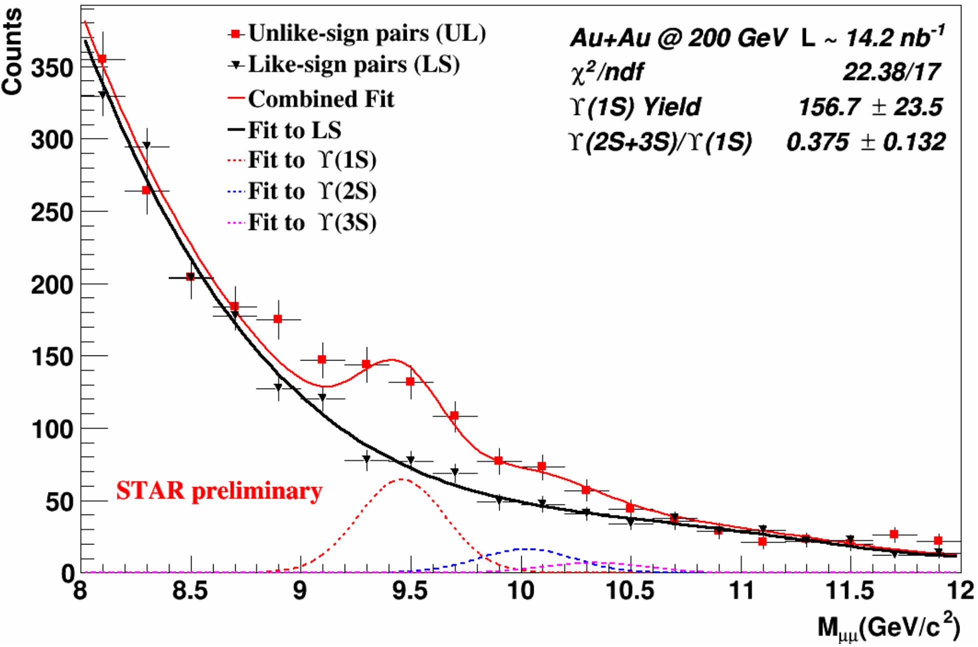
- comover dissociation model agree qualitatively with data
- Comparison with the QGP model work in progress.

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

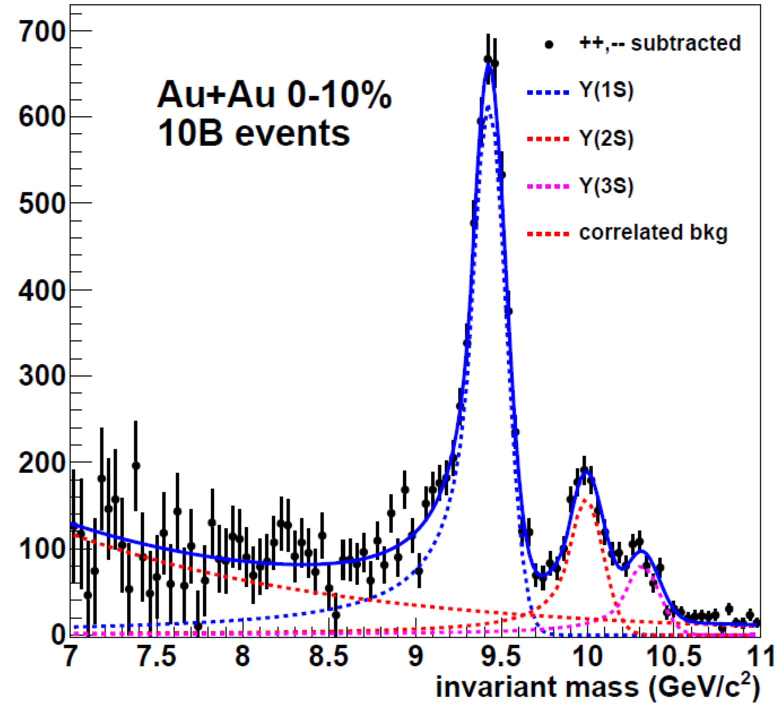
Outlook: Υ Production in Au+Au at 200 GeV

NEW!

STAR: Υ(2S+3S) from the di-muon channel



Future Detector at RHIC: sPHENIX



- Using STAR MTD
  - Lower brehmsstrahlung compared to dielectron channel.
- Hint of less melting of Υ(2S+3S) at RHIC than at LHC?

- sPHENIX being designed with separation of Υ states in mind.
- Still exploring tracking options.

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**

- Similar suppression of D mesons and light hadrons (at high-p_T > 4 GeV/c)
- Significant D^0 and low-p_T HF electron v2 → charm flow
- Electrons from bottom similarly suppressed to those from charm for 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**

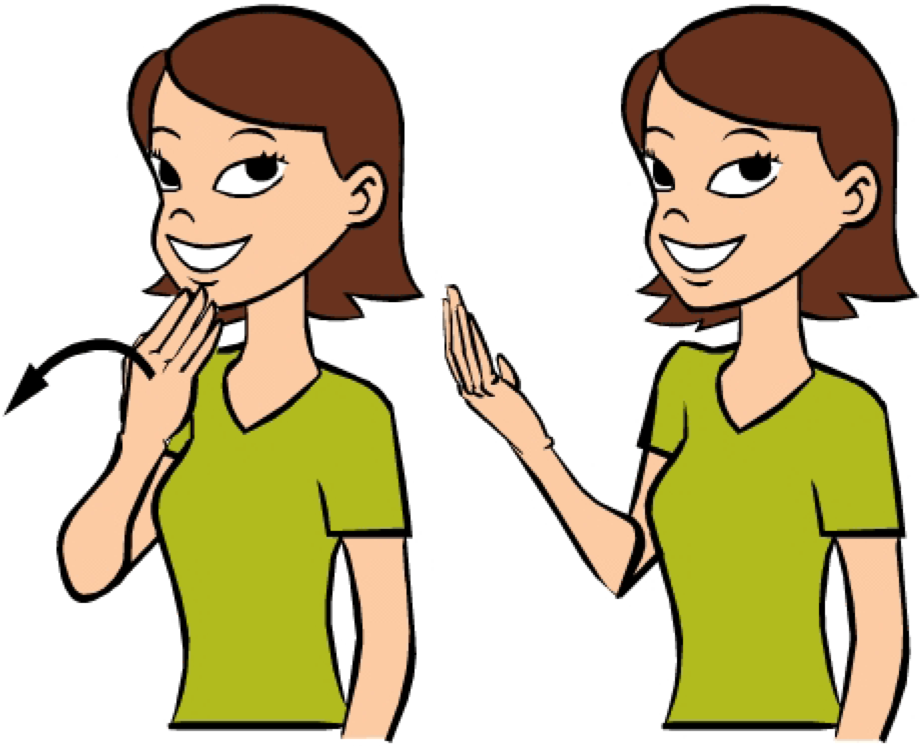
- ψ' larger suppression than J/ψ at mid and backward rapidity
  - comover dissociation model agree qualitatively with data
  - Forward rapidity: larger relative suppression of ψ' at LHC compared to RHIC

✧ **Υ in Au+Au at 200 GeV:** hint for less Υ(2S+3S) suppression at RHIC than LHC.

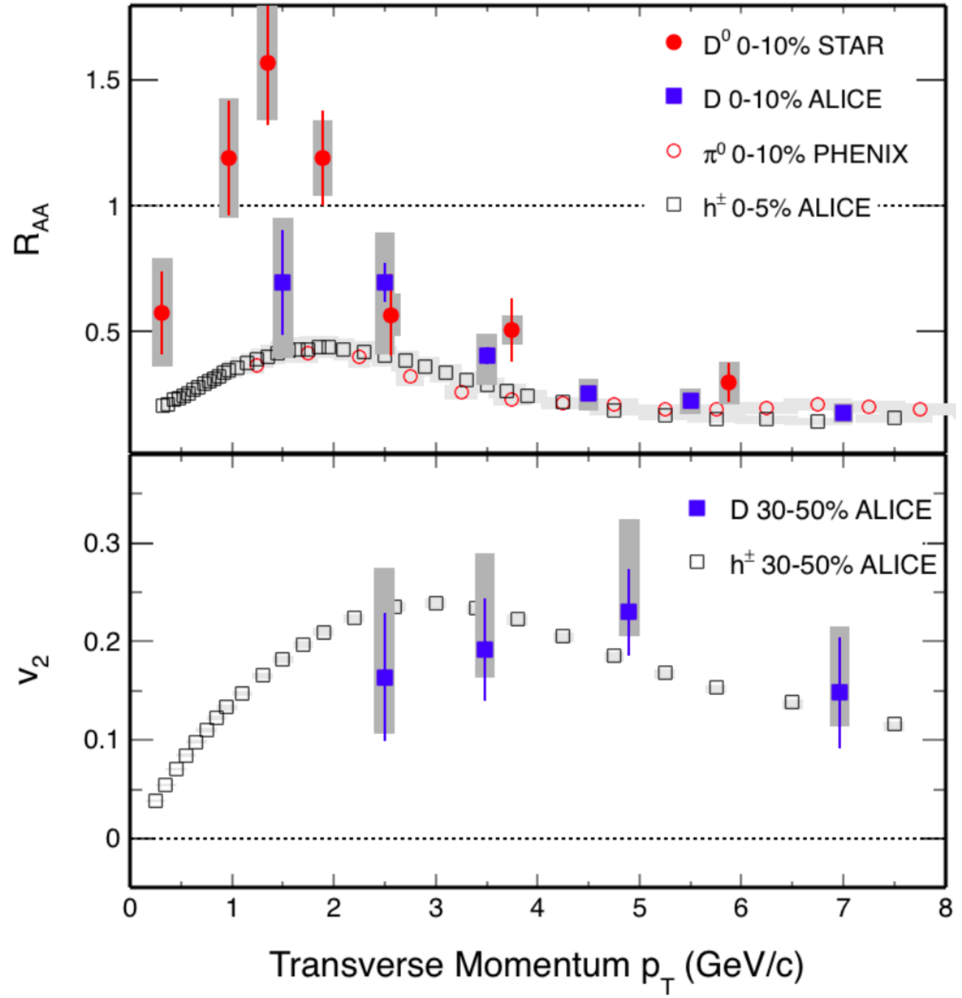
➢ Stay Tuned …!

✧ **More statistic:** decrease uncertainties, increase p_T reach, centrality separation → more surprises…

Thank you



The Story so Far — D mesons



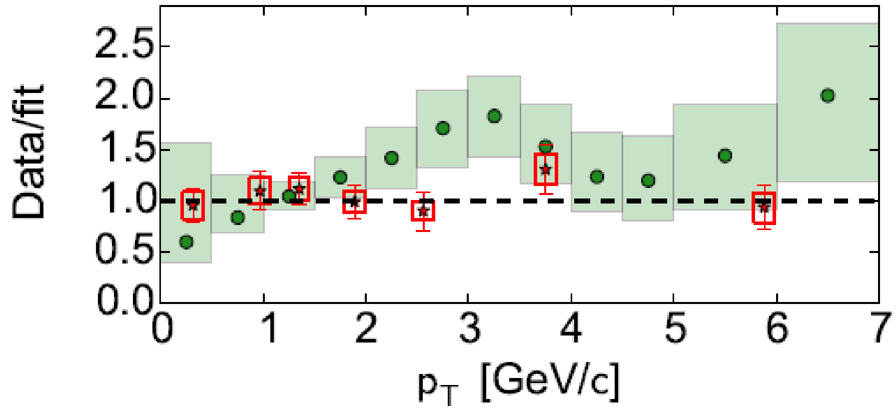
STAR:PRL 113 (2014) 142301
PHENIX:PRL 101 (2008) 232301
ALICE: PRL 111 (2013) 102301
arXiv:1509.06888 (2015)

What NEW on Open Heavy Flavor?

First Results from PHENIX VTX: b/c separation

Invariant yield:

PHENIX unfolded D^0 p_T spectra agrees within uncertainties with measurements from STAR.



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