Υ production at the STAR experiment

with a focus on new U+U results

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EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Outline

- Quarkonia in heavy ion collisions
- ϒ measurements with the STAR experiment
- Results ($\sqrt{s_{NN}}$=193..200 GeV, mid-rapidity)
  - p+p → pQCD baseline
  - d+Au → CNM effects
  - Au+Au and U+U → sQGP modification
- Outlook
  - New high-statistics measurements, $\sqrt{s}$=500 GeV p+p
  - Muon Telescope Detector (MTD)

Quarkonia in the sQGP

- Debye screening of heavy quark potential
  → Quarkonium states are expected to dissociate

  T. Matsui, H. Satz, Phys.Lett. B178, 416 (1986)

Charmonia: J/Ψ, Ψ', χ_c **Bottomonia:** $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_B

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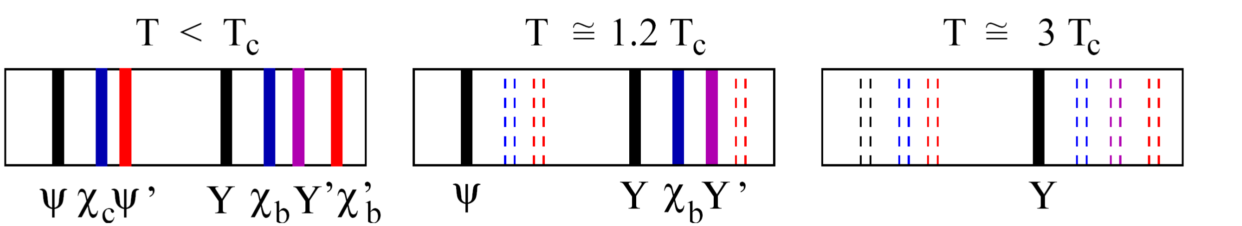
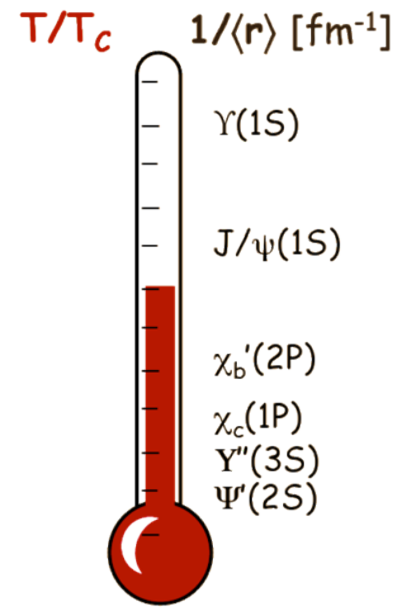
  Charmonia: J/Ψ, Ψ', χ_c Bottomonia: Υ(1S), Υ(2S), Υ(3S), χ_B

- Sequential melting: Different states are expected to melt at different temperatures

  Á. Mócsy, P. Petreczky, Phys. Rev. D77, 014501 (2008)



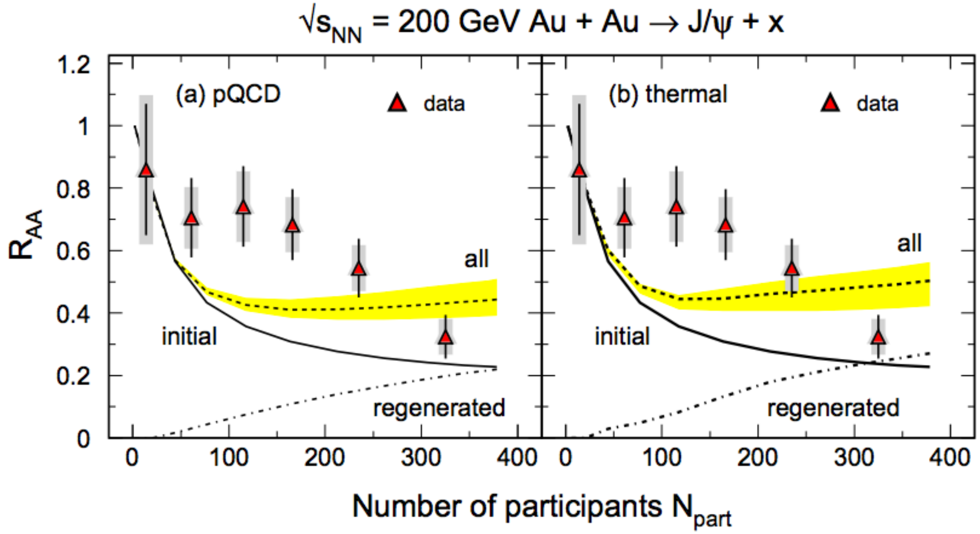


Quarkonia may serve as sQGP thermometer

ϒ measurements at RHIC

- J/ψ yield is strongly affected by recombination, feed-down, co-mover absorption

→ P. Chaloupka's talk



Model:
R. Rapp et al., Prog.Part.Nucl.Phys. 65 (2010) 209

Data:
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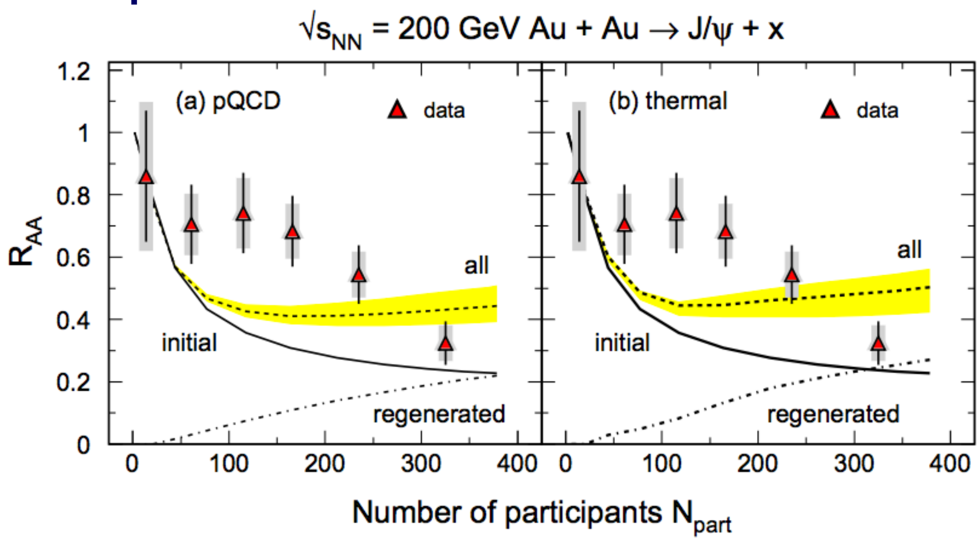


Model:
R. Rapp et al., Prog.Part.Nucl.Phys. 65 (2010) 209

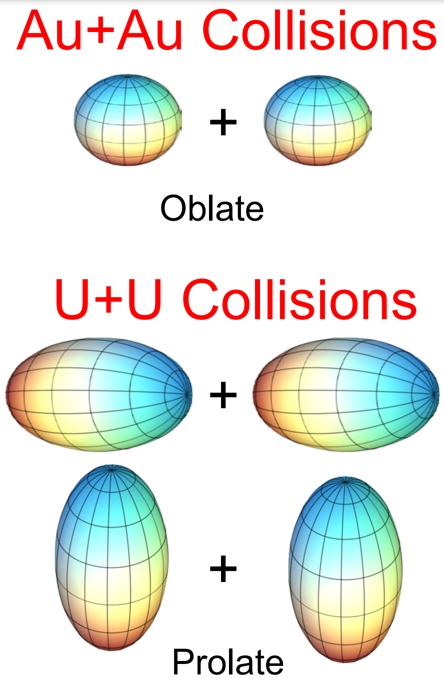
Data:
PHENIX, Nucl.Phys. A 774 (2006) 747

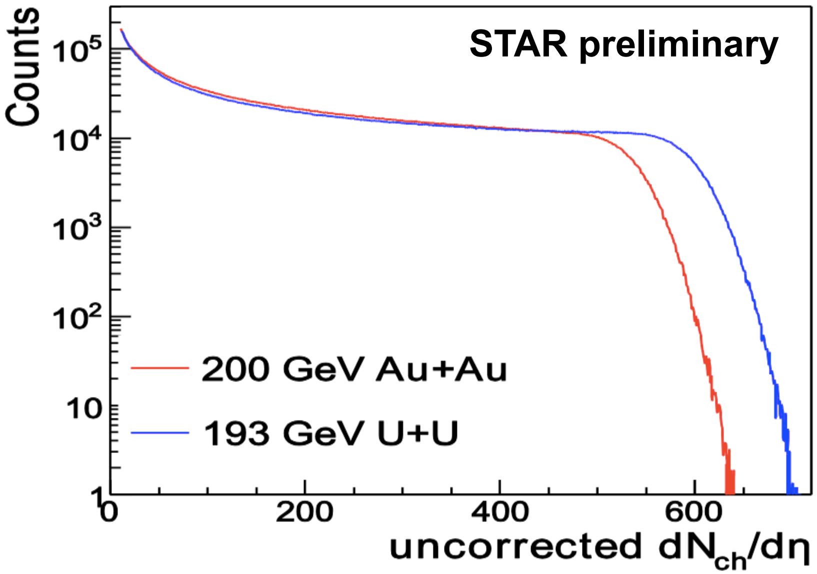
- ϒ recombination and co-mover absorption are negligible at RHIC energies

ϒ states provide a cleaner probe at RHIC

- However: Low production rate makes it a difficult measurement
  Requires good acceptance and specific triggering

U+U: Higher energy densities

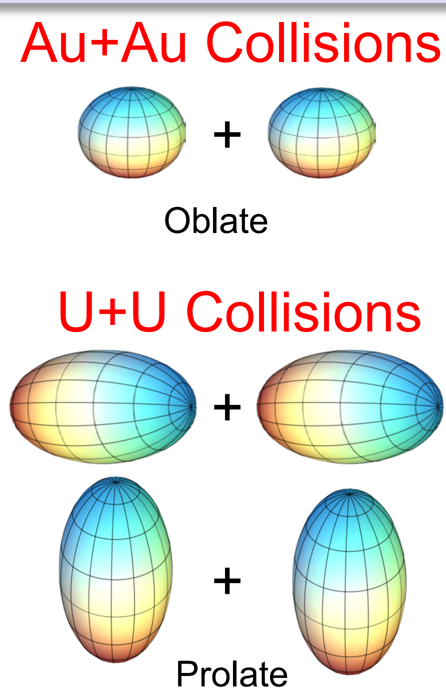


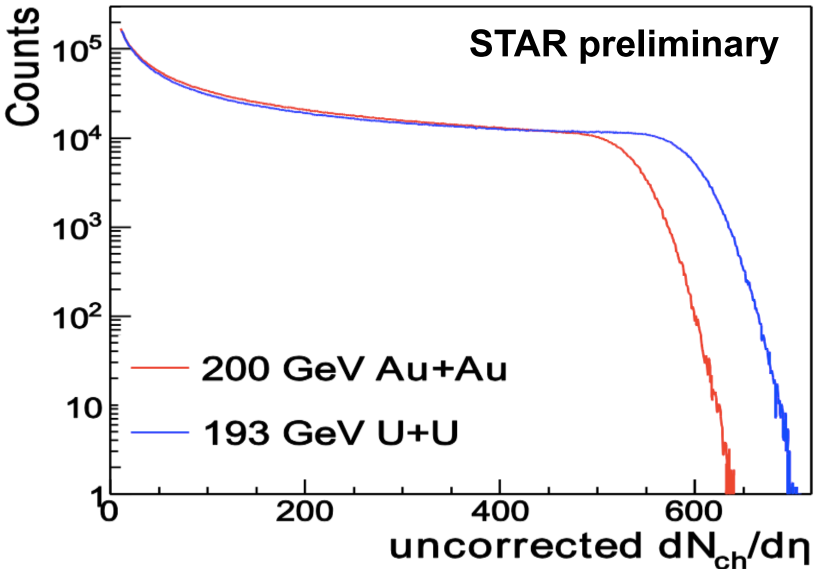


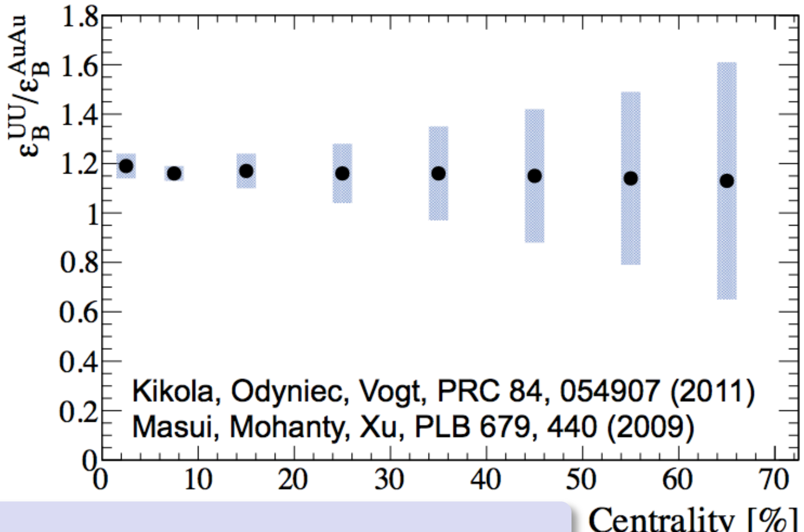
RHIC $\sqrt{s_{NN}}$=193 GeV U+U data (2012)

- Reach higher N_{part} than in Au+Au

U+U: Higher energy densities





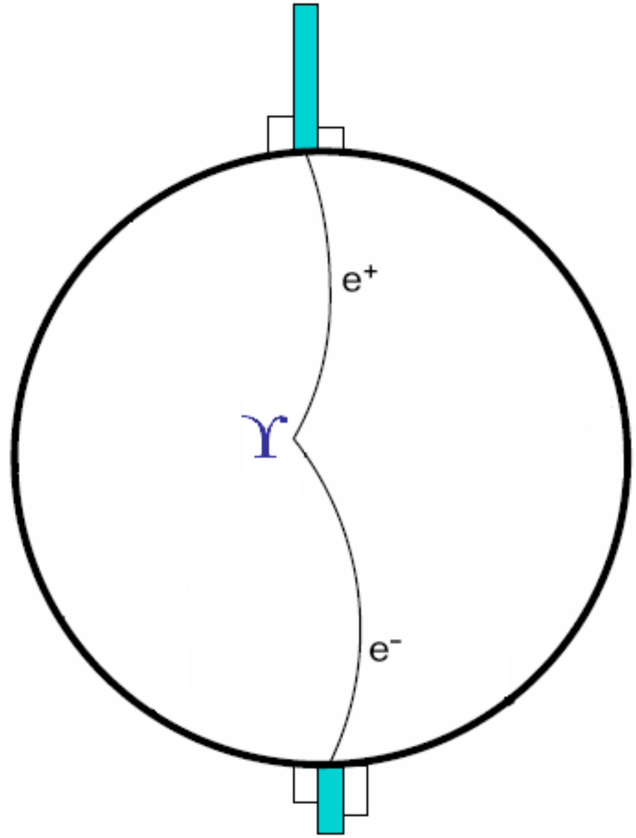


RHIC $\sqrt{s_{NN}}$=193 GeV U+U data (2012)

- Reach higher N_{part} than in Au+Au
- Provide higher energy density

Way to test the sequential melting hypothesis

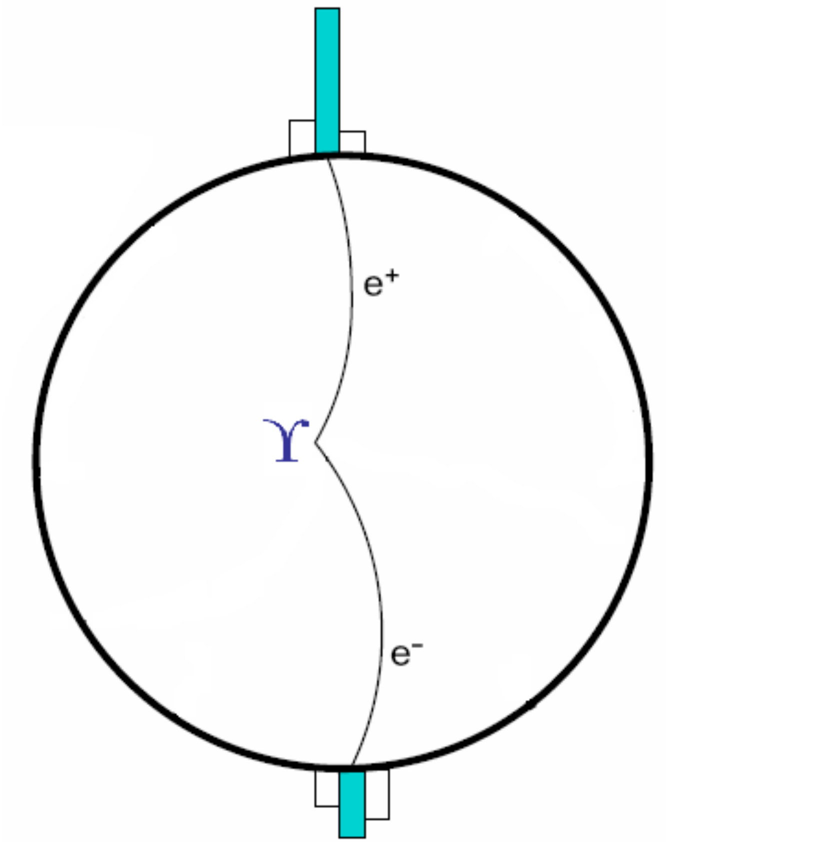
ϒ measurements in RHIC/STAR

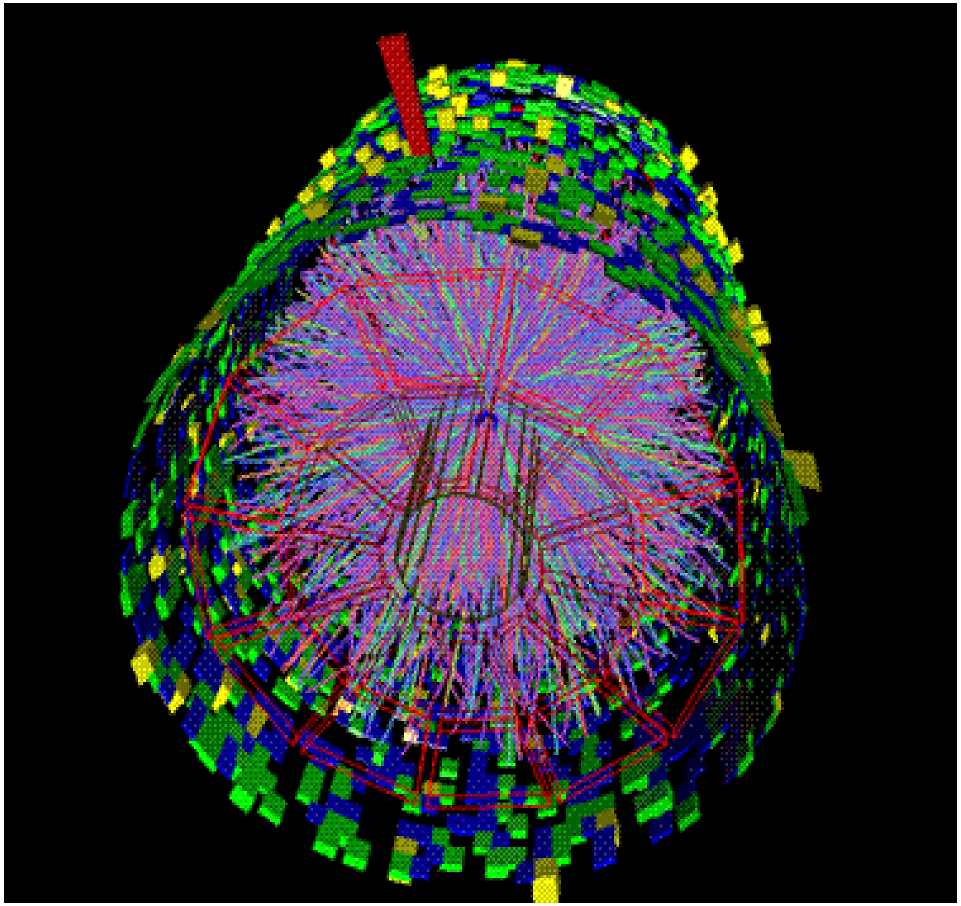


ϒ → e^+e^- (BR ~ 2%)

- Large invariant mass (m_{ee}~10 GeV/c^2)
- Back-to-back electron-positron pair
- Rather energetic electrons (typically >3 GeV)

ϒ measurements in RHIC/STAR



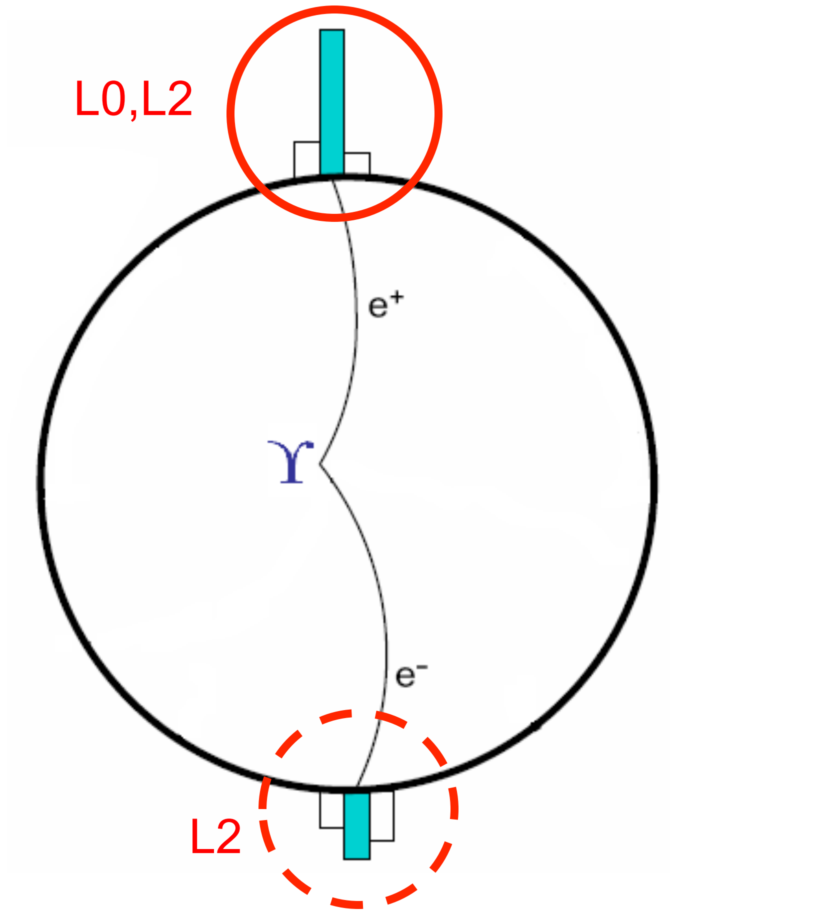


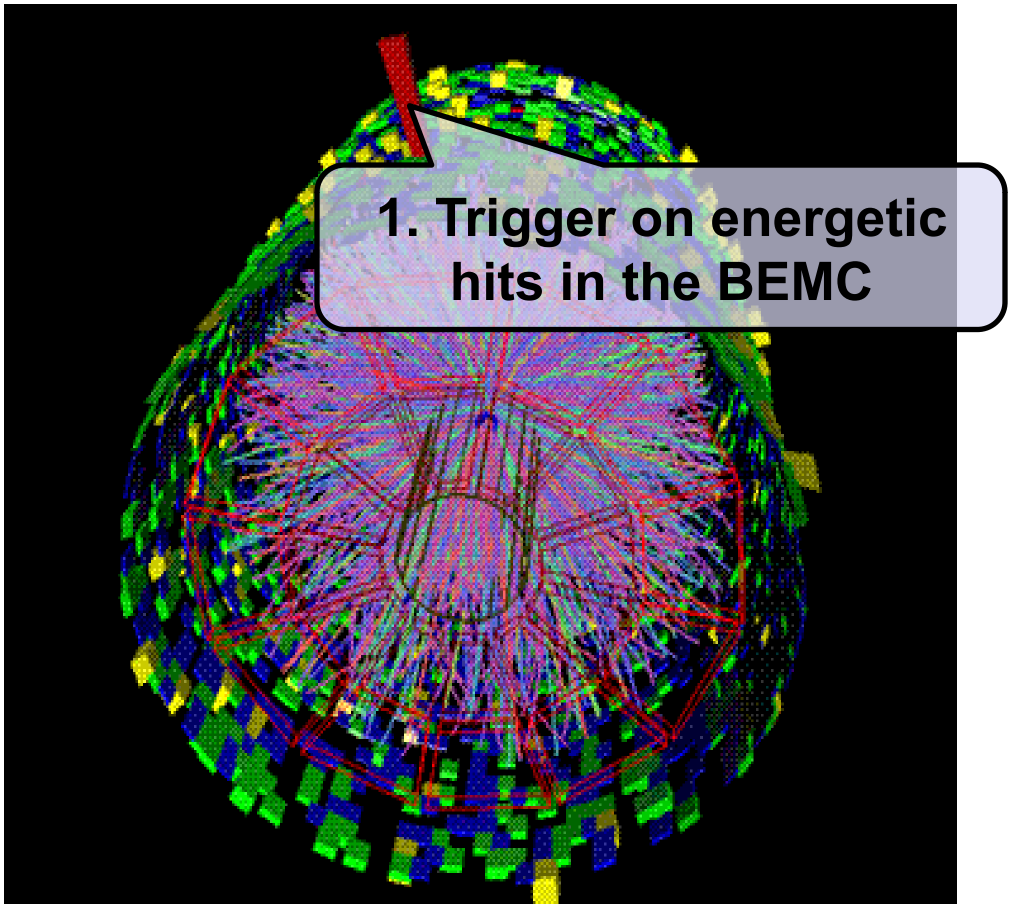
$\Upsilon \rightarrow e^+e^-$ (BR ~ 2%)

a central Au+Au event in STAR

- Large invariant mass (m_{ee}~10 GeV/c^2)
- Back-to-back electron-positron pair
- Rather energetic electrons (typically >3 GeV)

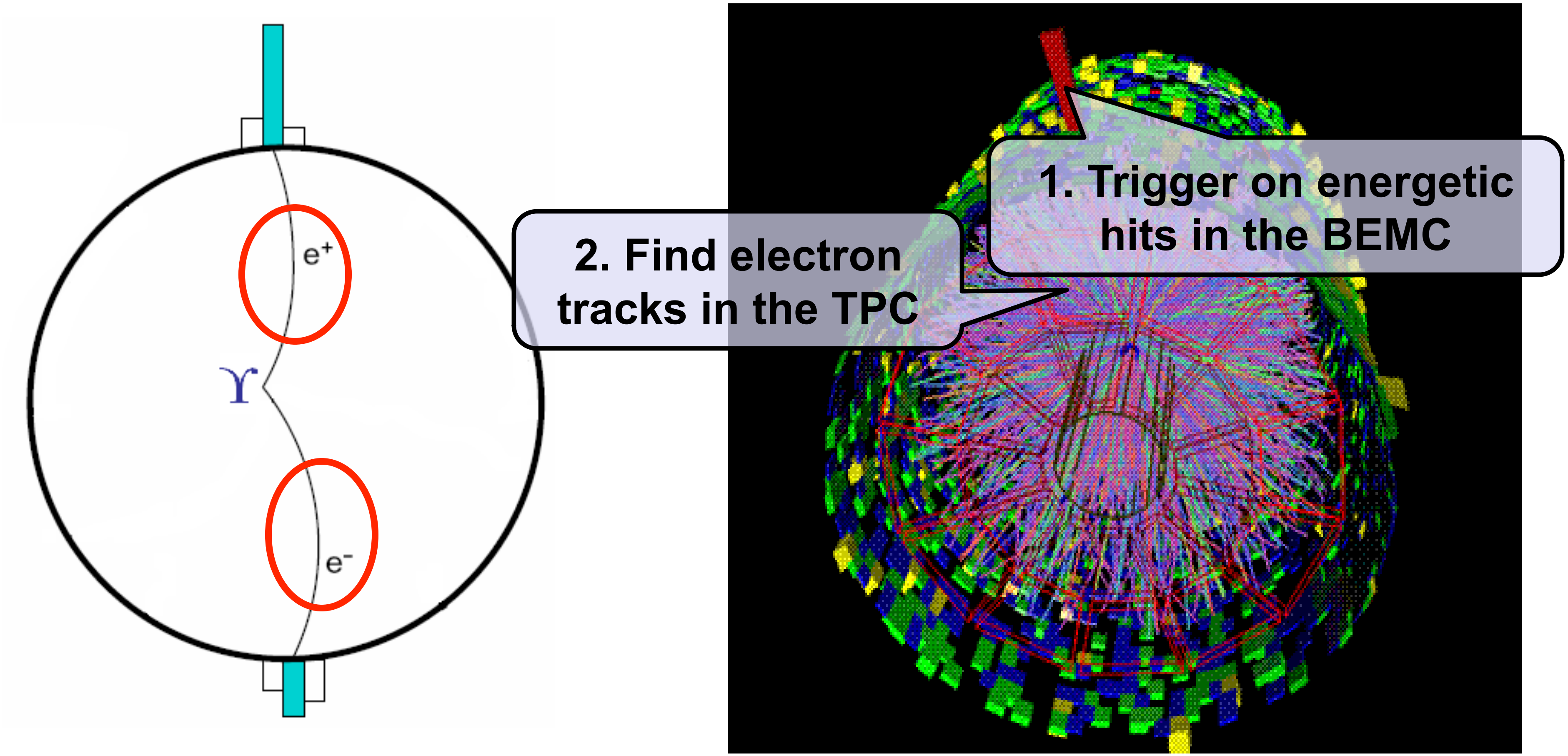
1. Triggering on ϒ events





- **L0**: 'High tower trigger' saves events with high energy hit in the Barrel Electromagnetic Calorimeter **(**BEMC) tower
- **L2** *in p+p and d+Au only* – software trigger: coarse reconstruction of cluster energy, opening angle, invariant mass

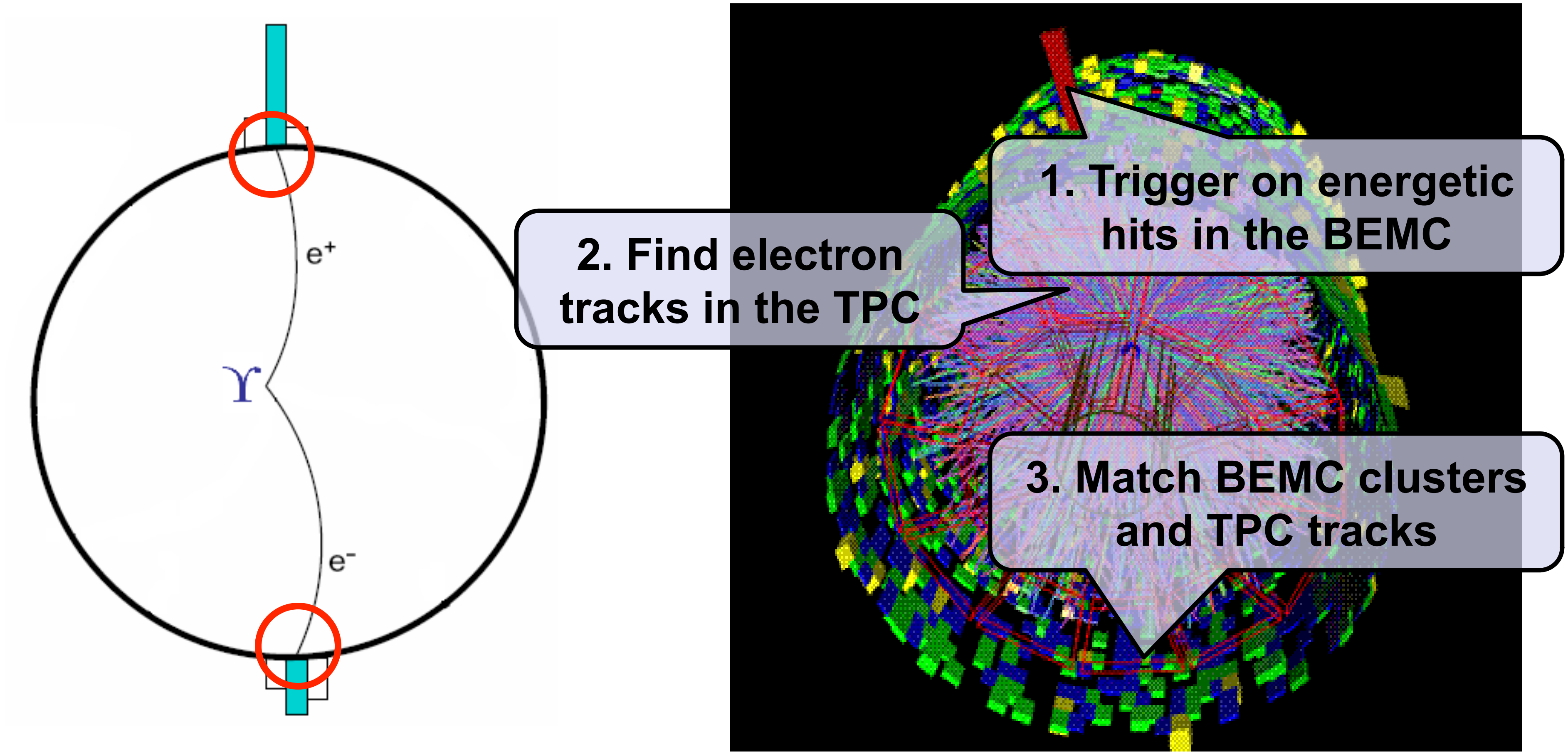
2. Finding electron tracks



- Find tracks in the Time Expansion Chamber (TPC) based on Fractional energy loss d*E*/dx

  $-1.2 < n\sigma_e < 3$ *(A+A analyses)*

3. Matching



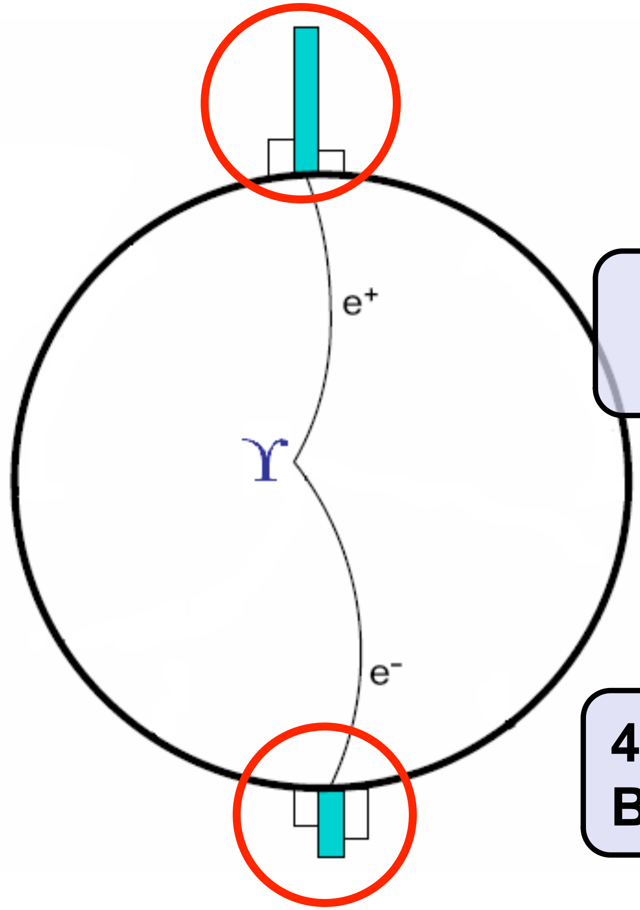
- Clusterize energy in the BEMC

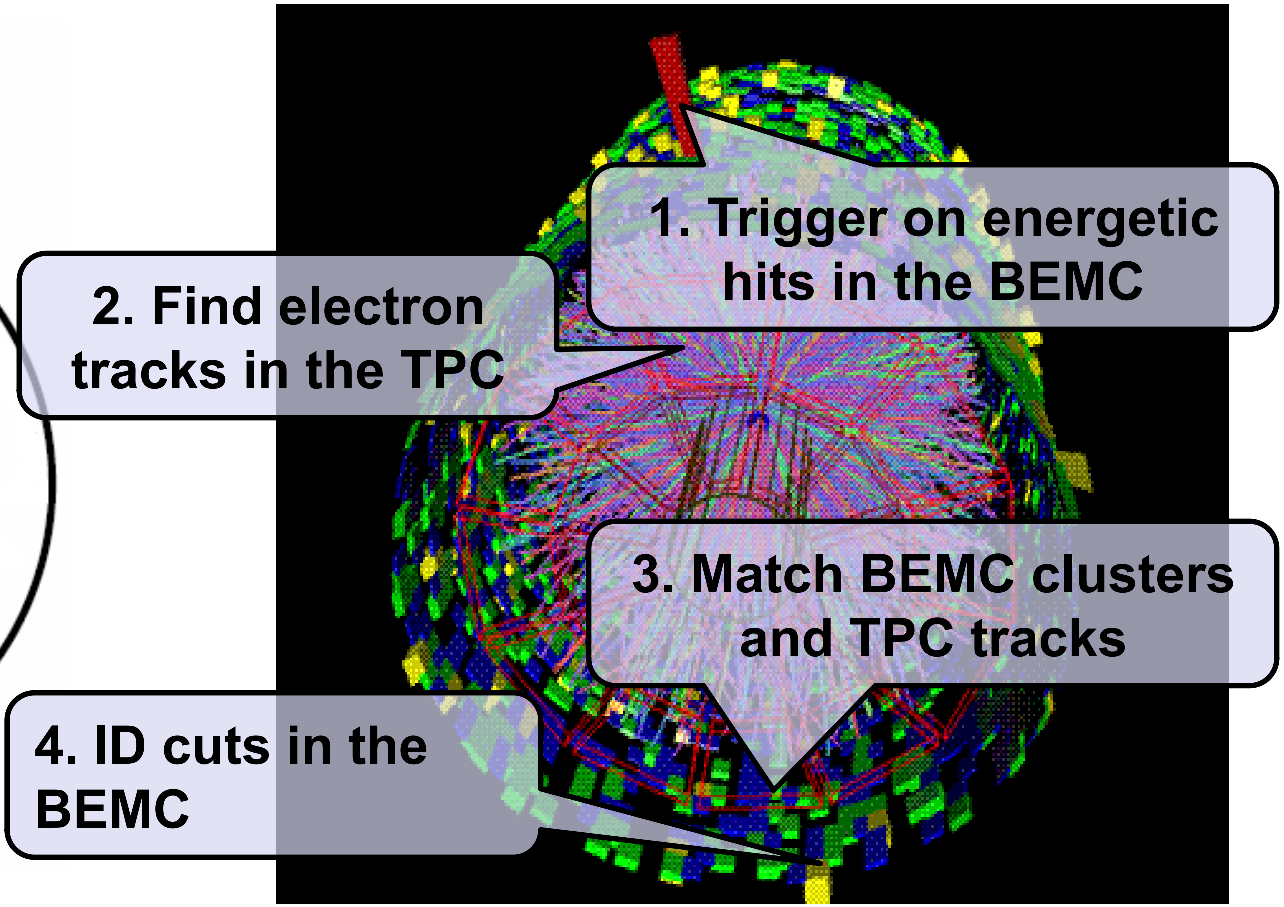
  Cluster: 3 adjacent towers with most of the energy deposit

- Project TPC tracks onto clusters to match them

  $\Delta R_{match} = \sqrt{(\Delta\eta^2+\Delta\varphi^2)} < 0.04$

4. ID in the calorimeter

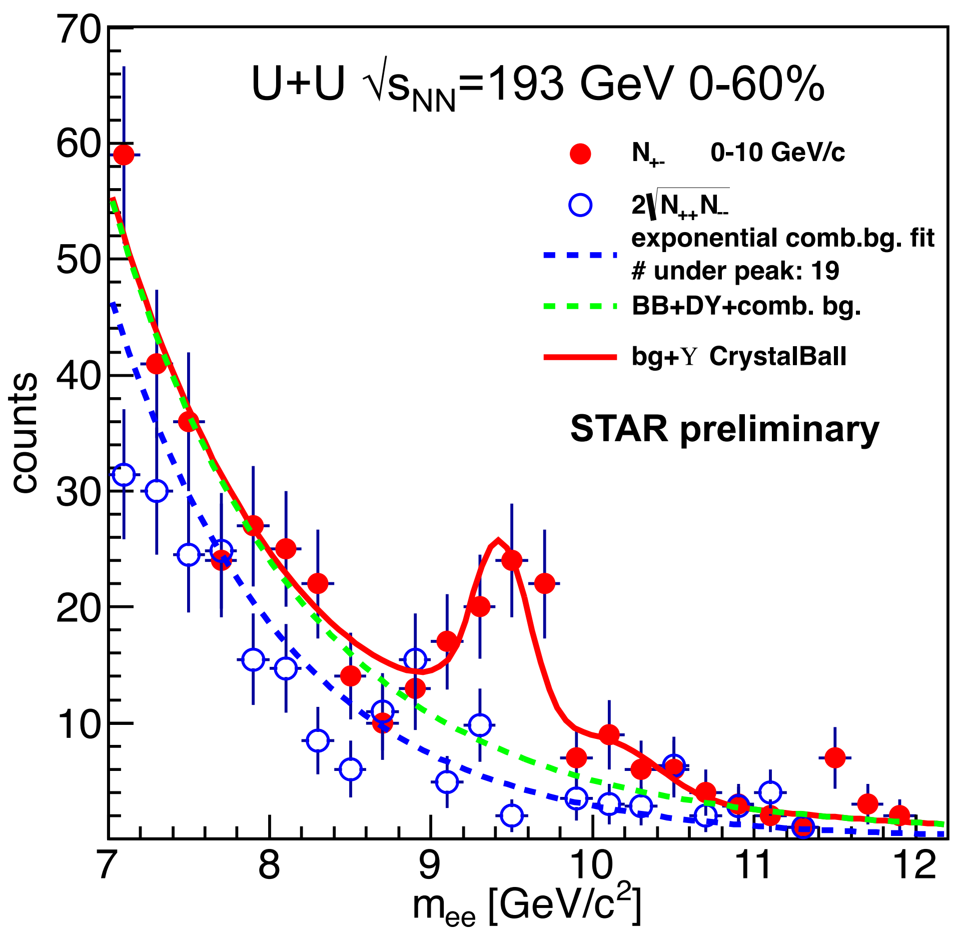




- Cluster energy matches track momentum
  $0.75<E/p<1.4$ *(U+U analysis)*
- Energy deposit is compact, mostly in a single tower
  triggered $e^{\pm}$: $E_{tower}/E>0.7$, associated $e^{\pm}$: $E_{tower}/E>0.5$ *(U+U analysis)*

Peak extraction (U+U example)

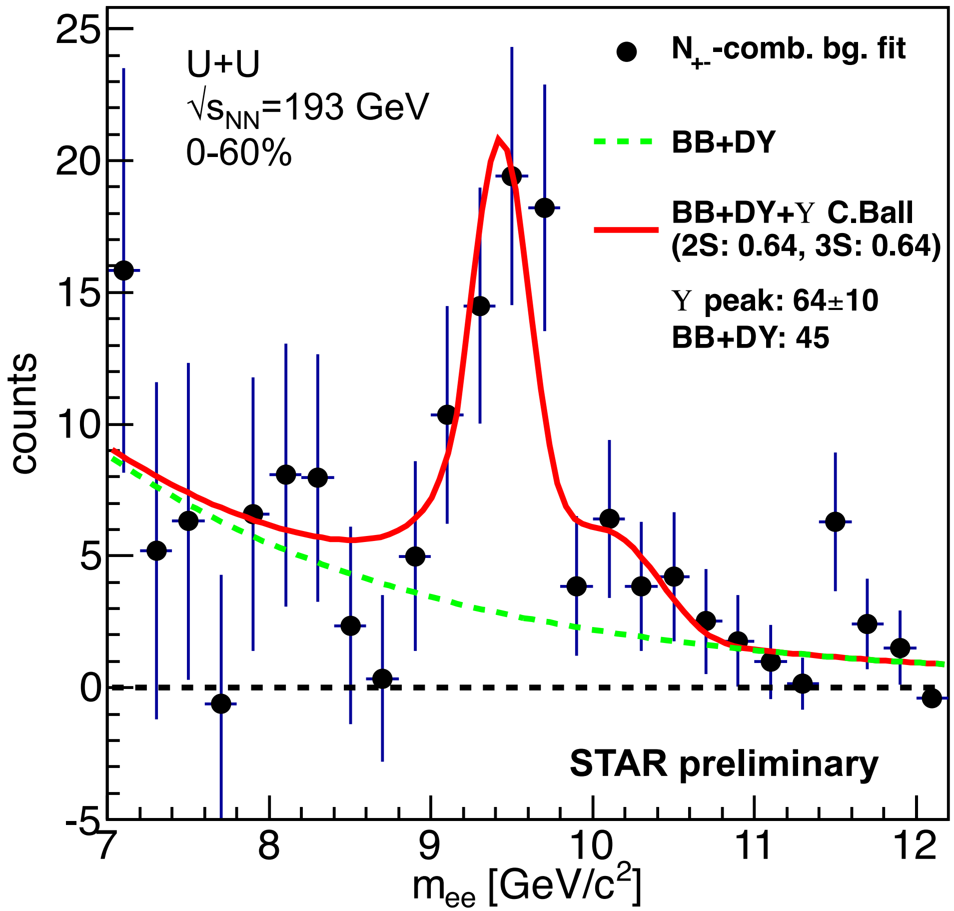
e⁺e⁻ pair invariant mass



- Combinatorial background is fitted with exponential, then subtracted

Peak extraction (U+U example)

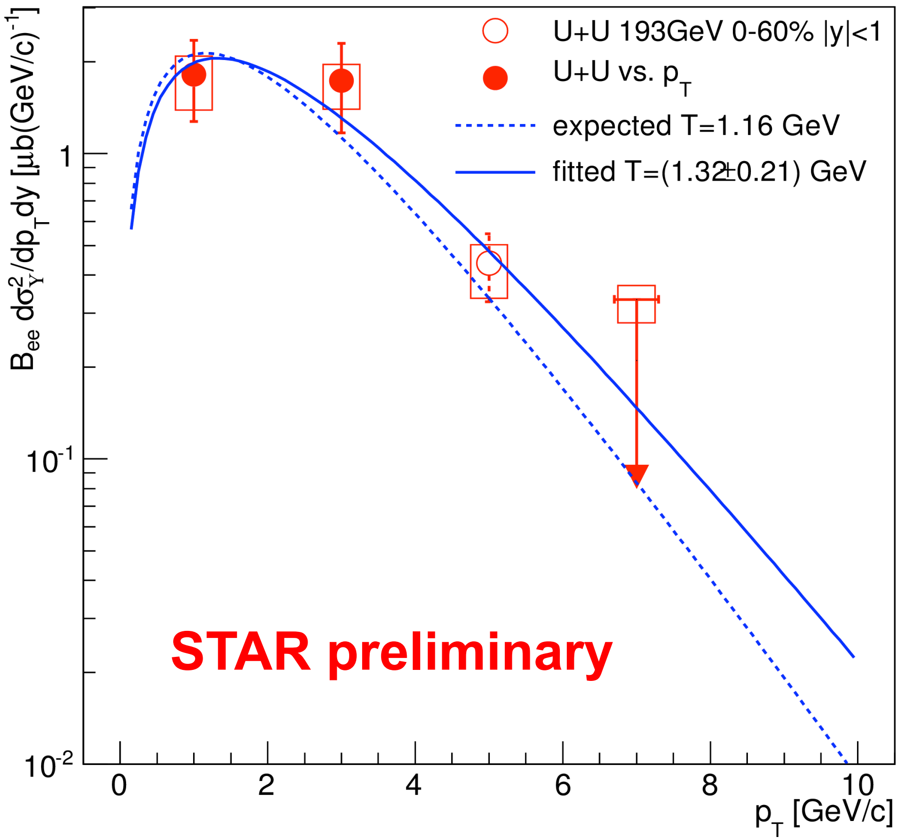
comb. bg subtracted
e^+e^- pair invariant mass



- Combinatorial background is fitted with exponential, then subtracted
- Shape of Drell-Yan is from pQCD calculations; open $b\bar{b}$ contribution is from PYTHIA
- ϒ peak shape is from embedded MC simulation
- Normalization of ϒ peak and Drell-Yan+$b\bar{b}$ is fitted simultaneously

Note: log-likelihood method applied in the fits

ϒ x-section and p_T-spectrum in U+U



$$f(p_T) = \frac{p_T}{\exp(p_T / T + 1)}$$

Expected T is extrapolated from ISR, CDF and CMS pp ($p\bar{p}$) results

PLB91, 481 (1980).
PRL88, 161802 (2002).
PRD83, 112004 (2011)

ϒ cross section (STAR preliminary)

U+U 193 GeV, 0-60% centrality

$$B_{ee} \left. \frac{d\sigma^{\Upsilon}_{AA}}{dy} \right|_{|y|<1} = (4.37 \pm 1.09 \; {}^{+0.65}_{-1.01}) \; \mu b$$

stat. syst

Major systematic uncertainties (%) (STAR preliminary)	
Geometrical acceptance	+1.7 -3.0
Trigger efficiency	+1.1 -3.6
Tracking efficiency	11.8
TPC electron identification	+4.0 -6.4
TPC-BEMC matching	5.4
BEMC electron identification	5.9
Embedding p_T and y shapes	2.1
Signal extraction	+4.8 -18

ϒ in p+p and d+Au

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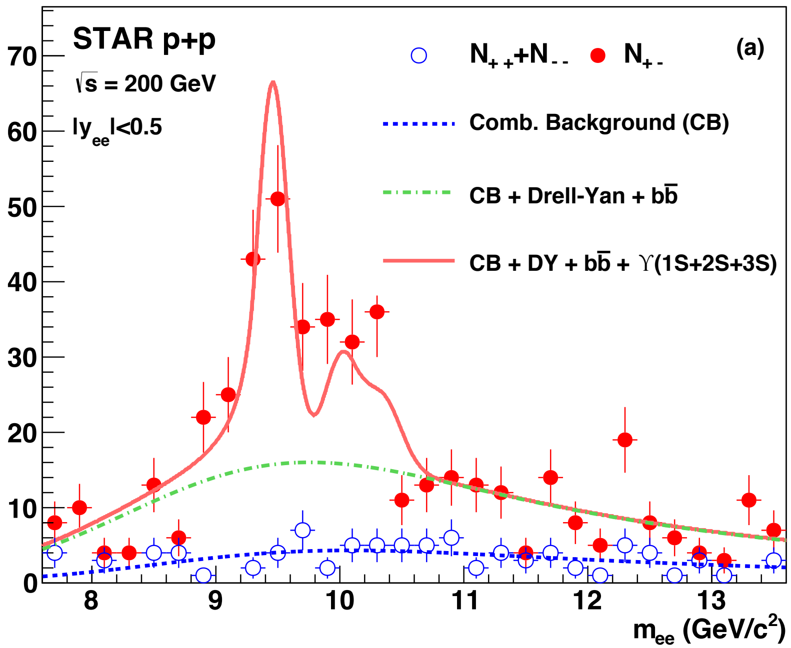

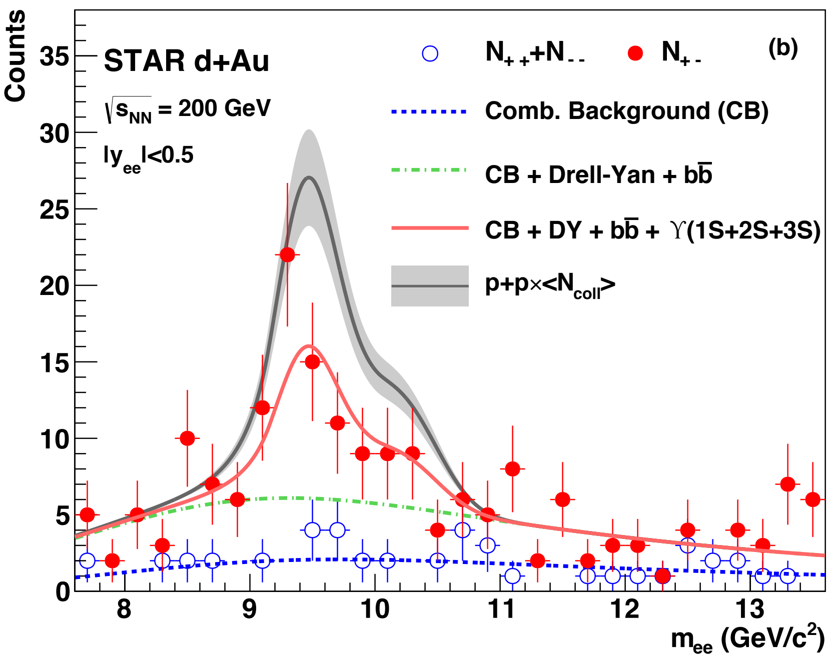

ϒ in p+p 200 GeV, |y|<0.5, L0 & L2

$\int L\,dt$ = 20.0 pb^{-1}

N_Υ(total)= 152 ± 23 (stat. + fit)

$$\sum_{n=1}^{3} \mathcal{B}(n\mathrm{S}) \times \frac{d\sigma(n\mathrm{S})}{dy} = 64 \pm 10^{+14}_{-12}\ \mathrm{pb}$$

ϒ in d+Au 200 GeV, |y|<0.5, L0 & L2

$\int L\,dt$ = 28.1 nb^{-1}

N_Υ(total)= 46 ± 13 (stat. + fit)

$$\sum_{n=1}^{3} \mathcal{B}(n\mathrm{S}) \times \frac{d\sigma(n\mathrm{S})}{dy} = 12.2 \pm 3.4^{+2.1}_{-1.9}\ \mathrm{nb}$$

ϒ in Au+Au

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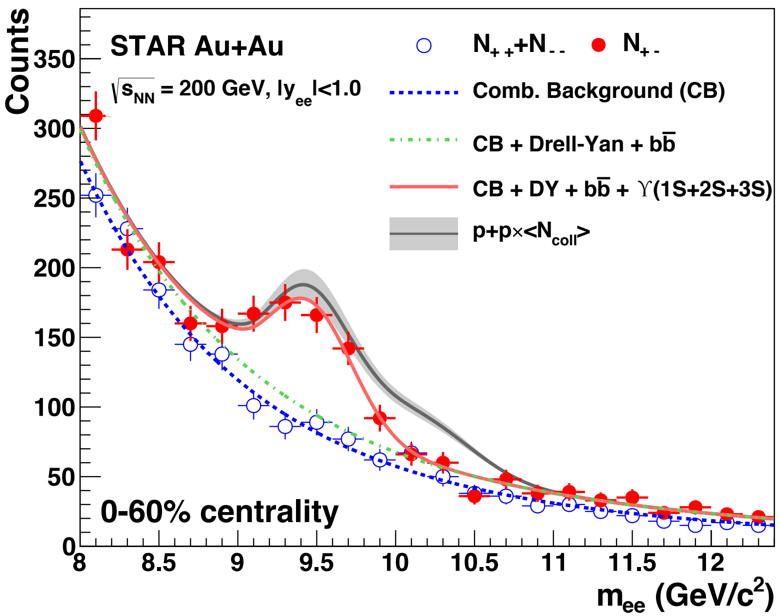
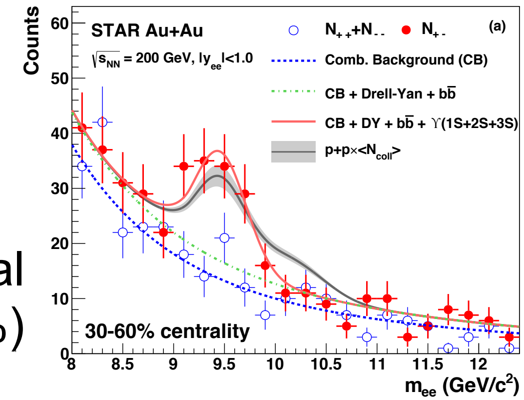


ϒ in Au+Au 200 GeV, |y|<1

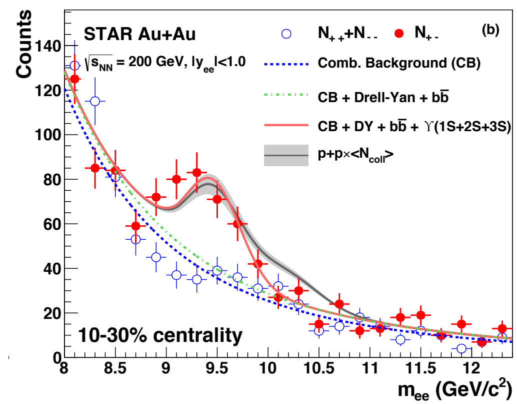
$\int L\,dt$ = 1075 μb^{-1}

N_{Υ} = 254 ± 29

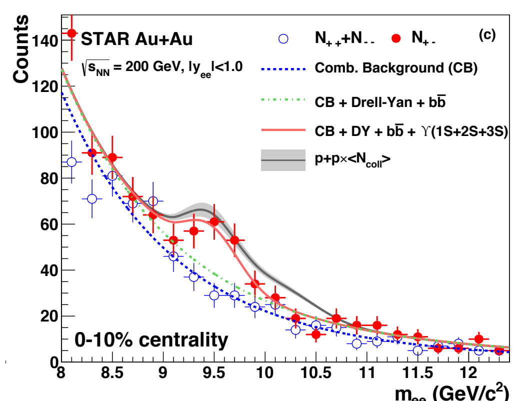
mid-peripheral (30-60%)



mid-central (10-30%)

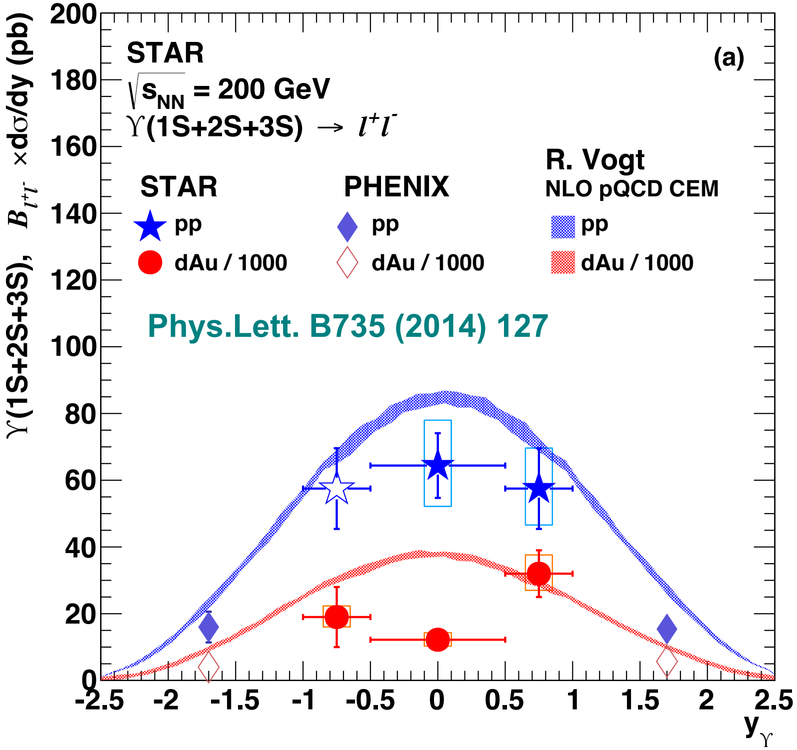


central (0-10%)



centrality bins

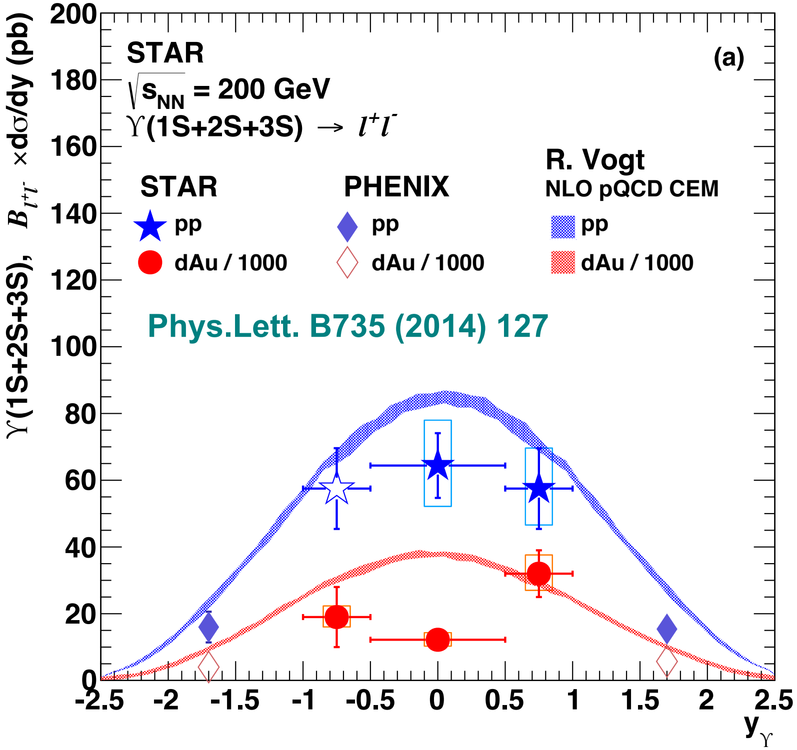
ϒ in p+p – QCD baseline



- p+p ϒ cross section vs. y, compared to pQCD predictions

R. Vogt, Phys. Rep. 462125, 2008

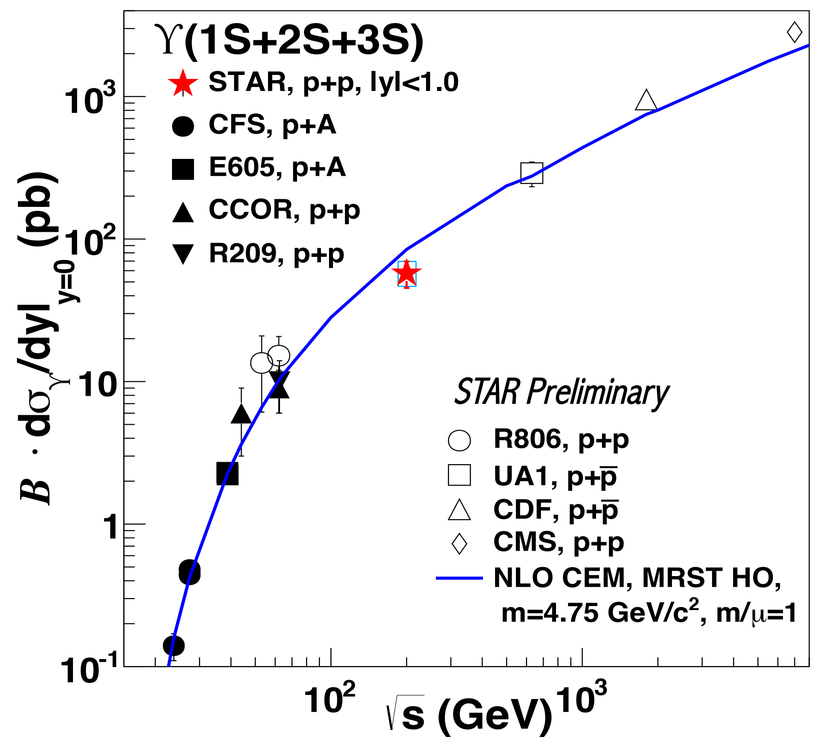
ϒ in p+p – QCD baseline



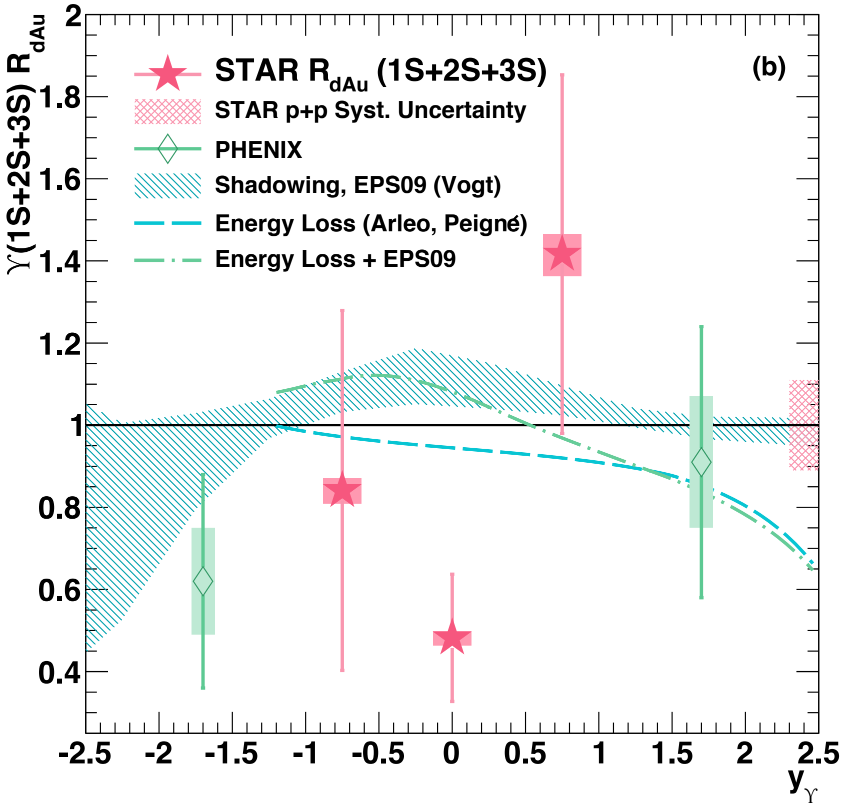
- p+p ϒ cross section vs. y, compared to pQCD predictions

R. Vogt, Phys. Rep. 462125, 2008

- p+p ϒ cross section, compared to world data trend



ϒ R_{dAu} – CNM effects



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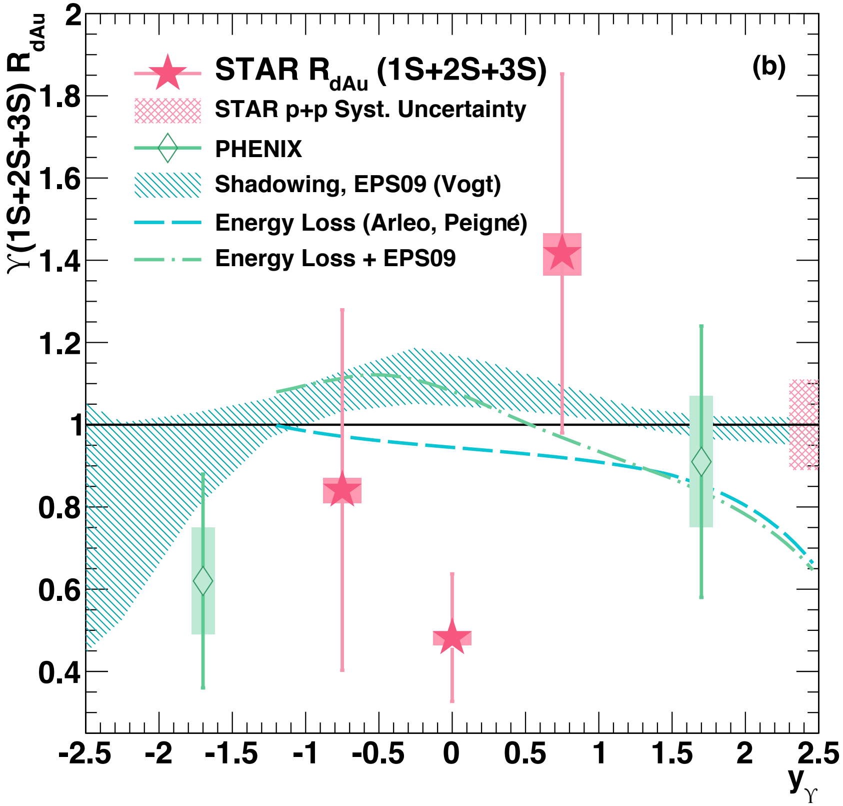
- Models include
  - Gluon nPDF (Anti)shadowing
  - Initial parton energy loss
- Indication of suppression at mid-rapidity beyond models

R_{dAu}=0.48 ± 0.14(stat) ± 0.07(syst) ± 0.02 (pp stat) ± 0.06 (pp syst)

|y|<0.5

ϒ R_{dAu} – CNM effects



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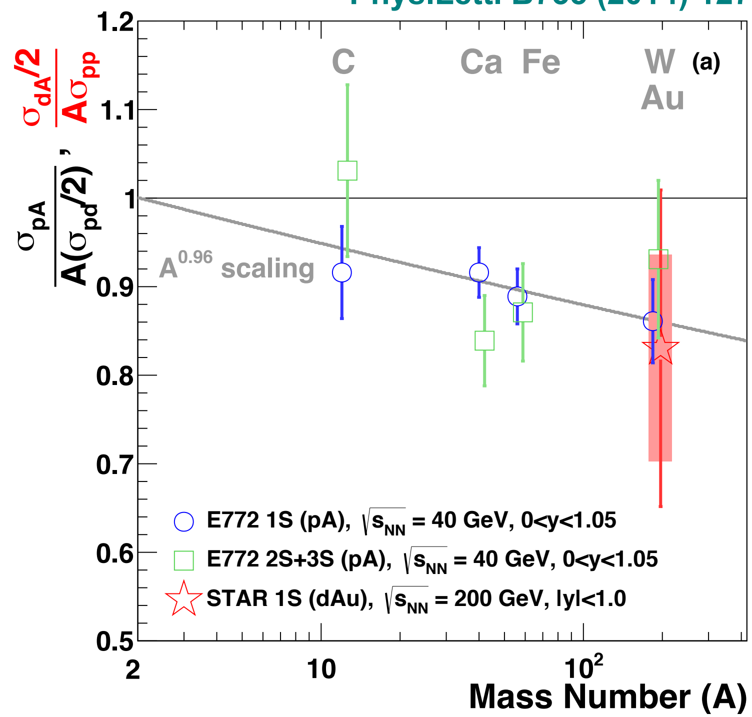
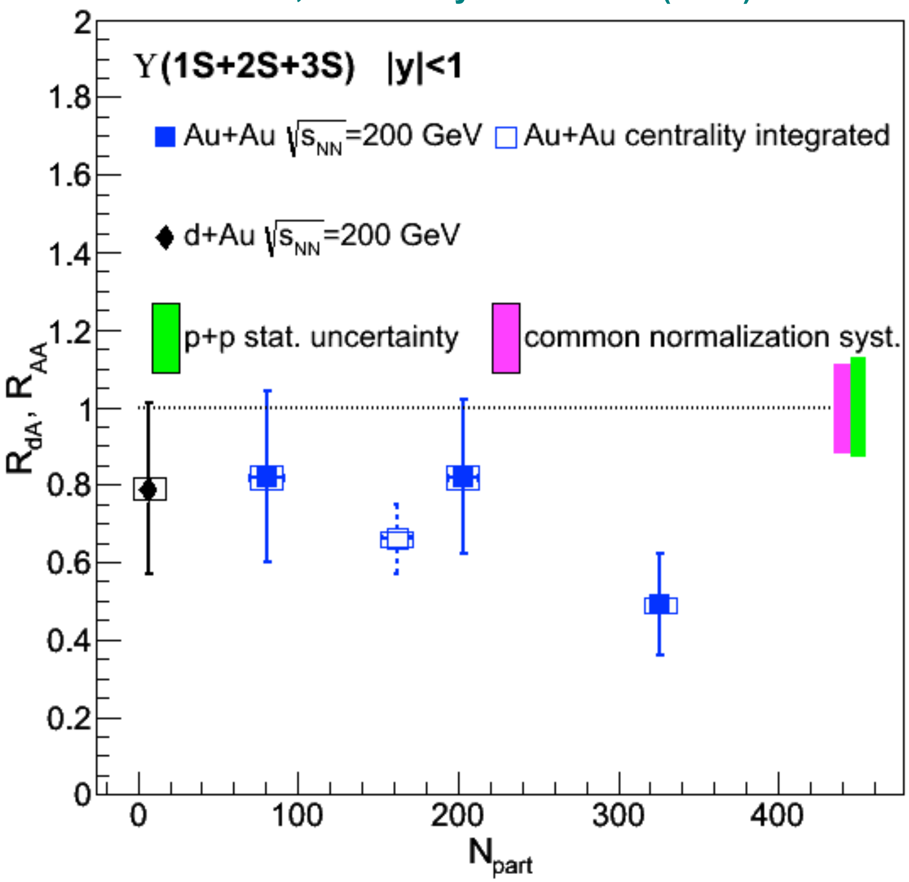


- STAR data consistent with E772

ϒ R_{AA}

Au+Au, d+Au: Phys.Lett. B735 (2014) 127

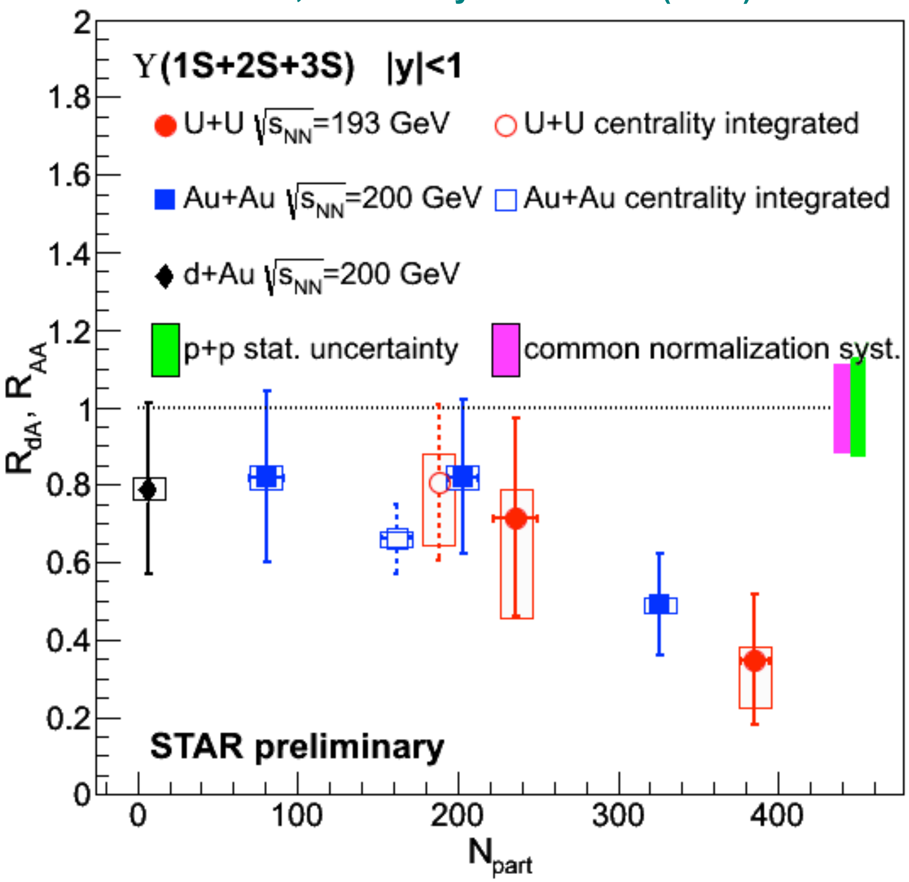


Au+Au data

- Peripheral data and d+Au (|y|<1) is consistent with no suppression
- Significant suppression in central data

ϒ R_{AA}

Au+Au, d+Au: Phys.Lett. B735 (2014) 127



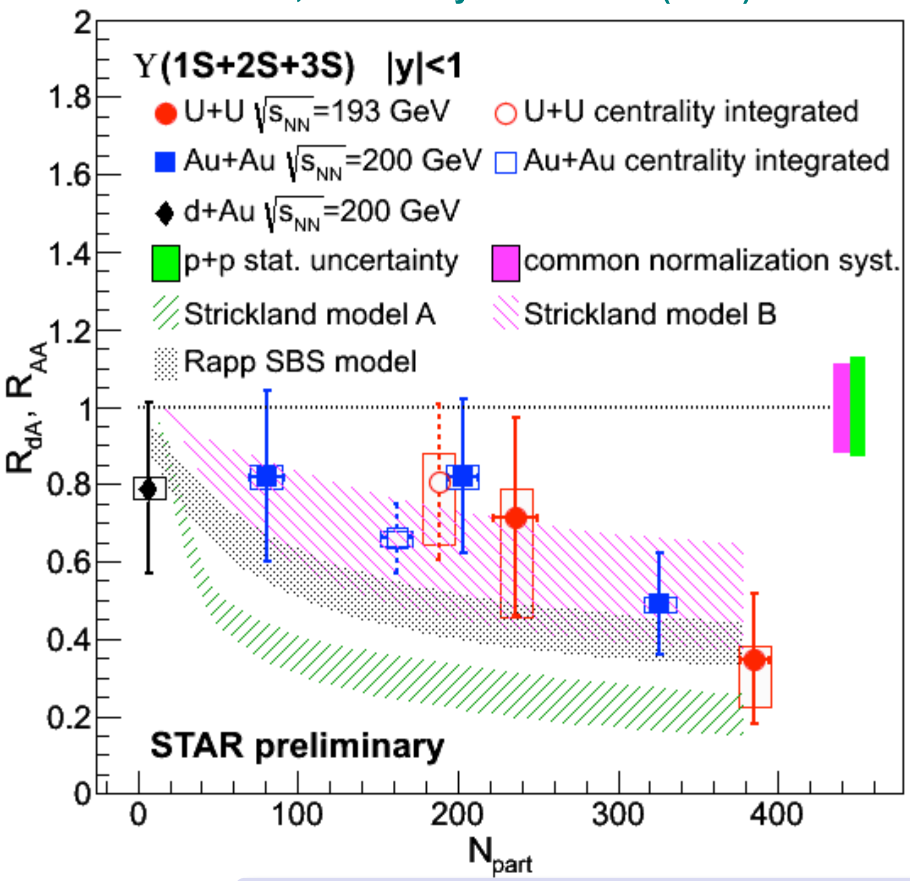
Au+Au and U+U data

- Peripheral data and d+Au (|y|<1) is consistent with no suppression
- Significant suppression in central data

Trend in U+U follows and extends trend in Au+Au

ϒ R_{AA} – data vs. models

Au+Au, d+Au: Phys.Lett. B735 (2014) 127



Model calculations:

- Strong binding scenario, CNM effects included
  Emerick, Zhao, Rapp, Eur. Phys. J A48, 72 (2012)
- Potential model based on heavy quark internal energy 'B' assumes **428 < T < 443 MeV**
  Strickland, Bazov, Nucl. Phys. A879, 25 (2012)
- Potential model based on heavy quark free energy 'A' disfavored

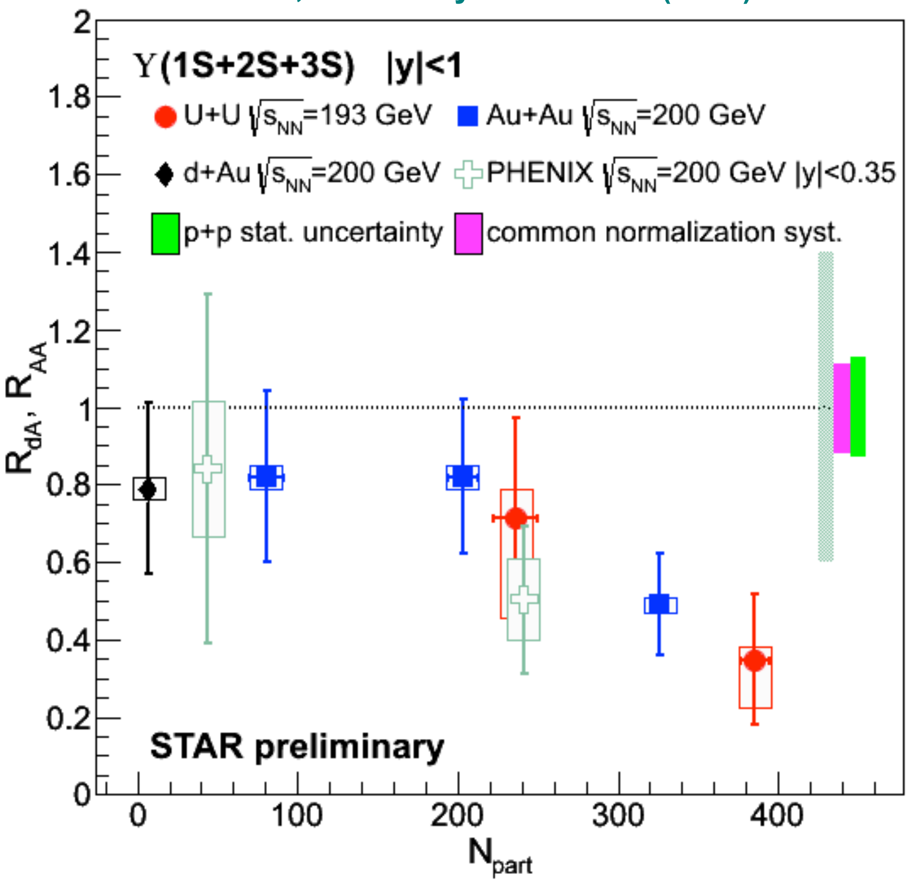
ϒ suppression indicates color deconfinement

However: CNM effects need further study

→ **Planned p+Au run at RHIC for 2015**

ϒ R_{AA} – RHIC comparison

Au+Au, d+Au: Phys.Lett. B735 (2014) 127

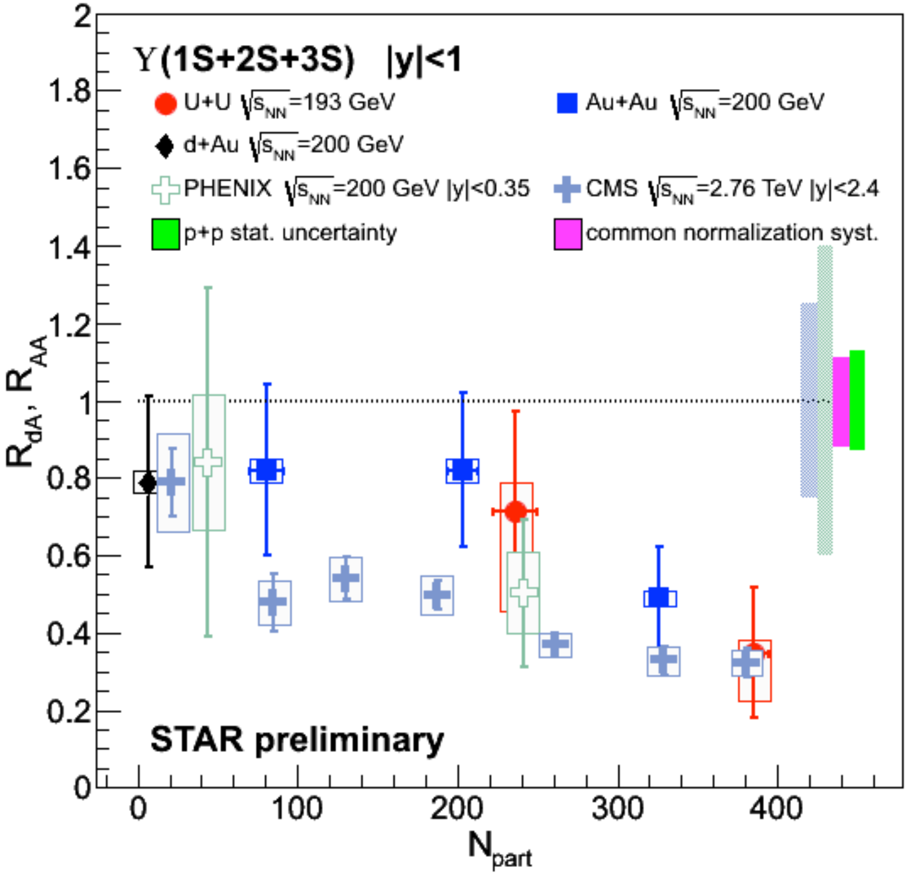


PHENIX Collaboration, arXiv:1404.2246

- STAR vs. PHENIX: data are consistent

ϒ R_{AA} – RHIC & LHC comparison

Au+Au, d+Au: Phys.Lett. B735 (2014) 127



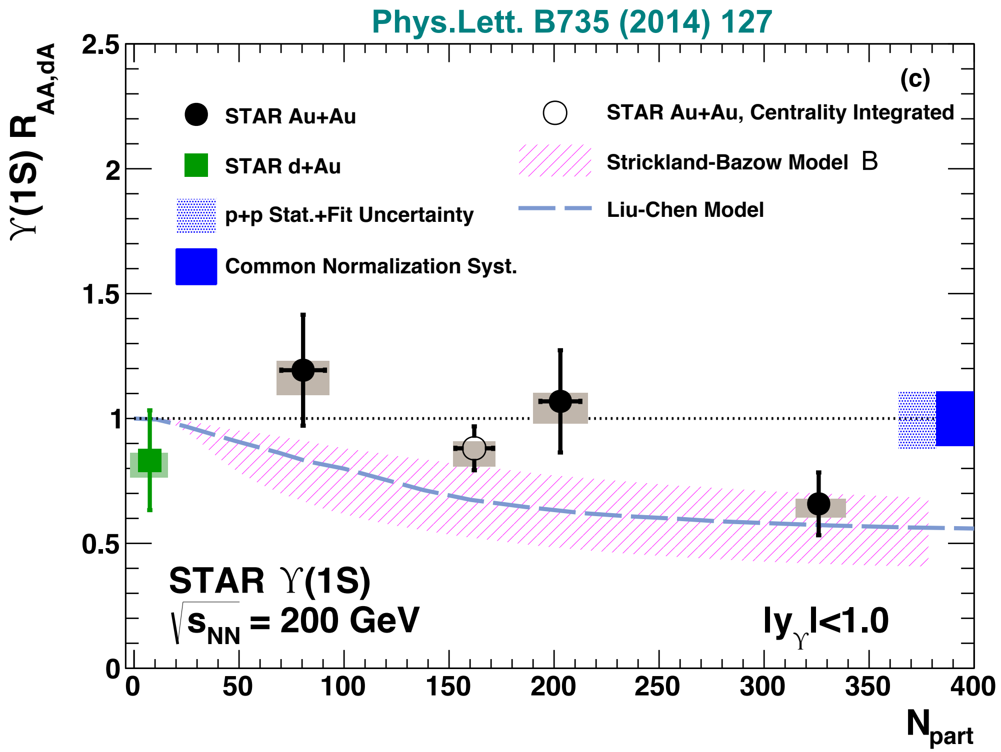
PHENIX Collaboration, arXiv:1404.2246
CMS Collaboration, PRL 109 (2012) 222301

- STAR vs. PHENIX: data are consistent
- RHIC vs. LHC:
  - High-N_{part} suppression comparable at LHC and RHIC
  - Suppression of ϒ appears to be ~flat at LHC

  → is suppression driven by the energy density?

Note the uncertainties, however

ϒ(1S) R_{AA} in Au+Au



Model calculations

- Strickland-Bazov model B: Hot and cold effects
  Nucl. Phys. A879, 25 (2012)
- Liu-Chen model: Dissociation of Quarkonium No CNM effects
  Phys. Lett. B697 (2011) 32

- ϒ(1S) R_{AA} is consistent with unity in d+Au and peripheral and mid-central Au+Au
- Indication of suppression consistent with model calculation in central Au+Au

Excited ϒ states in Au+Au

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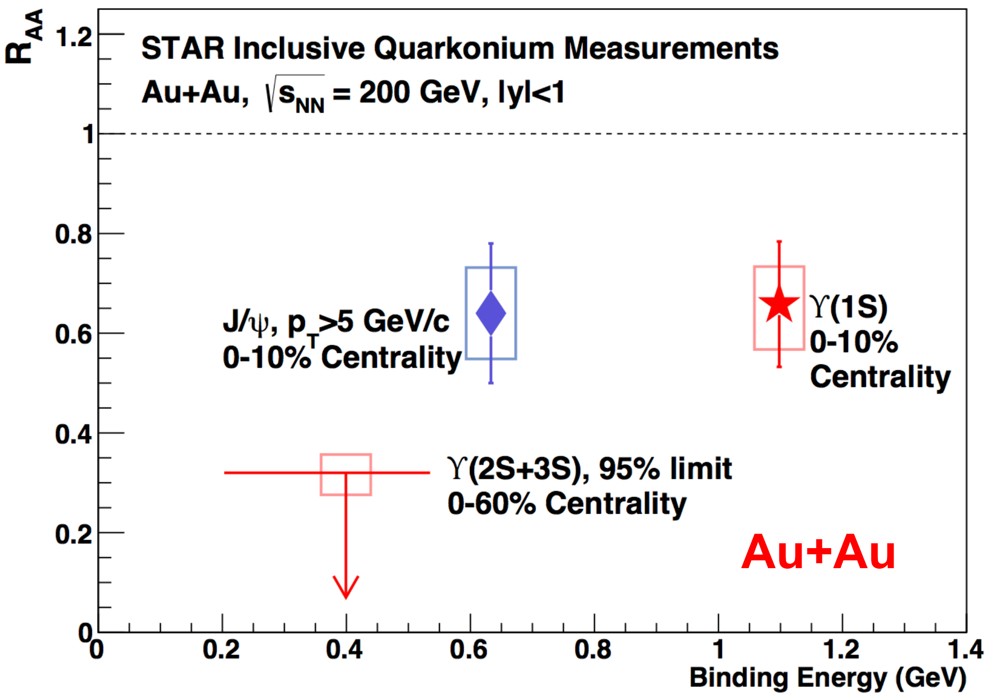

Central Au+Au:

- Excited states ϒ(2S) and ϒ(3S) consistent with complete melting
- ϒ(1S) suppression is similar to high-p_T J/ψ

Excited ϒ states in Au+Au

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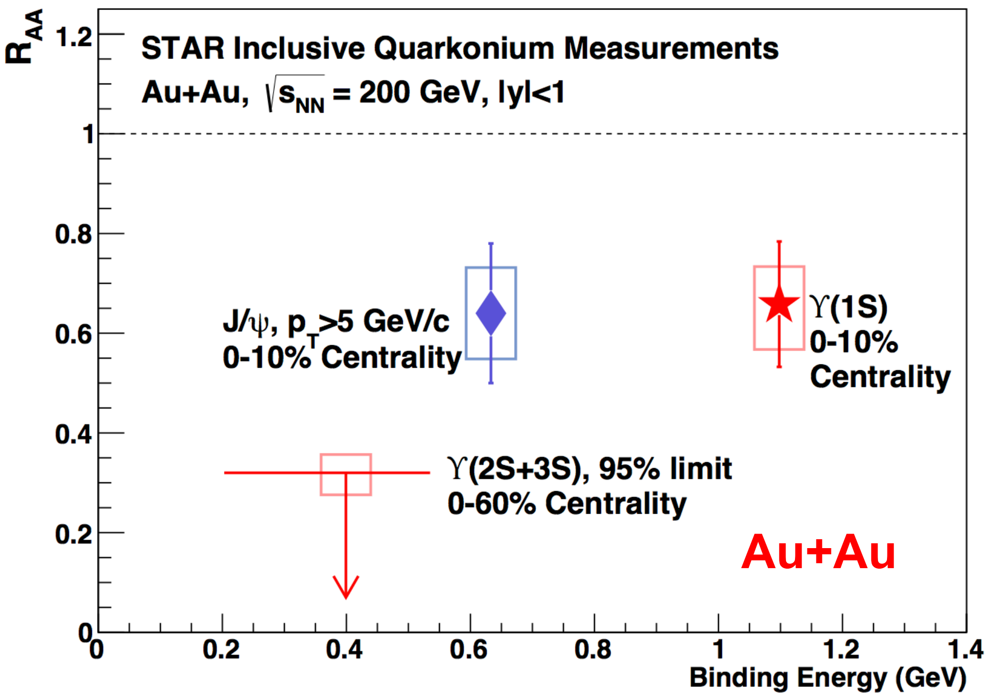
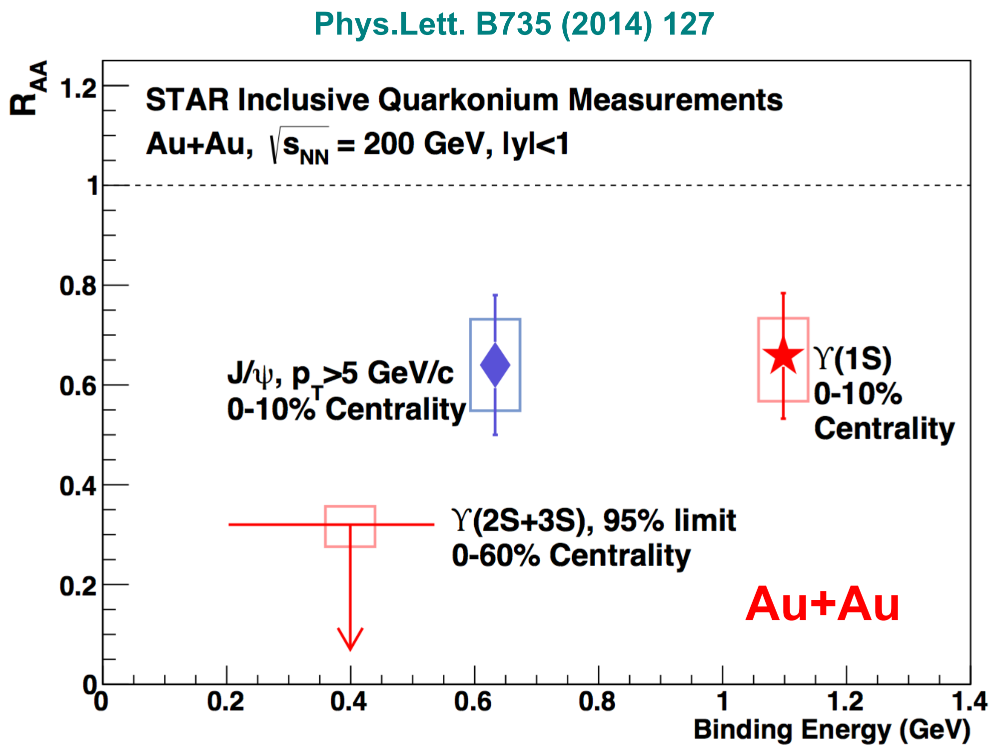


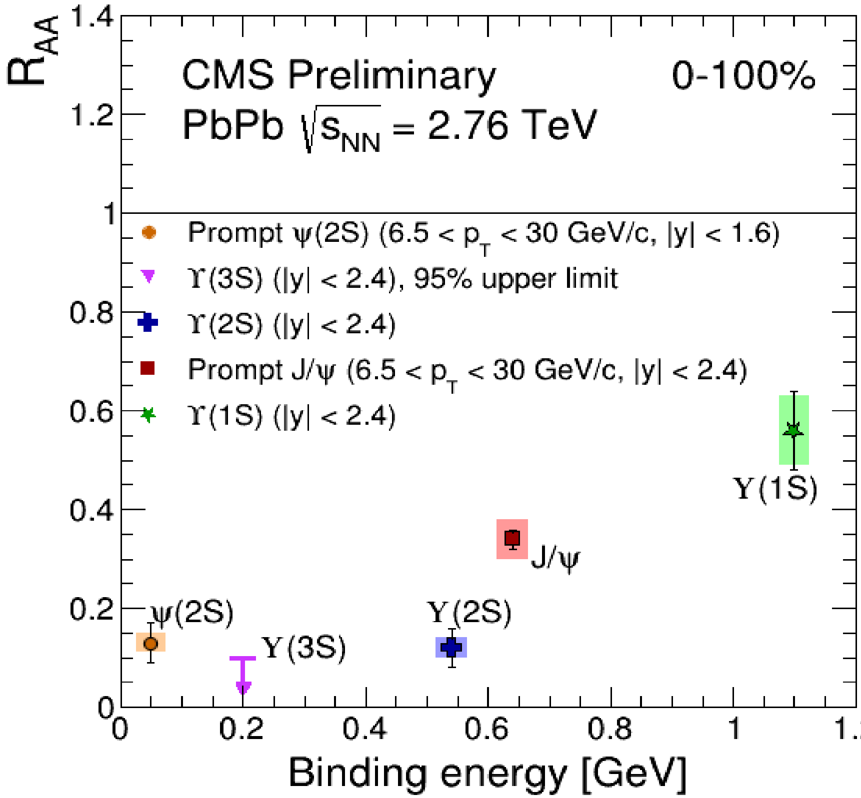
Central Au+Au:

- Excited states ϒ(2S) and ϒ(3S) consistent with complete melting
- ϒ(1S) suppression is similar to high-p_T J/ψ

ϒ suppression pattern supports sequential melting

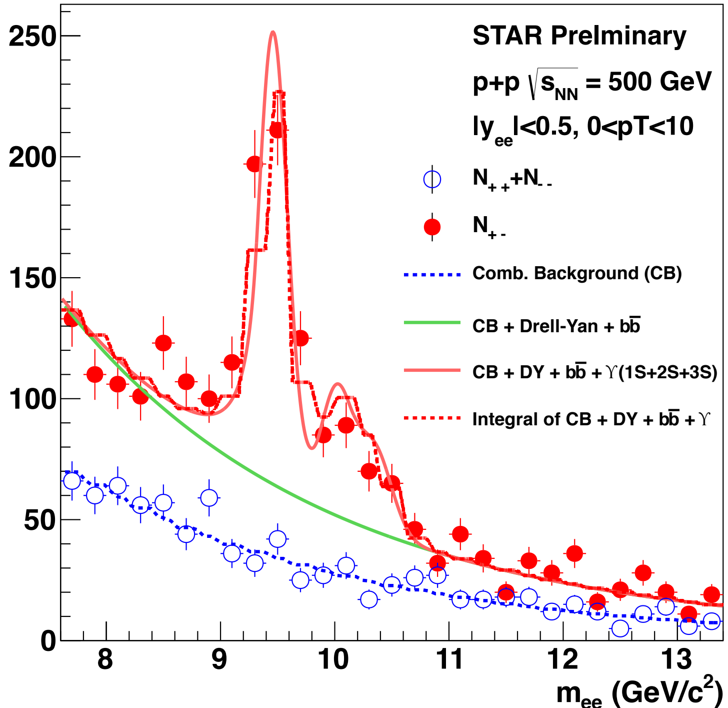
Excited ϒ states – LHC comparison

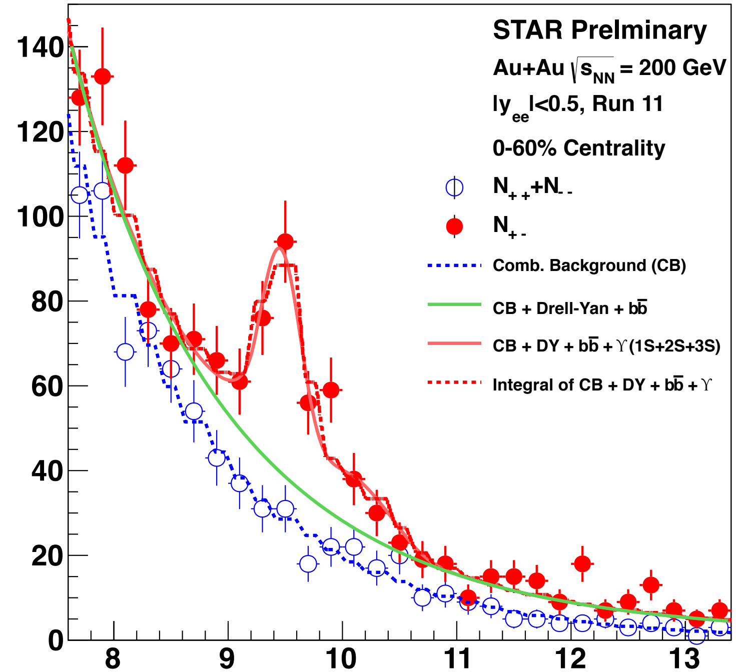




- RHIC $\sqrt{s_{NN}}$=200 GeV Au+Au and LHC $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb collisions: Similar suppression of central ϒ(1S)

Outlook: analyses underway





p+p $\sqrt{s}$=500 GeV, 2011

~ 22 pb^{-1}

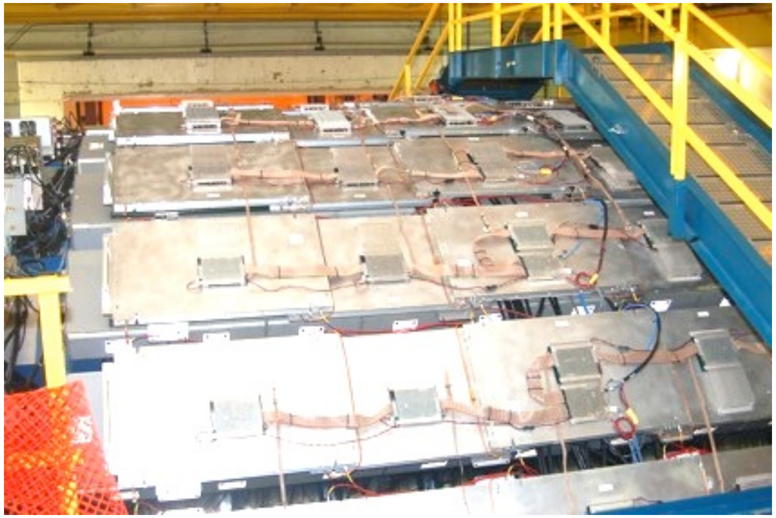
- Double x-section, L0-only
- p_T spectrum
- Excited-to-ground ratio

Au+Au $\sqrt{s_{NN}}$=200 GeV, 2011

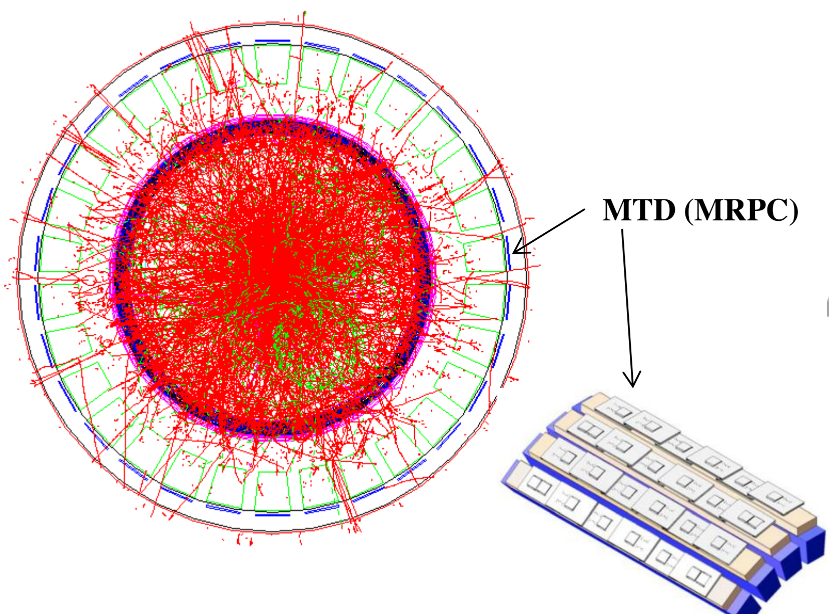
~ 2800 ub^{-1}

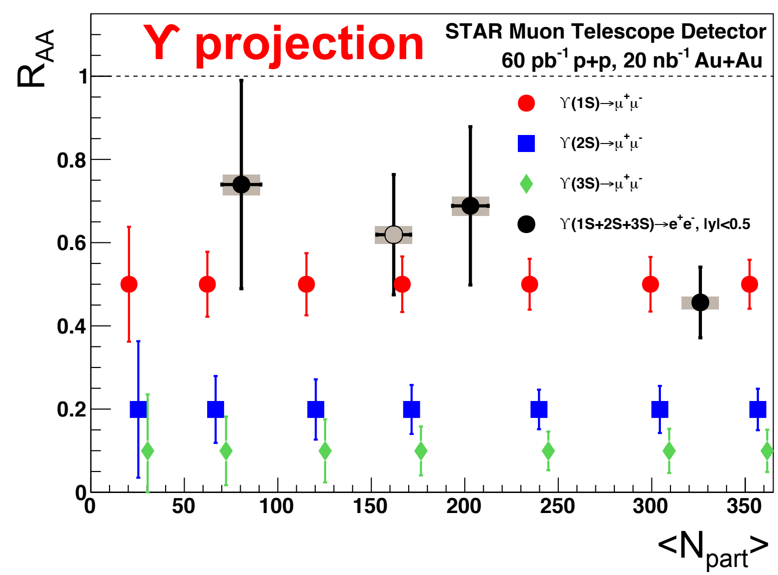
- same setup as in 2010

Outlook: Muon Telescope Detector



- Outermost, gas detector
- Physics goal: **Precision measurement of heavy quarkonia through the muon channel**
- Acceptance:
  45% in azimuth, |y|<0.5





Outlook: Muon Telescope Detector

- Outermost, gas detector
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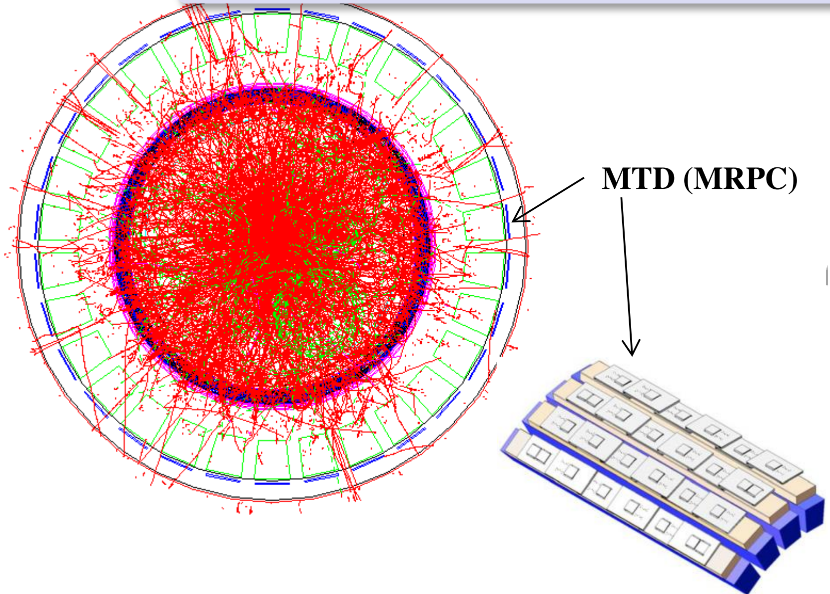
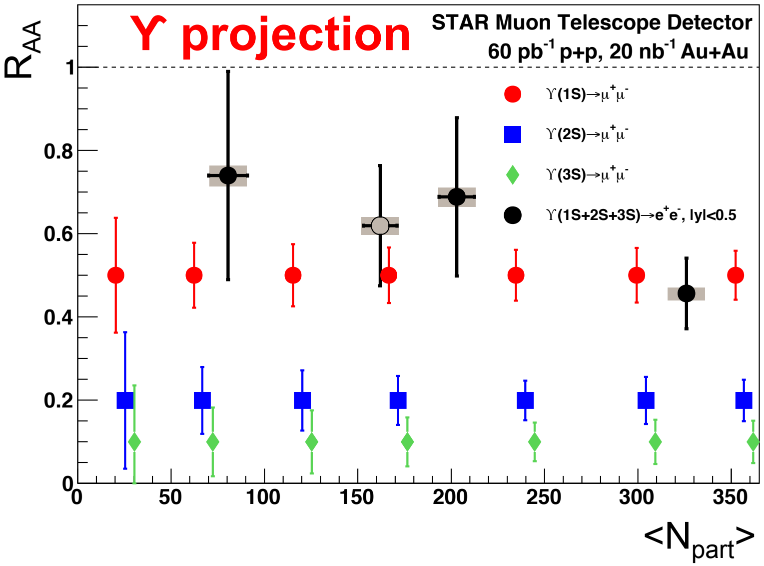
  45% in azimuth, |y|<0.5

Complete in 2014, sampled ~13.8 nb^{-1} in Au+Au data





Summary

- Strong ϒ suppression in $\sqrt{s_{NN}}$=200 GeV central Au+Au data
- New $\sqrt{s_{NN}}$=193 GeV U+U measurement confirms Au+Au trend and extends it to higher N_{part}
- Similar R_{AA} at RHIC and LHC in most central collisions
- Sequential melting: ground state is suppressed, no evidence for surviving excited states in central Au+Au collisions
- Unexpected suppression in mid-rapidity d+Au

CNM effects need further studies → upcoming p+A run

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  CNM effects need further studies → upcoming p+A run

Stay tuned for new $\Upsilon \rightarrow \mu^+\mu^-$ results with MTD

Thank You!

AGH University of Science and Technology
Alikhanov Institute for Theoretical and Experimental Physics
Argonne National Laboratory
Brookhaven National Laboratory
Central China Normal University
Cracow University of Technology
Creighton University
Czech Technical University in Prague
Frankfurt Institute for Advanced Studies (FIAS)
Indian Institute of Technology. Mumbai
Indiana University, CEEM
Institute of High Energy Physics - Beijing
Institute of High Energy Physics - Protvino
Institute of Modern Physics, Lanzhou
Institute of Nuclear Physics PAS
Institute of Physics. Bhubaneswar
Instituto de Fisica da Universidade de Sao Paulo
Joint Institute for Nuclear Research
Kent State University
Korea Institute of Science and Technology Information
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
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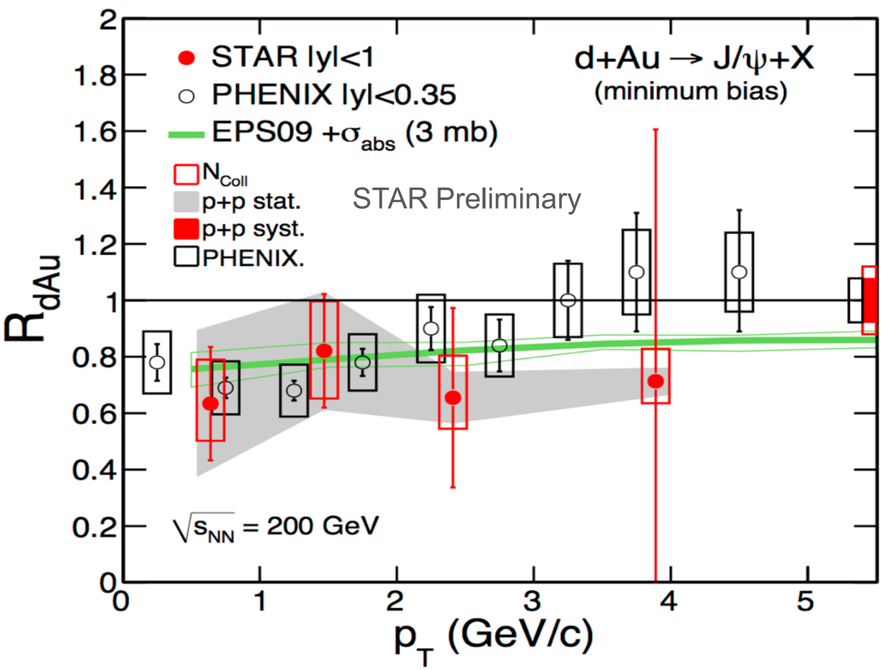
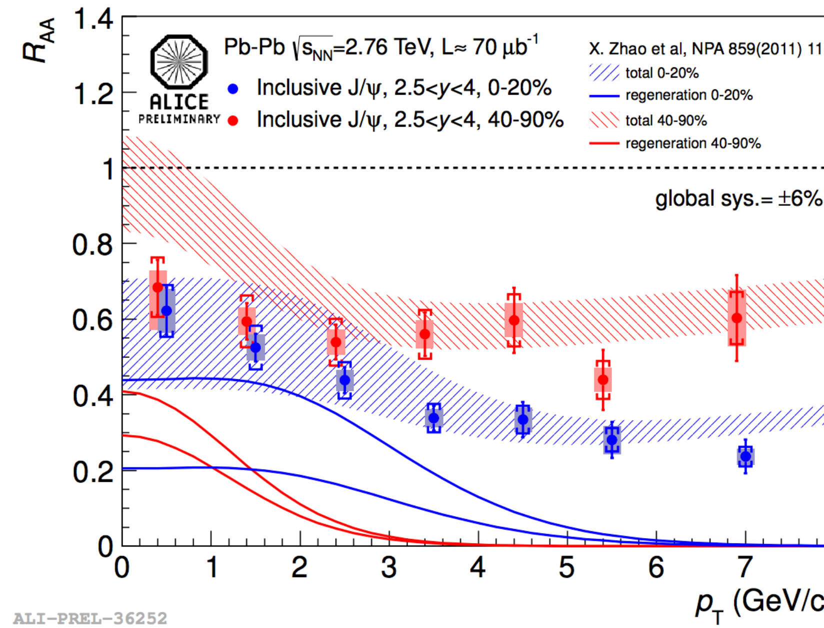
University of Jammu
University of Kentucky
University of Rajasthan
University of Science and Technology of China (USTC)
University of Texas - Austin
University of Washington
University of Zagreb
Valparaiso University
Variable Energy Cyclotron Centre. Kolkata
Warsaw University of Technology
Wayne State University
World Laboratory for Cosmology and Particle Physics (WLCAPP)
Yale University

STAR Collaboration

High-pT J/ψ – motivation





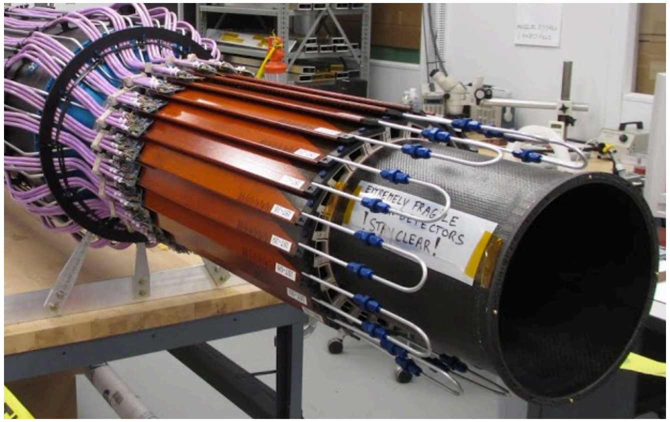
R_{dAu} ~ 1 at high P_T
→ CNM effects do not play a strong role

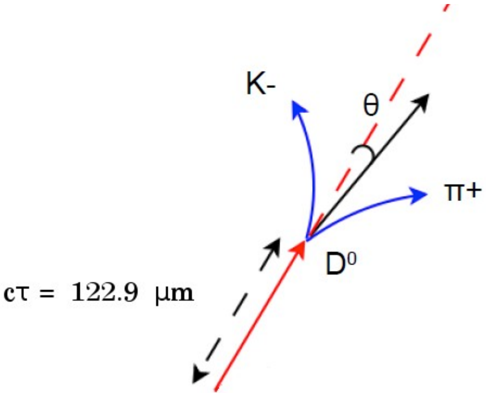
Less regeneration at high P_T

PHENIX data: Phys. Rev. C 87, 034904 (2013)

Model: Eskola, Paukkuenna, Salgado, Nucl.Phys.A830, 599 (2009)

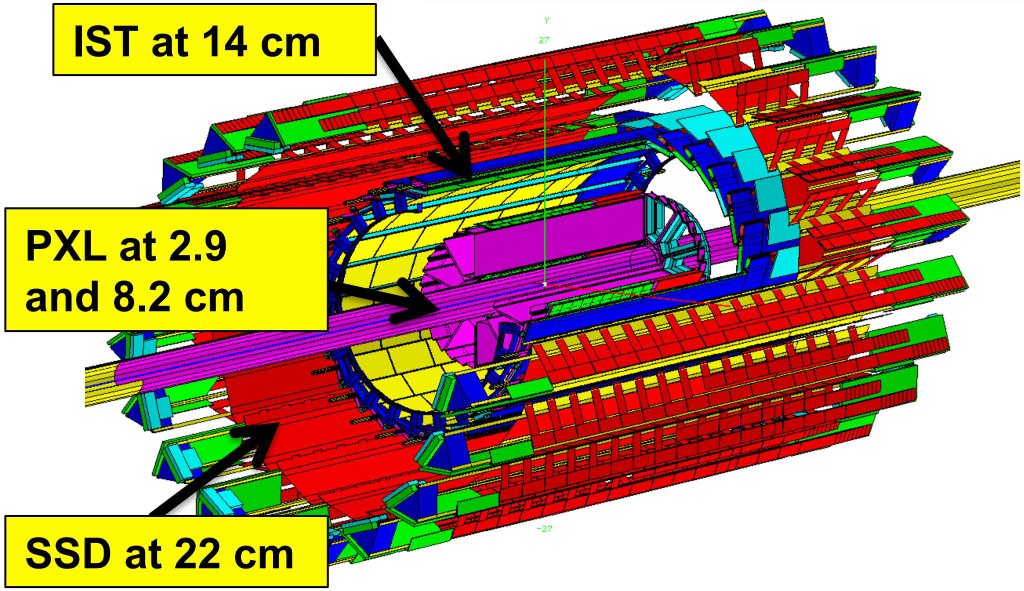
Outlook: Heavy Flavor Tracker

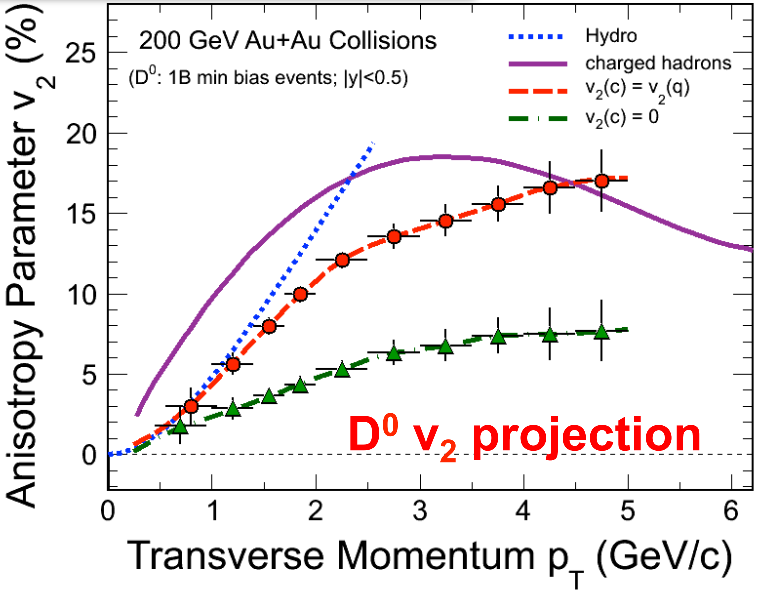




- Innermost, silicon detectors (3 subsystems)
- Resolves secondary vertex
- Physics goal: **Precision measurement of heavy quark production**

Complete and taking data in Run14





Rapp WBS & SBS

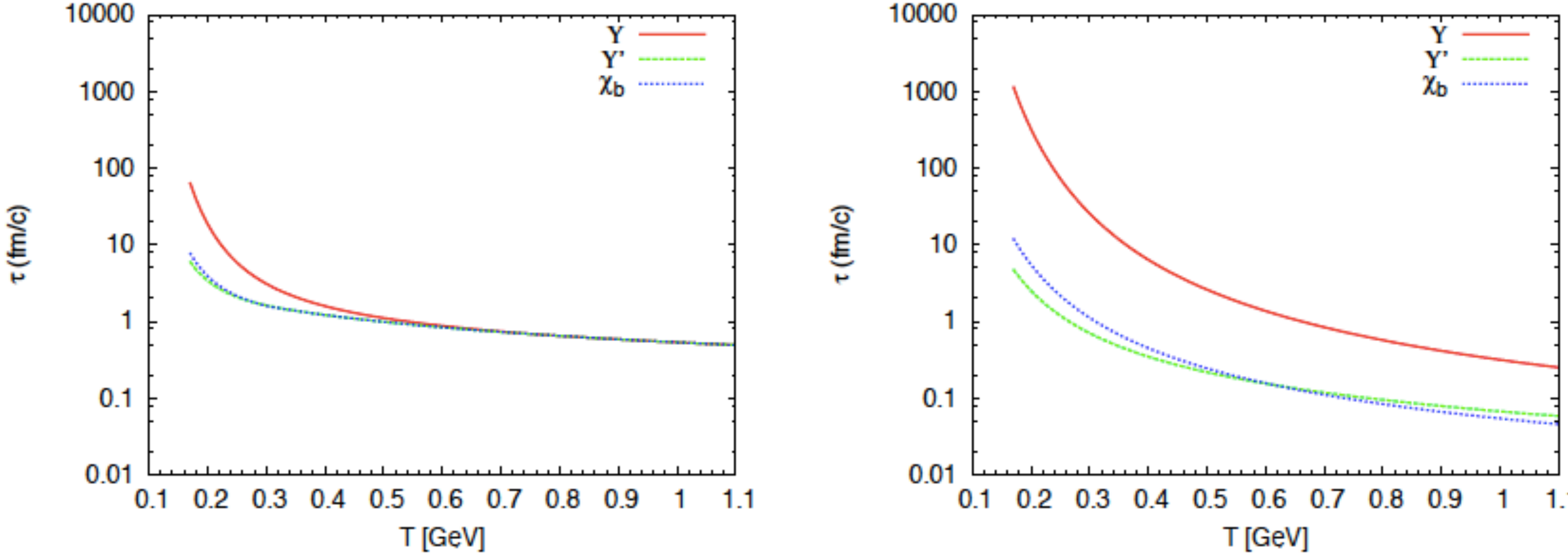
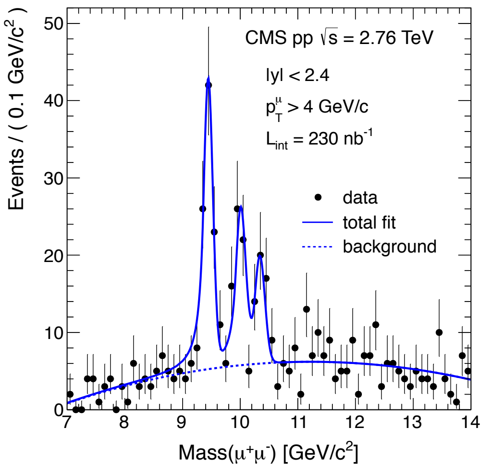
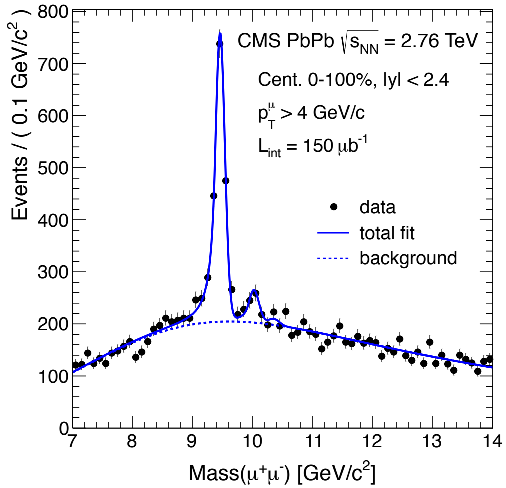


FIG. 2: Bottomonium lifetimes in the QGP for the two binding scenarios defined in the text; left panel: WBS with quasifree dissociation; right: SBS with gluo-dissociation; solid lines: Υ, dashed lines: Υ', dotted lines: χ_b.

- **Emerick, Zhao, Rapp, Eur. Phys. J A48, 72 (2012)**

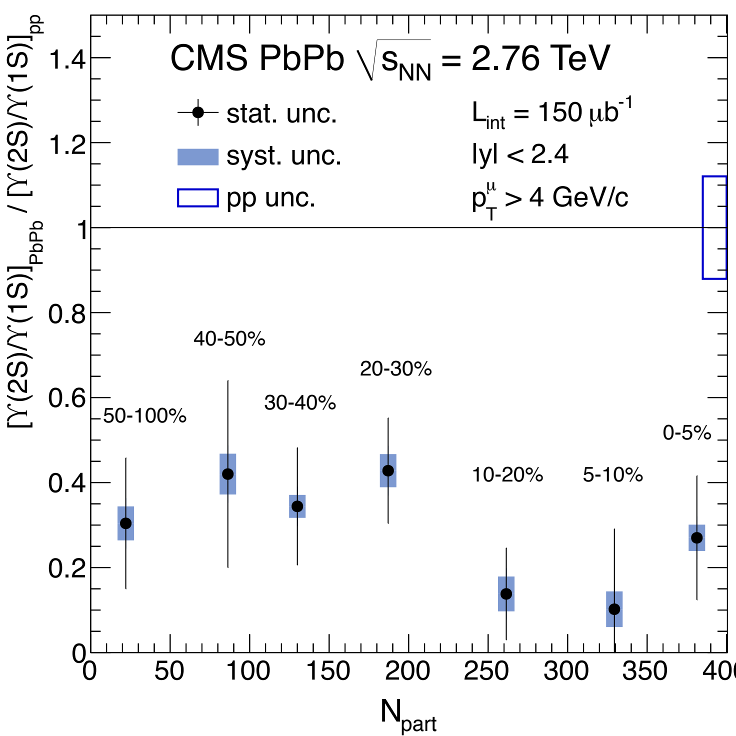
CMS

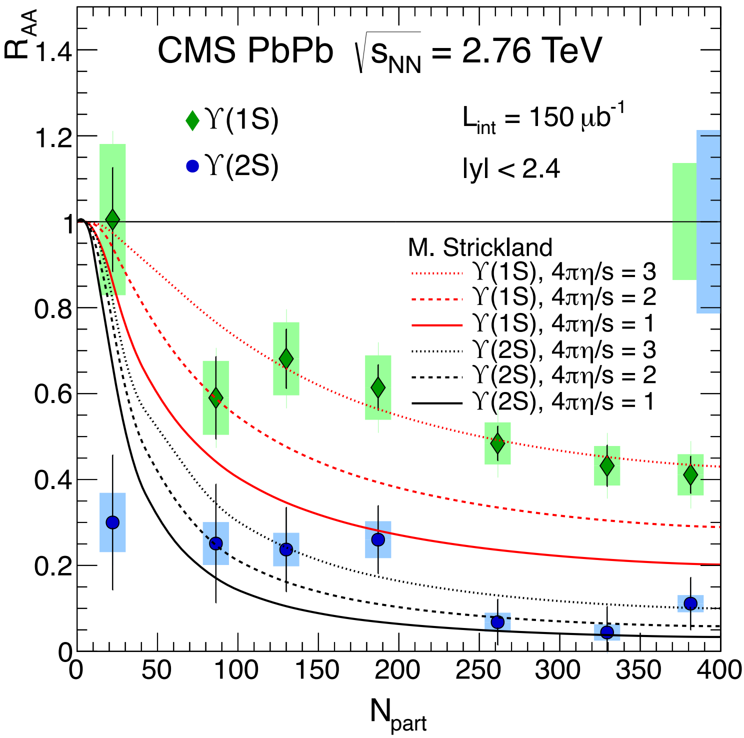




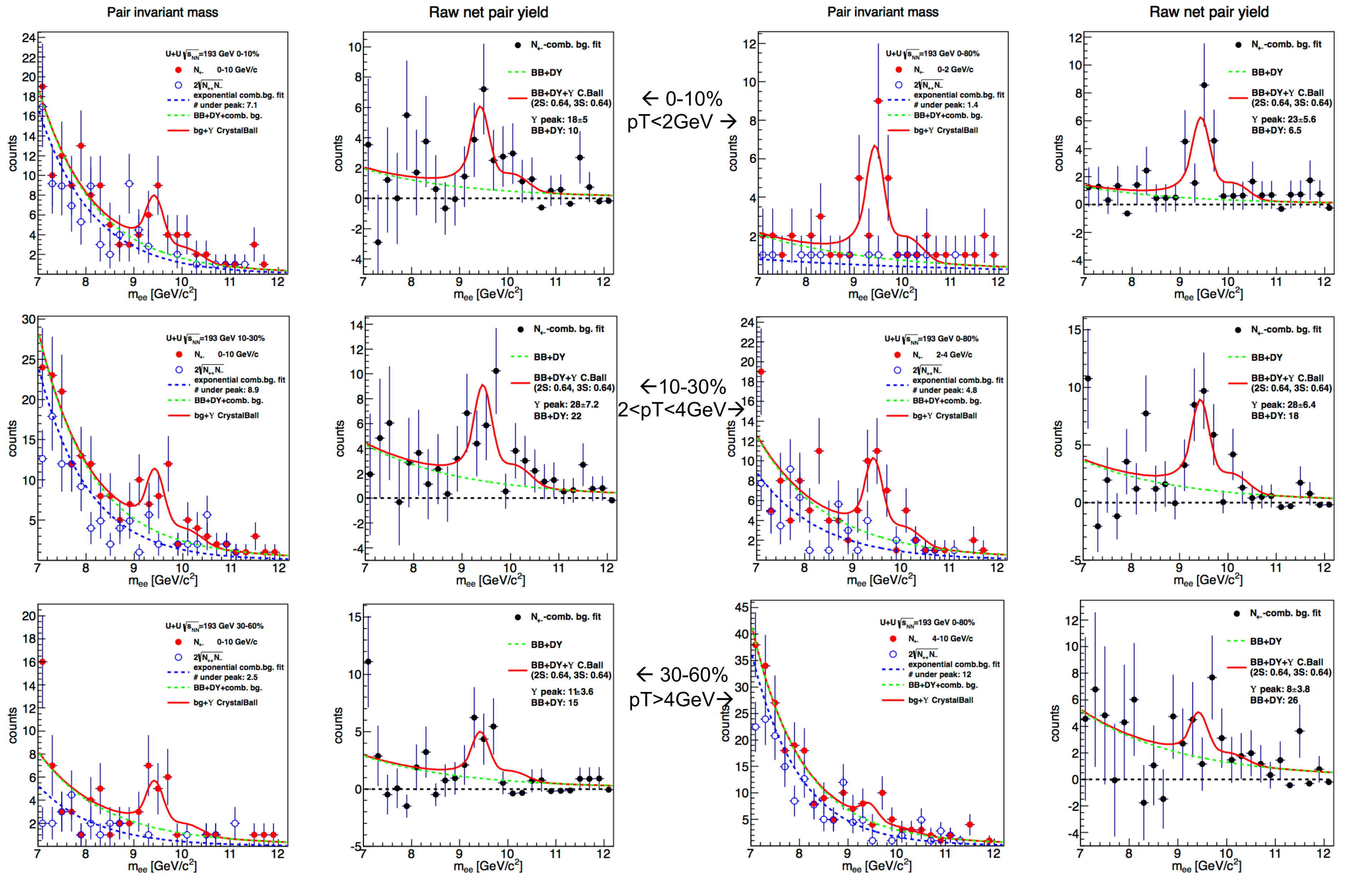
CMS Collaboration, PRL 109 (2012) 222301

- CMS 2.76 TeV Pb+Pb



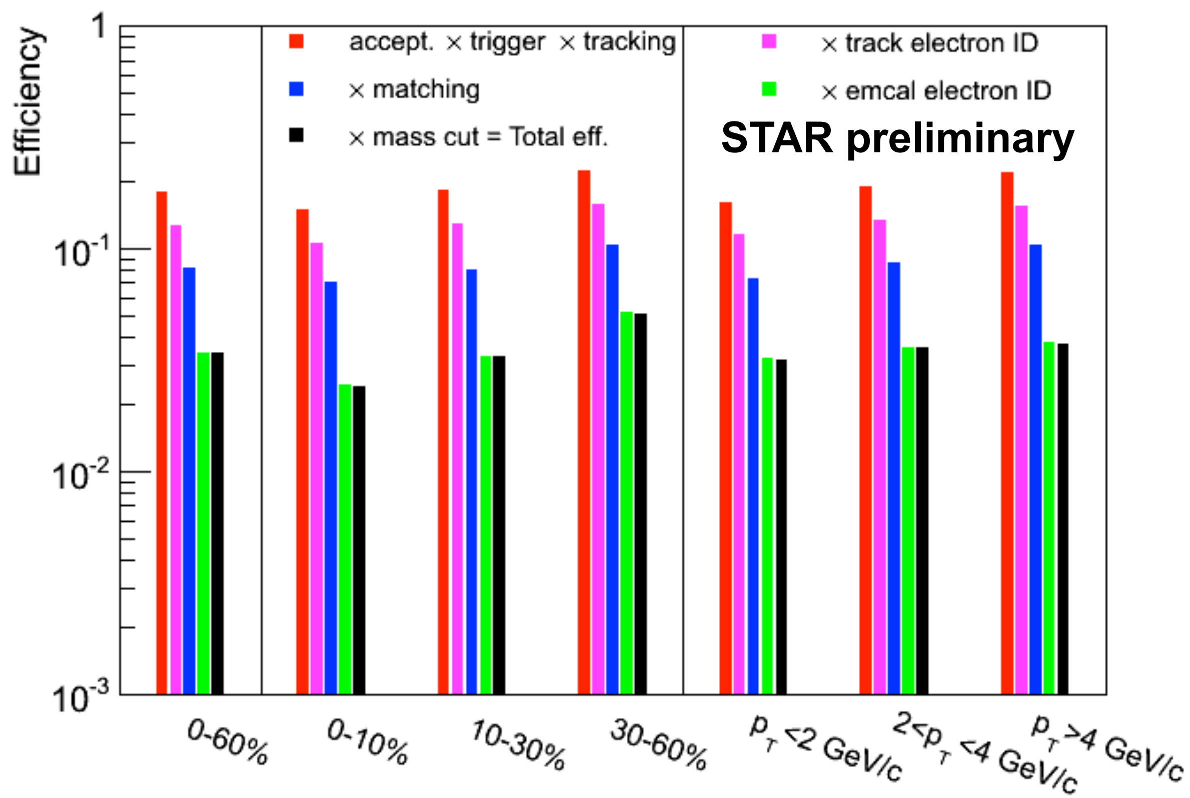


Peak extraction



U+U acceptance and efficiency

- 15M high-tower-triggered U+U 193 GeV events (263 μb^{-1})
- Divided into 3 centrality bins:
  - 0 – 10 %
  - 10 – 30 %
  - 30 – 60 %
- or… 3 bins in p_T^{Υ}:
  - 0 – 2 GeV/c
  - 2 – 4 GeV/c
  - 4< GeV/c



- Total acceptance & efficiency for $\Upsilon \rightarrow e^+e^-$ reconstruction: ~ 2-3%

Nuclear modification

- p+p : pQCD baseline
- Nuclear modification factor ($R_{dA,AA}$)

$$R^{\Upsilon}_{dA,AA} = \frac{1}{\langle N_{coll} \rangle} \frac{N^{\Upsilon}_{dA,AA} \varepsilon^{-1}_{dA,AA}}{N^{\Upsilon}_{pp} \varepsilon^{-1}_{pp}}$$

- d+Au: generally considered as proxy for CNM
- A+A: hot nuclear matter effects – sQGP

R_{AA}=1 if no modification by the medium