BES II and Future Dilepton Measurements at STAR

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TU Darmstadt, Germany

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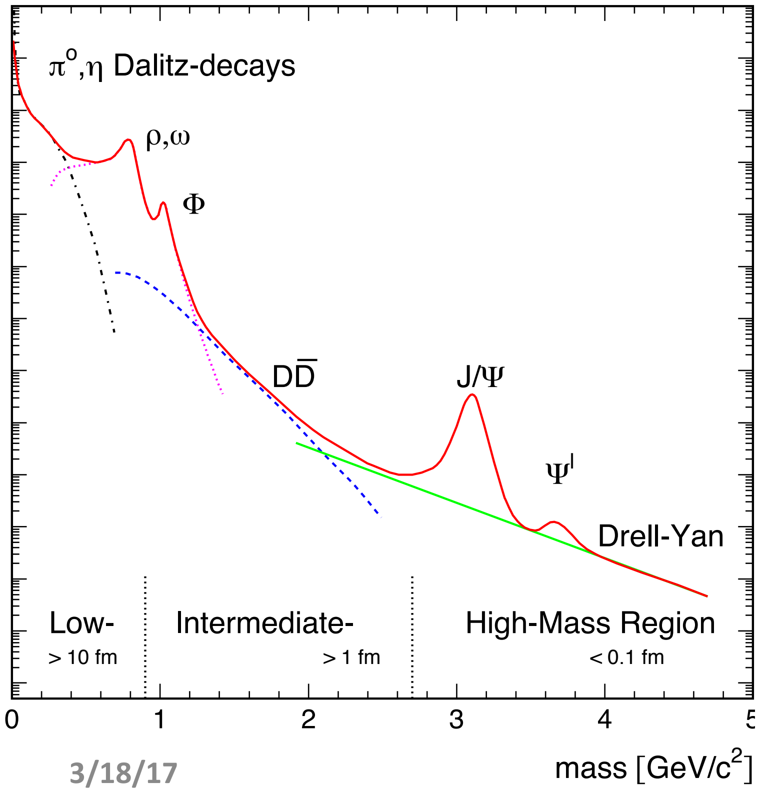
Outline

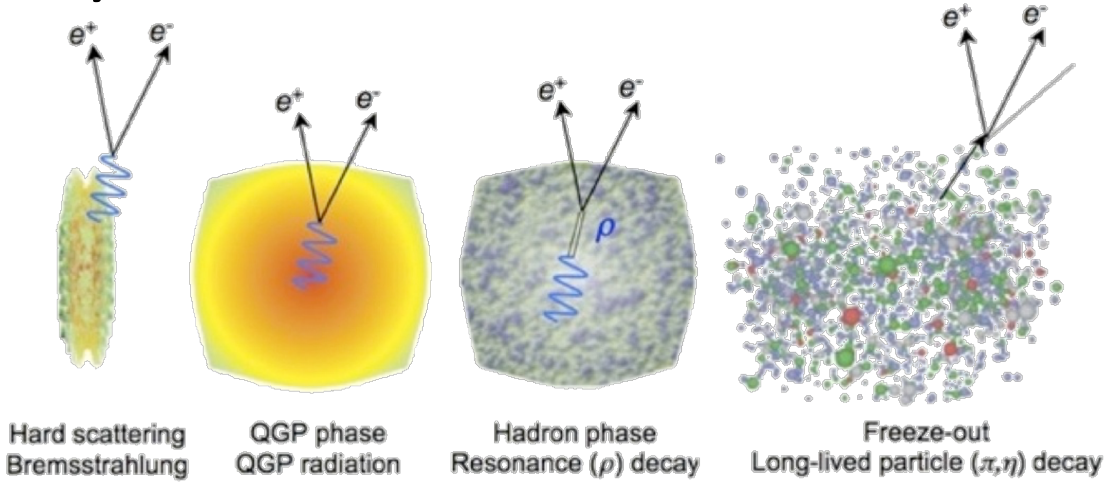
- Motivation for dilepton physics at STAR
- Dileptons results in Beam Energy Scan Phase I
- Beam Energy Scan Phase II
  - Physics goals
  - Detector upgrades
- Near future dilepton studies at STAR
  - Measurement of $\mu^+\mu^-$ continuum at STAR
  - Studies of correlated charm in IMR
  - Low p_T dilepton pairs in Isobar collisions
- Summary

Motivation for Dilepton Physics at STAR

Dileptons provide an excellent penetrating probe of the medium

- Leptons have low interaction cross section with QGP medium – they carry information to the final state
- Dilepton pairs are created throughout the entire lifetime of the system





Low Mass Range (LMR) M_{ll} < 1.1 GeV/c^2

- In-medium modification of vector mesons
- Link to chiral symmetry restoration

Intermediate Mass Range (IMR) 1.1 < M_{ll} < 3.0 GeV/c^2

- Dominant contribution from semi-leptonic correlated charm decays
- QGP thermal radiation

High Mass Range (HMR) M_{ll} > 3.0 GeV/c^2

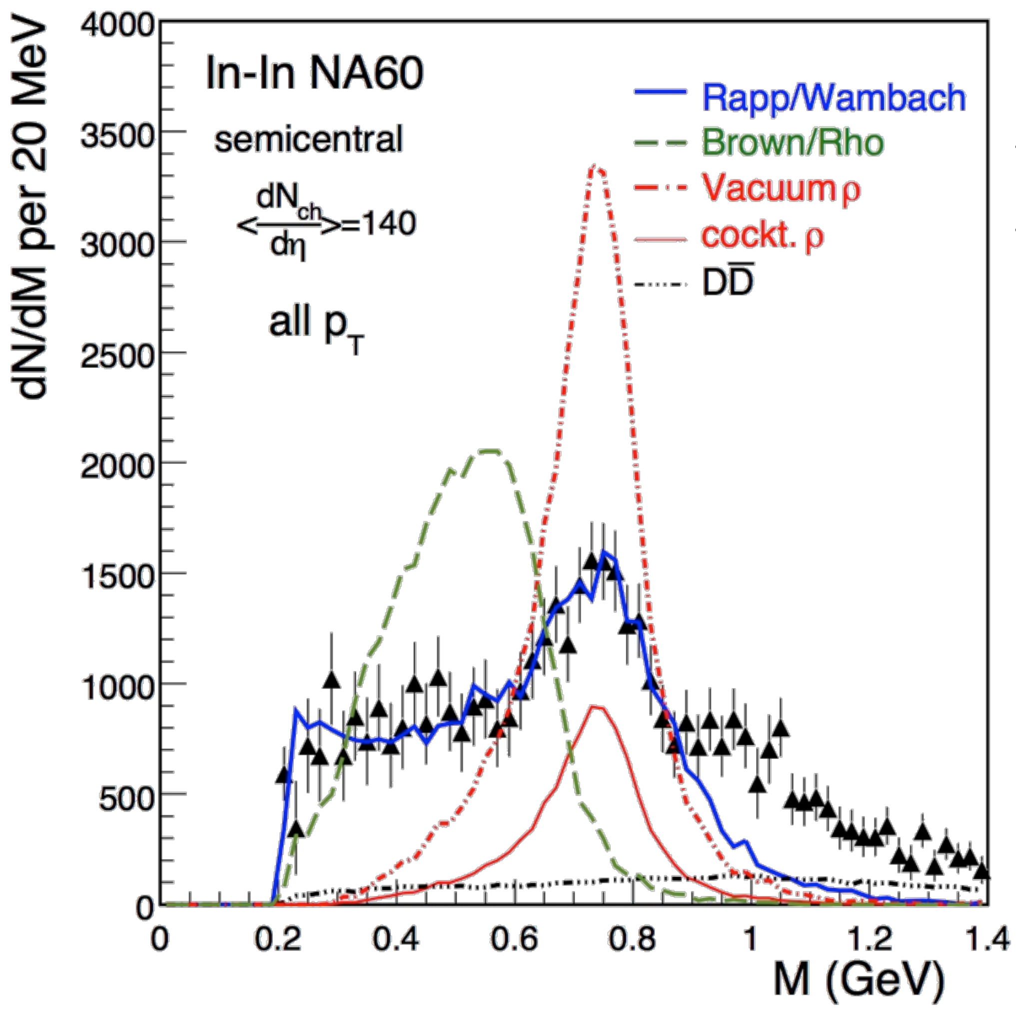
- Primordial emission, Drell-Yan, J/ψ and Upsilon suppression

NA60 : Low Mass Range

PRL 96 (2006) 162302

NA60's dimuon measurement:

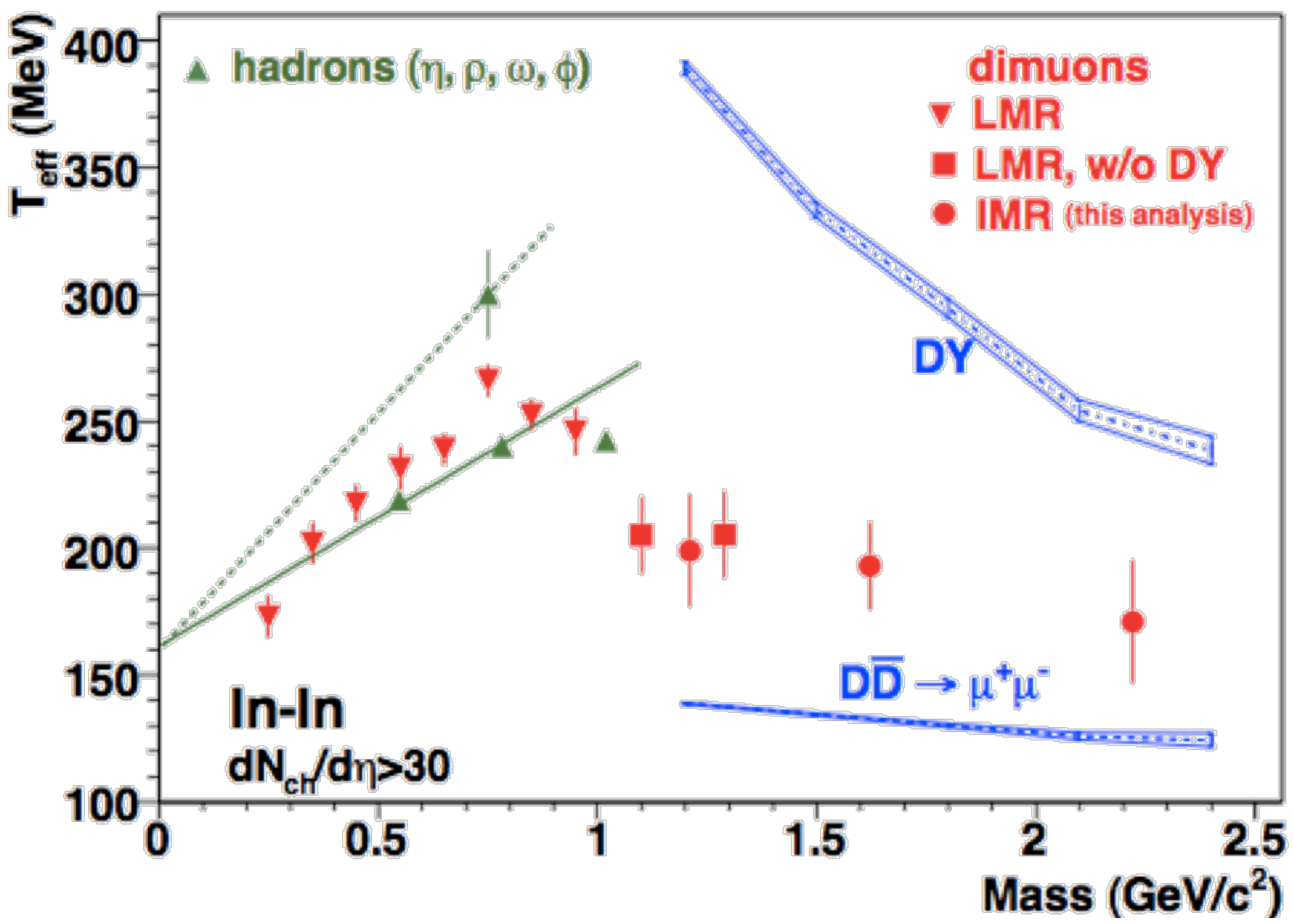
- Compare ρ broadening/melting models
- Data favors Rapp/Wambach model - ρ broadening through interactions with hadronic medium
- Link to chiral symmetry restoration?



EPJ C61 (2009) 711

NA60 : Intermediate Mass Region

PRL 100 (2008) 022302



NA60, EPJ C 59 (2009) 607

Measurment of inverse slope parameter (T_{eff}) from m_T distribution

- T_{eff} = 205 $\pm$ 12 MeV
- Indicative of thermal radiation from partonic medium
- No mass dependence visible in IMR

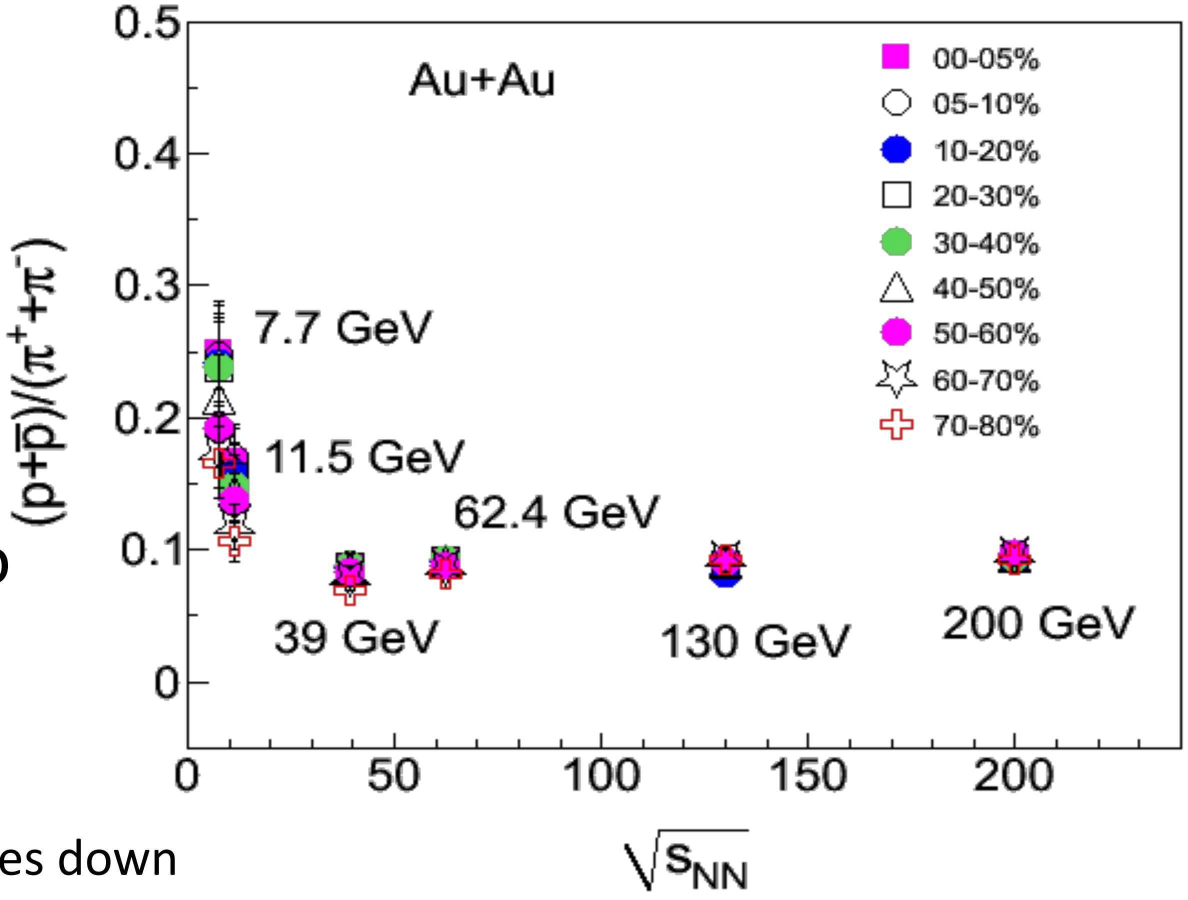
Challenge to disentangle correlated charm from QGP thermal radiation

- STAR upgrades (Muon Telescope Detector & Heavy Flavor Tracker) will help – more later

STAR Dielectron Results in Beam Energy Scan Phase I

STAR Dielectrons in BES I

- BES I beam energies : $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27.0, 39.0, and 62.4 GeV
- Insufficient statistics available below 19.6 GeV for dielectron analyses
- Probe a wide range of initial conditions
- Approximately constant total baryon density in the $\sqrt{s_{NN}}$ range from 19.6 to 200 GeV

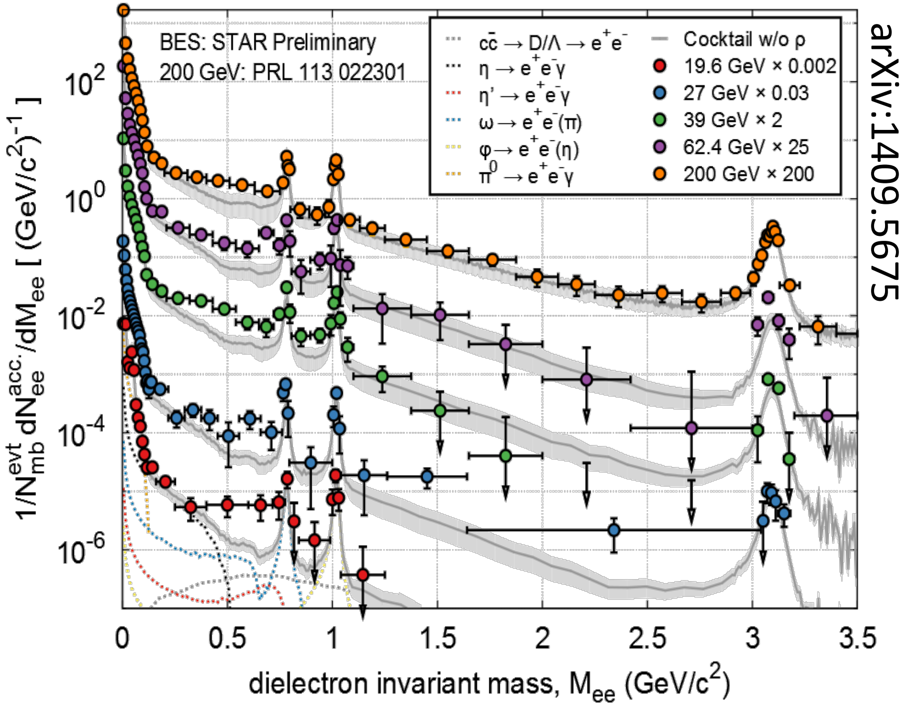


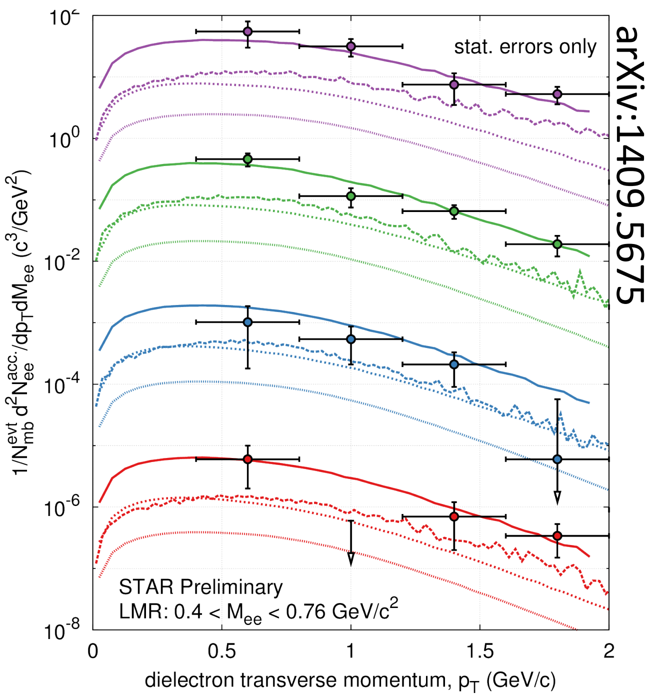
How does LMR excess yield evolve?

- Are in-medium modification effects visible at all energies down to $\sqrt{s_{NN}}$ = 19.6 GeV?
- Is the enhancement consistent with model predictions at these energies?

Beam Energy Scan Dielectrons:
2010 – 2011 Au+Au at
62.4, 39, 27, and 19.6 GeV

STAR Dielectrons in BES I

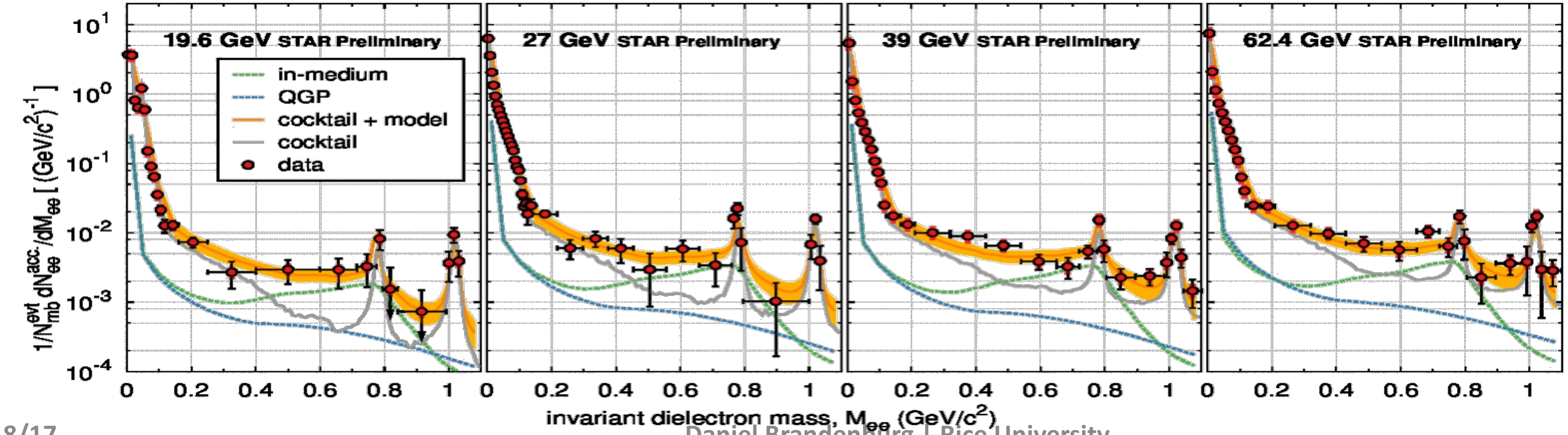




Sustained LMR excess from top RHIC energy to 19.6 GeV

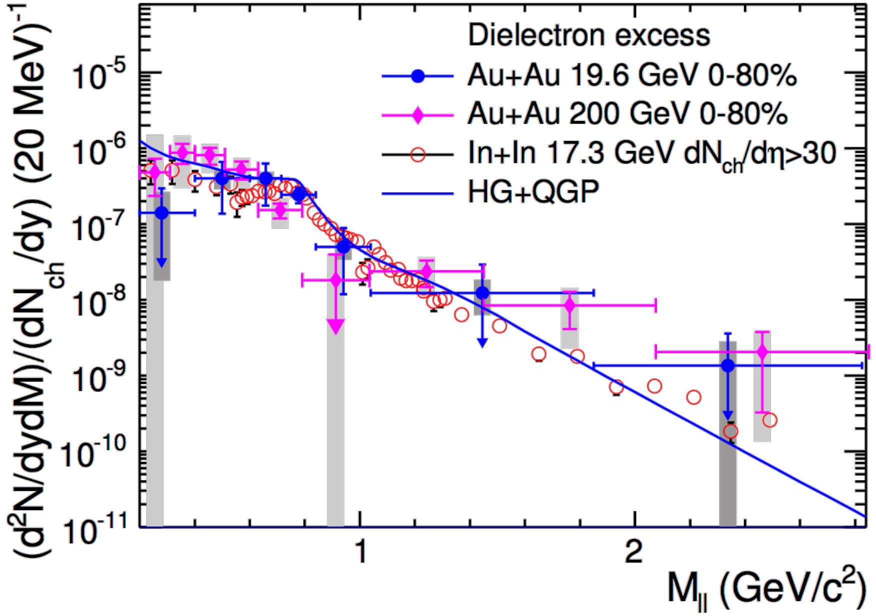
Robust theoretical description

- In-medium ρ broadening + QGP
- Expected to depend on total baryon density

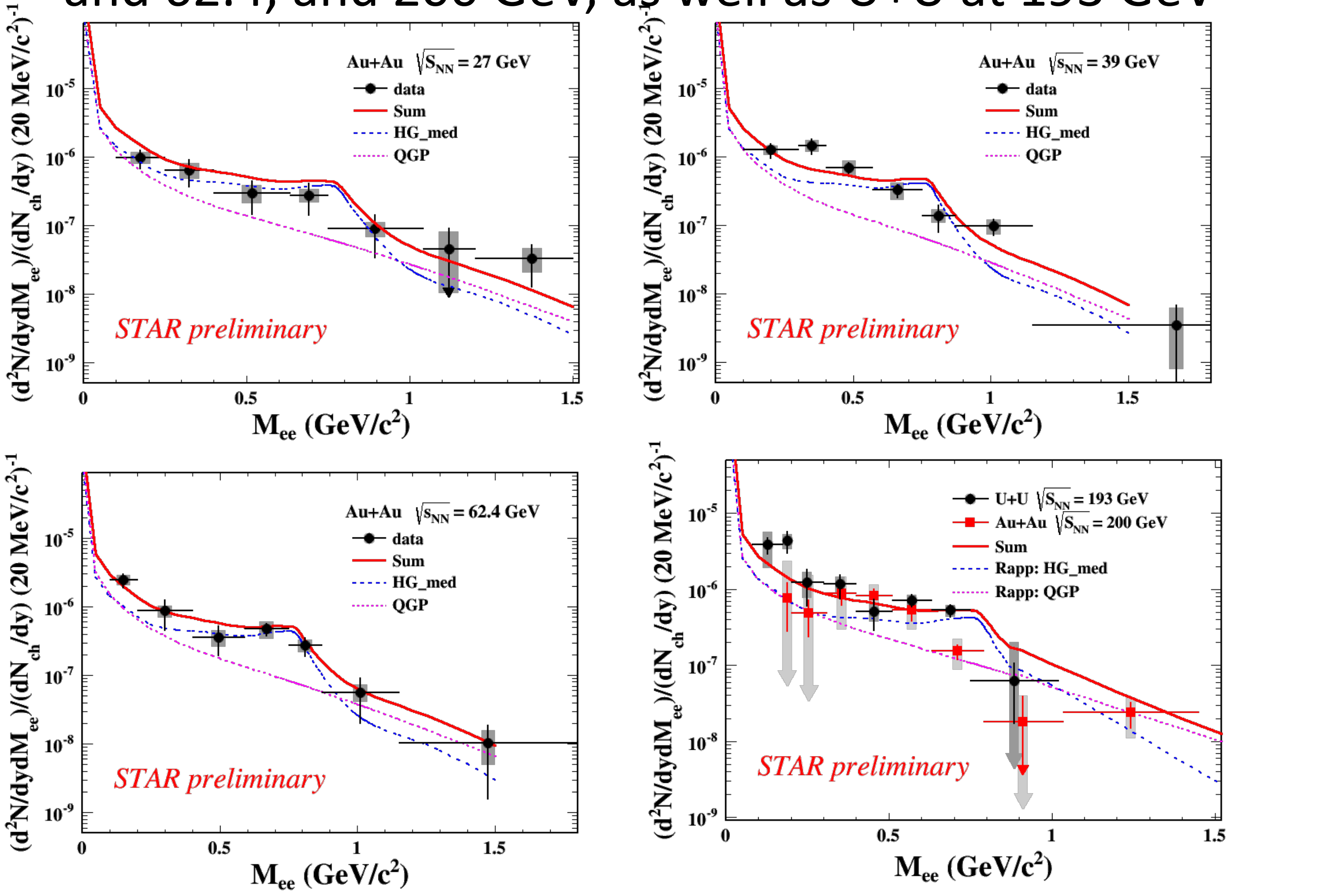


STAR Acceptance Corrected Excess Spectra

- Au+Au at 19.6 and 200 GeV
- Normalized to $(dN_{ch}/dy)_{y=0}$ to cancel out volume effects
- 17.3 GeV (NA60) and 19.6 GeV consistent



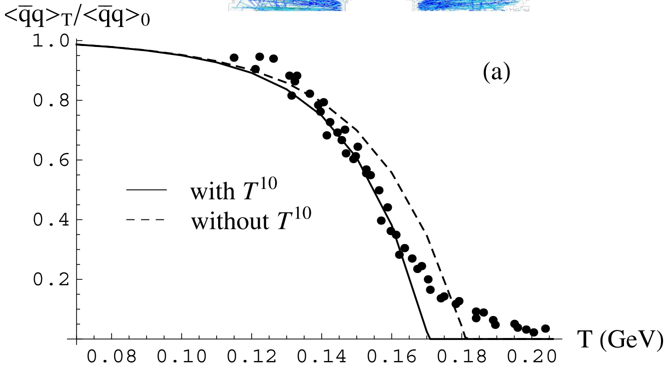
Acceptance-corrected spectra for Au+Au at 27, 39, and 62.4, and 200 GeV, as well as U+U at 193 GeV



Acceptance-corrected excess mass spectra well described by broadened ρ spectral function (SF)

Hohler & Rapp: “Is ρ-meson melting compatible with chiral restoration?”

Link to Chiral Symmetry Restoration



Strong Experimental evidence that ρ meson "melts"

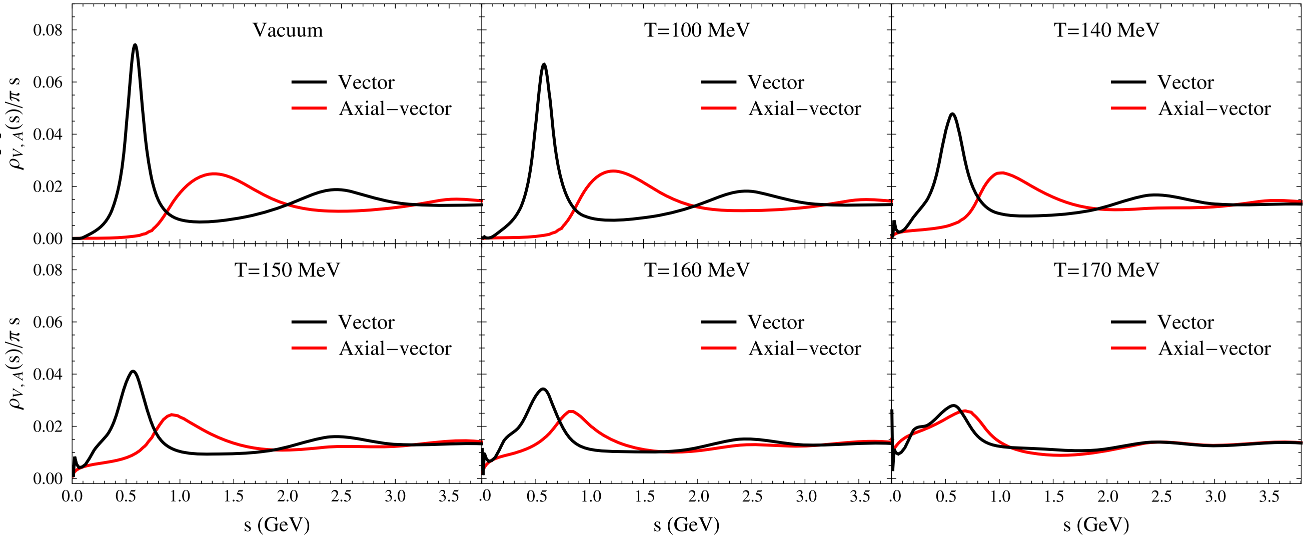
Input for Phenomenological approach:

- Vector meson SF from phenomenological model, verified against experimental data
- T dependence of condensate, from lattice QCD

QCD Sum Rules : constrain vector / axial vector SFs individually $$\frac{1}{M^2}\int ds \frac{\rho_{V/A}(s)}{s} e^{-s/M^2} = \sum_n C_n \langle O_n \rangle$$

Weinberg sum rules : difference between vector & axial vector SFs $$\int ds(\rho_V - \rho_A) s^n = f_n$$

Output:



Quantatively compatible with (approach to) chiral restoration

Hohler, Rapp
PLB 731 (2014) 103

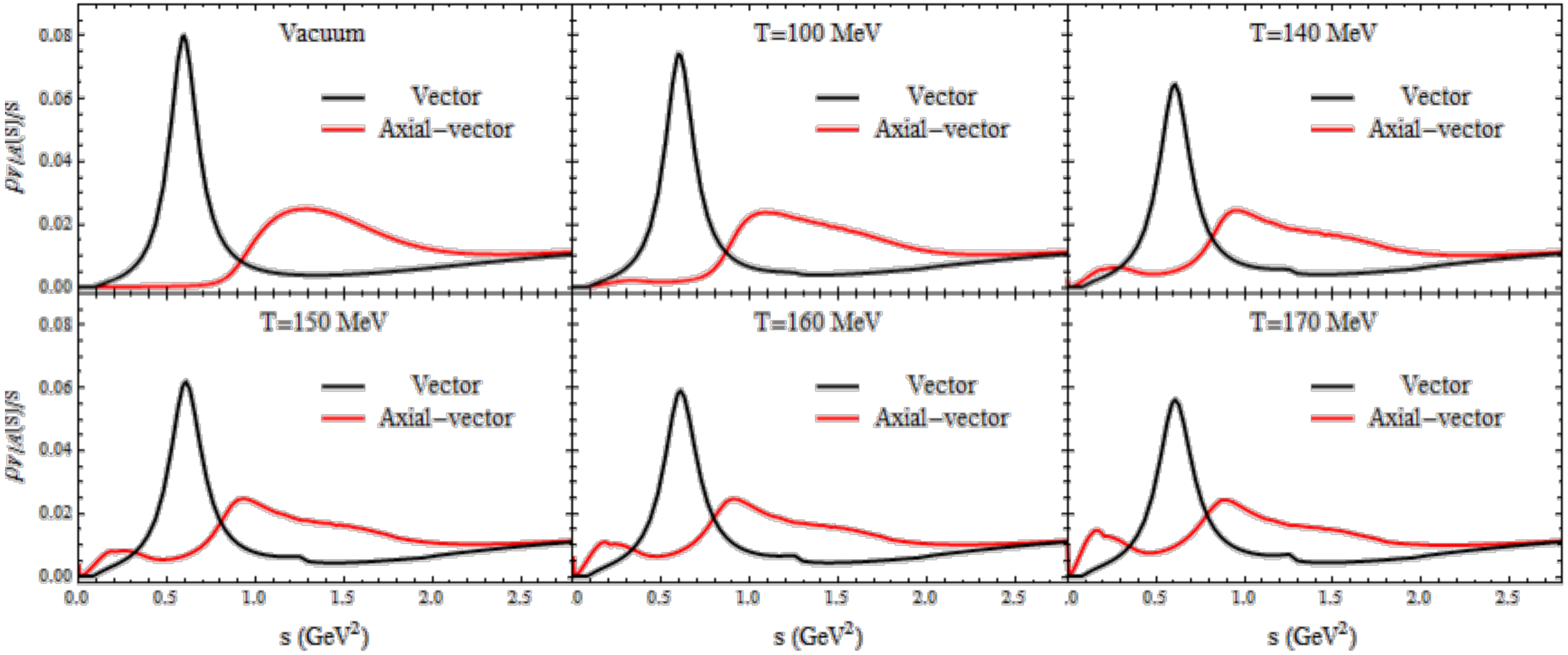
But, still need microscopic calculations of $a_1(1260)$ …
(Massive Yang-Mills)

Link to Chiral Symmetry Restoration

Effective Chiral Lagrangian

- Gauge ρ and a_1 into chiral pion Lagrangian
  - Massive Yang Mills in hot pion gas – starting point for evaluation of chiral restoration in medium

Supports "burning" of chiral-mass splitting as a mechanism for chiral restoration



Hohler, Rapp, Annals Phys 368 (2016) 70

Beam Energy Scan Phase II
2019 - 2020

RHIC Beam Energy Scan Phase II

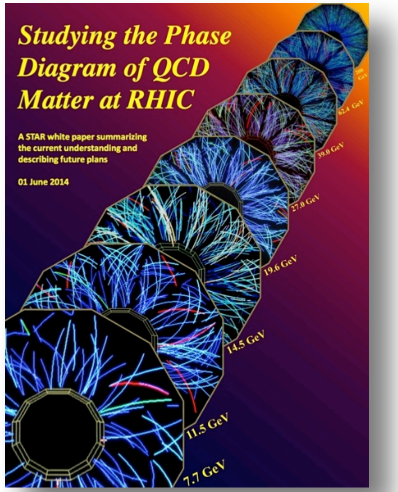
Purpose: Refine our understanding of the phase structures of QCD matter

- Beam time : 2019 - 2020
- Revisit lower BES I energies (19.6 GeV and below), possibly add 9.1 GeV
- Gain significantly more statistics – necessary for dilepton measurements!
- Systematically study dielectron continuum from $\sqrt{s_{NN}}$ = 7.7 to 19.6 GeV

Table 2. Event statistics (in millions) needed for Beam Energy Scan Phase-II for various observables.

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	80	100	120	200	400
Dileptons	100	160	230	300	400
Required Number of Events	**100**	**160**	**230**	**300**	**400**

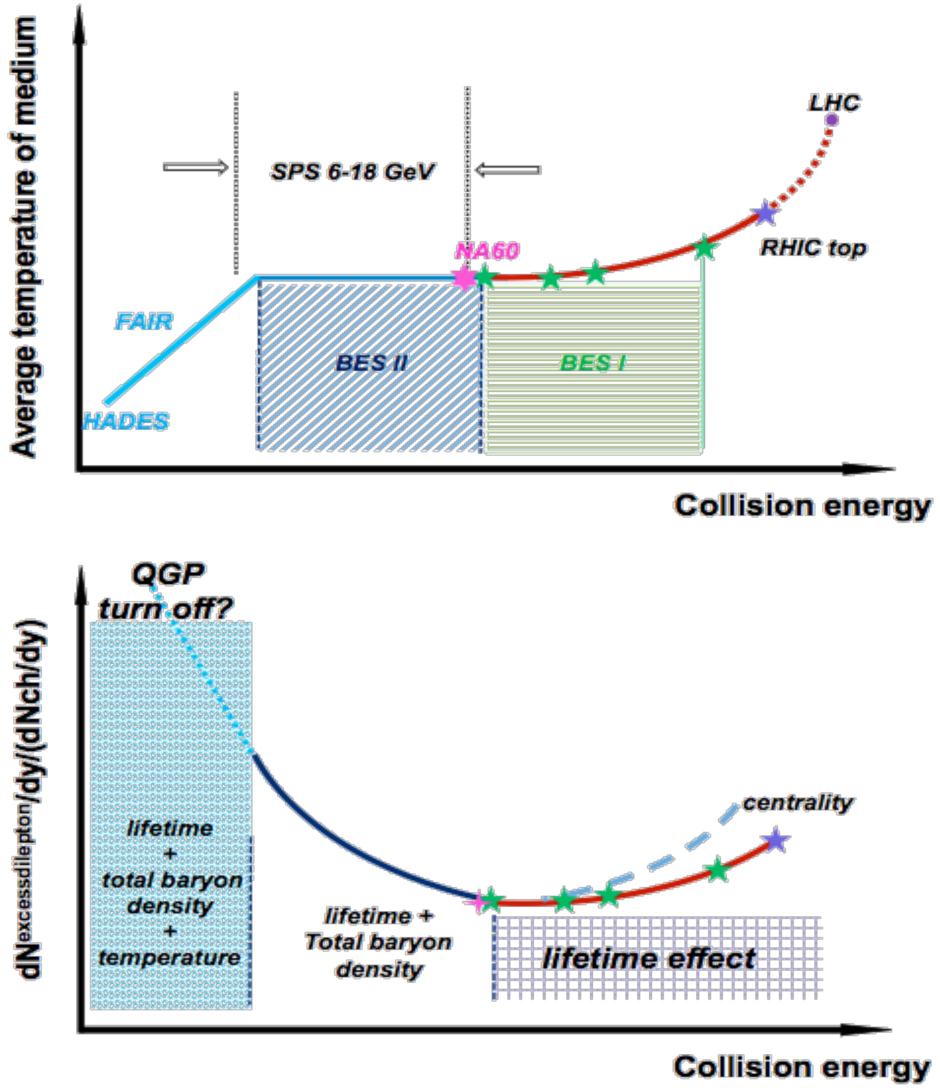
STAR Whitepaper for BES II



Dileptons in BES II

BES I : $\sqrt{s_{NN}}$ = 19.6 to 62.4 GeV
- Dilepton emission dominant in T_C region
- **~constant total baryon density**
- Emission proportional to lifetime

BES II : $\sqrt{s_{NN}}$ = 7.7 to 19.6 GeV
- Average temperature of medium ~constant
- Probe life time + baryon density dependence of the ρ-meson spectral function



Ruan, Rapp – TPD'14

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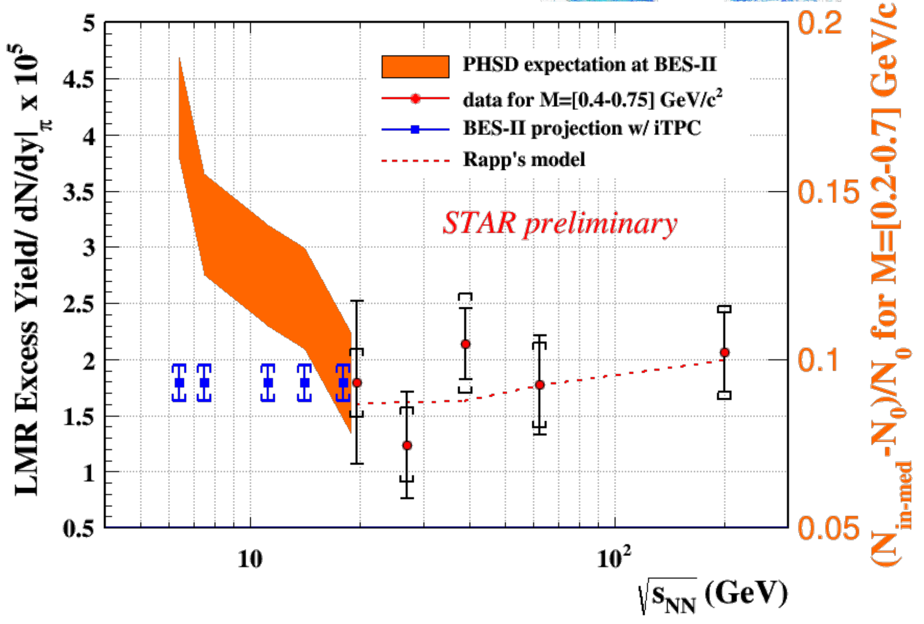
BES II : $\sqrt{s_{NN}}$ = 7.7 to 19.6 GeV

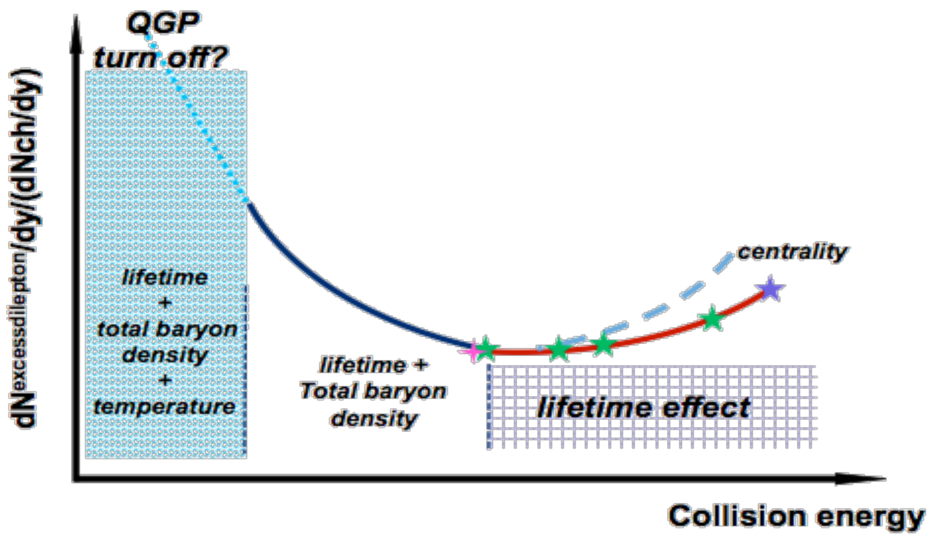
- Average temperature of medium ~constant
- Probe life time + baryon density dependence of the ρ-meson spectral function
- **Total baryon density expected to increase by ~2x**
- Close to QCD critical point?
  - Increase in correlation length
  - Critical slow down – anomalous increase in fireball lifetime

Linking top RHIC energies with SPS, FAIR energies

- Comparison with NA60, HADES, CBM
- At FAIR energies, probe lifetime + total baryon density + temperature

NA60+ proposed at SPS – overlap with RHIC and FAIR



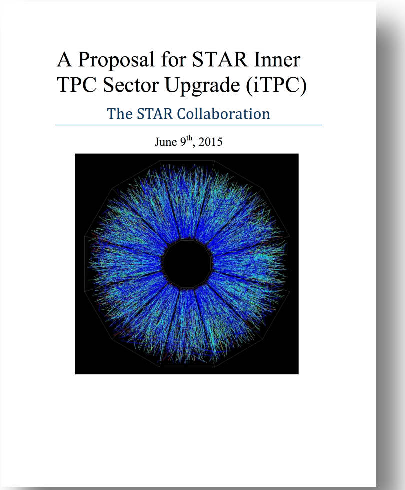


Ruan, Rapp – TPD'14

BES II Detector Upgrades : iTPC

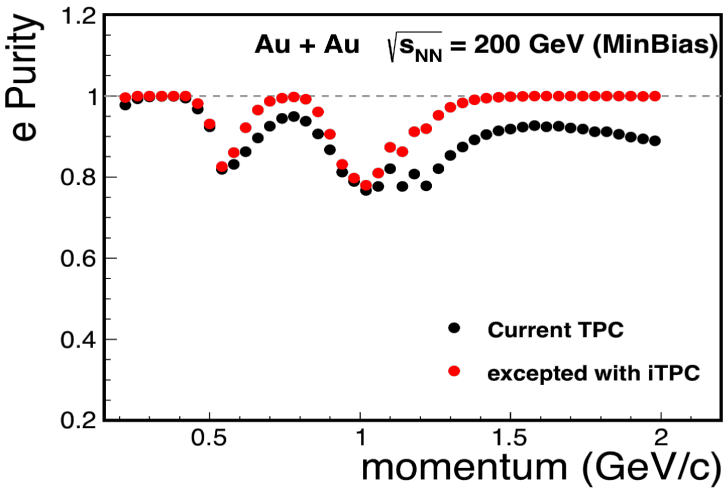
STAR proposal to upgrade the inner sector of its TPC

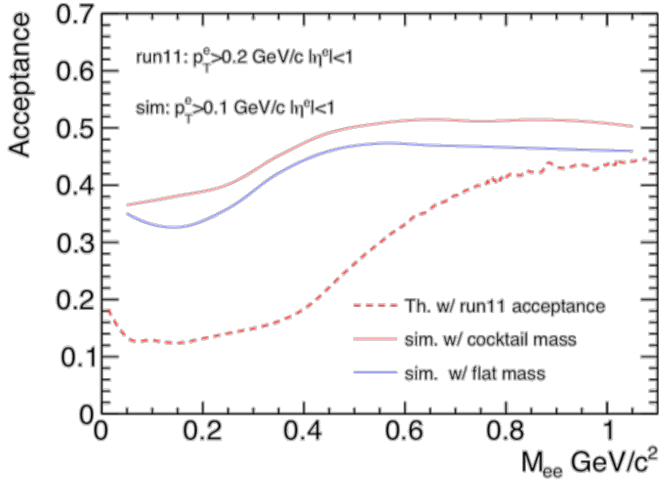
- Increase rapidity coverage
- Lowers p_T threshold
- Improves dE/dx (PID) resolution

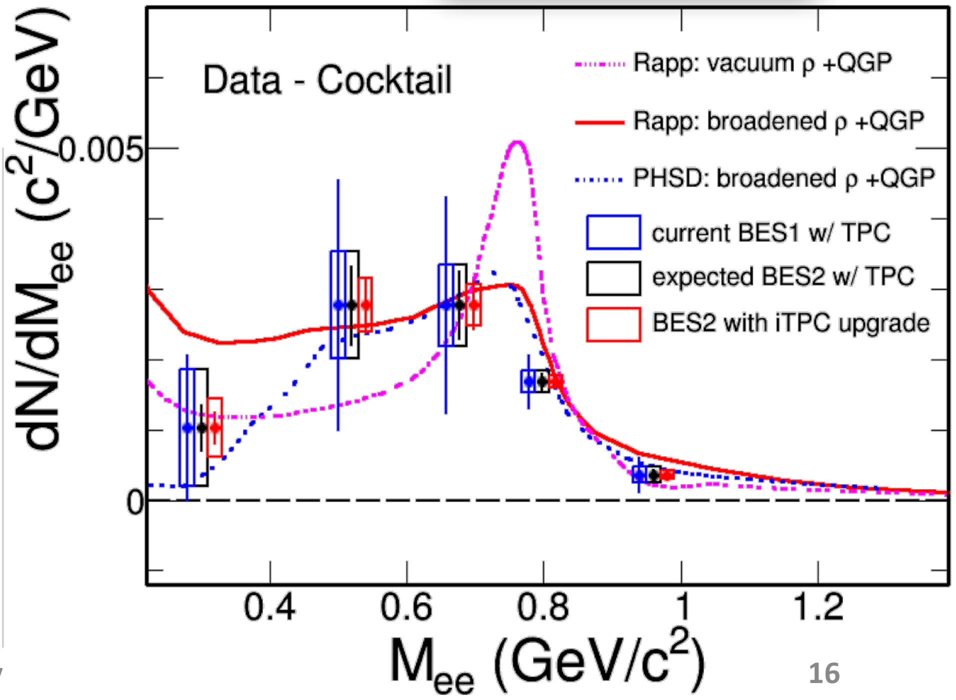


Substantial improve dielectron systematics

- Systematics expected to be reduced by ~2x
- Improved PID → increased electron purity
- Lower p_T threshold → better acceptance in LMR







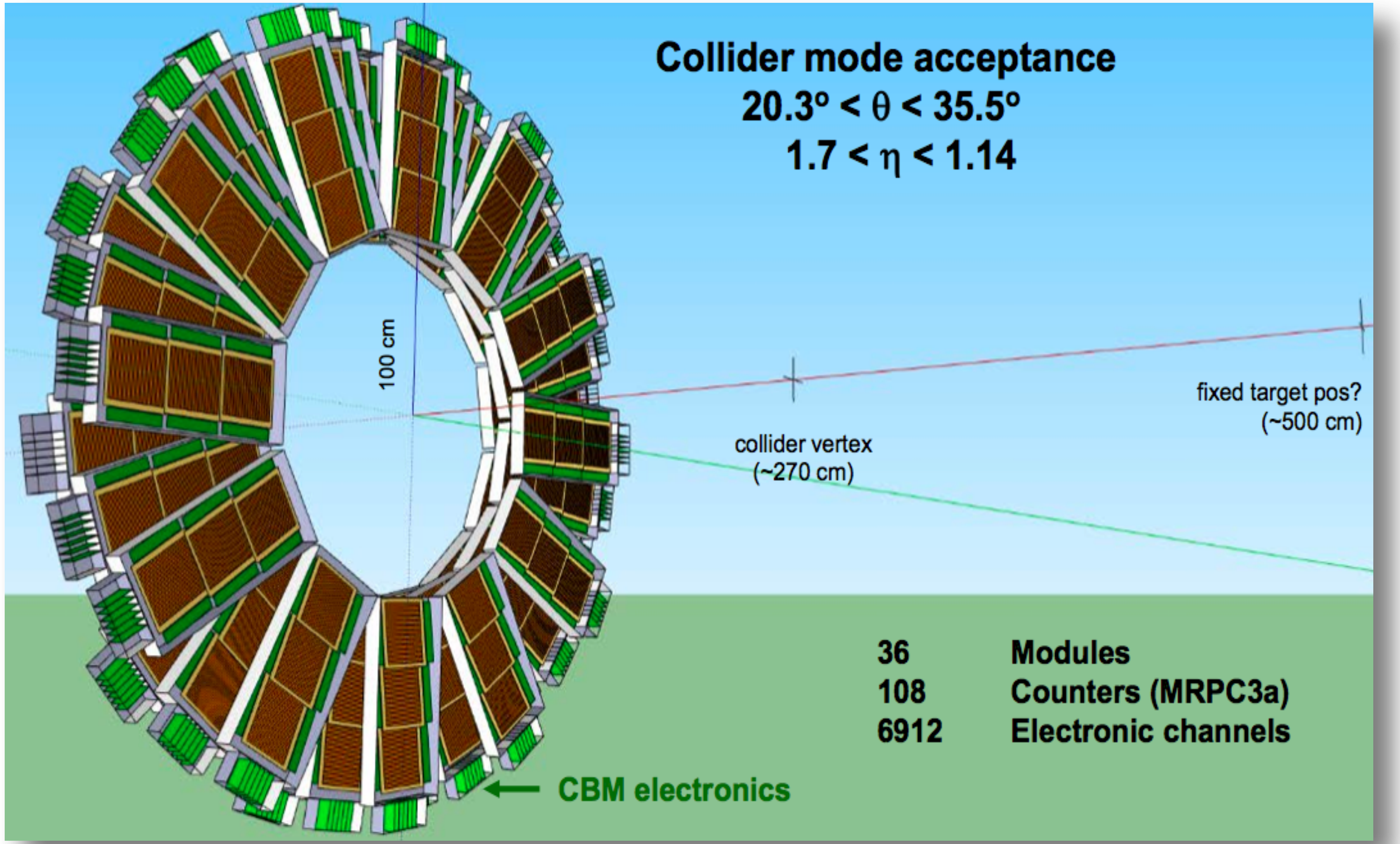
BES II Detector Upgrades : eTOF

STAR proposal to install CBM TOF

- Endcap TOF (eTOF) mounted on east pole tip
- Increases PID rapidity coverage
- Takes advantage of large iTPC coverage

Dielectron Measurement:

- Allows rapidity differential



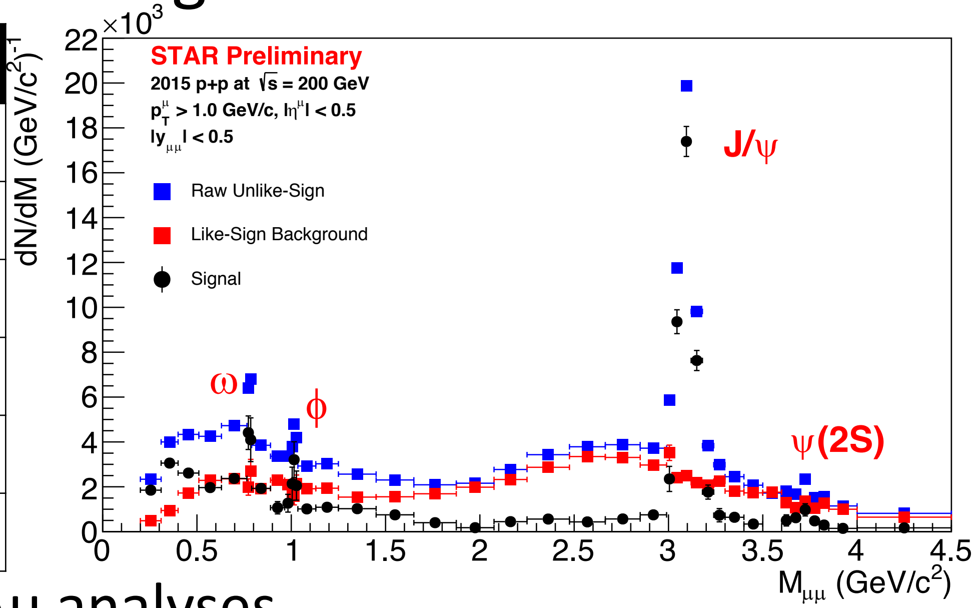
- LMR excess expected to depend on total baryon density
- π yields drop by 2x from y=0 to y=1.2 →"baryon density" drops by factor of two.
- Analysis at y=1.2 is equivalent to lowering the beam energy

Near Future STAR Dilepton Measurements current - 2018

Measurements of $\mu^+\mu^-$ Continuum at STAR

- STAR's Muon Telescope Detector upgrade (completed 2014) allows for new studies of the dimuon continuum at RHIC energies with STAR.

Species	Energy (GeV)	~Sampled Luminosity
p+p (63% MTD)	500	28 pb^{-1}
p+p	200	122 pb^{-1}
p+Au	200	409 nb^{-1}
d+Au	200	94 nb^{-1}
Au+Au 2014	200	14 nb^{-1}
Au+Au 2016	200	12 nb^{-1}

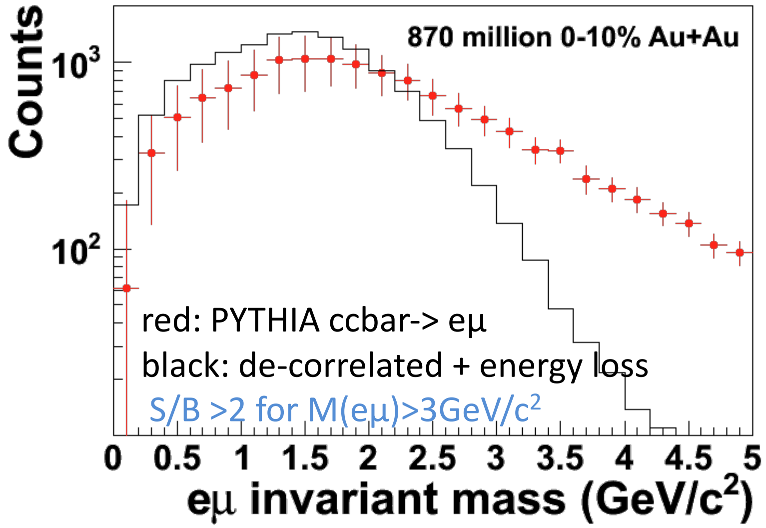


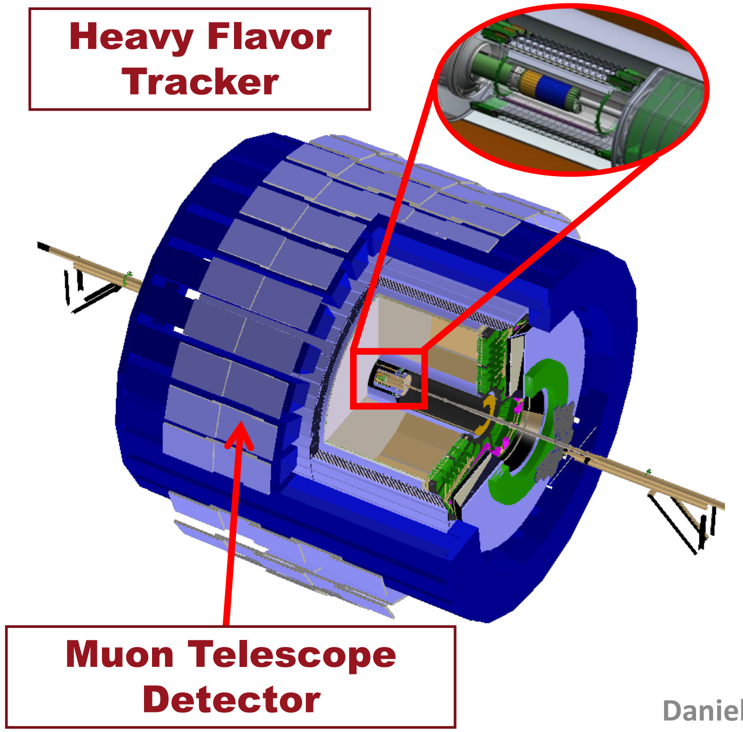
- High quality p+p data set : provides baseline for Au+Au analyses
  - Clear ω, ρ, J/ψ, and ψ(2S) peaks visible in p+p collisions @ $\sqrt{s_{NN}}$ = 200 GeV
- High statistic Au+Au data samples triggered by dedicated dimuon trigger
- Dimuon channel – fewer background source in LMR compared to e^+e^-channel
- Analysis of data from p+p and Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV is ongoing

Disentangling Correlated Charm in IMR

Heavy Flavor Tracker:

- Provides precise tracking
- Allows charm to be better distinguished via secondary vertex reconstruction
- Analyses ongoing with 2014 & 2016 data



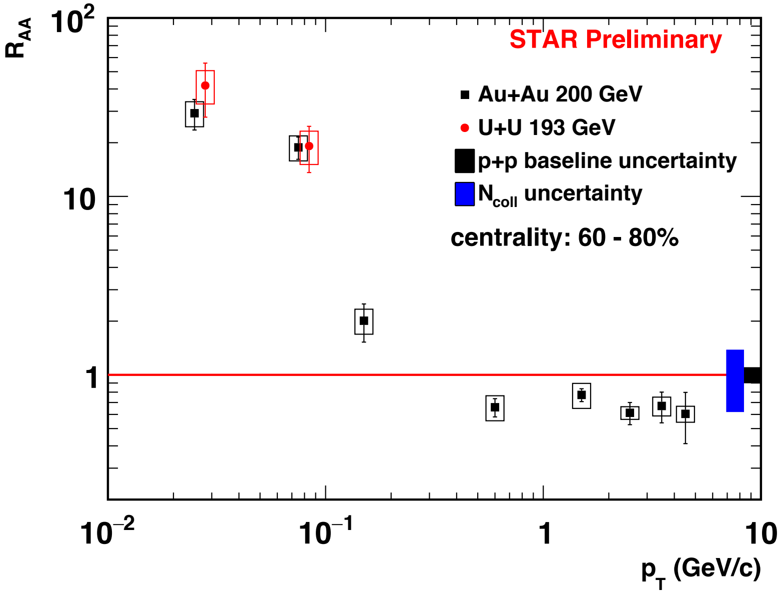


Muon Telescope Detector:

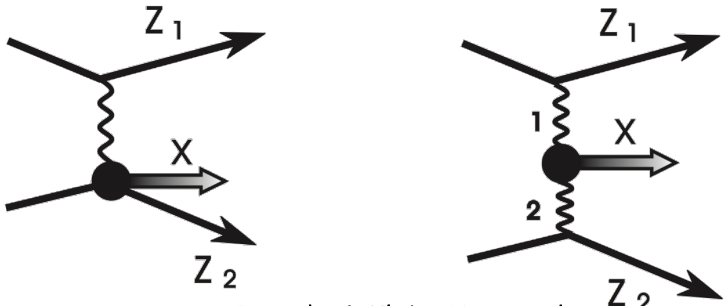
- Allows for a dedicated e-μ trigger
- Gain handle on charm contribution via e-μ correlation
- Study possible charm modification in medium

Isobaric Collisions : Low p_T Excess

- STAR and ALICE have observed significant excess production of J/ψ in peripheral A+A collisions at low p_T (p_T < 300 MeV/c)



- Two potential sources:
  - Photo-nuclear $\propto Z^2$
  - Photon-Photon $\propto Z^4$



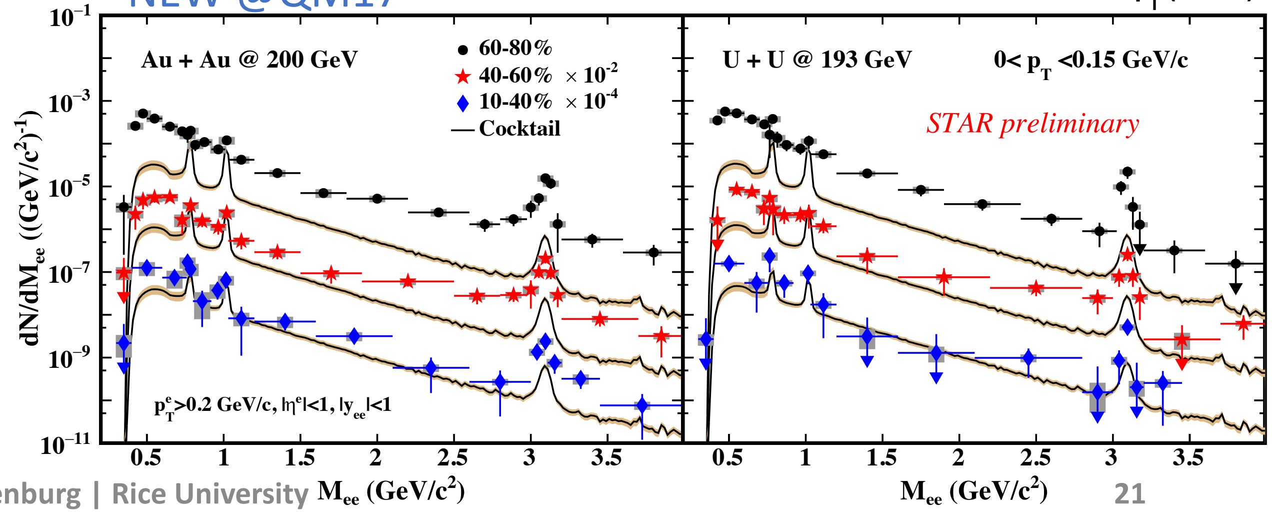
Bertulani, Klein, Nystrand, Ann.Rev.Nucl.Part.Sci. 55 (2005) 271

Investigate Z-dependence of low-p_T dielectron excess:

- Measure & compare in A=96 isobars:
  - $^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$
  - $^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$

Proposed for 2018

NEW @QM17

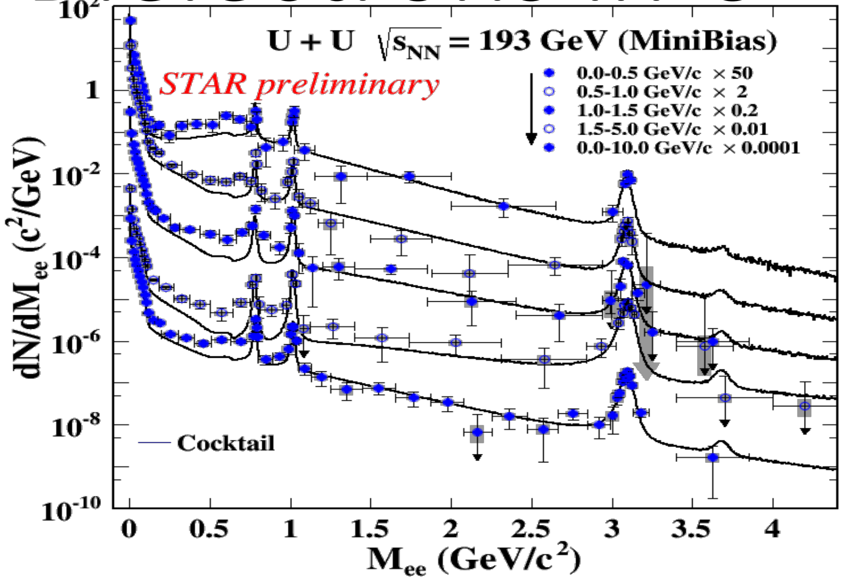


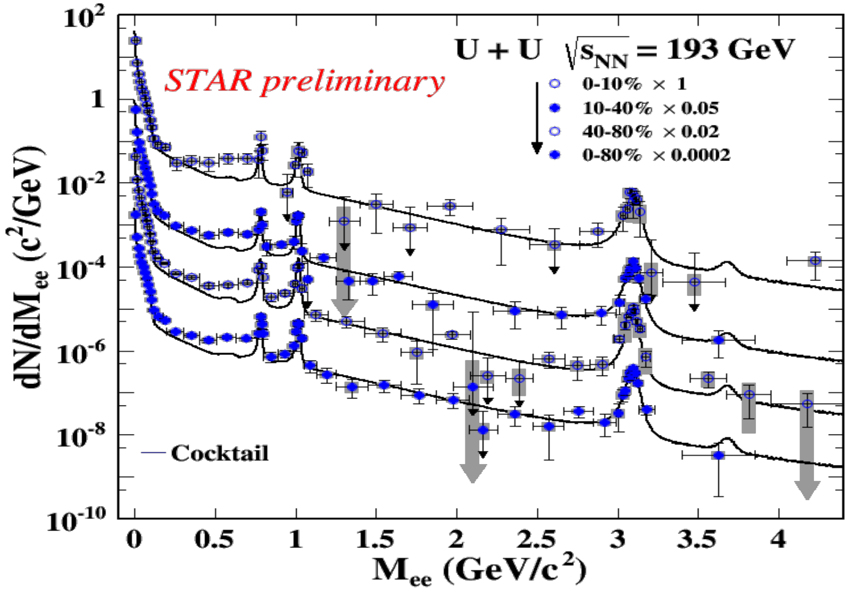
Summary

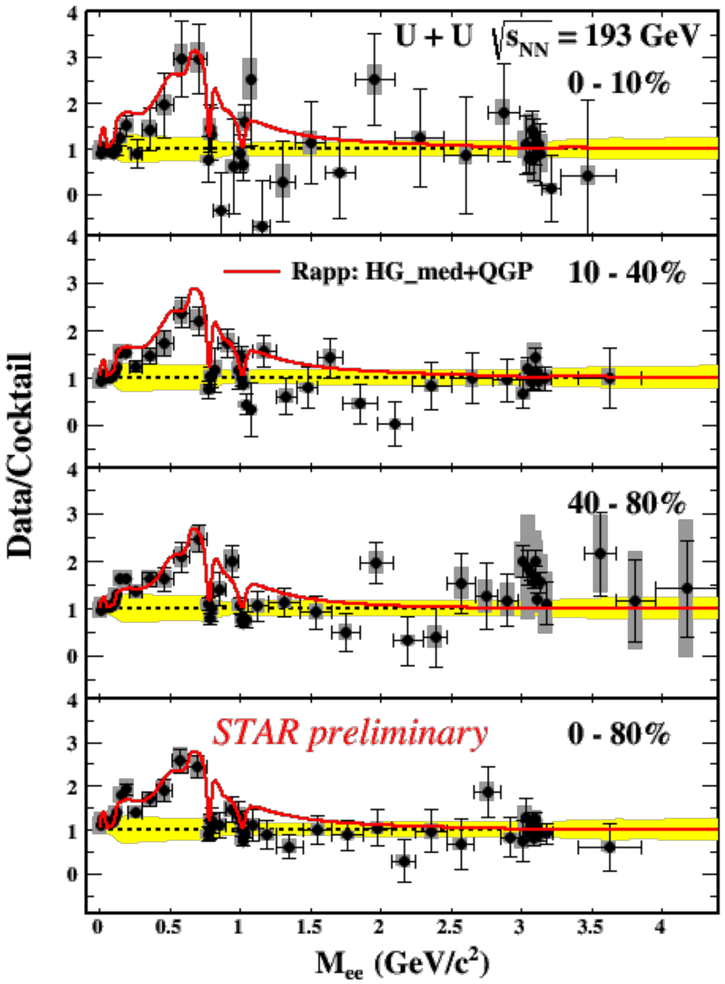
- At SPS, NA60 and CERES demonstrated the physics potential of accurate dilepton measurements
- STAR has developed a strong dilepton program
  - Detailed study of dielectron production in Au+Au and U+U @ top RHIC energy
  - BES I – Allowed measurement of low mass excess down to 19.6 GeV, compare with SPS energy
- Progress in thermal field theory computations of dilepton production in heavy-ion collisions has led to robust description of LMR excess
- BES Phase II (2019-2020): systematic dilepton measurements down to $\sqrt{s_{NN}}$ = 7.7 GeV
  - Probe dependence on total baryon density
  - Measure p_T distribution's inverse slope parameter (T_{eff})
  - Look for anomalous increase in yield → indicative of critical behavior
  - Utilize iTPC and eTOF upgrades to reduce systematic uncertainties & add rapidity differential measurements
- Near Future dilepton measurements at STAR
  - New STAR measurements of $\mu^+\mu^-$ continuum thanks to MTD upgrade
  - New methods of distinguishing correlated charm contributions (MTD and HFT)
  - Investigation of low p_T excess dilepton yield through isobaric collisions

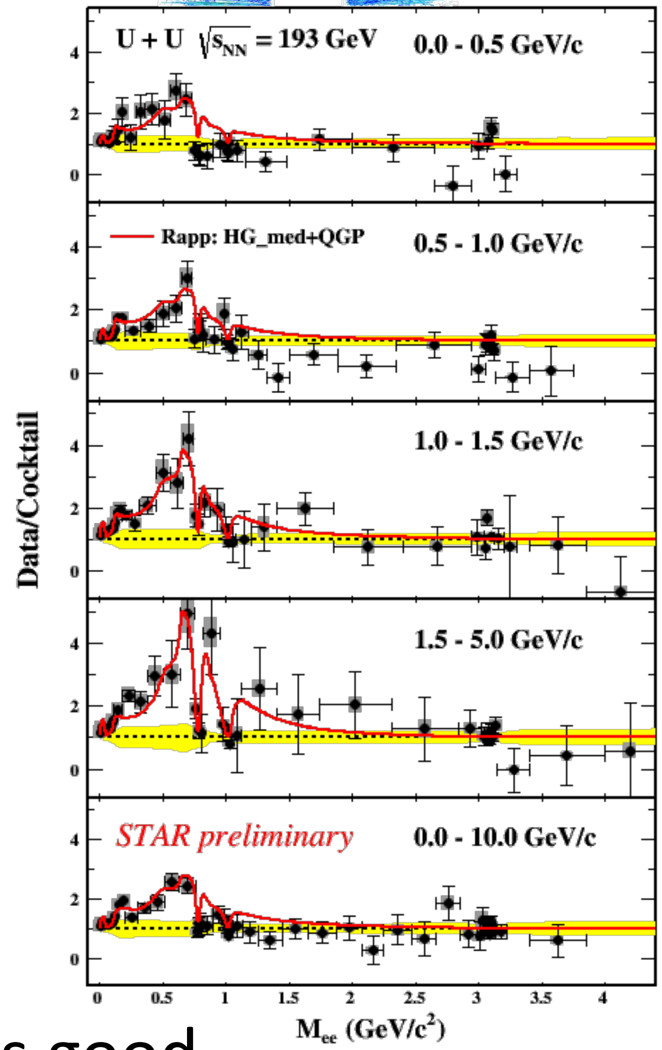
Thank you

Dielectrons in U+U @ $\sqrt{s_{NN}}$ = 193 GeV





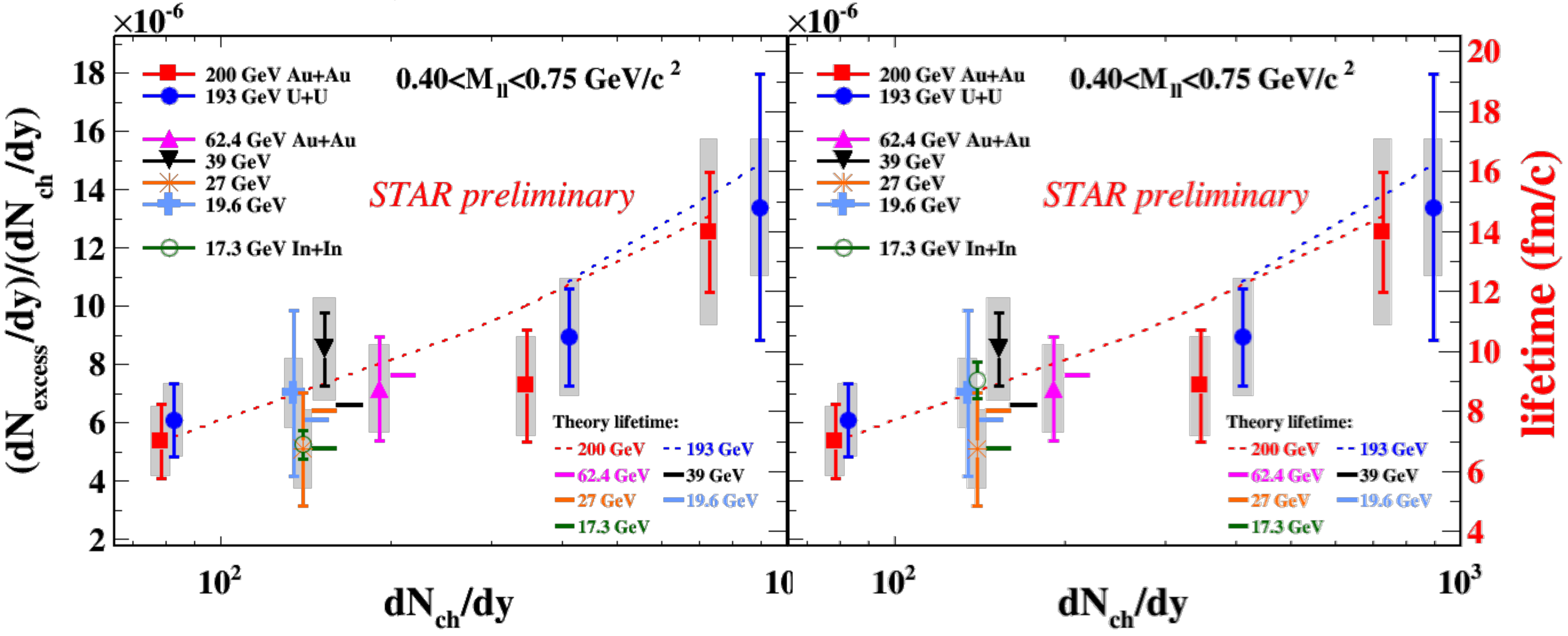




Rapp model consistently shows good agreement across p_T and centrality differentials

In+In@17.3 GeV
NA60, Eur. Phys. J. C 59 (2009) 607

In+In@17.3 GeV
NA60, AIP Conf. Proc. 1322 (2010) 1



AuAu@200 GeV, 19.6 GeV
STAR, PLB 750 (2015) 64

Isobaric collisions at RHIC in 2018

Quantities	Systems		
	U+U	Ru+Ru	Zr+Zr
Centrality	60-80	47-75	47-75
Multiplicity ($\|\eta\|<0.5$)	12-52	12-52	12-52
N_{part}	21 ± 1	21 ± 1	21 ± 1
B^2 (fm^{-4})	30.8 ± 0.1	30.1 ± 0.1	26.2 ± 0.1
B^4 (fm^{-8})	1984 ± 4	2121 ± 4	1672 ± 4

Table 5.2: Results obtained from the Glauber model calculations [87] for different colliding systems. The estimations of the magnetic fields are done at the time of the collisions (t=0) and at the center of the participant zone. The multiplicity is obtained using two-component model that is tuned to fit Au+Au data.

source: STAR Note 657

RHIC Beam Use Request For Runs 17 and 18

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0657

Physics process	47-75% Zr+Zr (data/cocktail)	47-75% Ru+Ru (data/cocktail)	Difference between Zr+Zr and Ru+Ru
Photonuclear	14.3 ± 0.4	16.1 ± 0.4	1.8 ± 0.6 (3.0 σ)
Two-photon	14.2 ± 0.4	17.4 ± 0.4	3.2 ± 0.6 (5.3 σ)

Table 5.3: The expected di-electron data over cocktail ratios in the mass region 0.4-0.76 GeV/c^2 for p_T<0.15 GeV/c with 1.2 billion minimum-bias isobar collisions and the projected differences for the two physics scenarios in Zr+Zr and Ru+Ru collisions.

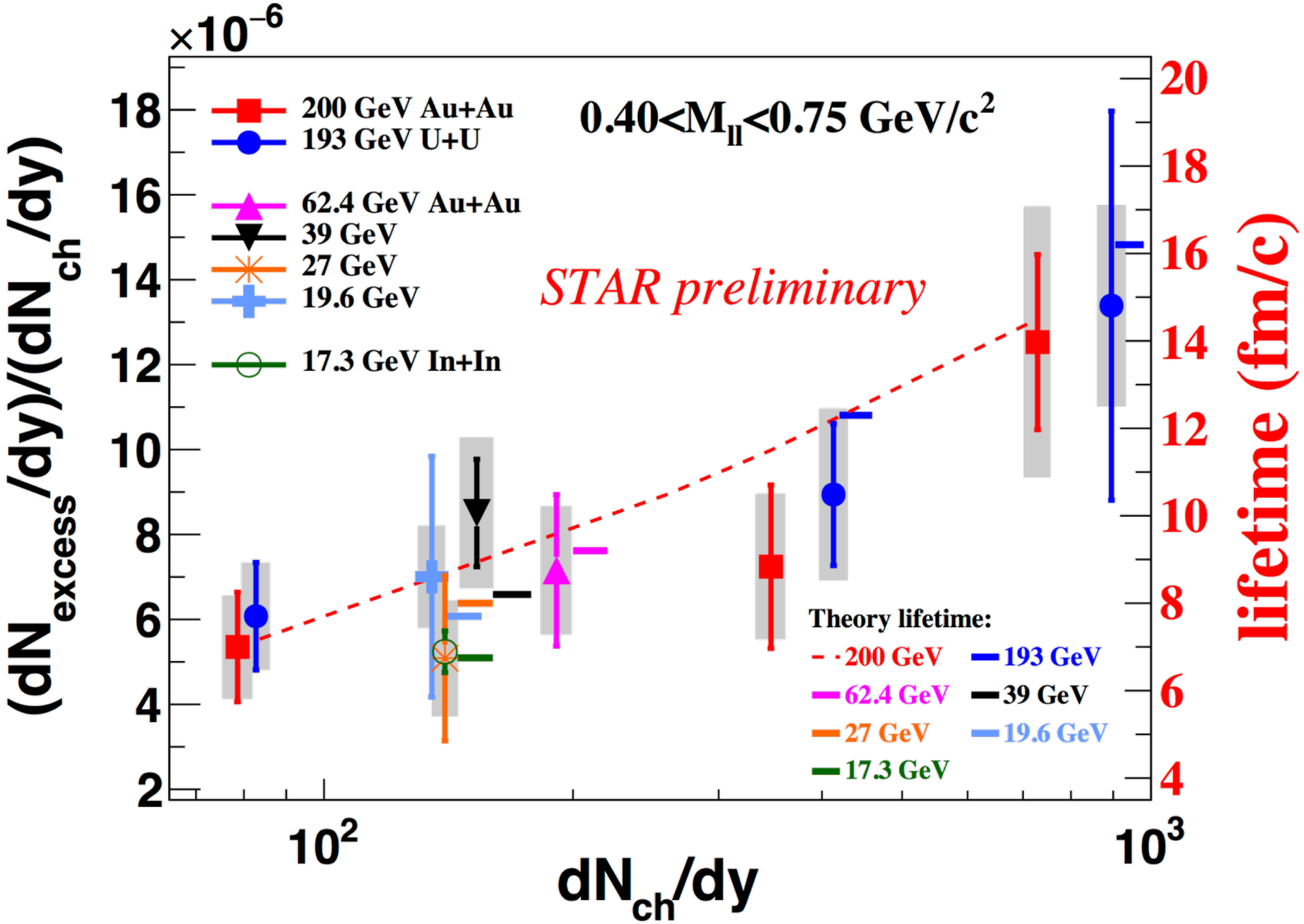
Physics process	47-75% Zr+Zr (data/cocktail)	47-75% Ru+Ru (data/cocktail)	Differences between Zr+Zr and Ru+Ru
Photonuclear	17.5 ± 1.7	20.0 ± 1.7	2.5 ± 2.4 (1.0 σ)
Two-photon	17.3 ± 1.7	21.8 ± 1.7	4.5 ± 2.4 (1.9 σ)

Table 5.4: The expected di-electron data over cocktail ratios in the mass region 3.0-3.2 GeV/c^2 for p_T<0.15 GeV/c with 1.2 billion minimum-bias isobar collisions and the projected differences for the two physics scenarios in Zr+Zr and Ru+Ru collisions.

Excess yield and Medium Lifetime

- Normalized excess yields in LMR proportional to medium life time (QGP+HG) for $\sqrt{s_{NN}}$=17.3–200 GeV
  - nearly constant total baryon density
  - emission rates dominated around T_C
- Yields in U+U@193GeV and Au+Au@200GeV
  - higher yields in central than in lower energies
  - observe increase from peripheral to central

➢ Indications of longer medium lifetime in central UU@193GeV and central AuAu@200GeV



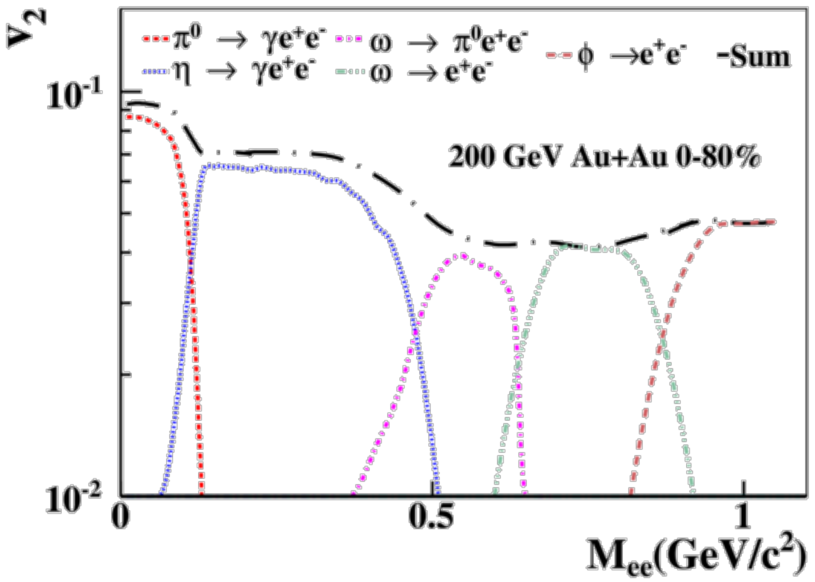
First Measurements of Dielectron v_2

STAR, PRC 90 (2014) 64904

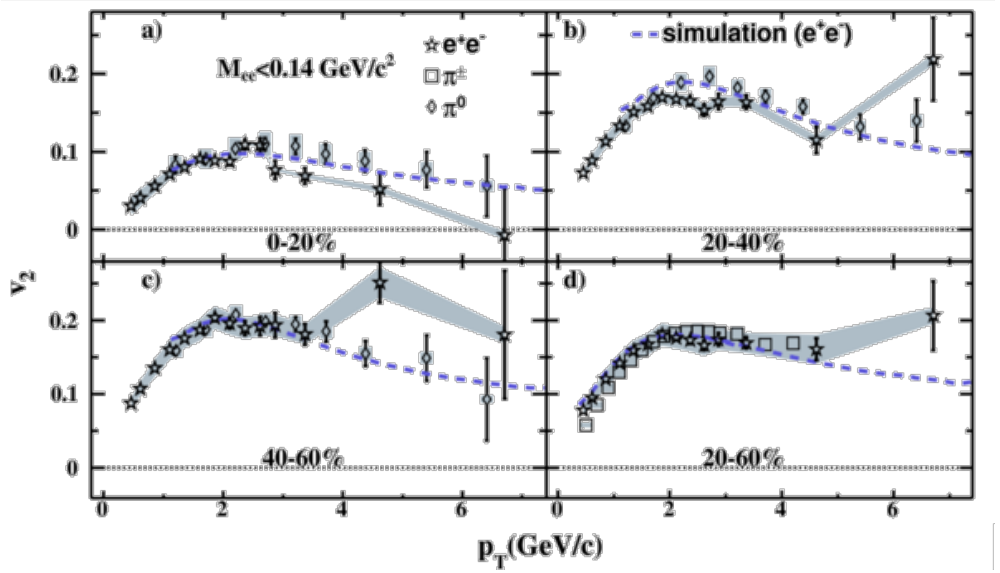
➢challenge: isolate v_2 of excess dielectrons

$$v_2^{\text{total}}(m_{ee}) = v_2^{\text{signal}}\left[\frac{N_S}{N_B+N_S}\right](m_{ee}) + v_2^{\text{background}}\left[1-\frac{N_S}{N_B+N_S}\right](m_{ee})$$

cocktail simulations based on published light-hadron v_2 measurements



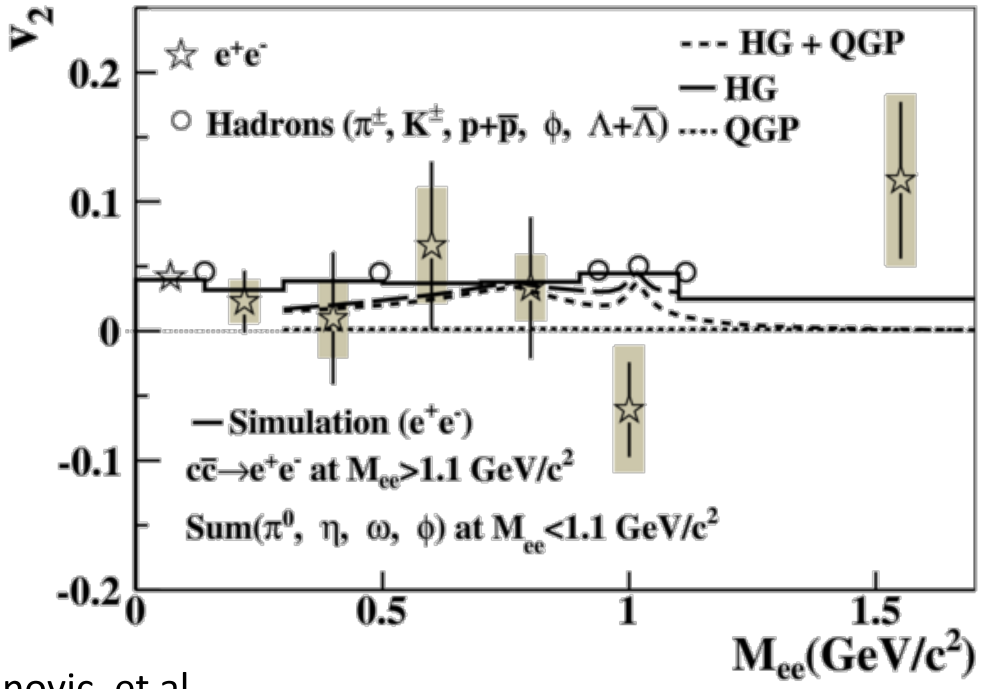
v_2 from π^0 Dalitz decay consistent with simulations based on published π v_2



Dielectron v_2 : proof of principle

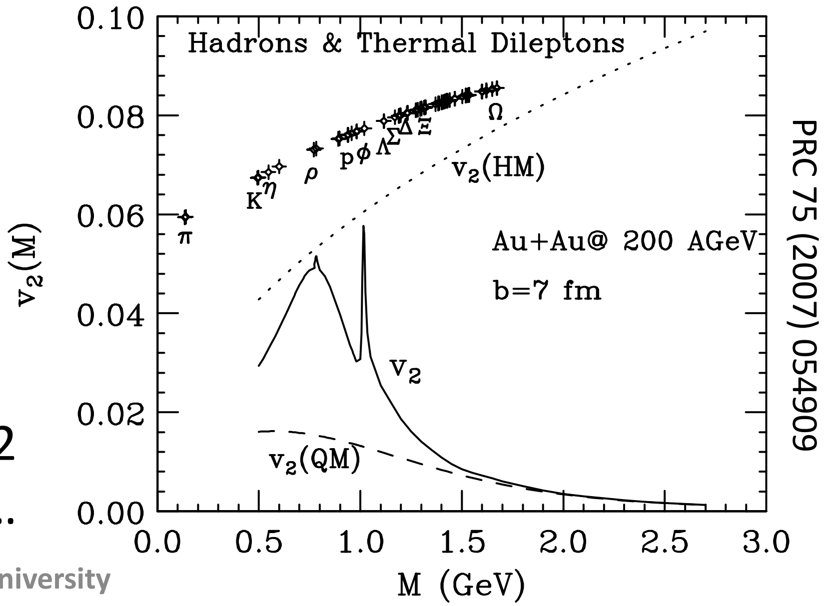
PRC 90 (2014) 64904

- based on combined Run 10 and 11 data (760M events)
- p_T integrated v_2 of dielectrons in STAR acceptance



Vujanovic, et al.,
PRC89 (2014)034904

to distinguish between HG and QGP v2
need uncertainties < 4% …

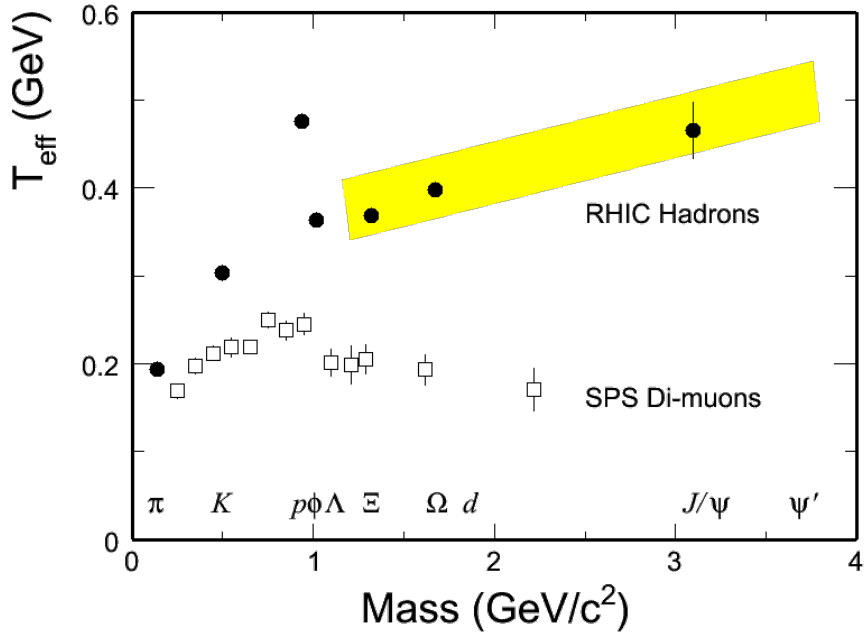


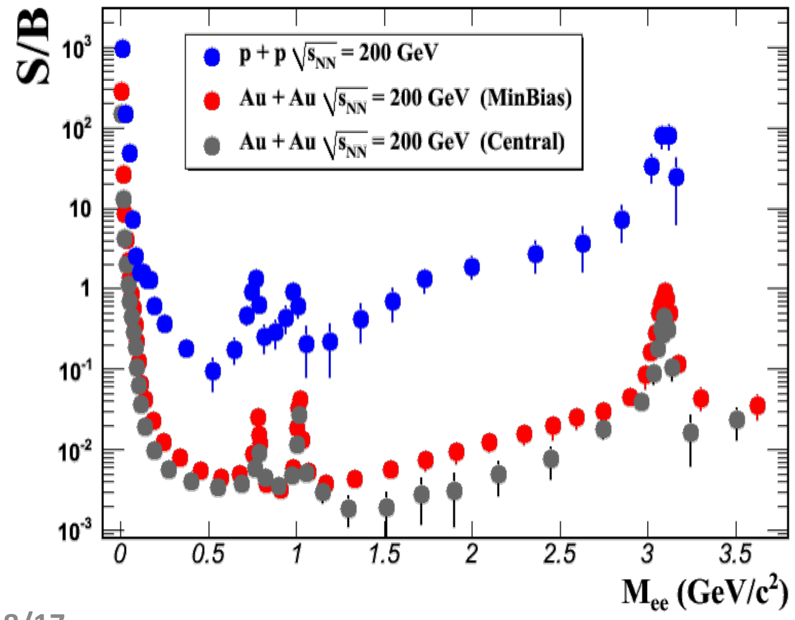
Chatterjee et al
PRC 75 (2007) 054909

What to expect at RHIC

Opportunities:

- expect significant increase of partonic source contribution
- Beam Energy Scan provides unique opportunities to
  - systematically study in-medium ρ broadening
  - on-set of QGP thermal radiation

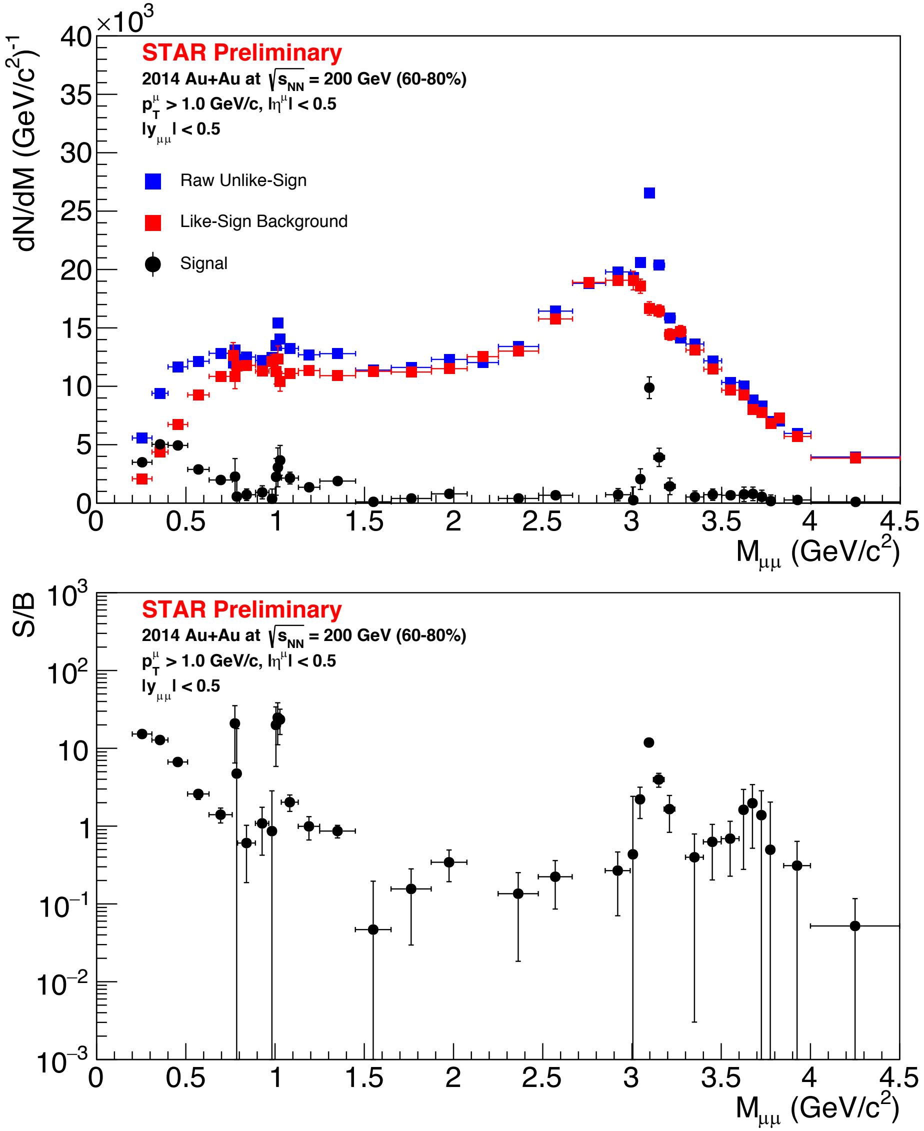




Challenges:

- increased particle multiplicities at higher $\sqrt{s_{NN}}$ lead to significant increase in combinatorial backgrounds
- STAR at 200 GeV for M_{ee}~ 0.5 GeV/c^2
  - p+p: S/B ~1/10
  - Au+Au: S/B ~1/250

$\mu^+\mu^-$ in Run14 Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV



Data Triggered by dedicated Dimuon Trigger

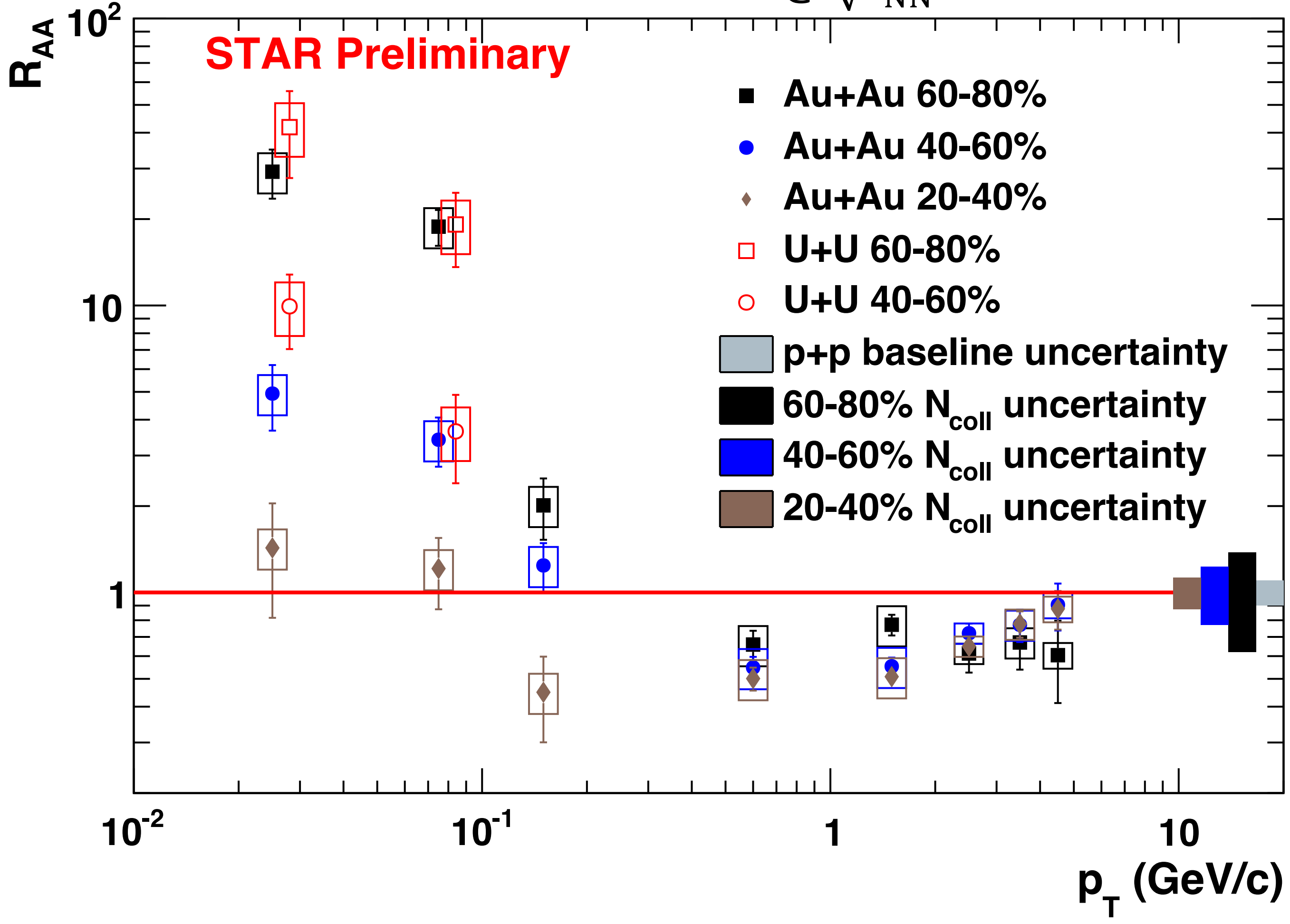
In 60-80% Au+Au :

→Clear ϕ and J/ψ peaks

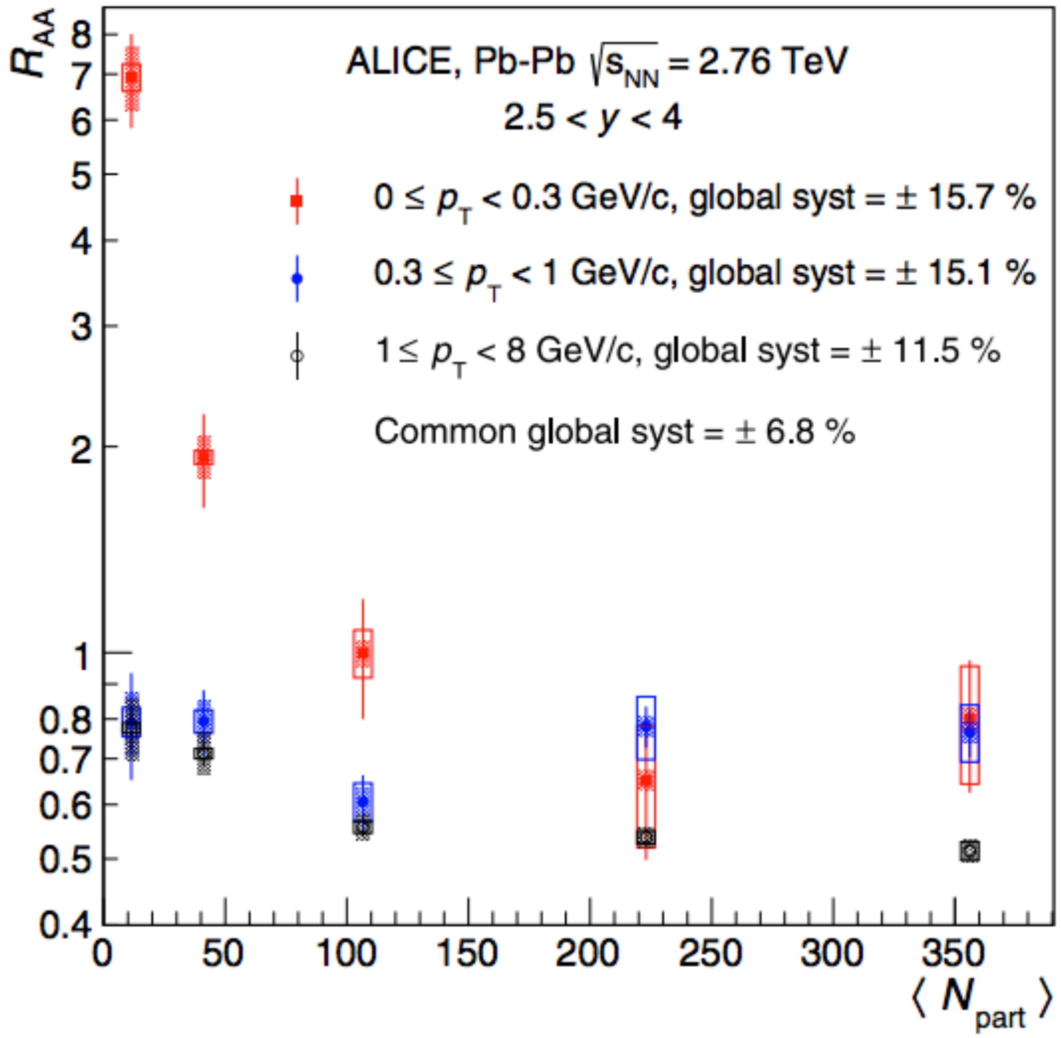
→S/B > ~1/10
(~1/100 to 1/250 in e^+e^-)

Significantly more data in semi-central and central collisions

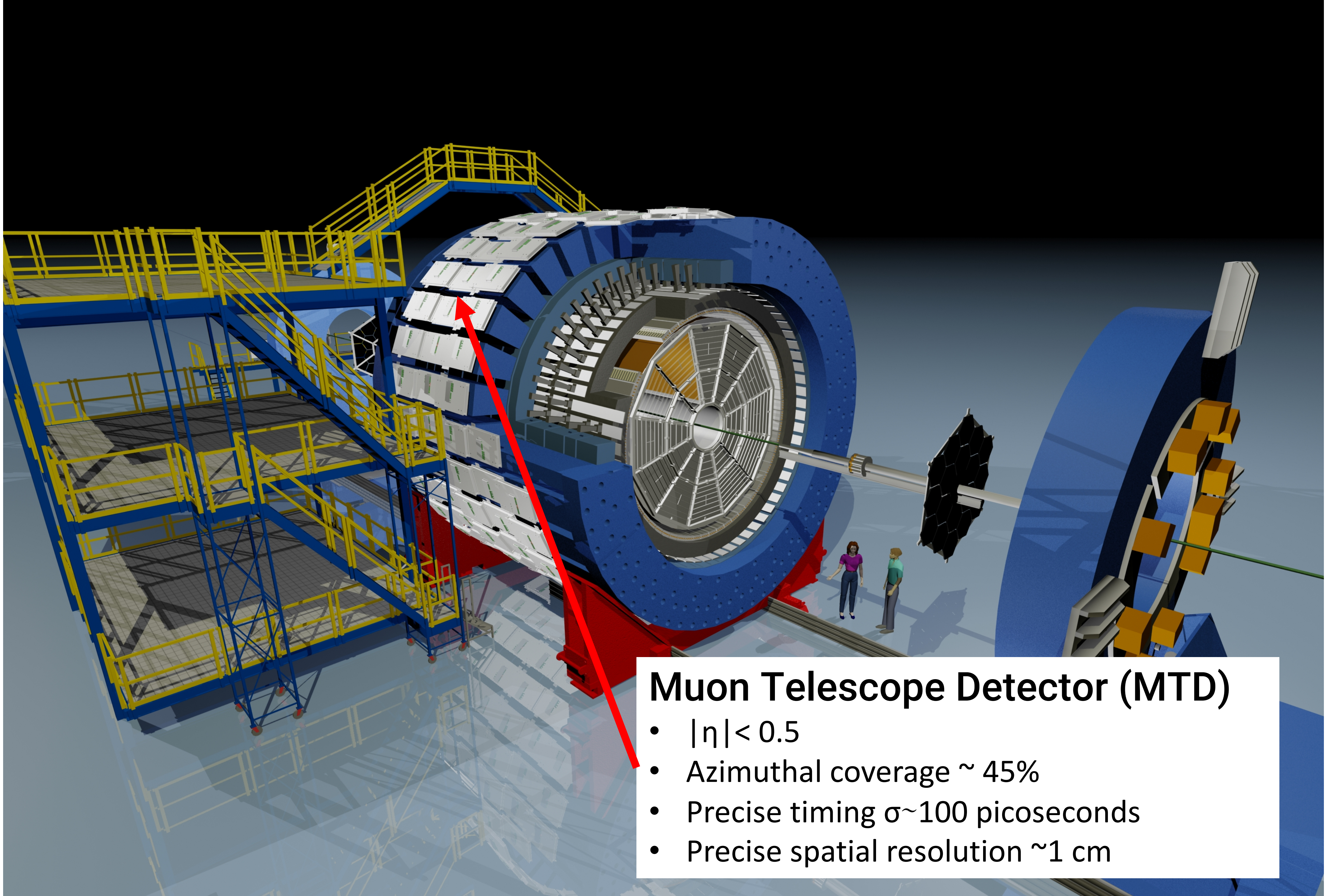
J/ψ R_{AA} for Au+Au collisions @ $\sqrt{s_{NN}}$ = 200 GeV and U+U collisions @ $\sqrt{s_{NN}}$ = 193 GeV



J/ψ R_{AA}



PRL**116**, 222301 (2016)

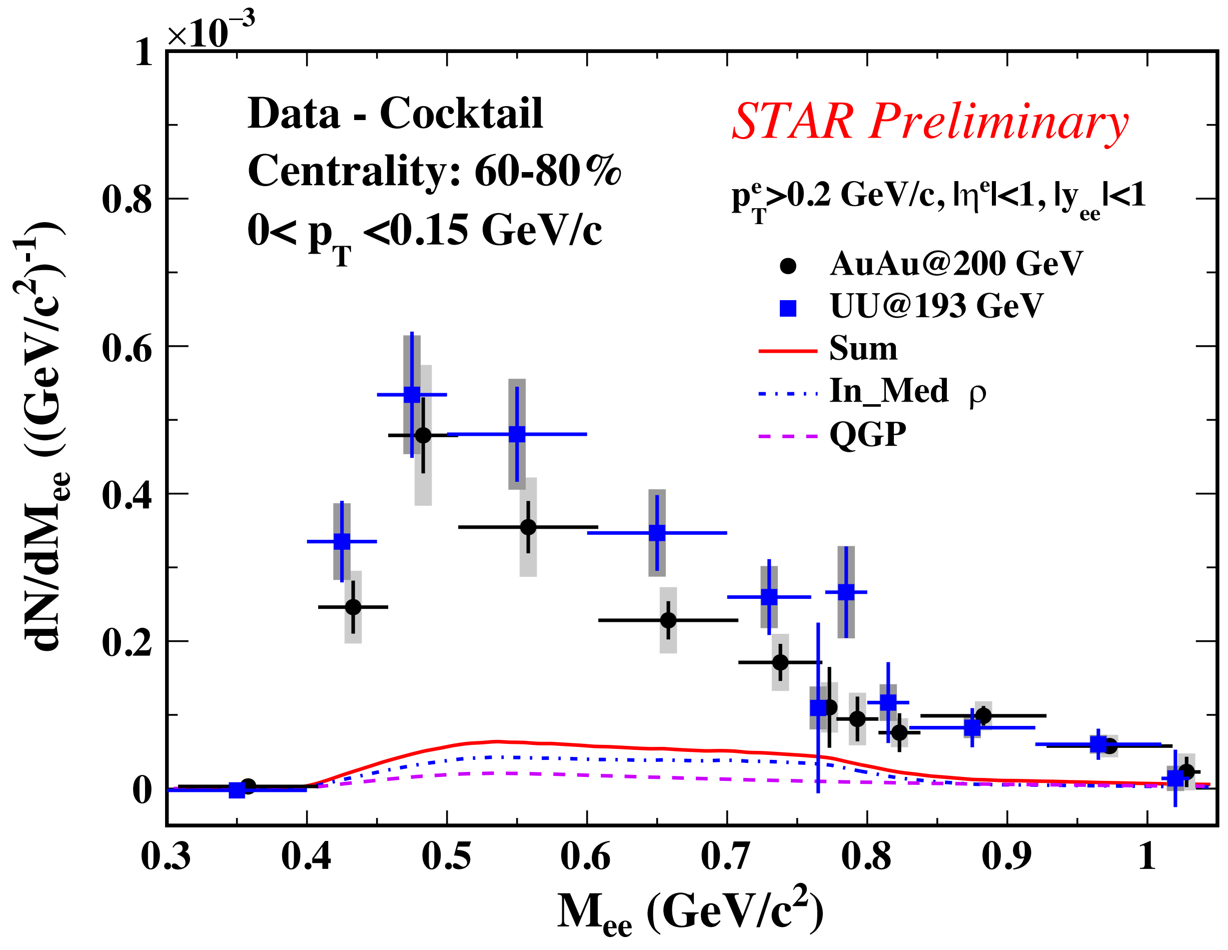


Muon Telescope Detector (MTD)

- $|\eta| < 0.5$
- Azimuthal coverage ~ 45%
- Precise timing σ~100 picoseconds
- Precise spatial resolution ~1 cm

→Excess is consistent in Au+Au and U+U

→Excess cannot be explained by hadronic contributions modified by medium



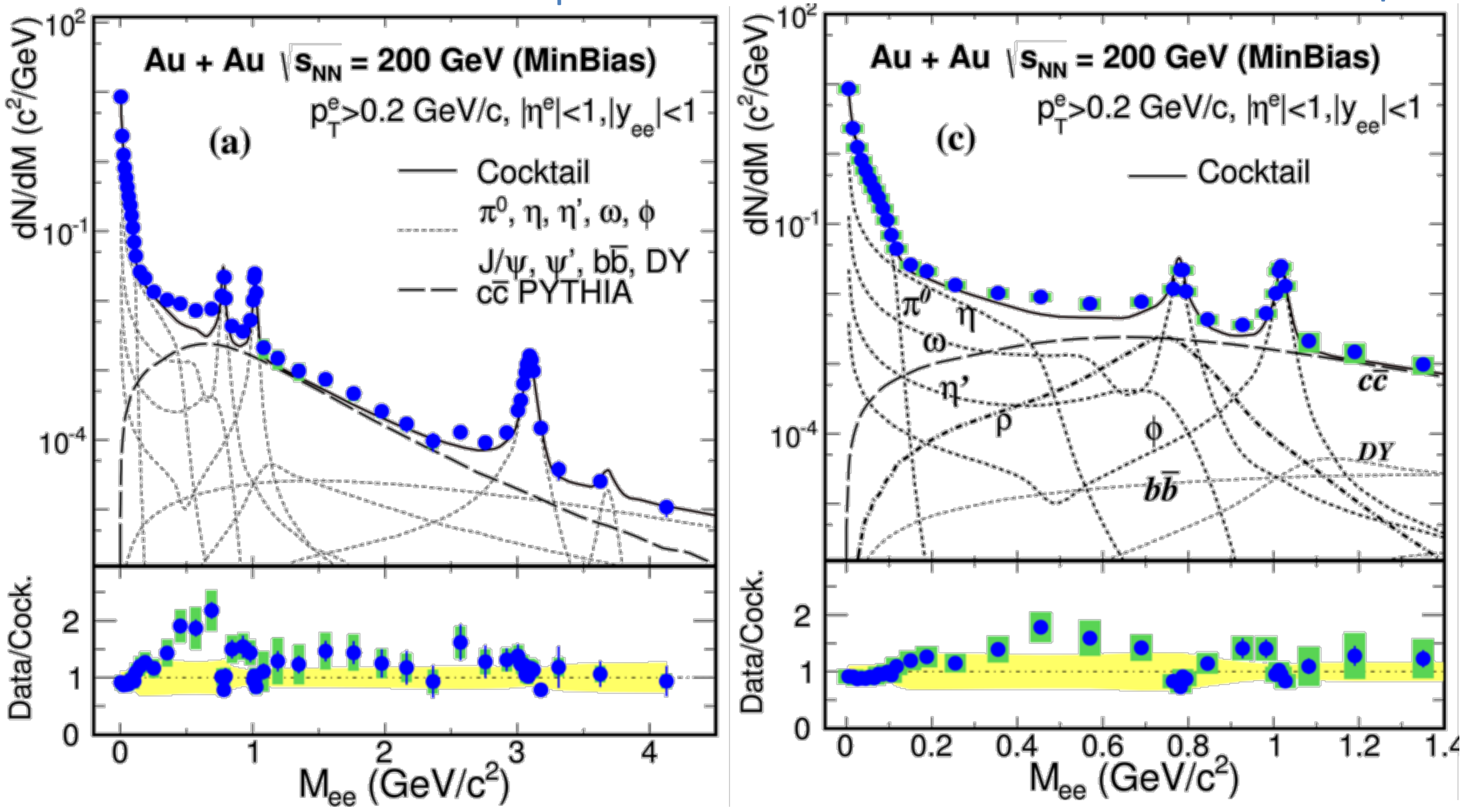
STAR Dielectron Results in Au+Au & U+U Collisions @ RHIC Top Energies

Dielectrons in Au+Au @ $\sqrt{s_{NN}}$ =200 GeV

Run 10: PRL 113 (2014) 022301; Run 10+11: PRC 92 (2015) 024912

Hadron Cocktail excl. ρ

Hadron Cocktail incl. vacuum ρ



R. Rapp, Phys.Rev. C 63 (2001) 054907

O. Linnyk et al., Phys. Rev. C 85 024910 (2012)

Low Mass Range

- Significant enhancement w.r.t. hadronic cocktail **w/o** ρ

Intermediate Mass Range

- Dominant contribution from correlated charm decay
- Consistent with cocktail within uncertainties

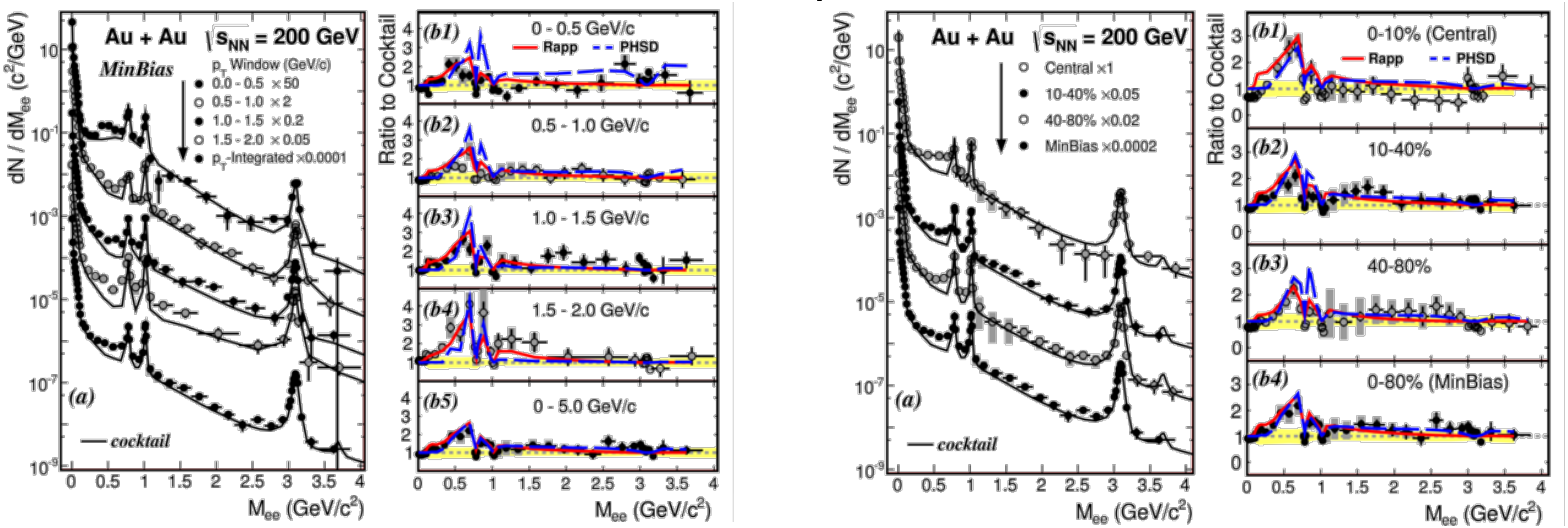
Heavy Flavor Tracker Upgrade:

Data from 2014+2016

- Includes Heavy Flavor Tracker upgrade for precise secondary vertex reconstruction
- Will help disentangle contributions in IMR (Charm modification, QGP thermal radiation, etc.)
- Analyses are ongoing

Dielectrons in Au+Au @ $\sqrt{s_{NN}}$ =200 GeV

STAR



- Data/Cocktail "enhancement factor" in LMR does not show strong dependence on centrality or p_T.
- Model calculations (Rapp & PHSD) give a reasonably good description across p_T and centrality differentials.

Dielectrons in U+U @ $\sqrt{s_{NN}}$ = 193 GeV

Expected to have ~20% higher energy density compared to Au+Au @ 200 GeV

- Kikola *et al.*, PRC84 054907 2011
- Expect longer medium lifetime
- Expect higher excess yield in LMR

Significant excess yield in ρ-like mass region (300 < M_{ee}<760 MeV/c^2)

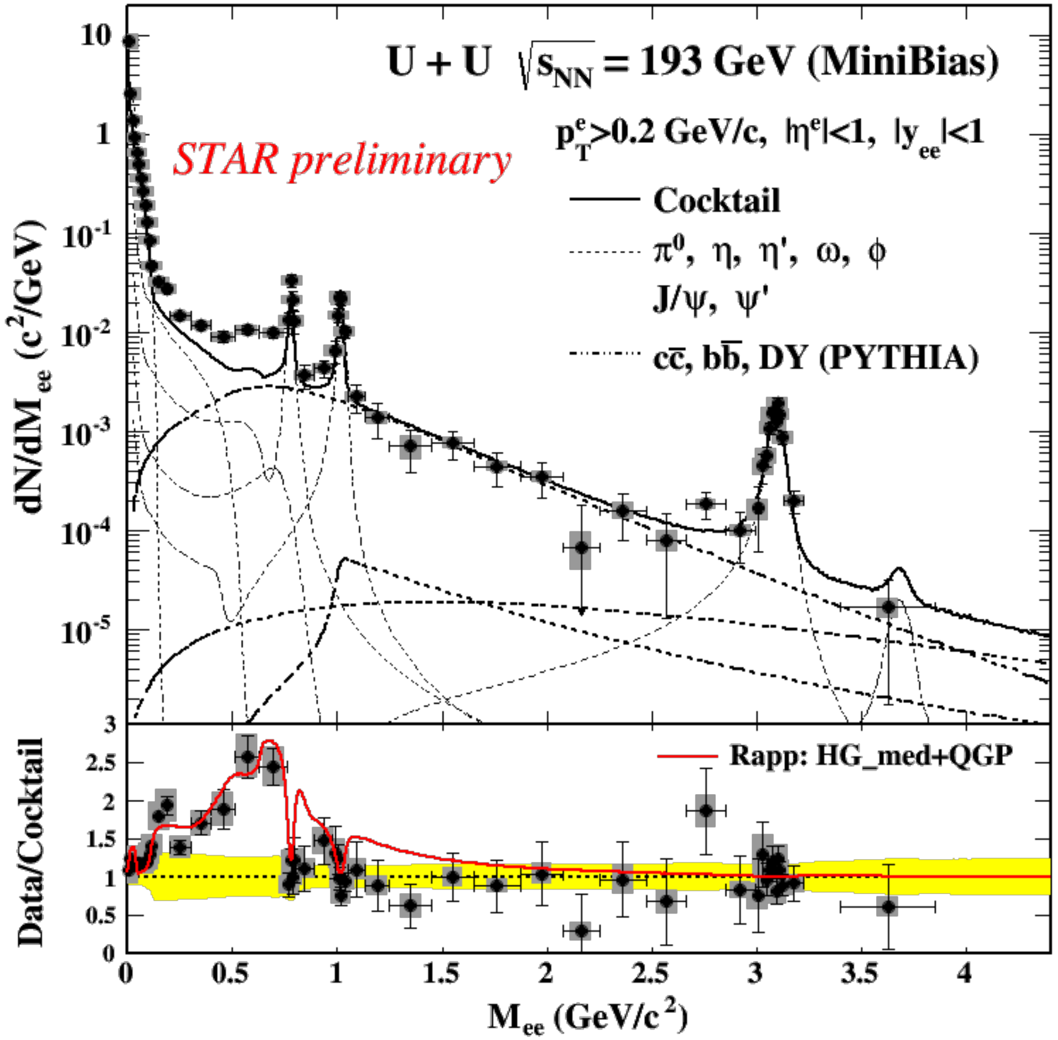
- Data/cocktail = 2.1 ± 0.1 (stat) ± 0.2 (syst) ± 0.3 (cocktail)
- Large contribution (~48%) from charm in this range
  - σ_{cc}=797 μb, σ_{bb}=3.7 μb, σ_{DY}=42nb
- Model vs. data shows good agreement

Model simulation:

R. Rapp – Adv. High energy Phys. (2013) 148253

Cocktail simulations:

STAR, PRC 92 (2015) 024912

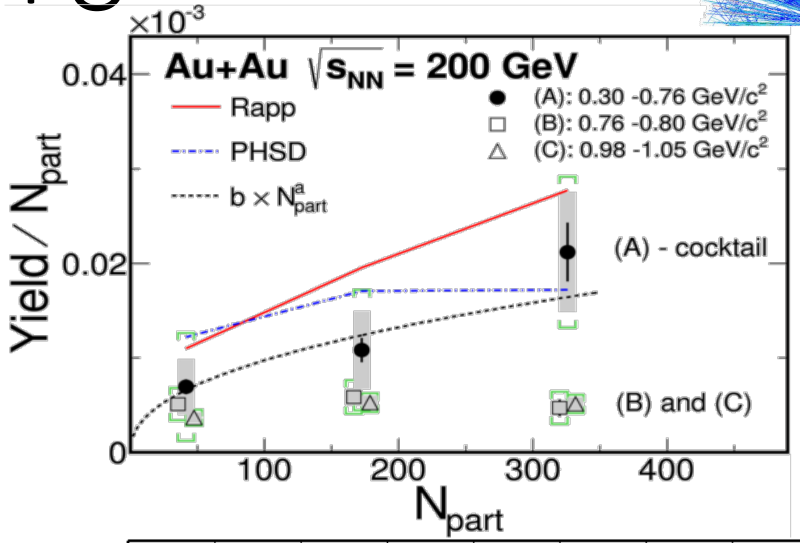


Shuai Yang, QM2015

Dielctrons in Au+Au and U+U

What have we learned?

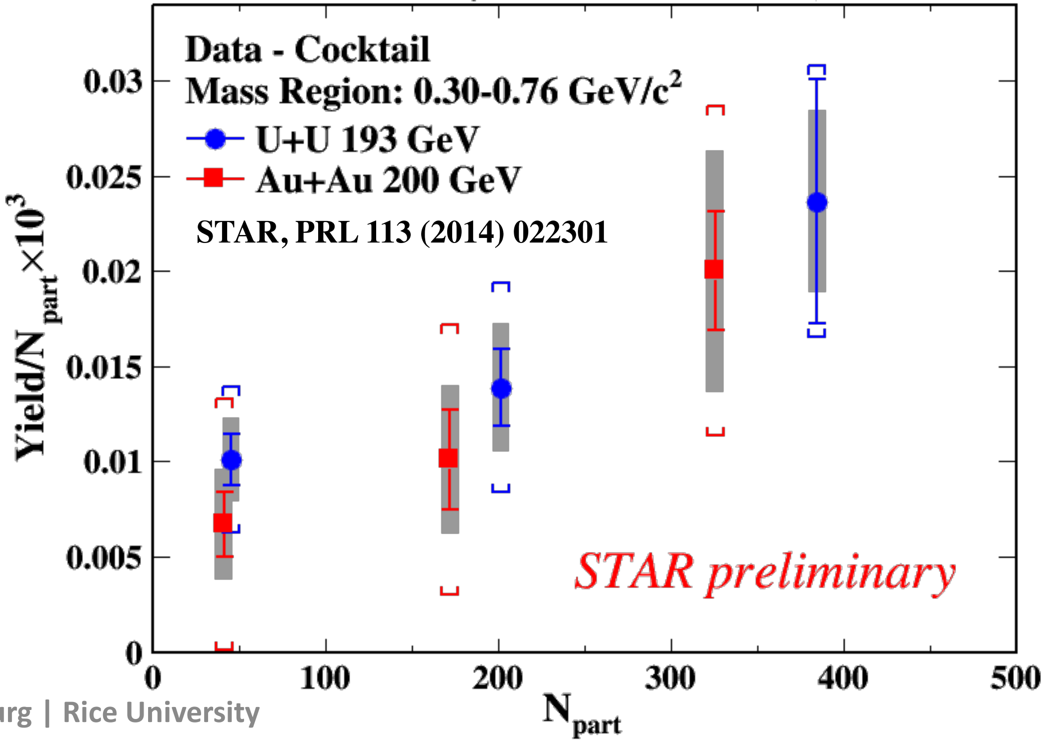
- Excess yield in ρ-like mass region increases faster than N_{part} scaling $\rightarrow \sim(Npa_{rt})^{\alpha}$, α=1.44$\pm$0.10 (Au+Au @ 200 GeV)



A: ρ-like 0.30-0.76 GeV/c^2

B: ω-like 0.76-0.80 GeV/c^2

C: φ-like 0.98-1.05 GeV/c^2

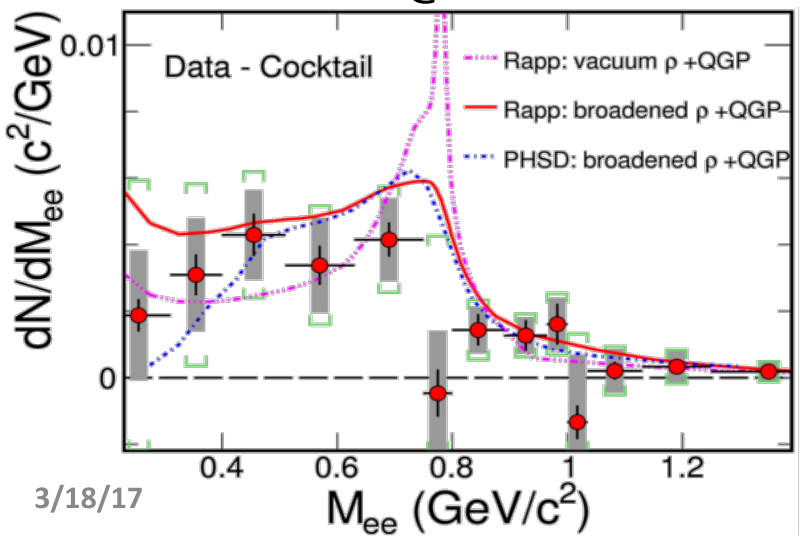


Dielctrons in Au+Au and U+U

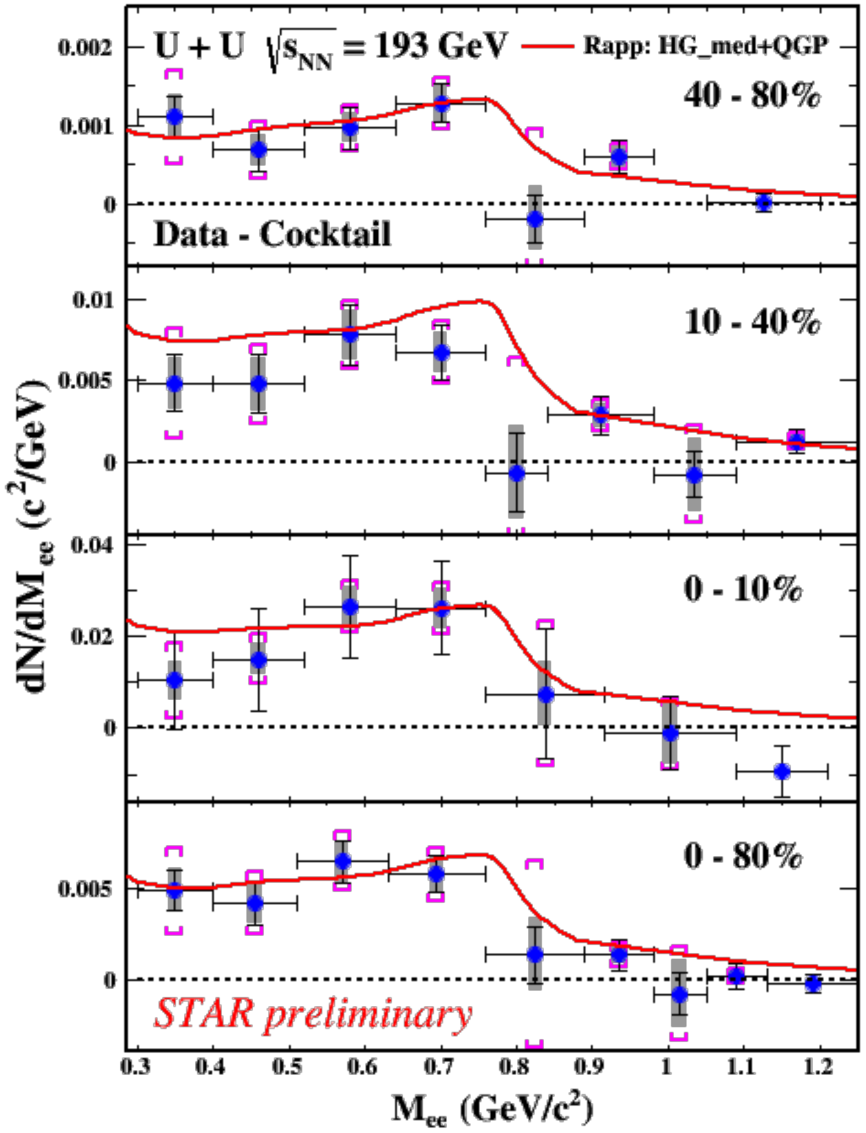
What have we learned?

- Vacuum ρ disfavored by data
- Both Rapp & PHSD models consistently describes the data
- LMR excess shows little dependence on p_T or centrality

Au+Au @ 200 GeV



PRC 92 (2015) 024912



Dielctrons in Au+Au and U+U

What have we learned?

- Vacuum ρ disfavored by data
- Both Rapp & PHSD models consistently describes the data
- LMR excess shows little dependence on p_T or centrality

Strong motivation to further explore production dynamics + models' ability to describe data

- measure excess yield in ρ-like mass region vs. $\sqrt{s_{NN}}$