Di-lepton measurements from STAR: current status and future perspective

Lijuan Ruan
(*Brookhaven National Laboratory*)

Outline:

- **Motivation and Introduction**
- **Recent results from STAR**
- **Future perspectives from STAR**
- **Conclusions and outlook**

What have we learnt so far at RHIC

A hot, dense medium with partonic degrees of freedom created at RHIC:

Jet quenching

Baryon enhancement, number of constituent quark scaling in elliptic flow

…

Next:

Is the system thermalized and how does the system thermalize?

What are the properties of the strongly-coupled system?

What is the phase structure of QCD matter?

What exotic particles are produced at RHIC?

What is the mechanism for partonic energy loss?

Does QCD matter demonstrate novel symmetry properties?

What is the nature of the initial state in nuclear collisions

…

STAR decadal plan: C. Gagliardi QM2011

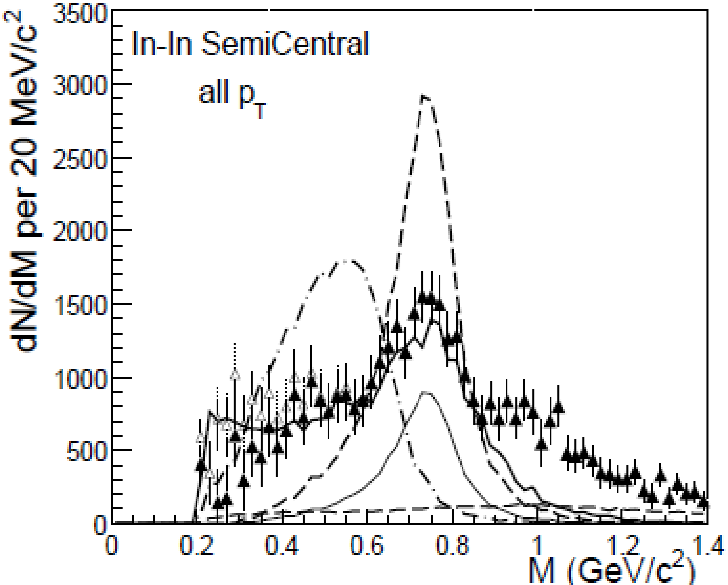
STAR's di-lepton program

The initial temperature of sQGP; the mass origin of hadrons; color screening features of heavy quarkonia …

Measurements	Physics
low mass di-leptons	**thermal radiation of QGP;** **in-medium modifications of vector meson (ρ ω ϕ), chiral symmetry restoration**
intermediate mass di-leptons	**thermal radiation of QGP;** **heavy flavor modification; resonances in sQGP**
large mass: heavy quarkonia	**T of QGP, color screening, quarkonium production mechanism**

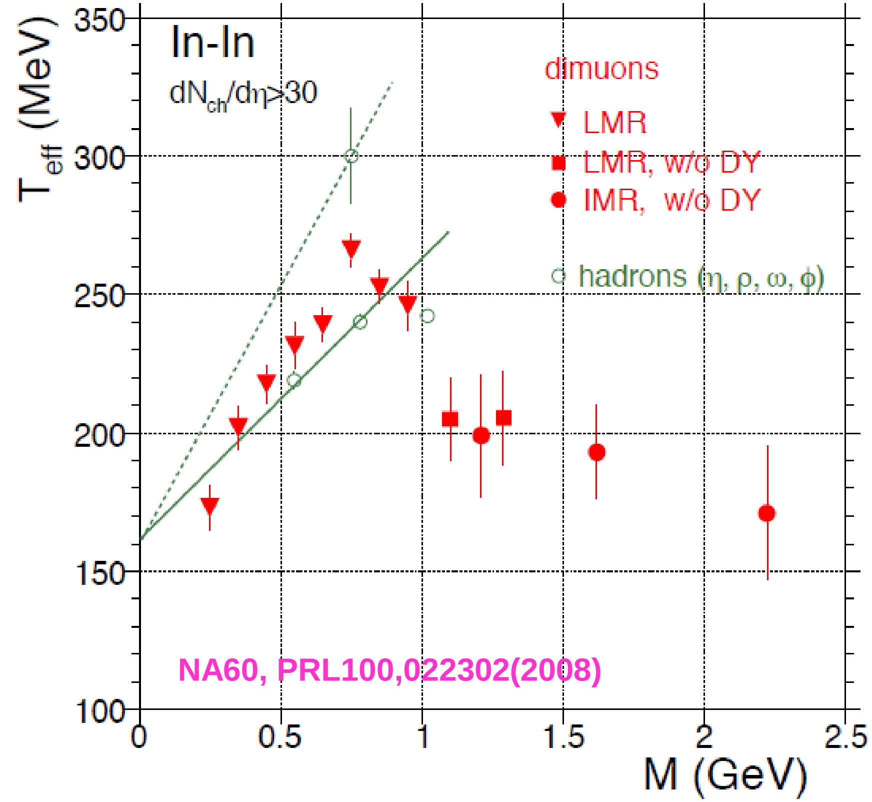
BROOKHAVEN NATIONAL LABORATORY

Di-muon continuum at NA60



NA60, PRL96,162302(2006)

FIG. 4: Comparison of the excess mass spectrum for the semicentral bin to model predictions, made for In-In at $dN_{ch}/d\eta$=140. Cocktail ρ (thin solid), unmodified ρ (dashed), in-medium broadening ρ [4, 5] (thick solid), in-medium moving ρ related to [6, 7] (dashed-dotted). The errors are purely statistical. The systematic errors of the continuum are about 25% (see text). The open data points show the difference spectrum resulting from a decrease of the η yield by 10% (which should also be viewed as a systematic error).

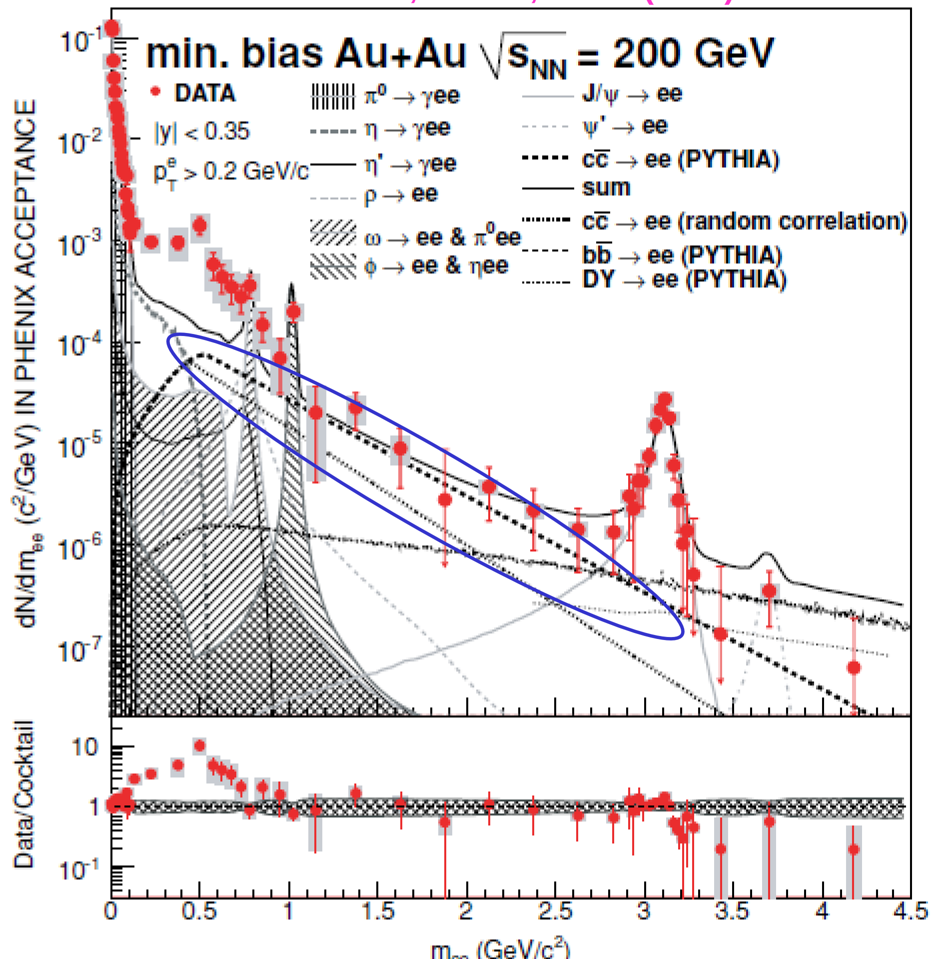


NA60, PRL100,022302(2008)

1. In-medium modifications of rho0 spectra in In-In collisions at NA60
2. Intermediate mass di-muons show less radial flow.

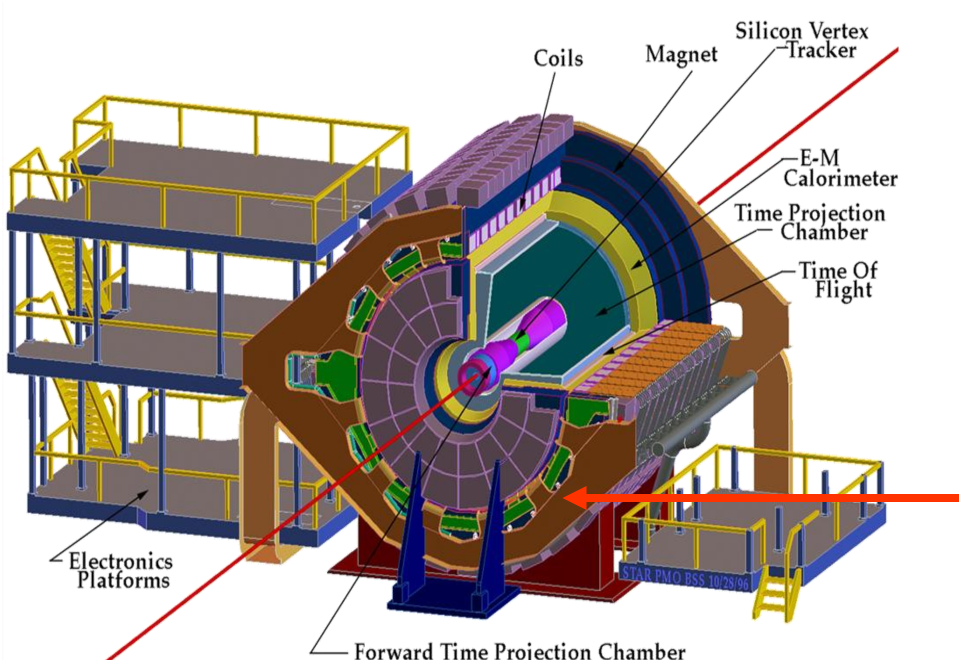
Di-electron Spectrum at PHENIX

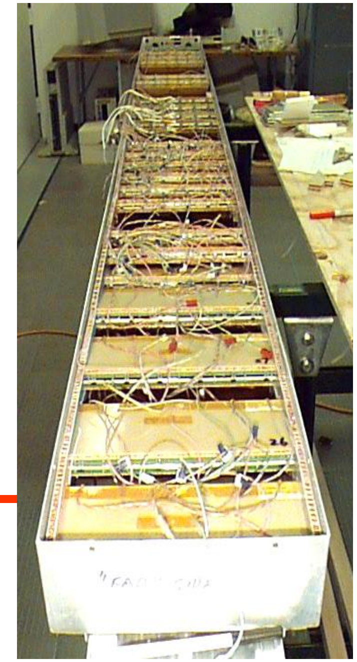
PHENIX, PRC81,034911(2010)



1. In-medium modifications of rho0 can not explain the enhancement at 0.15-0.7 GeV/c^2
2. Charm contribution to di-lepton spectra is significant at low mass at RHIC.
3. Charm contribution to di-lepton spectra might be dominant in the intermediate mass region. Its correlation makes a big difference to access the thermal radiation contribution from QGP.

STAR detector: TPC, EMC & MRPC-TOF





Time Projection Chamber

1. **Tracking**
2. **Ionization energy loss (dE/dx):**
   (π, K) < 0.7 or > 3 GeV/c,
   proton < 1 or > 3 GeV/c
3. **Coverage $-1<\eta<1$**

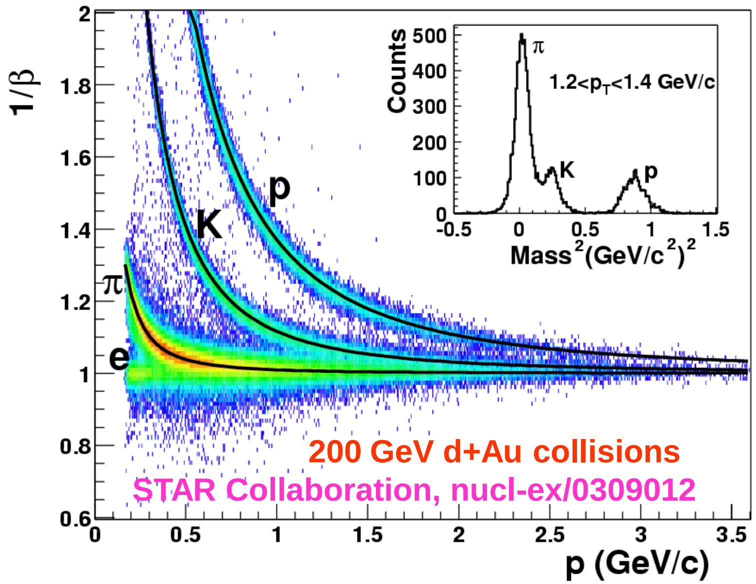
Electro-magnetic Calorimeter

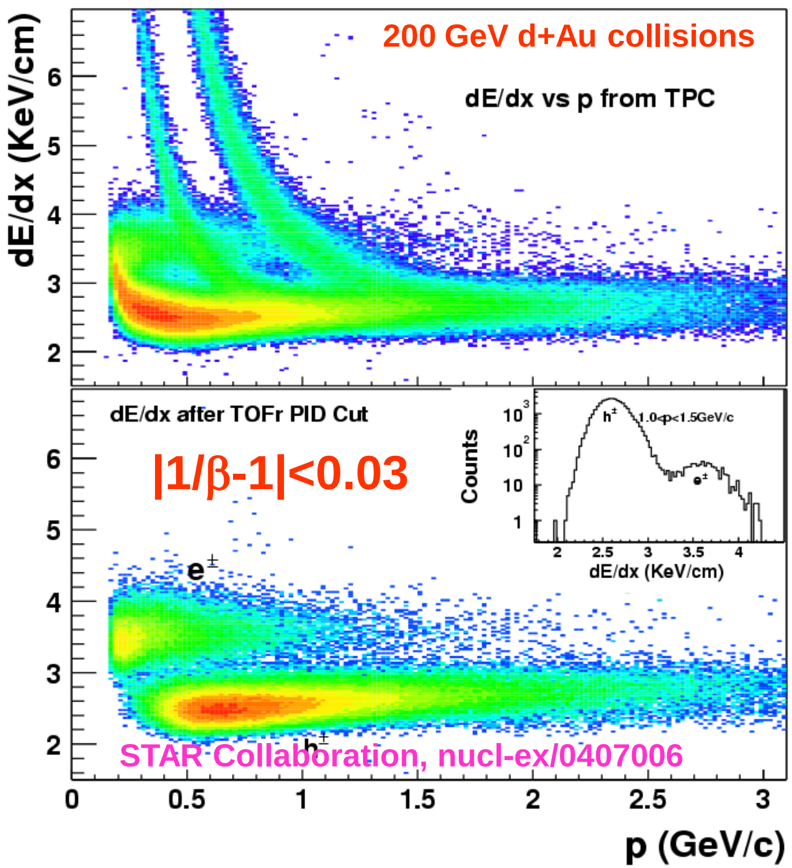
1. **electrons and photons**

A new technology (TOF) ----
Multi-gap Resistive Plate Chamber
adopted from CERN-Alice.

1. **Good timing resolution,**
   (π, K) ~ 1.6 GeV/c, proton ~ 3 GeV/c
2. **Coverage: $-0.9<\eta<0.9$**
3. **Coverage**
   (4% y2008, 72% y2009, 100% y2010)

STAR Time of Flight detector performance





TOF PID: (π, K) ~ 1.6, proton ~ 3 GeV/c
STAR Collaboration, PLB616(2005)8

TOF enables clean electron PID up to P_T < 3 GeV/c.
STAR Collaboration, PRL94(2005)062301

M. Shao et al., NIMA 558(2006)419

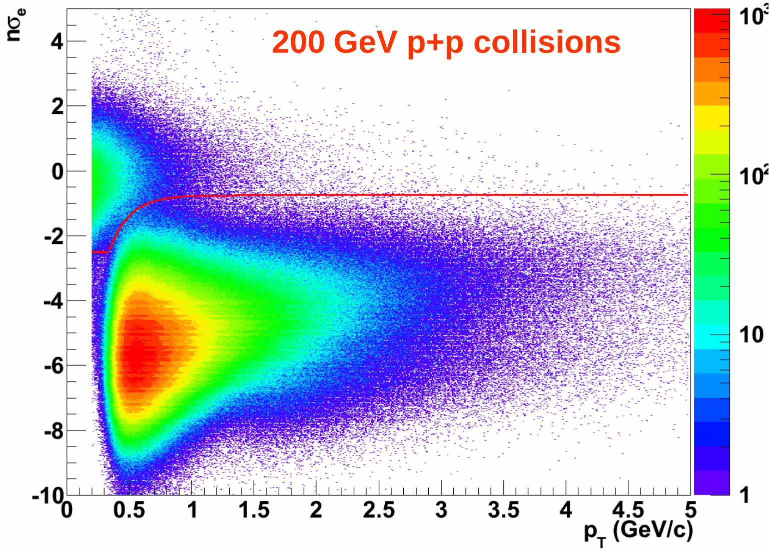
Data sets for di-electron analyses

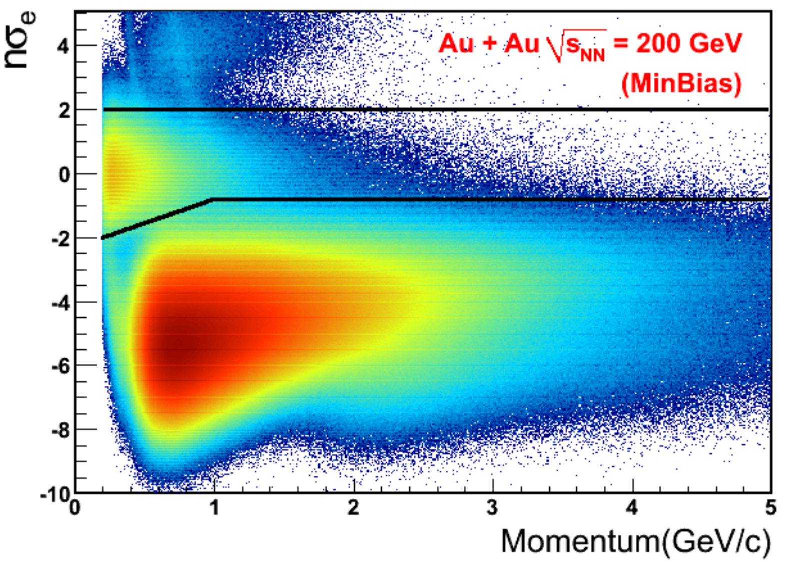
large acceptance of the TOF system and low material budget * at mid-rapidity

Run period	Collision energy	Beam species	Detector
2009	200 GeV	p+p	TPC+TOF(72%) +EMC
2010	200 GeV	Au+Au	TPC+TOF+EMC
	62 GeV	Au+Au	TPC+TOF+EMC
	39 GeV	Au+Au	TPC+TOF+EMC
2011	200 GeV	Au+Au	TPC+TOF+EMC
	27 GeV	Au+Au	TPC+TOF+EMC
	19 GeV	Au+Au	TPC+TOF+EMC

*** beam pipe (0.29% radiation length), beam pipe wrap (0.14%), air (0.17%), IFC (0.45%)**

Electron identification capability





$|1/\beta-1|<0.03$

$|1/\beta-1/\beta_{expected}|<0.025$

Clean electron identification obtained with TPC+TOF:

Electron purity: 99% in p+p and 97% in minbias Au+Au

Hadron contamination contribution to di-lepton is insignificant and taken as part of systematic uncertainties.

Di-electron signal and background

Di-electon signal:

e+e- pairs from light flavor meson and heavy flavor decays (charmonia and open charm correlation):

$\pi^0 \rightarrow \gamma e^+e^-$, $\eta \rightarrow \gamma e^+e^-$, $\eta' \rightarrow \gamma e^+e^-$,

$\omega \rightarrow e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\rho^0 \rightarrow e^+e^-$, $\phi \rightarrow e^+e^-$, $\phi \rightarrow \eta e^+e^-$,

$J/\psi \rightarrow e^+e^-$, ccbar$\rightarrow e^+e^-$, bbar$\rightarrow e^+e^-$, Drell-Yan contribution

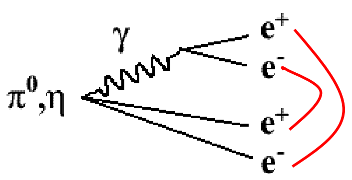
In Au+Au collisions, we search for QGP thermal radiation signals and vector meson in-medium modifications.

Background:

1. Random combinatorial background

2. Correlated cross pairs (from two e+e- pairs from one meson decays)

3. Possible jet contributions

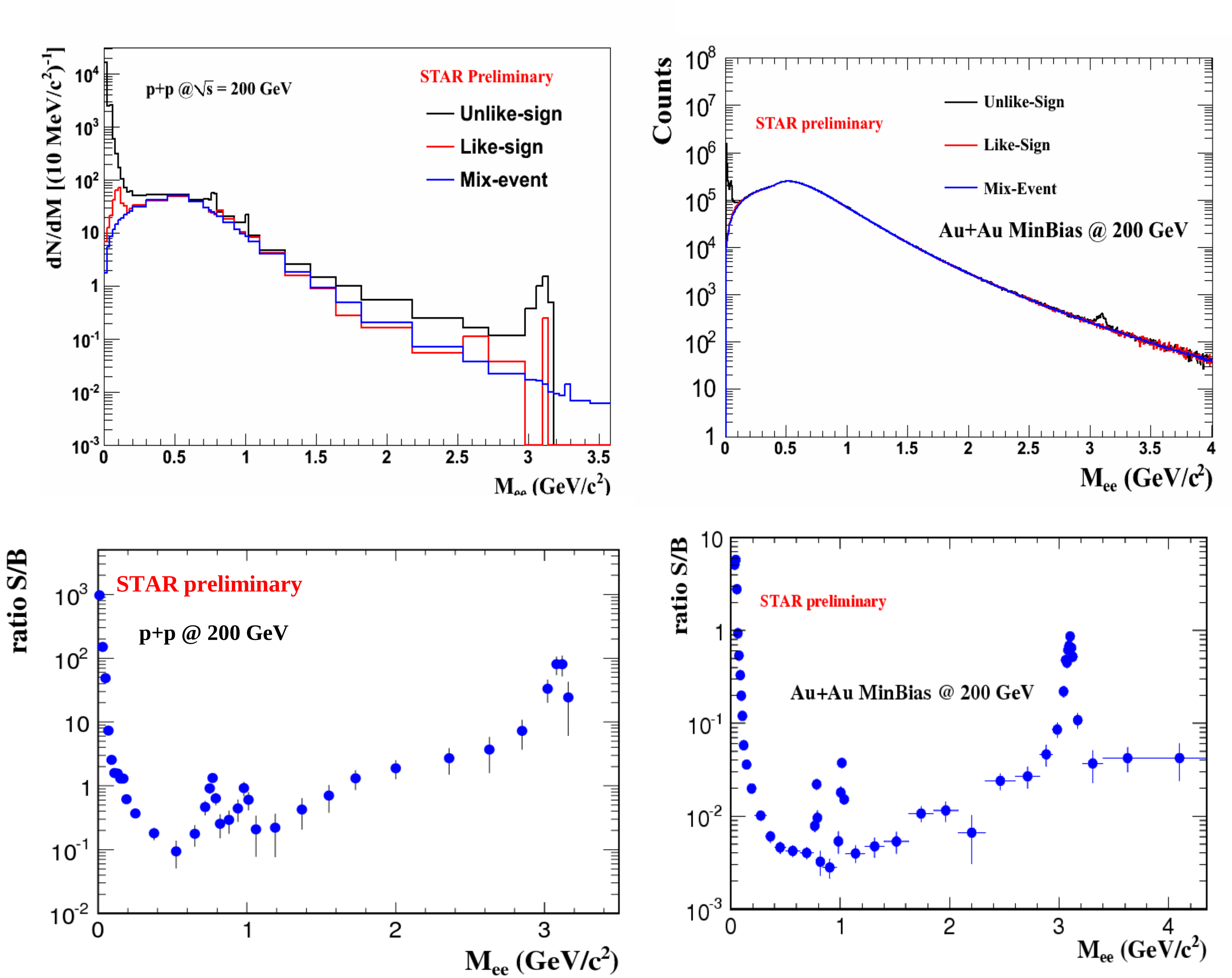


Type 1$\rightarrow$ reconstructed by mixed-event technique

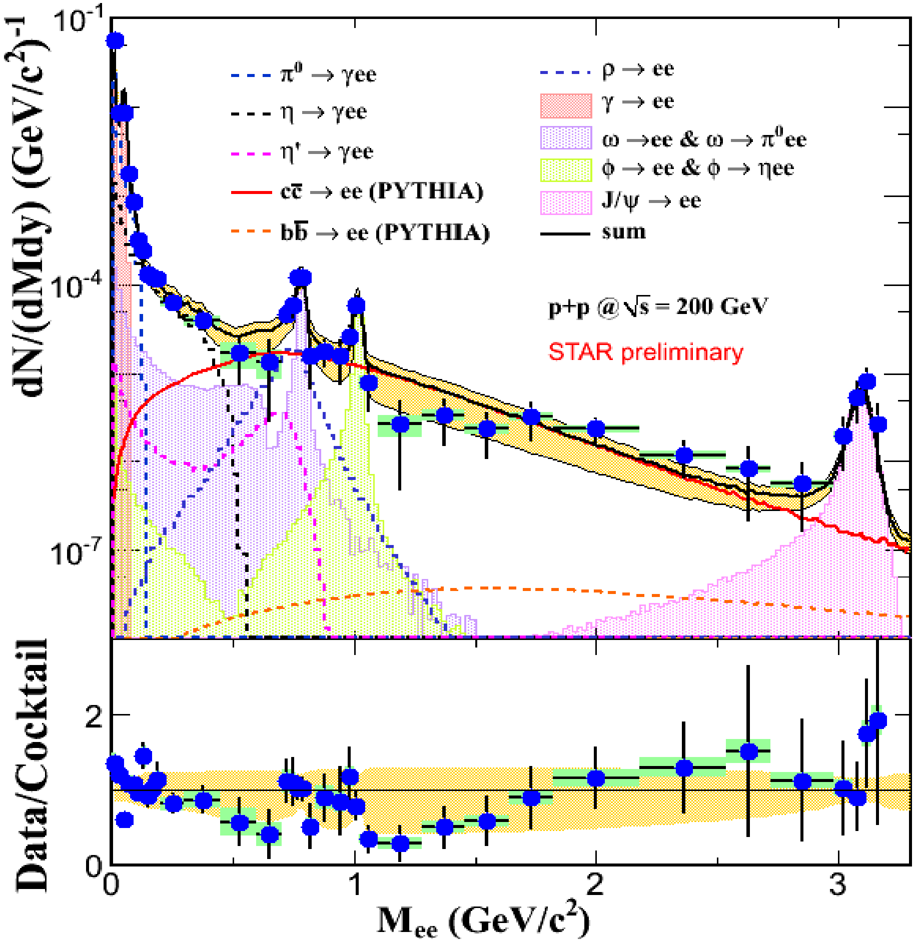
Type 2 and 3$\rightarrow$ like sign technique

BROOKHAVEN NATIONAL LABORATORY

Di-electron signals in p+p and Au+Au



Di-lepton production in 200 GeV p+p



STAR acceptance: $|y_{ee}|<1$, $|\eta_e|<1$, $p_T>0.2$ GeV/c

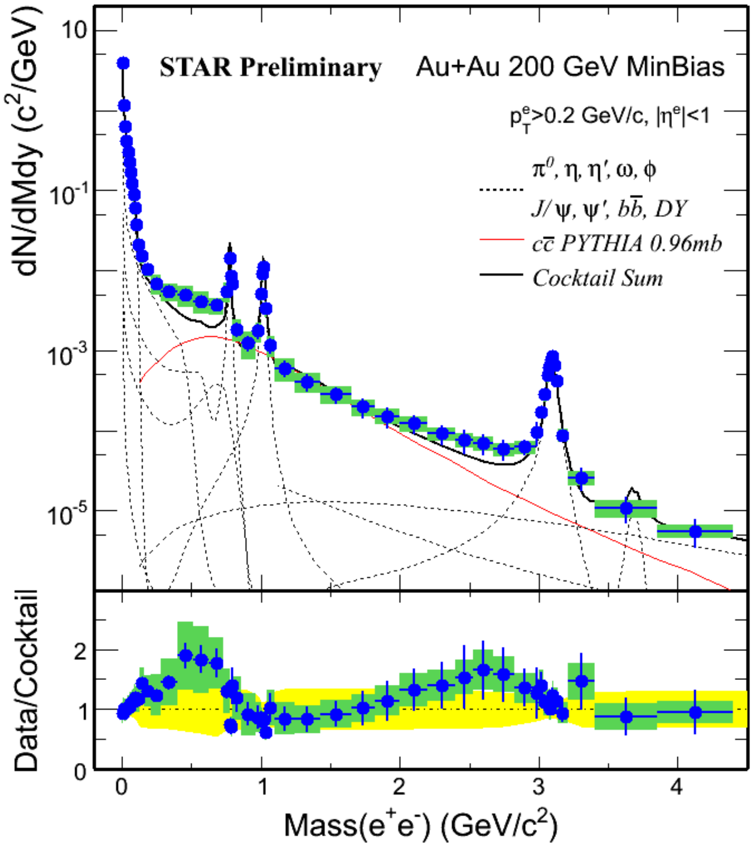
cocktail simulation is consistent with di-electron spectrum in p+p collisions at 200 GeV

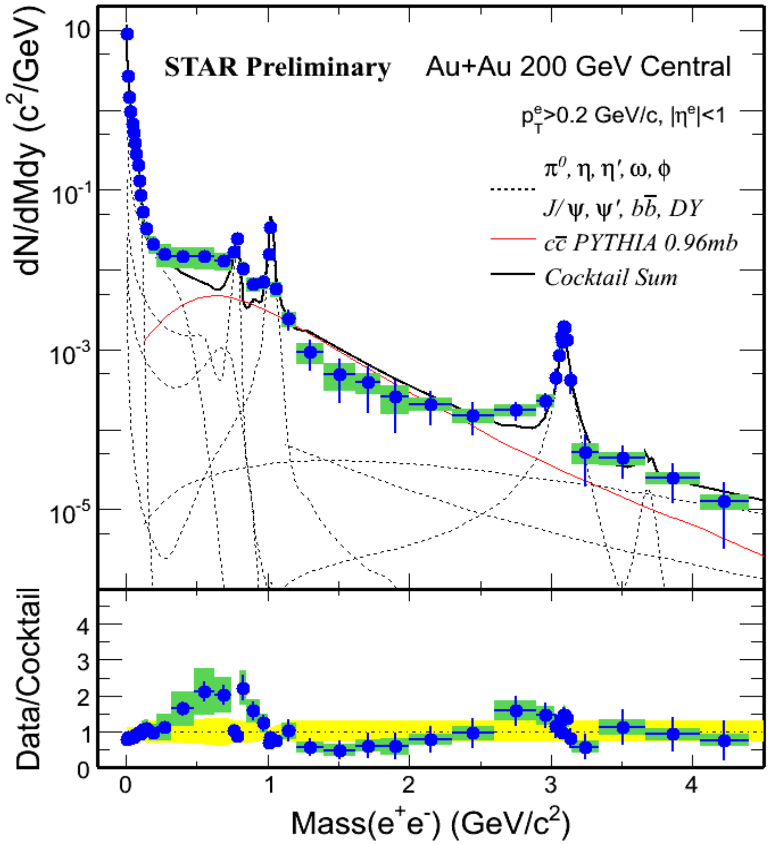
charm correlation contribution dominates in the intermediate mass region (1.1-2.9 GeV/c^2)

Simulation: charm correlation contribution is from PYTHIA .

B. Huang QM2011,SQM2011; J Zhao QM2011

Di-lepton spectra in 200 GeV Au+Au



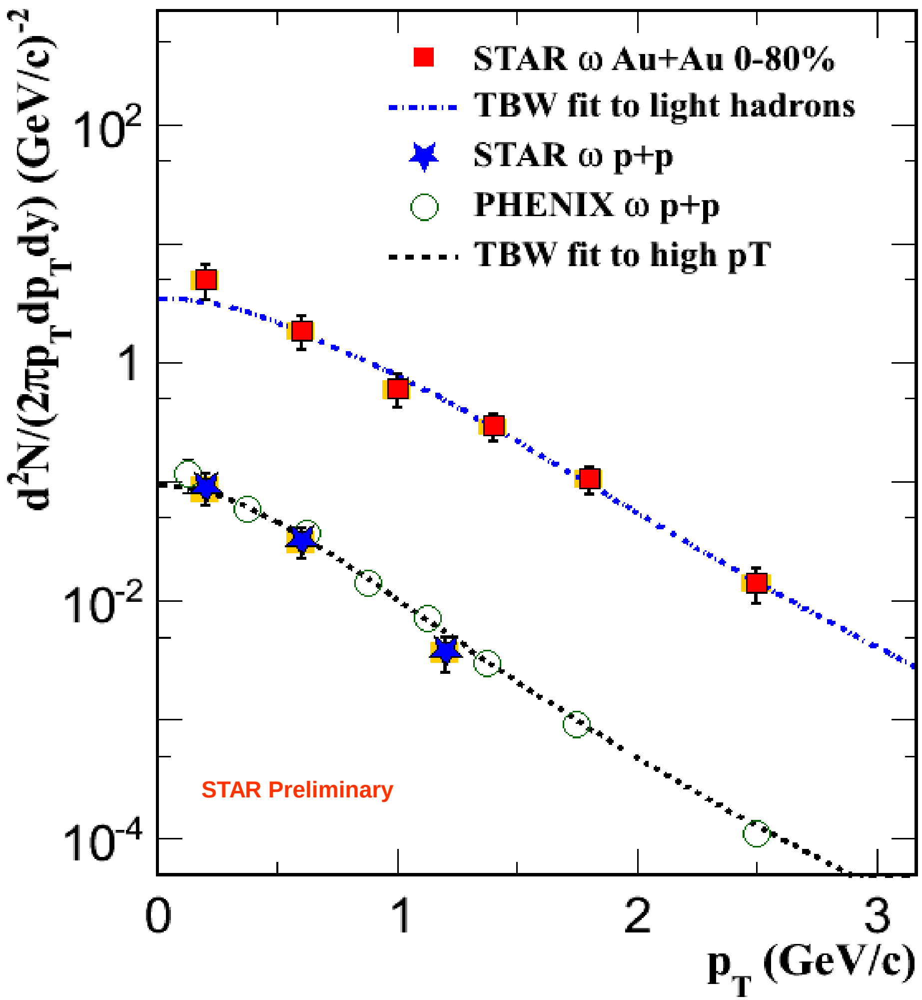


Enhancement factor in $0.15<M_{ee}<0.75$ Gev/c^2

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	1.53 ± 0.07 ± 0.41 (w/o ρ) 1.40 ± 0.06 ± 0.38 (w/ ρ)	1.72 ± 0.10 ± 0.50 (w/o ρ) 1.54 ± 0.09 ± 0.45 (w/ ρ)

J. Zhao QM2011, B. Huang SQM2011

ω→ee spectra in 200 GeV p+p and Au+Au



B. Huang QM2011, SQM2011; J Zhao QM2011

- ω→ee measurements via di-lepton channel in p+p and Au+Au at STAR
- ω→ee flow pattern is similar to light hadrons

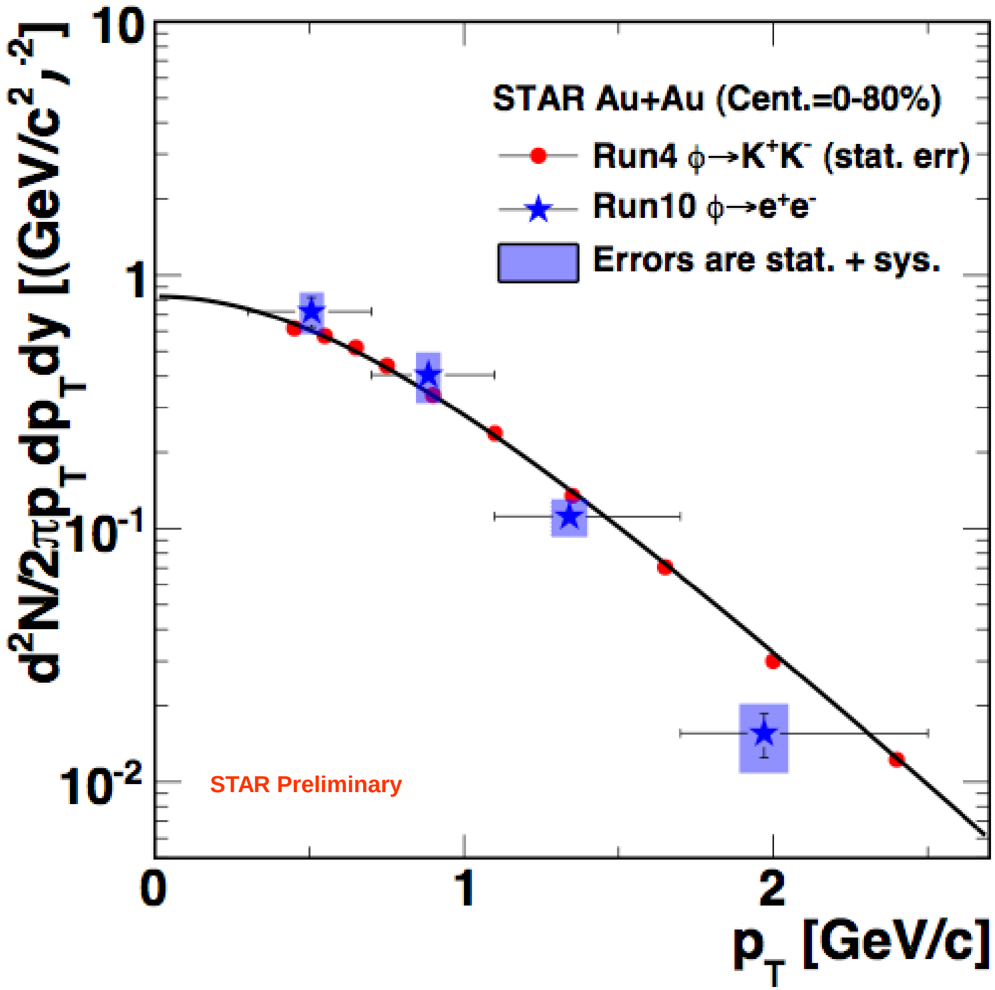
Tsallis Blast-wave(TBW) fit:

<β>=0 in p+p,

<β>=0.47 in 0-80% AuAu.

Z.Tang et al., arXiv:1101.1912

$\phi \rightarrow$ee spectra in 200 GeV Au+Au

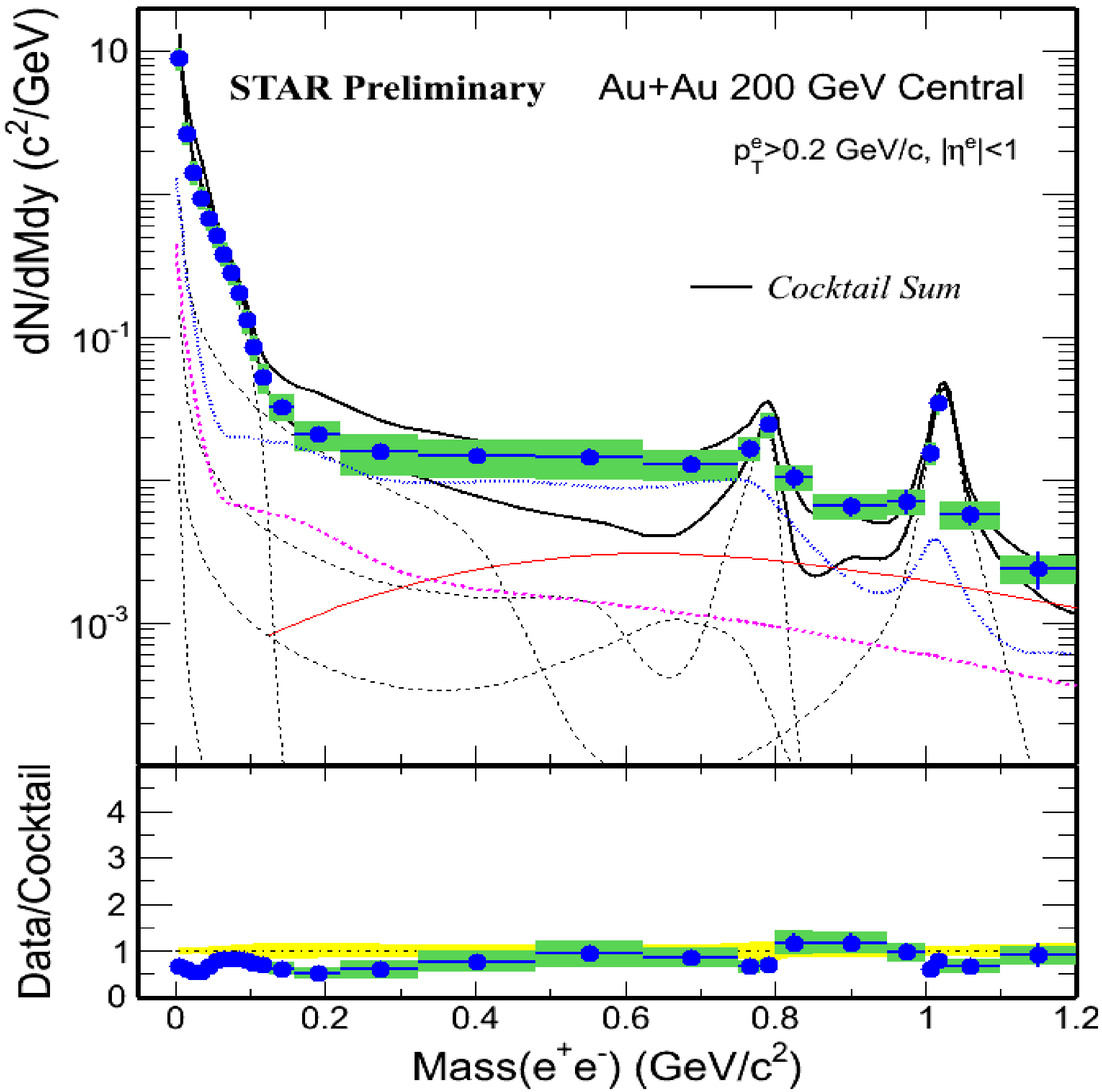


- The invariant yield of ϕ via di-lepton channel in Au+Au is consistent with that from hadronic decay channel.

- mass and width between data and simulation: consistent

M. Wada SQM2011

Compared to theoretical calculations within STAR acceptance



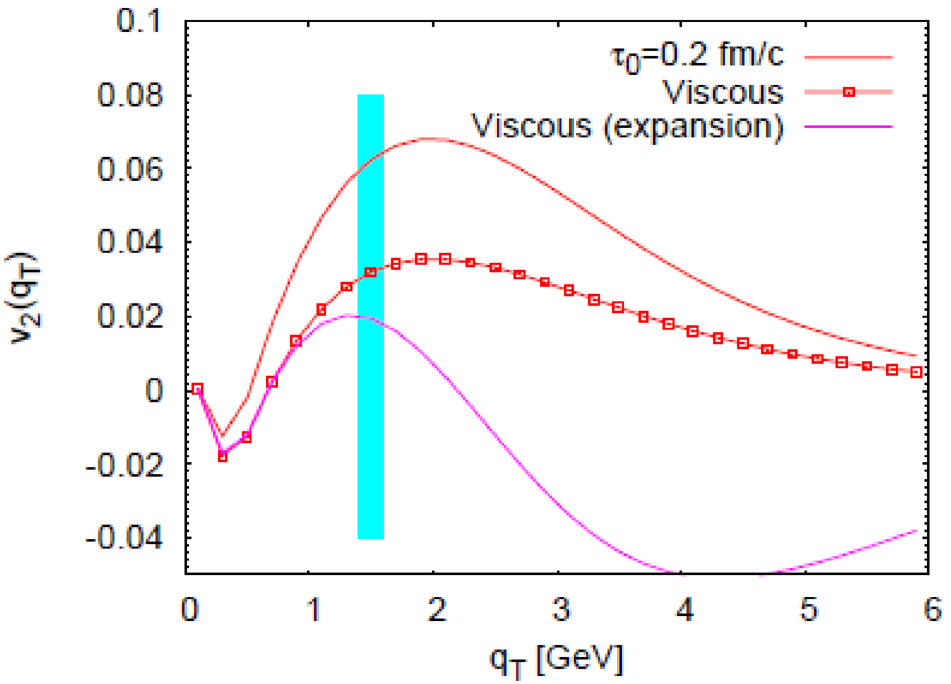
HG_med, QGP
from R. Rapp

Blue dotted:
HG_medium
Pink dotted:
QGP

Solid lines:
upper: cocktail
+ HG+QGP
lower: cocktail

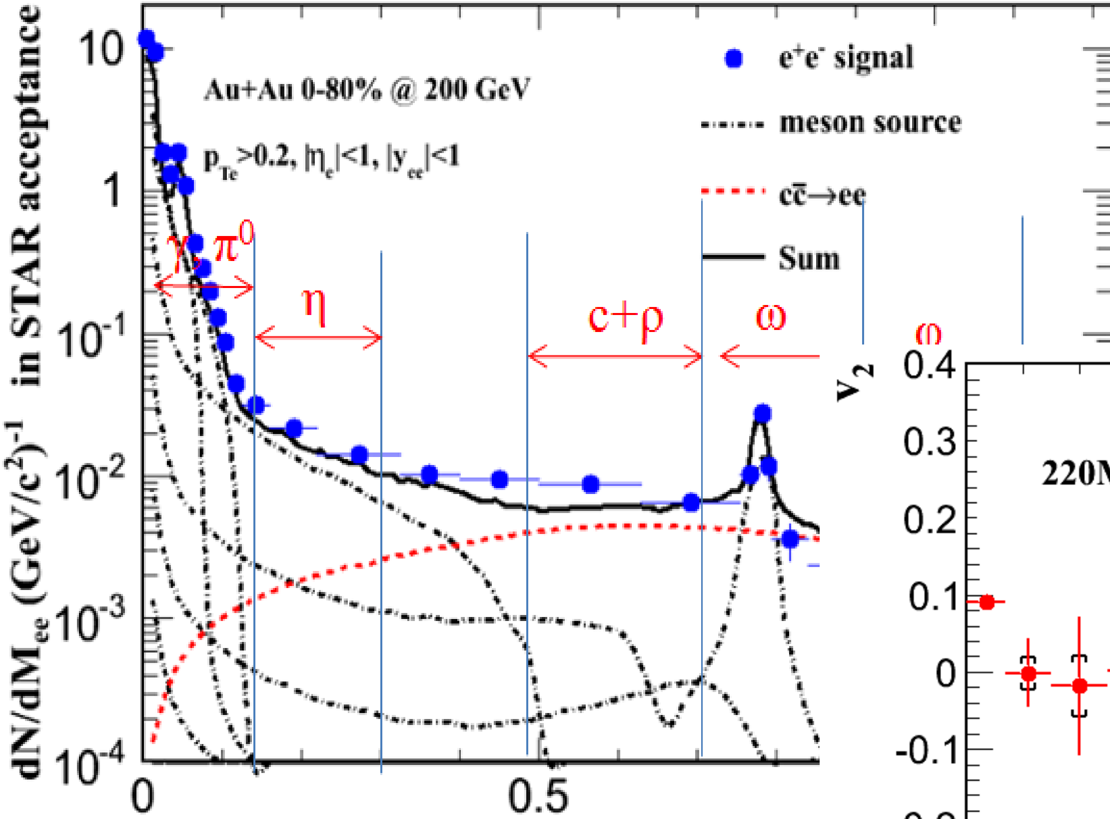
Di-lepton elliptic flow

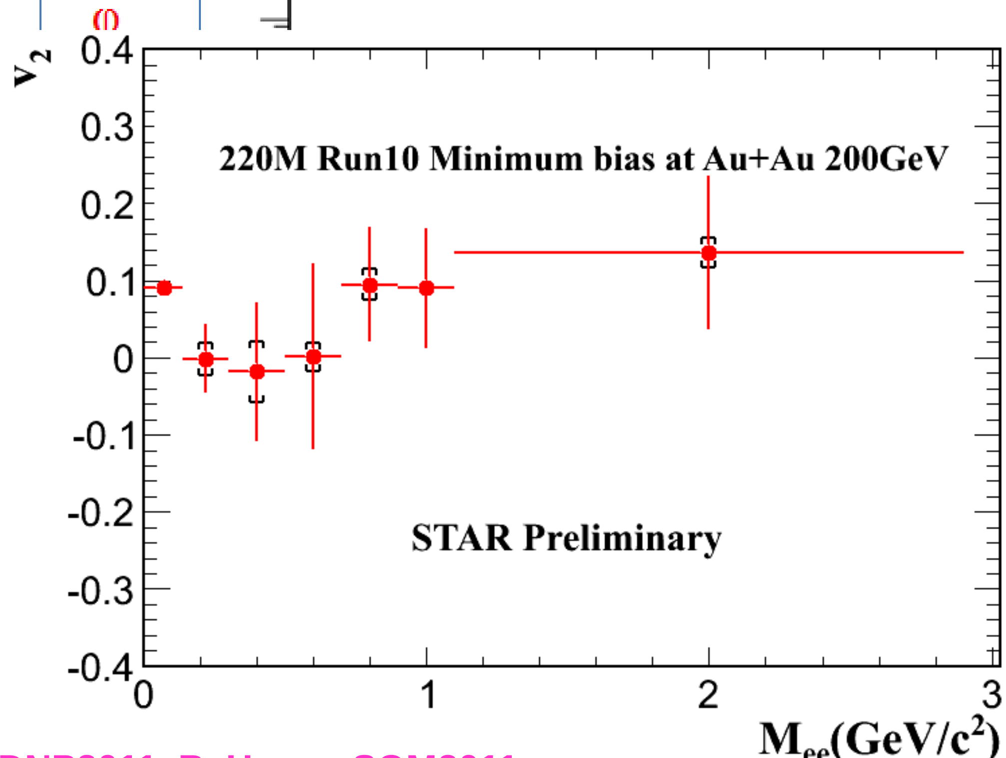
- Elliptic flow, caused by anisotropic pressure gradient, sensitive to early time dynamics in the system evolution
- From the measurements of hadron elliptic flow versus centrality, we can obtain the medium properties: eta/s
- Di-lepton elliptic flow from QGP thermal radiation, zero impact from hadronic phase, could provide direct constraints on QGP dynamics (eta/s, T, t_0…) together with spectrum measurements



K. Dusling NPA839(2010)70

v_2 versus M_{ee} at 200 GeV Au+Au

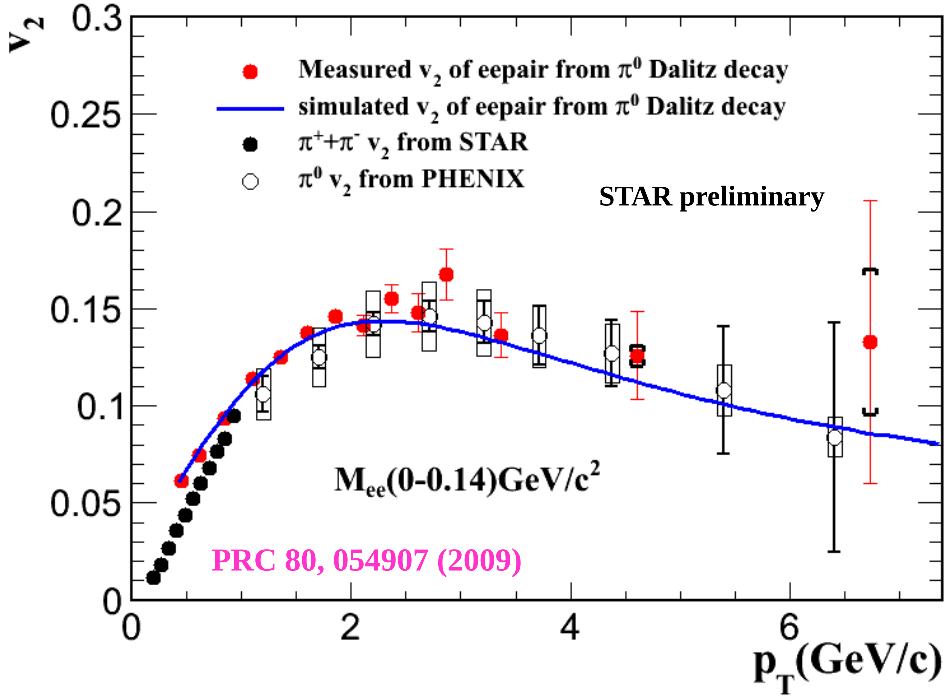


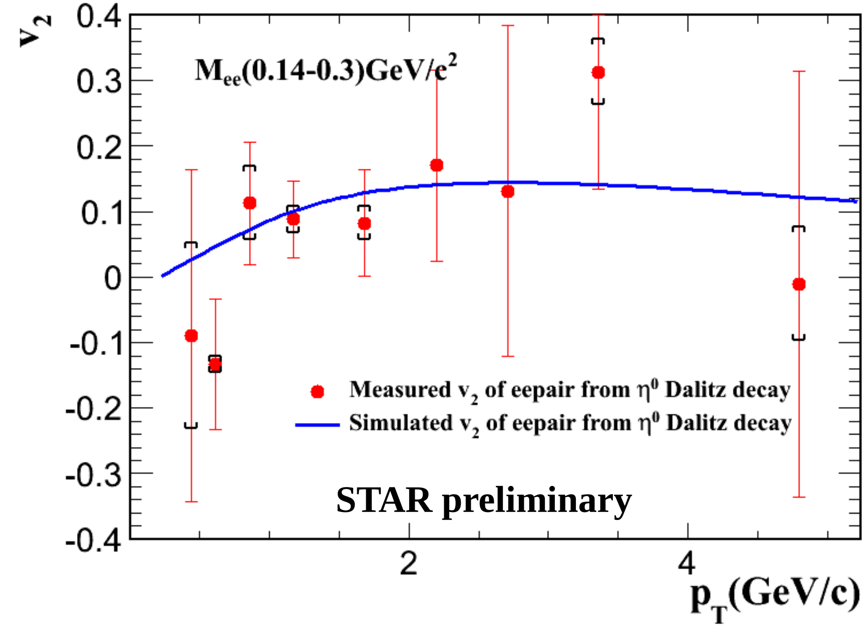


700 M minbias data from run11 is on disk.

X. Cui DNP2011, B. Huang SQM2011

v_2 of di-electrons from π^0 and η Dalitz decay





To provide a comparison (blue) curve from simulation:

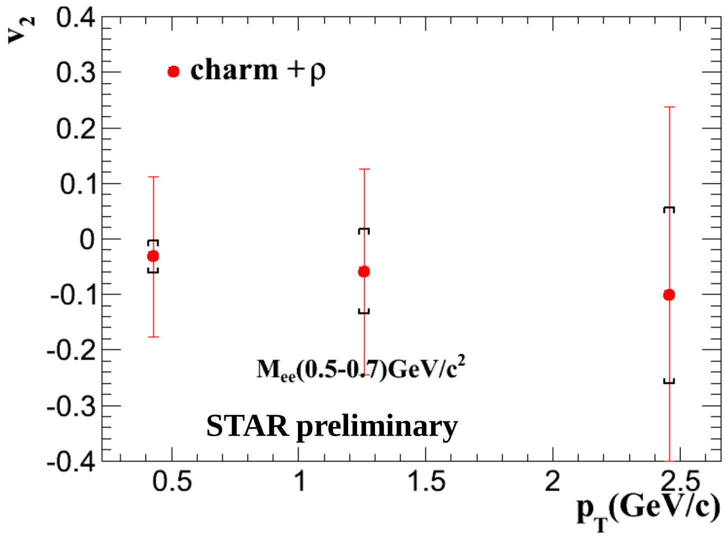
1. Parameterize π meson v_2 results
2. Do the Dalitz decay simulation and obtain expected v_2 of di-electrons pairs from π^0 Dalitz decay.
3. This is consistent with our di-electrons v_2 results.

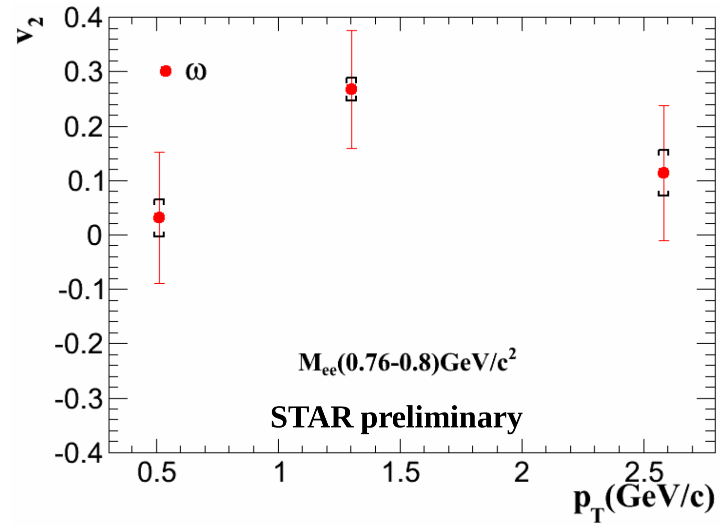
To provide a comparison (blue) curve from simulation:

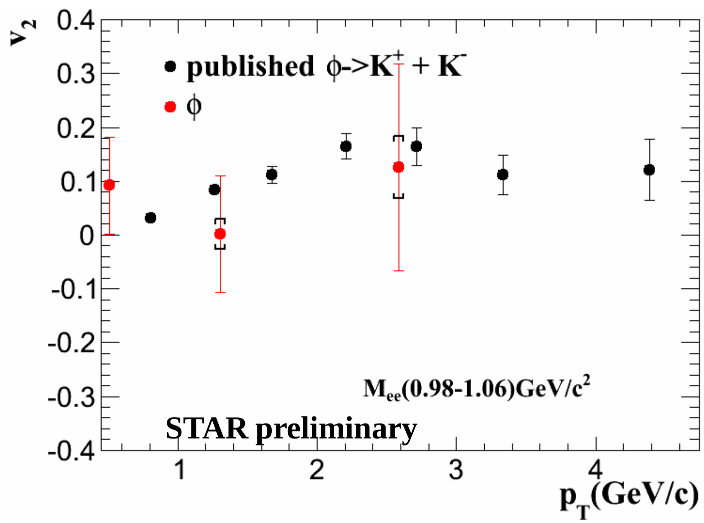
- Assume η v_2 same as K_S
- do the same Dalitz decay procedure

X. Cui DNP2011, B. Huang SQM2011

v_2 of di-electrons at $0.5<M_{ee}<1.1$ GeV/c^2





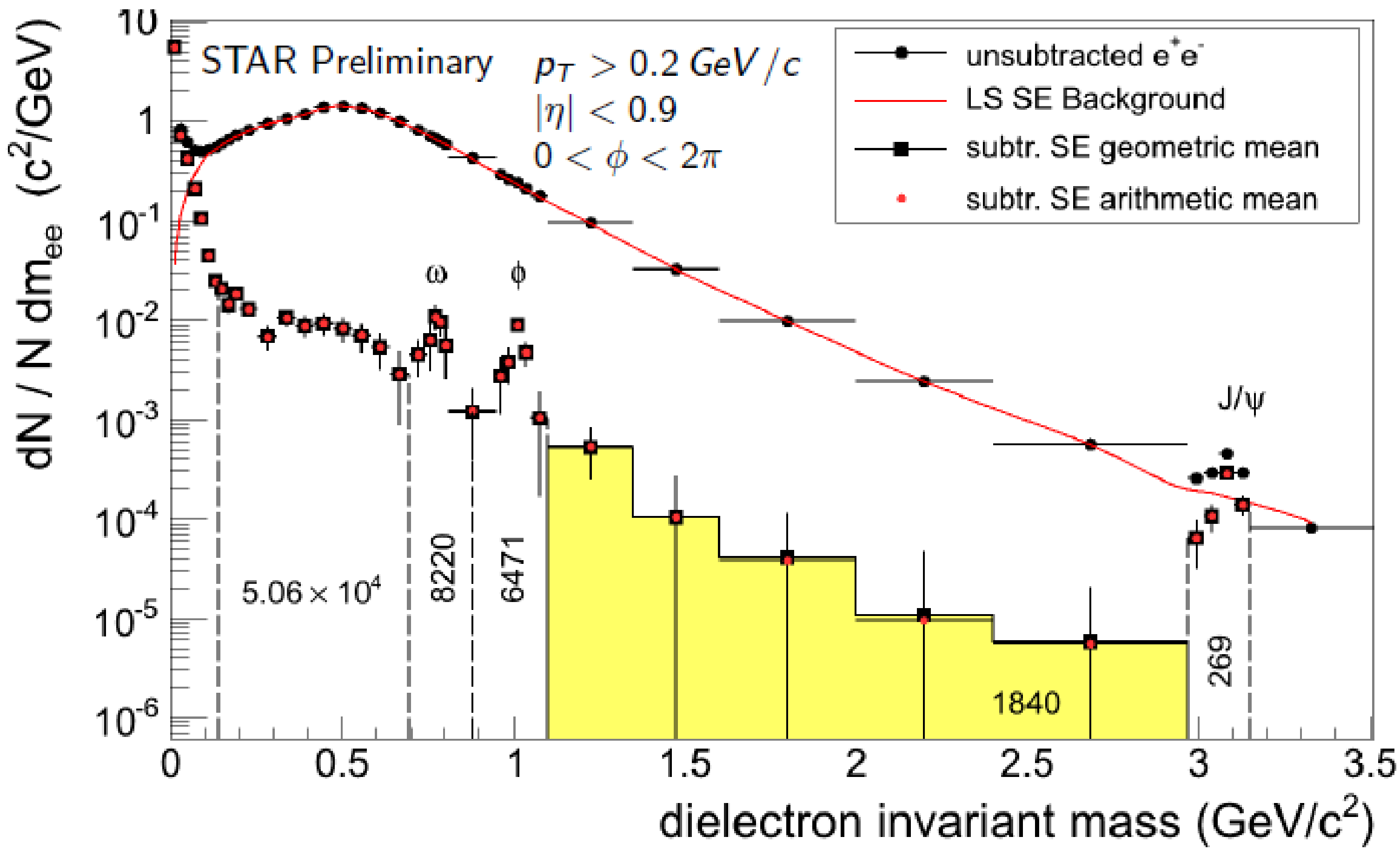


X. Cui DNP2011

The elliptic flow of ϕ→ee is consistent with the result of ϕ→KK within errors

ϕ→KK: PRL99(2007)112301

Di-lepton results in 39 GeV Au+Au



Raw, efficiency correction to be done.

P. Huck CPOD2011

To the future

The current status:

- Di-lepton spectrum in 200 GeV p+p collisions:

  cocktail simulation consistent with data

  charm correlation contribution dominates at intermediate mass

- Di-lepton in 200 GeV Au+Au collisions:

  a possible low mass enhancement with respect to cocktail expectation

  at Mee 0.15-0.75 GeV/c^2

  $\omega \rightarrow ee$ shows a similar flow velocity at freeze-out as light hadrons

  ϕ yields are similar between di-leptonic decay and hadronic decay channel

  di-lepton v_2 from low to high mass measured

Towards the future:

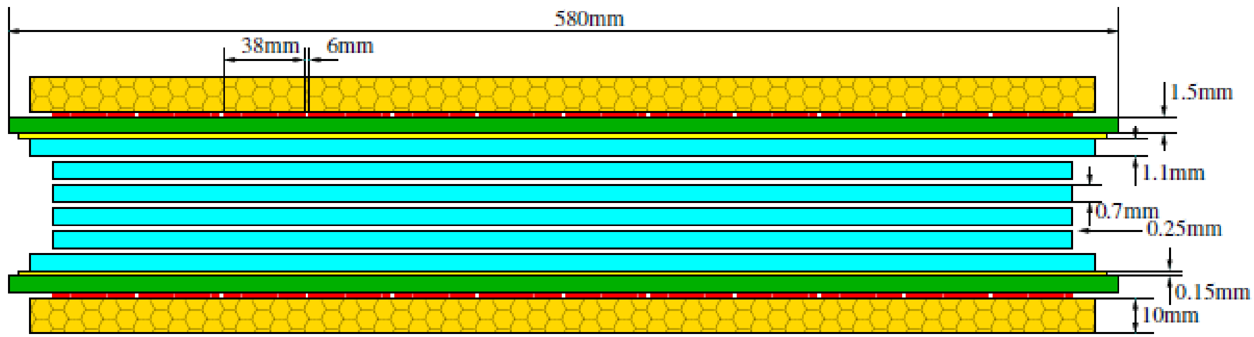
Differential measurements (M_{ee}, p_T, v_2) are on-going

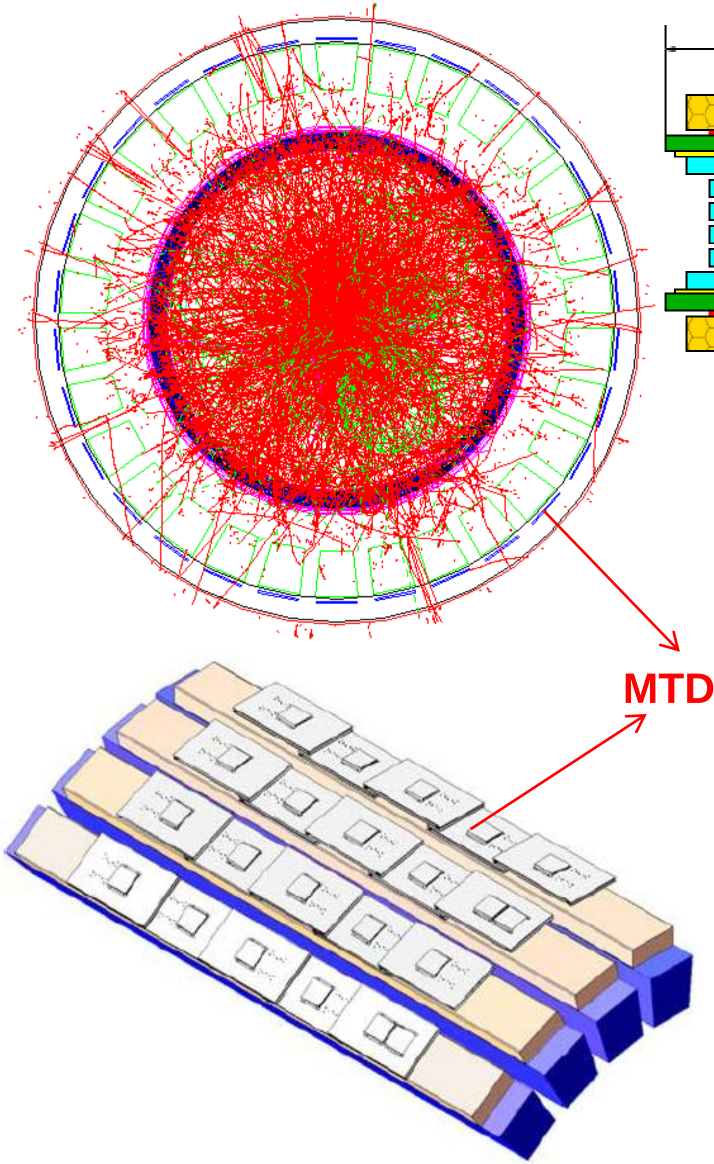
Energy dependence (19-200 GeV) can be systematically studied at STAR

e-μ correlation (spectrum and v_2) to distinguish heavy flavor production from initial lepton pair production with MTD upgrade

BROOKHAVEN NATIONAL LABORATORY

Concept of design of the STAR-MTD





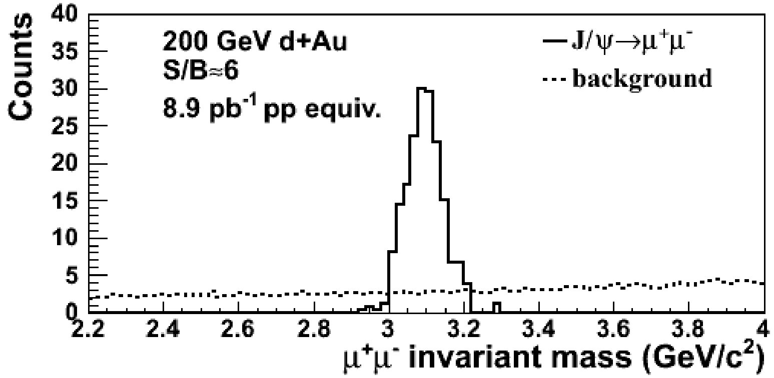
Multi-gap Resistive Plate Chamber (MRPC): gas detector, avalanche mode

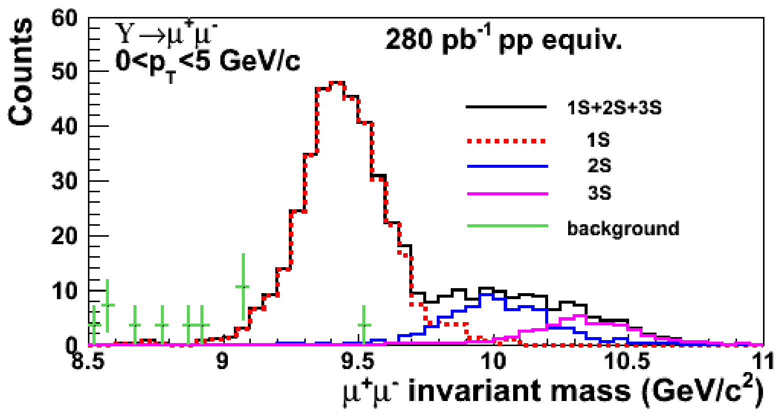
A detector with long-MRPCs covers the whole iron bars and leave the gaps in-between uncovered. Acceptance: 45% at $|\eta|<0.5$

118 modules, 1416 readout strips, 2832 readout channels

Long-MRPC detector technology, electronics same as used in STAR-TOF

High mass di-muon capabilities





1. J/ψ: S/B=6 in d+Au and S/B=2 in central Au+Au
2. With HFT, study B→J/ψ X; J/ψ→μμ using displaced vertices
3. Excellent mass resolution: separate different upsilon states

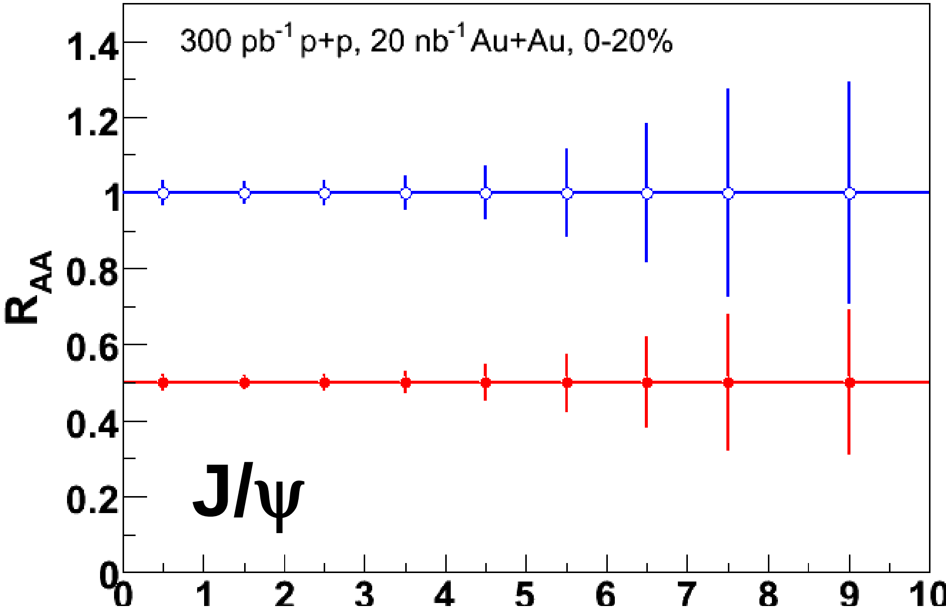
Heavy flavor collectivity and color screening, quarkonia production mechanisms:
J/ψ R_{AA} and v_2; upsilon R_{AA} …

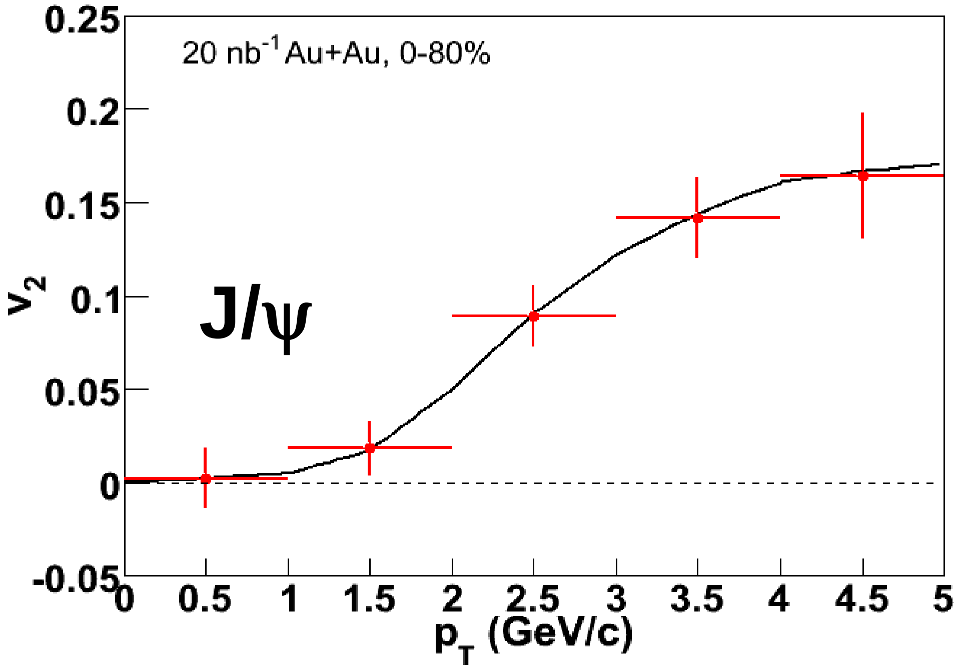
Z. Xu, BNL LDRD 07-007; L. Ruan et al., Journal of Physics G: Nucl. Part. Phys. 36 (2009) 095001

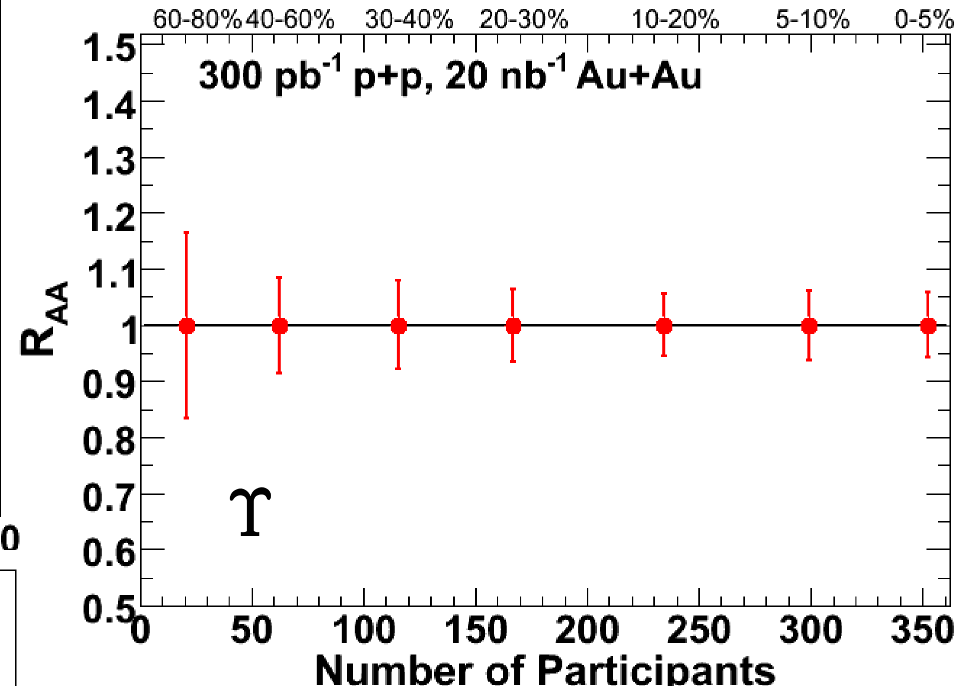
Quarkonium dissociation temperatures – Digal, Karsch, Satz

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

Future measurement projection





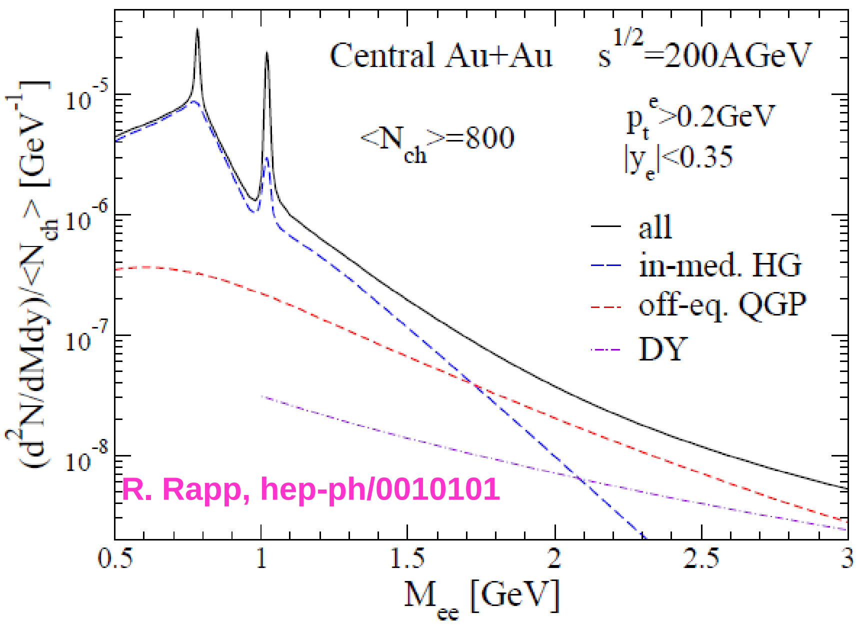


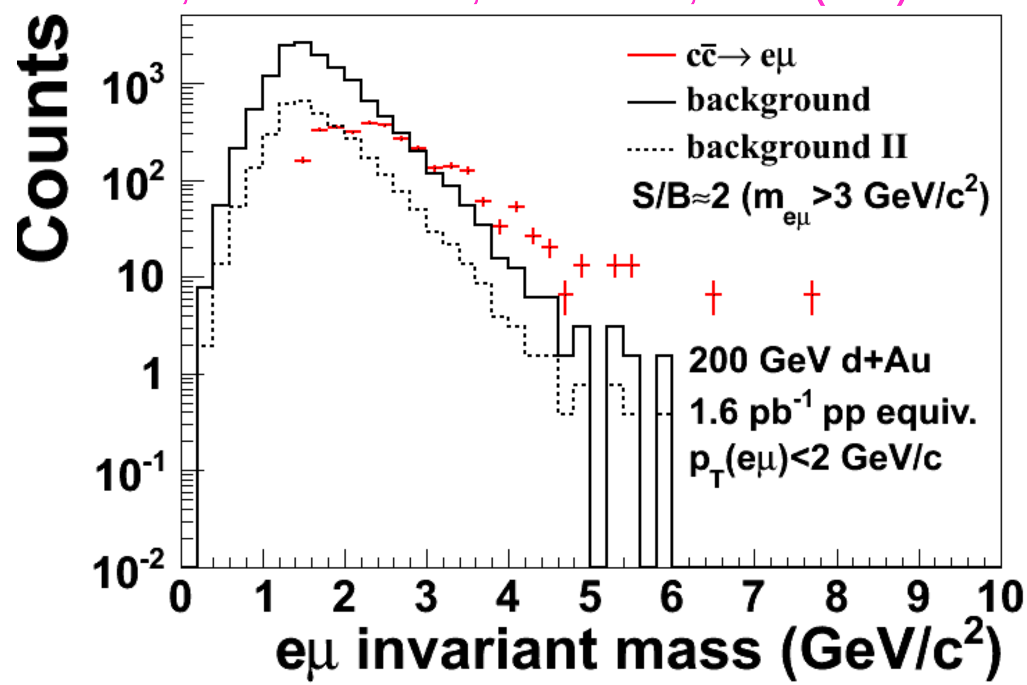
J/ψ R_{AA} and v_2;
ϒ (1S+2S+3S) R_{AA} versus N_{part}…

300 pb^{-1} 200 GeV p+p (~24 weeks RHIC run)
20 nb^{-1} 200 GeV Au+Au (~12 weeks)

Different Upsilon states in 500 GeV p+p collisions can be measured with good precision from 12 weeks run.

Measure charm correlation with MTD upgrade: ccbar→e+μ

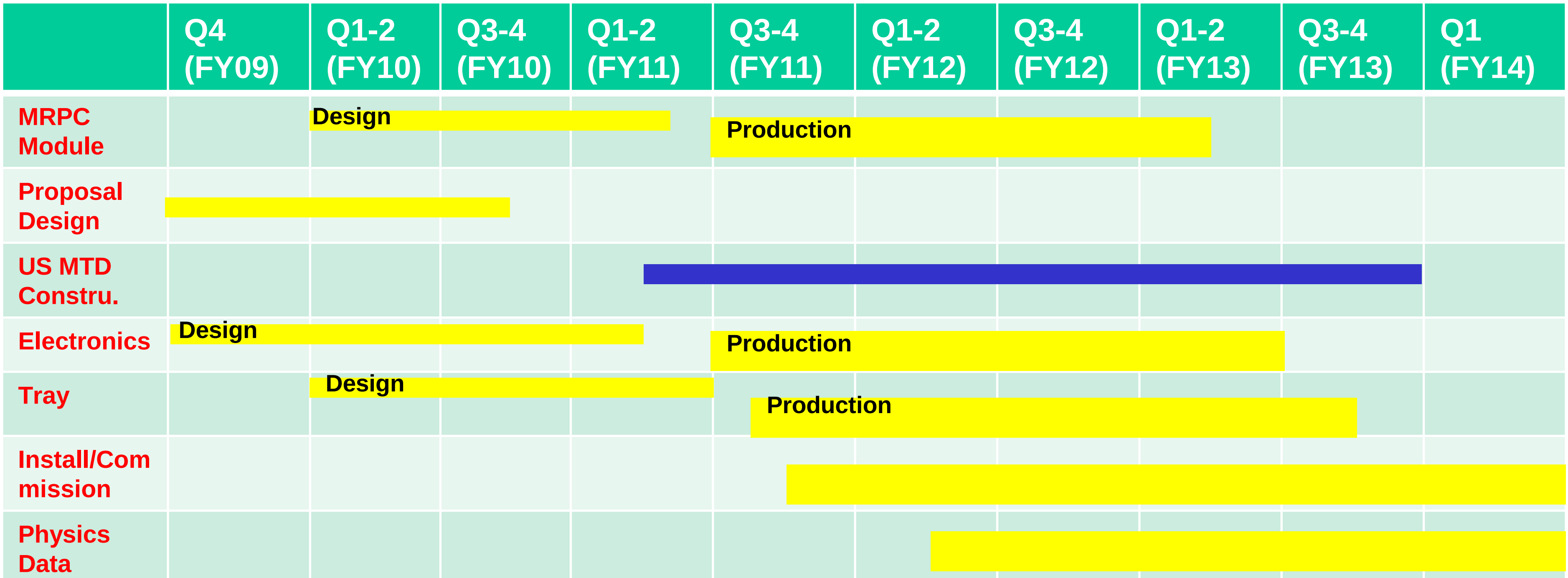




eμ correlation simulation with Muon Telescope Detector (MTD) at STAR from ccbar: S/B=2 (M_{eu}>3 GeV/c^2 and $p_T(e\mu)$<2 GeV/c)
S/B=8 with electron pairing and tof association

MTD: construction starts in FY2011; project completion in FY2014

MTD schedule



10% installation for Run12, 43% for Run13, 80% for Run 14.
Finish the project by Mar, 2014

MTD institutions: Brookhaven National Laboratory, University of California, Berkeley, University of California, Davis, Rice University, University of Science & Technology of China, Texas A&M University, University of Texas, Austin, Tsinghua University, Variable Energy Cyclotron Centre

US institutions: the electronics, the assembly of the trays and the operation of the detector

Chinese and Indian institutions: the fabrication of the MRPC modules

Di-lepton measurements at STAR

	FY09/10/11	FY12/13	From FY14 on
Detector components	TPC+TOF+EMC	TPC+TOF+EMC+MTD(p)	TPC+TOF+EMC+MTD+ HFT
Measurements	J/psi→ee, Upsilon→ee J/psi R_{AA}, v_2 vs. p_T &N_{part}, Upsilon R_{AA} vs. N_{part} di-electron continuum di-electron spectra, v_2 vs. p_T	FY12 (10% MTD): first e-μ measurement FY13 (43% MTD): J/psi→μμ, Upsilon→μμ J/psi R_{AA},v_2, vs. p_T & N_{part}, first look at different Upsilon states di-muon continuum e-μ v_2	B→J/psiX→μμX Precise measurements on different Upsilon states R_{AA} versus N_{part}, J/psi→μμ R_{AA}, v_2 versus p_T & N_{part}, di-muon continuum, e-μ spectra and v_2 D v_2 and R_{AA}
Physics	Color screening features, quarkonia production mechanisms, vector meson in-medium modifications, low mass enhancement, Intermediate mass	Better understanding on thermal radiation from QGP at intermediate mass and vector meson in-medium modifications	Measure thermal radiation from QGP at intermediate mass, vector meson in-medium modifications, color screening features

Search for muonic hydrogenlike atoms

- Discovery potential with μ-π, μ-K, u-pbar atoms (size: a few hundred fm)

- By measuring the production rate of muonic hydrogenlike atoms and light flavor spectra, we can obtain the information of soft thermal lepton production from an initial plasma with a temperature of a couple of hundred MeV

Atom	μ p_T (GeV/c)	Hadron p_T	Atom p_T	dN/dy
$\mu - \pi$	[0.17,0.3]	[0.22,0.4]	[0.39,0.7]	9×10^{-5}
$\mu - K$	[0.17,0.3]	[0.8,1.4]	[0.97,1.7]	1×10^{-5}
$\mu - \overline{p}$	[0.17,0.3]	[1.5,2.7]	[1.7,3.0]	4×10^{-6}
$\mu - \pi$	> 1.5	> 2	> 3.5	3×10^{-9}

Coombes et al., PRL37(1976)249
Aronson et al., PRL48(1982)1078
Baym et al., PRD48(1993)R3957
Kapusta and Mocsy PRC59(1998)2937

STAR decadal plan

Summary

- STAR has started the di-lepton program with a bright future enabled by the TOF upgrade :

  Di-lepton spectrum from low to high mass measured in 200 GeV p+p and Au+Au collisions

  Di-lepton v_2 from low to high mass measured in 200 GeV Au+Au collisions

  Energy dependence (19-200 GeV) can be nicely and systematically studied at STAR

  Differential measurements (M_{ee}, p_T, v_2) are on-going

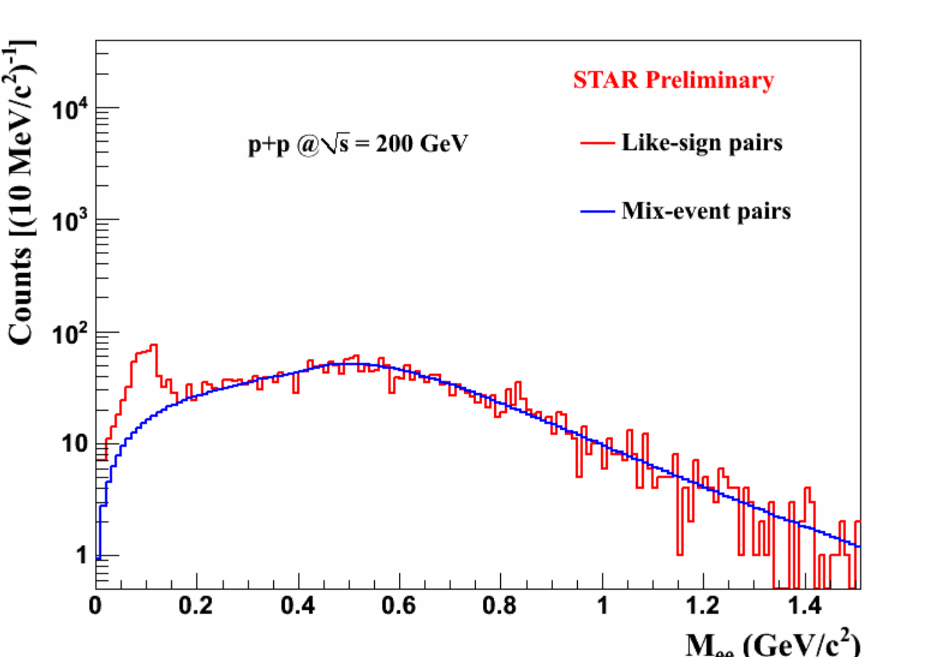
  Well-defined path to understand QGP properties using di-leptons with current data sets and future detector upgrades

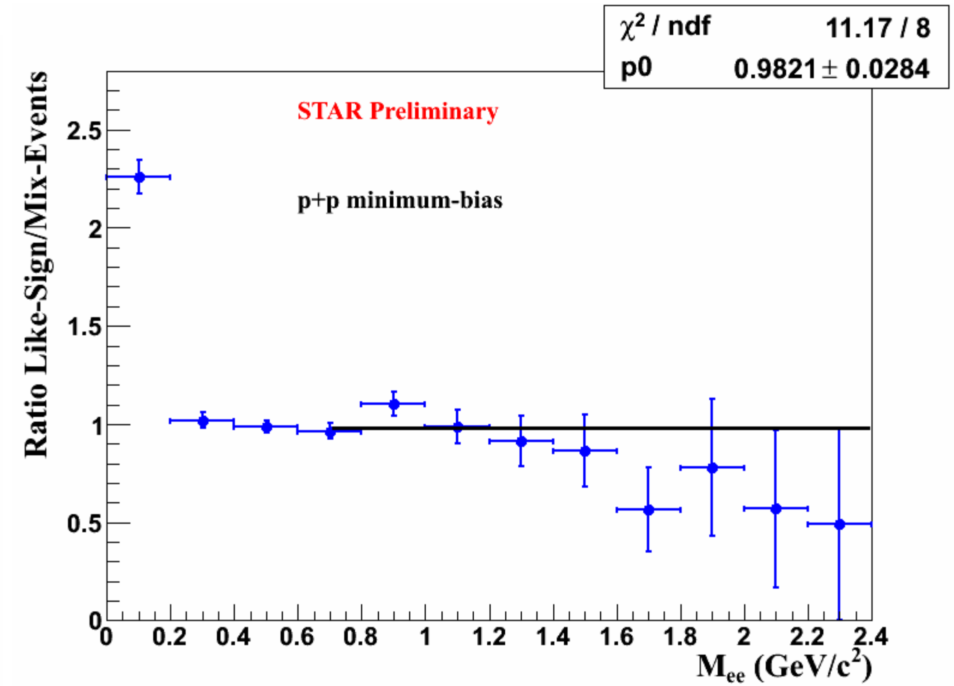
- Future with the MTD:

  e-μ correlation (spectrum and v_2) to distinguish heavy flavor production from initial lepton pair production

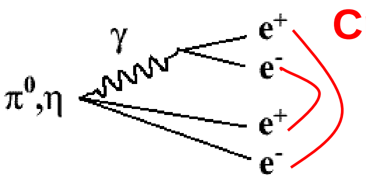
Backup

Di-lepton background





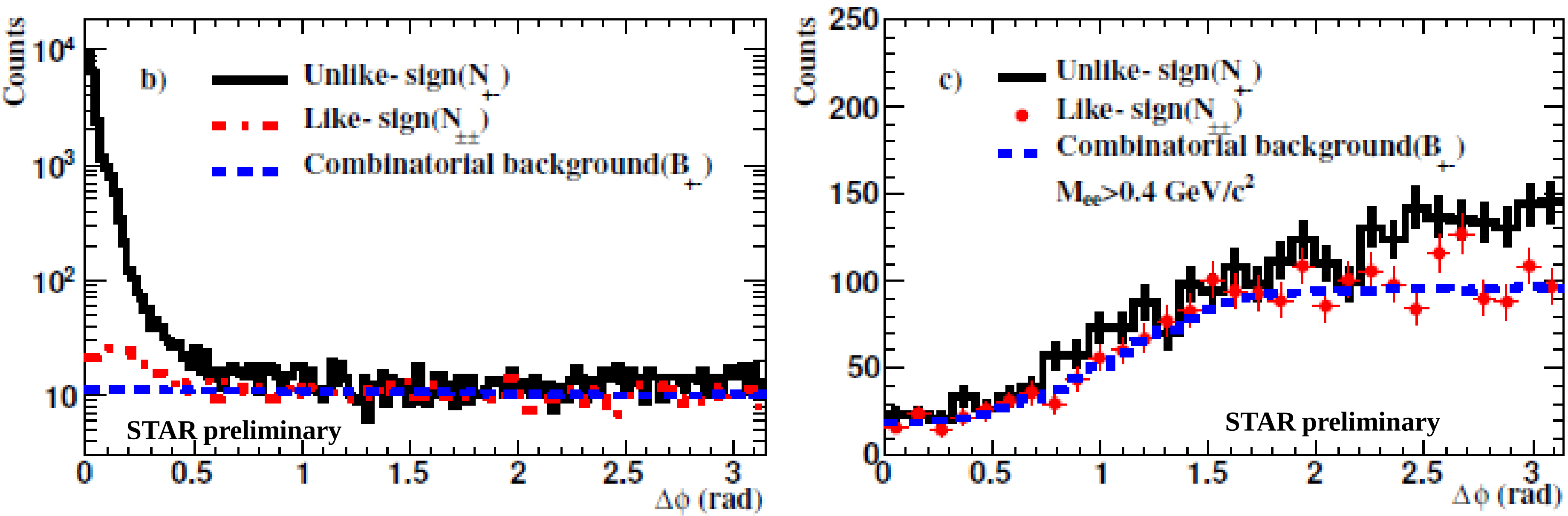
Mixed-event normalized to like-sign within 0.4 - 1.5 GeV/c^2



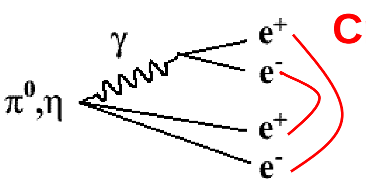
Cross-pair bg. can only be described by like-sign method.

For minimum bias events, we subtracted like-sign bg at M_{ee}<0.7 GeV/c^2, mixed-event bg subtraction was applied at M_{ee}>0.7 GeV/c^2.

Di-lepton azimuthal angle distribution



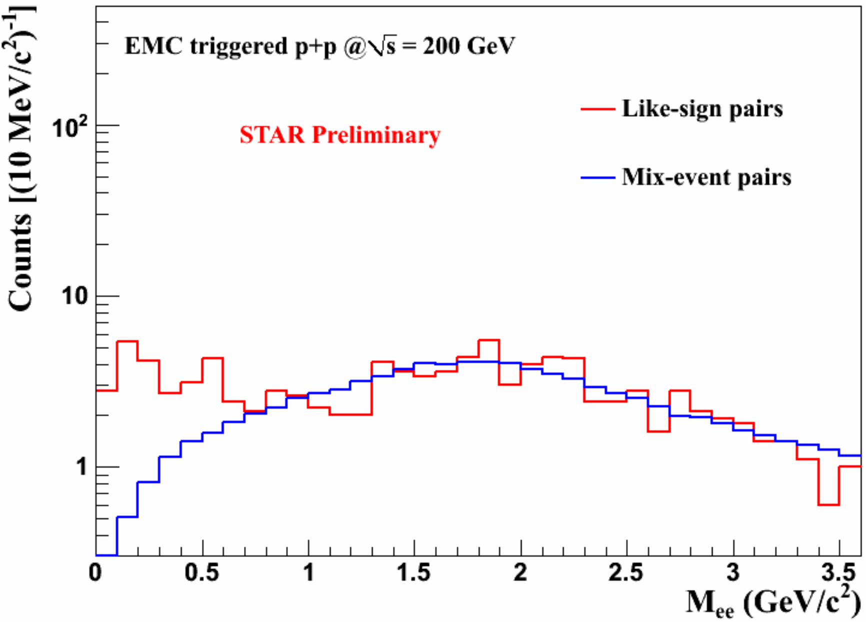
Mixed-event normalized to like-sign within 0.4 - 1.5 GeV/c^2

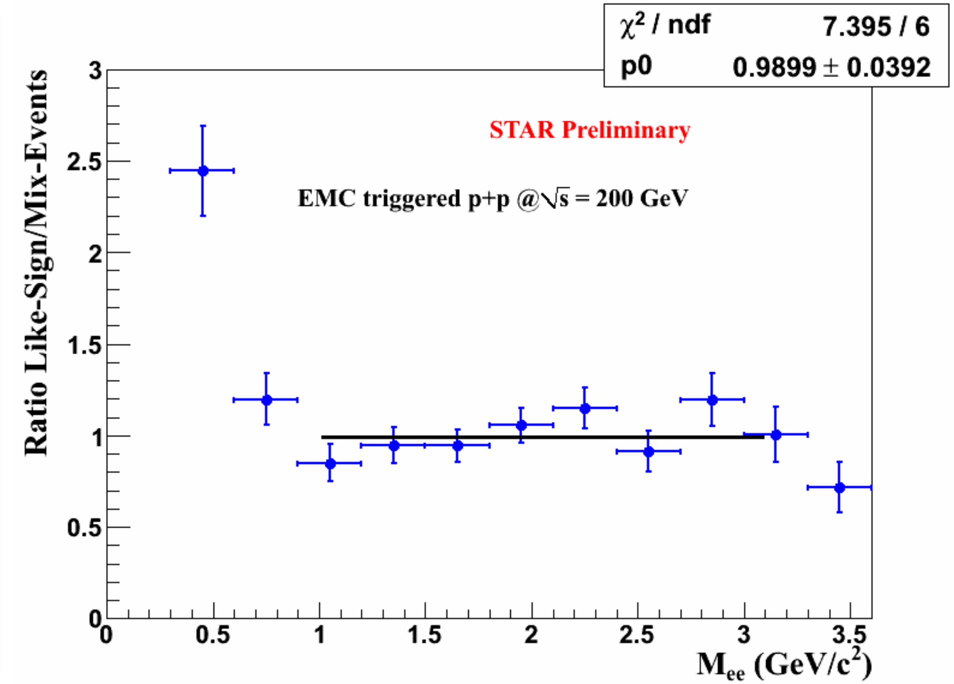


Cross-pair bg. can only be described by like-sign method.

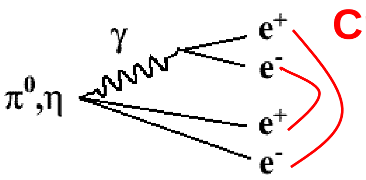
For minimum bias events, we subtracted like-sign bg at M_{ee}<0.7 GeV/c^2, mixed-event bg subtraction was applied at M_{ee}>0.7 GeV/c^2.

Di-lepton background





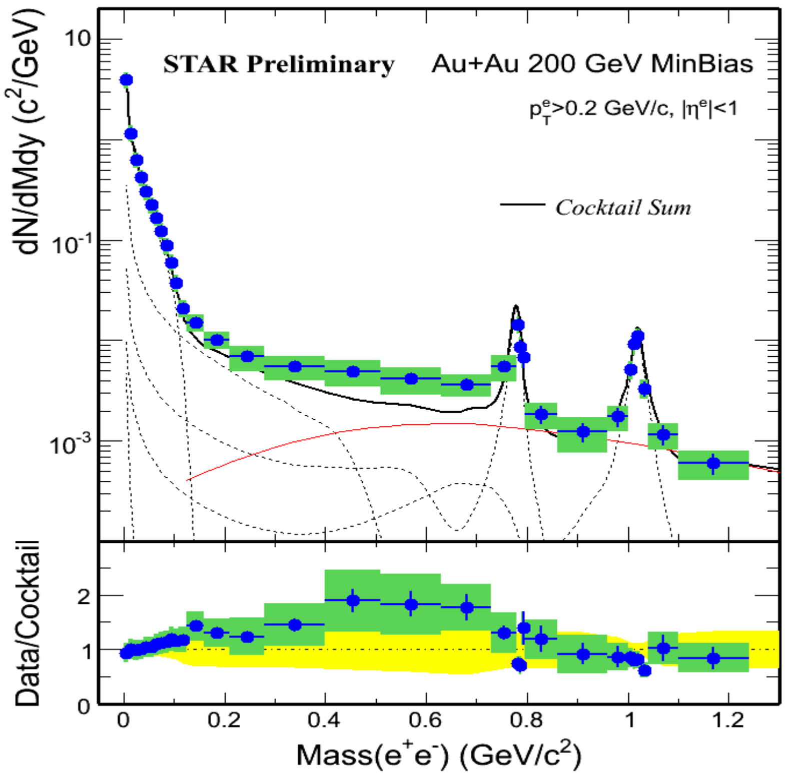
Mixed-event normalized to like-sign within 1 - 3 GeV/c^2

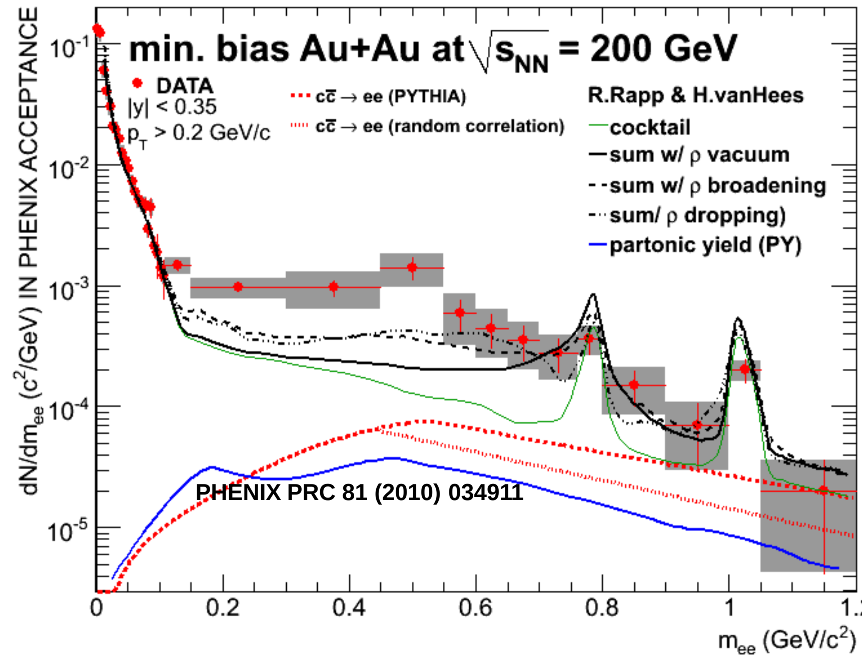


Cross-pair bg. can only be described by like-sign method.

For minimum bias events, we subtracted like-sign bg at M_{ee}<0.7 GeV/c^2, mixed-event bg subtraction was applied at M_{ee}>0.7 GeV/c^2.

Low mass enhancement





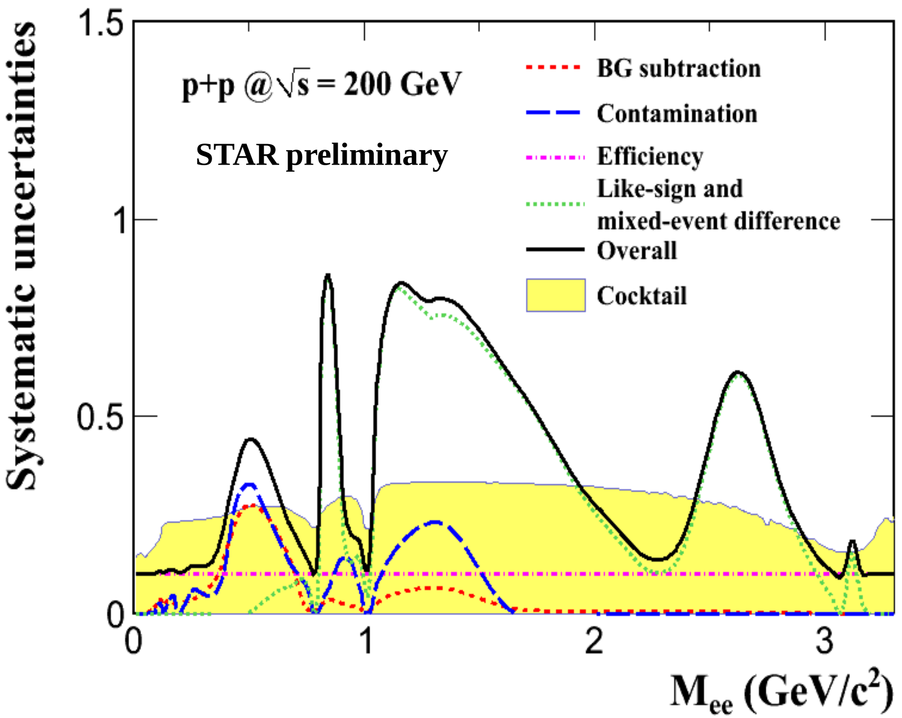
Enhancement factor in $0.15<M_{ee}<0.75$ Gev/c2

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	1.53 ± 0.07 ± 0.41 (w/o ρ) 1.40 ± 0.06 ± 0.38 (w/ ρ)	1.72 ± 0.10 ± 0.50 (w/o ρ) 1.54 ± 0.09 ± 0.45 (w/ ρ)
PHENIX	4.7 ± 0.4 ± 1.5	7.6 ± 0.5 ± 1.3
Difference	2.0 σ	4.2 σ

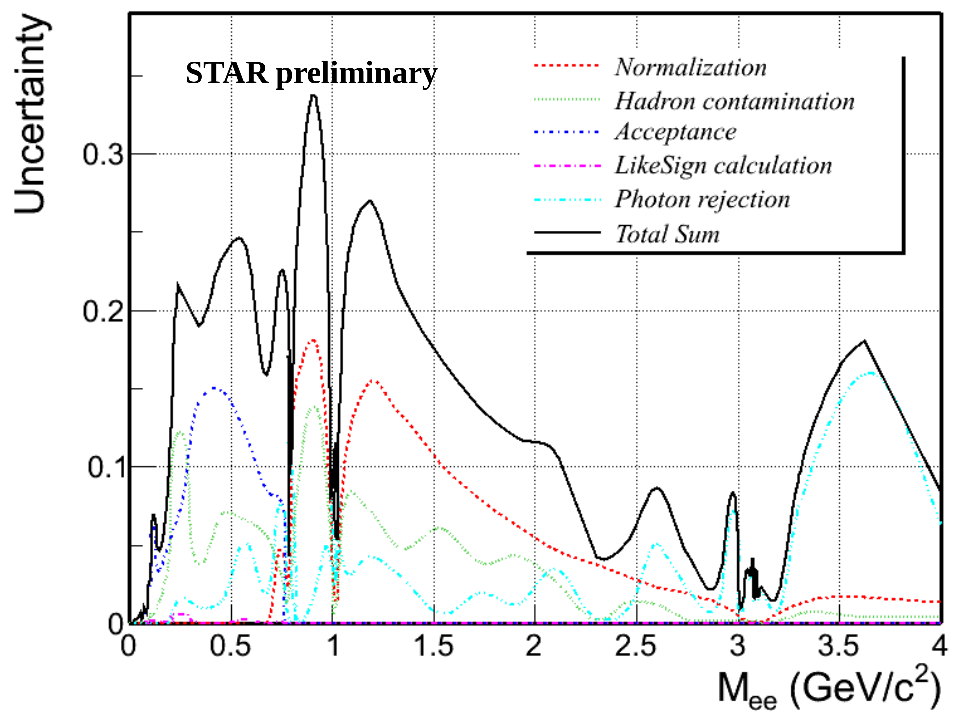
Note: Acceptance difference etc.

Systematic uncertainties

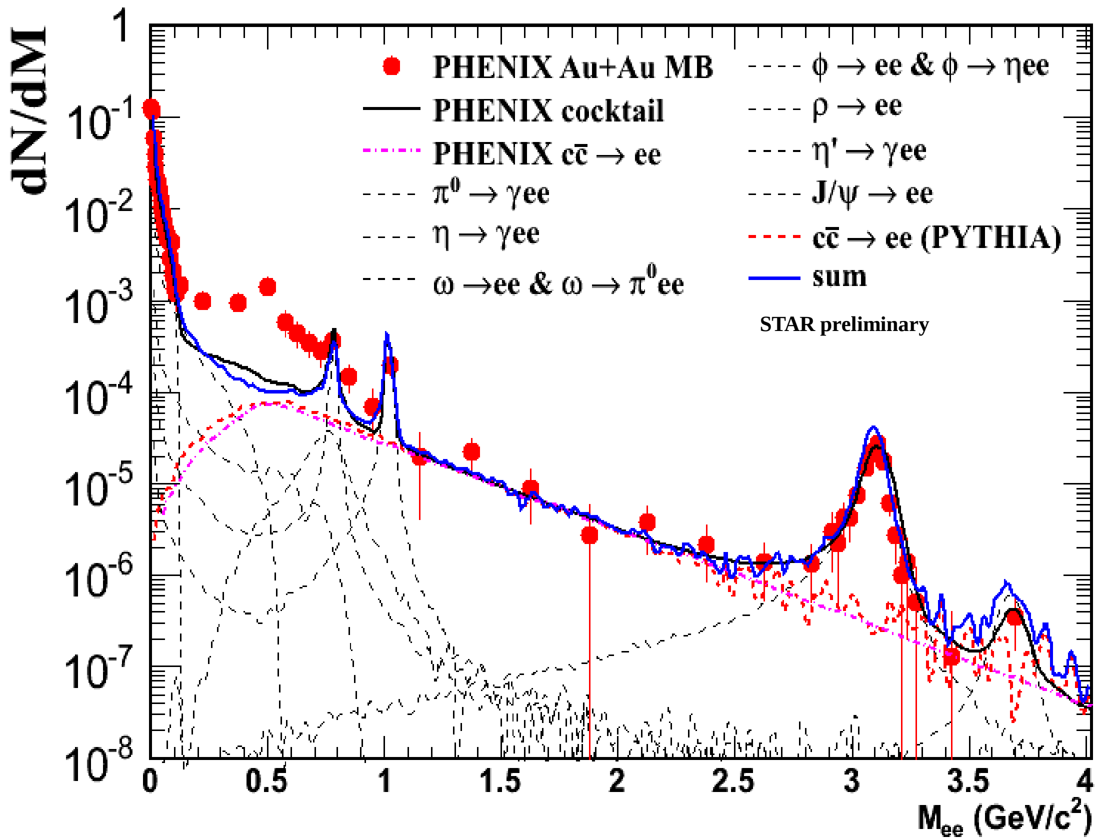
p+p:



Au+Au:



Reproduce PHENIX cocktail



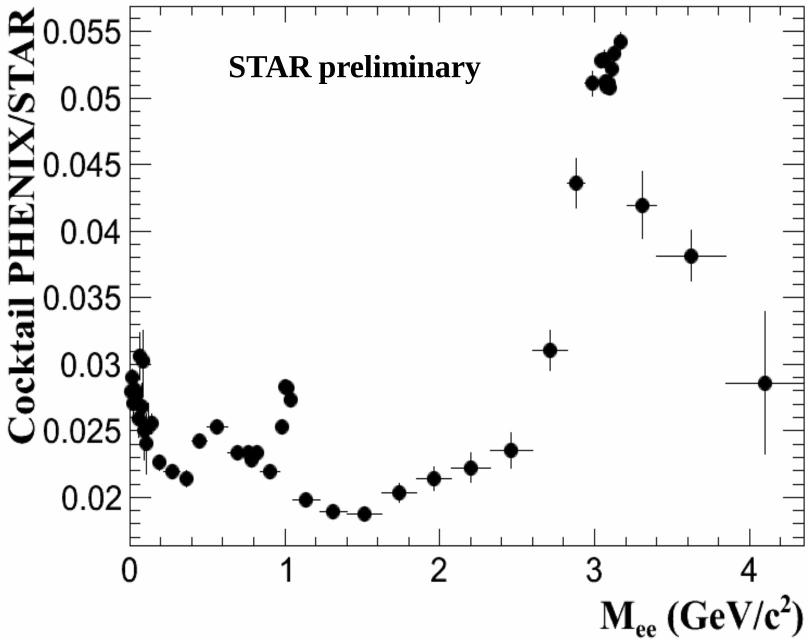
Reproduce the cocktail within PHENIX acceptance by our method.

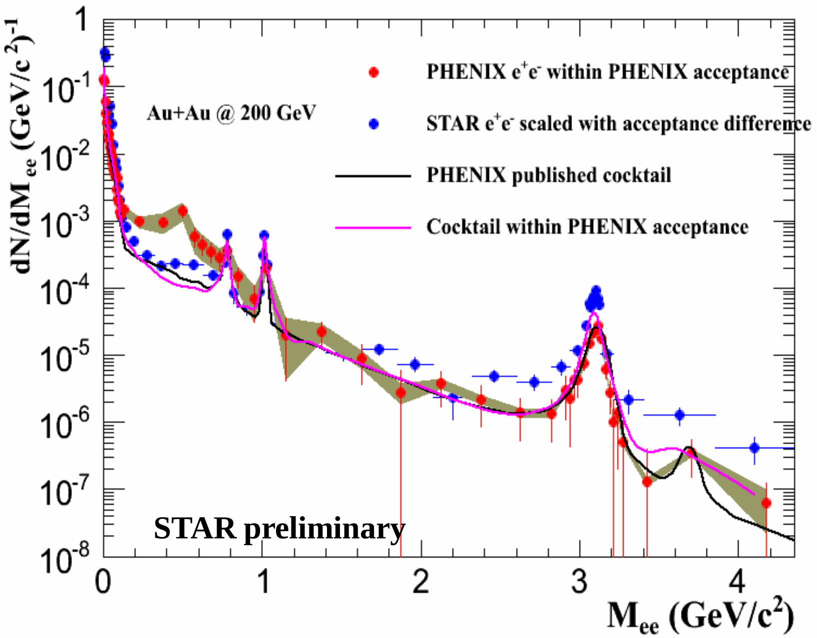
The momentum resolution are still from STAR.

Scaled by all the yields from PHENIX paper[1], we can reproduce the PHENIX cocktail.

[1]. Phys. Rev. C 81, 034911 (2010).

Check with acceptance difference





Acceptance difference:

Scaled by the acceptance difference.

$$\frac{\text{Cocktail in PHENIX acceptance}}{\text{Cocktail in STAR acceptance}}$$

Scaled by same meson and charm yields.

Difference at low mass is not from the simulation but from the measurements.

BROOKHAVEN NATIONAL LABORATORY

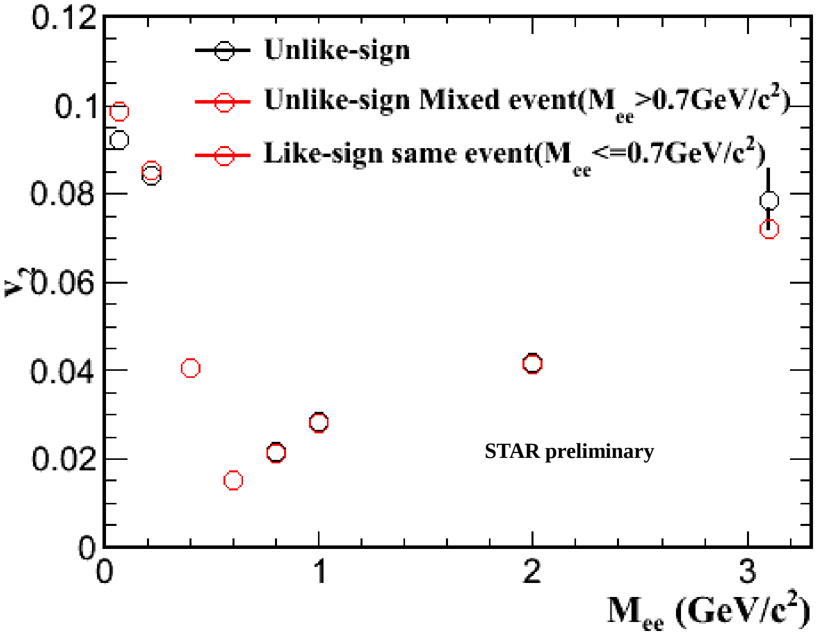
v_2 standard event-plane method

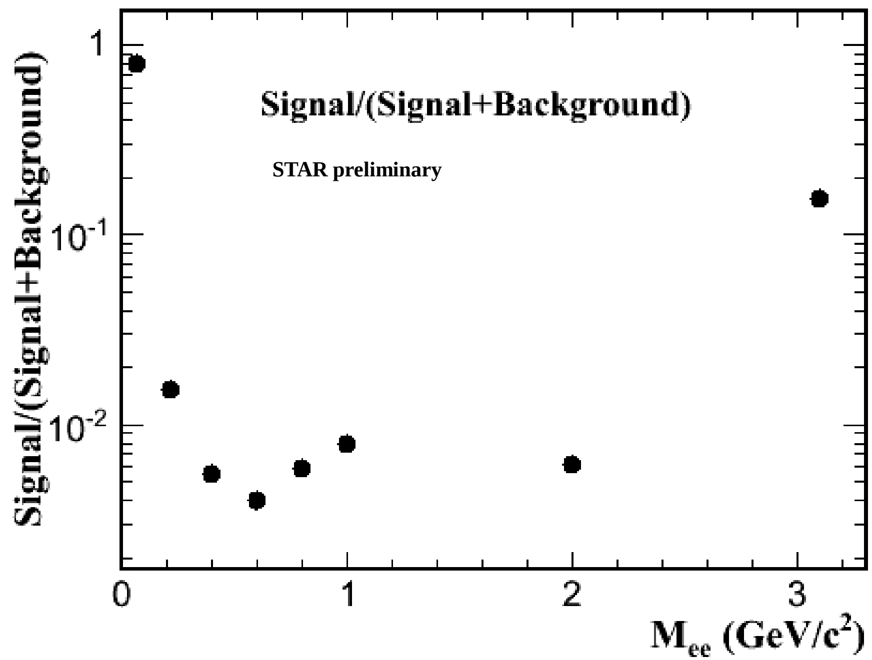
$$v_2^{Total}(M) = v_2^B(M) * \frac{N_B}{N_{(S+B)}}(M) + v_2^s * \frac{N_S}{N_{(S+B)}}(M)$$

$$v_2^{Total}(M) - v_2^B(M) * \frac{N_B}{N_{(S+B)}}(M) = v_2^s * \frac{N_S}{N_{(S+B)}}(M)$$

v_2^{Total} is flow of unlike-sign pairs.
$v_2^B(M)$ is flow of background calculated using the like-sign or mixed events pairs.
v_2^S is flow of signal.
N_S is the signal number, N_B is the background (like-sign) number.
$N_{(S+B)}$ is unlike-sign number.

Unlike-sign and background v_2





$$v_2^{Total}(M) - v_2^B(M) * (1 - \frac{Ns}{N_{(S+B)}}(M)) = v_2^S * \frac{N_S}{N_{(S+B)}}(M)$$

Unlike-sign v_2

Background v_2

Signal/(Signal+Background)

Signal flow