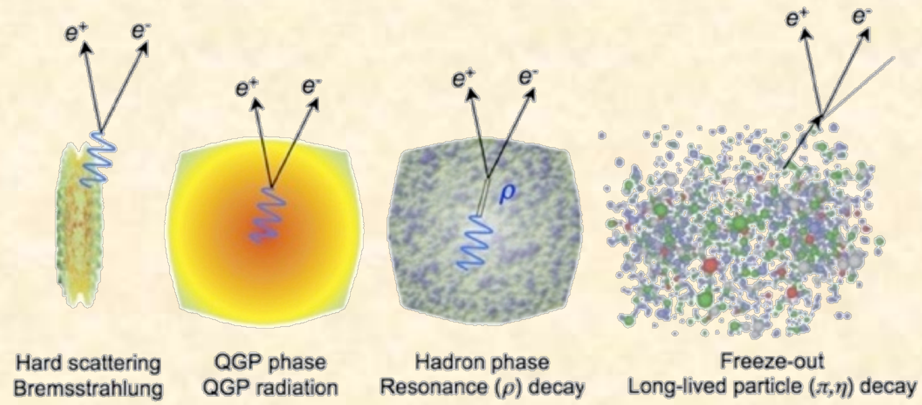
The STAR Dilepton Program

Frank Geurts (Rice University)
for the STAR Collaboration

Outline

- Introduction & Motivation
- Electron Identification in STAR
- Dielectron Production at $\sqrt{s_{NN}}$= 200 GeV
  - p+p and Au+Au results
  - elliptic flow of dielectrons
- Results from Beam Energy Scan Program
- STAR Dilepton Present & Future
- Summary

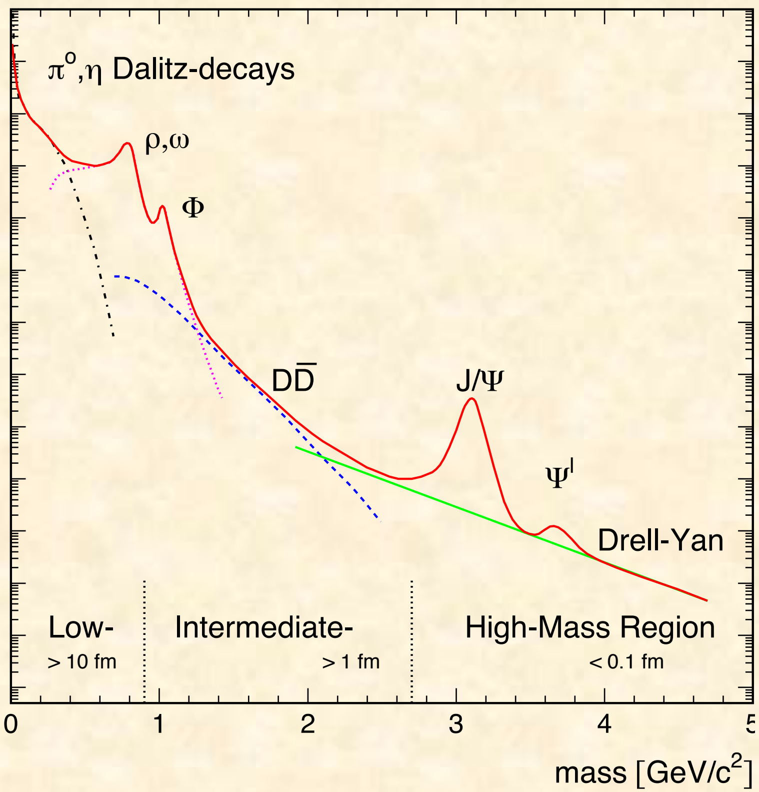
Dilepton Physics



Dileptons are excellent penetrating probes

- very low cross-section with QCD medium
- created throughout evolution of system

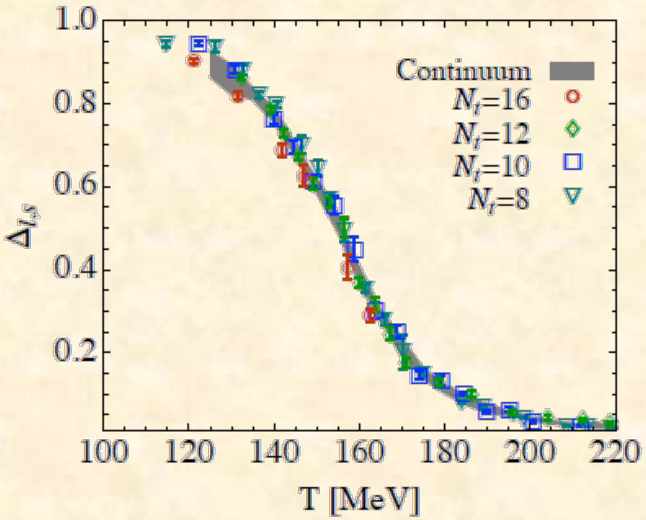
Rapp & Wambach, Adv.Nucl.Phys. 25 (2000) 1



- High Mass Range (HMR)
  - $M_{ee} > 3$ GeV/c^2
  - primordial emission, Drell-Yan
  - J/Ψ and ϒ suppression
- Intermediate Mass Range (IMR)
  - $1.1 < M_{ee} < 3$ GeV/c^2
  - QGP thermal radiation
  - heavy-flavor modification
- Low Mass Range (LMR)
  - $M_{ee} < 1.1$ GeV/c^2
  - in-medium modification of vector mesons
  - possible link to chiral symmetry restoration

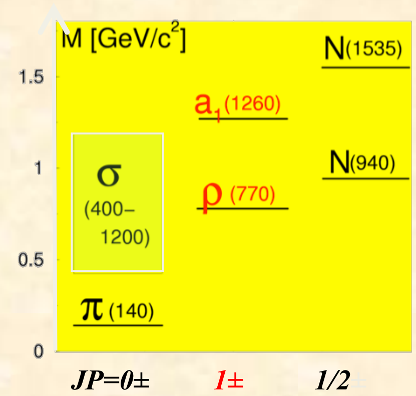
Motivation: Chiral Symmetry Restoration

Wuppertal-Budapest Collab.
arXiv:1109:5030

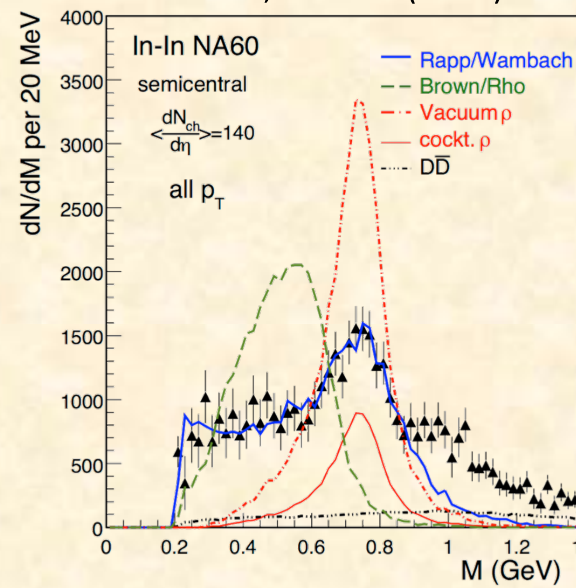


... ideally, by using a chiral order parameter
e.g. the quark condensate

– not experimentally accessible



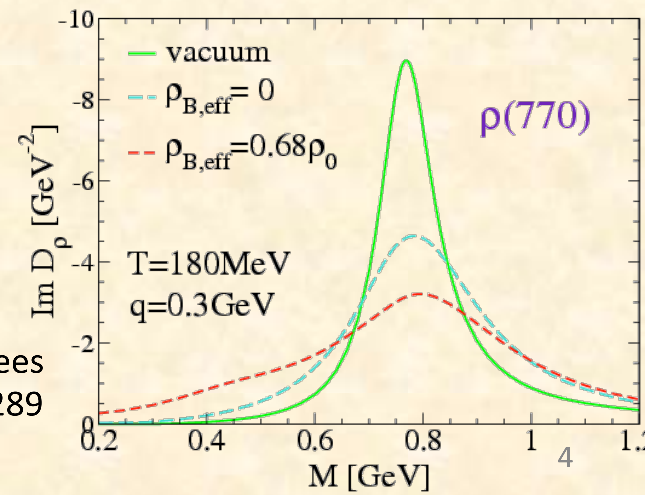
NA60, EPJ C59 (2009) 607



- use chiral partners, *i.e.* hadronic states which transform through chiral transformations

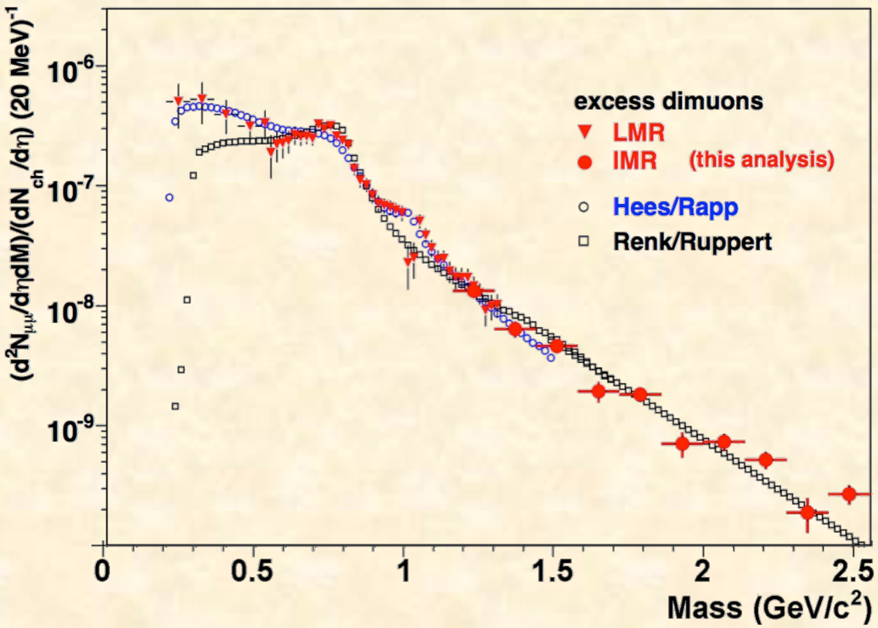
$$a_1 \leftrightarrow \rho + \pi$$

  – relative differences sensitive to chiral order parameters
- Study in-medium properties of ρ and a_1 mesons
  – axial state a_1: background too large
  – vector state ρ: dilepton measurements



Rapp, Wambach, van Hees
arXiv:0901.3289

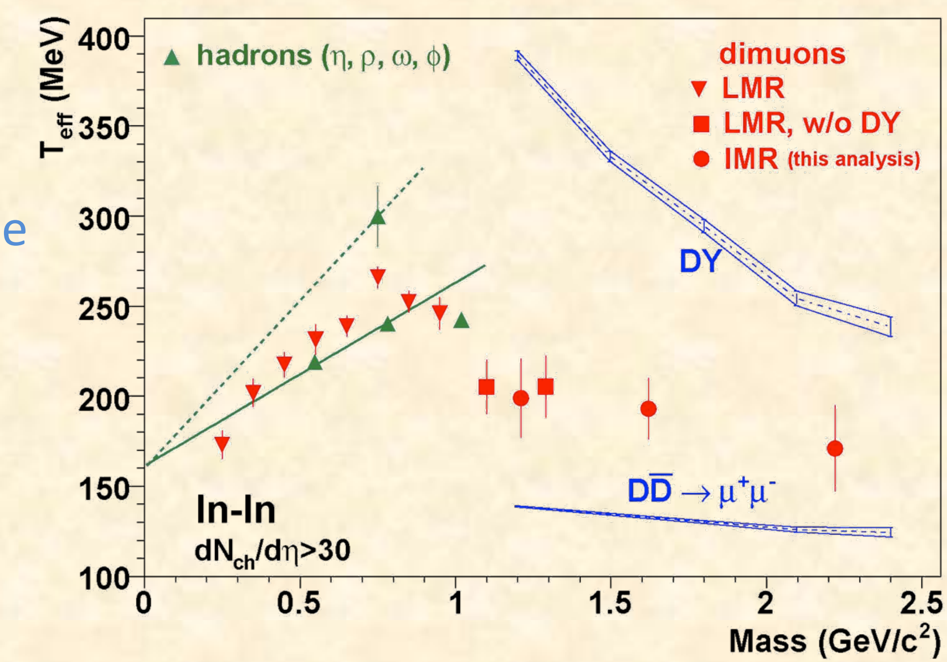
Motivation: Thermal Radiation



dimuon measurements at SPS

- LMR: dominated by HG
- IMR: from HG and/or QGP
  - HG : $\pi a_1 \to \mu^+\mu^-$ (Hees/Rapp)
  - QGP: $qq \to \mu^+\mu^-$ (Renk/Ruppert)

NA60, Eur. Phys. J. C 59 (2009) 607



m_T distributions

- LMR: inverse slope show mass dependence
  - radial flow
- IMR: no indication of mass dependence
  - thermal radiation from partonic phase
  - elliptic flow?

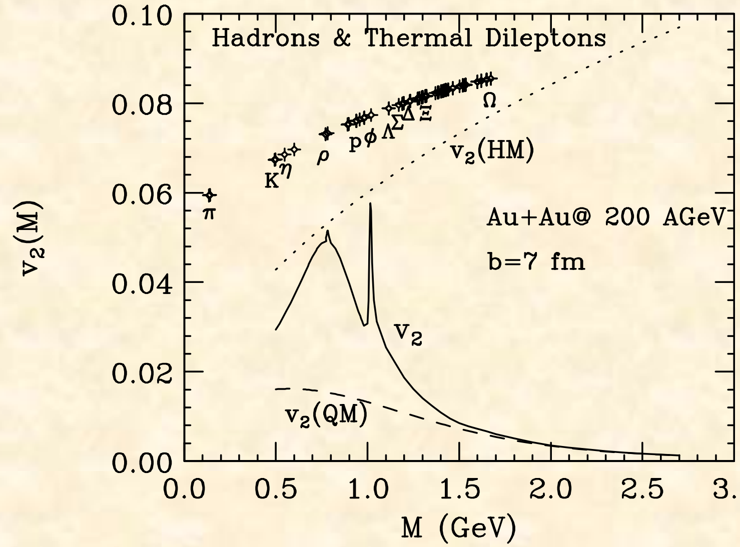
Motivation: Dilepton Elliptic Flow

Elliptic flow is generated very early stage

- dileptons can further probe this early stage
- possibly constrain QGP EoS

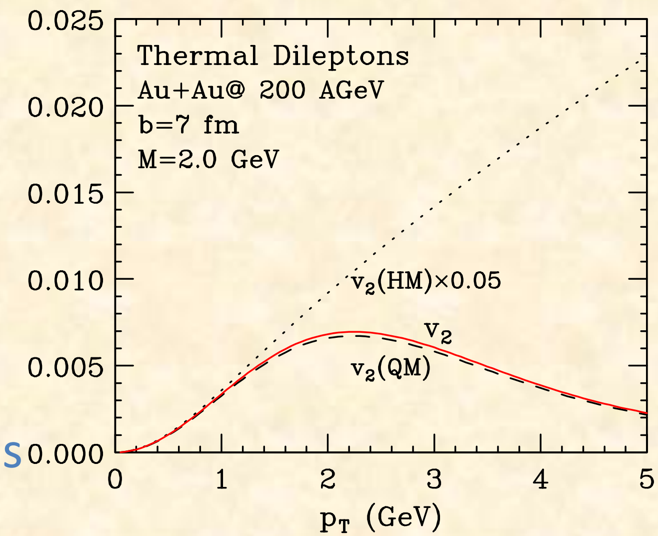
Combination of p_T and M_{ll} can set observational windows on specific stages of the expansion

Chatterjee *et al.*, Phys Rev. C 75 (2007) 054909

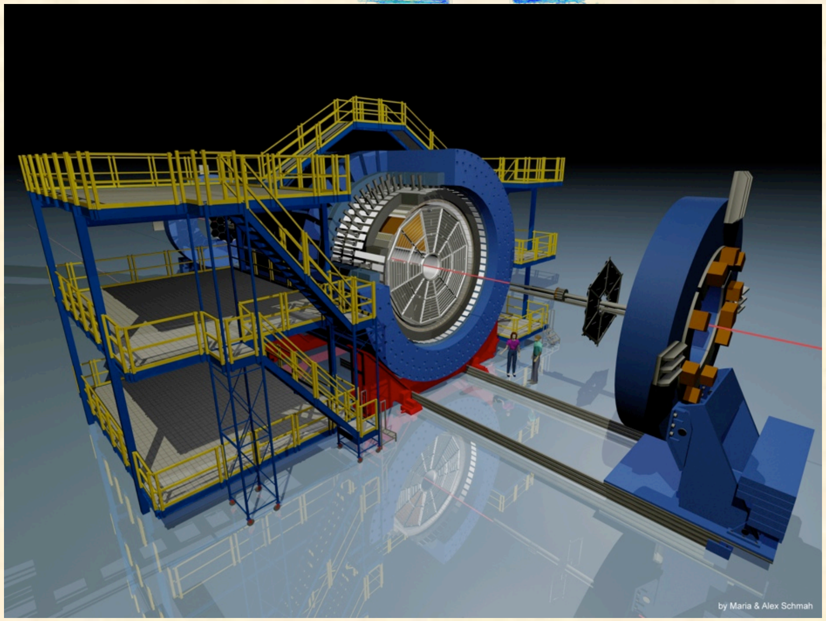


Expect interesting structures in p_T-integrated $v_2(M)$:

- high-mass dileptons
  - hot early stage
  - flow is still weak
- low-mass dileptons
  - flow strong, temperature low
- modulations from the contributions of vector mesons
  - strong variations of relative weights on/off resonances

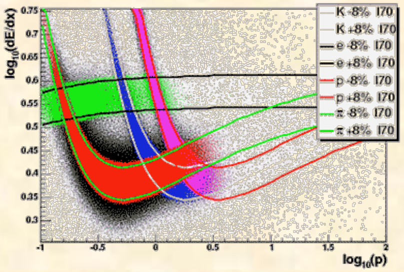


The STAR Detector



Large acceptance electron ID

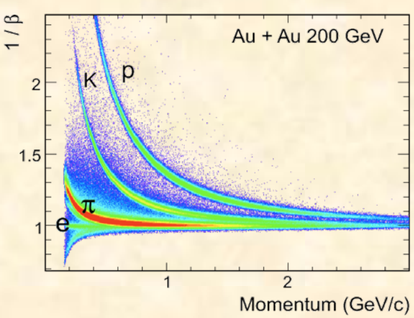
- Time Projection Chamber
- Time-of-Flight detector
  - 2009: 72% completed (p+p)
  - 2010: fully commissioned
- Electromagnetic Calorimeter



<u>Time Projection Chamber</u>

$0<\phi<2\pi$, $|\eta|<1$

- Tracking
- dE/dx PID



<u>Time-of-Flight Detector</u>

$0<\phi<2\pi$, $|\eta|<0.9$

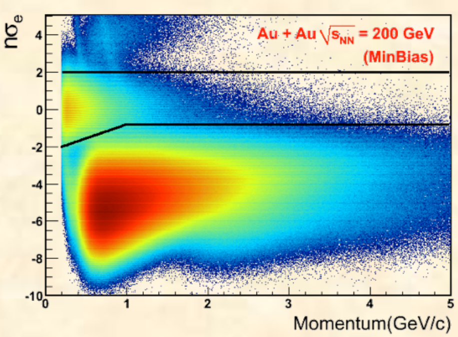
- Time resolution < 100ps
- Significantly improves PID

TOF cut removes "slow" hadrons

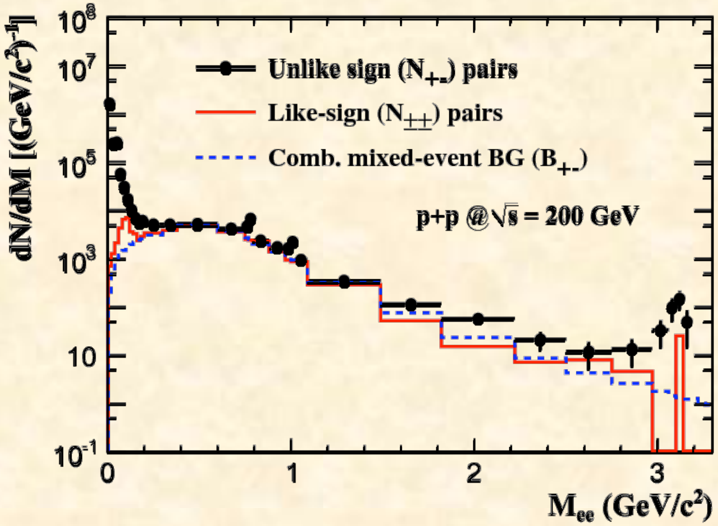
- improves electron purity

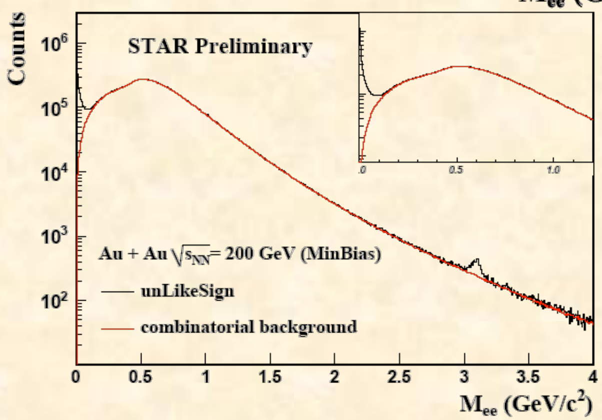
  central events ~92%

  min-bias events ~95%



e^+e^- Invariant Mass & Background





Combine both methods:

p+p: LS < 0.4 GeV/c^2 < ME

Au+Au: LS < 0.75 GeV/c^2 < ME×LS

carefully normalized using overlap in M_{ee}

Background sources

- combinatorial background (non-physical)
- correlated background

  e.g. double Dalitz decay, jet correlation.

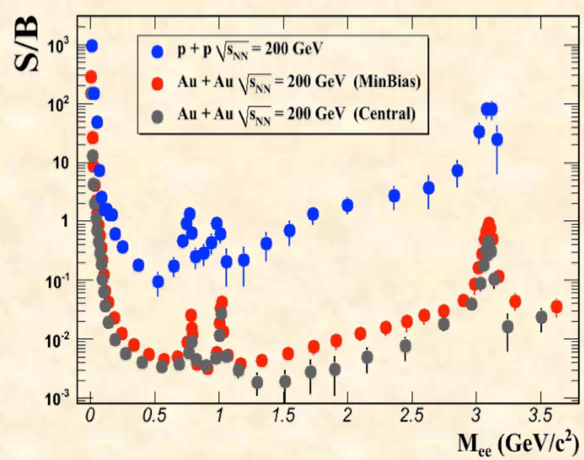
Background methods

- mixed-event method: combinatorial only
  - improve statistics
- like-sign method: combinatorial & correlated BG
  - correct for acceptance differences
- pair cuts remove photon conversions

Other signals (meson decays)

Remove by comparing real data with simulations for hadron contamination

- Hadron Simulation Cocktail

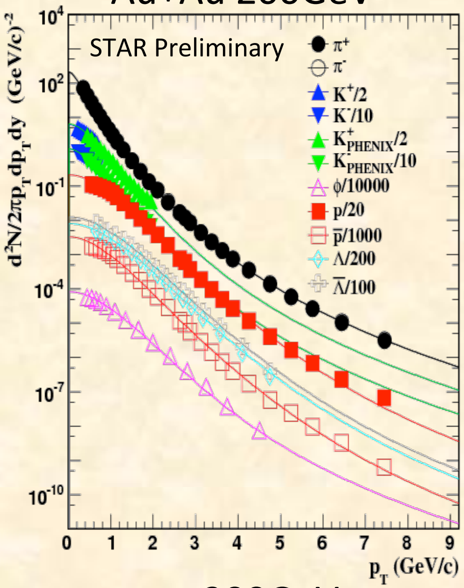


S/B @ M_{ee}~ 0.5 GeV/c^2:

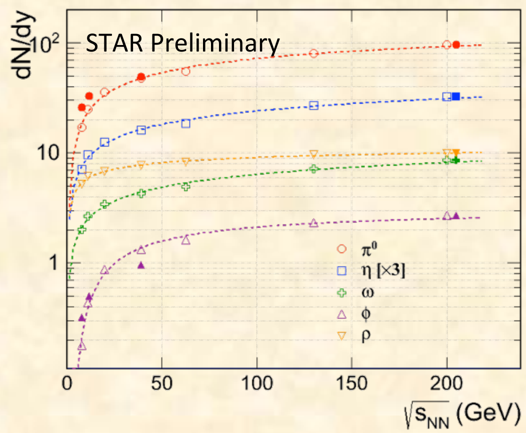
- ➢ 1/10 for p+p
- ➢ 1/250 for Au+Au central

Hadronic Background Simulation

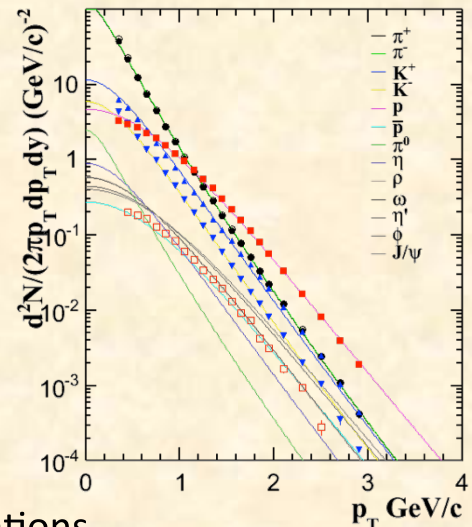
Au+Au 200GeV



Au+Au 39 & 62GeV



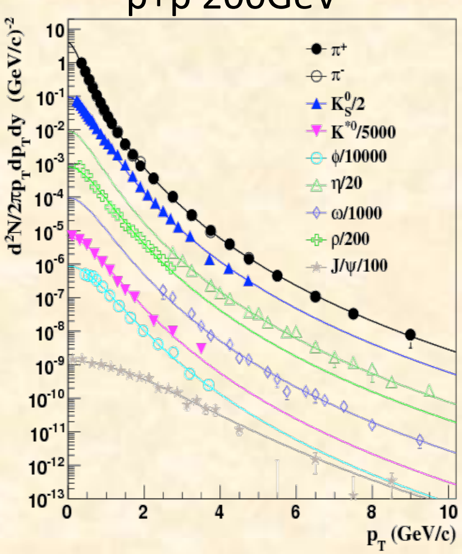
Au+Au 19.6 GeV



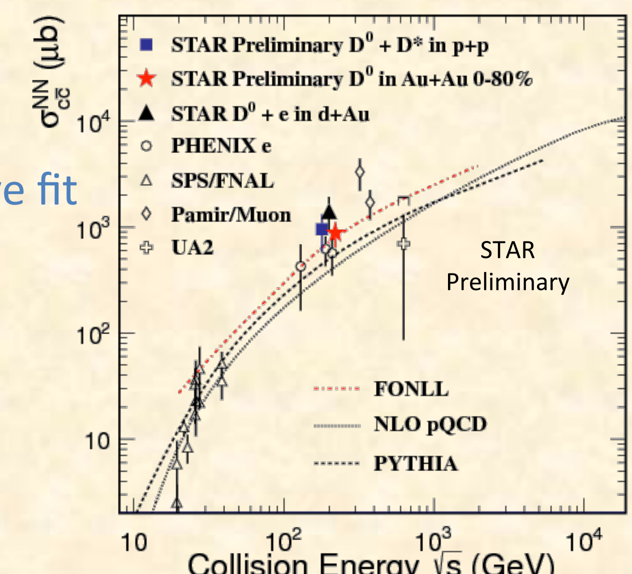
- TBW fit from NA49 data
- π yield from STAR

- Extrapolated from AMPT calculations
- Scaled to measurements at 200GeV

p+p 200GeV

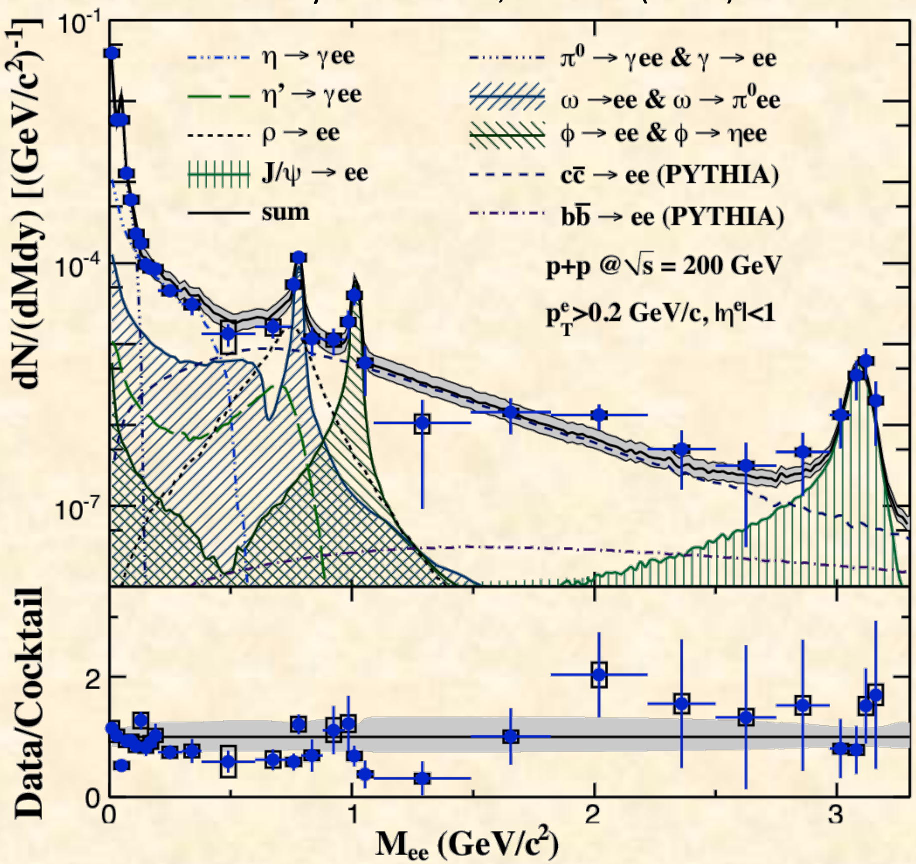


- Hadrons: flat |y|<1.0, and flat full azimuth input distribution
  - p_T distribution from Tsallis blast-wave fit to measured particle spectra
- Heavy flavor sources
  - STAR measurements, and PYTHIA simulation
  - N_{bin} scaled in Au-Au
  - at low energy: FONLL



Production in p+p at 200 GeV

Phys. Rev. C 86, 024906 (2012)



- Understand the p+p reference

Cocktail simulation consistent with data

L. Ruan (STAR), Nucl. Phys. A855 (2011) 269

Charm contribution dominates IMR

– scaled with STAR charm cross-section

Adams et al (STAR), Phys. Rev. Lett. 94 (2005) 062301

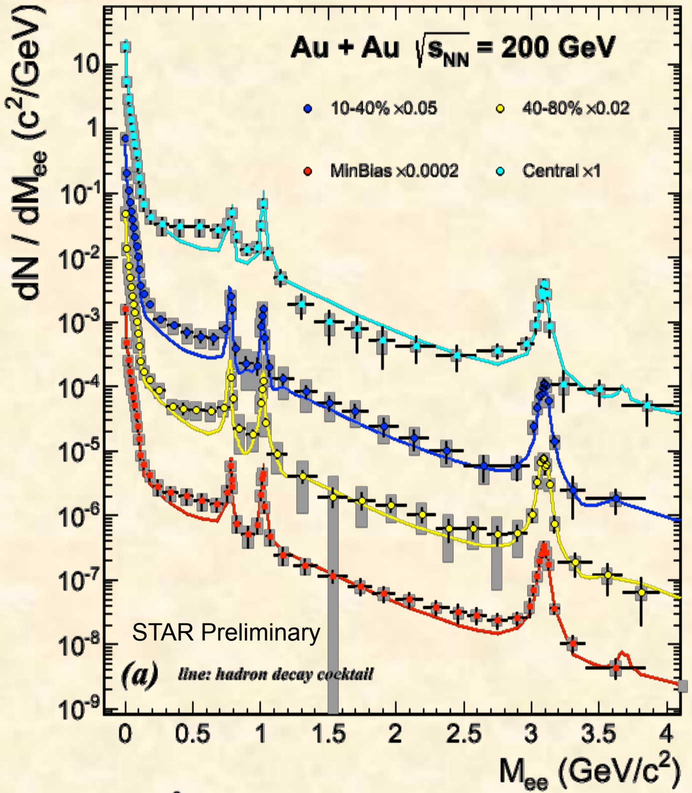
Based on ~107M events with 70% TOF coverage.

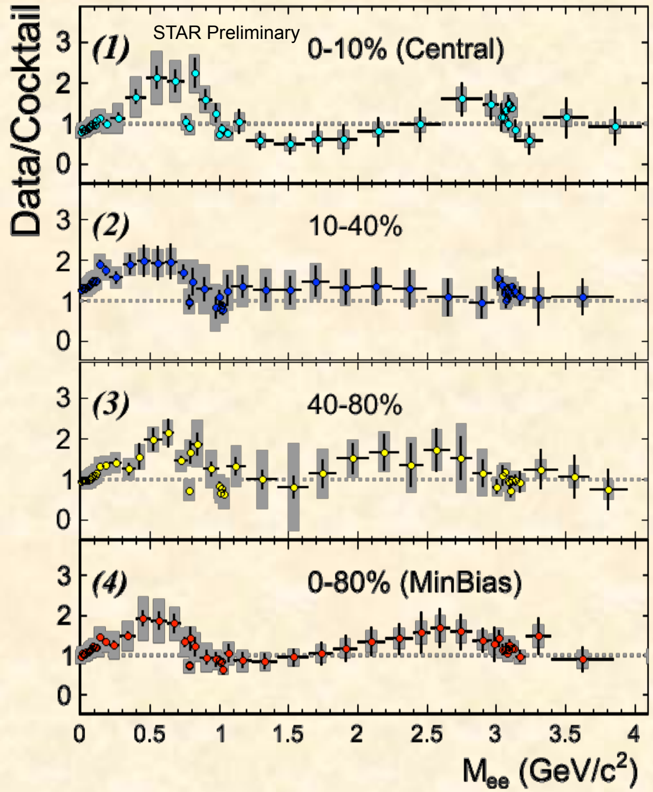
– RHIC Run12 p+p ~700M events, 100% TOF

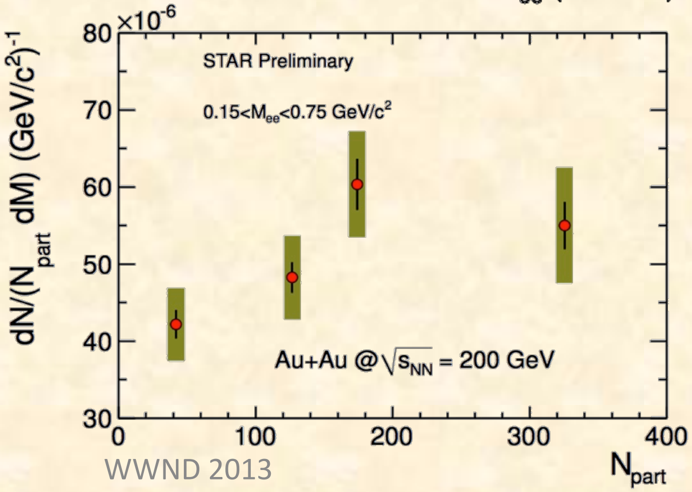
Uncertainties:

- vertical bars: statistical
- boxes: systematic
- grey band: cocktail simulation systematic
- not shown: 11% normalization

Production in Au+Au at 200 GeV







LMR enhancement scaled by N_{part} vs. centrality

Low Mass:

- ➢ enhancement

when compared to cocktail (w/o ρ meson)

Intermediate Mass:

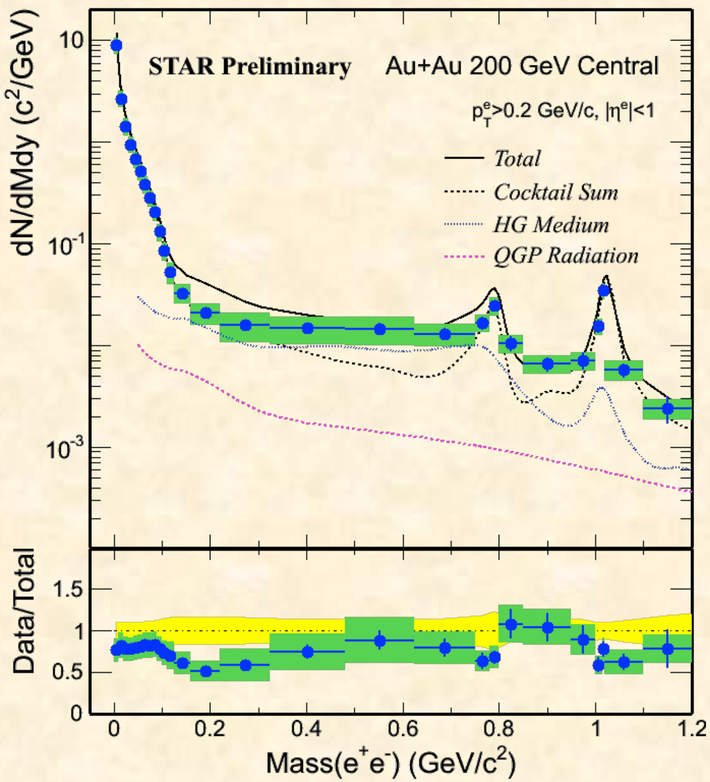
cocktail “overshoots” data in central collisions but, consistent within errors

modification of charm?

difficult to disentangle (modified) charm from thermal QGP contributions

- ➢ future detector upgrades required

Compare to Rapp, Wambach, v. Hees



- STAR central 200 GeV Au+Au
- hadronic cocktail (STAR)

Ralf Rapp (priv. comm.)

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

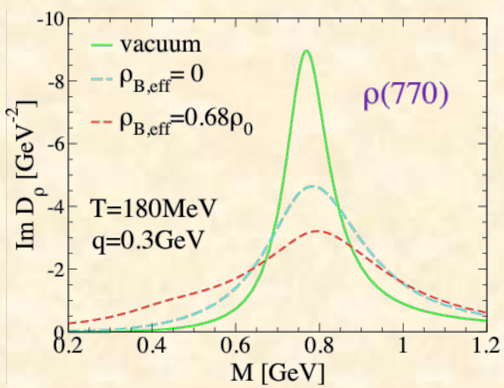
R. Rapp & J. Wambach, EPJ A 6 (1999) 415

Complete evolution (QGP+HG)

cocktail + HG + QGP:

➢ Agreement w/in uncertainties

Rapp, Wambach, van Hees arXiv:0901.3289



➢ hadronic phase: ρ "melts" when extrapolated close to phase transition boundary
  - total baryon density plays the essential role

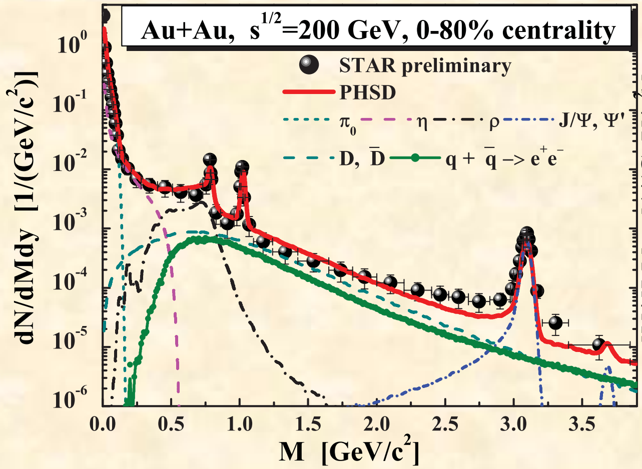
➢ top-down extrapolated QGP rate closely coincides with bottom-up extrapolated hadronic rates

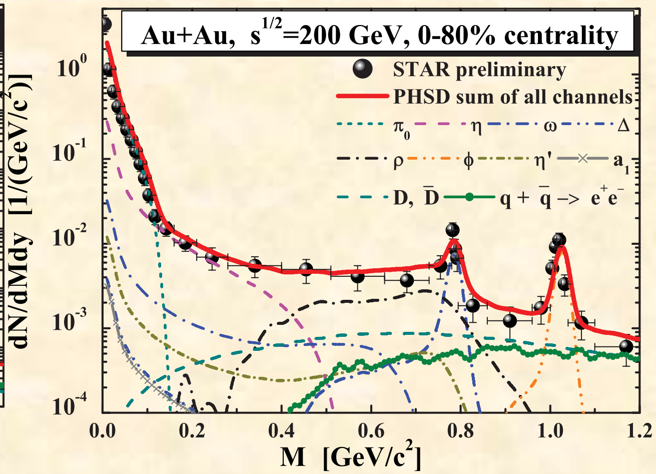
Compare to Theory: PHSD Model

O. Linnyk et al., Phys. Rev. C 85 024910 (2012)
H. Xu et al., Phys. Rev. C 85 024906 (2012)

Parton-Hadron String-Dynamics

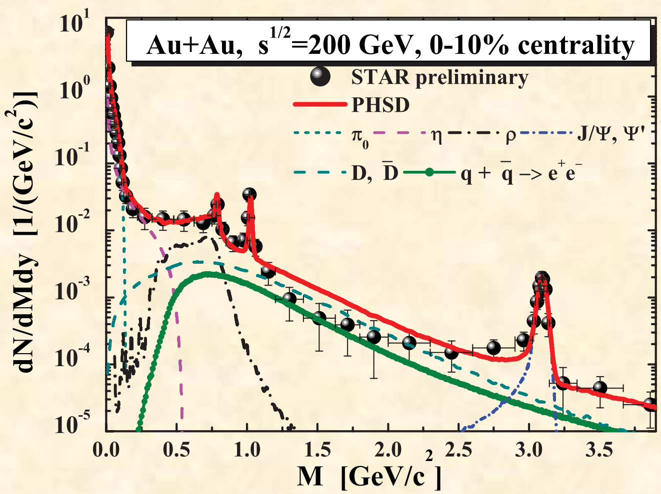
1. Collisional broadening of vector mesons
2. Radiation from QGP

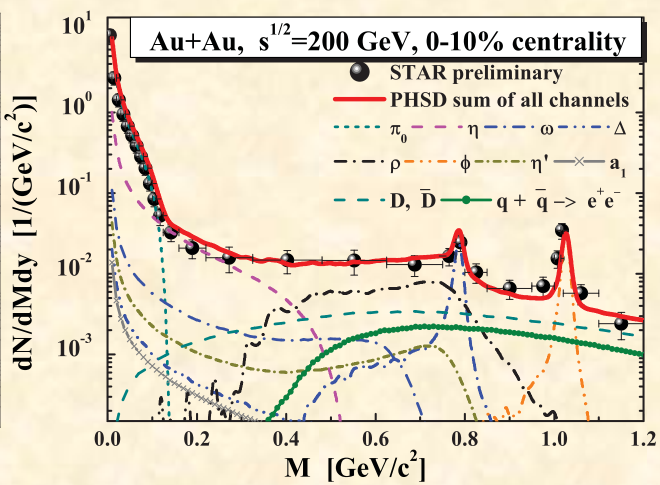




<u>Minimum bias collisions</u> (0-80%):

- Generally good agreement

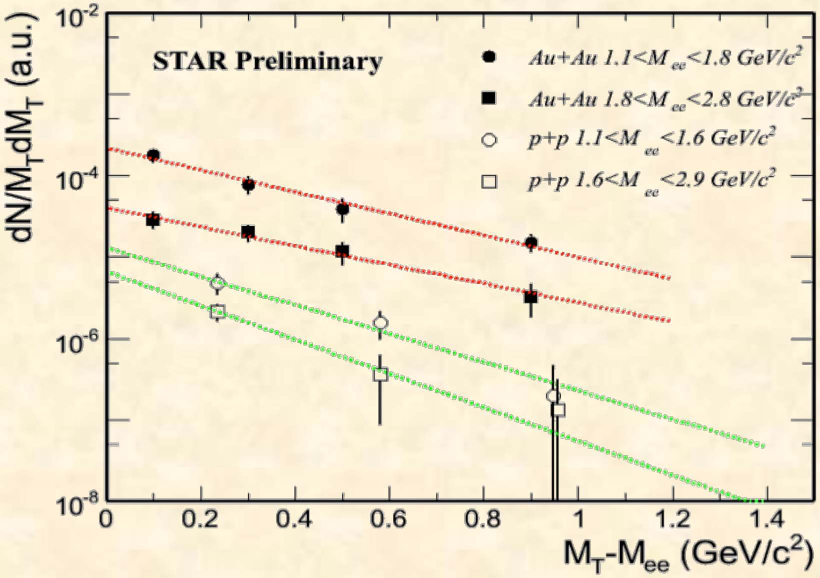




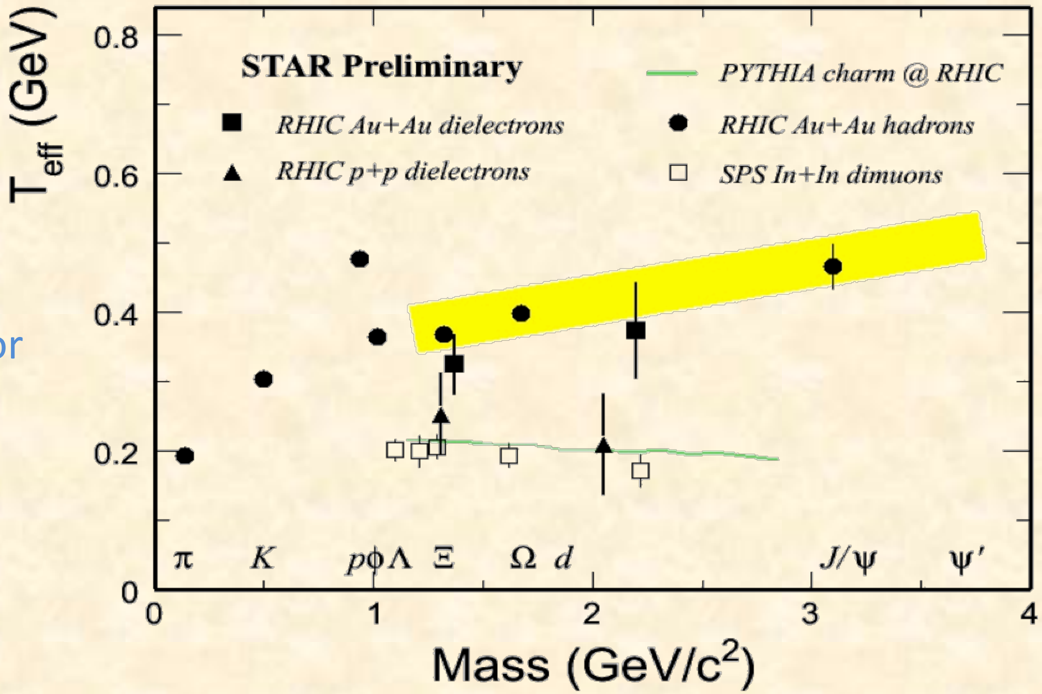
<u>Central collisions</u> (0-10%):

- PHSD roughly in line with LMR region

IMR: Transverse Mass Spectra



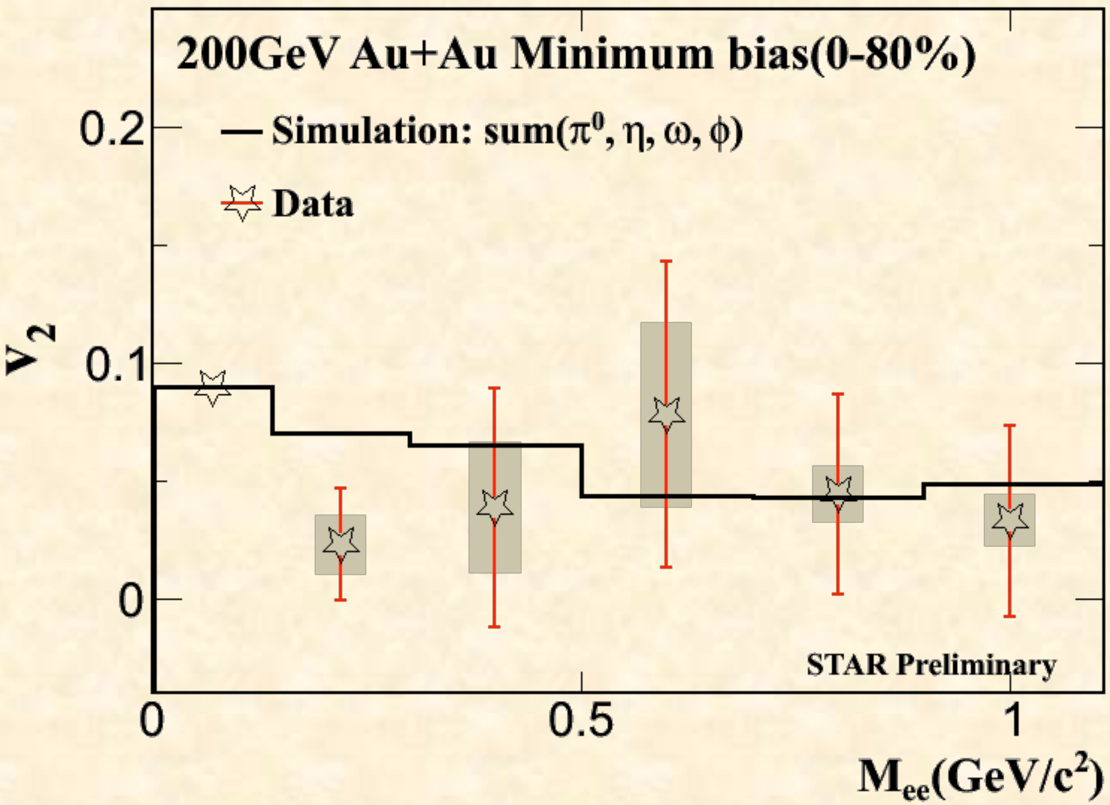
- RHIC: Au+Au 200 GeV (minbias)
  - inclusive dielectron
- SPS: In+In 17.2 GeV
  NA60 -- PRL 100, 022302 (2008)
  - charm/Drell-Yan subtracted



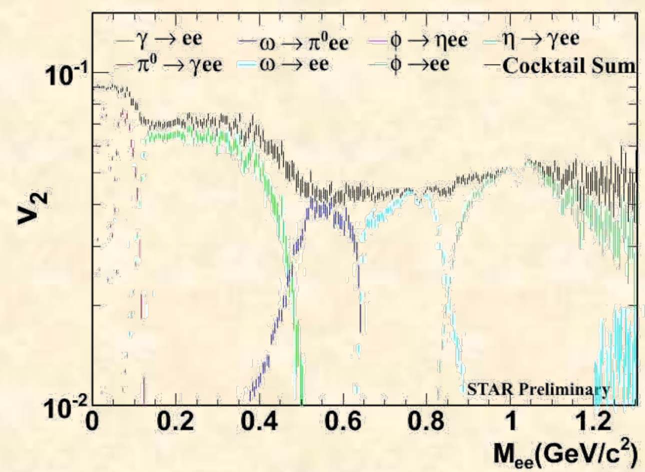
- ➢ p+p results consistent with PYTHIA
- ➢ m_T slope in Au+Au larger than in p+p
  - hint of thermal dilepton production and/or charm modification
- ➢ inclusive dilepton slope in Au+Au (RHIC) is larger than SPS (charm/DY subtracted)

Elliptic Flow in Au+Au at 200 GeV

First measurements from STAR



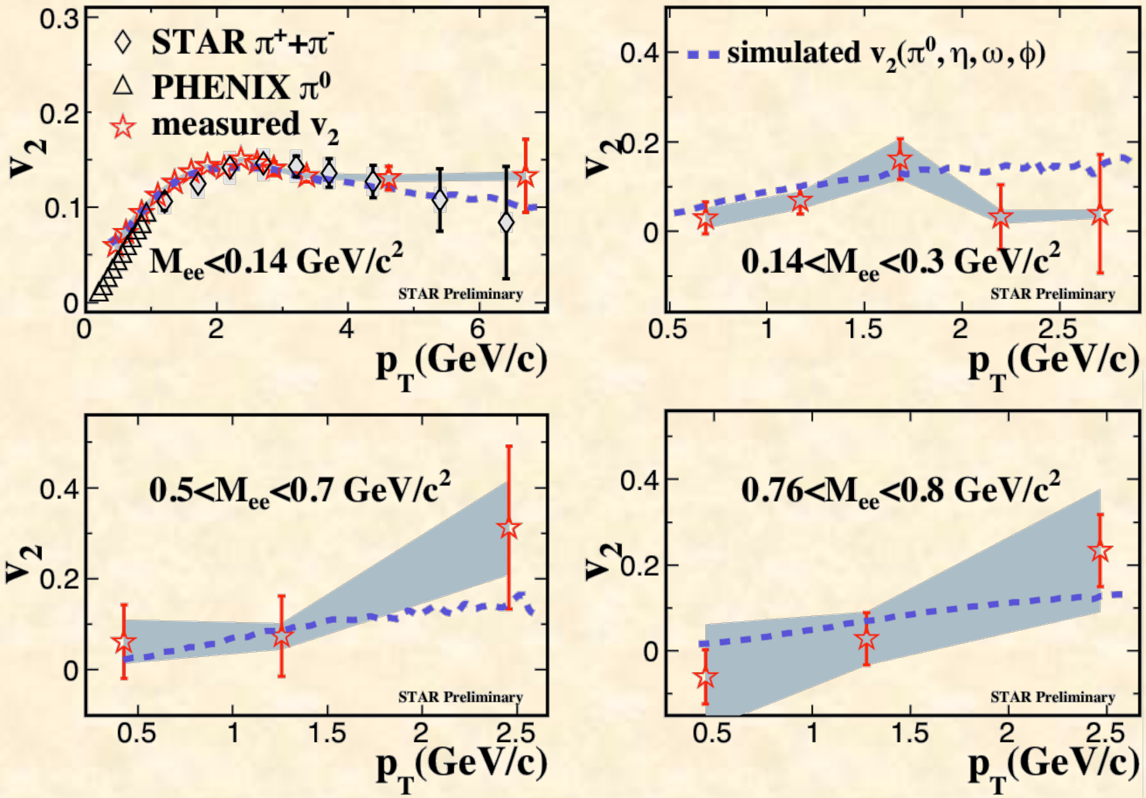
- 700M min-bias events
  - combined 2010/2011
- Background:
  - Like-Sign M_{ee}<0.7 GeV/c^2
  - Mixed-Event M_{ee}>0.7 GeV/c^2
- Event-Plane method: TPC
- Cocktail contributions:



- ➢ dielectron $v_2(M_{ee})$: data and simulations consistent
  - work in progress to include IMR v_2

Dielectron v_2 p_T Dependence

Au+Au $\sqrt{s_{NN}}$= 200GeV 0-80% centrality



Comparison with measured $v_2(p_T)$

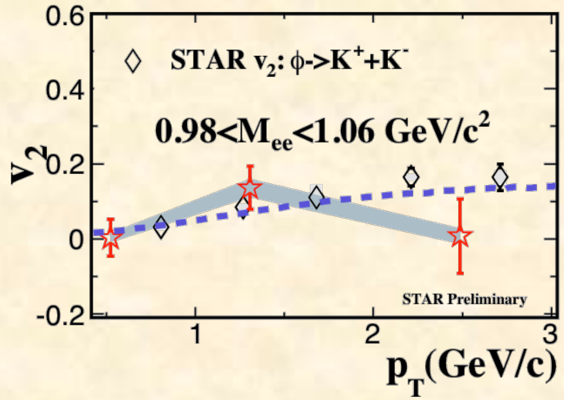
$\pi^{\pm}$ (STAR) and π^0 (PHENIX)

$M_{ee} < 0.14$ GeV/c^2

PHENIX, PRC 80 (2009) 054907

$\phi \rightarrow K^+K^-$ (STAR)

$0.98 < M_{ee} < 1.06$ GeV/c^2



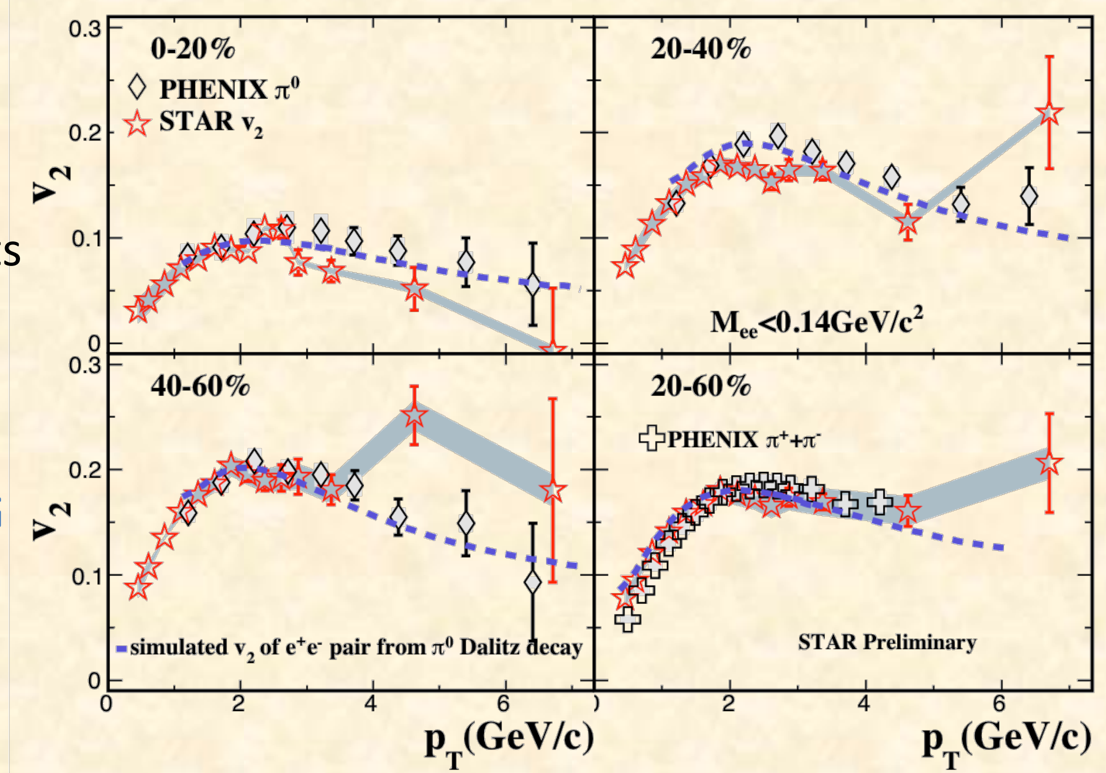
➢ $v_2(p_T)$ consistent with simulations & measurements

Dielectron v_2 Centrality Dependence

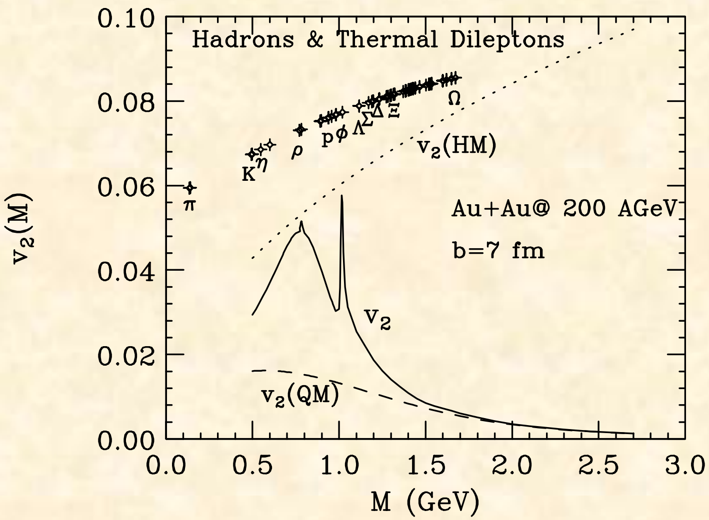
Centrality dependence $v_2(p_T)$

$M_{ee}<0.14$ GeV/c^2

- consistent with simulations
- consistent with measurements



Can we distinguish between HG and QGP v_2 contributions?



Recall: need uncertainties to be <4% (compared with model differences) … no, not yet.

➤ Require more Au+Au min-bias data and e-μ measurements at higher M_{ee} to disentangle charm contributions

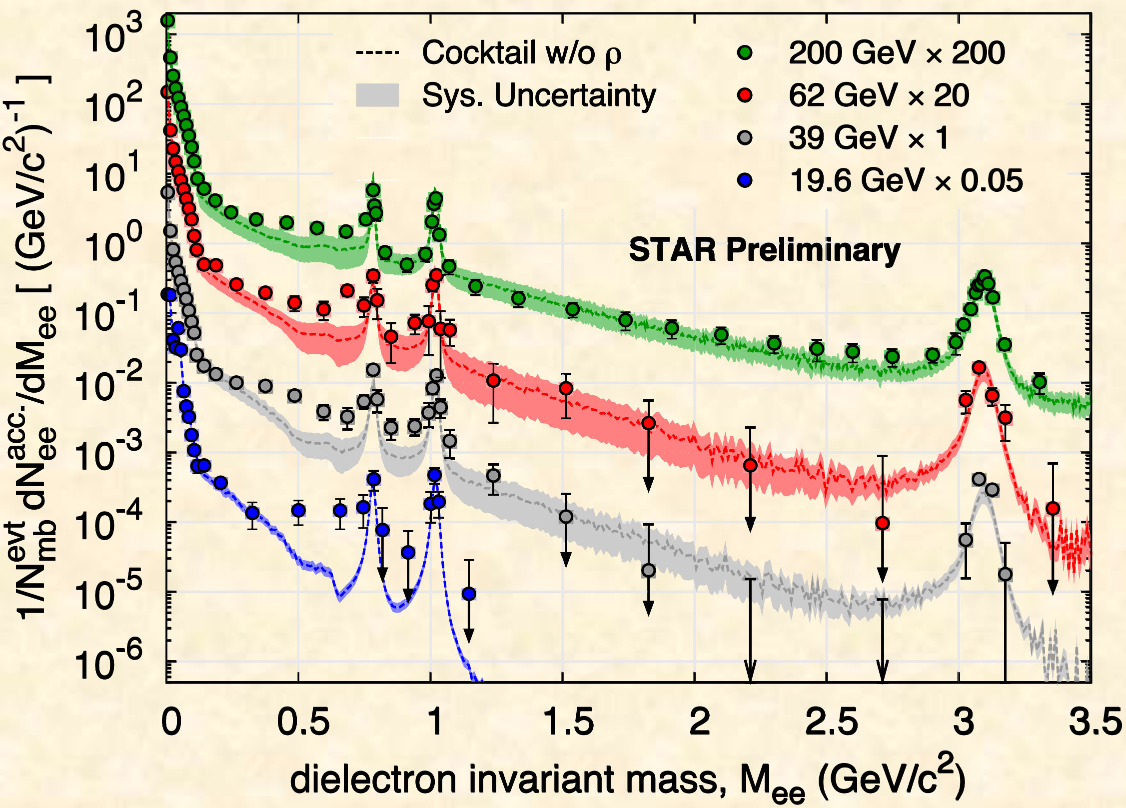
Dielectron Production at lower $\sqrt{s_{NN}}$

Observed Low-Mass enhancement at top RHIC energy

- in-medium modification effects?
- indication of chiral symmetry restoration?

Explore Low Mass Range down to SPS energies

- possible enhancement, consistent model description?



Beam Energy Scan Dielectrons:

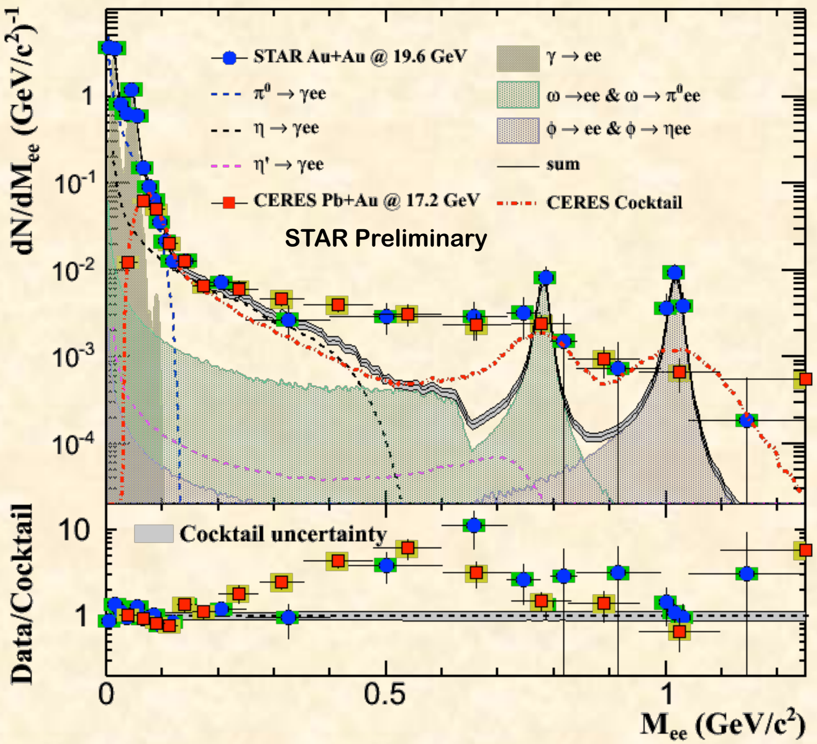
2010 - 2011

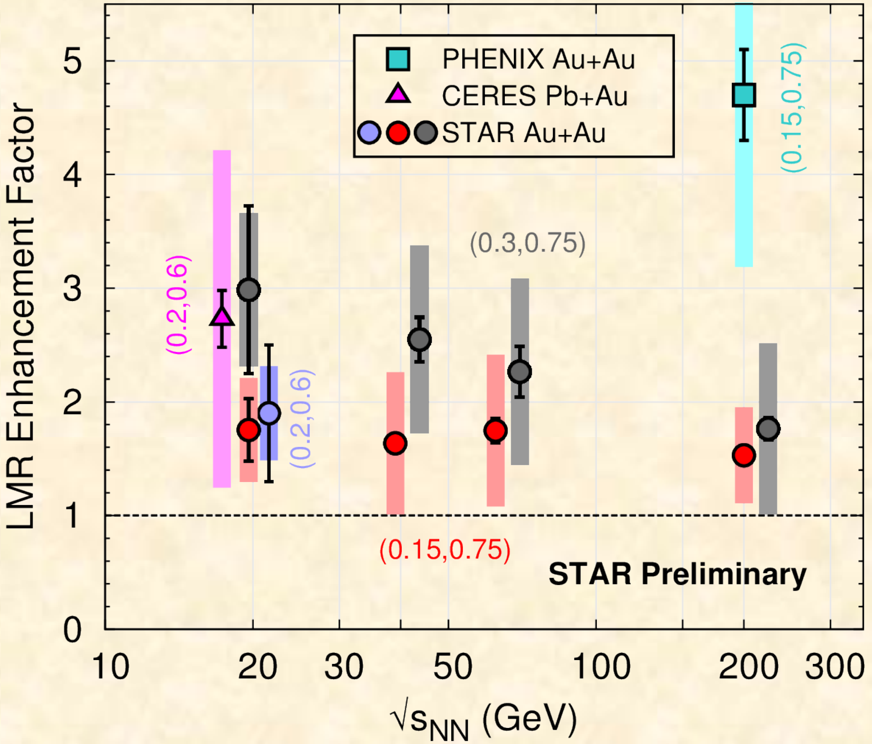
Au+Au at 62.4, 39, and 19.6 GeV

STAR data samples:

55M, 99M, and 34M min-bias events

LMR Enhancement *vs.* $\sqrt{s_{NN}}$





- STAR enhancement comparable to CERES
  note: different experimental acceptances

- LMR excess over hadronic cocktail observed for all energies (excl. ρ)
- systematic measurement of LMR enhancement factor

STAR Au+Au at 19.6 GeV/c

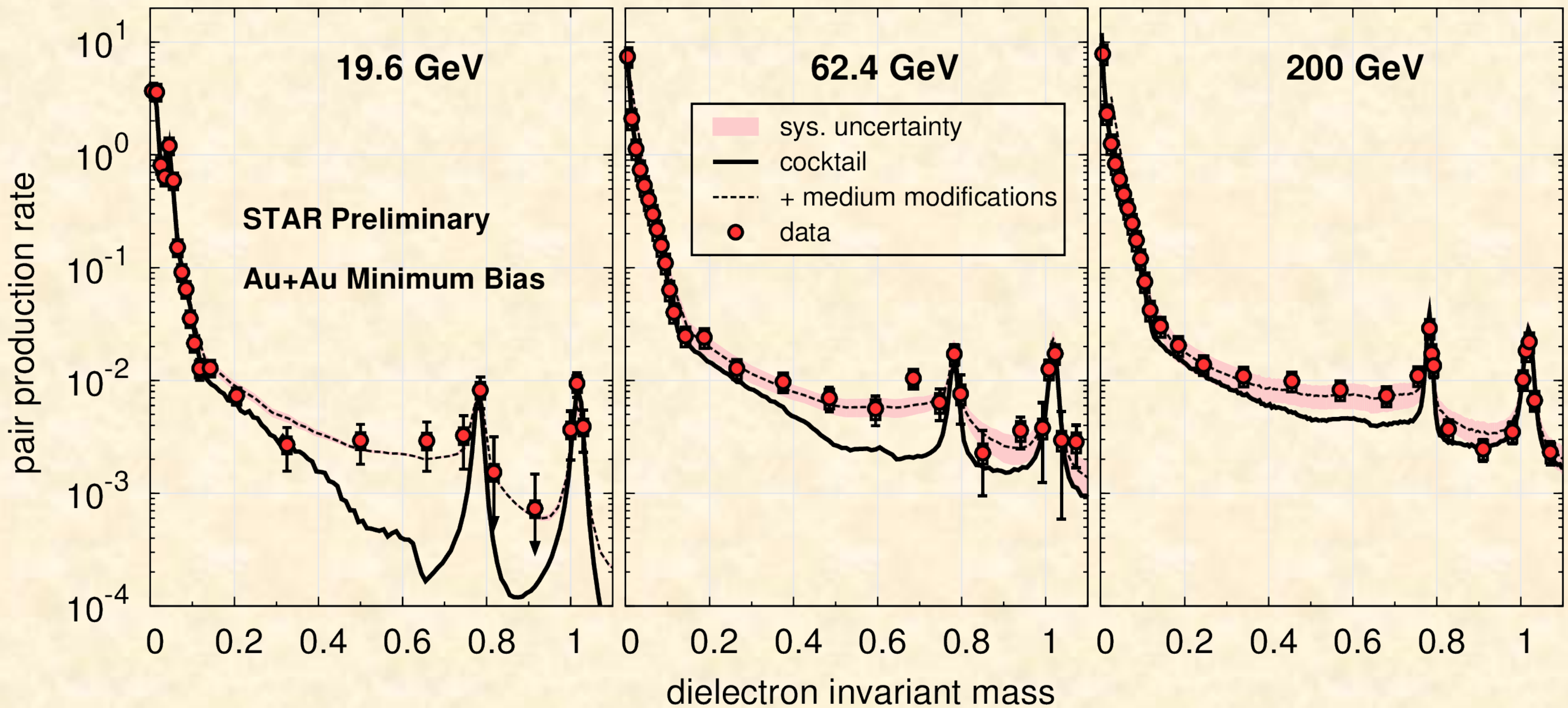
- min-bias (0 - 80%)
- p_T>0.2GeV/*c*, |η|<1, $|y_{ee}|$<1

CERES Pb+Au at 17.3 GeV/c

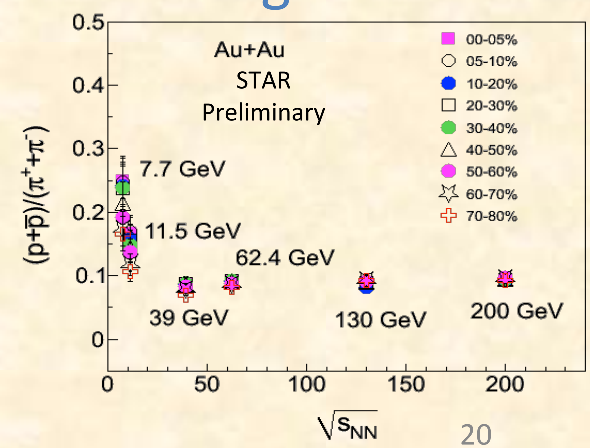
CERES, Eur.Phys.J. C 41 (2005) 475

- semi-central (0-28%)
- p_T>0.2GeV/*c*, 2.1<η<2.65, θ_{ee}>35mrad

Compare to Theory: in-medium ρ



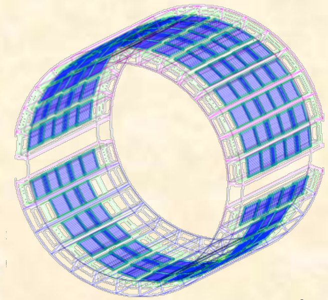
- Robust theoretical description top RHIC down to SPS energies
  - calculations by Ralf Rapp (priv. comm.)
  - black dotted curve: cocktail + in-medium ρ
- Measurements consistent with in-medium ρ broadening
  - expected to depend on total baryon density
  - tool to look for chiral symmetry restoration



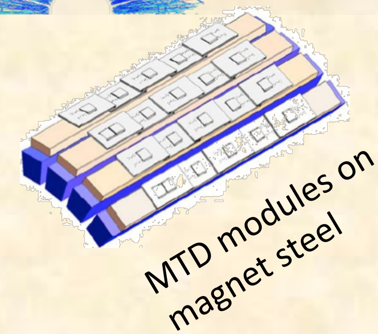
STAR Dileptons: Present & Future (1)

- <u>2009 – 2011</u>
  - **TPC + TOF + EMC**
    - dielectron continuum
    - dielectron spectra, and v_2 (p_T)
  - vector meson in-medium modifications
  - LMR enhancement
  - modification in IMR?

- <u>2012-2013</u>
  - **TPC + TOF + EMC + MTD** (partial)
    - e-μ measurements
  - IMR: Improve our understanding of thermal QGP radiation
  - LMR: vector meson in-medium modifications



STAR MTD Barrel



MTD modules on magnet steel

Muon Telescope Detector

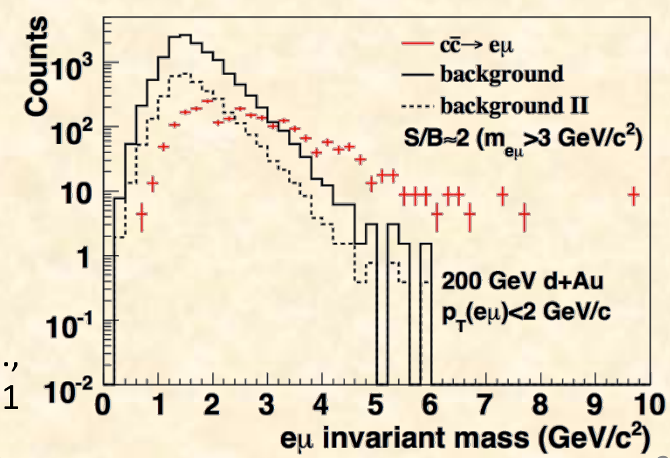
for more details, see F. Videbaek's presentation

➢ single μ's from heavy-flavor semi-leptonic decays

– e-μ correlations to disentangle heavy quark decays from initial dilepton pairs

$$c + \overline{c} \rightarrow e + \mu \ (e)$$

➢ improve understanding of QGP thermal radiation in IMR

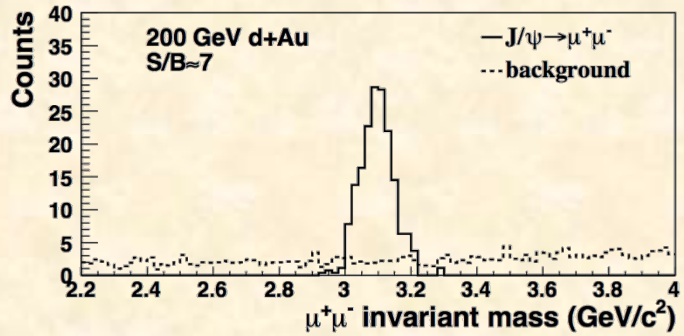


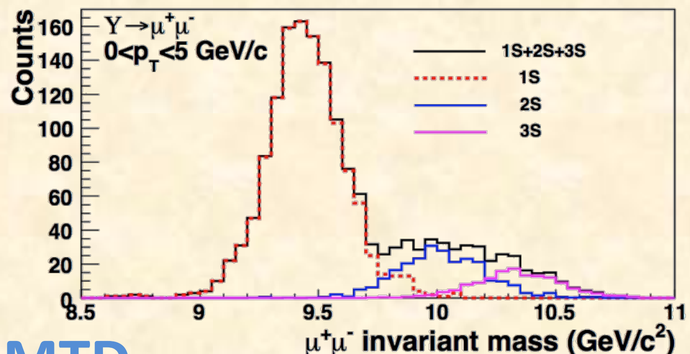
L.Ruan et al.,
J.Phys.G. 36 (2009) 095001

STAR Dileptons: Future (2)

- <u>2014 and beyond</u>
  - **TPC + TOF + EMC + MTD + HFT**
    - dimuon continuum
    - e-μ spectra and v_2
  - LMR: vector meson in-medium modifications
  - IMR: measure thermal QGP radiation

L.Ruan et al., J.Phys.G. 36 (2009) 095001





<u>BES Phase II</u>

- improve statistics for existing low energy samples
  - *e.g.* comparable to CERES statistics at 19.6 GeV
- further probe lower energies
  - LMR enhancement vs. increasing total baryon density

<u>Full MTD</u>

large area μ ID, with |η|<0.8

dimuon measurements:

- light vector mesons, resonances
- QGP thermal radiation
- quarkonia and DY production,

Summary

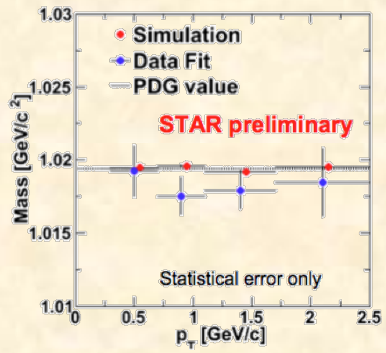
- STAR detector very well suited for dilepton physics
  - recent TOF upgrade allows for large acceptance electron ID
- Dielectron in p+p and Au+Au at $\sqrt{s_{NN}}$=200 GeV: centrality and p_T differentials
  - observe low mass enhancement
- Dielectron elliptic flow measurements in Au+Au at $\sqrt{s_{NN}}$=200 GeV
  - $v_2(M_{ee},p_T)$ results consistent with other measurements & cocktail simulations
  - need increase in statistics to distinguish HG and QGP contributions
- Dielectron measurements in Au+Au at $\sqrt{s_{NN}}$= 19.6 – 62.4 GeV
  - low mass enhancement down to SPS energies, with comparable magnitude
  - consistent with in-medium ρ broadening
  - robust and consistent description for $\sqrt{s_{NN}}$= 19.6, 62.4, and 200 GeV
- Future STAR upgrades enable further exploration of the dilepton continuum
  - upcoming MTD upgrade allows for large acceptance μ ID
  - QGP thermal radiation measurements

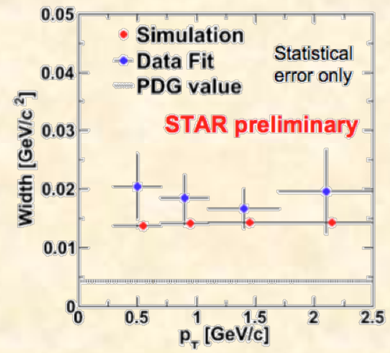
BACKUP

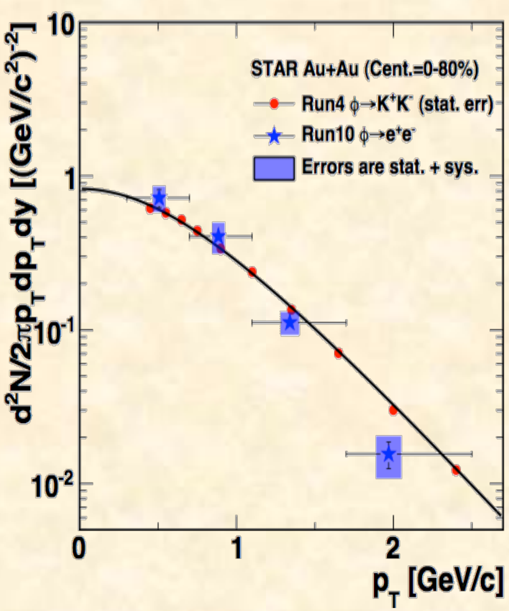
Leptonic Decay of ϕ and ω Mesons

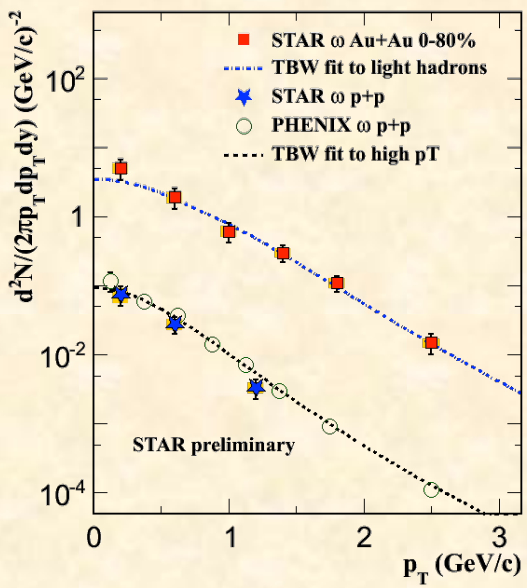
Lifetimes comparable to fireball

- hadronic decay daughters interact with hadronic medium
  - sensitive to lifetime of that medium
- leptonic decay daughters do not interact with QCD medium
  - look for medium modifications to resonance mass & width
  - sensitive to chiral phase transition
  - small branching ratio







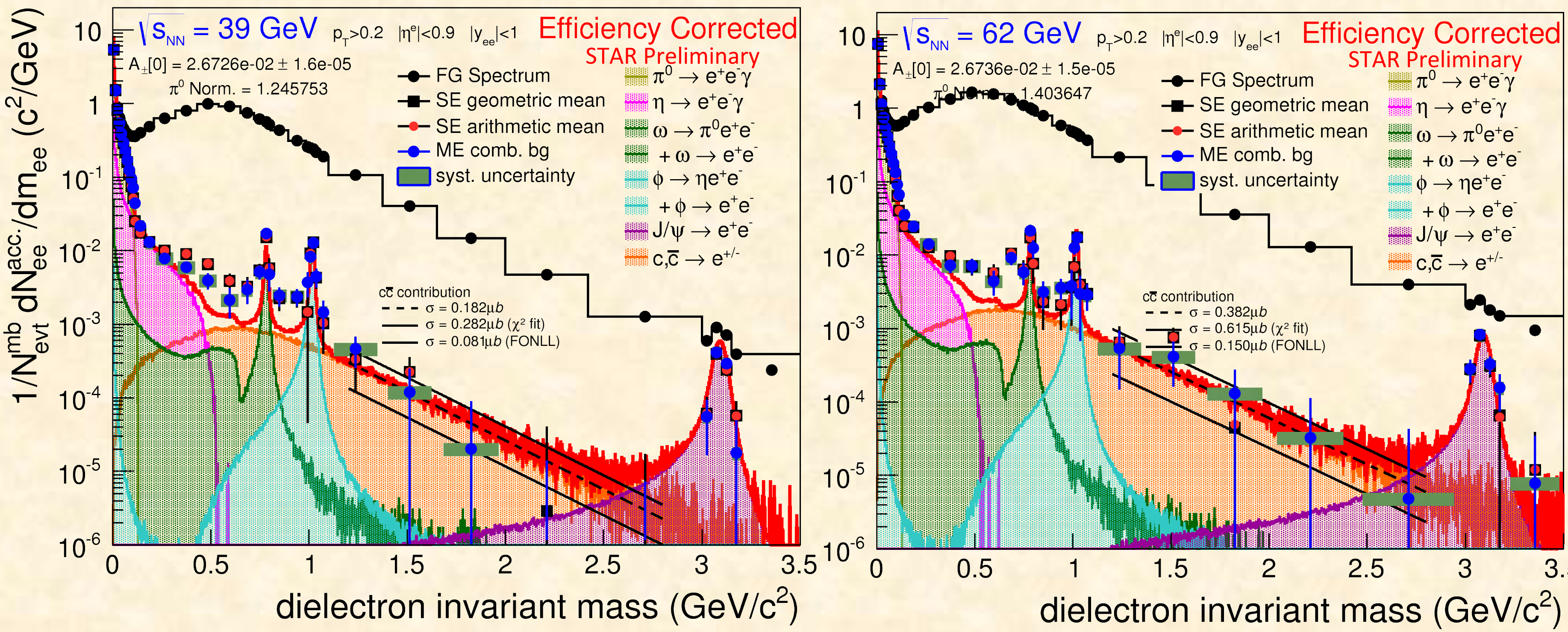


- No evidence of ϕ mass shift or width broadening
  - beyond known detector effects
- ϕ yield in dilepton decay channel consistent with hadronic channel

ω p_T shapes agree with light hadrons

ω mass and width are under study

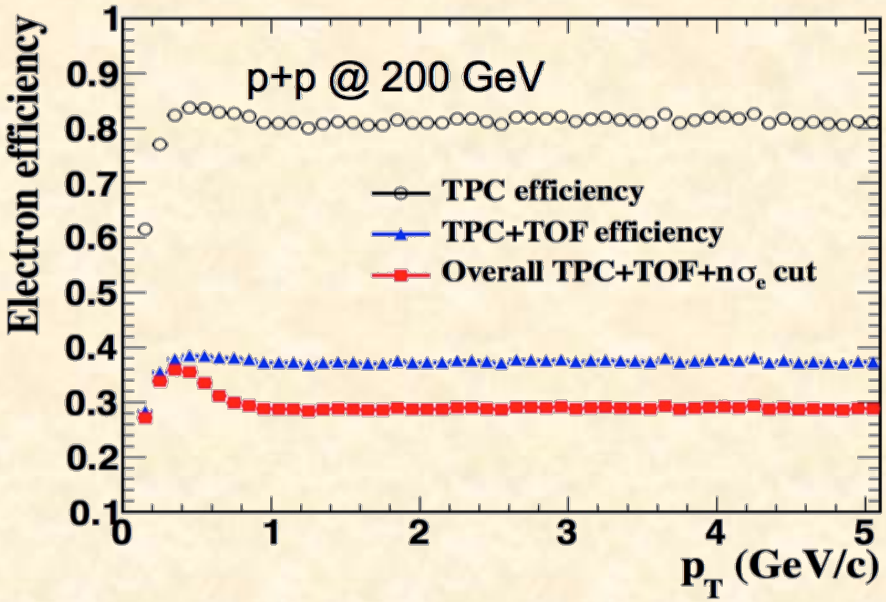
Dielectron M_{ee} for 39 and 62GeV

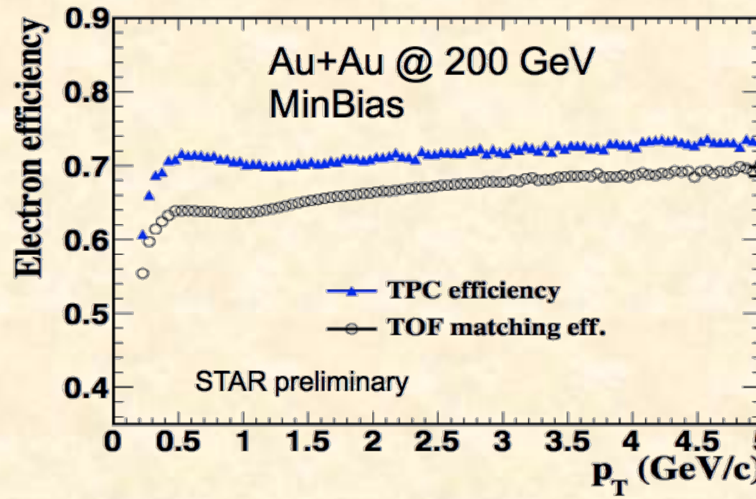


Efficiency Correction

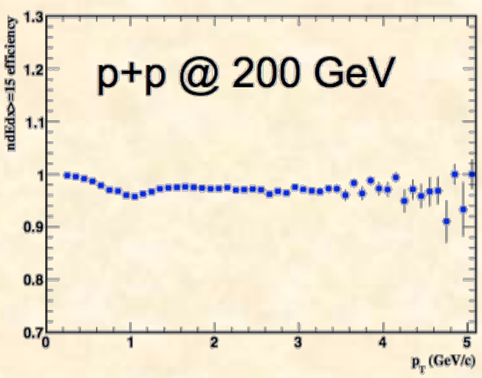
Ingredients:

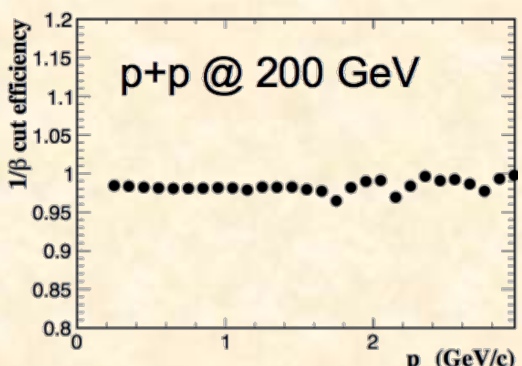
- TPC efficiency, TPC-TOF matching efficiency
- $n\sigma_e$(TPC PID selection), $1/\beta$ (TOF PID selection)

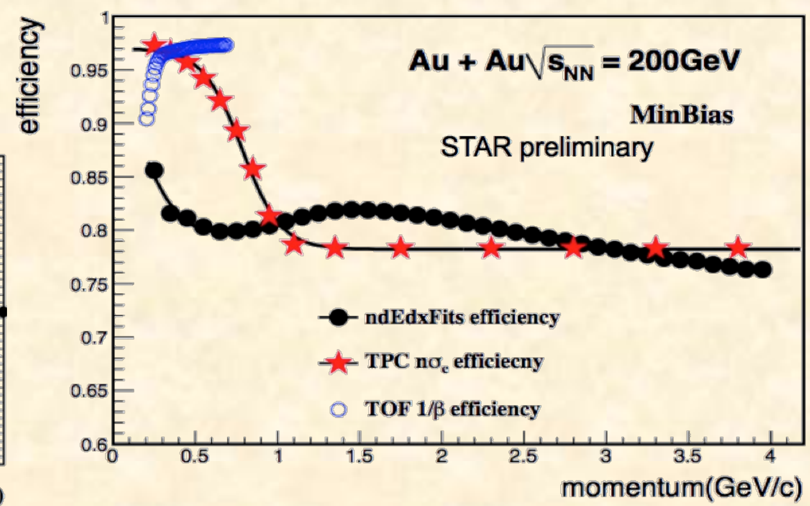




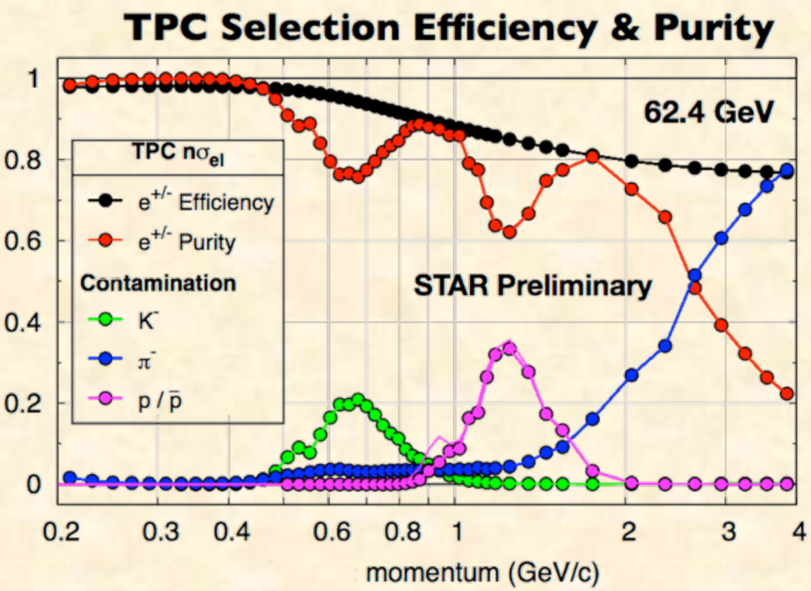
B.Huang, TRW (2012)

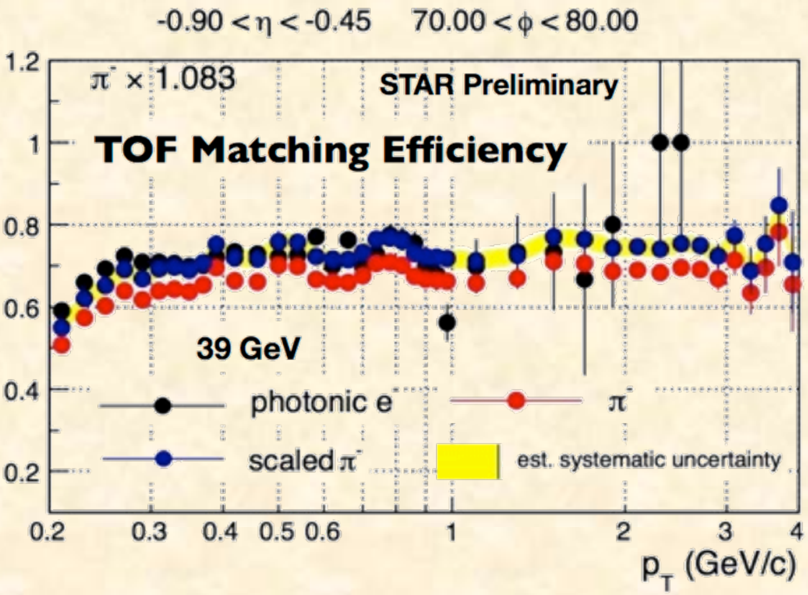






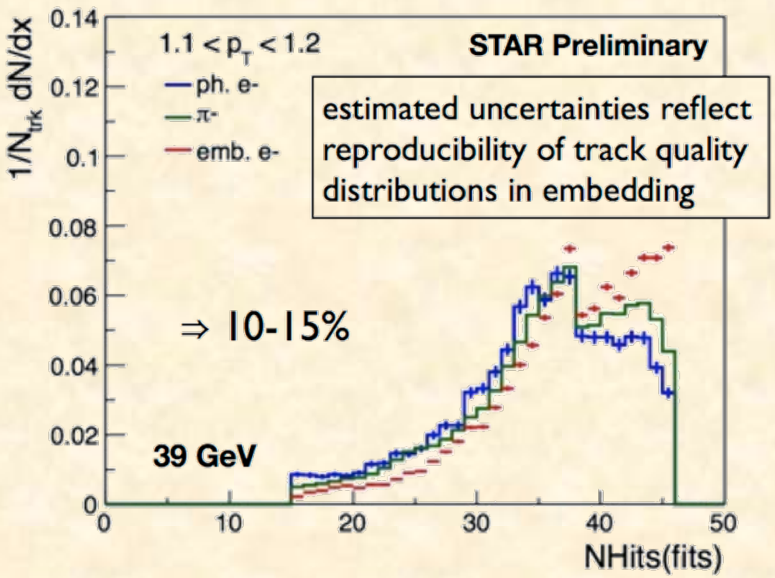
Efficiency Corrections (BES)

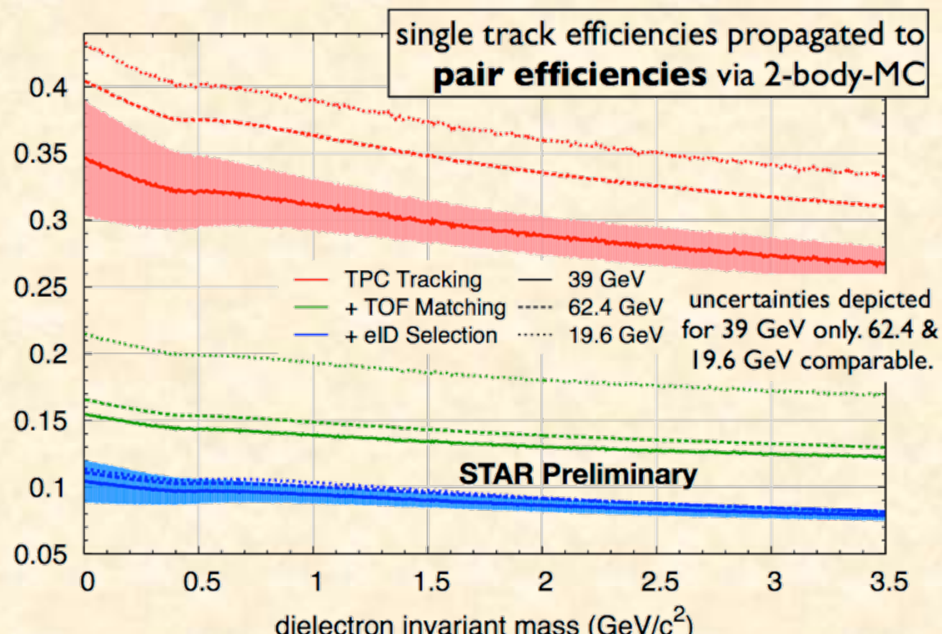




P.Huck, TRW (2012)

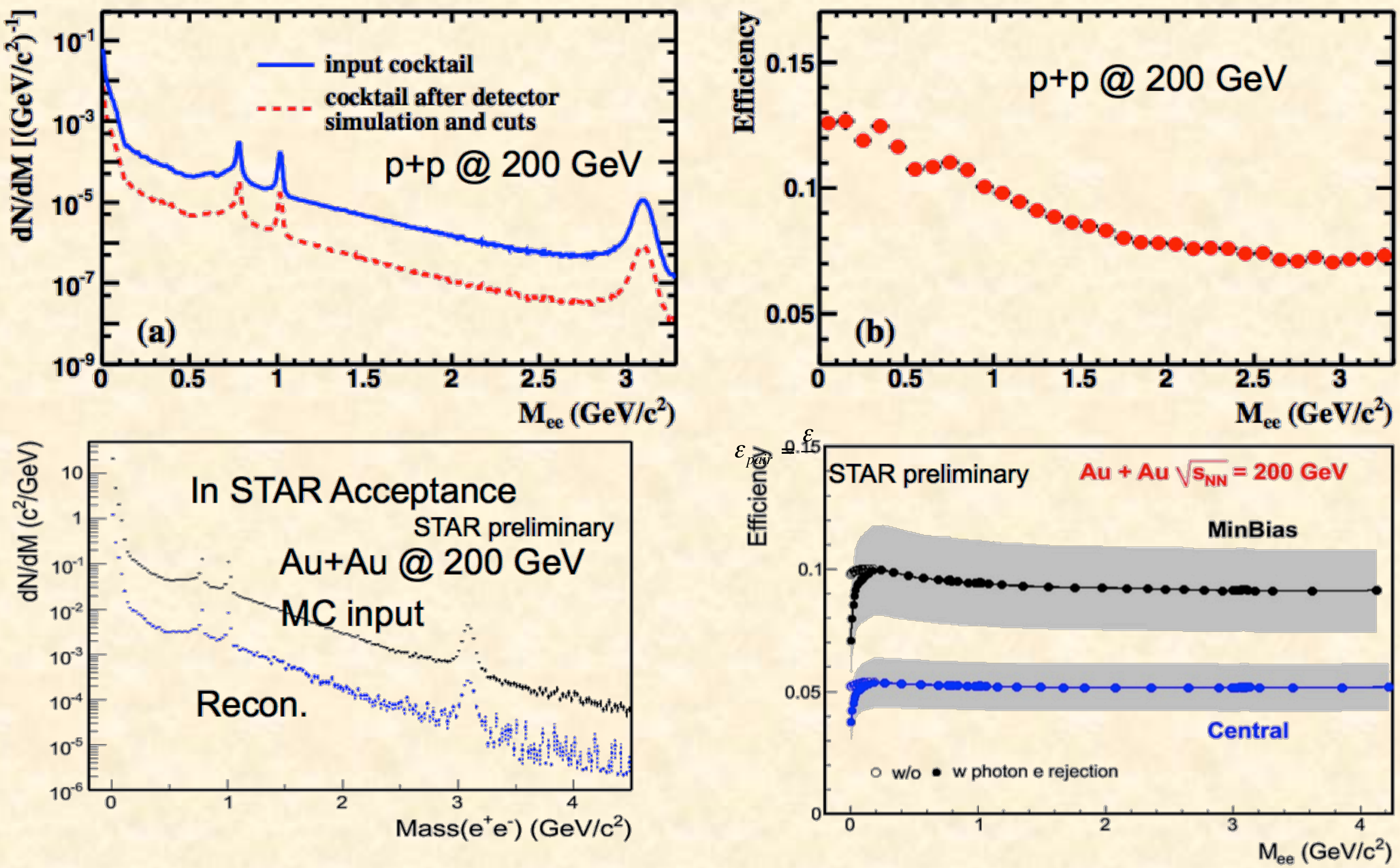
Systematic Uncertainty of Track Quality Cuts





Electron Pair Efficiency

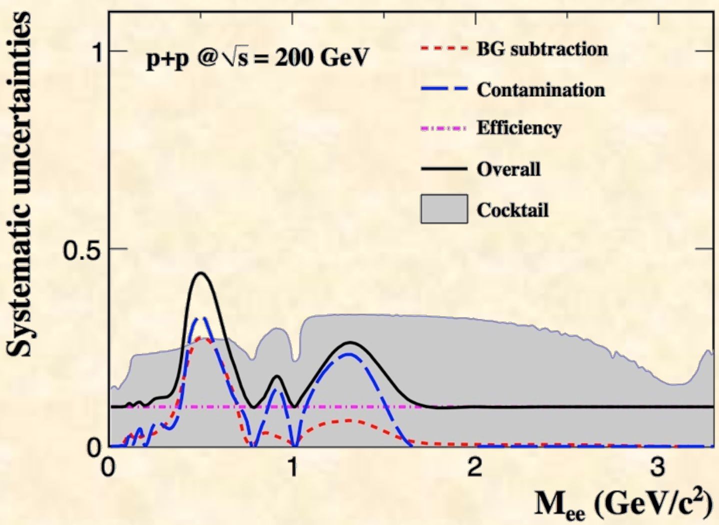
B.Huang, TRW (2012)



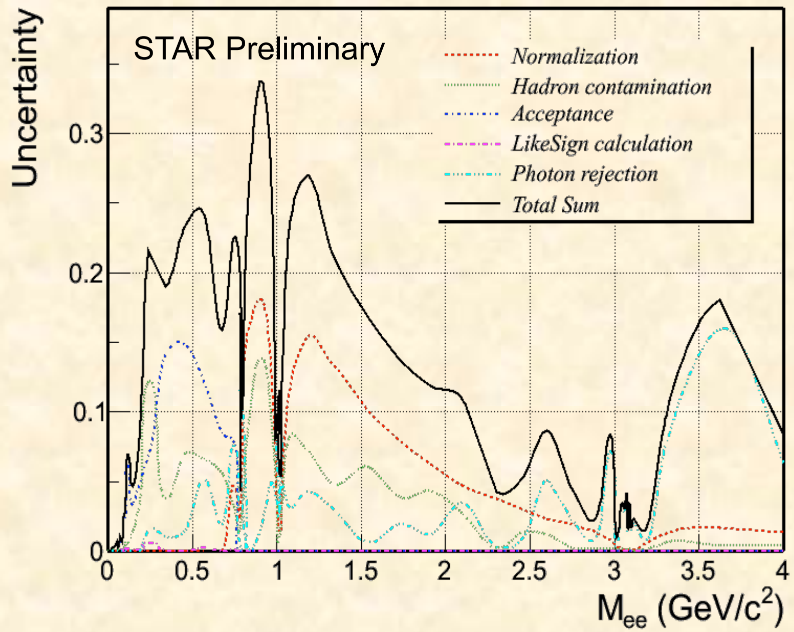
pair efficiency = (cocktail sampled single $e^{\pm}$ eff.) / (input cocktail)

Systematic Uncertainties

p+p@200GeV
- Background subtraction 0 - 27%
- hadron contamination 0 - 32%
- efficiency ~10%
- total normalization ~11%
- cocktail simulation 14 - 33%



Au+Au@200GeV



Au+Au@19.6GeV

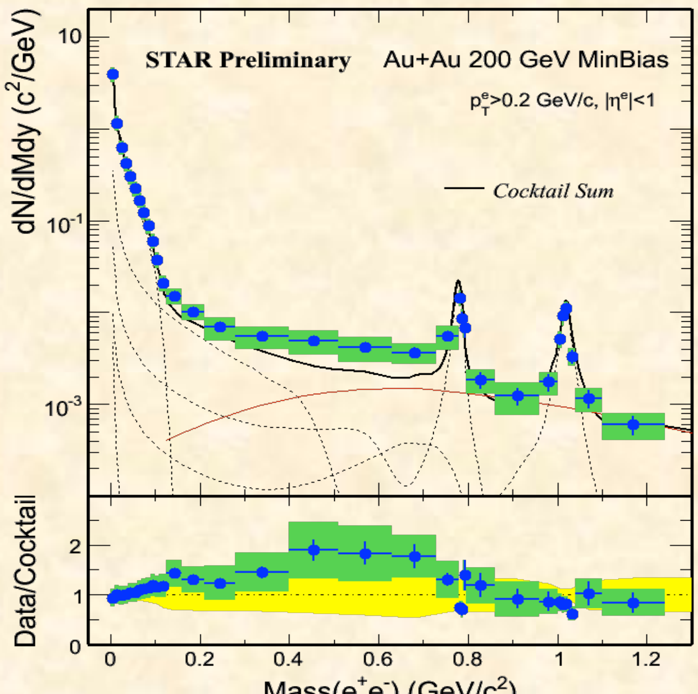
Tracking efficiency 7%

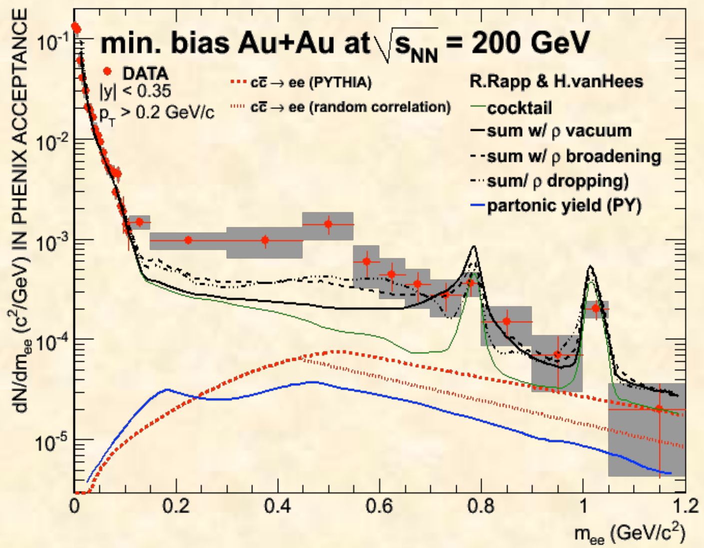
TOF matching 5%

Pair uncertainties (summed) 17%

cocktail uncertainties 12-20%

PHENIX & STAR Enhancement Factor



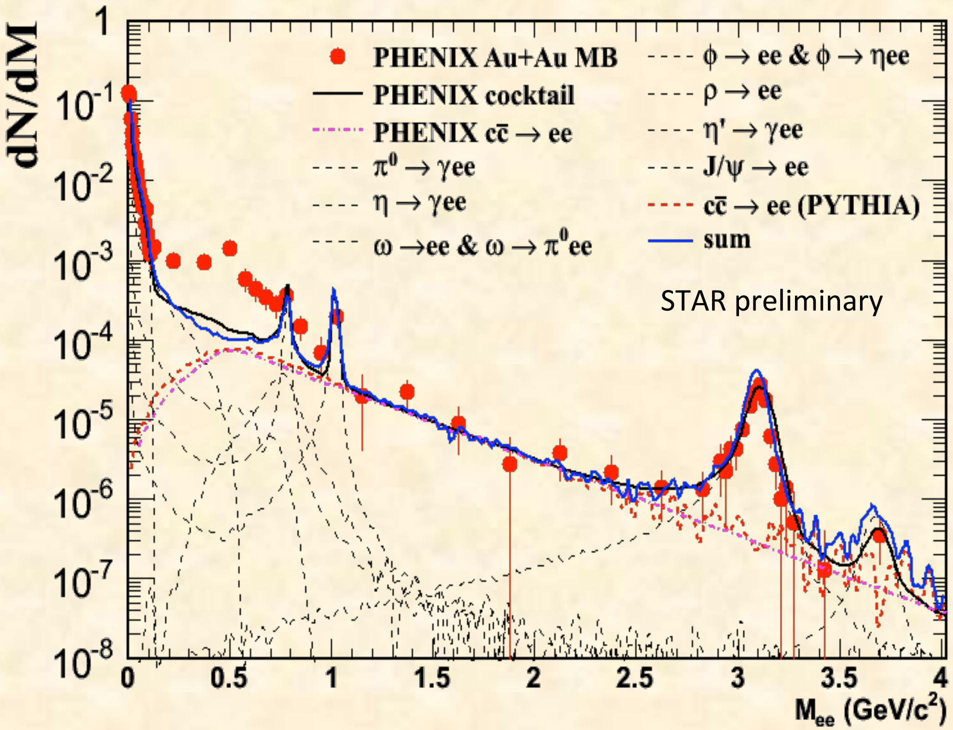


QM/SQM2011

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)
PHENIX	4.7 ± 0.4 ± 1.5	7.6 ± 0.5 ± 1.3
Difference	2.0 σ	4.2 σ

Reproducing the PHENIX Cocktail

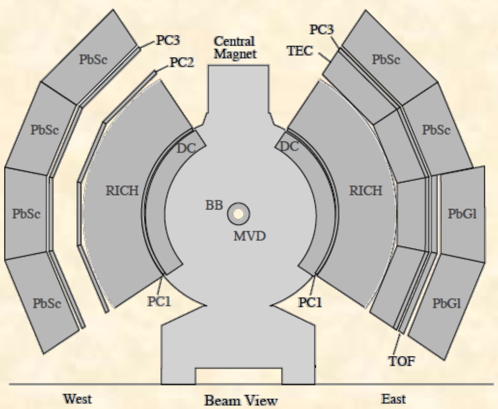


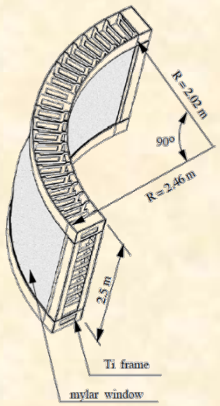
- Reproduce the cocktail within PHENIX acceptance by our method.
- The momentum resolutions are still from STAR.

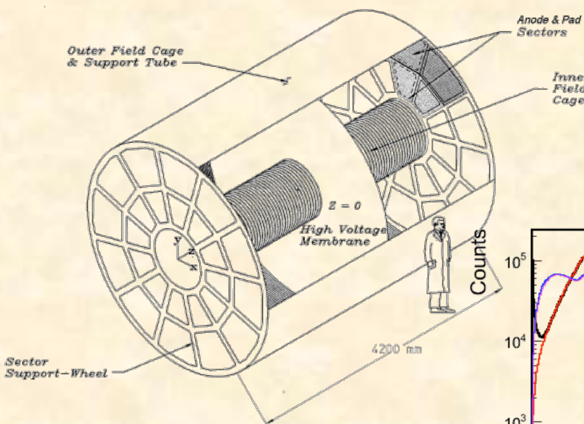
SQM2011

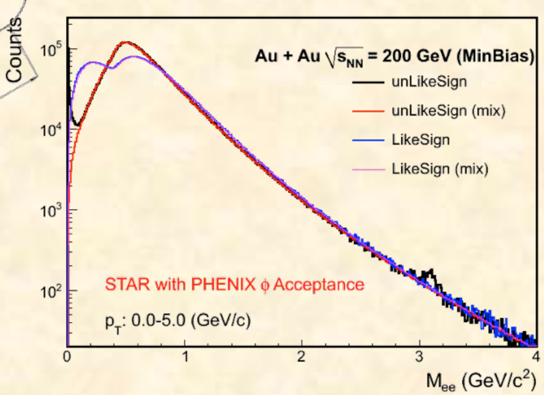
Scaled by all the yields from PHENIX paper[1], STAR reproduces the PHENIX cocktail.
[1]. Phys. Rev. C 81, 034911 (2010).

STAR with PHENIX Acceptance

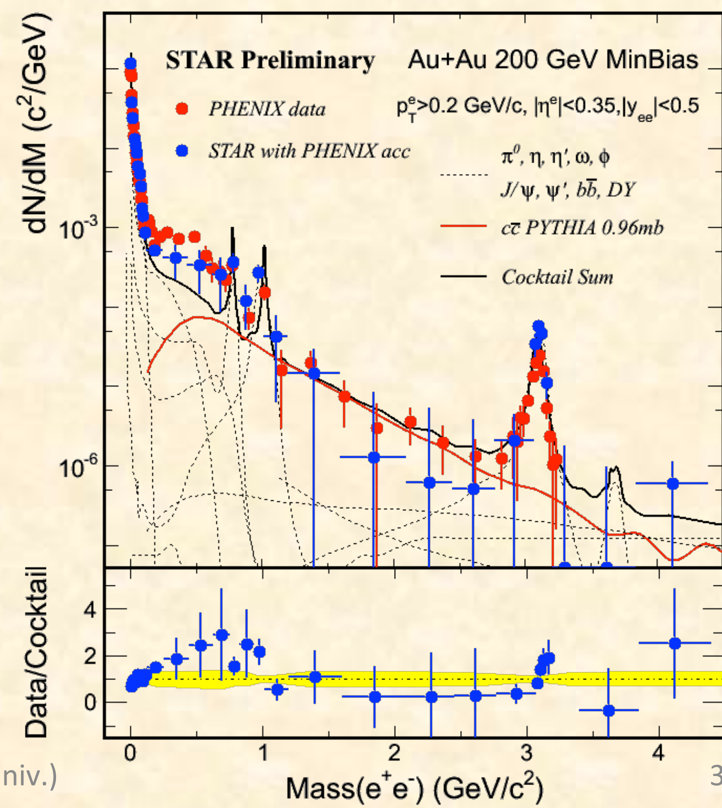








- STAR
  - 12 sectors east and west barrel
  - 2π coverage, |η|<1
- PHENIX
  - 20 sectors east and west arm
  - π coverage, |η|<0.35



Hard Probe 2012