Energy Dependence of Dilepton Production at RHIC

Frank Geurts (Rice University)

for the STAR Collaboration

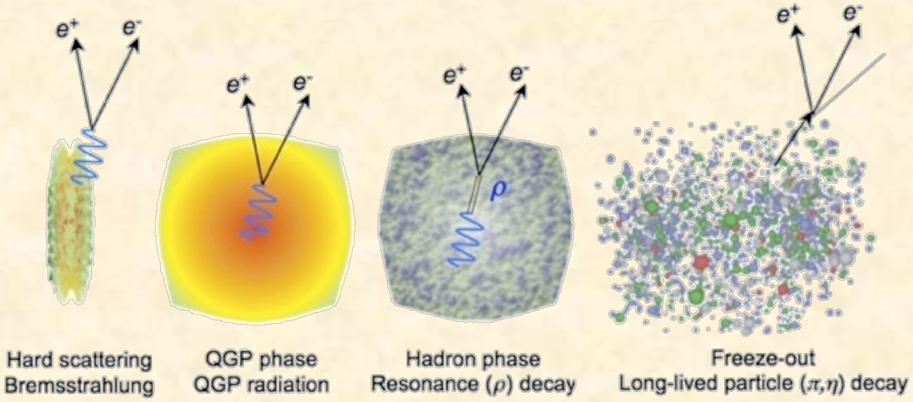
Outline

- Introduction & Motivation
  - QGP thermal radiation & chiral symmetry restoration
  - dilepton measurements at SPS
  - dilepton measurements at RHIC
- Electron Identification in STAR
- Dielectron Production in Au+Au at $\sqrt{s_{NN}}$= 200 GeV
- Results from Beam Energy Scan Program Phase 1
- STAR Dilepton Future: BES Phase 2
- Summary

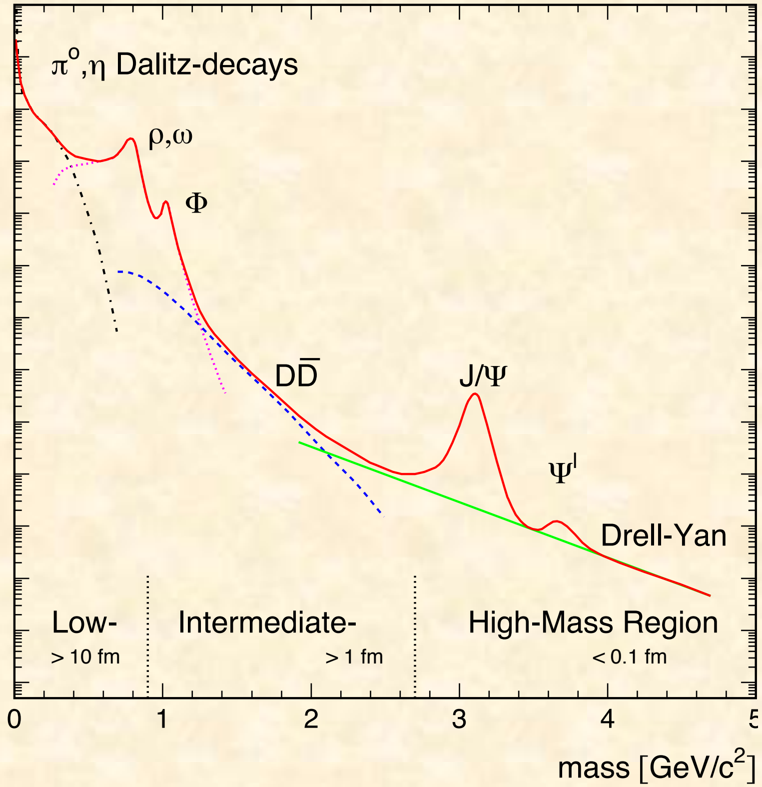
Dilepton Physics

Dileptons are excellent penetrating probes

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



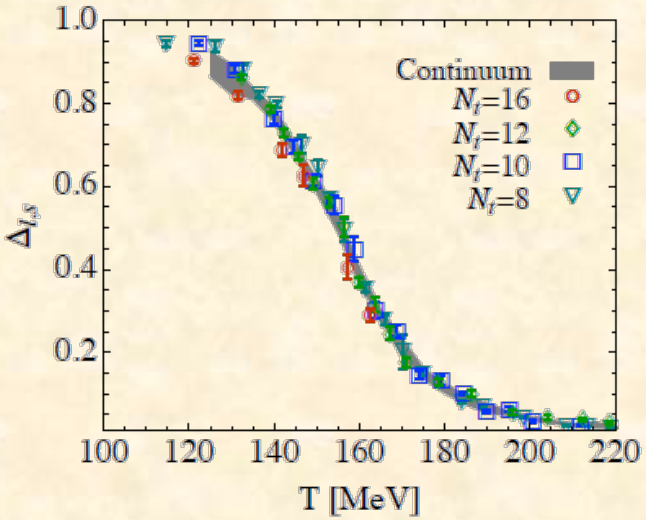
Rapp & Wambach, Adv.Nucl.Phys. 25 (2000) 1



- 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

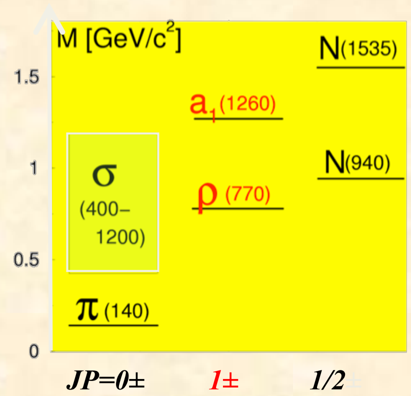
Motivation: Chiral Symmetry Restoration

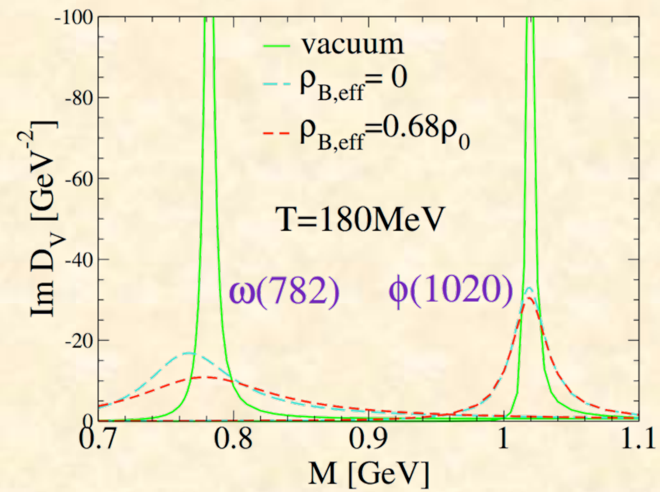
Wuppertal-Budapest Collab.
arXiv:1109:5030



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

– not experimentally accessible

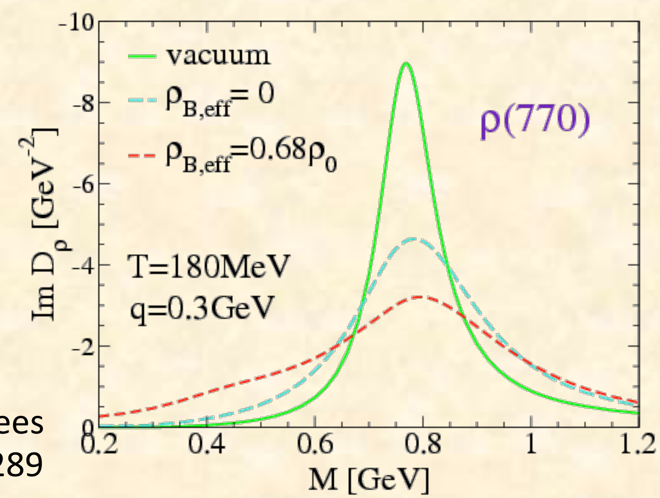




- use chiral partners, *i.e.* hadronic states which transform through chiral transformations

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

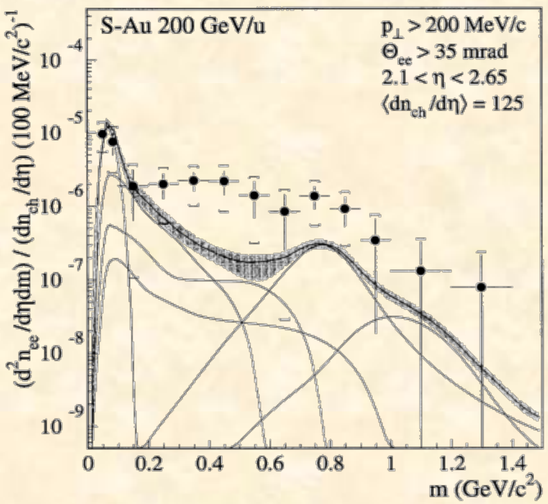
  – relative differences sensitive to chiral order parameters
- Study in-medium properties of ρ and a_1 mesons
  – axial state a_1: background too large
  – vector state ρ: dilepton measurements

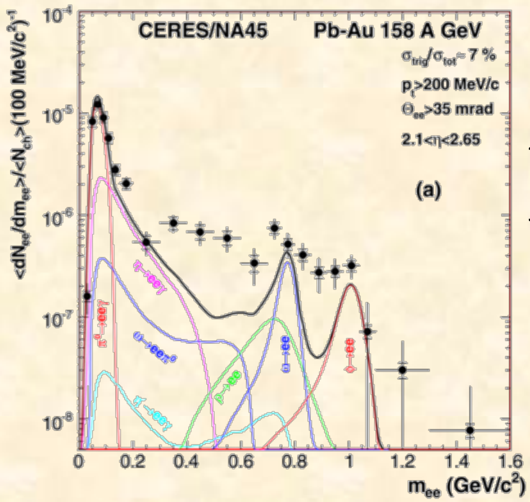


Rapp, Wambach, van Hees
arXiv:0901.3289

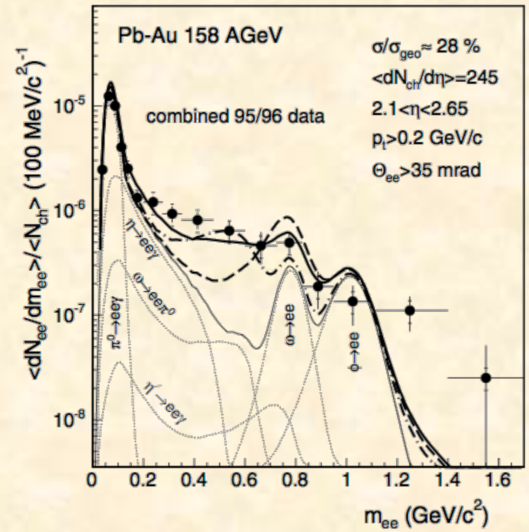
SPS Dielectrons: CERES

First observation of a significant LMR enhancement – PRL 75 (1995) 1272





PLB 666 (2008) 425



EPJ C41 (2005) 475

dashed = vacuum ρ; dash-dotted = DM; solid = RB

Vacuum ρ unable to describe this data

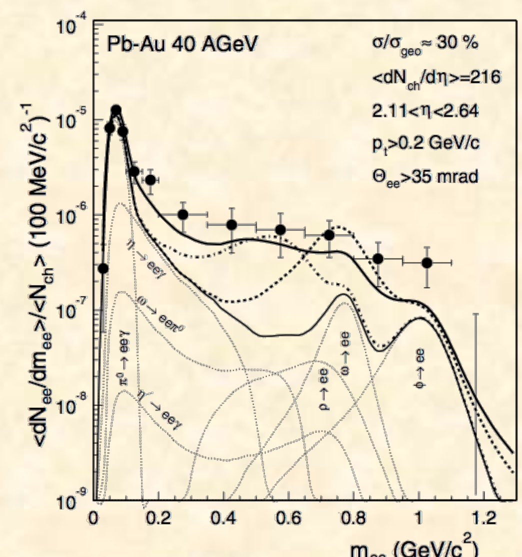
Introduce in-medium modifications

- decrease of ρ mass (Brown-Rho)
  - mass expected to scale with q-qbar condensate
- broadening of ρ spectral function (Rapp-Wambach)
  - hadronic (baryons) scattering

Both rely on high baryon densities

Both showed good agreement with 158 and 40 AGeV

➢ Quark-Hadron duality?



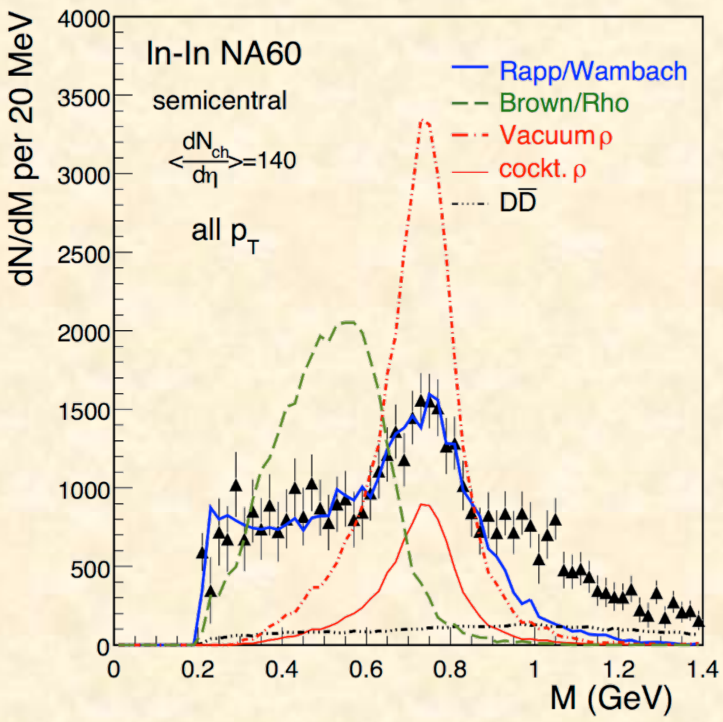
PRL 91 (2003) 042301

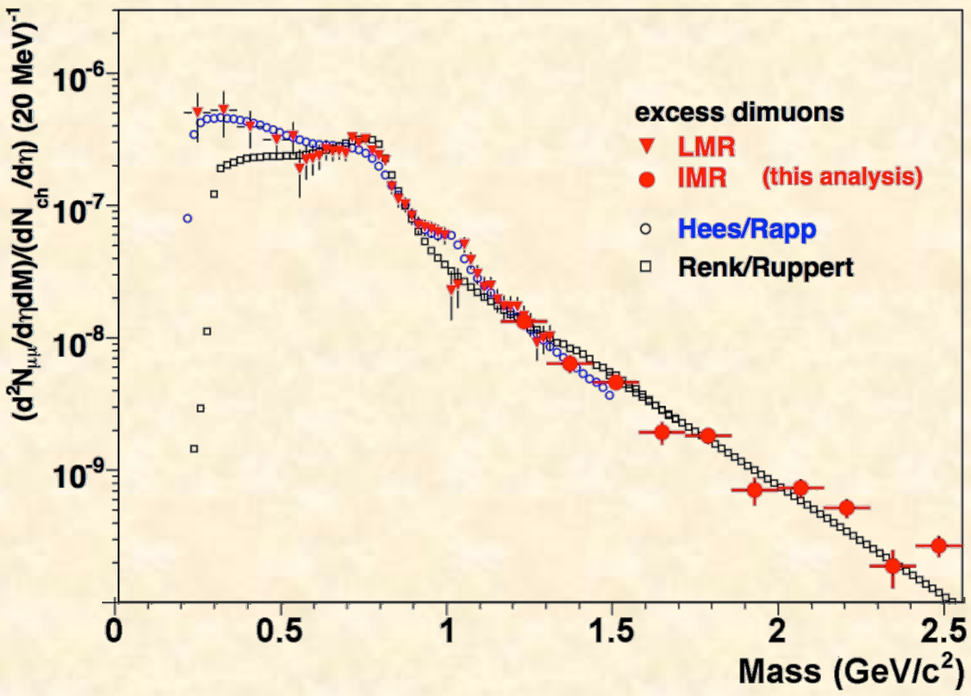
SPS Dimuons: NA60

Excess in LMR $\mu^+\mu^-$ – EPJ C61 (2009) 711

- rules out: Dropping-Mass scenario
- very good agreement with Resonance Width Broadening for $M_{\mu\mu} < 0.9$ GeV/c^2

Excess in IMR from prompt dimuons

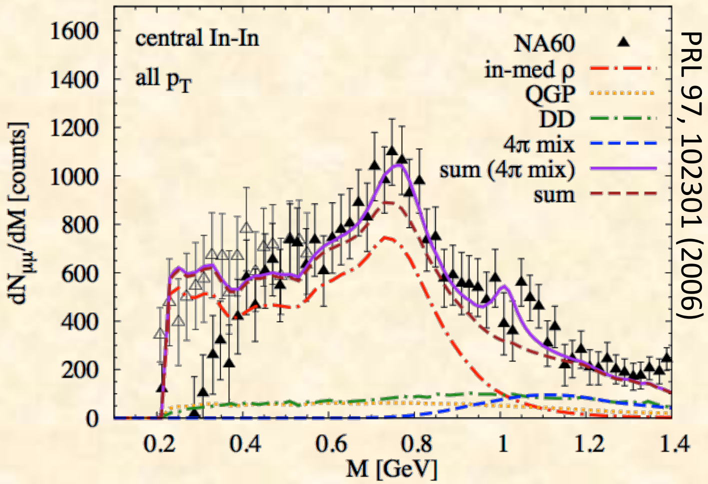




Both hadronic (HR) and partonic (RR) calculations describe IMR excess

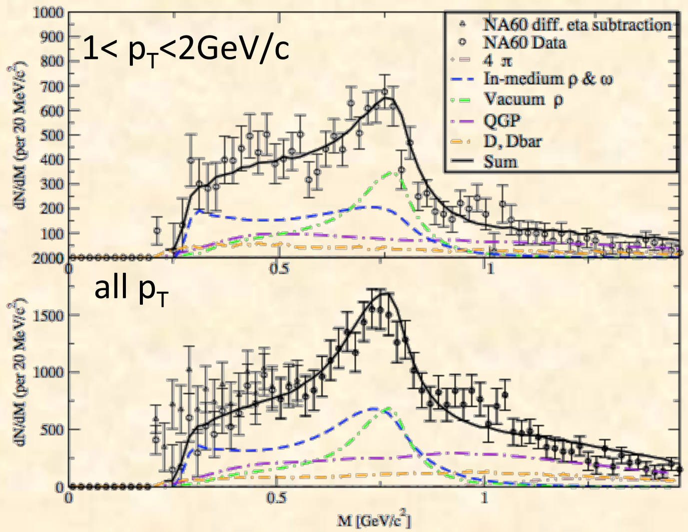
Quark-Hadron duality

van Hees/Rapp: hadronic processes



PRL 97, 102301 (2006)

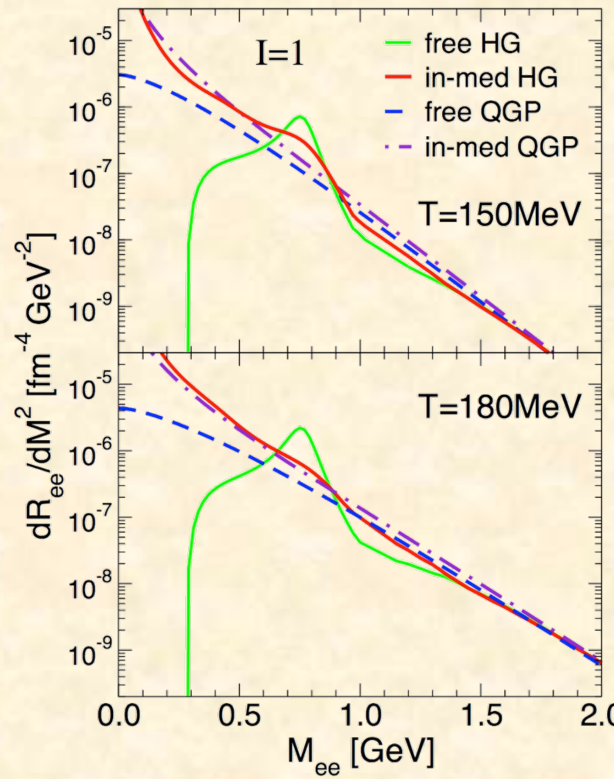
Renk/Rupert: partonic processes



PRL 100, 162301 (2008)

Thermal IMR Dilepton Rates:

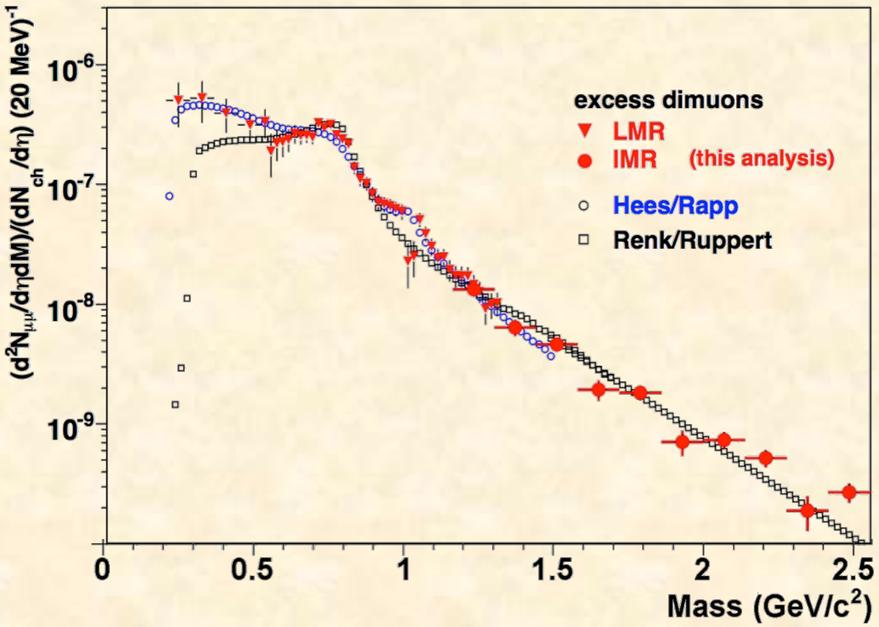
perturb. q-qbar annihilation rates closely coincide with in-medium hadronic rates



Rapp, Wambach, van Hees, arXiv 0901.3289

- This suggests hadronic rates approach χSR

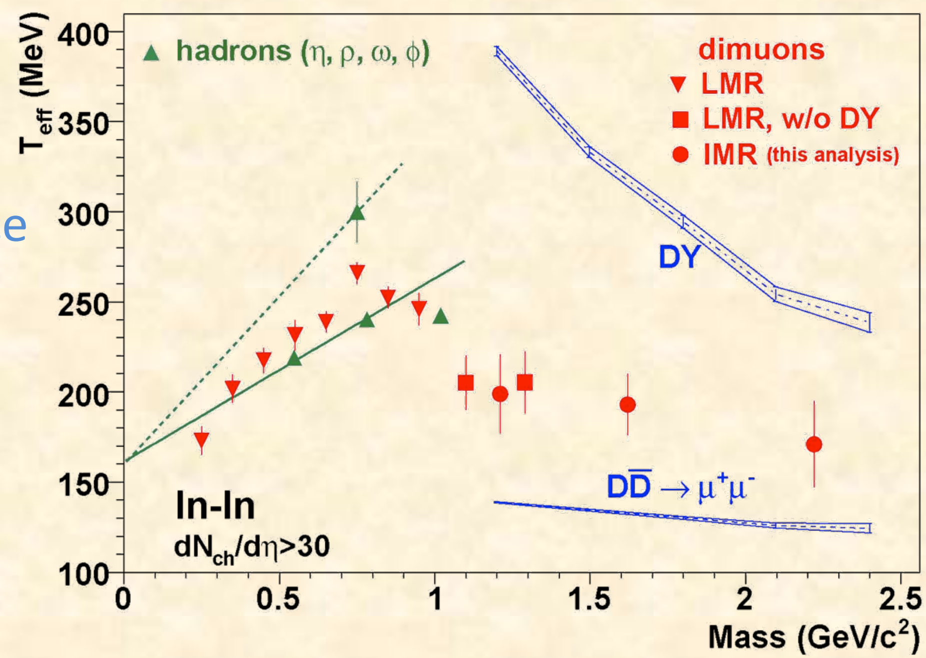
Thermal Radiation at SPS



dimuon measurements at SPS

- LMR: dominated by HG
- IMR: from HG and/or QGP

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

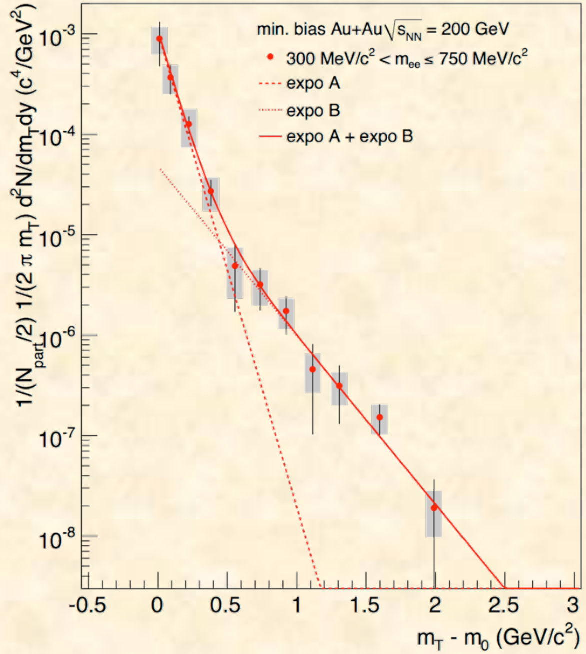


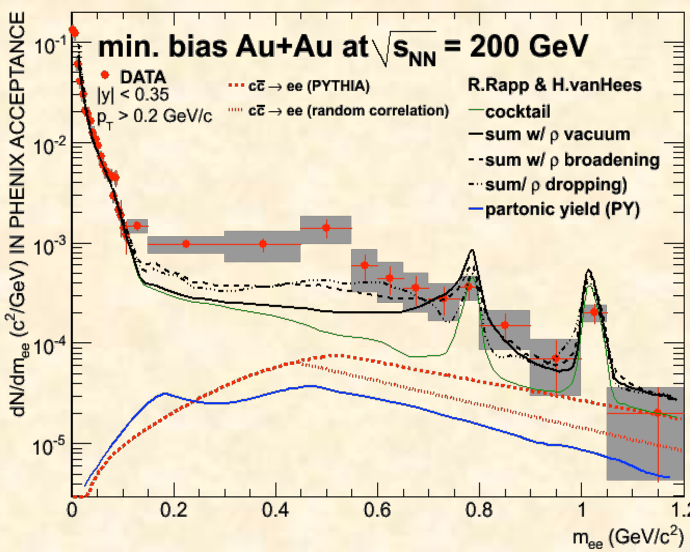
m_T distributions

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

RHIC Dielectron LMR Measurements

- SPS $\sqrt{s_{NN}} \leq 17.2$ GeV
  - significant net-baryon density, μ_B~250MeV (at $T_{ch} \approx 160$ MeV)
  - baryons main contributor
- RHIC $\sqrt{s_{NN}} = 200$GeV
  - μ_B<<T, *i.e.* vanishing net-baryon density at higher $\sqrt{s_{NN}}$
  - but comparable total baryon densities
- ➢ Expect LMR enhancement





Phys.Rev.C 81, 034911 (2010)

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

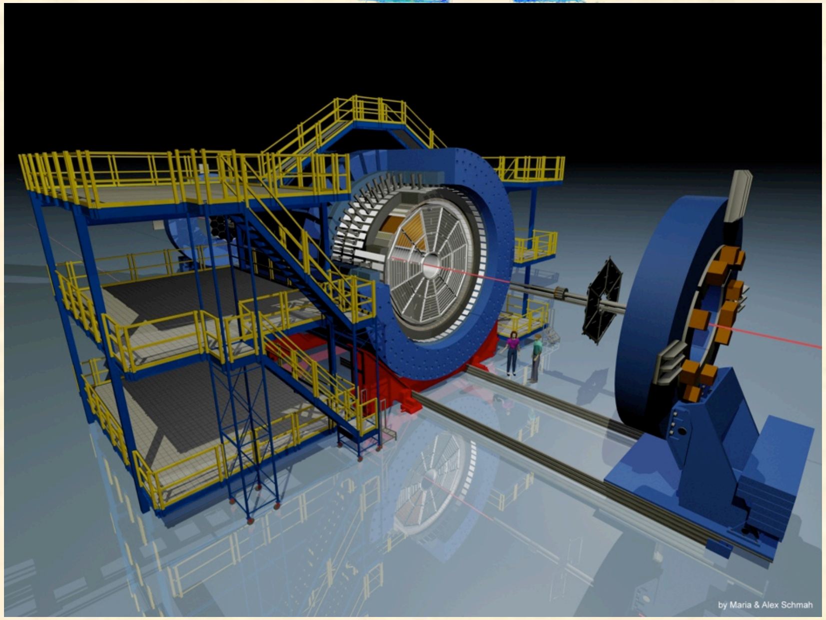
- observes (large) LMR enhancement
- yet to be explained by models
- intriguing p_T dependence

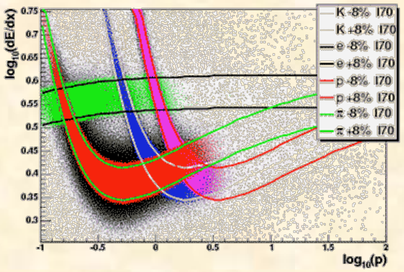
- STAR Au+Au @ $\sqrt{s_{NN}}$=200GeV
  - LMR enhancement, but less than PHENIX
- ➢ STAR Beam Energy Scan
  - close the gap between RHIC & SPS
  - excitation function

The STAR Detector at RHIC

Large acceptance electron ID

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

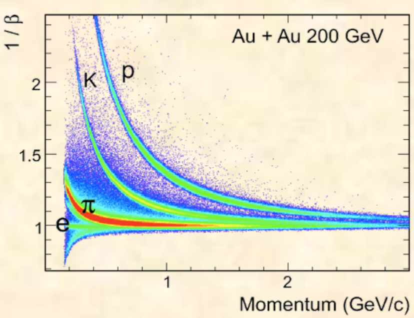




<u>Time Projection Chamber</u>

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

- Tracking
- dE/dx PID



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

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

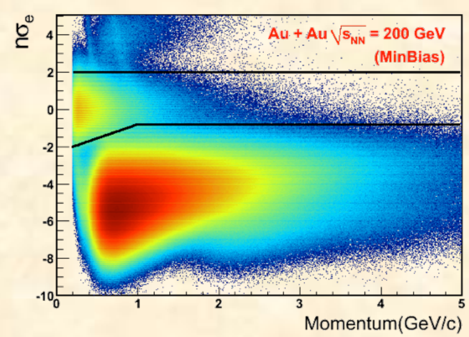
- Time resolution < 100ps
- Significantly improves PID

TOF cut removes “slow” hadrons

- improves electron purity

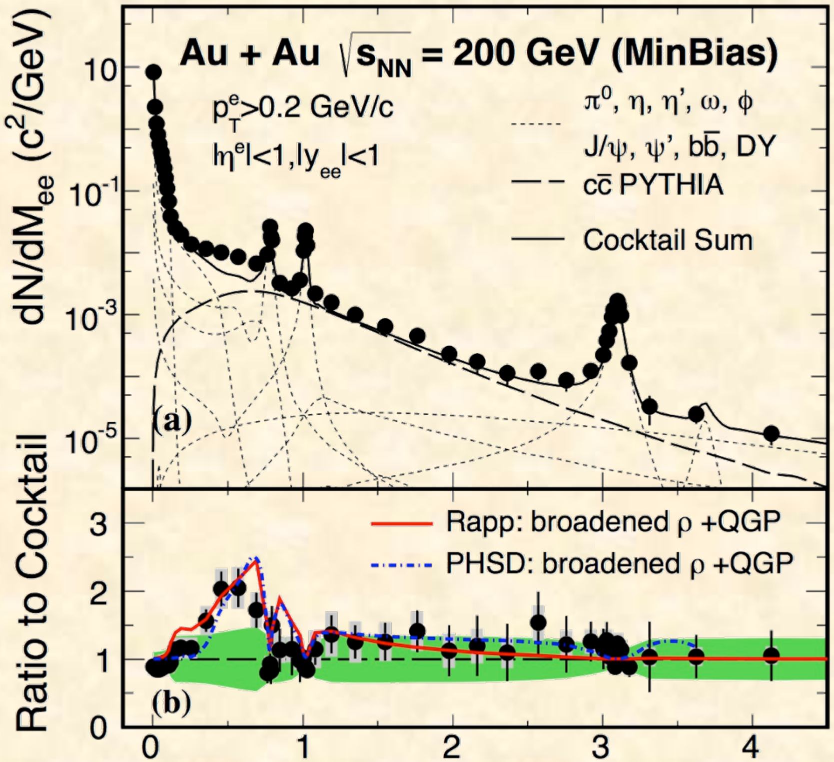
  central events ~92%

  min-bias events ~95%



Production in Au+Au at 200 GeV

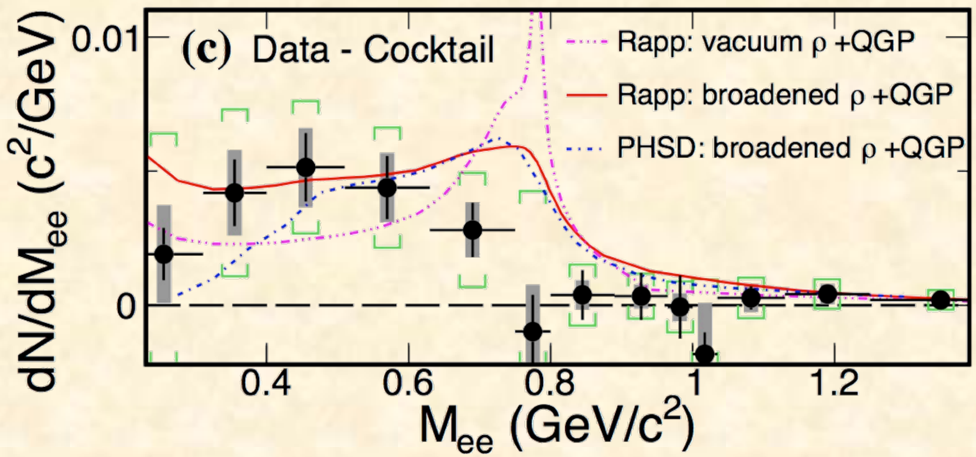
STAR Collaboration arXiv:1312.7397 (subm. to PRL)



Low Mass Range:

- enhancement

when compared to cocktail (w/o ρ meson)



Intermediate Mass Range:

within errors consistent with cocktail

thermal QGP radiation?

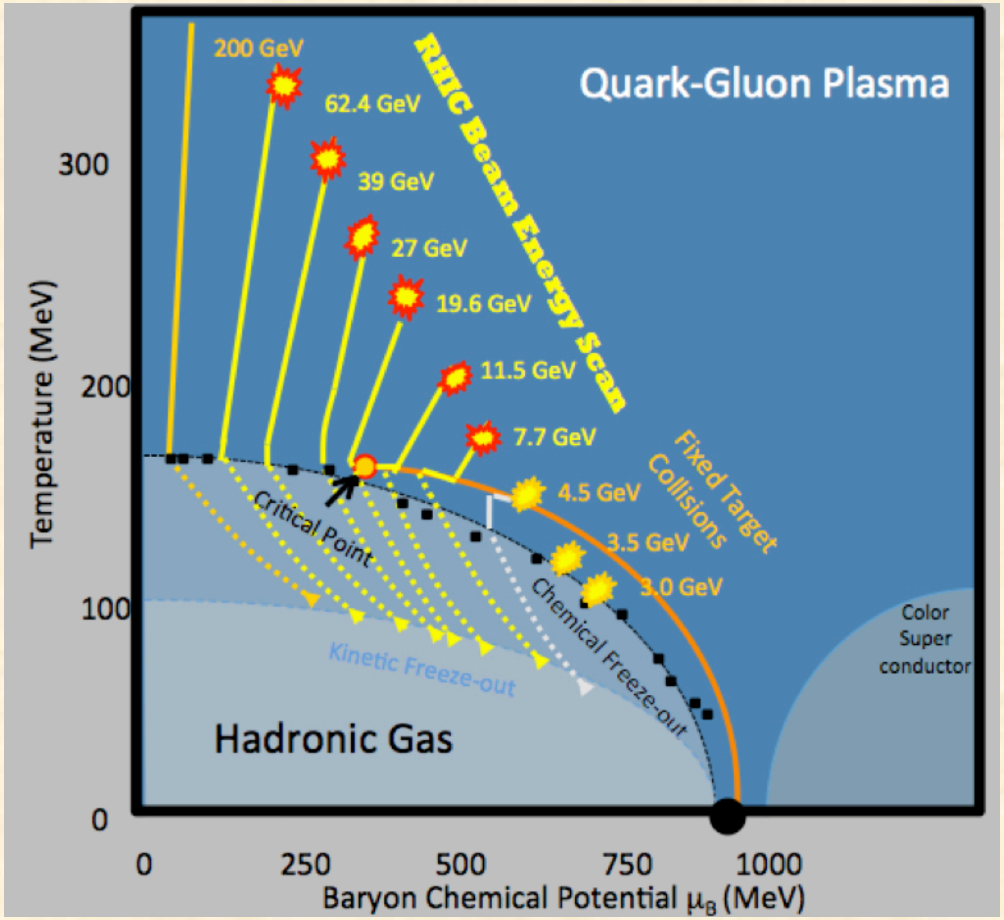
modification of charm?

difficult to disentangle (modified) charm from thermal QGP contributions

- Ongoing Run-14 with new upgrades will address this

RHIC Beam Energy Scan

- Systematically study dielectron continuum from $\sqrt{s_{NN}}$ = 19.6 – 200 GeV
- Phase I: 2010 – 2011
  - TPC + TOF for ePID
  - low material budget



Energy	19.6 GeV	27 GeV	39 GeV	62.4 GeV	200 GeV
MB events	35.8M	(70M)	99.4M	54.6M	240M

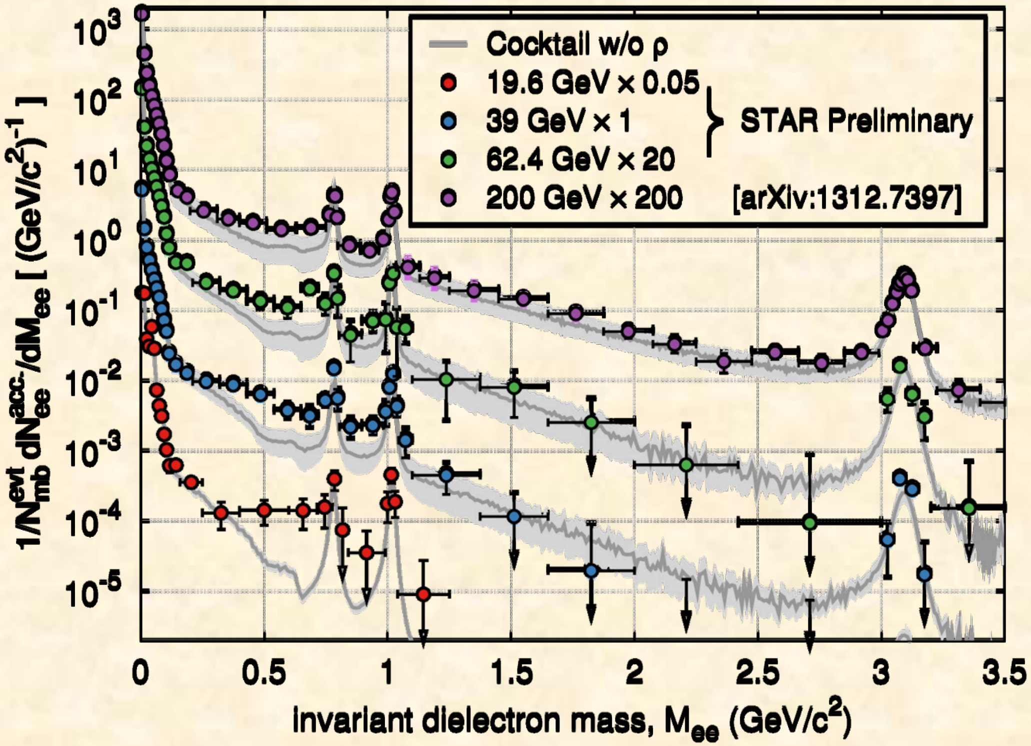
Dielectron Production at lower $\sqrt{s_{NN}}$

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:

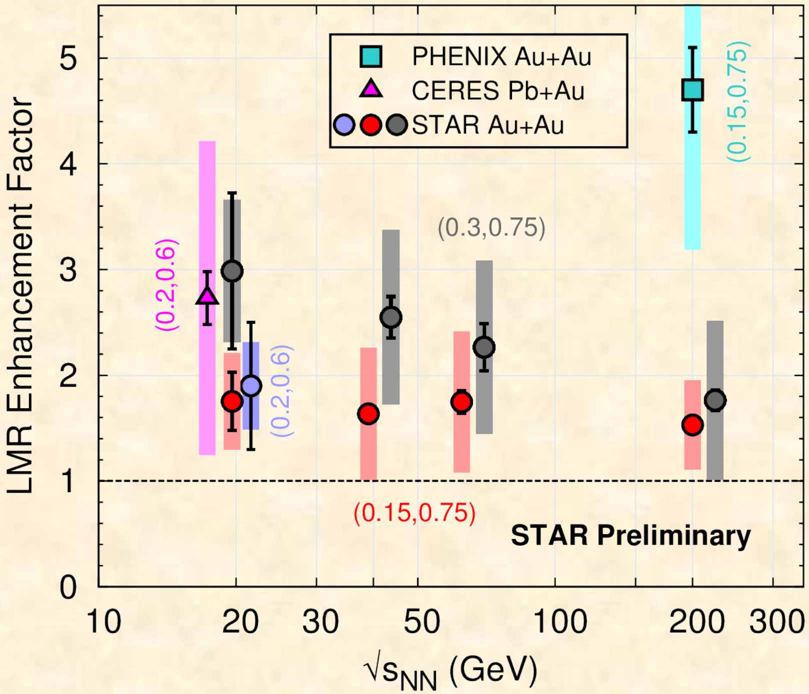
2010 - 2011

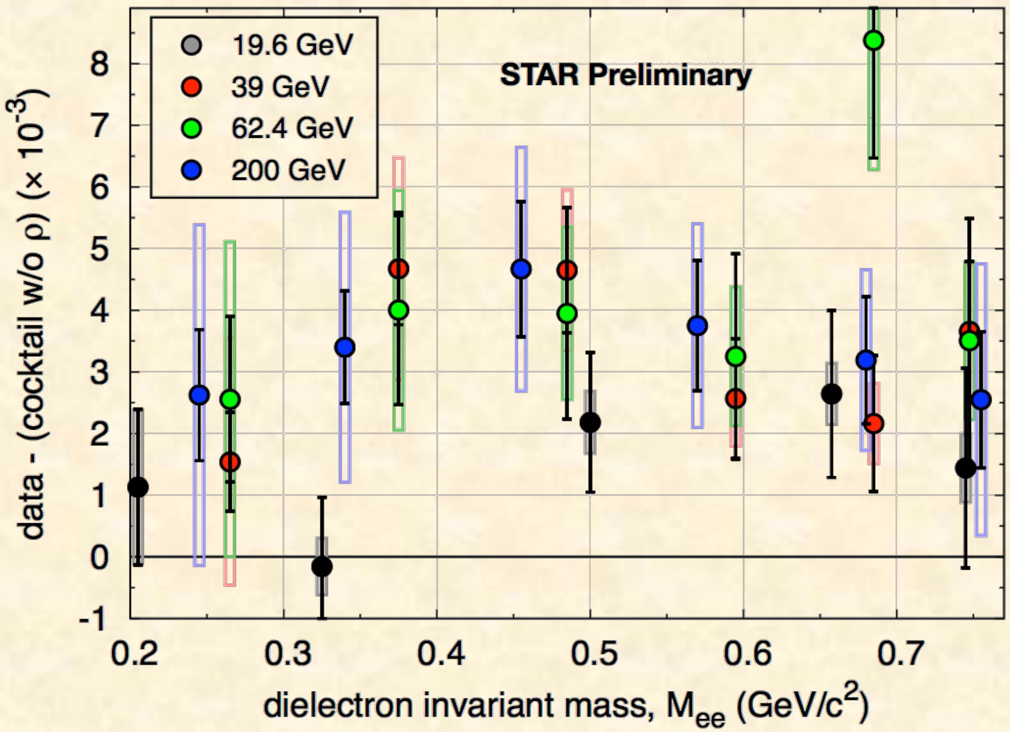
Au+Au at 62.4, 39, 27, and 19.6 GeV

STAR data samples:

55M, 99M, 70M, and 34M min-bias events

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





STAR Au+Au at 19.6 GeV/c

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

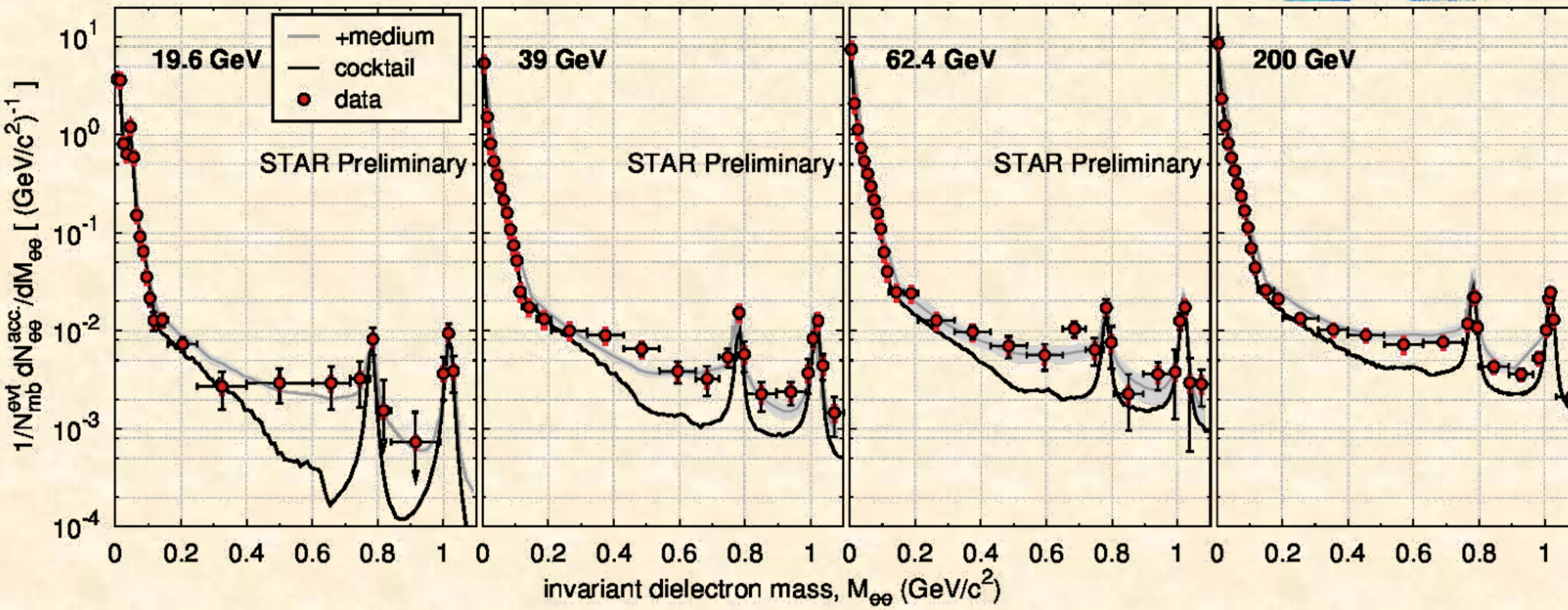
CERES Pb+Au at 17.3 GeV/c

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

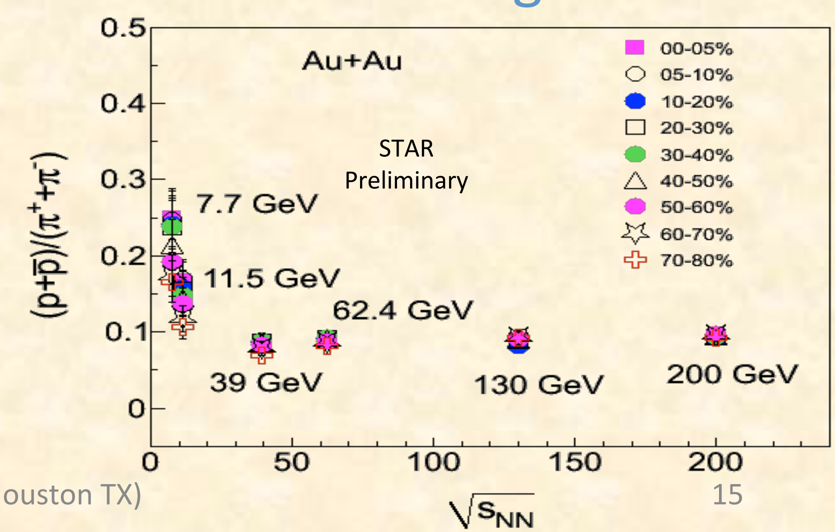
- LMR excess over hadronic cocktail observed for all energies (excl. ρ)
- systematic measurement of LMR excess

Compare to Theory: in-medium ρ



- Robust theoretical description top RHIC down to SPS energies
  - calculations by Ralf Rapp*
  - grey curve: cocktail + in-medium ρ
- Consistent with in-medium ρ broadening
  - expected to depend on total baryon density
  - tool to look for chiral symmetry restoration

*) Adv. High Energy Phys. 2013 (2013) 148253, priv. comm.



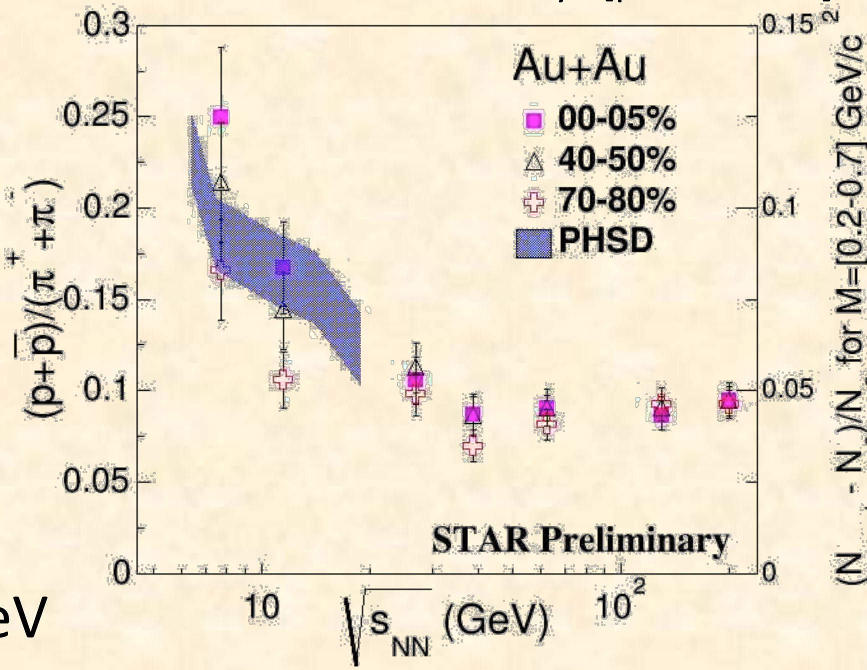
Beam Energy Scan: Phase-2

STAR

Bigger Context:

Refine our understanding of phase structures of QCD matter

PHSD calculations by Olena Linnyk [priv. comm.]



- Phase 2: 2018 – 2019
  - revisit lower energies
  - improve statistics

➢ STAR/PHENIX White Papers in prep.

- Systematically study dielectron continuum from $\sqrt{s_{NN}}$ = 7.7 – 19.6 GeV

Energy	7.7 GeV	9.1 GeV	11.5 GeV	14.6 GeV	19.6 GeV
MB events	100M	160M	230M	300M	400M

Summary

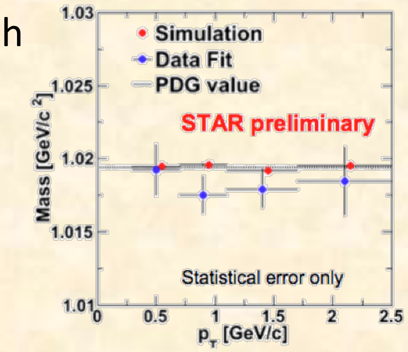
- Measurements at SPS consistently show strong LMR enhancement
  - well-described by in-medium resonance-width broadening of the ρ meson
- Measurements at RHIC confirm LMR enhancement
  - expected as total baryon density hardly changes
  - very strong enhancement measured by PHENIX: models that describe SPS, fail describing PHENIX LMR. Additional source?
  - same models succeed describing preliminary STAR results
- 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 model description for $\sqrt{s_{NN}}$= 19.6, 39, 62.4, and 200 GeV
- STAR upgrades enable further exploration of the dilepton continuum
  - 2014-2016: measure QGP thermal radiation in IMR at 200 GeV
  - 2018-2019 (BES Phase II): probe lower beam energies with improved statistics

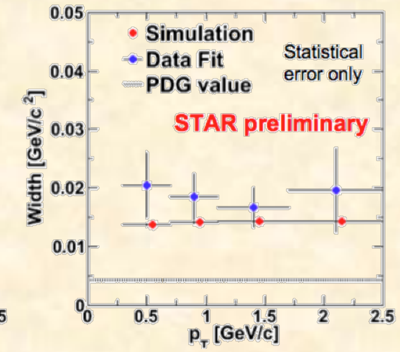
BACKUP

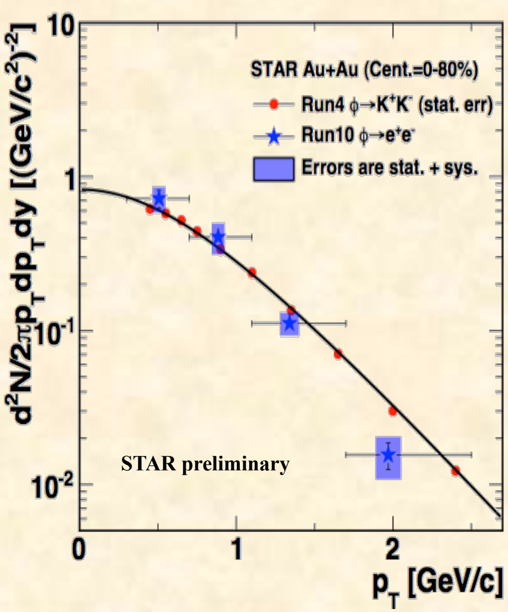
Leptonic Decay of ϕ and ω Mesons

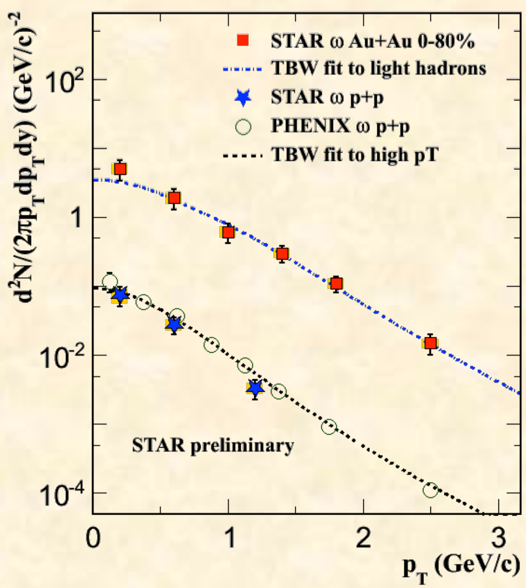
Lifetimes comparable to fireball

- 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







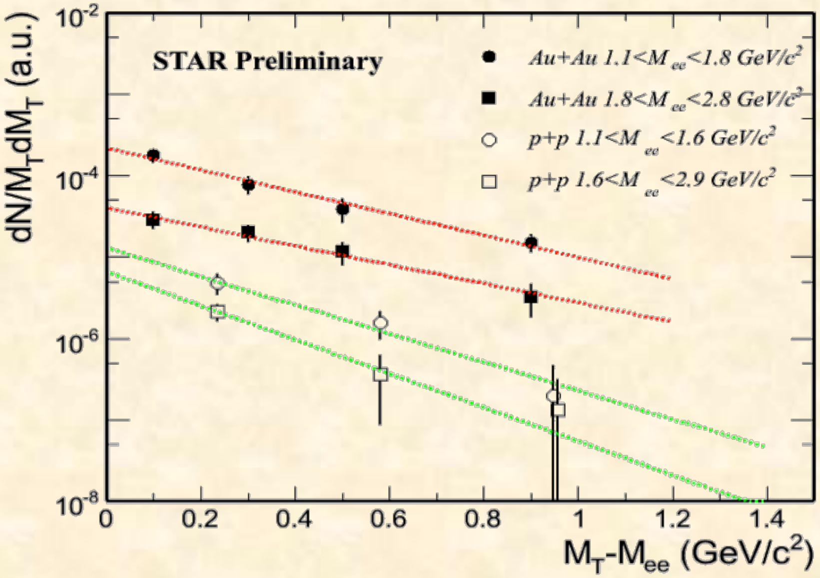


- No evidence of ϕ mass shift or width broadening
  - beyond known detector effects
- ϕ yield in dilepton decay channel consistent with hadronic channel

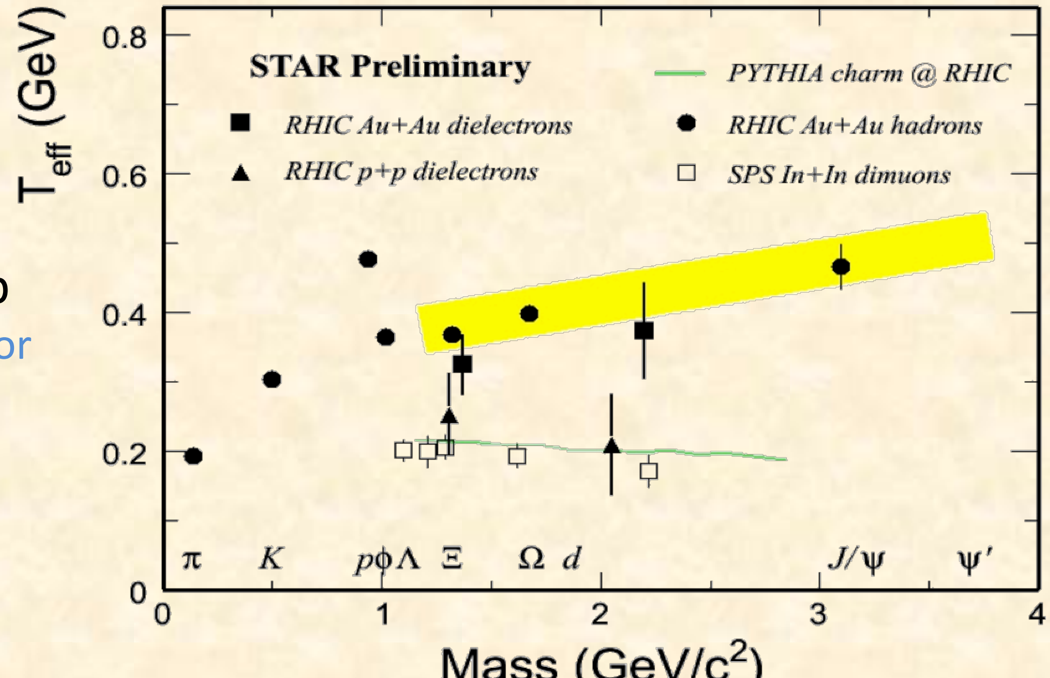
ω p_T-shapes agree with light hadrons

ω mass and width are under study

IMR: Transverse Mass Spectra

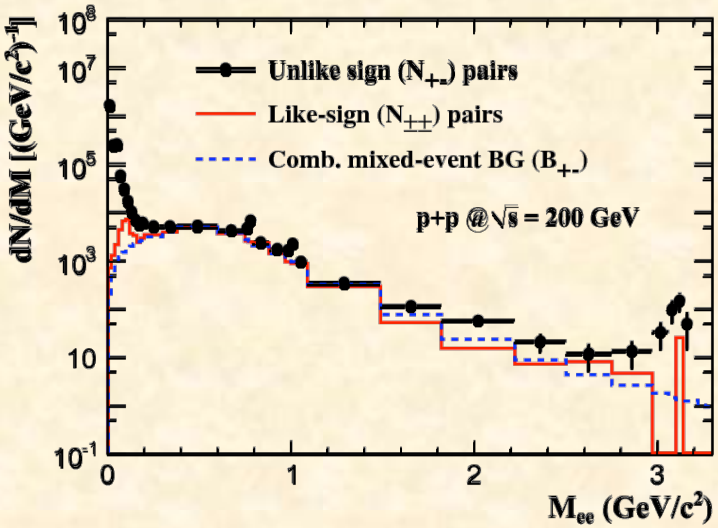


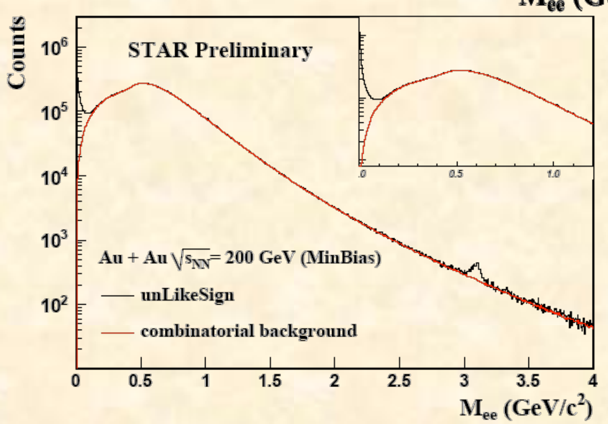
- RHIC: Au+Au 200 GeV (minbias)
  - inclusive dielectron
- SPS: In+In 17.2 GeV
  - NA60 -- PRL 100, 022302 (2008)
  - charm/Drell-Yan subtracted



- 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)

e^+e^- Invariant Mass & Background





Combine both methods:

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.

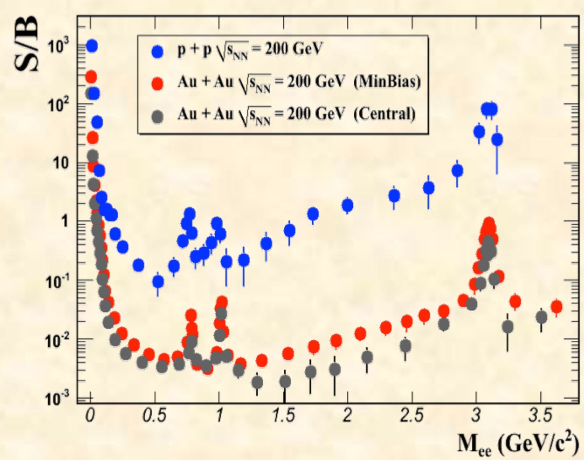
Background methods

- 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

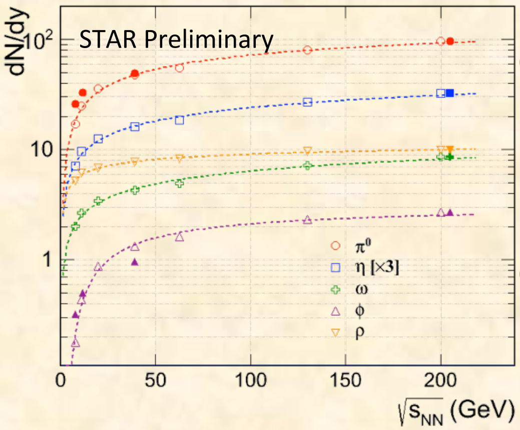


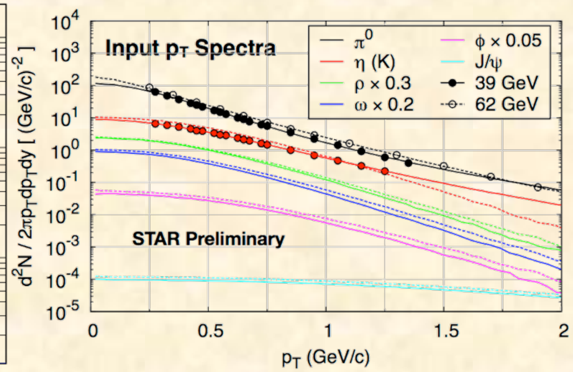
S/B @ M_{ee}~ 0.5 GeV/c^2:

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

Hadronic Background Simulation

Au+Au 39 & 62.4 GeV

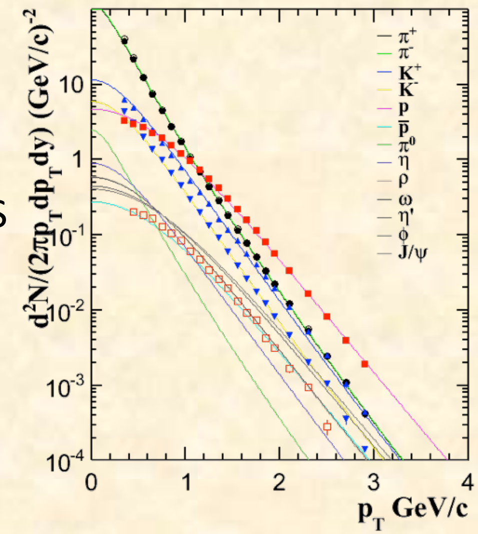




19.6 GeV:

- TBW fit from SPS data
- meson/π from SPS
- π yield from STAR

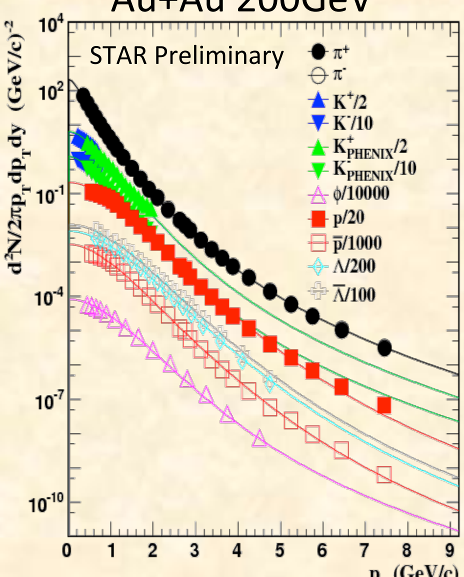
Au+Au 19.6 GeV



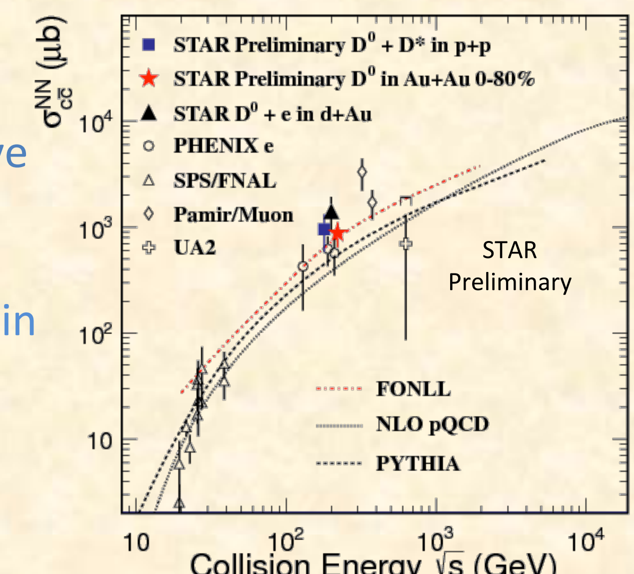
39 & 62.4 GeV:

- π p_T from STAR, η based on K
- Extrapolated from AMPT calculations
- Scaled to measurements at 200GeV

Au+Au 200GeV



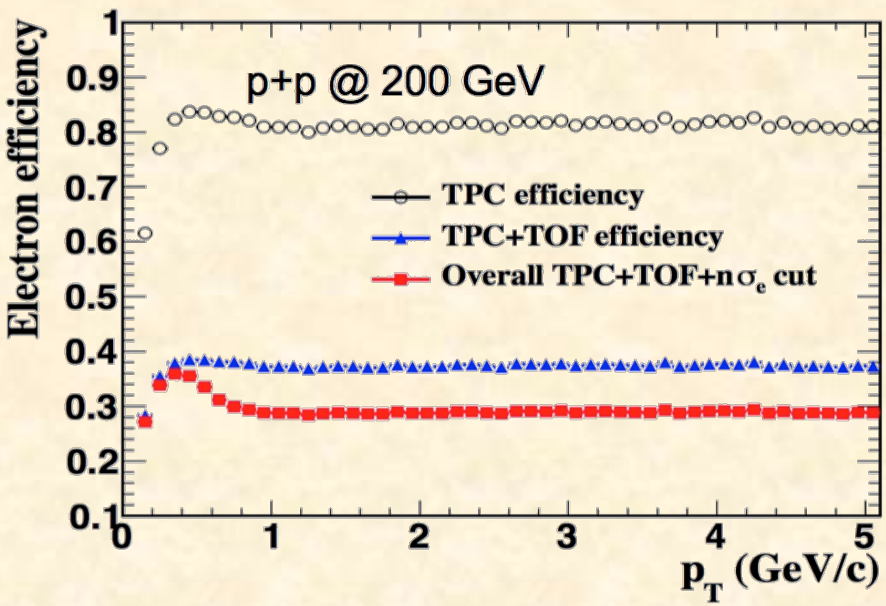
- Hadrons: flat |y|<1.0, and flat full azimuth input distribution
  - p_T distribution from Tsallis blast-wave fit to measured particle spectra
- Heavy flavor sources
  - STAR measurements (0.80±0.36 mb in p+p) , and PYTHIA simulation
  - N_{bin} scaled in Au-Au

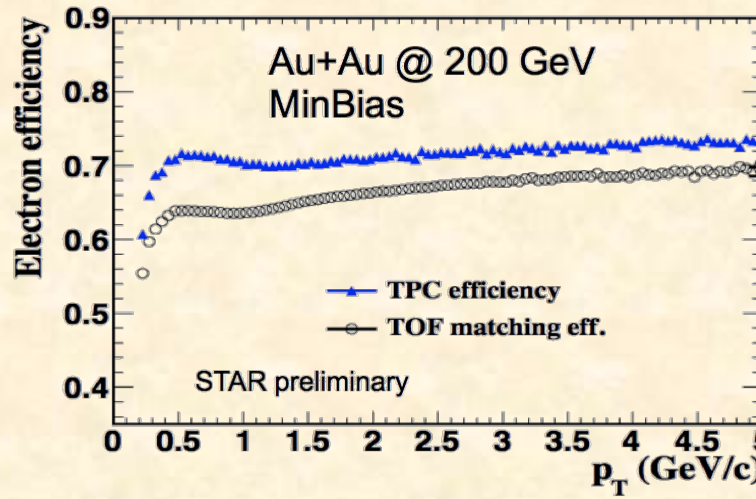


Efficiency Correction

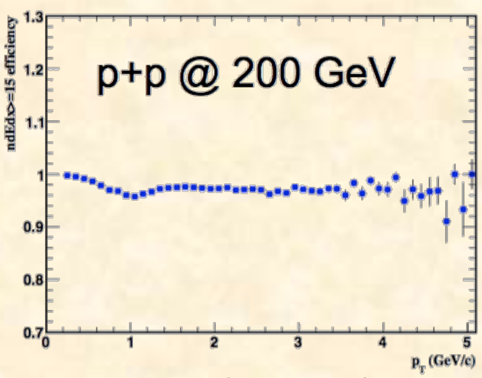
Ingredients:

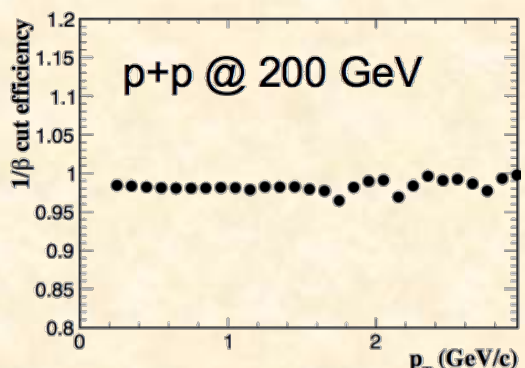
- TPC efficiency, TPC-TOF matching efficiency
- $n\sigma_e$(TPC PID selection), $1/\beta$ (TOF PID selection)

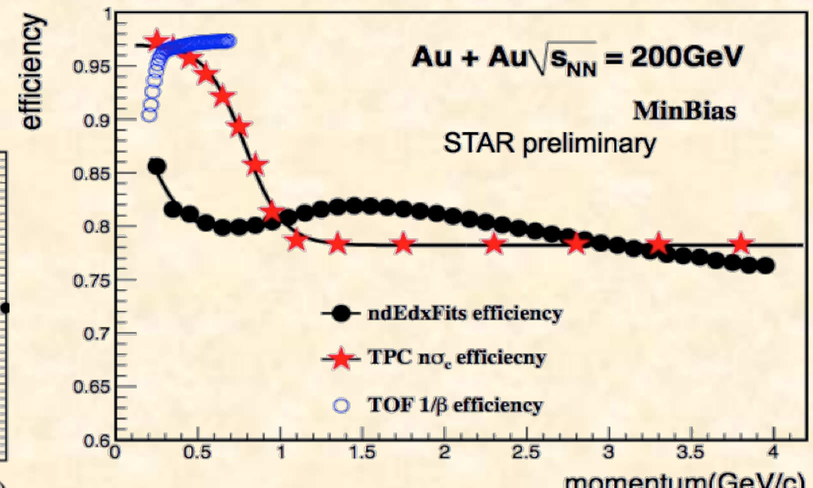




B.Huang, TRW (2012)

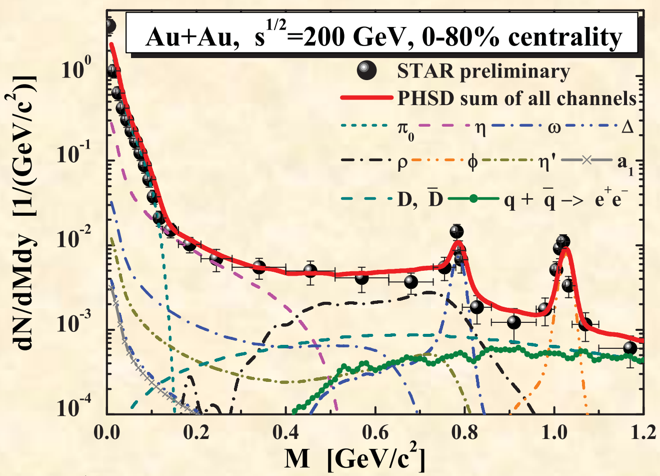


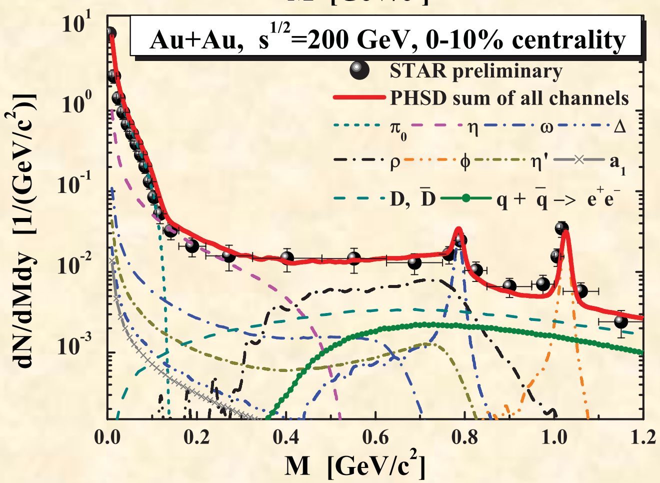




Compare to Theory: PHSD Model

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

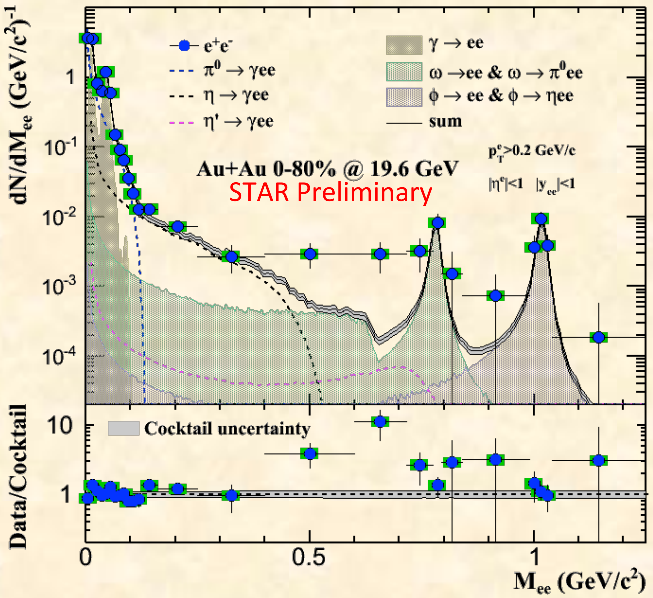
<u>Minimum bias collisions</u> (0-80%):

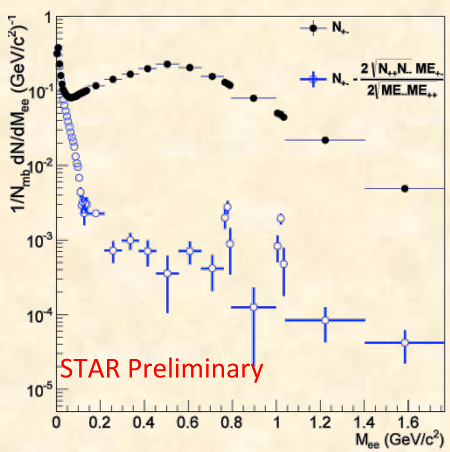
➢ Generally good agreement

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

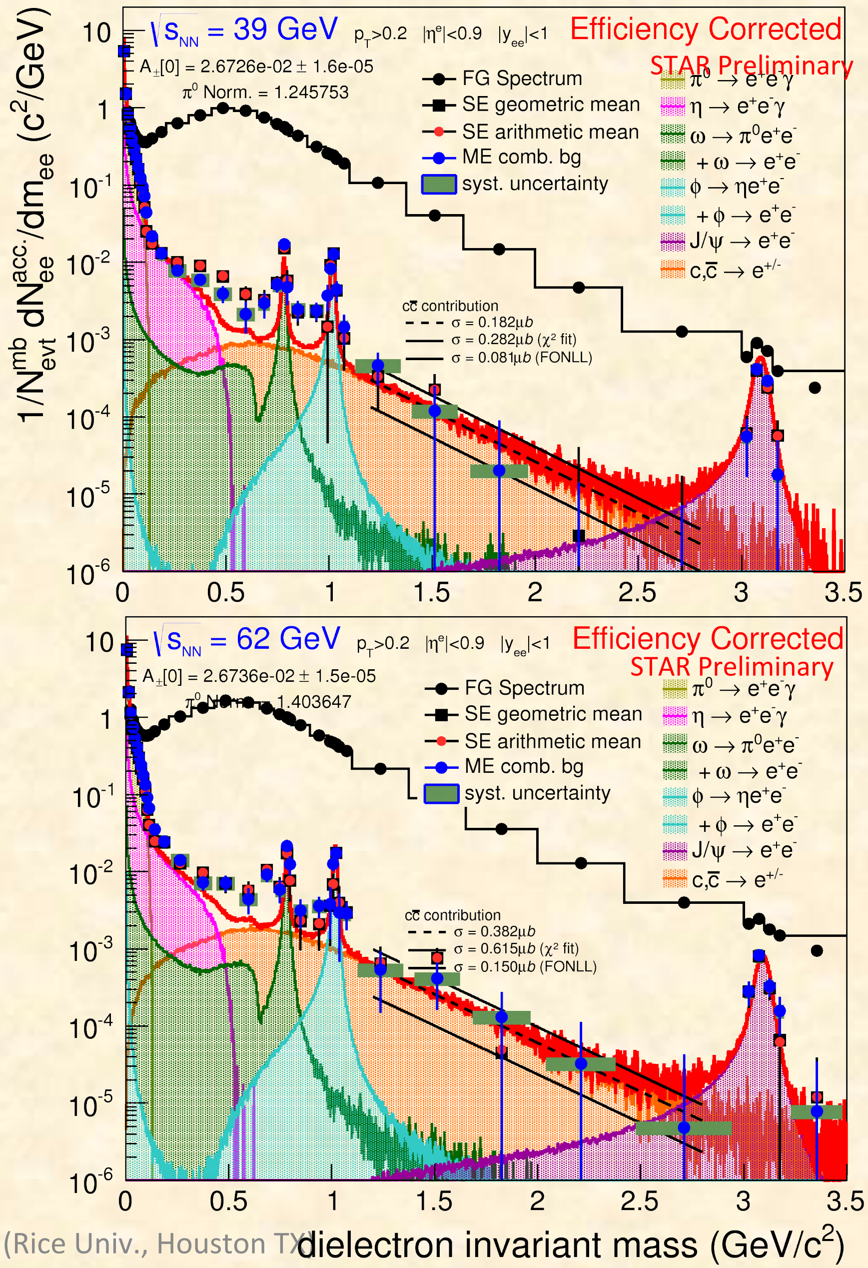
➢ PHSD roughly in line with LMR region

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





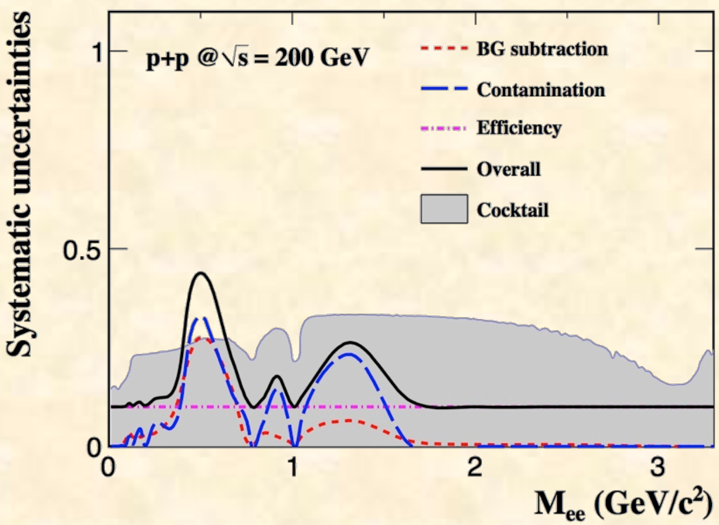
$\sqrt{s_{NN}}$ = 27 GeV cocktail in progress



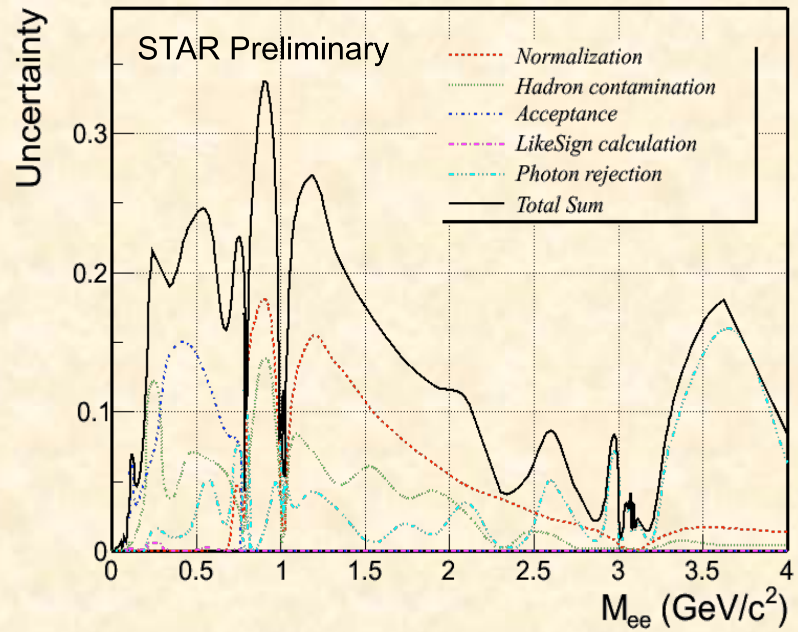
Systematic Uncertainties

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%