Dilepton measurements at RHIC: past, present, future

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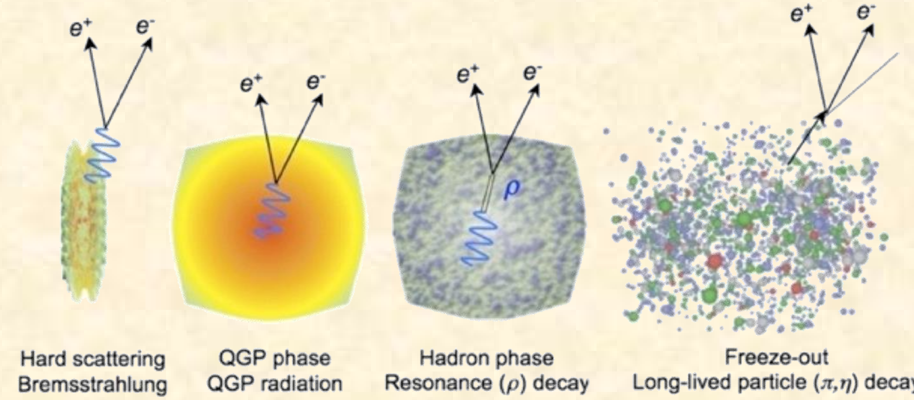
Outline

- Motivation
- Past
  - dielectron spectra and v_2 at $\sqrt{s_{NN}}$=200GeV
- Present
  - direct photon at $\sqrt{s_{NN}}$=200GeV
  - dielectron spectra from Beam Energy Scan
- Future
  - recent detector upgrades
  - Beam Energy Scan – Phase 2
- Summary

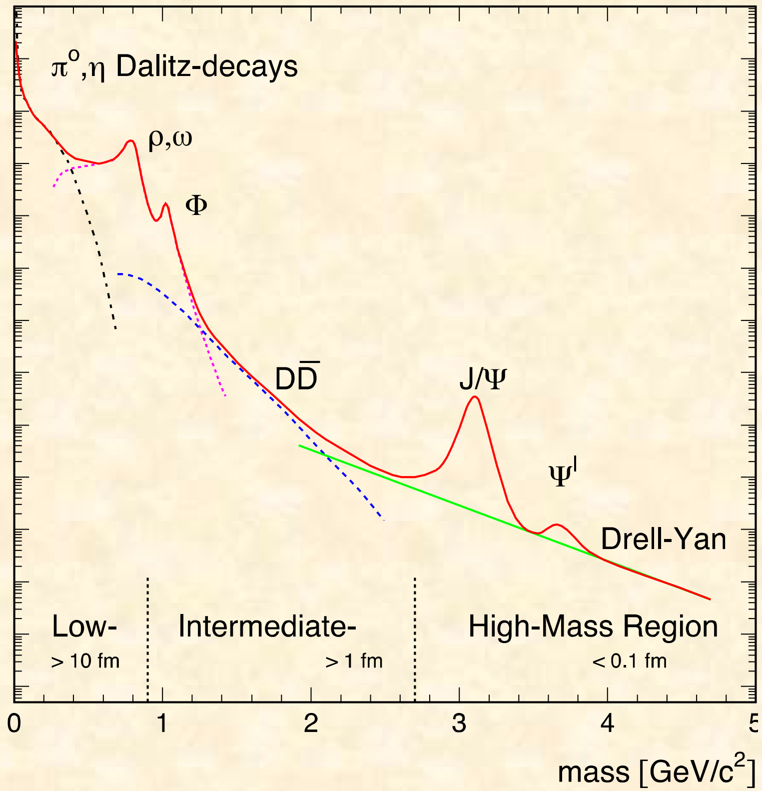
Dilepton Physics

<u>Dileptons are excellent penetrating probes</u>

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



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



- High Mass Range (HMR)

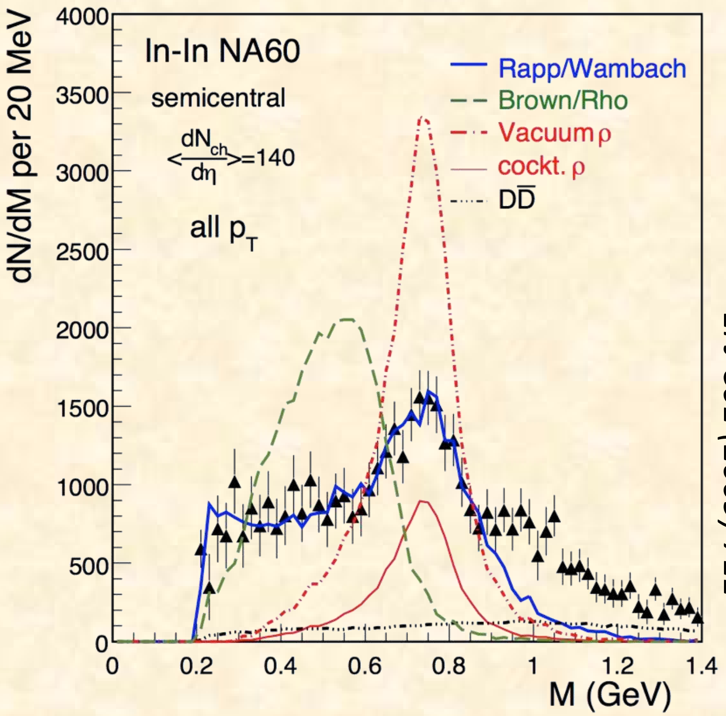
  $M_{ee} > 3$ GeV/c^2
  - primordial emission, Drell-Yan
  - J/Ψ and ϒ suppression
- Intermediate Mass Range (IMR)

  $1.1 < M_{ee} < 3$ 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
  - fireball lifetime measurement

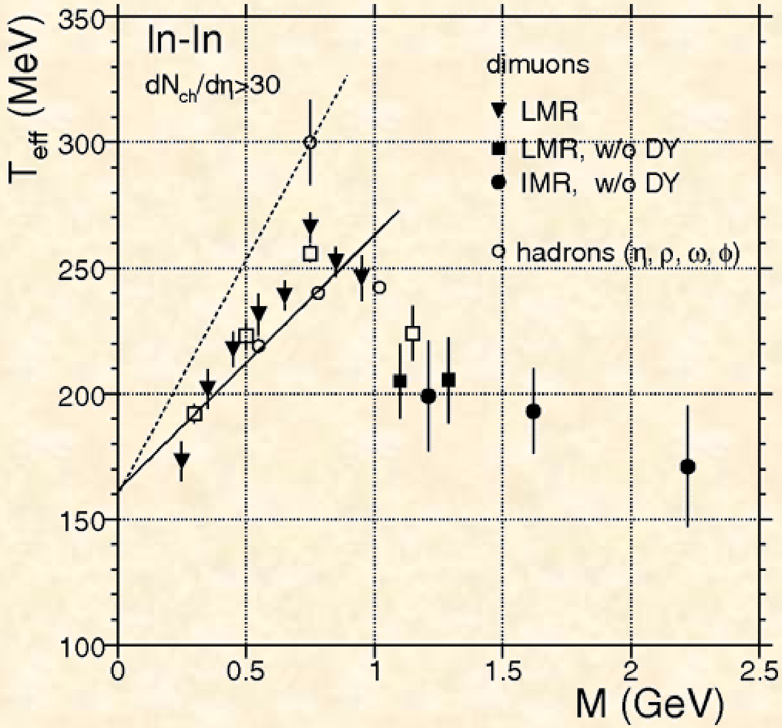
What did we learn from SPS?

PRL 96 (2006) 162302



EPJ C61 (2009) 711

PRL 100 (2008) 022302



Precise dimuon mass spectrum

- favors ρ broadening through interactions with hadronic medium

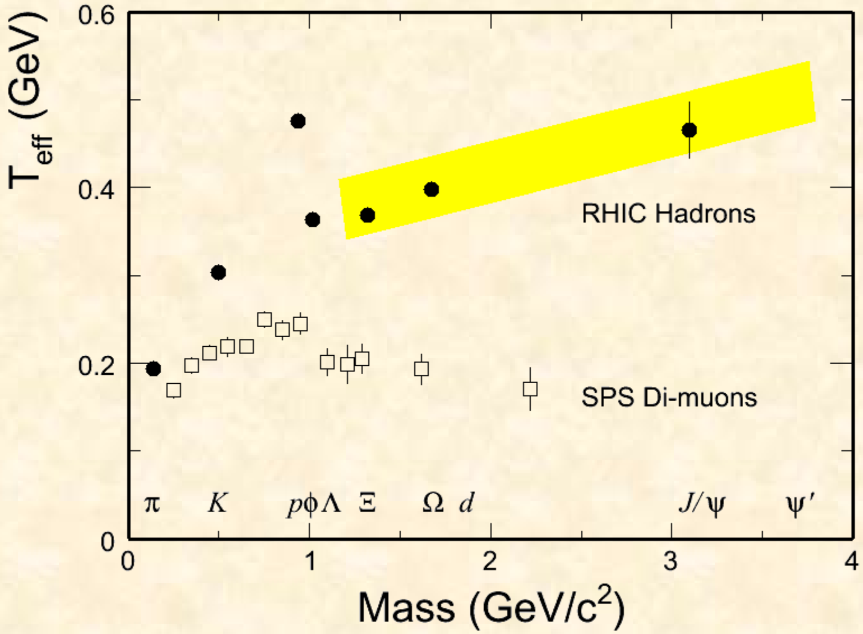
Inverse slope parameter from m_T distributions

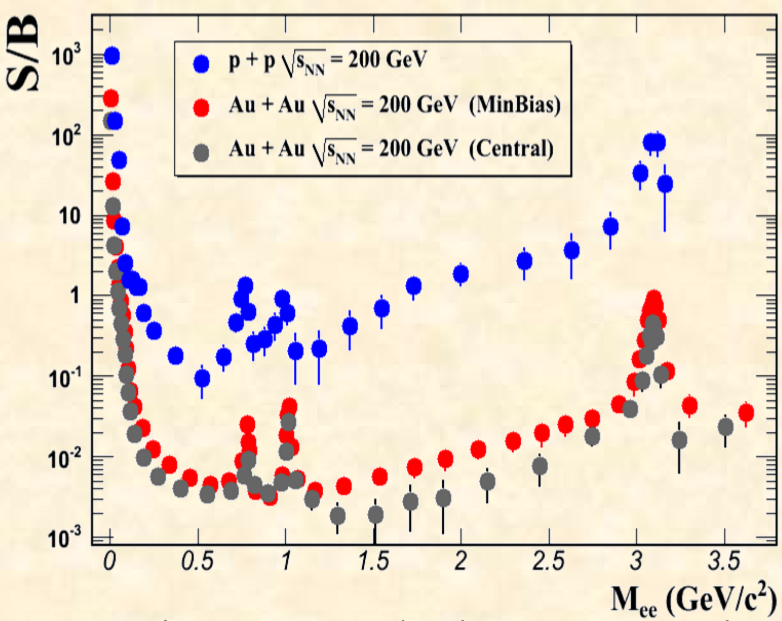
- IMR: no indication of mass dependence
- indicative of thermal radiation from partonic medium, T=205 ± 12 MeV

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





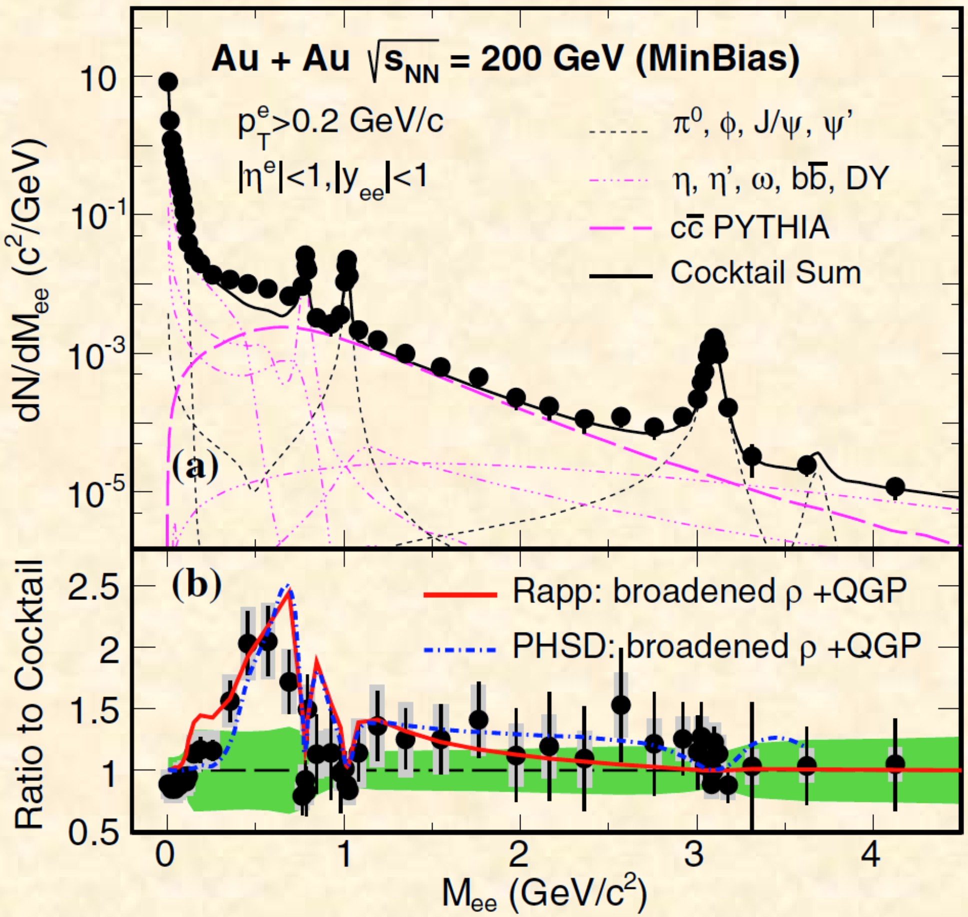
Challenges:

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

Production in Au+Au at 200 GeV

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

PRL 113 (2014) 022301



Low Mass Range:

- enhancement

  when compared to cocktail (w/o ρ)

Model calculations with in-medium broadened ρ spectrum function describe LMR excess

Intermediate Mass Range:

within errors consistent with cocktail

- dominated by correlated charm contributions
- thermal QGP radiation
- modification of charm?

difficult to disentangle

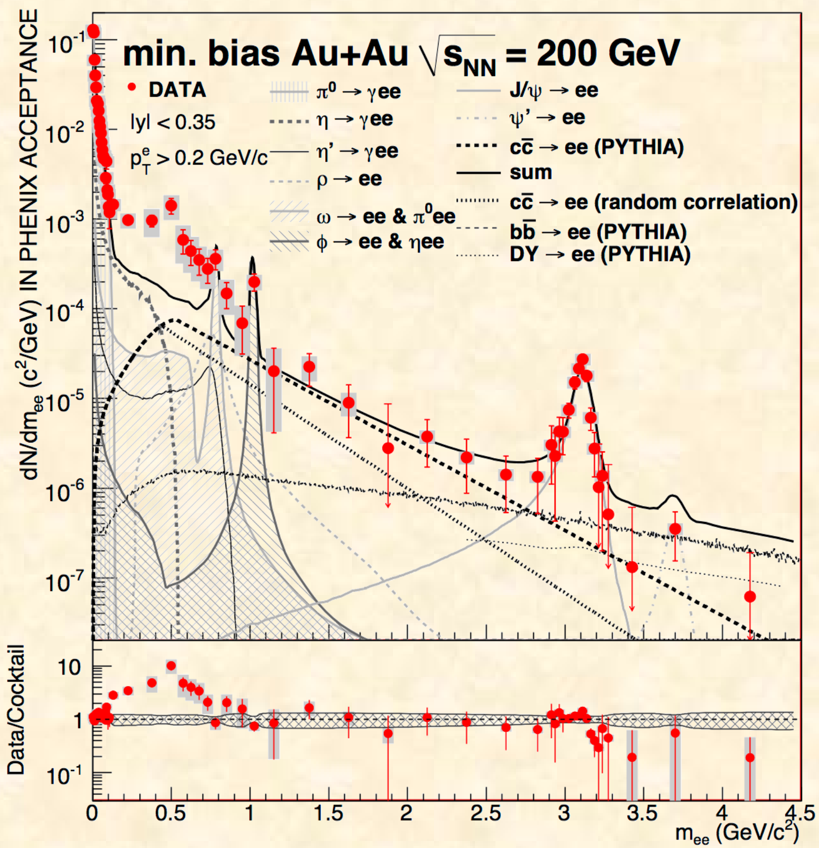
Run-14/16 with new upgrades will address this

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

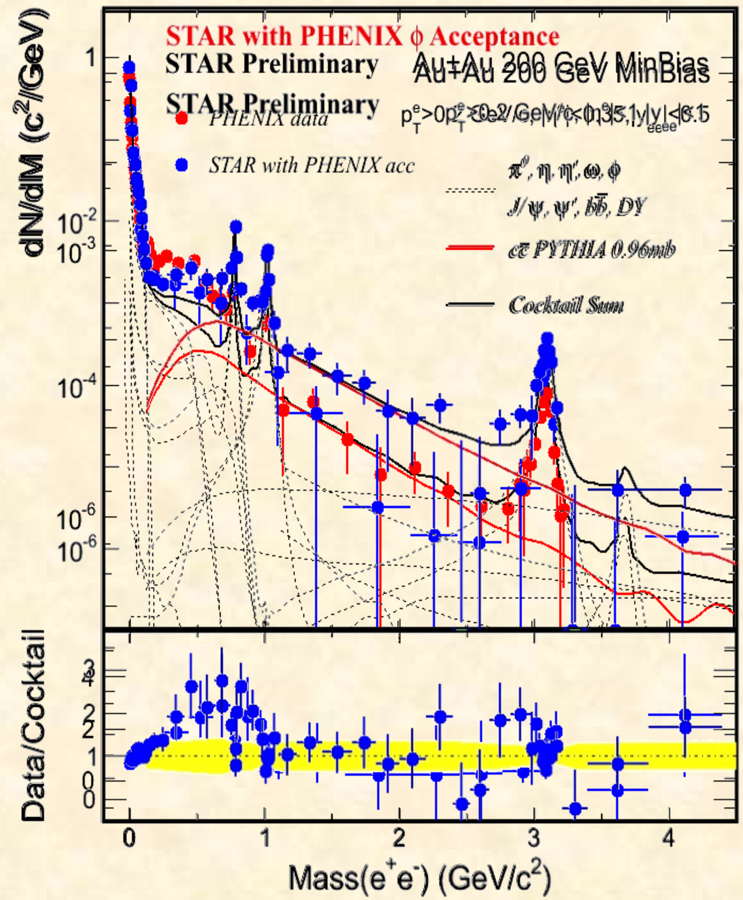
O. Linnyk et al., Phys. Rev. C 85 024910 (2012)

RHIC: PHENIX *vs.* STAR

PHENIX – PRC 81 (2010) 034911



STAR in PHENIX acceptance



Hard Probes 2012

Large quantitative differences in the low-mass , low-p_T region remain unresolved

Work in progress: STAR combines Run 10 and 11 data sets

PHENIX HBD analysis Run-10 data, waiting on top centrality

Latest Analysis with the PHENIX HBD

RICE

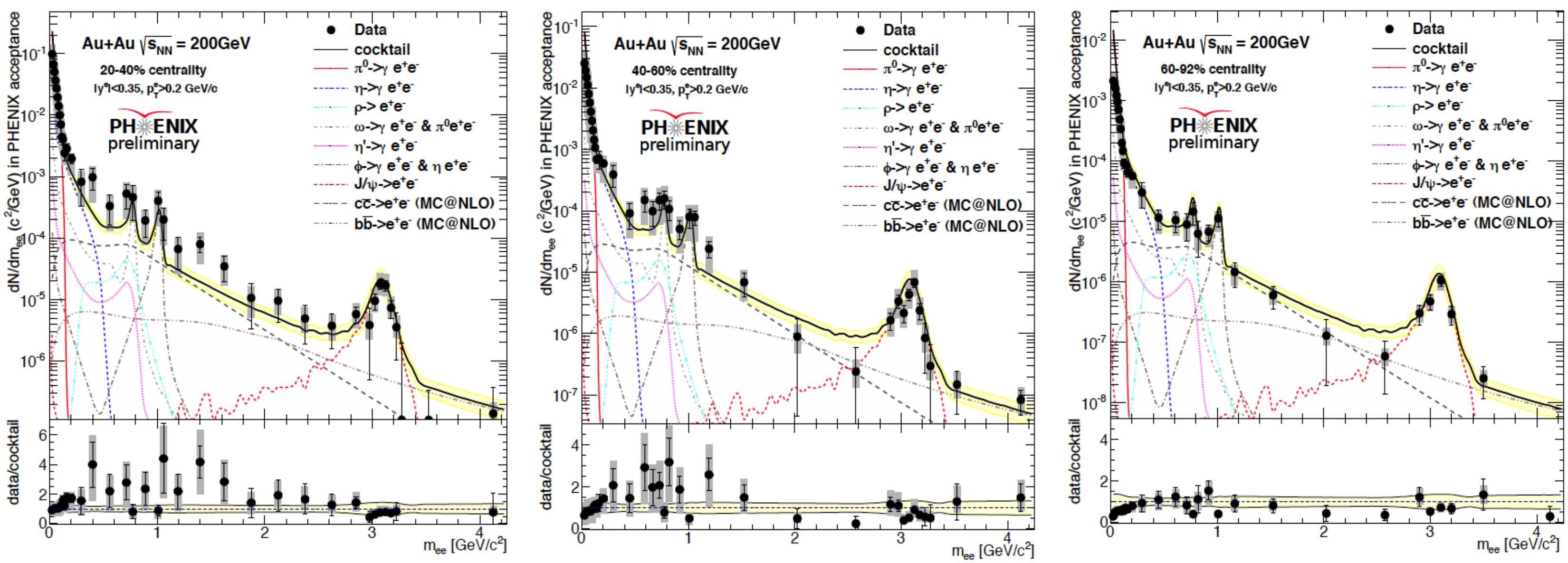
Mihael Makek at TPD'14

The preliminary result
2010 Au+Au Run, sqrt(s_{NN})=200 GeV

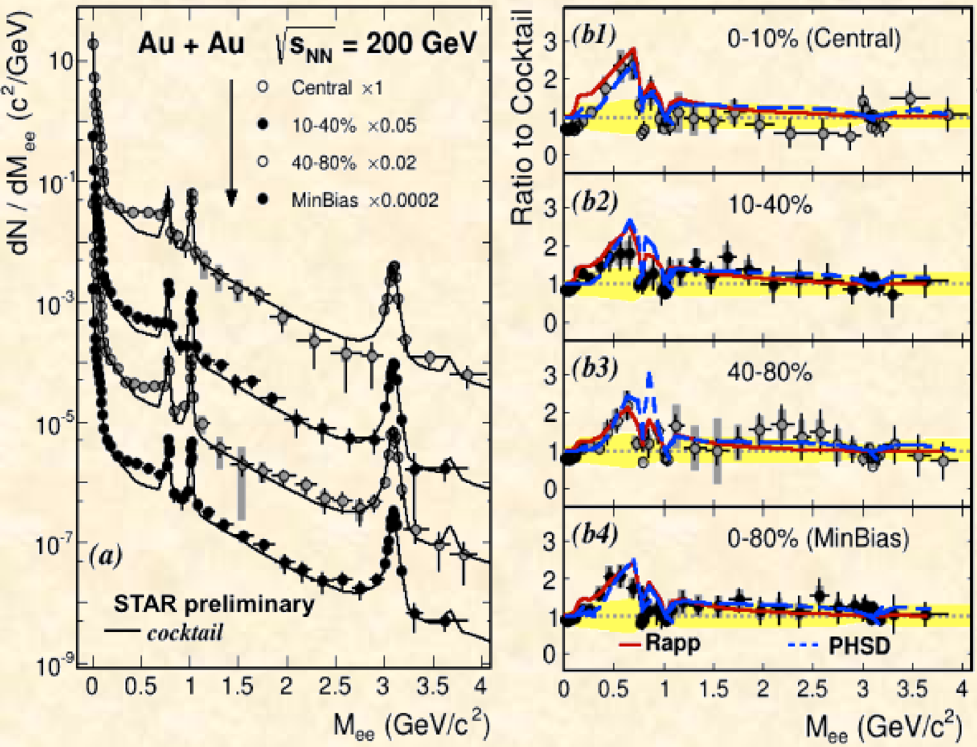
20-40%

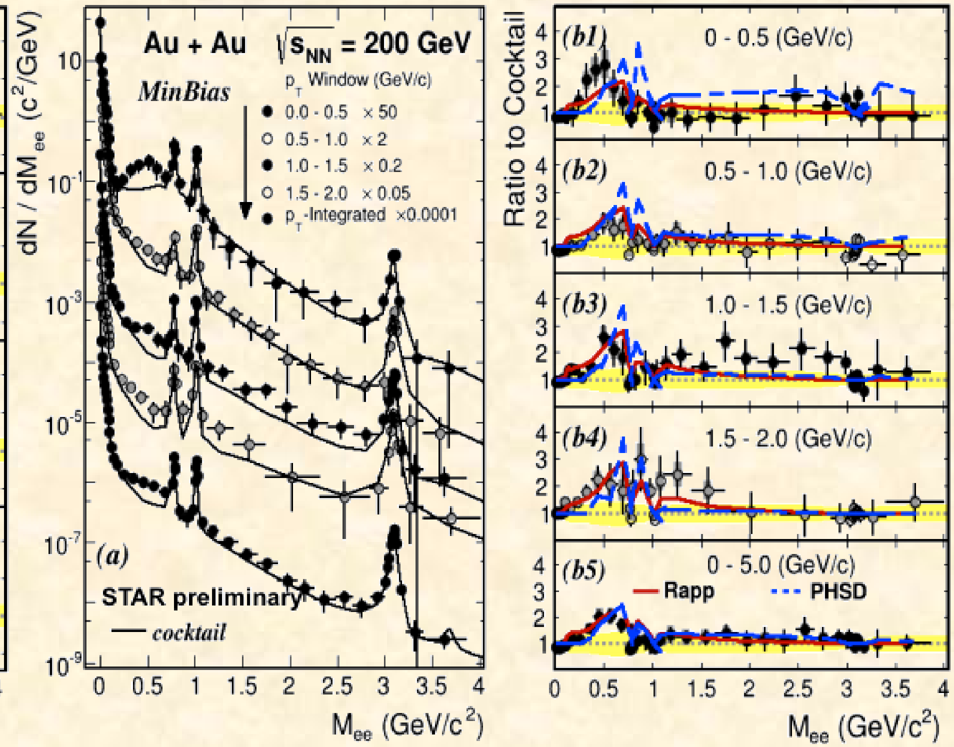
40-60%

60-92%



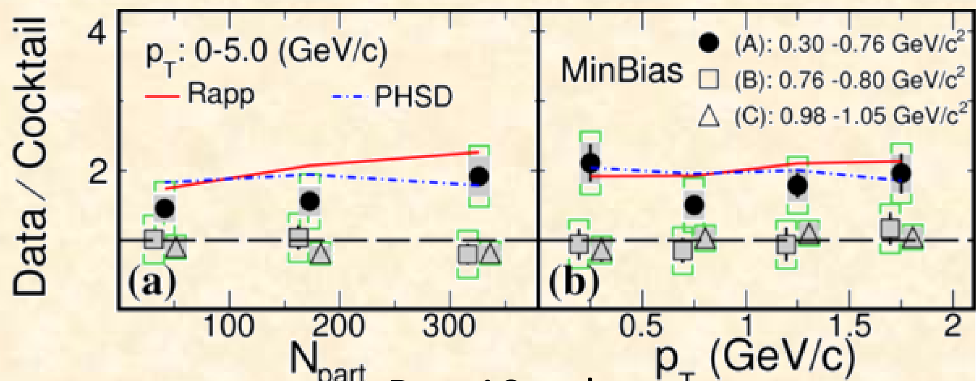
Centrality and p_T Dependence





Combined statistics of Run 10 and 11

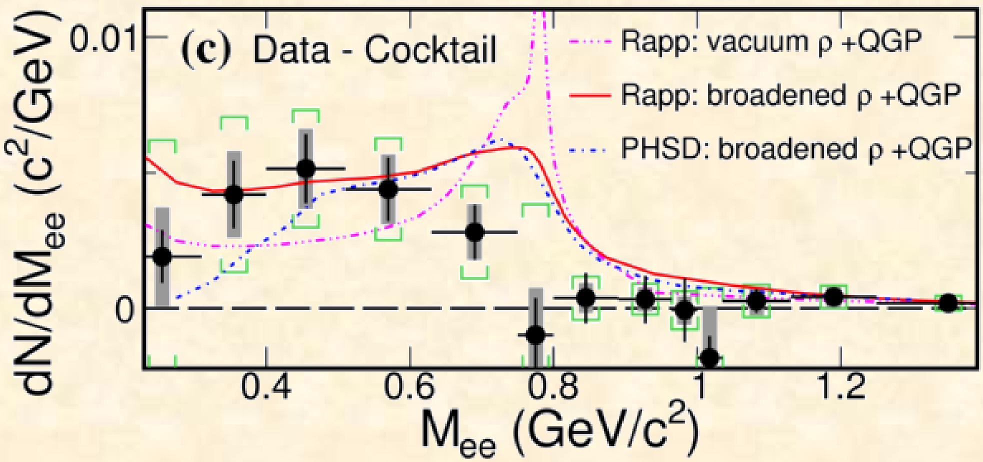
- Data/cocktail: No strong dependence on centrality or p_T
- Model calculations continue to give a reasonable description



Run 10 only – PRL 113 022301

Low-Mass Excess: Rapp & PHSD

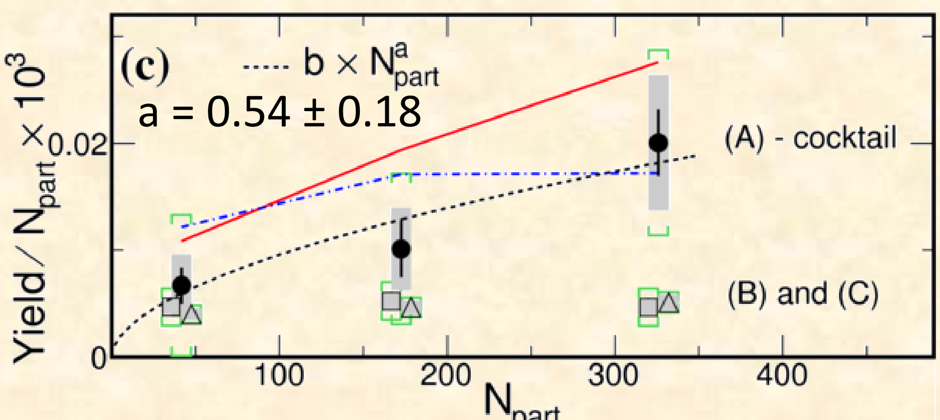
PRL 113 022301



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



Both models describe NA60 & STAR

- agreement w/in uncertainties
- vacuum ρ disfavored
- low-mass dielectron yield increase ~$(N_{part})^{\alpha}$ with α=1.54±0.18

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)

PHSD (Linnyk, priv.comm.)

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

Collisional broadening & radiation from QGP

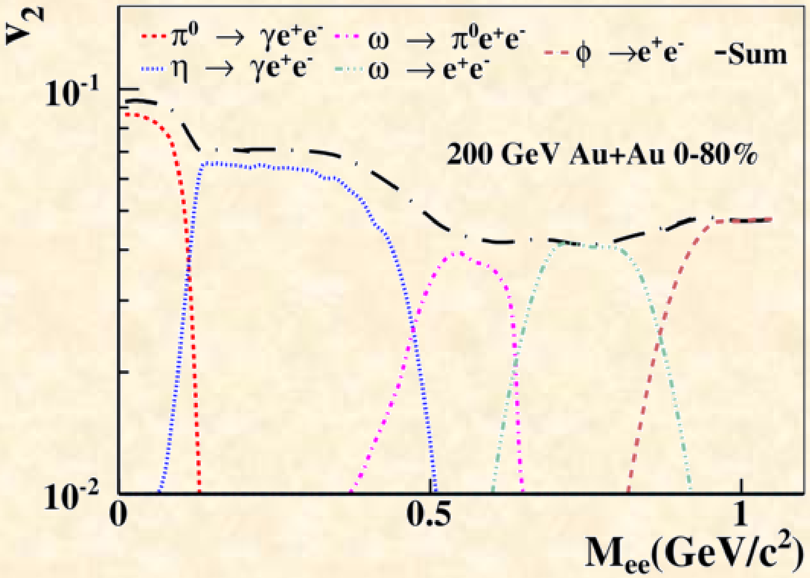
First Measurements of Dielectron v_2

STAR, PRC 90 (2014) 64904

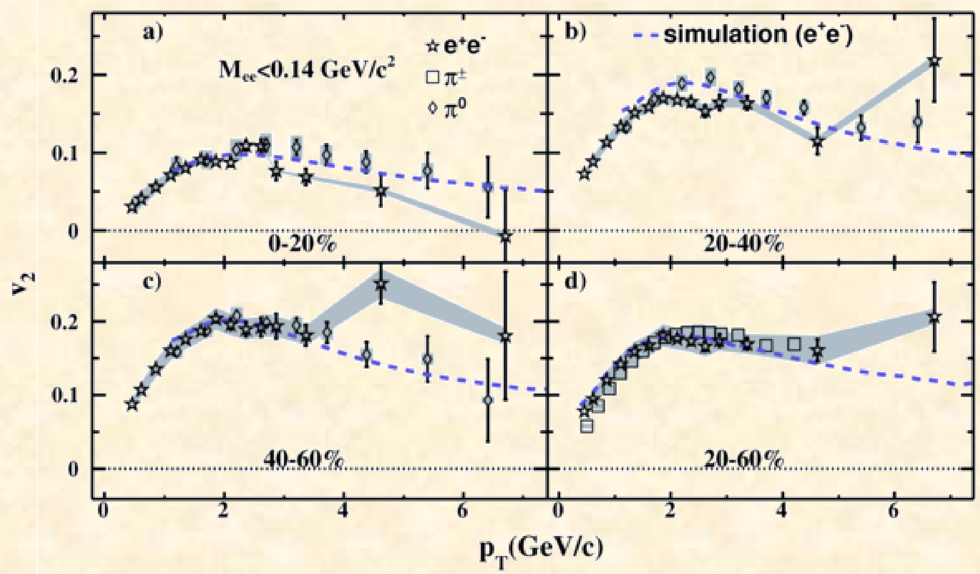
➢ Challenge: isolate v_2 of excess dielectrons

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

Cocktail simulations based on published light-hadron v_2 measurements



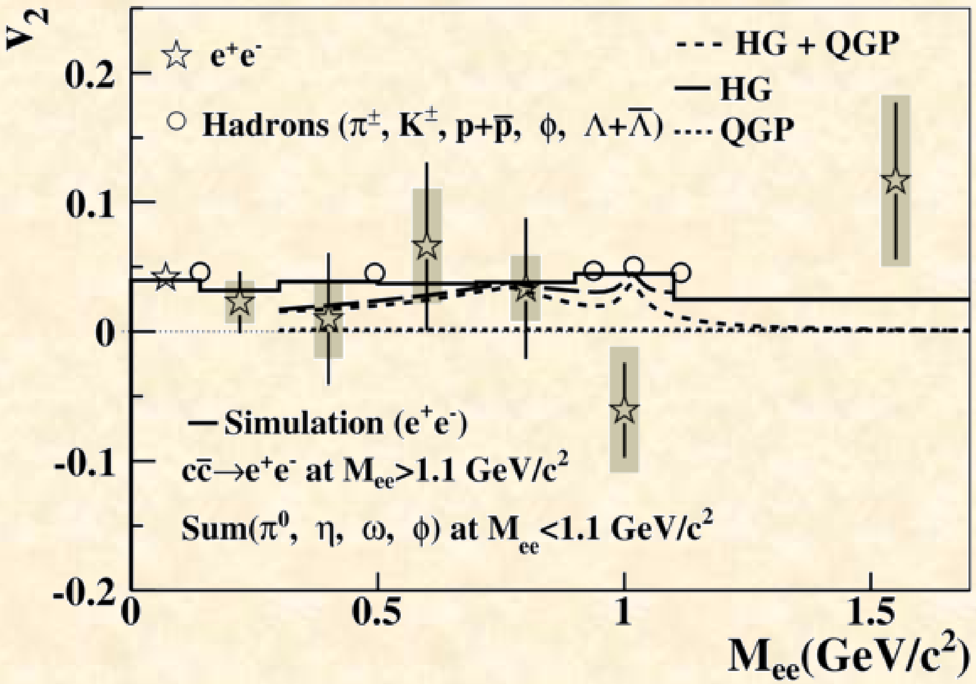
v_2 from π^0 Dalitz decay consistent with simulations based on published π^0 v_2



Proof-of-Principle Measurement

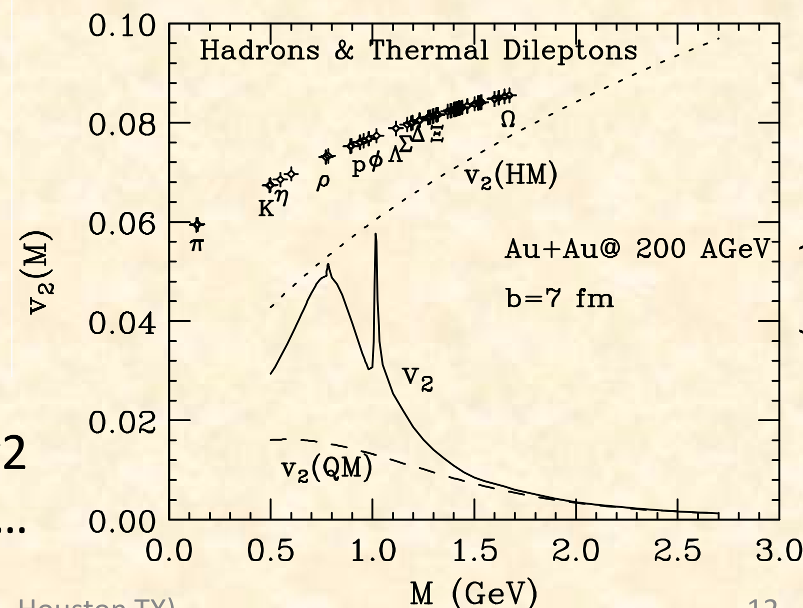
PRC 90 (2014) 64904

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



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

➢ Given the current precision: dielectron v_2 is consistent with cocktail simulations and measured hadron v_2

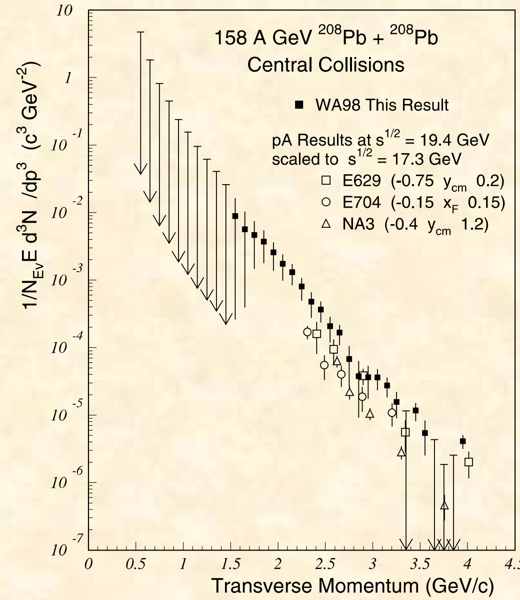


Chatterjee et al PRC 75 (2007) 054909

Direct photon measurements

Two methods:

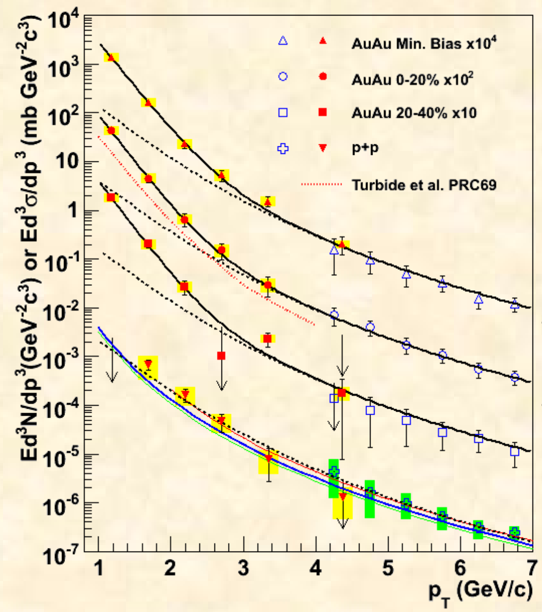
- real photons: measure inclusive spectrum and subtract sources such as from hadron decays
  - e.g WA98
  - establish mostly upper limits
- virtual photons: measure dileptons and use relation between virtual photon and direct photon
  - PHENIX, based on a method proposed by UA1



WA98, PRL 85 (2000) 3595

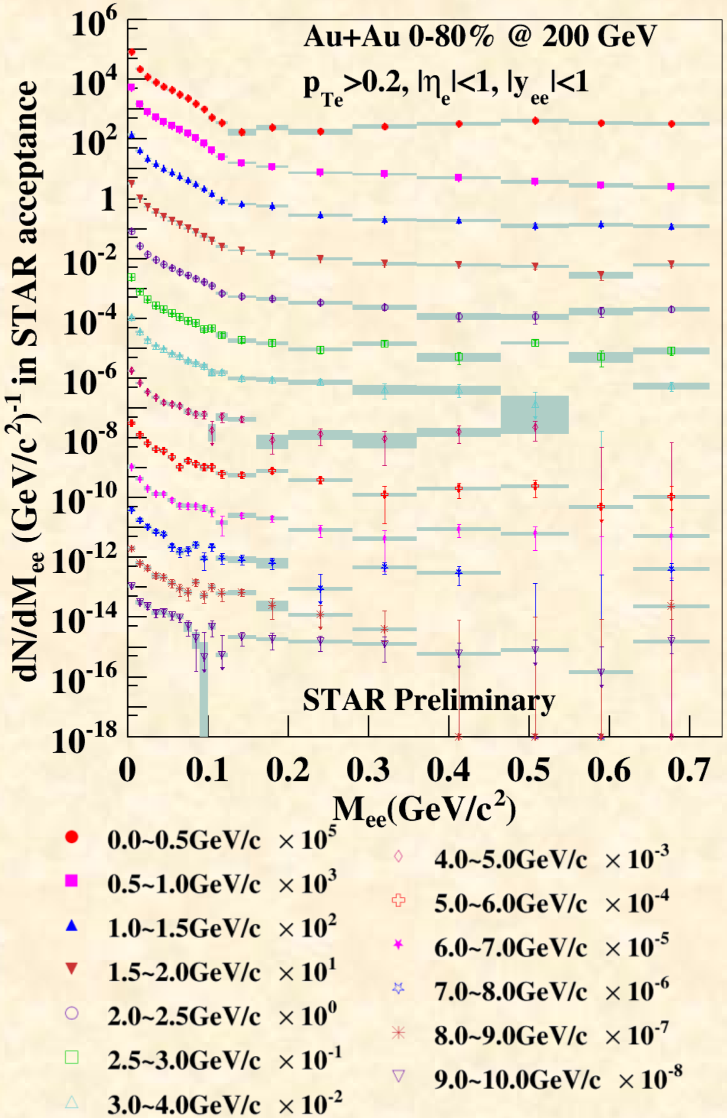
Virtual photons:

- any process that radiates γ will also radiate γ^*
- for $M << p_T$ such a γ^* is "almost real"
- extrapolate $\gamma^* \rightarrow e^+e^-$ to M=0 will give the direct-γ yields



PHENIX, PRL 104 (2010) 132301

Recent Measurements from STAR



p_T<5 GeV/c – Run10+11 (MinBias)
5<p_T<10GeV/c – Run11 (EMC trig)

- Using similar method as PHENIX

PRC 81 (1020) 034911

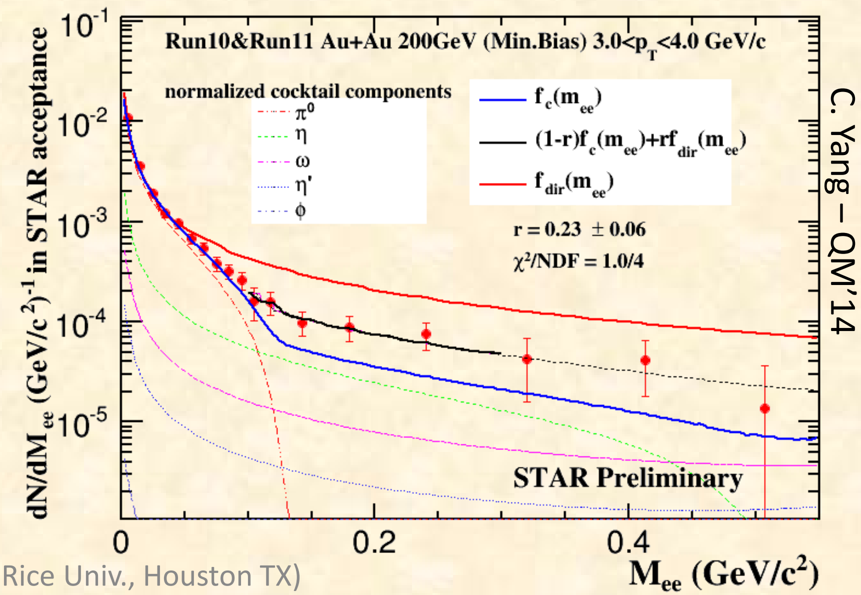
$$\frac{dN_{ee}}{dM} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M^2}}\left(1+\frac{2m_e^2}{M^2}\right)\frac{S(M)}{M}dN_\gamma$$

$$S = dN_{\gamma^*}/dN_\gamma \approx 1 \quad \text{for } p_T >> M \text{ and } M >> m_e$$

with $M < 0.3$ GeV/c^2 and $p_T > 1$ GeV/c

- apply 2-component fit

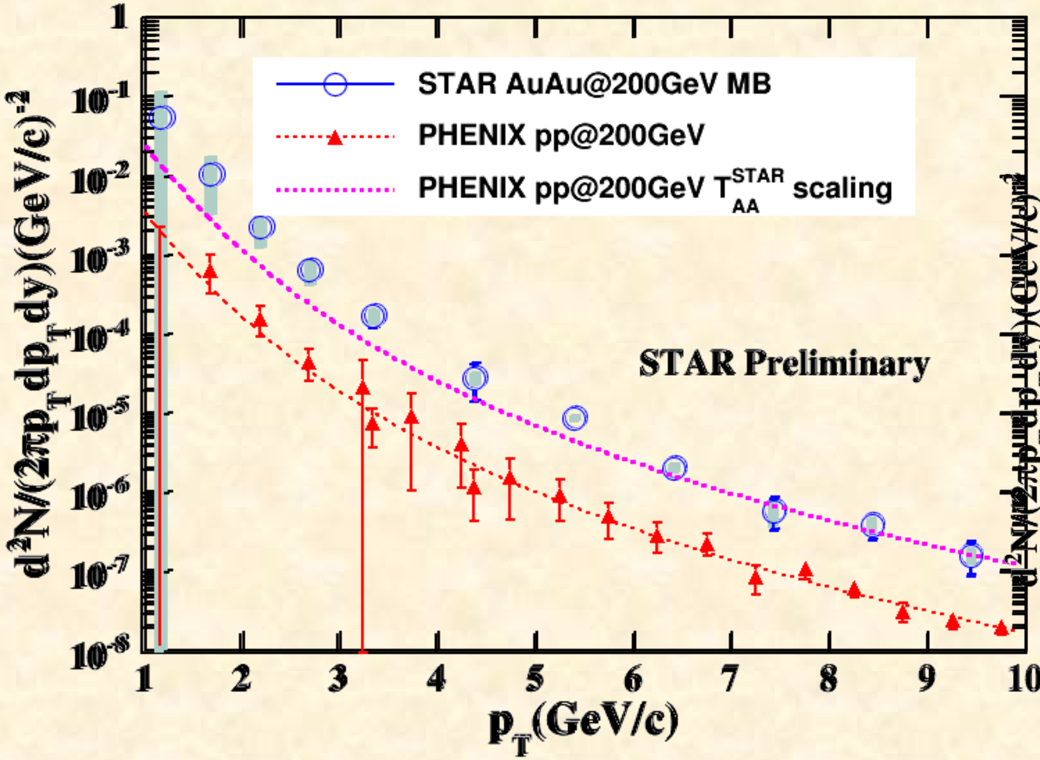
$$(1-r)f_{\text{cocktail}}(M_{ee}) + r f_{\text{direct}}(M_{ee})$$

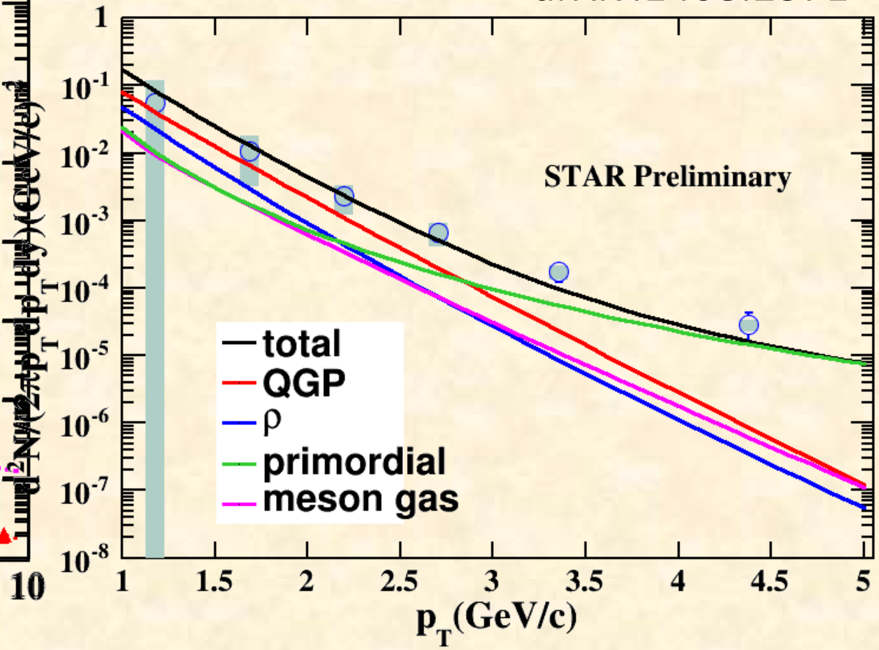


C. Yang – QM'14

Direct Virtual Photon Invariant Yield

B. Huang, TPD’14
arXiv:1408.2371





- Large uncertainty for $p_T < 2$ GeV/*c* due to lack of η measurements
- Comparison with PHENIX
  - high p_T – consistent with T_{AA}-scaled fit to p+p data
  - for 1-5 GeV/$_c$ observe excess when compared to this p+p reference
- Theory calculations consistent within uncertainty
  - includes contributions from QGP, ρ, meson gas, and primordial production

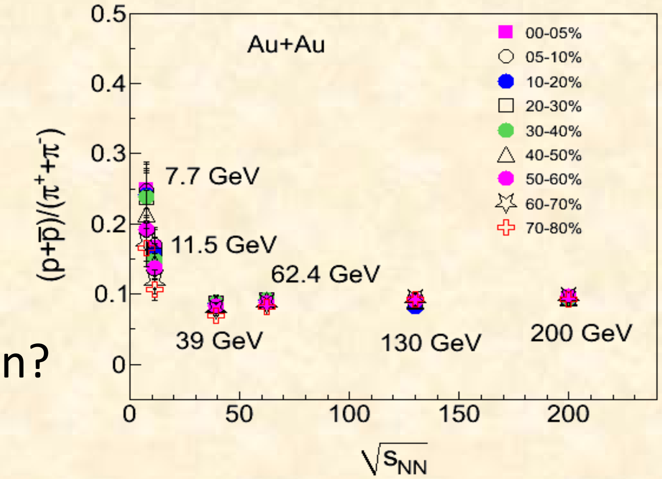
Dielectron Production at lower $\sqrt{s_{NN}}$

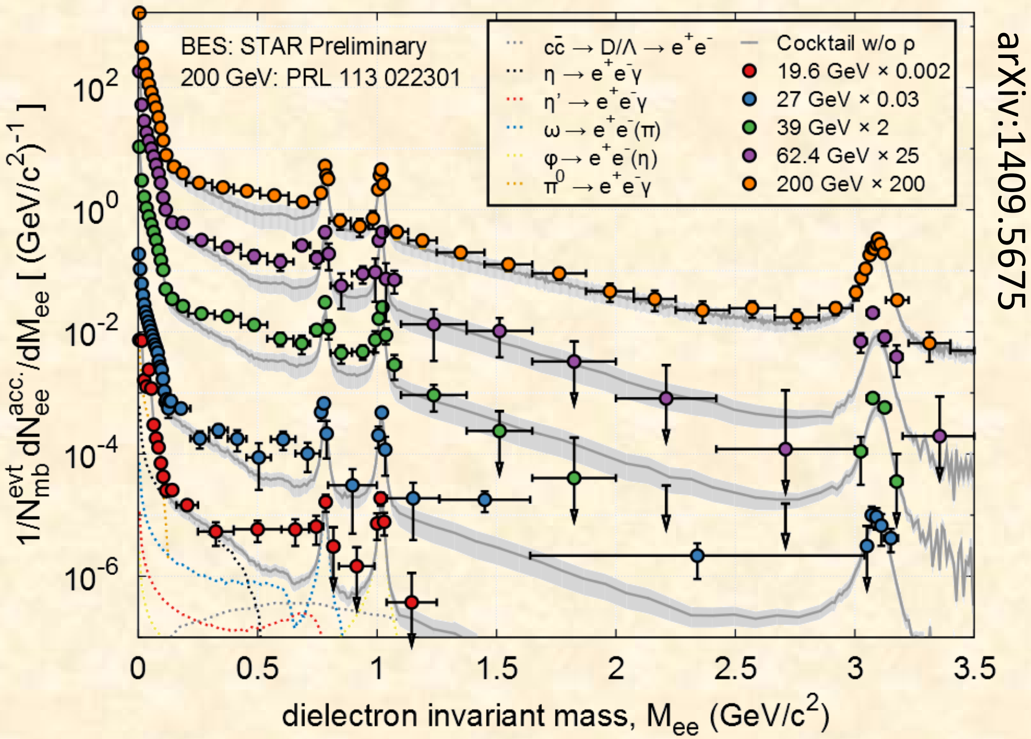
Observed low-mass enhancement at top RHIC energy

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

Explore low-mass range down to SPS energies

- change initial conditions, net-baryon density
- ~constant total-baryon density
- possible enhancement, consistent model description?





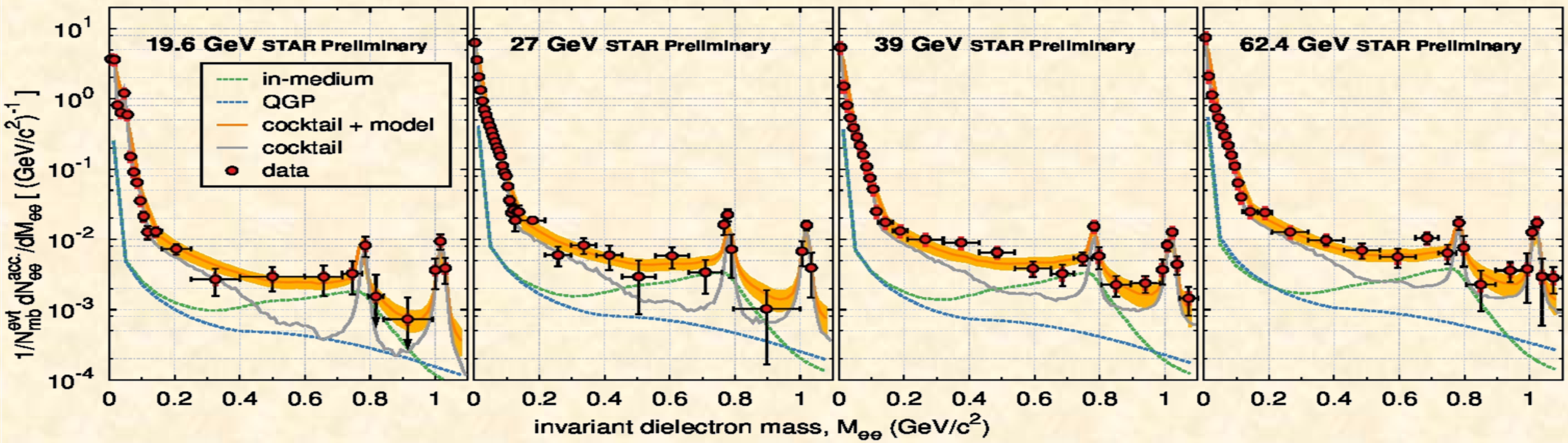
Beam Energy Scan Dielectrons:

2010 – 2011 Au+Au at

62.4, 39,

27, and 19.6 GeV

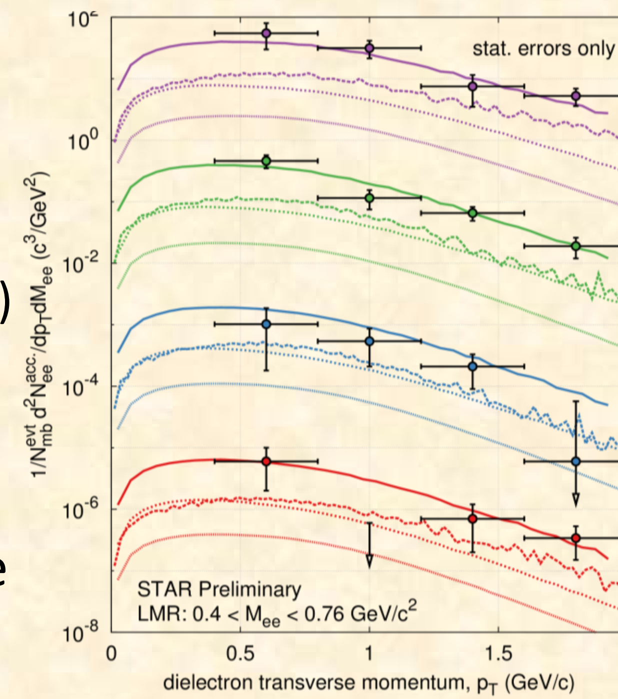
Compare to Theory: In-Medium ρ



Butterworth, TPD'14

- ➢Sustained low-mass excess radiation
  - ➢ top RHIC down to SPS energies
- ➢Robust theoretical description
  - – black dotted curve: cocktail + in-medium ρ (Rapp)
- ➢Consistent with in-medium ρ broadening
  - – expected to depend on total baryon density

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

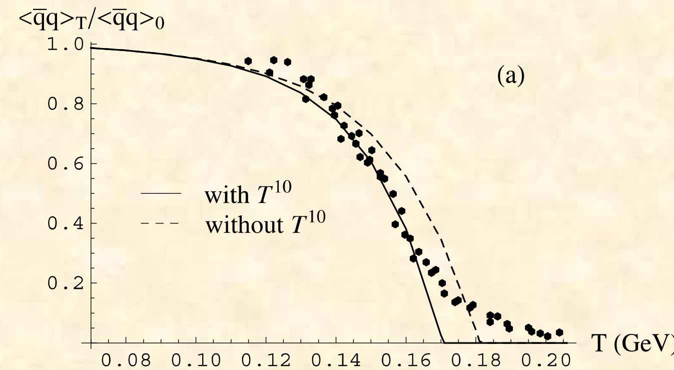


arXiv:1409.5675

A Phenomenological Approach

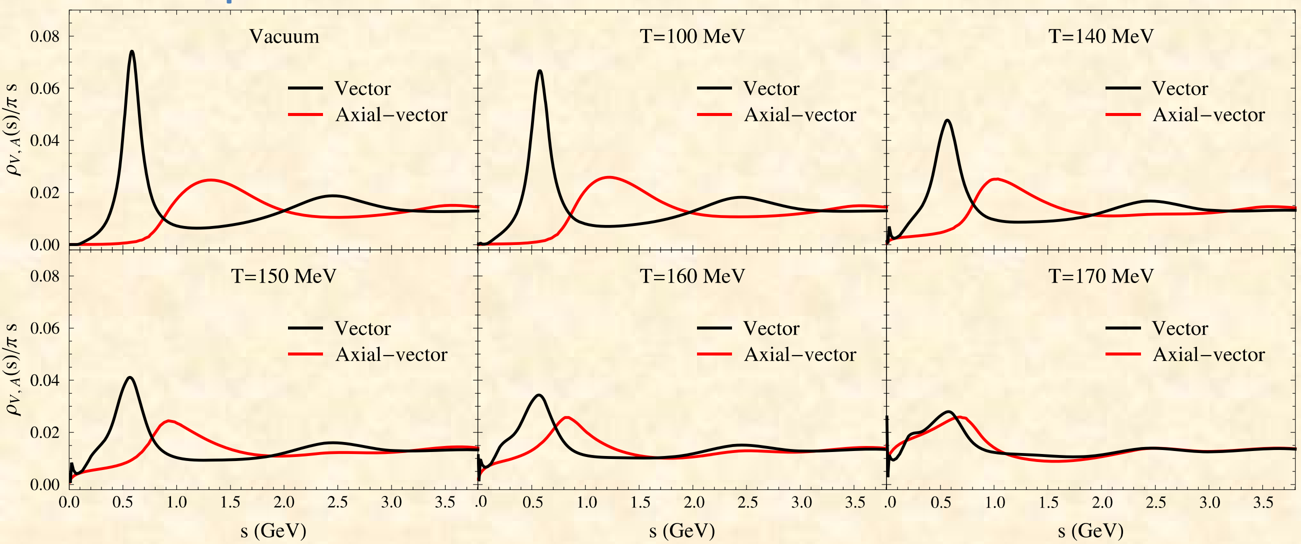
Experiment: Strong evidence ρ meson "melts"

- Input
  - vector SF (ρ meson) from phenomenological model, verified against experimental data
  - T dependence of the condensate: from LQCD
- QCD sum rules
  - constrain vector/axial-vector SFs individually
- Weinberg sum rules
  - difference between vector & axial-vector SFs
- Output …



$$\frac{1}{M^2}\int ds \frac{\rho_{V/A}(s)}{s} e^{-s/M^2} = \sum_n C_n \langle O_n \rangle$$

$$\int ds (\rho_V - \rho_A) s^n = f_n$$



Hohler at TPD'14:

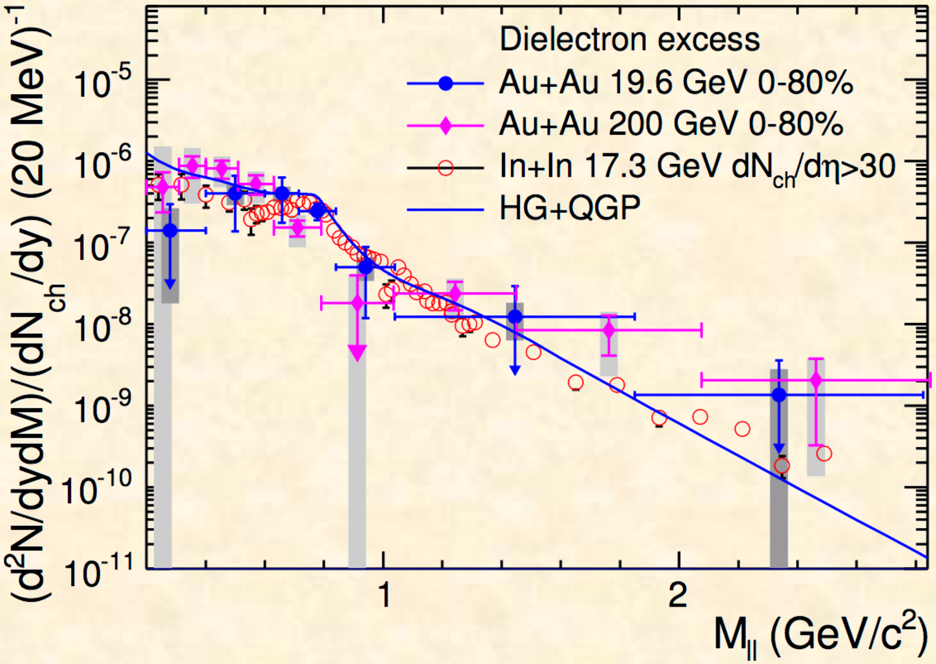
But, still need microscopic calculations of $a_1(1260)$. (Massive Yang-Mills)

Work in progress …

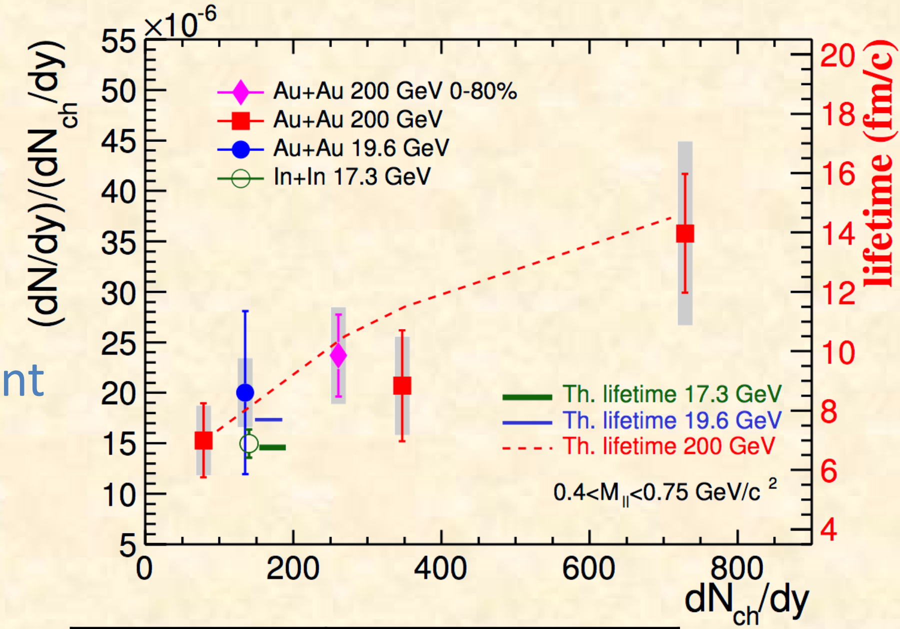
Hohler, Rapp – PLB 731 (2014) 103

Excess Yields and Medium Lifetimes

STAR arXiv:1501.05341
subm. to PLB



- Acceptance corrected STAR excess spectra for 200GeV and 19.6GeV
  - normalized to $(dN_{ch}/dy)_{y=0}$
  - compared to NA60 dimuon excess (17.3GeV)



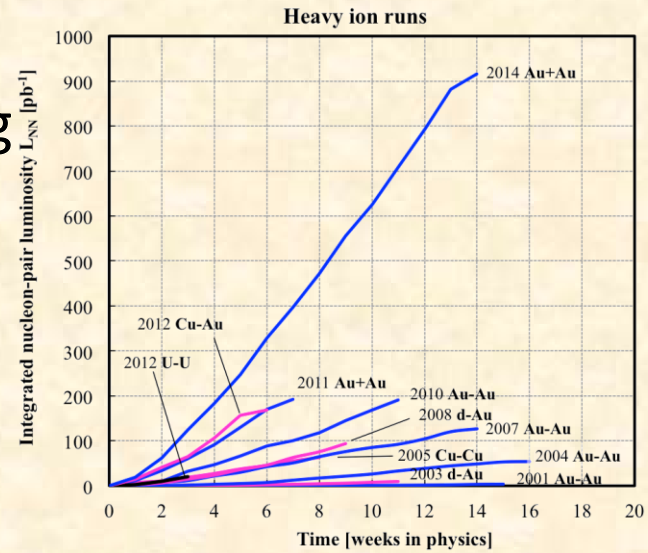
- Integrated LMR excess yields
  - 17.3GeV (NA60) and 19.6GeV consistent
  - 200GeV yields larger than in 19.6GeV
  - centrality dependence in 200GeV
- Lifetime of medium in 200GeV longer
  - in central compared to peripheral
  - when compared to 17.3GeV

17.3 GeV	6.8 ± 1.0 fm/c
19.6 GeV	7.7 ± 1.5fm/c
200GeV	10.5 ± 2.1 fm/c

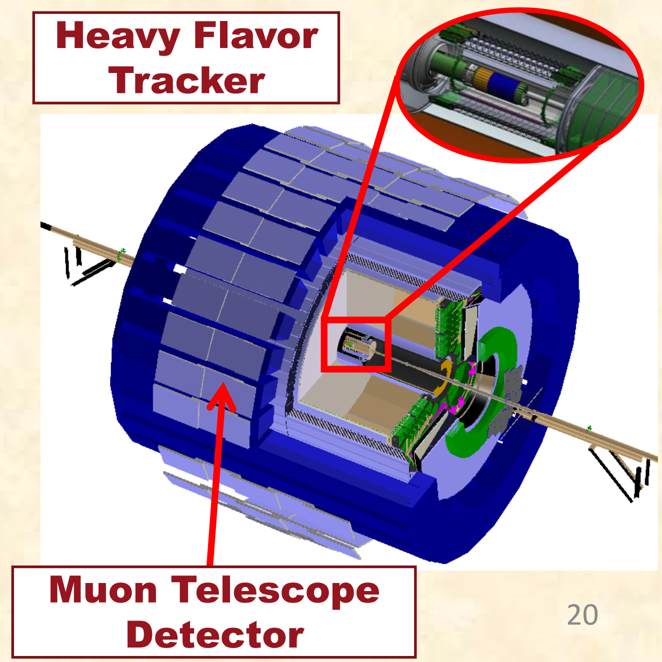
Immediate Future: 2014-2016

- RHIC upgrades
  - fully implemented stochastic cooling
- STAR upgrades
  - Heavy Flavor Tracker
  - Muon Telescope Detector

    dedicated muon triggers: e.g. *e*-muon



- 2014: Au+Au statistics
  - 200 GeV: 1.2B events
  - 14.6 GeV: 20M events
- 2015: p+p (9wks), p+Au,Al (5+2wks)
- 2016: Au+Au (10wks)



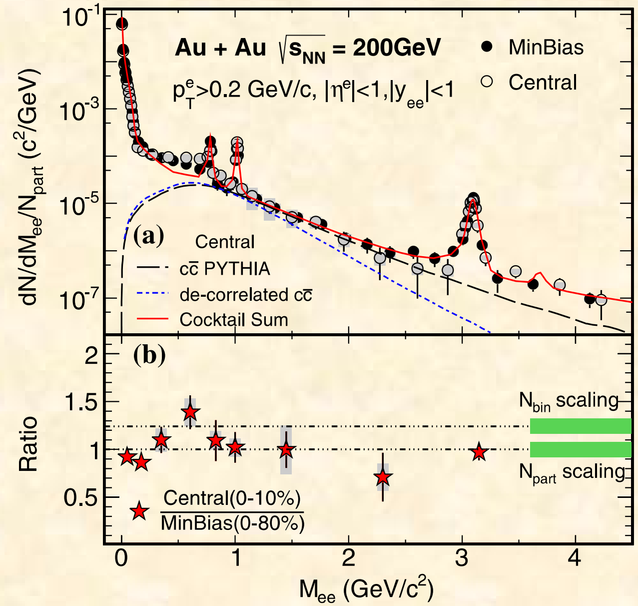
MTD Dilepton Physics

Significant charm contribution spanning low and intermediate-mass range

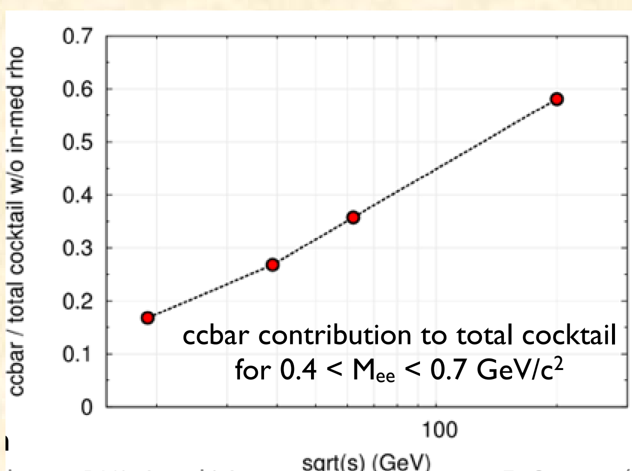
- also relevant in LMR at high energies
- distinguish thermal and charm production
- ➢ use e-μ correlation to get a handle on charm contributions

Dimuon continuum:

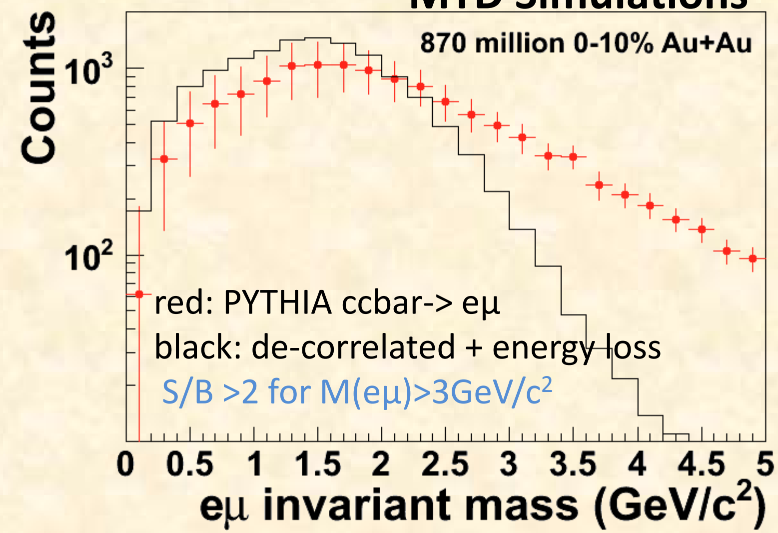
- ➢ LMR: vector meson in-medium modifications
- ➢ IMR: radiation from QGP
- ➢ Dimuon elliptic flow



PRL 113 022301



MTD Simulations



BES-2 Dileptons: 2018-2019

BES Phase 1: 19.6 – 200 GeV

- Dilepton emission dominant in T_C region and constant baryon density
  - ➢ emission proportional to lifetime

BES Phase 2: 7.7 – 19.6 GeV

- ➢ Probe life time + baryon density dependence of the ρ spectral function

Close to CP, expect increase in correlation lengths. Critical slowing down?

Look for anomalous increase in the lifetime of the fireball

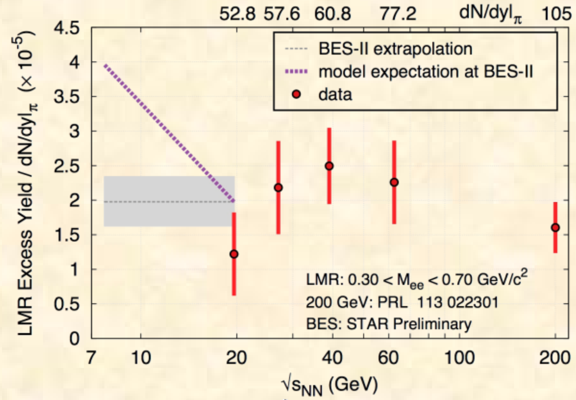
Down to FAIR energies

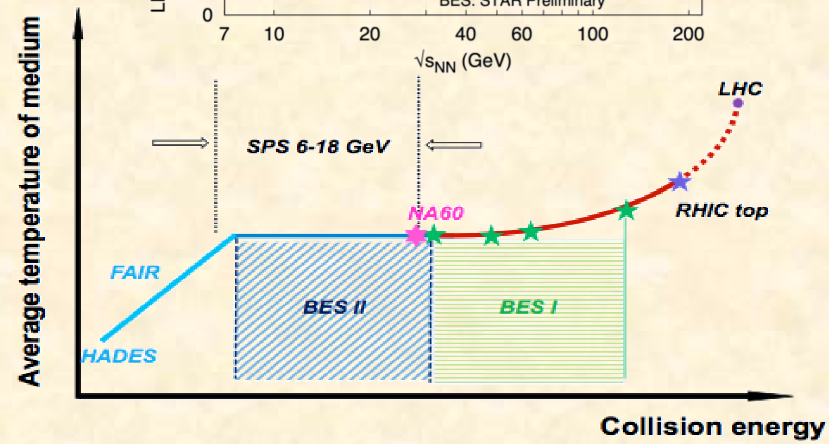
– CBM, HADES

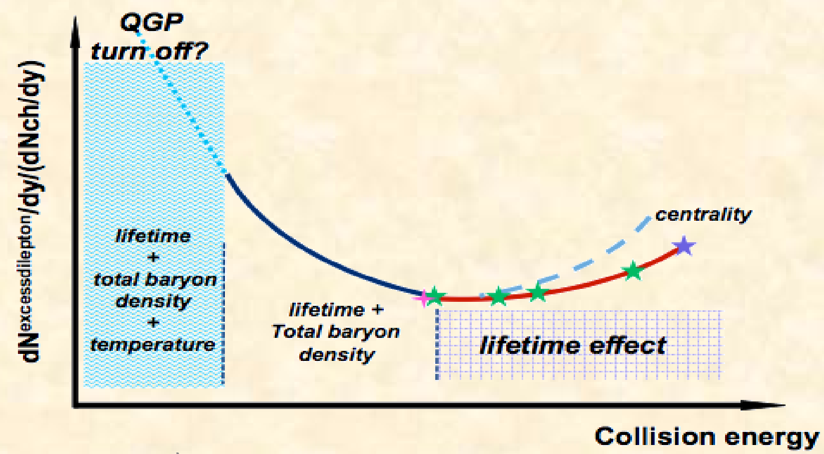
- probe lifetime, total baryon density, and temperature dependence

At SPS: proposed NA60+

- overlap with RHIC and FAIR







Ruan, Rapp – TPD'14

Summary

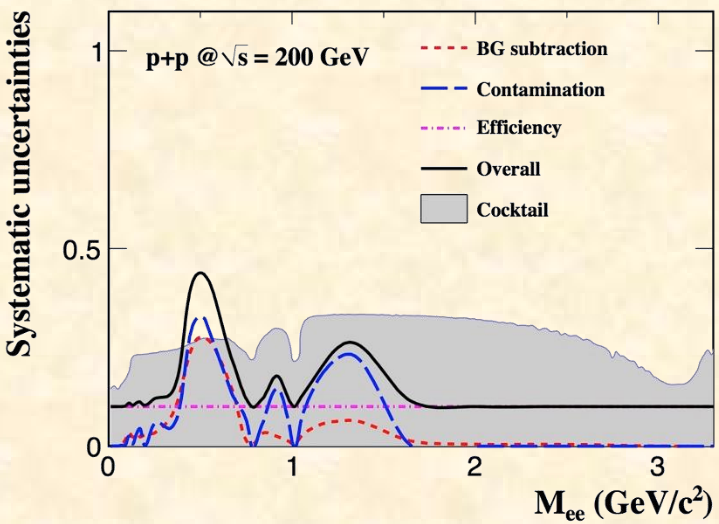
- At SPS, NA60 and CERES demonstrated the physics potential of accurate dilepton measurements
- At RHIC, PHENIX & STAR both developed a strong dilepton program
  - BES phase-1 program allowed for a continued systematic measurement from top RHIC down to top SPS energies
- At the same time, important progress thermal field theory computations of dilepton production in heavy-ion collisions
- Detector upgrades improve and/or enable new detection capabilities
  - 2014-2016: high statistics A+A, p+p, and p+A
  - dilepton program: revisit top energies, disentangle charm, dimuon continuum.
- BES Phase 2 (2018-2019): systematic dilepton measurements down to $\sqrt{s_{NN}}$=7.7 GeV
  - measure baryon density dependence
  - measure p_T slopes both in LMR and IMR
  - look for anomalous increases in yield, suggestive of a critical point

BACKUP

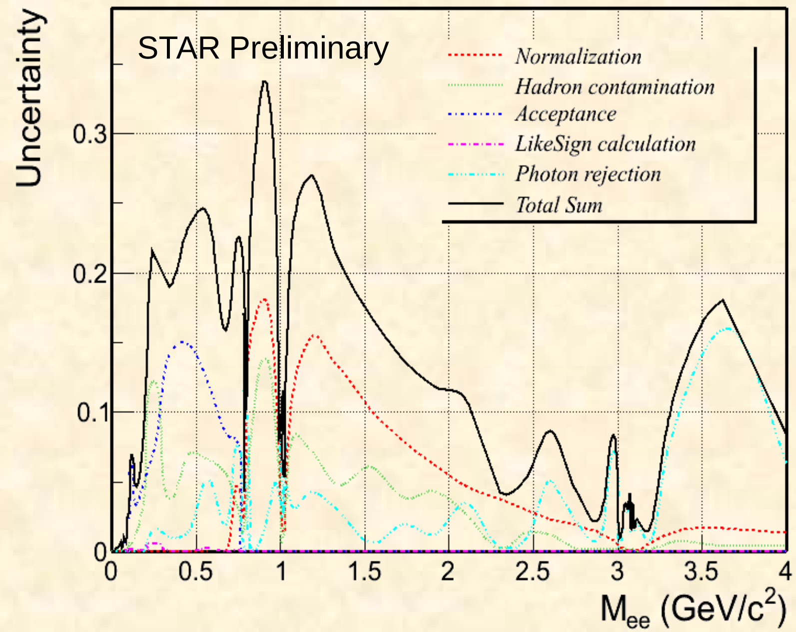
Systematic Uncertainties

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%

Recent Measurements by STAR

Similar method as is used by PHENIX PRC 81 (2010) 034911

$$\frac{d^2N_{ee}}{dM} = \frac{2\alpha}{3\pi}\frac{L(M)}{M}S(M,q)dN_{\gamma}$$

✓ pass STAR acceptance
✓ normalize to 0-30MeV/c²

$$L(M) = \sqrt{1 - \frac{4m_e^2}{M^2}}\left(1 + \frac{2m_e^2}{M^2}\right)$$

$$S(M,q) = \frac{dN_{\gamma^*}}{dN_{\gamma}}$$

cocktail normalized to 0-30MeV/c²

Direct photons can be measured by the associated dielectron production.

$S = 1$ => direct virtual photon ($p_T \gg M$, $M \gg m_e$)

$$(1-r)\,f_c + r\,f_{dir}$$

: two-component fit to dielectron continuum.

cocktail component

direct virtual photon component

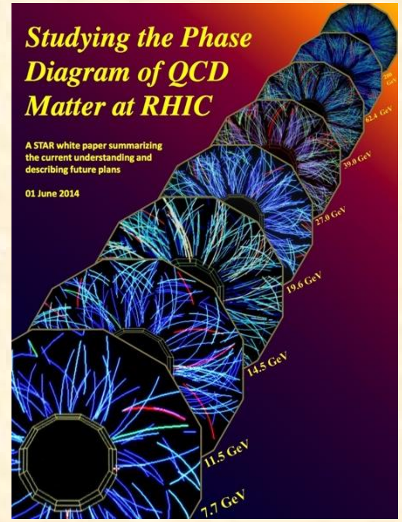
$$r = \frac{yield\ of\ direct\ virtual\ photon}{yield\ of\ inclusive\ photon}$$

RHIC Beam Energy Scan: Phase-2

Larger Context:

Refine our understanding of phase structures of QCD matter

- Phase 2: 2018 – 2019
  - revisit lower energies
  - improve statistics
- ➢ STAR/PHENIX White Papers
- Systematically study dielectron continuum from $\sqrt{s_{NN}}$ = 7.7 – 19.6 GeV



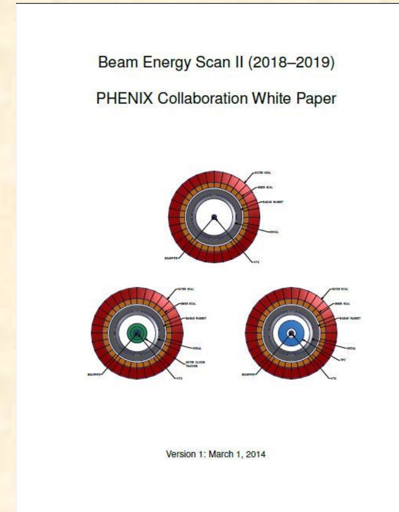
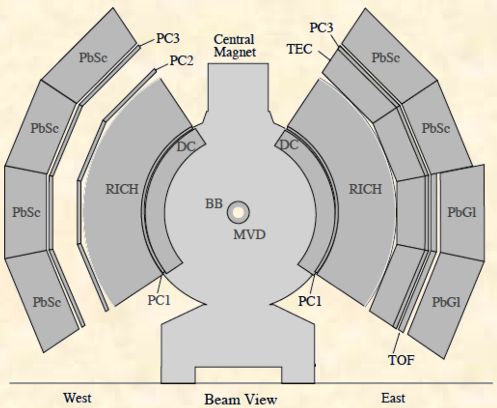


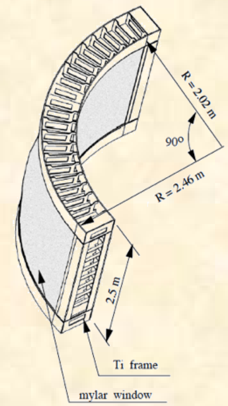
Table 2. Event statistics (in millions) needed for Beam Energy Scan Phase-II for various observables.

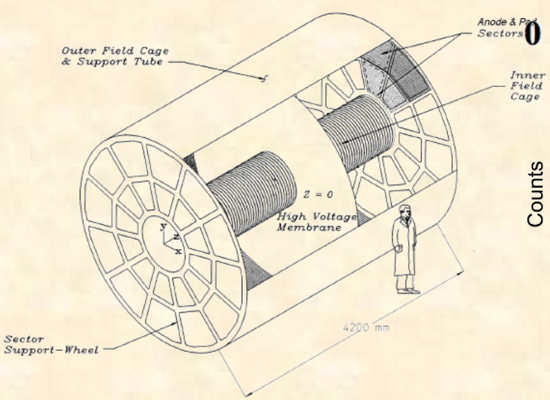
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
u_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to p_T = 5 GeV/c	–		160	125	92
Elliptic Flow (ϕ mesons)	100	150	200	200	400
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	50	75	100	100	200
Azimuthal Femtoscopy (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**

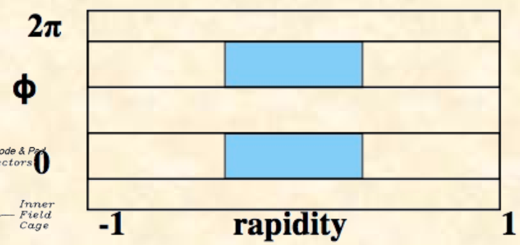
STAR with PHENIX Acceptance

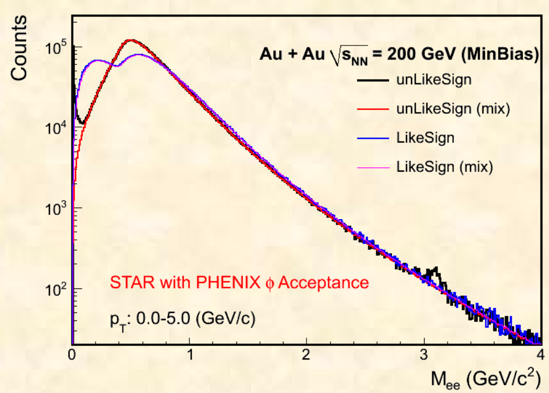
- **STAR**
  - 12 sectors east and west barrel
  - 2π coverage, |η|<1
- **PHENIX**
  - 20 sectors east and west arm
  - π coverage, |η|<0.35

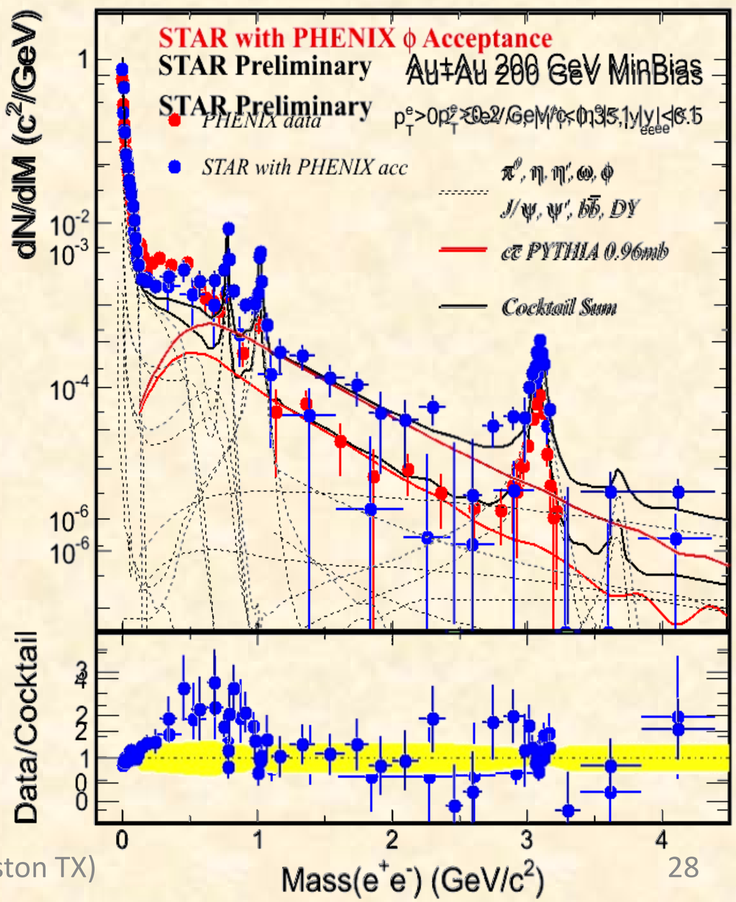












- LMR enhancement still ~2 after PHENIX ϕ cut
- Full PHENIX acceptance cut: large uncertainties

Direct photon comparison

Chi Yang, QM'14

1. To measure eta meson in 1-2 GeV/c ($\eta \rightarrow \gamma + \gamma$).
2. Get the p+p reference from STAR Run12 data.
3. To obtain the inverse slope parameter.