Di-lepton Production in Heavy-Ion Collisions at RHIC energies

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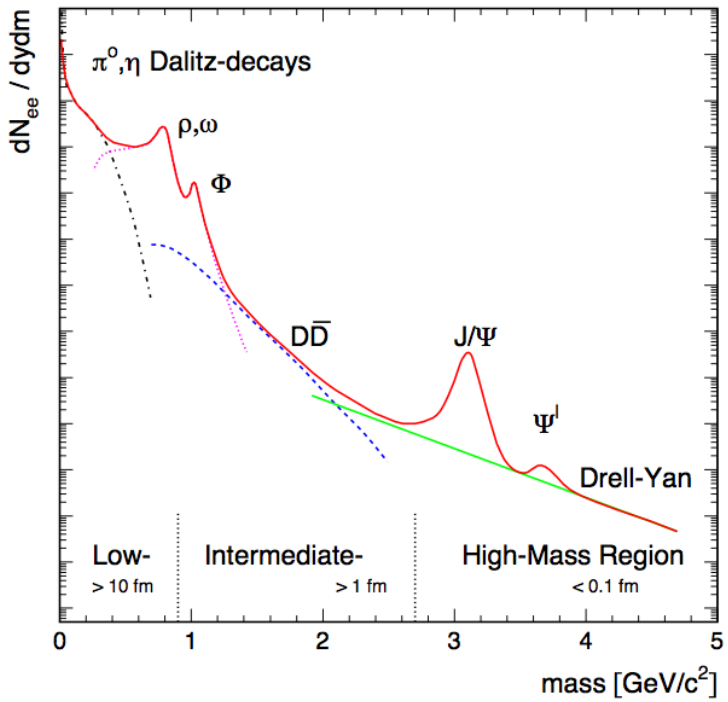
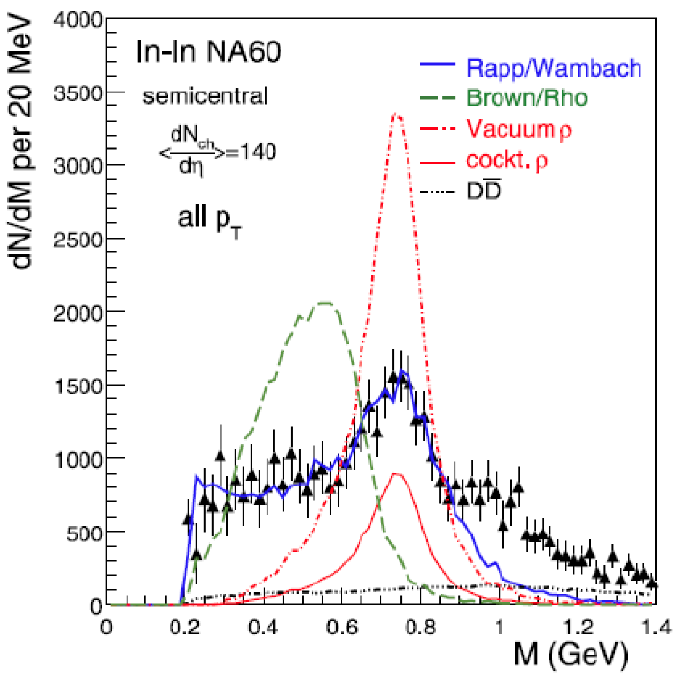
Many thanks to: Xin Dong, Patrick Huck, Haojie Xu, Qun Wang and Jie Zhao

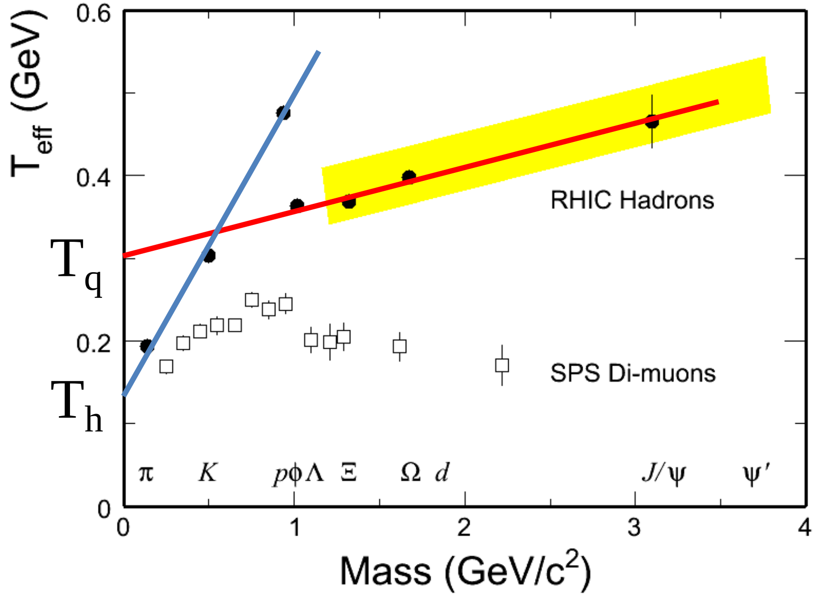
- Introduction.
- The sources.
- Discussion in LMR/IMR.
- Summary.

ATHIC2012 @ Pusan, Korea
14-17 Nov 2012

Introduction - I







NA60: Eur.Phys.J.C59:607-623 (2009)

RHIC 200 GeV, NPA 757,102 (2005)

$$T_{\mathrm{eff}} = T_0 + M v_T^2$$

LMR Chiral symmetry restoration
Vector meson production: in-medium effect

IMR Heavy quark correlation
QGP thermal radiation

HMR Heavy quarkonia production
Drell-Yan

Electromagnetic probes =>

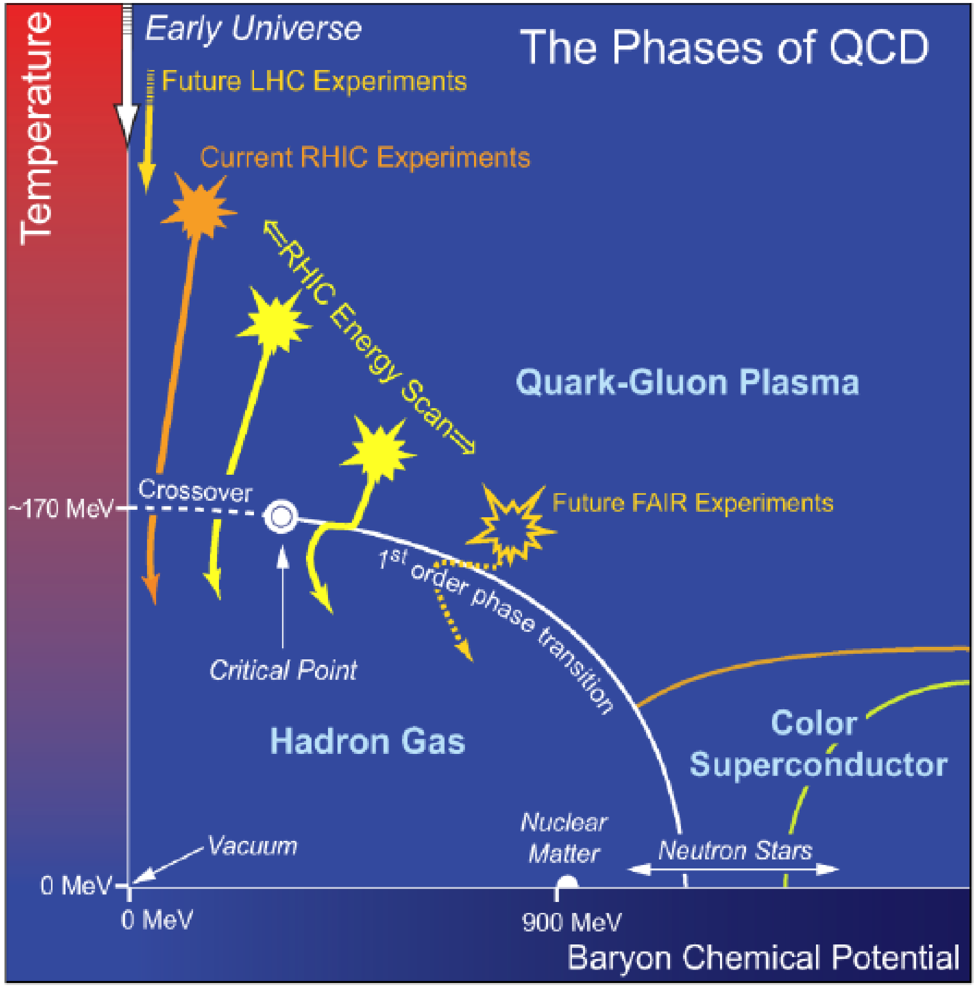
Do not participate in strong interactions.

Bring undistorted information as where they are produced.

Penetrate medium properties.

Challenge: Time-space integrated from every stages.

Introduction - II



RHIC Energy Scan Program:

- Mapping QCD phase boundary.
- Search for QCD critical point.

Observables: fluctuations, flow, correlations …

What about "di-lepton"?

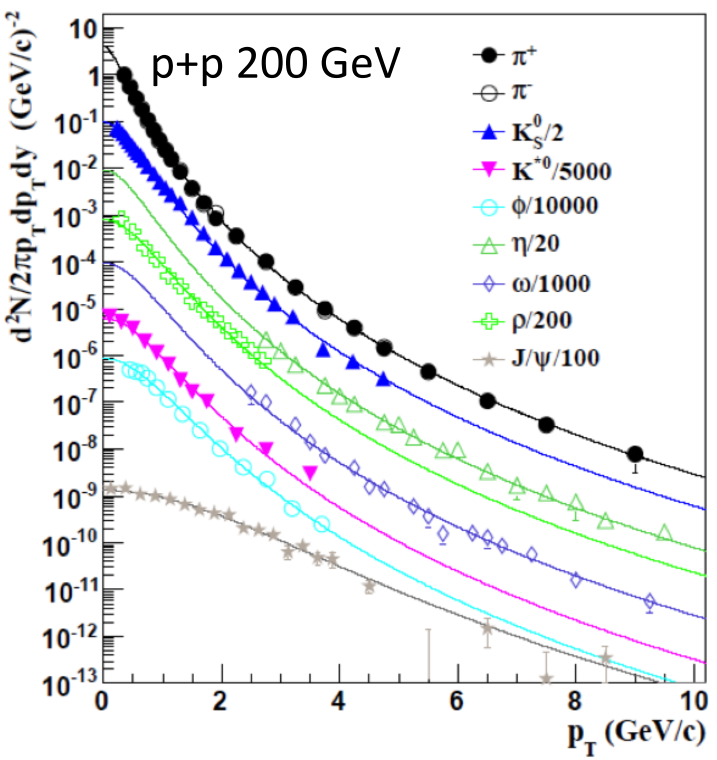
- Mass spectra
- m_T slope
- v_2

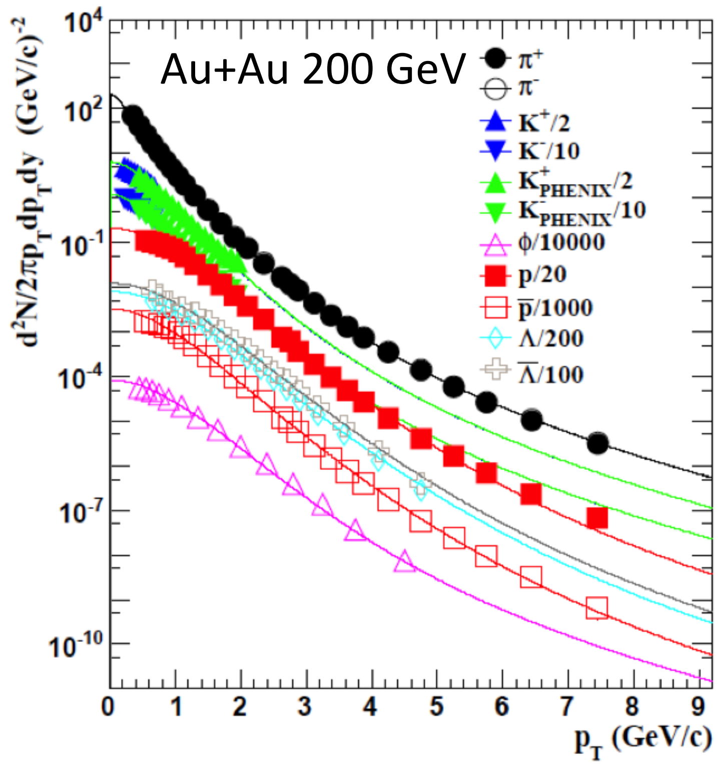
How are the behaviors in HG/QGP phase:

- light meson freeze-out
- ρ meson
- charm correlation
- thermal di-leptons

Hadron decay cocktails

Input meson p_T spectra --- Tsallis Blast-Wave(TBW) fit to measurements.





$$\frac{dN}{m_T dm_T} \propto m_T \int_{-Y}^{+Y} cosh(y)dy \int_{-\pi}^{+\pi} d\phi \int_{0}^{R} rdr$$
$$\times\left(1+\frac{q-1}{T}(m_T cosh(y)cosh(\rho) - p_T sinh(\rho)cos(\phi))\right)^{-1/(q-1)}$$

ρ is related to average flow velocity.
q-1 is the degree of non-equilibrium.
T is the freeze-out temperature.

Z. Tang, et.al., PRC79 051901 (R).

Hadron decay cocktails

Kroll-Wada Formula:

$$\frac{dN}{dm_{ee}} \propto \sqrt{1-\frac{4m_e^2}{m_{ee}^2}} \cdot \left(1+\frac{2m_e^2}{m_{ee}^2}\right) \cdot \frac{1}{m_{ee}} \cdot \left(1-\frac{m_{ee}^2}{M_h^2}\right)^3 |F(m_{ee}^2)|^2$$

QED | Phase Space | Form Factor

N.M. Kroll, et al., Phys Rev, 98 (1955) 5.

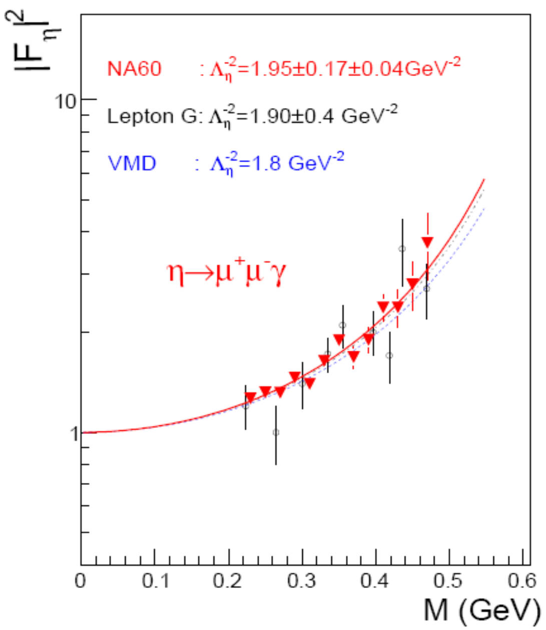
Two-body: Breit-Wigner

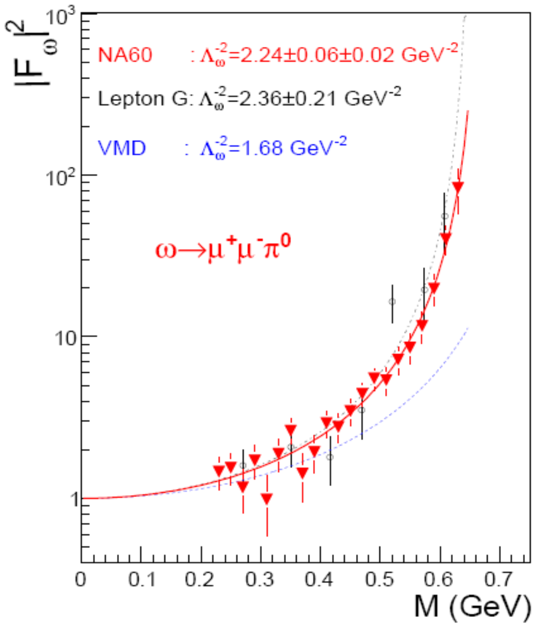
Dalitz: Kroll-Wada

FF: parameterized from measurement.

Phase Space term for ω, ϕ:

$$(1-\frac{m_{ee}^2}{m_h^2})^3 \Rightarrow ((1+\frac{m_{ee}^2}{m_\omega^2 - m_{\pi^0}^2})^2 - \frac{4m_\omega^2 m_{ee}^2}{(m_\omega^2 - m_{\pi^0}^2)^2})^{\frac{3}{2}}$$

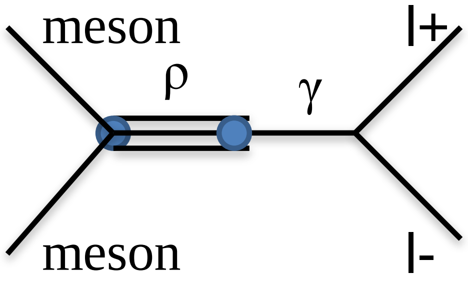




$$|F(m_{ee}^2)|^2 = \frac{1}{(1-m_{ee}^2 \cdot \Lambda^{-2})^2 + \Gamma_0^2 \cdot \Lambda^{-2}}$$

NA60: PLB677 (2009) 260.

ρ broadening

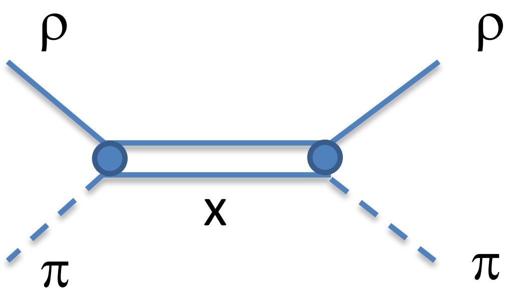


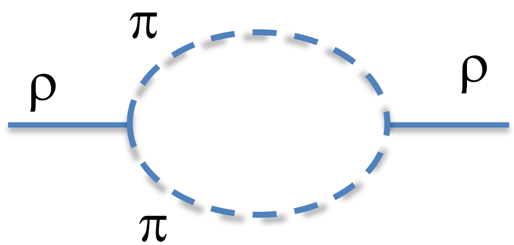
ρ self-energy changes due to interactions with medium.

ρ interaction with meson gas.

ρ pionic decays.

pion-baryon scatterings.

(1)


(2)


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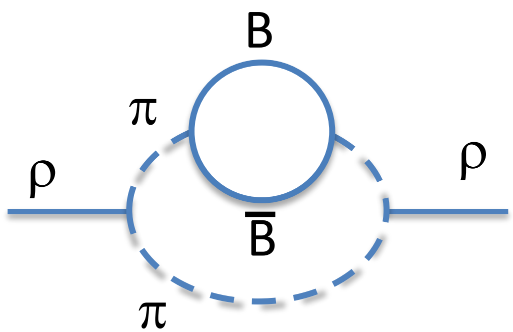
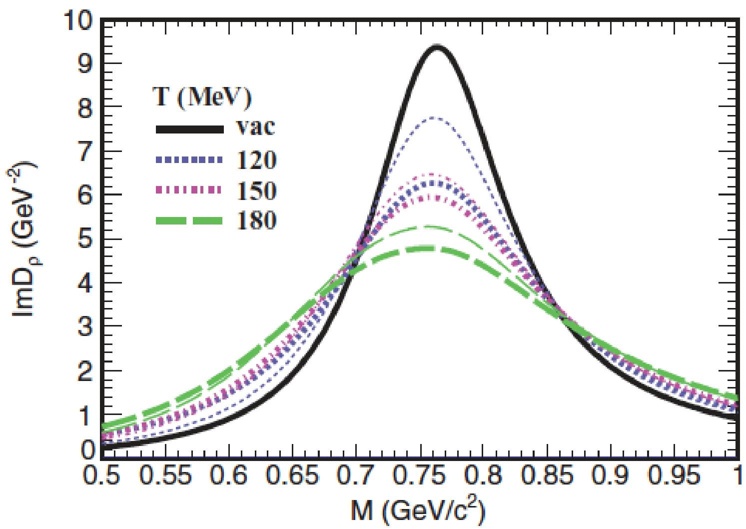


Emission rate:

$$\frac{dN_{ll}}{d^4x d^4p} = -\frac{\alpha}{4\pi^4}\frac{1}{M^2} n_B(p\cdot u)\left(1+\frac{2m_l^2}{M^2}\right) \times\sqrt{1-\frac{4m_l^2}{M^2}}\,\mathrm{Im}\Pi^R(p,T).$$

V-m propagator:

$$\mathrm{Im}D_V^R = \frac{\mathrm{Im}\Pi_V^R}{\left(p^2-m_V^2+\mathrm{Re}\Pi_V^R\right)^2+\left(\mathrm{Im}\Pi_V^R\right)^2},$$

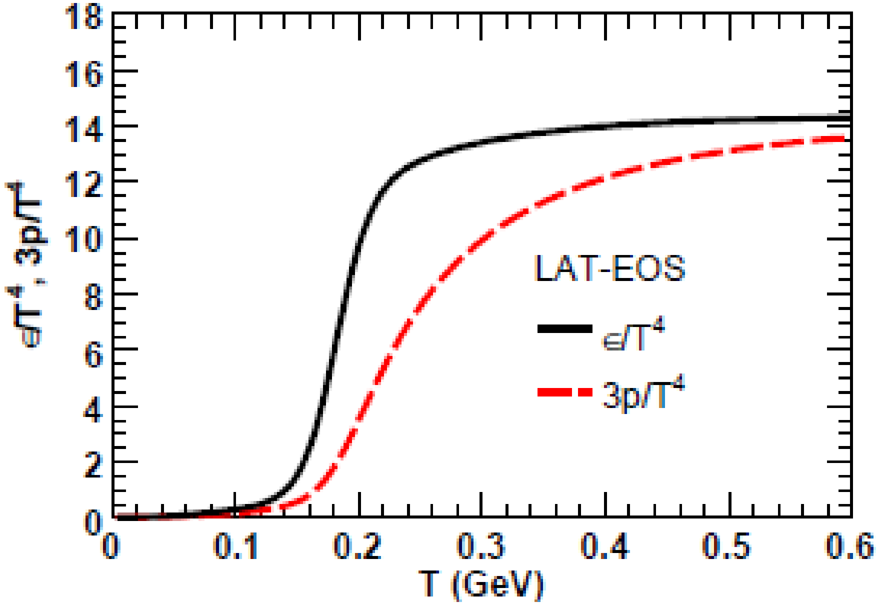


H. Xu, *et al.*, Phys. Rev. C 85 024906 (2012)

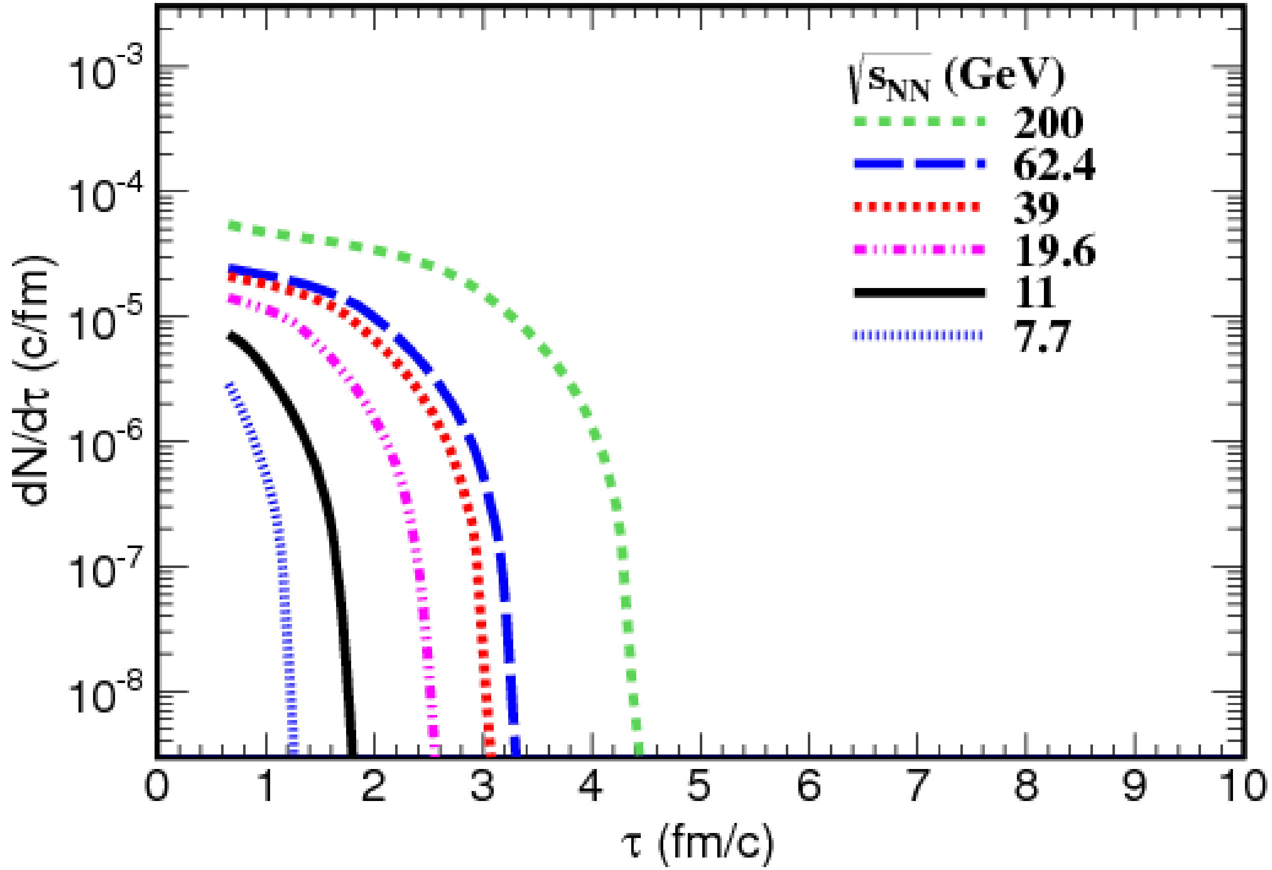
Space-time evolution

B. Schenke, et. al., PRC82, 014903 (2010)

(2+1)D ideal hydrodynamics
Lattice EOS
Parameters: S95P-PCE



P. Huovinen and P. Petreczky, NPA837 (2010) 26.

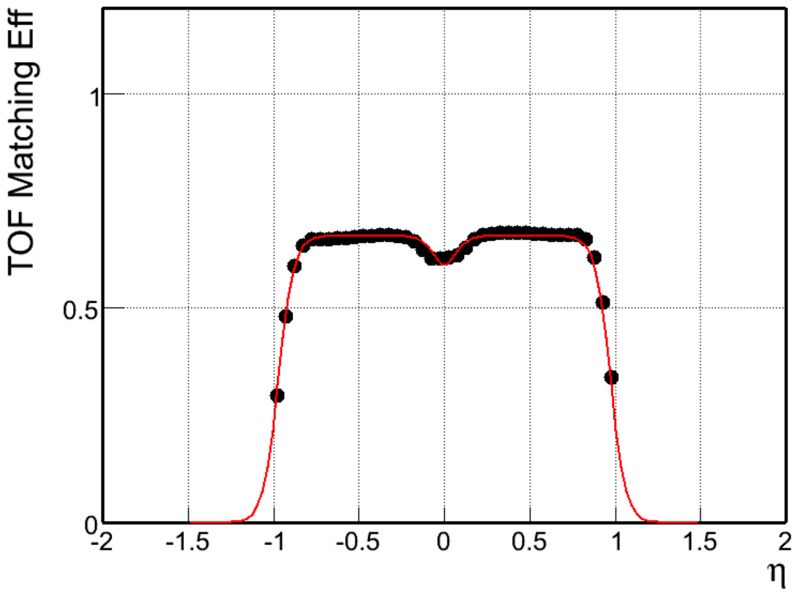


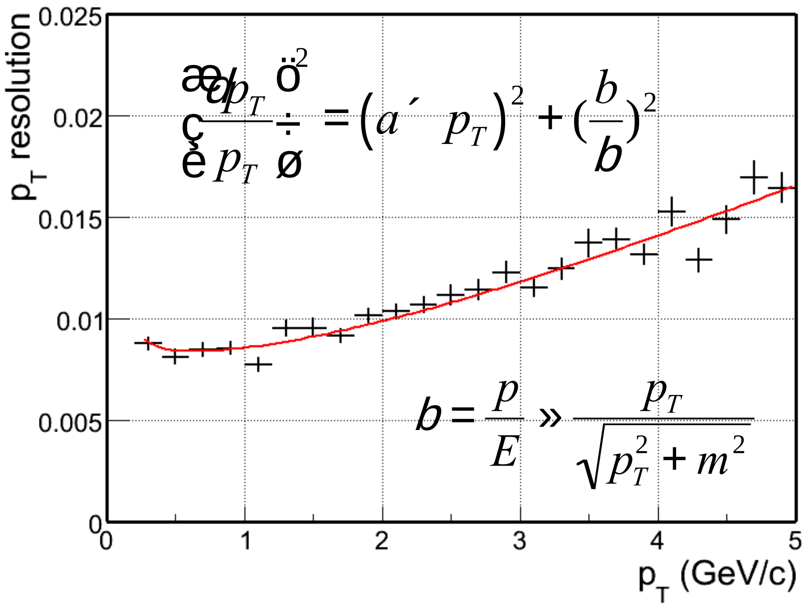
Higher energy =>
larger initial temperature
longer evolution time.

Detector acceptance and response

To compare the calculation with measurement, we have to also consider:

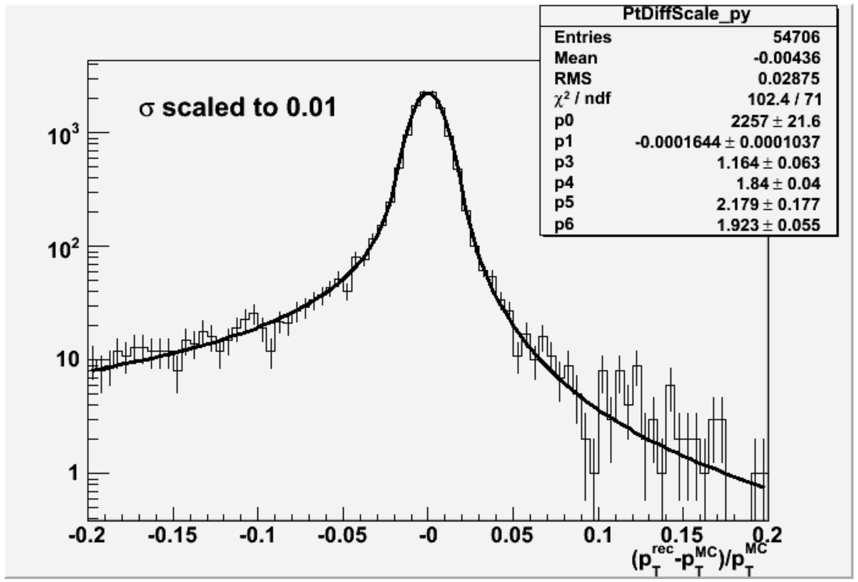
- Detector acceptance
- Mass/momentum resolution
- Electron bremsstrahlung.





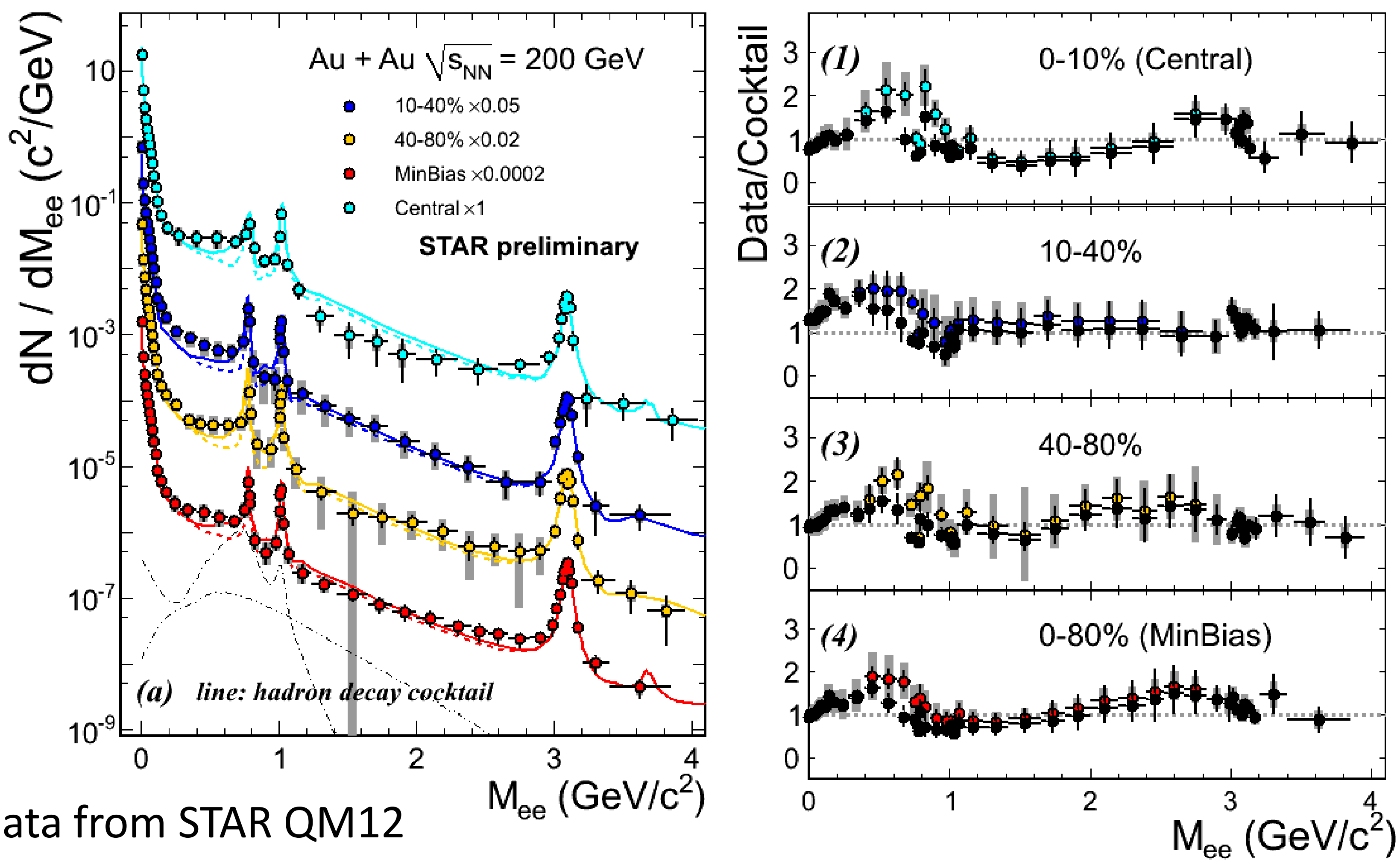
$$\left(\frac{\delta p_T}{p_T}\right)^2 = (a \times p_T)^2 + \left(\frac{b}{\beta}\right)^2$$

$$\beta = \frac{p}{E} \approx \frac{p_T}{\sqrt{p_T^2 + m^2}}$$



Double-crystal-ball function for energy loss

Di-electron production in Au+Au 200 GeV

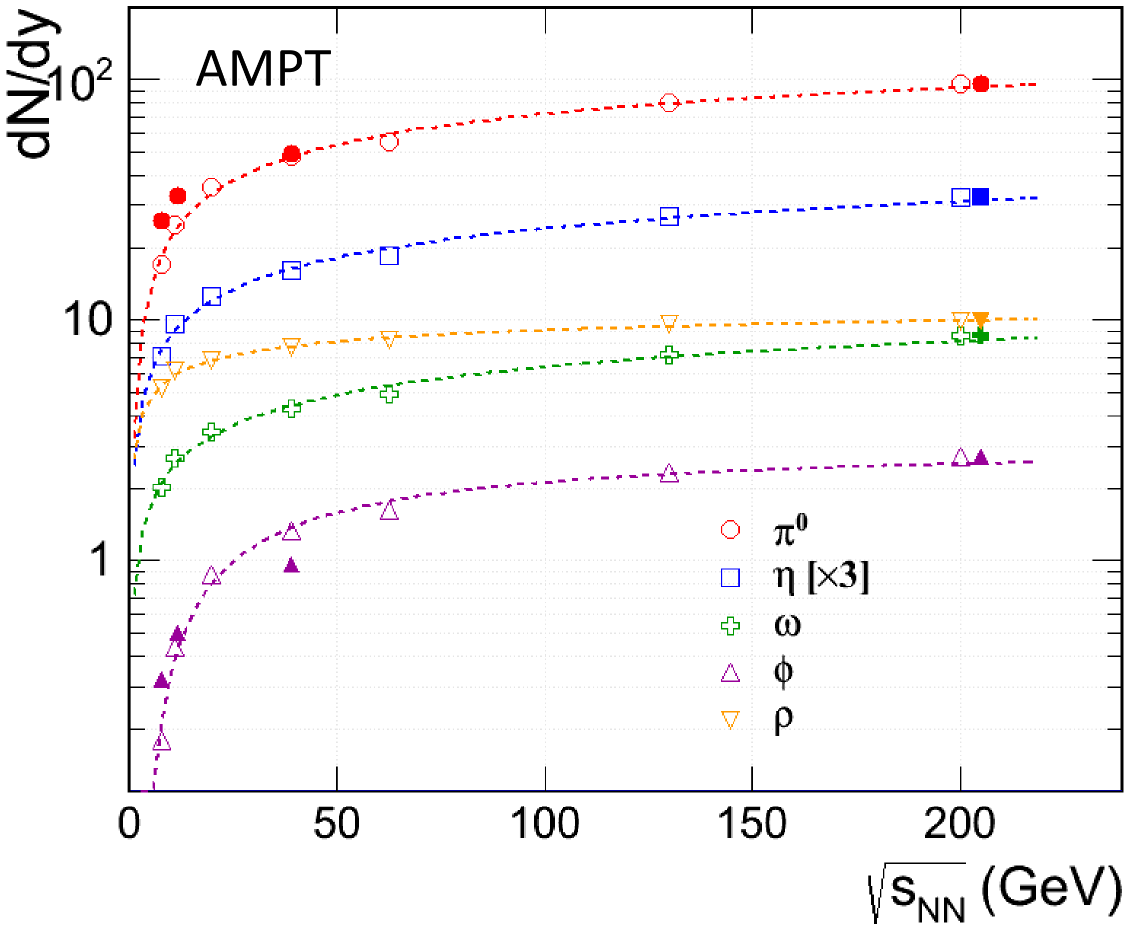


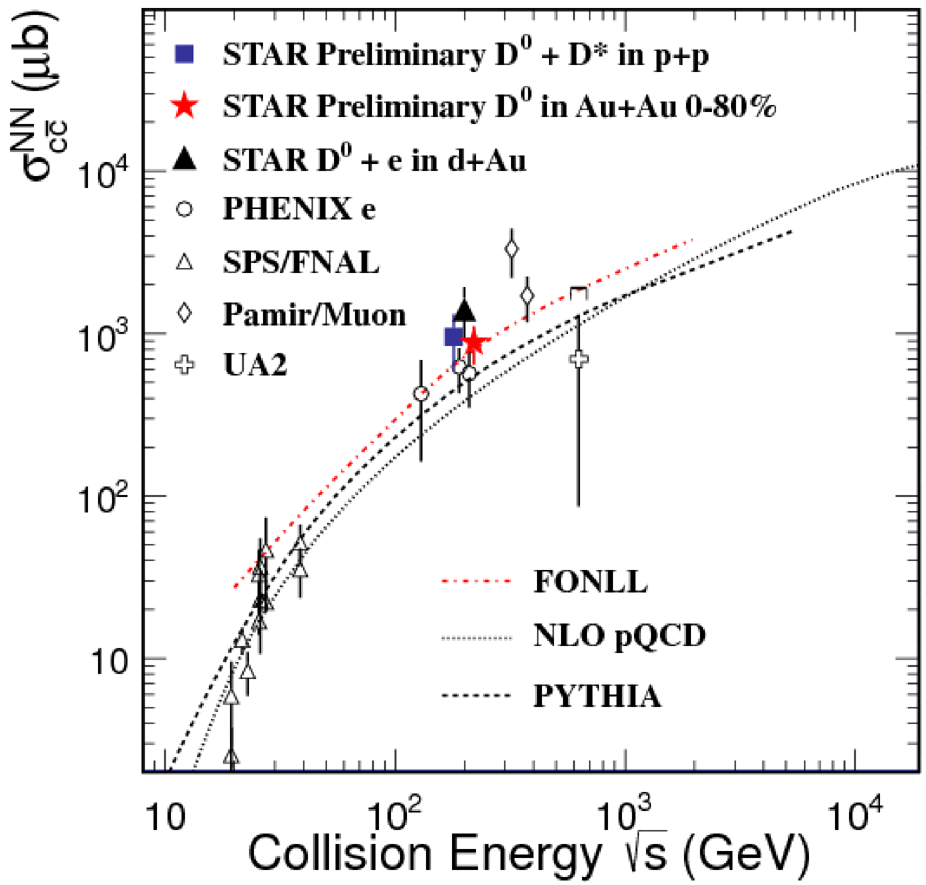
Data from STAR QM12

- ✧ LMR Enhancement compare with cocktail w/o ρ. Weak centrality dependence.
- ✧ In-medium ρ plays important role, data over cocktail w/ ρ are more close to 1.

Extrapolation to lower energies

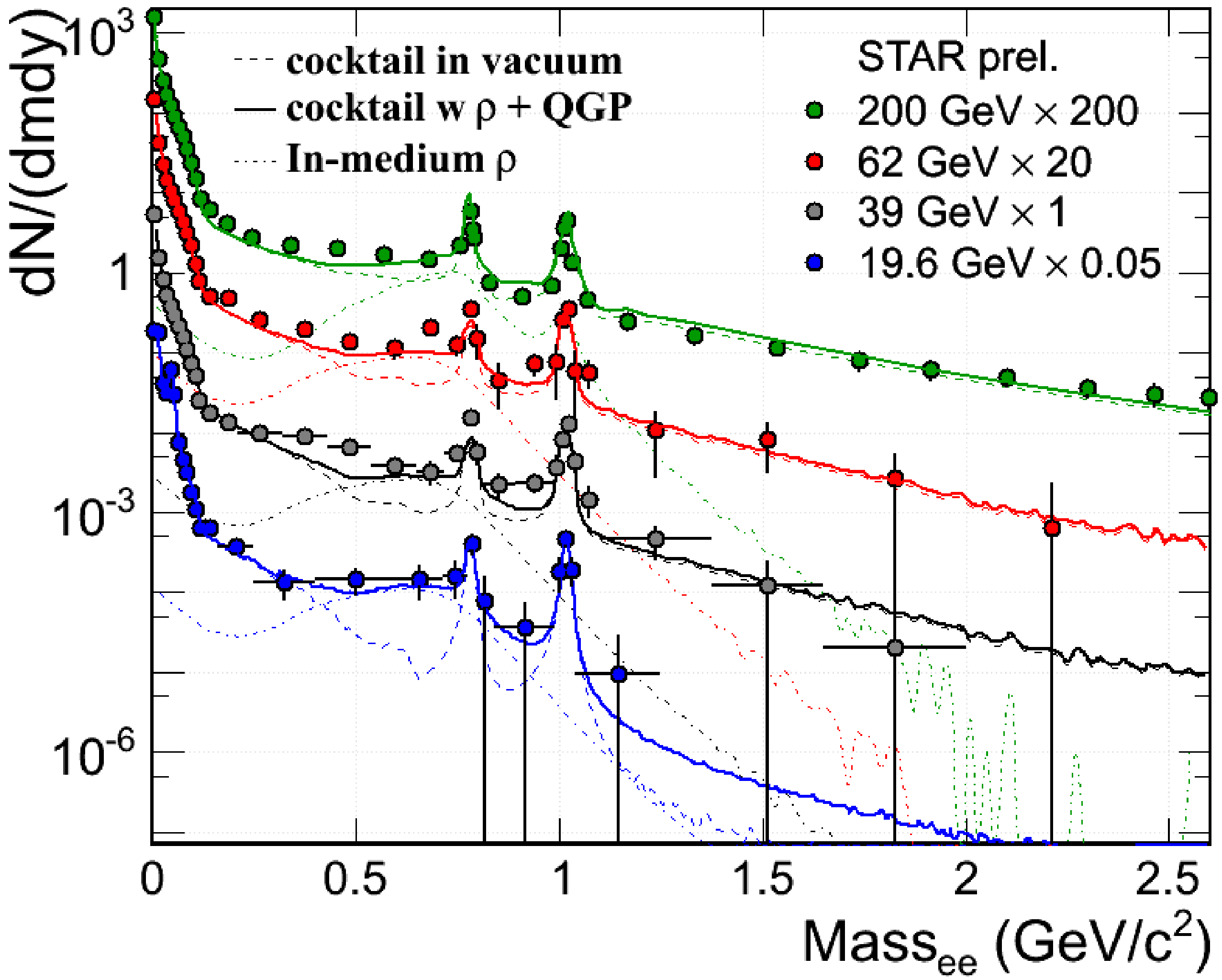
dN/dy and p_T distributions from AMPT calculations.
Charm cross section: NLO calculation for low energies.





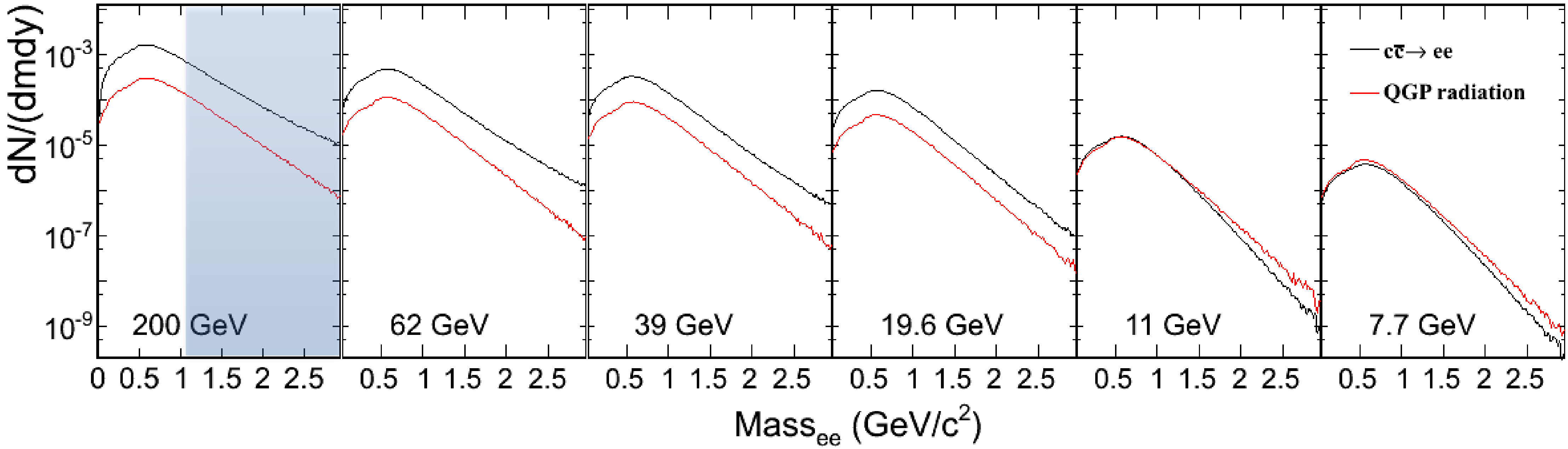
Scale to measurements at 200 GeV (solid symbols), some difference at lower energy.

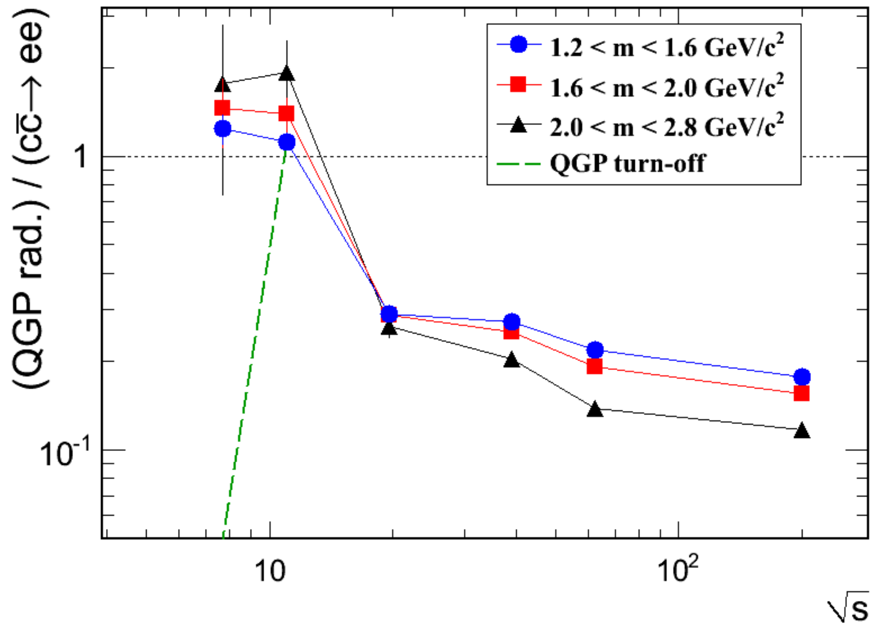
Di-lepton production at lower energies



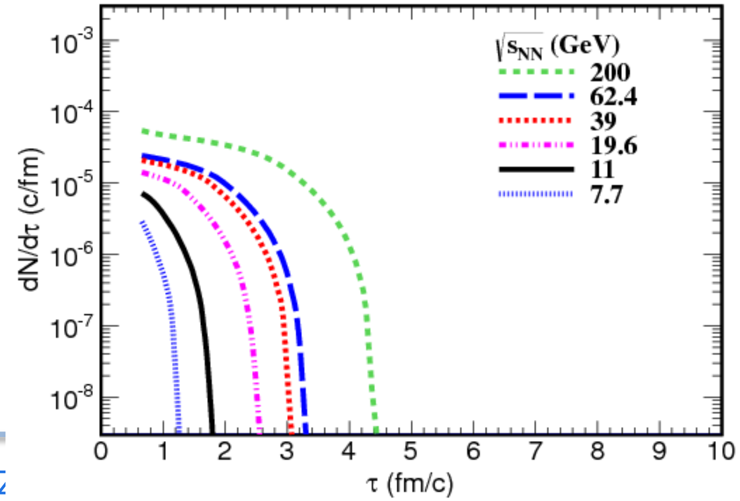
- RHIC BES Program: explore LMR down to SPS energy.
- Observed low-mass enhancement in all energies.
- In-medium ρ w/ finite baryon density describe LMR enhancement well.

IMR signal / background

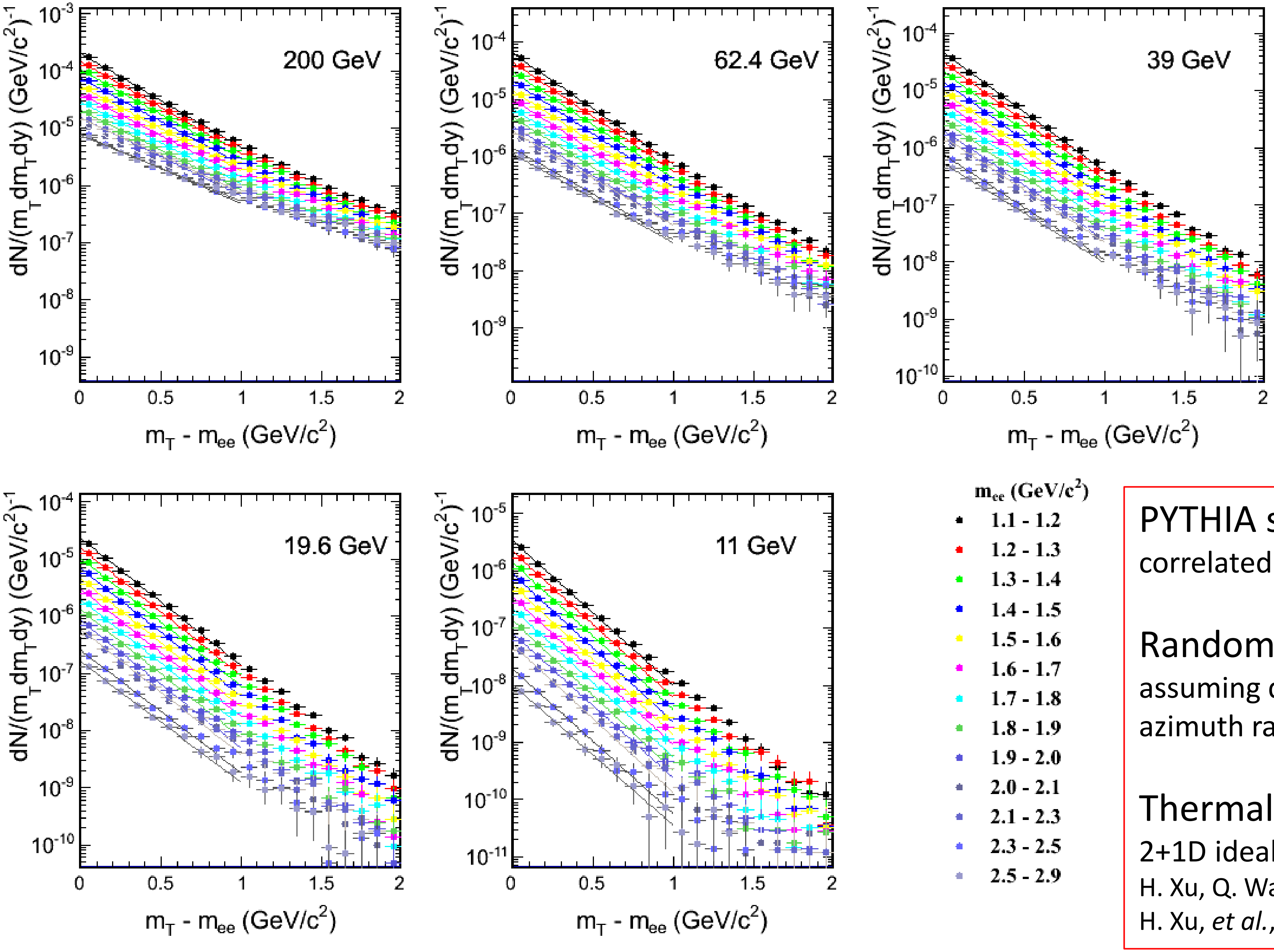




- ✧ Signal / b.g. ratio is ~ a few percent in higher energies.
- ✧ Signal enhanced in lower energy, relative large emission rate even for a short-lived QGP system.
- ✧ Test possible phase transition.



m_T slope of in the IMR

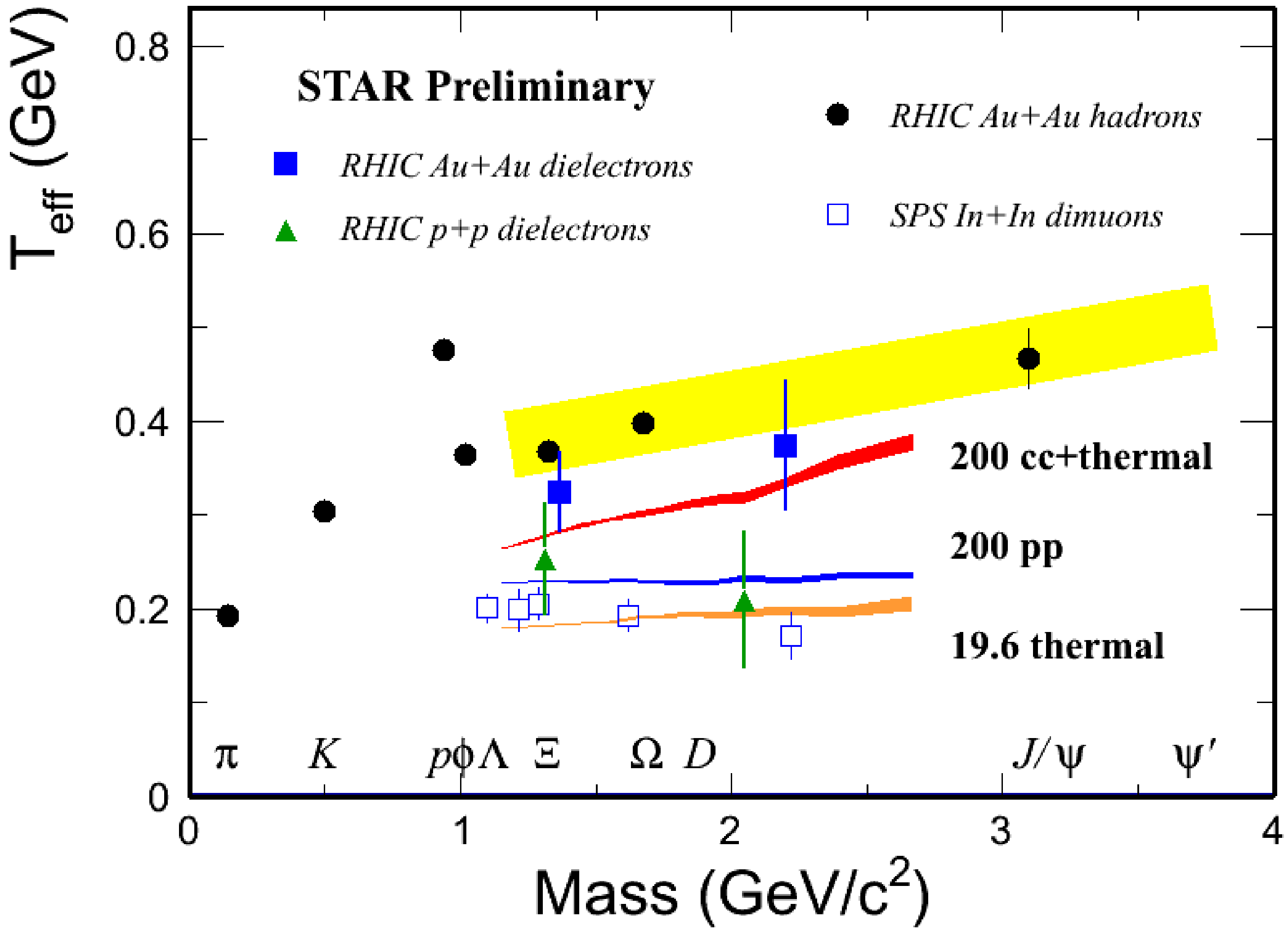


PYTHIA simulation:
correlated charm at BES energies.

Random Phase-space:
assuming decay daughters azimuth randomly washed out.

Thermal:
2+1D ideal hydro
H. Xu, Q. Wang (priv. comm).
H. Xu, *et al.*, PRC 85 024906 (2012).

m_T slope of in the IMR



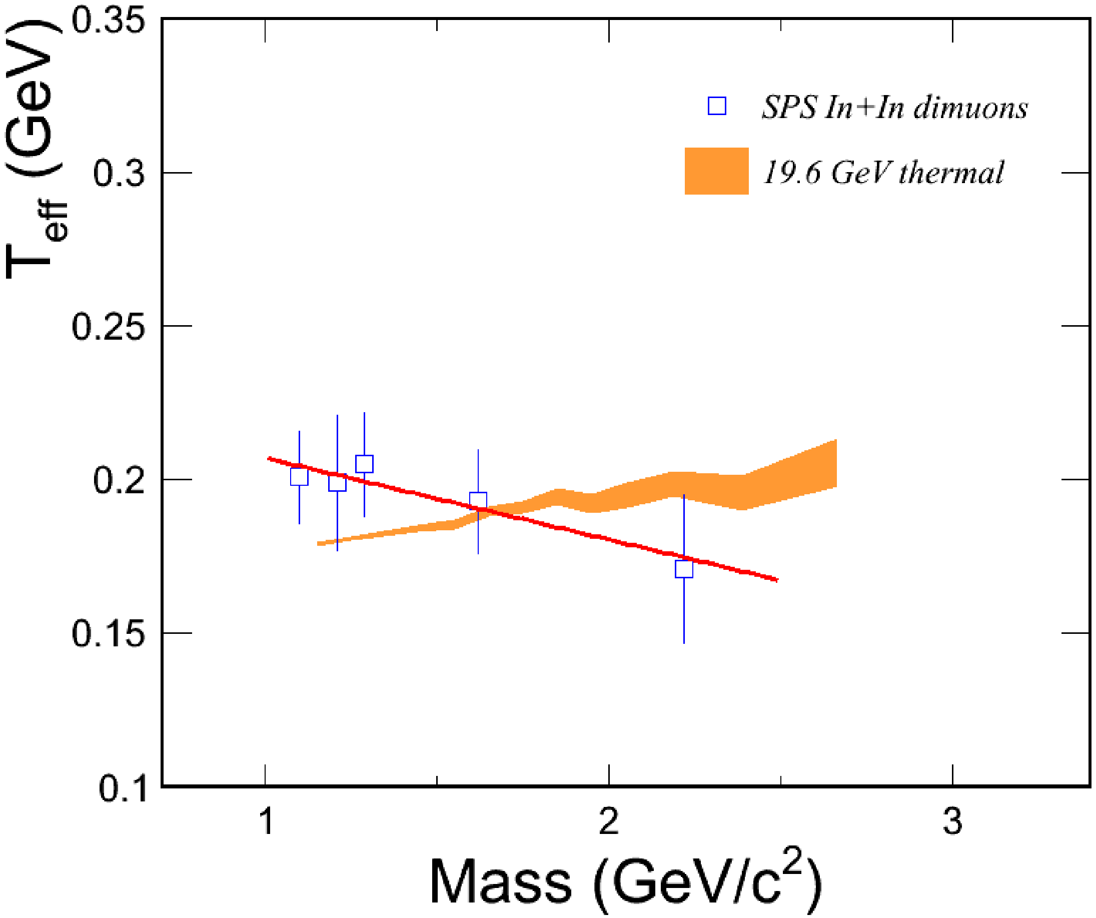
Y. Zhang CPOD2011

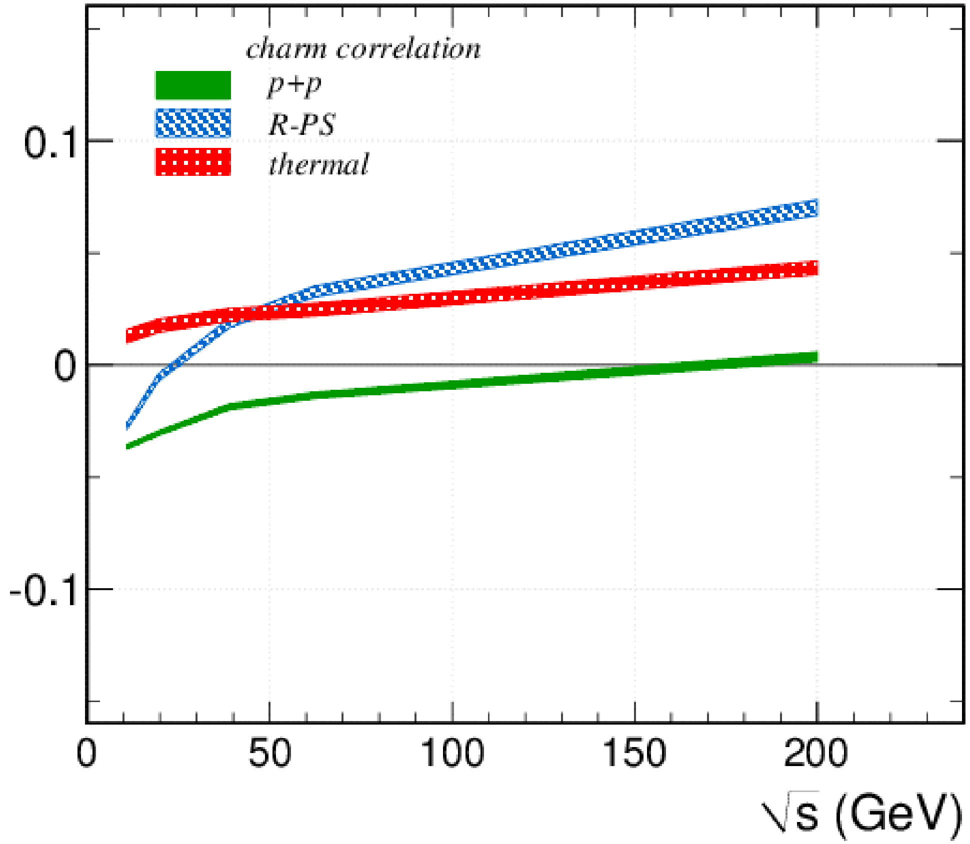
Within errors 19.6 GeV agrees with NA60 (~17 GeV), seems opposite trend.

Charm correlation in p+p is consistent with STAR p+p data (QM11).

Charm correlation modified by medium. Thermal + charm reproduce STAR Au+Au data well.

Possible observation at phase transition?



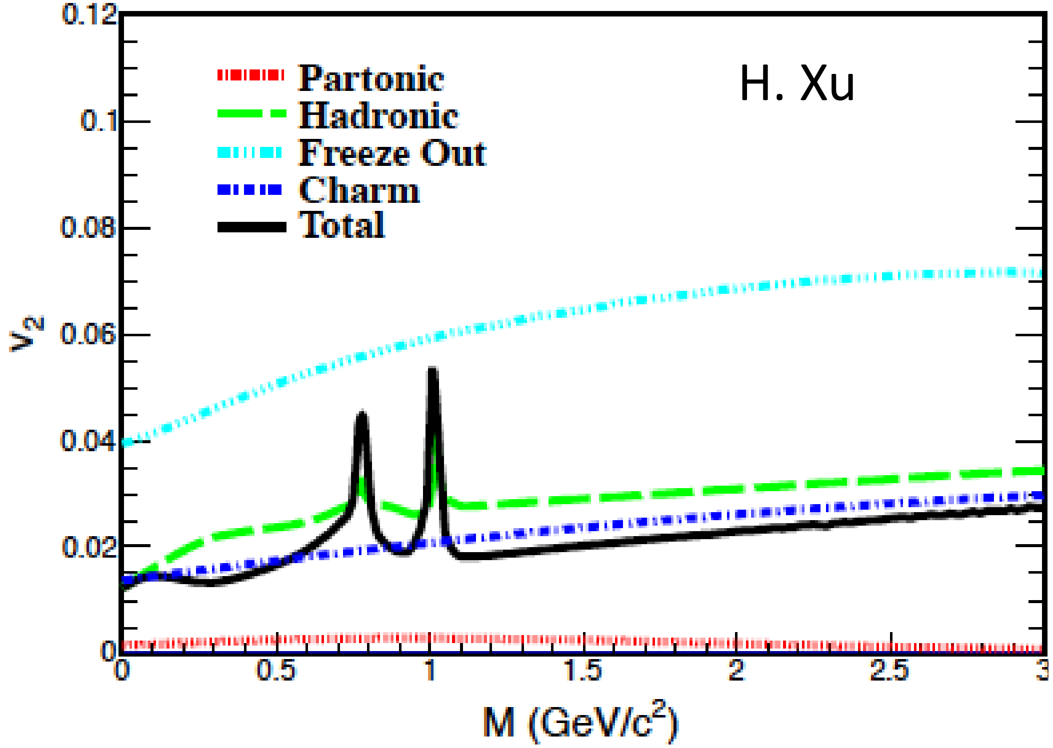


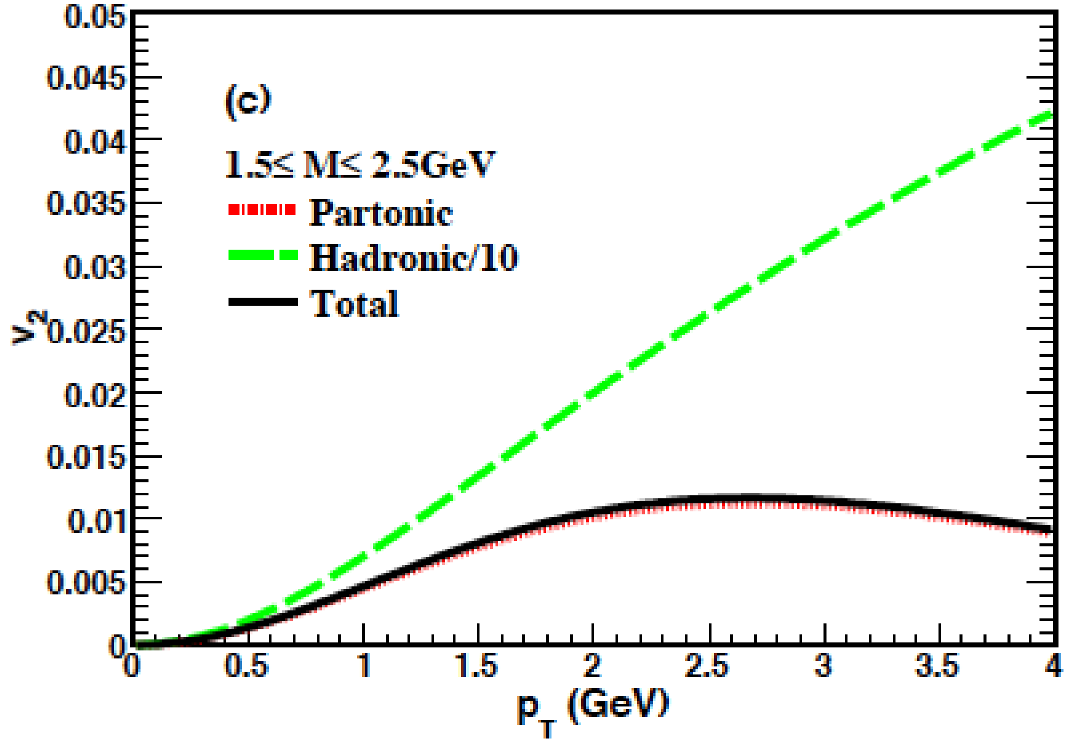
High energy dominant by charm correlation, lower energy charm and thermal contributions are comparable.

Both T_{eff} and its slope in medium are significant higher than the system w/o medium.

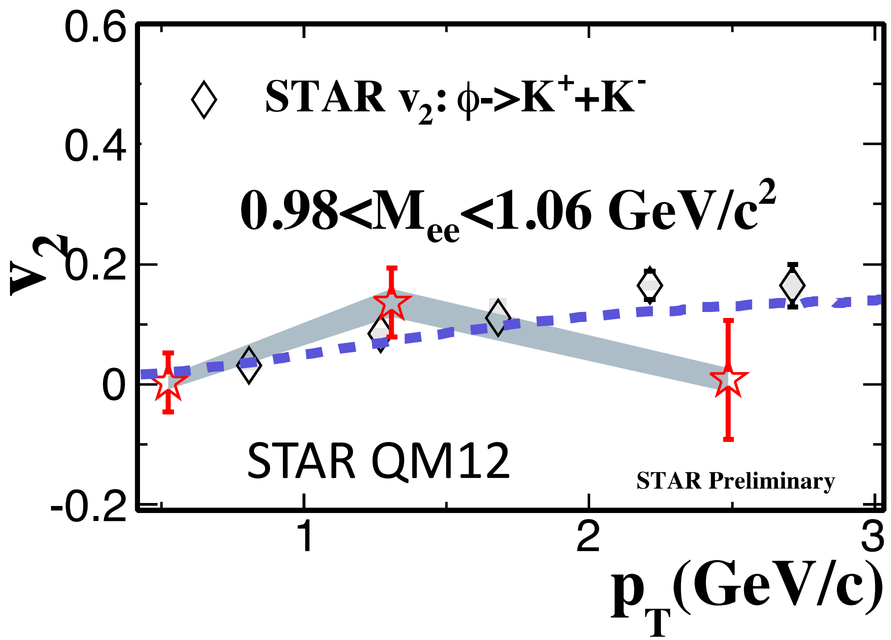
Phase transition could happen if the T_{eff} increases dramatically or the sign of its slope changes from negative to positive.

Di-electron v_2





- Sensitivity to separate hadronic/partonic.
- Experimental data $M_{ee} < \sim 1$ GeV/c, expecting more statistics + upgrade for IMR and high p_T.



Summary

- Experimental data shows LMR enhancement compared with vacuum cocktails.

  - In-medium ρ broadening explains the enhancement reasonably for each RHIC BES energies from 19.6 to 200 GeV.

- IMR QGP radiative signals may enhanced over correlated charm background in lower energy.

  - Future detector upgrades will also help for background suppression.

  - May be sensitive to the possible phase transition.

- IMR slope with naïve assumption seems agree with data reasonably for both SPS and RHIC energies.

- Di-lepton v_2 is ideal probe for distinguish partonic/hadronic processes.

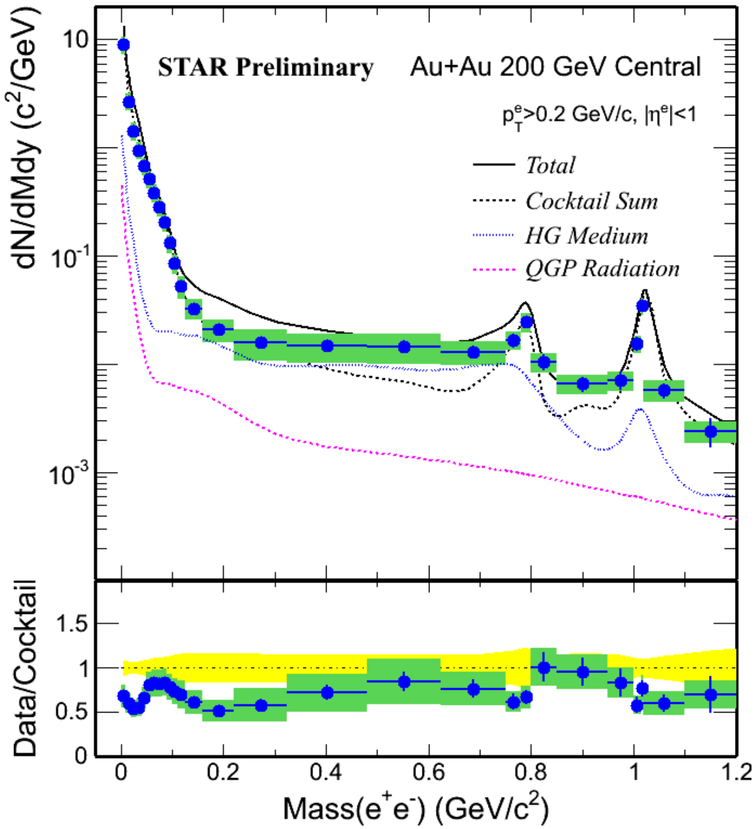
  - High sensitivity at IMR and large p_T.

  - Need future experimental data for comparison.

Looking forward to BES Phase-II and increasing luminosity of RHIC runs.

Backup Slides

LMR compare with models (I)



Ralf Rapp (priv. comm.)

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

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

Complete evolution:

Cocktail (in vacuum) + HG + QGP =>

- ρ "melts" when extrapolated close to phase transition boundary.
- agreement w/in uncertainties.

H. Xu, Q. Wang (priv. comm.)

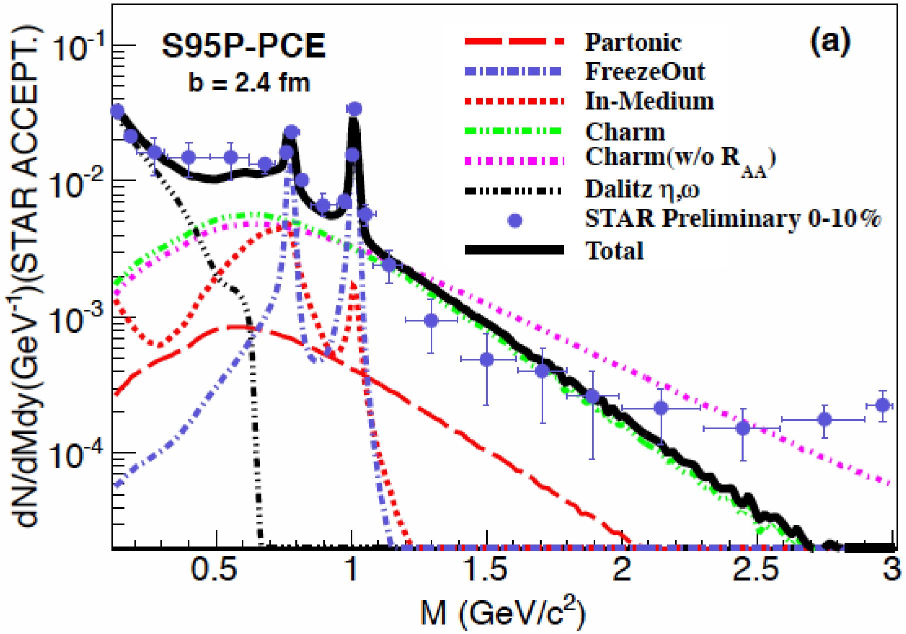
H. Xu, *et al.*, Phys. Rev. C 85 024906 (2012).

In-medium ρ: Multi-body effective theory

Partonic (QGP): 2+1D ideal hydro

FreezeOut + IM + QGP =>

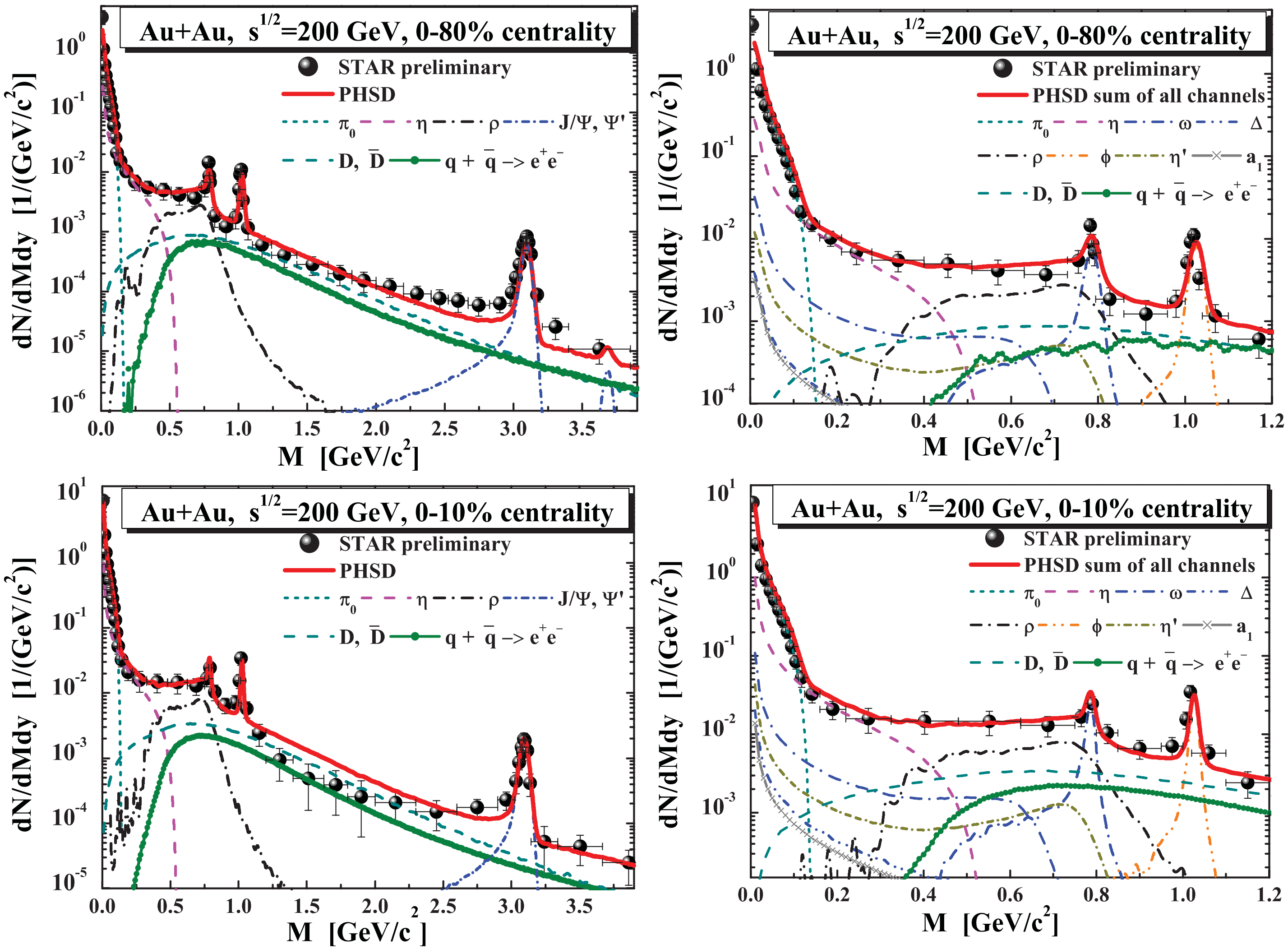
- agree w/in uncertainties.



LMR compare with models (II)

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

Parton-Hadron String-Dynamics



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

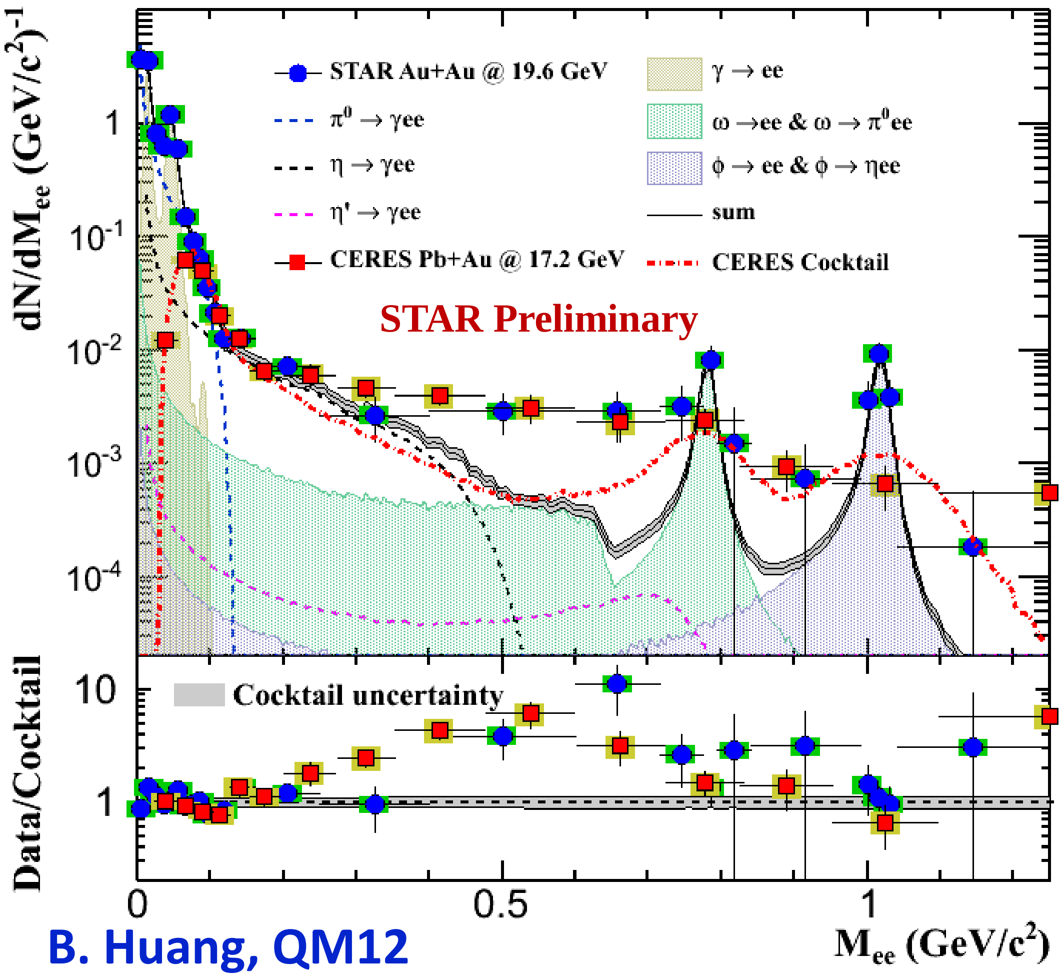
Minimum bias collisions (0-80%):

- Generally good agreement

Central collisions (0-10%):

- PHSD roughly in line with LMR region
- Similar as STAR cocktail, overshot IMR.

Compare with SPS energy



B. Huang, QM12

Enhancement factor	$0.2<M_{ee}<0.6$ GeV/c^2
STAR	$1.9 \pm 0.6 \pm 0.4$
CERES	$2.73 \pm 0.25 \pm 0.65 \pm 0.82$[decays]

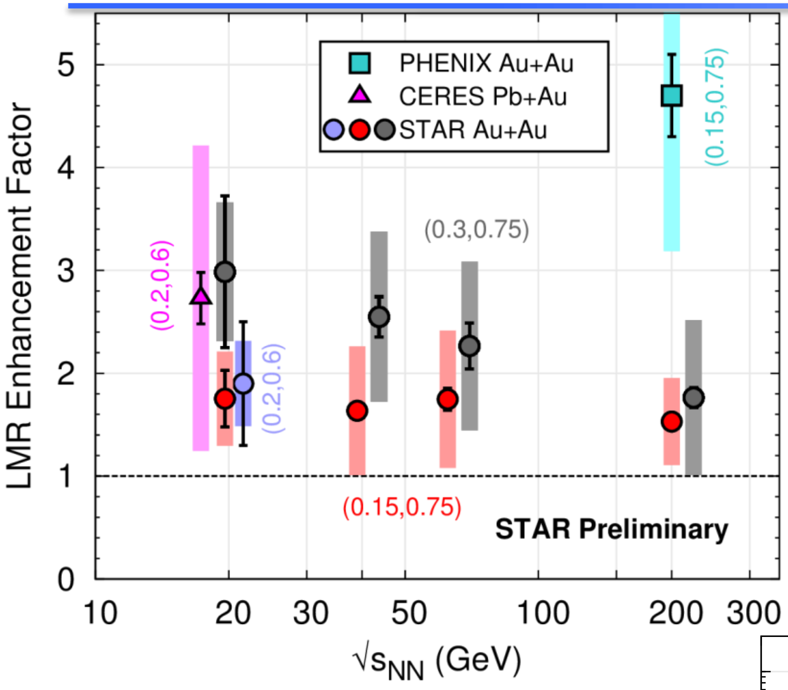
- π yield is from STAR π^{+-} measurement, other meson yields derived from SPS meson/π^0 ratio.

➢ Different centrality & acceptance:
- STAR Au+Au:
  0-80% centrality
  $p_T>0.2$ GeV/c, $|\eta|<1$, $|y_{ee}|<1$.
- CERES Pb+Au:
  0-28% centrality.
  $p_T>0.2$ GeV/c, $2.1<\eta<2.65$, $\theta_{ee}>35$mrad.

➢ Different detector resolution.

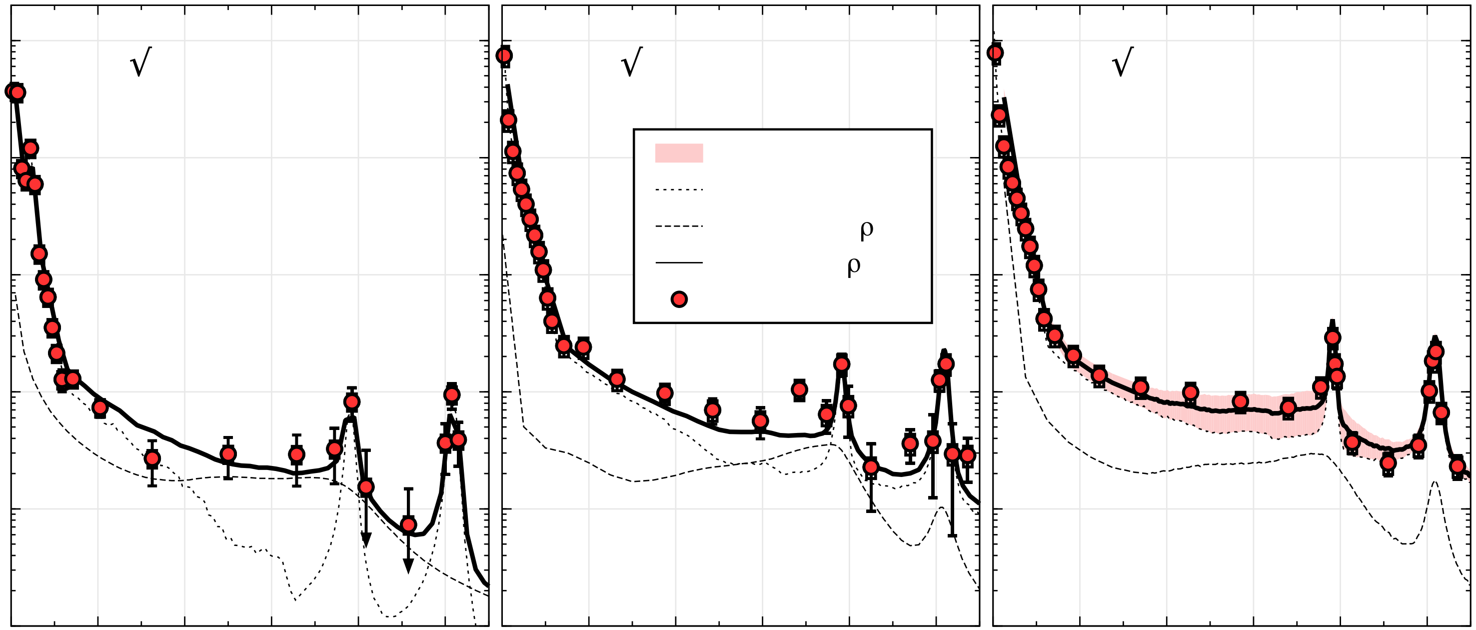
Low mass enhancement comparable to CERES w/in uncertainties.

LMR enhancement vs. collision energies



- LMR enhancement factor shows no significant energy dependence from 19.6 to 200 GeV.

- Theoretical calculations of in-medium ρ broadening with total baryon density from 19.6-200 GeV reproduce LMR excesses.



by Ralf Rapp (priv. comm.)

Adv. Nucl.Phys. 25, 1 (2000)
arXiv:nucl-th/0204003v1

In-vacuum rho line shape

$$\frac{dN}{dm_{ee}dp_T} \propto \frac{m_{ee}M_\rho\Gamma_{ee}}{(M_\rho^2 - m_{ee}^2)^2 + M_\rho^2(\Gamma_{\pi\pi} + \Gamma_{ee}\Gamma_2)^2} \times PS,$$

ρ line shape:

P-wave of ππ channel: $$\Gamma_{\pi\pi} = \Gamma_0 \frac{M_\rho}{m_{ee}} \left(\frac{m_{ee}^2 - 4M_\pi^2}{M_\rho^2 - 4M_\pi^2}\right)^{3/2},$$

S-wave of ee channel: $$\Gamma_{ee} = \Gamma_0 \frac{M_\rho}{m_{ee}} \left(\frac{m_{ee}^2 - 4m_e^2}{M_\rho^2 - 4m_e^2}\right)^{1/2},$$

PRC 78, 044906 (2008)
PRC 86, 024906 (2012)

$$PS = \frac{m_{ee}}{\sqrt{m_{ee}^2 + p_T^2}} e^{-\frac{\sqrt{m_{ee}^2 + p_T^2}}{T}}.$$