QGP Physics − From Fixed Target to LHC

10. Thermal Photons and Dileptons

Prof. Dr. Johanna Stachel, PD Dr. Klaus Reygers
Physikalisches Institut
Universität Heidelberg
SS 2011

Motivation for Measuring Direct Photons in Heavy-Ion Collisions

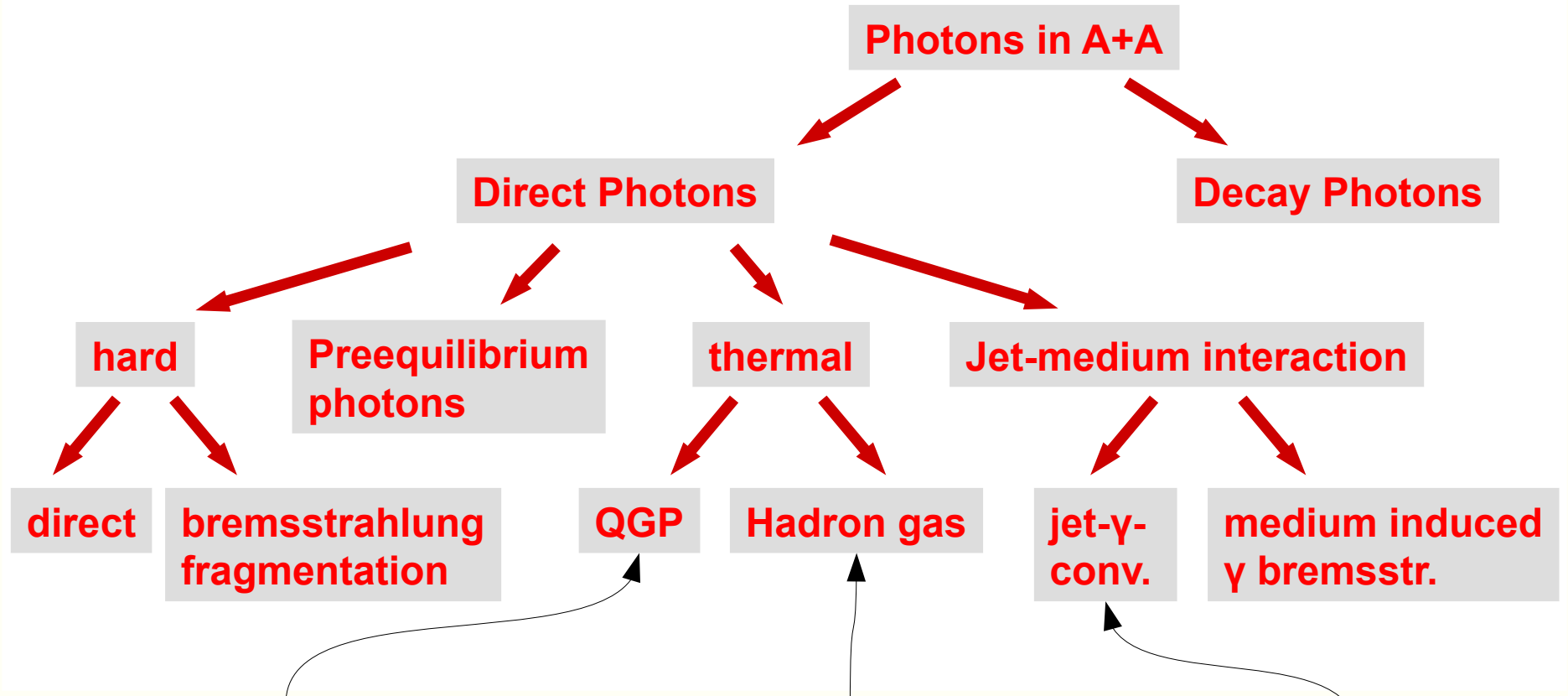
High p_T (> 6 GeV/c):

- High-p_T direct photons produced in initial hard parton-parton scatterings
- Photons leave the subsequently produced medium (quark-gluon plasma !?) unaltered
- Test hard scattering predictions
- Measure rate of hard processes

Low / Intermediate p_T:

- Low p_T thermal direct photons expected to reflect the initial temperature of the thermalized fireball
- Temperatures above T_c indicate quark-gluon plasma phase
- Search for evidence for jet-plasma interactions?

Known and Expected Photon Sources

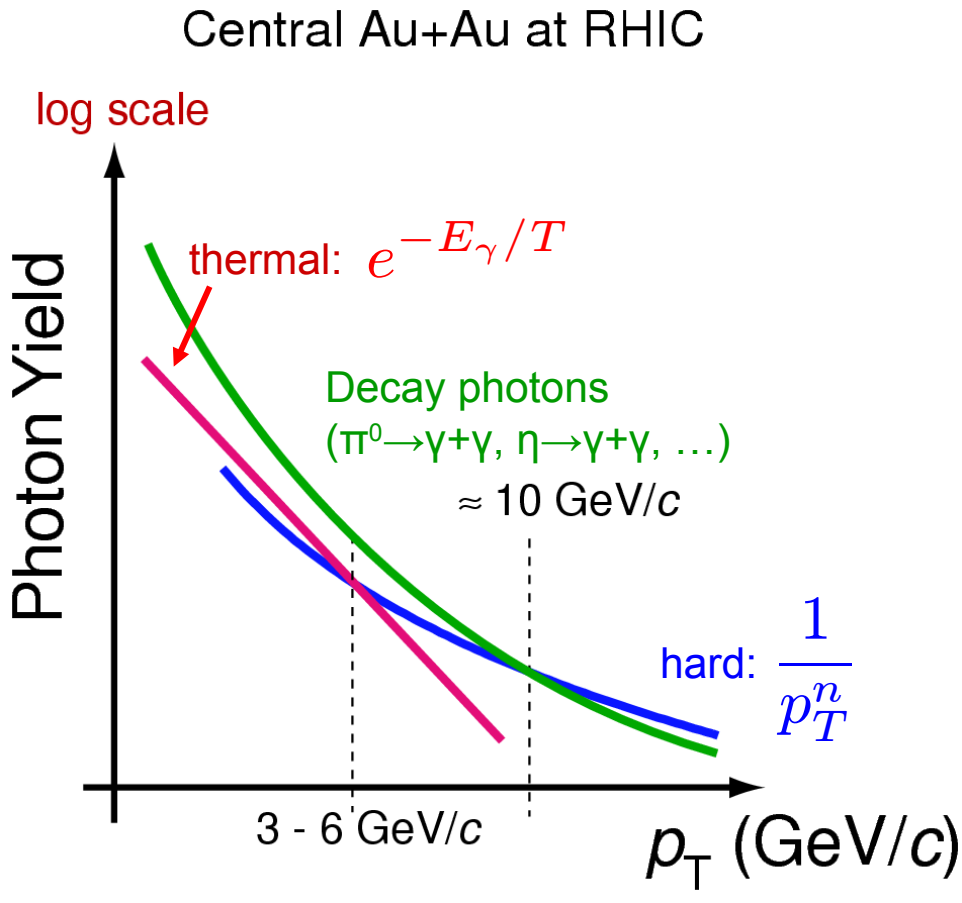


$$\text{e.g.}: g + q_{\text{QGP}} \rightarrow q + \gamma$$

gluon jet

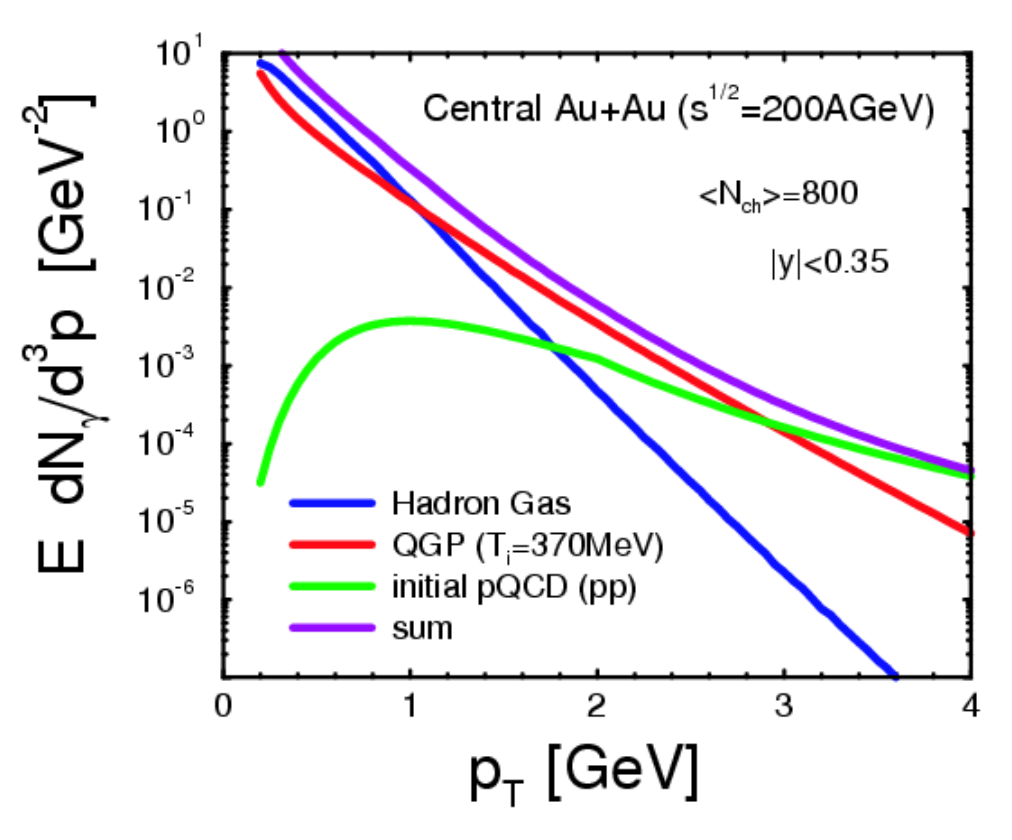
$$\sigma_{jet(q)\rightarrow\gamma(p)} \propto \delta(q-p)$$

Schematic Photon Spectrum in A+A



- Thermal photons expected to be significant contribution below p_T ~ 3 GeV/c
- Hard photons dominant direct photon source for p_T > ~ 6 GeV/c
- Jet-photon conversion might be significant contribution below p_T ~ 6 GeV/c

Calculation: Sources of Direct Photons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV



Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

Window for thermal photons from QGP in this calculation: p_T = 1 - 3 GeV/c

Direct Photons in A+A Collisions: Measurements

- So far (2011) only two measurements
  - Central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 17.3 GeV (WA98)
  - Central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)

- After an photon excess has been established experimentally, one needs to figure out whether there is a contribution from thermal direct photons. This needs theoretical guidance.

- Methods:
  - Measure photons with electromagnetic calorimeter (WA98, PHENIX)
  - Measure virtual photons ($\gamma^* \rightarrow e^+e^-$),

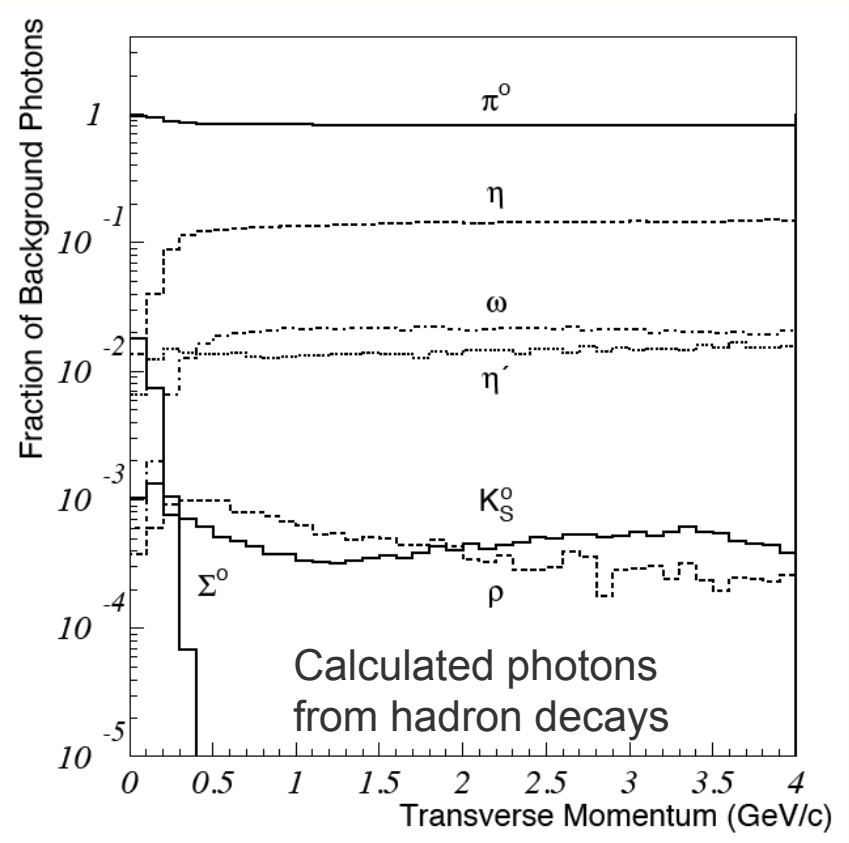
    and assume $\left.\frac{\gamma_{\mathrm{direct}}}{\gamma_{\mathrm{inclusive}}} = \frac{\gamma^*_{\mathrm{direct}}}{\gamma^*_{\mathrm{inclusive}}}\right|_{m_{ee}<30\ \mathrm{MeV}}$ (PHENIX)

Subtraction Method

WA98, nucl-ex/0006007 (→ link)

Systematic uncertainties
partially cancel in this ratio

$$\gamma_{\mathrm{direct}} := \gamma_{\mathrm{inclusive}} - \gamma_{\mathrm{decay}} = (1 - \frac{1}{R_\gamma})\gamma_{\mathrm{inclusive}} \quad \text{with } R_\gamma = \frac{(\gamma_{\mathrm{inclusive}}/\pi^0)_{\mathrm{meas}}}{(\gamma_{\mathrm{decay}}/\pi^0)_{\mathrm{calc}}}$$

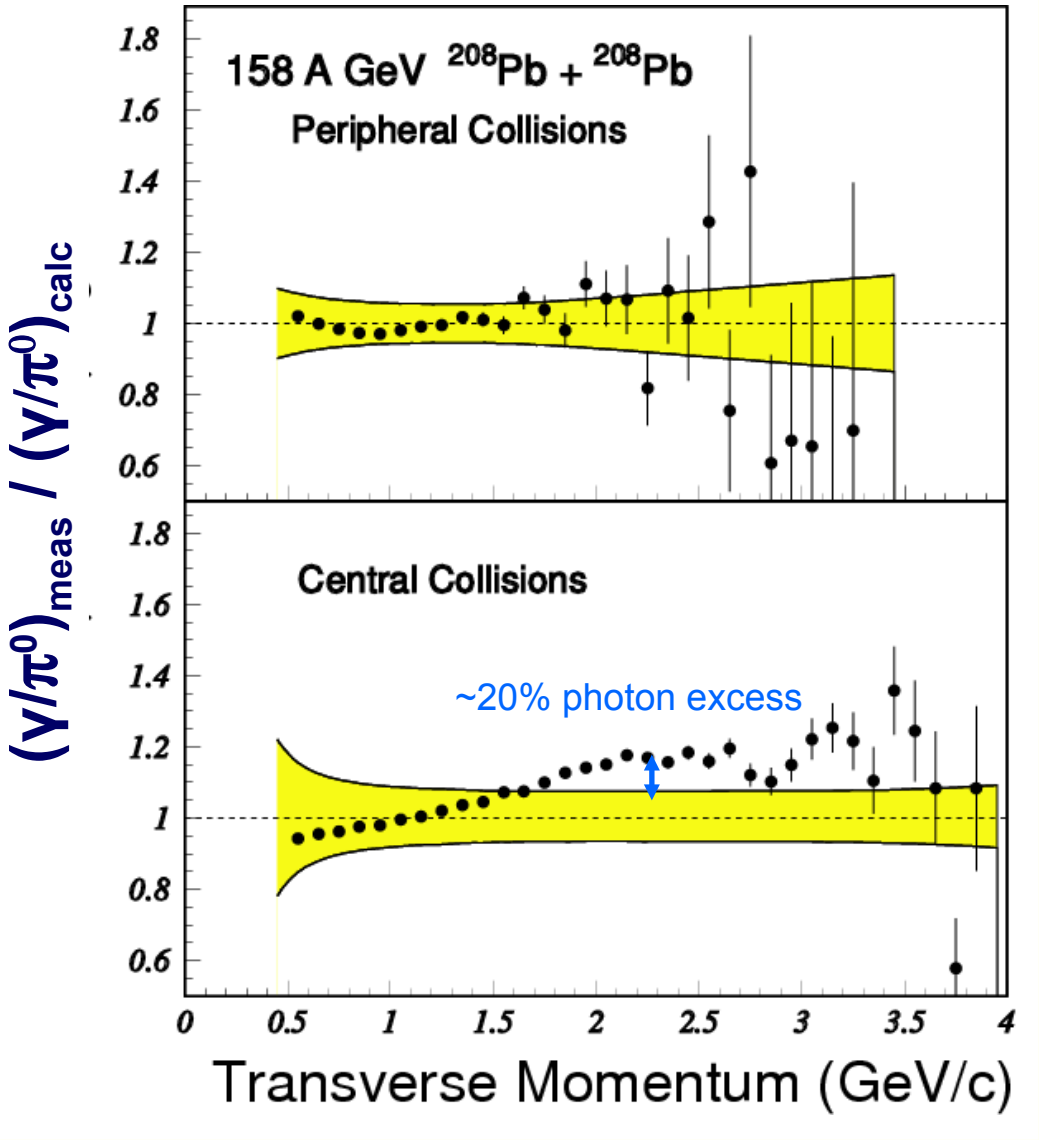


Based on the measured π^0 (and η) p_T spectrum, the expected decay photons are calculated (assuming m_T scaling for unmeasured particle species)

The double ratio *R* contains the statistical and systematic significance of the direct photon signal.

For the extraction of the direct photon spectrum, only systematic errors that canceled in the double ratio *R* need to be added

Direct Photon Measurement by WA98



- No signal in peripheral collisions
- 20% photon excess in central Pb+Pb collisions

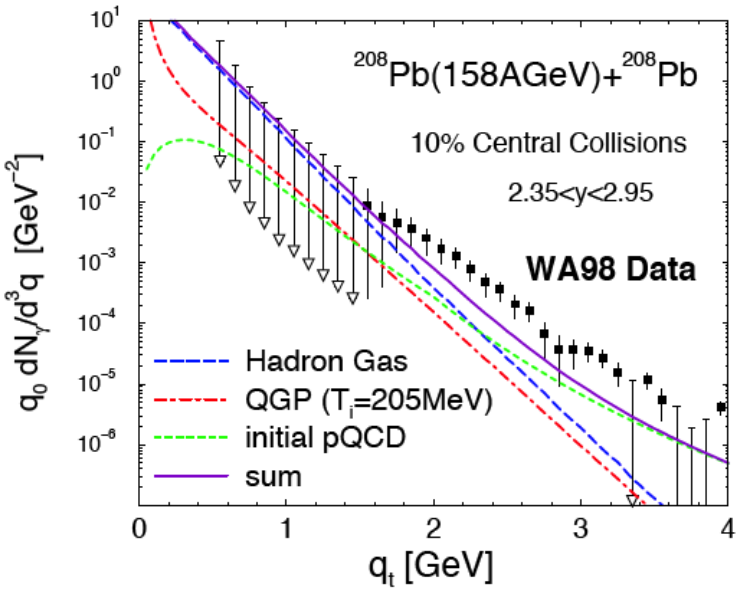
158 AGeV Pb + Pb:

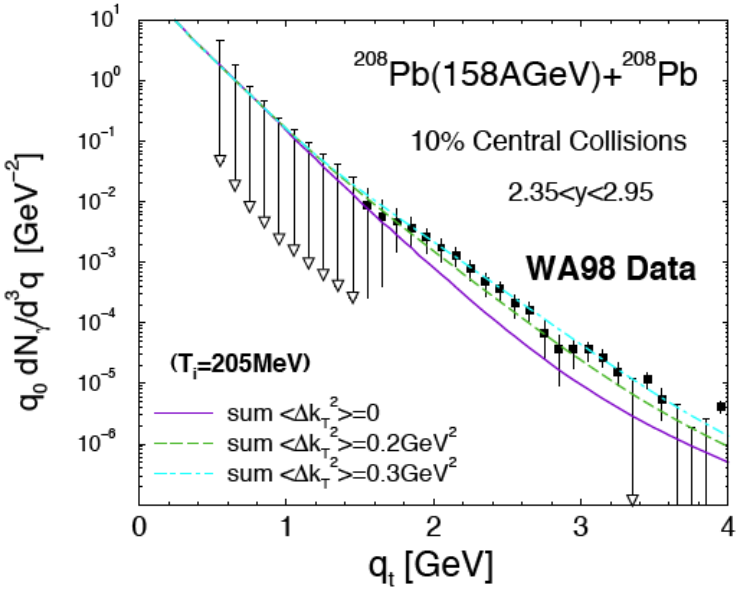
$$\sqrt{s_{NN}} = 17,3 \text{ GeV}$$

Phys.Rev.Lett.85:3595-3599,2000

Interpretation of the WA98 Data

Ch. Gale, arXiv:0904.2184 (→ link)





Theoretical ingredients:

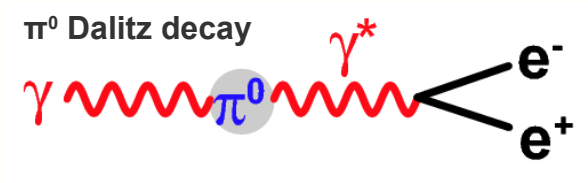
- (schematic) fireball evolution
- Photon emission rates from a gas of hadrons
- Photon emission rates from the QGP complete to lading order in α_s
- Estimate of the Cronin effect deduced from p+A collisions

Conclusions:

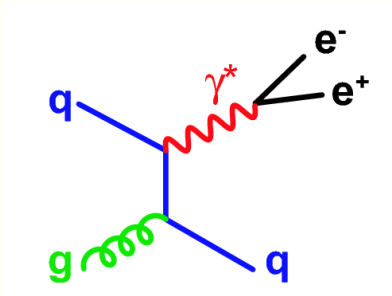
- Data consistent with QGP scenario ($T_i \approx 200 - 270$ MeV), however, QGP contribution is small
- Data also consistent with hadronic scenario (Cronin enhancement alone could explain the data)

Internal Conversion Method: How to Avoid the π^0 Background at the Expense of a Factor ~1000 in Statistics

- Internal conversion
  - Any source of real photons also emits virtual photons
  - Well known example:

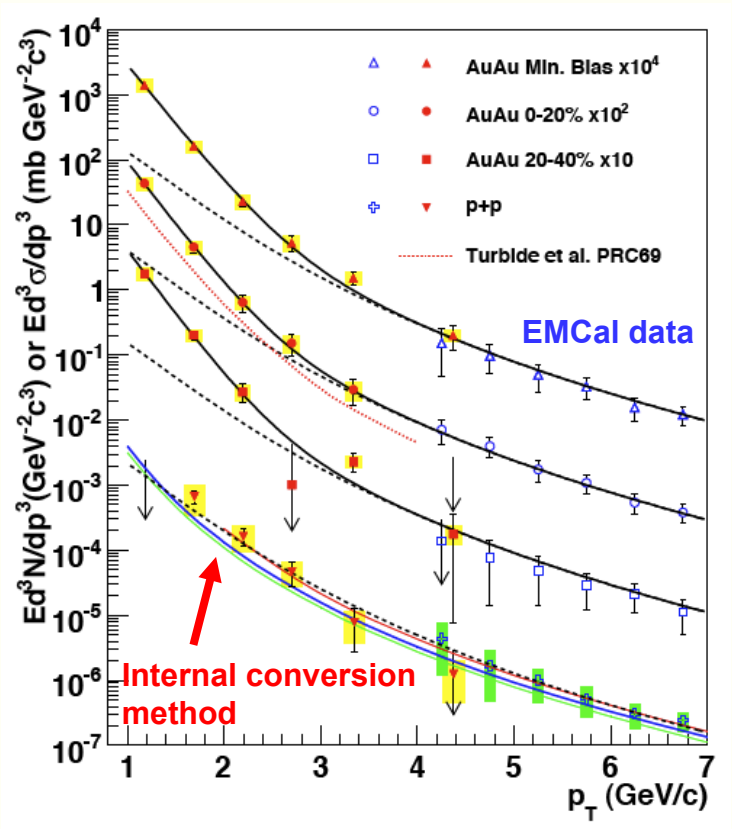


  - Rate and m_{ee} distribution calculable in QED
    (Kroll-Wada formula, see next slide)
- Hadron decays: $m_{ee} < M_{hadron}$
- Essentially no such limit for point-like processes



- Motivation
  - Measure direct photons where thermal photons dominate and calorimeter measurements are difficult

PHENIX, arXiv:0804.4168v1



More Details on the Internal Conversion Method: Kroll-Wada Formula

Number of virtual photons per real photon (in a given $\Delta\eta\,\Delta\varphi\,\Delta p_T$ interval):

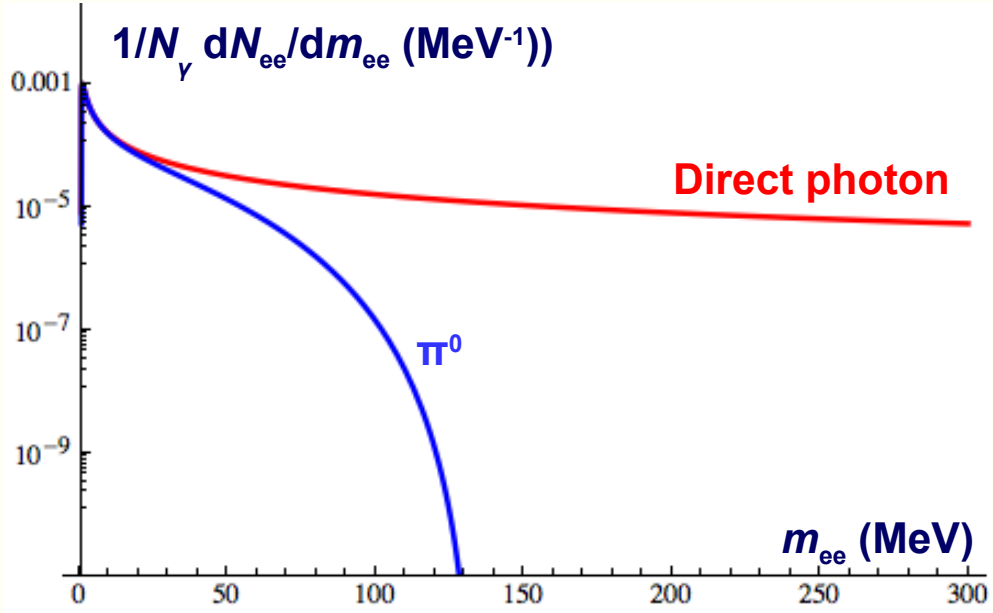
$$\frac{1}{N_\gamma}\frac{\mathrm{d}N_{ee}}{\mathrm{d}m_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

Hadron decay:

$$S = \underbrace{|F(m_{ee}^2)|^2}_{\text{form factor}}\underbrace{(1-\frac{m_{ee}^2}{M_h^2})^3}_{\text{phase space}}$$

Point-like process:

$$S = \underbrace{1}_{\text{holds for } p_{T,ee} >> m_{ee}}$$



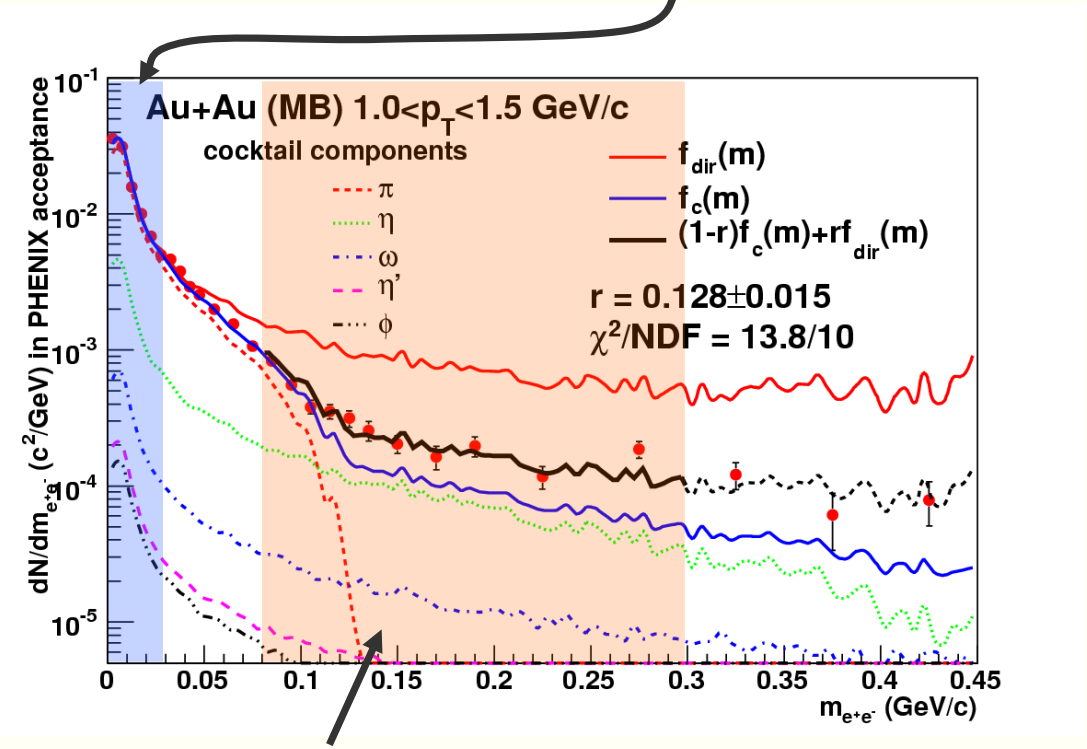
PHENIX measurement:
$80 < m_{ee} < 300$ MeV

→ **There are 0.002 e+e- pairs with $80 < m_{ee} < 300$ MeV for every real photon**

Extraction of the Direct Photon Signal: Two-Component Fit

$$f(m_{ee}) = (1 - r) \cdot f_{\text{cocktail}}(m_{ee}) + r \cdot f_{\text{direct}}(m_{ee})$$

Separately normalized to data at m_{ee} < 30 MeV



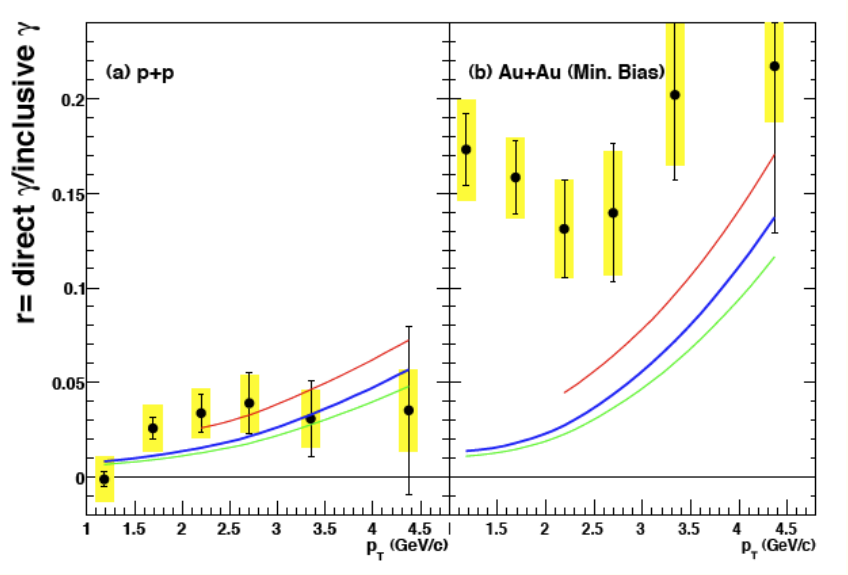
Fit range: 80 < m_{ee} < 300 MeV

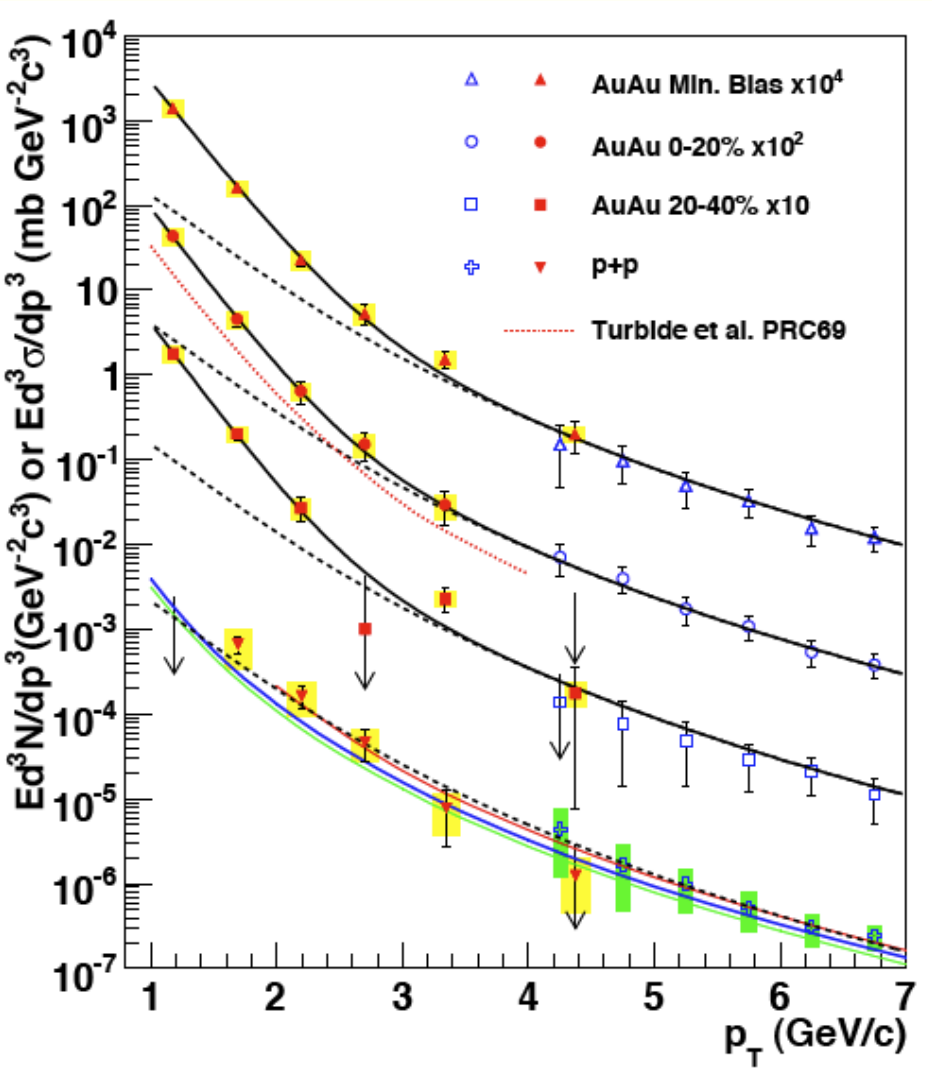
- Interpret deviation from hadronic cocktail (π^0, η, ω, η', φ) as signal from virtual direct photons
- Extract fraction *r* with two-component fit

$$r = \left. \frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}} \right|_{m_{ee}<30\ \text{MeV}}$$

- Fit yields good χ^2/NDF (13.8 / 10)

Internal Conversion Methods: Results





- Enhancement in Au+Au above p+p described by an exponential (as expected for a thermal source)

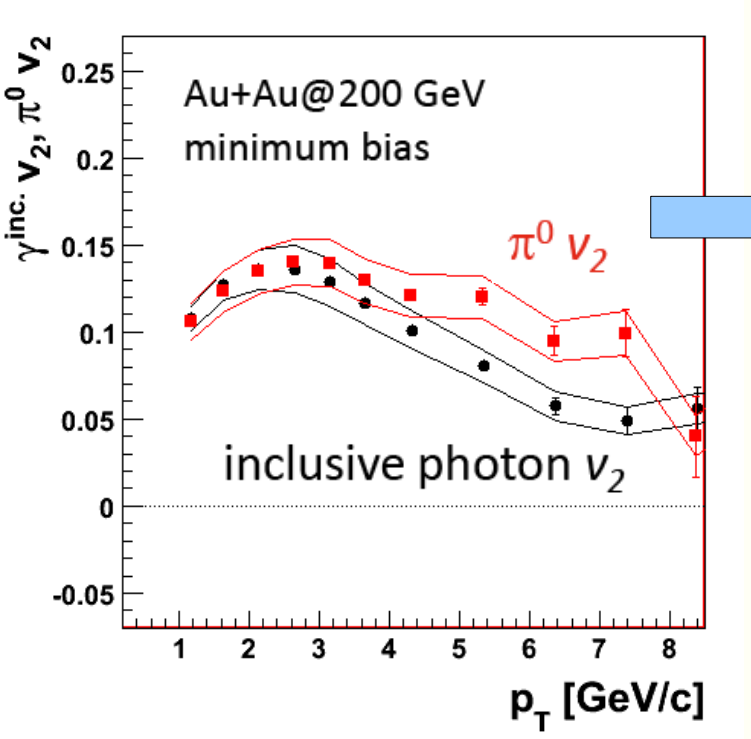
$$Y_{Au+Au} = N_{\mathrm{coll}} \cdot Y_{p+p} + A \cdot e^{-p_T/T}$$

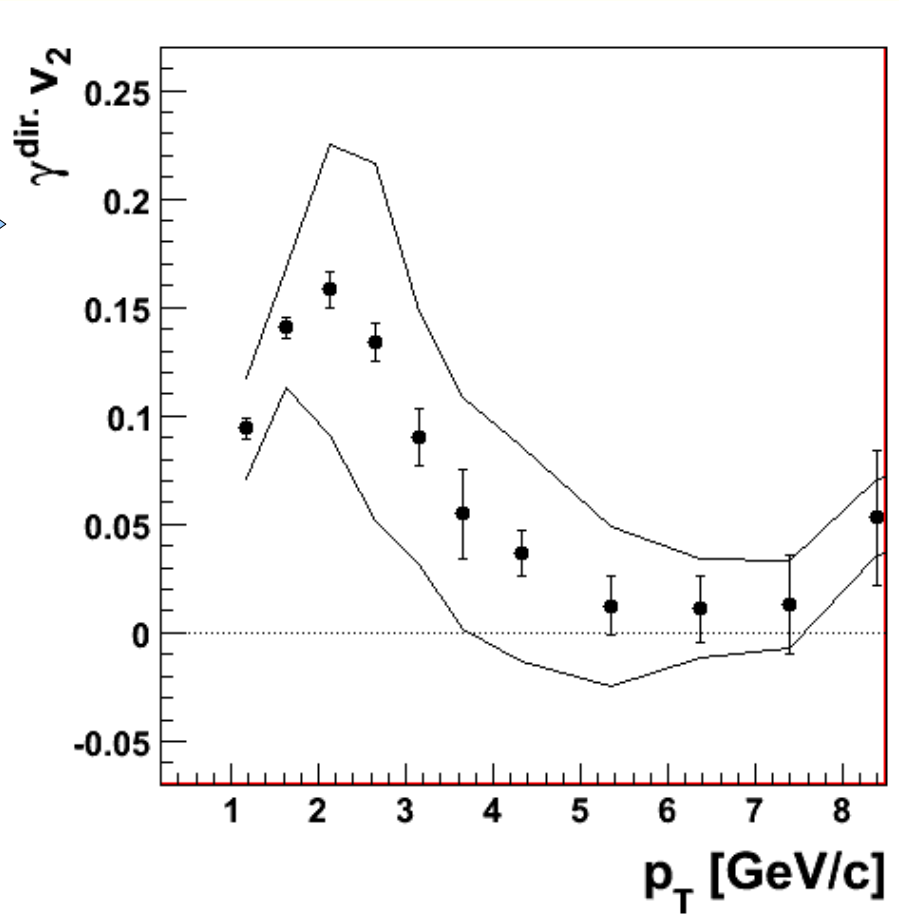
- Slope parameter (0-20%):
  T = (221 ± 23 ± 18) MeV
- Initial temp. from hydro:
  T_i = 300 … 600 MeV

Expected to be a lower limit for the initial temperature T_i!

Direct Photon v_2 (PHENIX)

PHENIX, arXiv:1105.4126 (→ link)

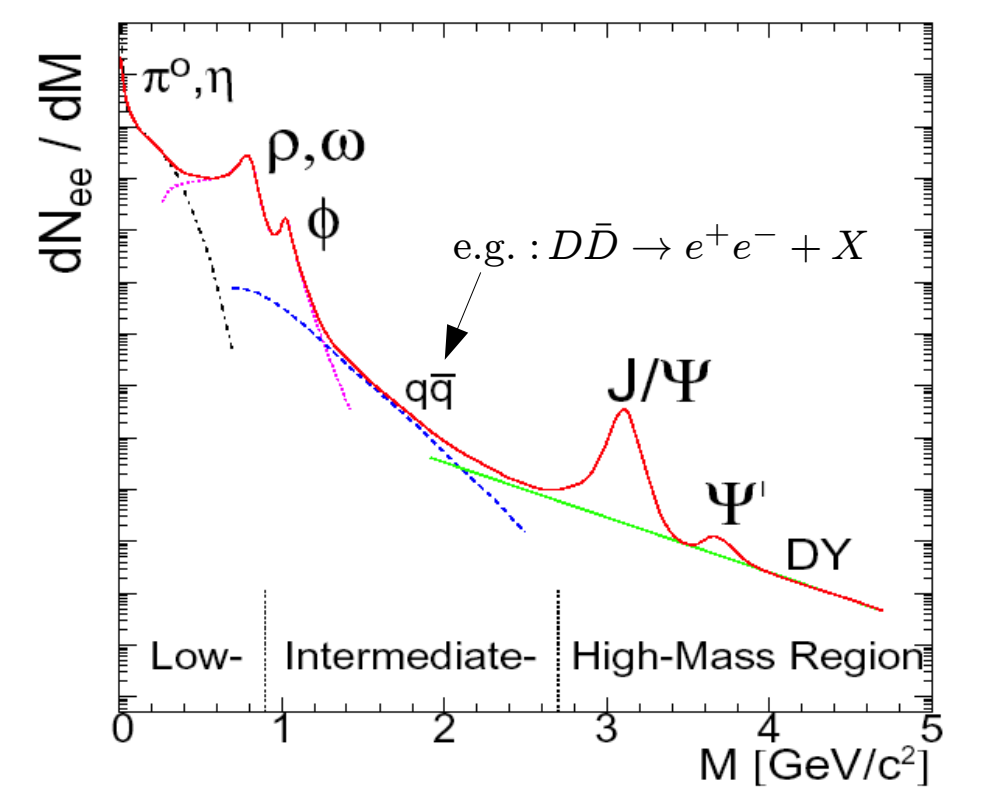




$$v_2^{\mathrm{dir.}\,\gamma} = \frac{R_\gamma \cdot v_2^{\mathrm{incl.}} - v_2^{\mathrm{decay.}\,\gamma}}{R_\gamma - 1}$$

Large direct photon v_2 is a challenge to theory because most thermal photons are expected to be created early (when the temp. is largest and) when v_2 has not fully built up

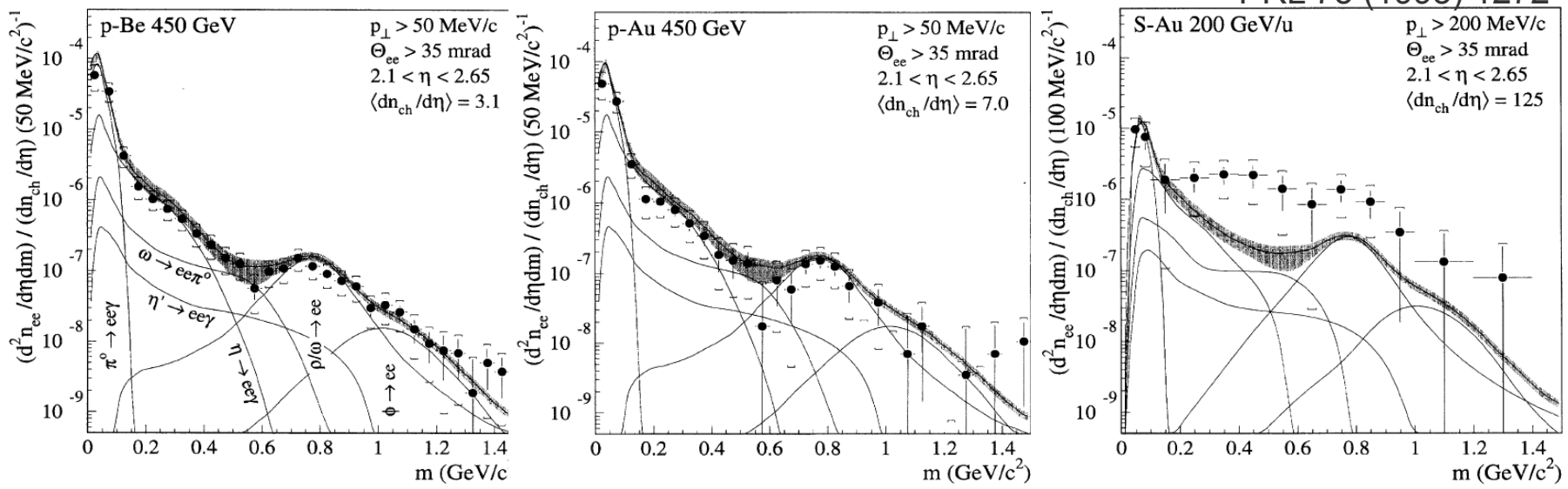
Motivation for Studying Dileptons in Heavy-Ion Collisions



- Search for modifications of vector mesons in the medium
  - Broadening vs. mass shift
  - Effects of chiral symmetry restoration?
- Thermal emission (both from QGP and hadronic phase)
- High-Mass region: J/Ψ suppression/enhancement

Discovery of Low Mass Dilepton Enhancement

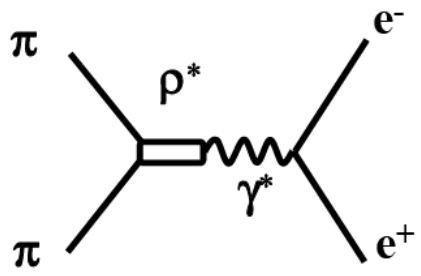
PRL 75 (1995) 1272



Discovery of low mass dilepton enhancement in 1995

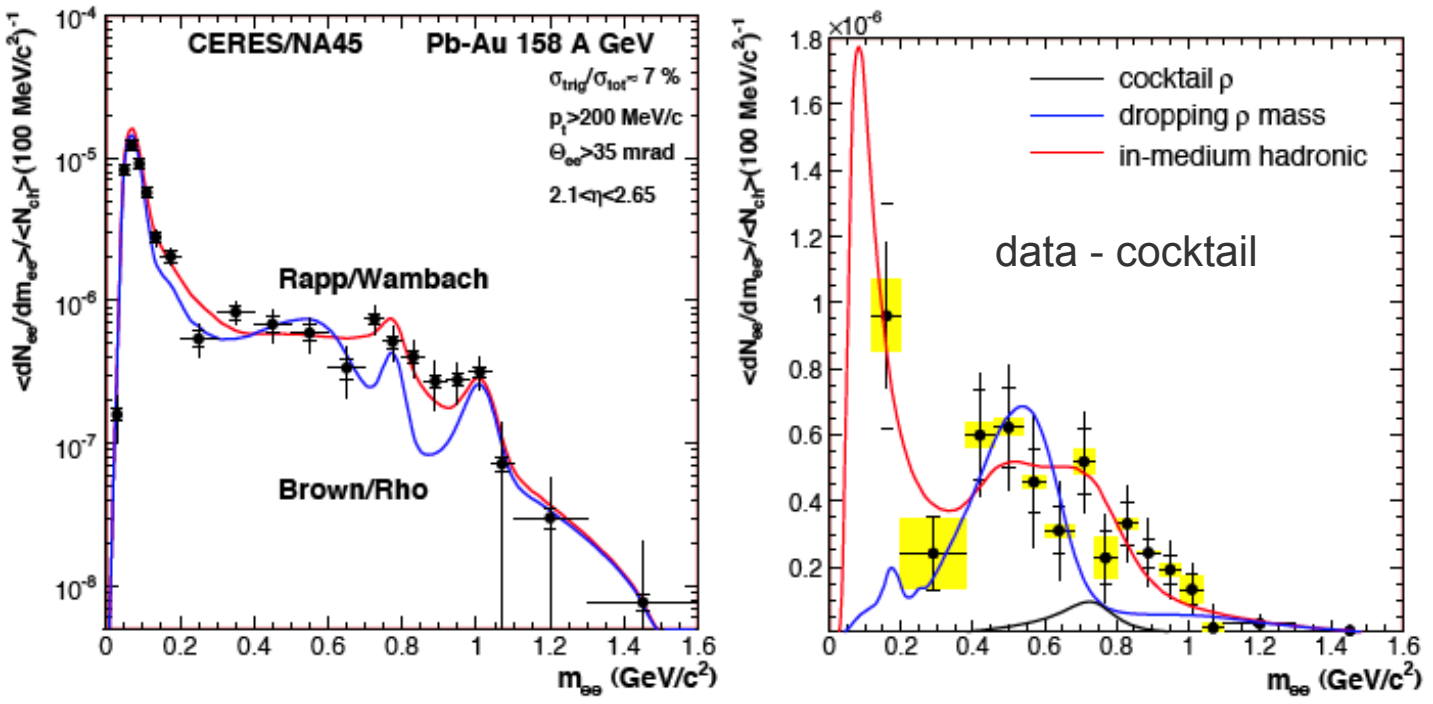
- p-Be and p-Au well described by decay cocktail
- Significant excess in S-Au (factor ~5 for m > 200 MeV)
- Onset at ~ 2 m_π suggested π−π annihilation
- Maximum below ρ meson near 400 MeV

Hints towards modified ρ meson in dense medium



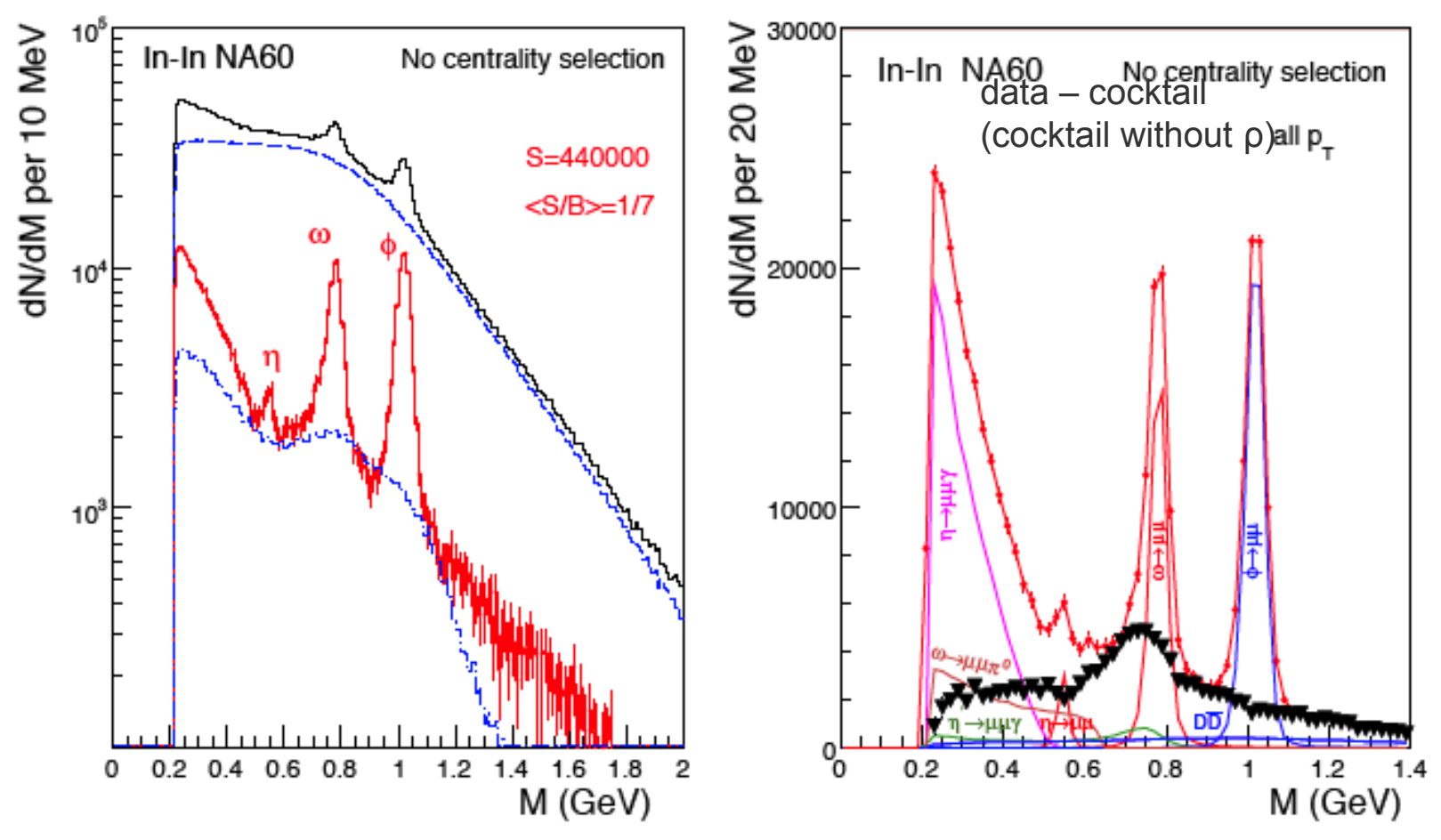
A. Drees,
Hard Probes 2004 (→ link)

Dilepton Spectrum in Pb+Pb at 158 *A* GeV (Ceres)

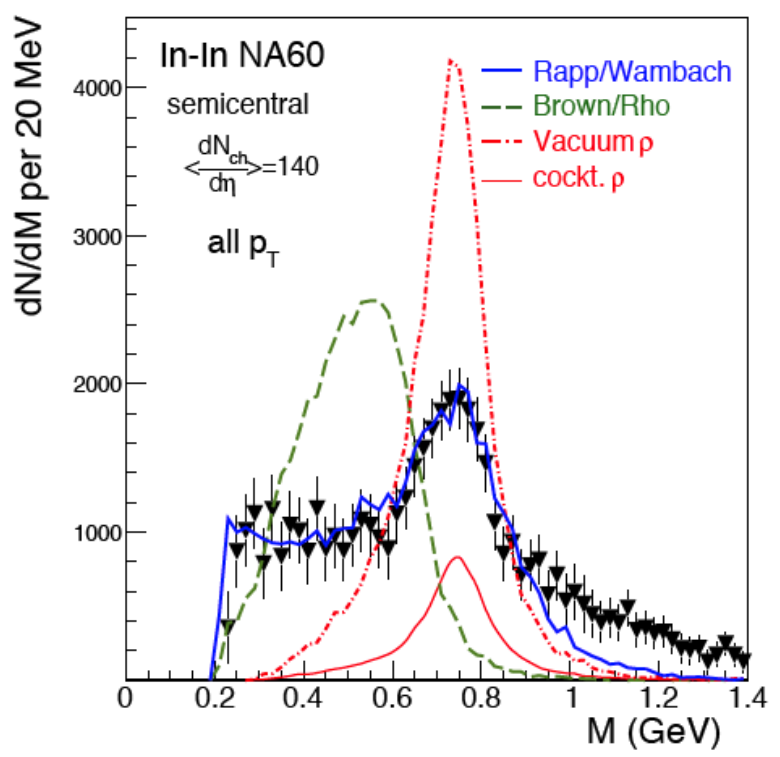


- Di-Electron Excess (factor ~ 2.6) also measured in Pb+Au at 158 *A* GeV
- Even stronger enhancement (factor ~ 5.9) found in Pb+Au at 40 *A* GeV (effect of higher baryon density?)
- Difficult to distinguish between calculations with dropping ρ mass (Brown/Rho) and broadening of the ρ (Rapp/Wambach). Data seem to favor ρ broadening.

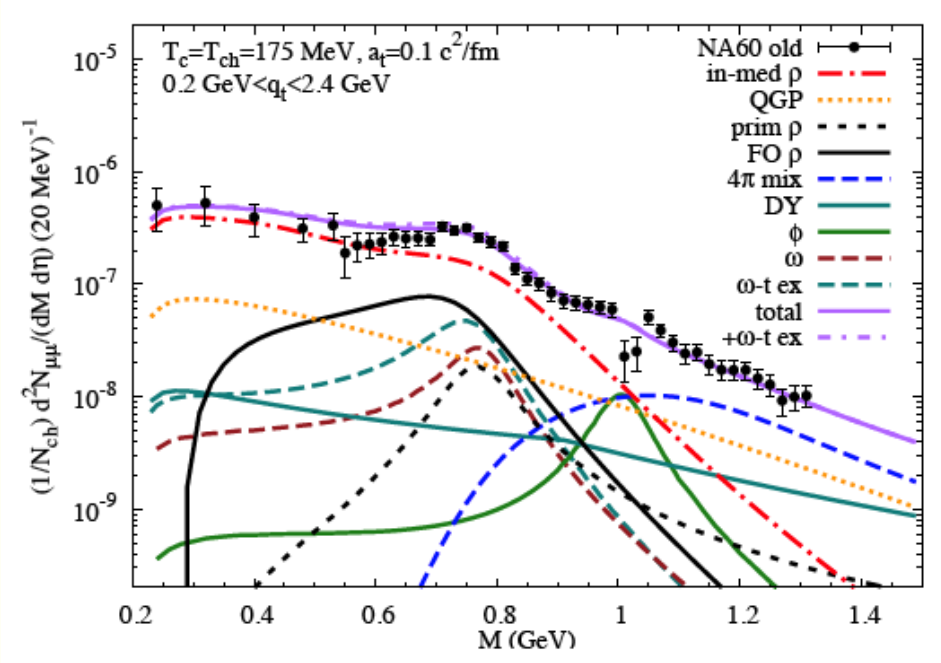
Dimuon Data from NA60



NA60 Data Described by Broadening of the ρ Meson

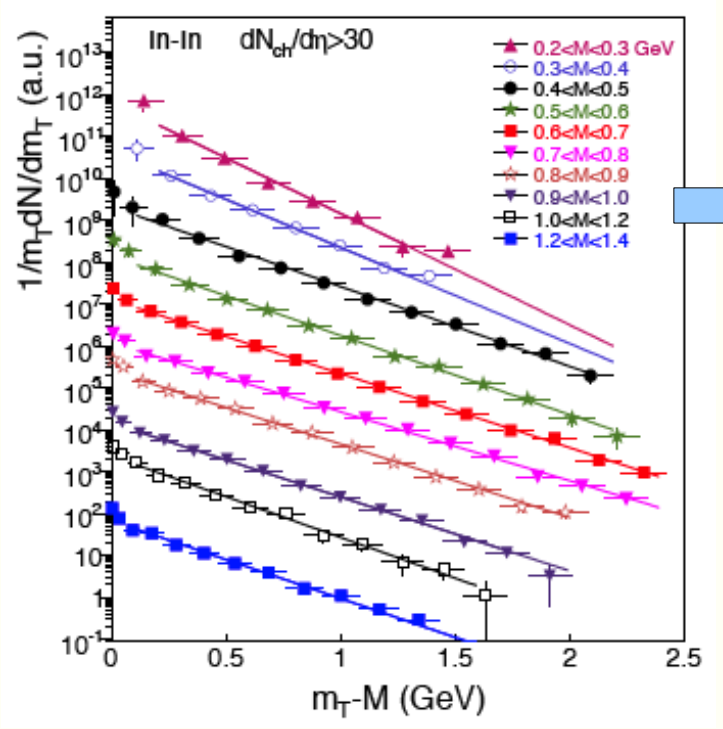


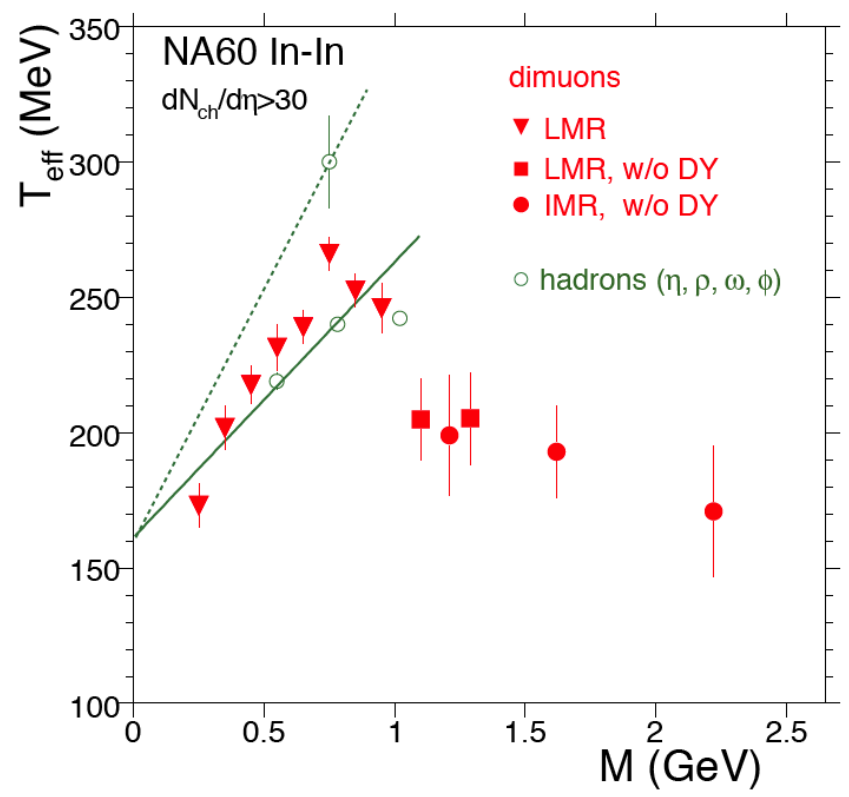
Calculation: Rapp, arXiv:1010.1719



- Data rule out mass shift of the ρ meson (Brown/Rho model)
- Excess above cocktail for interpreted as thermal contribution

Interpretation of the Dimuon Excess for $M > 1$ GeV as Thermal Contribution





- Excess dimuons (data – cocktail, except for the ρ) described by an exponential in m_T
- Increase of T_{eff} interpreted as radial flow ($T_{eff} \sim T + M\, v^2_{flow}$)
- Lower T_{eff} for $M > 1$ GeV taken as evidence for emission at early times (QGP) when flow has no yet fully built up. $T_{eff} > T_c$ evidence for QGP?

Points to Take Home

- Photons and dileptons are interesting because, once produced, they leave the medium without further interaction
- This provides a handle to study properties of the medium at early times
- The PHENIX measurement using the internal conversion method provides evidence for thermal radiation and initial temperatures greater than 300 MeV in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- Puzzling result: Thermal photon v_2 at RHIC as large as v_2 of hadrons
- Dilepton measurements sensitive to in-medium modification of vector mesons and thermal radiation