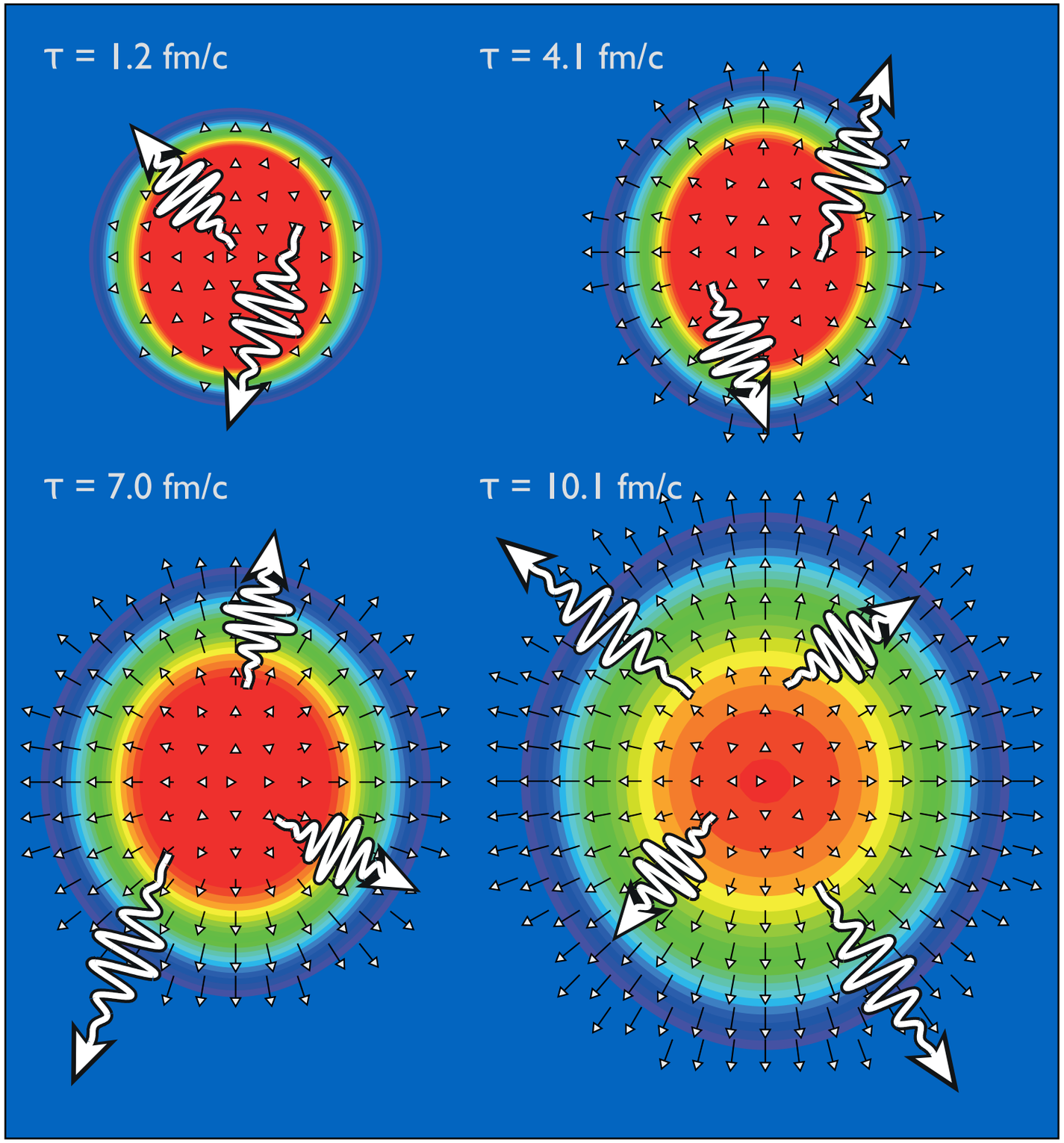
Quark-Gluon Plasma Physics

10. Thermal Photons and Dileptons

Prof. Dr. Klaus Reygers
Prof. Dr. Johanna Stachel
Heidelberg University
SS 2019

The role of direct photons in heavy-ion physics



- Escape medium unscathed
- Produced over the entire duration of the collision (unlike low-p_T hadrons)
  - Test of space-time evolution, in particular of the hydro paradigm
- Experimental access to initial QGP temperature (?)

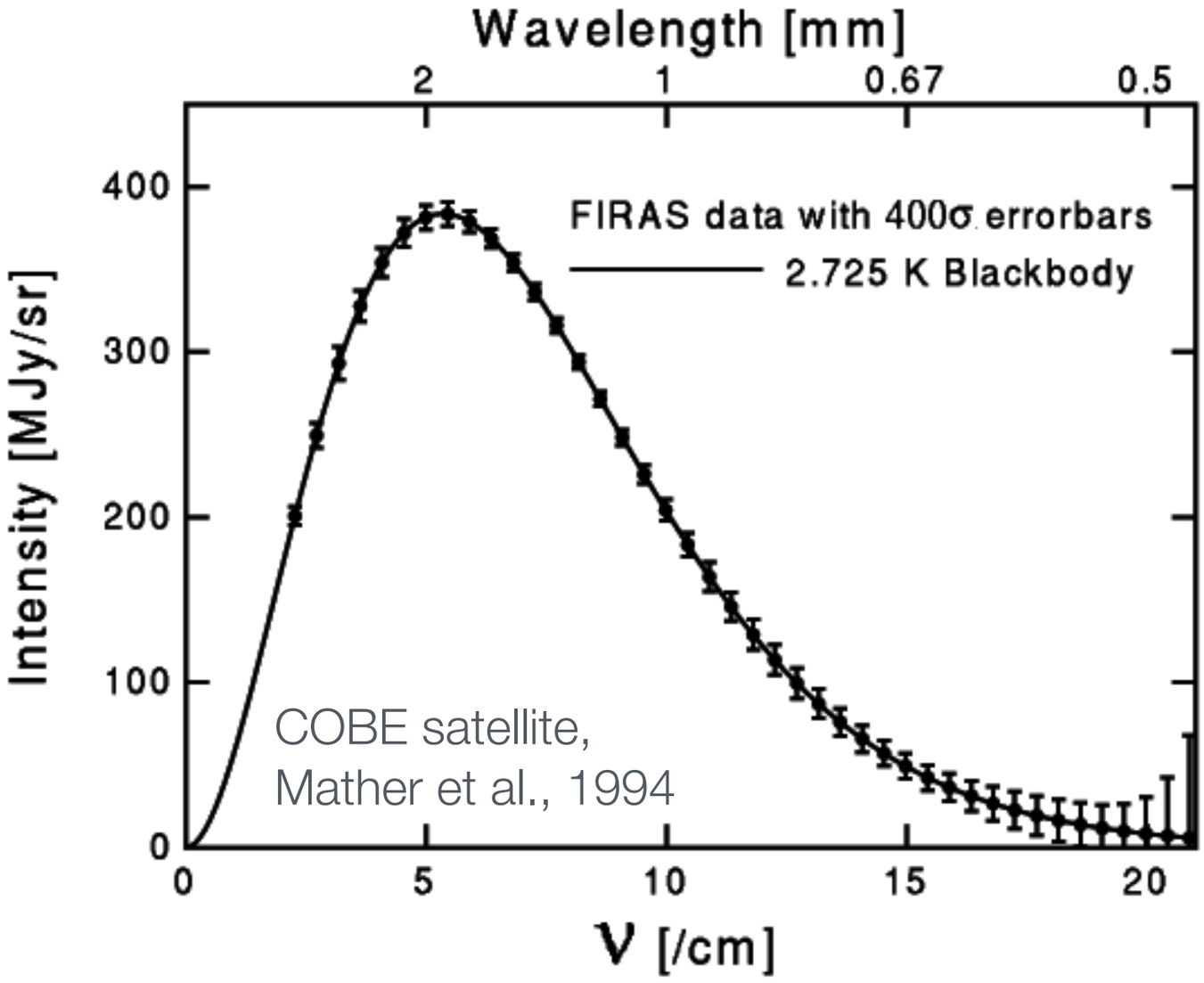
QGP photon rate r_γ (lowest order):

$$E_\gamma \frac{dr_\gamma}{d^3p} \propto \alpha\alpha_s T^2 e^{-E_\gamma/T} \log \frac{E_\gamma T}{k_c^2}$$

Total emission rate:

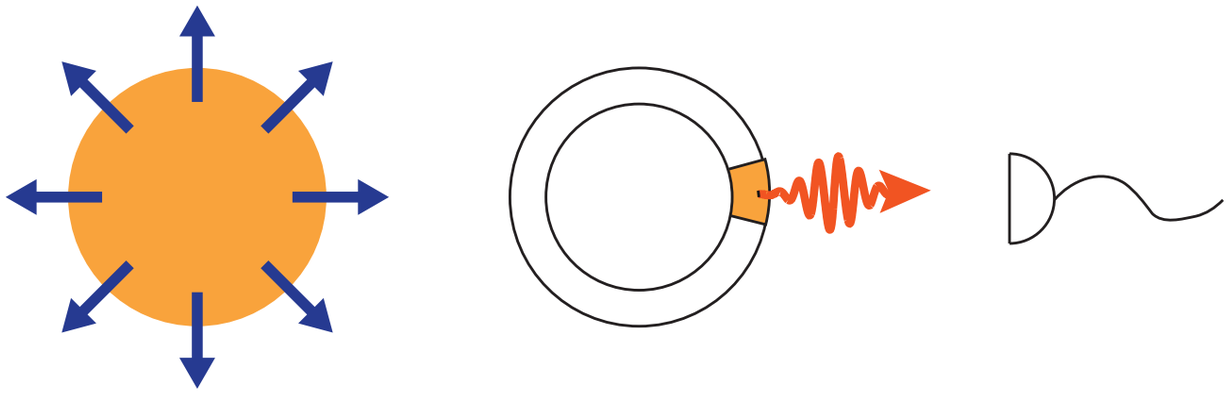
$$r_\gamma \propto T^4$$

Example:
Temperature of the universe from Planck spectrum



Difference in heavy-ion collisions: photons not in thermal equilibrium

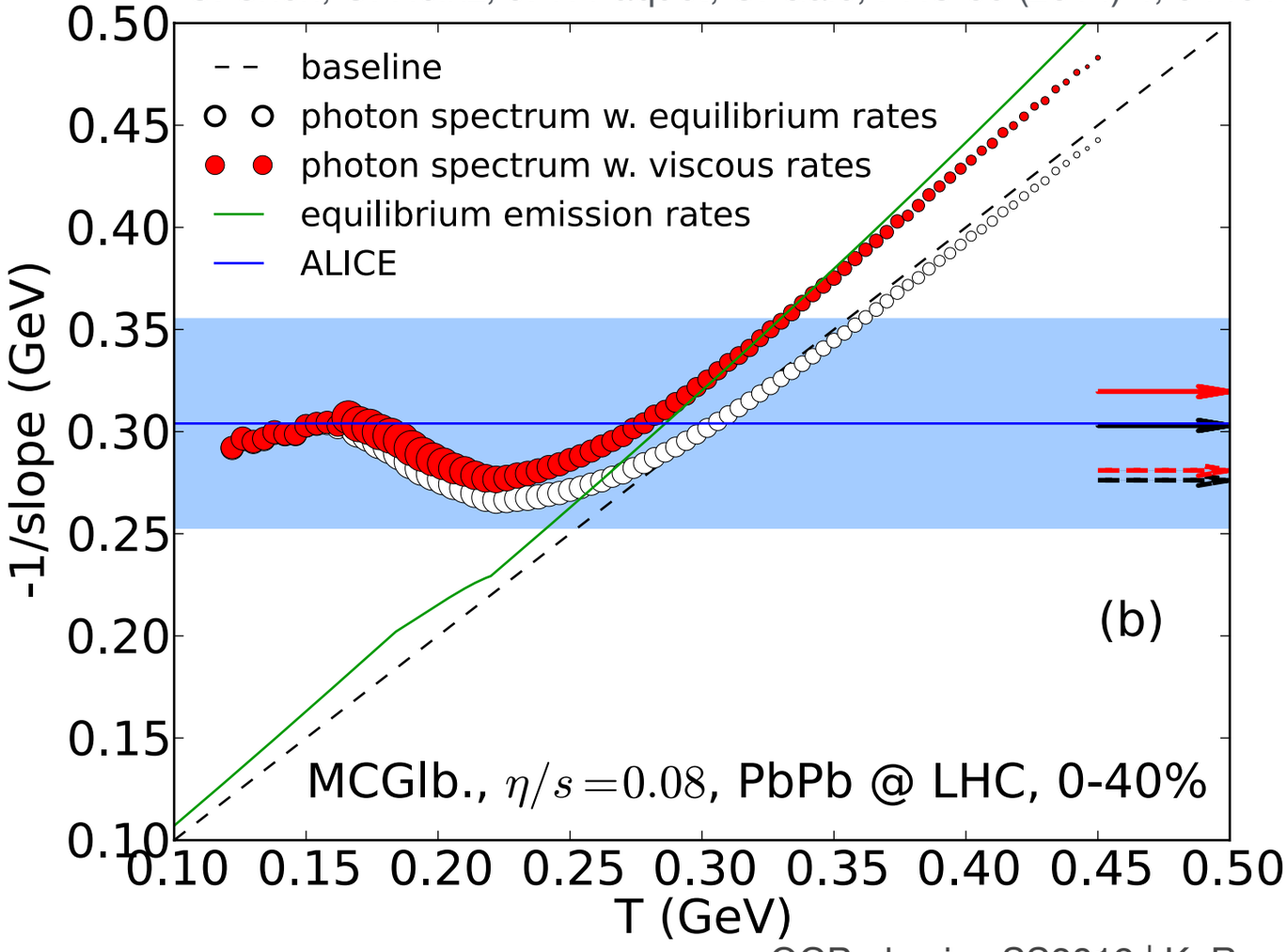
A complication for the temperature measurement: Blueshift due to radial flow



$$E_\gamma \frac{\mathrm{d}^3 N_\gamma}{\mathrm{d}^3 p_\gamma} \propto e^{-E_\gamma / T_{\mathrm{eff}}}$$

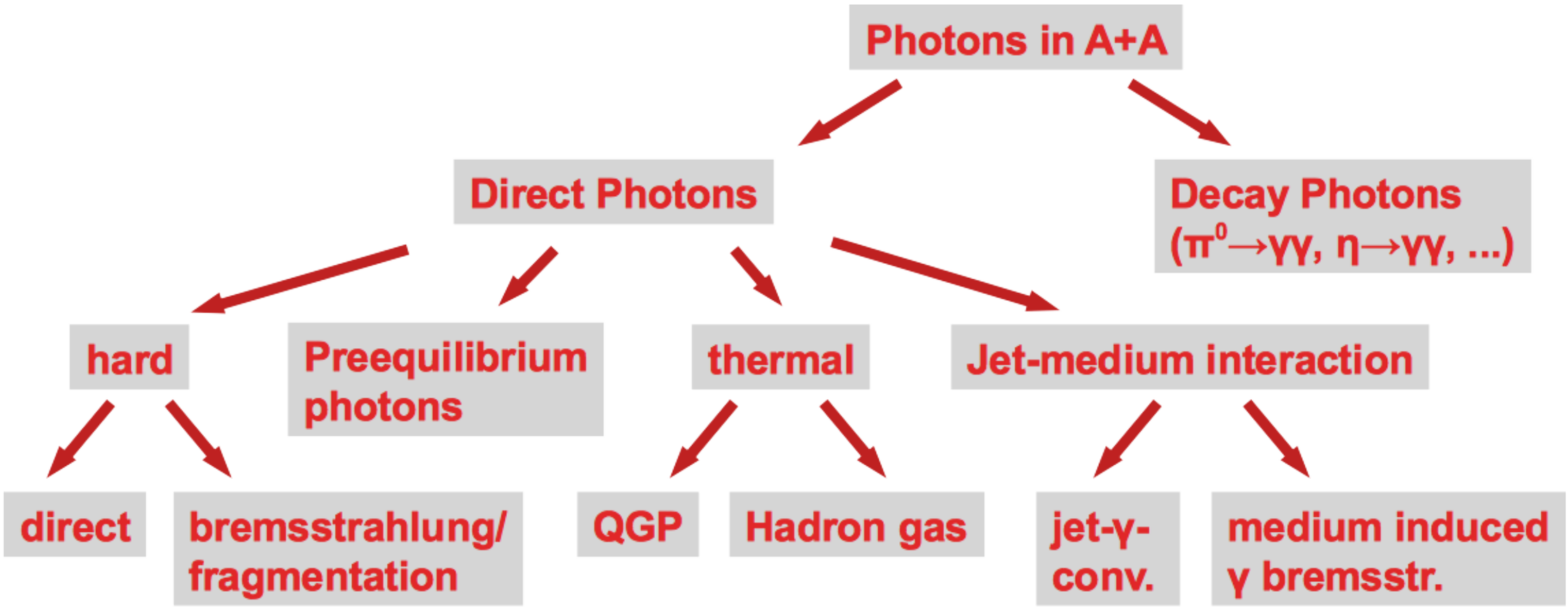
$$T_{\mathrm{eff}} = \underbrace{\sqrt{\frac{1+\beta_{\mathrm{flow}}}{1-\beta_{\mathrm{flow}}}}}_{2 \text{ for } \beta_{\mathrm{flow}}=0.6} \times T$$

C. Shen, U. Heinz, J.-F. Paquet, C. Gale, PRC 89 (2014) 4, 044910



- Large blueshift at late times when $T \approx 150$ - 200 MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

Known and expected photon sources in heavy-ion collisions

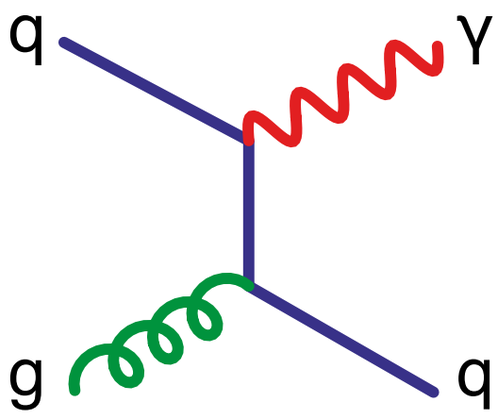


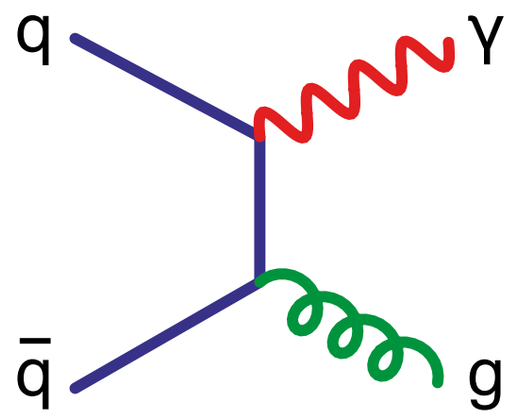
$$\gamma_{\text{direct}} := \gamma_{\text{incl}} - \gamma_{\text{decay}}$$

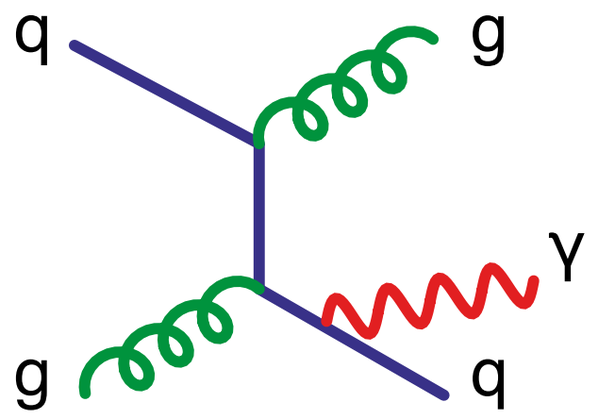
Small signal (O(10)% or smaller) at low p_T ($1 < p_T < 3$ GeV/c), where thermal photon from the QGP are expected

Feynman diagrams:
Photon production in the QGP and in the HG

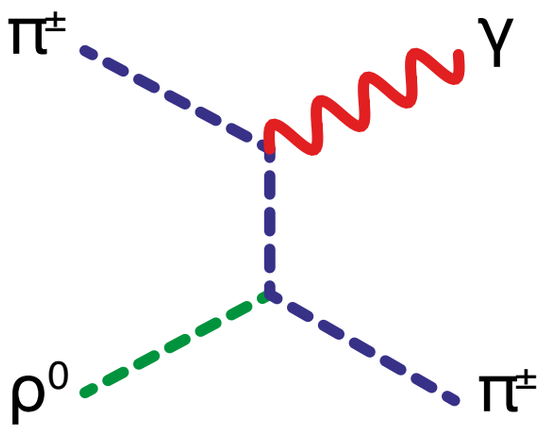
QGP

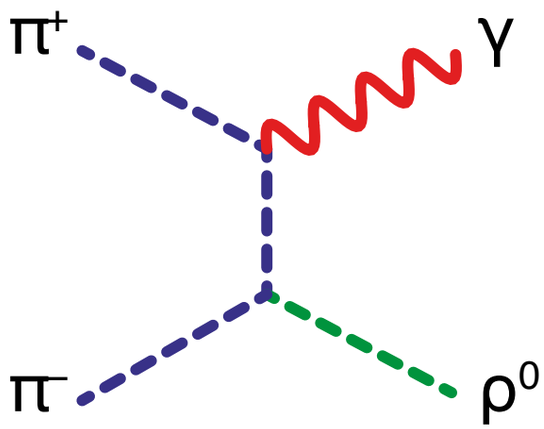


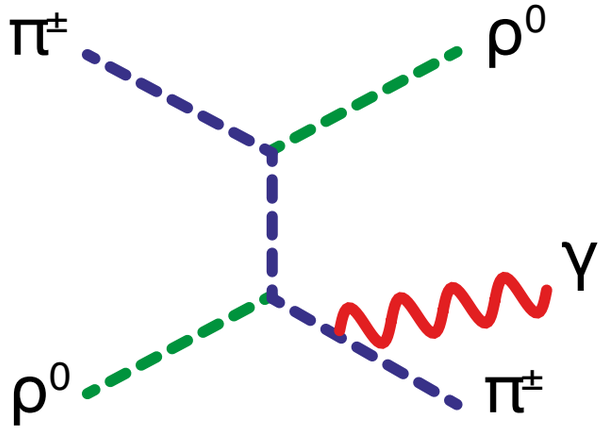




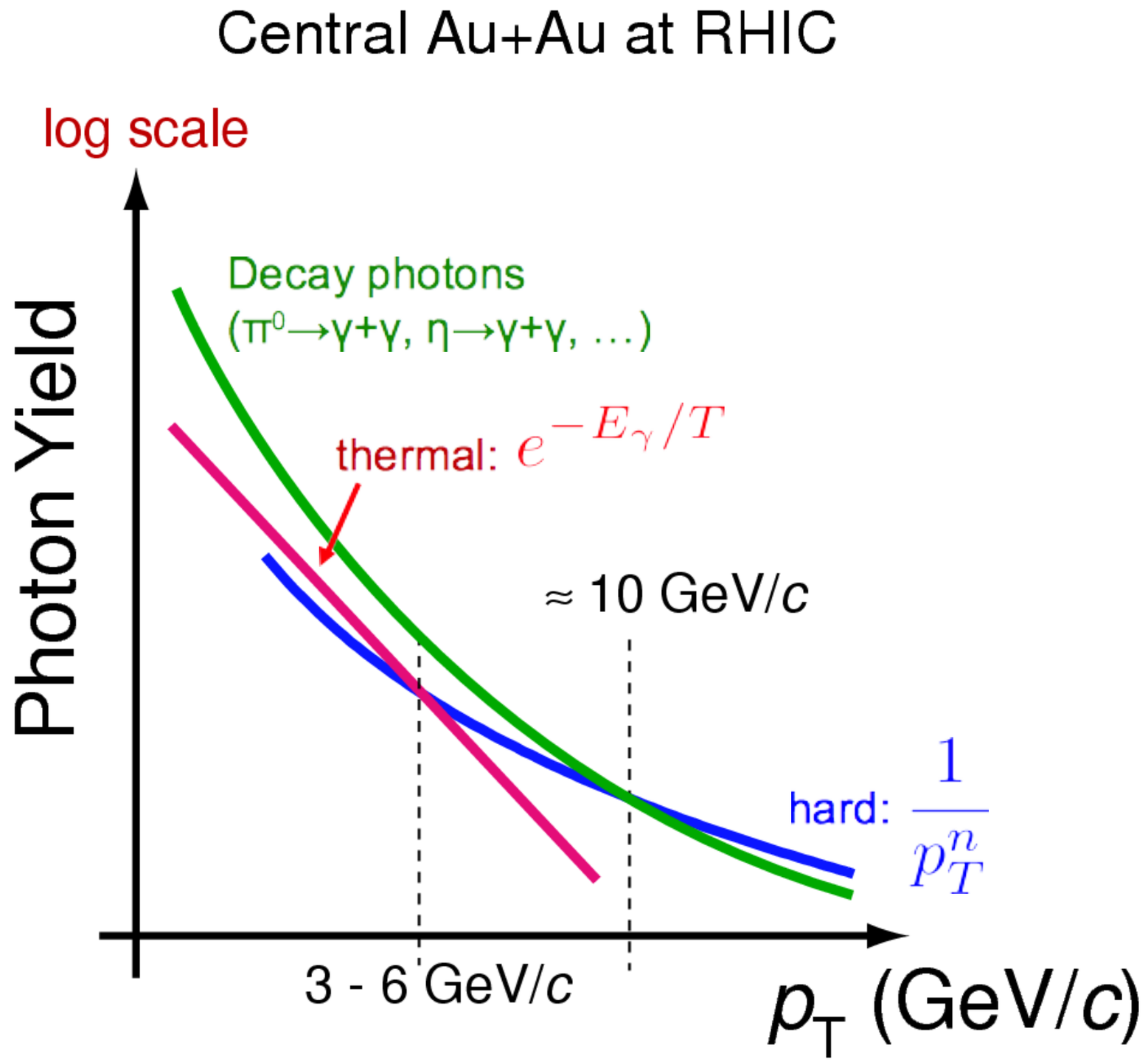
hadron gas





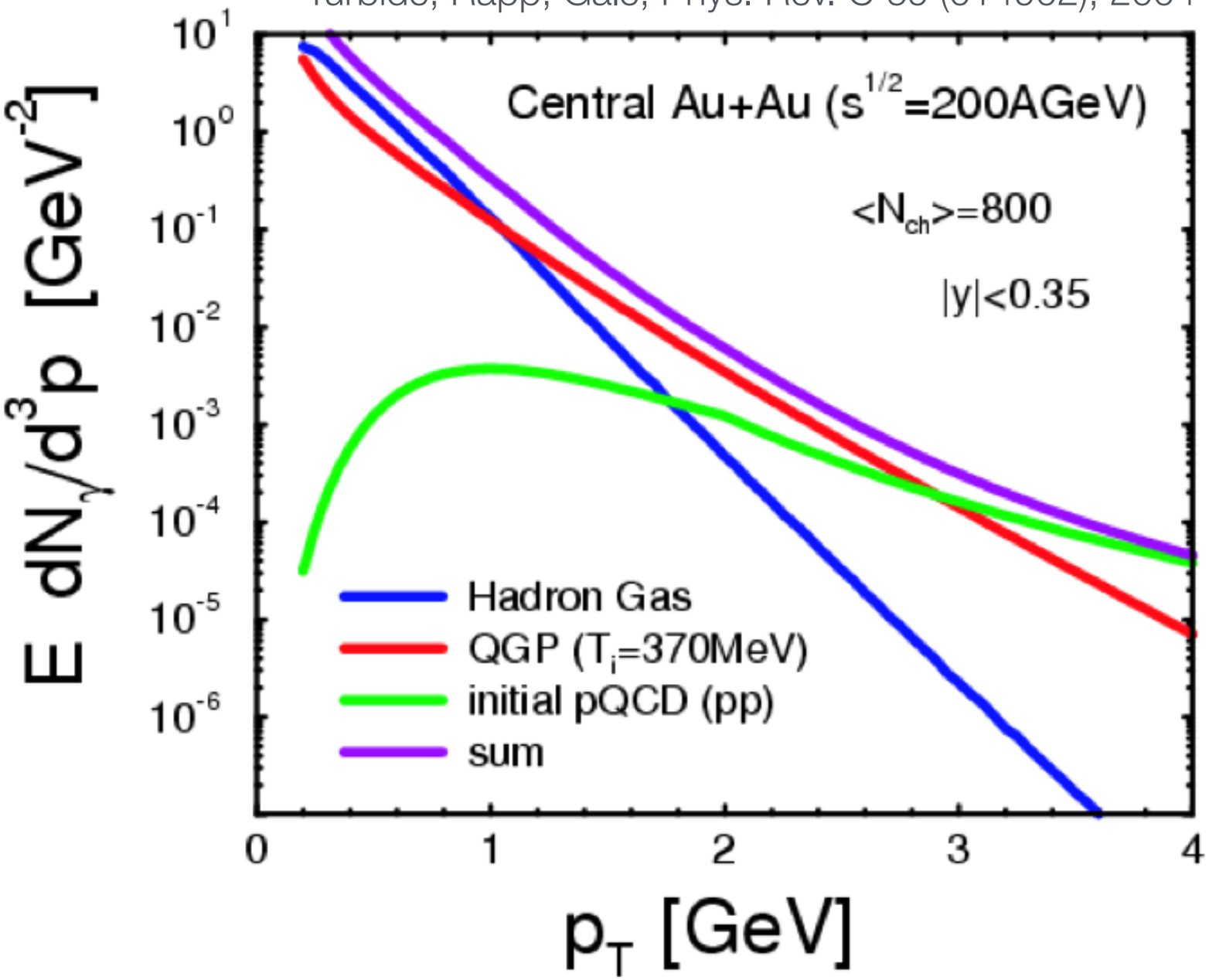


Schematic photon spectrum in A+A collisions



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

The Statistical Subtraction Method

- Idea: Cancellation of uncertainties common to photon and π^0 measurement

$$\gamma_{\text{direct}} = \gamma_{\text{incl}} - \gamma_{\text{decay}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\text{incl}}$$

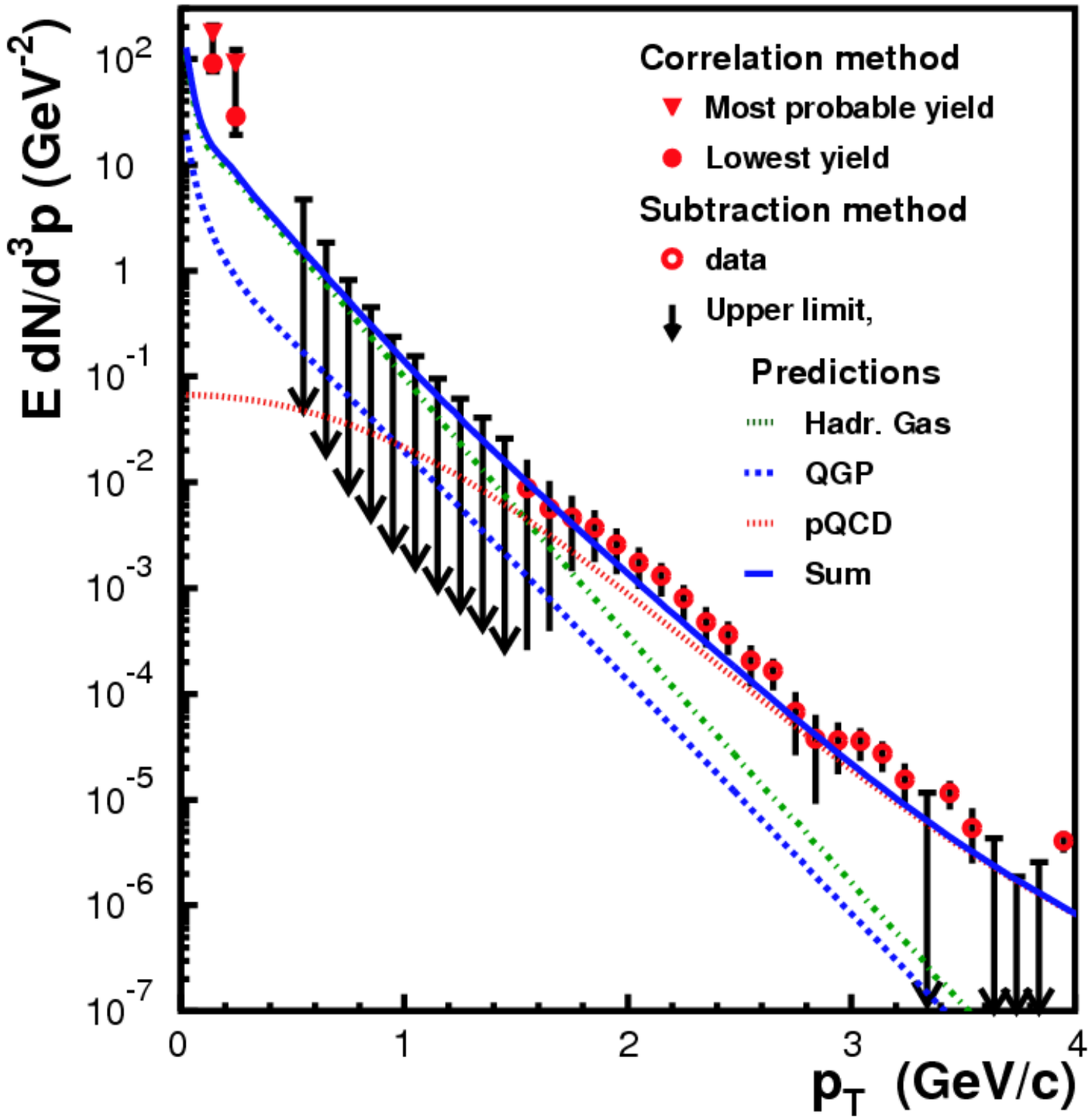
$$R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}} \equiv \frac{\gamma_{\text{incl}}}{\pi^0_{\text{param}}} \Big/ \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}}$$

measured

decay photon calculation ("cocktail")

- Which uncertainties cancel (partially)?
  - Calorimeter: global energy scale, energy non-linearity
  - Photon conversions: conversion probability, photon selection
- Method pioneered by WA80/98 at the CERN SPS
  - WA98 made the first direct-photon measurement in A-A
  - Interpretation at SPS energies difficult (initial state effect or QGP photons?)

CERN SPS results:
Direct photons in Pb-Pb at $\sqrt{s_{NN}}$ = 17.3 GeV



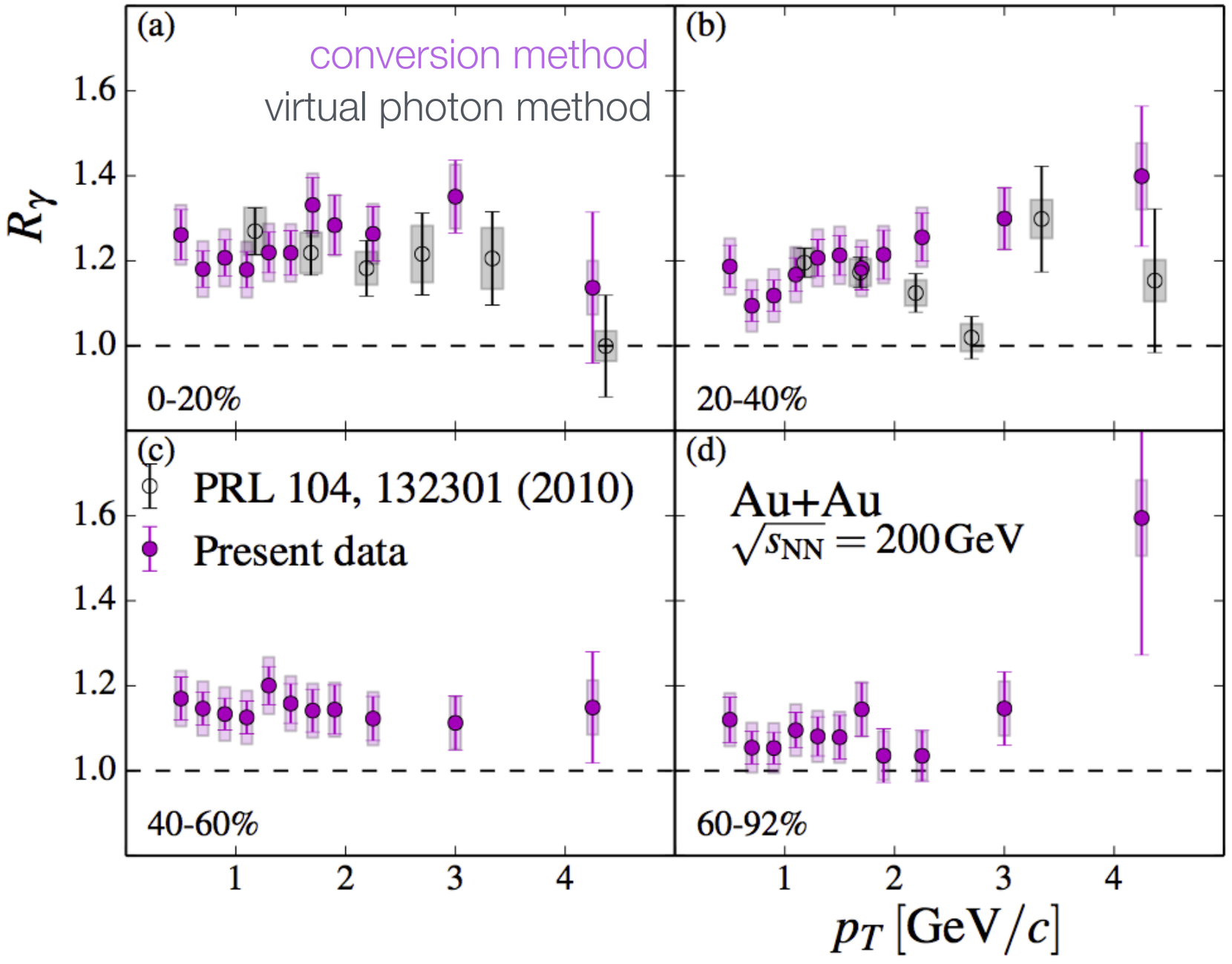
Consistent with QGP scenario, but data can also be explained without a QGP

PRL 85 (2000) 3595
PRL 93 (2004) 022301 (low p_T points: HBT)

Direct photon excess in Au-Au at $\sqrt{s_{NN}}$ = 200 GeV

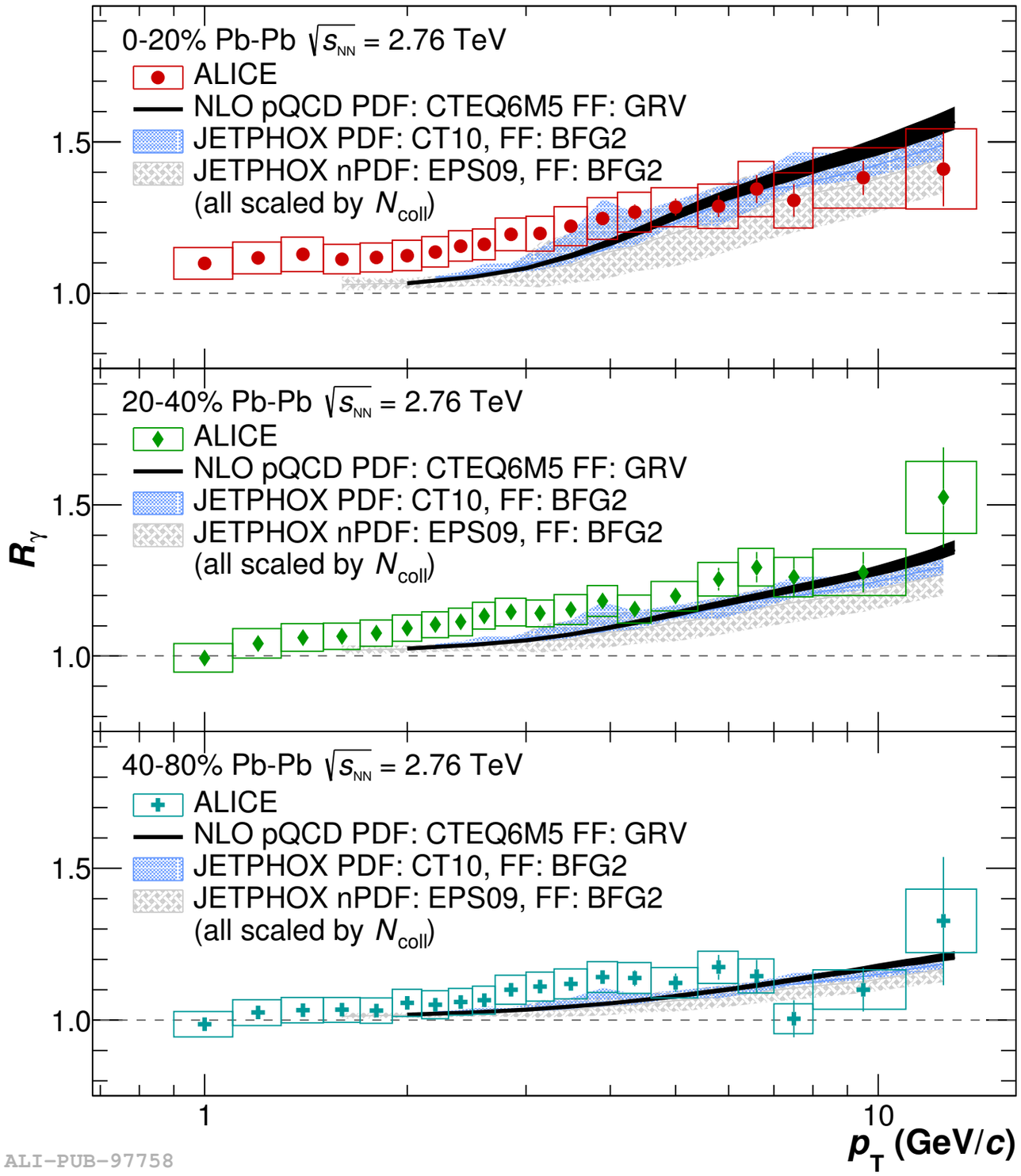
$$R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}}$$

PHENIX, arXiv:1405.3940



- Two experimental techniques
  - Virtual photons ($\gamma^* \rightarrow e^+e^-$), extrapolated to $m_{\gamma^*} = 0$
  - Photon conversion combined with π^0 tagging using e.m. calorimeter
- 20-25% excess in central Au-Au

Direct photon excess in Pb-Pb at the LHC



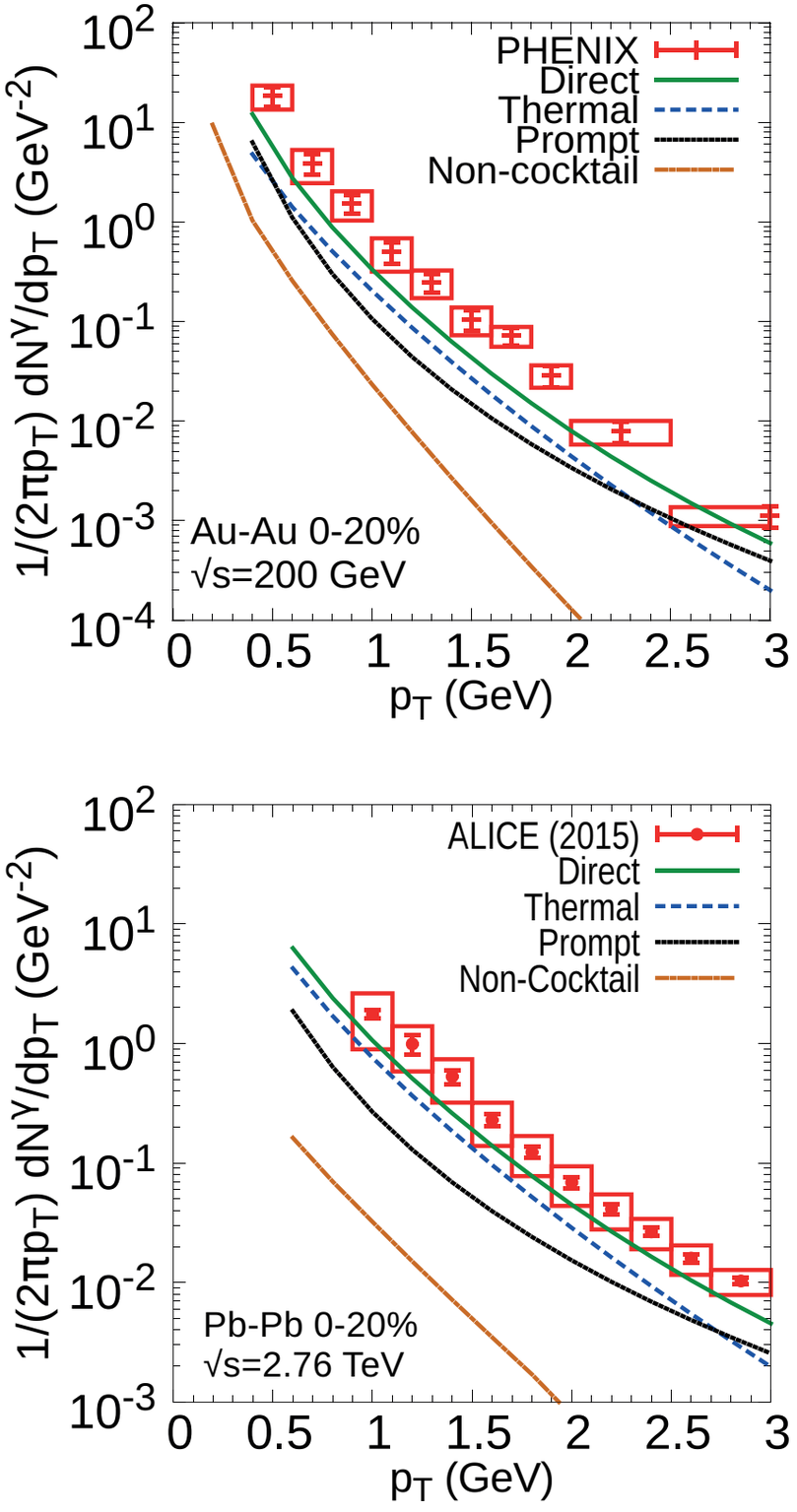
$$R_\gamma^{\mathrm{pQCD}} = 1 + N_{\mathrm{coll}} \frac{\gamma_{\mathrm{pQCD}}}{\gamma_{\mathrm{decay}}}$$

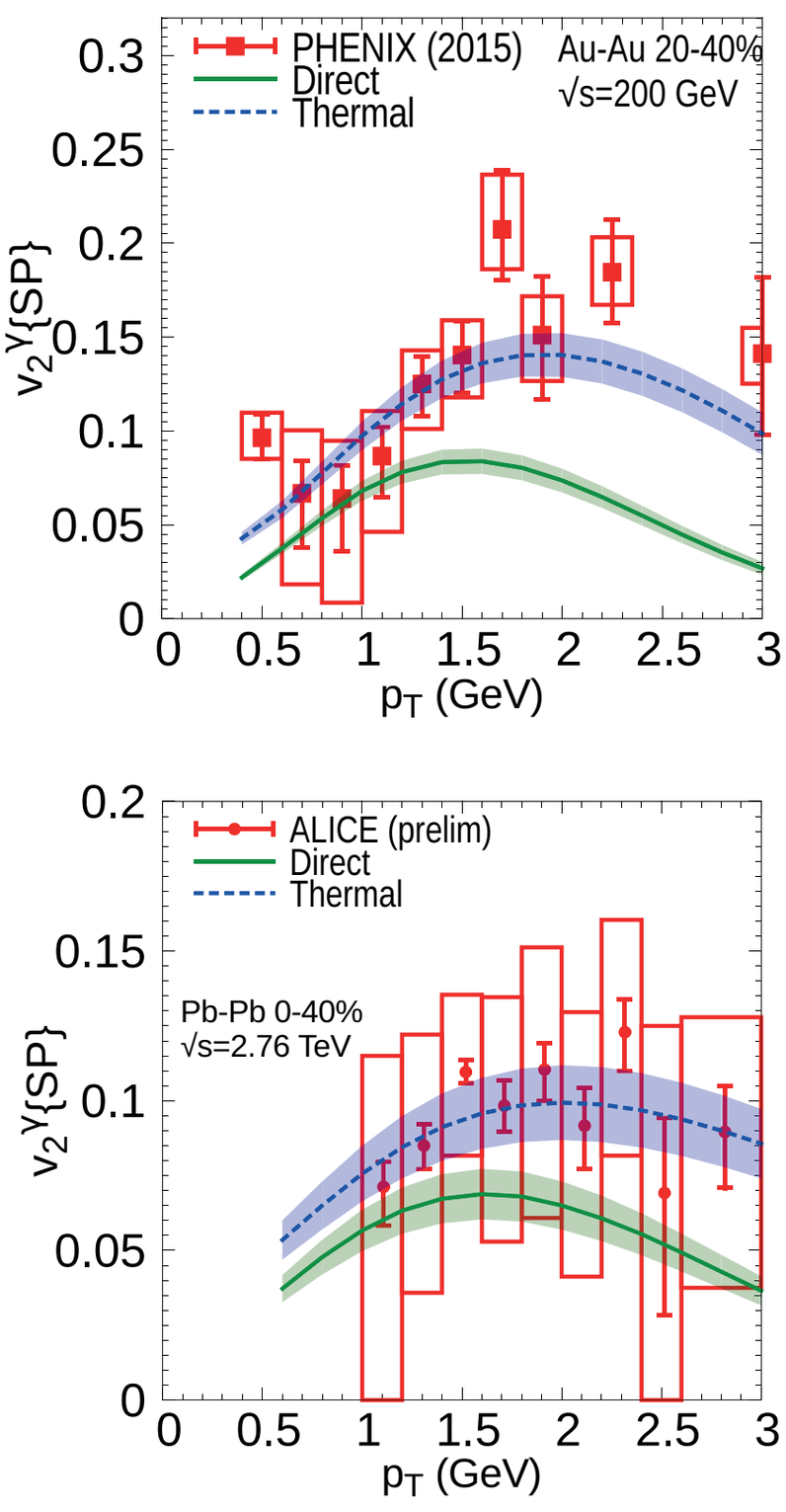
calculated based measured π^0 spectrum

- pQCD agrees with data for $p_T \gtrsim 5$ GeV/c
- Evidence for an additional photon source at lower p_T

ALICE, Physics Letters B 754 (2016) 235

The direct photon puzzle





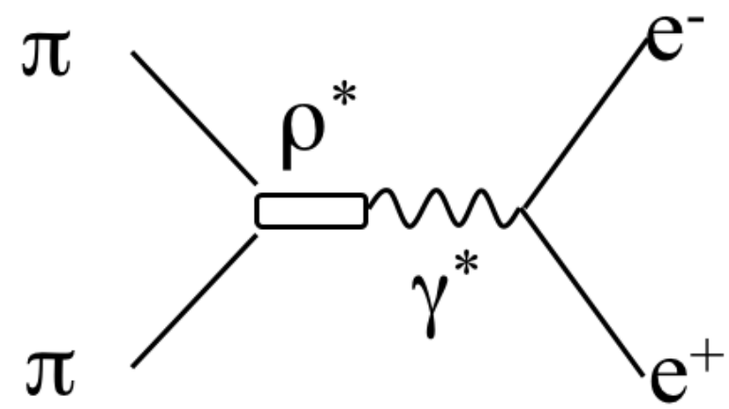
- Au-Au at RHIC
  - Models fail to describe direct photon data
- Puzzle has two parts
  - Yields
  - v_2
- Pb-Pb at the LHC
  - Similar trends
  - However, no puzzle with current uncertainties

Plots: Paquet et al., arXiv:1509.06738

Dileptons: Motivation

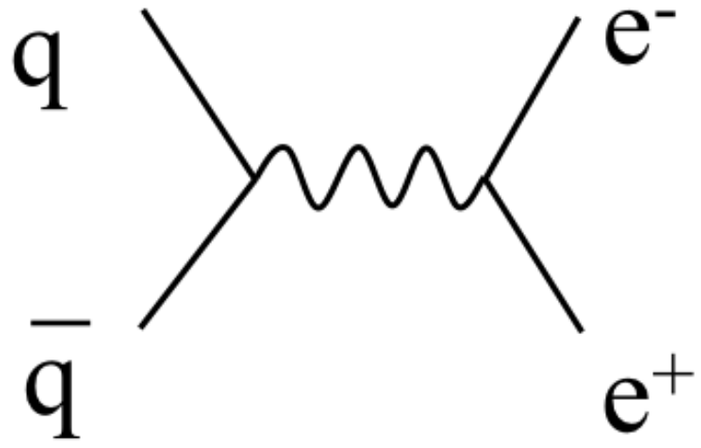
- Like photons, negligible final state interaction
- Search for in-medium modifications of vector mesons (M_{ee} < 1 GeV)
  - ρ can decay in the medium ($\tau_{\rho,vacuum} \approx 1.3$ fm/c < medium lifetime)
  - Broadening of the ρ in the medium, relation to chiral symmetry restoration?

hadron gas

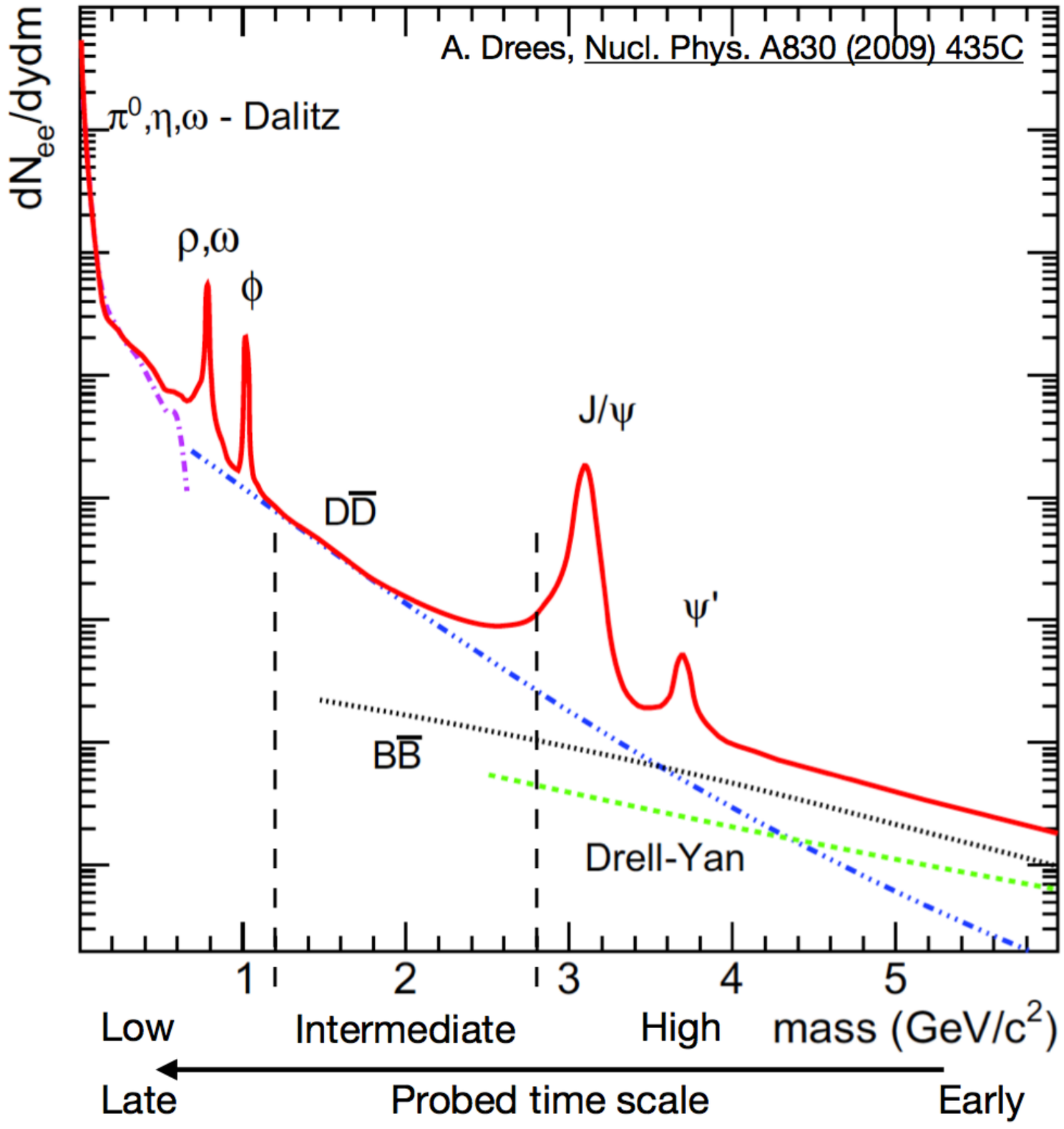


quark-gluon plasma

- Thermal radiation from the QGP and access to early temperature? (M_{ee} > 1 GeV)
  - spectrum ~ exp(-m_{ee}/T)
- Constrains space-time evolution
- Pioneering measurements by CERES at the CERN SPS
  - Di-electron excess for m_{ee} > 200 MeV
  - Hints towards modified ρ meson in dense medium

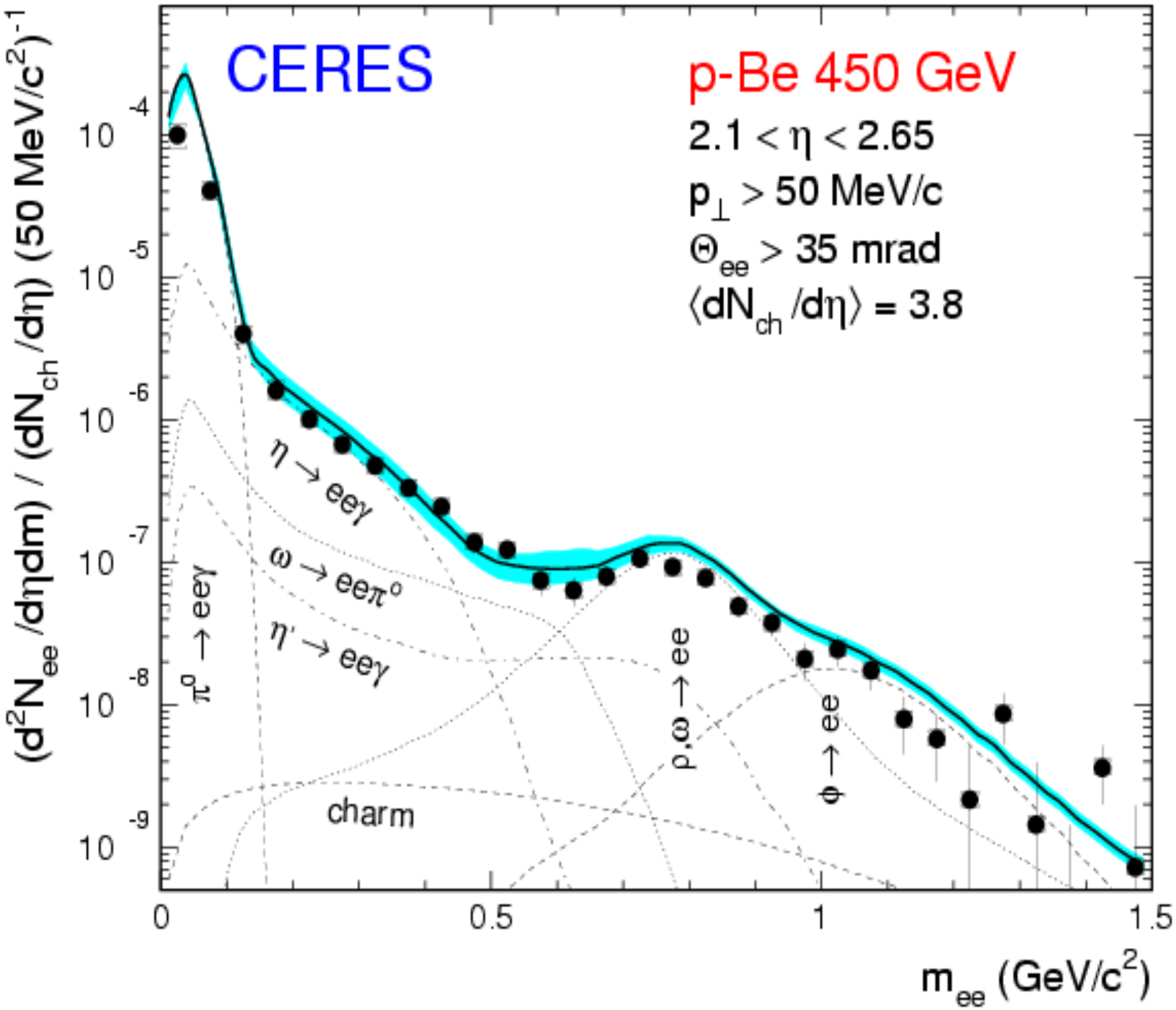


Schematic dilepton mass spectrum



CERN SPS results: p+A

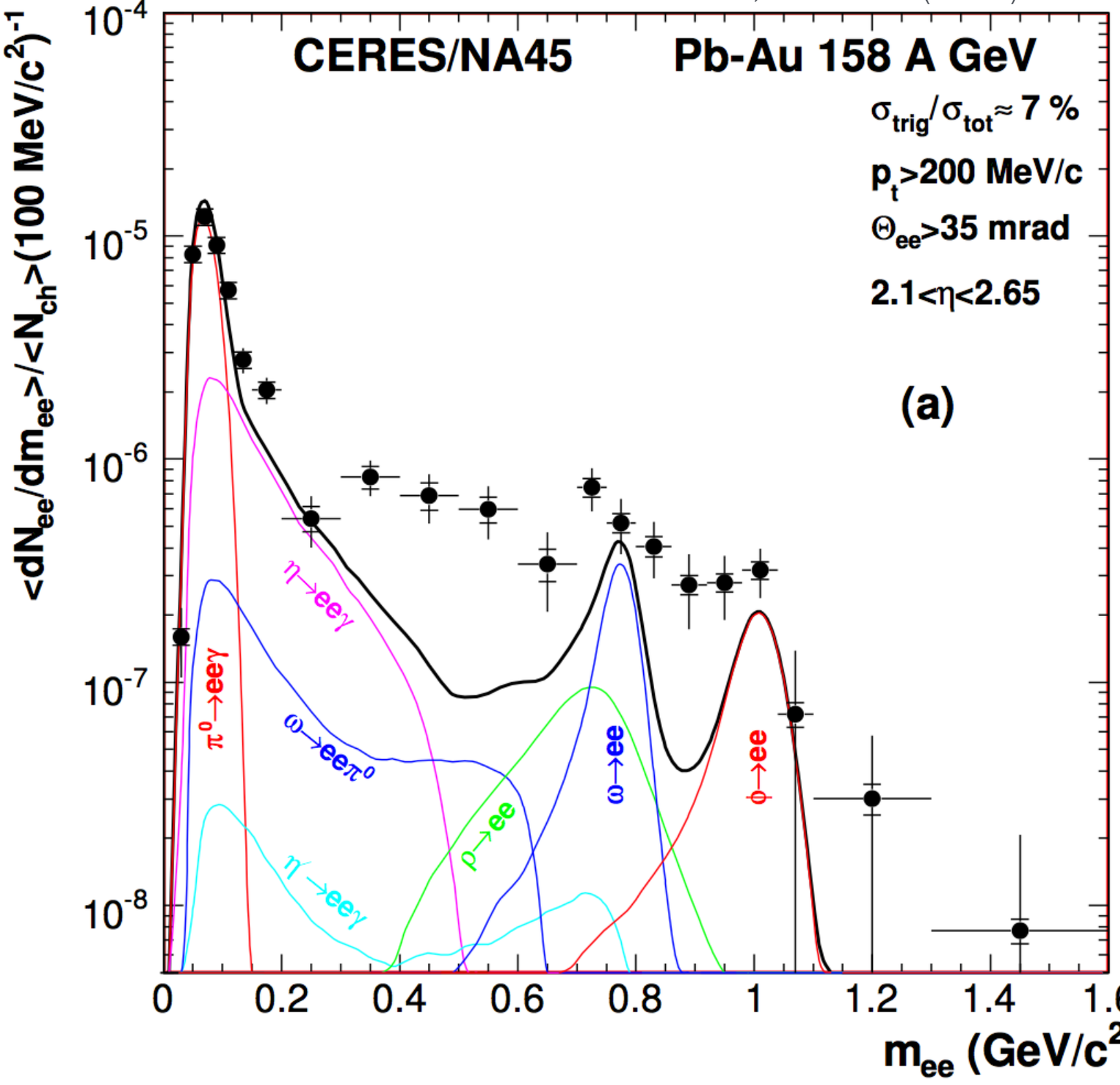
CERES, EPJ C 41 (2005) 475



Dielectron mass spectrum in p+Be (and also p+Au) well described by cocktail auf e^+e^- pairs from hadron decays

CERN SPS results: Pb-Au

CERES, PLB 666 (2008) 425



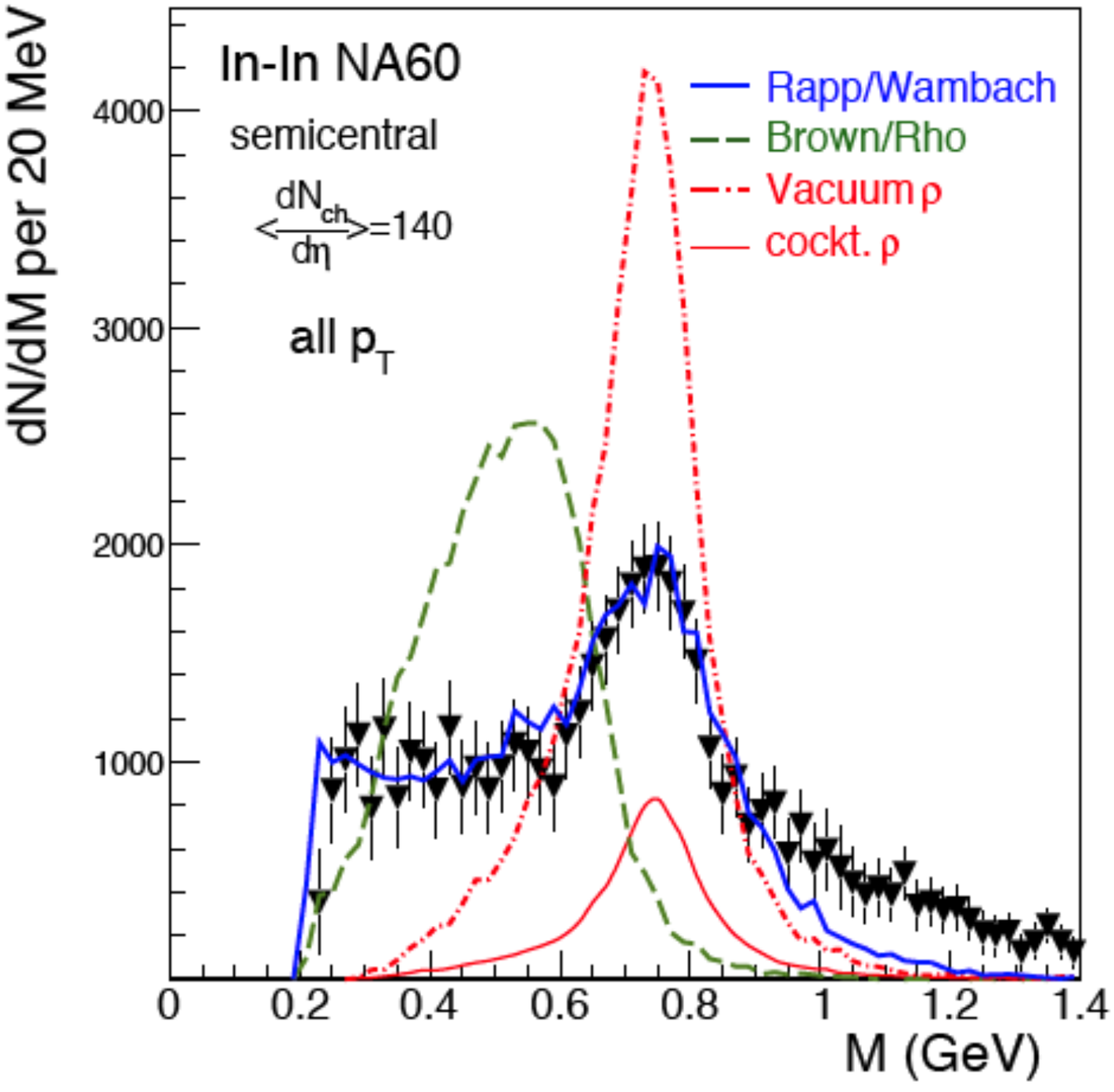
Significant excess above cocktail in Pb-Au

Onset at ~ 2 m_π suggests π–π annihilation

Theory calculations assuming a broadened can explain the data

Dimuons in In-In at the CERN SPS: Support for in-medium broadening of the ρ meson

NA60, EPJ C61, 2009

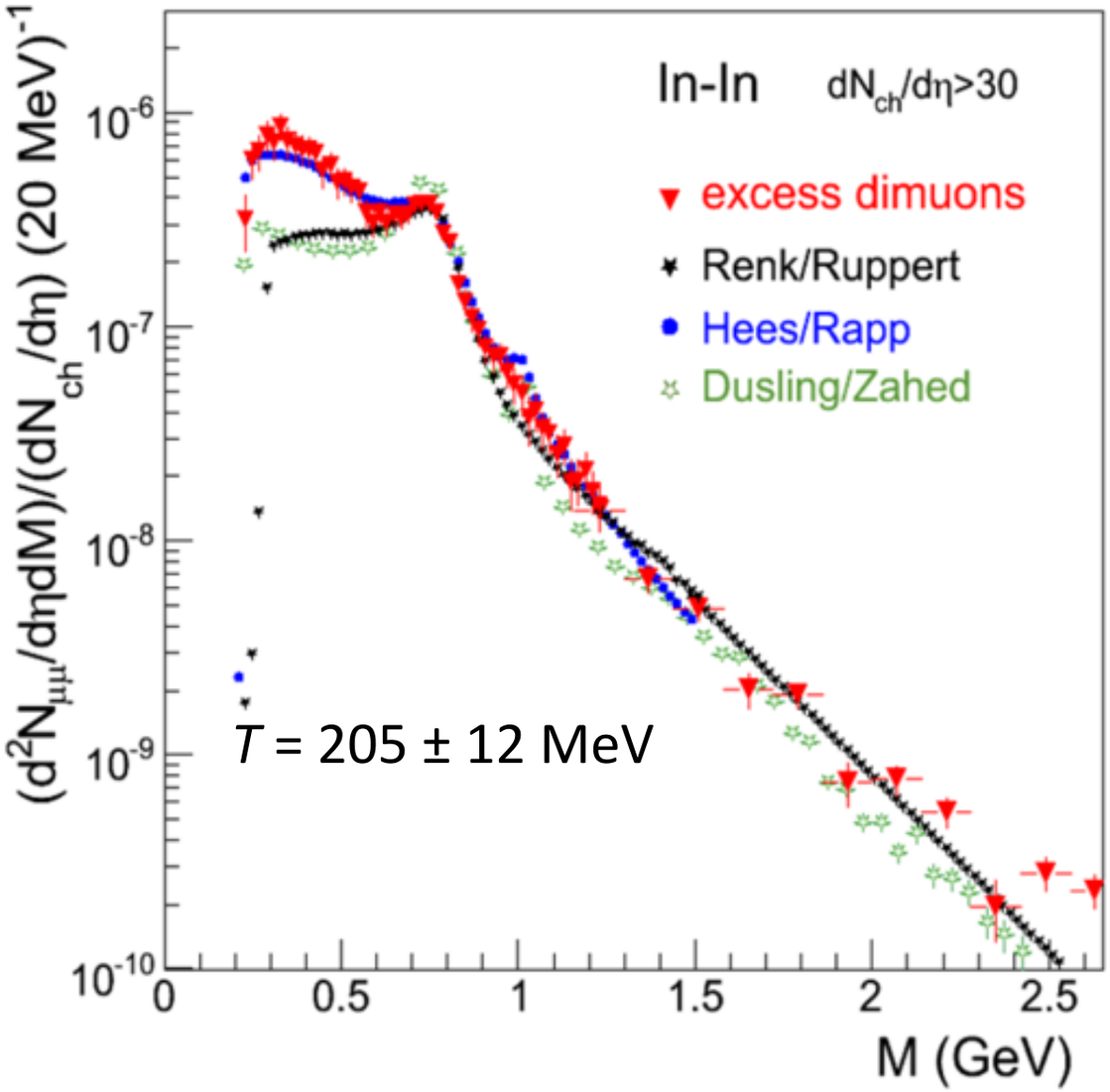


data – cocktail (except for ρ)

QGP temperature via dimuons at SPS energies?

NA60, Eur. Phys. J. C 61 (2009) 711, Eur. Phys. J. C 59 (2009) 607

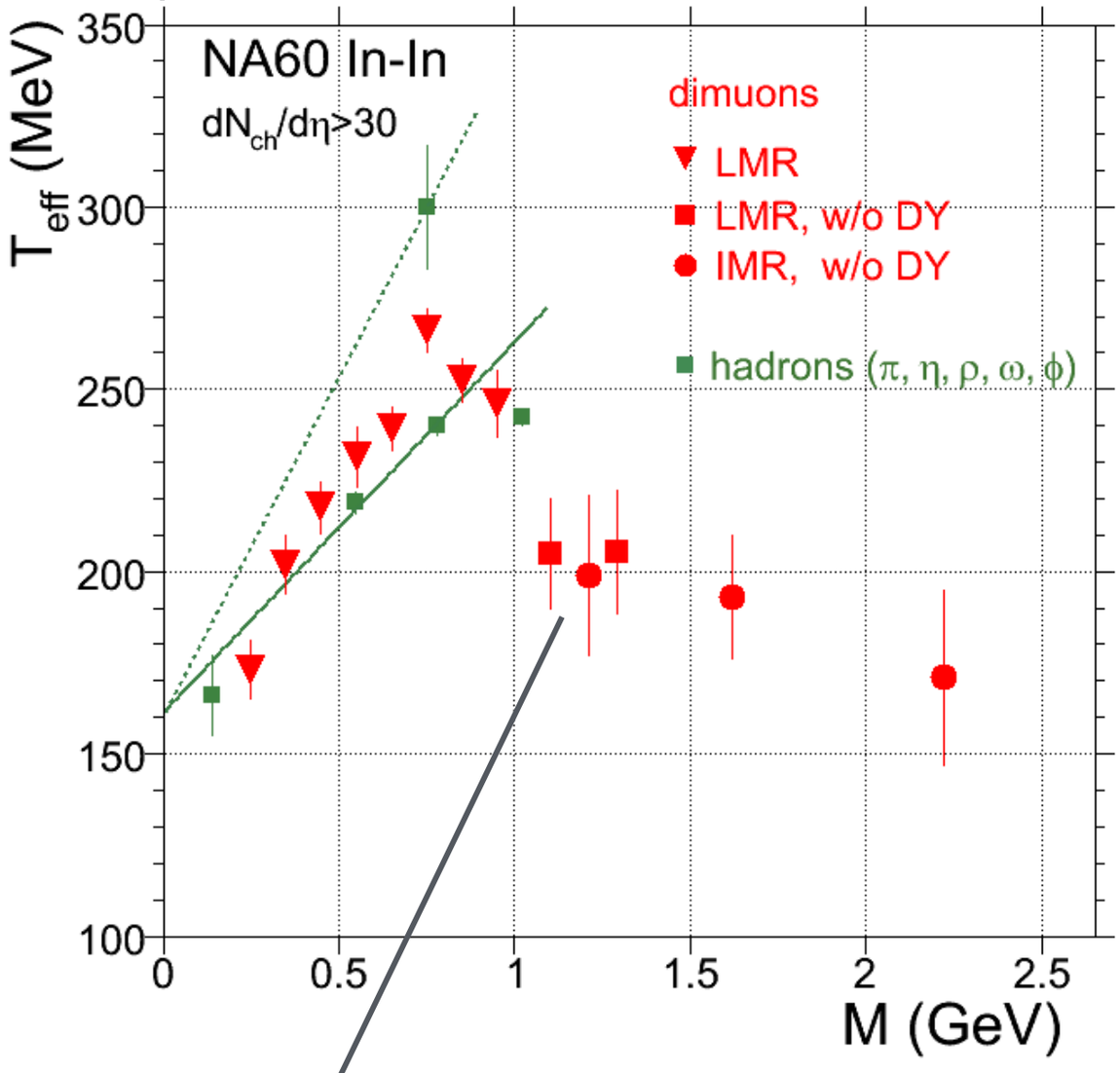
Temperature via dimuon mass spectrum: unaffected by radial flow



$$dN/dM \propto M^{3/2} \times \exp(-M/T)$$

for $M > 1$ GeV

Slope of dimuon m_T spectra: Hadron gas + flow for $M < 1$ GeV, non-flowing partonic source for $M > 1$ GeV?



$T_{eff} \approx 200$ MeV for $M > 1$ GeV consistent with slope of mass spectrum!

Summary/questions thermal photons and dileptons

- 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
- Direct photon puzzle
  - Measured yield and v_2 above state-of-the-art hydrodynamic calculations at RHIC (while these models nicely fit hadronic observables)
  - Similar trend at the LHC, but no puzzle with current uncertainties
- Di-electrons and di-muons
  - Point to modifications of the ρ meson width in a hadron gas
  - Di-muons at the CERN SPS seem to indicate $T_{QGP} \approx 200$ MeV
  - No time to cover dielectric measurements at RHIC and the LHC