Quark-Gluon Plasma Physics

11. Thermal Photons and Dileptons

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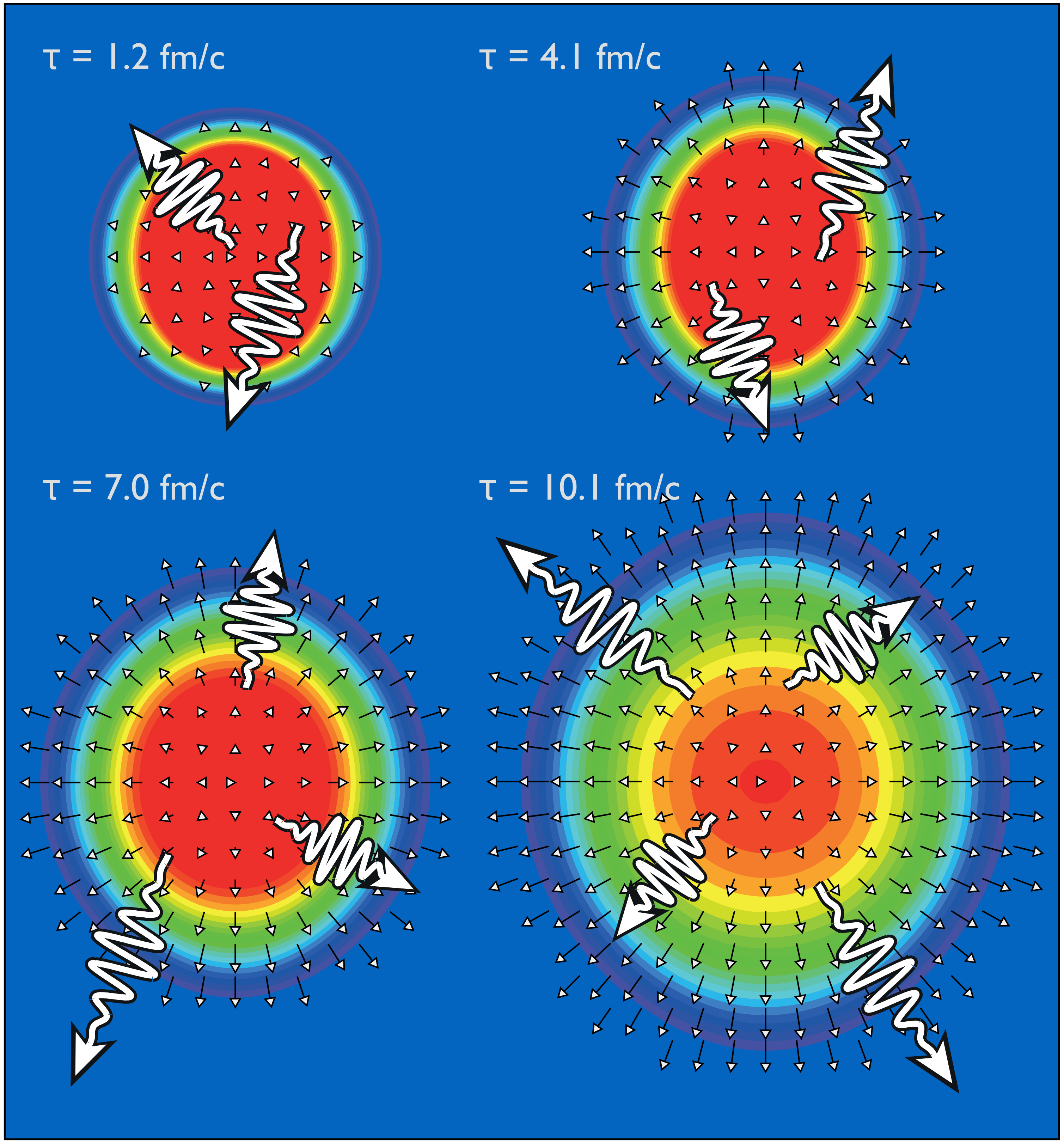
The role of direct photons in heavy-ion physics



- 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 (?)

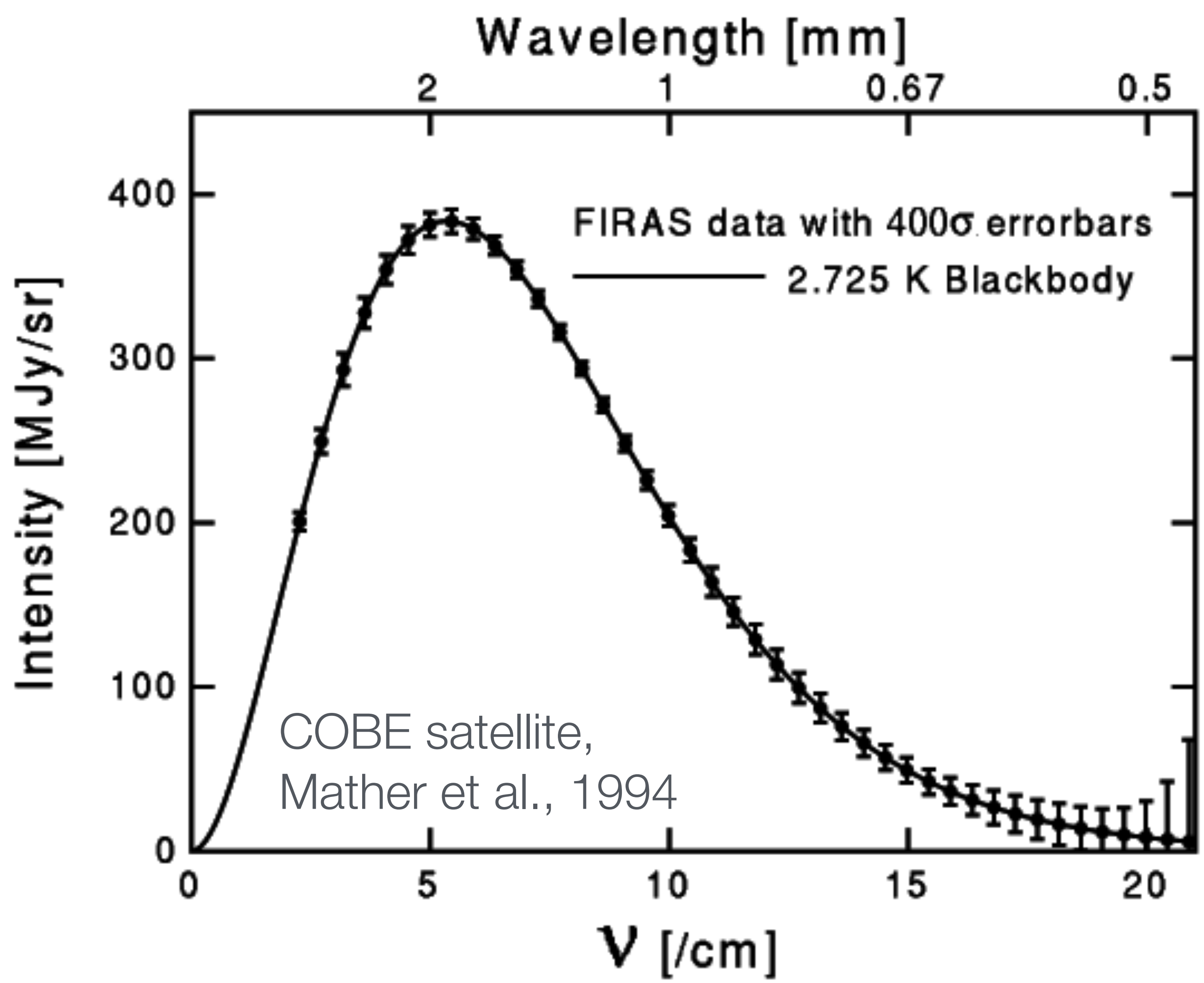
QGP photon rate r_γ (lowest order):

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

Total emission rate:

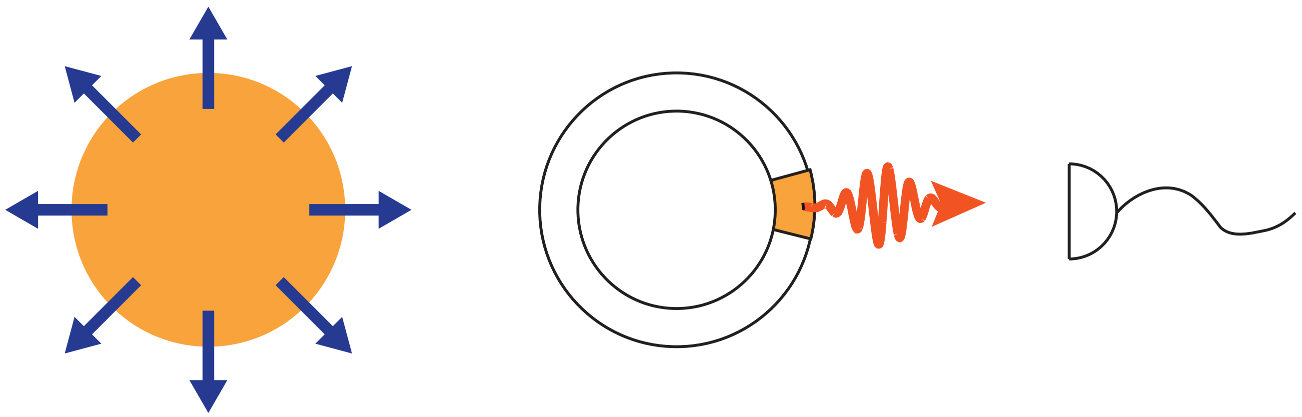
$$r_\gamma \propto T^4$$

Example:
Temperature of the universe from Planck spectrum



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

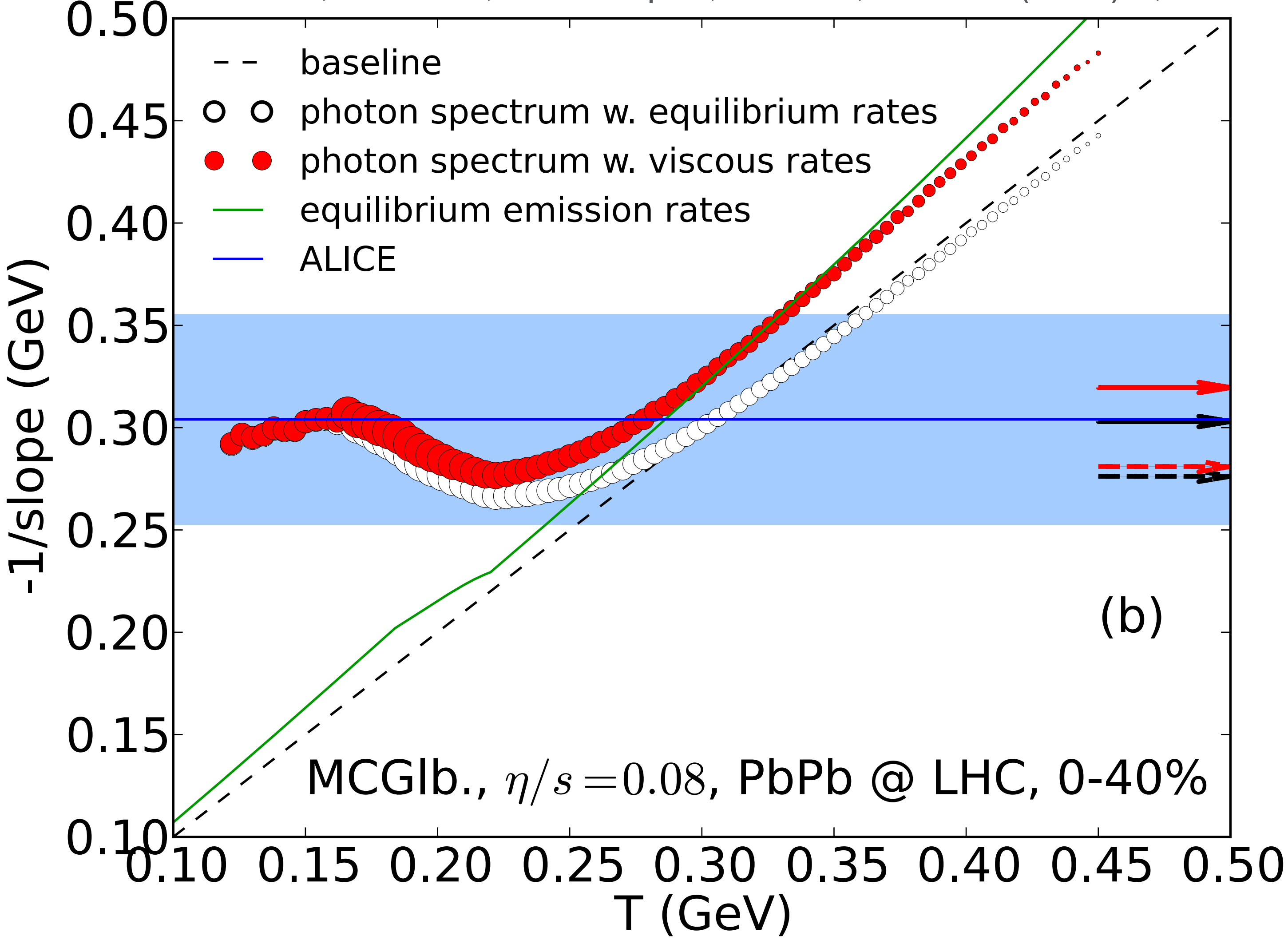
A complication for the temperature measurement: Blueshift due to radial flow



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

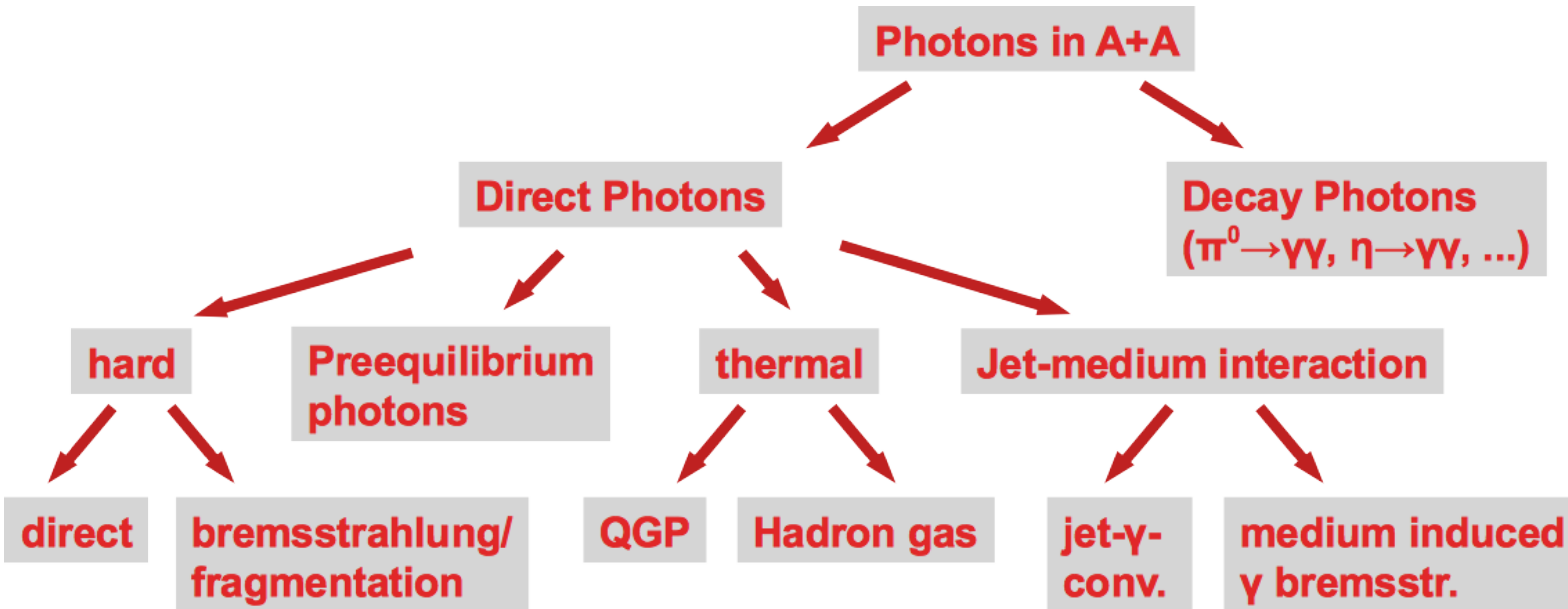
$$T_{\text{eff}} = \underbrace{\sqrt{\frac{1 + \beta_{\text{flow}}}{1 - \beta_{\text{flow}}}}}_{2 \text{ for } \beta_{\text{flow}} = 0.6} \times T$$

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

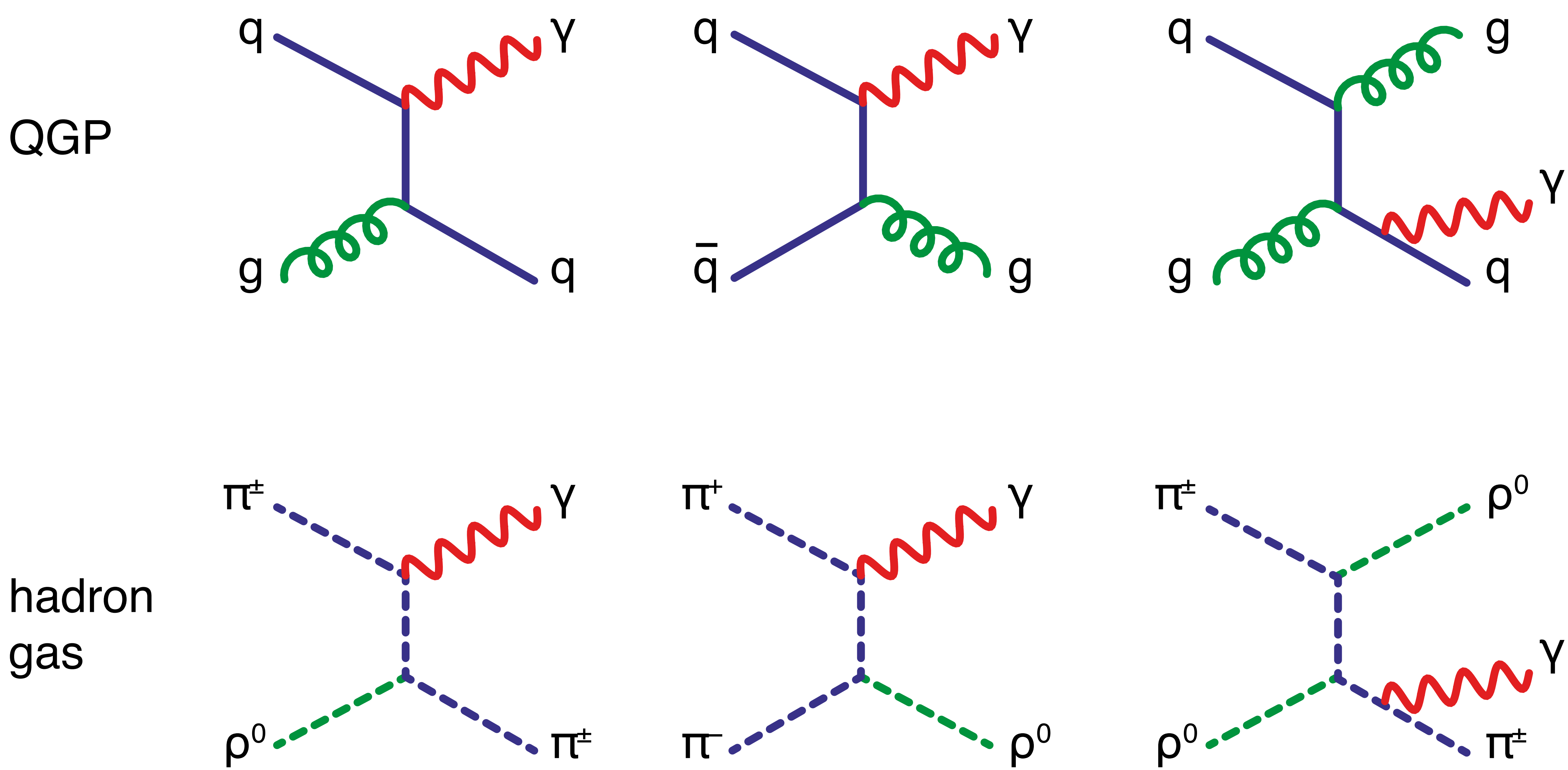
Known and expected photon sources in heavy-ion collisions



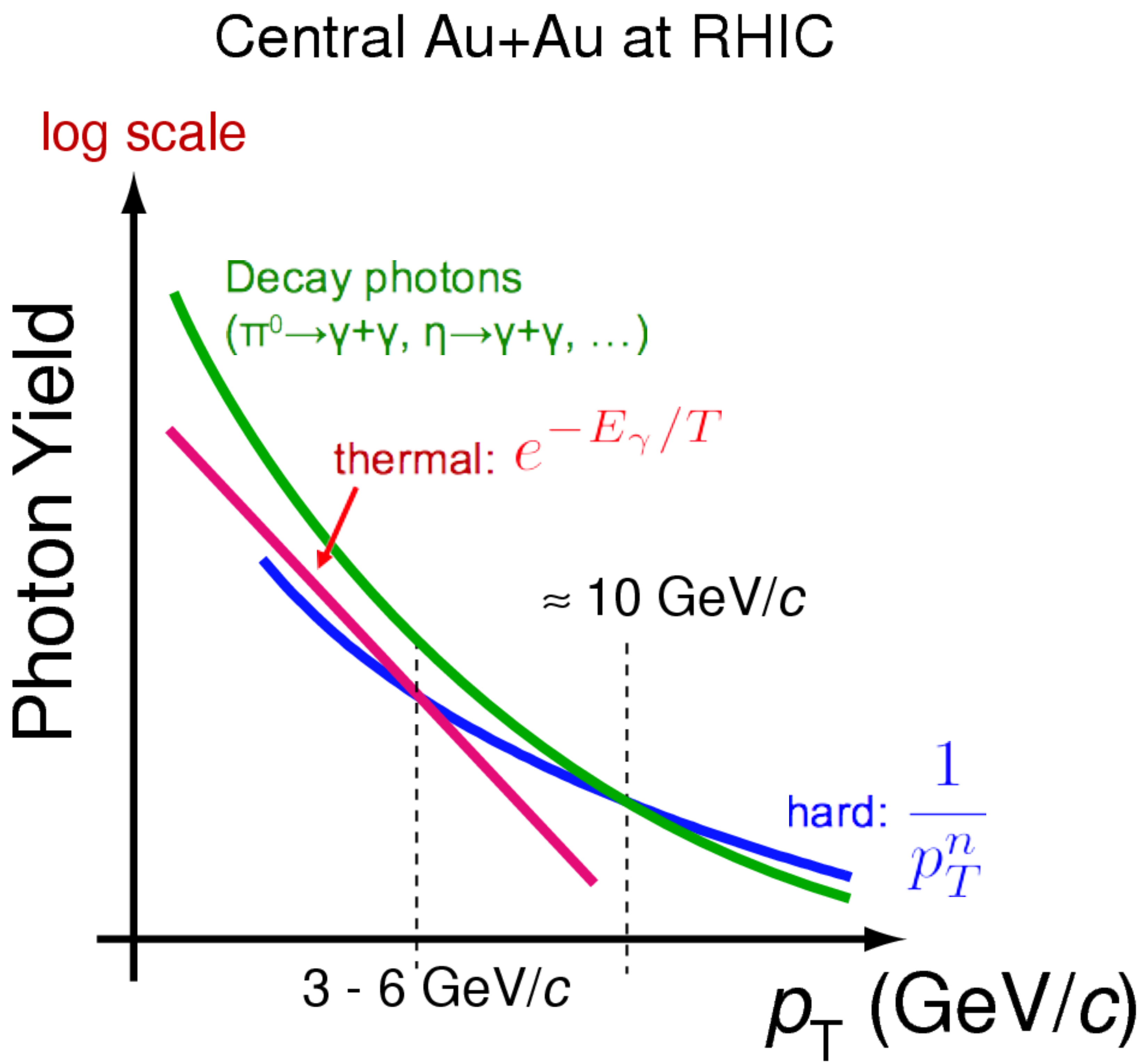
$$\gamma_{\mathrm{direct}} := \gamma_{\mathrm{incl}} - \gamma_{\mathrm{decay}}$$

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

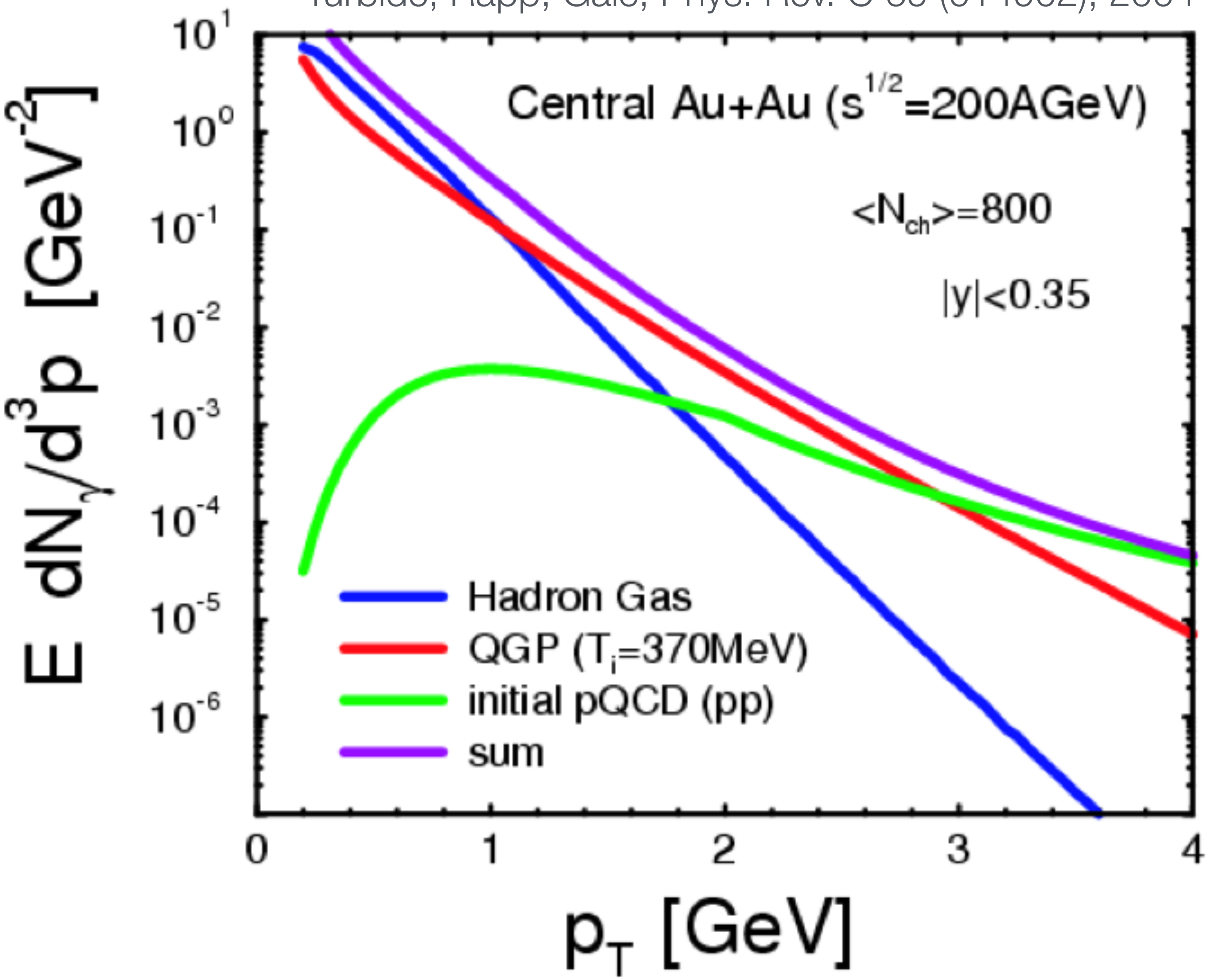


Schematic photon spectrum in A+A collisions



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

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

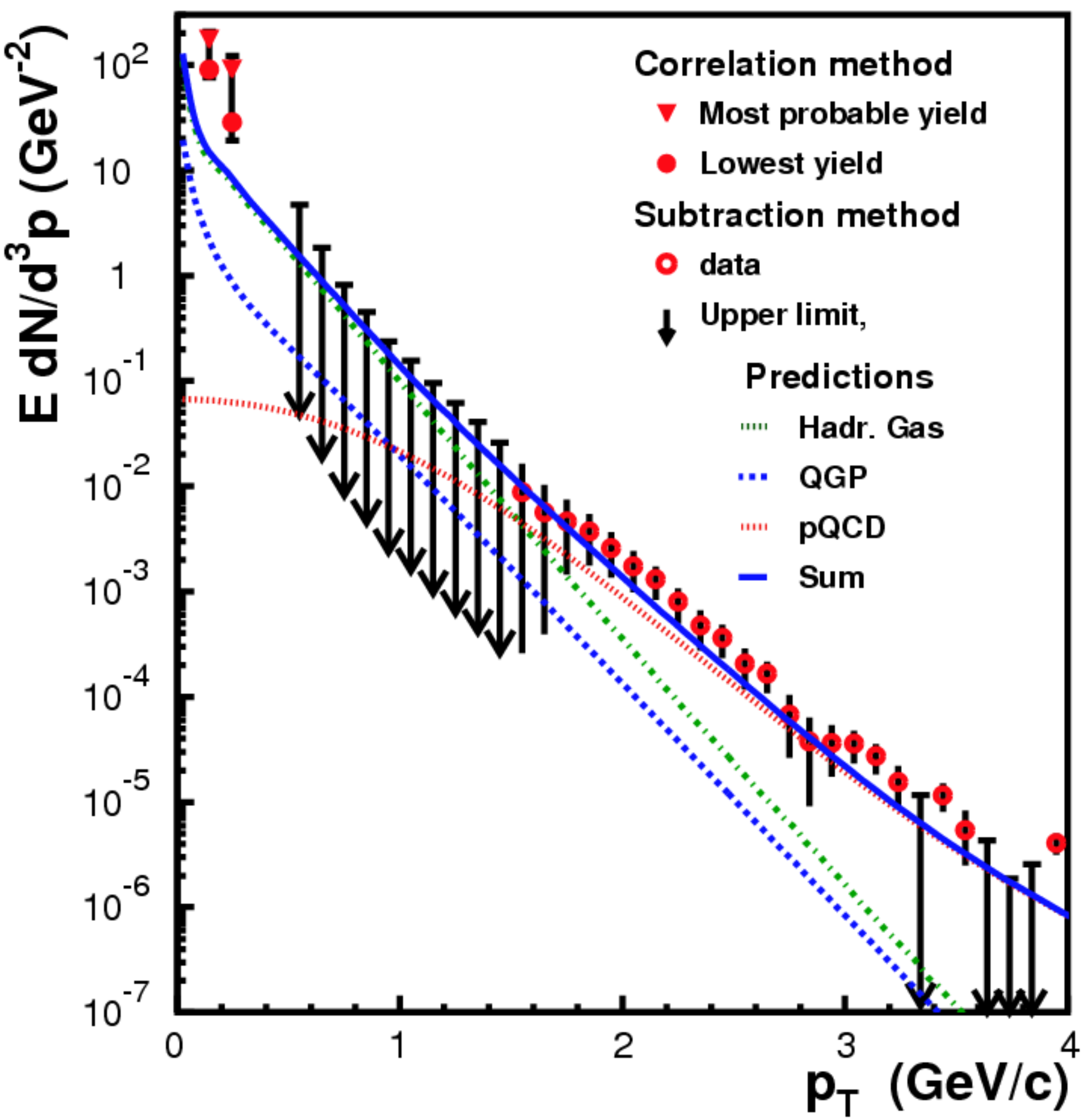
$$R_\gamma = \frac{\gamma_{\mathsf{incl}}}{\gamma_{\mathsf{decay}}} \equiv \boxed{\frac{\gamma_{\mathsf{incl}}}{\pi^0_{\mathsf{param}}}} \Big/ \boxed{\frac{\gamma_{\mathsf{decay}}}{\pi^0_{\mathsf{param}}}}$$

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



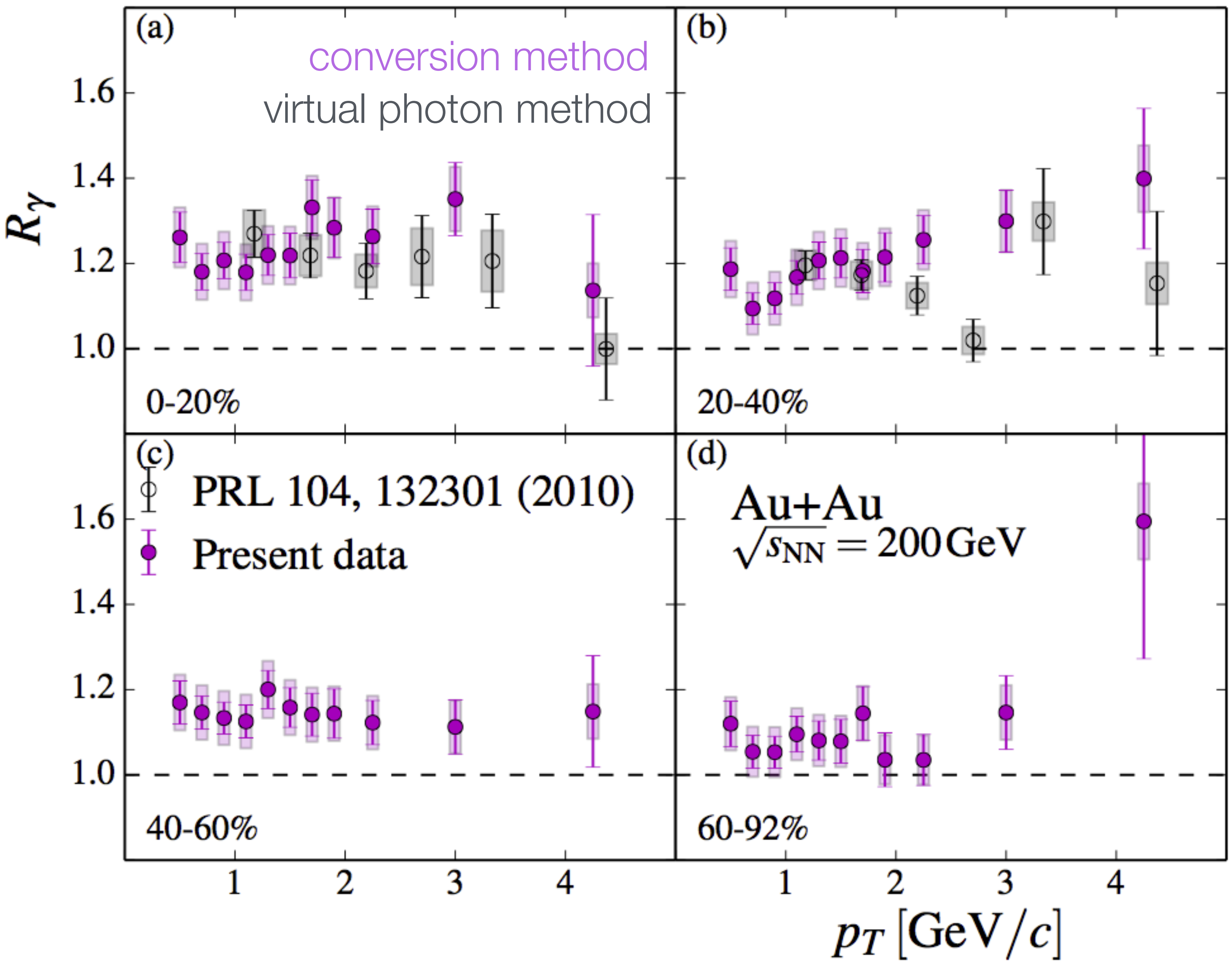
Consistent with QGP scenario, but data can also be explained without a QGP

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

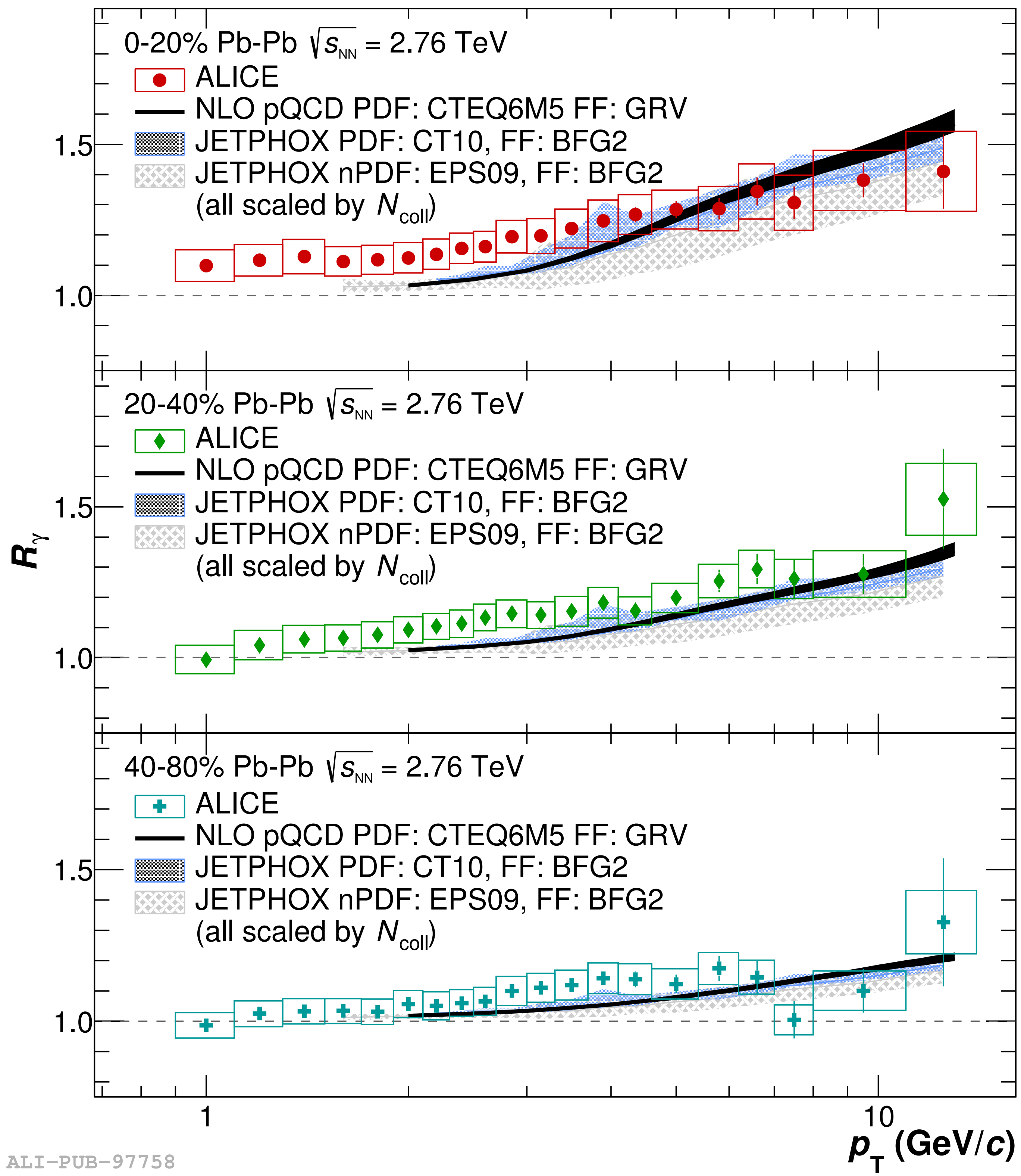
$$R_\gamma = \frac{\gamma_{incl}}{\gamma_{decay}}$$

PHENIX, arXiv:1405.3940



- Two experimental techniques
  - Virtual photons ($\gamma^* \to e^+e^-$), 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



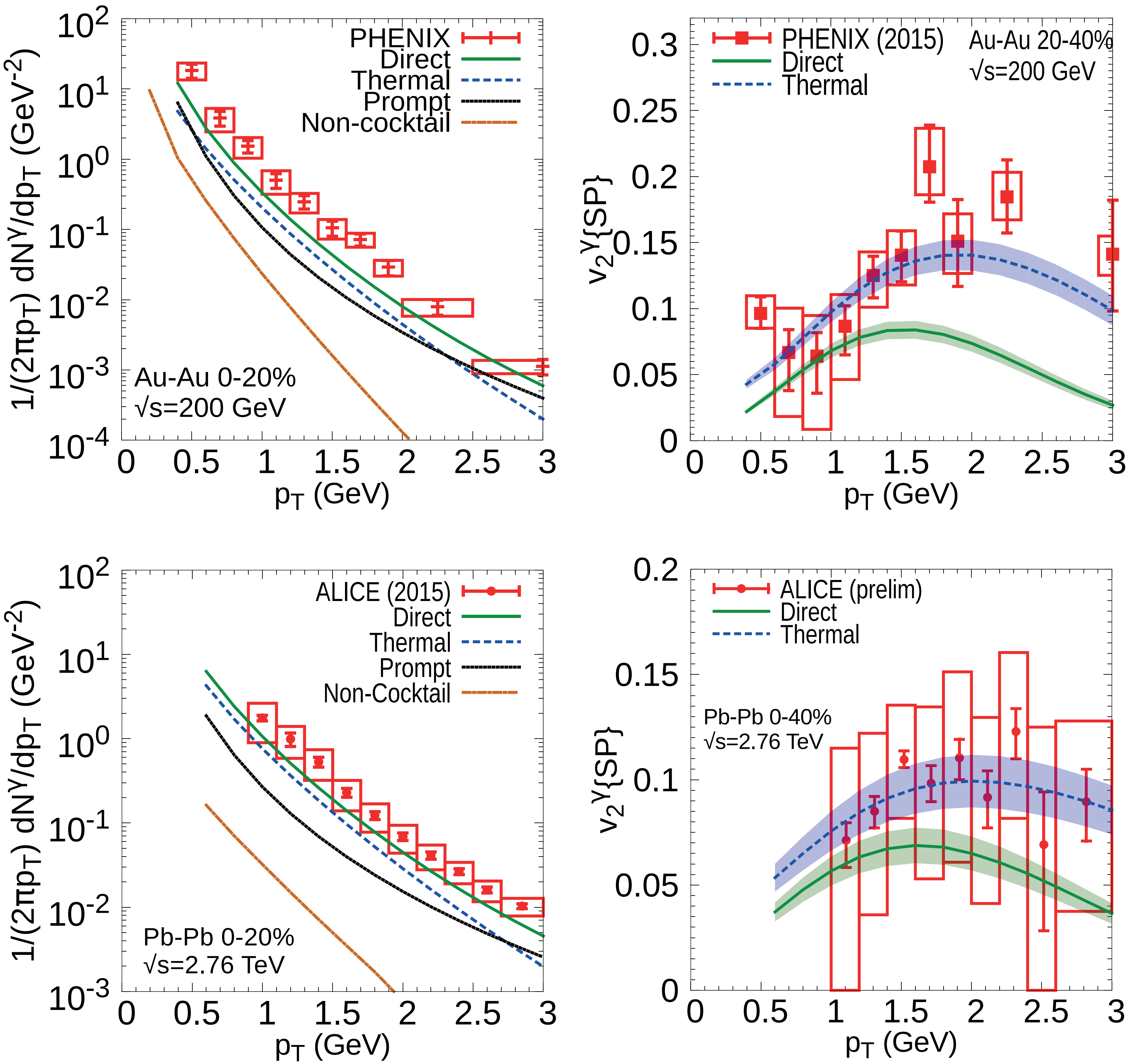
$$R_\gamma^{\mathrm{pQCD}} = 1 + N_{\mathrm{coll}} \frac{\gamma_{\mathrm{pQCD}}}{\gamma_{\mathrm{decay}}}$$

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

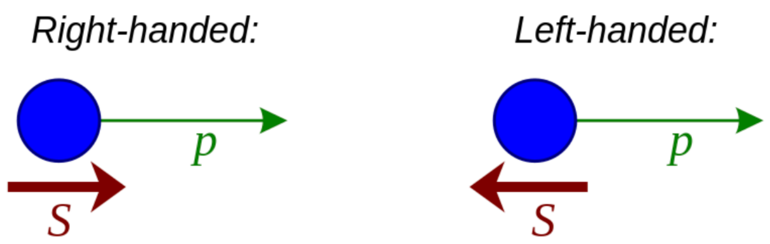
Plots: Paquet et al., arXiv:1509.06738

Chiral symmetry

Consider a u,d-quark spinor $q(x) = \begin{pmatrix} u(x) \\ d(x) \end{pmatrix}$. One can introduce right-handed and left-handed quark fields (projections with positive/negative chirality):

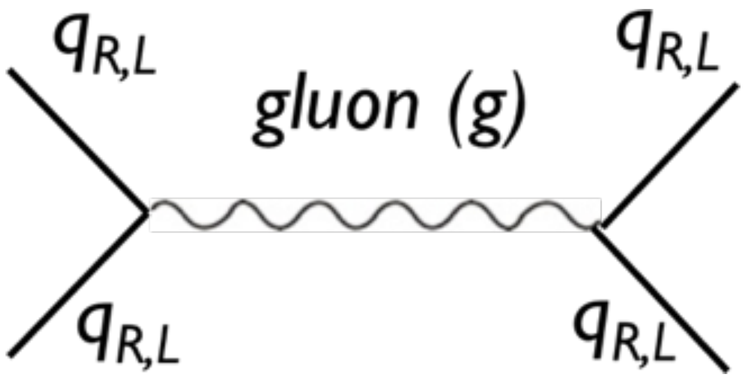
$$q_{\mathrm{R,L}} = \frac{1}{2}(1 \pm \gamma_5)q$$

For massless particles (photons, gluons) chirality is the same as helicity.



For massless quarks (m_q = 0), the QCD Lagrangian has a **global symmetry** related to the **conserved right- or left-handedness** (chirality) of the massless spin 1/2 particles.

The right- and left-handed components of the massless quark fields do not mix. Right-handed quarks stay right-handed, left-handed quarks stay left-handed.



Chiral symmetry breaking

At low temperatures, the chiral symmetry is spontaneously broken.

The order parameter is the chiral condensate:

$$\langle \bar{q} q \rangle \neq 0 \quad \text{for} \quad T < T_c$$

Chiral symmetry is restored above T_c.

Vacuum expectation value of the quark condensate:

$$\langle 0 | \bar{q} q | 0 \rangle \approx (-250\,\text{MeV})^3$$

corresponds to 5 quark-antiquark pairs per fm^3

The spontaneous breaking of a global symmetry is accompanied by **(almost) massless Goldstone bosons**. For two quark flavors, these are the pions which are much lighter than other hadrons (e.g. $m_\pi \approx 140$ MeV $\ll m_{proton}$).

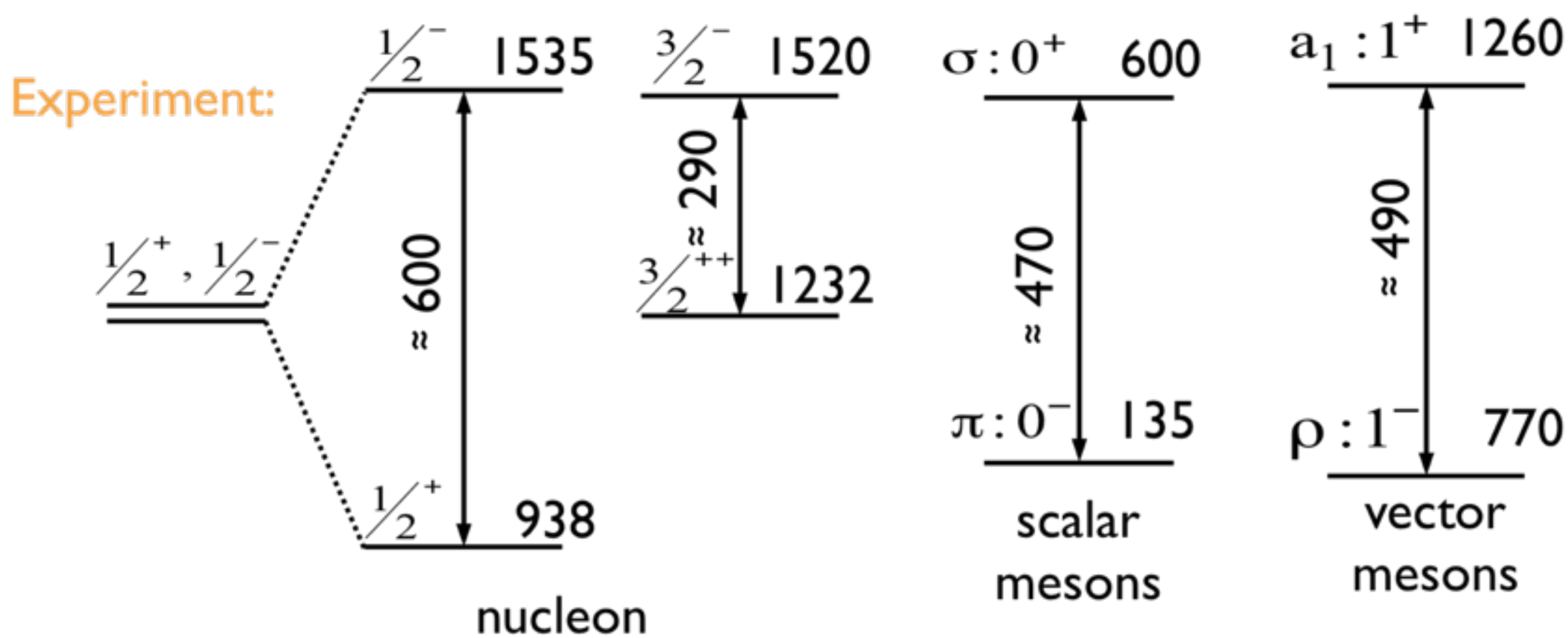
The small u,d quark masses break chiral symmetry explicitly, but this can be considered a small effect for low-energy QCD.

Chiral symmetry breaking and the hadron spectrum

The quark condensate cannot be directly observed. However, it affects the hadron spectrum.

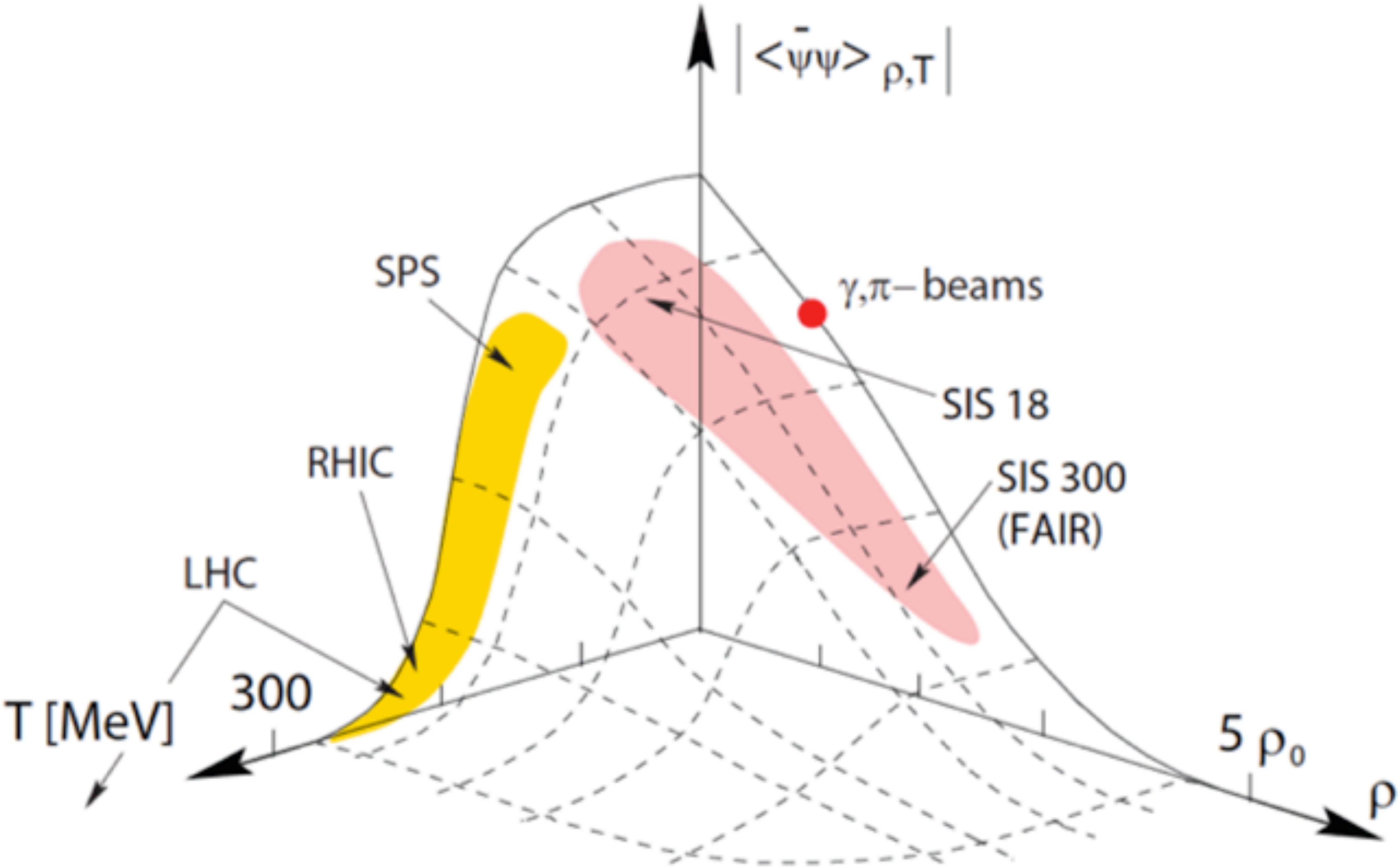
If the ground state were chirally symmetric, chiral partners (e.g. the ρ and the a_1 meson) would have the same mass.

Experimentally, a large mass splitting is observed:



The restoration of chiral symmetry affects hadron properties: Chiral partners become degenerate (significant modifications of the hadron "spectral function").

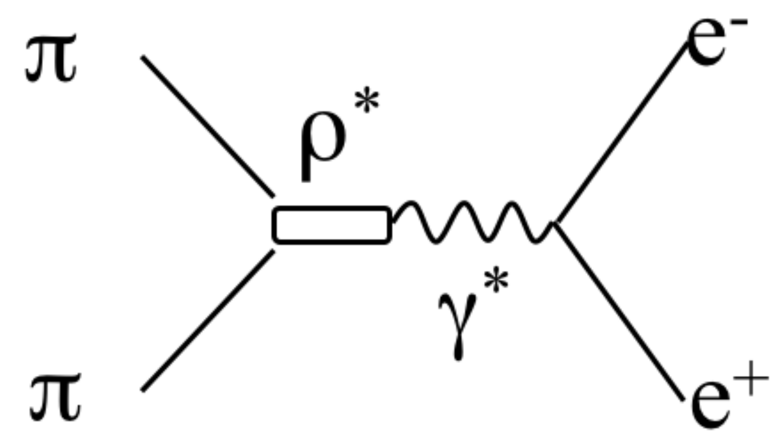
Chiral condensate as a function of temperature and density



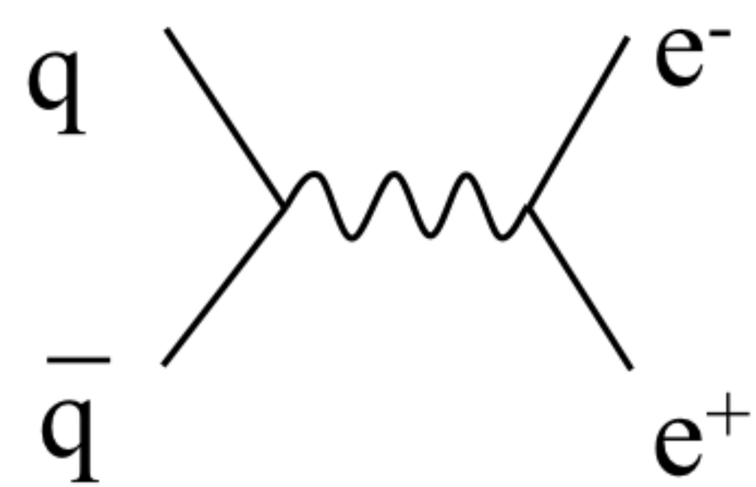
Dileptons: Motivation

- Like photons, negligible final state interaction
- Flip side: rare probe, $N_{ee}/N_{hadron} \approx 10^{-4}$
- Search for in-medium modifications of vector mesons (M_{ee} < 1 GeV)
  - ρ can decay in the medium ($\tau_{\rho,\mathrm{vacuum}} \approx 1.3$ fm/c < medium lifetime)
  - Broadening of the ρ in the medium, relation to chiral symmetry restoration?
- Thermal radiation from the QGP and access to early temperature? (M_{ee} > 1 GeV)
  - spectrum ~ $(m_{ee}T)^{3/2} \exp(-m_{ee}/T)$
- 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

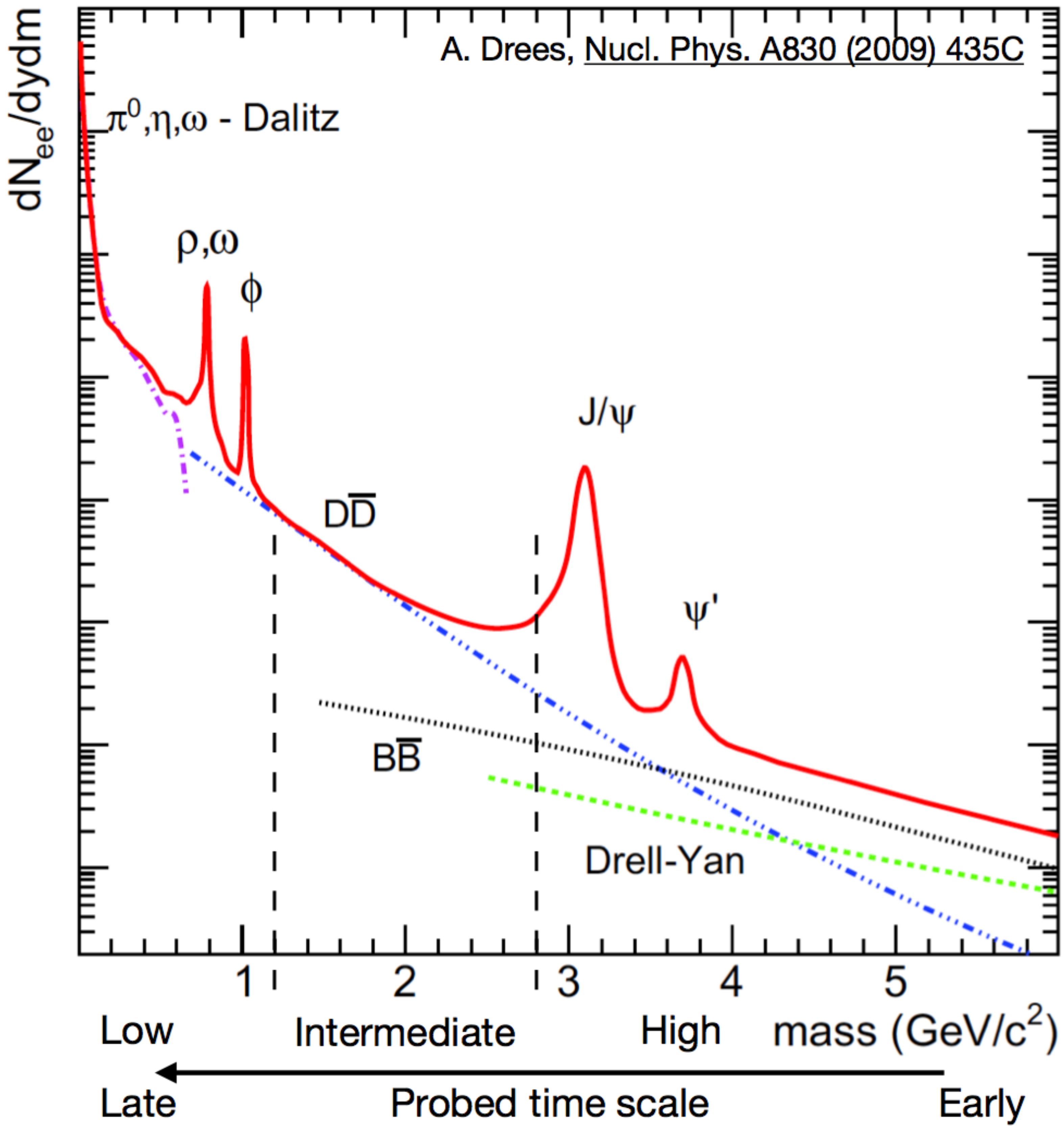
hadron gas



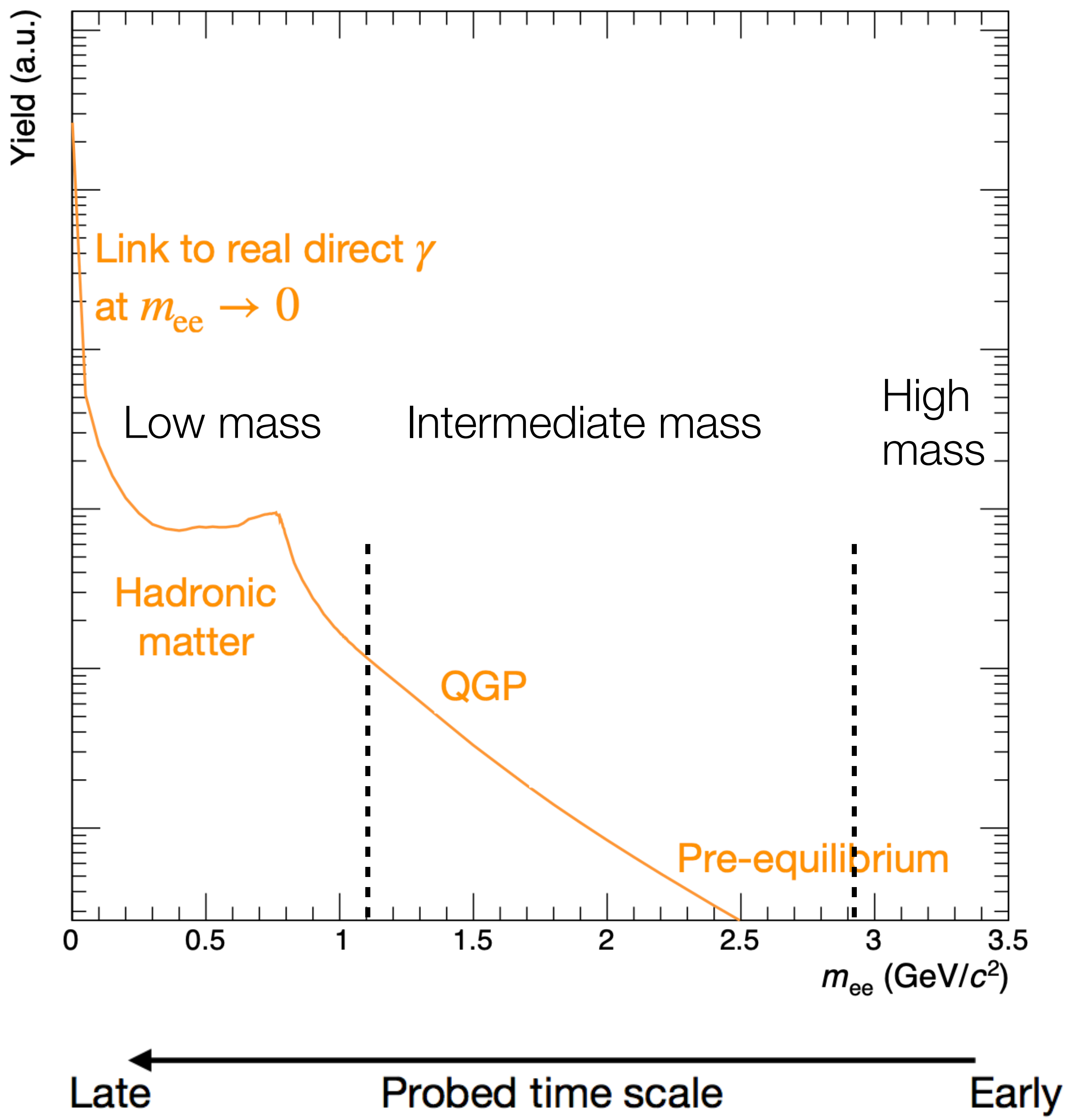
quark-gluon plasma



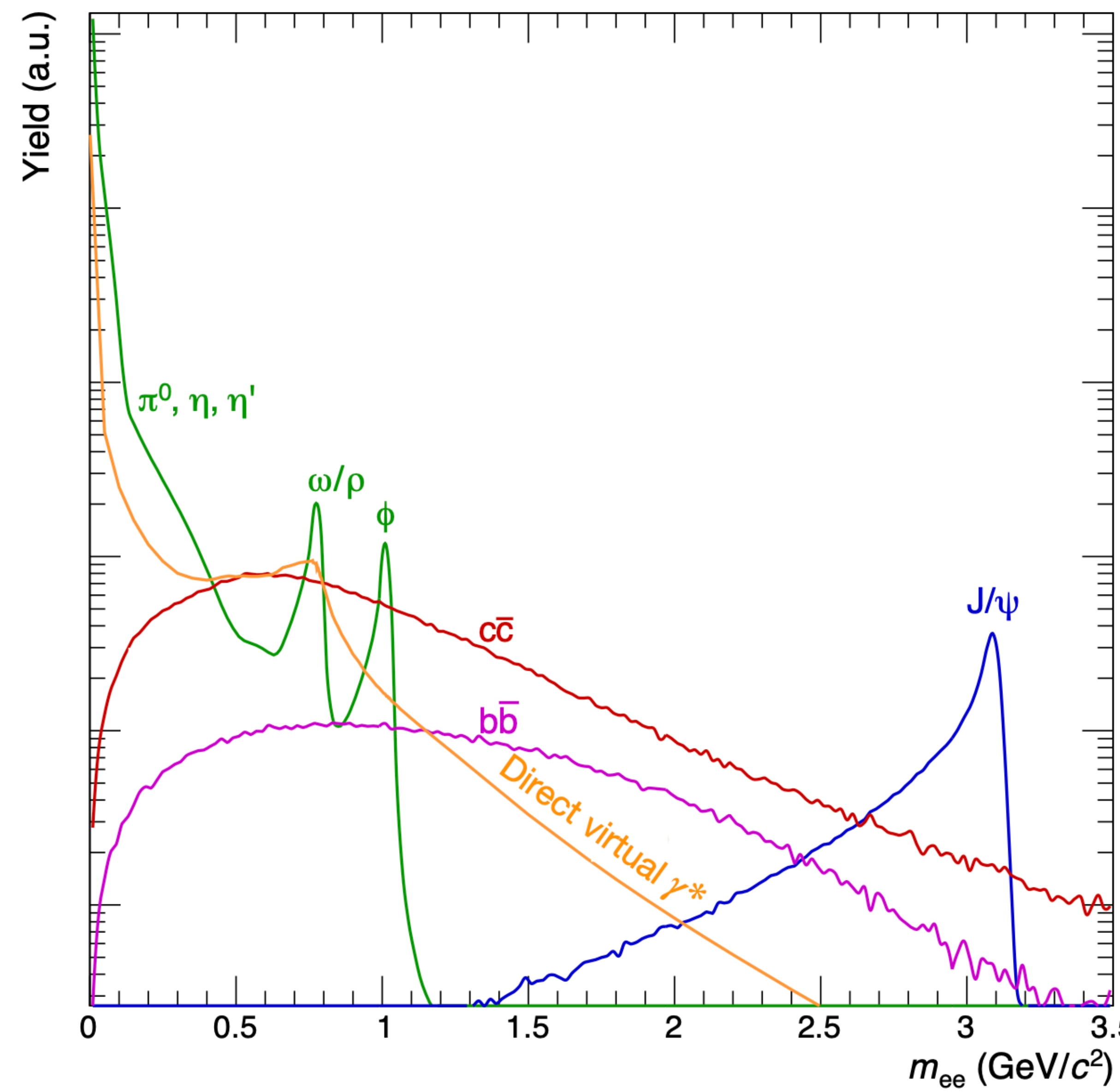
Schematic dilepton mass spectrum



Schematic dilepton mass spectrum at LHC energies: Signal and background

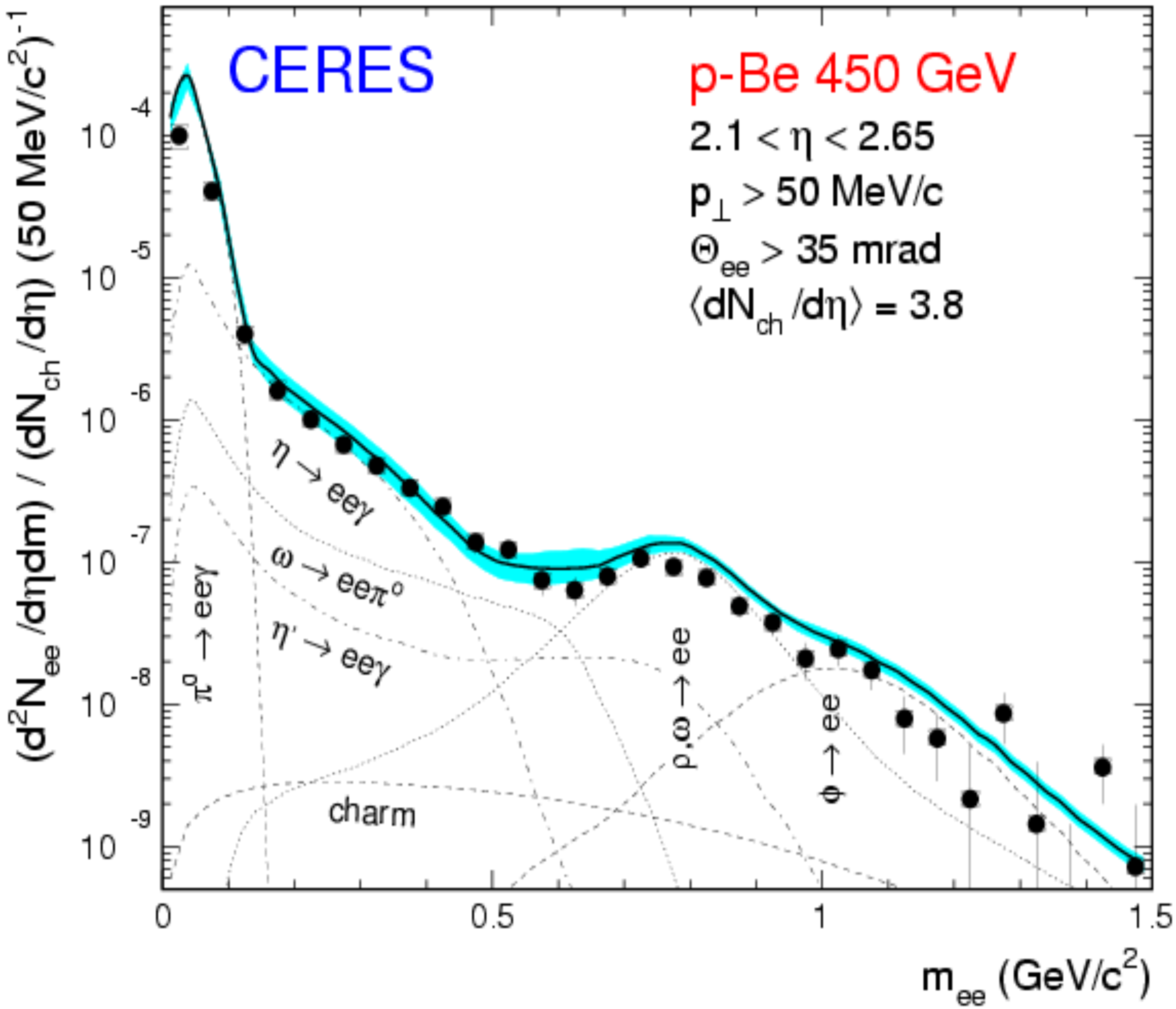


Raphaelle Bailhache, Hard Probes 2023



CERN SPS results: p+A

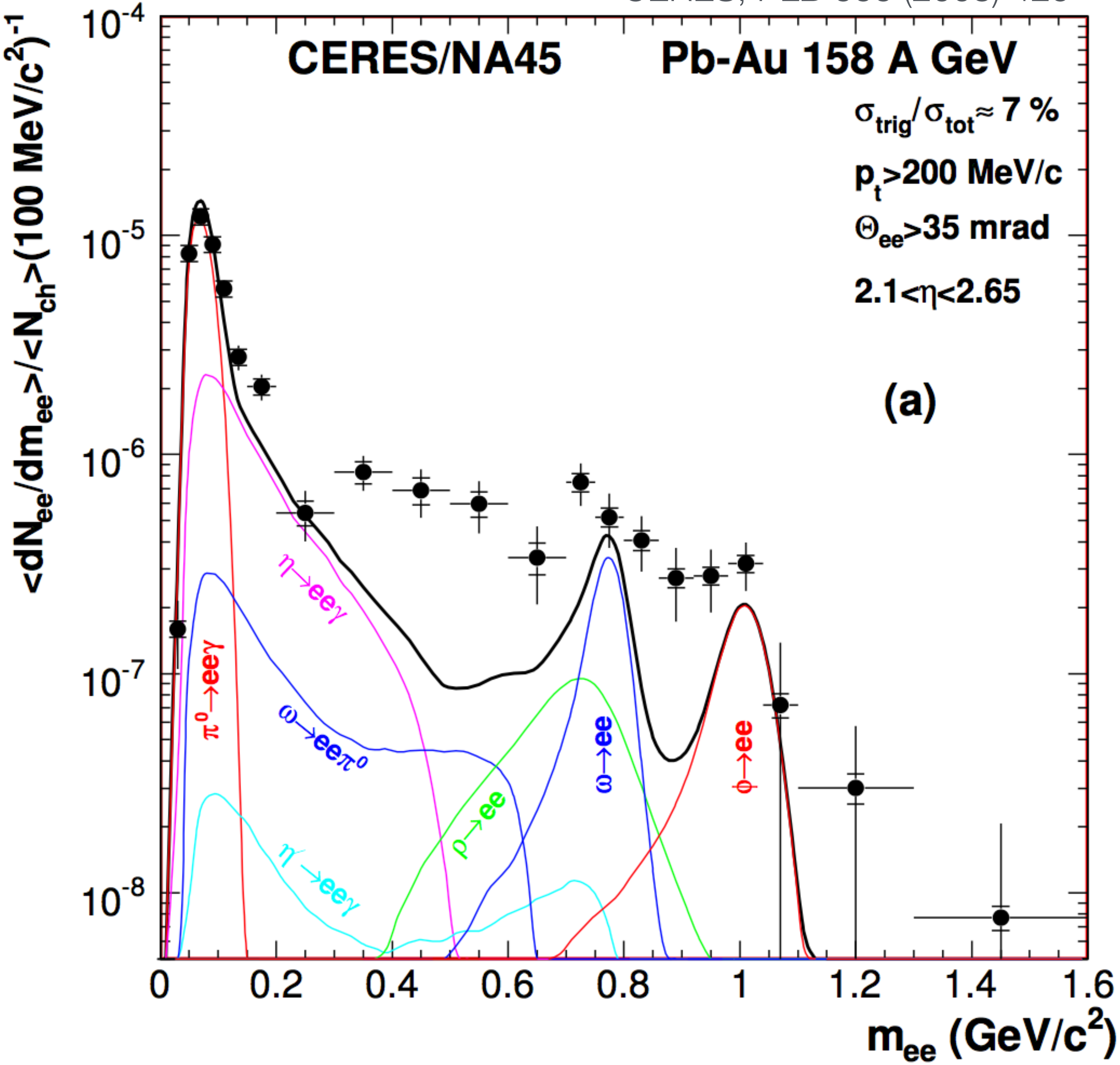
CERES, EPJ C 41 (2005) 475



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



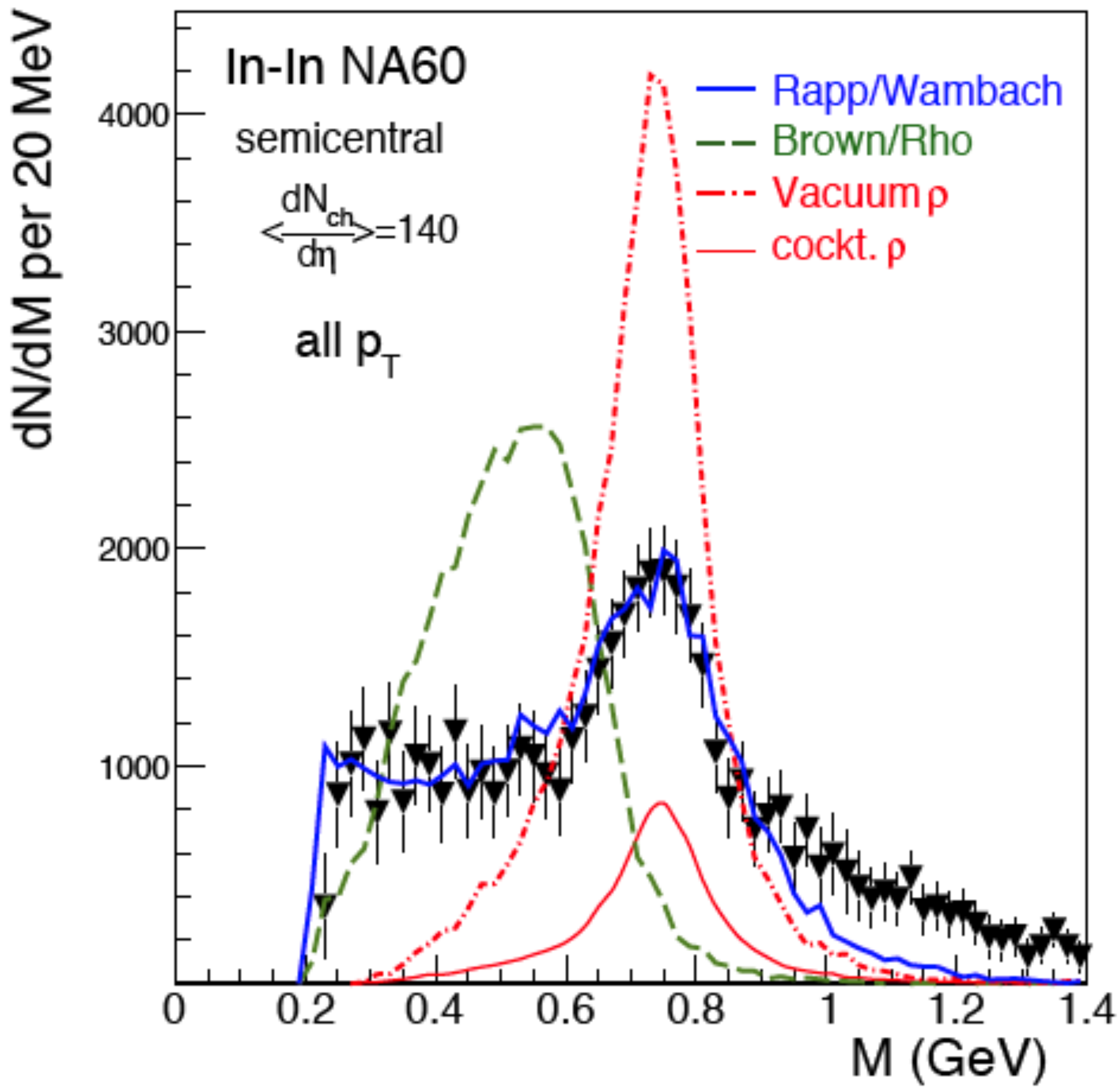
Significant excess above cocktail in Pb-Au

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

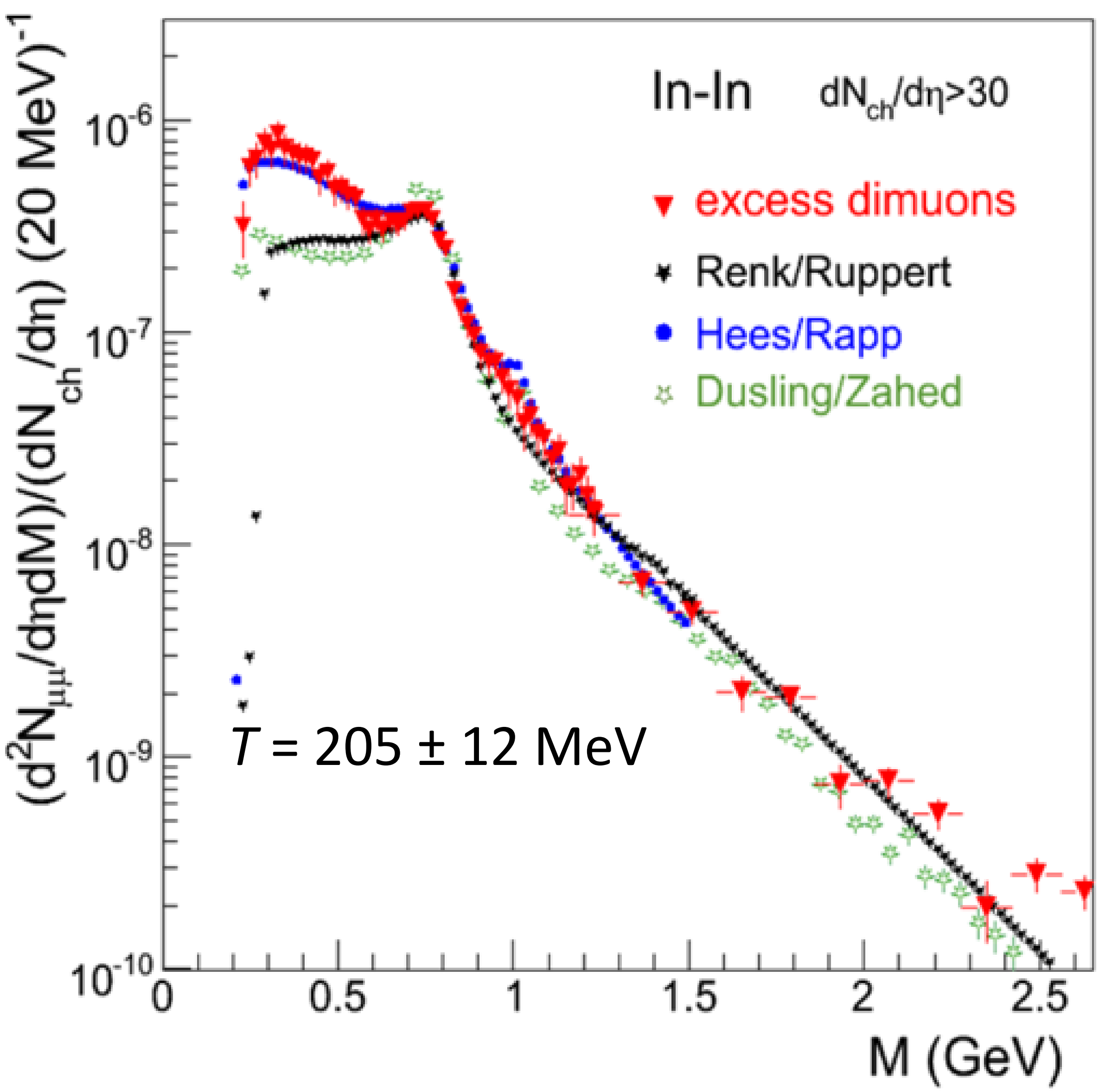


data – cocktail (except for ρ)

QGP temperature via dimuons at SPS energies?

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

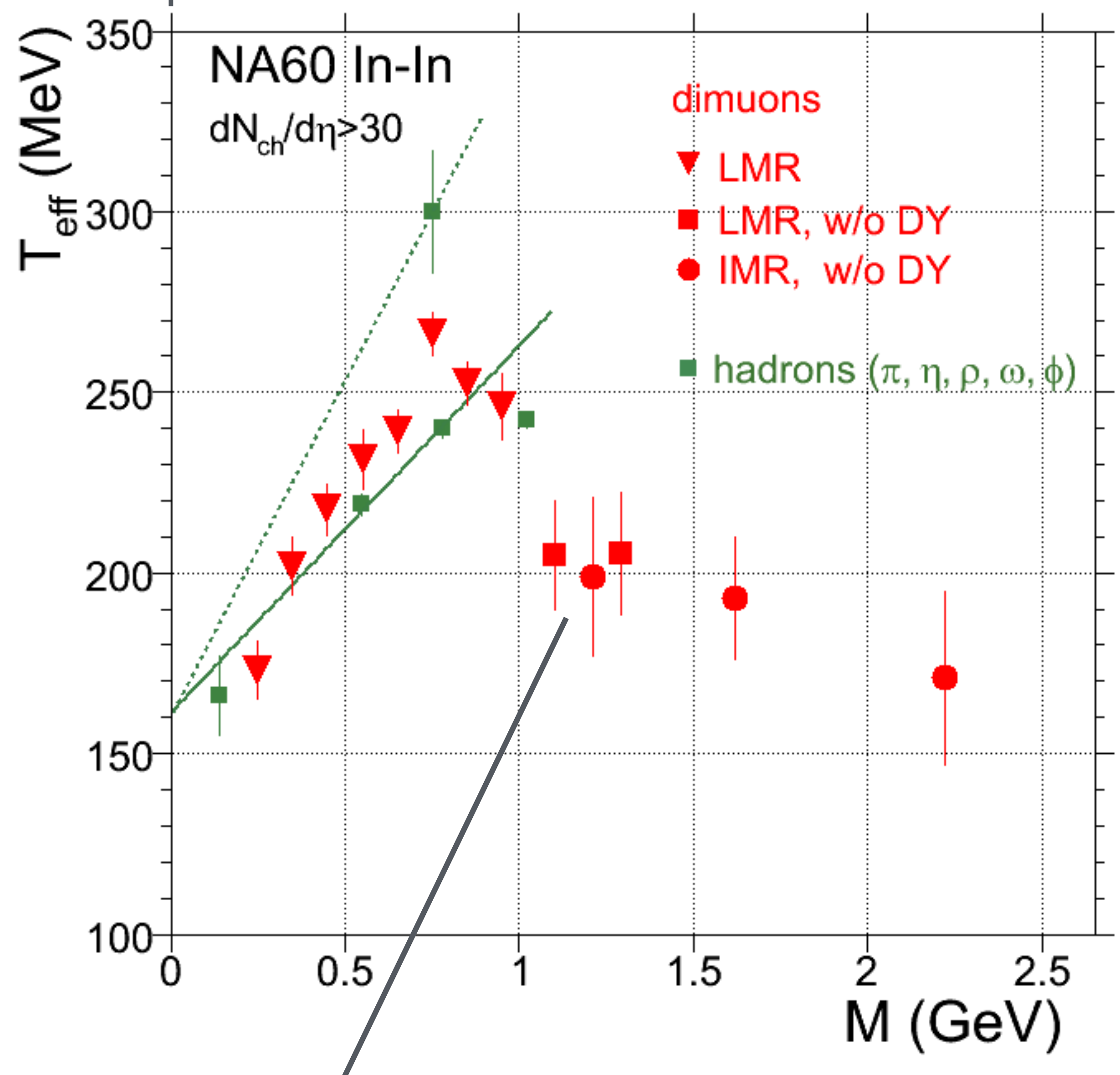
Temperature via dimuon mass spectrum: unaffected by radial flow



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

for $M > 1$ GeV

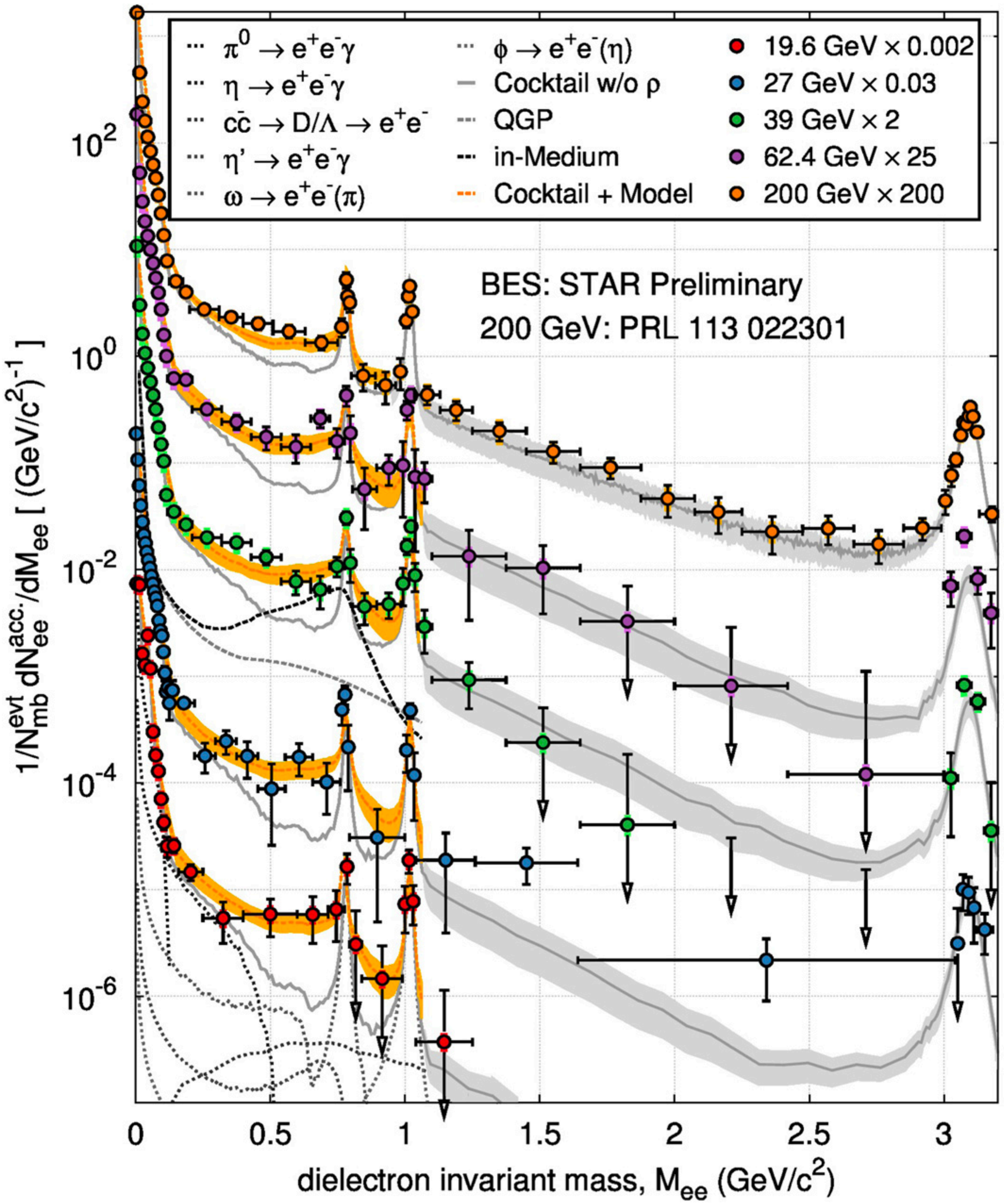
Slope of dimuon m_T spectra: Hadron gas + flow for $M < 1$ GeV, non-flowing partonic source for $M > 1$ GeV?



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

Dielectrons at RHIC

Nuclear Physics A 931 (2014) 1–12



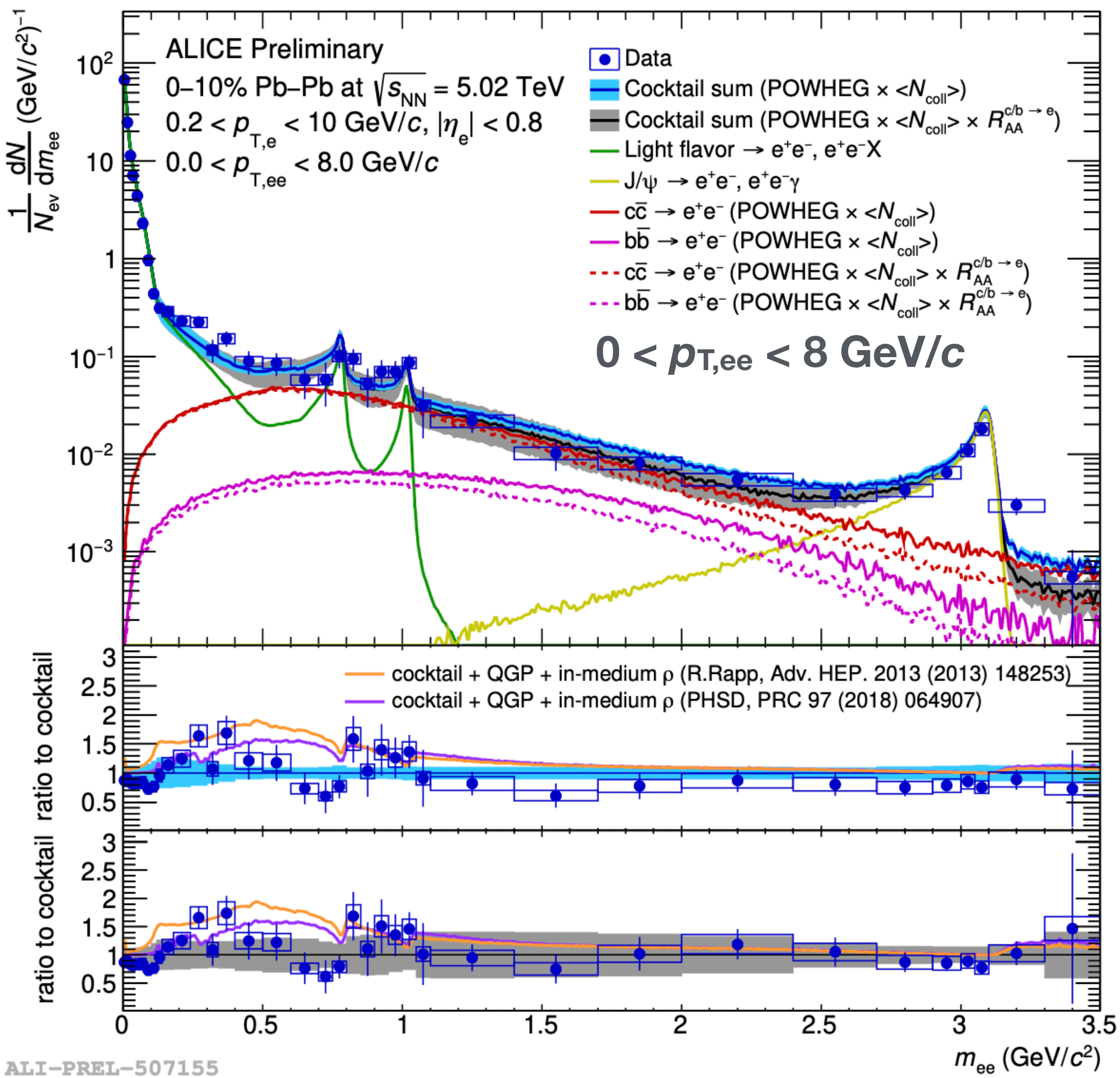
Excess above cocktail observed below the ρ mass at all center-of-mass energies.

Model with model meson–baryon re-scattering during the evolution describes the data.

Enhancement explained by broadening of the ρ meson ("melting ρ scenario")

However, connection to chiral symmetry restoration still debated.

Dileptons at the LHC



No significant excess above the hadronic cocktail within uncertainties

Need more statistics to be sensitive to medium effects.

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