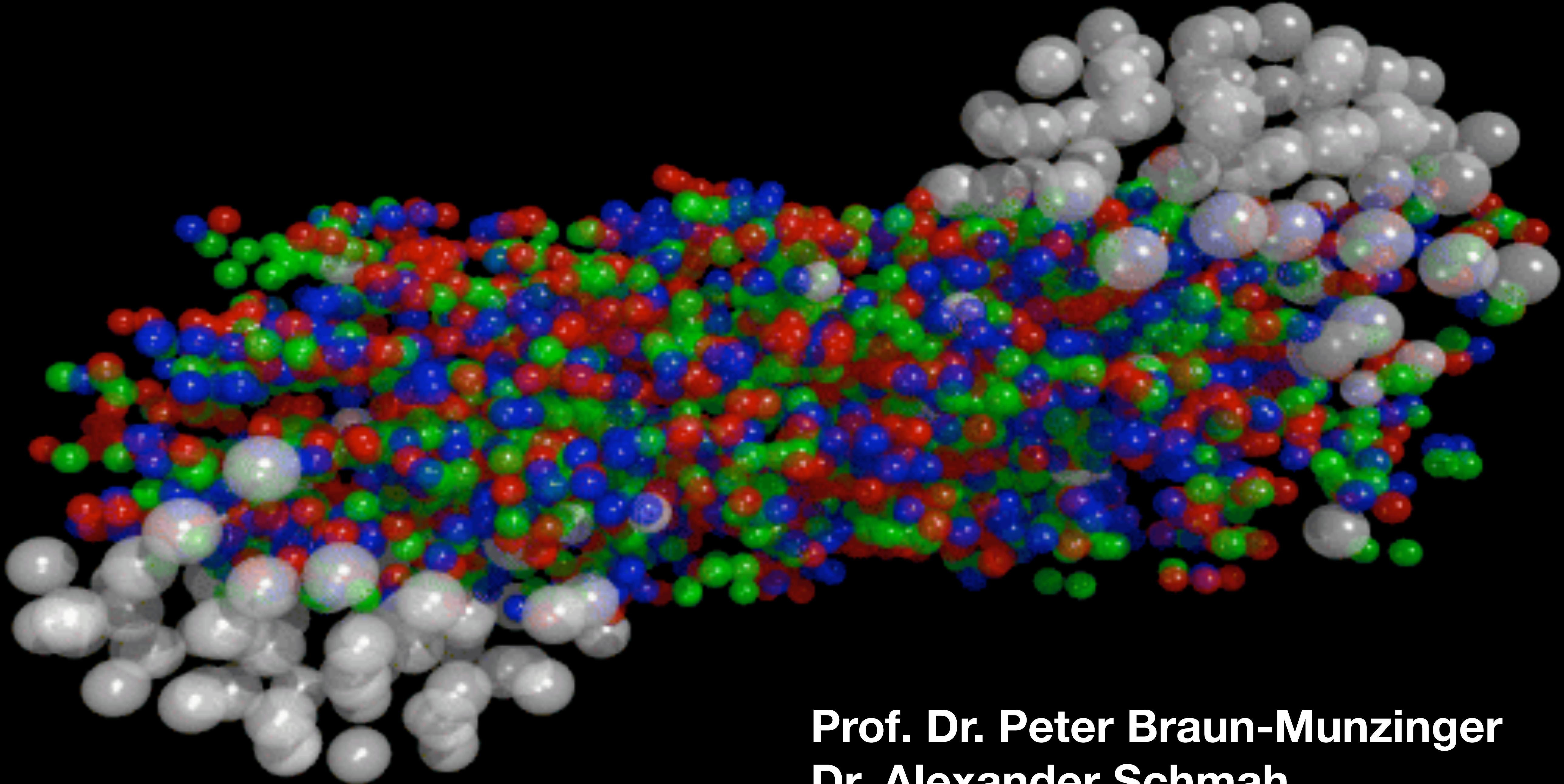
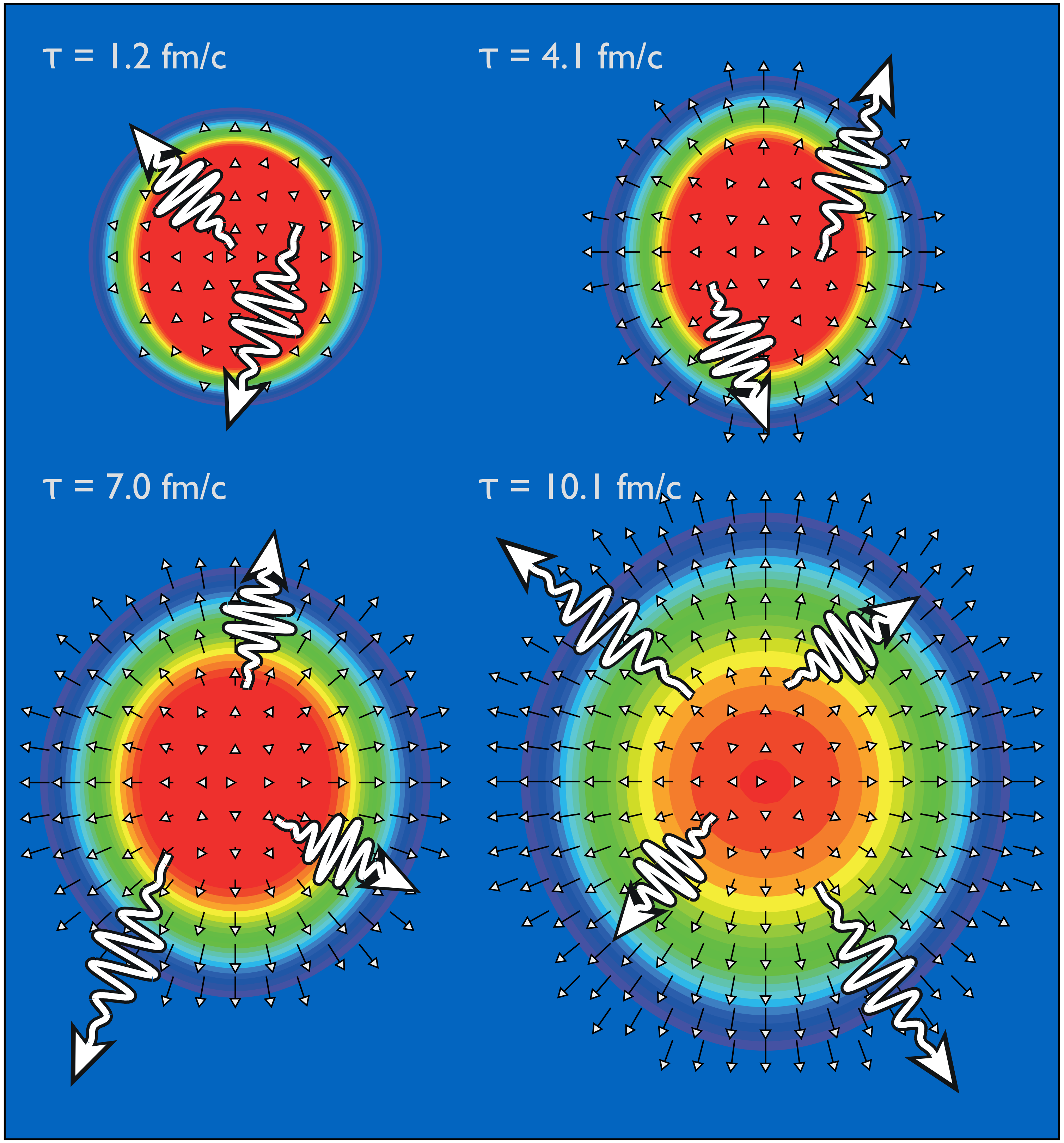
Quark-Gluon Plasma Physics

11. Thermal Photons and Di-Leptons



Prof. Dr. Peter Braun-Munzinger
Dr. Alexander Schmah
Heidelberg University
SS 2021

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 (?)

Annu. Rev. Nucl. Part. Sci. 2005. 55:517–54

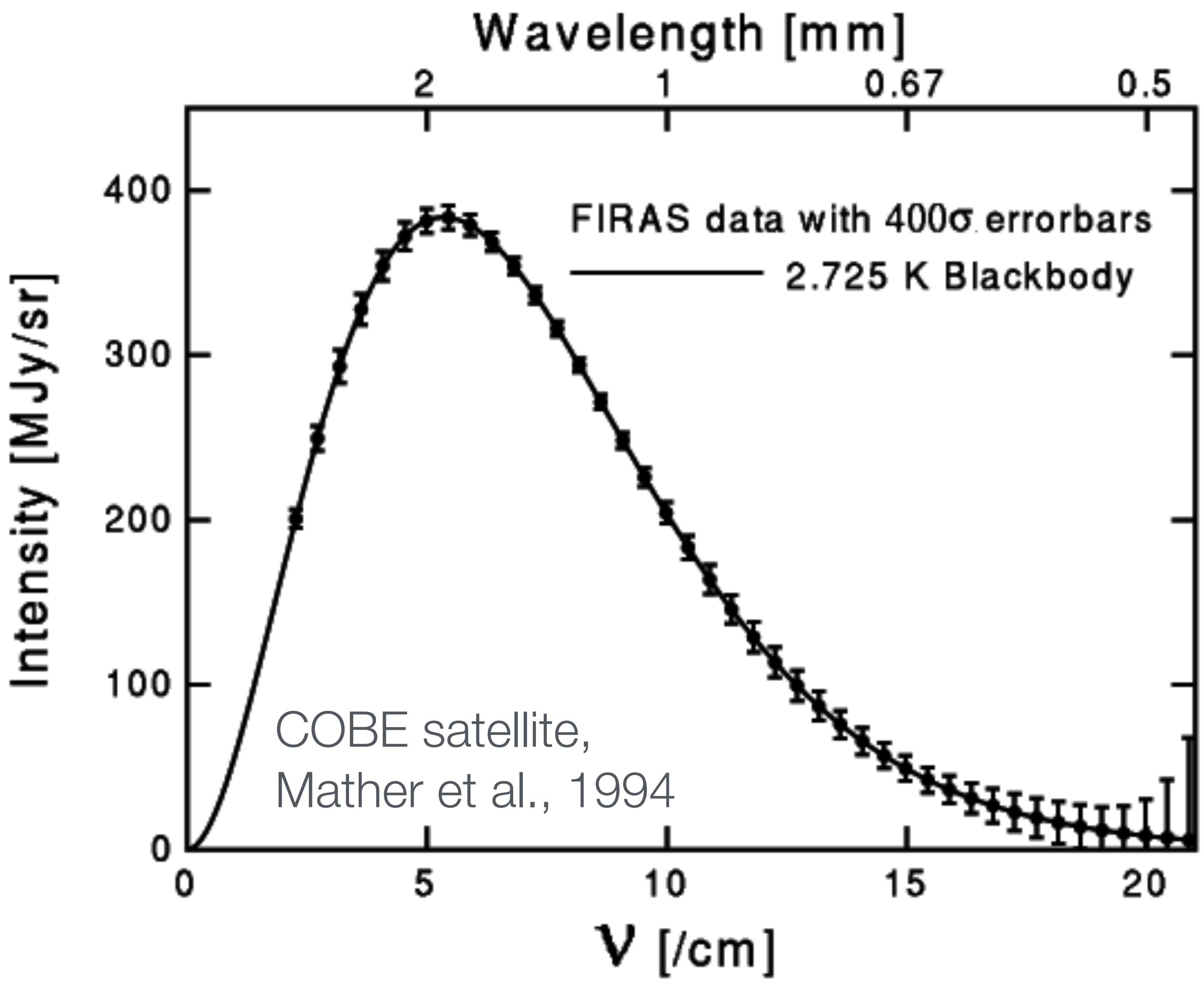
QGP photon rate r_γ (lowest order):

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

Total emission rate:

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

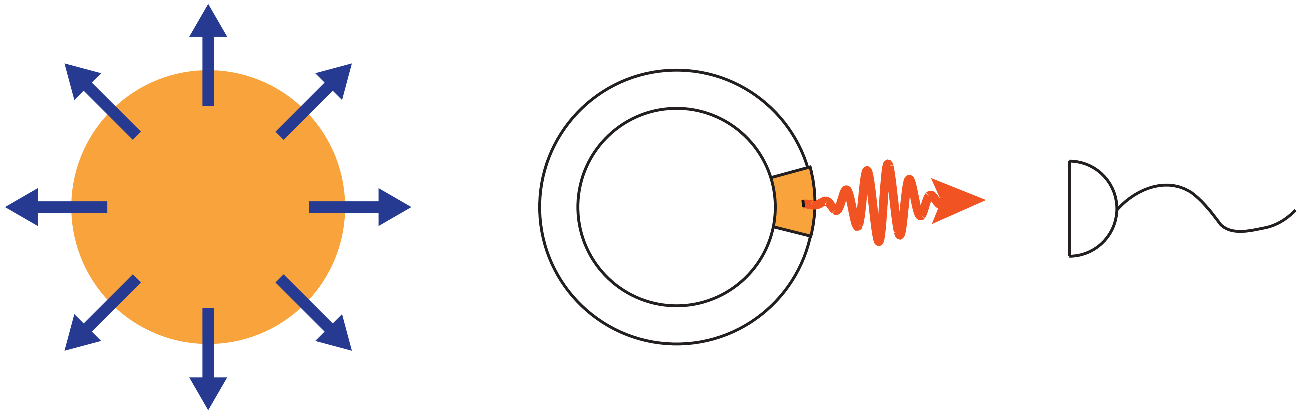
Example:
Temperature of the universe from Planck spectrum



COBE satellite,
Mather et al., 1994

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

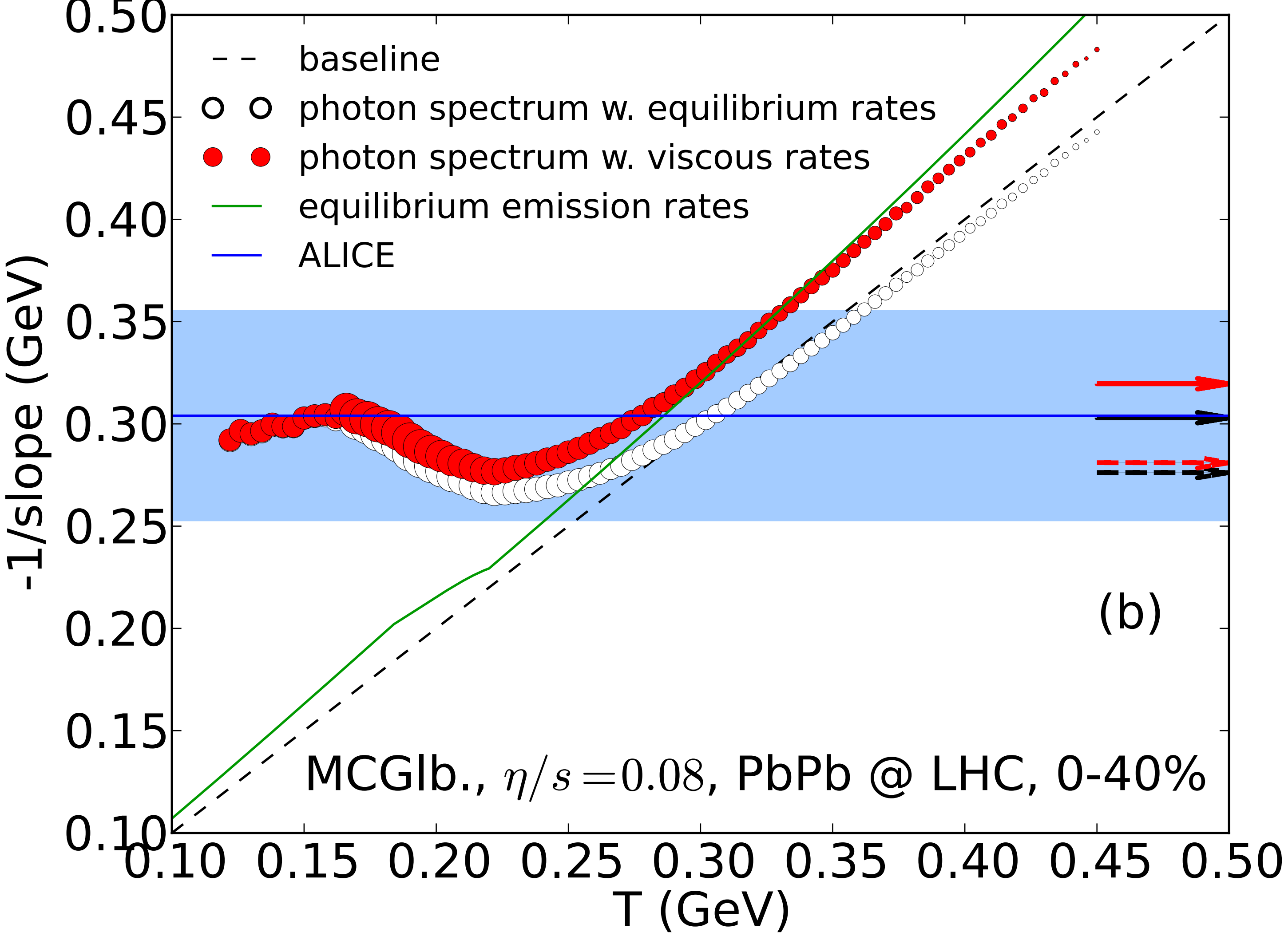
A complication for the temperature measurement: Blueshift due to radial flow



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

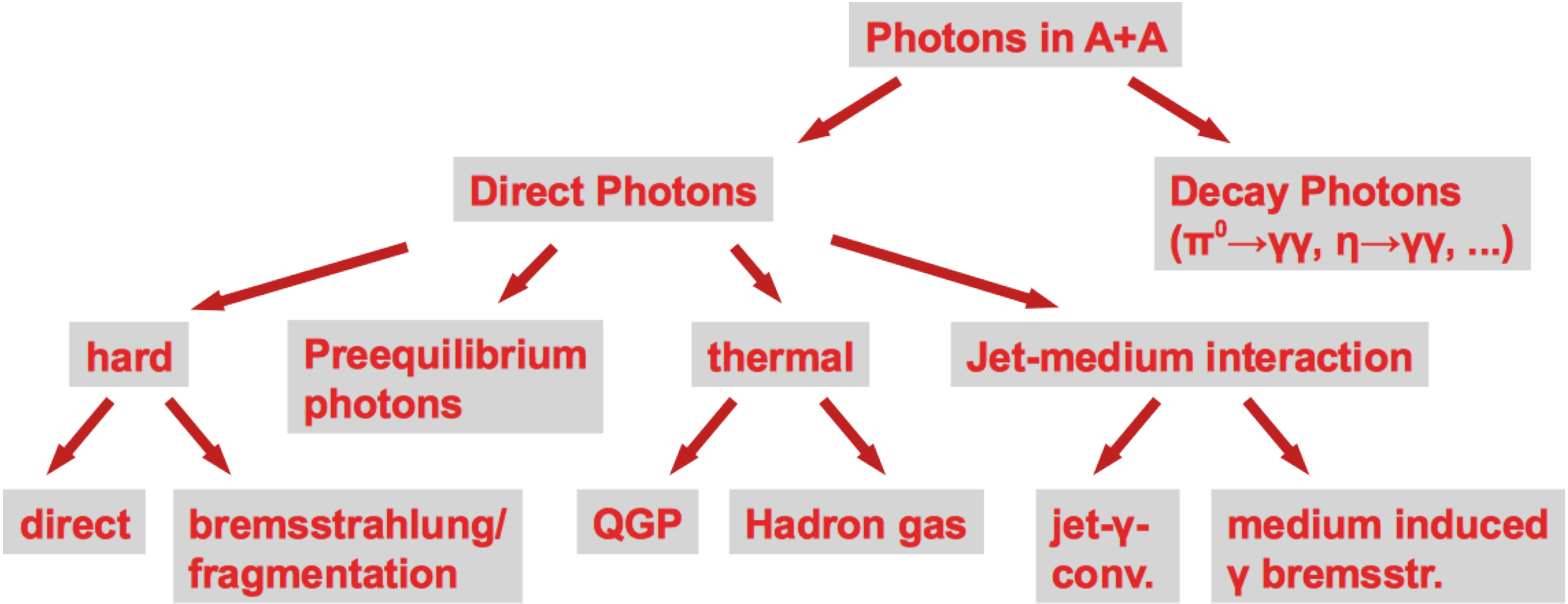
$$T_\mathrm{eff} = \underbrace{\sqrt{\frac{1+\beta_\mathrm{flow}}{1-\beta_\mathrm{flow}}}}_{2 \text{ for } \beta_\mathrm{flow}=0.6} \times T$$

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



Photons in A+A

Direct Photons

Decay Photons ($\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, ...)

hard

Preequilibrium photons

thermal

Jet-medium interaction

direct

bremsstrahlung/ fragmentation

QGP

Hadron gas

jet-γ-conv.

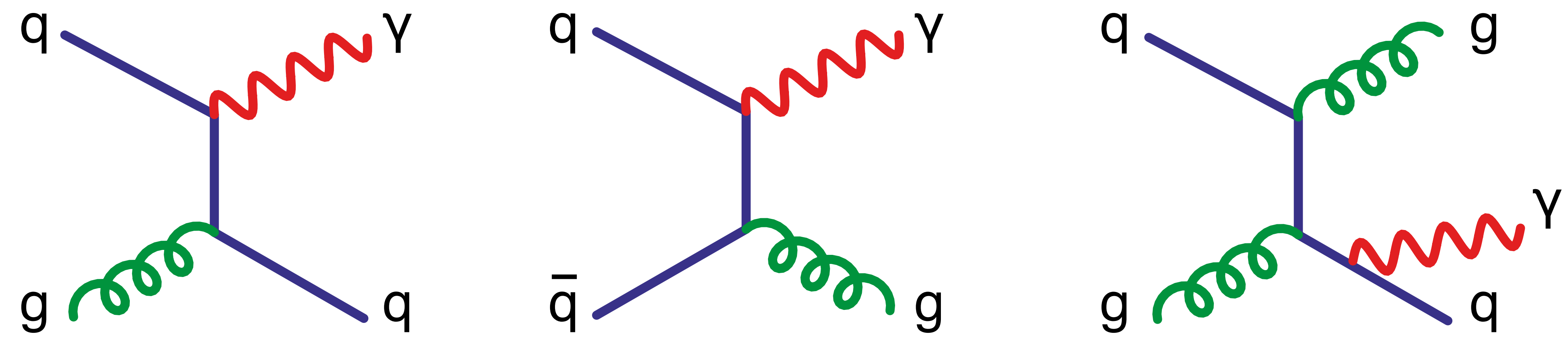
medium induced γ bremsstr.

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

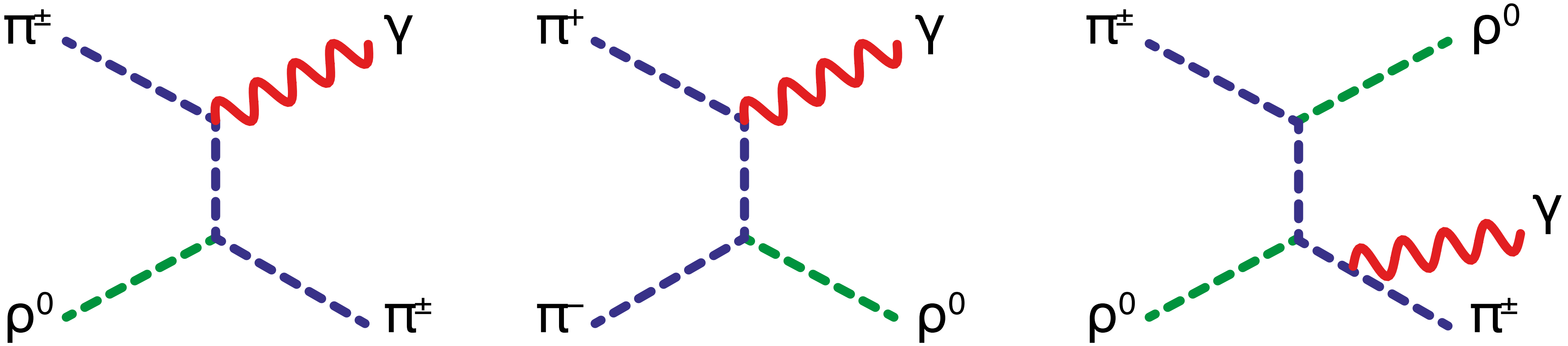
Small signal (O(10)% or smaller) at low p_T ($1 < p_T < 3$ GeV/c), where thermal photon from the QGP are expected

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

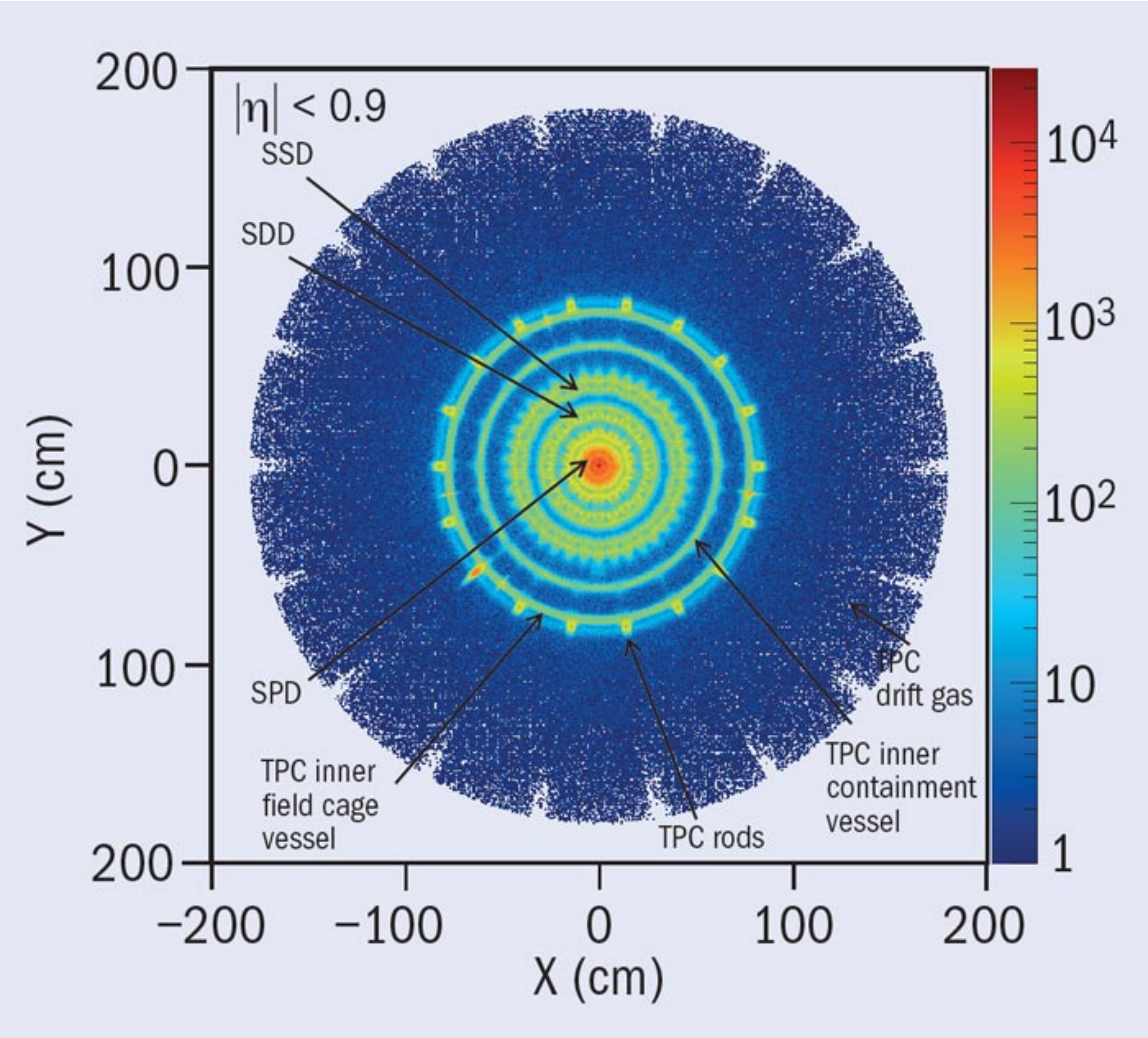
QGP

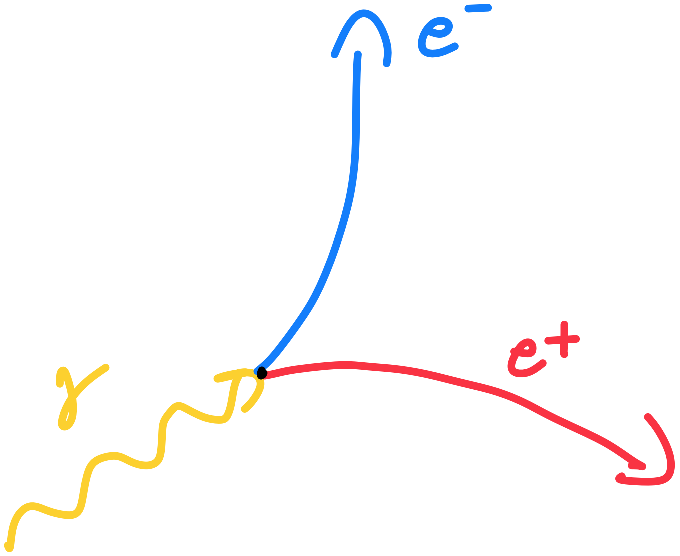


hadron gas



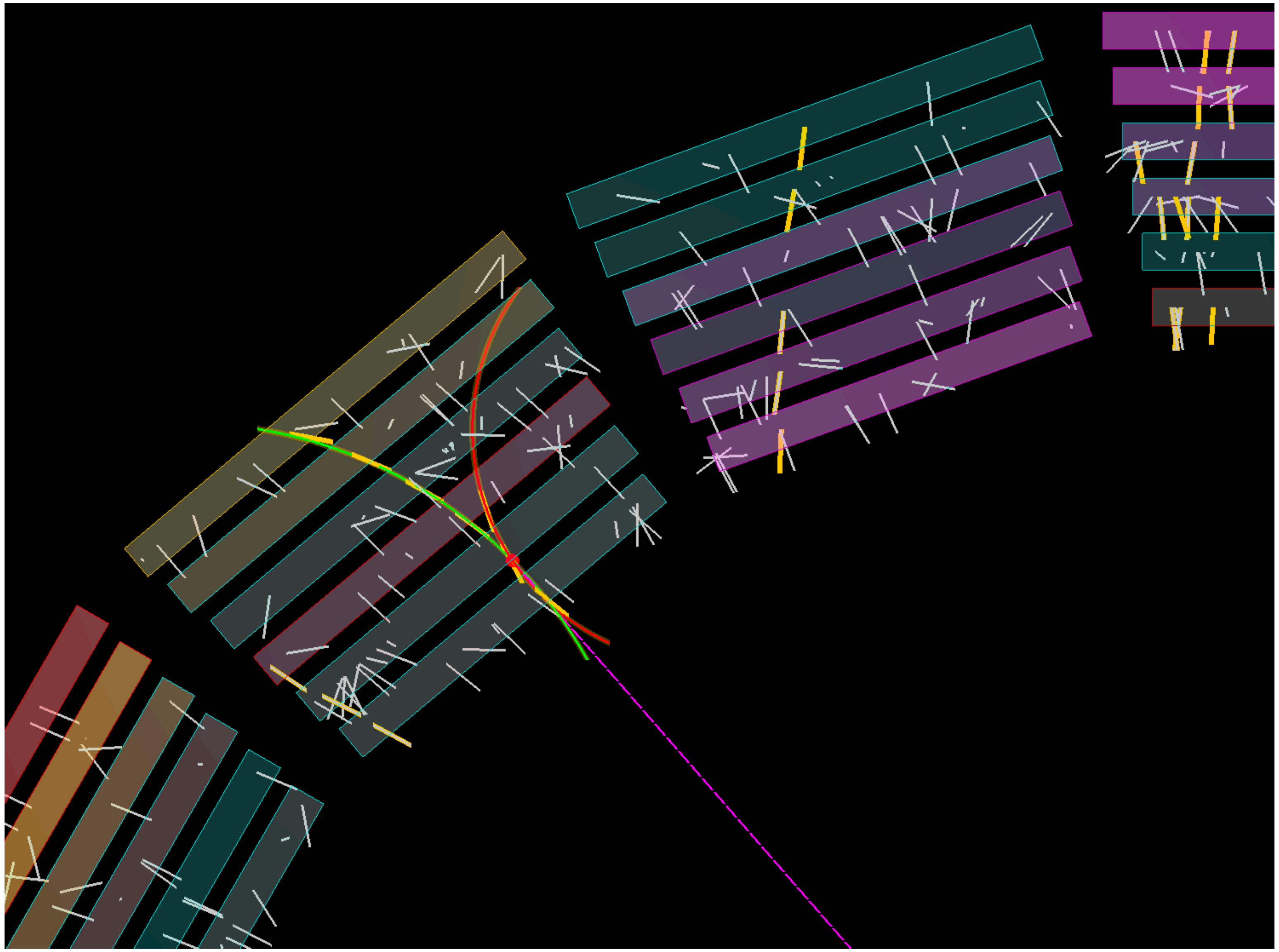
Photon Conversion Method





Photon can convert into an electron positron pair once its close to some nucleus (energy-momentum conservation)

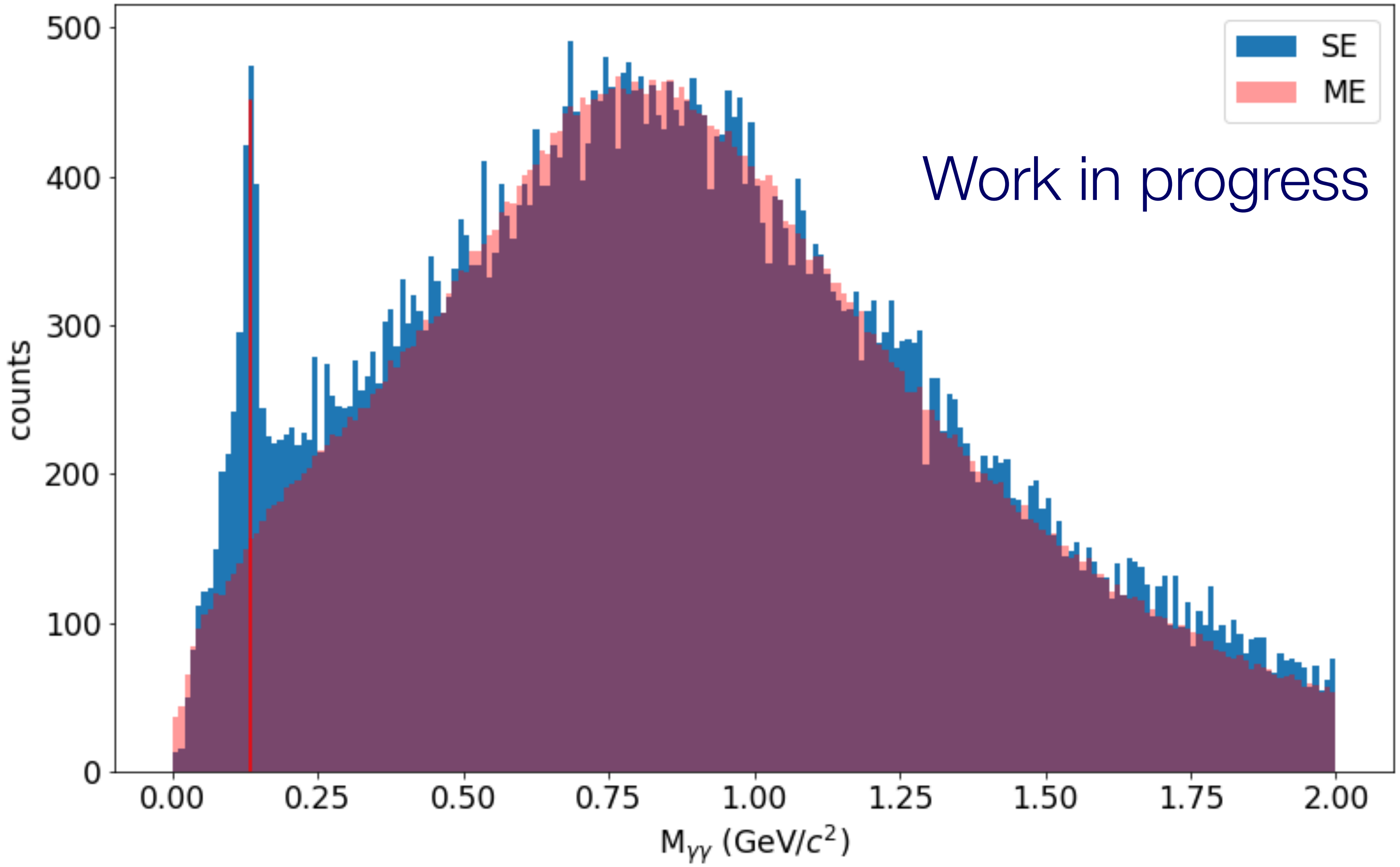
Photon Conversion in ALICE TRD



- Photons convert very far outside the production vertex (radius ~ 3m)
- Kalman filter or helix fitting for tracking

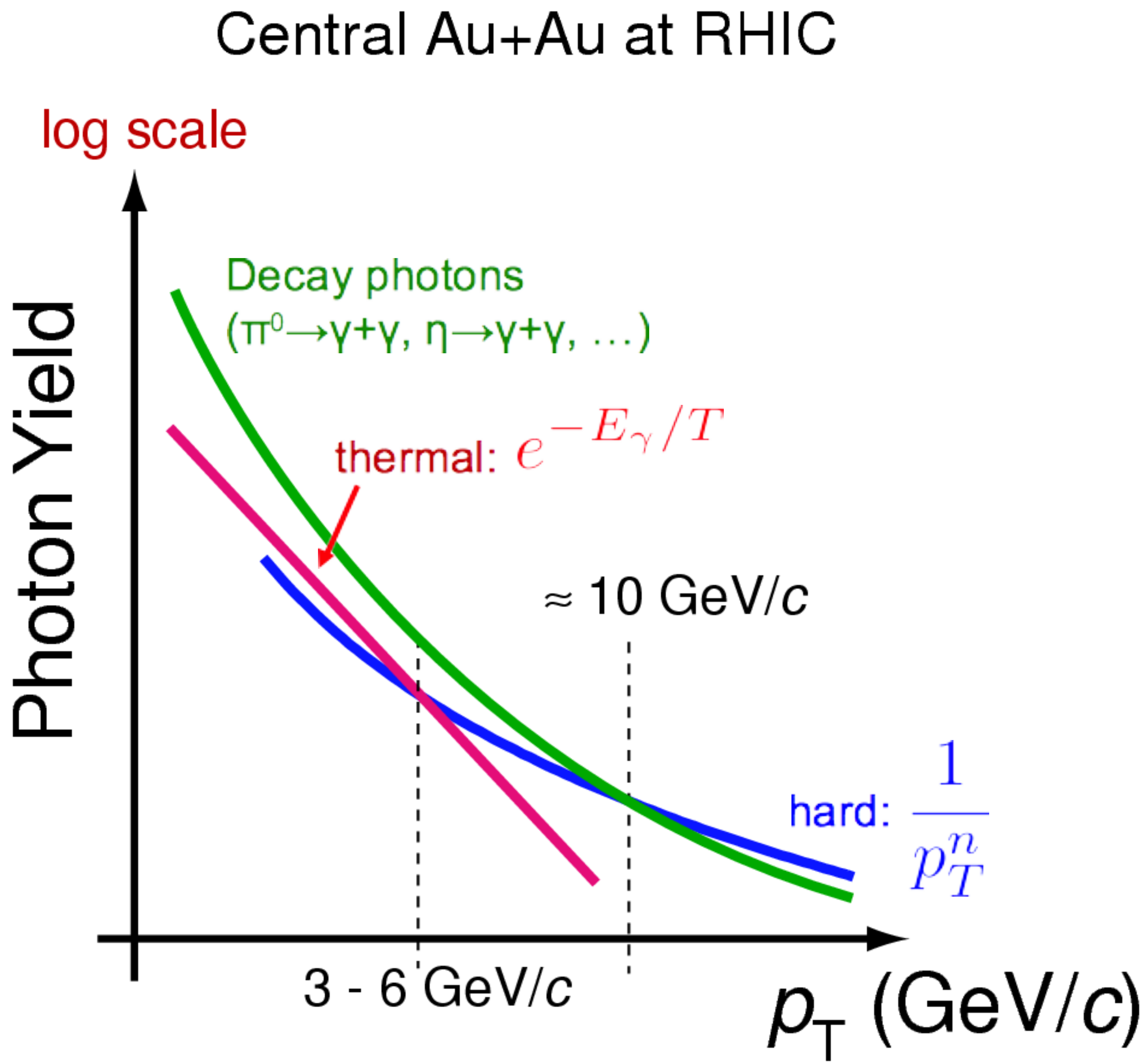
π^0 reconstructed from PCM in ALICE TRD

Martin Kroesen private communication



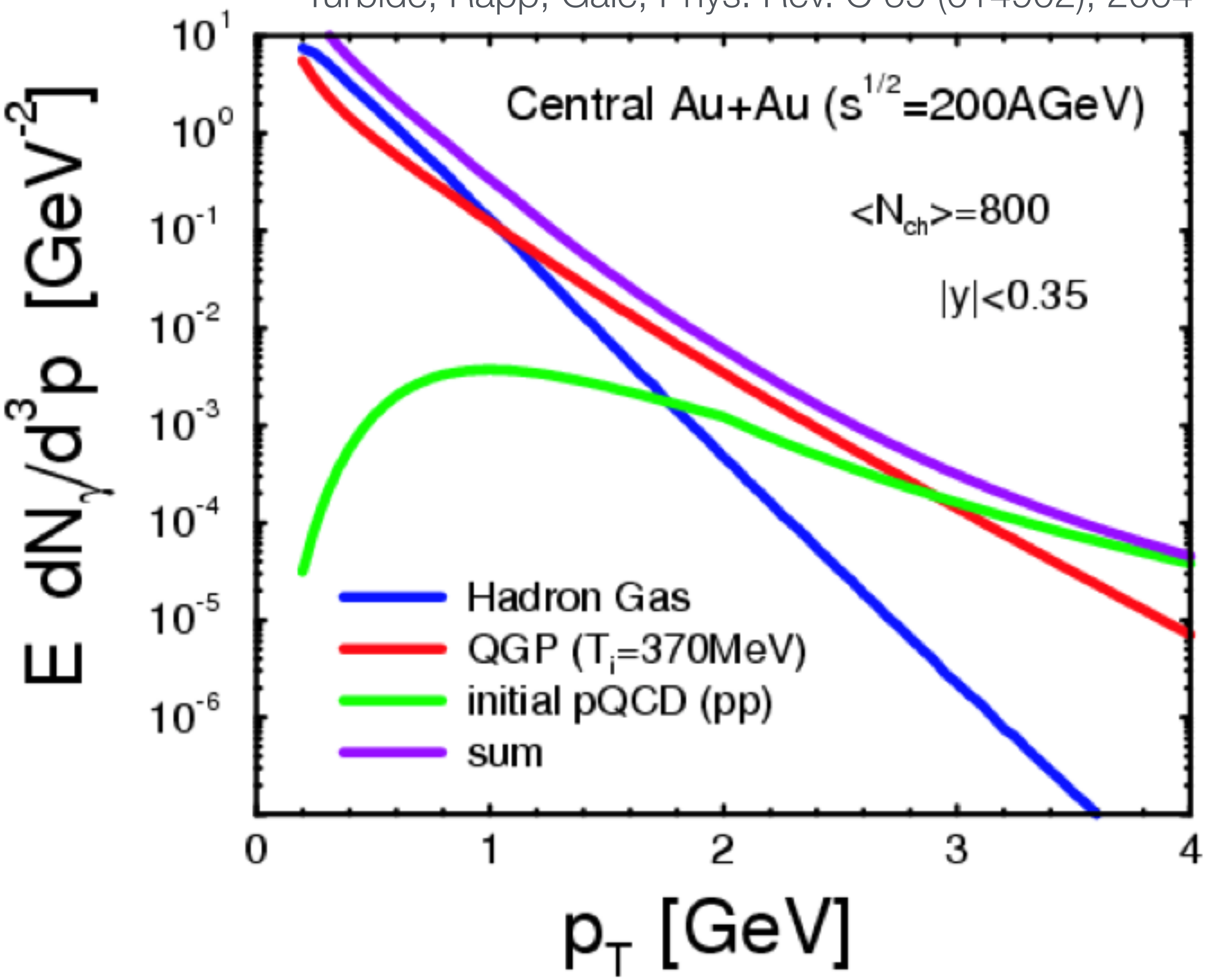
- ALICE Transition Radiation Detector used as conversion material and for tracking
- $\pi^0 \to \gamma\gamma \to e^+e^- + e^+e^-$
- ME = mixed event method for background determination

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

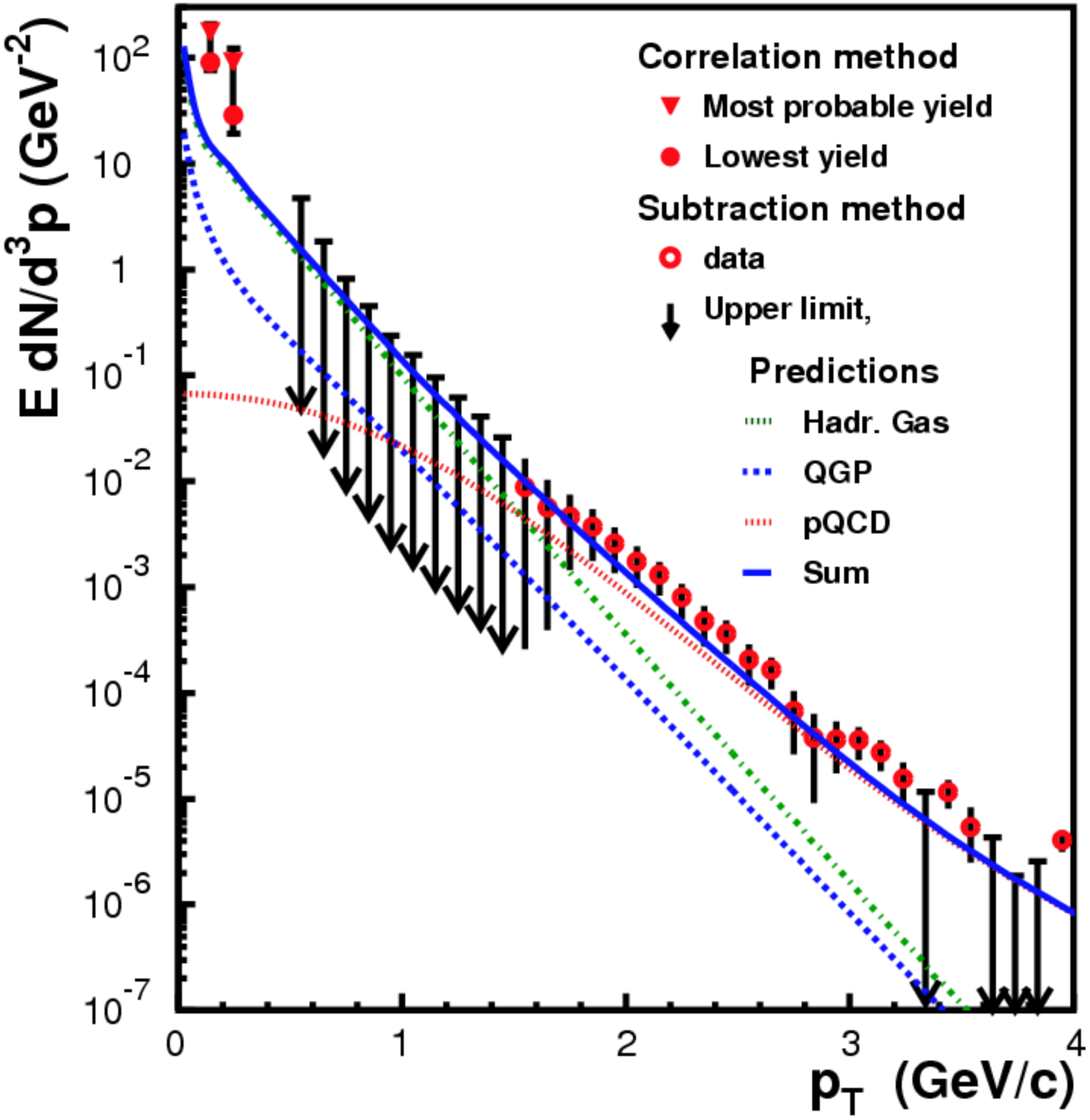
- Idea: Cancellation of uncertainties common to photon and π⁰ measurement

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

$$R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}} \equiv \underbrace{\boxed{\frac{\gamma_{\text{incl}}}{\pi^0_{\text{param}}}}}_{\text{measured}} \Big/ \underbrace{\boxed{\frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}}}}_{\text{decay photon calculation ("cocktail")}}$$

- 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



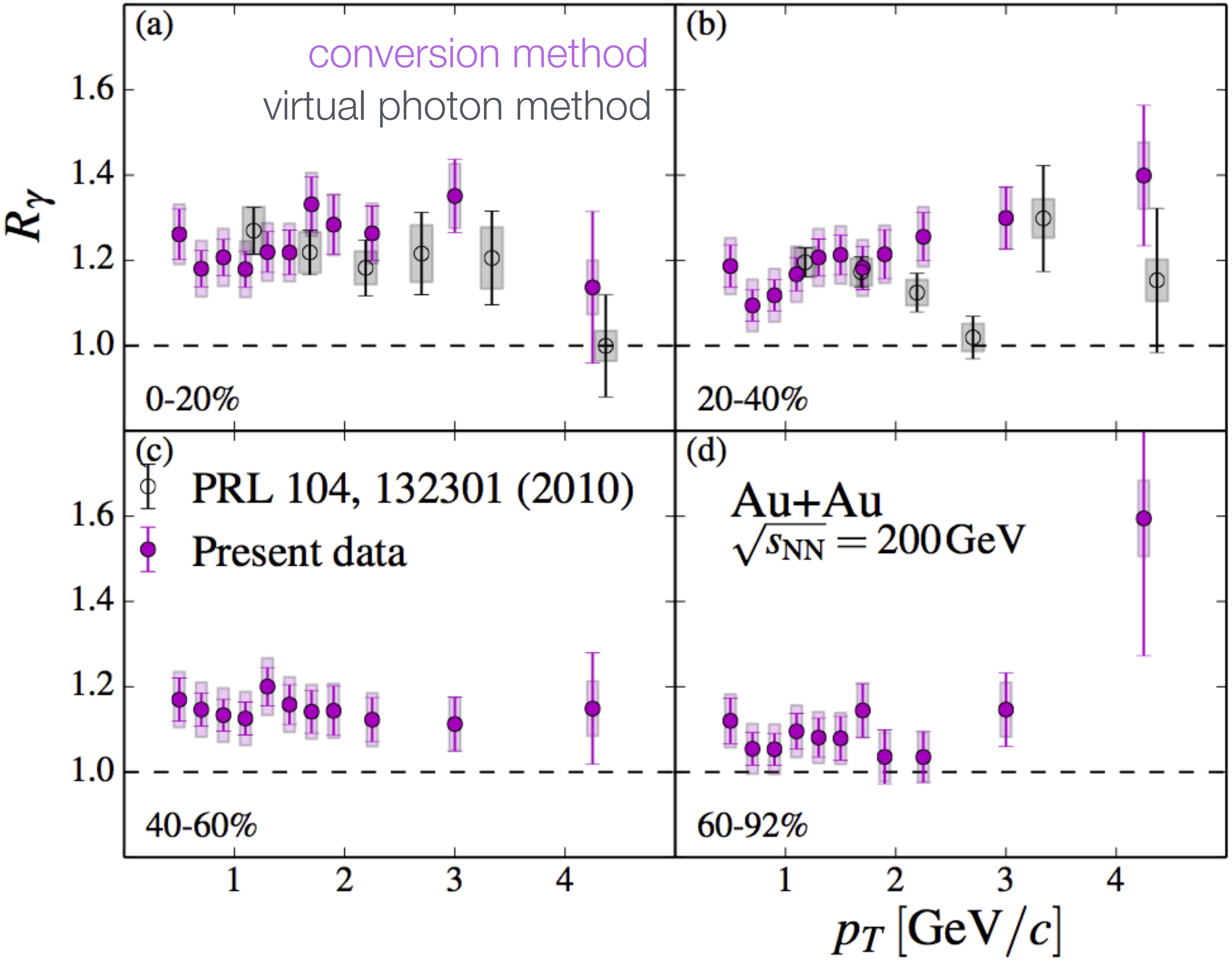
Consistent with QGP scenario, but data can also be explained without a QGP

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

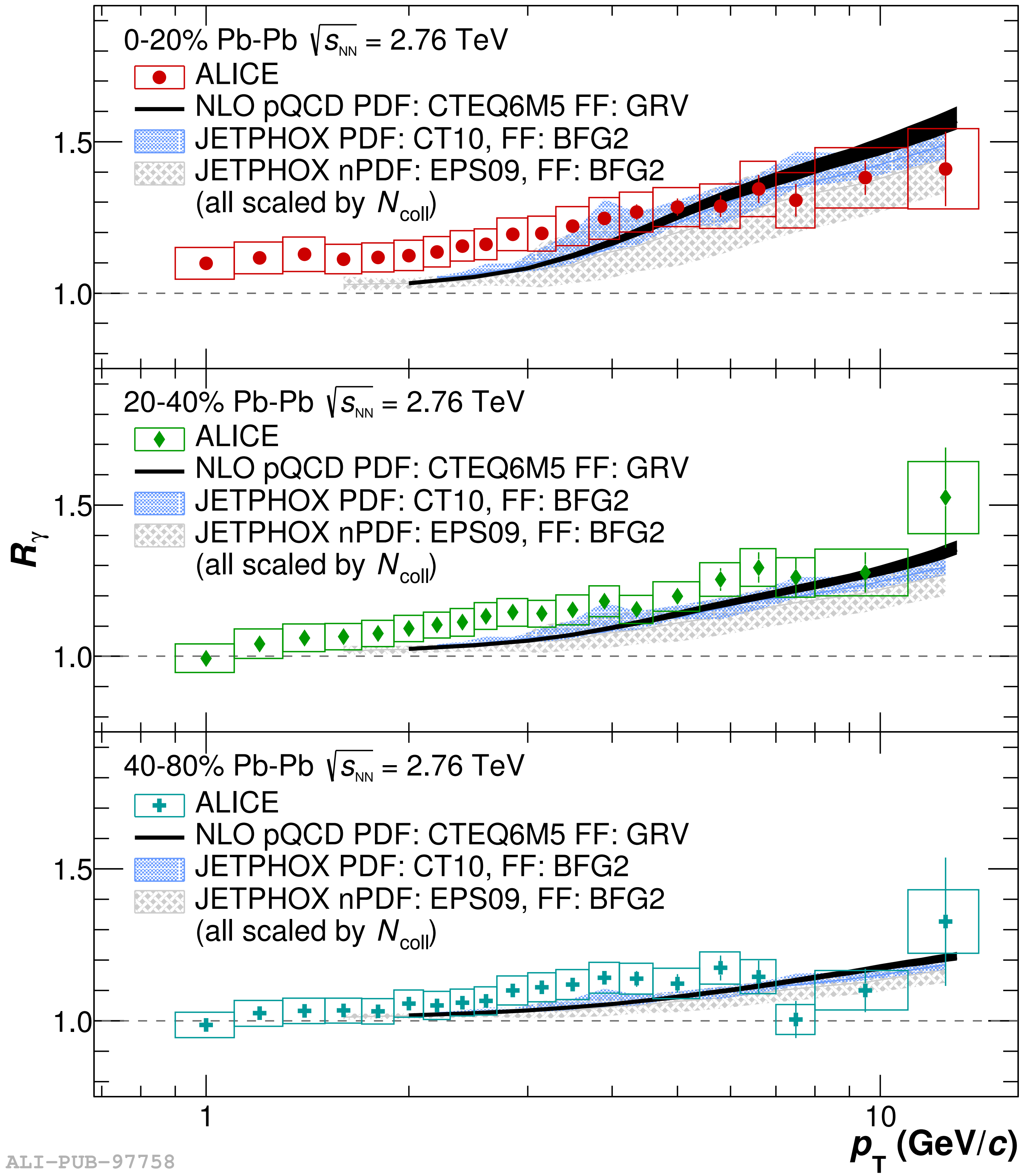
$$R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}}$$

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



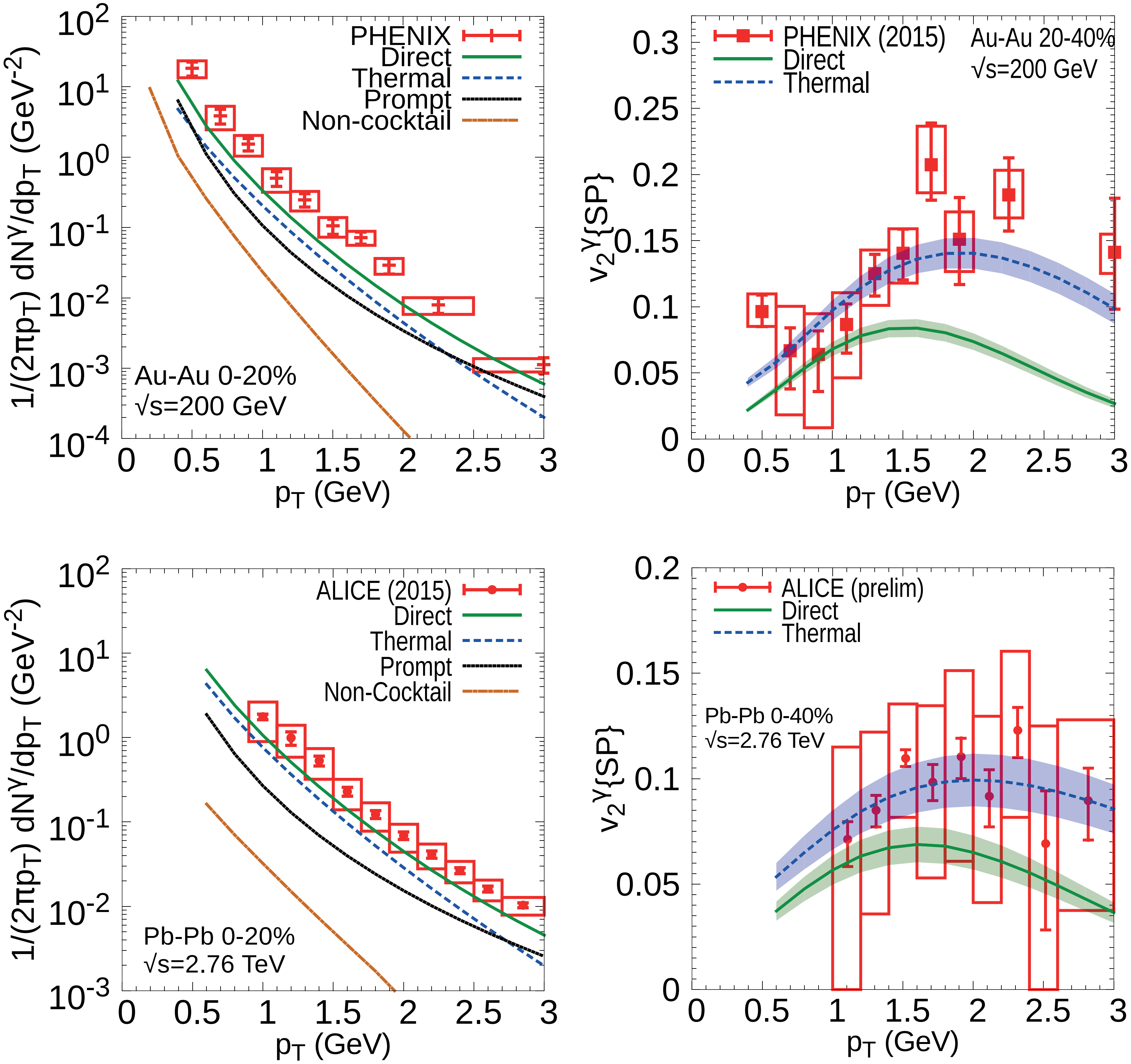
$$R_\gamma^{\text{pQCD}} = 1 + N_{\text{coll}} \frac{\gamma_{\text{pQCD}}}{\boxed{\gamma_{\text{decay}}}}$$

calculated based
measured π⁰ 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



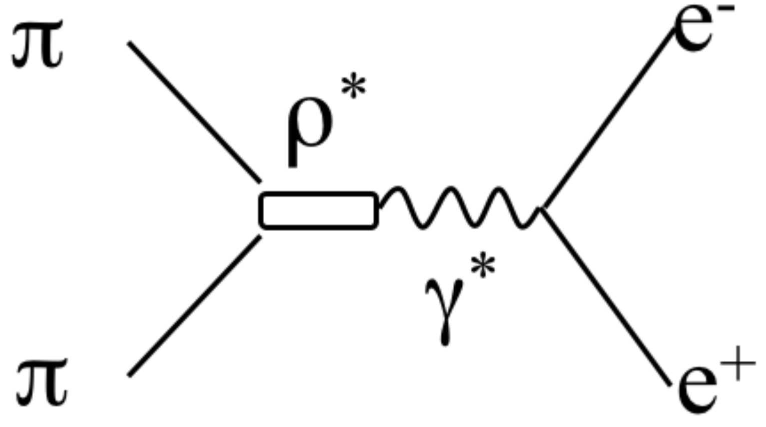
- Au-Au at RHIC
  - Models fail to describe direct photon data
- Puzzle has two parts
  - Yields
  - v_2
- Pb-Pb at the LHC
  - Similar trends
  - However, no puzzle with current uncertainties

Plots: Paquet et al., arXiv:1509.06738

Dileptons: Motivation

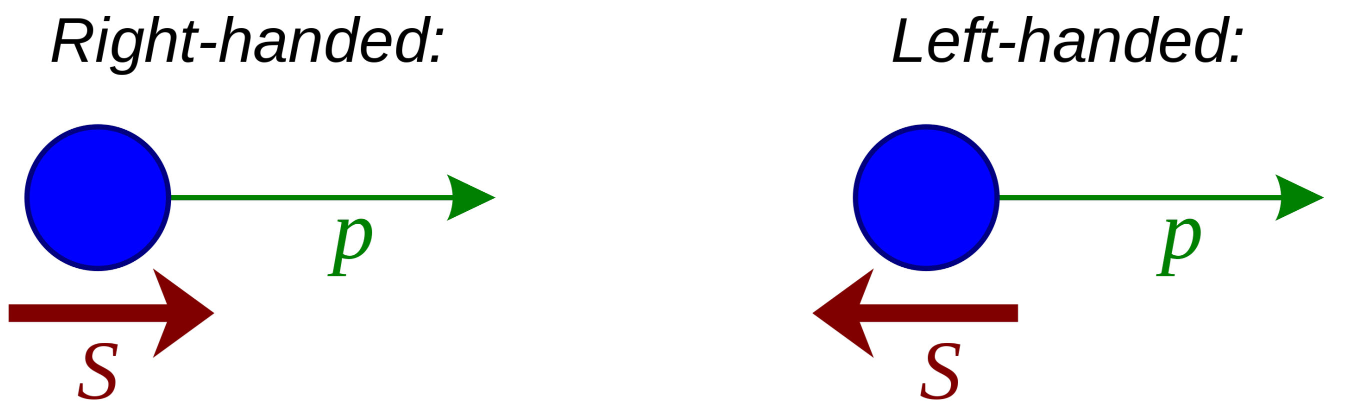
- Like photons, negligible final state interaction
- Search for in-medium modifications of vector mesons ($M_{ee} < 1$ GeV)
  - ρ can decay in the medium ($\tau_{\rho,\text{vacuum}} \approx 1.3\ \text{fm}/c$ < medium lifetime)
  - Broadening of the ρ in the medium, relation to chiral symmetry restoration?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

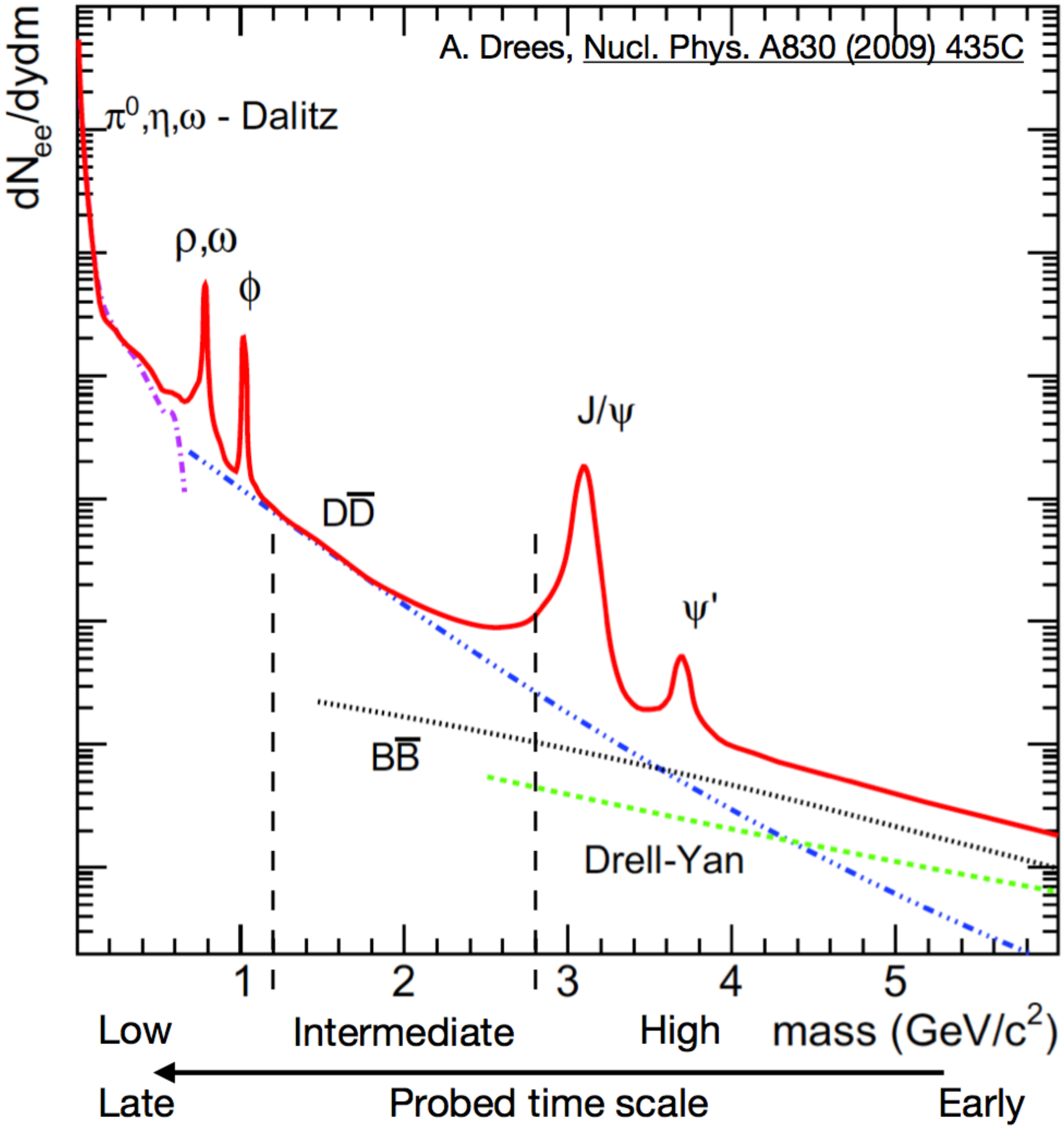
Chiral Symmetry Restoration



Definition of helicity. For massless particles helicity = chirality. Chirality has a more abstract definition. It is Lorentz invariant.

- Chiral symmetry is spontaneously broken in nature. It would only be realized if the quark masses would be zero. But the masses are small, so it is an approximate symmetry of the strong interaction.
- Explicit breaking of chiral symmetry due to current masses caused by the Higgs field.
- Spontaneous breaking of chiral symmetry is due to a non-vanishing expectation value of the two quark condensate $< \bar{q}q >$. This is causing the main part of hadron masses.
- In heavy-ion collisions the thermal excitation of the QCD vacuum can melt the two quark condensate $< \bar{q}q > \rightarrow 0$. The masses of particles will drop therefore.

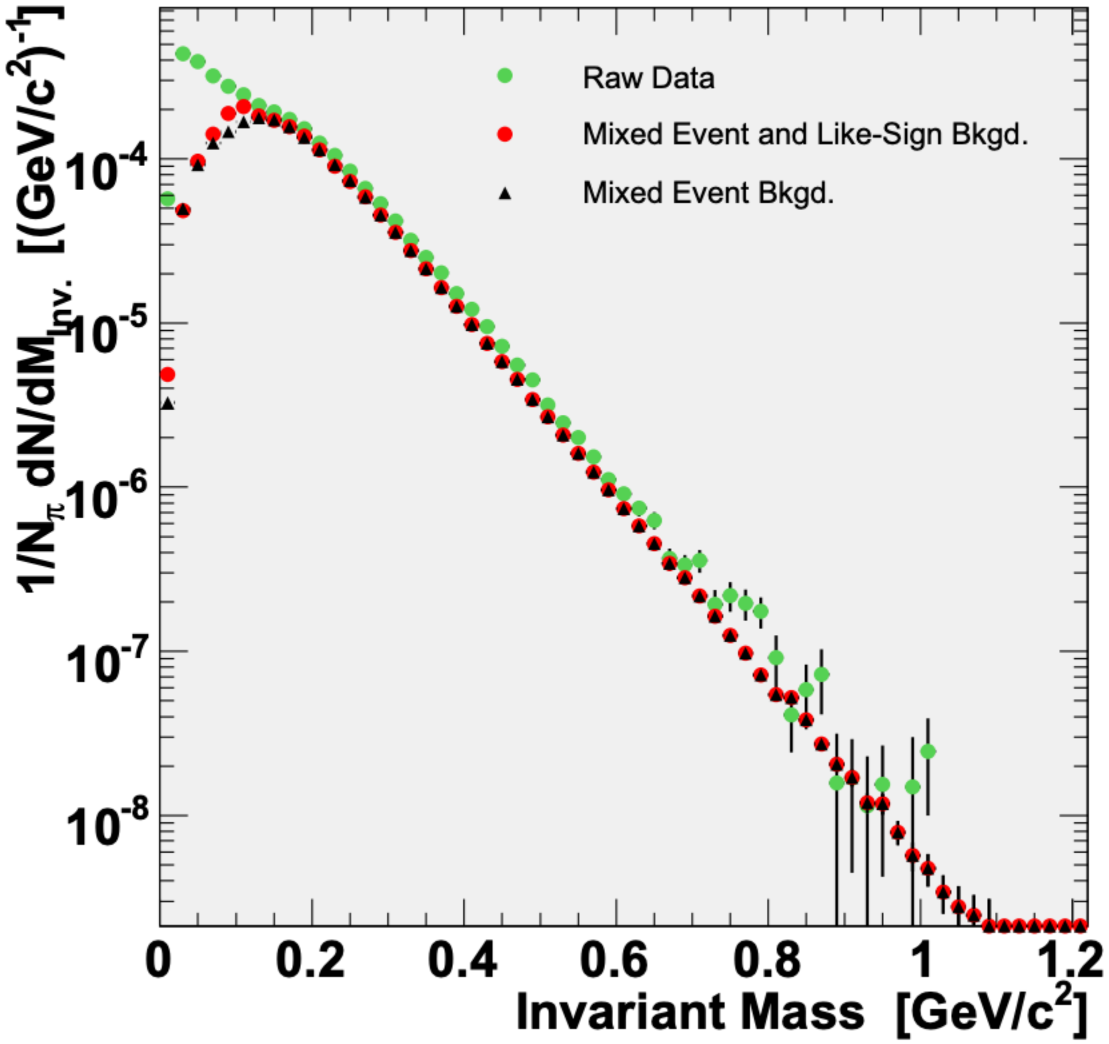
Schematic dilepton mass spectrum

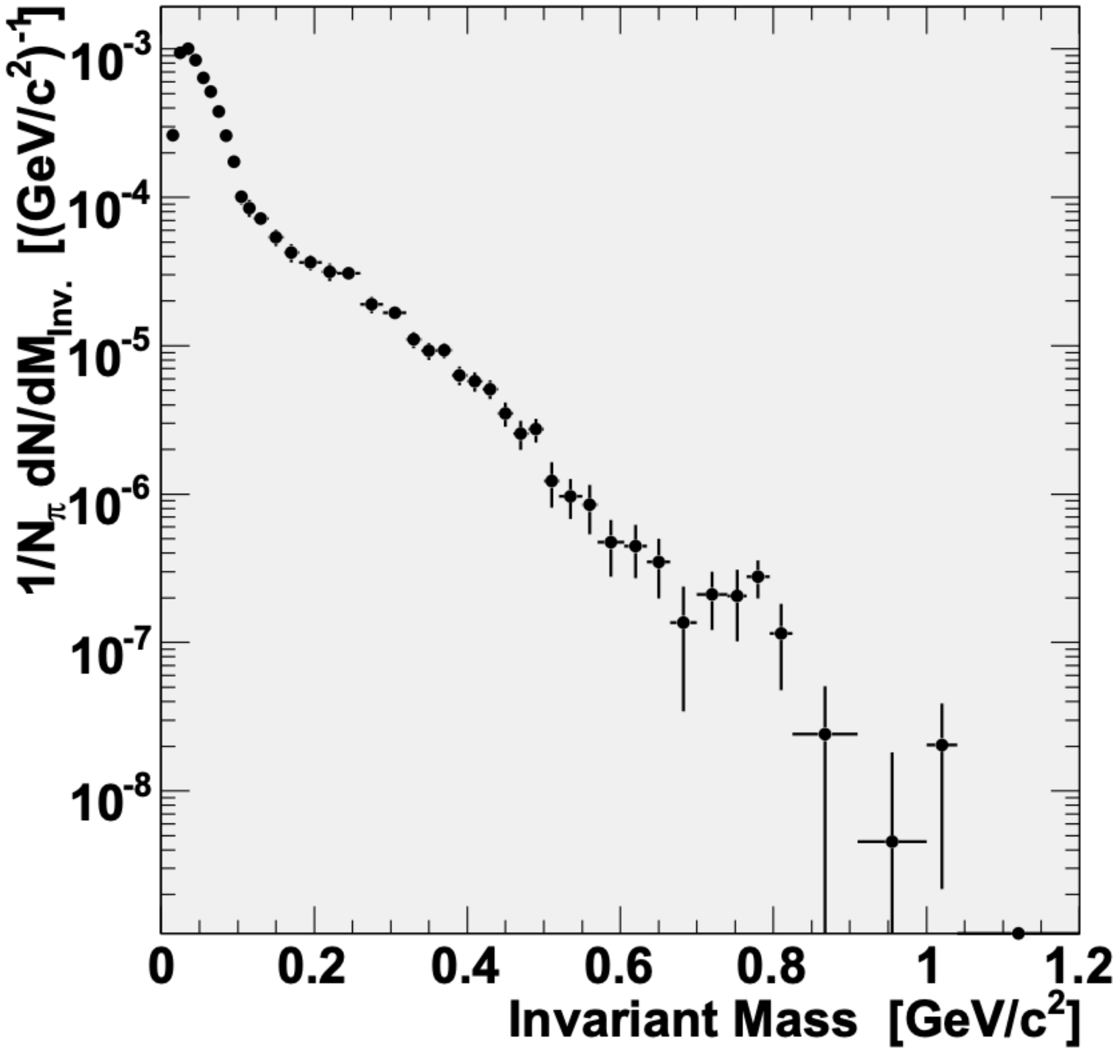


Drell-Yan: annihilation of a quark - anti-quark pair in high energy collisions

Signal-to-Background and Significance

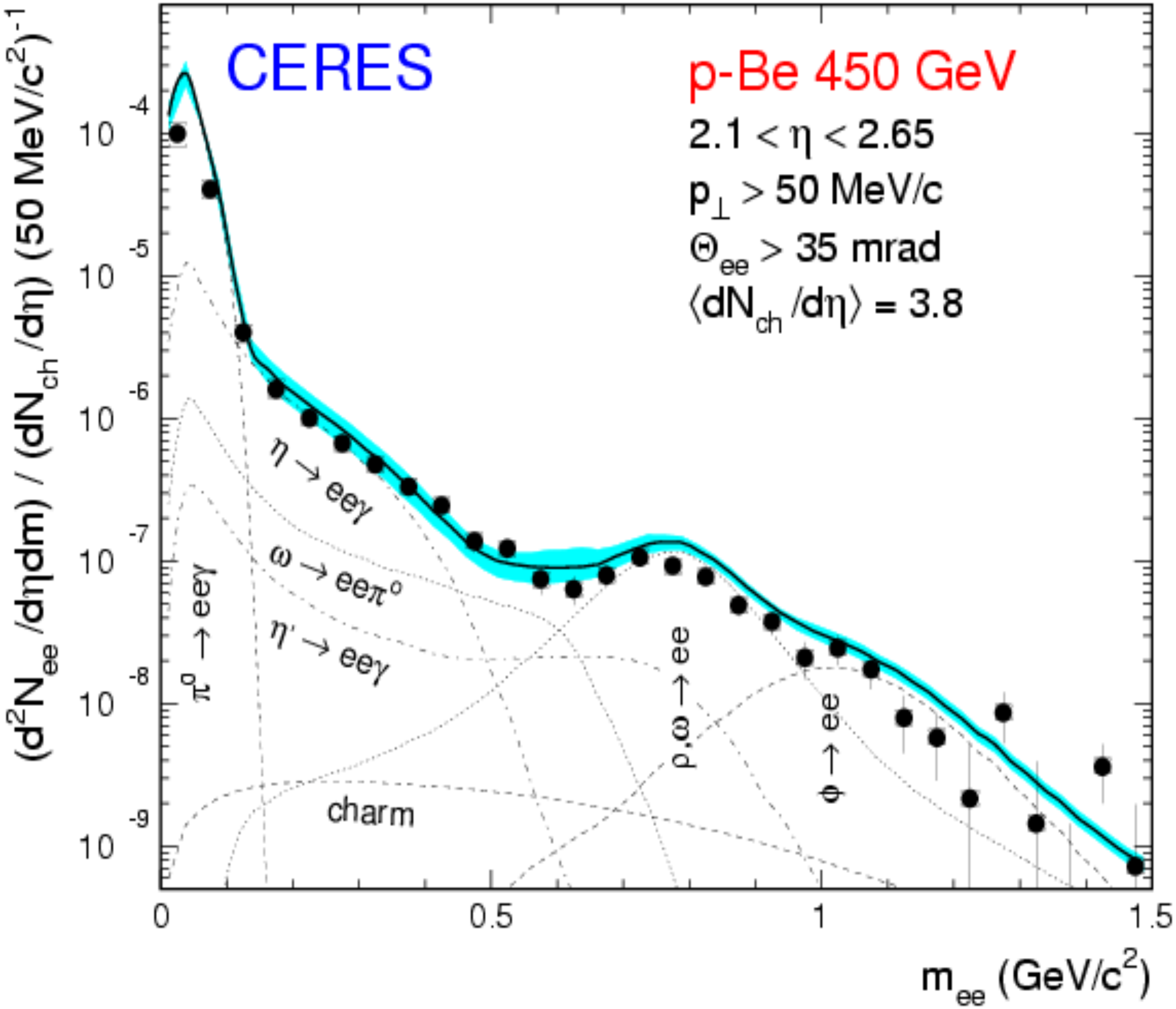
Doktorarbeit Simon Lang





- Signal-to-background ratio can be very small in heavy ion collisions
- Background determined by mixed event technique
- Significance of a signal given by $\Sigma = \dfrac{S}{\sqrt{S+B}}$, with S = signal, B = background
- Acceptance: Fraction of produced particles flying into the detector geometry

CERN SPS results: p+A

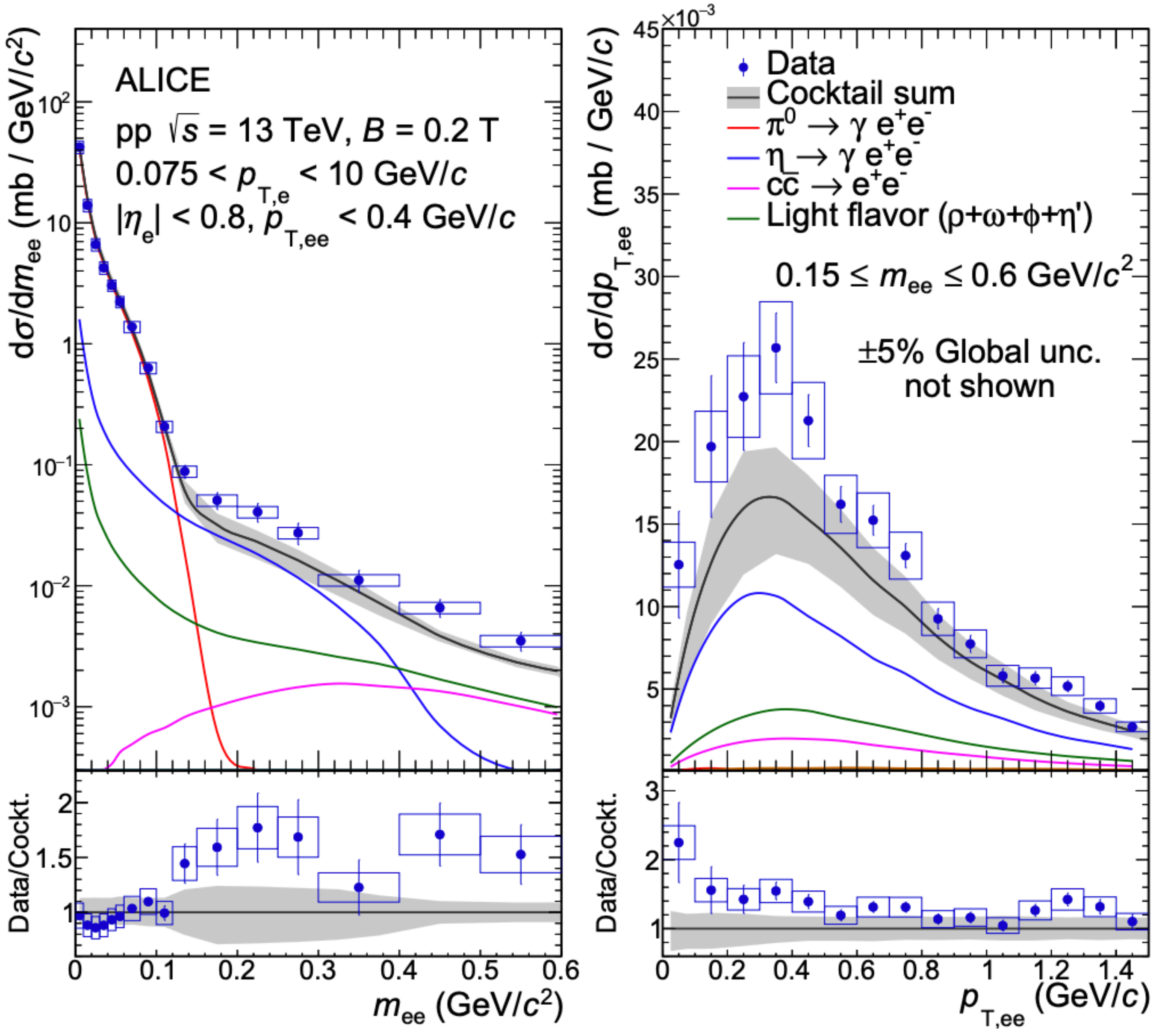


CERES, EPJ C 41 (2005) 475

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

Soft Di-Electron excess in p+p from ALICE

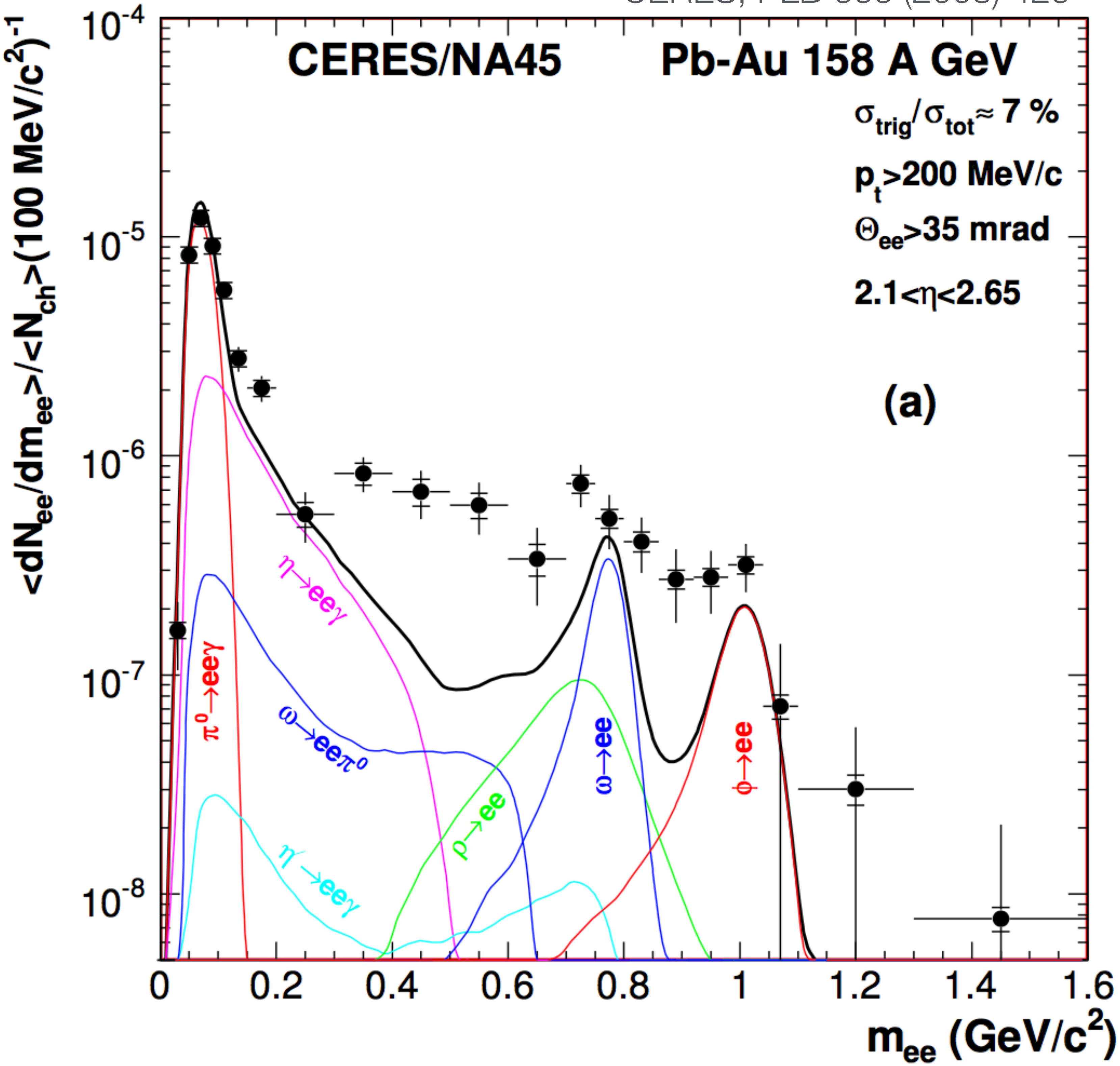
arXiv:2005.14522v2



- Excess of 1.6 sigma of di-leptons at low transverse momenta over the hadronic cocktail.
- Cannot be explained so far by bremsstrahlung or thermal di-electron production.

CERN SPS results: Pb-Au

CERES, PLB 666 (2008) 425



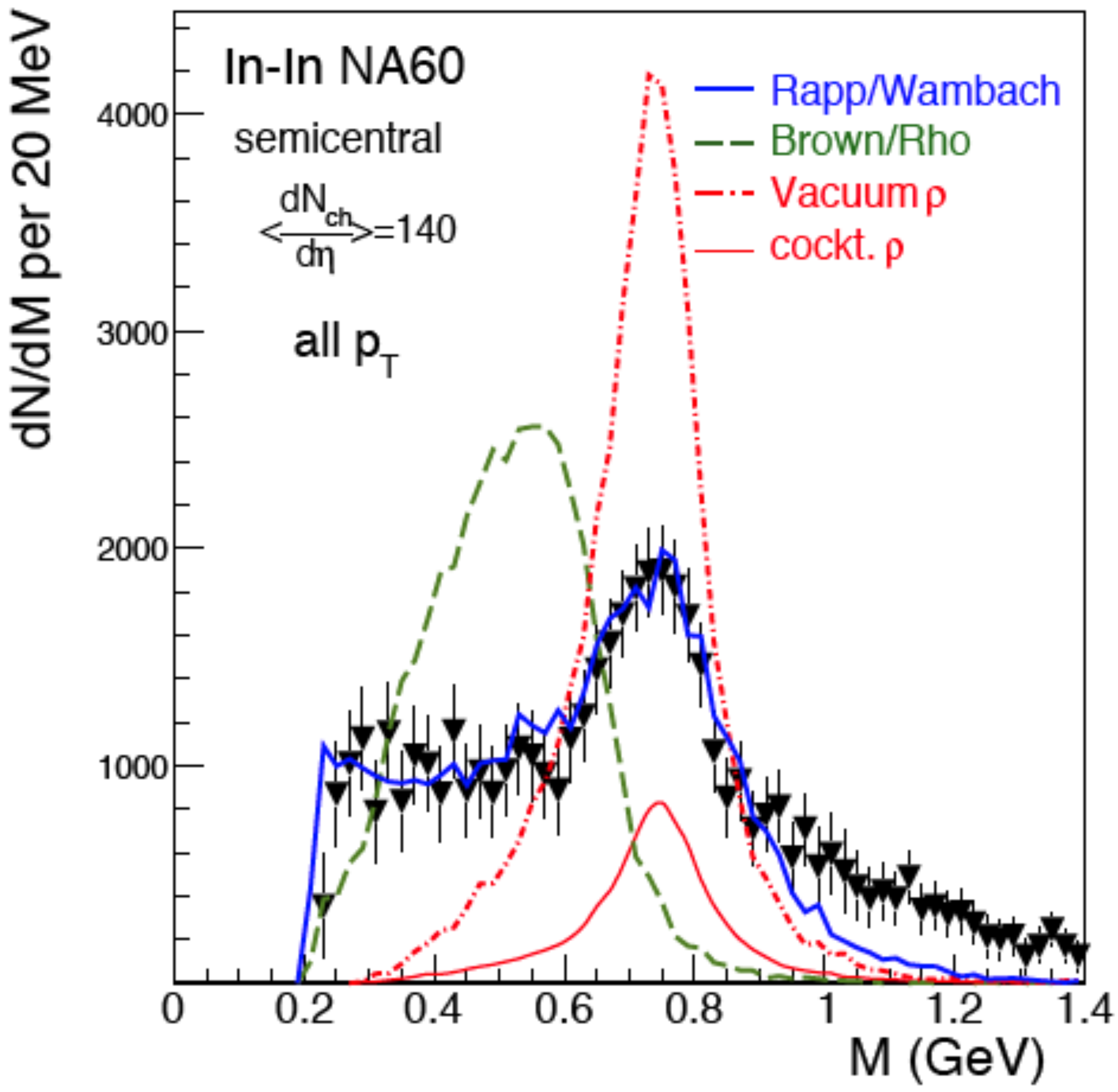
Significant excess above cocktail in Pb-Au

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

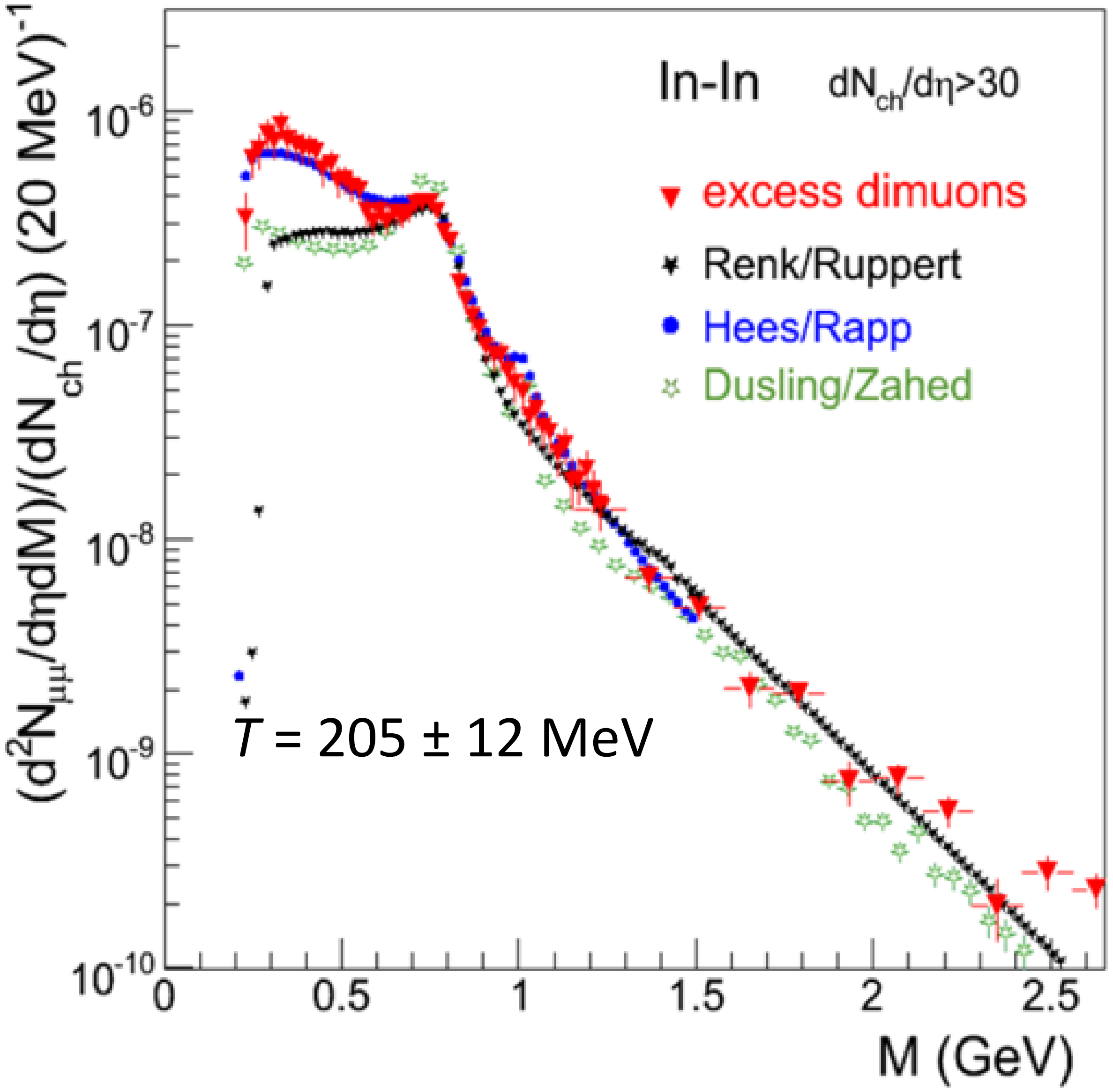


data – cocktail (except for ρ)

QGP temperature via dimuons at SPS energies?

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

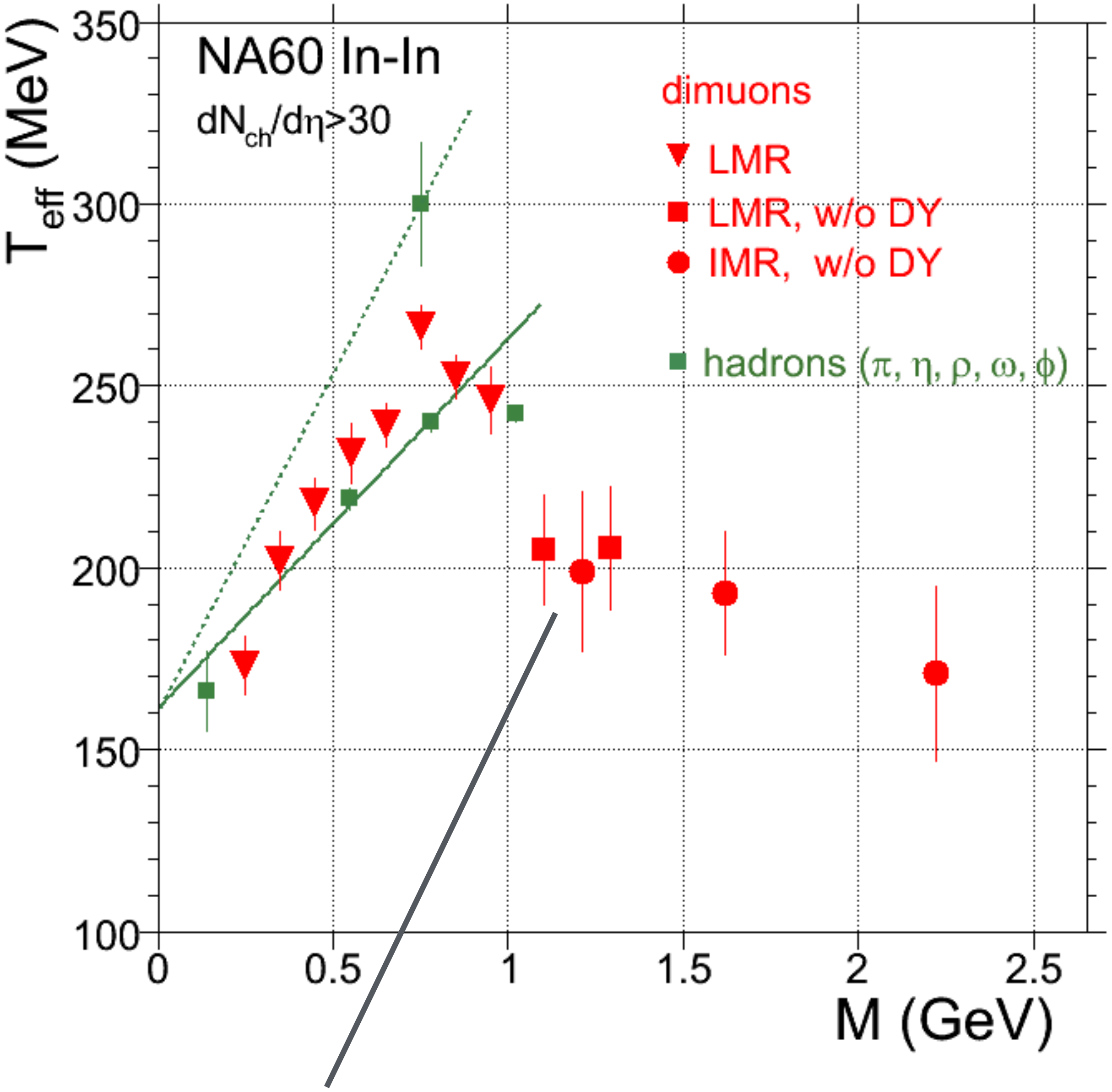
Temperature via dimuon mass spectrum: unaffected by radial flow



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

for $M > 1$ GeV

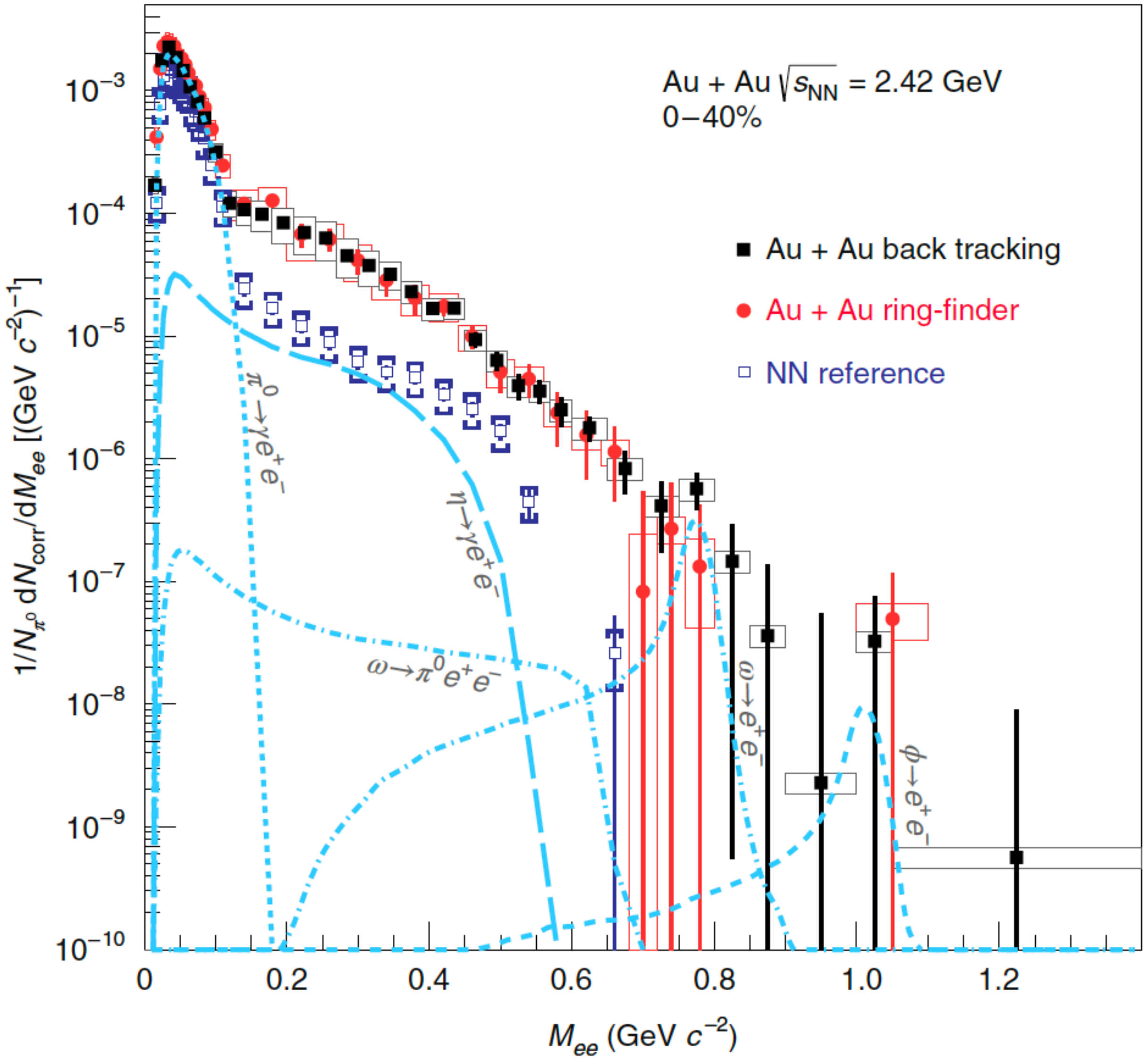
Slope of dimuon m_T spectra: Hadron gas + flow for $M < 1$ GeV, non-flowing partonic source for $M > 1$ GeV?

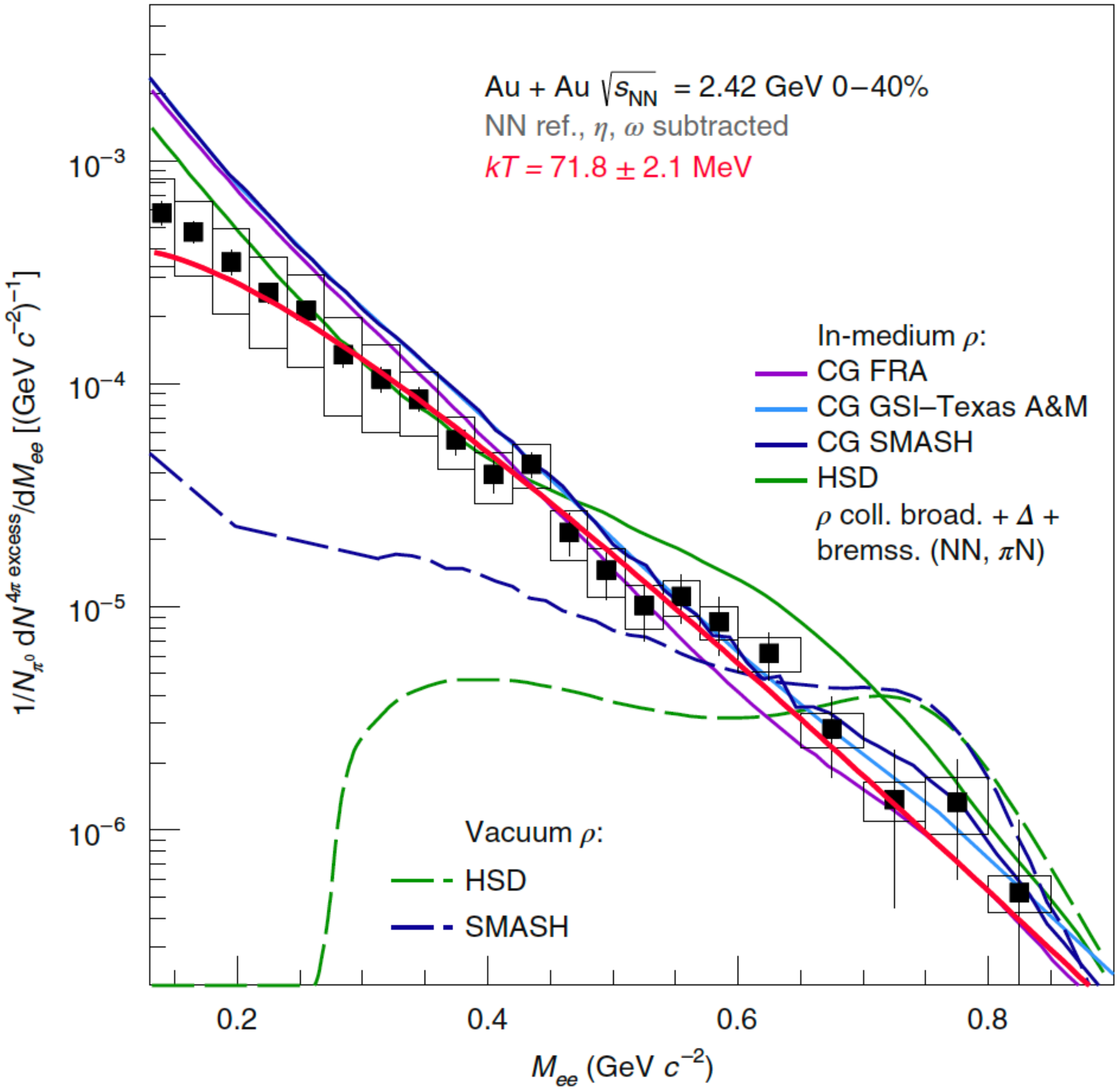


$T_{eff} \approx 200$ MeV for $M > 1$ GeV consistent with slope of mass spectrum!

Di-Lepton Spectroscopy at large μ_B

Nature Phys. 15 (2019) 10, 1040-1045

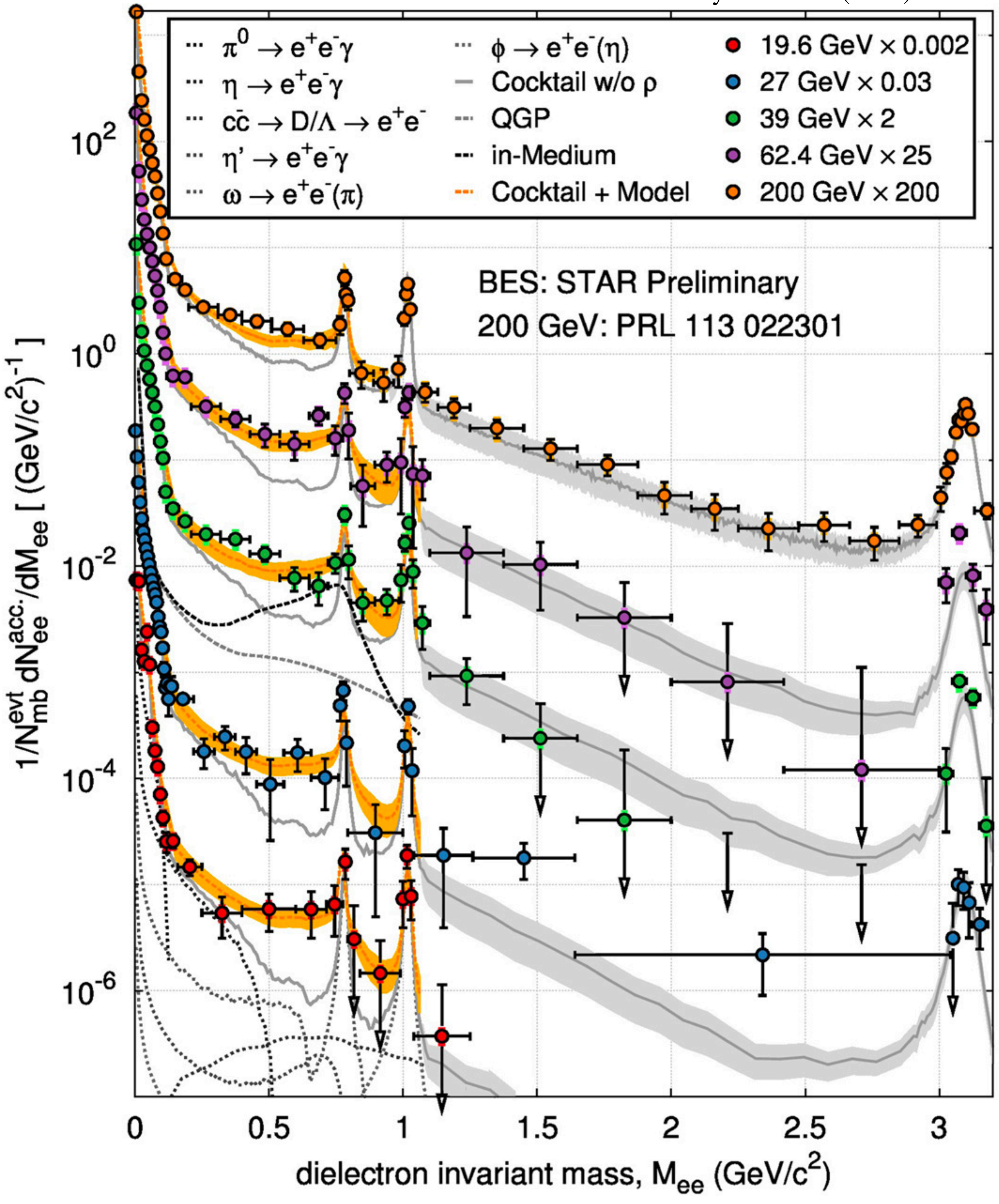




- HADES @ SIS18 data
- Excess yield over cocktail and NN reference can be explained by ρ collisional broadening + Δ, NN bremsstrahlung

Results from the Beam Energy Scan

Nuclear Physics A 931 (2014) 1–12



- STAR RHIC Beam Energy Scan
- Cocktail only does not describe the data below the η.
- Cocktail + Model with meson-baryon re-scattering during the evolution → collisional broadening of the ρ meson.

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 $T_{\mathrm{QGP}} \approx 200$ MeV