UNIVERSITÄT
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Electromagnetic Probes: Recent Developments

Quark Matter 2014 Student Day, May 18, 2014

Klaus Reygers
Physikalisches Institut
University of Heidelberg

Outline

- Electro-weak particles (W, Z, high-p_T direct photons) as probes of the initial nuclear wave function

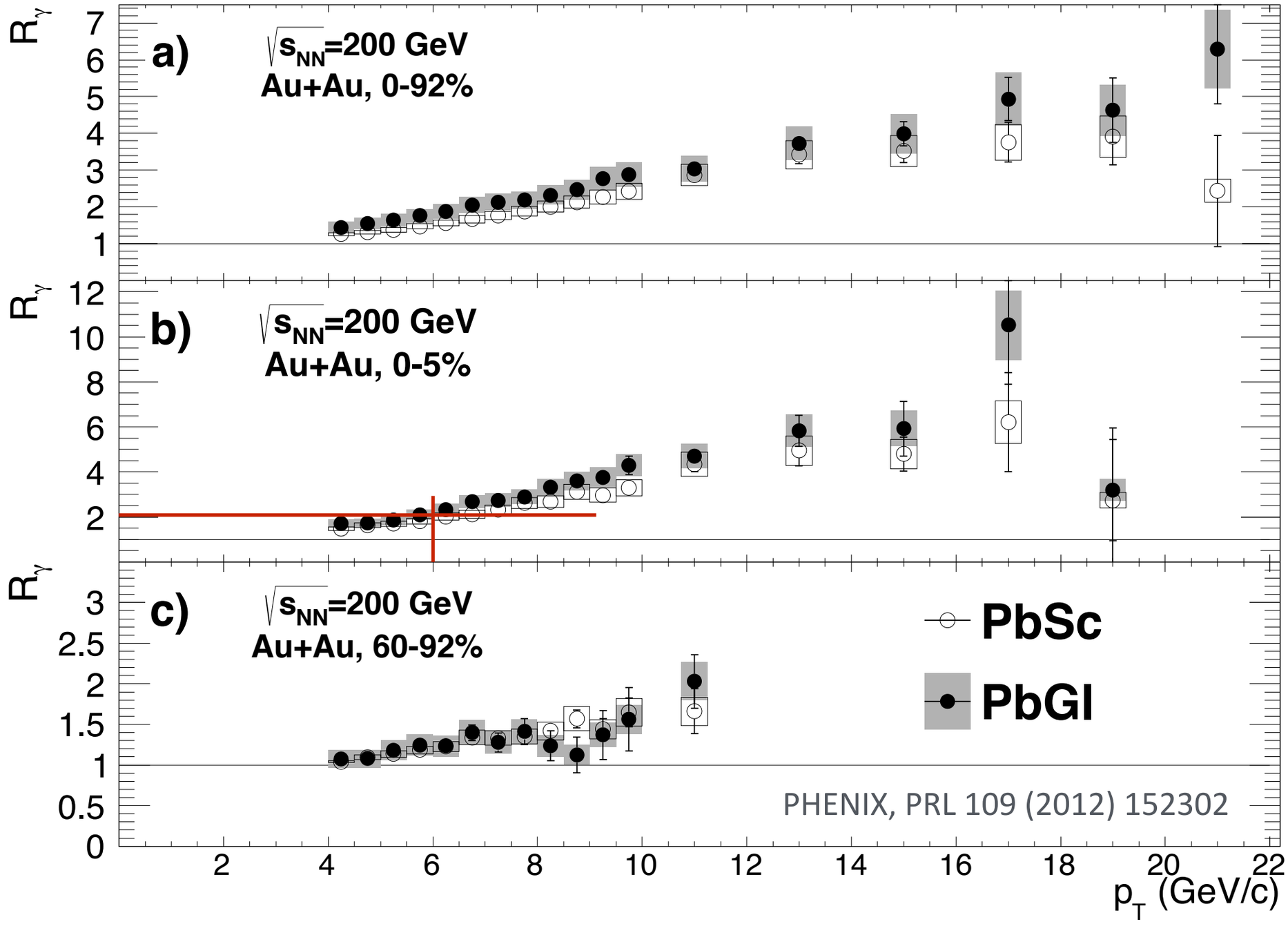
- Low-p_T direct photons ($p_T < 4$ GeV/c)
  - Experimental methods
  - Spectra and flow
  - Direct-photon (flow) puzzle

- Dileptons

1. Probes of the initial wave function

High p_T (> 4 GeV/c) direct photons at RHIC

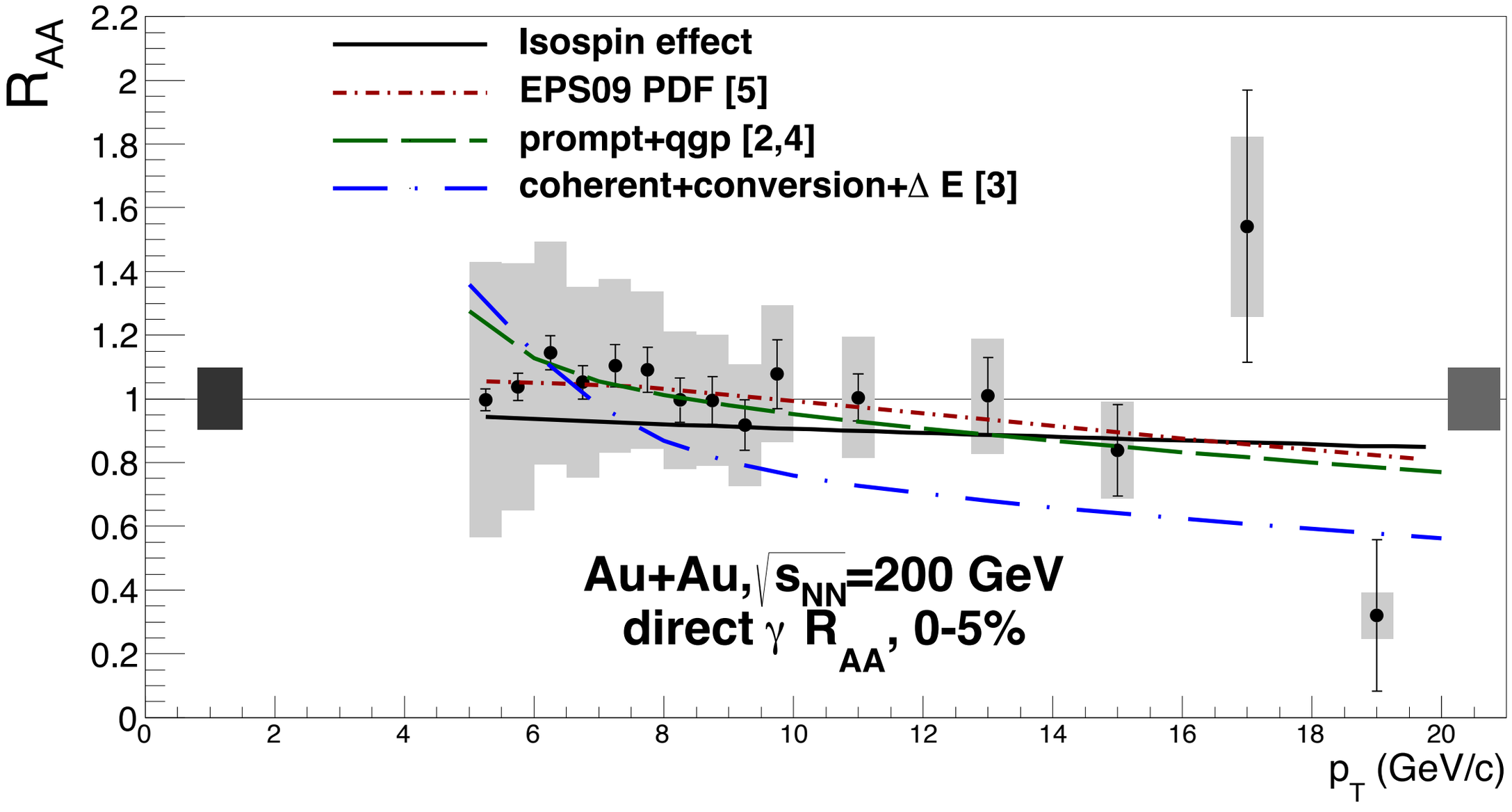
$$R_\gamma = \gamma_{\text{inclusive}} / \gamma_{\text{decay}} = 1 + \gamma_{\text{direct}} / \gamma_{\text{decay}}$$



$\gamma_{\text{direct}} = \gamma_{\text{decay}}$ at $p_T \approx 6$ GeV/c in central Au+Au at RHIC

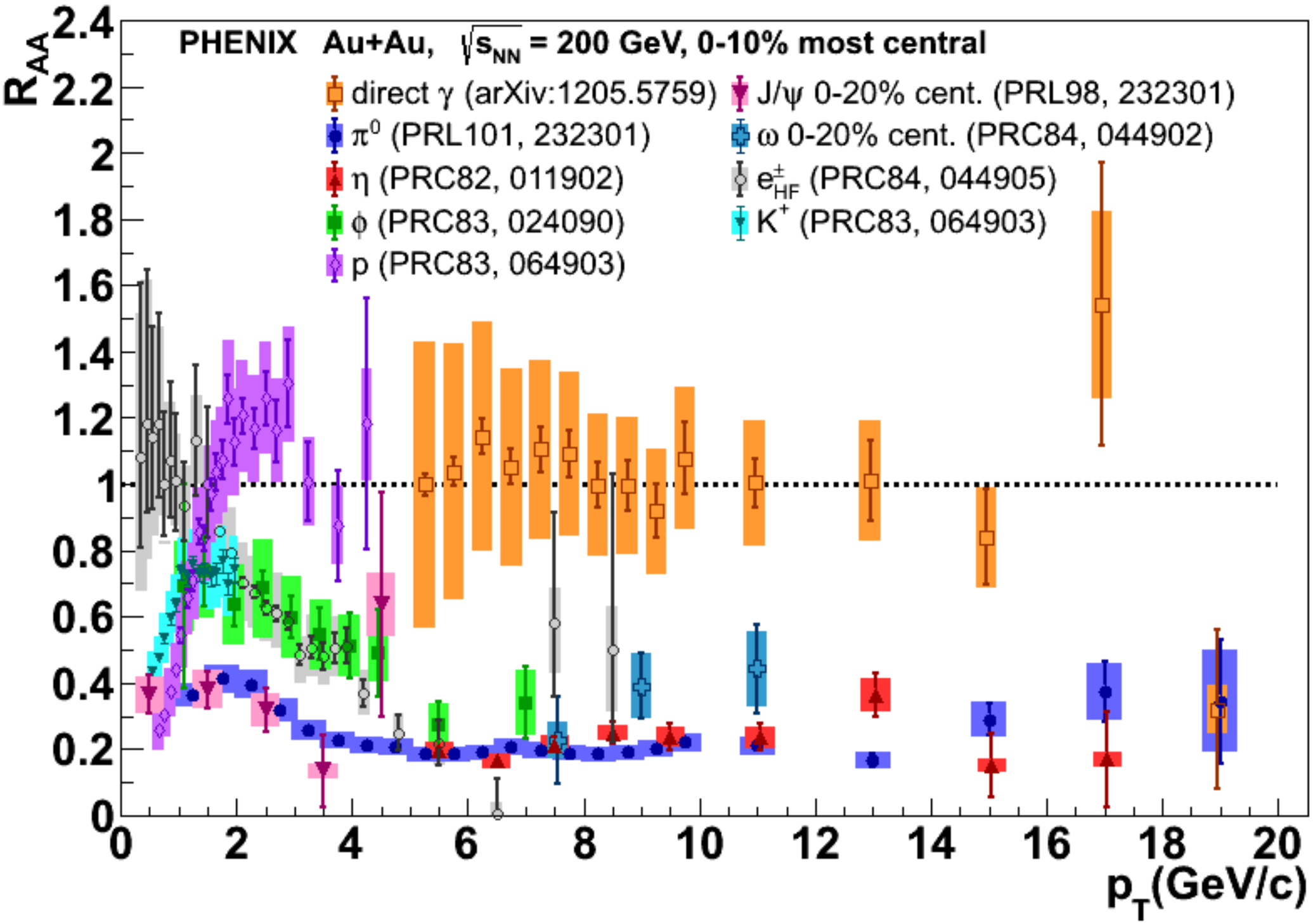
Direct photon $R_{AA} \approx 1$ in central Au+Au at RHIC confirms T_{AB} scaling

$$R_{AA}(p_T) = \frac{1/N_{AA}^{evt} d^2 N_{AA}/dp_T dy}{\langle T_{AA} \rangle \times d^2\sigma_{pp}/dp_T dy}$$



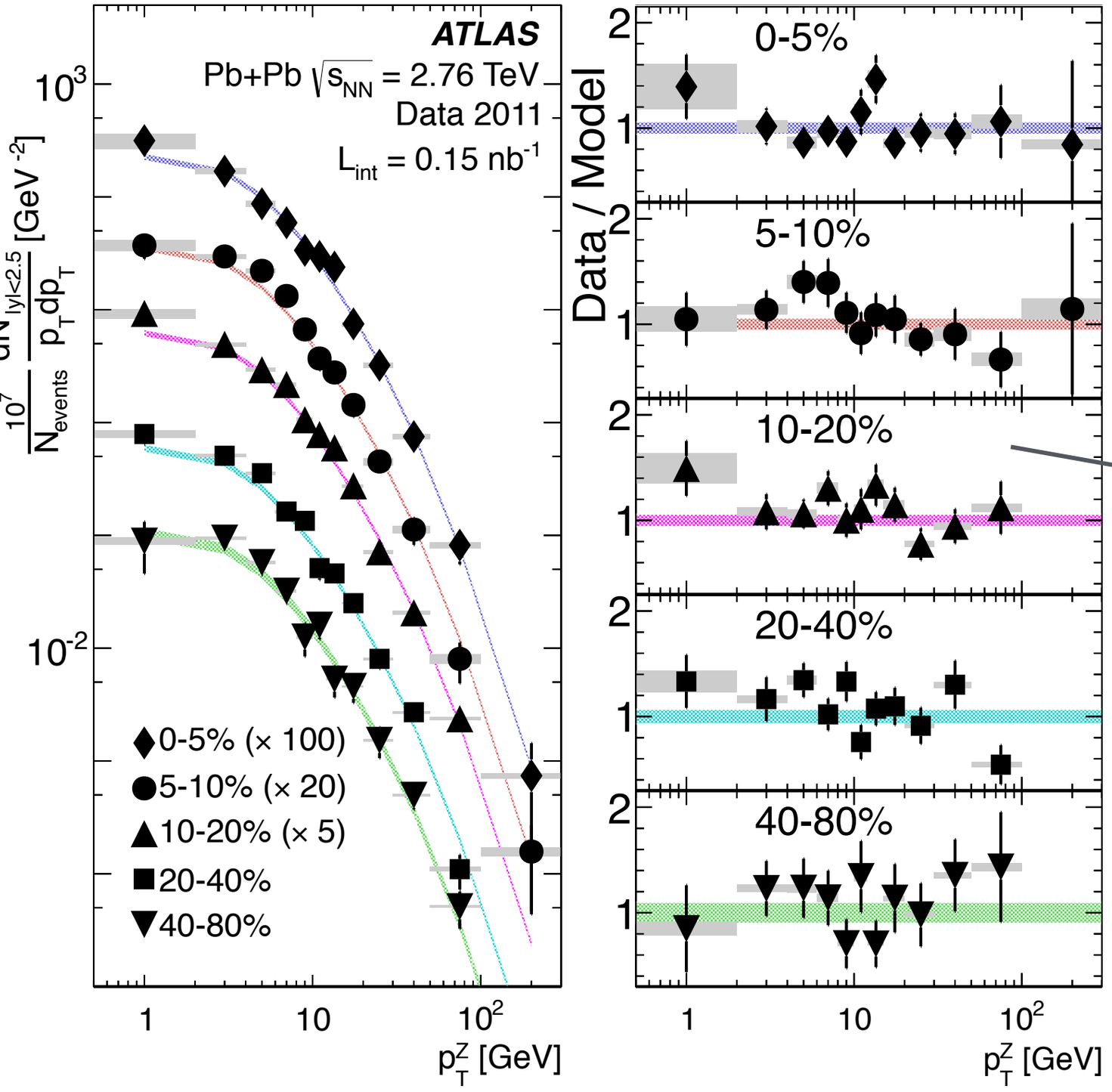
- Isospin effect + modification of nuclear PDF's consistent with the data
- However, no strong constraints on nuclear pdf within current certainties

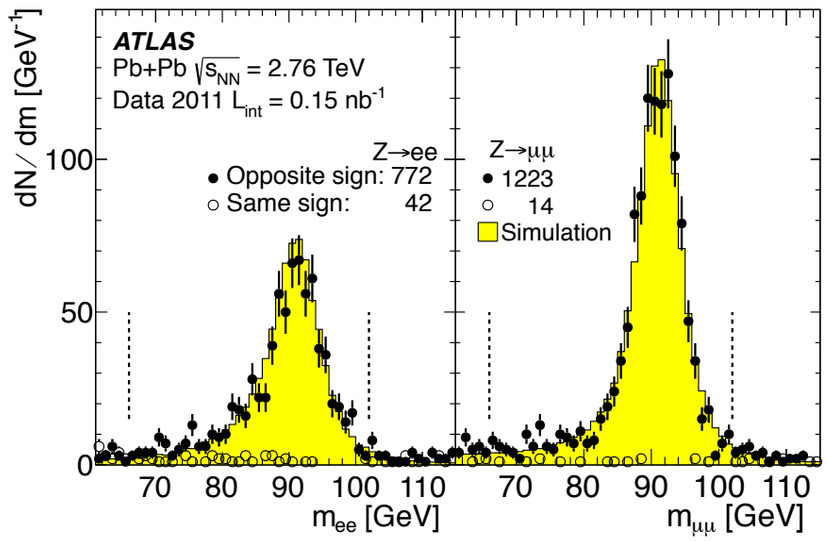
Reminder: T_{AB} scaling of high-p_T direct photons is a cornerstone of the parton energy loss interpretation of hadron suppression



T_{AB} Scaling confirmed at the LHC with Z, W, and Direct Photons

Z bosons in ATLAS





Model: PYTHIA, normalized to the NNLO p+p cross section, scaled by T_{AA}

Isolated Photon in ATLAS, Nucl. Phys. A (2013) 577c

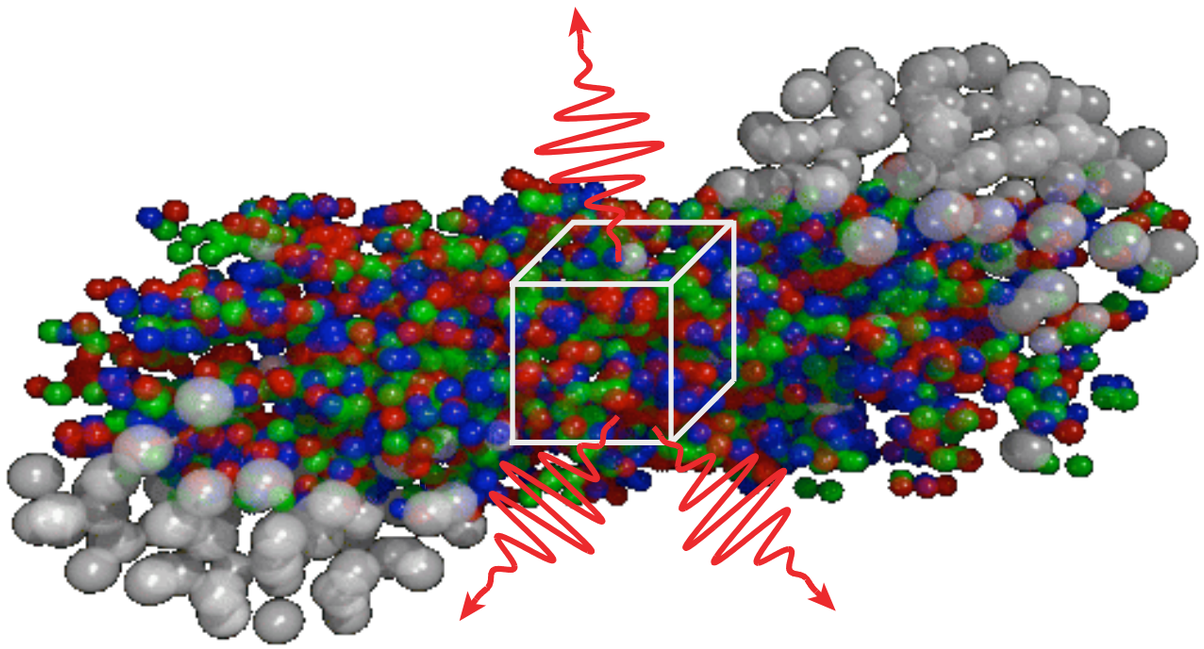
Isolated Photon in CMS, PLB 710 (2012) 256

Z and W in CMS, Nucl. Phys. A (2014)

2. Low-p_T Direct Photons ($p_T < 4$ GeV/c)

Motivation for low p_T direct photons: Thermal photons from the quark-gluon plasma (1/2)

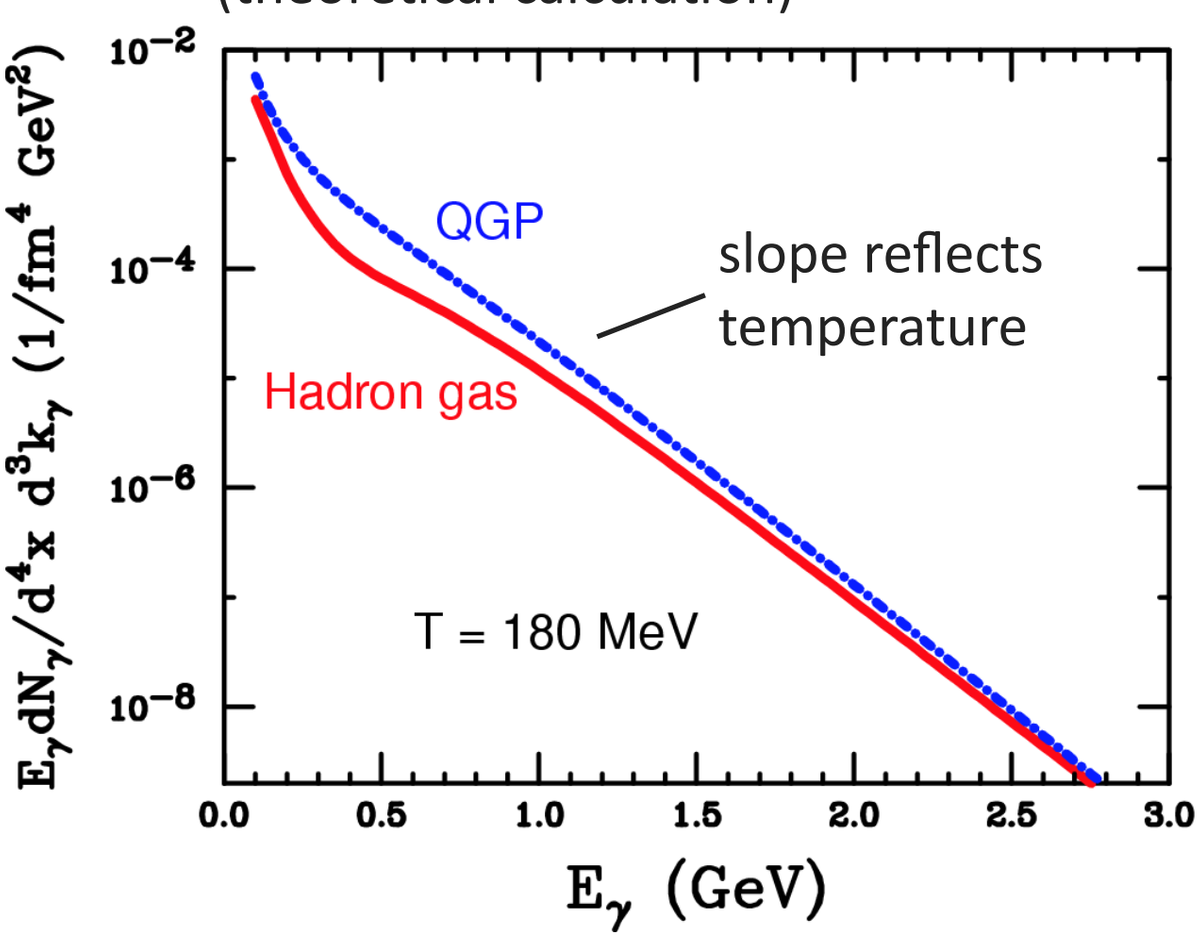
- Photons produced in scatterings of quark and gluons in thermal equilibrium
- Photons not in thermal equilibrium ($\lambda_{mfp} \approx 500$ fm), but energy spectrum reflects QGP temperature



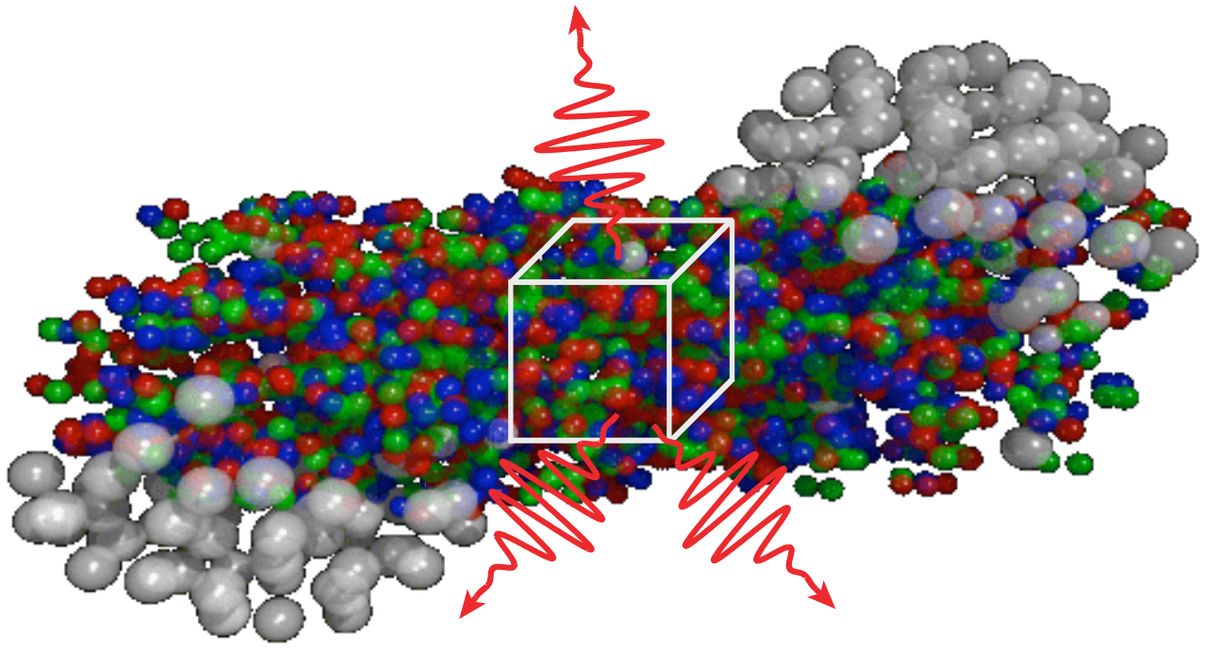
QGP photon rate (lowest order):

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

Photon rate: yield per unit time and volume as a function of photon energy (theoretical calculation)



Motivation for low p_T direct photons: Thermal photons from the quark-gluon plasma (2/2)



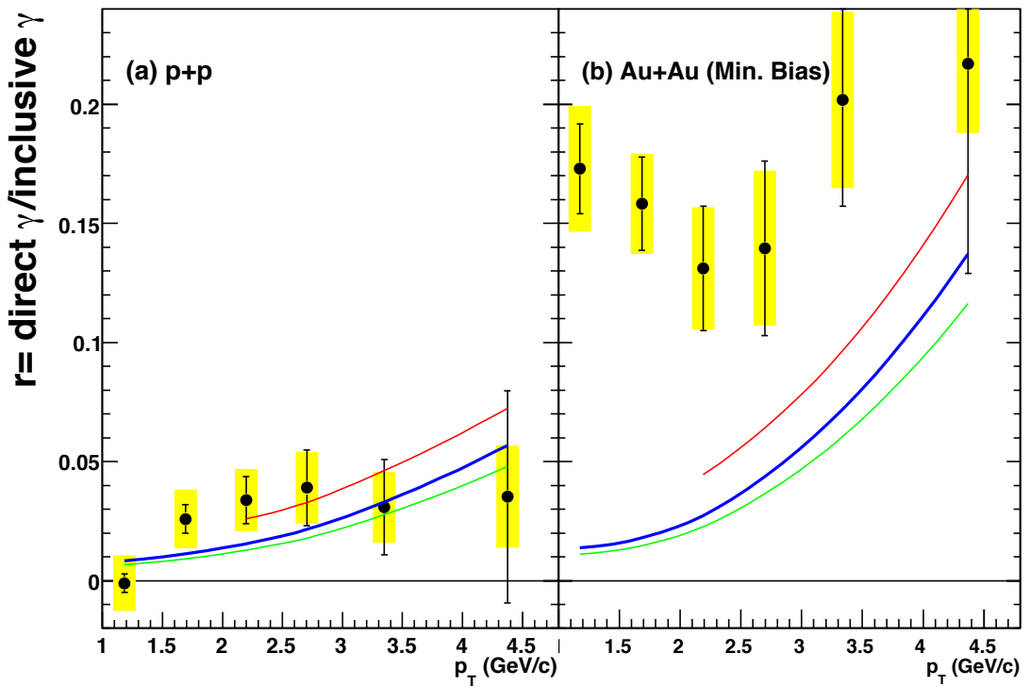
- Hadron spectra (π, K, p): only from late hadron gas phase
- Thermal photon spectrum has contribution from all stages of the time evolution (including the hadron gas phase)
- Thermal photons measurement + modeling of space-time evolution (hydrodynamics) ⇒ initial QGP temperature

Is this a valid line of reasoning?

Direct photons in heavy-ion collisions: Experimental methods

- Real photons with calorimeters
  - Challenging at low p_T (energy scale and resolution, hadronic background)
- Real photons with external conversions
  - Good momentum resolution at low p_T
  - Need to know material budget with high precision
- Real photons from external conversions,
  in case of π^0 decay partner photon with calorimeter
  - π^0 background from measurement of the partner photon with a calorimeter: material budget uncertainty cancels completely
  - Traded for energy scale uncertainty of the calorimeter
- Virtual photons with masses $m_{ee} \gtrapprox 100$ MeV
  - Background from neutral pion strongly suppressed
  - Needs lot's of statistics
  - Extrapolation to $m = 0$ (i.e., to real photons) relies on theory
    (➙ Kroll-Wada formula)

Low-p_T Direct Photon Spectra at RHIC (PHENIX, virtual photon method)

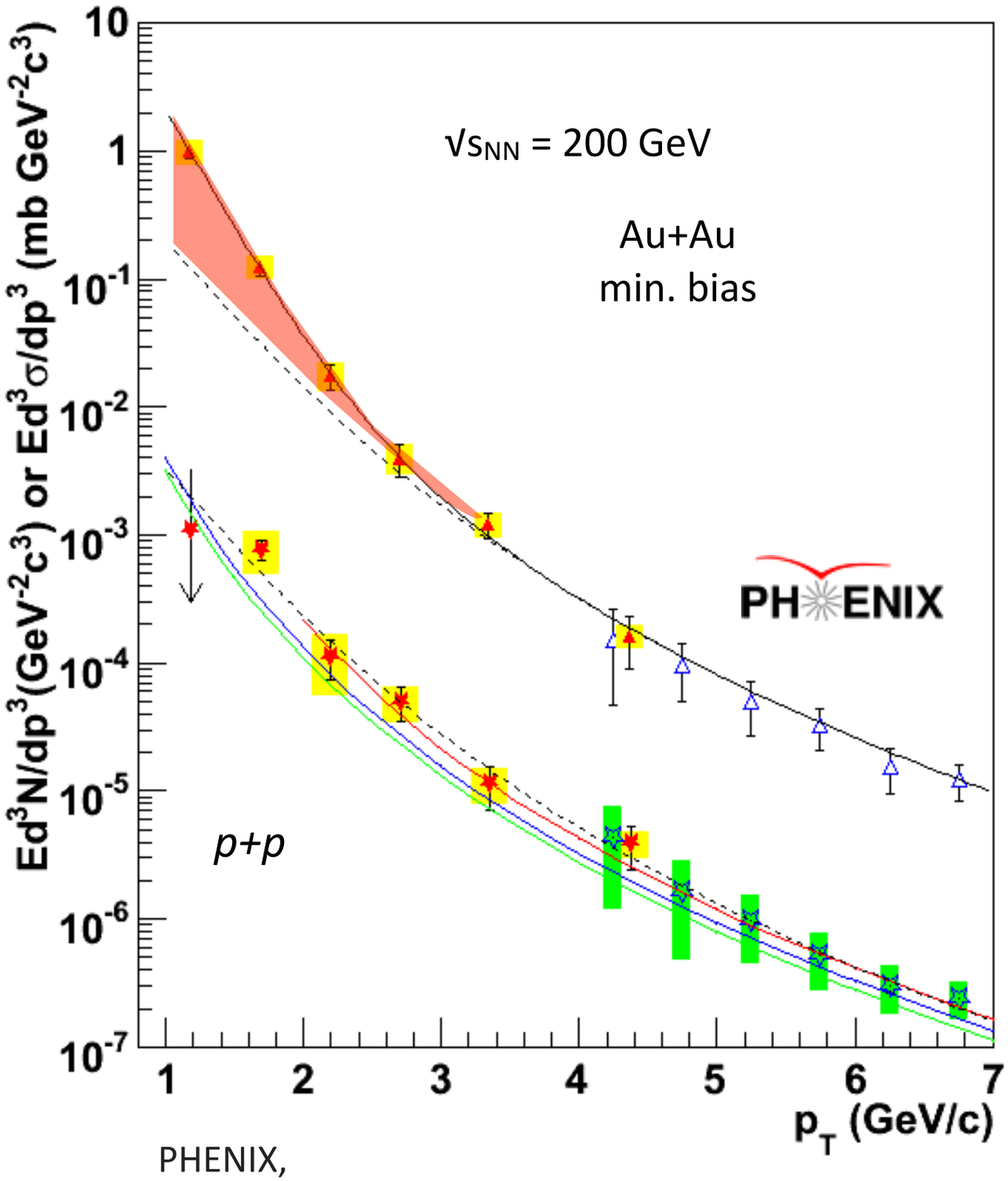


- Enhancement in Au+Au above p+p describe by an exponential

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

- Slope parameter (0 - 20%):
  T = (221 ± 23 ± 18) MeV

- Initial QGP temp. from fitting hydro to data: T_i = 300 - 600 MeV



PHENIX,
PRL, 104, 132301 (2010); PRC, 81, 034911 (2010)

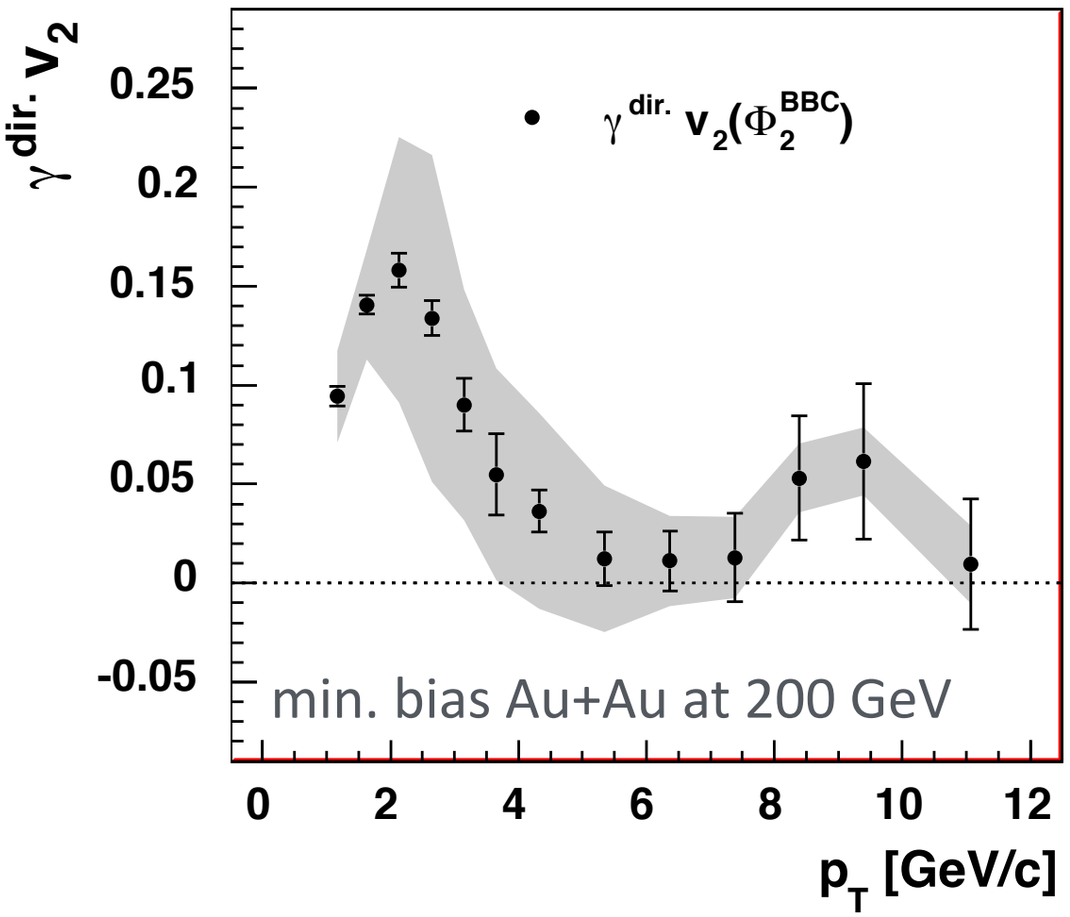
How to interpret the slope parameter T_{slope} ?

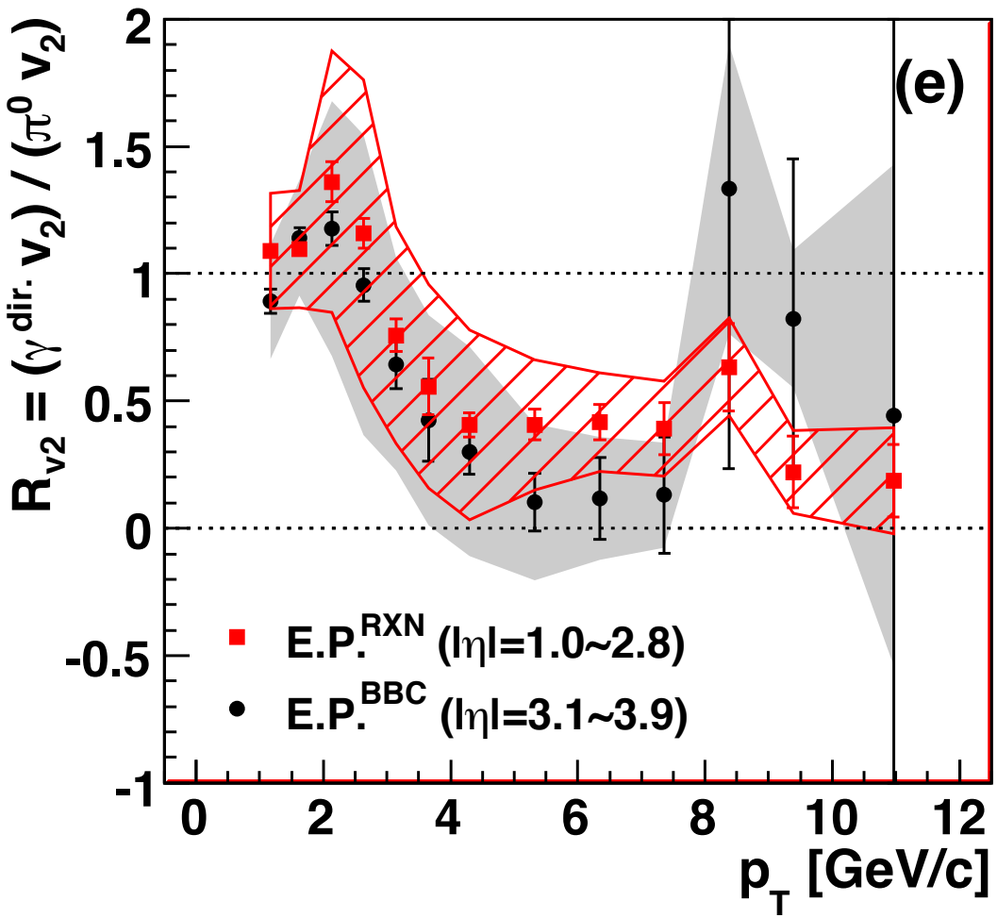
- T_{slope}: effective average of temperatures over space-time evolution(?)

- T_{slope} >> T_c = 150 - 160 MeV could indicate that photons predominantly come from early hot QGP phase

- In this case, expect small elliptic flow signal (v_2 ≈ 2 - 3% or so at maximum) as collective flow needs time to build up

The direct-photon flow puzzle:
Surprisingly large direct-photon v_2 measured by PHENIX



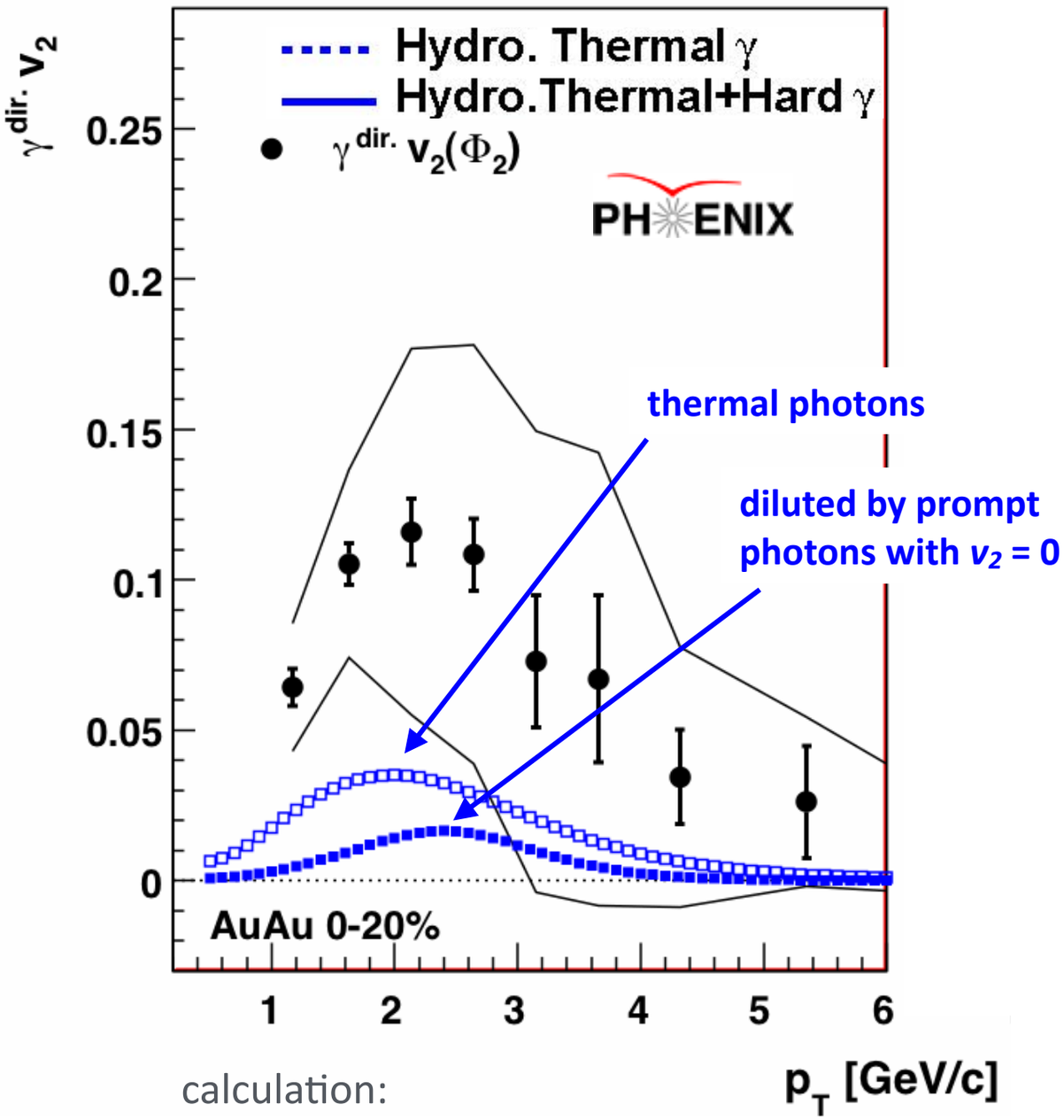


$$v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma v_2^{\gamma,\mathrm{incl}} - v_2^{\gamma,\mathrm{decay}}}{R_\gamma - 1}$$

- Direct-photon v_2 at $p_T \approx 2$ GeV/c similar to neutral pion v_2
- Direct-photon mostly form late phase when flow has fully built up?

Direct-photon v_2 not reproduced by hydrodynamic calculations

PHENIX, Quark Matter 2011



calculation:
Holopäinen, Räsänen, Eskola,
arXiv:1104.5371

- Dilution of thermal photon v_2 due to prompt component with $v_2 = 0$
- Assumption: net $v_2 \approx 0$ from
  - Fragmentation photons ($v_2 > 0$)
  - Jet-photon conversion ($v_2 < 0$)
  - Medium induced bremsstrahlung ($v_2 < 0$)

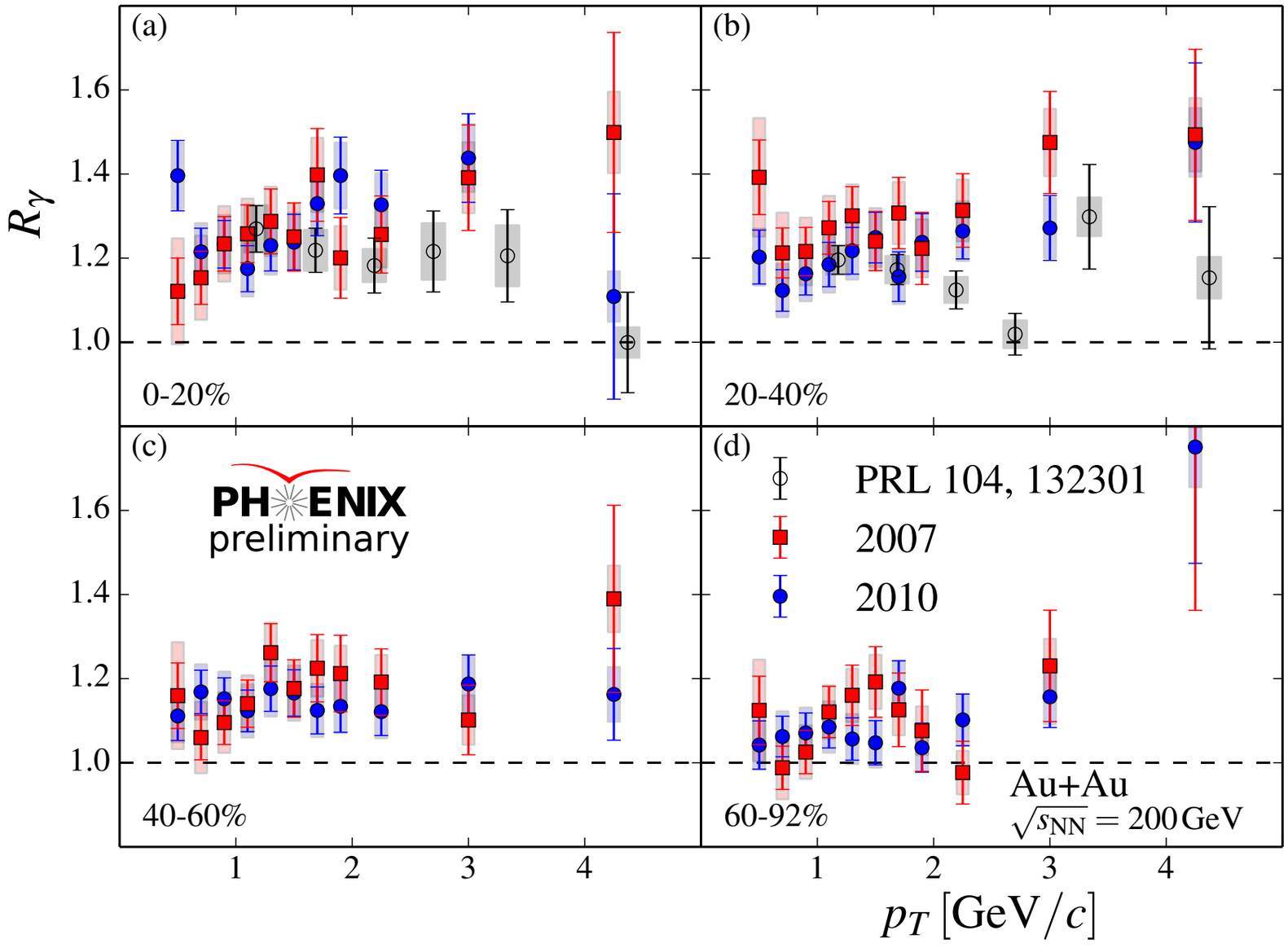
[Turbide, Gale, Frodermann, Heinz,
Phys. Rev. C 77, 024909 (2008)]

- PHENIX: Data a challenge to theory
- Charles Gale (theorist):
  "Theory a challenge to the data"

Photon excess R_γ confirmed with real photons (PHENIX, external conversion + EMCal)

B. Bannier, 2014

see also PHENIX, arXiv:1405.3940

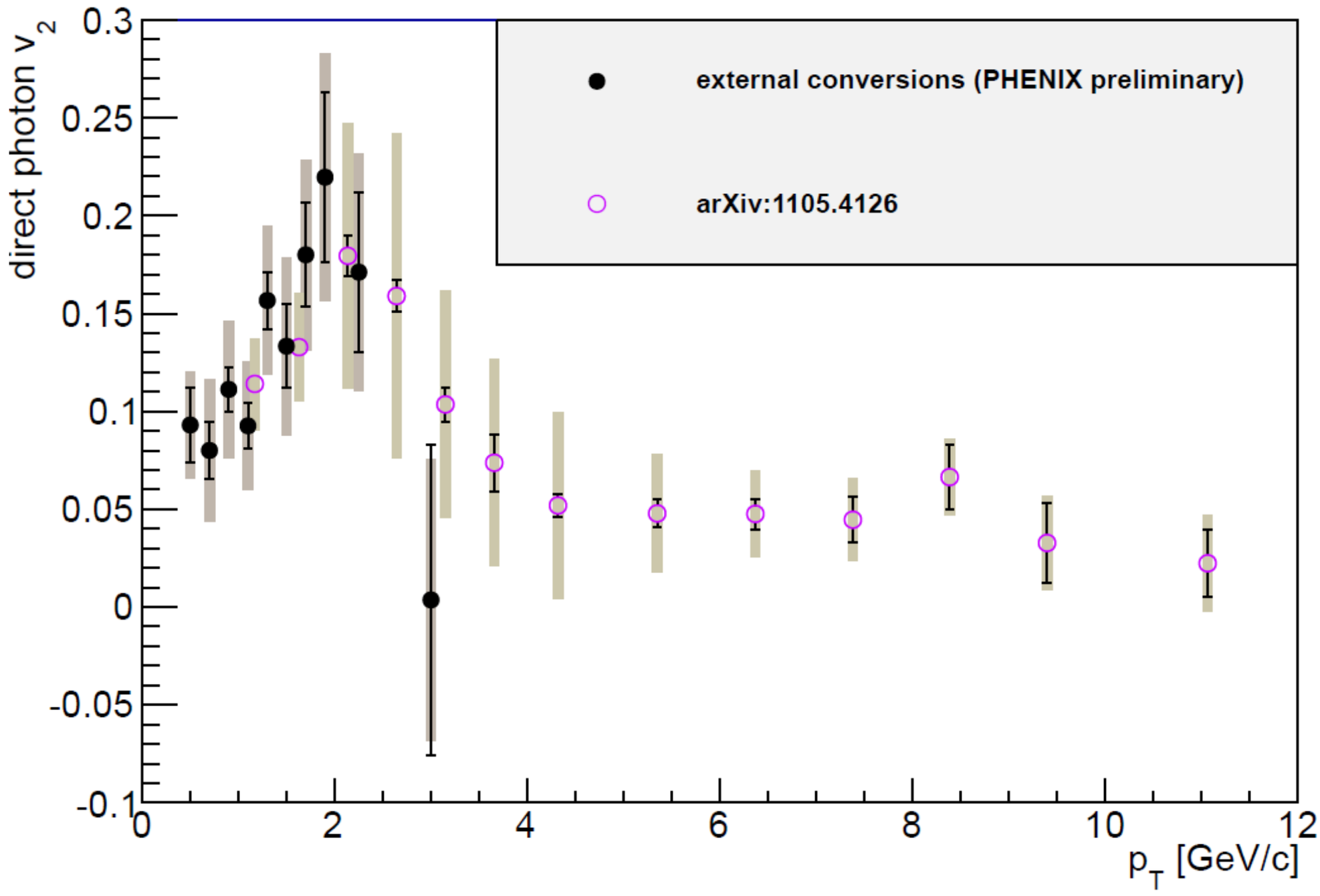


R_γ from real photons (red, blue) consistent with R_γ from virtual photons

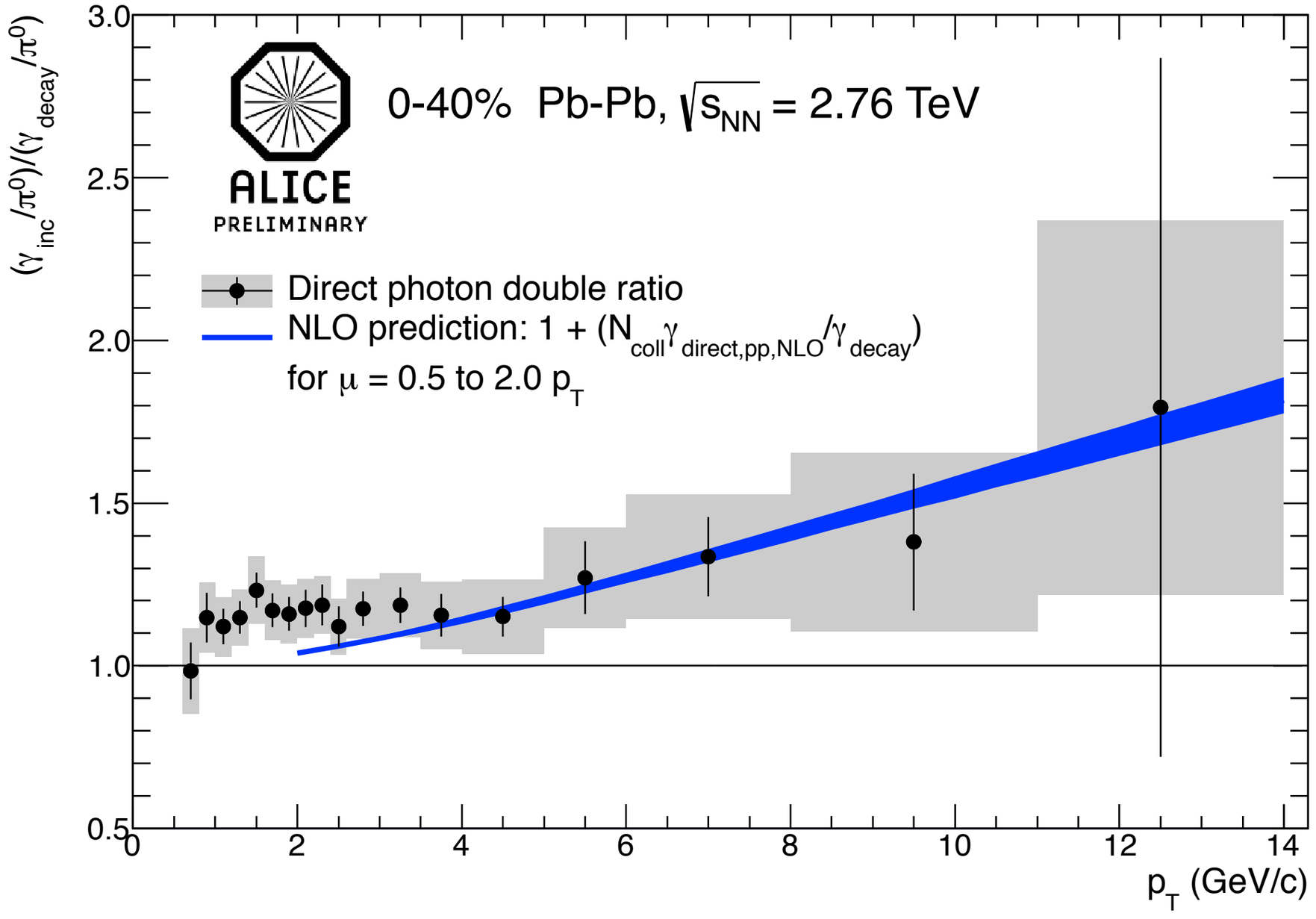
Centrality dependence:

$$\left.\frac{dN_{\gamma,\mathrm{direct}}}{dy}\right|_{p_T > p_{T,\mathrm{min}}} (N_{\mathrm{part}}) \propto N_{\mathrm{part}}^{\alpha} \text{ with } \alpha \approx 1.5 \text{ for } p_{T,\mathrm{min}} = 0.4, \ldots, 1.4\,\mathrm{GeV}/c$$

Direct-photon v_2 at RHIC also confirmed with real photons



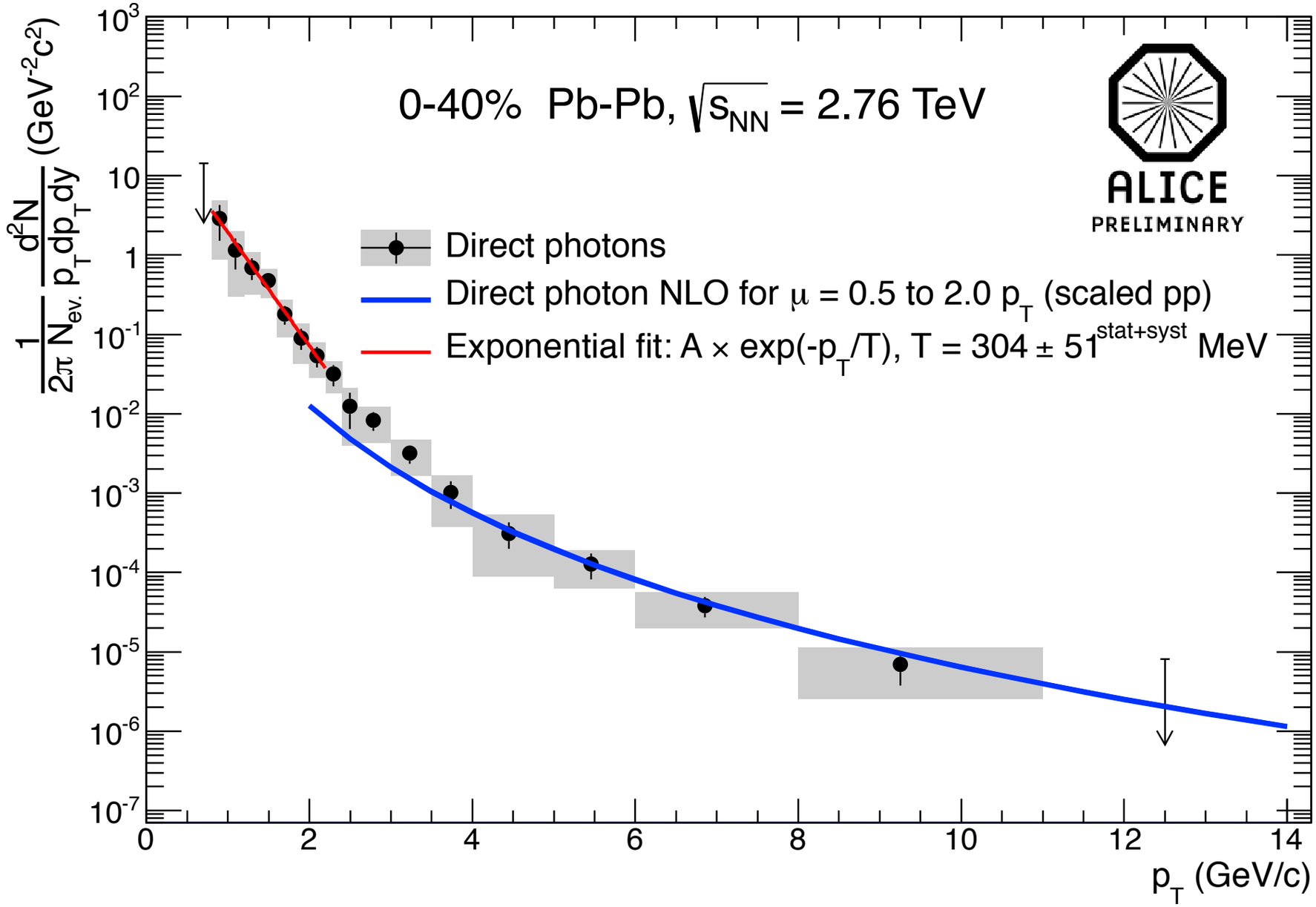
Low-p_T direct-photon excess at the LHC (ALICE, external conversions)



$$R_\gamma = \frac{(\gamma_{\text{inclusive}}/\pi^0)_{\text{meas}}}{(\gamma_{\text{decay}}/\pi^0)_{\text{calc}}}$$

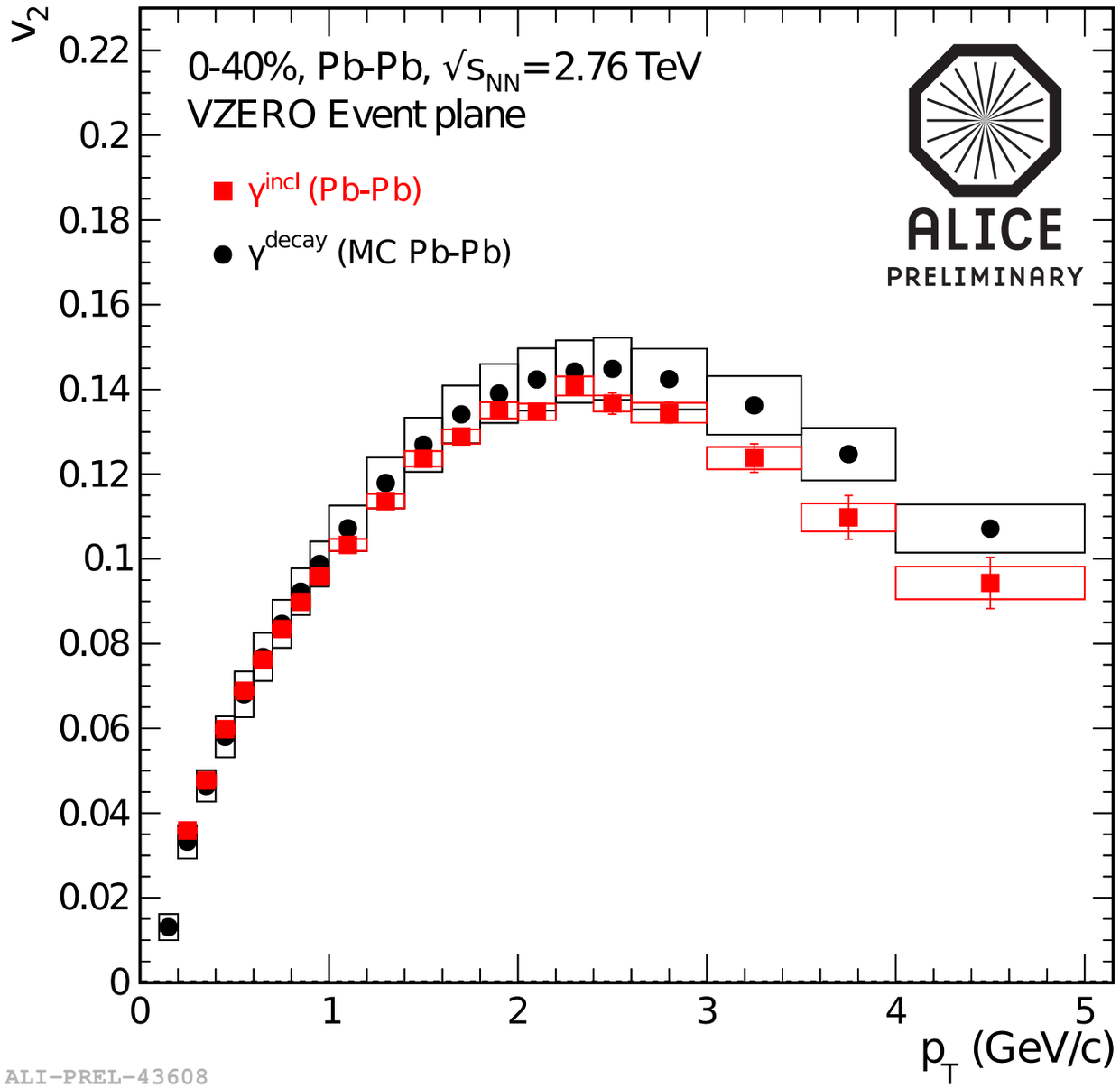
- ~ 20% direct-photon excess for $1 < p_T < 4$ GeV/c
- Uncertainty dominated by material budget uncertainty, correlated in p_T

Low-p_T Direct photon spectrum at the LHC (ALICE, external conversions)



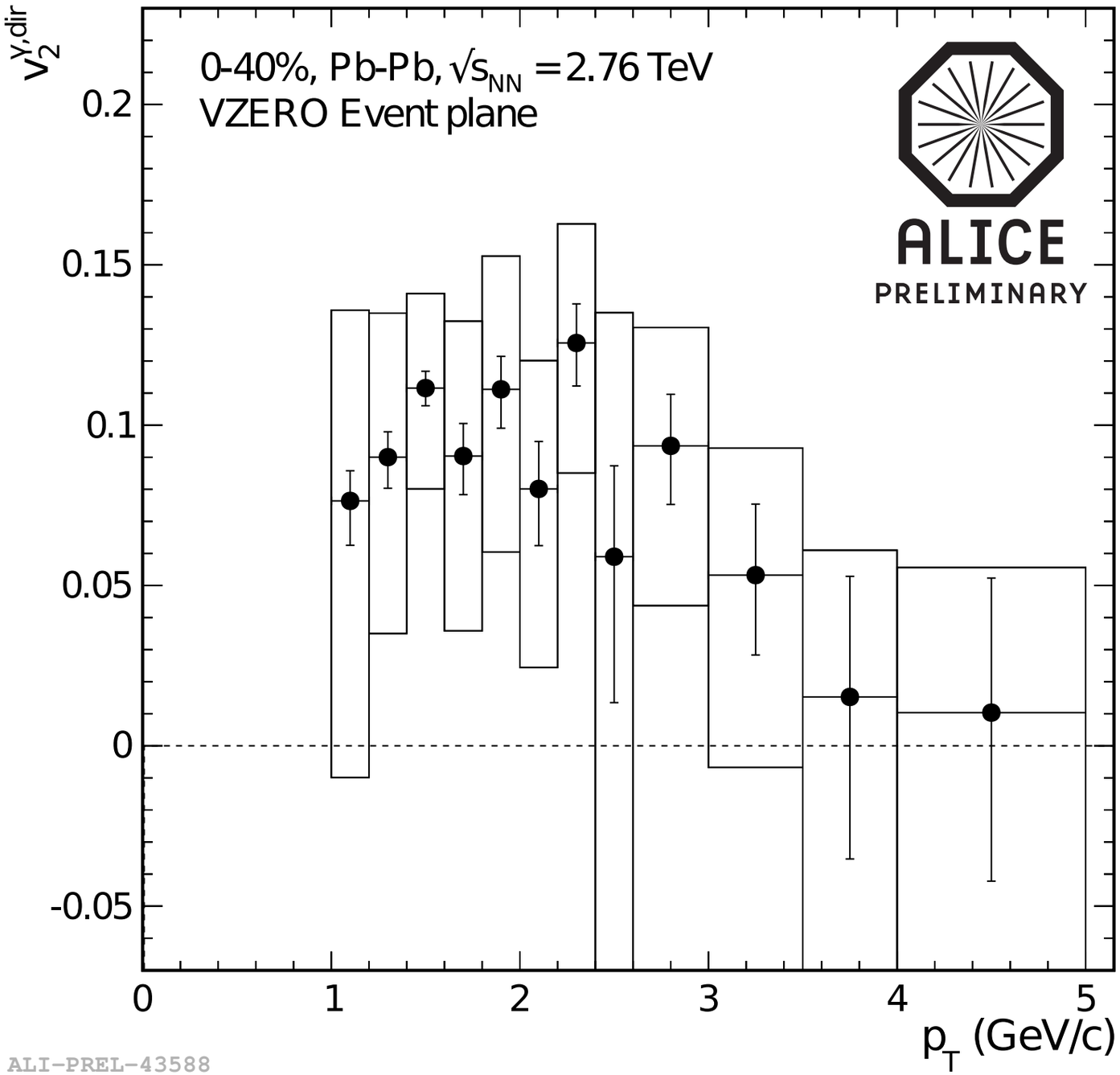
- Direct-photon spectrum described by pQCD photons for p_T > 4 GeV/c
- Low-p_T direct photon spectrum at the LHC also described by an exponential: $T = (304 \pm 51^{stat+sys})$ MeV

Direct-photon flow at the LHC: Inclusive and Decay Photon v_2



- $v_2^{\gamma,incl} \approx v_2^{\gamma,decay}$ for $p_T < 3$ GeV/c
- Thus, if there is a significant direct-photon component in this p_T range, its v_2 must be very similar the decay photon v_2

Large Direct-Photon Elliptic Flow also at the LHC



ALI-PREL-43588

- Maybe many direct photons from late stage with temp. $T \approx 160$ MeV?
- Then large inverse slope parameter due to Doppler blueshift with typical hadronic flow velocity $\beta_{\mathrm{flow}} \approx 0.6\ c$?

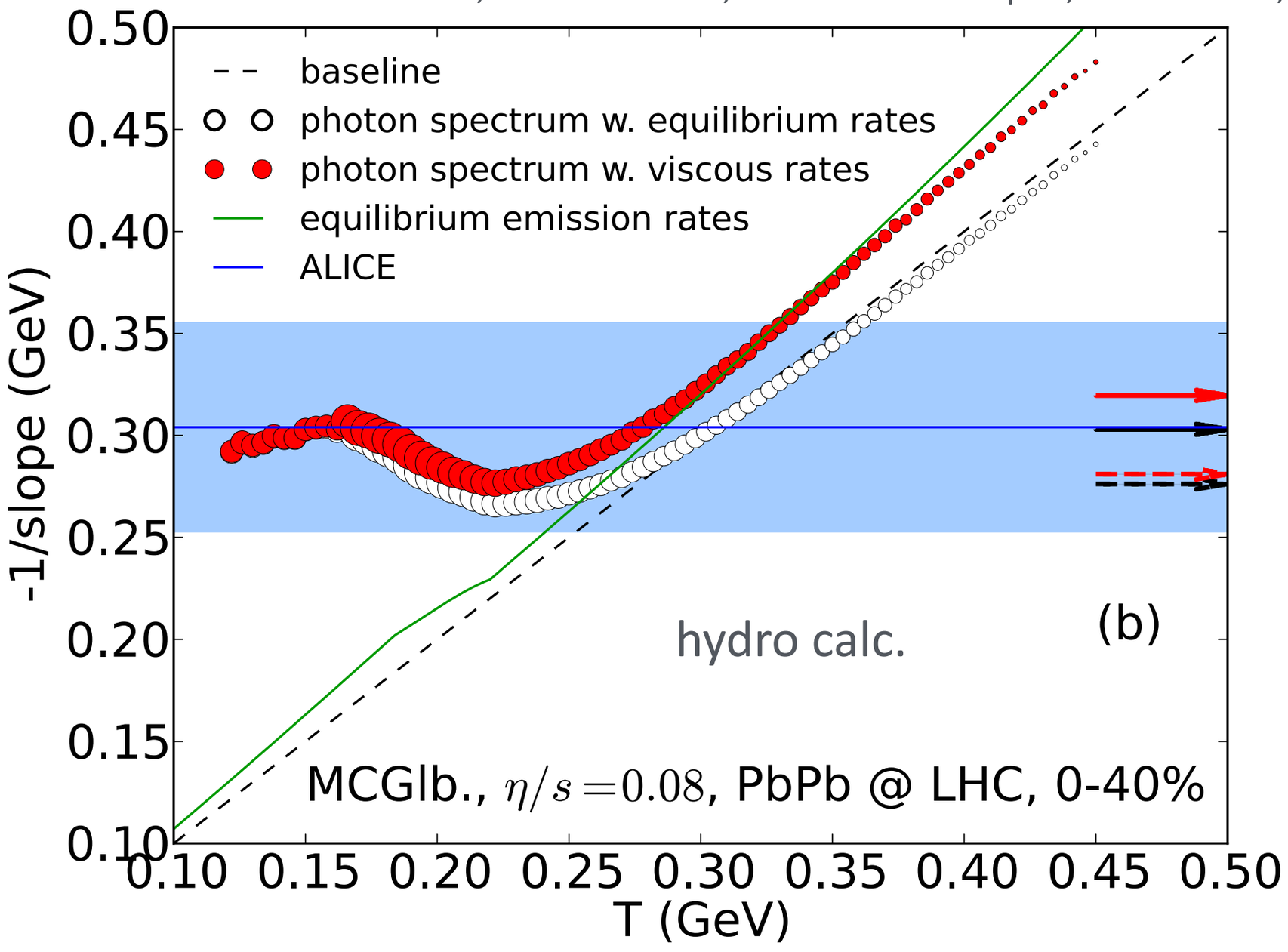
$$T_{\mathrm{slope}} = \underbrace{\sqrt{\frac{1+\beta_{\mathrm{flow}}}{1-\beta_{\mathrm{flow}}}}}_{=2 \text{ for } \beta_{\mathrm{flow}}=0.6} T$$

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

sys. uncertainty dominated by R_γ, error propagation not trivial

The effect of Doppler blueshift on the fitted T_{slope}

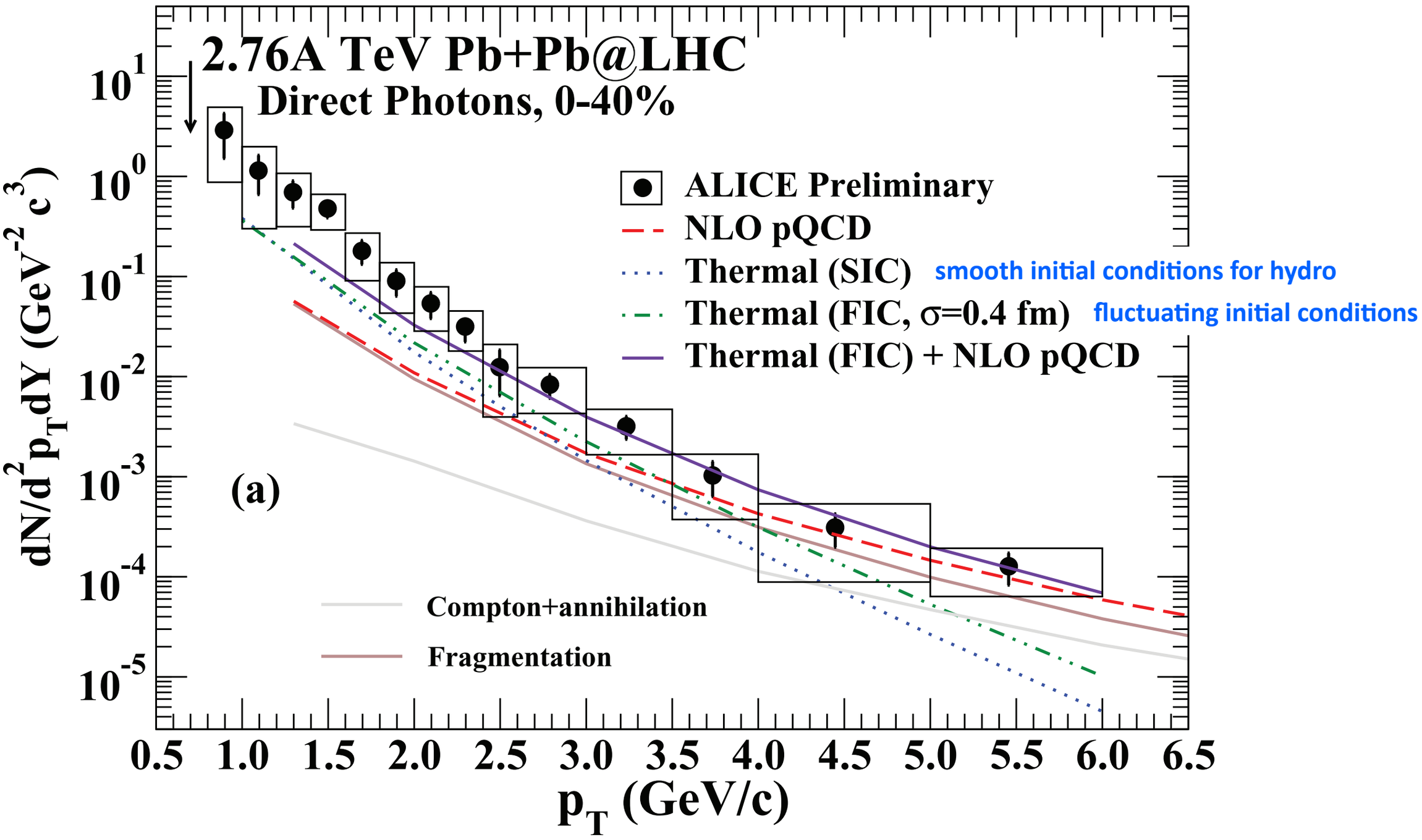
Chun Shen, Ulrich W Heinz, Jean-Francois Paquet, Charles Gale, arXiv: 1308.2440



- About 50-60% of the thermal photons from hydro cells with $T < 250$ MeV
- These are strongly blue shifted, resulting in $T_{slope} > T$
- Similar at RHIC

Comparison to theory at the LHC: Direct-photon spectrum ...

R. Chatterjee et al., Phys. Rev. C 88 (2013) 034901

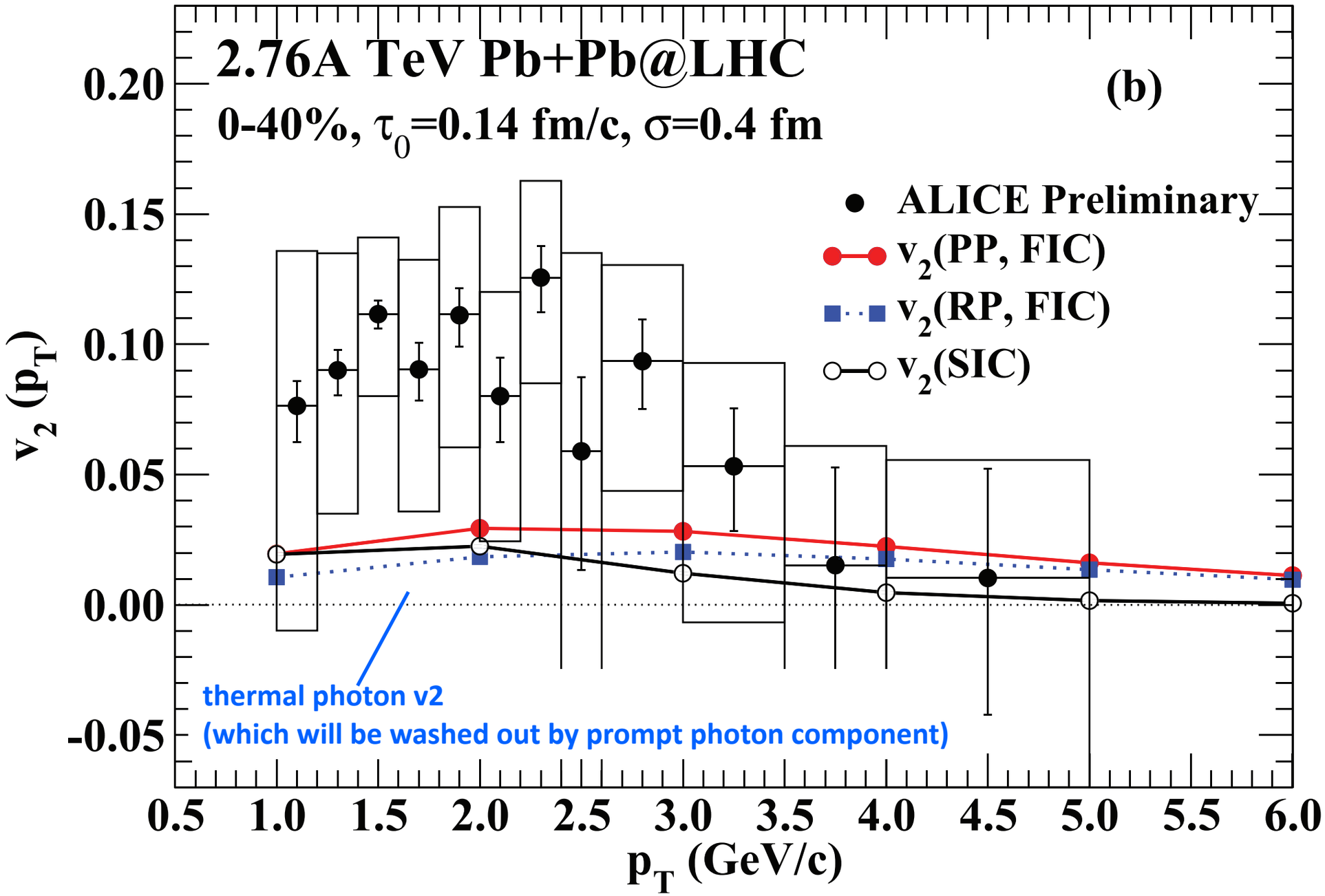


smooth initial conditions for hydro

fluctuating initial conditions

Not enough direct photons in calculation for $1 < p_T < 2$ GeV/c (general feature of most hydro models, also at RHIC)

… and direct-photon v_2



- Larger direct-photon v_2 than expected from theory
- Looks like a confirmation of the RHIC puzzle,
  however, sizable (correlated) systematic uncertainties!

Recap: The direct-photon puzzle

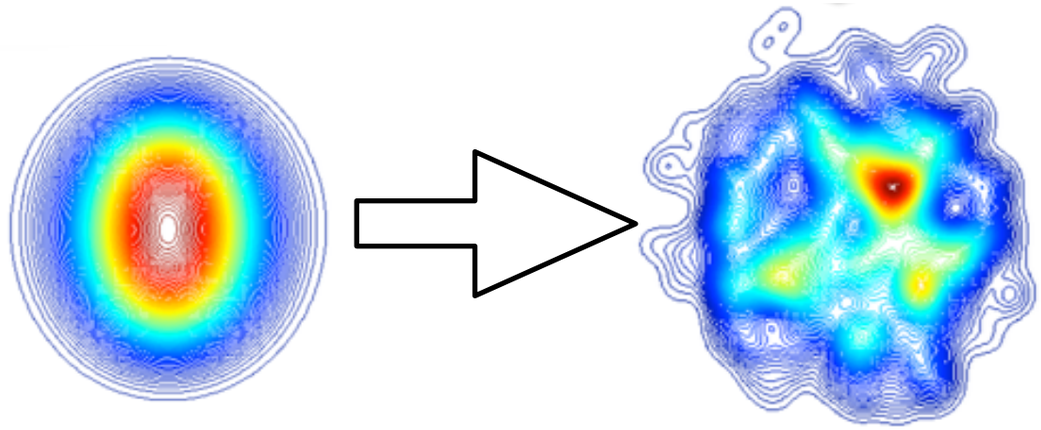
- Large direct-photon v_2, similar in magnitude to pion v_2
- First observed by PHENIX with R_γ from virtual photons, confirmed later by PHENIX with real photons
- Qualitative similar observation by ALICE with external conversions, however, current uncertainties larger than at RHIC
- Hydro models underpredict direct-photon excess and v_2
- Challenges “standard model” for the space-time evolution of heavy-ion collisions and/or photon production rates in the QGP and the hadron gas
- Calls into question the relation between the observed slope parameter T of the direct-photon spectrum and the initial QGP temperature

Will thermal photons as QGP thermometer remain an unfulfilled promise?

Further info: EMMI rapid reaction task force on the direct-photon flow puzzle (Feb. 2014)

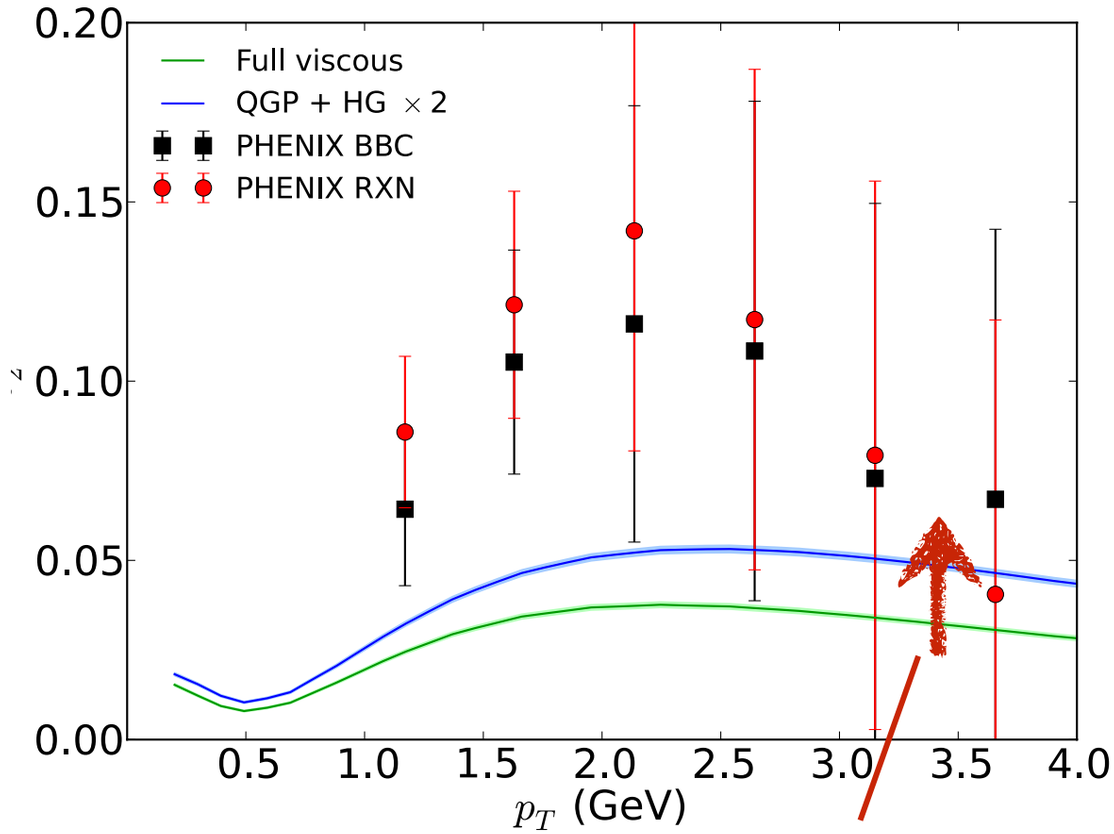
Towards a solution of the direct-photon puzzle (1/4): Improved hydro calculations

- Viscous hydro + viscous corrections to photon rates ➜ makes v_2 smaller



- Full viscous hydro with fluctuating initial conditions
  ➜ higher thermal photon yields
  ➜ little effect on v_2

- Increase HG rates? ➜ need factor much larger than 2 (up to 20 depending on calc.), seems unrealistic



Effect of a factor 2 increase in the HG rates

Chun Shen, Ulrich Heinz, 2014

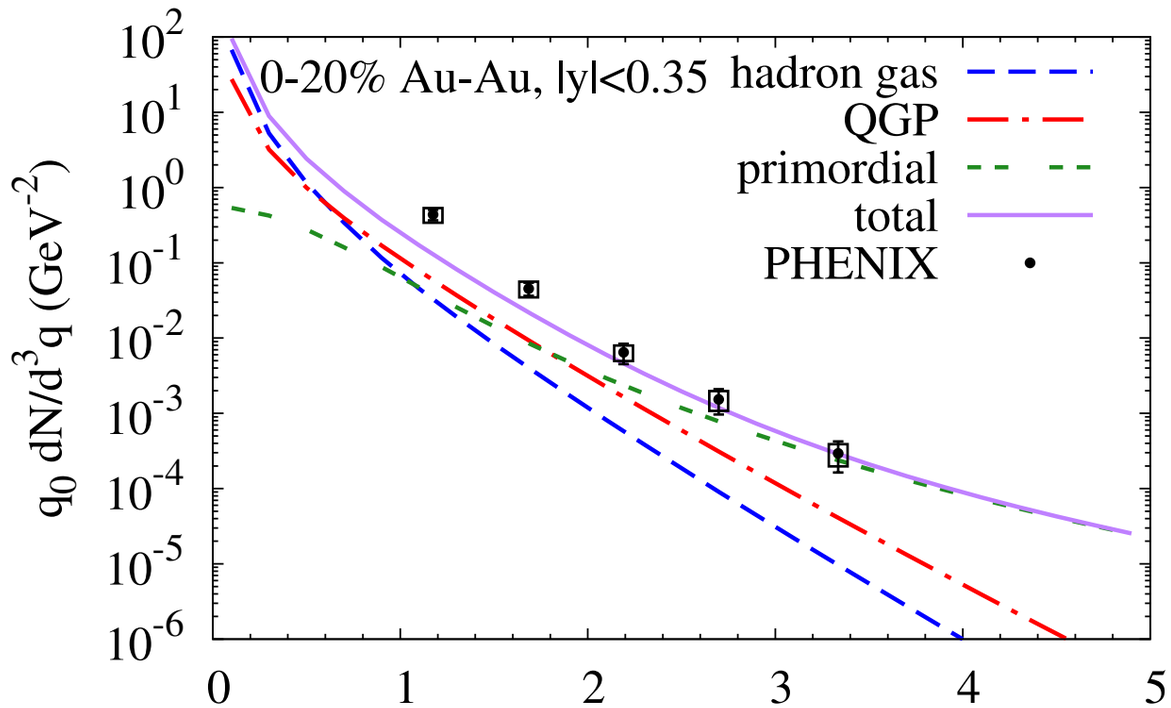
Charles Gale, 2014

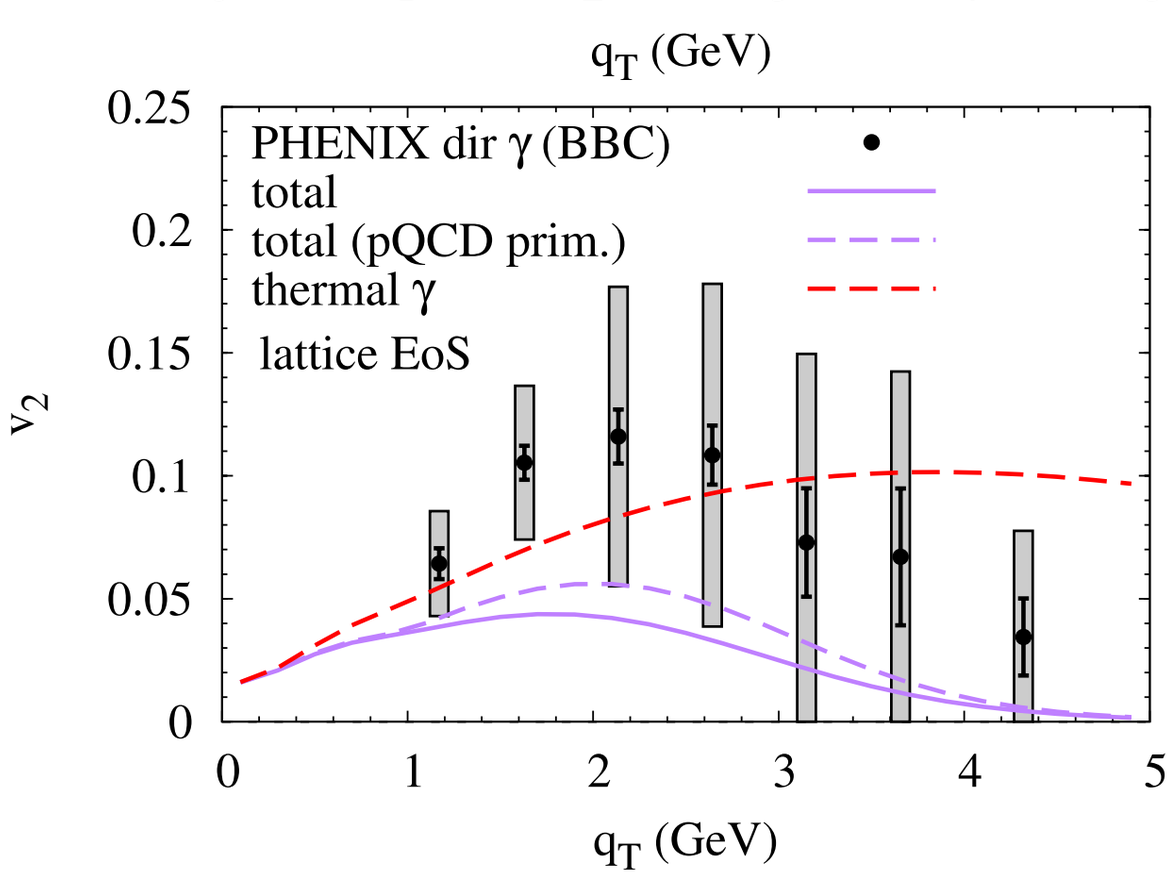
Improvements in hydro calculations (viscous effects, fluctuating initial conditions) don't solve the puzzle

Towards a solution of the direct-photon puzzle (2/4): Tweak space-time evolution and HG rates

- Faster build up of flow implemented in schematic fireball model
  - nearly full v_2 at the end of the mixed phase
- Larger HG photon rates including contribution from baryons and anti-baryons
- Possibly larger photon rates in the transition region close to T_c (studied with ideal hydro calc.)

Rapp, van Hees,
arXiv:1108.2131, arXiv:1404.2846

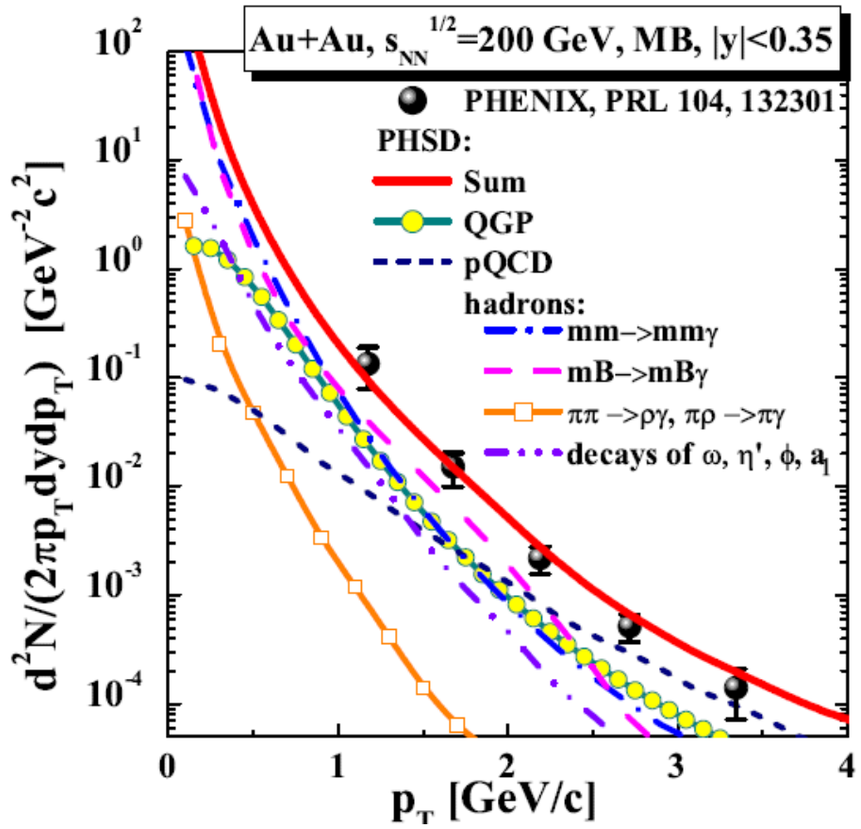


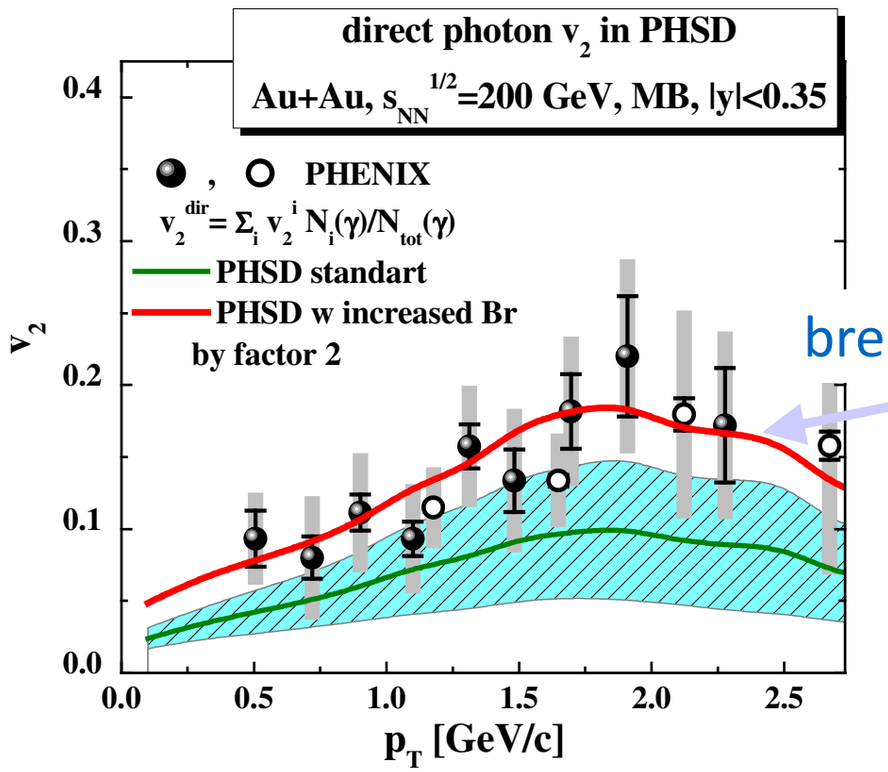


Towards a solution of the direct-photon puzzle (3/4): Large contribution from hadron-hadron bremsstrahlung

O. Linnyk et al, arXiv:1304.7030
E. Bratkovskaya, 2014

- PHSD model
  - Non-equilibrium transport model for partonic and hadronic phase
  - Quarks and gluon in the QGP: dynamical quasi-particles with finite mass and width
  - Explicit phase transition to hadrons and excited stated (strings)
- Meson-meson and baryon meson bremsstrahlung conjectured to be a major photon source
  - m + m → m + m + γ
  - m + B → m + B + γ
- Could solve the puzzle, rigoros theoretical treatment difficult
- Would imply little sensitivity of thermal photons to QGP





Towards a solution of the direct-photon puzzle (4/4): Further ideas

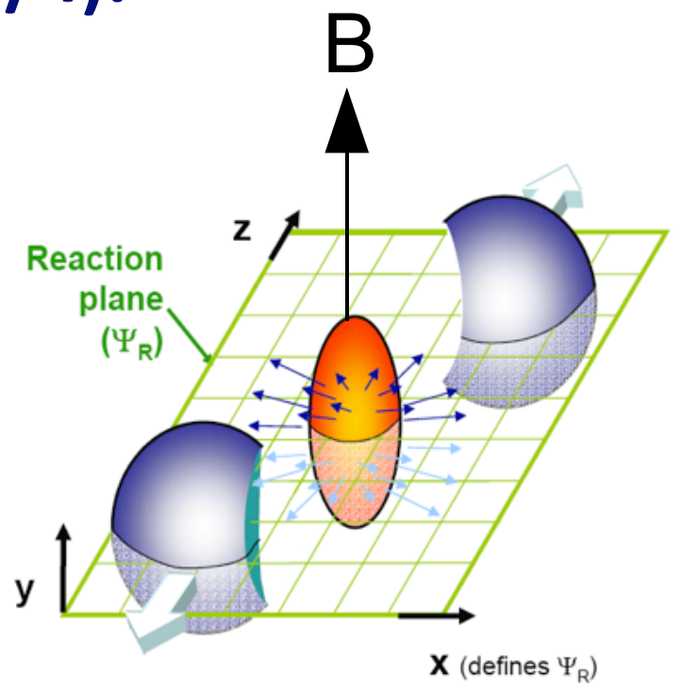
- Early time magnetic field effect?
  - Correct centrality dependence?
  - Could be ruled out by a measurement of a relatively large direct-photon v_3 (?)

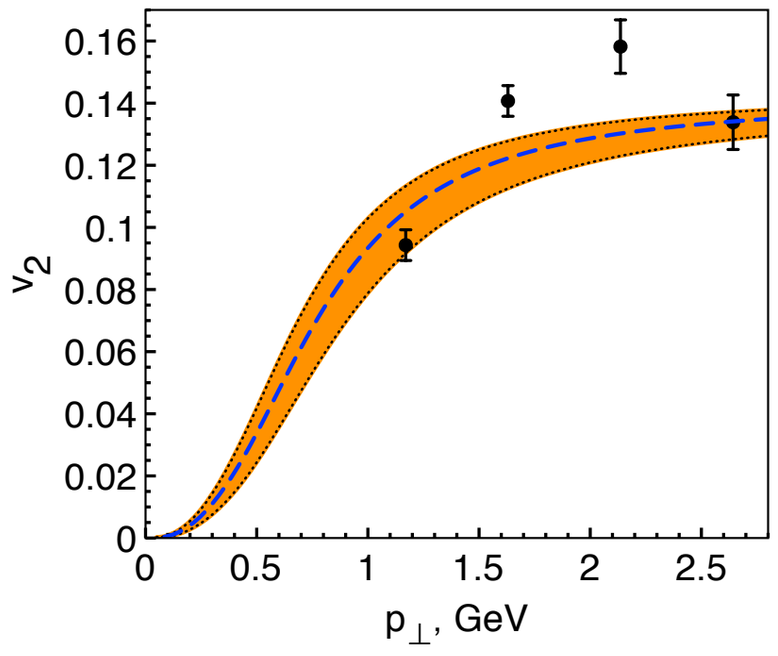
  Basar, Kharzeev, Skokov., arXiv:1206.1334

- Photons from the Glasma phase?

  McLerran et al., arXiv:1202.3679

- Initial flow before hydro evolution starts?
  - IP-Glasma initial conditions contain initial flow, however, effect seems to be small
- Further checks on the theory side
  - pQCD component under control?
  - Same definition of “direct photons” as used by experiments? (decay γ’s from short-lived resonances?)



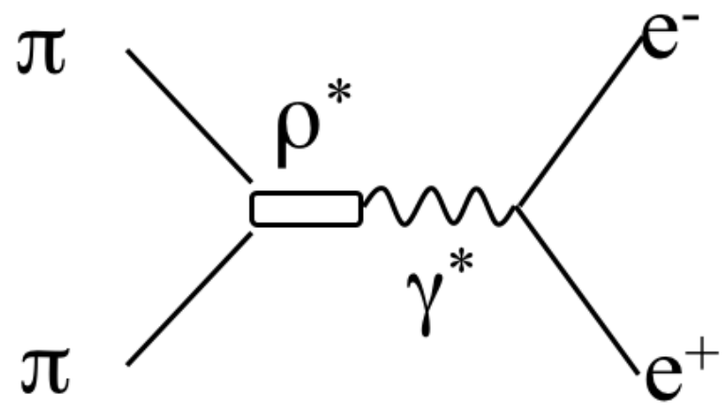


3. Dileptons

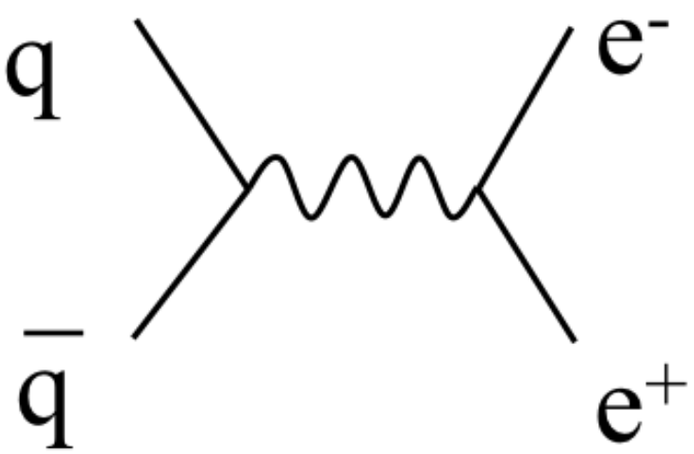
Dileptons: Motivation

- 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?
- Thermal radiation from the QGP and access to early temperature? (M_{ee} > 1 GeV)
- Constrains space-time evolution

hadron gas

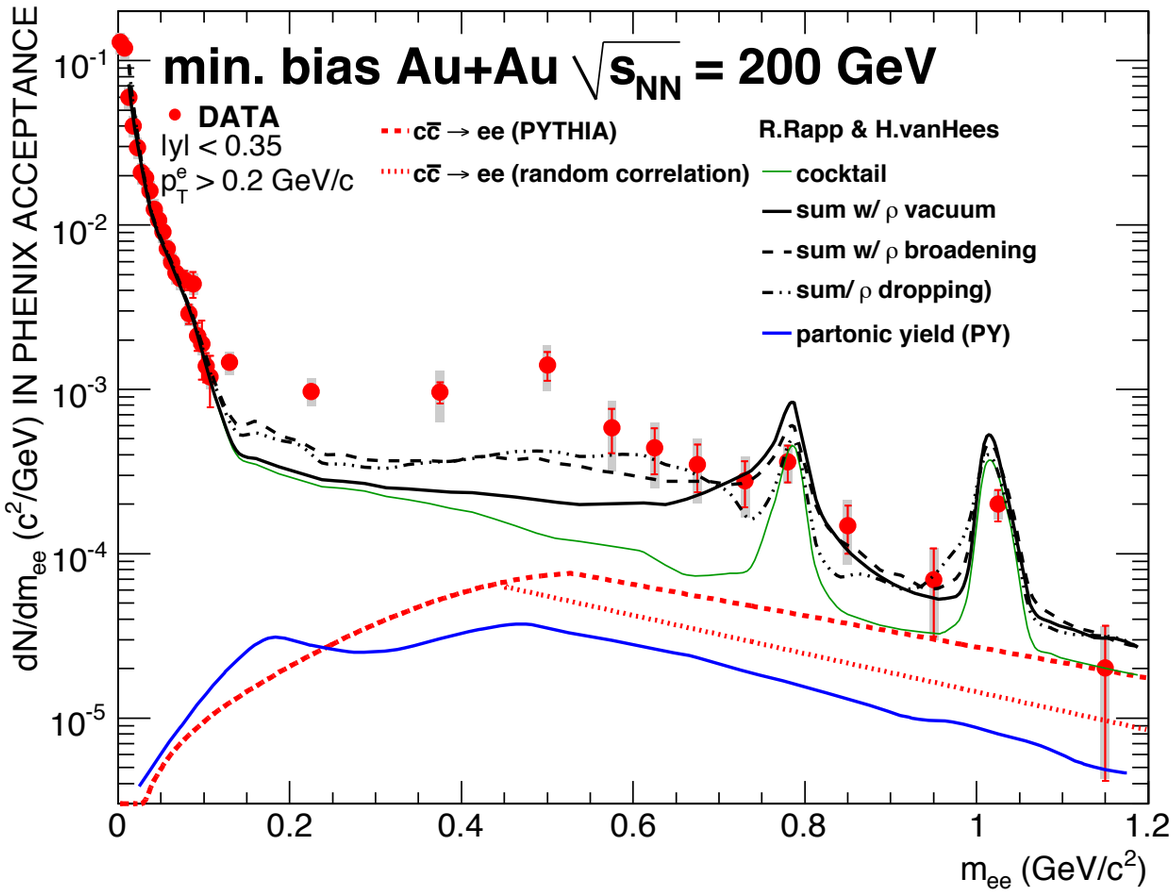


quark-gluon plasma

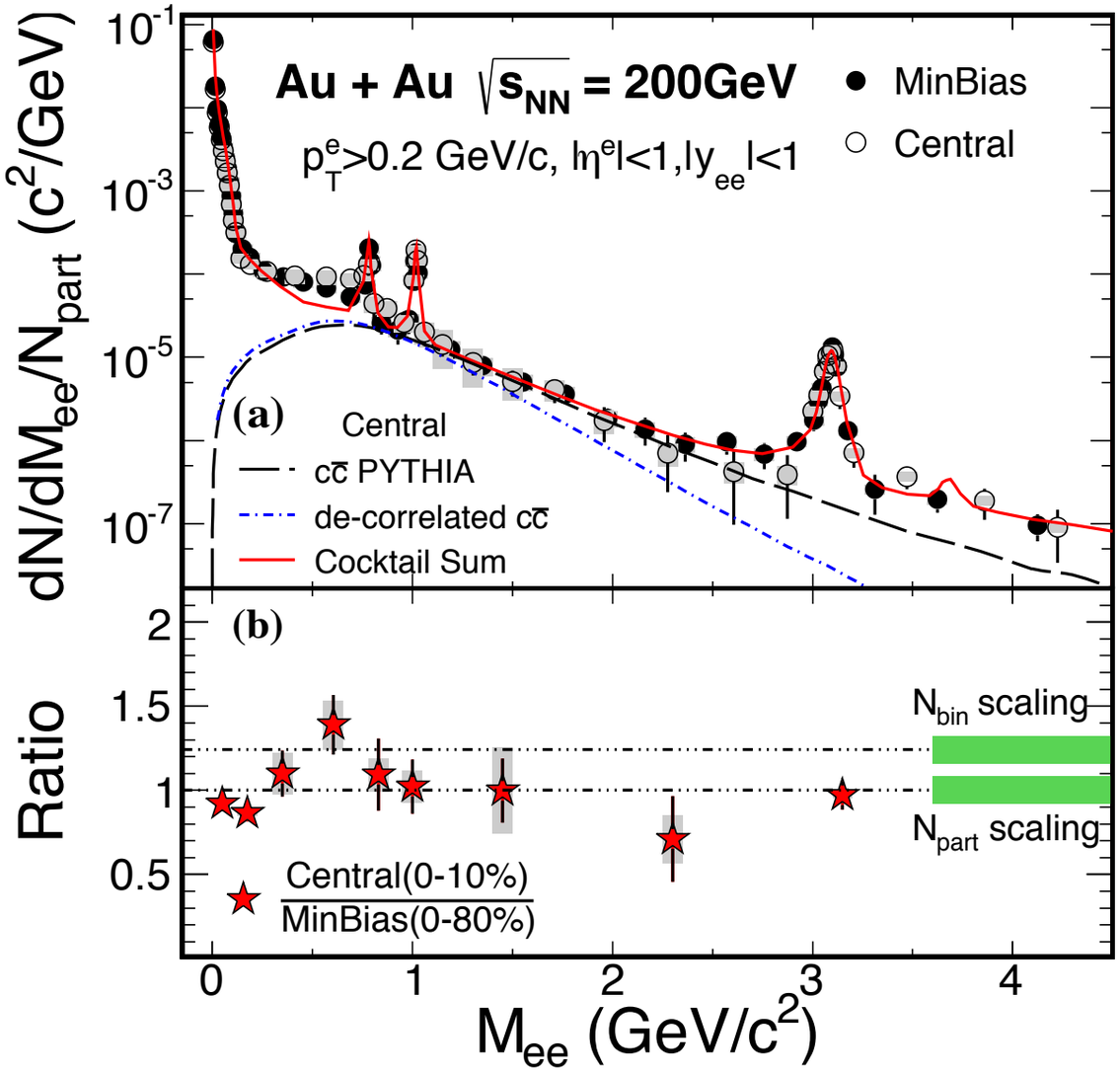


Low mass dielectron excess in Au+Au collisions at RHIC: Disagreement between STAR and PHENIX remains to be solved

PHENIX, arXiv:0912.0244

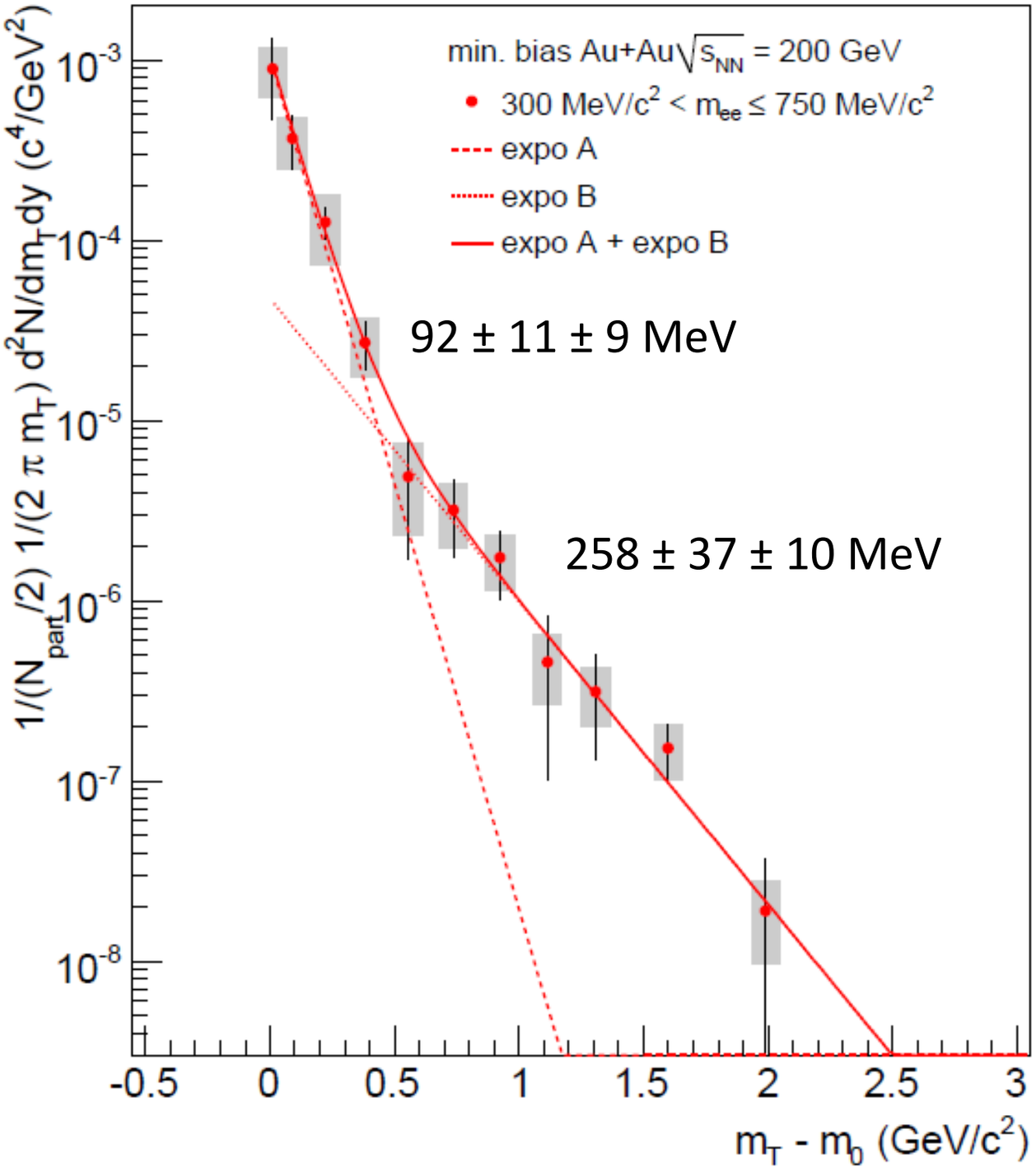


STAR, arXiv:1312.7397v3



Much larger excess in PHENIX, beyond thermal contributions from the hadron gas with medium modified ρ mesons.

Dielectron m_T spectrum in the mass range of the excess (PHENIX)



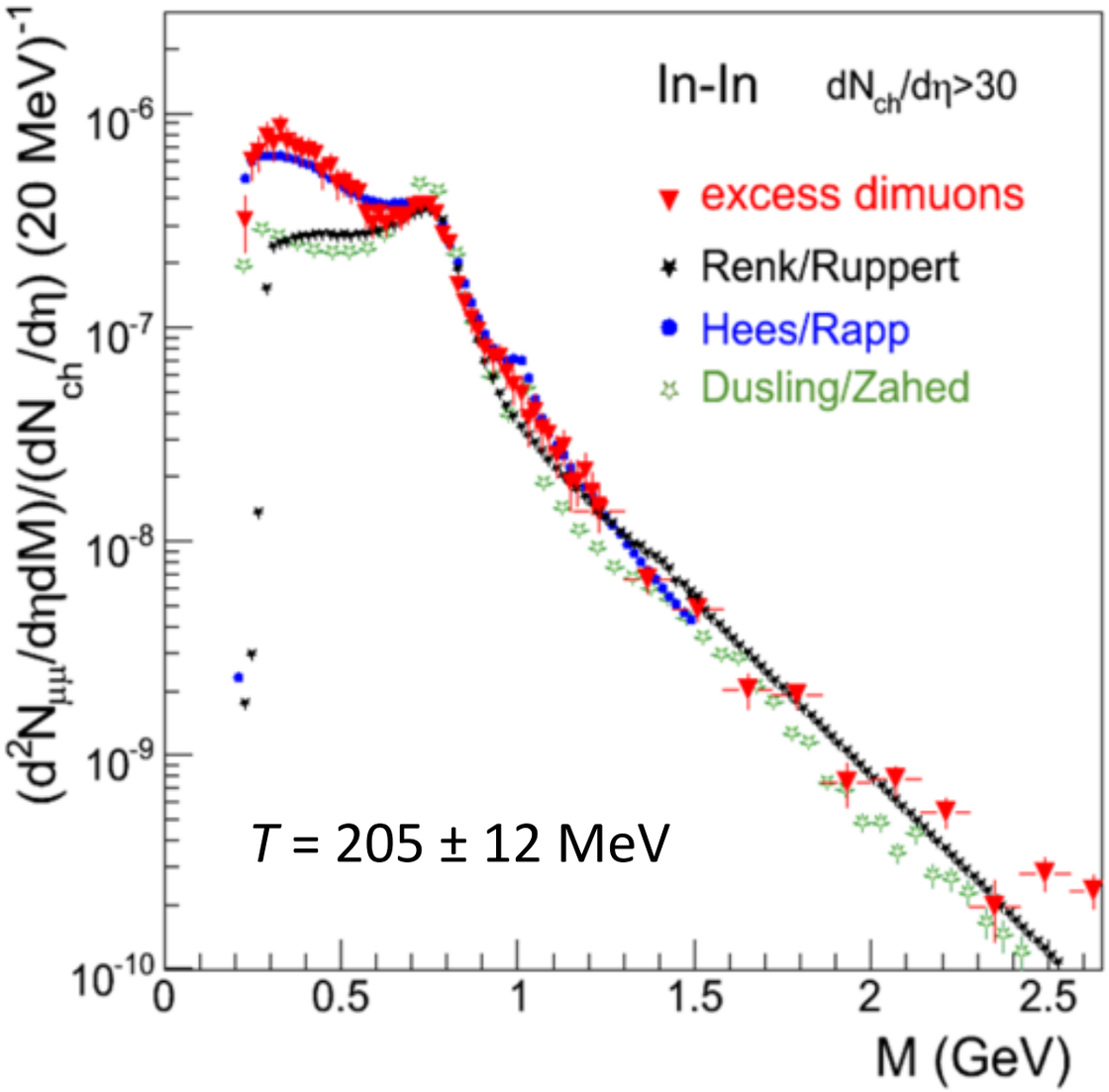
- Cocktail subtracted
- Two components
  - $T \approx 260$ MeV
  - $T \approx 100$ MeV

PHENIX, arXiv:0912.0244

QGP temperature via dimuons at SPS energies?

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

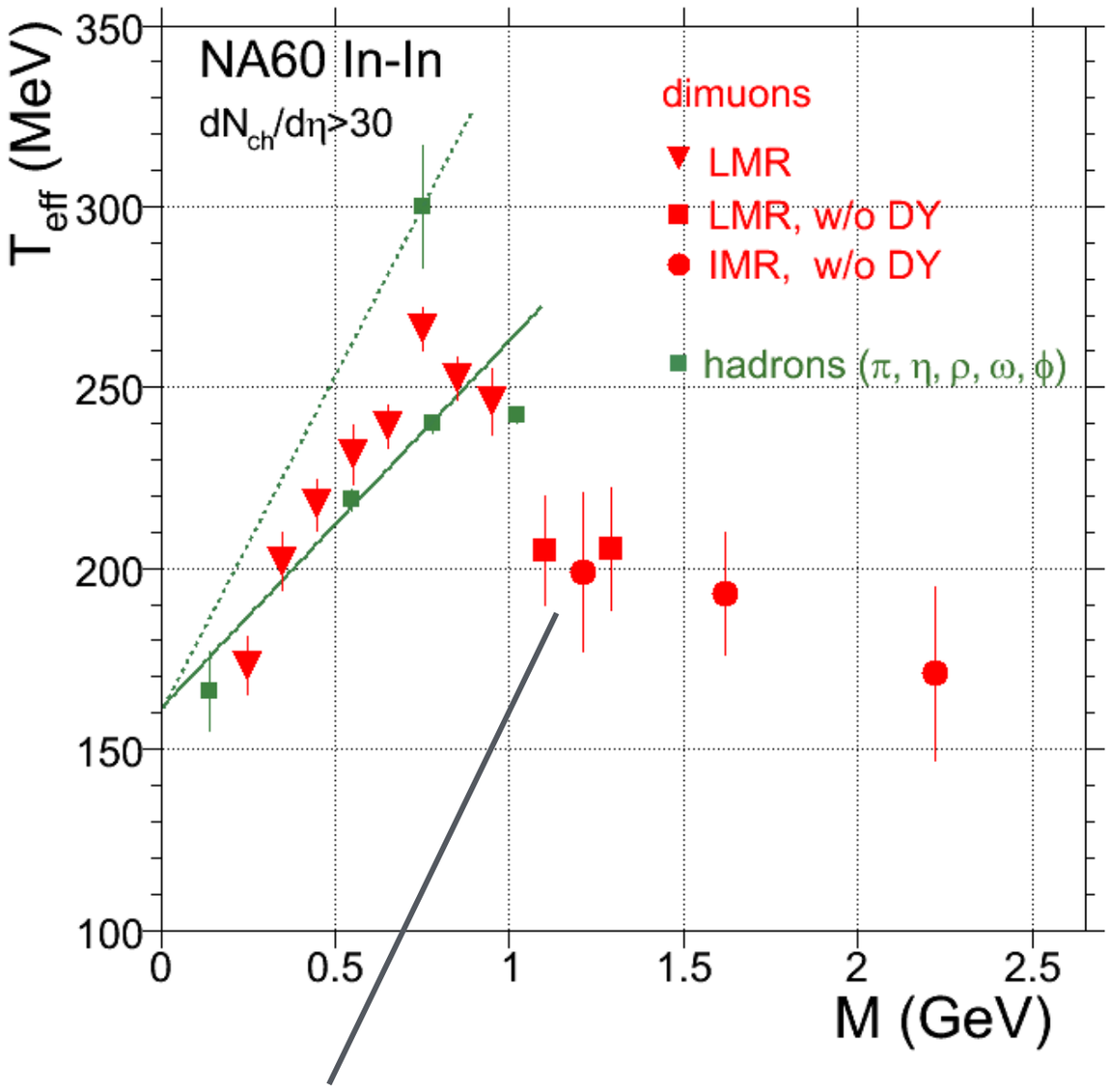
Temperature via dimuon mass spectrum:
unaffected by radial flow



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

for $M > 1$ GeV

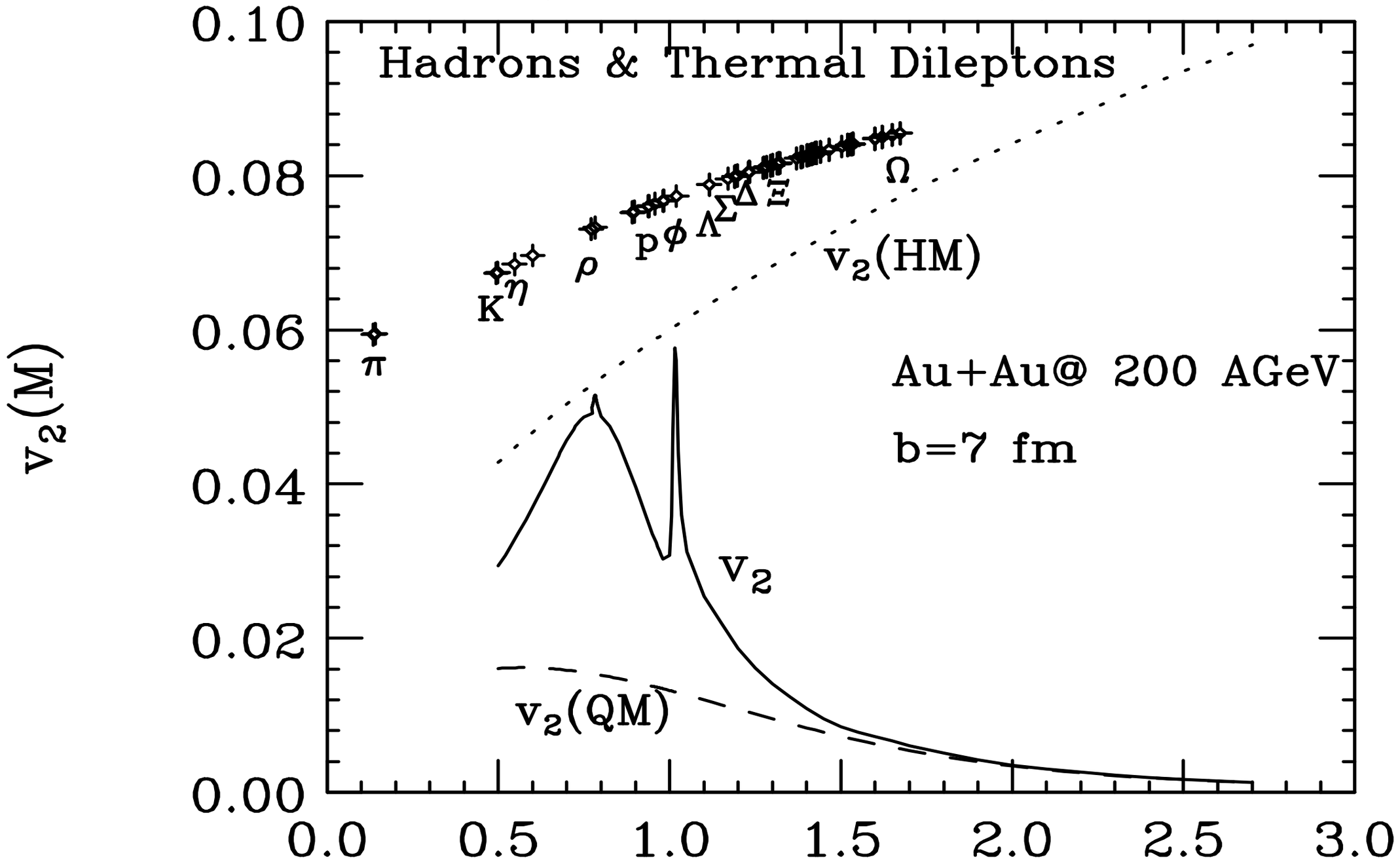
Slope of dimuon m_T spectra:
Hadron gas + flow for $M < 1$ GeV,
non-flowing partonic source for $M > 1$ GeV?



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

Mass dependence of dilepton v_2 as a probe of the time evolution time evolution of flow

R. Chatterjee, D. K. Srivastava, U. Heinz, C. Gale, PRC 75 (2007) 054909



First steps in this direction: STAR, arXiv:1402.1791

Conclusions

- T_{AB} scaling in heavy-ion collisions at RHIC and the LHC confirmed with W and Z bosons and high-p_T direct photons
- Direct-photon flow puzzle at RHIC (and the LHC?) for $p_T < 4$ GeV/c
- Large direct-photon v_2, similar in magnitude to pion v_2
- Direct-photon spectra and v_2 not well reproduced by standard hydro calculations
- Large v_2 suggests that thermal photons mostly come from the late hadron gas phase
- Calls into question whether thermal photons can be used to determine the initial QGP temperature
- Need to get a consistent picture including dilepton data

Let's see how the saga continues!