QGP Physics − from Fixed Target to LHC

10. Thermal Photons and Dileptons

Prof. Dr. Klaus Reygers, Prof. Dr. Johanna Stachel

Physikalisches Institut, Universität Heidelberg

SS 2015

Motivation for Measuring Direct Photons in Heavy-Ion Collisions

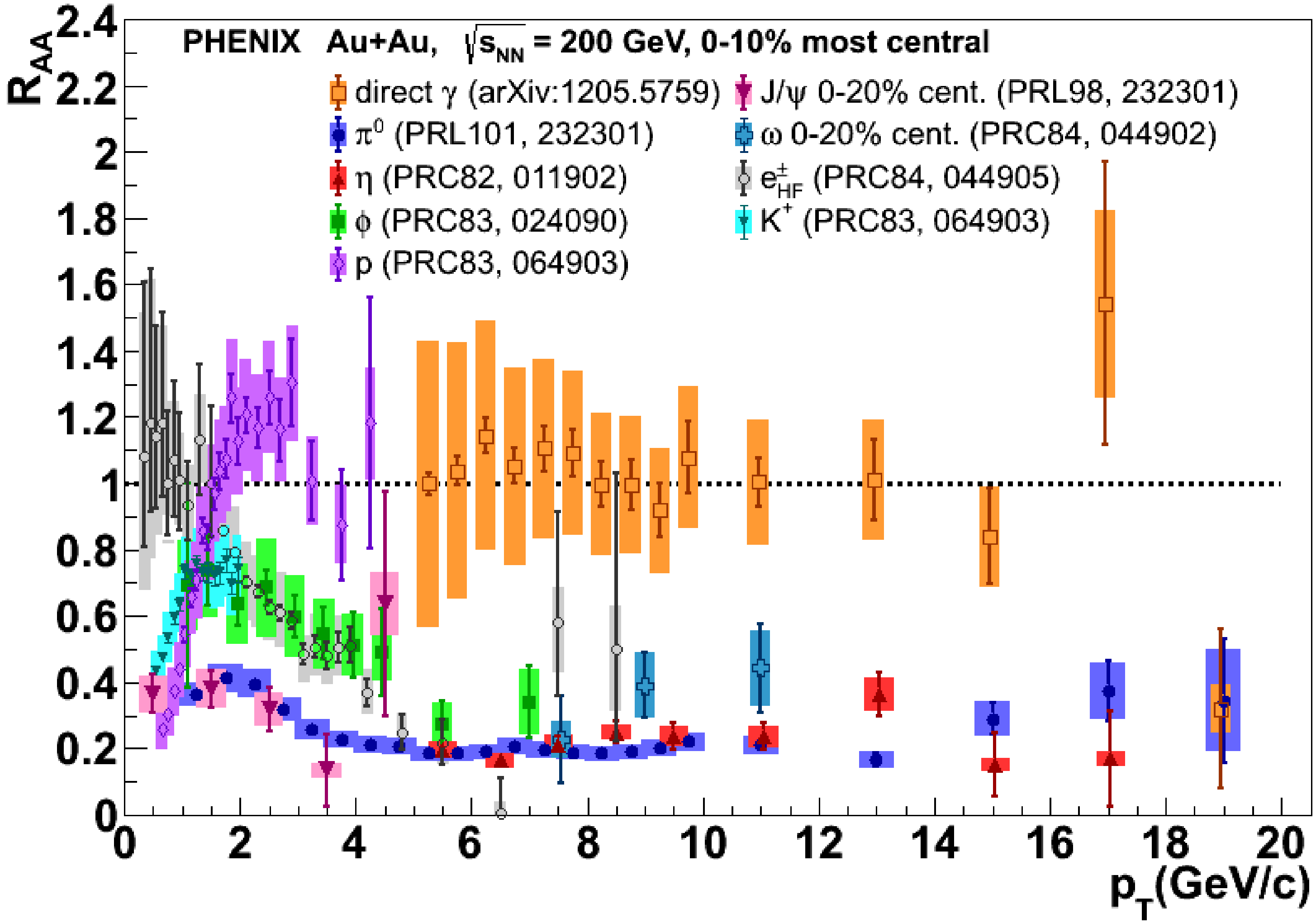
High p_T (> 6 GeV/c):

- 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

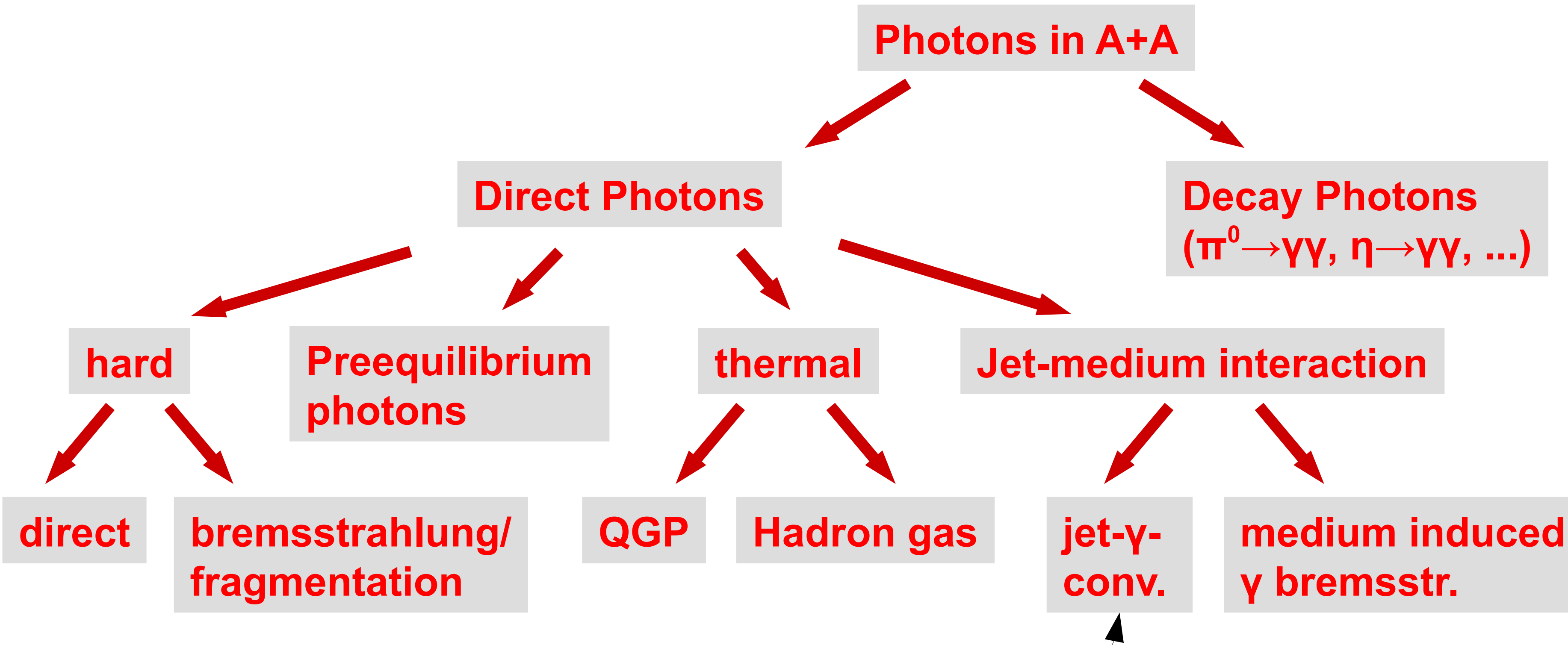
Low / Intermediate p_T:

- 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?

Reminder: High-p_T Direct Photons Confirm T_{AB} Scaling



Known and Expected Photon Sources



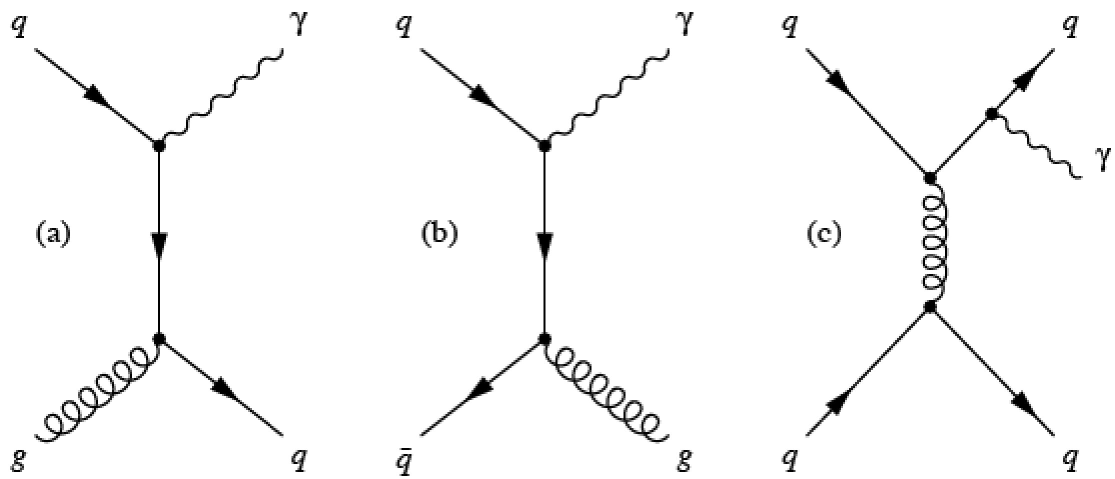
$$\text{e.g.}: g + q_{\text{QGP}} \rightarrow q + \gamma$$

gluon jet

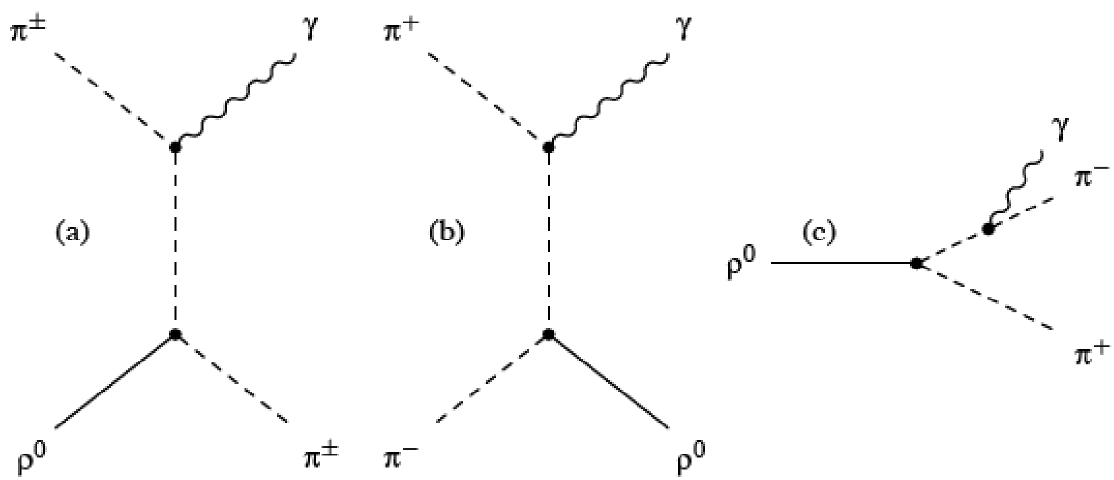
$$\sigma_{jet(q)\rightarrow\gamma(p)} \propto \delta(q-p)$$

Photon Production: Feynman Diagrams

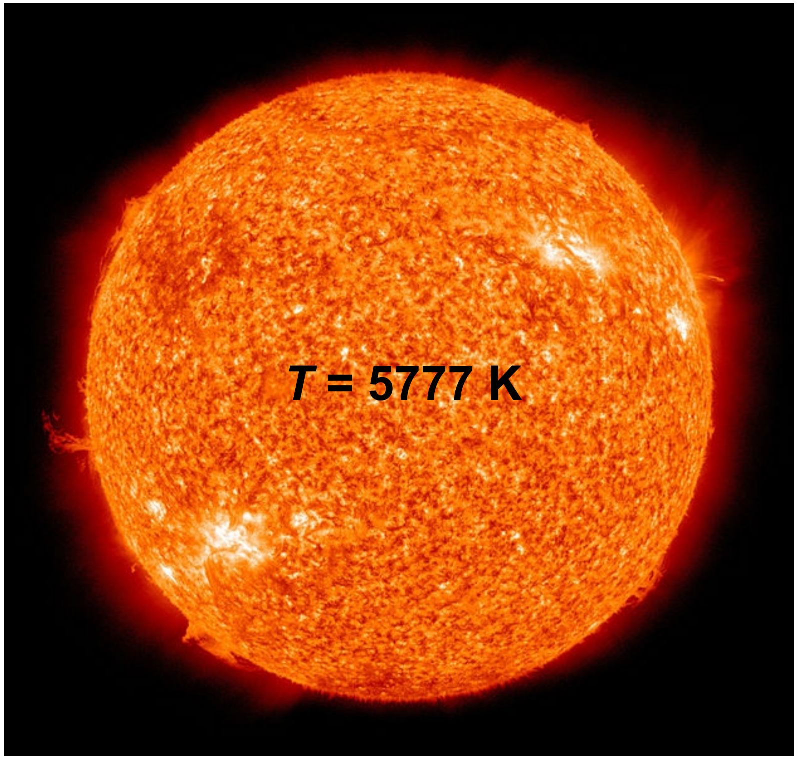
QGP:



Hadron gas:

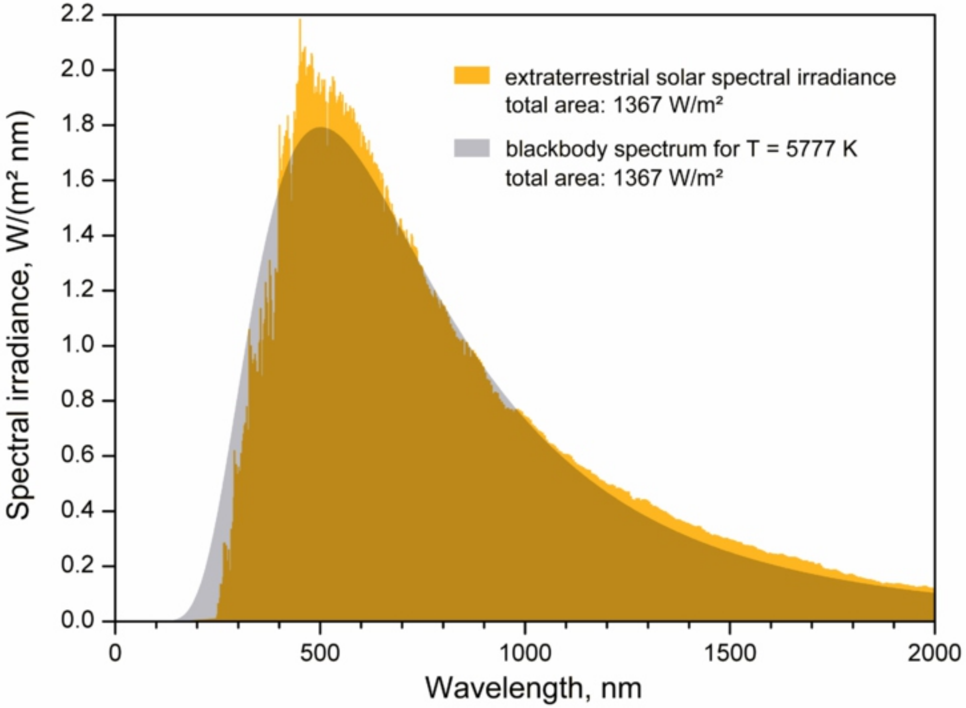


Measuring Temperatures via the Planck Spectrum



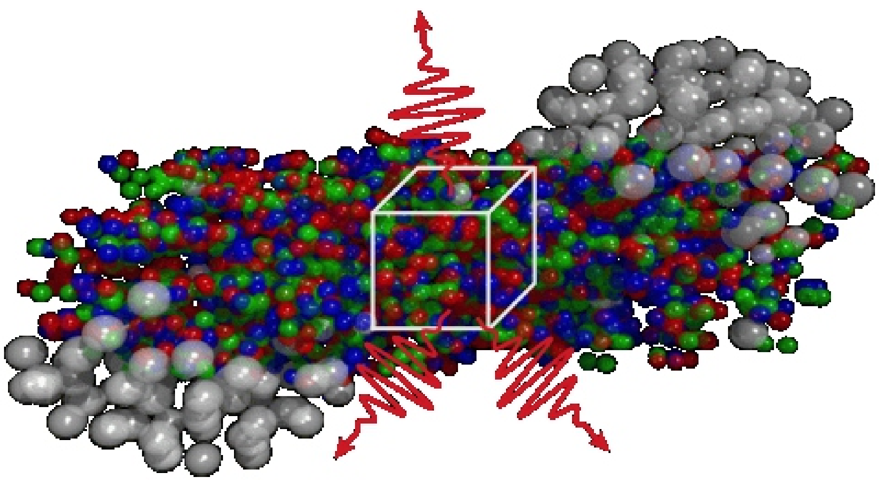
source: http://en.wikipedia.org

source: http://en.wikipedia.org



Analog, but slightly different: Photons from the quark-gluon plasma

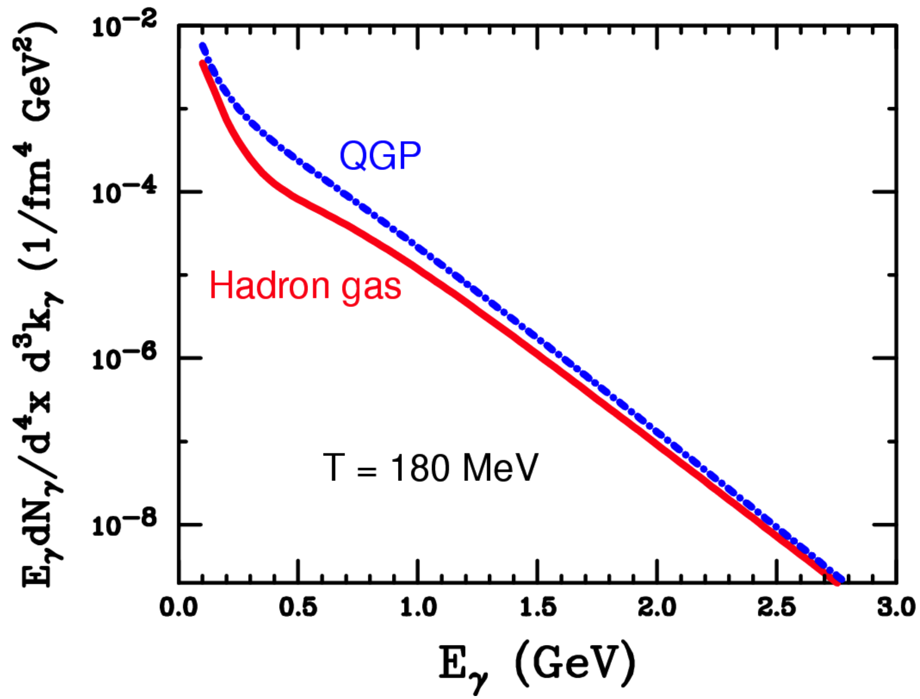
- Photons produced in scatterings of quark and gluons in thermal equilibrium
- Photons not in thermal equilibrium ($\lambda_{mfp} \approx 500$ fm), but energy spectrum reflects QGP temperatures



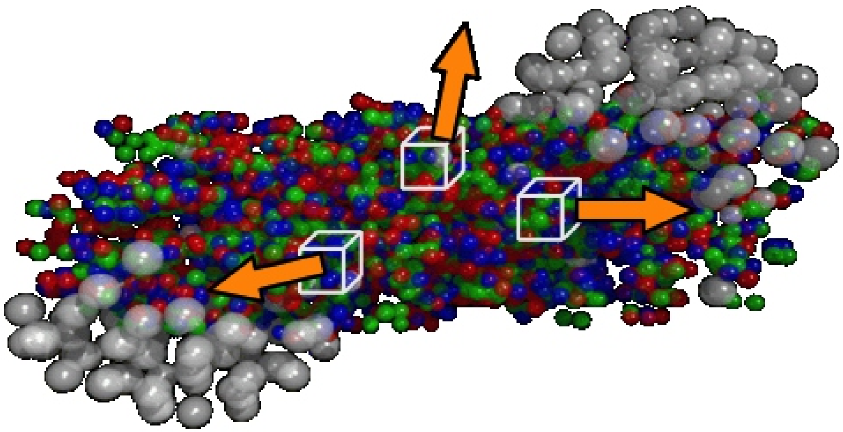
QGP photon rate (lowest order):

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

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



What can we Learn from Thermal Photons Measurements?

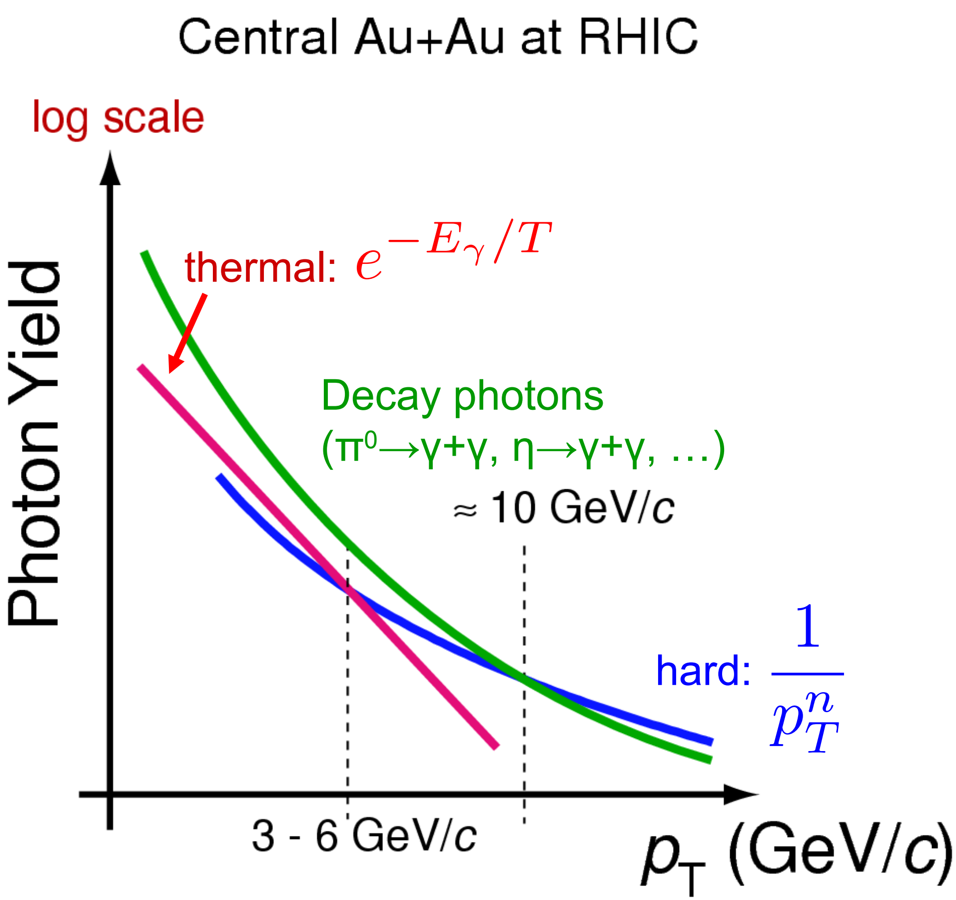


- The QGP expands in longitudinal and transverse direction and cools rapidly
- It lives only for about 3×10^{-23} s
- What information can one extract from a measured thermal photon spectrum?

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

⇒ Initial QGP temperature

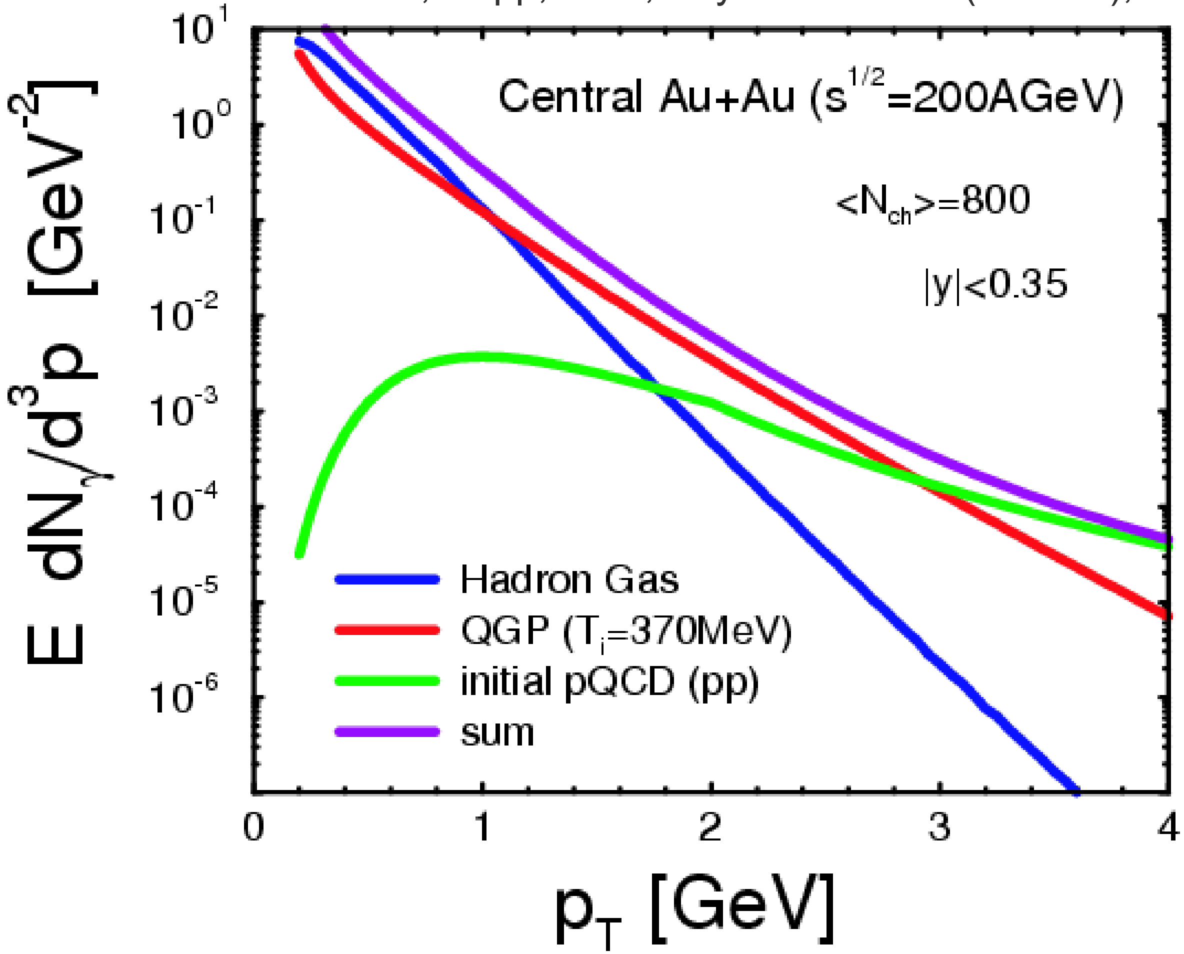
Schematic Photon Spectrum in A+A



- Thermal photons expected to be significant contribution below $p_T \sim 3$ GeV/c
- Hard photons dominant direct photon source for $p_T > \sim 6$ GeV/c
- Jet-photon conversion might be significant contribution below $p_T \sim 6$ 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 (2015) only three measurements in the p_T range where thermal photons might be an important source
  - Central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 17.3 GeV (WA98)
  - Central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (PHENIX)
  - Central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2760 GeV (ALICE, preliminary)

- 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.

- Experimental methods:
  - Measure photons with electromagnetic calorimeter (WA98, PHENIX)
  - Measure photons via external conversion in e+e- pairs (ALICE, PHENIX)
  - Measure virtual photons ($\gamma^* \rightarrow e^+e^-$),

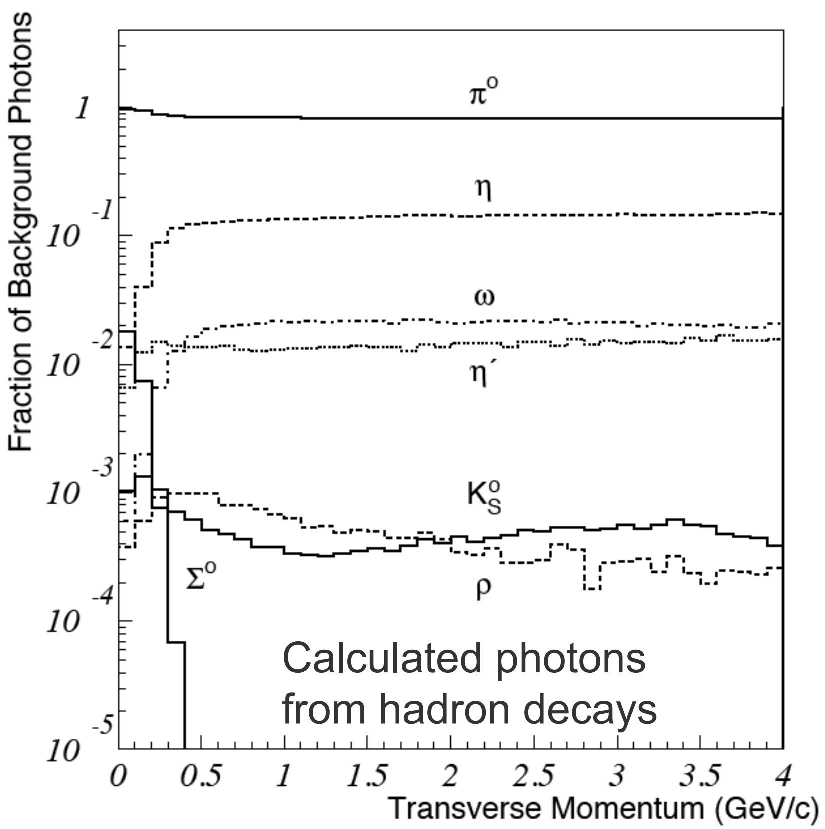
  and assume $\frac{\gamma_\text{direct}}{\gamma_\text{inclusive}} = \left.\frac{\gamma^*_\text{direct}}{\gamma^*_\text{inclusive}}\right|_{m_{ee} < 30\,\text{MeV}}$ (PHENIX)

Subtraction Method

WA98, nucl-ex/0006007 (→ link)

Systematic uncertainties partially cancel in this ratio

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

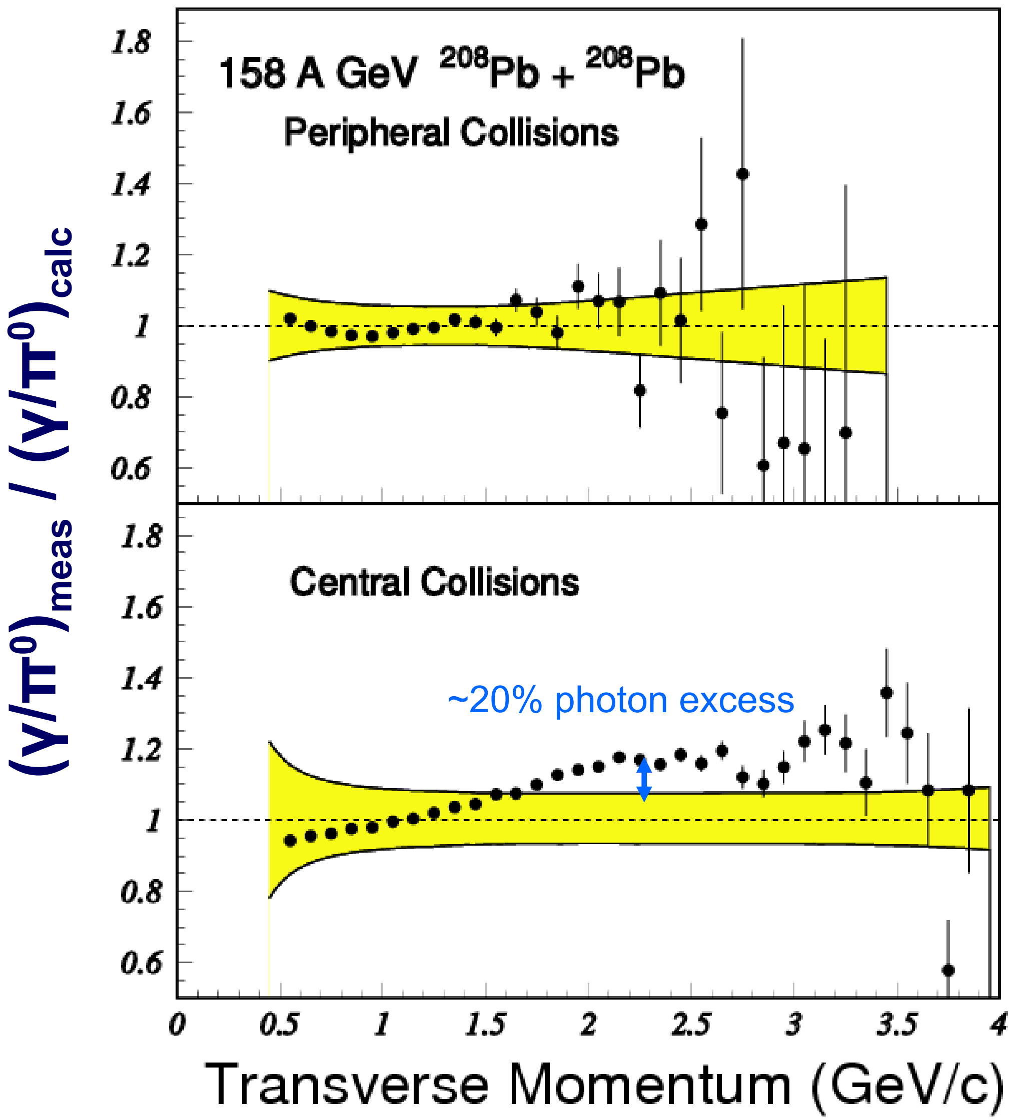


Based on the measured π^0 (and η) p_T spectrum, the expected decay photons are calculated (assuming m_T scaling for unmeasured particle species)

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 which dropped out in the double ratio *R* need to be added

Direct Photon Measurement by WA98

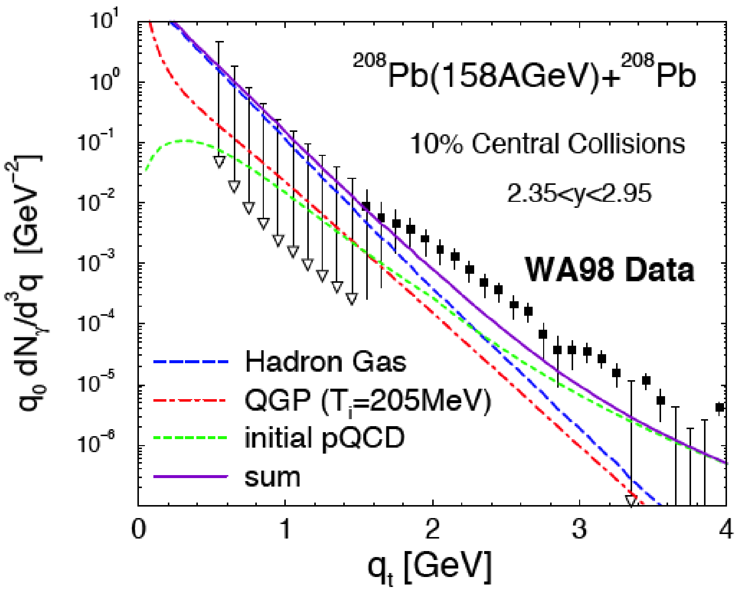


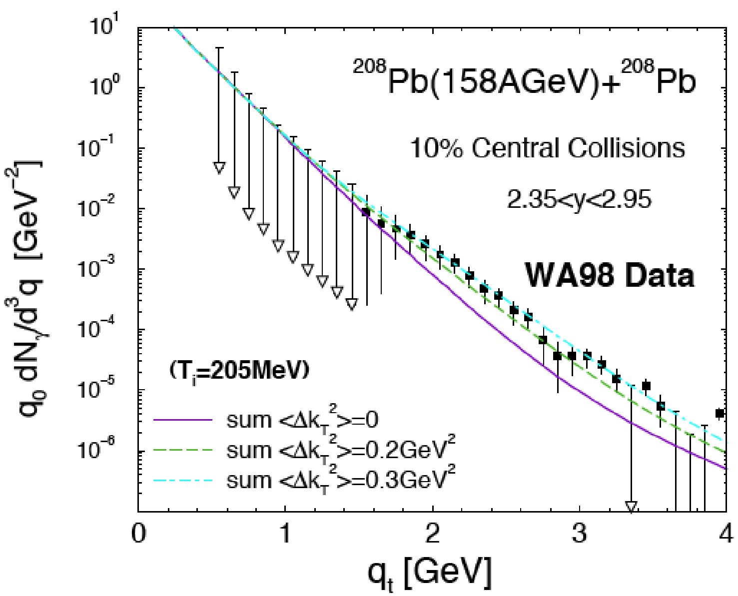
- No signal in peripheral collisions
- 20% photon excess in central Pb+Pb collisions

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

Interpretation of the WA98 Data

Ch. Gale, arXiv:0904.2184 (→ link)





Theoretical ingredients:

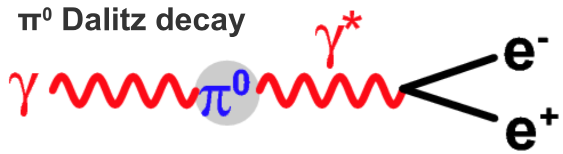
- (schematic) fireball evolution
- Photon emission rates from a gas of hadrons
- Photon emission rates from the QGP complete to lading order in α_s
- Estimate of the Cronin effect deduced from p+A collisions

Conclusions:

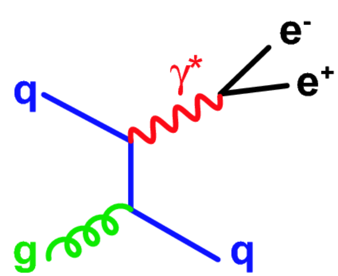
- Data consistent with QGP scenario ($T_i \approx 200 - 270$ MeV), however, QGP contribution is small
- Data also consistent with hadronic scenario (Cronin enhancement alone could explain the data)

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:

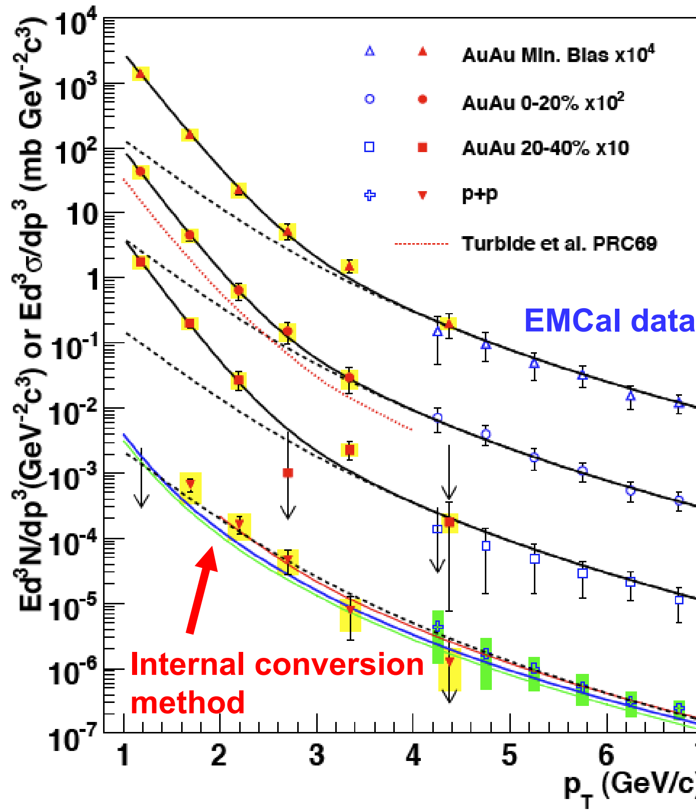


  - Rate and m_{ee} distribution calculable in QED
    (Kroll-Wada formula, see next slide)
- Hadron decays: $m_{ee} < M_{hadron}$
- Essentially no such limit for point-like processes



- 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

PHENIX, Phys.Rev., C81 (2010) 034911 (→ link)

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

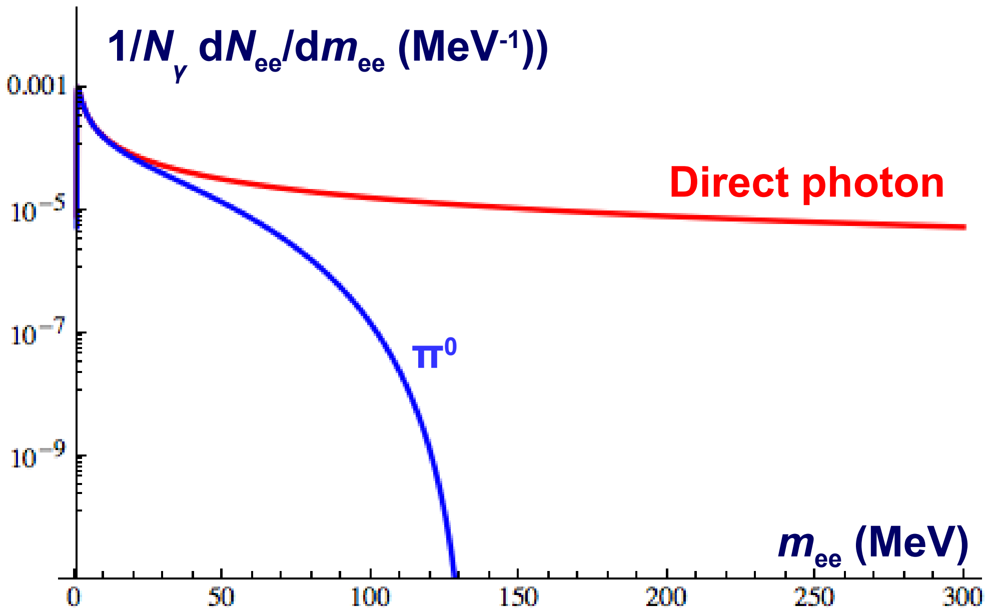
$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

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:

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



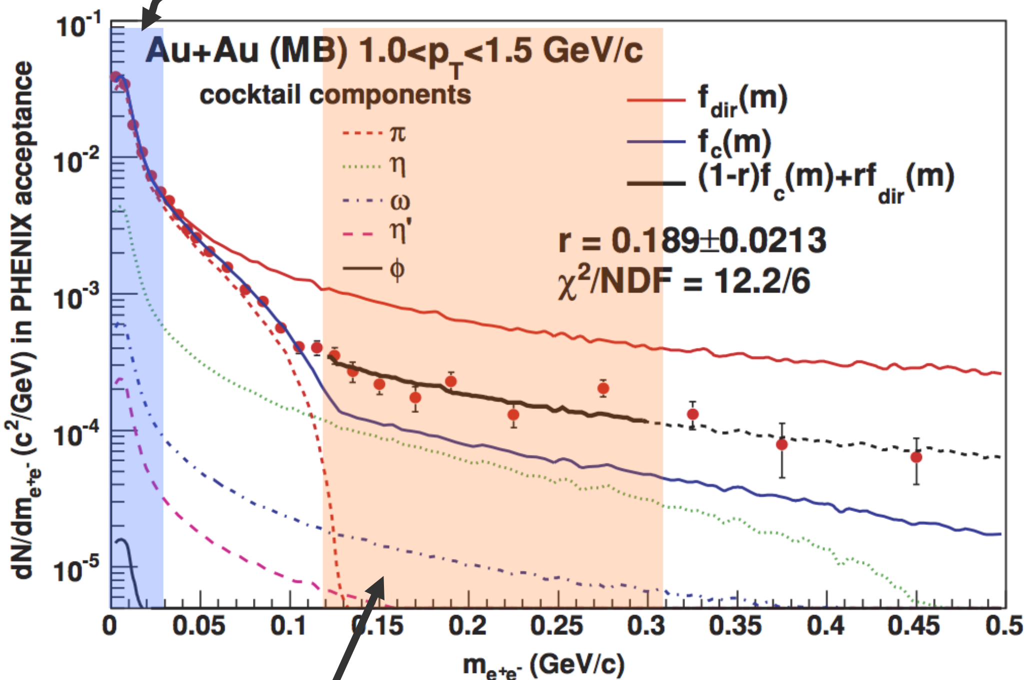
PHENIX measurement:
$80 < m_{ee} < 300$ MeV

→ **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



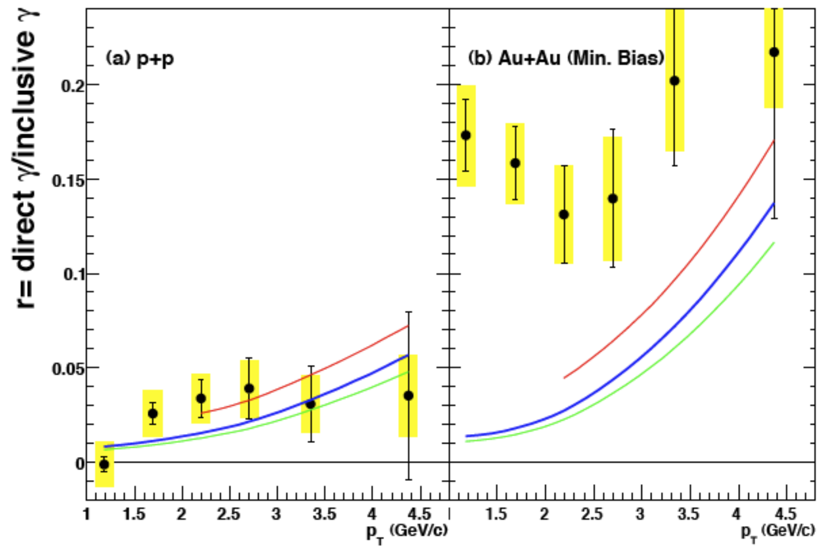
Fit range: 120 < m_{ee} < 300 MeV

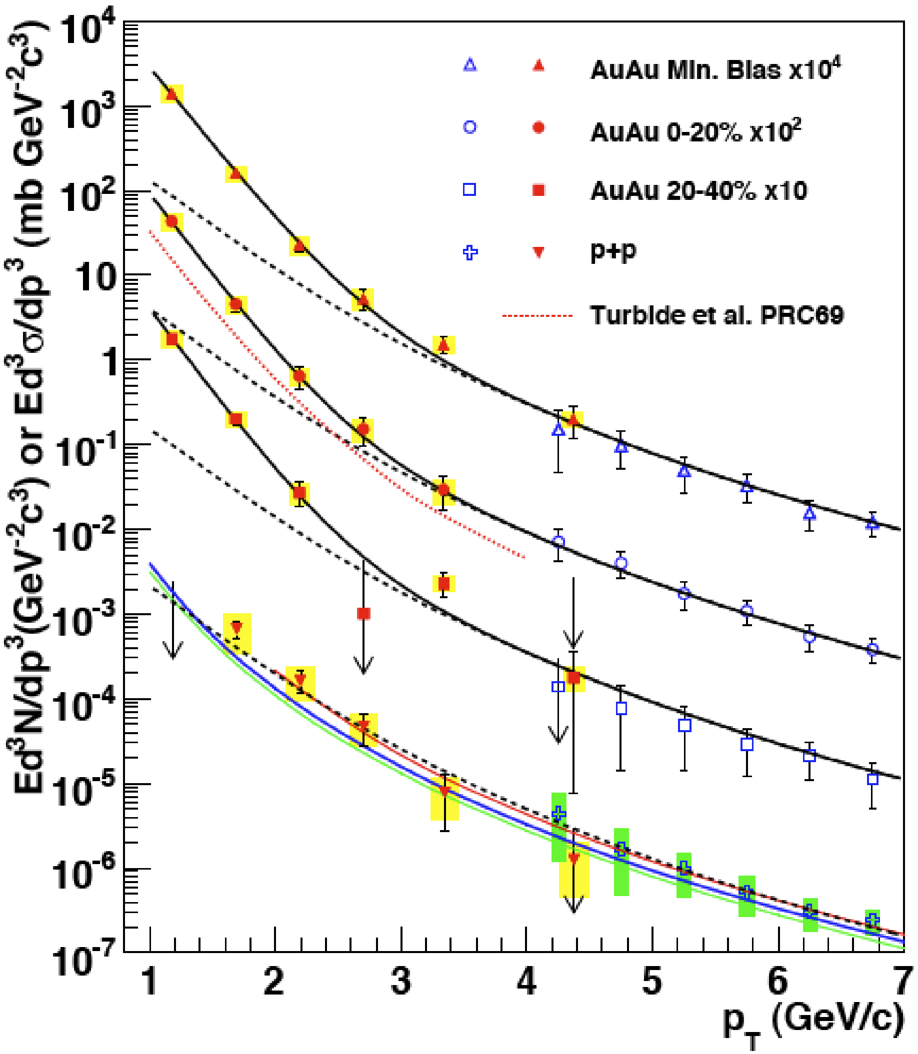
- Interpret deviation from hadronic cocktail (π^0, η, ω, η', φ) as signal from virtual direct photons
- Extract fraction r with two-component fit

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

- χ^2/NDF: (12.2 / 6)

Internal Conversion Methods: Results





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

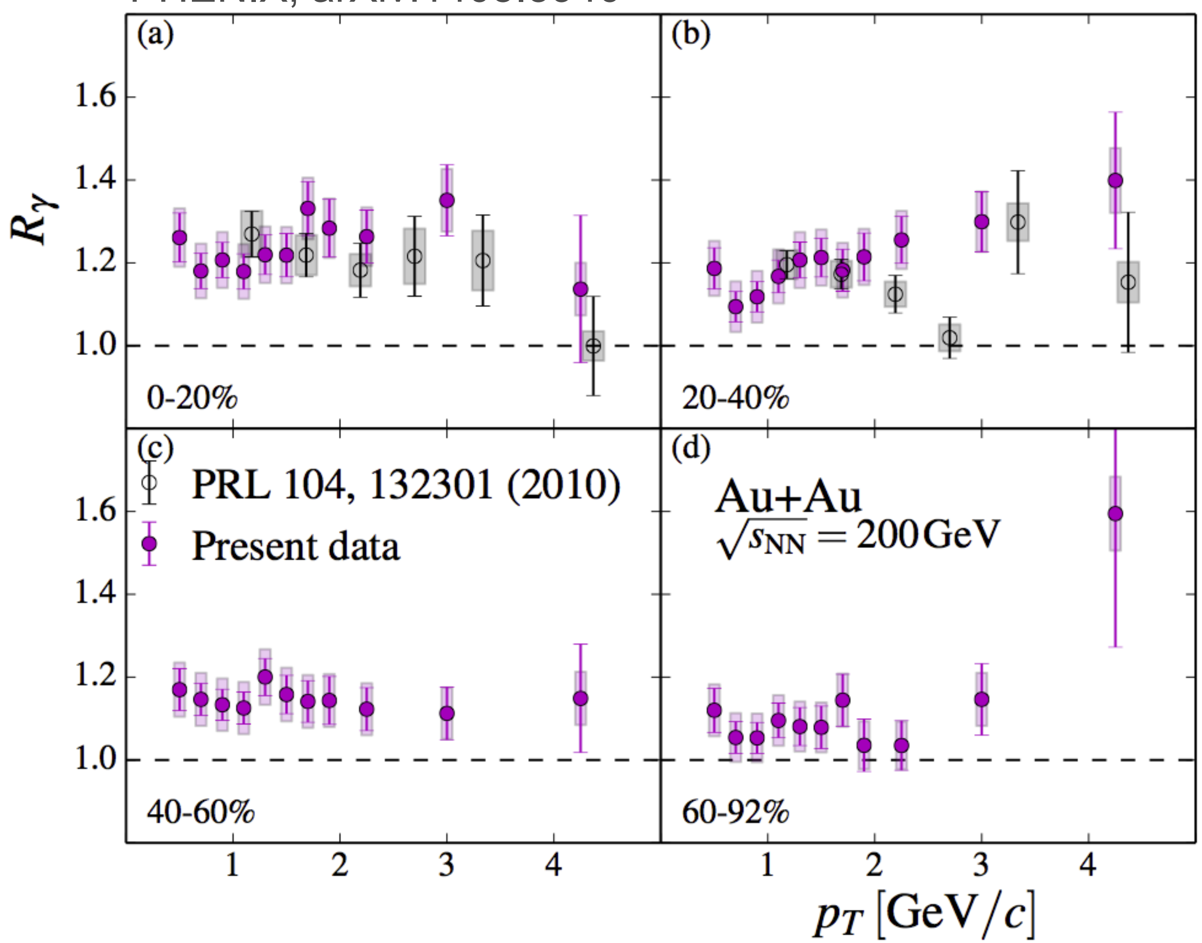
$$Y_{Au+Au} = N_{\text{coll}} \cdot Y_{p+p} + A \cdot e^{-p_T/T}$$

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

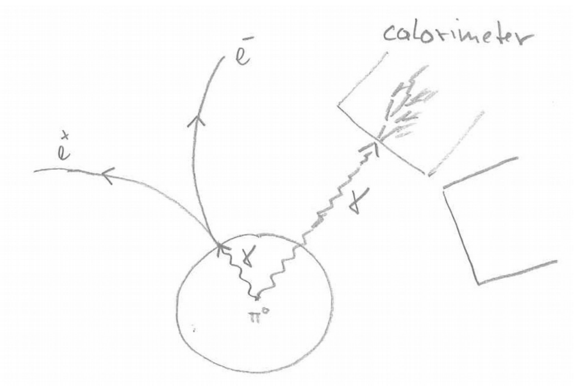
Expected to be a lower limit for the initial temperature T_i!

Confirmation with Real Photons from Conversions (I)

PHENIX, arXiv:1405.3940

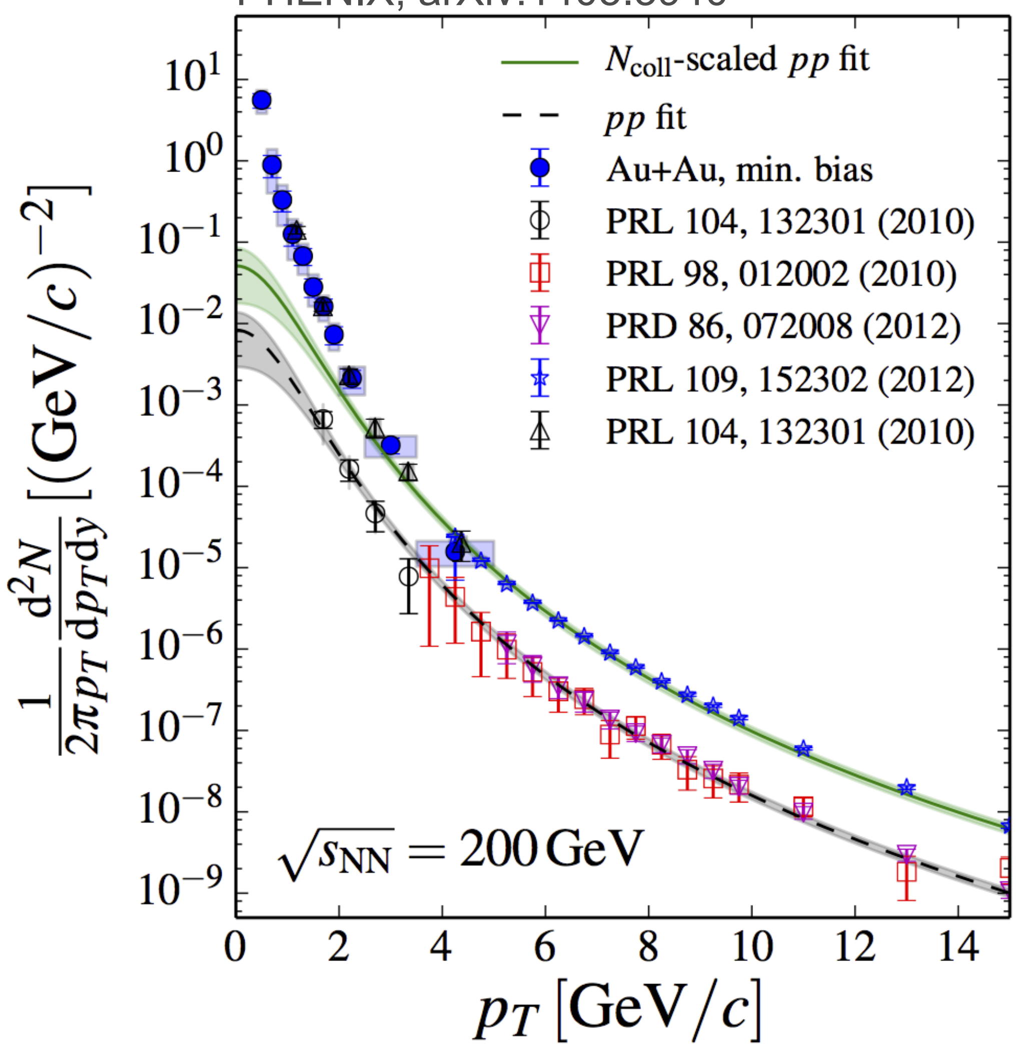


- photon conversions
- tagging of π^0 decay photon by measuring the second photon with a calorimeter
- Material budget uncertainty traded for energy scale uncertainty of the calorimeter



Confirmation with Real Photons from Conversions (II)

PHENIX, arXiv:1405.3940



Shape in Au+Au qualitatively different from shape of fit function for pp

Fit function for pp data supposed to represent the hard scattering contribution:

$$\text{inv. yield} = a \times \left(1 + \frac{p_T^2}{b}\right)^c$$

Initial Conditions for Hydro Modeling: Constraint for Initial Temperature from Hadron Multiplicity

Entropy density from Bjorken model from approximately constant entropy per final-state hadron ($S/n_{\mathrm{hadron}} \approx 4$ in natural units):

$$s_{\mathrm{Bj}} = \frac{1}{A\tau_0} \frac{dS}{dy}\bigg|_{y=0} \approx \frac{1}{A\tau_0} k \frac{dn_{\mathrm{hadron}}}{dy}\bigg|_{y=0} \quad \text{with} \quad k \approx 4$$

Relation between entropy density and temperature in an ideal gas of quarks and gluons:

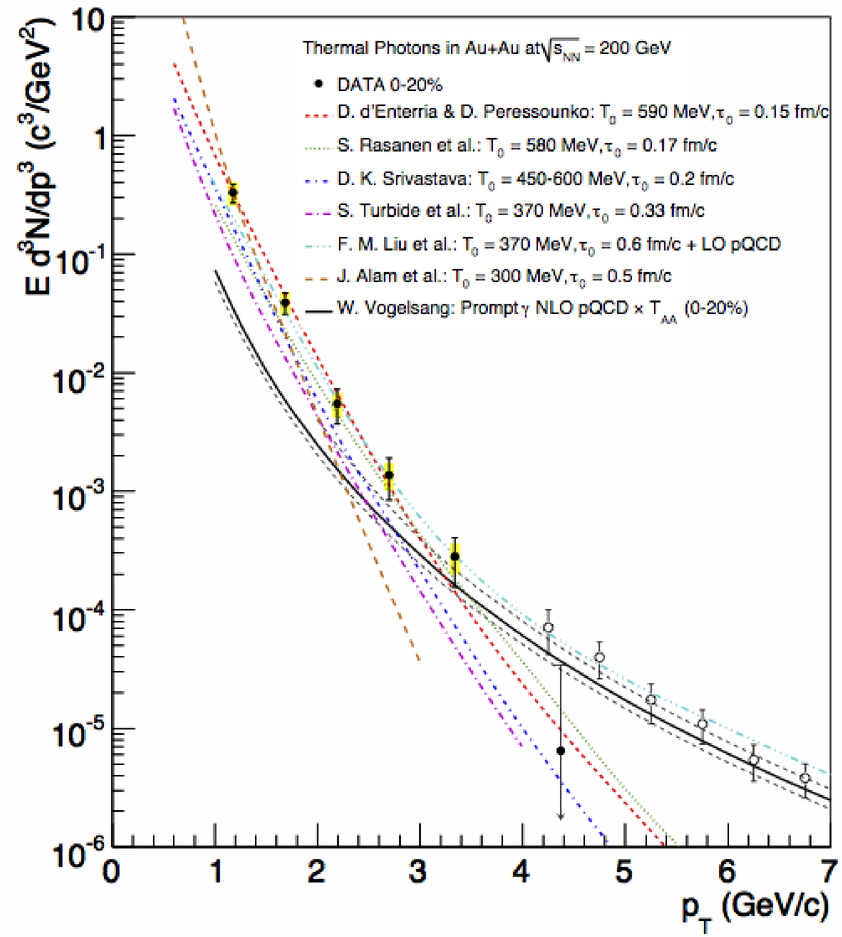
$$s_{\mathrm{id}} = 4 g_{\mathrm{QGP}} a T^3 \quad \text{with } a = \frac{\pi^2}{90} \text{ and } g_{\mathrm{QGP}} = 37 \ (42.25) \text{ for } 2 \ (2.5) \text{ quark flavors}$$

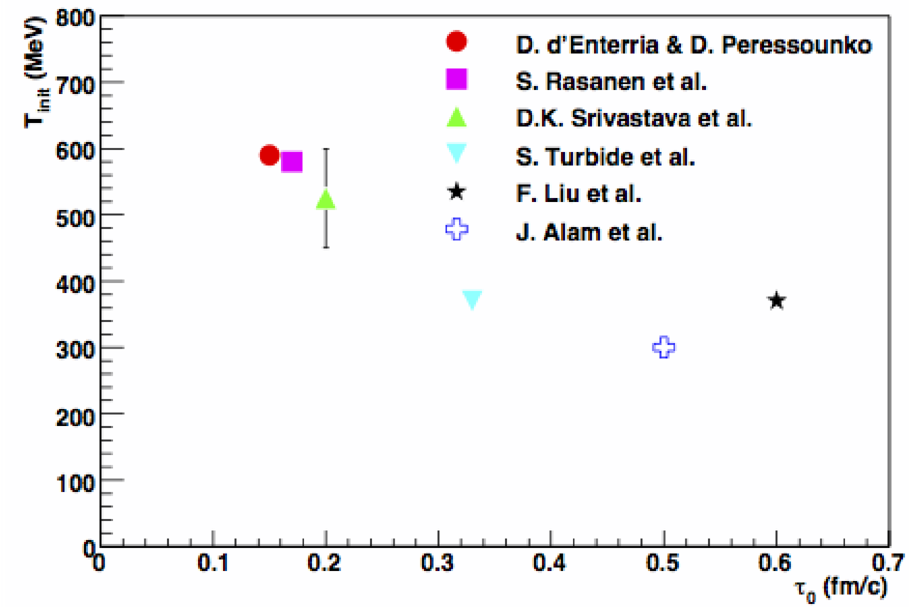
$$s_{\mathrm{Bj}} = s_{\mathrm{id}} \quad \Rightarrow \quad \boxed{T_{\mathrm{init}}^3 = \frac{dn_{\mathrm{hadron}}}{dy}\bigg|_{y=0} \times \frac{k}{4 g_{\mathrm{QGP}} a A \tau_0}}$$

Numerical example (central Au+Au at RHIC):

$$\frac{dn}{dy} = \frac{3}{2} \times 800, \ k = 4, \ A \approx \pi (5\,\mathrm{fm})^2 \quad \Rightarrow \quad \begin{aligned} T_{\mathrm{init}} &= 290\,\mathrm{MeV} \text{ for } \tau_0 = 1\,\mathrm{fm}/c \\ T_{\mathrm{init}} &= 550\,\mathrm{MeV} \text{ for } \tau_0 = 0.15\,\mathrm{fm}/c \end{aligned}$$

Direct Photons at RHIC: Initial Temperature from Model comparison

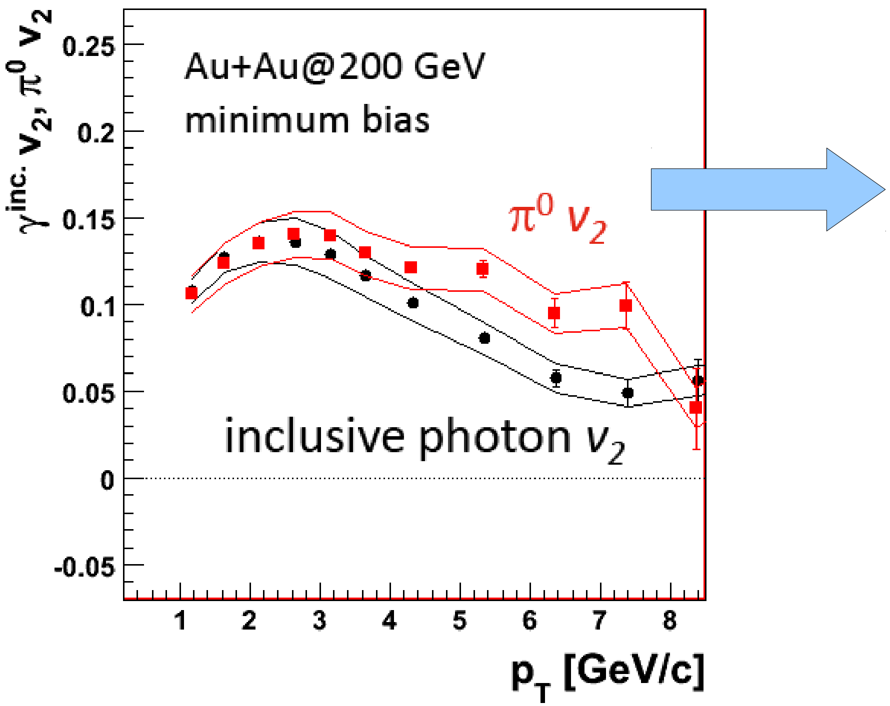


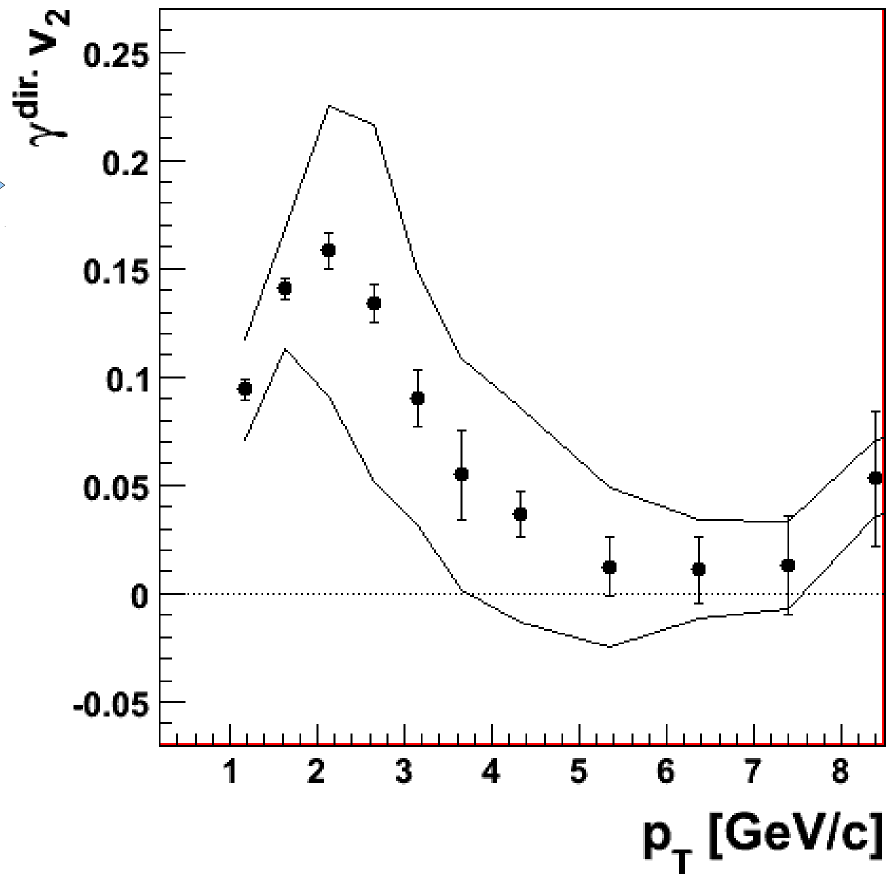


T_{init} = 300 … 600 MeV

Direct Photon v_2 (PHENIX)

PHENIX, Phys. Rev. Lett. 109, 122302 (2012) (→ link)



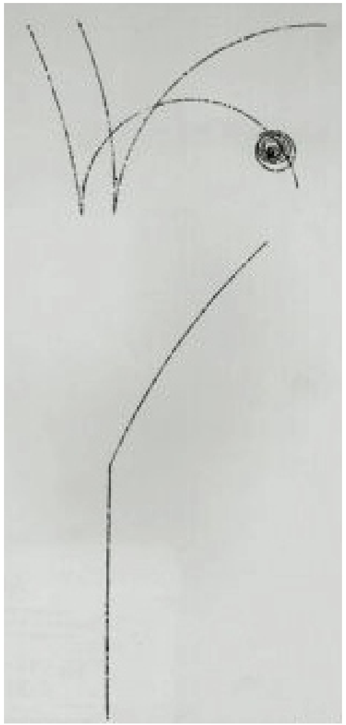


$$v_2^{\mathrm{dir.}\,\gamma} = \frac{R_\gamma \cdot v_2^{\mathrm{incl.}} - v_2^{\mathrm{decay.}\,\gamma}}{R_\gamma - 1}$$

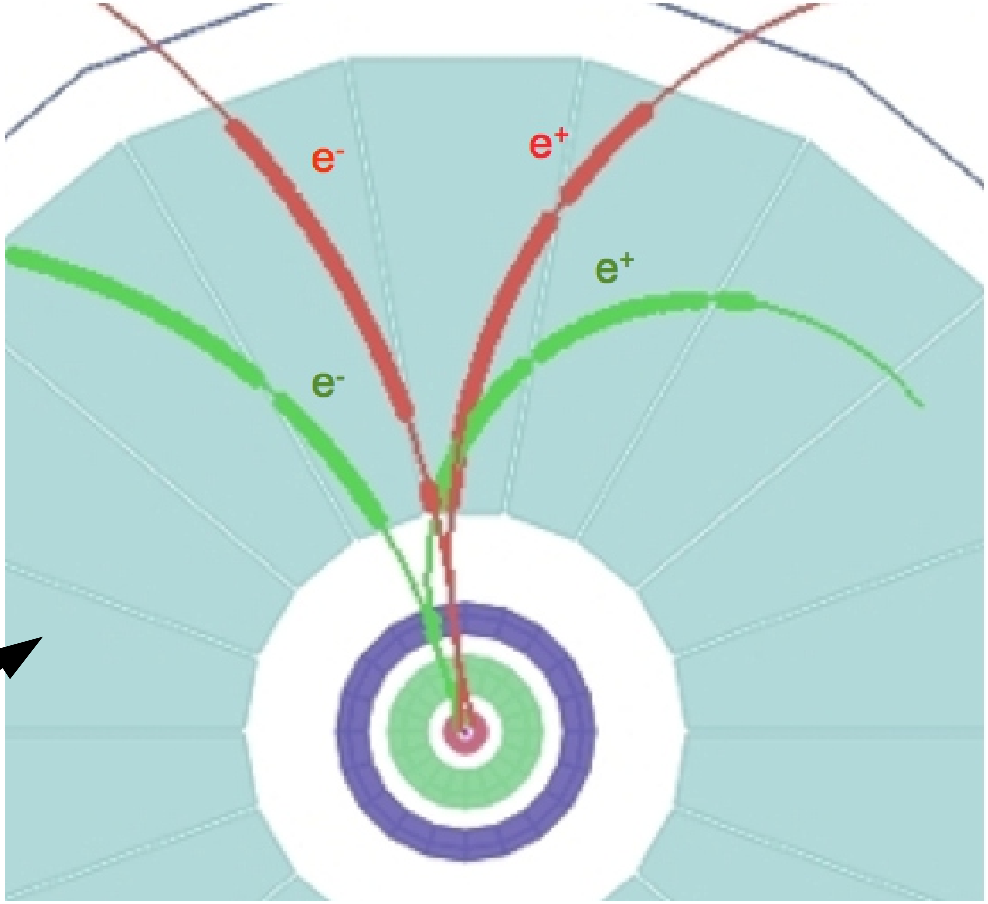
Large direct photon v_2 is a challenge to theory because most thermal photons are expected to be created early (when the temp. is largest and) when v_2 has not fully built up

ALICE: Measuring Photons with Conversions

ca. 1950



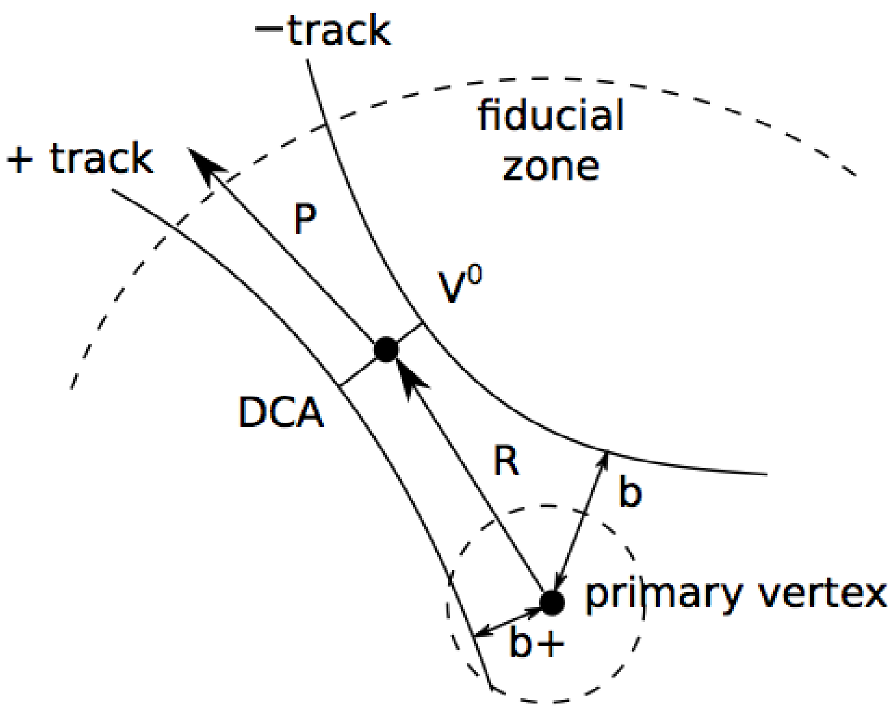
2013



Excellent photon momentum resolution and rather pure photon samples at the expense of loss in statistics

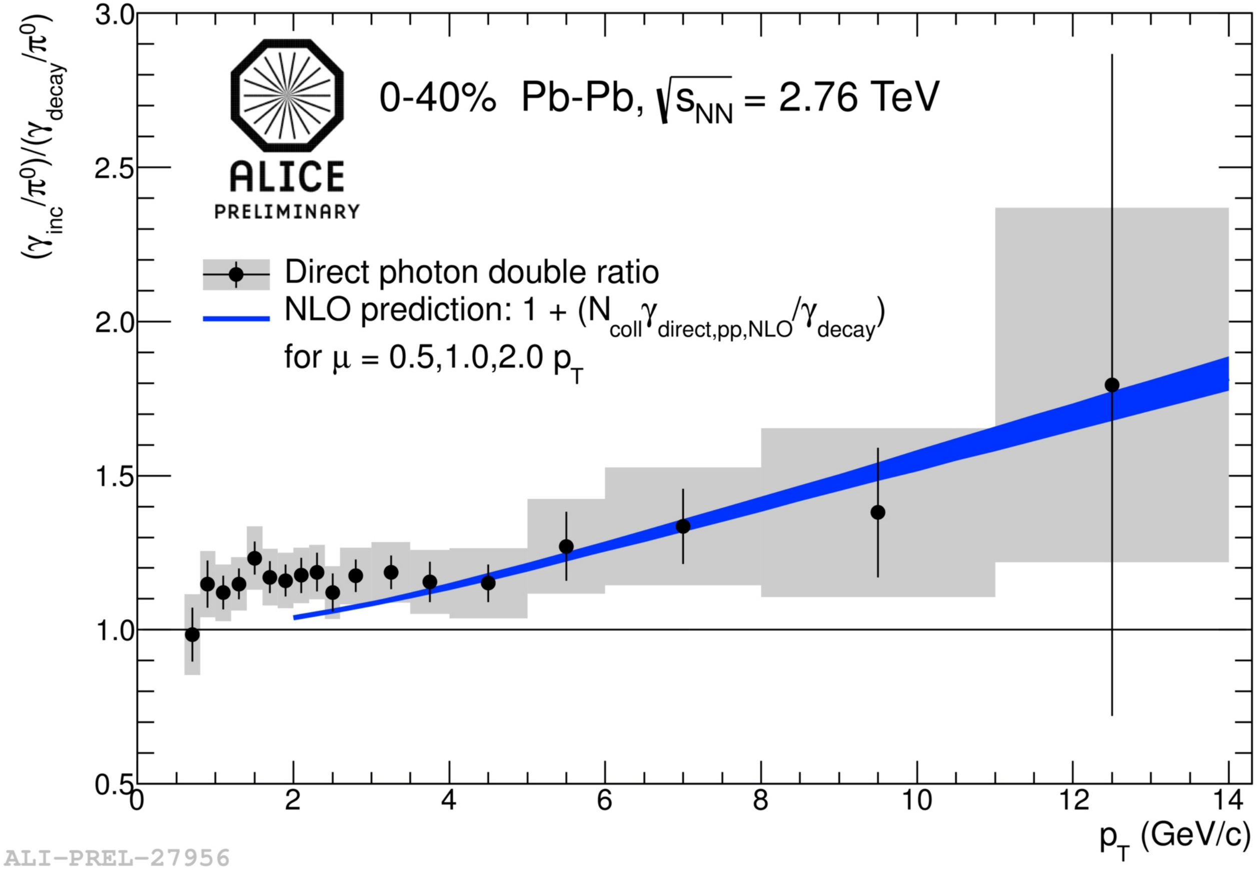
Photon conv. probability in ALICE (for R < 180 cm):
p_{conv} = 8.5% for p_T > ~3 GeV/c

Photon Conversion Analysis – Reconstruction of Secondary Vertices (V0's)



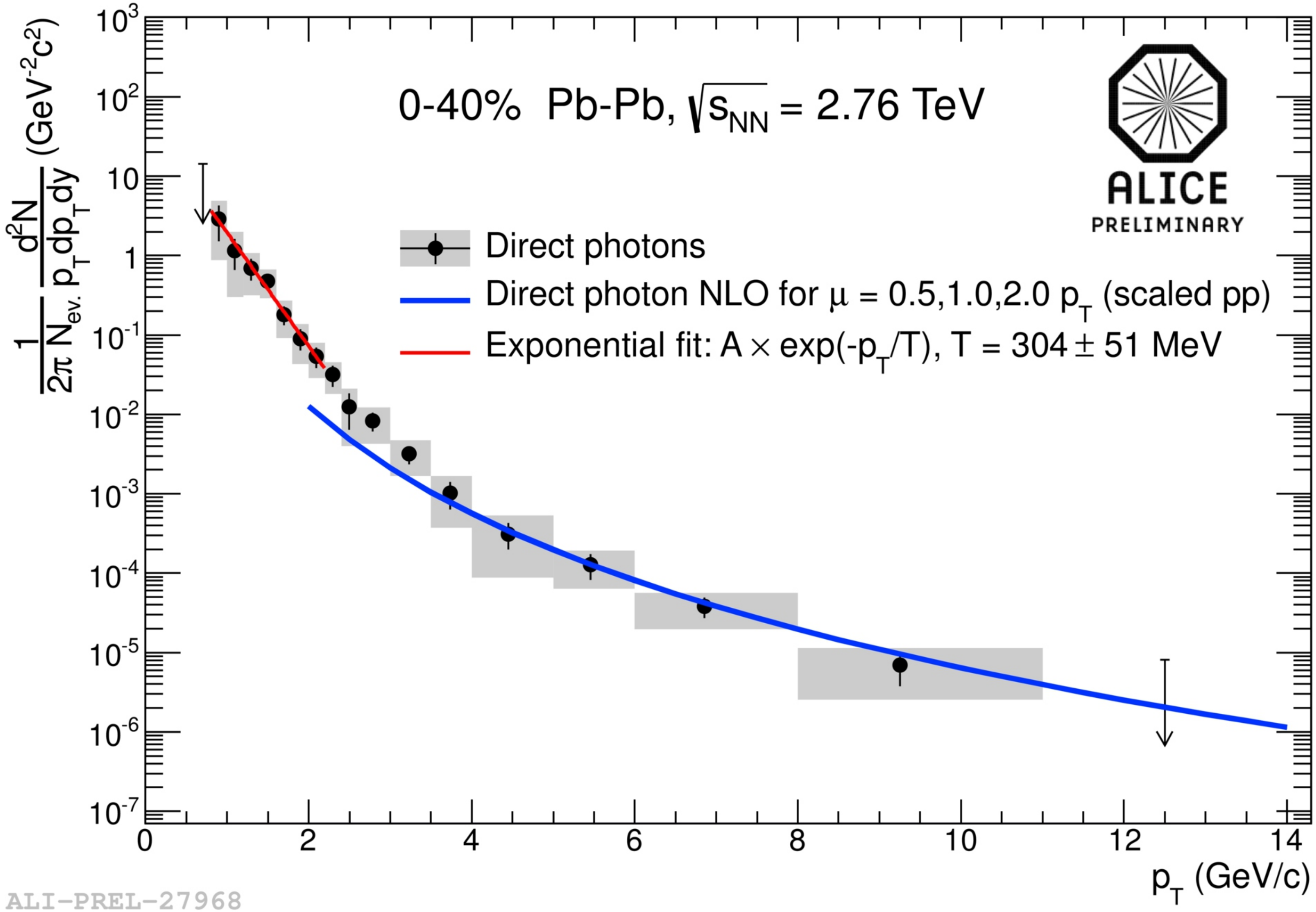
- Consider charged tracks with large impact parameter *b*
- Accept pairs of such tracks with small distance of closest approach (DCA) as V0's
- V0's mainly from
  - $K_s^0 \rightarrow \pi^+\pi^-$ ($c\tau$ = 2.7 cm)
  - $\Lambda \rightarrow p+\pi$ ($c\tau$ = 7.9 cm)
  - converted γ's
- Cuts based on decay kinematics and electron ID to obtain rather pure photon sample

Pb+Pb at 2.76 TeV: Photon Excess in Central Collisions

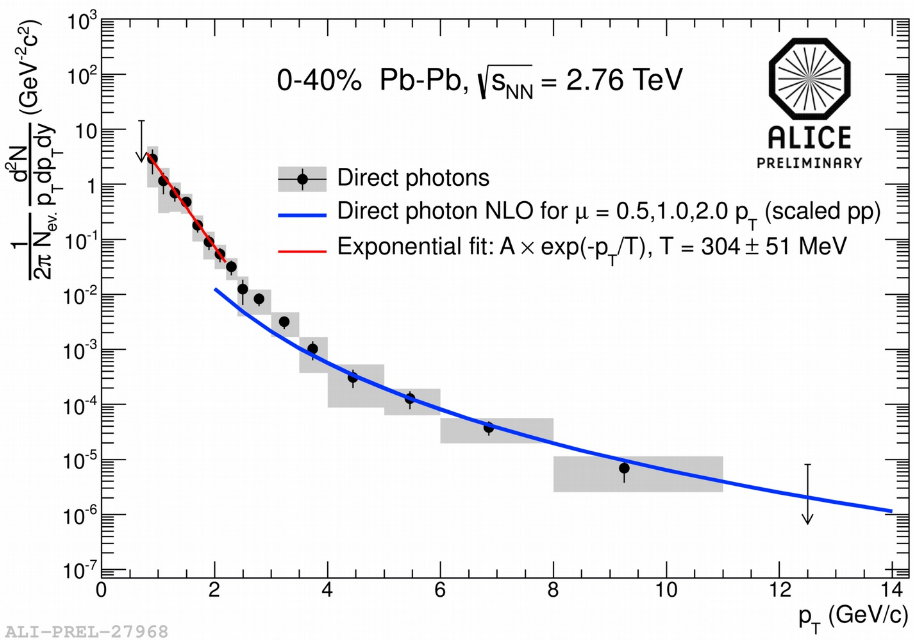


- Photon excess of about 15-20% (for $1 < p_T < 5$ GeV/*c*)
- Comparison with pQCD: Thermal photon component below 3 GeV/*c*?

Direct Photon Spectrum in Pb+Pb at 2.76 TeV (ALICE)



An Unsolved Puzzle

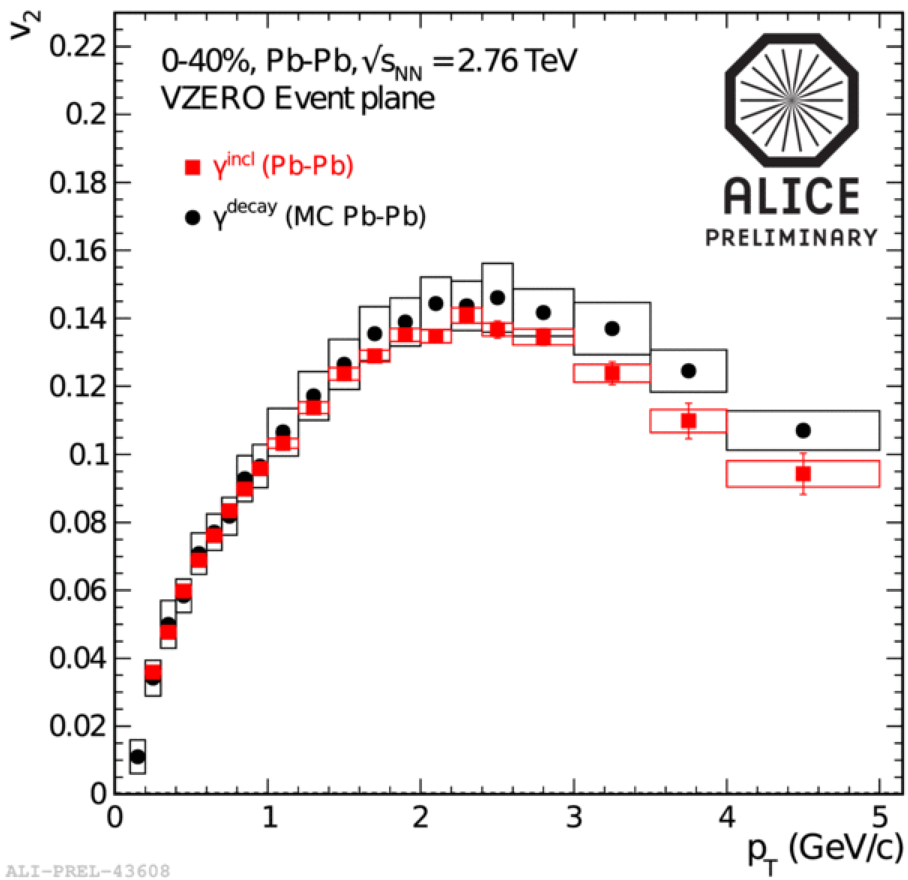


- For a static source inverse slope parameter reflects temperature
- For a moving source the observed inverse slope parameter is also affected by Doppler blueshift:

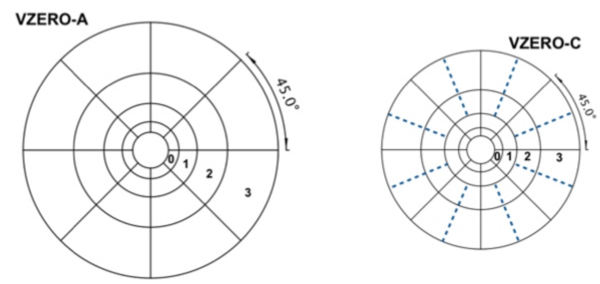
$$T_{\text{slope}} = \underbrace{\sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}}}_{=2 \text{ for } \beta_{\text{flow}}=0.6} T$$

- Could thermal photon production be dominated by the late stage of a heavy-ion collision ($T \approx 150$ MeV, $\beta_{\text{flow}} \approx 0.6$)?

Comparison of Inclusive Photon v_2 and Decay Photon v_2 in Central Pb+Pb Collisions at 2.76 TeV (ALICE)



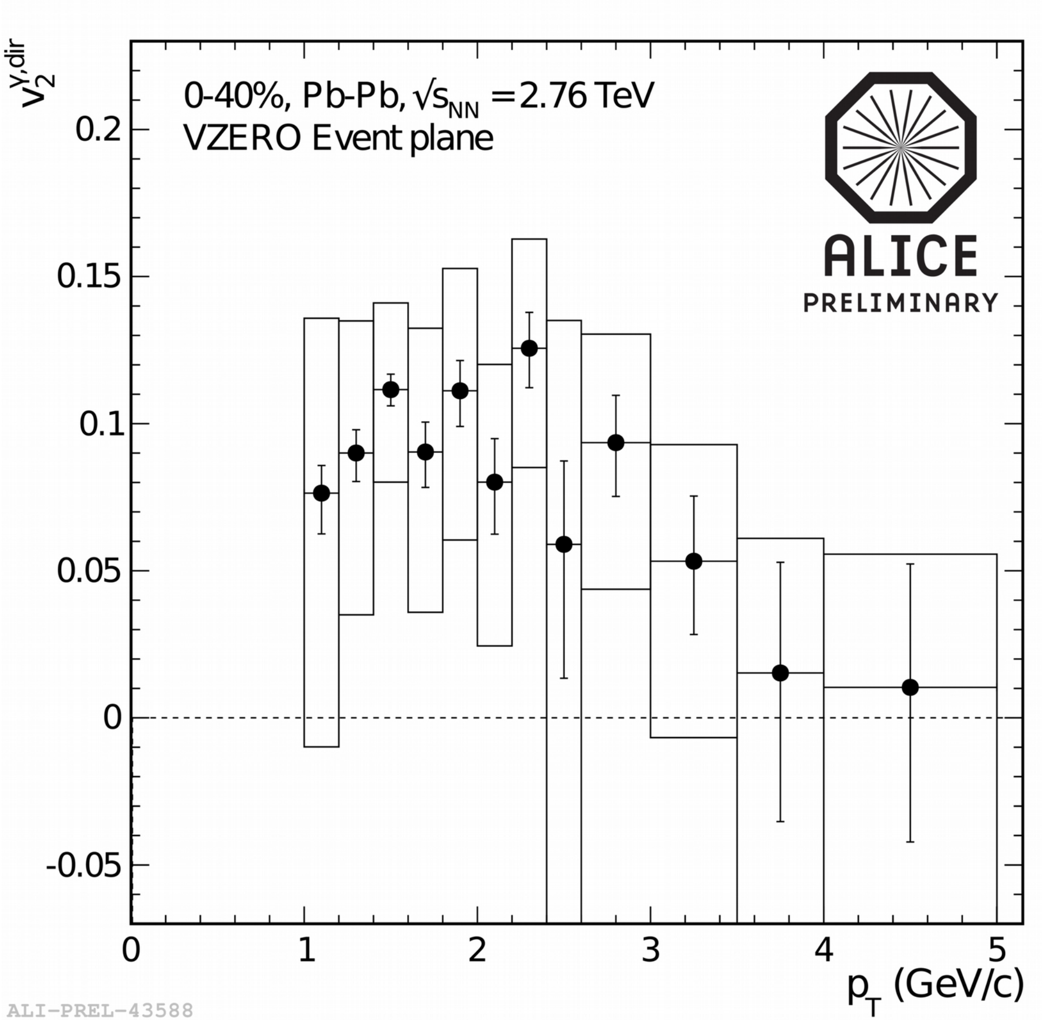
- Event plane from particle anisotropy in VZERO detectors



$2.8 < \eta < 5.1$ $-3.7 < \eta < -1.7$

- Inclusive photon v_2 compared with decay photon v_2 calculated based on measured pion v_2
- v_2(inc) ≈ v_2(decay) for $p_T < 2$ GeV/c:
- Thus, if we there are direct photons their v_2 must be similar to the decay photon v_2

Direct Photon v_2 in Central Pb+Pb at 2.76 TeV



$$v_2^{\gamma,\mathrm{inc}} = \frac{N_{\gamma,\mathrm{dir}}}{N_{\gamma,\mathrm{incl}}} v_2^{\gamma,\mathrm{dir}} + \frac{N_{\gamma,\mathrm{decay}}}{N_{\gamma,\mathrm{incl}}} v_2^{\gamma,\mathrm{decay}}$$

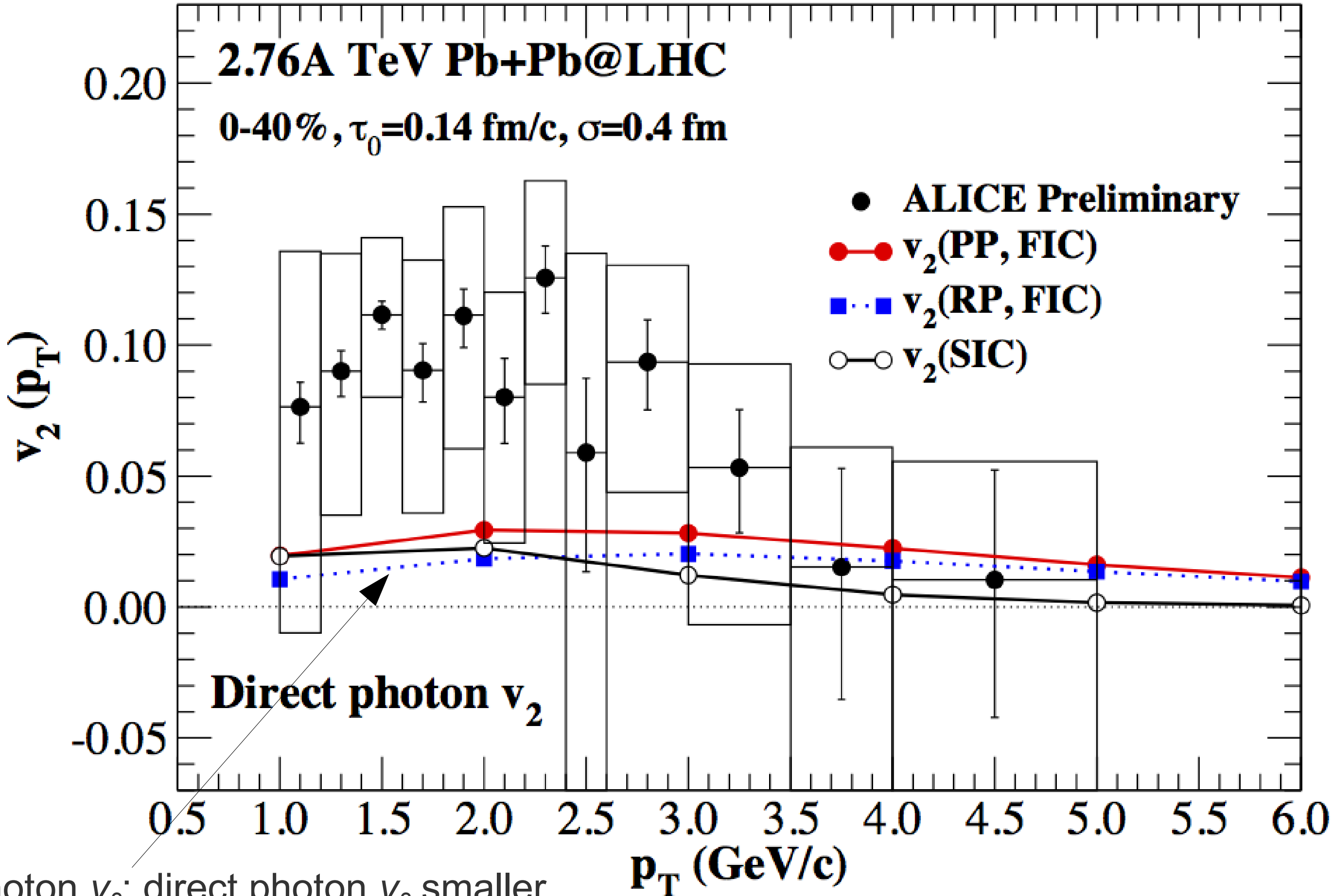
$$\Rightarrow v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma v_2^{\gamma,\mathrm{incl}} - v_2^{\gamma,\mathrm{decay}}}{R_\gamma - 1}$$

$$\text{where } R_\gamma = \frac{N_{\gamma,\mathrm{incl}}}{N_{\gamma,\mathrm{decay}}} = 1 + \frac{N_{\gamma,\mathrm{dir}}}{N_{\gamma,\mathrm{decay}}}$$

Direct photon v_2 similar in magnitude to the pion v_2
(confirming the finding of PHENIX)

Tension Between Direct Photon v_2 Data and Hydrodynamic Calculations

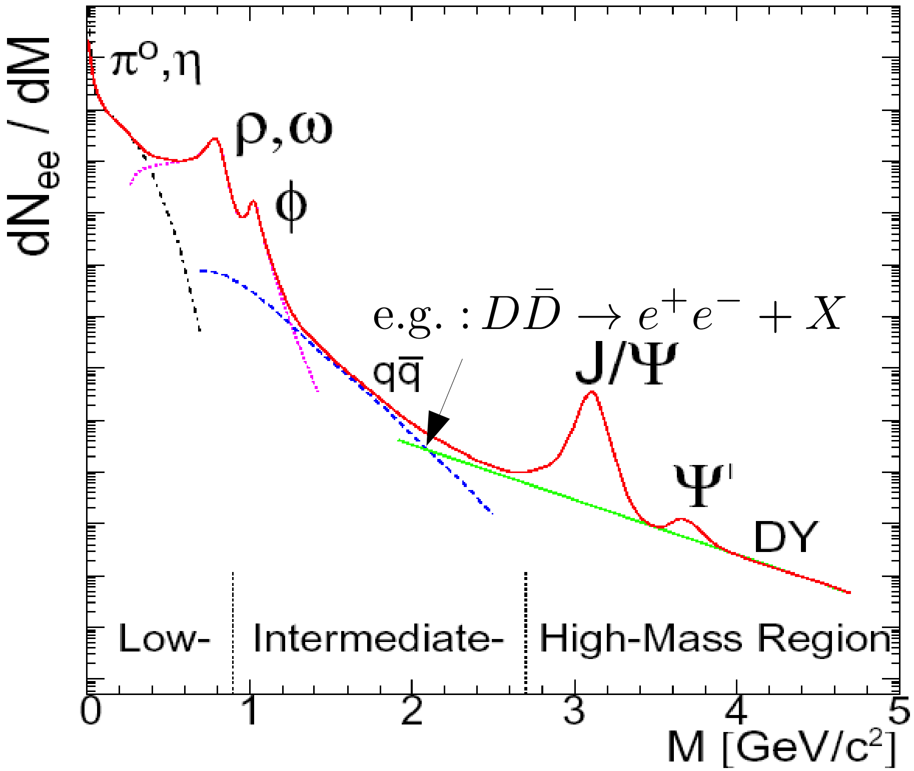
Chatterjee et al., arxiv:1305.6443 (→ link)



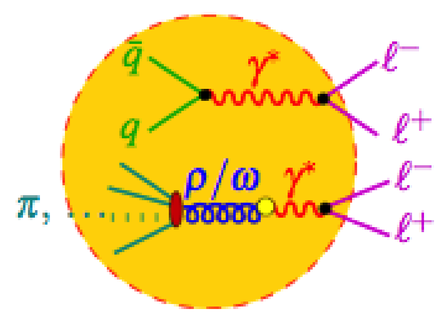
Thermal photon v_2; direct photon v_2 smaller due to prompt photon component ($v_{2,\mathrm{prompt}} = 0$)

Direct photon v_2 data challenge the standard hydro models

Motivation for Studying Dileptons in Heavy-Ion Collisions

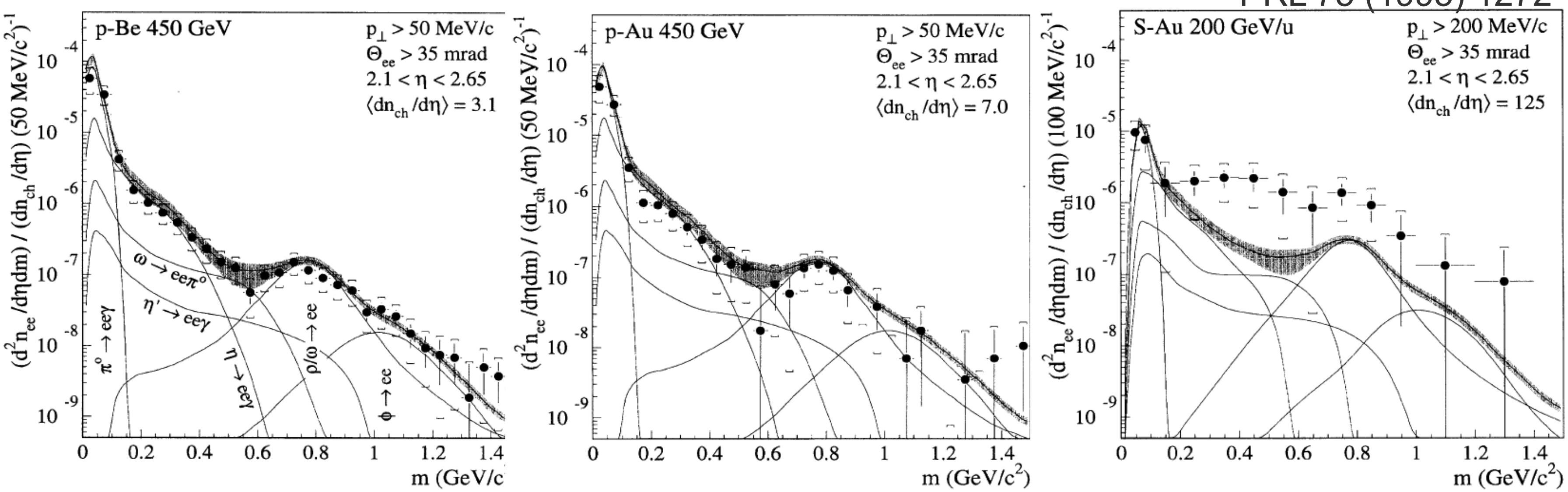


- Search for modifications of vector mesons in the medium
  - Lifetime shorter (ω,ρ) or similar (φ) to that of the medium
  - Broadening vs. mass shift
  - Effects of chiral symmetry restoration?
- Thermal emission (both from QGP and hadronic phase)
- High-Mass region: J/Ψ suppression/enhancement



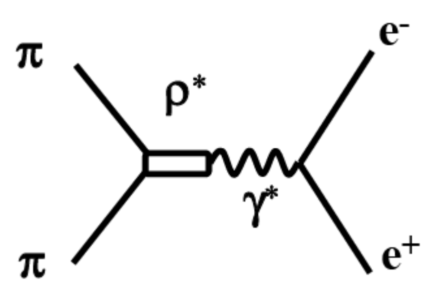
Discovery of Low Mass Dilepton Enhancement

PRL 75 (1995) 1272



Discovery of low mass dilepton enhancement in 1995

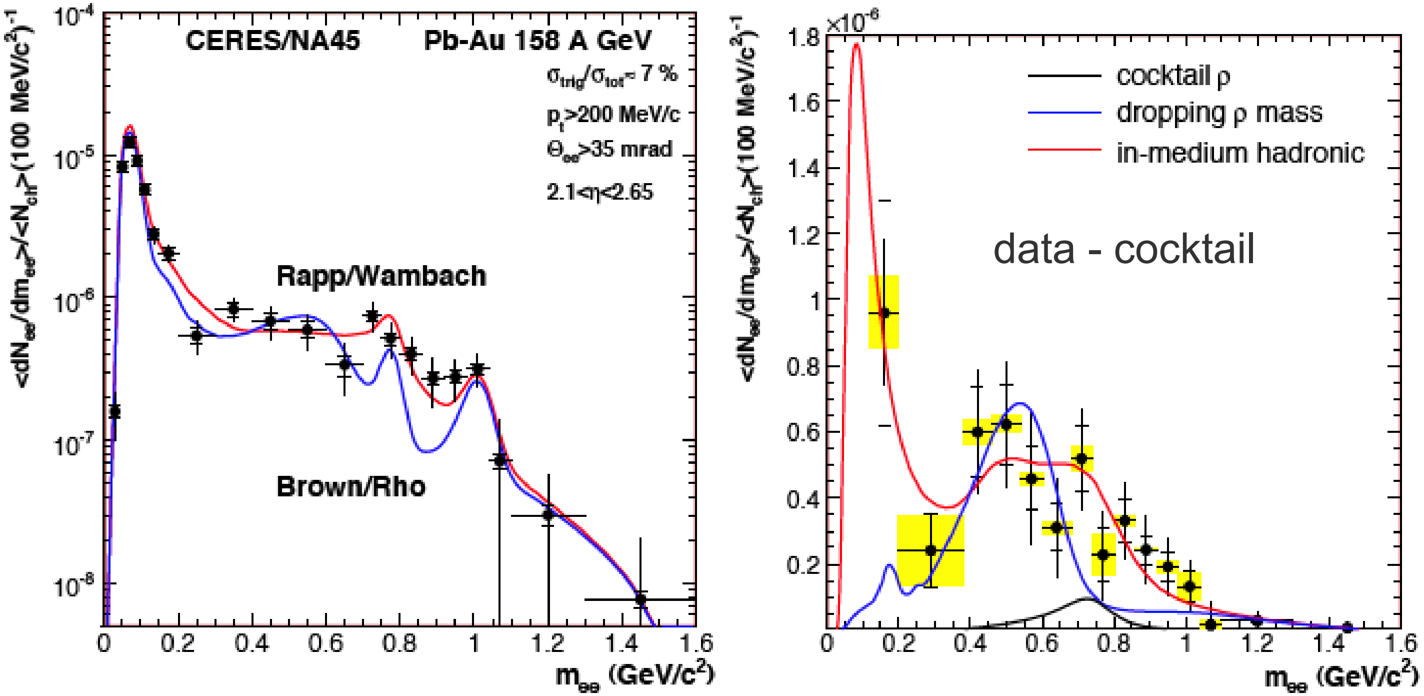
- p-Be and p-Au well described by decay cocktail
- Significant excess in S-Au (factor ~5 for m > 200 MeV)
- Onset at ~ 2 m_π suggested π−π annihilation
- Maximum below ρ meson near 400 MeV



A. Drees,
Hard Probes 2004 (→ link)

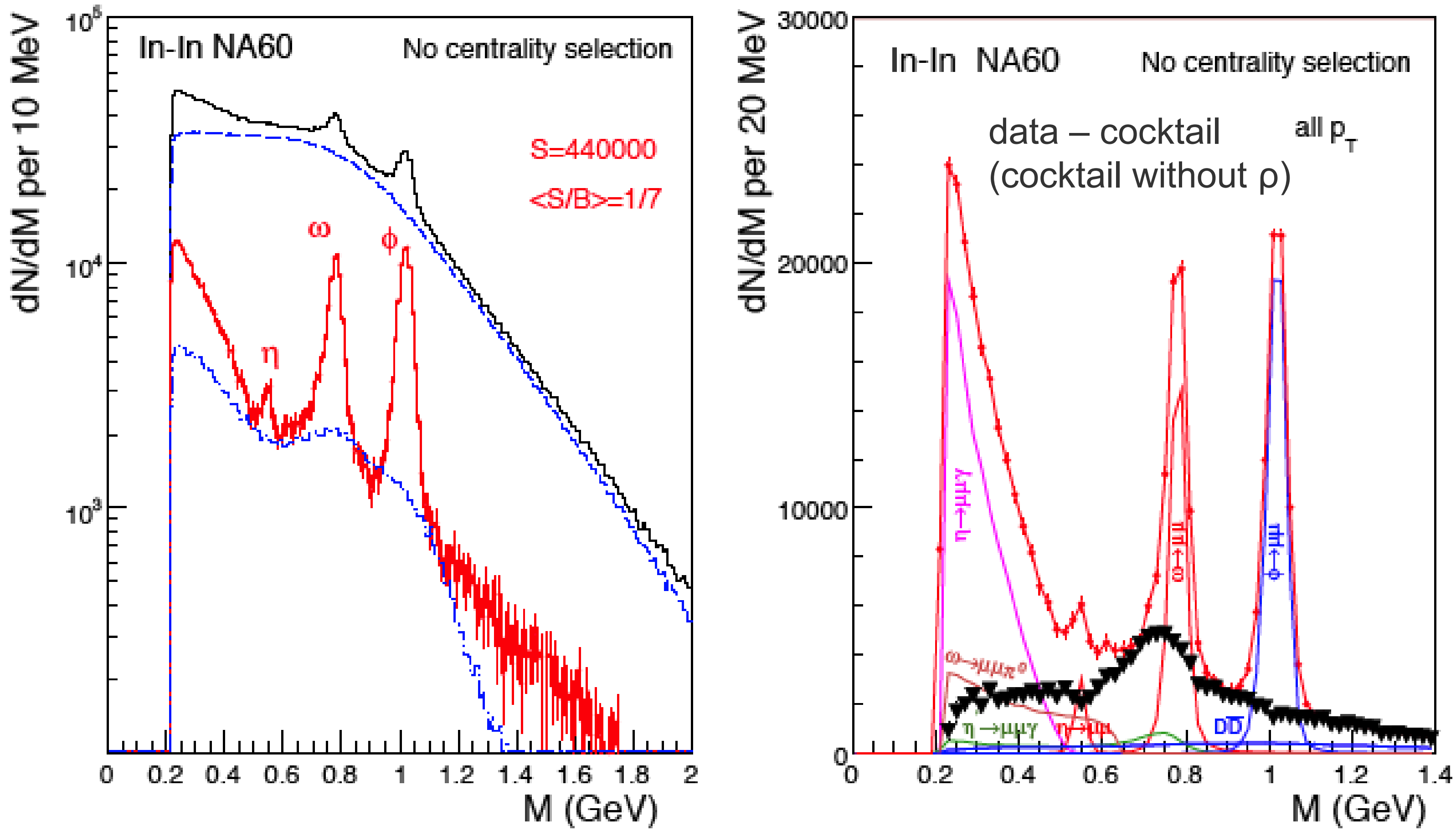
Hints towards modified ρ meson in dense medium

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

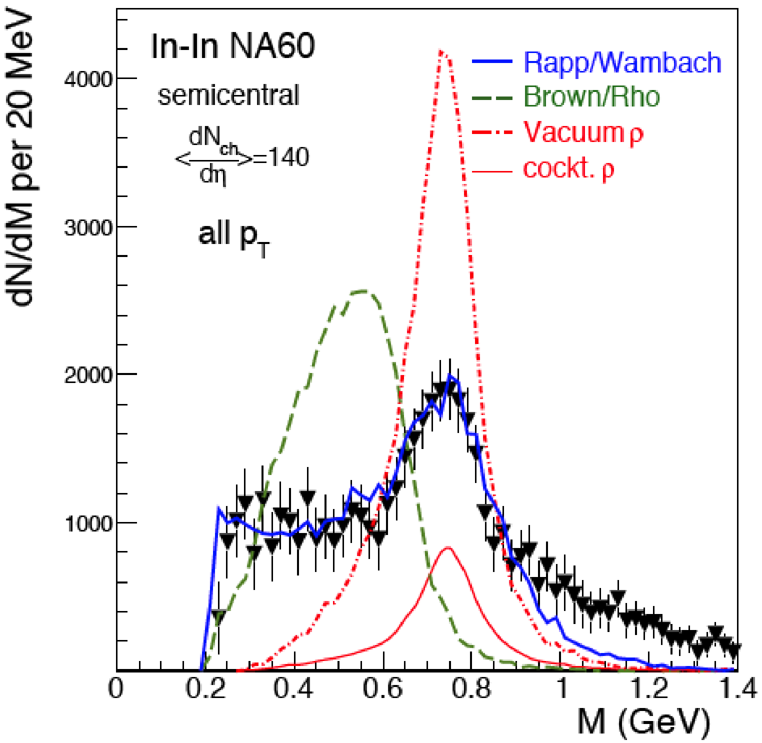


- Di-Electron Excess (factor ~ 2.6) also measured in Pb+Au at 158 *A* GeV
- Even stronger enhancement (factor ~ 5.9) found in Pb+Au at 40 *A* GeV (effect of higher baryon density?)
- Difficult to distinguish between calculations with dropping ρ mass (Brown/Rho) and broadening of the ρ (Rapp/Wambach).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

Dimuon Data from NA60

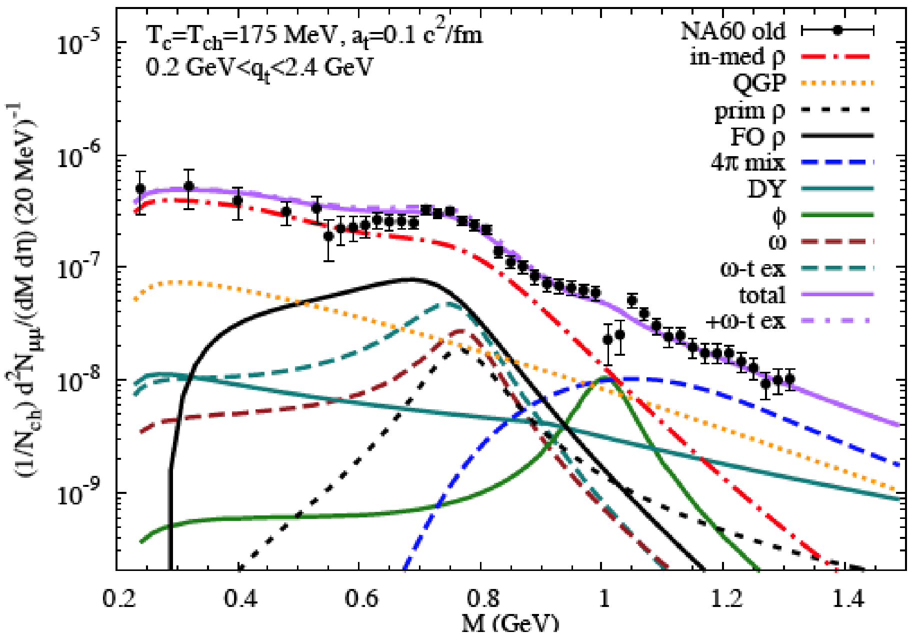


NA60 Data Described by Broadening of the ρ Meson



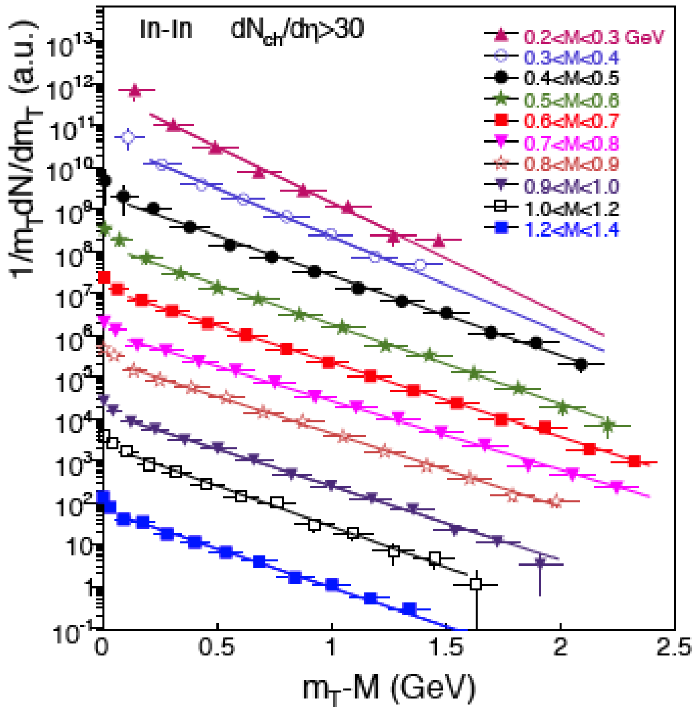
Phys. Rev. Lett. 96 (2006) 162302

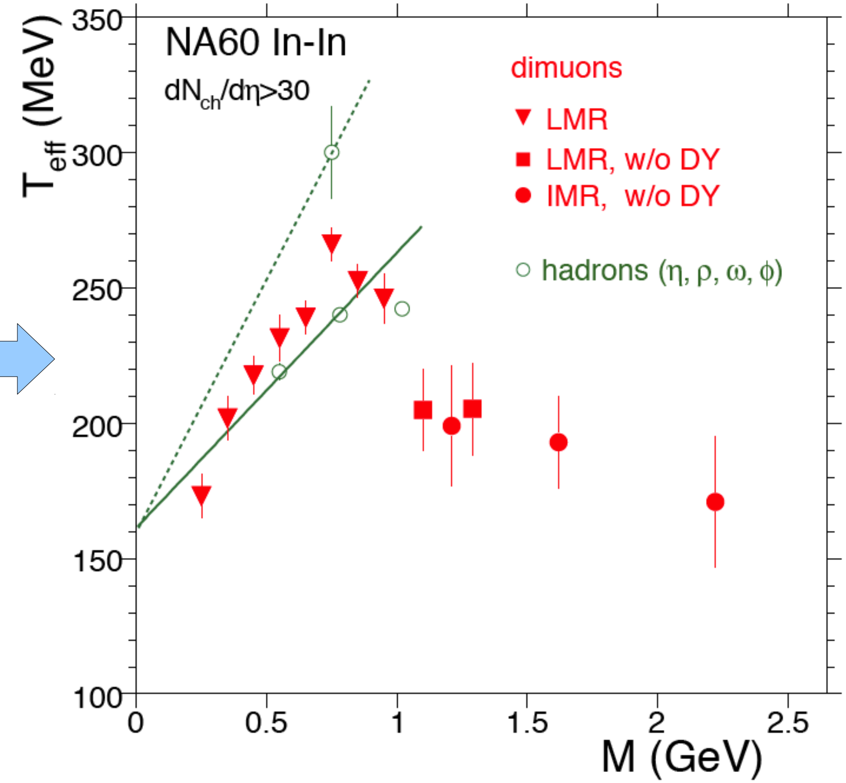
Calculation: Rapp, arXiv:1010.1719



- 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 measurements using the internal and external conversion methods 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
- ALICE:
  - Direct photon excess measured with external conversion method
  - Large direct photon v_2, in qualitative agreement with RHIC result
- Dilepton measurements sensitive to in-medium modification of vector mesons and thermal radiation