# QGP Physics − from Fixed Target to LHC

## 11. Thermal Photons and Dileptons

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# Motivation for Measuring Direct Photons in Heavy-Ion Collisions

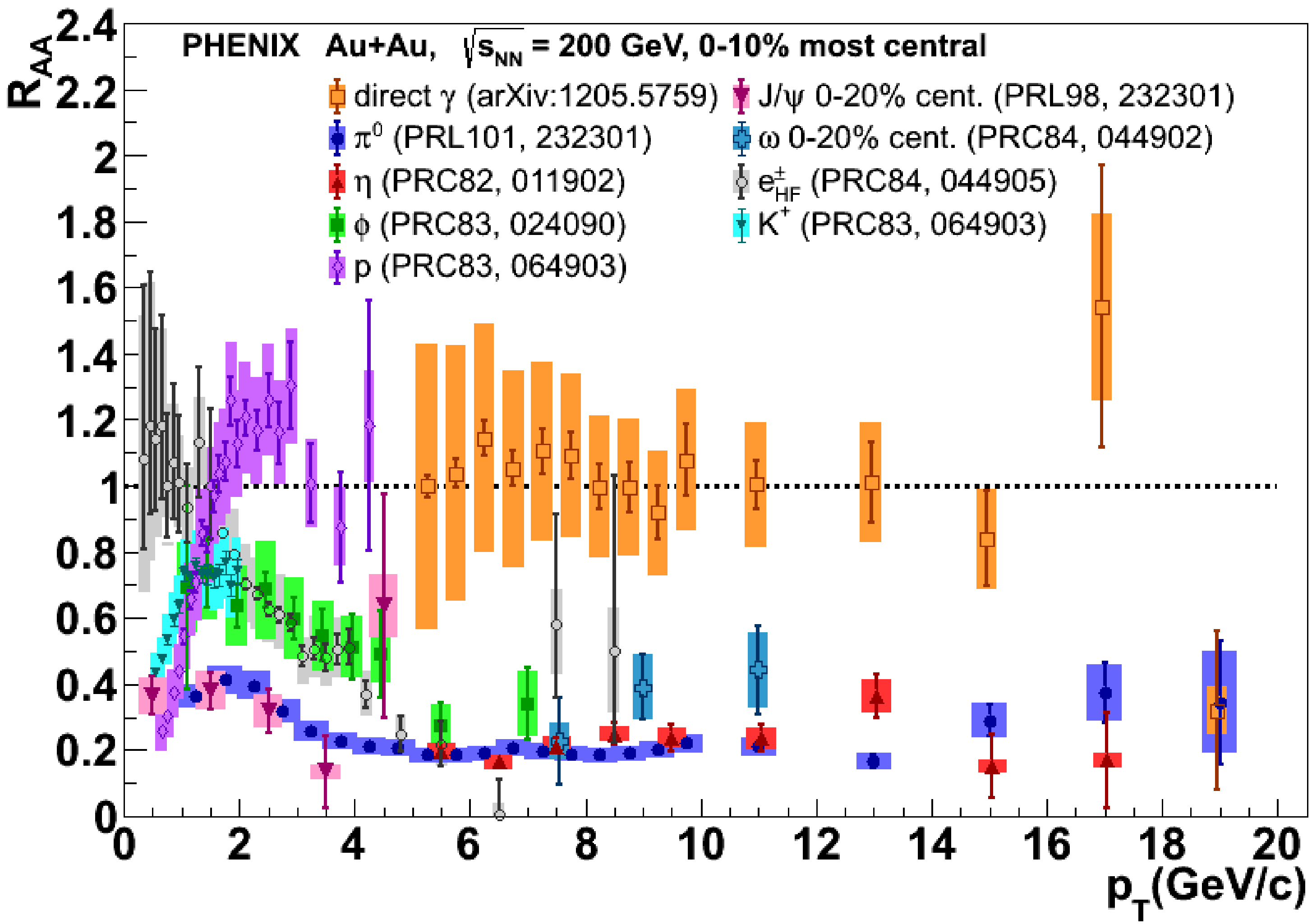
## High $p_T$ (> 6 GeV/$c$):

- 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

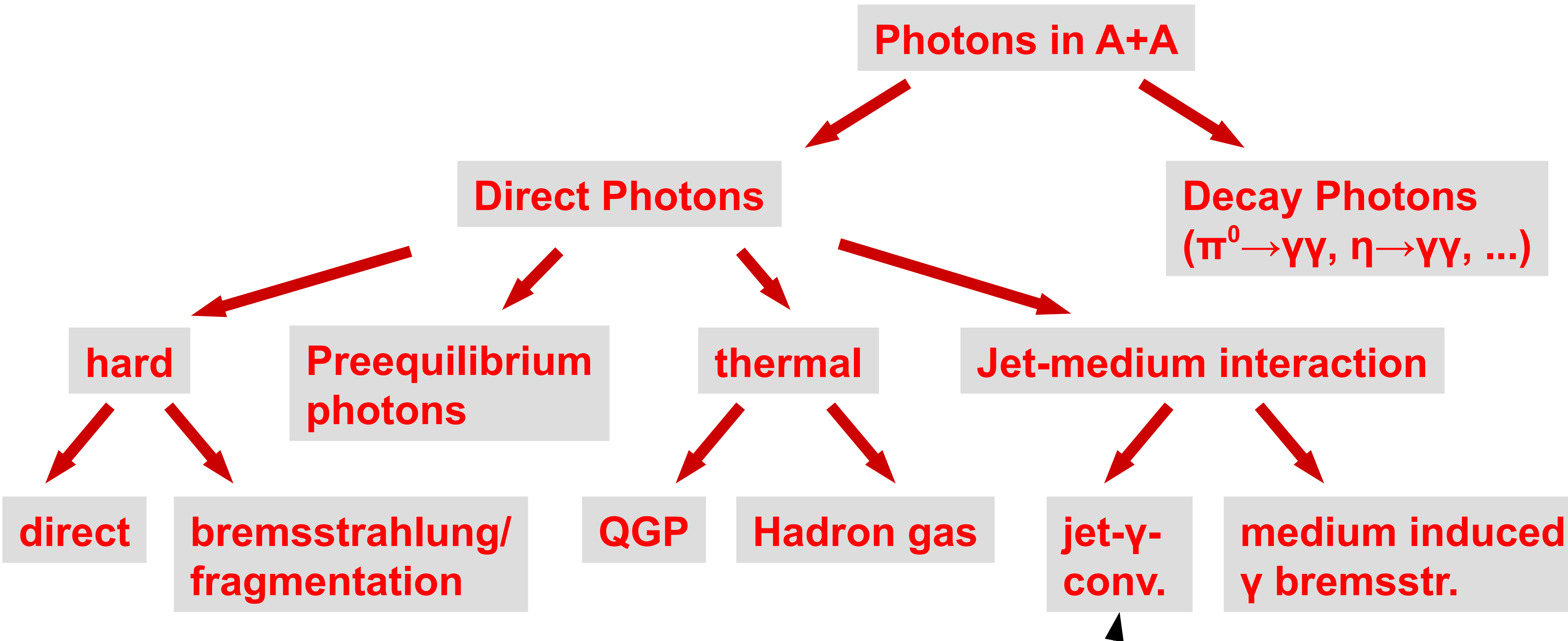
## Low / Intermediate $p_T$:

- 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



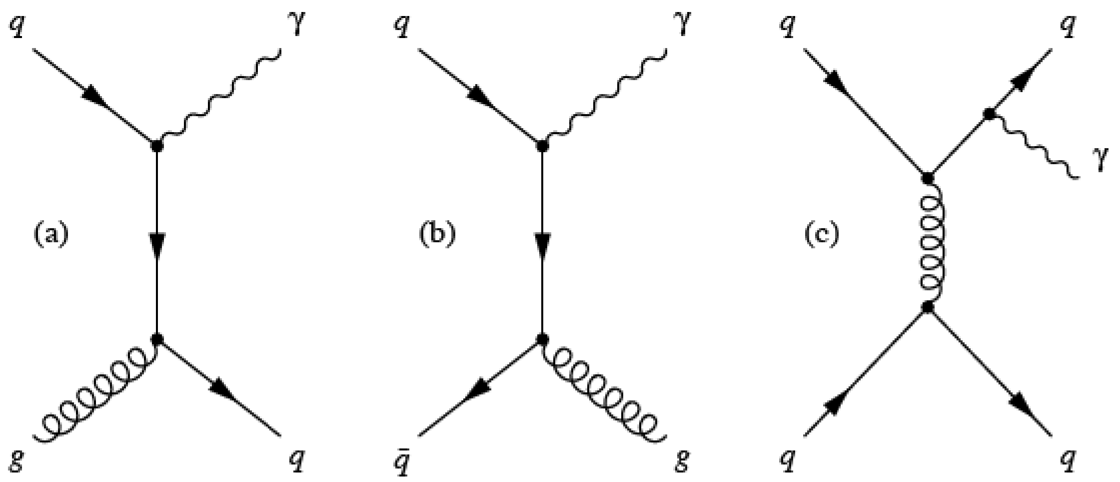

$$\text{e.g.}: g + q_{\text{QGP}} \rightarrow q + \gamma$$

gluon jet

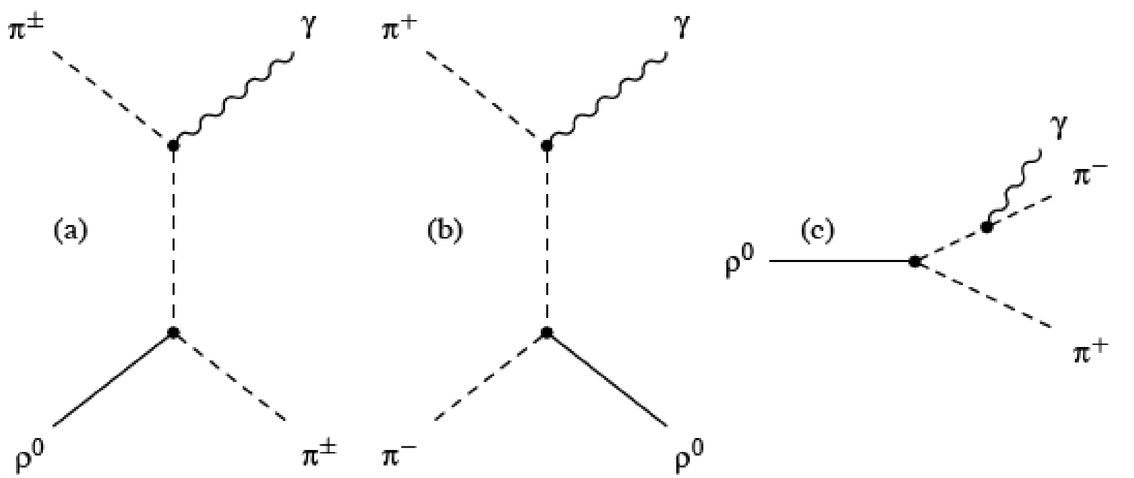
$$\sigma_{jet(q)\rightarrow\gamma(p)} \propto \delta(q-p)$$

# Photon Production: Feynman Diagrams

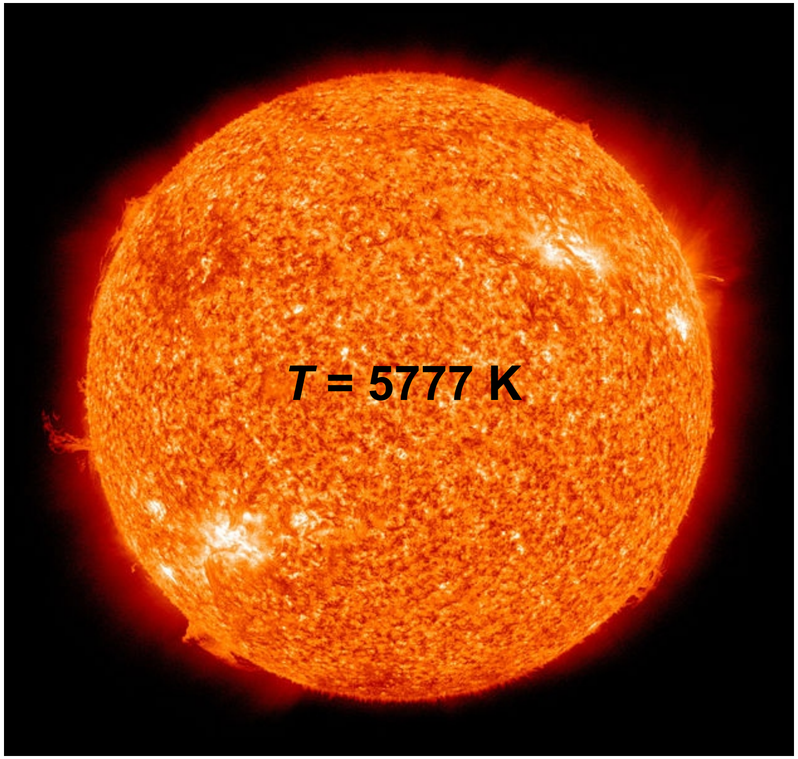
QGP:




Hadron gas:

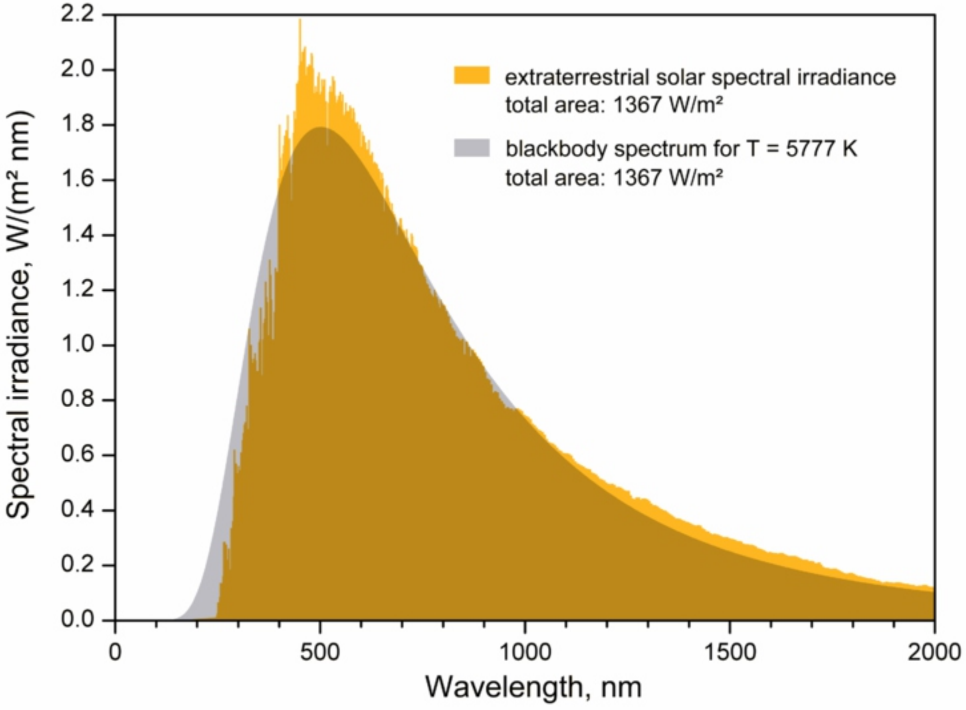


# Measuring Temperatures via the Planck Spectrum



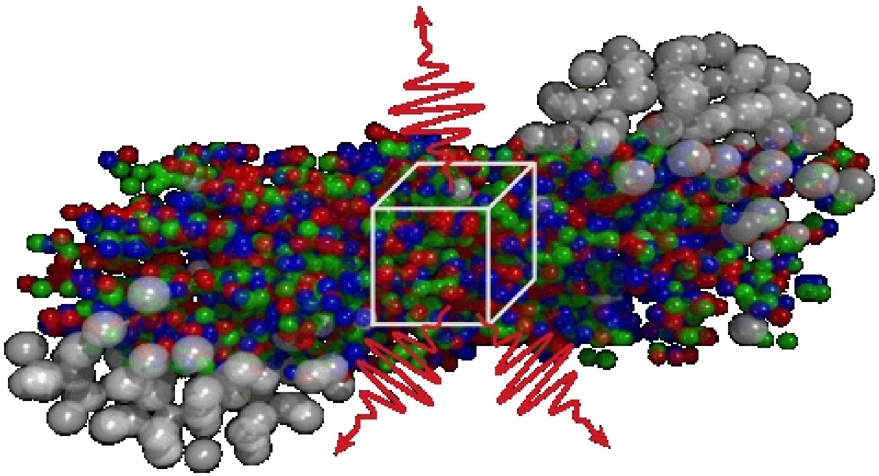

source: http://en.wikipedia.org

source: http://en.wikipedia.org



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

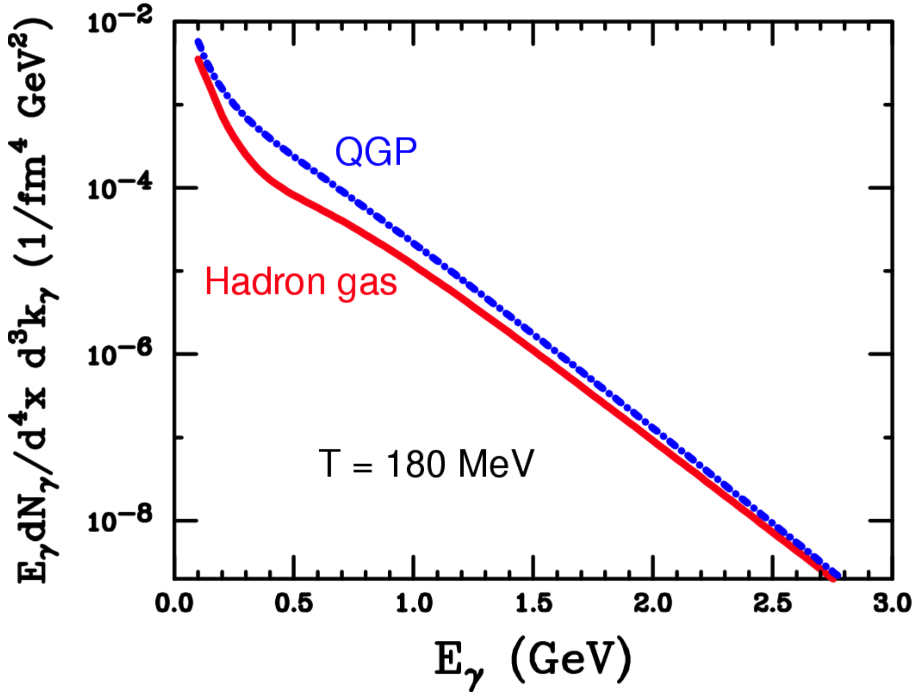
- Photons produced in scatterings of quark and gluons in thermal equilibrium
- Photons not in thermal equilibrium ($\lambda_{mfp} \approx 500$ fm), but energy spectrum reflects QGP temperatures



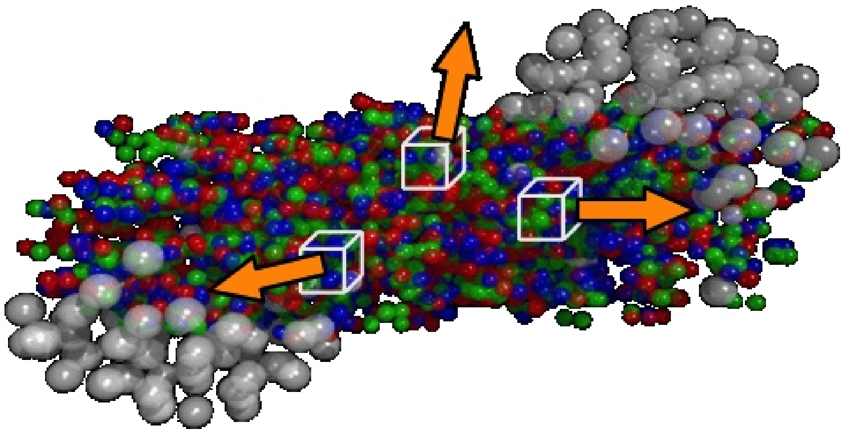
QGP photon rate (lowest order):

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

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



# What can we Learn from Thermal Photons Measurements?

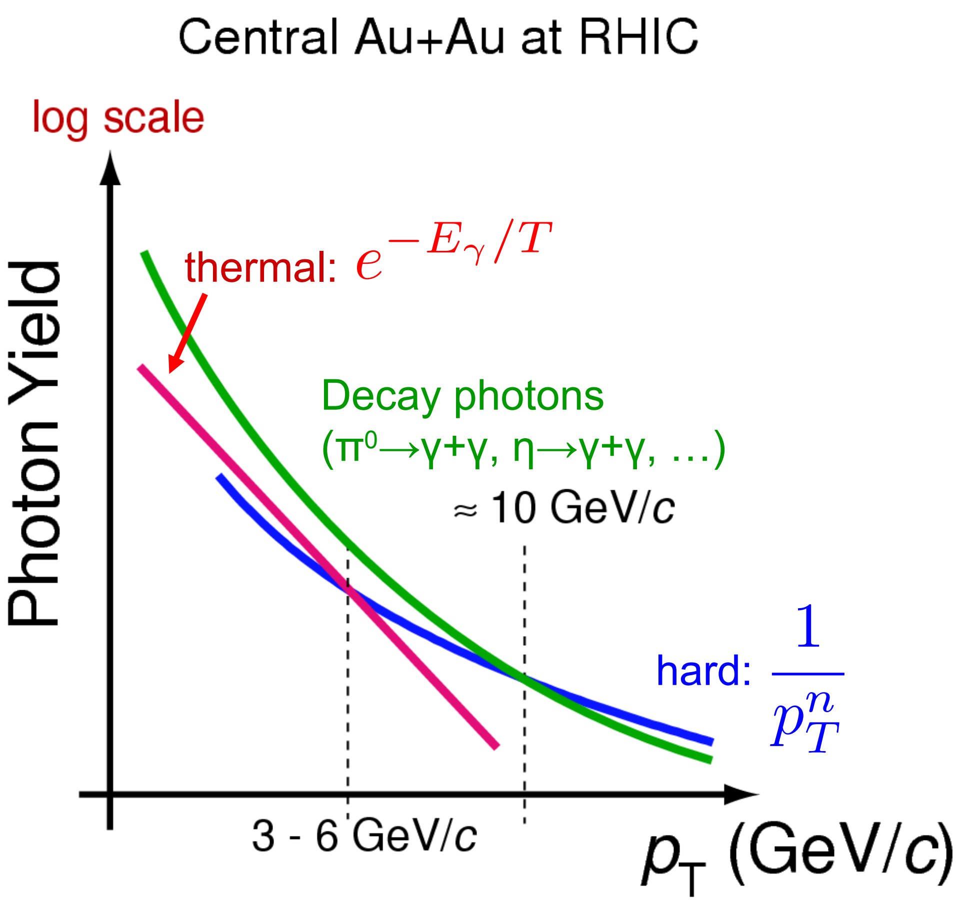


- The QGP expands in longitudinal and transverse direction and cools rapidly
- It lives only for about $3 \times 10^{-23}$ s
- What information can one extract from a measured thermal photon spectrum?

- 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

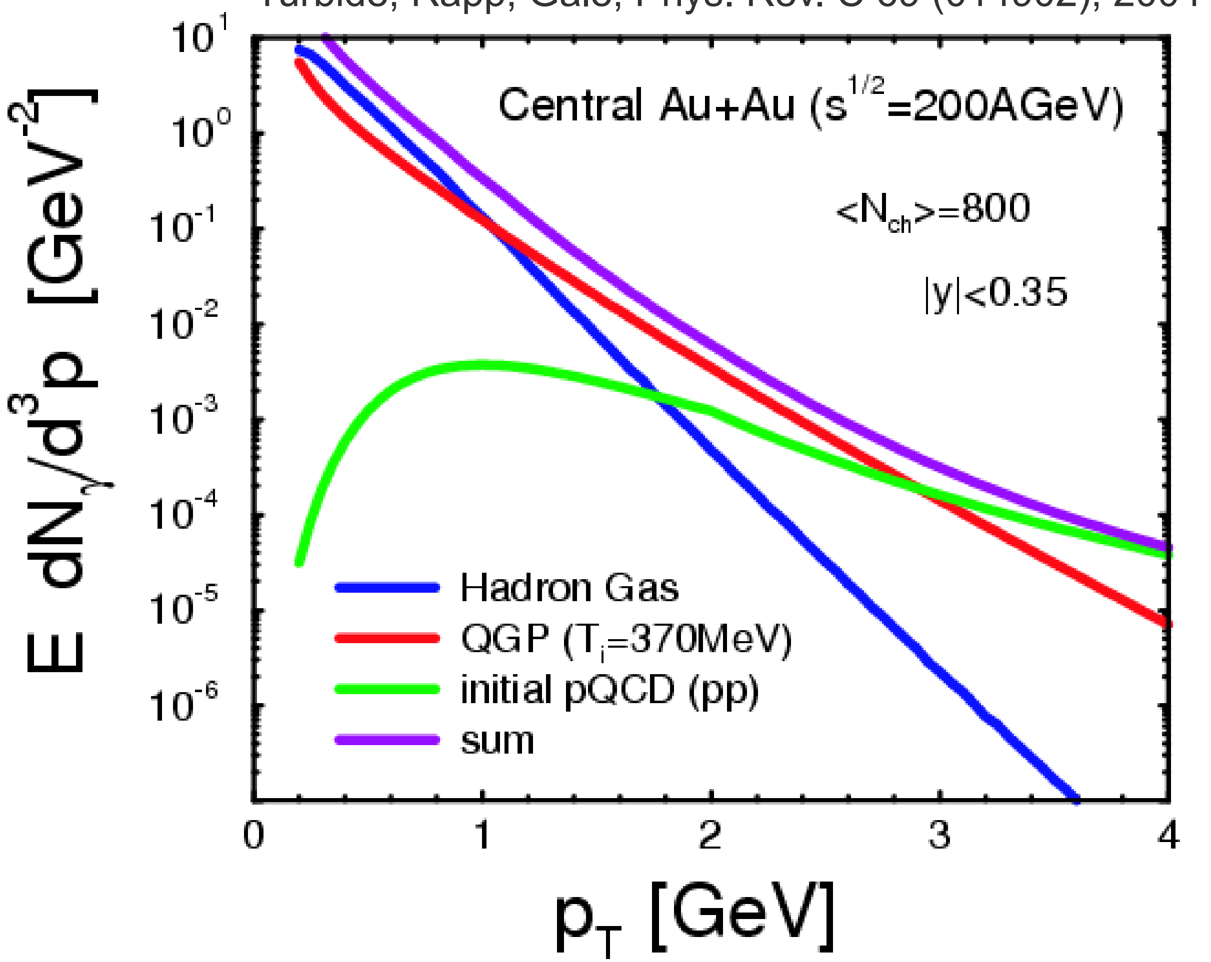
# Schematic Photon Spectrum in A+A




- 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 (2013) 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)
  - Measure virtual photons ($\gamma^* \to e^+e^-$),

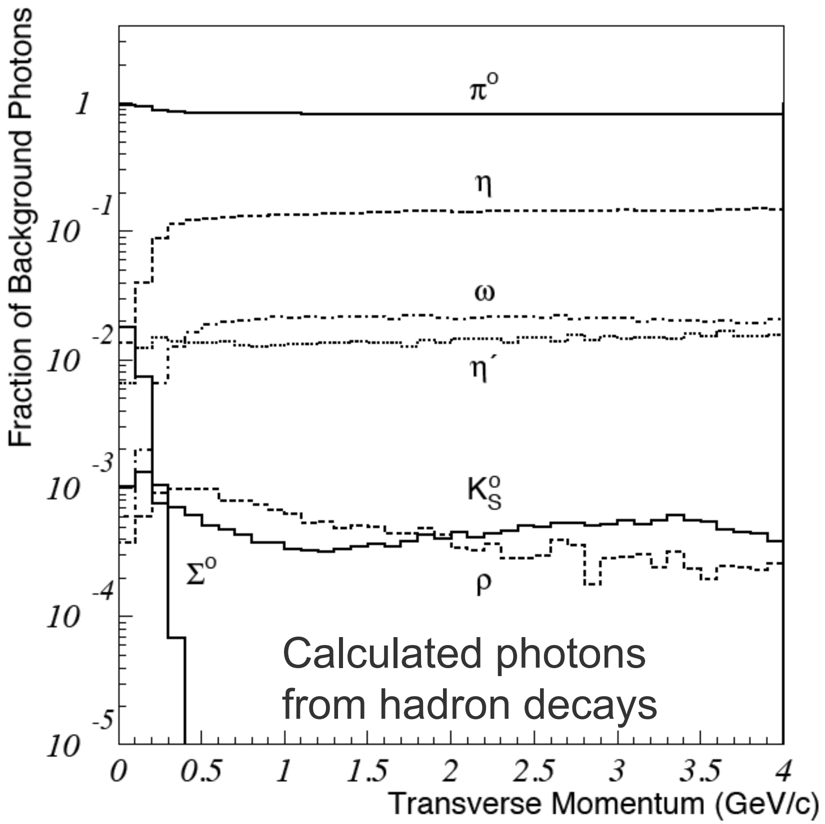
  and assume $$\frac{\gamma_\text{direct}}{\gamma_\text{inclusive}} = \left.\frac{\gamma^*_\text{direct}}{\gamma^*_\text{inclusive}}\right|_{m_{ee}<30\,\text{MeV}}$$ (PHENIX)

# Subtraction Method

WA98, nucl-ex/0006007 (→ link)

Systematic uncertainties partially cancel in this ratio

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

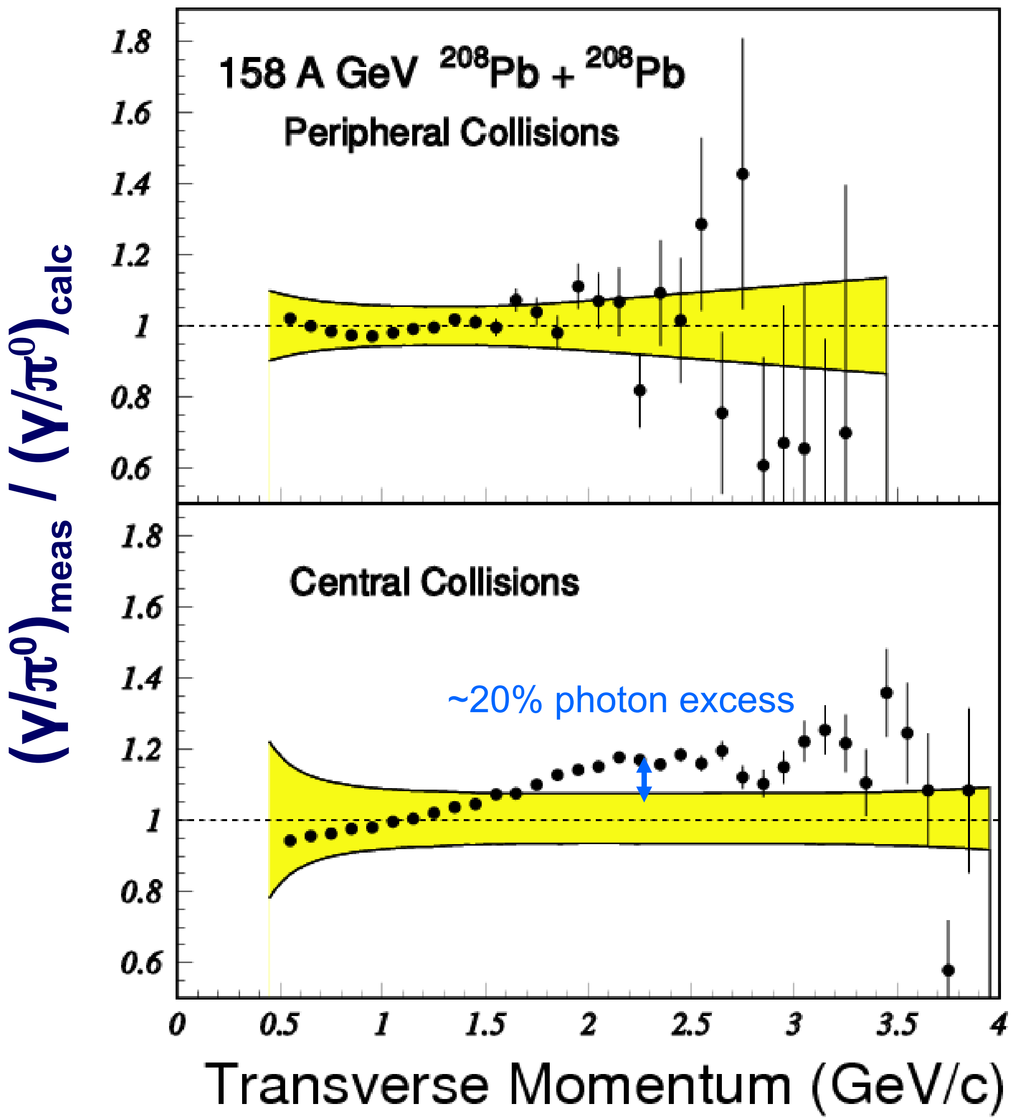



Based on the measured $\pi^0$ (and η) $p_T$ spectrum, the expected decay photons are calculated (assuming $m_T$ scaling for unmeasured particle species)

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

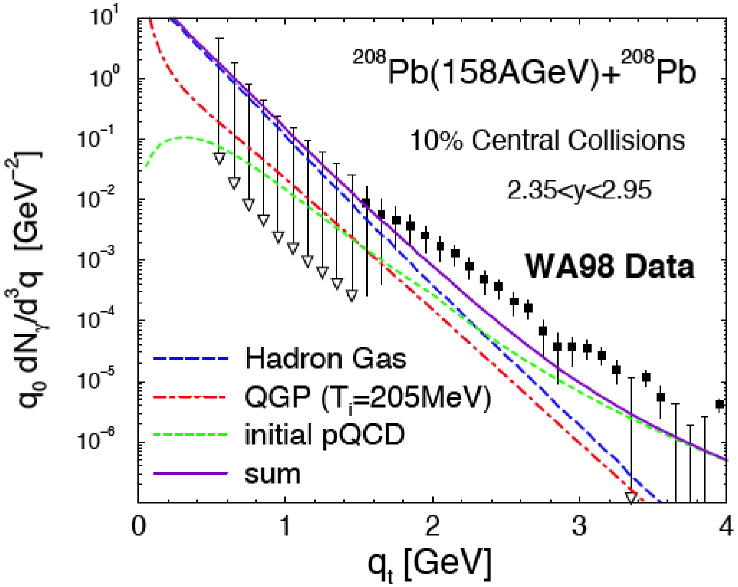
**158 AGeV Pb + Pb:**

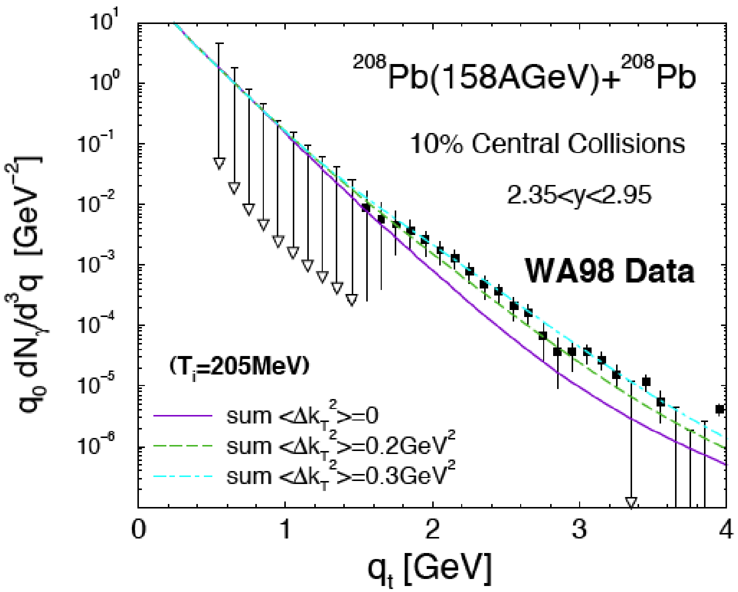
$$\sqrt{s_{NN}} = 17,3 \text{ GeV}$$

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

# Interpretation of the WA98 Data

Ch. Gale, arXiv:0904.2184 (→ link)




Theoretical ingredients:

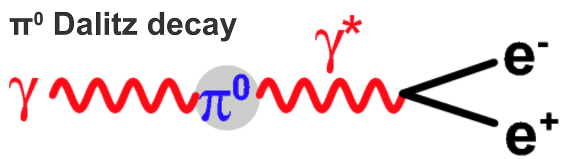
- (schematic) fireball evolution
- Photon emission rates from a gas of hadrons
- Photon emission rates from the QGP complete to lading order in $\alpha_s$
- Estimate of the Cronin effect deduced from p+A collisions

Conclusions:

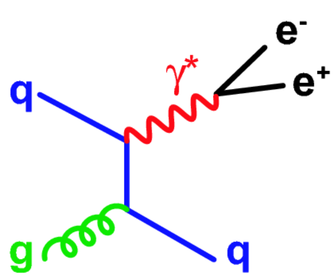
- Data consistent with QGP scenario ($T_i \approx 200 - 270$ MeV), however, QGP contribution is small
- Data also consistent with hadronic scenario (Cronin enhancement alone could explain the data)

# Internal Conversion Method: How to Avoid the $\pi^0$ Background at the Expense of a Factor ~1000 in Statistics

- Internal conversion
  - Any source of real photons also emits virtual photons
  - Well known example:

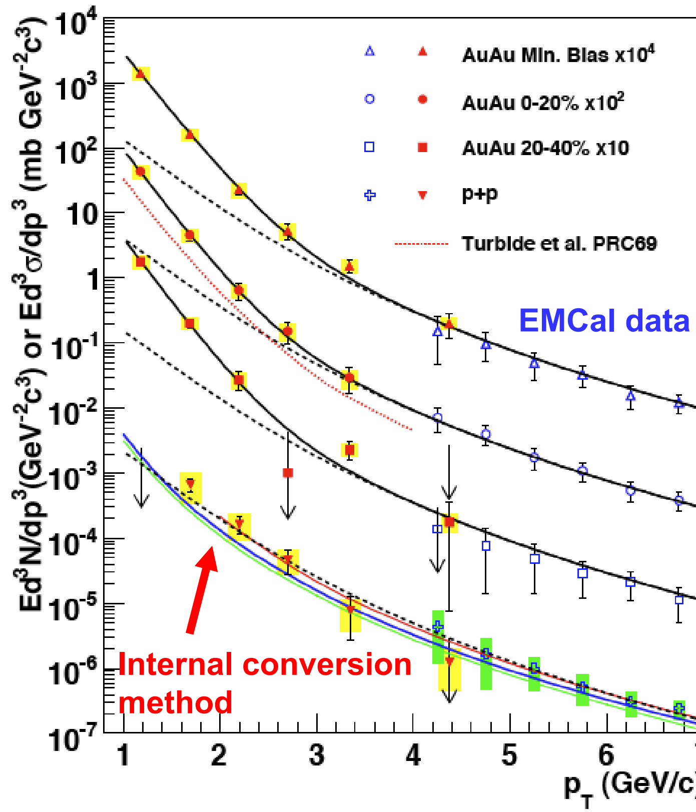



  - Rate and $m_{ee}$ distribution calculable in QED
    (Kroll-Wada formula, see next slide)
- Hadron decays: $m_{ee} < M_{hadron}$
- Essentially no such limit for point-like processes




- 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 $\Delta\eta\ \Delta\varphi\ \Delta p_T$ interval):

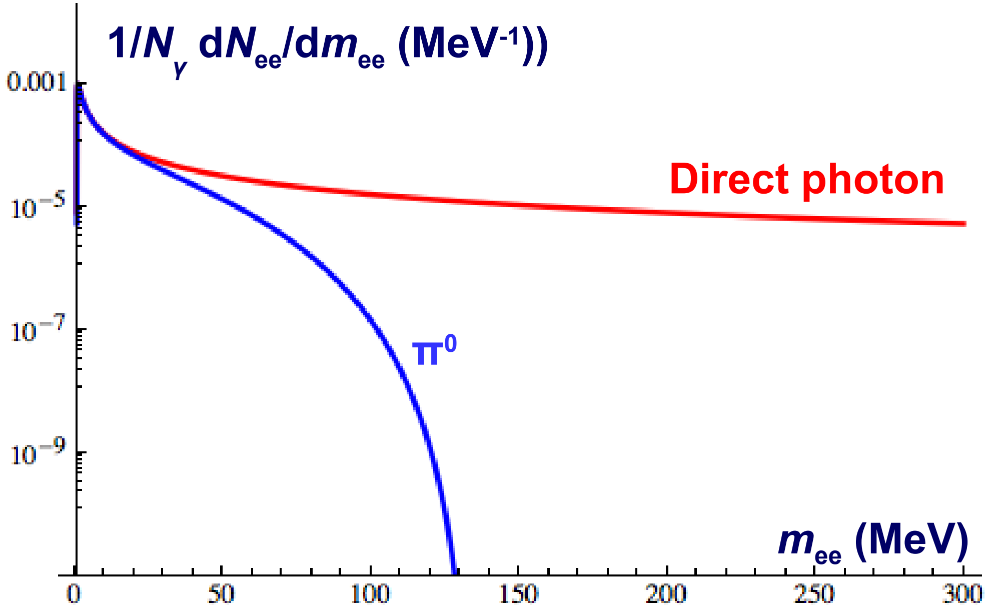
$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

Hadron decay:

$$S = \underbrace{|F(m_{ee}^2)|^2}_{\text{form factor}}\underbrace{\left(1-\frac{m_{ee}^2}{M_h^2}\right)^3}_{\text{phase space}}$$

Point-like process:

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



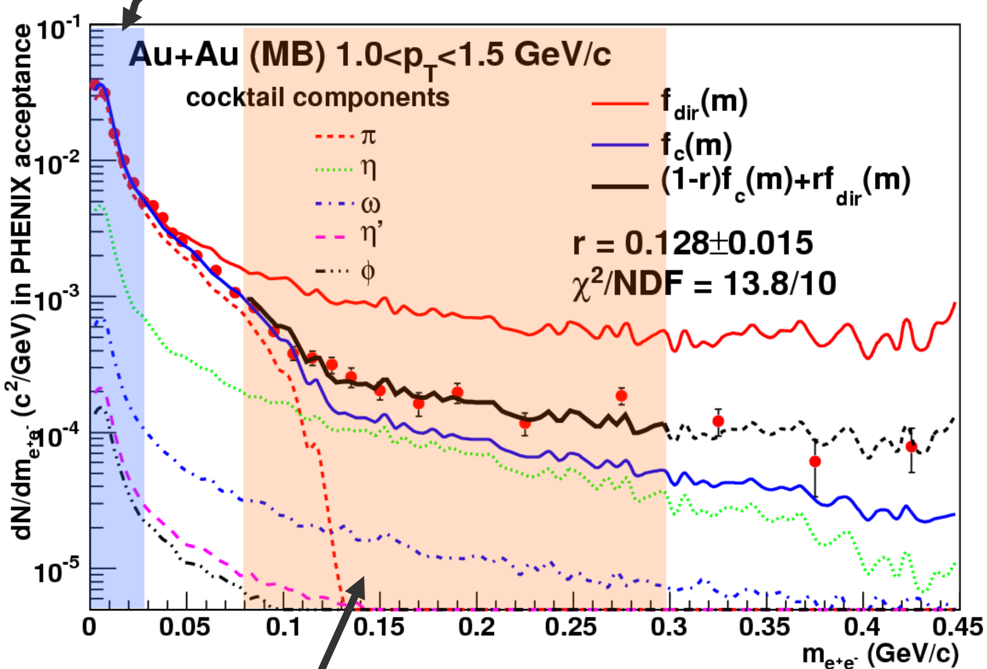

PHENIX measurement:
$80 < m_{ee} < 300$ MeV

→ **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

$$f(m_{ee}) = (1-r)\cdot f_{\mathrm{cocktail}}(m_{ee}) + r\cdot f_{\mathrm{direct}}(m_{ee})$$

**Separately normalized to data at $m_{ee}$ < 30 MeV**



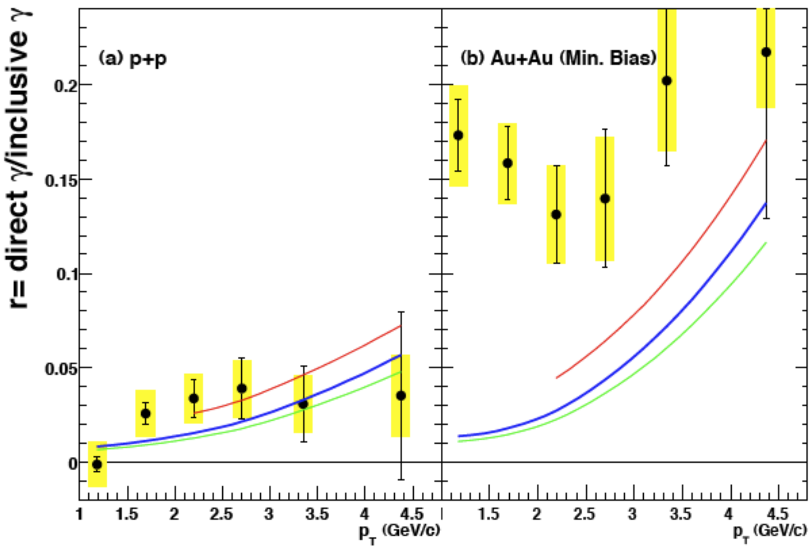

**Fit range: 80 < $m_{ee}$ < 300 MeV**

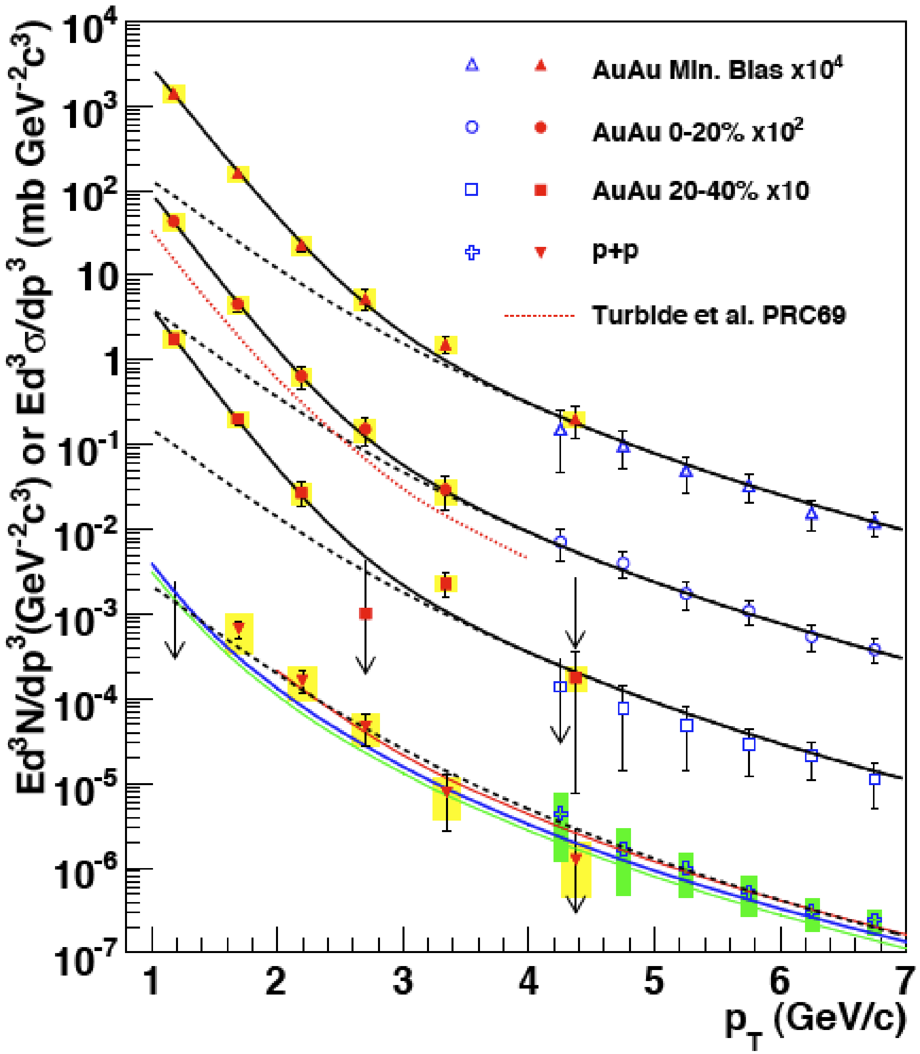
- Interpret deviation from hadronic cocktail ($\pi^0$, η, ω, η', φ) as signal from virtual direct photons
- Extract fraction $r$ with two-component fit

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

- Fit yields good $\chi^2$/NDF (13.8 / 10)

# 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%): $T = (221 \pm 23 \pm 18)$ MeV
- Initial temp. from hydro: $T_i = 300 \ldots 600$ MeV

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

# 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 ($S/n_{\text{hadron}} \approx 4$ in natural units):

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

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

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

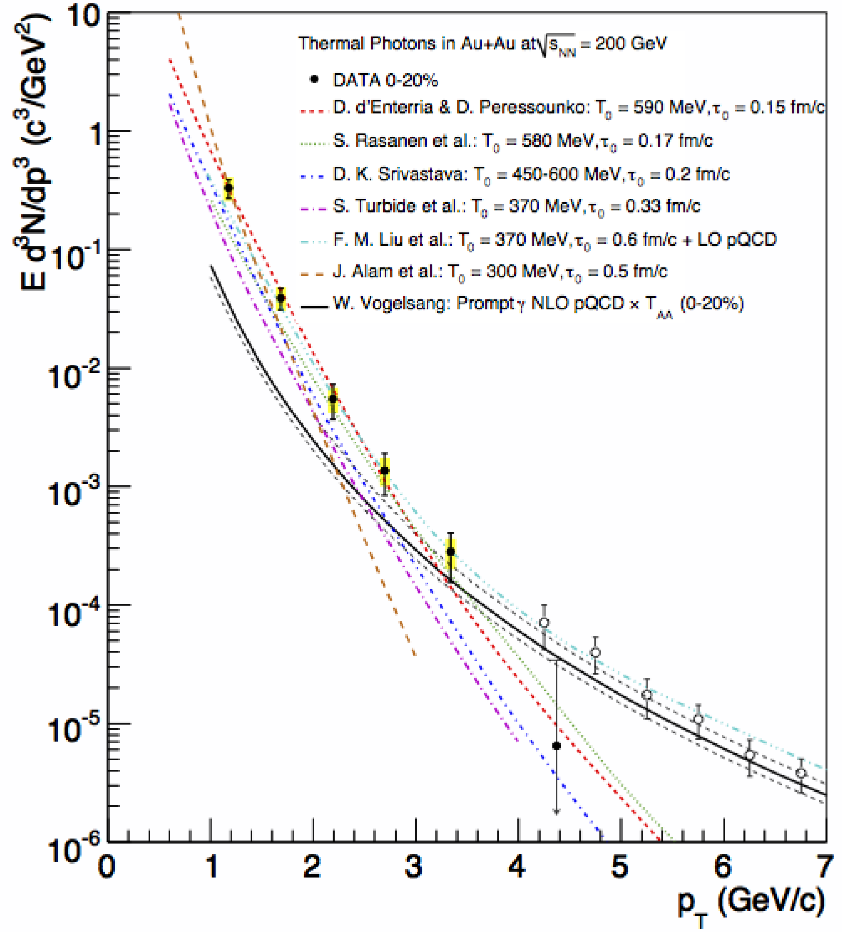
$$s_{\text{Bj}} = s_{\text{id}} \quad \Rightarrow \quad \boxed{T_{\text{init}}^3 = \left.\frac{dn_{\text{hadron}}}{dy}\right|_{y=0} \times \frac{k}{4 g_{\text{QGP}} a A \tau_0}}$$

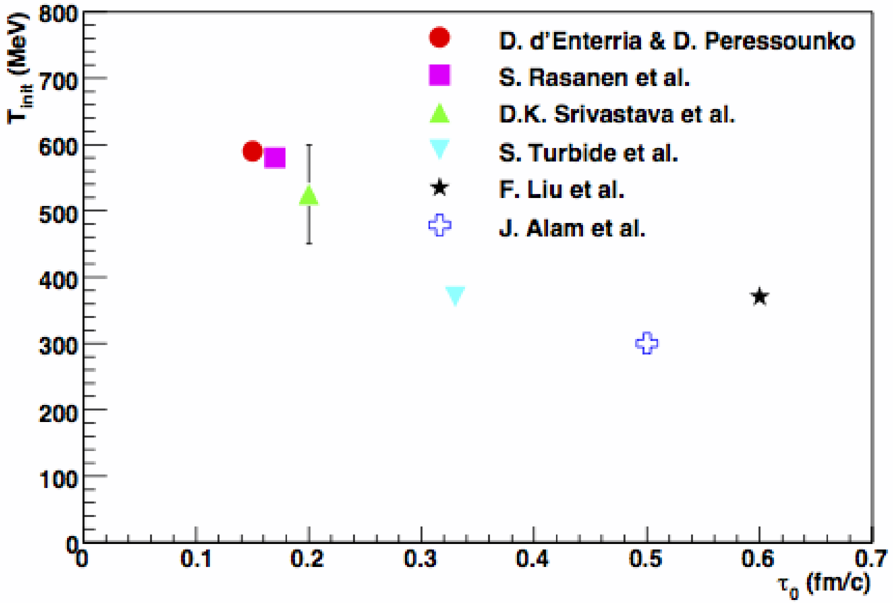
Numerical example (central Au+Au at RHIC):

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

$$T_{\text{init}} = 550\,\text{MeV for } \tau_0 = 0.15\,\text{fm}/c$$

# Direct Photons at RHIC: Initial Temperature from Model comparison

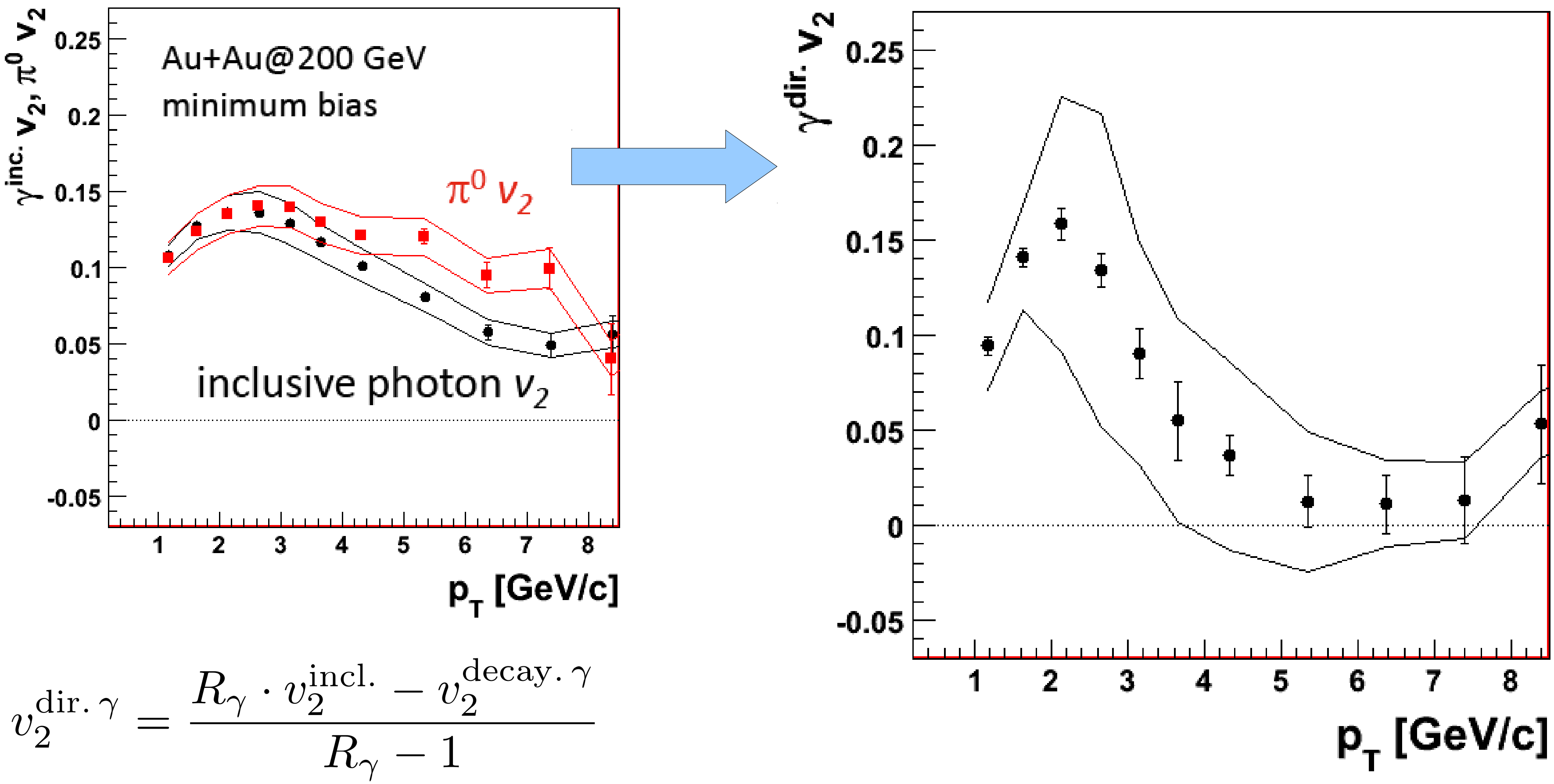



$T_{init}$ = 300 … 600 MeV

# Direct Photon $v_2$ (PHENIX)

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

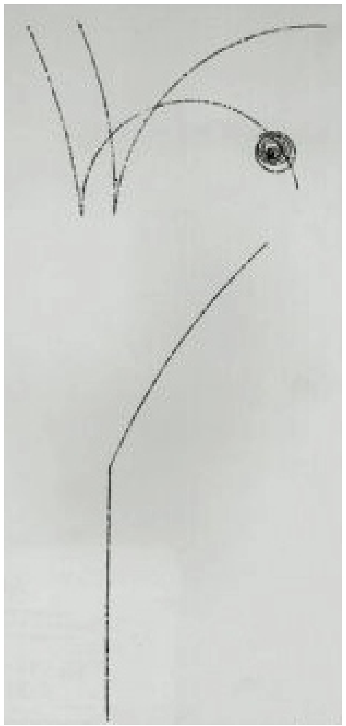



$$v_2^{\text{dir.}\,\gamma} = \frac{R_\gamma \cdot v_2^{\text{incl.}} - v_2^{\text{decay.}\,\gamma}}{R_\gamma - 1}$$

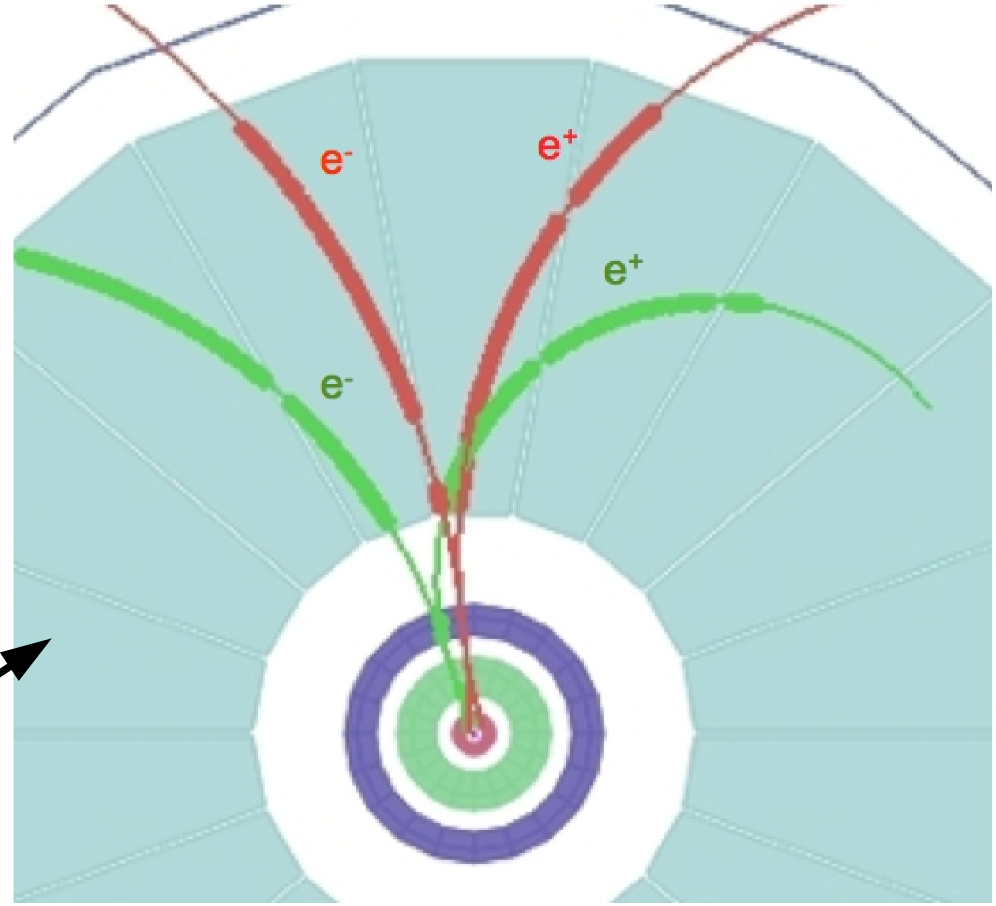
Large direct photon $v_2$ is a challenge to theory because most thermal photons are expected to be created early (when the temp. is largest and) when $v_2$ has not fully built up

# ALICE: Measuring Photons with Conversions

ca. 1950



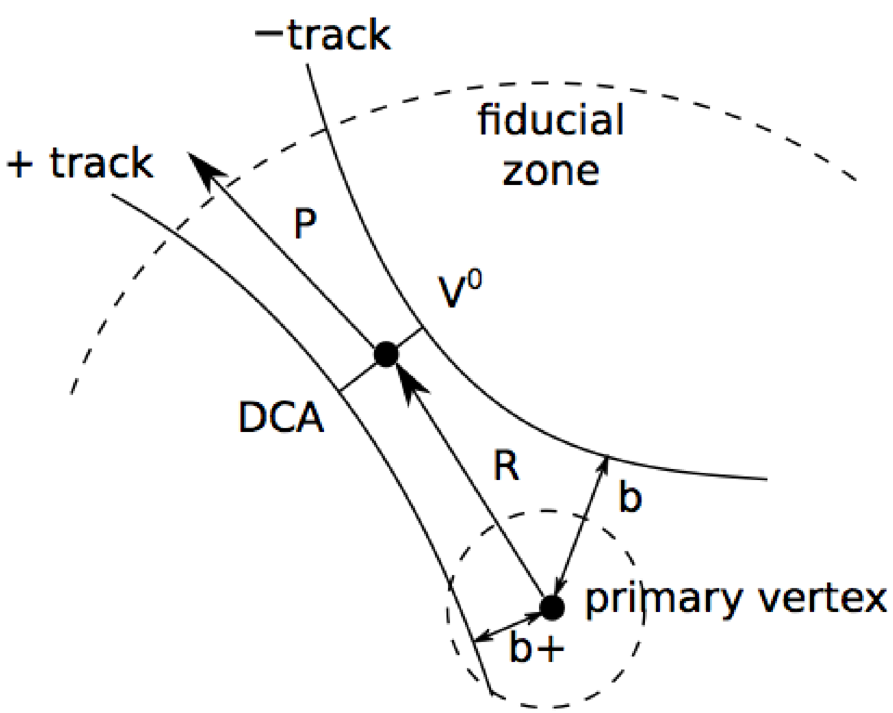
2013




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

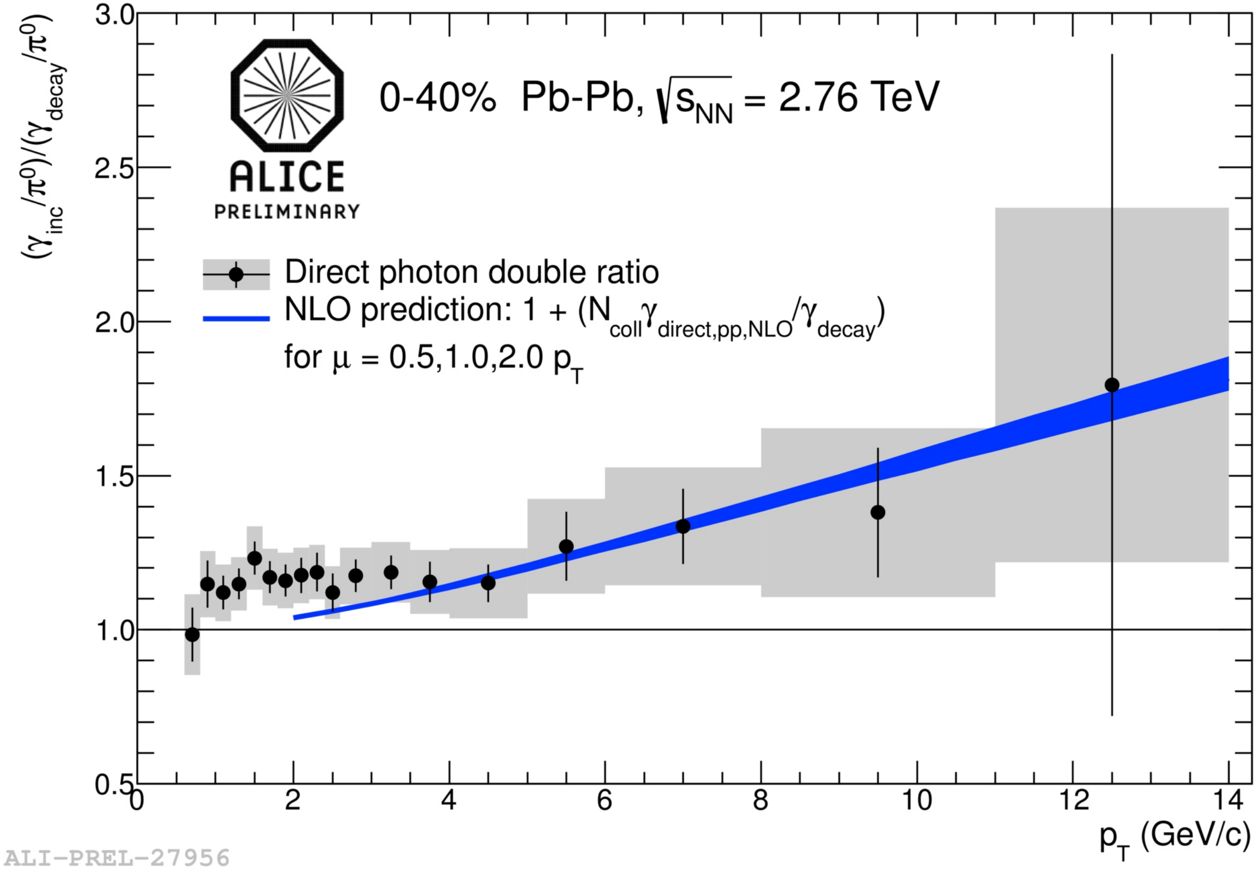
Photon conv. probability in ALICE (for $R$ < 180 cm):
$p_{\mathrm{conv}}$ = 8.5% for $p_T$ > ~3 GeV/$c$

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



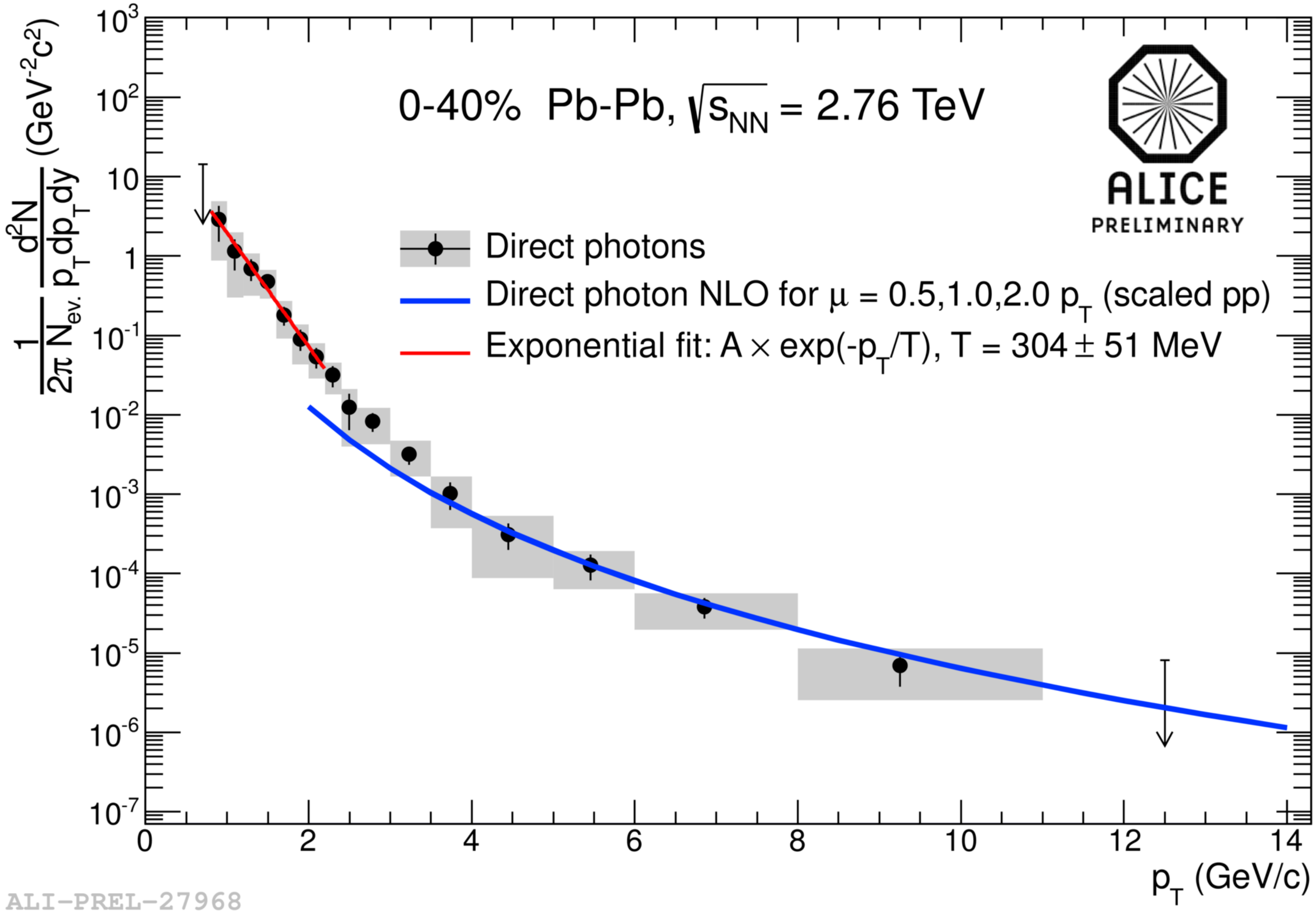

- Consider charged tracks with large impact parameter b
- Accept pairs of such tracks with small distance of closest approach (DCA) as V0
- V0's mainly from
  - $K_s^0 \rightarrow \pi^+\pi^-$ ($c\tau$ = 2.7 cm)
  - $\Lambda \rightarrow p+\pi$ ($c\tau$ = 7.9 cm)
  - converted γ's
- Cuts based on decay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

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

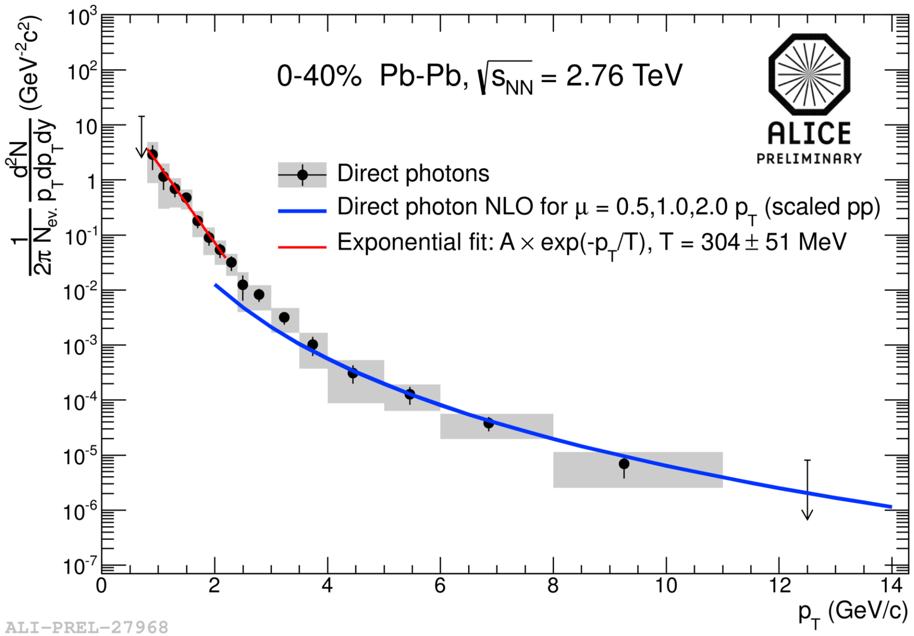



- Photon excess of about 15-20% (for $1 < p_T < 5$ GeV/$c$)
- Comparison with pQCD: Significant thermal photon component below 3 GeV/$c$

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



# An Unsolved Puzzle

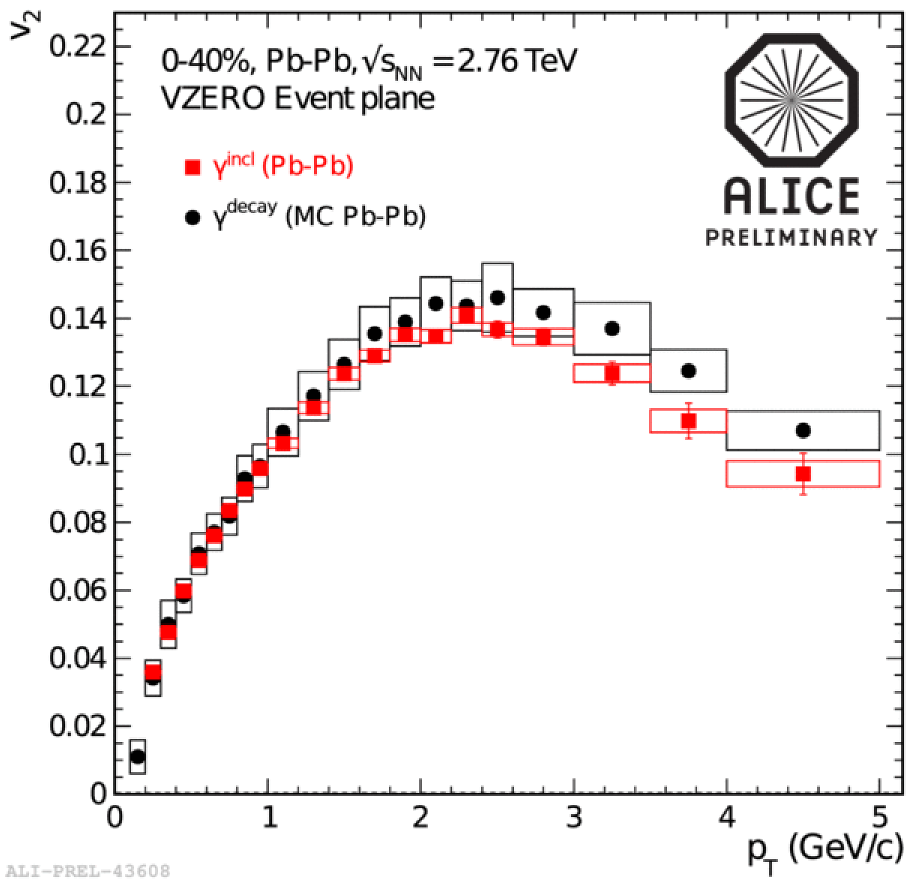



- For a static source inverse slope parameter reflects temperature
- For a moving source the observed inverse slope parameter is also affected by Doppler blueshift:

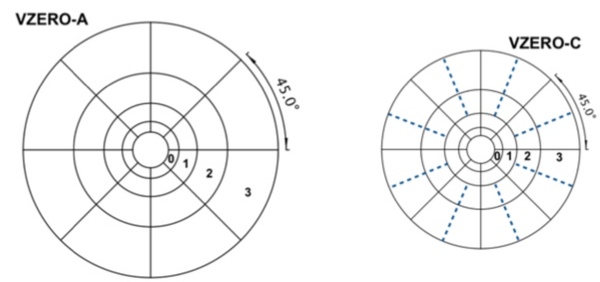
$$T_{\text{slope}} = \underbrace{\sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}}}_{=2 \text{ for } \beta_{\text{flow}}=0.6} \, T$$

- 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)



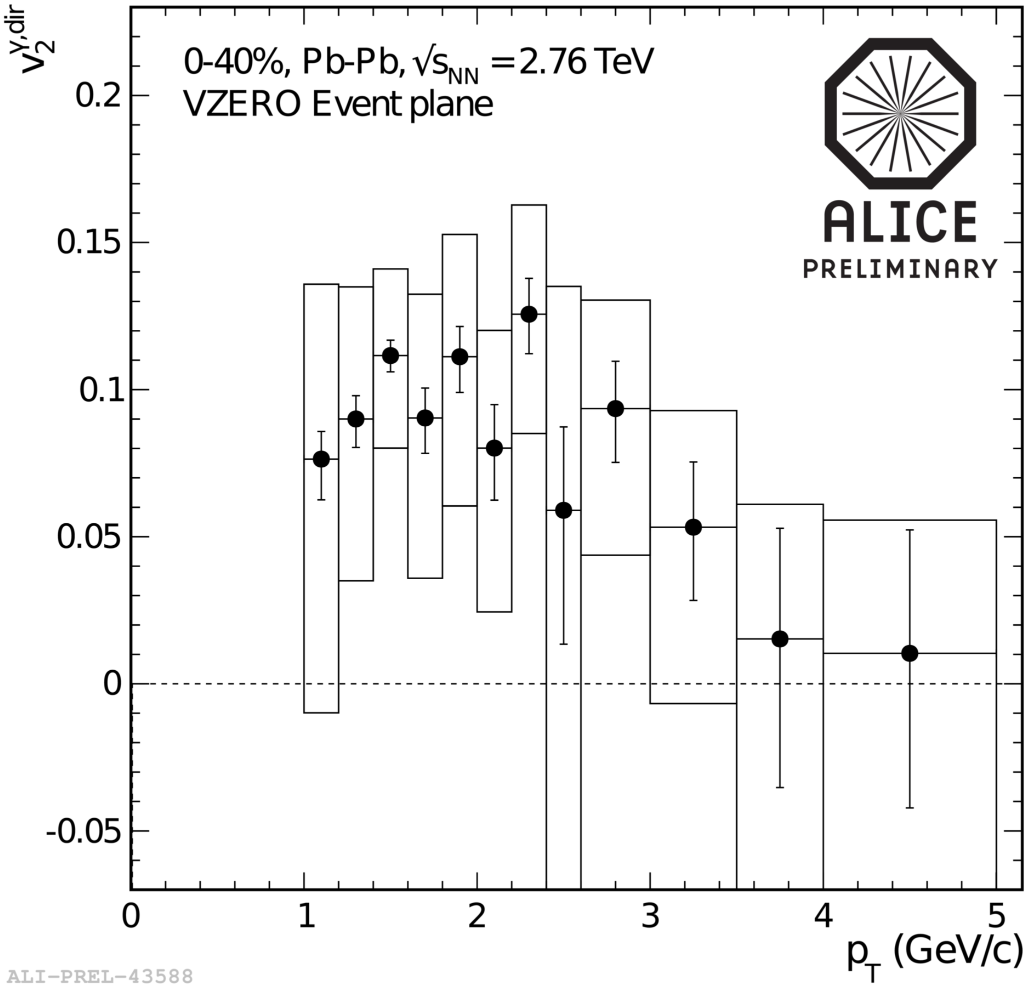

- Event plane from particle anisotropy in VZERO detectors




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

- 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




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

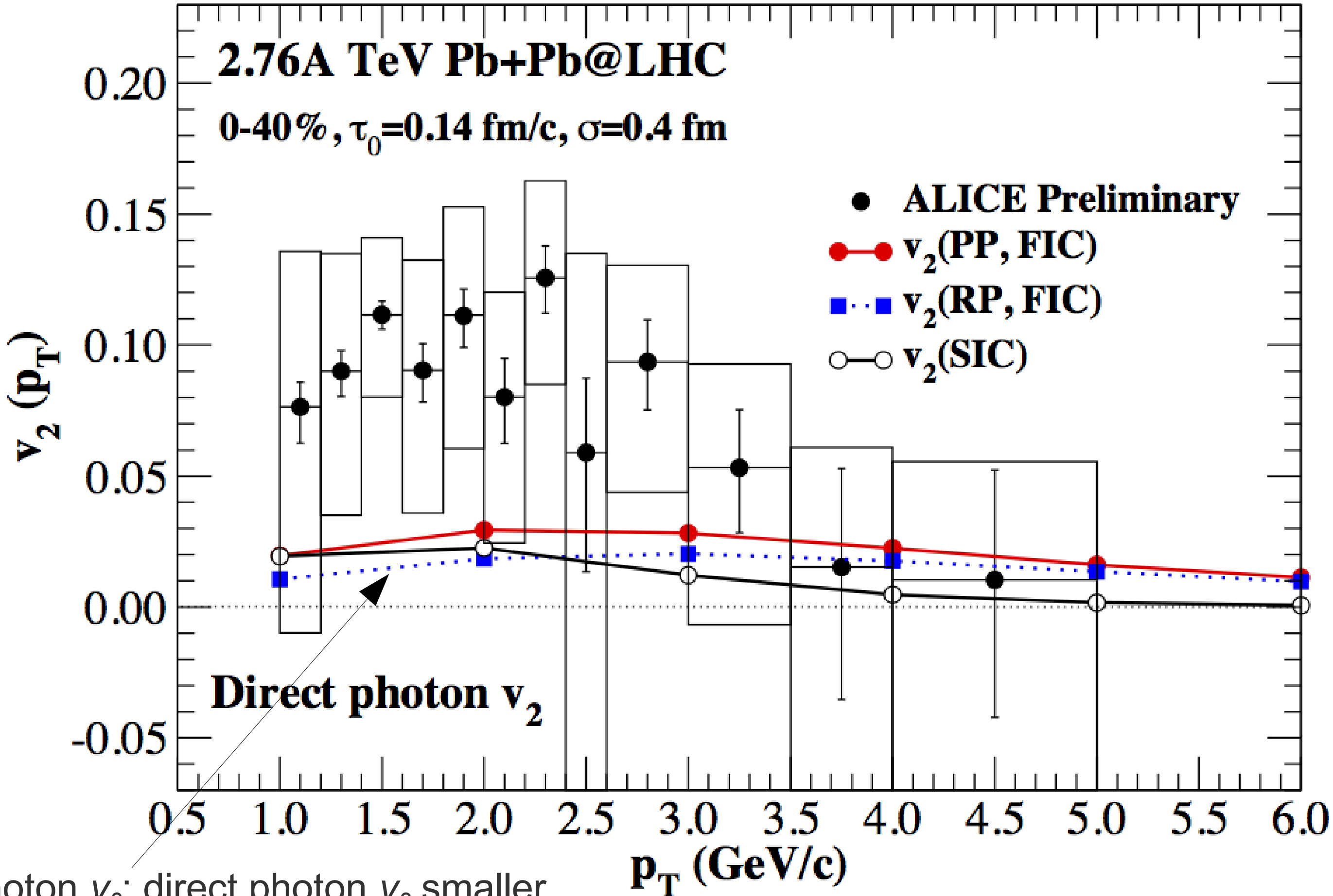
$$\Rightarrow \boxed{v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma v_2^{\gamma,\mathrm{incl}} - v_2^{\gamma,\mathrm{decay}}}{R_\gamma - 1}}$$

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

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

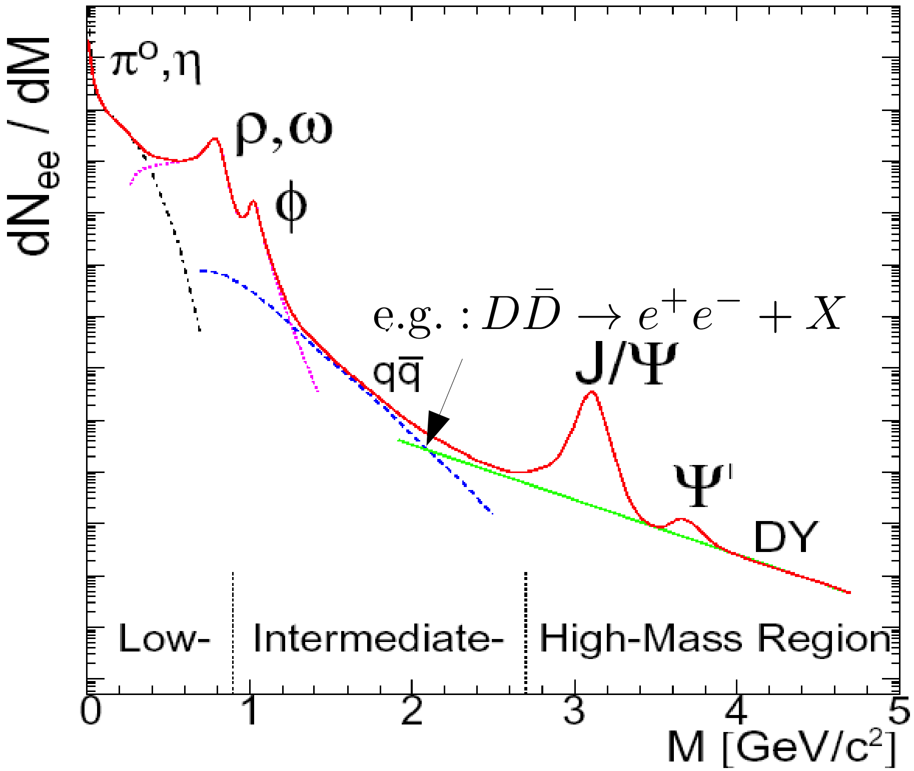
Chatterjee et al., arxiv:1305.6443 (→ link)



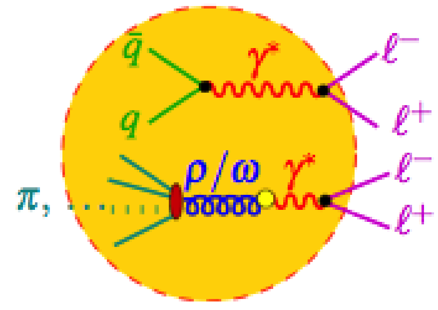

Thermal photon $v_2$; direct photon $v_2$ smaller due to prompt photon component ($v_{2,\text{prompt}} = 0$)

Direct photon $v_2$ data challenge the standard hydro models

# Motivation for Studying Dileptons in Heavy-Ion Collisions

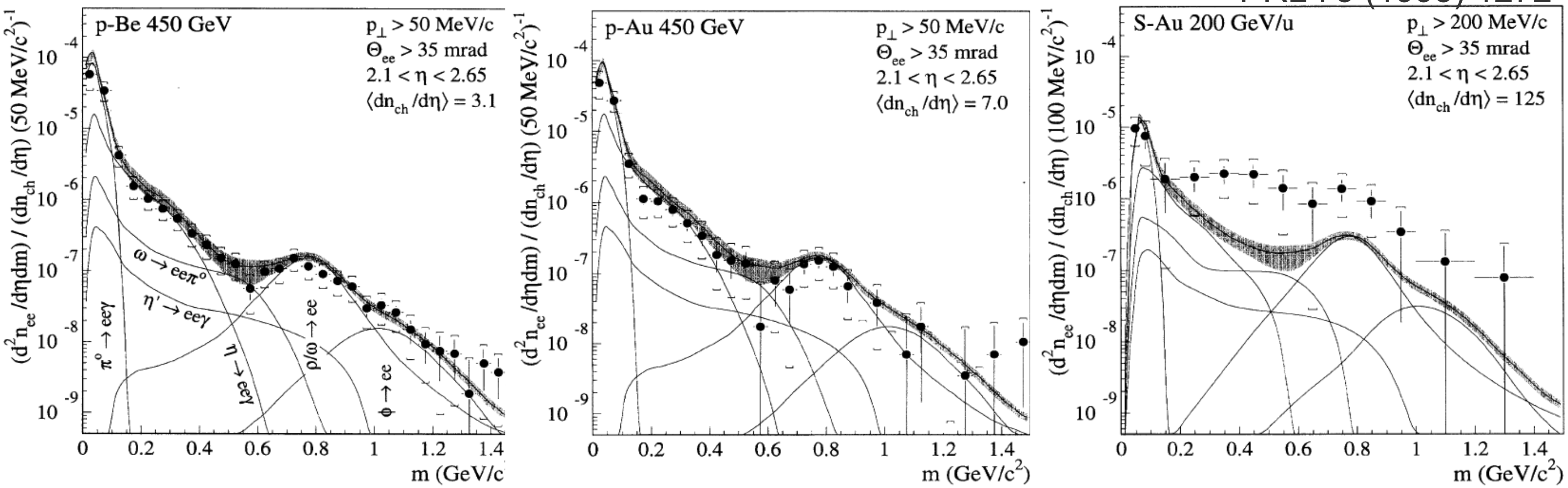



- Search for modifications of vector mesons in the medium
  - Lifetime shorter (ω,ρ) or similar (φ) to that of the medium
  - Broadening vs. mass shift
  - Effects of chiral symmetry restoration?
- Thermal emission (both from QGP and hadronic phase)
- High-Mass region: J/Ψ suppression/enhancement



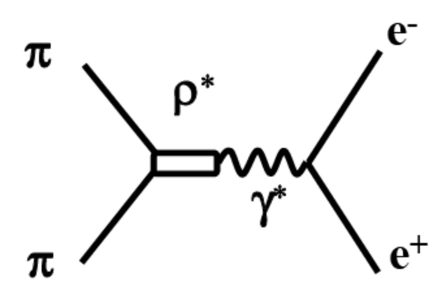
# Discovery of Low Mass Dilepton Enhancement

PRL 75 (1995) 1272




Discovery of low mass dilepton enhancement in 1995

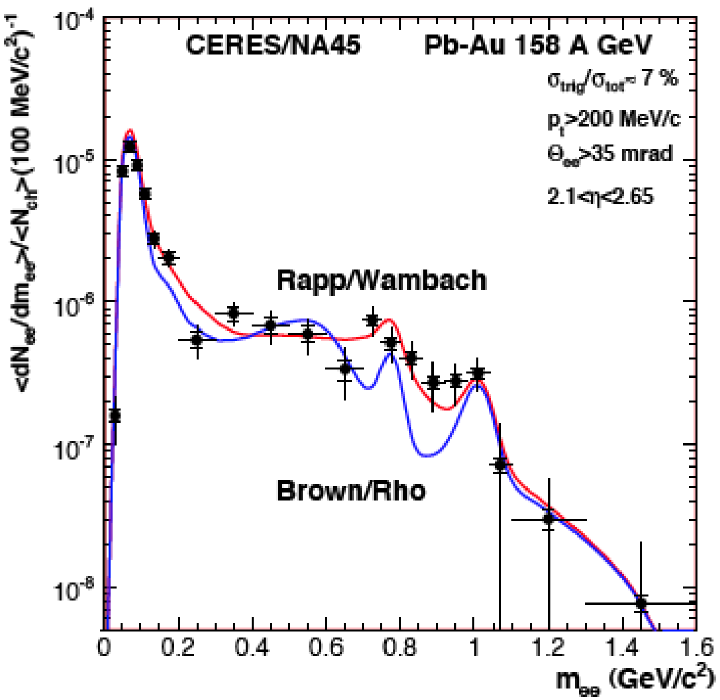
- p-Be and p-Au well described by decay cocktail
- Significant excess in S-Au (factor ~5 for $m$ > 200 MeV)
- Onset at ~ 2 $m_\pi$ suggested π−π annihilation
- Maximum below ρ meson near 400 MeV

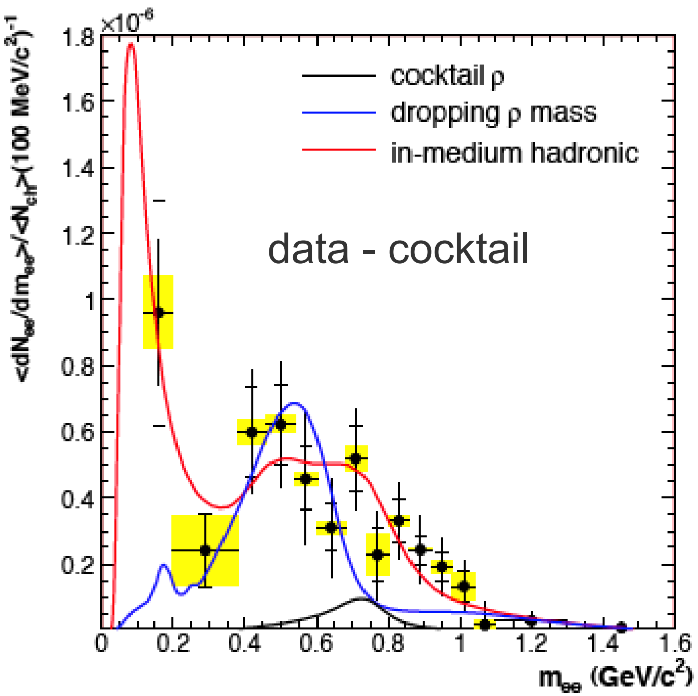



Hints towards modified ρ meson in dense medium

A. Drees,
Hard Probes 2004 (→ link)

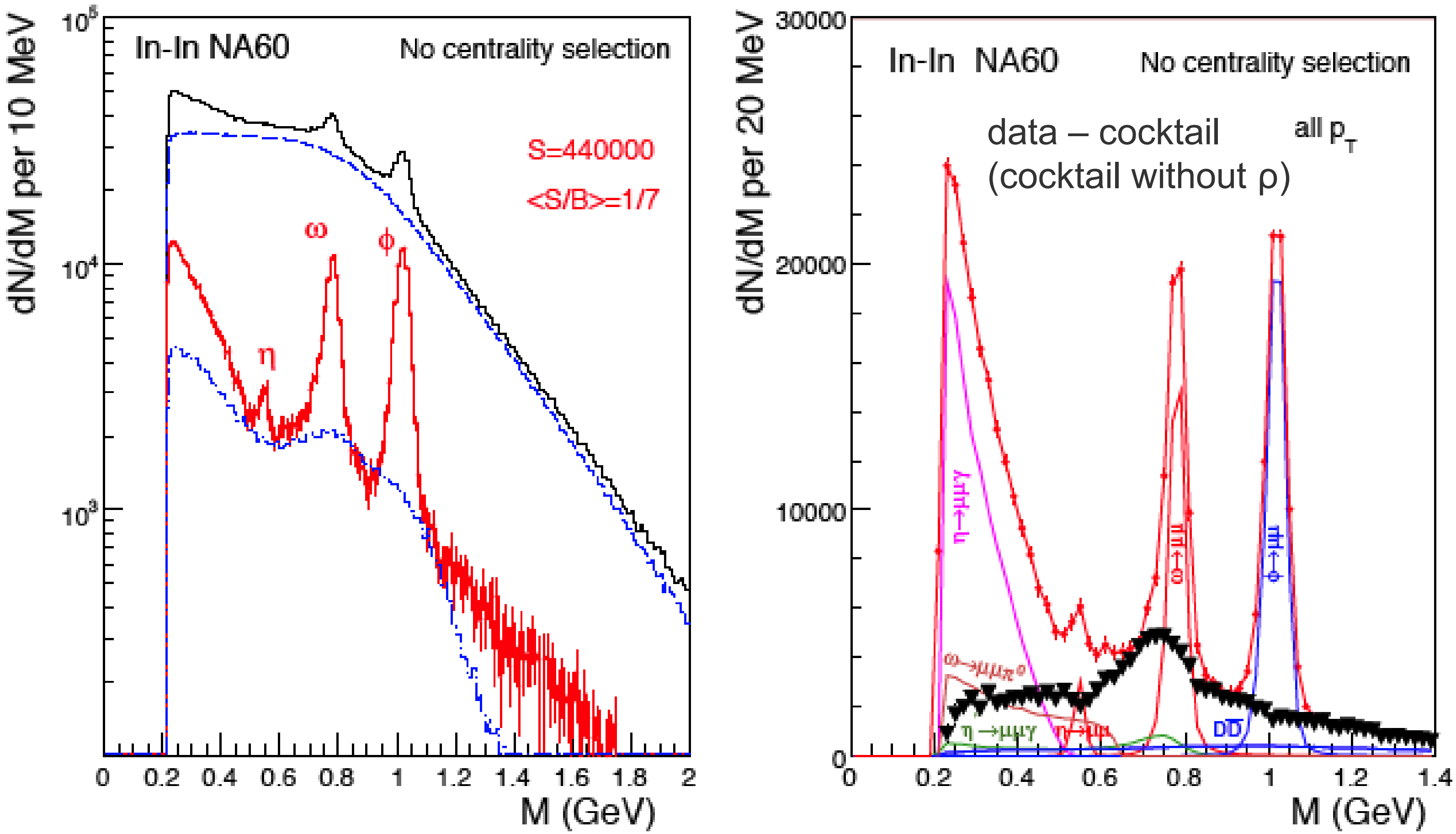
# Dilepton Spectrum in Pb+Pb at 158 *A* GeV (Ceres)



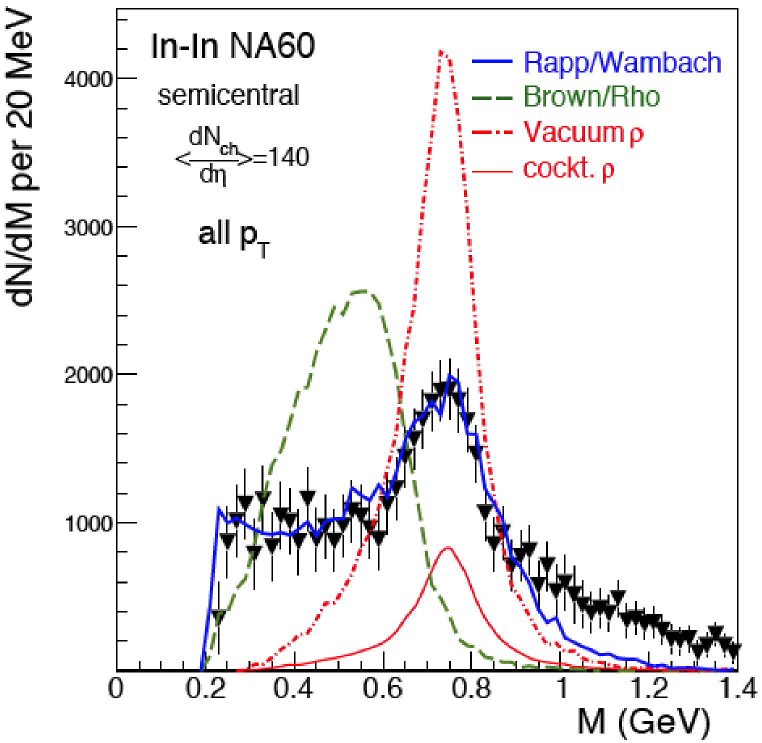




- Di-Electron Excess (factor ~ 2.6) also measured in Pb+Au at 158 *A* GeV
- Even stronger enhancement (factor ~ 5.9) found in Pb+Au at 40 *A* GeV (effect of higher baryon density?)
- Difficult to distinguish between calculations with dropping ρ mass (Brown/Rho) and broadening of the ρ (Rapp/Wambach).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

# Dimuon Data from NA60

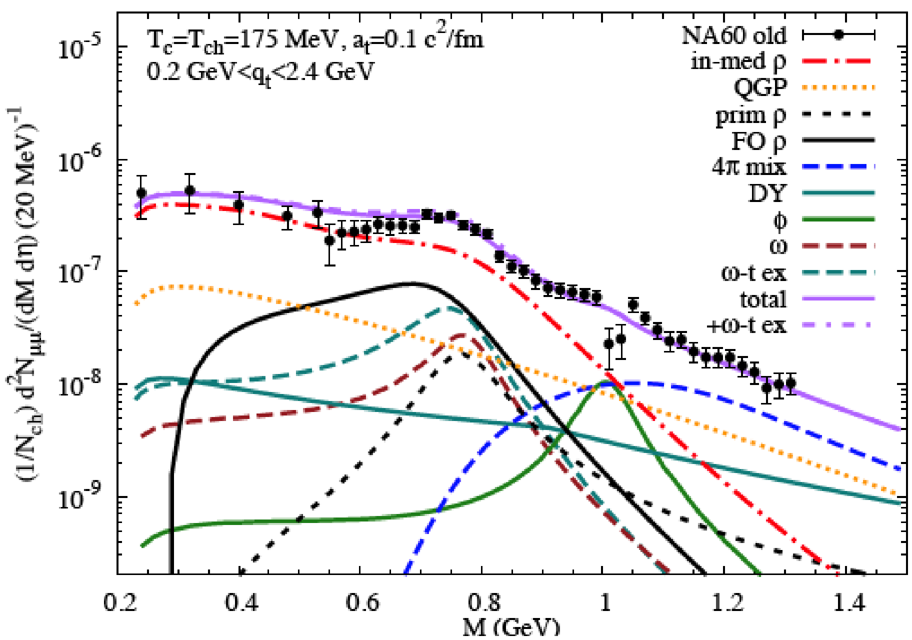


# NA60 Data Described by Broadening of the ρ Meson



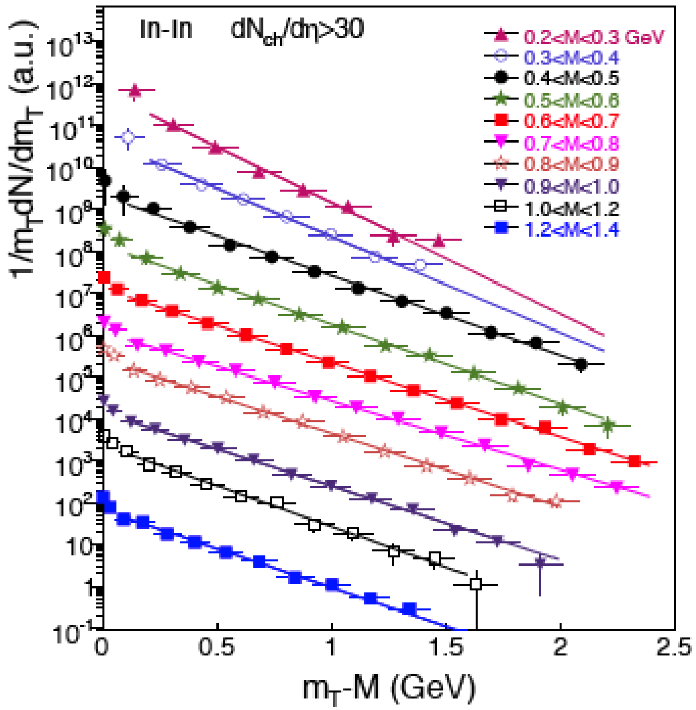

Phys. Rev. Lett. 96 (2006) 162302

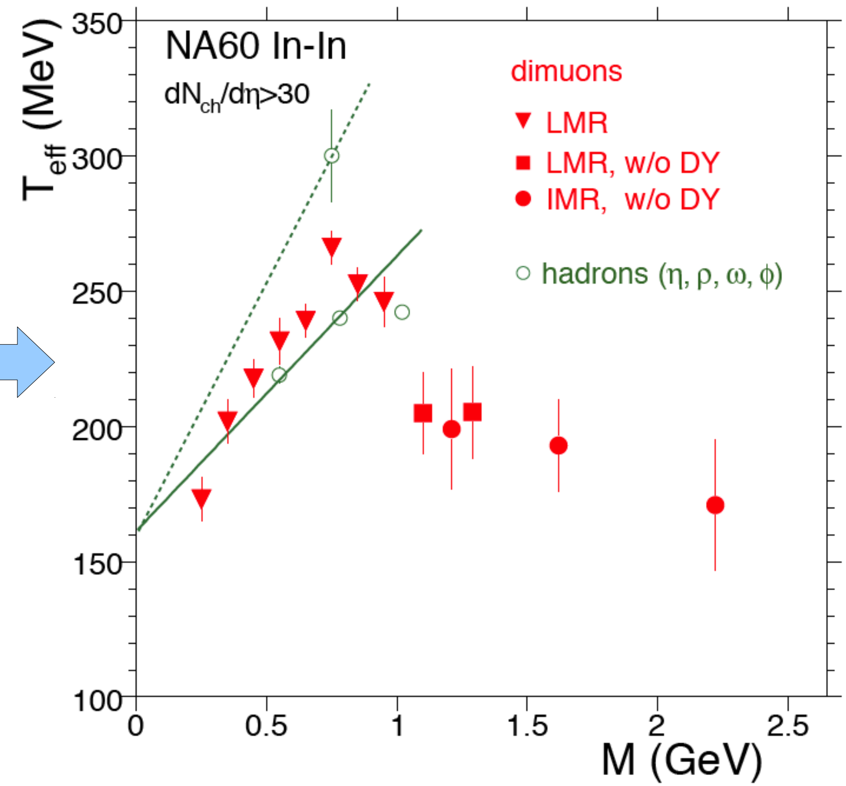
Calculation: Rapp, arXiv:1010.1719




- 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 measurement using the internal conversion method 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