Direct photon production in heavy-ion collisions at NICA and FAIR energies

D. Blau and D. Peresunko, NRC Kurchatov Institute

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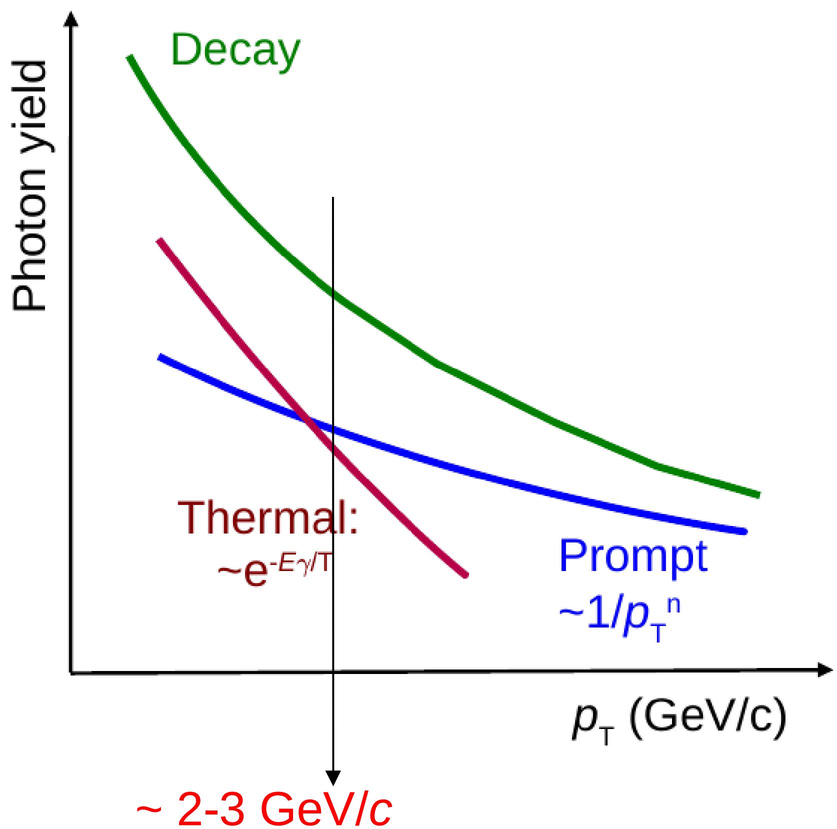
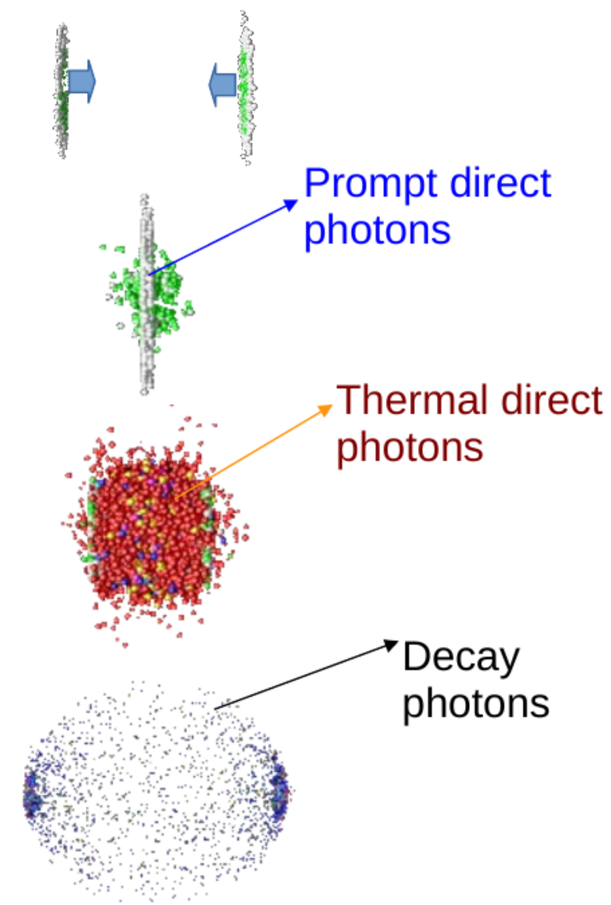
Motivation

- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
- Photons are produced at different collision times
- Photons don't interact strongly and carry out information about collision, even the earliest stage

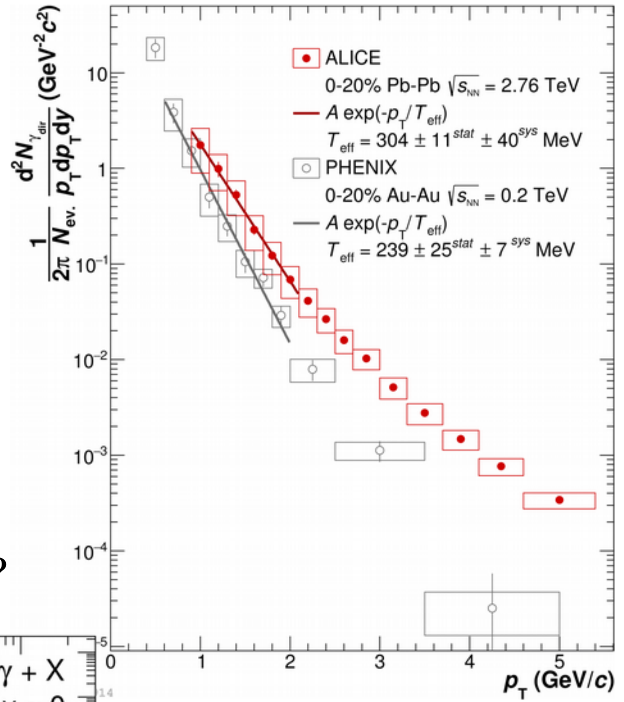


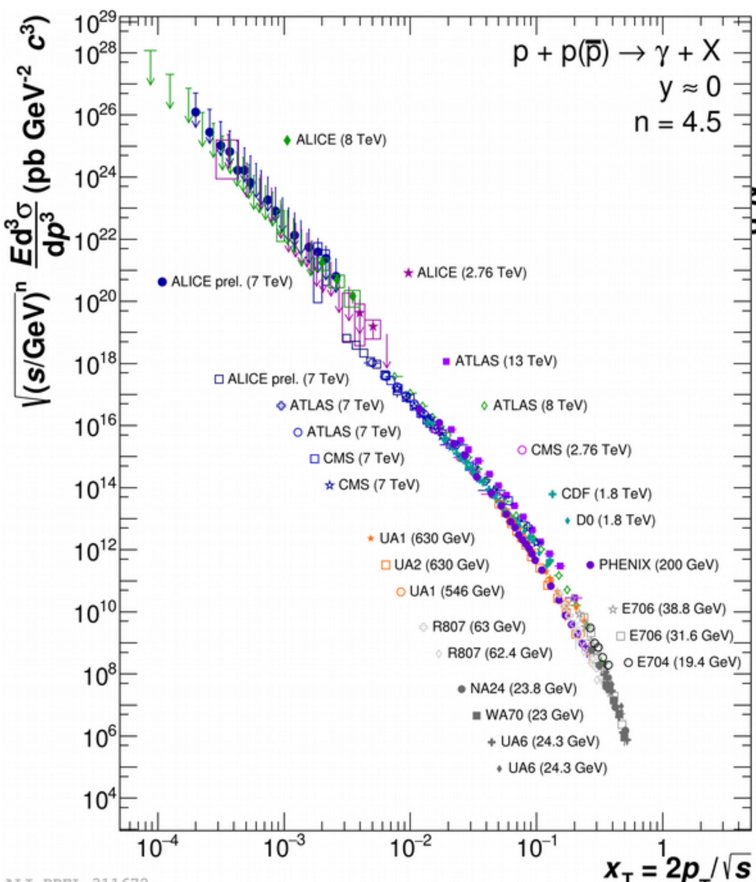


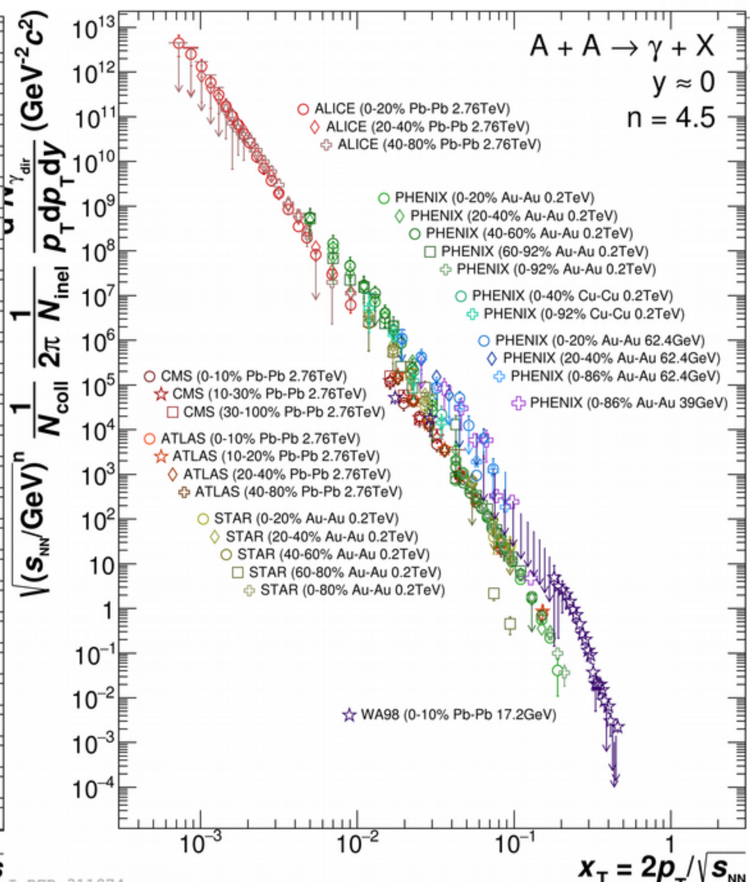
Motivation

What we can study with direct photons:

- ✓ Perturbative QCD (e.g. x_T scaling properties at large x_T)
- ✓ Properties of QGP (e.g. Temperature)
- ✓ Critical point (critical opalescence?)
- ✓ Development of collective effects (v_n coefficients of direct photons)
- ✓ Rapidity dependence on initial stage (not studied before?)



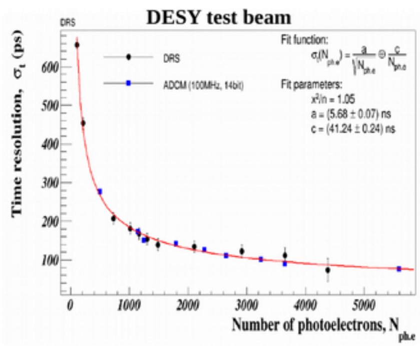


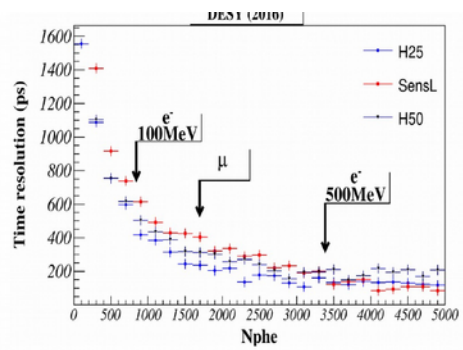


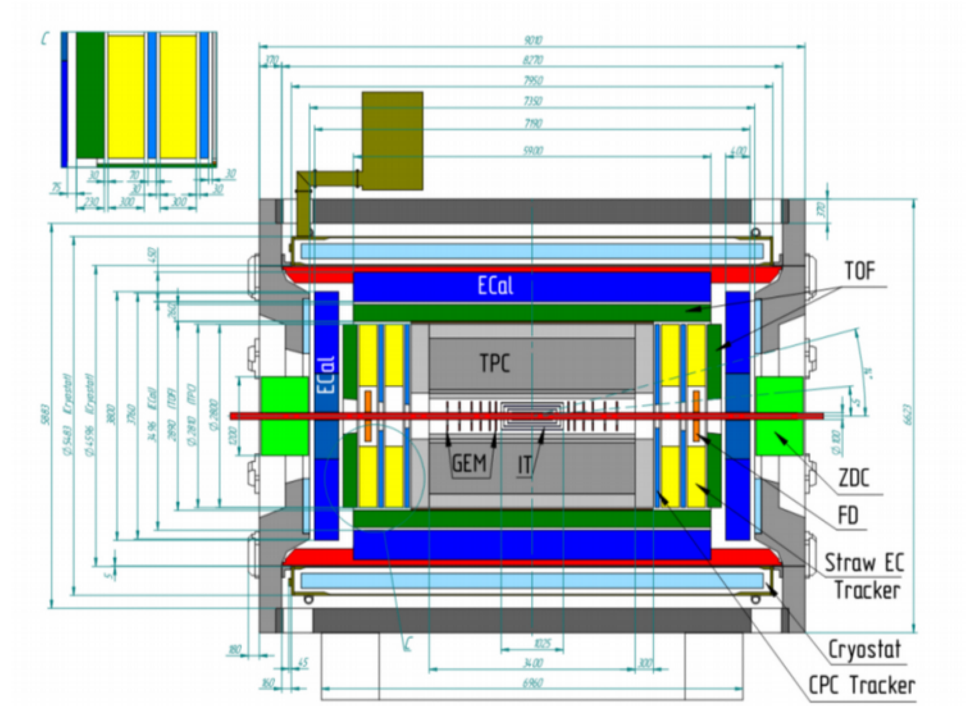
MPD Electromagnetic calorimeter

Advantages of MPD electromagnetic calorimeter:

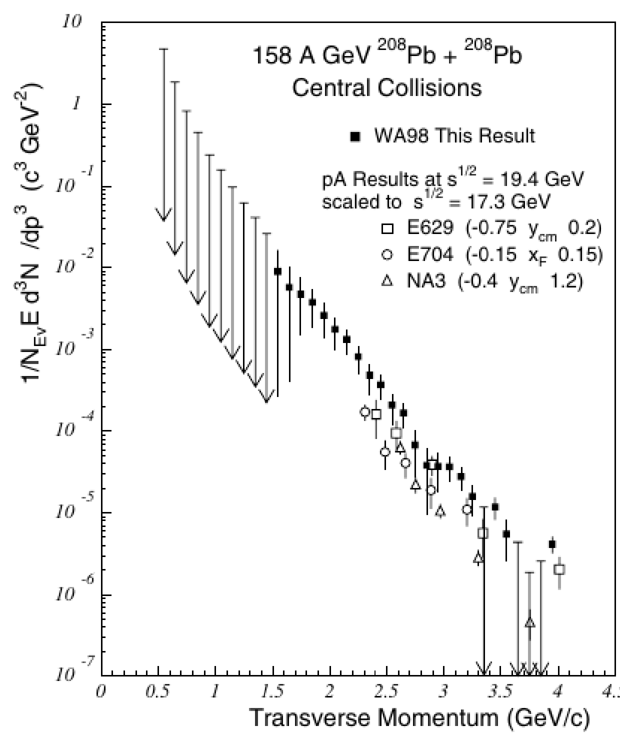
- ✓ Large acceptance (|y|<1.2, full azimuthal angle coverage).
- ✓ Excellent timing resolution (quoted to be ~500 ps at 100 MeV) [1]







- ❑ The only competitors at $\sqrt{s_{NN}} \sim 10$ GeV is SPS experiment WA98 finished about 20 years ago [2][3]



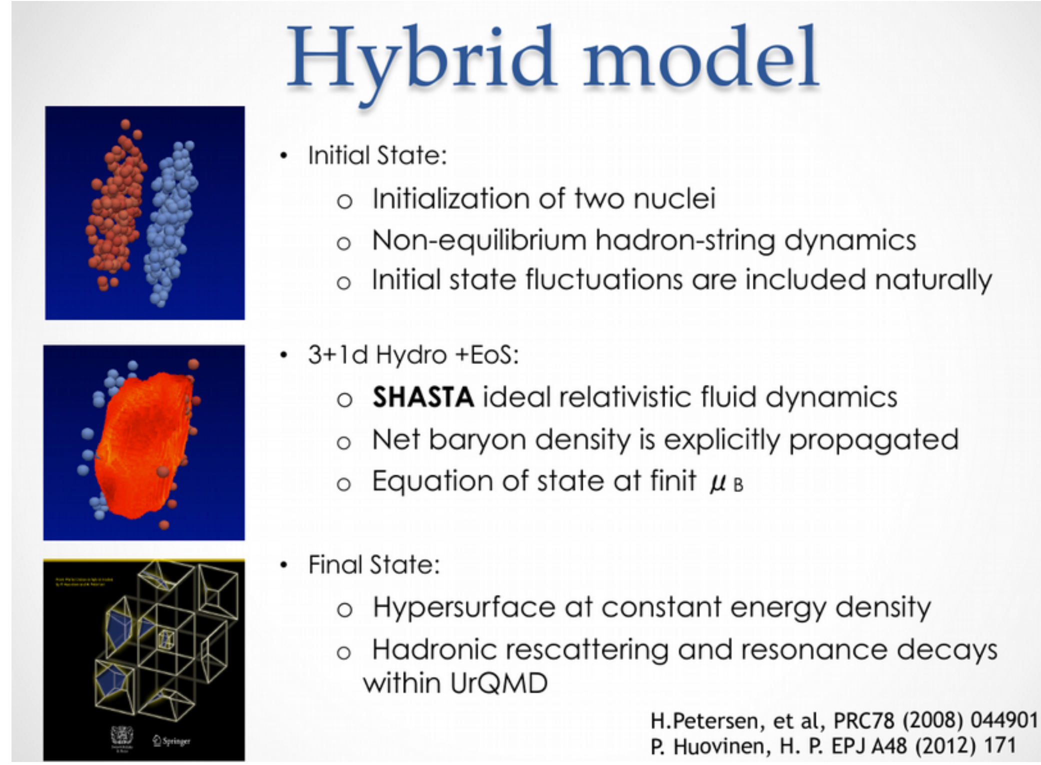
[1] TDR of the Electromagnetic calorimeter (ECal) rev. 3.6 (2018)
[2] M. M. Aggarwal et al, Phys. Rev. Lett. 85, 3595 (2000)
[3] T. Peitzmann, Pramana – J. Phys. V. 60 Issue 4 pp 651-661 (2003)

Our simulations

- Goal: to obtain predictions for future observables based on current knowledge of direct photon rates from hot hadronic matter and state-of-the-art hydrodynamic calculations

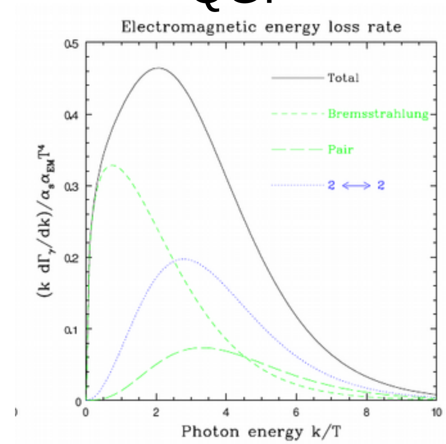
- Studies at SPS energy [1]

- Our simulation setup:
  - UrQMD v3.4 with hybrid model (3+1d hydro, bag model EoS, hadronic rescattering and resonances within UrQMD)
  - Parameterizations of thermal radiation from hadron gas [2] and QGP [3]
  - π^0 yield is calculated with UrQMD hydro mode off (cto 45 0).
  - Calculations are done at fixed b = 4.5 fm

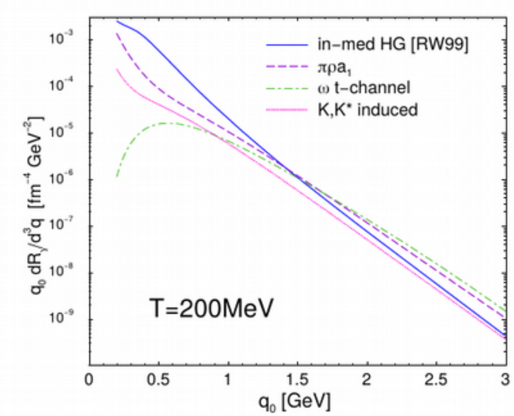


Direct photon rate parameterizations from theoretical models:

QGP



Hadron gas

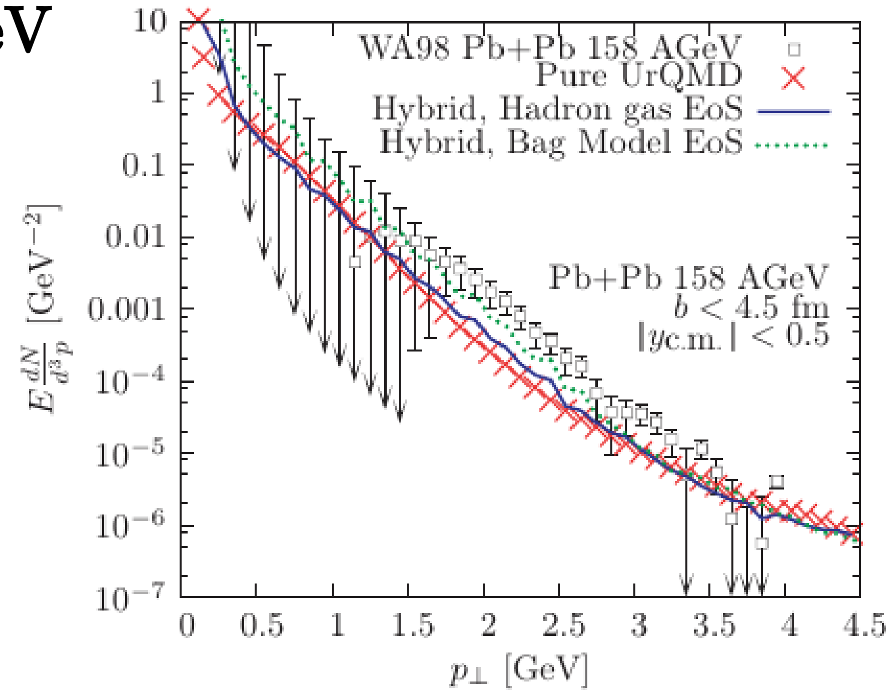


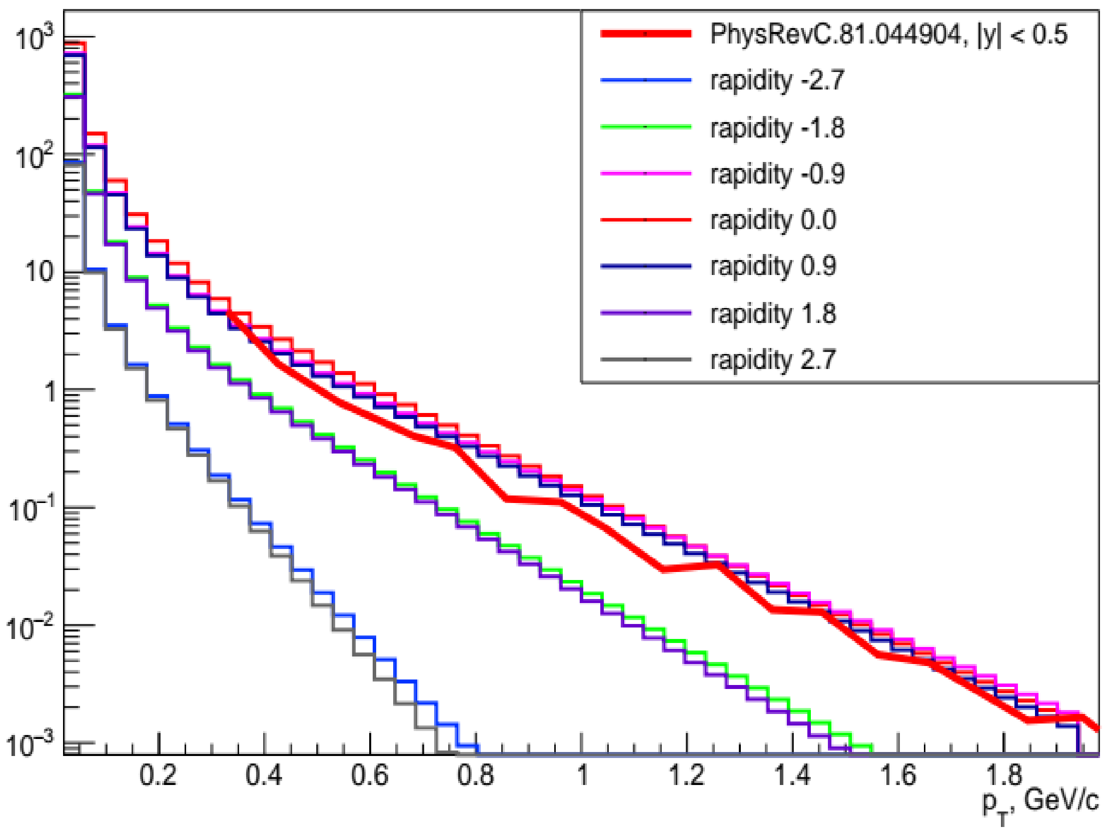
[1] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[2] S. Turbide, R. Rapp, and C. Gale, Phys. Rev.C 69(2004) 014903
[3] P. Arnold, G. D. Moore, L. G. Yaffe, JHEP12(2001) 009

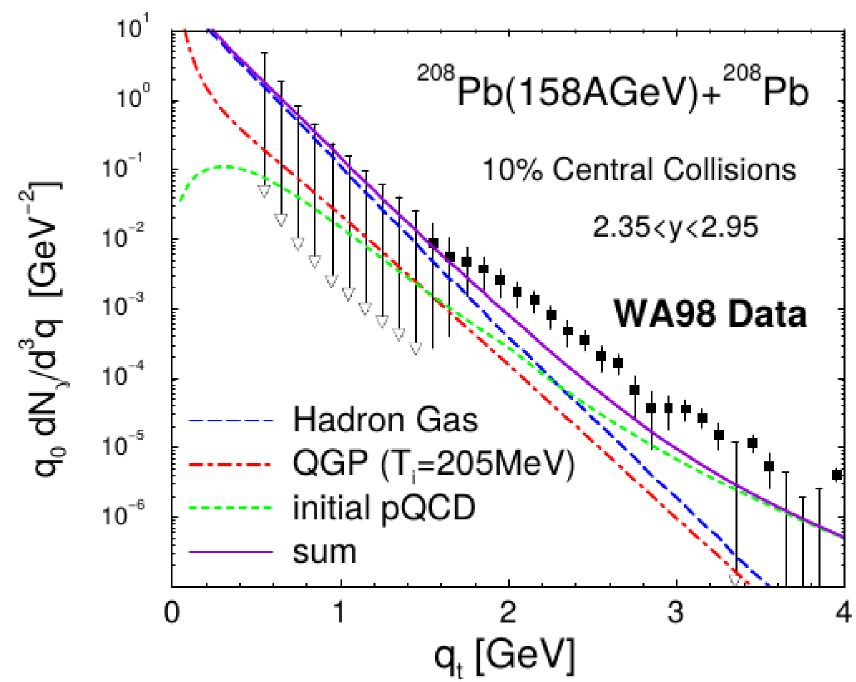
Calculations for Pb-Pb at $\sqrt{s_{NN}}$=158 AGeV

Compare thermal gamma yields with previous calculation from [1] and [2]. In our calculations same cuts on rapidity and impact parameter is made, but small changes in rate formula exists

Good agreement with previous calculations.
All models tend to underestimate data!





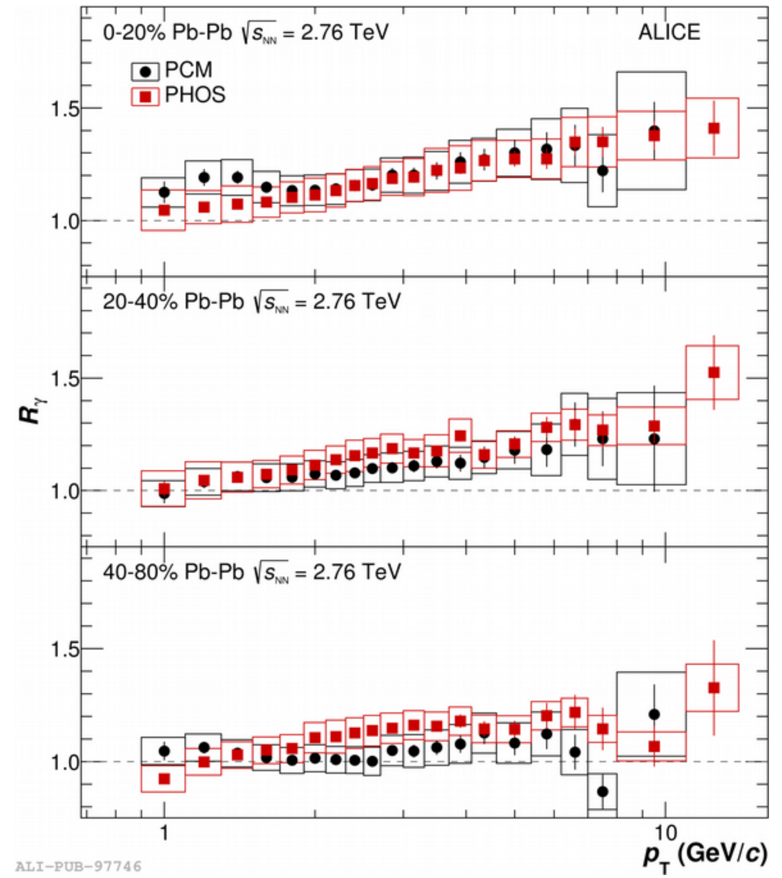


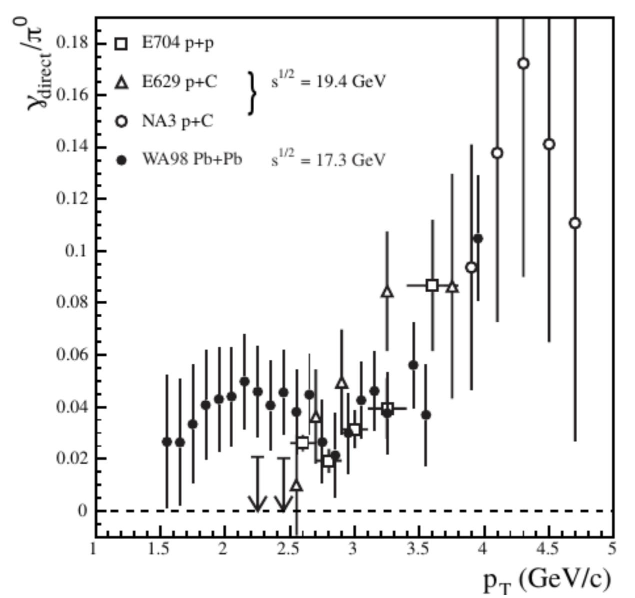
[1] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[2] S. Turbide, R. Rapp, and C. Gale, Phys. Rev.C 69(2004) 014903

Ratio to π^0 yield

- The key question: whether we can measure direct photon with MPD?
- The main challenge is to measure small signal from the inclusive photons spectrum (decay photons + direct photons).
- Fraction of direct photons should be larger than expected systematic uncertainties.

- R_γ ratio – ratio of inclusive photon spectrum to decay photons spectrum. If direct photons are there, it is above 1.
- In ALICE (Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV) R_γ is about 5-10% at 1 GeV/c [1] (note that above 3 GeV/c main contribution is from prompt photons). Syst. uncertainties on the same level.
- In WA98 (Pb-Pb at $\sqrt{s_{NN}}$=17.2 GeV) γ^{dir}/π^0 on the level of 4% at 2 GeV/c [2].

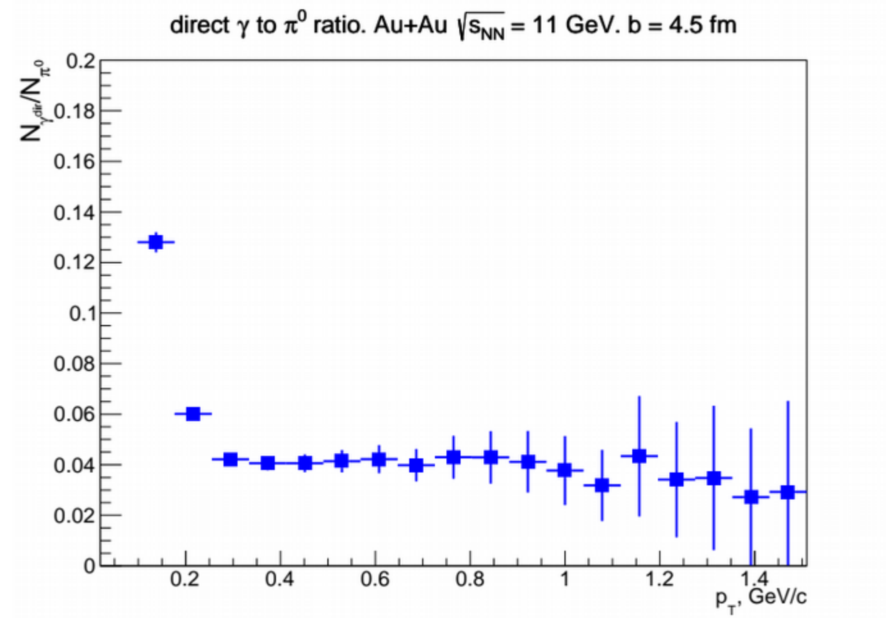


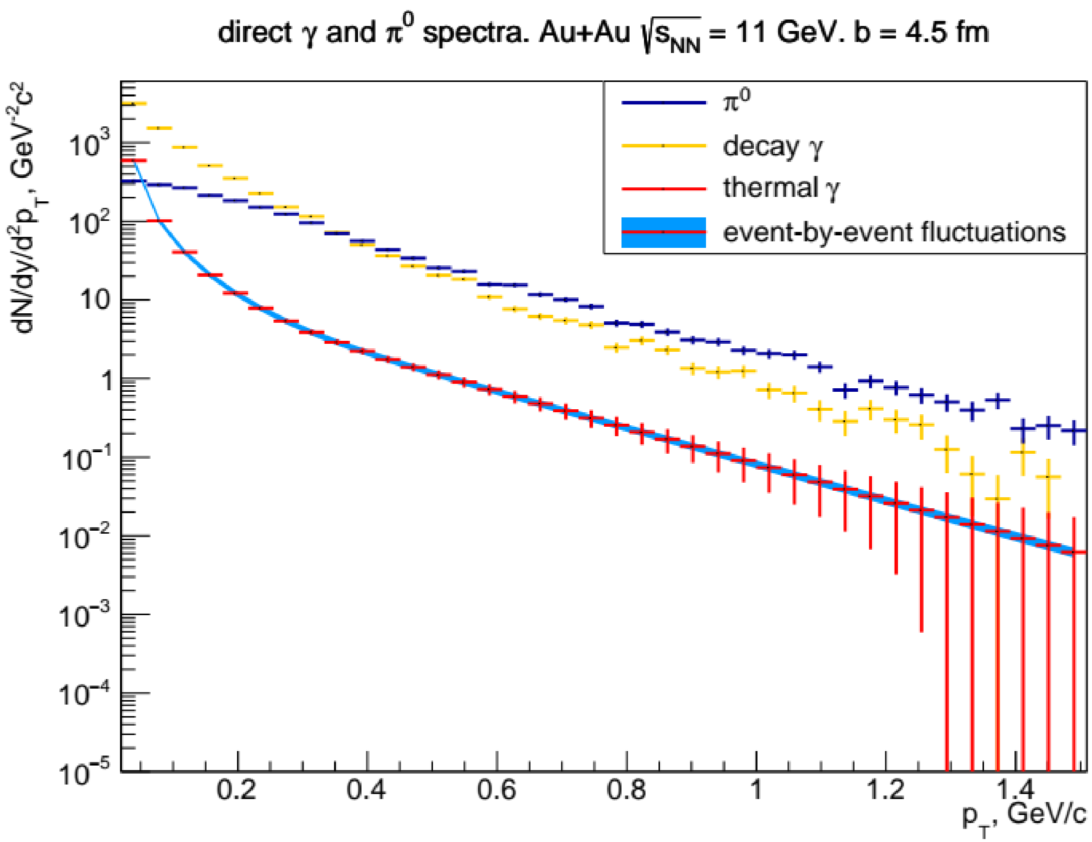


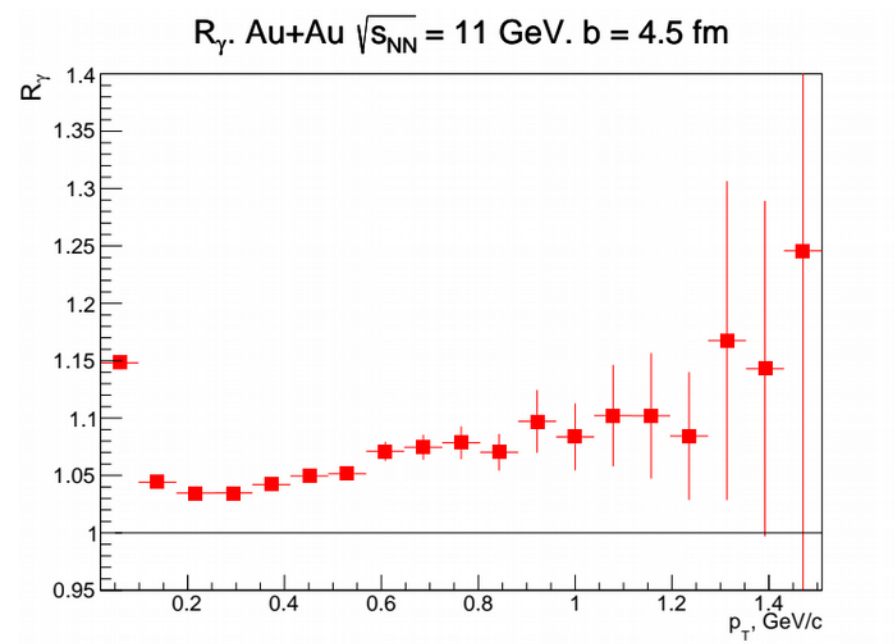
[1] J. Adam et al. (ALICE Collaboration) Phys. Lett.B 754(2016) 235-248
[2] T. Peitzmann, Pramana – J. Phys. V. 60 Issue 4 pp 651-661 (2003)

Calculations at $\sqrt{s_{NN}}$ = 11 GeV

- Despite lower direct gamma yield, ratio γ/π^0 is similar to WA98 results.
- R_γ is ~ 5-10% at 1 GeV/c – looks feasible to measure!
- Fluctuations due to initial conditions are relatively small (20-30%)
- Statistical uncertainty in direct γ: 50 events
- Statistical uncertainty in π^0: 1000 events

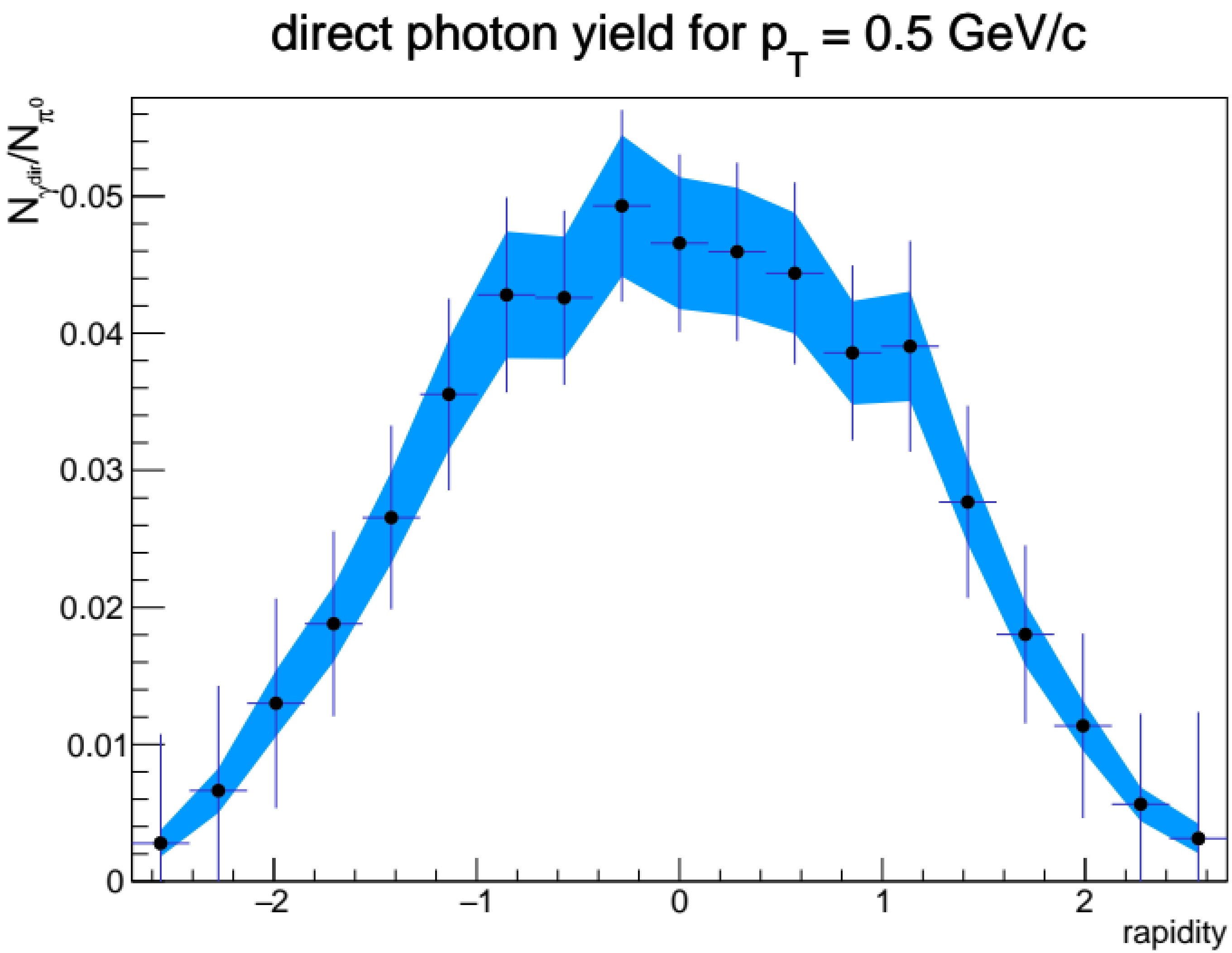






Calculations at $\sqrt{s_{NN}} = 11$ GeV

- Rapidity dependence of direct gamma to π^0 ratio.
- Can we for the first time measure rapidity dependence of direct photon yield?
- Would be very exciting!



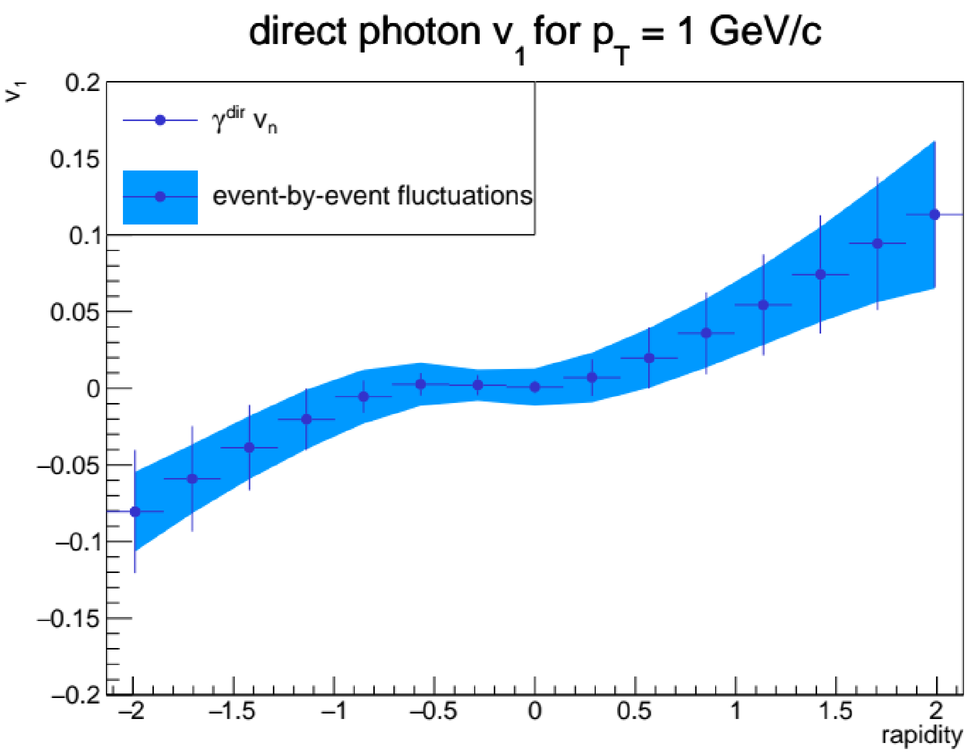
Calculations at $\sqrt{s_{NN}} = 5$ GeV

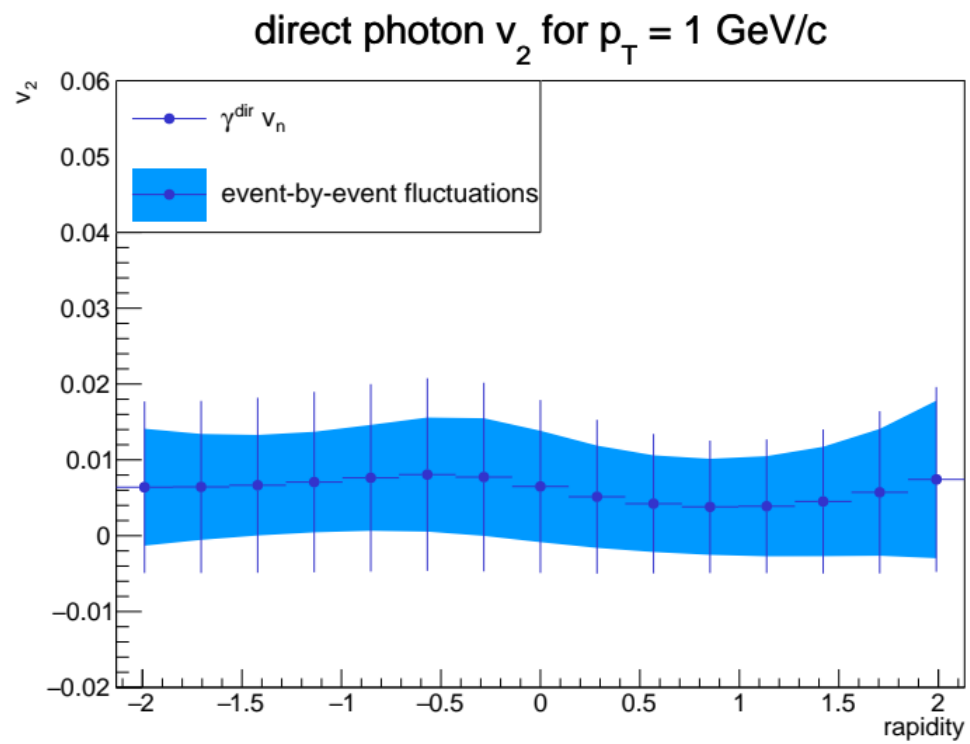
- Will be added later

Collective flow of direct γ at $\sqrt{s_{NN}} = 11$ GeV

Direct photon flow puzzle: flow of direct photons is large (close to the flow of hadrons) which is difficult to explain within current theoretical models.
We look at anisotropy of direct photon yield using UrQMD in hydro mode...

- ✓ v_1 similar to those of hadrons
- ✓ v_2 2-3 times smaller (consistent with predictions at other energies)





Conclusions

- Direct photon simulations using UrQMD are performed and tested for **SPS energy 158 AGeV**, compared to **WA98** results and previous simulations.

- Results of direct gamma spectrum predictions at NICA **top energy** (√sNN = **11 GeV**) and NICA **low energy** / FAIR **top energy** (√sNN = **5 GeV**).

- **Direct γ to π^0 and R_γ ratios** are calculated. R_γ is about 5-10% at 1 GeV for √sNN = **11 GeV**. Measurement of direct gamma at NICA looks feasible.

- Direct γ **yield** and v_n coefficients dependence on **rapidity** are shown. v_1 is similar to those of hadrons. v_2 is 2-3 times smaller (consistent with simulations at high energies).

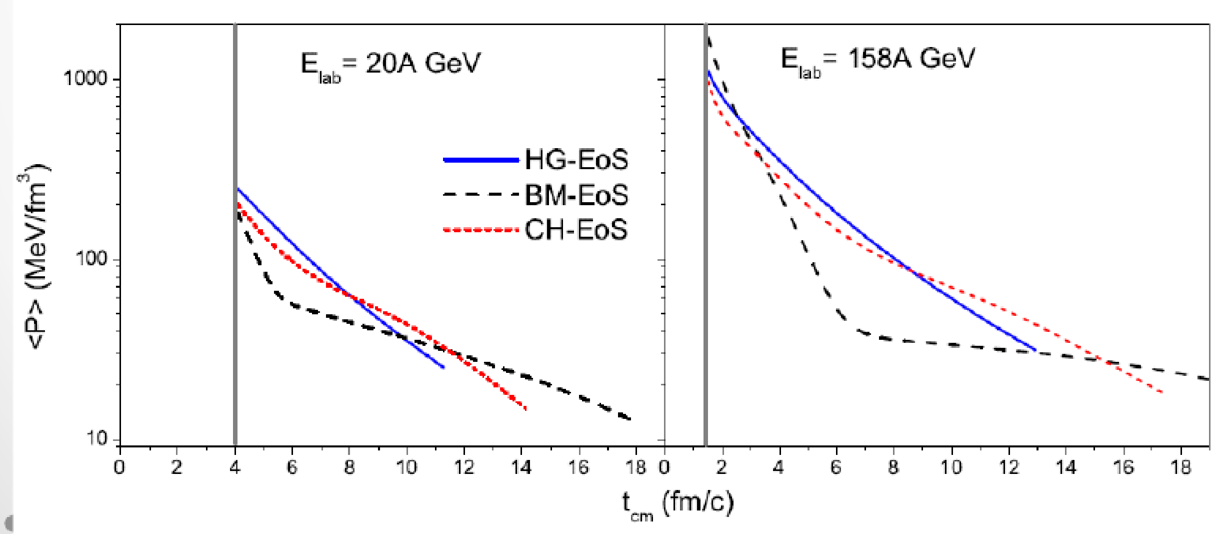
Backup

Hybrid model details: Equations of State

Ideal relativistic one fluid dynamics:

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu (n u^\mu) = 0$$

- HG: **Hadron gas** including the same degrees of freedom as in UrQMD (all hadrons with masses up to 2.2 GeV)
- CH: **Chiral EoS** from quark-meson model with first order transition and critical endpoint (most realistic)
- BM: **Bag Model EoS** with a strong first order phase transition between QGP and hadronic phase



D. Rischke et al., NPA 595, 346, 1995,

D. Zschiesche et al., PLB 547, 7, 2002

Papazoglou et al., PRC 59, 411, 1999

J. Steinheimer, et al., J. Phys. G38 (2011) 035001

M.Bleicher

Ingredients: QGP rate

"Photon Emission from Quark-Gluon Plasma: Complete Leading Order Results"
Peter Arnold, Guy D. Moore, Laurence G. Yaffe JHEP 0112:009,2001

For the convenience of readers interested in just the bottom line, we summarize our results here. The complete leading-order photon emission rate may be written as

$$\nu_e(\mathbf{k}) = \mathcal{A}(k)\left[\ln(T/m_\infty) + C_{\rm tot}(k/T)\right], \tag{1.7}$$

with

$$C_{\rm tot}(k/T) \equiv \tfrac{1}{2}\ln(2k/T) + C_{2\leftrightarrow 2}(k/T) + C_{\rm brem}(k/T) + C_{\rm annih}(k/T), \tag{1.8}$$

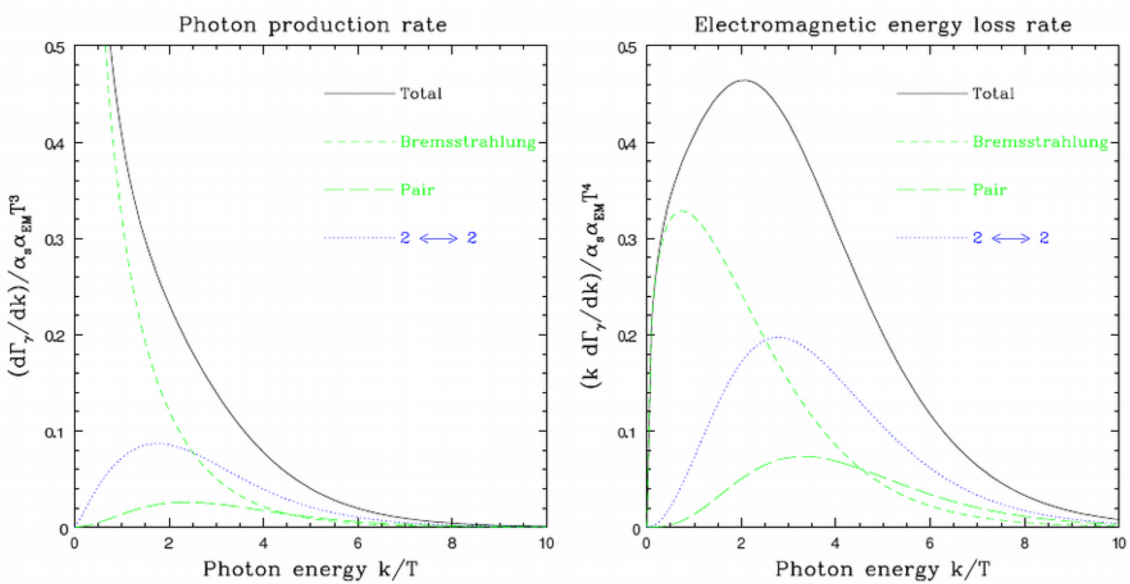


FIG. 9. Total photon emission rate, together with the bremsstrahlung, inelastic pair annihilation and $2 \leftrightarrow 2$ contributions, for two-flavor QCD with $\alpha_s = 0.2$. The left panel shows $d\Gamma_\gamma/dk$, divided by $\alpha_s\,\alpha_{\rm EM}\,T^3$, while the right panel shows rates weighted by photon energy.

Ingredients: hadronic rate

“Hadronic Production of Thermal Photons”
Simon Turbide, Ralf Rapp, Charles Gale Phys.Rev.C69:014903,2004

APPENDIX A: PARAMETERISATIONS

The photon emission rates have been calculated from the Lagrangian describe in Sec. II and by the VMD interaction

$$\mathcal{L}_{em} = -Cm_\rho^2 A^\mu \rho_\mu^0 \qquad \text{(A1)}$$

where A^μ is the photon field and C is a constant adjusted by the experimental decay $\rho^0 \to e^+e^-$, which gives C=0.059. In order to respect the Ward Identity in a direct way, we multiply each Feynman amplitude by the square of the averaged space-like form factor of Eq. (10). Time-like form factors have been defined to be normalised to one for on-shell decays. We quote below parametrisations which include the axial meson a_1 as exchange particle for non-strange initial states. In the following, the photon energy (E) and the temperature (T) are both in GeV. Parameterisations for $K^* \to K + \pi + \gamma$ and $K + K \to \rho + \gamma$ do not appear because their rates have been found to be negligible.

$$E\frac{dR_{\pi+\rho\to\pi+\gamma}}{d^3p} = F^4(E)\,T^{2.8} exp\left(\frac{-(1.461T^{2.3094}+0.727)}{(2TE)^{0.86}} + (0.566T^{1.4094} - 0.9957)\frac{E}{T}\right)\ (\text{fm}^{-4}\text{GeV}^{-2}) \qquad \text{(A2)}$$

$$E\frac{dR_{\pi+\pi\to\rho+\gamma}}{d^3p} = F^4(E)\,\frac{1}{T^5} exp\left(-(9.314T^{-0.584} - 5.328)(2TE)^{0.088} + (0.3189T^{0.721} - 0.8998)\frac{E}{T}\right) \qquad \text{(A3)}$$

$$E\frac{dR_{\rho\to\pi+\pi+\gamma}}{d^3p} = F^4(E)\,\frac{1}{T^2} exp\left(-\frac{(-35.459T^{1.126}+18.827)}{(2TE)^{(-1.44T^{0.142}+0.9996)}} - 1.21\frac{E}{T}\right) \qquad \text{(A4)}$$

$$E\frac{dR_{\pi+K^*\to K+\gamma}}{d^3p} = F^4(E)\,T^{3.75} exp\left(-\frac{0.35}{(2TE)^{1.05}} + (2.3894T^{0.03435} - 3.222)\frac{E}{T}\right) \qquad \text{(A5)}$$

$$E\frac{dR_{\pi+K\to K^*+\gamma}}{d^3p} = F^4(E)\,\frac{1}{T^3} exp\left(-(5.4018T^{-0.6864} - 1.51)(2TE)^{0.07} - 0.91\frac{E}{T}\right) \qquad \text{(A6)}$$

$$E\frac{dR_{\rho+K\to K+\gamma}}{d^3p} = F^4(E)\,T^{3.5} exp\left(-\frac{(0.9386T^{1.551}+0.634)}{(2TE)^{1.01}} + (0.568T^{0.5397} - 1.164)\frac{E}{T}\right) \qquad \text{(A7)}$$

$$E\frac{dR_{K^*+K\to\pi+\gamma}}{d^3p} = F^4(E)\,T^{3.7} exp\left(\frac{-(6.096T^{1.889}+1.0299)}{(2TE)^{(-1.613T^{2.162}+0.975)}} - 0.96\frac{E}{T}\right) \qquad \text{(A8)}$$

$F(E)$ is the form factor, cf. Sec. II B