Direct photon production in heavy-ion collisions at NICA energies

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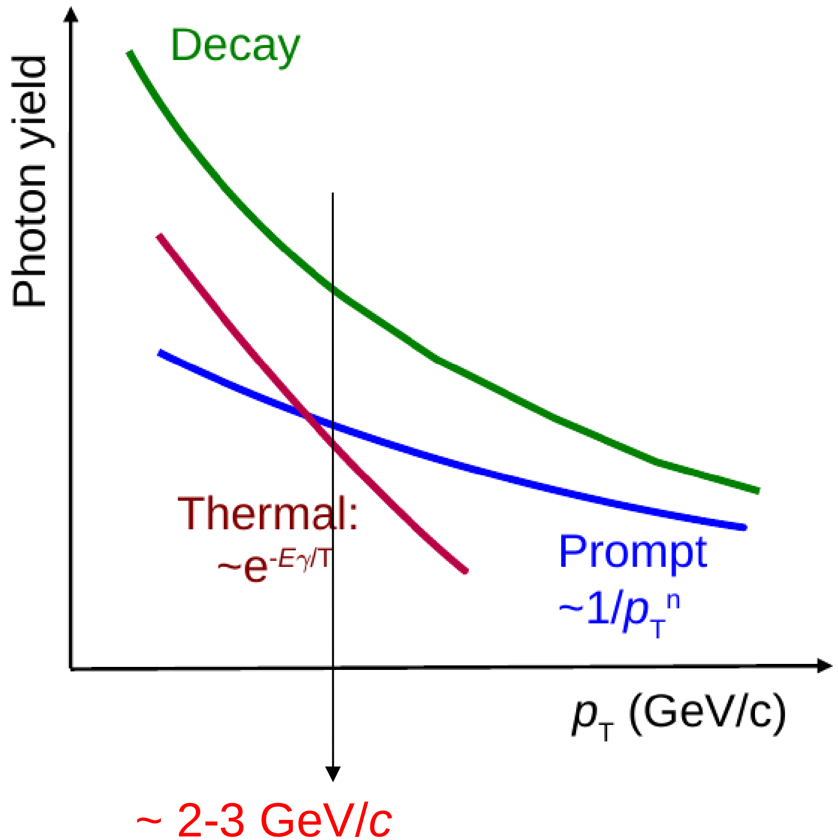
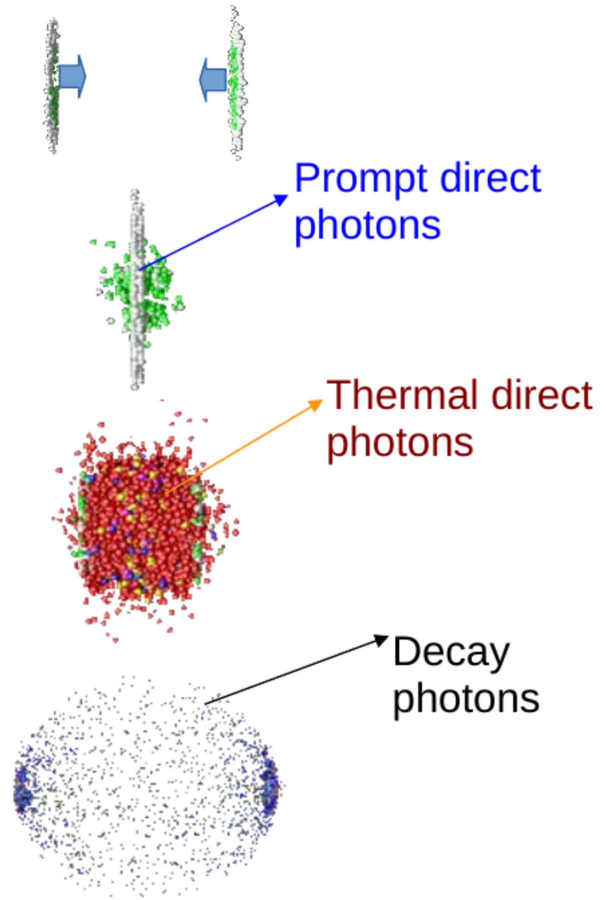
V-th Collaboration Meeting of the MPD Experiment at the NICA Facility
24.04.2020

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

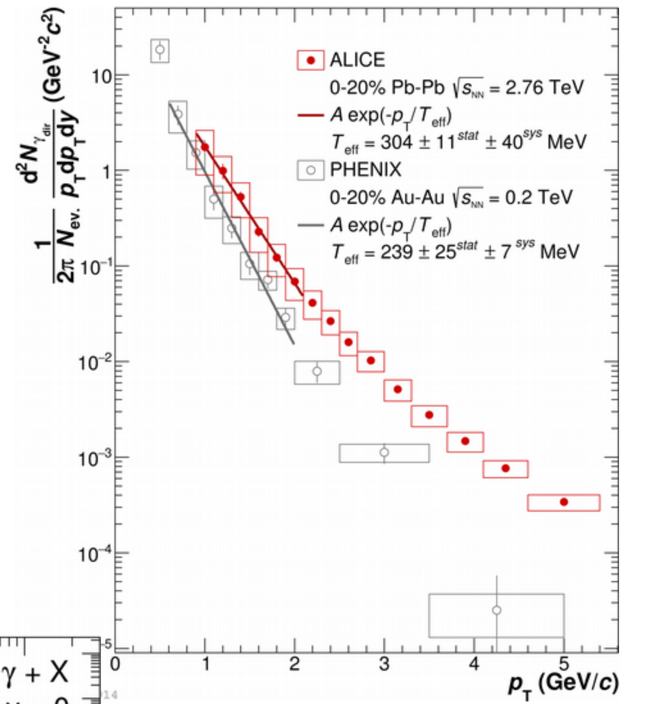


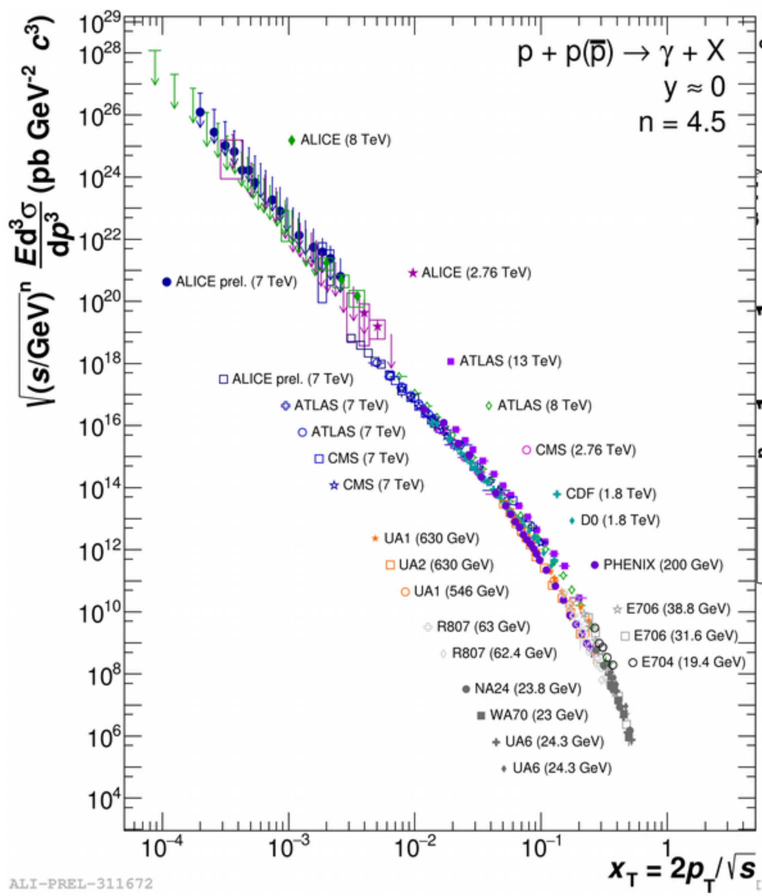


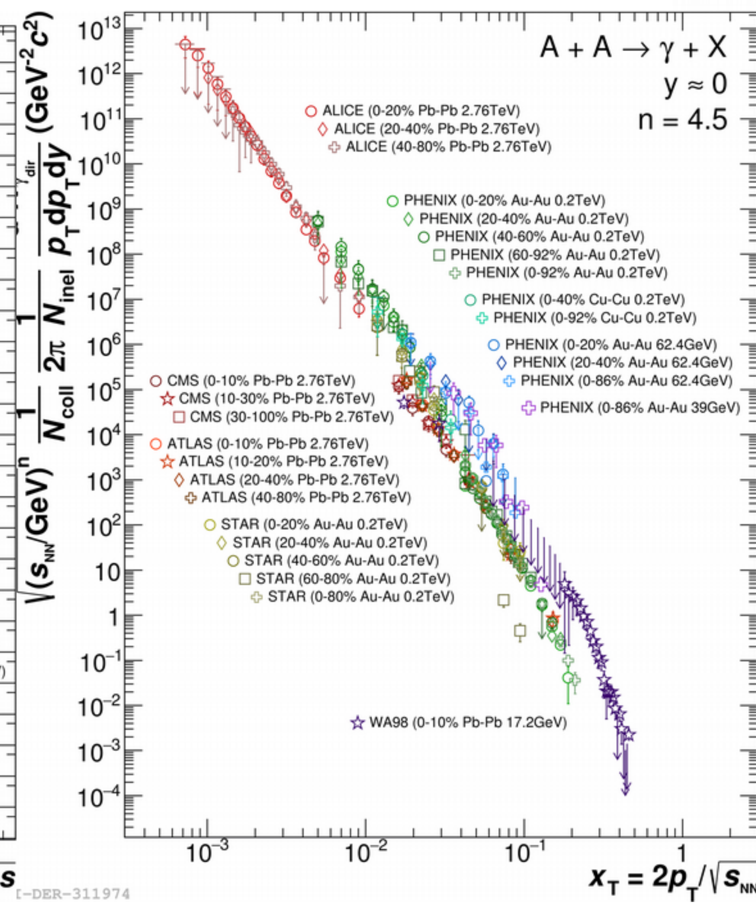
Motivation

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?)



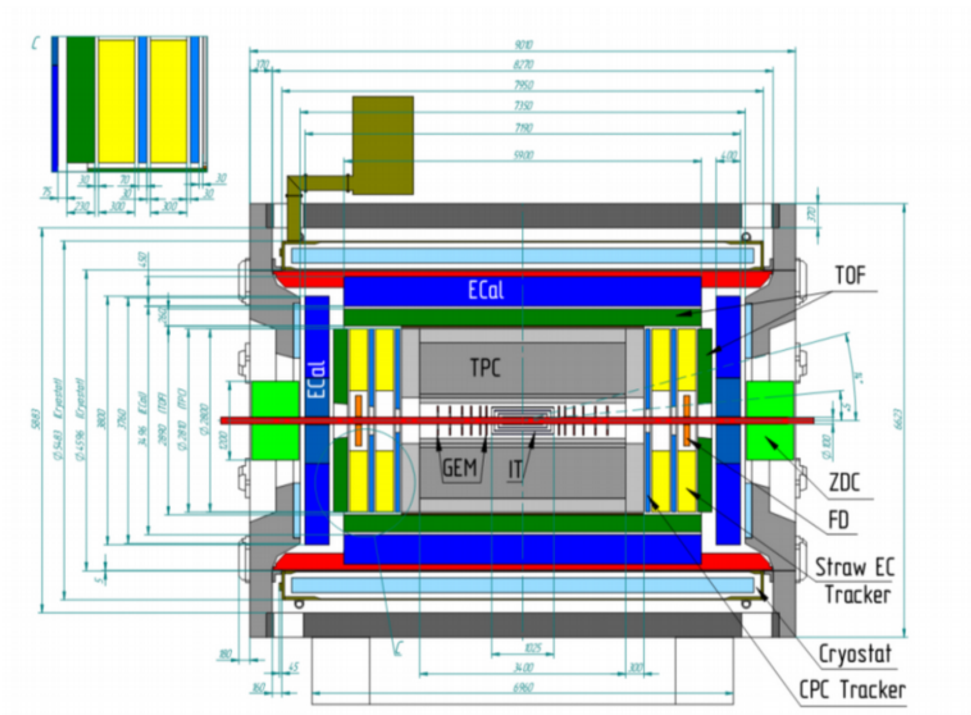


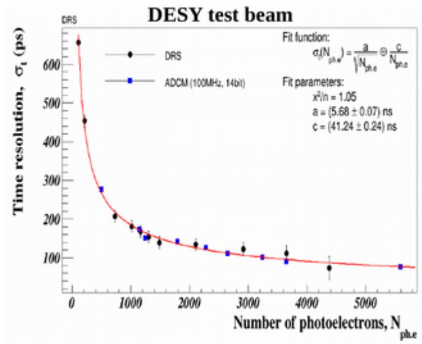


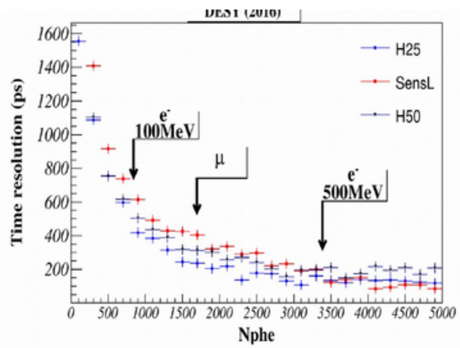
MPD Electromagnetic calorimeter

Advantages of MPD electromagnetic calorimeter:

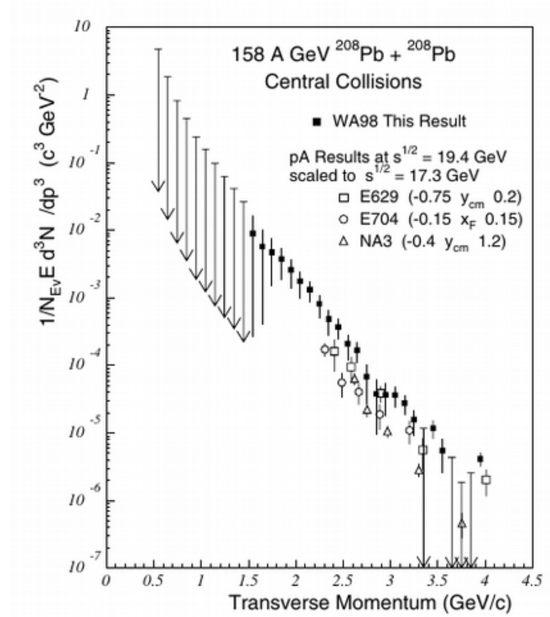
- ✓ Large acceptance (|y|<1.2, full azimuthal angle coverage).
- ✓ Excellent timing resolution (quoted to be 200-500 ps at 100 MeV)







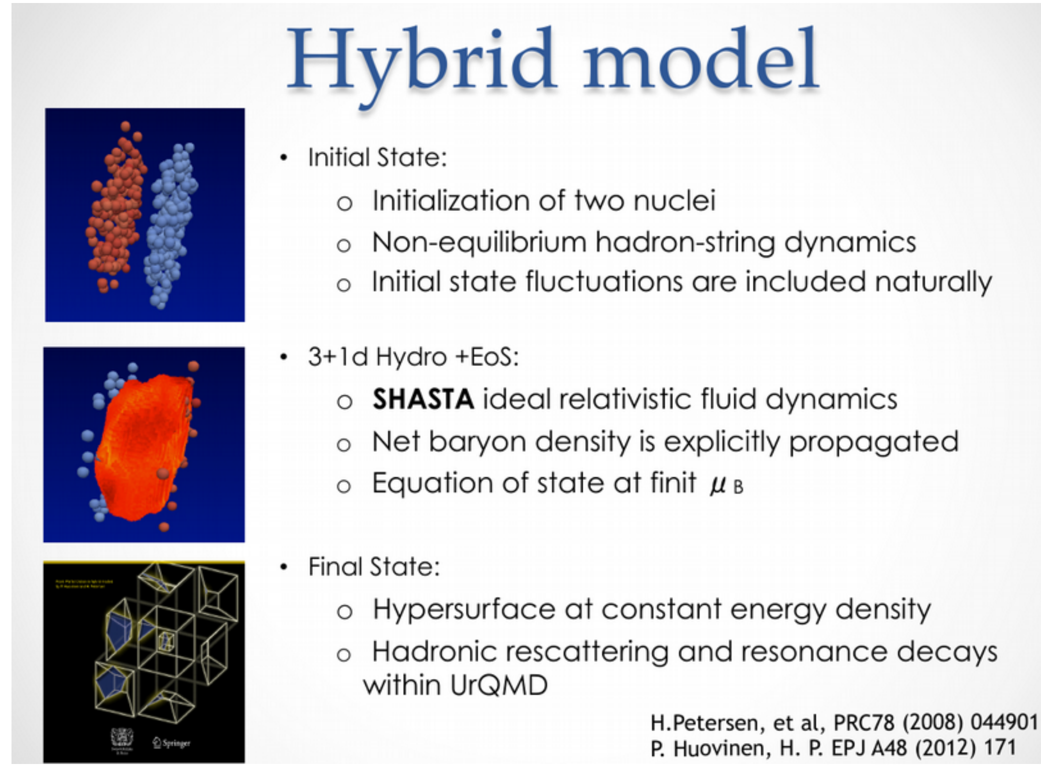
- The only competitors at ~ 10 GeV sqrt(s_{NN}) energy is SPS experiment WA98 finished about 20 years ago.
- M M Aggarwal et al, (WA98 Collaboration), Phys. Rev. Lett. 85, 3595 (2000)



See also nice review by T. Peitzmann: “Direct photon production in heavy-ion reactions at SPS and RHIC” Pramana – J. Phys. V. 60 Issue 4 pp 651-661 (2003)

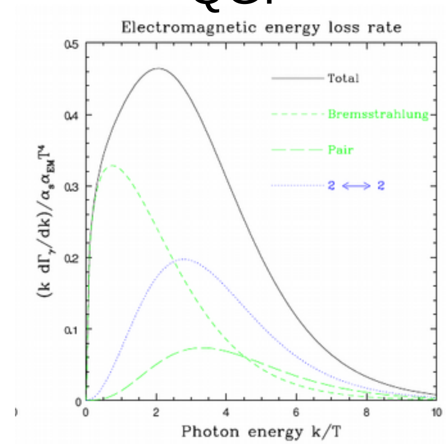
Our simulations

- 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
- Previous works on this topic: see B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904 (calculations at SPS energy)
- We use the same approach:
  - UrQMD v3.4 with hybrid model (3+1d hydro, bag model EoS, hadronic rescattering and resonances within UrQMD)
  - At each step of hydrodynamic evolution for each of 200x200x200 cell we know: energy density E_i, temperature T_i, baryonic chemical potential μ_{bi}, proportion of QGP phase.
  - For each cell, for each timestep we calculate direct photon rates for Hadronic phase and QGP phase. Integrate over all cells and steps.

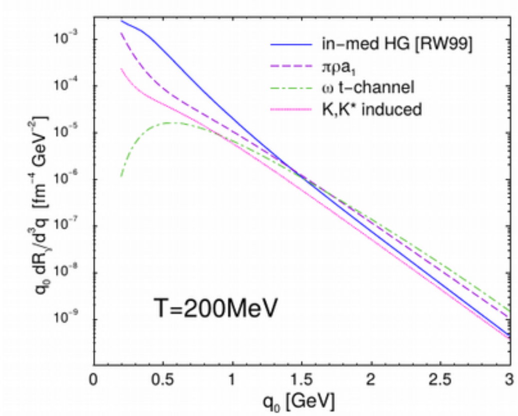


Direct photon rate parameterizations from theoretical models:

QGP



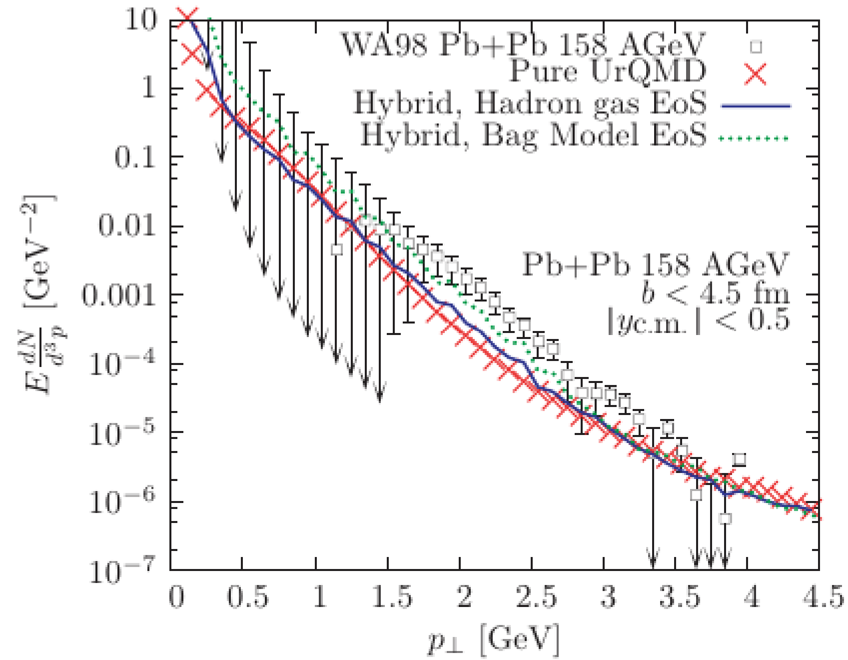
Hadron gas



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

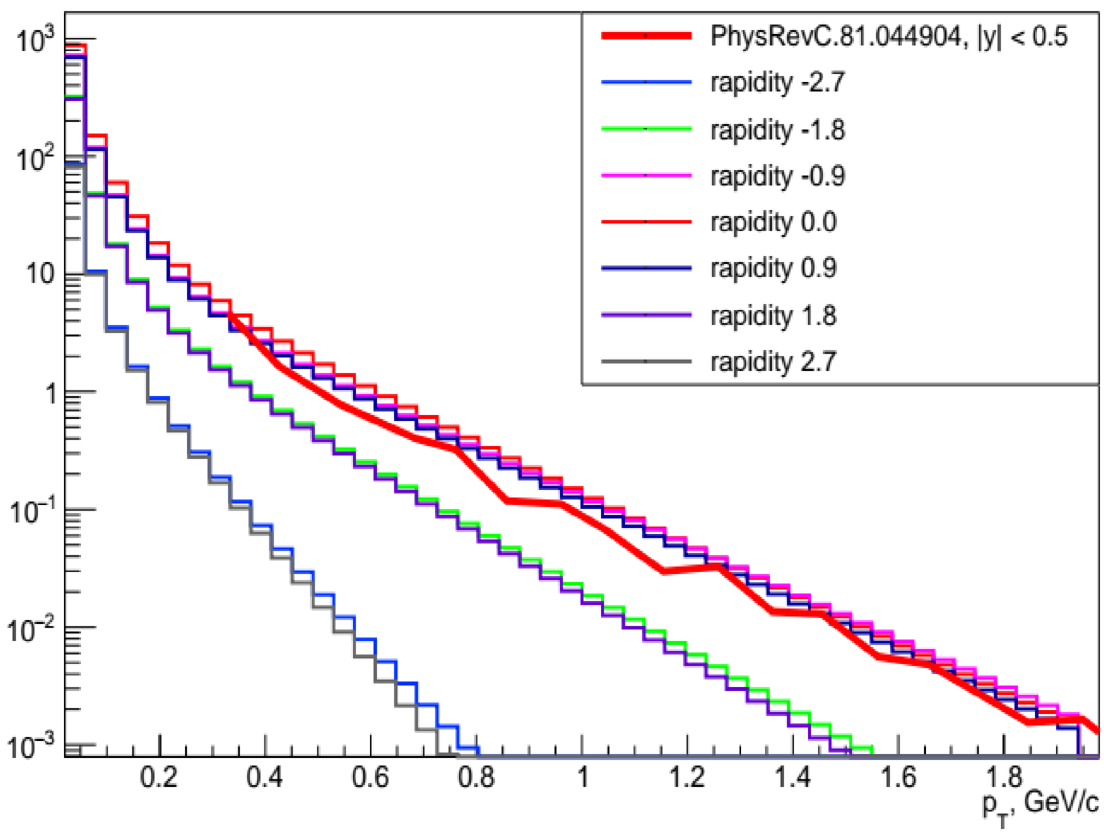
Compare thermal gamma yields with previous calculation from S. Turbide et al. and M. Bleicher at al. In our calculations same cuts on rapidity and impact parameter is made, but small changes in rate formula exists (N_f, for example)

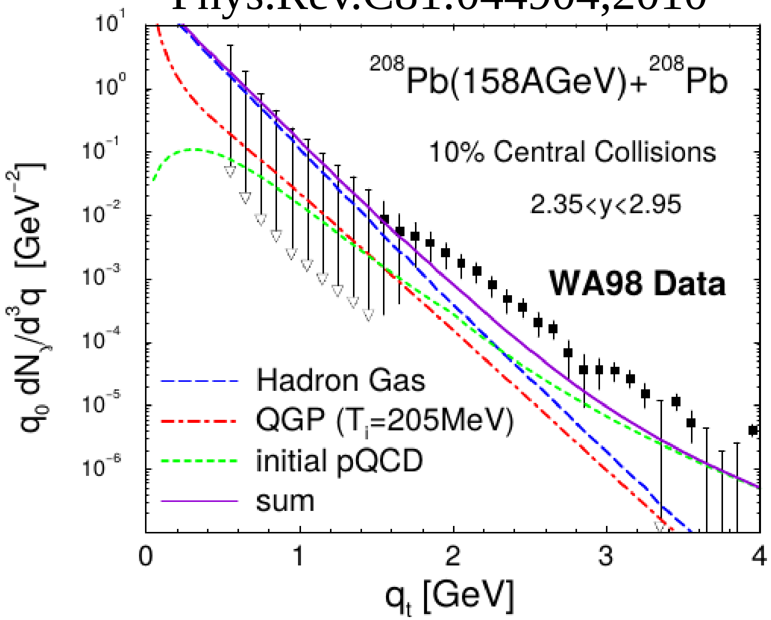
Good agreement with previous calculations.
All models tend to underestimate data!



B. Bauhle, M. Bleicher
Phys.Rev.C81:044904,2010

direct photon yield. Pb-Pb at 158 AGeV, Bag Model. b < 4.5 fm





S.Turbide, R. Rapp, C. Gale
Phys.Rev.C69:014903,2004

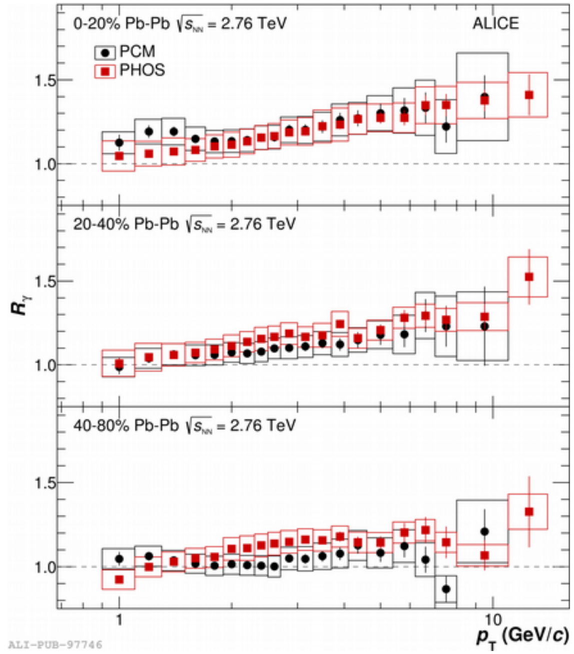
Ratio to π^0 yield

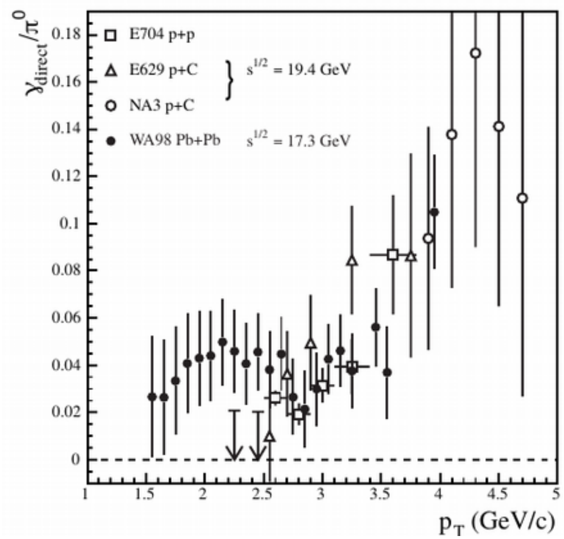
R_γ in ALICE Pb-Pb (note that above 3 GeV/c main contribution is from prompt photons)

- 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, syst. uncertainties on the same level. In WA98 (Pb-Pb at $\sqrt{s_{NN}}$=17.2 GeV) – on the level of 4% at 2 GeV/c.

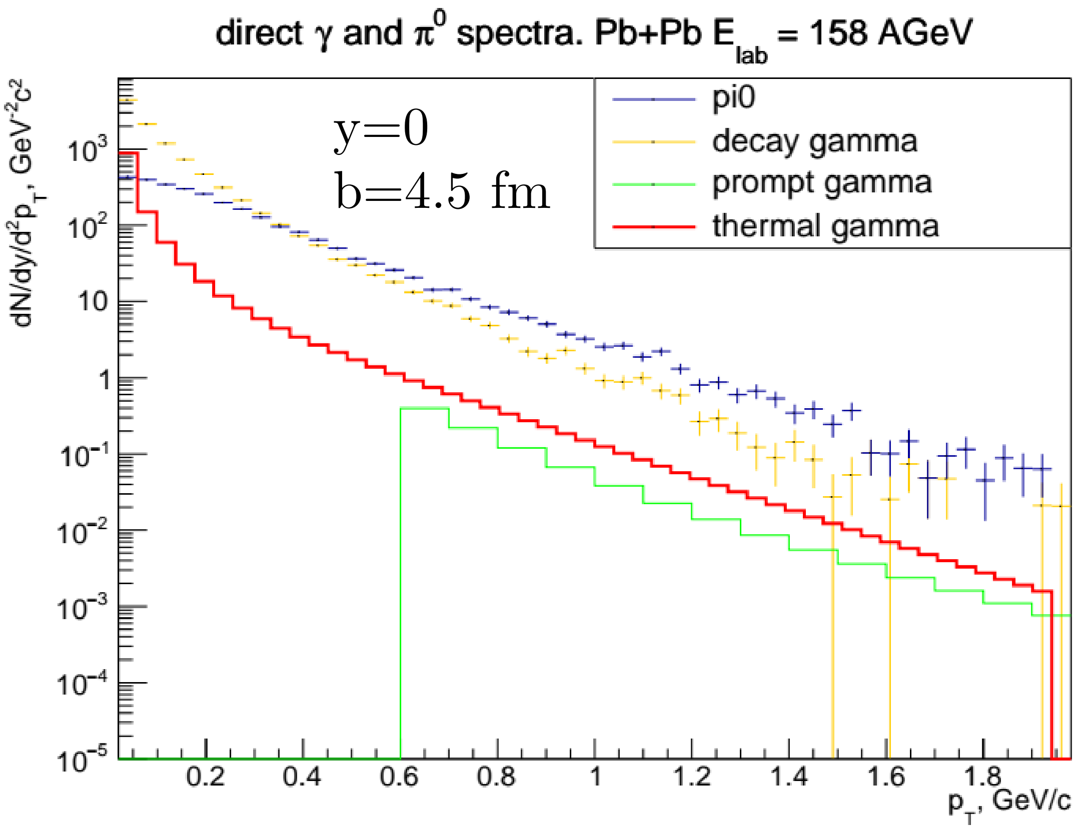
- Calculate π^0 yield from UrQMD with hydro mode off (cto 45 0).
- Calculate decay photon spectrum.

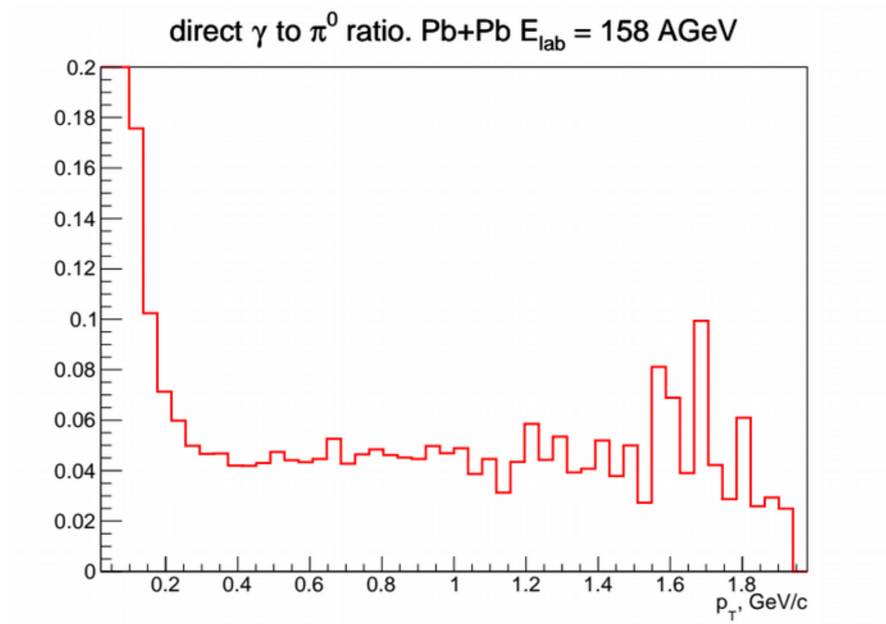


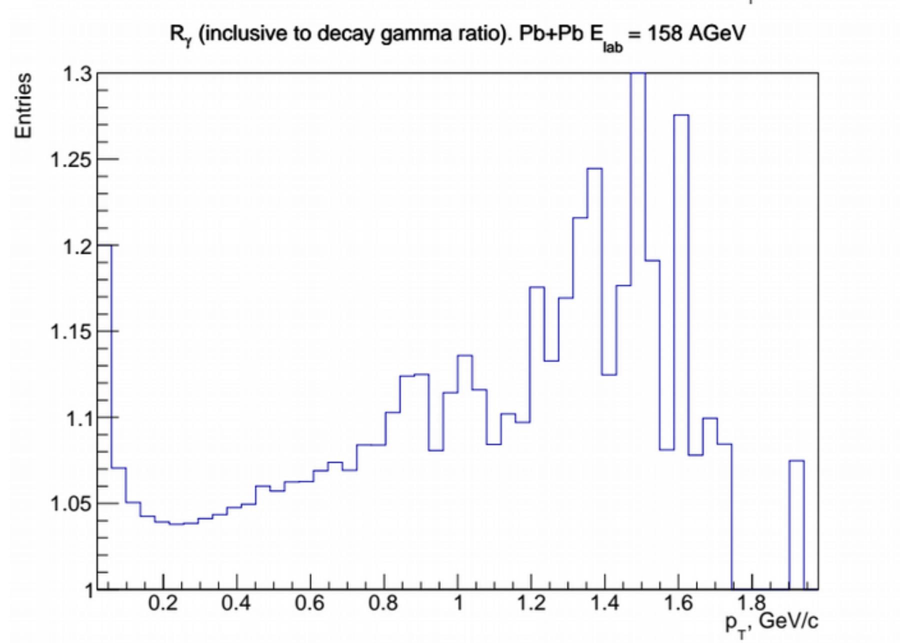


T. Peitzmann Pramana – J. Phys. V. 60 Issue 4 pp 651-661 (2003)

Our predictions for SPS energy (Pb-Pb at $\sqrt{s_{NN}}$=17.2 GeV)





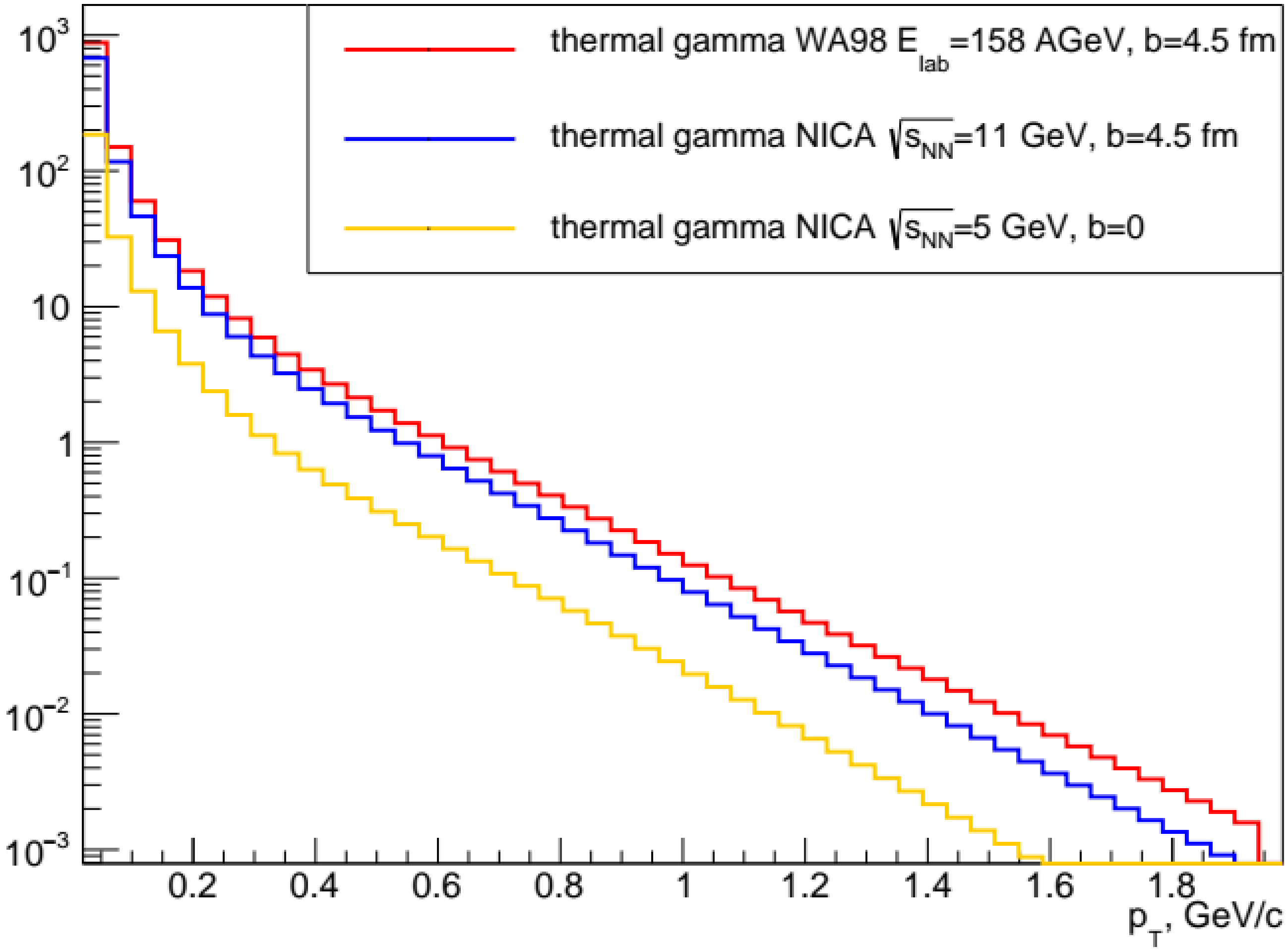


Compare direct γ to π^0 ratio.
Note: prompt photons (pQCD) not included yet in the ratio.

γ/π^0 about 4%.

Calculations at NICA energies

Change system to Au-Au and set lower energies ...

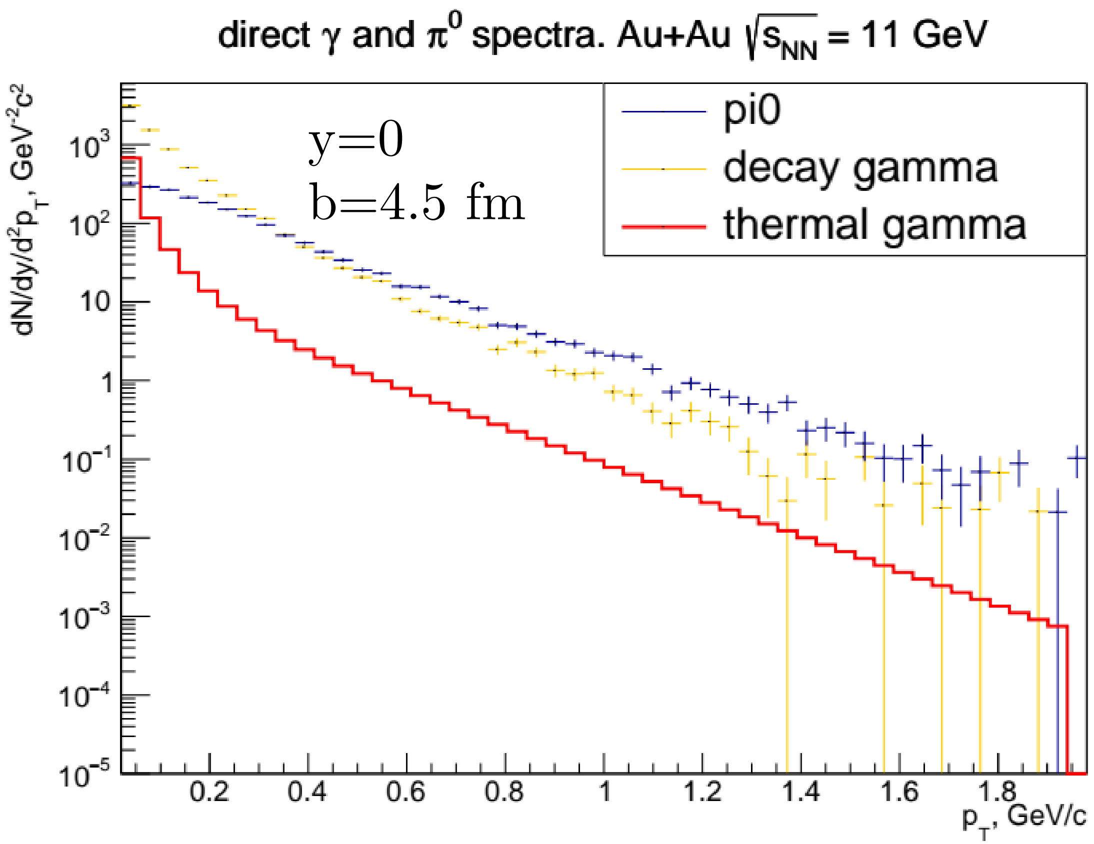


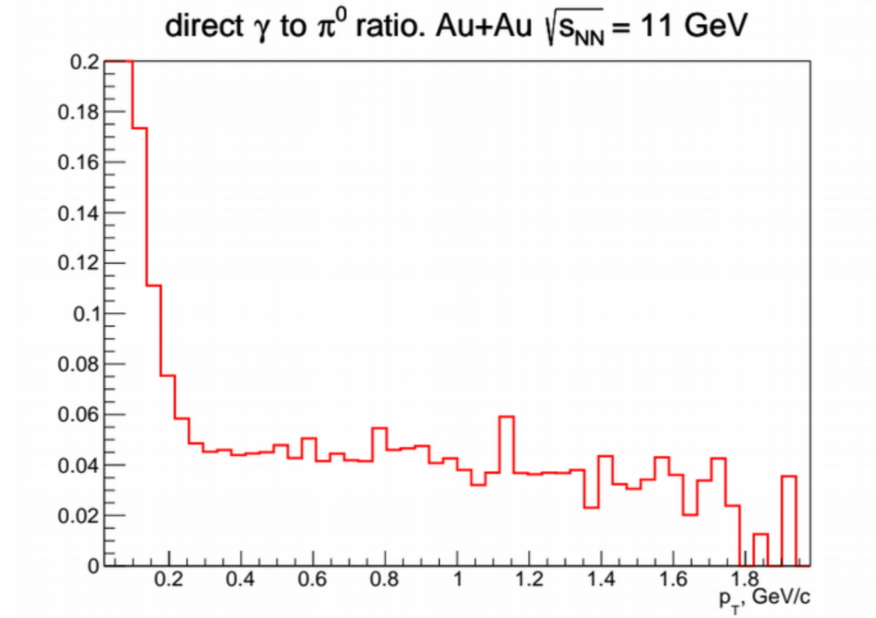
Differential direct photon yield ~ T^2

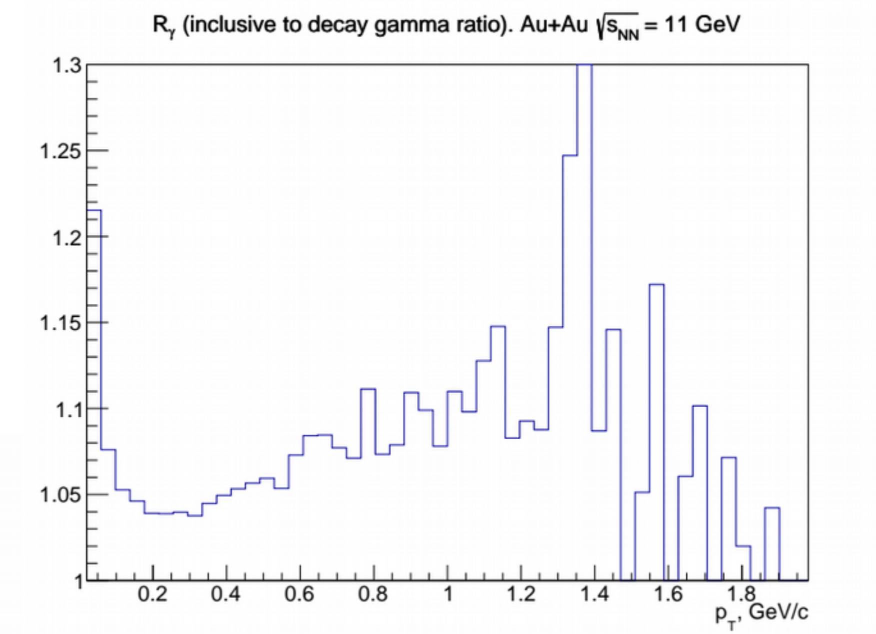
Total yield ~T^4

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

Calculate the same dependencies at the top NICA energy.
Despite lower direct gamma yield, ratio γ/π^0 is similar to WA98 results.

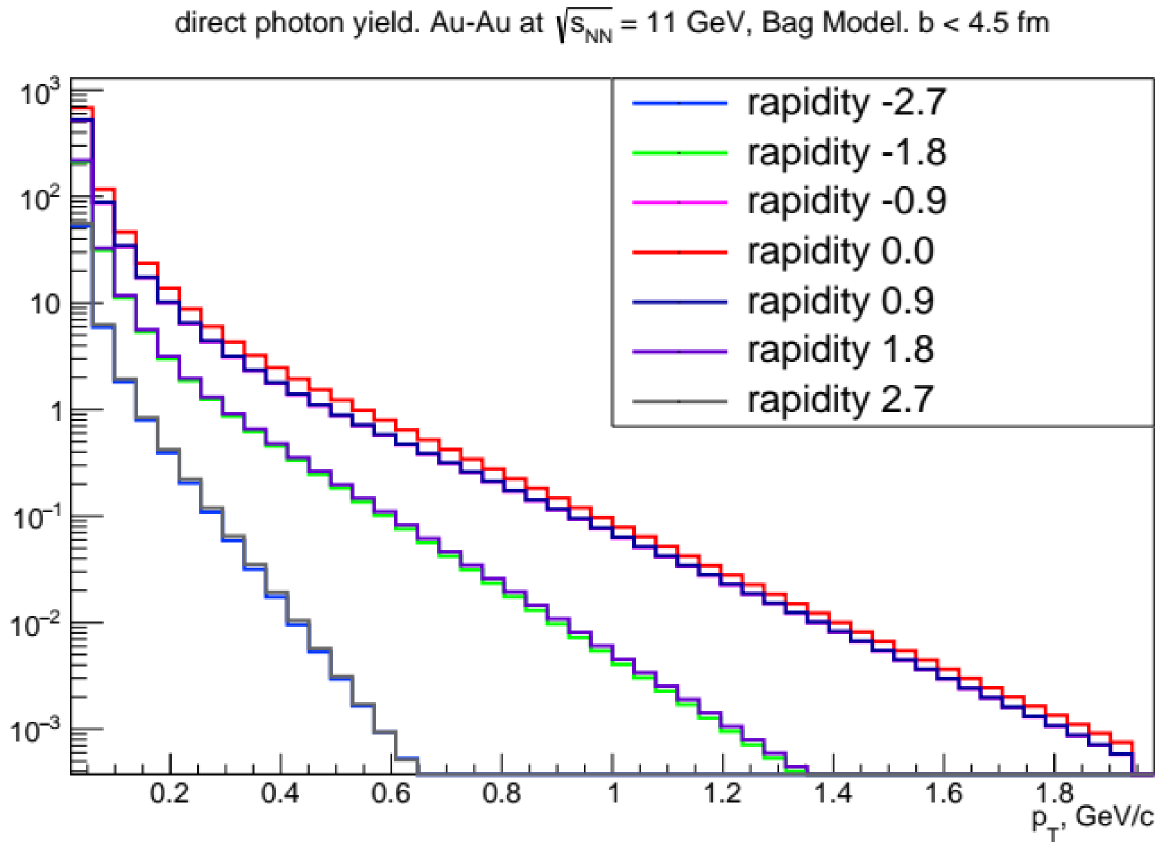


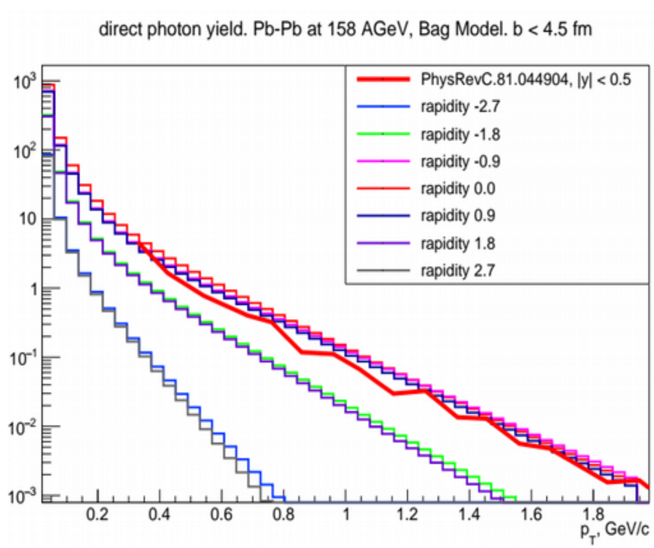


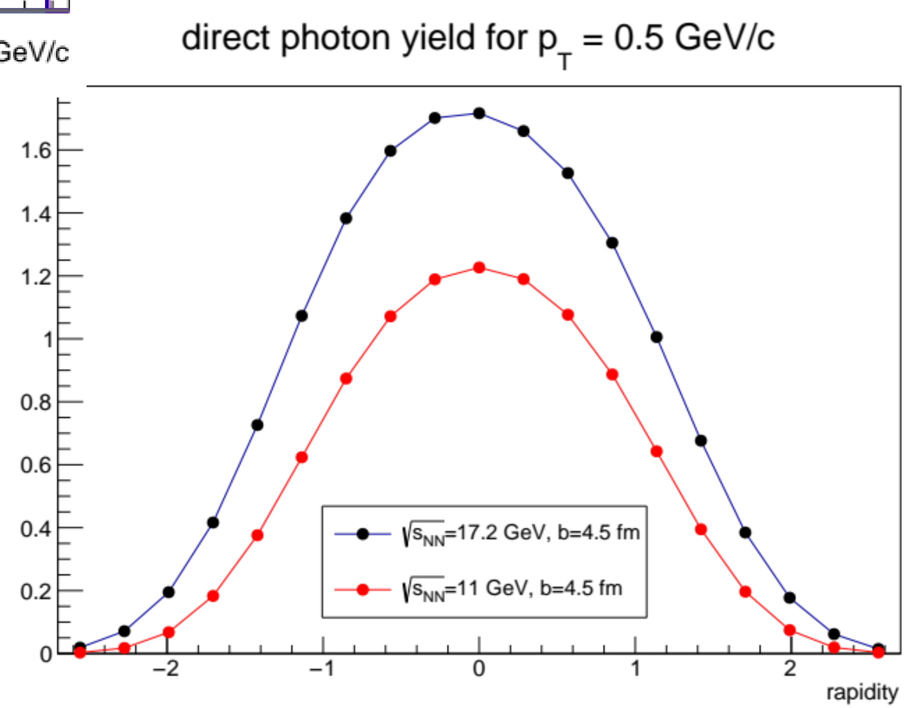


Calculations at $\sqrt{s_{NN}}$ = 11 GeV

Calculate the same dependencies at the top NICA energy.
Rapidity dependence similar to one at SPS energy

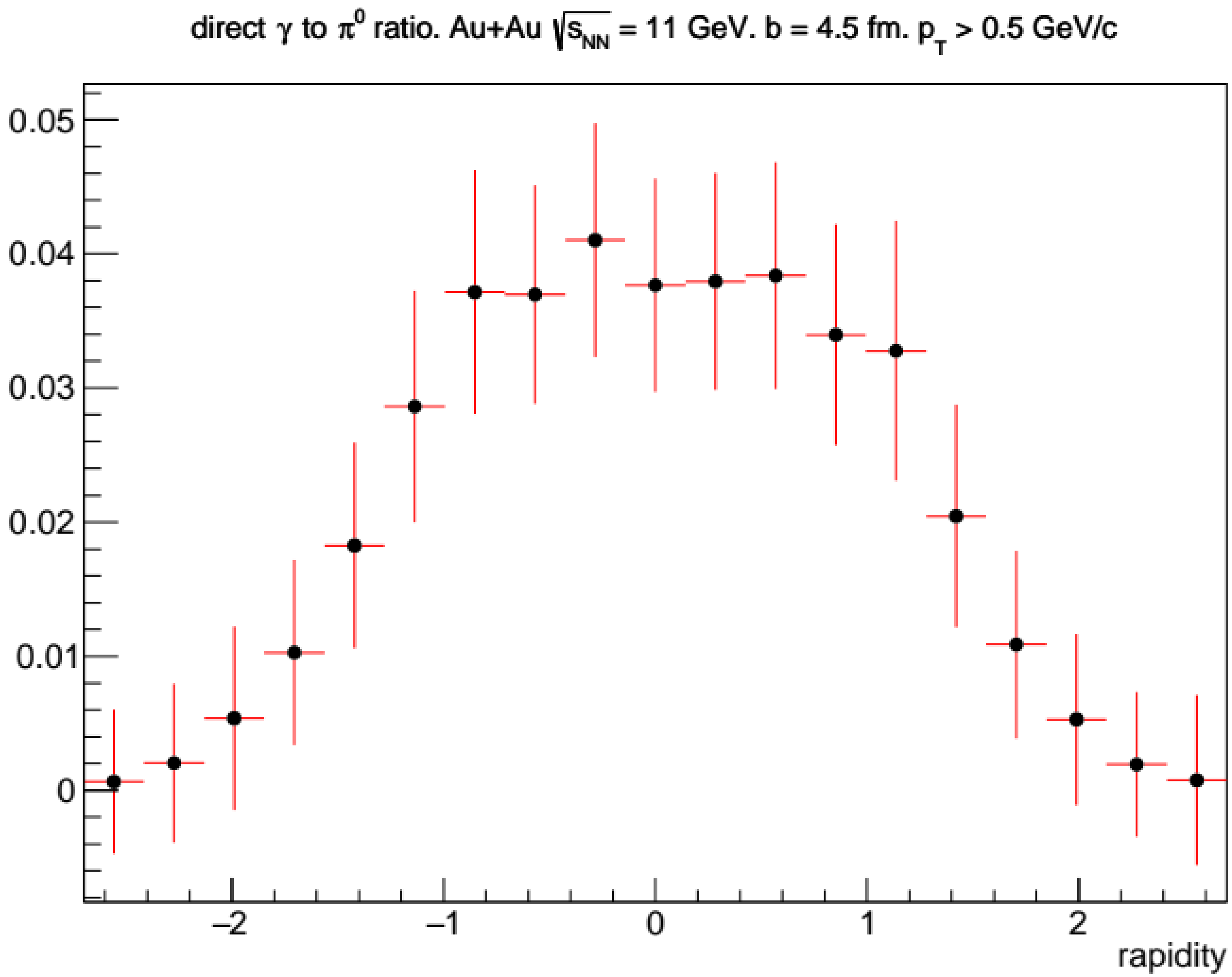






Calculations at $\sqrt{s_{NN}}$ = 11 GeV

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!

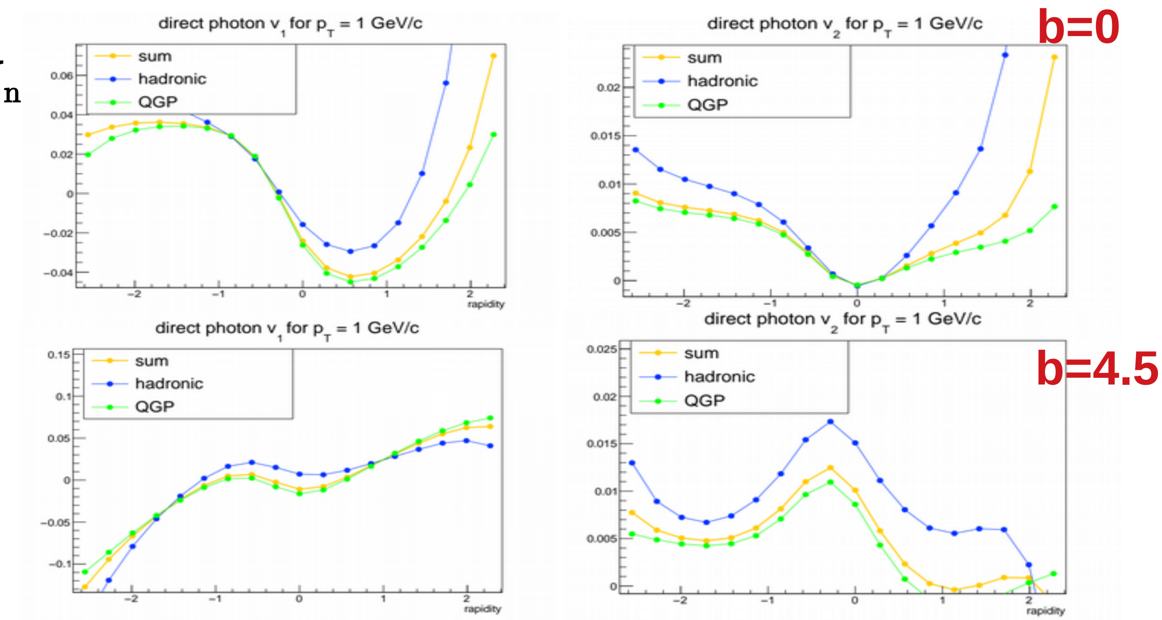


Conclusions

- 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 **MPD top energy** (√sNN = **11 GeV**) regime were obtained. **Direct gamma to π0 and Rγ ratios** are calculated.
- Updates are being presented at ECAL meetings.

- Future plans:

  - Prepare final plots for direct gamma spectrum at NICA energies (**5, 11 GeV**), as well as ratios (increase statistics etc).
  - Prepare **paper draft** (target journal probably Nuclear Physics)
  - **Estimate systematic uncertainties** on direct gamma spectrum and Rγ with detector performance studies (using MPDRoot). Is it feasible to measure direct photons with **MPD detector**?
  - Further works on **direct gamma v_n**
  - Comparison of different **EOS** and to **other models** (UrQMD + VHLLE – Yu. Karpenko), SMASH + hydro ???



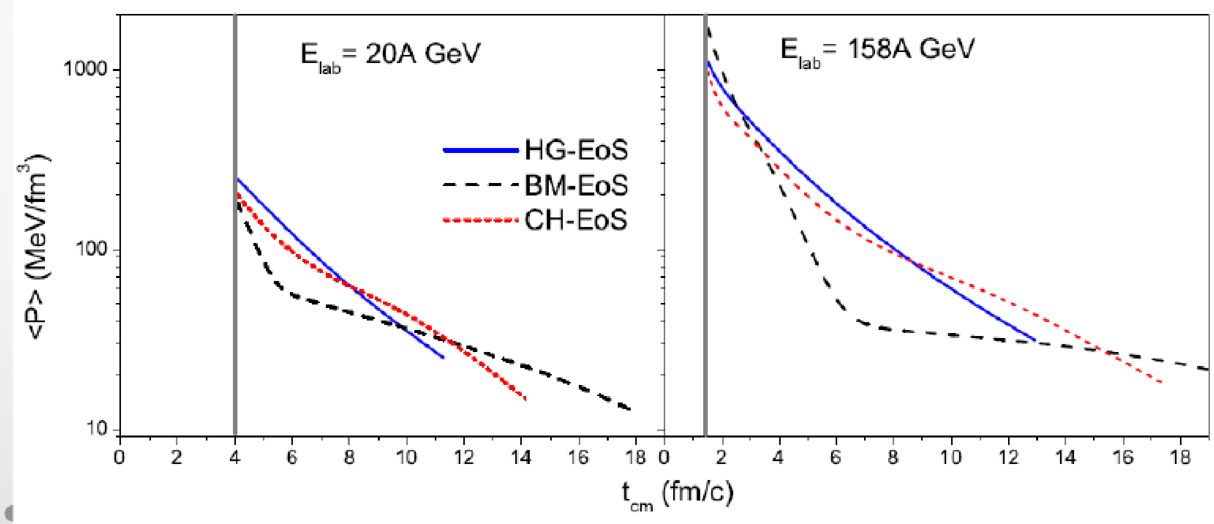
Backup

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

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

with

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

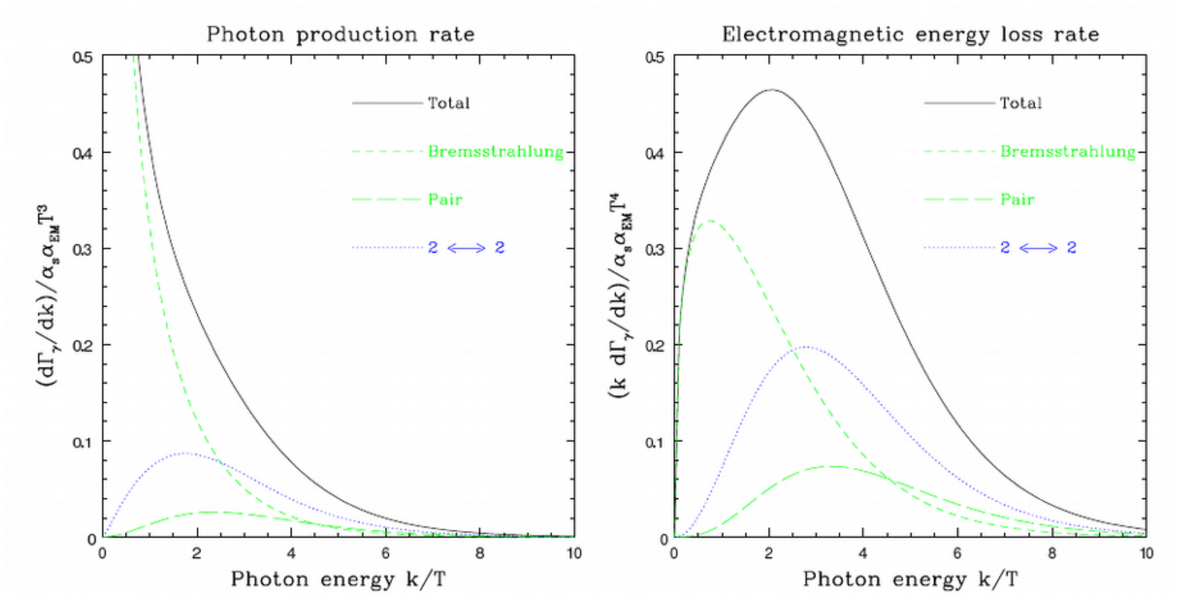


FIG. 9. Total photon emission rate, together with the bremsstrahlung, inelastic pair annihilation and $2 \leftrightarrow 2$ contributions, for two-flavor QCD with $\alpha_s = 0.2$. The left panel shows $d\Gamma_\gamma/dk$, divided by $\alpha_s\, \alpha_{\rm EM}\, T^3$, while the right panel shows rates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

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

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.

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

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

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

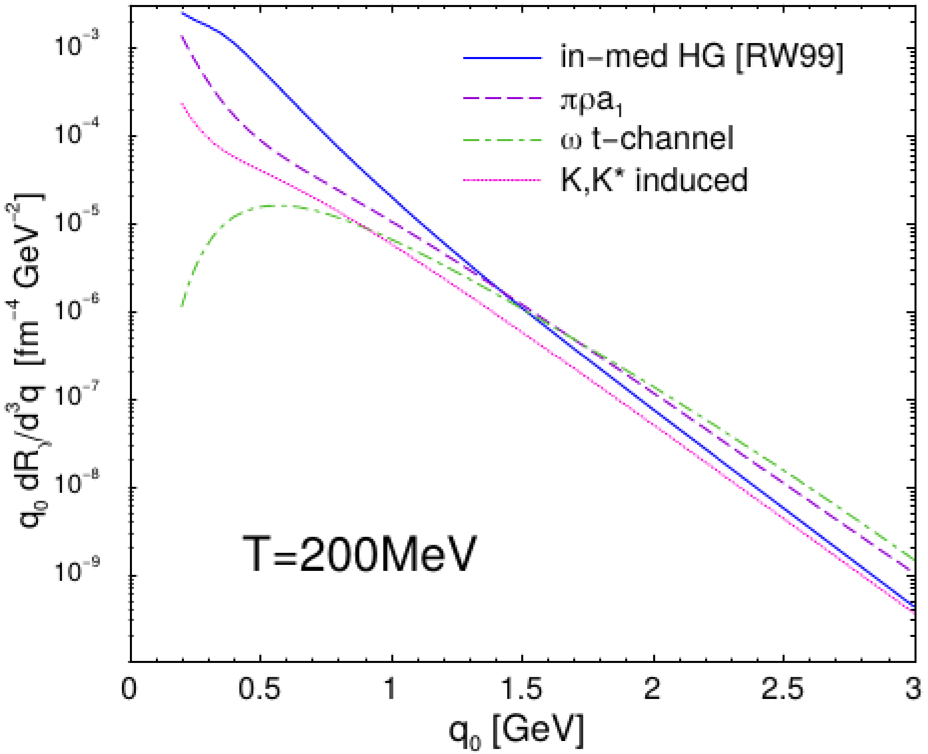
$$E\frac{dR_{\pi+K^*\to K+\gamma}}{d^3p} = F^4(E)\,T^{3.75} exp\left(-\frac{0.35}{(2TE)^{1.05}} + (2.3894T^{0.03435} - 3.222)\frac{E}{T}\right) \quad \text{(A5)}$$

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

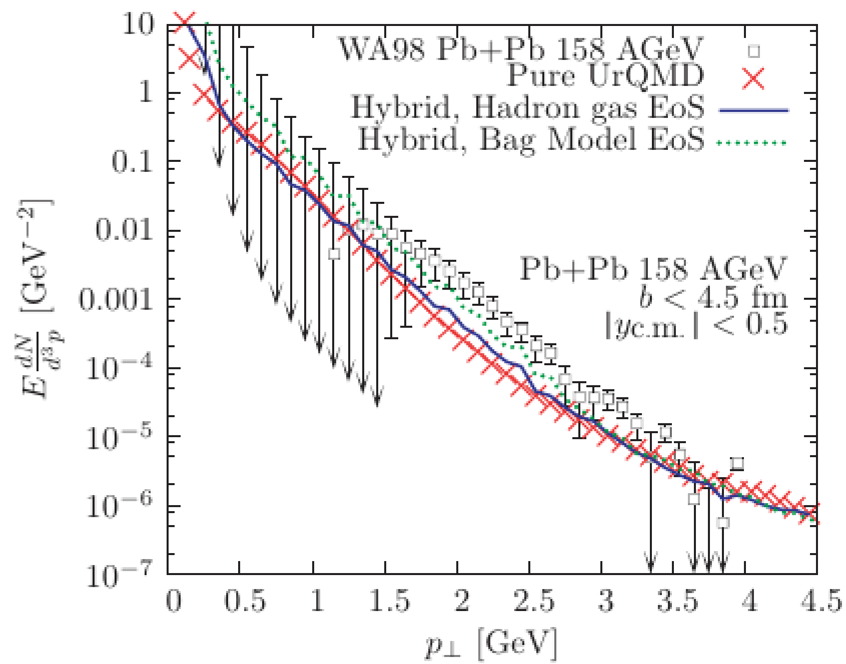
$$E\frac{dR_{\rho+K\to K+\gamma}}{d^3p} = F^4(E)\,T^{3.5} exp\left(-\frac{(0.9386T^{1.551}+0.634)}{(2TE)^{1.01}} + (0.568T^{0.5397} - 1.164)\frac{E}{T}\right) \quad \text{(A7)}$$

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

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



- Different models



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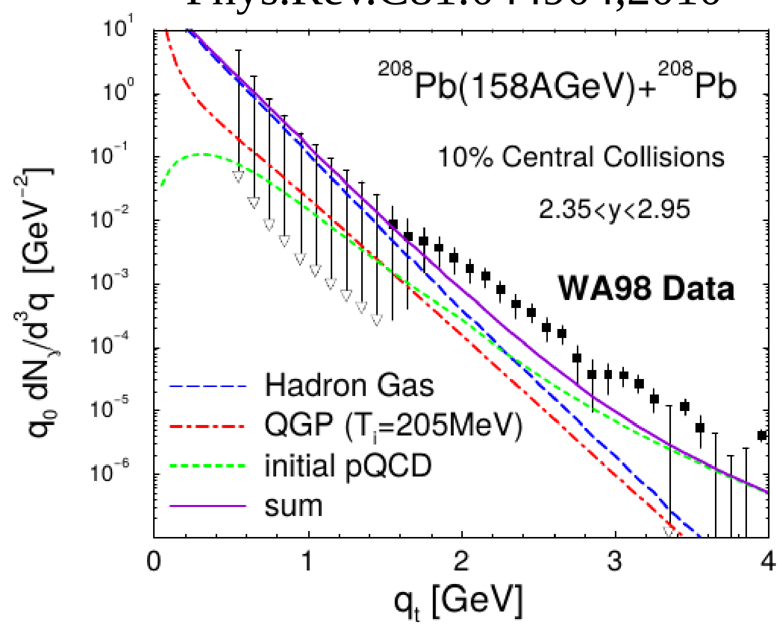


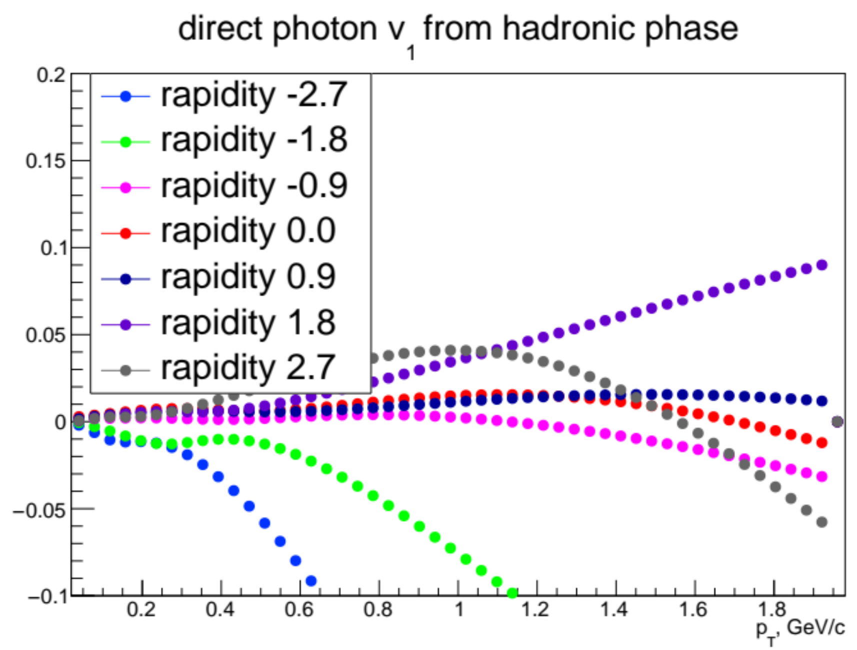
S.Turbide, R. Rapp, C. Gale
Phys.Rev.C69:014903,2004

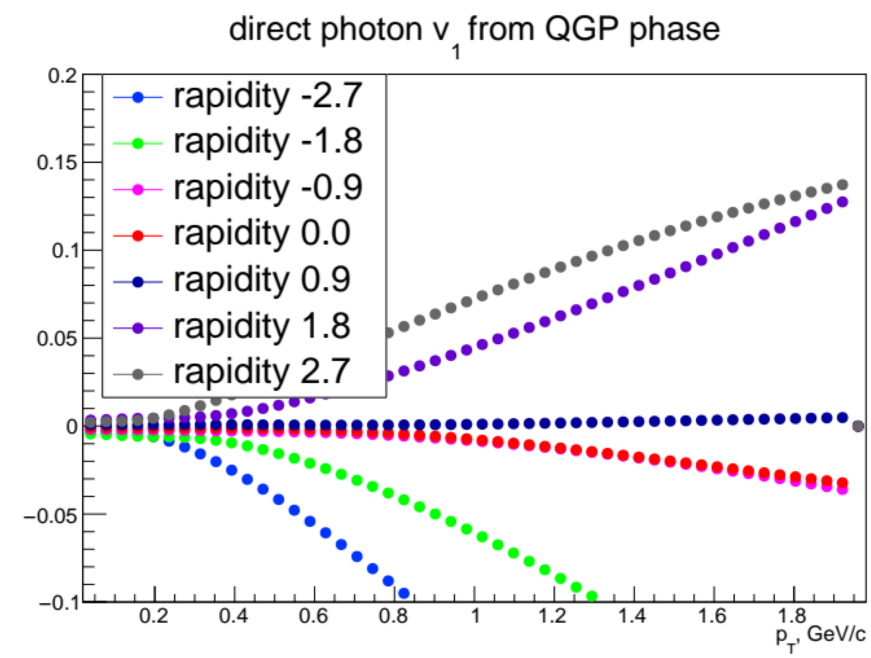
Collective flow: vn of direct photons

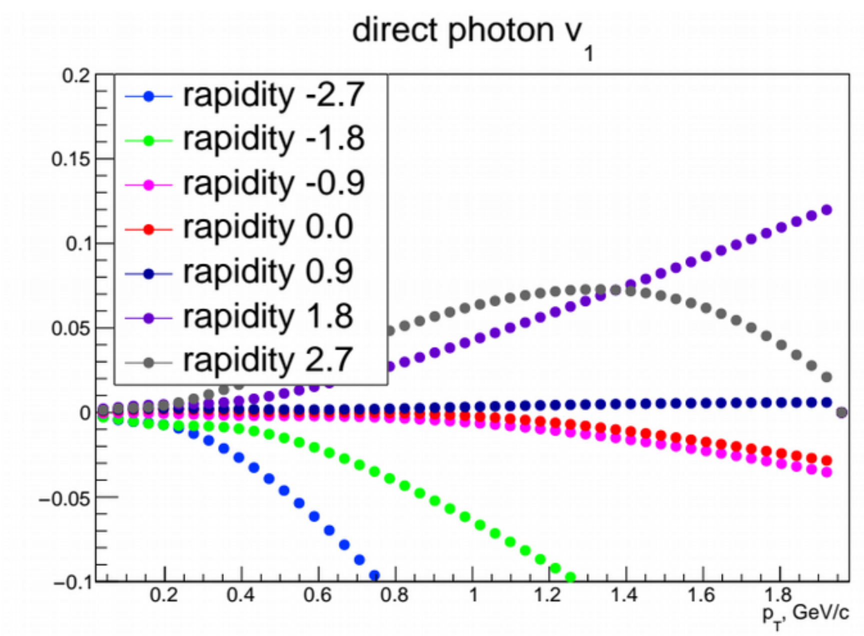
Direct photon flow puzzle: flow of direct photons is large (close to the flow of hadrons) which is difficult to explain within current theoretical models.
We look at anisotropy of direct photon yield using UrQMD in hydro mode...

Note: only few events were simulated. Due to fluctuations of initial state of collision anisotropies at few first time steps are different, while the later stages produce more similar flows.

v1, b=4.5 fm


direct photon v_1 from hadronic phase
rapidity -2.7
rapidity -1.8
rapidity -0.9
rapidity 0.0
rapidity 0.9
rapidity 1.8
rapidity 2.7
0.2
0.15
0.1
0.05
0
−0.05
−0.1
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
p_T, GeV/c


direct photon v_1 from QGP phase
rapidity -2.7
rapidity -1.8
rapidity -0.9
rapidity 0.0
rapidity 0.9
rapidity 1.8
rapidity 2.7
0.2
0.15
0.1
0.05
0
−0.05
−0.1
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
p_T, GeV/c


direct photon v_1
rapidity -2.7
rapidity -1.8
rapidity -0.9
rapidity 0.0
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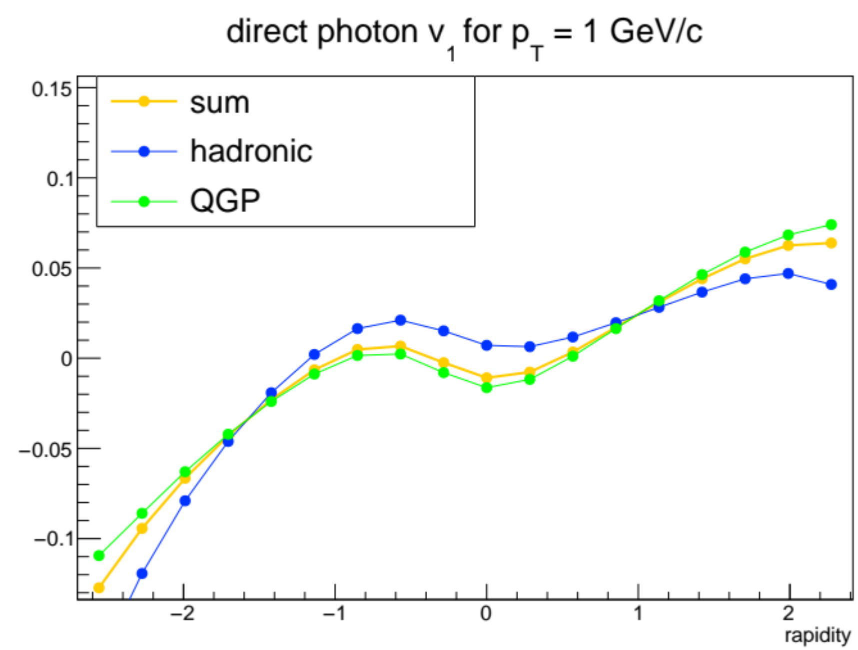
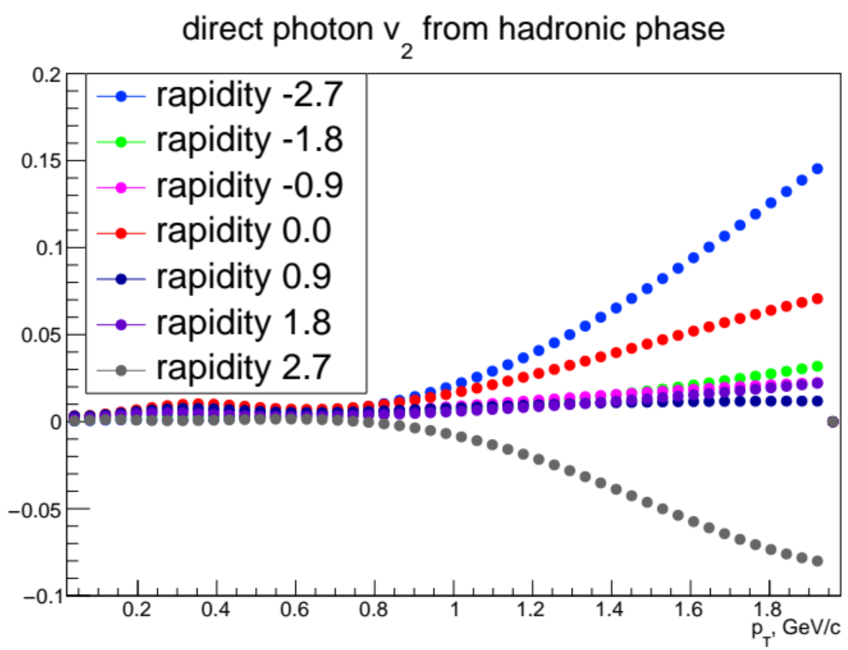
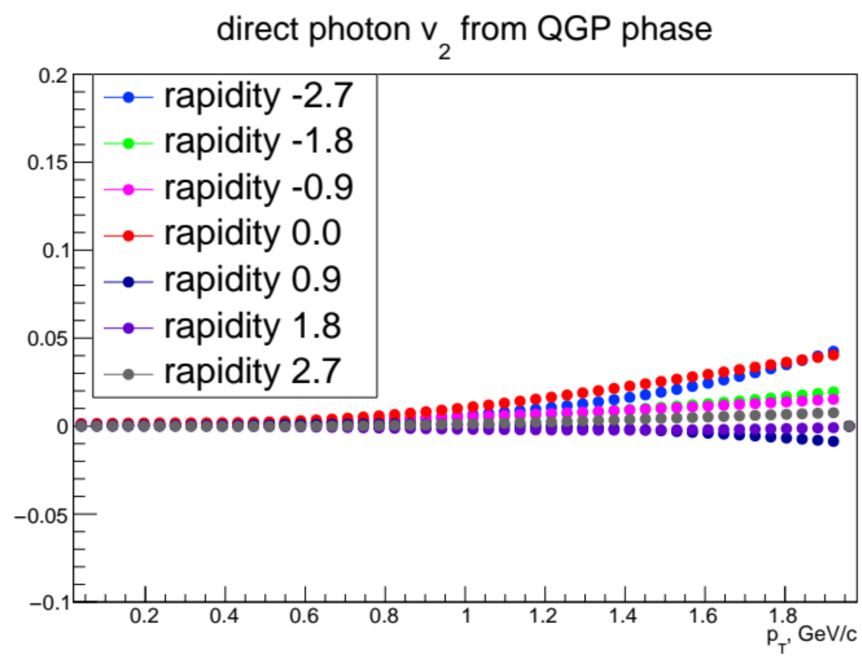
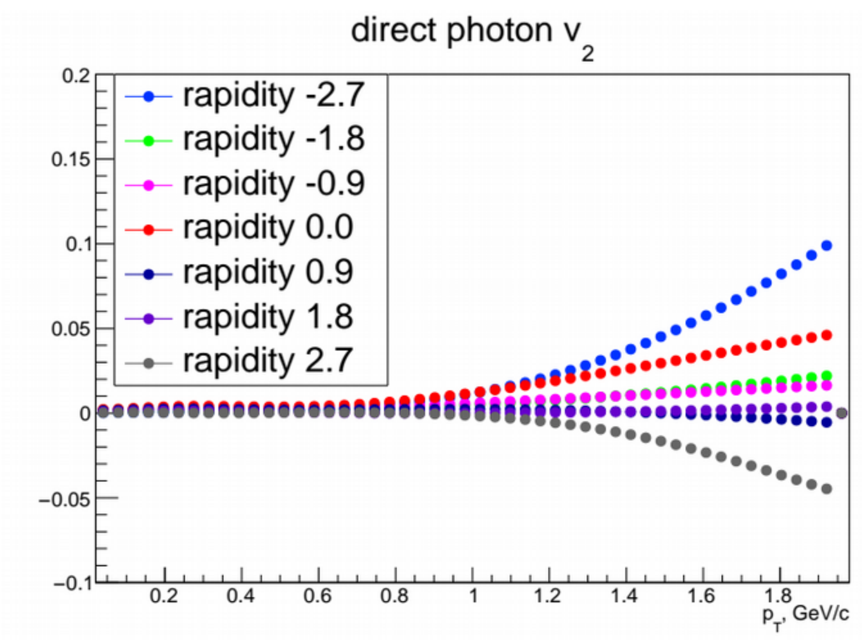
p_T, GeV/c

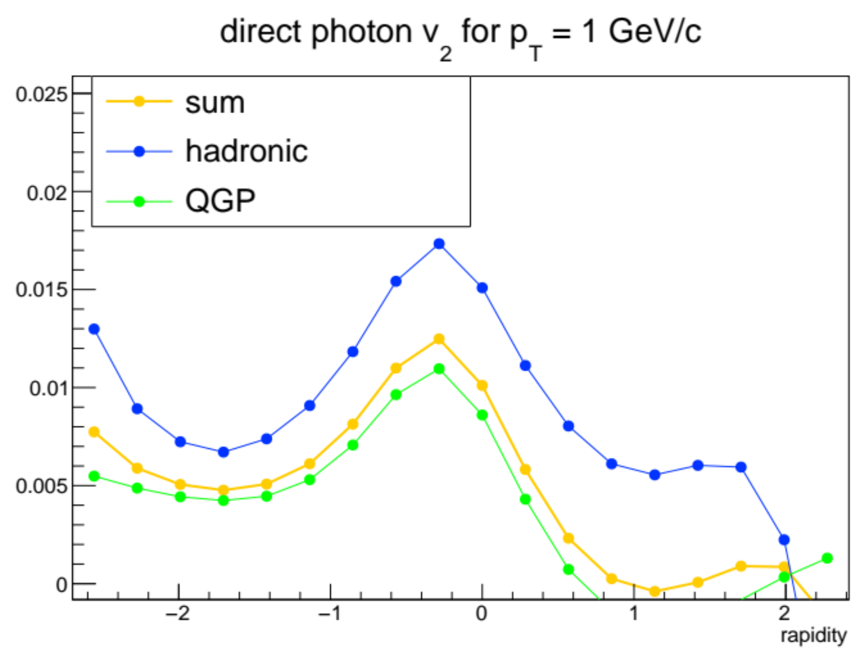

direct photon v_1 for p_T = 1 GeV/c
sum
hadronic
QGP
0.15
0.1
0.05
0
−0.05
−0.1
−2 −1 0 1 2
rapidity

v2, b=4.5 fm

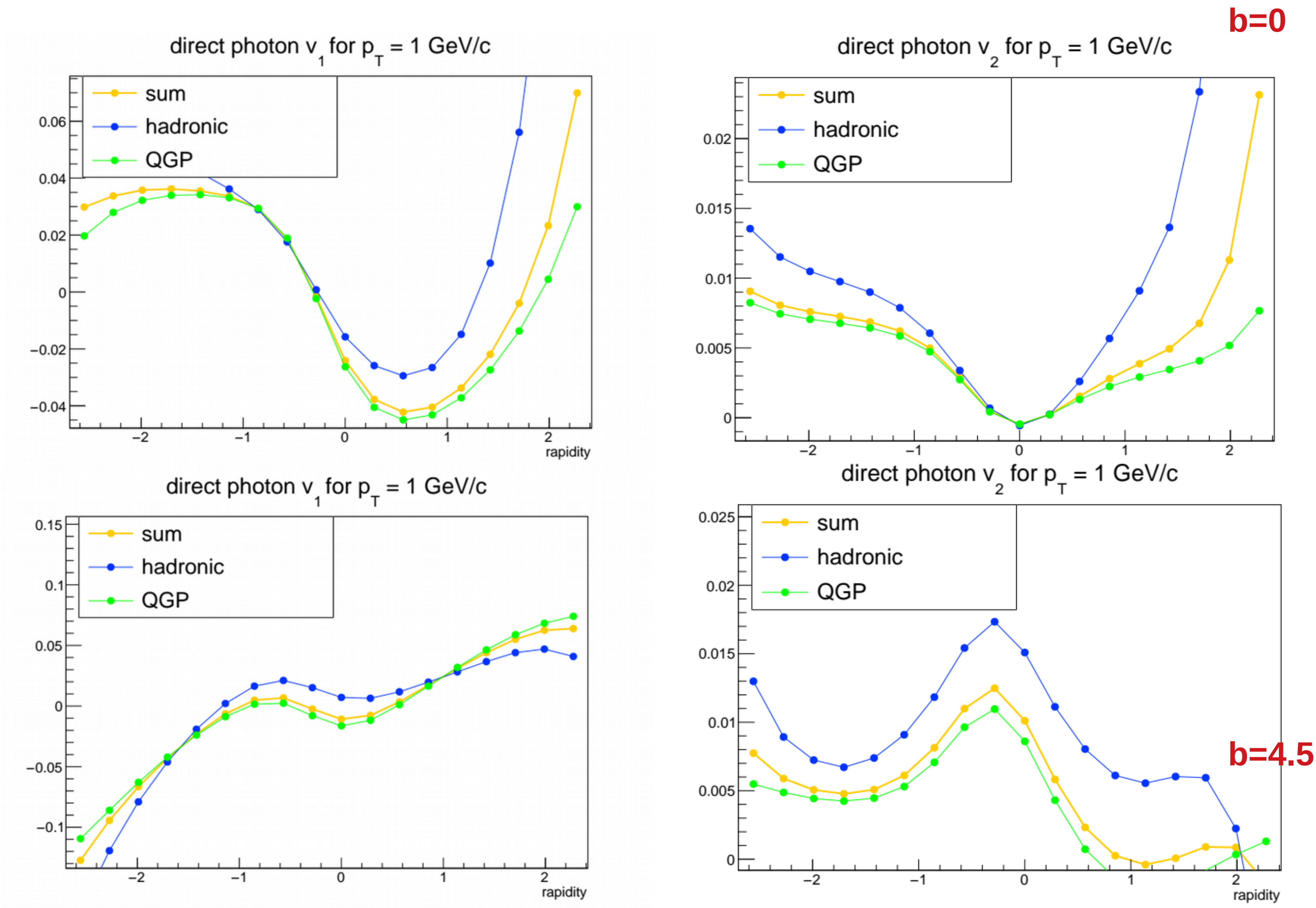

direct photon v_2 from hadronic phase
rapidity -2.7
rapidity -1.8
rapidity -0.9
rapidity 0.0
rapidity 0.9
rapidity 1.8
rapidity 2.7
p_T, GeV/c


direct photon v_2 from QGP phase
rapidity -2.7
rapidity -1.8
rapidity -0.9
rapidity 0.0
rapidity 0.9
rapidity 1.8
rapidity 2.7
p_T, GeV/c


direct photon v_2
rapidity -2.7
rapidity -1.8
rapidity -0.9
rapidity 0.0
rapidity 0.9
rapidity 1.8
rapidity 2.7
p_T, GeV/c

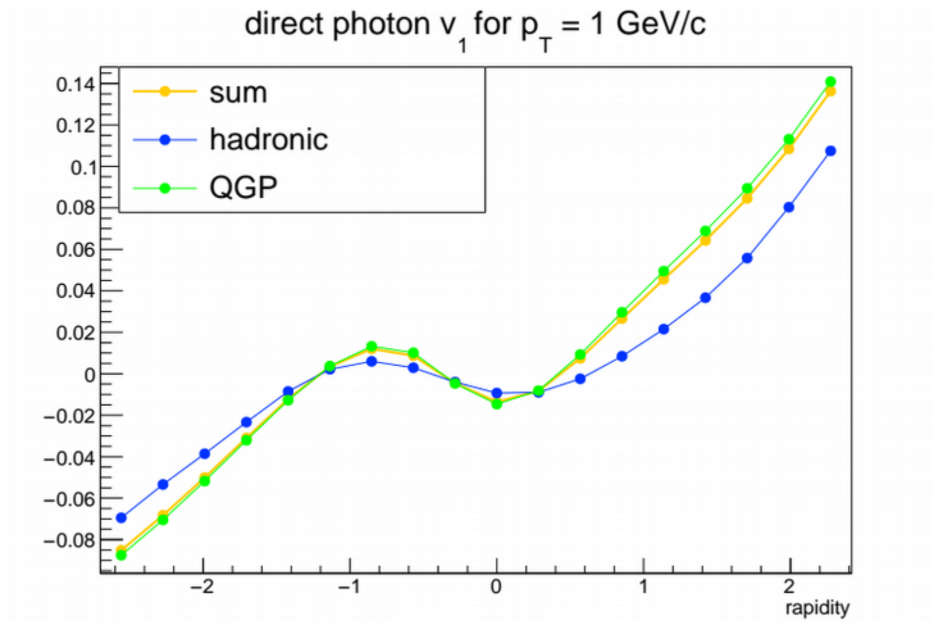

direct photon v_2 for p_T = 1 GeV/c
sum
hadronic
QGP
rapidity

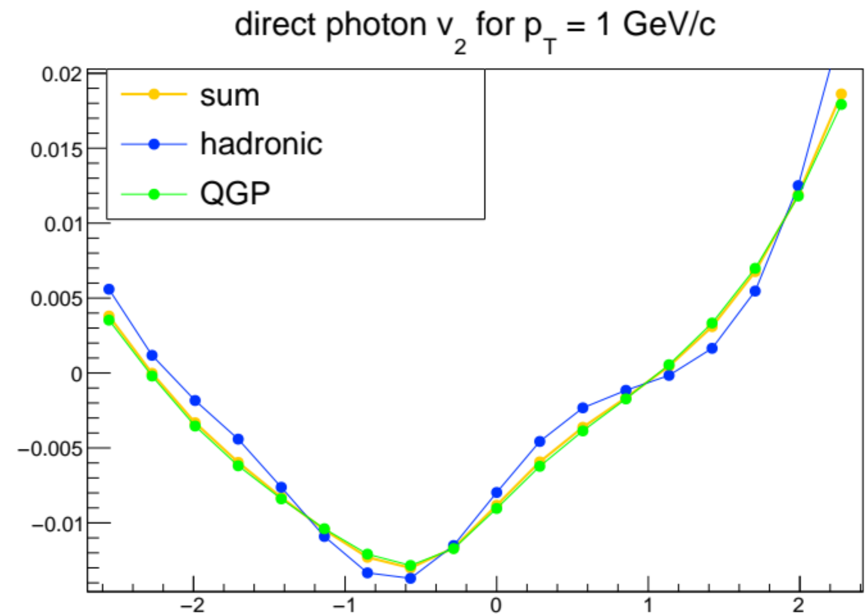
Very sensible to impact parameter

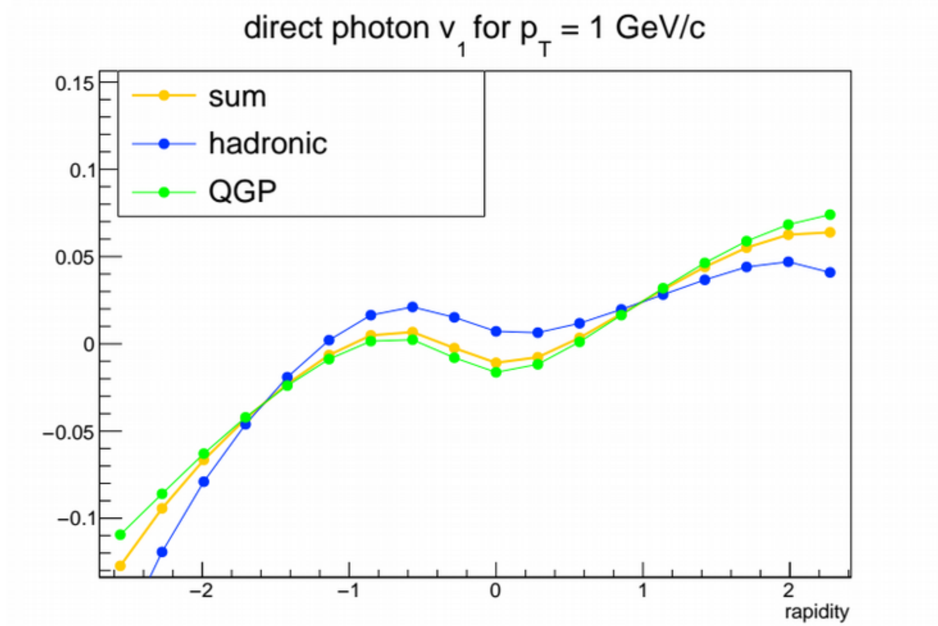


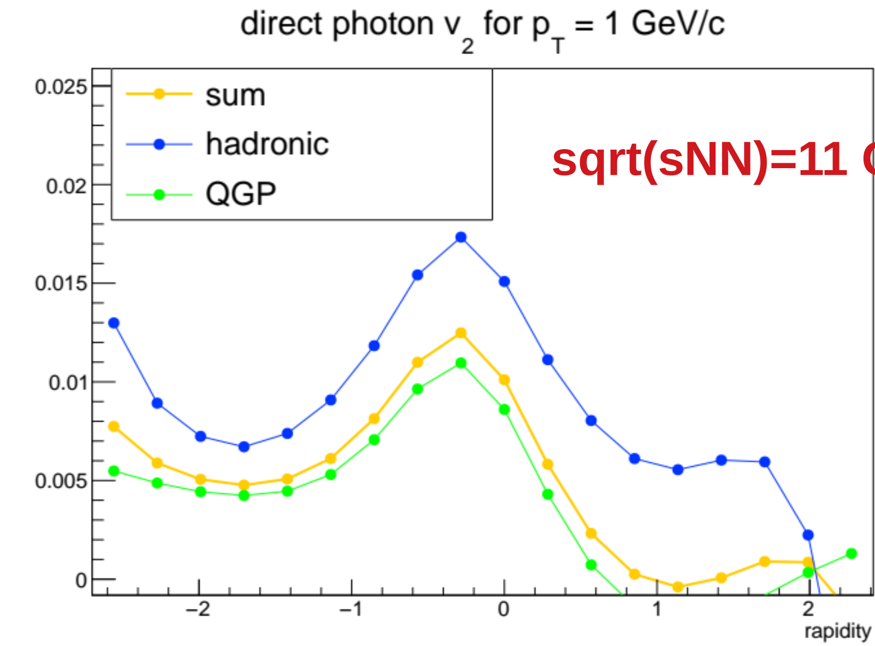
Very sensible to energy. b=4.5

sqrt(sNN)=17.2 GeV









sqrt(sNN)=11 GeV