Direct photon production in heavy-ion collisions at NICA energy

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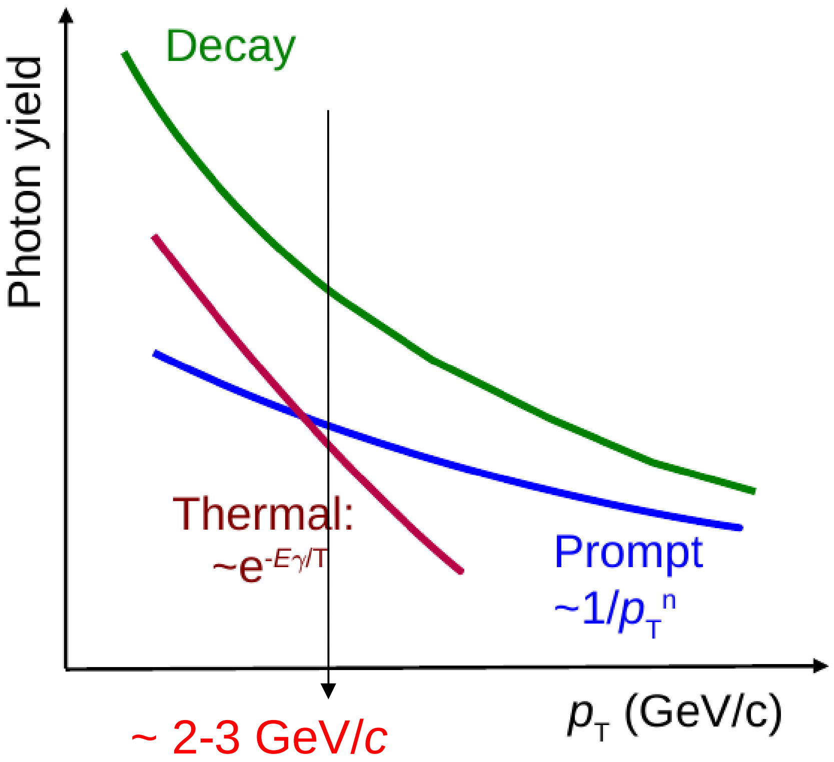
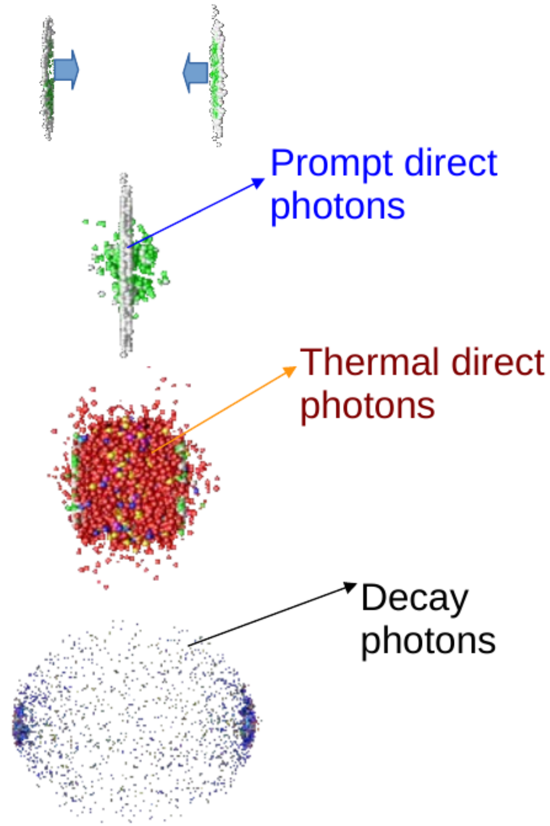
Direct and decay photons

- 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



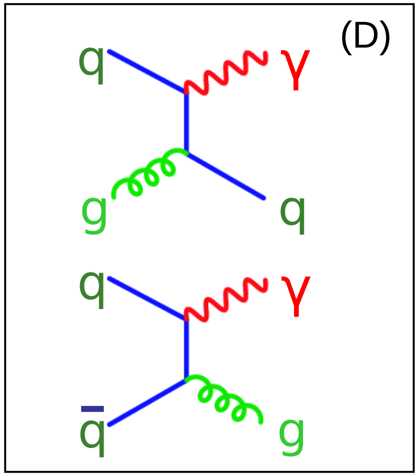


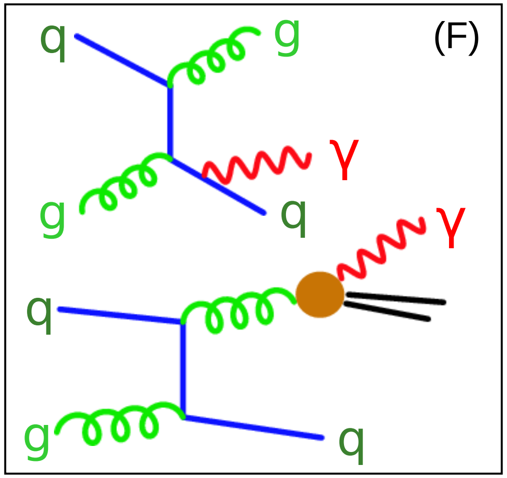
Motivation

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?)

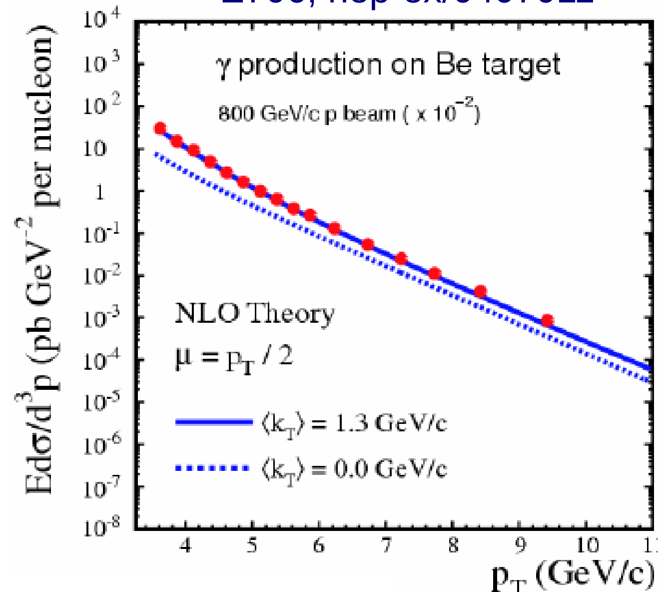
Calculation of prompt photon yield





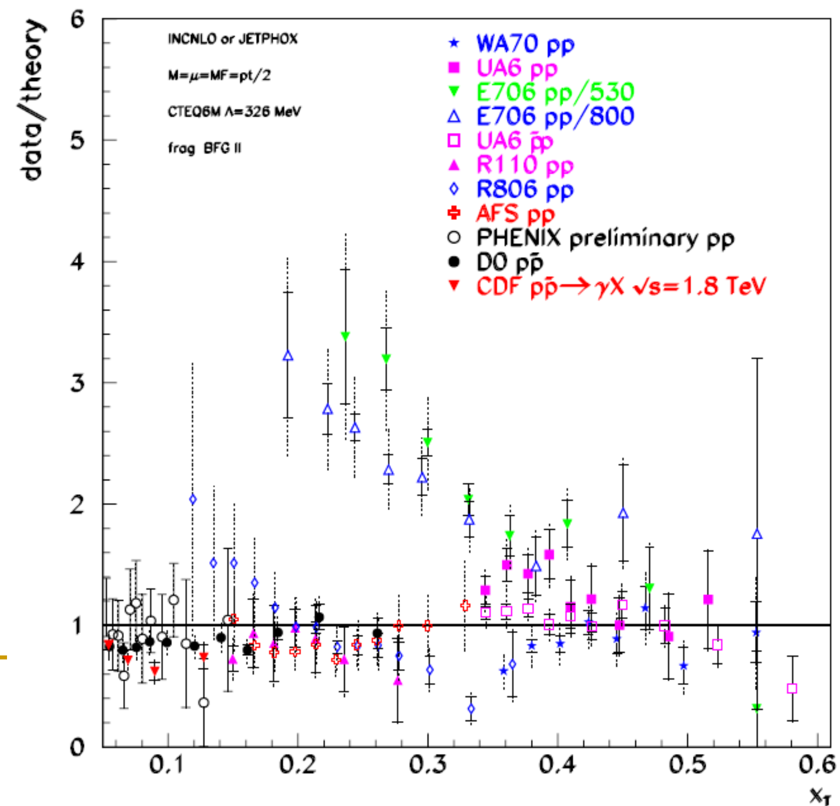
Straightforward calculations result in 2-5 smaller yield.
=>Fenomenological $\langle k_T \rangle$ broadening

E706, hep-ex/0407011

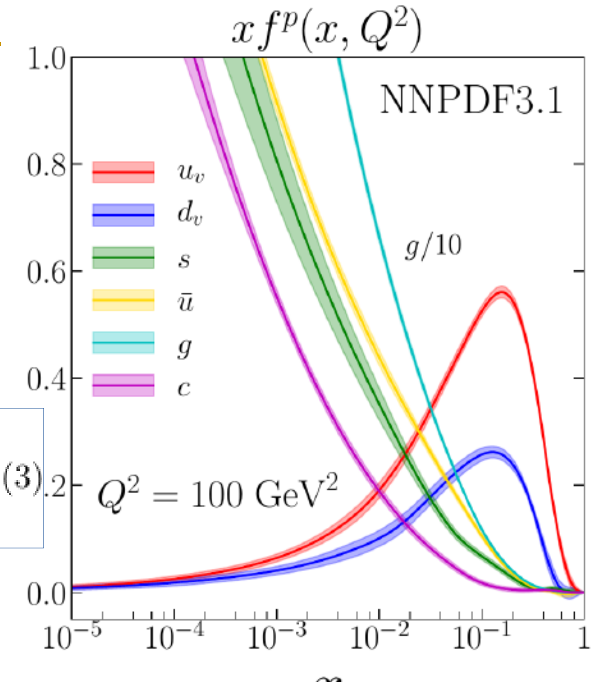


L.E. Gordon and W. Vogelsang, Phys. Rev. D 48 (1993) 3136; Phys. Rev. D 50 (1994) 1901
developed technique to perform joined recoil and threshold resummations

P. Aurenche et al., Phys.Rev.D73:094007, 2006
developed package Jetphox
https://lapth.cnrs.fr/PHOX_FAMILY/jetphox.html



Prompt photon yield calculation

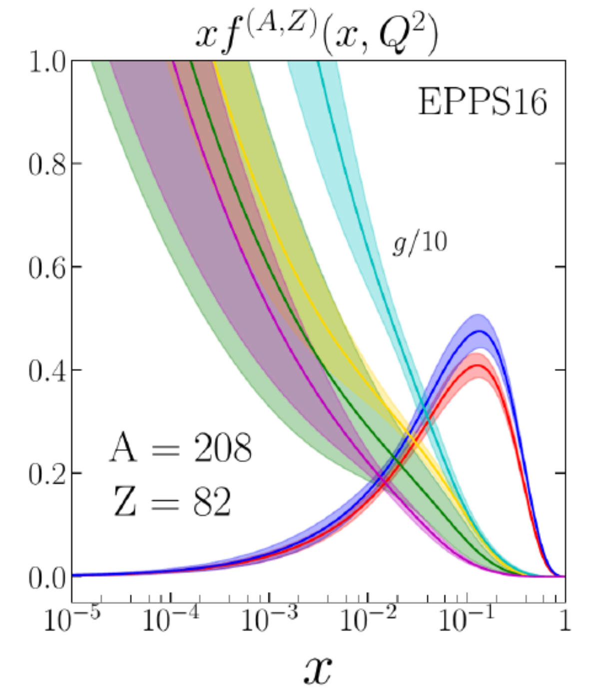


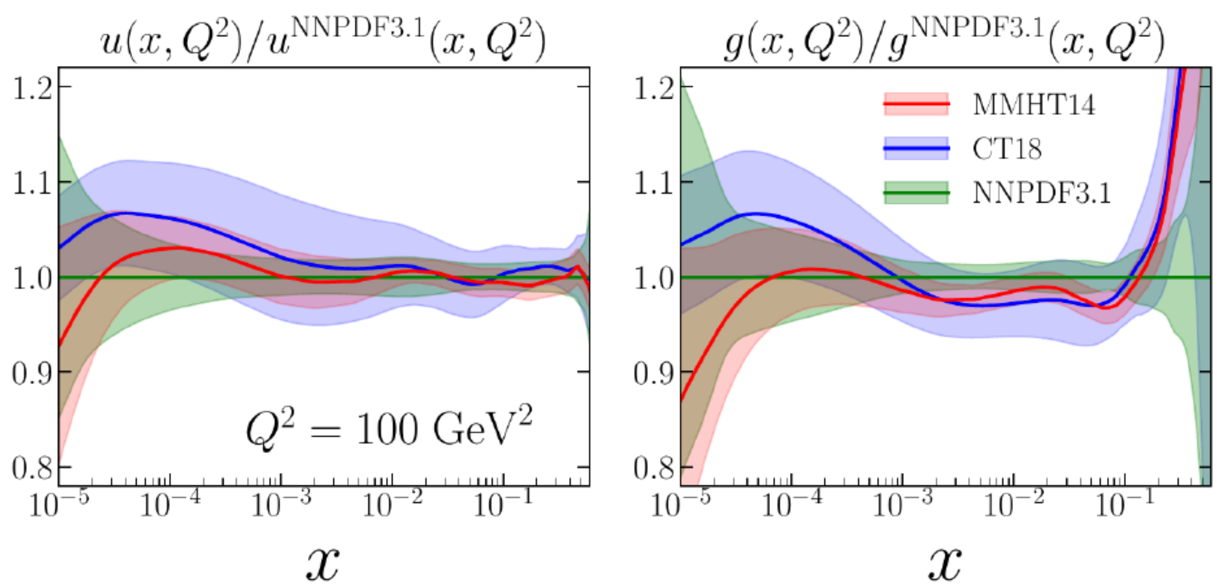
Direct photon spectrum in pp is a convolution of PDF, cross-section and FF

$$\frac{d\sigma^{(\mathrm{D})}}{d\vec{p}_T d\eta} = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 \; F_{i/h_1}(x_1, M) \; F_{j/h_2}(x_2, M) \frac{\alpha_s(\mu_R)}{2\pi} \left(\frac{d\widehat{\sigma}_{ij}}{d\vec{p}_T d\eta} + \frac{\alpha_s(\mu_R)}{2\pi} K_{ij}^{(\mathrm{D})}(\mu_R, M, M_F) \right) \quad (3)$$

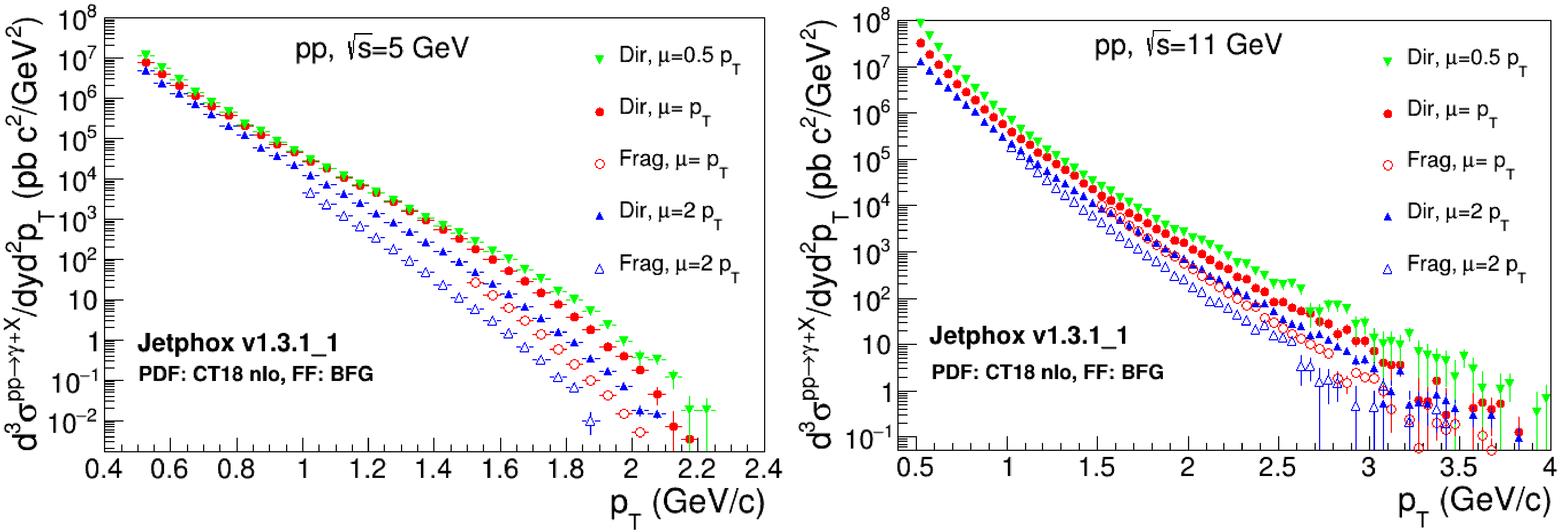
P. Aurenche et al., Phys.Rev.D73:094007, 2006

Present PDF parameterizations agree at mid-x but have large uncertainties at low-x and high-x regions.





Direct and fragmentation contributions



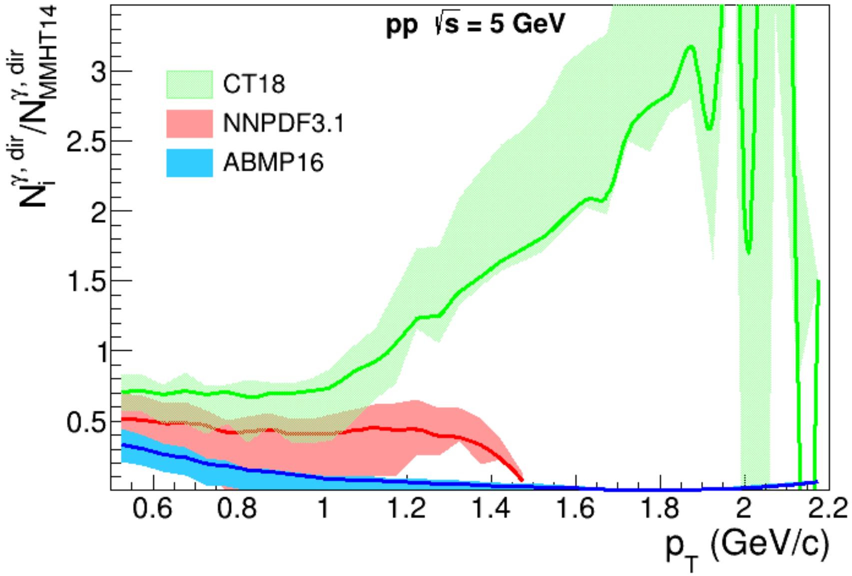
Parameters renormalisation scale μ_R, initial-state factorisation scale μ_I and fragmentation scale μ_F are arbitrary parameters and usually varied in range $\mu_R = \mu_I = \mu_F = \mu = p_T/2 \ldots 2p_T$ to estimate theoretical uncertainties

For small μ and p_T FF is not defined, can not estimate fragmentation contribution

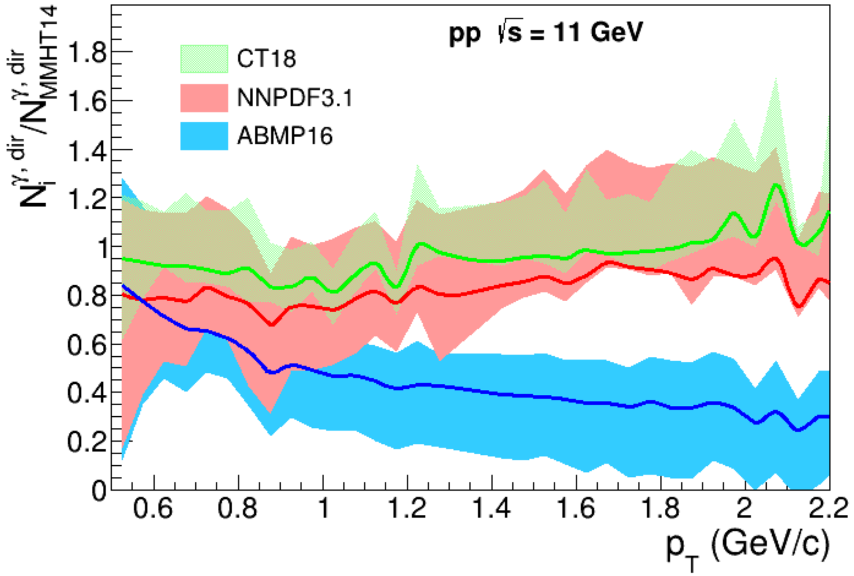
Fragmentation contribution is small at NICA/FAIR energies, neglect in the rest of presentation

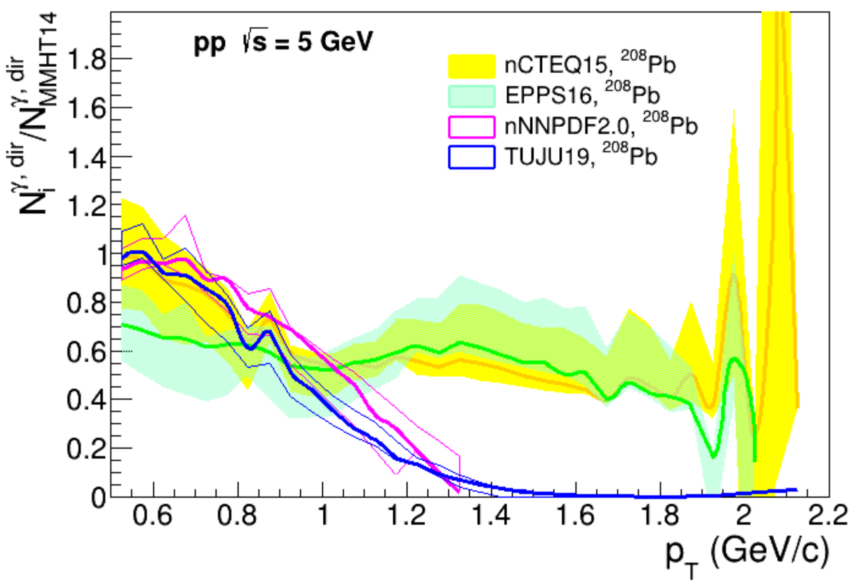
Uncertainties due to PDF choice

Ratio of prompt direct photon spectra calculated with different PDFs

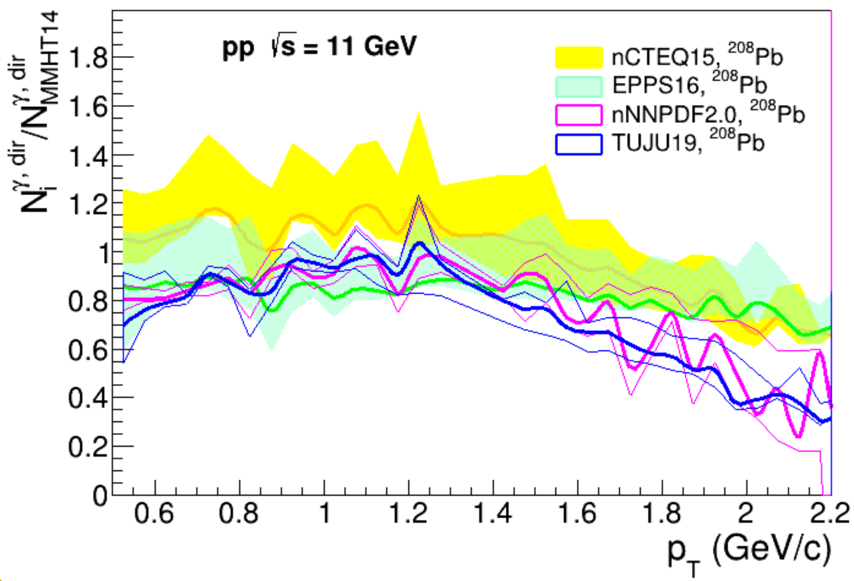


Proton PDFs





Nuclear PDFs



At mid-*x* PDFs agree, but high-*x*~1 especially at low √*s* are poorly constrained

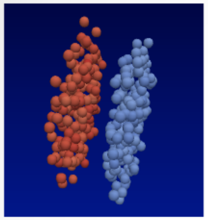
Thermal photon yield

$$\frac{d^3 N^{\gamma, therm}}{dy\, d^2 k_T} = \int_{\Omega} dV\, dt\, R_{\gamma}\left(k, T(x), \mu(x), u(x)\right)$$

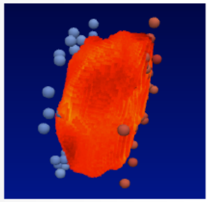
- UrQMD v3.4 with hybrid model (3+1d hydro, bag model EoS, hadronic rescattering and resonances within UrQMD)
- Parameterizations of thermal radiation from hadron gas [2] and QGP [3]
- π^0 yield is calculated with UrQMD hydro mode off (cto 45 0).
- Calculations are done at fixed b = 4.5 fm

[1] S. Turbide, R. Rapp, and C. Gale, PRC 69(2004) 014903
[2] P. Arnold, G. D. Moore, L. G. Yaffe, JHEP12(2001) 009

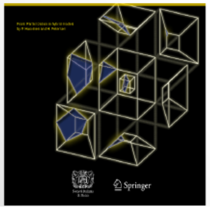
Hybrid model



- Initial State:
  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Initial state fluctuations are included naturally



- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Equation of state at finit μ_B

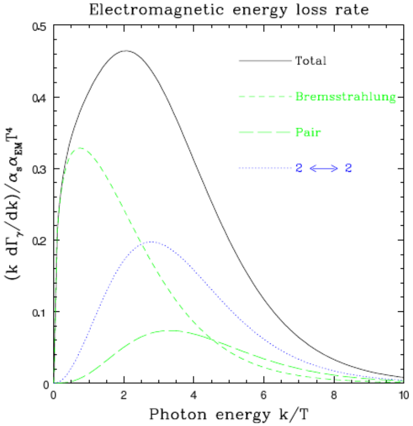


- Final State:
  - Hypersurface at constant energy density
  - Hadronic rescattering and resonance decays within UrQMD

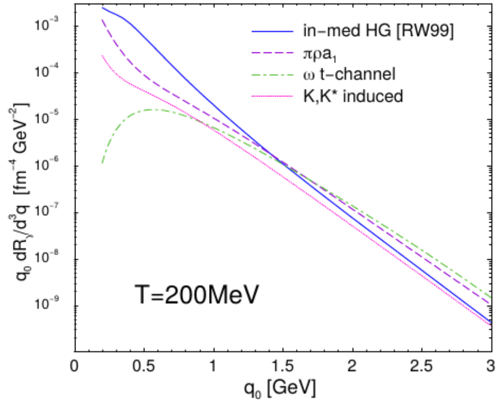
H.Petersen, et al, PRC78 (2008) 044901
P. Huovinen, H. P. EPJ A48 (2012) 171

Direct photon rate parameterizations:

QGP

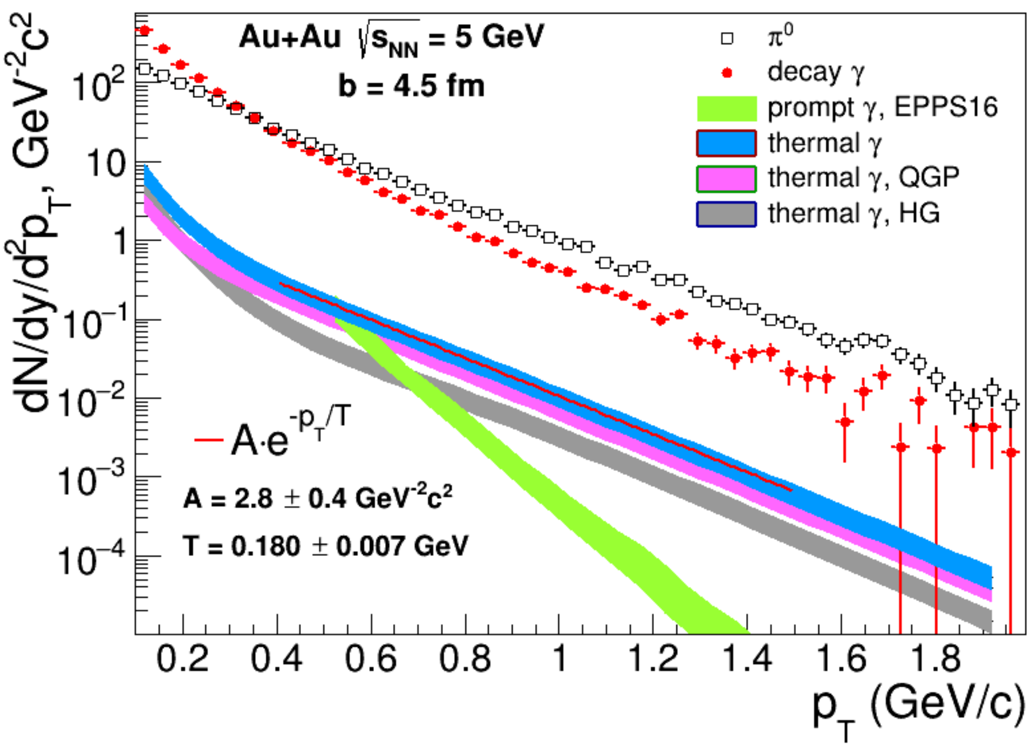


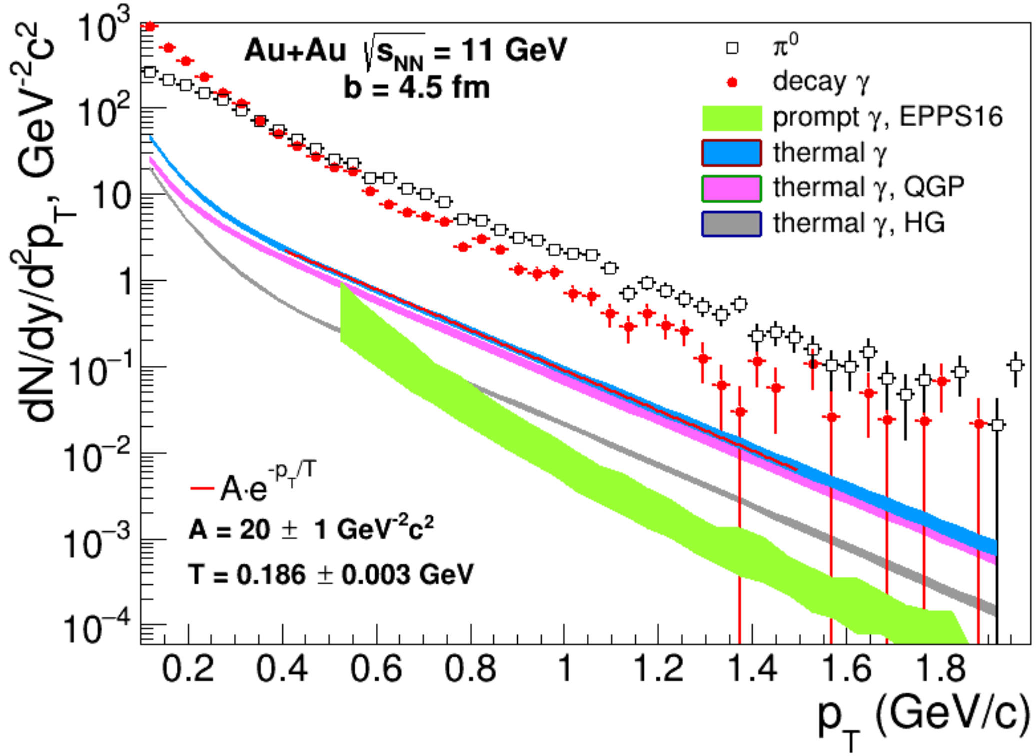
Hadron gas



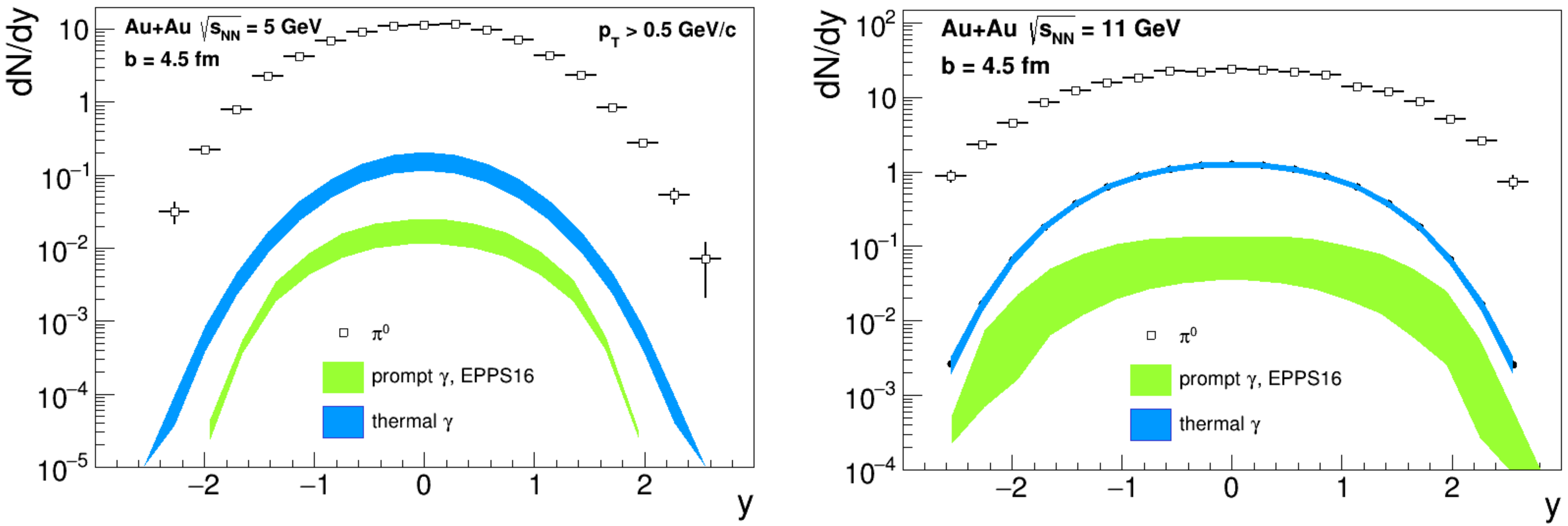
Direct and decay photon yield

- Direct photon yield ~20 times smaller than decay photon one
- Absolute yield of direct photons larger at larger $\sqrt{s_{NN}}$ as temperature and lifetime increases
- Prompt photon contribution is small and its importance decrease with decrease of $\sqrt{s_{NN}}$
- Event-by-event fluctuations (blue band) increase when decrease $\sqrt{s_{NN}}$
- What is the range of applicability of thermal emission model? p_T<5T? 10T? 100 T?





Rapidity distributions



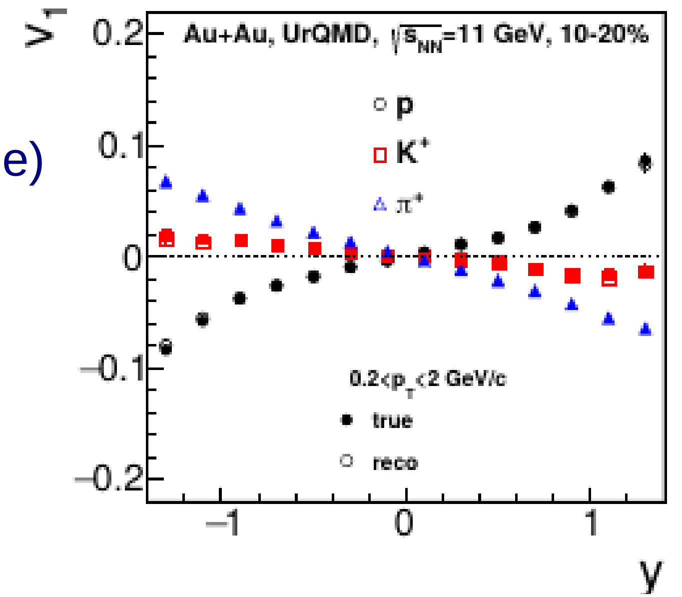
Thermal direct photon rapidity distribution narrower than one of π^0 and of prompt direct photons

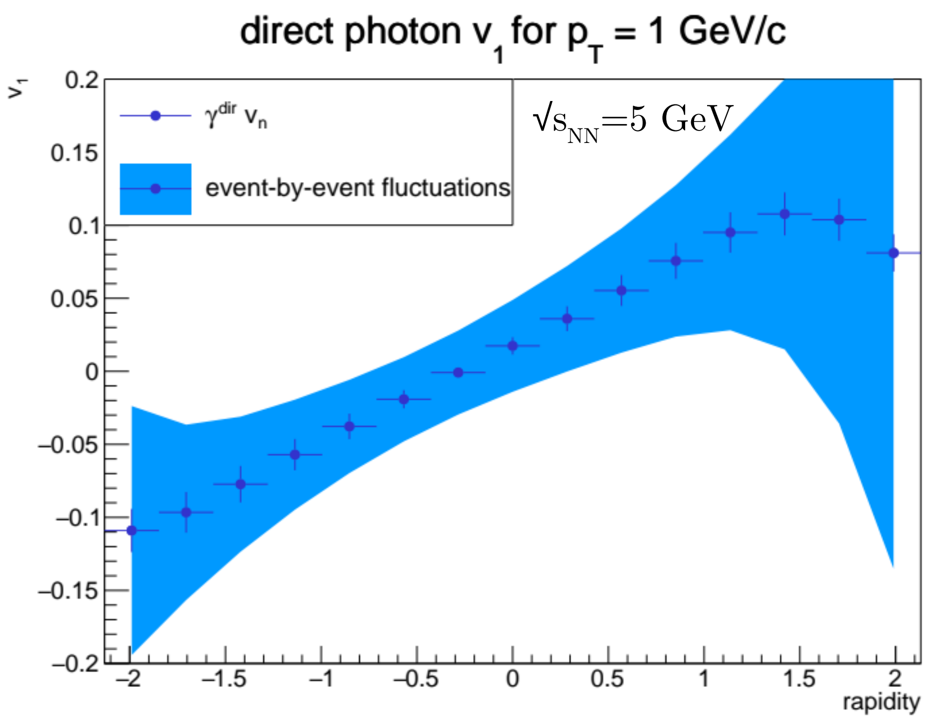
P.Parfenov et al, EPJ Web of Conf. 204, 07010 (2019)

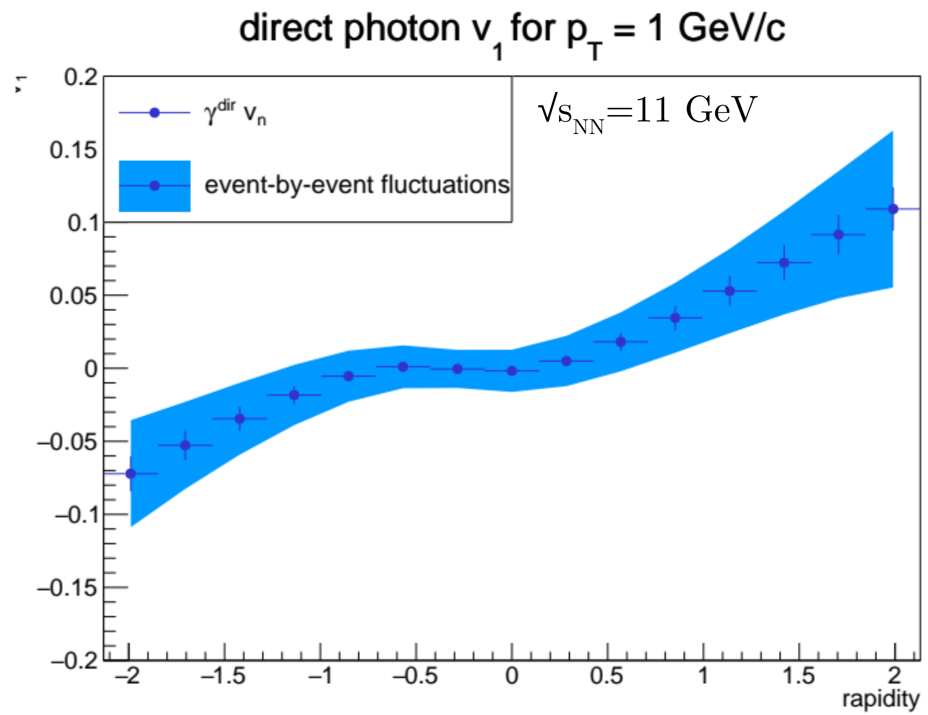
Collective flow

Direct photon flow measured at RHIC and LHC energies considerably larger than hydro predictions (photon flow puzzle)

- v_1 ~5 times smaller, shape similar to one of protons
- Fluctuations of v_1 dramatically increase with decrease of $\sqrt{s_{NN}}$
- (ToDo) Look at correlation of direct photon and hadron (proton) flow (select events with given flow)?

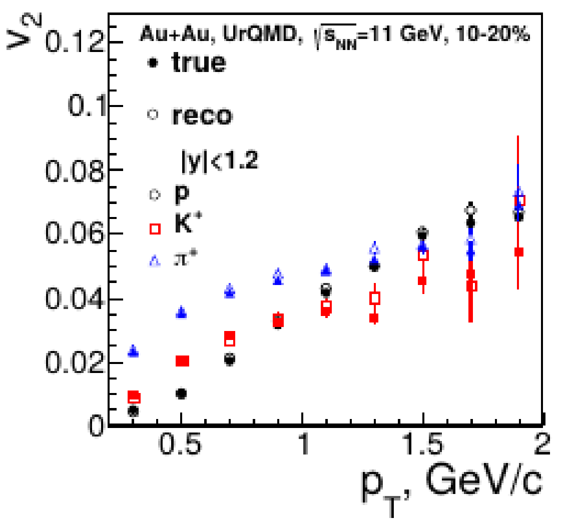




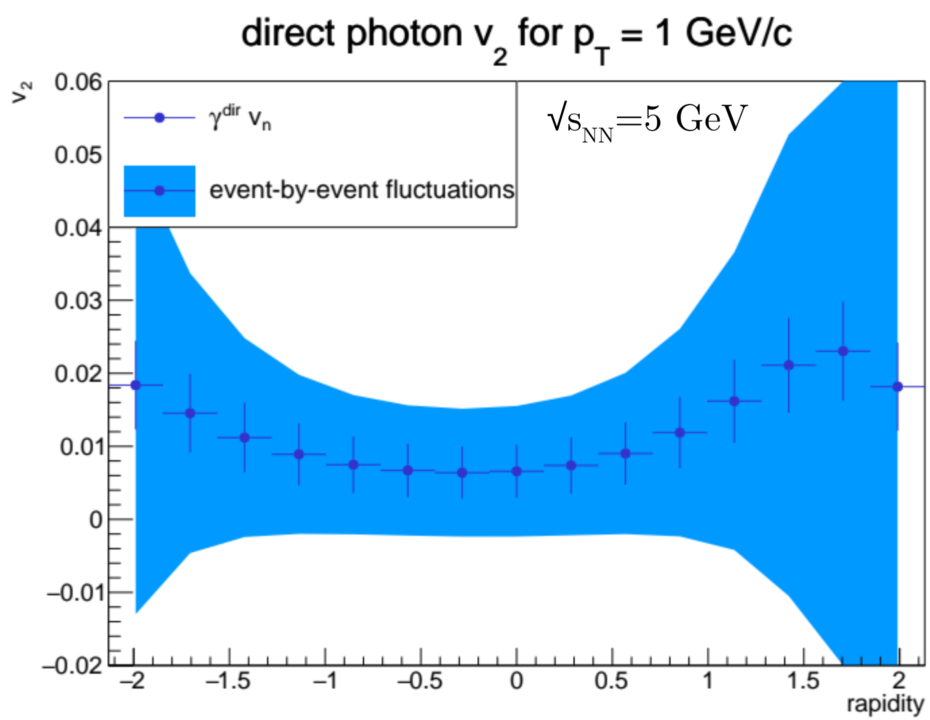


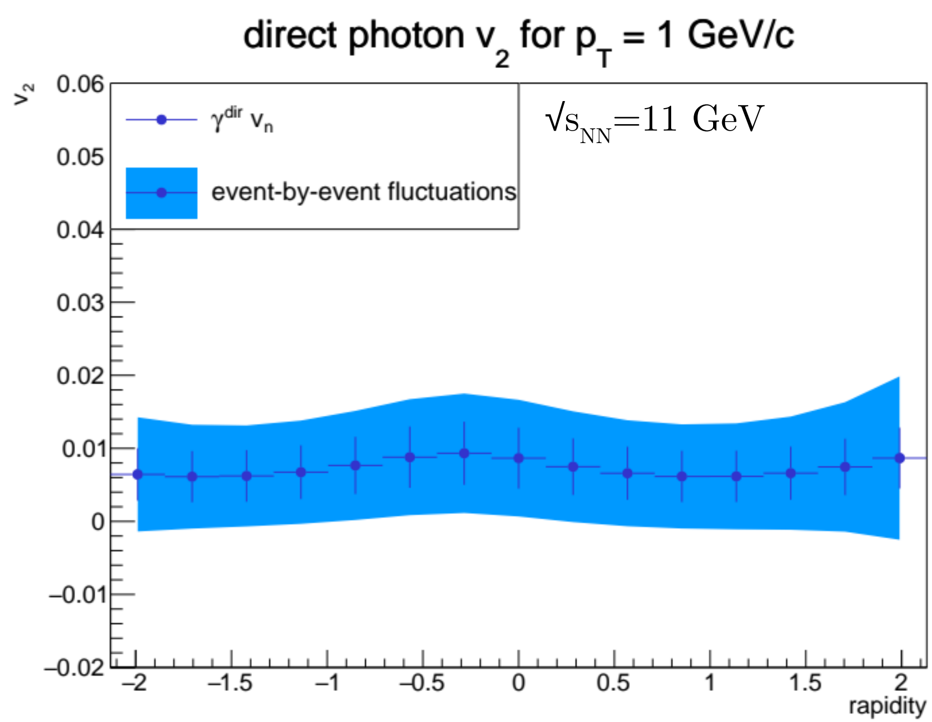
Elliptic flow

P.Parfenov et al, EPJ Web of Conf. 204, 07010 (2019)

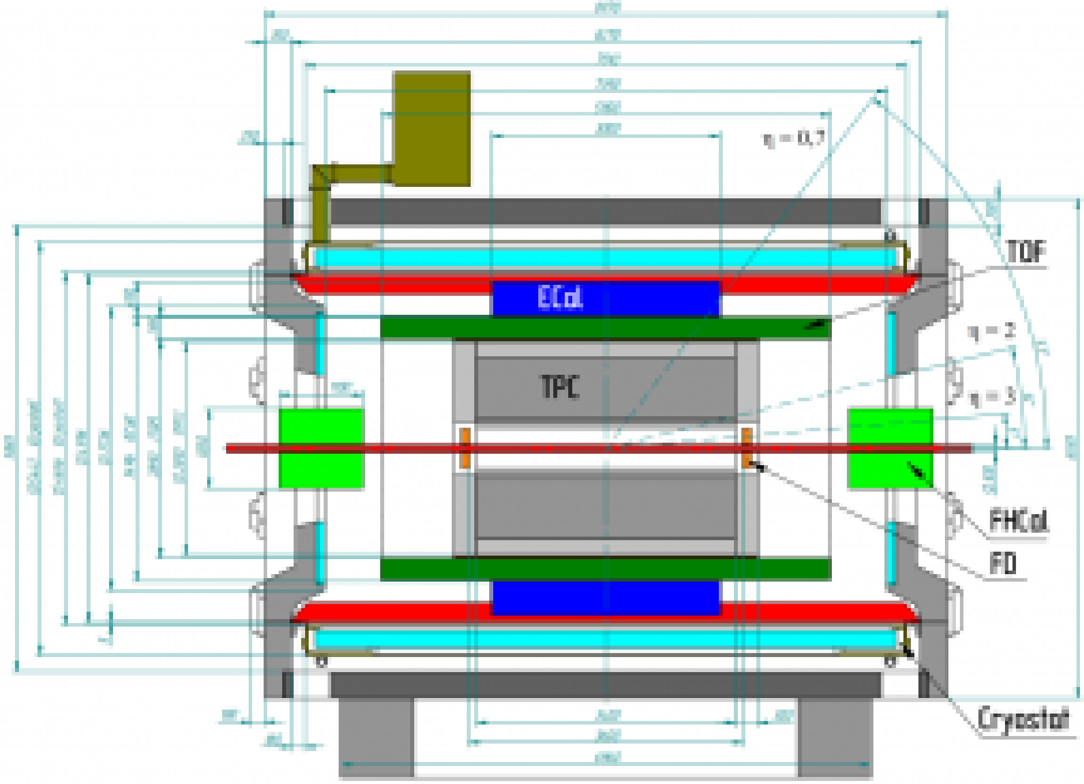


- v_2 about 5 times smaller (consistent with predictions at other energies)
- Fluctuations dramatically increase with decrease of $\sqrt{s_{NN}}$
- (ToDo) Look at correlations between photons and hadrons



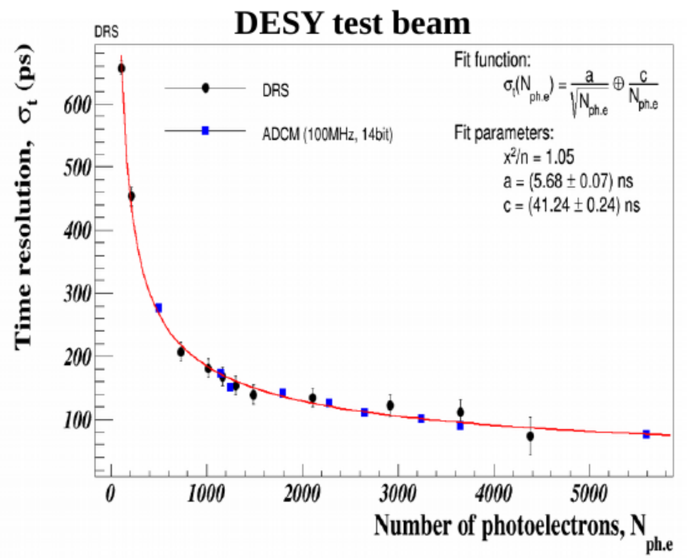


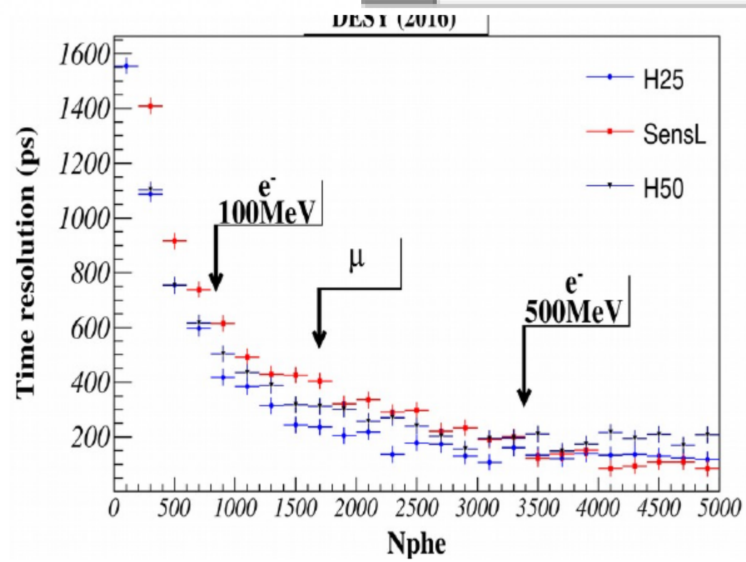
Possibility to measure direct photons with ECAL



Advantages of MPD electromagnetic calorimeter:

- Large acceptance |y|<1.2, full azimuthal angle coverage (?)
- Good energy resolution
- Photon PID: excellent timing resolution, expected to be ~ 500 ps at 100 MeV [1]





[1] TDR of the Electromagnetic calorimeter (ECal) rev. 3.6 (2018)

Direct photon reconstruction

Direct photon spectrum calculated as difference between inclusive and decay photons

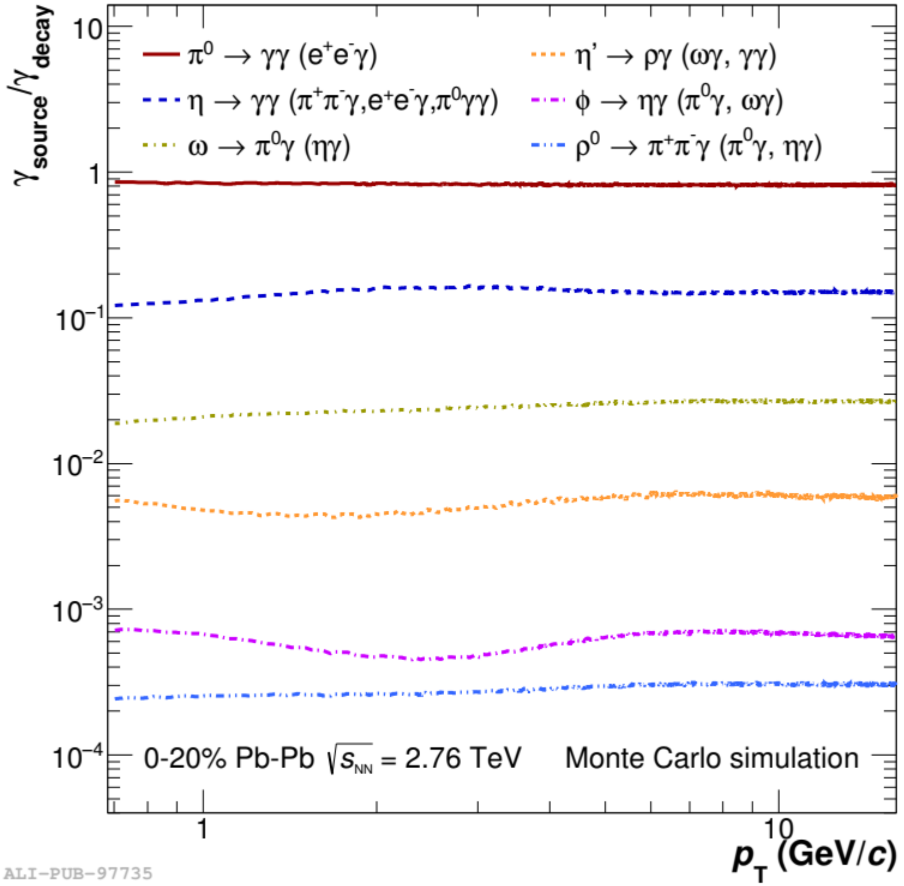
$$N_\gamma^{dir} = N_\gamma^{incl} - N_\gamma^{decay}$$

Up to ~90% of decay photons comes from π^0 decays. Some largest sys. uncertainties (fully: energy scale, partially: non-linearity, material budget) cancel in ratio

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{decay}} = \frac{\dfrac{N_\gamma^{incl}}{N_{\pi^0, meas}}}{\dfrac{N_\gamma^{decay}}{N_{\pi^0, MC}}}$$

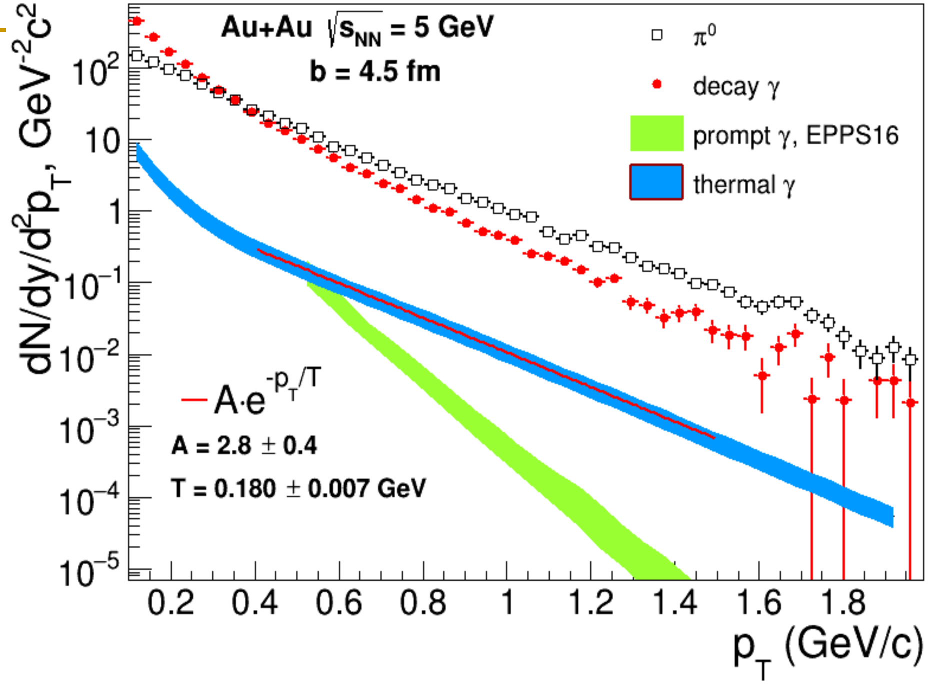
Direct photon spectrum calculate as

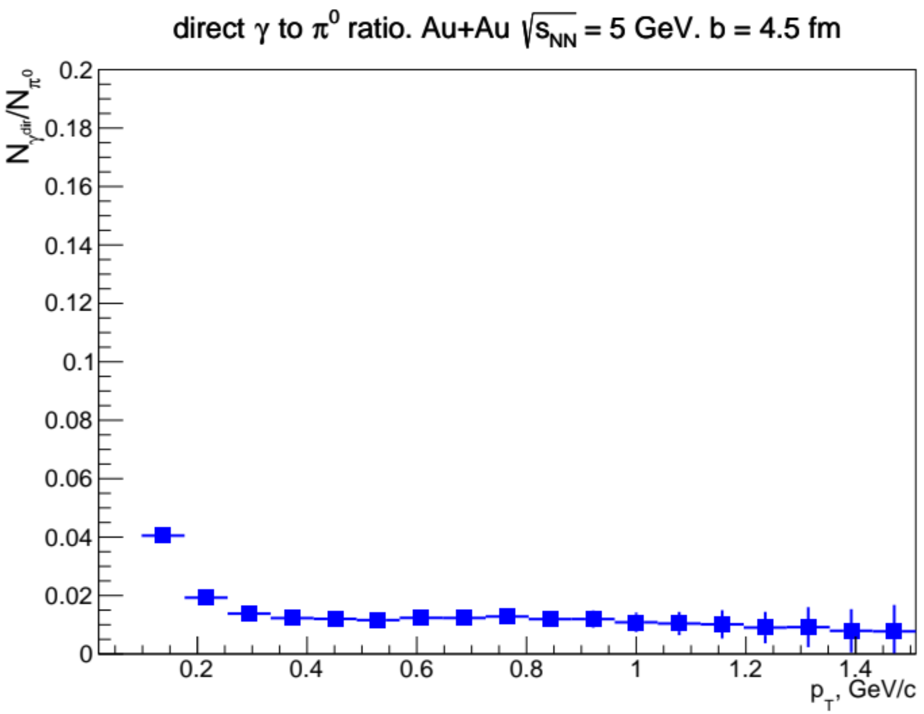
$$N_\gamma^{dir} = N_\gamma^{incl}\left(1 - \frac{1}{R_\gamma}\right)$$

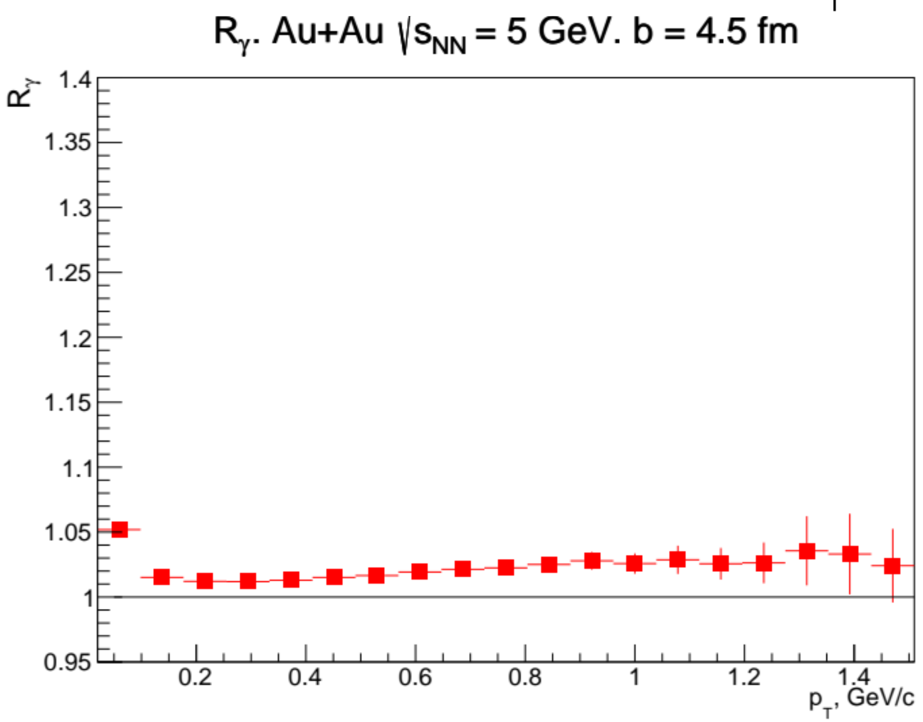


Au-Au, $\sqrt{s_{NN}}$ = 5 GeV

- $R_\gamma \sim 2\%$ at 1 GeV/c modest dependence on p_T
- Requires precise measurement of π^0 spectrum and good purity of photon spectrum
- Actual direct photon yield might be larger as usually hydro calculations under-predict spectrum by factor 2-5

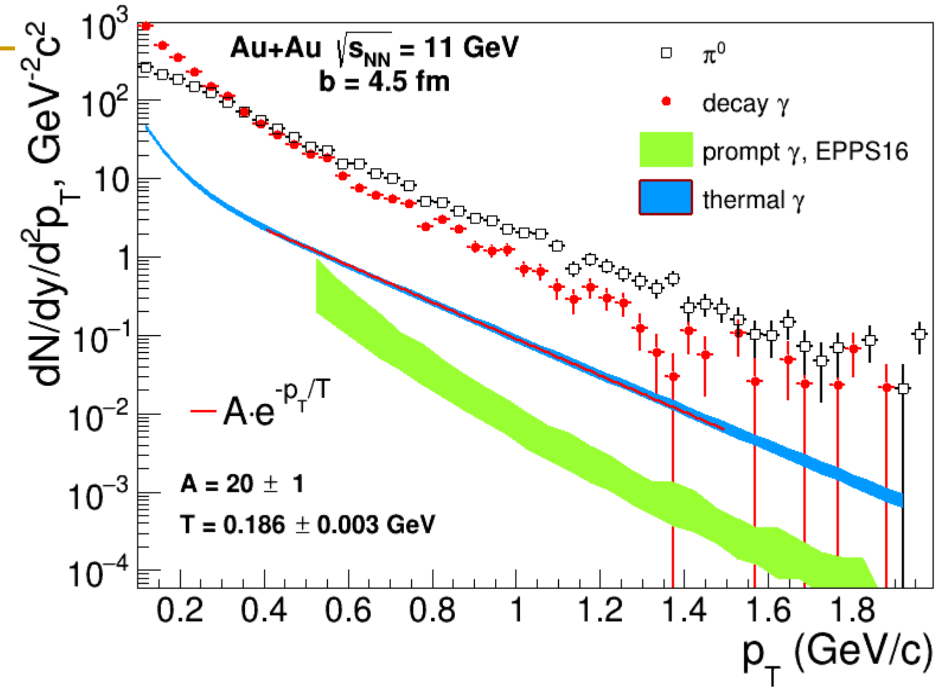


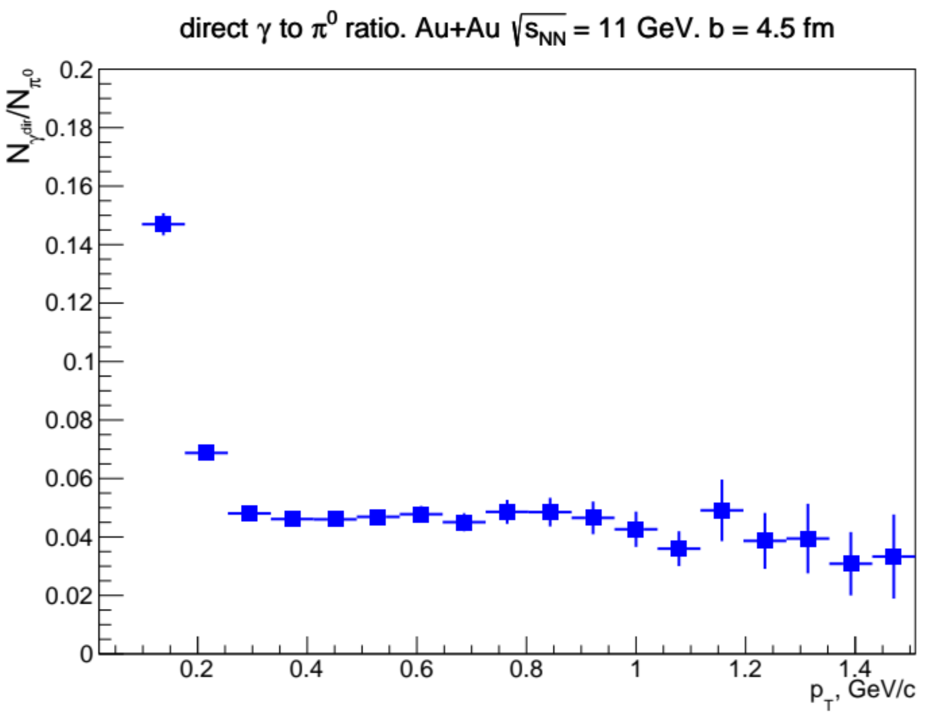


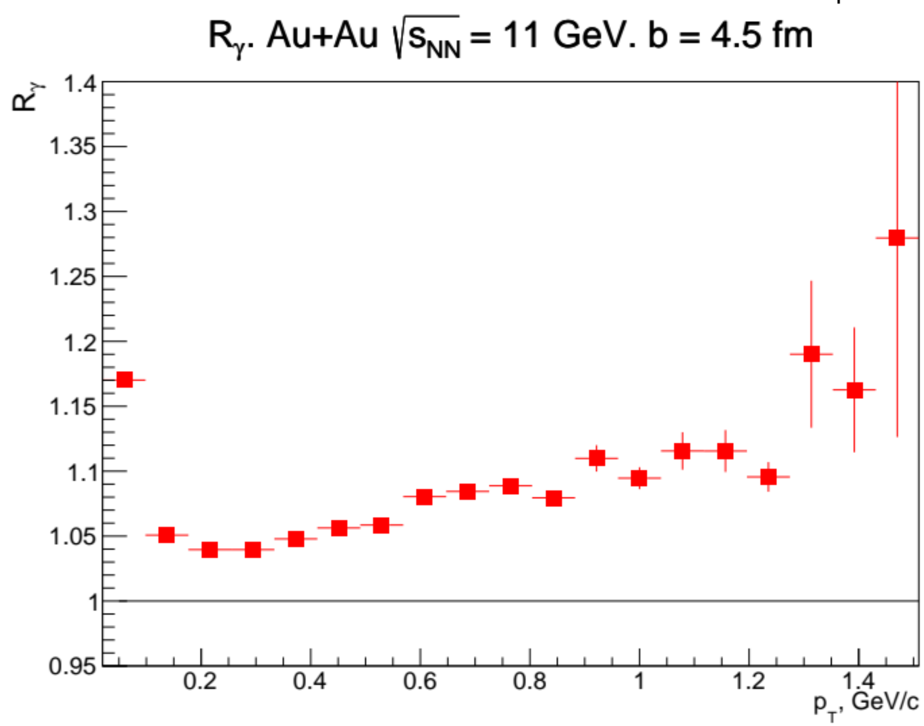


Au-Au, $\sqrt{s_{NN}} = 11$ GeV

- R_γ is ~ 5-10% at 1 GeV/c – looks feasible to measure!
- Event-by-event variations of the direct photon yield due to fluctuations of the initial conditions are modest (20-30%)

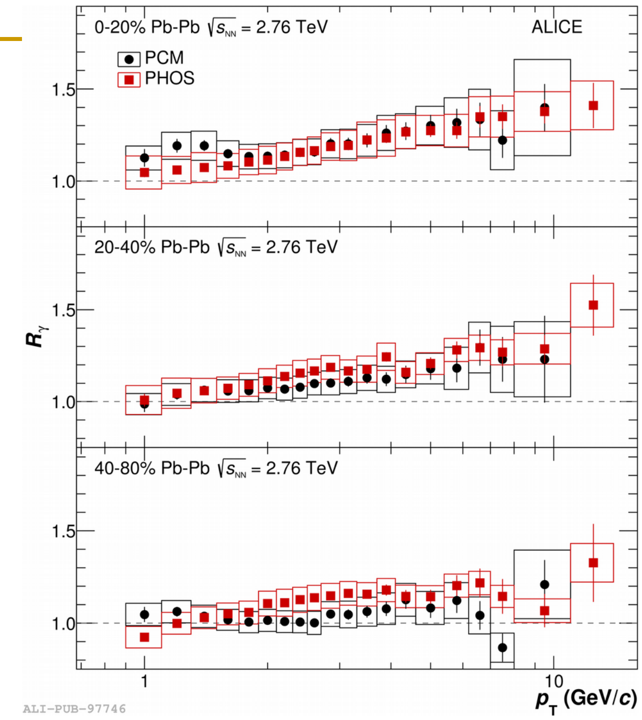


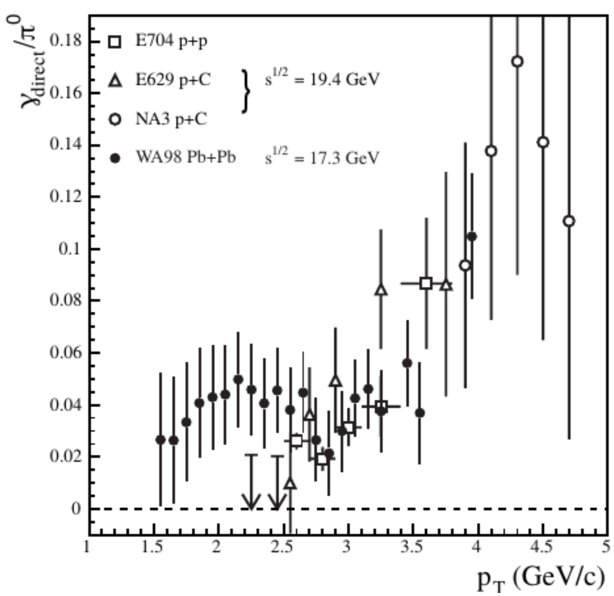


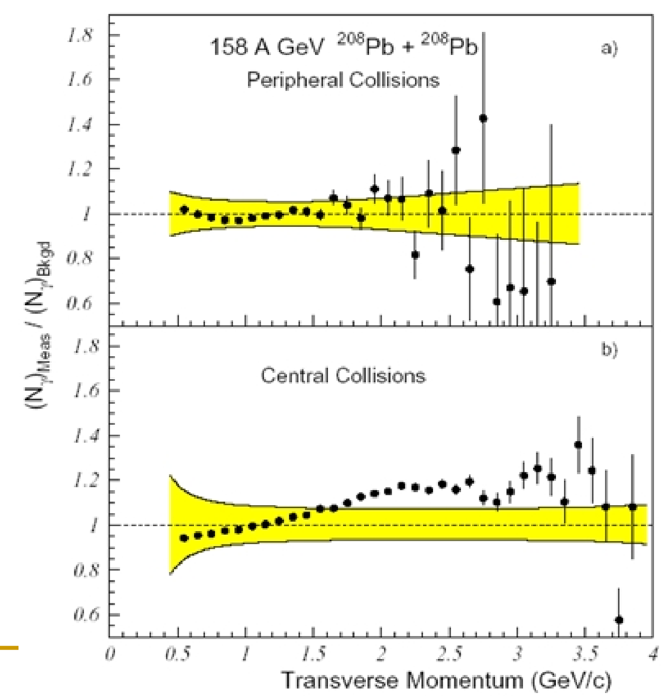


Ratio R_γ and ratio to π^0 yield

- R_γ ratio – ratio of inclusive photon spectrum to decay photons spectrum. If there is a contribution from direct photons, 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], R_γ is about 20% at 2 GeV/c



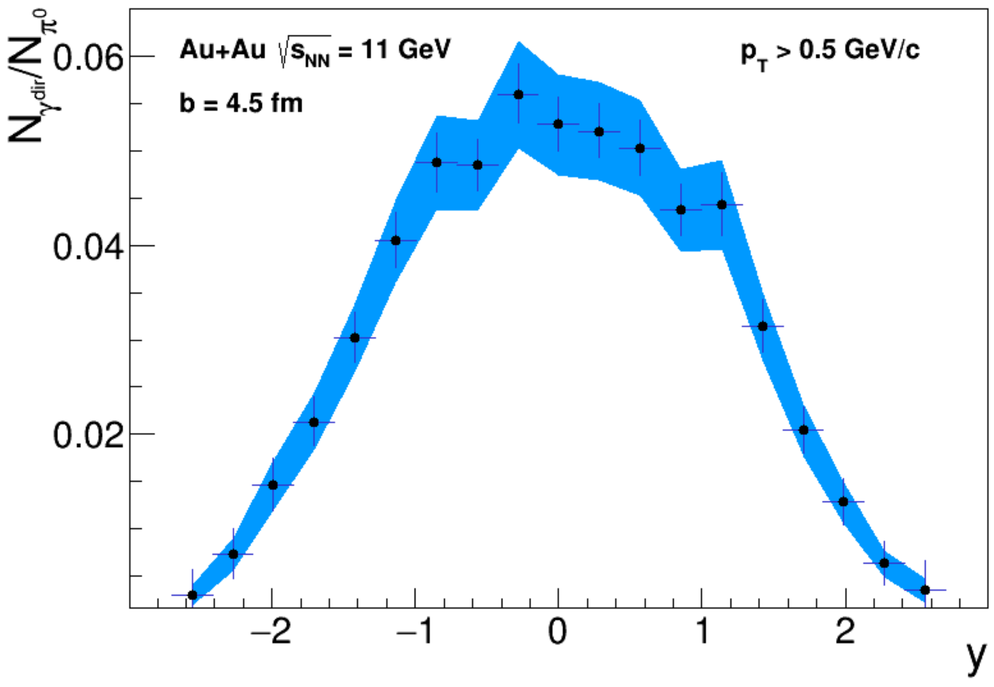


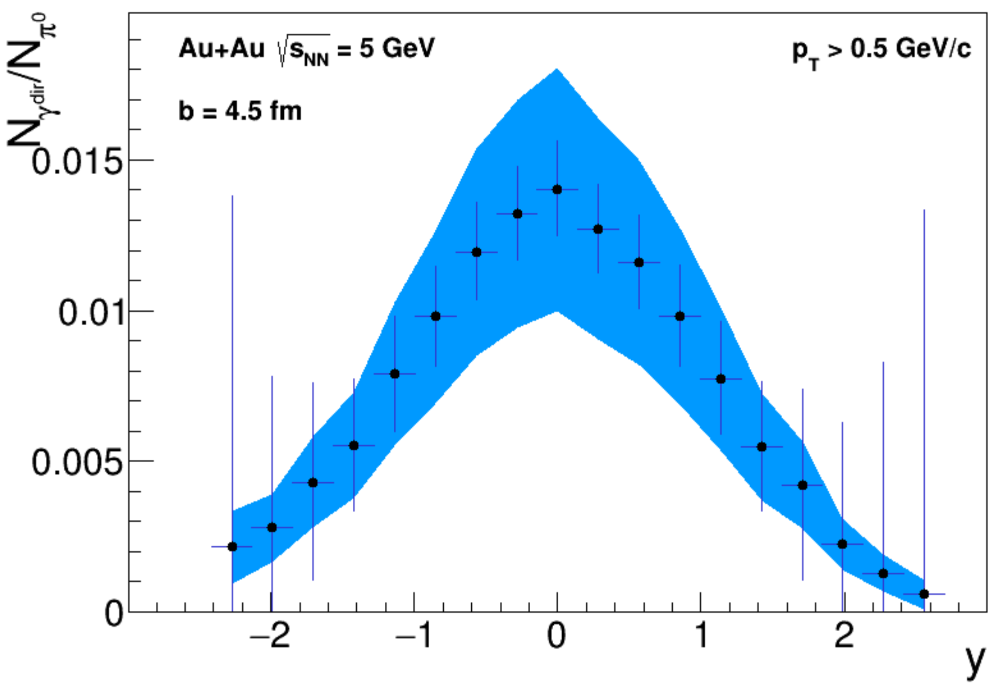


[1] J. Adam et al. (ALICE Collaboration) Phys. Lett.B 754(2016) 235-248
[2] T. Peitzmann, Pramana – J. Phys. V. 60 Issue 4 pp 651-661 (2003)

Rapidity dependence

- Can we for the first time measure rapidity dependence of direct photon yield? Would be very exciting!
- Thermal photon emission is more spherically symmetric
  => maximum of γ/π^0 ratio at mid-rapidity



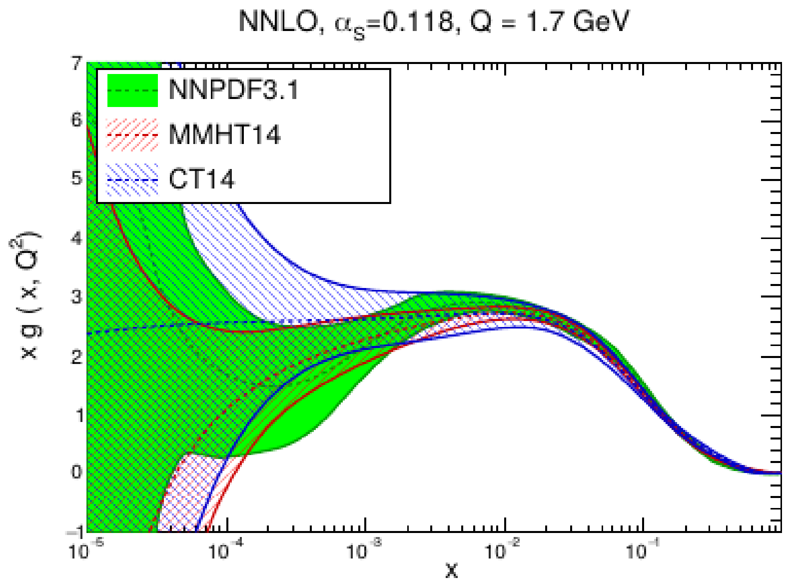


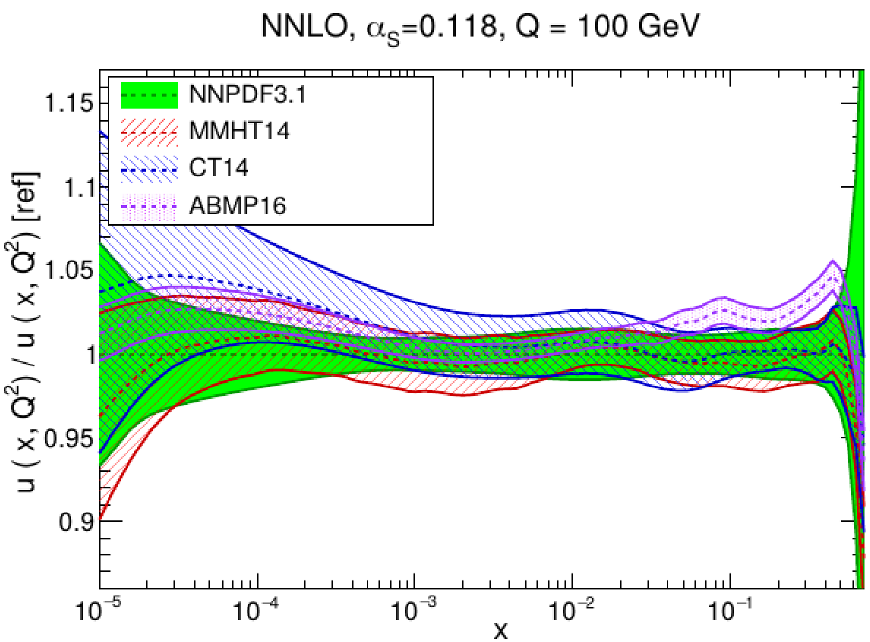
Conclusions

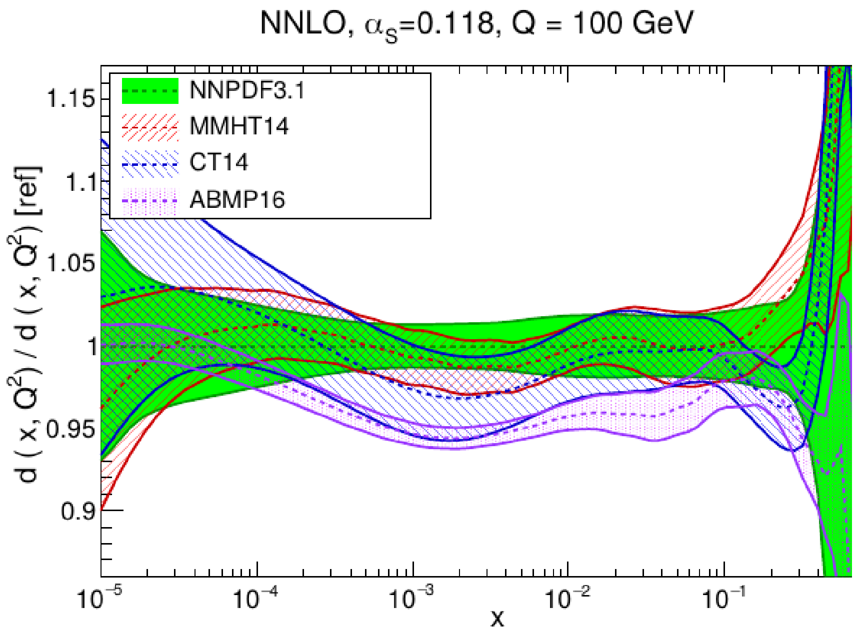
- Predictions of direct photon spectrum, rapidity distributions and flow at NICA top ($\sqrt{s_{NN}}$ = 11 GeV) and low energy ($\sqrt{s_{NN}}$ = 5 GeV).
- Direct γ to π^0 and R_γ ratios are calculated. R_γ is about 5% at 1 GeV for $\sqrt{s_{NN}}$ = 11 GeV. Measurement of direct gamma at NICA looks feasible.
- Direct photon rapidity distribution are calculated. It appeared to be somewhat narrow than one of final hadrons
- Collective flow v_1 and v_2 coefficients dependence on rapidity are calculated. v_1 is similar to those of protons but 2-5 times smaller. v_2 is about 5 times smaller (consistent with simulations at high energies).
- As a cross-check, direct photon simulations using UrQMD are performed and tested for SPS energy 158 AGeV, compared to WA98 results and previous simulations.

Backup

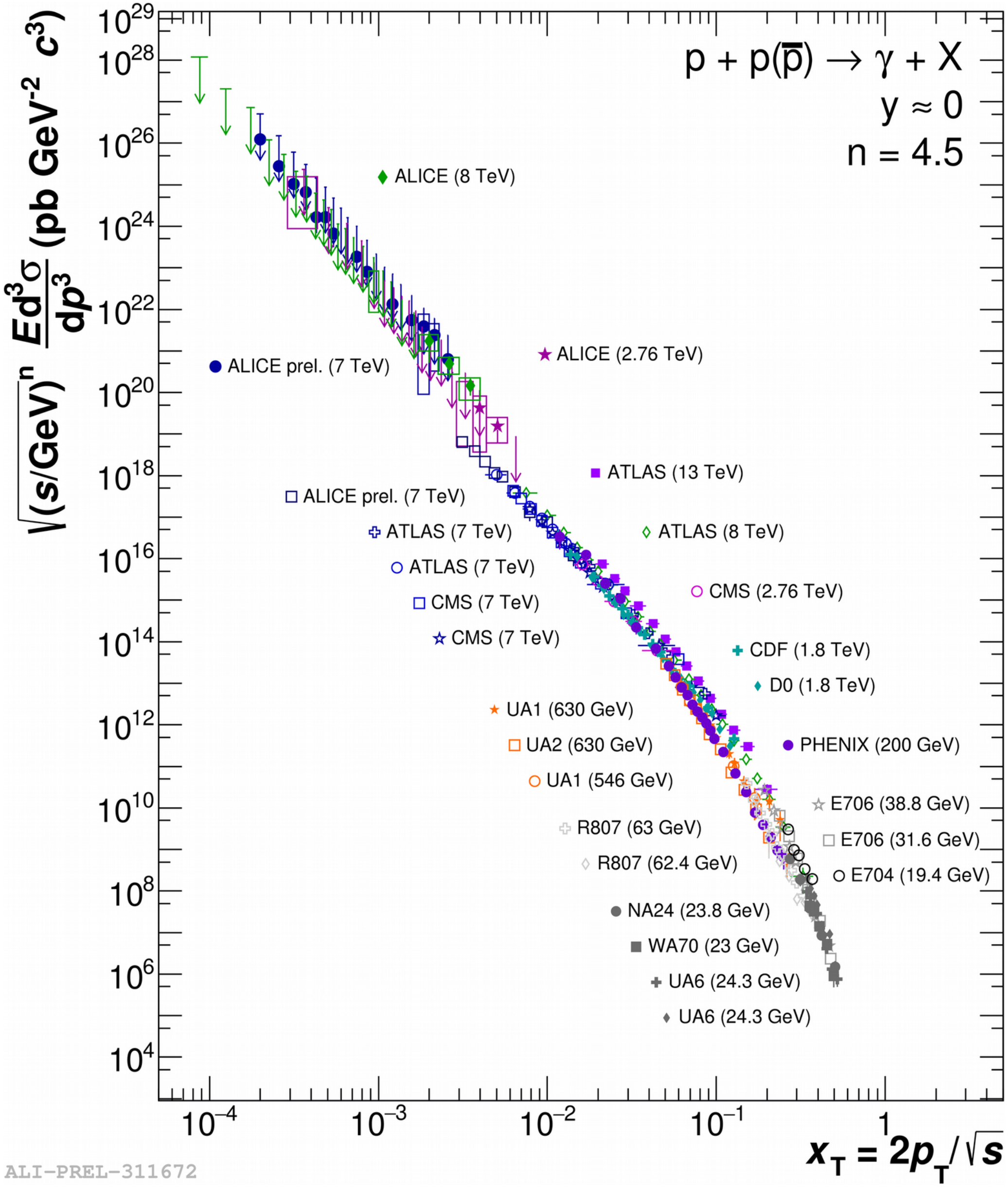
Prompt direct photons comparison of PDF

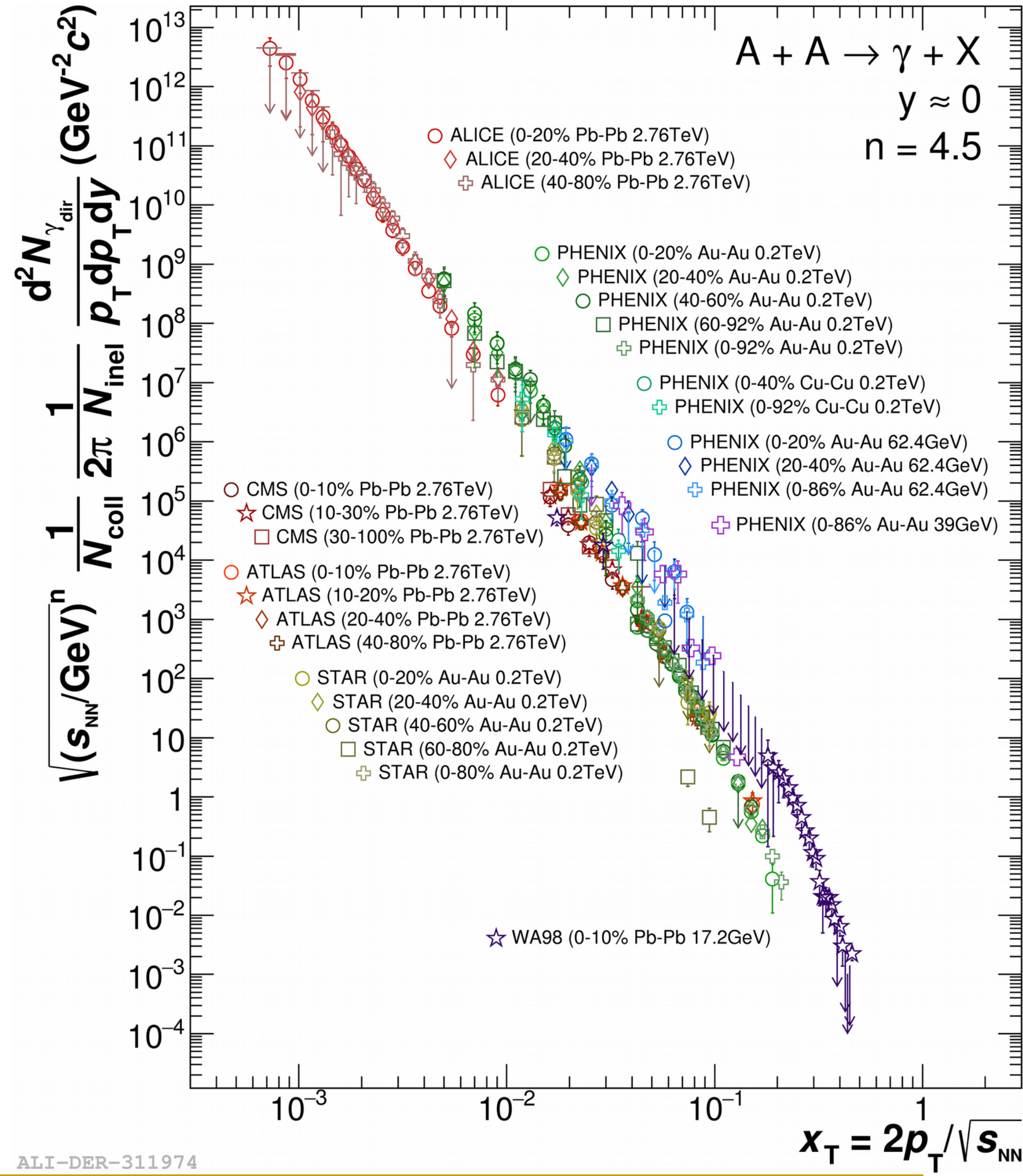






Direct photon scaling

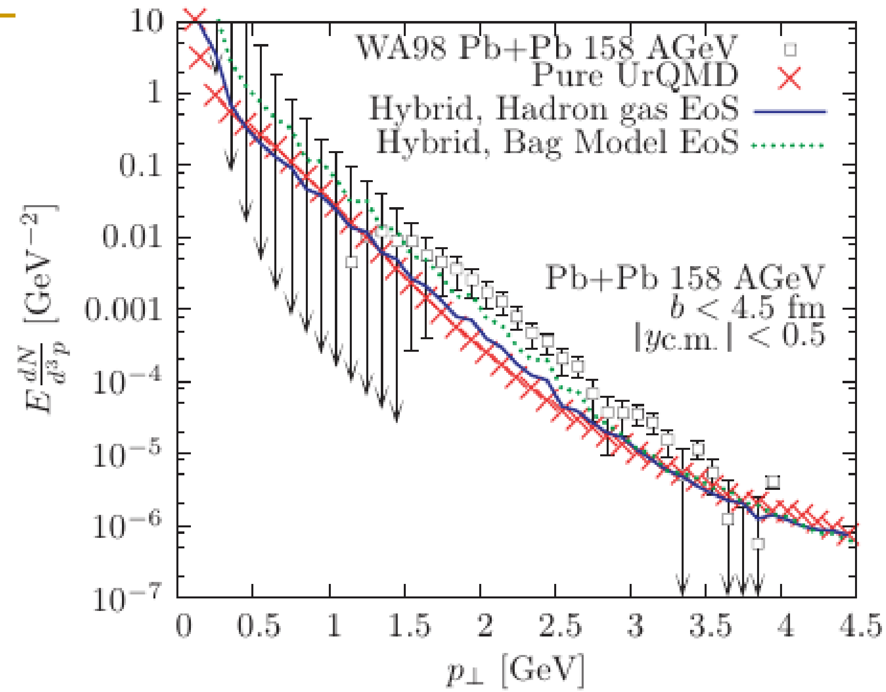


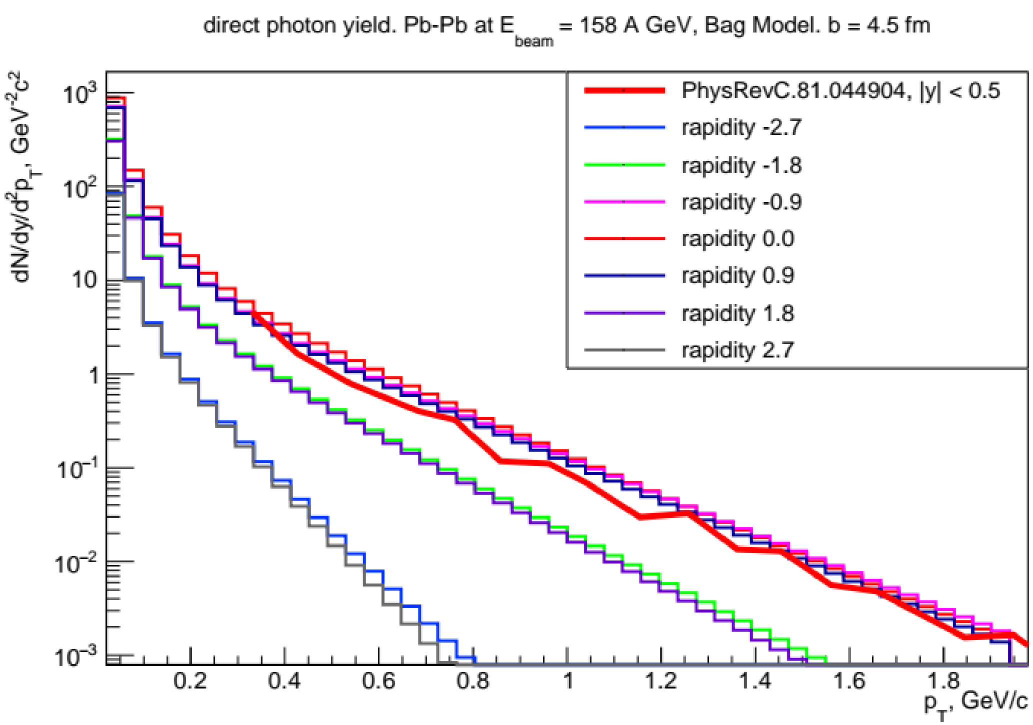


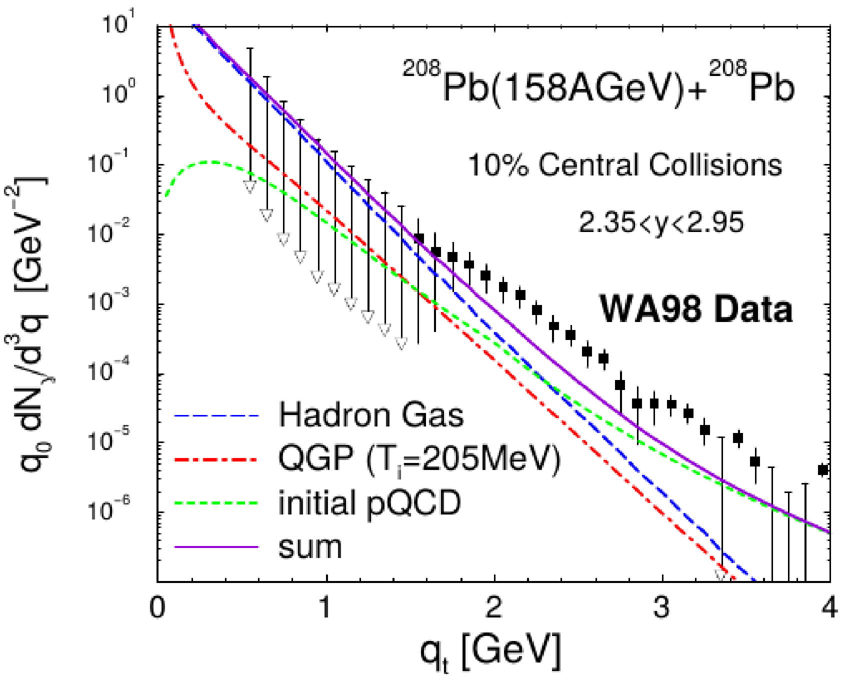
Calculations for Pb-Pb at $\sqrt{s_{NN}} = 17.2$ GeV

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!







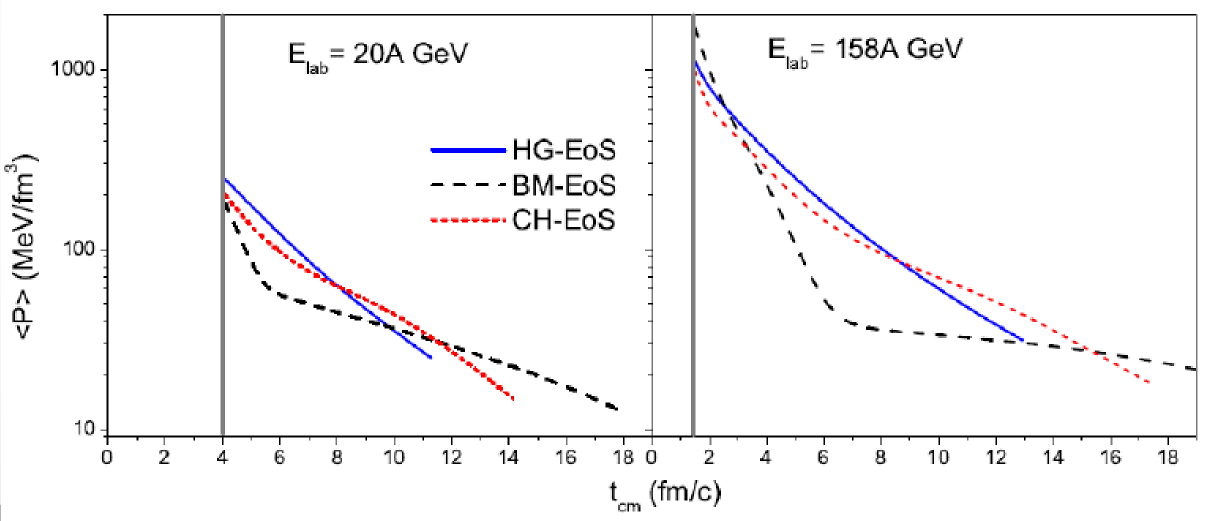
[1] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[2] S. Turbide, R. Rapp, and C. Gale, Phys. Rev.C 69(2004) 014903

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,

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