Progress on estimation of the direct photon yields and flow in Au+Au collisions at 4-11 GeV

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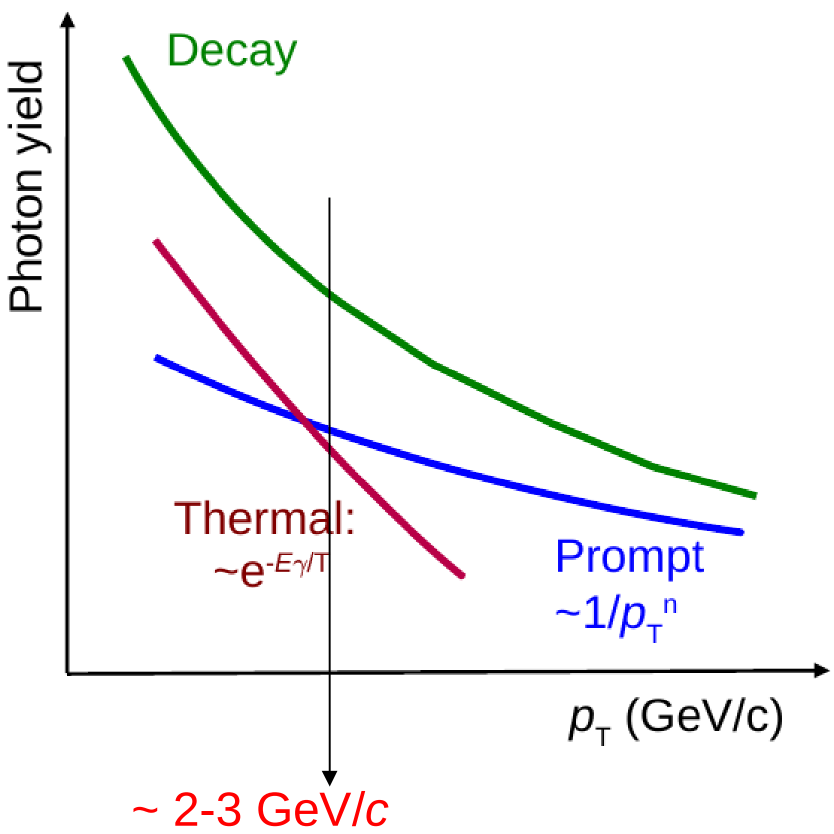
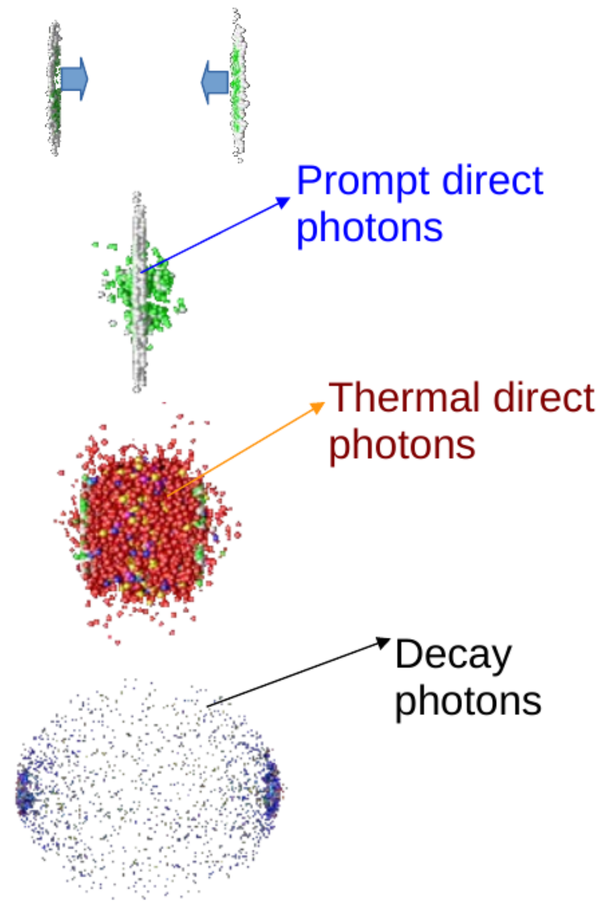
Motivation

- 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

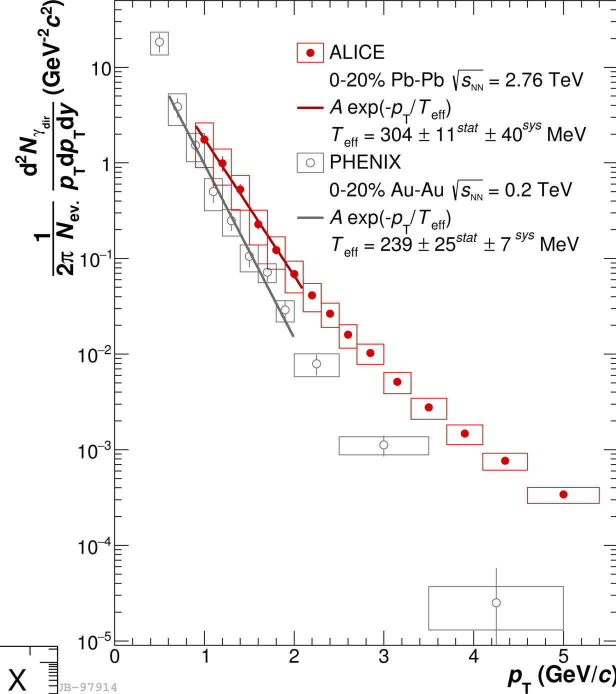


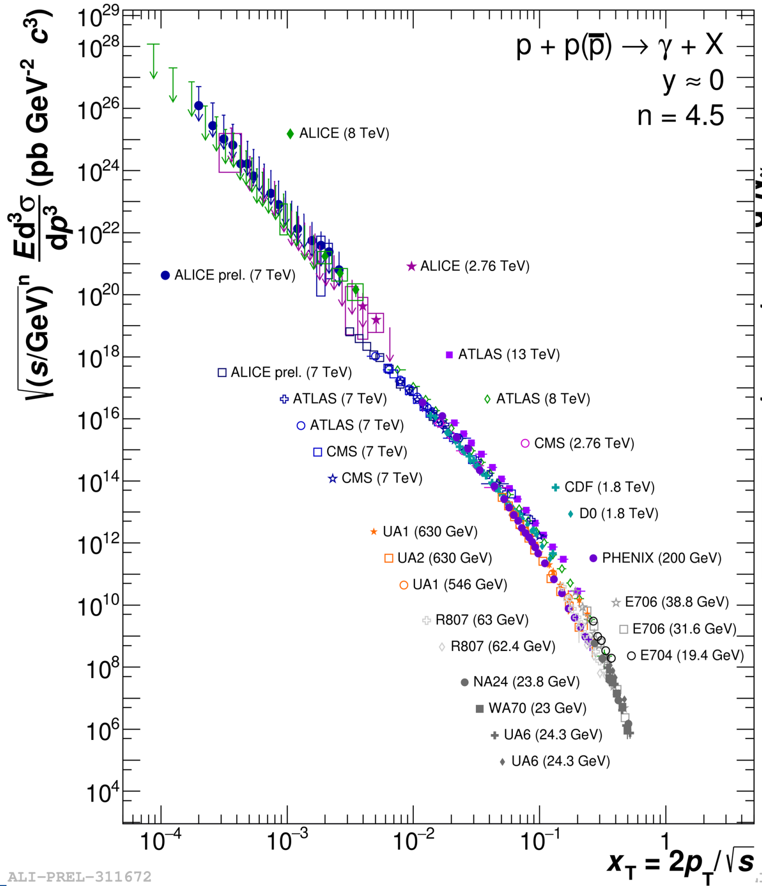


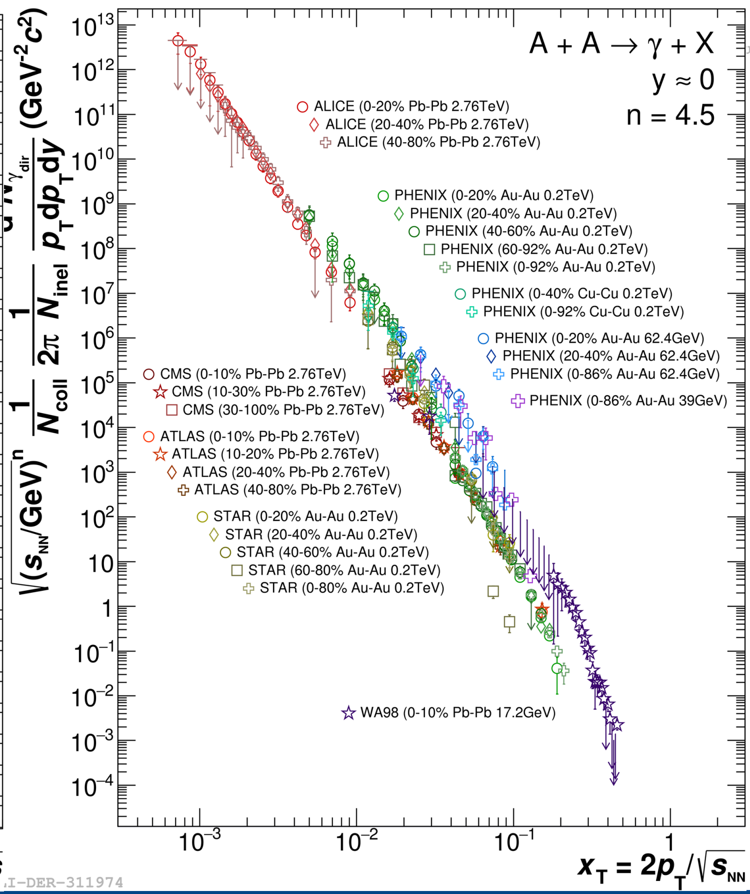
Motivation

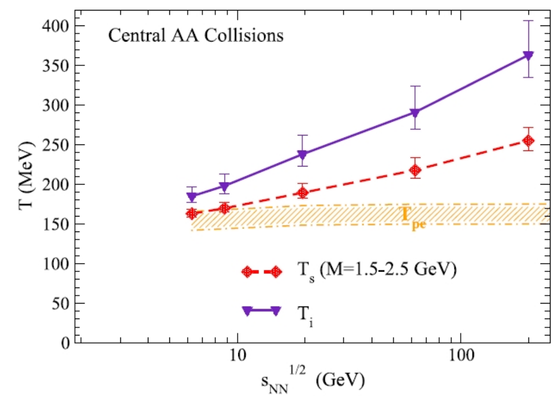
What we can study with direct photons:

- ✓ 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?)







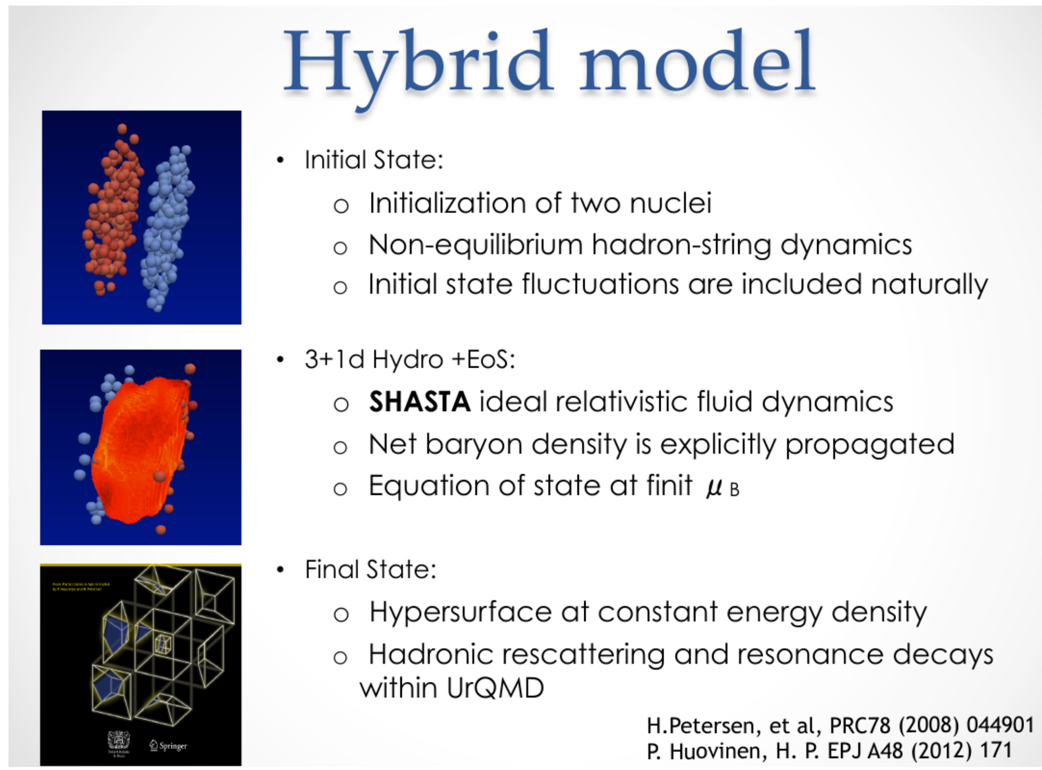


R. Rapp, H. van Hees
Physics Letters B 753 (2016) 586–590

Goal of the direct photon simulation studies

- ✓ Estimate thermal direct photon yield and direct photon excess ratio (R_γ) for top and low NICA energies for central and semi-central collisions.
  - Use UrQMD model in hybrid mode (transport + hydro code) [1]
  - Use parameterizations of thermal radiation from hadron gas [2] and QGP [3]
- ✓ Estimate prompt direct photon yield using Jetphox model [4]
- ✓ Compare with previous studies (M. Bleicher et al.) [5,6]
- ✓ Estimate direct photon elliptic flow

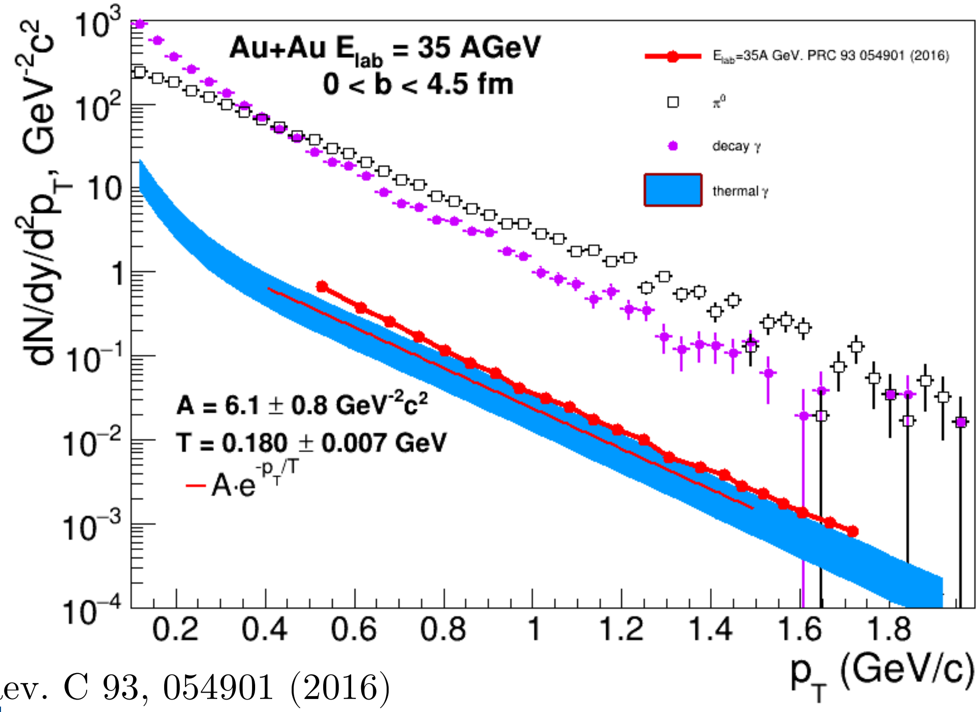
[1] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[2] S. Turbide, R. Rapp, and C. Gale, Phys. Rev.C 69(2004) 014903
[3] P. Arnold, G. D. Moore, L. G. Yaffe, JHEP12(2001) 009
[4] P. Aurenche et al., Phys.Rev.D73:094007, 2006 https://lapth.cnrs.fr/PHOX_FAMILY/jetphox.html
[5] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[6] S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 93, 054901 (2016)



Simulation setup

- ✓ UrQMD v3.4 with hybrid model (3+1d hydro, **bag model** EoS, hadronic rescattering and resonances within UrQMD)
- ✓ π^0 and decay photon spectrum are calculated **within the same simulation**
- ✓ impact parameter range 0<b<9 fm
- ✓ In hydrodynamical evolution, for each volume we calculate thermal gamma yield based on T, energy density (e), QGP fraction, baryonic chemical potential. We integrate these yields over time (until freeze-out time) and space.
- ✓ Two extreme cases: calculate thermal gamma emission from the volume above freeze-out criterion ($e > e_{freezeout}$), or calculate for all volumes. Reality somewhere in between (all volumes interact during hydro evolution). Comparing these options one can estimate theoretical uncertainties

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

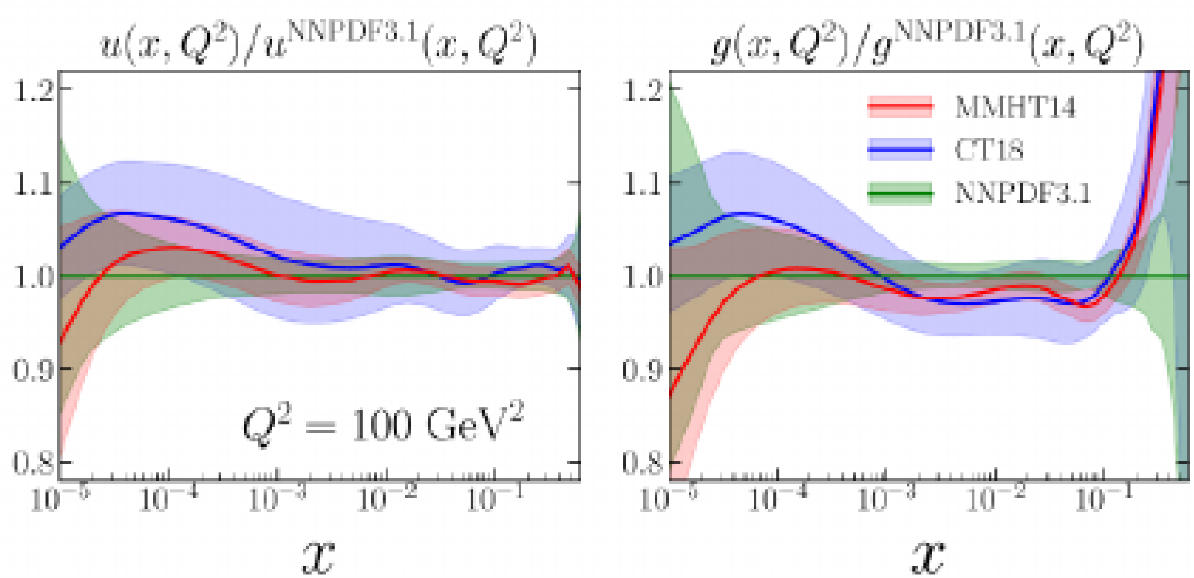


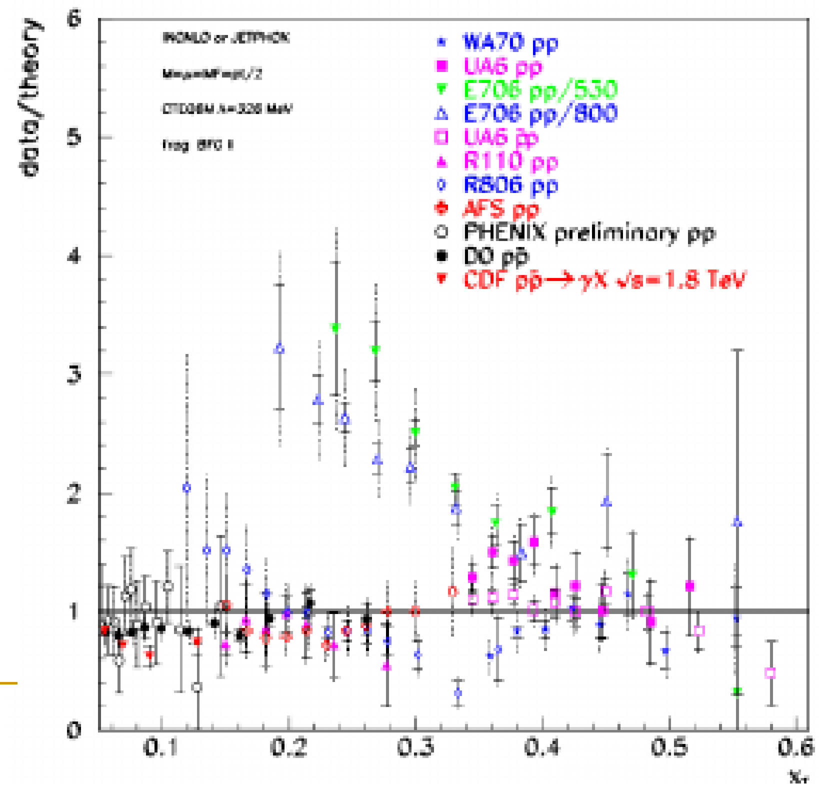
Why simulations in PRC 93 054901 (2016) and PRC 81 044904 (2010) have almost the same yield despite ~5 times difference in energy (35 vs 158 AGeV)?

Comparison with S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 93, 054901 (2016)

Prompt photons calculation

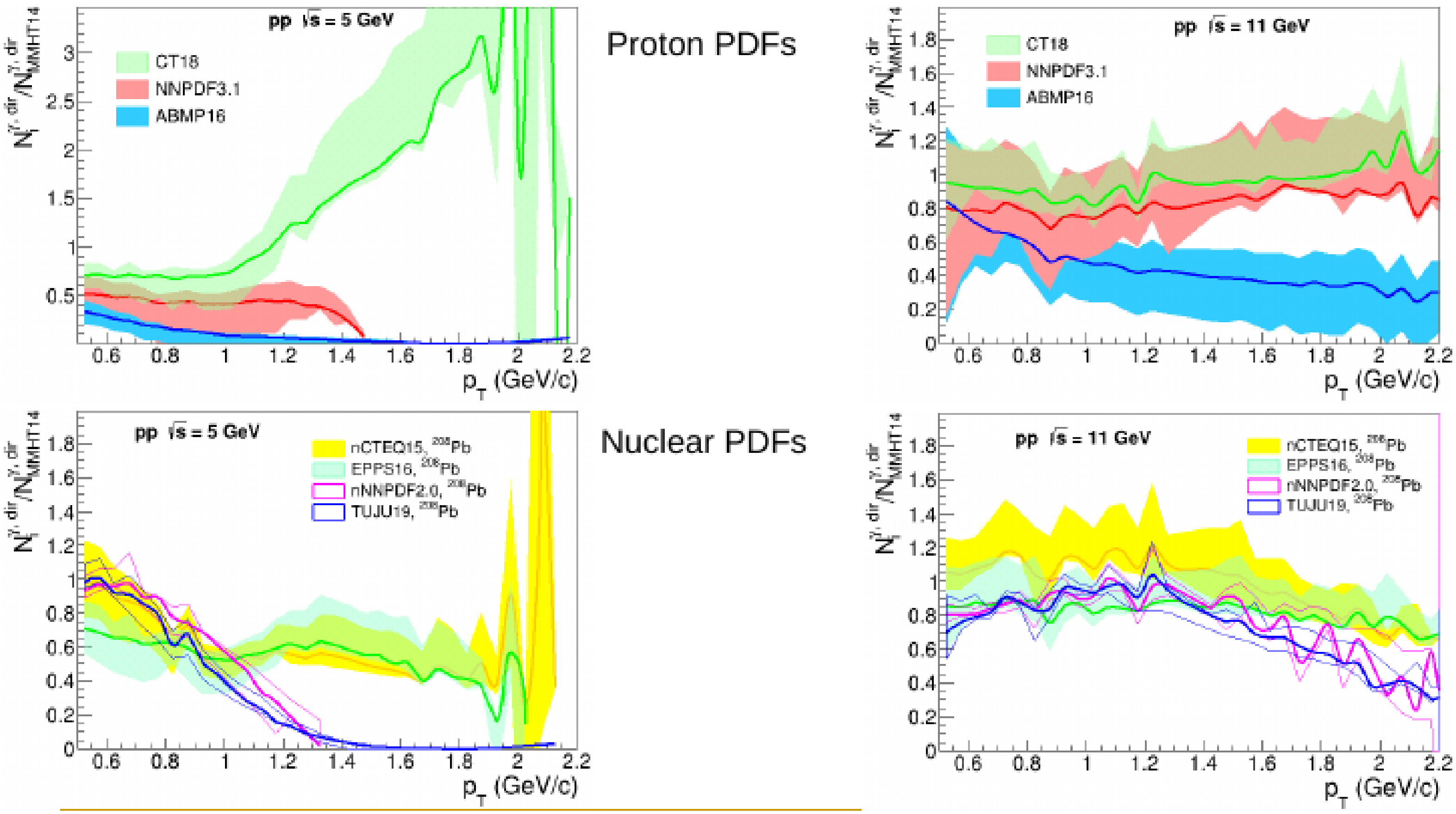
- Most widely used and powerful framework for prompt photons calculation is JetPHOX: P. Aurenche et al., Phys.Rev.D73:094007, 2006 https://lapth.cnrs.fr/PHOX_FAMILY/jetphox.html
- It was able to reproduce results from low energy experiments
- Prompt photon spectra is a convolution from PDF, cross section and FF
- Currently several parameterizations exist, uncertainty is large, especially at low and high x.





Prompt photons calculation

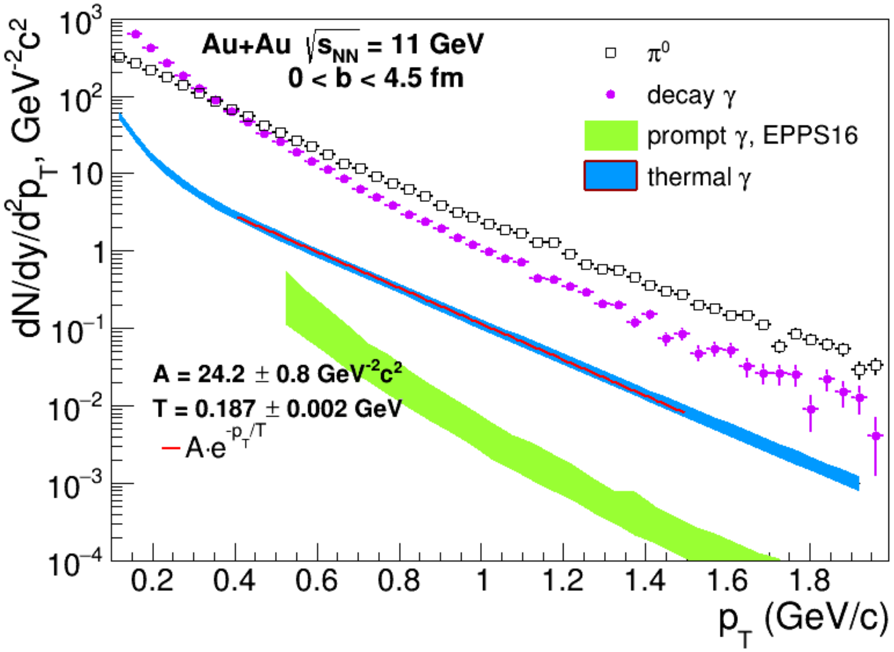
- Resulting uncertainties in prompt photons yield are rather large, especially at low $\sqrt{s_{NN}}$ and large p_T.
- To calculate yield in AA we need to scale it on pp cross section divided on N_{coll} σ_{NN} = 31 mb (from PDG booklet)
- N_{coll} taken from the analysis note “Centrality determination in MPD experiment using multiplicity of produced charged particles” by Petr Parfenov, Dim Idrisov, Vinh Ba Luong, and Arkadiy Taranenko (**thanks**!)
-



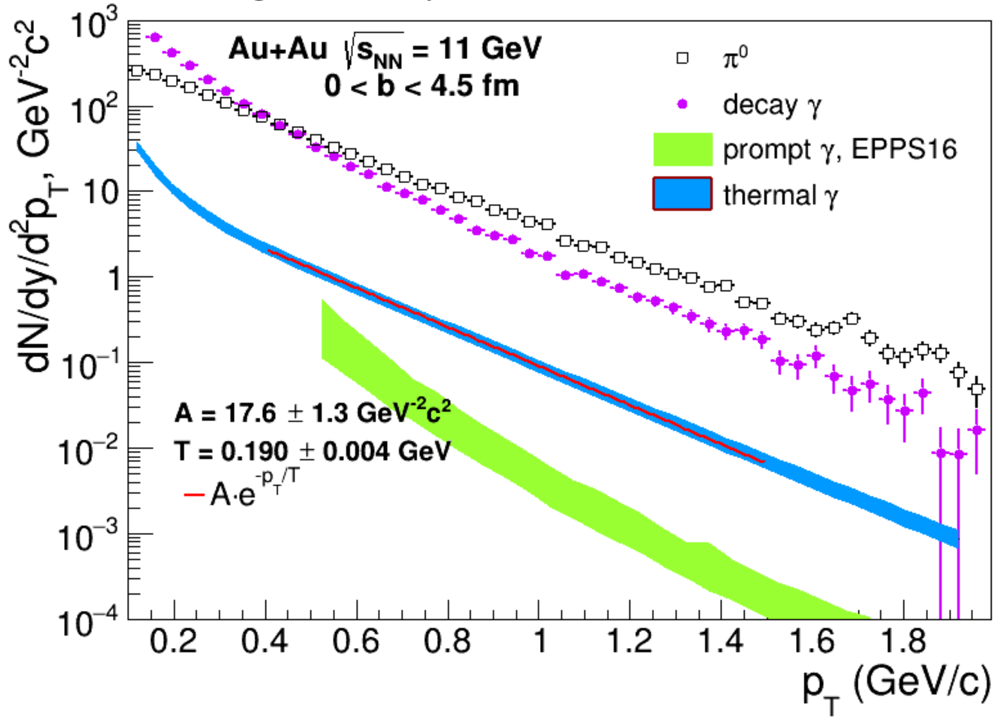
Calculations at $\sqrt{s_{NN}}$ = 11 GeV

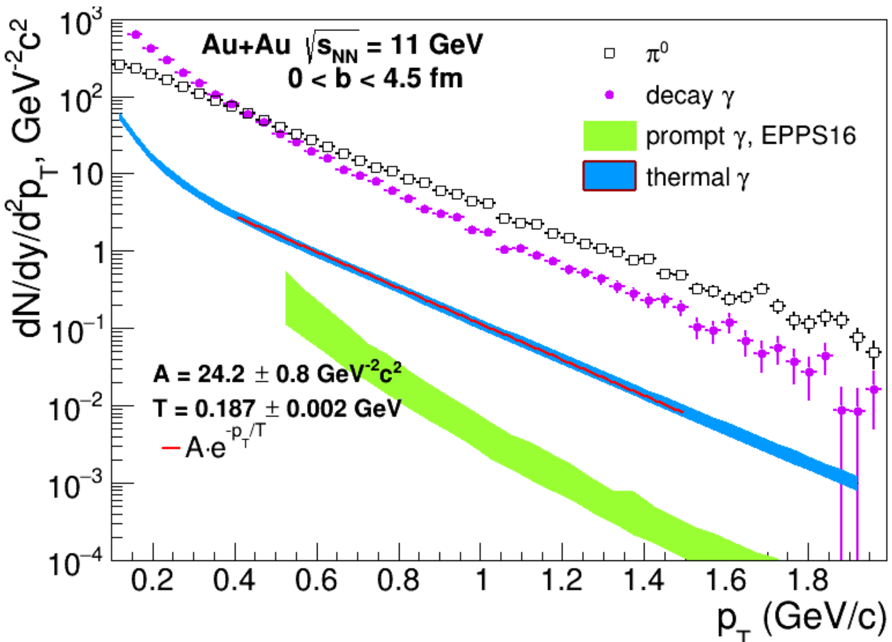
- Small contribution from prompt photons (inserting correct values for N_{coll} makes it even smaller)
- Harder spectra from pions and decay photons than with pure cascade option due to the radial flow
- 30% smaller thermal photon yield if calculate emission only above freeze-out condition

A: direct photons from hybrid mode, pions from pure cascade, full integral



C: direct photons and pions from hybrid mode, integral only above freeze-out condition



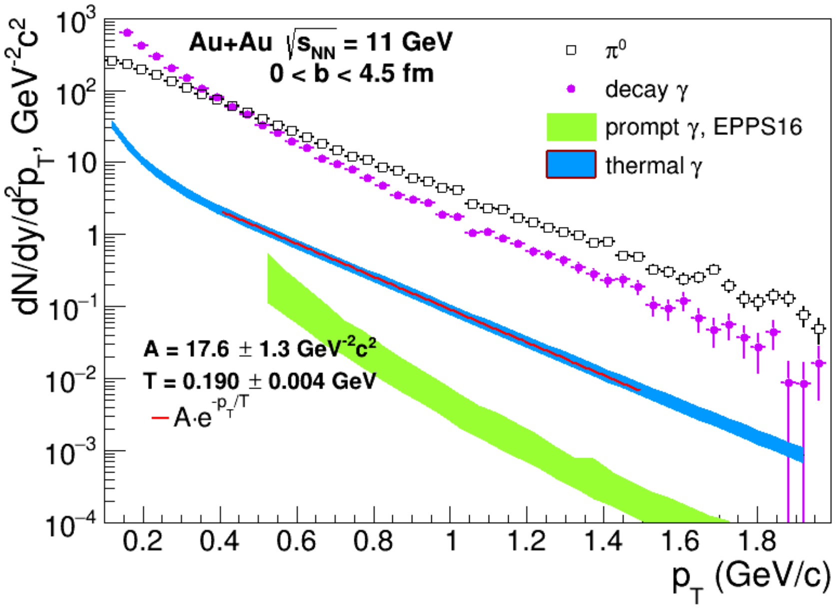


B: direct photons and pions from hybrid mode, full integral

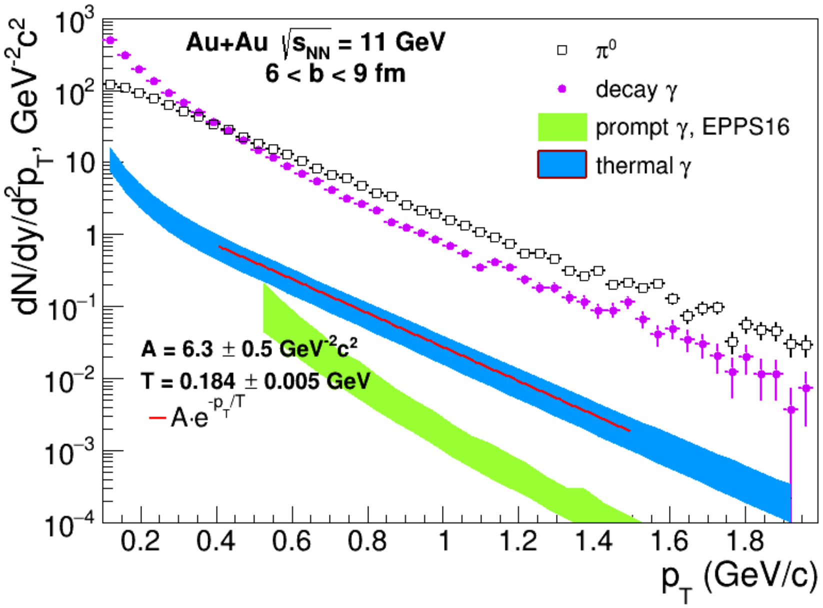
Centrality dependence at 11 GeV

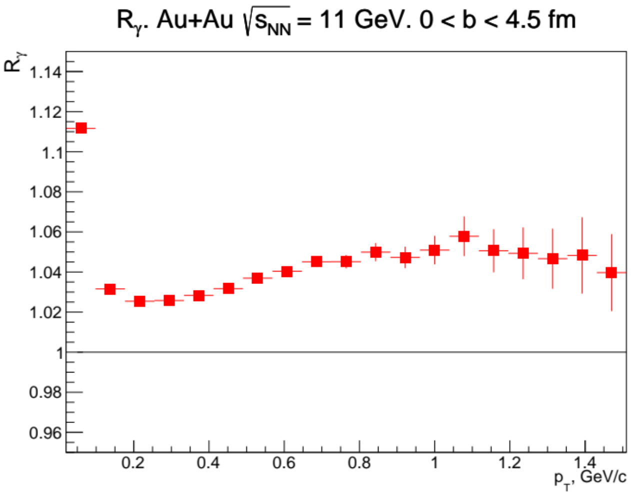
- Compare 0-10% and 20-40%
- Yield smaller by ~ 3 times. Much larger event-by-event fluctuations
- R_γ for 20-40% is about 3-4%.

b<4.5 fm

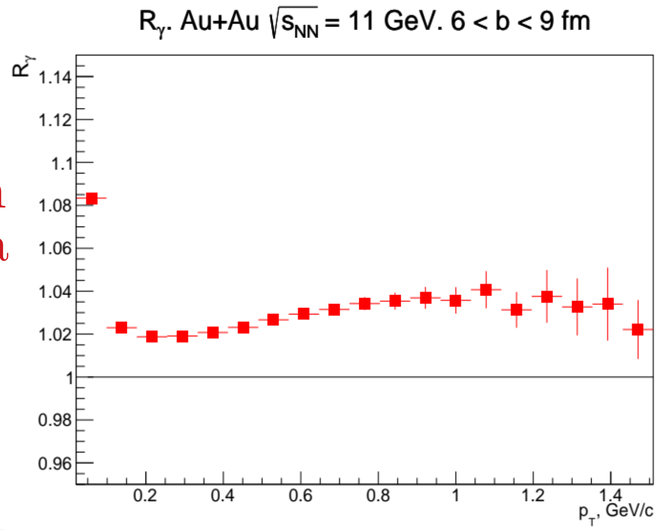


6<b<9 fm

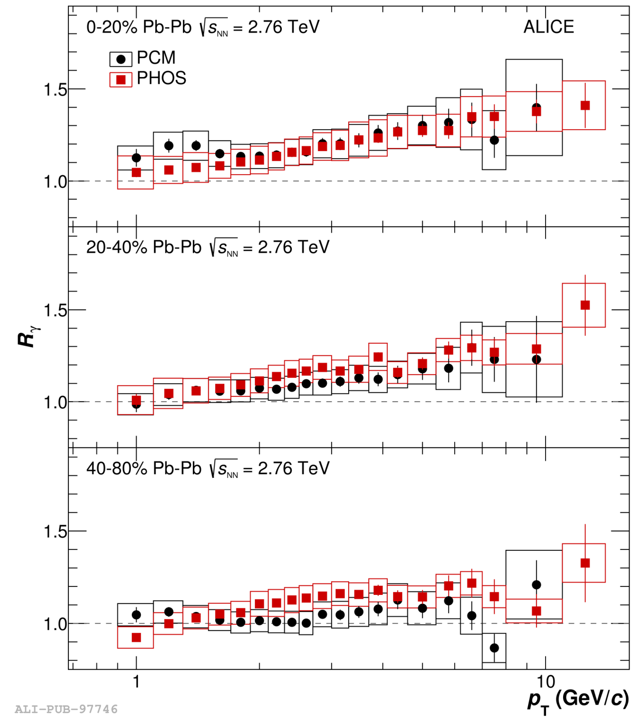




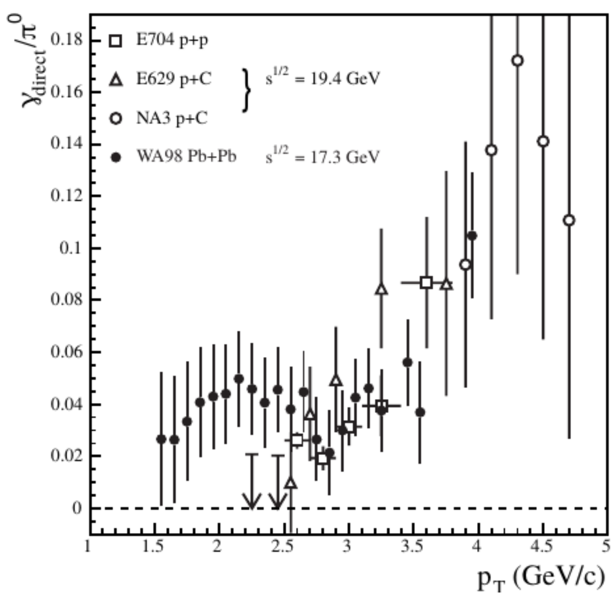
Note: R_γ doesn't contain prompt gamma contribution

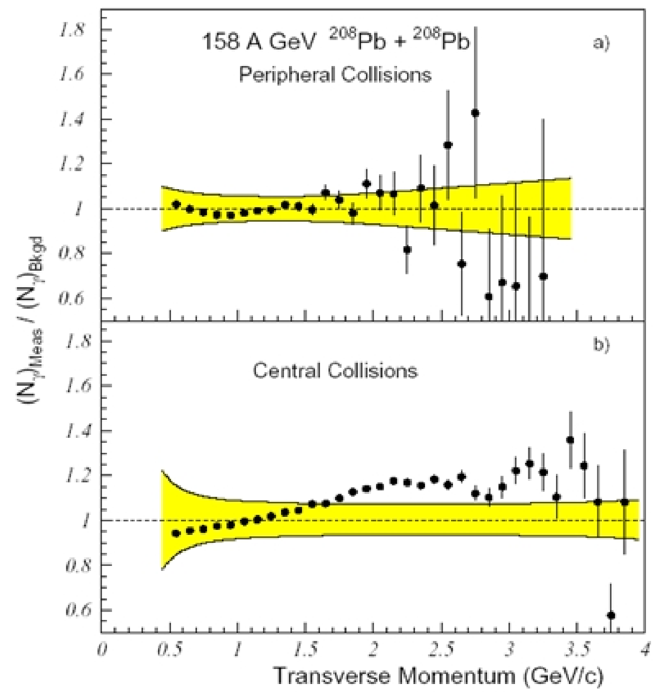


Gamma ratio R_γ and ratio to π^0 yield



- 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

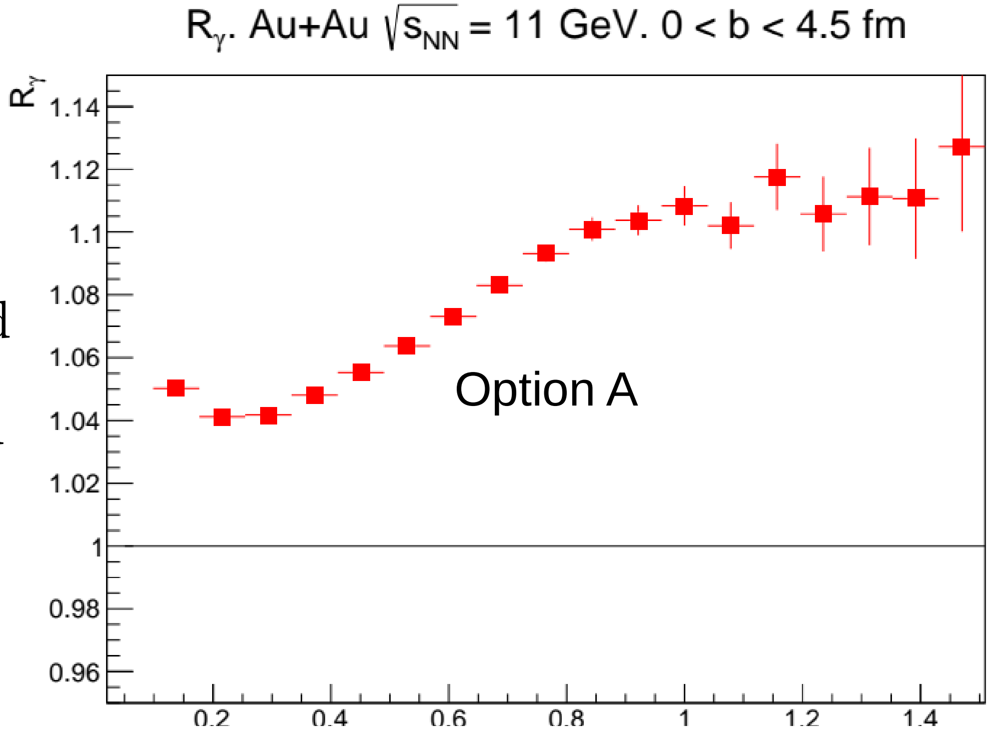


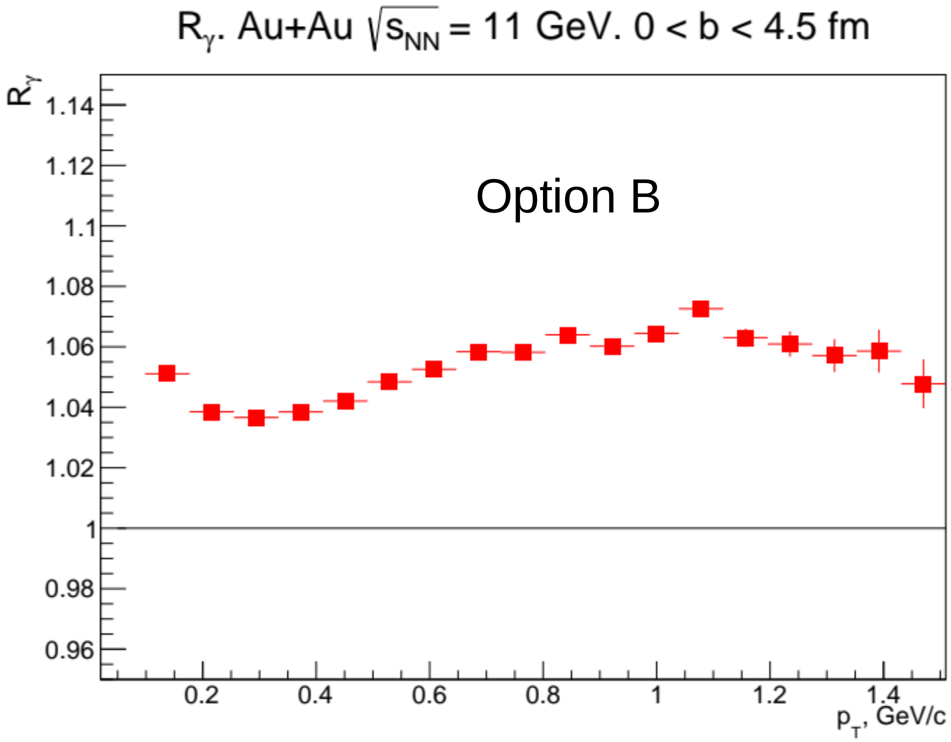


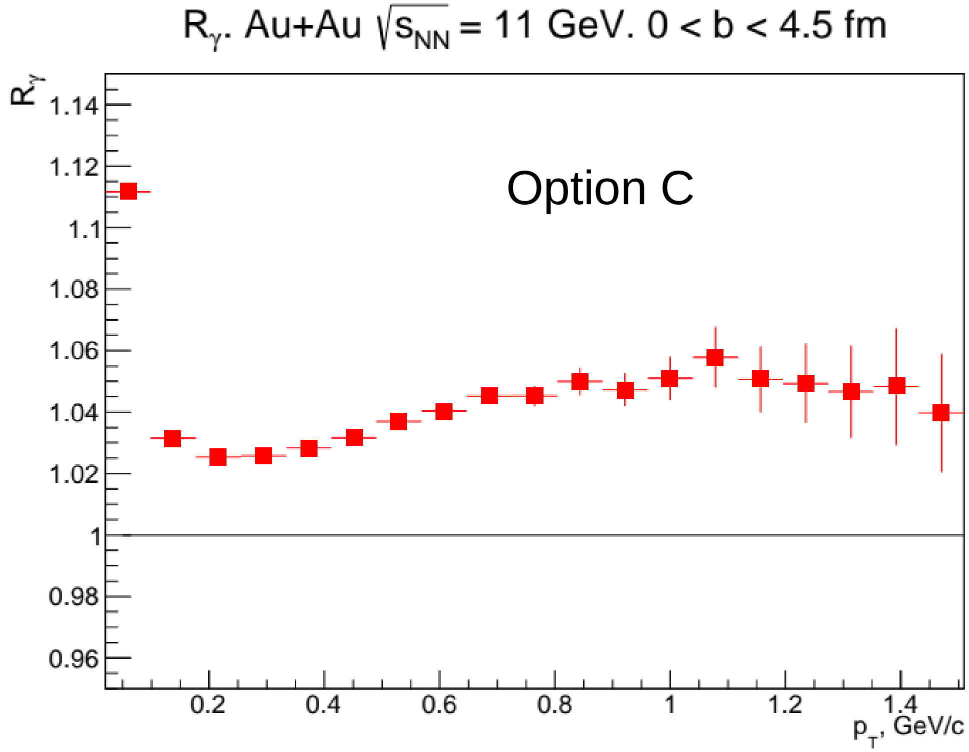
[1] J. Adam et al. (ALICE Collaboration) Phys. Lett.B 754(2016) 235-248
[2] T. Peitzmann, Pramana – J. Phys. V. 60 Issue 4 pp 651-661 (2003)

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

- Three options considered:
- A: direct photons from hybrid mode, pions from pure cascade, full integral
- B: direct photons and pions from hybrid mode, full integral
- C: direct photons and pions from hybrid mode, integral only above freeze-out condition
- Note: no prompt direct photon contribution here!

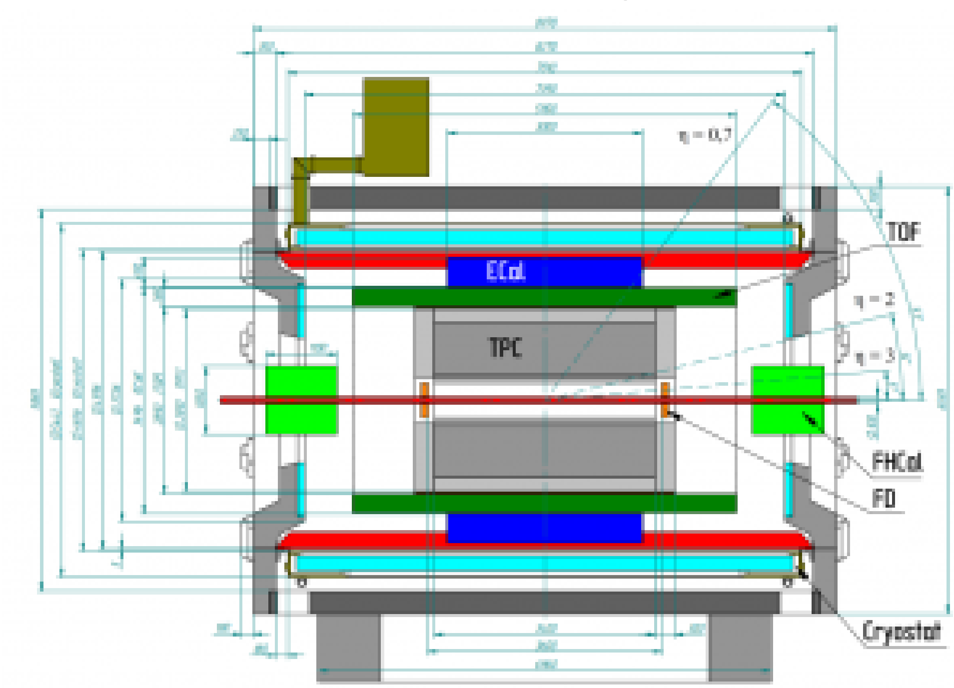






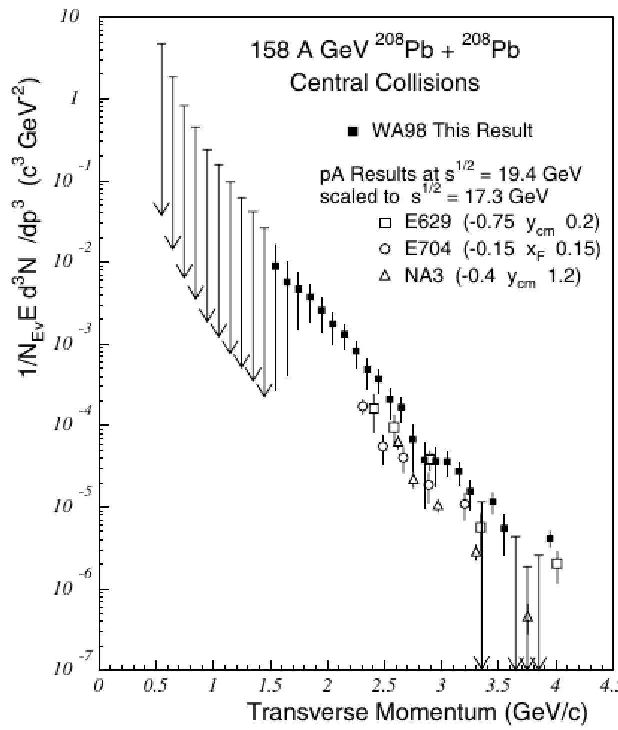
Challenges in measuring of direct photons

MPD Stage 1



The main systematic uncertainties are expected due to:
- uncertainty in inclusive gamma spectrum due to large contamination → need good photon PID (could be possible with good timing resolution about 200-300 ps [1]).
- uncertainty in π^0 spectrum. Need good energy resolution and large statistics.

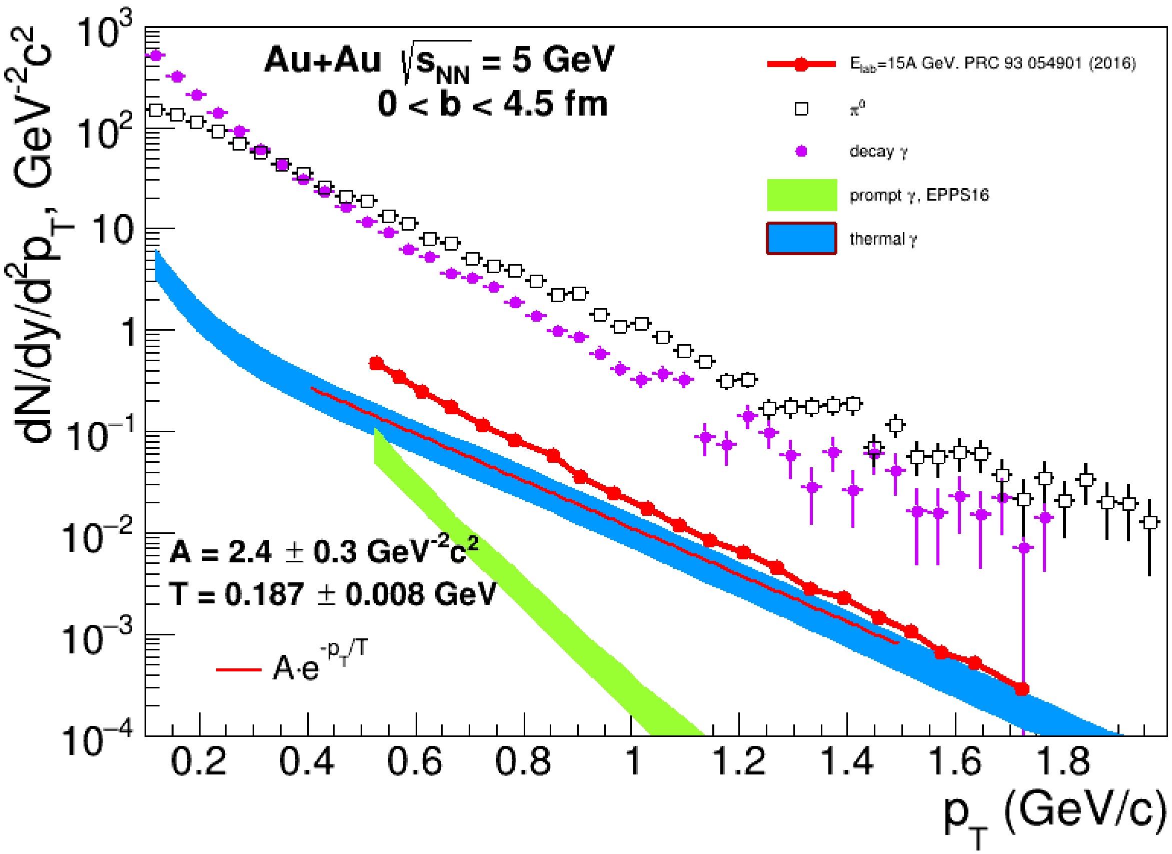
- The only successful measurement of direct photons in AA collisions at similar $\sqrt{s_{NN}}$ was obtained in WA98 experiment [2][3] with very low material budget before calorimeter.

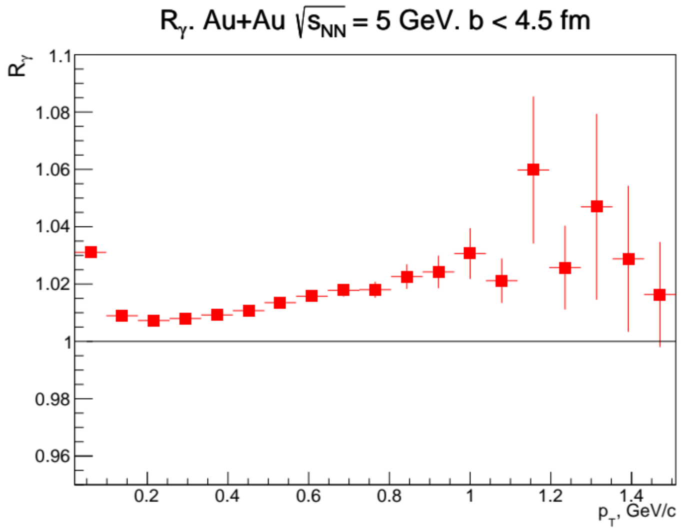


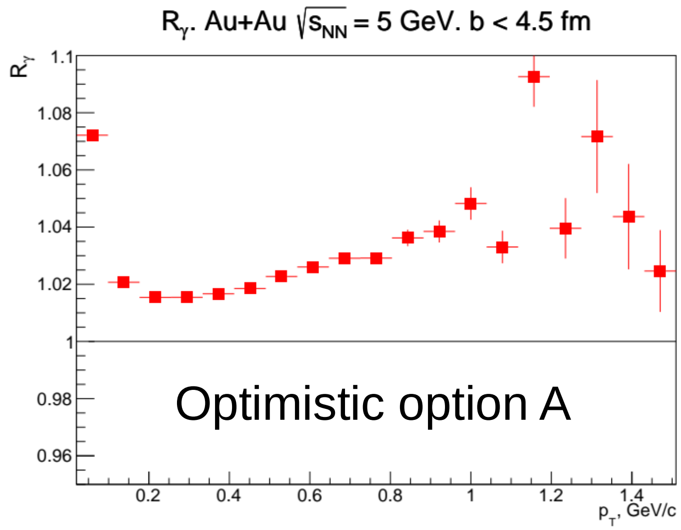
[1] TDR of the Electromagnetic calorimeter (ECal) rev. 3.6 (2018)
[2] M. M. Aggarwal et al, Phys. Rev. Lett. 85, 3595 (2000)
[3] T. Peitzmann, Pramana – J. Phys. V. 60 Issue 4 pp 651-661 (2003)

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

- Conservative option C
- Much smaller yield than at 11 GeV due to smaller hydro evolution time
- Consistent with M.Bleicher and co at E=15 AGeV.





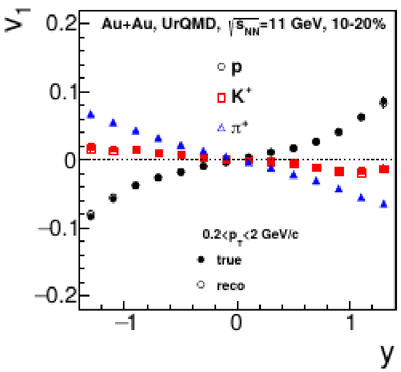


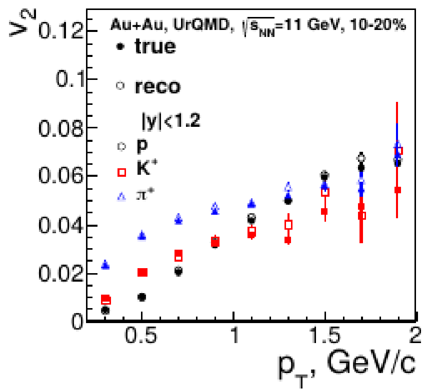
Collective flow of direct γ at $\sqrt{s_{NN}} = 11$ GeV

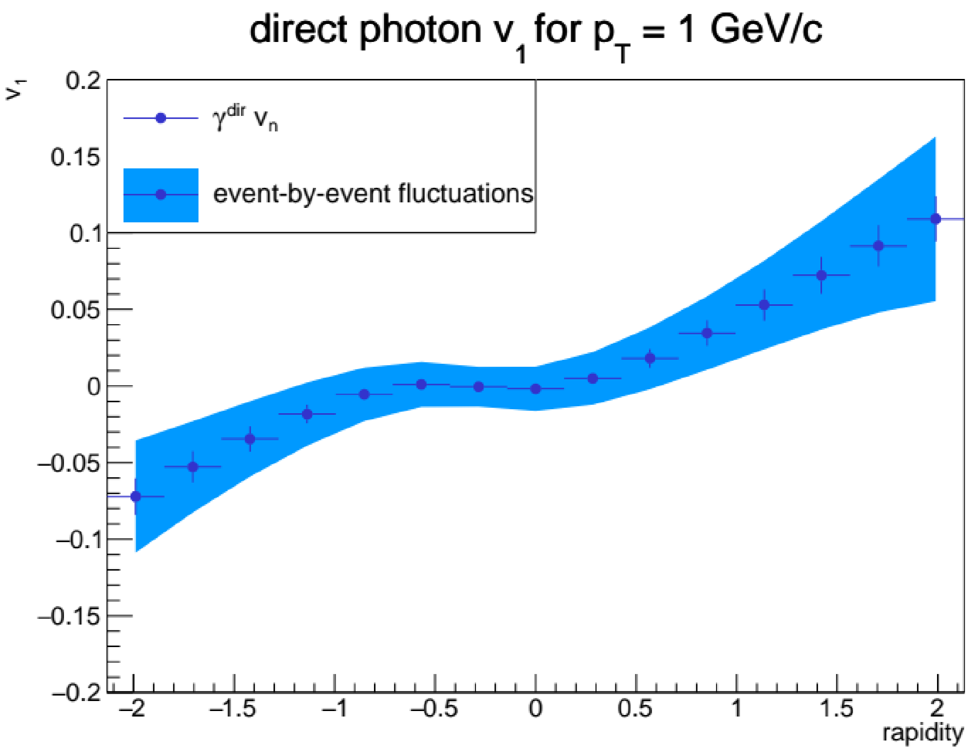
Direct photon flow puzzle: flow of direct photons is large (close to the flow of hadrons) which is difficult to explain within current theoretical models.
We look at anisotropy of direct photon yield using UrQMD in hydro mode...

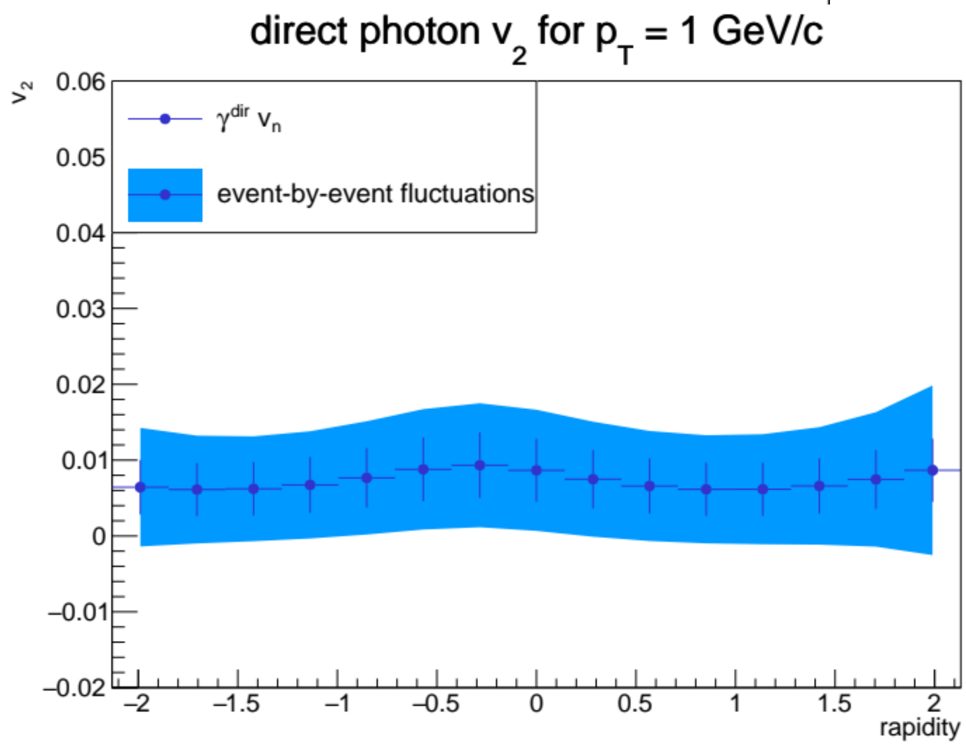
- ✓ v_1 similar to those of hadrons
- ✓ v_2 about 5 times smaller (consistent with predictions at other energies)

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



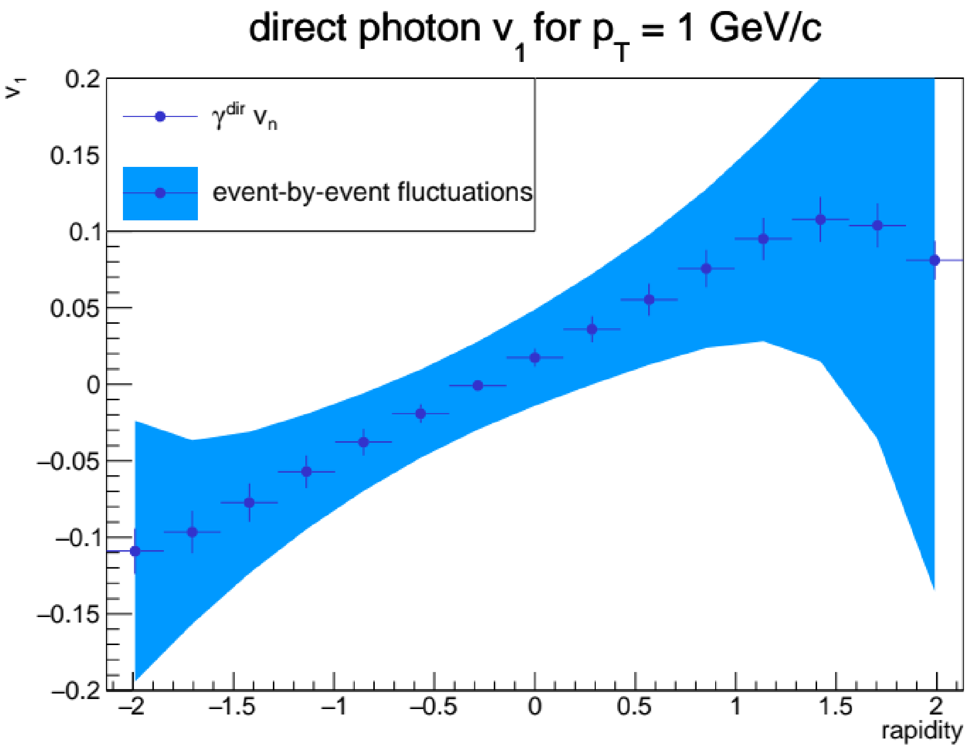


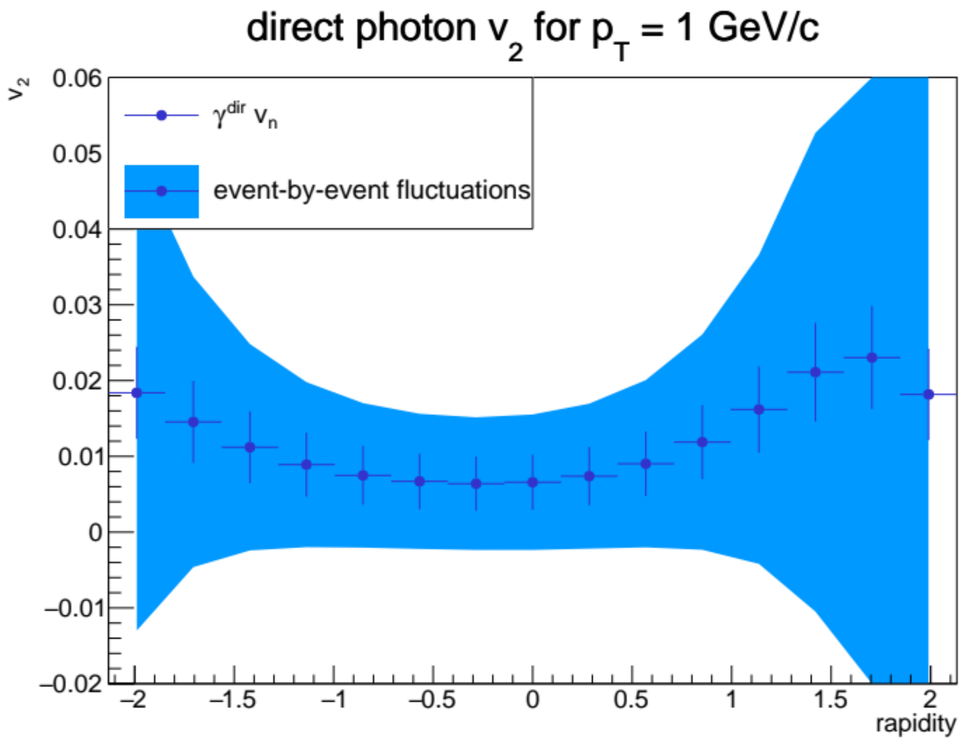




Collective flow of direct γ at $\sqrt{s_{NN}} = 5$ GeV

Similar magnitude, much larger fluctuations





Conclusions

- Direct photon simulations using UrQMD are performed and tested for several energies, compared to results from Marcus Bleicher et al. for energies between 15 and 158 AGeV. Results are consistent, but several options could be used to obtain slightly different results.
- Results of thermal direct gamma spectrum predictions at NICA **top energy** ($\sqrt{s_{NN}}$ = **11 GeV**) and NICA **low energy** / FAIR **top energy** ($\sqrt{s_{NN}}$ = **5 GeV**).
- Simultations of prompt direct gamma yield obtained with JetPhox package show small magnitude compared to thermal gamma yield.

- $\mathbf{R_\gamma}$ **ratios** are calculated. $\mathbf{R_\gamma}$ is about 5-10% at 1 GeV for $\sqrt{s_{NN}}$ = **11 GeV**. Measurement of direct gamma at NICA looks feasible.

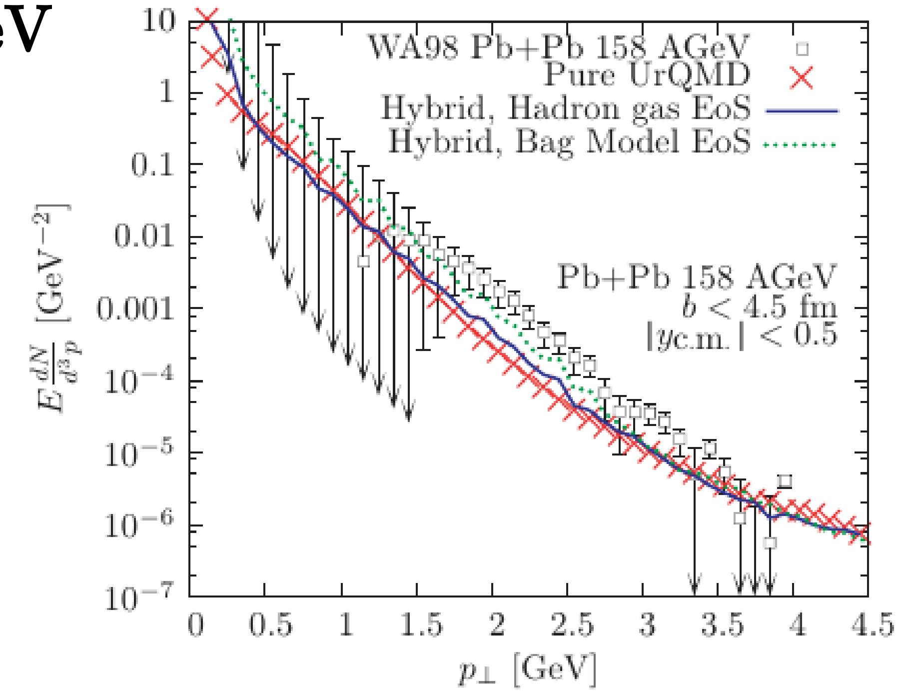
- Direct $\boldsymbol{\gamma}$ $\mathbf{v_n}$ coefficients dependence on **rapidity** are shown. $\mathbf{v_1}$ is similar to those of hadrons. $\mathbf{v_2}$ is about 5 times smaller (consistent with simulations at high energies).

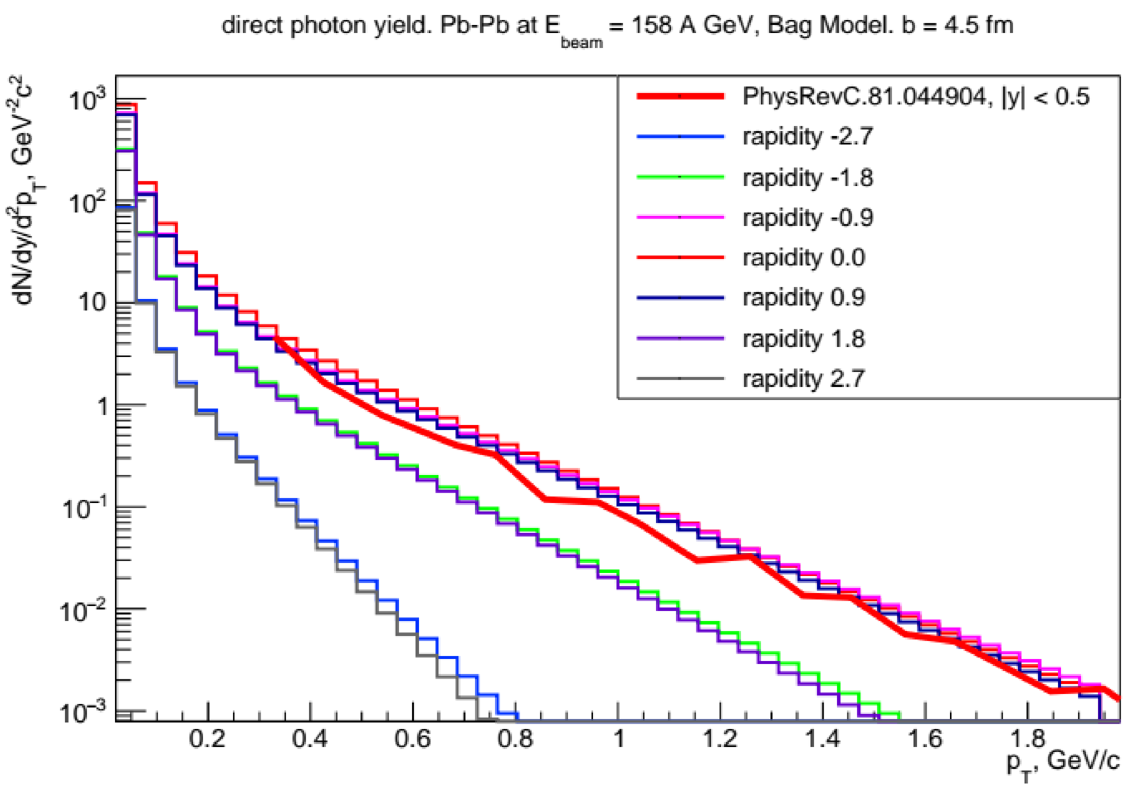
Backup

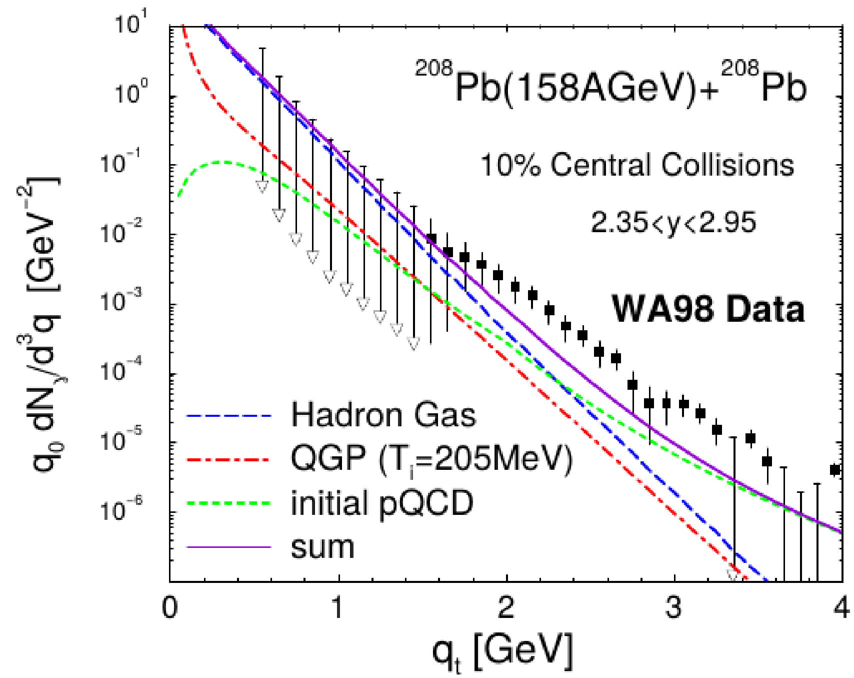
Calculations for Pb-Pb at $\sqrt{s_{NN}}$= 17.2 GeV

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!





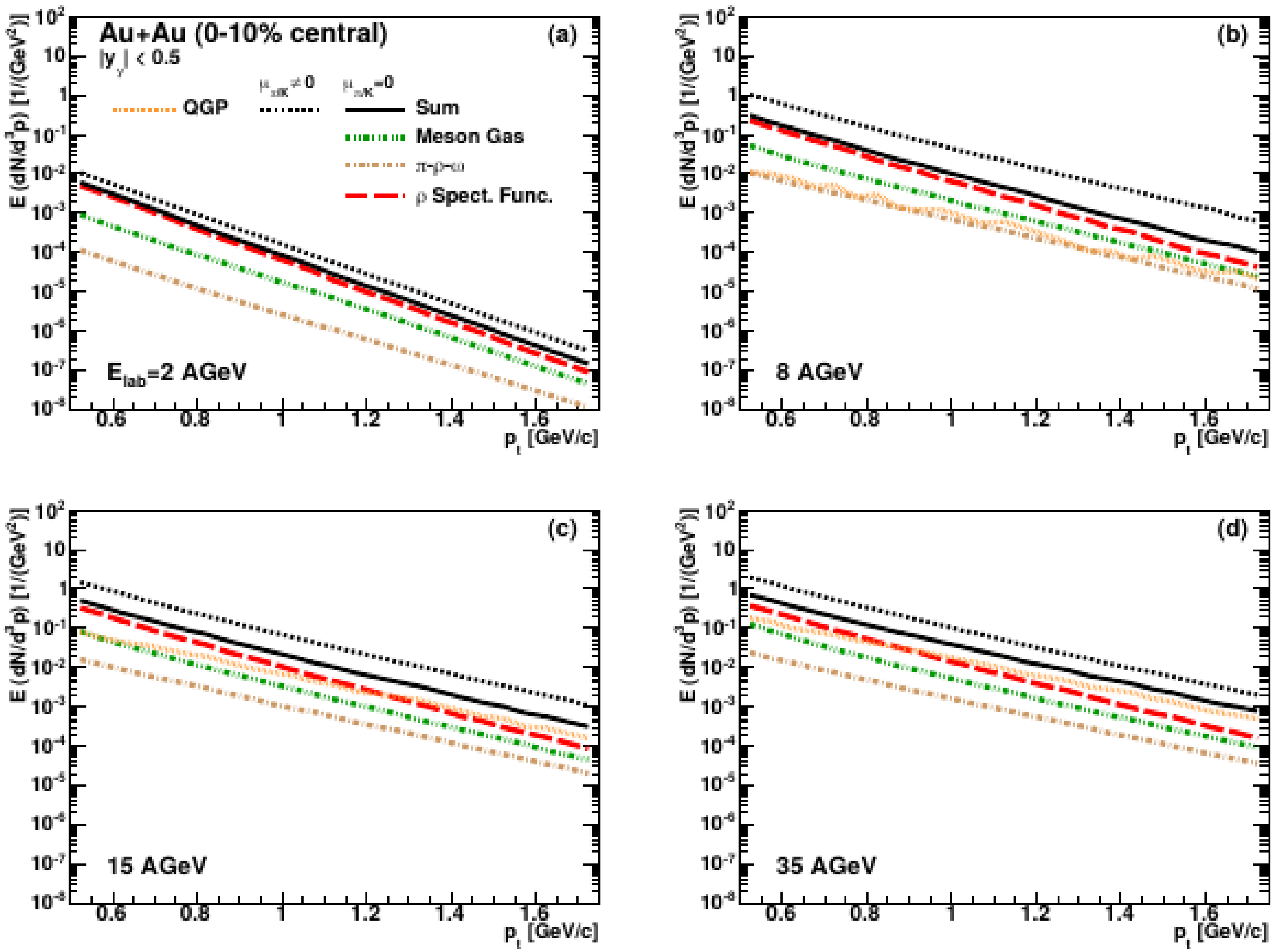


[1] B. Bäuchle and M. Bleicher, PhysRevC 81 (2010) 044904
[2] S. Turbide, R. Rapp, and C. Gale, Phys. Rev.C 69(2004) 014903

Calculations for Au-Au at 2-35 AGeV

- HG EOS (not BagModel!)
- Discussions on non-equilibrium dynamics
(additional contribution from hadrons)

S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 93, 054901 (2016)



Centrality, %	N_{ch}^{min}	N_{ch}^{max}	$\langle b \rangle$, fm	RMS	b_{min}, fm	b_{max}, fm	$\langle N_{part} \rangle$	RMS	N_{part}^{min}	N_{part}^{max}	$\langle N_{coll} \rangle$	RMS	N_{coll}^{min}	N_{coll}^{max}
0 - 10	191	335	2.95	1.10	1.35	4.23	319.67	31.99	276.85	369.85	711.32	94.14	588.81	856.96
10 - 20	134	191	5.27	0.71	4.23	6.11	240.05	27.89	207.43	276.85	486.03	69.79	401.46	588.81
20 - 30	93	134	6.83	0.60	6.11	7.49	179.04	23.03	154.10	207.43	330.11	52.68	269.79	401.46
30 - 40	63	93	8.08	0.56	7.49	8.63	131.69	19.21	112.07	154.10	219.43	40.06	176.50	269.79
40 - 50	41	63	9.17	0.56	8.63	9.68	94.40	16.02	78.61	112.07	140.58	30.37	110.33	176.50
50 - 60	25	41	10.17	0.58	9.68	10.65	64.72	13.28	52.32	78.61	84.95	22.40	64.38	110.33
60 - 70	14	25	11.11	0.62	10.65	11.56	41.70	10.69	32.51	52.32	47.59	15.68	34.34	64.38
70 - 80	7	14	12.02	0.70	11.56	12.46	24.71	8.25	18.48	32.51	24.27	10.20	16.75	34.34
80 - 90	3	7	12.94	0.86	12.46	13.50	13.30	6.00	8.88	18.48	11.33	6.20	7.27	16.75
90 - 100	1	2	14.17	1.07	13.50	15.00	4.97	3.05	1.02	8.88	3.55	2.64	-1.06	7.27

Table 18: Geometric properties (b, N_{part}, N_{coll}) of Au+Au collisions at $\sqrt{s_{NN}}$=11.5 GeV from UrQMD model for centrality classes defined by sharp cuts in the charged particle multiplicity distribution, simulated with an NBD-Glauber fit. The mean values and the RMS are obtained with a Glauber Monte Carlo calculation.

Centrality, %	N_{ch}^{min}	N_{ch}^{max}	$\langle b \rangle$, fm	RMS	b_{min}, fm	b_{max}, fm	$\langle N_{part} \rangle$	RMS	N_{part}^{min}	N_{part}^{max}	$\langle N_{coll} \rangle$	RMS	N_{coll}^{min}	N_{coll}^{max}
0 - 10	108	203	2.89	1.11	1.46	4.08	318.54	32.37	279.34	362.01	673.60	88.84	566.43	798.75
10 - 20	77	108	5.08	0.80	4.08	5.90	244.20	30.80	212.53	279.34	474.69	73.41	396.03	566.43
20 - 30	54	77	6.61	0.68	5.90	7.27	184.53	26.27	159.56	212.53	329.60	57.84	272.25	396.03
30 - 40	37	54	7.86	0.64	7.27	8.40	137.24	22.39	117.94	159.56	223.34	45.44	182.96	272.25
40 - 50	25	37	8.92	0.62	8.40	9.40	100.53	18.86	85.14	117.94	148.03	34.92	118.87	182.96
50 - 60	16	25	9.86	0.64	9.40	10.34	71.76	16.19	58.96	85.14	94.84	27.24	73.22	118.87
60 - 70	9	16	10.80	0.70	10.34	11.24	47.49	13.78	38.00	58.96	55.30	20.48	41.45	73.22
70 - 80	5	9	11.70	0.76	11.24	12.17	29.46	10.80	22.00	38.00	29.98	13.86	20.89	41.45
80 - 90	2	5	12.67	0.95	12.17	13.21	16.18	8.50	12.29	22.00	14.41	9.28	10.45	20.89

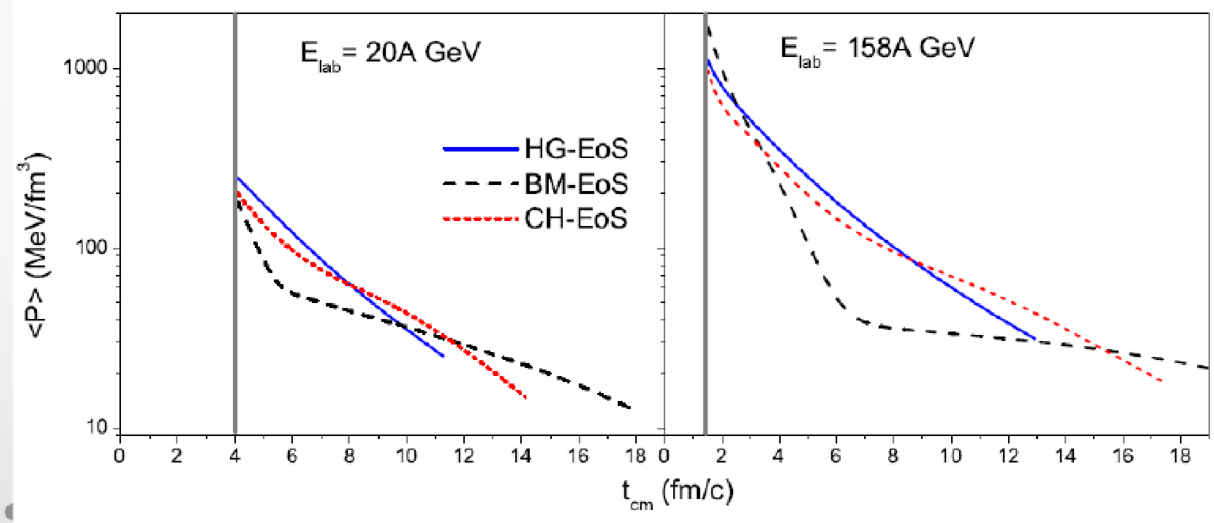
Table 12: Geometric properties (b, N_{part}, N_{coll}) of Au+Au collisions at $\sqrt{s_{NN}}$=4.5 GeV from UrQMD model for centrality classes defined by sharp cuts in the charged particle multiplicity distribution, simulated with an NBD-Glauber fit. The mean values and the RMS are obtained with a Glauber Monte Carlo calculation.

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



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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

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

with

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

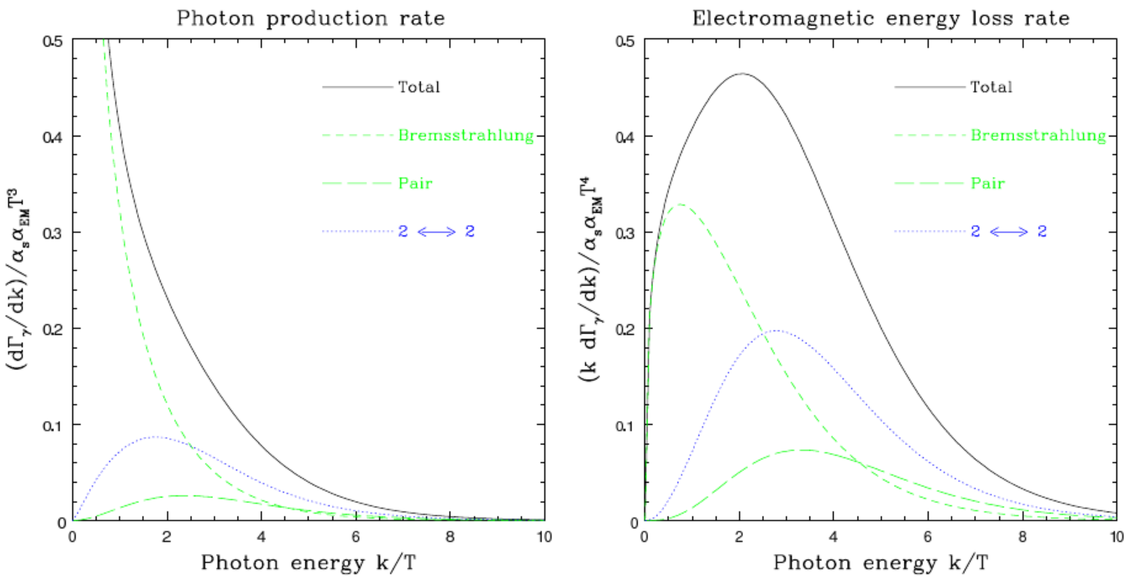

FIG. 9. Total photon emission rate, together with the bremsstrahlung, inelastic pair annihilation and $2 \leftrightarrow 2$ contributions, for two-flavor QCD with $\alpha_s = 0.2$. The left panel shows $d\Gamma_\gamma/dk$, divided by $\alpha_s\,\alpha_{\rm EM}\,T^3$, while the right panel shows rates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

$$\mathcal{L}_{em} = -Cm_\rho^2 A^\mu \rho_\mu^0 \tag{A1}$$

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.

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

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

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

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

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

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

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

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