TWENTY-FIRST LOMONOSOV
CONFERENCE August, 24-30, 2023
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

ALICE

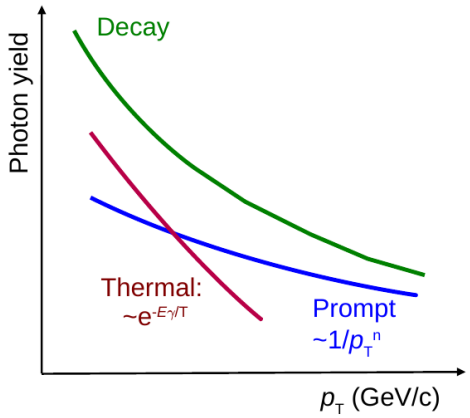
Real and virtual direct photon measurements with ALICE

D.Peresunko
NRC "Kurchatov institute"

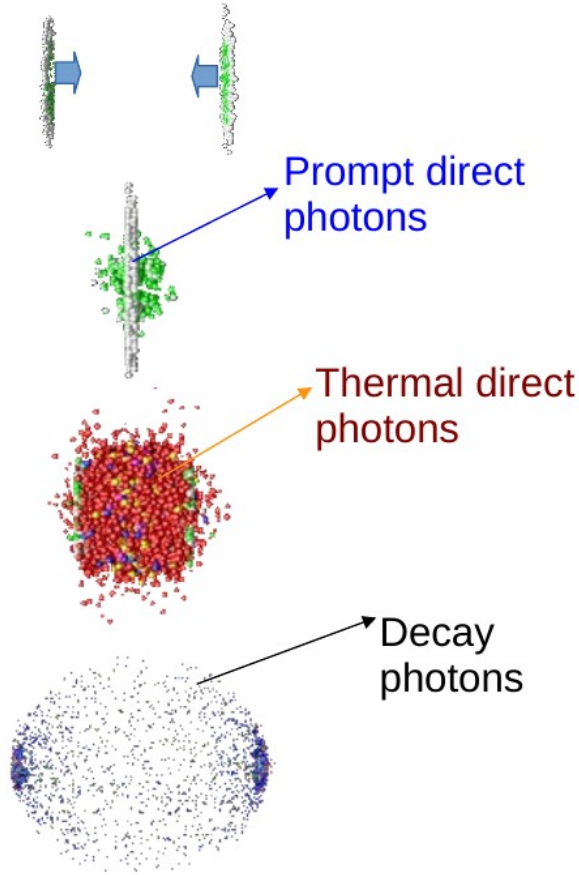
for the ALICE collaboration

Photon classification

- **Decay photons:** photons from decays of final hadrons
- **Direct photons** – photons not originating from hadron decays but produced in electromagnetic interactions in course of collision
  - Prompt direct photons: ones from interaction of partons of incoming nucleons
  - Thermal direct photons: thermal radiation of hot matter
  - Direct photons measured as a difference $N_\gamma^{dir} = N_\gamma^{incl} - N_\gamma^{dec}$
  - Can not be identified event-by-event



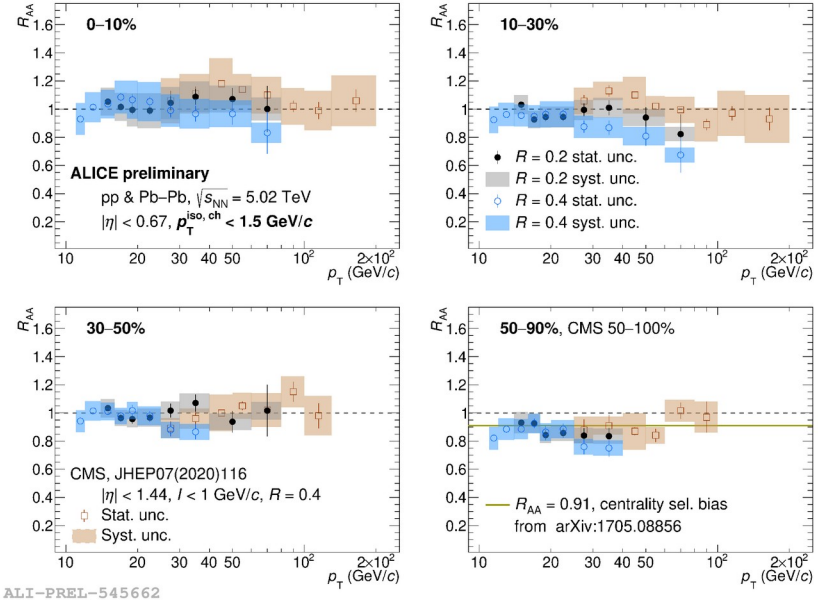
- **Isolated photons**: photons without hadronic activity in some cone (R~0.4) around the photon
- Difference between direct and isolated photons diminish at high p_T
- Can be measured in event-by-event basis
- Purity rapidly decreases with decrease of p_T, can not be measured at low p_T<10-20 GeV/c

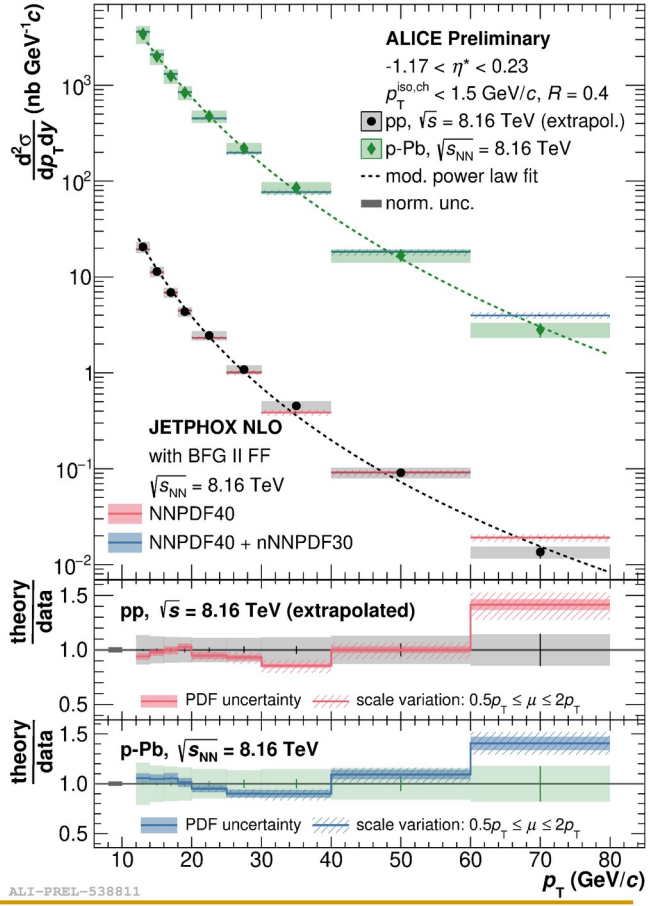


Isolated photons in pp, p-Pb and Pb-Pb

- Isolated photon production in pp collisions agree with NLO pQCD predictions
- In p-Pb, Pb-Pb collisions R_{AA} agrees with unity
  - Support for Glauber model
  - No significant modification of initial state in pA, AA

$$R_{AA} = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T}$$

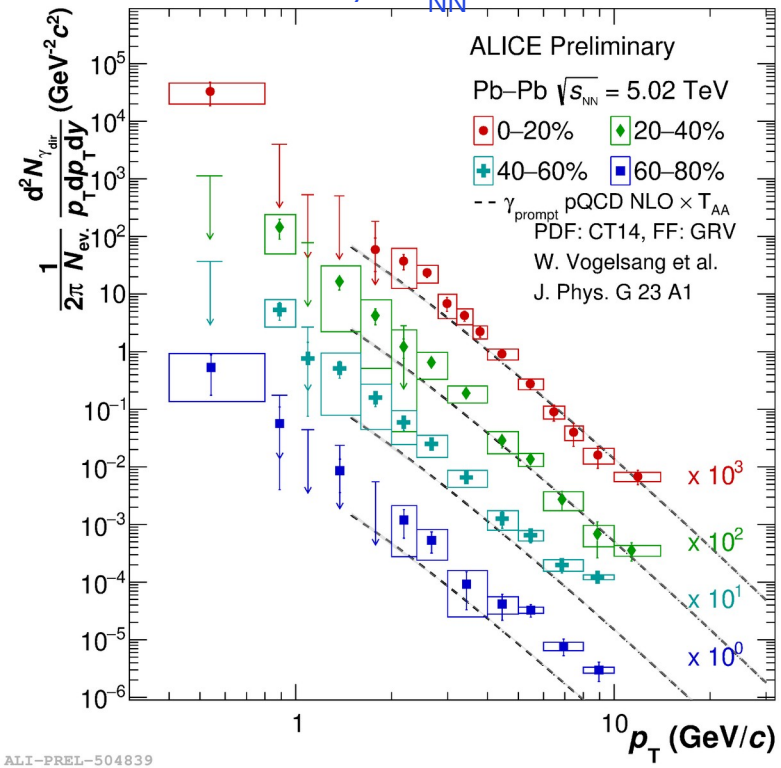




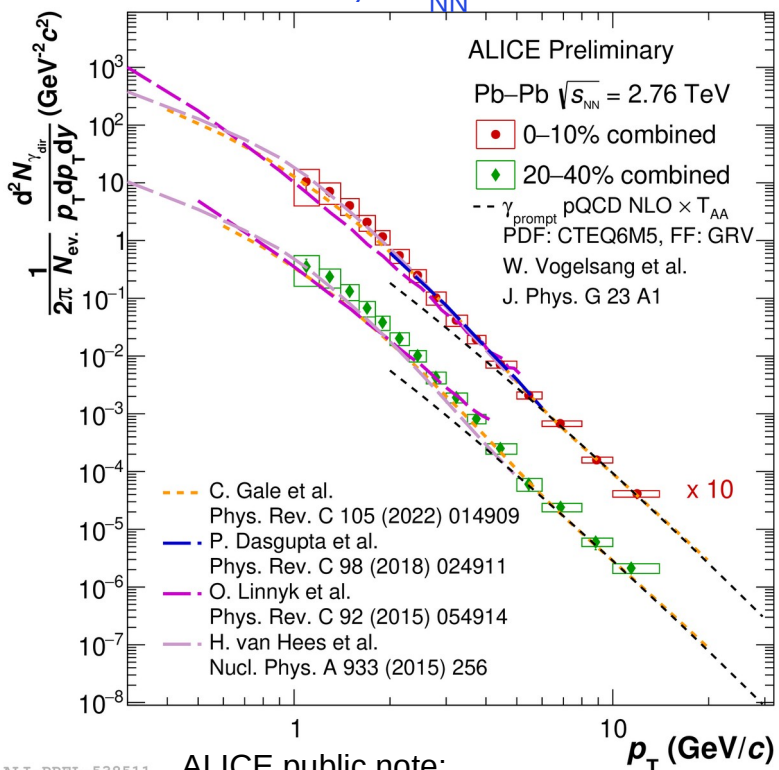
Thermal photons in Pb-Pb collisions

- Direct photon spectrum was measured at both energies provided by LHC
- At high p_T>5 GeV/c direct photon spectrum agrees with pQCD predictions scaled with the number of nucleon-nucleon collisions
- In central collisions there is clear excess at low p_T<4 GeV/c due to thermal emission

Pb-Pb, $\sqrt{s_{NN}}$=5.02 TeV



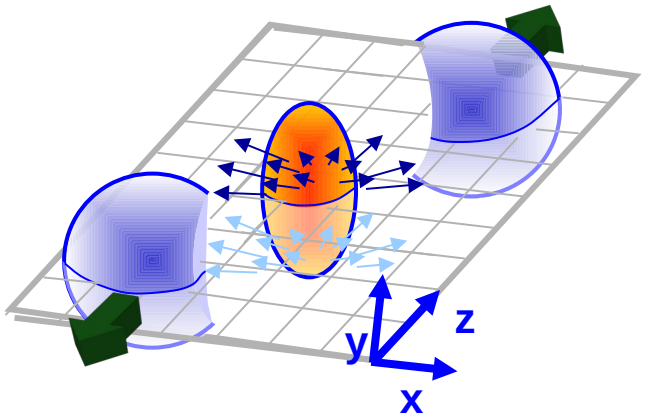
Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV

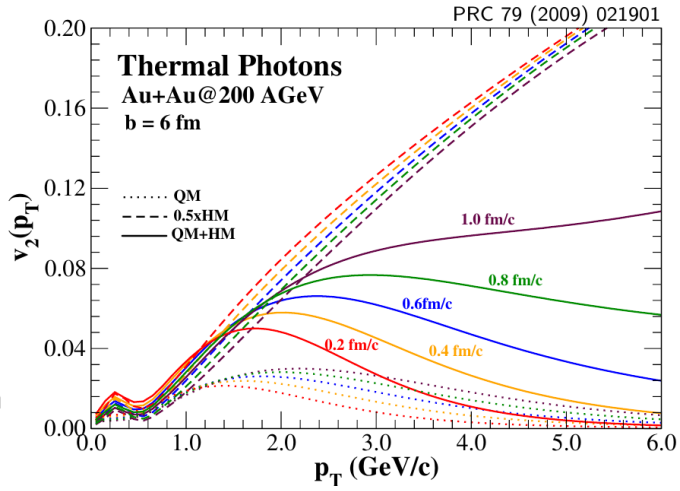


ALICE public note:
https://alice-notes.web.cern.ch/node/864

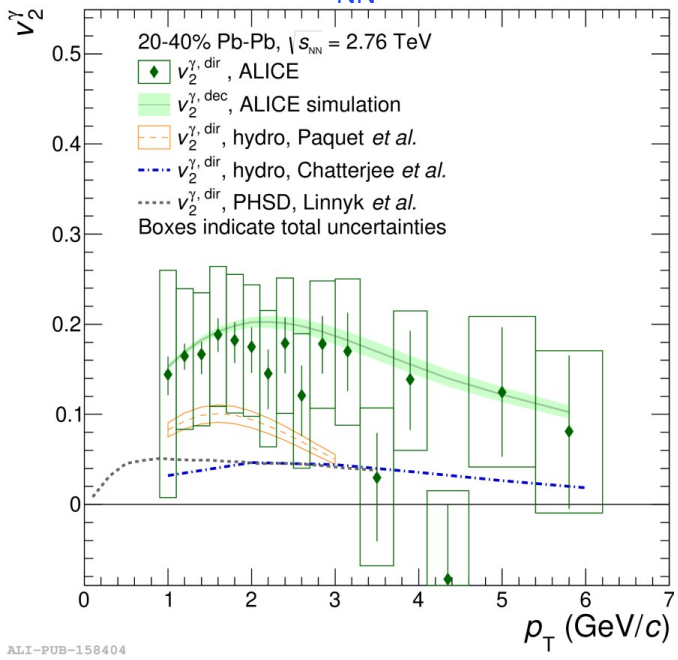
Direct photon collective flow

Phys.Lett.B 789 (2019) 308-322





Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV



$$\frac{dN}{d\phi} = 1 + 2v_1\cos\left(\phi - \Psi_{RP}\right) + 2v_2\cos\left[2\left(\phi - \Psi_{RP}\right)\right] + 2v_3\cos\left[3\left(\phi - \Psi_{RP}\right)\right] + \ldots$$

- Direct photon flow similar to flow of decay photons and stronger than predictions of hydrodynamic models (direct photon flow puzzle)
- However, uncertainties too large to make final conclusion

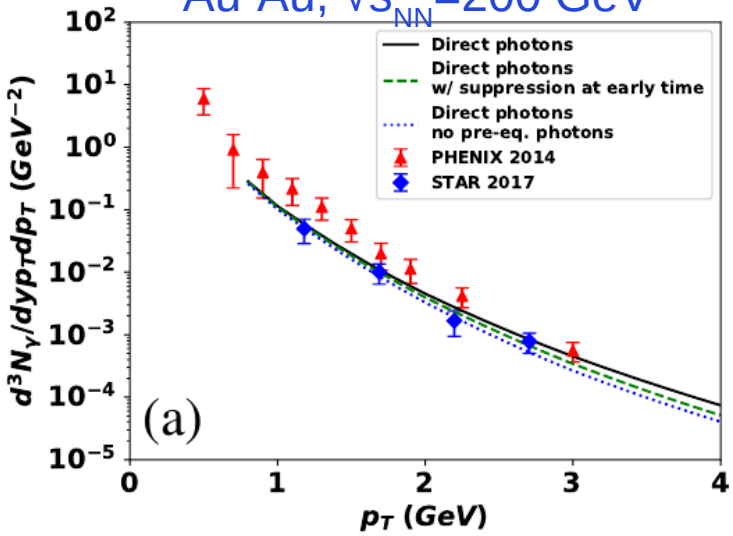
$$v_n^{dir} = v_n^{decay} + \frac{R}{R-1}\left(v_n^{incl} - v_n^{decay}\right)$$

Direct photon puzzle

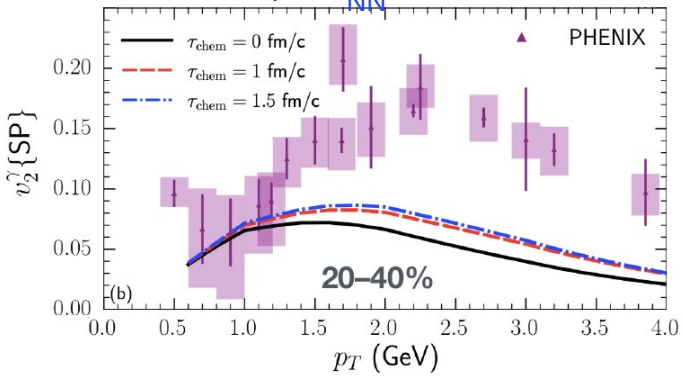
- Spectra
  - PHENIX: factor 2-5 higher than predictions
  - STAR: consistent with predictions
  - ALICE Pb-Pb 2.76 TeV: up to factor 2 higher, but consistent within uncertainties
- Flow
  - PHENIX: $v_2^{\gamma} \sim v_2^{\pi}$ and much larger than theory predictions
  - ALICE: $v_2^{\gamma} \sim v_2^{\pi}$, statistically consistent with predictions

C.Gale, J-F. Paquet, B. Schenke, C. Shen, Quark Matter 2019, arxiv 2002.05191

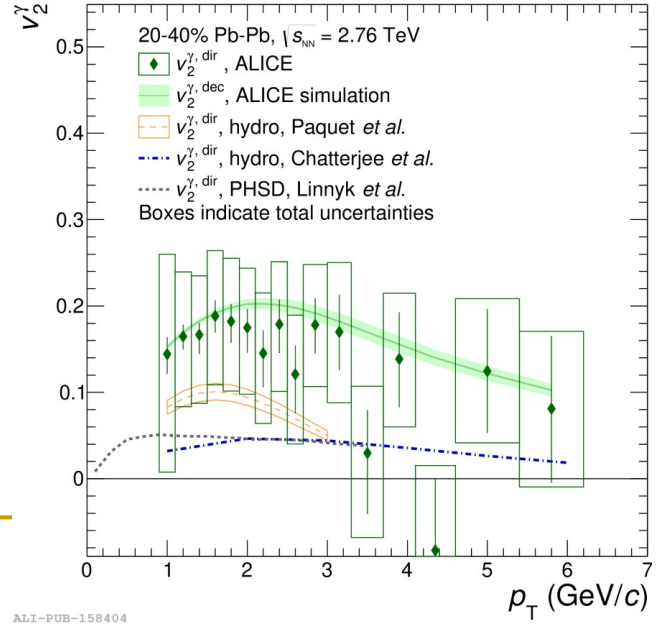
Au-Au, $\sqrt{s_{NN}}$=200 GeV



Au-Au, $\sqrt{s_{NN}}$=200 GeV

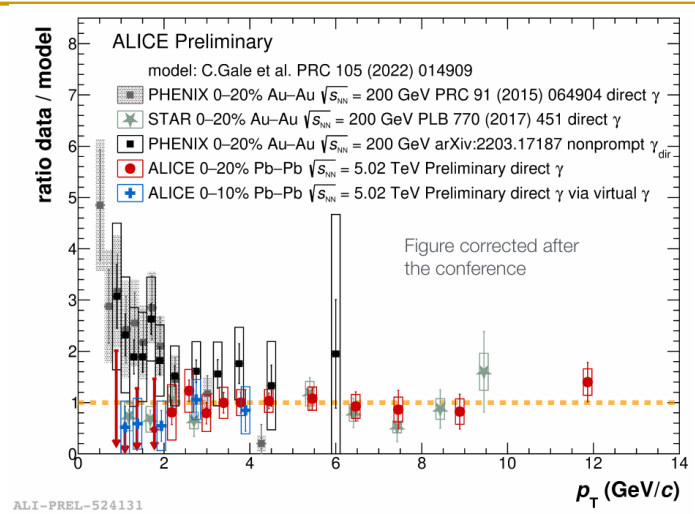


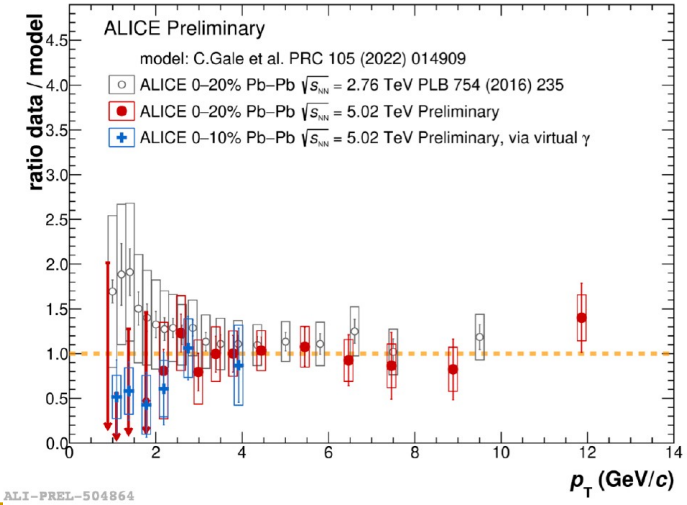
ALICE: Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV



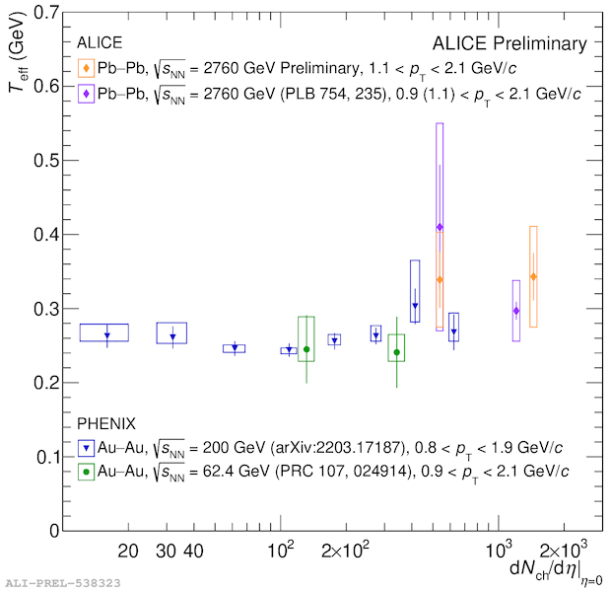
Photon puzzle at LHC

- New ALICE 5.02 TeV data consistent with theory predictions
- Conversion method now uses self-normalized material budget estimate what considerably decreased uncertainties, see arXiv:2303.15317

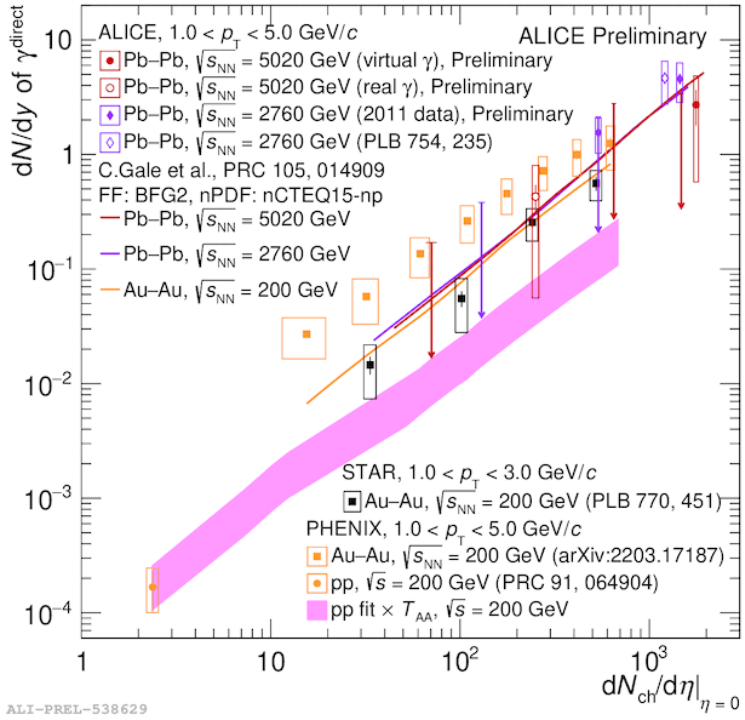




Scaling of the direct photon slope and yield with $dN_{ch}/d\eta$

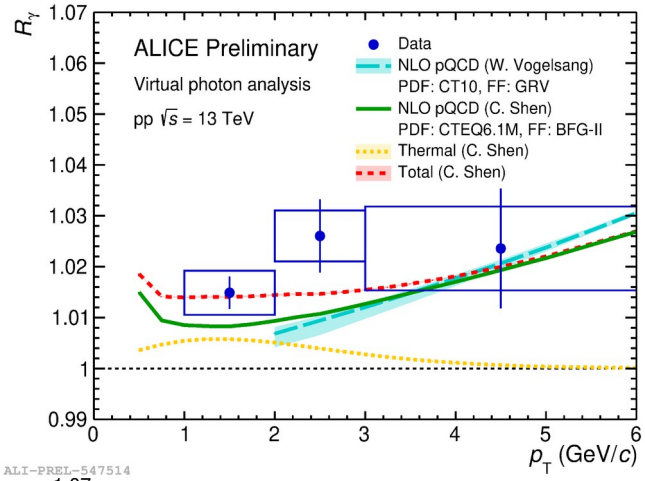


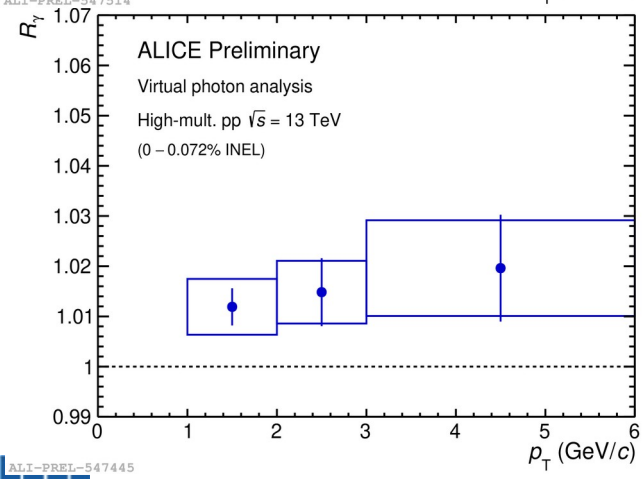
- Effective slope of direct photon spectrum at $1.1<p_T<2.1$ GeV/c is higher, but consistent within uncertainties to slope at RHIC energy



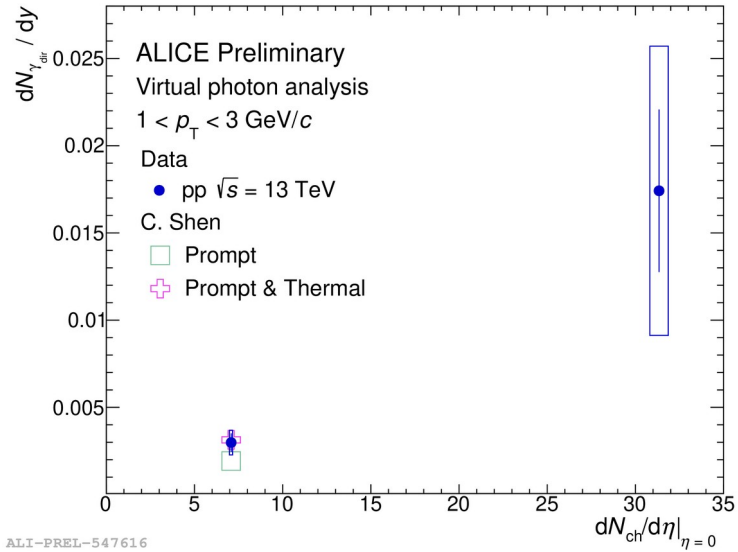
- Integrated direct photon yield is consistent with extrapolation of PHENIX results and of STAR results at RHIC

Direct photons in pp collisions



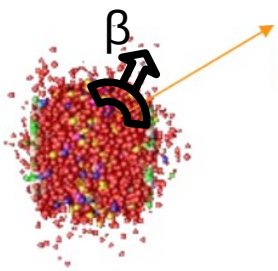


- New high-precision data produced with internal conversion method show direct photon yield down to $p_T = 1$ GeV/c
- Direct photon spectrum agrees with pQCD predictions and with predictions including thermal emission
- In high-multiplicity pp collisions direct photon yield increases proportional to multiplicity



$$R_\gamma = \frac{N_\gamma^{incl} / N_\pi^{measured}}{N_\gamma^{decay} / N_\pi^{simulated}} \approx \frac{N_\gamma^{incl}}{N_\gamma^{decay}}$$

Real and virtual photons



$$E_\gamma \frac{d^3N_\gamma}{d^3p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}}$$

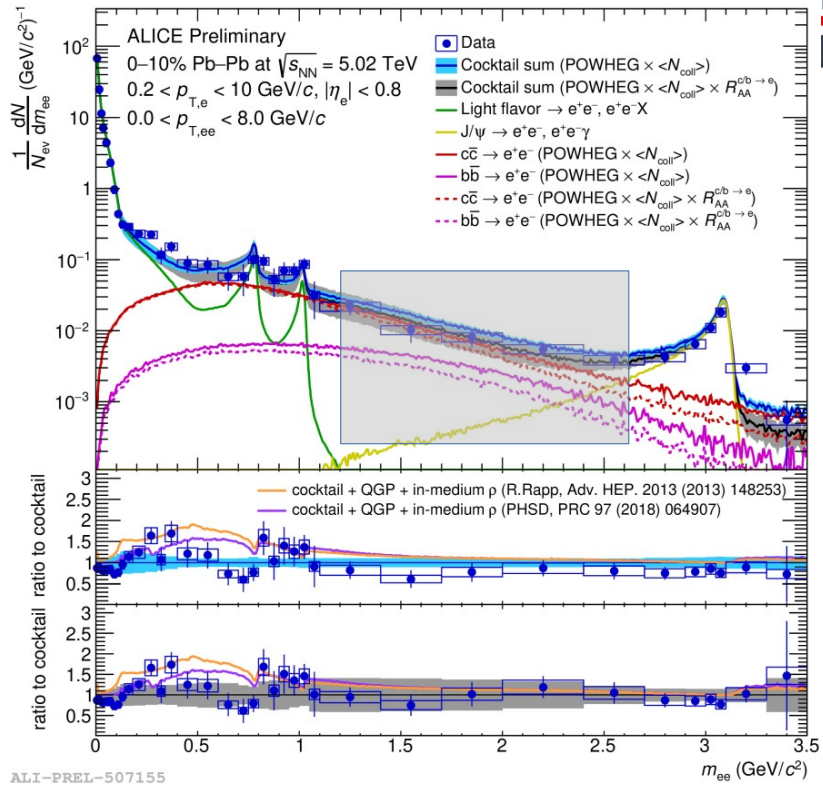
$$T_{\text{eff}} = \sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}} \times T$$

Real photons:

- Thermal contribution significant at p_T<3-5 GeV/c
- Slope strongly affected by collective flow
- Integrate contributions from pre-equilibrium phase till hadronic gas freeze-out

Virtual photons:

- Intermediate mass region provides true temperature
- May contain pre-equlibrium contribution
- Excess in low-mass region can be related to real photon yield via Kroll-Wada formula



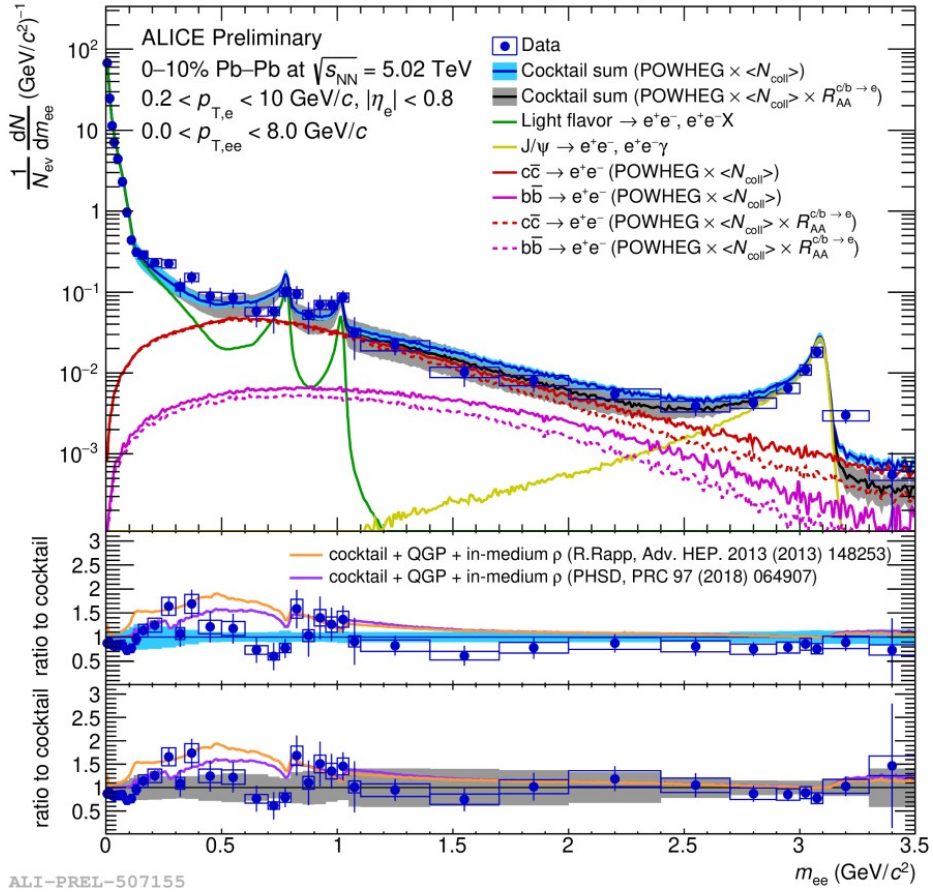
N.M.Kroll and W.Wada, Phys. Rev. 98 (1955) 1355

$$\frac{1}{N_\gamma}\frac{dN}{dM_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}\left(1-\frac{M_{ee}^2}{M^2}\right)^3 |F(M_{ee}^2)|^2$$

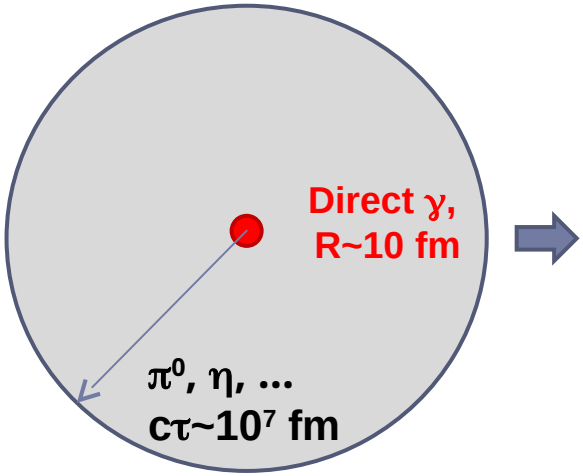
$$\frac{dN}{dM_{ee}} \propto (M_{ee}T)^{3/2} e^{-M_{ee}/T}$$

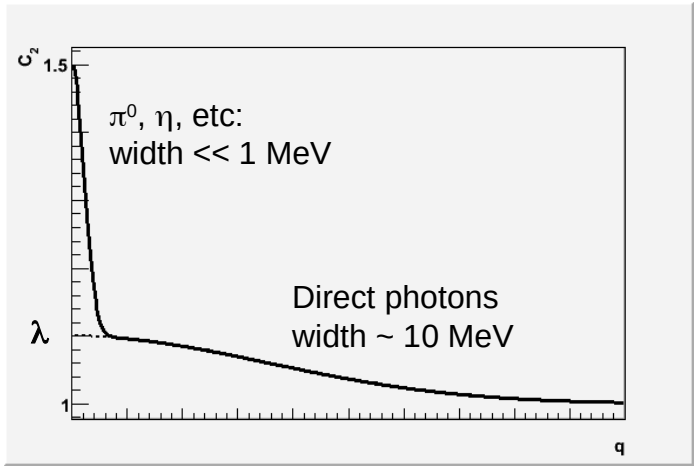
Dileptons at LHC

- Hint for an excess at low m_{ee}
  - Consistent with additional thermal radiation from the medium
- Need to control heavy-flavour background
  - DCA_{ee} studies in Pb-Pb
- Extract fraction of direct photons by fitting the m_{ee} spectra (m_{ee} < 0.4 GeV/c^2)
- No significant excess at medium mass region 1.1<m_{ee}<2.5 GeV/c^2



Direct photon Bose-Einstein correlations



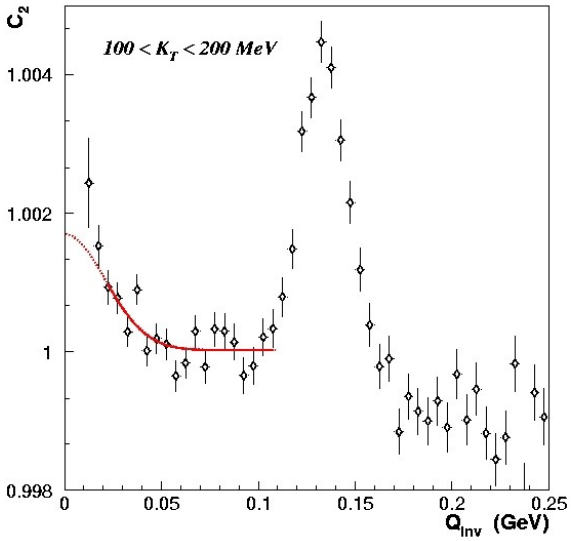


- No need to select direct photons: correlations between decay-decay or decay-direct have tiny width
- Space-time dimensions of hot matter
- Correlation strength λ reflects proportion of direct photons

$$\lambda = \frac{1}{2}\frac{N^{Direct\ pairs}}{N^{All\ pairs}} = \frac{1}{2}\left(\frac{N_{\gamma}^{dir}}{N_{\gamma}^{all}}\right)^{2} \sim 10^{-3}$$

Direct photon Bose-Einstein correlations

WA98: Phys.Rev.Lett. 93 (2004) 022301



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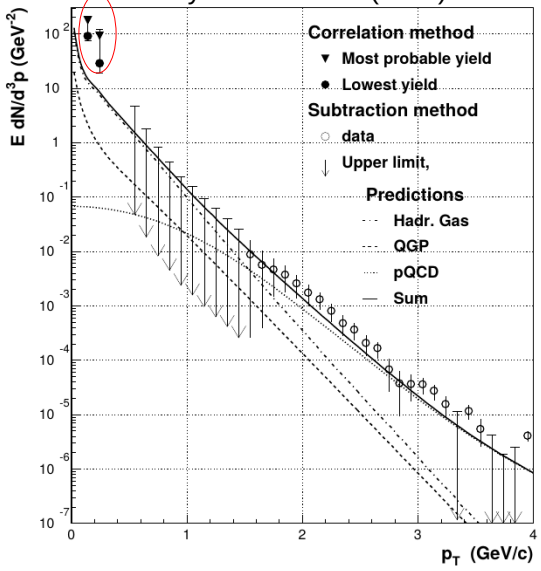
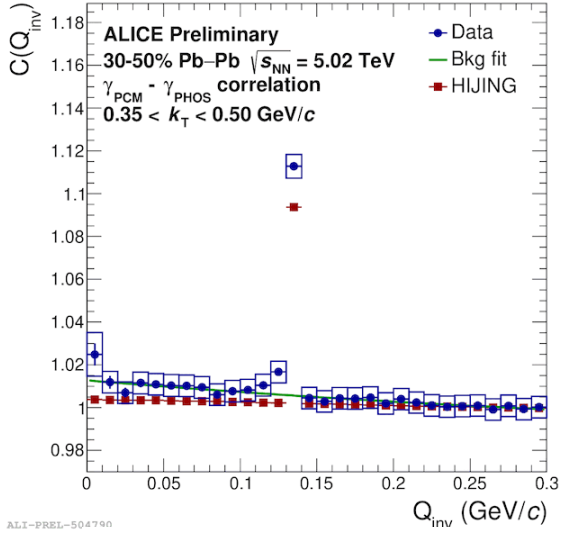
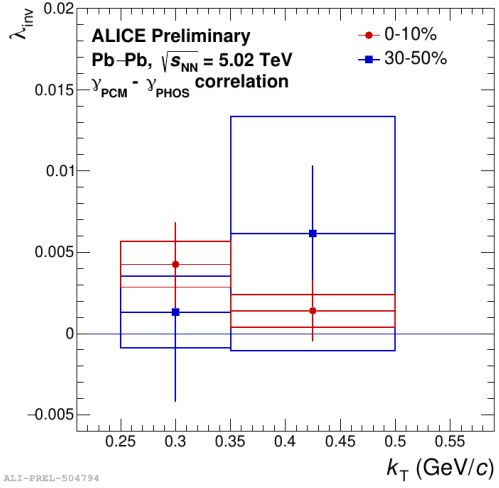






- WA98 extracted correlation radius and *lower limit* of direct photon yield
  - Fortunate experimental setup: fixed target, EM calorimeter at 21 m from IP
  - Good resolution and photon identification, large distance between clusters
- ALICE made first attempt with pairs converted photon-PHOS
  - Some hint of correlation is observed

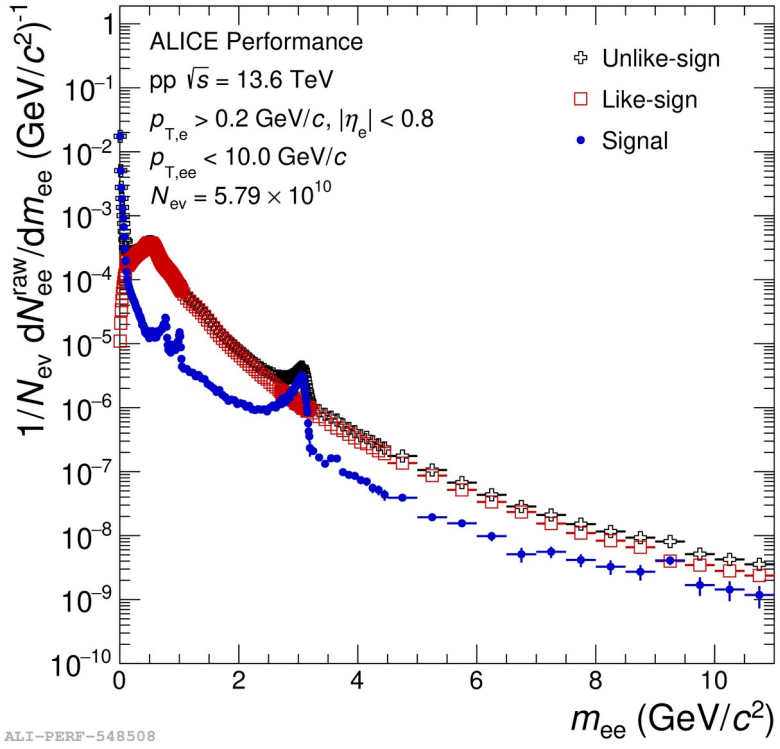
Conclusions

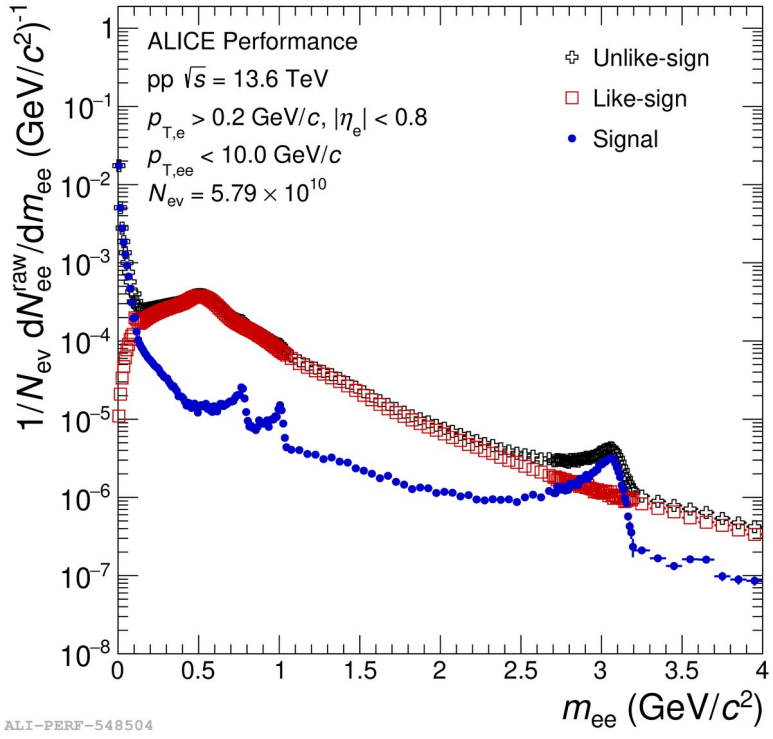
- Direct photons measured in pp, pA and AA collisions
- Fix initial stage of collision with prompt direct photons
- Clearly see thermal direct photons in central AA collisions and possible hint in pp collisions
- Hydrodynamic calculations reproduce ALICE results on spectra and collective flow of thermal direct photons

This work was supported by the Russian Science Foundation grant RSF 22-42-04405

Backup slides

ALICE performance in Run3





THE ALICE DETECTOR