

Direct photon production and HBT correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE experiment

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on behalf of the ALICE collaboration
Physikalisches Institut, Universität Heidelberg



ALICE



FSP ALICE
Erforschung von
Universum und Materie

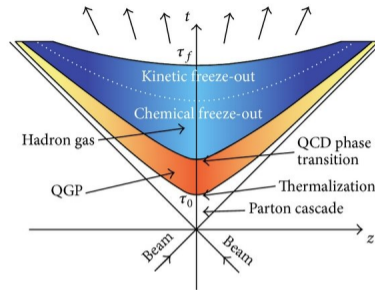


**UNIVERSITÄT
HEIDELBERG**
ZUKUNFT
SEIT 1386

HGS-HiRe for FAIR
Heinrich Graduate School for Hadron and Ion Research

Motivation for measuring direct photons

- Study QCD under extreme conditions (@LHC: high T , low μ_B) and investigate the properties and the dynamics of the quark-gluon plasma
- Direct photons are created during all stages of a heavy-ion collision
- They leave the medium without further interaction
- Thermal photons are sensitive to the medium **temperature** and **collective flow** at photon production time
 \rightsquigarrow integrated effective medium temperature
- Pre-equilibrium photons are sensitive to the saturation momentum Q_s [1]



Sources in AA: Direct photons

- Prompt photons
- Jet-medium interaction
- Pre-equilibrium photons
- Thermal photons from QGP and hadron gas
- Decay photons from π^0 , η , ...

[1] See for example J. Churchill et al. PRC 103 (2021) 024904

Motivation for measuring direct photons

Direct photon signal if

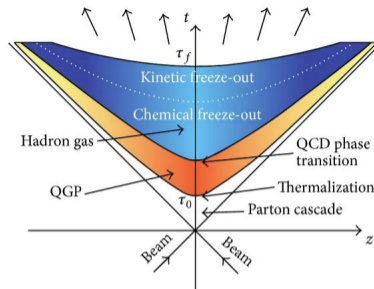
$$R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} > 1$$

Sources dominate in different p_T regions:

Power-law, calculable with pQCD $p_T \gtrsim 5 \text{ GeV}/c \rightarrow$

[2] Comparable contribution for $3 \lesssim p_T \lesssim 5 \text{ GeV}/c \rightarrow$

\approx Exponential spectrum $\propto T^2 e^{-E/T}$ $p_T \lesssim 3 \text{ GeV}/c \rightarrow$



S. Shi arXiv:0907.2265

Sources in AA: Direct photons

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[2] O. Garcia-Montero et al. PRC 102 (2020) 024915, C. Gale et al. PRC 105 (2022) 014909

Motivation for measuring direct photons

Direct photon signal if

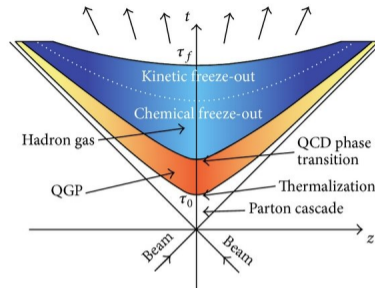
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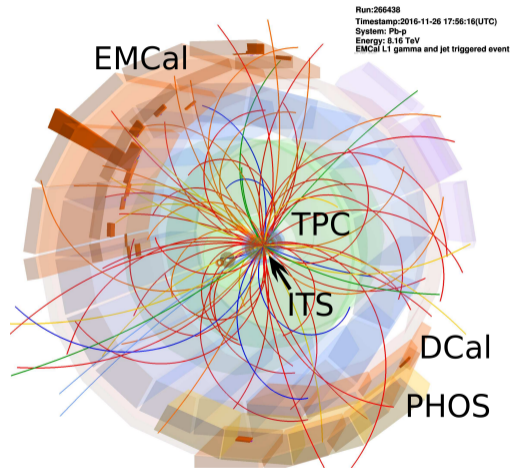
EMCal: sampling calorimeter at $R = 4.3$ m,
 $80 < \varphi < 187^\circ$, $|\eta| < 0.7$
cell size $\approx 6 \times 6$ cm²

DCal:

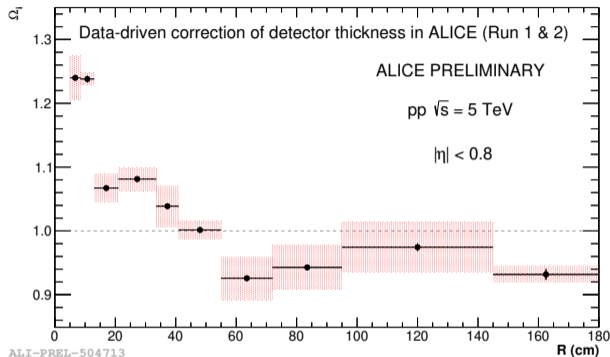
$0.22 < |\eta| < 0.7$, $260 < \varphi < 320^\circ$
 $|\eta| < 0.7$, $320 < \varphi < 327^\circ$

PHOS: homogeneous calorimeter
with PbWO₄ crystals at $R = 4.6$ m,
 $\Delta\varphi = 70^\circ$, $|\eta| < 0.12$
cell size $\approx 2.2 \times 2.2$ cm²

PCM: photon conversion method
 $\gamma X \rightarrow e^+e^- X$ in the detector material
with probability $\approx 8.5\%$ ($R < 1.8$ m)
tracking with ITS ($|\eta| < 2.0$) and TPC ($|\eta| < 0.9$)
 $e^+ e^-$ identification with TPC and TOF
 π^0 down to $p_T \approx 0.3$ GeV/ c



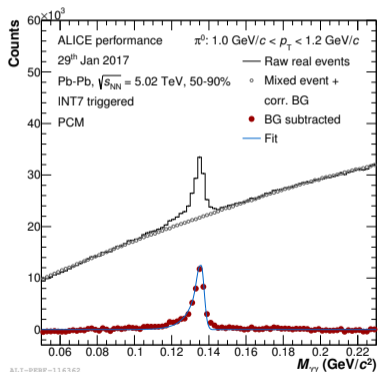
- Conversion probability is determined by the amount and composition of detector material
- But: local imperfections in the material implementation in simulation
⇒ Locally incorrect reconstruction efficiency,
systematic uncertainty 4.5%
- **New data-driven correction:**
efficiency-weights $\Omega(R_{\text{conv}})$
⇒ Systematic uncertainty reduced to 2.5%
and more correct efficiency



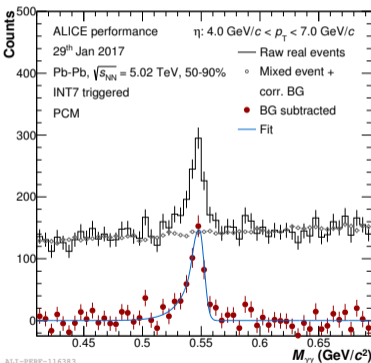
Direct photon signal if

$$R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} > 1$$

- 1) Measure π^0 , η via $\gamma\gamma$ decay channel
- 2) Simulation of decays of π^0 , η , ω , η' , ... into photons



π^0



η

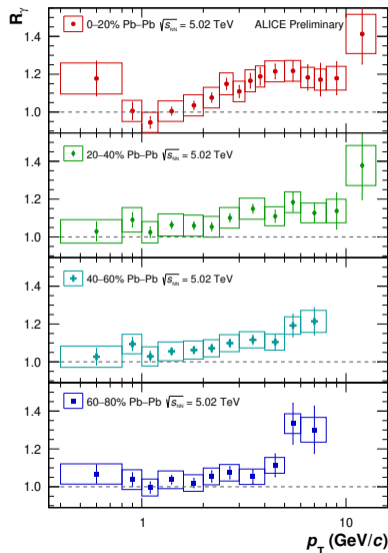
For cancellation of uncertainties:

$$R_\gamma = \frac{\gamma_{\text{inc}}/\pi_{\text{meas}}^0}{\gamma_{\text{decay}}/\pi_{\text{sim}}^0}$$

New results:

Using Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

Method: PCM



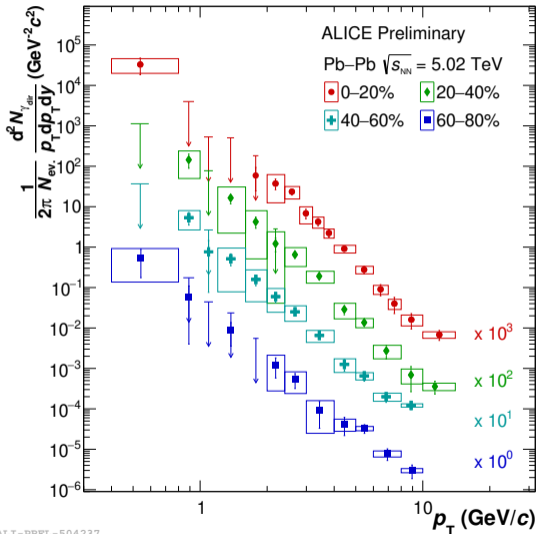
0-20%

20-40%

40-60%

60-80%

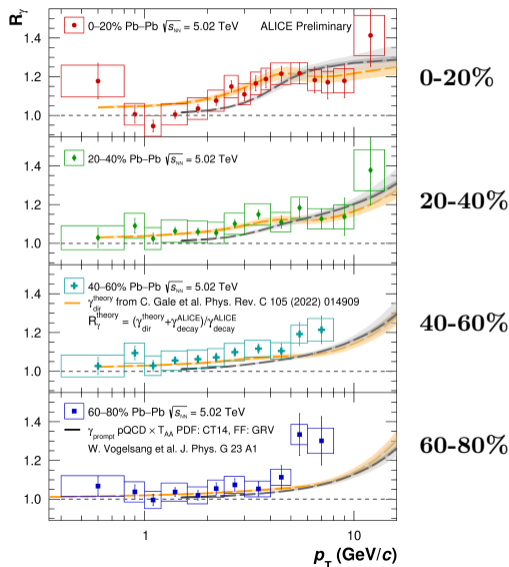
- Four centrality classes
- $0.4 < p_T < 14$ GeV/c
- **Direct photon excess** for $p_T \gtrsim 3$ GeV/c, which can be attributed to prompt (hard scattering) photons
- At low p_T , where thermal radiation should dominate, R_γ is close to 1
 \Rightarrow There can only be a small thermal and pre-equilibrium photon contribution



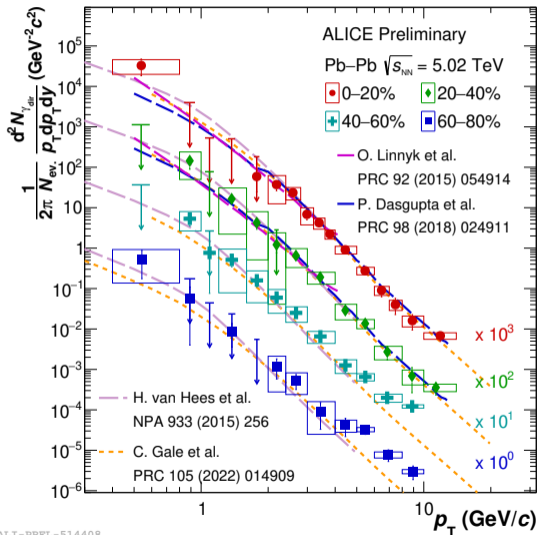
- Direct photon spectra

$$\gamma_{\text{dir}} = \gamma_{\text{inc}} \cdot \left(1 - \frac{1}{R_\gamma}\right)$$
- Upper limits (90% CL) are given where γ_{dir} is consistent with 0

Direct photon excess ratios in comparison to theory



- Within the uncertainties, data is consistent with NLO pQCD calculation of **prompt photons** in pp collisions, scaled with T_{AA}
Calculation by W. Vogelsang, using PDF: CT14, FF: GRV
 - Hydrodynamic model calculation of **direct photons**, including not only prompt but also **thermal** and **pre-equilibrium** photons, predict a small R_γ of about 5% at low p_T , and can describe the data better than the calculation including only prompt photons
- Model by C. Gale et al.: IP-Glasma + K ϕ MP ϕ ST + MUSIC viscous hydrodynamics, prompt γ with PDF: nCTEQ15-np, FF: BFG-II
- Bands represent (theoretical and) experimental uncertainties

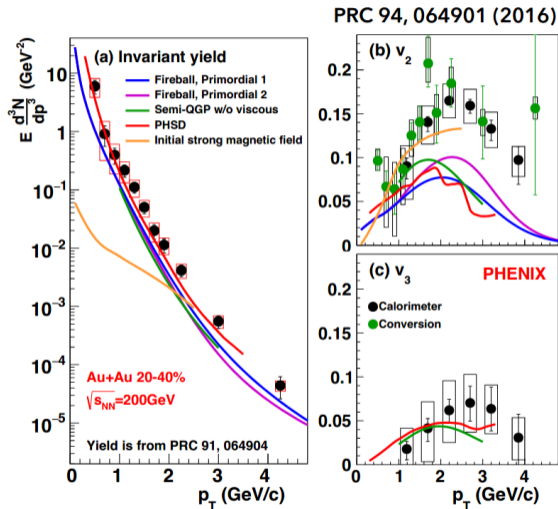


- Direct photon spectra in comparison with *different* model calculations of **direct photons**:
 - Microscopic transport approach PHSD (O. Linnyk et al.)
 - Relativistic hydrodynamics models (others), using different initial conditions, thermalization times, hadronization temperatures, with (C. Gale et al.) and without pre-equilibrium γ (others)
- The measurement is **not yet sensitive to the differences** between the predictions of the different models
- Dominating **uncertainties**:
 - High and low p_T : statistical uncertainty
 - Mid- p_T : systematic uncertainties: γ reconstruction efficiency (material, electron/positron identification), decay γ (η contribution)

What about the direct photon puzzle?

- The term **direct photon puzzle** was introduced after the direct photon elliptic flow coefficient v_2 was measured for the first time by PHENIX in 2012, unexpectedly large
- Still a topic **last QM** conference 2019 \rightarrow
- Large yield (early emission) and large v_2 (late emission) difficult to explain simultaneously

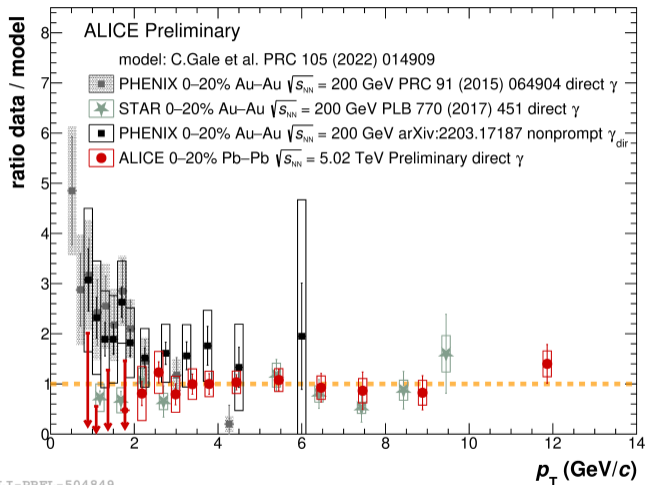
\Rightarrow How does the new ALICE measurement fit into the picture?



W. Fan (PHENIX Collaboration) QM 2019

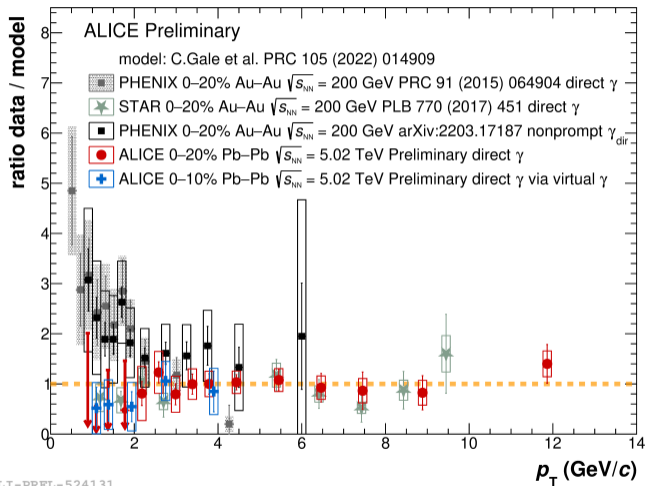
What about the direct photon puzzle?

NEW



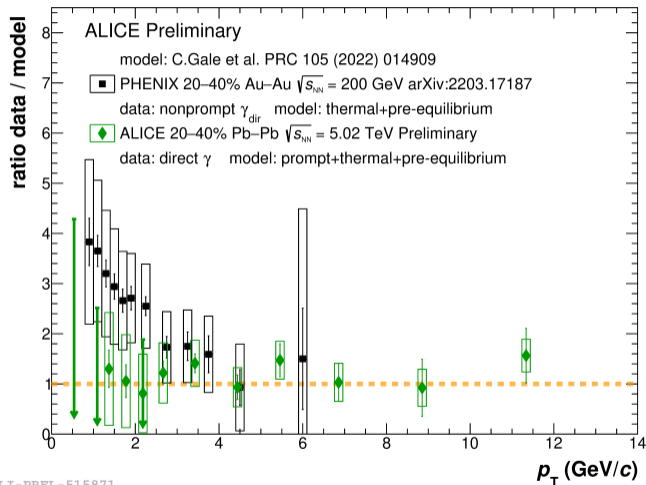
ALI-PREL-504849

- Comparing measured direct photon spectra with model calculations for the respective collision energies $\sqrt{s_{NN}} = 200$ GeV and 5.02 TeV
- Just looking at the spectra, there is **no puzzling discrepancy** between state-of-the art models and **new ALICE measurement**



ALI-PREL-524131

- Comparing measured direct photon spectra with model calculations for the respective collision energies $\sqrt{s_{NN}} = 200$ GeV and 5.02 TeV
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- Similar finding by measurement via virtual photons,
[Talk by Jerome Jung, T13, Thursday 15:20](#)



ALI-PREL-515871

- Comparing measured direct photon spectra with model calculations for the respective collision energies $\sqrt{s_{NN}} = 200$ GeV and 5.02 TeV
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- Similar finding by measurement via virtual photons,
[Talk by Jerome Jung, T13, Thursday 15:20](#)
- The same conclusion for 20-40% centrality class, from real γ

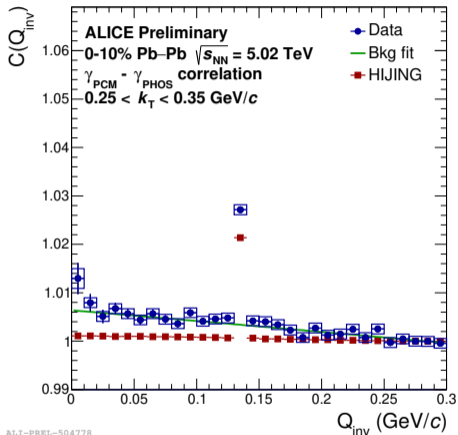
New: Bose-Einstein $\gamma\gamma$ correlations

Using Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Method: PCM-PHOS

- Motivation: Correlation function $C(Q_{\text{inv}})$ is sensitive to the **source size** R and the **direct photon fraction**
- Method: $C(Q_{\text{inv}}) = \frac{A(Q_{\text{inv}})}{B(Q_{\text{inv}})}$
 A: γ_1, γ_2 from same events
 B: γ_1, γ_2 from mixed events
 $Q_{\text{inv}} = M_{\gamma\gamma}$
 Correction for detector effects
- π^0 peak is visible and slope from correlations in particle showers
- Small hint of an HBT-like effect, quantified with correlation strength λ_{inv} from a fit using

$$C(Q_{\text{inv}}) = 1 + \lambda_{\text{inv}} \exp(-R_{\text{inv}}^2 Q_{\text{inv}}^2)$$
- In bins of $k_T = \frac{p_{T,\text{pair}}}{2}$ and centrality
- Possible complementary method to determine R_γ down to $p_T \approx 0.25 \text{ GeV}/c$

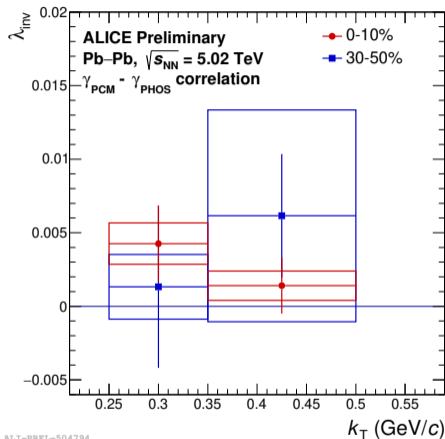


See poster by Mike Sas, Wednesday 18:54

terminology used from PRL 93 (2004) 022301, D. Peressounko et al.

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ALI-PREL-504794

See poster by Mike Sas, Wednesday 18:54

terminology used from PRL 93 (2004) 022301, D. Peressounko et al.

- **First measurement** of direct photons in **Pb–Pb collisions** at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
- **Direct photon signal** for $p_T \gtrsim 3 \text{ GeV}/c$ can be attributed to prompt photons
- R_γ at low p_T is close to 1
 \Rightarrow we cannot yet claim a significant signal of an additional direct photon source like thermal photons or pre-equilibrium photons
- But, calculations including **thermal+pre-equilibrium+prompt photons**, which model also the evolution of the **temperature and flow** of the medium, are **in agreement** with the measurement as well
 \Rightarrow no puzzling discrepancy between model and data

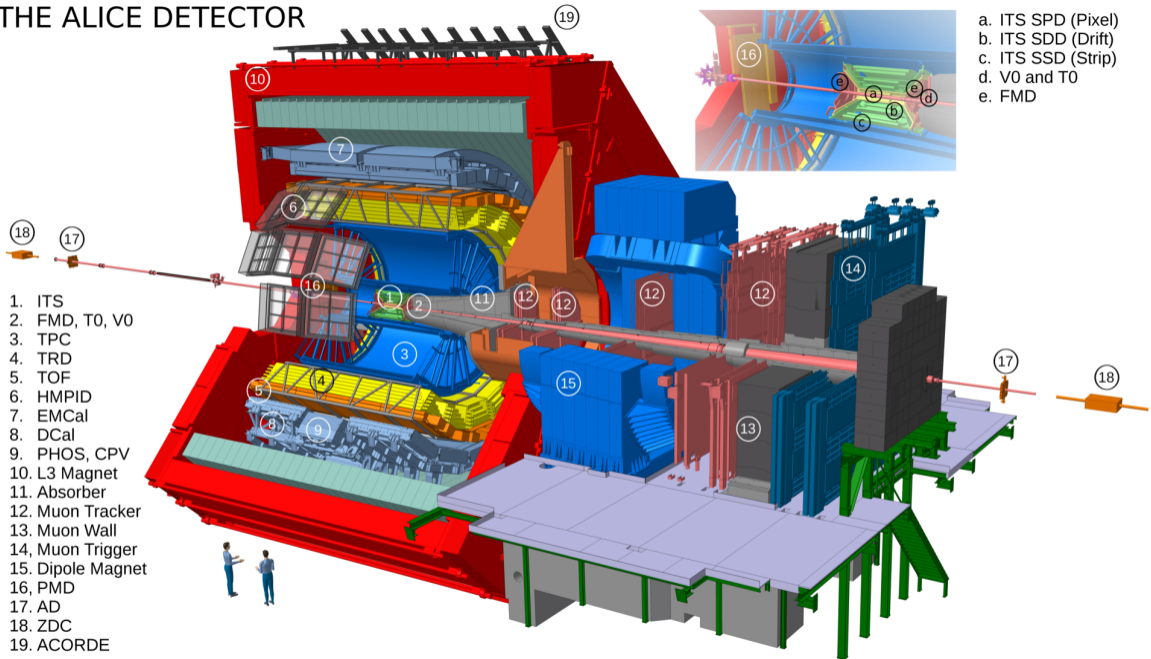
- Analysis will be extended to full LHC Run 2 dataset and next heavy-ion data taking planned for 2022



- More data will allow for a more precise measurement
 - ↪ **Composition** of direct photons at low p_T ?
 - ↪ Effective medium **temperature** can be extracted in case of a more significant direct photon signal
 - ↪ Direct photon **flow coefficients** v_n provide complementary information on space-time evolution
- Presented first analysis aiming at photon HBT correlations with LHC data
 - ↪ Possible complementary method to determine R_γ at very low p_T

Thank you!

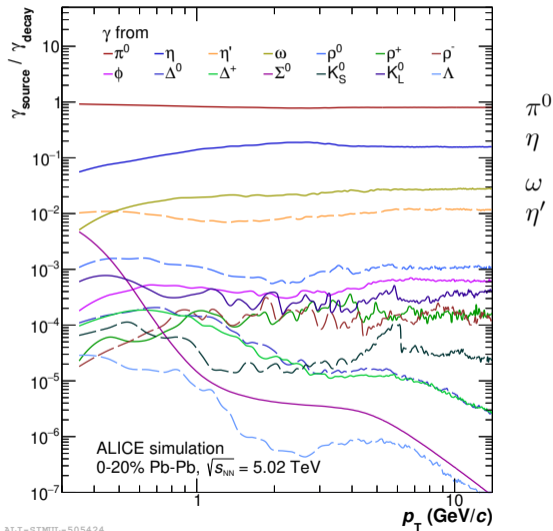
THE ALICE DETECTOR



Direct photon signal if

$$R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} > 1$$

- 1) Measure π^0 , η via $\gamma\gamma$ decay channel
- 2) Simulation of decays of π^0 , η , ω , η' , ...



- Production rate depends on the medium temperature:

$$r_\gamma(E, T) \propto T^2 e^{-E/T} \log\left(\frac{ET}{k_c^2}\right)$$

- blue-shift due to radial flow

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

- averaged over time

- Inverse slope $\Rightarrow \langle T_{\text{eff}} \rangle$

- Measurements from ALICE and PHENIX:

exponential spectral shape with $T_{\text{eff}}^{\text{LHC}} > T_{\text{eff}}^{\text{RHIC}}$

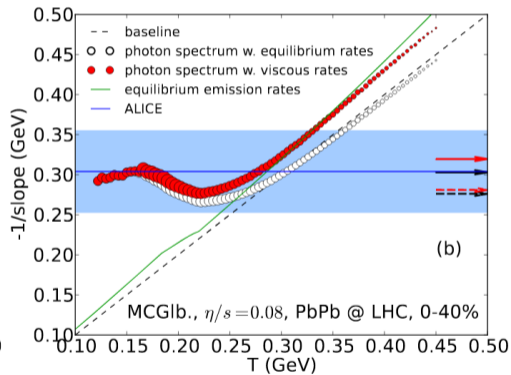
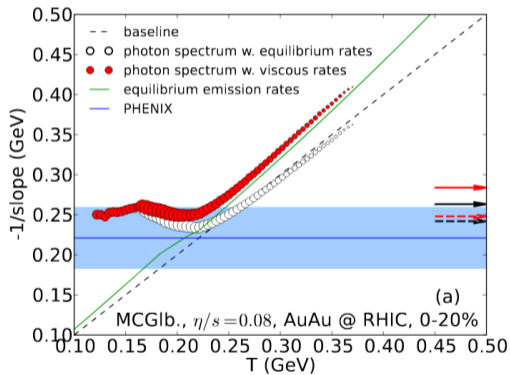
due to higher T and/or stronger radial flow

$$T_{\text{eff}}^{\text{RHIC}} = (221 \pm 19^{\text{stat}} \pm 19^{\text{syst}}) \text{ MeV}$$

PHENIX Collaboration, Phys.Rev.Lett. 104 (2010) 132301

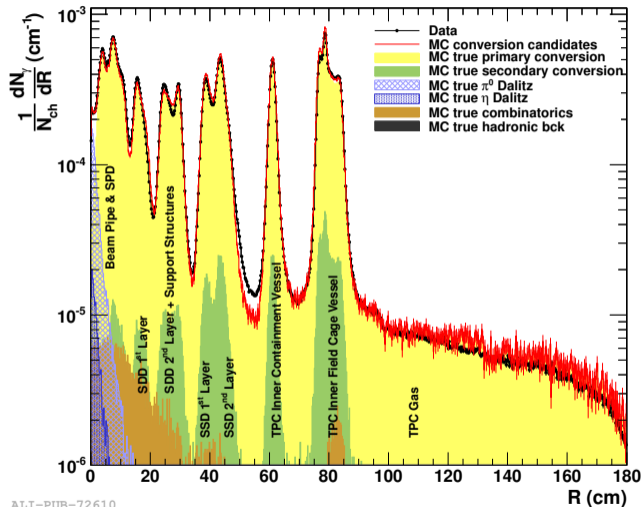
$$T_{\text{eff}}^{\text{LHC}} = (297 \pm 12^{\text{stat}} \pm 41^{\text{syst}}) \text{ MeV}$$

ALICE Collaboration, Phys.Lett. B754 (2016) 235



C. Shen et al. Phys. Rev. C 89, 044910 (2014)

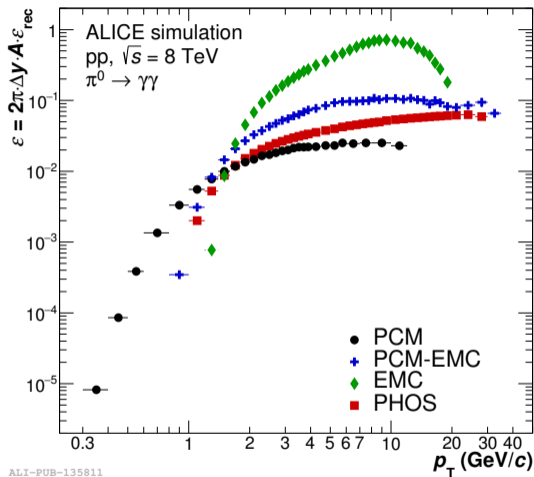
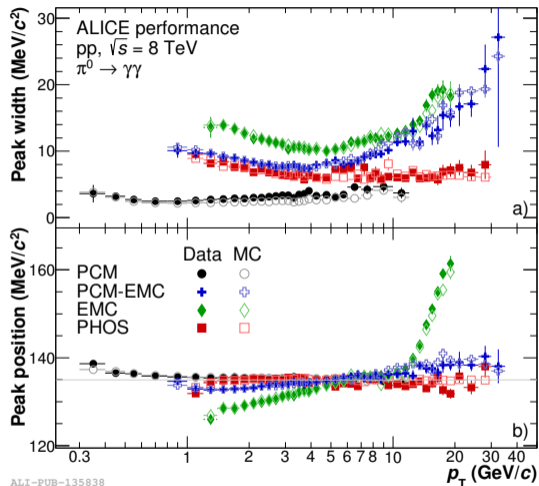
Material budget in data and MC before correction



ALI-PUB-72610

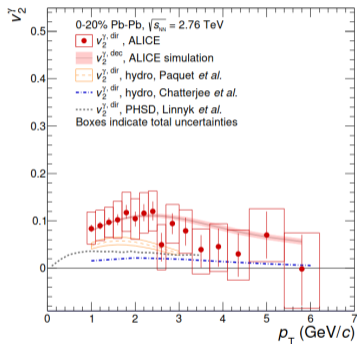
Int.J.Mod.Phys.A 29 (2014) 1430044

Complementarity of the methods

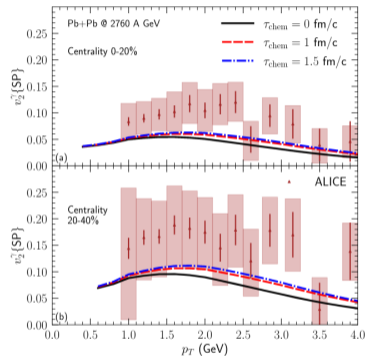
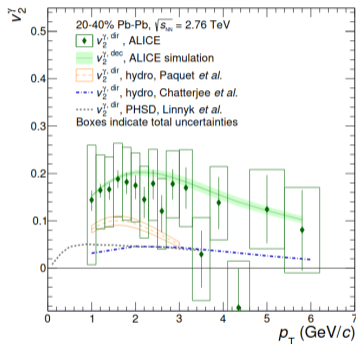


Eur. Phys. J. C (2018) 78: 263

Direct photon elliptic flow $\sqrt{s_{NN}} = 2.76$ TeV ALICE

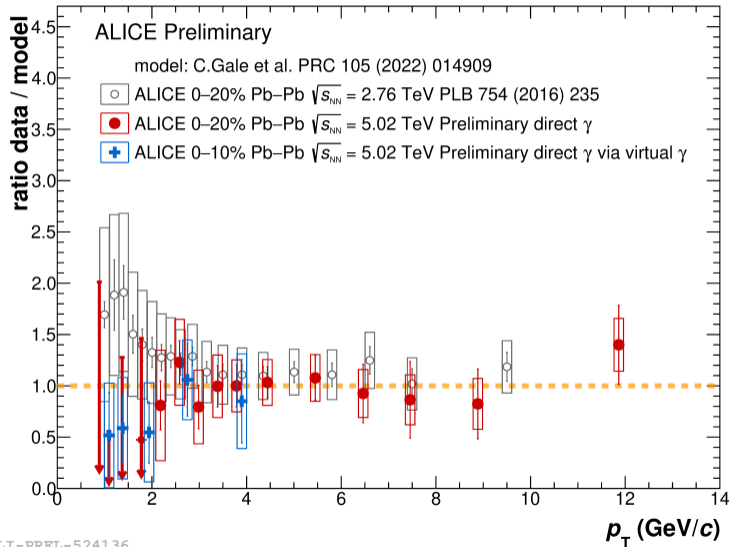


PLB 789 (2019) 308



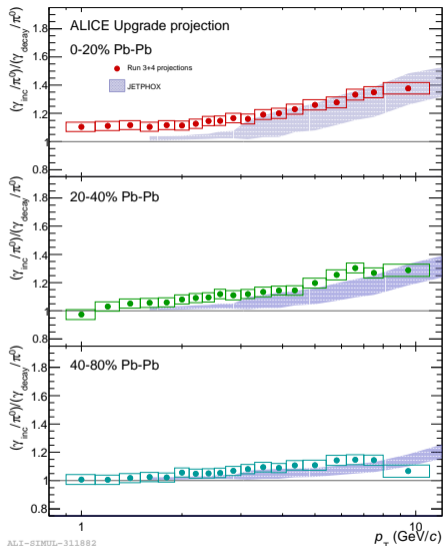
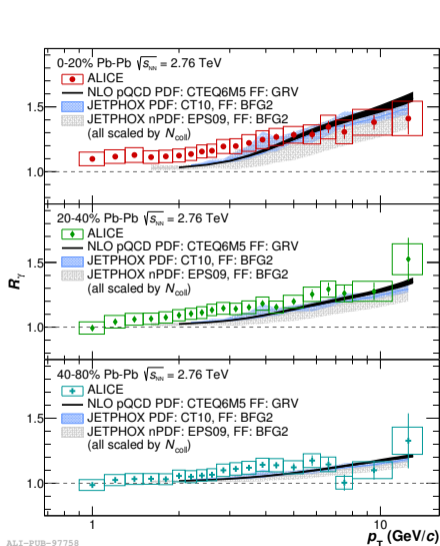
PRC 105 (2022) 014909

Ratios of measurements at LHC energies to theory

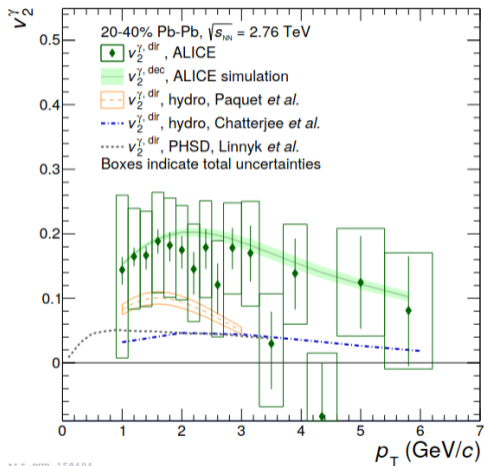


ALI-PREL-524136

Uncertainties projection Run 1 \rightarrow Run 3+4

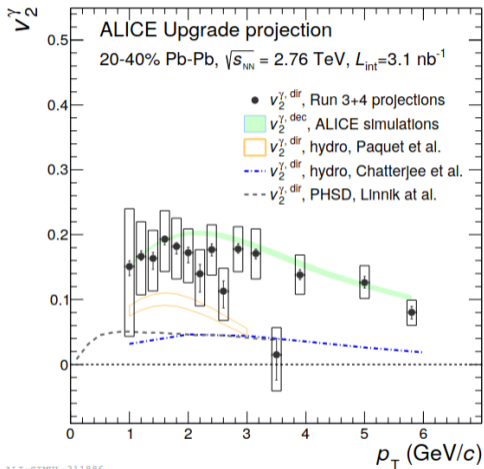


Uncertainties projection Run 1 \rightarrow Run 3+4



ALI-PUB-158404

arXiv:1812.06772



ALI-SIMUL-311886

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