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

Meike Charlotte Danisch
on behalf of the ALICE collaboration
Physikalisches Institut, Universität Heidelberg

QUARK MATTER KRAKÓW 2022

ALICE

FSP ALICE
Erforschung von Universum und Materie

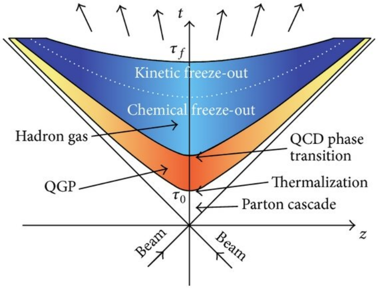
UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

HGS-HIRe for FAIR
Helmholtz 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]



S. Shi arXiv:0907.2265

Sources in AA: Direct photons

- Prompt photons
- Jet-medium interaction
- Pre-equilibrium photons
- Thermal photons from QGP and hadron gas

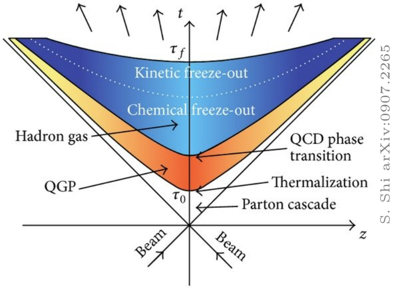
- Decay photons from π^0, η, ...

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

Motivation for measuring direct photons

Direct photon signal if

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



Sources dominate in different p_{T} regions:

Power-law, calculable with pQCD $p_{\mathrm{T}} \gtrsim 5\,\mathrm{GeV}/c$ →

[2] Comparable contribution for $3 \lesssim p_{\mathrm{T}} \lesssim 5\,\mathrm{GeV}/c$ →

≈ Exponential spectrum $\propto T^2 e^{-E/T}$ $p_{\mathrm{T}} \lesssim 3\,\mathrm{GeV}/c$ →

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

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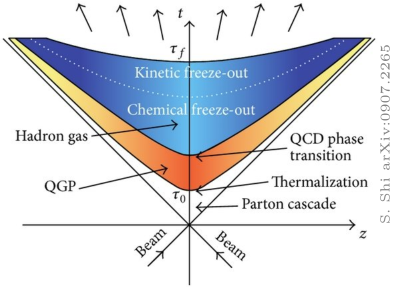

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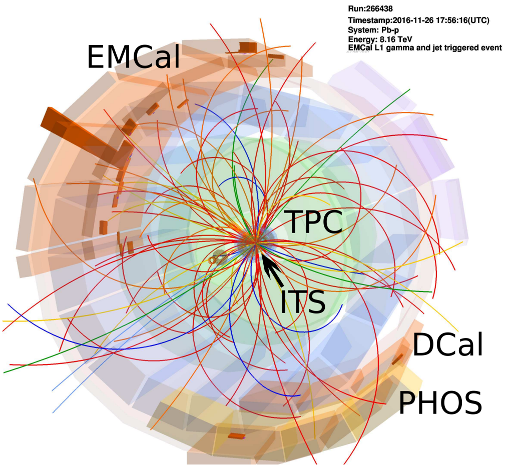
Measurement of inclusive photons

EMCal: sampling calorimeter at $R = 4.3\,\mathrm{m}$,
$80 < \varphi < 187°$, $|\eta| < 0.7$
cell size $\approx 6 \times 6\,\mathrm{cm}^2$
DCal:
$0.22 < |\eta| < 0.7$, $260 < \varphi < 320°$
$|\eta| < 0.7$, $320 < \varphi < 327°$

PHOS: homogeneous calorimeter
with $PbWO_4$ crystals at $R = 4.6\,\mathrm{m}$,
$\Delta\varphi = 70°$, $|\eta| < 0.12$
cell size $\approx 2.2 \times 2.2\,\mathrm{cm}^2$

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

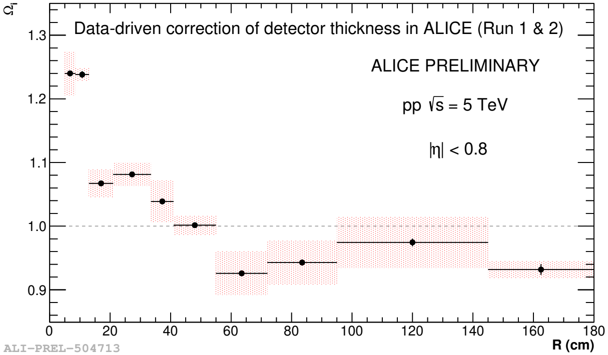


Measurement of inclusive photons

NEW

ALICE

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

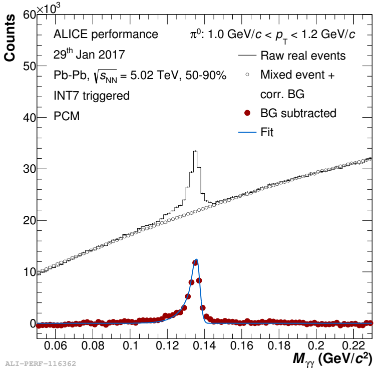


Simulation of decay photons

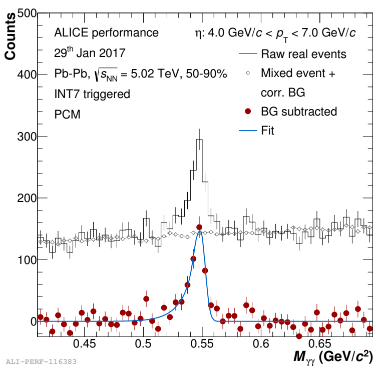
Direct photon signal if

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

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:

$$R_\gamma = \frac{\gamma_{\mathrm{inc}}/\pi^0_{\mathrm{meas}}}{\gamma_{\mathrm{decay}}/\pi^0_{\mathrm{sim}}}$$

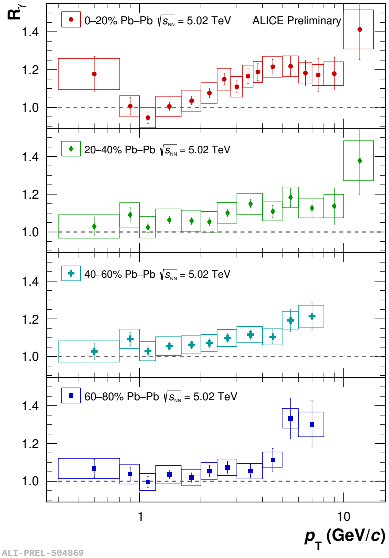
New results:

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

Method: PCM

Direct photon excess ratios in 5.02 TeV Pb–Pb

NEW



0-20%

20-40%

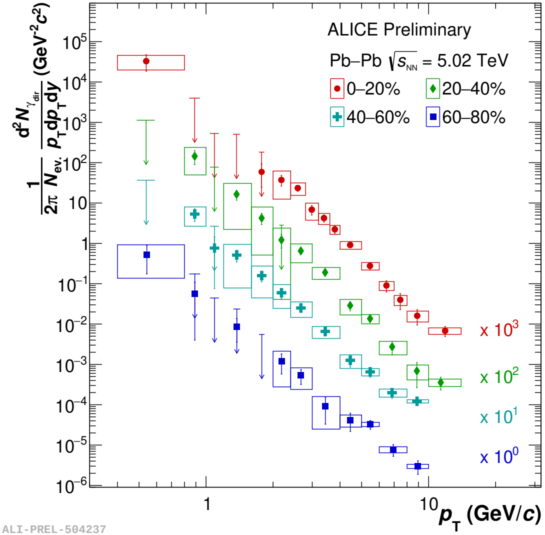
40-60%

60-80%

- Four centrality classes
- $0.4 < p_T < 14\,\mathrm{GeV}/c$
- **Direct photon excess** for $p_\mathrm{T} \gtrsim 3\,\mathrm{GeV}/c$, 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 in 5.02 TeV Pb–Pb

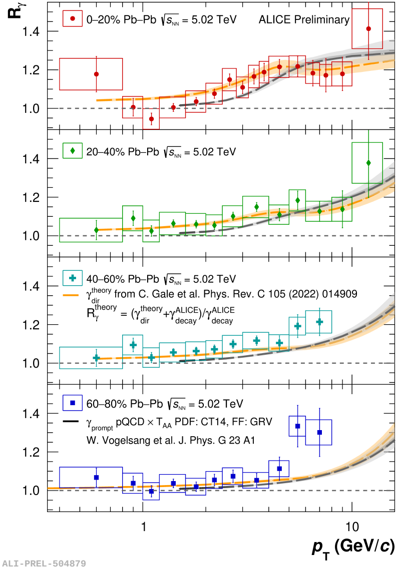
NEW



- Direct photon spectra
  $\gamma_{\rm dir} = \gamma_{\rm inc} \cdot (1 - \frac{1}{R_\gamma})$
- Upper limits (90% CL) are given where $\gamma_{\rm dir}$ is consistent with 0

Direct photon excess ratios in comparison to theory

NEW



0-20%

20-40%

40-60%

60-80%

- 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 calulation including only prompt photons

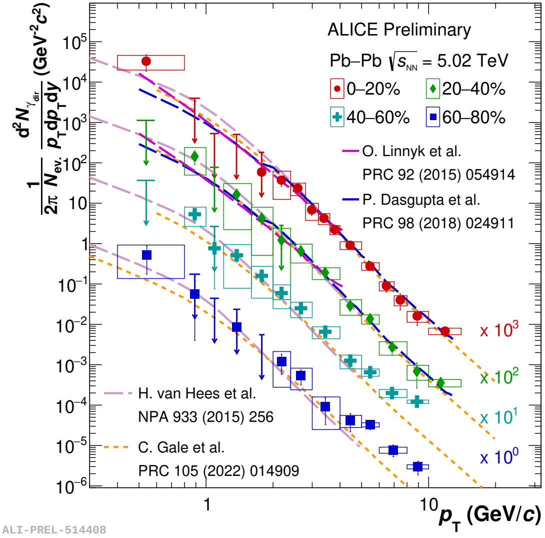
  Model by C. Gale et al.: IP-Glasma + KøMPøST + MUSIC viscous hydrodynamics, prompt γ with PDF: nCTEQ15-np, FF: BFG-II

- Bands represent (theoretical and) experimental uncertainties

Direct photon spectra in comparison to theory

NEW

ALICE



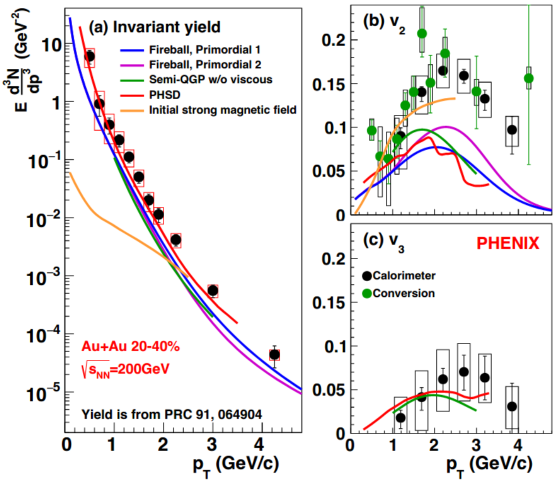
- Direct photon spectra in comparison with *different* model calculations of **direct photons**:
  - Microscopic transport approach PHSD (O. Linnyk et al.)
  - Relativistic hydrodynamics models (others), using different initial conditions, thermalization times, hadronization temperatures, with (C. Gale 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 uncertinties: 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 →
- Large yield (early emission) and large v_2 (late emission) difficult to explain simultaneously

⇒ How does the new ALICE measurement fit into the picture?

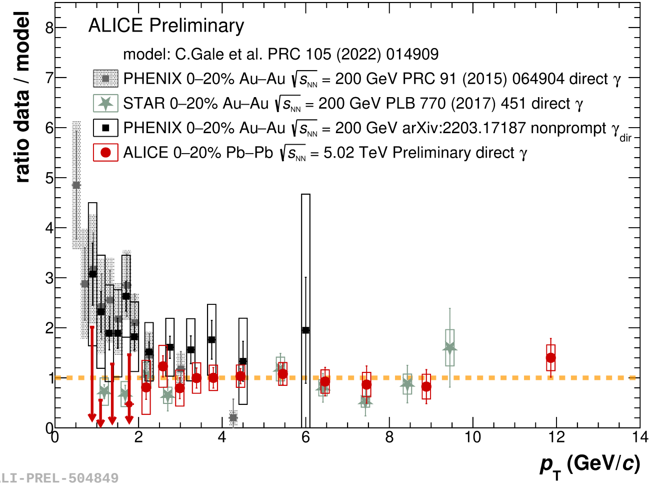
PRC 94, 064901 (2016)



W. Fan (PHENIX Collaboration) QM 2019

What about the direct photon puzzle?

NEW



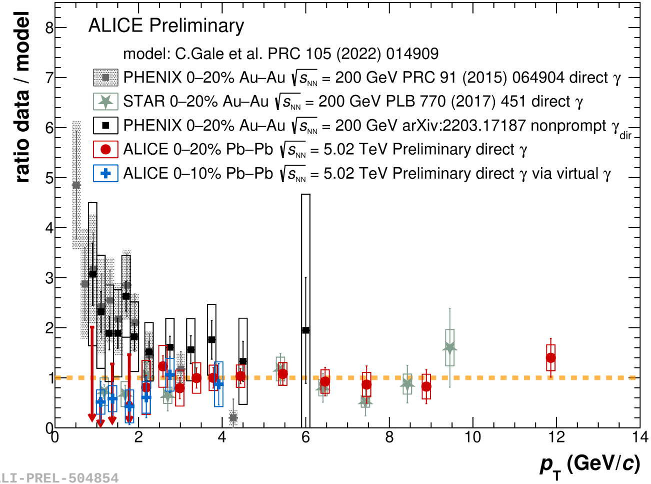
ALI-PREL-504849

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

What about the direct photon puzzle?

NEW

ALICE



ALI-PREL-504854

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- Similar finding by measurement via virtual photons, Talk by Jerome Jung, T13, **Thursday 15:20**

What about the direct photon puzzle?

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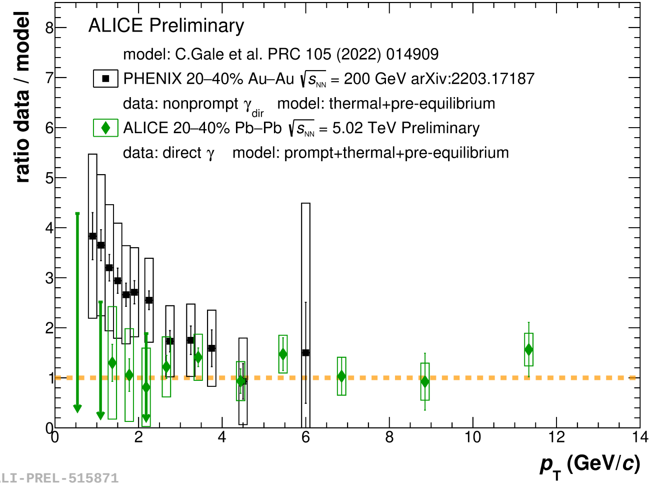
ALICE



ALI-PREL-515871

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

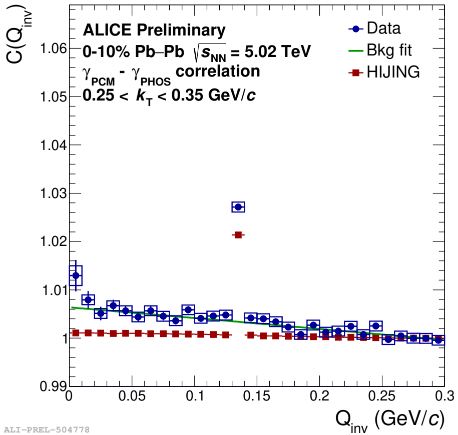
New: Bose-Einstein $\gamma\gamma$ correlations

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

Method: PCM-PHOS

Bose-Einstein $\gamma\gamma$ correlations in Pb–Pb collisions NEW

- Motivation: Correlation function $C(Q_{\mathrm{inv}})$ is sensitive to the **source size** R and the **direct photon fraction**
- Method: $C(Q_{\mathrm{inv}}) = \frac{A(Q_{\mathrm{inv}})}{B(Q_{\mathrm{inv}})}$
  A: γ_1, γ_2 from same events
  B: γ_1, γ_2 from mixed events
  $Q_{\mathrm{inv}} = M_{\gamma\gamma}$
  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
  $$C(Q_{\mathrm{inv}}) = 1 + \lambda_{\mathrm{inv}} \exp(-R_{\mathrm{inv}}^2 Q_{\mathrm{inv}}^2)$$
- In bins of $k_{\mathrm{T}} = \frac{p_{\mathrm{T,pair}}}{2}$ and centrality
- Possible complementary method to determine R_γ down to $p_{\mathrm{T}} \approx 0.25\,\mathrm{GeV}/c$



See poster by Mike Sas, Wednesday 18:54

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

Bose-Einstein $\gamma\gamma$ correlations in Pb–Pb collisions NEW

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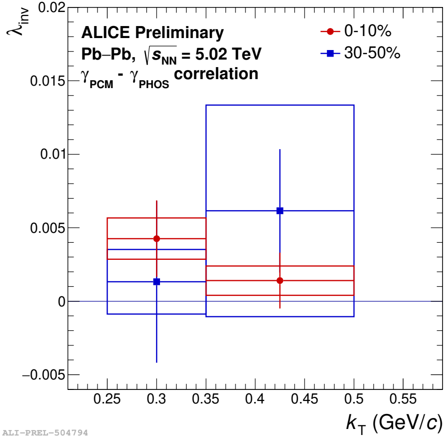

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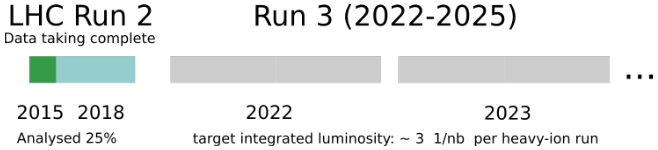
Summary and outlook

- **First measurement** of direct photons in **Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV**
- **Direct photon signal** for $p_{\mathrm{T}} \gtrsim 3\,\mathrm{GeV}/c$ 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

Summary and outlook

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



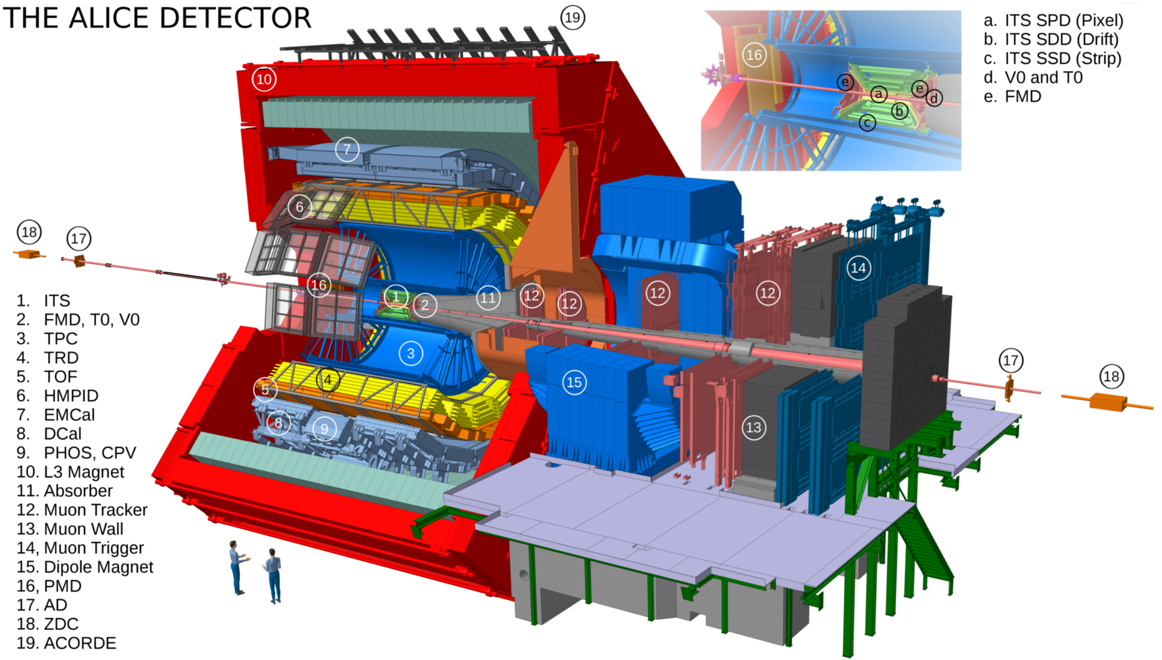
arXiv:1812.06772

- More data will allow for a more precise meaurement
  ⇝ **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



a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

Simulation of decay photons

Direct photon signal if

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

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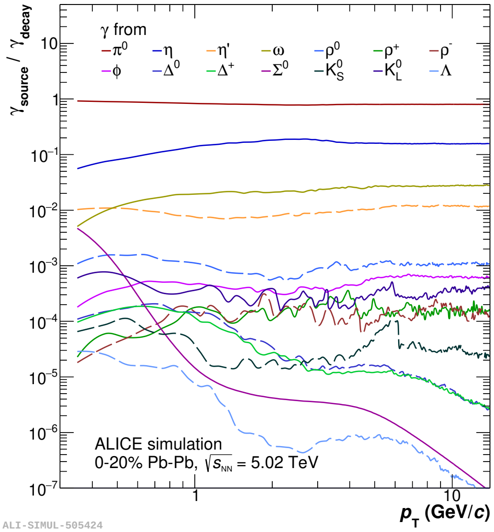


π^0

η

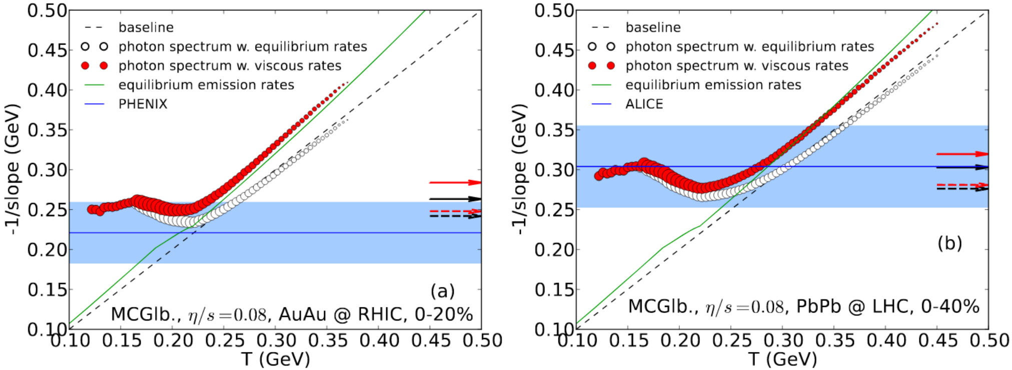
ω

η'

Effective averaged medium temperature

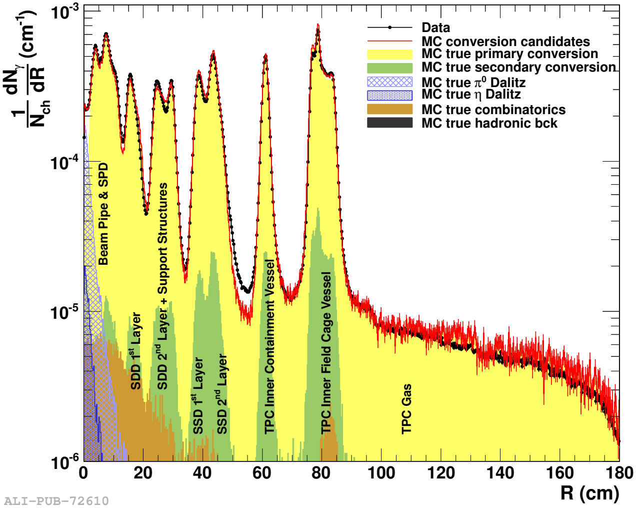
- Production rate depends on the medium temperature:
  $r_\gamma(E,T) \propto T^2 e^{-E/T} \log(\frac{ET}{k_c^2})$
- blue-shift due to radial flow
  $T_{\mathrm{eff}} = \sqrt{\frac{1+\beta_{\mathrm{flow}}}{1-\beta_{\mathrm{flow}}}} \cdot T$
- averaged over time
- Inverse slope $\Rightarrow \langle T_{\mathrm{eff}} \rangle$
- Measurements from ALICE and PHENIX:
  exponential spectral shape with $T_{\mathrm{eff}}^{\mathrm{LHC}} > T_{\mathrm{eff}}^{\mathrm{RHIC}}$
  due to higher T and/or stronger radial flow
  $T_{\mathrm{eff}}^{\mathrm{RHIC}} = (221 \pm 19^{\mathrm{stat}} \pm 19^{\mathrm{syst}})$ MeV
  PHENIX Collaboration, Phys.Rev.Lett. 104 (2010) 132301
  $T_{\mathrm{eff}}^{\mathrm{LHC}} = (297 \pm 12^{\mathrm{stat}} \pm 41^{\mathrm{syst}})$ MeV
  ALICE Collaboration, Phys.Lett. B754 (2016) 235

Inverse slope parameter and medium temperature



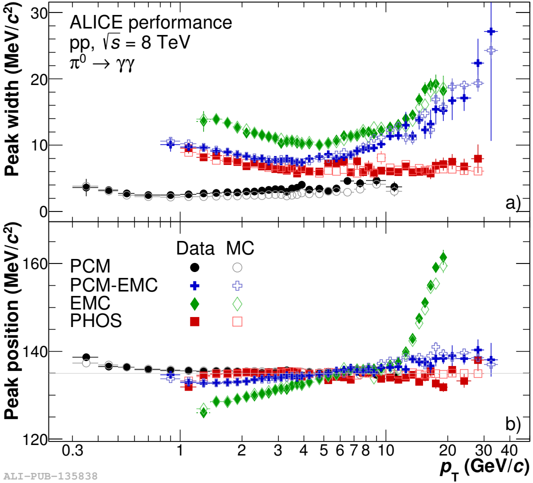
C. Shen et al. Phys. Rev. C 89, 044910 (2014)

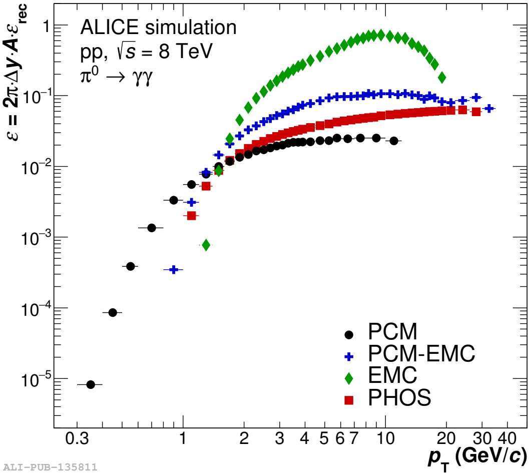
Material budget in data and MC before correction



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

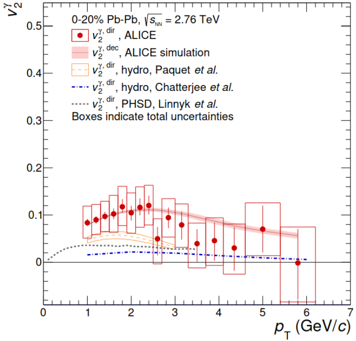
Complementarity of the methods

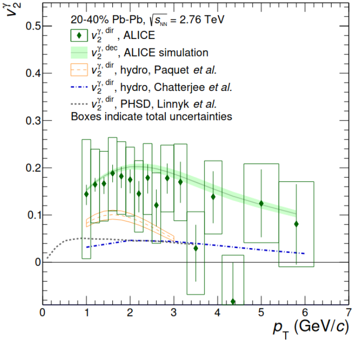




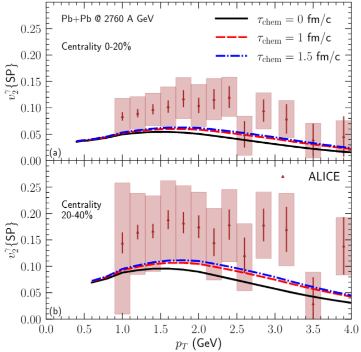
Eur. Phys. J. C (2018) 78: 263

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



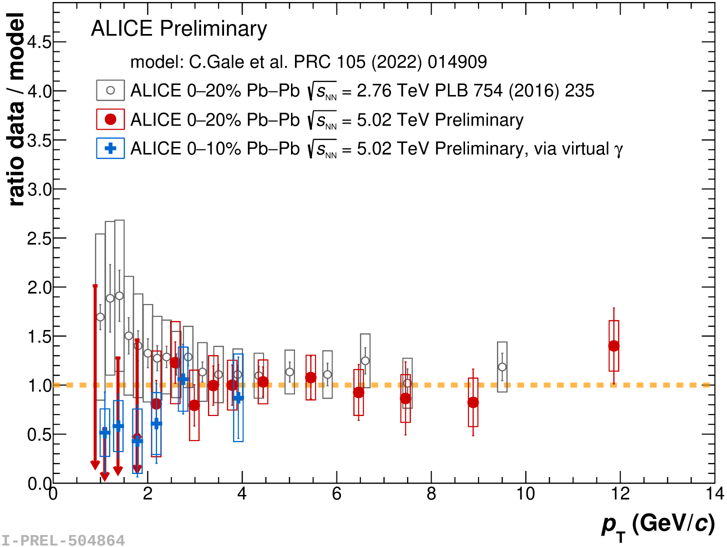


PLB 789 (2019) 308



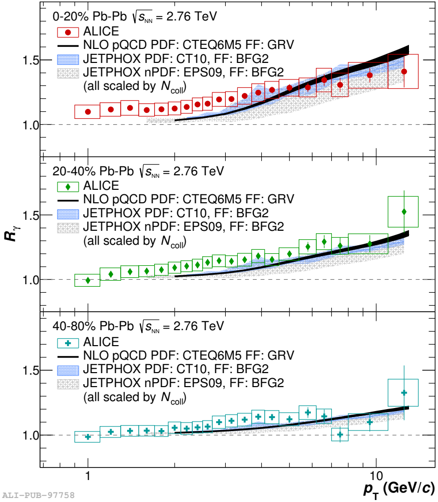
PRC 105 (2022) 014909

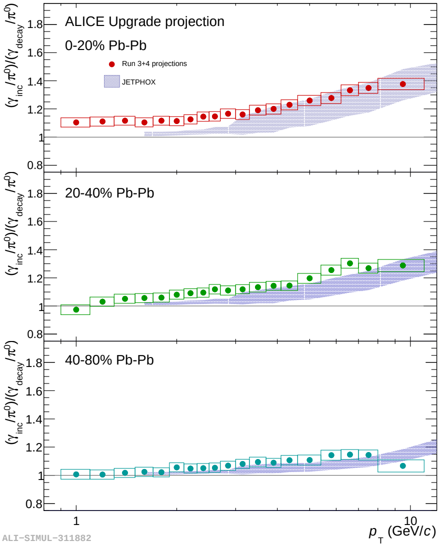
Ratios of measurements at LHC energies to theory



ALI-PREL-504864

Uncertainties projection Run 1 → Run 3+4





PLB 754 (2016) 235 arXiv:1812.06772

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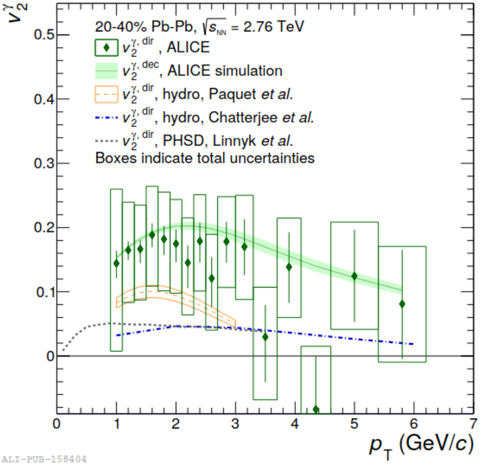

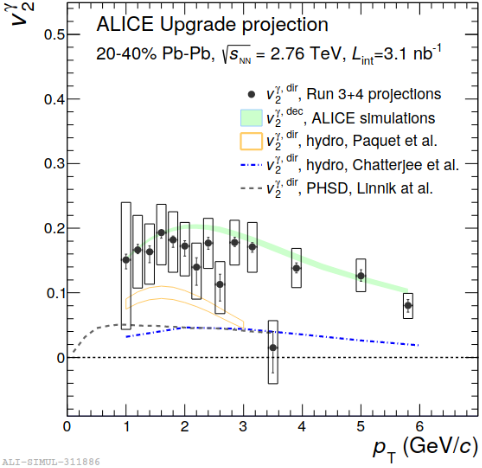

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