Direct photon measurements

Meike Charlotte Danisch
Physikalisches Institut Heidelberg

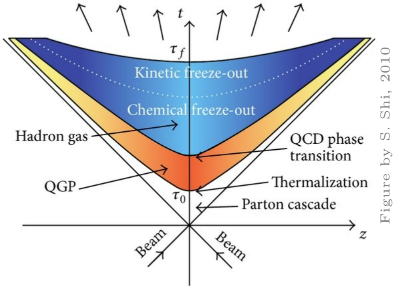
EMMI Rapid Reaction Task Force (RRTF):
Real and virtual photon production at ultra-low transverse momentum and low mass at LHC
GSI Darmstadt, 1-5 August 2022

Covered by this talk

- Motivation for direct photon measurements
  (direct photons = photons that do not originate from hadron decays)
- Experimental results of direct photon measurements
  not: other EM probes: virtual photons via dielectroms
- Measurements with the goal to observe thermal radiation
  not: with the goal to investigate Low's theorem
- Results from RHIC and LHC energies
- Focus on AA collisions
- Comparison to theoretical calculations
- A small outlook: LHC Run 3 and 4, ALICE 3 (LHC Run 5 and beyond)

Motivation for measuring direct photons

- Created during all stages of a heavy-ion collision
  Leave the medium without further interaction
  ⇒ Provide unique information
- **Prompt photons**: observed in all collision systems, can be calculated with pQCD, well described. Initial hard scatterings, fragmentation, medium modification
- **Thermal photons**
  - have been observed
  - are sensitive to the medium **temperature** and **collective flow** at photon production time
  - Tension between experiment and theory (yields, v_2)
- **Jet-medium** photons and **pre-equilibrium** photons have not yet been measured
  - Pre-equilibrium photons: 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

ALICE

- Created during all stages of a heavy-ion collision
  Leave the medium without further interaction
  $\Rightarrow$ Provide unique information

Quantities ...	Observables...
temperature of the medium	(thermal) photon spectra
emission time / flow(t)	direct photon v_2
initial conditions	v_3, v_2 [2]
viscosity	v_3, v_2 [2]
source size	HBT [3]
direct photon fraction	R_γ, HBT
electrical conductivity of the medium	spectra [4]

[2] See for example PRC 91, 024908 (2015)

[3] PRL 93 (2004) 022301

[4] See for example arXiv:2112.12497 [nucl-th]

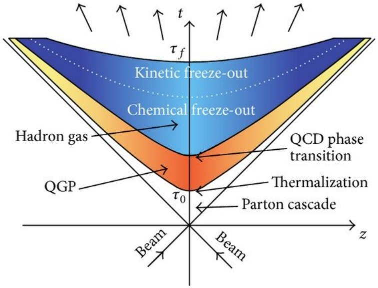


Figure by S. Shi, 2010

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, ...

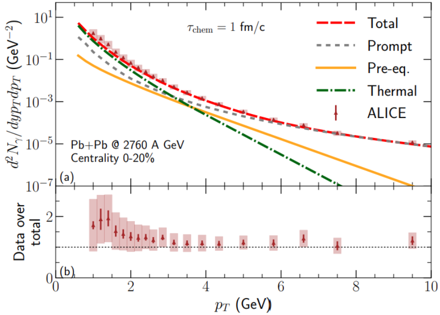
Outline of this talk

1) Medium temperature
2) Flow, initial conditions
3) Pre-equilibrium phase, saturation momentum
4) Medium size

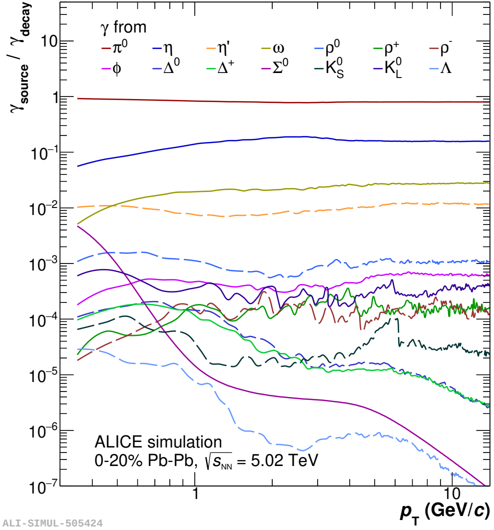
Medium temperature

Have to isolate thermal γ from other γ:

- Simulate decay photons based on hadron measurements and m_T scaling.
  direct = inclusive - decay
- Thermal photons dominate low p_T region.
  Subtract prompt = N_{coll}-scaled-(pQCD or pp)



PRC 105, 014909 (2022)



π^0

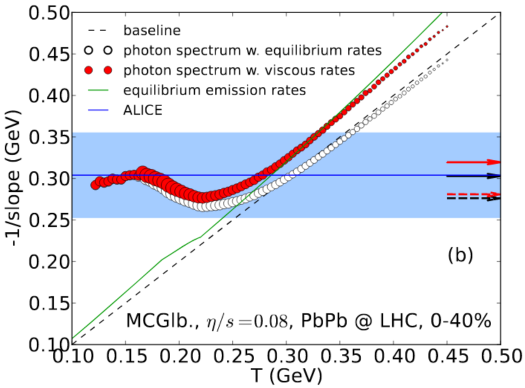
η

ω

η'

Medium temperature

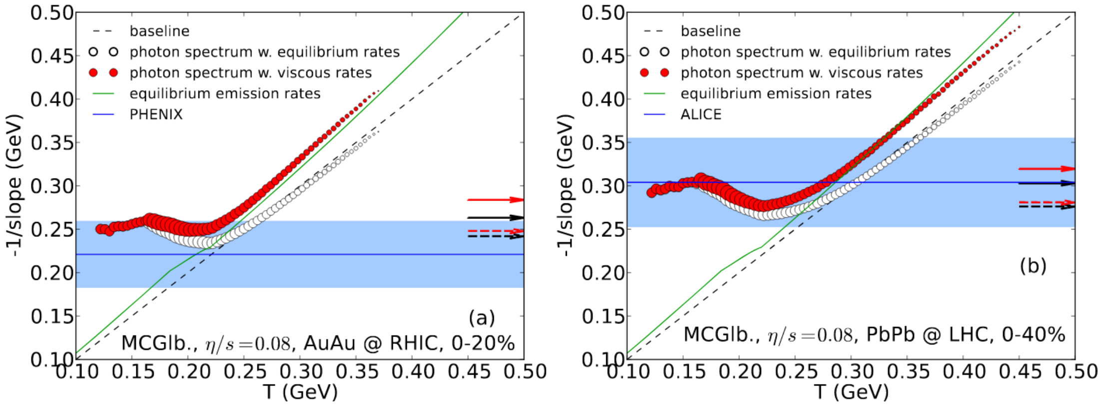
- Production rate $r_\gamma(E_\gamma, T)$ depends on the medium temperature T
- If source was at rest and had a constant T: approximately exponential spectrum with inverse slope $= T$
- But: source cools down: $r_\gamma(E_\gamma, T(t))$
  $\Rightarrow$ r_γ-weighted time-average
- And: blue-shift due to radial flow $\beta(t)$
  $\Rightarrow$ effective temperature T_{eff}
- Also: average over medium volume V(t)
- Actual temperature T(t,x) by model comparison when $\beta(t)$ and V(t) are known



red points: effect of radial flow, faster coolong after chemical freeze-out, increasing volume

Phys. Rev. C 89, 044910 (2014)

Medium temperature



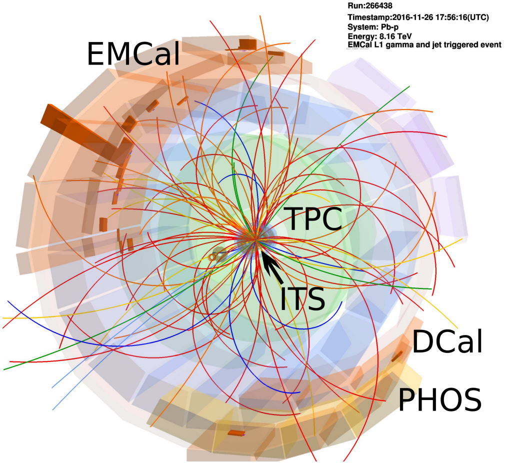
expect larger T_{eff} at LHC than at RHIC energies

Direct photon measurements at LHC

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

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

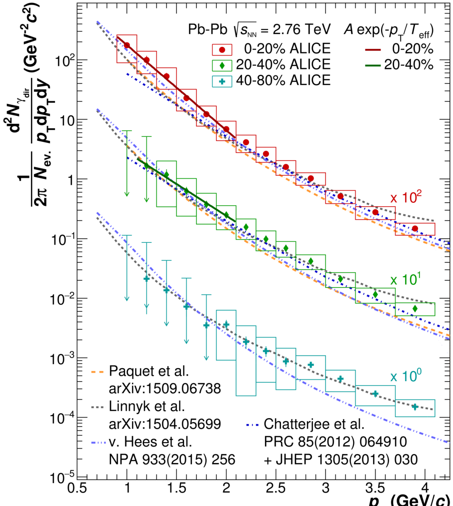
PCM: photon conversion method
$\gamma\,X \to e^+e^-\,X$ in the detector material
with probability $\approx 8.5\%$ ($R < 1.8\,\text{m}$)
tracking with ITS ($|\eta| < 2.0$) and TPC ($|\eta| < 0.9$)
e^+ e^- identification with TPC and TOF
π^0 down to $p_T \approx 0.3\,\text{GeV}/c$



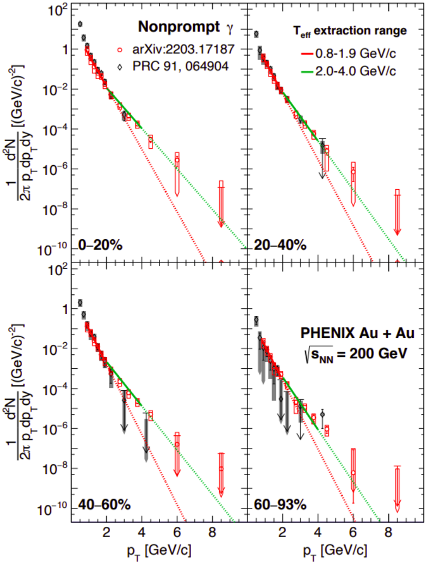
Medium temperature at LHC

- Pb–Pb $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$
- Measurement with PCM and PHOS
- $\approx 15\,\mathrm{M}$ events
- pQCD calculation of prompt photons subtracted
- $T_{\mathrm{eff}} = (297 \pm 12^{\mathrm{stat}} \pm 41^{\mathrm{syst}})$ MeV
  0-20% centrality class,
  $p_T = 0.9\text{-}2.1\,\mathrm{GeV}/c$
- $T_{\mathrm{eff}} = (410 \pm 84^{\mathrm{stat}} \pm 140^{\mathrm{syst}})$ MeV
  20-40% centrality class,
  $p_T = 1.1\text{-}2.1\,\mathrm{GeV}/c$

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



Medium temperature at RHIC



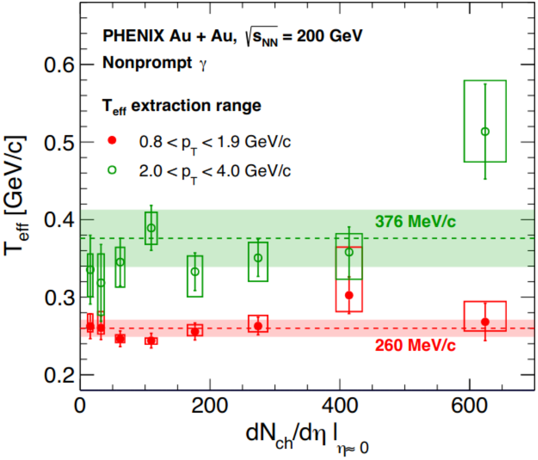
- Au–Au $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$
- Large statistics: 10^{10} events
- Nonprompt direct photons: N_{coll} scaled pp spectra fitted and subtracted
- Fit two p_{T} ranges: 0.8-1.9 and 2.4-4.0 GeV/c
- η/π^0 ratio for decay photons from world data in pp collisions, and accounting for radial flow with $K^{\pm}/\pi^{\pm}$ in AA

arXiv:2203.17187

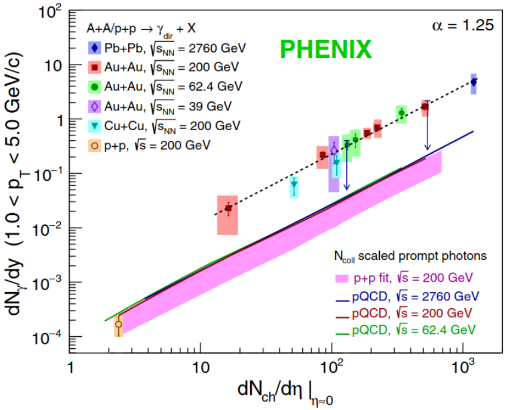
Medium temperature at RHIC

- T_{eff} smaller than at LHC as expected
- T_{eff} seems to be independent of multiplicity (while the actual T depends on it)
- T_{eff} depends on the p_{T} integration range (QGP and hadron gas ?)

arXiv:2203.17187



Scaling with system size



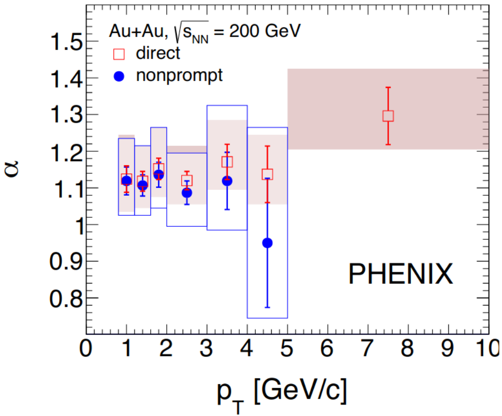
$$\frac{dN_\gamma}{dy} = A \times (\frac{dN_{\mathrm{ch}}}{d\eta})^\alpha$$

Above pQCD and N_{coll}-scaled pp

Same power for different collision systems, energies

PRL 123, 022301 (2019)

arXiv:2203.17187



Integrated direct/nonprompt photon yields

For different integration ranges

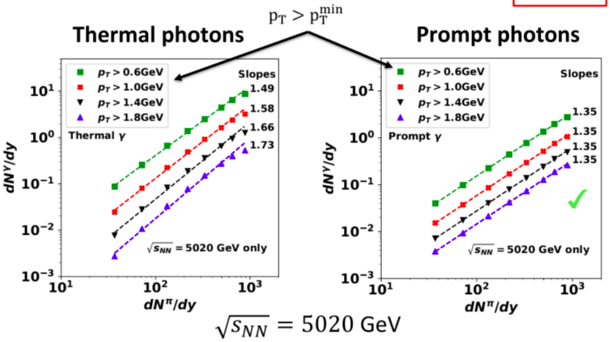
Scaling with system size

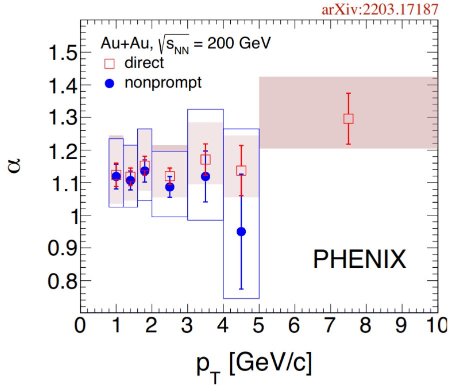
- Thermal photons expected to scale with larger α than prompt photons
- Thermal and prompt photons have different relative importance in different pT regions.
  $\Rightarrow \alpha$ is expected to change with p_{T}

Calculation by J.-F. Paquet, Hard Probes 2018

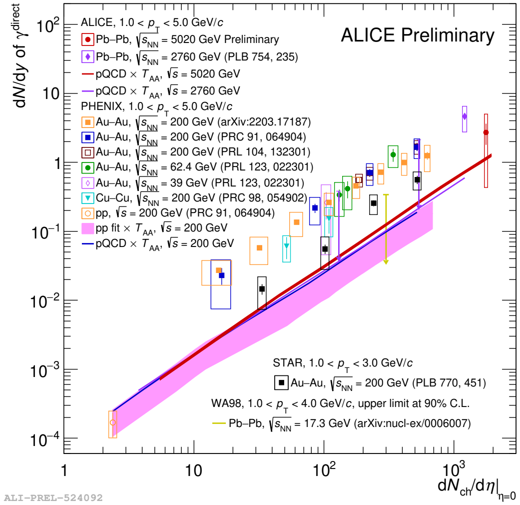
Photon vs pion multiplicity using centrality

Preliminary results





Direct photon yields



Not understood:

- PHENIX and STAR measurements show an offset
- ALICE 2.76 TeV measurement is more in line with PHENIX
- ALICE 5.02 TeV measurement via dielectrons is more in line with STAR

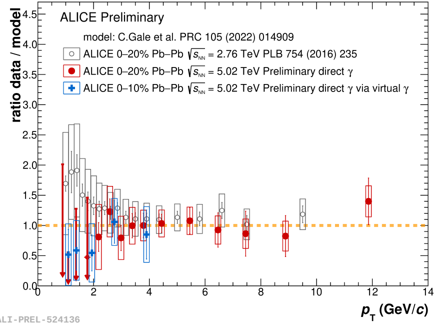
→ What about theoretical expectations?

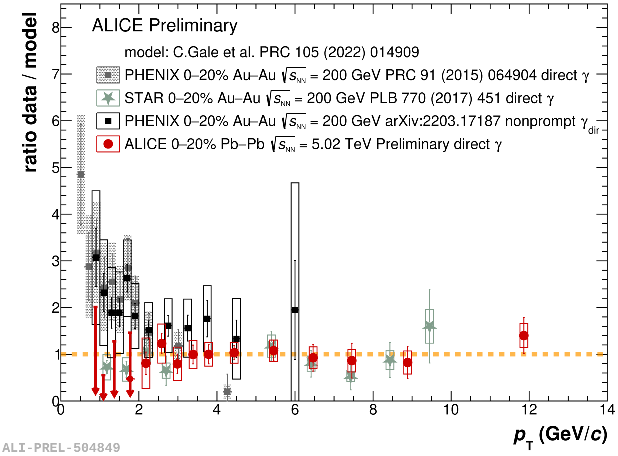
Direct photon yields

NEW

ALICE

- Comparing measured direct photon spectra with model calculations for the respective collision energies
- **No puzzling discrepancy** between state-of-the art models and **new ALICE measurement** (yields)



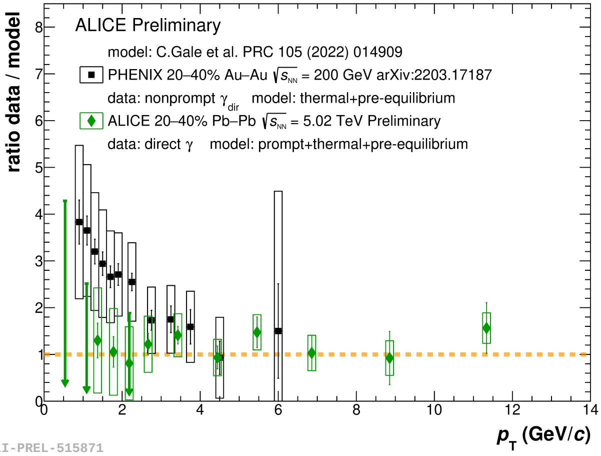


central events

Direct photon yields

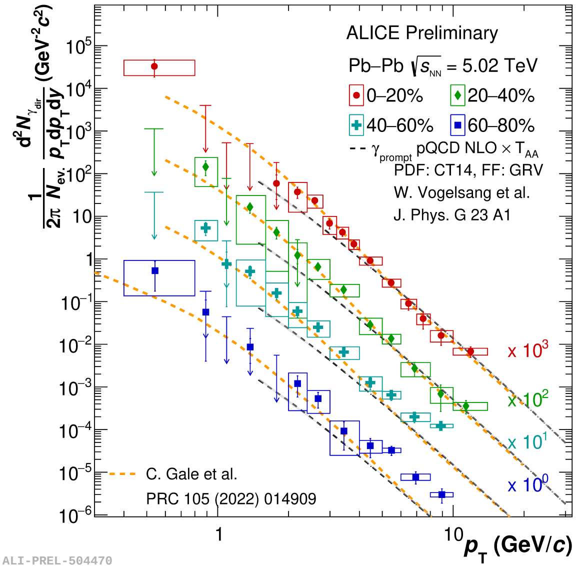
- Comparing measured direct photon spectra with model calculations for the respective collision energies
- **No puzzling discrepancy** between state-of-the art models and **new ALICE measurement** (yields)

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



semi-central events

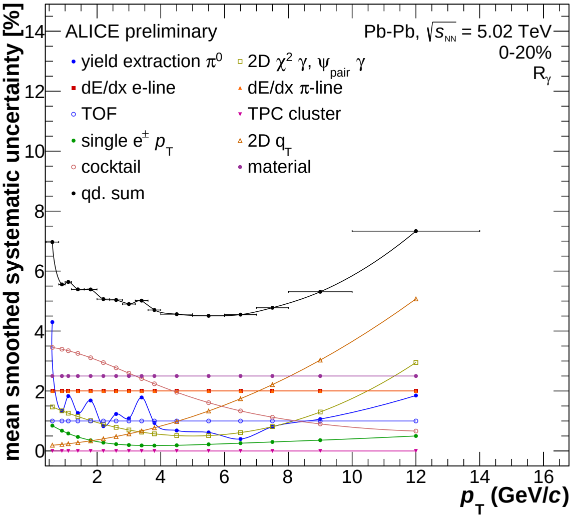
Direct photon spectra at 5.02 TeV



ALI-PREL-504470

- Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV
- Photon conversion method (PCM)
- NEW detector thickness correction, removal of pile-up, invariant mass background description, measured η/π^0 ratio for decay photons
- 25% of Run 2 statistics (2015 dataset: 76M events)
- no T_{eff} measurement possible (yet)

Systematic uncertainties of R_γ for PCM



$$R_\gamma = \frac{\gamma_{\text{inc}}/\pi^0_{\text{meas}}}{\gamma_{\text{decay}}/\pi^0_{\text{sim}}} \quad (1)$$

$$\gamma_{\text{dir}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = \gamma_{\text{inc}}(1 - \frac{1}{R_\gamma}) \quad (2)$$

Dominating contributions:

- π^0 yield extraction
- cocktail (decay photon simulation)
- material budget
- dE/dx: electron identification

Outlook

Steps forward:

- Larger statistics from future LHC runs helps decay photon estimation (inv. mass of π^0, η, ...)
- For PCM **essential**: correctness of Monte Carlo simulation (material, dE/dx)
- PHOS measurement

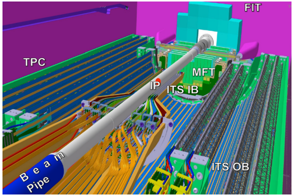
LHC Run 3 + 4

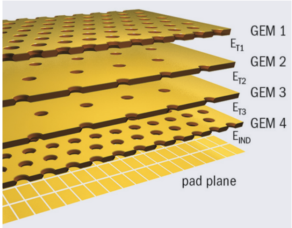
Larger statistics

Relevant for PCM:

- Overall, similar material budget
- ITS has improved tracking efficiency
- tungsten wires for material calibration
- TPC continous readout ⇒ larger event pile-up ⇒ maybe no TPC-only tracks usable

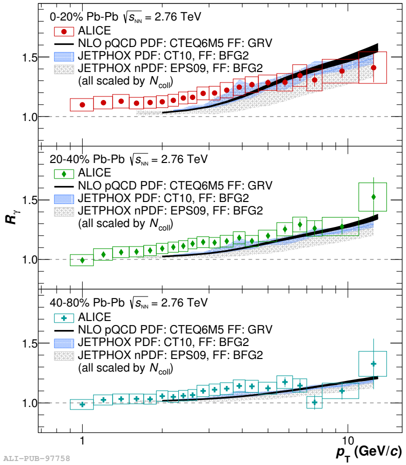
PHOS, EMCal hardware unchanged wrt Run1+2



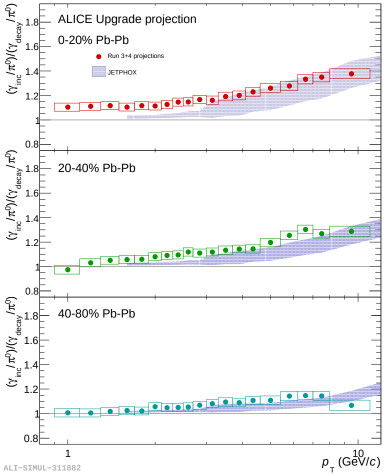


Uncertainties projection Run 1 → Run 3+4

$$R_\gamma = \frac{\gamma_{\rm inc}/\pi^0_{\rm meas}}{\gamma_{\rm decay}/\pi^0_{\rm sim}} \qquad (3)$$



PLB 754 (2016) 235

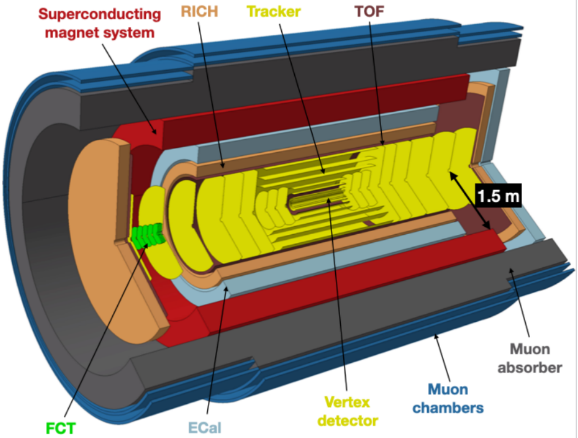


arXiv:1812.06772

≈ 50% smaller uncertainties

- significance depends on the size of the direct photon signal
- should allow for $T_{\rm eff}$ extraction

ALICE 3



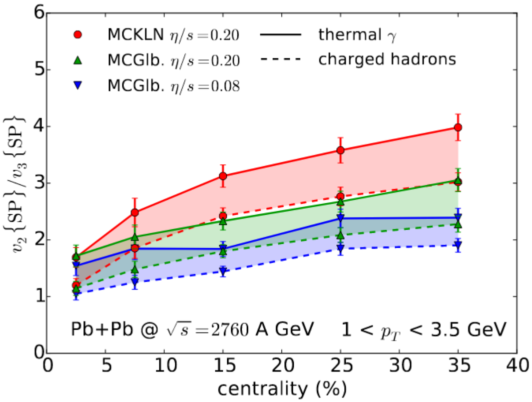
- LHC run 5 and beyond
- Profit from the forward rapidity detector setup
- Photon conversion probability decreases for decreasing energy
- Forward region: Much higher reconstruction efficiency for a given (low) p_{T}
  $\Rightarrow$ reduced yield extraction, cocktail uncertainty

Outline of this talk

1) Medium temperature
2) Flow, initial conditions
3) Pre-equilibrium phase, saturation momentum
4) Medium size

Flow coefficients motivation

- Measurement goal: direct photon flow coefficients v_n
- Hadron measurements reflect anisotropy/flow at freeze-out
- Direct photon v_2 reflects medium flow/anisotropy integrated over the whole medium lifetime
- $v_2 \Rightarrow$ photon production times
- $v_3 \Rightarrow$ initial conditions (also here, direct photons are ideal messengers)
- $v_2/v_3 \Rightarrow$ viscosity



Phys. Rev. C91, 024908 (2015)

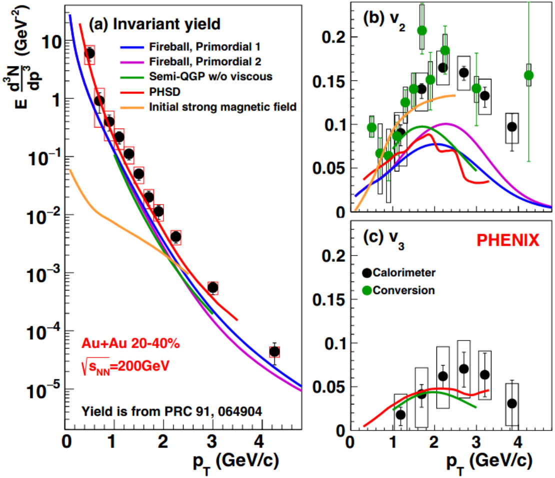
Direct photon puzzle at RHIC

- Elliptic flow coefficient v_2 unexpectedly large
- At high p_{T} expect

  $v_2^{\gamma,\mathrm{dir}} \approx v_2^{\gamma,\mathrm{prompt}} = 0$
- At low $p_{\mathrm{T}} \lesssim 3\,\mathrm{GeV}/c$ expect

  $v_2^{\gamma,\mathrm{dir}} \approx v_2^{\gamma,\mathrm{thermal}} > 0$ but $< v_2^{\mathrm{hadron}}$
- Large yield (early emission) and large v_2 (late emission) difficult to explain simultaneously
- Only explicable with additional photon source or anisotropy

PRC 94, 064901 (2016)

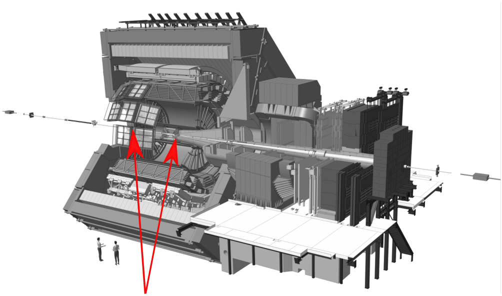


Elliptic flow measurement in LHC Run 1

- Inclusive photon $v_2^{\gamma,\mathrm{inc}}$ with scalar product method
  Reference particles in V0 detectors in forward direction
- Decay photon $v_2^{\gamma,\mathrm{dec}}$ from simulation based on meson v_2 measurements

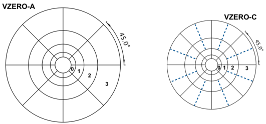
$$v_2^{\gamma,\mathrm{inc}} = \frac{N_{\gamma,\mathrm{dir}}}{N_{\gamma,\mathrm{inc}}} \cdot v_2^{\gamma,\mathrm{dir}} + \frac{N_{\gamma,\mathrm{dec}}}{N_{\gamma,\mathrm{inc}}} \cdot v_2^{\gamma,\mathrm{dec}}$$

$$\Rightarrow v_2^{\gamma,\mathrm{dir}} = \frac{v_2^{\gamma,\mathrm{inc}} R_\gamma - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}$$



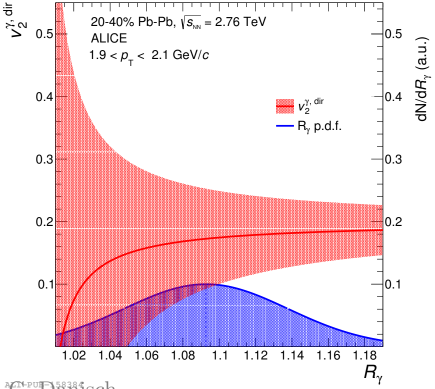
V0 detectors:

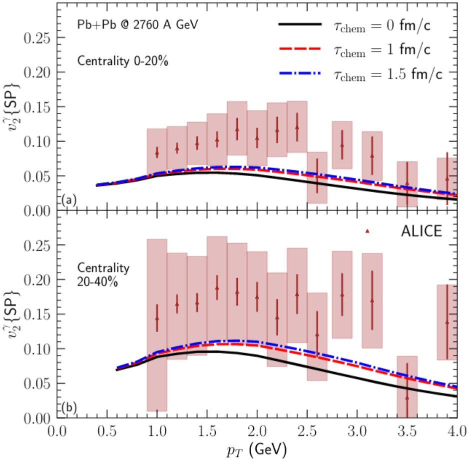
$2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$



Direct photon puzzle at LHC?

- $v_2^{\gamma,\text{dir}}$ is larger than predicted but consistent within the uncertainties
- The smaller R_γ, the larger the uncertainties on $v_2^{\gamma,\text{dir}}$

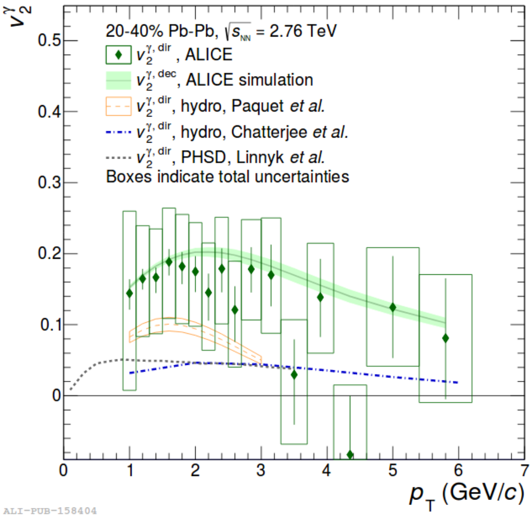


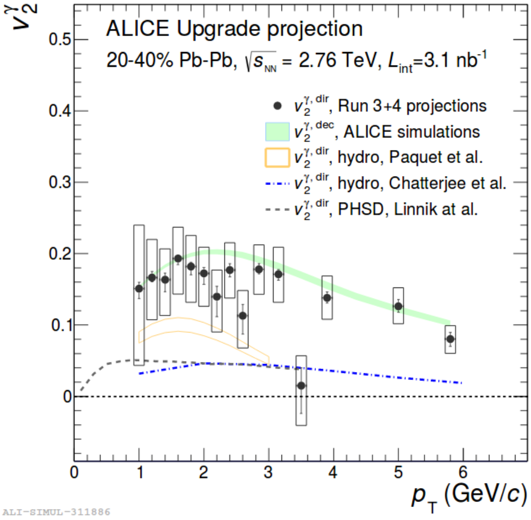


PLB 789 (2019) 308, PRC 105 (2022) 1, 014909

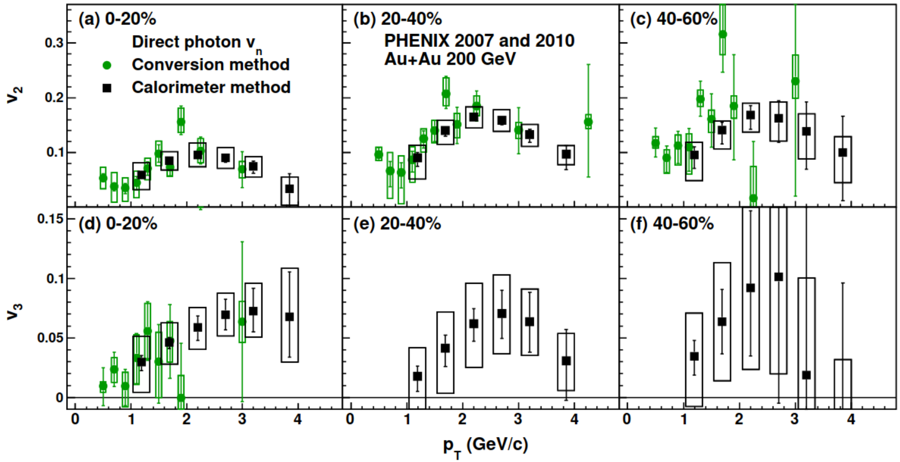
τ_chem: how fast the quarks are produced and equilibrate in an initially purely gluonic system

Direct photon puzzle at LHC? Run 3 + 4





Triangular flow v_3



Even larger uncertainties than v_2

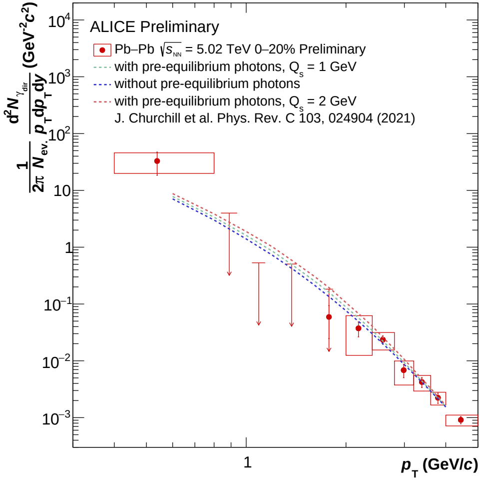
PRC 94 (2016) 6, 064901

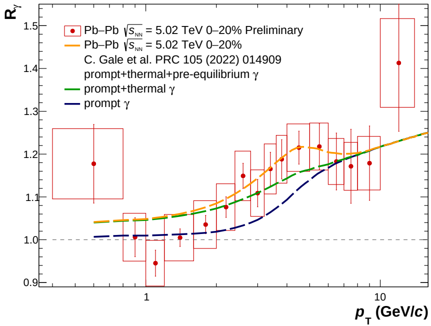
So far, only measured by PHENIX. Also in ALICE in Run 3+4 ?

Outline of this talk

1) Medium temperature
2) Flow, initial conditions
3) Pre-equilibrium phase, saturation momentum
4) Medium size

Pre-equilibrium photons





- R_γ can be sensitive at intermediate p_T
- Saturation momentum Q_s sensitivity for far future measurements

Outline of this talk

1) Medium temperature
2) Flow, initial conditions
3) Pre-equilibrium phase, saturation momentum
5) Medium size

Bose-Einstein $\gamma\gamma$ correlations

Motivation:

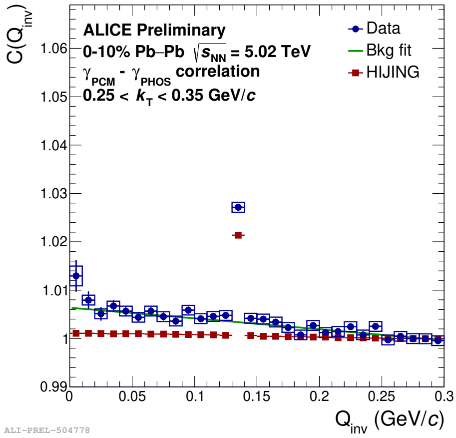
- Correlation function is sensitive to the **source size** R and the **direct photon fraction**
- The source size at the moment of kinetic freeze-out can be measured with hadrons
- With photons, sensitive to earlier times
- Alternative method to determine the **direct photon fraction** which does not require simulation of decay photon spectra

Requirement: Need to measure photon pairs with very small opening angles

Bose-Einstein $\gamma\gamma$ correlations in Pb–Pb with ALICE

- 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
  $Q_{\text{inv}} = M_{\gamma\gamma}$, combine PCM and PHOS
  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 $k_{\text{T}} = \frac{p_{\text{T,pair}}}{2}$ and centrality
- Possible complementary method to determine R_γ down to $p_{\text{T}} \approx 0.25\,\text{GeV}/c$



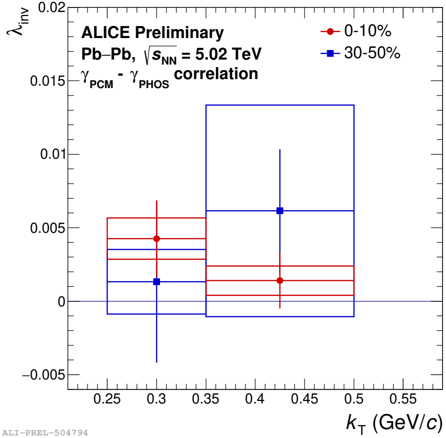
terminology used from PRL 93 (2004) 022301, D. Peressounko et al.

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

- 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
  $Q_{\mathrm{inv}} = M_{\gamma\gamma}$, combine PCM and PHOS
  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

  $$C(Q_{\mathrm{inv}}) = 1 + \lambda_{\mathrm{inv}} \exp(-R^2_{\mathrm{inv}} Q^2_{\mathrm{inv}})$$

- In bins of $k_{\mathrm{T}} = \frac{p_{\mathrm{T,pair}}}{2}$ and centrality
- Possible complementary method to determine R_γ down to $p_{\mathrm{T}} \approx 0.25\,\mathrm{GeV}/c$



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

Open questions

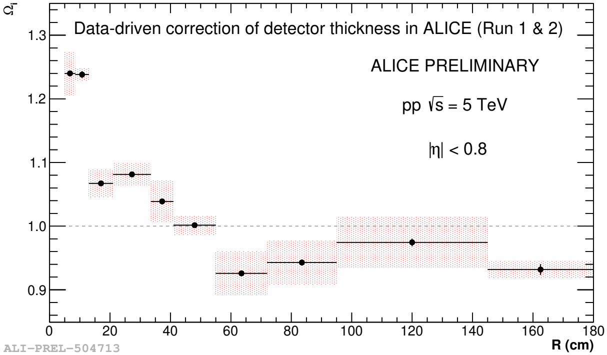
ALICE

- Direct photon yields: what is the reason for the tension between experiments ?
- What is the value of T_{eff} in 5TeV Pb–Pb collisions ?
- Why does T_{eff} not depend on collision centrality?
- Is v_2 with smaller uncertainties at LHC (Run3+4) consistent with models or not ?
  If not, how can the large value be explained ?
- What is the role of pre-equilibrium photons ?
- How does the medium affect fragmentation photons? What is the role of jet-medium interactions ?
- How can we significantly reduce systematic uncertainties ?
- What about direct (thermal?) photons in small collision systems ?
- ...

Thank you!

Data-driven correction of detector thickness

- 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 $\Omega(R_{\mathrm{conv}})$
  ⇒ Systematic uncertainty reduced to 2.5% and more correct efficiency

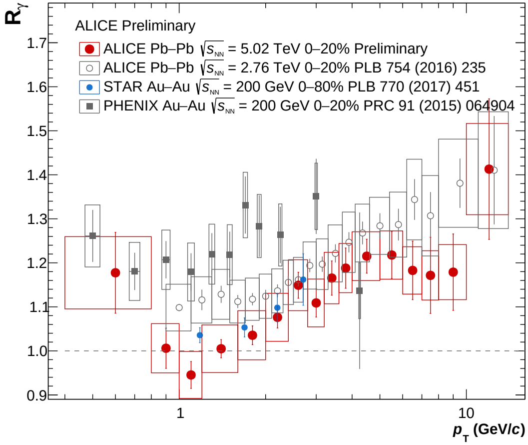


Systematic uncertainties in the 2010 data analysis

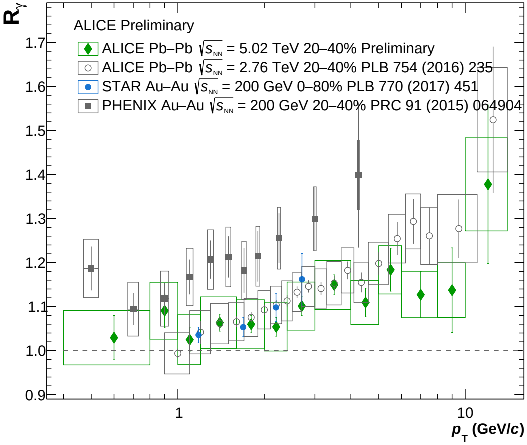
Centrality	0–20%		20–40%		40–80%	
p_T (GeV/c)	1.2	5.0	1.2	5.0	1.2	5.0
γ_{incl} yield						
Track quality (A)	0.6	0.6	0.2	0.2	0.2	0.7
Electron PID (A,B)	1.5	6.9	0.9	4.8	0.7	4.0
Photon selection (A,B)	4.0	1.8	2.4	2.1	1.5	1.3
Material (C)	4.5	4.5	4.5	4.5	4.5	4.5
γ_{incl}/π^0						
Track quality (A)	0.7	1.7	0.8	0.4	0.6	1.3
Electron PID (A,B)	1.2	4.8	0.9	3.8	0.9	4.0
Photon selection (A,B)	3.2	3.2	3.0	1.5	2.5	2.4
π^0 yield (A)	1.6	2.9	1.7	2.7	0.5	3.0
Material (C)	4.5	4.5	4.5	4.5	4.5	4.5
γ_{decay}/π^0						
π^0 spectrum (B)	0.5	1.2	0.8	1.8	0.5	3.2
η yield (C)	1.4	1.4	1.4	1.4	1.4	1.4
η shape (B)	1.6	0.5	1.2	0.2	1.0	0.2
Total R_γ	6.2	8.1	5.7	7.0	5.7	8.3
Total γ_{incl}	6.2	8.5	5.2	6.9	4.8	6.2

Table 1: Summary of the systematic uncertainties of the PCM analysis in percentage. Uncertainties are characterized according to three categories: point-by-point uncorrelated (A), correlated in p_T with magnitude of the relative uncertainty varying point-by-point (B), and constant fractional uncertainty (C). Items in the table with categories (A,B) summarize sources of uncertainties which are either of type A or B.

LHC and RHIC

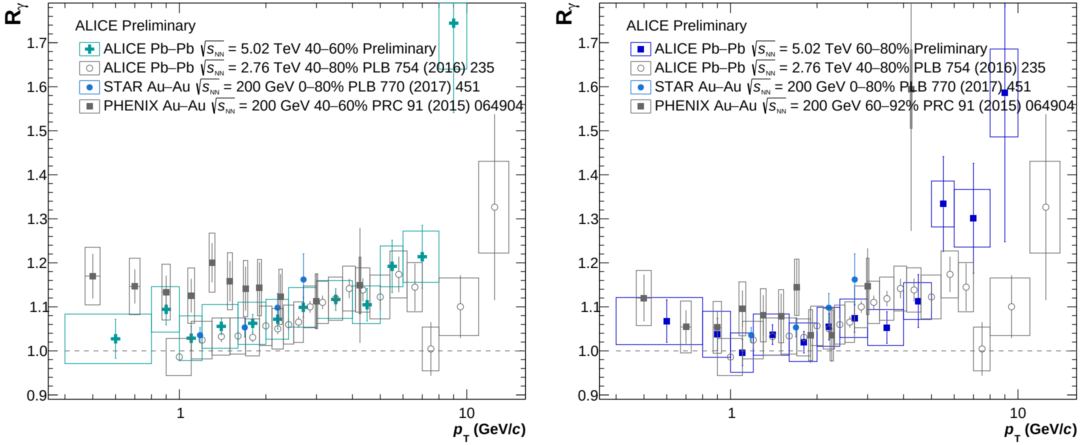


ALICE Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV 0–20% Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV 0–20% PLB 754 (2016) 235
STAR Au–Au $\sqrt{s_{NN}}$ = 200 GeV 0–80% PLB 770 (2017) 451
PHENIX Au–Au $\sqrt{s_{NN}}$ = 200 GeV 0–20% PRC 91 (2015) 064904
R_γ
p_T (GeV/c)



ALICE Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV 20–40% Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV 20–40% PLB 754 (2016) 235
STAR Au–Au $\sqrt{s_{NN}}$ = 200 GeV 0–80% PLB 770 (2017) 451
PHENIX Au–Au $\sqrt{s_{NN}}$ = 200 GeV 20–40% PRC 91 (2015) 064904
R_γ
p_T (GeV/c)

LHC and RHIC



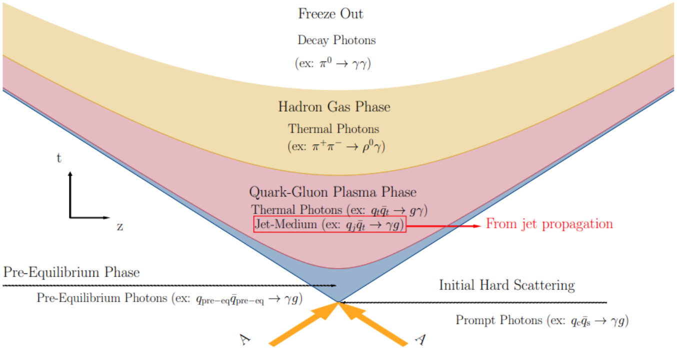
ALICE Preliminary
ALICE Pb–Pb √s_NN = 5.02 TeV 40–60% Preliminary
ALICE Pb–Pb √s_NN = 2.76 TeV 40–80% PLB 754 (2016) 235
STAR Au–Au √s_NN = 200 GeV 0–80% PLB 770 (2017) 451
PHENIX Au–Au √s_NN = 200 GeV 40–60% PRC 91 (2015) 064904
ALICE Pb–Pb √s_NN = 5.02 TeV 60–80% Preliminary
PHENIX Au–Au √s_NN = 200 GeV 60–92% PRC 91 (2015) 064904
R_γ
p_T (GeV/c)

Dataset and MC for 5.02 TeV

- First measurement of direct photons in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$
- So far, 2015 dataset has been analyzed (76M usable events)
- Centrality classes 0–20, 20–40, 40–60, 60–80%
- MC simulation 28M events
- For the π^0 analysis, MC spectra were weighted in order to have a realistic p_{T} distribution for calculating the efficiency

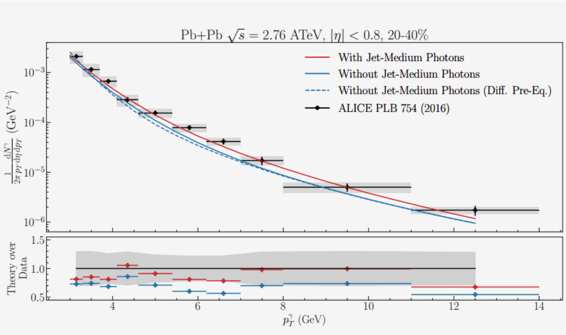
Jet-medium photons

- For the **composition** of direct photons, it is important to have a good estimate of all sources
- Jet-medium photons were theoretically so far not so well established



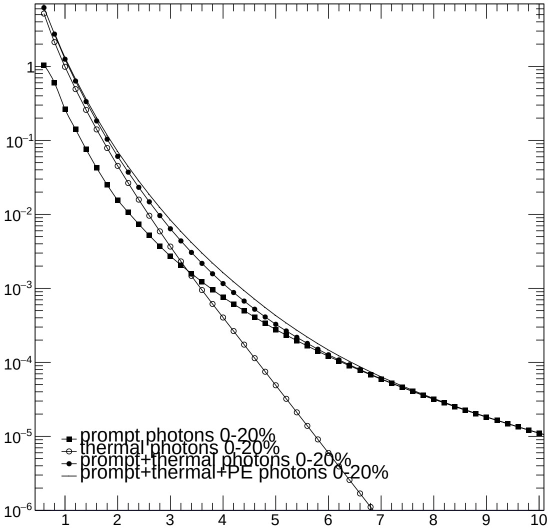
Jet-medium photons

- New calculation was presented at QM
- Event generation with JETSCAPE, realistic jet distribution and hydro background
- Photons from e.g. the interacion of a quark within a jet, and a thermal quark from the QGP
- Observation: in the region $5 < pT < 10\,\text{GeV/c}$ this contribution makes up nearly 30% of all photons
- Here spectra for 2.76TeV but work will be extended to 5TeV and photon v_2



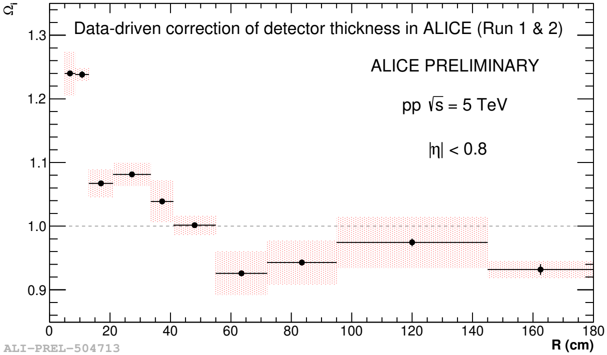
https://indico.cern.ch/event/895086/contributions/4705762/

Model contributions 5.02 TeV



Data-driven correction of detector thickness

- 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 $\Omega(R_{\text{conv}})$
  $\Rightarrow$ Systematic uncertainty reduced to 2.5% and more correct efficiency



New PHENIX measurement

- 10^{10} 200 GeV Au-Au collisions
- 10-fold increase in statistics compared to previous measurement
- Photon conversion method
- η meson for decay photons from global data analysis [Y. Ren, A. Drees 2021]
- Subtraction of prompt photons from direct photons, N_{coll}-scaled from pp collisions $\Rightarrow$ non-prompt direct photons
- Fit two exponential functions to two different p_{T} regions and obtain two different effective temperatures. Speculate that one is from the QGP and one from the HG. Effective temperature does not depend on the multiplicity of the collision
- How integrated yield scales with multiplicity does not depend on pT

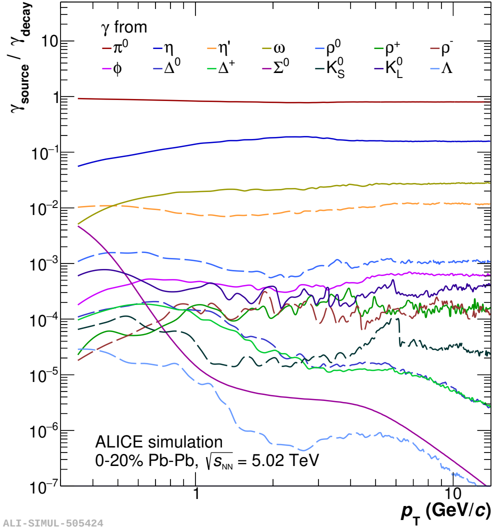
Simulation of decay photons

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', ...



π^0

η

ω

η'

Cocktail simulation

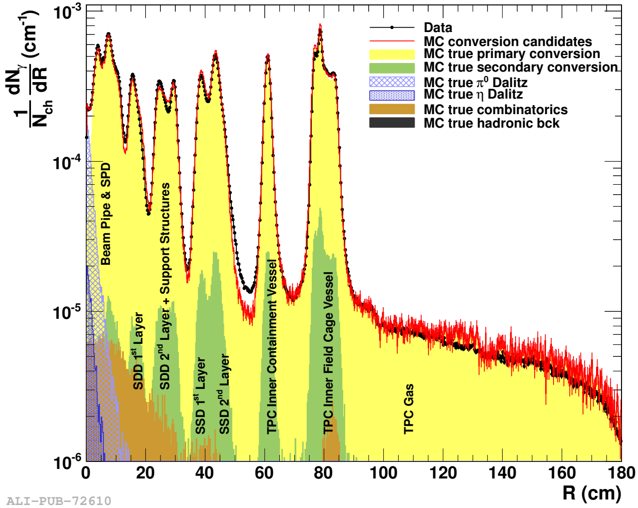
decay photon yields in 2.76 TeV

- π^0 measured via $\gamma\gamma$ then parametrized
- measured η in p–Pb, not enough statistics in Pb–Pb
- η from m_T scaling of π^0 from scaling of p_T spectra from K^0_s (similar mass, similar radial flow)
- η/π^0 ratio fixed to reproduce measured value at $p_\mathrm{T} > 5\,\mathrm{GeV}/c$ in $\sqrt{s_\mathrm{NN}} = 200\,\mathrm{GeV}/c$
- ω from m_T scaling of π^0

decay photon v_2 in 2.76 TeV

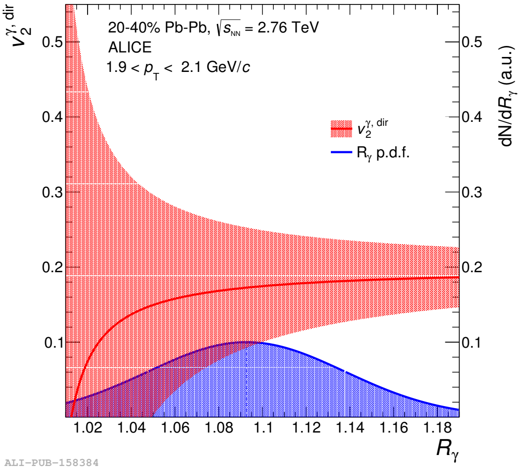
- π^0 v_2 from charged pion v_2 measured under the same conditions
- η and ω from charged and neutral kaons with KE_T scaling

Material budget in data and MC before correction



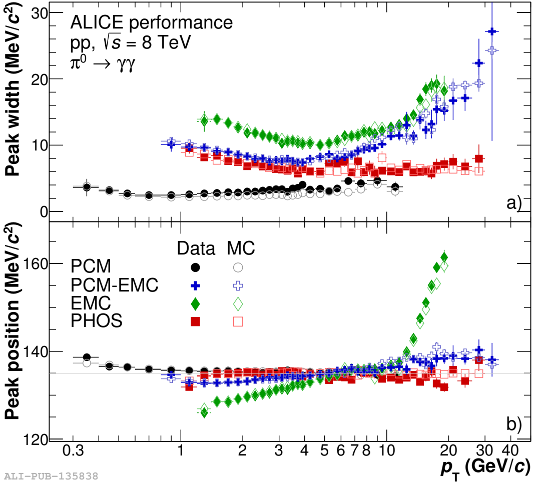
Int.J.Mod.Phys.A 29 (2014) 1430044

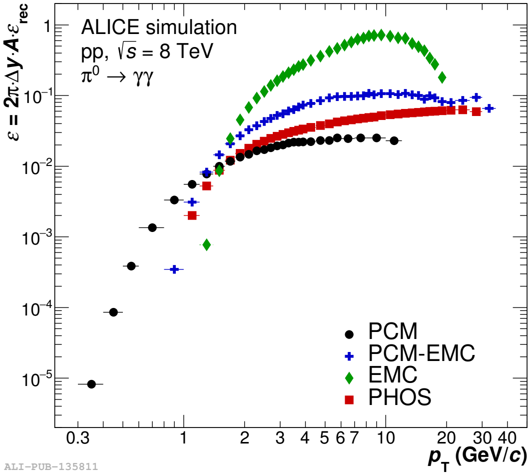
Elliptic flow uncertainties



Phys.Lett. B789 (2019) 308

Complementarity of the methods





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