UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

ALICE

Measurement of the medium radiation in heavy-ion collisions with ALICE

Meike Charlotte Danisch, Physikalisches Institut Heidelberg

EMMI workshop
New Vistas in Photon Physics in Heavy-Ion Collisions

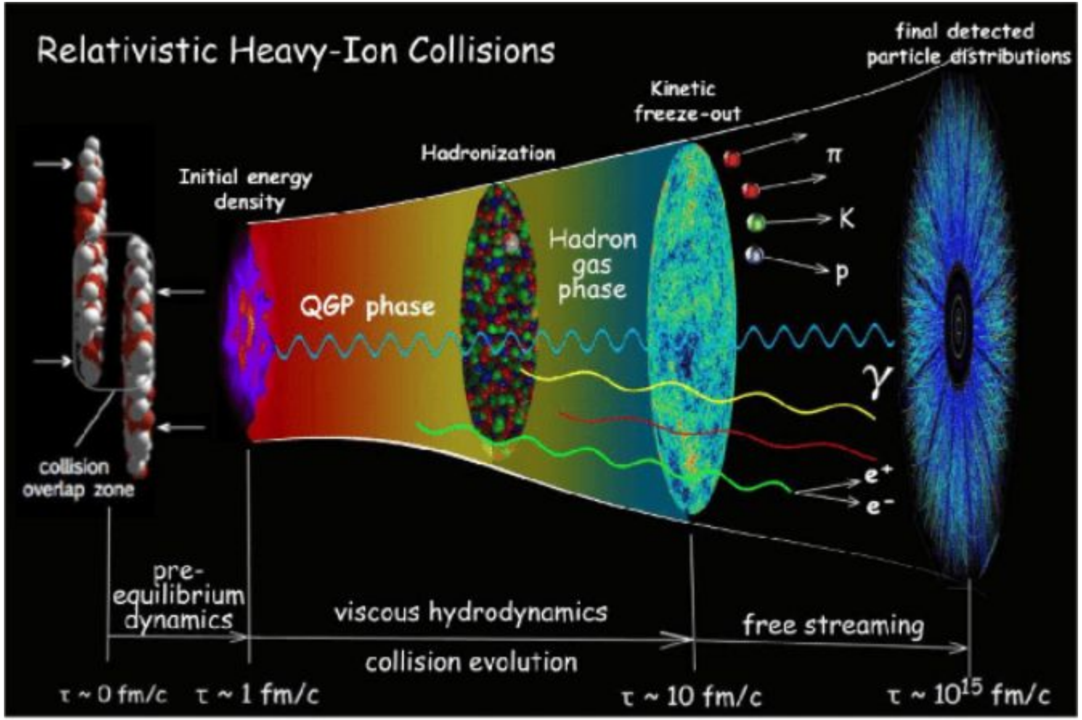
Kraków, Sep 19 – 22, 2022

FSP ALICE
Erforschung von Universum und Materie

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

THE SETTING...

ALICE



C. Shen, U. Heinz, Nucl. Phys. News 25 (2015)

Photons are created at all stages and escape unscathed

Goal: measure photons from medium

- Pre-equilibrium
- Thermal:
  - Quark-gluon plasma
  - Hadron matter

MOTIVATION

Quantities ...	Observables...	
temperature of the medium	(thermal) photon spectra	
emission time / flow(t)	direct photon v_2	
initial conditions	v_3, v_2 [2]	(anisotropic flow coefficients)
viscosity	v_3, v_2 [2]	
source size	HBT [3]	(photon-photon correlations)
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]

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

DIRECT PHOTONS (METHOD)

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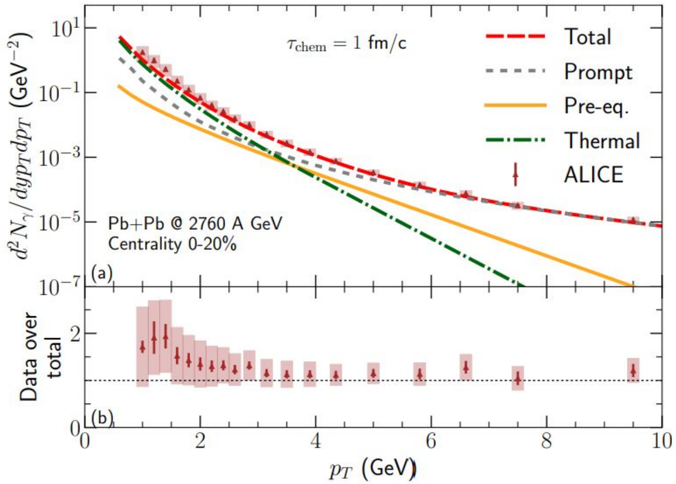
direct = inclusive
 − decay

1. **Inclusive** photon spectrum vs. p_T
   - Via calorimeter or conversion method
   - Corrections from Monte Carlo simulations
2. **Decay** photon spectrum from hadron measurements
3. **Direct** photon spectrum
4. Non-prompt direct photon spectrum

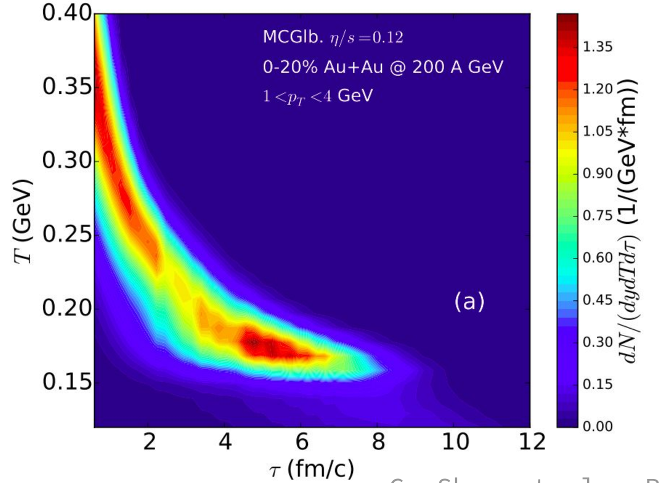
direct photons =
 prompt photons (pQCD or scaled pp)
 + pre-equilibrium photons
 + **thermal** photons
 + jet-medium photons



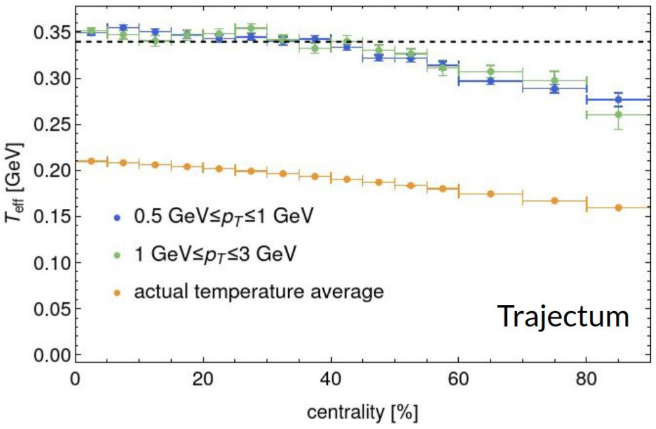
Phys. Rev. C 105, 014909 (2022)

THERMAL PHOTONS (MOTIVATION)

- 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: $r_\gamma(E_\gamma, T(t))$
  $\Rightarrow r_\gamma$-weighted time-average
- And: blue-shift due to radial flow $\beta(t)$
  $\Rightarrow$ effective temperature T_{eff} > T
- Also: average over medium volume V(t)
- Actual temperature T(t,x) by model comparison when $\beta(t)$ and V(t) are known



C. Shen et al., PRC 91 (2015)



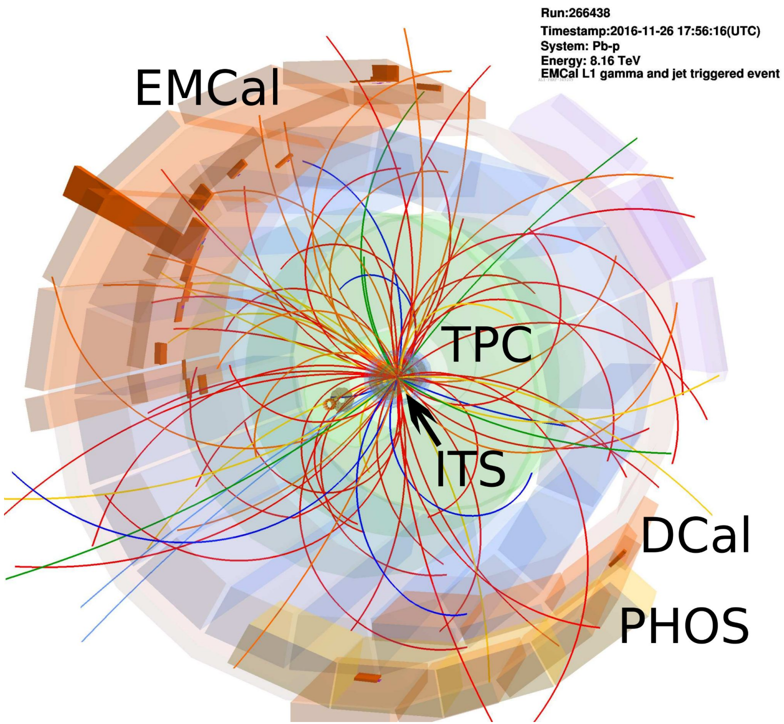
Govert Nijs, Wilke van der Schee, Mike Sas (2022)

CALORIMETERS

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 $\approx 2.2 \times 2.2\,\mathrm{cm}^2$

→ See also talk by Mike Sas on Thursday:
Electromagnetic probes in ALICE



PERFORMANCE

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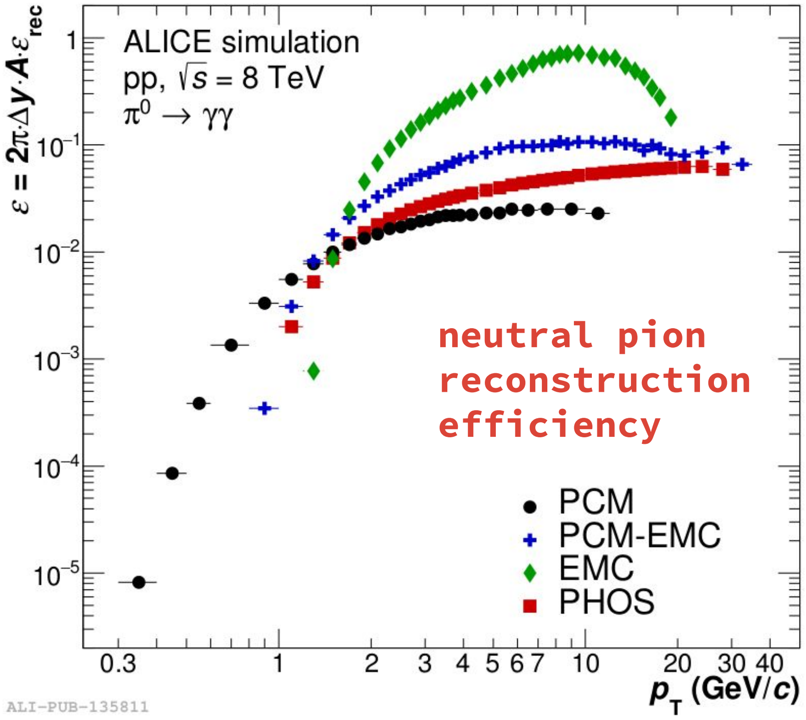
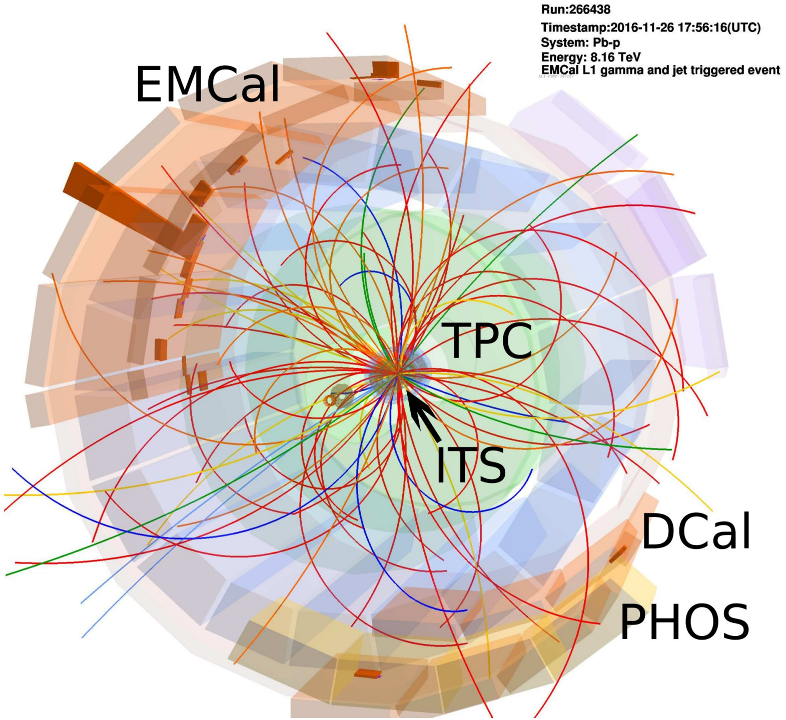
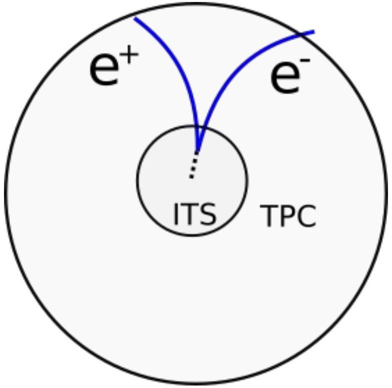
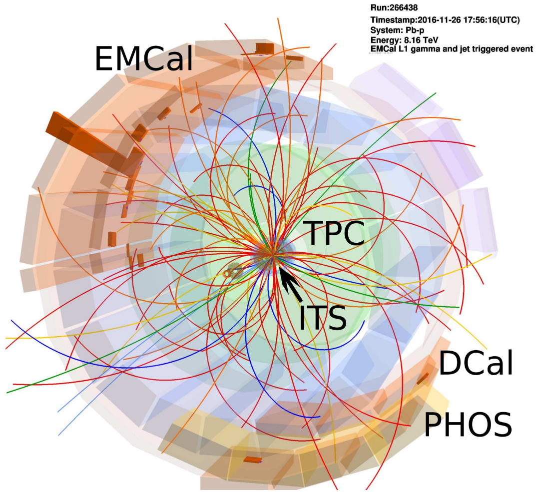




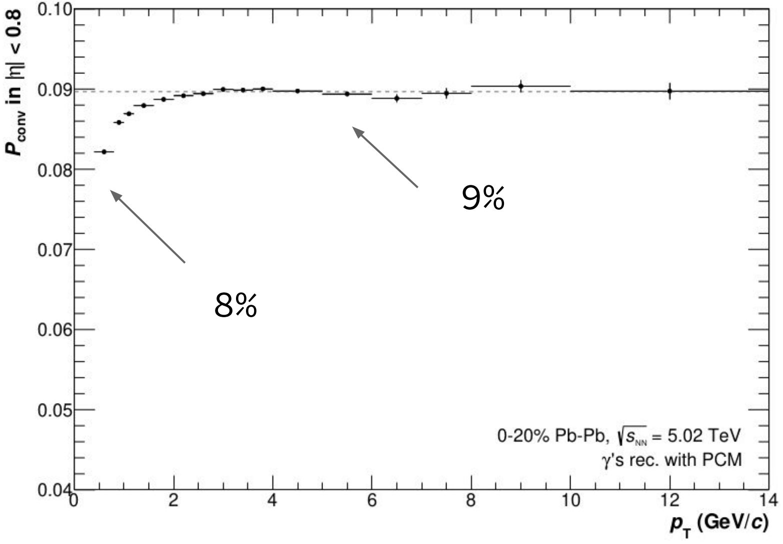
PHOTON CONVERSION METHOD (PCM)

- **Tracking** of electron positron pair
- **Identification** via specific energy loss and time of flight
- **Secondary vertex** reconstruction
- Corrections for **detector thickness** in Monte Carlo (MC) simulations (data-driven)
- **Corrections** to data from MC simulations: reconstruction efficiency, conversion probability

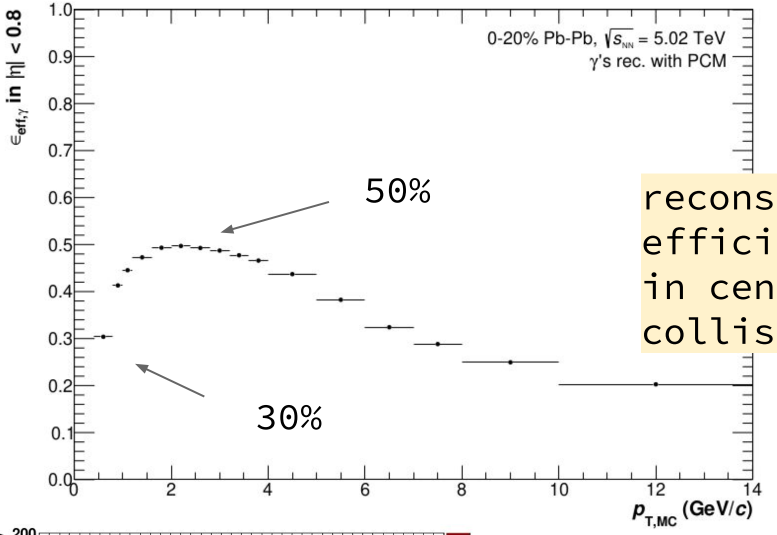




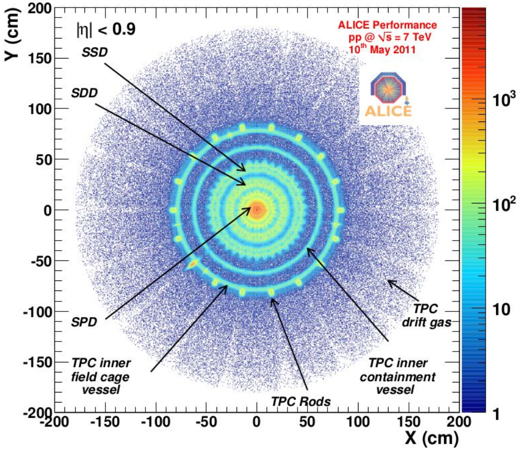
PHOTON CONVERSION METHOD



conversion probability



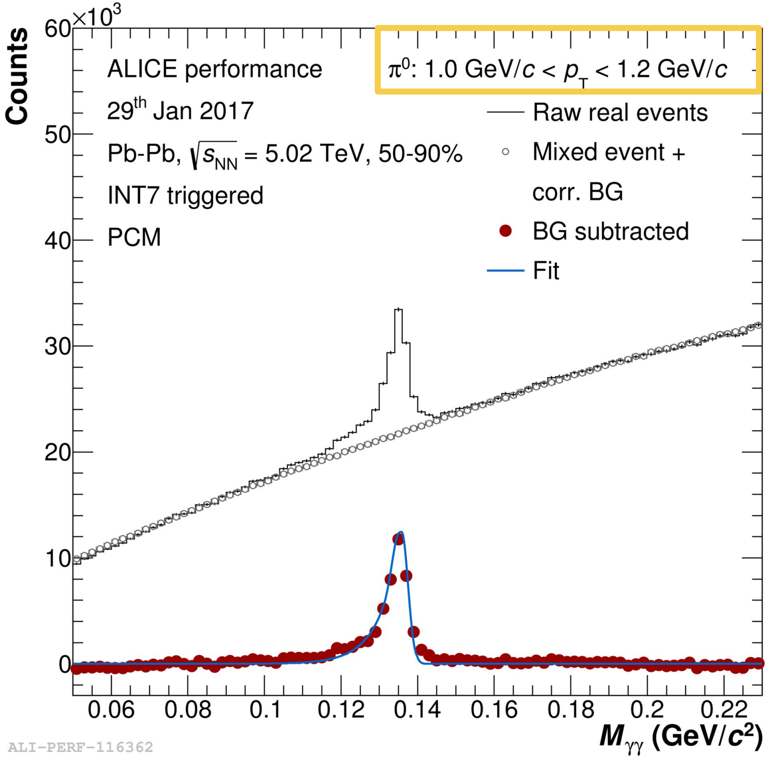
reconstruction efficiency in central collisions



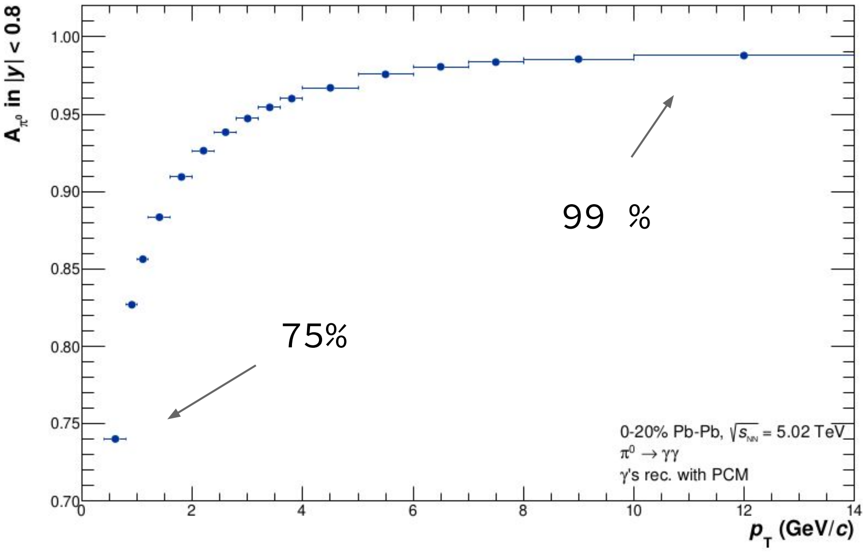
conversion points (in the plane perpendicular to the beams)

DECAY PHOTON BACKGROUND

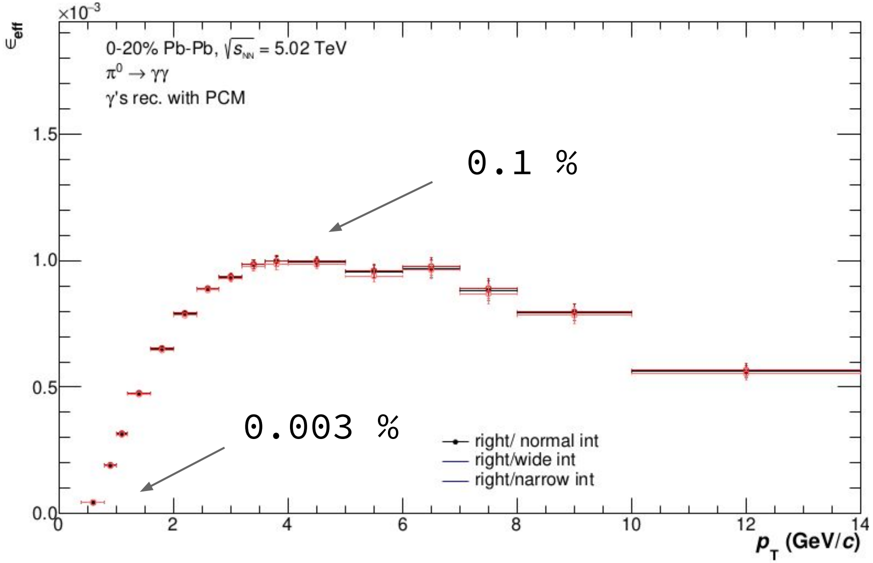
- measure hadrons which decay into photons
- neutral pion and eta meson via 2 photon decay channel
- η/π^0 ratio
- PYTHIA simulation of decays
- most relevant: $\pi^0, \eta, \omega, \eta'$



DECAY PHOTON BACKGROUND: PION CORRECTIONS



acceptance



reconstruction efficiency

DIRECT PHOTONS SPECTRA RESULTS

Pb-Pb 5.02 TeV,

PCM (color) dielectrons (black)

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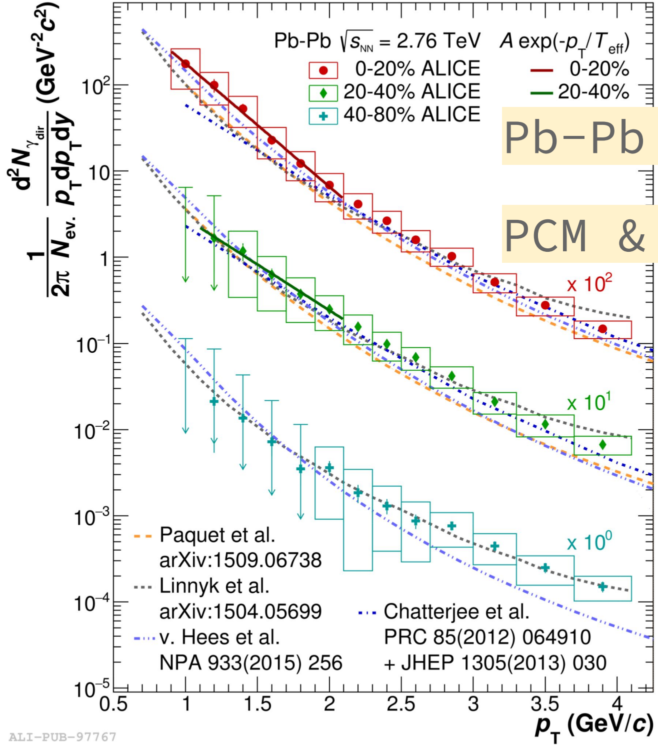
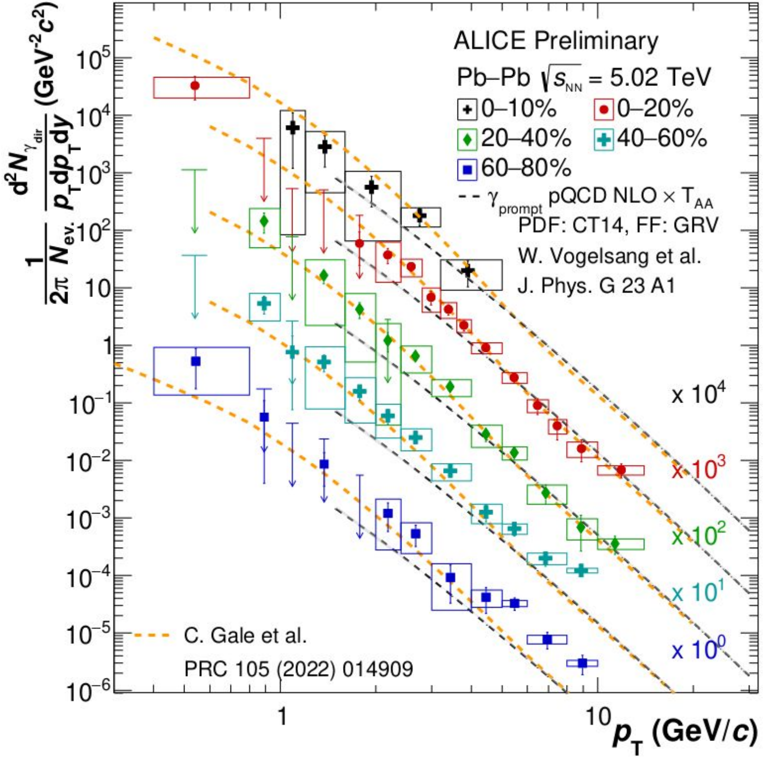


Pb-Pb 2.76 TeV,

PCM & PHOS

in agreement with models



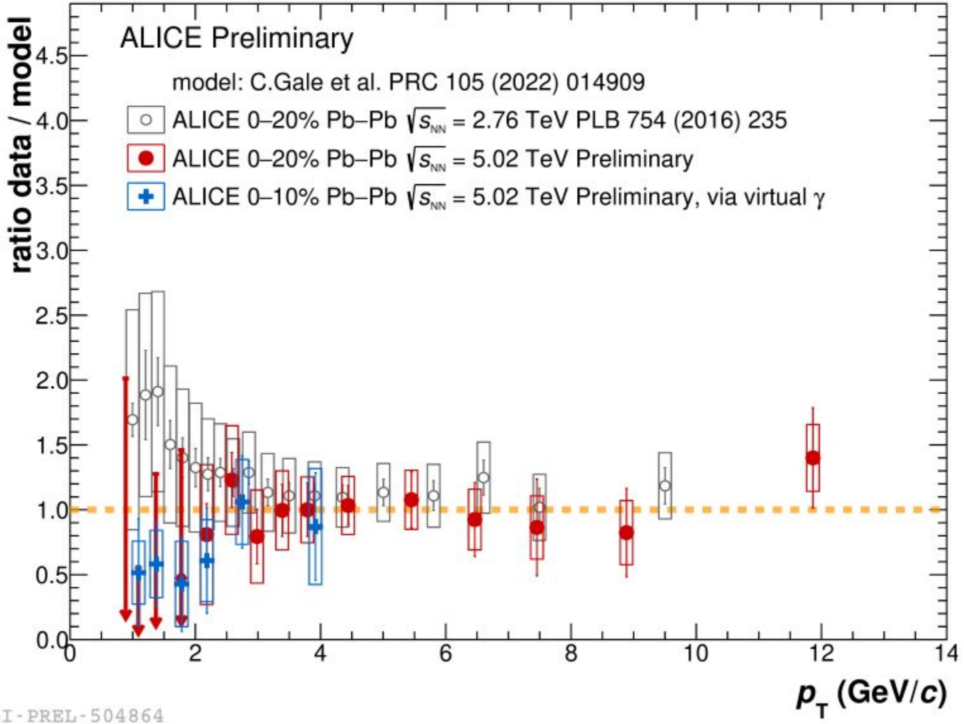
0-20% T eff = (297 ± 12 stat ± 41 syst) MeV

DIRECT PHOTONS SPECTRA RESULTS

Important result:

Measurements are in agreement with each other and with model calculation

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

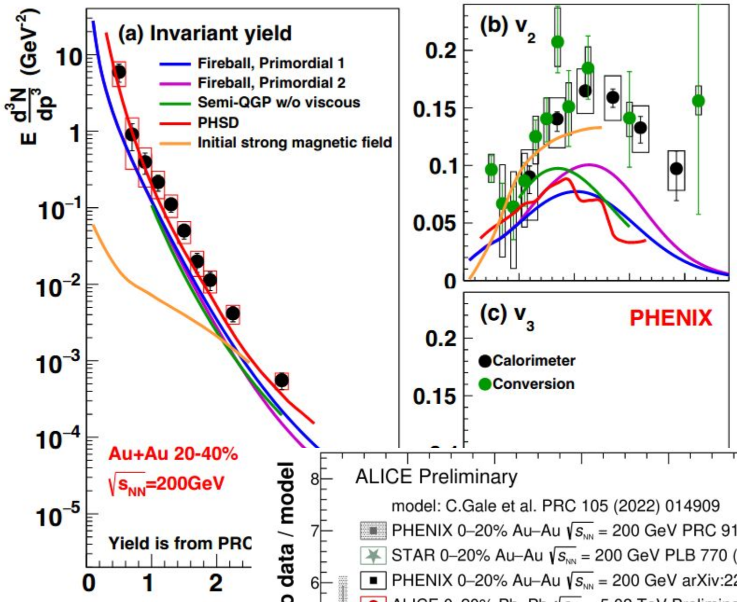


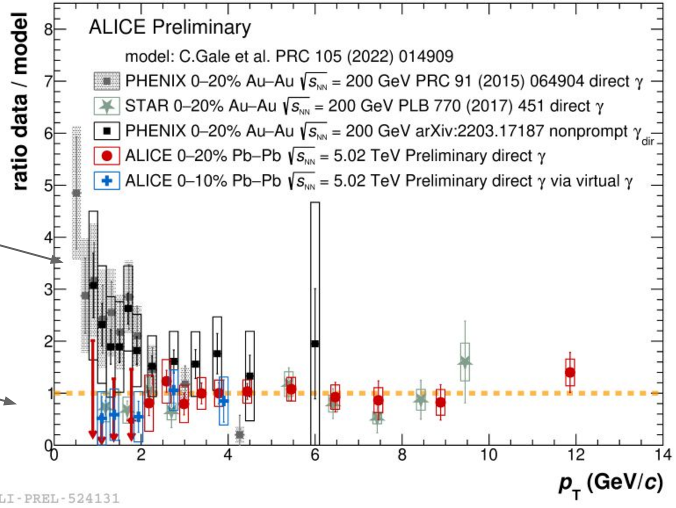
ALI-PREL-504864

DIRECT PHOTON PUZZLE

- **Direct photon puzzle** (PHENIX): large direct photon yields and large v_2 difficult to explain simultaneously
- **Also not understood:** large PHENIX yields on their own
- In contrast, models are in agreement with ALICE and STAR measurements

PRC 94, 064901 (2016)





OUTLOOK

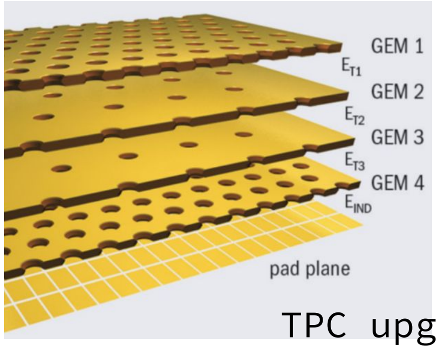
- Many questions still open
- Need more data and smaller uncertainties

- Analysis of full LHC **Run 2** dataset
  - so far, 25% of statistics ⇒ **effective temperature ?**
- LHC **Run 3 & 4:**
  - upgraded ITS
  - upgraded TPC
  - larger statistics
  - material calibration wires

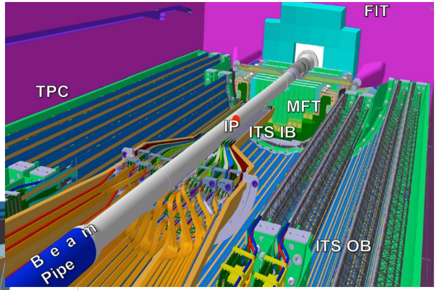
⇒ **HBT**

⇒ v_n

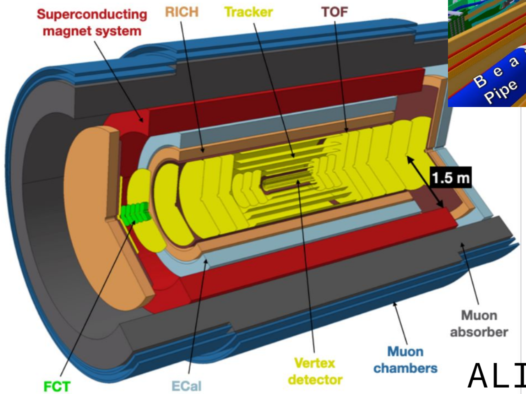
- **ALICE 3**
  - forward detector setup ⇒ higher reconstruction efficiency at low pT



TPC upgrade



ITS upgrade

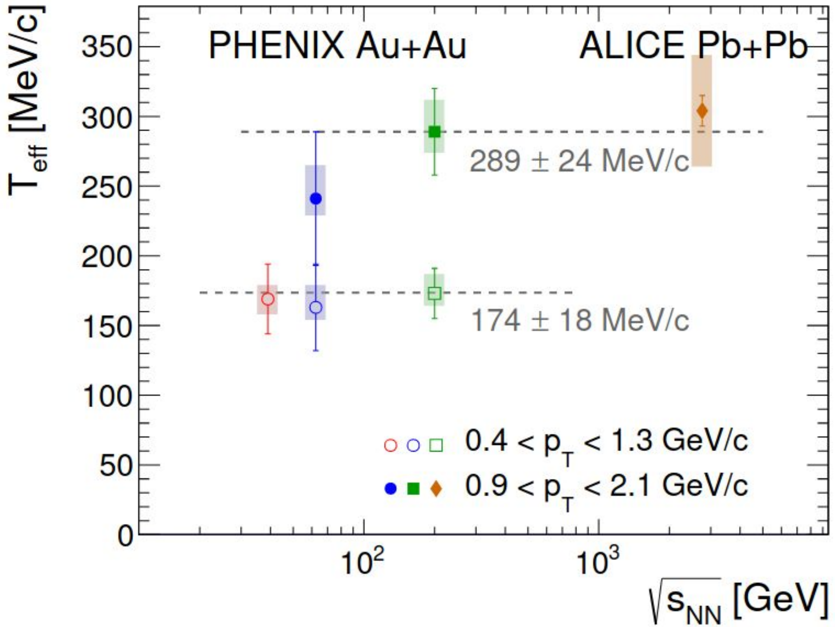


ALICE 3

THANK YOU!

THANK YOU!

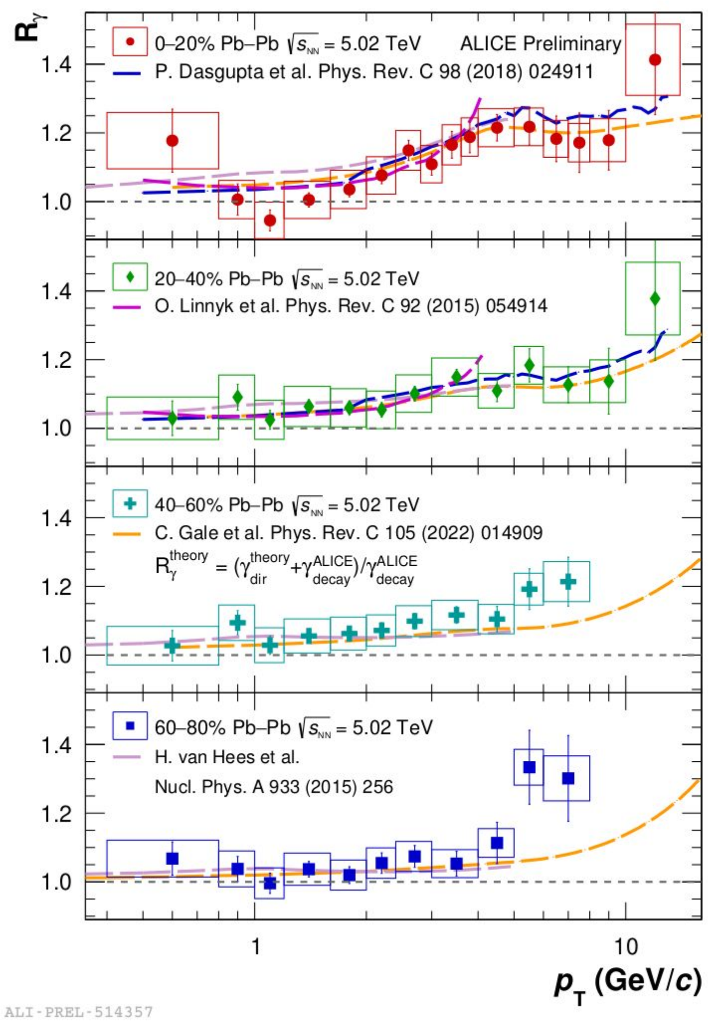
EFFECTIVE TEMPERATURES



arXiv:2203.12354 [nucl-ex]

DIRECT PHOTON EXCESS

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



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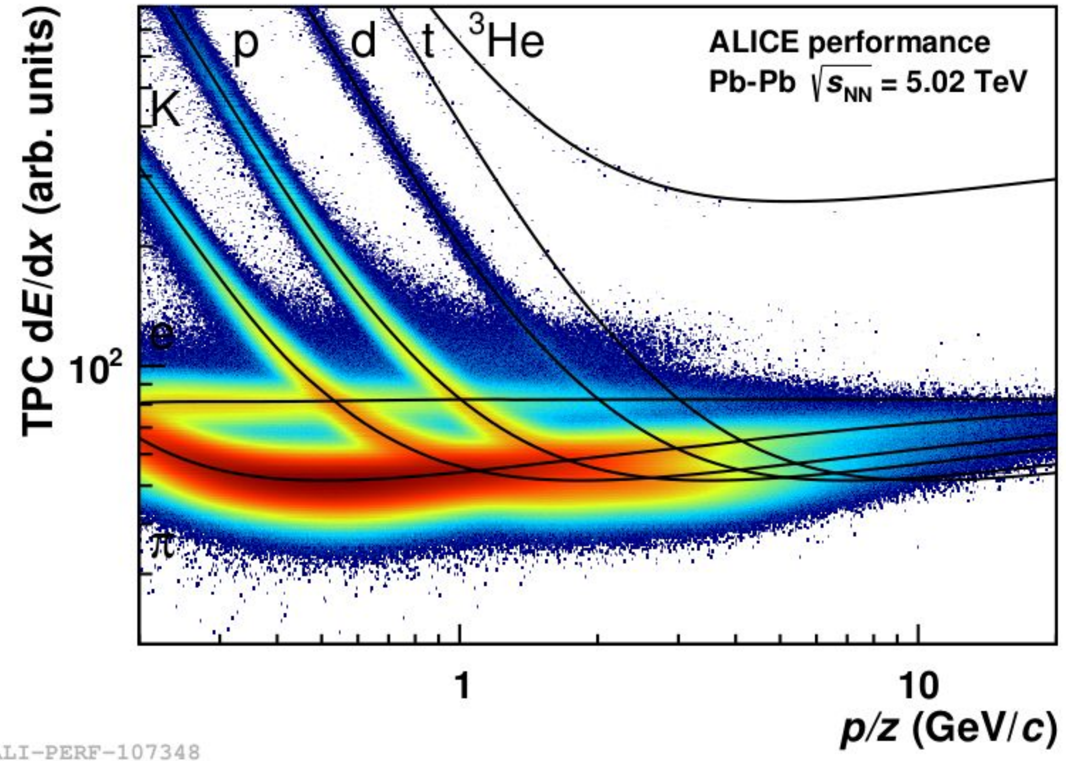
SPECIFIC ENERGY LOSS IN THE TPC



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DETECTOR THICKNESS CORRECTION

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$$\omega_i(r_i) = \frac{\left(\frac{N_\gamma^{\rm rec}(r_i)}{N_\gamma^{\rm rec}(r_{\rm gas})}\right)^{\rm DATA}}{\left(\frac{N_\gamma^{\prime,\rm rec}(r_i)}{N_\gamma^{\prime,\rm rec}(r_{\rm gas})}\right)^{\rm MC}},$$

$$\Omega_i(r_i) = \frac{\left(\frac{N_\gamma^{\rm rec}(r_i)}{N_{\rm ch}^{\rm rec}}\right)^{\rm DATA}}{\left(\frac{N_\gamma^{\prime,\rm rec}(r_i)}{N_{\rm ch}^{\rm rec}}\right)^{\rm MC}}$$

DIELECTRON INVARIANT MASS SPECTRUM

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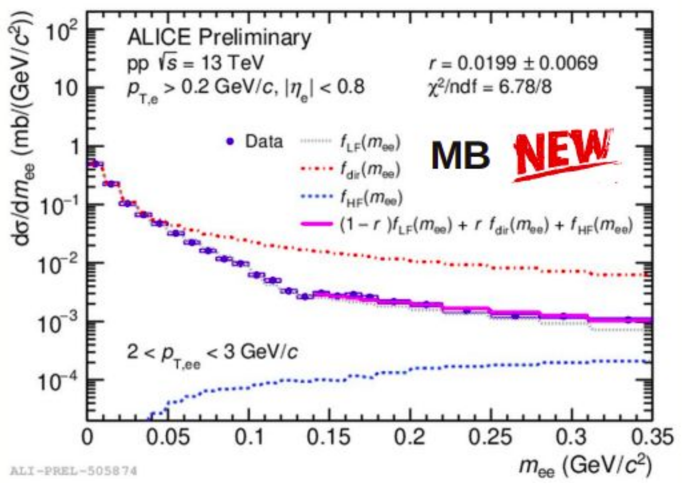


Direct photons in pp

→ Important baseline for Pb–Pb

→ Search for possible thermal contributions in HM pp events

Kroll-Wada formula f_{dir} used for extraction:

$$f_{fit} = r \times f_{dir} + (1-r) \times f_{LF} + f_{HF}$$

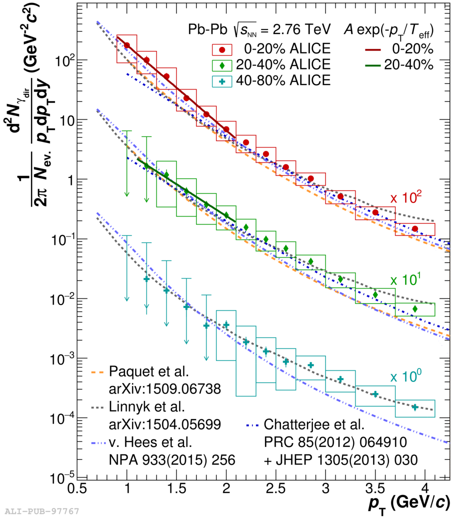
Direct-photon fraction r :

as shown by Jerome Jung, QM 2022

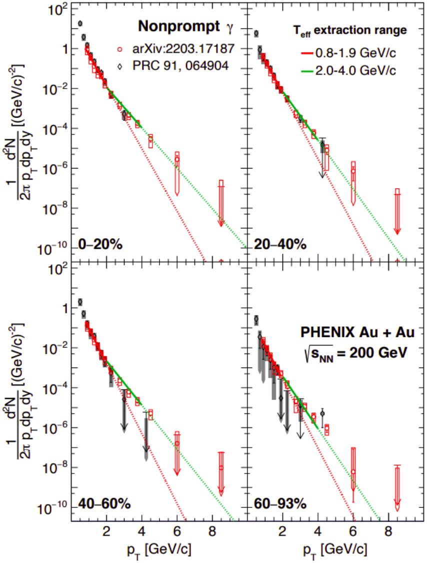
Medium temperature at LHC

- 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



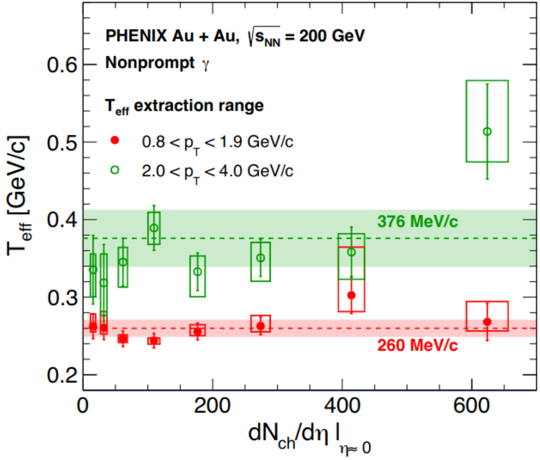
- Au–Au $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$
- Large statistics: 10^{10} events
- Nonprompt direct photons: N_{coll} scaled pp spectra fitted and subtracted
- Fit two p_{T} ranges: 0.8-1.9 and 2.4-4.0 GeV/c
- η/π^0 ratio for decay photons from world data in pp collisions, and accounting for radial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

arXiv:2203.17187

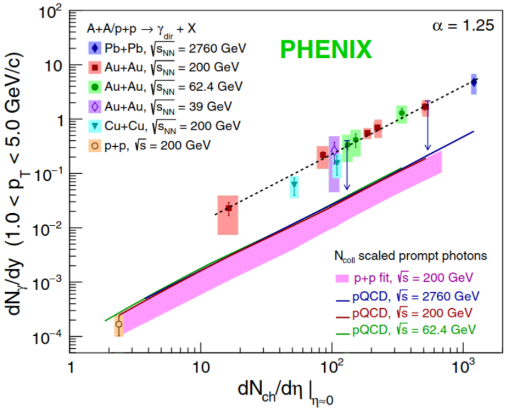
Medium temperature at RHIC

- 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



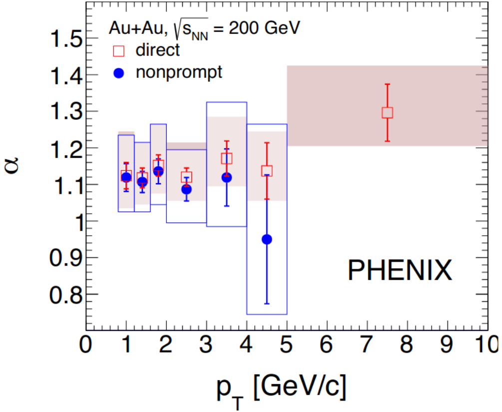
$$\frac{dN_\gamma}{dy} = A \times \left(\frac{dN_{\rm ch}}{d\eta}\right)^\alpha$$

Above pQCD and $N_{\rm coll}$-scaled pp

Same power for different collision systems, energies

PRL 123, 022301 (2019)

arXiv:2203.17187

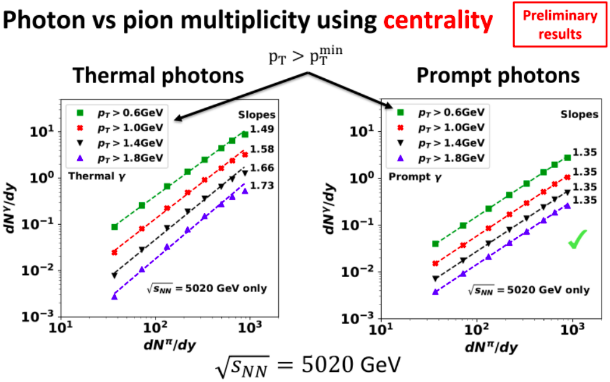


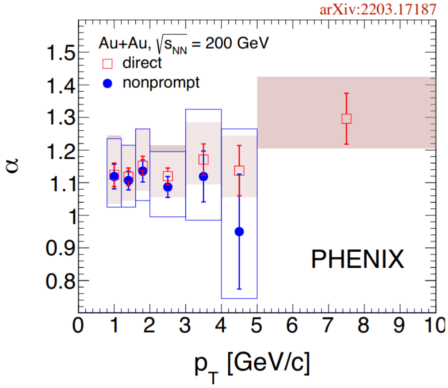
Integrated direct/nonprompt photon yields

For different integration ranges

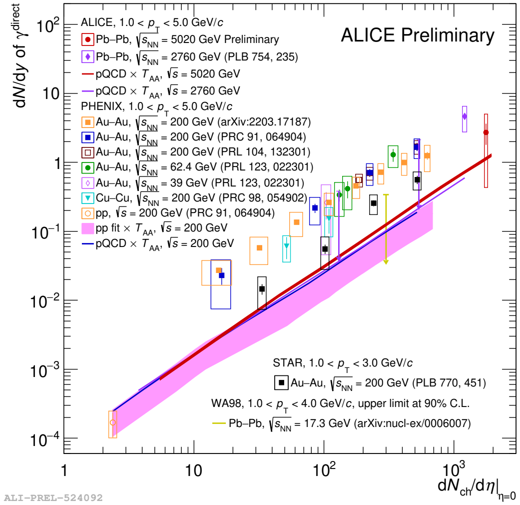
Scaling with system size

- 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





Direct photon yields

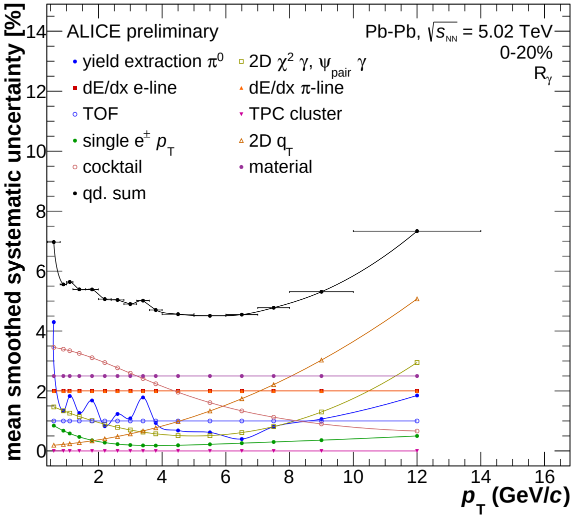


Not understood:

- 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?

Systematic uncertainties of R_γ for PCM



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

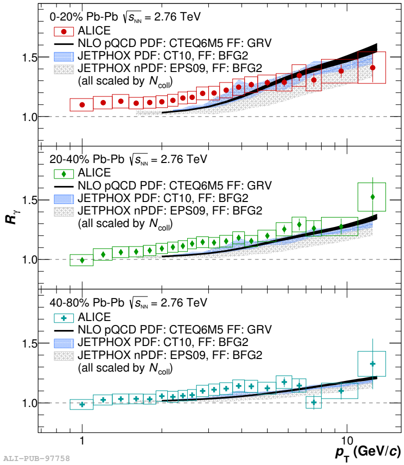
$$\gamma_{\text{dir}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = \gamma_{\text{inc}}(1 - \frac{1}{R_\gamma}) \quad (2)$$

Dominating contributions:

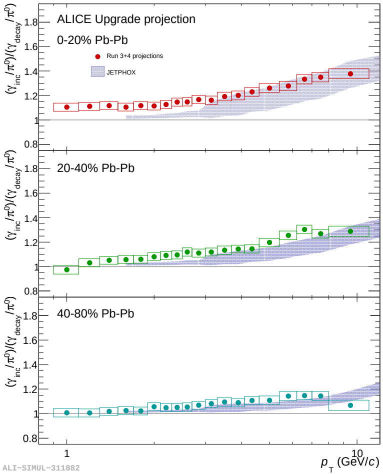
- π^0 yield extraction
- cocktail (decay photon simulation)
- material budget
- dE/dx: electron identification

Uncertainties projection Run 1 → Run 3+4

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



PLB 754 (2016) 235

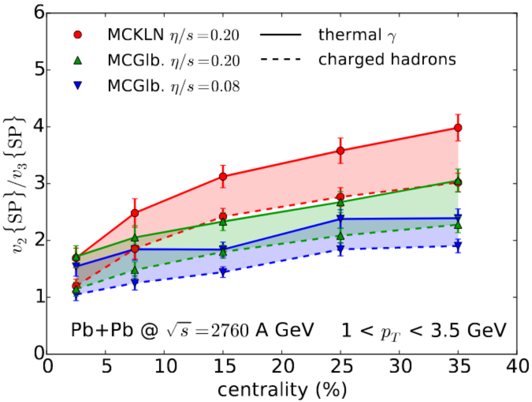


arXiv:1812.06772

≈ 50% smaller uncertainties
- significance depends on the size of the direct photon signal
- should allow for T_{eff} extraction

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

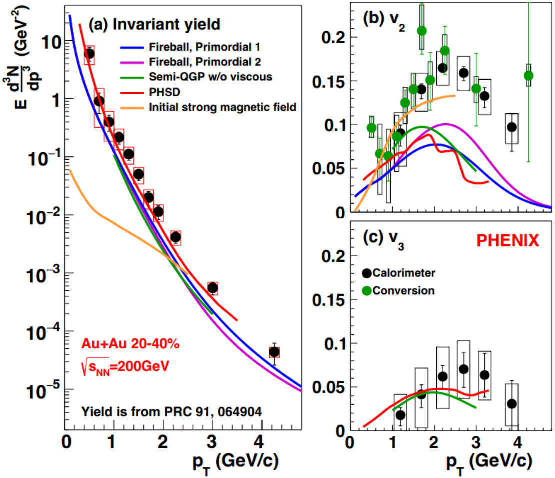


Phys. Rev. C91, 024908 (2015)

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)

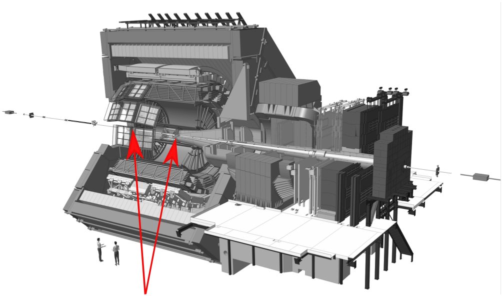


Elliptic flow measurement in LHC Run 1

- 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

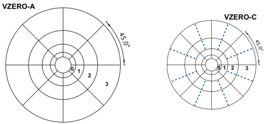
$$v_2^{\gamma,\mathrm{inc}} = \frac{N_{\gamma,\mathrm{dir}}}{N_{\gamma,\mathrm{inc}}} \cdot v_2^{\gamma,\mathrm{dir}} + \frac{N_{\gamma,\mathrm{dec}}}{N_{\gamma,\mathrm{inc}}} \cdot v_2^{\gamma,\mathrm{dec}}$$

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



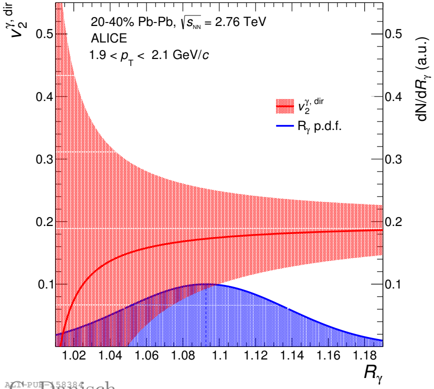
V0 detectors:

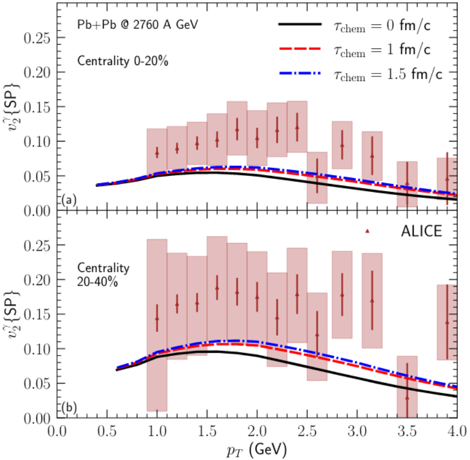
$2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$



Direct photon puzzle at LHC?

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

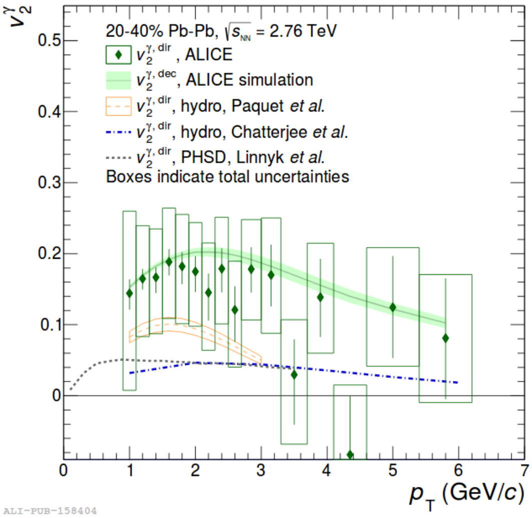


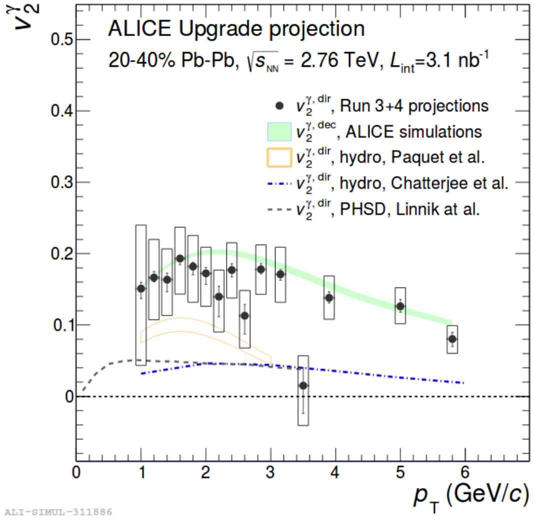


PLB 789 (2019) 308, PRC 105 (2022) 1, 014909

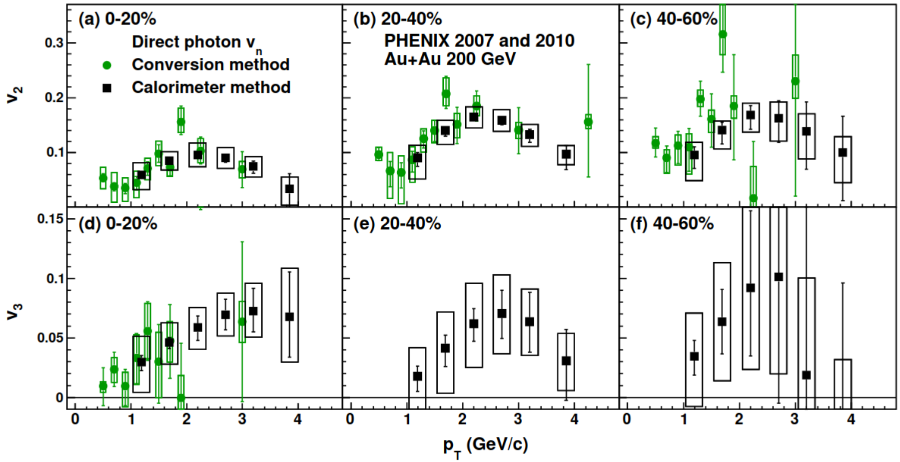
τ_{chem}: how fast the quarks are produced and equilibrate in an initially purely gluonic system

Direct photon puzzle at LHC? Run 3 + 4





Triangular flow v_3

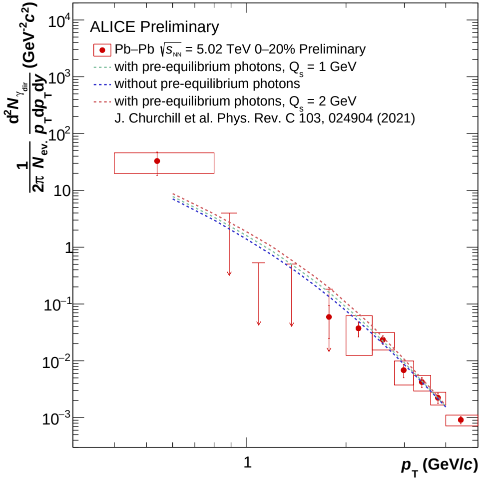


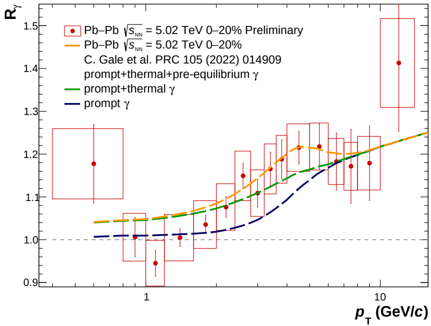
Even larger uncertainties than v_2

PRC 94 (2016) 6, 064901

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

Pre-equilibrium photons





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

Bose-Einstein $\gamma\gamma$ correlations

Motivation:

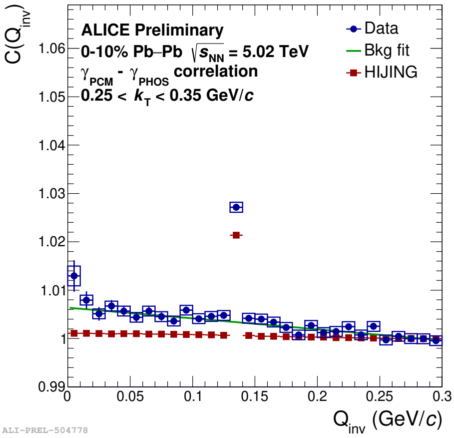
- Correlation function is sensitive to the **source size** R and the **direct photon fraction**
- The source size at the moment of kinetic freeze-out can be measured with hadrons
- With photons, sensitive to earlier times
- Alternative method to determine the **direct photon fraction** which does not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

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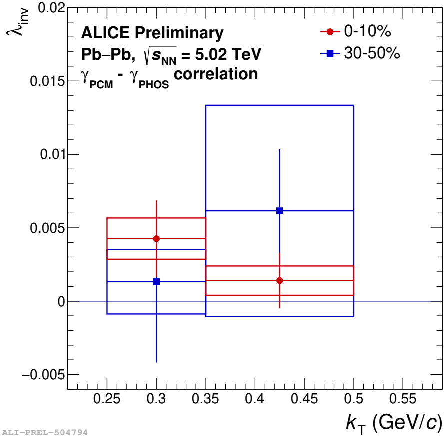


terminology used from PRL 93 (2004) 022301, D. Peressounko et al.

Open questions

- 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 ?
- ...

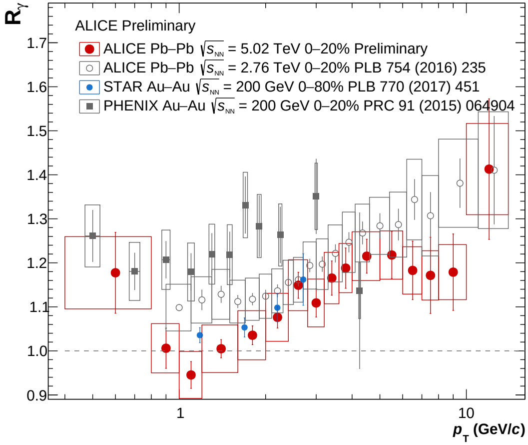
Systematic uncertainties in the 2010 data analysis

ALICE

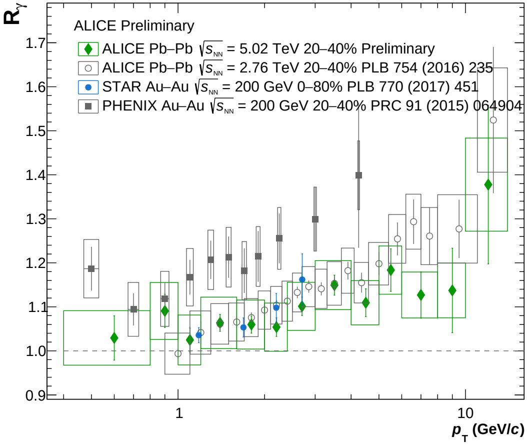
Centrality	0–20%		20–40%		40–80%	
p_T (GeV/c)	1.2	5.0	1.2	5.0	1.2	5.0
γ_{incl} yield						
Track quality (A)	0.6	0.6	0.2	0.2	0.2	0.7
Electron PID (A,B)	1.5	6.9	0.9	4.8	0.7	4.0
Photon selection (A,B)	4.0	1.8	2.4	2.1	1.5	1.3
Material (C)	4.5	4.5	4.5	4.5	4.5	4.5
γ_{incl}/π^0						
Track quality (A)	0.7	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

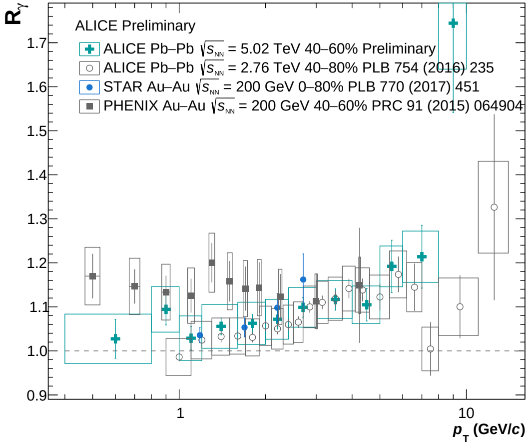


ALICE Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV 0–20% Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV 0–20% PLB 754 (2016) 235
STAR Au–Au $\sqrt{s_{NN}}$ = 200 GeV 0–80% PLB 770 (2017) 451
PHENIX Au–Au $\sqrt{s_{NN}}$ = 200 GeV 0–20% PRC 91 (2015) 064904
R_γ
p_T (GeV/c)

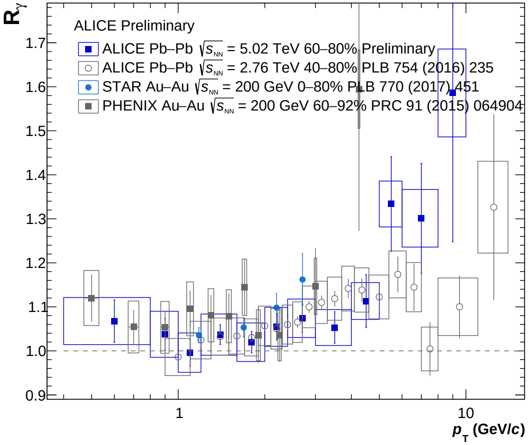


ALICE Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV 20–40% Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV 20–40% PLB 754 (2016) 235
STAR Au–Au $\sqrt{s_{NN}}$ = 200 GeV 0–80% PLB 770 (2017) 451
PHENIX Au–Au $\sqrt{s_{NN}}$ = 200 GeV 20–40% PRC 91 (2015) 064904
R_γ
p_T (GeV/c)

LHC and RHIC



ALICE Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV 40–60% Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV 40–80% 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 40–60% PRC 91 (2015) 064904
R_γ
p_T (GeV/c)



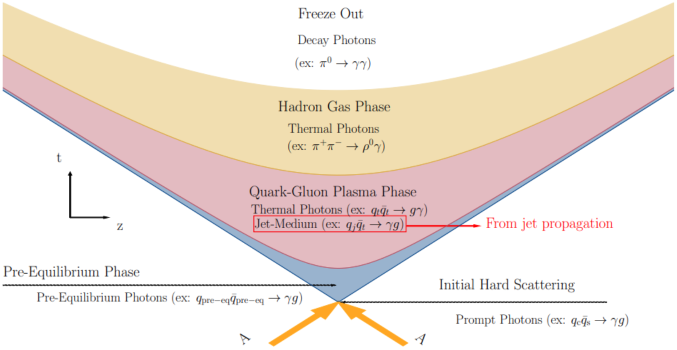
ALICE Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV 60–80% Preliminary
ALICE Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV 40–80% PLB 754 (2016) 235
STAR Au–Au $\sqrt{s_{NN}}$ = 200 GeV 0–80% PLB 770 (2017) 451
PHENIX Au–Au $\sqrt{s_{NN}}$ = 200 GeV 60–92% PRC 91 (2015) 064904
R_γ
p_T (GeV/c)

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

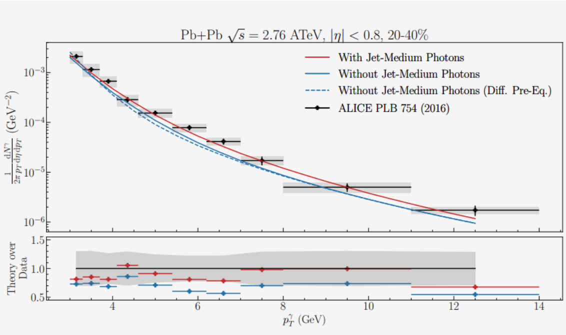
Jet-medium photons

- 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

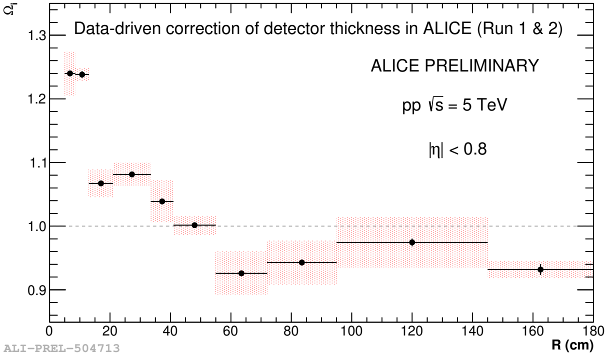
- New calculation was presented at QM
- Event generation with JETSCAPE, realistic jet distribution and hydro background
- Photons from e.g. the interacion of a quark within a jet, and a thermal quark from the QGP
- Observation: in the region $5 < pT < 10\,\mathrm{GeV/c}$ this contribution makes up nearly 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/

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

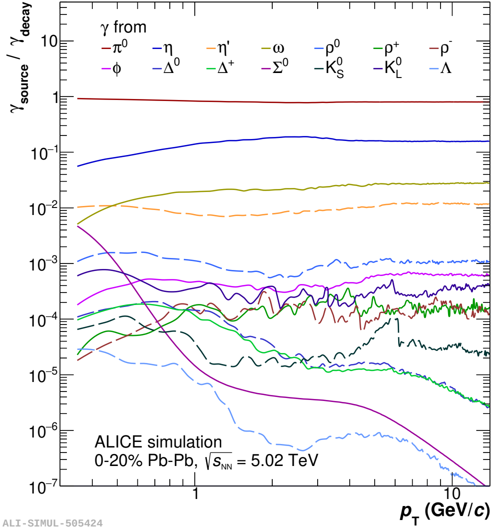
Simulation of decay photons

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

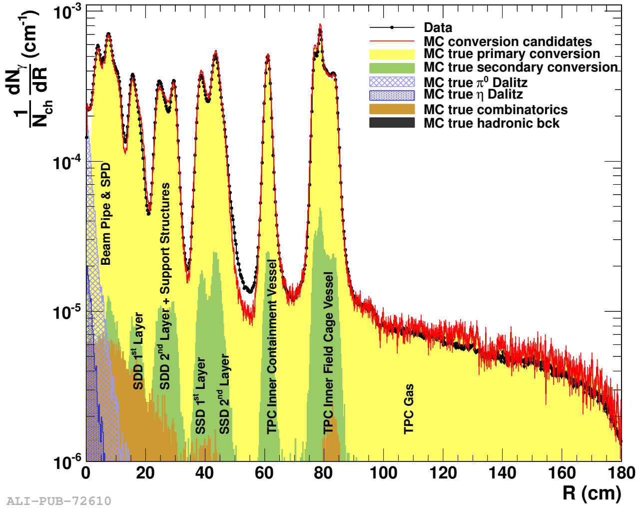
decay photon yields in 2.76 TeV

- 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_s^0 (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

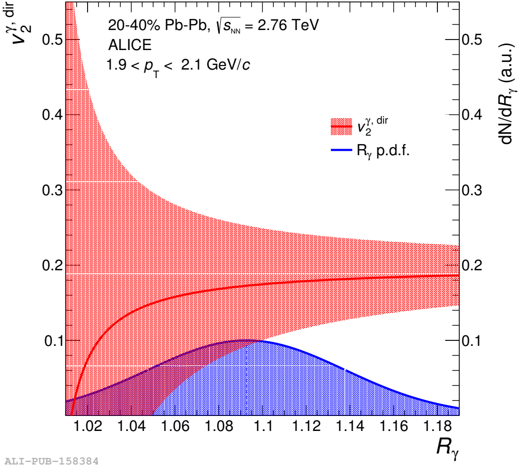
- π^0 v_2 from charged pion v_2 measured under the same conditions
- η and ω from charged and neutral kaons with KE_T scaling

Material budget in data and MC before correction



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

Elliptic flow uncertainties



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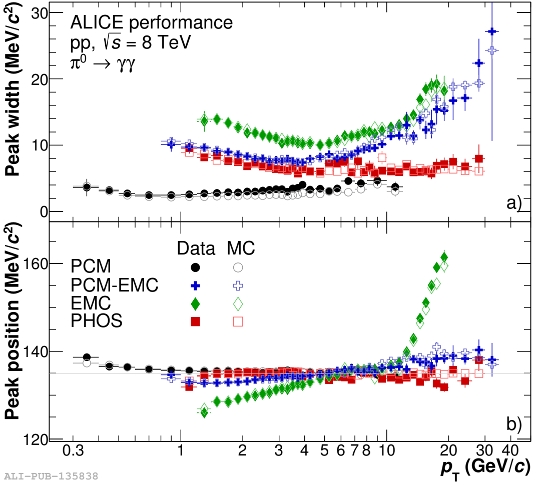
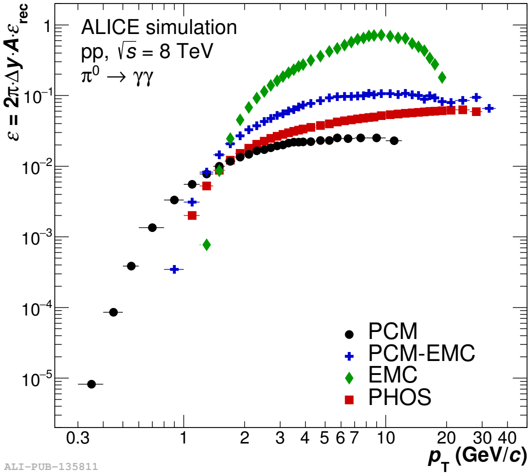
Complementarity of the methods





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