Direct-photon production and HBT correlations in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 (2.76) TeV with the ALICE experiment

A. Marin for the ALICE Collaboration

2023 HARD PROBES Aschaffenburg

GSI

ALICE

Motivation: Direct photons

Carry information on the medium's temperature and space-time evolution.
Large background from neutral meson decays ($\pi^0,\eta,\omega,\ldots$).

Prompt photons: F. Jonas, talk 74

- Dominant at high p_T (p_T>~5 GeV/c), power-law shape
- Initial hard scattering
- Described by NLO pQCD

Pre-equilibrium photons:

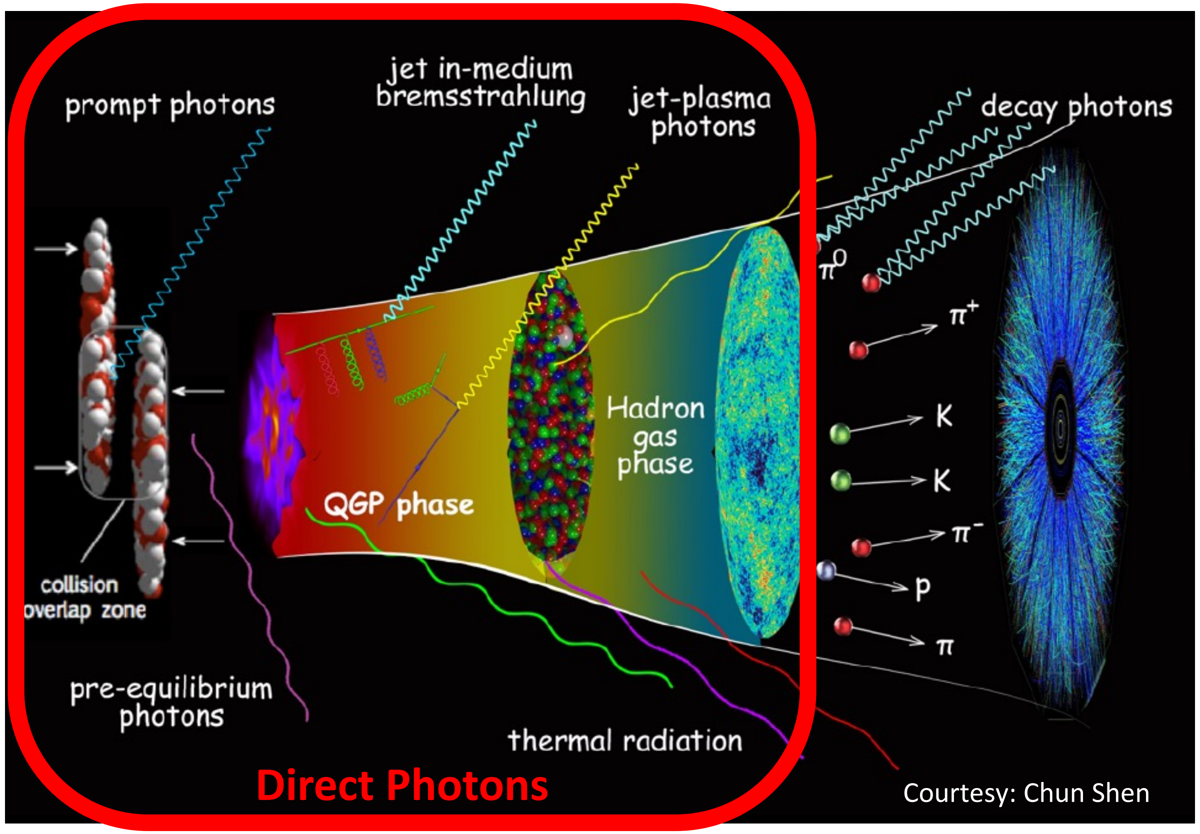
- Sensitive to the saturation momentum

Jet-medium interactions:

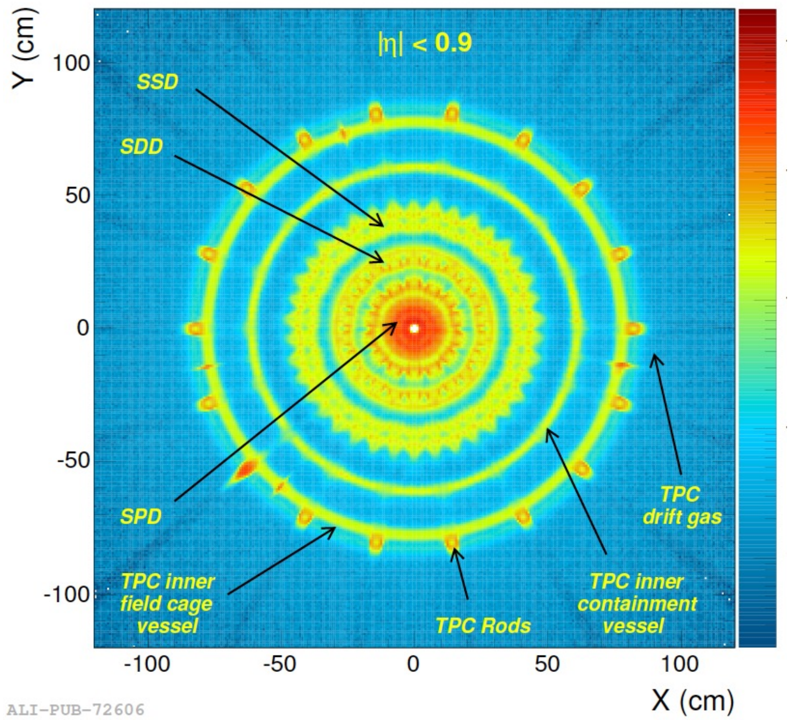
- Scattering of hard partons with thermalized partons

Thermal photons:

- Dominant at low p_T (p_T<~3 GeV/c) with exponential shape
- Emitted by thermalized medium
- Comparison to models employing hydrodynamics



Measurement of inclusive photons



EMCal/DCal: sampling calorimeter

10 modules at 4.4 m from ALICE IP.

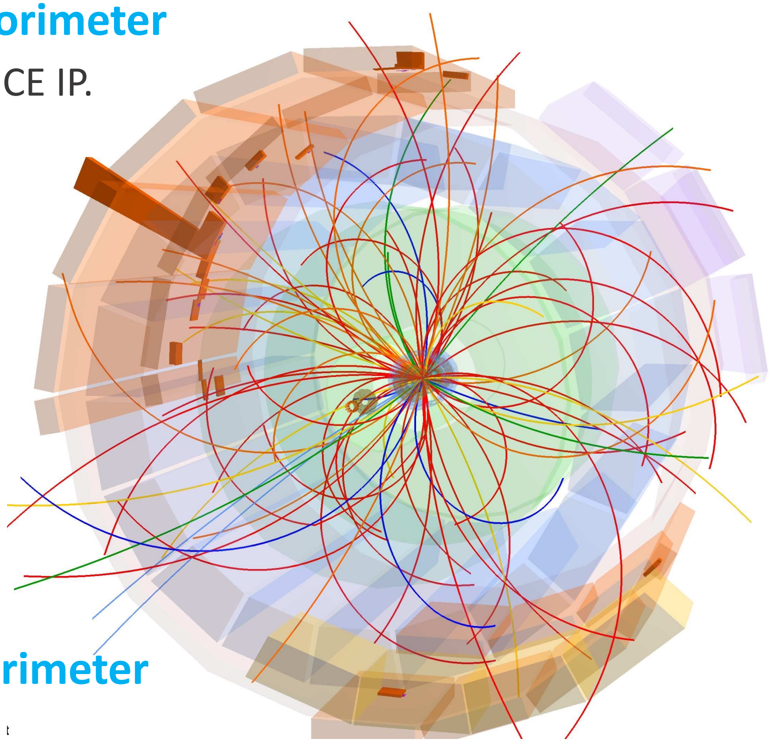
EMCal:

|η|<0.7, 80°<φ<187°.

DCAL:

0.22<|η|<0.7, 260°< φ <320°

|η|<0.7 , 320°< φ <327°



PHOS: homogeneous calorimeter

$PbWO_4$ crystal

3 modules at 4.6 m from ALICE IP

|η|<0.12, 260°<φ<320°

J. Lühder, poster 52

N. Stangmann, poster 105

J. Koenig, poster 109

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

Photon conversion method (PCM):

Photon conversion in detector material ITS and TPC

|η|<0.9, R < 180 cm, 0°<φ<360°, X/X_0=11.4±0.5 sys %

10-15% low p_T direct photon excess at LHC energies

6% uncertainty, largest contribution: 4.5% sys X/X_0

Can this uncertainty be reduced?→Improve R_γ uncertainty

NEW

Data-driven precision determination of the material budget in ALICE

RD: Real Data
MC: Monte Carlo

arxiv: 2303.15317

ω_i : TPC-gas based calibration weights

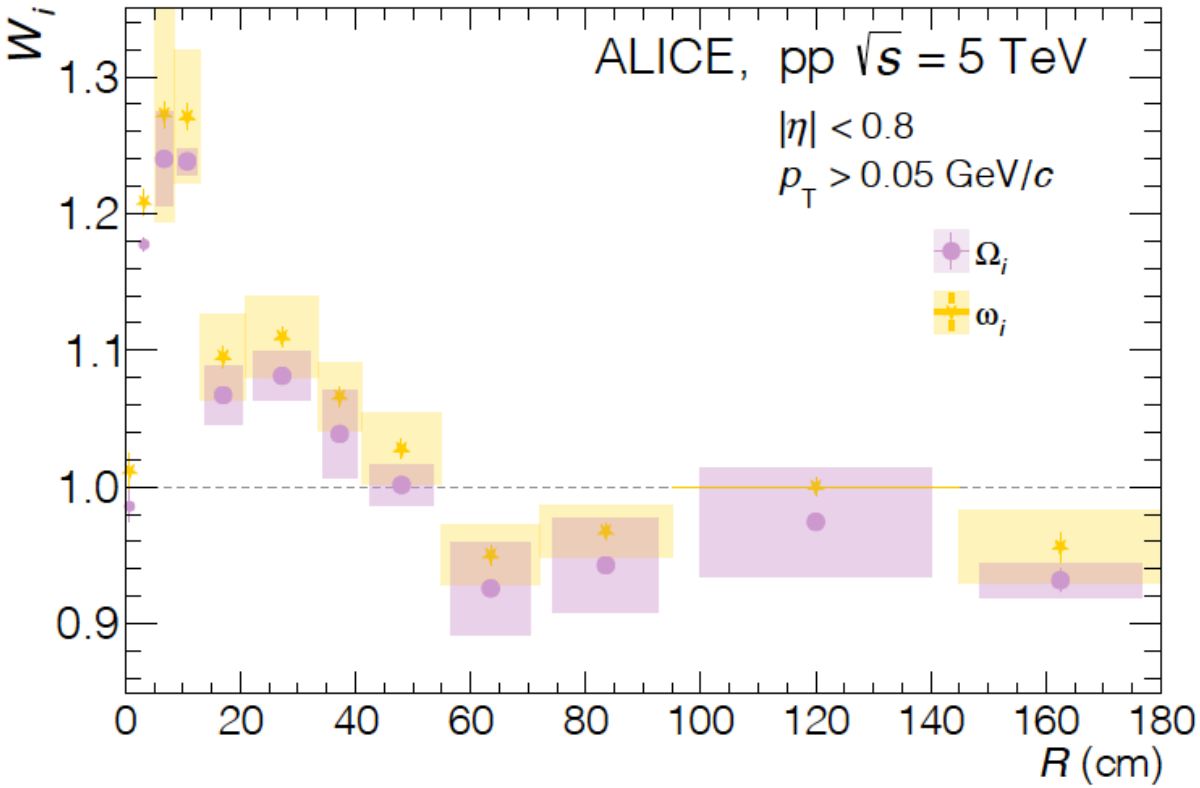
$$\omega_i = \frac{N^{\mathrm{rec,RD}}_{\gamma,i} / N^{\mathrm{rec,RD}}_{\gamma,\mathrm{gas}}}{N'^{\mathrm{rec,MC}}_{\gamma,i} / N'^{\mathrm{rec,MC}}_{\gamma,\mathrm{gas}}}$$

Ω_i: pion-isospin-symmetry

$$\Omega_i = \frac{N^{\mathrm{rec,RD}}_{\gamma,i} / N^{\mathrm{rec,RD}}_{\mathrm{ch}}}{N'^{\mathrm{,rec,MC}}_{\gamma,i} / N^{\mathrm{rec,MC}}_{\mathrm{ch}}}$$

Use Ω_i to correct ε_γ:

$$\varepsilon^{\mathrm{MC,corr}}_{\gamma}(p_\mathrm{T}) = \frac{\Sigma_i W_i \times \mathrm{d}N^{\mathrm{rec,MC}}_{\gamma,i} / \mathrm{d}p_\mathrm{T}}{\mathrm{d}N^{\mathrm{prod}}_{\gamma} / \mathrm{d}p_\mathrm{T}}$$



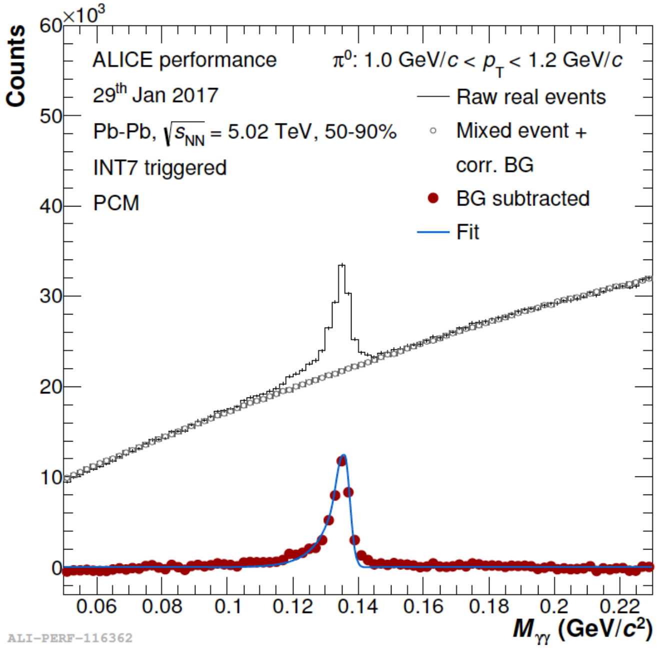
Reduce X/X_0 systematic uncertainty: 4.5% → 2.5%
Mitigate local imperfections in X/X_0 implementation in simulations

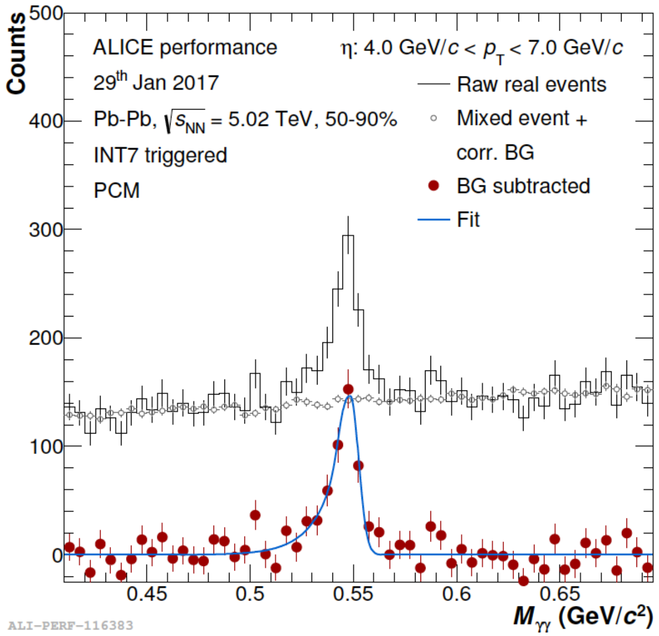
R_γ: γ_{inc} , neutral mesons and decay photons

$$R_\gamma = N_{\gamma,\mathrm{inc}}/N_{\gamma,\mathrm{dec}} \approx \left(\frac{N_{\gamma,\mathrm{inc}}}{\pi^0}\right)_{\mathrm{meas}} / \left(\frac{N_{\gamma,\mathrm{dec}}}{\pi^0}\right)_{\mathrm{sim}}$$

Direct photon signal if $R_\gamma > 1$

$$N_{\gamma,\mathrm{dir}} = N_{\gamma,\mathrm{inc}} - N_{\gamma,\mathrm{dec}} = (1 - \frac{1}{R_\gamma}) \cdot N_{\gamma,\mathrm{inc}}$$





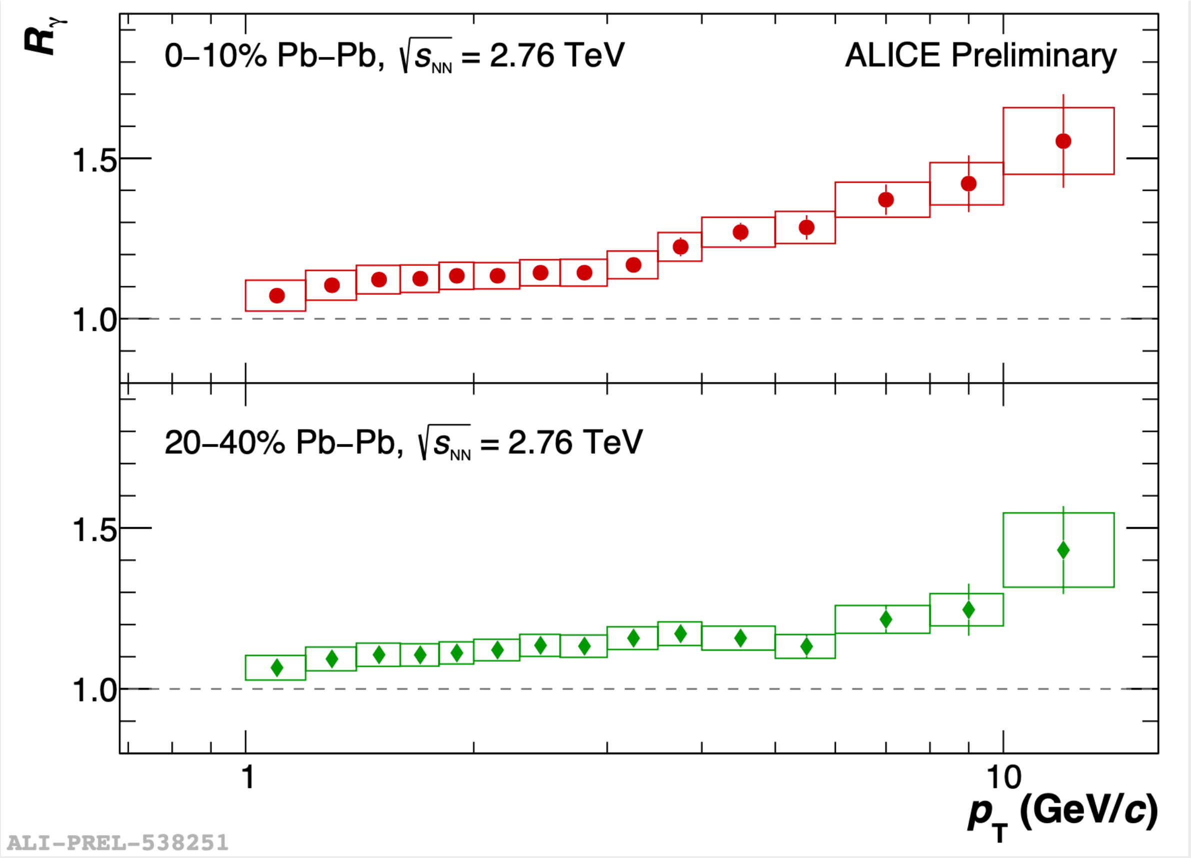
- Measure π^0 and η via $\gamma\gamma$ decay
- Simulation of π^0, η, ω, η' decays into γ

NEW

Direct photon R_γ in Pb – Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

Combination of PCM (2011) with Ω_i + PHOS (2010)

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



In agreement with published results

New centrality available: 0-10%

Smaller uncertainties

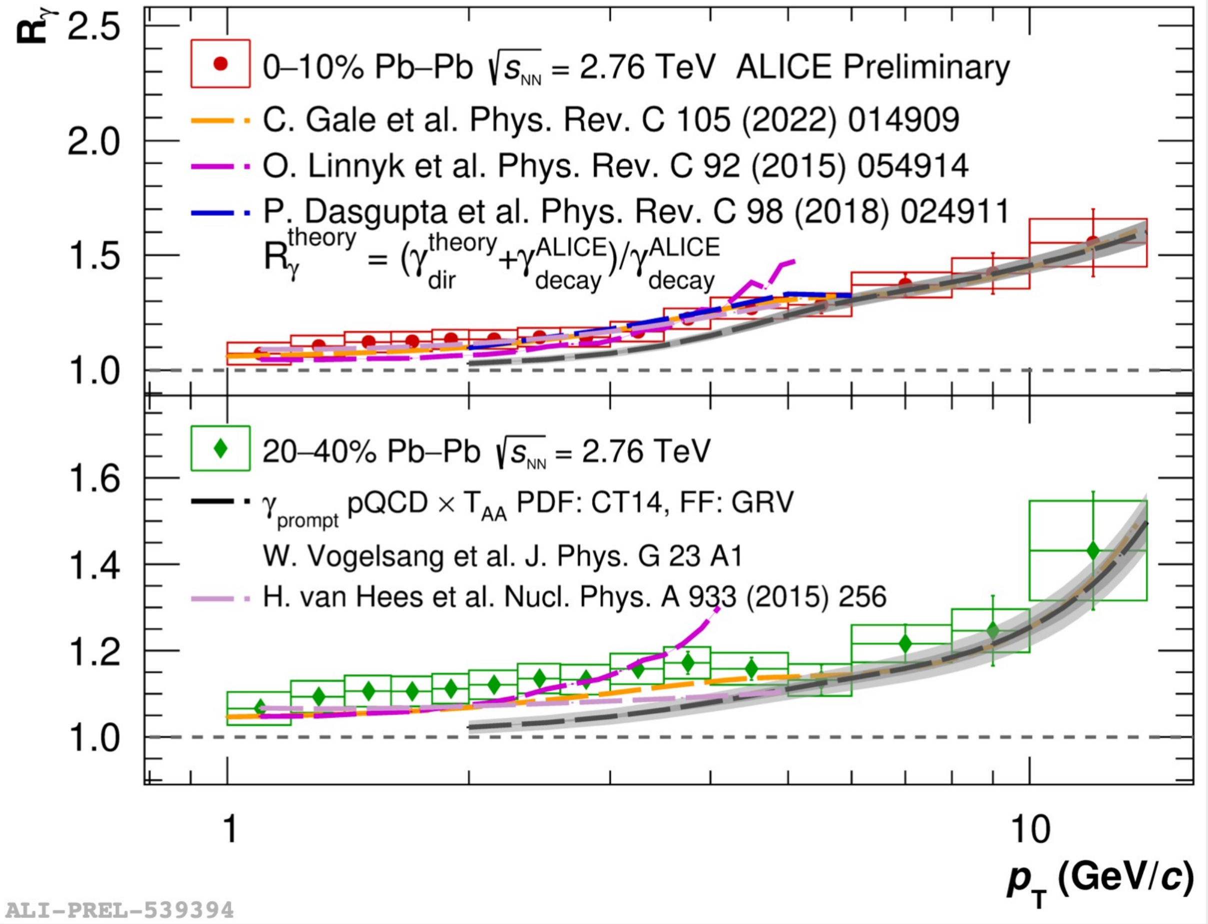
Significant excess for p_T > 1 GeV/c

- 0-10%: 3.1 σ (1.0 GeV/c < p_T < 1.8 GeV/c)
- 20-40%: 3.4 σ (1.0 GeV/c < p_T < 2.3 GeV/c)

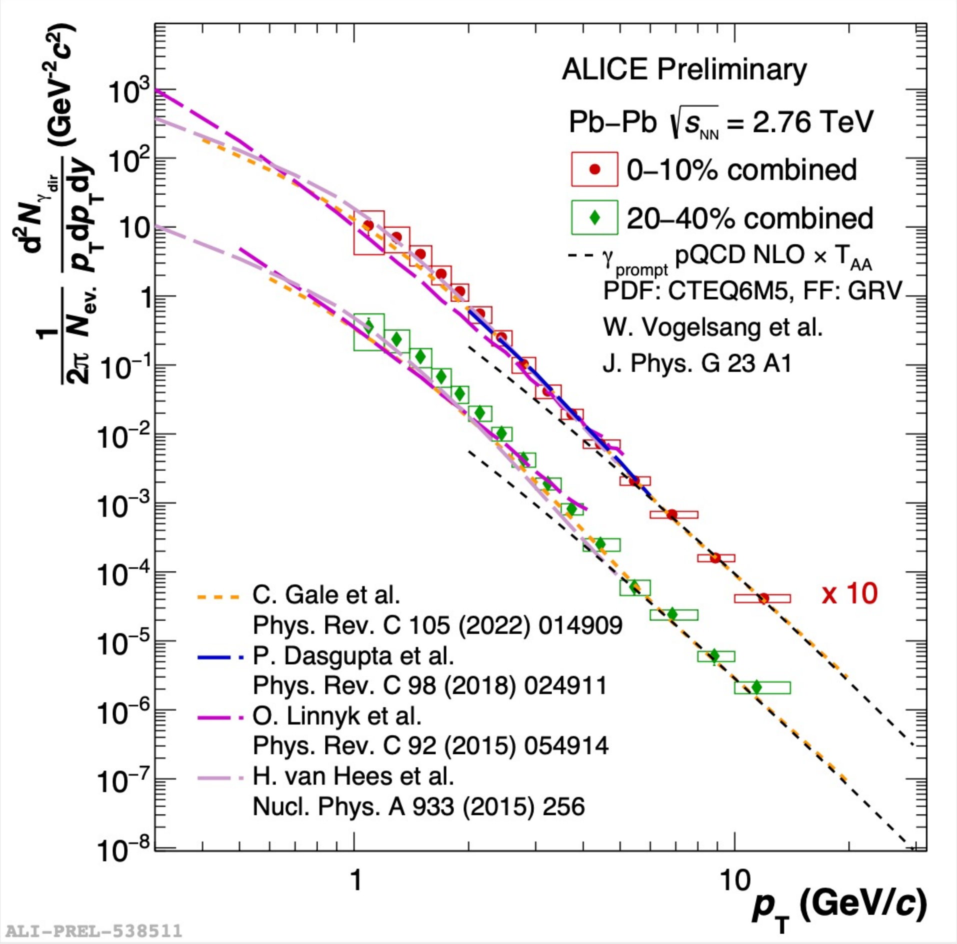
Low p_T : thermal radiation

High p_T : prompt photons

QGP thermal emission: Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

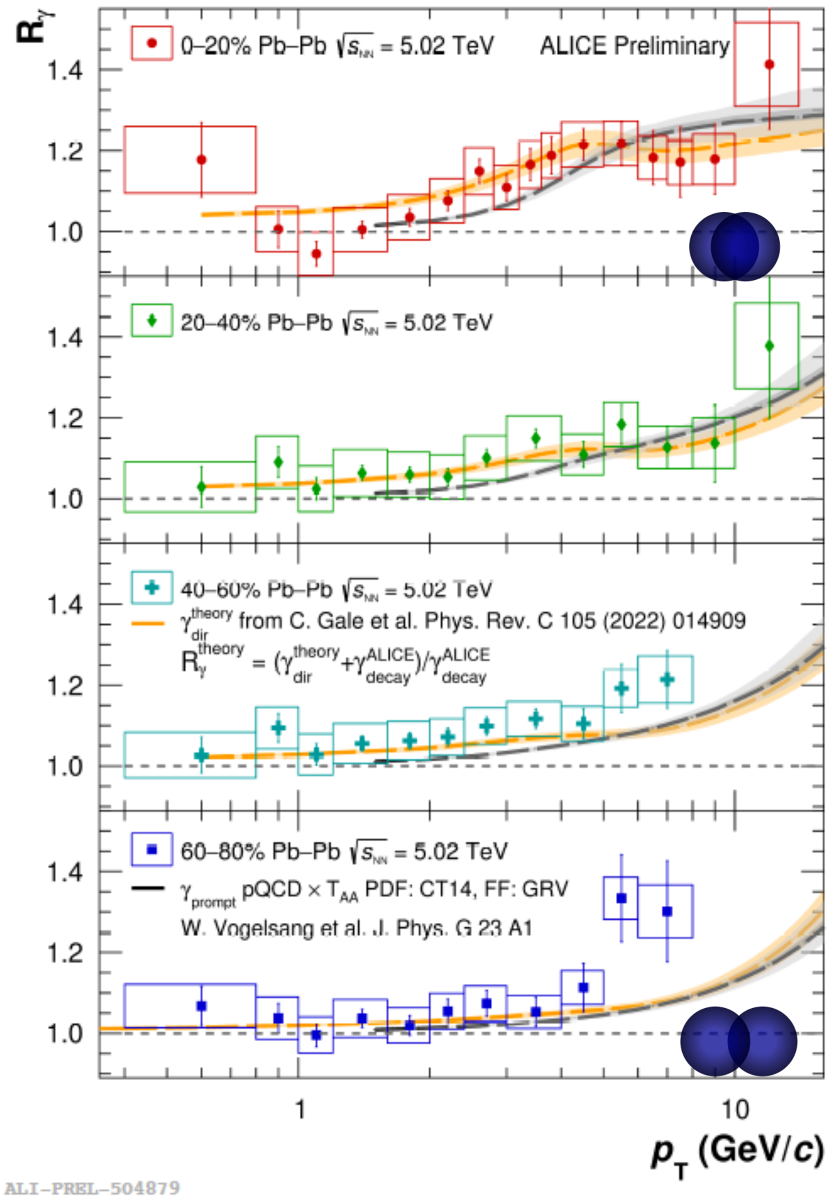


$$N_{\gamma,\mathrm{dir}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot N_{\gamma,\mathrm{inc}}$$



- Excess beyond known prompt yield 1 < p_T < 4 GeV/c
- Models that include thermal +(pre-equilibrium) + prompt photons are able to describe the data
- Not yet possible to discriminate among different models

QGP thermal emission: Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



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

- At low p_T :
  R_γ is close to 1 → small thermal contribution

- For p_T > 2-3 GeV/c:
  Excess → pre-equilibrium and prompt photons

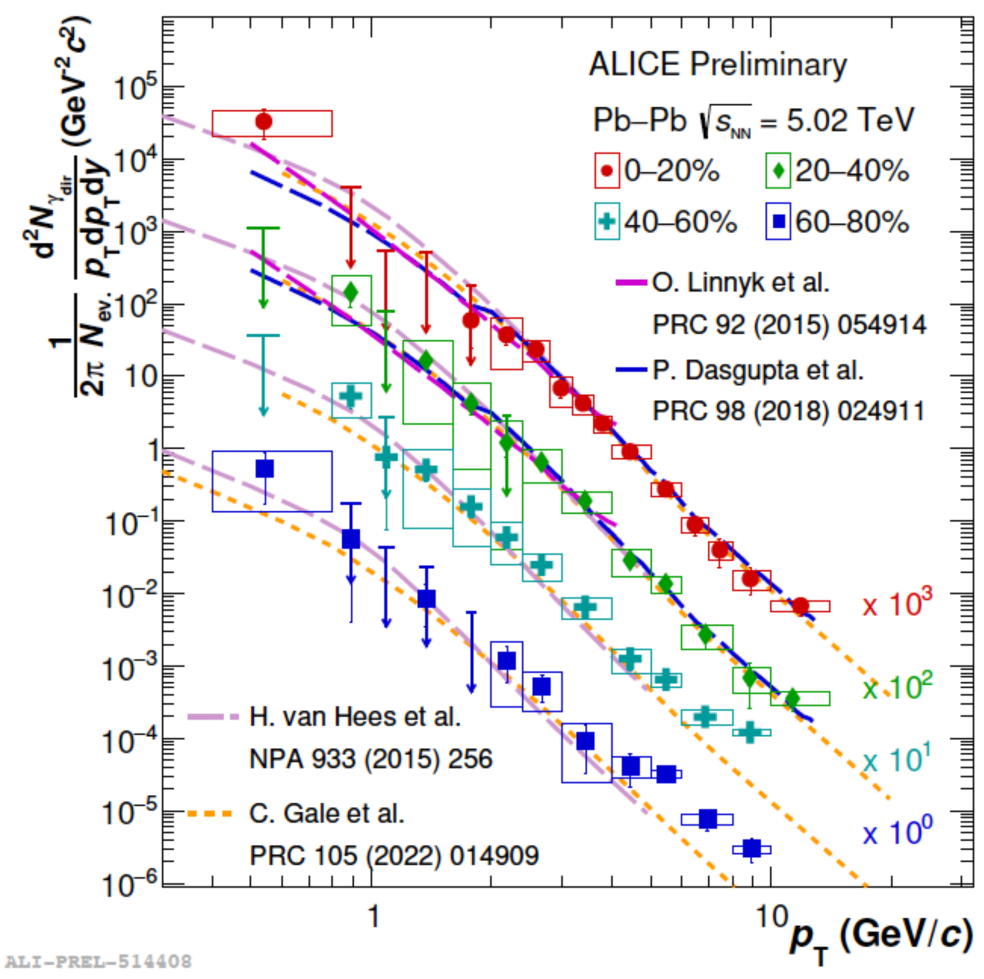
- Data consistent with NLO pQCD calculation of prompt photons x T_{AA}
  Calculation by W. Vogelsang, using PDF: CT14, FF: GRV

- Thermal+ pre-equilibrium photons + prompt photon: $R_\gamma \sim 1.05$ →
  Better data description better than with only prompt photons
  IP-Glasma initial conditions + KøMPøST+ MUSIC viscous hydrodynamics ,
  prompt γ PDF:nCTEQ15-np, FF: BFG-II

Bands represent (theoretical and) experimental uncertainties

QGP thermal emission: Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE



$$N_{\gamma,\mathrm{dir}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot N_{\gamma,\mathrm{inc}}$$

- Upper limits (90% CL) given where $N_{\gamma,\mathrm{dir}}$ consistent with 0
- Different model calculations of direct photons:
  - Microscopic transport approach (PHSD)
  - Relativistic hydrodynamic, different initial conditions, thermalization times, hadronization temperatures, with and without pre-equilibrium γ
- At high p_T consistent with pQCD

Not yet possible to favor a model over the other

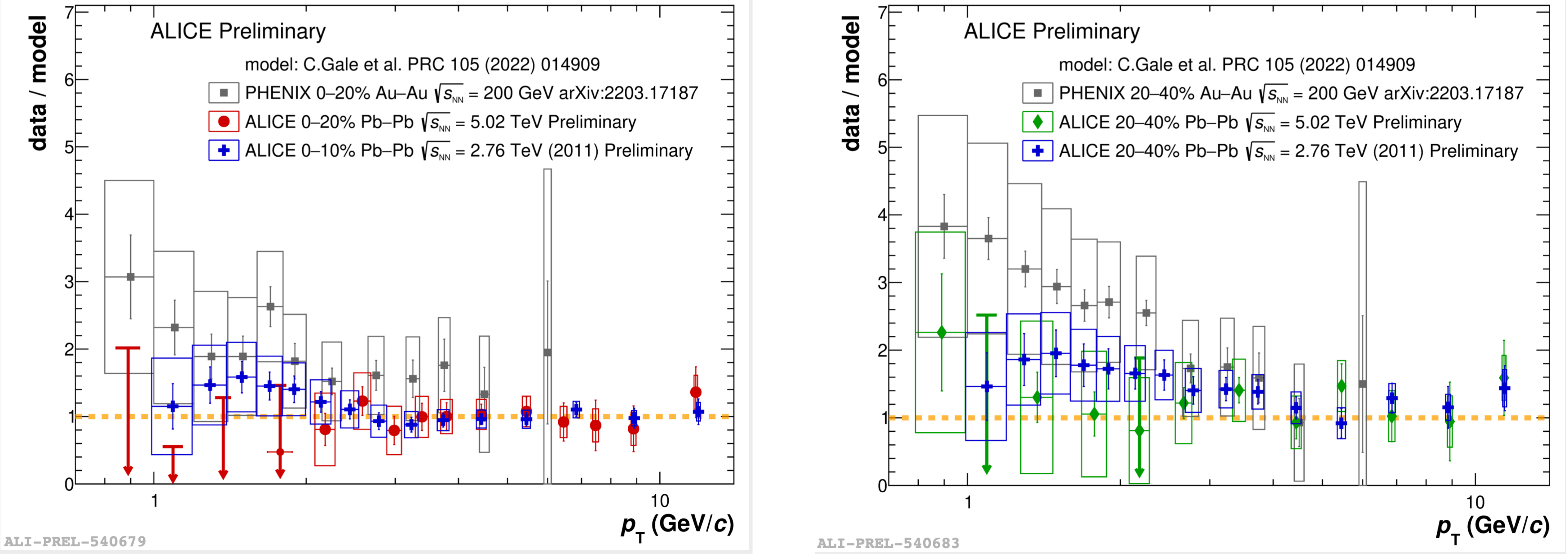
Expect more precise results with the full Run 2 data and Run 3

R. Bailhache, talk 44

Direct photon puzzle in yields?

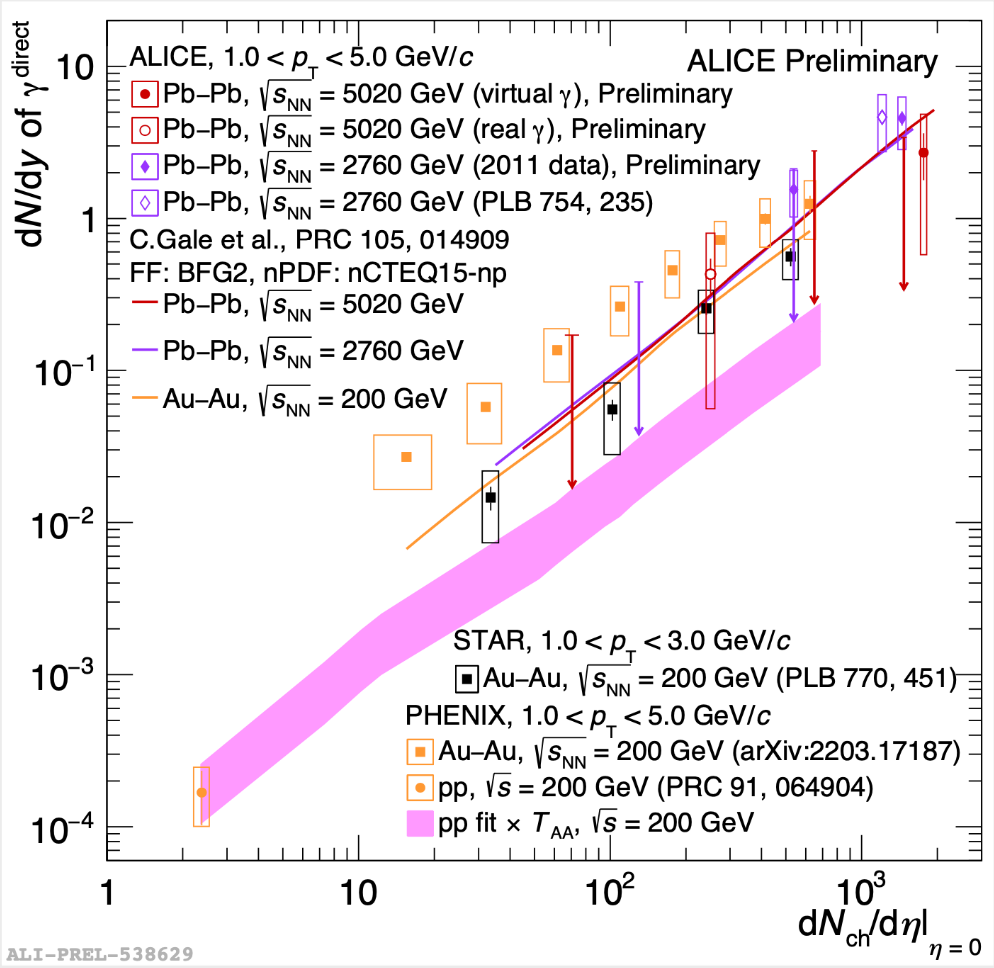
NEW

Ratio between direct photon production and their respective state-of the-art model calculation



Good agreement between ALICE data and model predictions
Slight tension at low p_T for the PHENIX data
Future: puzzle involving direct photon flow?

Integrated direct photon yield vs dN_{ch}/dη



- Integrated direct photon yield (1 < p_T < 5 GeV/c) vs dN_{ch}/dη
- ALICE data points follow similar trend as observed in PHENIX and STAR experiments and as predicted by hydro model

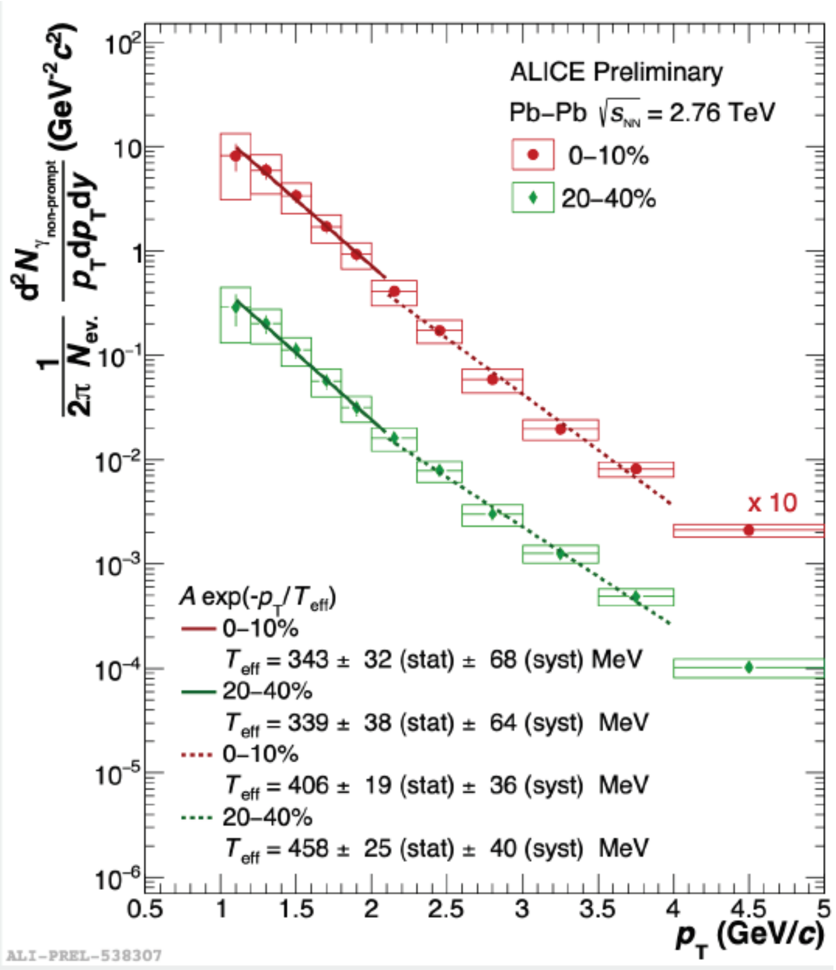
Universal power-law scaling of direct γ yield vs N_{ch} seen for different systems and collision energies

R. Bailhache, talk 44

NEW

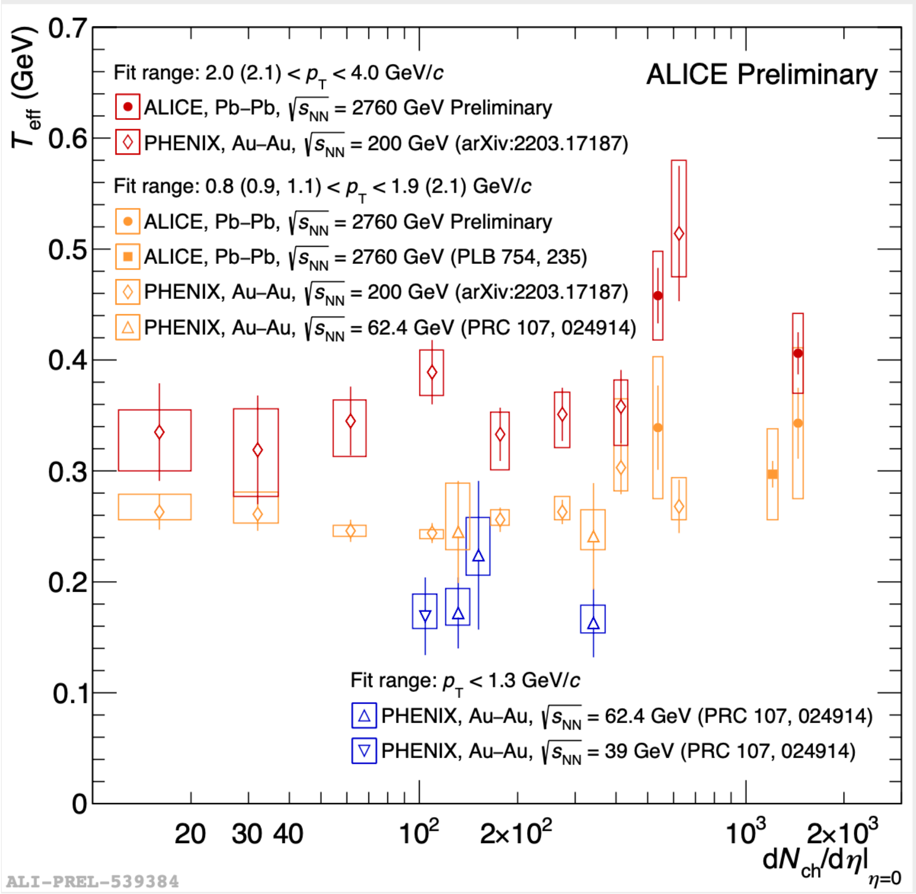
T_{eff} from non-prompt photons

Non-prompt γ = direct γ – T_{AA} . pQCD



is T_{eff} (2.1 < p_T < 4 GeV/c) > T_{eff} (1.1 < p_T < 2.1 GeV/c) ?

pre-equilibrium photons? earlier time emission?



Bose-Einstein $\gamma\gamma$ correlations in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

HBT interferometry (two-particle correlations)

Space – time dimensions of emitting source

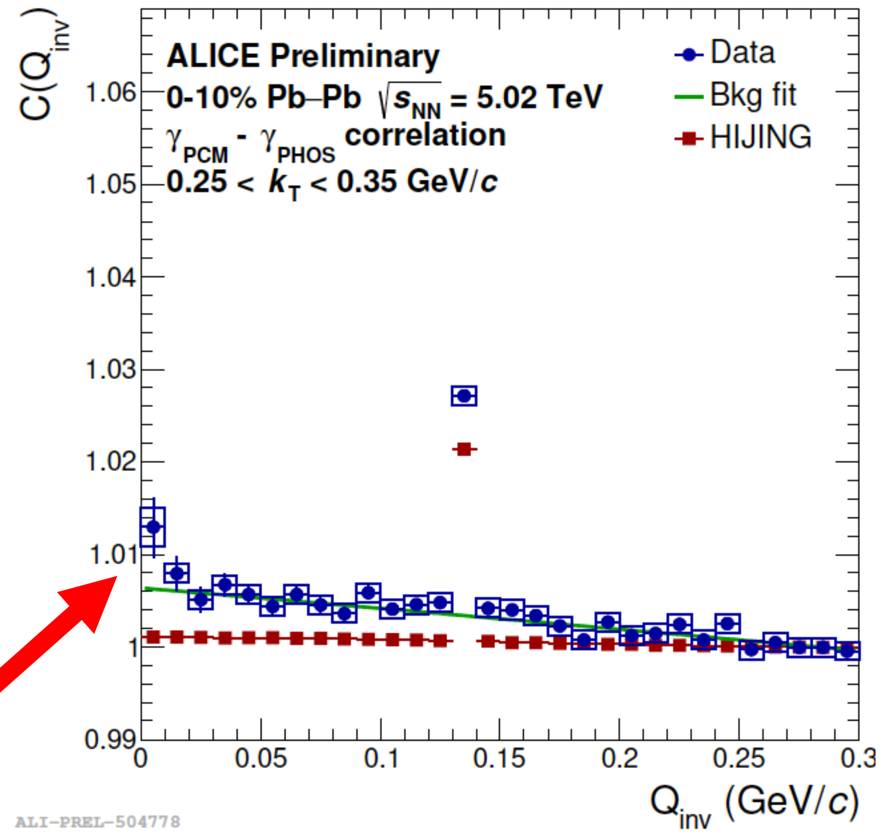
$\gamma\gamma$-HBT → source size, direct photon fraction

Correlation function:

γ_{PHOS} - γ_{PCM}

$C(Q_{inv}) = A(Q_{inv})/B(Q_{inv})$

Bins of k_T (average pair momentum) and centrality



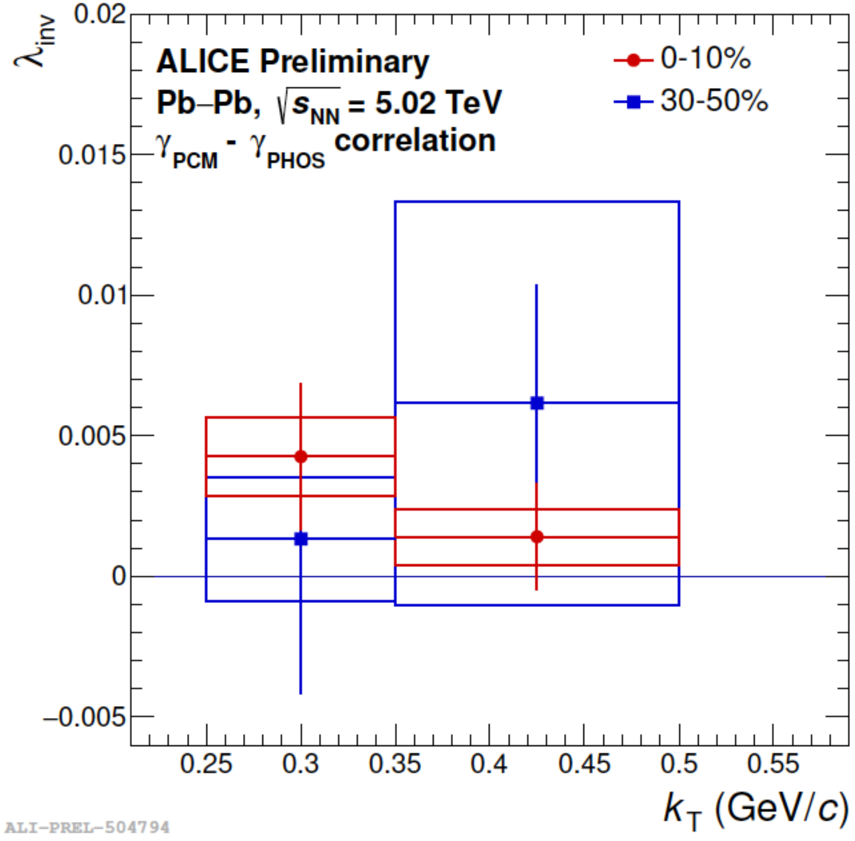
Small hint of a HBT-like effect at lower Q_{inv}

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

Bose-Einstein $\gamma\gamma$ correlations in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE

Sensitive to the source size and to the direct photon fraction



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

$\lambda_{\rm inv}$ not significantly different from zero

$$r_\gamma = \frac{N_{\rm dir}}{N_{\rm inc}} = \sqrt{2\lambda}$$

WA98, PRL 93,022301 (2004)

Ongoing: Measurements performed in the LCMS

Summary

- Direct photon production in Pb-Pb collisions with improved X/X_0 uncertainties
  - at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV
    - Significant excess for $p_{\mathrm{T}} > 1$ GeV/c
    - T_{eff} as function of dN_{ch}/dη extracted in two p_{T} ranges. Consistent values at similar dN_{ch}/dη

  - at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV
    - Significant excess of prompt photons at $p_{\mathrm{T}} > 3$ GeV/c
    - R_γ at lower p_{T} consistent with unity

Integrated direct γ yields follow power law scaling with dN_{ch}/dη

Model calculations consistent with the data, no yet possible to discriminate

- Photon HBT provides a complementary method to obtain R_γ, and possibly the source size

- Stay tuned for results with full Run 2 statistics and Run 3 data

Thank you

Backup slides

Data-driven precision determination of the material budget in ALICE

arxiv: 2303.15317

$$\omega_i = \frac{P_i^{\rm RD} \times \varepsilon_{\gamma,i}^{\rm RD} \times \varepsilon_{\gamma,\rm gas}^{\rm MC}}{P_i^{\rm MC} \times \varepsilon_{\gamma,i}^{\rm MC} \times \varepsilon_{\gamma,\rm gas}^{\rm RD}},$$

$$\Omega_i = \frac{P_i^{\rm RD} \times \varepsilon_{\gamma,i}^{\rm RD} \times \varepsilon_{\rm track}^{\rm MC}}{P_i^{\rm MC} \times \varepsilon_{\gamma,i}^{\rm MC} \times \varepsilon_{\rm track}^{\rm RD}}.$$

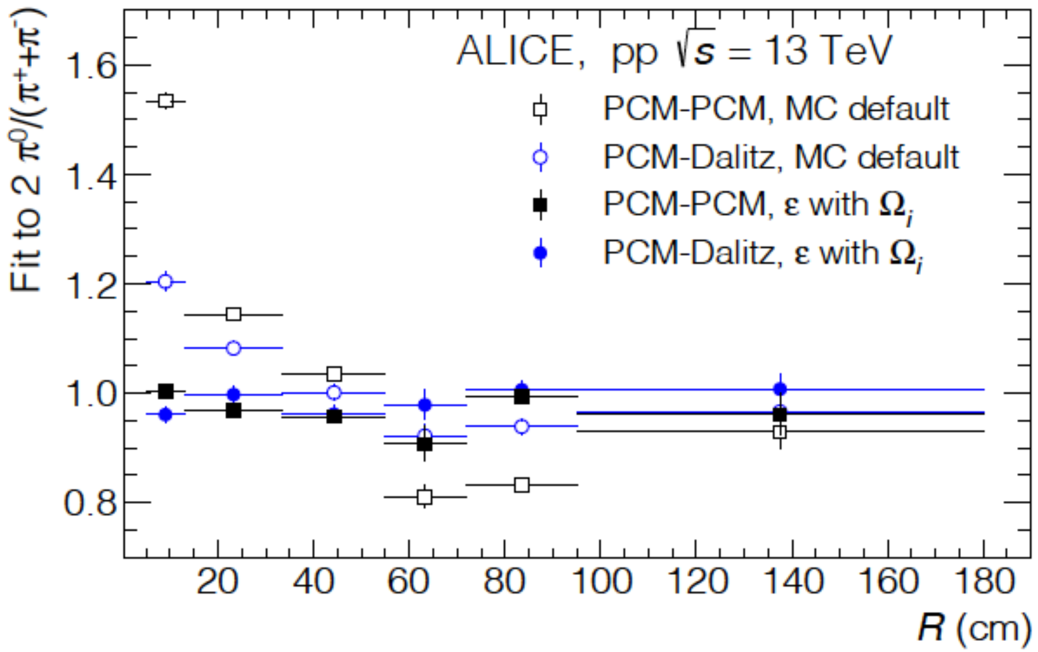
$$\frac{\Omega_i}{\omega_i} = \frac{\varepsilon_{\gamma,\rm gas}^{\rm RD} \times \varepsilon_{\rm track}^{\rm MC}}{\varepsilon_{\gamma,\rm gas}^{\rm MC} \times \varepsilon_{\rm track}^{\rm RD}}$$

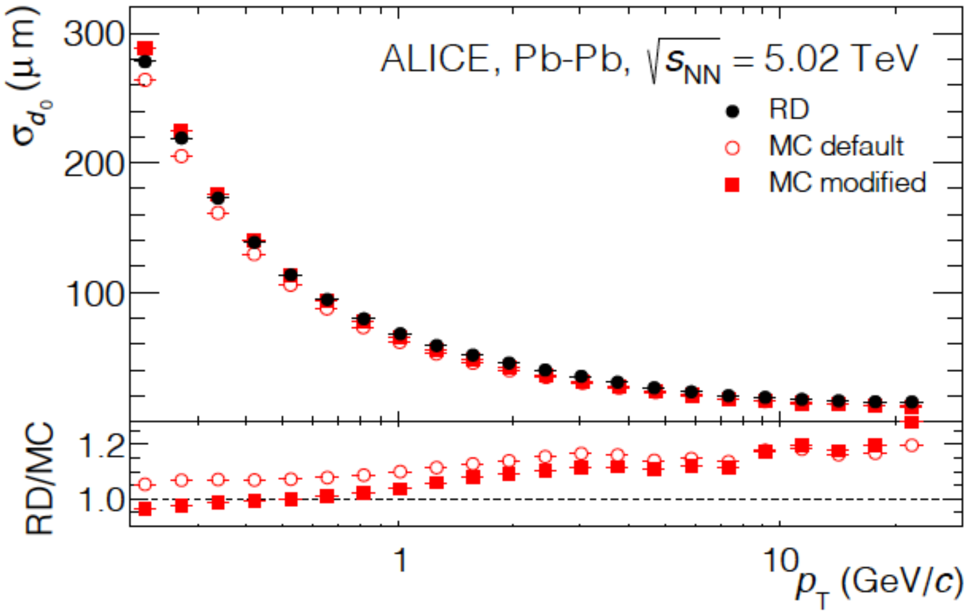
	Ω_i		ω_i	
	5 cm $< R <$ 8.5 cm	95 cm $< R <$ 145 cm	8.5 cm $< R <$ 13 cm	72 cm $< R <$ 95 cm
V^0 finder	2.74 %	2.9%	2.2%	1.83%
Generator	0.16%	2.9%	3.2 %	0.62 %
$p_{\rm T,min}$	Negligible	Negligible	Negligible	Negligible
$\sigma_{\rm sys}$	2.74%	4.1%	3.8%	1.93%

R interval	R range (cm)	Ω_i	$\sigma_{\rm stat}$ %	$\sigma_{\rm sys}$ %	$\sigma_{\rm total}$ %
0	0–1.5	0.9859	1.2	-	-
1	1.5–5	1.177	0.42	-	-
2	5–8.5	1.240	0.36	2.7	2.8
3	8.5–13	1.238	0.42	0.77	0.9
4	13–21	1.067	0.34	2.0	2.1
5	21–33.5	1.081	0.25	1.7	1.7
6	33.5–41	1.039	0.35	3.1	3.1
7	41–55	1.001	0.30	1.5	1.5
8	55–72	0.926	0.35	3.7	3.7
9	72–95	0.943	0.19	3.7	3.7
10	95–145	0.975	0.62	4.1	4.1
11	145–180	0.932	0.89	1.4	1.6
average	5–180	1.04	0.312%	2.5%	2.5%

Data-driven precision determination of the material budget in ALICE

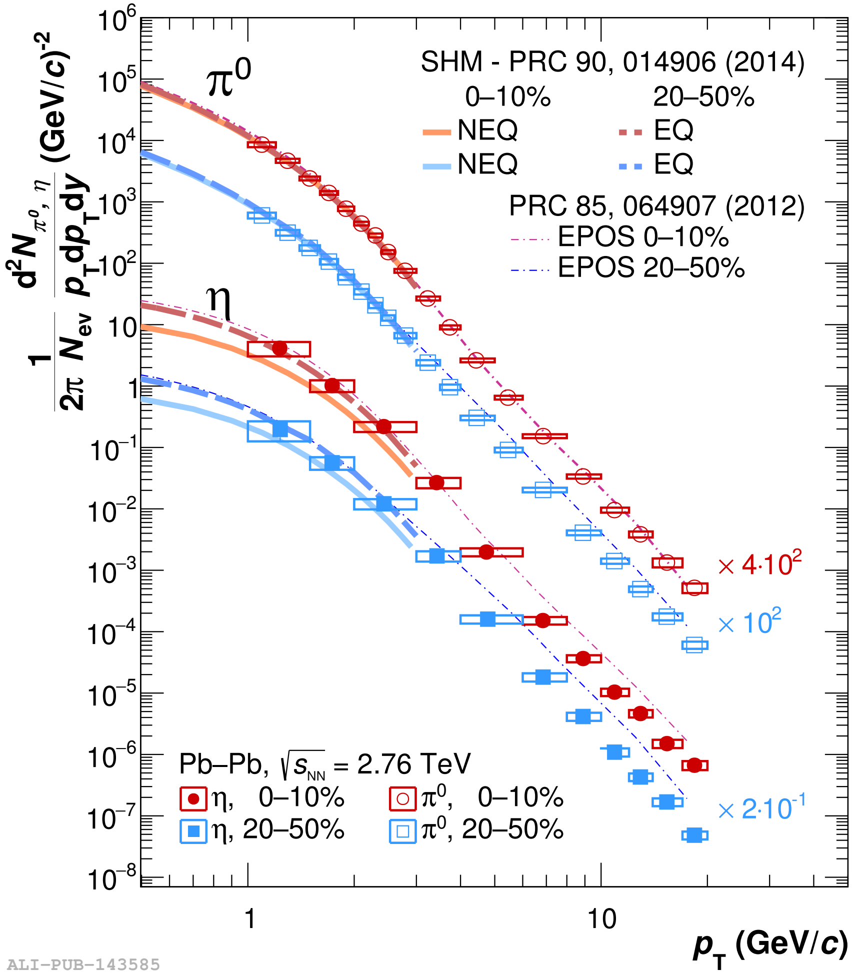
arxiv: 2303.15317

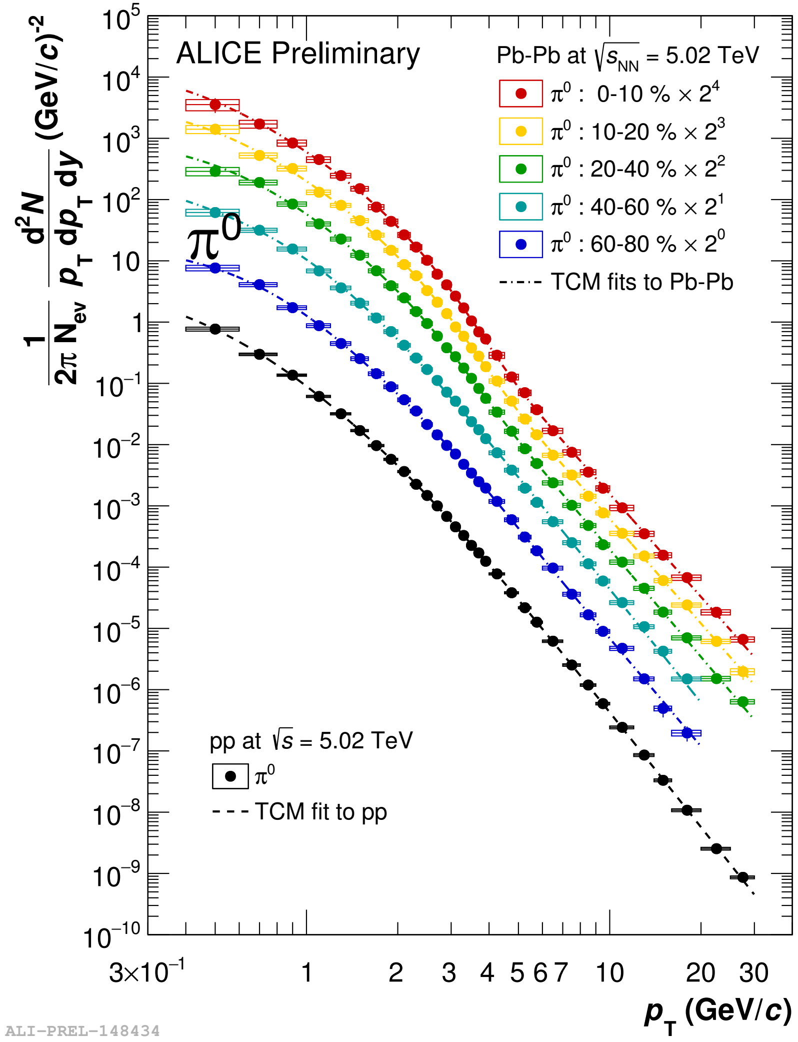




π^0,η: Pb-Pb at $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

EPJ C 74 (2014); PRC98, 044901 (2018)





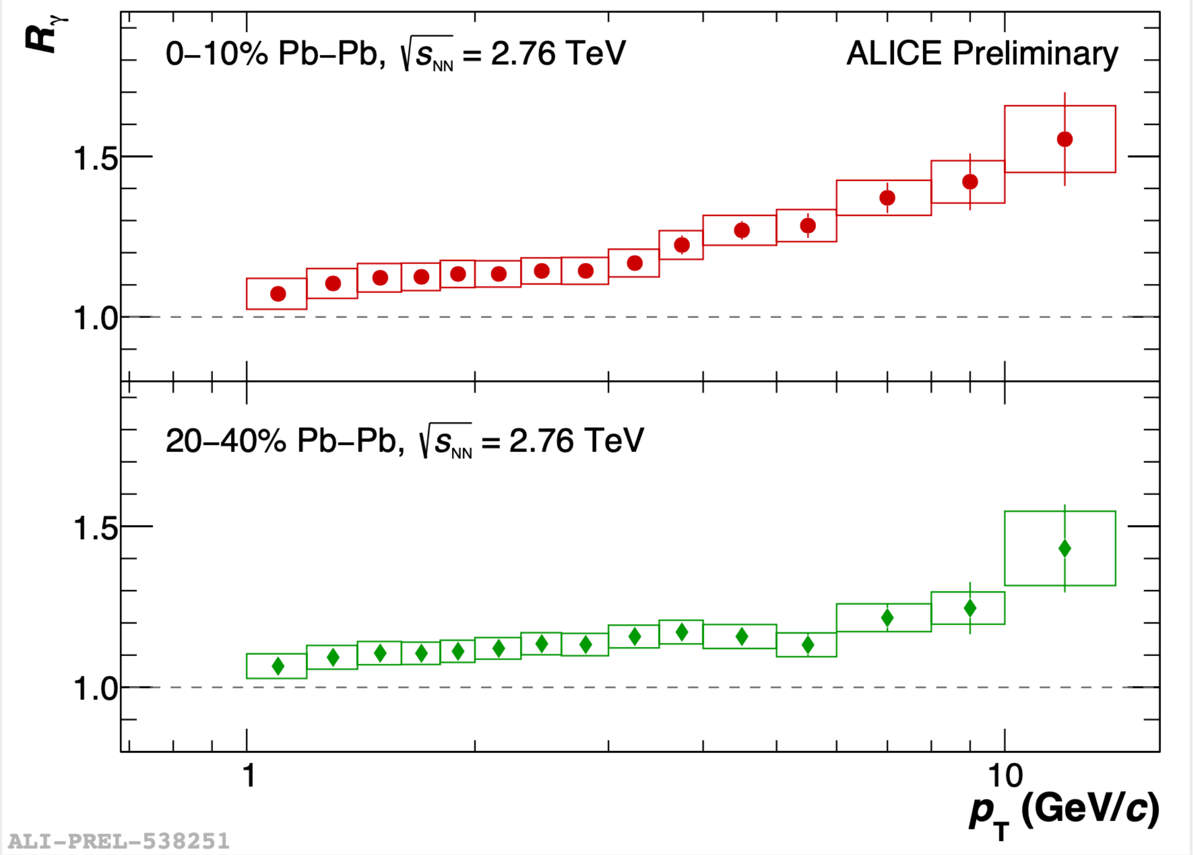
First η measurement in Pb-Pb at the LHC

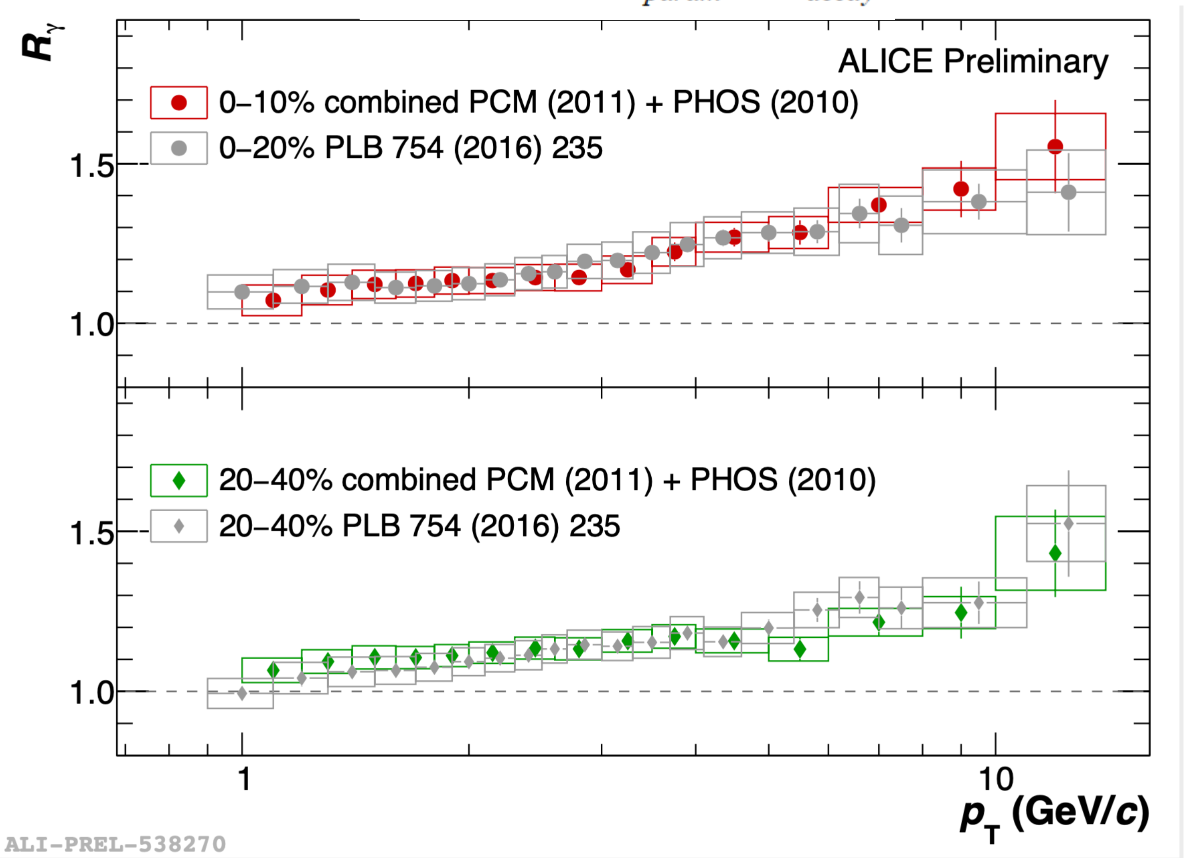
NEW

Direct photon R_γ in Pb – Pb $\sqrt{s_{NN}}$ = 2.76 TeV

Combination of PCM (2011) with Ω_i + PHOS (2010)

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





Significant excess for p_T > 1 GeV/c

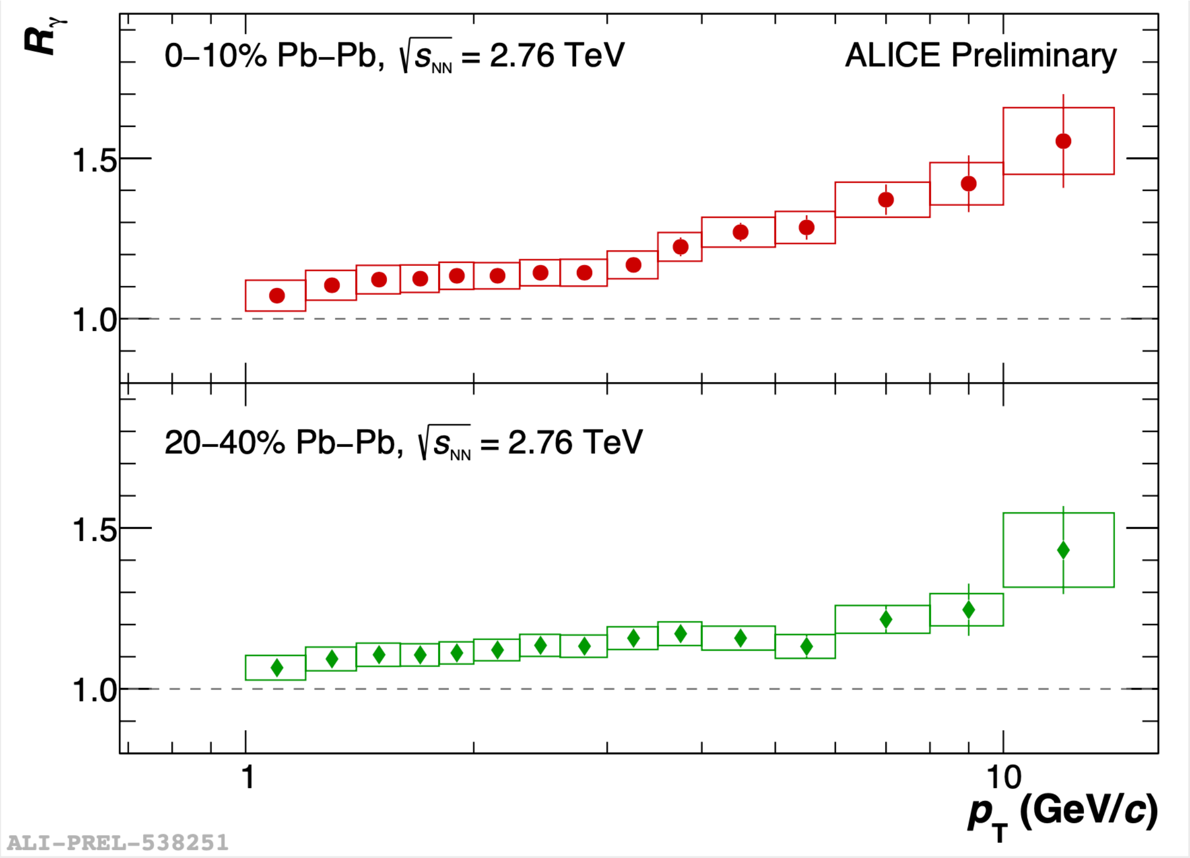
Low p_T : thermal radiation
High p_T : prompt photons

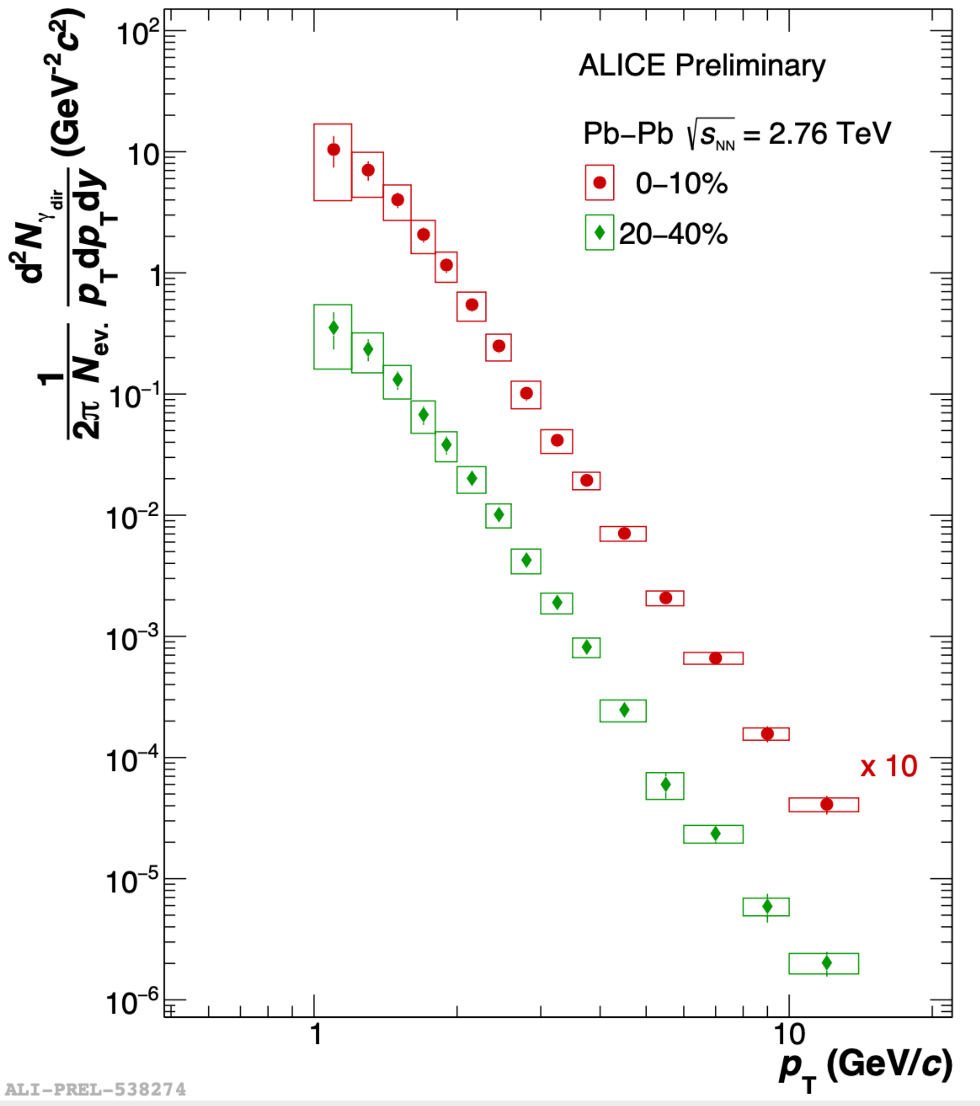
In agreement with published results
New centrality available: 0-10%
Smaller uncertainties

NEW

Direct photon R_γ in Pb – Pb $\sqrt{s_{NN}}$ = 2.76 TeV

Combination of PCM(2011) with Ω_i +PHOS(2010)

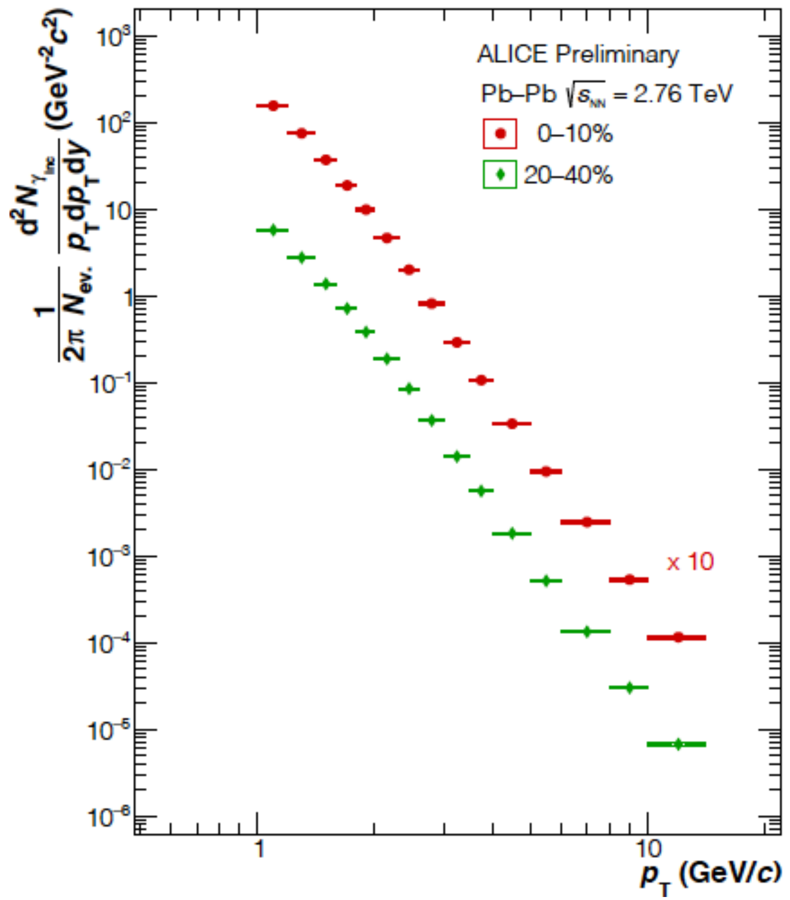


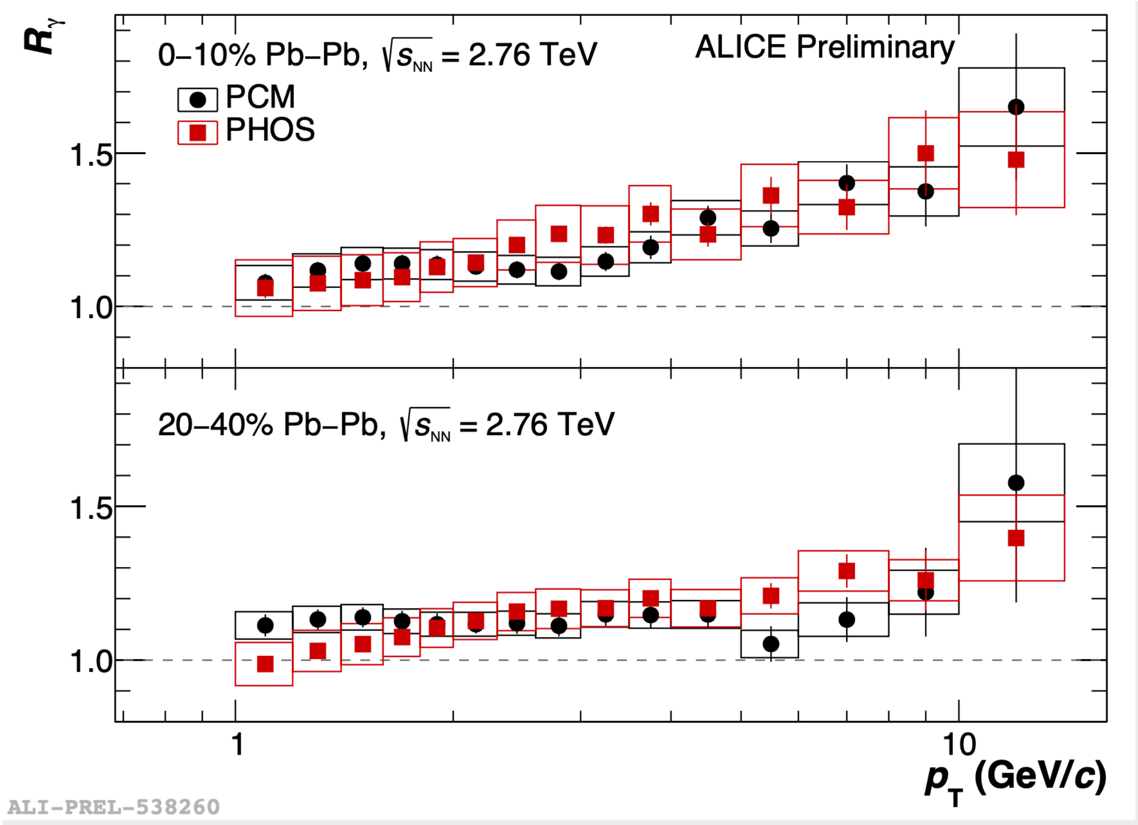


Significant excess for p_T > 1 GeV/c

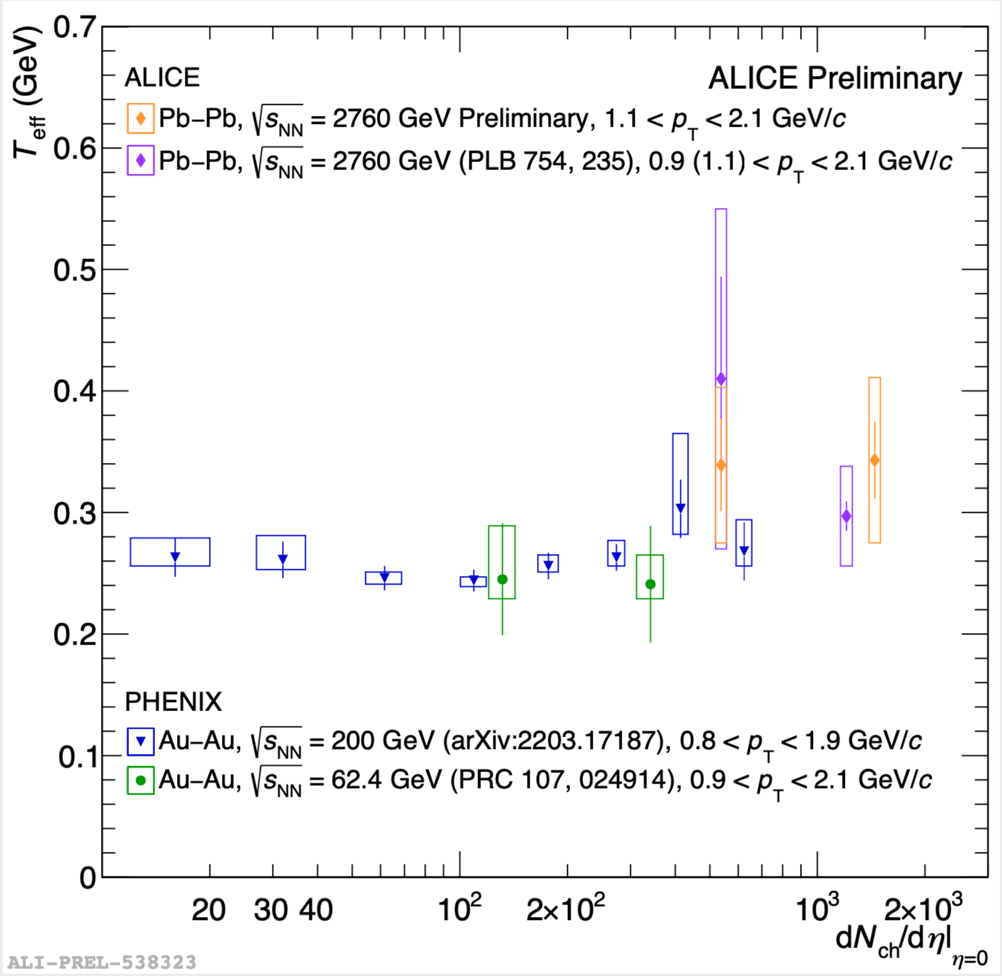
Low p_T : thermal radiation
High p_T : prompt photons

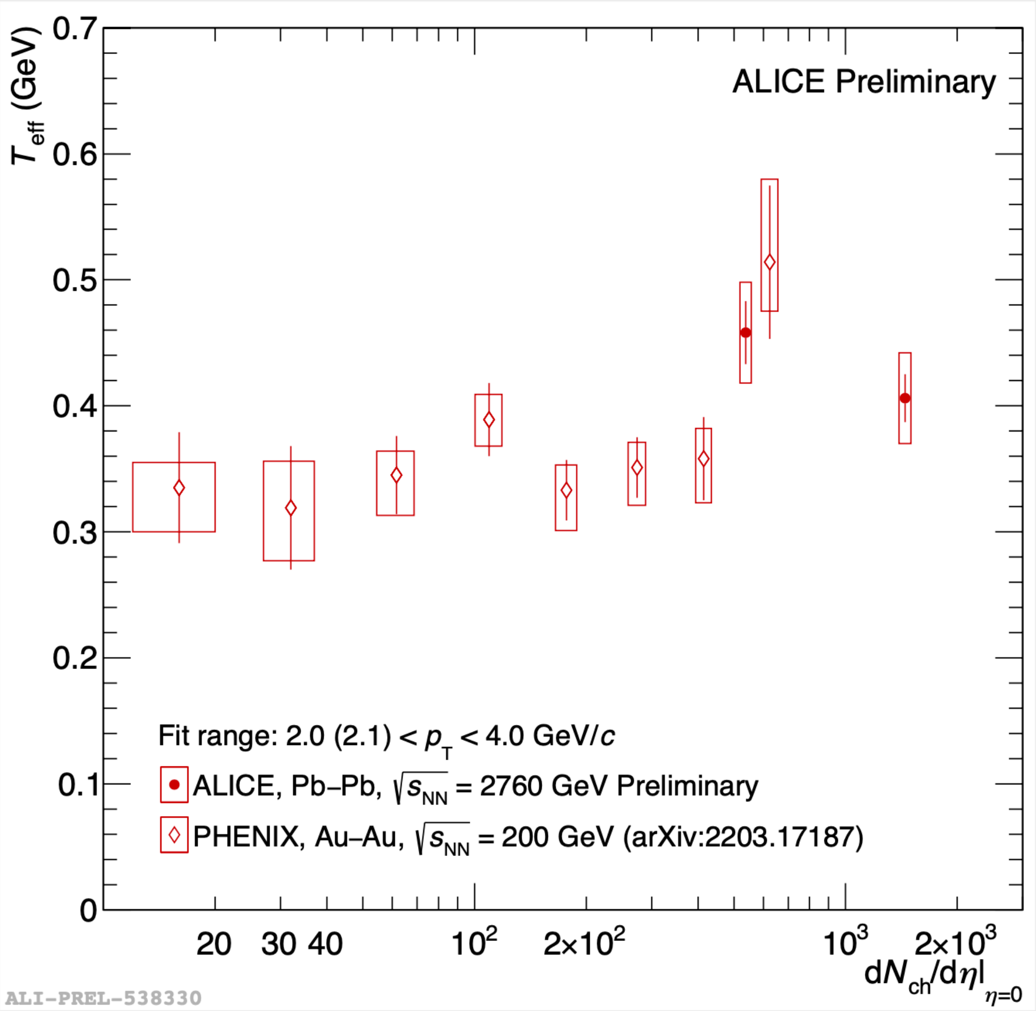
Inclusive γ and R_γ in Pb-Pb 2.76 TeV



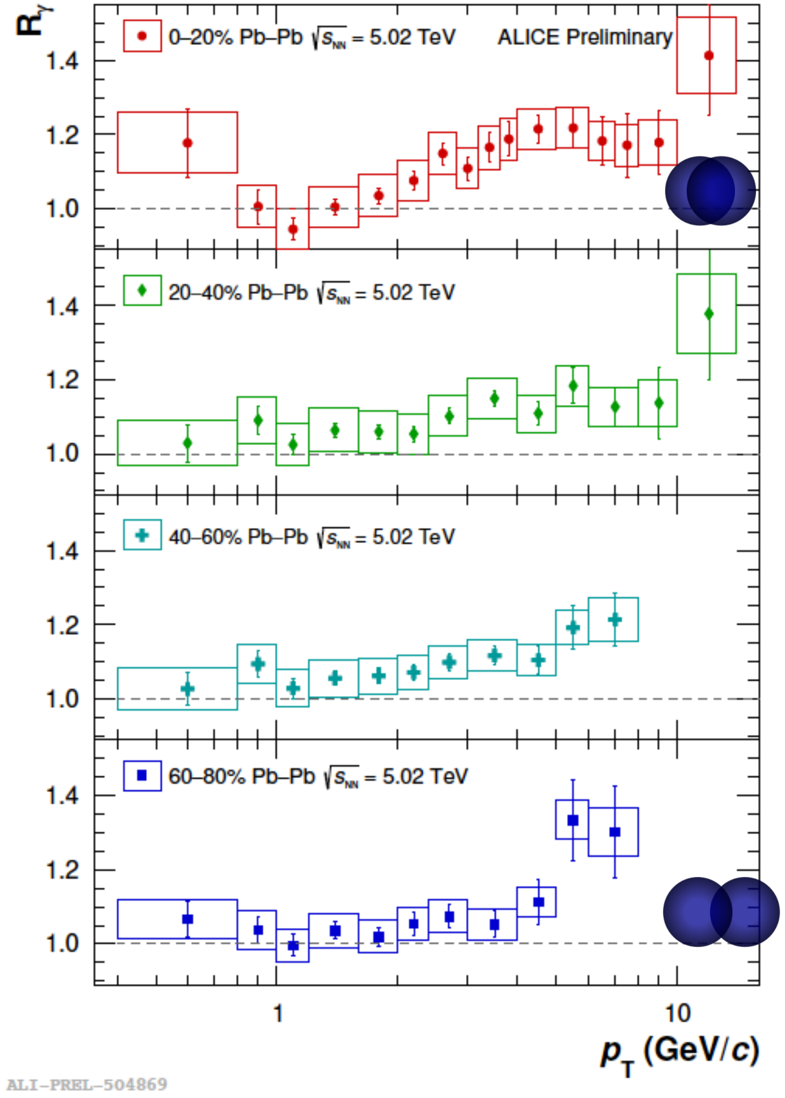


T_{eff} from non-prompt photons





Direct photon R_γ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



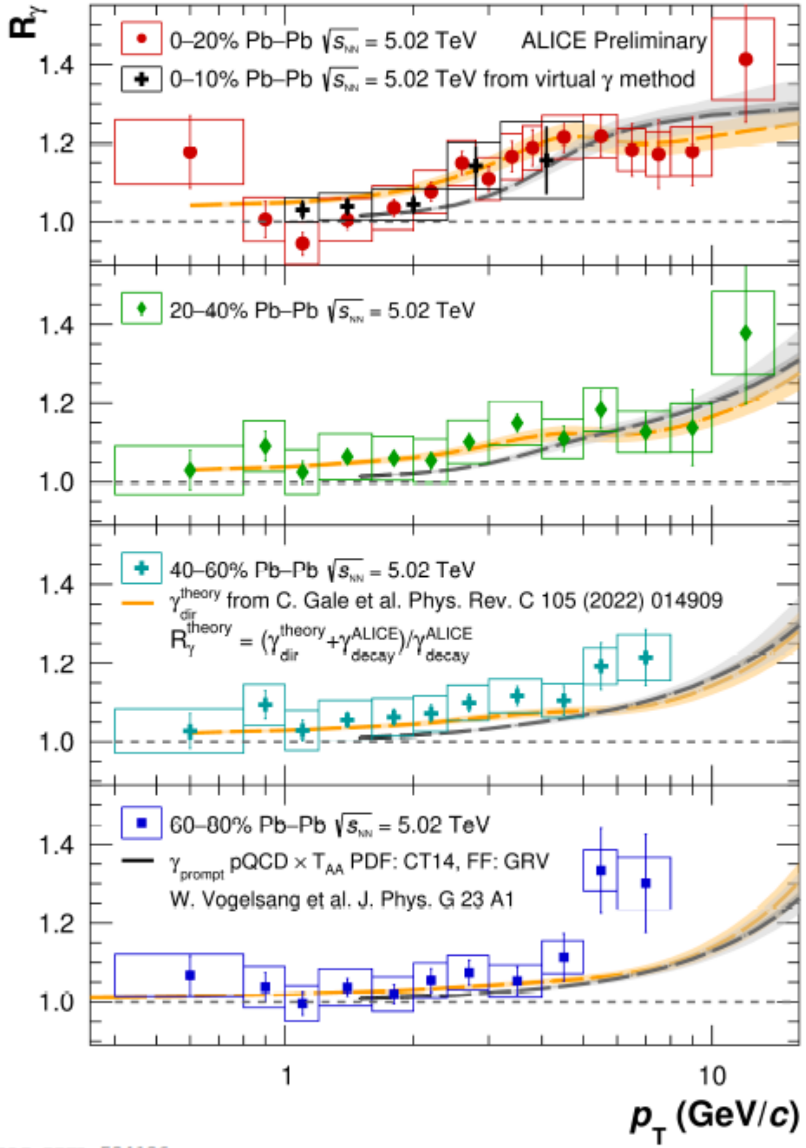
At low p_T :

R_γ is close to 1 → small thermal contribution

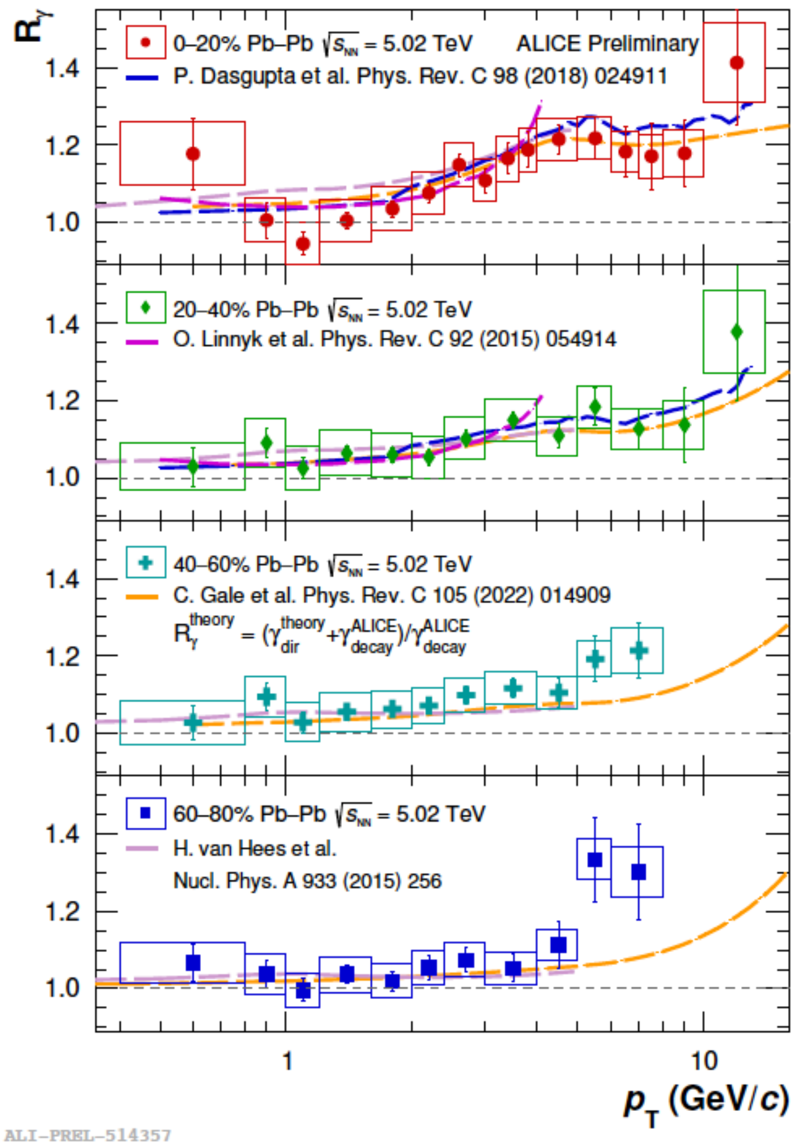
For p_T > 2-3 GeV/c:

- Excess which can be attributed to pre-equilibrium and prompt (hard scattering) photons

QGP thermal emission: Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

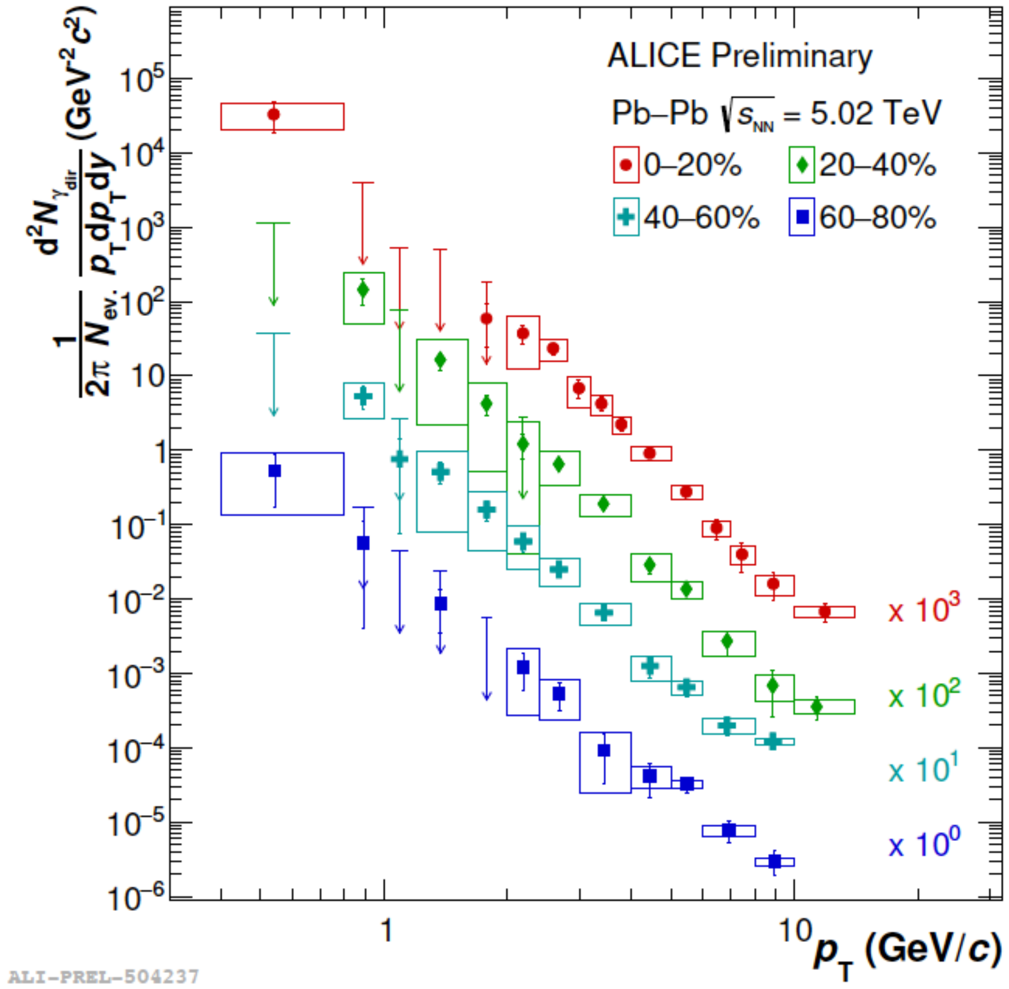


ALI-PREL-524126



ALI-PREL-514357

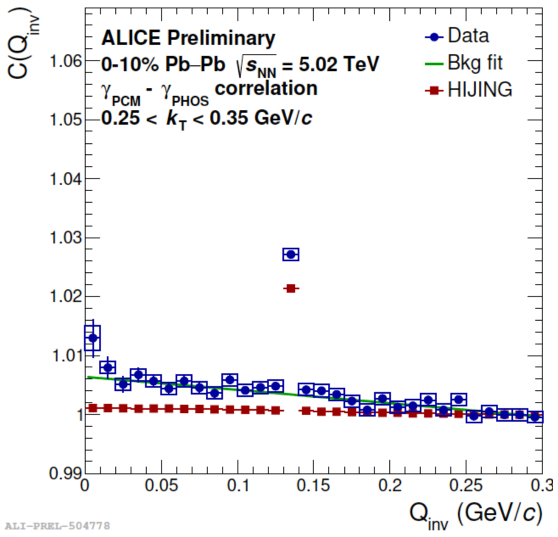
Direct photon spectra in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

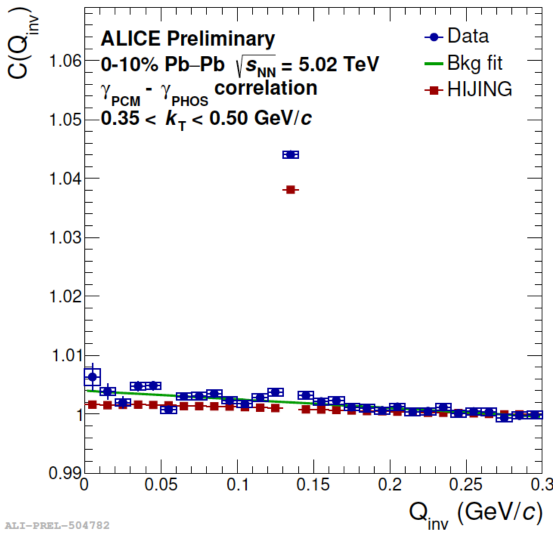


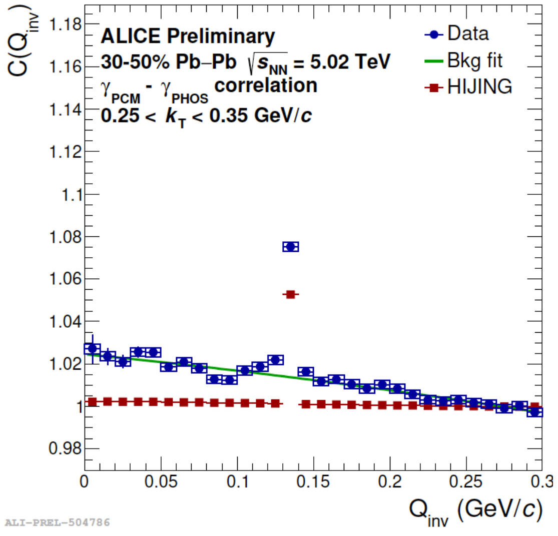
$$N_{\gamma,\mathrm{dir}} = N_{\gamma,\mathrm{inc}} - N_{\gamma,\mathrm{dec}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot N_{\gamma,\mathrm{inc}}$$

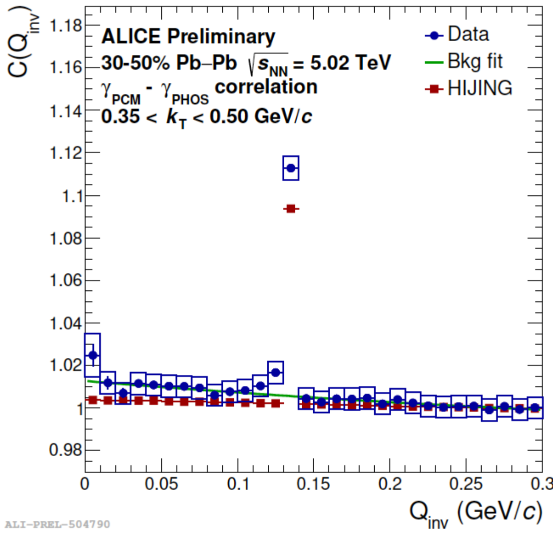
Upper limits (90% CL) given where γ_{dir} consistent with 0

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

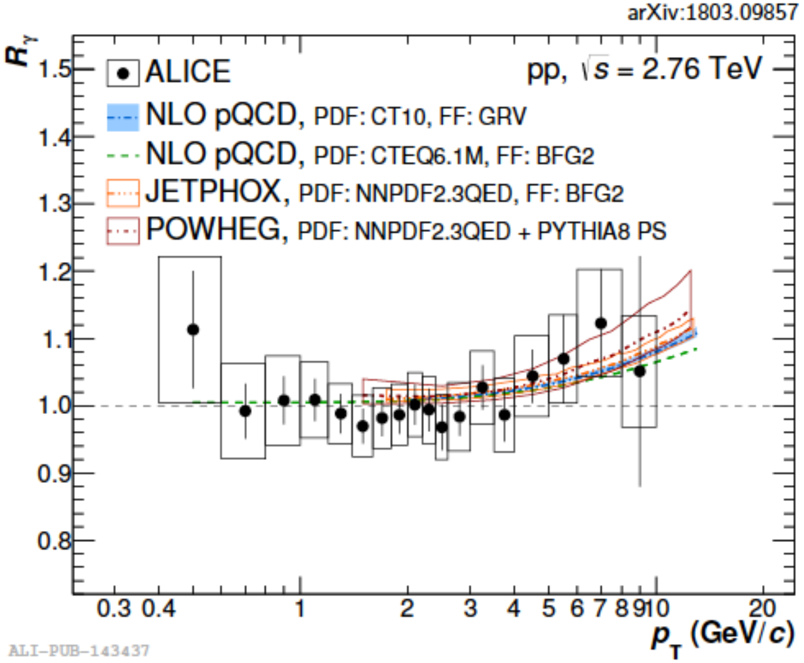


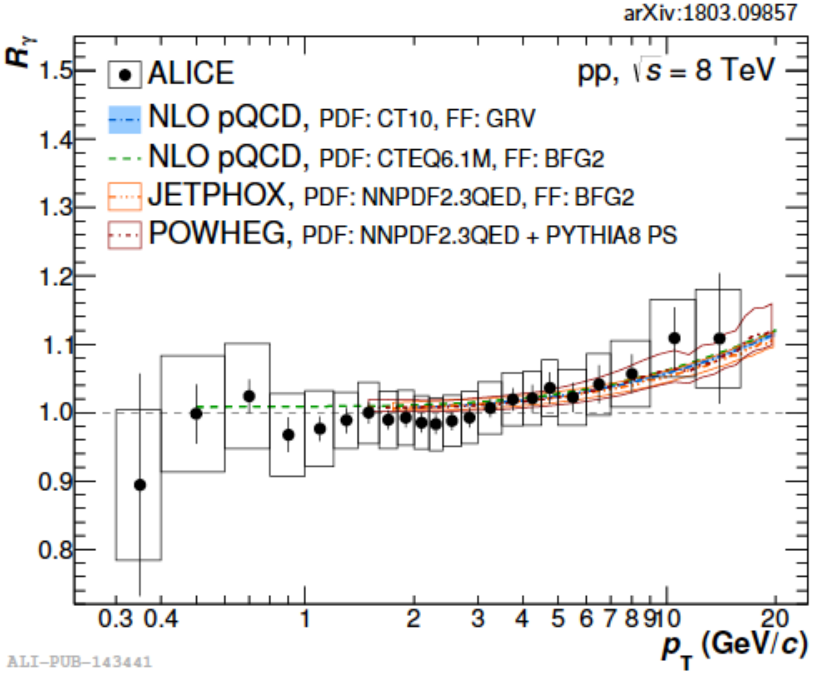






Direct γ in pp collisions



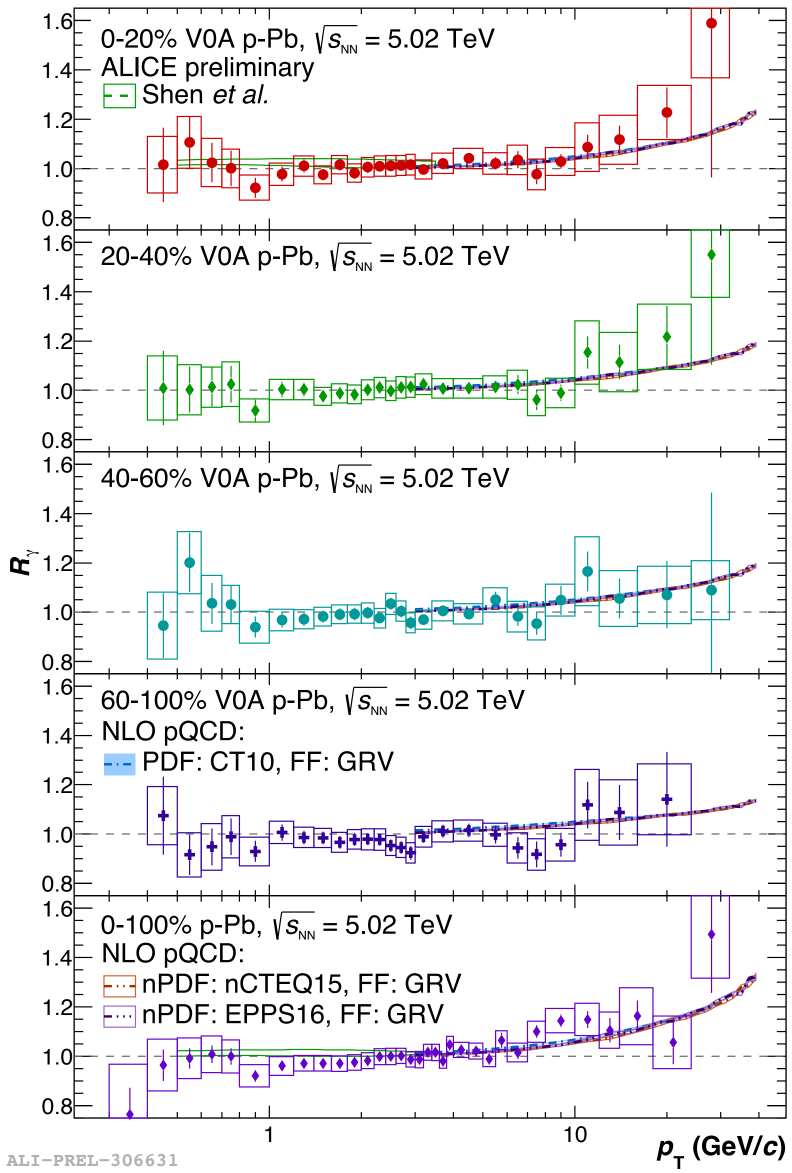


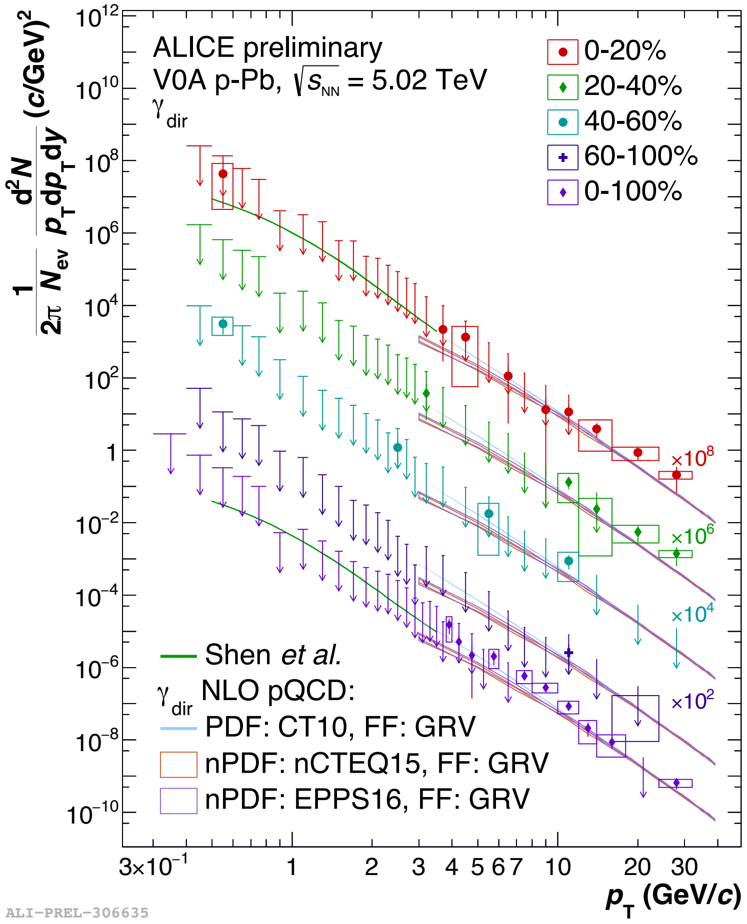
Combination of several reconstruction techniques via BLUE method.
Theoretical NLO pQCD prediction plotted as

$$R_\gamma^{pQCD} = 1 + N_{coll} \frac{\gamma_{pQCD}}{\gamma_{decay}}$$

No significant excess observed at low p_T.
About 1 − 2σ deviation from unity for pT > 7 GeV/c

Direct γ in pPb collisions





No significant excess observed at low p_T.
Accuracy is not yet sufficient to confirm/exclude thermal radiation in p-Pb collisions

Run 2 larger statistics. Explore 0-1%