Direct photon production results from ALICE in pp, p-Pb, and Pb-Pb collisions

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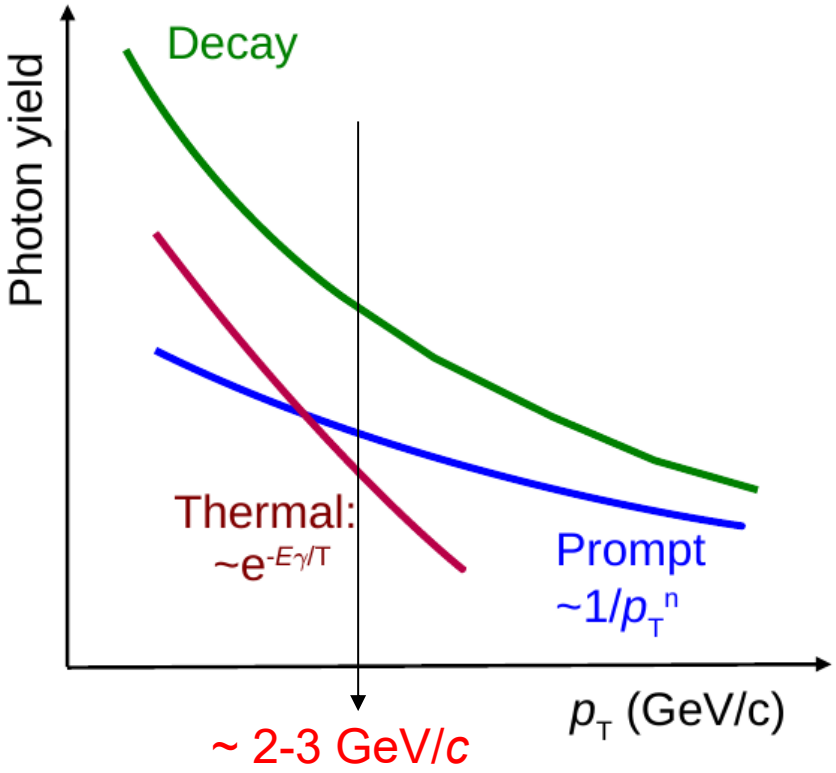
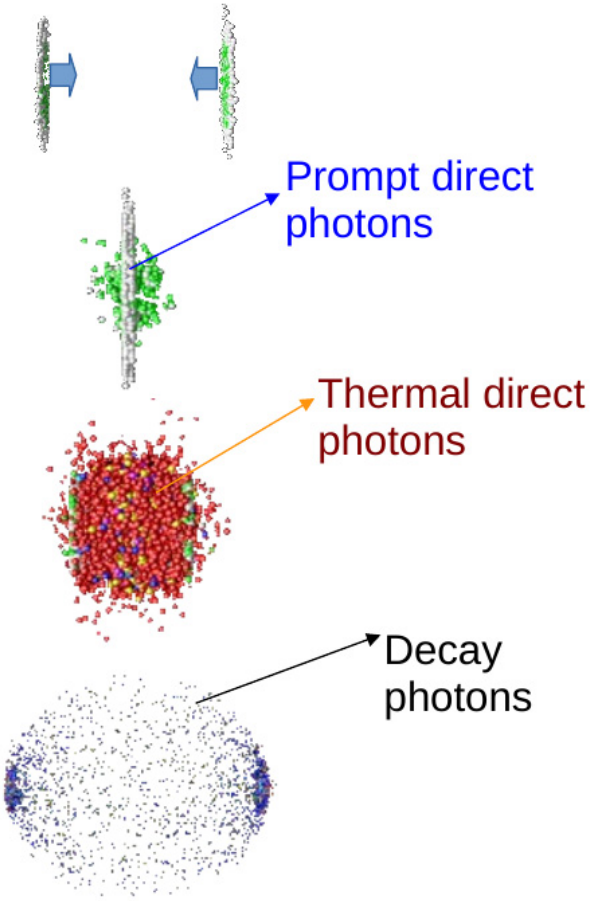
Direct photons – a probe to study QGP

- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
- Photons are produced at different collision times
- Photons don't interact strongly and carry out information about collision, even the earliest stage

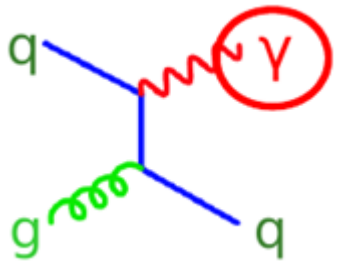


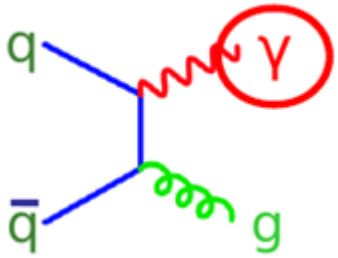


- High p_T: test of initial conditions:
  - N_{coll} scaling
  - PDF modification
- Low p_T: test of hot matter evolution:
  - spectrum
  - collective flow

Direct photons – motivation to measure in pp and pA collisions

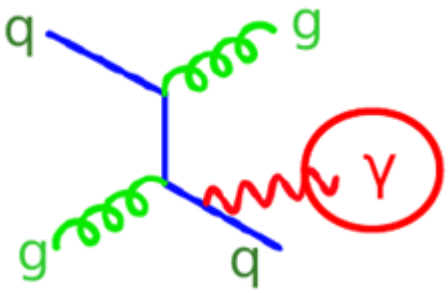
Direct photons – a test of QCD in pp collisions

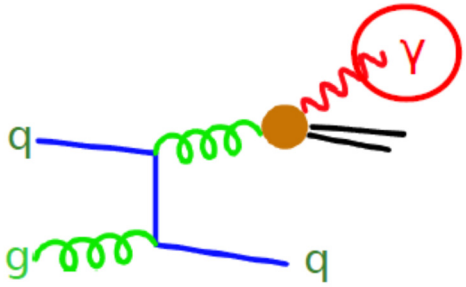




$$\frac{d\sigma^{\gamma,\mathrm{dir}}}{dp_{\mathrm{T}}d\eta} = F_{i/h} \otimes \sigma_{ij} \otimes D_{\gamma/k}$$

$F_{i/h}$ – nucleon structure function
σ_{ij} – cross-section of the elementary process
$D_{\gamma/k}$ – fragmentation function

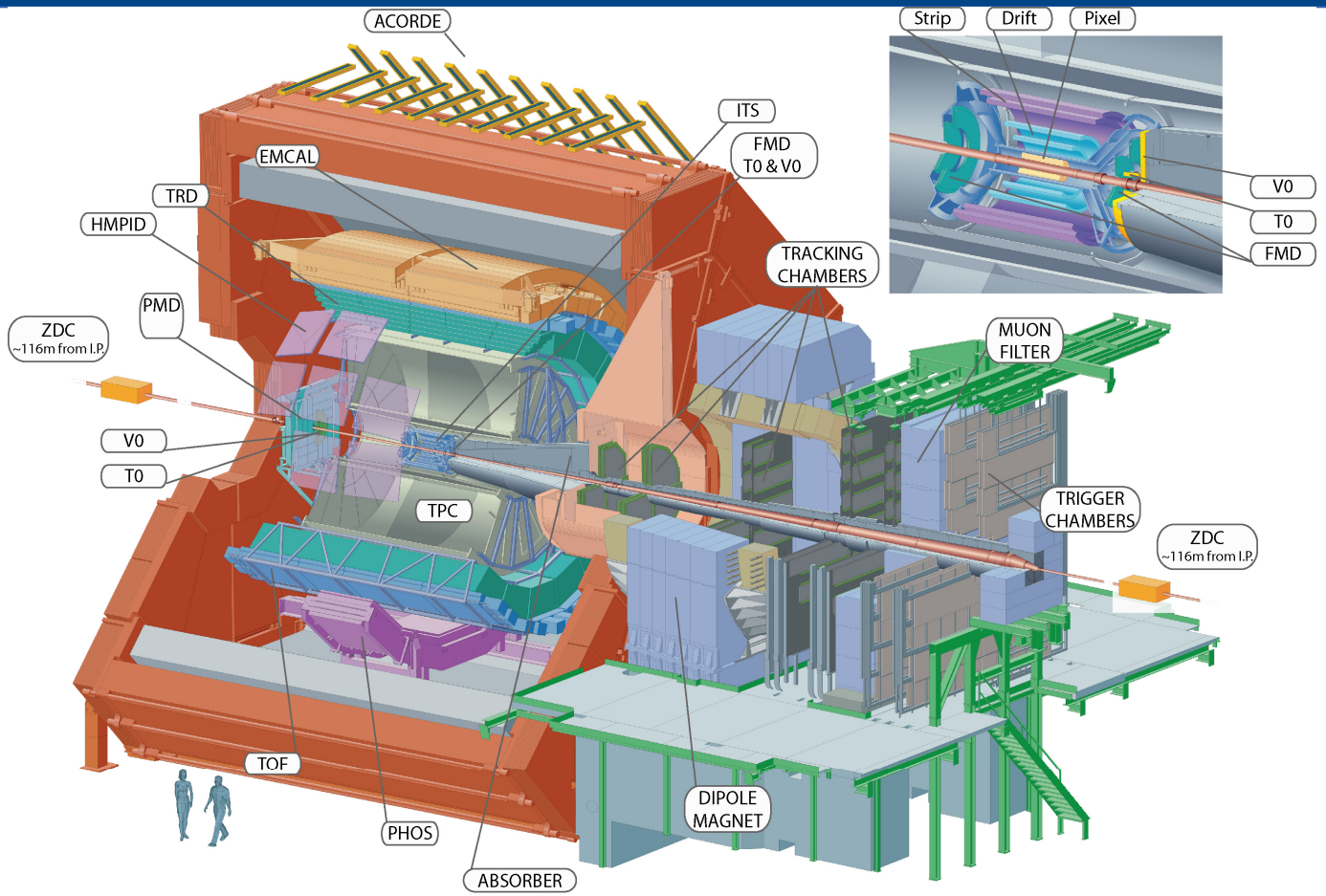




Main sources of prompt direct photons: Compton scattering, annihilation, bremsstrahlung, gluon fragmentation

Test of modification in pA collisions due to cold nuclear matter effects

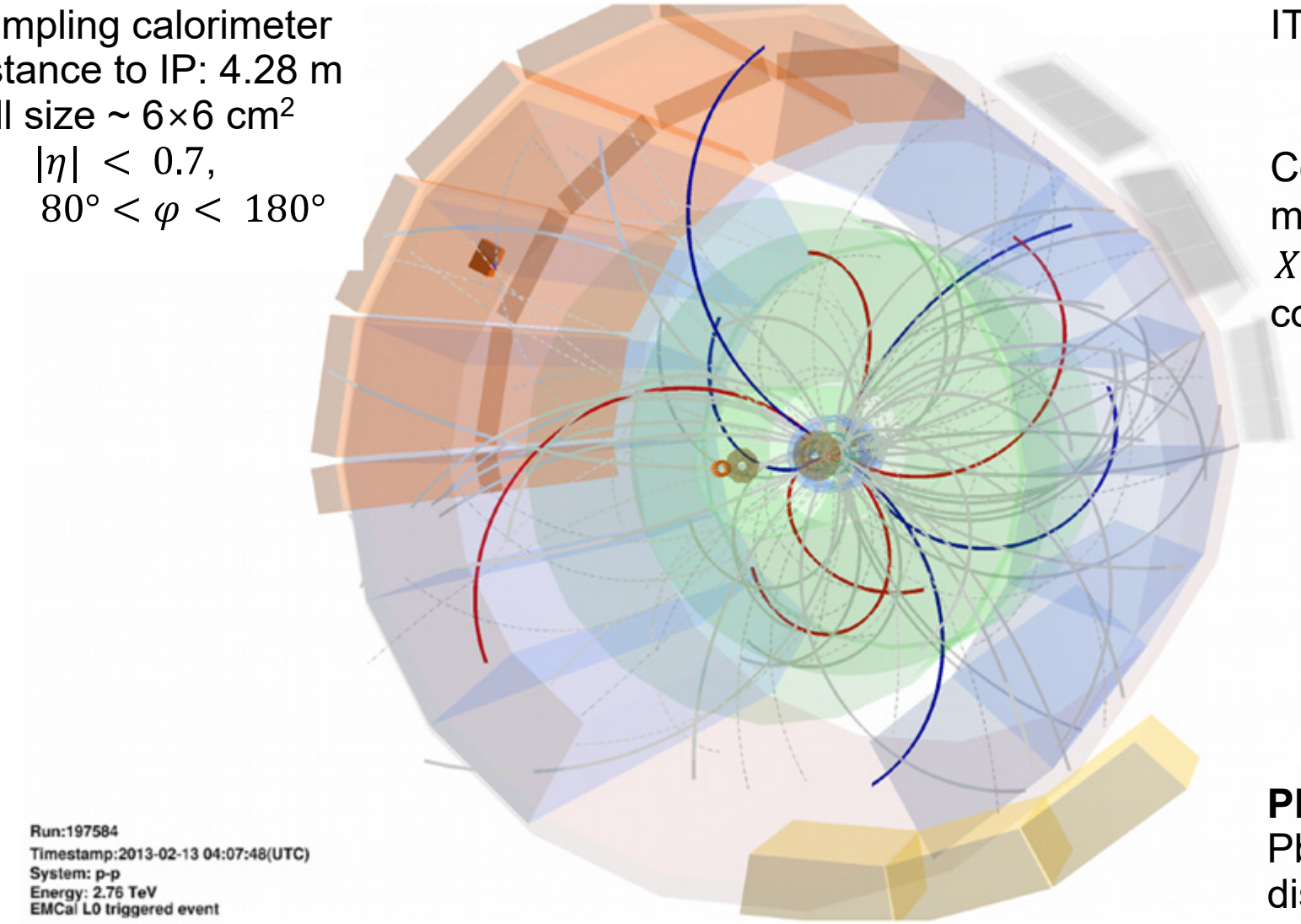
The ALICE experiment at the LHC



- ALICE is dedicated to study the Quark-Gluon Plasma (QGP)
- Good tracking and PID capabilities are coupled with electromagnetic-probe measurements with the help of EMCal, PHOS detectors, and Photon Conversion method (PCM) using ALICE tracking system
- Measurements in all colliding systems provided by the LHC: Pb-Pb ($\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV), Xe-Xe ($\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV), p-Pb ($\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV) and pp ($\sqrt{s} =$ 0.9, 2.76, 5.02, 7, 8 and 13 TeV)

ALICE detector setup from 2011-2013

EMCal calorimeter
Pb/scintillator
Sampling calorimeter
distance to IP: 4.28 m
cell size ~ 6×6 cm^2
$|\eta| < 0.7$,
$80° < \varphi < 180°$



Photon conversion method (PCM)
ITS and TPC
$|\eta| < 0.9$,
$0° < \varphi < 360°$
Conversion in detector material
$X/X_0 = (11.4 \pm 0.5)\%$
conv. Probability ~ 8%

PHOS calorimeter
$PbWO_4$ crystals
distance to IP: 4.6 m
cell size 2.2×2.2 cm^2
$|\eta| < 0.12$,
$260° < \varphi < 320°$

Direct photon extraction

Subtraction method

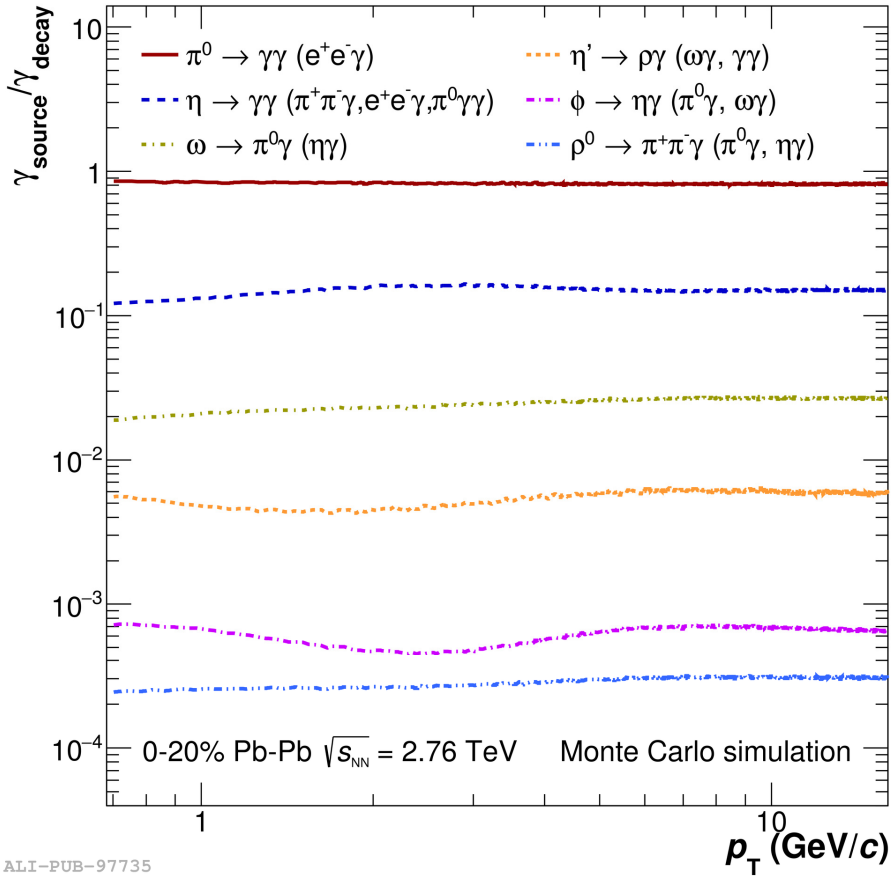
$$\gamma_{\mathrm{dir}} = \gamma_{\mathrm{inc}} - \gamma_{\mathrm{decay}} = \left(1 - \frac{\gamma_{\mathrm{decay}}}{\gamma_{\mathrm{inc}}}\right)\gamma_{\mathrm{inc}}$$
$$= \left(1 - \frac{1}{R_\gamma}\right)\gamma_{\mathrm{inc}}$$

Inclusive photons: all photons that are produced
Decay photons: calculated by decay simulation from measured or m_T scaled hadron spectra (so called cocktail)

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

Numerator: measured inclusive γ spectrum per measured π^0
Denominator: estimated sum of all decay photons per π^0

Advantage of double ratio: cancellation of some large systematic uncertainties

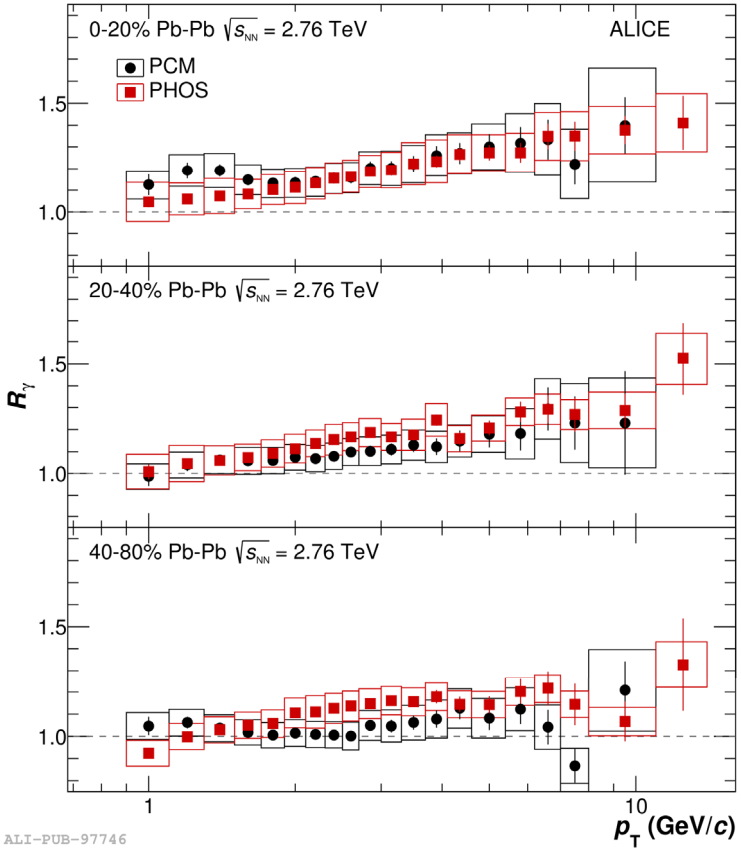


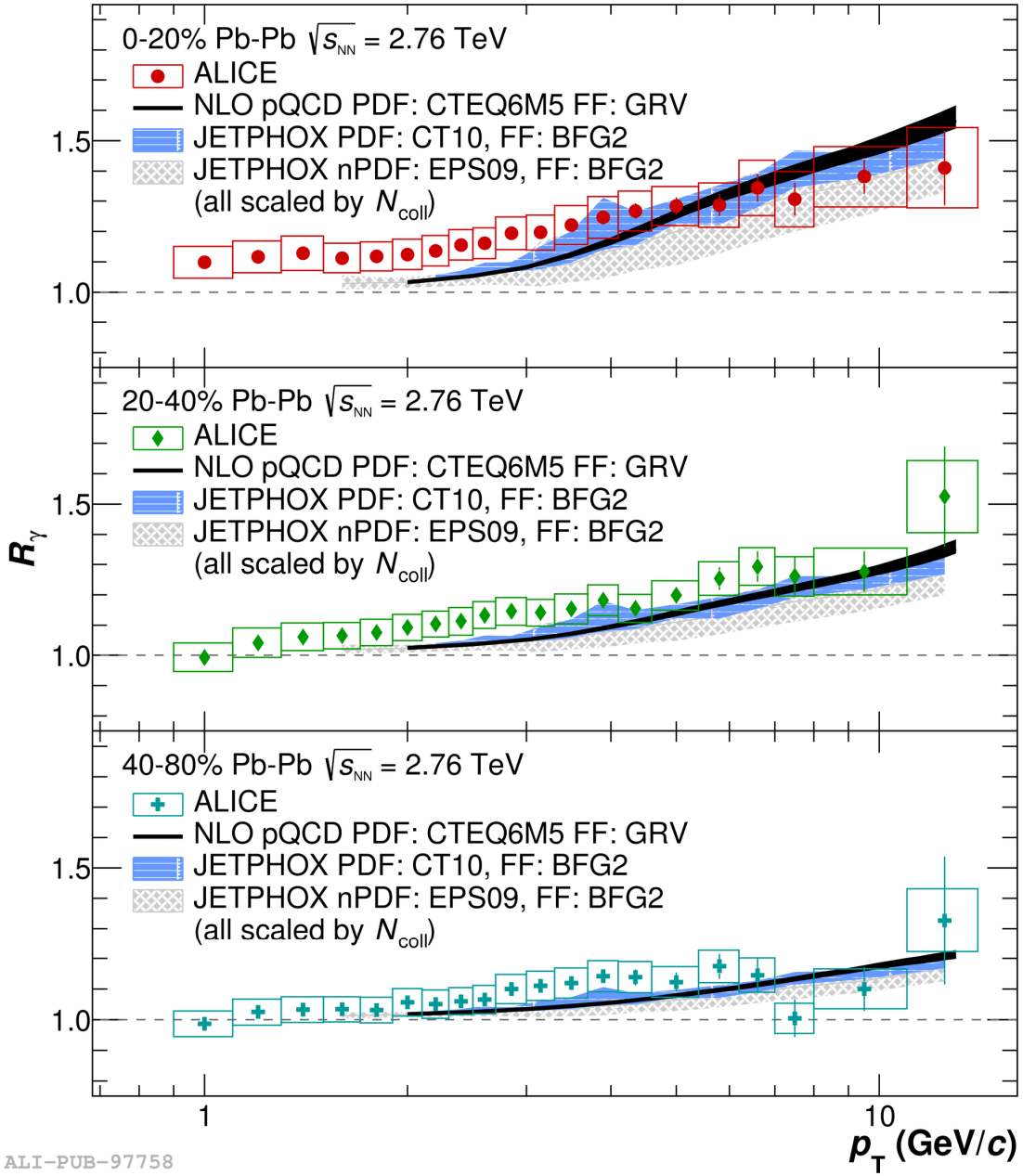
Phys. Lett. B 754 (2016) 235

Direct photons in Pb-Pb collisions

- ✓ At low p_{T} (<2-3 GeV/c)
  ~ 8%-15% excess in 0-20% ;
  ~ 8%-9% in 20-40%
- ✓ At high p_{T} (above ~5 GeV/c) in agreement with NLO pQCD and JETPHOX

Different measurements produce consistent results

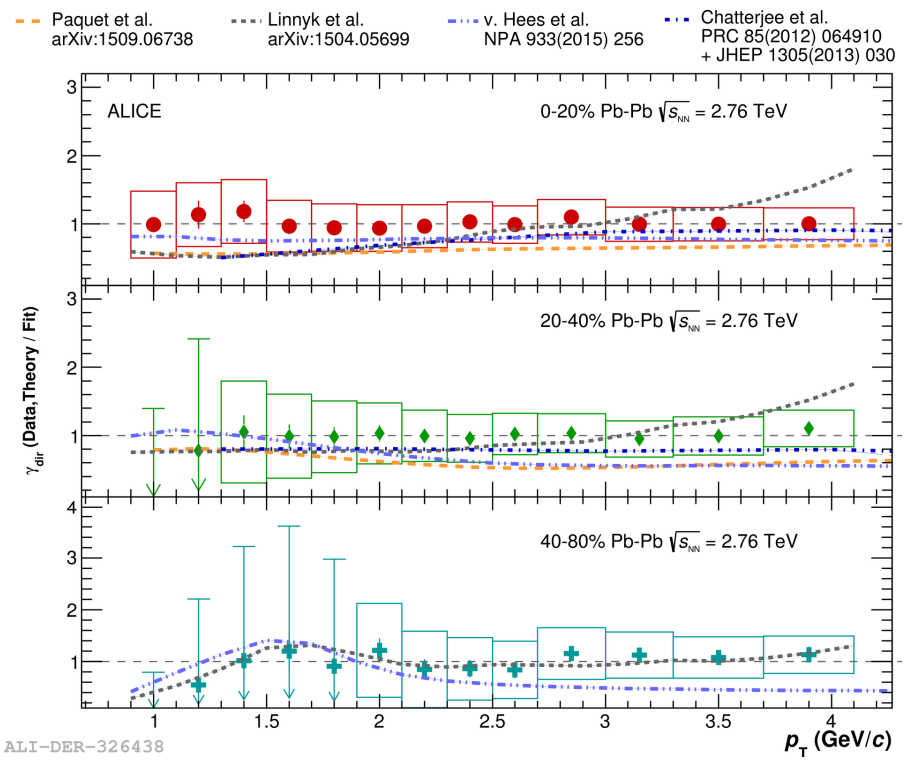


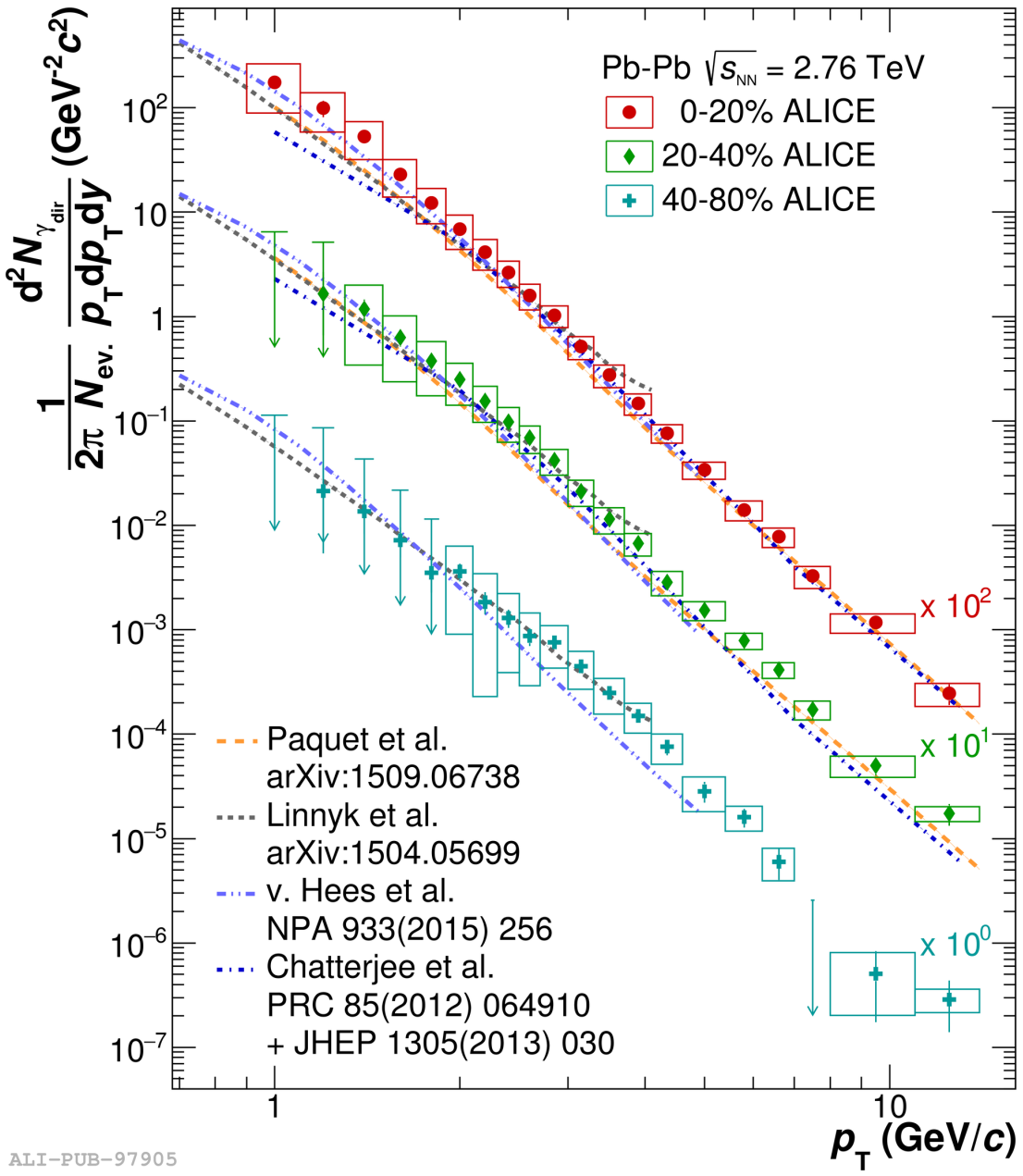


Phys. Lett. B 754 (2016) 235

Direct photons in Pb-Pb collisions

Comparison with hydro models:
Underpredicted, but within uncertainties





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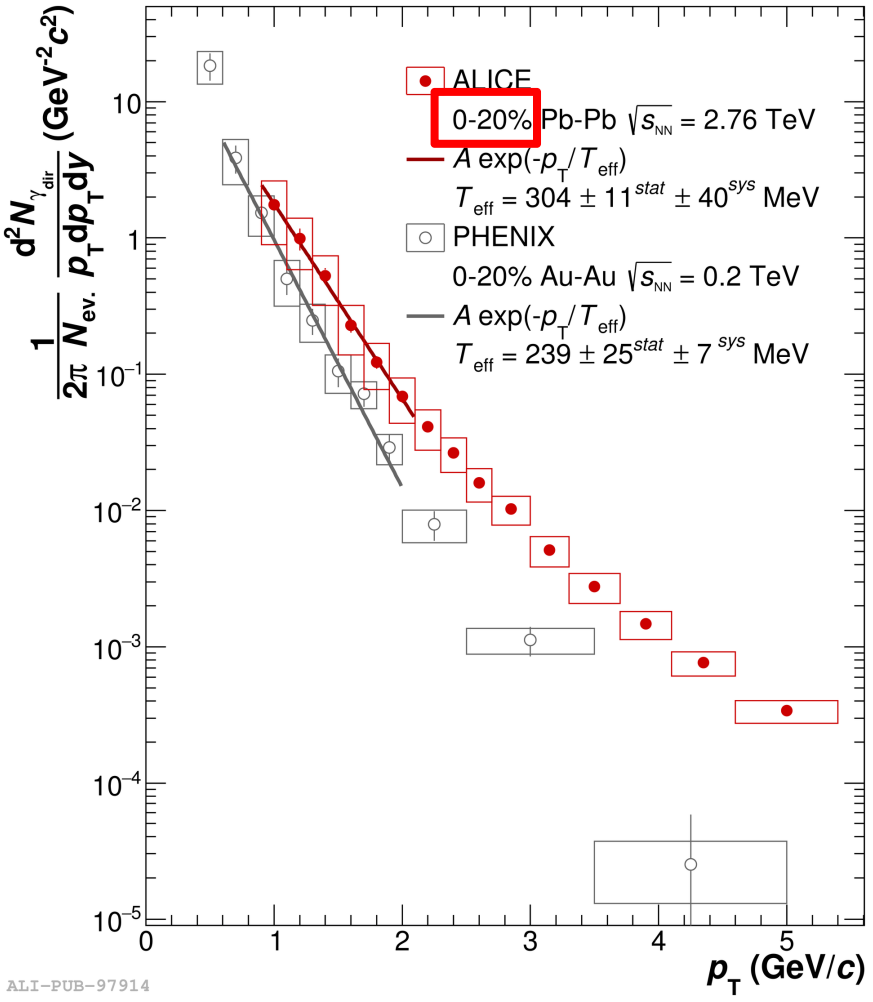
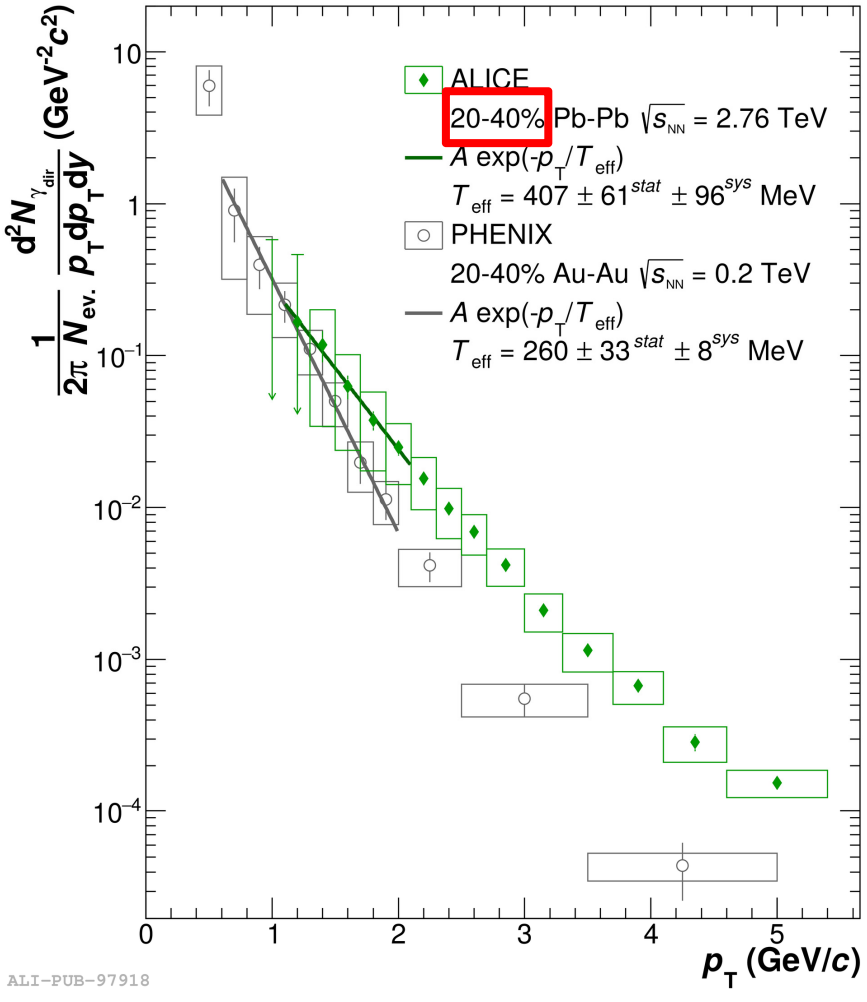
Direct photons in Pb-Pb collisions

- Effective temperature can be extracted from the low-p_T part of the spectrum
- Both absolute yield of direct photons and effective slope increase with increasing the collision energy





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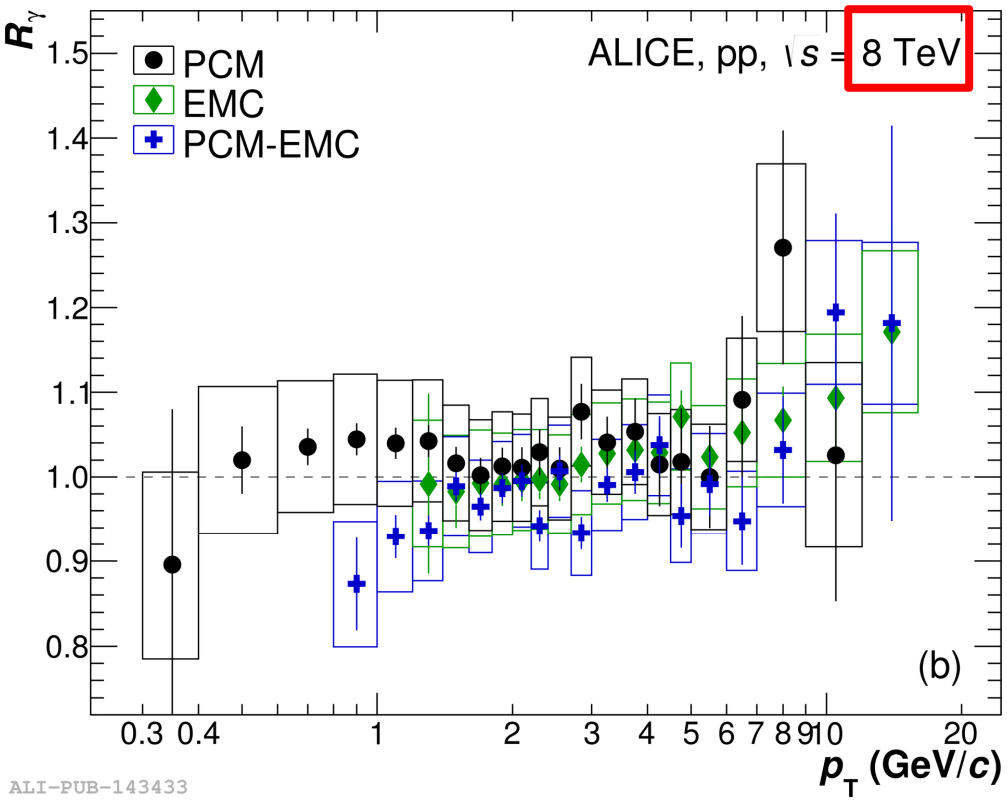
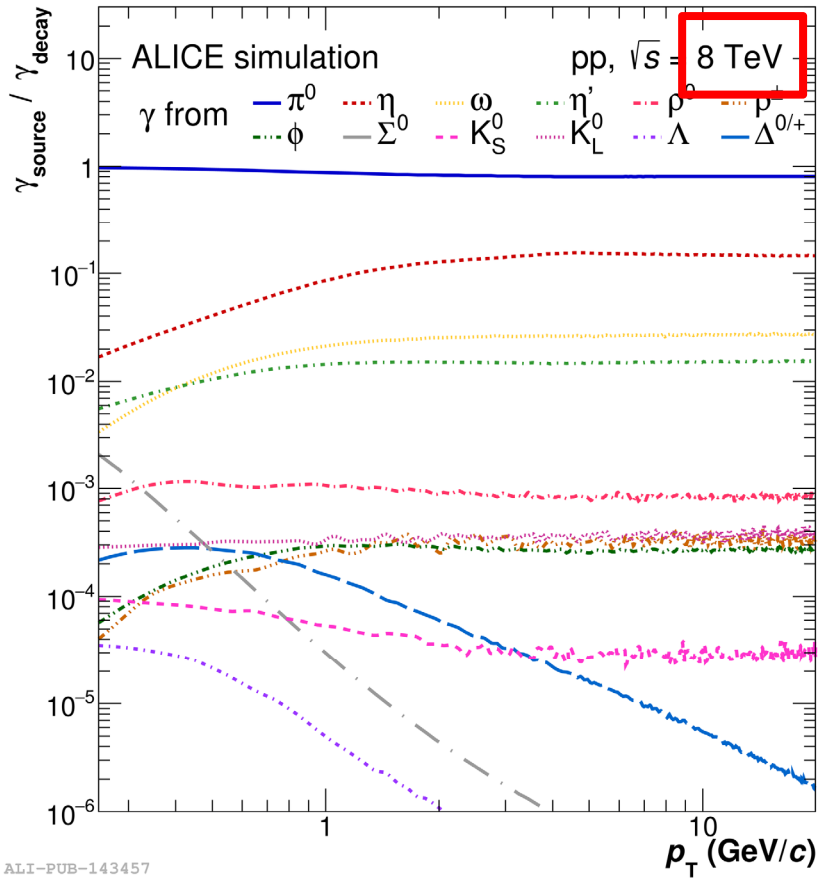
Direct photons in pp collisions

- Proton-proton collisions at $\sqrt{s} = 2.76$ and 8 TeV are analyzed
- PCM, EMCal and PCM-EMC methods are used

Systematic uncertainties of individual meas. are dominated by p_T-independent ones: material budget unc. of 4.5% PCM, 2.8% EMC

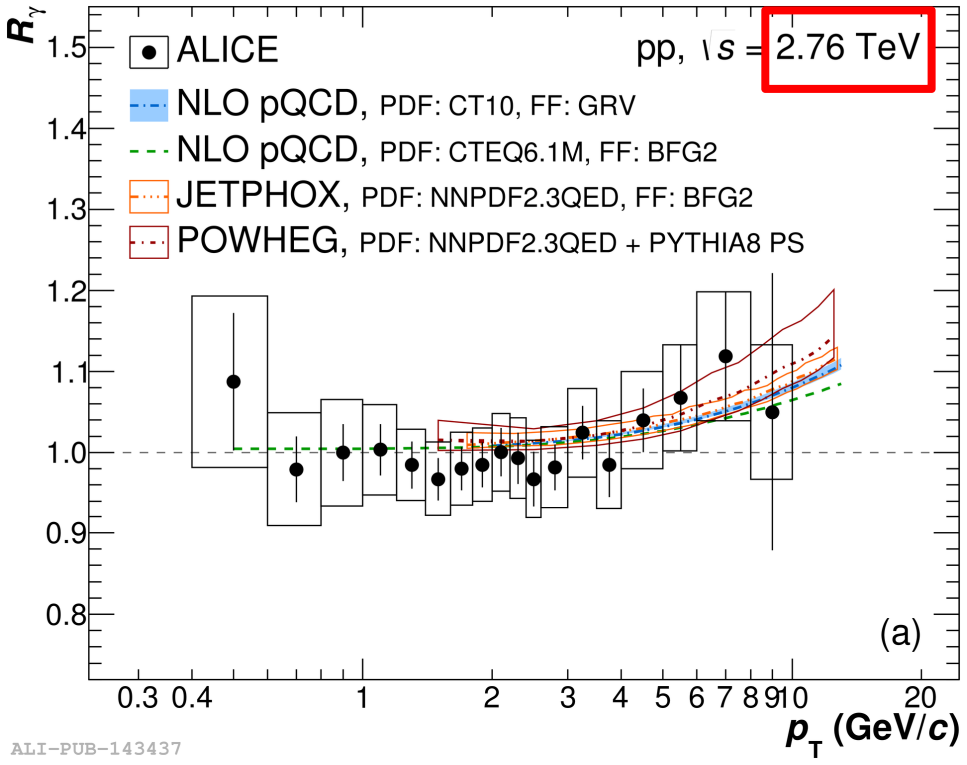


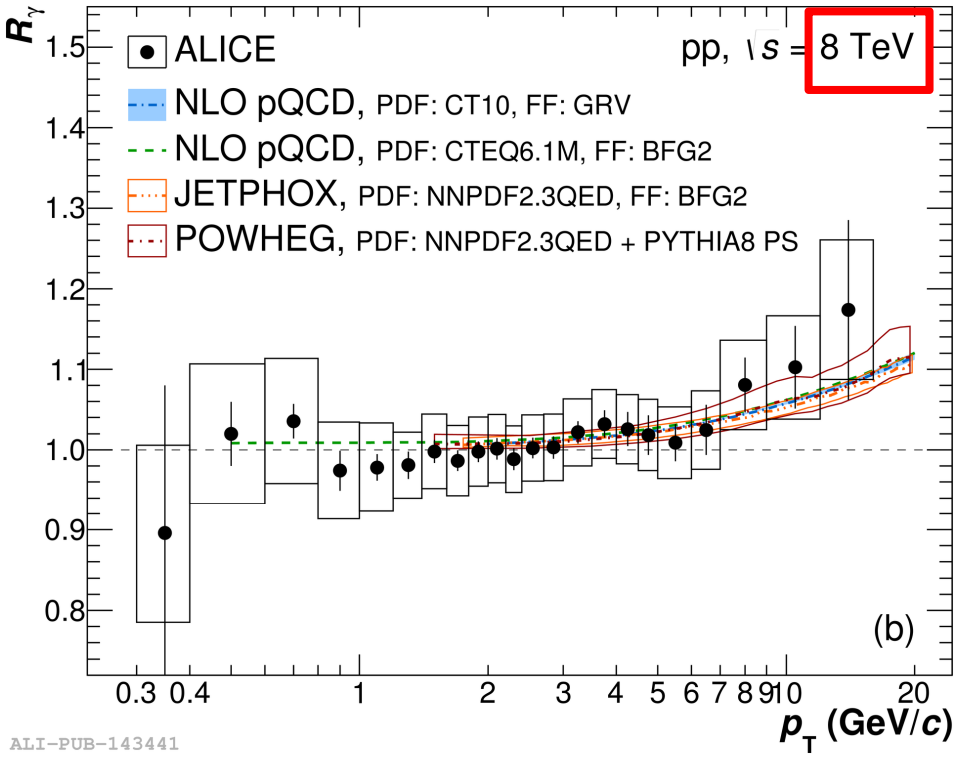


Phys. Rev. C 99 (2019) 024912

Direct photons in pp collisions

- High p_{T} (>4 GeV/c) – in agreement with pQCD
- Low p_{T} (<2-3 GeV/c) – no thermal radiation excess visible within uncertainties





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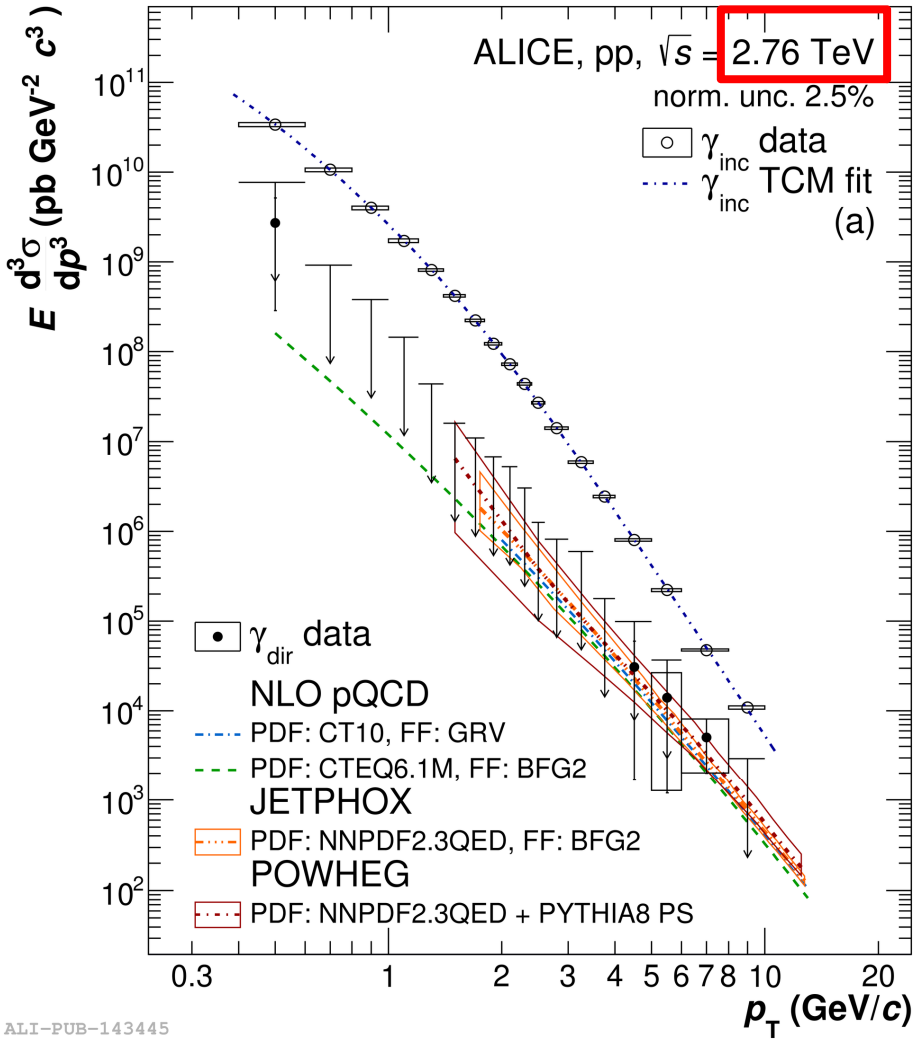
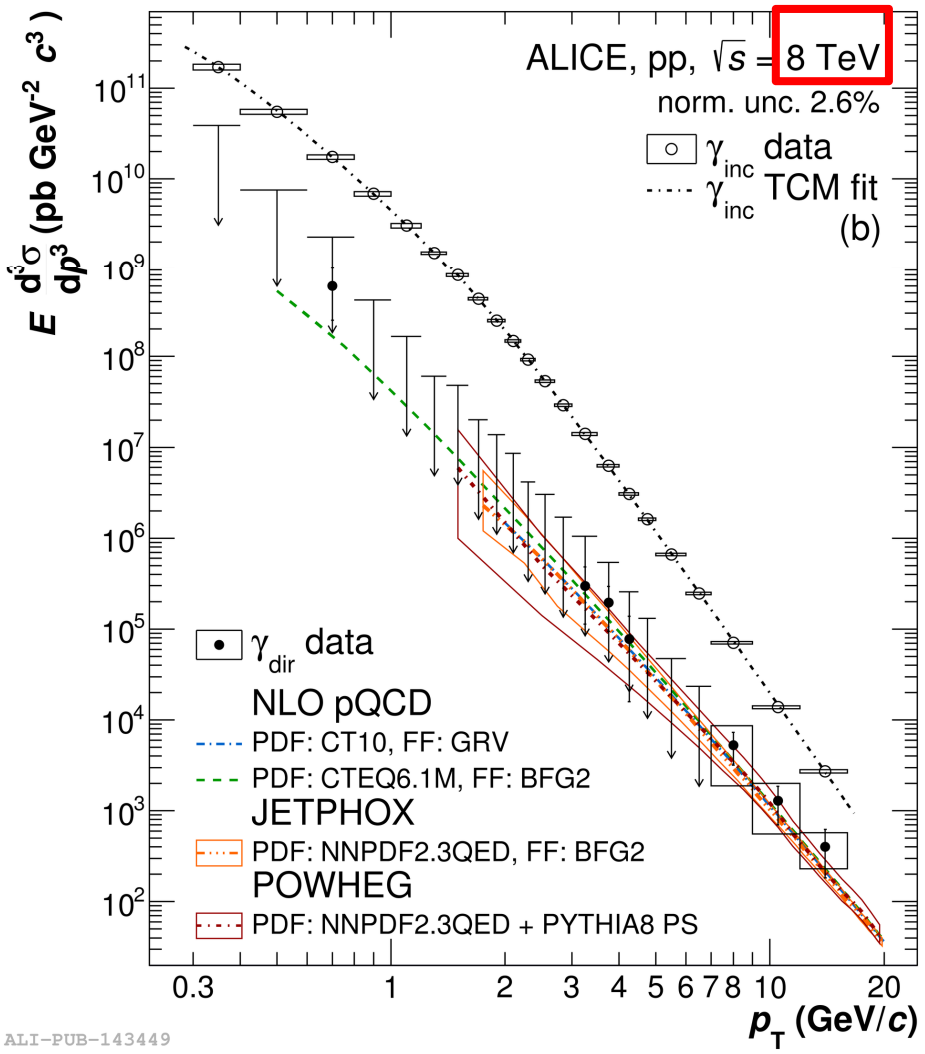
Direct photons in pp collisions

- NLO pQCD calculations are able to reproduce measurements





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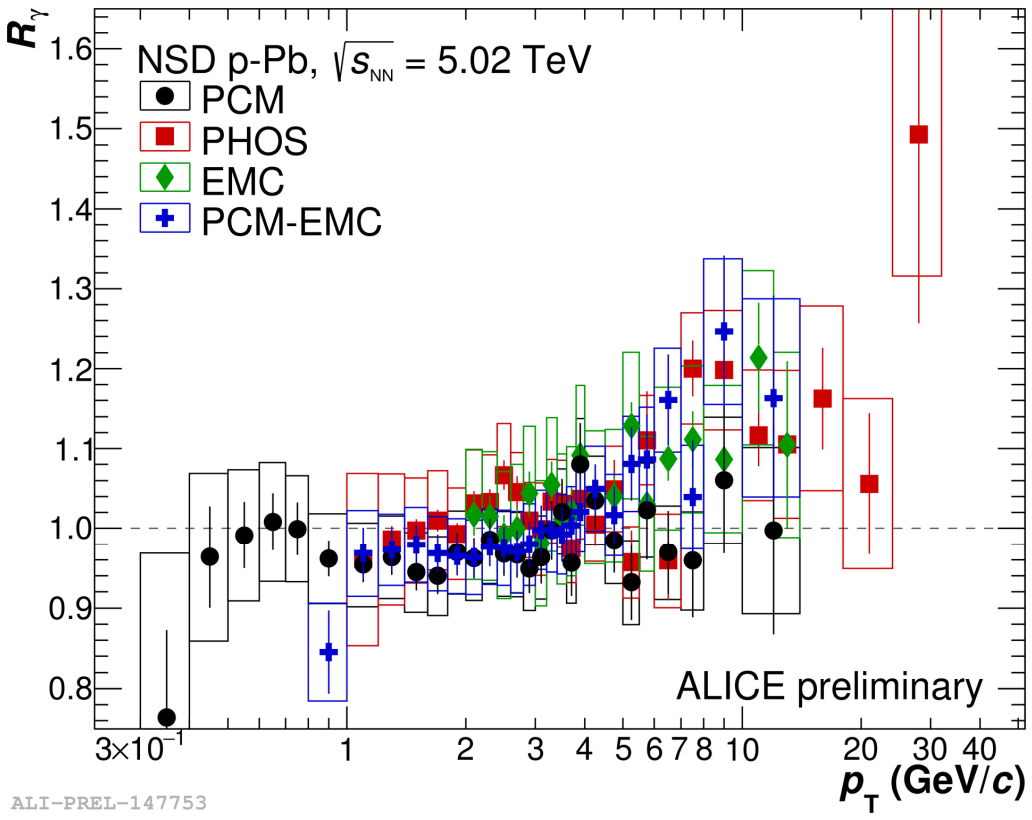
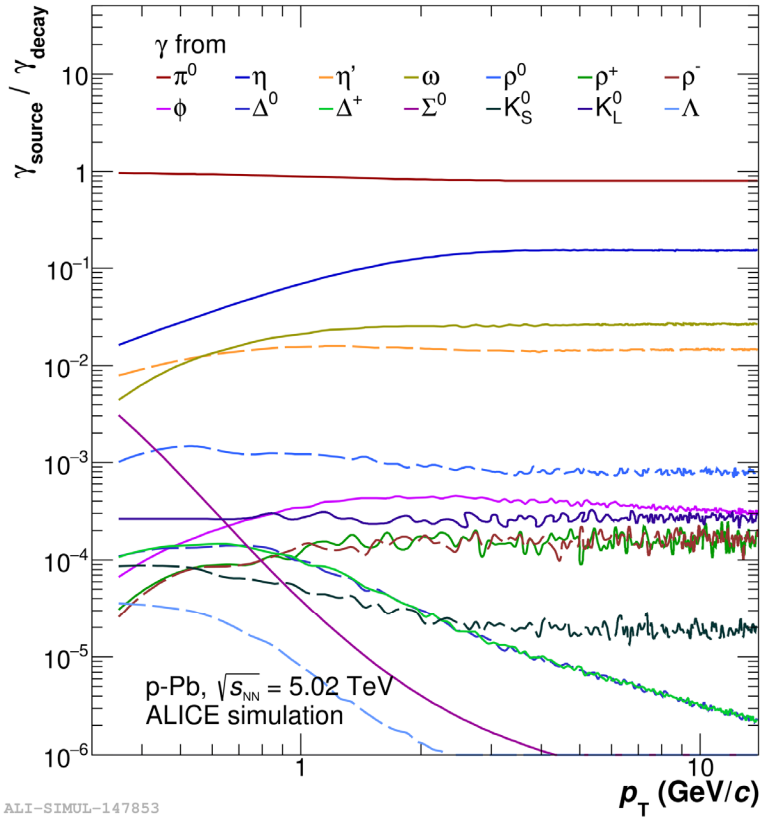
Direct photons in p-Pb collisions

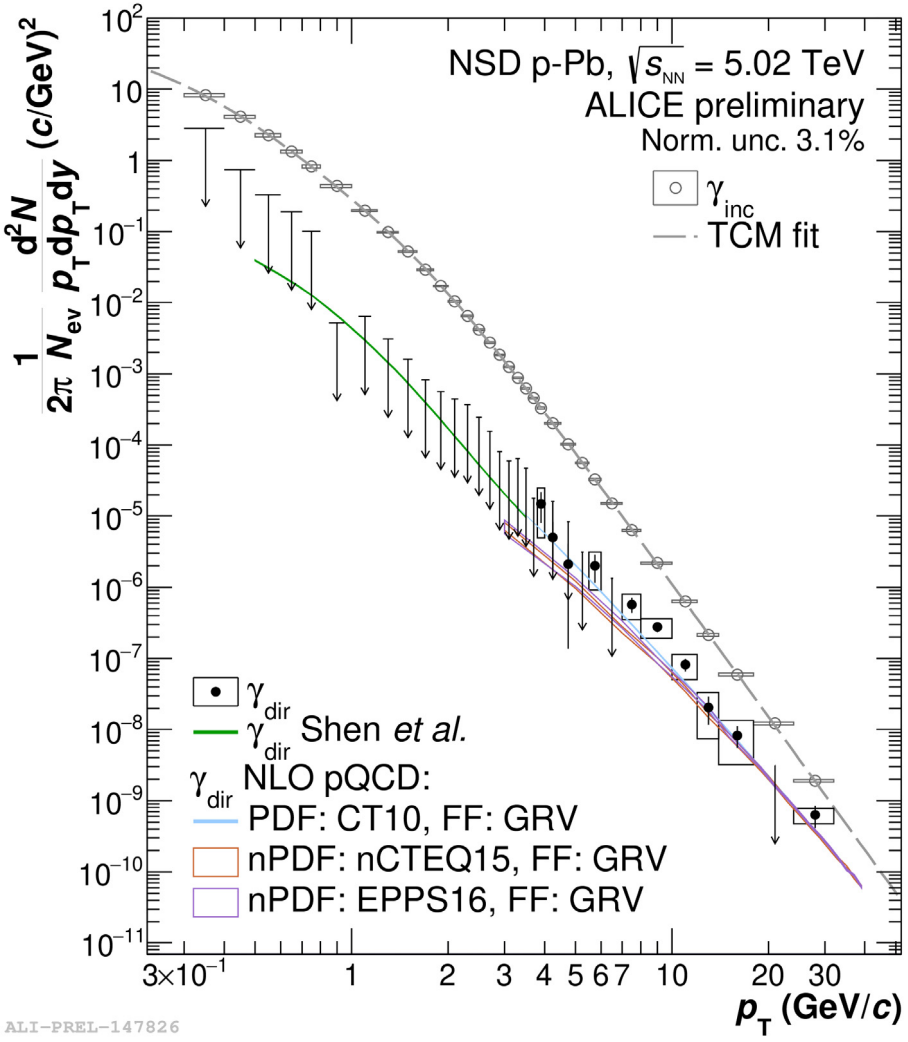
- p-Pb collisions at were analyzed using four methods: PCM, PHOS, EMC, PCM-EMC
- Possible modification of direct photon yield due to cold nuclear matter effects (modification of nucleon structure functions in nuclei, isospin effects, test scaling of production with N_{coll})

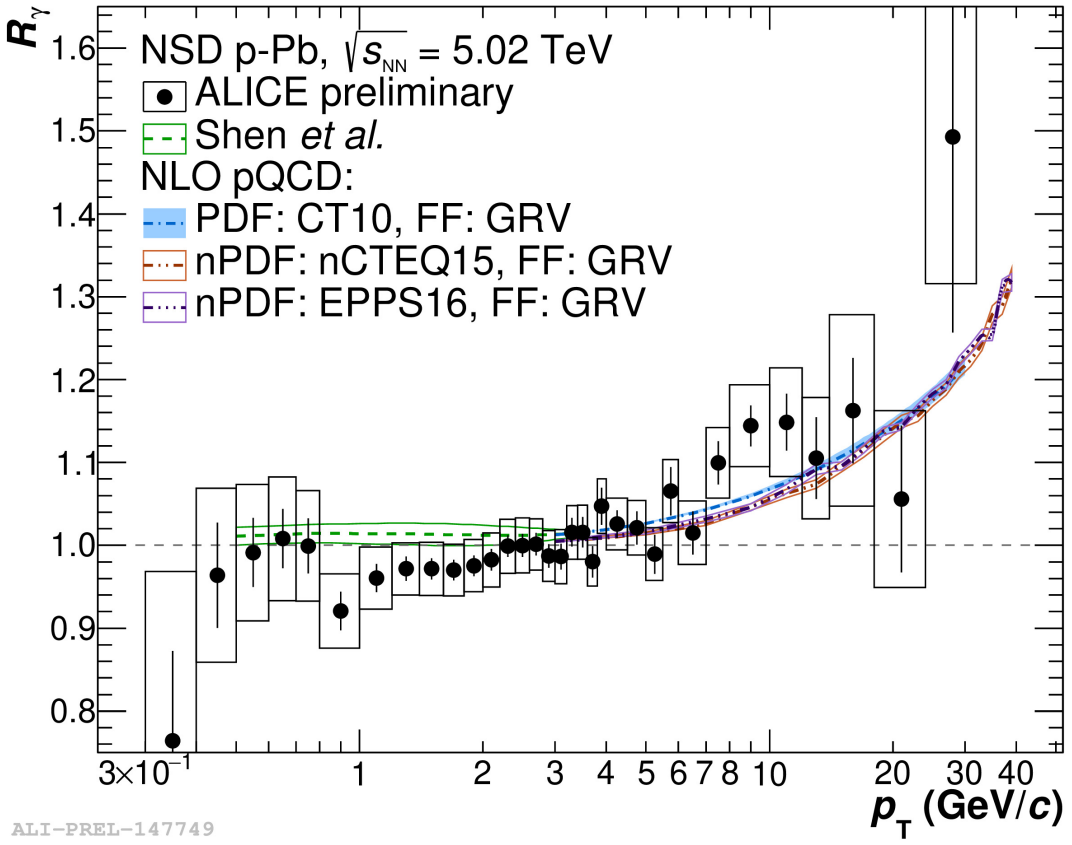




Direct photons in p-Pb collisions

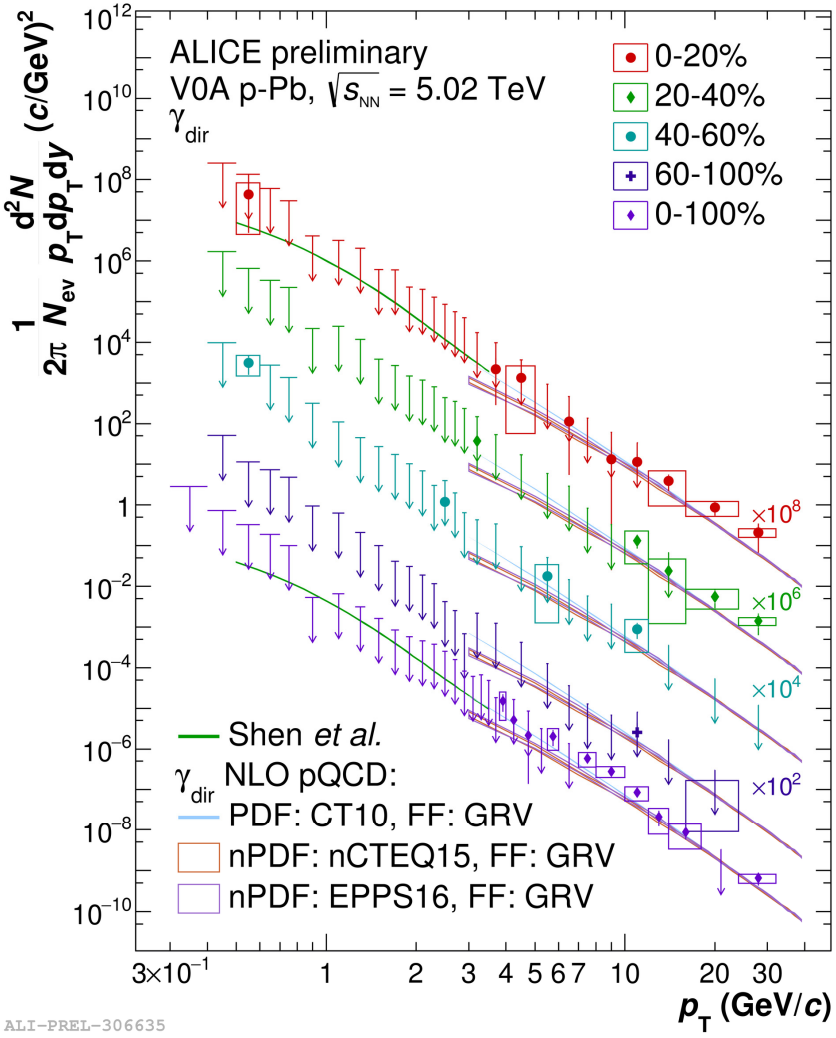
- Direct photon spectrum was calculated in wide p_{T} range up to 30 GeV/c, several NLO pQCD calculations are able to reproduce results
- No thermal radiation fraction is visible in low p_{T} within uncertainties

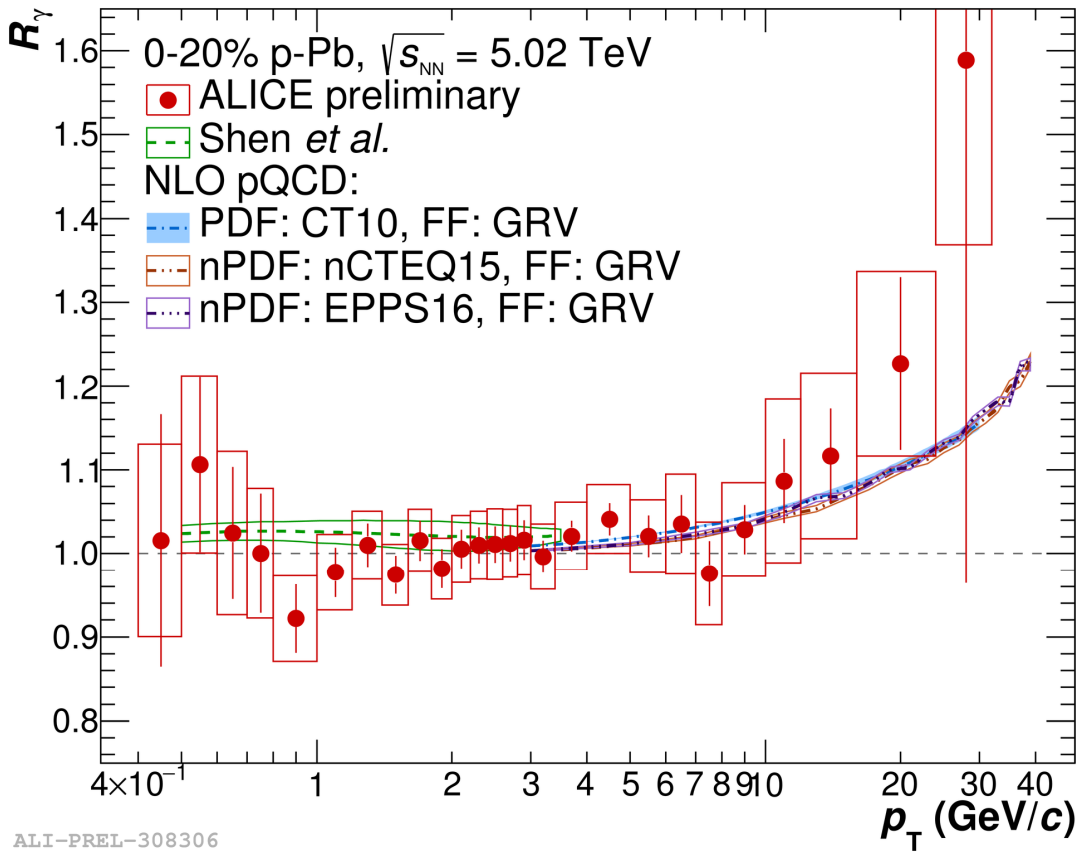




Direct photons in p-Pb collisions per multiplicity classes

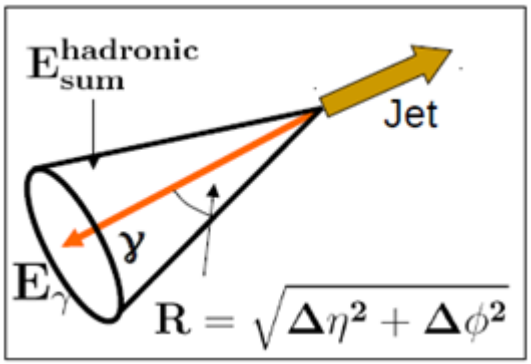
- Direct photon spectrum was calculated in 4 centrality classes
- Even in the most central 0-20% class no visible excess at low p_T is seen



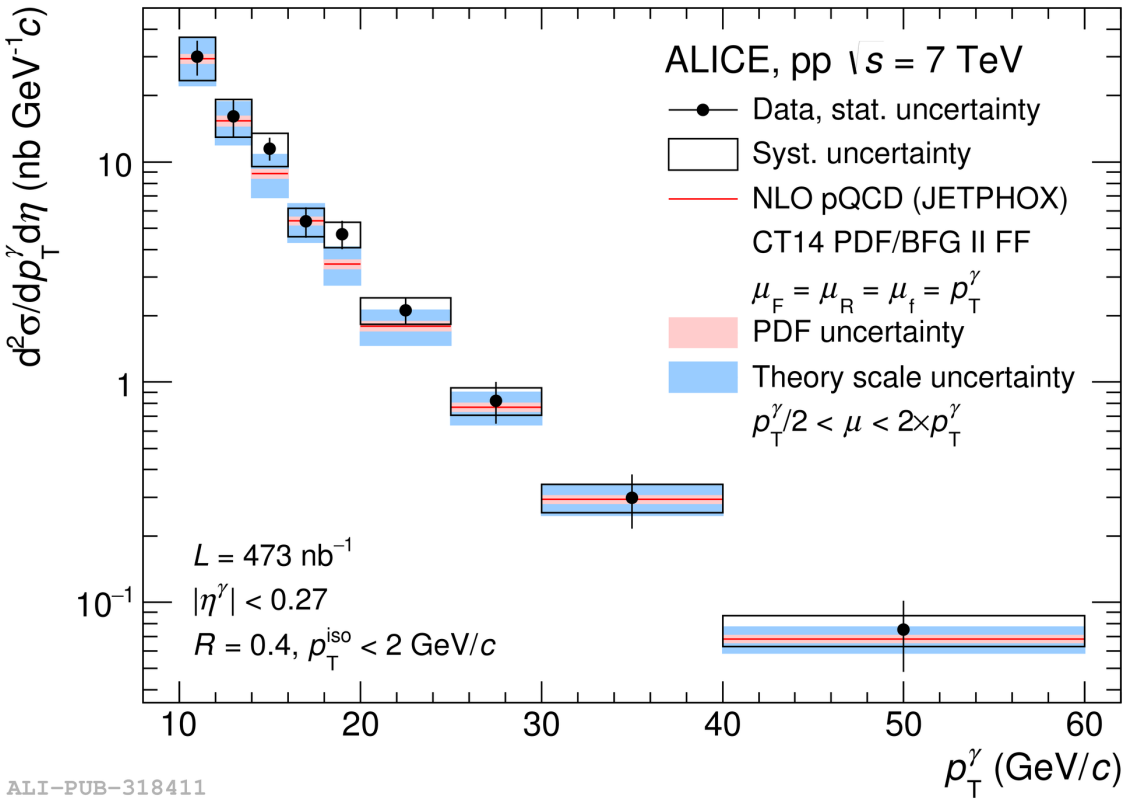


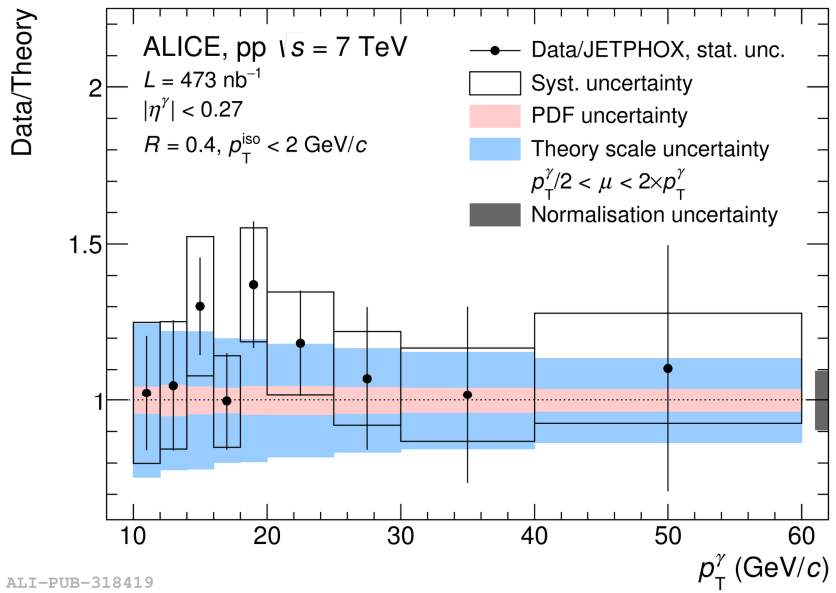
Isolated photons in pp collisions

- Another approach to study direct photons is the measurement of the isolated photons, i.e. photons without hadron activity in some cone
- System: pp at $\sqrt{s} = 7$ TeV
- Lower p_{T} (10 GeV/c) reach compared to other experiments
- The measurements are consistent with NLO pQCD predictions



$$p_{\mathrm{T}}^{\mathrm{iso}} = \sum p_{\mathrm{T}}^{\mathrm{cluster}} + \sum p_{\mathrm{T}}^{\mathrm{track}} < 2\ \mathrm{GeV}/c$$



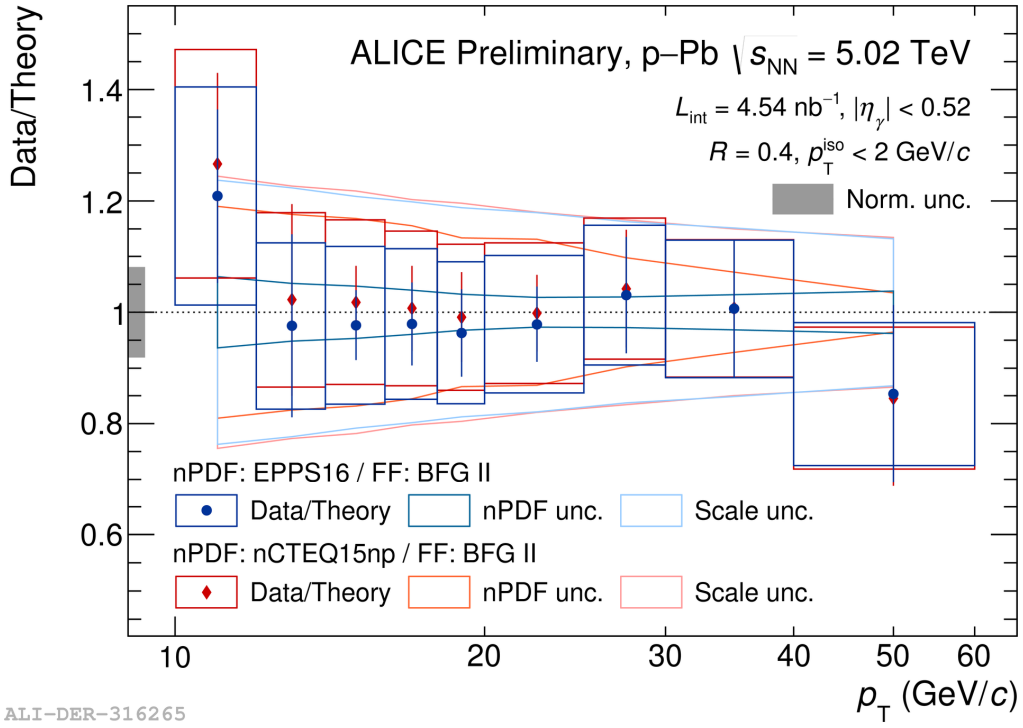


arXiv:1906.01371

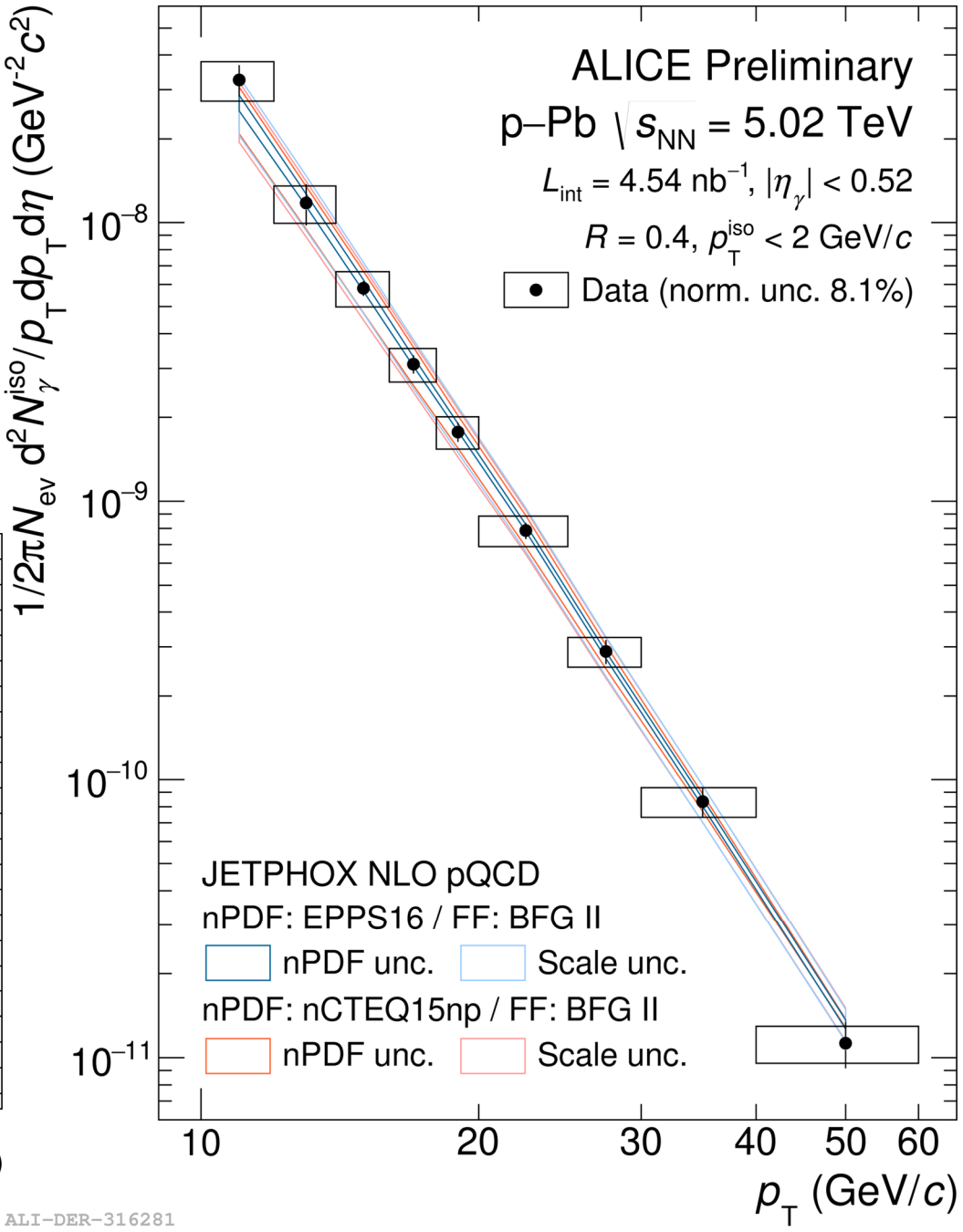
Isolated photons in p-Pb collisions

- Isolated photons production was also measured in p-Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
- The spectrum is also consistent with NLO pQCD predictions

$$p_{\mathrm{T}}^{\mathrm{iso}} - \mathrm{UE} < 2\ \mathrm{GeV}/c$$



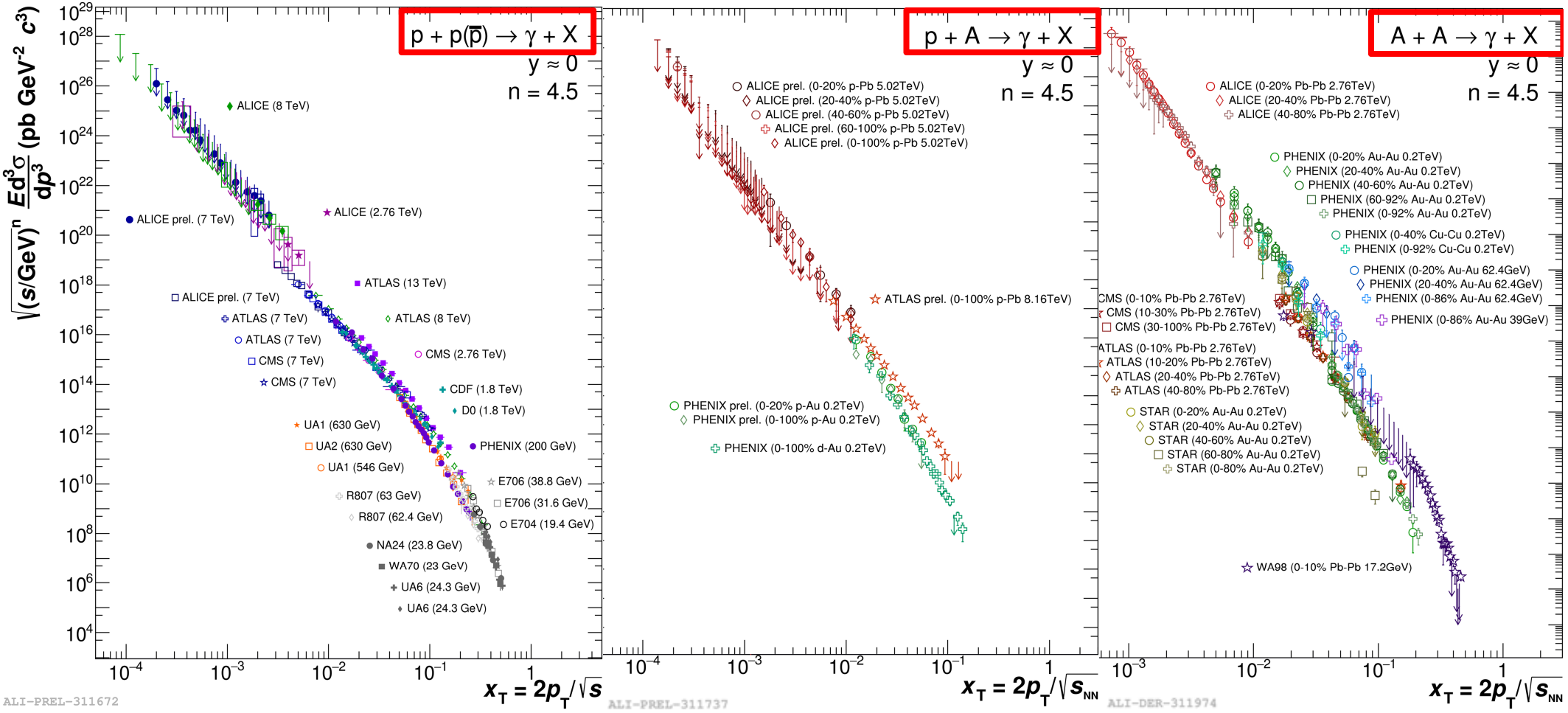
ALI-DER-316265



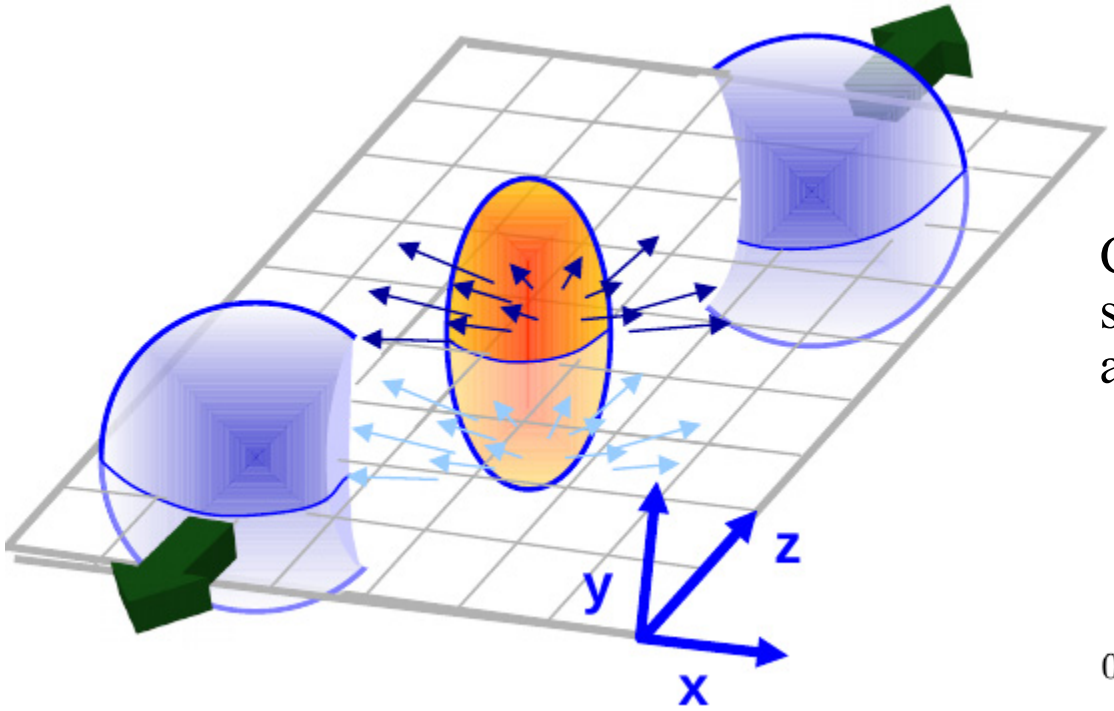
ALI-DER-316281

Summary of γ_{dir} production at different $\sqrt{s}$ energy

- Universal scaling for pp collisions with x_{T} if scaled by $\sqrt[n]{s}$ with $n = 4.5$
- Scaling is approximate
- Direct and isolated photon results included

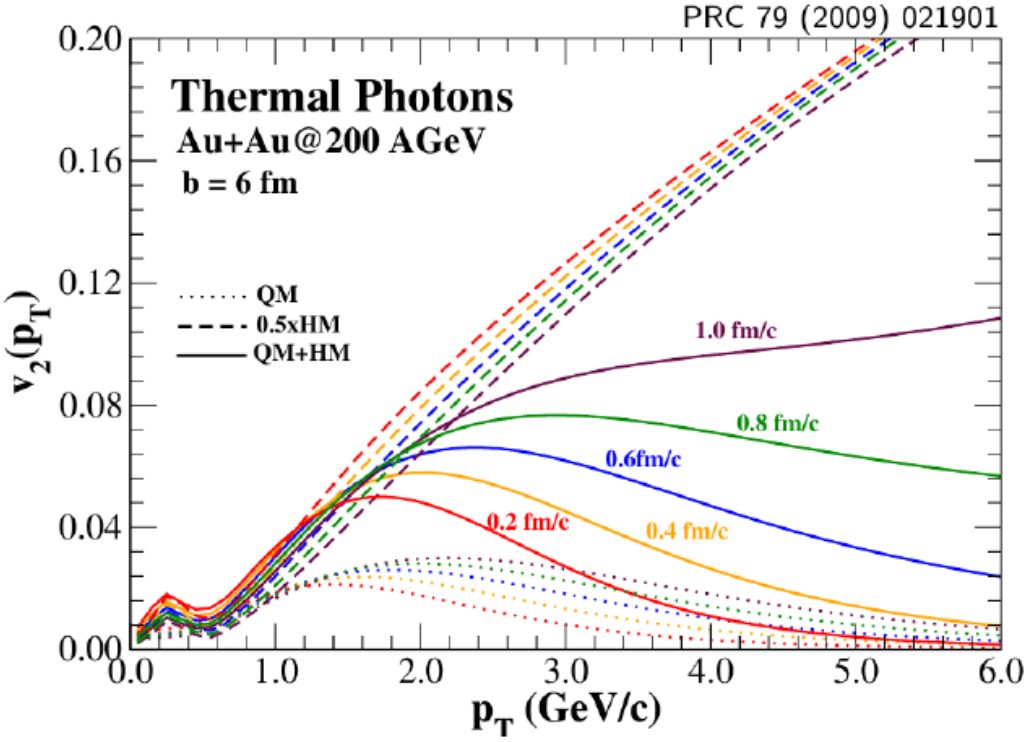


Direct photon flow – an unsolved puzzle?



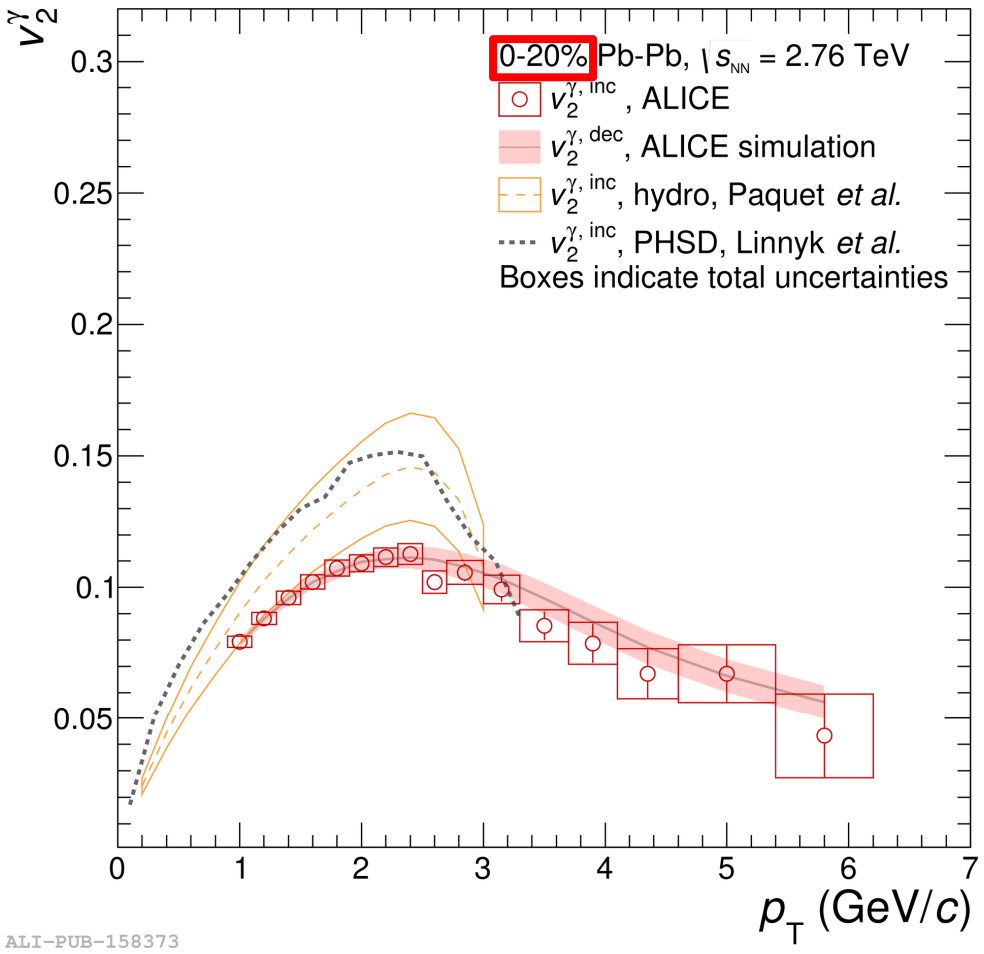
Collective expansion transforms initial spatial asymmetry of fireball to asymmetry in momentum space

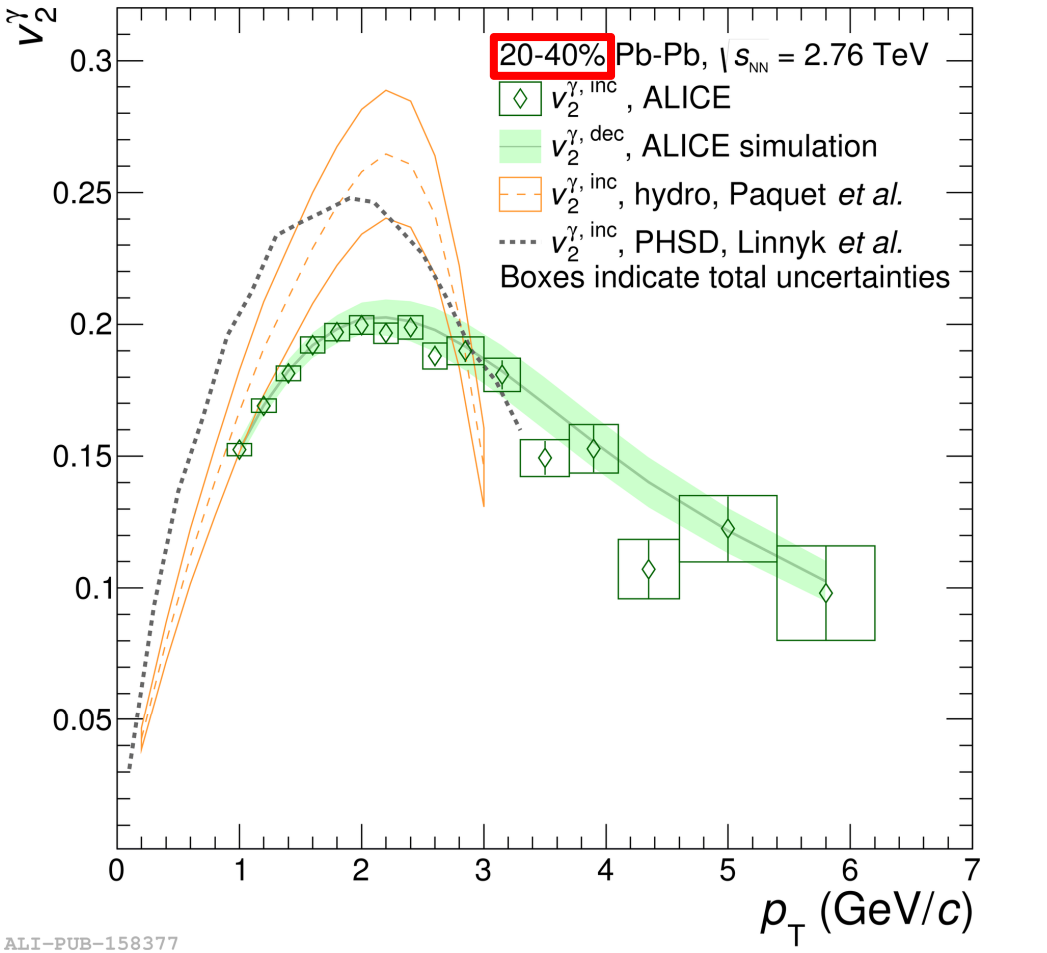
Thermal photons, emitted early from hotter fireball carry smaller collective flow than those, emitted at later stages
=> one can test development of collective flow with direct photons



Direct photon flow in Pb-Pb collisions

- Measurements are done with PCM and PHOS
- Inclusive gamma v_2:
  - $\boldsymbol{p_T < 3\ GeV/c}$: ${v_2}^{\gamma\,\mathrm{inc}} = {v_2}^{\gamma\,\mathrm{dec}} \Rightarrow$ Either no contribution of γ_{dir} or ${v_2}^{\gamma\,\mathrm{dir}} = {v_2}^{\gamma\,\mathrm{dec}}$
  - Theory predicts $\sim 30 - 40\%$ higher flow
  - $\boldsymbol{p_T > 3\ GeV/c}$: ${v_2}^{\gamma\,\mathrm{inc}} < {v_2}^{\gamma\,\mathrm{dec}} \rightarrow$ prompt photon contribution



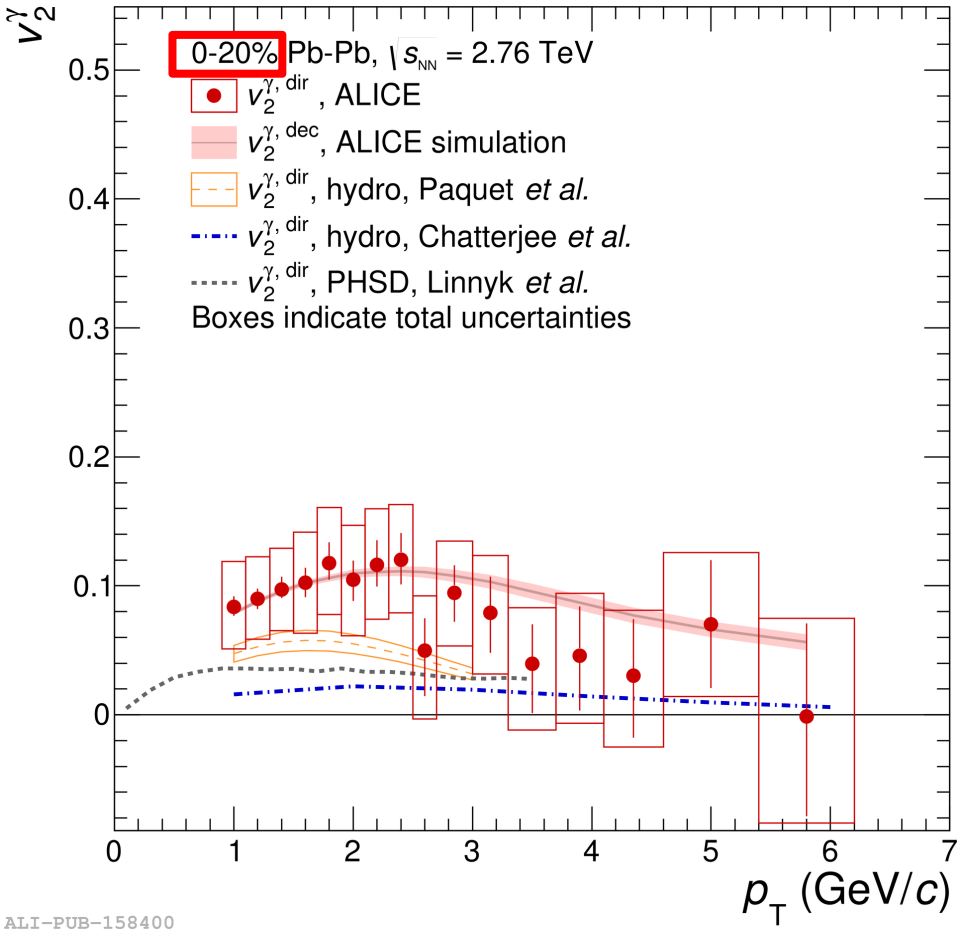


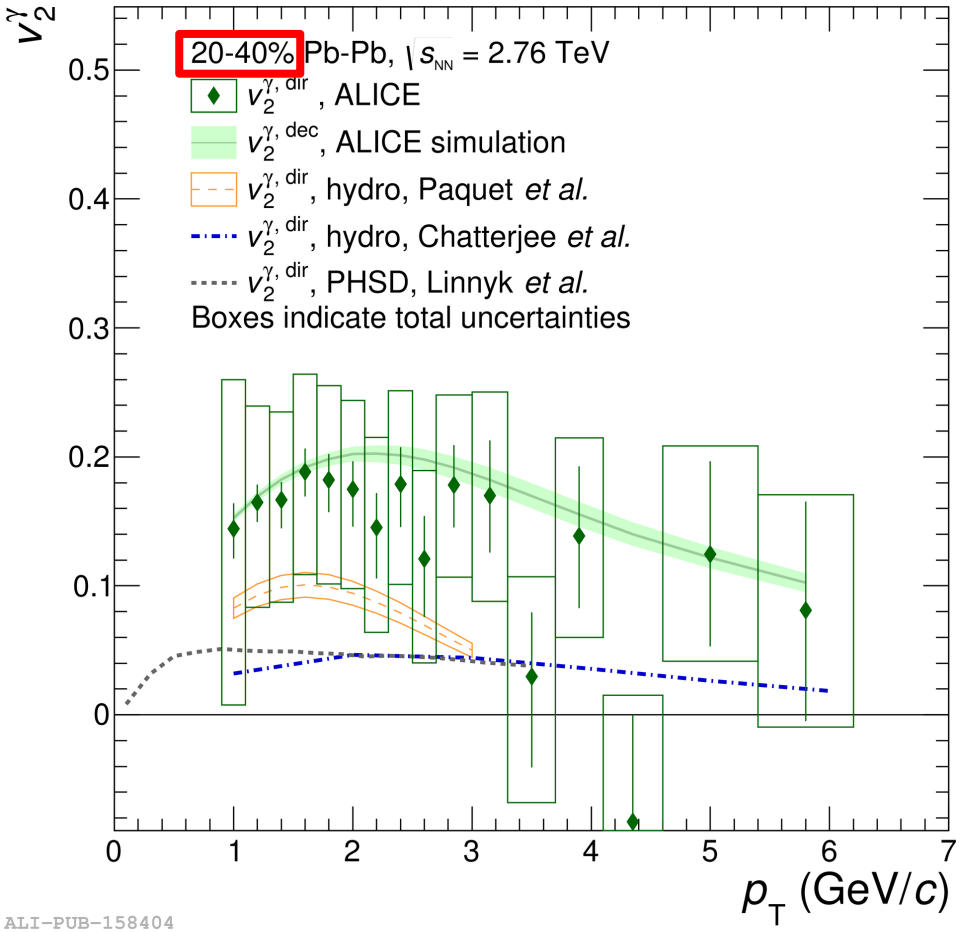
Phys. Lett. B 789 (2019) 308-322

Direct photon flow in Pb-Pb collisions

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

- Large v_2 for $p_\mathrm{T} < 3$ GeV/c, comparable to hadron flow (for 20-40% - too large uncertainties for conclusions)
- Hydro models underpredict direct photon flow → models need further development, hint for late direct photons production, and early flow formation





Phys. Lett. B 789 (2019) 308-322

Conclusions

- Direct photon production at LHC energies is studied in different systems:
  - in pp and p-Pb collisions:
    No significant direct photon excess observed in thermal photon region (p_{T}<2-3 GeV/c)
    Consistent with N_{coll} scaled NLO pQCD calculations at higher p_{T}
  - in Pb-Pb collisions:
    Direct photon excess for p_{T}< 3 GeV/c observed with 2.6σ for 0-20% and 1.5σ in 20-40% centrality classes
    Spectrum consistent with N_{coll} scaled NLO pQCD calculations at high p_{T} (>4 GeV/c)
    At low p_{T} spectrum consistent with hydrodynamic model predictions

- Inclusive photon production at LHC energies is studied in pp and p-Pb collisions:
  - The measurements are consistent with NLO pQCD calculations

- Direct photon flow was measured with 2 independent reconstruction techniques in Pb–Pb collisions
  - Direct photon flow v_2 in centrality classes 0-20% & 20-40% of similar size as the charged hadron flow and inclusive photon flow, but compatible with 0 within ~1σ in p_{T} range (0.9 < p_{T} < 2.1 GeV/c)
  - Direct photons confirm creation in Pb-Pb collisions of hot matter with significant collective expansion

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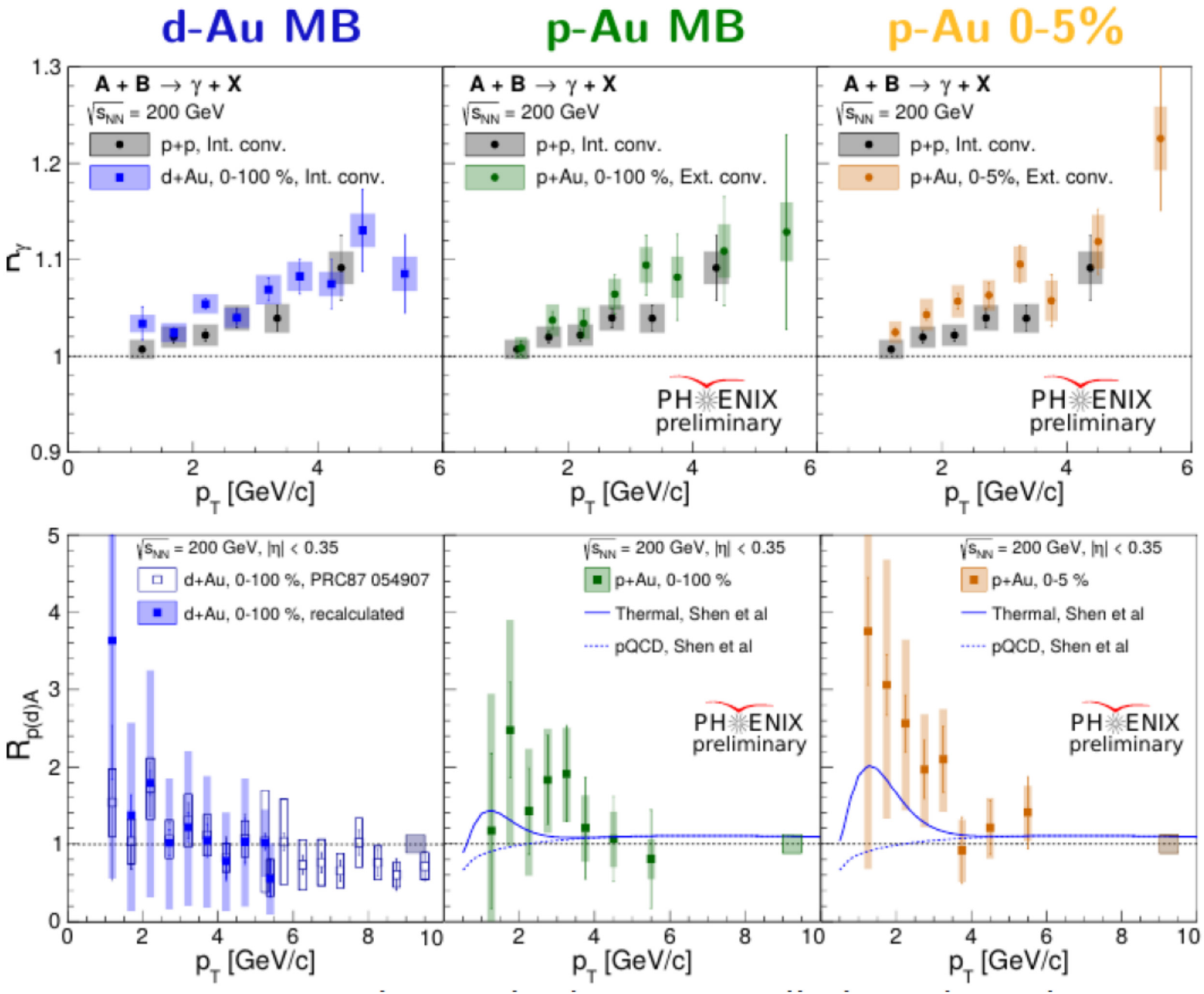
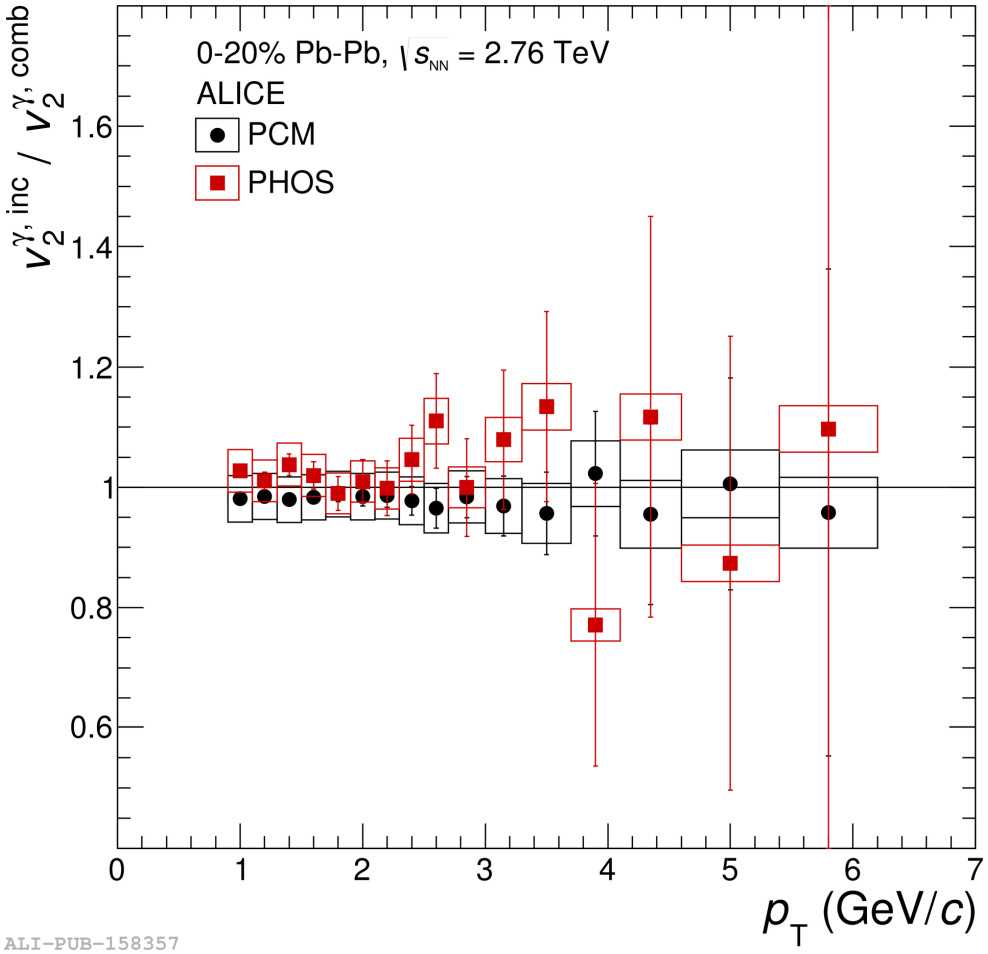
Backup

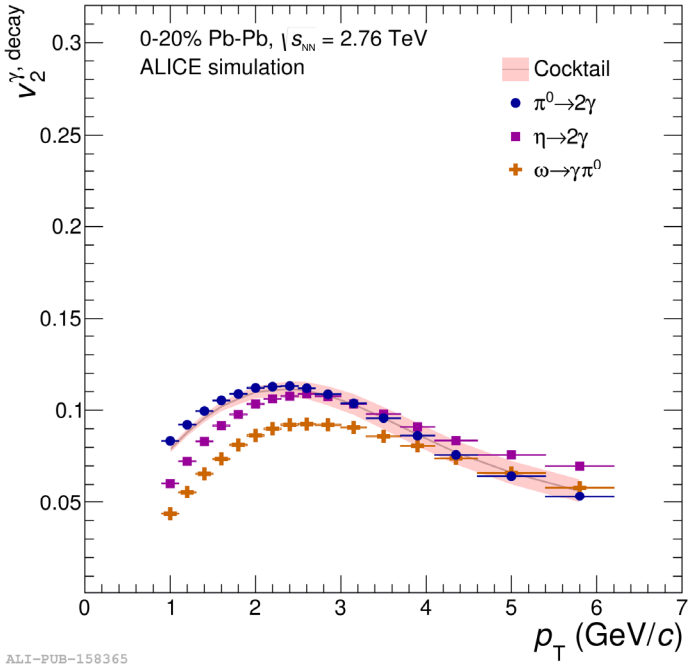
PHENIX in p-Au and d-Au

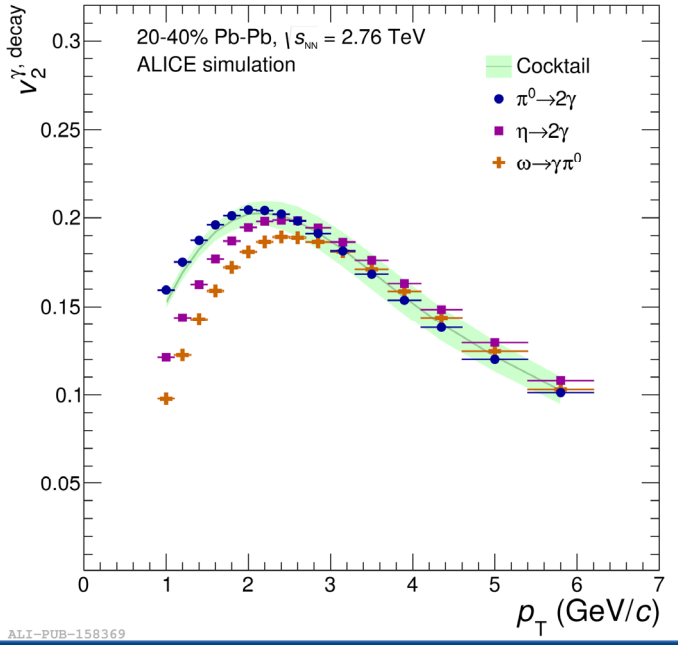


Flow additional figures

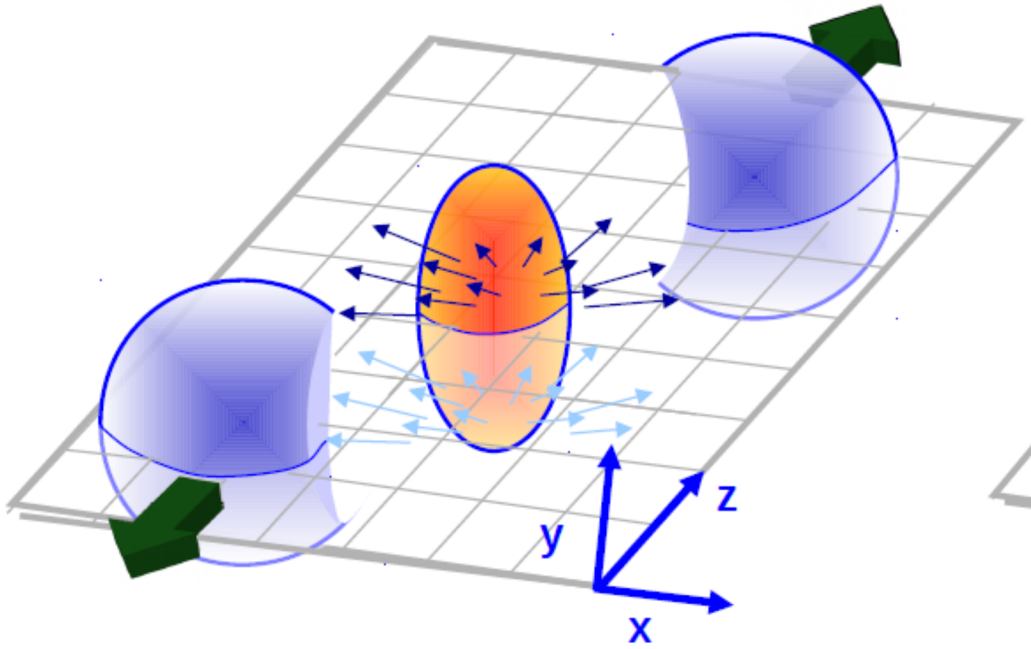
PHOS and PCM show consistent results

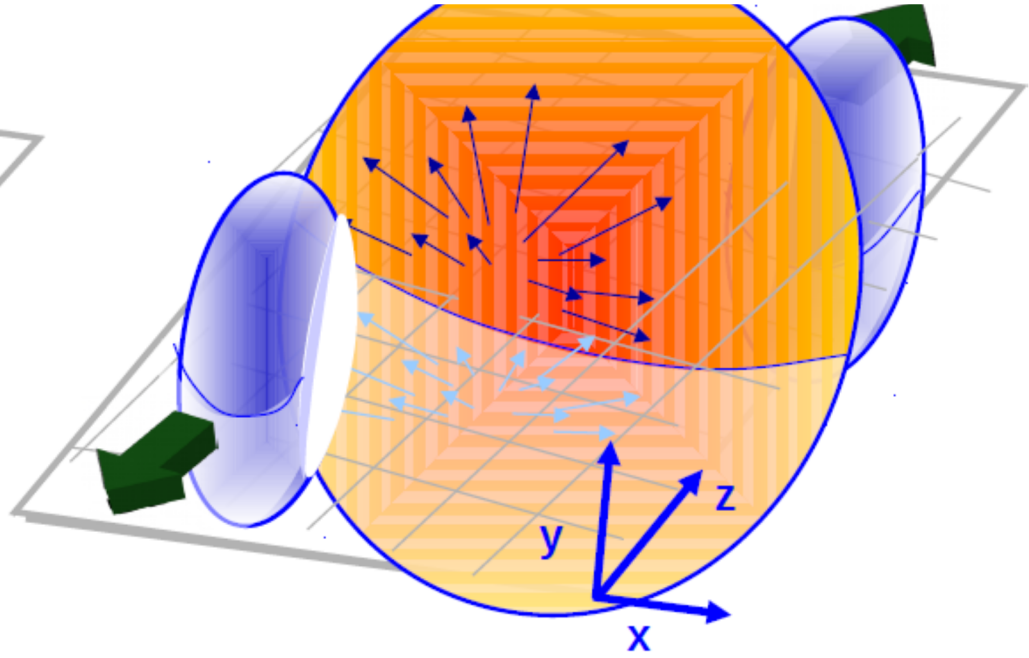






Flow additional figures





Collective flow – asymmetry in particle production, common for all soft particles in event.

$$\frac{dN}{d\phi} = 1 + 2\,v_1 \cos\left(\phi - \Psi_{RP}\right) + 2\,v_2 \cos\left[2\left(\phi - \Psi_{RP}\right)\right] + 2\,v_3 \cos\left[3\left(\phi - \Psi_{RP}\right)\right] + \ldots$$

v_1 - directed, v_2 – elliptic, v_3 – triangular flow, ...

World data for isolated photons production