Direct photon and neutral meson production results from ALICE experiment

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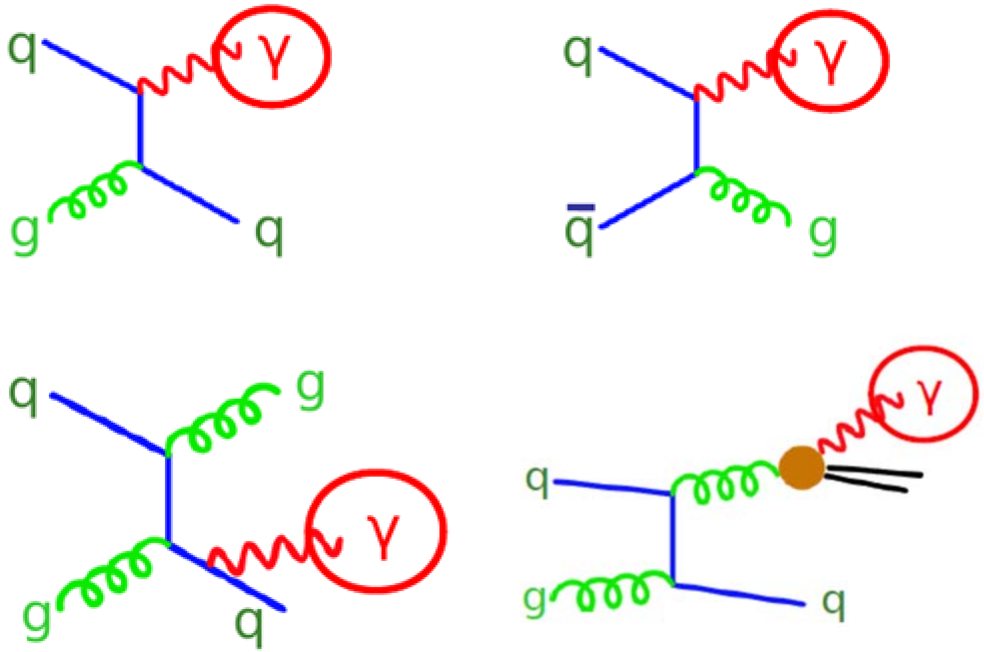
MIPT

Direct photons and neutral mesons in pp and p–Pb collisions

- Test pQCD predictions: constraints on parton distribution functions (PDFs) and fragmentation functions (FFs)
- Provide baseline for AA collisions

- p-Pb collisions:
  - ✓ Modifications due to cold nuclear effects
  - ✓ Search for thermal radiation & hot medium effects in high multiplicity collisions

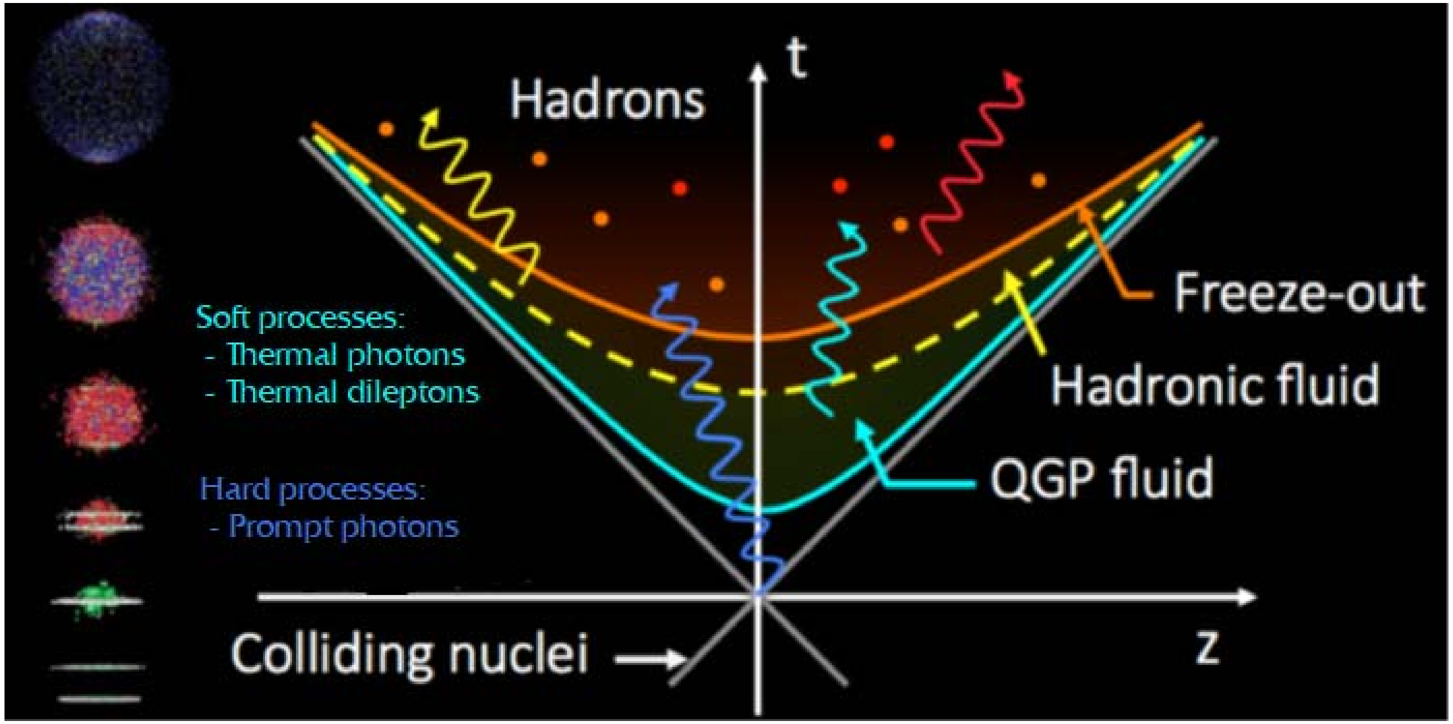


$$\frac{d\sigma^{\gamma,\mathrm{dir}}}{dp_{\mathrm{T}}d\eta} = F_{i/h} \otimes \sigma_{ij} \otimes D_{\gamma/k}$$

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

Direct photons and neutral mesons in Pb–Pb collisions

- Neutral mesons: study parton energy loss and collective effects in hot medium
- Direct photon spectrum:
  - ✓ Low and intermediate p_T – study thermal & pre-equilibrium contribution from the medium and collective flow formation and evolution.
  - ✓ High p_T – test of initial conditions.



Photon detection in ALICE

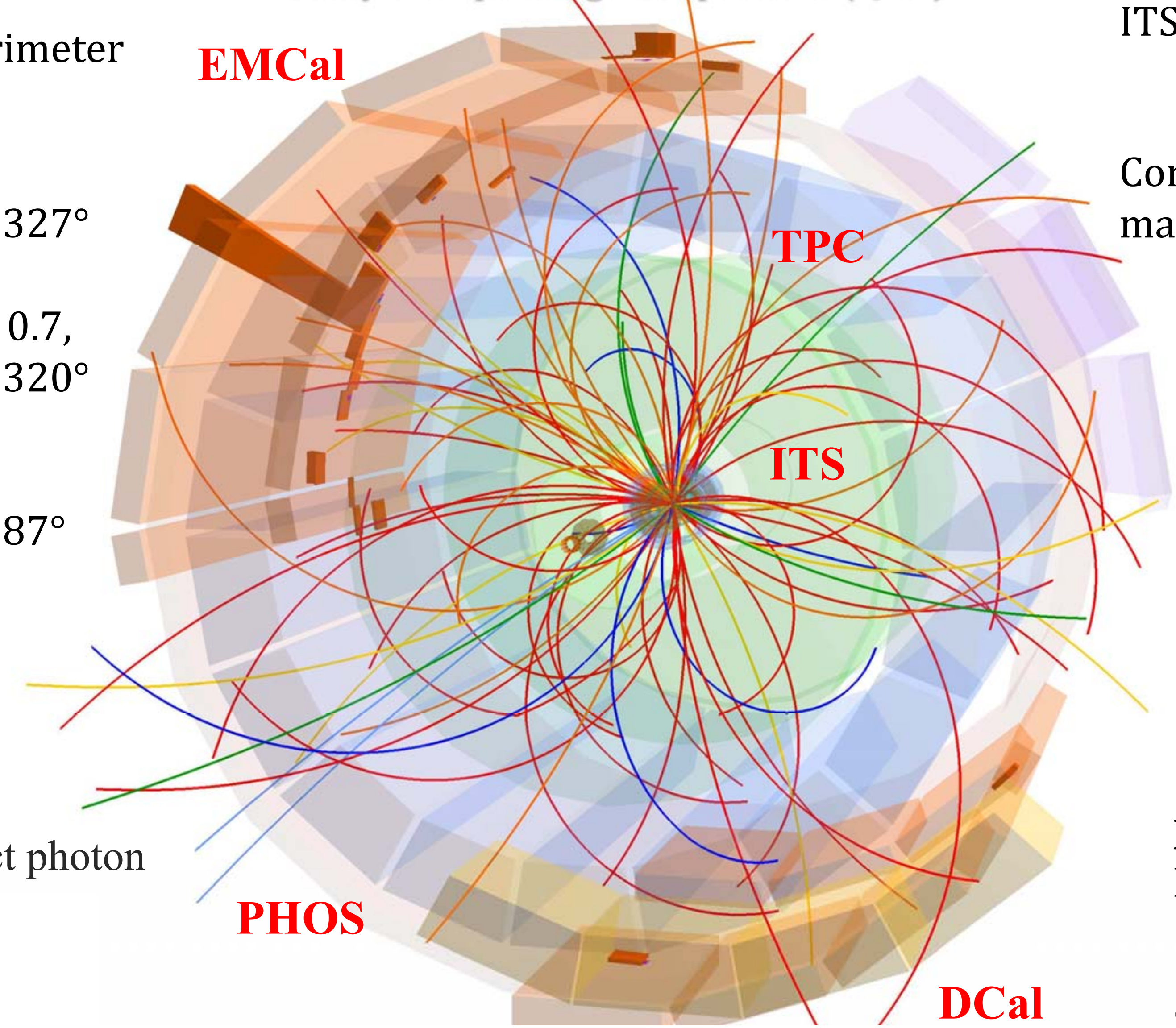
EMCal calorimeter
Pb/scintillator sampling calorimeter

DCal:
$|\eta| < 0.7$,
$320° < \varphi < 327°$

DCal:
$0.22 < |\eta| < 0.7$,
$260° < \varphi < 320°$

EMCal:
$|\eta| < 0.7$,
$80° < \varphi < 187°$

ALICE is an experiment at the LHC designed to study the quark-gluon plasma (QGP)



Photon conversion method (PCM)
ITS and TPC
$|\eta| < 0.9$,
$0° < \varphi < 360°$
Conversion in detector material

Measure
Inclusive/direct photon
$\pi^0 \rightarrow \gamma\gamma$
$\eta \rightarrow \gamma\gamma$
$\omega \rightarrow \pi^+\pi^-\pi^0$

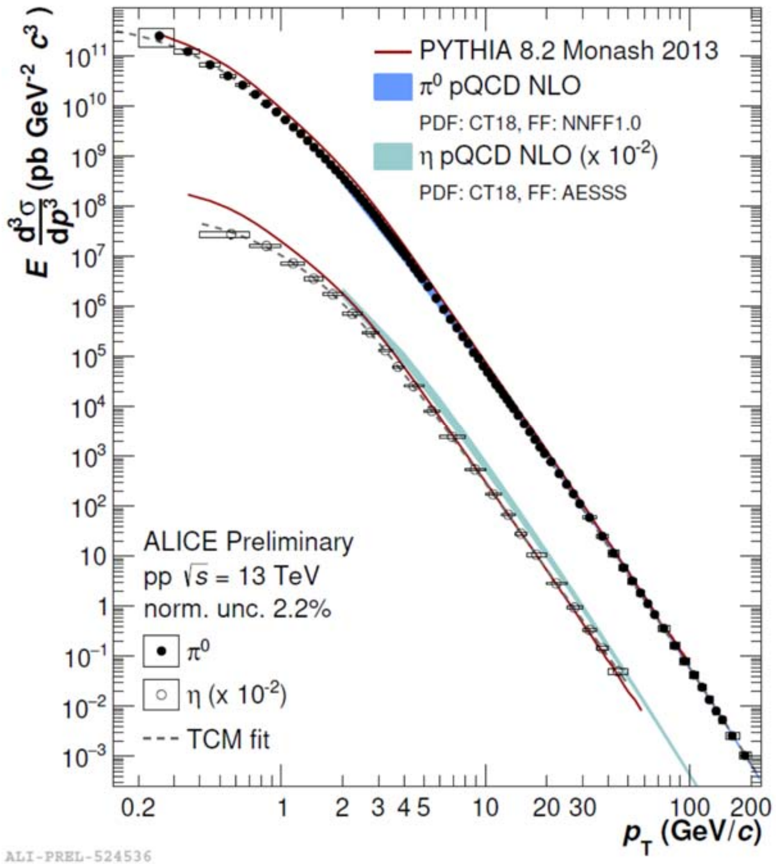
PHOS calorimeter
$PbWO_4$ crystals

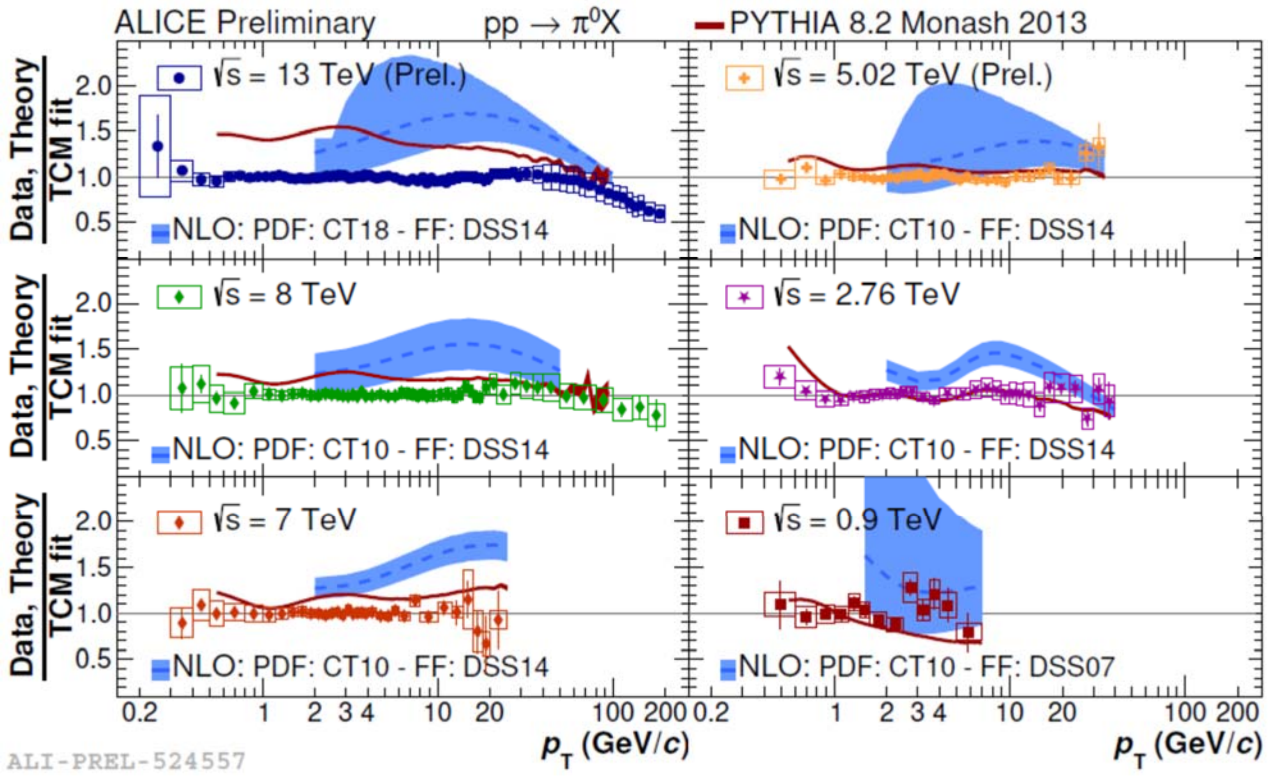
$|\eta| < 0.12$,
$260° < \varphi < 320°$

Complementary techniques: result in excellent precision and p_T range!

π^0 meson measurements in pp

- Wide range of measurements: $\sqrt{s} = 0.9, 2.76, 5.02, 7, 8, 13$ TeV.
- **New results** for $\sqrt{s} = 13$ TeV provide a span over p_{T} from 0.2 to 200 GeV/c
  - ✓ small angle decay photons from high energy π^0 overlap: shower shape analysis
- Data at low $\sqrt{s}$ (about 1-5 TeV) reproduced by PYTHIA 8.2 with Monash 2013. Above, discrepancies observed with increasing $\sqrt{s}$
- NLO pQCD calculations generally overestimate data.

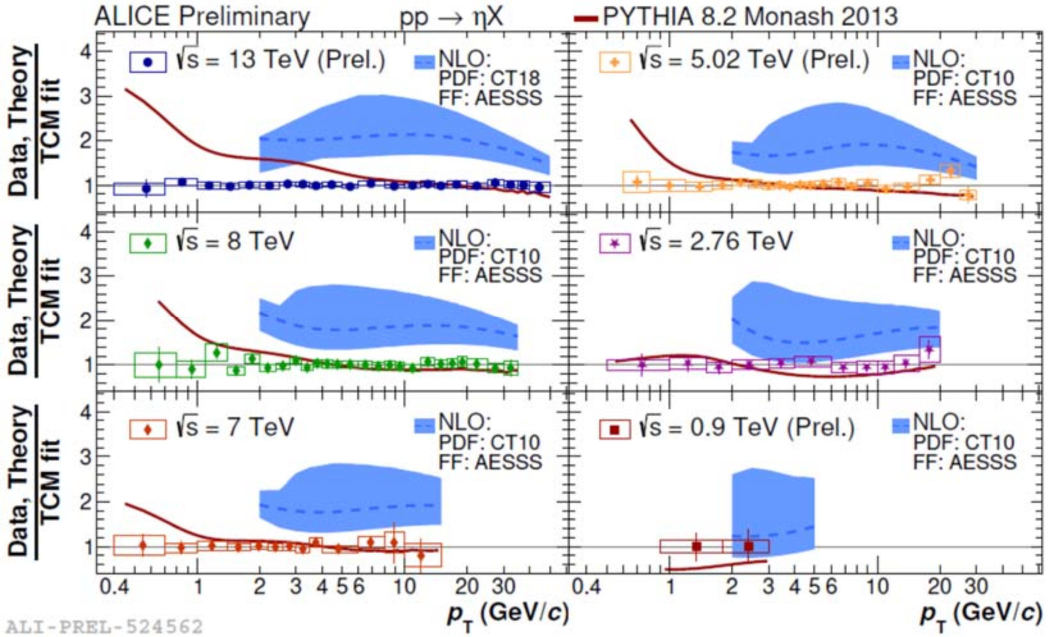


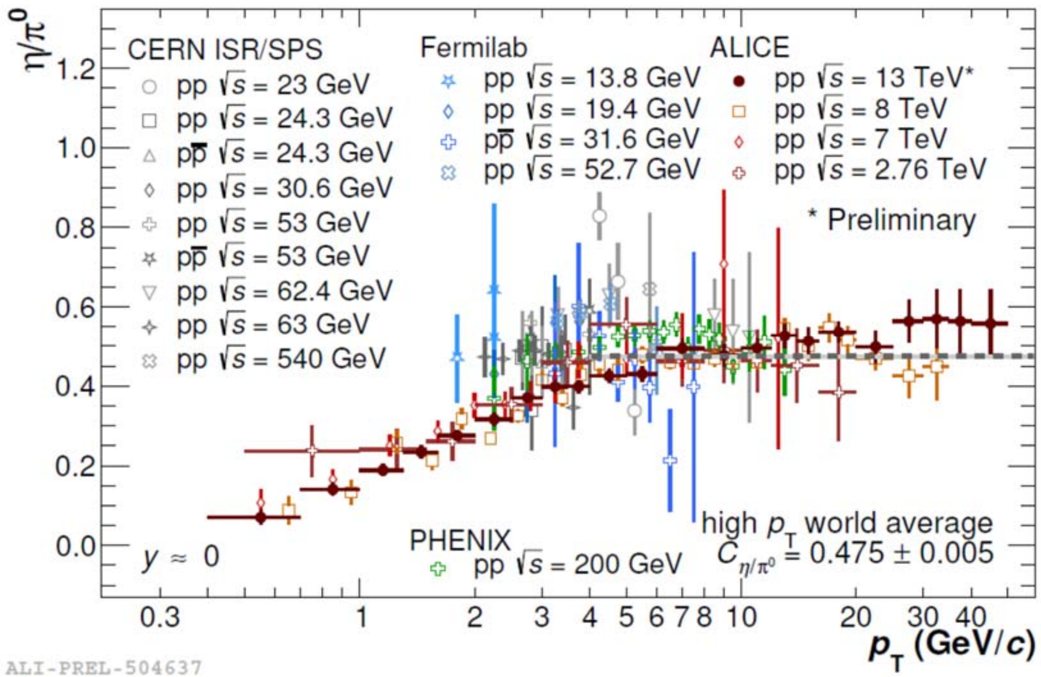


Eur. Phys. J. C 78 (2018) 263, Eur. Phys. J. C 77 (2017) 339, PLB 717 (2012) 162-172, Eur. Phys. J. C 74 (2014) 3108

η meson measurements in pp

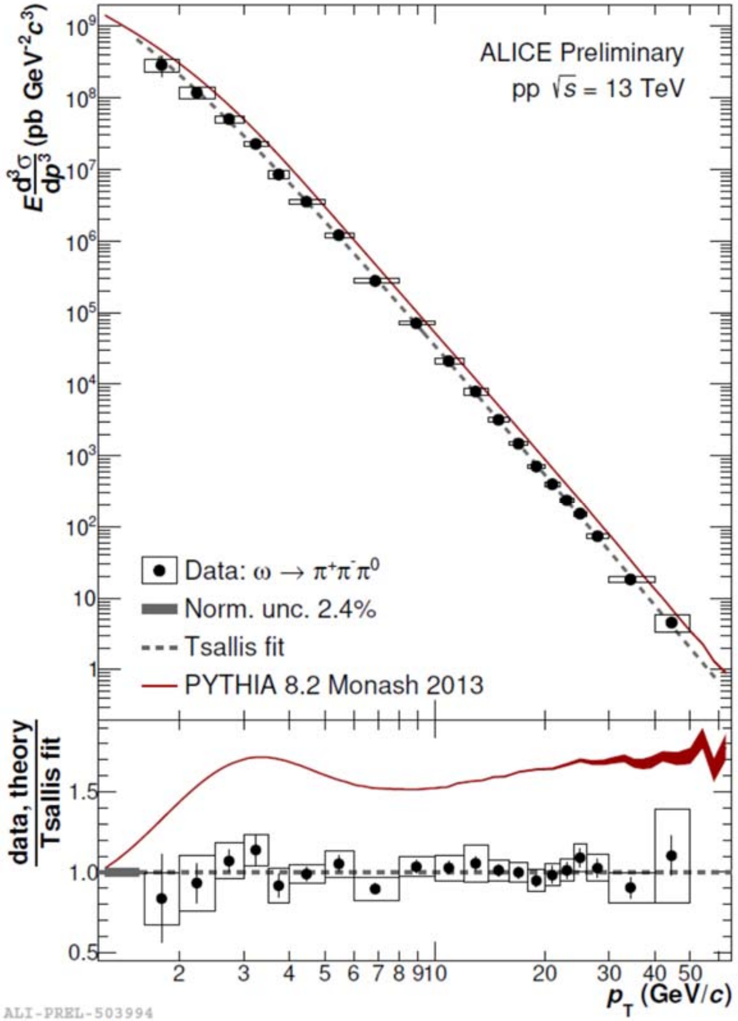
- **New results** for $\sqrt{s} = 13$ TeV
  Same observations as for π^0
- NLO pQCD calculations generally overestimate data.
- One of the reasons is not up-to-date FF parameterization for η
- $\eta/\pi^0 = 0.475 \pm 0.05$ for high p_T
  - ✓ universal behavior independent on collision energy

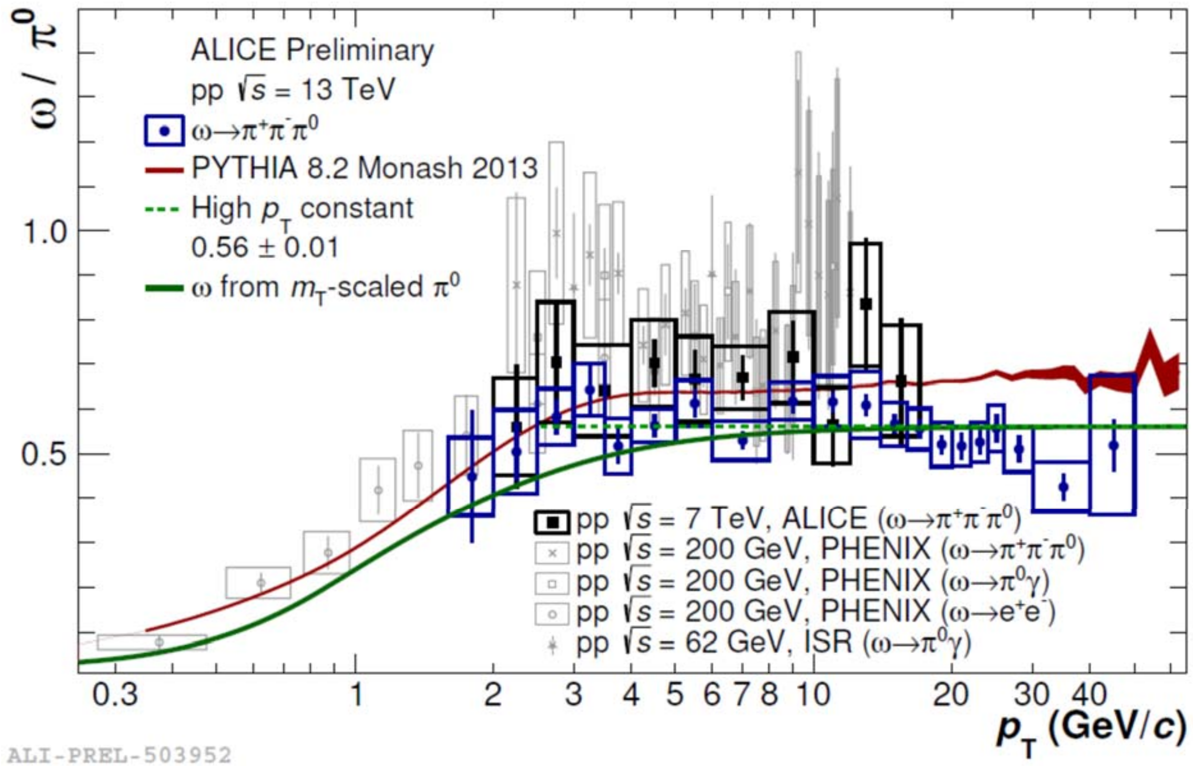




ω meson measurements in pp

- **New results** for $\sqrt{s} = 13$ TeV
- PYTHIA 8.2 with Monash 2013 tune overestimates data
- ω/π^0 is consistent with theory predictions and measurements at lower energies.

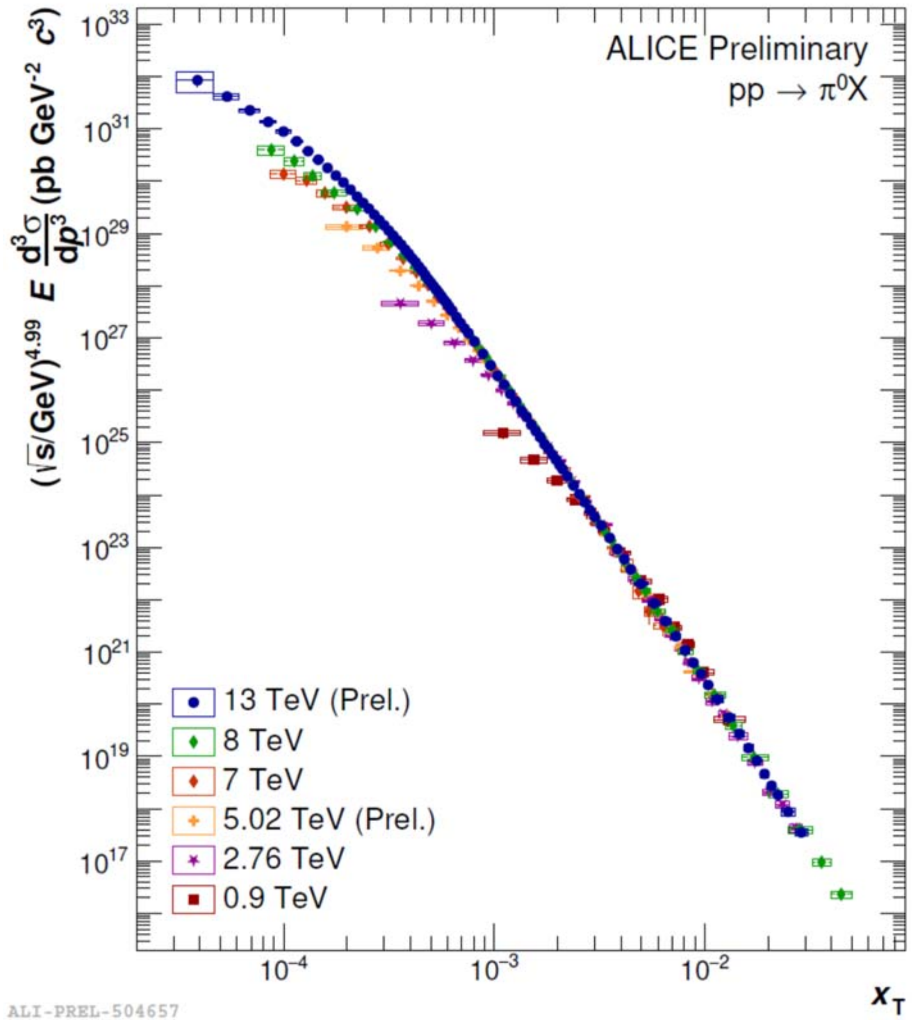




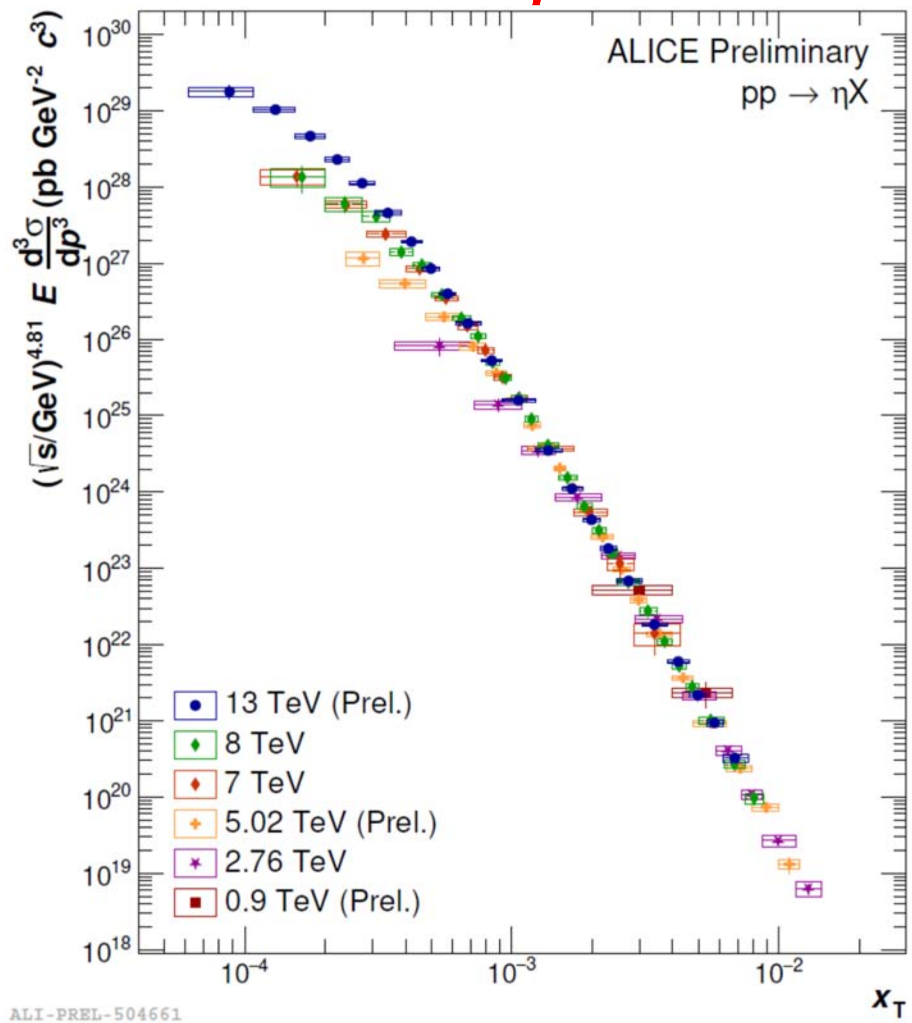
x_T scaling in pp

- Universal scaling of light neutral meson spectra for pp collisions with $x_T = 2\, p_T / \sqrt{s}$ if scaled by $\sqrt[n]{s}$
- $n = 4.99 \pm 0.05$
- **New results** for $\sqrt{s} = 13$ TeV in agreement with lower energies

π^0

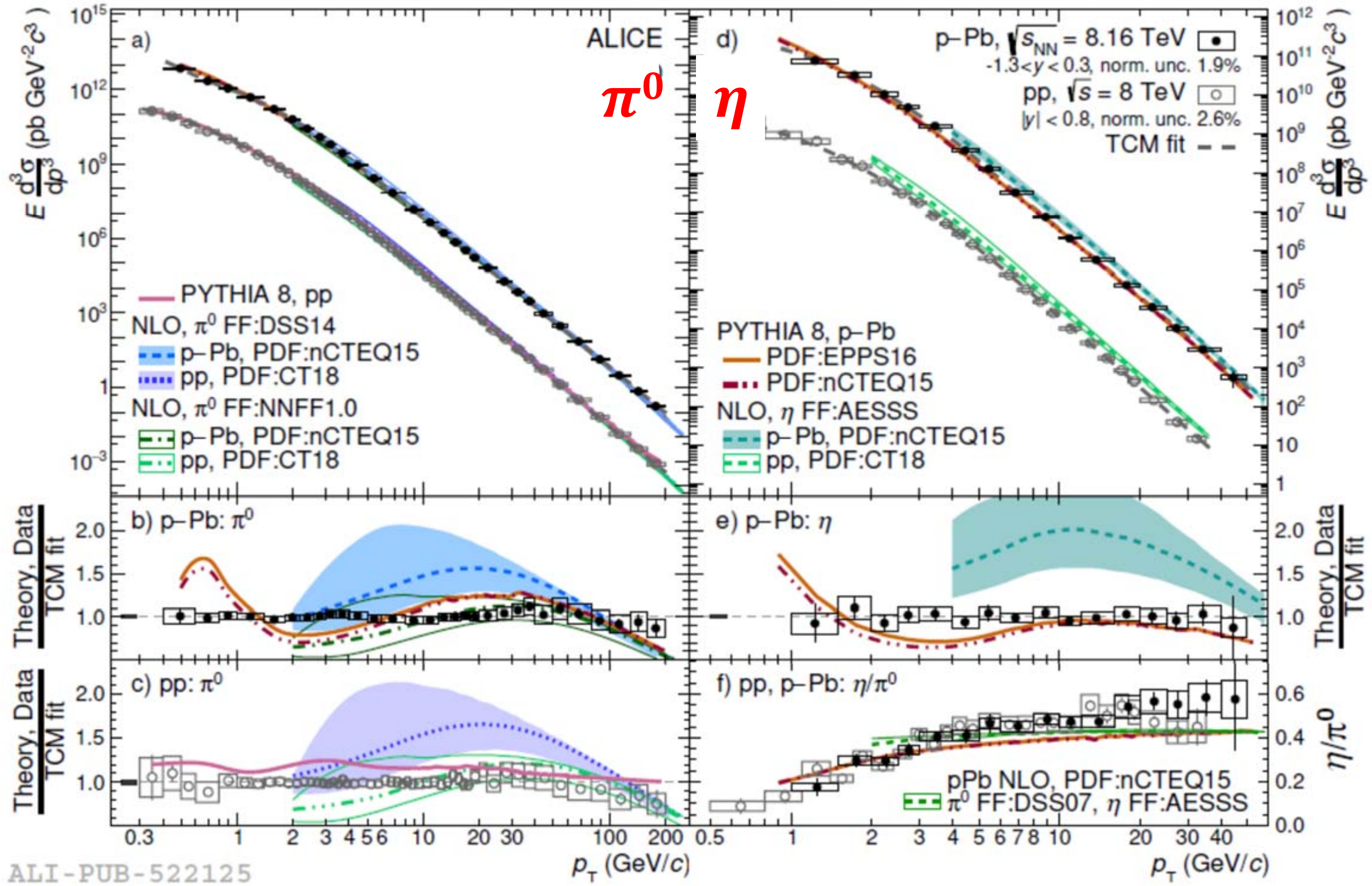


η



Neutral meson measurements in p–Pb

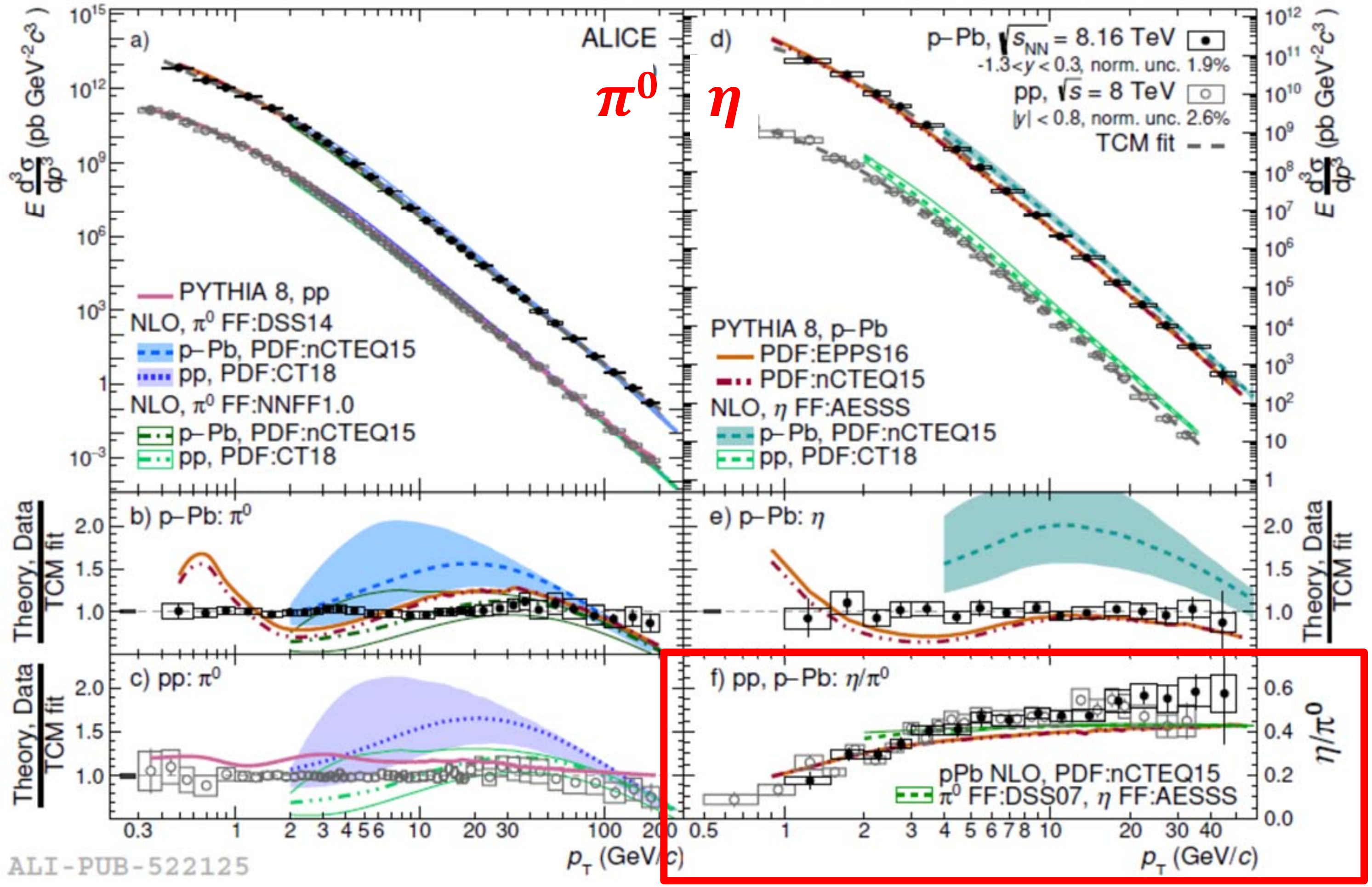
- $\sqrt{s_{NN}} = 8.16$ TeV: p_T range up to 200 GeV/c.
- Spectra:
  - ✓ NLO pQCD calculations overestimate data.
  - ✓ PYTHIA 8 does not describe the shape at low and high p_T.



Phys. Lett. B 827 (2022) 136943

Neutral meson measurements in p–Pb

- $\sqrt{s_{NN}} = 8.16$ TeV: p_T range up to 200 GeV/c.
- Spectra:
  - ✓ NLO pQCD calculations overestimate data.
  - ✓ PYTHIA 8 do not describe the shape at low and high p_T.
  - ✓ η/π^0 ratio: reproduced better by pQCD.



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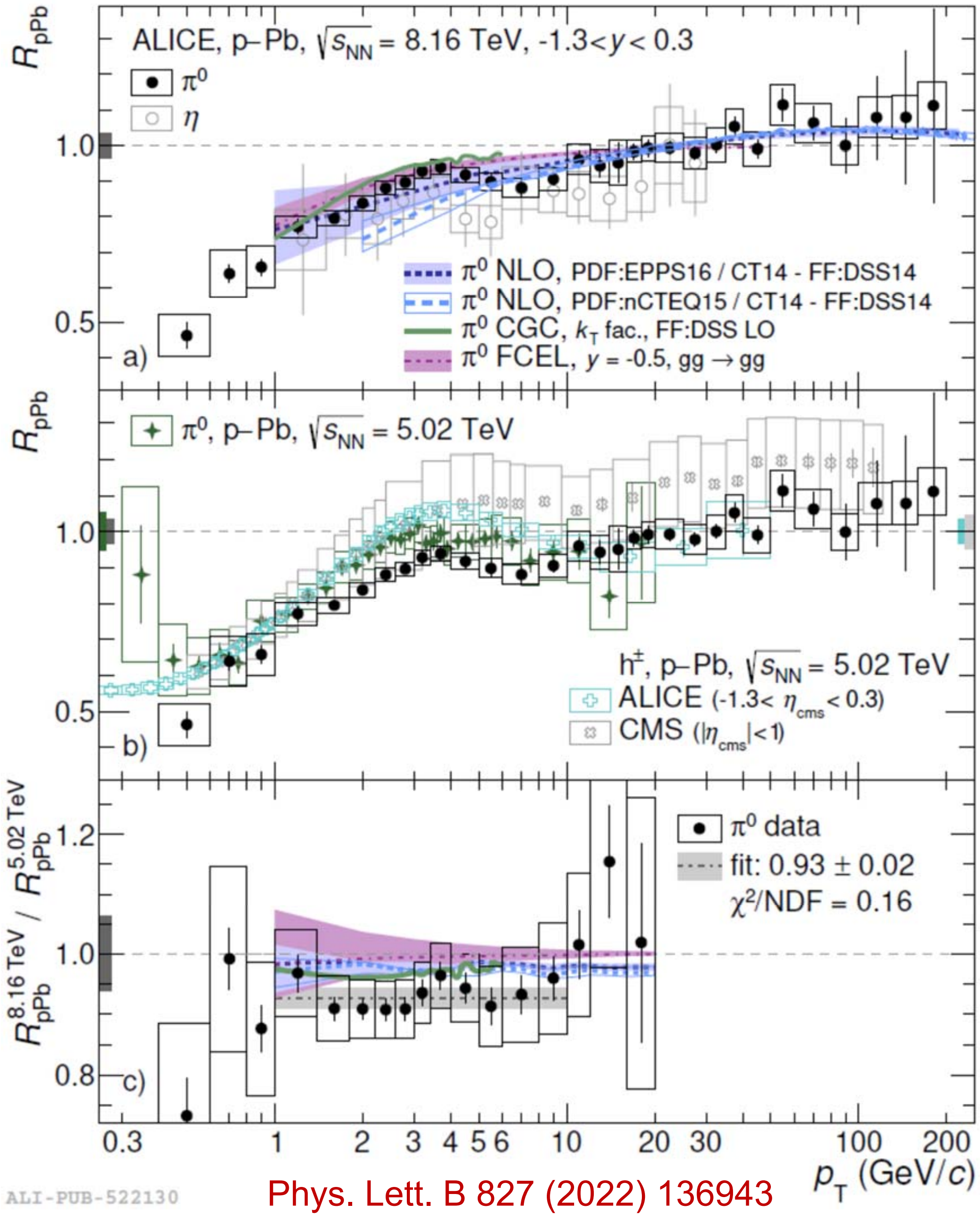
Neutral meson measurements in p–Pb

- Nuclear modification factor is used to study parton energy loss in pA and AA collisions:

$$R_{pA} = \frac{d^2N^{pA}/d\eta dp_T}{\langle N_{coll}\rangle\, d^2N^{pp}/d\eta dp_T}$$

$$R_{AA} = \frac{d^2N^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, d^2N^{pp}/d\eta dp_T}$$

- R_{pPb} is consistent with unity above 10 GeV/c and shows suppression below.
- Consistent with theory predictions.



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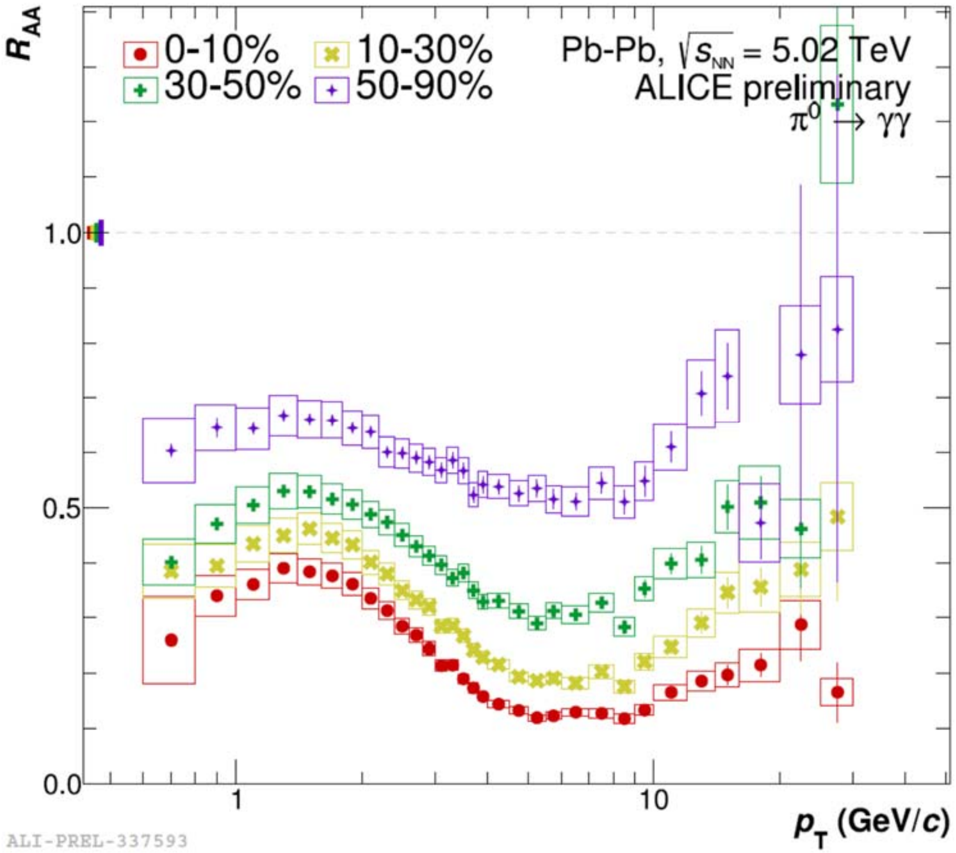
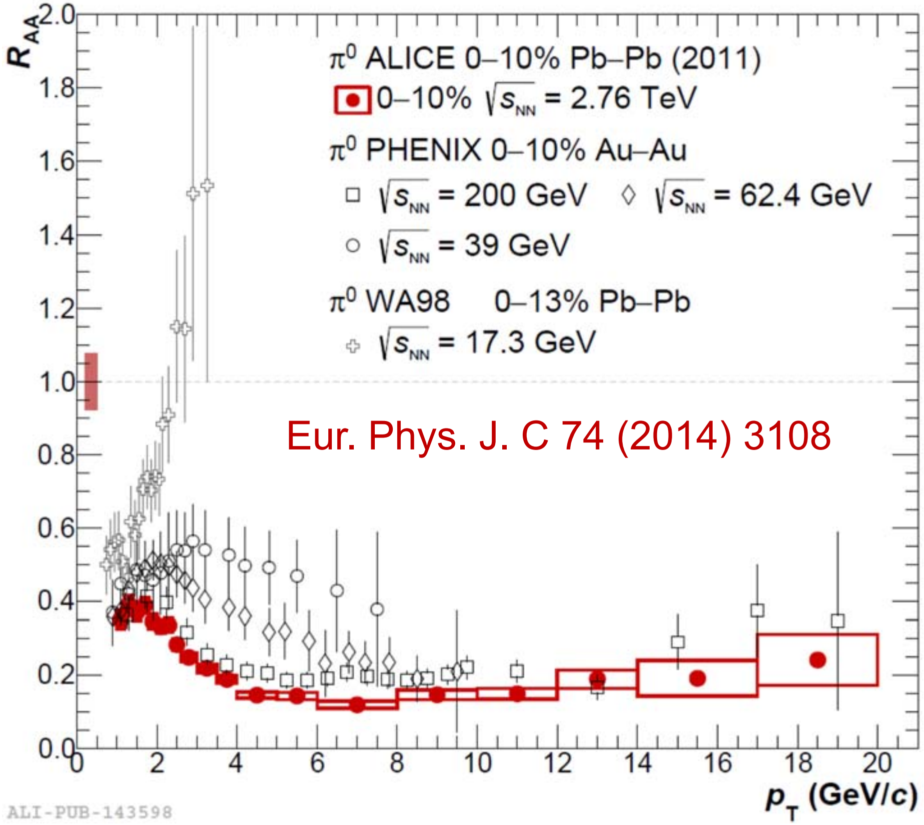
Neutral meson measurements in Pb–Pb

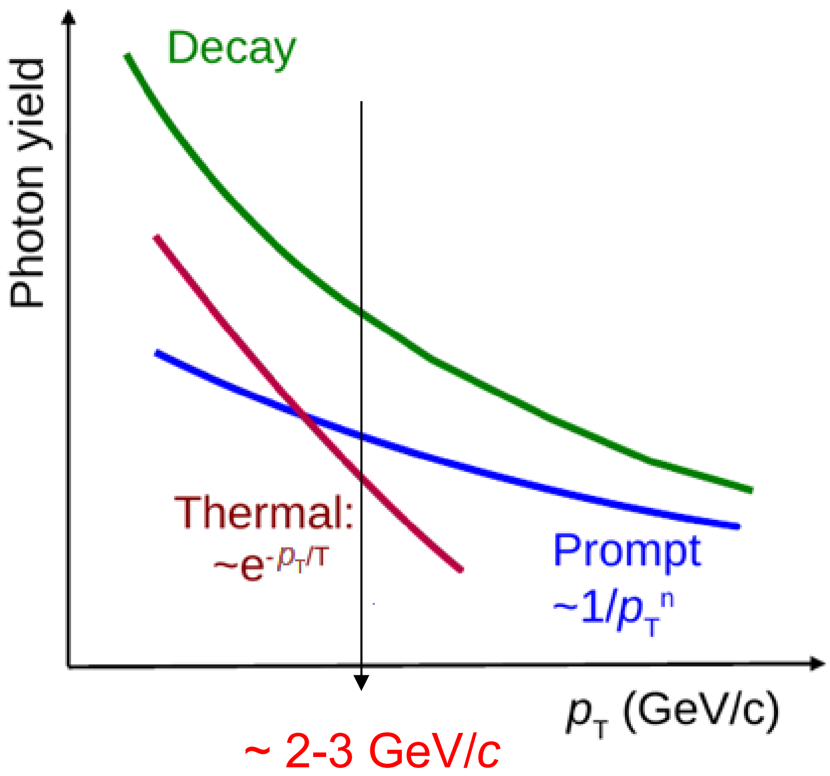
- π^0 R_{AA} from Run 2 Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV:
  - ✓ Similar magnitude of suppression as at $\sqrt{s_{NN}} = 2.76$ TeV
  - ✓ $0.6 < p_T < 30$ GeV/c

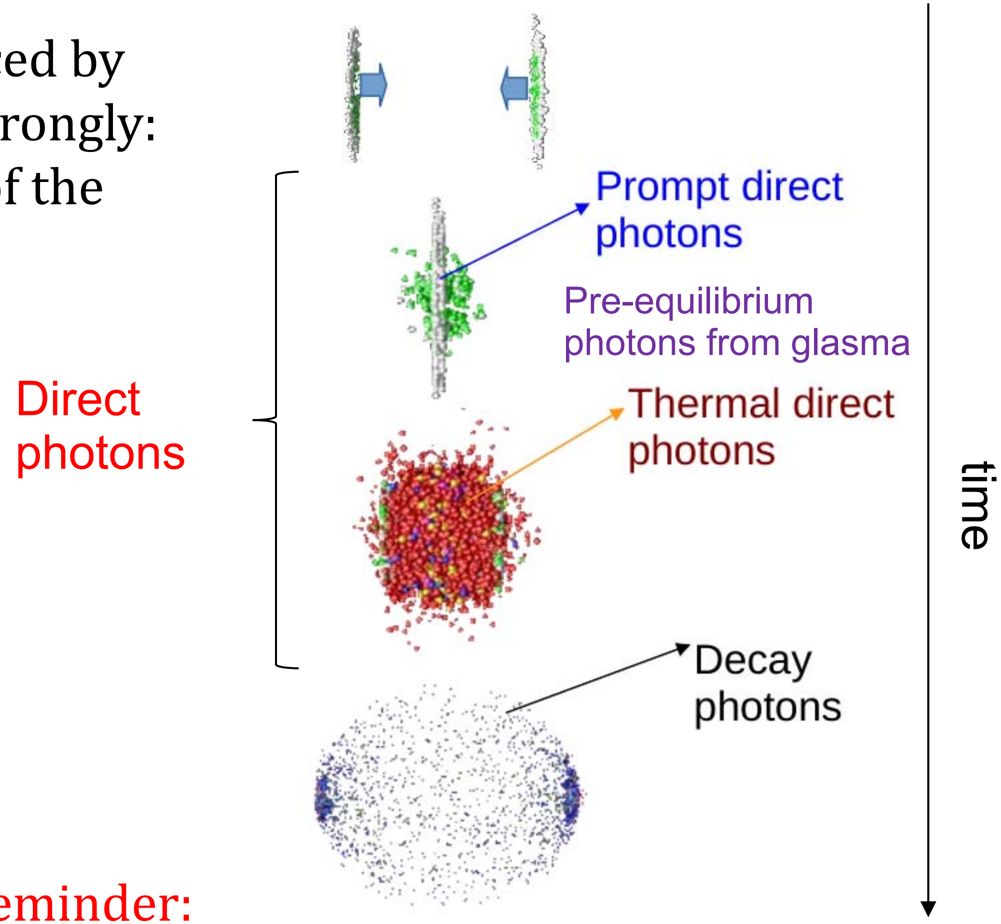




Direct photons – a probe to study QGP

- Photons in heavy-ion collisions are produced by different mechanisms and don't interact strongly: carry out information about the dynamic of the collision.





Reminder:

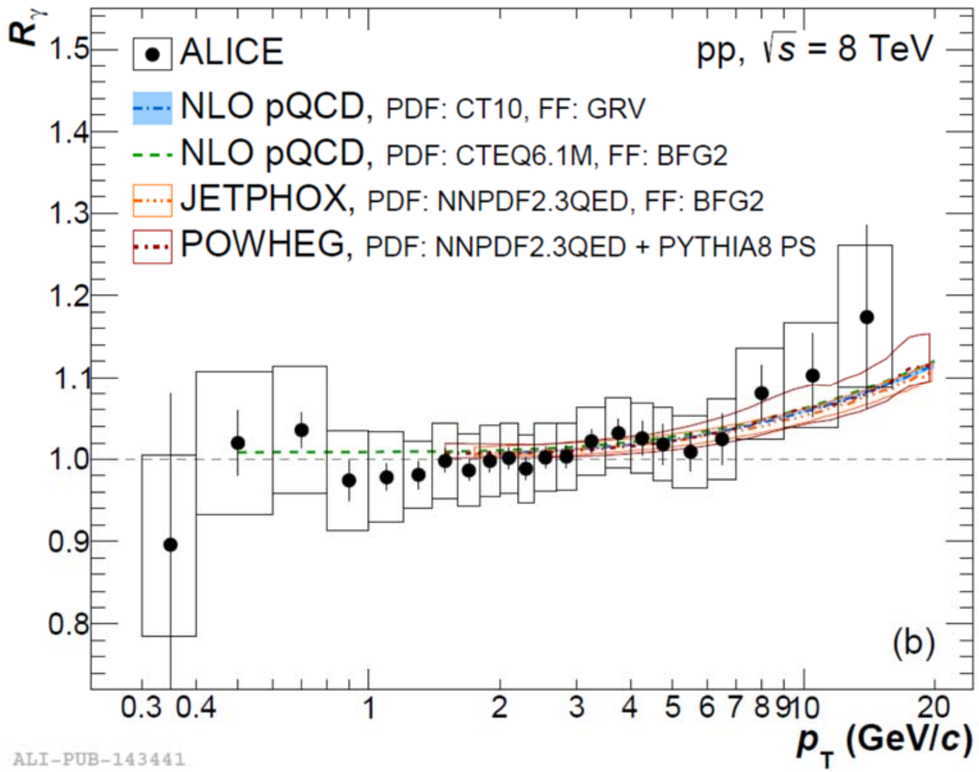
- High p_T: test of initial conditions:
  - Number of binary nucleon-nucleon collisions (N_{coll}) scaling
  - PDF modification
- Low p_T: test of hot matter evolution:
  - spectrum
  - collective flow

Direct photons in pp and p–Pb collisions

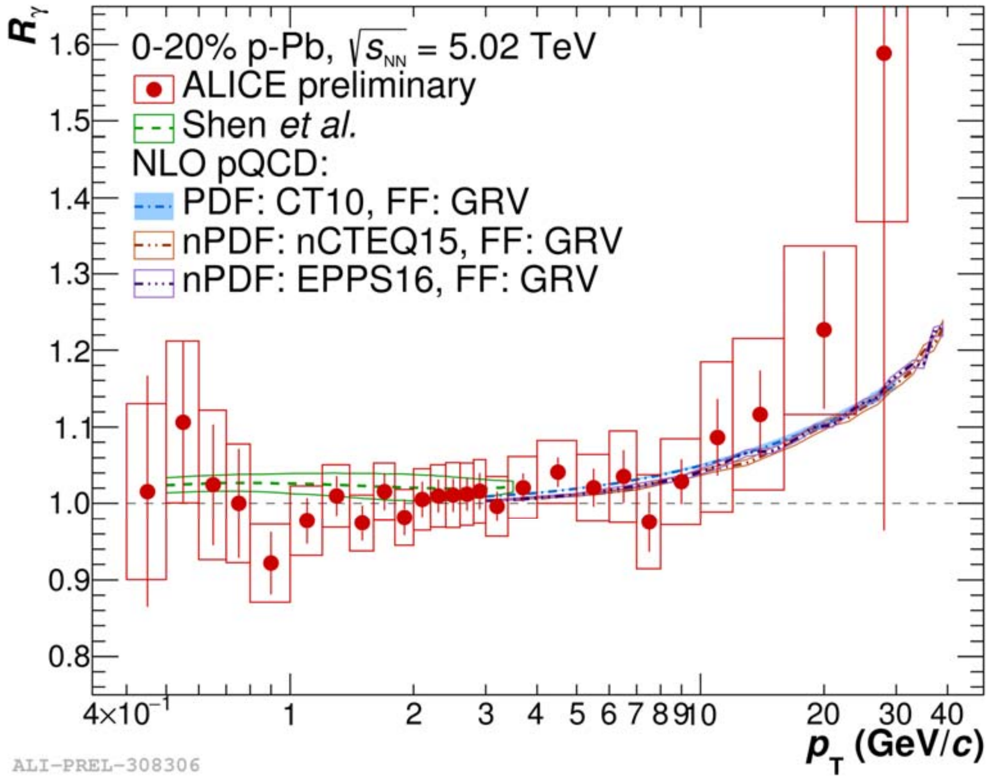
$$R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} \approx \frac{\gamma_{\text{inc}}/\pi^0}{\gamma_{\text{decay}}/\pi^0_{\text{param}}}$$

- High p_T (>4 GeV/c) – in agreement with pQCD
- Low p_T (<2-3 GeV/c) – no thermal radiation excess visible within uncertainties
- Data reproduced by NLO pQCD calculations and NLO Monte Carlo generators

pp at $\sqrt{s} = 8$ TeV



High multiplicity p − Pb collisions

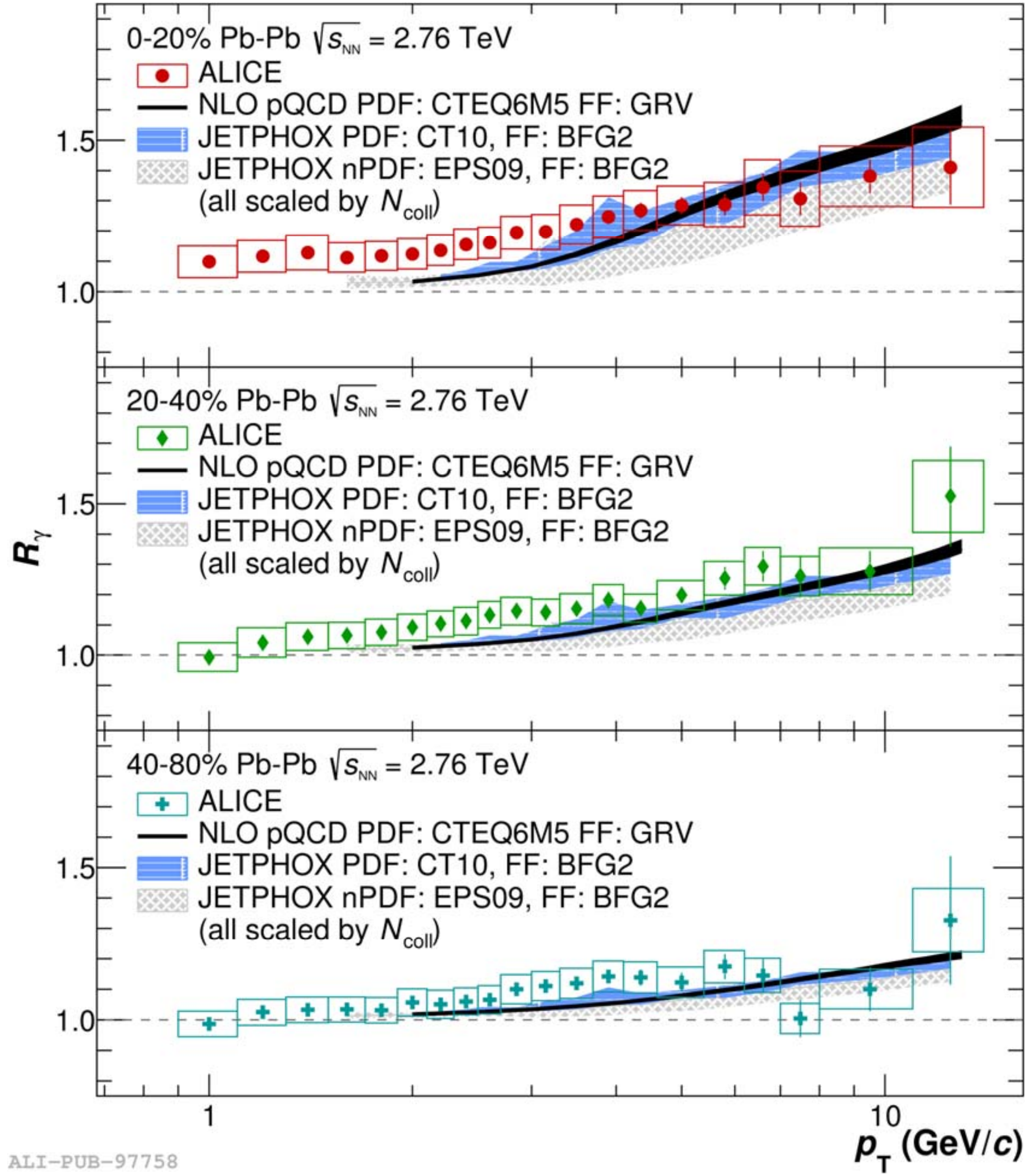


Phys. Rev. C 99 (2019) 024912
Hydro calculations: C. Shen et al. Phys. Rev. C95 (2017) 014906

Direct photons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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

- ✓ At low p_T (<2-3 GeV/c): hint for an excess above pQCD
  - ~ 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

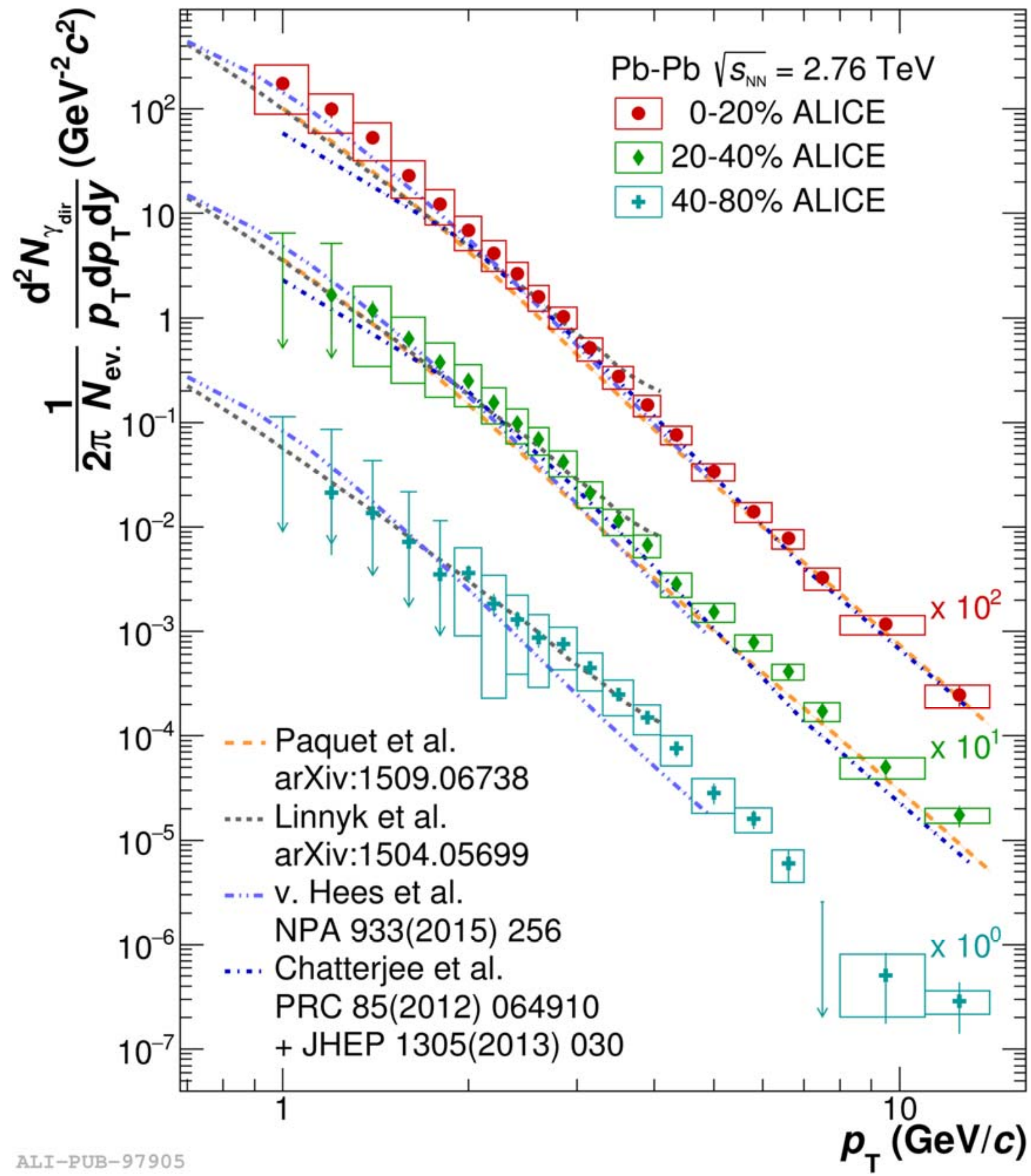


Phys. Lett. B 754 (2016) 235

Direct photons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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

Hydro models including thermal and pre-equilibrium photons can reproduce the data within uncertainties

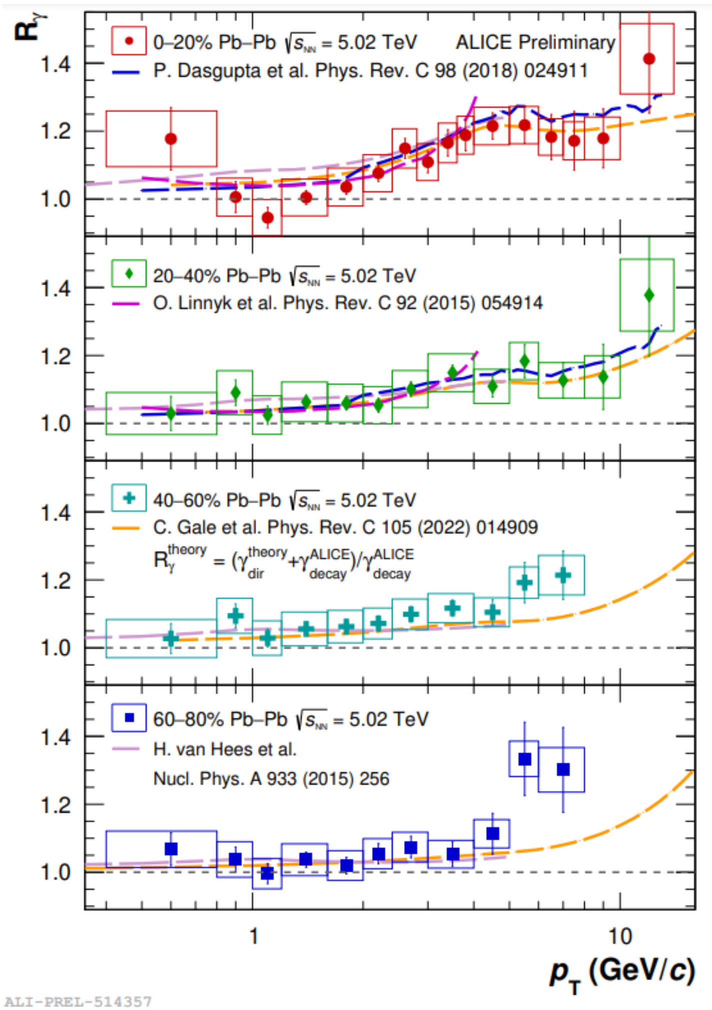


Phys. Lett. B 754 (2016) 235

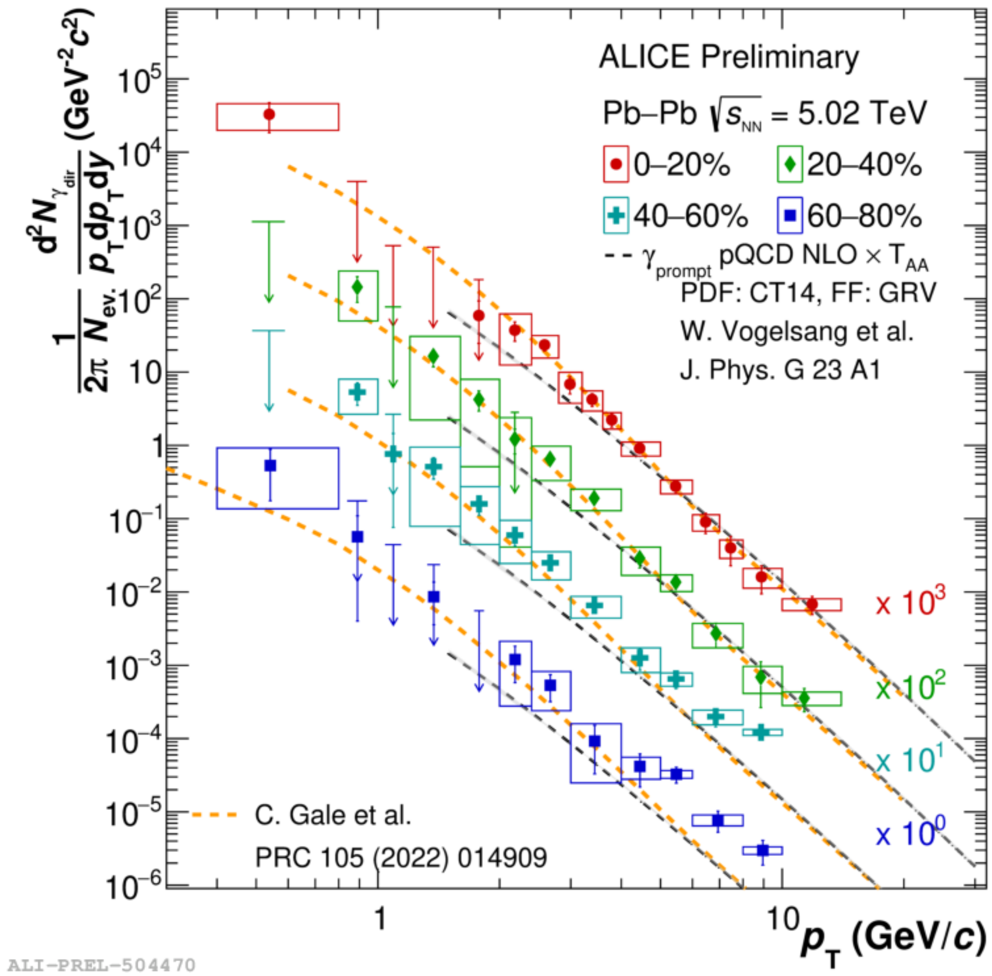
Direct photons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- ✓ At low p_T (<2-3 GeV/c) consistent with unity (large uncertainties)
- ✓ At high p_T (above ~5 GeV/c) in agreement with NLO pQCD

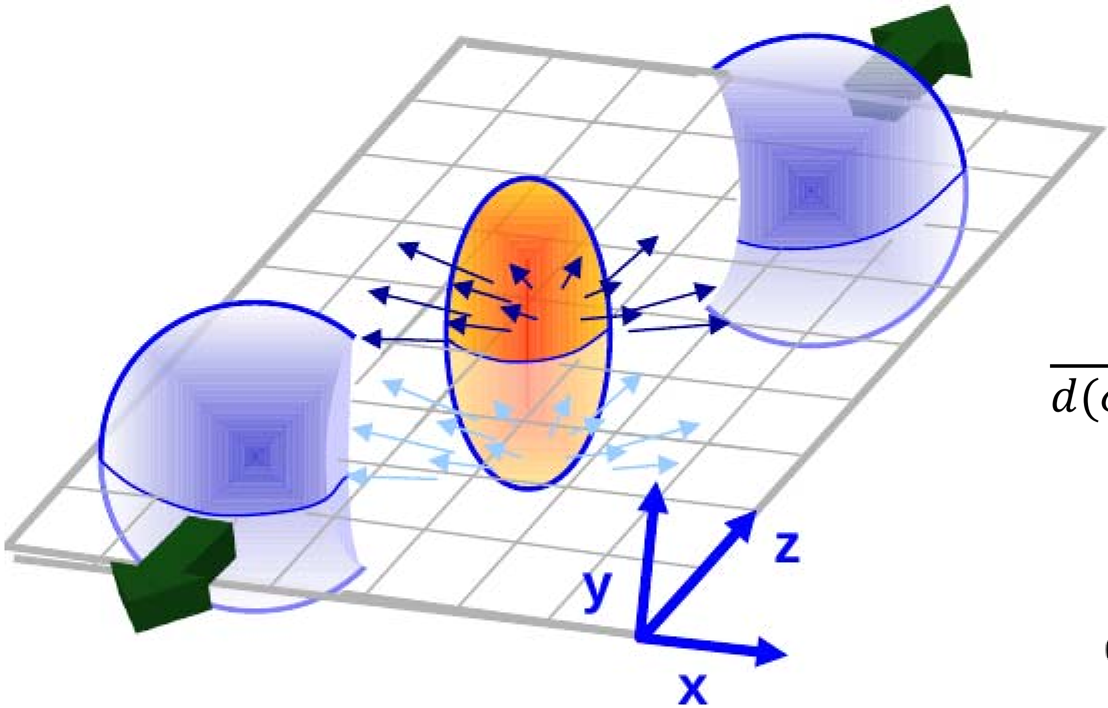
Different models (pQCD, microscopic transport, hydrodynamical) reproduce data: can't favor any one of them



NEW!



Direct photon flow – an unsolved puzzle?

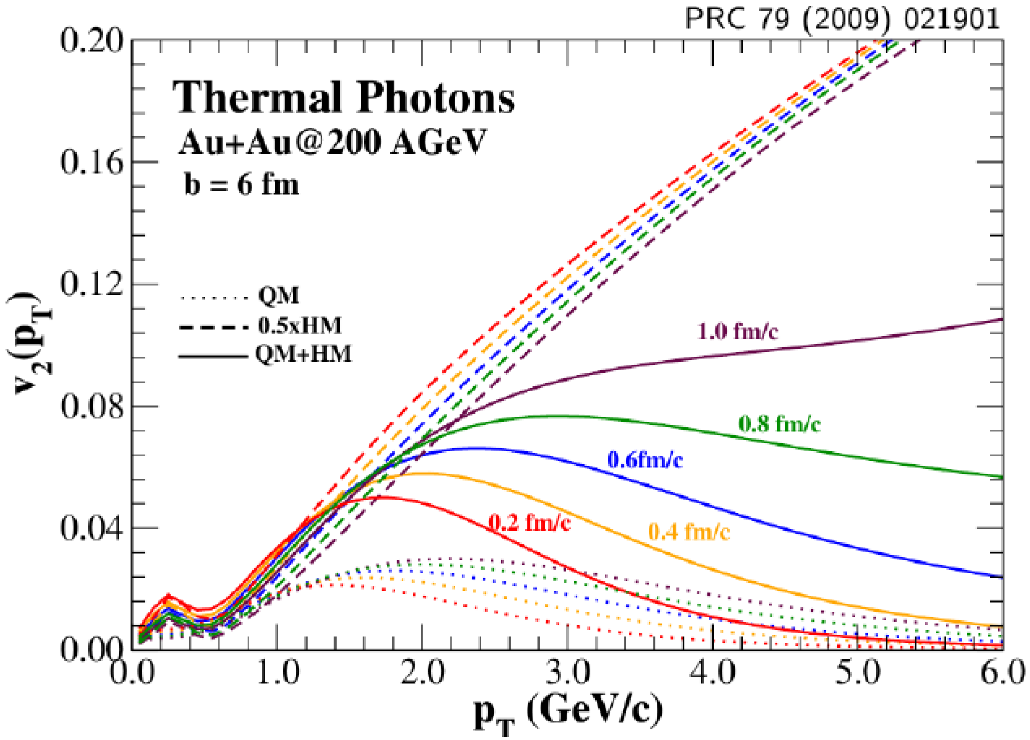


Collective expansion transforms initial spatial asymmetry of fireball to asymmetry in momentum space

$$\frac{dN}{d(\varphi - \Psi_{RP})} \sim 1 + 2\sum_{i=1} v_n(p_T, \eta)\cos[n(\varphi - \Psi_{RP})]$$

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

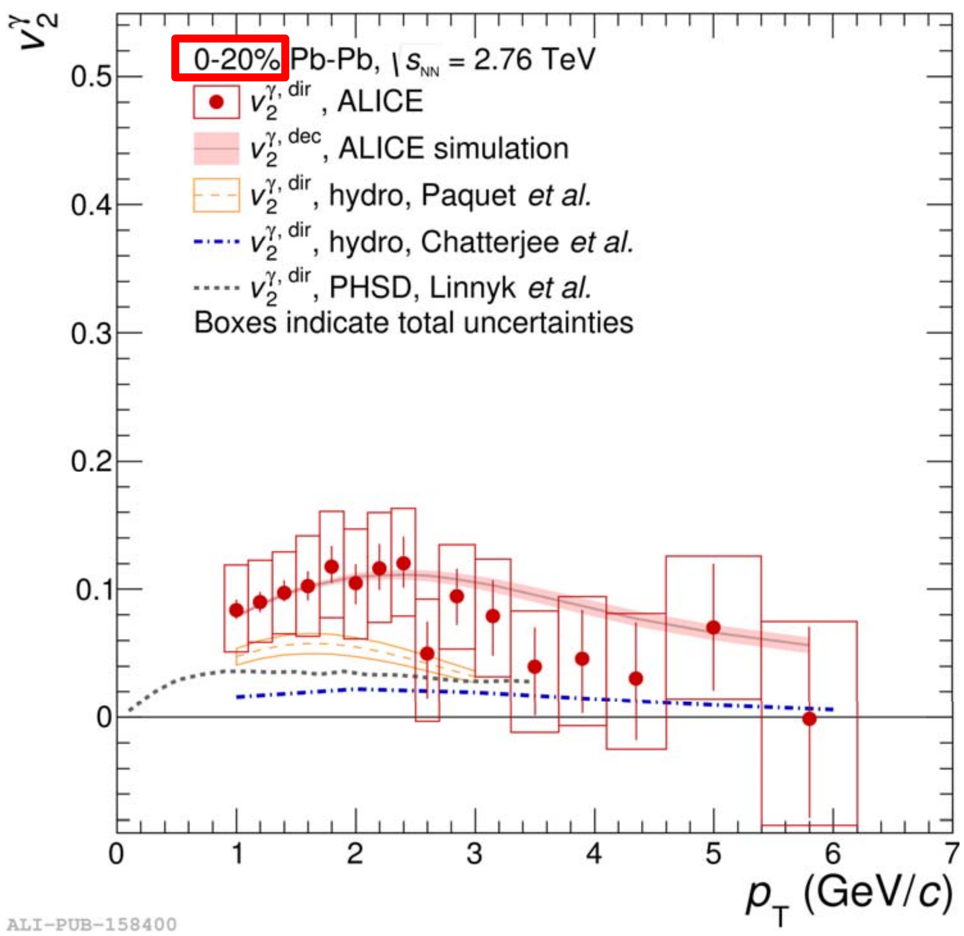
Thermal photons, emitted early from hotter fireball carry smaller collective flow than those, emitted at later stages => one can test development of collective flow with direct photons

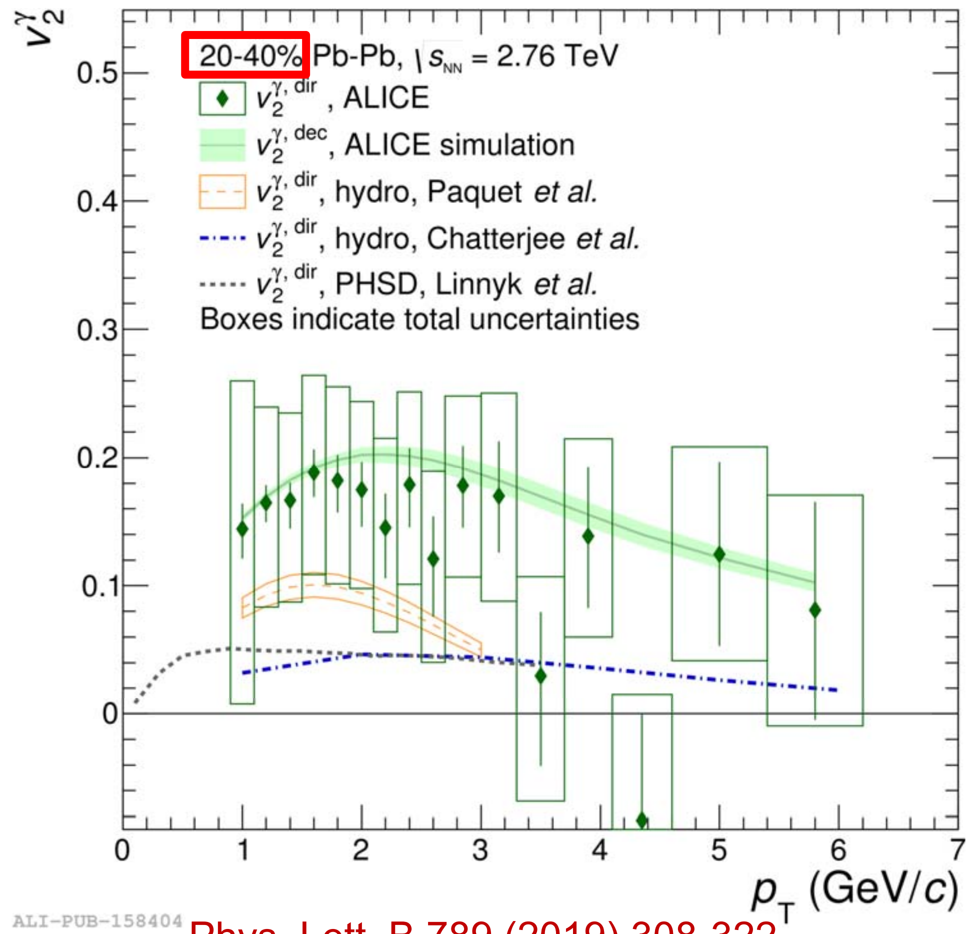


Direct photon flow in Pb–Pb collisions

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

- Large v_2 for $p_T < 3$ GeV/c, comparable to hadron flow (for 20-40% - too large uncertainties for conclusions)
- Hydro models tend to underpredict direct photon flow
- Hint for late direct photon production and/or early flow formation





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

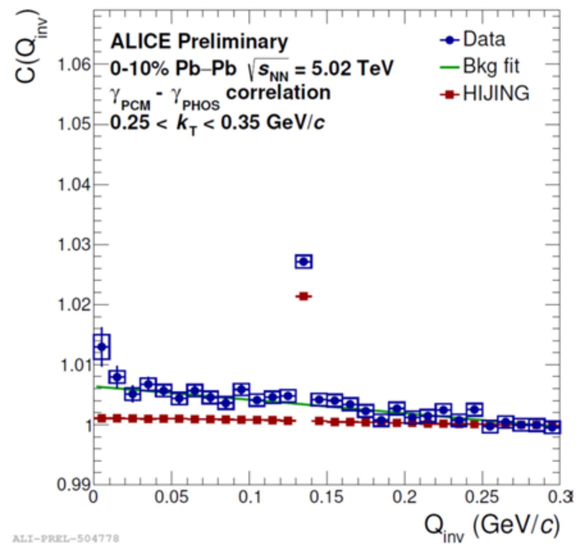
Conclusions

- Neutral meson spectra in pp, p–Pb and Pb–Pb collisions measured to large p_{T} constrain models
  - New results in pp at $\sqrt{s} = 13$ TeV and p–Pb at $\sqrt{s_{NN}} = 8.16$ TeV with unprecedented p_{T} coverage

- Direct photons suggest creation of hot matter in Pb–Pb collisions with significant collective expansion
  - New results in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV are dominated with statistical and systematical uncertainties.

- Expect higher precision with Run 3 data (~ 100 times more data)
  - ✓ Access to further observables e.g. HBT measurements

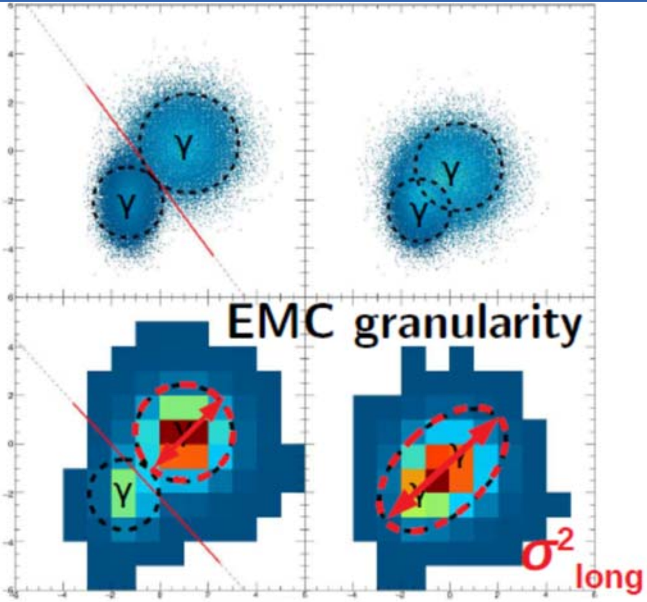
First look with Run 2 data



Research is supported by grant RSF 22-42-04405

Backup slides

Merged clusters method for neutral mesons measurements



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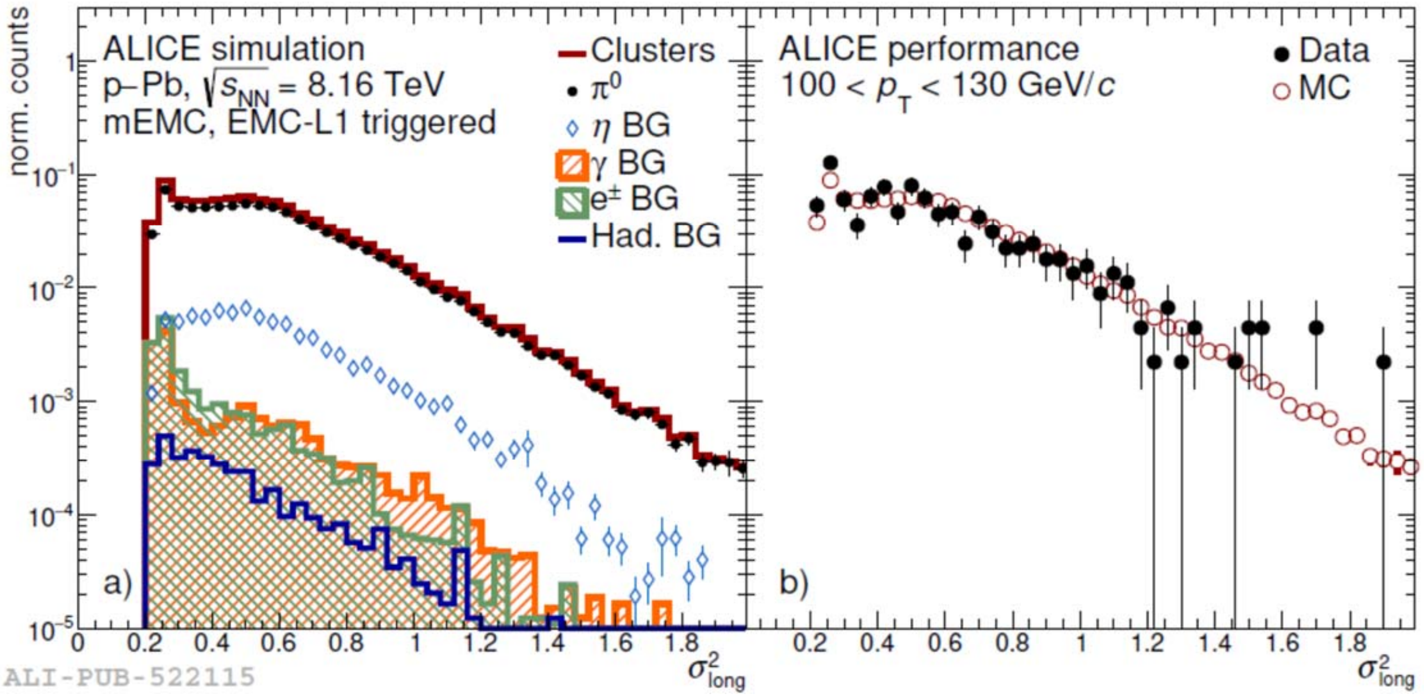
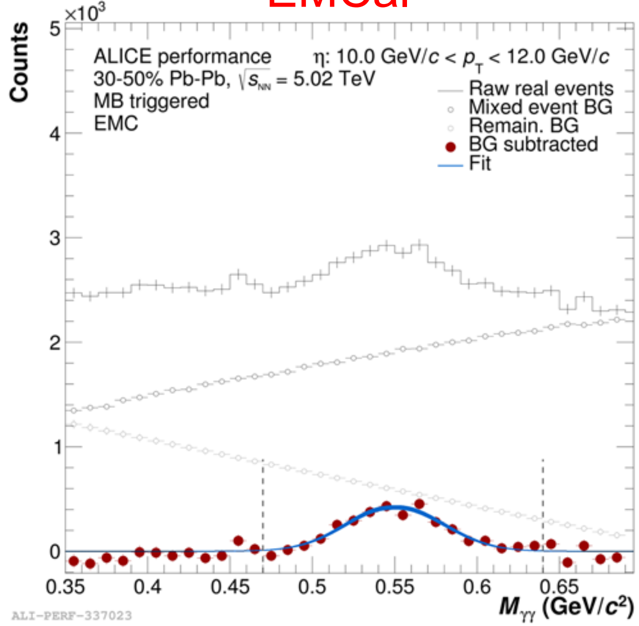
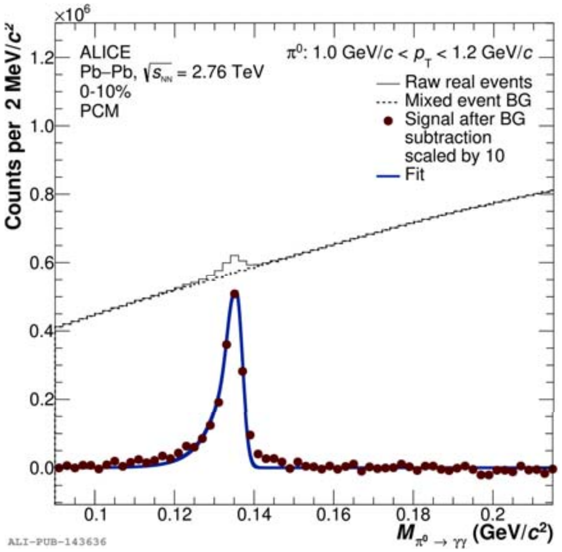


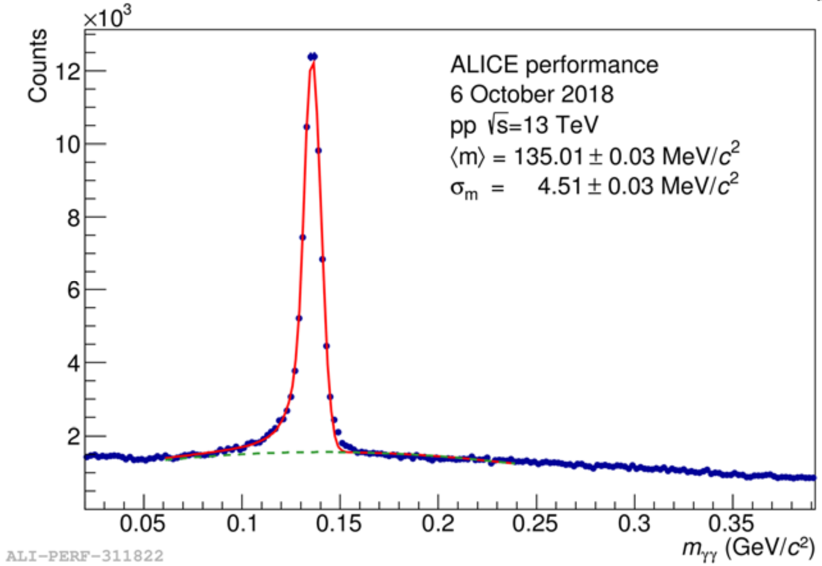
Physics performance: neutral meson measurements

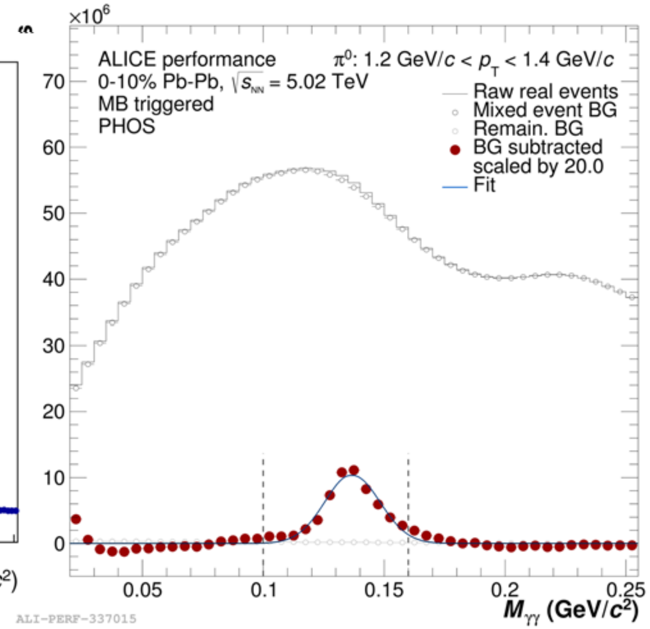
- PHOS, EMCal, PCM are able to reconstruct neutral mesons in low and high multiplicity environments down to low p_T
- Excellent precision and p_T range thanks to combination of all methods

EMCal







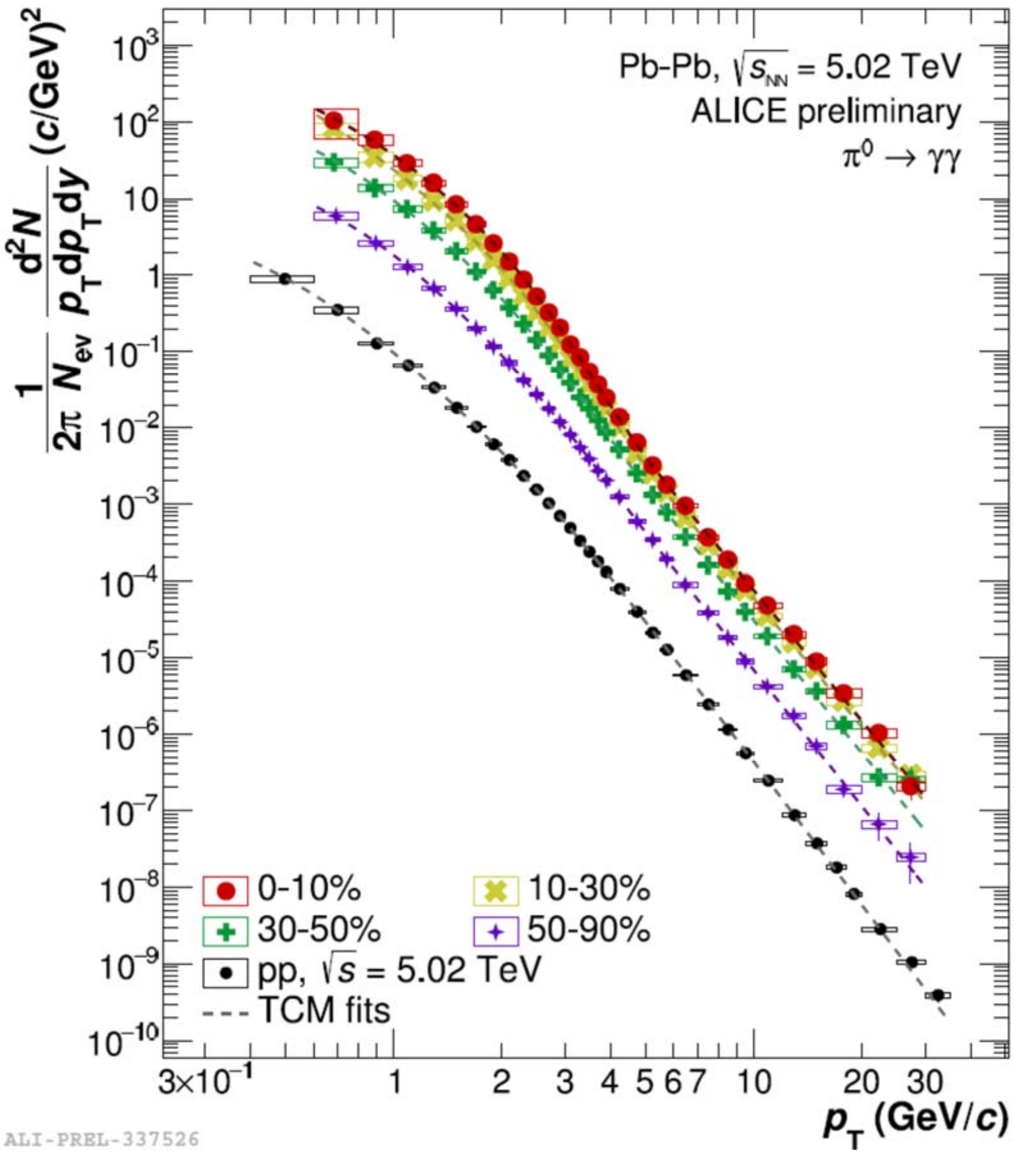


PCM

PHOS

Neutral meson measurements in Pb-Pb

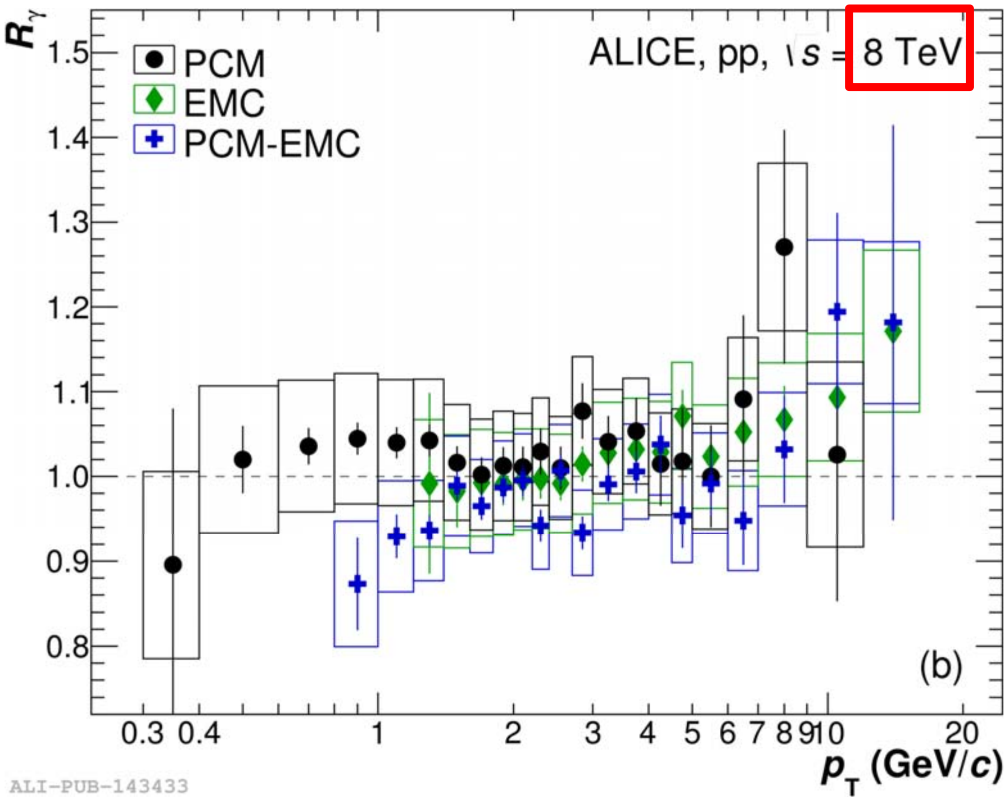
- Study parton energy loss in hot medium via π^0 and η spectra modification relative to pp collisions (R_{AA})

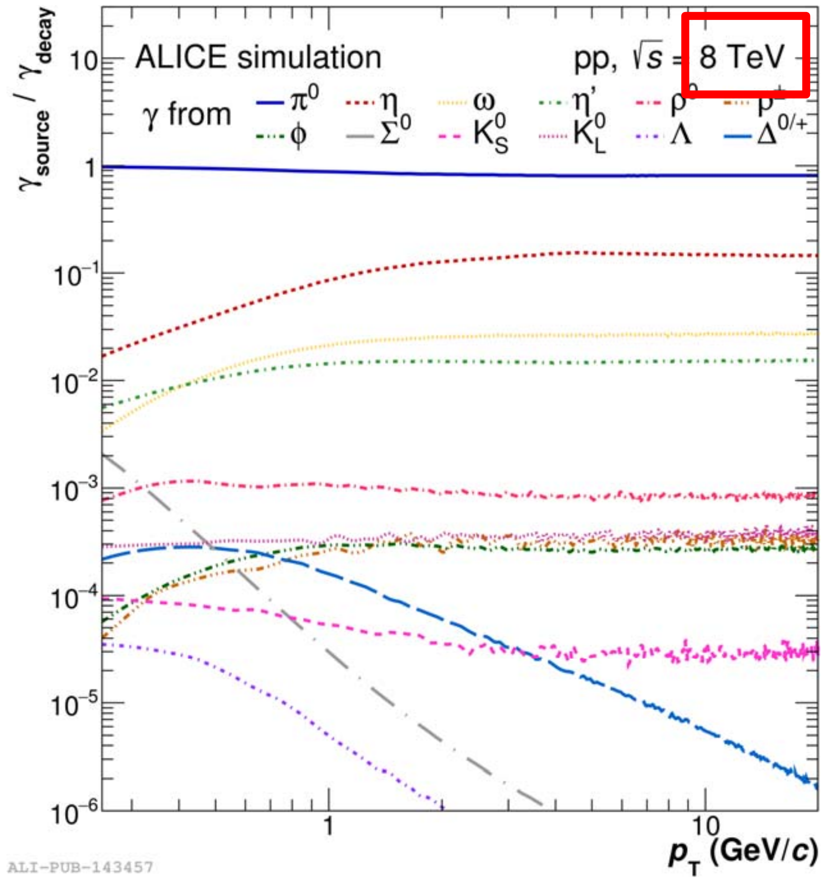


Direct photons in pp collisions

- 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

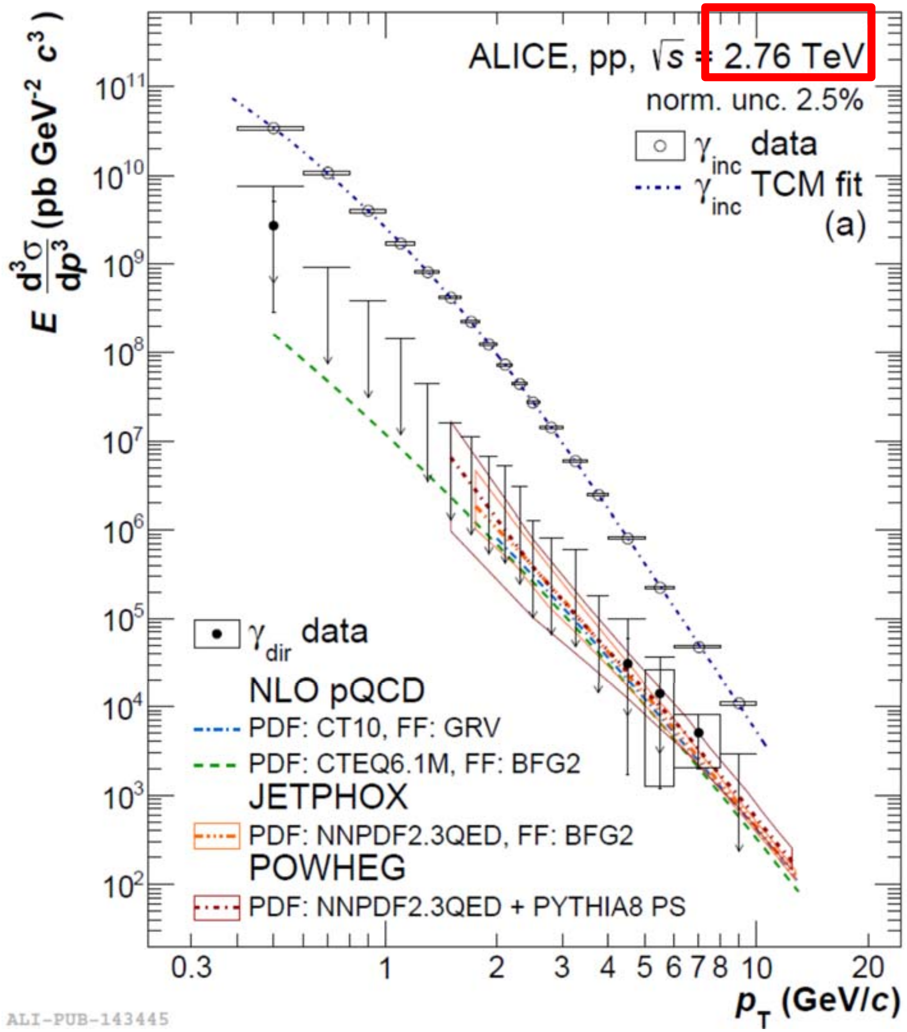


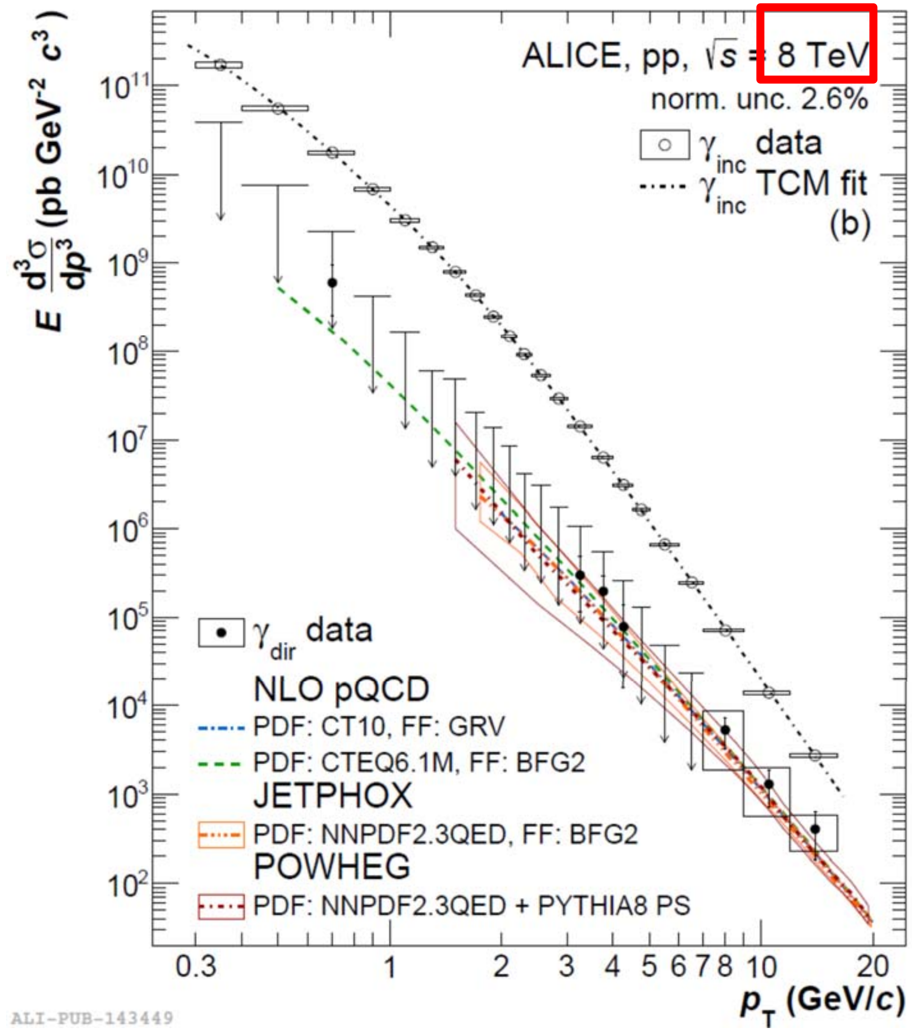


Phys. Rev. C 99 (2019) 024912

Direct photons in pp collisions

- NLO pQCD calculations are able to reproduce measurements





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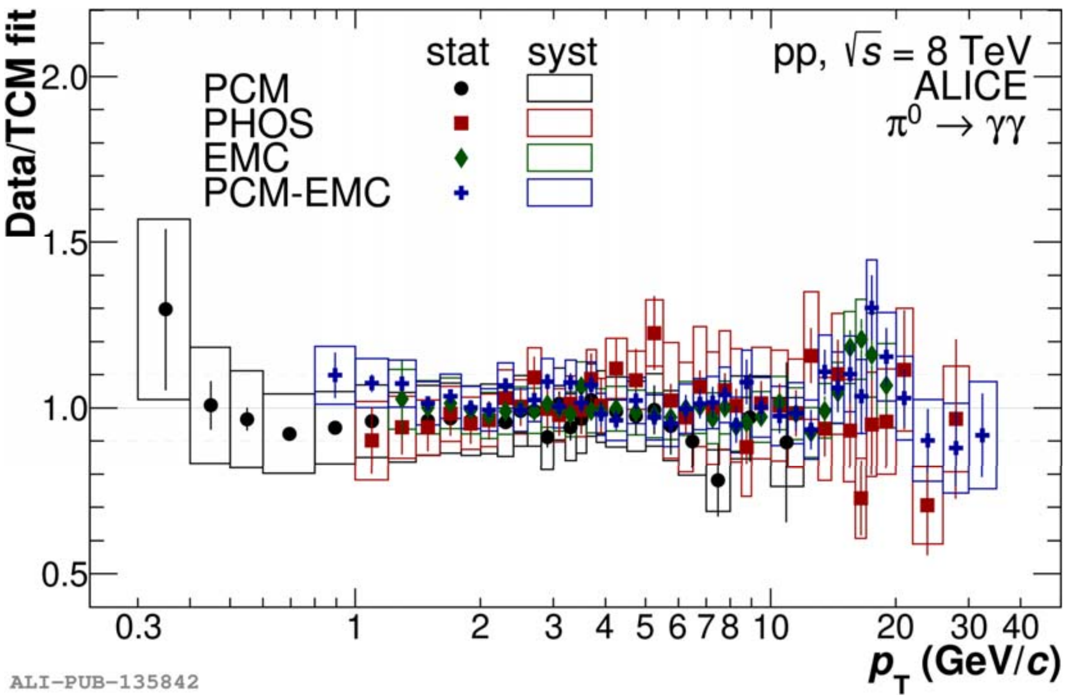
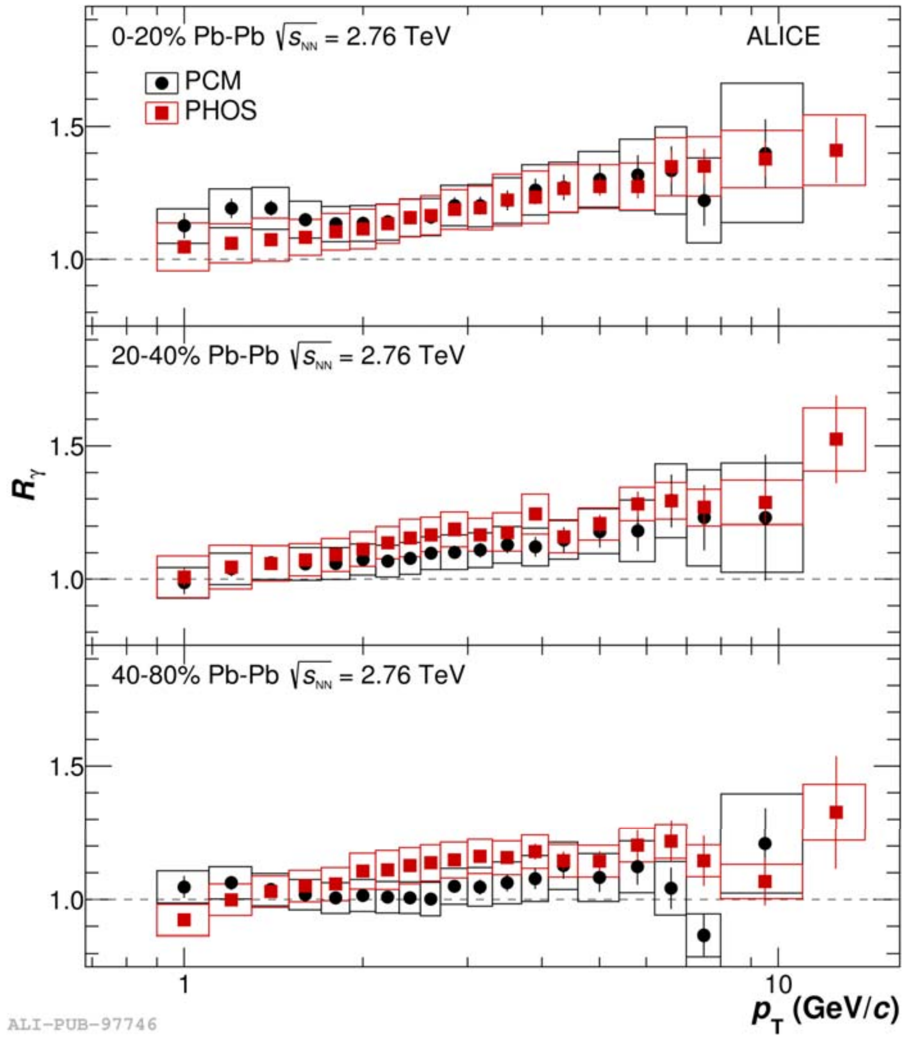
Comparison of methods

- Different measurements produce consistent results

Direct photons in Pb-Pb

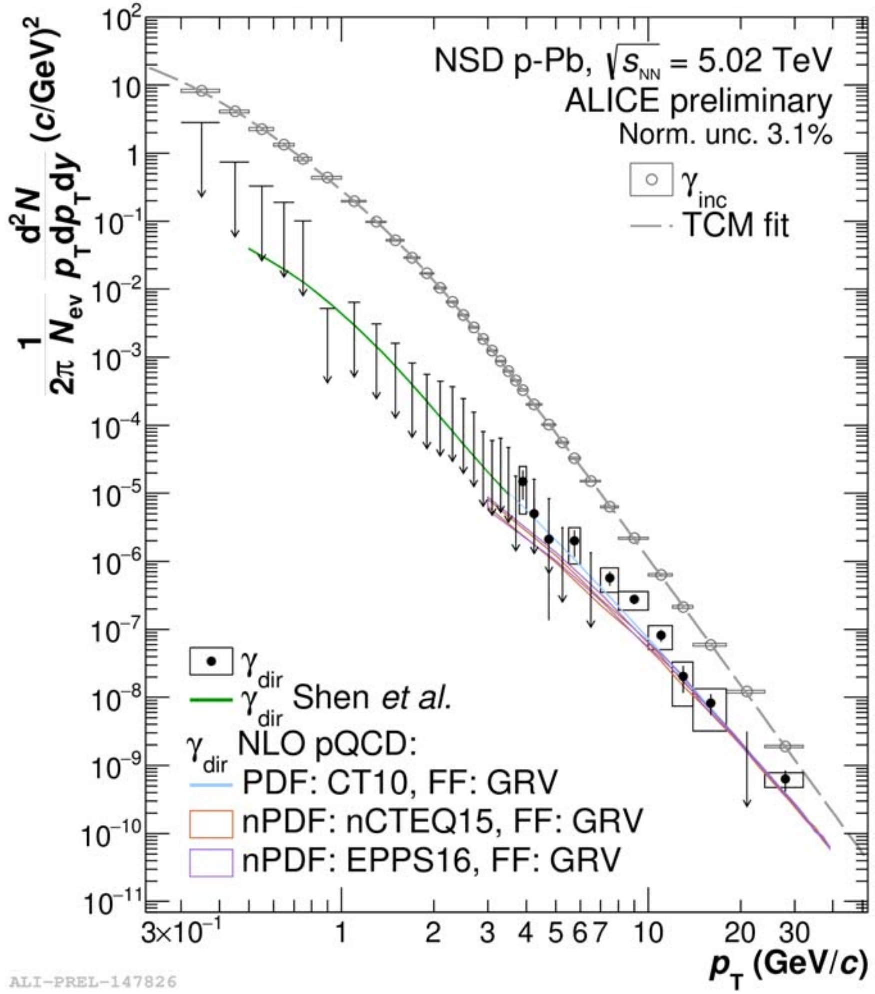
Neutral mesons

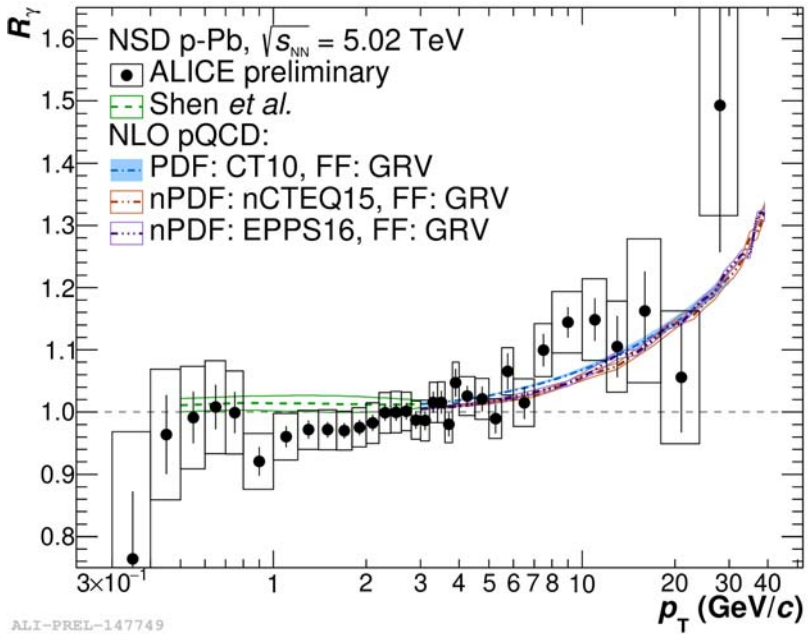


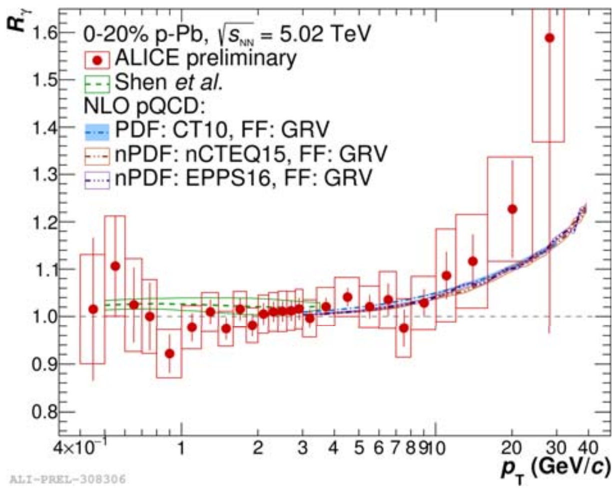


Direct photons in p-Pb collisions

- 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 at low p_{T} within uncertainties, even in most central 0-20% centrality



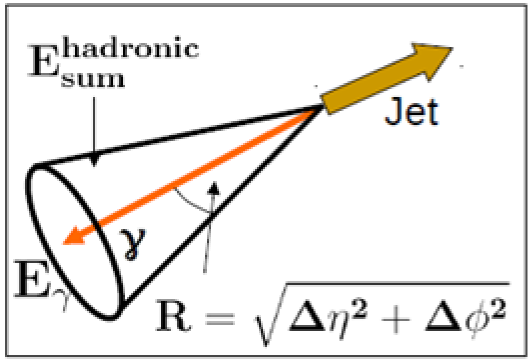


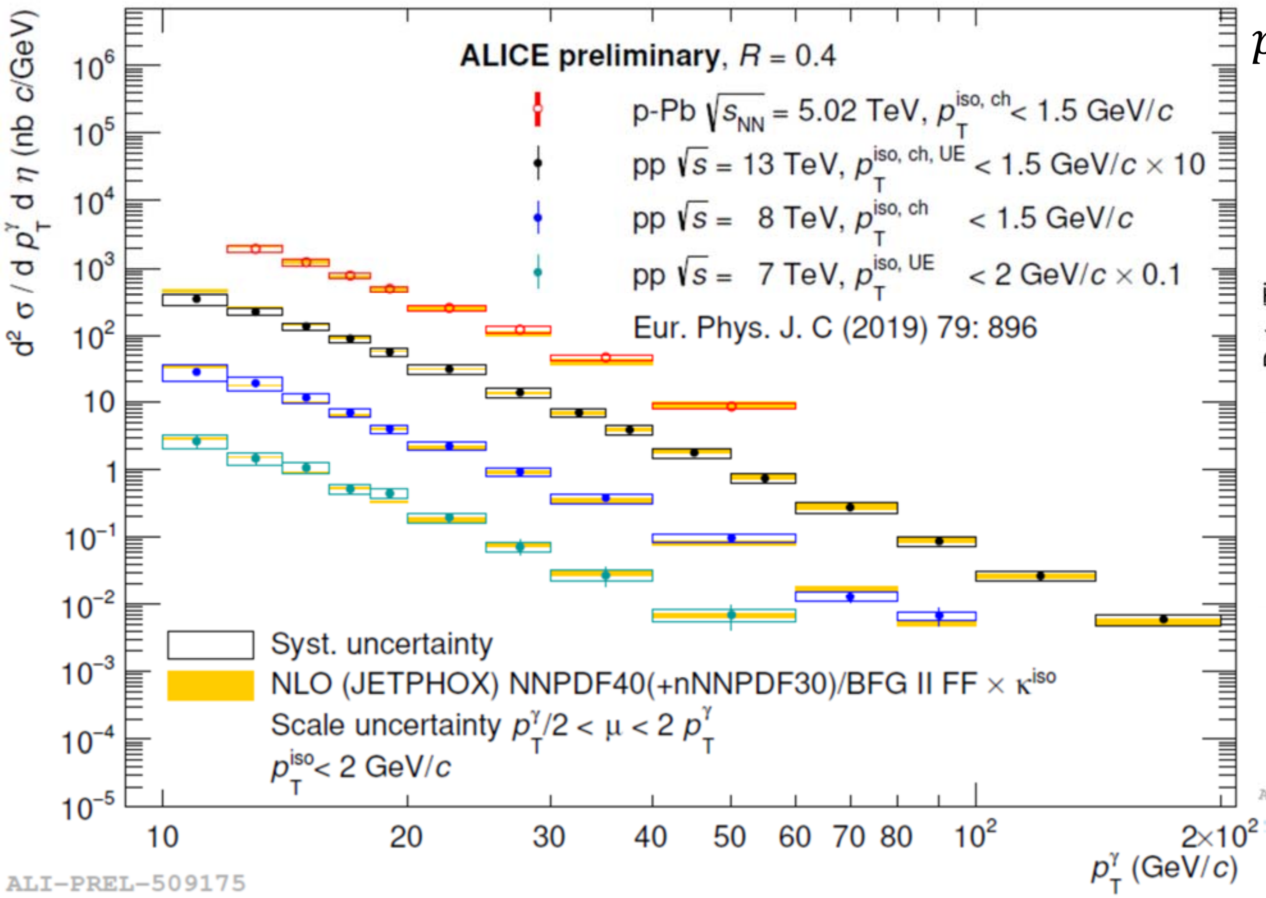


C. Shen et al. Phys. Rev. C95 (2017) 014906

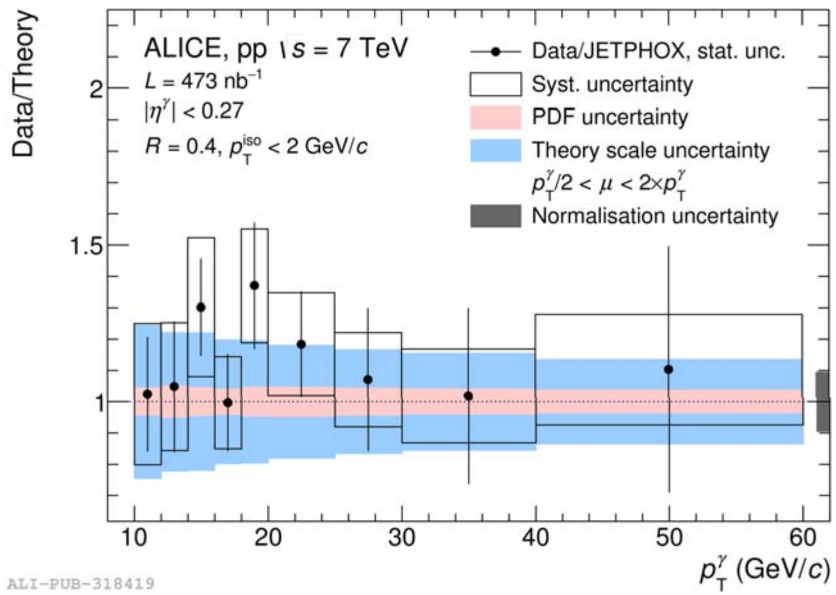
Isolated photons in pp and p-Pb collisions

- Access to direct prompt photons through isolation techniques
- Lower p_{T} (10 GeV/c) reach compared to other LHC experiments
- The measurements are consistent with NLO pQCD predictions





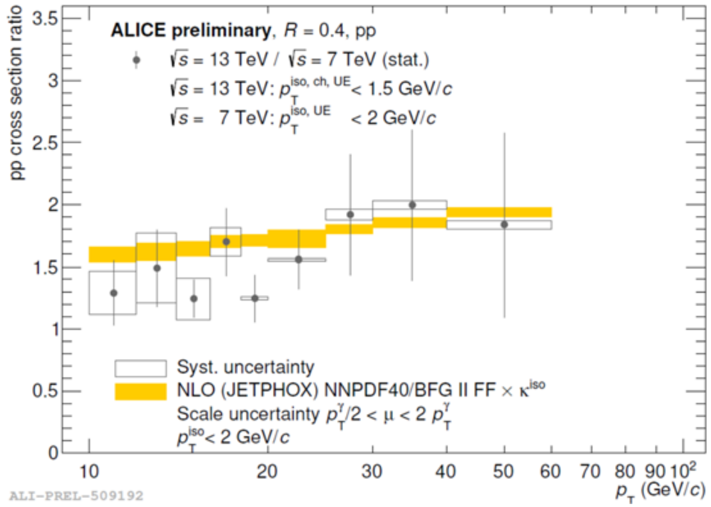
$$p_{\mathrm{T}}^{\mathrm{iso}} = \sum p_{\mathrm{T}}^{\mathrm{cluster}} + \sum p_{\mathrm{T}}^{\mathrm{track}} < 2\ \mathrm{GeV}/c$$

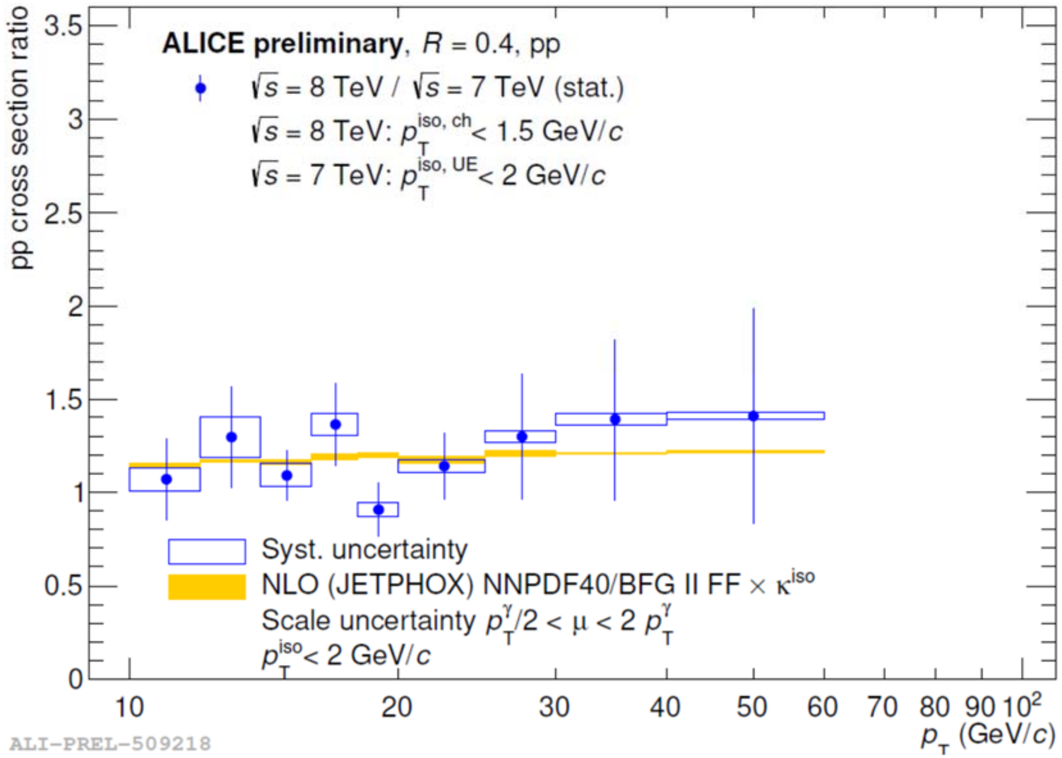


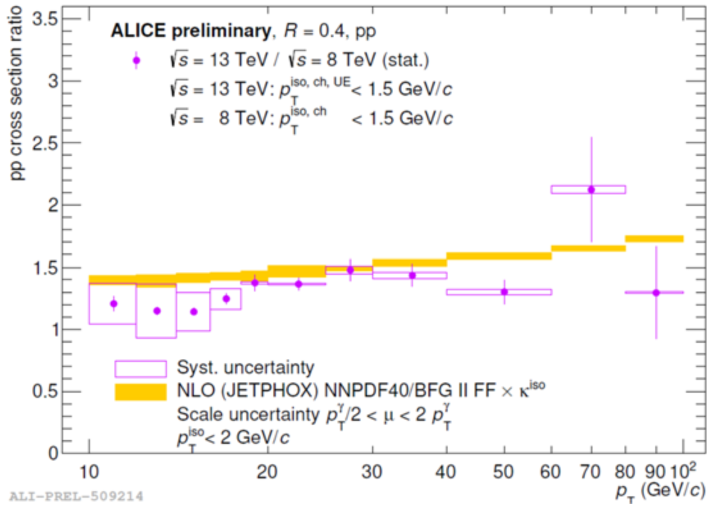
Eur. Phys. J. C (2019) 79: 896

Isolated photons in pp and p-Pb collisions

- Access to direct prompt photons through isolation techniques
- Lower p_T (10 GeV/c) reach compared to other LHC experiments
- The measurements are consistent with NLO pQCD predictions

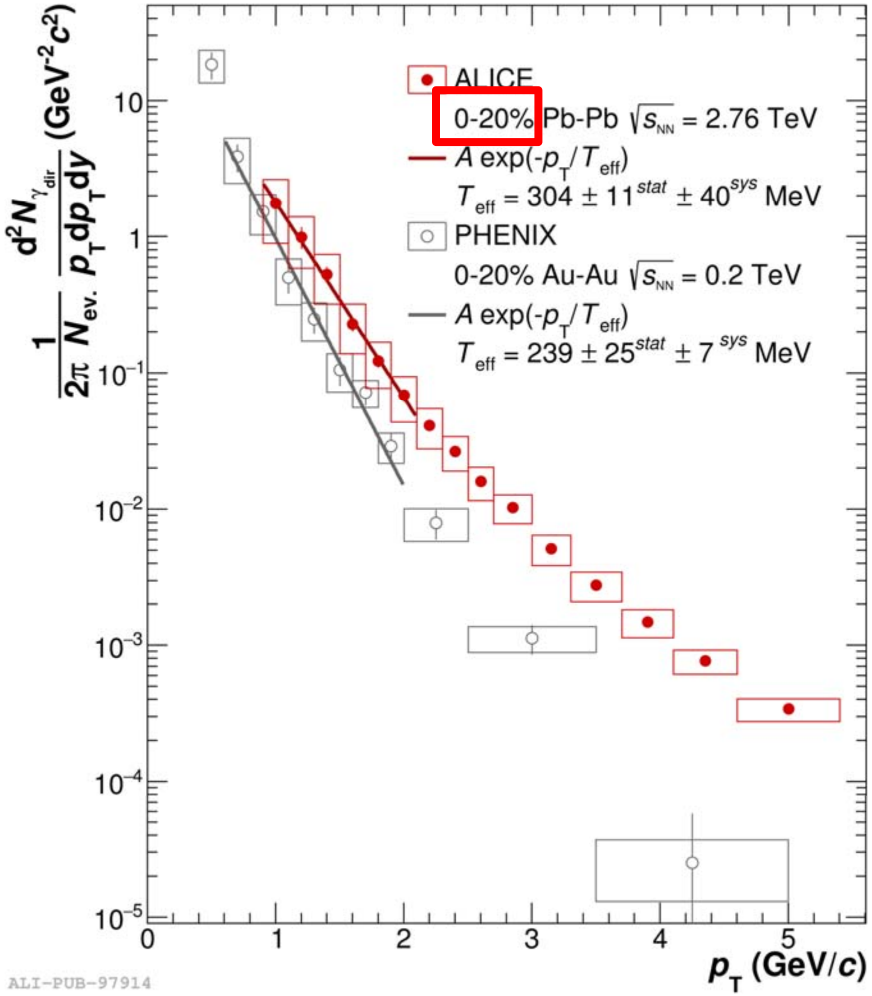


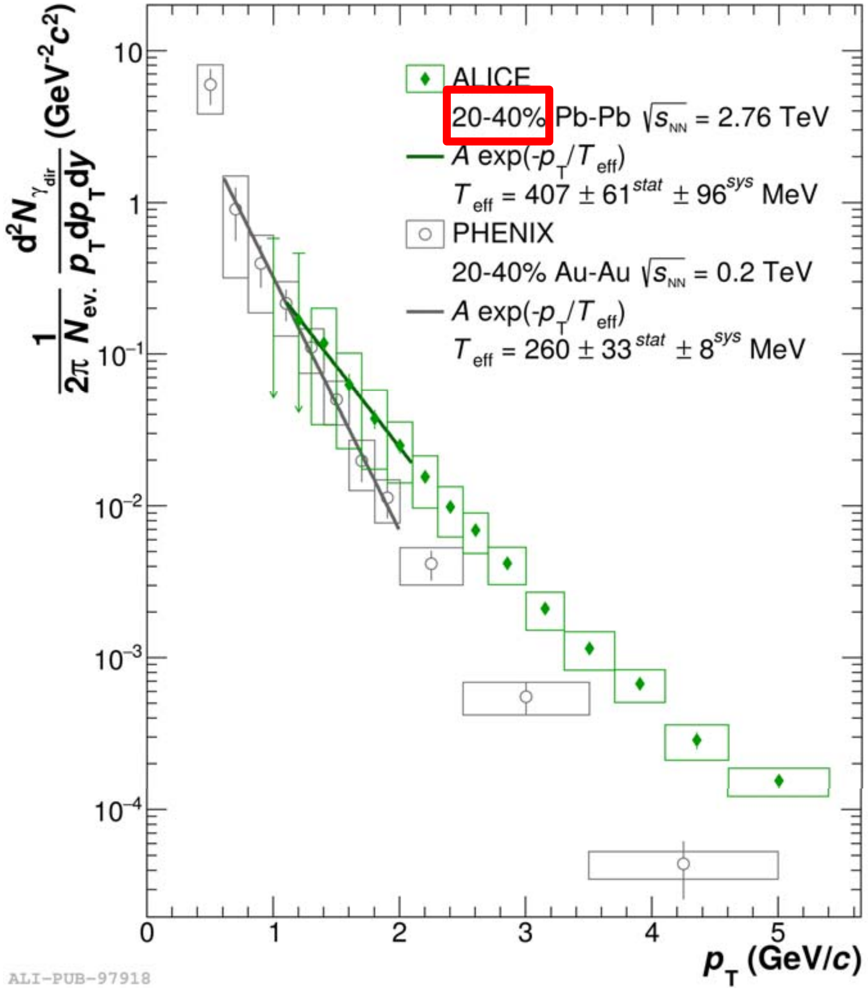




Direct photons in Pb-Pb collisions

- 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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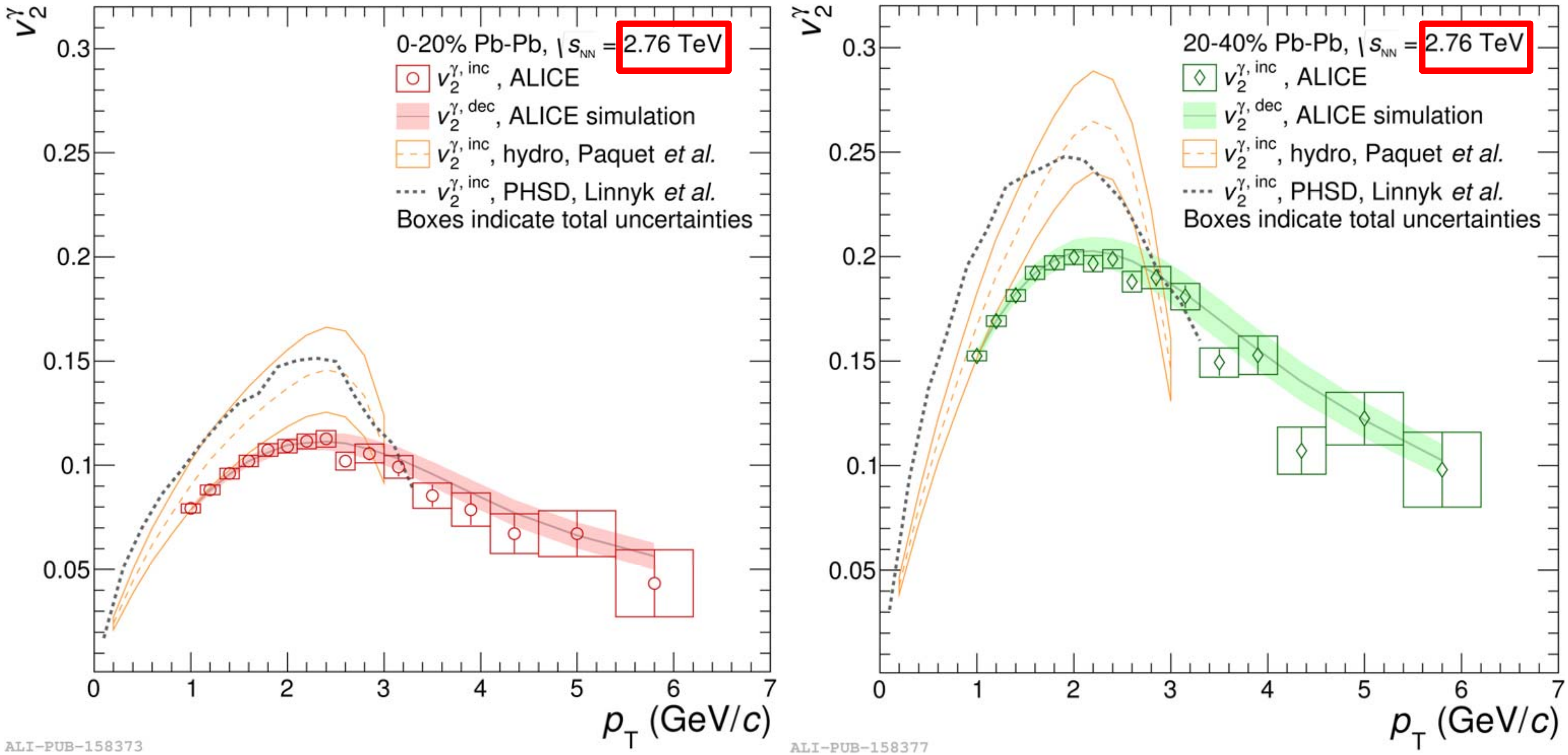
Direct photon flow in Pb-Pb collisions

- Measurements are done with PCM and PHOS
- Inclusive gamma v_2:
  - $v_2^{\gamma\,\mathrm{inc}} = v_2^{\gamma\,\mathrm{dec}} \Rightarrow$ Either no contribution of γ_{dir} or $v_2^{\gamma\,\mathrm{dir}} = v_2^{\gamma\,\mathrm{dec}}$
  - Theory predicts $\sim 30-40\%$ higher flow



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