Neutral meson and direct photon measurement in pp and Pb–Pb collisions at midrapidity with the ALICE experiment at the LHC

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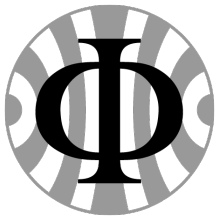
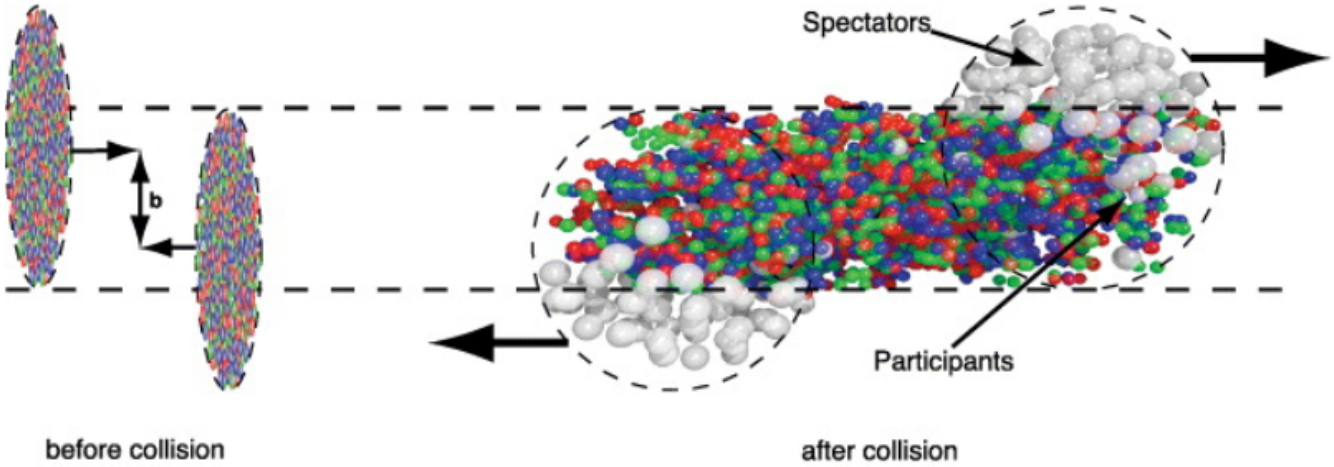
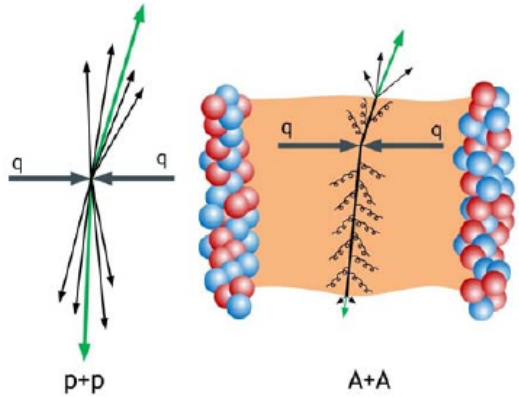


Quark-Gluon Plasma (QGP) in A–A collisions

QGP forms in A–A collisions: hot and dense medium, strongly interacting



- collective expansion
- deconfined quarks and gluons, interact with medium
- parton interactions result in energy loss (jet quenching): can be highlighted through the comparison with pp collisions (vacuum scenario)



Motivations

Neutral mesons as probes of the QGP:

- in pp collisions, allow the study of particle production and constraint of fragmentation functions
- in Pb–Pb collisions, give insights on the bulk properties of the medium, collective effects and particle energy loss
- in both cases, the comparison to models is used to test predictions and improve the theoretical description
- π^0 and η are input for background estimates to direct photons

Direct photons

- do not interact with the medium, thus carry unmodified information about early stages of the collisions
- photons are emitted throughout collision evolution
- hard to measure above a large electromagnetic background

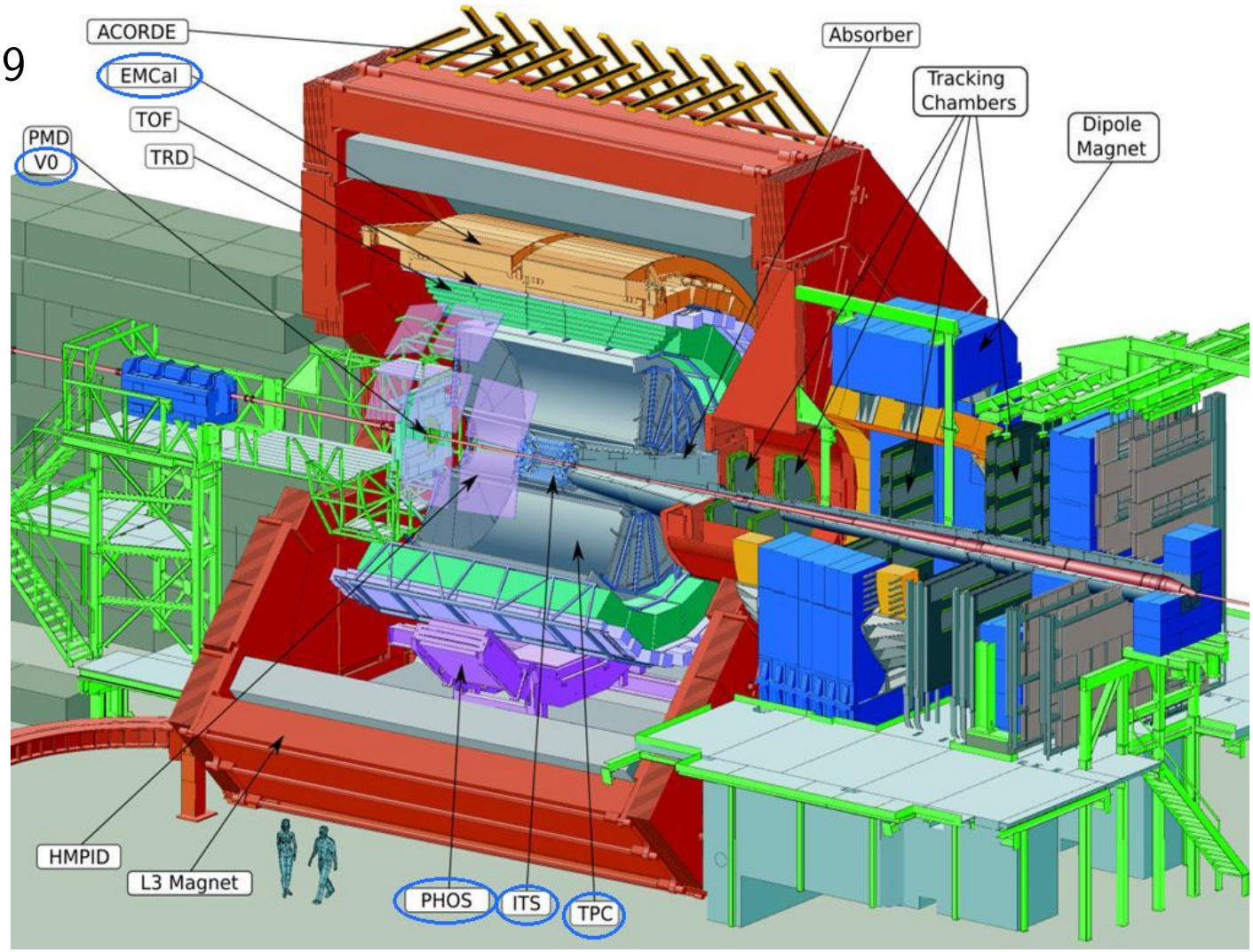
The ALICE experiment

Central barrel: $|\eta| < 0.9$

V0: multiplicity estimation

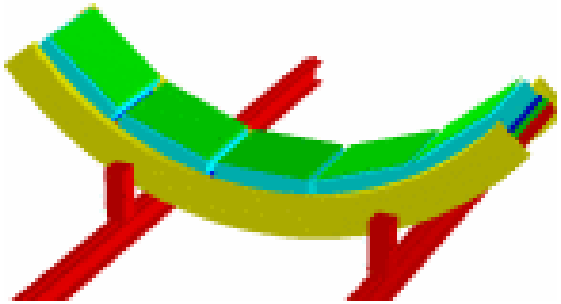
ITS: vertex finding and tracking

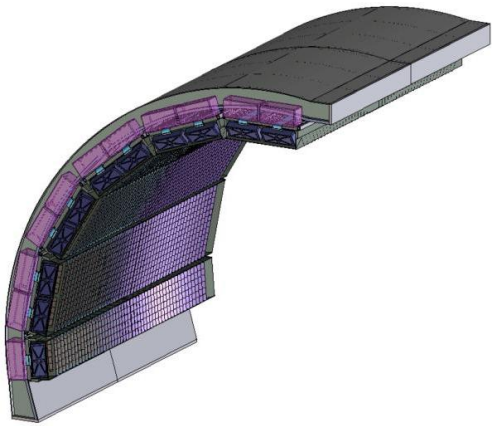
TPC: tracking and particle identification

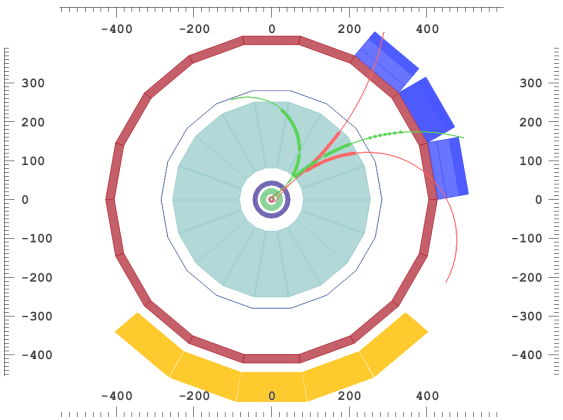


PHOS and **EMCal**: calorimetry

Photon detection with the ALICE experiment (RUN 1)





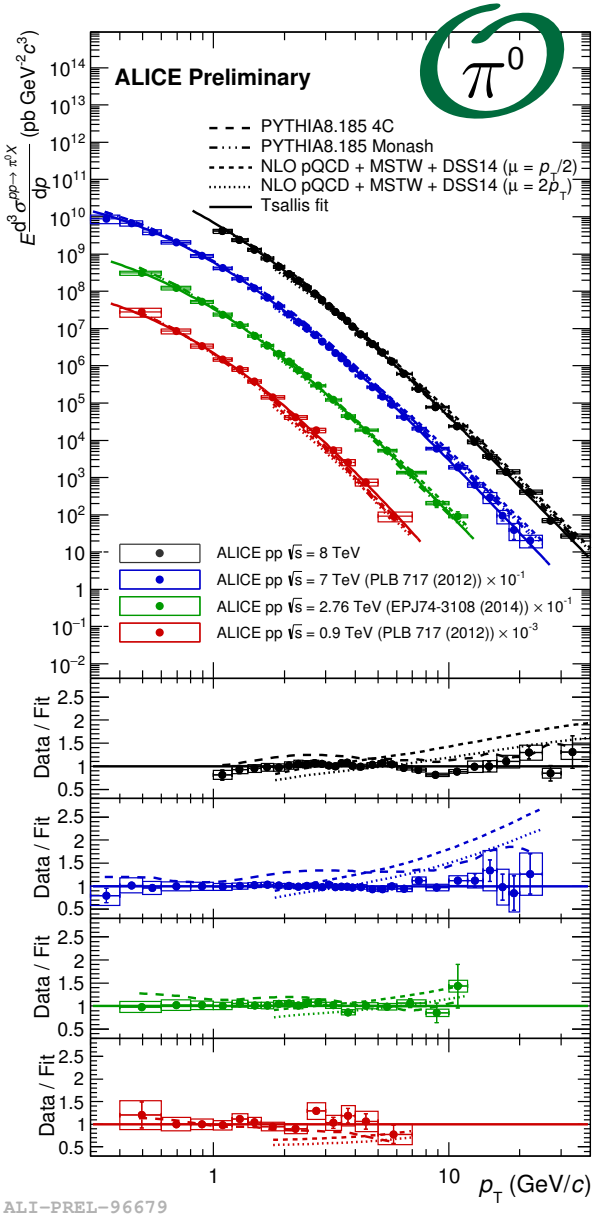


- PHOS calorimeter:
  - $PbWO_4$ crystals
  - $|\eta| < 0.13$, $260^\circ < \phi < 320^\circ$
- EMCal calorimeter:
  - Pb/scintillator sampling calorimeter
  - $|\eta| < 0.7$, $80^\circ < \phi < 180^\circ$
- Photon Conversion Method (PCM):
  - ITS and TPC
  - $|\eta| < 0.9$, $0^\circ < \phi < 360^\circ$
  - conversion in detector material:
    - $\triangleright$ $X/X_0 = (11.4 \pm 0.5)\%_{(|\eta| < 0.9,\ R < 180\ cm)}$
    - $\triangleright$ conv. probability $\sim 8\%$

$\rightarrow$ Photon candidates are extracted from V^0 (neutral secondary vertex particles) sample

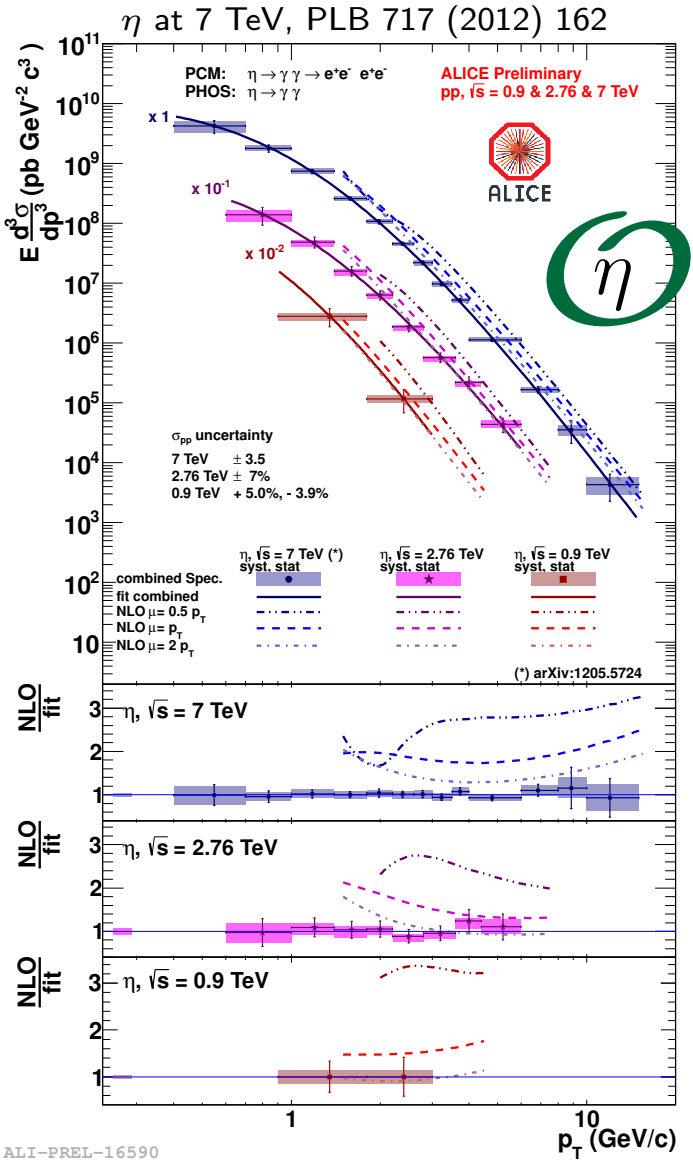
π^0 and η in pp collisions

Neutral meson invariant cross section (PCM + PHOS)



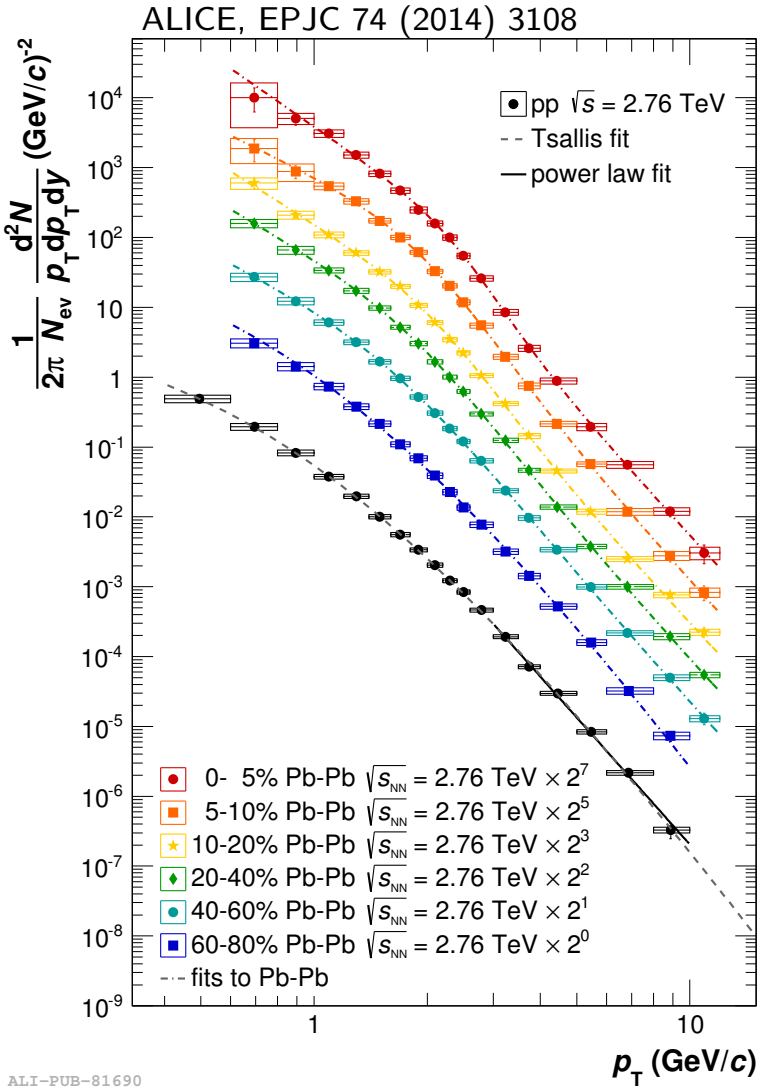
- π^0 compared to PYTHIA8 and NLO pQCD (PRD 91 (2015) 014035)
- measurements help constrain models → good description at intermediate p_T, larger discrepancy towards higher p_T

- η compared to NLO pQCD by W. Vogelsang (PDF: CTEQ6M5, FF: AES)
- reference at 2.76 TeV is used to calculate nuclear modification factor (R_{AA}) in Pb-Pb at the same center of mass energy



π^0 and η in Pb–Pb collisions

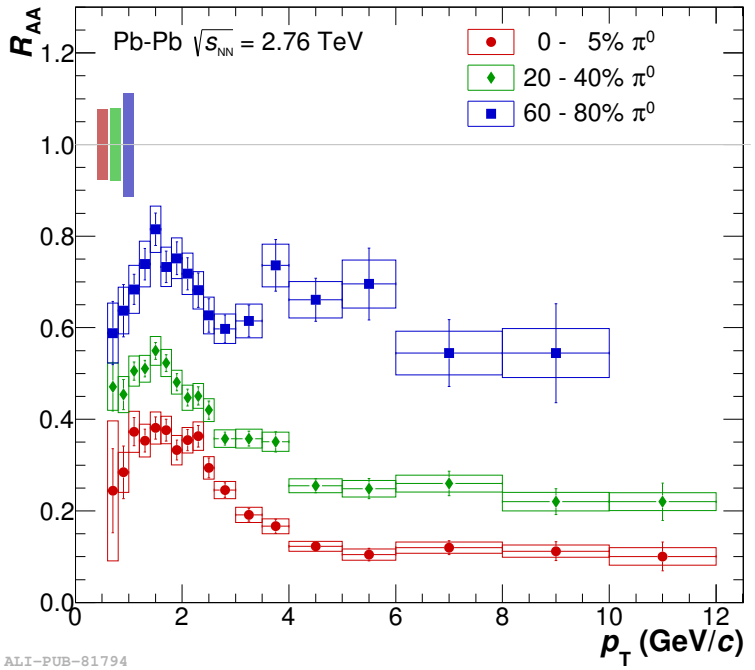
π^0 from 2010 data (PCM + PHOS)



- not enough statistics for η measurement in 2010 data

$$R_{AA}(p_T) = \frac{\mathrm{d}^2N/\mathrm{d}p_T\mathrm{d}y|_{\mathrm{AA}}}{\langle T_{AA}\rangle \times \mathrm{d}^2\sigma/\mathrm{d}p_T dy|_{\mathrm{pp}}}$$

- $\langle T_{AA}\rangle$: nuclear overlap function, related to the pp cross section via $\langle T_{AA}\rangle = \langle N_{coll}\rangle/\sigma^{pp}_{inel}$
- suppression due to interaction with medium is larger for more central collisions



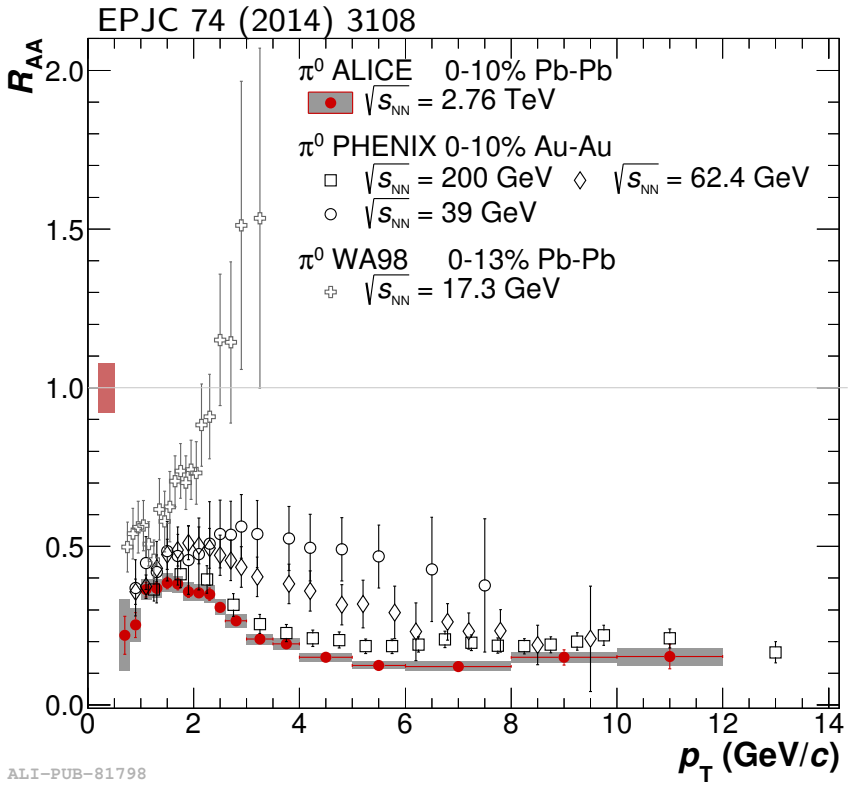
Neutral pion R_{AA} collision energy dependence

- **ALICE** π^0 R_{AA} in 0-10% central collisions compared with results from **PHENIX** (PRL 109 (2012) 152301 and PRL 101 (2008) 232301) and **WA98** results (PRL 100 (2008) 242301)

- R_{AA} supression stronger for higher collisions energy: decrease due to higher energy density dominates over increase expected from harder initial parton spectra

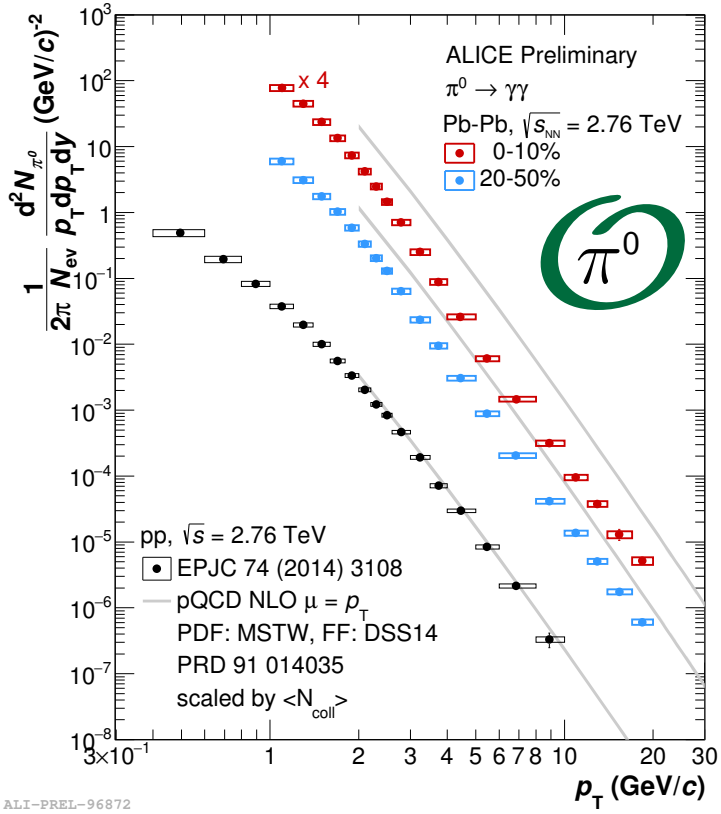
- maximum value of the ratio also shifts towards lower p_T going to higher energy

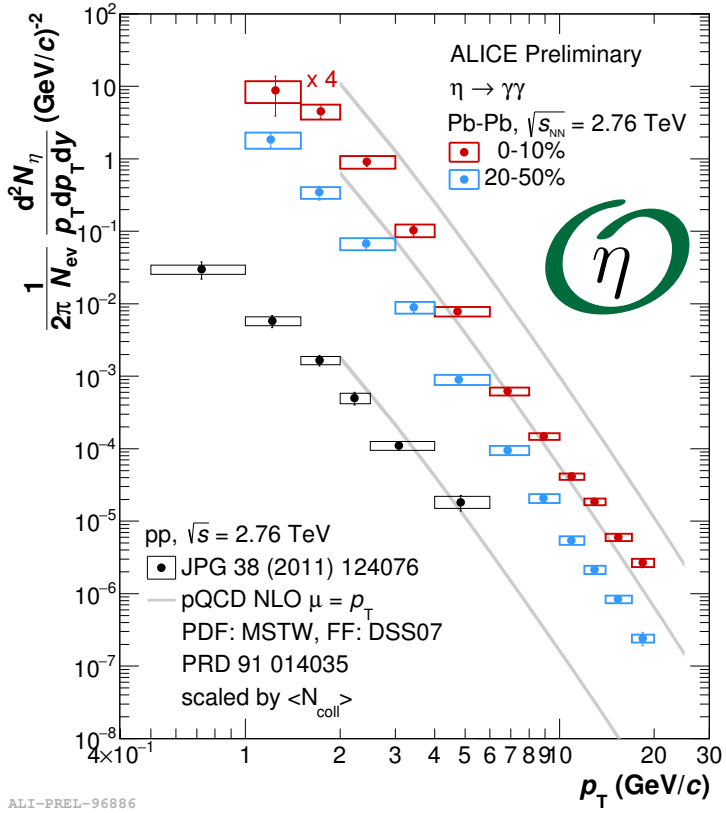
- at high p_T, R_{AA} is expected to rise due to a flatter spectra in A–A than in pp $\rightarrow$ region accessible with 2011 Pb–Pb data



Neutral mesons from 2011 data (PCM + EMCal)

- increased luminosity Pb–Pb run in 2011, ∼10 times more statistics
- combined PCM and EMCal measurement

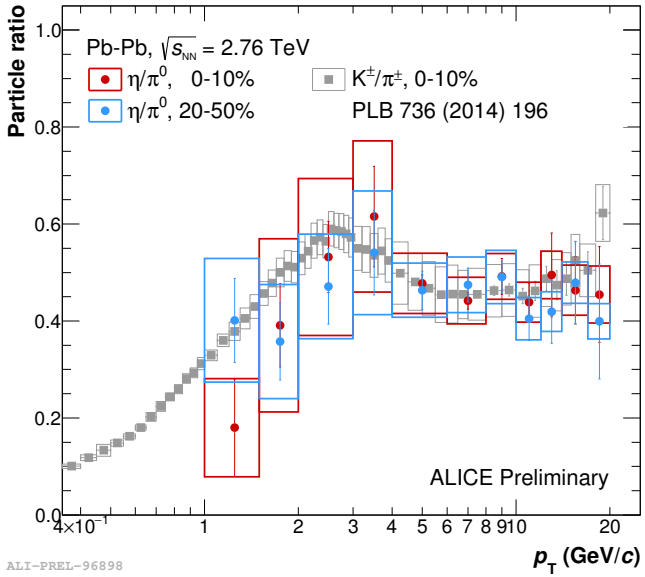


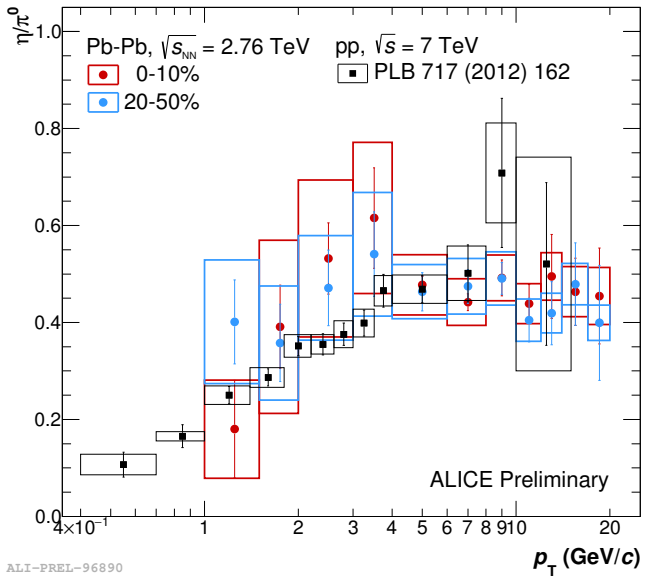


- π^0 consistent with 2010 data, measurement extended to 20 GeV/c
- **first η measurement in Pb–Pb** at the LHC

η/π^0 ratio in Pb–Pb 2011 data (PCM + EMCal)

- η/π^0 measured in Pb–Pb collisions in two centrality classes
- compared to other ALICE results: η/π^0 in pp at 7 TeV and to $K^{\pm}/\pi^{\pm}$ in 0-10% Pb–Pb at 2.76 TeV
  - comparison could highlight differences due to the presence of a hot and dense medium and from particle flow (expected to be similar for η and kaons)
  - cannot differentiate with current uncertainties





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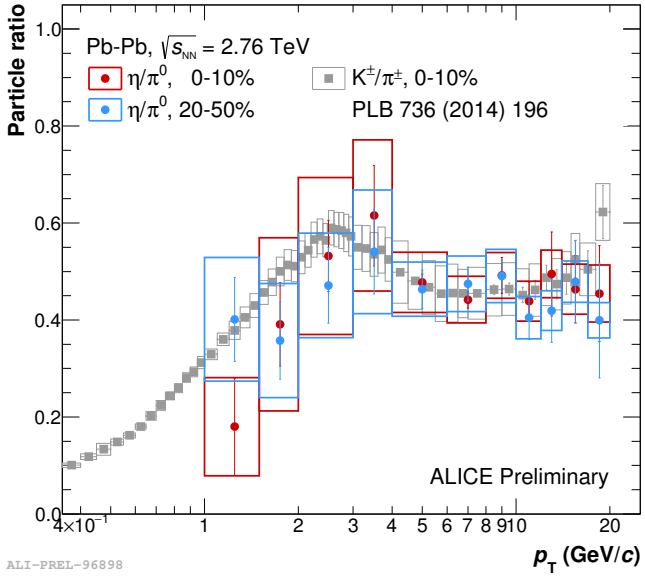
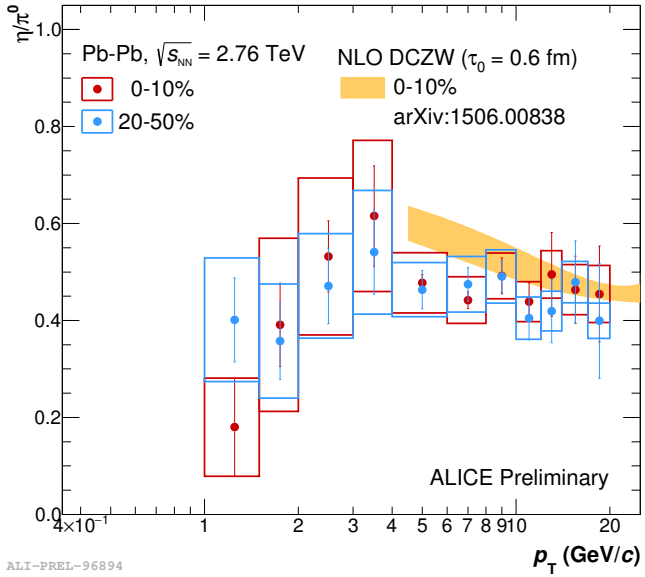
- compared to other ALICE results: η/π^0 in pp at 7 TeV and to $K^{\pm}/\pi^{\pm}$ in 0-10% Pb–Pb at 2.76 TeV
  - comparison could highlight differences due to the presence of a hot and dense medium and from particle flow (expected to be similar for η and kaons)
  - cannot differentiate with current uncertainties
- pQCD NLO calculation for 0-10% cent. class agrees within uncertainties
  $\rightarrow$ p_{T} region 4–6 GeV/c sensitive to initial transport coefficient (= parameter describing energy loss in medium)





Direct photons in Pb–Pb collisions

Direct photons in Pb–Pb collisions

▷ direct photons = photons not coming from particle decays

▷ emitted during all stages of the system evolution, can be classified in

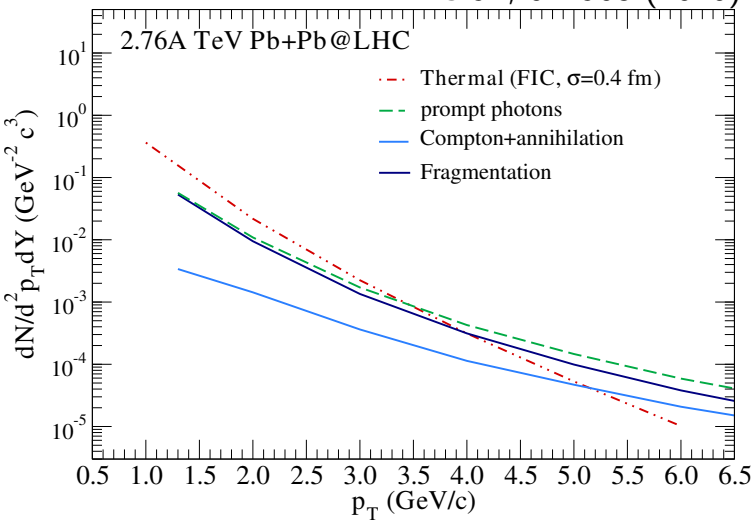
- thermal photons: dominant at low p_T, coming from thermal radiation of QGP and hadron gas
- prompt photons: dominant at high p_T, from initial hard scattering
- from jet-medium interaction: hard partonic scattering, in-medium bremsstrahlung

▷ extraction of direct photon measurement:

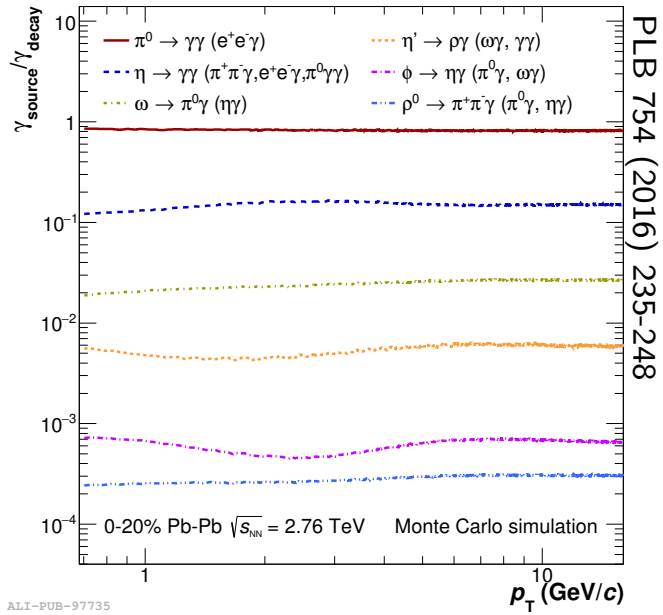
$$\gamma_{\text{direct}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = (1 - \frac{1}{R_\gamma}) \cdot \gamma_{\text{inc}}$$

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

PRC 94, 014903 (2016)

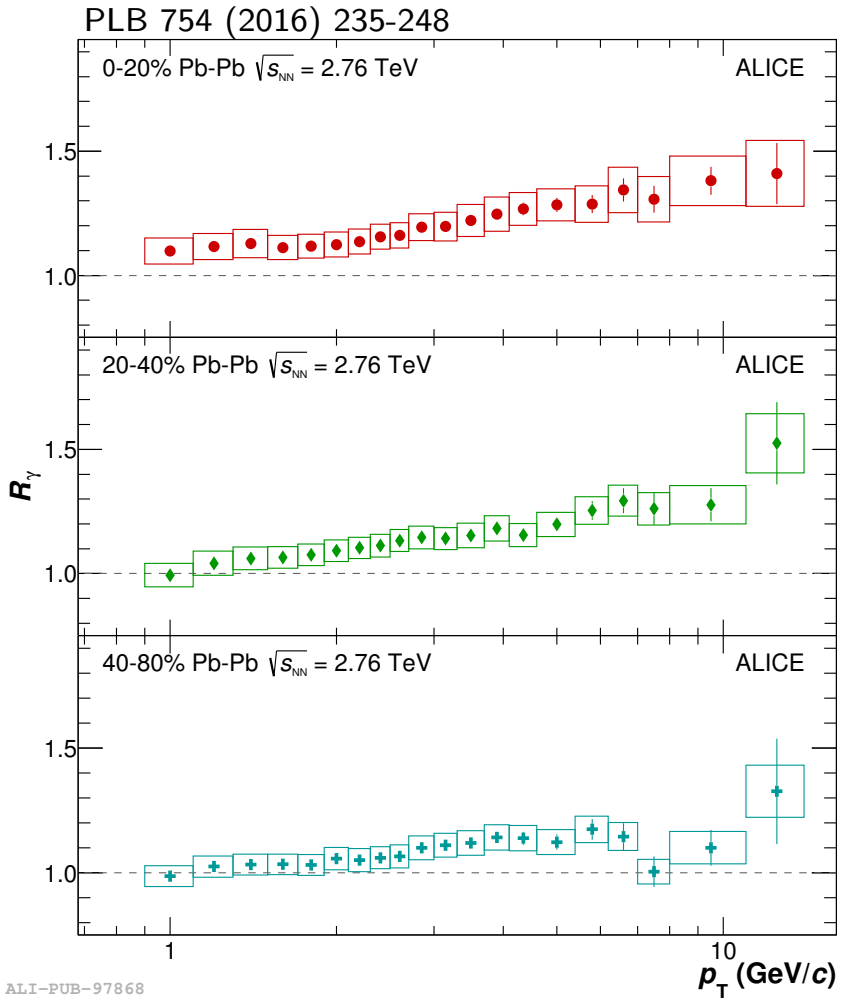


PLB 754 (2016) 235-248



Direct photons in 2010 Pb–Pb data (PCM + PHOS)

- ▷ inclusive photon spectra measured with combined PCM + PHOS (PLB 754 (2016) 235-248) in 3 centrality classes with 2010 Pb–Pb data
- ▷ R_γ excess at high p_T for all centralities



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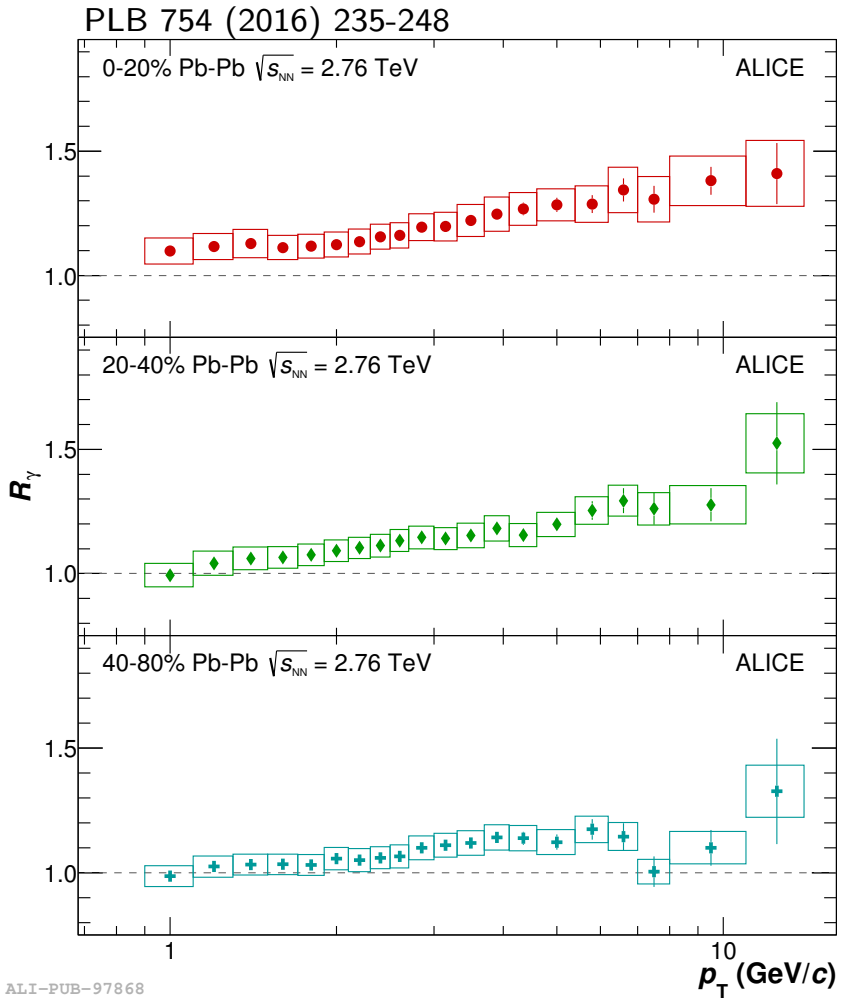
▷ at low p_T, $\sim$ 20% excess in 0-20% and $\sim$ 9% in 20-40% due to thermal radiation of the medium



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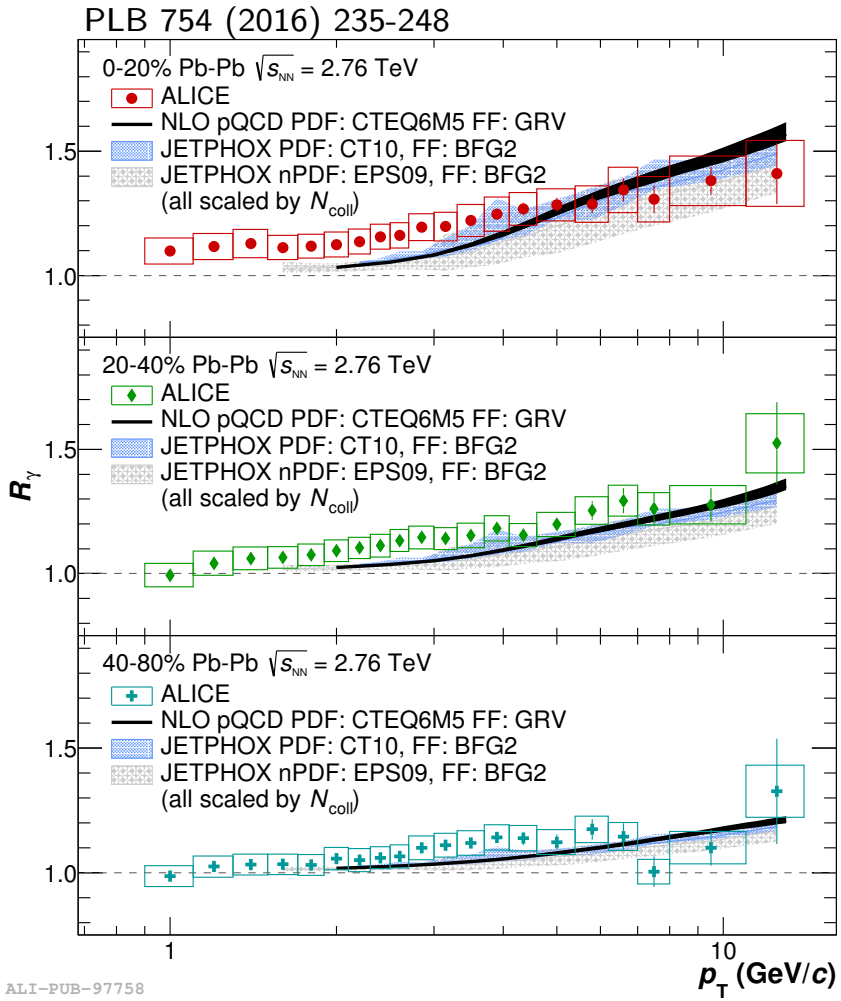
▷ R_γ excess at high p_T for all centralities

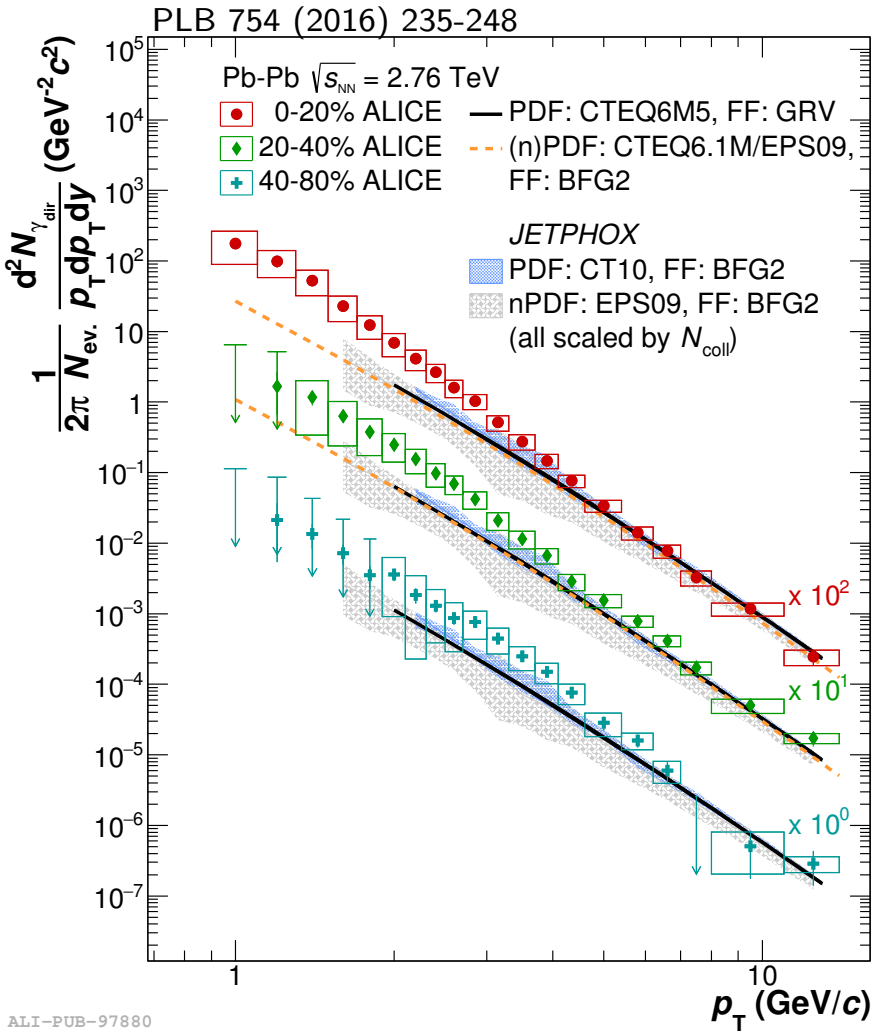
▷ at low p_T, $\sim$ 20% excess in 0-20% and $\sim$ 9% in 20-40% due to thermal radiation of the medium

▷ in agreement with NLO/JETPHOX pQCD above 5 GeV/c



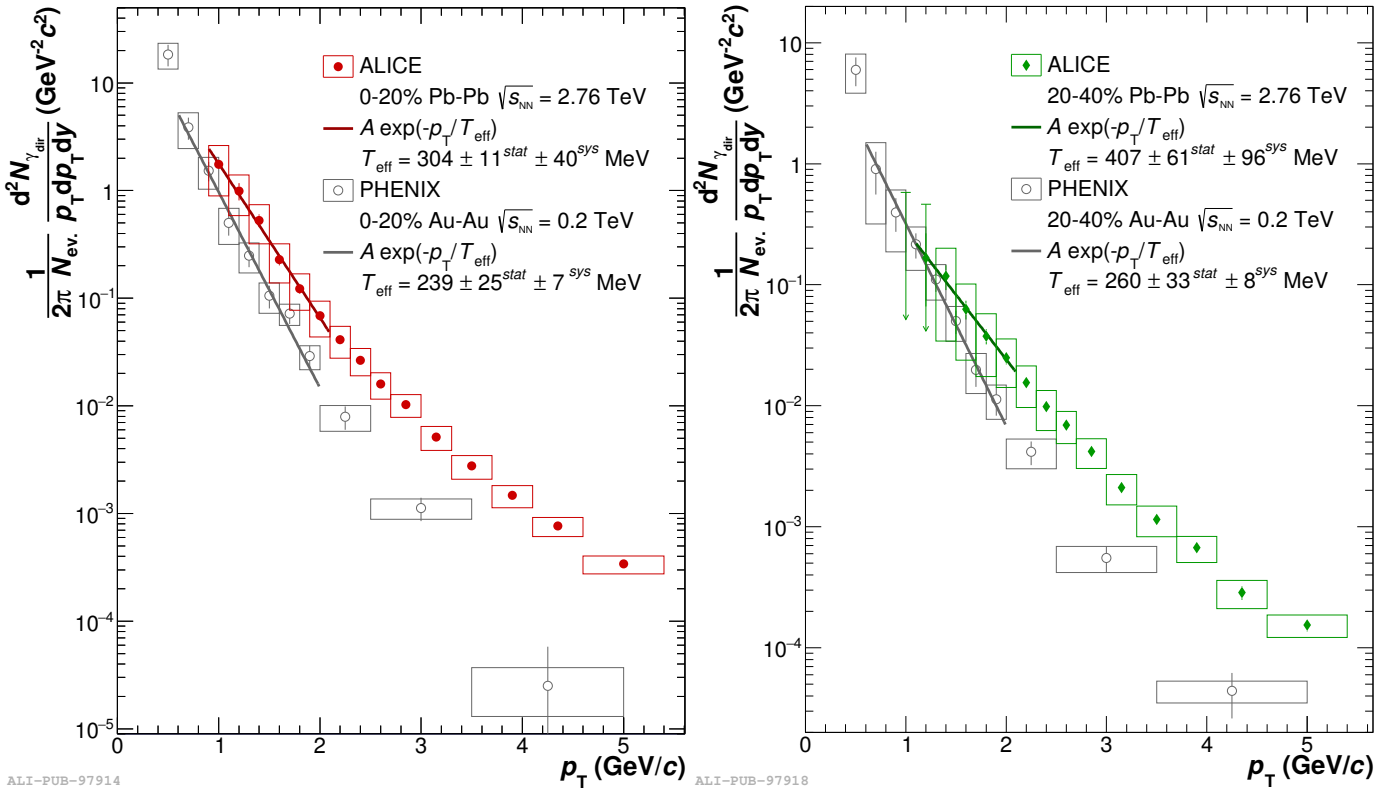
Direct photons in 2010 Pb–Pb data (PCM + PHOS)

- ▷ direct photon spectra measured in 3 centrality classes in the range $0.9 < p_T < 14$ GeV/c
- ▷ at low p_T, upper limits with 90% CL given for more peripheral collisions
- ▷ comparison with pQCD NLO and JETPHOX shows again good agreement above 5 GeV/c and excess yields for 0-20% and 20-40% central collisions



Comparison direct photon spectra ALICE - PHENIX

ALICE results compared with PHENIX direct photon measurement in Au–Au at 200 GeV (PRL104 (2010)132301, PRC91/6 (2015) 064904)

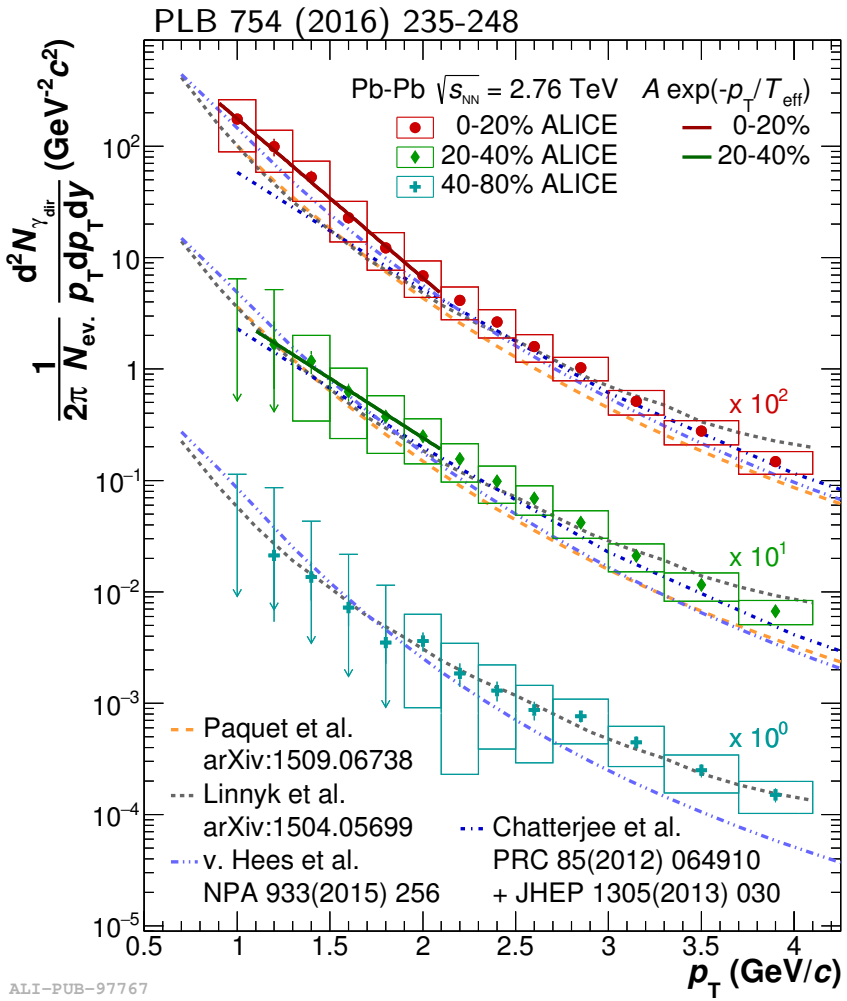


▷ exponential fit to low p_T excess: inverse slope parameter larger at higher collision energy and consistent in both centrality classes

Direct photon spectra comparison to models

Several models, all assume QGP formation and include pQCD photons at high $p_{\mathrm{T}} \rightarrow$ have different space-time evolution treatment:

- **Paquet et al.**: 2+1 viscous hydro with IP-GLASMA initial conditions, $\tau_0 = 0.4$ fm/c, $\langle T_{\mathrm{init}}^{0-20\%} \rangle = 385$ MeV
- **Linnyk et al.**: off-shell transport, microscopic description of evolution
- **v. Hees et al.**: ideal hydro with initial flow, $\tau_0 = 0.2$ fm/c, $T_{\mathrm{init}}^{0-20\%} = 682$ MeV
- **Chatterjee et al.**: 2+1 hydro, fluctuating initial conditions, $\tau_0 = 0.14$ fm/c, $T_{\mathrm{init}}^{0-20\%} \approx 740$ MeV



Summary

Neutral mesons and direct photons are measured in ALICE with independent methods (calorimeters, EMCal and PHOS, and photon conversions, PCM)

▷ results in pp

- neutral pion and η meson cross sections measured at several collision energies with combined PCM and PHOS analysis
- comparison with PYTHIA and NLO pQCD calculations:
  - describe well intermediate p_{T} region (below 5 GeV/c)
  - predict harder spectra at high p_{T}

Summary

▷ results in Pb–Pb at 2.76 TeV

- neutral mesons measurements:
  - π^0 measured with PCM + PHOS (2010 data) and PCM + EMCal (2011 data) and η measured with PCM + EMCal (2011 data)
  - π^0 R_{AA} has larger suppression in more central collisions and its magnitude scales with the collision energy
  - with current uncertainties, no clear dependence of η/π^0 on collision system, mass or s quark content observed

- direct photon measurement:
  - inclusive and direct photon spectra measured in 3 centrality bins
  - below $p_T = 3$ GeV/c, direct photon excess observed for 0-20% and 20-40% $\Rightarrow$ thermal radiation of the medium
  - photon spectrum above 5 GeV/c in agreement with NLO pQCD

Outlook

Many papers on track for publication:

- Neutral mesons analysis in **pp at 8 TeV** with combined PCM, EMCal and PHOS analyses
- Neutral mesons analysis in **p–Pb at 5.02 TeV** with combined PCM, EMCal and PHOS analyses (not discuss in this presentation)
- Neutral mesons analysis in **Pb–Pb at 2.76 TeV** with combined PCM, EMCal and PHOS analyses

Updates on the direct photon analysis:

- additional inputs from measured particle spectra in comparison to the previous cocktail simulation

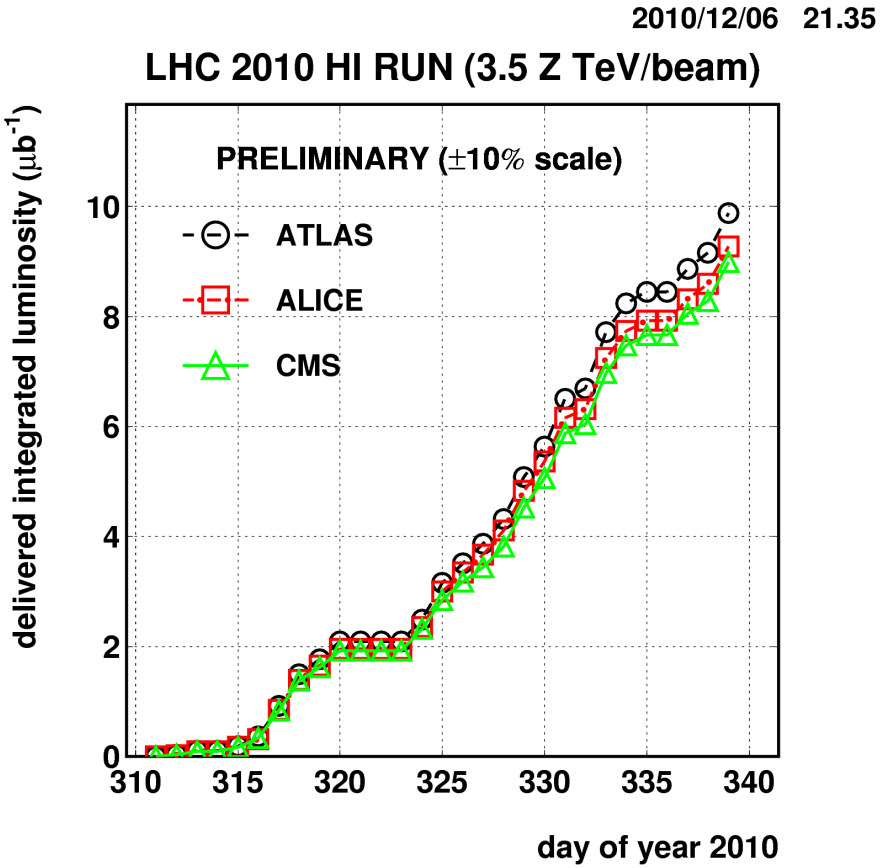
Ongoing LHC RUN2 analyses:

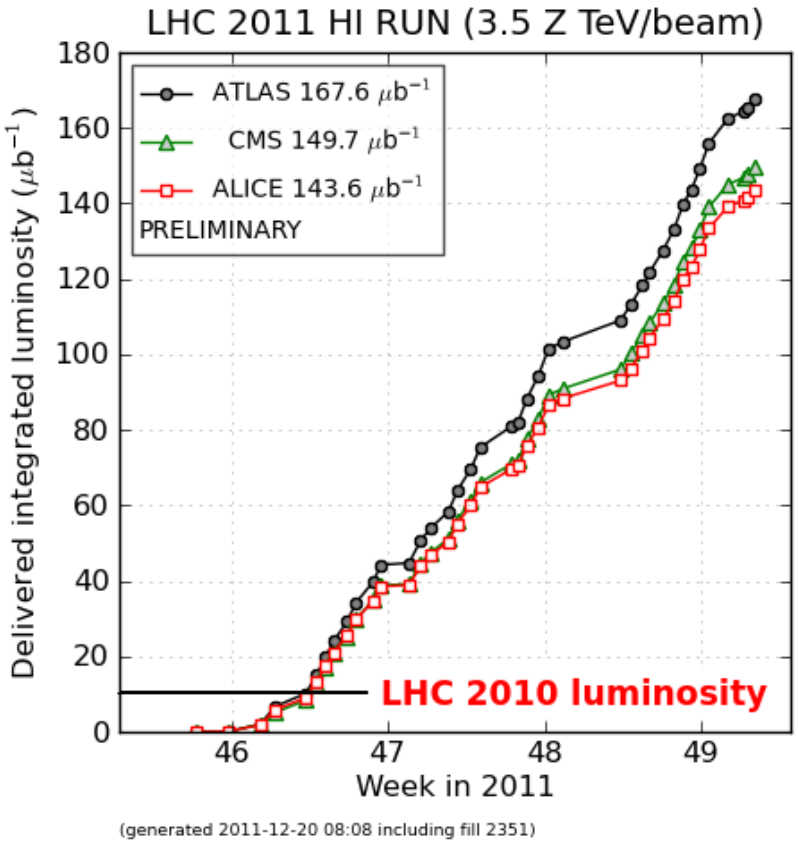
- neutral mesons and direct photons in pp at 13 TeV and 5 TeV
- neutral mesons and direct photons in Pb–Pb at 5 TeV

$\Rightarrow$ ongoing studies to improve material budget estimation will help reduce the related systematic uncertainty

Back up

Luminosity 2010 vs 2011





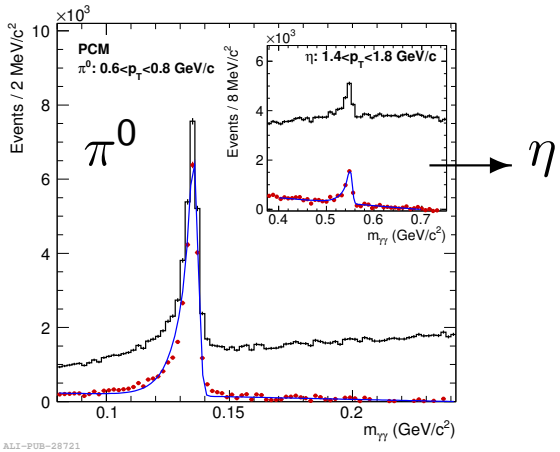
⇒ with large statistics collected in 2011 measurement of differential invariant cross section is possible

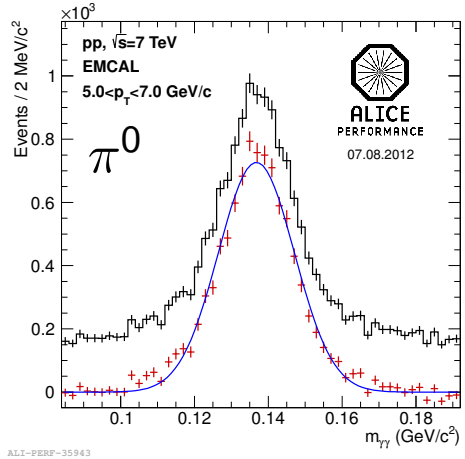
Invariant mass reconstruction

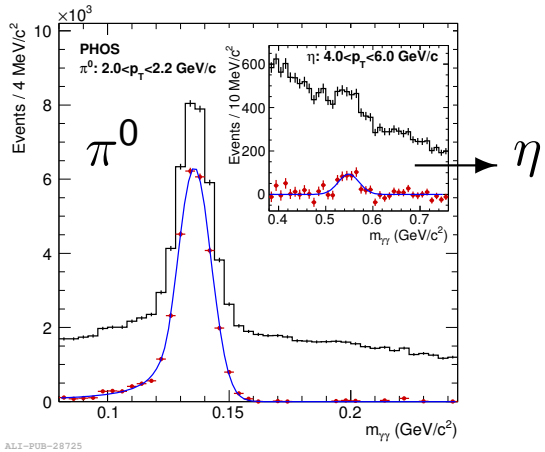
Photon candidates are combined into pairs

→ invariant mass calculated in p_T bins: $M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12})}$

pp

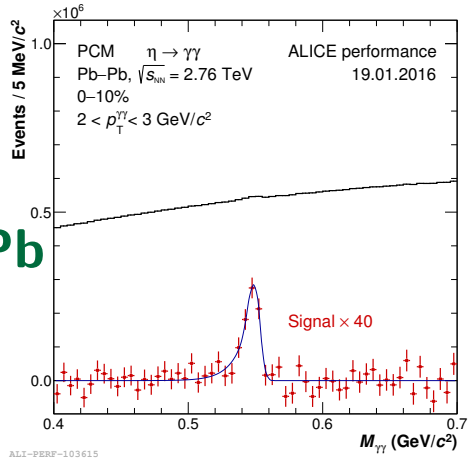


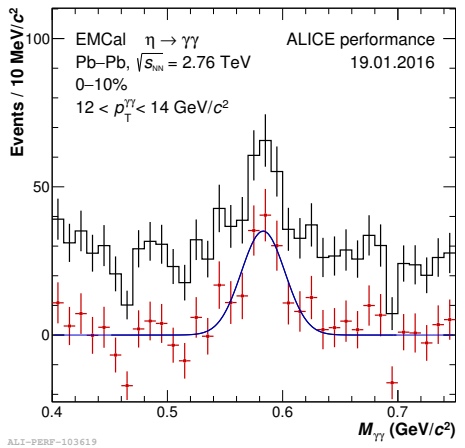




PCM **EMCal** **PHOS**

Pb-Pb



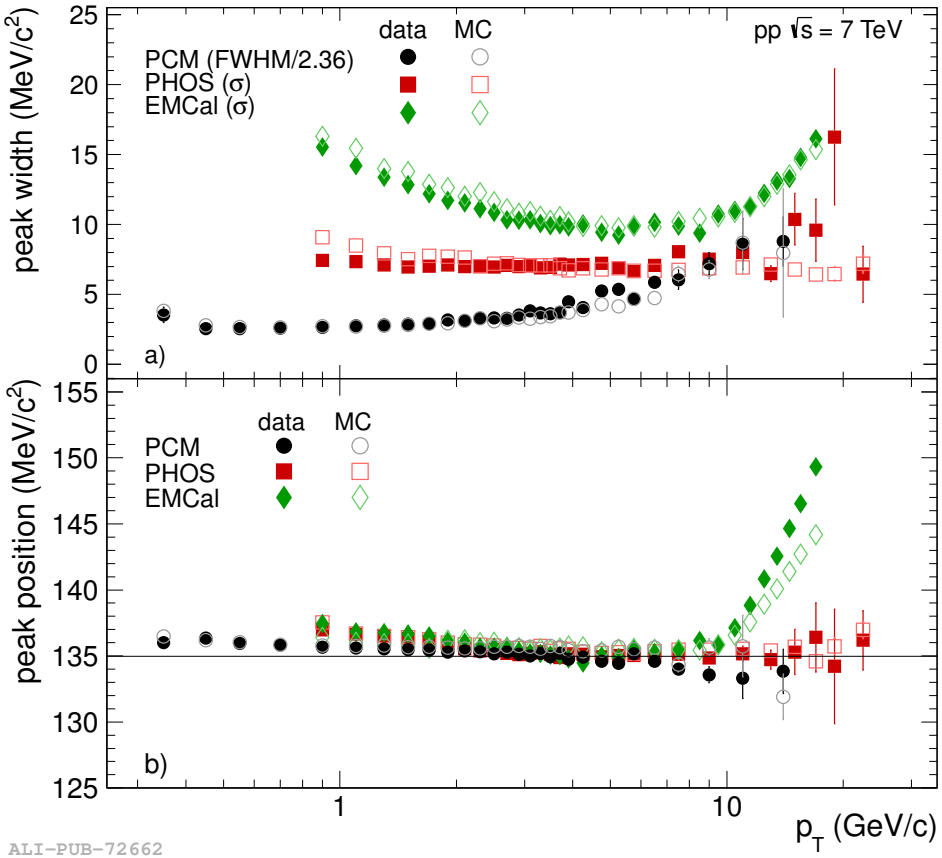


Histo: signal + background
Points: signal after background subtraction
Line: fit (for mass and width)

Neutral pion peak position and width

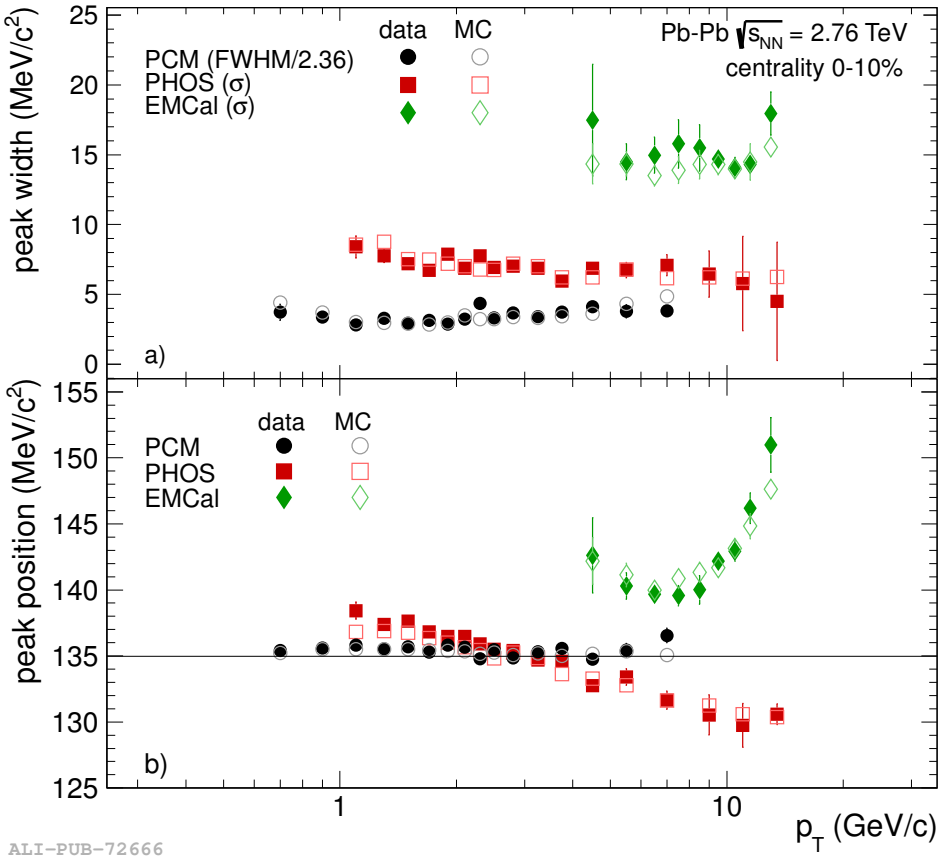
ALICE performance paper: Int. J. Mod. Phys. A 29 (2014) 1430044

pp



ALI-PUB-72662

Pb–Pb



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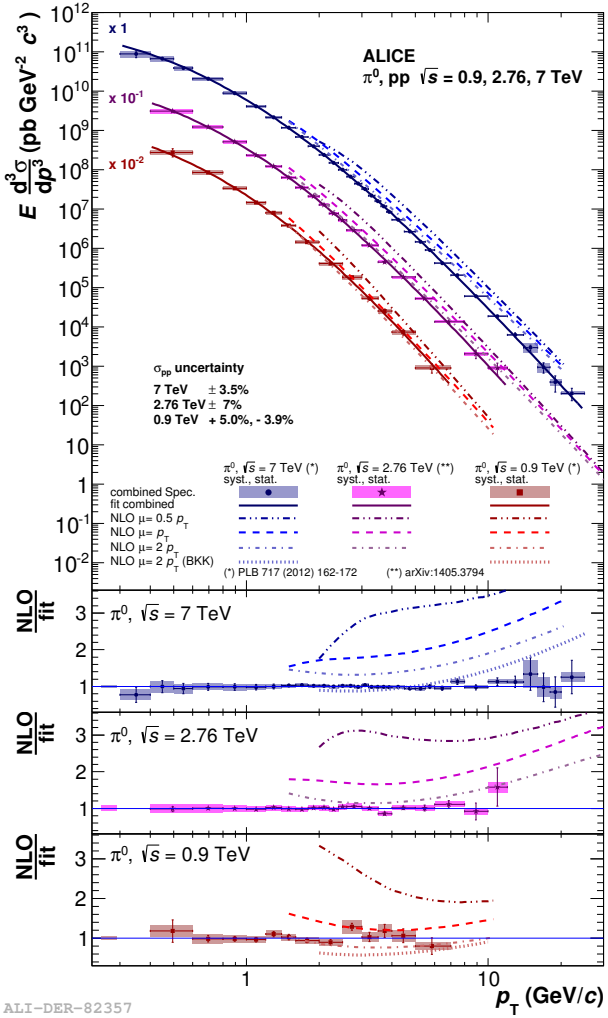
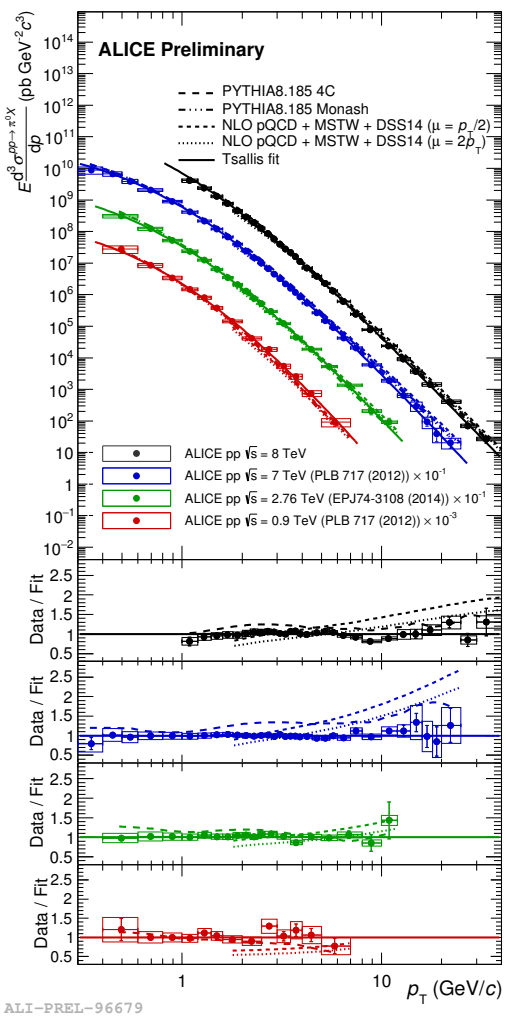
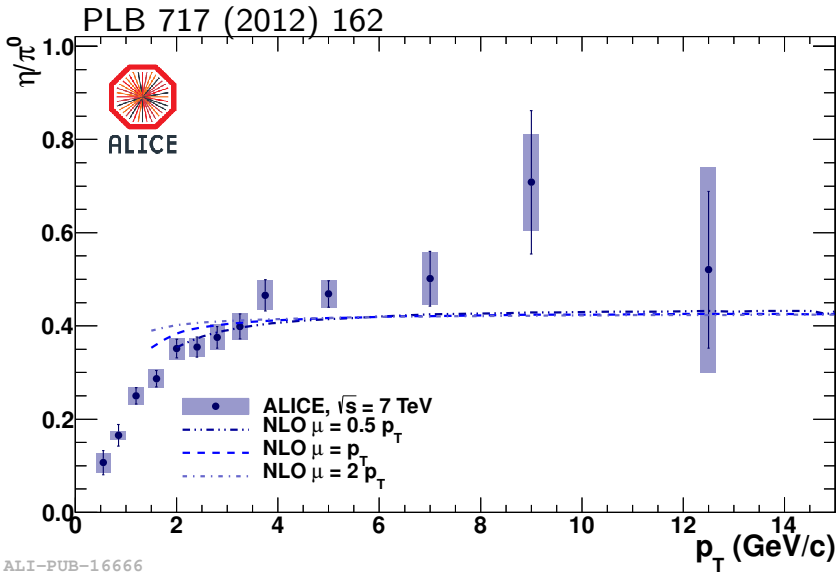
Neutral pion spectra in pp collisions (PCM + PHOS)

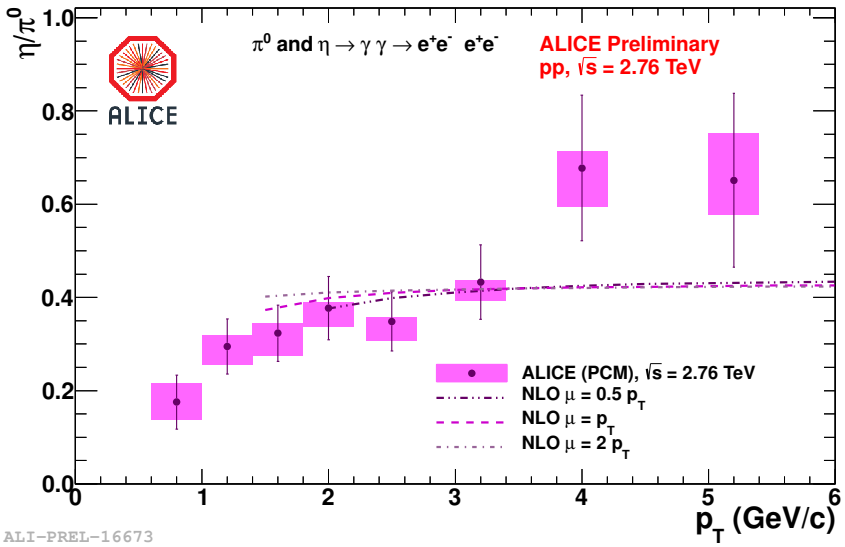
The NLO pQCD calculations are repeated considering the additional constraint given by 8 TeV results ⇒ large improvement





η/π^0 ratio in $\sqrt{s} = 2.76$ and 7 TeV (PCM + PHOS)

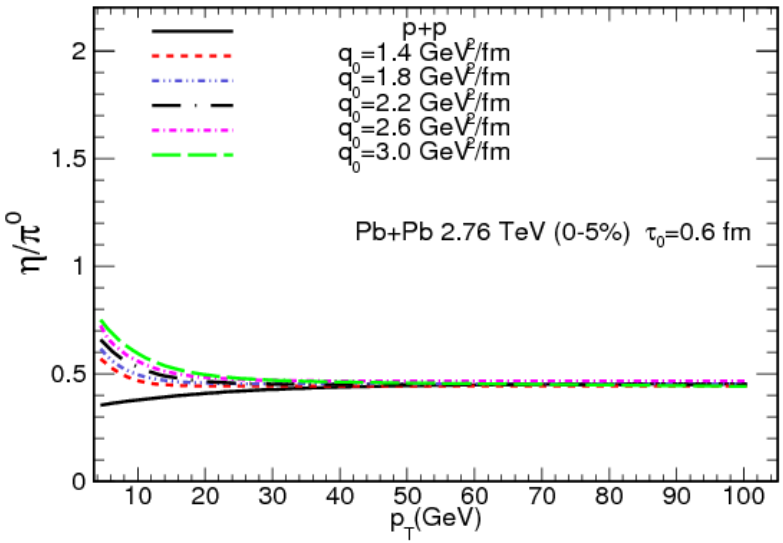




- η/π^0 ratio compared with pQCD NLO theory by W. Vogelsang
- η, PDF: CTEQ6M5, FF: AES
  π^0, PDF: CTEQ6M5, FF: DSS
- at both 7 and 2.76 TeV an increasing trend can be observed up to 2 GeV/c
- above 2 GeV/c the ratio flattens, as the NLO calculations suggest

DCZW prediction

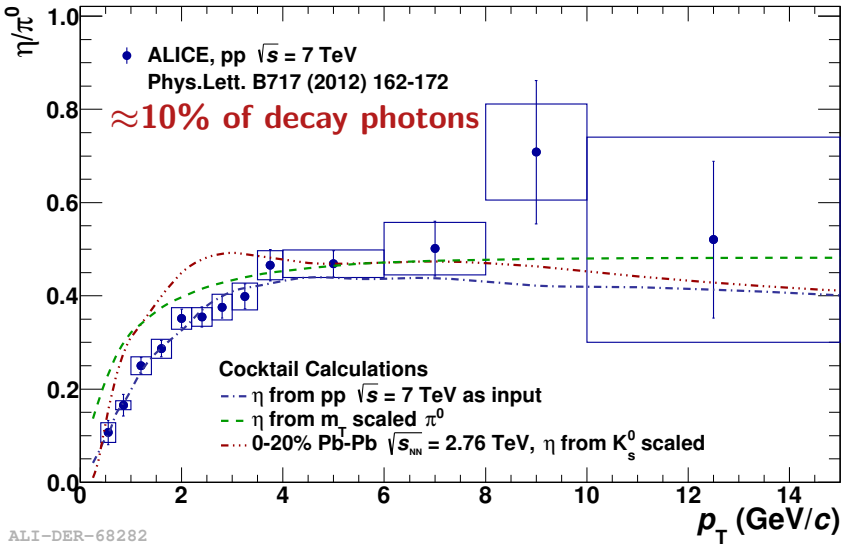
NLO pQCD theoretical prediction of η/π^0 ratio in Pb–Pb collisions at 2.76 TeV according to DCZW (PLB 750 (2015) 390-395)

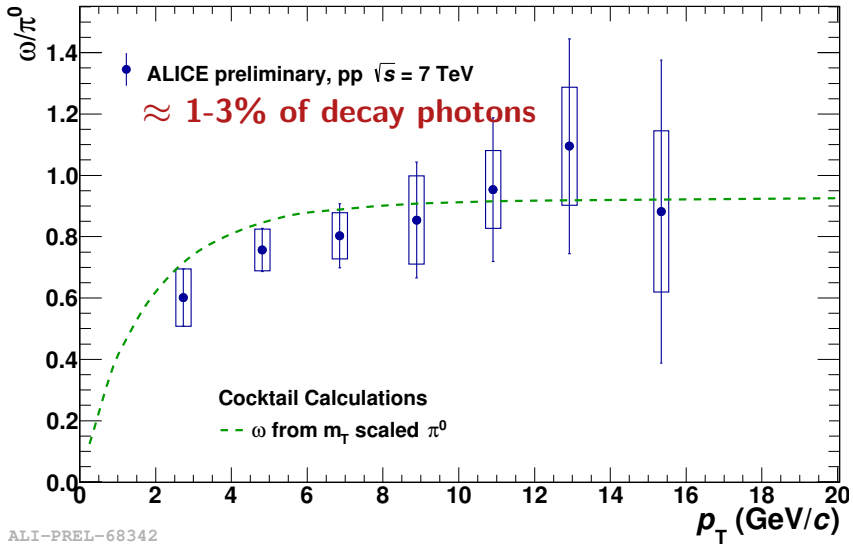


τ_0 is the initial time of the QGP medium

$\hat{q}_0$ initial values of the jet transport parameter $\rightarrow$ the larger $\hat{q}_0$ is, the stronger the jet-medium interaction will be

Assumptions for decay photon cocktail





- η & ω meson only measured in pp, φ meson measured in pp & 0-10% Pb–Pb collisions
- m_T scaling overestimates yield at low p_T consistently for all 3 mesons
- Systematic uncertainties on cocktail 5-10%