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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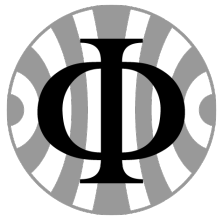


Motivations

Neutral mesons as probes of the Quark Gluon Plasma (QGP) allow

- in pp collisions, the study of particle production and constraint of fragmentation functions
- in Pb–Pb collisions, 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 are photons not coming from particle decays

- do not interact with the medium, thus carry unmodified information about early stages of the collisions
- hard to measure above a large electromagnetic decay background

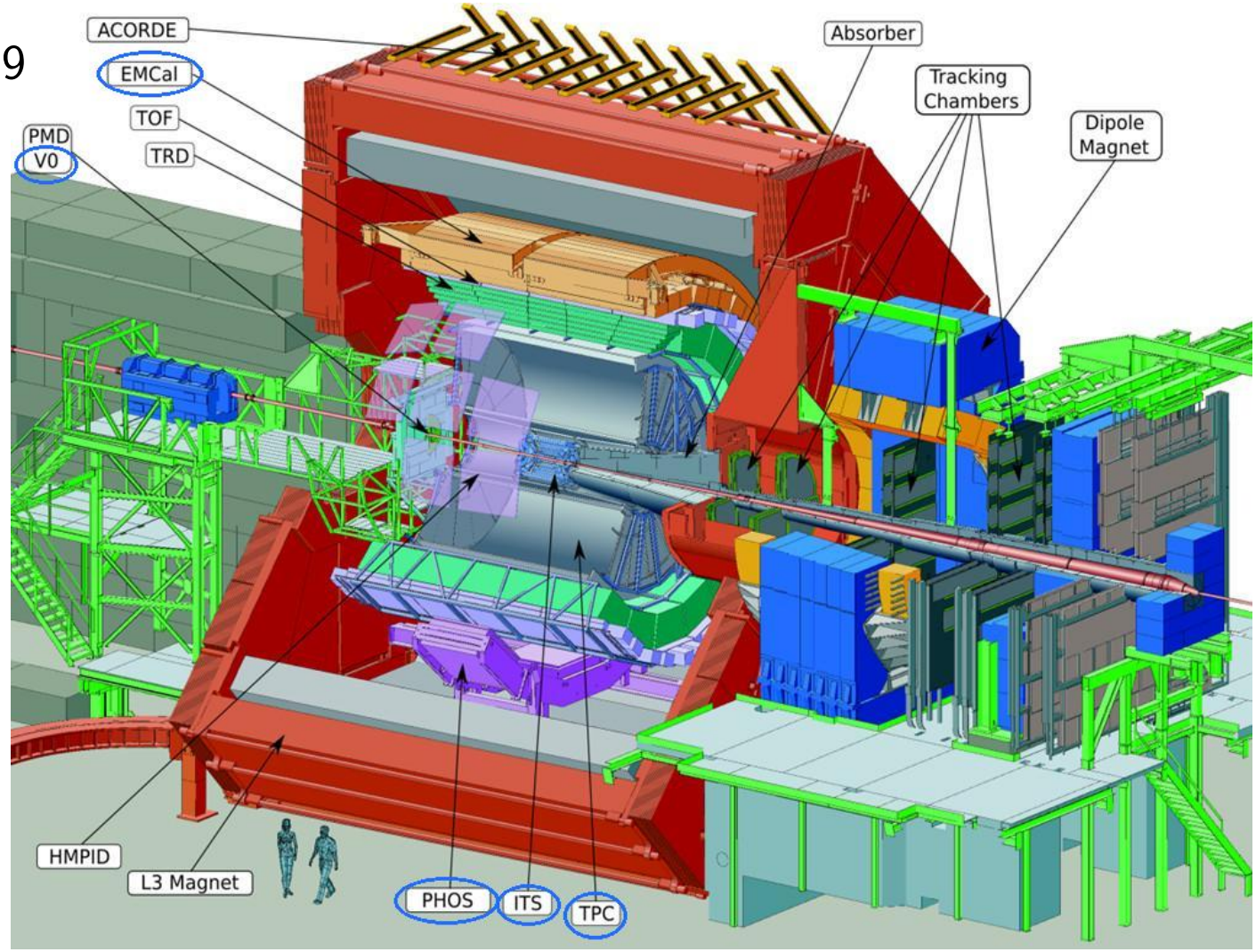
The ALICE experiment

Central barrel: $|\eta| < 0.9$

V0: multiplicity estimation

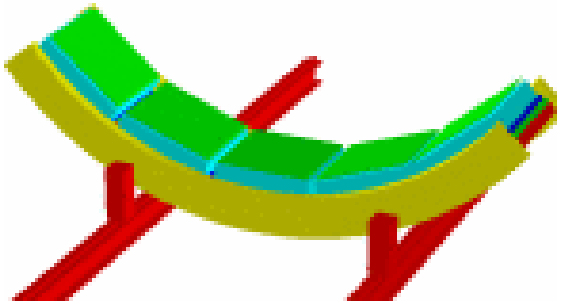
ITS: vertex finding and tracking

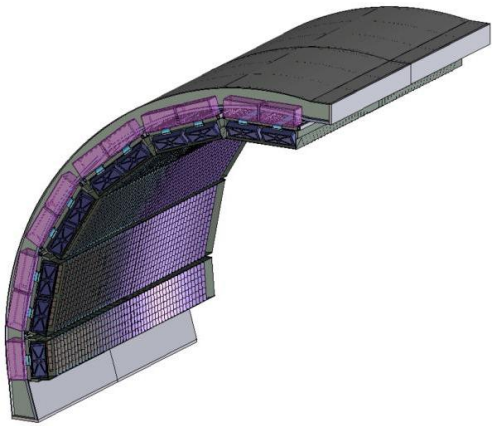
TPC: tracking and particle identification

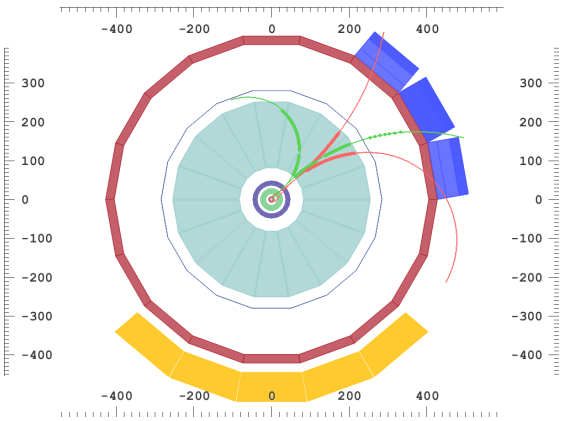


PHOS and **EMCal**: calorimetry

Photon detection with the ALICE experiment (RUN 1)







- PHOS calorimeter:
  - $PbWO_4$ crystals
  - 3 modules at 4.6 m from IP
  - $|\eta| < 0.13$, $260° < \phi < 320°$
- EMCal calorimeter:
  - 77 sampling layers,
    1.4 mm Pb and 1.7 mm scintillator
  - 10 modules at 4.4 m from IP
  - $|\eta| < 0.7$, $80° < \phi < 180°$
- Photon Conversion Method (PCM):
  - ITS and TPC
  - $|\eta| < 0.9$, $0° < \phi < 360°$
  - conversion in detector material:
    - ▷ conv. probability $\sim 8\%$
    - ▷ $X/X_0 = (11.4 \pm 0.5)\%_{(|\eta| < 0.9,\ R < 180\ cm)}$

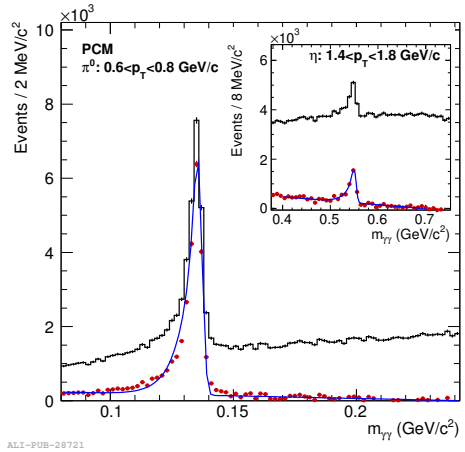
$\rightarrow$ Photon candidates are extracted from V^0s (neutral secondary vertex particles) sample

Invariant mass reconstruction

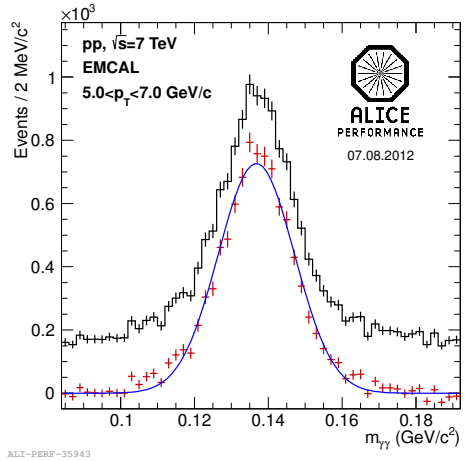
Photon candidates are combined into pairs

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

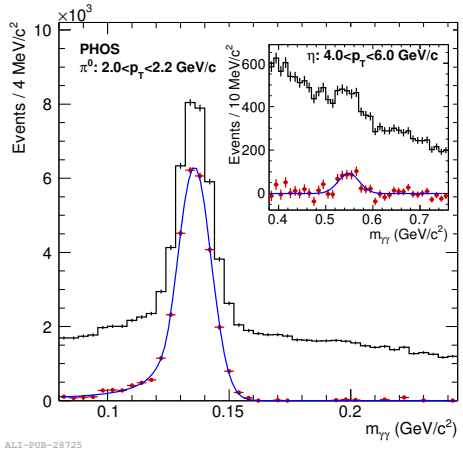
pp



PCM

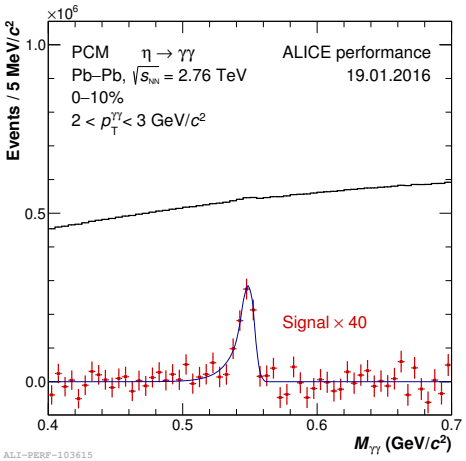


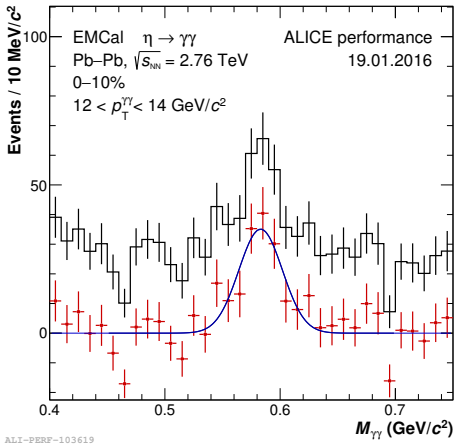
EMCal



PHOS

Pb-Pb



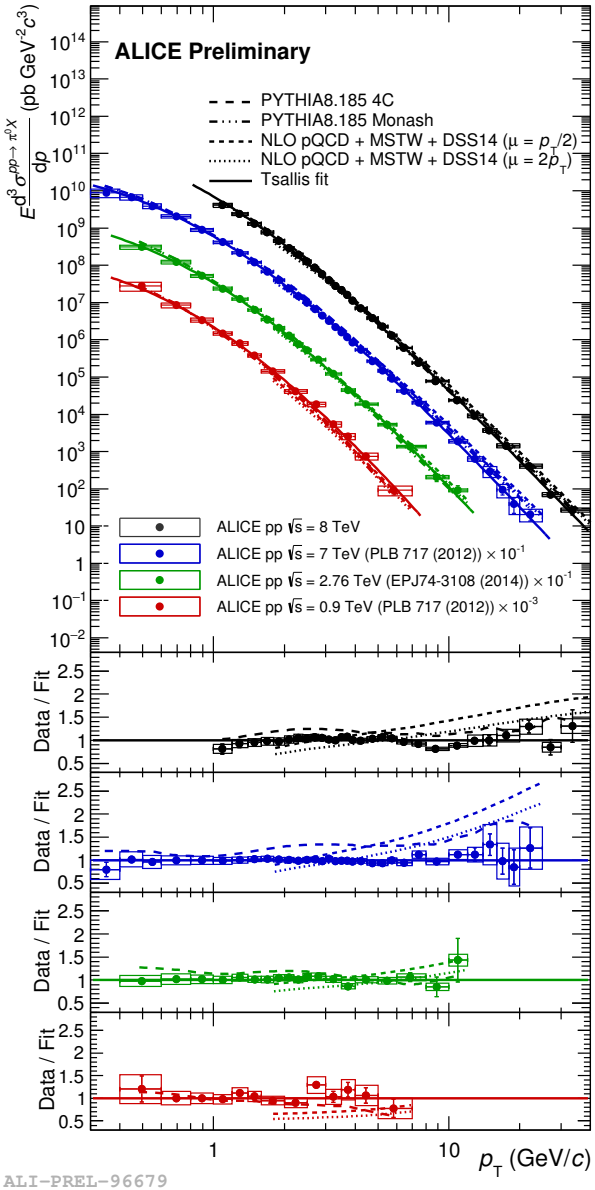


Histo: signal + background
Points: signal after background subtraction
Line: fit (for mass and width)

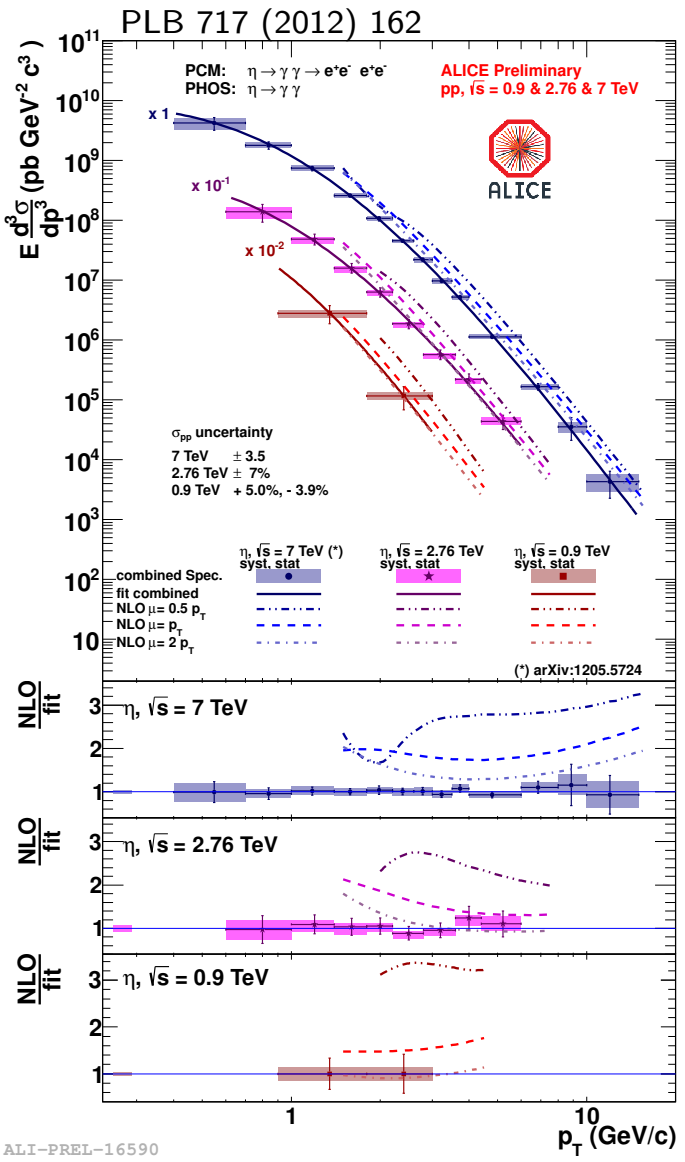
$$\frac{\Delta m}{m} \begin{cases} 3\%(\text{PCM}) \\ 5\%(\text{PHOS}) \\ 7\%(\text{EMCal}) \end{cases} \text{at } p_T = 3 \text{ GeV}/c \text{ in pp collisions}$$

π^0 and η in pp collisions

Neutral mesons invariant cross section (PCM + PHOS)



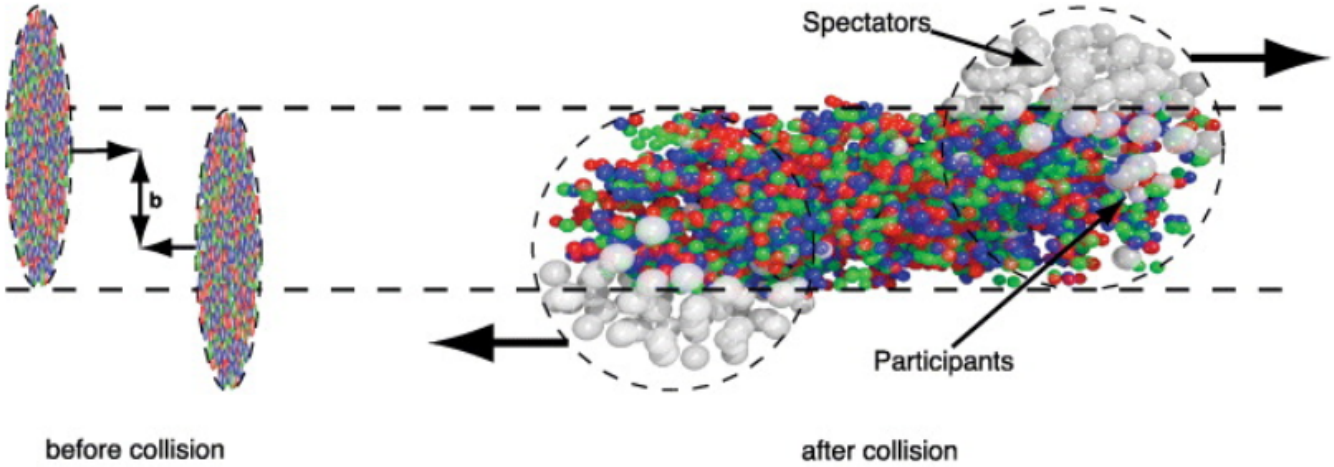
- π^0 compared to PYTHIA8 and NLO pQCD (PRD 91 (2015) 014035)
  → models give good description at intermediate p_T but a larger discrepancy towards higher p_T
- η compared to NLO pQCD by W. Vogelsang (PDF: CTEQ6M5, FF: AES)
- reference at $\sqrt{s} = 2.76$ TeV is used to calculate nuclear modification factor (R_{AA}) in Pb-Pb at the same center of mass energy



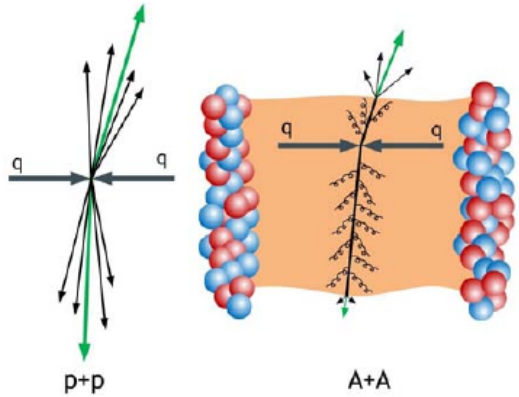
π^0 and η in Pb–Pb collisions

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

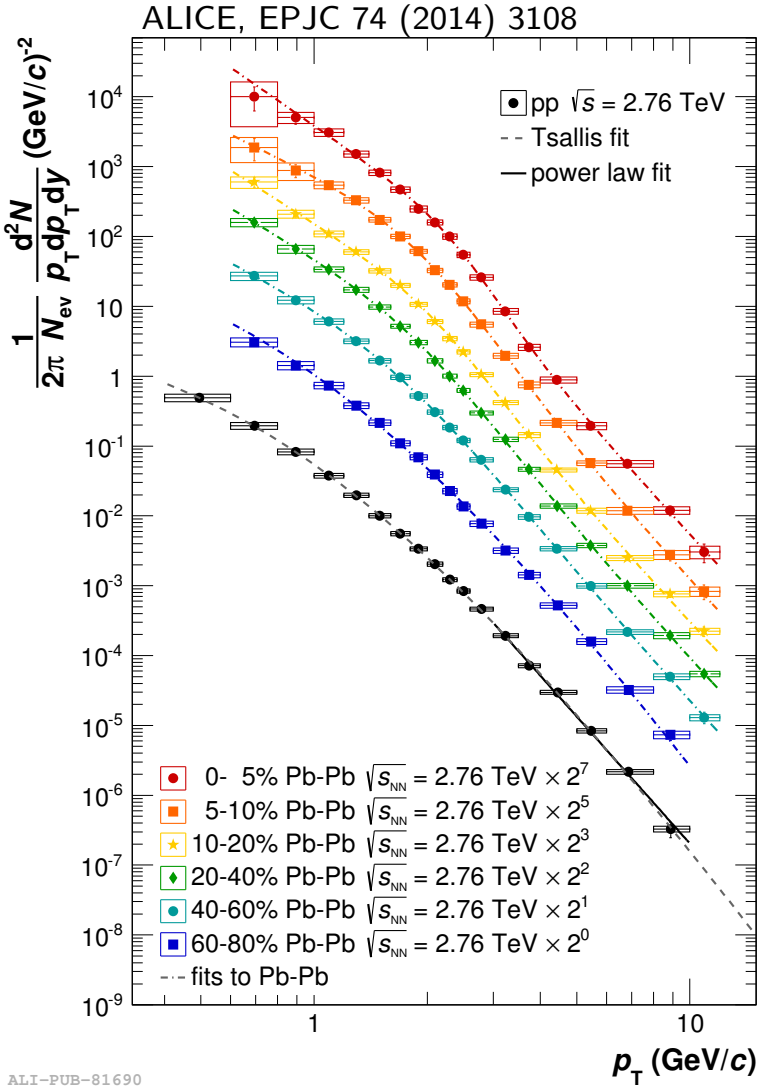
QGP forms in A–A collisions: hot and dense medium, strongly interacting



- 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)



π^0 from 2010 data (PCM + PHOS)

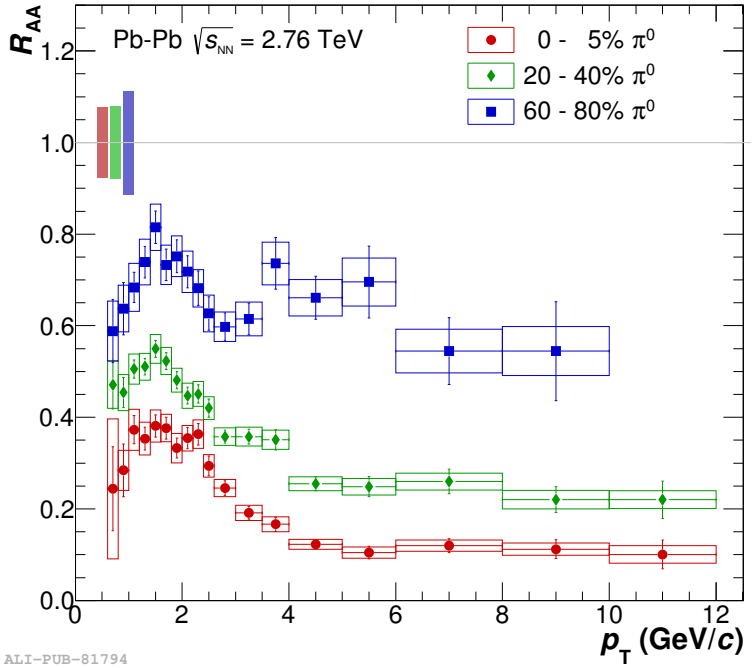


- not enough statistics for η measurement in 2010 data

- pp reference measurement at 2.76 TeV is used to calculate the nuclear modification factor

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

- suppression due to interaction with medium is larger for more central collisions



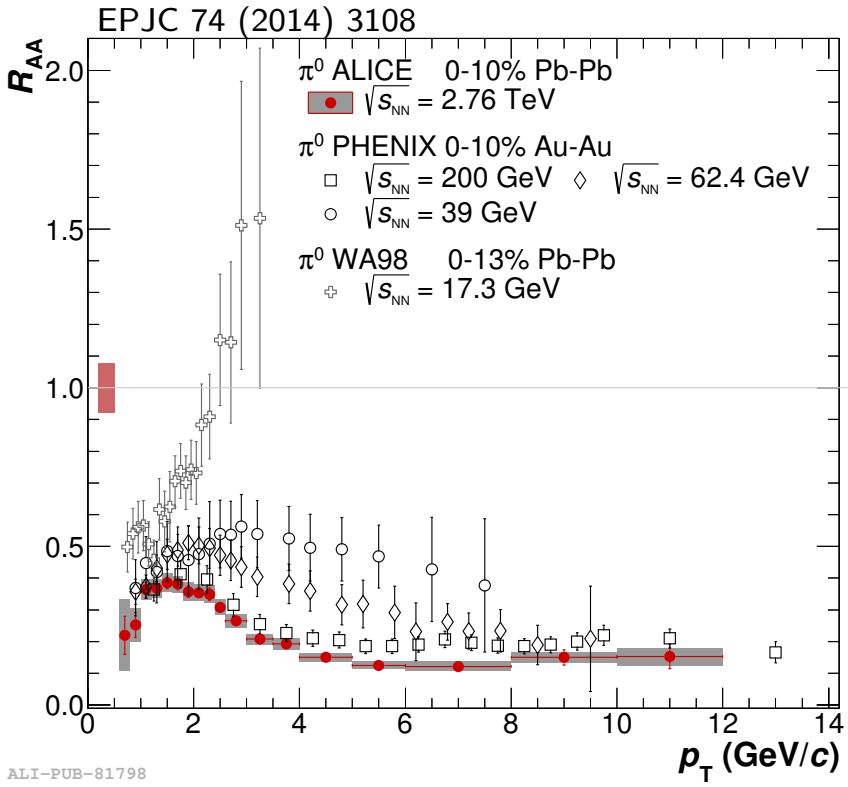
Neutral pion R_{AA} collision energy dependence

- **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 **SPS** 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

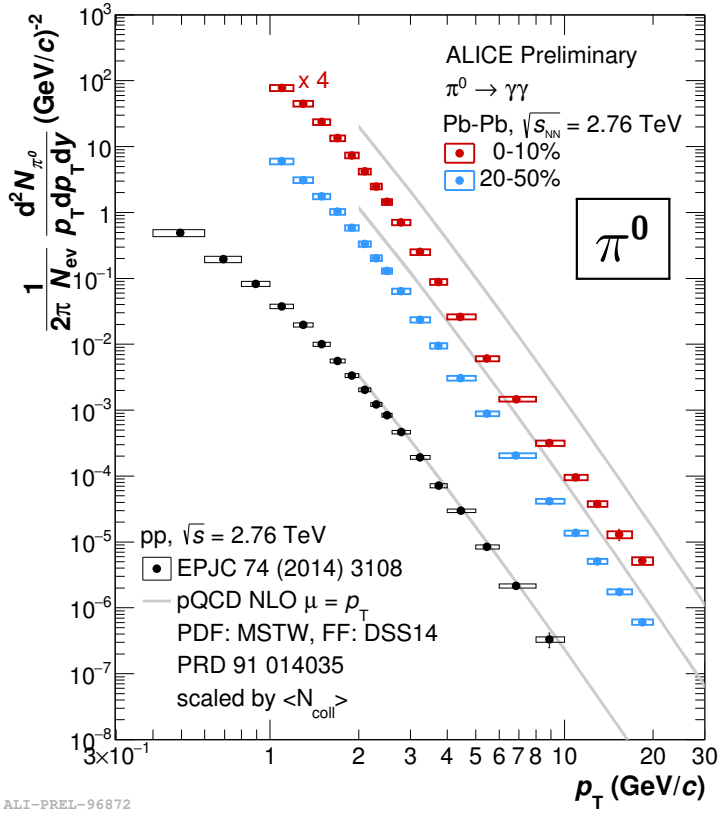
- maximum value of the ratio also shifts towards lower p_T going to higher energy

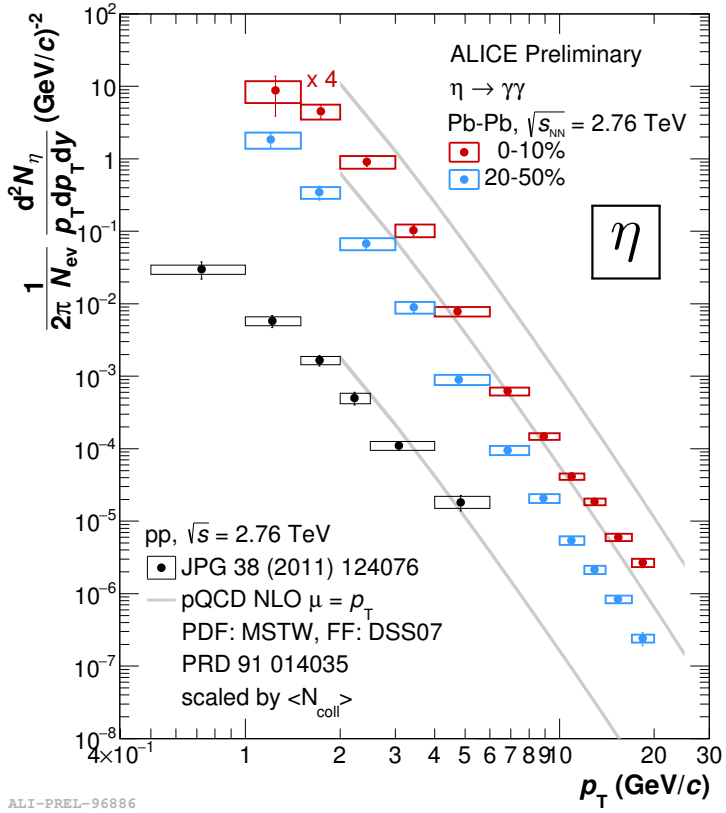
- at high p_T, R_{AA} is expected to rise due to a flatter spectra in A–A than in pp



Neutral mesons from 2011 data (PCM + EMCal)

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

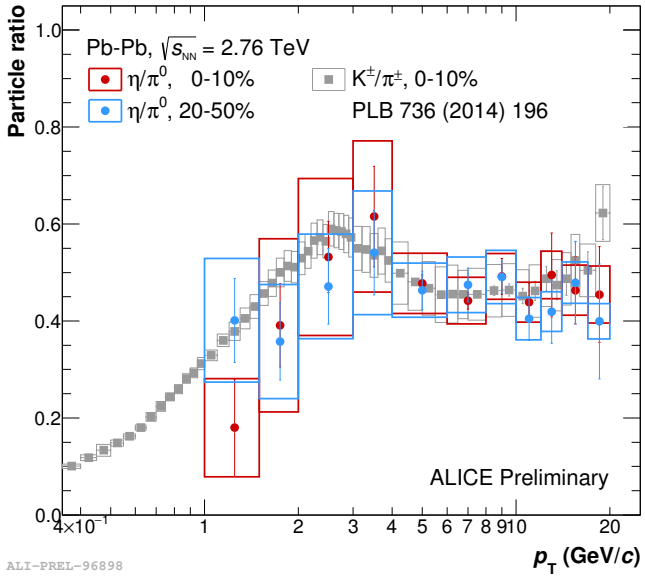


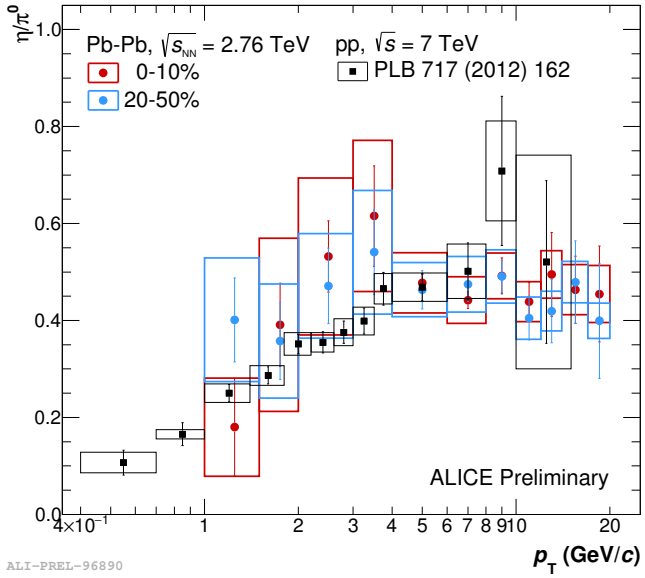


- π^0 consistent with 2010 data, measurement extended to 20 GeV/c
- **first η measurement in Pb–Pb** at the LHC

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 results from ALICE:
  - η/π^0 shows behaviour similar to $K^{\pm}/\pi^{\pm}$ result at same energy and centrality (0-10%)
  - with current uncertainties, no differences are observed between η/π^0 ratio measured in Pb–Pb and pp collisions





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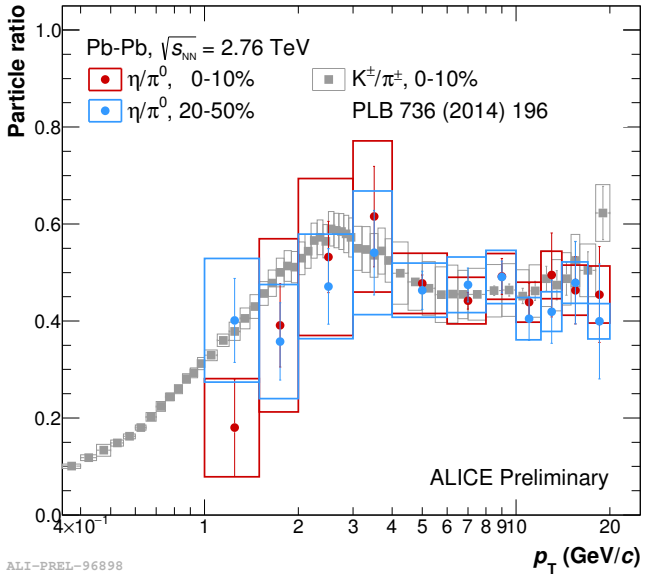
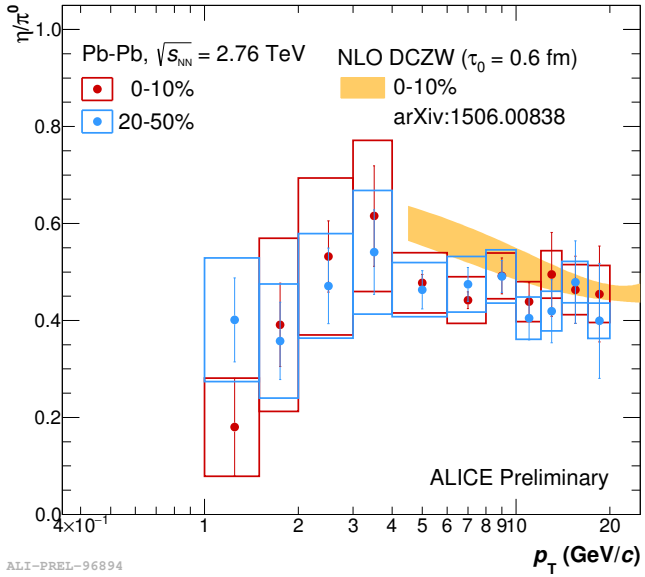
- pQCD NLO calculation for 0-10% cent. class agrees within uncertainties $\rightarrow$ p_{T} region 4–6 GeV/c sensitive to transport coefficient (= parameter describing energy loss in medium)





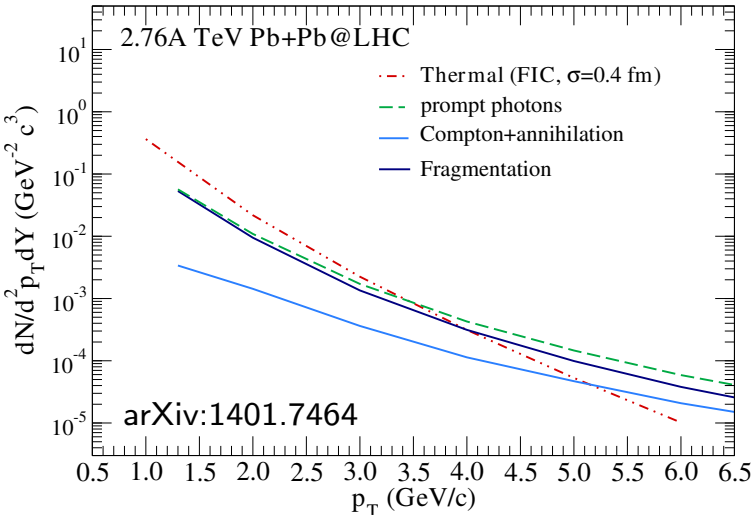
Direct photons in Pb–Pb collisions

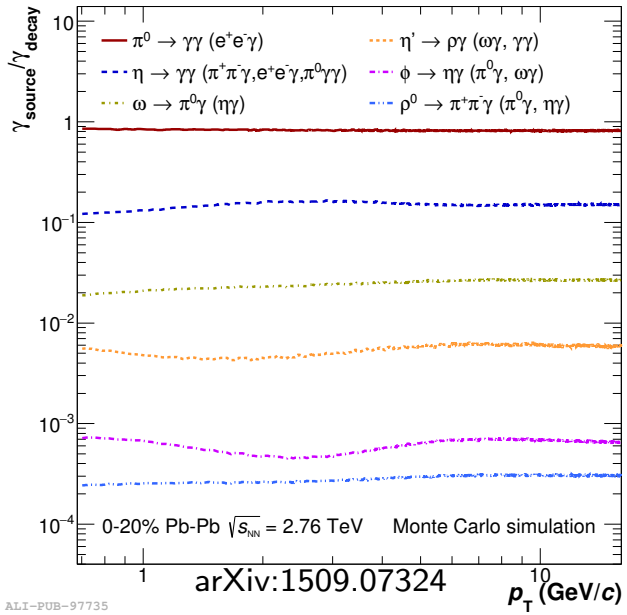
Direct photons in Pb–Pb collisions

- 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:

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

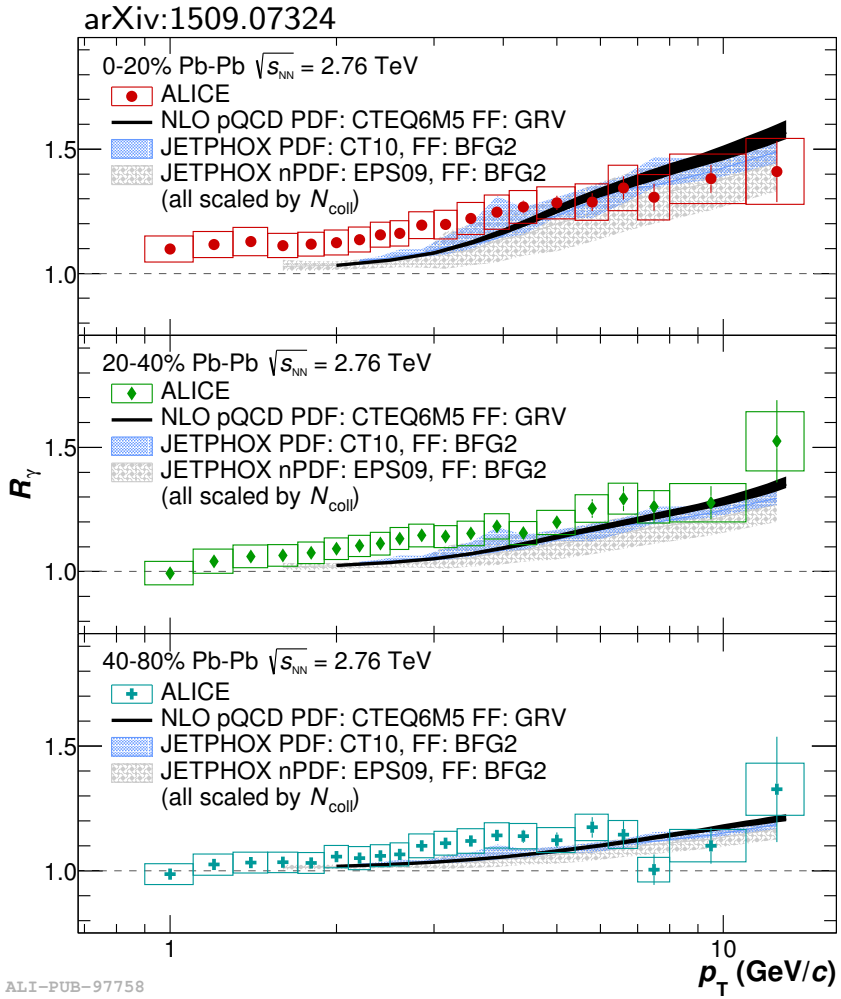
$$\text{with } R_\gamma = \frac{\gamma_{\text{inc}}}{\pi^0} \Big/ \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}}$$





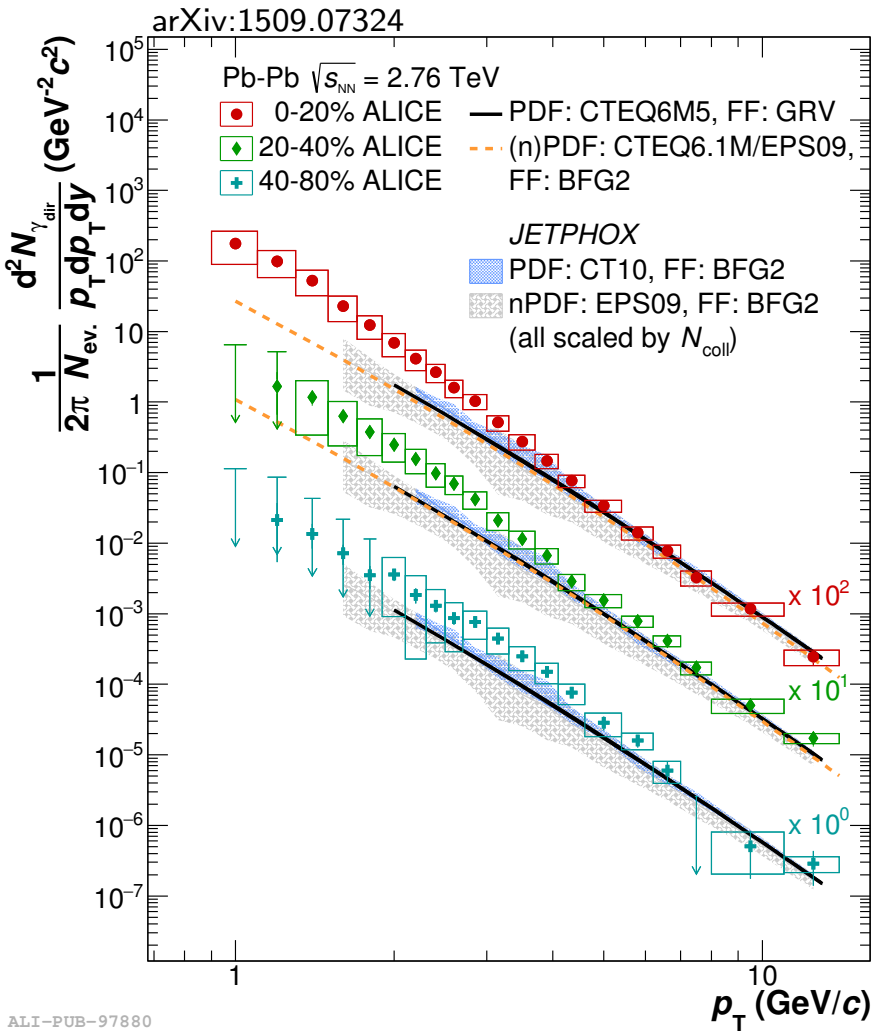
Direct photons in 2010 Pb–Pb data (PCM + PHOS)

- inclusive photon spectra measured with combined PCM + PHOS (arXiv:1509.07324) in 3 centrality classes with 2010 Pb–Pb data
- R_γ excess at high p_T for all centralities
- in agreement with NLO/JETPHOX pQCD above 5 GeV/c
- at low p_T, $\sim$ 20% excess in 0-20% and $\sim$ 9% in 20-40% due to thermal radiation of the medium



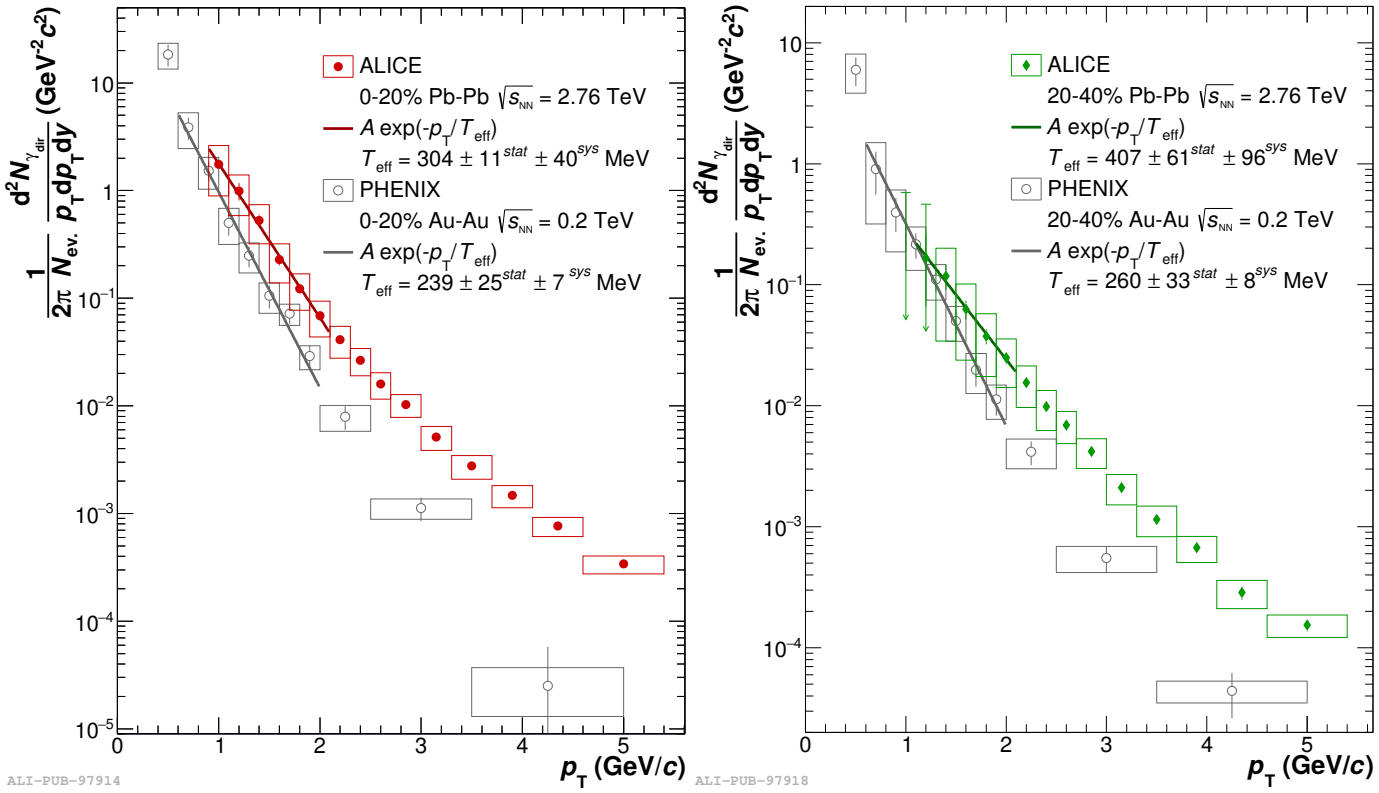
Direct photons in 2010 Pb–Pb data (PCM + PHOS)

- 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 PHENIX - ALICE

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

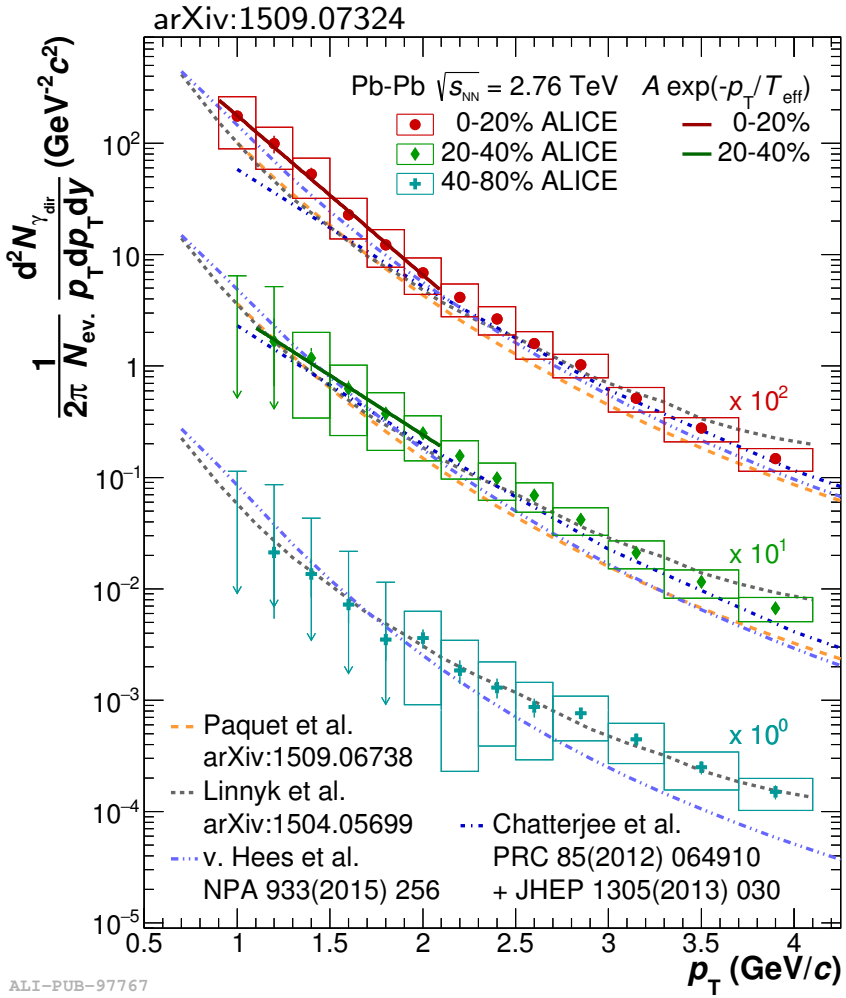


▷ exponential fit to low p_T excess: inverse slope parameter larger at higher collision energy and consistent in both centrality classes

Direct photon spectra comparison to models

Several models, all assume QGP formation and include pQCD photons at high $p_T \rightarrow$ 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

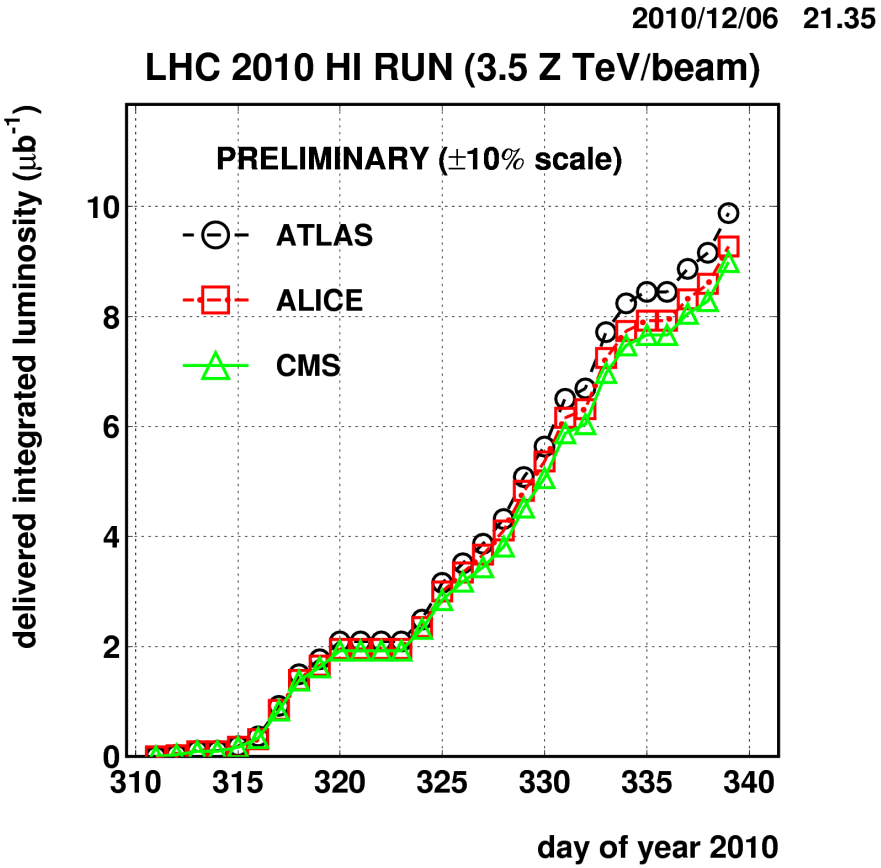
▷ results in Pb–Pb at 2.76 TeV

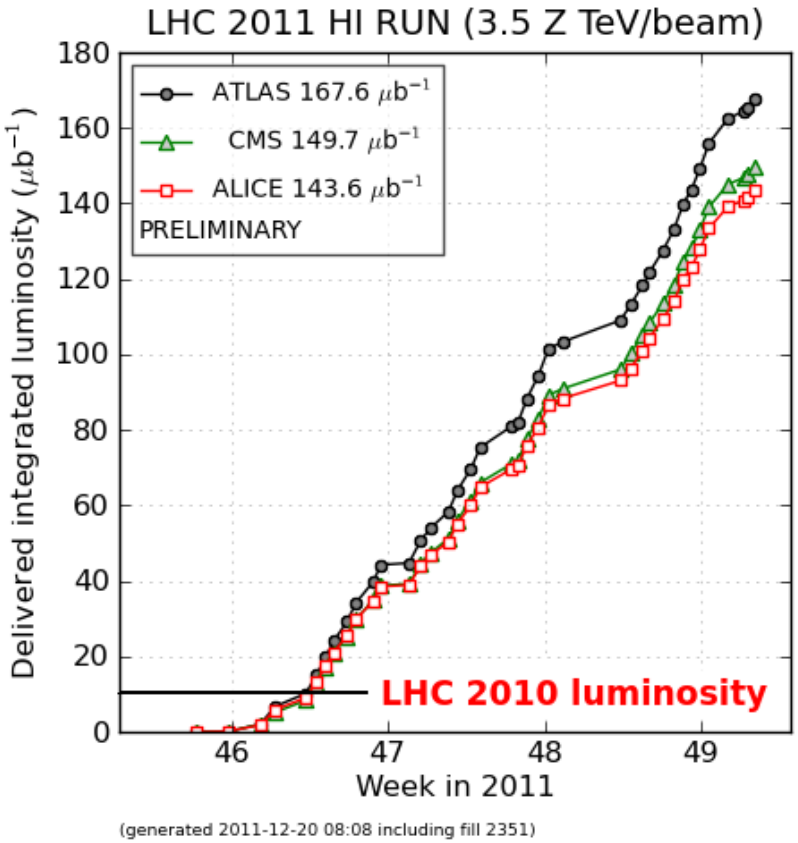
- neutral mesons measurements:
  - π^0 measured with PCM + PHOS (2010 data) and PCM + EMCal (2011 data) and η measured with PCM + EMCal (2011 data)
  - π^0 R_{AA} has larger suppression in more central collisions and its magnitude scales with the collision energy
  - with current uncertainties, no clear 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

Back up

Luminosity 2010 vs 2011



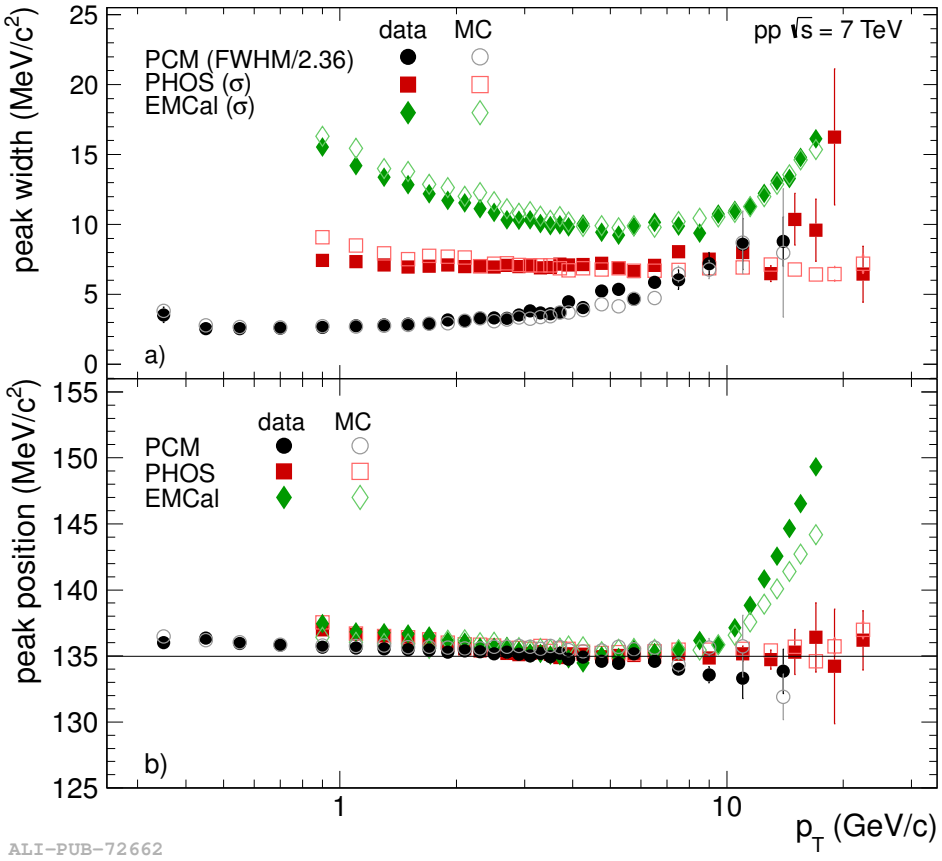


⇒ with large statistics collected in 2011 measurement of differential invariant cross section is possible

Neutral pion peak position and width

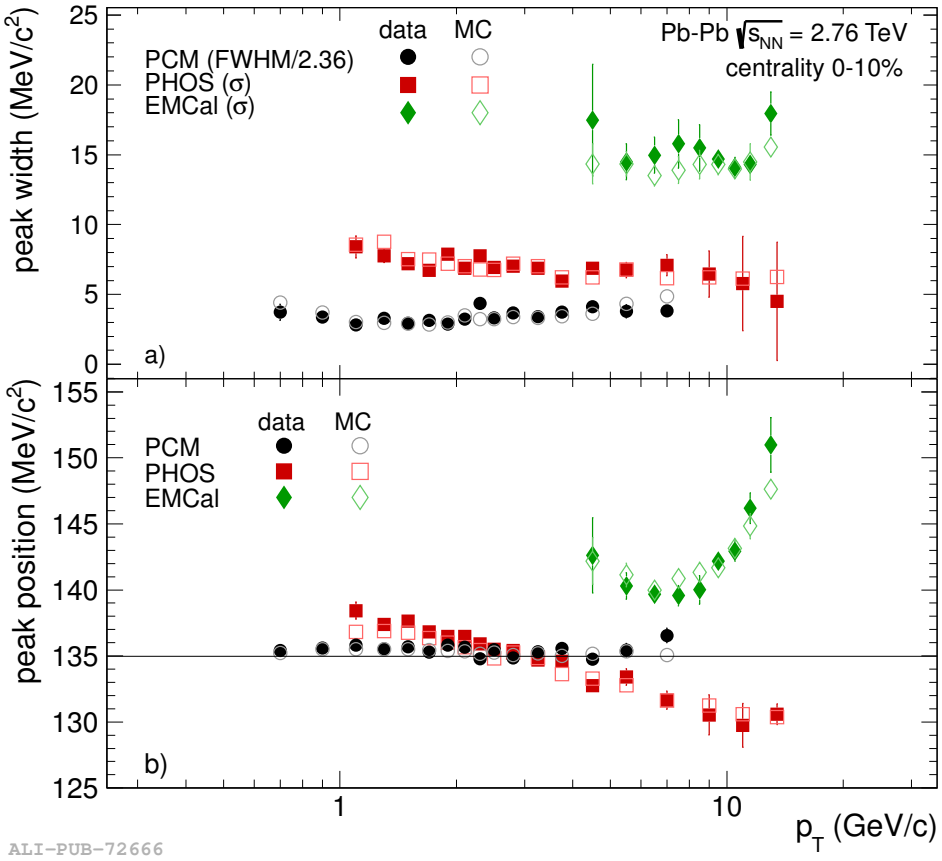
ALICE performance paper: Int. J. Mod. Phys. A 29 (2014) 1430044

pp



ALI-PUB-72662

Pb–Pb



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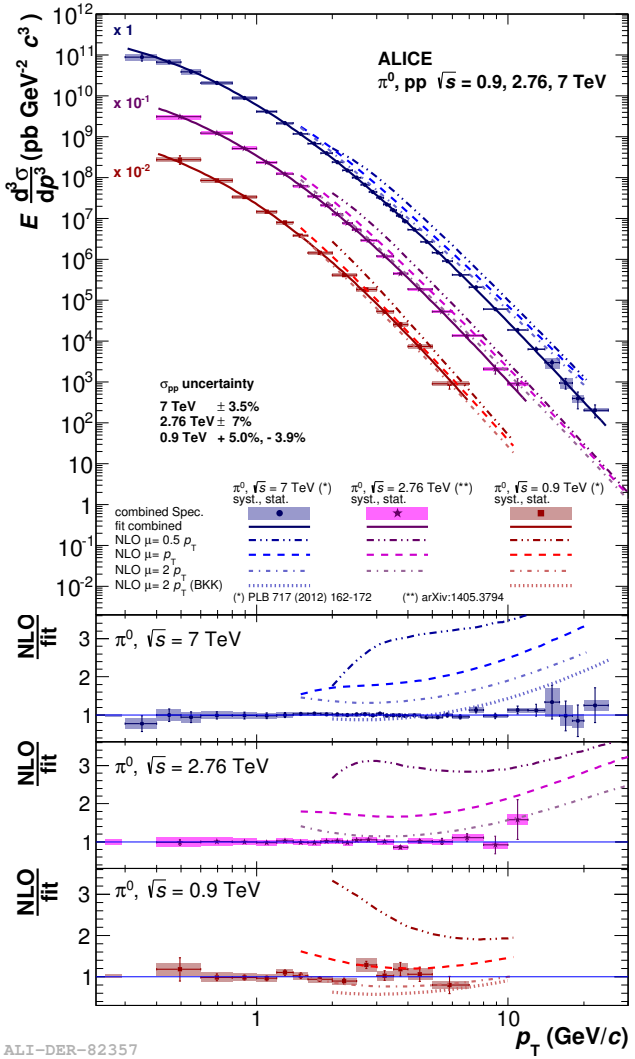
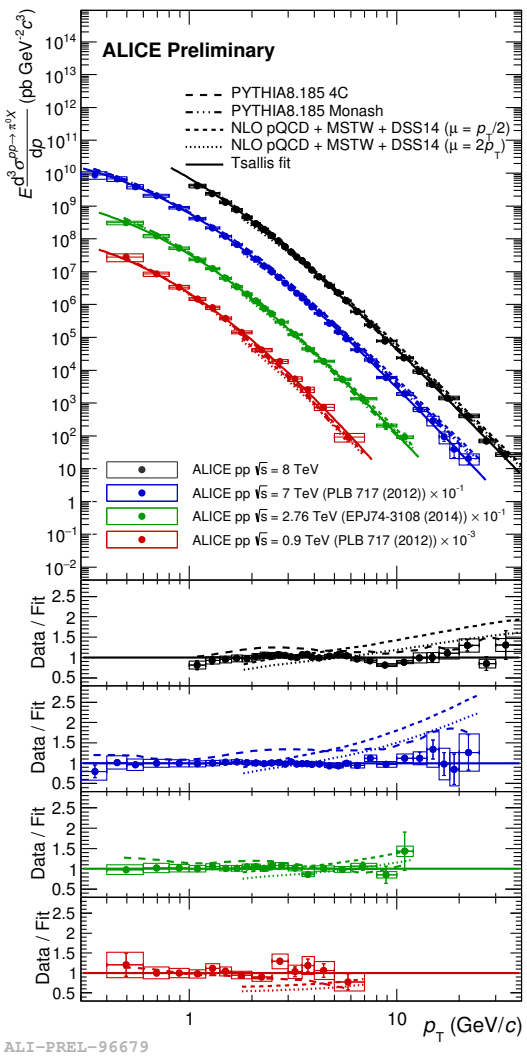
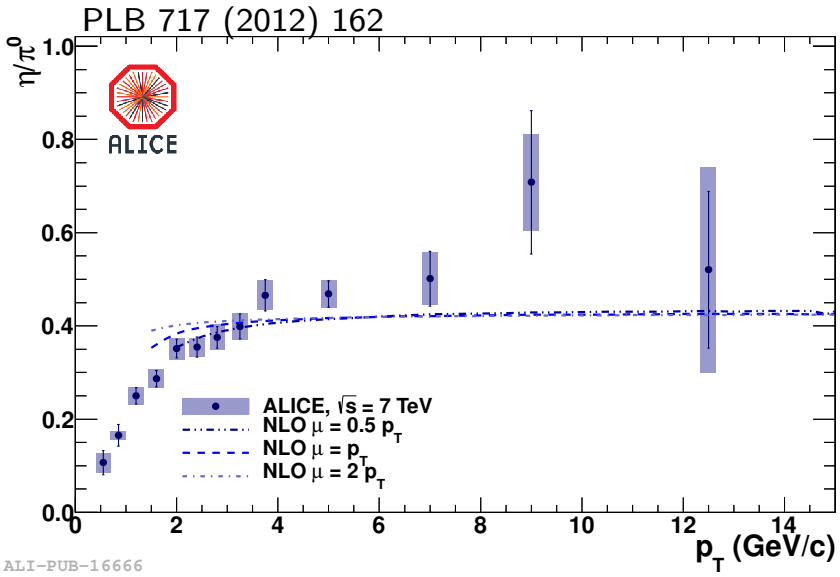
Neutral pion spectra in pp collisions (PCM + PHOS)

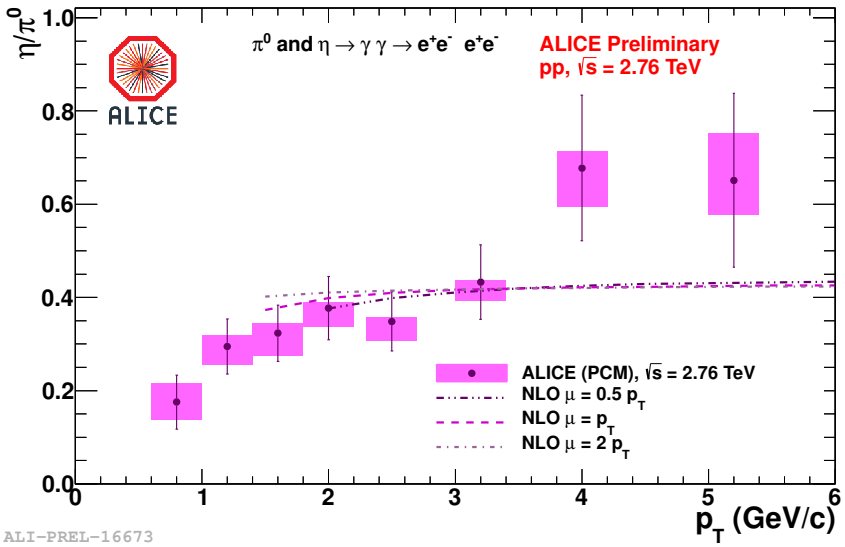
With additional constraint given by 8 TeV results, large improvement of NLO pQCD calculations





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

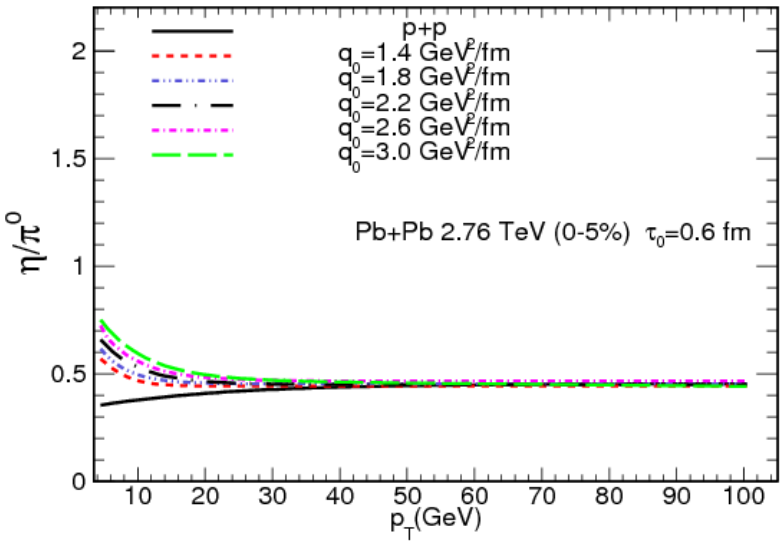




- η/π^0 ratio compared with pQCD NLO theory by W. Vogelsang
- η, PDF: CTEQ6M5, FF: AES
  π^0, PDF: CTEQ6M5, FF: DSS
- at both 7 and 2.76 TeV an increasing trend can be observed up to 2 GeV/c
- above 2 GeV/c the ratio flattens, as the NLO calculations suggest

DCZW prediction

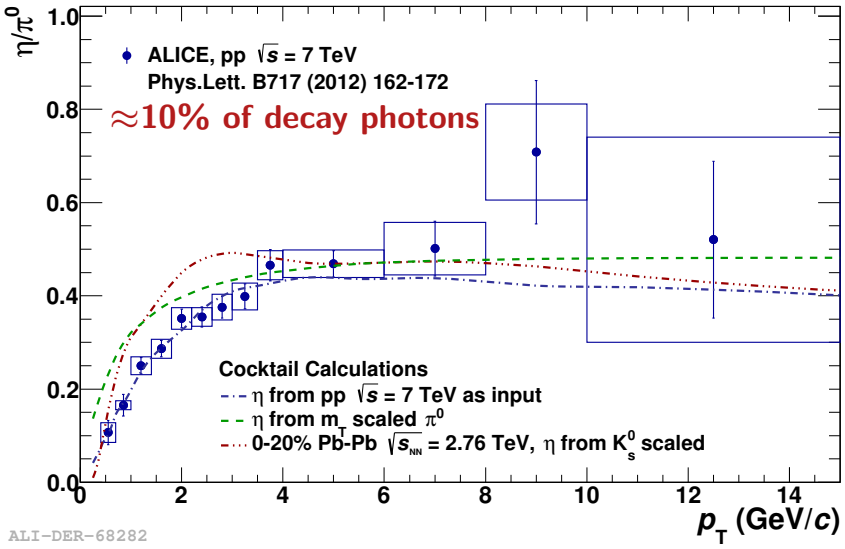
NLO pQCD theoretical prediction of η/π^0 ratio in Pb–Pb collisions at 2.76 TeV according to DCZW (PLB 750 (2015) 390-395)

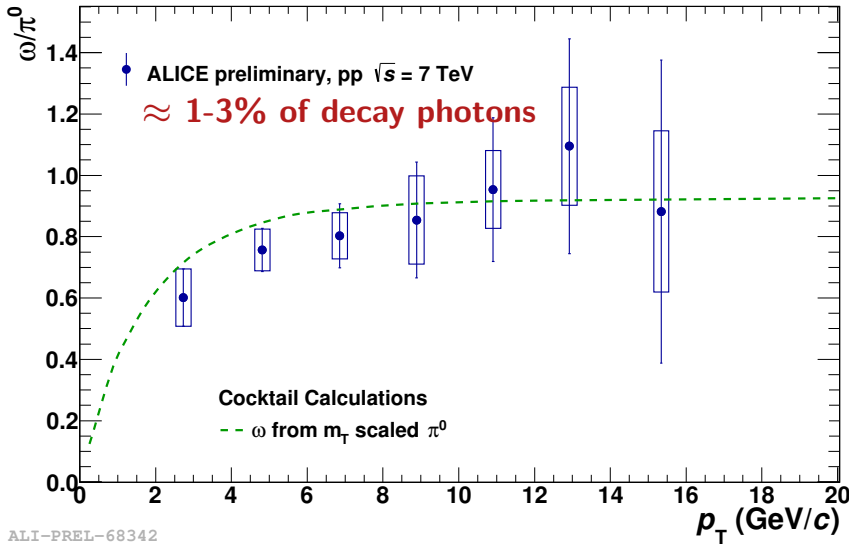


τ_0 is the initial time of the QGP medium

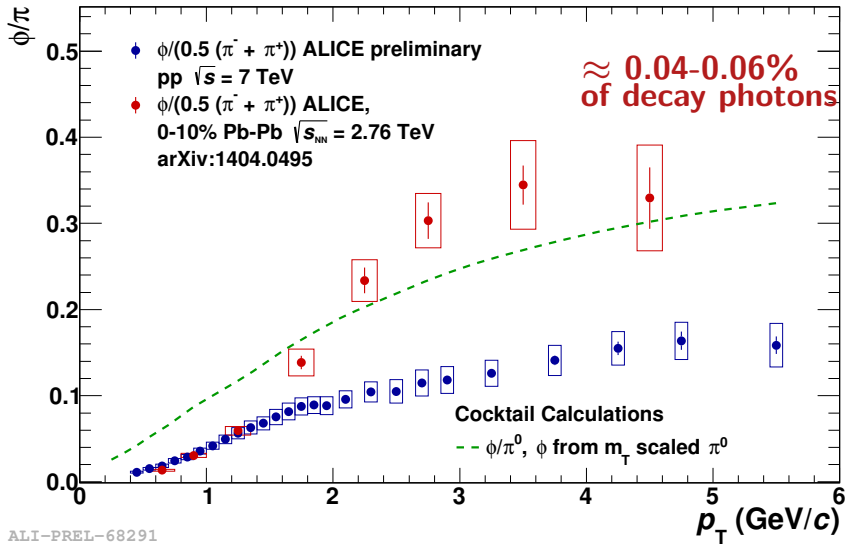
$\hat{q}_0$ initial values of the jet transport parameter $\rightarrow$ the larger $\hat{q}_0$ is, the stronger the jet-medium interaction will be

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%



Direct Photon Flow

$$\nu_n^{\text{direct }\gamma} = \frac{R_\gamma \cdot \nu_n^{\text{inc }\gamma} - \nu_n^{\text{decay }\gamma}}{R_\gamma - 1}$$

- $R_\gamma \cdot \nu_n^{\text{inc }\gamma}$: weighted inclusive photon ν_n due to extra photons compared to background
- $\nu_n^{\text{decay }\gamma}$: calculated decay photon ν_n from cocktail calculation

Inclusive photon ν_2 analysis method

Initial azimuthal asymmetry in coordinate space in non-central A+A

$\Rightarrow$ asymmetry in momentum space

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} \nu_n \cos(n(\phi - \Psi_n^{RP}))\right)$$

- ν_2 given by photon production with respect to event plane:

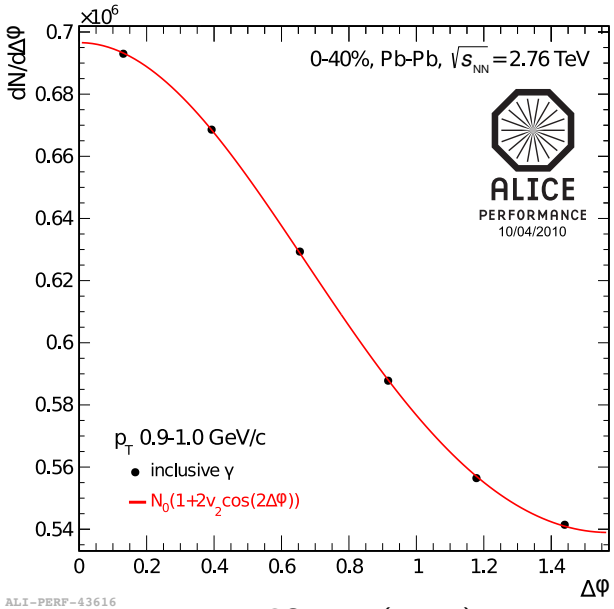
  $\nu_2 = \langle \cos(2(\phi - \Psi_2^{RP})) \rangle$

- event plane angle determined by using the VZERO detector:
  - VZEROA: $2.8 < \eta < 5.1$
  - VZEROC: $-3.7 < \eta < -1.7$

- reaction plane resolution obtained by the three sub-event method

- resolution correction for EP:

$$\nu_2 = \frac{\nu_2^{EP}}{\langle \cos(2\Psi_2^{EP} - \Psi_2^{RP}) \rangle} = \frac{\nu_2^{\mathrm{raw}}}{\text{resolution}}$$



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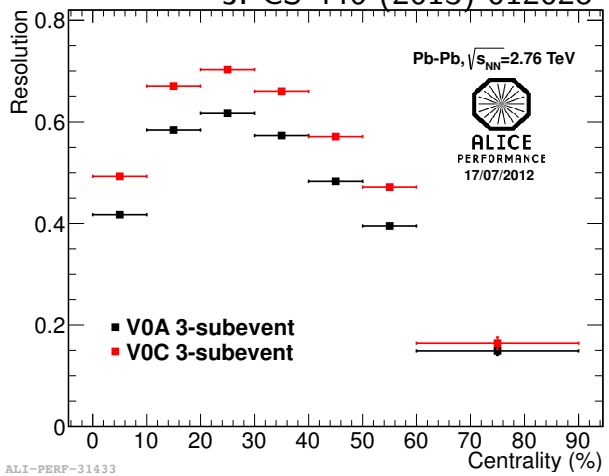


Cocktail simulation of decay photon ν_2

Decay photon ν_2:

- ν_2 of mesons scales with KE_T:

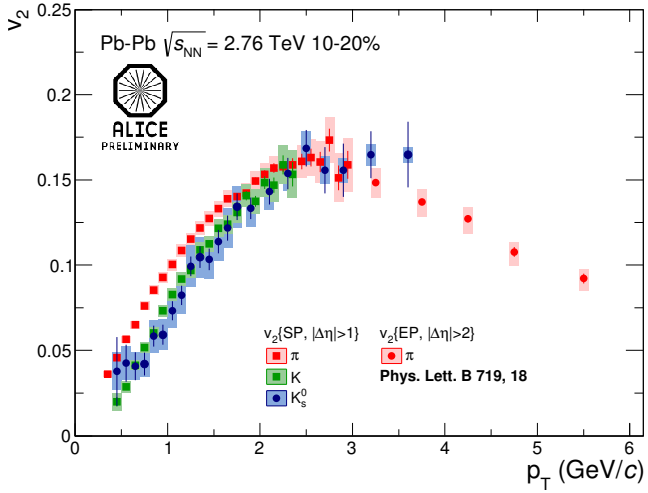
  $KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$

  $\Rightarrow \nu_2^{\pi^0} \approx \nu_2^{\pi^\pm}$ $(m^{\pi^0} \approx m^{\pi^\pm})$

  $\Rightarrow$ ν_2 of various mesons (X) calculated via KE_T (quark number) scaling from $\nu_2^{\pi^\pm}$

$$\nu_2^X(p_T^X) = \nu_2^{\pi^\pm}\left(\sqrt{(KE_T^X + m^{\pi^\pm})^2 - (m^{\pi^\pm})^2}\right)$$

- Decay photon ν_2 from different mesons obtained from cocktail calculation



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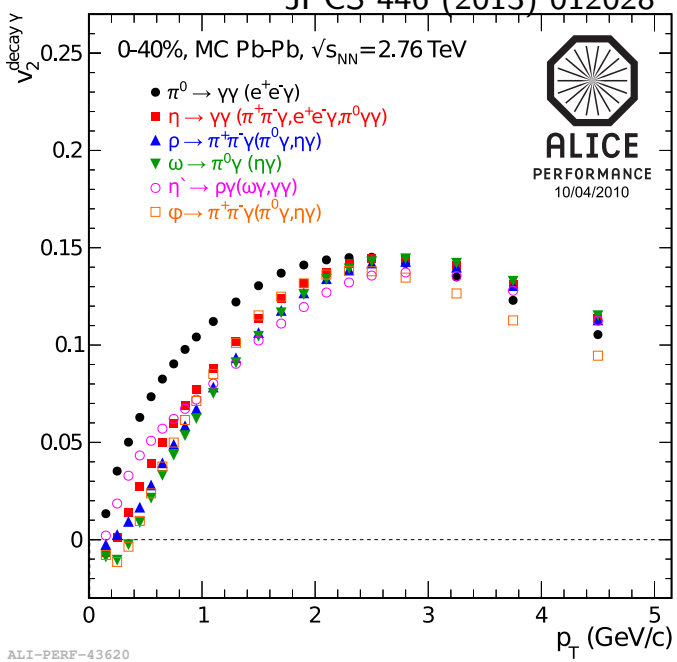


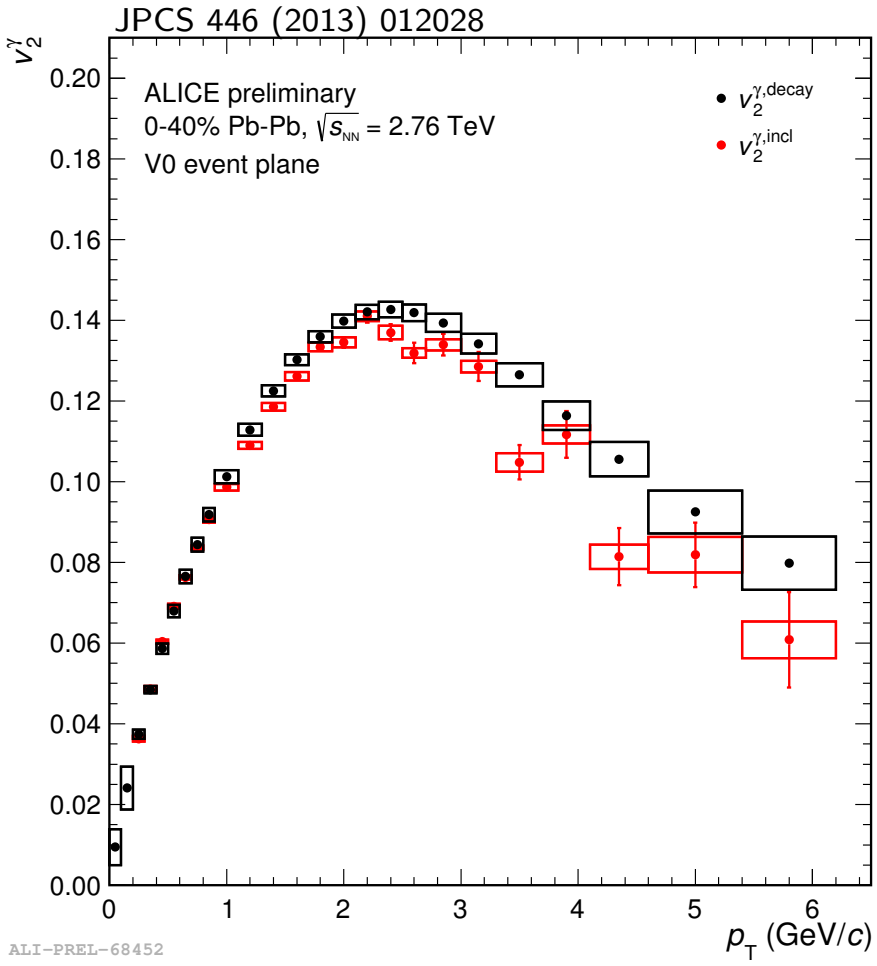
Comparison of inclusive and decay ν_2

- Above 3 GeV/c inclusive photons significantly smaller than decay photons

  $\rightarrow$ Direct photon ν_2 contribution with $\nu_2^{\mathrm{direct}} < \nu_2^{\mathrm{decay}}$

- Below 3 GeV/c consistent within uncertainties

  $\rightarrow$ Either contribution of direct photons with similar ν_2 or no direct photons

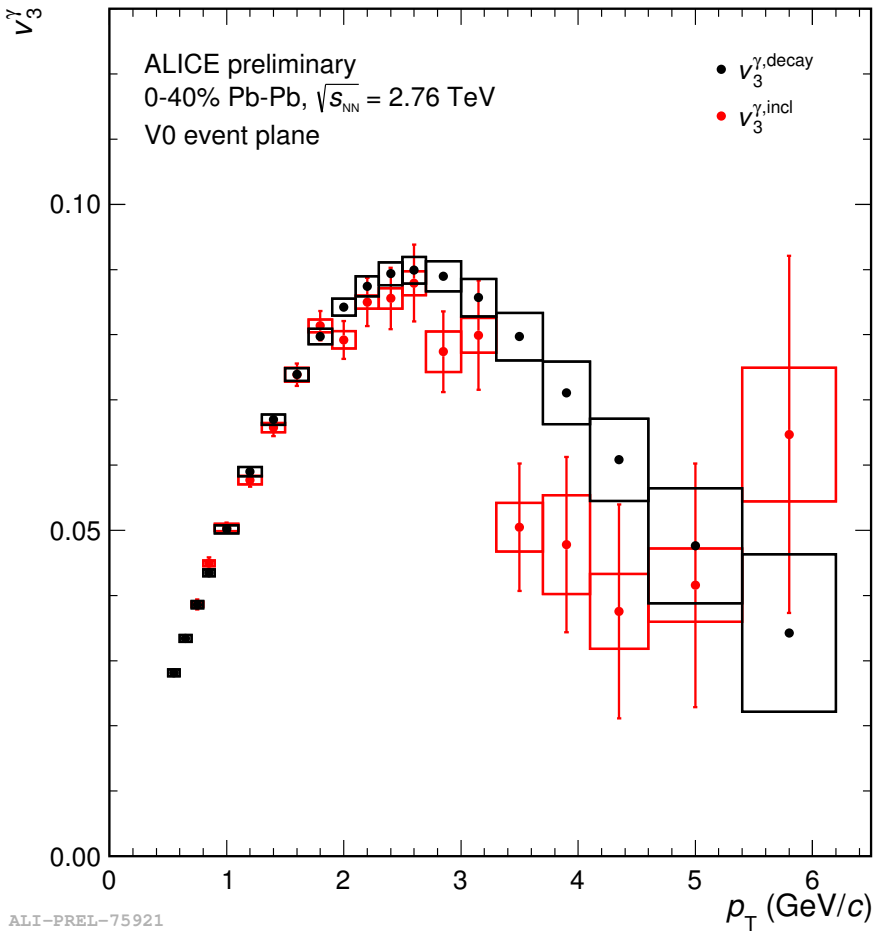


Inclusive photon ν_3

- First measurement of inclusive photon ν_3 at LHC
- Above 3 GeV/c inclusive photons consistently smaller than decay photons, with large statistical uncertainties

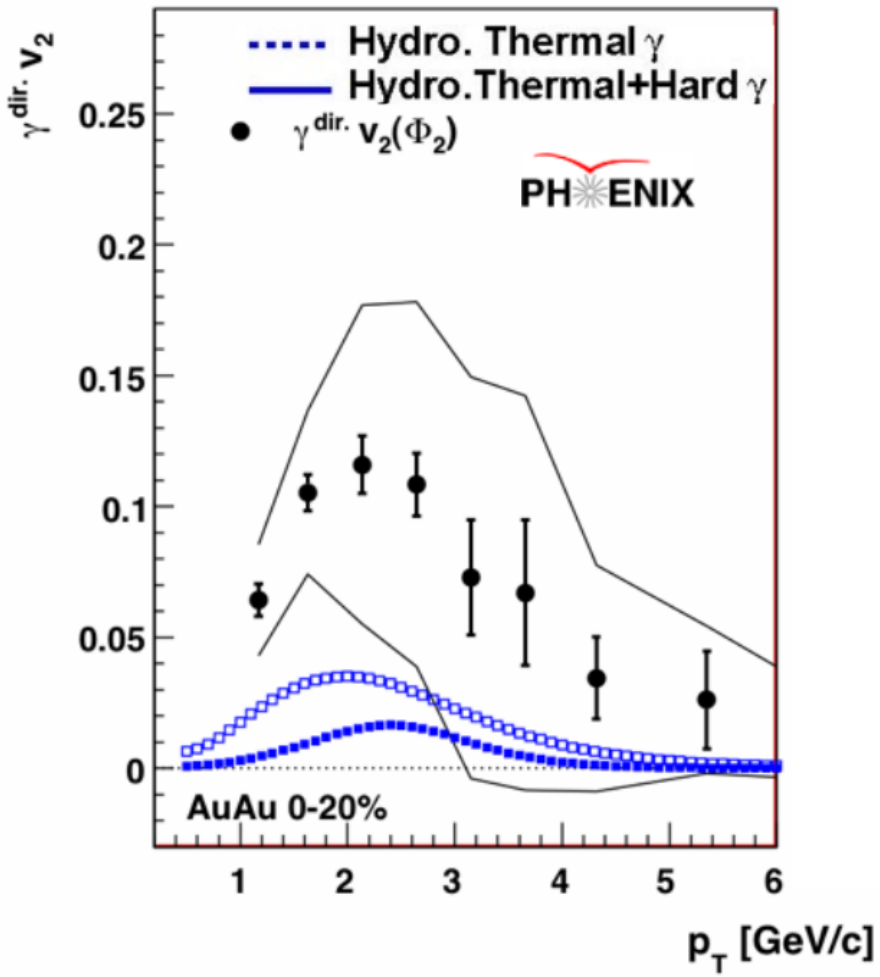
  $\rightarrow$ Direct photon ν_3 contribution with $\nu_3^{\mathrm{direct}} < \nu_3^{\mathrm{decay}}$ as expected for prompt photons
- Below 3 GeV/c mostly consistent within uncertainties

  $\rightarrow$ Either contribution of direct photons with similar ν_3 or no direct photons



Comparison with RHIC - PHENIX Direct Photon ν_2

QM 2011, E. Kistenev



- Direct photon ν_2 has been measured at RHIC with the Phenix experiment at $\sqrt{s_{NN}} = 200$ GeV
- Direct photon ν_2 comparable to that of other hadrons
- Theory not able to reproduce large ν_2 at low p_T
- Origin of the "photon puzzle"

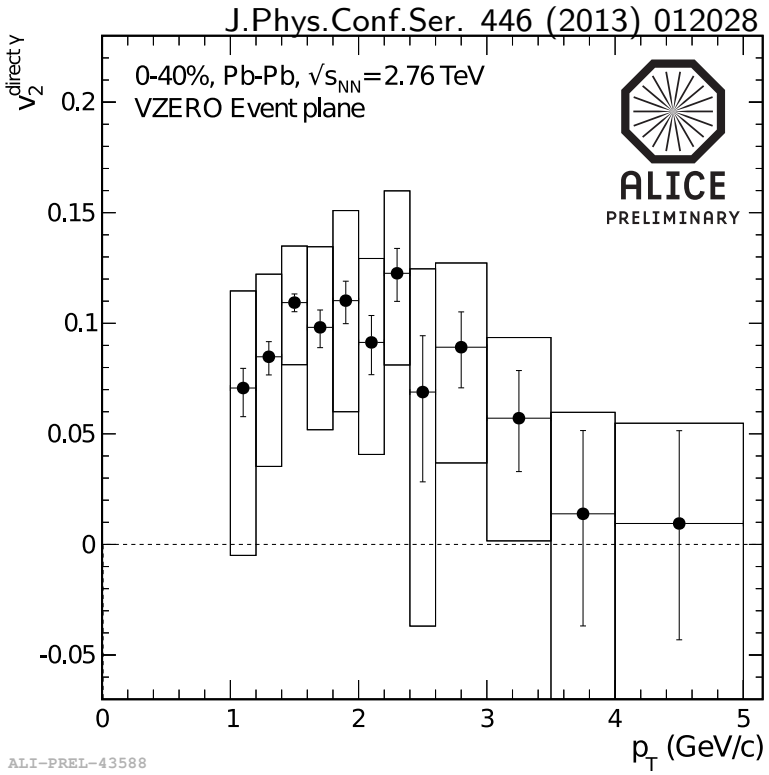
Direct Photon ν_2 0-40%

Direct photon ν_2:

$$\nu_2^{\text{direct }\gamma} = \frac{R_\gamma \cdot \nu_2^{\text{inc }\gamma} - \nu_2^{\text{decay }\gamma}}{R_\gamma - 1}$$

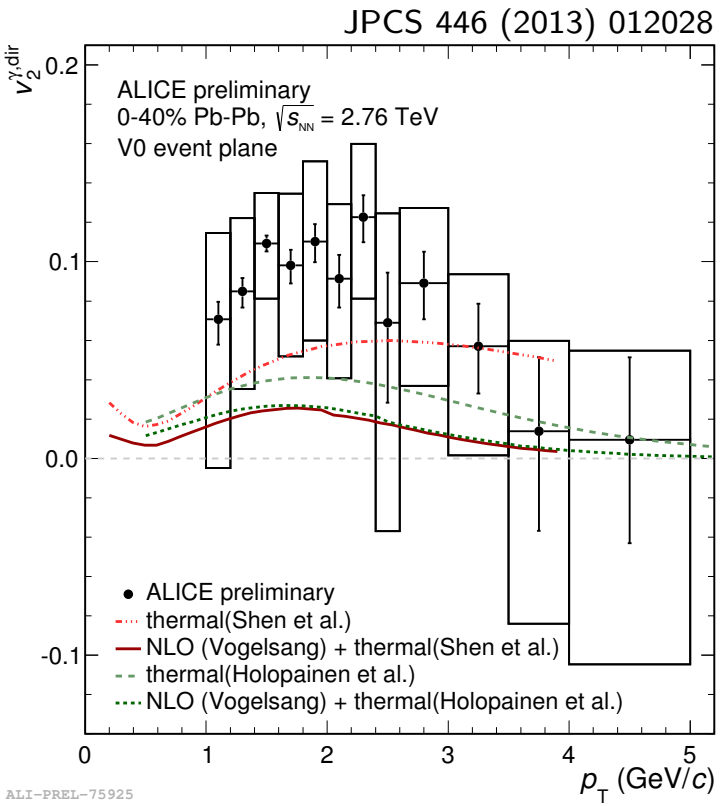
- $R_\gamma \cdot \nu_2^{\text{inc }\gamma}$: weighted inclusive photon ν_2 due to extra photons compared to background
- $\nu_2^{\text{decay }\gamma}$: calculated decay photon ν_2 from cocktail calculation

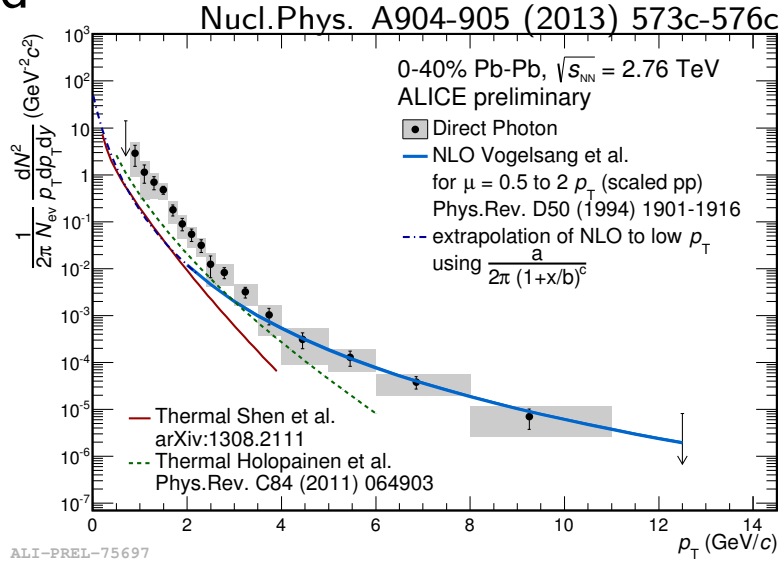
- Large direct photon ν_2 for $p_T < 3\,\mathrm{GeV/c}$ measured
- Magnitude of ν_2 comparable to hadrons
- Result points to late production times of direct photons after flow is established



Direct photon yield and flow

- Central points for direct photon yield and ν_2 underestimated by most theoretical calculations by factors of 2-10
- No significant deviation beyond 2σ





- Both measurements are coupled via R_γ, critical assessment of uncertainties and their correlations needed
- Theory curves composed out of different sources, experimentally not possible to distinguish those