π^0-hadron correlations in pp, p-Pb and Pb-Pb collisions at ALICE

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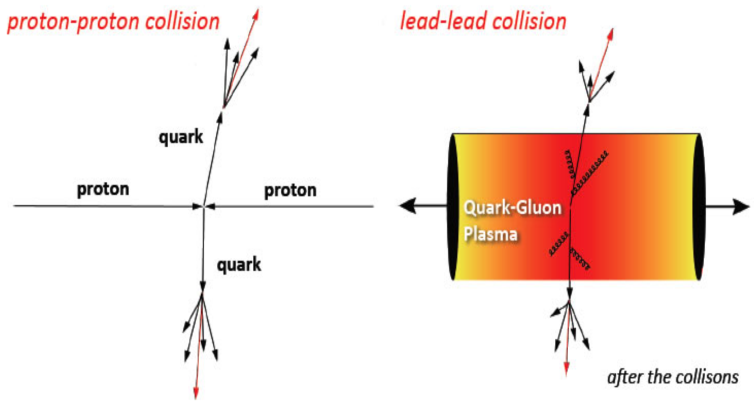
Physics motivation

- "Jet quenching" → strong evidence of QGP formation at AA collisions.
- Parton energy loss → theoretical models are still in development.
- Observables to study energy loss:
  - Particle and jet yields modification in AA collisions:

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



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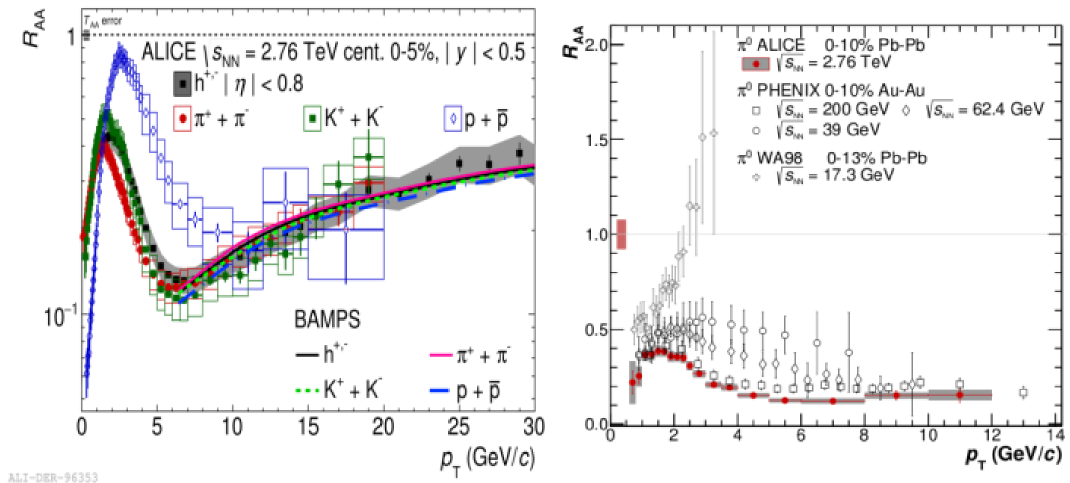
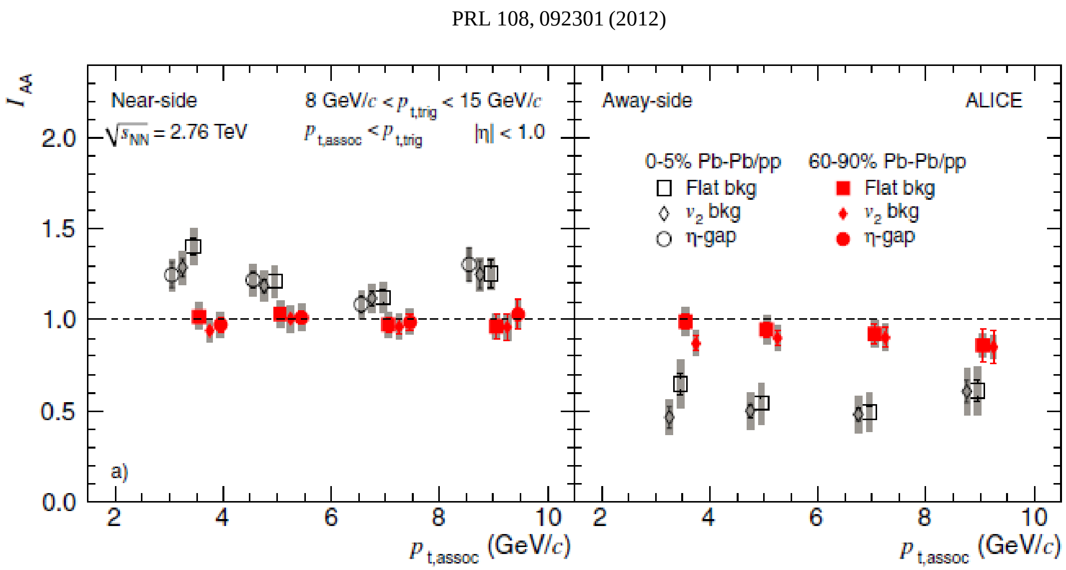
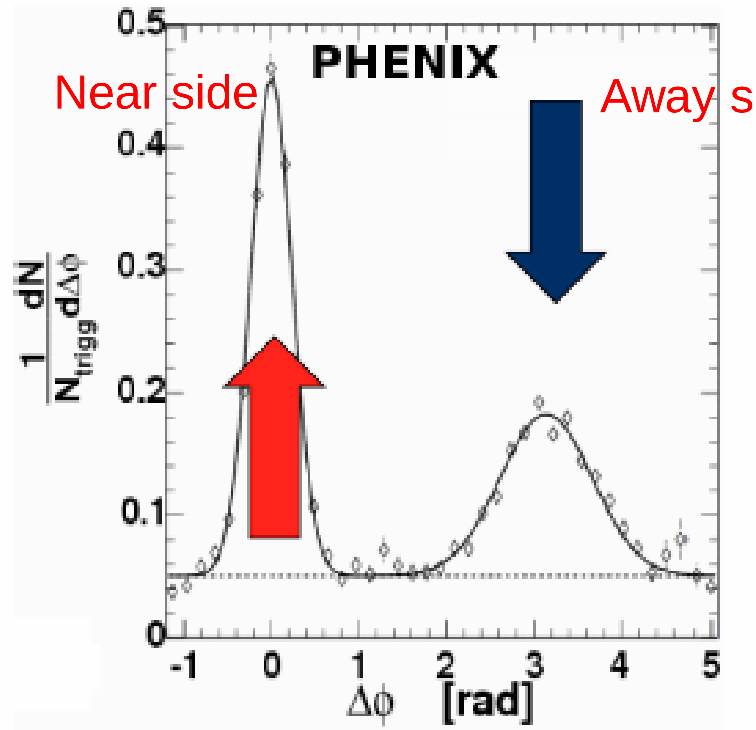


R_{AA} measurements with ALICE

- **2-particle correlations** (topic of this presentation):
  - Per-trigger yield in Δφ and ΔφΔη
  - Per-trigger yield modification (in Near side and in Away side):

$$I_{AA} = \frac{Y^{AA}}{Y^{pp}}$$





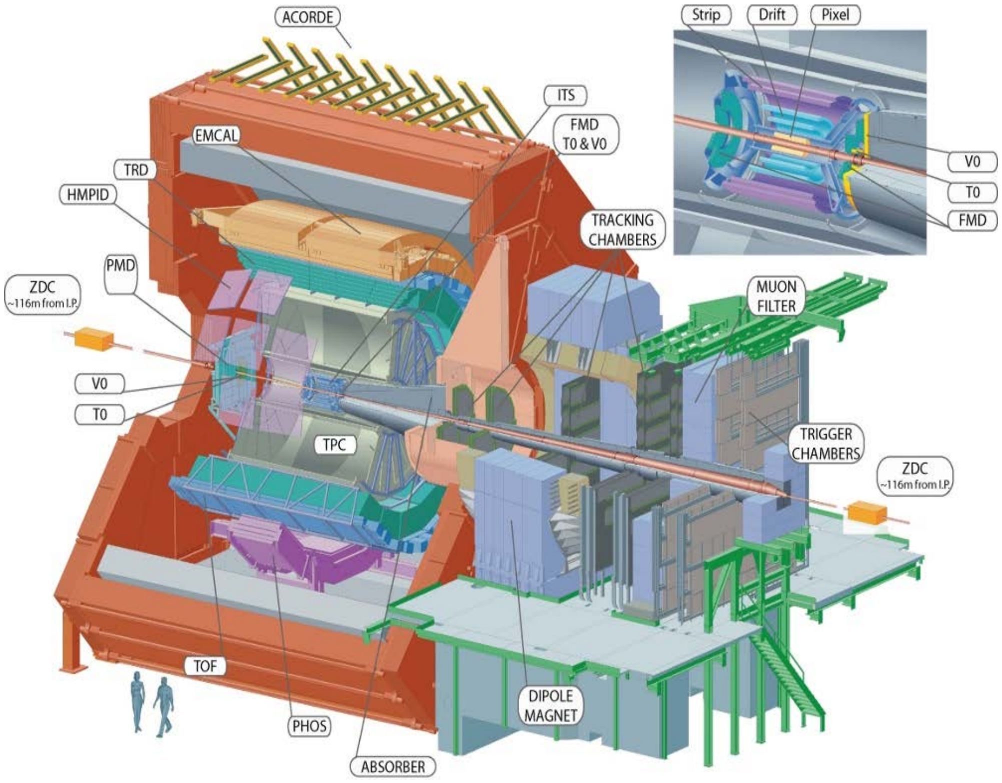
ALICE experiment

- **ALICE** (A Large Ion Collider Experiment) is dedicated to study QGP in AA collisions.
  - pp collisions at $\sqrt{s} = 0.7, \mathbf{2.76}, 5.02, 7, 8, 13$ TeV
  - p-Pb collisions at $\sqrt{s_{NN}} = \mathbf{5.02}$ TeV
  - Pb-Pb collisions at $\sqrt{s_{NN}} = \mathbf{2.76}, 5.02$ TeV

TPC – time-projection chamber. Provides tracking of charged particles and PID through dE/dx. p_T range: $0.1 < p_T < 100$ GeV/c. Acceptance: full azimuthal angle, $|\eta| < 0.9$.

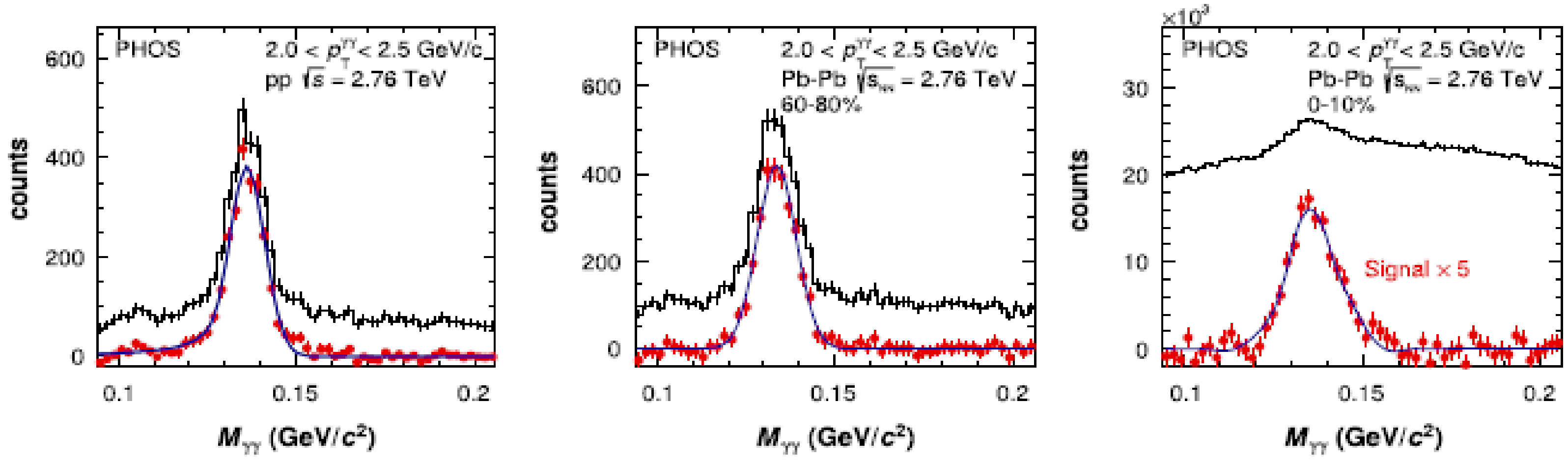
ITS – inner tracking system. Six layers of silicon detectors. Measure and identify charged particles down to ~ 0.1 GeV/c.

EMCal – electromagnetic calorimeter. Lead-scintillator design. Acceptance: $|\eta| < 0.7$, $80° < \varphi < 180°$



PHOS – Photon spectrometer. Based on $PbWO_4$ scintillating crystals. Acceptance: $|\eta| < 0.13, 260° < \varphi < 320°$

- Construct invariant mass of two clusters $M_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\theta_{12})}$
  Subtract combinatorial background. Calculate number of π^0 mesons from signal distribution. Correct for π^0 efficiency.
- Two papers with π^0 spectrums measured for pp collisions at $\sqrt{s} = 0.7$, 2.76 and 7 TeV and for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are published.

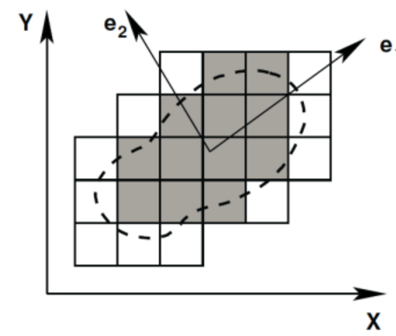


More details in presentation by D. Peresunko!

Neutral pion measurements with EMCAL

- Usual procedure with construction of two-cluster invariant mass and correction of combinatorial background could be avoided for EMCal.
- For EMCal π^0 cluster is merged for high p_T π^0s (above 6 GeV/c). For such clusters λ_0 parameter is generally > 0.3. In this analysis 2-local-maximum clusters are selected with parameterized $\lambda_{min}, \lambda_{max}$.
- Then new clusters are constructed with 3×3 cells around "seeds".
- λ_0 and invariant mass distributions are well reproduced by Monte-Carlo simulations.

$$\lambda_0^2 = 0.5(\delta_{\phi\phi} + \delta_{\eta\eta}) + \sqrt{0.25(\delta_{\phi\phi} - \delta_{\eta\eta})^2 + \delta_{\eta\phi}^2},$$



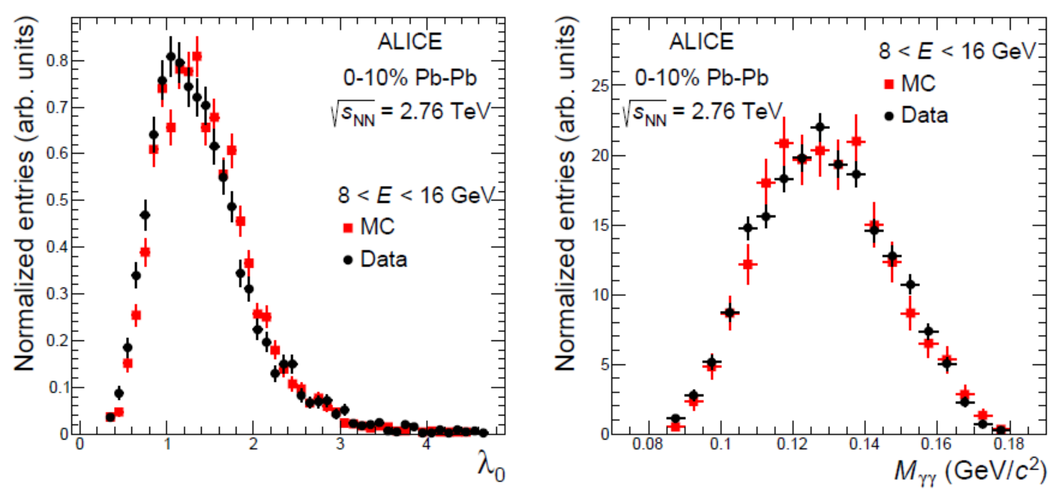
$$\delta_{\eta\eta} = \sum_i \frac{w_i \eta_i^2}{w_{tot}} - \left(\sum_i \frac{w_i \eta_i}{w_{tot}}\right)^2,$$

$$\delta_{\phi\phi} = \sum_i \frac{w_i \phi_i^2}{w_{tot}} - \left(\sum_i \frac{w_i \phi_i}{w_{tot}}\right)^2,$$

$$\delta_{\eta\phi} = \sum_i \frac{w_i \phi_i \eta_i}{w_{tot}} - \sum_i \frac{w_i \eta_i}{w_{tot}} \sum_i \frac{w_i \phi_i}{w_{tot}},$$

$$w = max(0, w_0 + \log(\frac{E_{cell}}{E_{cluster}})),$$

$$w_0 = 4.5$$



arXiv:1608.07201

Construction of correlation function

- Calculate correlation function of per-trigger yield:

$$Y(\Delta\varphi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta}$$

$$\Delta\varphi = \varphi_{trig} - \varphi_{assoc}$$

$$\Delta\eta = \eta_{trig} - \eta_{assoc}$$

$$C(\Delta\varphi) = \int Y(\Delta\varphi, \Delta\eta) d\Delta\eta$$

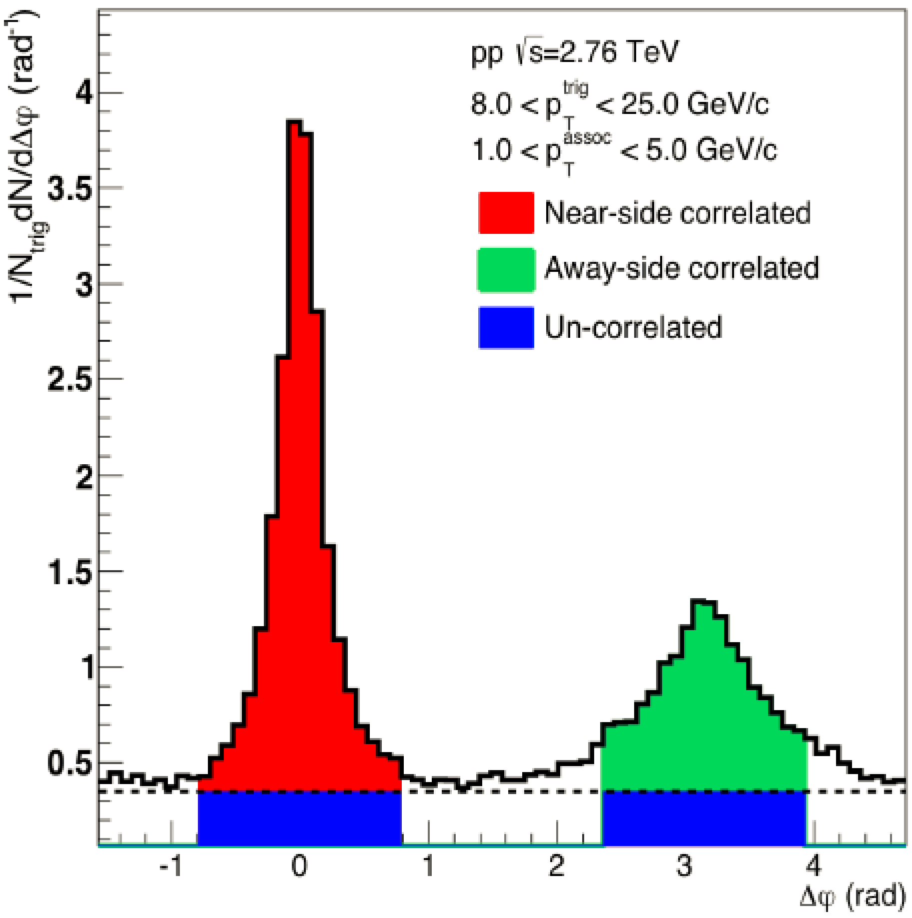
- π^0 is taken within 3σ range around the peak.
- Tracks: ITS+TPC tracks are used.
- Correct for detector non-uniformity in acceptance with mixed event technique:

$$Y(\Delta\varphi, \Delta\eta) = M(0,0) \frac{S(\Delta\varphi, \Delta\eta)}{M(\Delta\varphi, \Delta\eta)}$$

- Mixed event distribution is gathered for tracks from events with similar global characteristics: *z* of vertex and particle multiplicity.
- Apply corrections for:
  - Track efficiency and contamination from secondary particles,
  - π^0 purity and efficiency,
  - Pair p_T resolution.

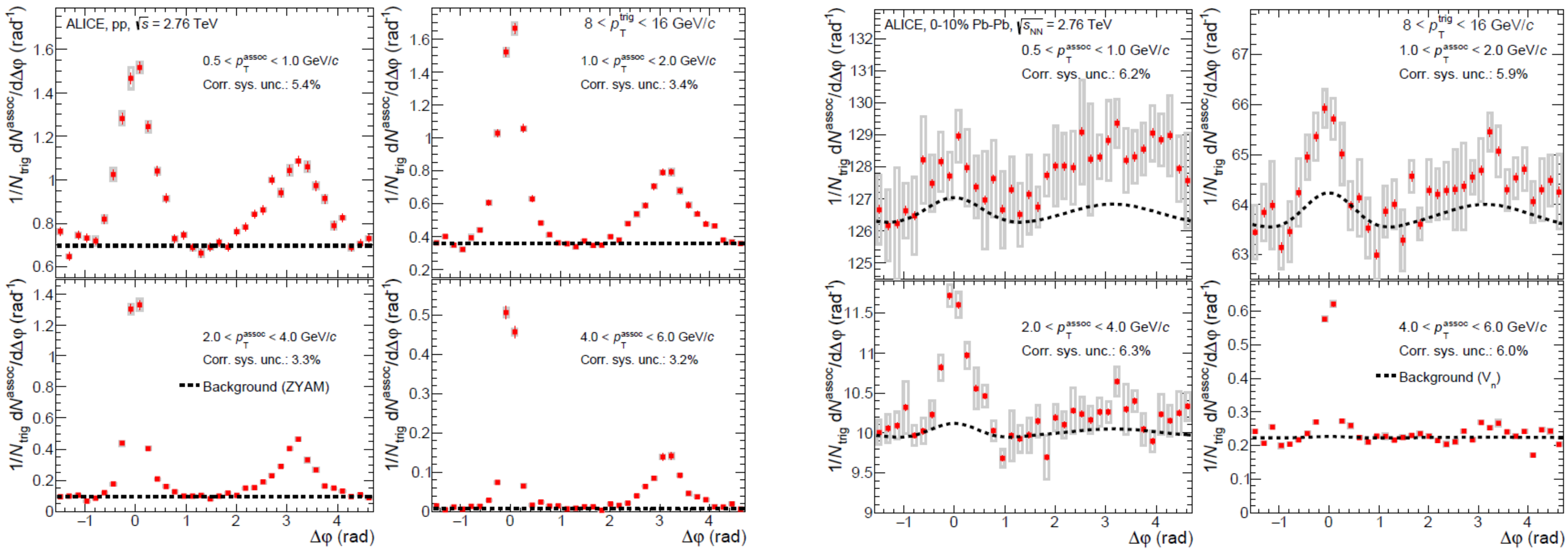
Calculation of per-trigger yield

- Jet-related contribution of the correlation function is separated from underlying event:
$$J(\Delta\varphi) = C(\Delta\varphi) - B(\Delta\varphi)$$
- B is calculated with ZYAM procedure (flat background) for pp and v_n subtraction for Pb-Pb:
$$B(\Delta\varphi) = B_0\left(1 + 2\sum_n V_n \cos(n\Delta\varphi)\right)$$
- V_n is approximately factorized:
$$V_n \approx v_n^{trig}\ v_n^{assoc}$$
- v_n coefficients (v_2– v_5) are taken from ALICE measurements: Phys. Lett. B719 (2013) 18–28, Phys. Lett. B708 (2012) 249–264.
- Near-side and away-side yields are then calculated within range $-0.7 < \Delta\varphi < 0.7$ rad (near side) and $-1.1 < \Delta\varphi - \pi < 1.1$ rad (away side).



Correlation function distribution for pp and Pb-Pb

- Background subtracted correlation distributions for pp (flat background) and Pb-Pb (v_n background).
- Trigger p_T range: 8-16 GeV/c
- Broading of away-side peak due to jet interaction with medium.
- For Pb-Pb away side peak grow with decreasing of p_T^{assoc} and becomes even higher then near-side peak.



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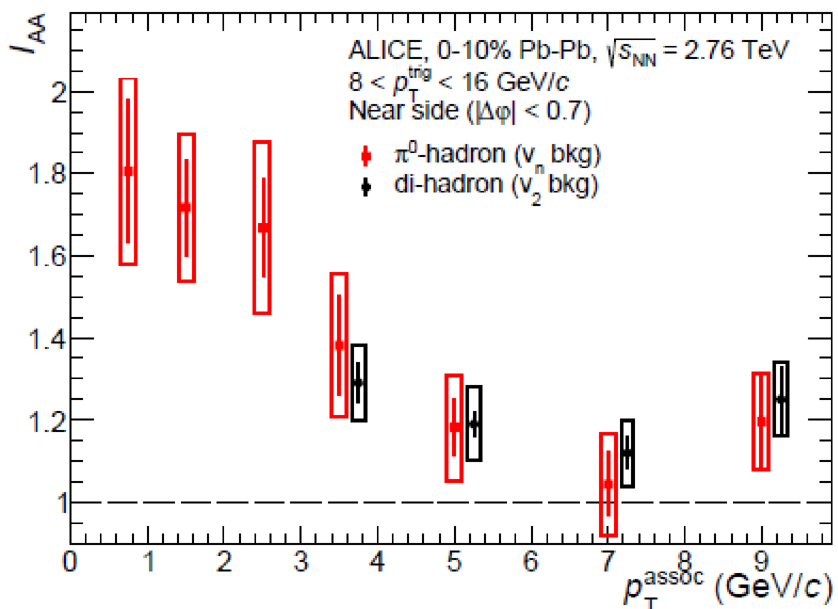
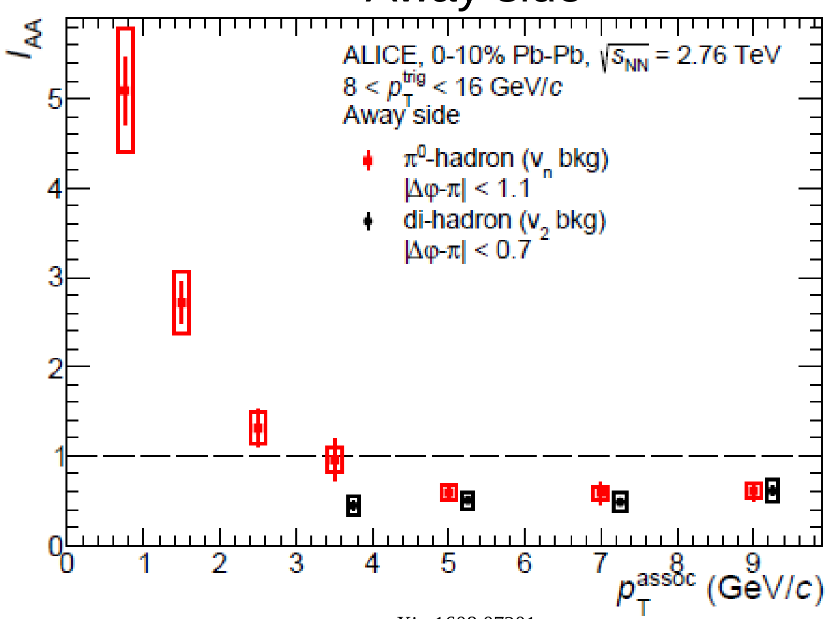
Nuclear modification factor I_{AA}

- Jet nuclear modification factor I_{AA} is calculated as a ratio of per-trigger yield in Pb-Pb collisions to the one from pp collisions.
- Near side: enhancement from 1.8 at low p_T to 1.2 at high p_T.
- Away side: enhancement up to 5 at low p_T and suppression due to medium interaction at high p_T.
- Origin of enhancement at low p_T for Near side could be:
  - Change of the fragmentation function?
  - Change of the quark vs gluon jet ratio?
  - Bias on the parton p_T spectrum?
- Origin of enhancement at low p_T for Away side could be:
  - k_T broadening?
  - Medium-excitation?
  - Fragments from radiated gluons?

Near side



Away side



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Systematic uncertainties

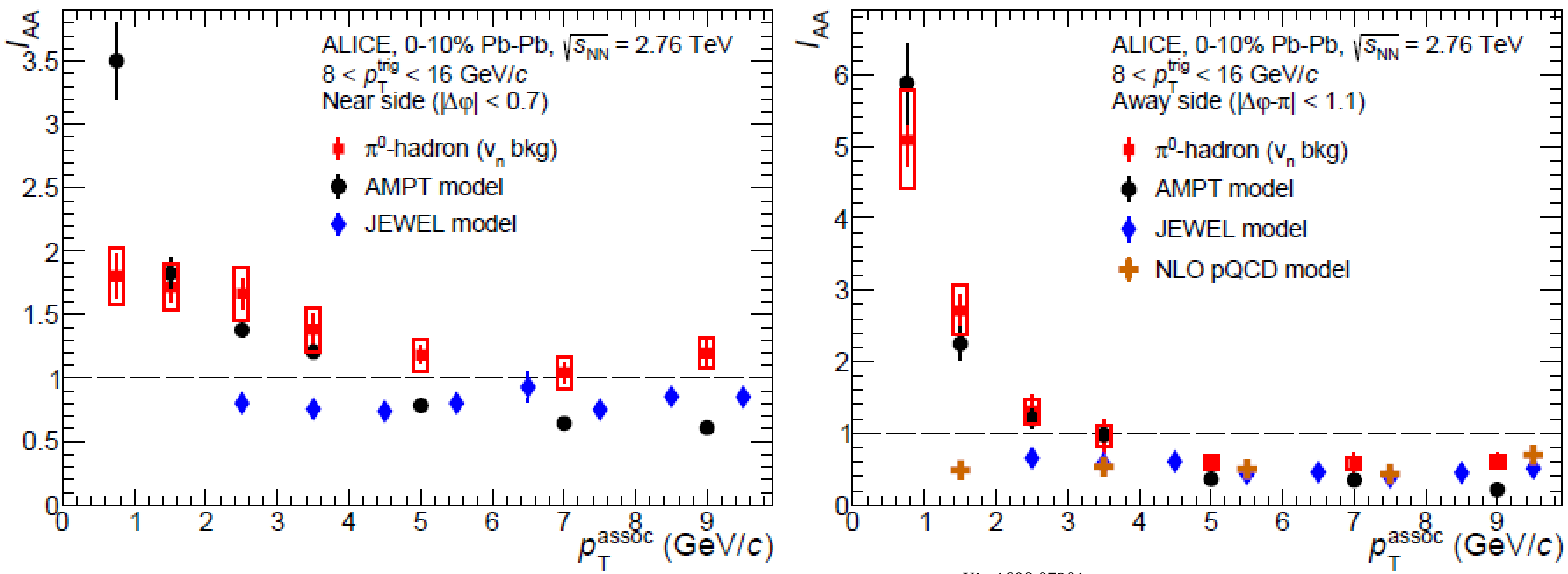
- Summary of systematic uncertainties for per-trigger yield and I_{AA} calculations.
- The largest uncertainty in $Y(\Delta\varphi)$ is due to tracking efficiency uncertainty.
- The largest uncertainty in I_{AA} is due to background subtraction in Pb-Pb.

Source	$Y(\Delta\varphi)$ pp	$Y(\Delta\varphi)$ Pb–Pb	I_{AA} (NS)	I_{AA} (AS)
Tracking efficiency	5.4%	6.5%	8.5%	8.5%
MC closure	1.0%	2.0%	1.2%	1.2%
TPC-only tracks	1.0%	3.5%	4.3%	3.8%
Track contamination	1.0%	0.9%	1.1%	1.1%
Shower shape (λ_0)	1.2%	0.7%	3.4%	2.6%
Invariant mass window	1.3%	1.0%	3.5%	3.3%
Neutral pion purity	0.3%	1.1%	0.6%	0.5%
Pair p_{T} resolution	1.0%	1.1%	0.3%	0.3%
Pedestal determination	–	–	9.4%	11.7%
Uncertainty on v_n	–	–	7.1%	5.1%
Total	6.7%	7.4%	12.6%	15.0%

Comparison to models

- **AMPT** model calculations (Guoliang Ma, Phys. Rev. Lett. 106 (2011) 162301)
- **NLO pQCD** calculations (Hanzhong Zhang, Phys. Rev. Lett. 98 (2007) 212301)
- **JEWEL** model calculations (Marco van Leeuwen, JHEP 03 (2013) 080)

- Only JEWEL model can qualitatively describe low-p_T enhancement both in near and away side I_{AA}. This enhancement is attributed to increase of soft-particles due to interaction of jet with medium.
- Models can't describe enhancement for high-p_T associated particles in the near side.
- Models describe suppression for high-p_T associated particles in the away side.



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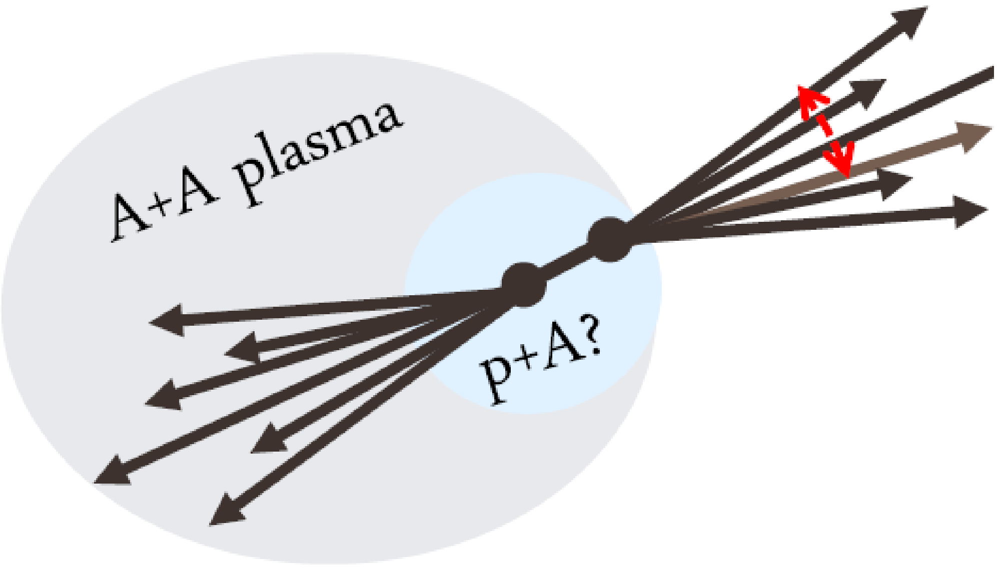
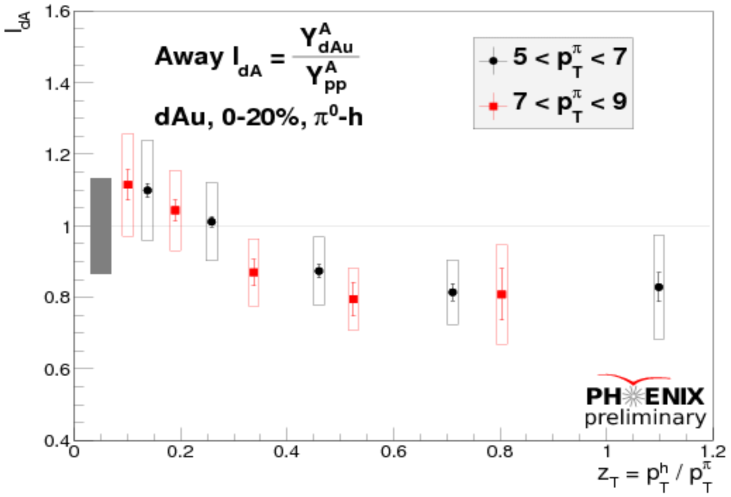
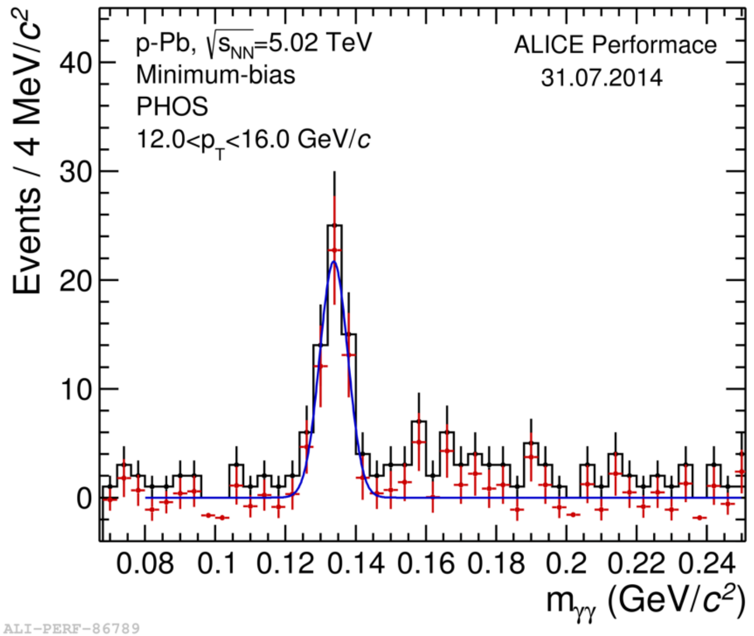
- Is there energy loss in p-Pb?
- Study Cold Nuclear Matter effects.
- Modification of per-trigger yield could be due to:
  - Collective flow,
  - k_T broadening (Kronin effect),
  - Nuclear shadowing,
  - Hadron fragmentation, energy loss.
- Enhancement or suppression?
- PHENIX showed that there might be an enhancement at low-p_T away side yield and suppression at high-p_T away side yield for most central d-Au collisions.

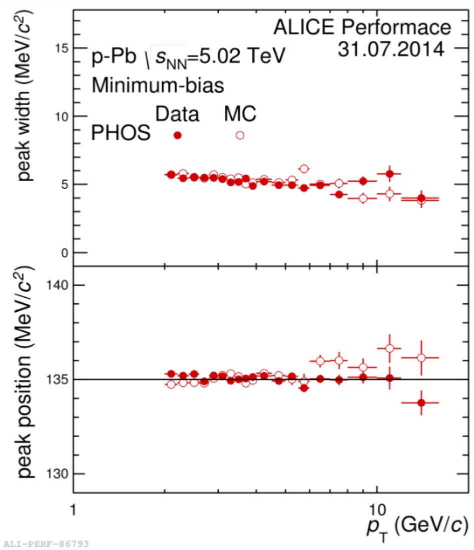


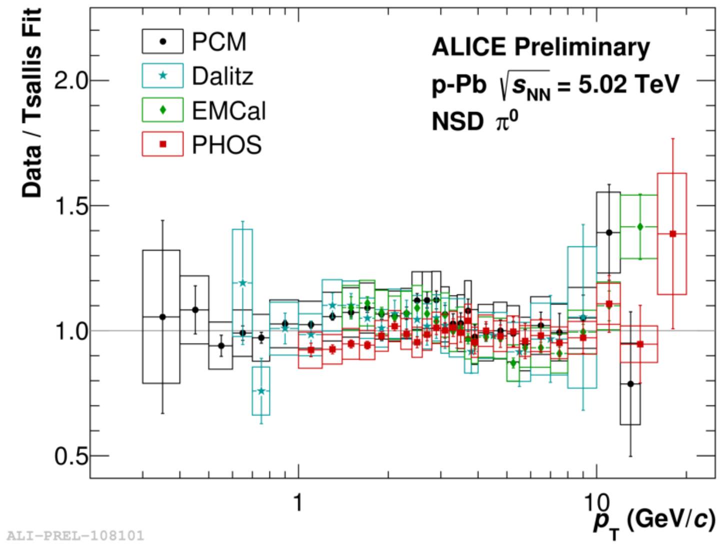


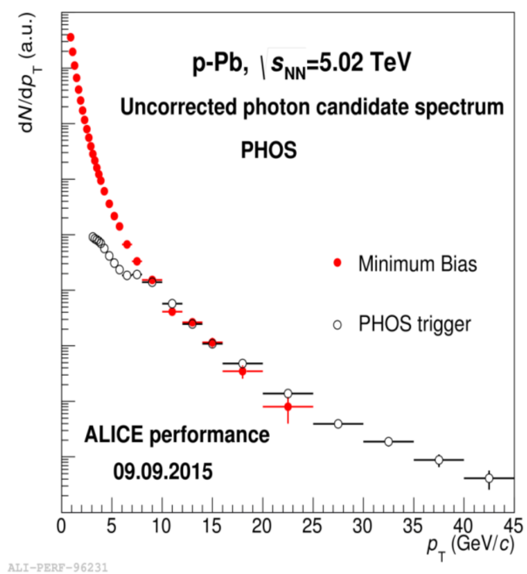
PHOS performance in p-Pb run

- π^0 peak position and width are well-reproduced with MC.
- Can measure π^0 up to 20-25 GeV/*c* with MB trigger and approximately twice higher with PHOS trigger.
- PHOS trigger threshold was 7 GeV.



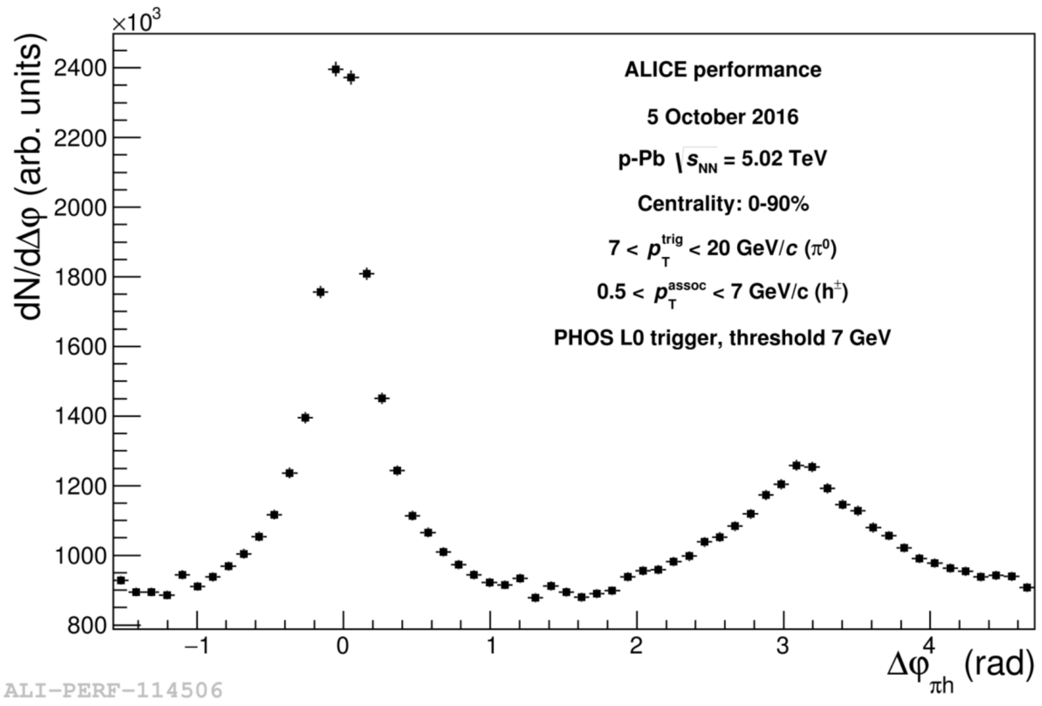






π^0-hadron correlations in p-Pb

- Measure $C(\Delta\varphi)$ with PHOS trigger data.
- $7 < p_T^{trig} < 20$ GeV/c,
- $0.5 < p_T^{assoc} < 7$ GeV/c.
- Near-side and away-side peaks are clearly visible with good statistics.
- Target for per-trigger yield and I_{p-Pb} in small centrality bins measurements.



Conclusions

- ALICE measured neutral pion – charged hadron correlation functions for pp and Pb-Pb collision (0-10% centrality) as well as I_{AA} in wide p_T range down to $p_T^{assoc} = 0.5$ GeV/c.
- I_{AA} for the near side shows enhancement from about 1.8 at low p_T to about 1.2 at high p_T.
- I_{AA} for the away side shows enhancement of about 5 at low p_T and suppression about 0.6 at high p_T.
- I_{AA} is compared to AMPT and JEWEL models as well as pQCD calculations which describe high-p_T suppression well but only AMPT can qualitatively describe low-p_T enhancement in near and away sides.
- ALICE performance for neutral pion – charged hadron correlation studies is presented. ALICE can measure high p_T π^0 with PHOS trigger data.

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Backup

Models description

- AMPT uses initial conditions of HIJING, followed by parton and hadron cascades with elastic scatterings for final-state interaction. String melting with a parton interaction cross section of 1.5 mb and parton recombination for hadronization is used with parameters from Phys. Rev. C83 (2011) 034904.
- JEWEL addresses the parton–medium interaction by giving a microscopic description of the transport coefficient, $\hat{q}$, which essentially defines the average energy loss per unit distance. Hard scatters are generated according to Glauber collision geometry, and partons suffer from elastic and radiative energy loss in the medium, including a Monte Carlo implementation of LPM interference effects. The JEWEL calculation includes the so called “recoil hadrons”, which are produced by fragmenting medium partons that interacted with the propagating hard parton.
- The pQCD calculation is performed at next-to-leading order (NLO). It uses nuclear parton distribution functions for initial-state cold nuclear matter effects, and a phenomenological model for medium-modified fragmentation functions. The evolution of bulk medium is done with a 3+1 dimensional ideal hydrodynamic model, and the value $\hat{q}$ is consistent with that of the JET collaboration, which was extracted using experimental data.

Photon PID in PHOS and EMCal

- Charged particle veto criterion is used to clean π^0 signal from charged particles. For this extrapolation of TPC and ITS tracks to EMCAL surface is made.
- PHOS also utilizes charged particle veto cut to clean signal from charged particles and shower shape cut to separate photons from hadrons (based on λ parameters).