Measurements of π^0-jet correlation $\sqrt{s}$ = 7 TeV pp collisions and in $\sqrt{s_{NN}}$ = 2.76 TeV central Pb-Pb collisions at ALICE experiment

2016/02/13

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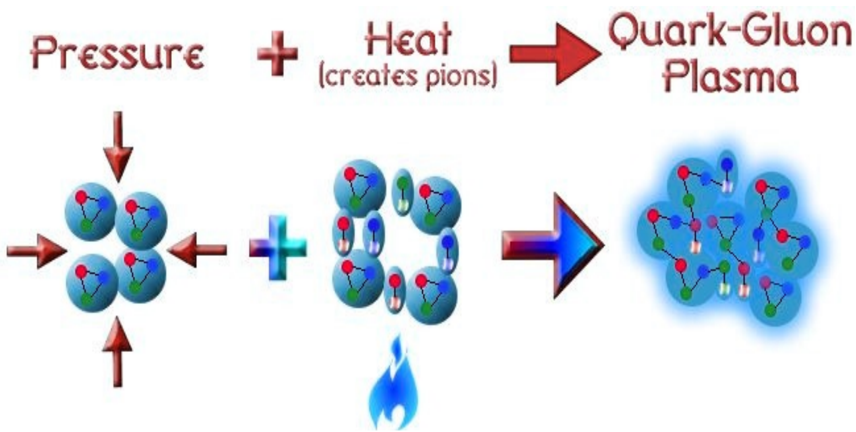
outline

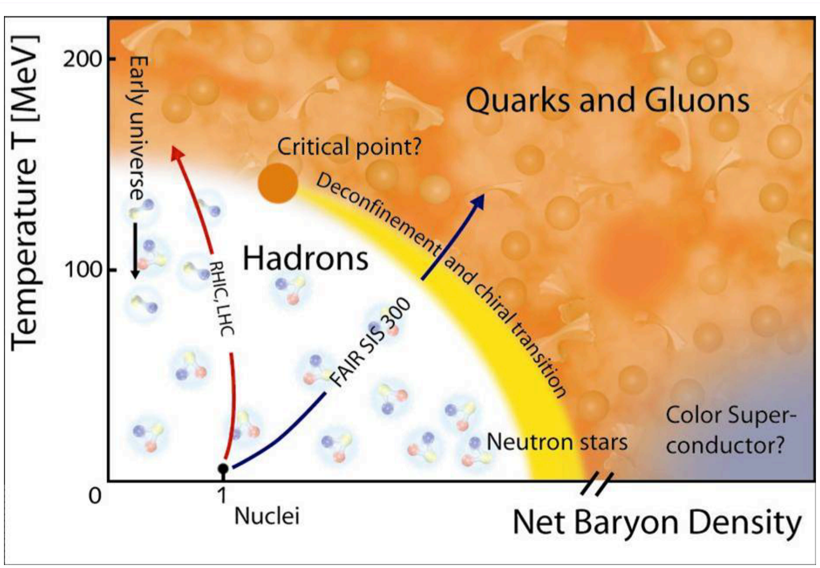
- Introduction
- Analysis procedure
- Correction
- Systematic uncertainties
- Results
- summary

Introduction

Quark-gluon plasma (QGP)



Quarks and gluons
- are confined in a hadron
- move freely beyond the boundary of hadrons at high temperature and energy density

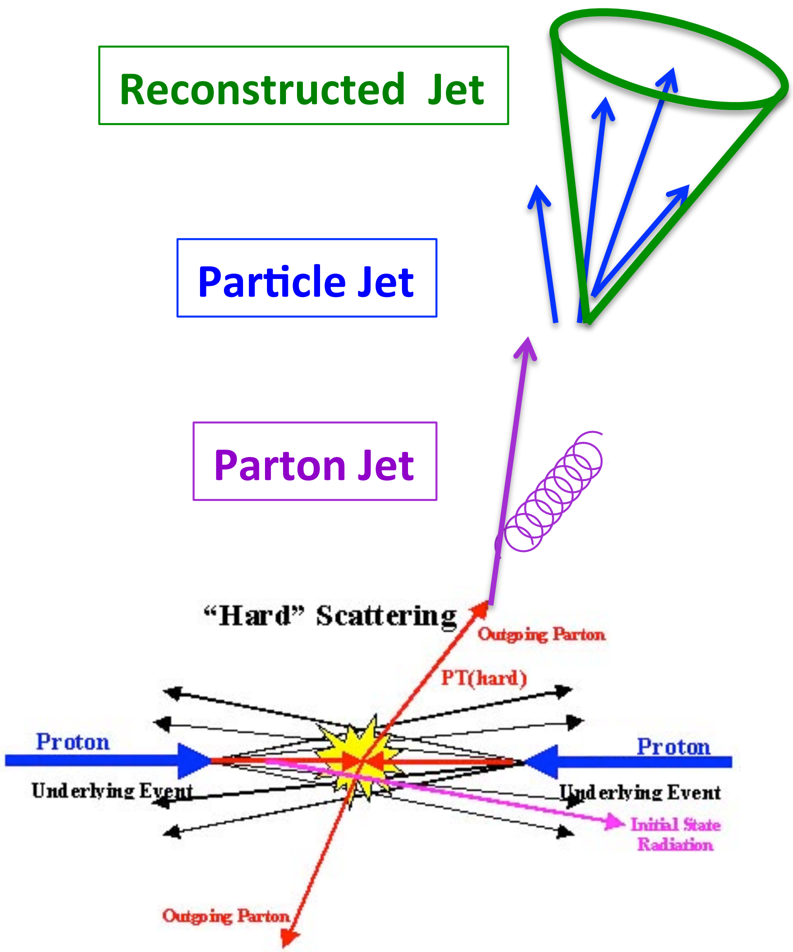


Quark-gluon plasma (QGP)
- created up to a few milliseconds after Big Bang
- T_c ~ 175 MeV, ε_c ~ 1 GeV/fm^3

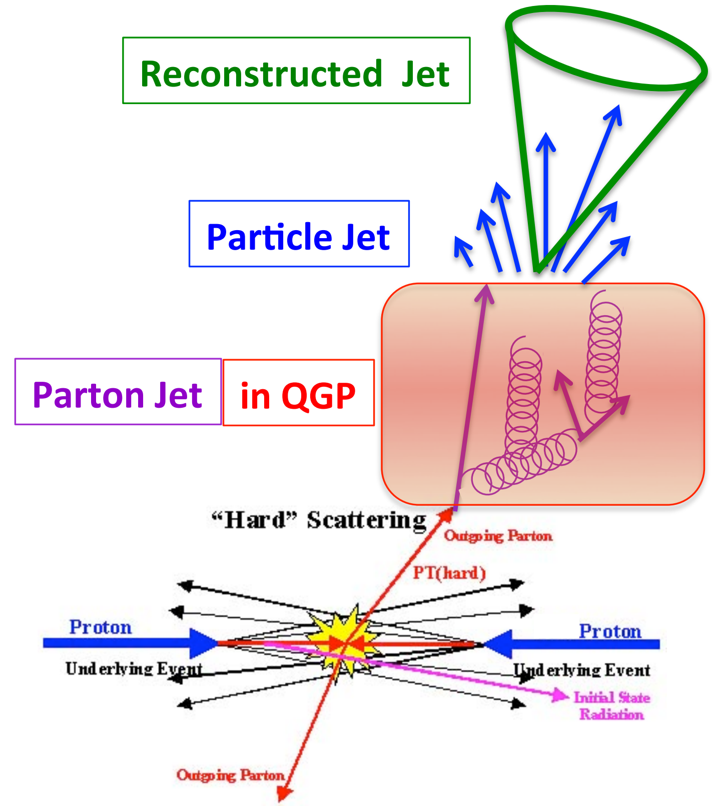
Ultra relativistic heavy ion collision (RHIC, LHC)

Jet

pp collision



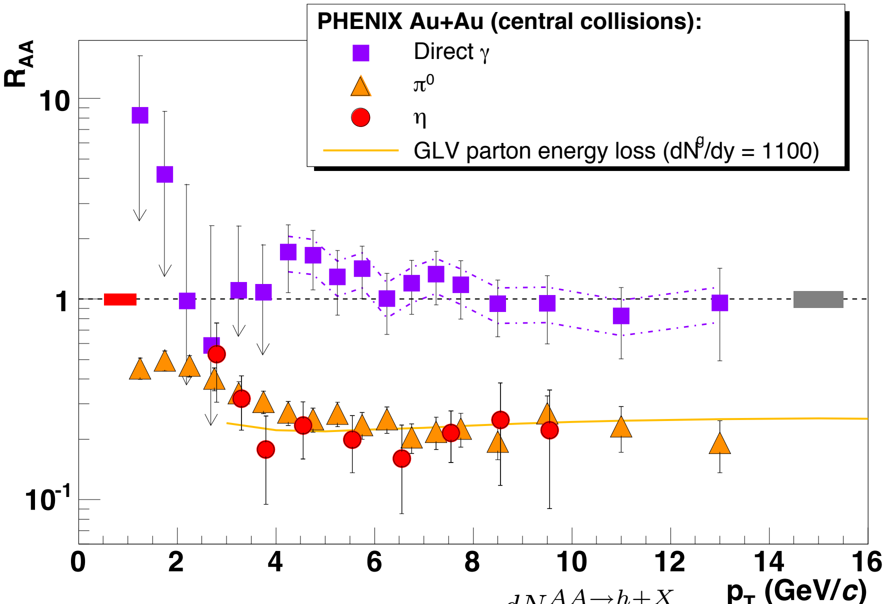
Heavy ion collision



$$\Delta E = \alpha_s C_R \hat{q} L^2$$
$$= \Delta E_{collisional} + \Delta E_{radiative}$$

- Jets in heavy ion collisions lose their energy by collisional and radiative energy loss

High p_T physics of heavy ion collisions at the RHIC



$$R^h_{AA}(p_T,b) \equiv \frac{\frac{dN^{AA\to h+X}}{d^2p_T}}{N_{bin}(b)\frac{dN^{pp\to h+X}}{d^2p_T}}$$

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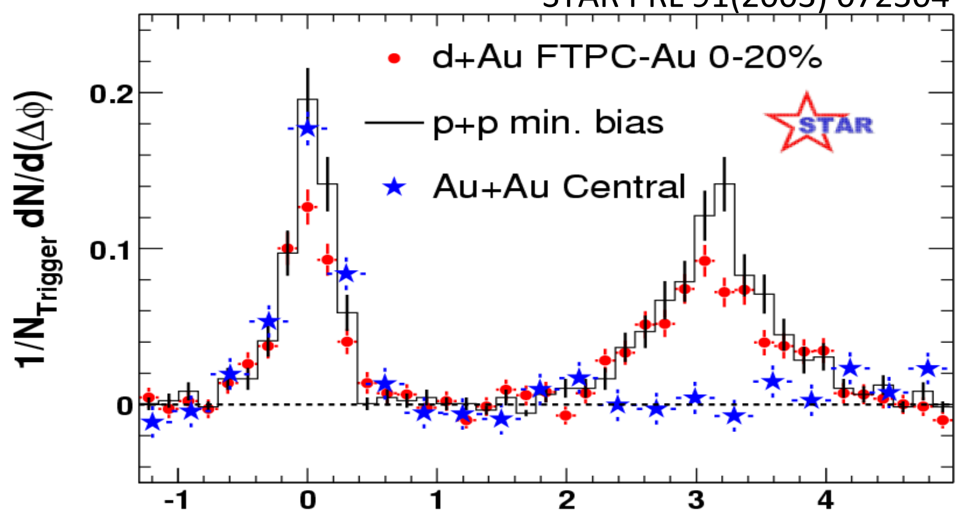


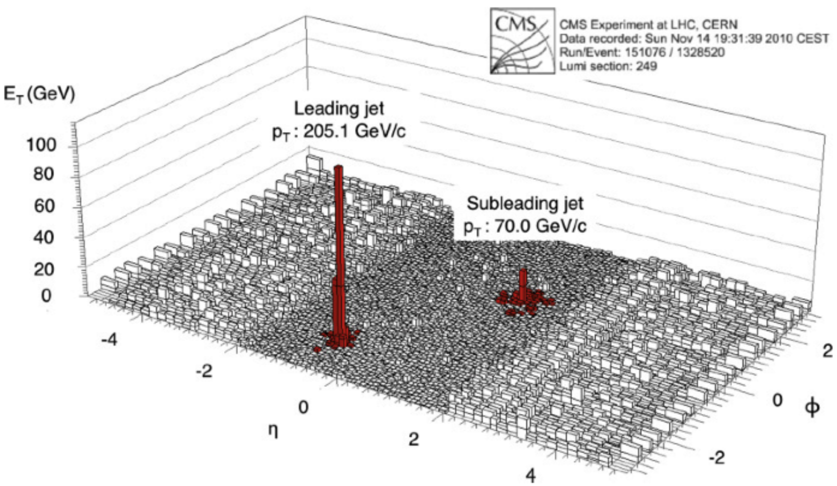
$4<p_T^{trig}<6GeV/c, 2<p_T^{asso}<p_T^{trig}$

- Suppression of particle production in high p_T region were measured with experiments at the RHIC
- Nuclear modification factor R_{AA}
  - Suppression of π^0 of Au+Au compared with pp collisions scaled by # of collisions
- Two particle correlation
  - Suppression of away side peak of Au+Au compared with pp collisions

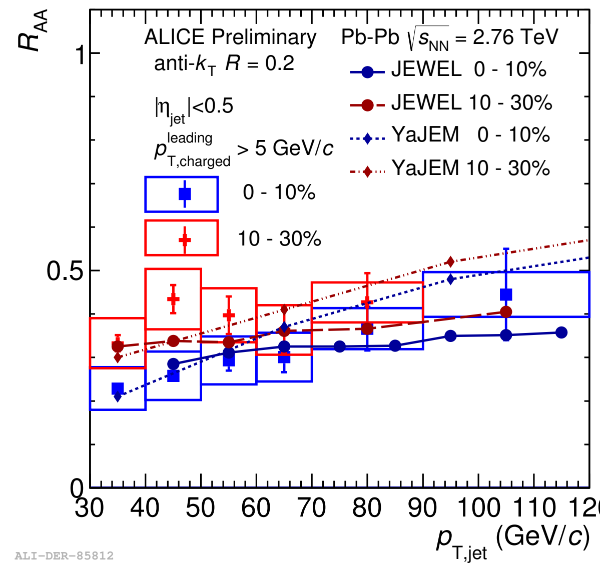
High p_T physics of heavy ion collisions at the LHC

ALICE

Di-jet energy unblance

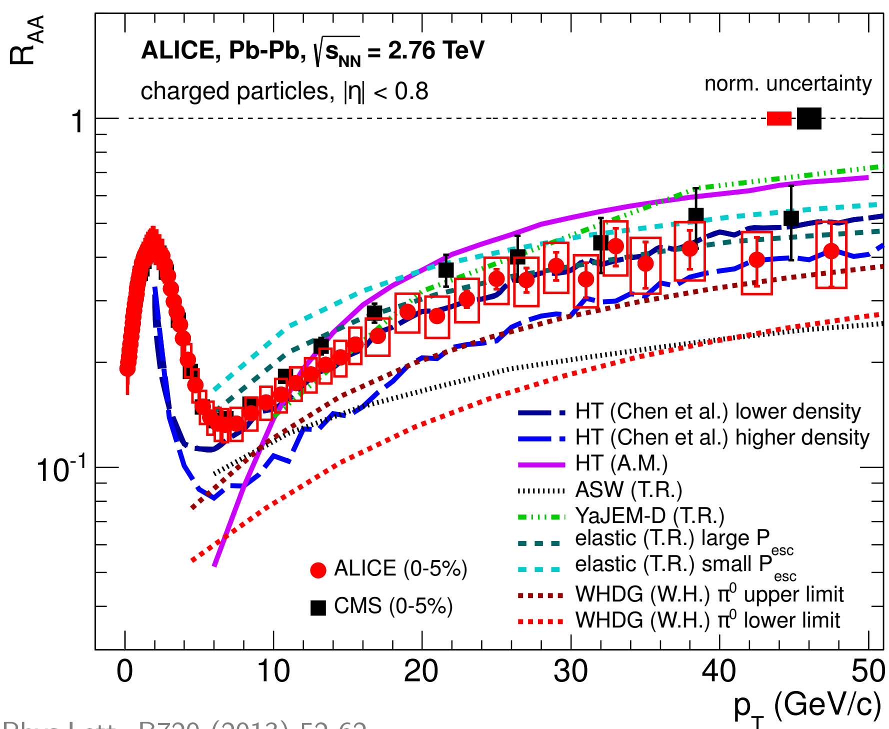


Nuclear modification factor R_{AA}



- The experiments at LHC started direct measurements for jet and jet modification
- Di-jet energy un-balance measurement
  - can see sharp peak with huge transverse energy as leading jet and small peak compared with leading jet energy at opposite side
- Nuclear modification factor R_{AA}
  - Suppression of jet yields in Pb-Pb collisions compared with pp collisions

Suppression of high momentum particles and surface bias



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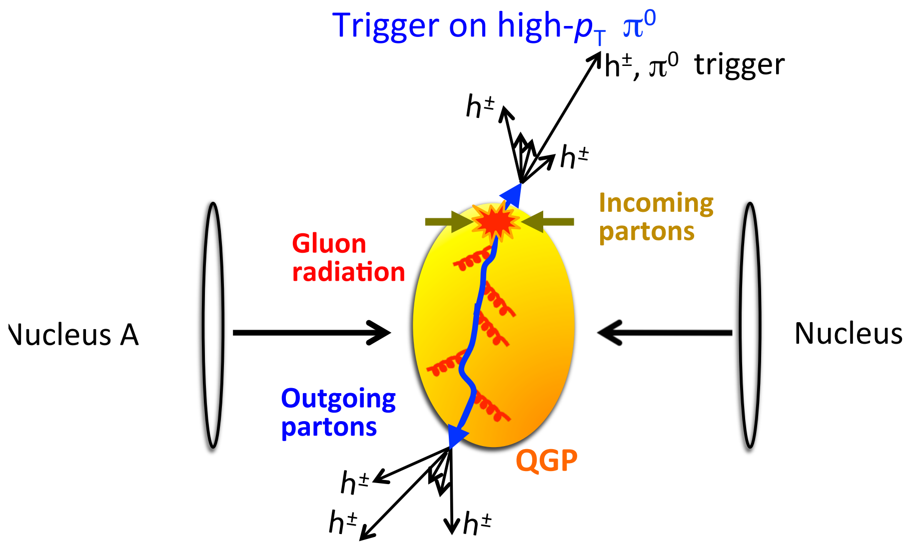
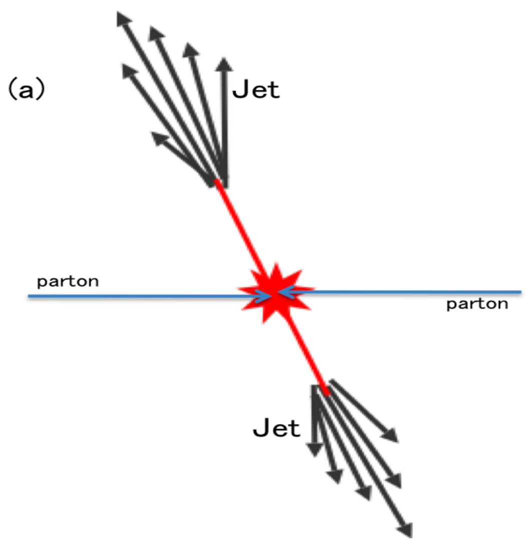


- Productions of high p_T particle are strongly suppressed in Pb-Pb collisions

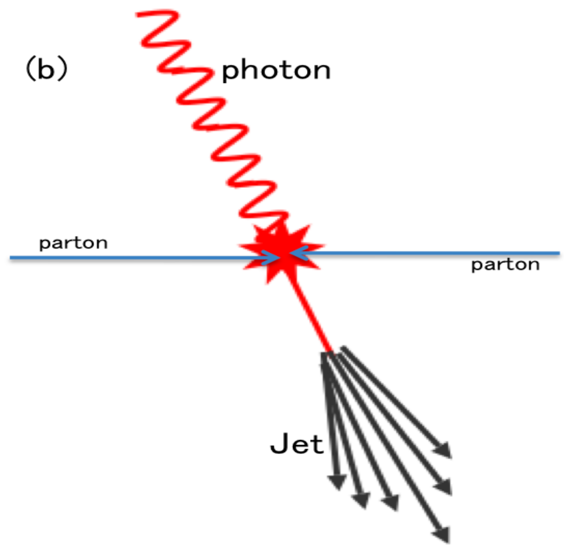
Select mostly high p_T particles produced close to the surface of the matter

Jet correlation

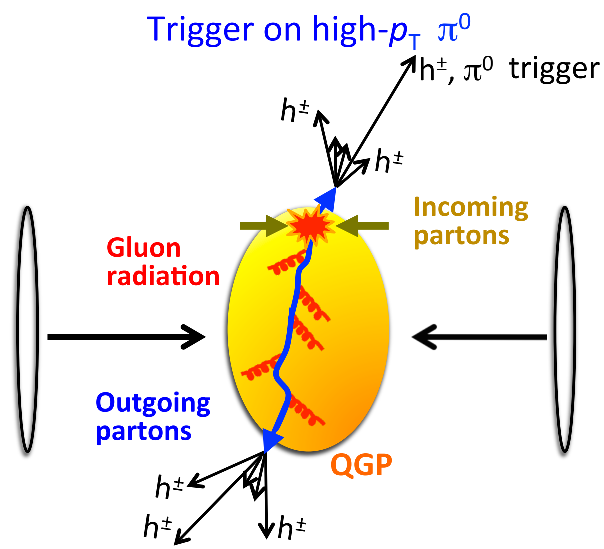
jet-jet



γ - jet



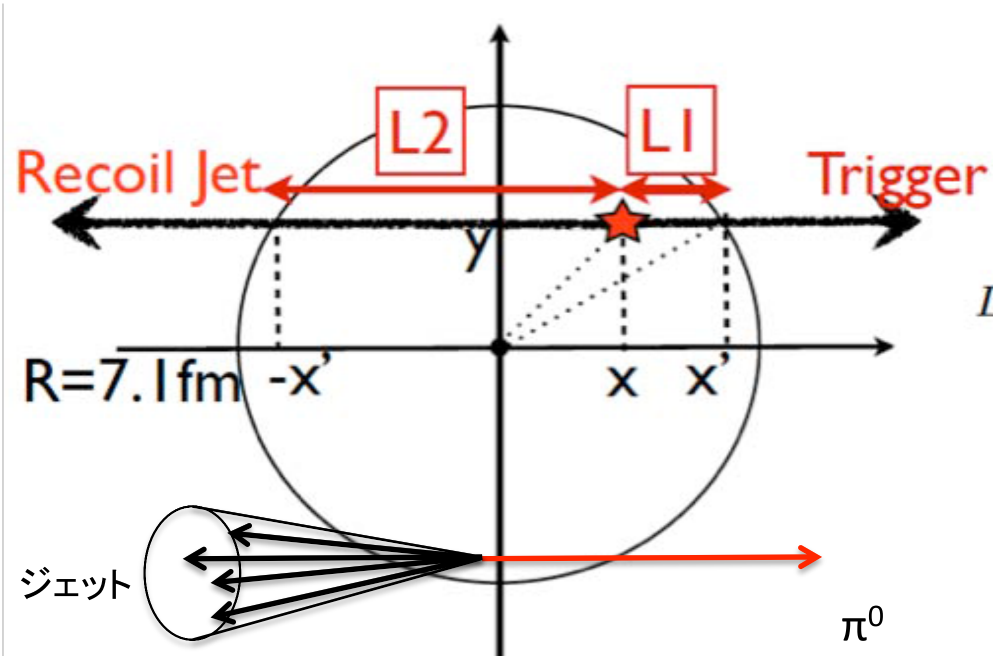
Hadron/π^0-jet



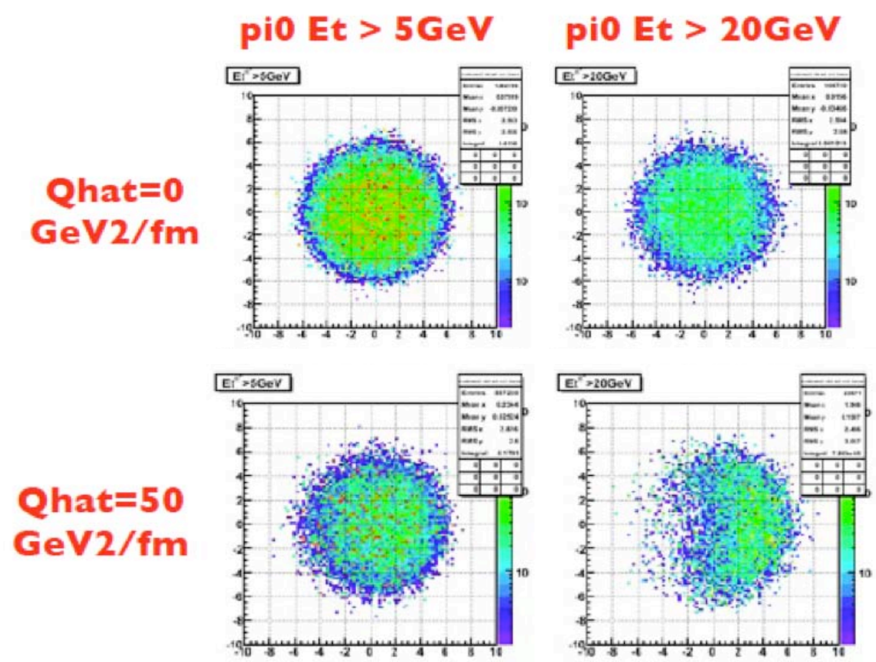
- Jet-jet correlation
  - > energy asymmetry
- γ-jet correlation
  -> Energy calibration ($p_T^{\gamma}=p_T^{parton}$)

- Hadron-jet correlation
  -> path length dependence of jet quenching by triggering high momentum hadron
- π^0-jet correlation
  -> can measure the jet quenching at the both (near and away) side
  without auto-correlation

π^0-jet correlation

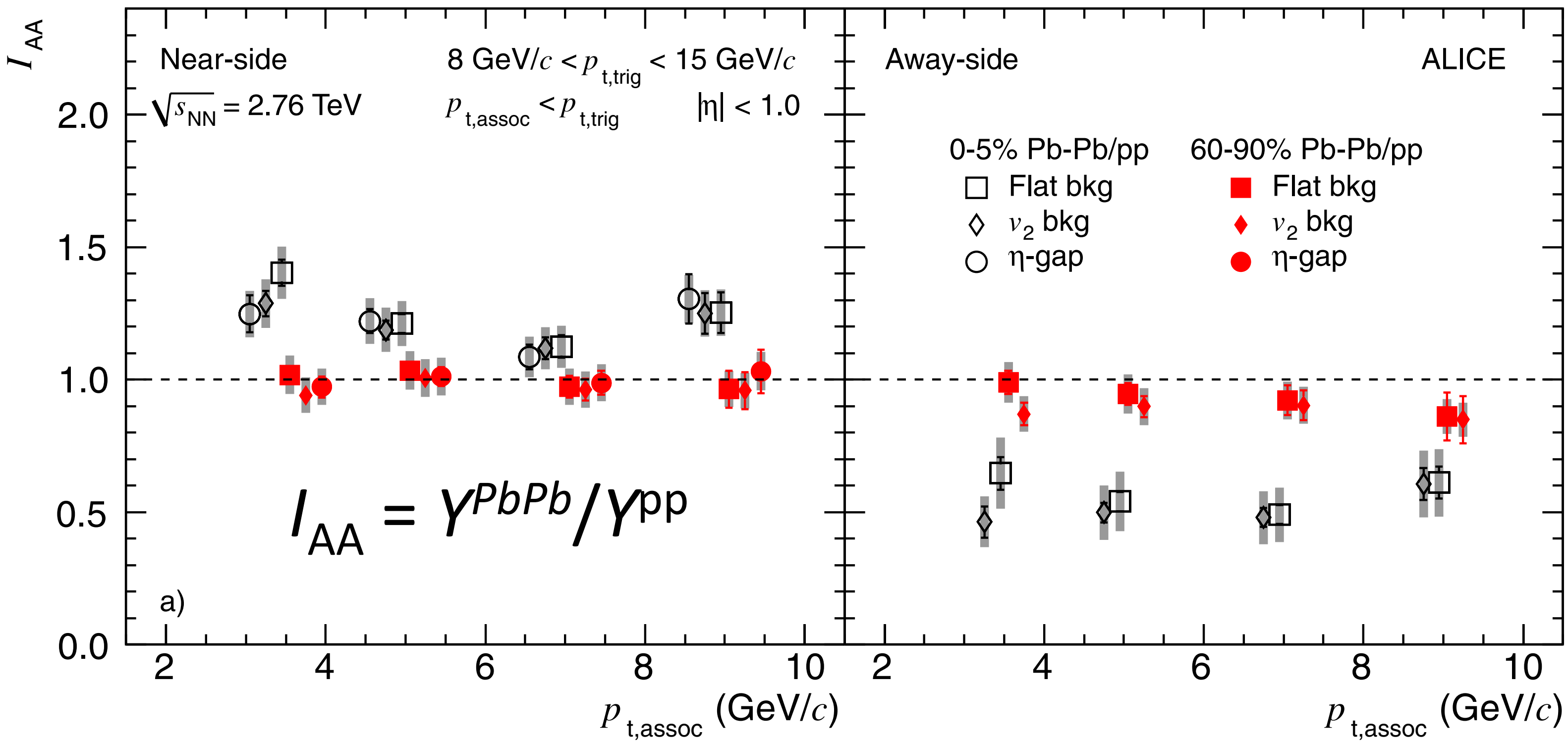


Trigger p_T : high, leading particle p_T : high



- Can control path length by tagging a recoil jet with triggered π^0 and changing p_T for π^0
- High p_T of π^0 -> longer path length of recoiling jets
- Direct measurement of path length dependence of “jet” quenching, not by hadron
- Observed enhancement of near side and suppression of away side from π^0- charged hadron

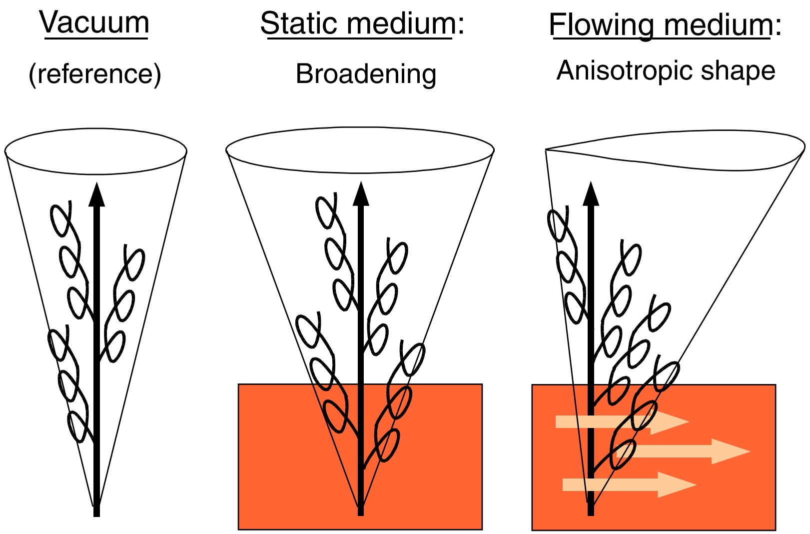
Ratio of per trigger yields I_{AA} in di-hadron correlation



- Enhancements in the near side
  - dominated jets produced at the surface of a matter by the surface bias
  - caused by the effects of re-distribution, a change of fragmentation function and the quark/gluon jet ratio in the final state
- Suppression in the away side
  - the path-length of away side jets become longer than near side jets by the surface bias

Physics motivation

- Physics motivation
  - check behavior of the surface bias in near and away side in high momentum regions
  - select jets of different path-length in a medium at near and away sides



- Yield measurement
  - The surface bias in a near and away side in high momentum regions
- Width measurement
  - The modification of jet shape

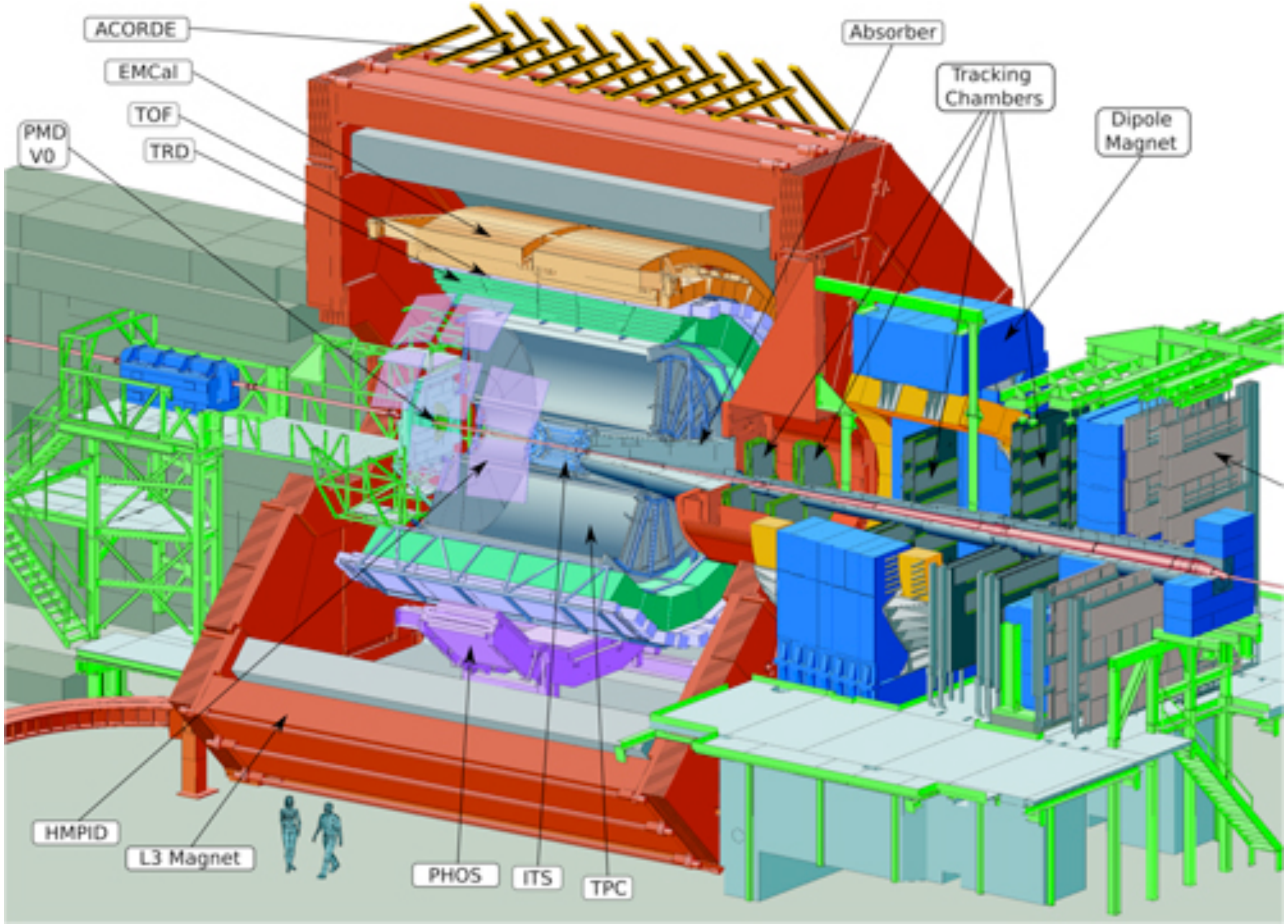
My activity

- Talk and poster
  - JPS 67th : Neutral pion and jet measurements in Pb-Pb collision at sqrt(sNN) = 2.76 TeV in ALICE (talk)
  - APW in Frascati : Hadron-jet and pi0-jet correlations in p+p and Pb+Pb (talk by D.sakata)
  - QM2012 : Jet-Hadron Azimuthal Correlation Measurements in pp Collisions at sqrt{s} = 2.76 TeV and 7 TeV with ALICE (poster)
  - JPS 68th : Neutral pion and jet measurements in Pb+Pb collisions at sqrt(sNN) = 2.76 TeV in ALICE (talk)
  - APW in Padova : pi0-jet correlations measurement for p+p and Pb+Pb 2.76 TeV (talk)
  - QM2014 : Jet azimuthal distributions with high pT neutral pion triggers in pp collisions from LHC-ALICE (poster)
  - ATHIC2014 : Jet azimuthal distributions with high pT neutral pion triggers in pp collisions at √s= 7 TeV from LHC-ALICE (talk)
  - TGSW2014 : Jet azimuthal distributions with high pT neutral pion triggers in pp collisions √s = 7 TeV from LHC-ALICE (talk)
  - QM2015 : Jet azimuthal distributions with high pT neutral pion triggers in pp 7 TeV and Pb-Pb 2.76 TeV collisions from ALICE at the LHC (poster)
- Detector work

  - DCal construction (M1)
  - Scalable Readout Unit(SRU) construction and test (M2)
  - EMCal commisioning (D1, D2)
  - Shift taking (M2, D2, D3)

analysis

A Large Ion Collider Experiment (ALICE)

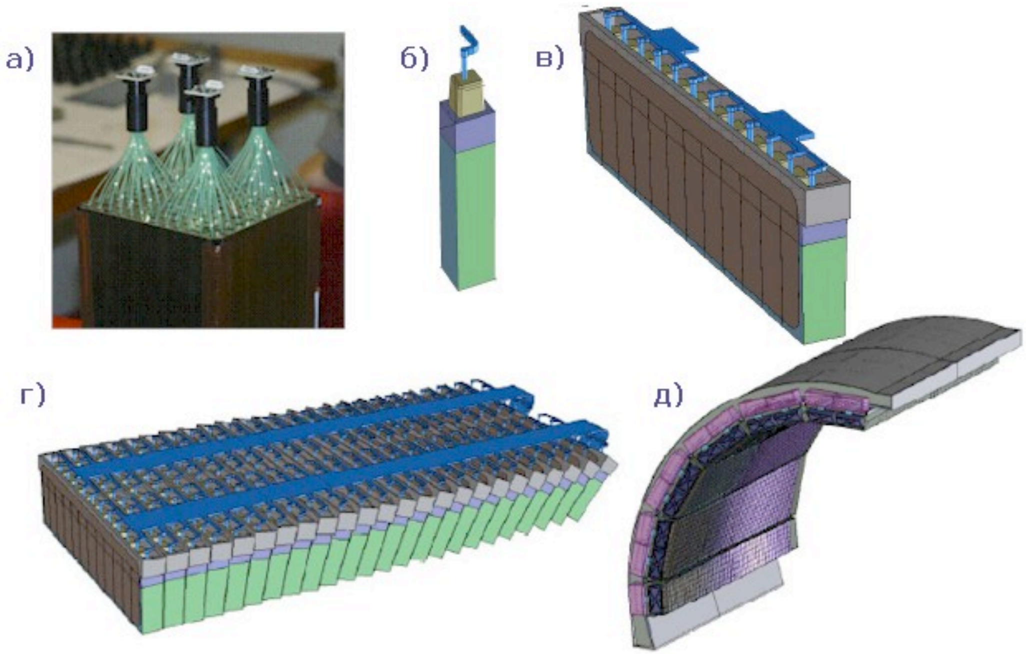


- Data set
  - pp collisions at √s = 7 TeV with EMCal triggered (7 M)
  - Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with centrality 0- 10 % and EMCal triggered (12M)

Particle reconstruction detectors

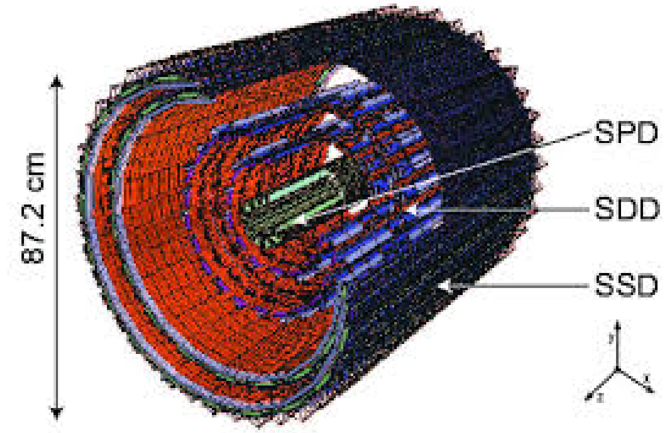
ALICE

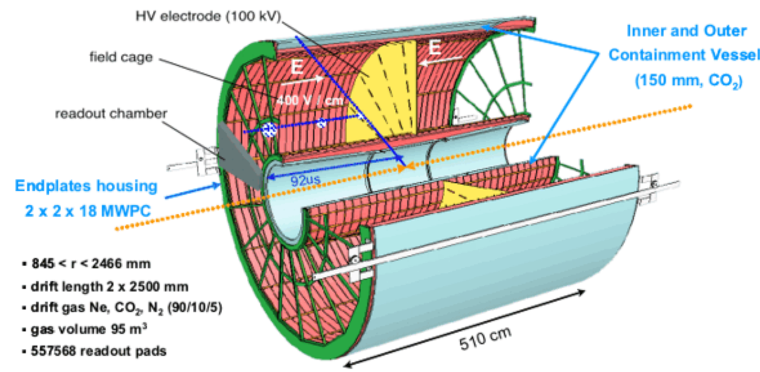
EMCal (π^0)



- EMCal : Pb-scintillator calorimenter
- Acceptance : $|\eta| < 0.7$, $\Delta\varphi = 110°$

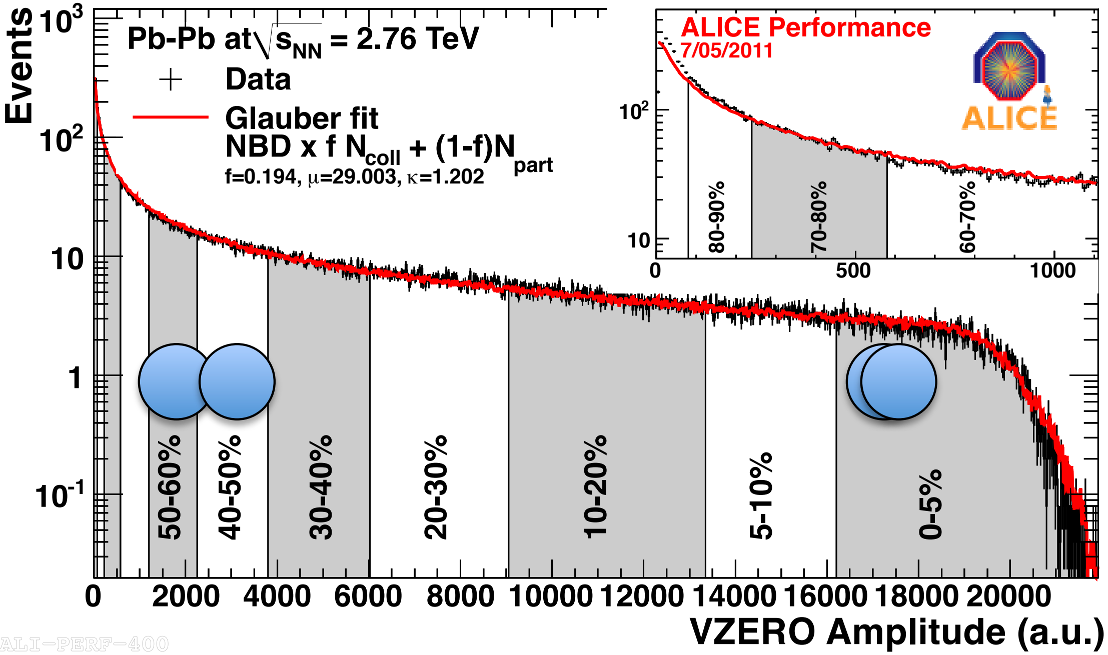
ITS and TPC (charged particle)



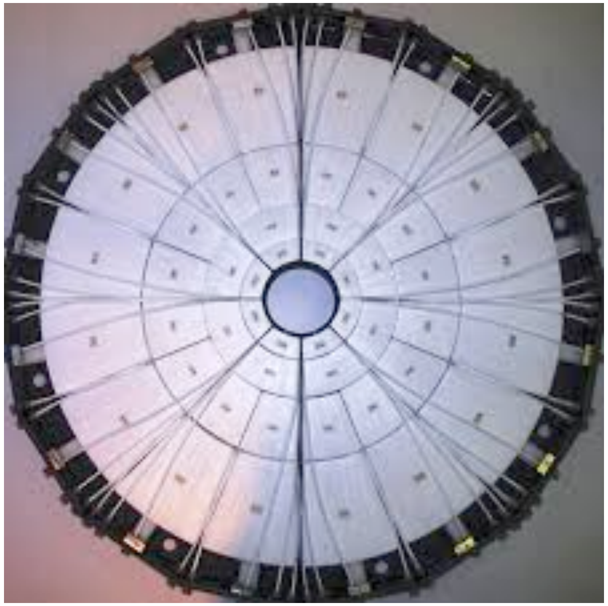


- ITS : Silicon-Pixel, Drift, Strip detector
- TPC : Time Projection Chamber
- Acceptance : $|\eta| < 0.9$, $\Delta\varphi = 360°$

Centrality determination



V0 detector



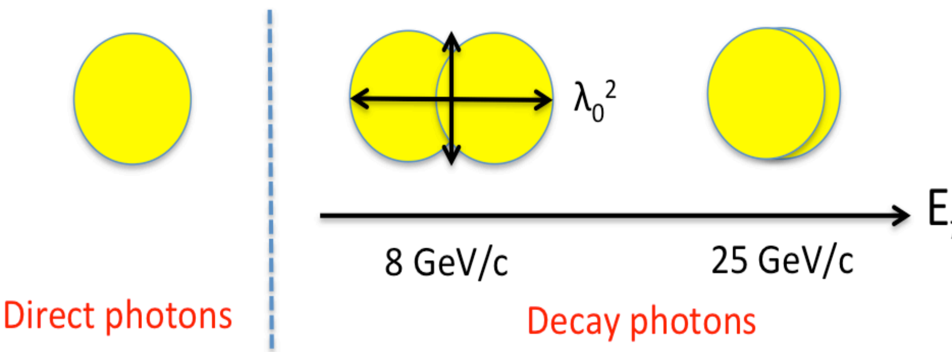
$-3.7 < \eta < -1.7$, $2.8 < \eta < 5.1$

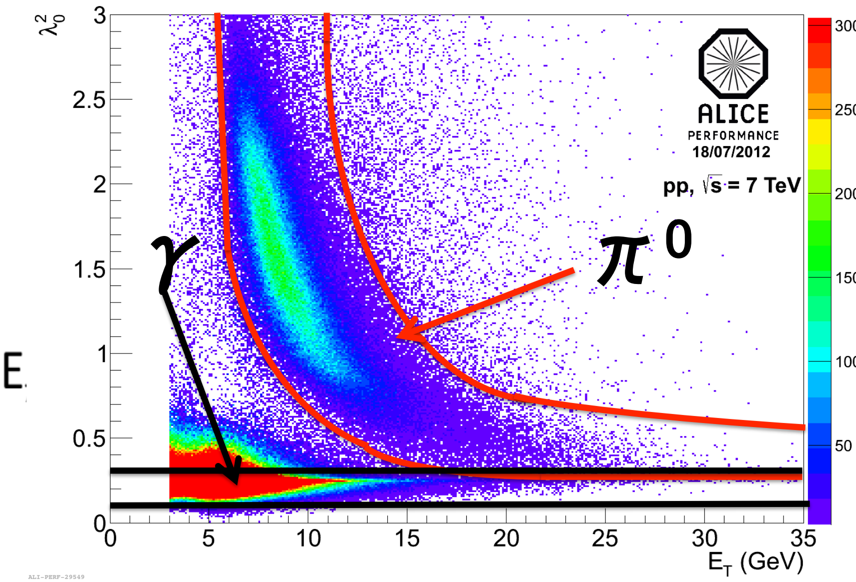
- Centrality
  - used to classify events instead of impact parameter
  - determinated from Glauber fitting to V0 detector amplitude

Energy dependence of shower shape

ALICE

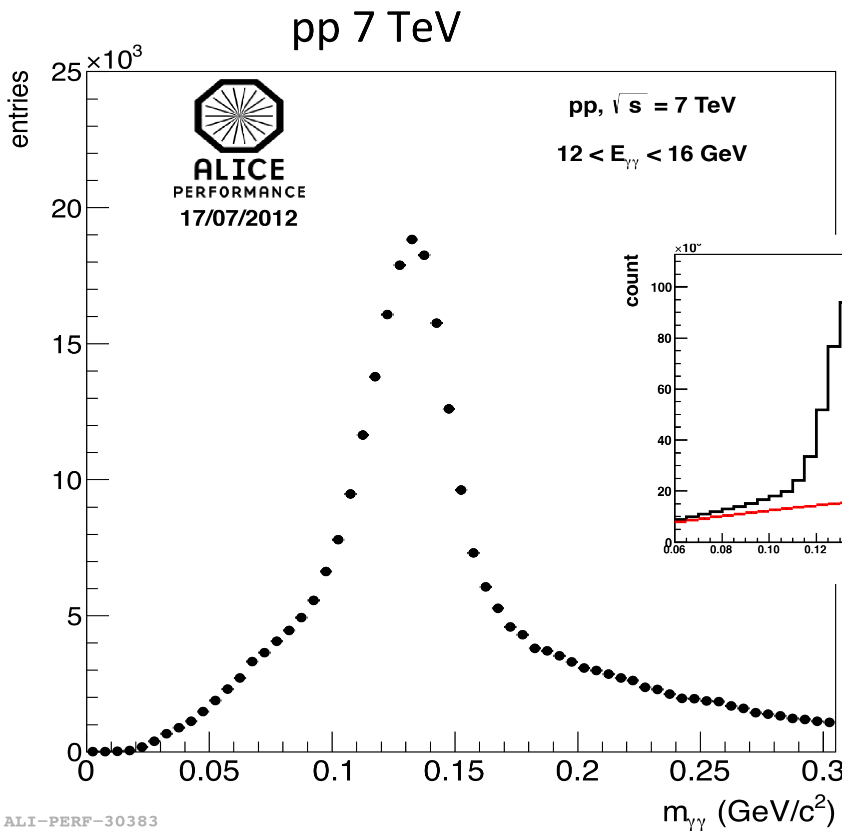
Shower shape

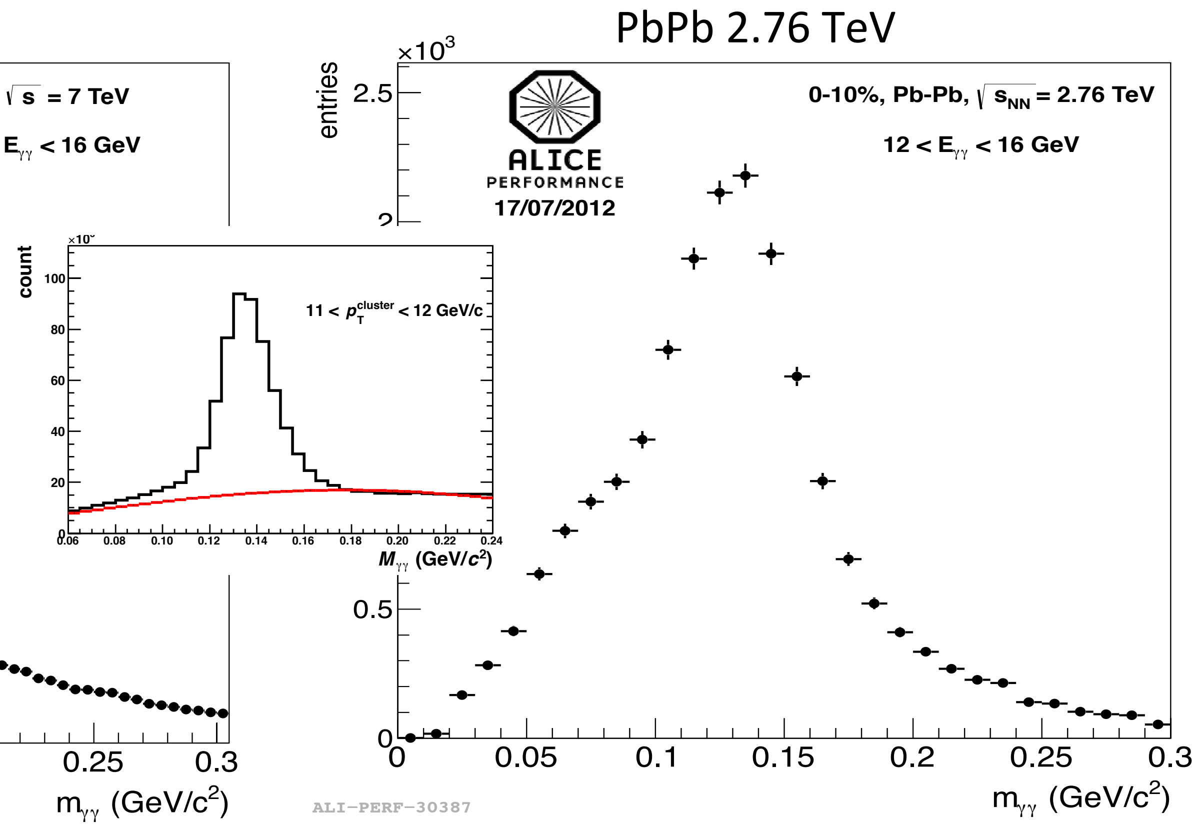




- The opening angle of the neutral mesons decay photon becomes smaller, when increasing the neutral meson energy due to Lorentz boost
- In the EMCAL, when the energy of π^0 is lager than 5 GeV
  - The two clusters of decay photon start to be close
  - The electromagnetic showers start to overlap

Invariant mass reconstruction (cluster splitting method)





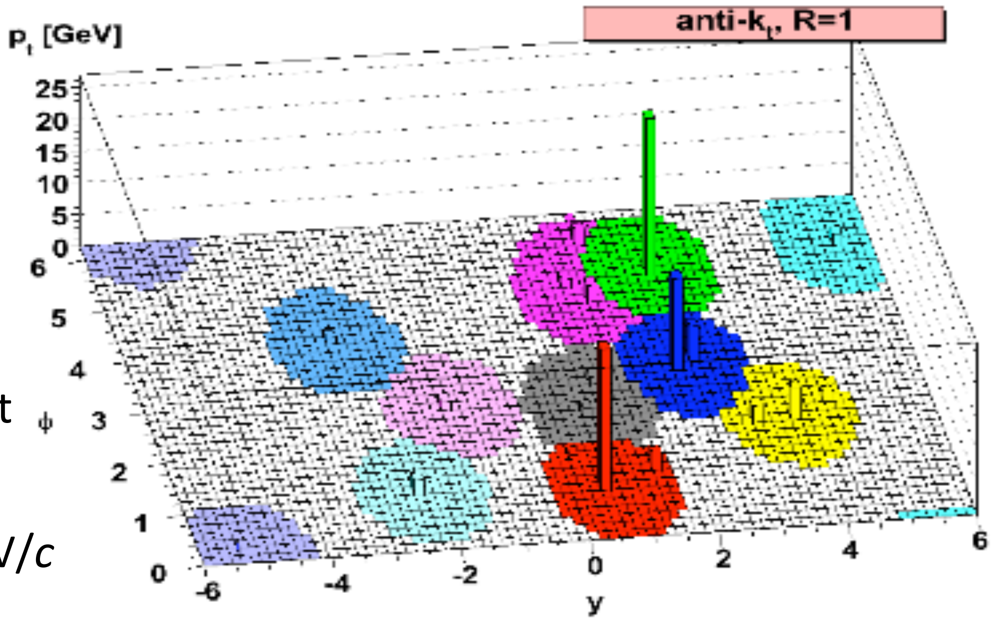
- 3σ invariant mass window from peak mean is selected as π^0
- We can identify π^0 up to 40 GeV/*c*

Charged jet reconstruction (FASTJET)

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R^2}{R^2} \begin{cases} p = 1 & k_T \text{ algorithm} \\ p = 0 & \text{Cambridge/Aachen algorithm} \\ p = -1 & \text{anti-}k_T \text{ algorithm} \end{cases}$$

Procedure of jet finding

1. Calculate particle distance : d_{ij}
2. Calculate Beam distance : $d_{iB} = k_{ti}^{2p}$
3. Find smallest distance (d_{ij} or d_{ib})
4. If d_{ij} is smallest combine particles
   If d_{ib} is smallest and the cluster momentum larger than threshold call the cluster Jet

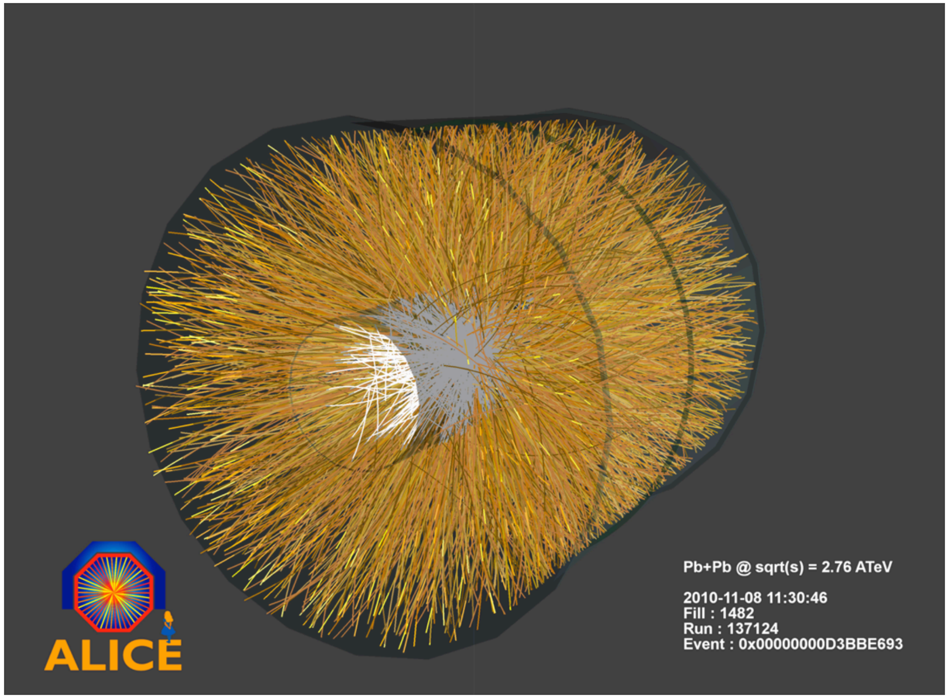


Parameters

- R size ($= \sqrt{\Delta\phi^2 + \Delta\eta^2}$) : 0.4
- p_T cut on a single particle : 0.15 GeV/*c*
- Jet energy threshold : 10 GeV/*c*
- Jet acceptance : $|\eta| < 0.5$, $0 < \phi < 2\pi$

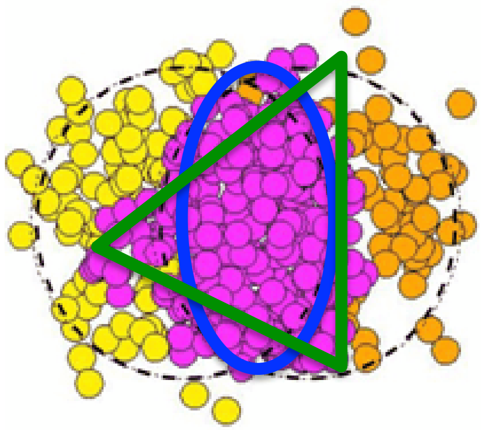
Background in Pb-Pb collisions

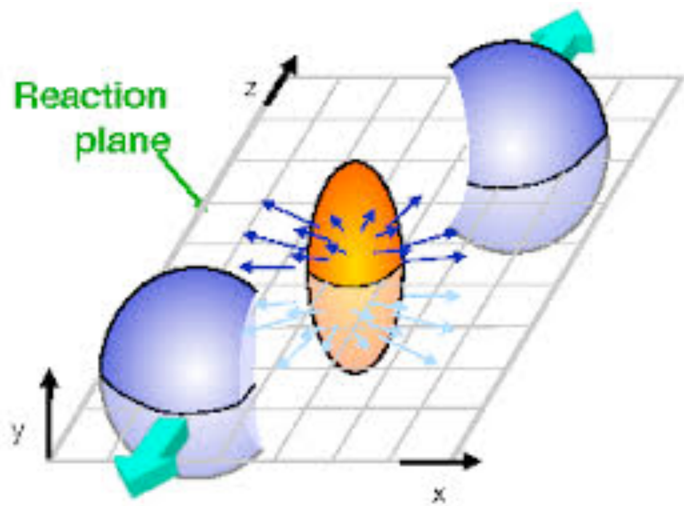
- Soft particle
  - Expansion (radial, elliptic)
- Hard particle
  - fake jet
  - combinatorial jet
- Dependence
  - centrality
  - event plane angle



Event plane reconstruction

ALICE



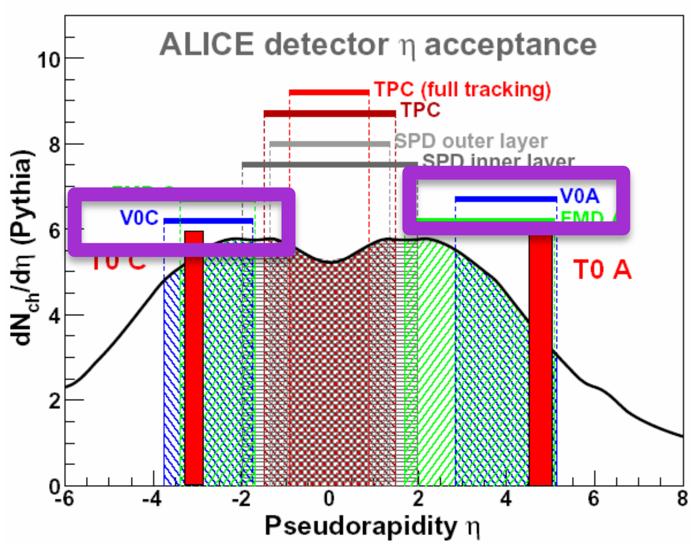


$$Q_y = \sum_{i=0} w_l \sin(n\phi_l) \quad , \quad Q_x = \sum_{i=0} w_l \cos(n\phi_l)$$

Re-centering

$$\Psi^{cor} = \frac{1}{n} \tan^{-1}\left(\frac{Q_y^{cor}}{Q_x^{cor}}\right)$$

$$Q_x^{cor} = \frac{Q_x - \langle Q_x \rangle}{\sigma_x}, \quad Q_y^{cor} = \frac{Q_y - \langle Q_y \rangle}{\sigma_y}$$



- Large η gaps to reduce non-flow effects
  - V0A side : > 0.9, V0C side : 2.0
- V0 gain and re-centering correction are applied

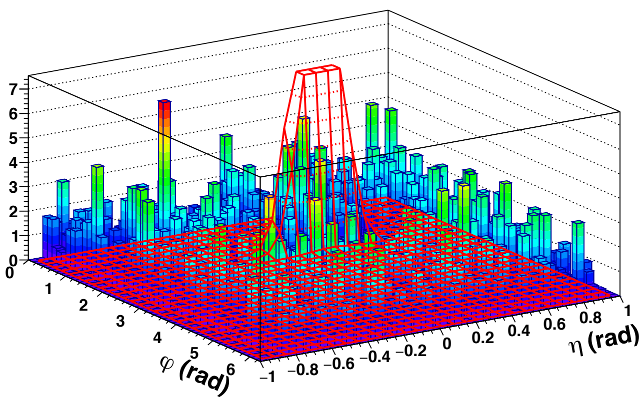
E-by-E calculation of BKG density in Pb-Pb collisions

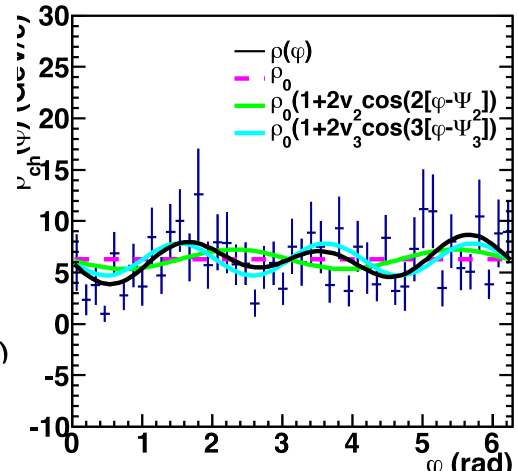
- In order to estimated the underlying event energy from hydrodynamic flow, fit to each event's $\frac{d\Sigma p_T}{d\varphi}$ distribution (with 0.2 < p_T < 5 GeV/c)

$$\rho(\varphi) = \rho_0 \times \left(1 + 2\left\{v_2^{\mathrm{obs}} \cos(2[\varphi - \Psi_{2,EP}]) + v_3^{\mathrm{obs}} \cos(3[\varphi - \Psi_{3,EP}])\right\}\right)$$

Jet p_T is corrected on a jet-by-jet basis, where A is the jet area and ρ_{local} is flow modulation UE energy density

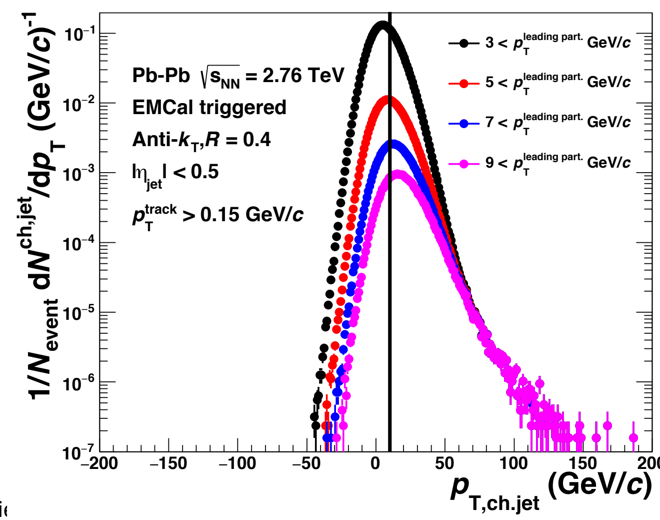
$$p_{T,chjet} = p_{T,chjet}^{raw} - \rho_{local} A \qquad \rho_{\mathrm{local}} = \frac{\langle\rho\rangle}{2R\rho_0} \int_{\varphi-R}^{\varphi+R} \rho(\varphi) d\varphi.$$





Number of bins in $\frac{d\Sigma p_T}{d\varphi}$ spectrum ≈ √N_entrie

Filled track p_T renge : 0.2 < p_T^{track} < 5 GeV/c



Correction

- Detector acceptance correction (event mixing method)
  - 100 events (pp) and 10 events (Pb-Pb) pool
  - Z vertex = (-10, 10) cm, 2 cm wide bins
  - Track multiplicity, 9 bins on multiplicity (pp)
  - Centrality, 10 bins (Pb-Pb)

$$C(\Delta\varphi) = \frac{\int N^{mixed}_{pair}(p_T^{\pi^0}, \Delta\varphi) d\Delta\varphi}{\int N^{same}_{pair}(p_T^{\pi^0}, \Delta\varphi) d\Delta\phi} \cdot \frac{N^{same}_{pair}(p_T^{\pi^0}, \Delta\varphi)}{N^{mixed}_{pair}(p_T^{\pi^0}, \Delta\varphi)}$$

$$\frac{1}{N^{\pi^0}_{trig}} \frac{dN^{jet}}{d\Delta\phi} = \frac{\int N^{same}_{pair}(p_T^{\pi^0}, \Delta\phi) d\Delta\phi}{N^{\pi^0}_{trig}(p_T^{\pi 0})} \cdot C(\Delta\phi)$$

- Jet yield corrections (Unfolding method)
  - Detector response (pp and Pb-Pb collisions)
  - BKG fluctuations (Pb-Pb collisions)

$$\mathbf{M}_m = \mathbf{R}^{\mathrm{tot}}_{m,t} \cdot \mathbf{T}_t = \mathbf{R}^{\mathrm{bkg}}_{m,d} \cdot \mathbf{R}^{\mathrm{det}}_{d,t} \cdot \mathbf{T}_t,$$

$\mathbf{R}^{det}_{d,t}$: Response matrix for detector effect
$\mathbf{R}^{bkg}_{m,d}$: Response matrix for bkg fluctuation

Systematic uncertainty

ALICE

- Shower shape parameter(λ_0^2) cut ~ 5 %
- Invariant mass window ~ 7 %
- Flat background in azimuthal correlation (only Pb-Pb) ~ 18 %
- π^0 identification purity (pair purity) : 10 %
- Unfolding method ~ 12 %

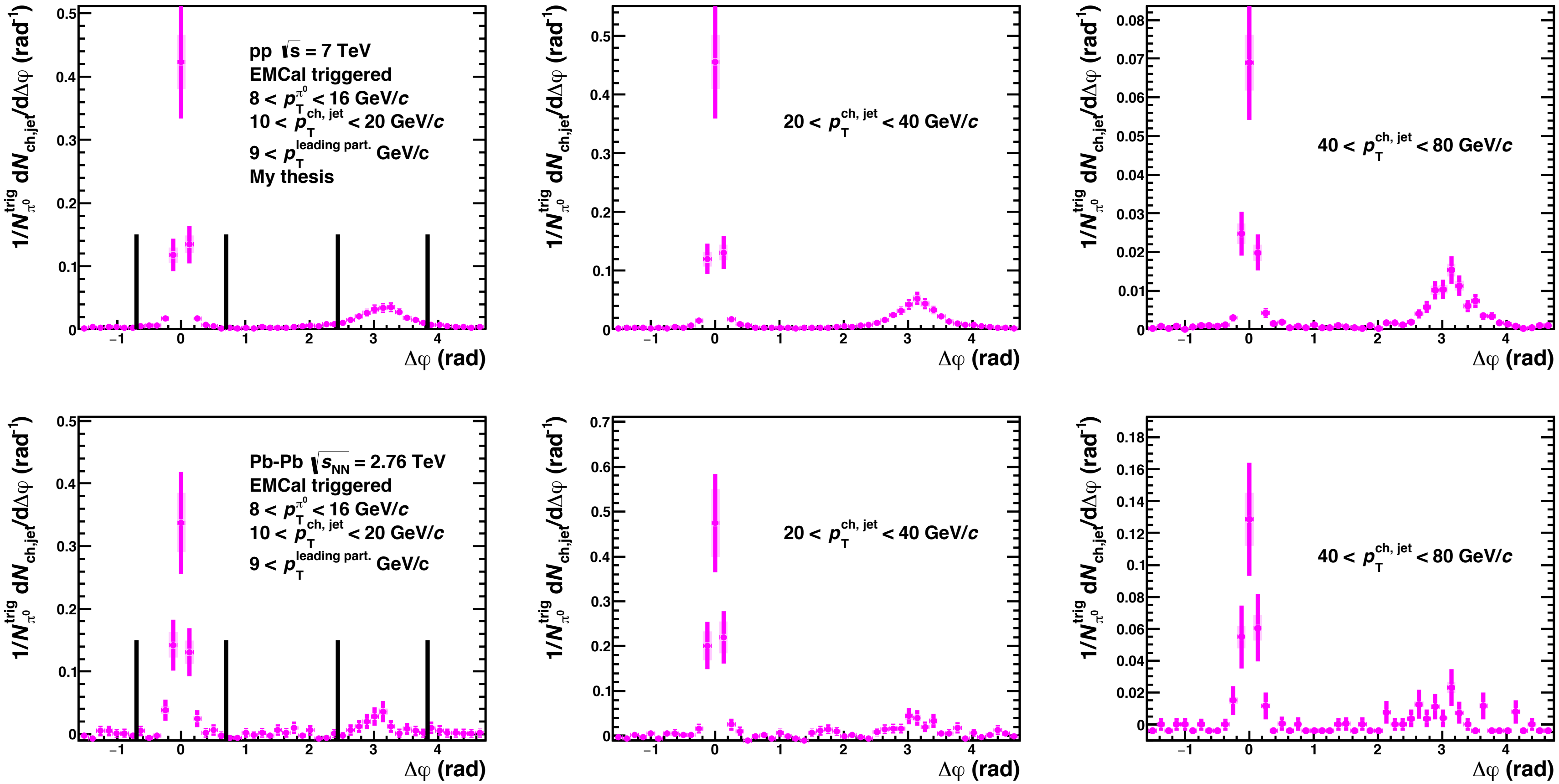
Result

π^0 p_T region : $8 < p_T < 16$ GeV/c

Jet p_T bin : [10-20], [20-40], [40-80] GeV/c

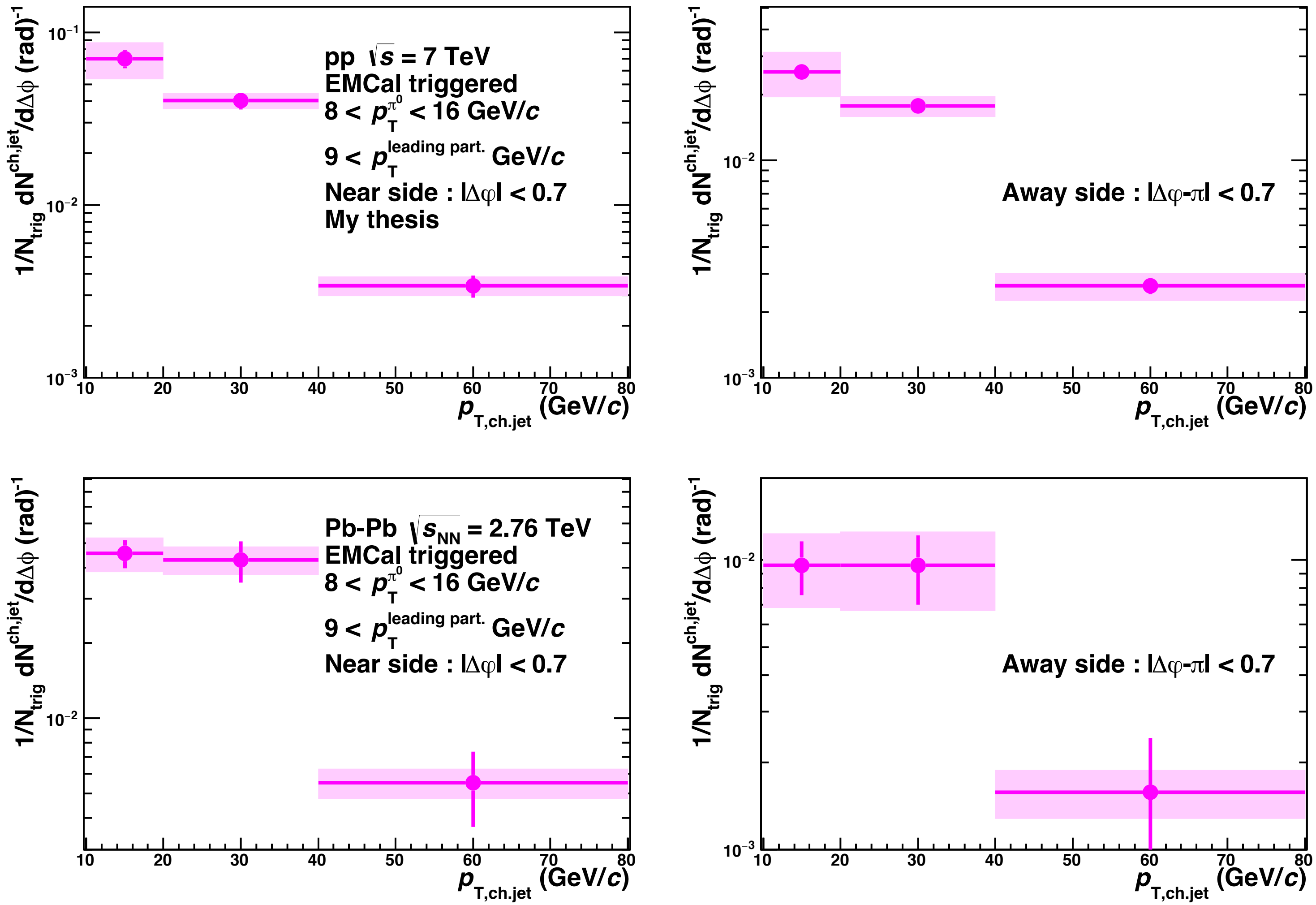
Leading particle p_T : 9 GeV/c $< p_T$ (azimuthal correlation, Yield), 5, 7, 9 GeV/c $< p_T$ (width)

Azimuthal correlation

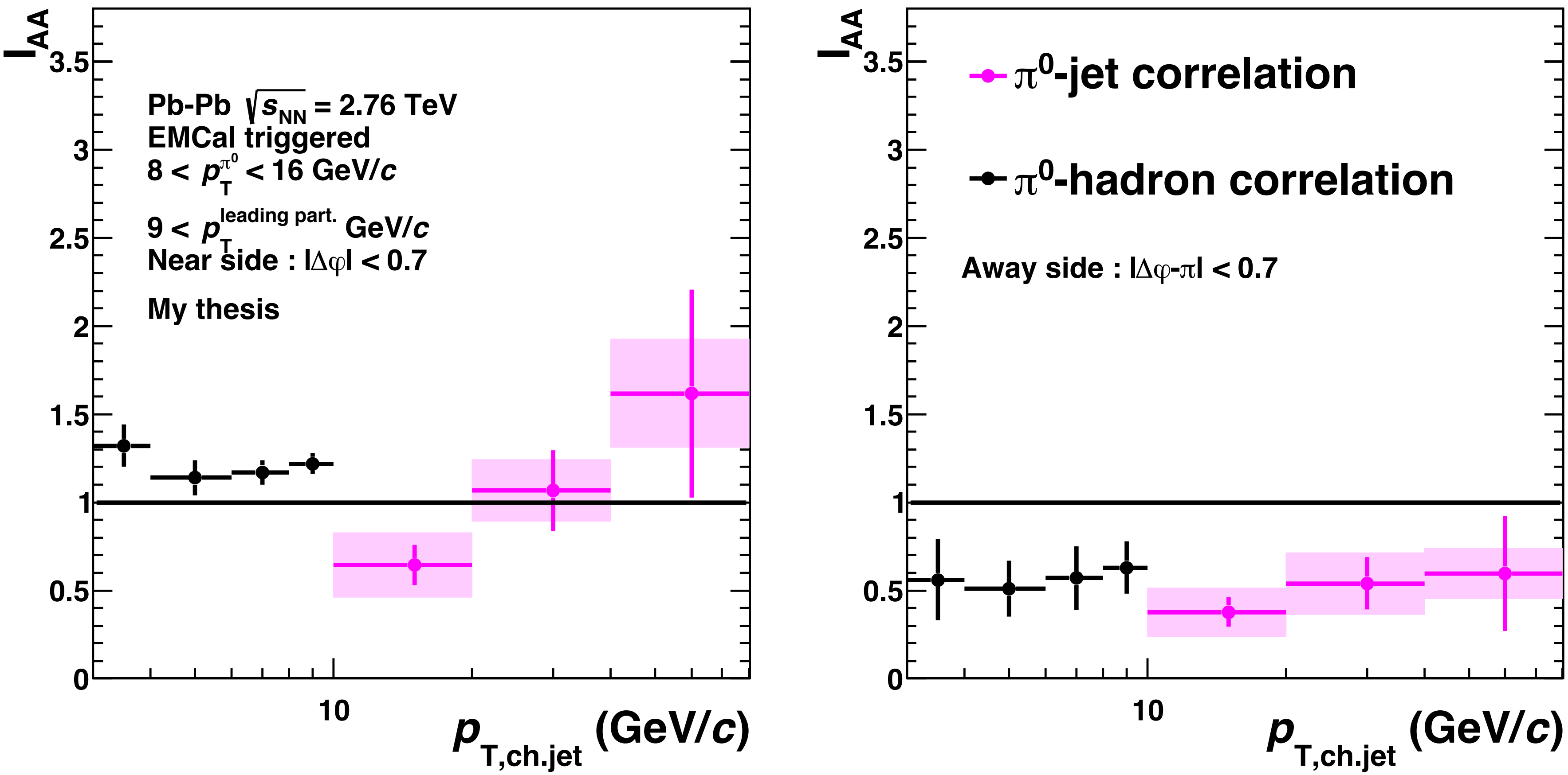


- Two jet-like peaks are observed, indicating that high p_T π^0 production is correlated with jet production
- Away side peaks in pp collisions become sharp with increasing the associated jet momentum regions

Near and away side jet yields with normalized # of trigger



Ratio of per trigger yields I_{AA}



$$I_{AA}(p_T^{\pi^0}, p_{T,ch.jet}) = \frac{Y_{Pb-Pb}(p_T^{\pi^0}, p_{T,ch.jet})}{Y_{pp}(p_T^{\pi^0}, p_{T,ch.jet})}$$

- Enhancement of jet yields on the near side
- Suppression of jet yields on the away side
- Same results with π^0-hadron correlation analysis

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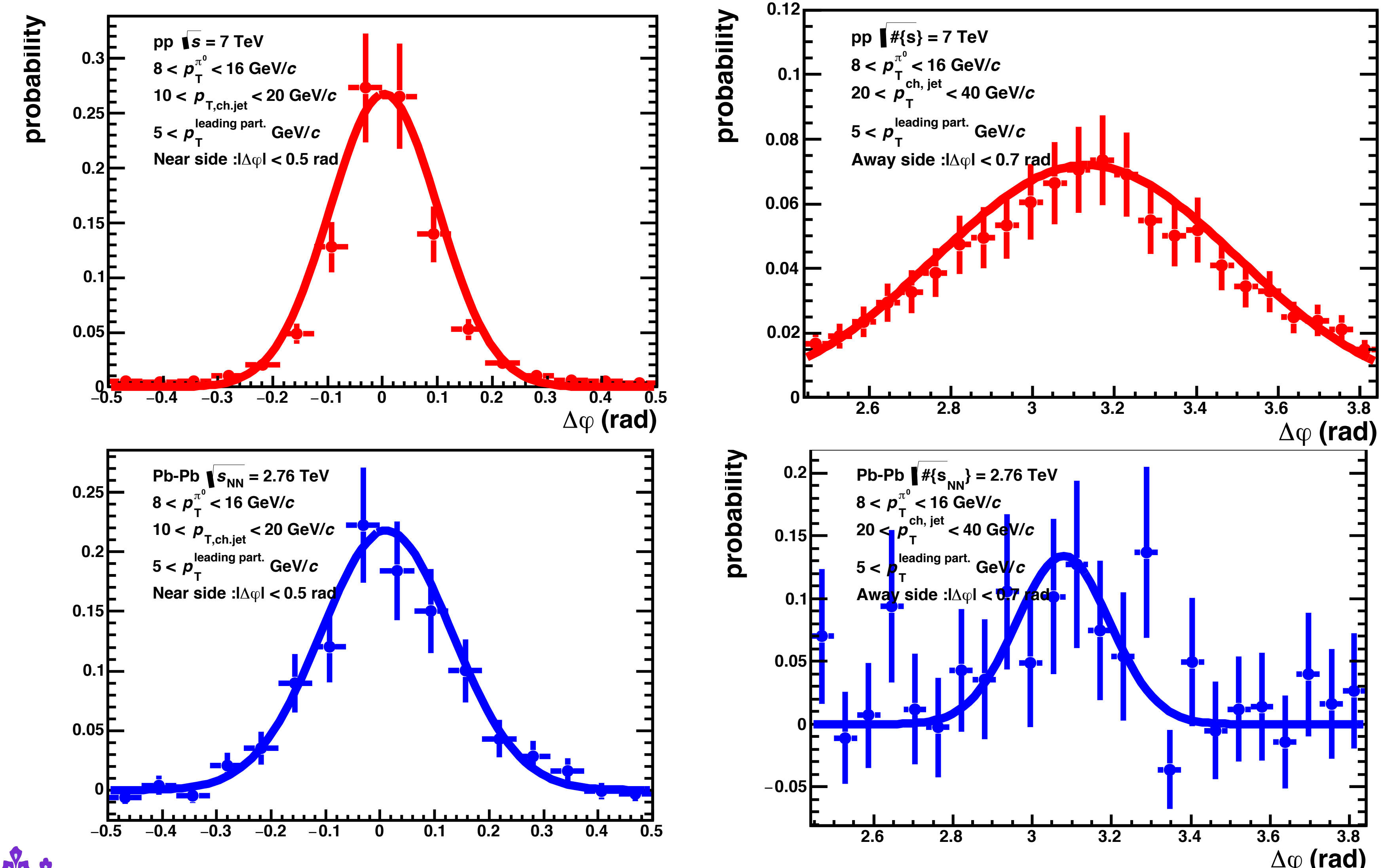
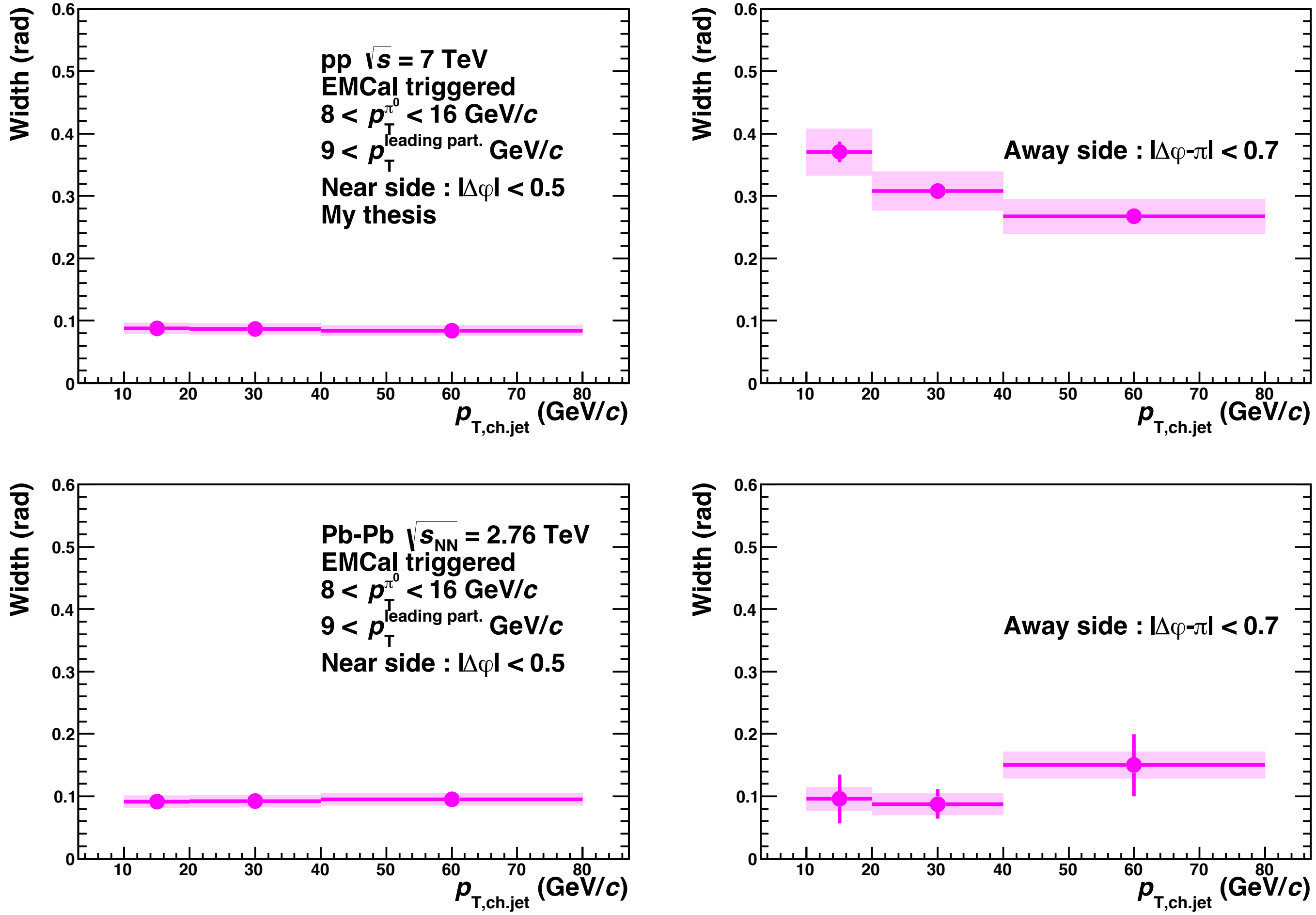
Gaussian fitting at near and away side peaks



Near and away side width as a function of jet p_T



- Near side widths are not seen the dependence of the jet momentum.
- Away side widths in pp collisions decrease with increasing jet momentum region.

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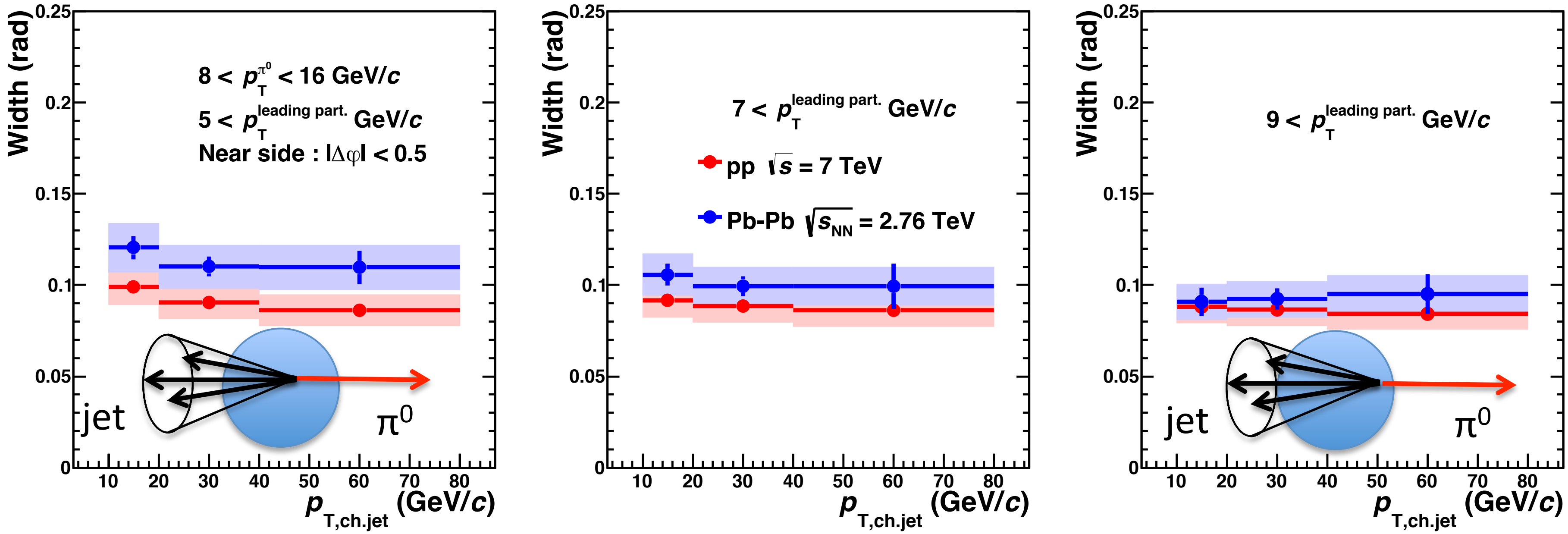
Leading part. p_T dependence of near side widths



- Differences of near side widths between pp and Pb-Pb collisions decrease with increasing thresholds of leading particle in a jet
  - path-length dependence of the effect of jet broading

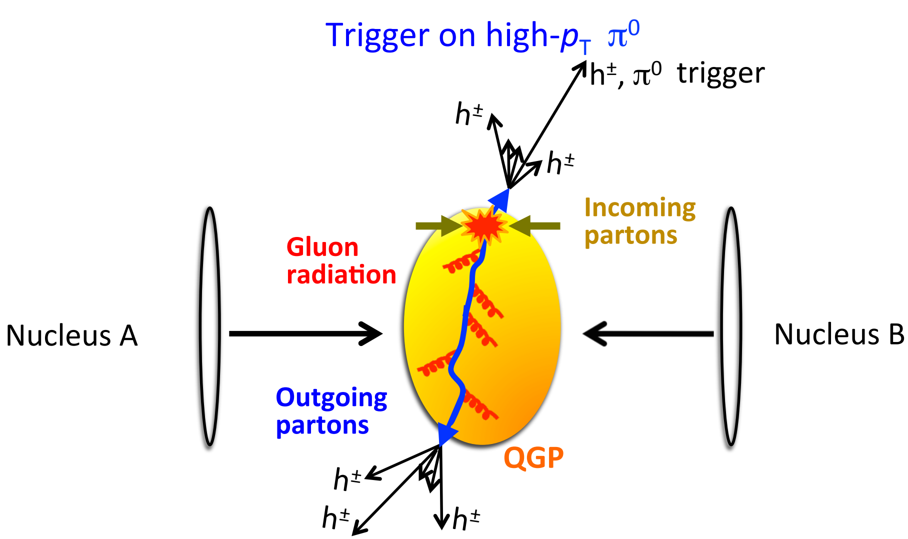
Summary

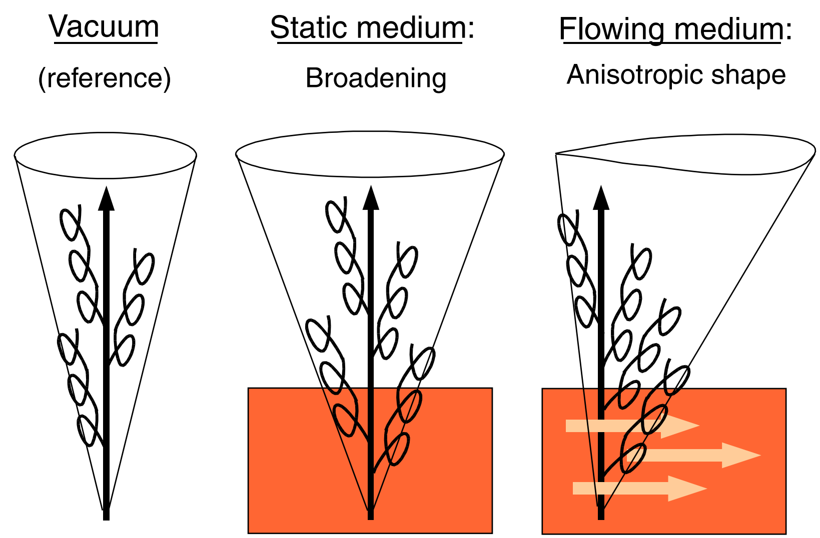
- π^0-jet correlations have been measured in pp at $\sqrt{s}$ = 7 TeV and Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
- Azimuthal correlation
  - High momentum π^0 production is correlated with jet production
- Near and away side jet yields
  - Select near side jets produced at the surface, and the path length of away side jets become longer than the near side jets
  - Enhancement and suppression are seen in high momentum regions as well as the particle level analysis.
- Width
  - Effect of jet broading in Pb-Pb collisions depends on the path length in the matter

Back up

Measurements of yields and widths in near and away side

- Yield measurements
  - check the surface bias in a near and away side with triggering high momentum hadron
- Width/shape measurements
  - check the modification of the jet shape in the matter

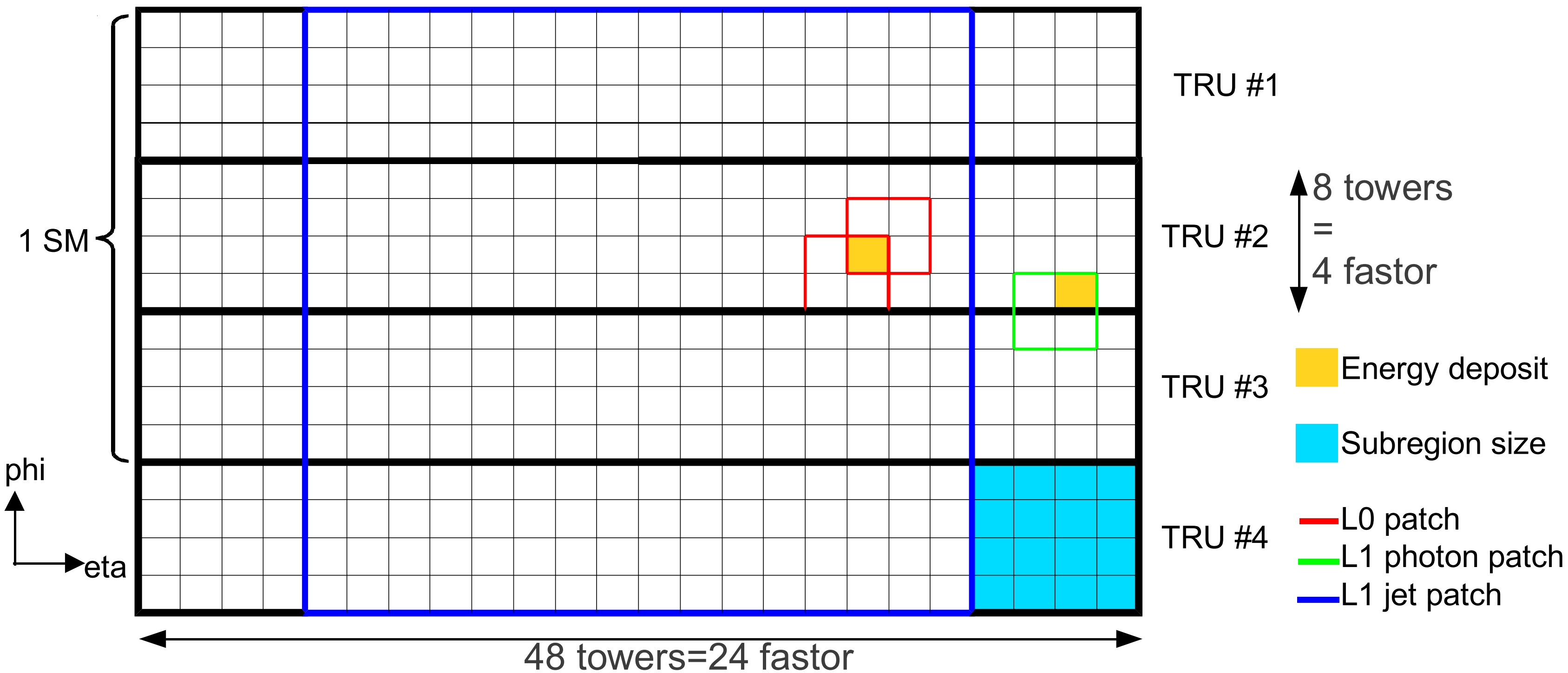




Event characterization

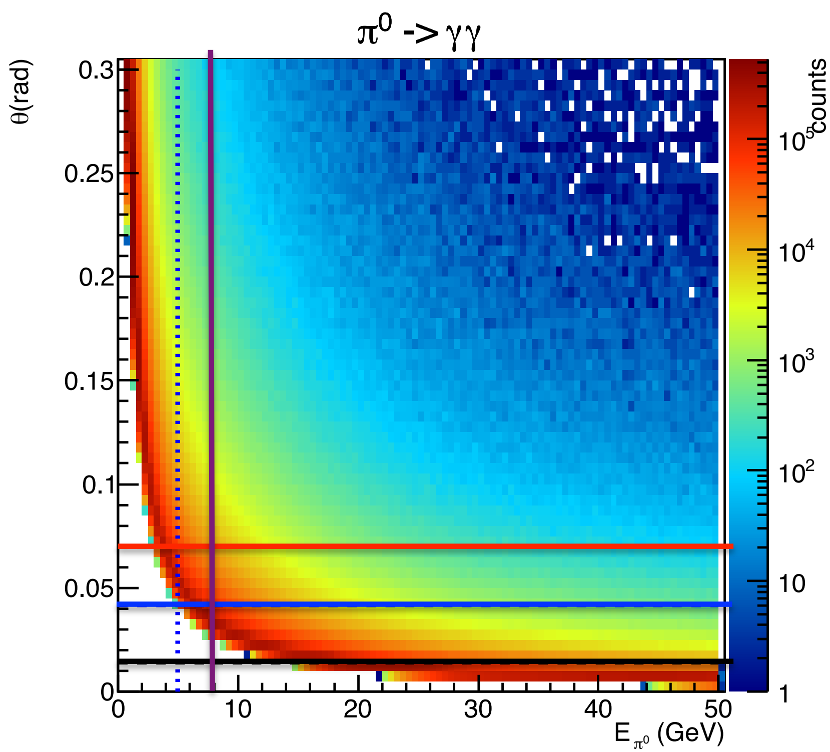
EMCal trigger determination

- L0 trigger : OR of the 32 L0 calculated by the TRUs (trigger threshold : 4.5, 5.5 GeV)
- L1- gamma trigger : Same patches as L0, but no boundary effect (trigger threshold : centrality)
- L1-jet trigger : Energy summed over a sliding window of 4 x 4 subregions
(1 jet patch = 16 x 16 fastOr = 64 x 64 towers)



π^0 reconstruction

Openning angle dependence of shower shape



: 5 cell : 3 cell : 1 cell

- Radiation length : 12.3 mm

$$X_0(g/cm^2) \approx \frac{716\ g\ cm^{-2}\ A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

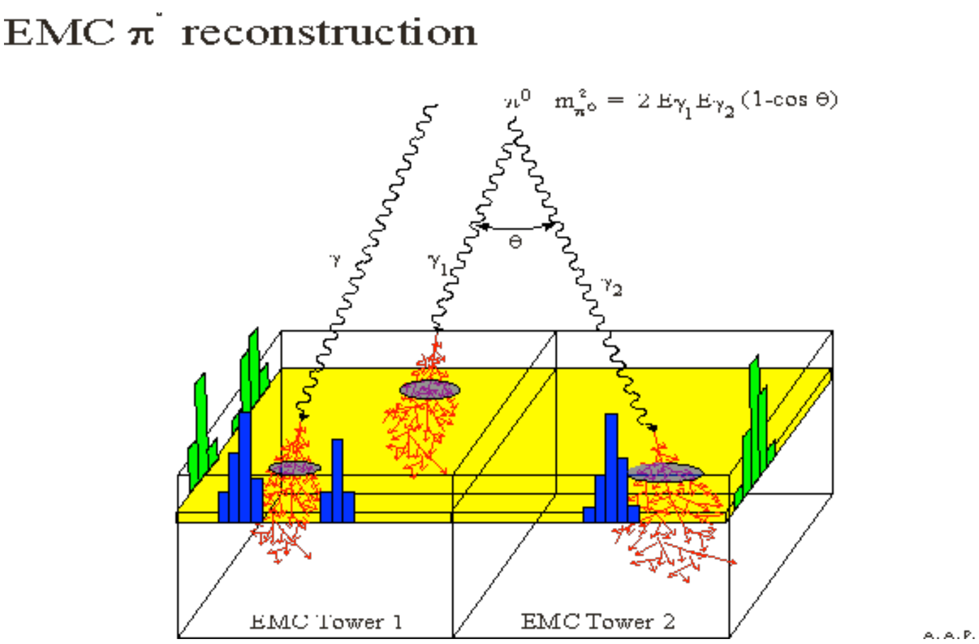
- Critical energy E_C : 8 MeV
- Moliere radius : 3.2 cm

$$R_M\ (g/cm^2) \sim \frac{21(MeV)X_0}{E_c(MeV)}$$

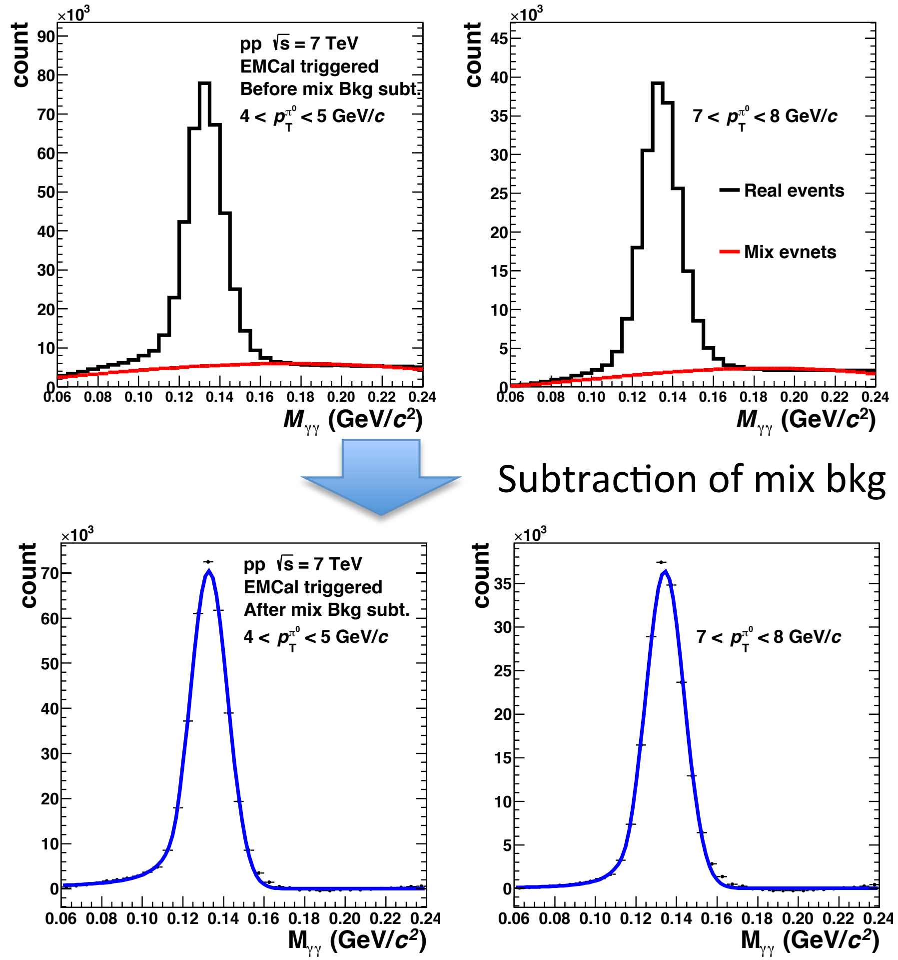
- EMCal cell size : 6 cm

- Photons deposit all energy in a 3x3 cluster on the EMCal

Invariant mass method ($4 < p_T < 8$ GeV/c)

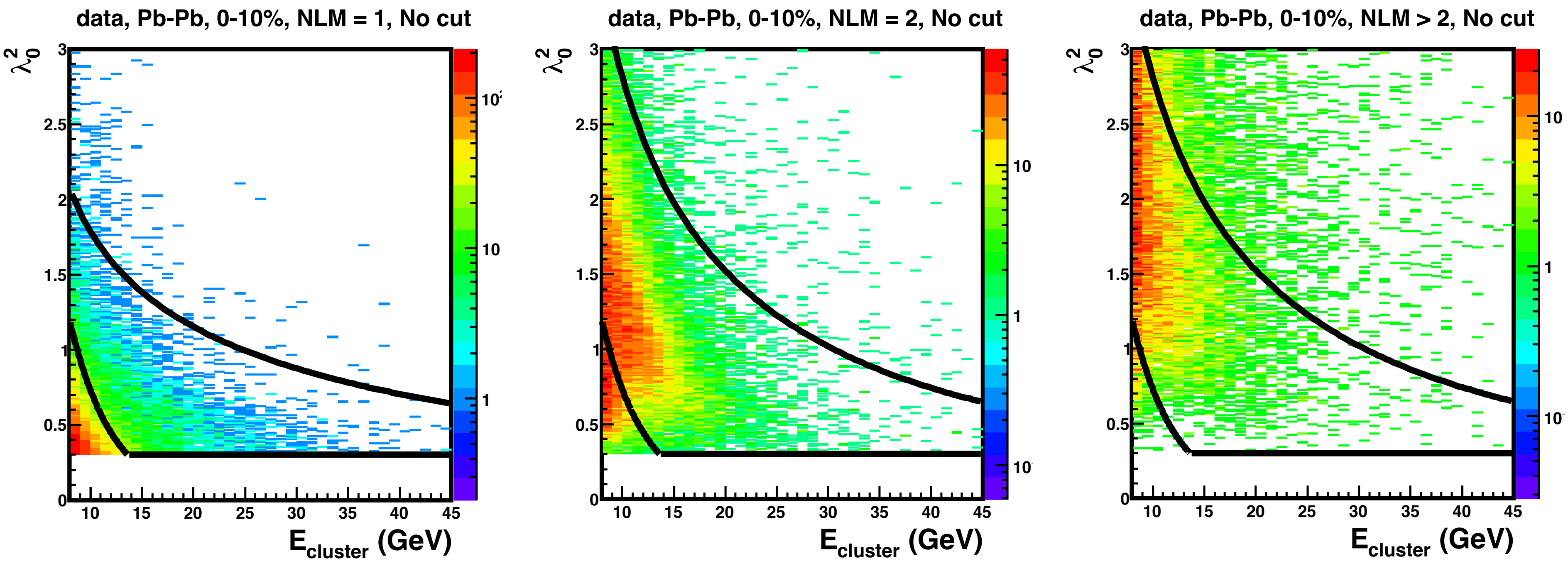


$$M_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\Delta\phi)}$$



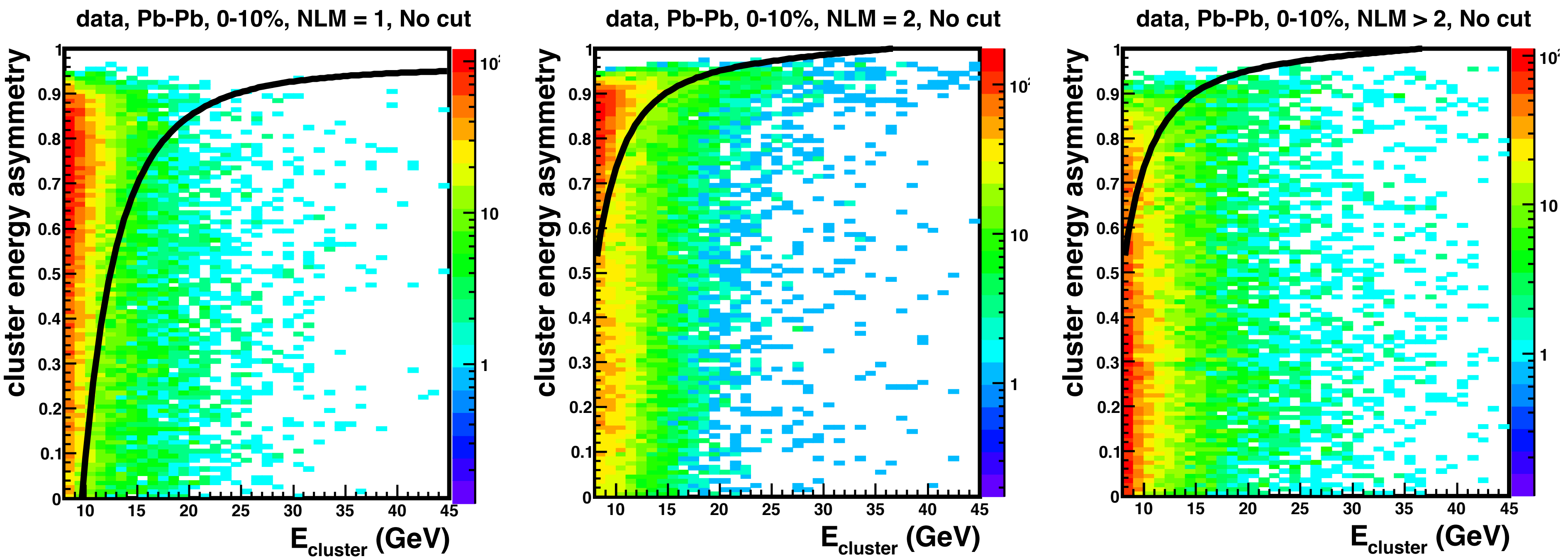
Fit function : Crystall ball function

Shower shape cut



$$\lambda^2_{0,max,min}(E) = e^{a+b*E} + c + d*E + e/E$$

Cluster energy asymmetry

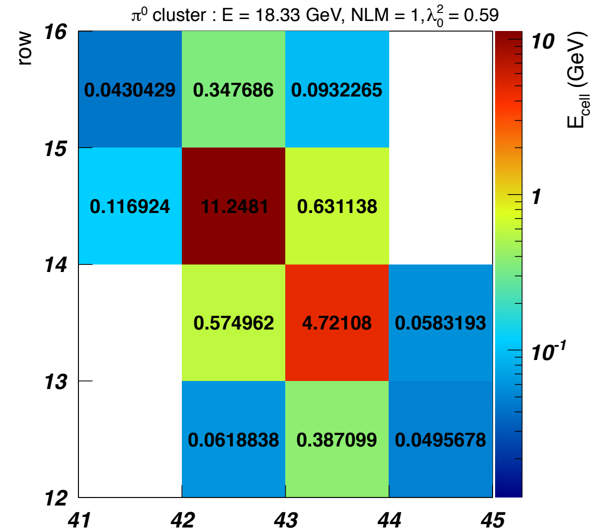


$$A_{min}(E) = a + b * E + c/E^3$$

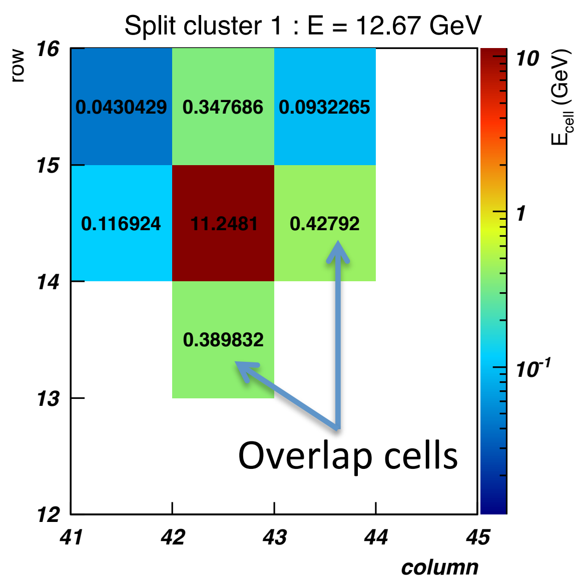
The procedure of cluster splitting method ($8 < p_T^{\pi 0}$)

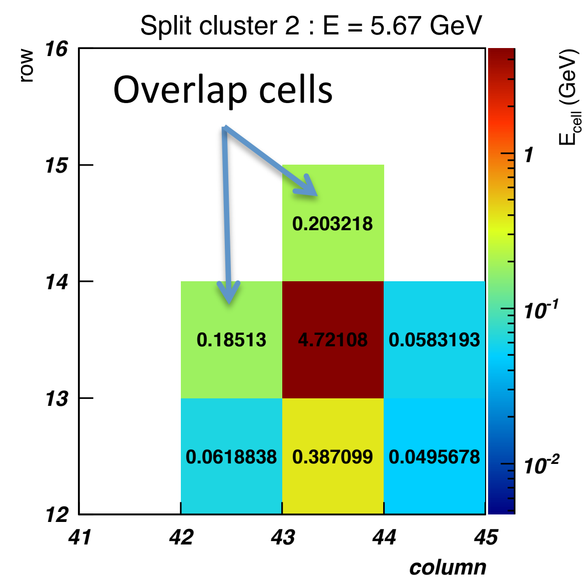
1. Select neutral cluster with $\lambda_0^2 > 0.3$, track matching etc.
2. Find local maxima in the cluster.
3. Split the cluster in new two sub-clusters taking the two highest local maxima cells and aggregate all towers around them.(form 3x3 cluster)
4. Get the two new sub-clusters, and calculate energy asymmetry and invariant mass

$$E(Local\,Max\,candidate) - E(ad\,jacent\,cell) > \Delta E_{LM}$$



- Overlap cell energy is calculated by using weight of each local maxima cell energy





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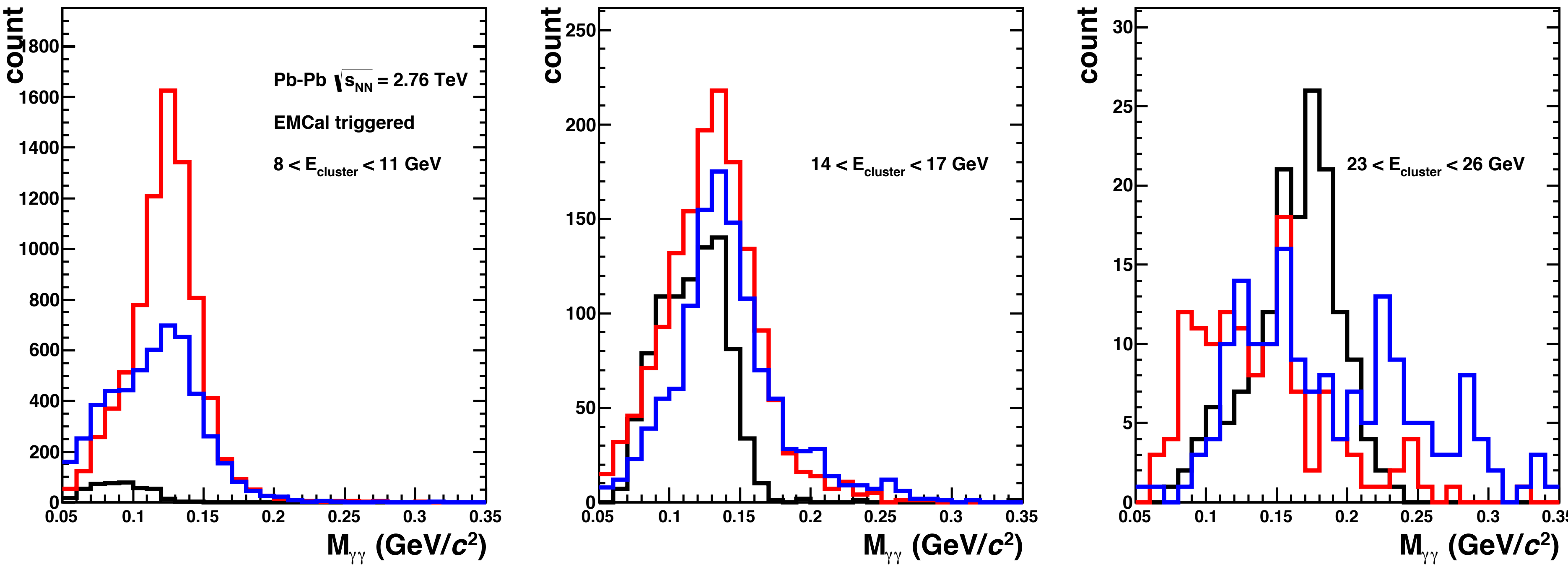
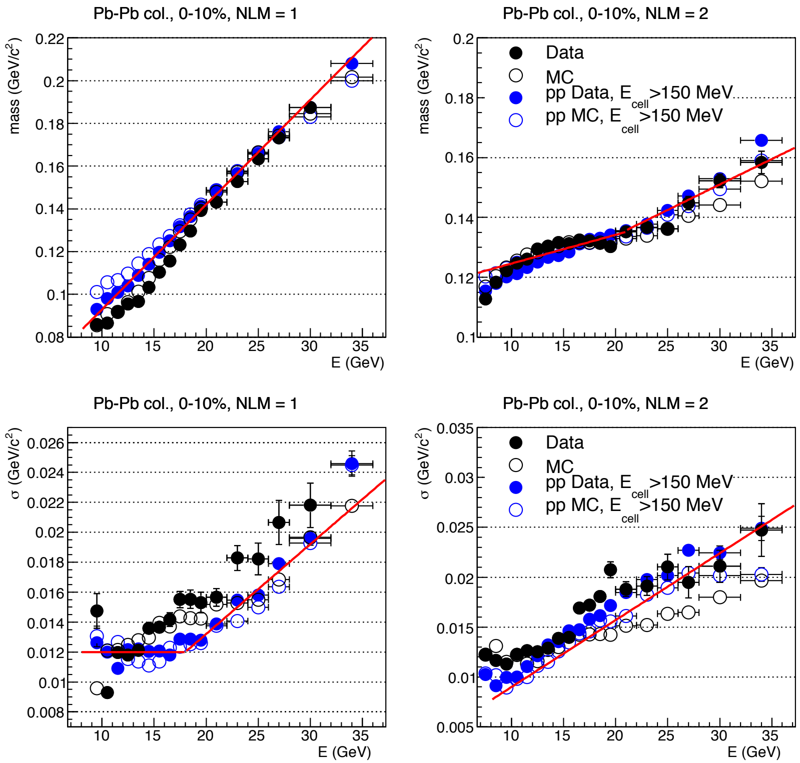
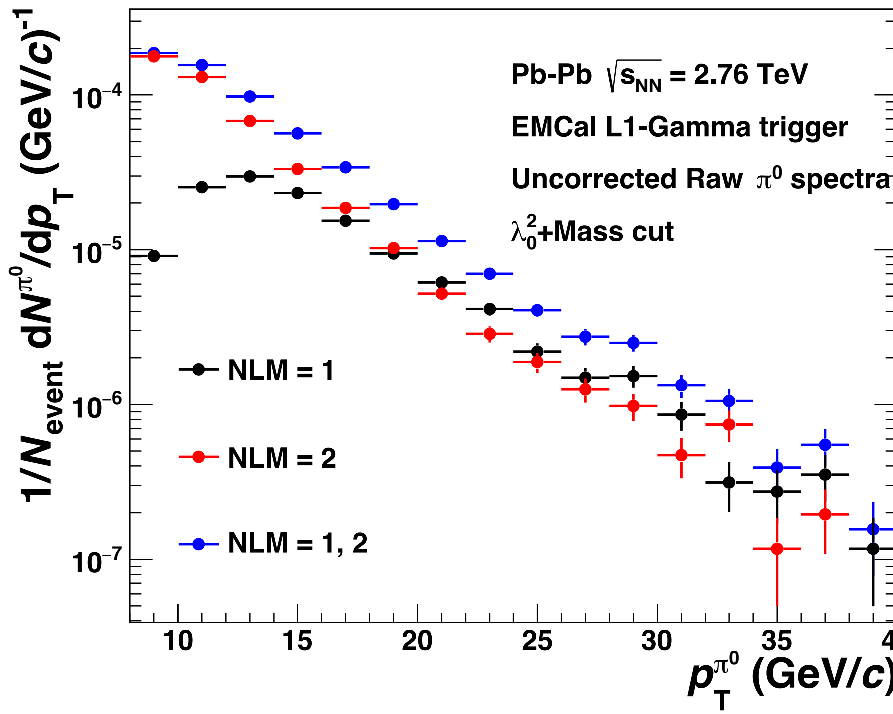
Mass distribution



Invariant mass cut and π^0 p_T distribution

From Gustavo's analysis note



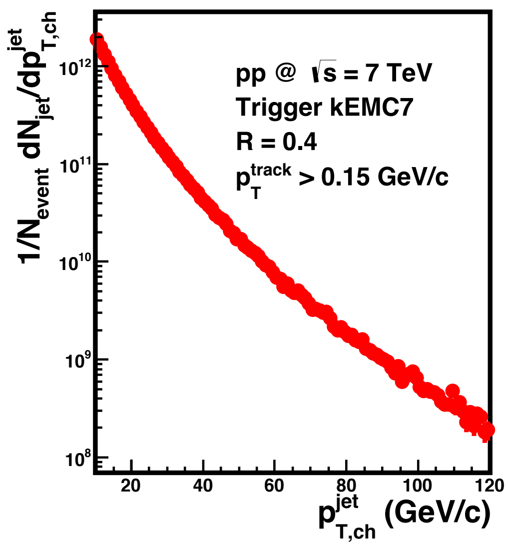


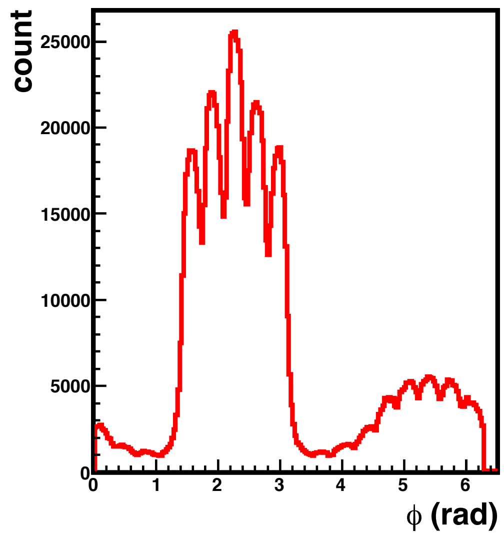
$$M(E), \sigma(E) = a + b * E$$

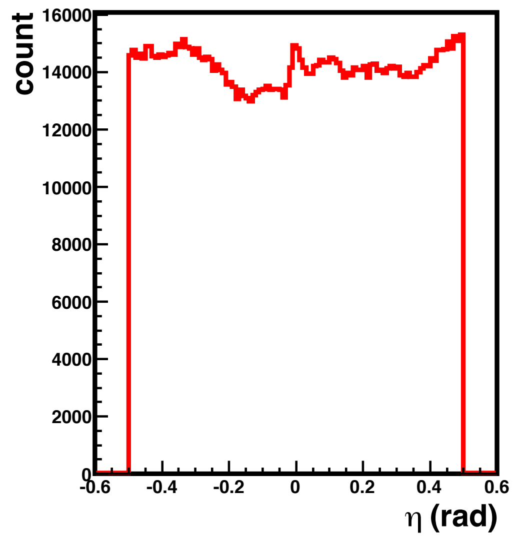
- Selected clusters as π^0 at 3σ from each mean points.

Jet reconstruction

Information of selected jet in pp 7 TeV





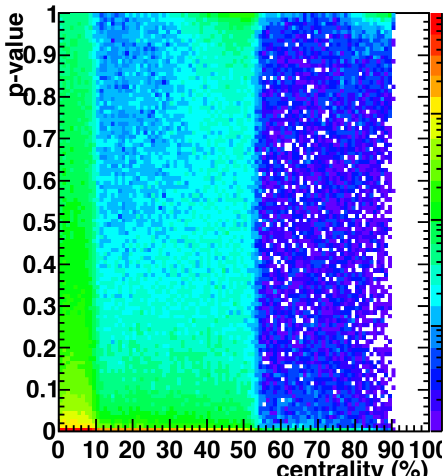


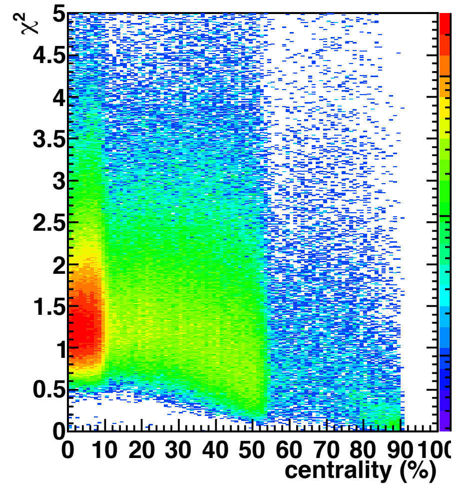
Fitting quality

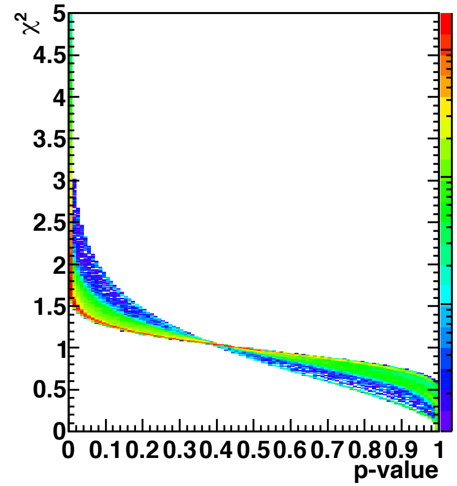
- Negative values
  - the check on the validity of the ρ(ϕ) approximation is the requirement that ρ(ϕ) has a minimum larger than or equal to 0

- p-values and goodness of fit
  - the fit criterion is a cut on the probability p whick is derived from the x^2 statistic (0.01 < p)

$$\chi^2 = \sum_{n=0}^{i} \left(\frac{x_i - \mu_i}{\sigma_i} \right)^2 \qquad \mathrm{CDF}(k, \chi^2) = \frac{1}{\Gamma\left(\frac{k}{2}\right)} \gamma\left(\frac{k}{2}, \frac{x}{2}\right) \qquad p = 1 - \mathrm{CDF}.$$





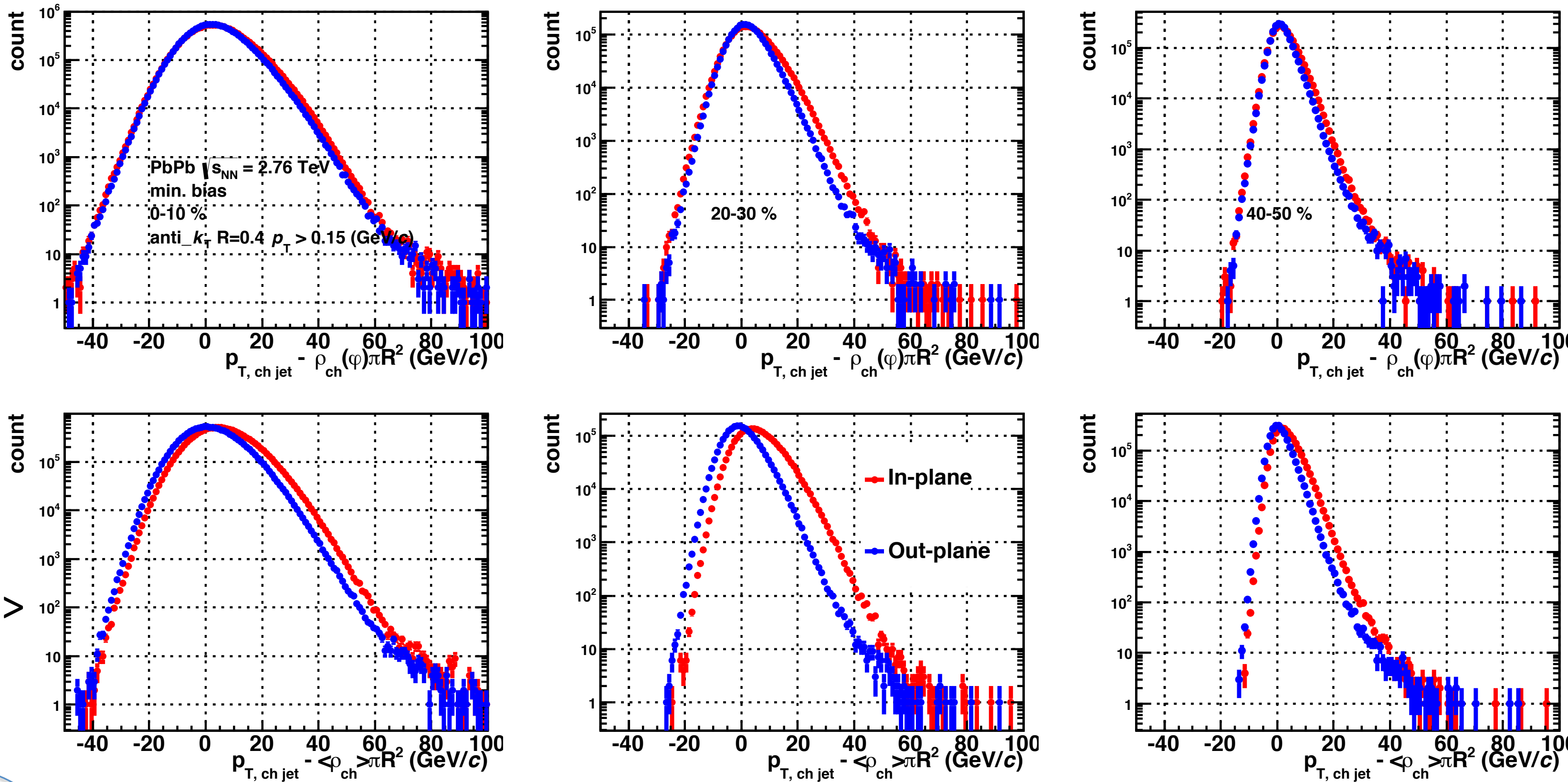


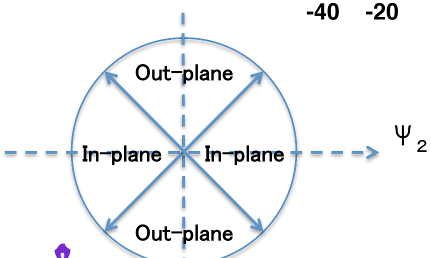
Jet p_T spectrum with two different event plane regions

Work in progress

Local ρ(ϕ)

Median <ρ>

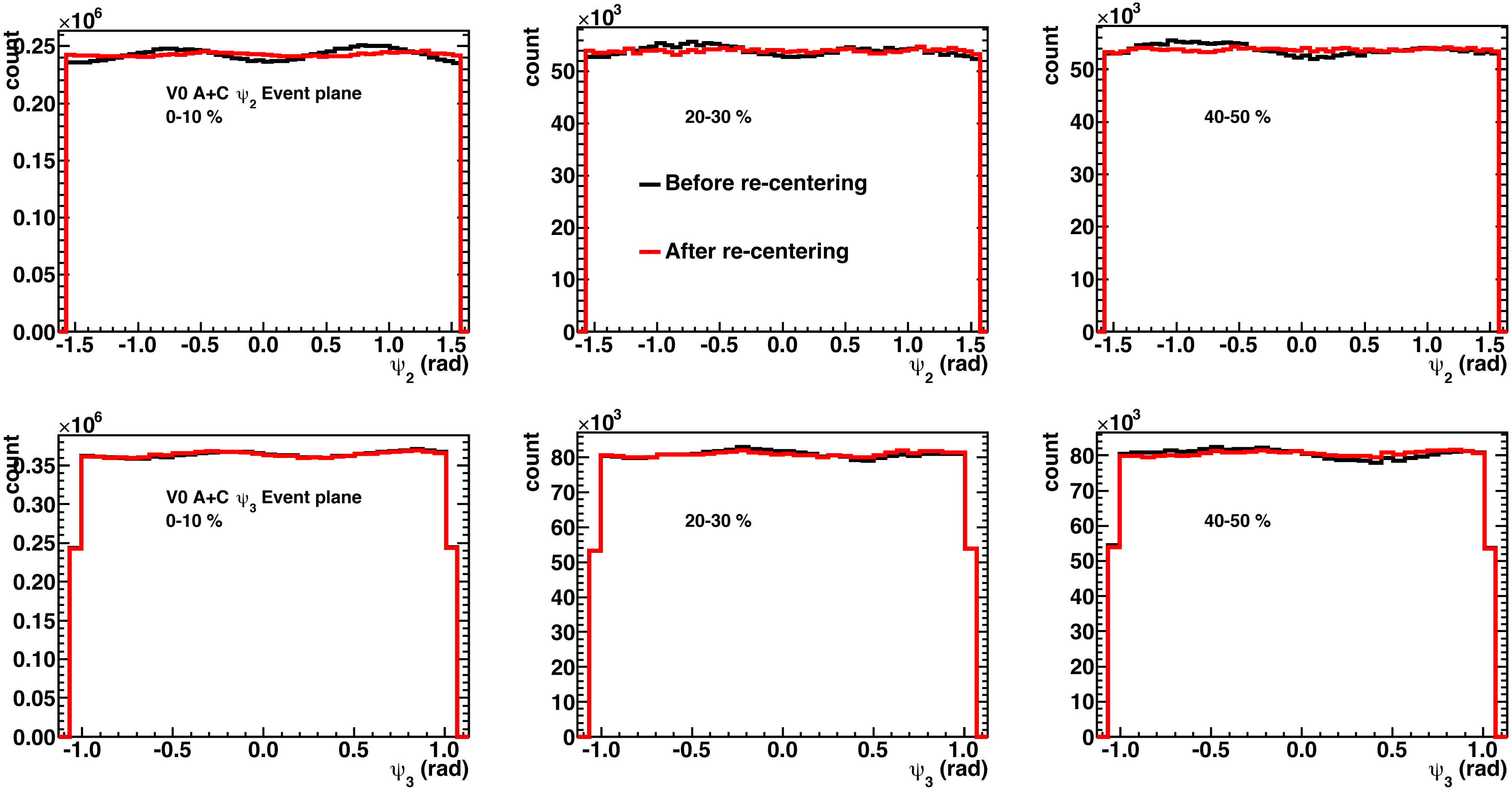




- Distributions of median method have the differences between in and out-of-plane due to flow effect

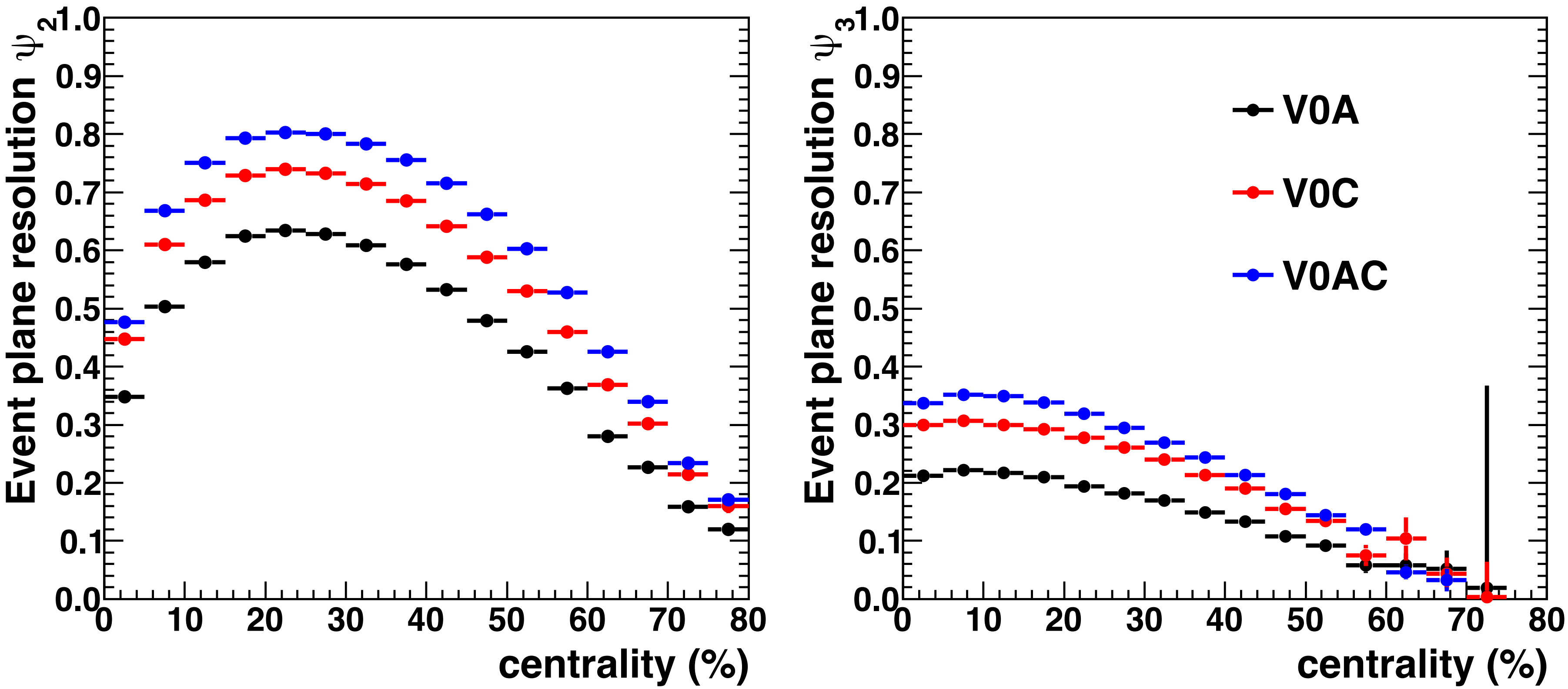
Event plane analysis

Event plane QA



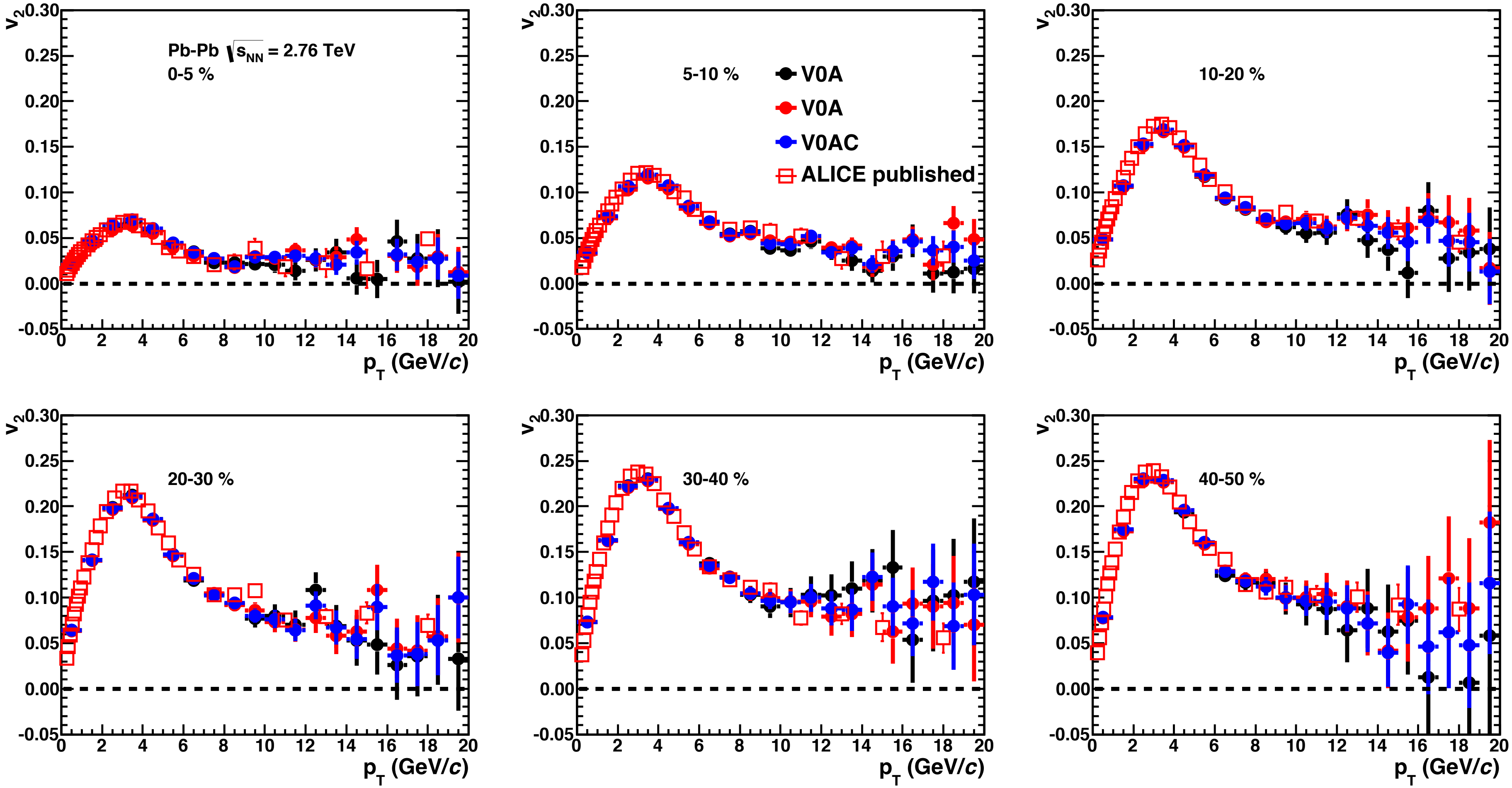
- Applied the V0 gain correction and re-centering correction

Event plane resolution

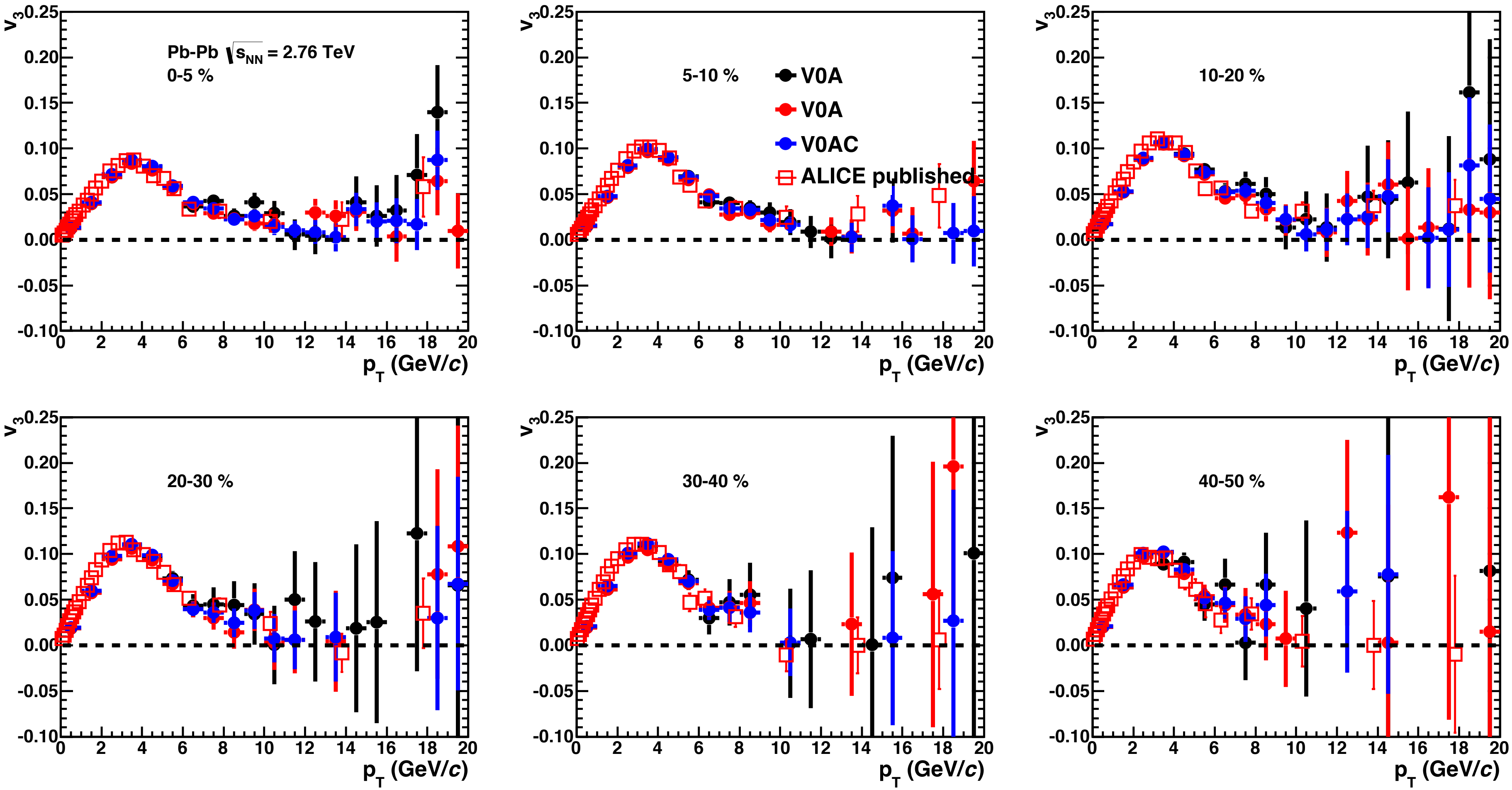


$$\langle \cos(n(\Psi_n^a - \Psi_n)) \rangle = \sqrt{\frac{\langle \cos(n(\Psi_n^a - \Psi_n^b)) \rangle \langle \cos(n(\Psi_n^a - \Psi_n^c)) \rangle}{\langle \cos(n(\Psi_n^b - \Psi_n^c)) \rangle}},$$

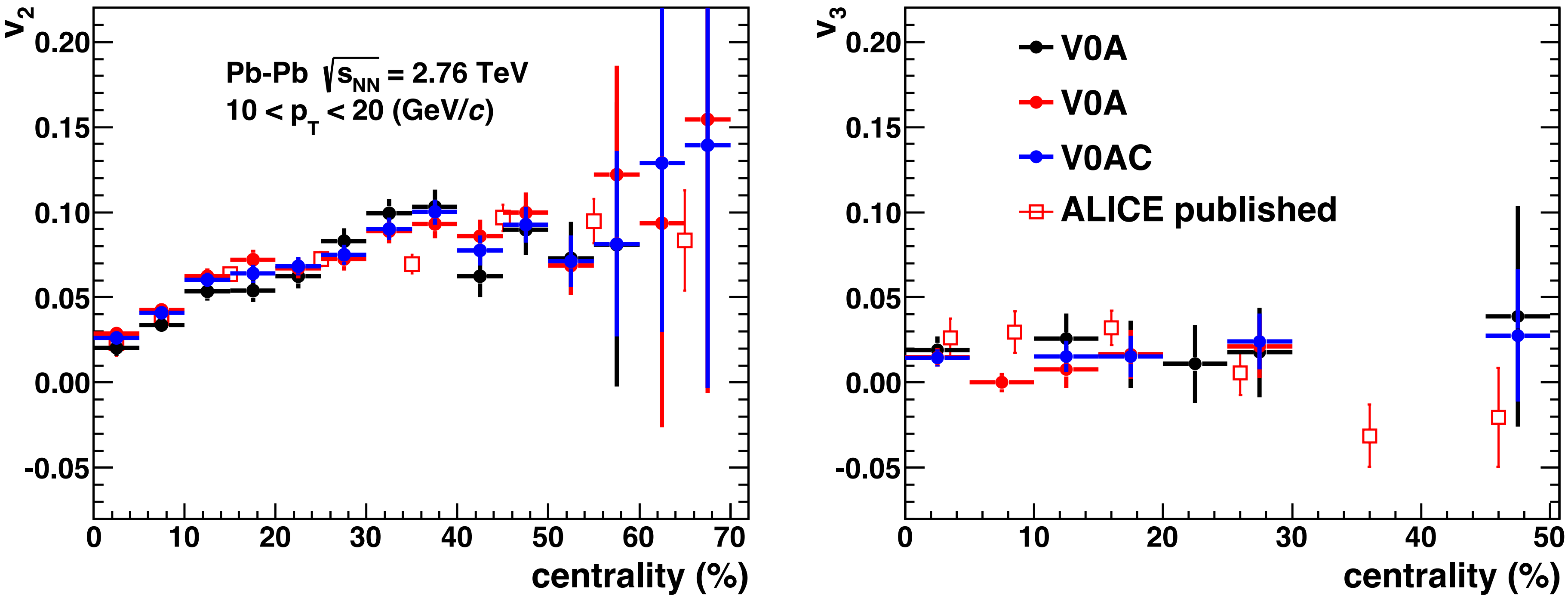
v_2 vs p_T (Charged particle)



v_3 vs p_T (Charged particle)



v_2, v_3 vs centrality



Random cone

- Random cone
  - background fluctuations are characterized by looking at the difference between the summed p_T of all particles in the random cone

$$\delta p_{\mathrm{T}} = \sum_i p_{\mathrm{T,i}} - A \cdot \rho,$$

- The δp_T distribution has two important role
  - peak and width of δp_T distribution include information of quality of BKG estimation
  - width shows the magnitude of the statistical fluctuations of the background energy density

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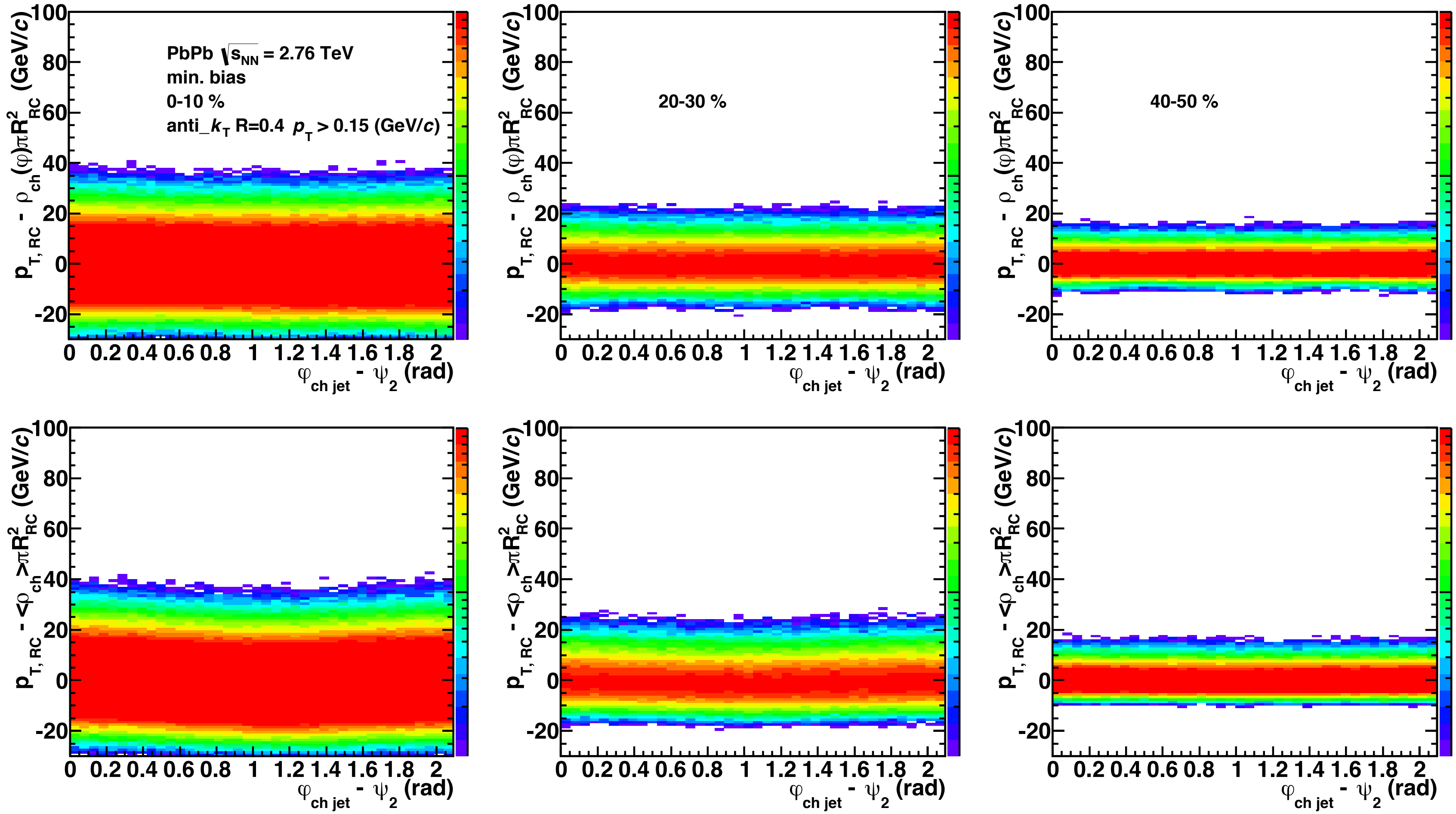
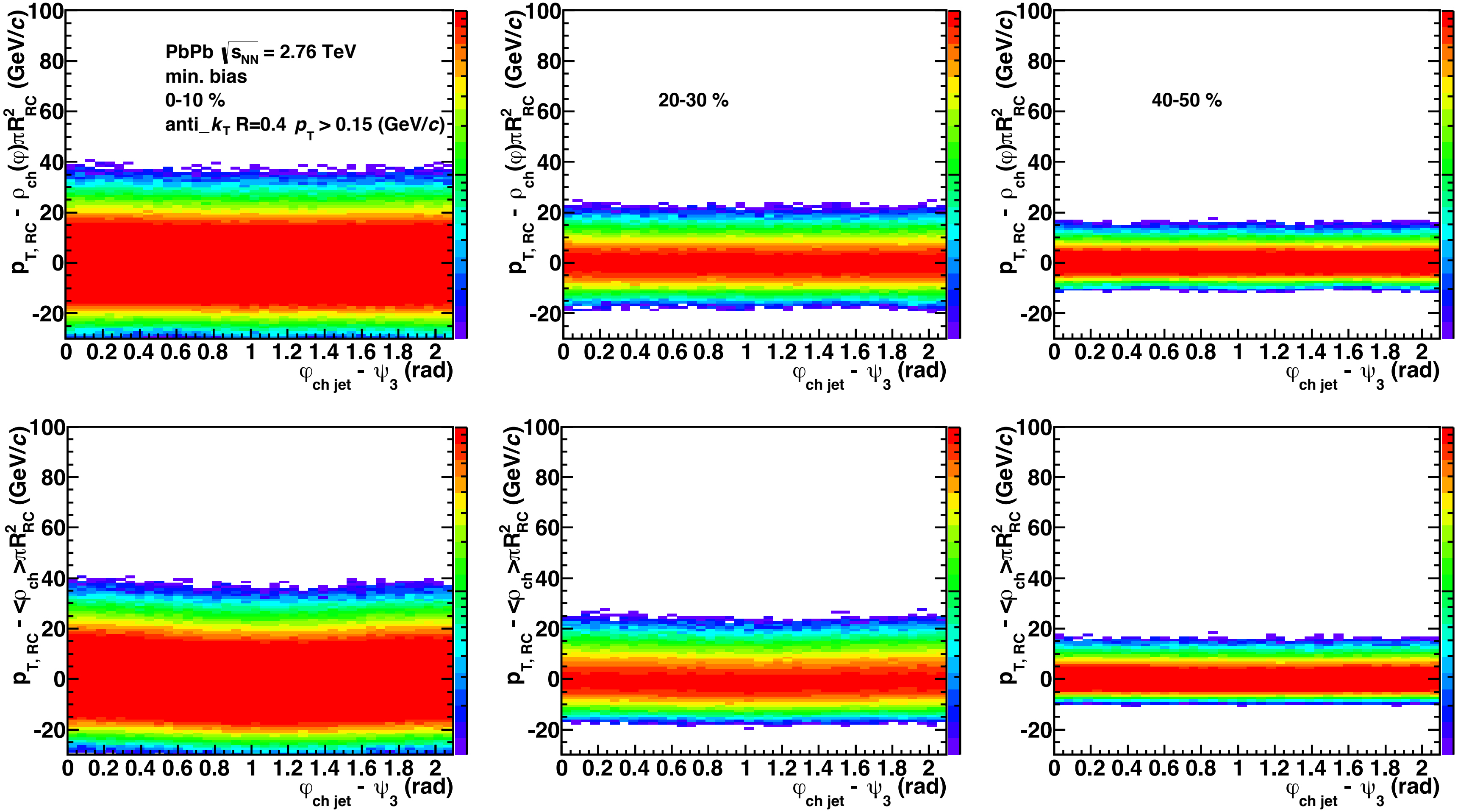
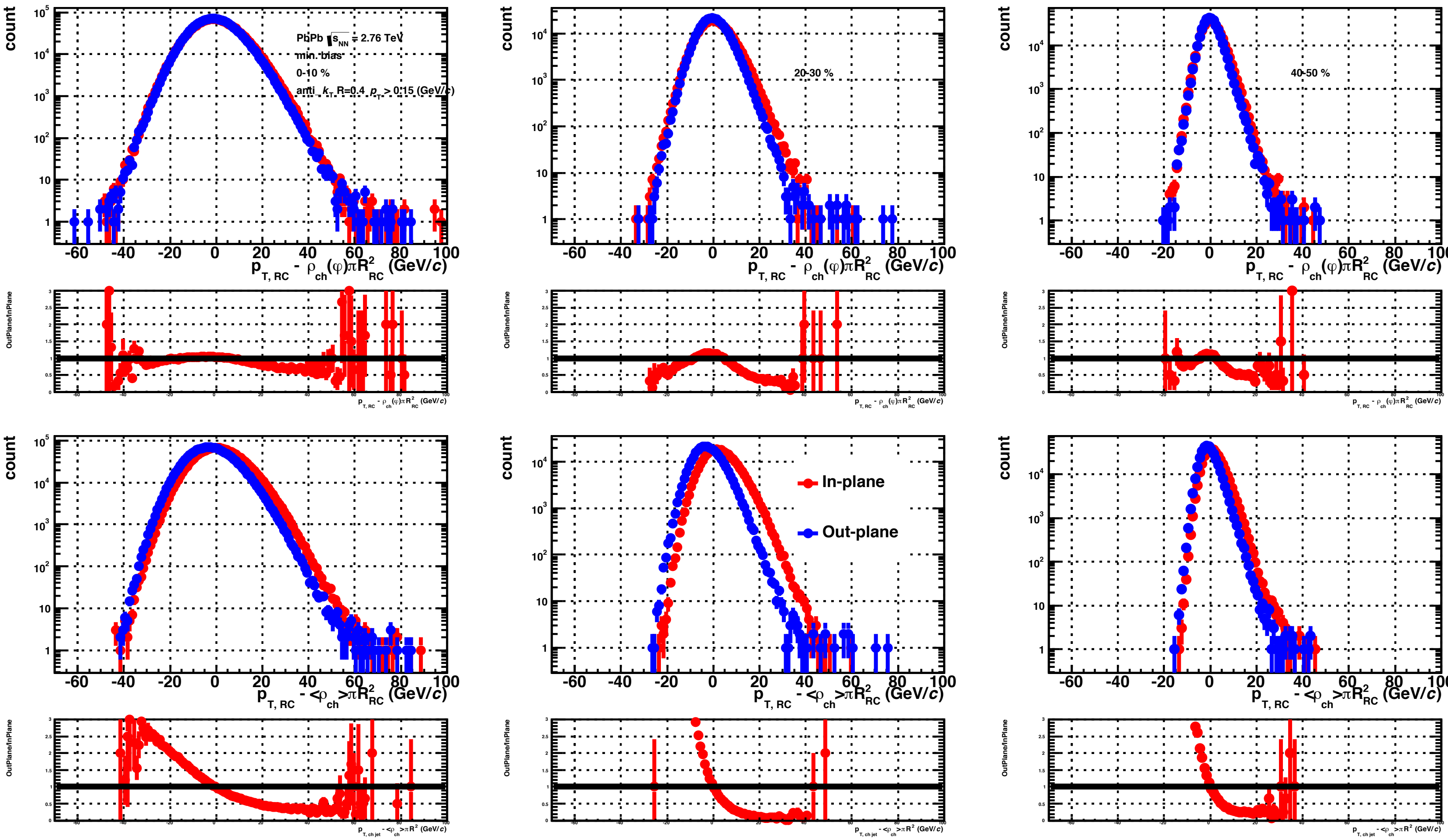
Event plane ψ_2 correlation



Event plane ψ_3 correlation



δp_T spectrum with two different event plane regions



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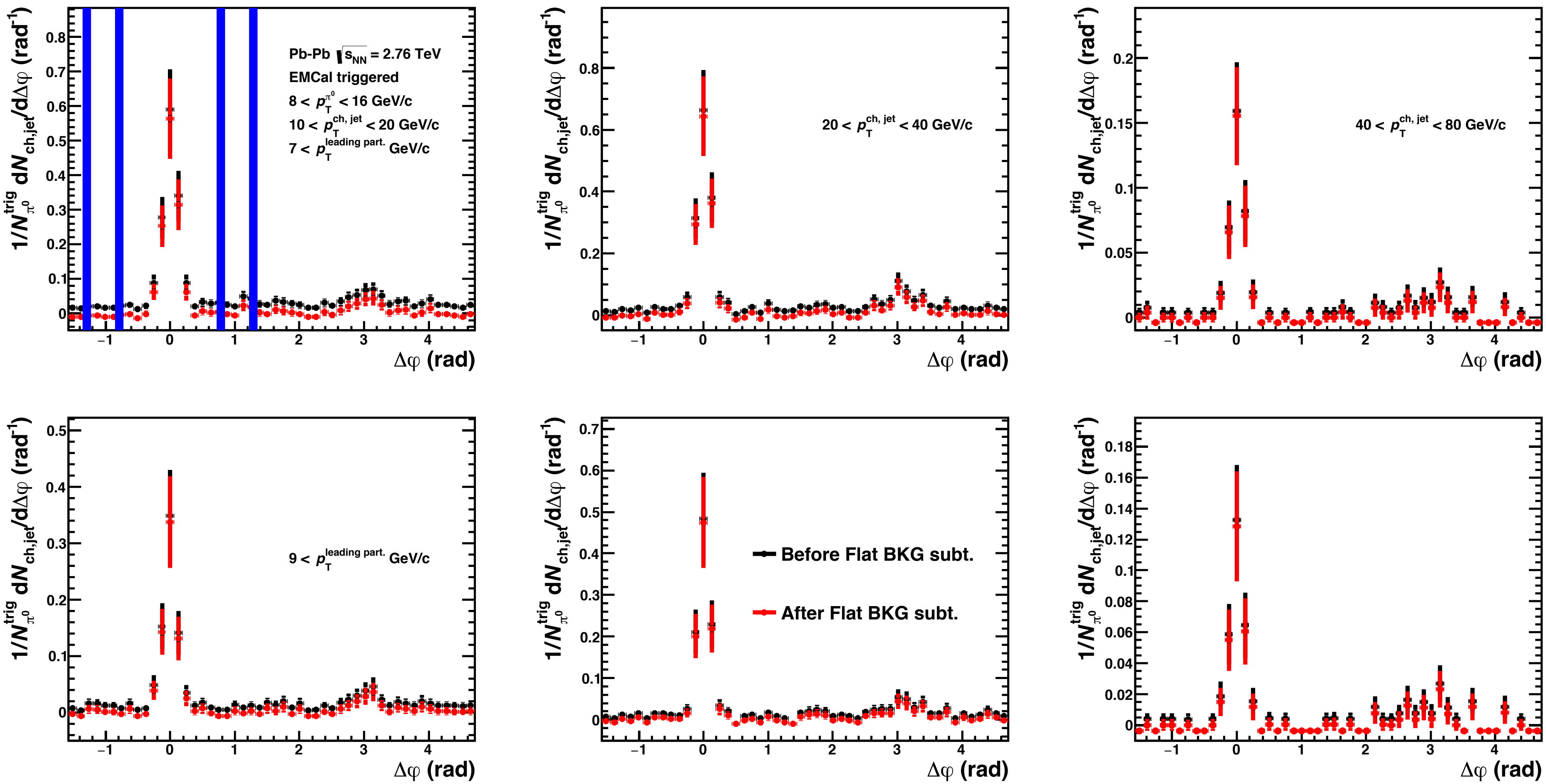
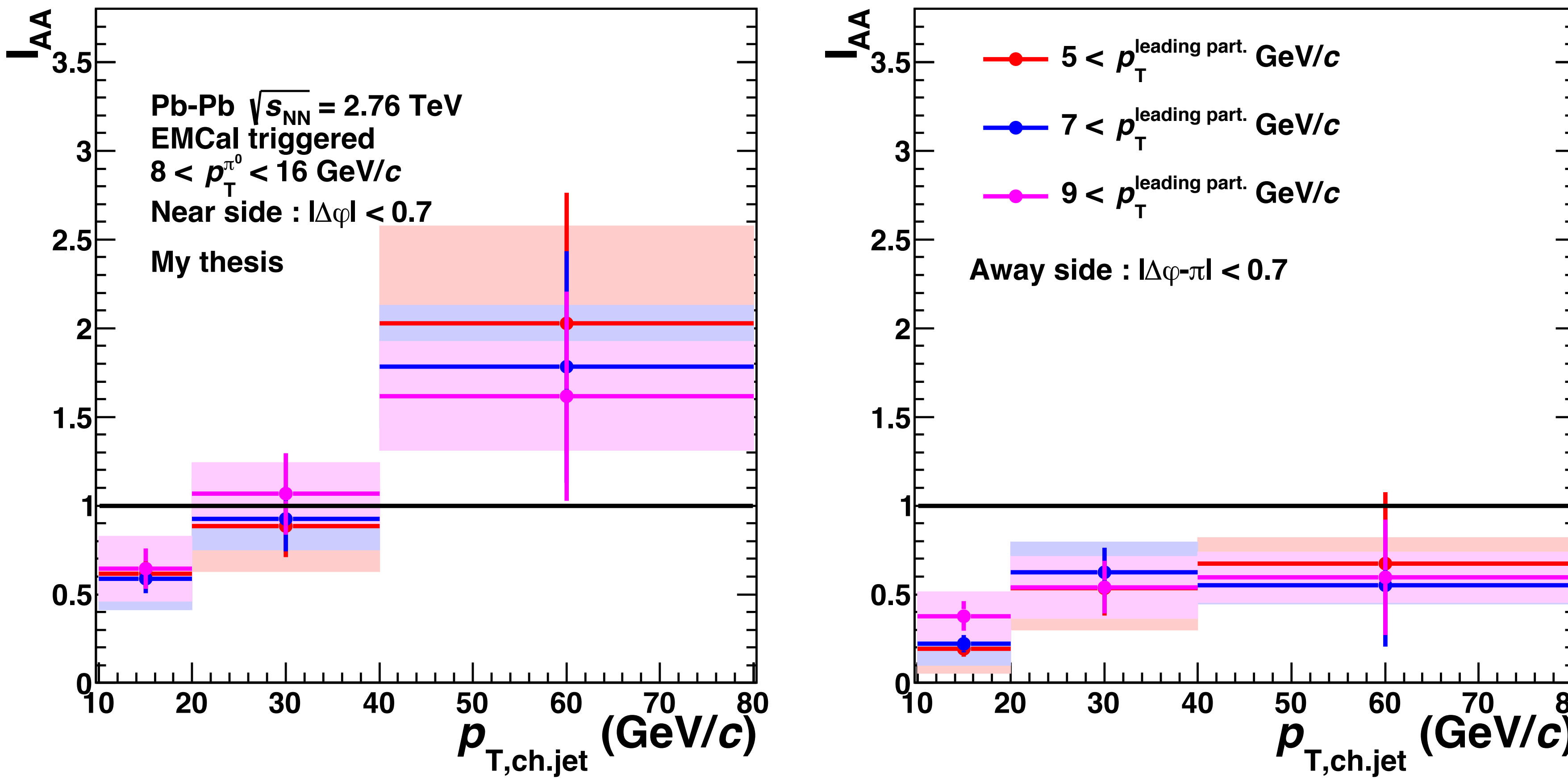
Results

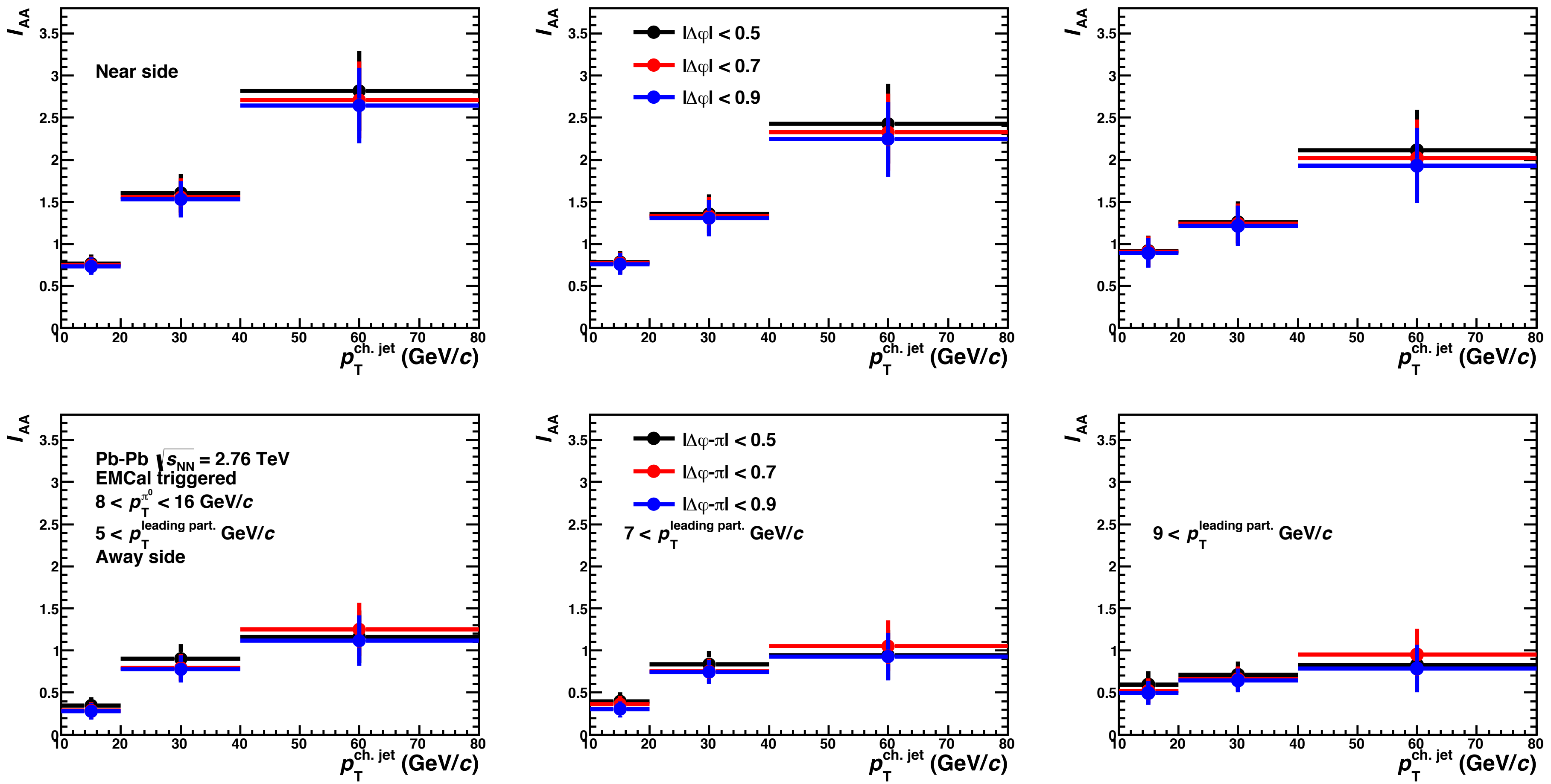
Flat background subtraction in azimuthal correlation



1. Take 4 bins in the valley region on the left and right side from a near side peak region
2. Calculate the average background value from 8 bins in valley regions

Leading particle p_T dependence of I_{AA}





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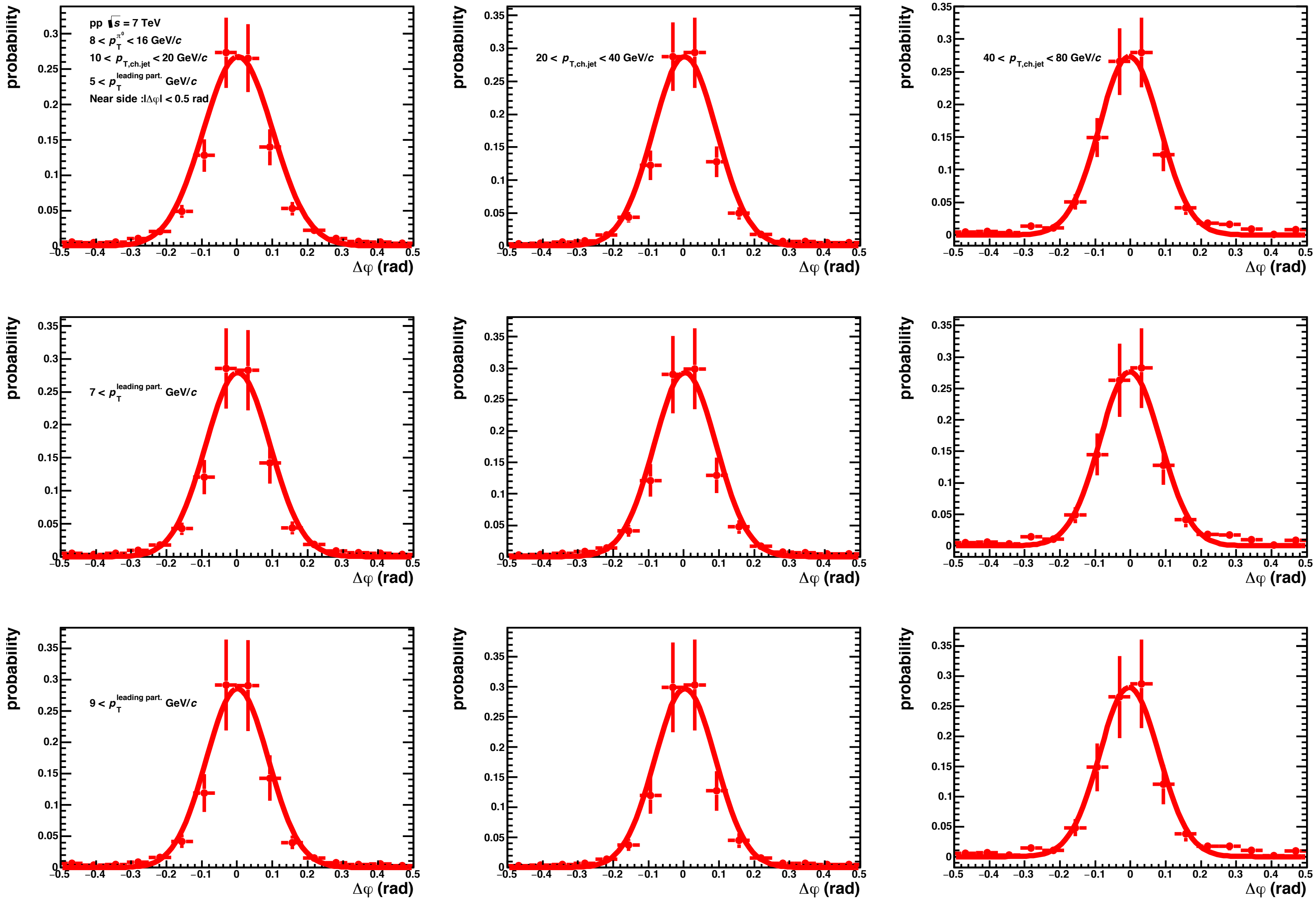
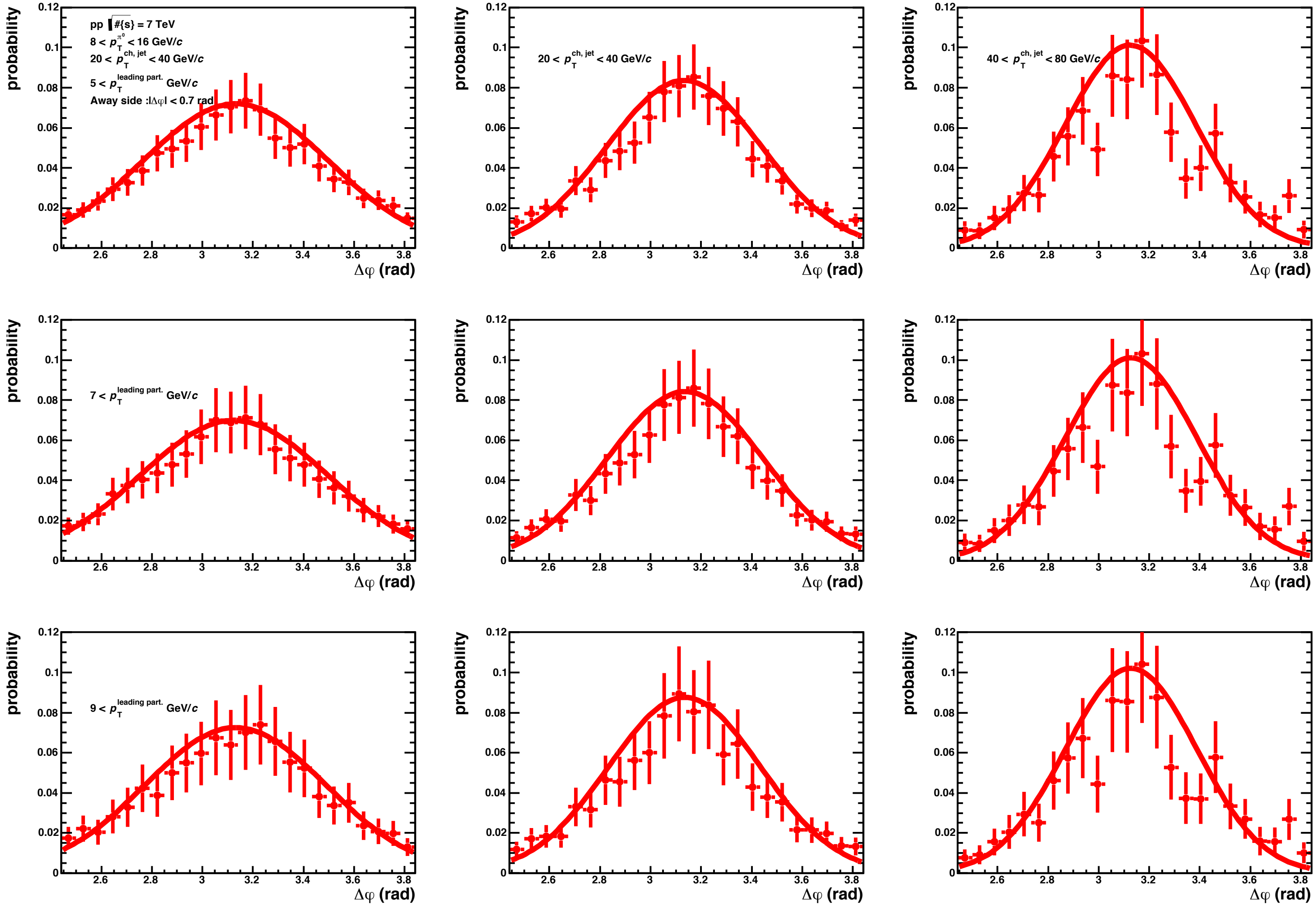
Near side peaks fitted by Gaussian function in pp 7 TeV

ALICE



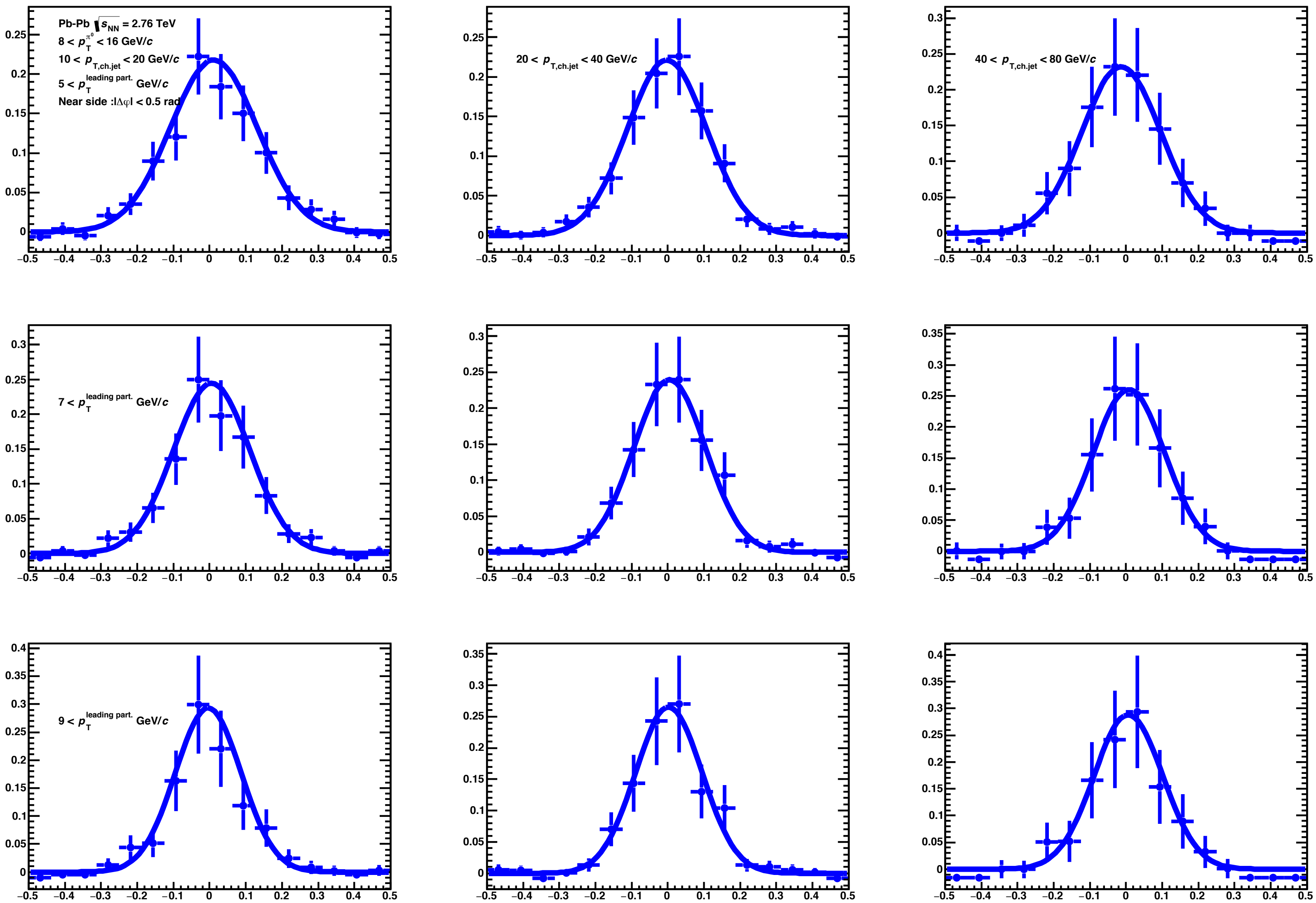
Fit range : $|\Delta\phi| < 0.5$

Away side peaks fitted by Gaussian function in pp 7 TeV



Fit range : |Δϕ-π| < 0.7

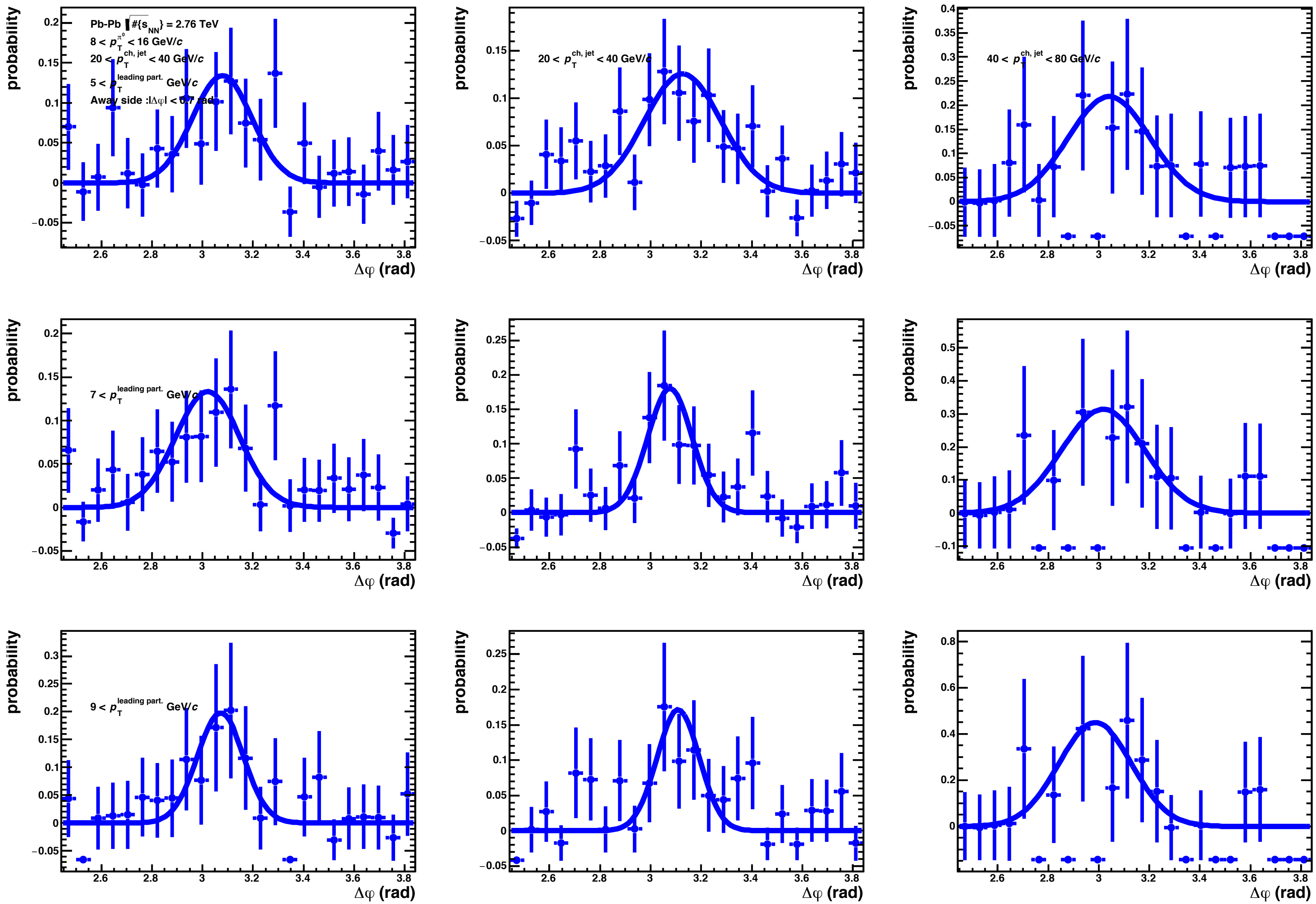
Near side peaks fitted by Gaussian function in Pb-Pb 2.76 TeV



Fit range : $|\Delta\phi| < 0.5$

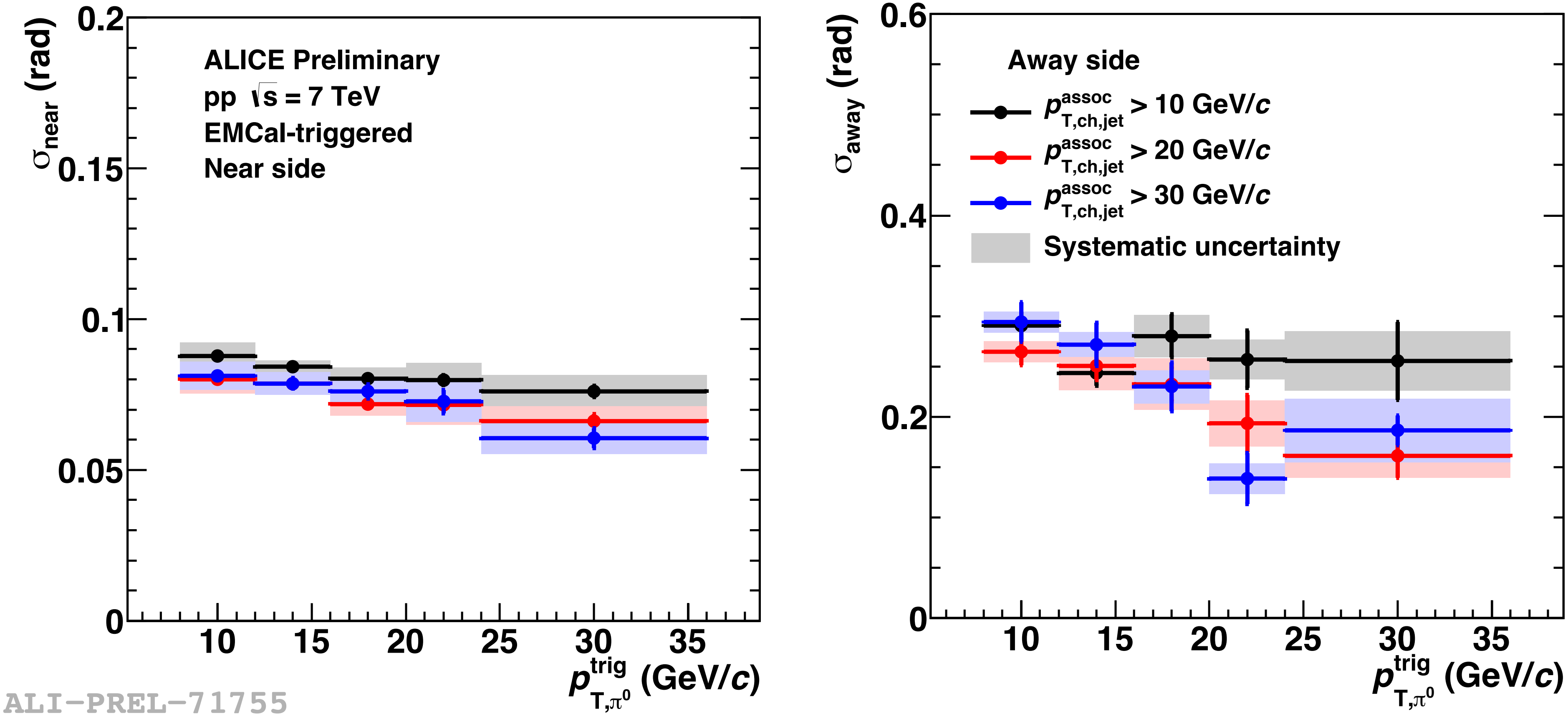
Away side peaks fitted by Gaussian function in Pb-Pb 2.76 TeV

ALICE



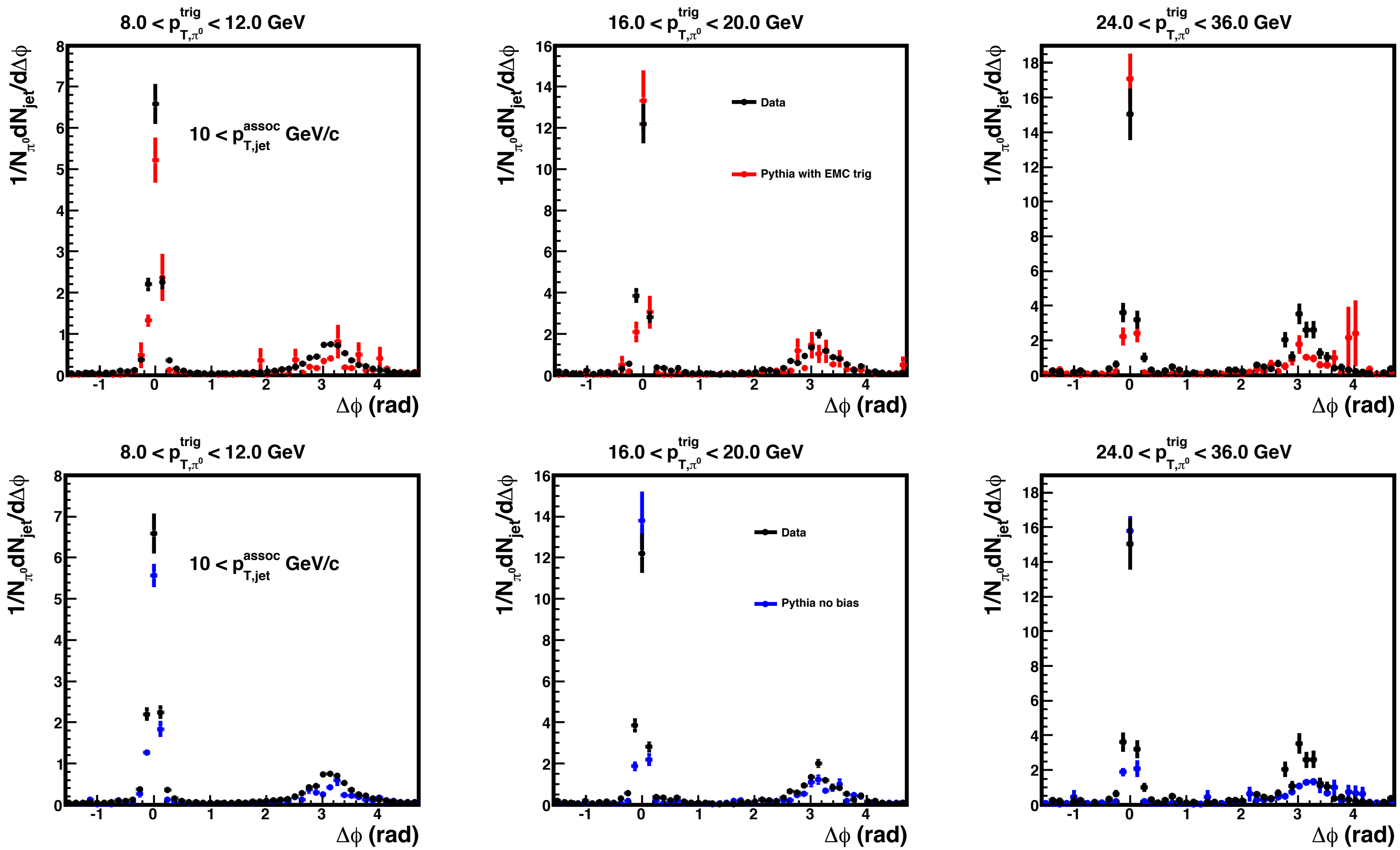
Fit range : |Δϕ-π| < 0.7

Near and away-side widths as a function of π^0 p_T



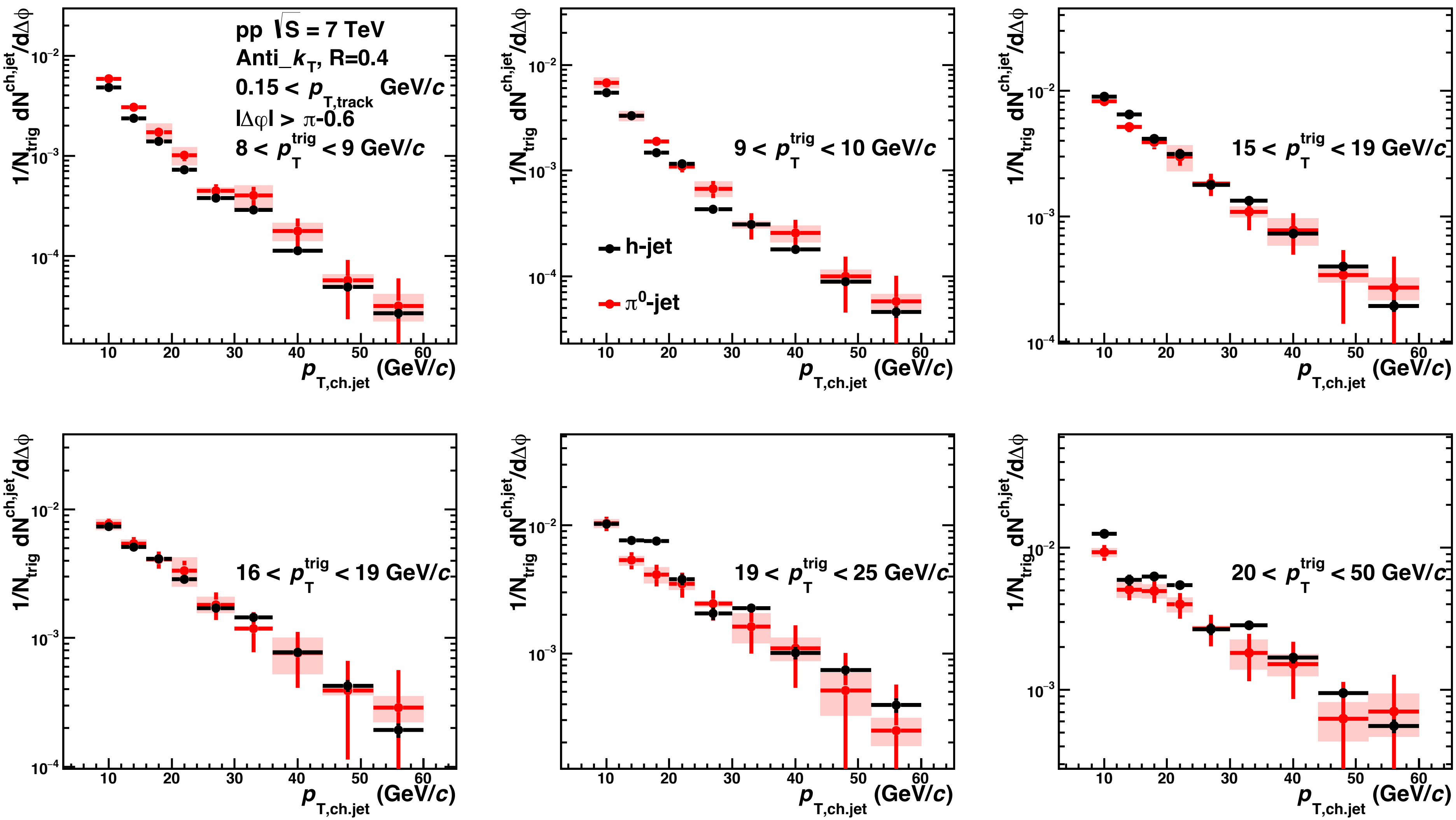
- Near and away-side widths decrease slightly with increasing trigger π^0 p_T
- Neutral particles (π^0 in this analysis) are produced close to a initial parton of hard scatterings

Azimuthal yield comparison to MC (corrected data vs particle level MC)



- PYTHIA calculations consistent with pp 7 TeV data

Comparison of away side jet yields to h-jet analysis



- Consistent with the results of h-jet analysis