Measurements of azimuthal correlation between jets and charged particles at LHC-ALICE experiment

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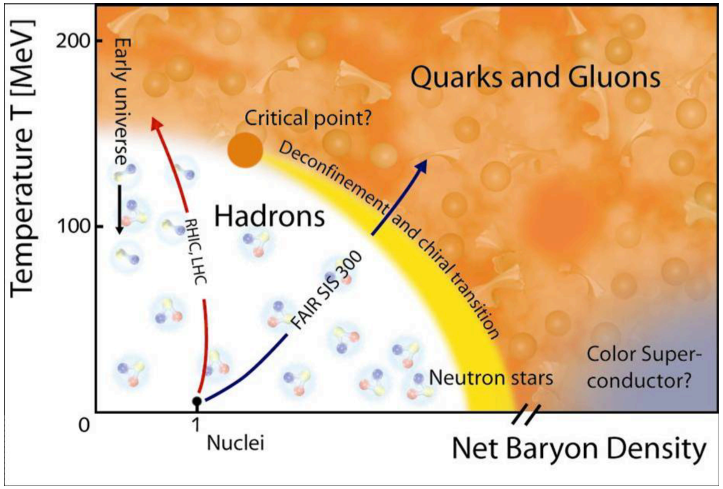
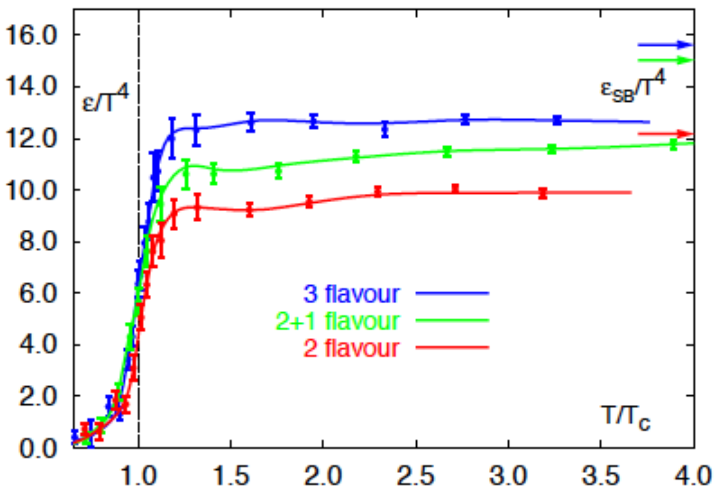
Outline

- Introduction
- Analysis Approach
- Jet Particle Correlation in pp
- Jet Particle Correlation in Pb-Pb
- summary & outlook

Introduction

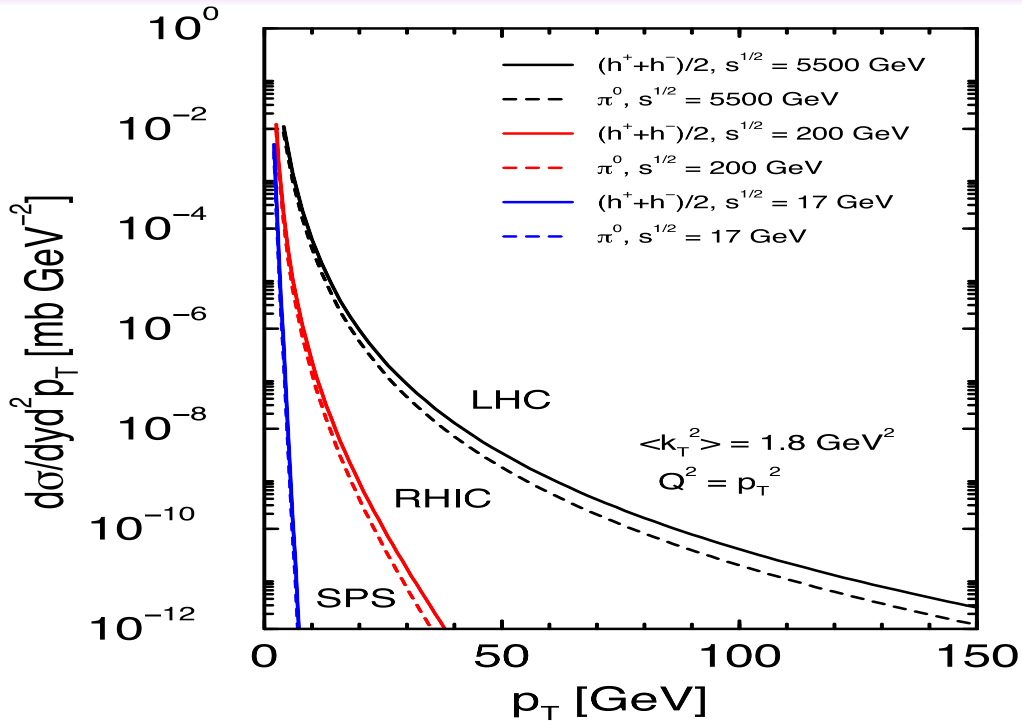
Quark Gluon Plasma (QGP)

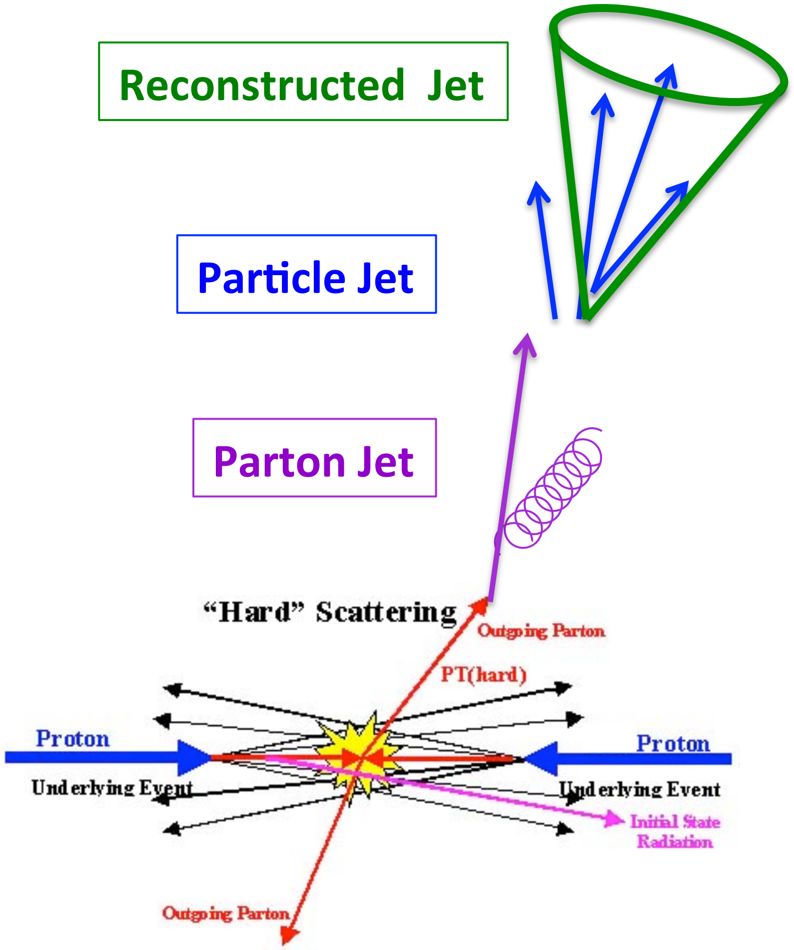




- Quark Gluon Plasma (QGP)
  - T_C ~175MeV
  - ε_C ~1GeV/fm^3
- Signatures of QGP at RHIC
  - Suppression high p_T particle production
  - Large anisotropic expansion
  - Modification heavy meson properties

Jet





- Experiments at LHC are suitable for Jet measurements.

Jet Modification

- Parton jet modification
  - Collision with quarks in QGP
  - Gluon Radiation

$$\Delta E(\theta_{\text{cone}}) = L \int_0^{\infty} d\omega \int_{\theta_{\text{cone}}}^{\pi} \frac{\omega dI}{d\omega dz d\theta} d\theta.$$

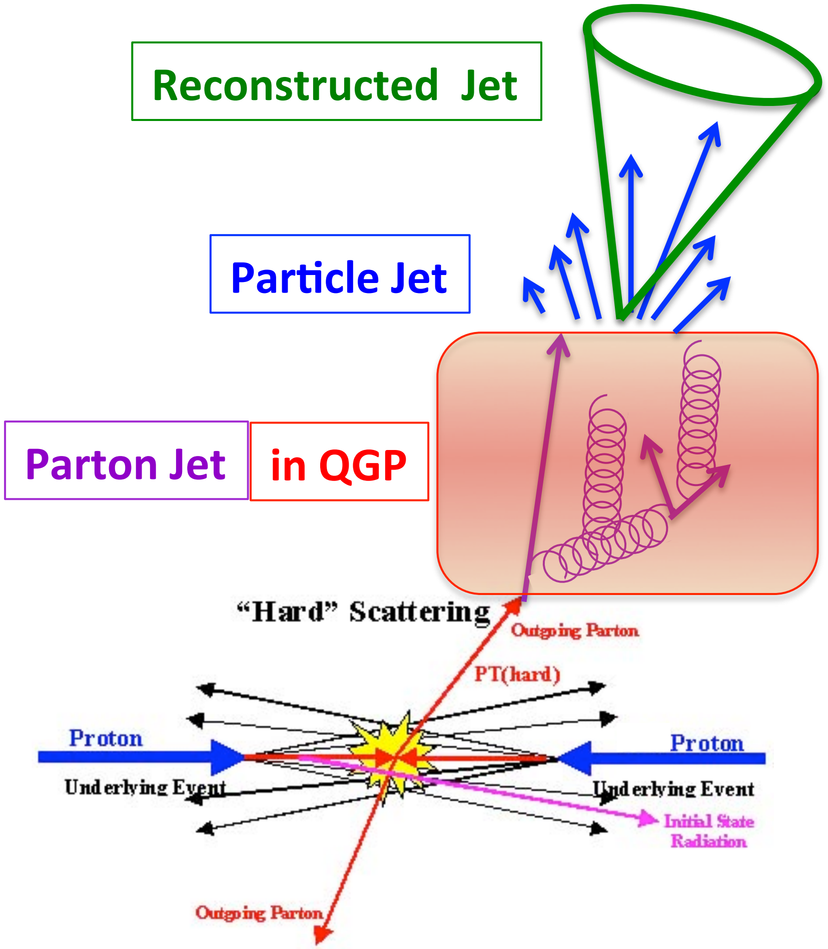
at $\vartheta_{cone}=0$ $\Delta E = \frac{\alpha_s N_c}{4} \hat{q} L^2, \ \hat{q} = \mu_D^2 / \lambda_g$

$\lambda_g = 1/\sigma\rho$, $\rho \sim dN_g/dy$ at GLV

gluon density

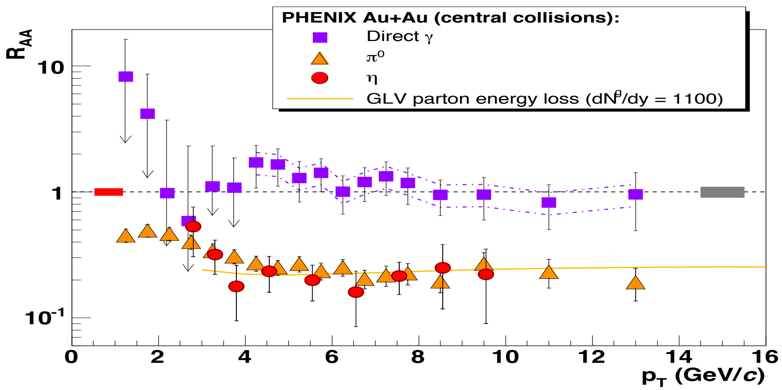
$\rho \sim \rho_0 \tau_0 \propto T_0^3$ at BDMS

initial temperature

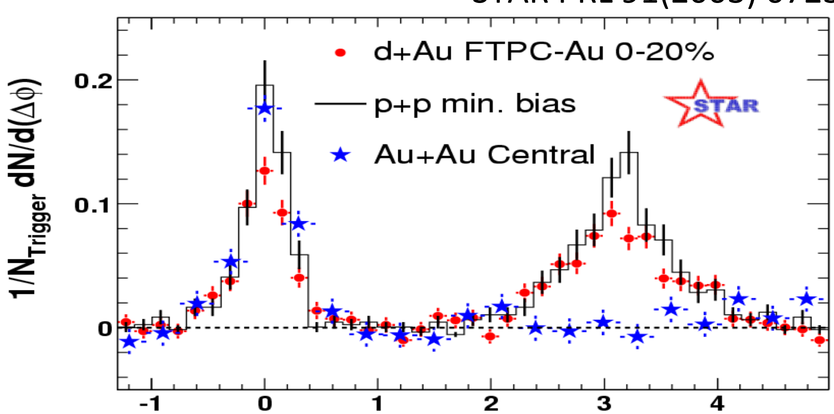


Indirect Measurements at RHIC

Phys. Rev. Lett. 96, 202301 (2006)



STAR PRL 91(2003) 072304

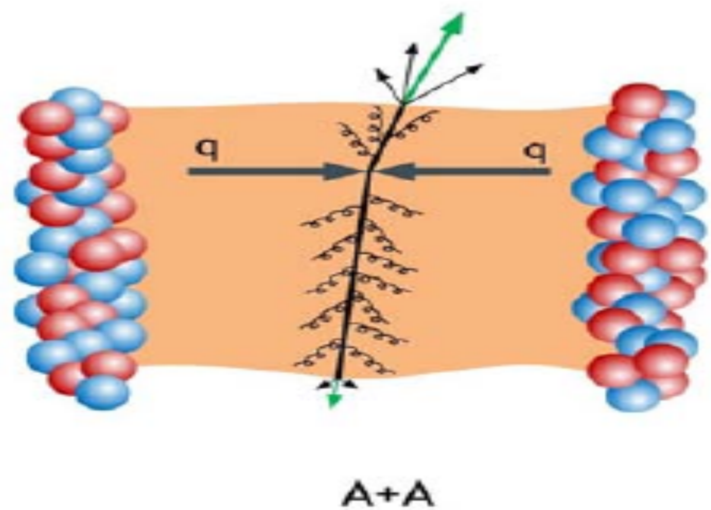


$4<p_T^{trig}<6GeV/c, 2<p_T^{asso}<p_T^{trig}$

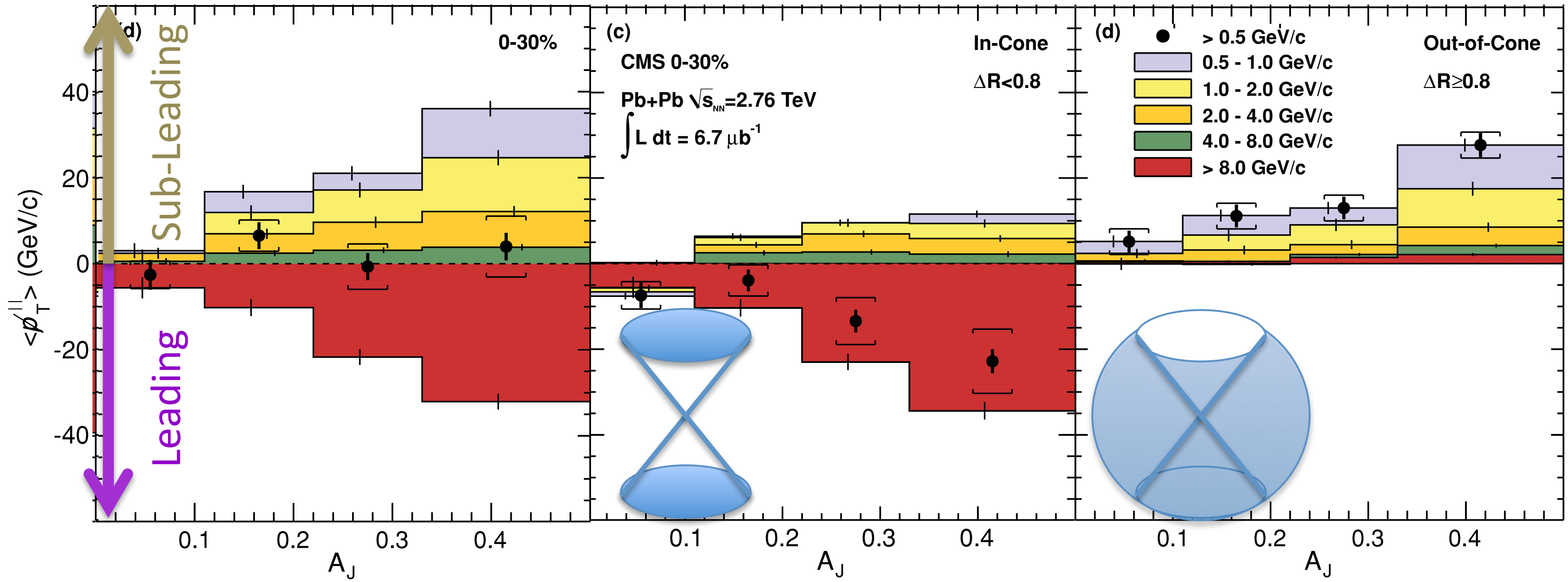
Jet was not reconstructed

Nuclear modification factor

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



Direct Measurement at LHC



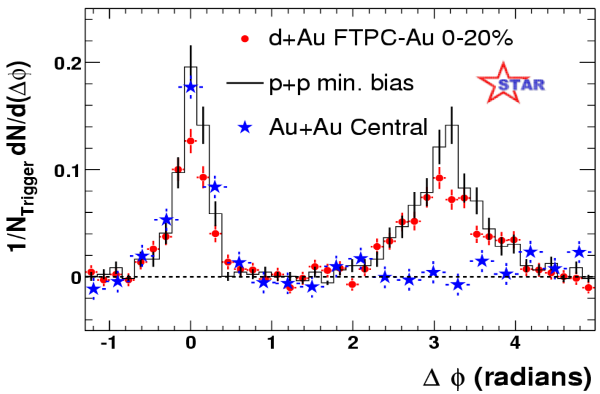
- **Particle production is modified**

$A_j = (E^{lead} - E^{sublead})/(E^{lead}+E^{sublead})$

  - However….
    - azimuthal information is minimized
    - we could not see the modification in jet bases

Motivation & Cogitations

Two Particle Correlation

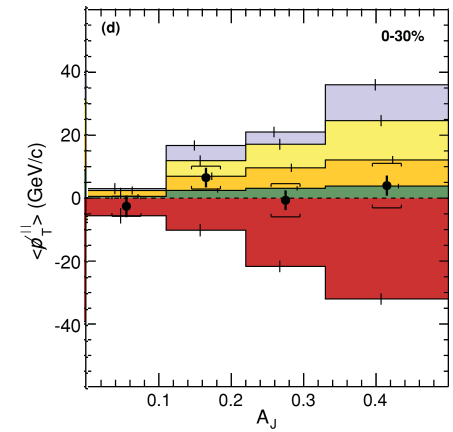


$\Delta E(\theta_{\mathrm{cone}})$

Energy Loss

Spread Angle

Momentum Asymmetry in Di-Jet



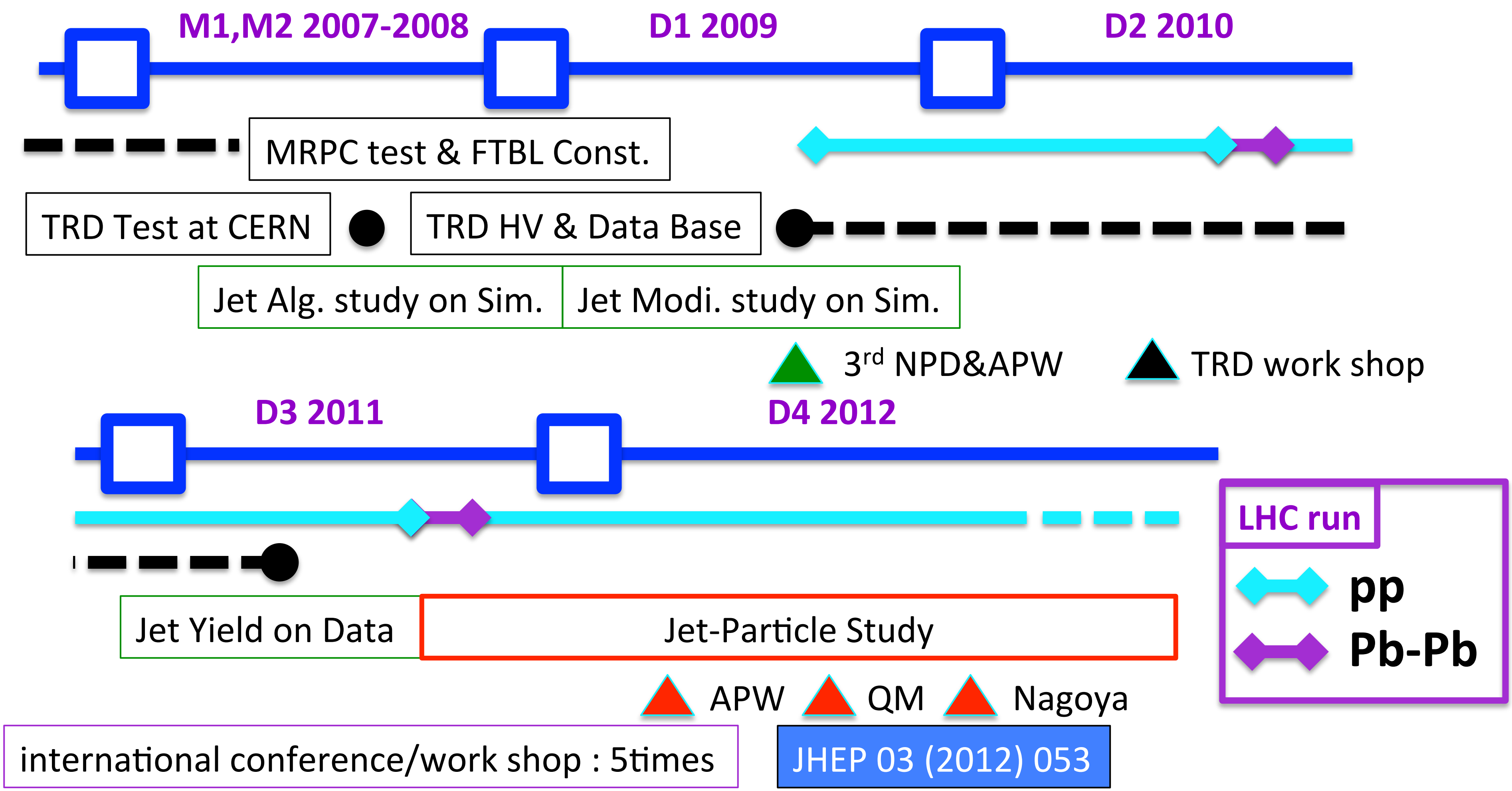
- **RHIC**
  - difficult to reconstruct jets due to collision energy
- **LHC**
  - minimized azimuthal information in current studies

comprehensive measurements are needed!

Jet and Charged Particle Azimuthal Correlation

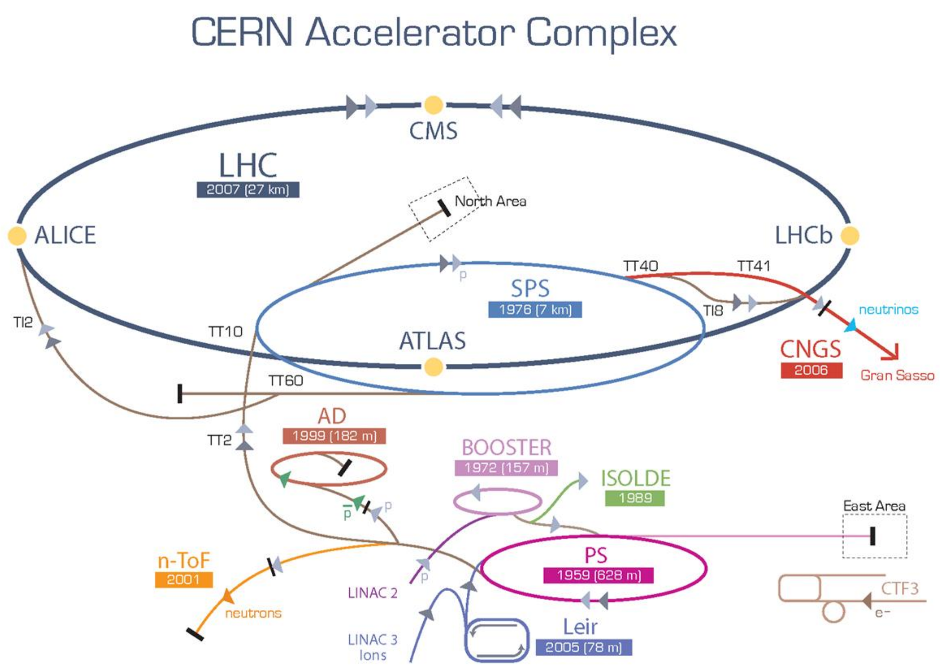
To draw out jet modification effect directly!!!

My Contribution

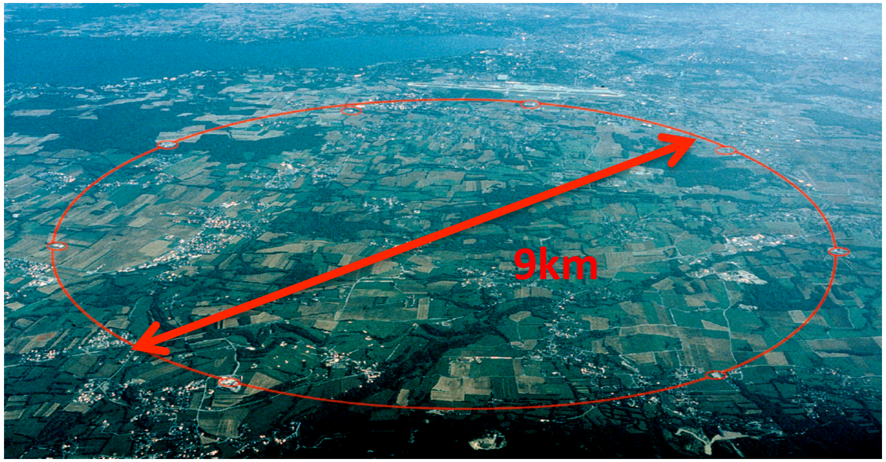


Analysis

Large Hadron Collider (LHC)



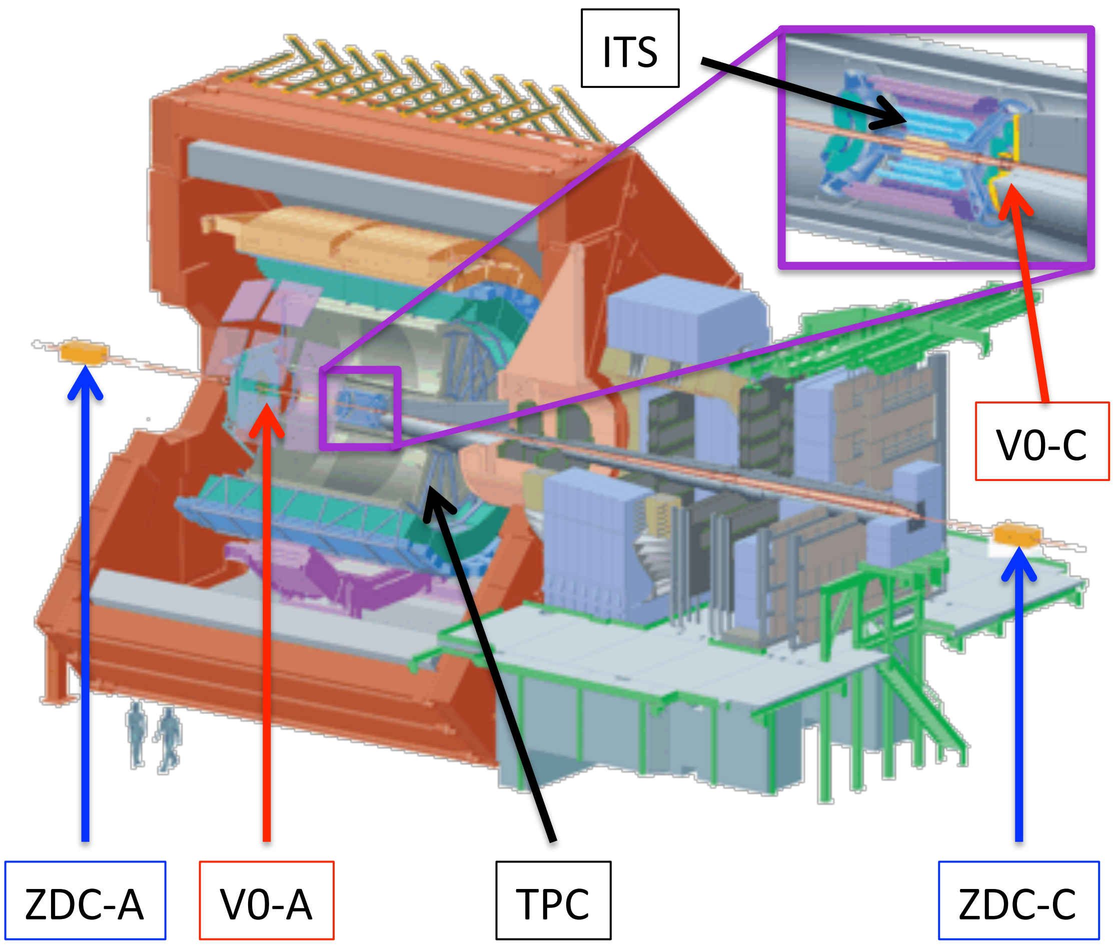
2009 : pp 900GeV
2010 : **pp 7TeV** **Pb-Pb 2.76TeV**
2011 : **pp 2.76TeV**,7TeV Pb-Pb 2.76TeV
2012 : pp 7TeV,8TeV p-Pb 2.76TeV



Properties

- Ring Property
  - R=9km, L=27km
- Top Energy
  - pp : 14TeV
  - Pb-Pb : 5.5TeV/nucleon

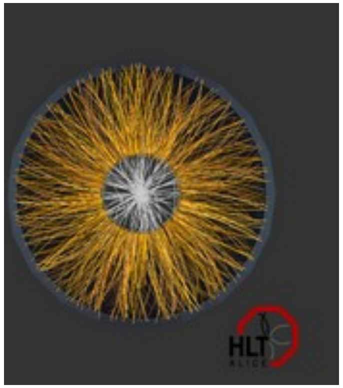
A Large Ion Collider Experiment (ALICE)



- ZDC (η=±8)
  - Trigger(offline)
- VZERO
  - Trigger
  - Centrality
  - Event Plane
- ITS+TPC (-0.9<η<0.9)
  - Trigger (ITS inner only)
  - Global Tracking

MB: SPD||(V0A||V0C)~93% efficiency
$|V_Z|<10$cm (offline)
ZDC timing (offline for Pb-Pb)

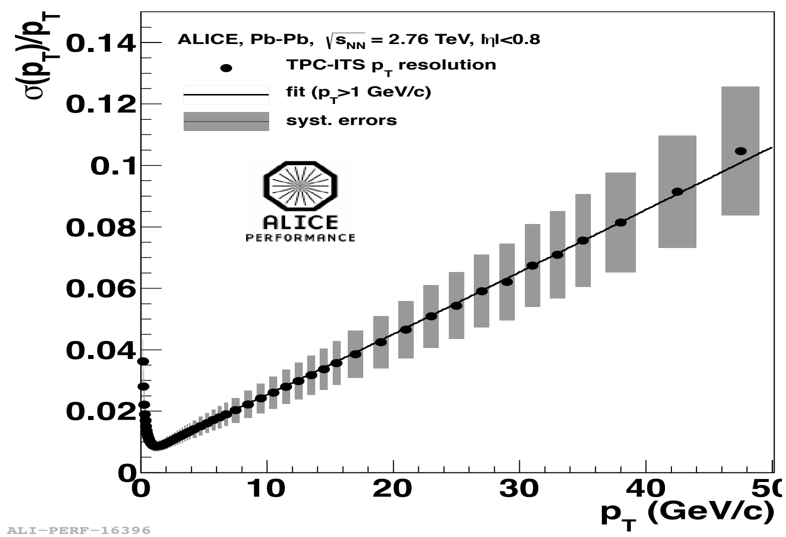
Charged Track Reconstruction

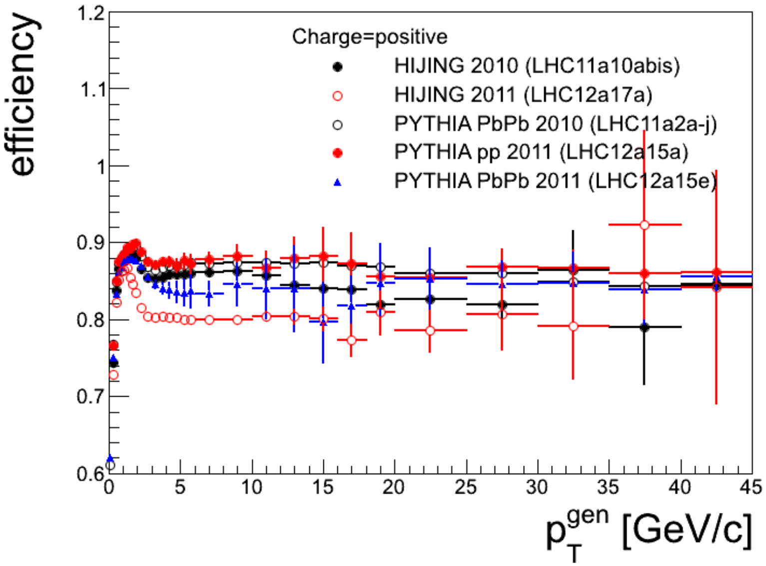


- Global Tracking (ITS+TPC)
  - with SPD & ITS refit
  - without SPD & ITS refit
  - without SPD

  (due to SPD problem)

@ p_T ~ 40GeV/c
$\sigma p_T/p_T$ < 10%
Efficiency ~ 80% PbPb
~ 85% pp

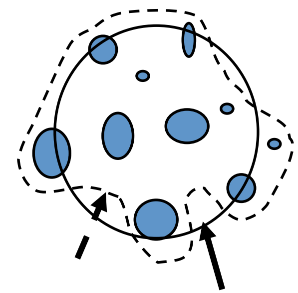




Jet Reconstruction (FASTJET)

FastJet: sequential clustering algorithms http://www.lpthe.jussieu.fr/~salam/fastjet/

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

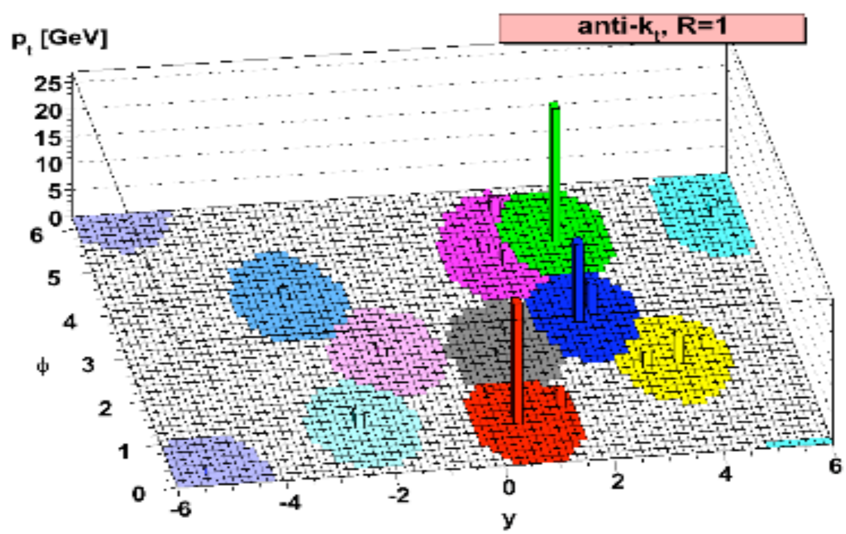


Procedure of Jet Finding
Calculate particle distance : d_{ij}
Calculate Beam distance : $d_{iB}=k_{ti}^{2p}$
Find smallest distance (d_{ij} or d_{iB})
If d_{ij} is smallest combine particles
If d_{iB} is smallest
and the cluster momentum
larger than threshold
call the cluster a Jet.

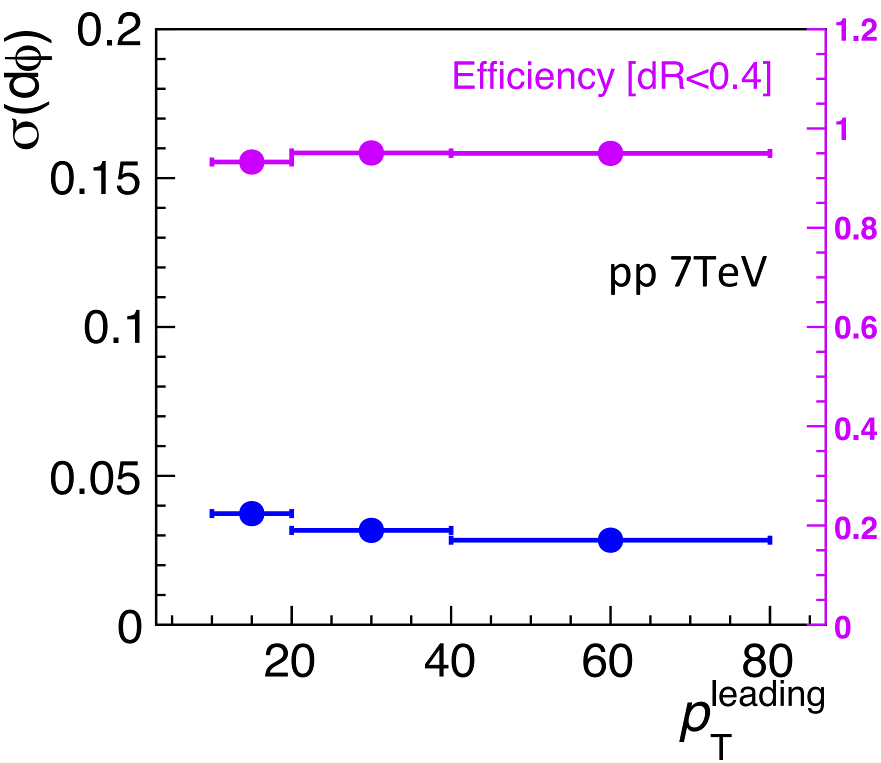
Parameters

- R size $(= \sqrt{d\phi^2 + d\eta^2})$: 0.4
- p_T cut of single particle : 0.15 GeV/c
- Jet enregy threshold : 10 GeV/c

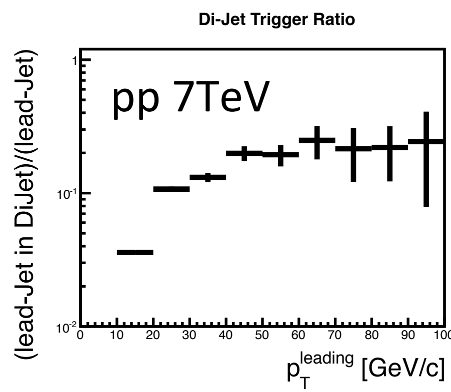
arXiv:0802.1189v2 [hep-pn] (2008)

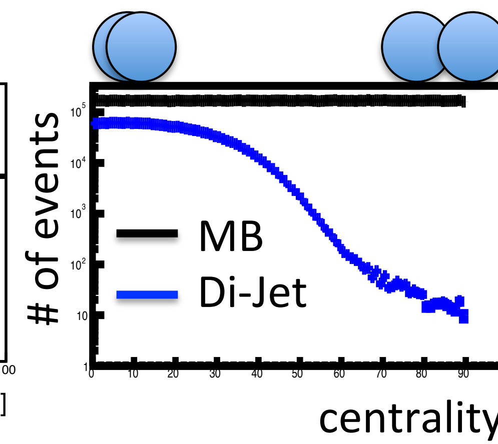


Di-Jet Event Selection



- Di-Jet Event Selection
  - p_T^{lead} >10GeV/c
  - $p_T^{lead} > p_T^{sub\text{-}lead}$ >10GeV/c
  - $\cos(\phi^{lead}-\phi^{sub\text{-}lead})<-0.5$

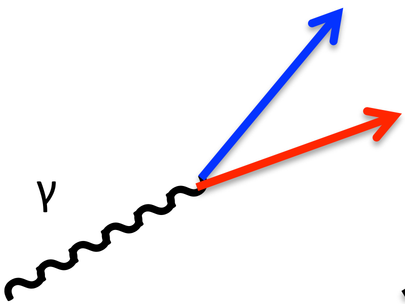


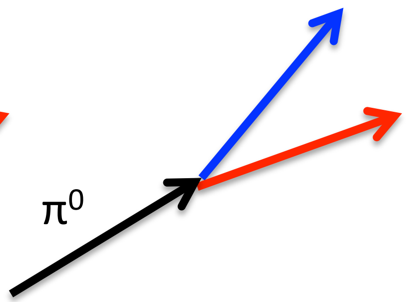


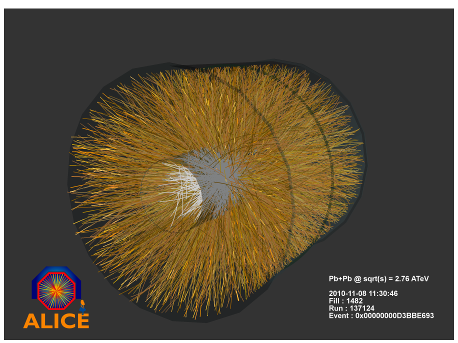
- Within the acceptance,

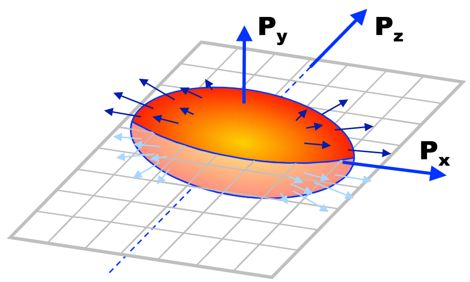
  almost leading jets are reconstructed as leading jets.

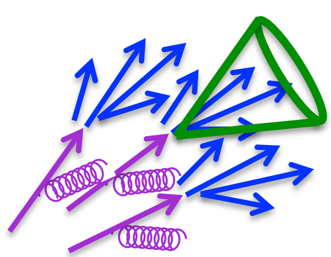
Backgrounds in Charged Jet











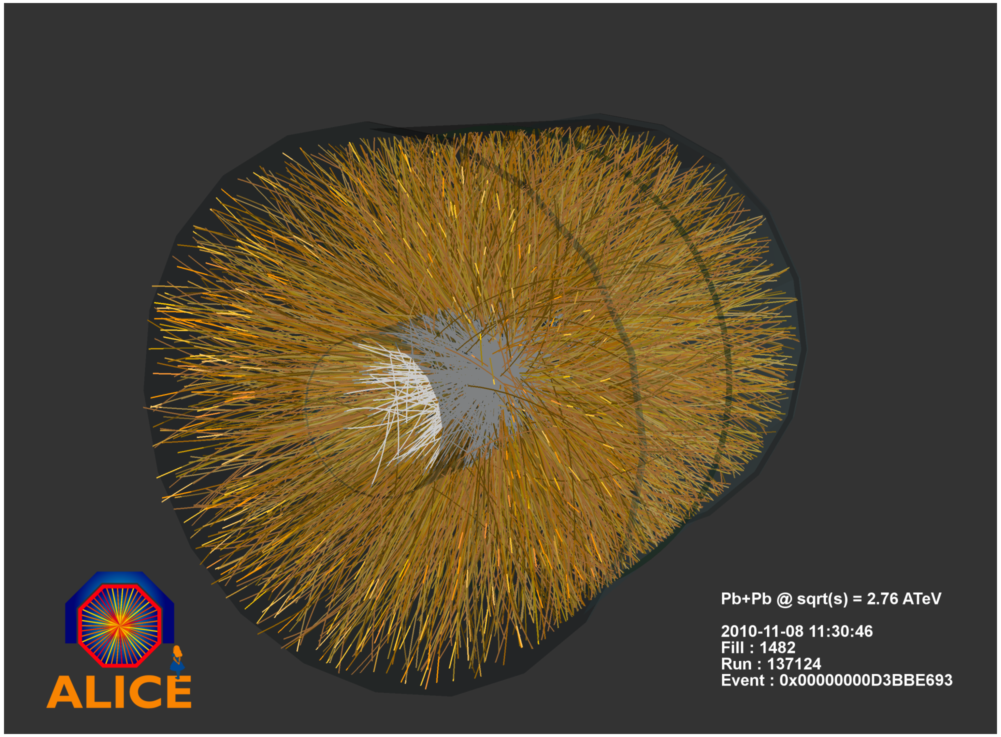
pp collision

Pb-Pb collision

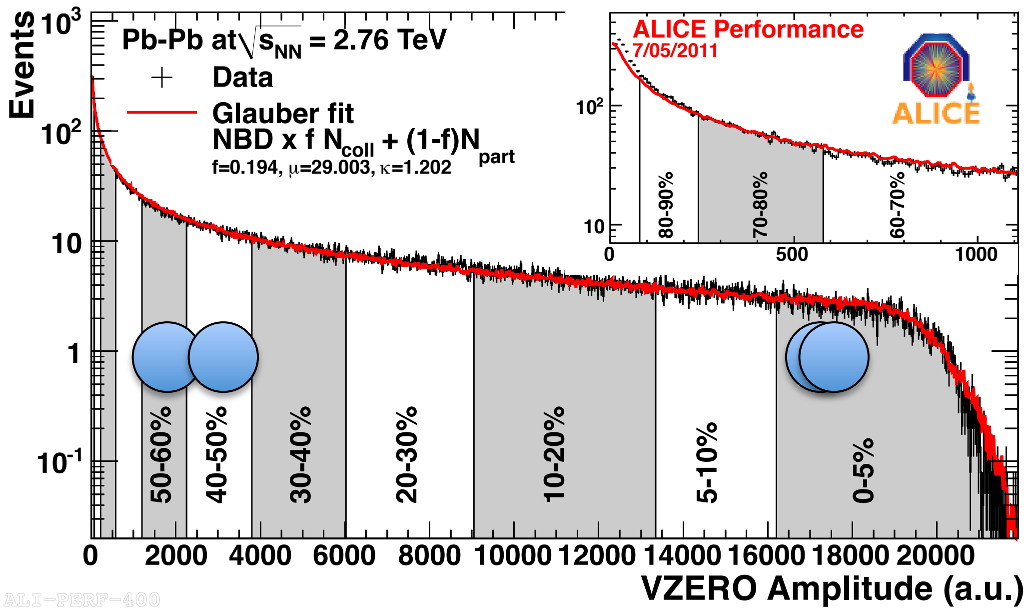
- Contaminations
  - γ conversion
  - Dalitz decay
- Soft particles
  - huge Num. of particles
  - anisotropic flow
- Hard particles
  - fake/combinatorial jet

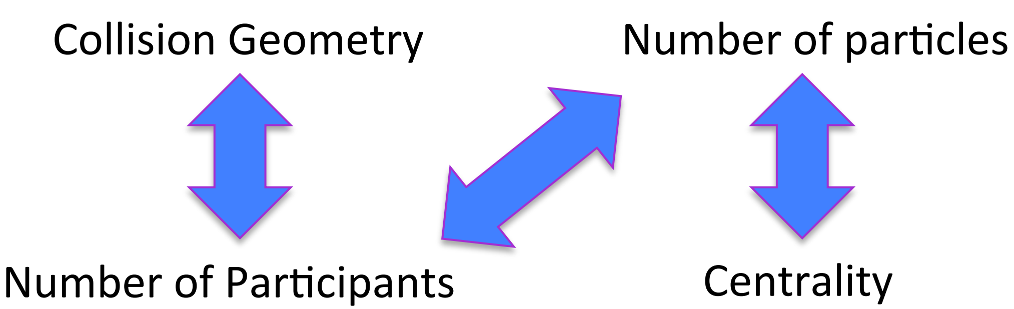
Backgrounds in Pb-Pb

- Soft Particle quark, gluon pair production in color field
  - quark recombination
  - Expansion(radial, elliptic..)
- Hard Particle
  - fake jet
  - combinatorial jet
- Event Characterization
  - centrality
  - event plane



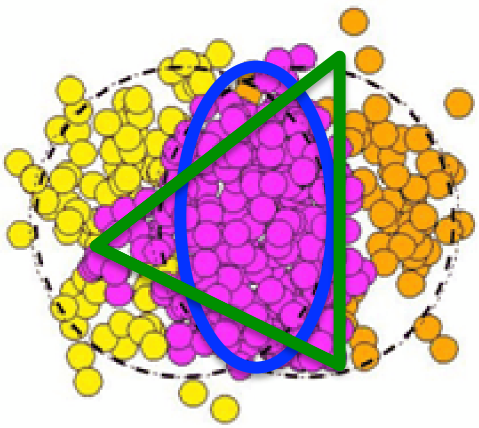
Centrality

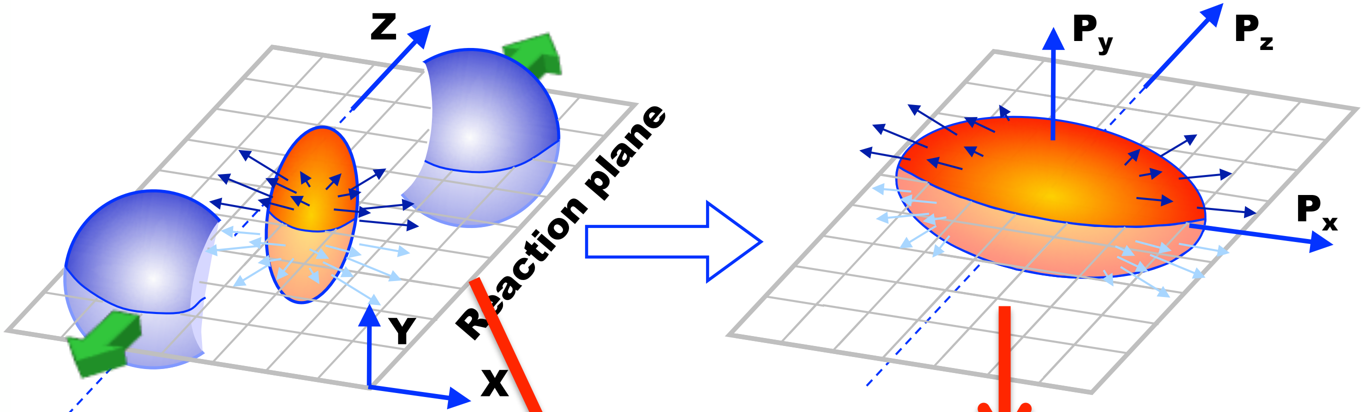


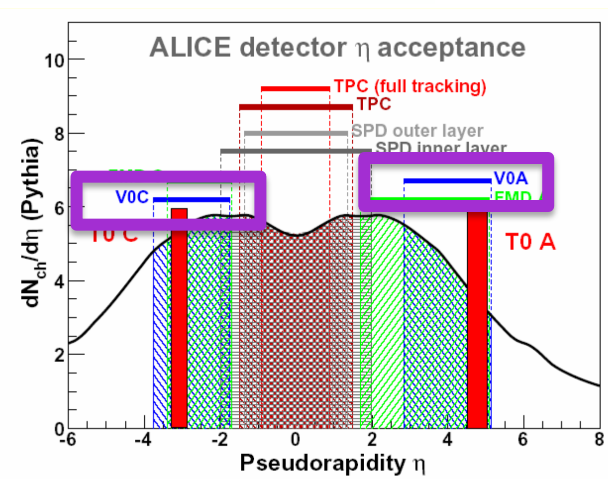


- Glauber Model
  - Thickness function
  - Wood-saxon distribution
- proportionality of particle production
  - number of collisions
- V0 amplitude

Event Plane





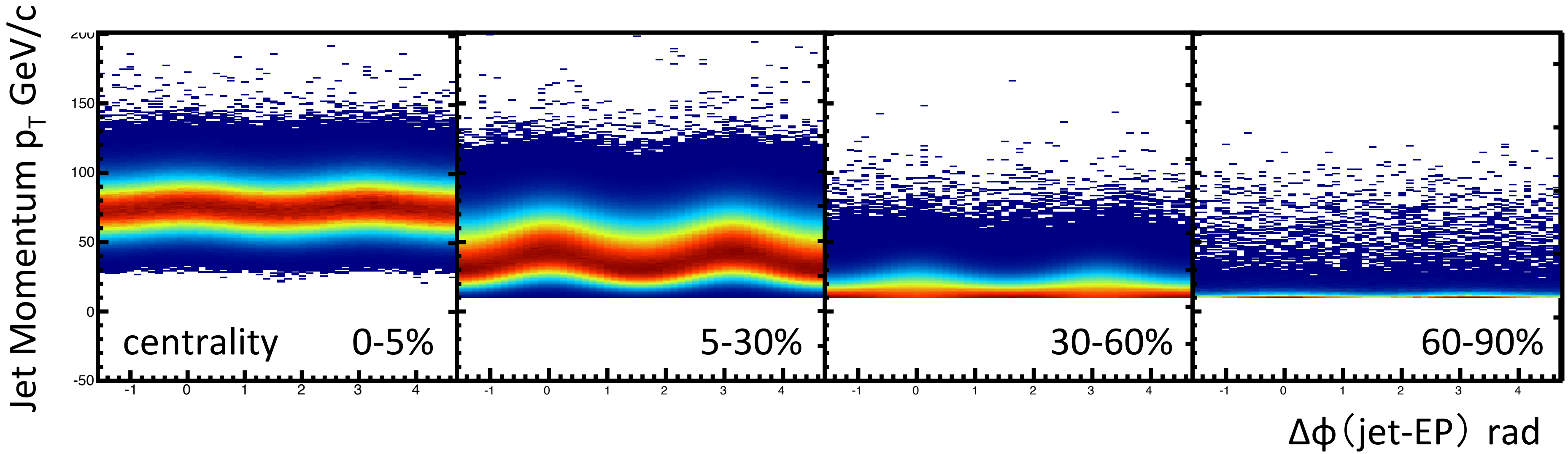


$-3.7 < \eta < -1.7$, $2.8 < \eta < 5.1$

$$\text{EP}: \psi_n = \frac{1}{n}\left(\tan^{-1}\frac{\sum_i w_i \sin n\phi_i}{\sum_i w_i \cos n\phi_i}\right)$$

- Points!!
  - Large η gaps to reduce non-flow effects
  - Re-centering calibration was applied
  - ψ_2, ψ_3 is reconstructed for the analysis

Jet Momentum w.r.t EP



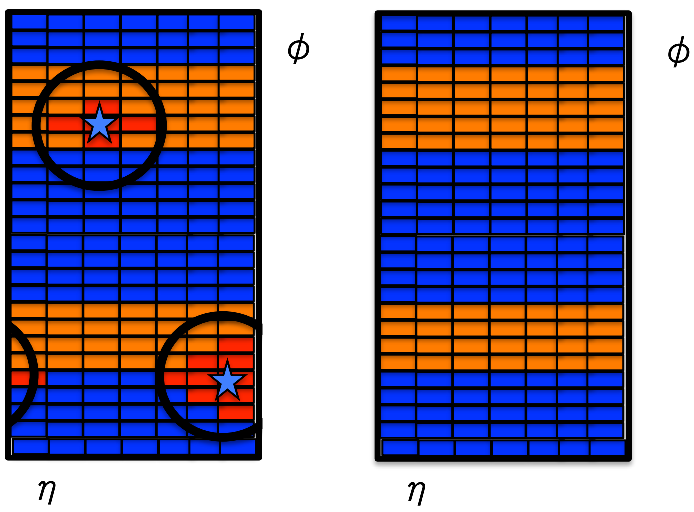
- Reconstructed jet's momentum is strongly biased on centrality and event plane.

→ **We have to correct jet momentum**

Back Ground Subtraction

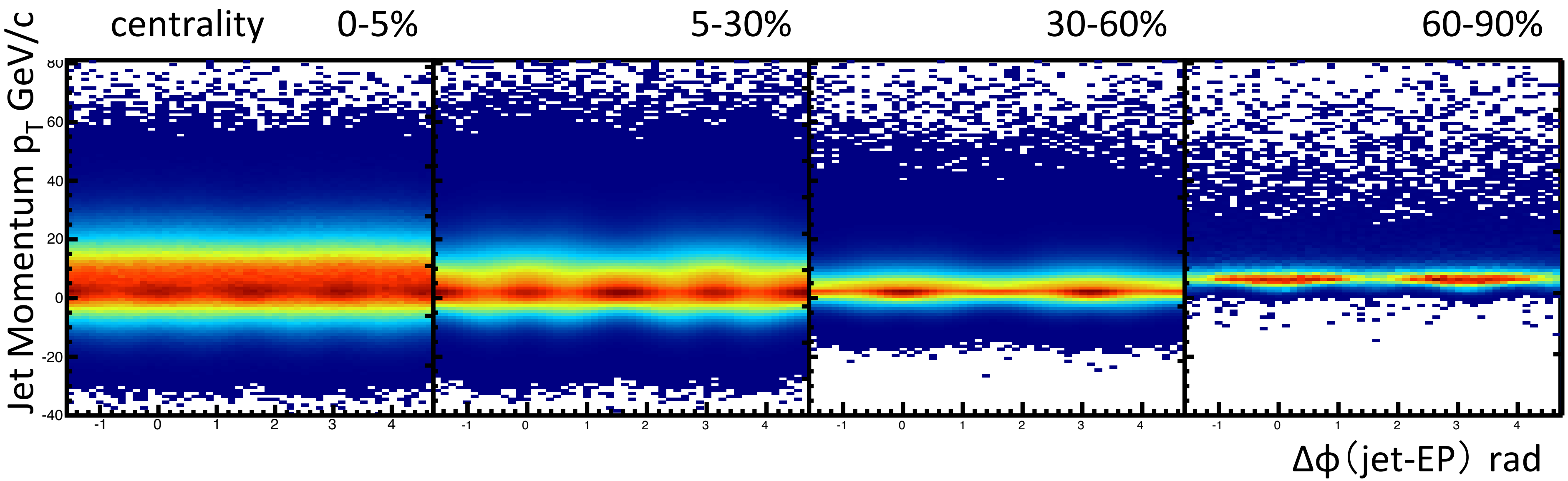
$$\frac{dp_T^{total}}{d\phi d\eta} \Leftrightarrow f = A + B\cos(2(\phi-\psi_2)) + C\cos(3(\phi-\psi_3))$$

$$p_T^{BKG} = Area \times \frac{dp_T^{total}}{d\phi d\eta}$$



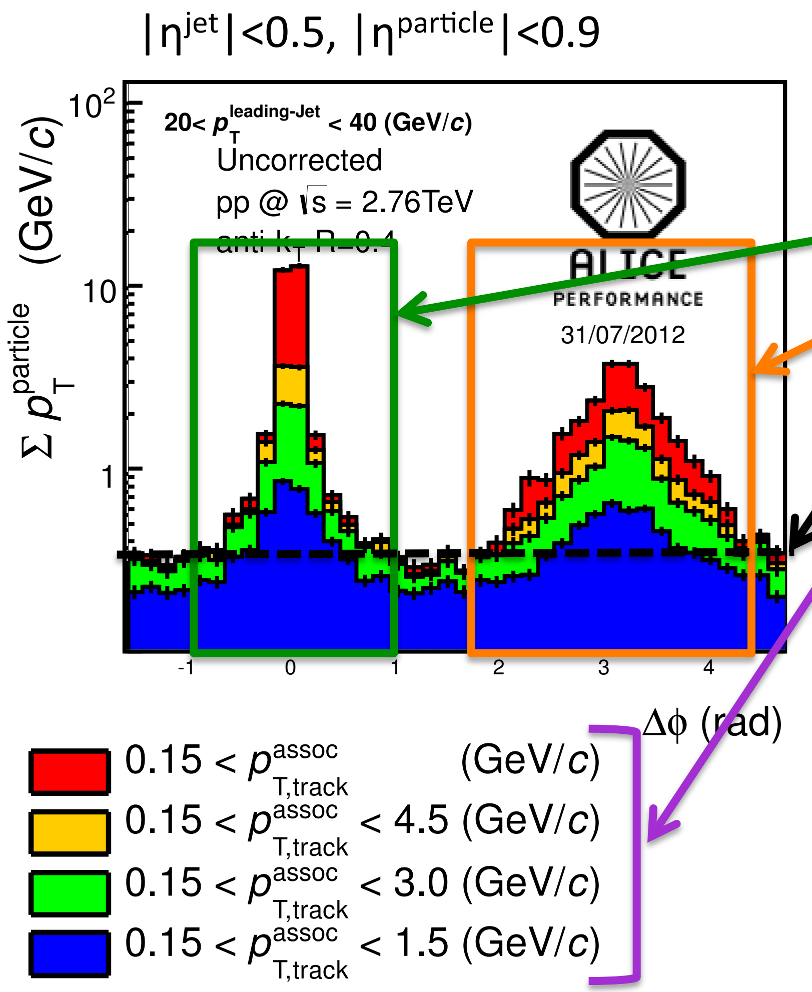
- Fill particle with their p_T into hist.
- Fit function to 2D histogram
- Subtract BKG from Jet p_T
- Calc. $<p_T^{BKG}>$ at ϕ (dR(jet-bin)>0.5)
- Correct bin value p_T^{bin} - $<p_T^{BKG}>$
- Fit function again
- Subtract BKG from jet again

Subtracted Jet Momentum



- We got uniform momentum distribution w.r.t EP after BKG subtraction.
- Still have slightly EP dependence in mid-central, peripheral due to pass length dependence of Jet modification.

Jet Particle Azimuthal Correlation



- Momentum distribution of associate particles w.r.t Jet axis.
  - Leading jet properties (p_T and $\sigma p_T/d\phi$)
  - Sub-leading jet properties
  - Underlying momentum
  - fragmentation function

$$\left.\frac{d(\sum p_T^{asso}(\Delta\phi))}{dn^{dijet}}\right|_{p_T^{min}<p_T^{lead}<p_T^{max}}$$

$$= \left.\frac{d(Eff \times (\sum p_T^{hard}(\Delta\phi) + \sum p_T^{BKG}(\Delta\phi)))}{dn^{dijet}}\right|_{p_T^{min}<p_T^{lead}<p_T^{max}}$$

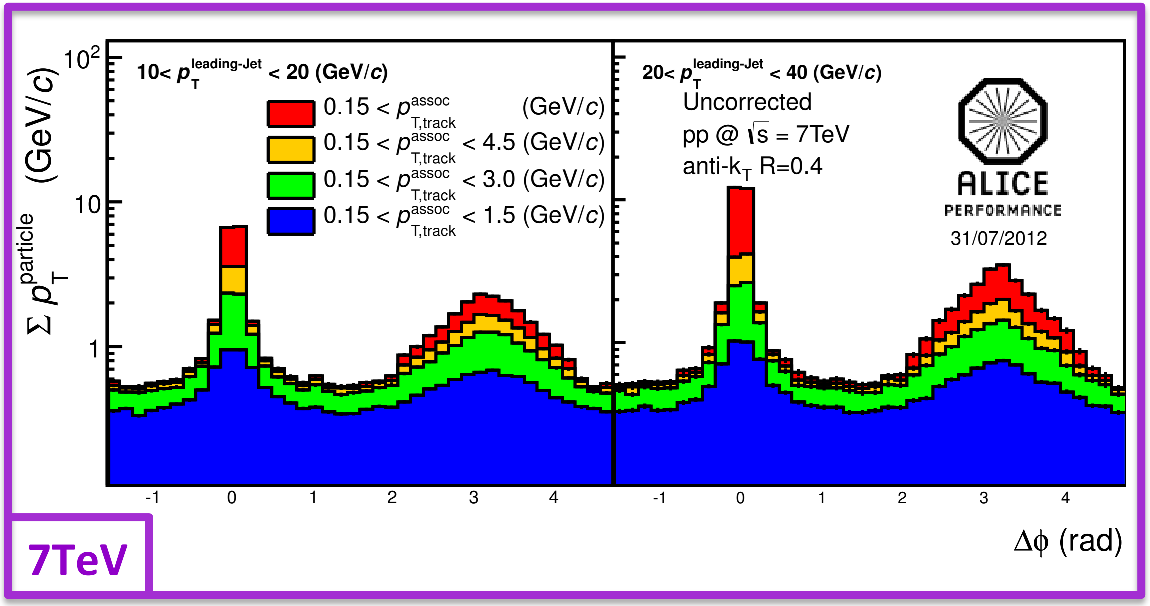
Eff : detector smearing effects

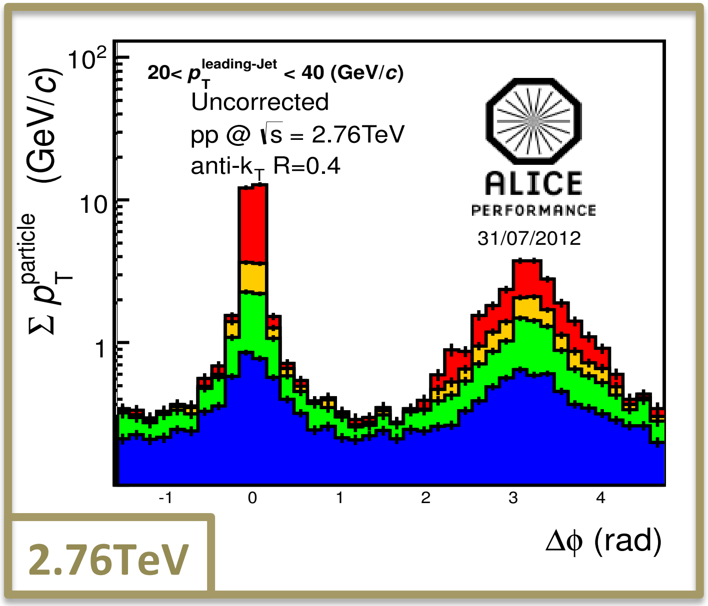
$p_T^{BKG} = p_T^{contami} + p_T^{hardBKG} + p_T^{softBKG}$

Results & Discussion

ALICE
A JOURNEY OF DISCOVERY

Momentum weighted Azimuthal Distribution w.r.t Jet Axis



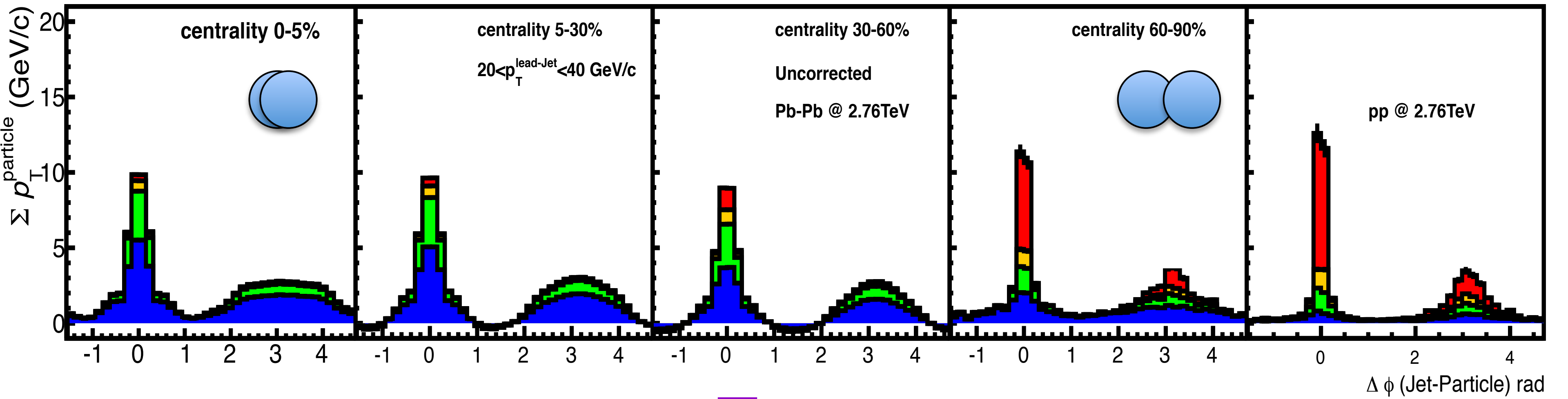


- Peak width and height depend on trigger jet momentum.
- Underlying momentum depend on center mass energy.

Pb-Pb BKD sub 前

Jet Particle Correlation in Pb-Pb

Pb-Pb 2.76TeV BKG is subtracted for Jet and associate distribution.

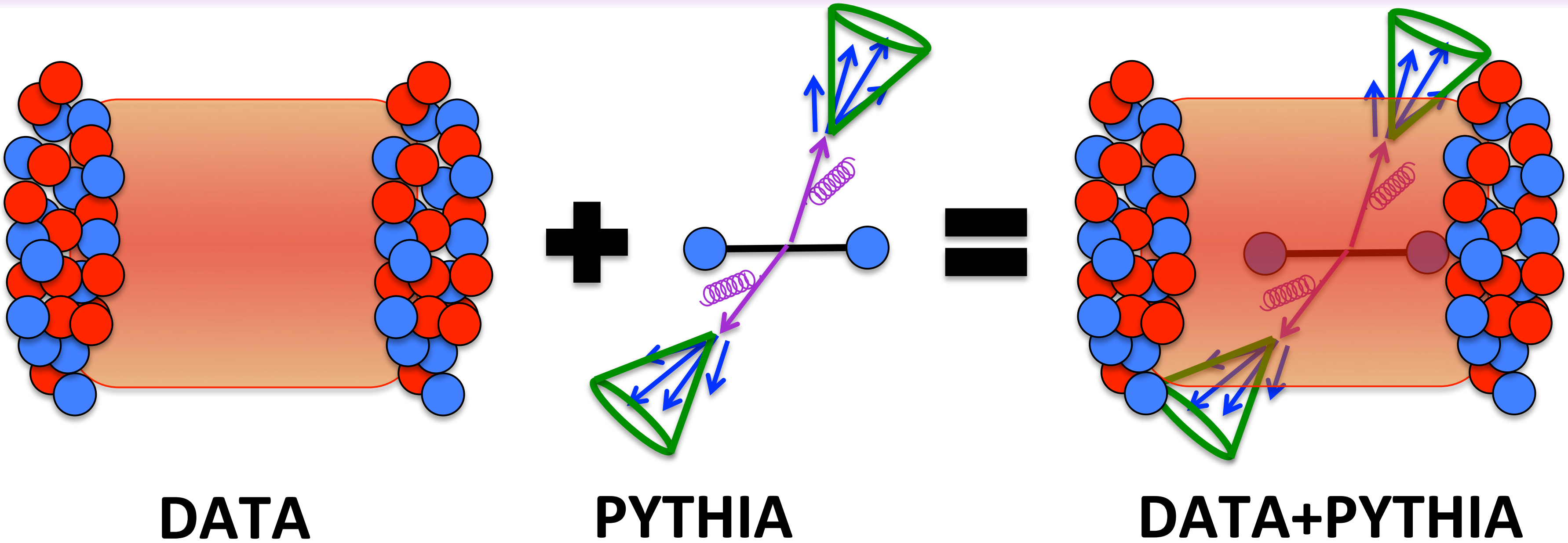


- $0.15 < p_{T,track}^{assoc}$ (GeV/c)
- $0.15 < p_{T,track}^{assoc} < 4.5$ (GeV/c)
- $0.15 < p_{T,track}^{assoc} < 3.0$ (GeV/c)
- $0.15 < p_{T,track}^{assoc} < 1.5$ (GeV/c)

We would like to minimize BKG flow effects!!!

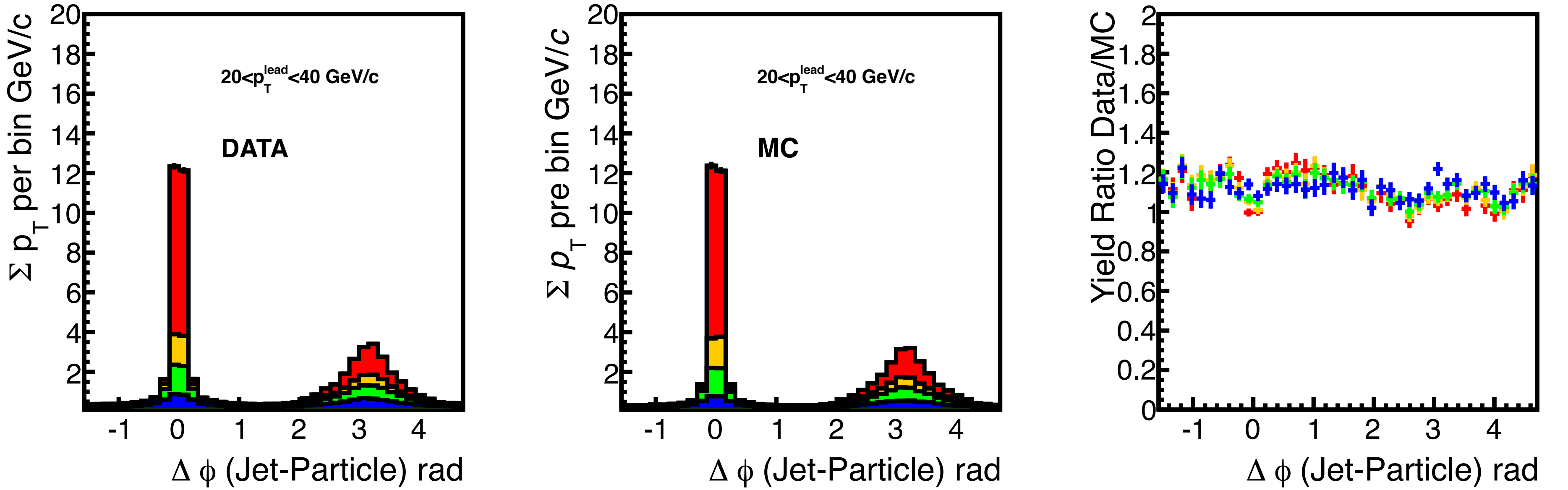
- Jet modification effects
  - jet momentum scale
  - associate distribution modification
- BKG flow effects
  - jet momentum scale
  - associate distribution modification

PYTHIA di-jet embedded Events



- DATA : MB event @ 2.76 TeV
- PYTHIA : **Di-Jet event** @ 2.76 TeV

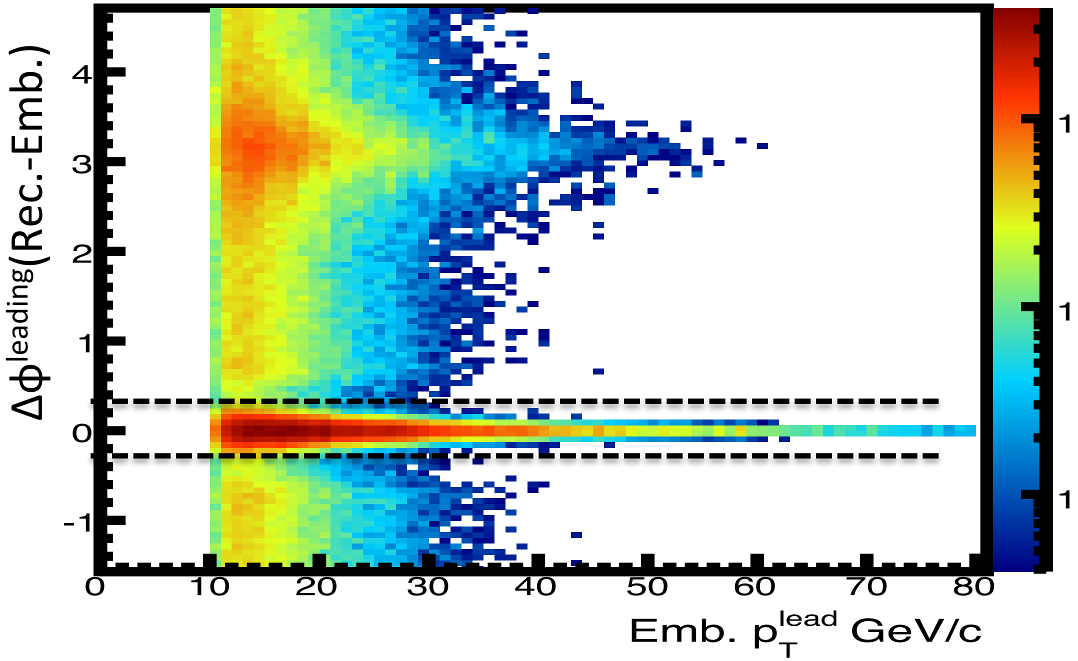
Comparing DATA with PYTHIA



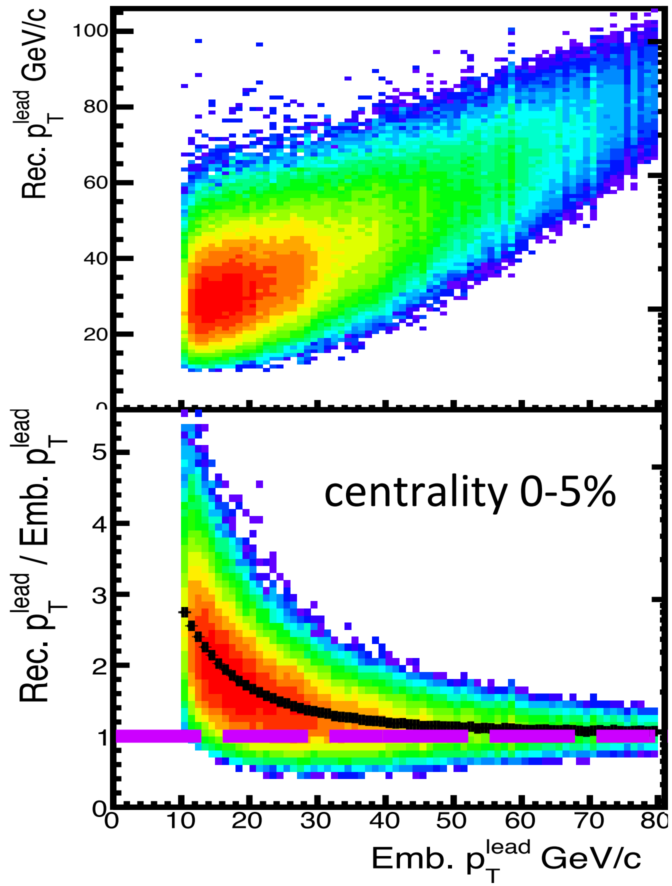
- **PYTIA Jet has good agreement with Jet on Data**
- $Y^{DATA}/Y^{MC} \sim 1.1$ in near/away side

Event Matching

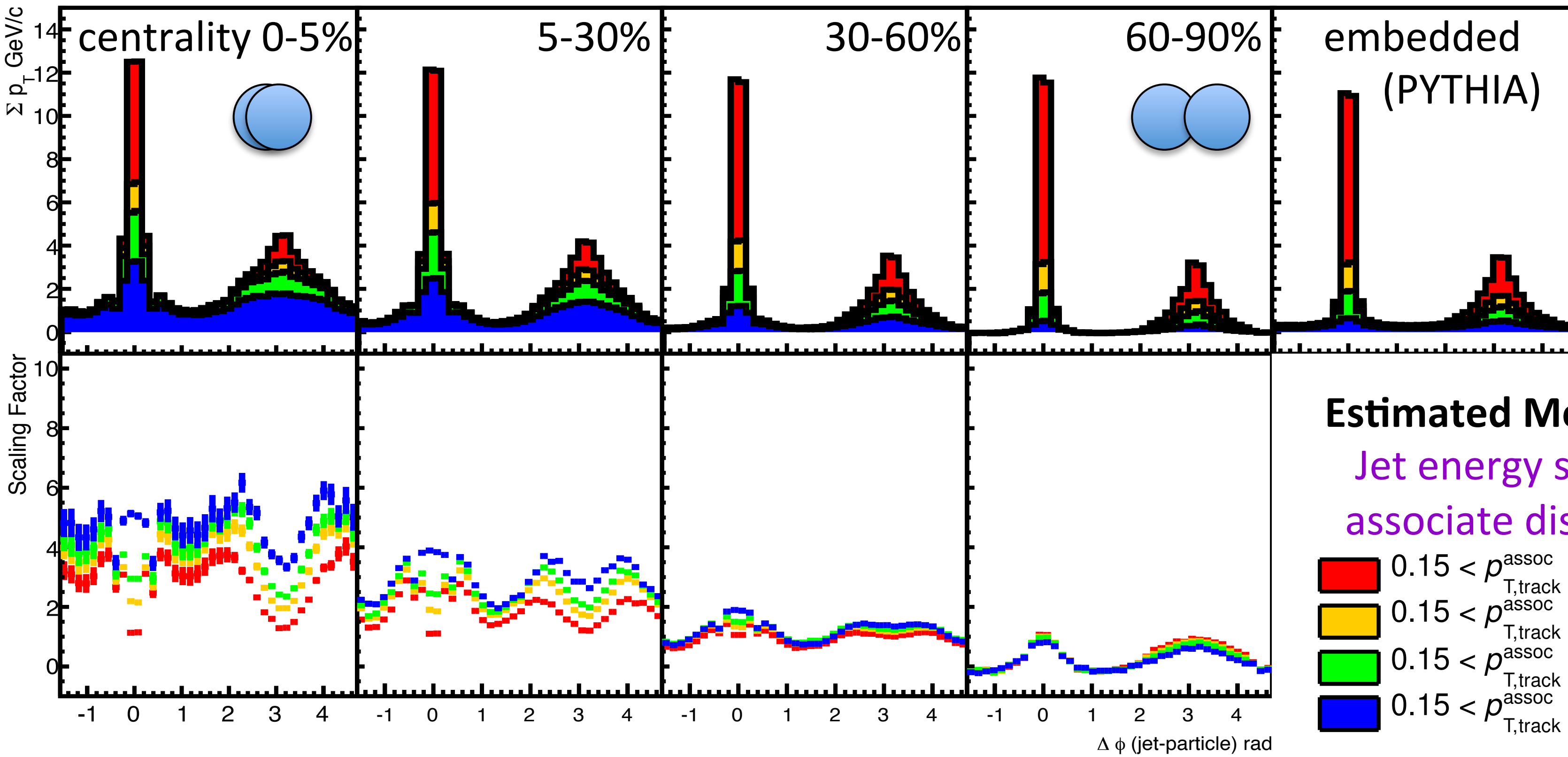
- Di-Jet event after rec.
- $\Delta\phi^{leading}$(Rec.-Emb.)<0.3



Momentum Correlation



Soft/Hard BKG Effects in J-P Correlation



Estimated Modification

Jet energy scale

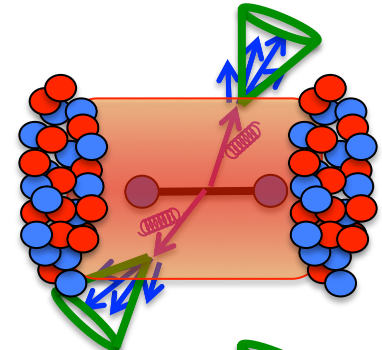
associate distribution

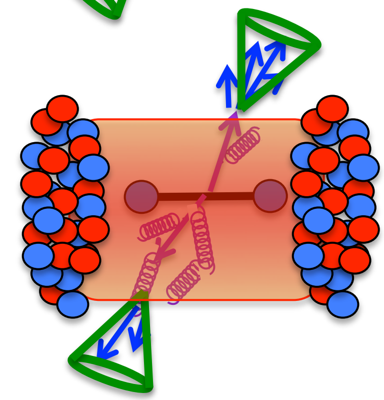
- $0.15 < p^{assoc}_{T,track}$ (GeV/c)
- $0.15 < p^{assoc}_{T,track} < 4.5$ (GeV/c)
- $0.15 < p^{assoc}_{T,track} < 3.0$ (GeV/c)
- $0.15 < p^{assoc}_{T,track} < 1.5$ (GeV/c)

Extract Info. of Jet Modification

$$\left.\frac{d(\sum p_T^{asso}(\Delta\phi))}{dn^{dijet}}\right|_{p_T^{min}<p_T^{lead}<p_T^{max}}$$

$$= \left.\frac{d(Eff \times (\sum p_T^{hard}(\Delta\phi) + \sum p_T^{BKG}(\Delta\phi)))}{dn^{dijet}}\right|_{p_T^{min}<p_T^{lead}<p_T^{max}}$$





$$\Sigma p_T^{PbPb}(\Delta\phi) = Eff^{PbPb}(\Sigma p_T^{hard\text{-}PbPb} + \Sigma p_T^{contami\text{-}PbPb} + \Sigma p_T^{BKGsoft} + \Sigma p_T^{BKGhard})$$

$$\Sigma p_T^{pp}(\Delta\phi) = Eff^{pp}(\Sigma p_T^{hard\text{-}pp} + \Sigma p_T^{contami\text{-}pp} + \Sigma p_T^{BKGsoft} + \Sigma p_T^{BKGhard})$$

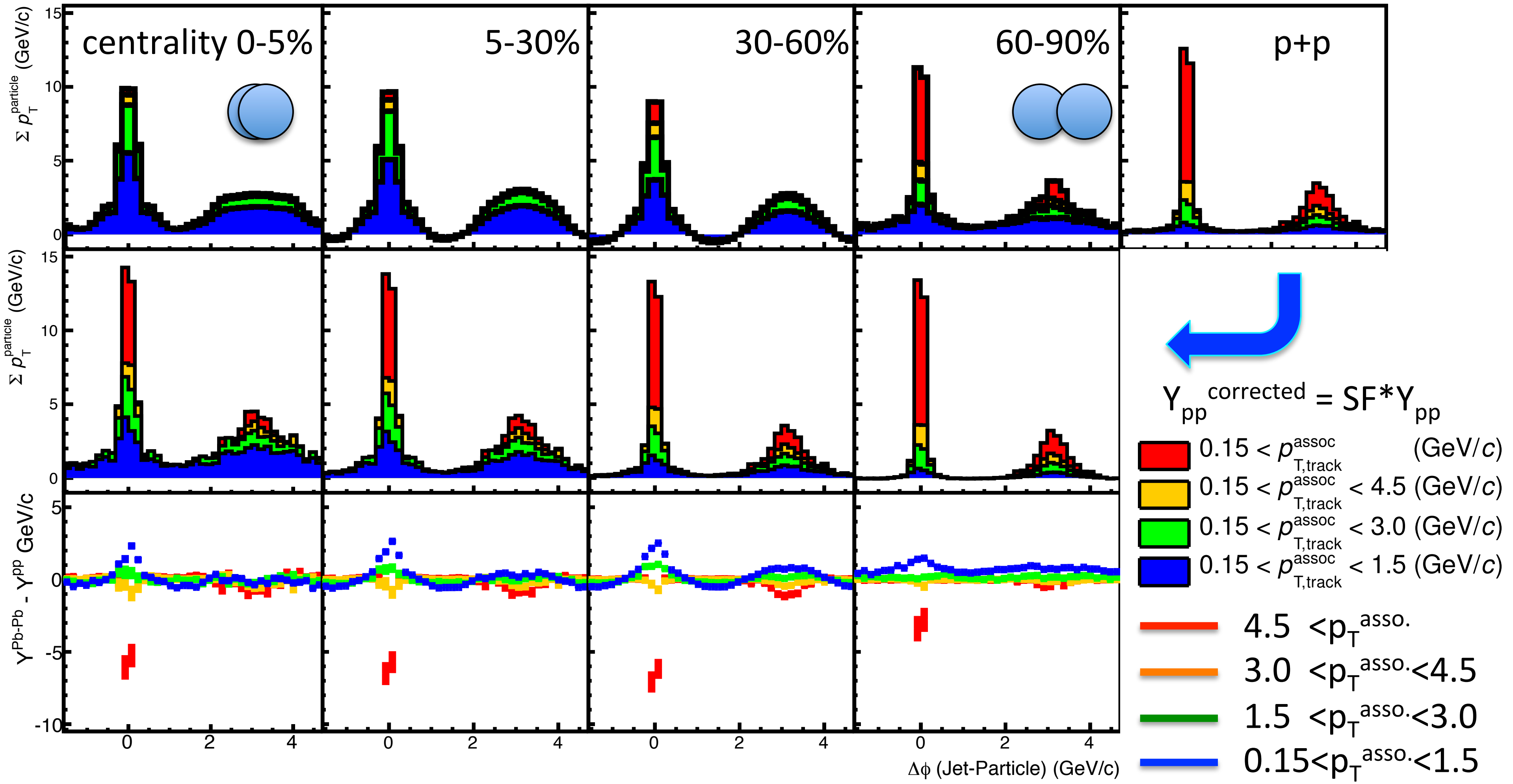
$$p_T^{lead\text{-}PbPb} = p_T^{hard\text{-}PbPb} + p_T^{contami\text{-}PbPb} + p_T^{BKGsoft} + p_T^{BKGhard}$$

$$p_T^{lead\text{-}pp} = p_T^{hard\text{-}pp} + p_T^{contami\text{-}pp} + p_T^{BKGsoft} + p_T^{BKGhard}$$

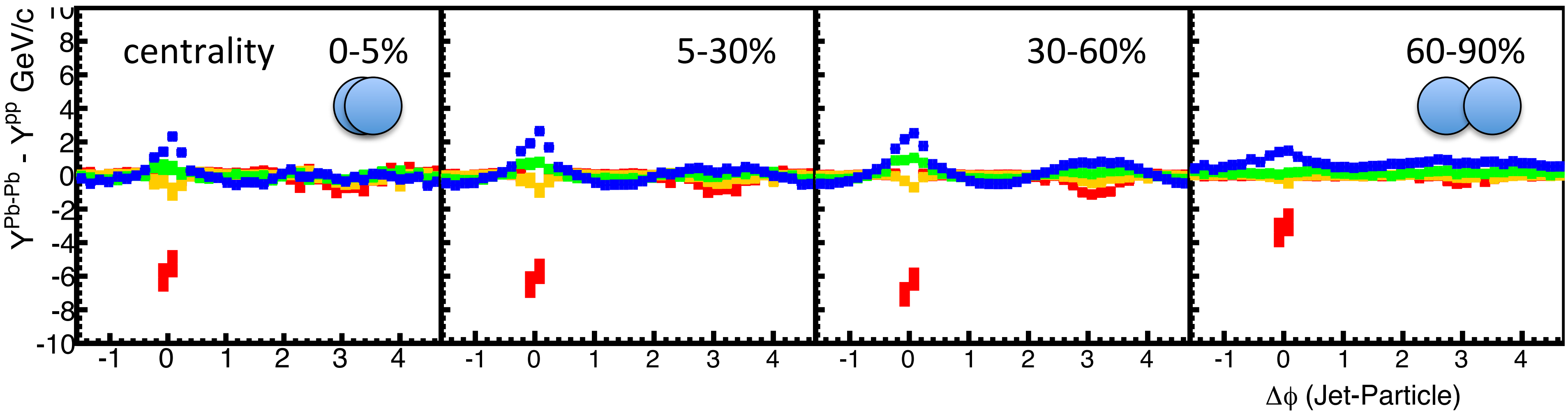
$$\Sigma p_T^{asso\text{-}PbPb} - \Sigma p_T^{asso\text{-}pp} = Eff^{PbPb}(\Sigma p_T^{hard\text{-}PbPb} - Eff^{pp}/Eff^{PbPb} \times \Sigma p_T^{hard\text{-}pp}) + Eff^{PbPb}\Sigma p_T^{contami\text{-}PbPb} - Eff^{pp}\ \Sigma p_T^{contami\text{-}pp}$$

contamination (in reconstructed track)	: 6% @ 0.3 GeV/c , <2 % @ 1GeV/c (for Pb-Pb) 6% @ 0.2 GeV/c , <2 % @ 1GeV/c (for pp)

Momentum Modification

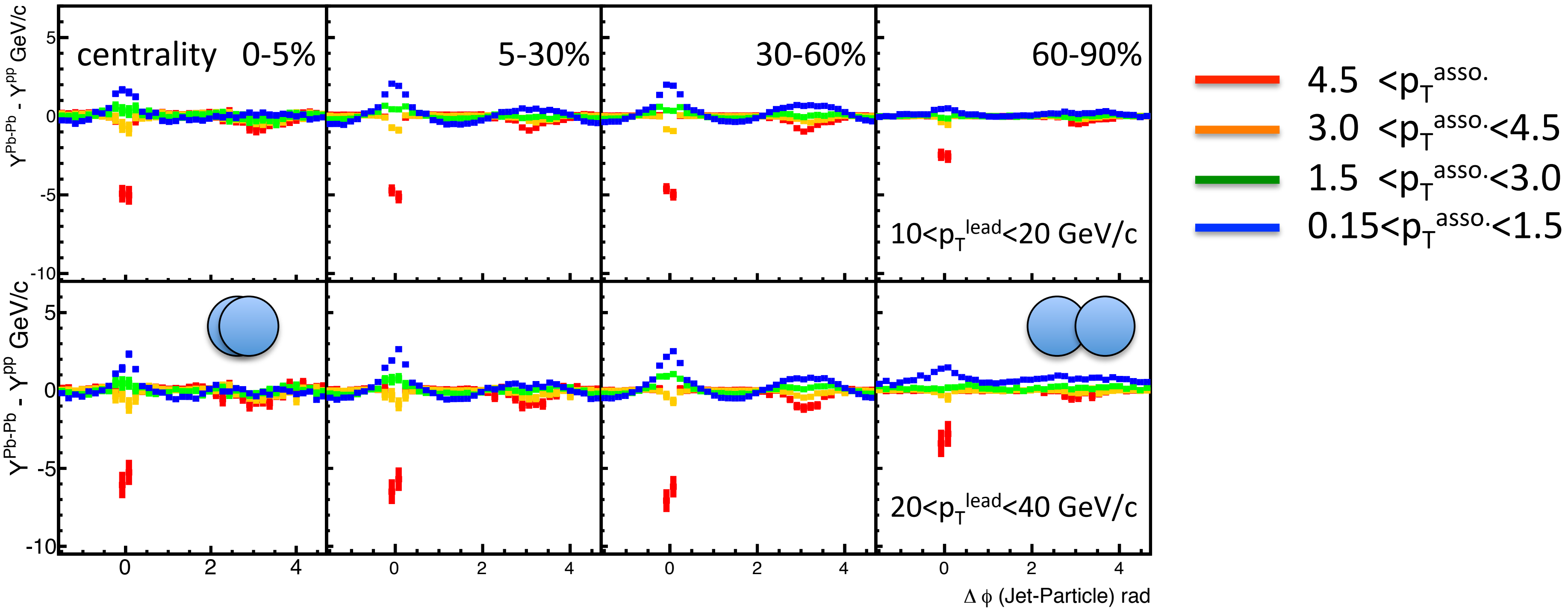


Momentum Modification



- Near Side
  - high p_T particle is suppressed, low p_T particles enhanced
  - modification is saturated? -> jet E scale effects due to jet modification?
- Away Side
  - high p_T particle is suppressed, low p_T particles enhanced
  - But difference of high p_T and low p_T decrease with centrality? -> jet E scale?

Trigger Momentum Dependence



- Suppression & enhancement stronger with trigger jet momentum.

Summary

- First Pb-Pb runs are analyzed for jet measurement.
- BKG subtraction technics are established.
- Jet Particle Correlation is also established.
- We see flow effects in jet modification.
- We could draw out jet modification effects in JPC
  - high p_T particles suppression with azimuthal info.
  - re-distribute to low p_T with large angel (cf CMS)
  - jet modification looks balanced
  - jet modification quantity larger with jet momentum

What's new?

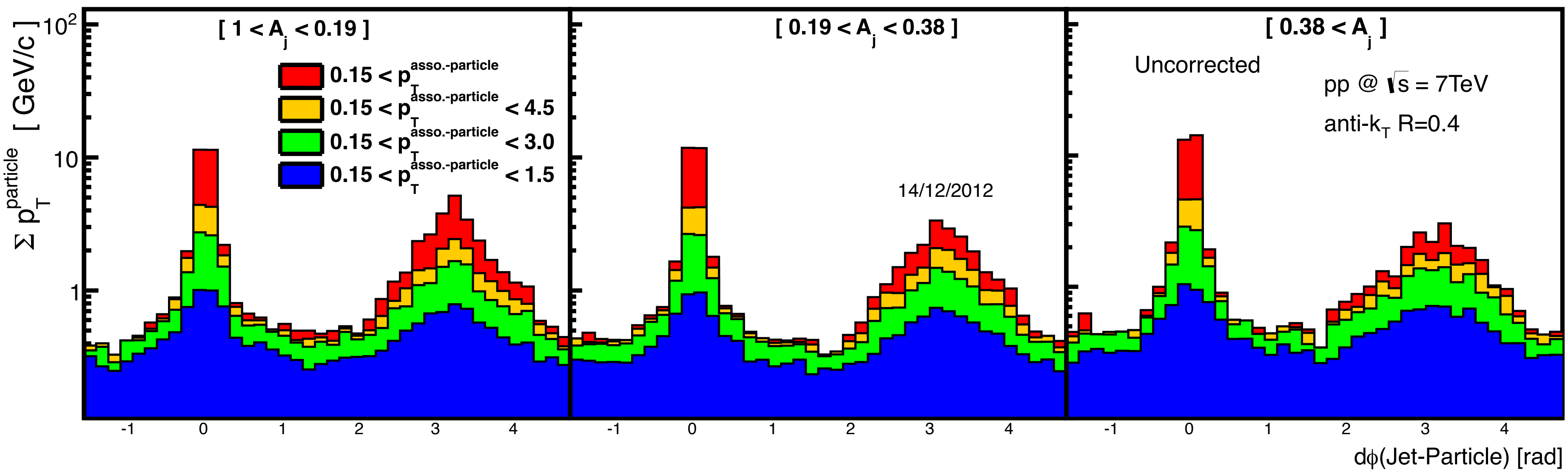
- ALICE get consistent results with CMS
- We measure detail of jet modification in leading jets and sub-leading jets individually.
- The measurement is a mile-stone of jet measurements of ALICE.
  - We can draw out more detail of modification with PID
    - proton ID ~ 5GeV/c with 3σ
    - proton/pion production ratio

Outlook

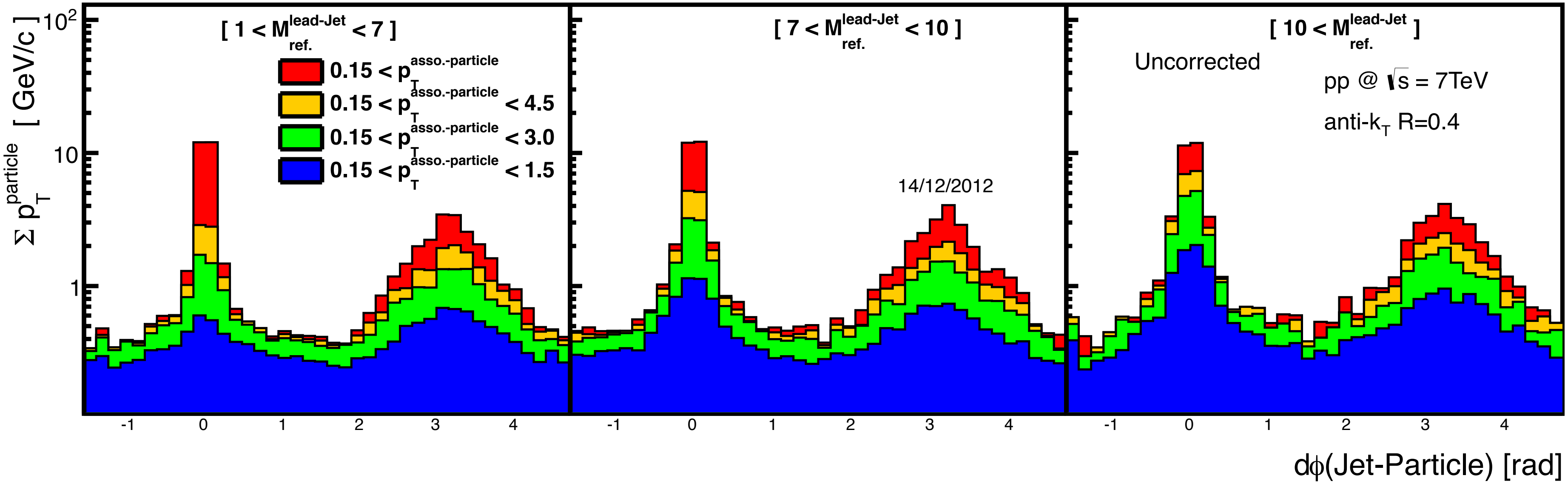
- Systematic uncertainty for embedded PYTHIA
  - Track Efficiency : 5% worth PbPb/pp
  - Track Momentum Res. : 3% worth PbPb/pp
  - Contamination : ±1% PbPb/pp
  - Jet Momentum Scale : ±5% Data <->PYTHIA
- Event Plane Calibration
- Quantification of Jet-Particle Correlation

Backup

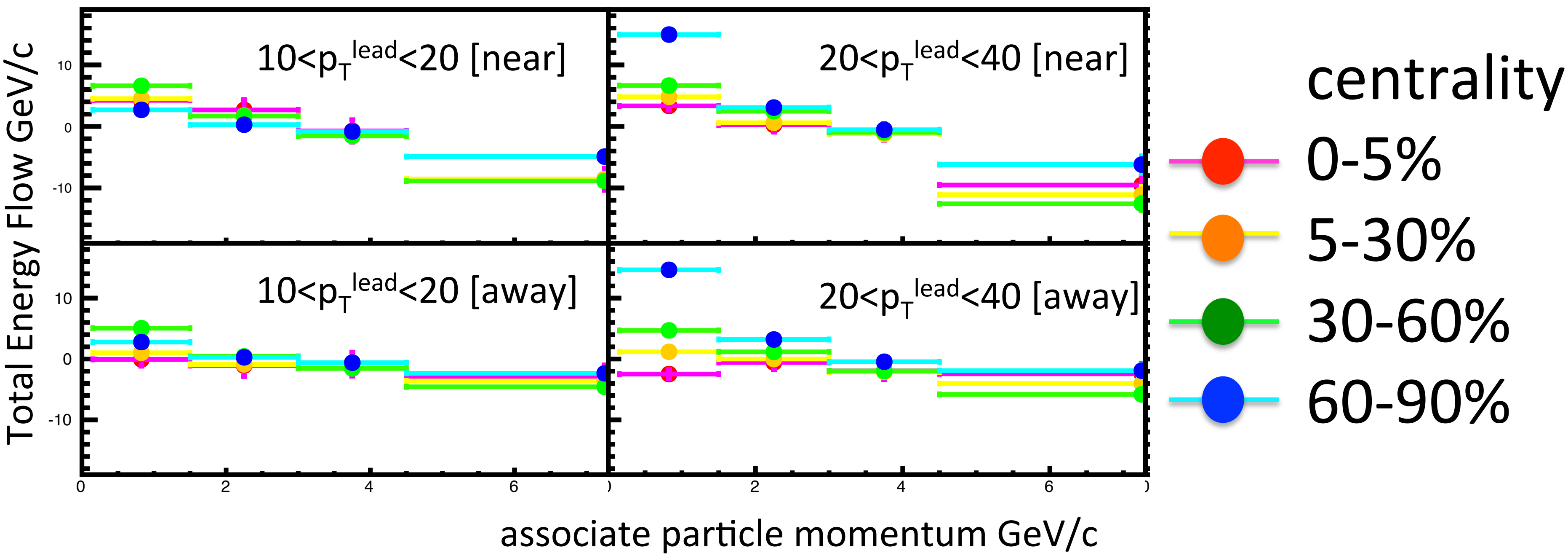
Jet Asymmetry Dependence



Multiplicity in Leading Jet



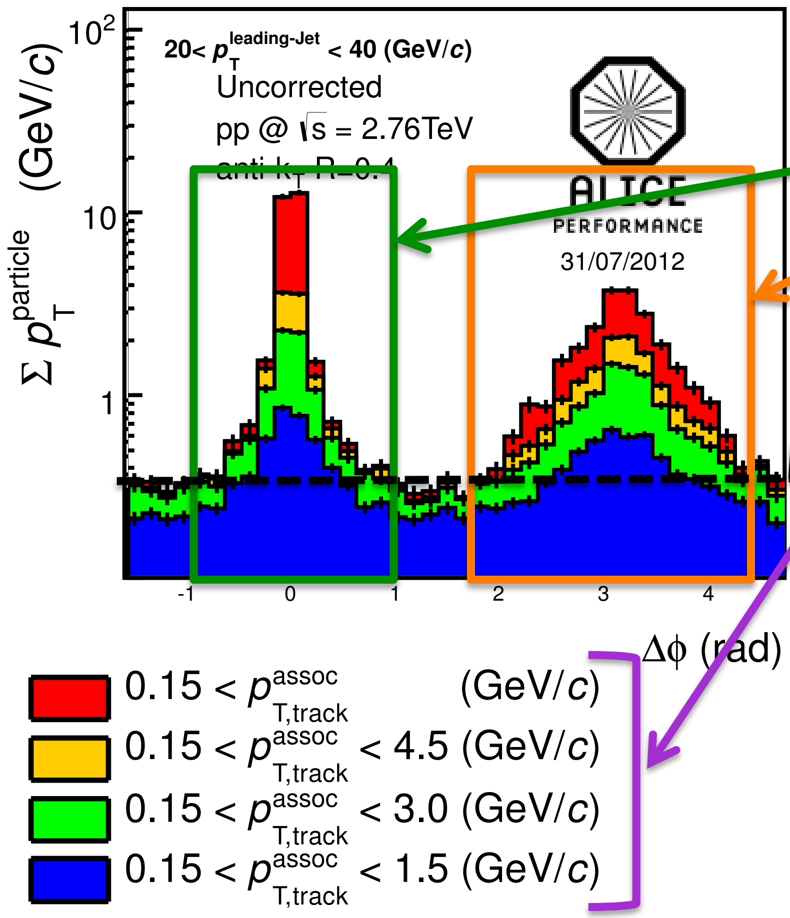
Energy Flow



- うーん。。。。

Jet Particle Azimuthal Correlation

$|\eta^{jet}|<0.5$, $|\eta^{particle}|<0.9$



- Momentum distribution of associate particles w.r.t Jet axis.
  - Leading jet properties (p_T and $\sigma p_T/d\phi$)
  - Sub-leading jet properties
  - Underlying momentum
  - fragmentation function
- Topics
  - pp
    - Trigger momentum dependence
    - Center mass energy dependence
  - Pb-Pb
    - Centrality dependence
    - Jet modification