Study of medium modified jet shape observables in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV using EPOS and JEWEL event generators

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Plan of the Talk

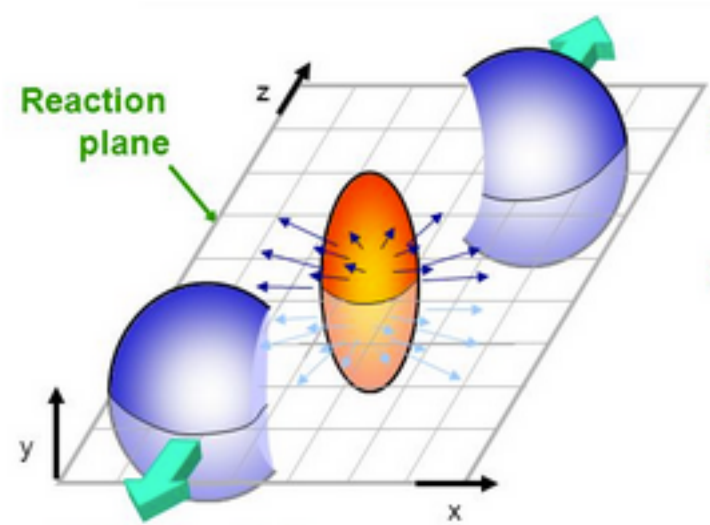
a) Motivation

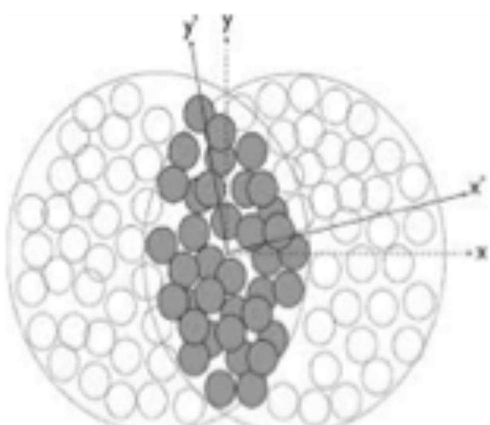
b) Use of Monte Carlo event generator EPOS (Energy conserving multiple scatterings, Parton Ladders, Off shell remnants, Saturation) and JEWEL (Jet Evolution With Energy Loss) – Justification…

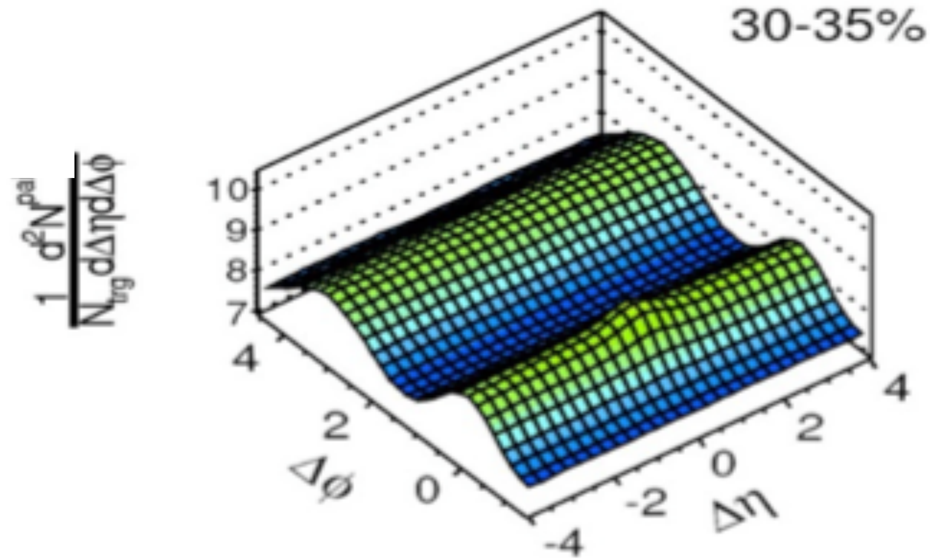
c) Results

d) Summary

Collectivity in heavy ion collisions



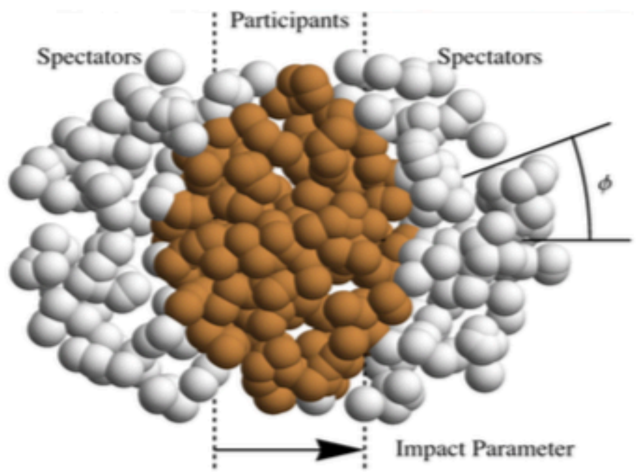


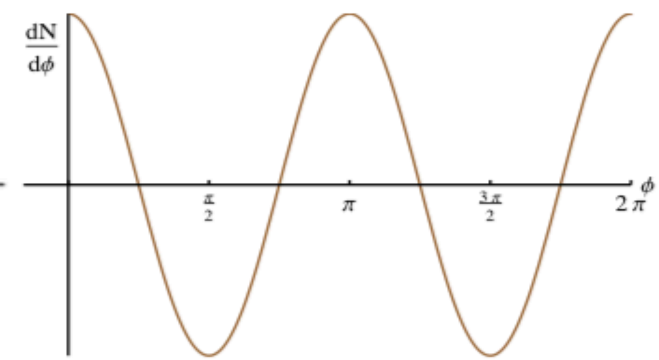


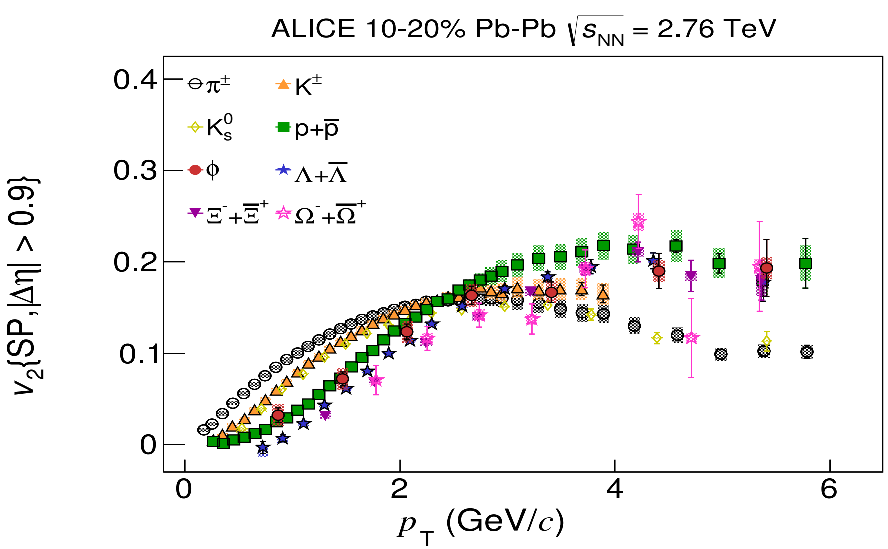
CMS 1201.3158

- Ridge : Well known feature from Pb-Pb collisions (indicates collective flow of a thermalized medium). Not expected in small collision systems(Initially)…

Collectivity in heavy ion collisions







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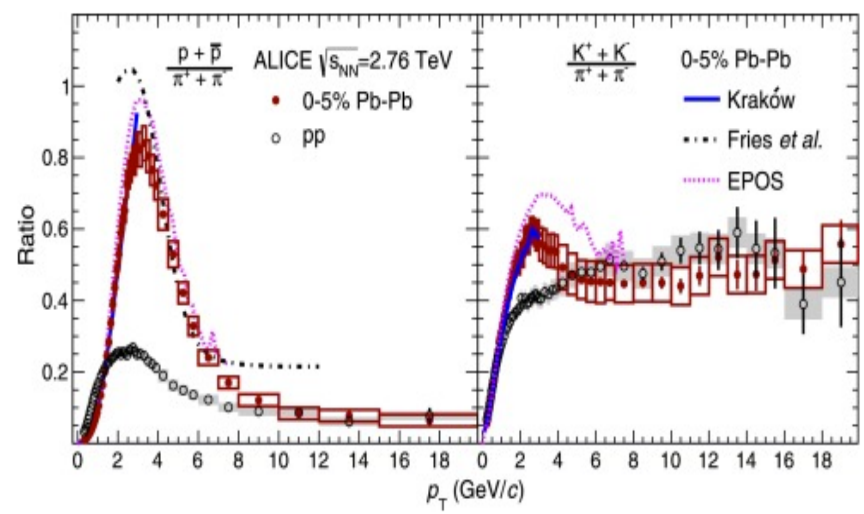
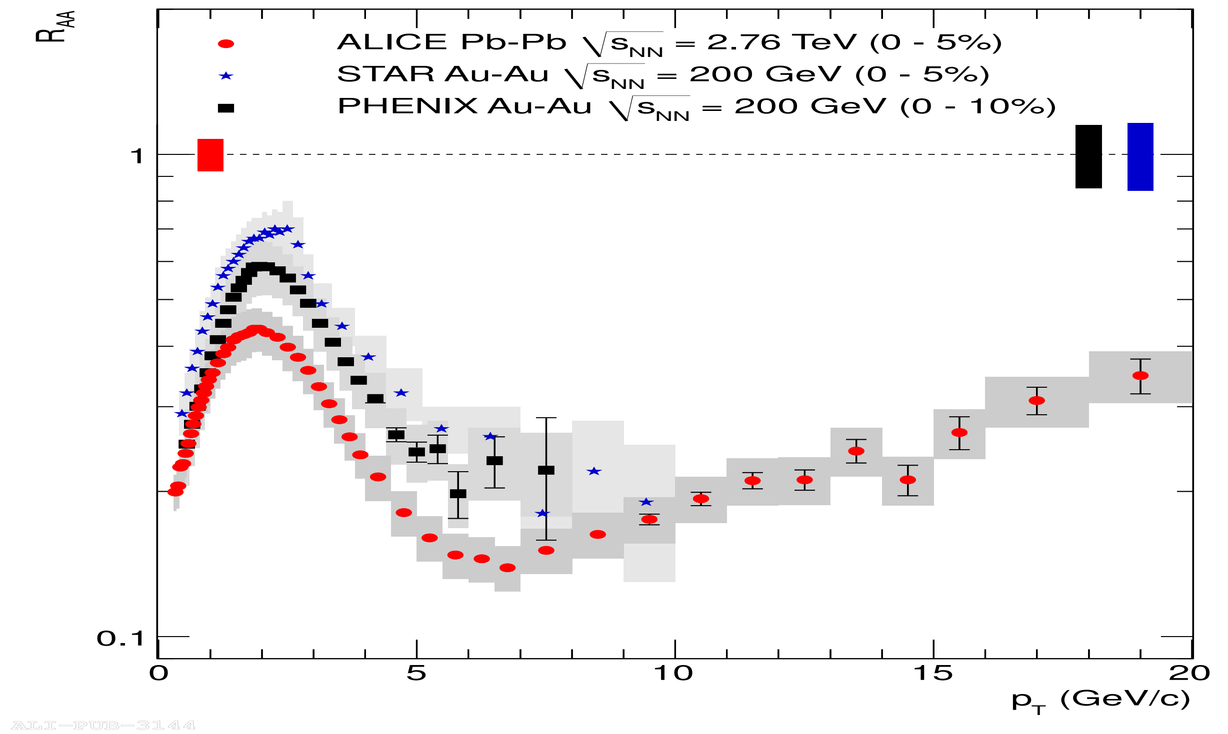


❖ **Ridge, v_2, mass dependence of spectra etc are the signatures of formation of thermalized de-confined medium in ultra-relativistic heavy ion collisions.**

Jet-medium interaction : Jet Quenching

Nuclear modification factor: $$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, d^2N_{ch}^{pp}/d\eta dp_T}$$

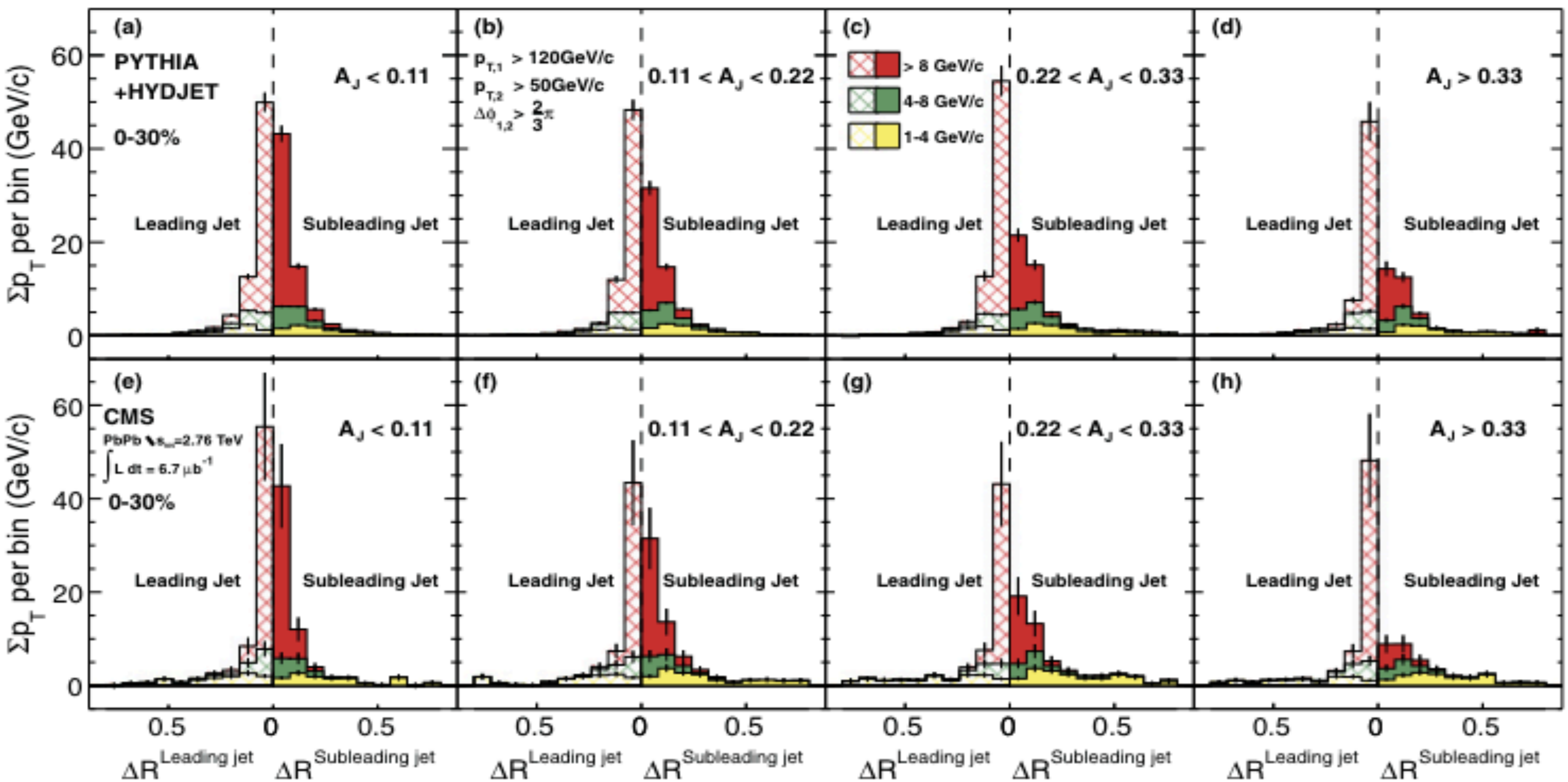


- ❖ **High pT particles originate from jet fragmentation.**
- ❖ **Jet looses energy in the medium and the less energy available for high p_T particle production.**

Jet-medium interaction : Dijet Asymmetry

CMS PRC 84 024906

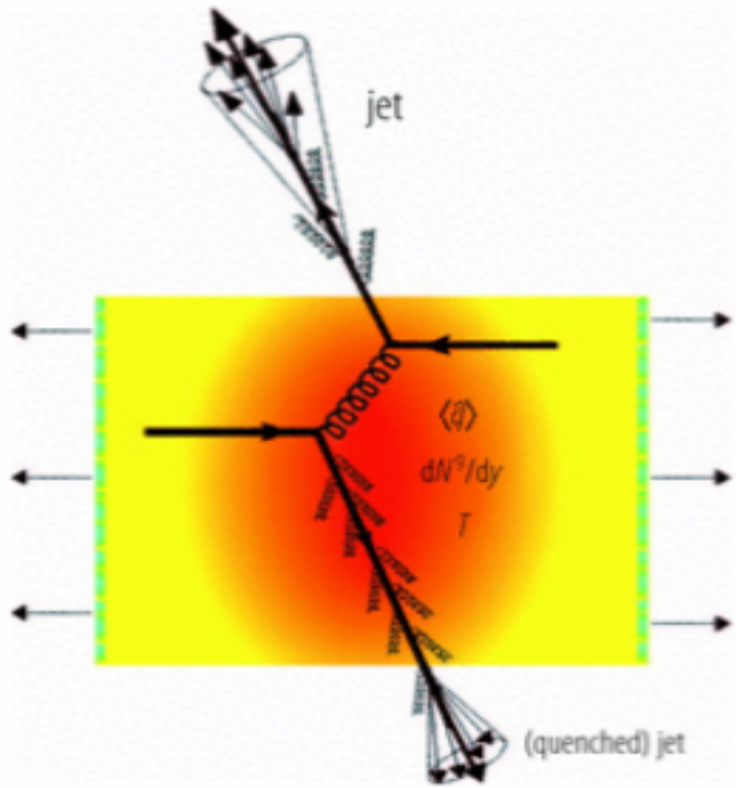
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}},$$

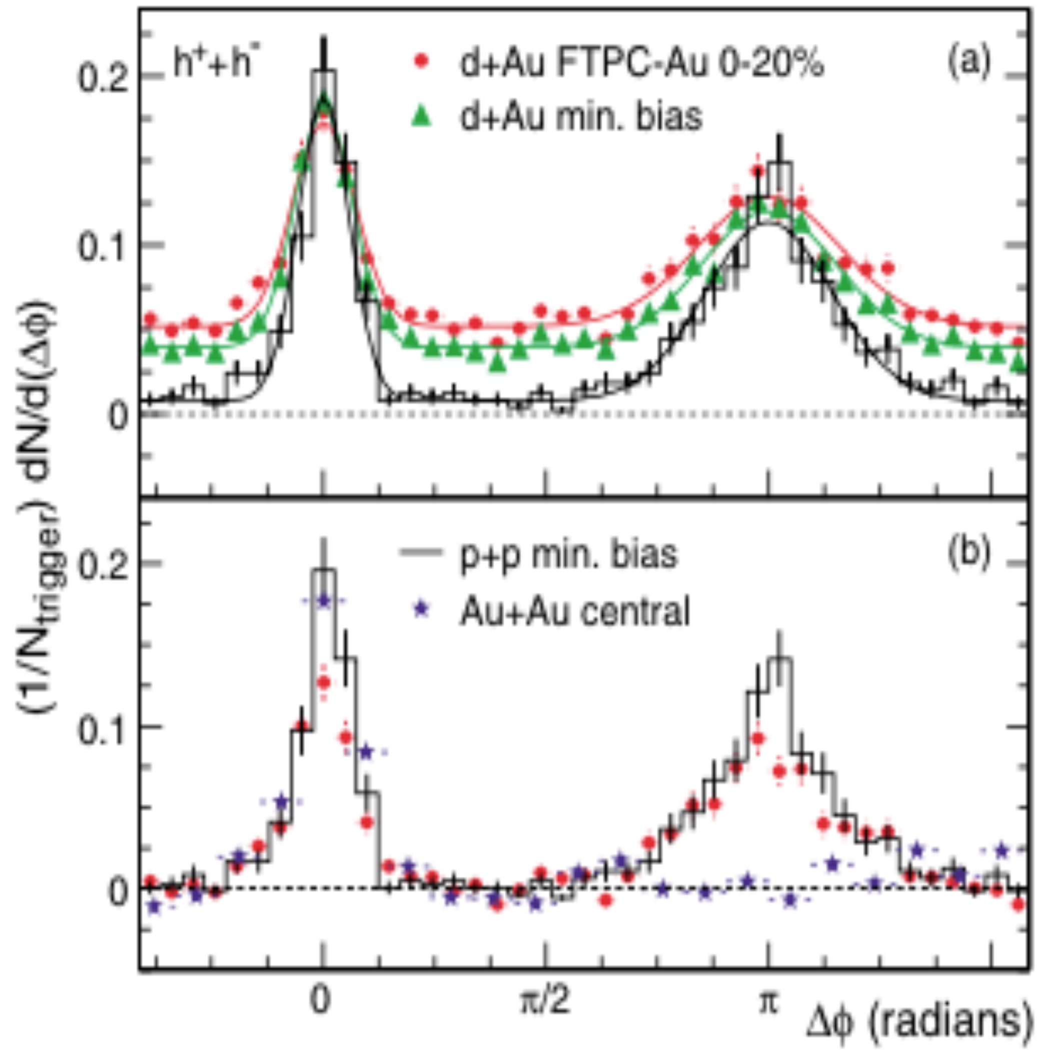


With increase in asymmetry, the away side jet will be more quenched and the quenched energy will produce low and intermediate p_T particles at larger jet cone → can be investigated in terms of correlation observables…

Jet-medium interaction : Suppressed away side correlation

PhysRevLett.90.082302.





- **The away side jet traverses larger distance inside the medium and gets more quenched.**

Description of a complete heavy ion event:

Jets + Hydrodynamically evolving deconfined medium

(High p_T phenomena) **(Low p_T phenomena)**

AND

Interaction between the two

(influences particle production strongly upto p_T 20 GeV/c)

In EPOS*: *PYTHIA generated jets traverse through hydrodynamically evolving medium.

In JEWEL*: *PYTHIA generated jets traverse through a static ensemble of partons whose phase space distribution and flavor composition are determined by an external medium model.

Jet Fragmentation in event generators (PYTHIA)

❖ **Not known properly and can't be constructed from first principle**

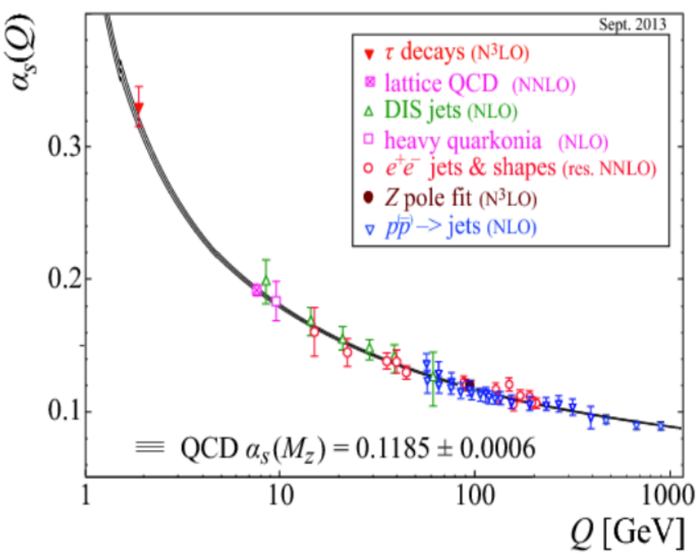
❖ **Completely model dependent**

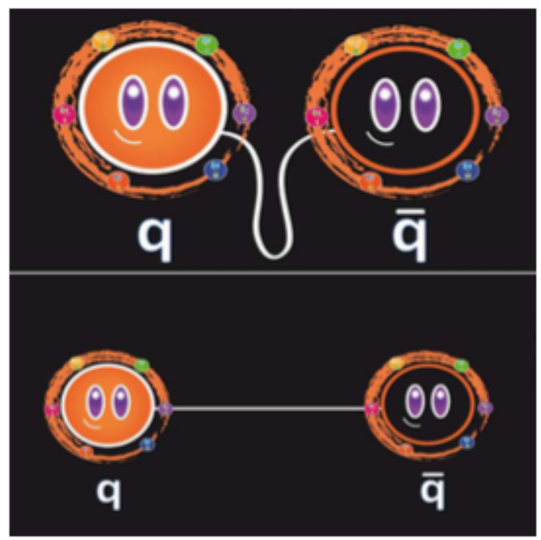
❖ **Based on experimentally observed information :**

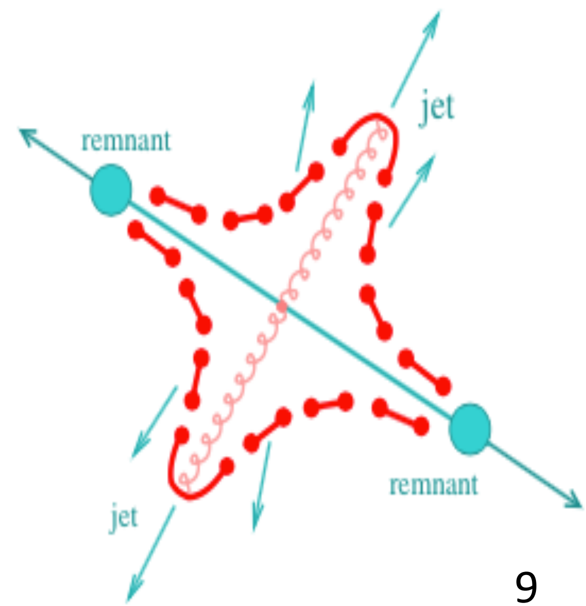
1) Quarks have never been observed as free.

2) Asymptotic freedom (quarks behave as free for large momentum transfer i.e when they are spatially very close).

These two features can be implemented using string dynamics (*F=-Kr*)

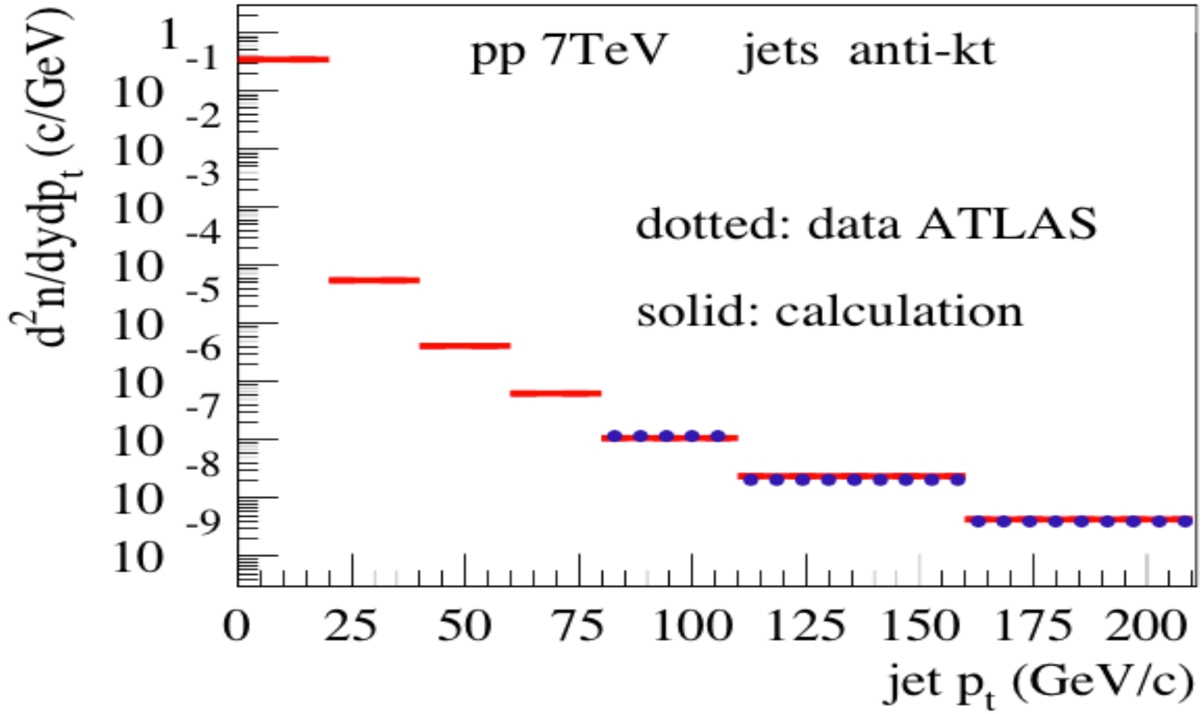






String fragmentation can explain the jet spectra in pp collisions at the LHC energies

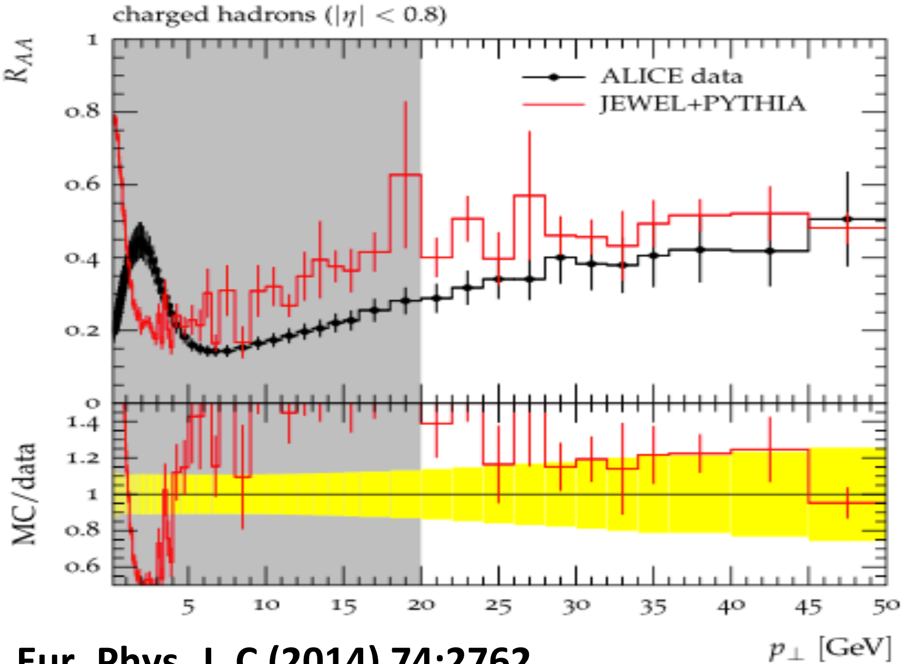
Phys. Rev. C 85, 064907 (2012)



- **PYTHIA can explain the inclusive p_T distribution of jets in pp collisions at 7 TeV**

- **We will investigate the modification to the jet substructure due to different schemes of jet-medium interactions as implemented in EPOS and JEWEL event generators.**

Jet-medium interaction: Nuclear modification factor

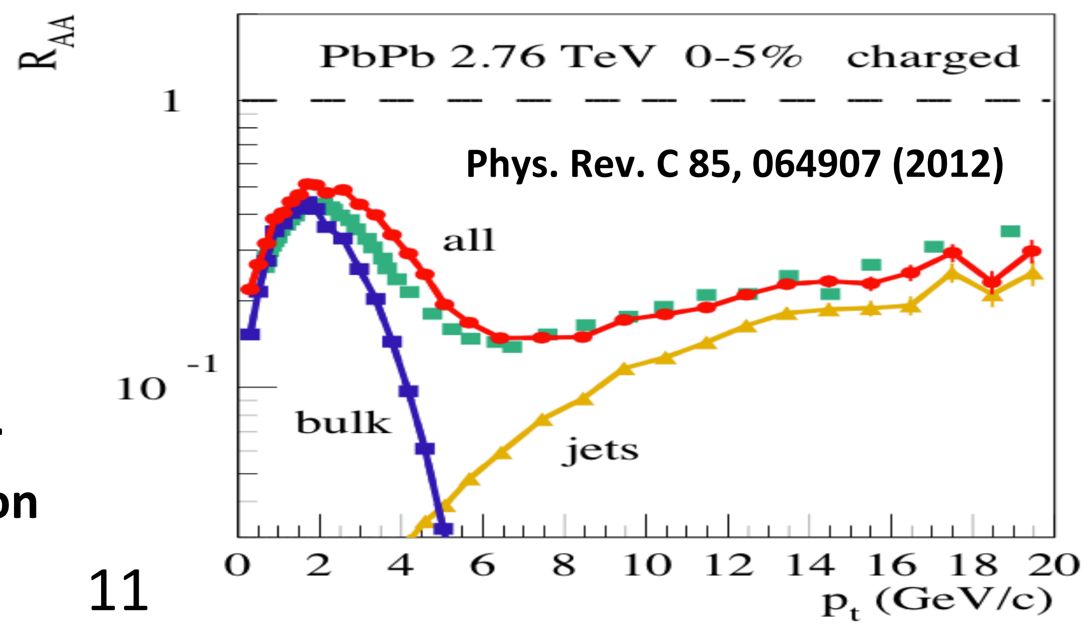


Eur. Phys. J. C (2014) 74:2762

- ❖ JEWEL can't explain the particle production upto pT 20 GeV/c.
- ❖ Somewhat expected as the medium is considered as static ensemble of partons!!.

The p_T region upto 20 GeV/c is important.

- ❖ EPOS can describe the nuclear Modification factor in a better Way.
- ❖ Interaction between jets and Hydordynamically evolving matter can describe the particle production in central heavy ion collisions.



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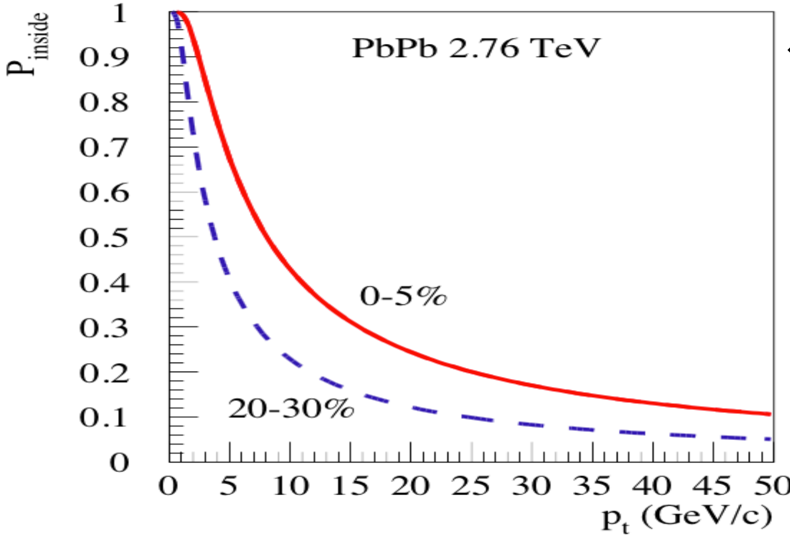
Jet-medium interaction in EPOS



- ❖ **Interaction between Jet and hydrodynamically evolving medium:**

- ❖ ***Partonic energy loss (primary)***

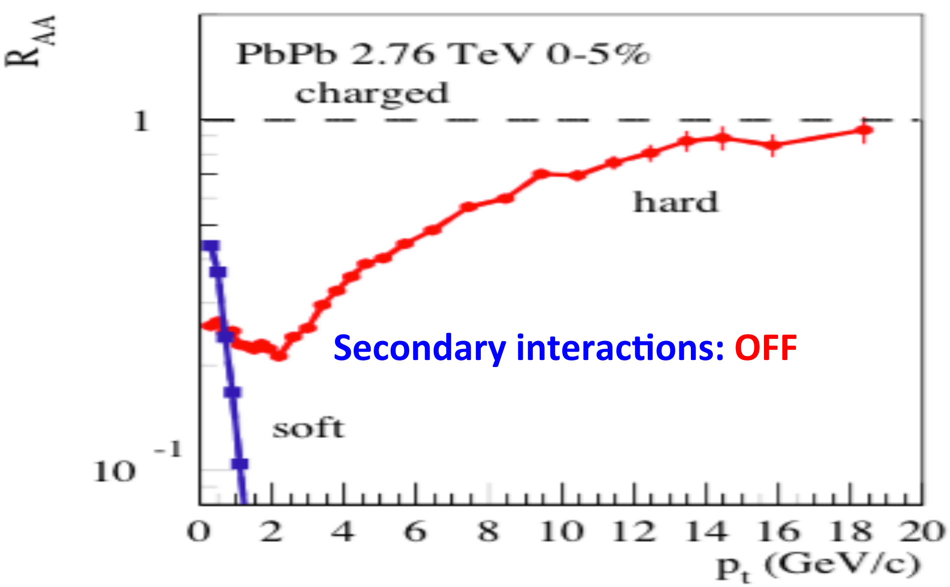
+

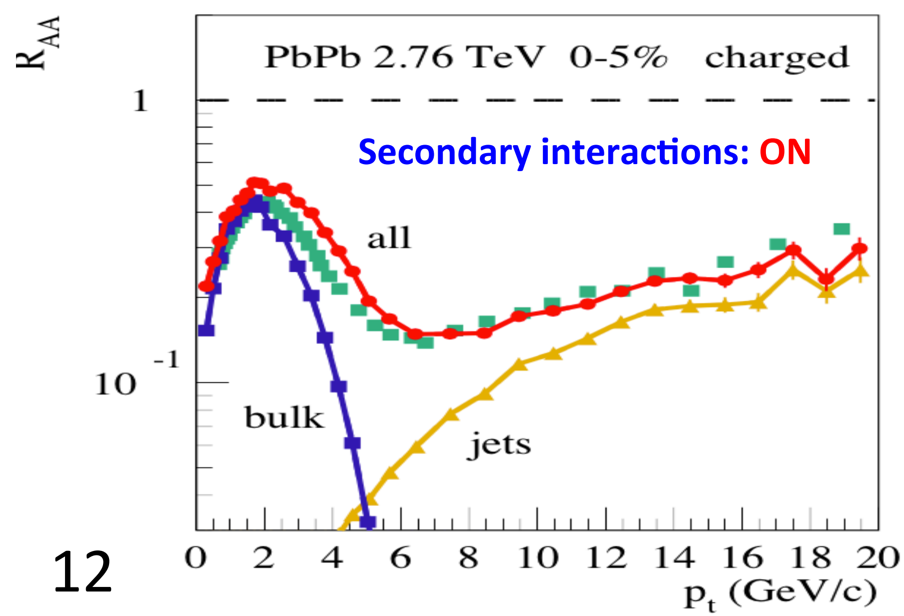
In medium Fragmentation + hadronic cascade (Secondary)

- ❖ **Probability of in medium fragmentation is significant For hadrons upto p_T ~20 GeV/c:**

$$\text{prob} \sim \exp\left(-\frac{t}{\gamma\tau_{\text{form}}}\right)$$

Phys. Rev. C 85, 064907 (2012)





Jet-medium interaction in EPOS

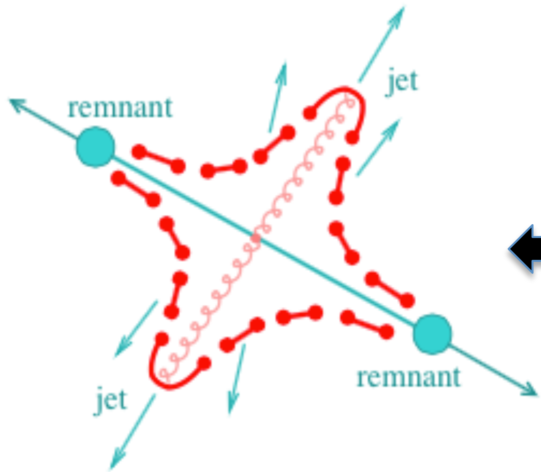


Figure **2**: (Color online) Flux tube breaking via $q-\bar{q}$ production, which screens the color field (Schwinger mechanism).

Lowest Multiplicity class

String fragmentation in low density region following usual Schwinger mechanism- creating Jet hadrons (corona).

Highest Multiplicity class

String fragmentation/flux tube breaking using partons from the bulk/core.
The probability of core-corona interaction is higher in higher multiplicity classes.

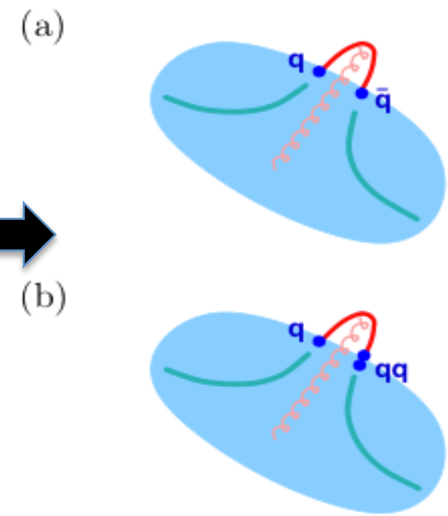
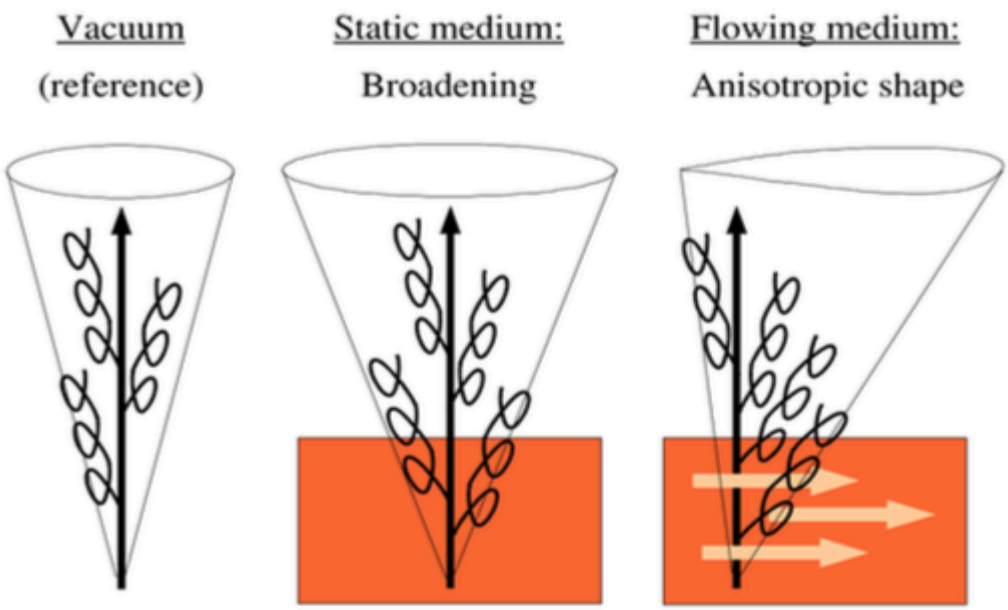


Figure **3**: (Color online) Escaping string segment, getting it's endpoint partons from the fluid. We show the case of a quark and an antiquark (a) and of a quark and a diquark (b). The rest of the string dissolves in matter.

Phys. Rev. Lett. 109, 129903 (2012)

Jet medium interaction: Jet peak shape broadening

- Interaction with longitudinal flowing medium
  Romatschke, Phys. Rev. C75 (2007) 014901
  Armesto, Salgado, Wiedemann, Phys. Rev. C72 (2005) 064910
  Armesto, Salgado, Wiedemann, PRL 93,242301 (2004)



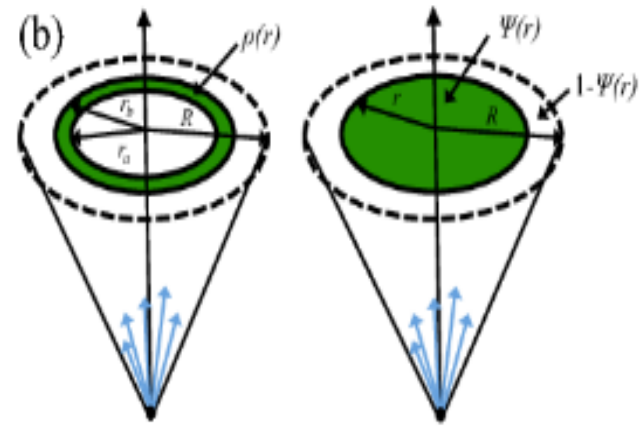
- Interaction with turbulent color fields
  Majumder, Muller, Bass, Phys. Rev. Lett. 99 (2007) 042301

- Double hump-shape in the energy distribution of the jet
  Armesto, Salgado, Wiedemann – PRL 93,242301 (2004)

❖ **Can be studied by measuring the centrality evolution of width of the jet peak in correlation studies.**

Jet Shapes

❖ ***Jet shape observables describe the the distribution of jet transverse momenta inside the jet cone and provide important information about the in-medium modification to the sub structure of the jet .***



❖ ***The differential jet shape:***

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{jet}}\sum_{jets}\frac{\sum_{tracks\in[r_a,r_b]} p_T^{track}}{p_{T,jet}}$$

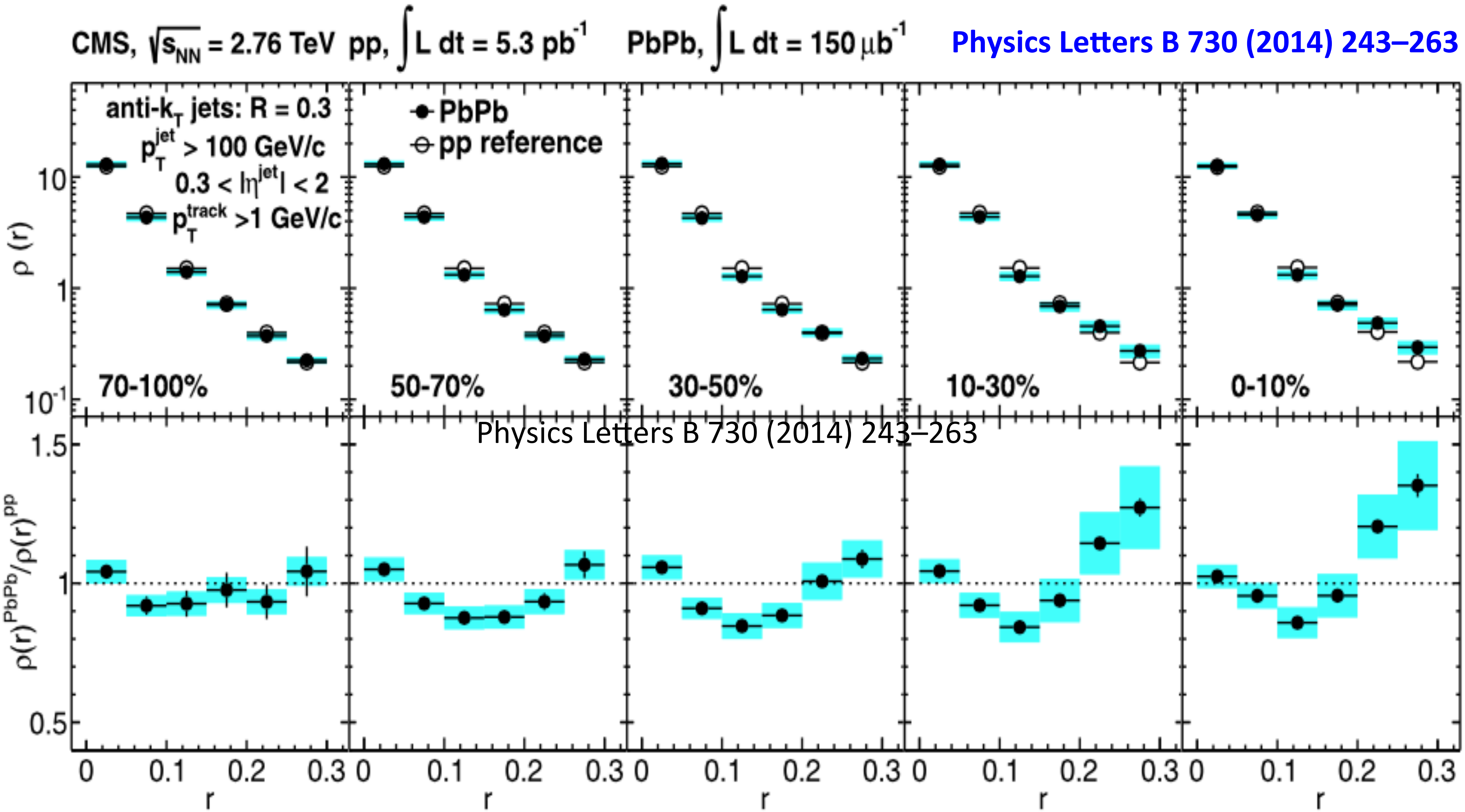
where the numerator denotes the summation of the momenta of all charged particles inside the annular ring between $r_a = r - \delta r/2$ and $r_b = r + \delta r/2$.

❖ ***Angularity:***

$$g = \sum_{i\in jet}\frac{p_{T,i}}{p_{T,jet}}|\Delta R_{jet,i}|$$

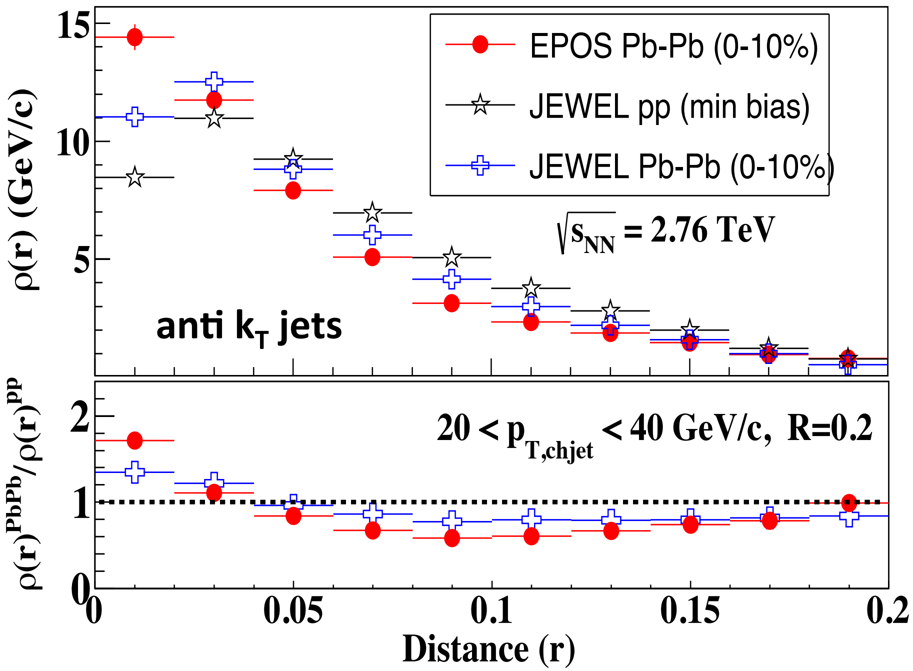
where $p_{T,i}$ denotes the transverse momentum of i-th constituent of the jet and $\Delta R_{jet,i}$ is the distance between i-th constituent of the jet and the jet axis in (η, ϕ) space.

Differential jet shape



❖ **In heavy ion collisions, the jet core has been found to be more collimated and harder compared to the pp collisions at the same reconstructed jet energy, accompanied by a broadening of the jet at it's periphery.**

Model Study: Differential jet shape



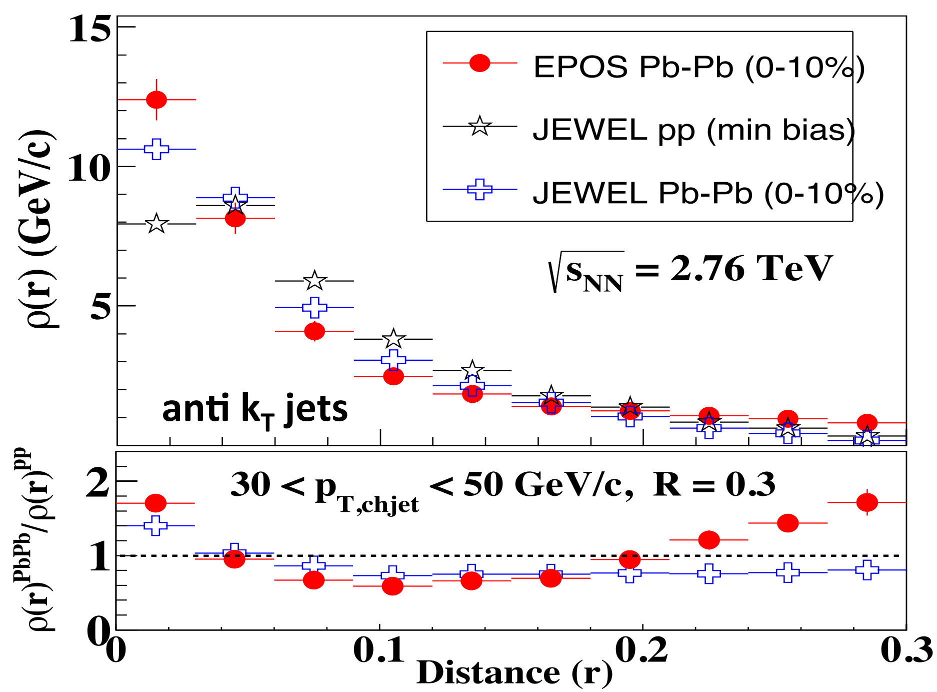
❖ EPOS With R=0.3 can qualitatively explain the data.

❖ JEWEL (recoil OFF) is unable to explain the pattern.

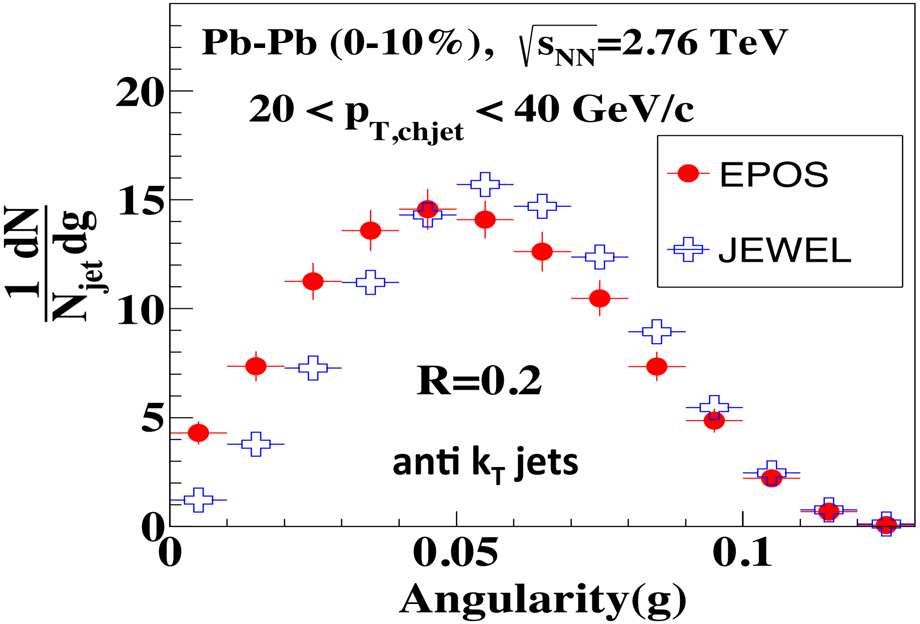
Results submitted to PRC…

❖ The energy lost by the jets in EPOS-3 appears at larger angles from the jet axis.

❖ The secondary jet-fluid Interactions during in-medium fragmentation and hadronic cascade plays an Important role.



Angularity



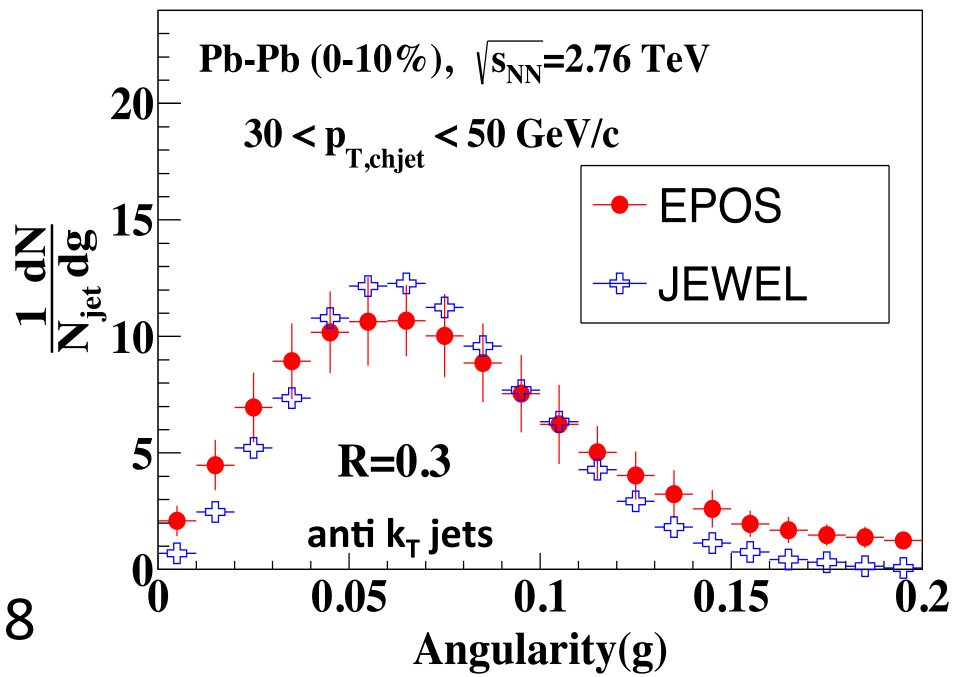
❖ Angularity measures the first moment of the constituent p_T distribution in the jet and measures the radial energy profile of the jet.

Results submitted to PRC…

❖ The jet core is harder in EPOS 3.

❖ Jet is broadened at the periphery.

❖ Consistent with differential jet shape measurement.



JEWEL with recoil ON can explain jet shapes BUT…

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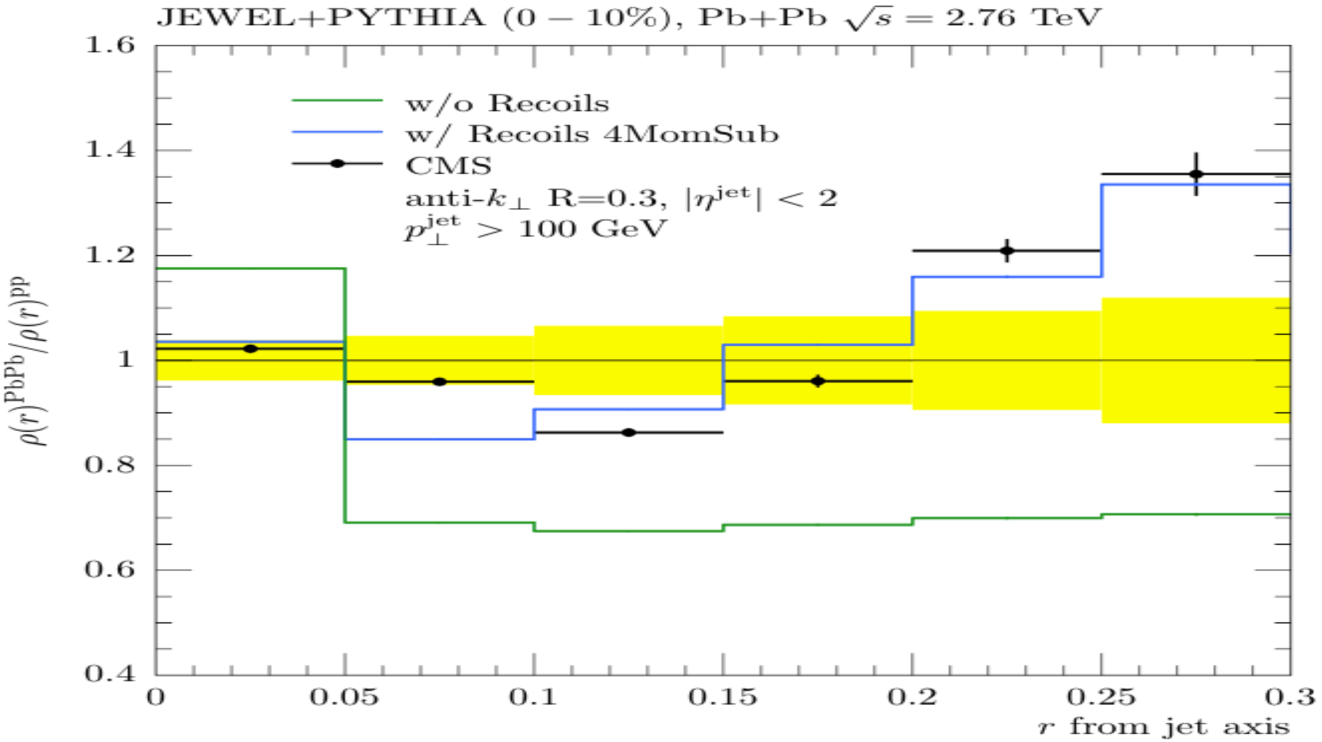


❖ ***The treatment of recoiling partons is still schematic.***

❖ ***It is currently also impossible to perform the subtraction for particles (for instance in the fragmentation functions), due to the mix of parton and hadron level in the subtraction.***

❖ ***Most importantly, it can't describe the nuclear modification factor along with collective behaviors in heavy ion collisions.***

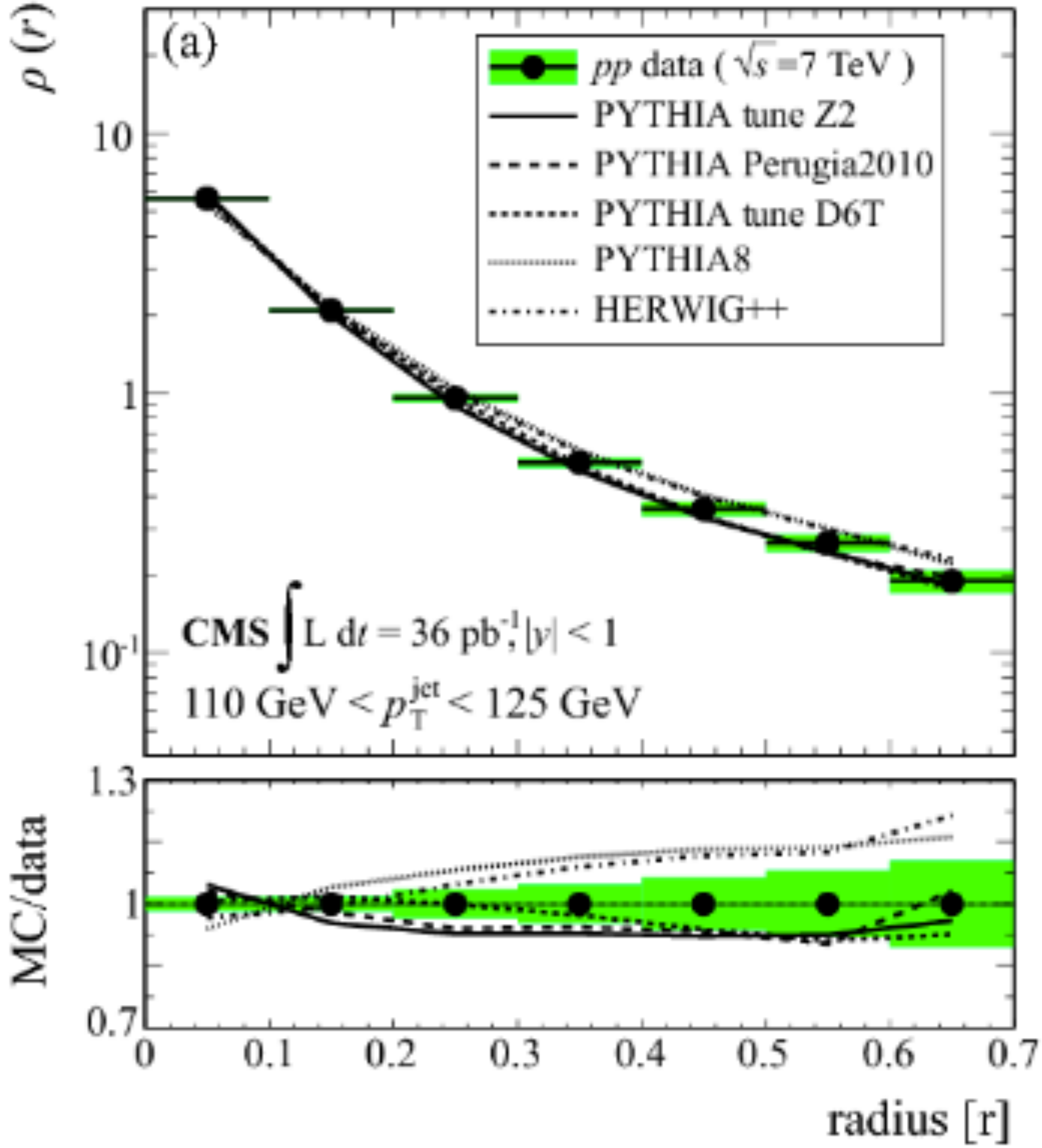
Summary and Outlook:

1. The interaction between jet and hydrodynamically evolving medium can explain the in-medium modification of the jet substructure in a better way compared to JEWEL (recoil OFF) event generator.

2**. In addition to the partonic energy loss, the secondary jet-fluid Interactions during in-medium fragmentation and hadronic cascade plays an Important role and can be instrumental in the realistic modeling of jet-medium interaction.**

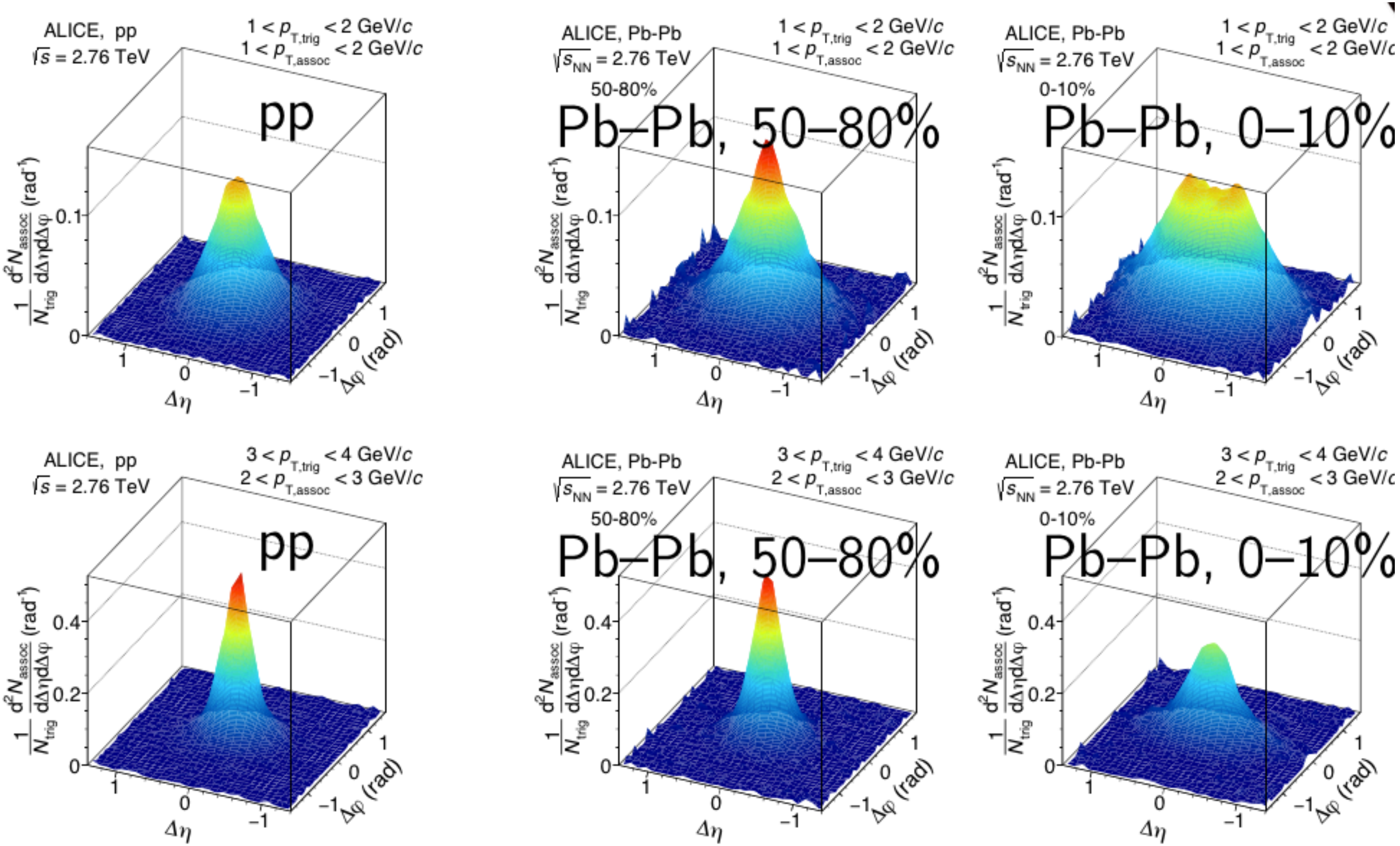
3. A better modeling of the background medium in JEWEL is required to describe of the broad spectrum of observables used to characterize the collectivity and jet-medium interaction in heavy ion collisions in a consistent way.

Thank You…



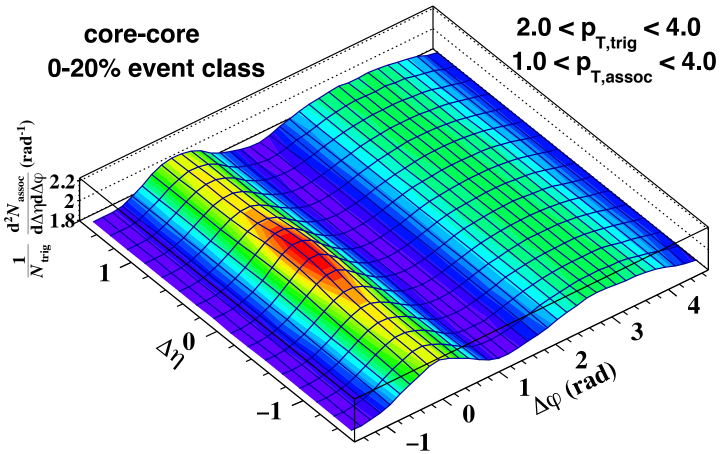
(a)
pp data (√s =7 TeV)
PYTHIA tune Z2
PYTHIA Perugia2010
PYTHIA tune D6T
PYTHIA8
HERWIG++
CMS ∫L dt = 36 pb⁻¹, |y| < 1
110 GeV < p_T^{jet} < 125 GeV
ρ (r)
MC/data
radius [r]

Jet medium interaction: Jet peak shape broadening

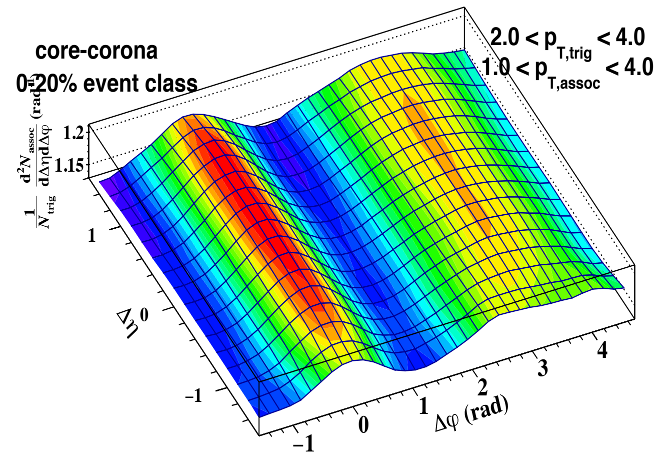


❖ **Indicates possible modification to the internal jet structure. Jet gets broadened in the central collisions!!**

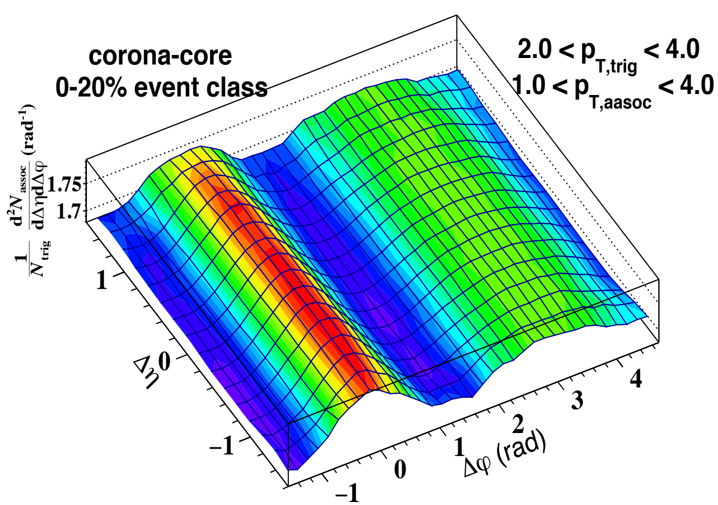
Results: Ridge from different origins



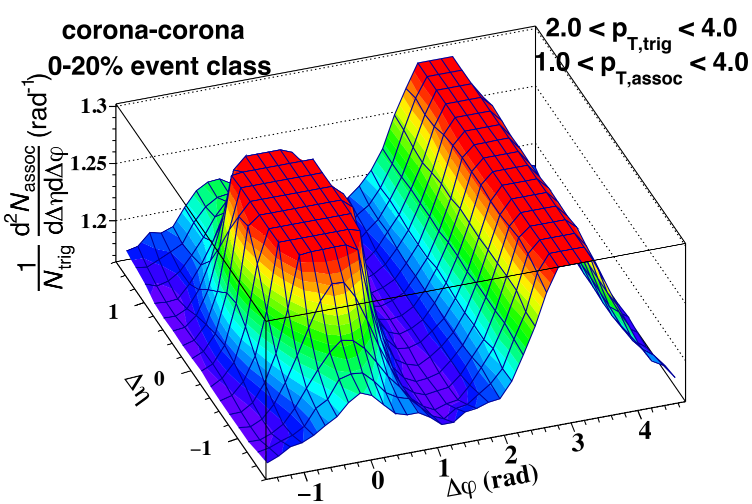
Hydrodynamics



Jet-medium interaction



Jet-medium interaction



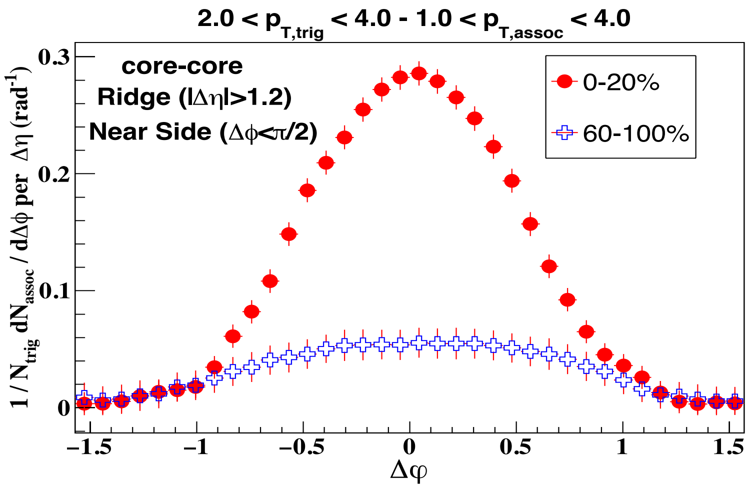
Fluxtube initial condition

+

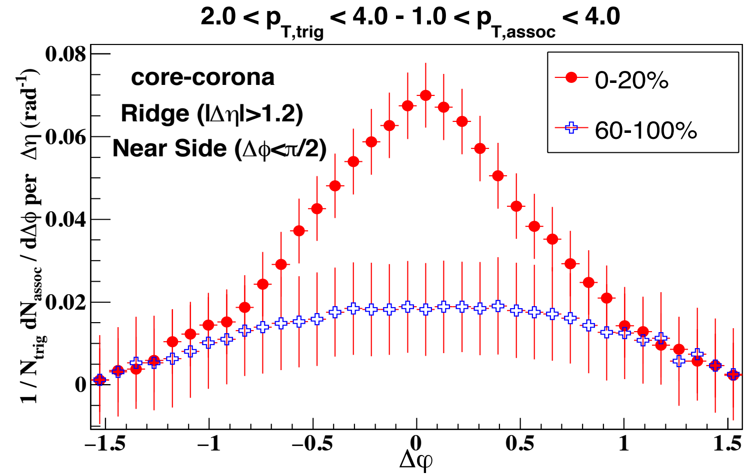
Jet-medium interaction

Results

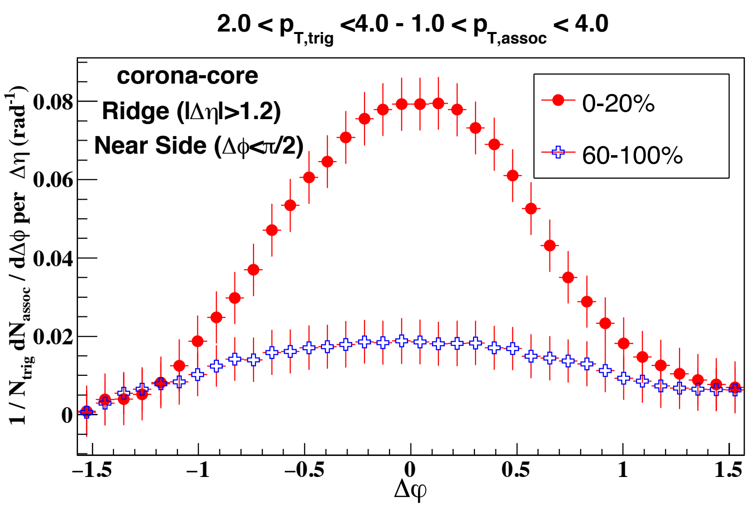
Multiplicity dependence of near side ridge from different origins



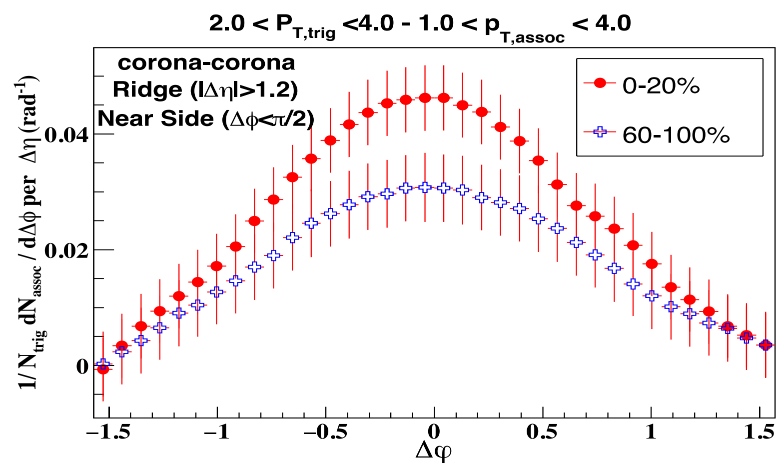
Hydrodynamics



Jet-medium interaction



Jet-medium interaction



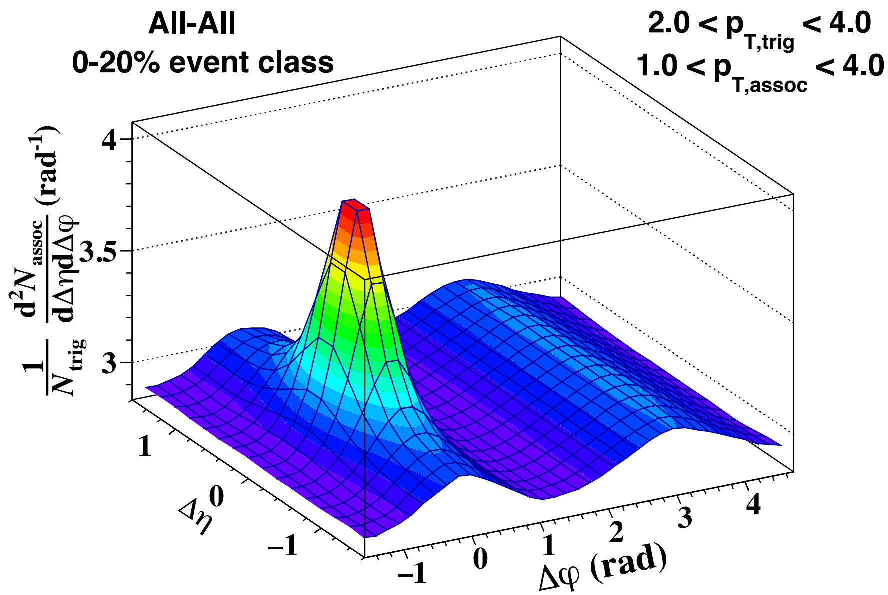
Fluxtube initial condition

+

Jet-medium interaction

Results

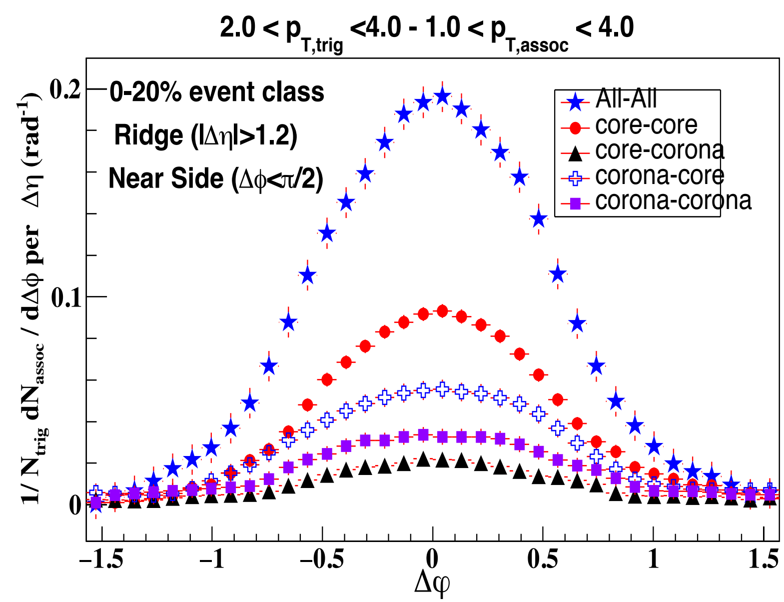
Relative contributions of different physics mechanisms towards "total" ridge



❖ Ridge in "total" calculation without any core-corona separation- termed as "All-All"

❖ The core and corona triggered correlations are normalized by total (core+corona) number of trigger particles in the trigger pT region.

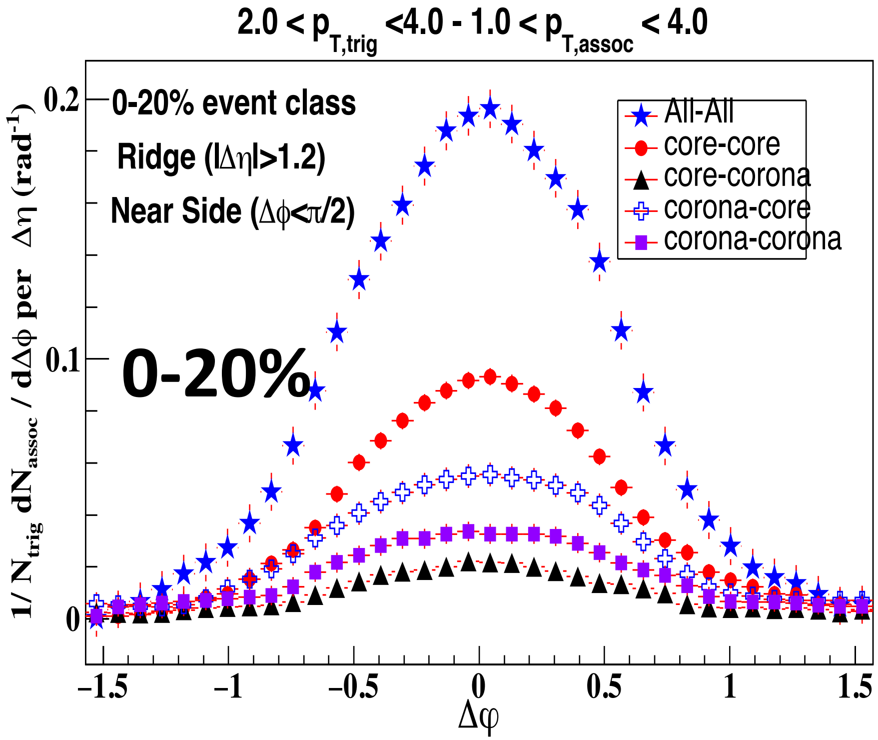
❖ Relative contribution of ridges from different origins towards "total" ridge

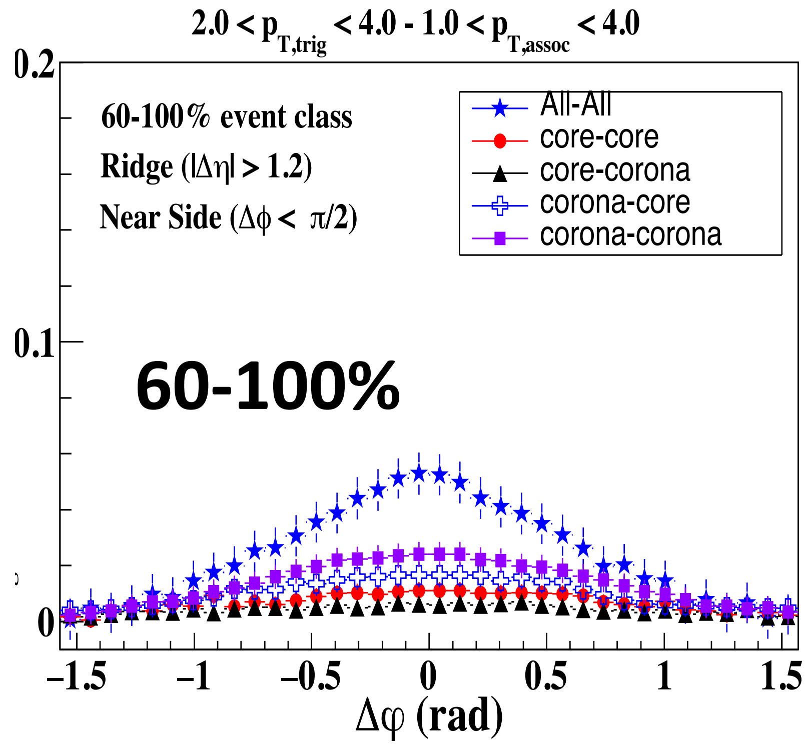


Hydrodynamics is playing the main role but jet- medium interaction and flux tube initial condition have non zero contributions.

Relative contributions of different physics mechanisms towards "total" ridge

Multiplicity dependence





- ❖ In the 60–100% event class, the total ridge ("All-All") is much smaller than the same in the 0–20% event class.
- ❖ Ridge in 0–20% event class is dominated by the core triggered correlations.
- ❖ Ridge in 60–100% event class is dominated by the corona triggered correlations.

PHYSICAL REVIEW C **95**, 044906 (2017)

Ridge from jet-medium interaction in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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(Received 21 August 2016; revised manuscript received 1 March 2017; published 13 April 2017)

In this paper we report the effect of the jet-medium interplay as implemented in the EPOS 3 model on the ridgelike structure observed in high-multiplicity p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. EPOS 3 takes into account hydrodynamically expanding bulk matter, jets and the jet-medium interaction. The basis of this model is multiple scatterings where each scattering finally produces flux tubes (strings). In the higher multiplicity event classes where the density of flux-tubes (strings) is higher, there is a finite probability that the strings will pick up quarks and antiquarks (or diquarks) from the bulk (core) for flux-tube breaking to produce jet hadrons (corona) instead of producing them via the usual Schwinger mechanism. This will eventually create a correlation between core and corona and also influence the corona-corona correlation because the corona particles containing quarks and antiquarks (or diquarks) from the bulk also carry the fluid information. We report the relative contributions of the core-core, core-corona, corona-core, and corona-corona correlations toward the ridge in high- and low-multiplicity p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the data generated by EPOS 3. The multiplicity evolution of the ridges in all the cases is also reported.

DOI: 10.1103/PhysRevC.95.044906

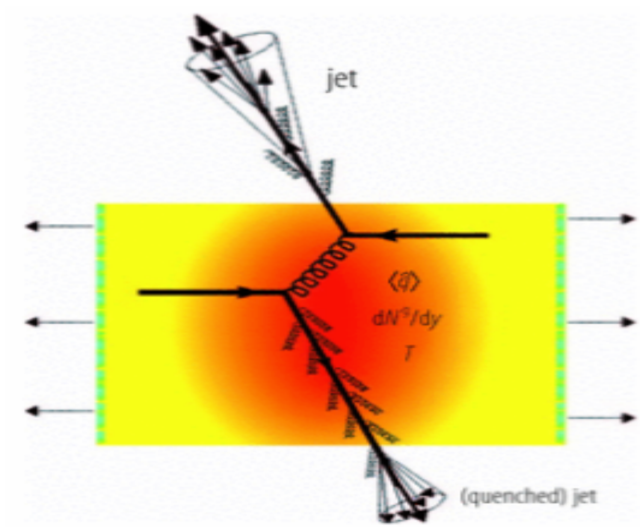
Possible contributors to Ridge (Known till date):

1) Hydrodynamics

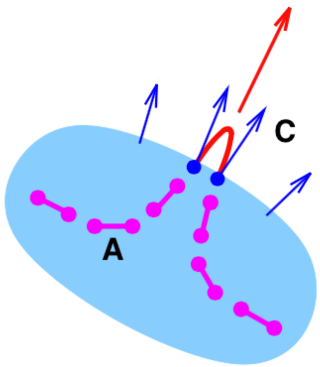
2) Flux tube like initial conditions (CGC)

3) Jet-medium interaction → Why should we bother about it??

4) Answer: Motivated by the experimentally observed pattern of fluid-jet interaction in heavy ion collisions…

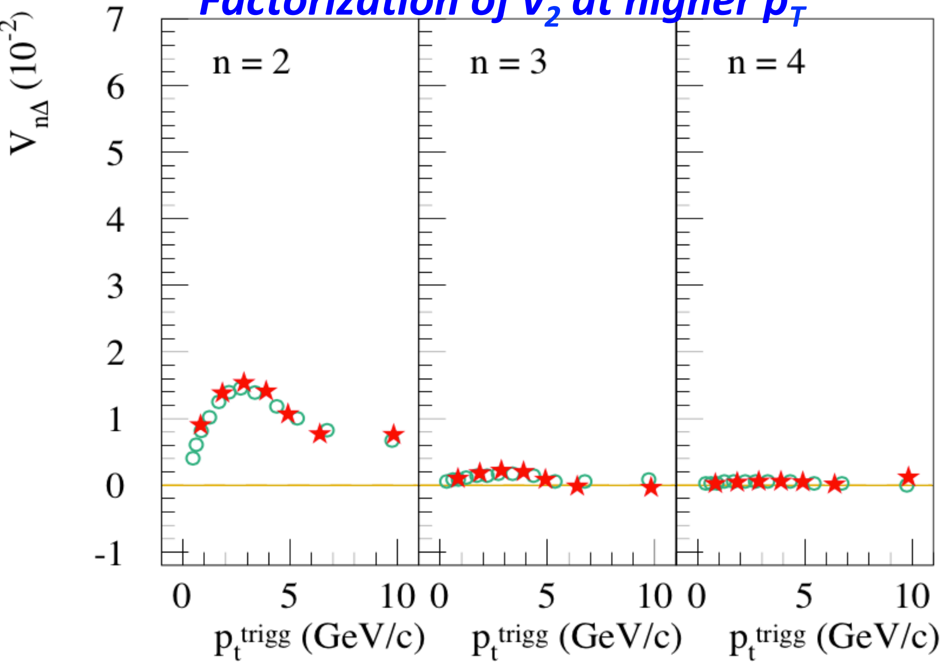


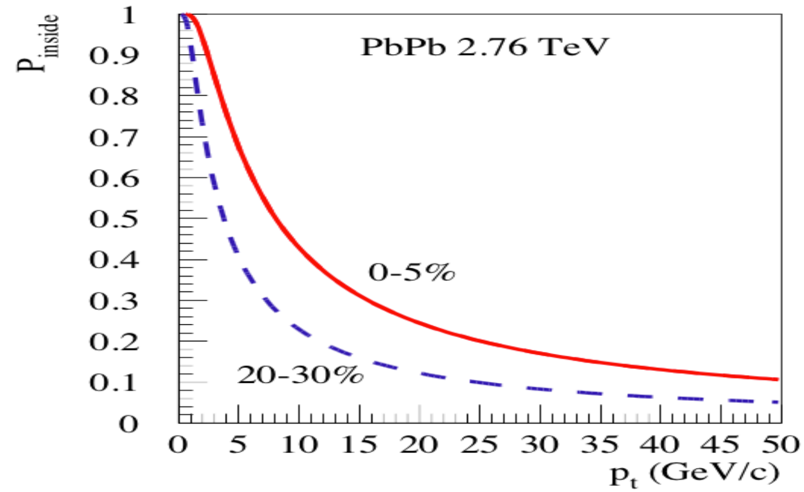
Effect of Jet-Fluid interaction on final state observables



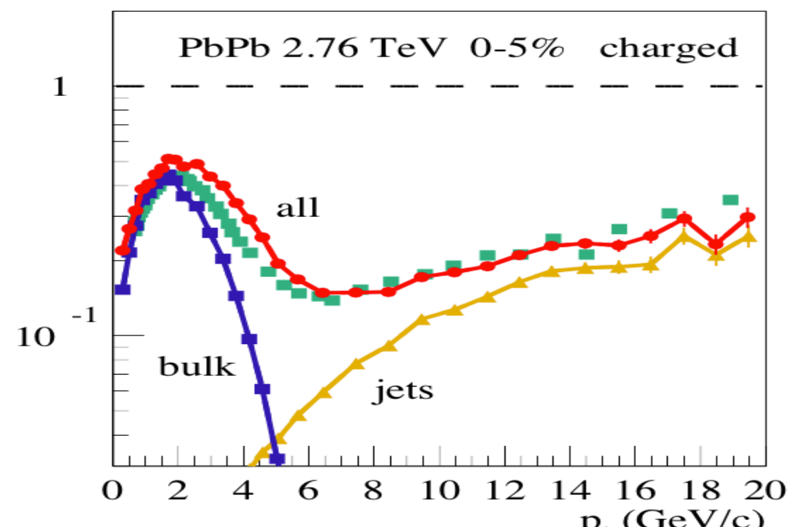
Phys. Rev. C 85, 064907 (2012)

Factorization of v_2 at higher p_T





Nuclear modification factor



❖ ***The secondary jet fluid interactions are extremely important to explain the Particle production upto pT 20 GeV/c.***

Width of the near side peak

- The near-side is fitted to characterize its shape evolution
- Fit function: background + Generalized Gaussian
  - Background:
    $C_1 + \sum_{n=2}^{4} 2V_n \cos(n\Delta\varphi)$
  - Generalized Gaussian:

$$N \times e^{-\left|\frac{d\varphi}{w\varphi}\right|^{\gamma\varphi} - \left|\frac{d\eta}{w\eta}\right|^{\gamma\eta}} \Longrightarrow N = C_2 \times \frac{\gamma_\varphi \gamma_\eta}{4 w_\varphi w_\eta \Gamma\left(\frac{1}{\gamma\varphi}\right)\Gamma\left(\frac{1}{\gamma\eta}\right)}$$

$\gamma = 1$: Exponential
$\gamma = 2$: Gaussian

- Characterize peak by variance of generalized Gaussian:
  $\sigma^2 = \frac{w^2\Gamma(3/\gamma)}{\Gamma(1/\gamma)}$
- No attempt to give physical meaning to parameters of the generalized Gaussian

Jet-medium interaction modifies the near side jet-peak width in Pb-Pb collisions

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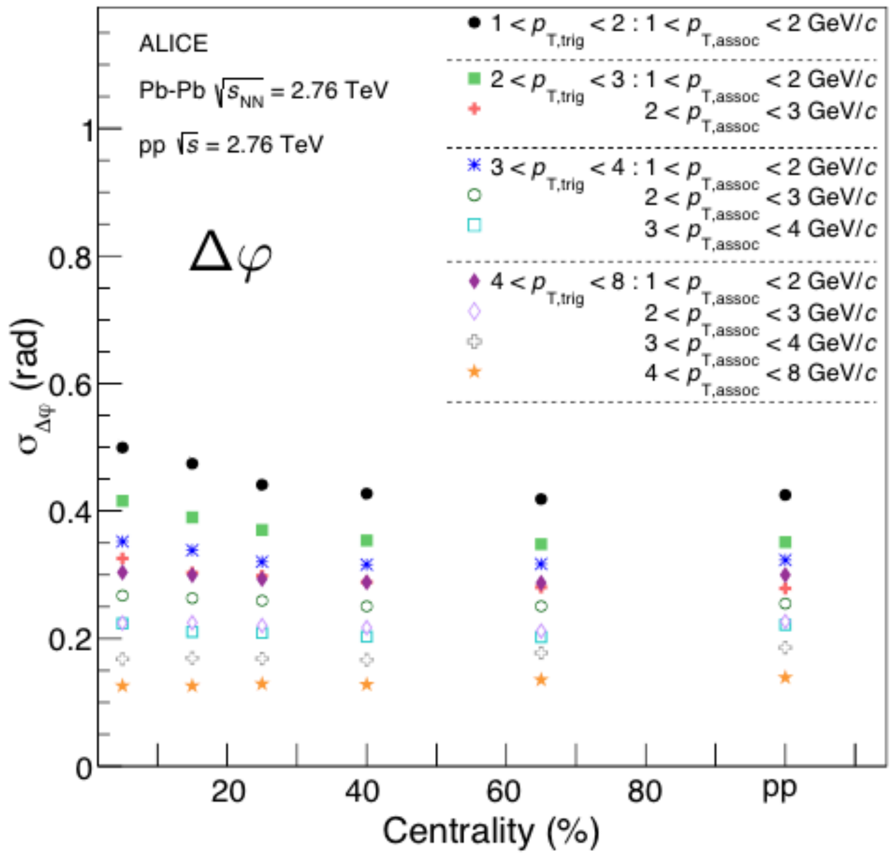
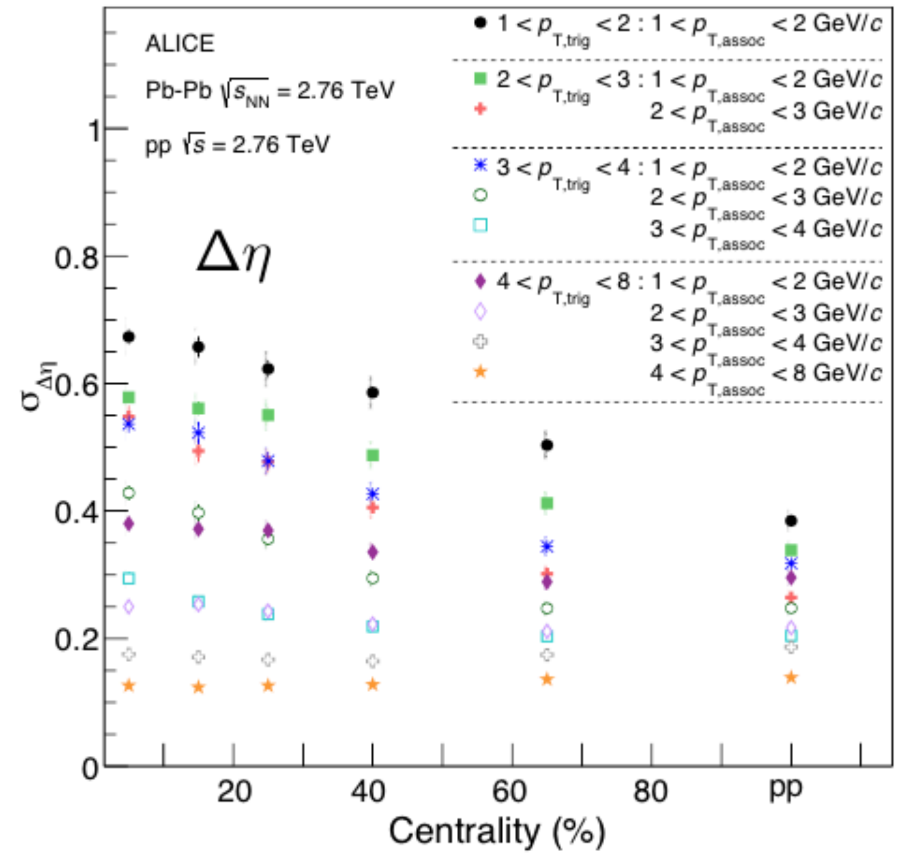




- Ordering of the width according to p_T
- Width in $\Delta\eta$ in 50–80% is already larger than in pp
- Very pronounced increase at low p_T in $\Delta\eta$

LONG RANGE ANGULAR CORRELATION—INITIAL STAGE EFFECT

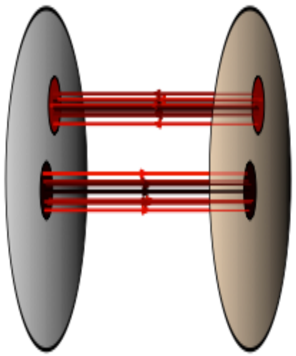
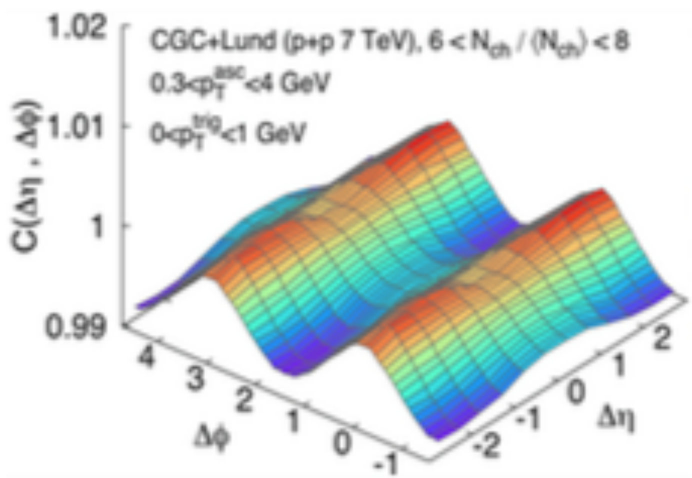


Figure 4: Glasma flux tubes. The transverse size of the flux tubes is of order

- Correlation function:
  - Partons from the same tube are correlated
  - Correlations between tubes are negligible



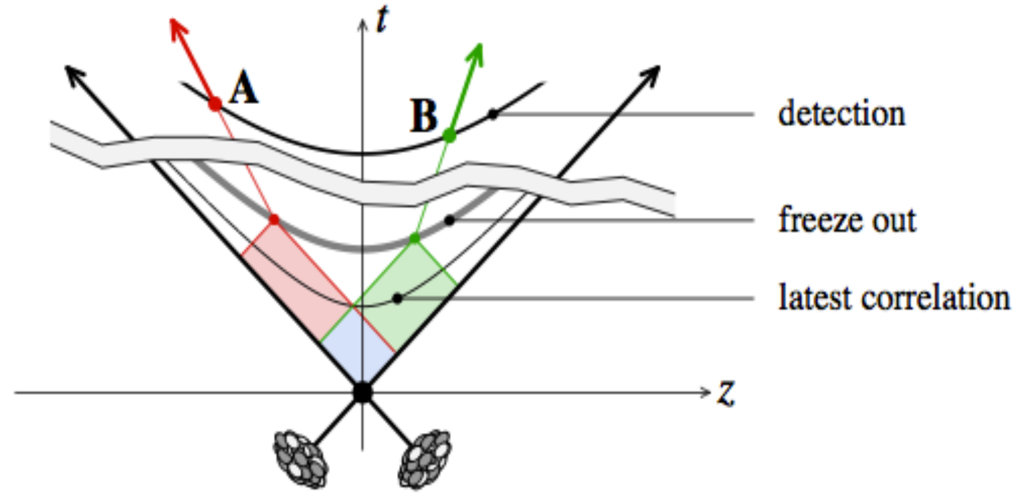


Figure 1: The red and green cones are the location of the events in causal relationship with the particles A and B respectively. Their intersection is the location in space-time of the events that may correlate the particles A and B.

◆ **If there is no medium formation due to the collision , the correlation between two correlated particles separated by large pseudorapidity difference must be originated at an earlier time → causality argument.**

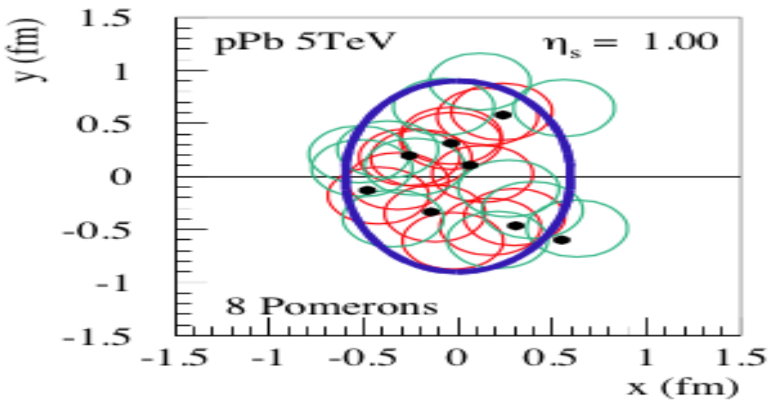
(carrying some signature of initial stage effect)

EPOS 3 is not a simple Hydro only Model:

It consists:

1) Flux tube initial conditions (CGC like).

2) Hydrodynamically expanding bulk matter (high density area or core)



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core-corona separation

3)Jets produced via Schwinger mechanism (low density area or corona)

4)Interaction between the Jet (corona) and bulk (core)

In principle different components mentioned above may contribute to the ridge like structure which has never been investigated…