Novelties of Lund strings in Heavy Ion Collisions

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PhD talks
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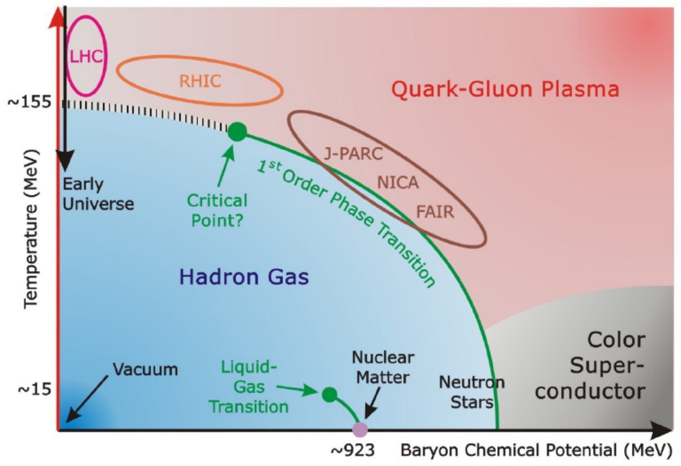
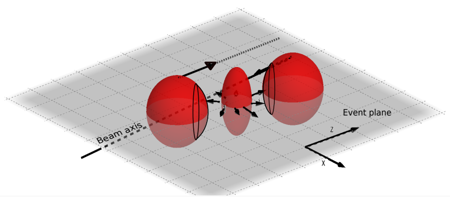
Why heavy ions and what are we looking for?



Conjectured QCD phase diagram

Anisotropy in collision geometry



Heavy ion collision in the lab frame

1. Initial eccentricities

$\downarrow\uparrow$

2. **Anisotropic flow coefficients**

$\downarrow$

3. Transport properties of the produced medium

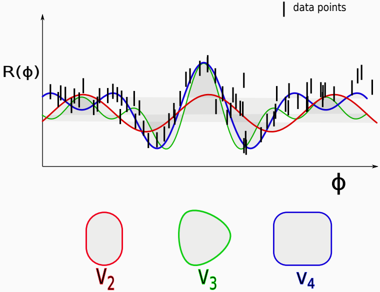
Fourier coefficients in particle distributions

$\frac{dN}{d\phi} \sim R(\phi) \propto 1 + 2\Sigma_{n=1}^{\infty} v_n cos(n\phi)$

$R(\phi) \propto 1 + 2v_2 cos(2\phi)$

$R(\phi) \propto 1 + 2v_2 cos(2\phi) + v_3 cos(3\phi)$

$R(\phi) \propto 1 + 2v_2 cos(2\phi) + v_3 cos(3\phi)$
$+ v_4 cos(4\phi)$



Angular particle distribution and geometrical interpretation of Fourier coefficients

Fourier coefficients in particle distributions

$\frac{dN}{d\phi} \sim R(\phi) \propto 1 +$

$R(\phi) \propto 1 + 2v_2c$

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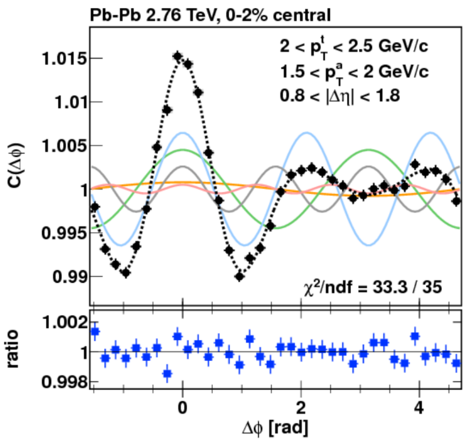
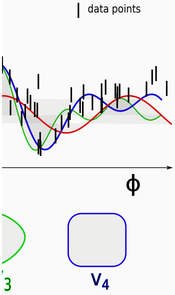
+ $v_4 cos(4\phi)$





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ion of Fourier

arXiv:1109.2501v3

The quest for the perfect fluid: Quark Gluon Plasma

To search for explanation of possible collective effects (fluid-like behaviour) in high multiplicity p-p collisions with string model

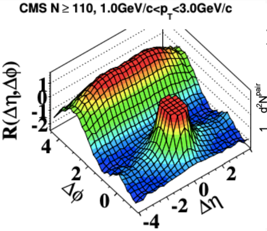


Figure 3: p-p

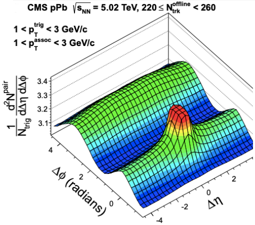


Figure 4: p-Pb

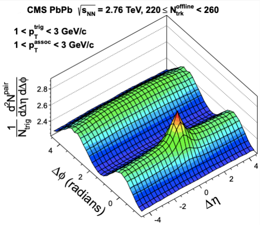
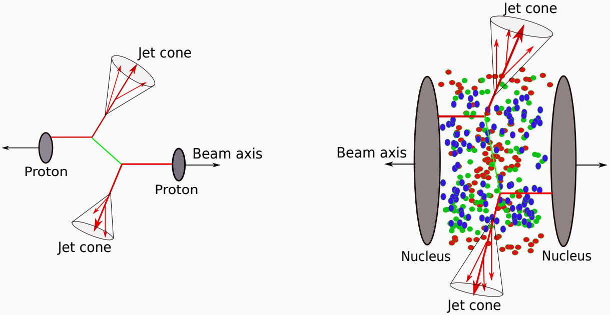


Figure 5: Pb-Pb

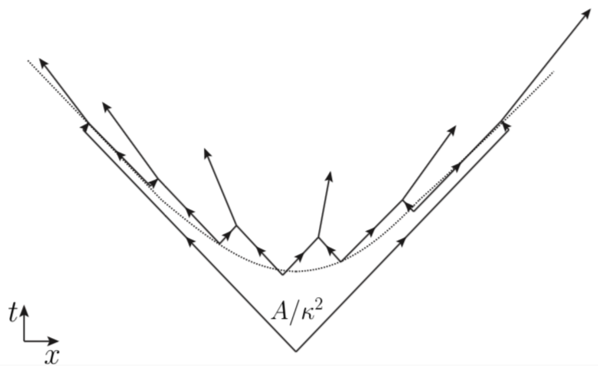
Messengers from the Deep: Jets



Jets in p-p and in A-A collisions

- Change in jet energies(quenching) observed in p-A and A-A collisions
- Is there any jet quenching in high multiplicity p-p events? Explanation in string model?

Lund string model



x-t diagram of a Lund string, with fragmentation hyperbola. The area enclosed by the quark lines is the coherence area A in units of the string tension κ

Shoving in Angantyr and advancements

1. Aspects of Angantyr:
   - A-A is treated as a collection of overlaid p-p collisions
   - Modifications needed when one nucleon in one nucleus collides with several nucleons in the other
   - No collective effects

Shoving in Angantyr and advancements

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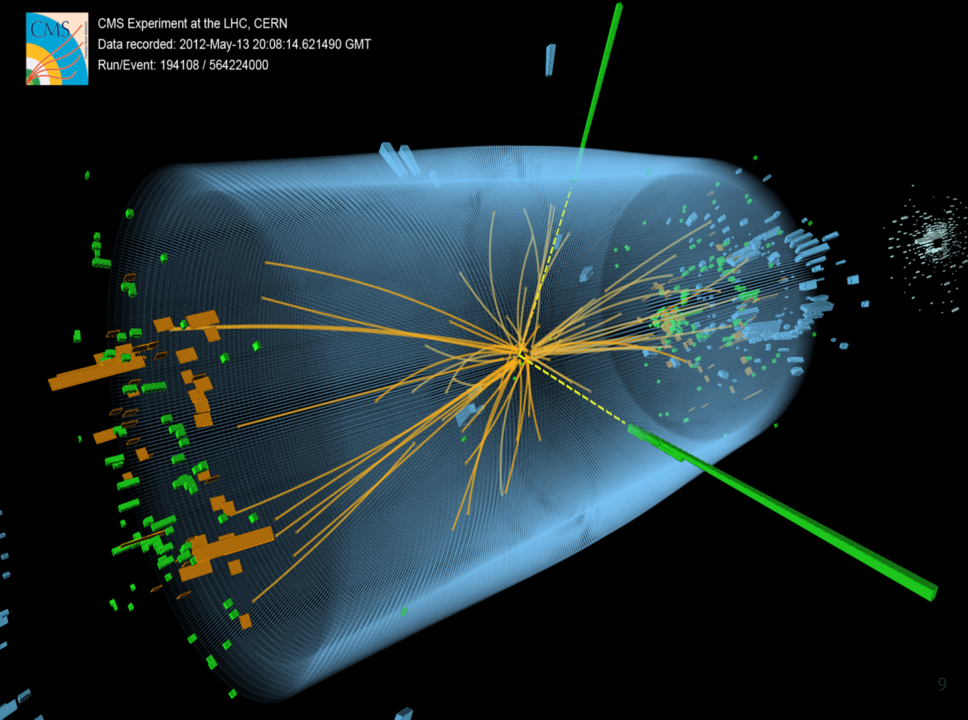
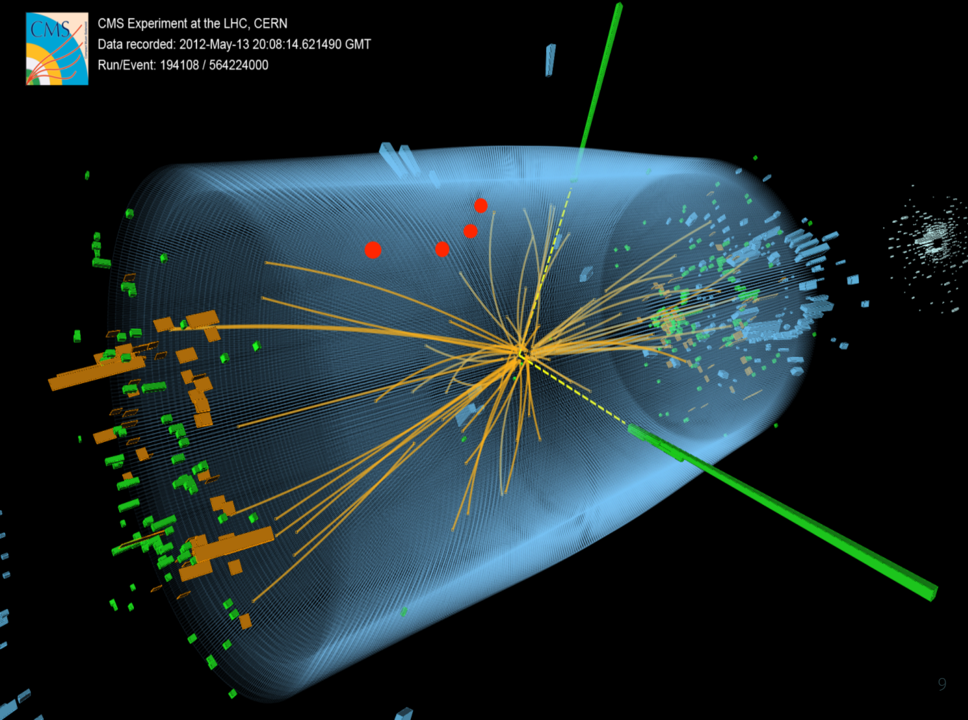
2. Mechanisms to study high-multiplicity p-p and A-A behaviours :
   - String shoving $\rightarrow$ Final-state collective effects?

Methodology

1. Parallel frame
2. Interaction force between two strings
3. Push distribution among hadrons


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000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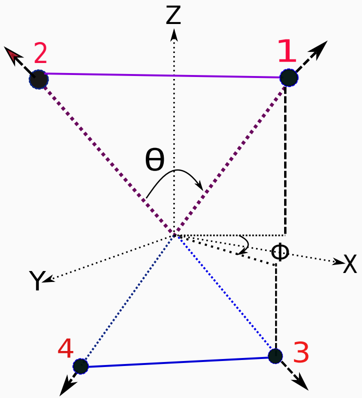
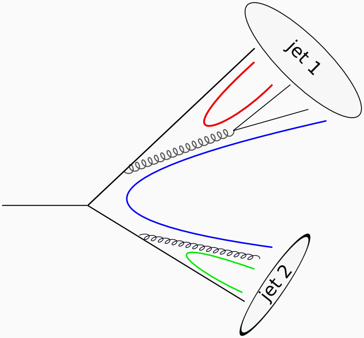
Run/Event: 194108 / 564224000

1. Lorentz invariant frame - the parallel frame



Schematic view of two strings in the parallel frame,
1,2,3,4 are partons(string-ends),
θ = opening angle, ϕ = skew angle.
All partons are considered as **massless!!**

Jets in parallel frames

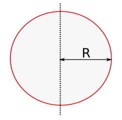


- Jets → quarks and gluons
- Interaction with partons following rule of least string length → modifies initial energy of jets

2. Interaction energy between strings

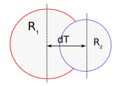
1. A string of radius R:

$$\mathit{Field}\ E(r_\perp) = C \exp\left(-\frac{r_\perp^2}{2R^2}\right) \tag{1}$$



2. Force $f(d_\perp)$ per unit length:

$$f(d_\perp) = \frac{dE_{int}}{dd_\perp} = \frac{g\kappa d_\perp}{R^2} exp\left(-\frac{d_\perp^2(t)}{4R^2}\right) \tag{2}$$



where g is a tunable parameter.

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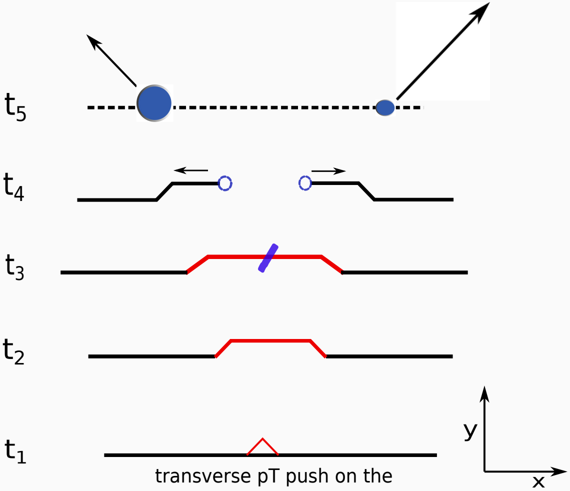
arXiv:1710.09725v1 [hep-ph] 26 Oct 2017

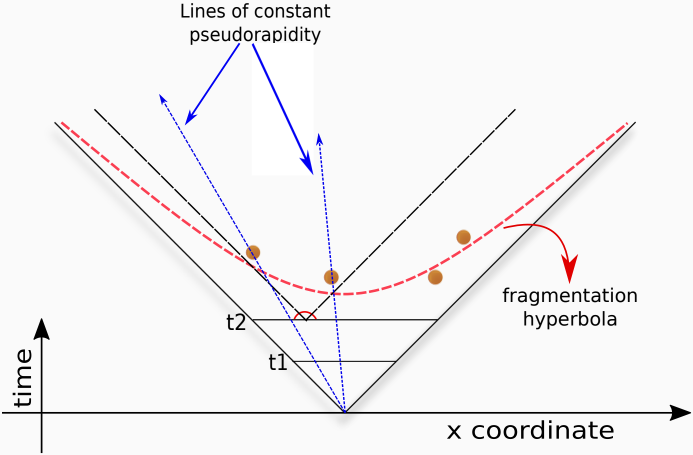
3. 'Push' distribution among hadrons



transverse pT push on the string

Parton vertices and hadronization

pseudorapidity $\eta = -ln(tan\frac{\theta}{2})$



Preliminary results

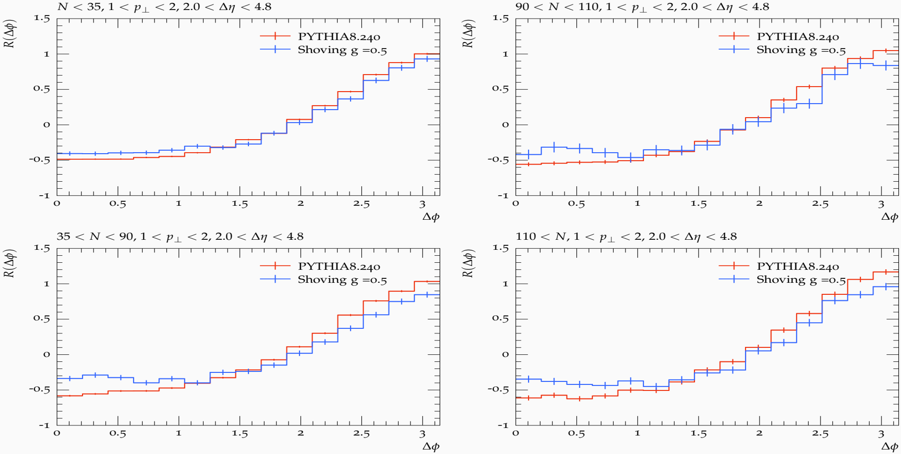
What are we looking at?

1. $S_N = \frac{1}{N(N-1)} \frac{d^2 N^{signal}}{d\Delta\phi d\Delta\eta}$
2. $B_N = \frac{1}{N^2} \frac{d^2 N^{mixed}}{d\Delta\phi d\Delta\eta}$
3. $\mathrm{R}(\phi) = \left\langle (< N > -1) \left(\frac{S_N}{B_N} - 1 \right) \right\rangle$

where <N> is the number of tracks per event averaged over the multiplicity bin, and the final $R(\Delta\eta, \Delta\phi)$ is found by averaging over multiplicity bins

- Analysis follows from: Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC, CMS Collaboration, arXiv:1009.4122v1 [hep-ex] 21 Sep 2010.

Di-hadron correlations in p-p at 7 TeV



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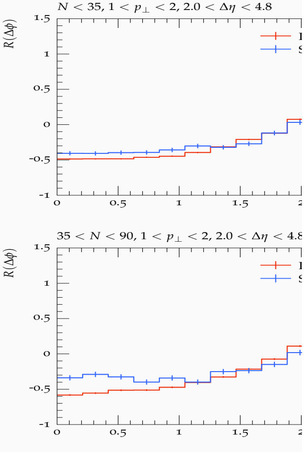

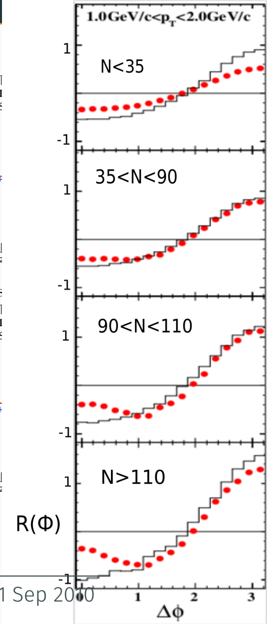

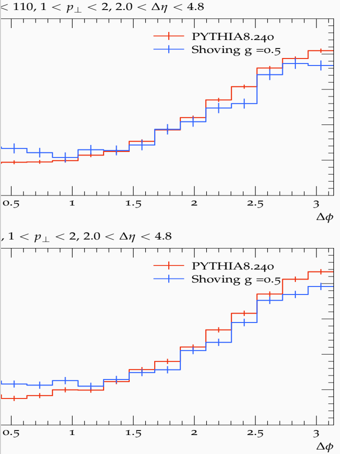

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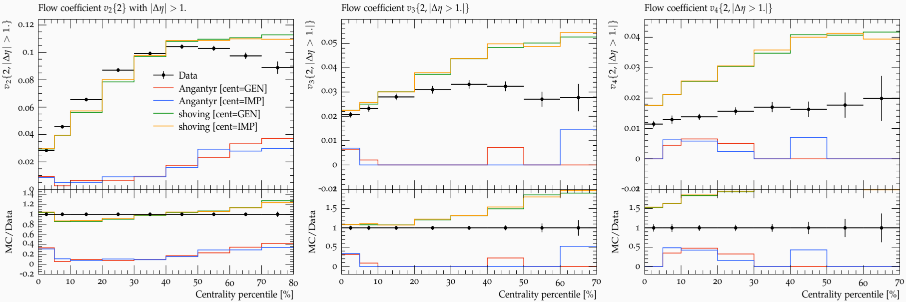
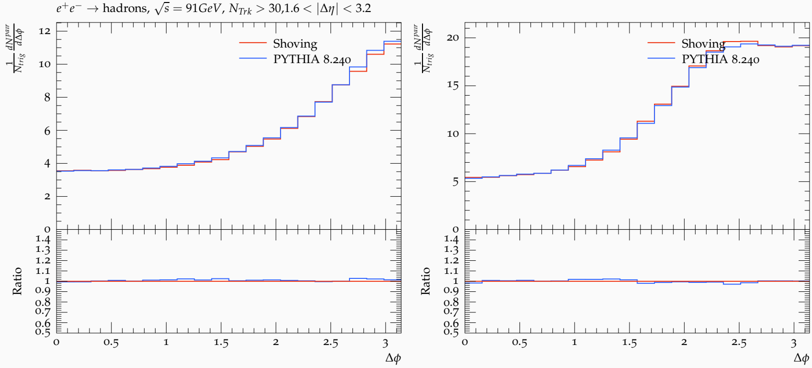
[1] arXiv:1009.4122v1 [hep-ex] 21 Sep 2010

Flow coefficients in Pb-Pb at 5.02 TeV



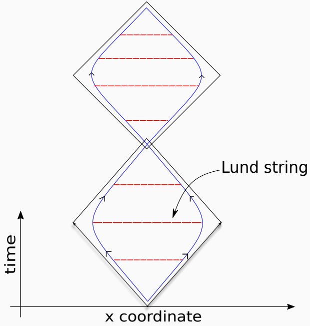
v_2, v_3 and v_4 coefficients calculated using Angantyr and shoving g=0.25, for generated centrality bins and impact parameter bins.

Two particle correlations in $e^+ - e^-$ at 91 GeV



arXiv:1906.00489v5 [hep-ex] 9 Oct 2019

Heavy quark scenario



1. **Motivation:** Strangeness and charmonium production in string picture
2. **Aim:** To study hadron production ratios
3. **Changes:** Mass term in kinematics, v < c

Conclusions

1. Summary
   - Shoving gives an observable collective effect in high multiplicity p-p, p-A and A-A events
   - No corresponding effect observed for $e^+ - e^-$ collisions
2. Next steps
   - Study of initial state anisotropy and its effects
   - Study with jets: search for jet quenching
   - Heavy quarks and hadron production ratios

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Extras

Fourier series and coefficients

1. Azimuthal angle ϕ is in the range 0 to 2 π
2. R(ϕ) = $\frac{dN}{d\phi}$ $\rightarrow$ periodic function representing azimuthal distribution
3. Fourier series representation:
   $r(\phi) = \frac{a_0}{2\pi} + \frac{1}{\pi}\Sigma_{n=1}^{\infty}[a_n cos(n\phi) + b_n cos(n\phi)]$,
   where $a_n = \int_{-\pi}^{\pi} r(\phi)cos(n\phi)d\phi, n \geq 0$ and
   $b_n = \int_{-\pi}^{\pi} r(\phi)sin(n\phi)d\phi, n \geq 1$
4. When there is a finite number of particles, these becomes
   $a_n = \Sigma r(\phi_i)cos(n\phi_i), n \geq 0$ and $b_n = \Sigma r(\phi_i)sin(n\phi_i), n \geq 1$
   where ϕ_i is the azimuthal angle of the i-th particle.

Fourier series and coefficients(contd.)

1. Introduce w_n and Ψ_n: $w_n = \sqrt{a_n^2 + b_n^2}, \frac{-\pi}{n} \leq \Psi_n < \frac{\pi}{n},$
2. $a_n = w_n cos(n\Psi_n)\ b_n = w_n sin(n\Psi_n)$
3. $a_n cos(n\phi) + b_n sin(n\phi) = w_n(cos(n\Psi_n)cos(n\phi) + sin(n\Psi_n)sin(n\phi))$

   = w$_n cos(n(\phi - \Psi_n))$
4. Therefore,

$$a_0 = w_0 cos(0\Psi_n) = w_0 = \int_{-\pi}^{\pi} \frac{dN}{d\phi} d\phi = N \tag{3}$$

5. The Fourier series representation can be written as:

$$r(\phi) = \frac{w_0}{2\pi}(1 + \Sigma_{n=1}^{\infty} 2\frac{w_n}{w_0} cos(n(\phi - \Psi_n))) \tag{4}$$

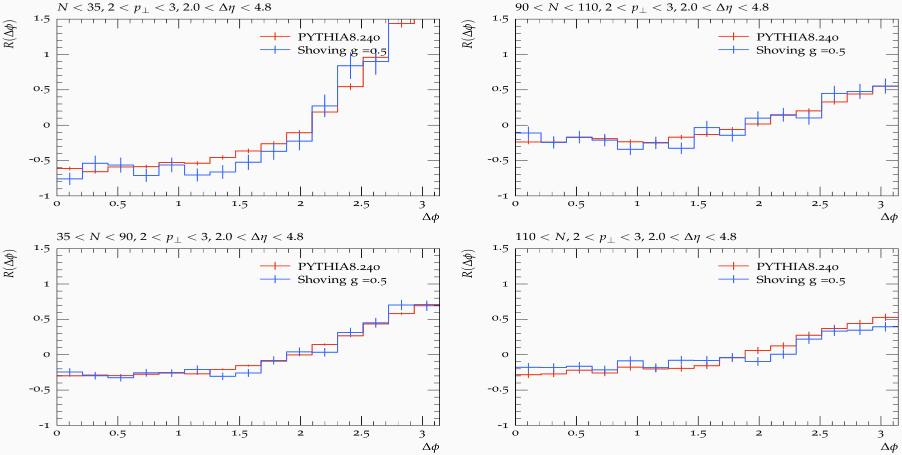
Fourier series and coefficients(contd.)

1. The average of cos(nϕ) = cos(n($\phi - \Psi_n$)) gives the coefficients of the series:

$$\langle cos(n\Delta\phi)\rangle = \frac{\int_{-\pi}^{\pi} cos(n\Delta\phi)(1 + +\Sigma_m 2v_m cos(m\Delta\phi))d\phi}{\int_{-\pi}^{\pi}(1 + +\Sigma_m 2v_m cos(m\Delta\phi))d\phi} \tag{5}$$

2. We get $\int_{-\pi}^{\pi} cos(n\Delta\phi)(1 + +\Sigma_m 2v_m cos(m\Delta\phi))d\phi = 2v_n\pi$ and $\int_{-\pi}^{\pi}(1 + +\Sigma_m 2v_m cos(m\Delta\phi))d\phi = 2\pi$
3. $$\langle cos(n\Delta\phi)\rangle = \frac{2v_n\pi}{2\pi} = v_n \tag{6}$$

Di-hadron correlations in p-p at 7 TeV



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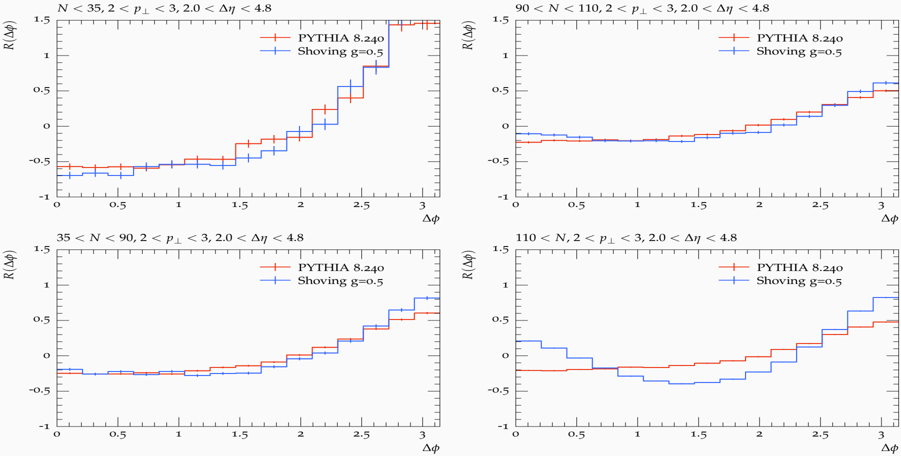
Di-hadron correlations in p-Pb



Note: Rivet analysis used is for p-p!

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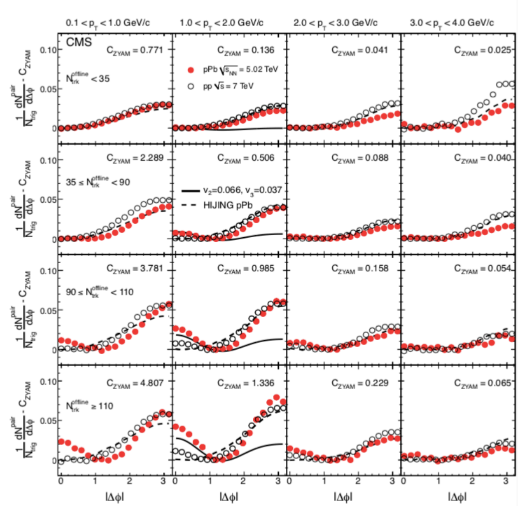
arXiv:1210.5482v3 [nucl-ex] 20 Mar 2013

Di-hadron correlations in p-Pb



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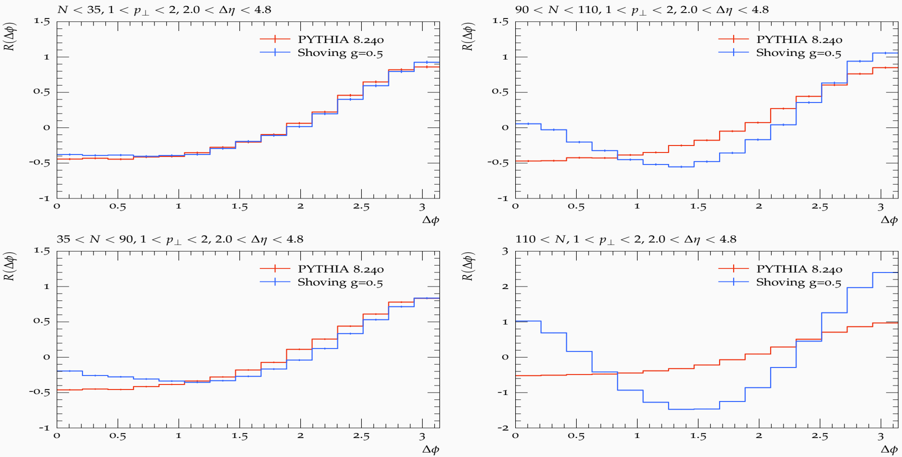

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