A Monte Carlo Study of Multiplicity Fluctuations in Pb–Pb Collisions at LHC Energies

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Association

with **Rohni Sharma**
(University of Jammu)

And helpful advice from **R.C. Hwa**
(University of Oregon)

Plan

- Introduction & Motivation
  - Intermittency
  - Erraticity
- MC Data Analysed
- Methodology & Analysis
- Observations
- Summary

Introduction Motivation

Inroduction & Motivation

- Dynamics of the initial processes in the HICs affects the final distribution of the particles produced

  S. Gavin & George Moschelli, PRC 85,014905 (2012)

- **Charged particle multiplicity fluctuations** is one of the sensitive probes of the properties of the system.
- Multiplicity distributions can be analysed in terms of its **Moments**.
- **Factorial Moments** are one of the convienent tools to study multiplicity fluctuations.
  - with the advantage that it filter out the statistical fluctuations.

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- **Factorial Moments**

$$F_q(\delta^d) = \frac{\langle n!/(n-q)! \rangle}{\langle n \rangle^q}$$

  - first used by A. Bialas and R. Peschanski[1] to explain unexpectedly large fluctuations in high multiplicity events recorded by the JACEE Collaboration.
  - where n is bin multiplicity, δ^d bin-size in a d-dimensional phase-space
  - and $\langle \ldots \rangle$ is over all events (Vertical Moments$--$ > Horizontally averaged Vertical Moments) or bins in an event(Horizontal Moments $--$ > Vertically averaged horizontal moments).

- Suggested as measure to study the fluctuations that are independent of the scale of the bin sizes (δ).
- A power-law

$$F_q(\delta) \propto \delta^{-\varphi_q} \qquad \text{over a range of small } \delta$$

or

$$F_q(M) \propto M^{\varphi_q} \qquad \text{over number of bins } M \ (M \propto 1/\delta)$$

is termed as **intermittency**

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However

- The method of the factorial moments F_q does not fully account for all the fluctuations that the system exhibits.
- Vertically averaged horizontal moments, can gauge the spatial fluctuations, neglecting the event space fluctutautions
- On the other hand, horizontally averaged vertical moments lose information about spatial fluctuation and only measure the fluctuations from event-to-event

Improvement

Hwa and Cao* proposed new moments:

Moments of Factorial Moment distributions

- Take into account the spatial fluctuations
- as well as the event space fluctuations.

Referred to as the **Erraticity Analysis of Fluctuations**.

* Z. Cao, R. Hwa, **Phys. Rev. Lett. 75**, 1268 (1995), PRD 53, 6608(1996); PRD

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Erraticity..

- In contrast to Sample factorial moments, Cao and Hwa defined event factorial moments as

$$F_q^e(M) = \frac{f_q^e(M)}{[f_1^e(M)]^q}$$

so as to have $P(F_q^e(M))$ distribution for a set of events where

$$f_q^e(M) = \langle n_m(n_m - 1)\ldots(n_m - q + 1)\rangle_h$$

with n_m being the multiplicity in the m^{th} bin.
Only bins with $n_m \geq q$ are considered
and q is a positive integer ≥ 2

- $F_q^e(M)$: numerical value, that describes the pattern of distribution of produced particles of the e^{th} event.
- Deviation of $F_q^e(M)$ from $\langle F_q^e(M)\rangle_v$ for each event can be defined as

$$\Phi_q(M) = \frac{F_q^e(M)}{\langle F_q^e(M)\rangle_v}$$

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Erraticity

- Whereas double moments ;
  For the vertical p^{th} order moments of the normalised q^{th} order factorial(horizontal) moments can be calculated as

$$C_{p,q}(M) = \langle \Phi_q^p(M) \rangle_v$$

  p is a positive real number and $\Phi_q^p(M)$ is

$$\phi_q^p(M) = \frac{[F_q^e(M)]^p}{\langle F_q^e(M) \rangle_v^p}$$

- And the power law behaviour

$$C_{p,q}(M) \propto M^{\psi_q(p)}$$

  is referred to as *erraticity* and from this one can define a measure **erraticity index** defined as

$$\mu_q = \frac{d\psi_q(p)}{dp}$$

- independent of M
  characterizes the fluctuations of spatial patterns.
  quantifies the degree of fluctuations in the generated data.

Advantages at LHC energies

- To understand the subject of dynamical fluctuations both these measure have been used to analyse the experimental data from different collision systems
- However at RHIC and lower energies, the total multiplicities are not enough to avoid substantial averaging that erases some aspects of the fluctuations
- Measures rely on the large bin multiplicities.
- At LHC energies, where multiplicities are higher, it is possible to have detailed study of the local properties in (η, ϕ) space for narrow p_{T} bins.

- To explore the dynamical properties of the system created in the HIC at these energies with these least studied tools (in the recent past)

Motivation

Intermittency

The footprints of a **Phase Transition** *that has fluctuations of all scales may then be possibly observed in the measurement of intermittency.**

* A. Bialas and R.C. Hwa, Phys. Lett B 253, 436 (1991).

...

- A study of the second order PT, in Ginzburg-Landau theory by Hwa and Nazirov** found that F_{q} satisfies power-law behavior

$$F_q \propto F_2^{\beta_q}, \quad \text{referred to as F-scaling}$$

$$\beta_q = (q-1)^{\nu}, \qquad \nu = 1.304 \ .$$

- Quark-hadron PT simulated in 2D Ising Model, is found to be in agreement***

** R.C. Hwa and M.T. Nazirov, Phys. Rev. Lett. 69, 741 (1992).

* * * Z. Cao, Y. Gao and R.C. Hwa, Z Phys. C 72, 661 (1996).

Erraticity

- Hwa and Yang in their recent work* proposed erraticty index as a measure to distinguish different criticality classes.
- A definitive value of μ from the LHC is called for deeper understanding of the hadronizatin process.
- For order parameter 4 μ is found to distinguish the four different cases viz., crirtica, pseudocritical, quasicritical and non-critical.
- $\mu_4 = 1.87 \pm 0.84^*$ for the critical case and $\mu_4 = 4.65 \pm 0.06$ for non-critical case.

$*$ PRC 85, 044914 (2012)

A MultiPhase Transport Model

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- In an attempt to develop and understand the methodology
  we have studied the charged particles generated at midrapidity in
  Pb–Pb collisions
  at =2.76 TeV
  using AMPT model (A Multi-Phase Transport Model)*
- Also since this has been quite useful in understanding recent
  experimental results**

∗ PRC 61, 067901 (2000),PRC 64, 011902 (2001)
∗∗ PRC 84, 044907, (2011)

A MultiPhase Transport Model

AMPT

- Hybrid model
- and consists of four main parts
  initial conditions, partonic interactions, hadronization and hadron rescattering.
- The initial conditions; are obtained from Heavy Ion Jet INteraction Generator (HIJING) model. There are two versions of the AMPT model
  - default (DF) and
  - string melting(SM)

  depending on how the partons are hadronized.

A MultiPhase Transport Model

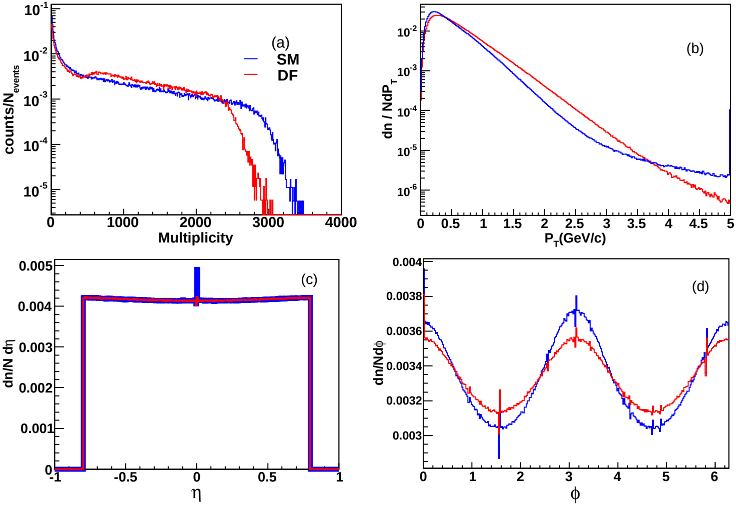
Data

- Analysis is done for Data generated using both the versions
- with parameters a =2.2, b=0.5, μ=1.8 and α= 0.47*
- $|\eta| \leq 0.8$ with full azimuthal coverage.
- 5 p_{T} bins (≤ 1 GeV/c and $\Delta p_{\mathrm{T}} = 0.1$ GeV/c).
- $0.2 \leq p_{\mathrm{T}} \leq 0.3$
  $0.3 \leq p_{\mathrm{T}} \leq 0.4$
  $0.4 \leq p_{\mathrm{T}} \leq 0.5$
  $0.6 \leq p_{\mathrm{T}} \leq 0.7$
  $0.9 \leq p_{\mathrm{T}} \leq 1.0$

  One should not integrate over all p_{T} because the superposition of different patterns at different Δp_{T} intervals can smear out all recognizable features.

* arXiv:1210.0512v3(2013)

Data

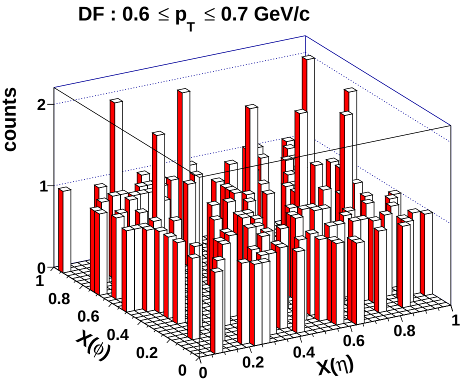


The charged particle data generated by MC:
a) Multiplicity distribution (b) p_{T} (c) η and (d) ϕ distributions, for DF(red) and SM (blue) verion.

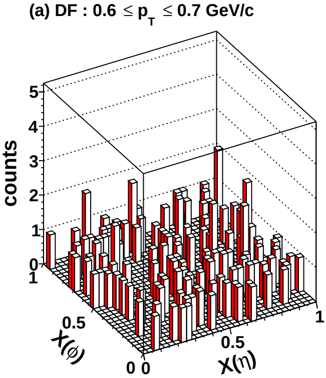
Methodology & Analysis

- The single-particle density distribution in η and ϕ is non flat and thus is converted to the cumulative variable* $X(\eta)$ and $X(\phi)$.
- $(X(\eta), X(\phi))$ phase space of an event in the selected p_{T} window is binned in a square matrix with M^2 cells.
- M depends on the multiplicity in the Δp_{T} interval, so that the important part of the M dependence is captured (M: 2 to 32)

∗ W. Ochs, Z Phys. C 50, 339 (1991).

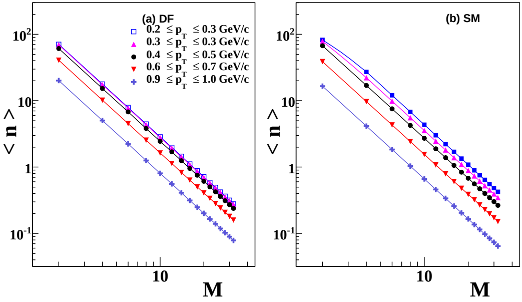


$(X(\eta), X(\phi))$ phase space of an event with $M = 32$



$(X(\eta), X(\phi))$ phase space of an event with $M = 32$ in DF and SM case

Methodology & Analysis



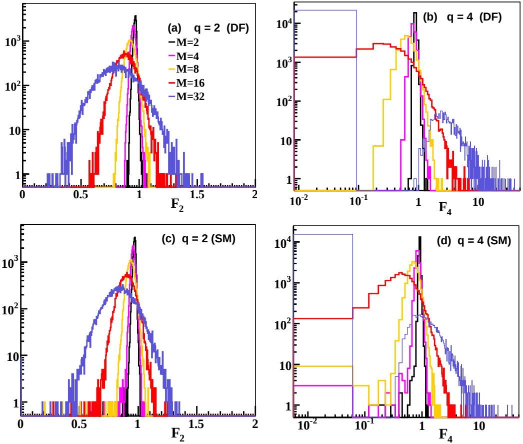
This figure shows the bin multiplicity dependence on M for the five p_{T} bins, in case of DF and the SM AMPT model

p_T **window**	**Default** $< N >$	**String Melting** $< N >$
$0.2 \leq p_T \leq 0.3$	285.2	434.8
$0.3 \leq p_T \leq 0.4$	279.2	355.5
$0.4 \leq p_T \leq 0.5$	243.7	271.6
$0.6 \leq p_T \leq 0.7$	163.3	155.5
$0.9 \leq p_T \leq 1.0$	80.5	66.1

Table : Average Multiplicity of the Simulated Data sets analyzed in different $p_T$windows
DF: 23424 events with $b \leq 5$
SM: 19669 events with $b \leq 5$

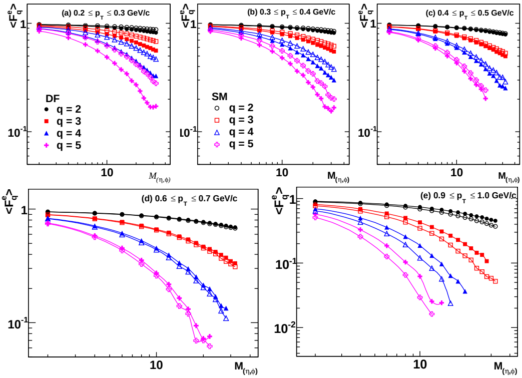
Methodology & Analysis

- Determine event factorial moments
- study M dependence and : hence the binning resolution
- $F_q^e(M) = 1$: For Poissonian



- This figure shows $P(F_q^e)$ distributions for order moment $q = 2$ and $q = 4$ for DF and SM ($0.3 \leq p_{\mathrm{T}} \leq 0.4$).
- (a) For q = 2 in DF (b) q = 4 in DF (c) q = 2 in SM and (d) q = 4 in SM. M values in multiples of 2 are shown only.
- Distributions become wider as M increases. And for higher q values i.e., 4, at higher M values long tails develope

M dependence of F_q^e



- M dependence of $\langle F_q \rangle$ in various p_{T} bins. Solid symbols for DF and open symbols for SM

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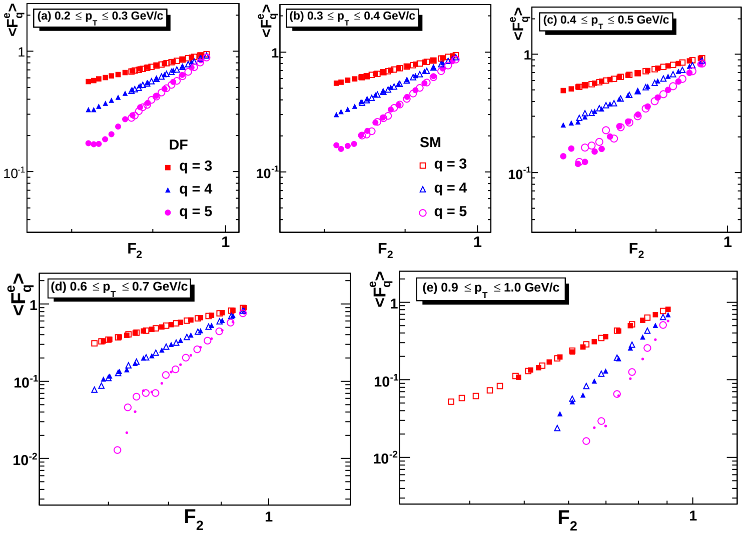
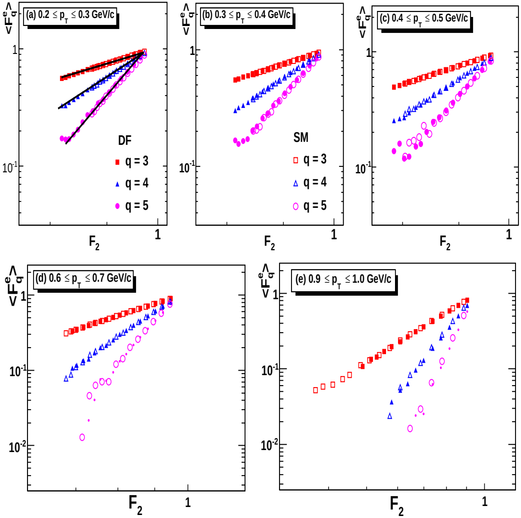
- For $F_q(M)$, we observe $F_q^{\mathrm{AMPT}}(M) \propto M^{\varphi_q^-}$, $\varphi_q^- < 0$.
- Negative intermittency.
- implying that the fluctuations are even less than Poissonian.
- AMPT : there are no rare high-multiplicity spikes anywhere in phase space.

F-Scaling...I

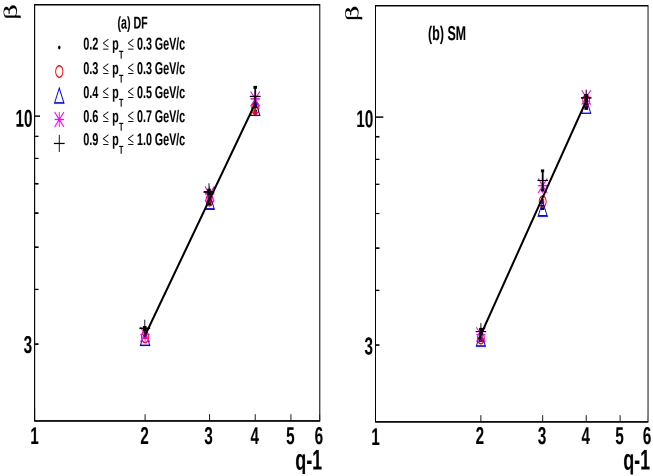

(a) 0.2 ≤ p_T ≤ 0.3 GeV/c
(b) 0.3 ≤ p_T ≤ 0.4 GeV/c
(c) 0.4 ≤ p_T ≤ 0.5 GeV/c
(d) 0.6 ≤ p_T ≤ 0.7 GeV/c
(e) 0.9 ≤ p_T ≤ 1.0 GeV/c
DF
SM
q = 3
q = 4
q = 5
<F^e_q>
F_2
1
10^-1
10^-2

F-Scaling...II



- Linearity in log-log plots
- Linear Fits performed give negative scaling exponent ν_-, defined as $\beta_q^{AMPT} = (q-1)^{\nu_-}$

β_q vs (q-1)



The slopes from these plots give the intermitency index ν

ν_-

p_{T}	ν_- **(Default)**	ν_- **(String Melting)**
$0.2 \leq p_{\mathrm{T}} \leq 0.3$	1.738 ± 0.008	1.753 ± 0.004
$0.3 \leq p_{\mathrm{T}} \leq 0.4$	1.774 ± 0.007	1.793 ± 0.005
$0.4 \leq p_{\mathrm{T}} \leq 0.5$	1.758 ± 0.006	1.755 ± 0.006
$0.6 \leq p_{\mathrm{T}} \leq 0.7$	1.824 ± 0.008	1.869 ± 0.016
$0.9 \leq p_{\mathrm{T}} \leq 1.0$	1.778 ± 0.013	1.781 ± 0.011

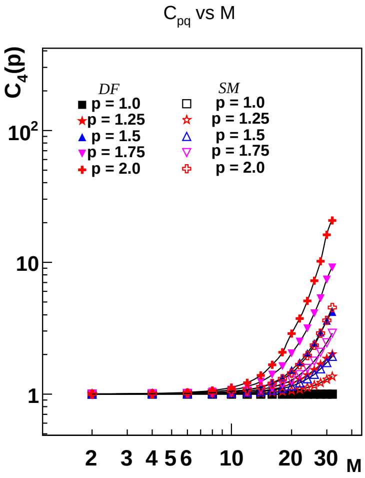
Table : Scaling exponents for negative intermittency in the Default and String Melting versions of the AMPT Model

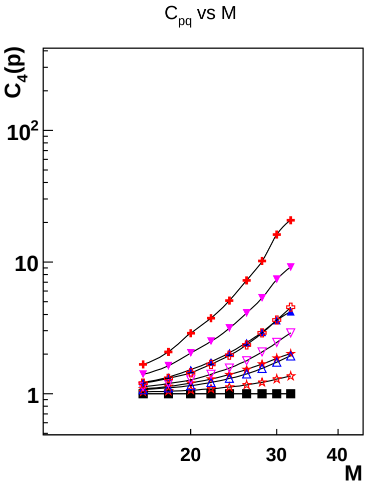
ν_-

No comaprison with ν as it is fundamentally different from ν_- on account of the difference between the positivity of φ_q and negativity of φ_q^-.

M dependence of the $C_{p,q}$

The double moments : Fluctuations in the flcutuations of the spatial patterns





DF and SM :$0.2 \leq p_{\mathrm{T}} \leq 0.3$

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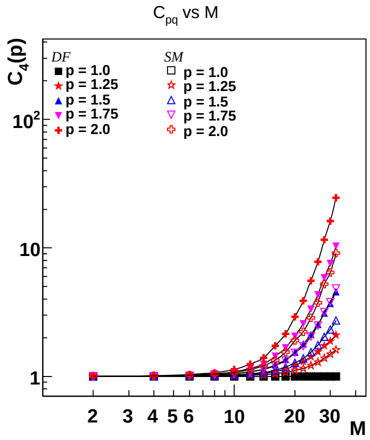

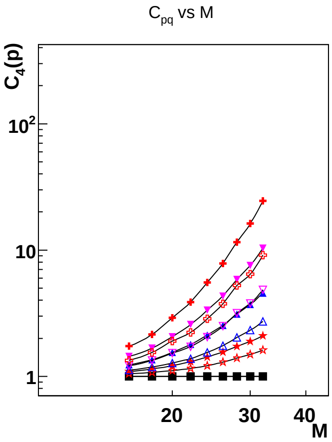

DF and SM :$0.3 \leq p_{\mathrm{T}} \leq 0.4$

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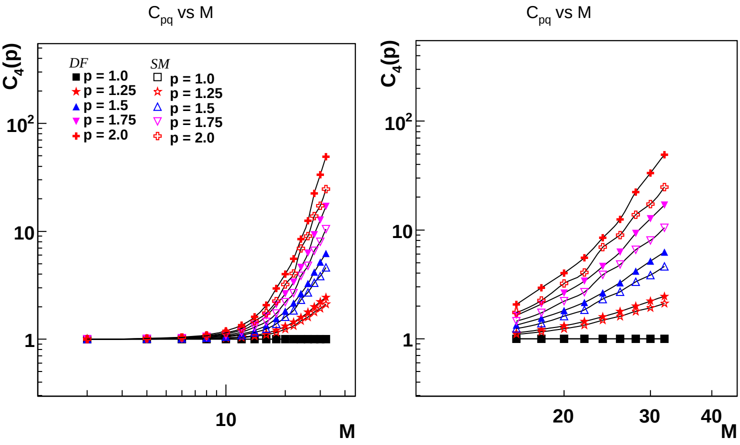

DF and SM :$0.4 \leq p_{\mathrm{T}} \leq 0.5$

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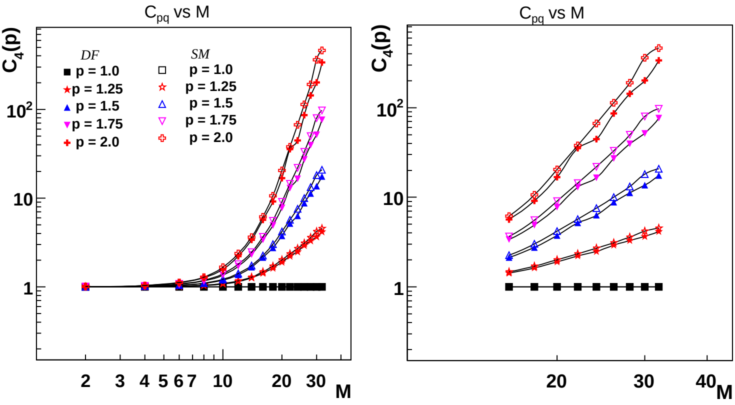

DF and SM :$0.6 \leq p_{\mathrm{T}} \leq 0.7$

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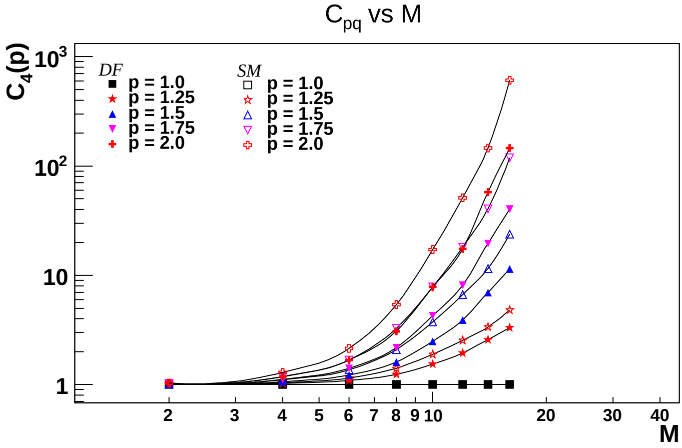
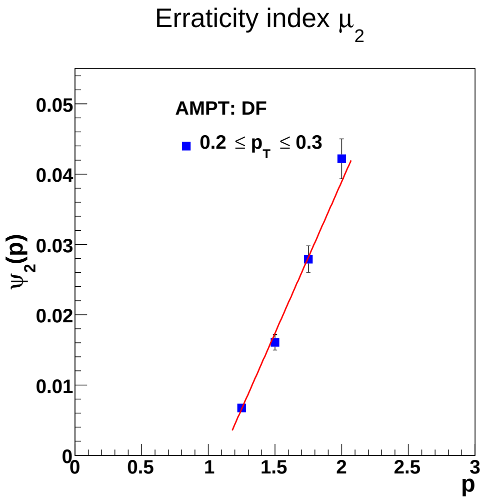


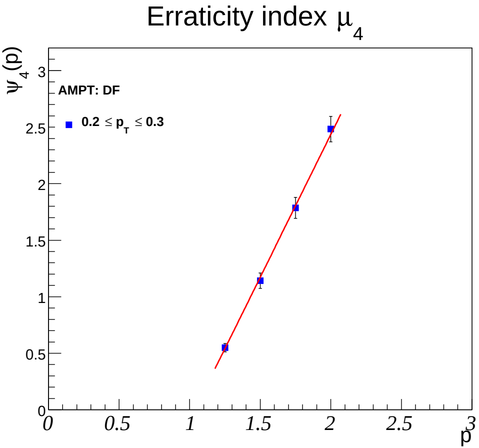
DF and SM :$0.9 \leq p_{\mathrm{T}} \leq 1.0$

μ_q



DF : $0.2 \leq p_{\mathrm{T}} \leq 0.3, \; q = 2$

μ_q



DF : $0.2 \leq p_{\mathrm{T}} \leq 0.3$, $q = 4$

Erraticity Index...μ

q	p_T	μ (Default)	μ (String Melting)
2	$0.2 \le p_T \le 0.3$	0.043 ± 0.002	0.016 ± 0.001
	$0.3 \le p_T \le 0.4$	0.045 ± 0.002	0.027 ± 0.001
	$0.4 \le p_T \le 0.5$	0.062 ± 0.003	0.048 ± 0.002
	$0.6 \le p_T \le 0.7$	0.154 ± 0.008	0.174 ± 0.011
	$0.9 \le p_T \le 1.0$	0.739 ± 0.043	1.014 ± 0.064
4	$0.2 \le p_T \le 0.3$	4.325 ± 0.243	2.481 ± 0.183
	$0.3 \le p_T \le 0.4$	4.532 ± 0.234	3.385 ± 0.235
	$0.4 \le p_T \le 0.5$	5.478 ± 0.258	3.935 ± 0.021
	$0.6 \le p_T \le 0.7$	5.64 ± 0.203	6.101 ± 0.214
	$0.9 \le p_T \le 1.0$	7.484 ± 0.361	7.359 ± 0.305

Table : Erraticity index in DF and SM versions of the AMPT Model, for q = 2 and 4 only

Summary

- First attempt to do this study at LHC energy.
- Factorial Moments for the charged particles decrease with increasing bin number contrary to the usual properties of intermittency observed at low energies.
- Events with localization of even moderate multiplicities in the small bins are not observed in the AMPT
- Confirms the absence of PT in AMPT
- Scaling exponents (ν_{-} and μ_q's) are determined
- Results can be used to compare with other models and experimental data values.
- A definitive value for μ_4 from experimental data can help uncover interesting physics.

Thank You

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