



Signals for fluctuating constituent numbers in small systems

2508.20390 [nucl-th]

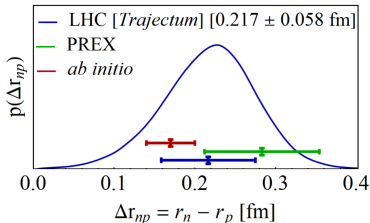
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Initial Stages Taipei, September 2025



Introduction

HIC & nuclear structure

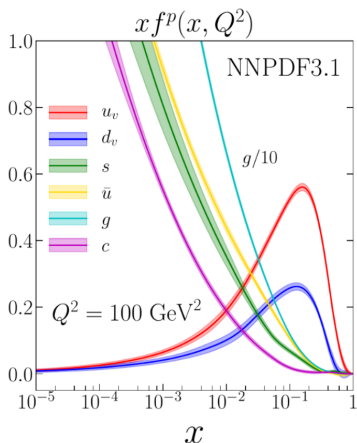


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- HIC always needed nuclear density as input for initial conditions
- Era of high precision data → Increased sensitivity to nuclear structure (e.g. neutron skin thickness, nuclear deformations) with constraining power

⇒ Sensitivity high enough for nuclear substructure?

Proton substructure

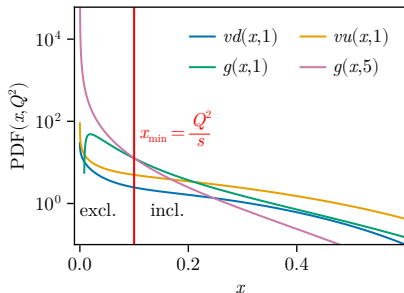


- Proton and neutron often used either without or with only fixed number of partons in IC models (e.g. TRENTo)
- Proton and neutron have much richer substructure including fluctuating number of partons

⇒ Include substructure and fluctuating number of partons in initial conditions

Sampling model

Sampling from PDF



- Sample momentum fraction of partons based on PDF
- Kinematic cut: $Q^2 = sxy$
 $\rightarrow x \geq \frac{Q^2}{s} = x_{min}$

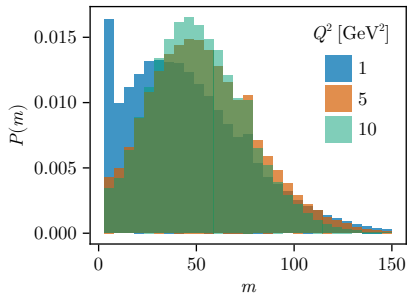
- Lower cutoff ensures finite maximal value of distribution and finite number of partons $m_{max} = 1/x_{min}$
- Assume strong correlation between partons \rightarrow all partons participate in interaction

Sampling algorithm

Sampling based on PDFs:

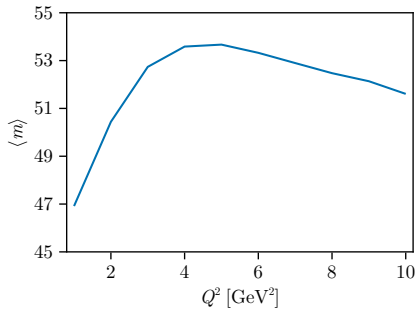
1. Draw momenta $x_{v,i}$ for valence quarks,
$$x_{tot} = \sum_{i=1,2,3} x_{v,i}$$
2. If $x_{tot} > 1$ return $m = 3$
3. Choose random quark flavour/gluon
4. Draw momentum of gluon/momentum pair of quark anti-quark pair and add to total momentum x_{tot} , update $m = m + 1$ or $+2$
5. If $x_{tot} > 1$ return m , else repeat from 2.

Distributions



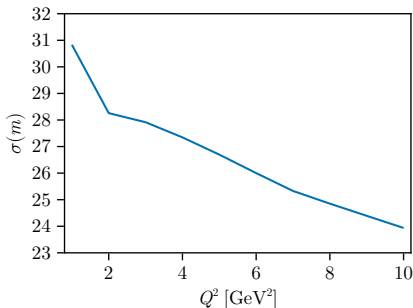
- Resulting distributions bounded from below by $m = 3$
- Distribution scale with Q^2 & reach large number of partons
- Low $Q^2 \rightarrow$ enhanced number of nucleons with only valence quarks

Parton cumulants

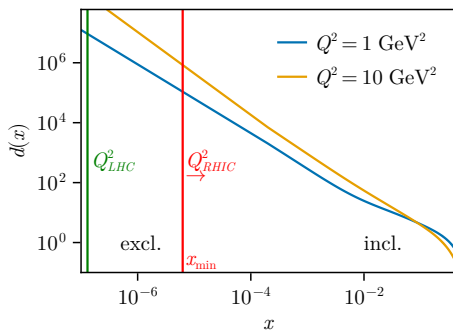


Standard deviation
decreases with Q^2
→ less fluctuations

Larger Q^2 probes smaller
scales → mean increases



Interplay between Q^2 and x_{\min}



- Higher Q^2 probes smaller scales
→ Distribution shifts to $x = 0$
- Lower cutoff x_{\min} increases with Q^2

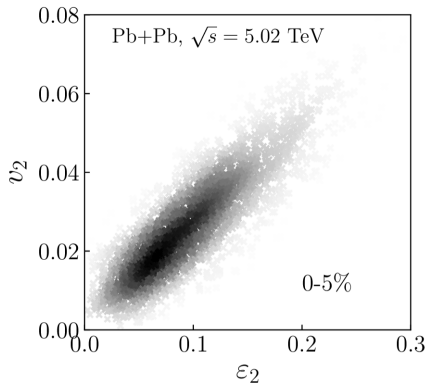
⇒ $\langle m \rangle$ increases then decreases with Q^2 due to cutoff

Extensions & Generalizations

- Sampling can be used at different energies through DGLAP equations
- Account for difference in protons and neutrons → proton/neutron PDF
- Include nuclear structure through nuclear PDFs
- Refine sampling by accounting for virtuality of partons

Sensitivity of observables

Method

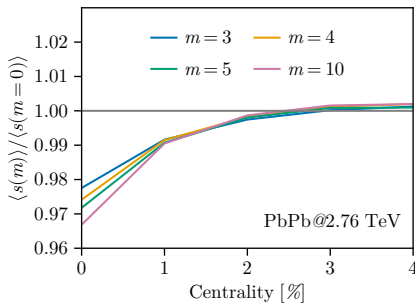


Taken from 2101.00168

Use proportionality of initial state quantities and final state observables to gauge dependence on m

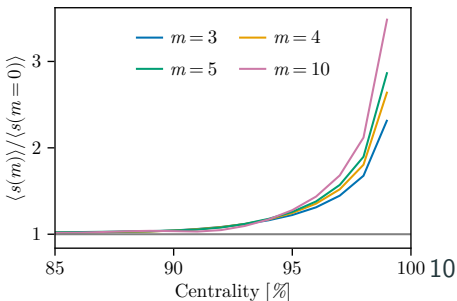
- $S \propto N_{ch}$
- $\langle p_T \rangle \propto E$
- $v_n \propto \epsilon_n$

Entropy density

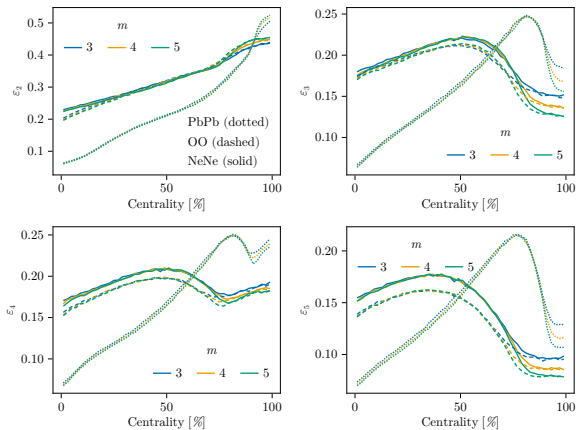


Entropy only sensitive
to m for large
centralities, because of
low N_{coll}

Ultra central collisions
have $N_{\text{coll}} \approx \text{const.}$
 \rightarrow sensitive to $\langle m \rangle$

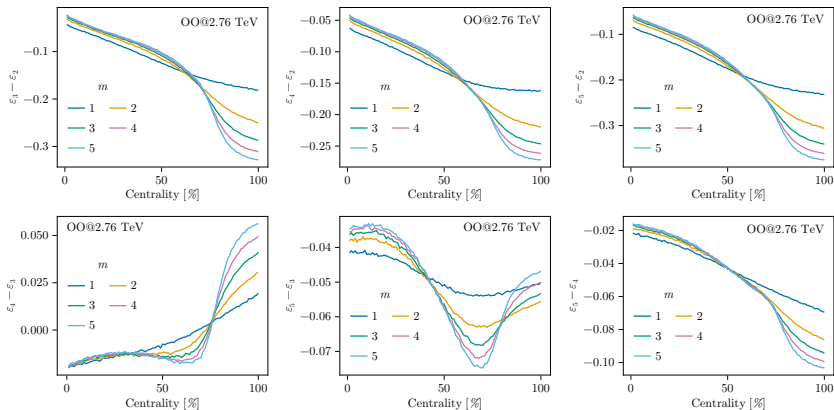


System dependence



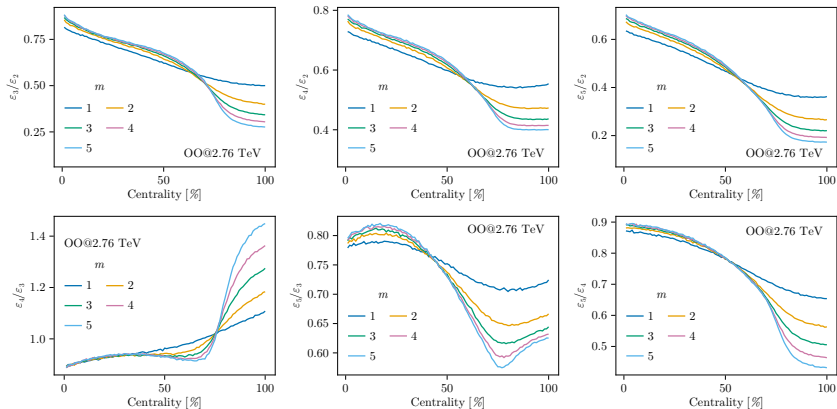
Same sensitivity at
same N_{coll}
→ Differences at
lower centralities
in small systems

Harmonics - difference



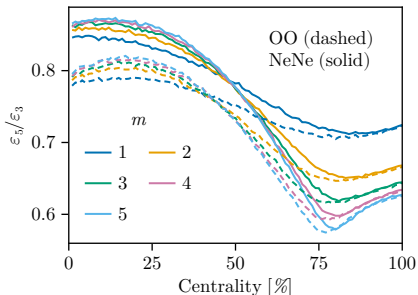
Use ratios and differences to isolate structure effects

Harmonics - ratios



Purely odd harmonic combination shows greatest sensitivity

Uneven harmonics



- Ratio of even harmonics driven by shape
- Ratio of purely uneven harmonics more sensitive to fluctuations & structure differences
⇒ higher sensitivity at lower centralities
- Different initial & final value and different slope
- Ratio within one system → smaller uncertainties

Conclusion & outlook

Conclusion

- Sampling algorithm for parton number based on PDF
 - Easy extension to to different energies (DGLAP) and inclusion of nuclear structure (nPDFs)
 - Event by event fluctuating parton number
- Examined sensitivity of observables on parton number using initial state estimators
 - Combination of odd harmonics ε_3 and ε_5 have biggest sensitivity

Outlook

- Implement sampling in initial state models, e.g. TRENTo
- Refine sampling through virtuality dependence, proton/neutron PDF, Q^2 dependence
- Use transverse momentum distribution PDFs to obtain initial conditions for fluid velocity
- Include v_3/v_5 to increase sensitivity on nuclear substructure

