Imaging subnuclear systems:
Concepts, objectives, applications

C. Weiss (JLab), CNF Imaging Workshop, Jefferson Lab, Aug.19-20, 2019
with G. Gavalian (JLab), N. Chrisochoides, Ch. Tsolakis, A. Angelopoulos (ODU), P. Sznajder (NCBJ Warsaw)

Subnuclear systems
• Scales, properties
• Scattering experiments

Workflow in measurements
• Model - data comparison

Using imaging techniques - tessellation
• Analysis of phase space distributions
• Visualization of proton structure

CNF Project “Next-generation imaging filters and mesh-based data representation for phase-space calculations in nuclear femtography”
Subnuclear systems: Scales

Emergent phenomena

- Interacting large systems develop complex structure that is not present in “parts”
- Common paradigm in life sciences and physics

Explore subnuclear systems

- Fundamental theory of strong interaction: Quantum Chromodynamics - quarks, gluons
- Understand proton/neutron as emergent phenomena: Structure, interactions

Interest

- Intellectual: Basic building blocks of “matter,” 99% of mass in visible Universe
- Applications: Nuclear structure and reactions, nuclear energy, astrophysics
Subnuclear systems: Properties

“Unusual” dynamical system

- Quantum mechanics: Constituents in proton are in “perpetual motion”
- Relativity: Energy = mass, conversion processes. Proton is “cauldron” filled with radiation energy and matter/antimatter

Implications for measurements and visualization

- Only average properties are measurable: Densities, correlations
- Formulation/visualization of spatial structure possible with appropriate concepts
Subnuclear systems: Scattering experiments

Electron scattering as microscope

- Incident energy determines spatial resolution
- Multi-GeV energies needed for resolving proton’s internal structure. $10^5 \times$ hard x-ray energy!
- Use particle accelerators and detectors: Large-scale facilities, world-wide effort
  JLab 12 GeV: Energy x intensity frontier

Information recorded

- Phase space distribution of particles produced in scattering events: types, momenta
- “Expression” of proton’s internal structure (in average sense)
- Large number of scattering events: $10^6$-$10^9$ in typical JLab experiments

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[for each scattering event]
Workflow: Measurements

- Phase space distributions as “meeting ground” between theoretical models and experimental data/simulations
- Uncertainty quantification essential - theoretical, experimental
- Operated with actual experimental data or Monte-Carlo simulations
- “Final” picture of proton from synthesis of multiple experiments and theoretical models
Workflow: Using imaging techniques

A) Phase space distributions: Use imaging techniques (tesselation, slicing, viewing, …) for representation and analysis of phase space data

B) Proton structure: Use imaging techniques for visualization of subnuclear system and synthesis of information
Imaging: Phase space distributions

- Phase space distributions = types + momenta of particles produced in scattering events. Multidimensional distribution with attributes.
- Large data volume: \( \sim 10^6-10^9 \) events in typical experiments

Operations needed in analysis
- View distributions - projections, cuts, features
- Compare distributions from different physics models
- Interpolate/refine distributions for simulations

New: Use tesselated representation
- 3-dim phase space divided in tetrahedral cells, generalizable to N-dim
- Compact, memory-efficient representation
- Adaptive mesh generation for accuracy
- Viewing/Slicing with ParaView
- Efficient interpolation/refinement for MC simulations

Used so far
- Dedicated tools FORTRAN/C++
- Uniform cells/bins

Presentation by G. Gavalian
Imaging: Visualization of proton

Tomographic image (set of projections) of quark density in proton along axis of high-energy scattering process

Image concept appropriate for relativistic quantum system

Synthetic image, constructed with information from theory and multiple experiments

Fundamental physics interest: Spatial size, internal motion of quarks, ...

New: Tesselated representation

- Viewing/Slicing with ParaView
- Next-generation visualization?
Summary

• Subnuclear systems have a composite internal structure with unique properties: internal motion, interactions

• The internal structure is expressed in the phase space distributions of particles produced in high-energy scattering experiments

• Novel applications of imaging methods using tessellated representation
  A) Analysis of phase space distributions
  B) Visualization of proton structure

• Looking forward to discussions!