CNF19-09 Visualizing Femto-Scale Dynamics

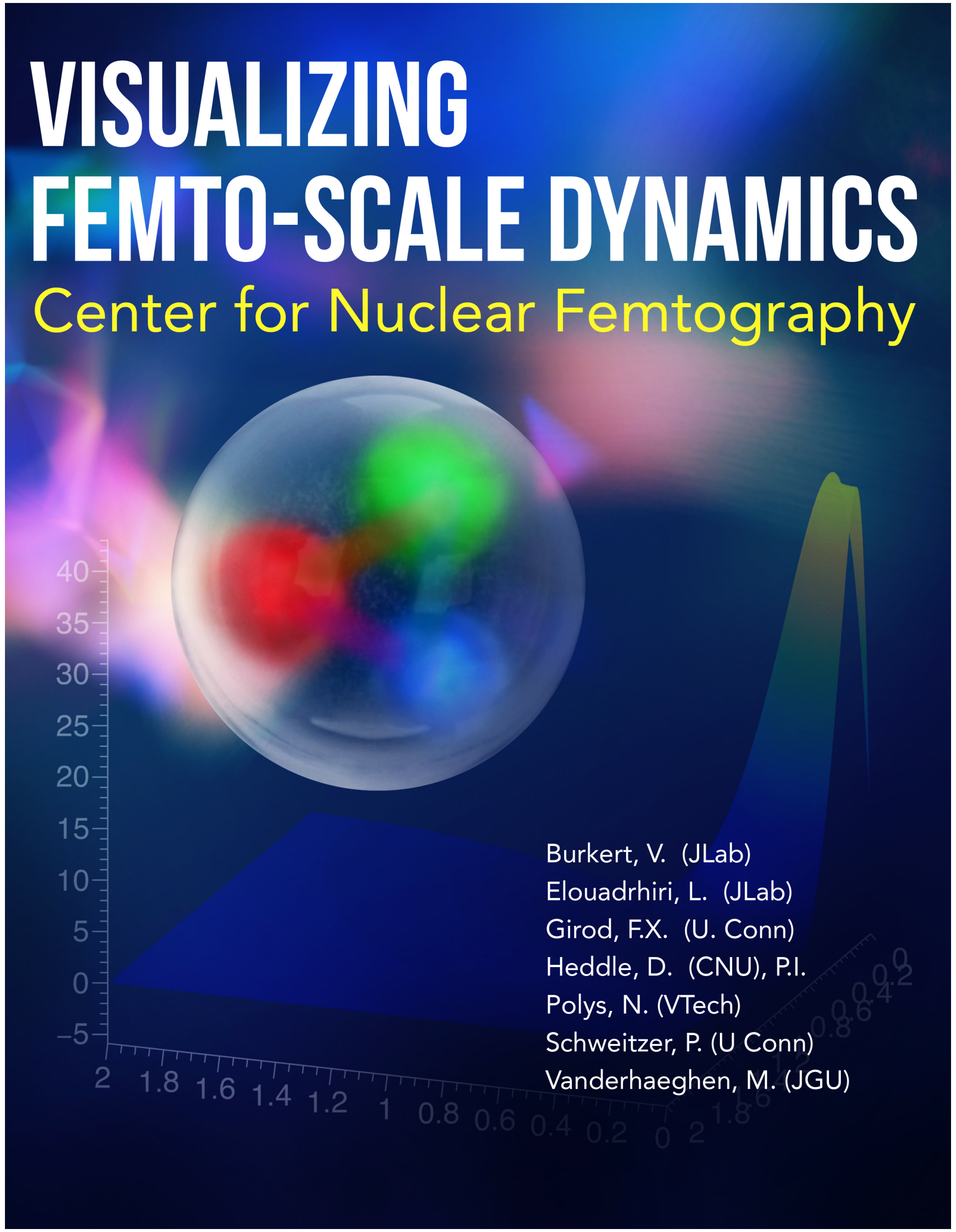
Mid-Term Report

V. Burkert

Jefferson Lab (Newport News)

N. Polys

Virginia Tech (Blacksburg)



CNF19-09 - Team and Expertise

David Heddle	Large scale data handling, event displays, tracking, teaching
Volker Burkert	Large scale experiments, analysis, scientific interpretation
Latifa Elouadrhiri	Experiment Technical Coordinator, analysis, outreach
Francois X. Girod	Simulation and analysis of data, data interpretation
Nicholas Polys	Process visualization, virtual reality, outreach, teaching
Peter Schweitzer	Theory, model builder, nuclear imaging
Marc Vanderhaeghen	Theory, GPDs, model builder, 2D/3D imaging

Introduction

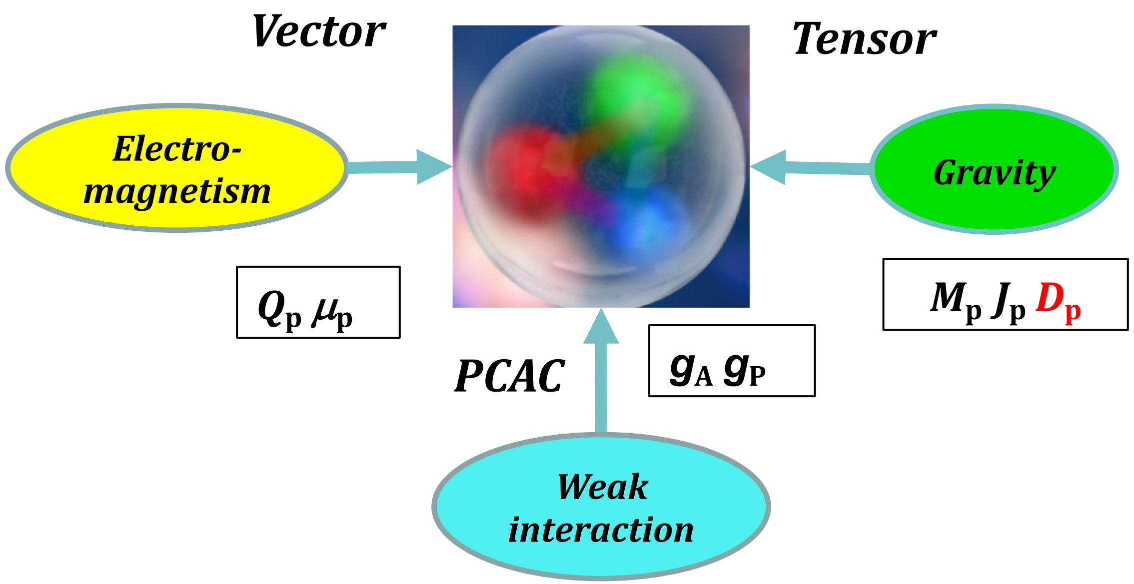
- Experiments at Jefferson Lab are generating the most comprehensive and the **most precise data ever** on the internal substructure of nucleons and nuclei.

- Major progress in theoretical formalism of the interior structure of the nucleon has led to **breakthroughs** in our understanding of the theory of quarks and gluons, through the Generalized Parton Distributions framework.

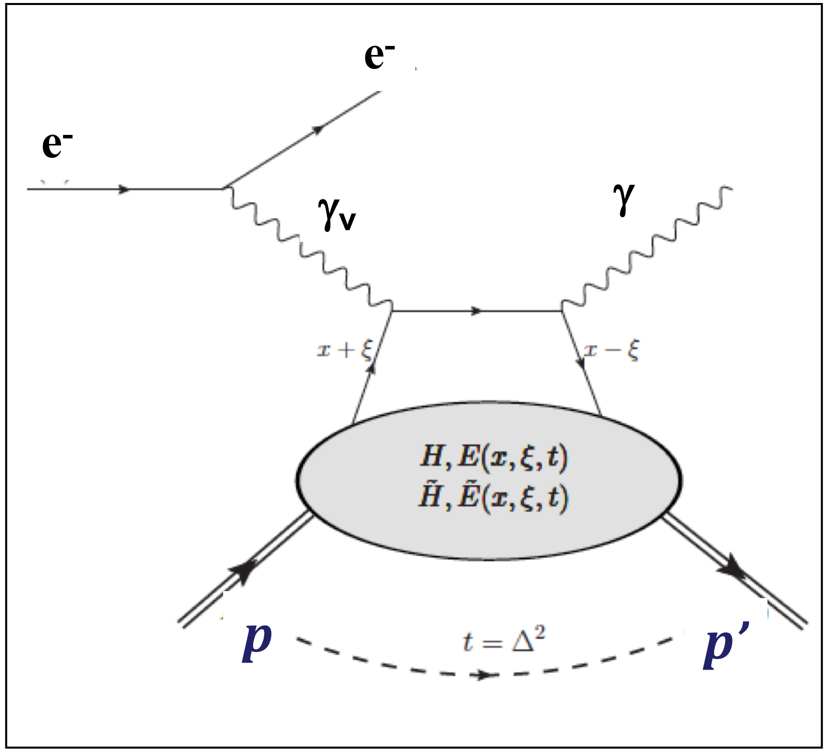
- Understanding the **mechanical and dynamical** nucleon substructure remains a big challenge. With high precision experiments a new direction in nuclear physics is opening up for exploration.

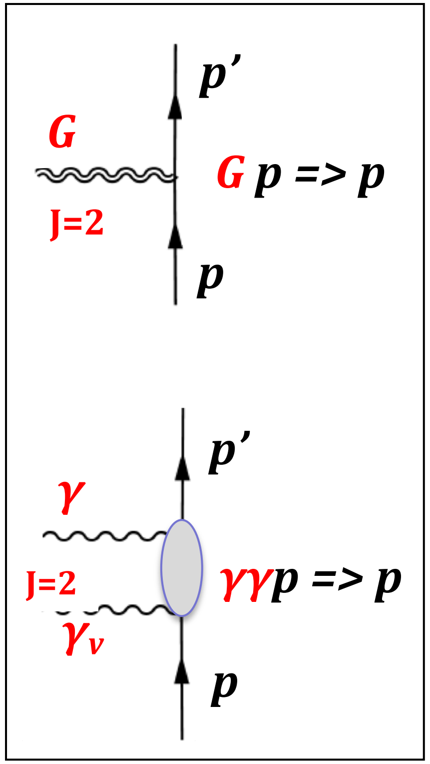
Gravity & mechanical properties

Probing the proton



Deeply virtual Compton scattering





The DVCS process mimics graviton-proton coupling with many orders of magnitude higher rate that makes the experiments feasible.

Goal of the Proposal

As part of this initial phase of the establishment of the Center for Nuclear Femtography, our project (CNF19-09) aims at the **characterization** and **visualization** of the internal **mechanical** properties of the nucleon focusing on the proton through DVCS data analysis.

CNF19-09 Road Map

- **Experimental observables** required to access the parton distributions of interest: Quantify the kinematic coverage (Jlab@12GeV vs EIC), specify the required precision for experimental DVCS observables.
- **Extraction of amplitudes** with controlled uncertainties (experimental, model). Comparison of different techniques: fitter programs, neural networks, model extractions.
- **Physical parameterizations** of Nucleon Form Factors and GPDs including all constraints will be compared and improved. Includes integral constraints (form factors), forward limits constraints, dispersive constraints, and LQCD input for moments of GPDs.
- **"Imaging"** means going from momentum space to coordinate space, and perform as next step a Fourier transform. This necessarily includes extrapolations, with controlled uncertainties.
- **Visualization** of final distributions in comprehensive pictures, providing 3D quark distributions (2D-spatial and 1D momentum), and converting GPDs to mechanical properties, such as normal and shear forces, pressure distributions, and mechanical sizes of particles. Also for use in outreach programs.

CNF19-09 - Mid-Term Deliverables

Mid-term deliverables are a **set of visualizations of physics quantities** based on the reference model and on a specific detector setup.

✓ **Reference Model**: Input data to the visualization tools will be based on a **reference model** (RM) using phenomenological, theory guided, parametrizations of existing data as form factors, extrapolated through the entire unmeasured kinematic space.

✓ **Data Fusion**: Selected a technology that accommodate transferring large, heterogeneous data sets from the reference model (RM) to analysis software and visualization. Defined the banks that the RM will produce, and provided the interface between data format's I/O package and the producers and consumers of the data.

✓ **Visualization**: Adapted visualization software tools for interactive 3D visualization software, produced set of movies highlighting the data and techniques, developed a VR to illustrate the structure and interaction of particles and forces in the nucleon.

CNF19-09 - Mid-Term Deliverables

Mid-term deliverables are a **set of visualizations of physics quantities** based on the reference model and on a specific detector setup.

- ✓ **Reference Model**: Input data to the visualization tools will be based on a **reference model** (RM) using phenomenological, theory guided, parametrizations of existing data as form factors, extrapolated through the entire unmeasured kinematic space.
- ✓ **Data Fusion**: Selected a technology that accommodate transferring large, heterogeneous data sets from the reference model (RM) to analysis software and visualization. Defined the banks that the RM will produce, and provided the interface between data format's I/O package and the producers and consumers of the data.
- ✓ **Visualization**: Adapted visualization software tools for interactive 3D visualization software, produced set of movies highlighting the data and techniques, developed a VR to illustrate the structure and interaction of particles and forces in the nucleon.

All Mid-Term Milestones have been met and on track to complete the end of project deliverables

Project Workflow

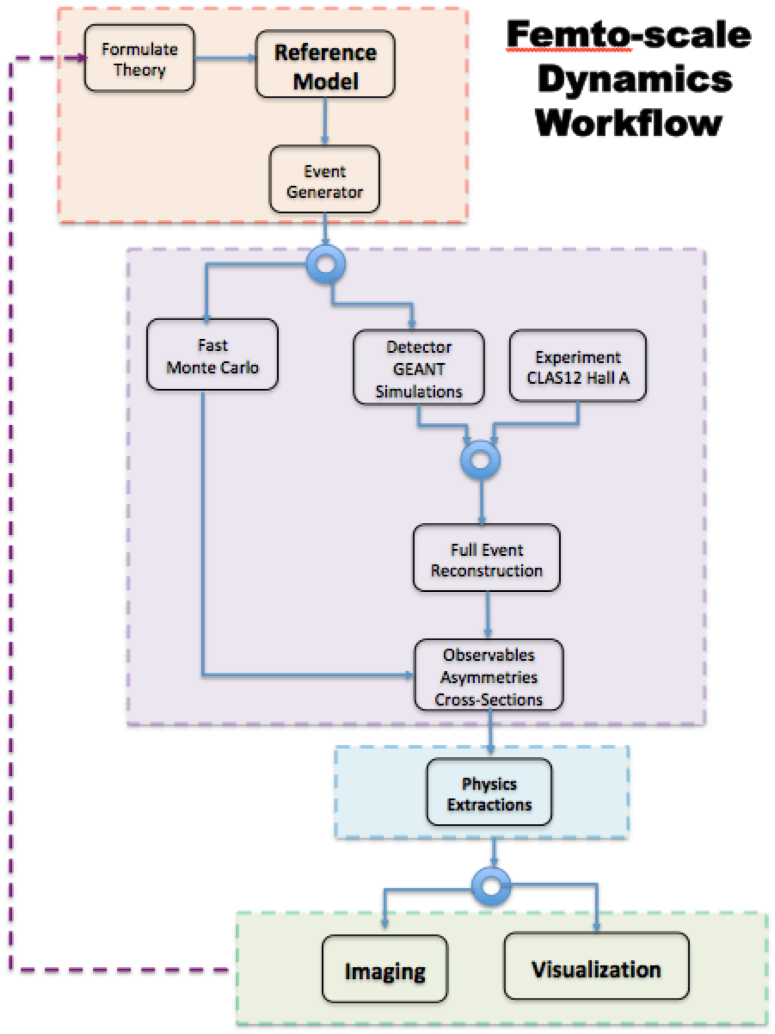
Develop a reference model and an event generator from cross sections & asymmetries to 4-momentum vectors.

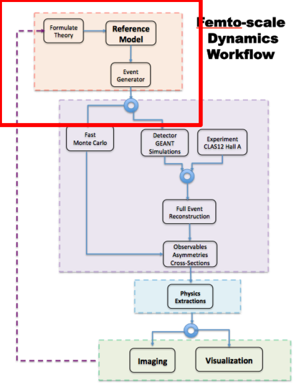
Fast Monte Carlo ➔ observables for display

Input to Geant4 simulations with full detector details, and event reconstruction (CLAS - CLAS12).

Extract initial physics quantities folded with acceptance, inefficiencies, etc.

Input results into imaging and visualization tools.



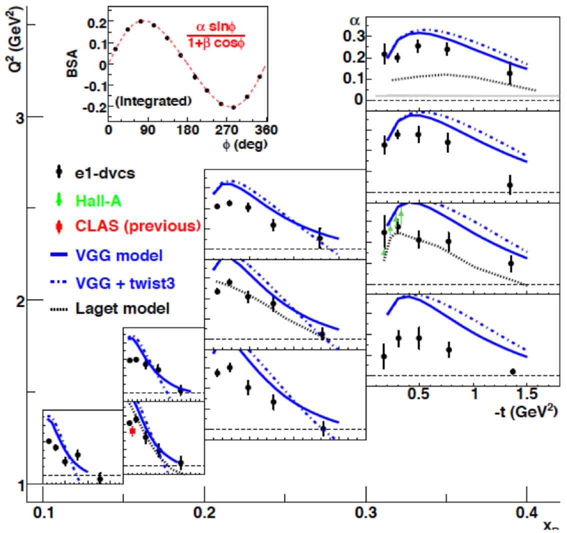


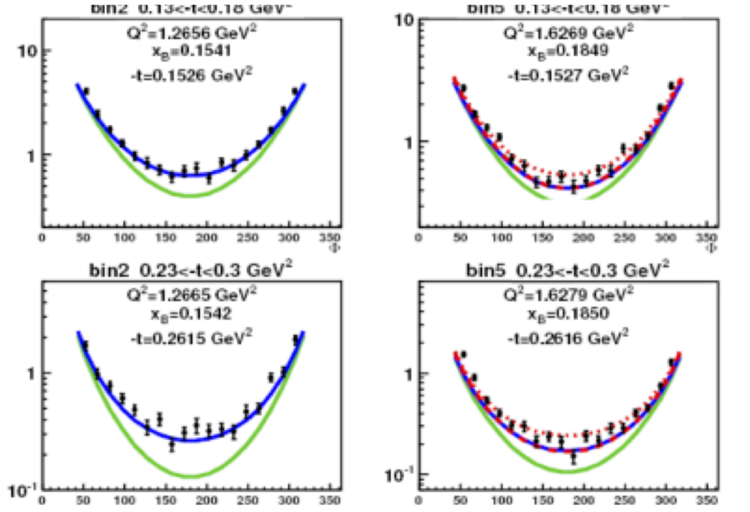
Femto-scale Dynamics Workflow

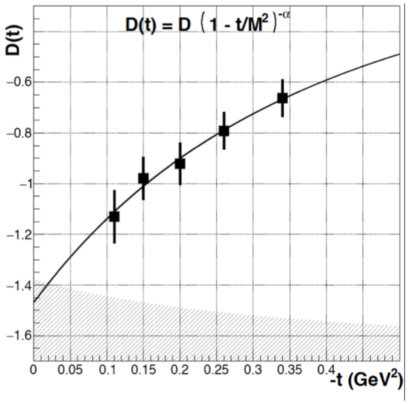
Project Status- RM

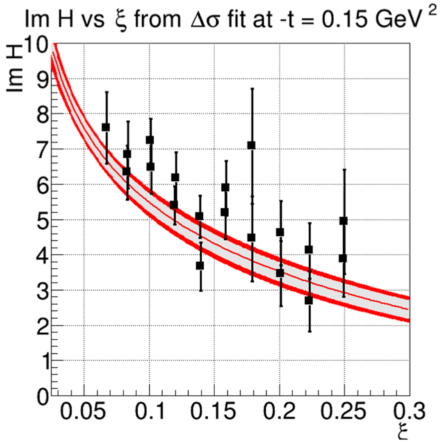
Parametrization

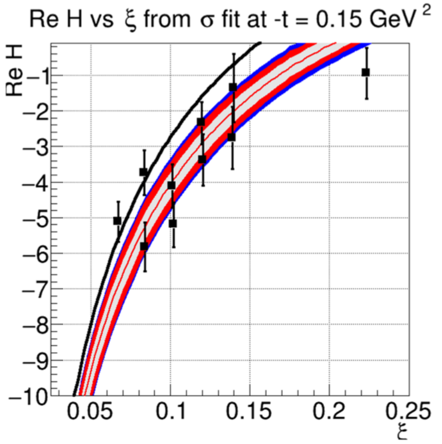
- **Developed RM based on DVCS data from CLAS6**
  - parameterization of Compton Form Factor $\mathcal{H}(\xi, t)$ extracted from existing DVCS data
  - beam spin asymmetries and diff. cross sections
  - parameterization with ξ at fixed value of t to get Re($\mathcal{H}$) and Im($\mathcal{H}$)
  - Use dispersion relation to extract $D(t)$.

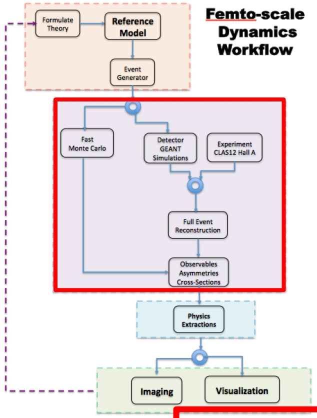








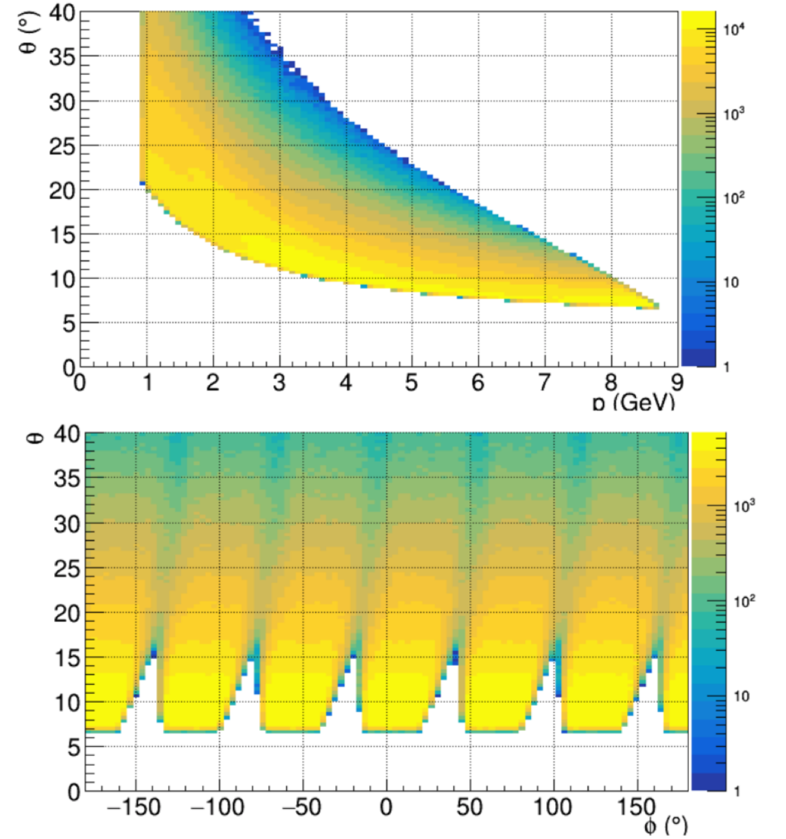




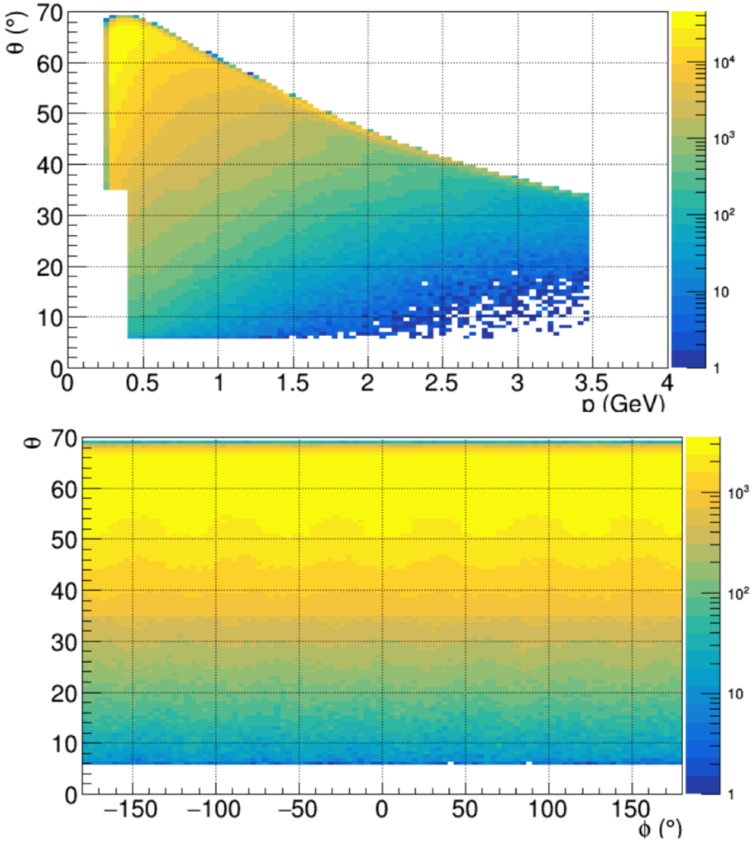
Project Status - Simulating DVCS process in Fast MC based on CLAS12

$e^-p \rightarrow e^-p\gamma$

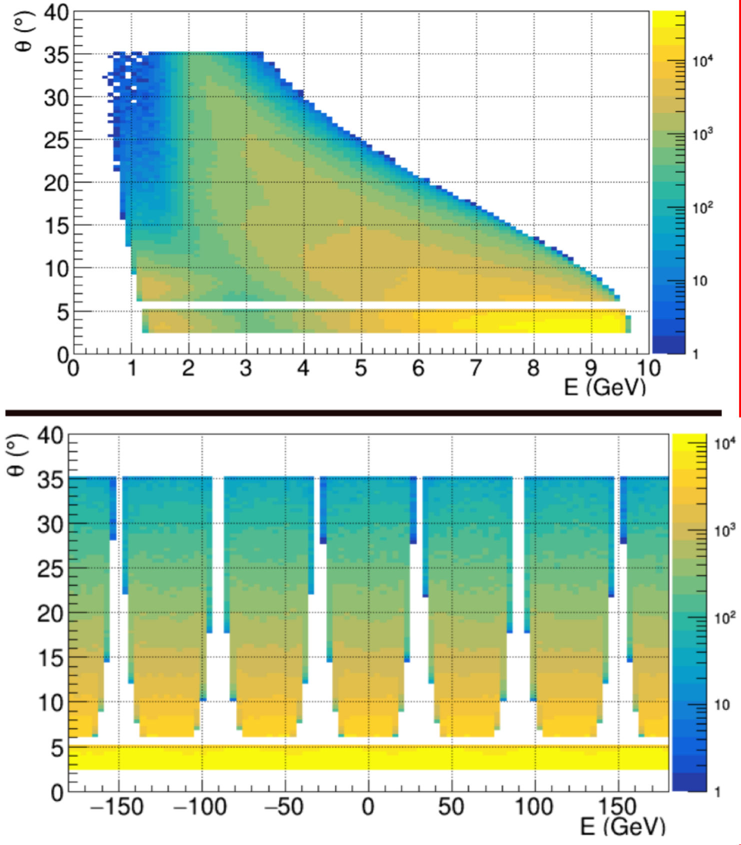
electrons

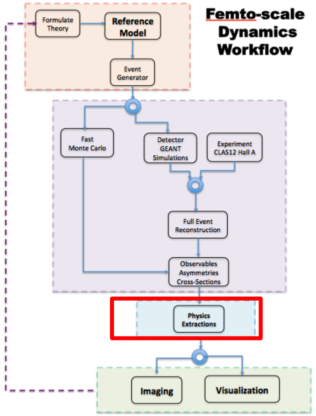


protons



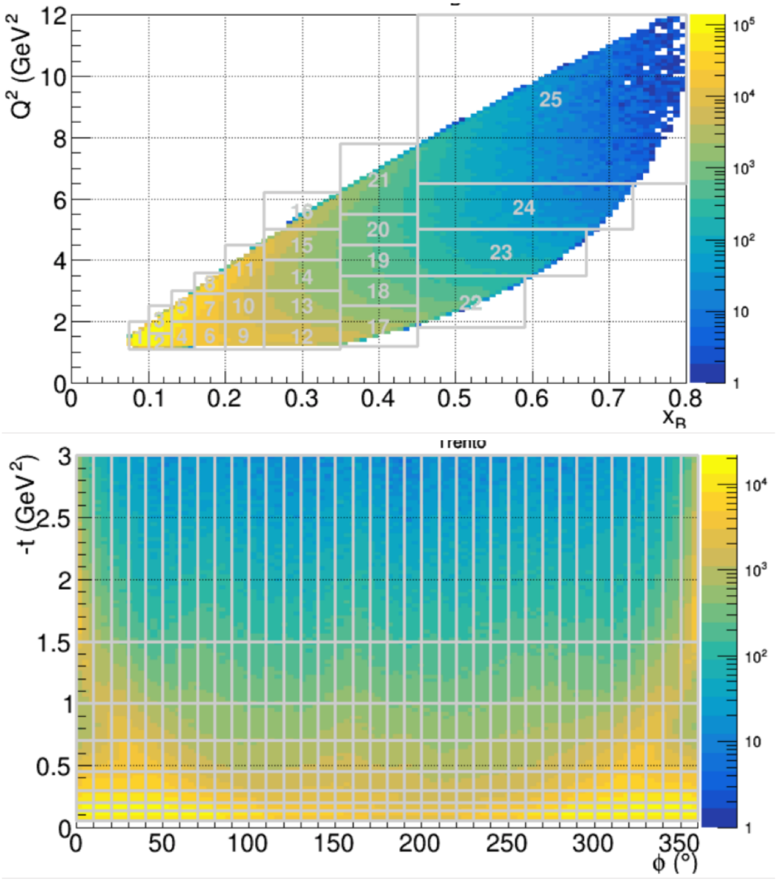
photons





Extraction of physics after FAST MC

Kinematics



Determine the Compton Form Factor $\mathcal{H}(\xi, t)$

$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

$$\mathrm{Re}\mathcal{H}(\xi,t) \stackrel{\mathrm{LO}}{=} D(t) + \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(x,t)$$

Details

Summary and Outlook I

- Developed a reference model for CFF $\mathcal{H}(\xi,t)$ based on data from CLAS 6 and from fits to world data.
- Projected simulated data to 11 GeV and CLAS12 detector properties.
- Analyzed the truncated data (cross sections & beam asymmetries) and extracted $\mathrm{Im}[\mathcal{H}(\xi,t)]$ and $\mathrm{Re}[\mathcal{H}(\xi,t)]$, fitted ξ and t dependencies.
- Use subtracted dispersion relation to extract *D(t)* and generate new images of forces and pressure distribution – visualize differences.

- Include polarized proton target projected 12 GeV data, both for longitudinal and transverse polarization – extract quark spin distribution and orbital angular momentum?
- Projections for Electron-Ion-Collider.

Visualization

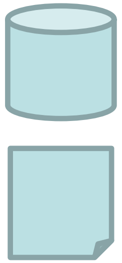
Nicholas

Project Status - Data Flow

Models, FastMC, Simulation

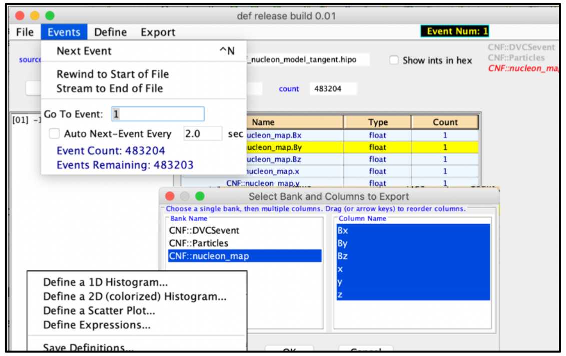
```
inline const T & NRVec<T>::operator[
{
    return v[i];
}

template <class T>
inline int NRVec<T>::size() const
{
    return nn;
}

template <class T>
```

HIPO4 archived data (raw or analyzed)

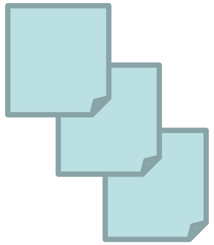


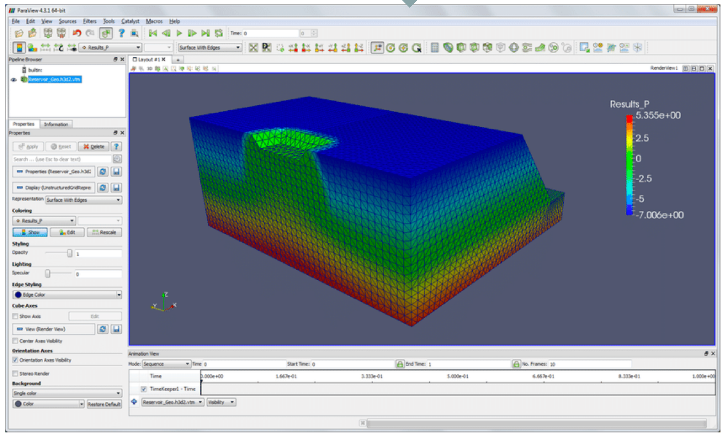
JSON Data Description

***def* Data Exporter for visualization formats**



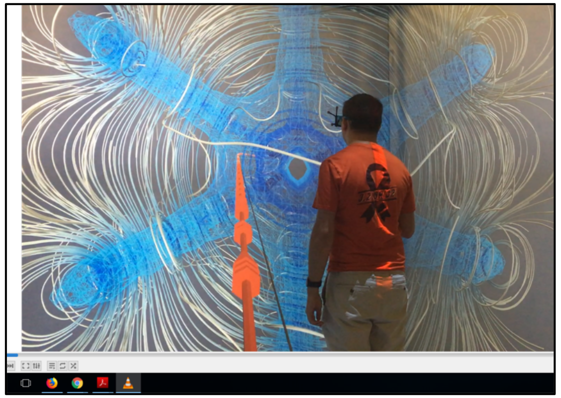
Exported data (e.g., csv)



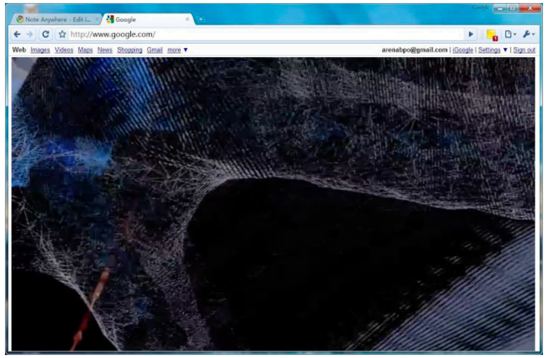


Visualization Engine (e.g., *ParaView*)

Multiple output streams for researchers and public



Virtual Reality (headsets, caves)



Web Accessible

Software: 3D Visualization

- For 3D visualization, we have adopted standards-based open-source, multi-platform applications.
- For our first end-to-end test of our process we have chosen ParaView (http://paraview.org), which is a powerful processing and visualization platform capable of producing many forms of scientific 3D visualization including images, animations, and VR displays, all of which we provide an advantageous analytic environment and dissemination means for scientists and the public.
- We created several visualization mappings in Paraview, which were exported to images, videos and the X3D format. The ISO-IEC X3D format allows users to explore these interactive 3D environments on the Web natively in a WWW browser or in any X3D application.

Visualization Demos

- As a demonstration of our analysis and production pipeline, we first tested data displays of charged particle trajectories (HIPO4 based) in the CLAS12 detector, "swimming" through the CLAS12 solenoid and torus. This involved exporting the field maps, detector geometries, and particle trajectories to ParaView in a format that required about 4GB of data transfer. The team worked together to implement visual representations such as color maps, glyphs, contours, and stream tubes.
- In next figures we show some demonstration of the magnetic field and trajectories through the field and wire chamber detectors.
- The team is now leveraging this production pipeline with the simulated nucleon data and producing a website.

Visualizing Femto-Scale Dynamics (CNF19-09)

- David Heddle (PI)
  Christopher Newport University (Newport News)
- Volker Burkert
  Jefferson Lab (Newport News)
- Latifa Elouadrhiri
  Jefferson Lab (Newport News)
- F.X. Girod
  University of Connecticut (Storrs)
- N. Polys, O. Stein, N. Gutkowski
  Virginia Tech (Blacksburg)
- P. Schweitzer
  University of Connecticut (Storrs)
- M. Vanderhaeghen
  Johannes Gutenberg University (Mainz)

VIRGINIA TECH | Advanced Research Computing

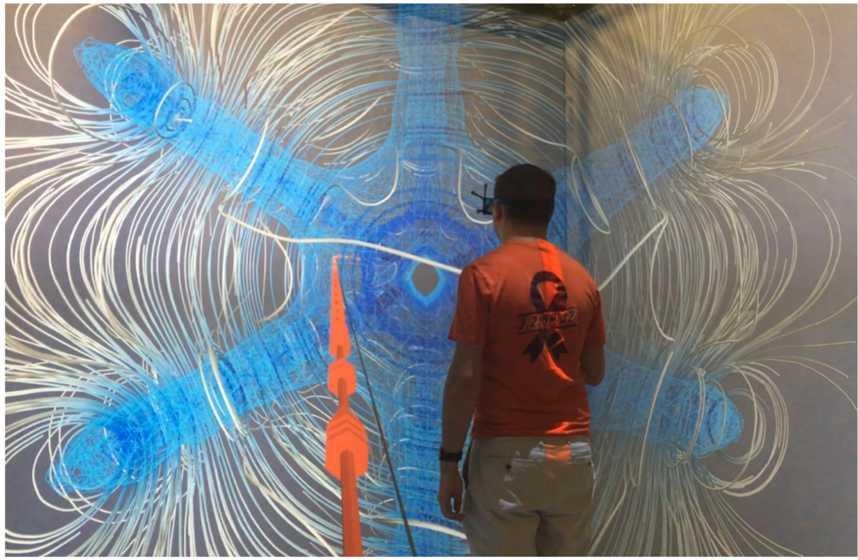
CENTER for NUCLEAR FEMTOGRAPHY

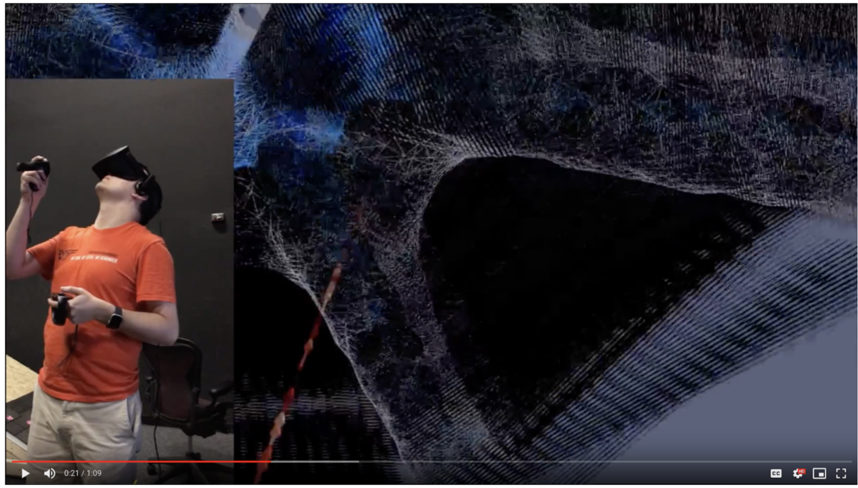
Jefferson Lab
Exploring the Nature of Matter

Femtographic Visualization

Established pipelines for femtography data:

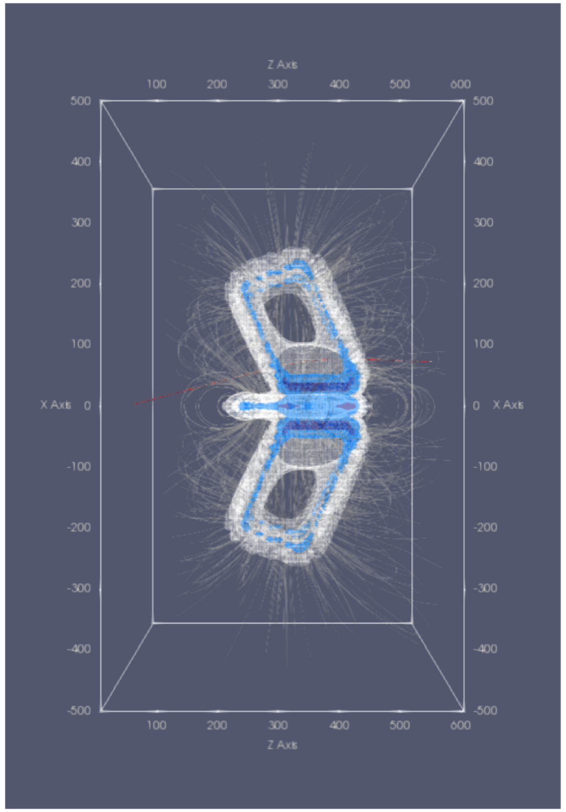
- Data loaders : geometry, scalar and vector fields
- Visualization design
  - Sampling *n* points and draw vectors with glyphs (arrows)
  - *m* Contours along the vector field
  - *o* streamtubes across the vector field
  - Coloring by vector magnitude
  - Volume rendering
- Publishing
  - Images
  - Movies
  - 3D models for WWW and Virtual Reality (CAVEs, HMD)



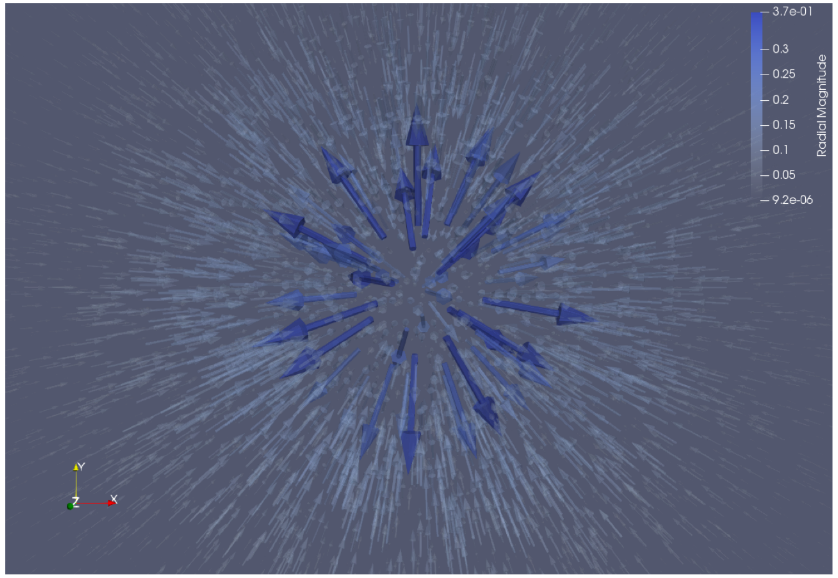


Data sets

1. CLAS-12 Magnet and detector geometry
    a. Magnetic field
    b. Particle trajectories



1. Fast MC DVCS simulation data
    a. Radial forces
    b. Tangential forces



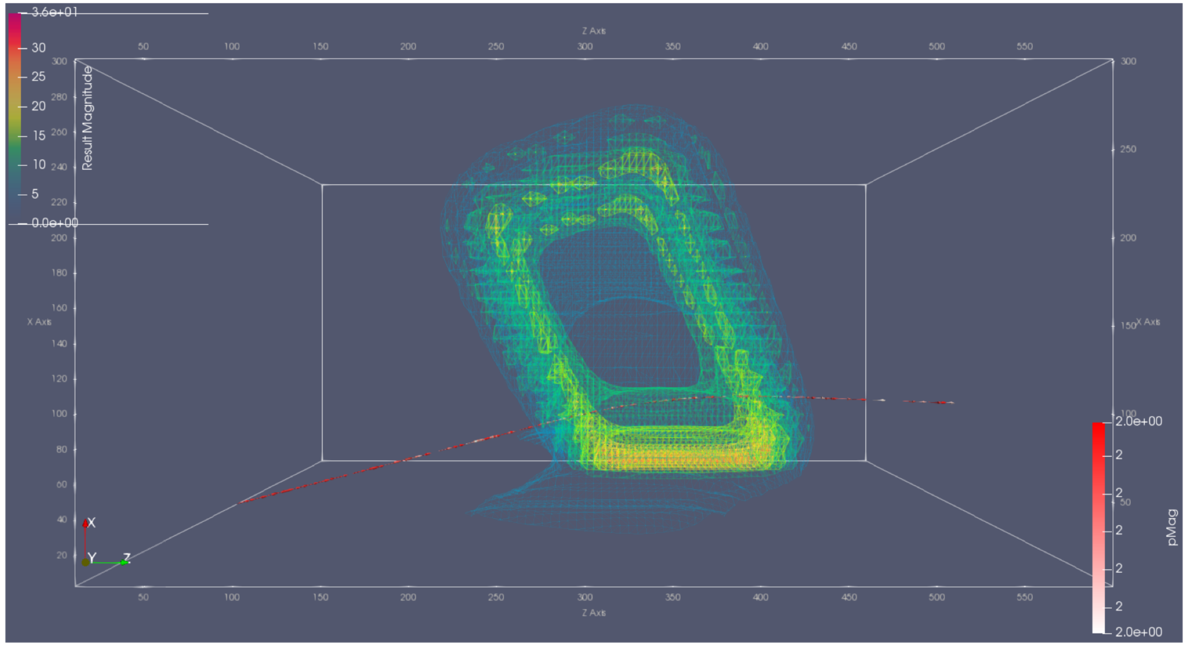
Software

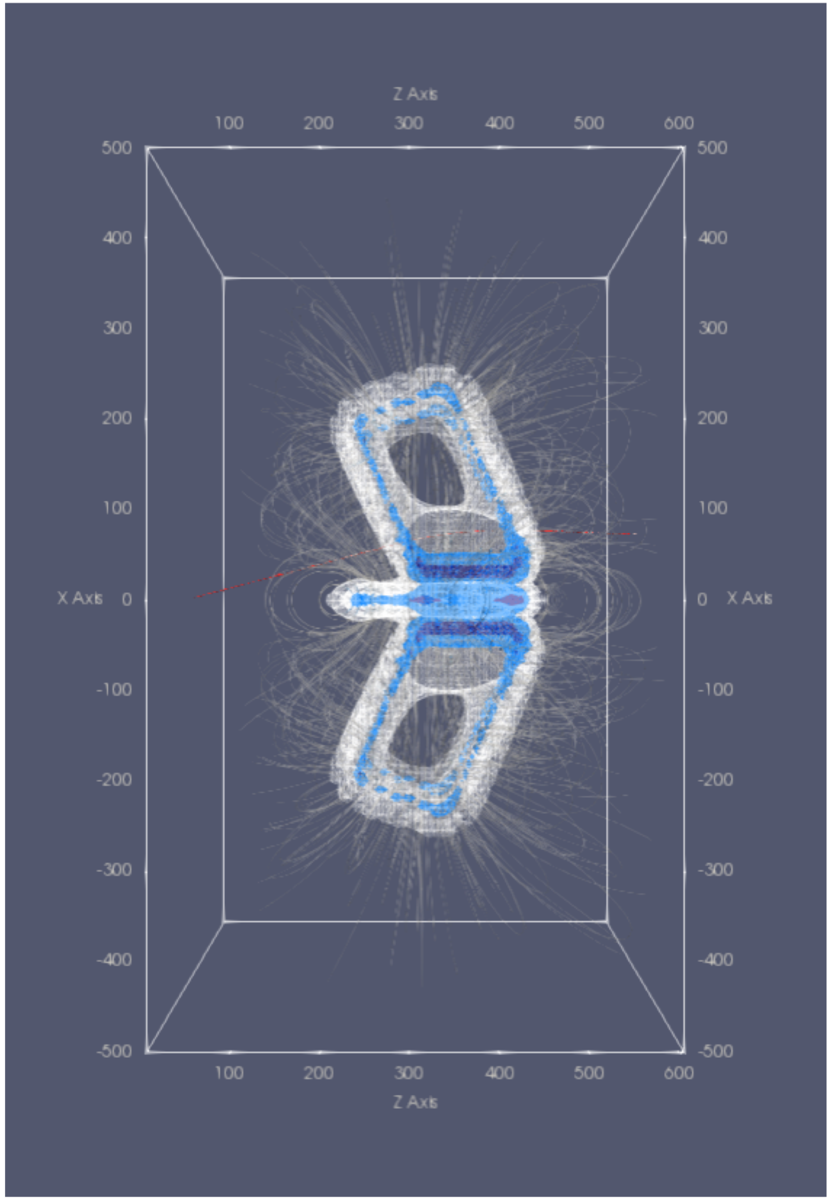
- Paraview 5.6 with Python
  - Filters, calculators
  - Basic VR support
  - Extensuble 3D (X3D) export

- Extensible 3D (X3D)
  - InstantReality (CAVE), ...
  - X3DOM, X_ITE (WWW, Web3D, WebVR)

Magnet & field

- Convert from cylindrical to Euclidean coordinates
- Vector field
  - Contoured, wireframed
  - Streamtubed, shaded

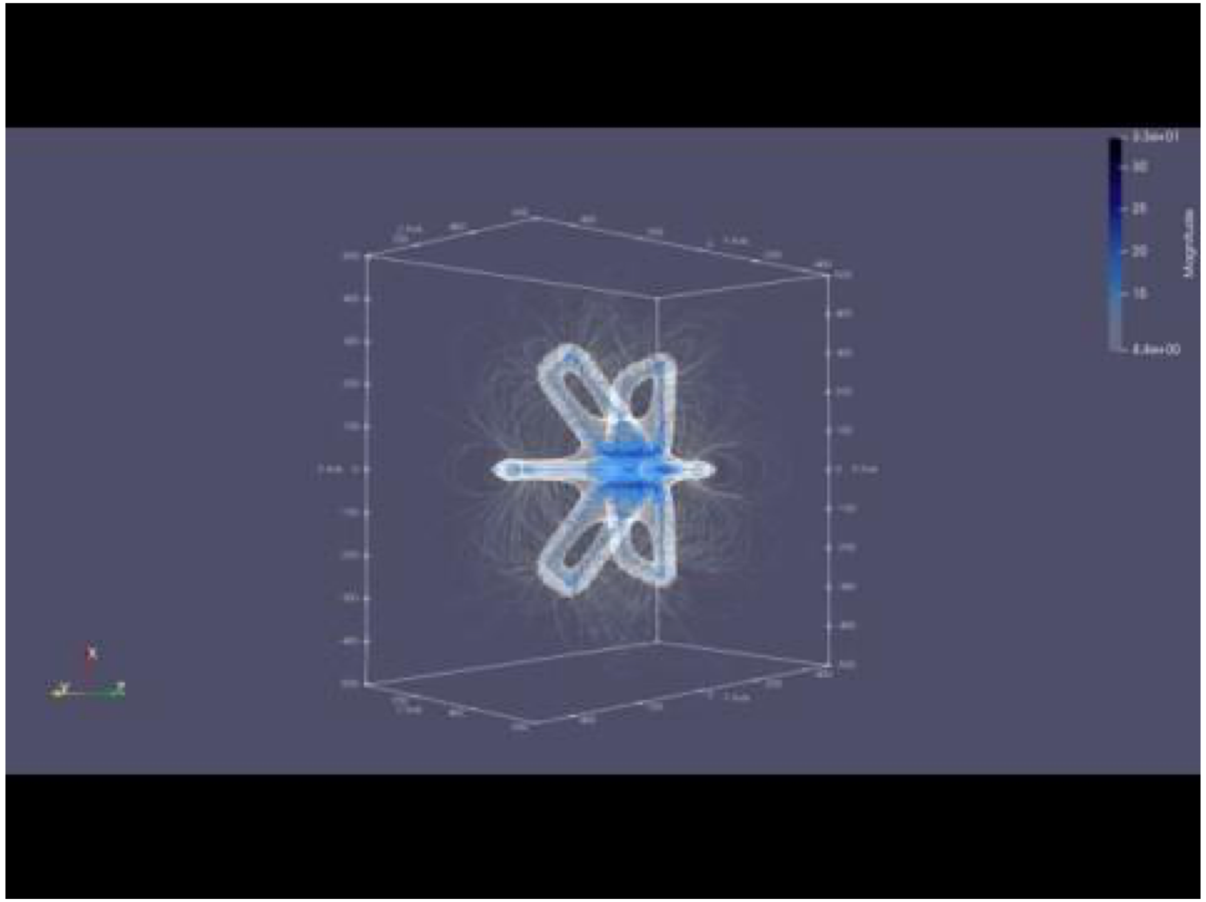




Magnet & Trajectory Update

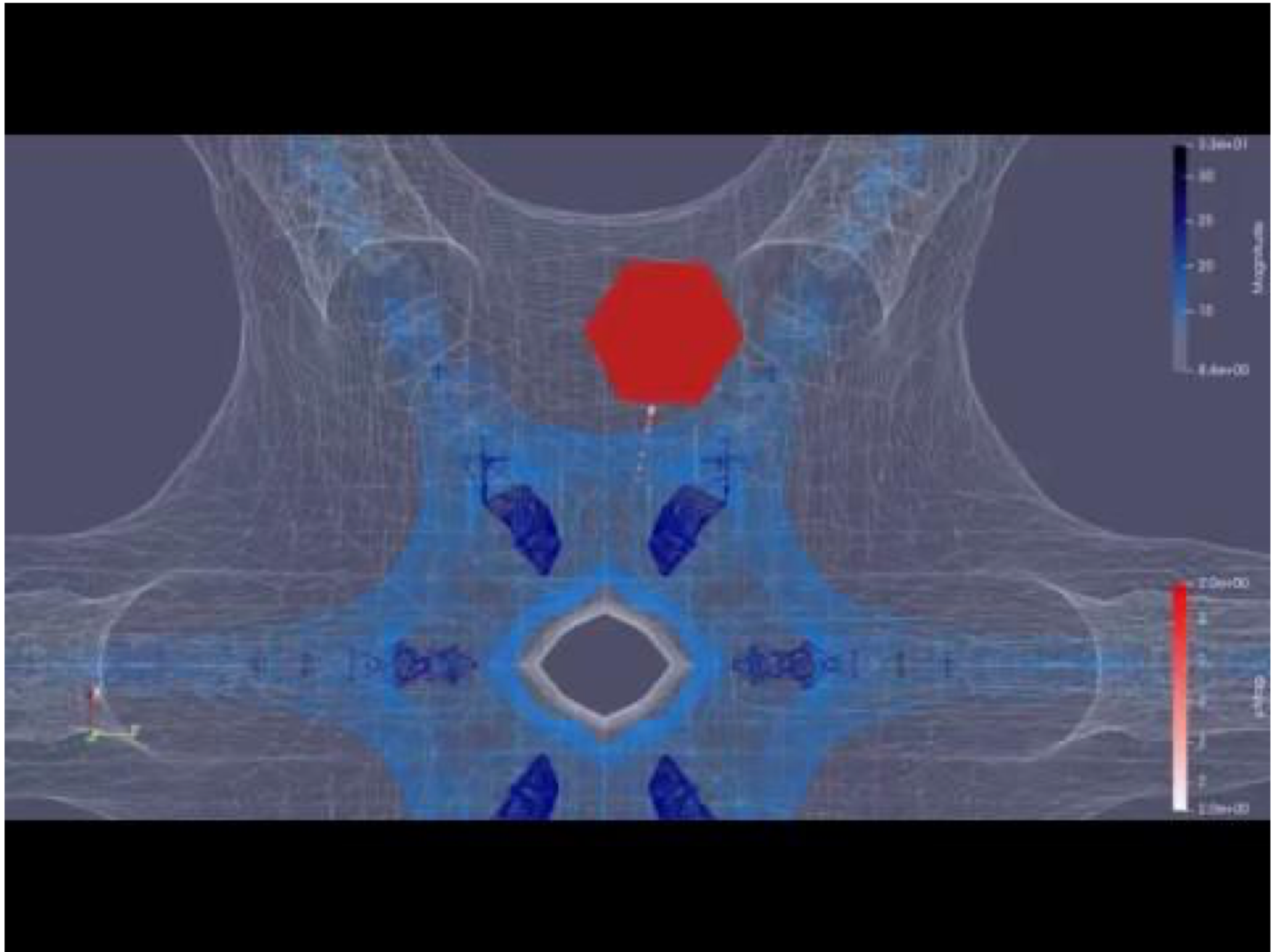
Magnet data in VR

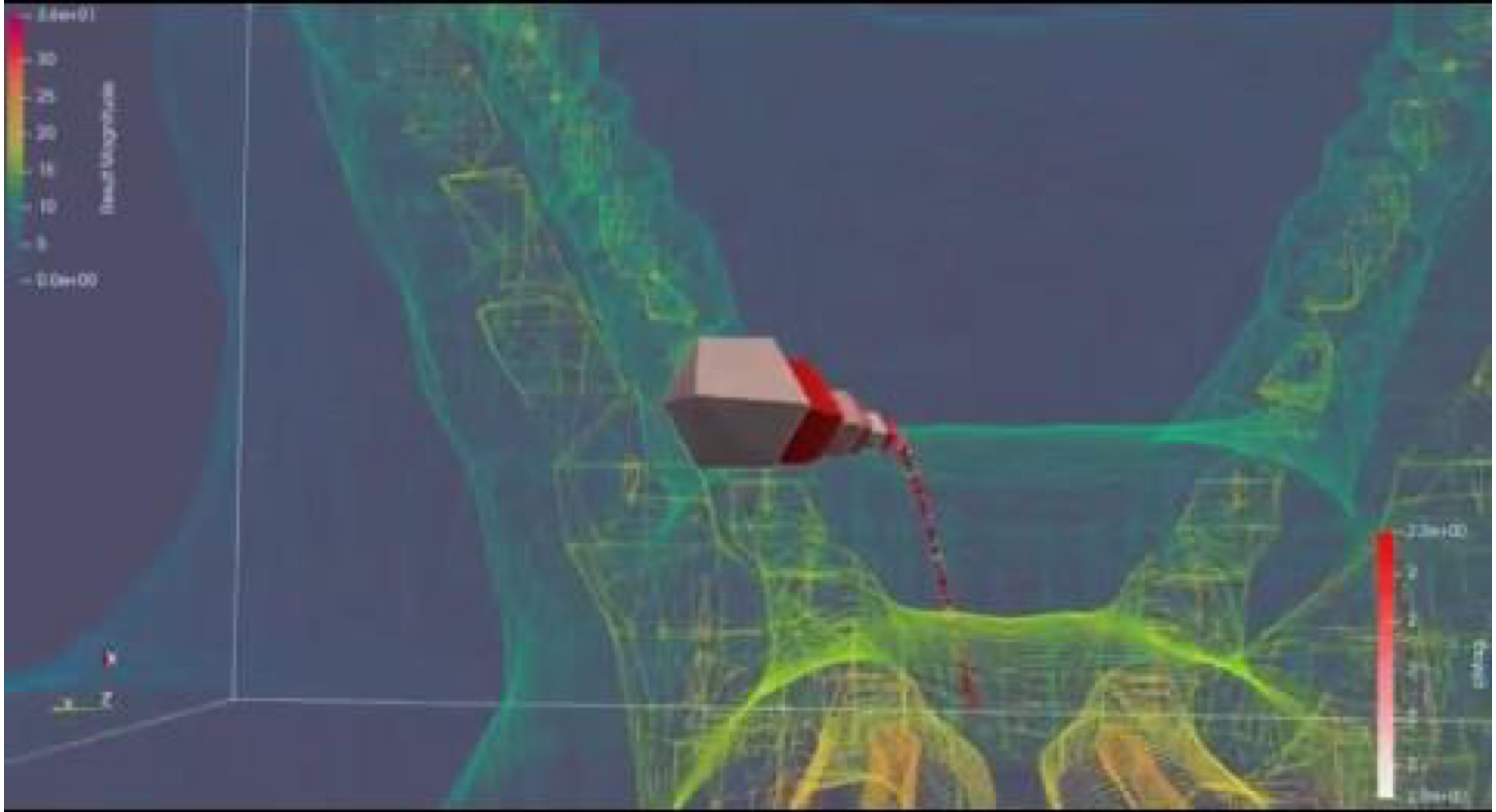
- VT HyperCube CAVE Display
- We also successfully tested the data pipeline To Oculus HMD headsets
- Continue to refine visual representations



Magnetic field w/ Trajectory

Loaded CSV, Videos, X3D, and Images exported

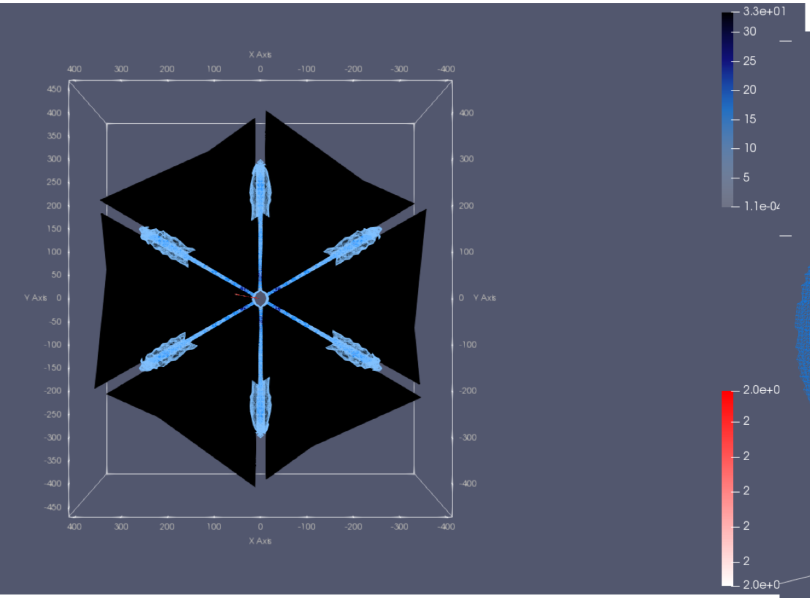


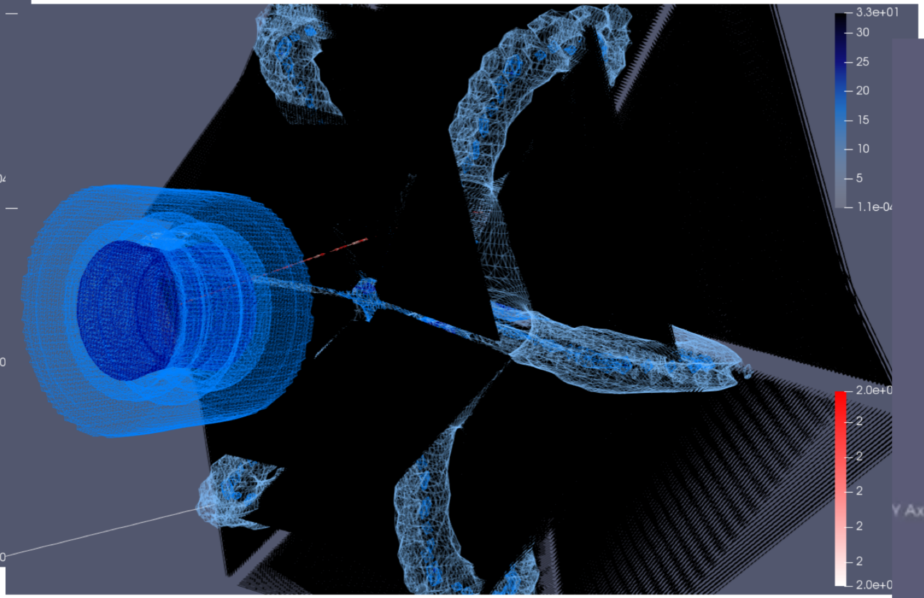

30
25
20
15
10
5

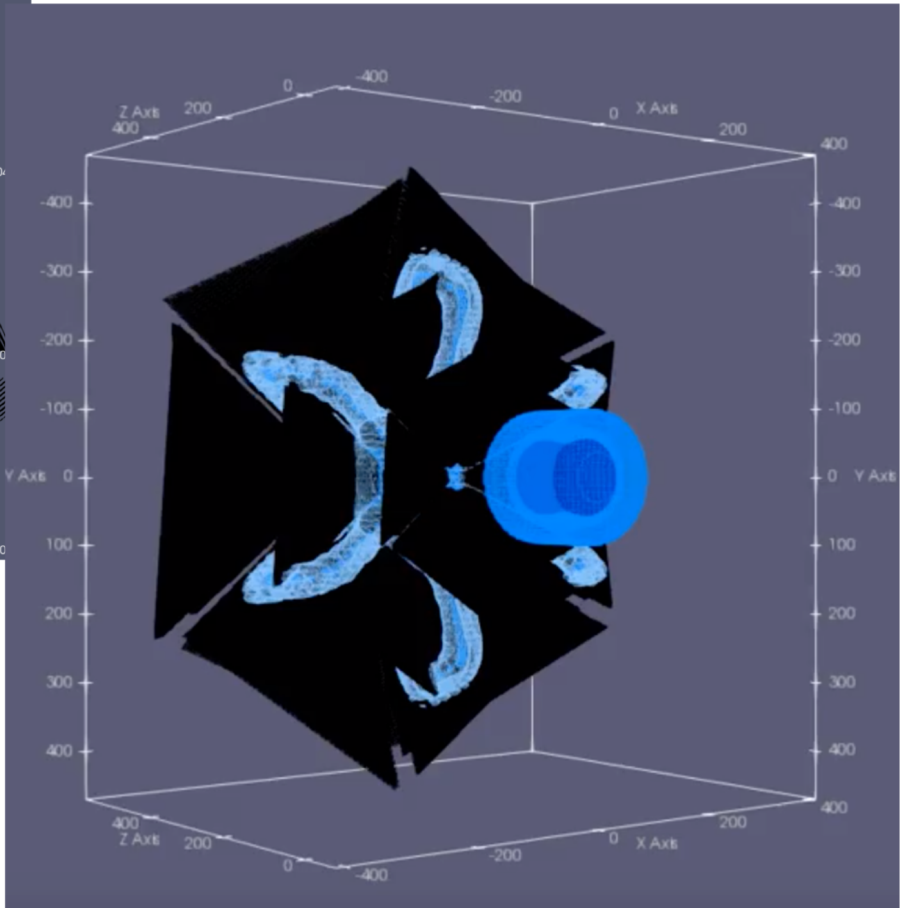
X3D export in VT HyperCube (CAVE)

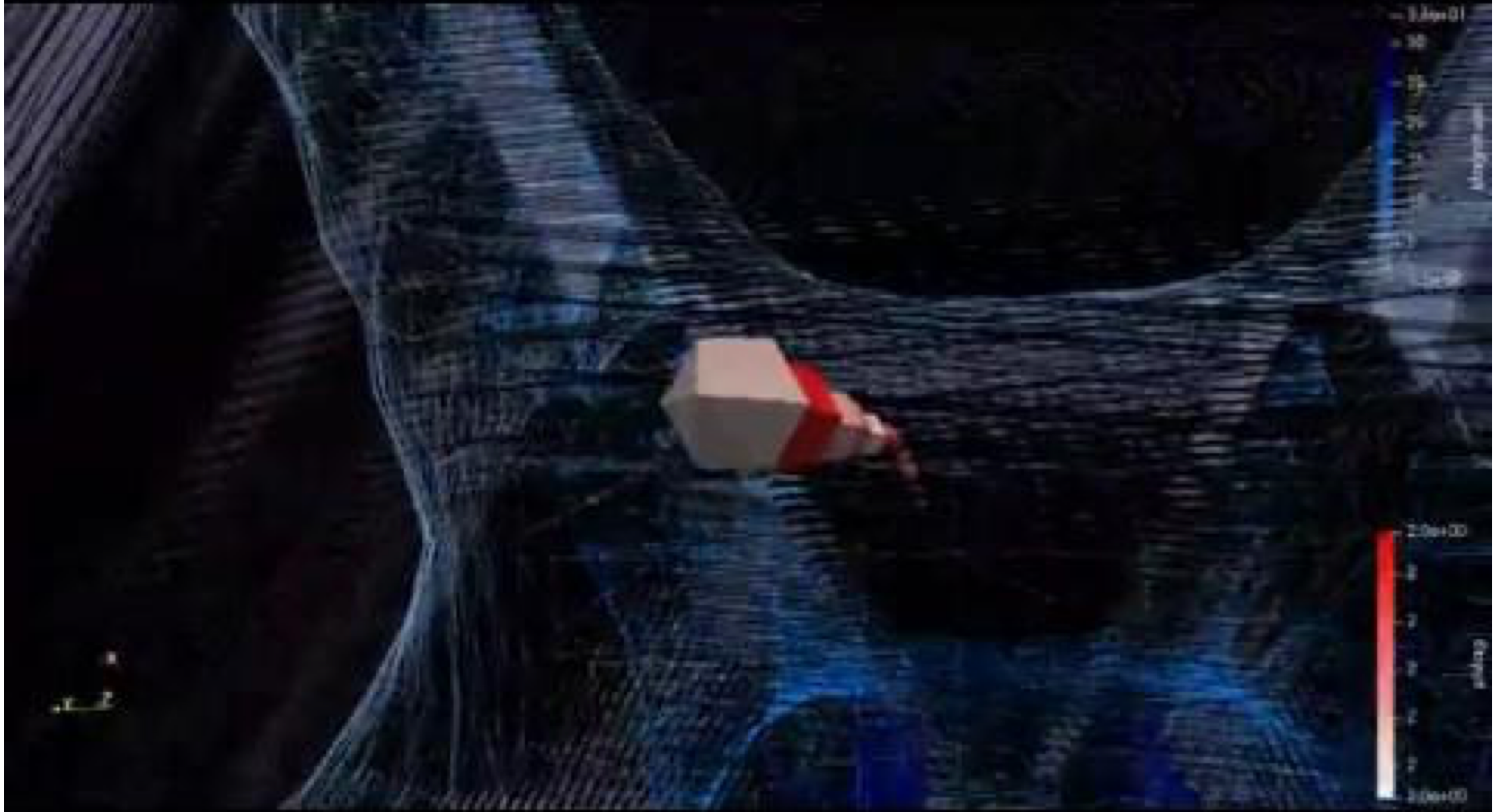
Detector Wires

26,000 detector wires' geometry







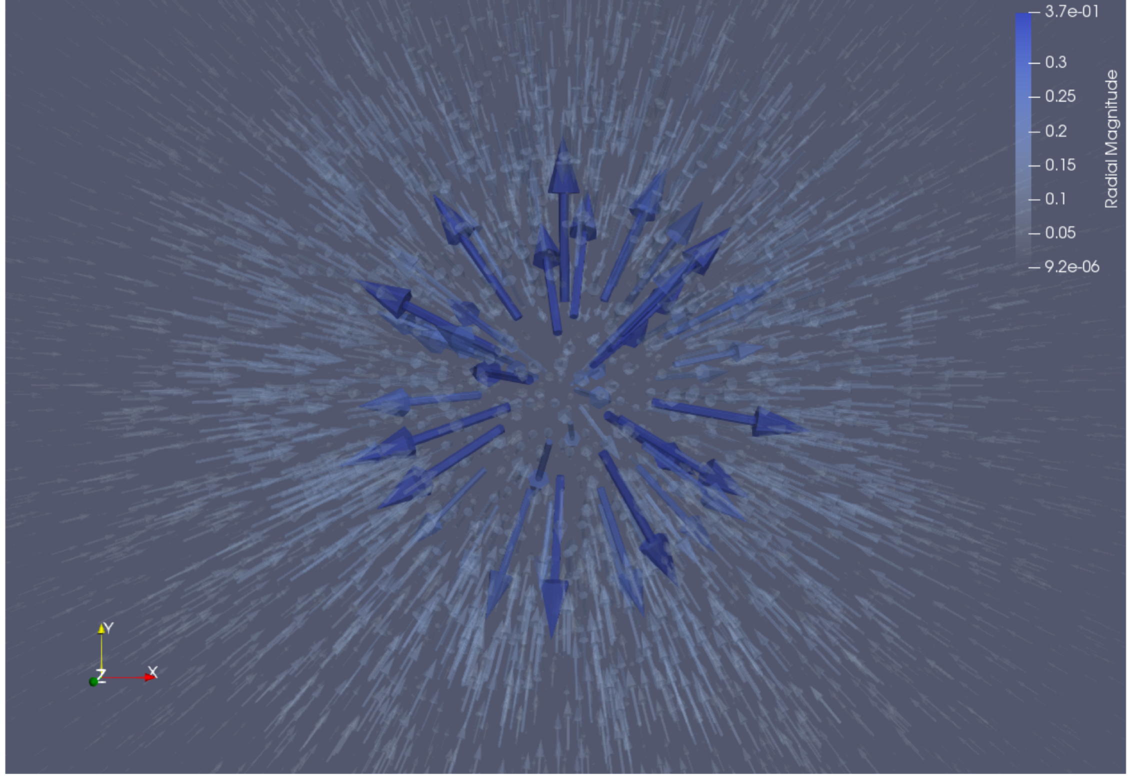


All together

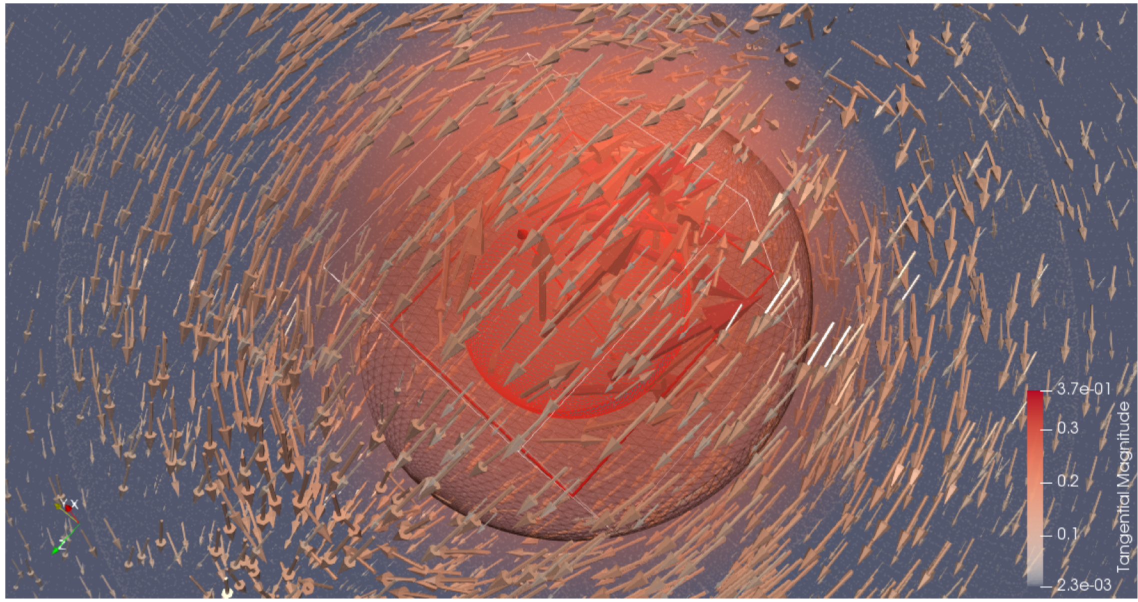
Nucleon Standard Model

Fast Monte Carlo DVCS:

- Radial forces



- Tangential forces



Arrow color and length by force magnitude

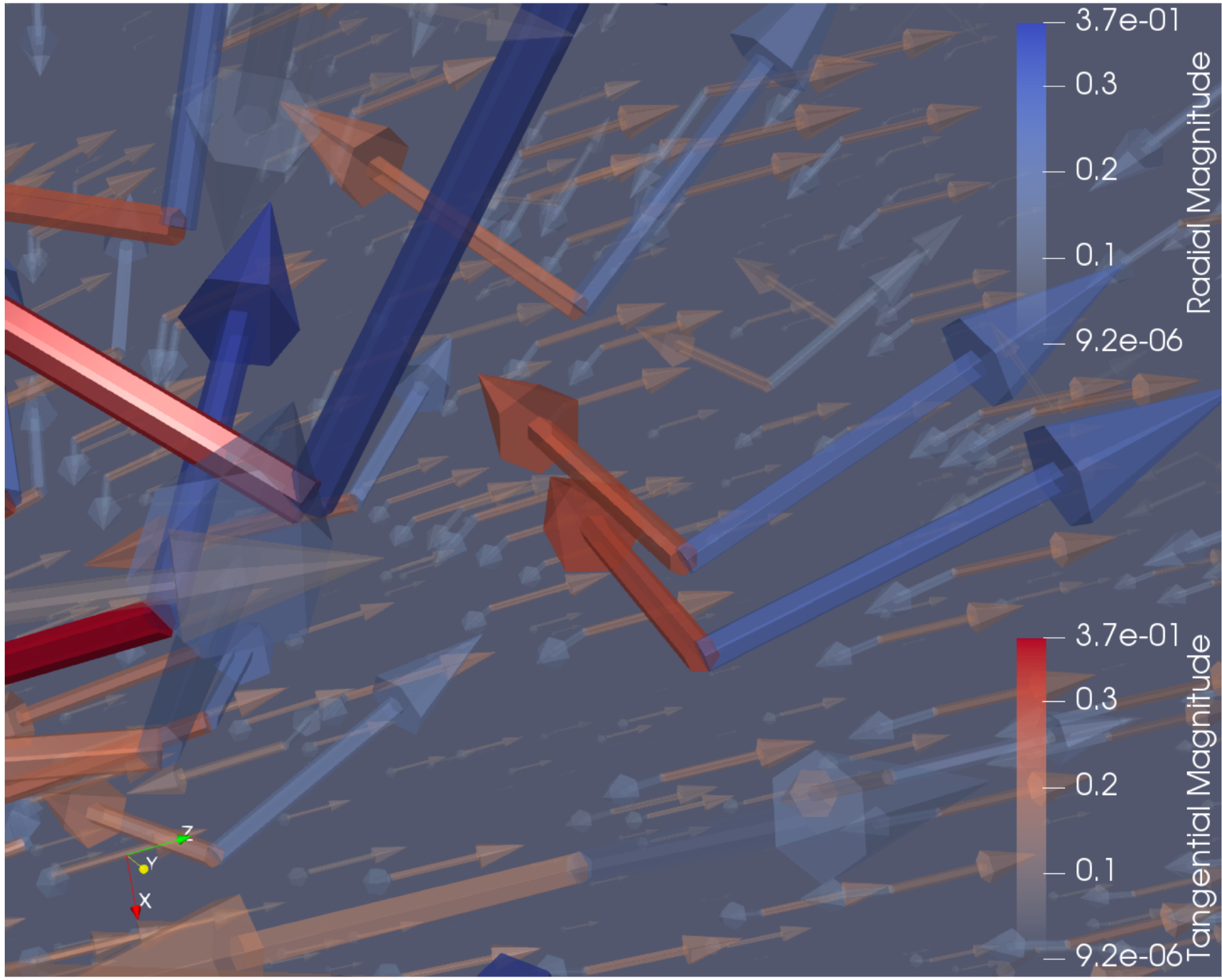
First Views

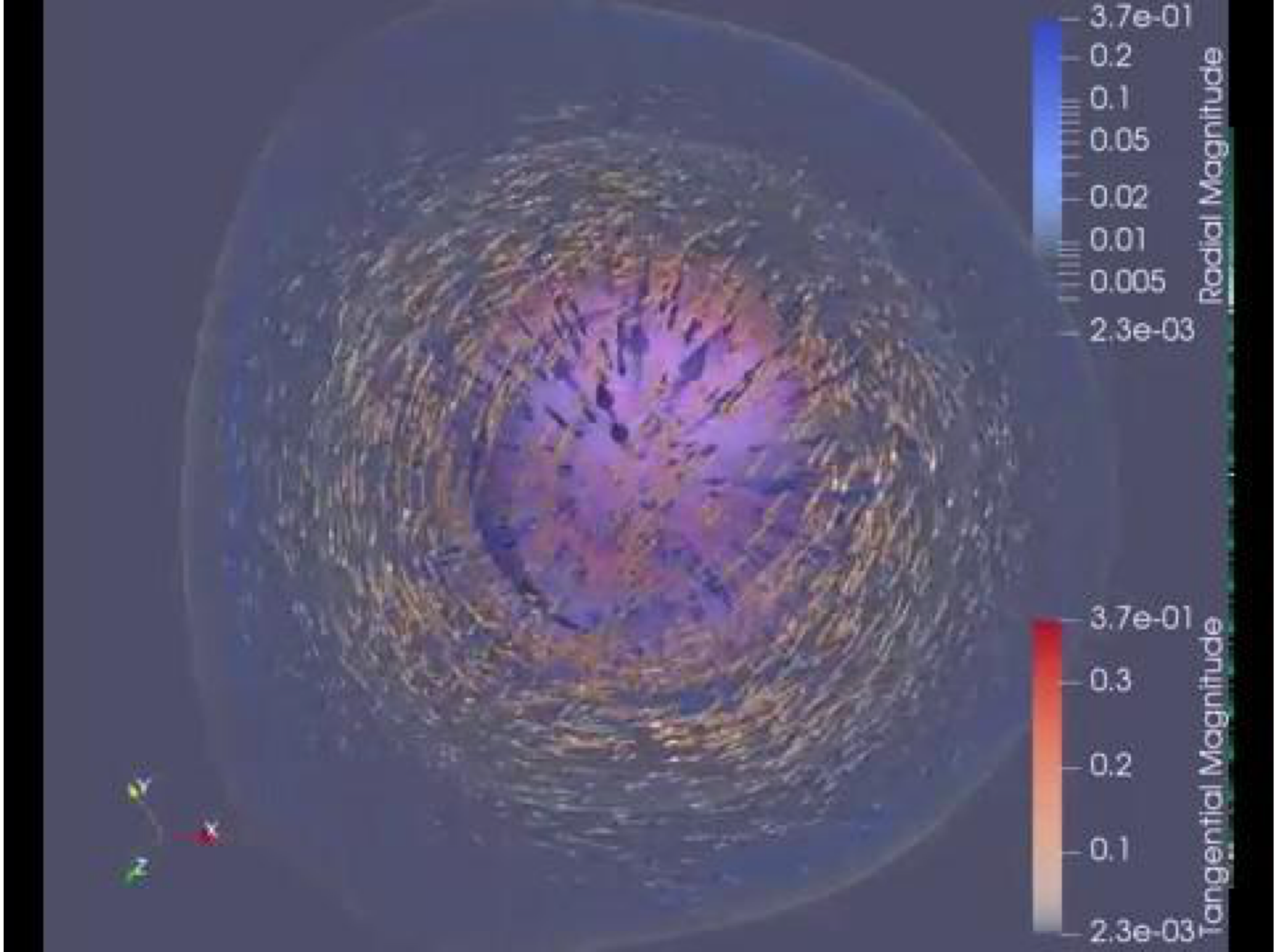
Blues: Radial forces *log scale*

Reds: Tangential forces *linear scale*

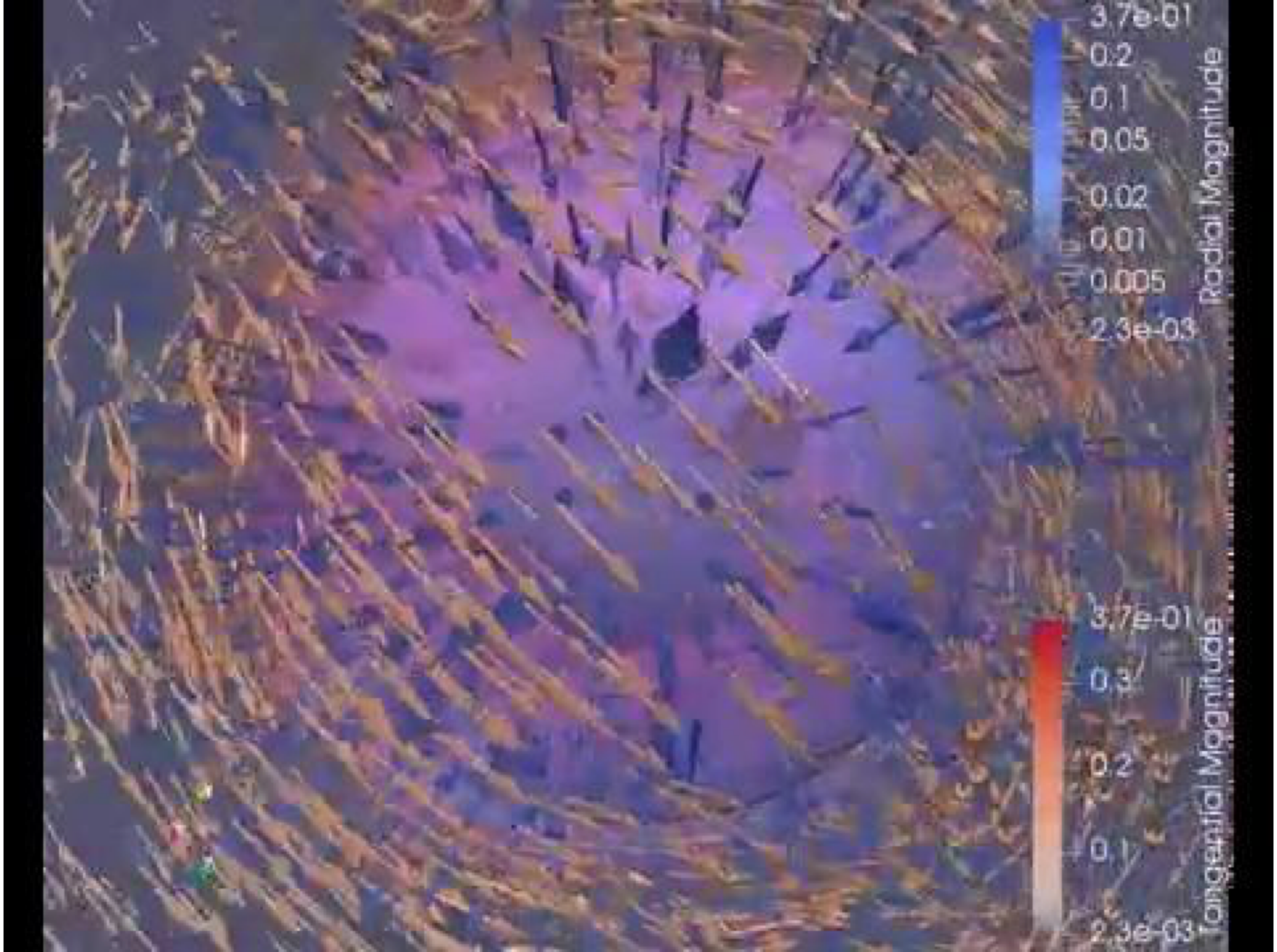
Max magnitude at .25 fm

Black sphere radius = .5 fm





3.7e-01
0.2
0.1
0.05
0.02
0.01
0.005
2.3e-03
Radial Magnitude
3.7e-01
0.3
0.2
0.1
2.3e-03
Tangential Magnitude
Y
X
Z



3.7e-01
0.2
0.1
0.05
0.02
0.01
0.005
2.3e-03
Radial Magnitude
3.7e-01
0.3
0.2
0.1
2.3e-03
Tangential Magnitude

Summary/Outlook II

- New views in instruments, experimental data
- New views of Standard Model simulations
- Reproducible with open source software
- Broad impact with online images, videos, 3D models
- Support for advanced VR visualization

Future Work

- Submit to SuperComputing 2019 Scientific Visualization Showcase
- Iterate designs to project wrap
  - FMC DVCS: animations, 3D models
- Publish
  - Paraview State Files for collaborator use
  - Website w imagery & videos
  - Web3D models w WebVR (via X3D)
- Next stage CNF Proposal, EIC proposal