ePIC-Analysis
Common Physics Analysis Software for the EIC

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ePIC and the Electron-Ion Collider

- Simulation, reconstruction, and physics studies to help design an optimal detector for future experiments at the EIC
- Analysis of the physics is the primary goal
Some (recent) History

From conceptual designs...

2021

ECCE

CORE

ATHENA

2022

... to proposal designs ...

... and to a future experiment
Different Designs… and Different Software*…

**Event Generation**
- **Fun4all**
- **DD4hep**
- **GEANT4** (A SIMULATION TOOLKIT)
- **DELPHES** (fast simulation)

**Fast Simulation**
- **EIC-Smear**

**Full Simulation**
- **Event**
- **Generation**
- **Reconstruction**
- **EICrecon**
- **JANA2**
- **Juggler** (Gaudi)

* not a complete list
Different Designs… and Different Software*

Event Generation

Full Simulation
- Fun4all
- DD4hep
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Fast Simulation
- DELPHES (fast simulation)
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Reconstruction
- EICrecon
- JANA2
- Juggler (Gaudi)

Requires adaptability of:
- Users and developers
- Code
  - Detector designs
  - Reconstruction algorithms
  - Physics Analysis
ePIC-Analysis: Common physics analysis framework

- Adapted to various upstream simulation sources
- Common physics reconstruction methods for DIS, SIDIS, and Jets
- Common physics analysis techniques
- Continuous Integration to benchmark detector design evolution

https://github.com/eic/epic-analysis
Simulation/Reconstructed data are hosted on S3 and xrootd
- MinIO Client for read-access to S3
- Streamable to ROOT: `TFile::Open( s3_URL )`

Tools in ePIC-Analysis
- Automated file retrieval (for streaming or downloading)
- Tracks major production version file trees
- Application of $Q^2$ weights
**Q^2 Weighting**

- Cross section falls rapidly with $Q^2 \rightarrow$ high $Q^2$ events are rare
  - Generate events in various bins of $Q^2$
  - Re-weight them using the cross sections to combine their data
  - Populates statistics even at very high $Q^2$
  - Allows for study of a broad range of $Q^2$, without having to wait for rare high $Q^2$ events

- ePIC-Analysis provides a common $Q^2$ weighting implementation

**Q2 Bins**

- 1 – 10 GeV$^2$
- 10 – 100 GeV$^2$
- 100 – 1000 GeV$^2$
- 1000 GeV$^2$ and above
Continuous Integration

- Runs for every git commit (on a pull request)
  • Could receive triggers from upstream simulation and reconstruction repositories
  • Make a change in geometry or reconstruction, check the impact on the physics

- Job matrices:
  • ePIC full simulation / Delphes fast simulation / previous designs
  • With / without radiative corrections
  • Kinematics reconstruction methods (electron / hadronic / mixed / …)

- Build tests and Valgrind

- Artifacts: plots
  • Coverage
  • Resolution
  • Multidimensional binning
Continuous Integration

Focusing on semi-inclusive pion production from electron and proton beam energies of 18 and 275 GeV

\[ e + p \rightarrow e + \pi^+ + X \]

Artifacts
- Histograms in bins of \((x, Q^2)\)
- \((\eta, p)\)

Semi-Inclusive Deep Inelastic Scattering (SIDIS) Cuts

- \(W > 3\) GeV
- \(0.01 < y < 0.95\)
- \(0.2 < z < 0.9\)
- \(x_F > 0\)
- \(p_T^{(\text{lab})} > 0.1\) GeV
Comparison of two different ePIC design options

- x distributions in bins of (p, η)
- Comparisons:
  - With and without radiative corrections
  - ePIC designs “Arches” and “BryceCanyon”
Comparison of two different ePIC design options

- x resolutions in bins of \((x,Q^2)\)
- Comparisons with previous designs
  - ePIC / ECCE / ATHENA
- Kinematics reconstructed by electron
  - poor resolution in the small y region (low \(Q^2\) and high \(x\))
Kinematics Reconstruction

- Study SIDIS in a particle collider context
- Kinematics \((x, Q^2, y)\) can be obtained from initial and final particle momenta
  - Need to develop tools for accurate reconstruction of these event kinematics

Available methods in **ePIC-Analysis**

<table>
<thead>
<tr>
<th>Method</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) Leptonic variables</td>
<td>(q \equiv q_i = k_2 - k_1, \ y_i = p_1.(k_1 - k_2)/p_1.k_1)</td>
</tr>
<tr>
<td>ii) Hadronic variables</td>
<td>(q \equiv q_h = p_2 - p_1, \ y_i = p_1.(p_2 - p_1)/p_1.k_1)</td>
</tr>
<tr>
<td>iii) Jacquet-Blondel variables</td>
<td>(Q^2_{JB} = (\vec{p}<em>{2L})^2/(1 - y</em>{JB}), \ y_{JB} = \Sigma/(2E(k_1)))</td>
</tr>
<tr>
<td>iv) Mixed variables</td>
<td>(\Sigma = \sum_E(E_h - p_h.z))</td>
</tr>
<tr>
<td>v) Double angle method</td>
<td>(q = q_i, y_m = y_{JB})</td>
</tr>
<tr>
<td>vi) (\theta y) method</td>
<td>(Q_{DA}^2 = \frac{4E(k_2)\cos^2(\theta(k_2)/2)}{\sin^2(\theta(k_2)/2) + \sin(\theta(k_2)/2)\cos(\theta(k_2)/2)\tan(\theta(p_2)/2)})</td>
</tr>
<tr>
<td></td>
<td>(y_{DA} = 1 - \frac{\sin(\theta(k_2)/2) + \cos(\theta(k_2)/2)\tan(\theta(p_2)/2)}{\sin(\theta(k_2)/2)})</td>
</tr>
<tr>
<td>vii) (\Sigma) method</td>
<td>(Q^2_{\Sigma} = \frac{4E(k_2)^2}{1 - y_{\Sigma}}, \ y_{\Sigma} = \frac{\Sigma + E(k_2)[1 - \cos(\theta(k_2))]}{\Sigma})</td>
</tr>
<tr>
<td>viii) (e\Sigma) method</td>
<td>(Q^2_{e\Sigma} = Q^2_i, \ y_{e\Sigma} = \frac{Q^2_i}{s_{e\Sigma}})</td>
</tr>
</tbody>
</table>

Kinematics Reconstruction With Machine Learning

AI for kinematics reconstruction shows promising results!

C. Pecar, 2\textsuperscript{nd} Workshop on AI for the EIC (Oct. 2022)

Output Data Structures

◆ ROOT objects
  • Specific TTrees
    • SIDIS
    • Jets
    • and more
  • Histograms

◆ Support for multidimensional binning of objects
  • 1D Binning of observables is not enough!
  • The cross section is multidimensional, thus we need to perform analysis in multidimensional bins
Multidimensional Binning

Problem: The need for multidimensional analysis caused deeply nested for loops to spread throughout epic-analysis

- Not maintainable and not generalized
- Very susceptible to bugs

```cpp
for (auto z_bin : z_bins) {
    for (auto y_bin : y_bins) {

        action_before_x_Q2_subloop( z_bin, y_bin );

        for (auto Q2_bin : Q2_bins) {
            for (auto x_bin : x_bins) {

                action_for_each_bin( z_bin, y_bin, Q2_bin, x_bin );

            }
        }

    }

    action_after_x_Q2_subloop( z_bin, y_bin );
}
```
Adage

https://github.com/c-dilks/adage

- Generalize multidimensional binning implementation with a Directed Acyclic Graph (DAG)
  - Fully connected layers of 1D bins
  - One full path from root node to leaf node == 1 multidimensional bin

- Store 1\textsuperscript{st} order functions as additional “control nodes”, between layers of 1D bin nodes
  - Executable during depth-first traversal
  - Attach your code to the data structure and run it!

![DAG Diagram]
for (auto z_bin : z_bins) {
    for (auto y_bin : y_bins) {
        action_before_x_Q2_subloop( z_bin, y_bin );
        for (auto Q2_bin : Q2_bins) {
            for (auto x_bin : x_bins) {
                action_for_each_bin( z_bin, y_bin, Q2_bin, x_bin );
            }
        }
        action_after_x_Q2_subloop( z_bin, y_bin );
    }
}
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    for (auto Q2_bin : Q2_bins) {
        for (auto x_bin : x_bins) {
            action_for_each_bin( z_bin, y_bin, Q2_bin, x_bin );
        }
    }
    action_after_x_Q2_subloop( z_bin, y_bin );
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            for (auto x_bin : x_bins) {
                action_for_each_bin( z_bin, y_bin, Q2_bin, x_bin );
            }
        }
        action_after_x_Q2_subloop( z_bin, y_bin );
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        }
    }
    action_after_x_Q2_subloop( z_bin, y_bin );
}
for (auto z_bin : z_bins) {
    for (auto y_bin : y_bins) {
        action_before_x_Q2_subloop( z_bin, y_bin );

        for (auto Q2_bin : Q2_bins) {
            for (auto x_bin : x_bins) {
                action_for_each_bin( z_bin, y_bin, Q2_bin, x_bin );
            }
        }

        action_after_x_Q2_subloop( z_bin, y_bin );
    }
}

control \{Q,x\}

traversal
for (auto z_bin : z_bins) {
    for (auto y_bin : y_bins) {
        action_before_x_Q2_subloop( z_bin, y_bin );

        for (auto Q2_bin : Q2_bins) {
            for (auto x_bin : x_bins) {
                action_for_each_bin( z_bin, y_bin, Q2_bin, x_bin );
            }
        }

        action_after_x_Q2_subloop( z_bin, y_bin );
    }
}
Adage

In Practice:

```c
// define bins
...

// define lambdas
action_before_x_Q2_subloop = ...;
action_after_x_Q2_subloop = ...;
action_for_each_bin = ...;

// attach lambdas to the DAG
Adage->BeforeSubloop( {"x","q2"}, action_before_x_Q2_subloop );
Adage->AfterSubloop( {"x","q2"}, action_after_x_Q2_subloop );
Adage->Payload( action_for_each_bin );

// run
Adage->Execute();
```
Additional Support
- Conditional execution of subloops
- Repeated subloops, with different control nodes
Summary

- ePIC-Analysis is a common framework for physics analysis
- Supports various upstream sources from the present as well as the past
- Was critical for the ATHENA proposal design
- Continues to support ePIC and will be integrated in the full software stack

● See David Lawrence’s talk: [EIC Software Overview](#)
Thanks to Our Contributors!

And many more who have contributed advice and help!
ePIC-Analysis Structure

- Fast simulation (Delphes)
- ATHENA Full simulation (DD4hep → Juggler)
- ECCE Full simulation (Fun4all → EventEvaluator)
- EPIC Full simulation (DD4hep → ElCrecon)

Analysis
- AnalysisDelphes
- AnalysisAthena
- AnalysisEcce
- AnalysisEpic

Output Data Structures (Adage, SimpleTree)

PostProcessor
Binned analysis, Plots, etc.

- ROOT: TTrees and Histograms
- Adage: multidimensional binning for anything
Kinematics Reconstruction

- Kinematics calculations performed in dedicated class(es)
  - Used for both reconstructed and MC generated particles
  - Inputs: beams, scattered electron, hadronic final state, and observed particles (single hadrons for SIDIS, jets, etc.)

- Calculations
  - Inclusive variables (x, Q2, W, y, ...)
    - 6 methods: electron, J.B., double angle, mixed, sigma, eSigma
  - SIDIS variables (p, p_T, z, \(\phi_h\), ...)
  - Jet variables (z, p_T, j_\perp, ...)
  - In general uses Lorentz invariant calculations; boost to specific frames when needed

- Future Plan
  - Cross check with upstream calculations from the reconstruction framework and/or upstream our methods