Far-Forward Detectors @ the EIC

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Electron Ion Collider
• In addition to the central detector → detectors integrated into the beamline on both the hadron-going (far-forward) and electron-going (far-backward) direction.
  • Requires special considerations for the machine-detector interface.

The far-forward system functions almost like an independent spectrometer experiment at the EIC!

We will focus on the detector setup for IP6, but I will discuss what we gain with IP8 at the end.
The Far-Forward Detectors

- B0 Silicon Tracker and Preshower
- PbWO4 EMCAL
- Focusing Quadrupoles
- Zero-Degree Calorimeter
- Roman Pots
- B1apf
- Off-Momentum Detectors

All simulations done in GEANT4
### The Far-Forward Detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Acceptance</th>
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<tbody>
<tr>
<td>Zero-Degree Calorimeter (ZDC)</td>
<td>$\theta &lt; 5.5$ mrad ($\eta &gt; 6$)</td>
</tr>
<tr>
<td>Roman Pots (2 stations)</td>
<td>$0.0^* &lt; \theta &lt; 5.0$ mrad ($\eta &gt; 6$)</td>
</tr>
<tr>
<td>Off-Momentum Detectors (2 stations)</td>
<td>$0.0 &lt; \theta &lt; 5.0$ mrad ($\eta &gt; 6$)</td>
</tr>
<tr>
<td>B0 Detector</td>
<td>$5.5 &lt; \theta &lt; 20.0$ mrad ($4.6 &lt; \eta &lt; 5.9$)</td>
</tr>
</tbody>
</table>
Far-Forward Processes at the EIC

- **e+p DVCS**
- **e+d exclusive J/Psi with p/n tagging**
- **e+He3 spectator tagging**
- **coherent/incoherent J/ψ production in e+A**
- **u-channel backward exclusive electroproduction**

**Meson structure:**
- $\text{ep} \rightarrow (\pi) \rightarrow e' \, n \, X$
- $\Lambda \rightarrow p \, \pi$ and $\Lambda \rightarrow n \, \pi^0$

**Rare isotopes**

**e+He4 DVCS**
Far-Forward Processes at the EIC

- Physics channels require tagging of **charged hadrons** (protons, pions) or **neutral particles** (neutrons, photons) at **very-forward rapidities** ($\eta > 4.5$).
- Different final states require tailored detector subsystems.
Far-Forward Processes at the EIC

- Physics channels require tagging of **charged hadrons** (protons, pions) or **neutral particles** (neutrons, photons) at **very-forward rapidities** ($\eta > 4.5$).
- Different final states require tailored detector subsystems.
- Various collision systems (e.g. $e+p$, $e+d$, $e+Au$) provide unique challenges.
- Placing of far-forward detectors uniquely challenging due to presence of machine components, space constraint, apertures, etc.

...and MANY more!
Physics channels require tagging of **charged hadrons** (protons, pions) or **neutral particles** (neutrons, photons) at **very-forward rapidities** ($\eta > 4.5$).

- Different final states require tailored detector subsystems.
- Various collision systems (e.g. $e+p$, $e+d$, $e+Au$) provide unique challenges.
- Placing of far-forward detectors uniquely challenging due to presence of machine components, space constraint, apertures, etc.
- Conceptual design and basic studies to establish requirements complete – we are moving on toward full engineering design!

...and MANY more!
Some general comments about simulations

- Detector simulations carried out using GEANT (GEometry ANd Tracking) – a well-developed code package used to simulate particle interactions with matter.
Some general comments about simulations

- Once particle + matter simulations are complete, need to be converted to useful form → digitization.
- Digitization takes the information the GEANT produces, and turns it into a mimicked signal in your simulated detector.

Cartoon of proton passing through silicon plane, and depositing a bit of energy.
Some general comments about simulations

- Reconstruction is taking the digitized information and turning it into a physical quantity (e.g. energy, momentum, etc.).
Far-Forward Detector Subsystems
B0 Detectors

Space for detectors
B0 Detectors

- Charged particle reconstruction and photon tagging.
- Precise tracking (~10um spatial resolution).
- Fast timing for background rejection and to remove crab smearing (~35ps).
- Photon detection (tagging or full reco).

Preliminary Parameters:
229.5cm x 121.1cm x 195cm
(Actual length will be shorter)

Electrons

Space for detectors

Hadrons

This is the opening where the detector planes will be inserted.
B0 Detectors in CAD

Lead Sheet

Detector Plates

Blue lines represent where element locations are along beamline

Length of Detector is 1.5m
B0 Integration

- Crystal EMCAL weight is \textasciitilde50\text{kg} (for PbWO4) → \textbf{support system and installation procedure for the blocks needs to be designed.}
  - Readout? → SiPMs optimal for size, but radiation loads in B0 substantial.
  - Access to B0 system requires removal of pump in front of magnet (see next slide) → not easy to simply reach in and replace PMTs.
B0 Integration

- Pump in front of detector package - only 13cm of space between pump and detector.
- Not currently in DD4HEP geometry - another source of secondaries (impact to be evaluated).

- Tracking planes separate into two pieces - top and bottom - for insertion into bore.
- Need concept for EMCAL.
B0-detectors

(5.5 < \(\theta\) < 20.0 mrad)

- High-precisions tracking detectors required for charged particle reconstruction.
- Tagging photons important in differentiating between coherent and incoherent heavy-nuclear scattering, and for reconstructing \(\pi^0 \rightarrow \gamma\gamma\).
Roman Pots

• Place roman pottery into the particle accelerator → learn the deep mysteries of the universe?
Roman pots at STAR – used to measure p+p elastic scattering.
Roman Pots are silicon sensors placed in a “pot”, which is then injected into the beam pipe, tens of meters or more from the interaction point (IP).

Momentum reconstruction carried out using matrix transport of protons through magnetic lattice.

Roman Pots at ~30 m from IP → $\theta \sim 0 - 5$ mrad

- $x_0, y_0$: Position at Interaction Point
- $\Theta^*_x, \Theta^*_y$: Scattering Angle at IP
- $x_D, y_D$: Position at Detector
- $\Theta^*_D, \Theta^*_y$: Angle at Detector
Roman Pots @ the EIC

Full GEANT4 simulation.

Protons
E = 275 GeV
0 < θ < 5 mrad
Two stations, separated by 2 meters, each with two layers (minimum) of silicon detectors.
- Silicon detectors placed directly into machine vacuum!
  - Allows maximal geometric coverage!
- Need space for detector insertion tooling and support structure.
Roman “Pots” @ the EIC

\[ \sigma(z) = \sqrt{\varepsilon \cdot \beta(z)} \]

\( \sigma(z) \) is the Gaussian width of the beam, \( \beta(z) \) is the RMS transverse beam size.
\( \varepsilon \) is the beam emittance.

- Low-pT cutoff determined by beam optics.
- The safe distance is \(~10\sigma\) from the beam center.
- \( 1\sigma \sim 1\text{mm} \)

- These optics choices change with energy, but can also be changed within a single energy to maximize either acceptance at the RP, or the luminosity.
Roman “Pots” @ the EIC
High Divergence: smaller $\beta^*$ at IP, but bigger $\beta (z = 30 m)$ -> higher lumi., larger beam at RP
Digression: Machine Optics

275 GeV DVCS Proton Acceptance

High Divergence: smaller $\beta^*$ at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

High Acceptance: larger $\beta^*$ at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP
Using the two configurations, we are able to measure the low-\( t \) region (with better acceptance) and high-\( t \) tail (with higher luminosity).

High Acceptance: larger \( \beta^* \) at IP, smaller \( \beta(z = 30m) \rightarrow \) lower lumi., smaller beam at RP
Digression: Machine Optics

100 GeV DVCS Proton Acceptance

Need both detector systems together here!

~25 cm
Digression: Machine Optics

100 GeV DVCS Proton Acceptance

Need both detector systems together here!

Improves low $p_t$ acceptance.
Off-Momentum Detectors

neutrons and photons

RP

ZDC

B2apf

B1apf
Off-Momentum Detectors

- Off-momentum protons $\rightarrow$ smaller magnetic rigidity $\rightarrow$ **greater bending in dipole fields**.
- Important for any measurement with nuclear breakup!

\[ x_L = \frac{p_{z,\text{proton}}}{p_{z,\text{beam}}} \]

<table>
<thead>
<tr>
<th>B1apf</th>
<th>OMD</th>
<th>RP</th>
<th>B2apf</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{neutrons and photons}</td>
<td>\text{Protons with (~50\text{-}60%) momentum w.r.t. steering magnets.}</td>
<td>\text{Protons with (~35\text{-}50%) momentum w.r.t. steering magnets.}</td>
<td>\text{OMD}</td>
</tr>
</tbody>
</table>
Off-Momentum Detectors

- Same technology choice(s) as for the Roman Pots.
- Need to also study use of OMD on other side for tagging negative pions.

Off-momentum detectors implemented as horizontal "Roman Pots" style sensors.

Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < θ < 5 mrad

EICROOT GEANT4 simulation.
Off-Momentum Detectors

Protons
$123.75 < E < 151.25 \text{ GeV}$
(45% < $xL$ < 55%)
$0 < \theta < 5 \text{ mrad}$

EICROOT GEANT4 simulation.
Digression: particle beams

• Angular divergence
  • Angular “spread” of the beam away from the central trajectory.
  • Gives some small initial transverse momentum to the beam particles.

• Crab cavity rotation
  • Can perform rotations of the beam bunches in 2D.
  • Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.

These effects introduce smearing in our momentum reconstruction.
Summary of Detector Performance (Trackers)

- Includes realistic considerations for pixel sizes and materials
  - More work needed on support structure and associated impacts.
- Roman Pots and Off-Momentum detectors suffer from additional smearing due to improper transfer matrix reconstruction.
  - This problem is close to being solved!
Summary of Detector Performance (Trackers)

- All beam effects included!
  - Angular divergence.
  - Crossing angle.
  - Crab rotation/vertex smearing.

Beam effects the dominant source of momentum smearing!
Zero-Degree Calorimeter

• Need a calorimeter which can accurately reconstruct photons and neutrons from our various final states (e.g. tagged DIS, incoherent vetoing in e+A, backward u-channel omega production).
• Neutrons and photons react differently in materials – need both an EMCAL and an HCAL!
Zero-Degree Calorimeter

• Need a calorimeter which can accurately reconstruct photons and neutrons from our various final states (e.g. tagged DIS, incoherent vetoing in e+A, backward u-channel omega production).
• Neutrons and photons react differently in materials – need both an EMCAL and an HCAL!
 Zero Degree Calorimeter (improved ALICE design):
  - Dimension: 60 cm x 60 cm x 168 cm
  - 30 m from IR
  - Detect spectator nucleon
  - Acceptance: +4.5 mrad, -5.5 mrad
  - Position resolution ~1.3 mm at 40 GeV
  - Full reconstruction of photons (EMCAL) and neutrons (HCAL)

Credit to Shima Shimizu (Kobe U., Japan)
Zero-Degree Calorimeter

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- Sufficient calorimeter depth (radiation lengths, $X_0$ for photons/electrons; nuclear interaction lengths, $\lambda_I$ for neutrons/hadrons)
  - Required for good energy resolution.
- Granularity needed for proper reconstruction of shower.
  - Finding the center of the shower needed to provide angular resolution to get neutron transverse momentum!

Credit to Shima Shimizu (Kobe U., Japan)
Zero-Degree Calorimeter

Credit to Shima Shimizu (Kobe U., Japan)
Preliminary Design of Zero-Degree Calorimeter with full support structure.
Zero-Degree Calorimeter
Understanding the support material is critical

• Support material provides interference for particles to make it to their respective detectors.

• Serves as a source for “secondary” particle production – can cause radiation damage to detectors.

Neutron radiation produced from e+p collisions at 10x275 GeV. → Most of the neutrons produced via interaction with the material!
Summary and Takeaways

- All FF detector acceptances and detector performance well-understood with currently available information.
  - Numerous impact studies done!
    - Yellow Report, Detector proposals, and stand-alone impact studies.
    - Final technology choices identified, along with suitable alternate designs for risk mitigation.
- More realistic engineering considerations need to be added to simulations as design of IR vacuum system and magnets progresses toward CD-2/3a.
  - Lots of experience in performing these simulations, so this work will progress rapidly as engineering design matures.
  - Already well-established line of communication between detector and physics parties and the EIC machine/IR development group ⇒ Crucial for success!!

Email me if you have any questions: ajentsch@bnl.gov
Momentum Resolution – Timing

For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?

- Because of the rotation, the Roman Pots see the bunch crossing smeared in x.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = 1.25 mm
- If the effective vertex smearing was for a 1cm bunch, we would have .125mm vertex smearing.
- The simulations were done with these two extrema and the results compared.

- From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to negligible from this contribution.
- This can be achieved with timing of ~ 35ps (1cm/speed of light).
Roman Pots

- Active sensor area very large (26cm x 13cm).
- “Potless” design could make better use of space.
- With AC-LGADS + ALTIROC ASIC, current estimates of power dissipation around 400-500 watts for entire subsystem, so roughly 100 watts/layer.
  - With potless design, leveraging experience from LHCb VELO for cooling would allow for cooling of the electronics within the vacuum.
- Support structure only to be placed between hadron pipe and wall to avoid interference with the ZDC.
Roman Pots

- Updated layout with current design for AC-LGAD sensor + ASIC.

- Current R&D aimed at customizing ASIC readout chip (ALTIROC) for use with AC-LGADs.

<table>
<thead>
<tr>
<th>ASIC size</th>
<th>ASIC Pixel pitch</th>
<th># Ch. per ASIC</th>
<th># ASICs per module</th>
<th>Sensor area</th>
<th># Mod. per layer</th>
<th>Total # ASICS</th>
<th>Total # Ch.</th>
<th>Total Si Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6x1.8 cm²</td>
<td>500 μm</td>
<td>32x32</td>
<td>4</td>
<td>3.2x3.2 cm²</td>
<td>32</td>
<td>512</td>
<td>524,288</td>
<td>1,311 cm²</td>
</tr>
</tbody>
</table>
Momentum Resolution – Comparison

• The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

\[ \Delta p_{t,total} = \sqrt{(\Delta p_{t,AD})^2 + (\Delta p_{t,CC})^2 + (\Delta p_{t,pxl})^2} \]

- Angular divergence
- Primary vertex smearing from crab cavity rotation.
- Smearing from finite pixel size.

• Beam angular divergence
  • Beam property, can’t correct for it – sets the lower bound of smearing.
  • Subject to change (i.e. get better) – beam parameters not yet set in stone

• Vertex smearing from crab rotation
  • Correctable with good timing (~35ps)

• Finite pixel size on sensor
  • 500um seems like the best compromise between potential cost and smearing

<table>
<thead>
<tr>
<th>( \Delta p_{t,total} ) [MeV/c]</th>
<th>Ang Div. (HD)</th>
<th>Ang Div. (HA)</th>
<th>Vtx Smear</th>
<th>250um pxl</th>
<th>500um pxl</th>
<th>1.3mm pxl</th>
</tr>
</thead>
<tbody>
<tr>
<td>275 GeV</td>
<td>40</td>
<td>28</td>
<td>20</td>
<td>6</td>
<td>11</td>
<td>26</td>
</tr>
<tr>
<td>100 GeV</td>
<td>22</td>
<td>11</td>
<td>9</td>
<td>9</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>41 GeV</td>
<td>14</td>
<td>-</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>
Roman Pots @ the EIC

• Updated layout with current design for AC-LGAD sensor + ASIC.

Based on eRD24 R&D work.

• Current R&D aimed at customizing ASIC readout chip (ALTIROC) for use with AC-LGADs.
Momentum Reconstruction with Roman Pots

• Use a matrix which describes the transport of a charged particle trajectory through the magnet lattice.
  • Matrix unique for different positions along the beam-axis (s)!
  • Transforms coordinates at detectors (position, angle) to original IP coordinates.
  • Proper usage assumes a reference orbit – all calculations MUST be done in that coordinate system!

\[ (x_{IP}, y_{IP}) \rightarrow M_1 \rightarrow M_2 \rightarrow M_3 \rightarrow (x_{det.}, y_{det.}) \]

\[ M_{transfer} = M_1 M_2 M_3 \ldots \]

Can represent full lattice with a single “transfer matrix” (also called “transfer map”).

\[ \begin{pmatrix} x_D \\ \Theta_x^D \\ y_D \\ \Theta_y^D \end{pmatrix} = \begin{pmatrix} a_{11} & L_{eff}^x & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & L_{eff}^y \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} x_0 \\ \Theta_x^* \\ y_0 \\ \Theta_y^* \end{pmatrix} \]

\[ x_0, y_0 : \text{Position at Interaction Point} \]
\[ \Theta_x^*, \Theta_y^* : \text{Scattering Angle at IP} \]
\[ x_D, y_D : \text{Position at Detector} \]
\[ \Theta_x^D, \Theta_y^D : \text{Angle at Detector} \]
Momentum Reconstruction with Roman Pots

\[
\begin{pmatrix}
1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\
-0.02114673 & 0.2055261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\
0.0000 & 0.0000 & -2.25541901 & 3.78031509 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & -0.17782524 & -0.14532313 & 0.0000 & 0.0000 \\
0.0573551 & 1.01363652 & 0.0000 & 0.0000 & 1.0000 & 0.02568709 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 \\
\end{pmatrix}
\begin{pmatrix}
\Delta p/p \\
\Delta p/p \\
\Delta p/p \\
\Delta p/p \\
\end{pmatrix}
\]

\[
\begin{pmatrix}
x_{ip} \\
y_{ip} \\
z_{ip} \\
\theta_{x,28m} \\
\theta_{y,28m} \\
\end{pmatrix}
\begin{pmatrix}
x_{28m} \\
y_{28m} \\
z_{28m} \\
\end{pmatrix}
\]

- Able to benchmark transport through lattice using machine codes, and comparing with what GEANT produces (e.g. what we calculate “by hand” with GEANT).
  - The machine magnet code is called MAD-X or BMAD.
- **Question**: what happens when our measured trajectory deviates too much from the reference orbit?

\[
(1.88)x_{ip} + (28.97)\theta_{x,28m} + (0.249)\frac{\Delta p}{p} = x_{28m}
\]

\[
(-0.0211)x_{ip} + (0.206)\theta_{x,28m} + (-0.033)\frac{\Delta p}{p} = \theta_{x,28m}
\]

![Diagram of RP station 1 and RP station 2 with coordinates and angles](image)
Momentum Reconstruction with Roman Pots

\[
\begin{pmatrix}
1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\
-0.02114673 & 0.20555261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\
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0.05735551 & 1.01363652 & 0.0000 & 0.0000 & 1.0000 & 0.02568709 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 \\
\end{pmatrix}
\begin{pmatrix}
x_{ip}
\theta_{x_{ip}}
y_{ip}
\theta_{y_{ip}}
z_{ip}
\Delta p/p
\end{pmatrix}
= \begin{pmatrix}
x_{28m}
\theta_{x_{28m}}
y_{28m}
\theta_{y_{28m}}
z_{28m}
\Delta p/p
\end{pmatrix}

\]

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  • The machine magnet code is called MAD-X or BMAD.
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**Longitudinal momentum fraction**

\[
x_L = \frac{p_{z,proton}}{p_{z,beam}}
\]

For a 275 GeV beam, a 270 GeV proton has an xL of 0.98.
A Simplistic General Method

• Begin with a set of “input tuning cards” which contain many reference trajectories for calculating the matrices.

Magnets (fields, bores, etc.)

<table>
<thead>
<tr>
<th>tuning cards</th>
<th>GEANT simulation</th>
<th>Hits in RP</th>
<th>Matrix calculation code</th>
</tr>
</thead>
<tbody>
<tr>
<td>xL = 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>xL = 0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>xL = 0.95</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

G4 magnetic field stepping parameters and numerical method.

6x6 matrix + orbit offsets for xL = 1.0
6x6 matrix + orbit offsets for xL = 0.97
6x6 matrix + orbit offsets for xL = 0.95

Matrix parameter fitting code.
A Simplistic General Method

- Plot the 36 matrix values (and 4 offsets) as a function of $x_L$.
- Fit the resulting plots with 2nd-degree polynomials.

\[
\begin{bmatrix}
1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\
-0.02114673 & 0.20555261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\
0.0000 & 0.0000 & -2.25541901 & 3.78031509 & 0.0000 & 0.0000 \\
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0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000
\end{bmatrix}
\]

- The 40 fit functions (36 matrix parameters + 4 offsets) then represent the ingredients to calculate the needed matrix in real-time at reconstruction.
- All that is needed is a lookup table to get the $x_L$ value for an event based on the coordinates at the Roman Pots.
A Simplistic General Method

- Extract $x_L$ value from lookup table for the $(\theta_{x,\text{rp}}, x_{\text{rp}})$ ordered pair.

- “Chromaticity plot” serves as a lookup table to use RP coordinates to find the $x_L$ value.

- $x_L$ is then used to evaluate the correct matrix for reconstruction.
A Simplistic General Method

• Now we can “build” the correct matrix with the correct offset values for a given trajectory and perform our kinematic reconstruction.

Detector “hit” coordinates

Lookup xL

Calculate matrix parameters and offsets from fit equations.

Reconstructed momentum vector.

\[
\begin{pmatrix}
1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\
-0.02114673 & 0.20555261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\
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0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 1.0000 \\
\end{pmatrix}
\]
Results - Momentum

• Comparing “static” BMAD matrix (left) with dynamic matrix calculation (right).

![Graph showing three-momentum comparison between static and dynamic matrix calculations for 0.75 < x_L < 1.0.](image-url)
Results - pT

- Comparing “static” BMAD matrix (left) with dynamic matrix calculation (right).
• The accelerator/machine folks are used to using BMAD/MAD-X → They do not know GEANT!
• As a result, we have to do our checks and studies in a common language to ensure errors/problems are caught early.
• The method presented will obviously be improved using machine learning methods, which is next on the list of things to do.