

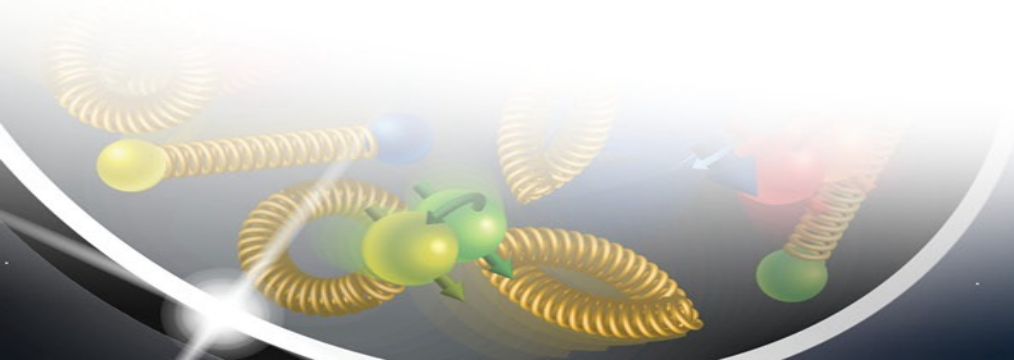


Refined Methods for Transfer Matrix Reconstruction Using Beamline Silicon Detectors for Exclusive Processes at the EIC

Alex Jentsch, for the proponents proposal #7
11/15/2022 – 8:10am
EIC Generic R&D Proposal: EICGENR&D2022_07

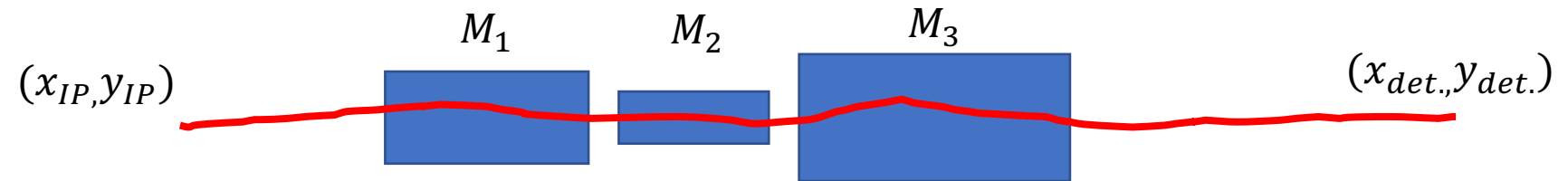
Preliminaries

- The EIC physics program includes reconstruction of final states with very far-forward protons, from many different possible collision systems.
 - e+p scattering, e+d/e+He3/e+A (proton(s) from nuclear breakup).
 - Produces protons with a broad range in longitudinal momentum, which then traverse the full hadron-going lattice (dipoles and quads).



Preliminaries

- The EIC physics program includes reconstruction of final states with very far-forward protons, from many different possible collision systems.
 - e+p scattering, e+d/e+He3/e+A (proton(s) from nuclear breakup).
 - Produces protons with a broad range in longitudinal momentum, which then traverse the full hadron-going lattice (dipoles and quads).
- Momentum reconstruction requires *transfer matrices* to describe particle motion through the magnets.



$$\begin{pmatrix} x_{ip} \\ \theta_{x,ip} \\ y_{ip} \\ \theta_{y,ip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & a_5 \\ b_0 & b_1 & b_2 & b_3 & b_4 & b_5 \\ c_0 & c_1 & c_2 & c_3 & c_4 & c_5 \\ d_0 & d_1 & d_2 & d_3 & d_4 & d_5 \\ e_0 & e_1 & e_2 & e_3 & e_4 & e_5 \\ f_0 & f_1 & f_2 & f_3 & f_4 & f_5 \end{pmatrix} \begin{pmatrix} x_{det.} \\ \theta_{x,det.} \\ y_{det.} \\ \theta_{y,det.} \\ z_{det.} \\ \Delta p/p \end{pmatrix}$$

$$M_{transfer} = M_1 M_2 M_3 \dots$$

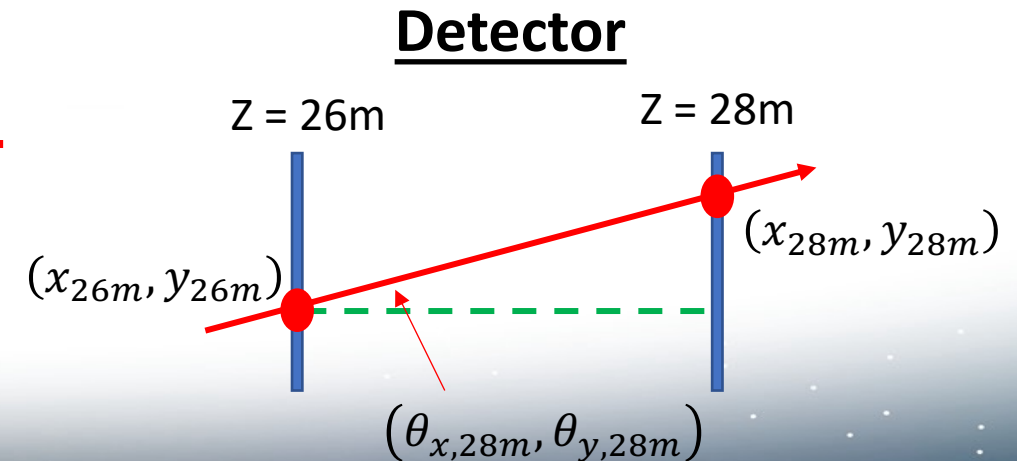
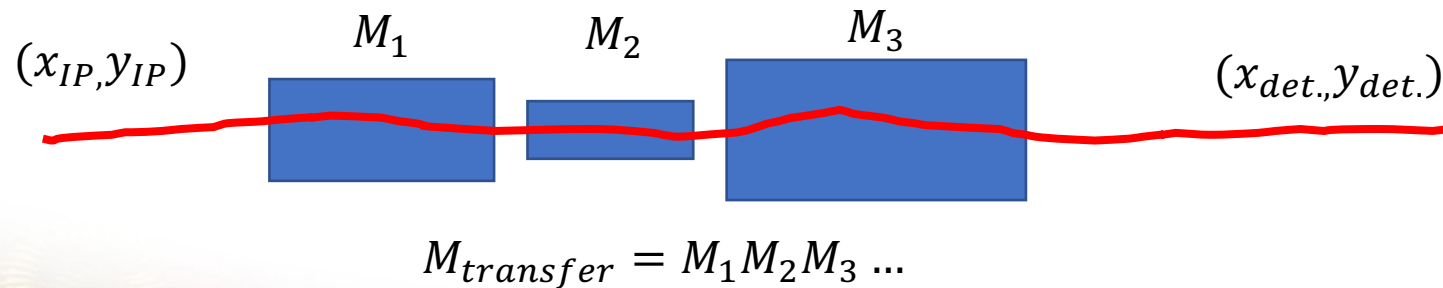
- Transforms coordinates at detectors (position, angle) to original IP coordinates.
- Matrix unique for different positions along the beam-axis!

Preliminaries

$$\begin{pmatrix} 1.88 & 28.97 & .0 & 0.0 & 0.0 & 0.25 \\ -0.0211 & 0.21 & 0.0 & 0.0 & 0.0 & -0.034 \\ 0.0 & 0.0 & -2.26 & 3.78 & 0.0 & 0.0 \\ 0.0 & 0.0 & -0.18 & -0.145 & 0.0 & 0.0 \\ 0.057 & 1.014 & 0.0 & 0.0 & 1.0 & 0.026 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{pmatrix} \begin{pmatrix} x_{ip} \\ \theta_{xip} \\ y_{ip} \\ \theta_{yip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} x_{28m} \\ \theta_{x,28m} \\ y_{28m} \\ \theta_{y,28m} \\ z_{28m} \\ \Delta p/p \end{pmatrix}$$

From BMAD – central trajectory 275 GeV proton

- Matrix describes how particles travel through the magnets toward the detector.

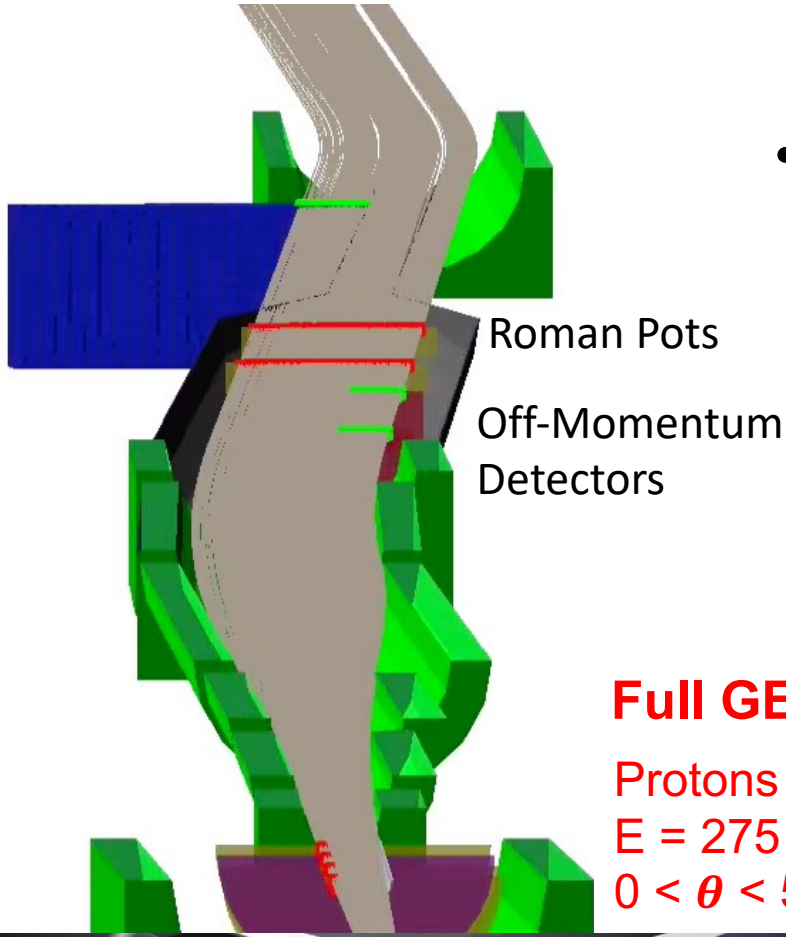


Matrix enables reconstruction of scattering information at the IP using only local hits at the detector.

The Problem

$$\begin{pmatrix} 1.88 & 28.97 & .0 & 0.0 & 0.0 & 0.25 \\ -0.0211 & 0.21 & 0.0 & 0.0 & 0.0 & -0.034 \\ 0.0 & 0.0 & -2.26 & 3.78 & 0.0 & 0.0 \\ 0.0 & 0.0 & -0.18 & -0.145 & 0.0 & 0.0 \\ 0.057 & 1.014 & 0.0 & 0.0 & 1.0 & 0.026 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{pmatrix} \begin{pmatrix} x_{ip} \\ \theta_{xip} \\ y_{ip} \\ \theta_{yip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} x_{28m} \\ \theta_{x,28m} \\ y_{28m} \\ \theta_{y28m} \\ z_{28m} \\ \Delta p/p \end{pmatrix}$$

From BMAD – central trajectory 275 GeV proton



- Protons from nuclear breakup, or high- Q^2 e+p interactions → protons can have large deviations from central orbit momentum → **require unique matrices!**

longitudinal momentum fraction

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

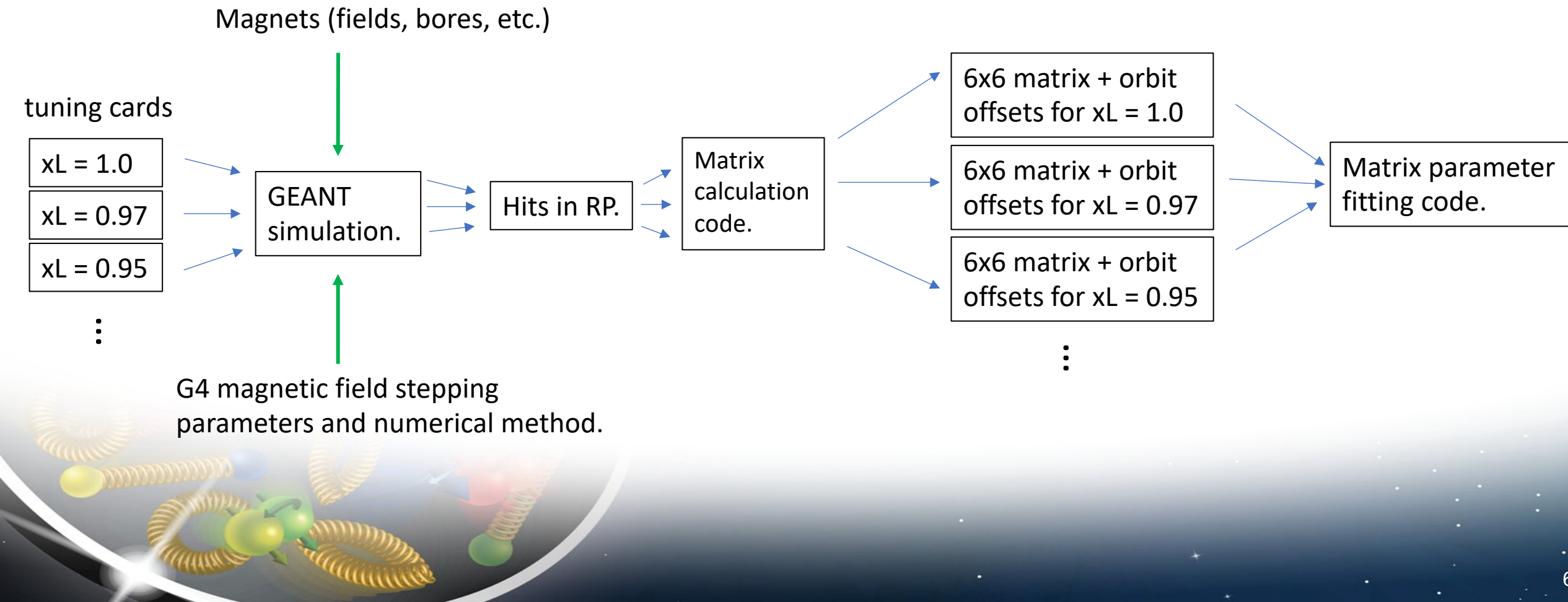
Full GEANT4 simulation.

Protons
E = 275 GeV
 $0 < \theta < 5$ mrad

For a 275 GeV beam, a 270 GeV proton has an x_L of 0.98.

The (current) Basic Solution

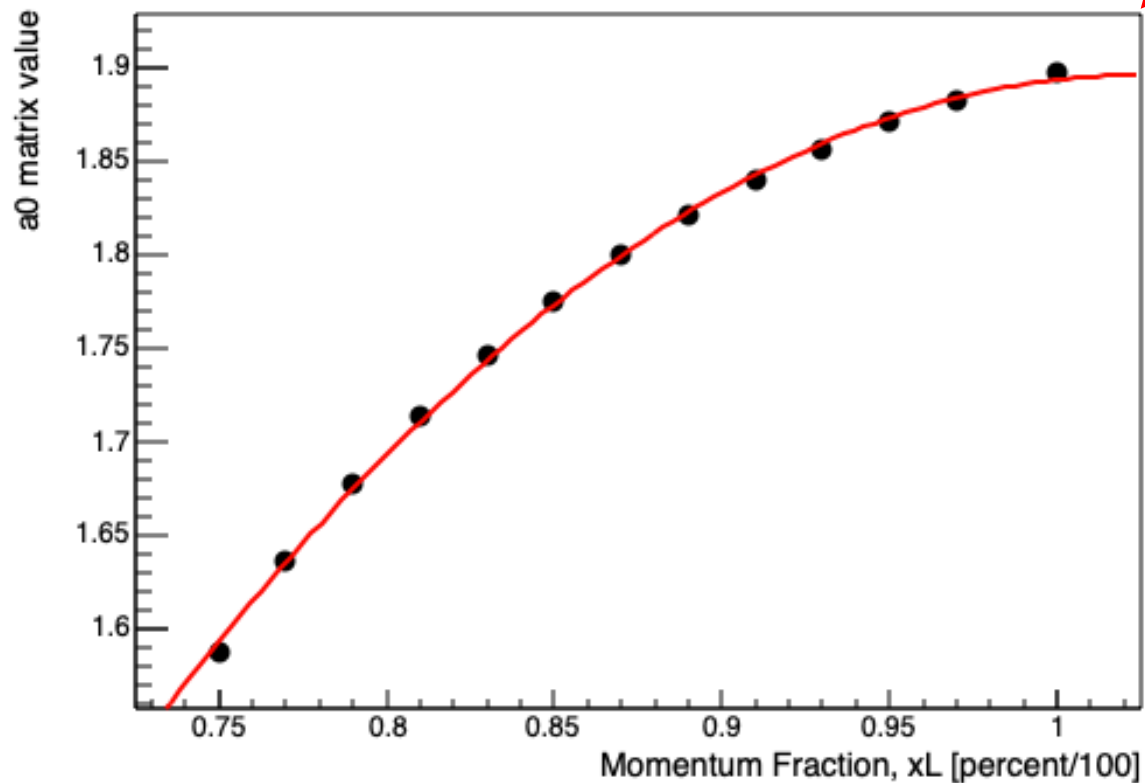
- Begin with a set of “input tuning cards” which contain the trajectories for calculating the matrices.



The (current) Basic Solution

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

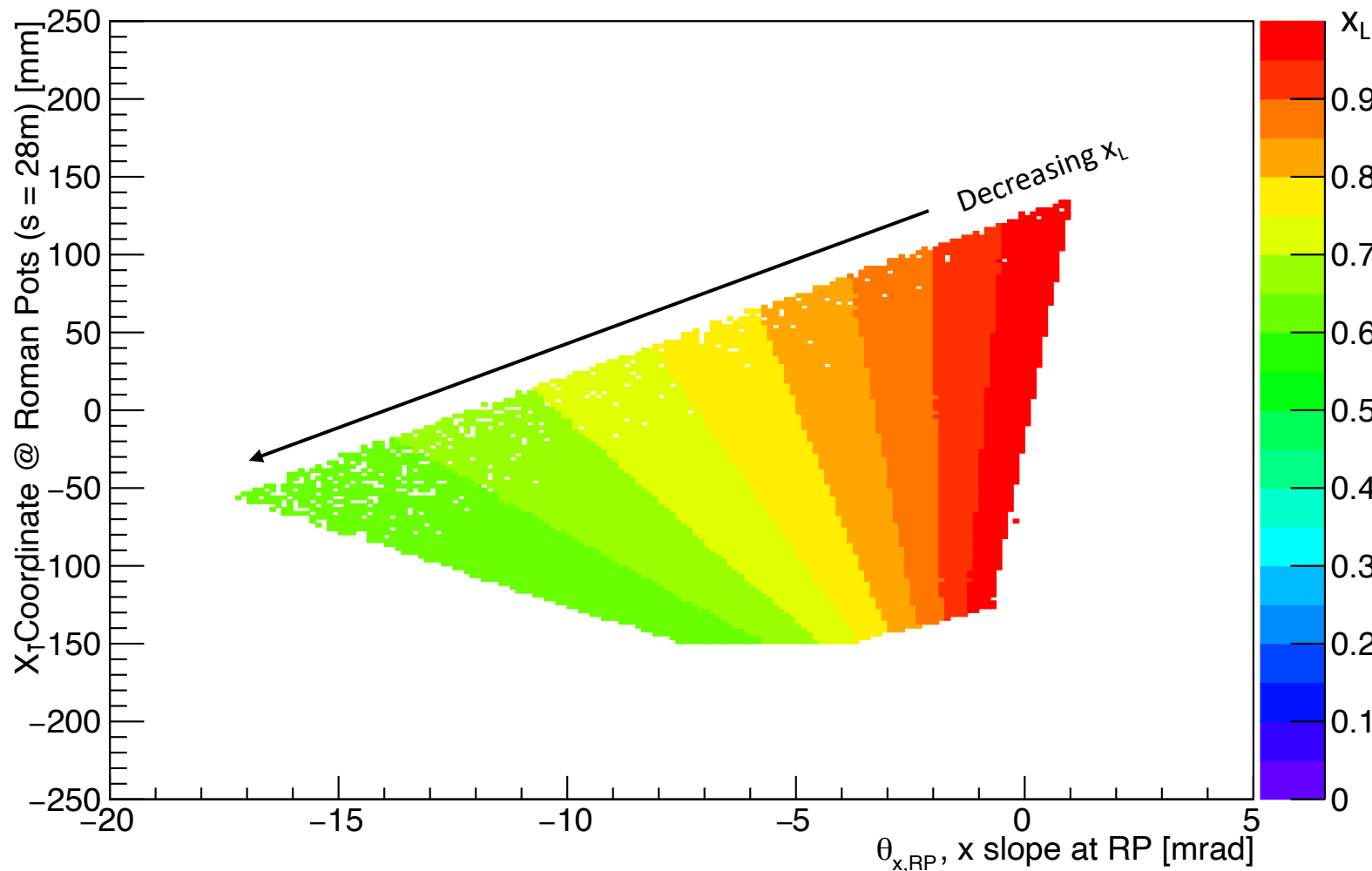
| | | | | | |
|-------------|-------------|-------------|-------------|--------|-------------|
| 1.88481537 | 28.96766544 | 0.0000 | 0.0000 | 0.0000 | 0.24906255 |
| -0.02114673 | 0.20555261 | 0.0000 | 0.0000 | 0.0000 | -0.03322467 |
| 0.0000 | 0.0000 | -2.25541901 | 3.78031509 | 0.0000 | 0.0000 |
| 0.0000 | 0.0000 | -0.17782524 | -0.14532313 | 0.0000 | 0.0000 |
| 0.05735551 | 1.01363652 | 0.0000 | 0.0000 | 1.0000 | 0.02568709 |
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1.0000 |



- The only needed additional component is a way to get x_L from the local detector hits, which is used to evaluate the matrix elements.

The (current) Basic Solution

- Extract x_L value from lookup table for the $(\theta_{x,rp}, x_{rp})$ @ $z = 28\text{m}$ ordered pair.

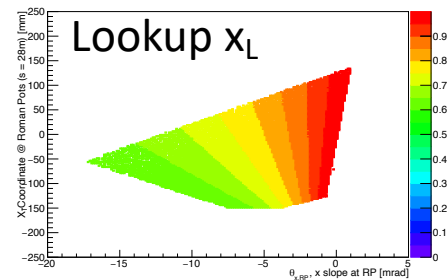


- “Chromaticity plot” serves as a lookup table.
- x_L is used to evaluate the correct matrix entries.

The (current) Basic Solution

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

Detector “hit”
coordinates



Calculate matrix parameters
and offsets from fit equations.

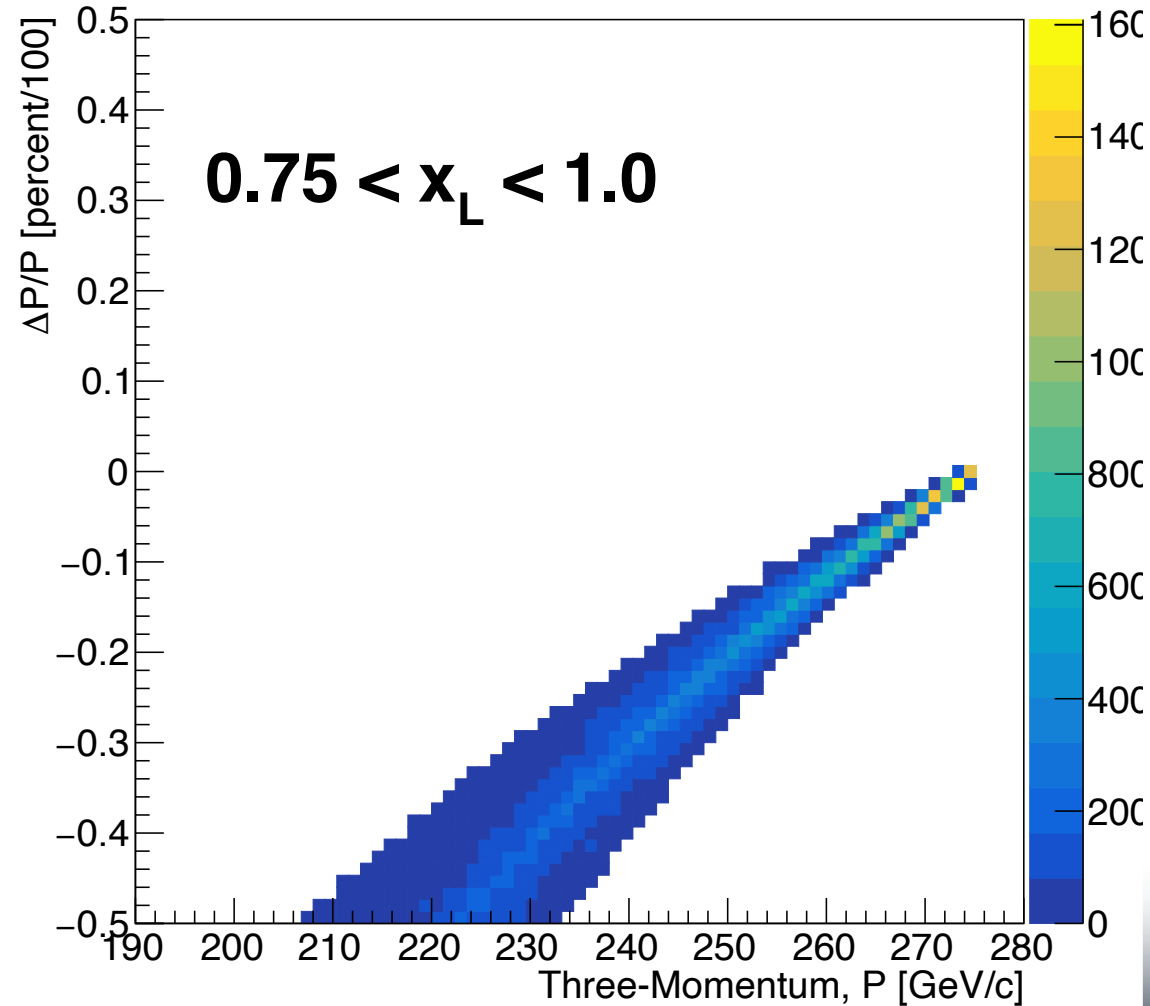
$$\begin{pmatrix} 1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\ -0.02114673 & 0.20555261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\ 0.0000 & 0.0000 & -2.25541901 & 3.78031509 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & -0.17782524 & -0.14532313 & 0.0000 & 0.0000 \\ 0.05735551 & 1.01363652 & 0.0000 & 0.0000 & 1.0000 & 0.02568709 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 \end{pmatrix}$$

Reconstructed
momentum vector.

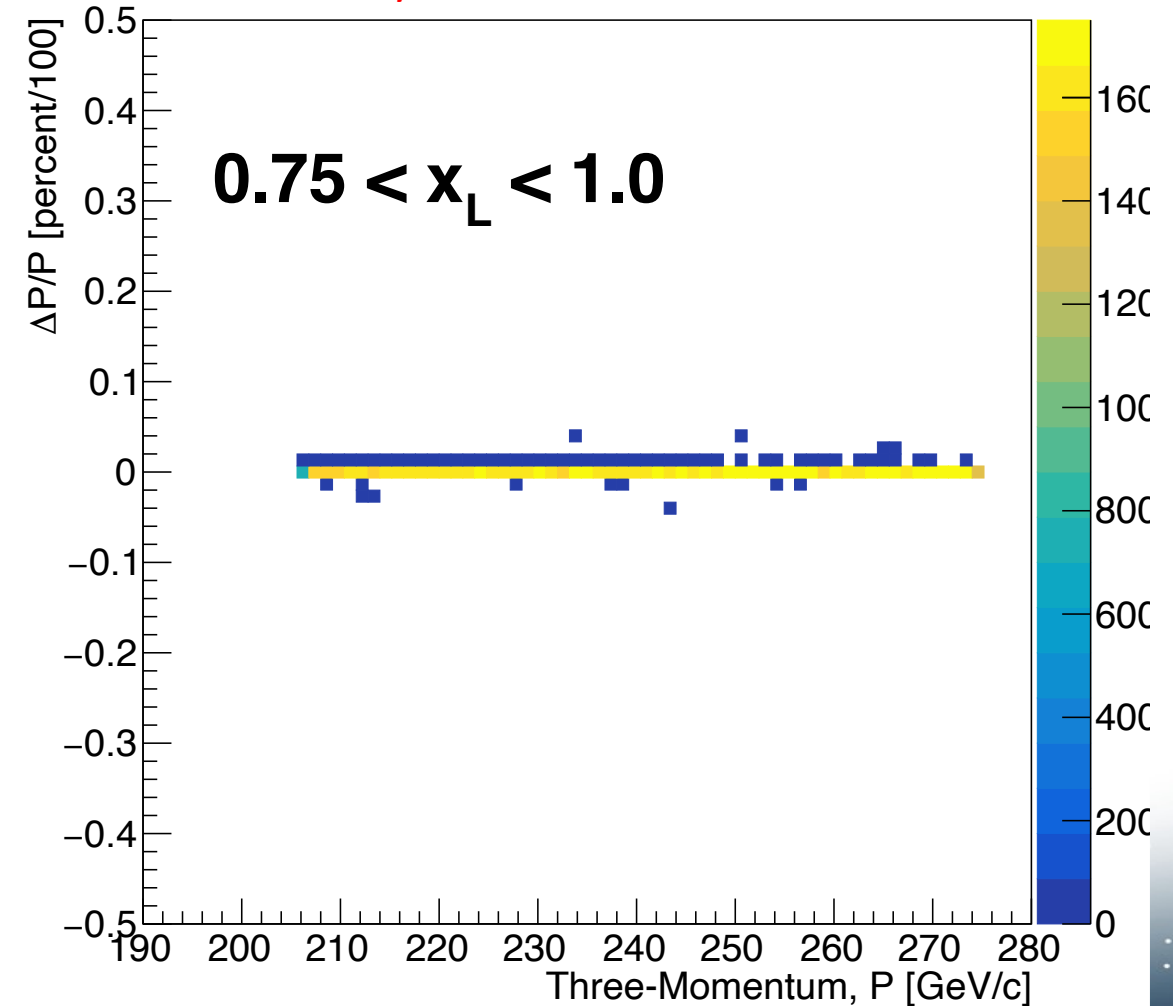
Results - Momentum

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

“static” BMAD matrix



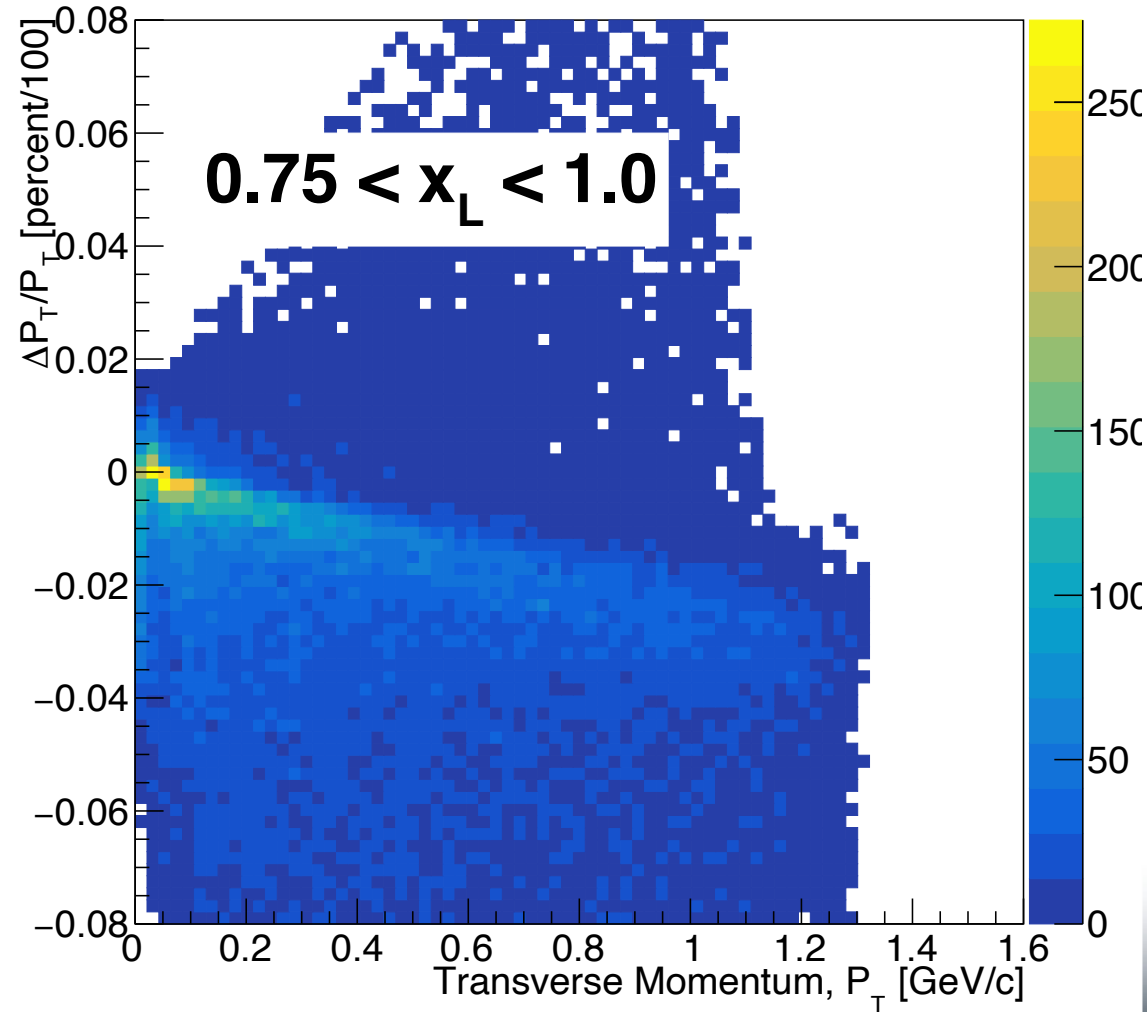
Dynamic matrix calculation



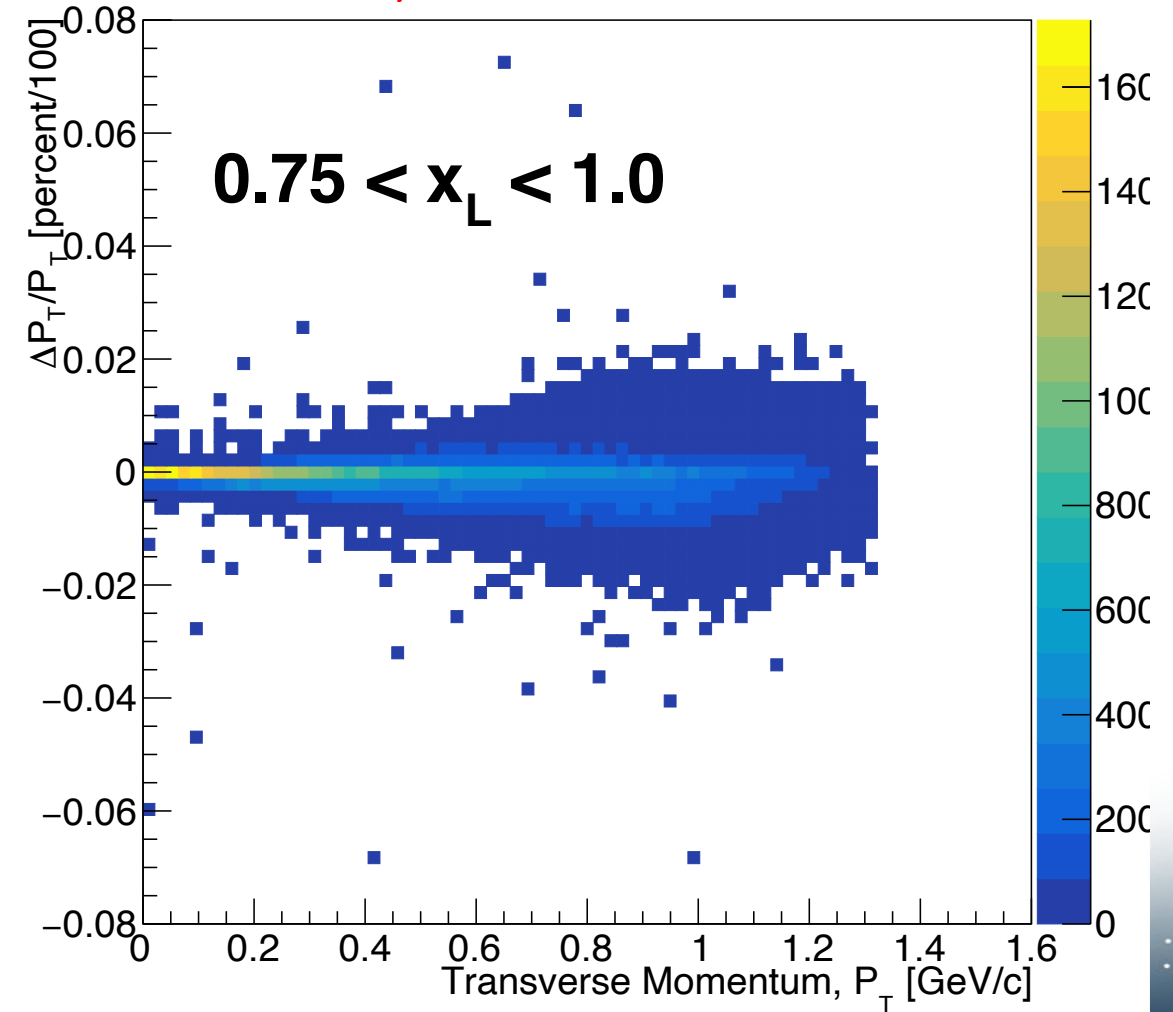
Results - p_T

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

“static” BMAD matrix

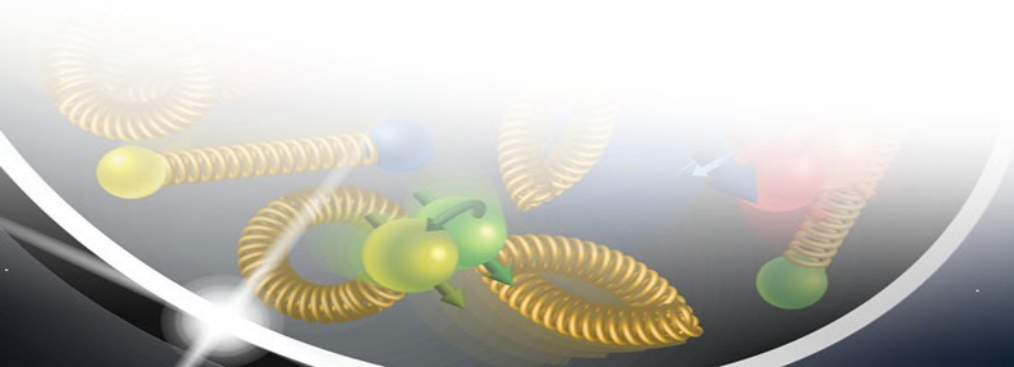


Dynamic matrix calculation



Drawbacks of current approach

- Solution dependent on choice of initial “tuning cards” (e.g. test trajectories).
 - Matrix may not capture non-linear effects for large angles/small x_L .
- Current approach will not be able to help with more-complicated interactions (e.g. Sullivan process), where tagged particles may not come from IP.
- The current method needs to be run separately for the Roman Pots and Off-Momentum Detectors.



Dedicated R&D can generalize approach to easily extend x_L range

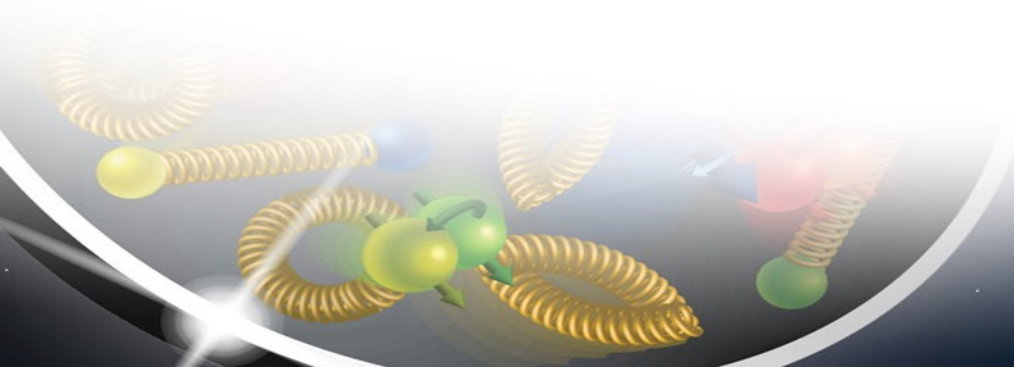
- The present method works reasonably well, and has the benefit of using calculated matrices following a similar method as BMAD.
- **But:** we care about describing a full range of momenta (present study only went down to x_L of 0.75).
- **A more modern method with ML techniques, integrated with the EPIC simulation framework would enable easy evolution of the reconstruction method as the detector descriptions are updated*.**



*Will also make it easier for more collaborators to get involved, long-term.

Takeaways and Next Steps

- General approach for accurately reconstructing far-forward particles demonstrated.
 - Would benefit from a more-modern approach using ML techniques to provide easier adaptability as the EIC far-forward design evolves.
 - Need to extend this approach to the off-momentum detectors.
 - More-challenging problem – particles more severely off-momentum ($x_L \sim 50\%$, or less).
- Once a method is put in place, integration with the EPIC detector framework would be required.



Timeline

- **January:**
 - Alex – integrate current code into EICRecon.
 - David – get familiar with ePIC simulation framework.
- **February (assuming SoW approved and money allocated):**
 - Alex – carry out basic tests of current code.
 - David – do same studies independently to ensure everything makes sense.
- **February to May:**
 - Begin work on algorithm development.
 - Come up with benchmarks to test progress.
- **May onward:**
 - Further testing, EICRecon integration, adaptability checks.
- **End of summer(ish):**
 - Begin working on outline of NIM paper (or equivalent).



Committee Questions

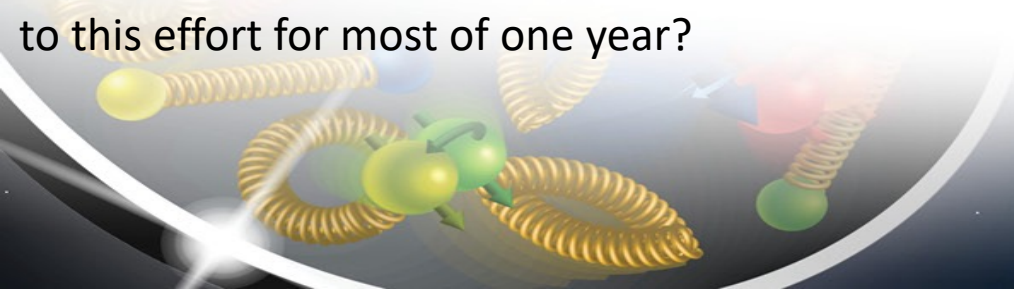
Q1: The problem seems well-suited for ML if suitable training samples can be obtained. This is in principle straightforward in simulation, but has thought been put into how to obtain such samples from data? For example, does the momentum resolution of the detectors match the precision on the momentum the proposed method provides? i.e. can you get from the detectors information useful for testing?

Q2: Will this work lead to specifications for measuring or constraining higher order multipoles in the magnets between the IR and the silicon detectors, or is this not expected to be an issue?

Q3: Is the maintenance of this code assured by the same team involved in this proposal?

Q4: How do you evaluate the risk of not delivering on time the proposed, tested code? Which aspects of the proposed work are mostly likely to introduce delays? (E.g., is the major uncertainty in the time needed to test machine learning techniques?)

Q5: This is nominally a 1 year project requesting support for 70% of a postdoc FTE. Is the plan then to divert an existing postdoc to this effort for most of one year?



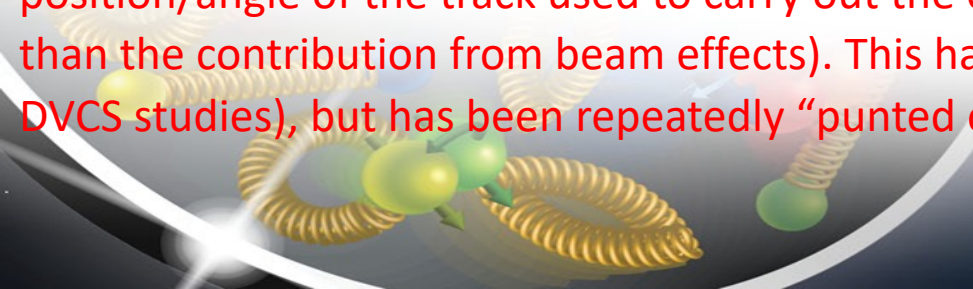
Committee Questions

Q1: The problem seems well-suited for ML if suitable training samples can be obtained. This is in principle straightforward in simulation, but has thought been put into how to obtain such samples from data?

From real data (e.g. from an active experiment), yes and no. There have been studies carried out in other experiments, but they generally cover fairly high longitudinal momentum fractions $> 80\%$, and often have elastic constraint to aid them (e.g. ATLAS, STAR). We may have more luck leveraging data from fixed target experiments, but it's unclear if much can be gleaned for the specific application here. It should be noted that fixed target experiments have done this sort of reconstruction using multi-pole expansion methods (similar to BMAD) in the past.

For example, does the momentum resolution of the detectors match the precision on the momentum the proposed method provides? i.e. can you get from the detectors information useful for testing?

That is part of the goal of this exercise – to ensure that the matrix reconstruction method **does not introduce momentum smearing inherently**, as the plots on the previous slides imply. If your matrix description is incorrect, then you cannot possibly hope to accurately reconstruct the momentum. If the matrix accurately describes the transport, then the uncertainties in the position/angle of the track used to carry out the calculation will now have some uncertainty, but at the $\sim 1\%$ level (e.g. smaller than the contribution from beam effects). This has been demonstrated in the case of on-momentum protons (e.g. Yellow Report DVCS studies), but has been repeatedly “punted on” for off-momentum studies, as no solution yet existed.



Committee Questions

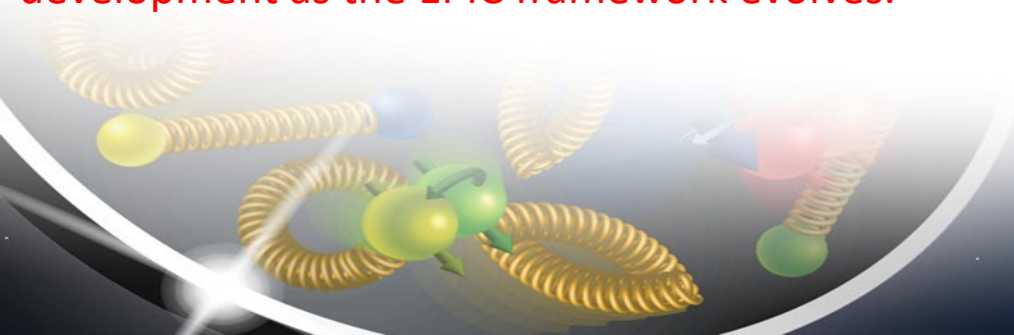
Q2: Will this work lead to specifications for measuring or constraining higher order multipoles in the magnets between the IR and the silicon detectors, or is this not expected to be an issue?

For most of our momenta, this doesn't have a large impact, but for particles with suitably small rigidity (low x_L) or high- p_T , it's possible these higher order modes will begin to cause problems (e.g. non-linearity in the particle transport). This is something that will need be part of the initial set of studies to establish a working solution.

Q3: Is the maintenance of this code assured by the same team involved in this proposal?

Yes – one of the primary deliverables is a code package which can be integrated with the EPIC software framework as a plugin in Jana2/EIC Recon, which will be maintained by the PIs, and the EPIC far-forward detector working group).

Another benefit of inclusion into the broader framework is the ease of including new collaborators, which will enable broader development as the EPIC framework evolves.



Committee Questions

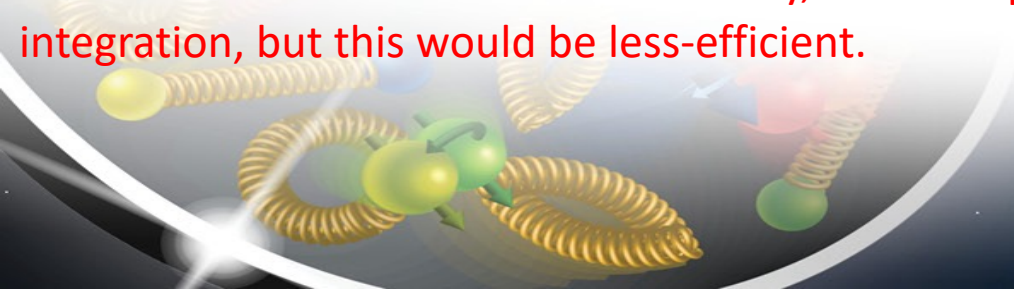
Q4: How do you evaluate the risk of not delivering on time the proposed, tested code? Which aspects of the proposed work are mostly likely to introduce delays? (E.g., is the major uncertainty in the time needed to test machine learning techniques?)

Machine learning applications here are fairly straightforward, and the input/output using the more conventional methods are already well-understood. As long as we have funded personnel, we don't expect major delays since we know how to proceed, and are familiar with the general transport of the particles through the beamline.

Q5: This is nominally a 1 year project requesting support for 70% of a postdoc FTE. Is the plan then to divert an existing postdoc to this effort for most of one year?

Yes, we think having a postdoc already a little familiar with the EIC will expedite the process, but we can also see this project being shared by two postdocs with a partial FTE each. If a current postdoc(s) is unable to use a partial FTE toward this effort, there are several collaborators in the EPIC far-forward working group who plan to hire postdocs in January/February to work on the EIC for a partial FTE.

The major tasks would be the development of the basic algorithm, and the inclusion/testing in the ePIC framework. In principle, some of this work could be done serially, with one postdoc beginning the work, and another taking over to focus on the software integration, but this would be less-efficient.

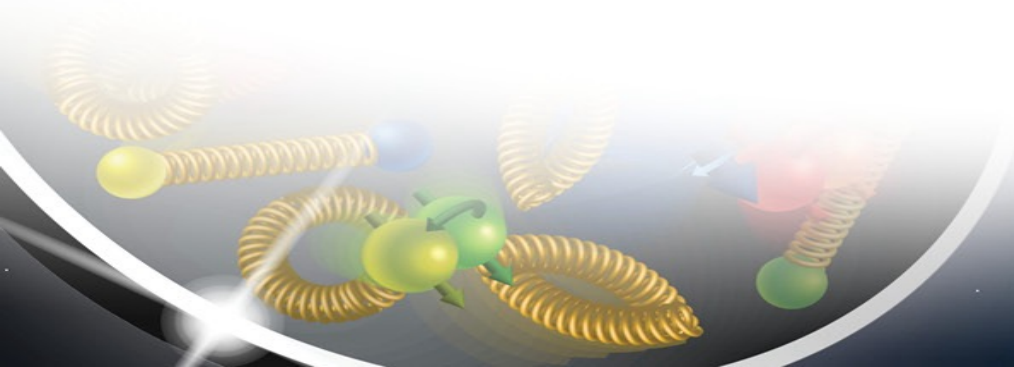


Funding

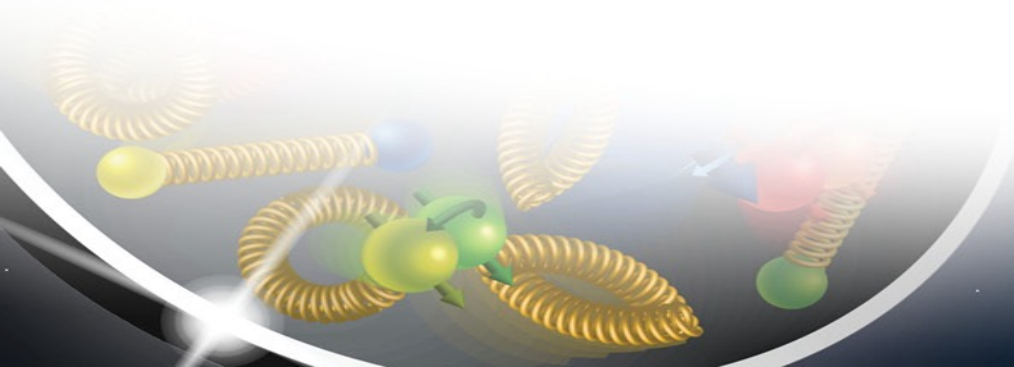
| | R&D Effort (FTE) | Proposal Funded | 100% Amount | 20% reduction | 40% reduction |
|-------------------------|------------------|-----------------|-------------|---------------|---------------|
| A. Jentsch | 10% | Yes | \$17k | \$17k | \$17k |
| Furletova & Higinbotham | 10% | No | N/A | N/A | N/A |
| M. Murray | 10% | No | N/A | N/A | N/A |
| Postdoc (TBD) | 70% | Yes | \$110k | \$85k | \$60k |
| TOTALS | 100% | - | \$127k | \$102k | \$76k |

Table I. Cost breakdown of collaborating institutions.

We envision a single postdoc working on this project to be most-efficient, but have a plan for an option using two postdocs with partial FTEs.



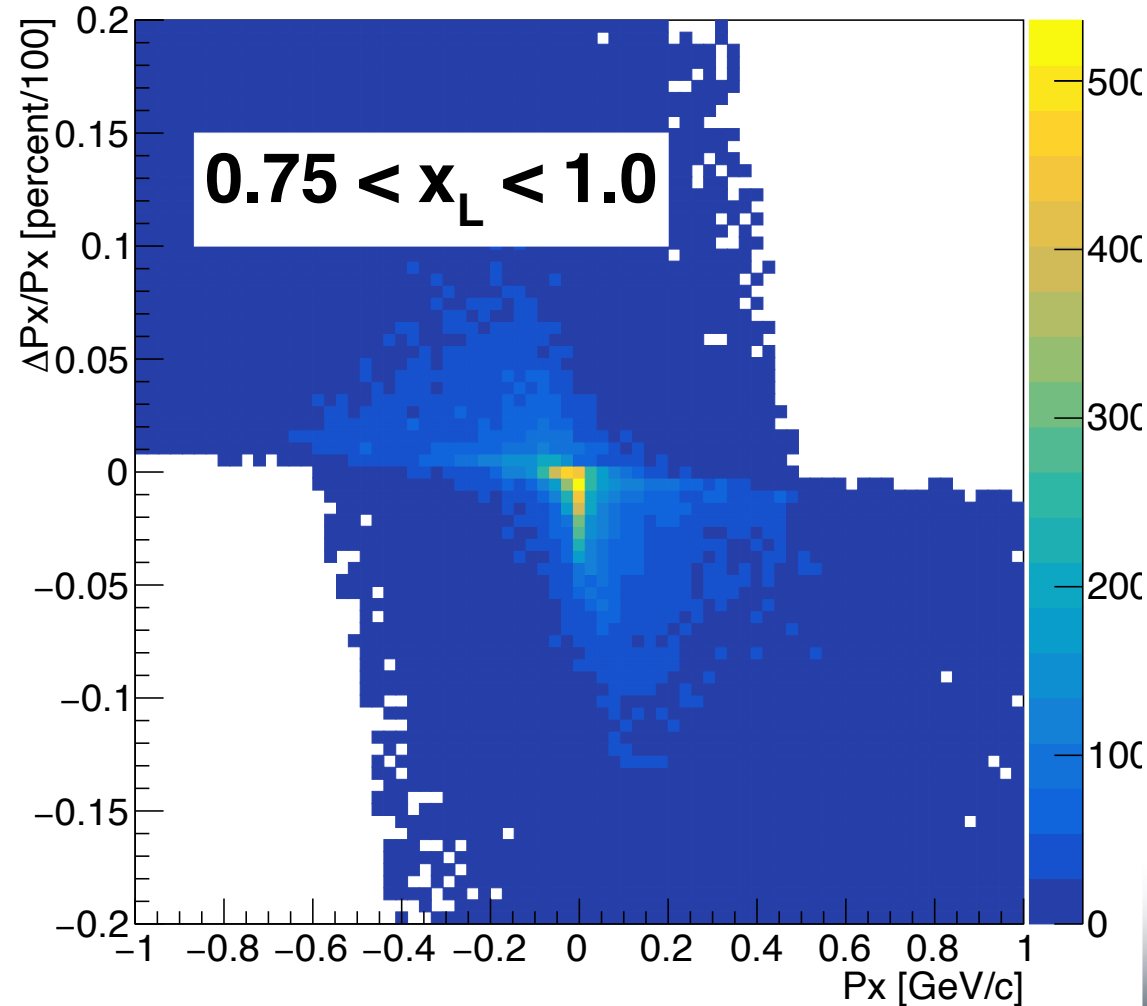
Backup



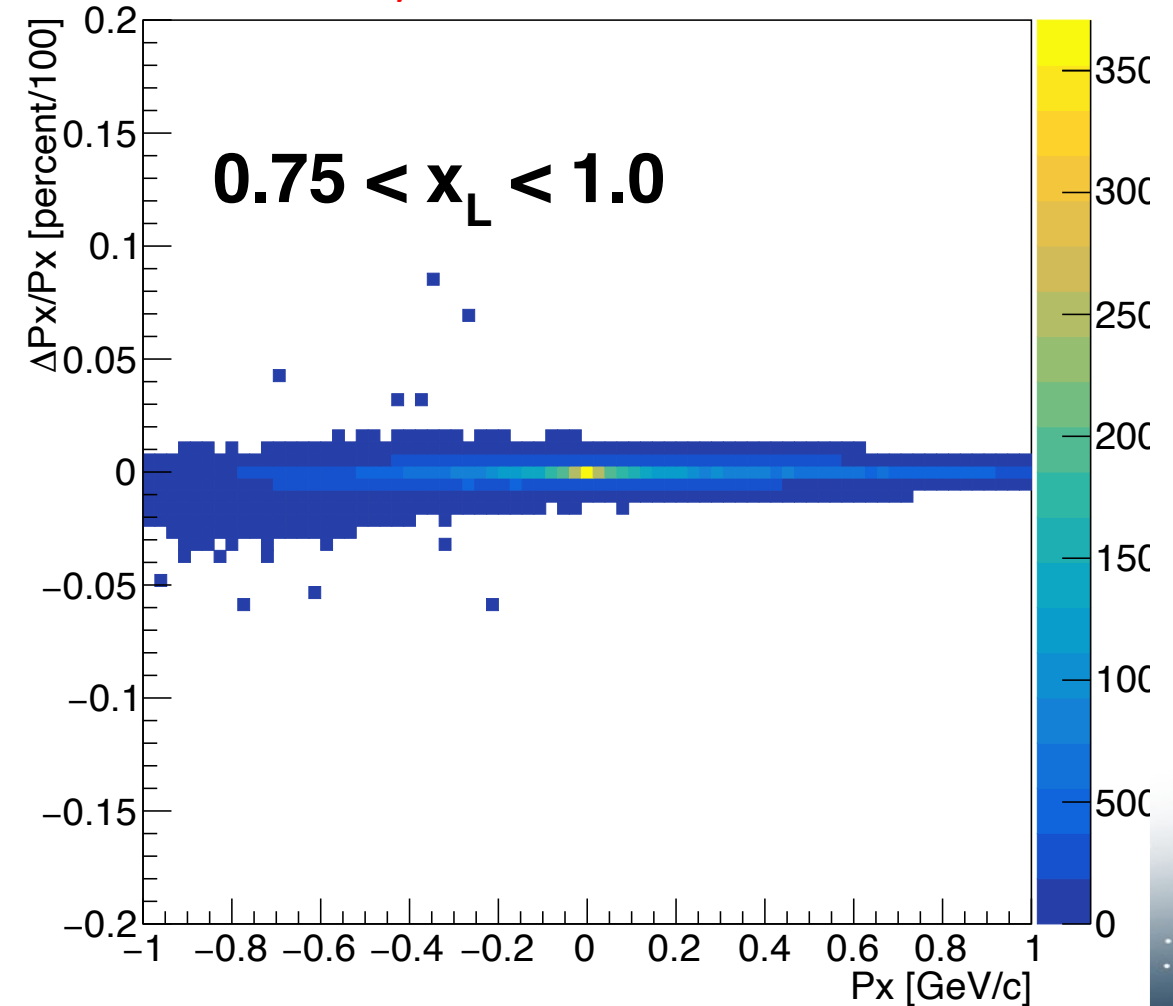
Results - Px

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

“static” BMAD matrix



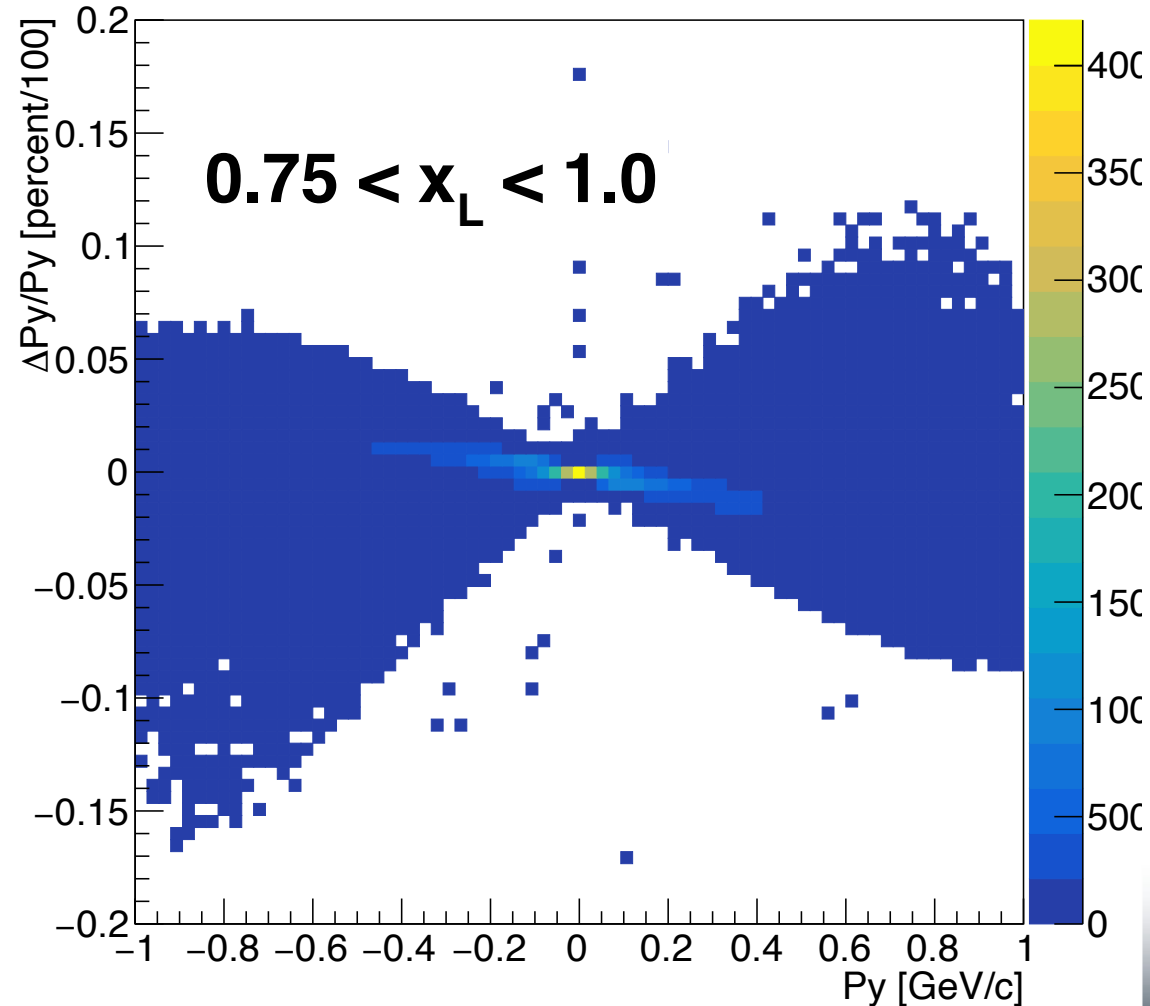
Dynamic matrix calculation



Results - Py

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

“static” BMAD matrix



Dynamic matrix calculation

