Incorporating Beam Effects into Simulation for the EIC

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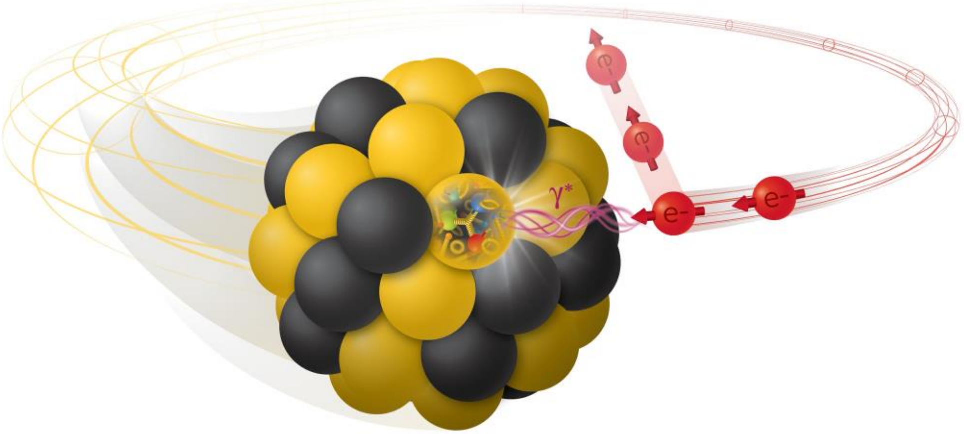
DIS 2022



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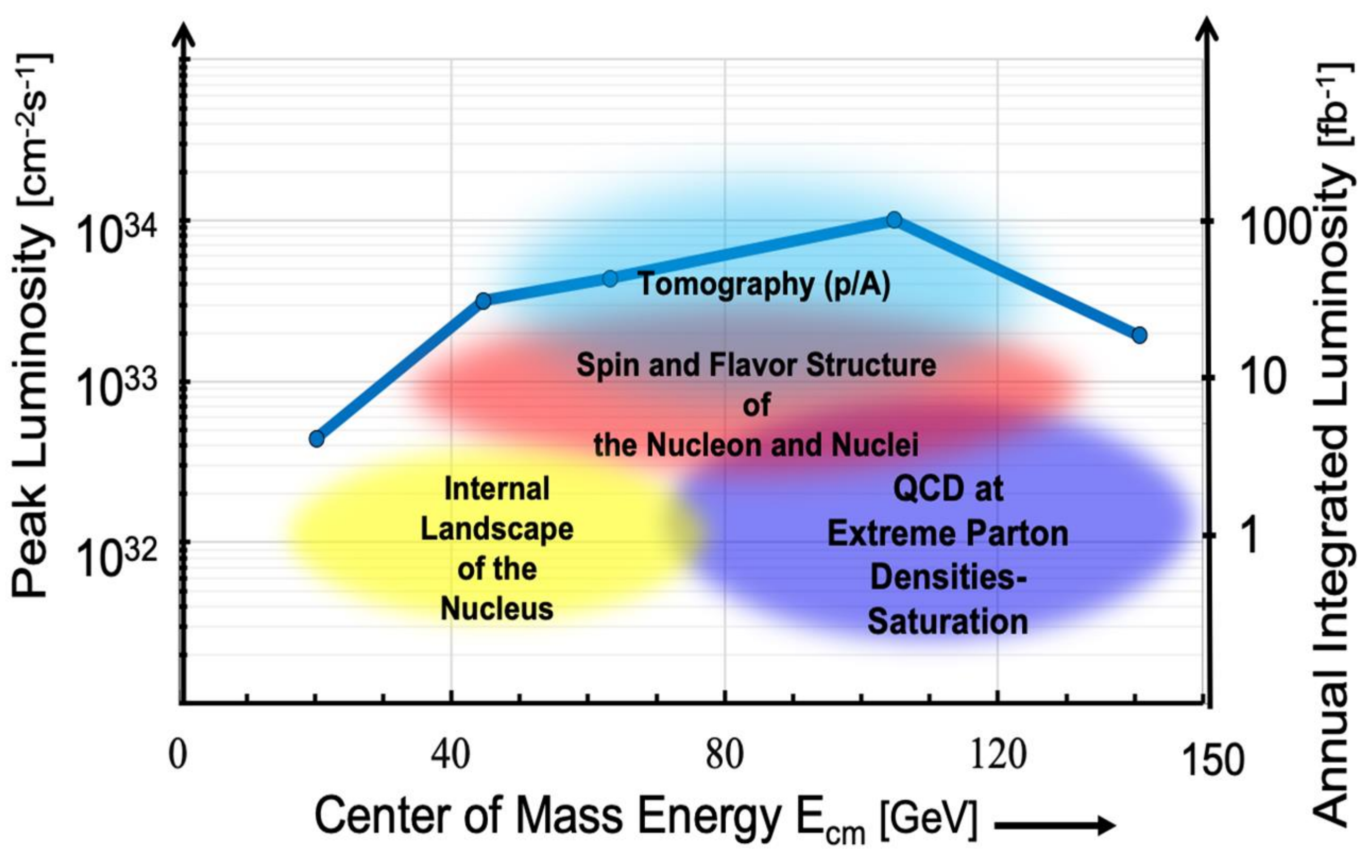
Outline

- Overview of the EIC and the Need for a Crossing Angle
- Simulating Beam Effects in PYTHIA
  - Collision Vertex
  - Beam Momenta
  - Final State Particle Distributions
- Simulating Beam Effects with an After-Burner
- Correcting for the Crossing Angle in Analyses
- Summary

Machine Requirements from Physics

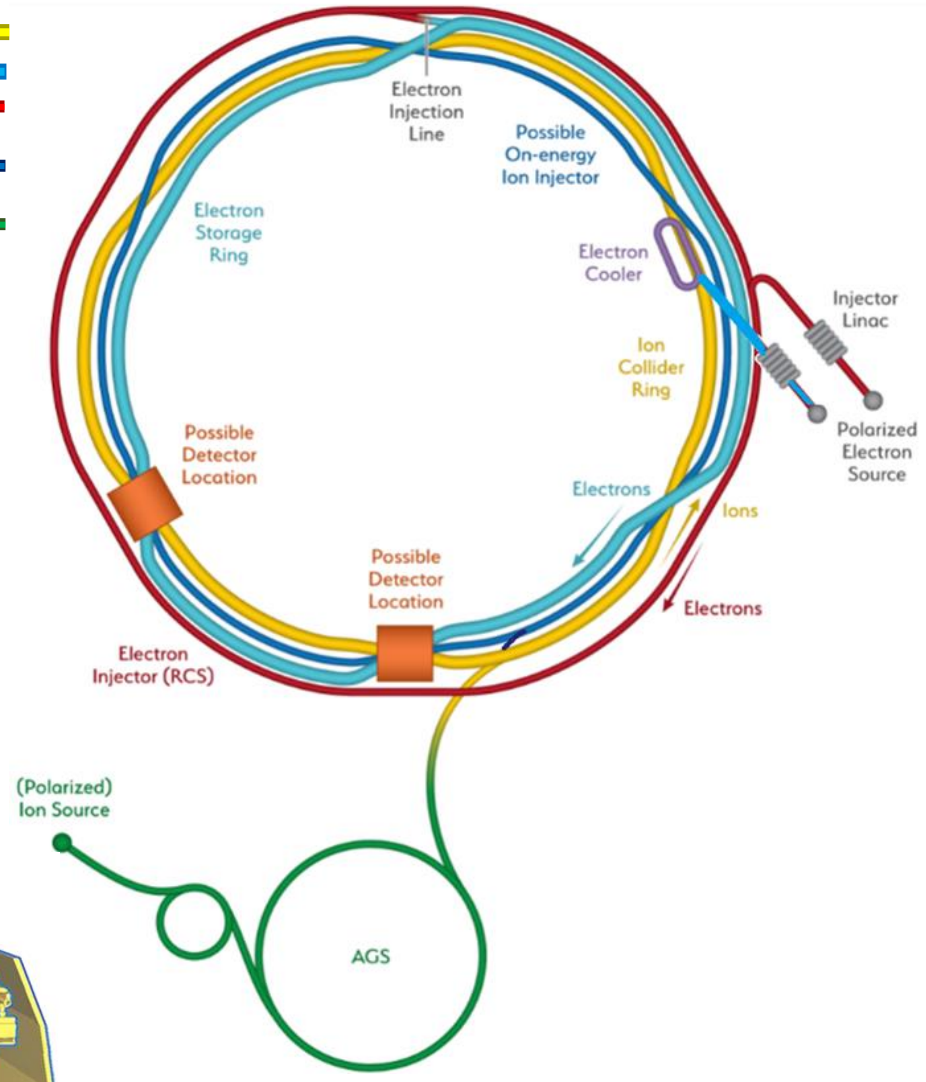


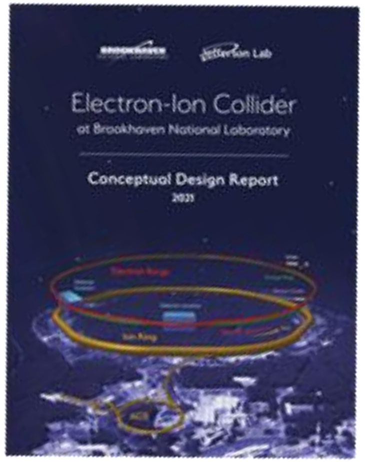
- Large Kinematic Coverage
  - Center of Mass energies $\sqrt{s}$: 20 – 140 GeV
  - Access large range in x and Q^2
- High luminosity
  - $10^{33} - 10^{34}$ $cm^{-2}s^{-2}$
  - Mapping structure of nucleons and nuclei in 3D
- Polarized electron and hadron (p, ^{3}He) beams
  - Explore spin structure of nucleons and nuclei
- Nuclear Beams (D to Pb)
  - Access high gluon densities – saturation
  - Study properties of cold nuclear matter

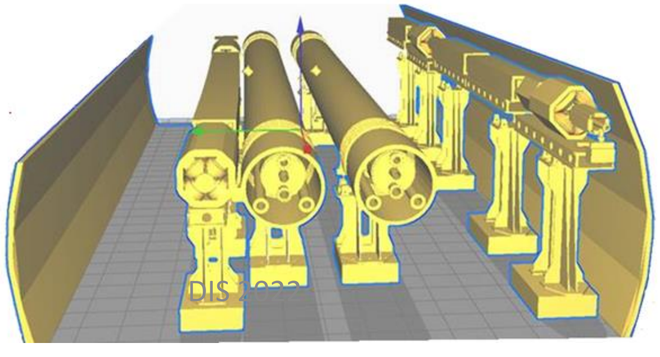
The EIC Concept

EIC design based on **existing** RHIC complex

- ❑ **Hadron storage ring 40-275 GeV** (existing)
  - ➢ RHIC Yellow Ring
  - ➢ many bunches, 1160 @ 1A beam current
  - ➢ bright beam emittance ε_{xp}= 9 nm, flat beam
  - ➢ need strong cooling
- ❑ **Electron storage ring (2.5–18 GeV, new)**
  - ➢ many bunches,
  - ➢ large beam current (2.5 A) ➔10 MW S.R. power
  - ➢ s.c. RF cavities
  - ➢ Energy independent radiation damping
- ❑ **Electron rapid cycling synchrotron** (**new**)
  - ➢ 1-2 Hz
  - ➢ Spin transparent due to high periodicity
- ❑ **High luminosity interaction region(s)** (**new**)
  - ➢ L = 10^{34}cm^{-2}s^{-1}
  - ➢ Superconducting magnets
  - ➢ 25 mrad Crossing angle with crab cavities
  - ➢ Spin Rotators (longitudinal spin)
  - ➢ Forward hadron instrumentation

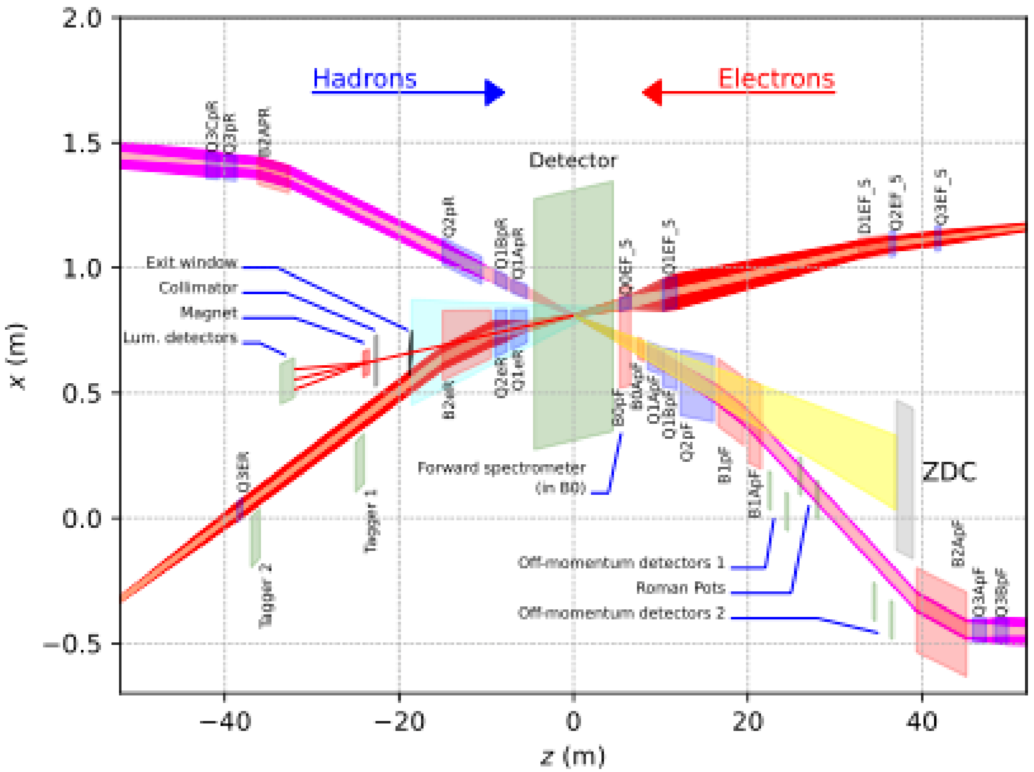




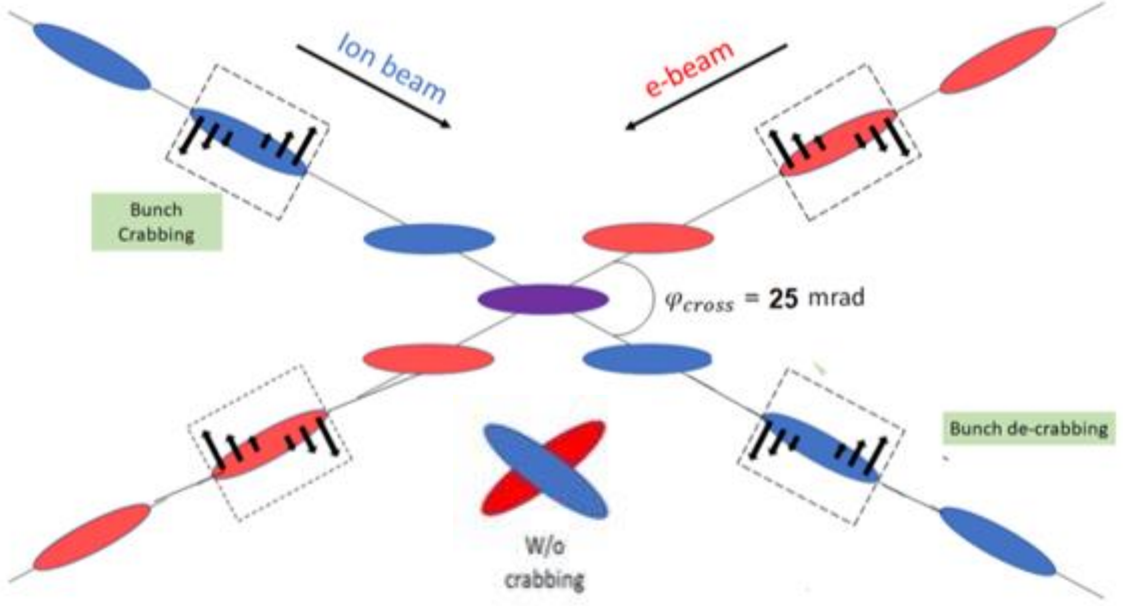


CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

Crossing Angle



- ❑ In order to avoid parasitic collisions and leave room for necessary beam elements and far-forward detectors, the beams will enter the IR with a substantial crossing angle (25 mRad for IP6)
- ❑ This will alter how the beams are transported with respect to the detector and the distribution of final state particles
- ❑ Need to simulate this crossing angle to run detector simulation and accurately model the conditions the detector will experience



- ❑ The crossing angle will kill luminosity as bunches will not fully overlap
- ❑ This is mitigated by rotating the bunches through half the crossing angle (crabbing) so they overlap
- ❑ Crabbing and other effects such as beam divergence and energy smearing are also simulated

Beam Effects in Simulation

- Need to incorporate the beam crossing angle into the event simulation to properly understand consequences on physics and detector design and properly propagate particles through the detector model

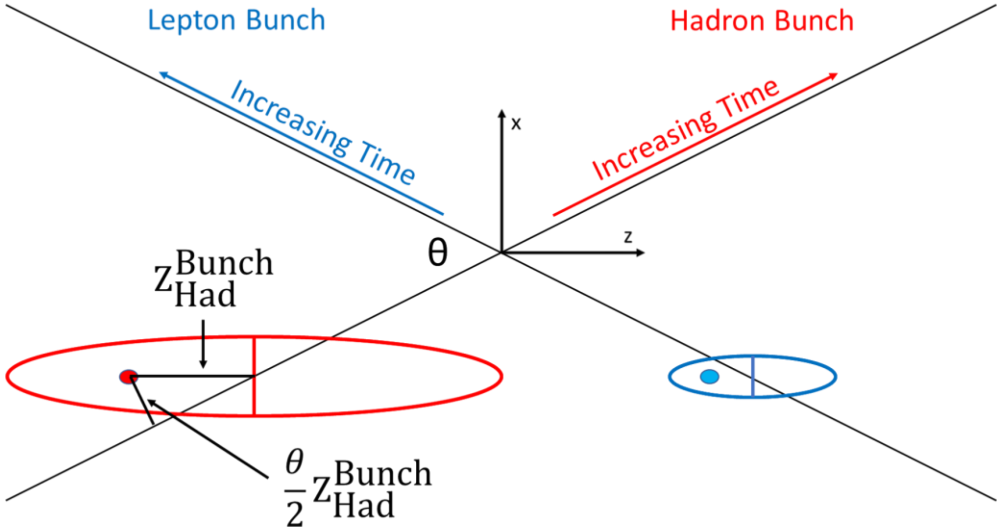
- Also want to simulate other beam effects such as angular divergence, beam energy spread, and crabbing momentum kicks

- Two approaches have been developed: A generator agnostic After-Burner (J. Huang, D. Romanov) that boosts particle 4-vectors into the correct frame, and a scheme that utilizes the internal PYTHIA-8 BeamShape class that allows changes to beam momentum / vertex position directly at the generator level. An independent Transport Model (J. Adam) which simulates the interaction vertex position has also been implemented

- All relevant beam parameters have been taken from the collider Conceptual Design Report. A technical note containing more detail on the different approaches can be found at: https://eic.github.io/resources/simulations.html (J. Adam, E.-C.Aschenauer, M. Diefenthaler, Y. Furletova, J. Huang, A. Jentsch, B. Page)

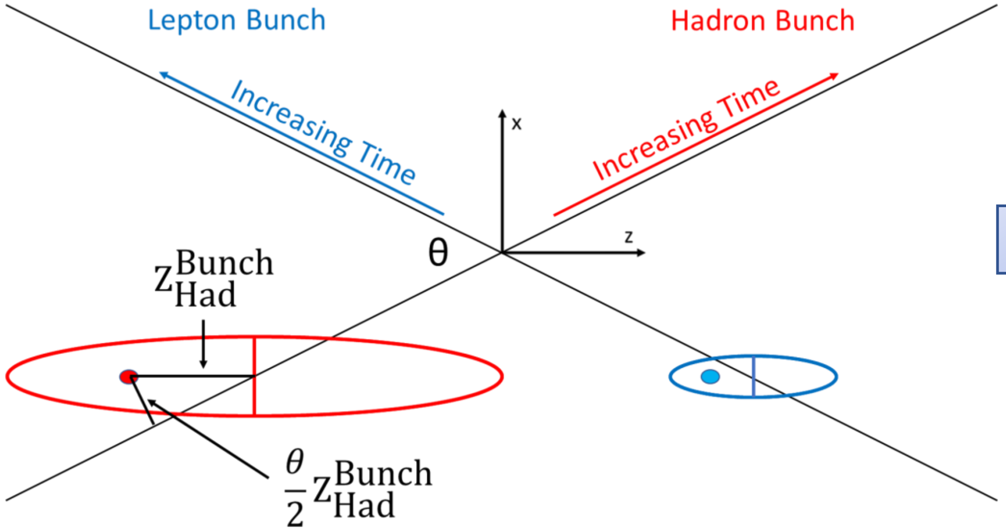
- In the following, focus on the vertex distributions, beam momenta, and final state particle distributions obtained from the PYTHIA-8 implementation and cross check with the After-Burner approach

PYTHIA-8 Vertex Model



1. Chose z (in in-bunch coordinates) of colliding particle in hadron and lepton bunch

PYTHIA-8 Vertex Model



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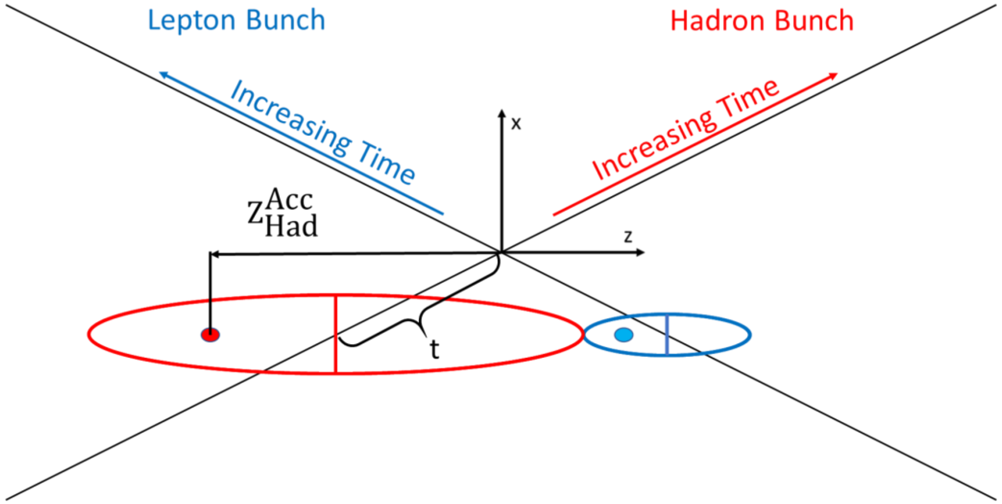
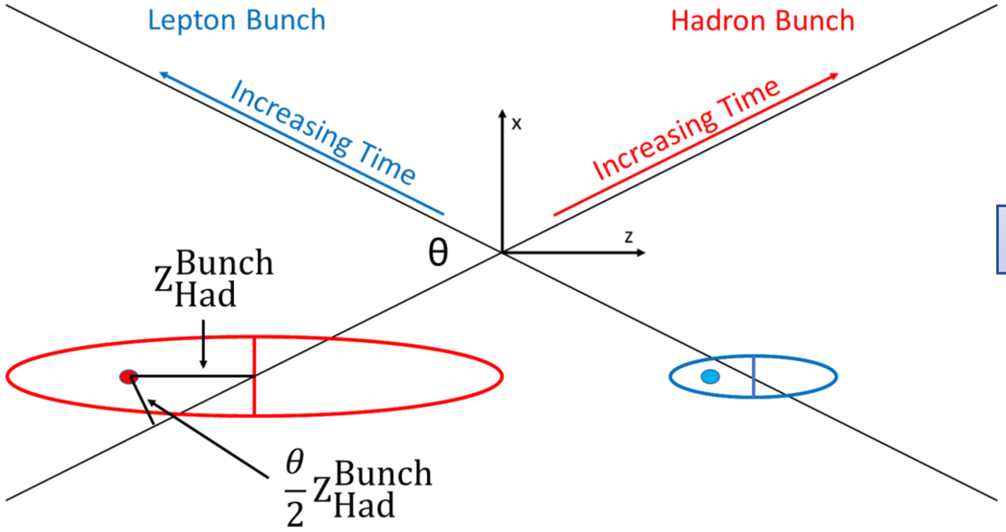


2. Propagate bunches forward in time until colliding particles overlap

PYTHIA-8 Vertex Model



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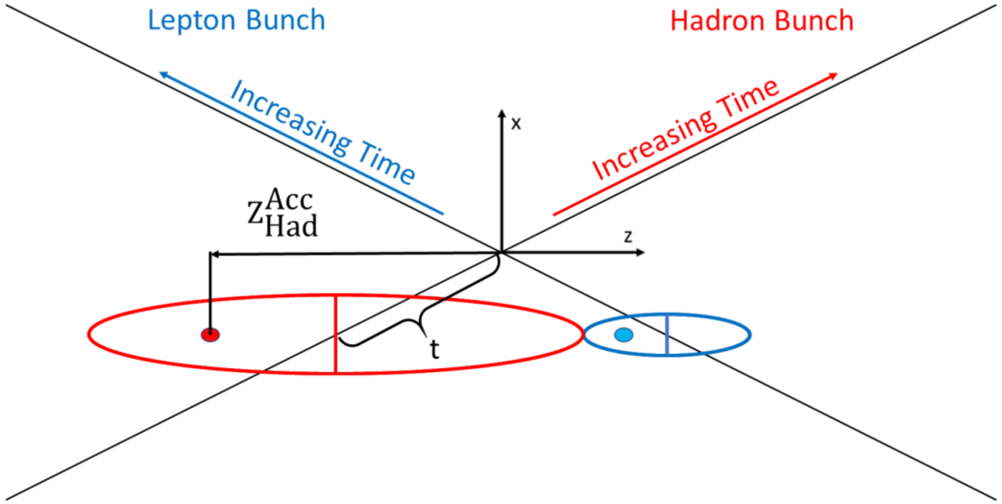

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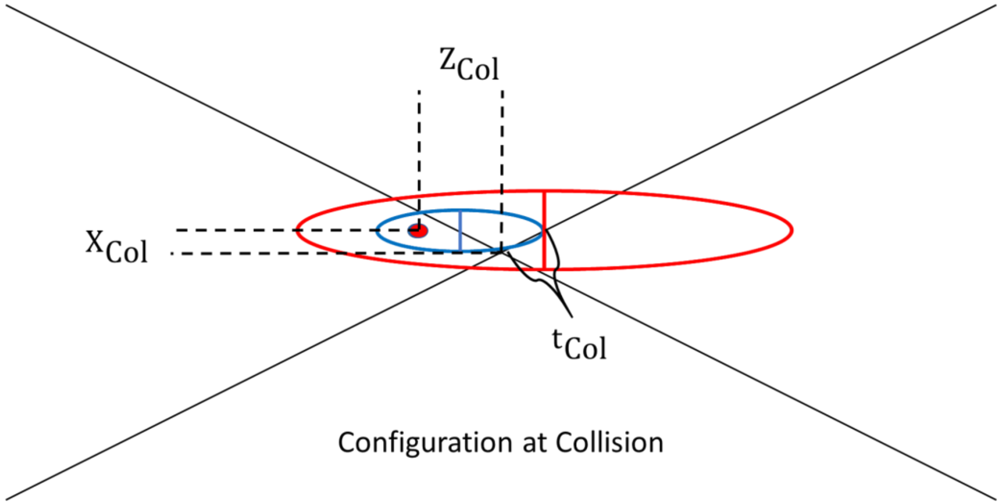
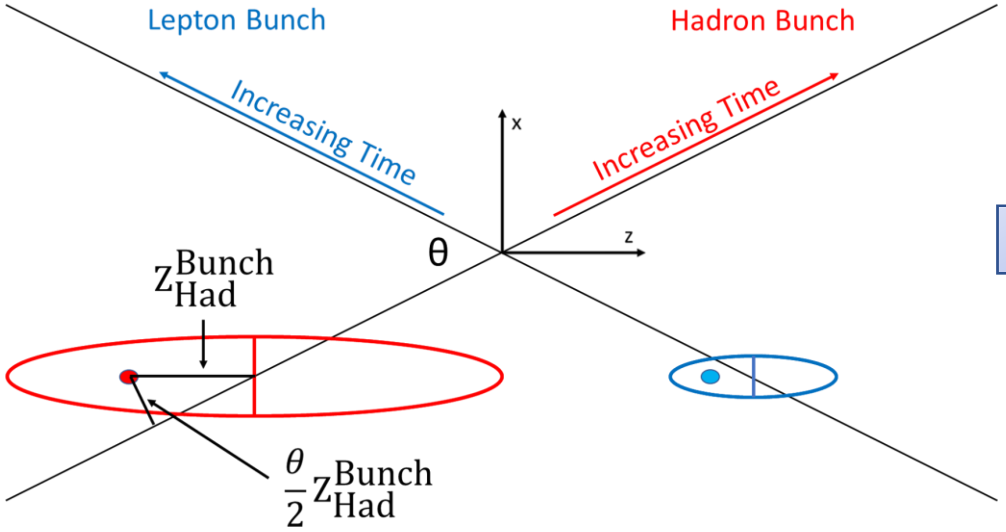


3. Randomly sample x and y positions according to bunch width and add to collision position

PYTHIA-8 Vertex Model



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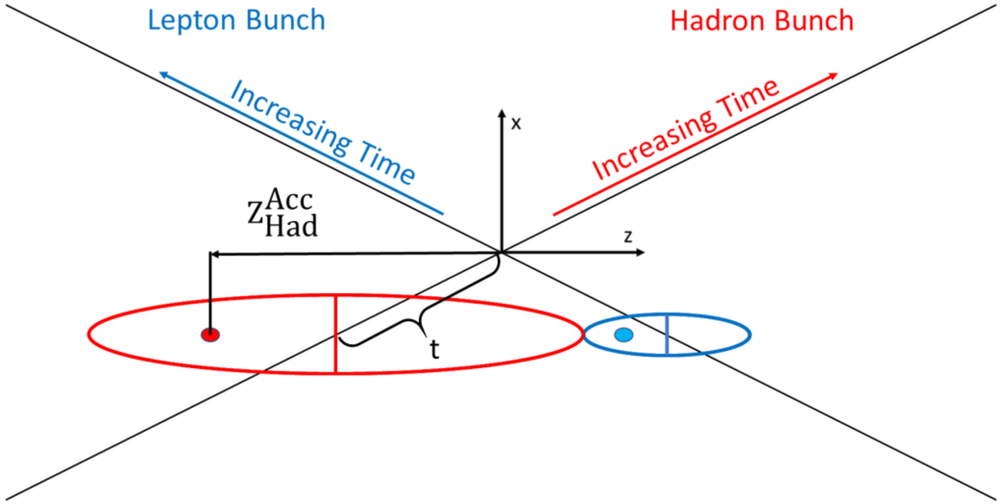

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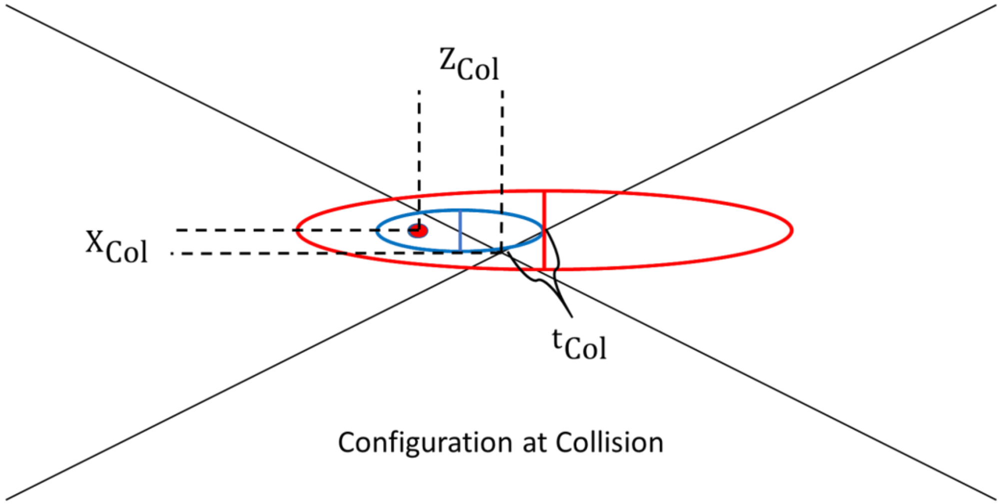

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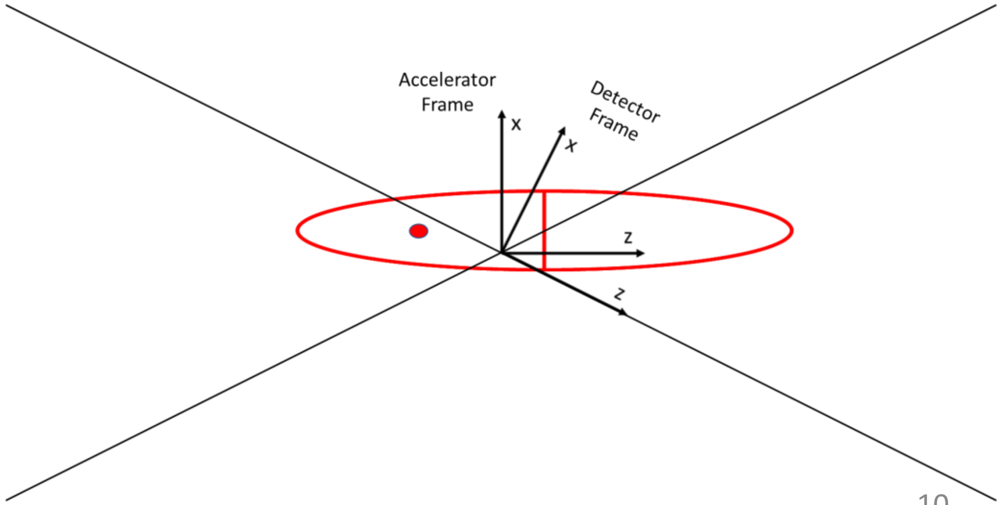
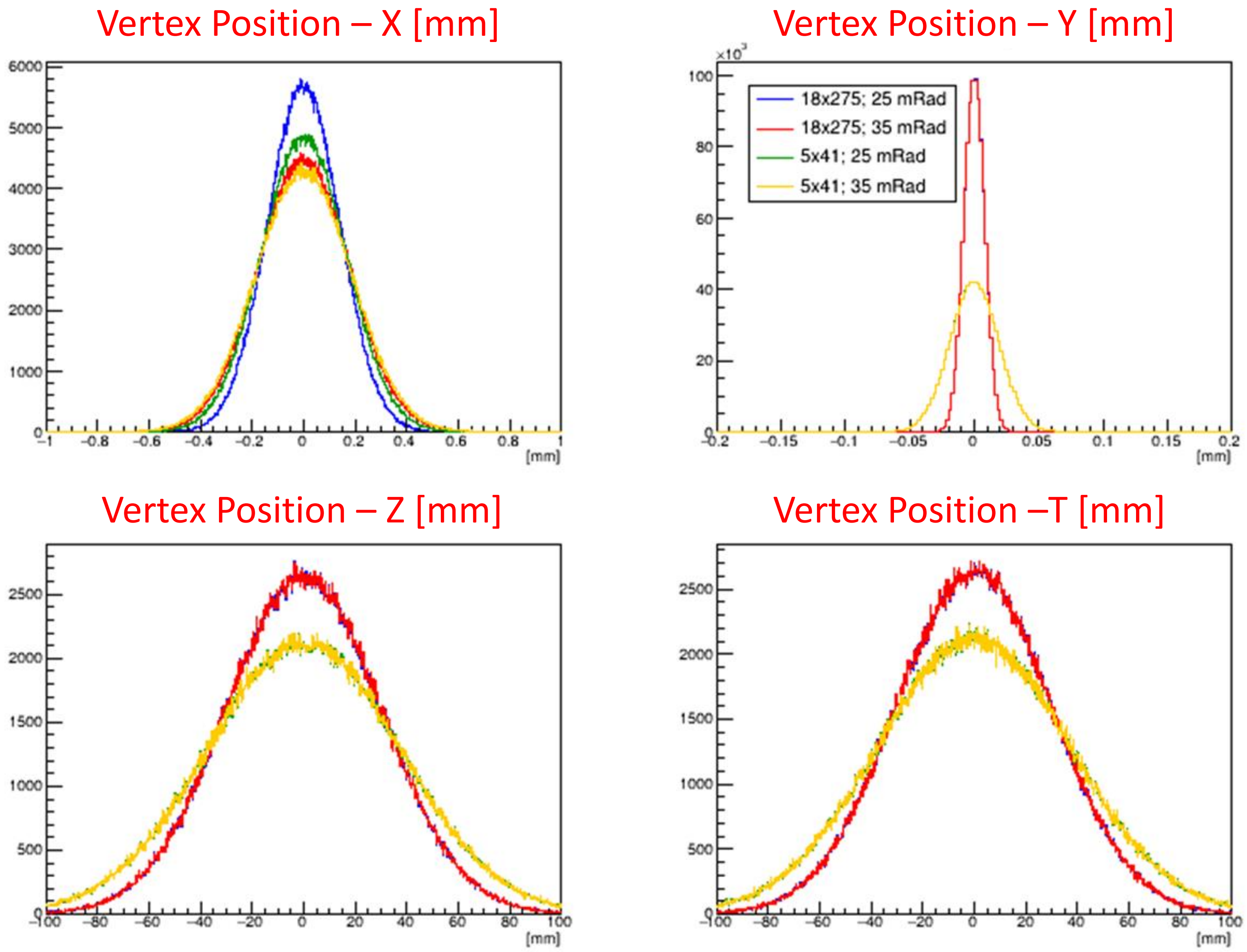


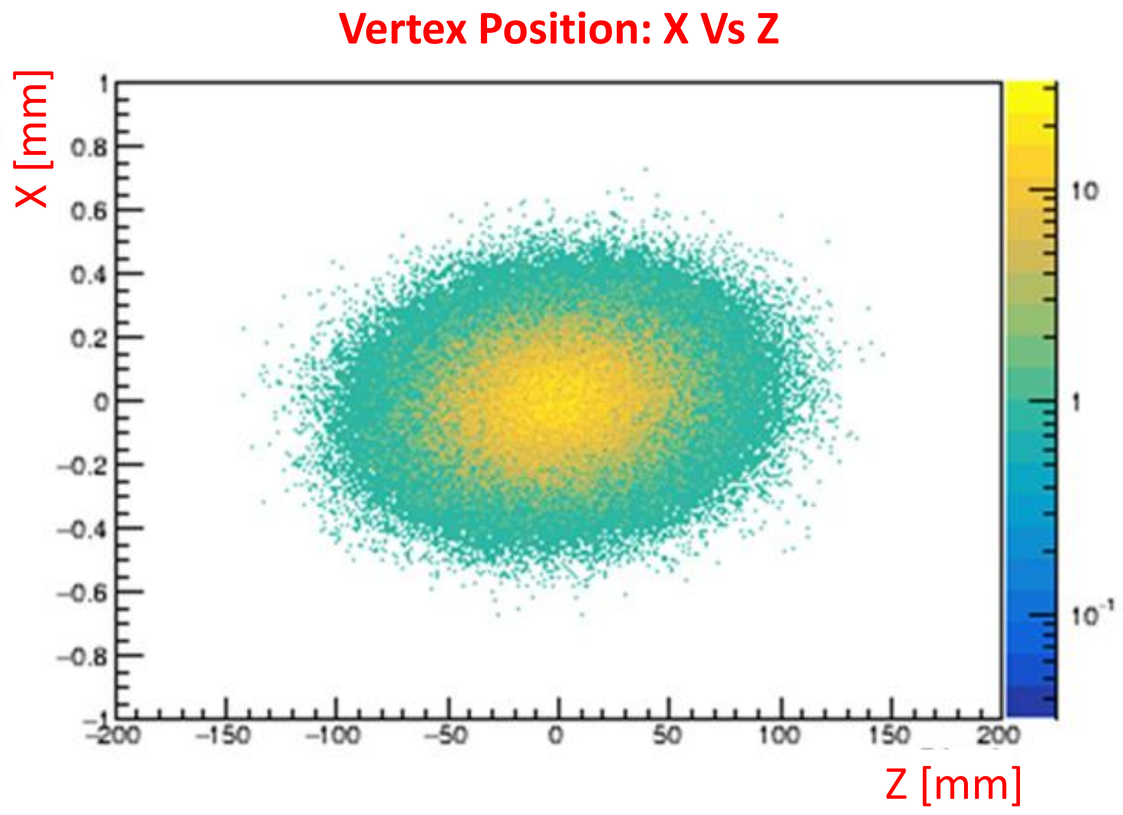
4. Rotate bunch to align with detector axis (electron beam)

PYTHIA-8 Vertex Distributions

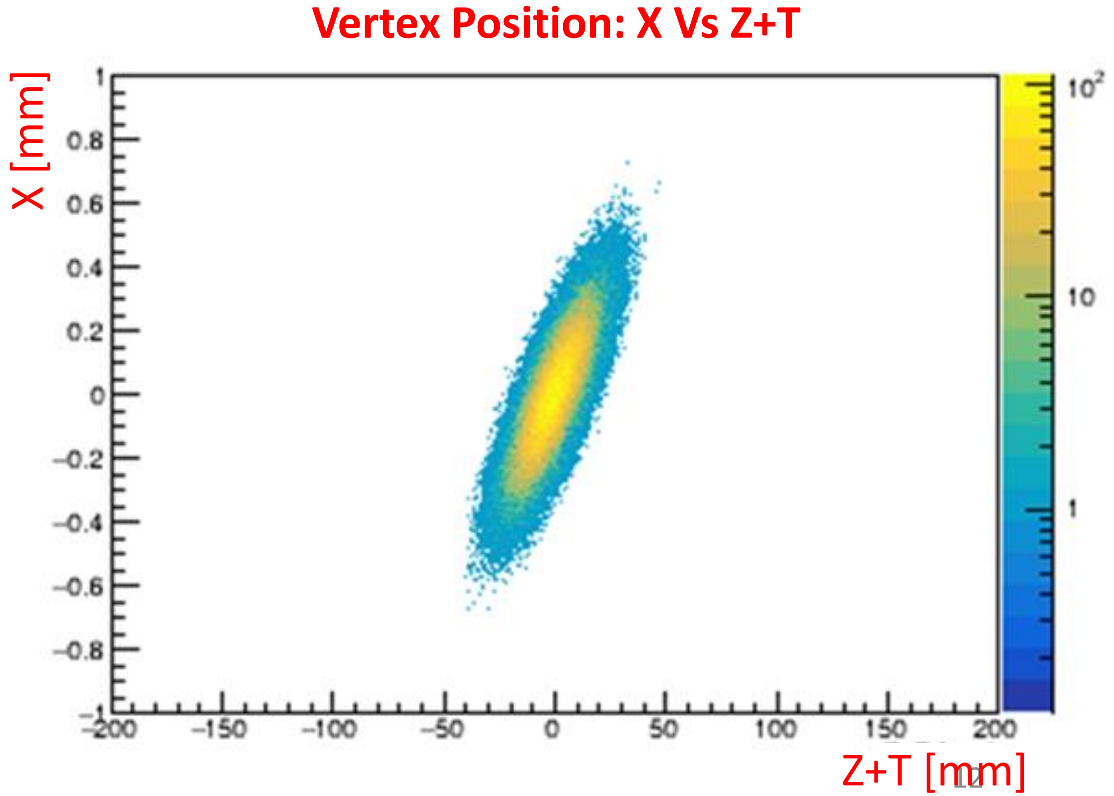


- X, Y, Z, and T distributions of the collision vertex shown for maximum and minimum energies and two crossing angles
- Characteristic widths are determined by beam parameters which depend on energy – degeneracy between crossing angle values broken in the X distributions as this is the plane of the crossing
- Note different X-axis scales: Vertex Y < Vertex X << Vertex Z (T)
- Vertex distributions have been cross-checked against a transport model and are found to be in good agreement

PYTHIA-8 Vertex Distributions



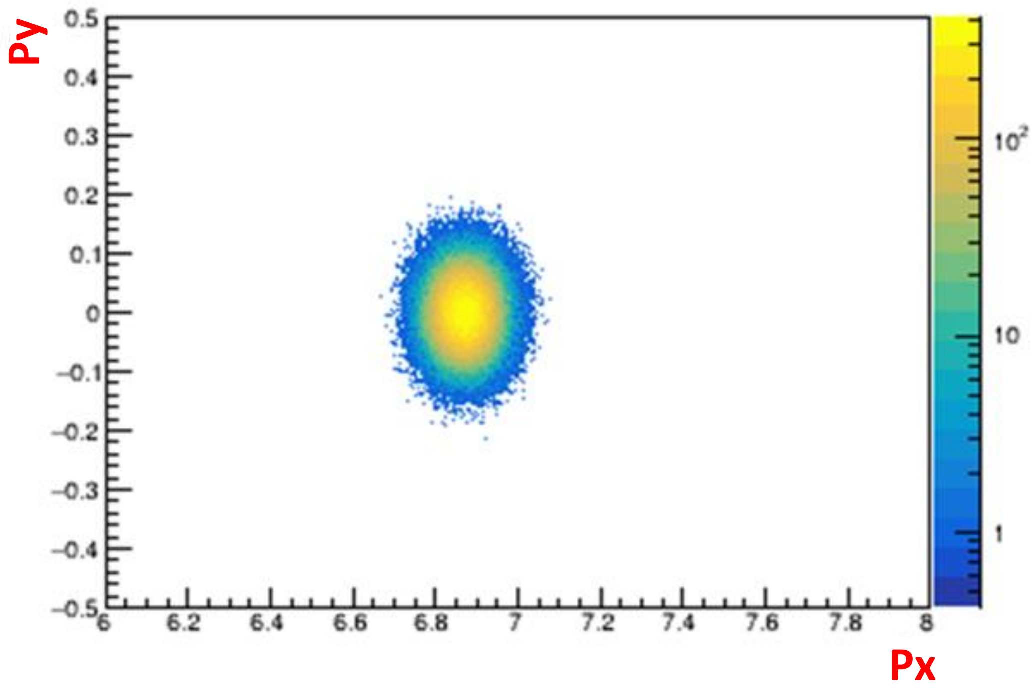
- ❑ Because of the impact of the crabbing rotation, can expect a correlation between the X and Z positions of the interaction vertex and the time of the collision
- ❑ No correlation seen between just X and Z positions



- ❑ If the Z position and time of the collision can be measured independently, the combination Z+T shows a strong correlation with X
- ❑ Extra constraint for reconstructing interaction vertex

Hadron Beam Momentum Distributions – Y Vs X

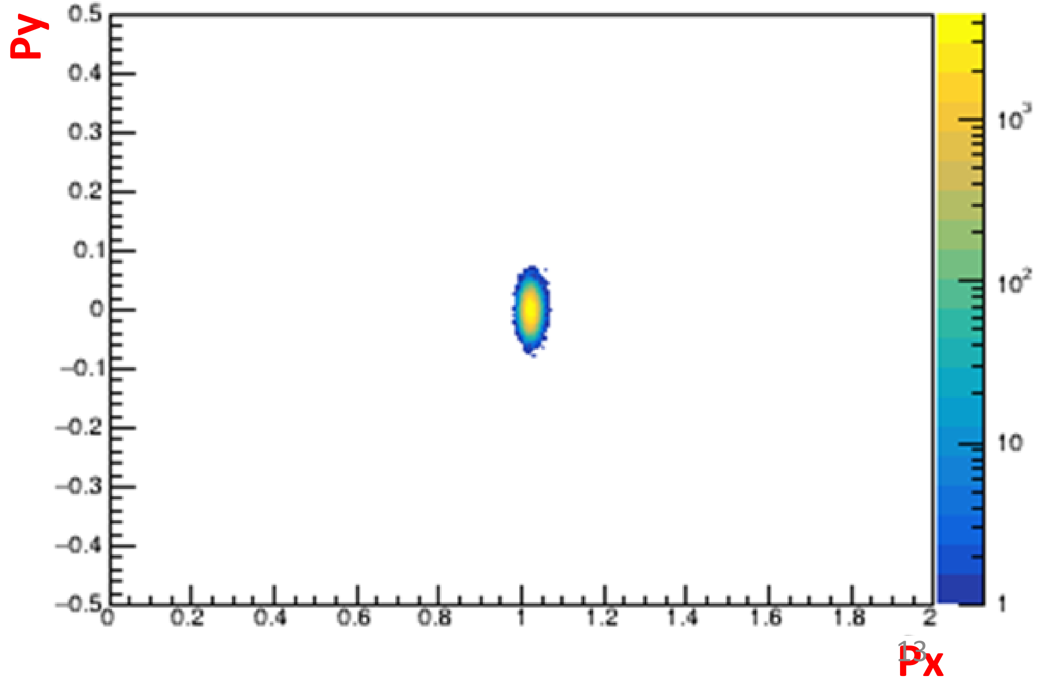
Beam Momentum: Py Vs Px 18x275



- As the detector is aligned with the lepton beam, full crossing angle is taken by the hadron beam

- Hadron beam acquires an x-component of momentum equal to the beam energy x Sin(xAngle): ~6.87 GeV and ~1.02 GeV for beam energies of 275 and 41 GeV, respectively with a 25 mRad crossing angle

Beam Momentum: Py Vs Px 5x41

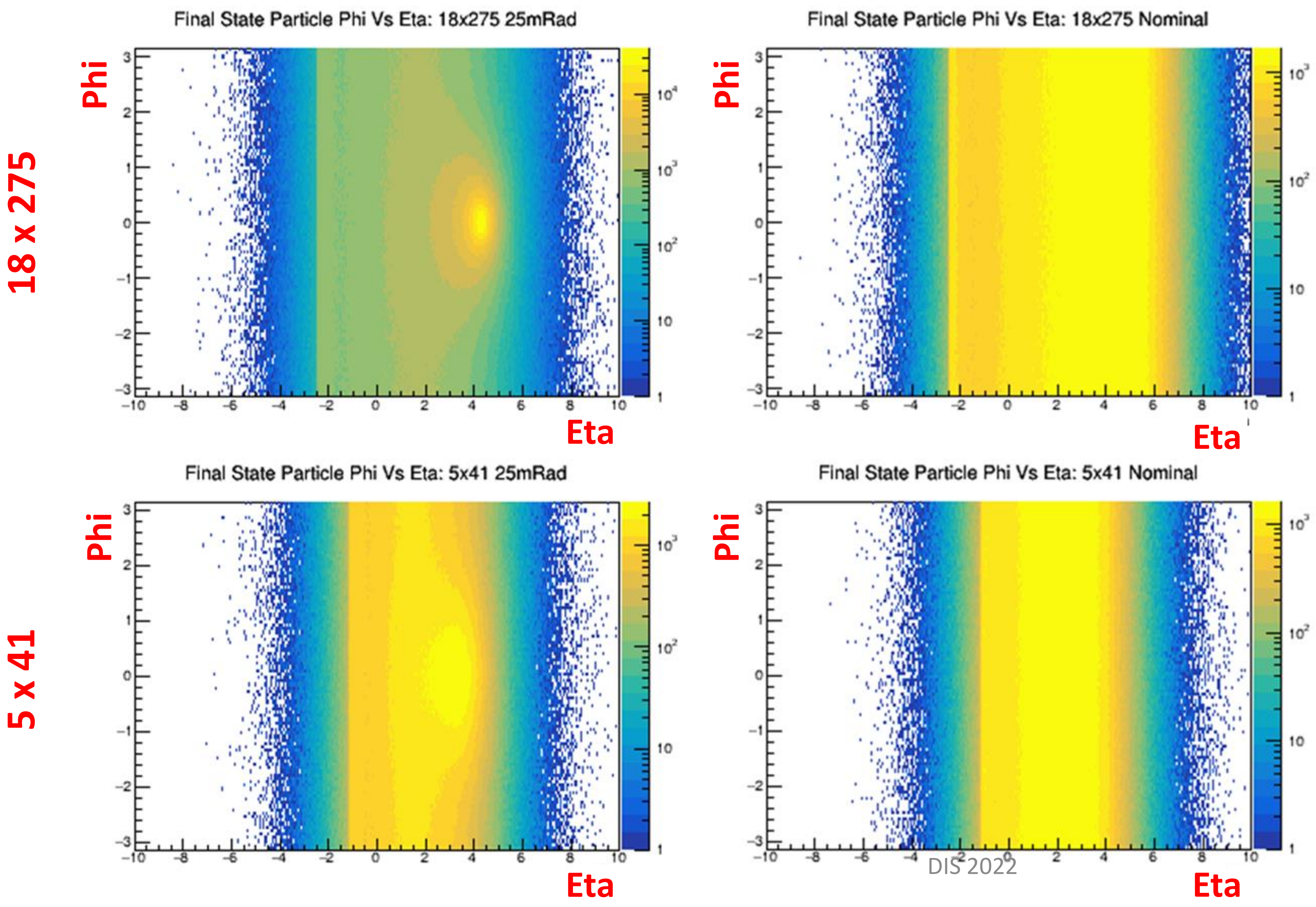


- The distribution of the X and Y components of the beam momentum is driven by the beam angular divergence with smaller contributions from crabbing kick and energy spread

- Note that divergence, crabbing, and energy spread represent irreducible uncertainties in the initial beam momentum

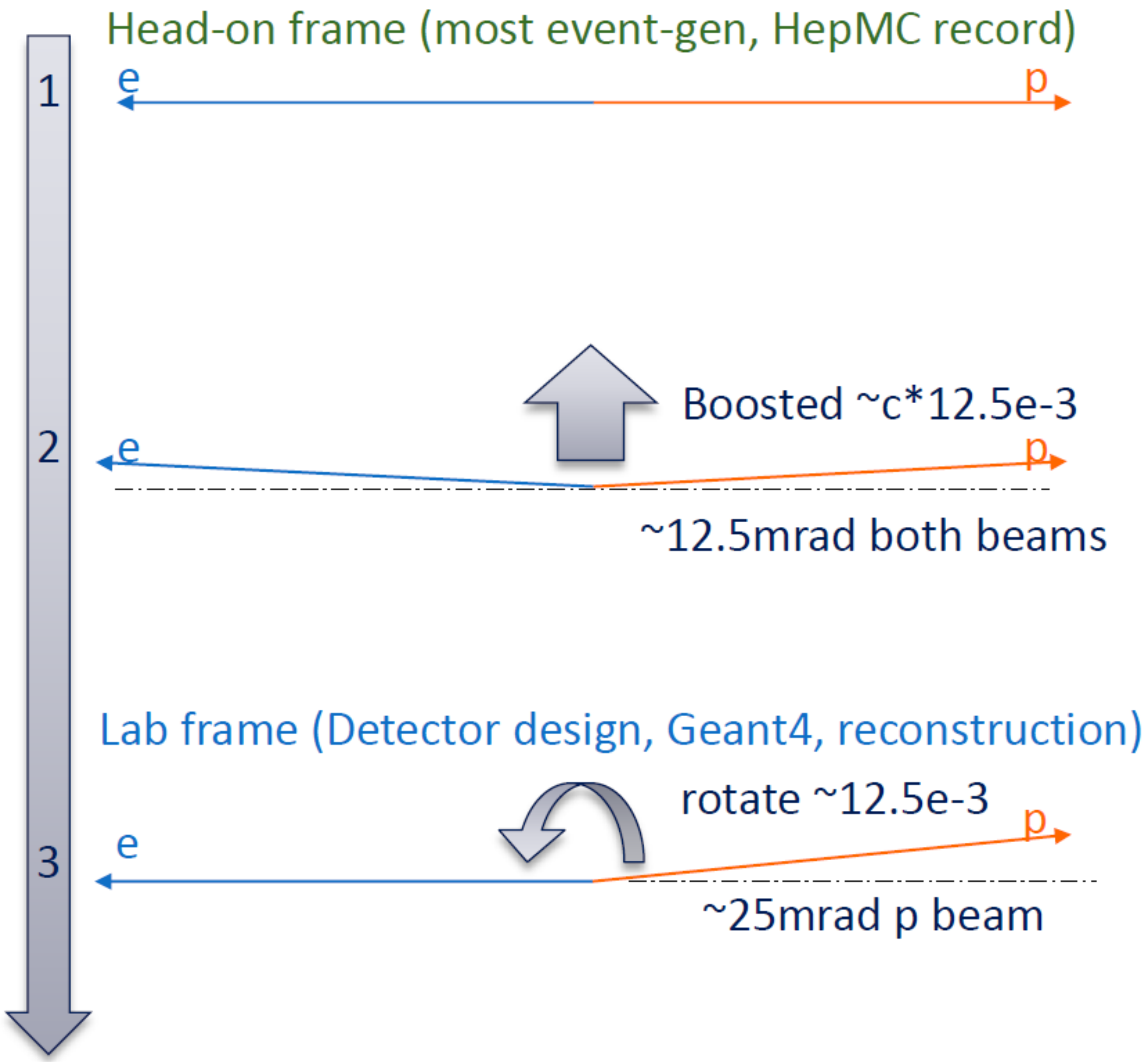
Final State Phi Vs Eta

25 mRad Crossing Angle | **No Crossing Angle**



- ❑ Crossing angle results in a concentration of final state particles in the direction of the beam
- ❑ For most relativistic beams, particle concentrations sit at beam rapidity – 25 milliradians = pseudorapidity of ~4.3
- ❑ Particle distributions opposite the hadron going direction are unaffected

Generator Agnostic After-burner



1. The algorithm input is the generator event described as a list of the four momenta of each final state particle in the head-on frame. In Figure 12, only the three vectors of the electron and proton beam are shown for simplicity and clarity purposes.

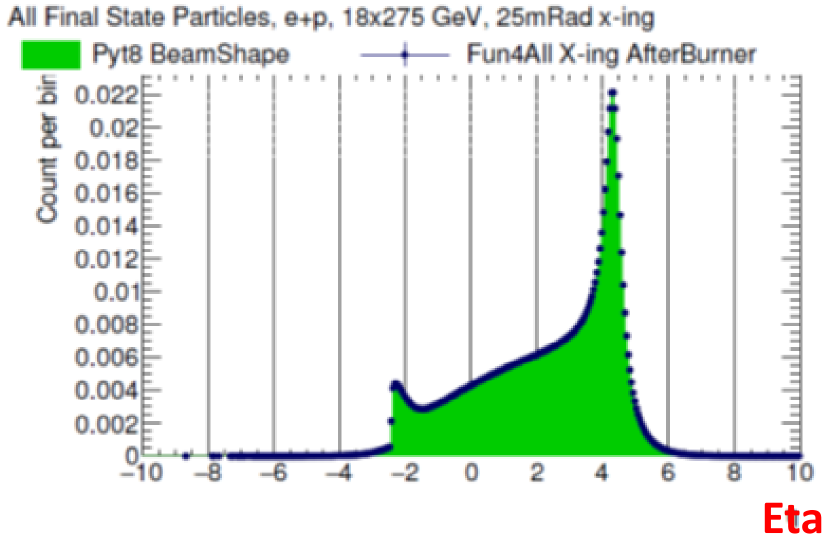
2. The head-on frame is first boosted sideways, perpendicular to the head-on colliding beam, and towards the beam crossing direction. The amplitude of the boost is $ctan(\theta_{CA}/2)$, if ignoring the beam divergence and crab-cavity kick. In the presence of these variations, the final boost direction and amplitude are chosen according to the final angle between the two beams at the lab frame.

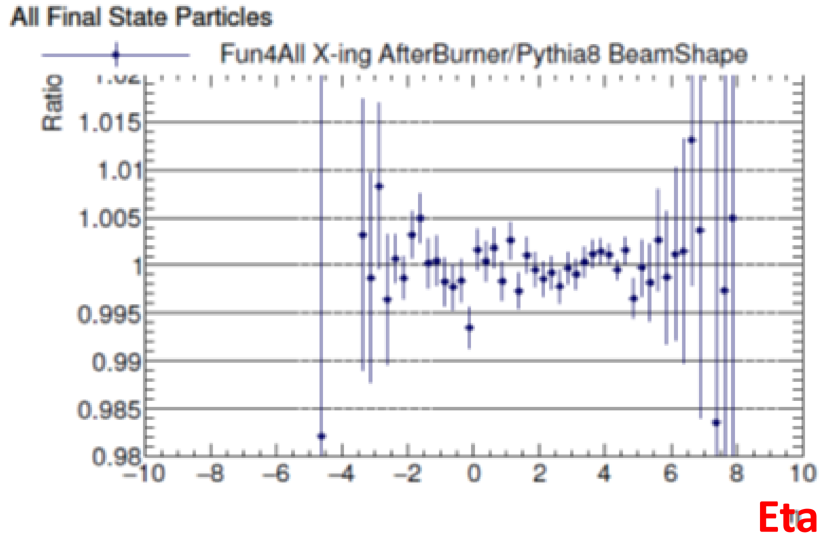
   - Note for relativistic beams, this boost is independent of the beam energy, which dramatically simplified the implementation.
   - Please also note the beam energy is not Lorentz invariant. This choice of the boost vector induces minimal changes in the beam energies of both beams between the two frames, i.e.

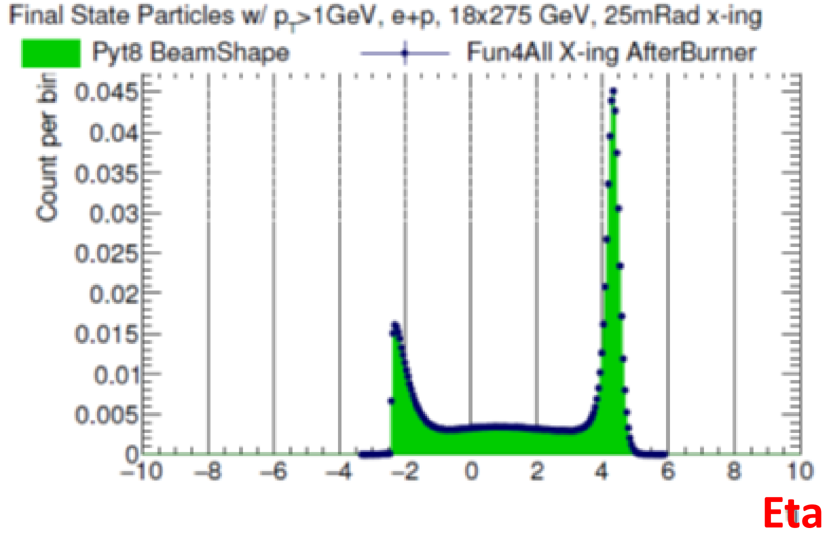
$$E_{\text{lab}} = E_{\text{head-on}}/cos(\theta_{CA}/2)$$

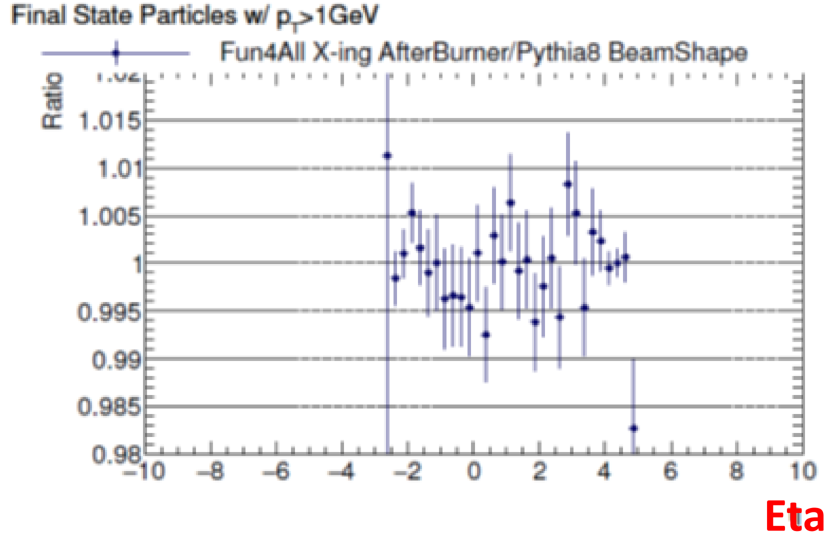
3. In the last step, a simple rotation of $\theta_{CA}/2$ around the vertical axis aligns the electron beam back to the $-z$ axis, which leaves the proton beam with the intended crossing angle of θ_{CA}. In the presence of the beam divergence and crab-cavity kick, the final rotation angle is $arccos(-\hat{p}_p \cdot \hat{p}_e)/2$ and the rotation axis is $\hat{p}_p \times \hat{p}_e$, where $\hat{p}_p$ and $\hat{p}_e$ are the final unit vector of the hadron and electron beam directions, respectively.

Pythia-8 Vs After-burner Comparison (Eta)





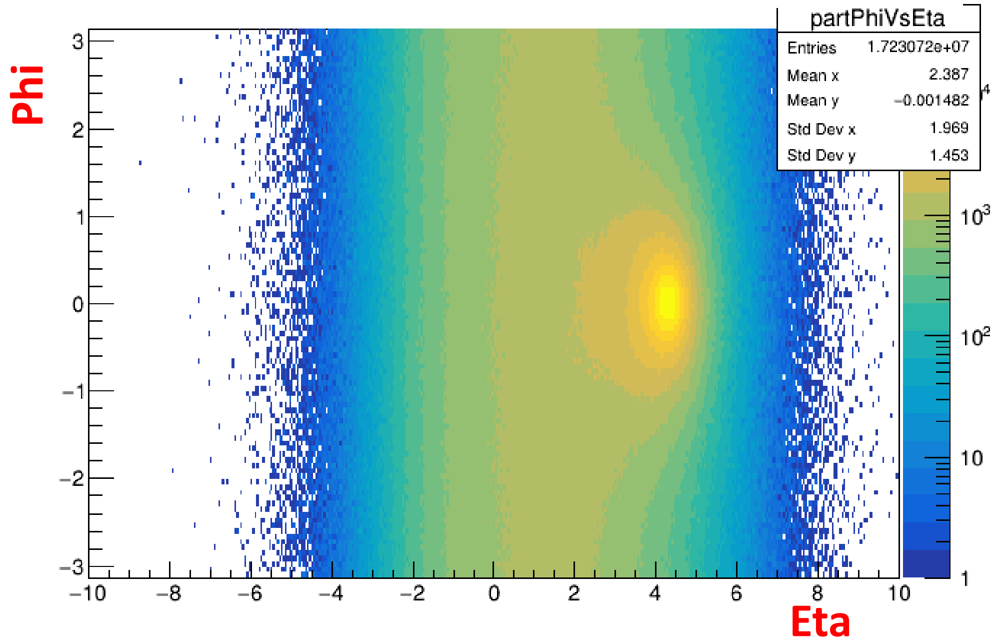




- Useful to have both PYTHIA and After-Burner solutions for beam effects simulation
- Need to make sure approaches are completely consistent
- Comparison of final state particle eta distribution for 18x275 and 25 mRad crossing angle show excellent agreement
- Similar check was made on final state particle phi with equally good agreement
- Vertex distributions also checked against an independent transport model

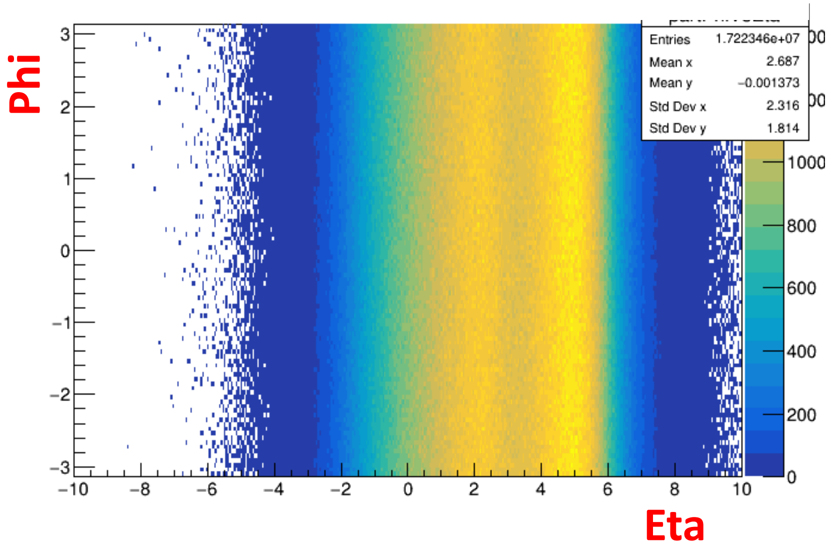
Transform to Head-On Frame

Beam Effects Included

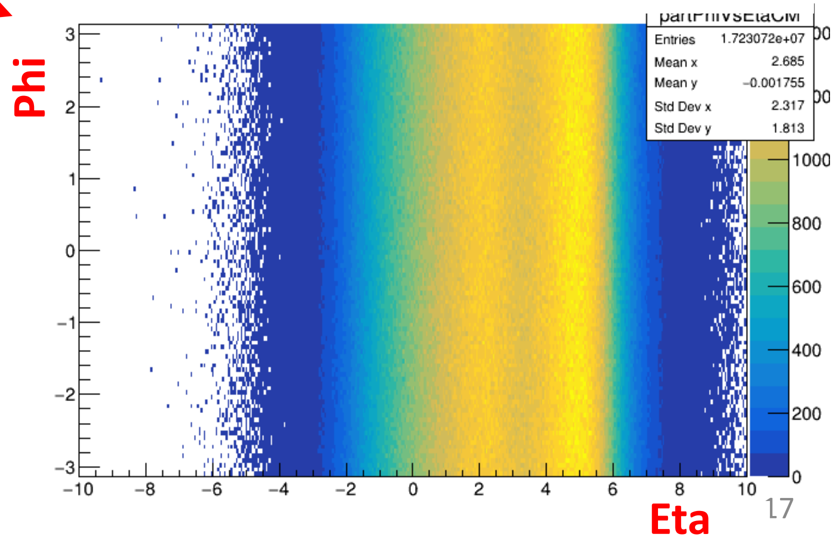


Transform

Default PYTHIA



Head-On Frame

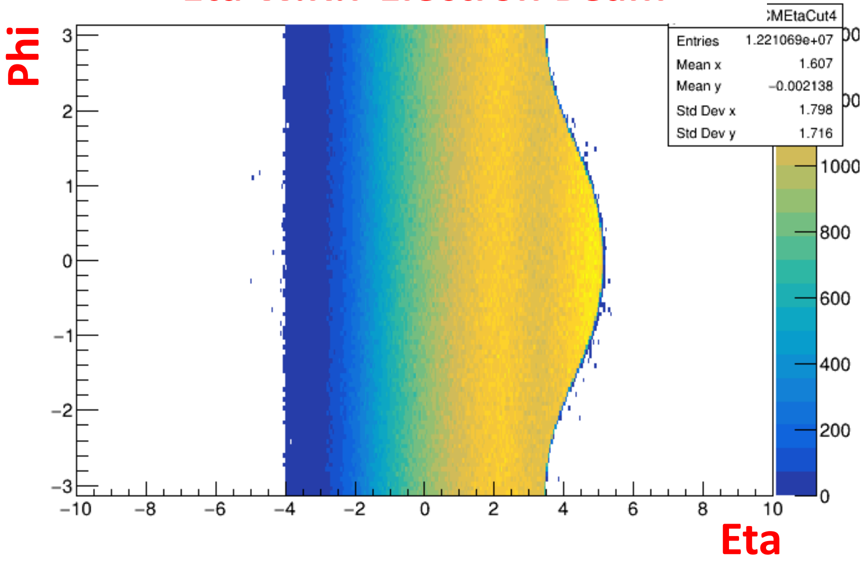


- ❑ Can correct for the impact of the crossing angle by boosting the final state system back into the head-on frame – also allows consistent definition of pseudorapidity
- ❑ Transform to head-on frame reproduces very well the final particle distribution obtained with default PYTHIA
- ❑ Cannot correct for random beam effects such as angular divergence

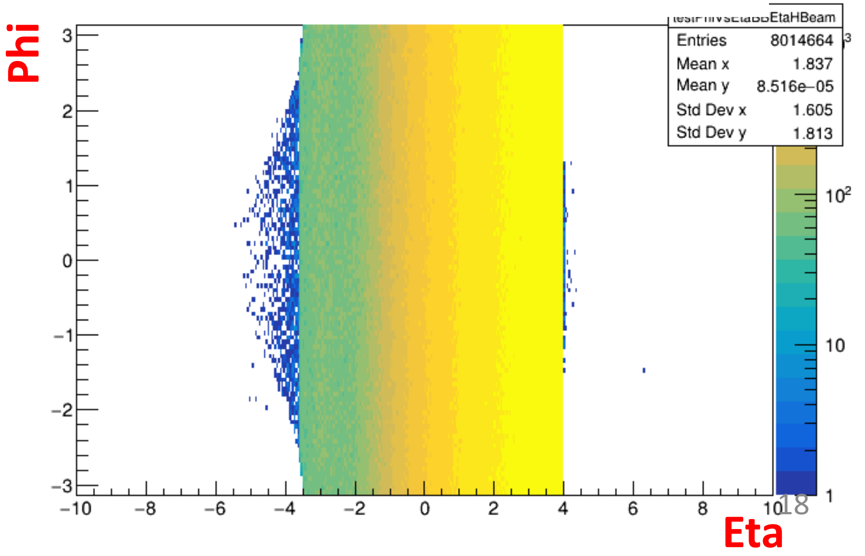
Acceptance Effects

- With infinite acceptance, can transform into the head-on frame and recover the particle distribution one would see without a crossing angle
- Detector acceptance is not infinite and restricting the particles used in the transformation can lead to features in the final distributions
- Accepting only particles with |eta| < 4.0 (where pseudorapidity is defined with respect to the incoming electron beam) and transforming to the head-on frame results in the figure at the top
- Alternately, can define pseudorapidity with respect to the outgoing hadron beam to define acceptance and transform – this leads to the distribution on the bottom without the 'bulge' in phi
- Implications for endcap design – center around hadron beam

Eta W.R.T Electron Beam



Eta W.R.T Hadron Beam



Summary

- The ambitious EIC physics program will place stringent constraints on the collider, detectors, and interaction regions – including a substantial crossing angle between the colliding beams

- Implementation of the crossing angle and other beam effects in monte carlo event generation is essential for detector simulation and realistic evaluation of physics observables

- Impacts of crossing angle and other beam effects on vertex distribution, beam momenta, and final state particle distributions were determined using a PYTHIA-8 specific model and presented. A comparison to an alternate After-Burner approach was also made

- A scheme for removing the effects of the crossing angle on final state particles was briefly discussed and the need to carefully consider detector acceptance effects was highlighted

- A more detailed description of this work with links to relevant code can be found in this technical note: https://eic.github.io/resources/simulations.html

- The PYTHIA-8 beam effects implementation can be found at: https://github.com/bspage912/eicSimuBeamEffects

Backup

Relevant Accelerator Parameters

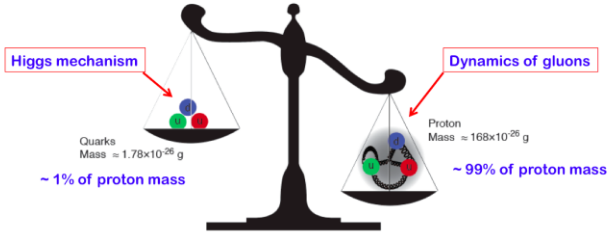
Table 4: Parameters used in the PYTHIA-8 implementation taken from Table 3.3 in the CDR. The designations h and v stand for horizontal (x direction) and vertical (y direction).

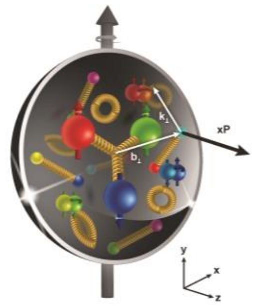
Species Energy [GeV]	Proton 275	Electron 18	Proton 41	Electron 5	Notes
RMS Emittance h/v [nm]	18/1.6	24/20	44/10	20/3.5	Used with β^* to determine bunch size
β^* h/v [cm]	80/7.1	59/5.7	90/7.1	196/21	Used with emittance to determine bunch size
RMS $\Delta\theta$ h/v [μrad]	150/150	202/187	220/380	101/129	Used to determine angular beam divergence
RMS Bunch Length [cm]	6	0.9	7.5	0.7	Used in vertex calculation
RMS $\frac{\Delta p}{p}$ [10^{-4}]	6.8	10.9	10.3	6.8	Used to set beam energy spread

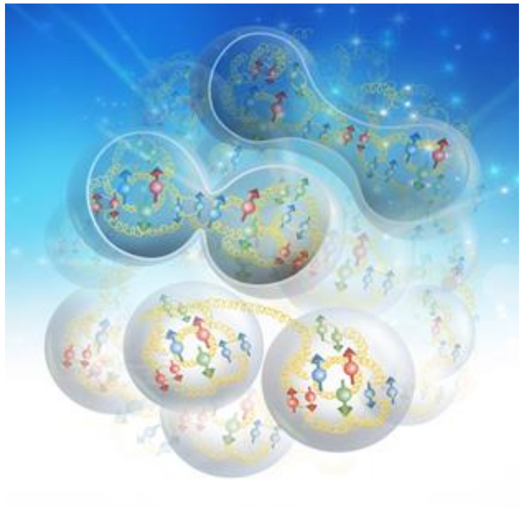
The EIC Physics Pillars

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?







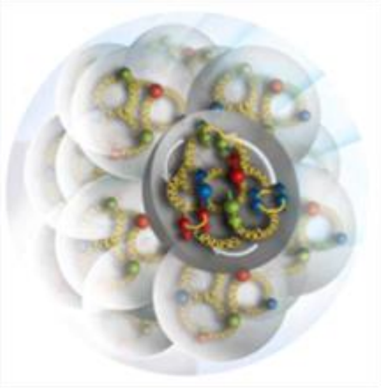
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

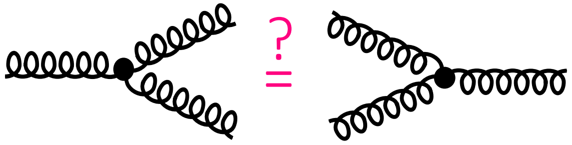
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?





PYTHIA-8 Vertex Model

- Determine the x, y, and z vertex of the collision along with the time of collision
- Assume each bunch is rotated through half the beam crossing angle and assume it stays in a fixed orientation throughout the colliding region
- Assume particles in bunch are distributed along z as a gaussian with a sigma of the RMS bunch length cited in CDR table 3.3, 3.4. Correct collision distribution should follow automatically
- Assume particles in bunch are distributed in x,y as a gaussian with sigma given by Sqrt(RMS emittance x beta*) as given in CDR table 3.3, 3.4
- Procedure:
    1. Chose z (in in-bunch coordinates) of colliding particle in hadron and lepton bunch
    2. Propagate bunches until colliding particles overlap – this sets collision z, t, and a central x offset
    3. Randomly sample an x value according to beam widths and add to central x offset. Randomly sample a y value
    4. Rotate system from ‘accelerator frame’ into ‘detector frame’

PYTHIA-8 Vertex Model

$$z_{\text{Had}}^{\text{Acc}} = \text{Cos}\left(\frac{\theta}{2}\right) \times t + z_{\text{Had}}^{\text{Bunch}}$$

$$z_{\text{Lep}}^{\text{Acc}} = -\text{Cos}\left(\frac{\theta}{2}\right) \times t + z_{\text{Lep}}^{\text{Bunch}}$$

Z-position of interacting bunch from each beam as a function of time given by this set of equations

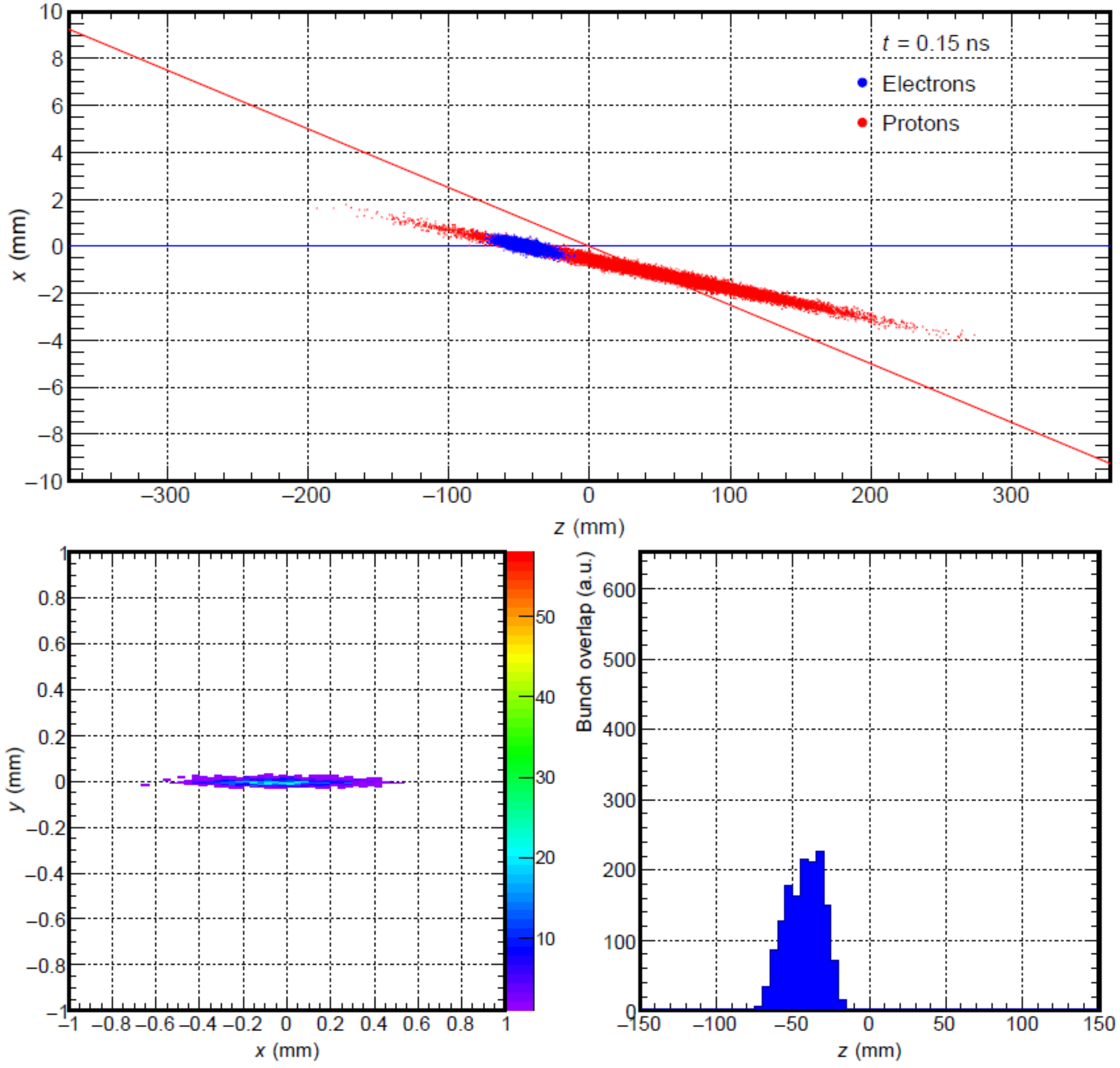
Collisioin occurs when Z_Had and Z_Lep are equal – can then solve the system to get time, z-position, and x-position of collision

$$t_{\text{Col}} = \frac{\left(z_{\text{Lep}}^{\text{Bunch}} - z_{\text{Had}}^{\text{Bunch}}\right)}{2 \times \text{Cos}\left(\frac{\theta}{2}\right)}$$

$$z_{\text{Col}} = \frac{\left(z_{\text{Lep}}^{\text{Bunch}} + z_{\text{Had}}^{\text{Bunch}}\right)}{2}$$

$$x_{\text{Col}} = t_{\text{Col}} \times \text{Sin}\left(\frac{\theta}{2}\right).$$

Transport Model Vertex

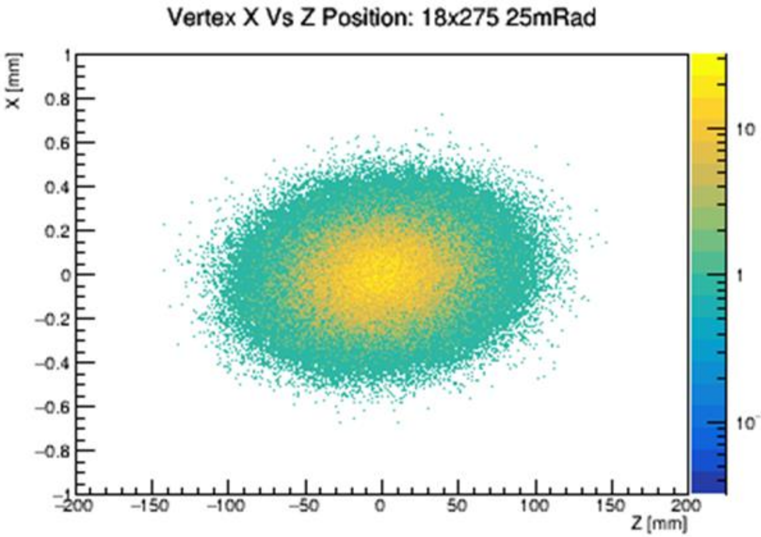


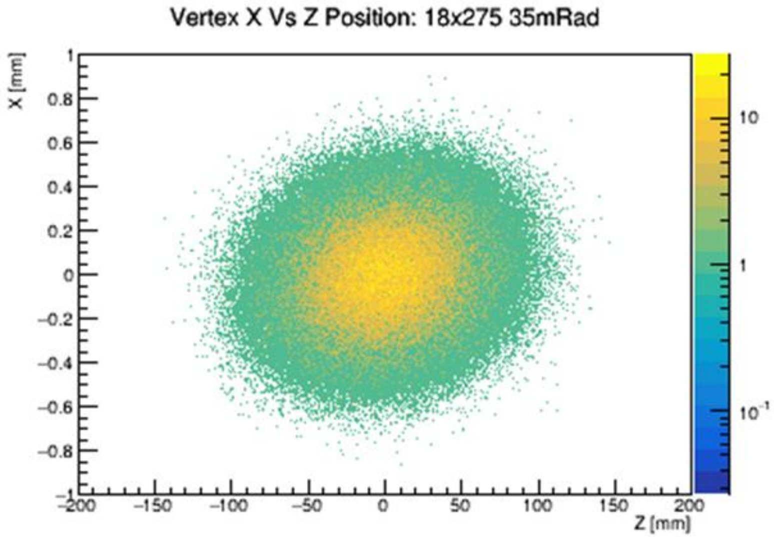
Developed by Jaroslav Adam – movie available at: https://eic.github.io/resources/simulations.html

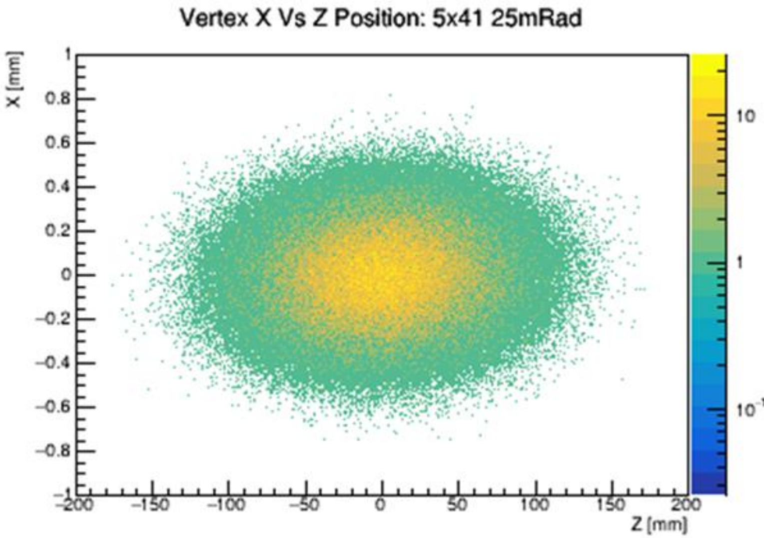
Species, energy (GeV)		Vertex size	Transport model	PYTHIA-8
proton 275	electron 18	σ_x (mm)	0.1894 ± 0.0014	0.1403 ± 0.0001
		σ_y (μm)	10.0675 ± 0.0013	8.0173 ± 0.0056
		σ_z (mm)	32.92 ± 0.12	30.24 ± 0.02
proton 100	electron 10	σ_x (mm)	0.2057 ± 0.0023	0.1313 ± 0.0001
		σ_y (μm)	12.2144 ± 0.0018	8.0221 ± 0.0057
		σ_z (mm)	36.00 ± 0.15	35.13 ± 0.02
proton 41	electron 5	σ_x (mm)	0.2429 ± 0.0020	0.1649 ± 0.0001
		σ_y (μm)	25.0197 ± 0.0060	19.0005 ± 0.0134
		σ_z (mm)	37.77 ± 0.28	37.62 ± 0.03
Au ion 110	electron 18	σ_x (mm)	0.3210 ± 0.0035	
		σ_y (μm)	15.1721 ± 0.0025	
		σ_z (mm)	36.00 ± 0.07	
Au ion 41	electron 5	σ_x (mm)	0.3130 ± 0.0022	
		σ_y (μm)	15.3381 ± 0.0048	
		σ_z (mm)	59.91 ± 0.36	

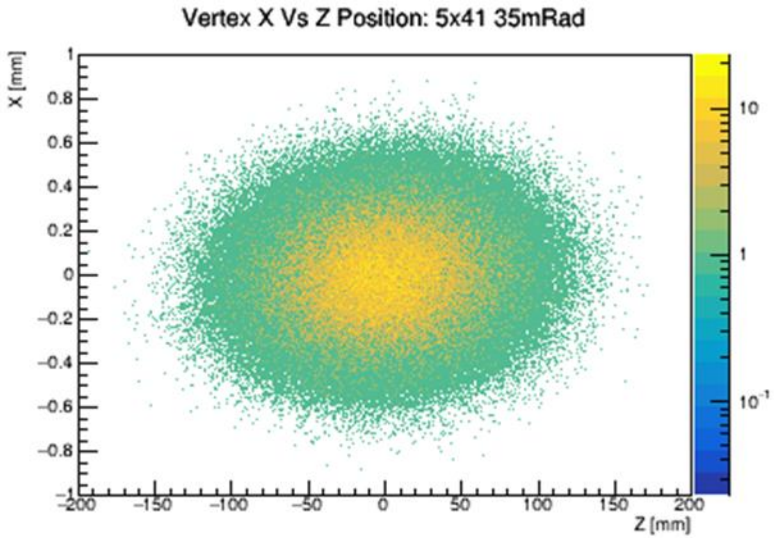
Table 3: Results on expected primary vertex size from the transport model for ep and e-Au beams and comparison to PYTHIA-8.

PYTHIA-8 Vertex Correlations (X Vs Z)

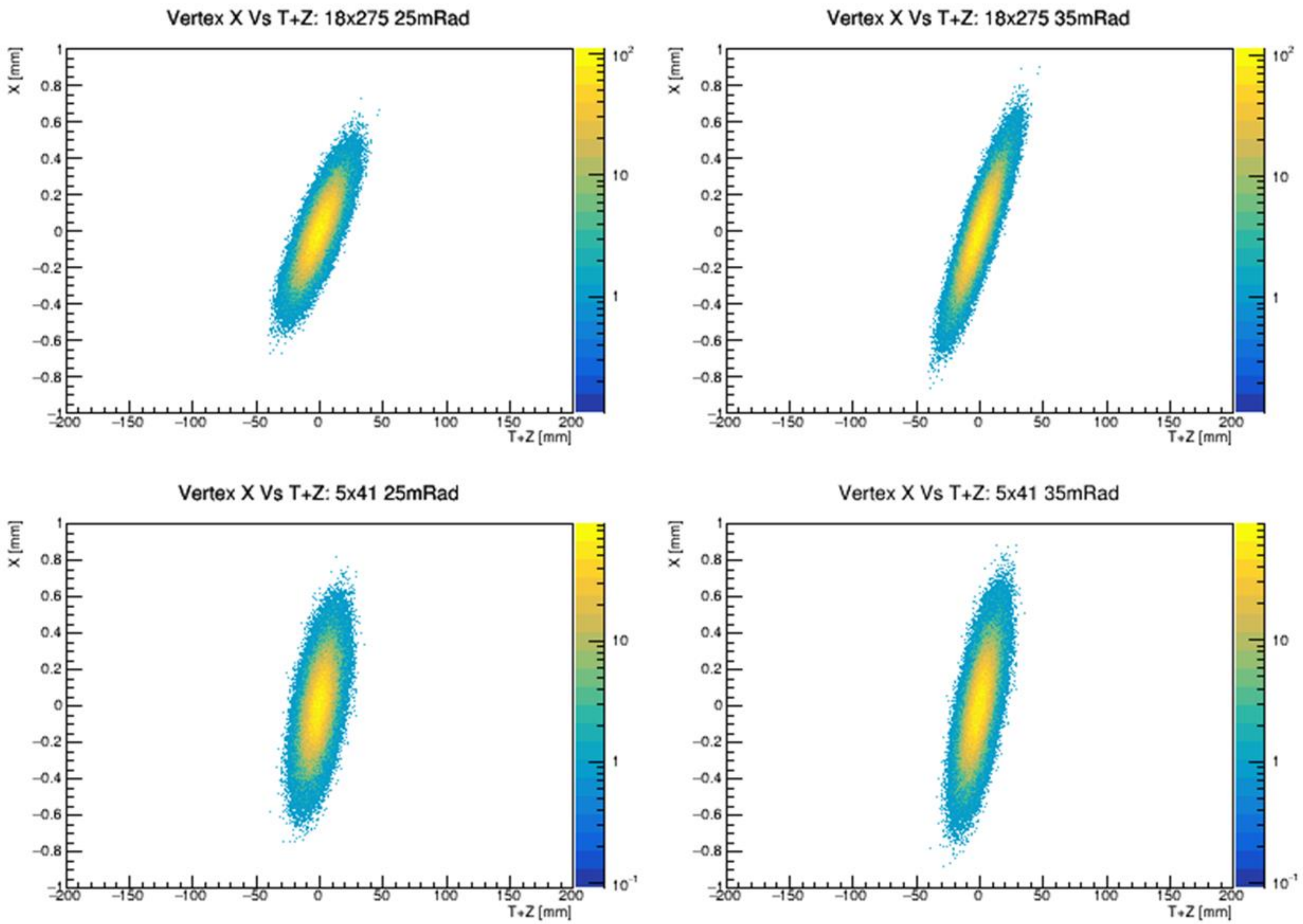




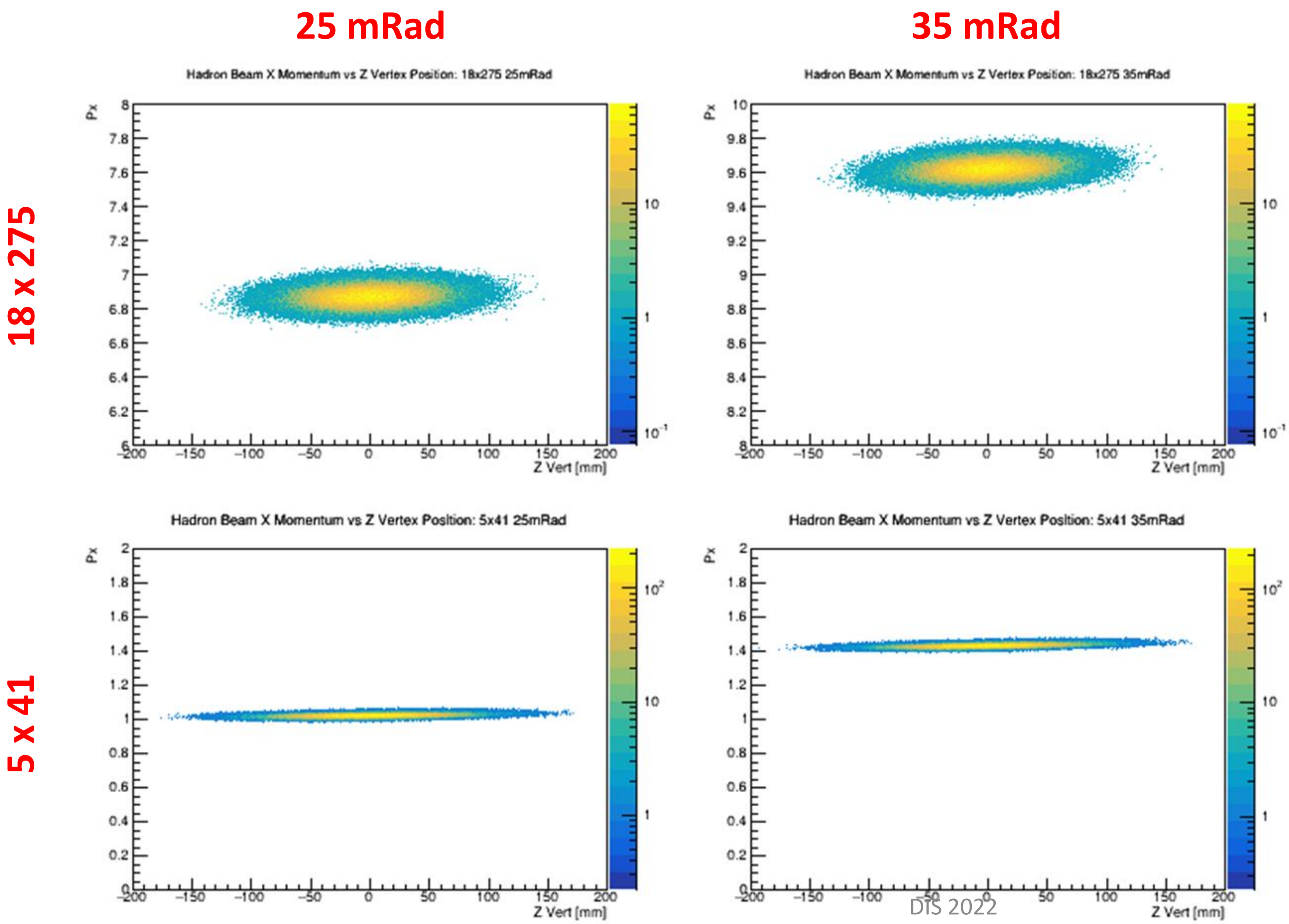




PYTHIA-8 Vertex Correlations – Add Timing



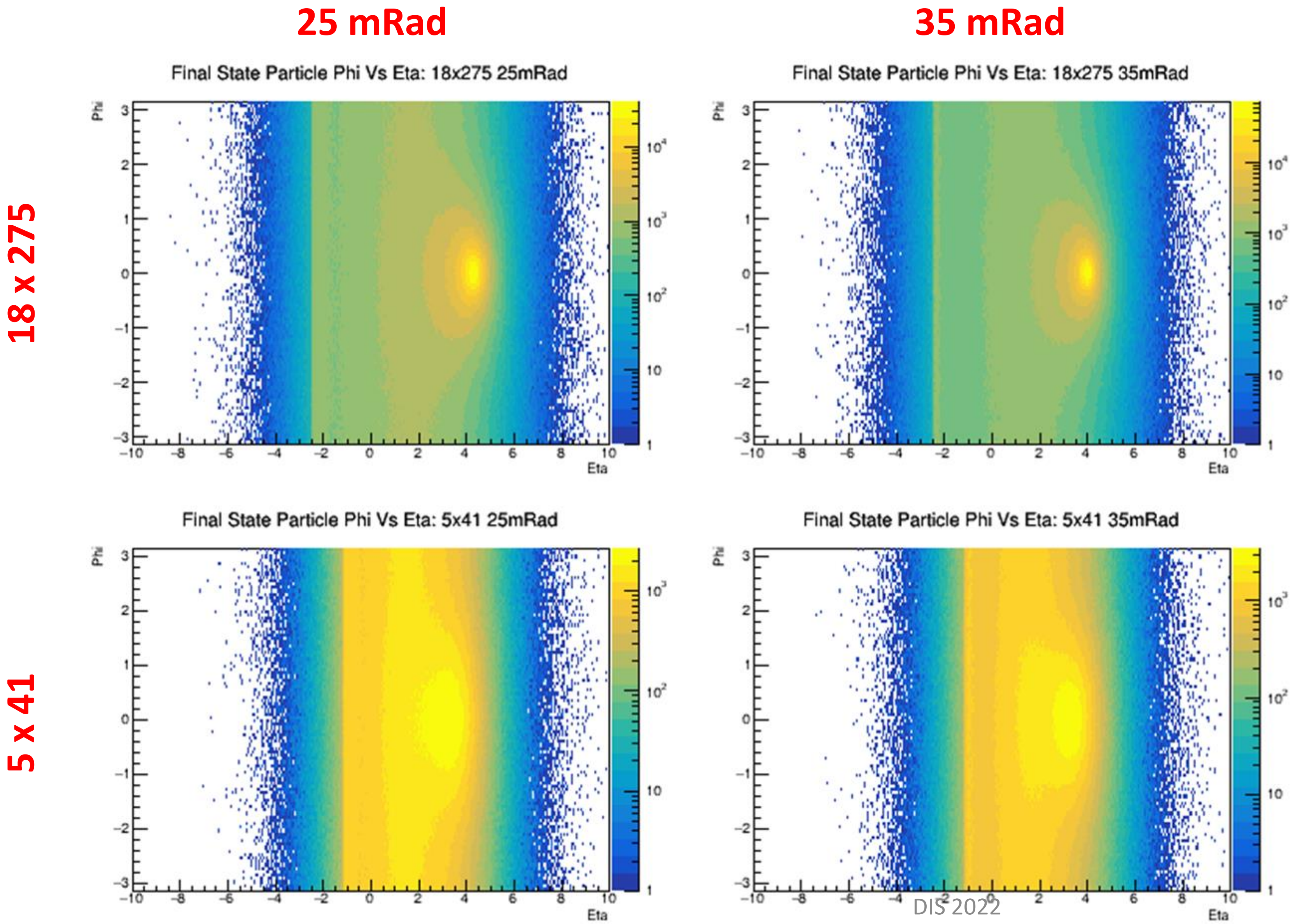
Momentum Distributions – X Vs Z-Vertex



Size of beam x-momentum is slightly dependent on z-position of the interaction

This is due to the crab rotation which introduces a differential momentum kick along the length of the bunch

Final State Phi Vs Eta



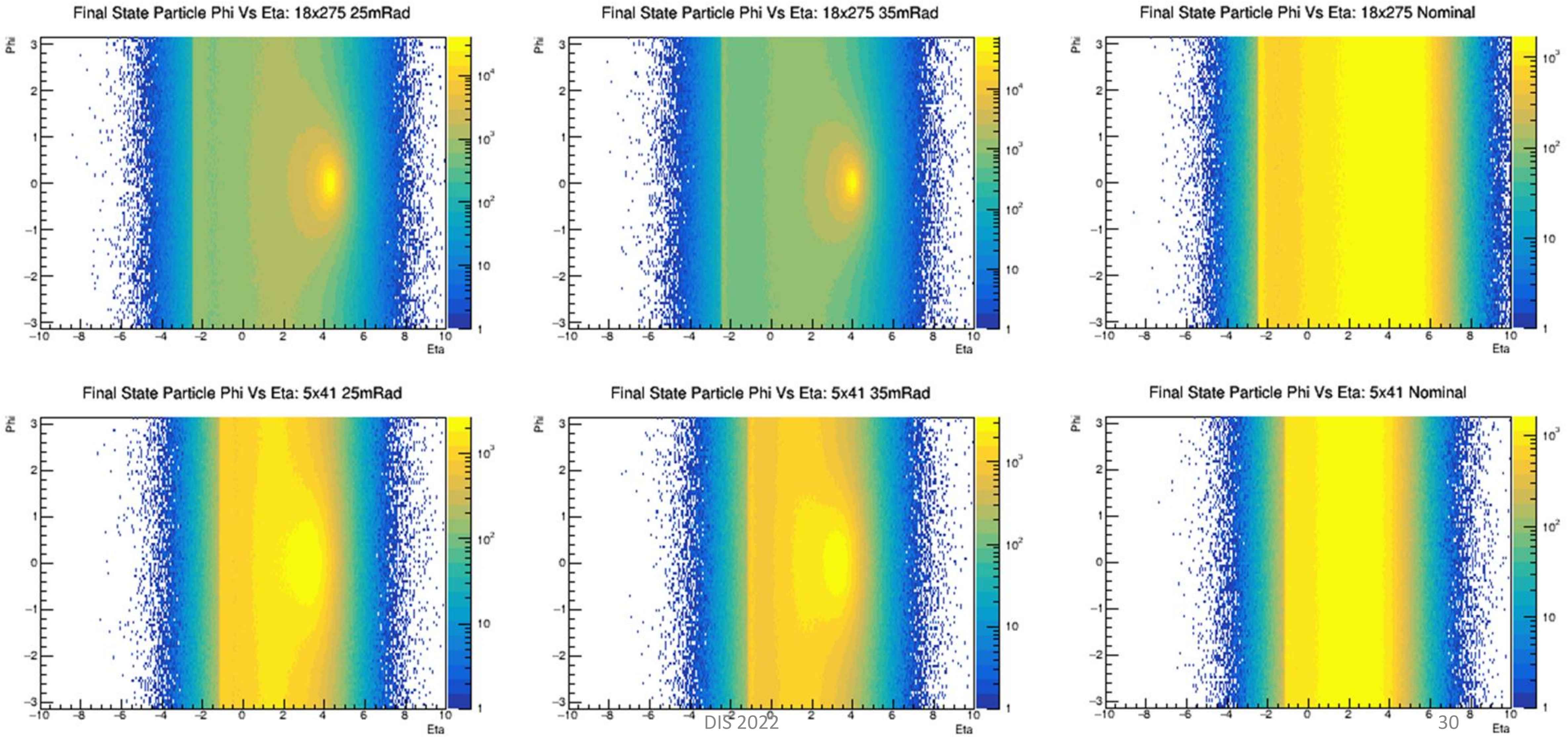
- Crossing angle results in a concentration of final state particles in the direction of the beam
- For most relativistic beams, particle concentrations sit at beam rapidity – 25 milliradians = pseudorapidity of ~4.3
- Particle distributions opposite the hadron going direction are unaffected

Final State Phi Vs Eta

25 mRad | **35 mRad** | **No Beam Effects**

18 x 275

5 x 41

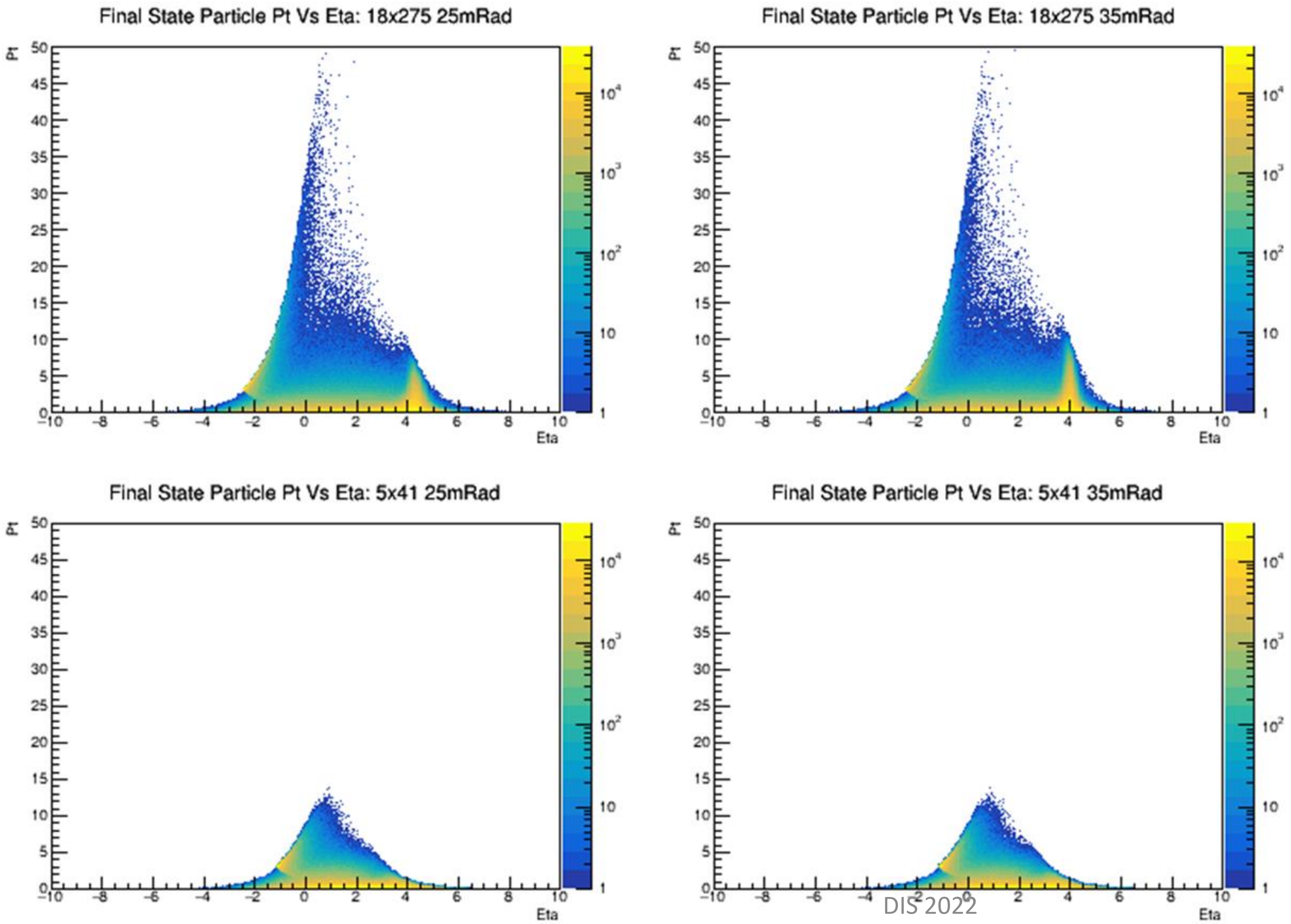


Final State P_T Vs Eta

25 mRad **35 mRad**

18 x 275

5 x 41

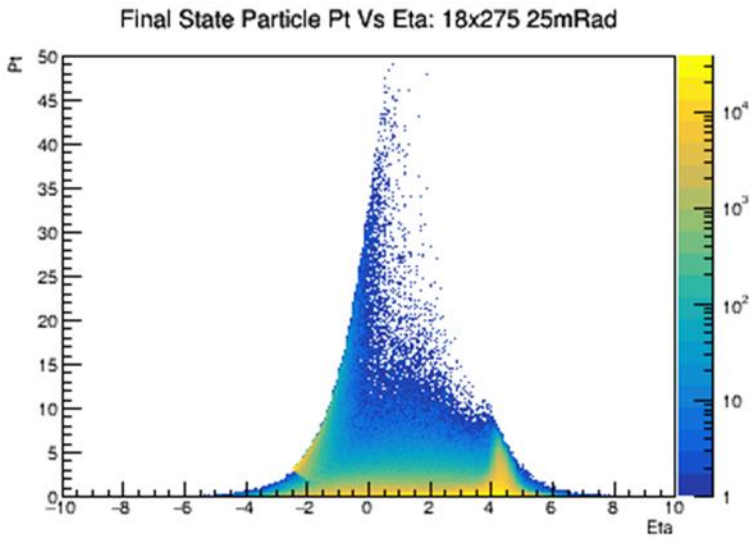


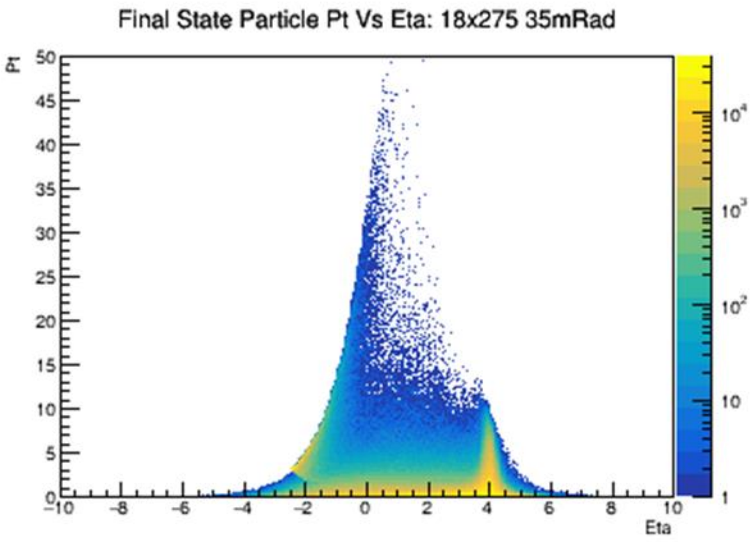
- Particles that are boosted into the peaks are also pushed to higher transverse momenta
- This is most visible for higher hadron beam momenta and a very minor effect for the lowest beam energy
- Particle distributions at backward rapidities are from the scattered beam electron which was not excluded in these plots

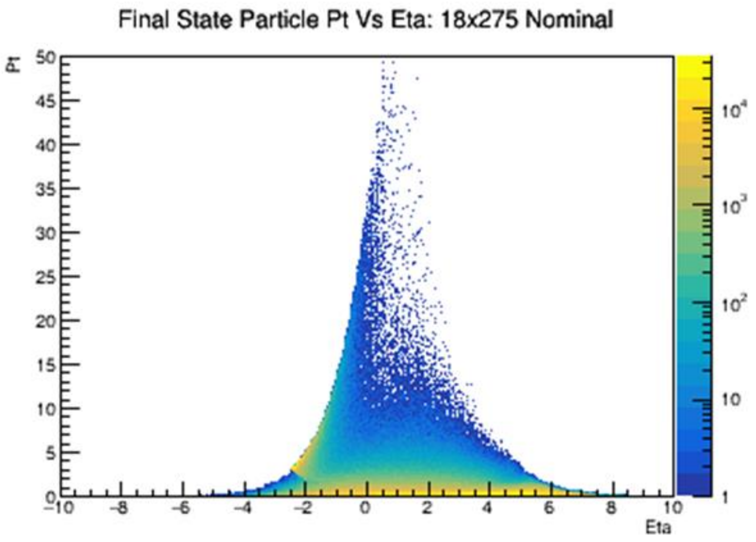
Final State P_T Vs Eta

25 mRad | **35 mRad** | **No Beam Effects**

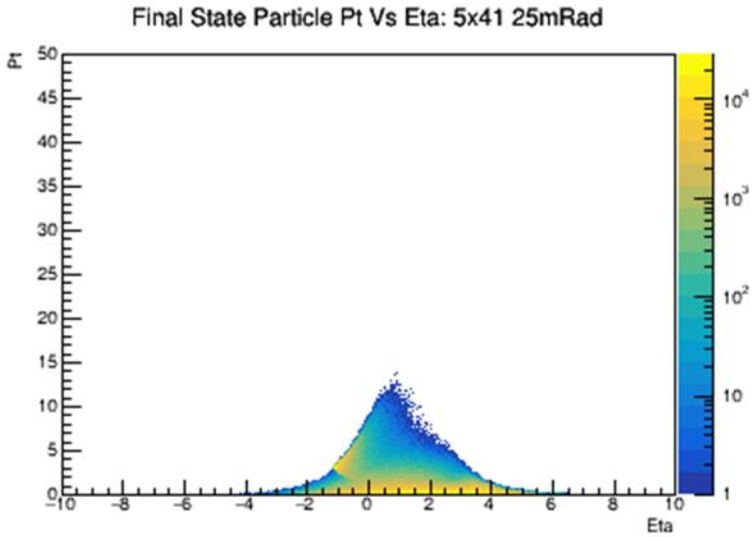
18 x 275

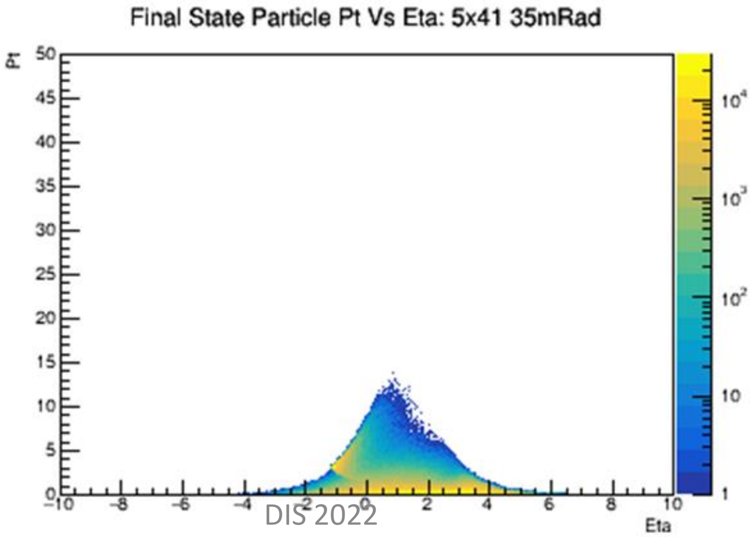


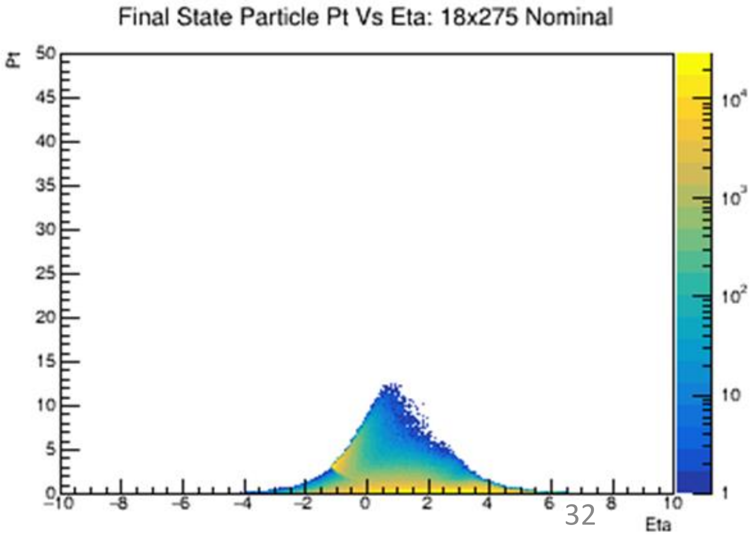




5 x 41





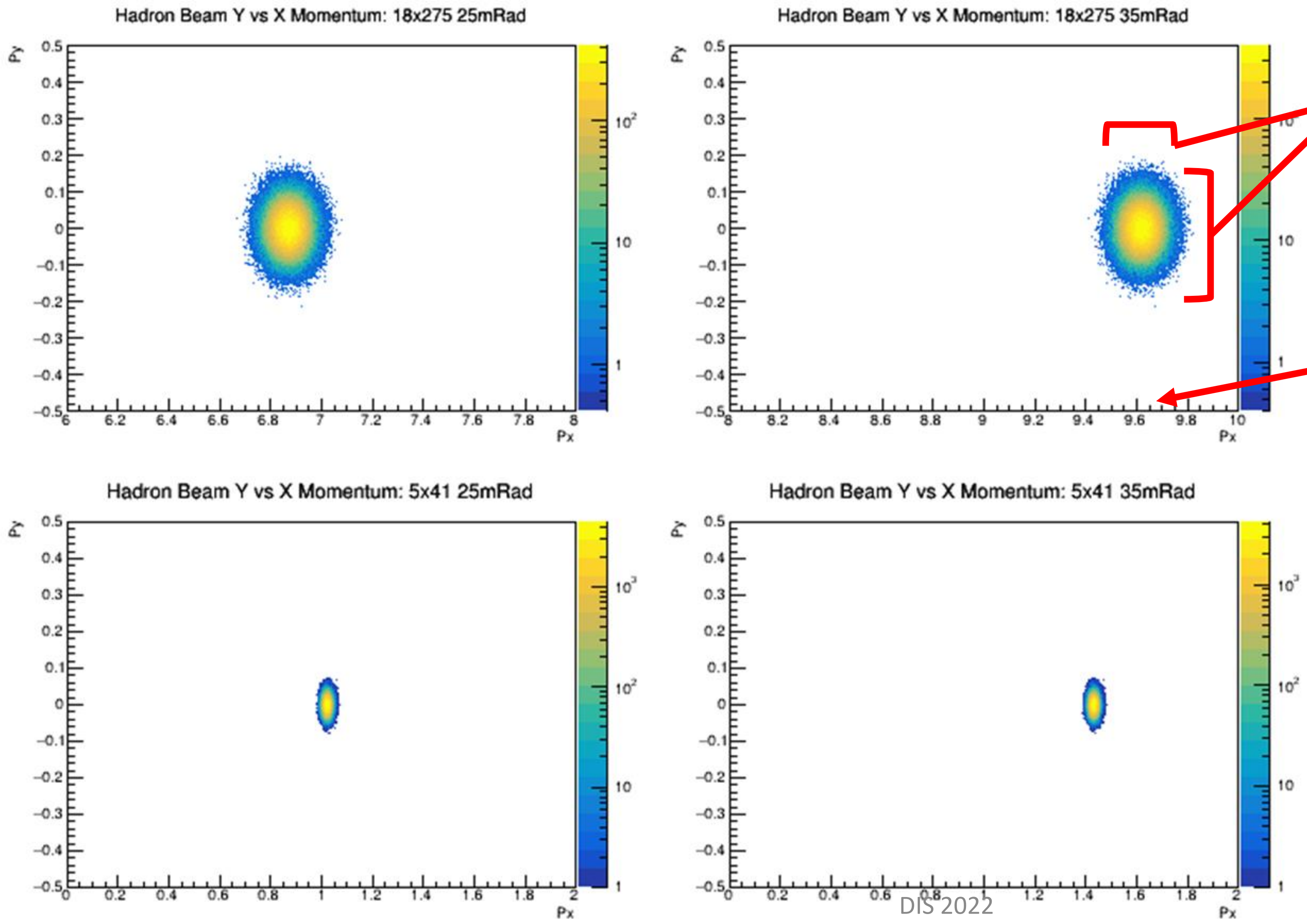


Hadron Beam Momentum Distributions – Y Vs X

25 mRad | 35 mRad

18 x 275

5 x 41

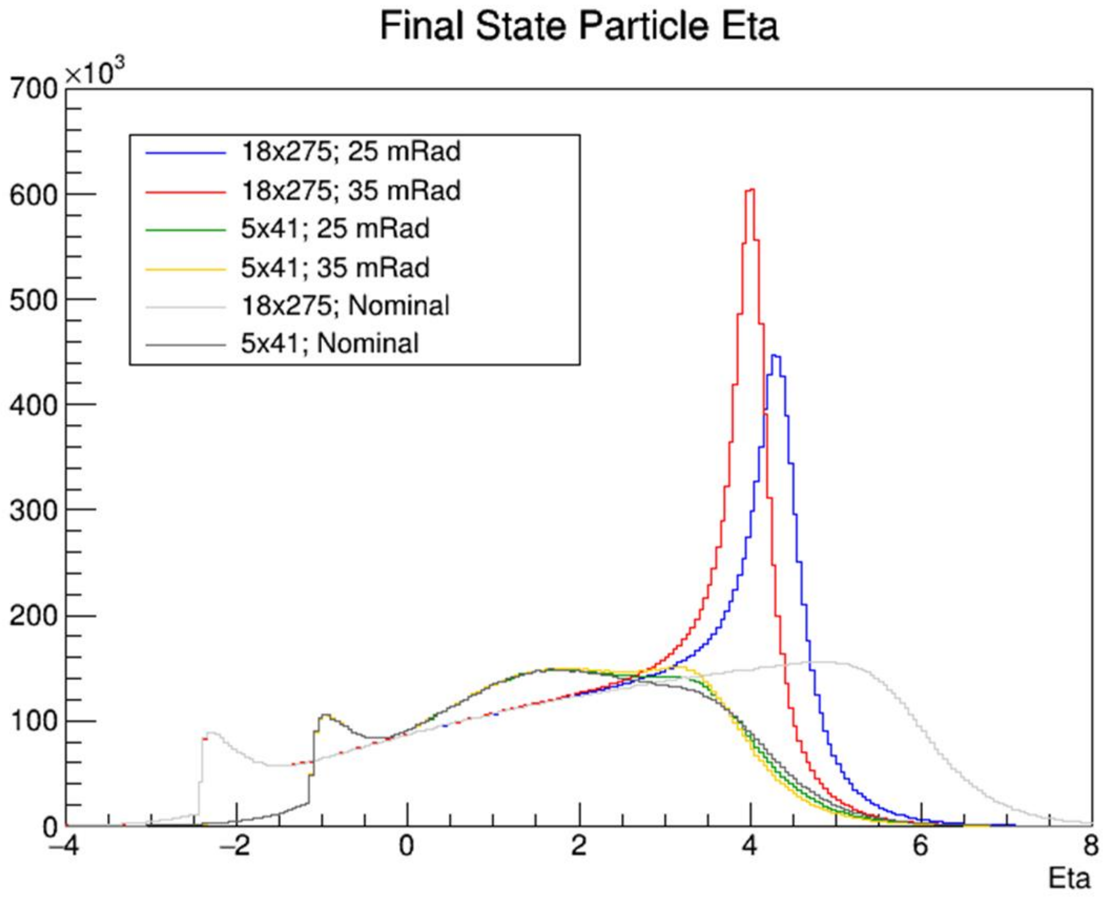


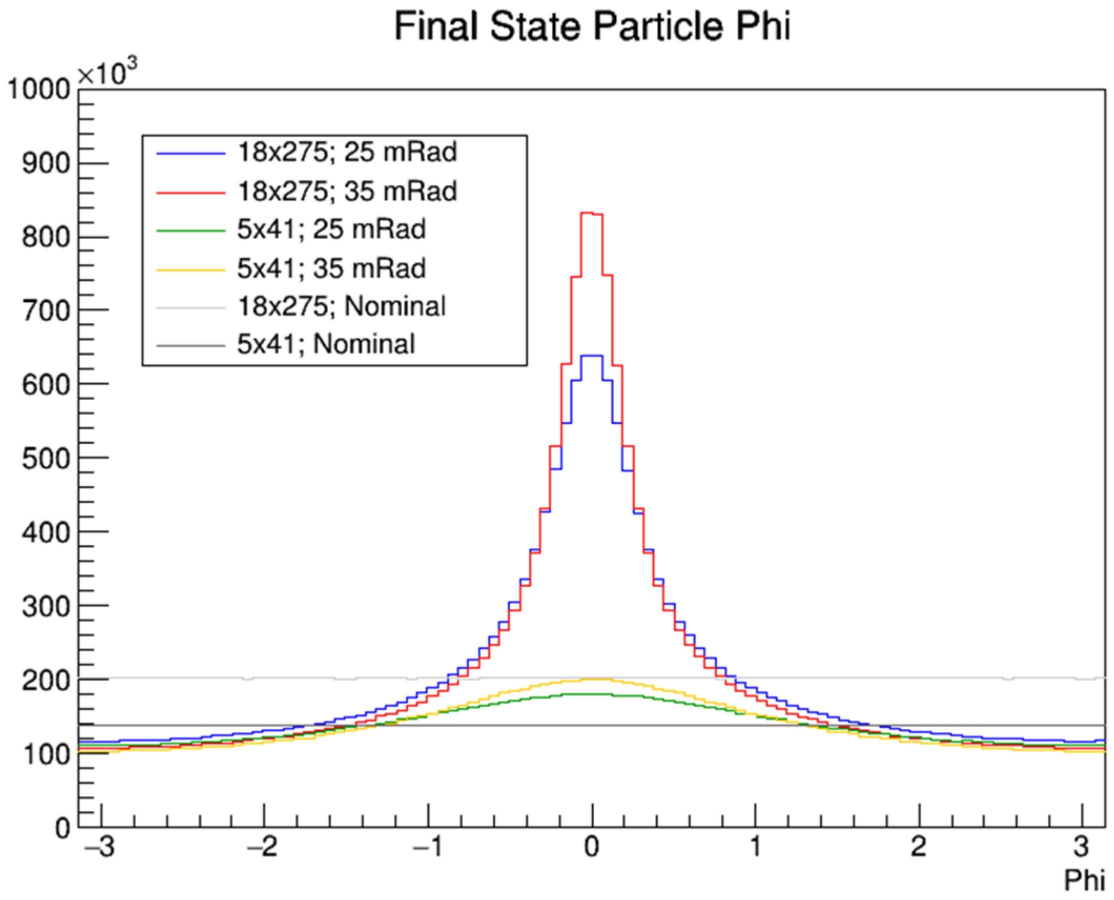
Width of spot is driven by angular divergence with minor contributions from energy spread and crabbing kick

Offset in X momentum due to crossing angle

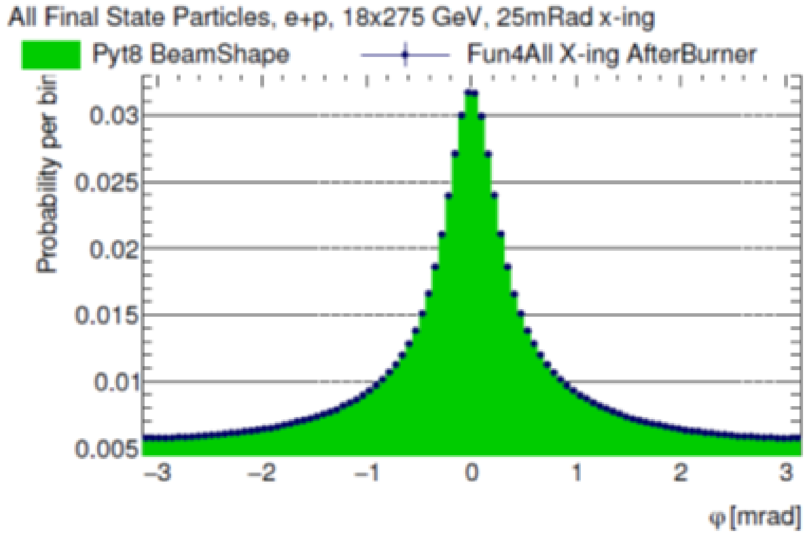
Smaller momentum deviations for 5x41 driven by lower hadron beam energy

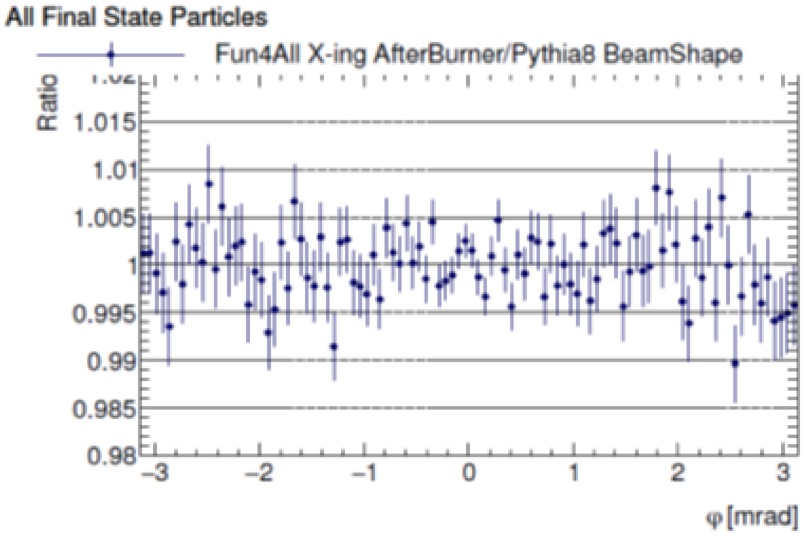
Final State Phi & Eta

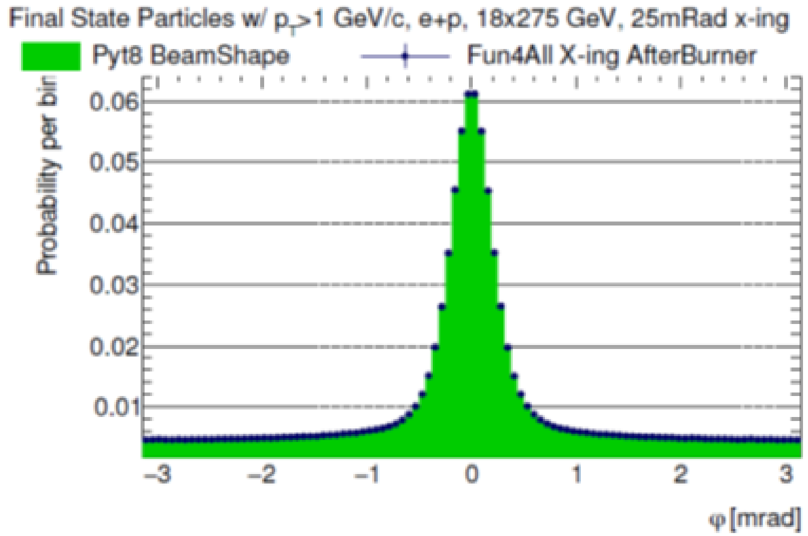


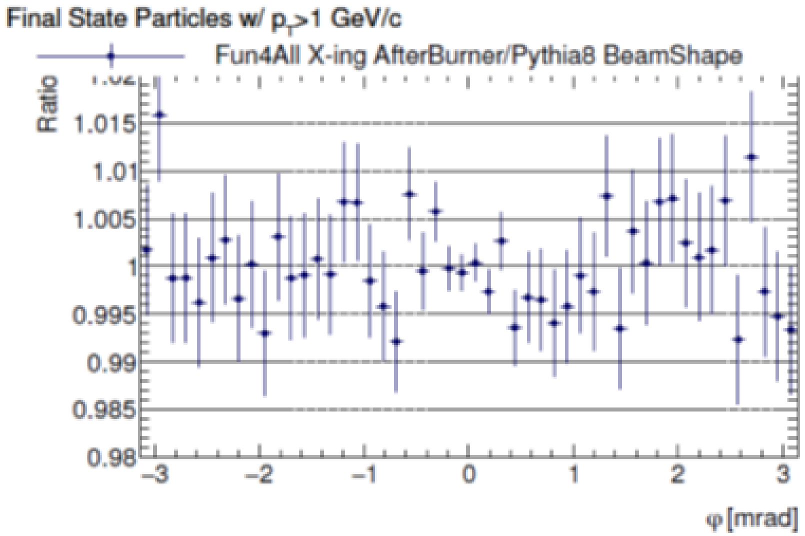


Pythia-8 Vs After-burner Comparison (Phi)

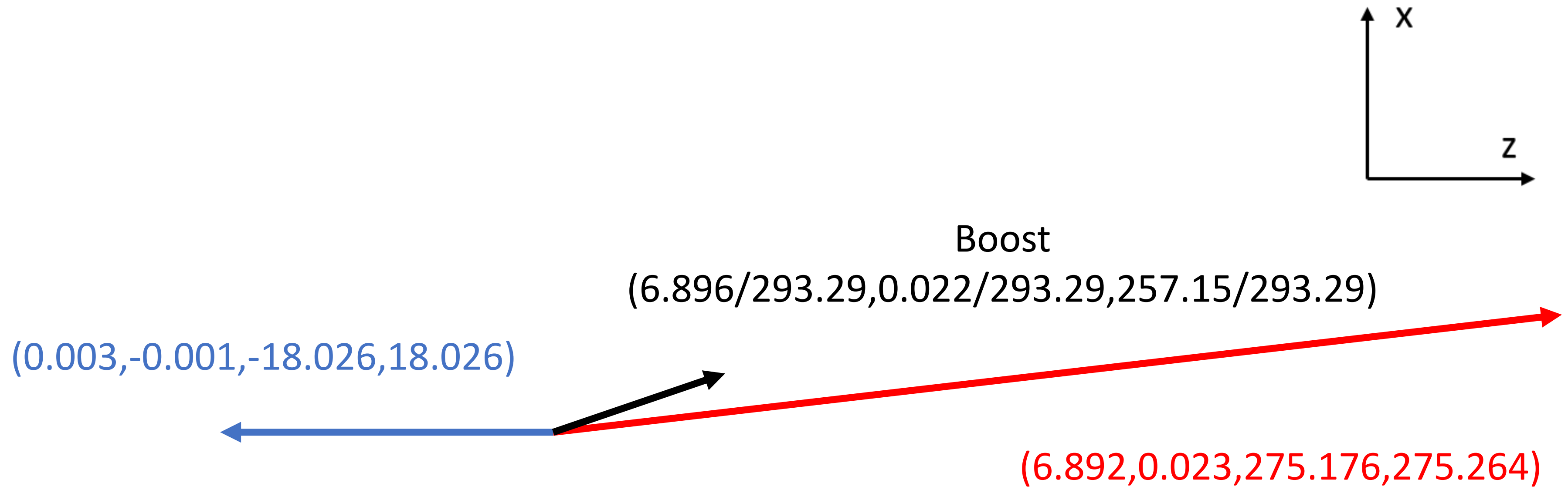






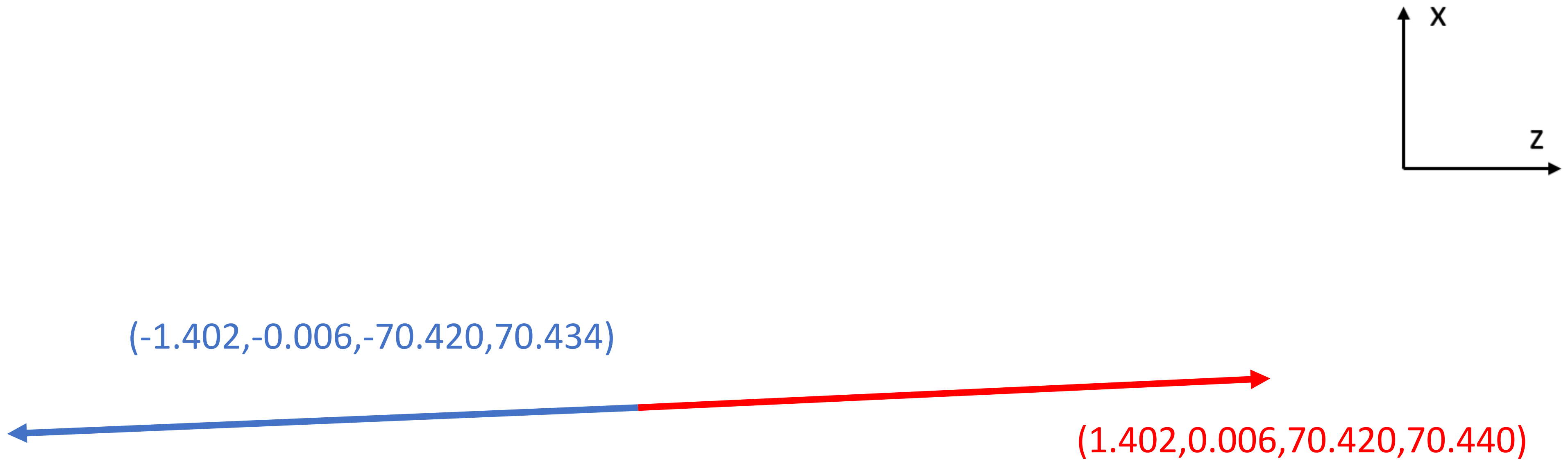


Head-On Frame Boost Procedure



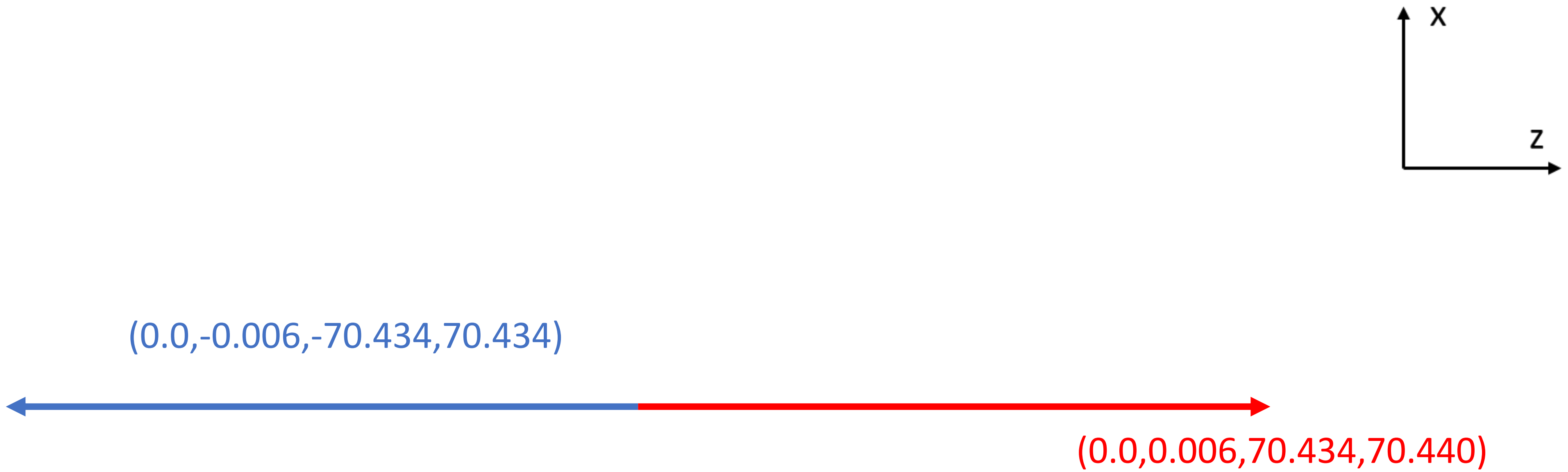
1. Initial Configuration in the Lab Frame (beam momenta from a random event)

Head-On Frame Boost Procedure



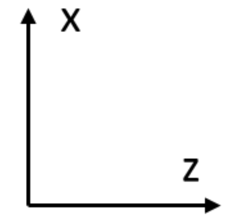
1. Initial Configuration in the Lab Frame (beam momenta from a random event)
2. Boost by sum of beam 4-momenta to get to CM Frame

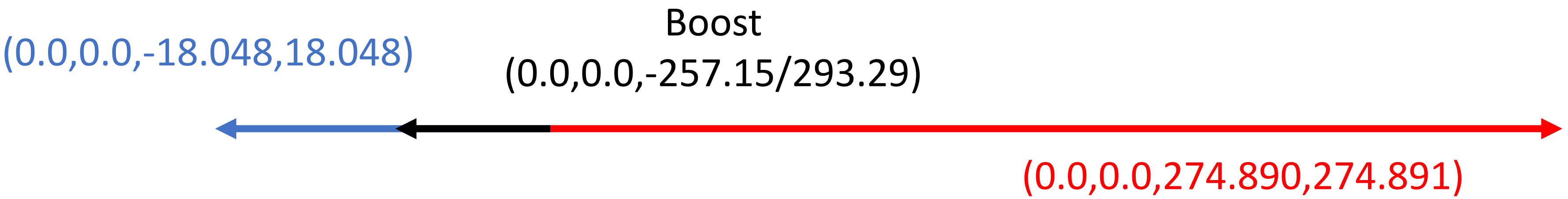
Head-On Frame Boost Procedure



1. Initial Configuration in the Lab Frame (beam momenta from a random event)
2. Boost by sum of beam 4-momenta to get to CM Frame
3. Rotate about y-axis to eliminate x-component of momentum

Head-On Frame Boost Procedure





1. Initial Configuration in the Lab Frame (beam momenta from a random event)
2. Boost by sum of beam 4-momenta to get to CM Frame
3. Rotate about y-axis to eliminate x-component of momentum
4. Rotate about x-axis to eliminate y-component of momentum (not shown)
5. Boost back along z to (nearly) restore original beam energies