Simulation of Beam Effects for the EIC

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EICUG Crossing Angle Task Force Meeting

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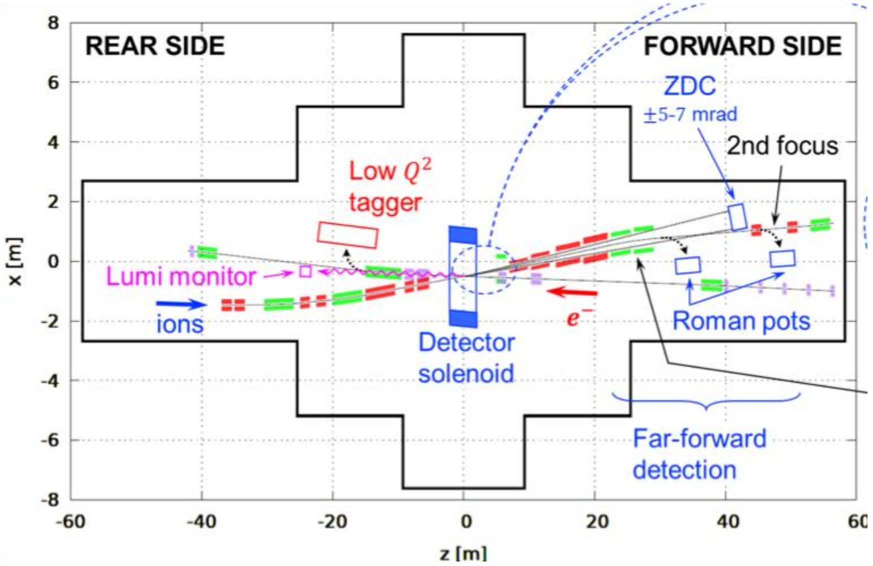
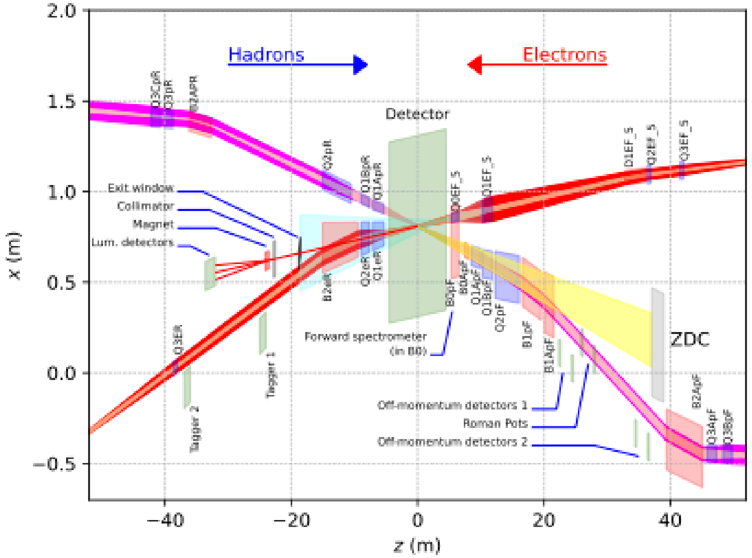




Intro and Motivation

- Both interaction regions at the EIC will feature significant beam crossing angles (25 mRad for IP6 and 35 mRad for IP8)
- Other effects such as intrinsic beam energy spread, beam divergence, and crabbing momentum kicks randomly change the momentum of the incoming beams
- The crossing angle and crab rotation also affect the position and time of the interaction vertex
- These beam effects will alter the kinematics of final state particles and position of the interaction vertex and need to be simulated accurately to assess the impact on physics measurements and detector design
- Two approaches have been developed: A generator agnostic After-burner 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 which simulates the interaction vertex position has also been implemented
- A technical note containing much more detail can be found at: https://eic.github.io/resources/simulations.html

Intro and Motivation

- This presentation will focus mostly on the PYTHIA-8 implementation, while also highlighting comparisons with the After-burner and vertex Transport model – Plots NC DIS with $Q^2 > 10\ GeV^2$

- The PYTHIA-8 implementation handles changes to:
  - Vertex position/time
  - Initial beam momenta
  - Final state particle kinematics

- Several effects are considered when determining alterations to the beam momenta:
  - Beam energy spread
  - Crossing angles in X and Y (100 microradian tilt of ESR in Y)
  - Angular divergence
  - Momentum kicks from crabbing

- All beam parameters used to determine the size of the effects are taken from the CDR (use the high-divergence settings in table 3.3 for this study)

PYTHIA-8 Vertex Model

- Determine the x, y, and z vertex of the collision along with the time of collision

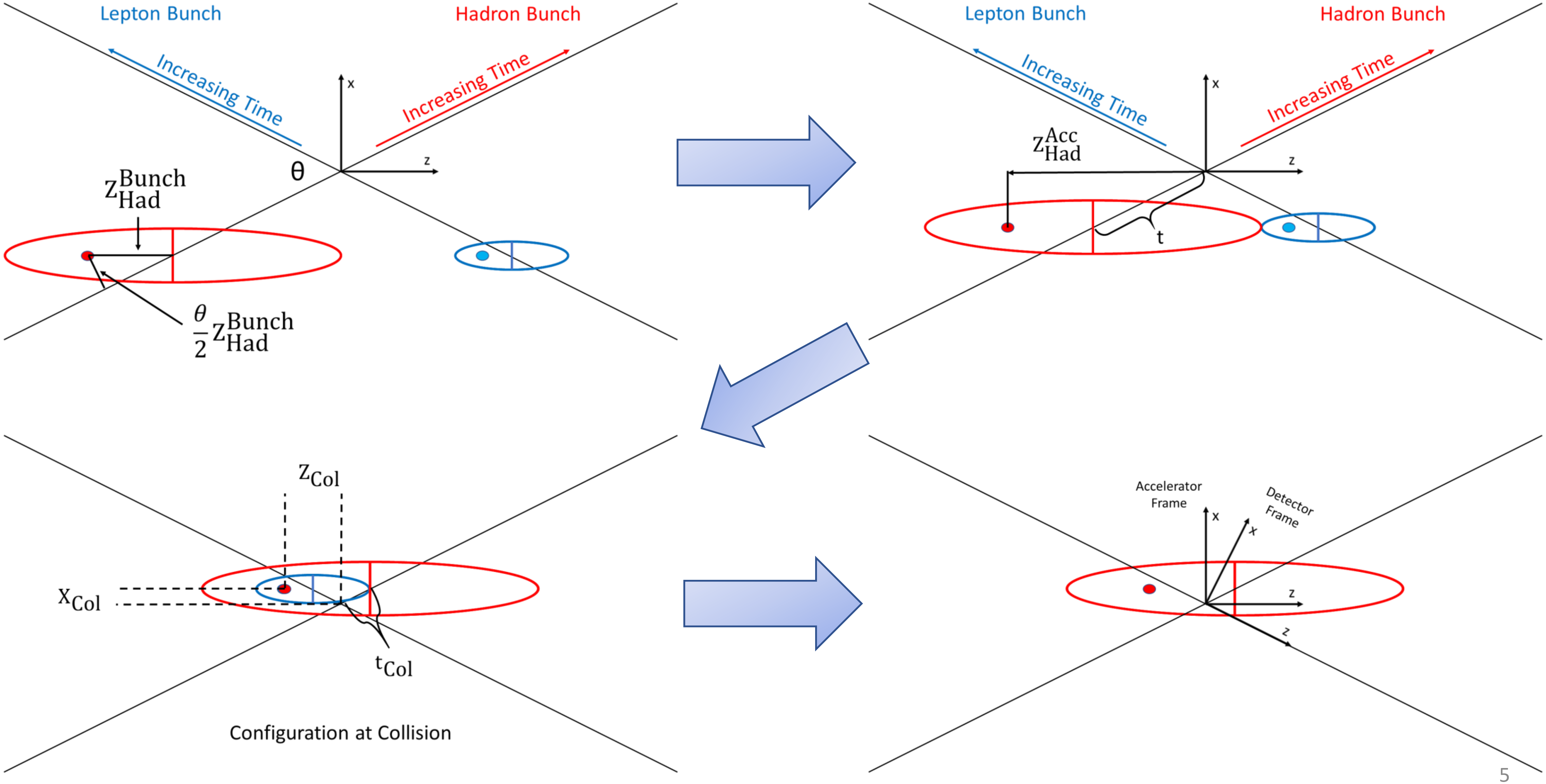
- Assume each bunch is rotated through half the beam crossing angle and assume it stays in a fixed orientation throughout the colliding region

- 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



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

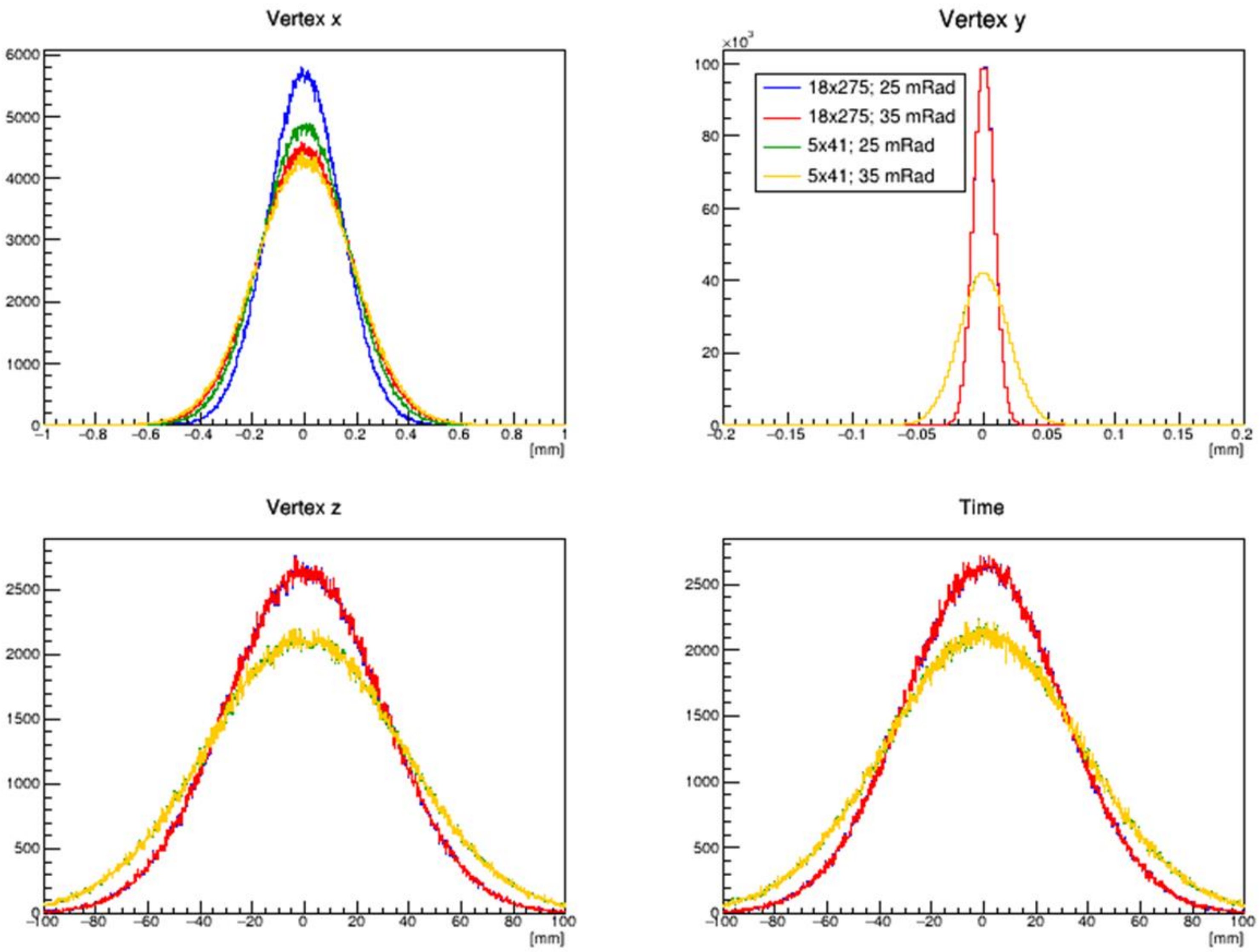
Collisioin occurs when Z_Had and Z_Lep are equal – can then solve the system to get time, z-position, and x-position of collision

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

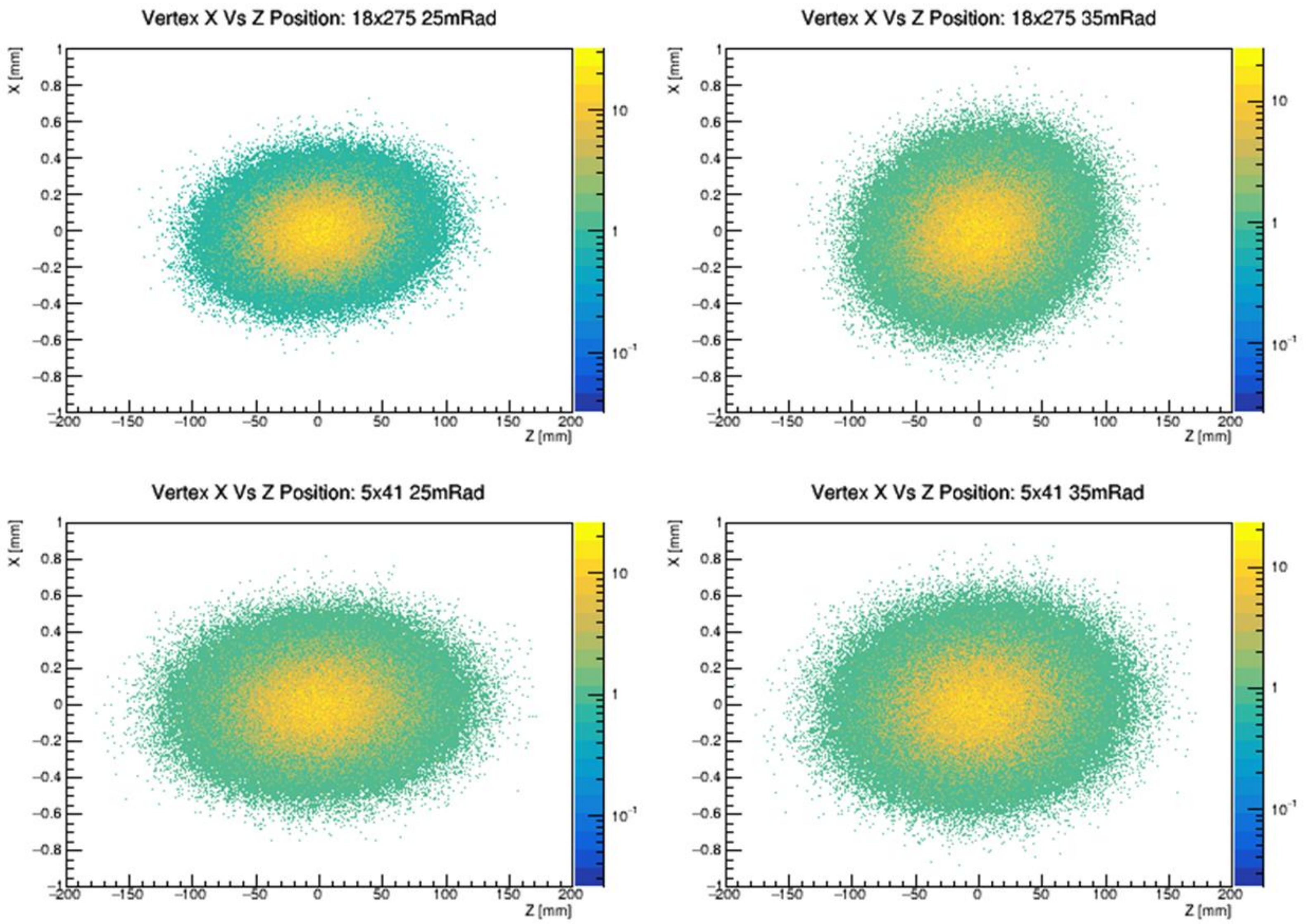
$$z_{\text{Col}} = \frac{\left(z_{\text{Lep}}^{\text{Bunch}} + z_{\text{Had}}^{\text{Bunch}}\right)}{2}$$

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

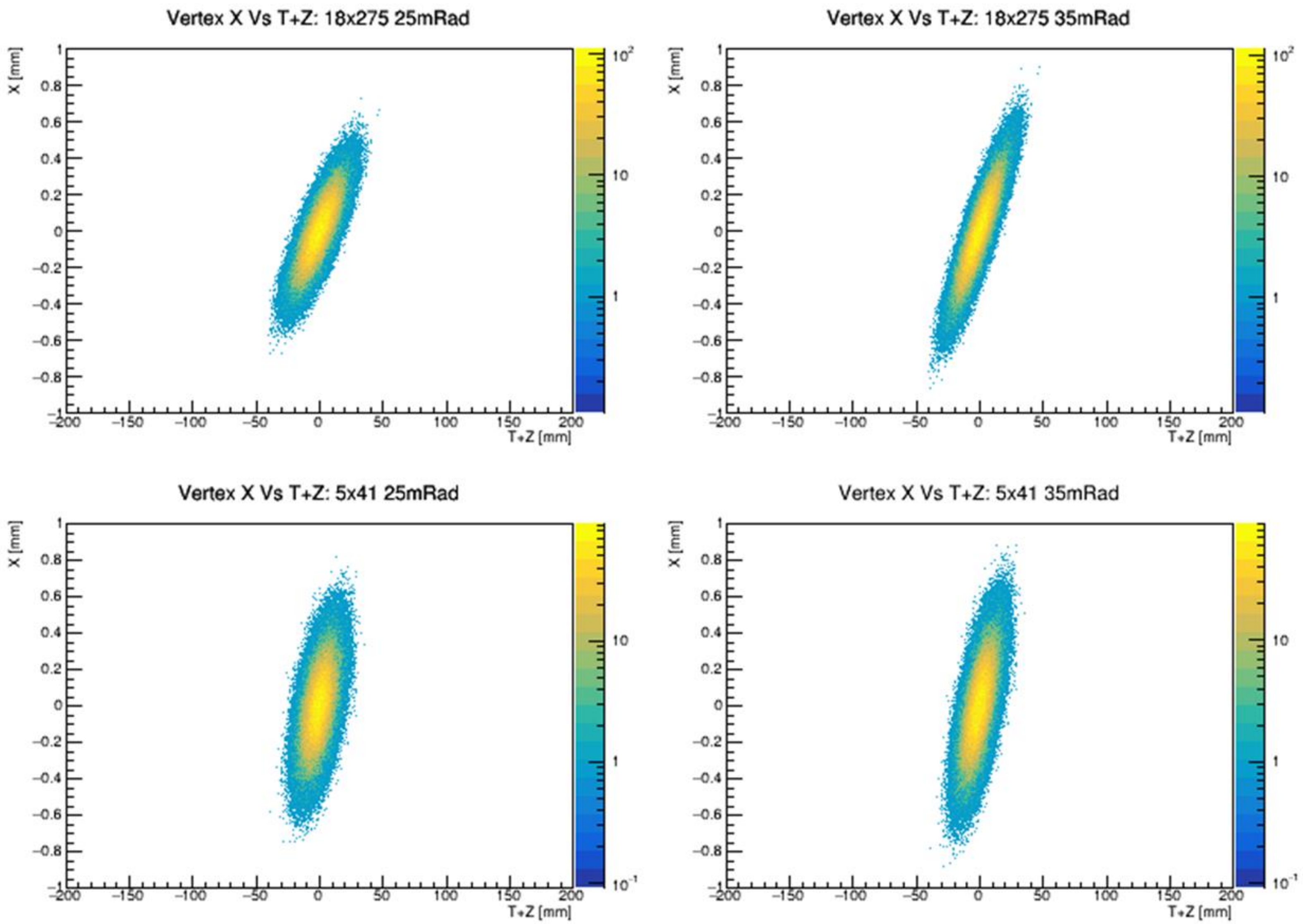
PYTHIA-8 Vertex Distributions



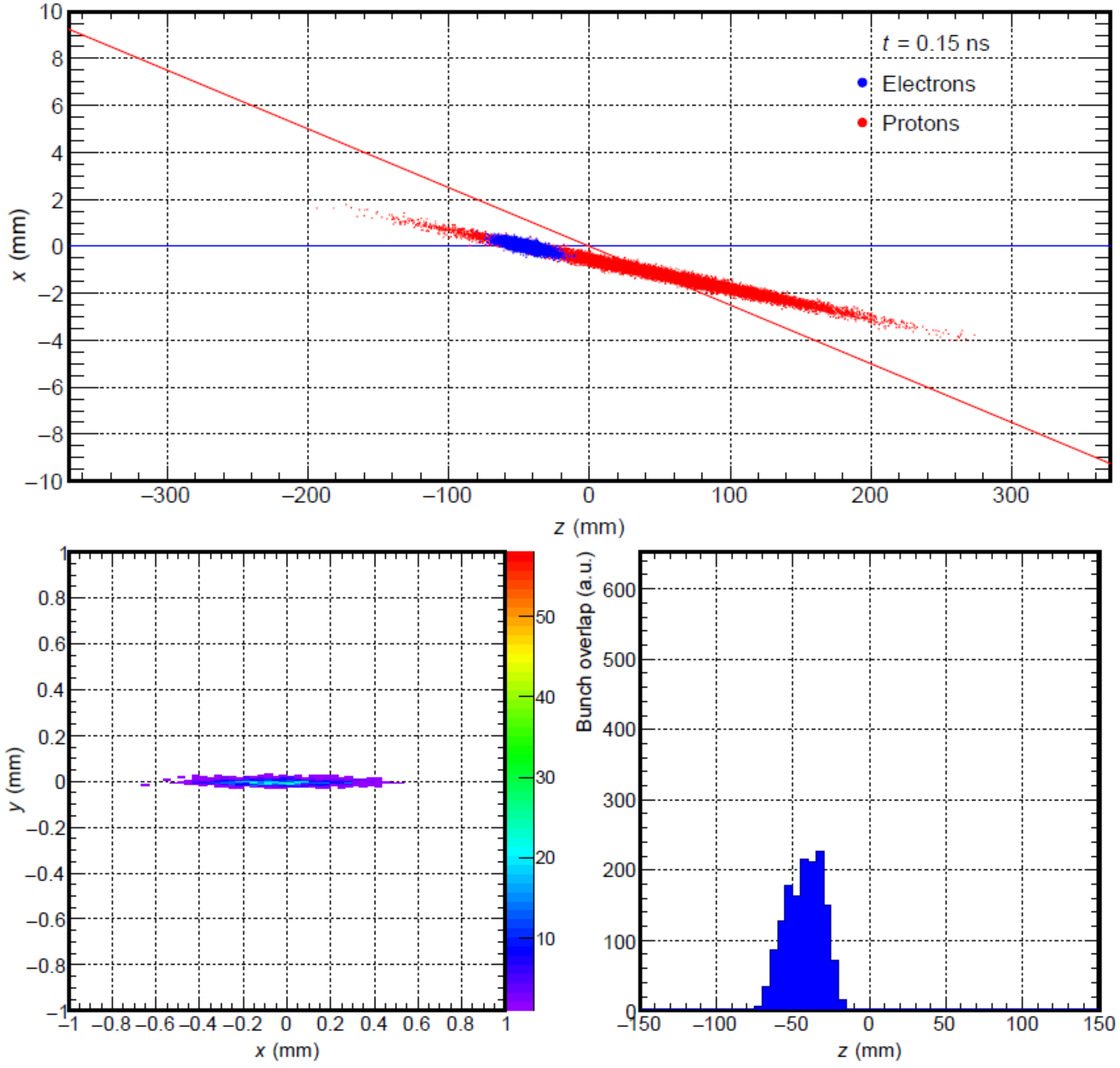
PYTHIA-8 Vertex Correlations (X Vs Z)



PYTHIA-8 Vertex Correlations – Add Timing



Transport Model Vertex

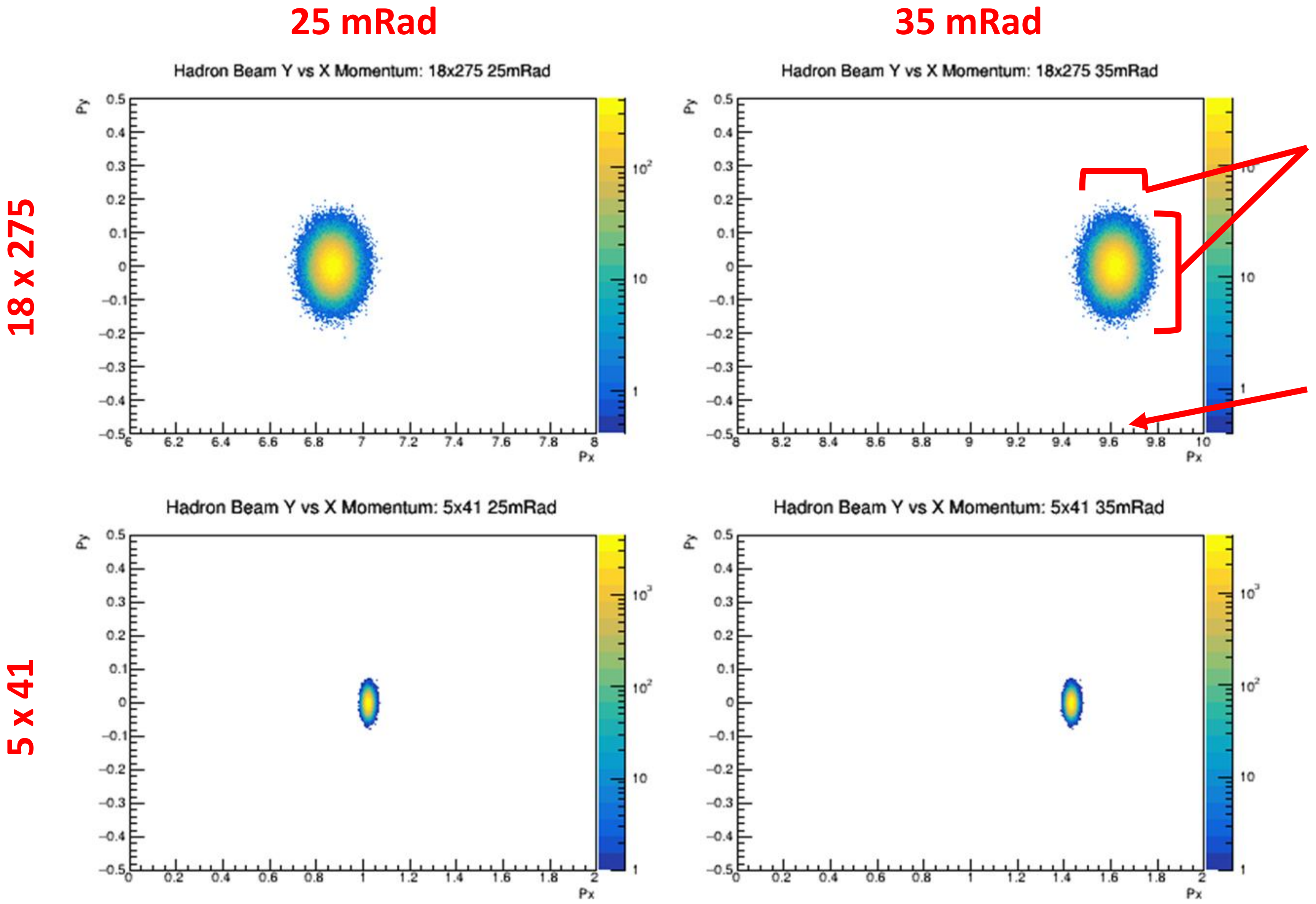


Developed by Jaroslav Adam – movie available at:
https://eic.github.io/resources/simulations.html

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.

Hadron Beam Momentum Distributions – Y Vs X



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

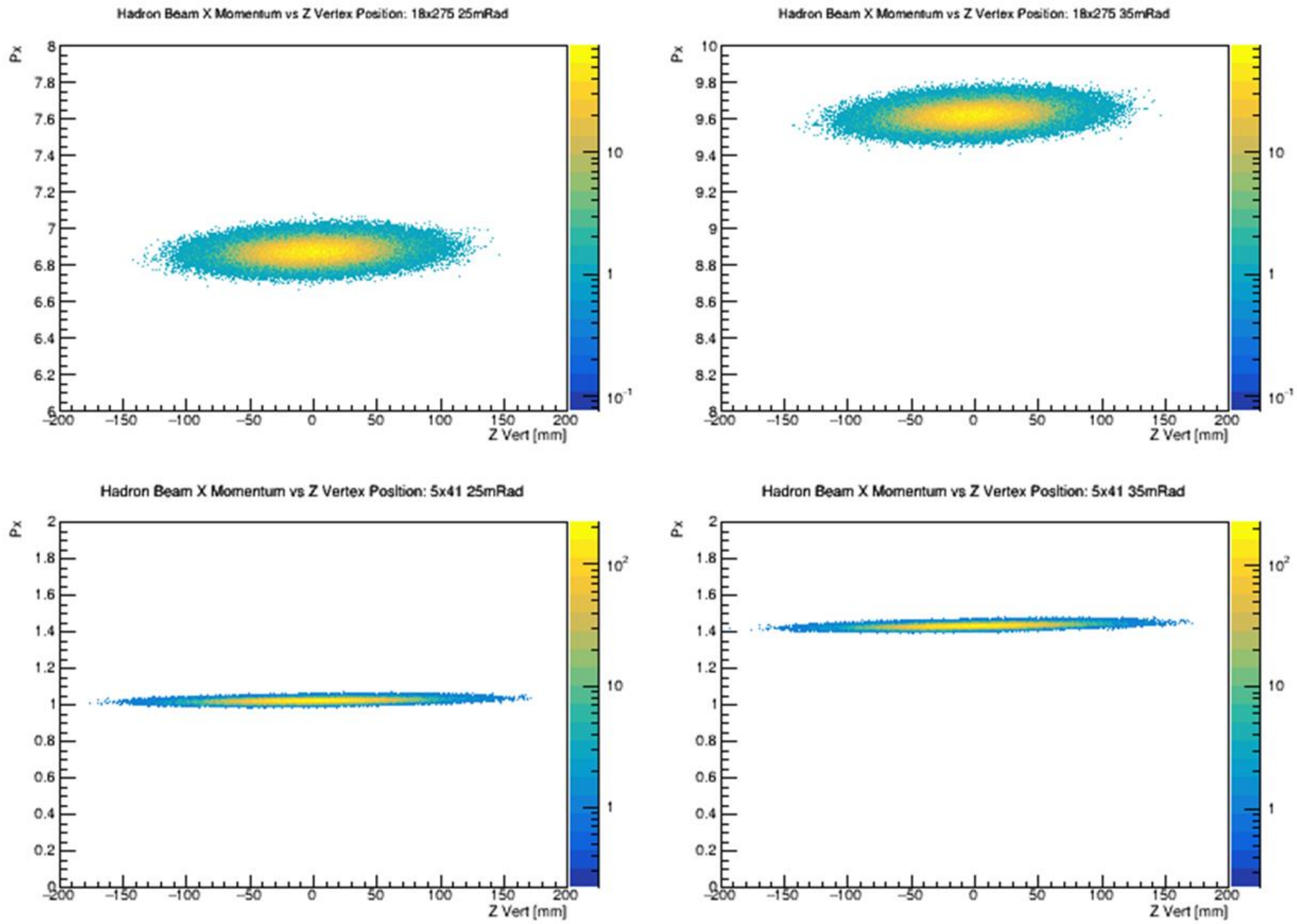
Smaller momentum deviations for 5x41 driven by lower hadron beam energy

Momentum Distributions – X Vs Z-Vertex

25 mRad | **35 mRad**

18 x 275

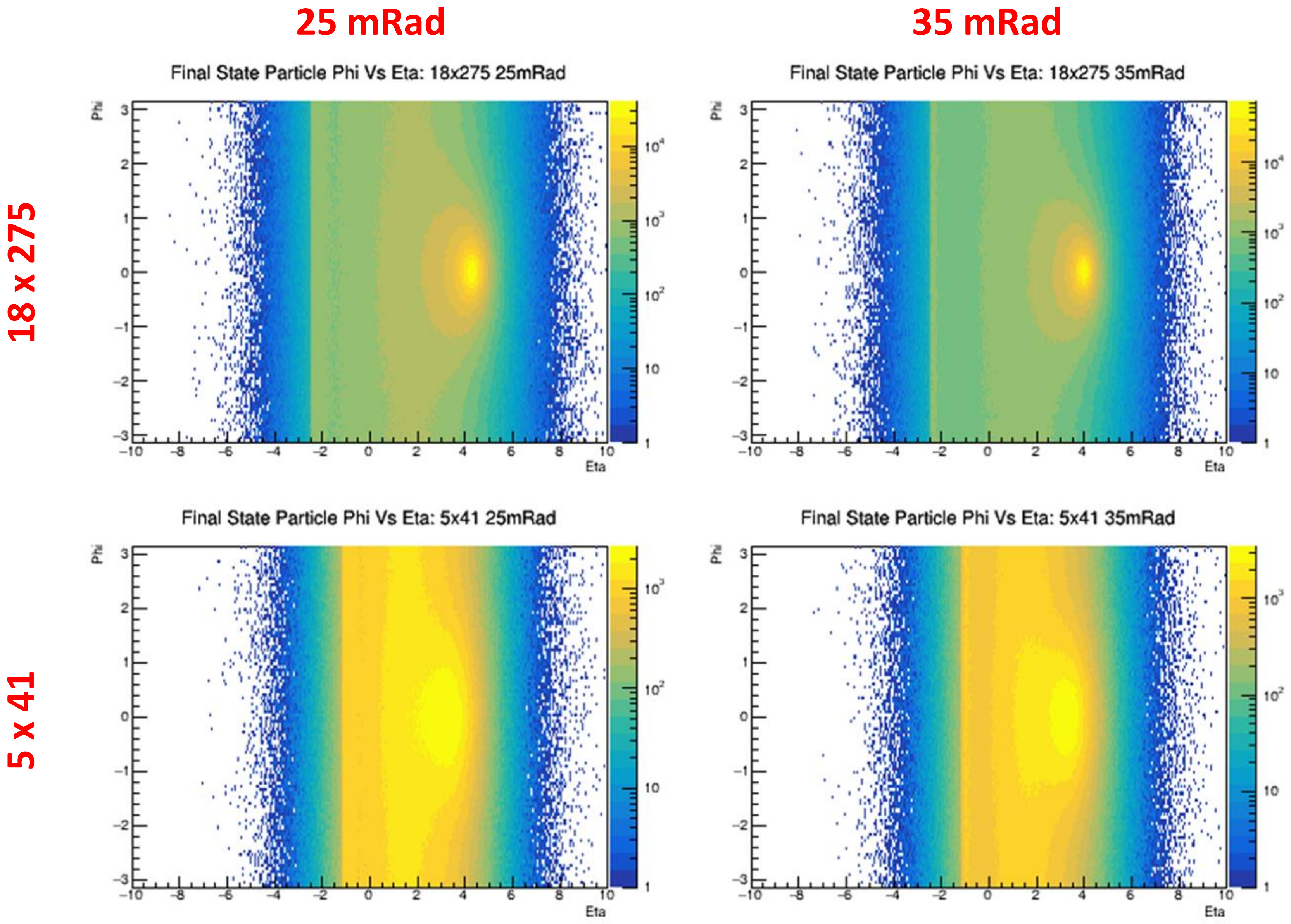
5 x 41



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

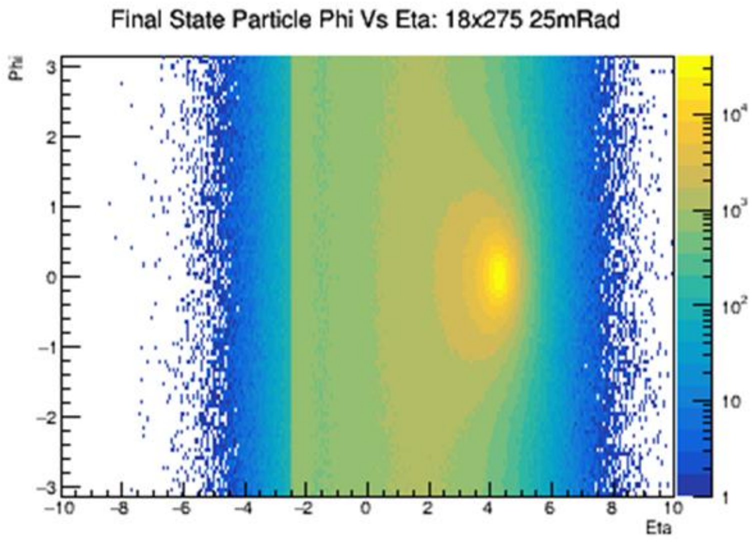


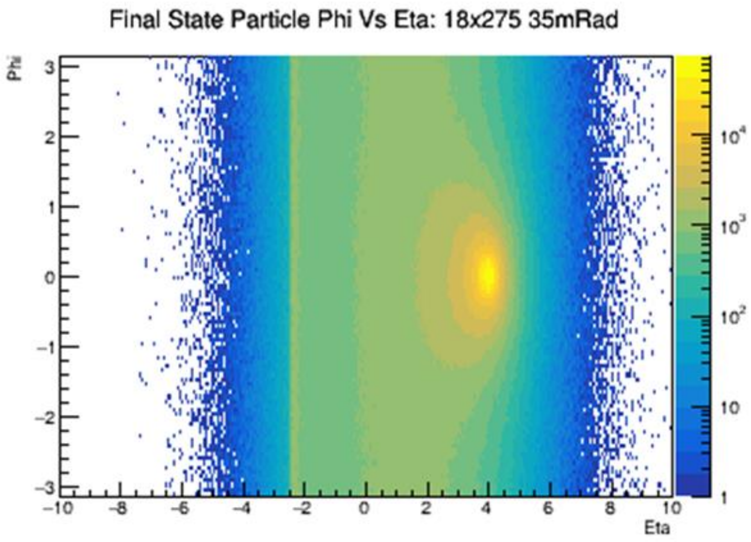
- Crossing angle results in a concentration of final state particles in the direction of the beam
- For most relativistic beams, particle concentrations sit at beam rapidity – 25 milliradians = pseudorapidity of ~4.3
- Particle distributions opposite the hadron going direction are unaffected

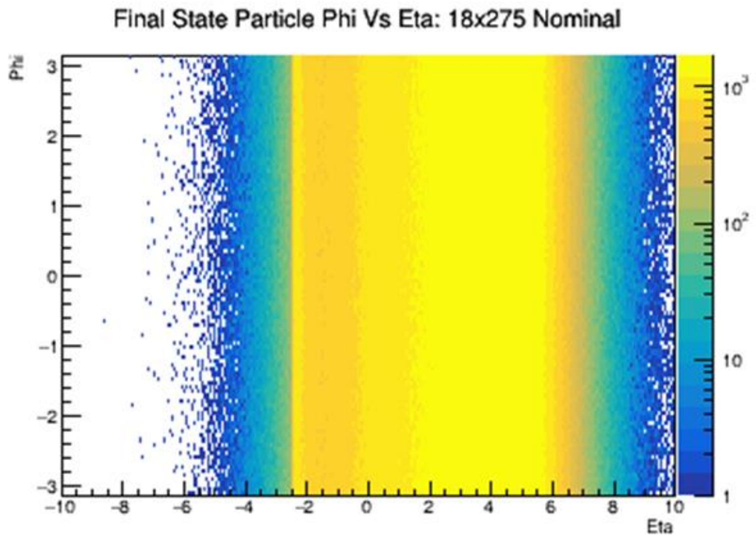
Final State Phi Vs Eta

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

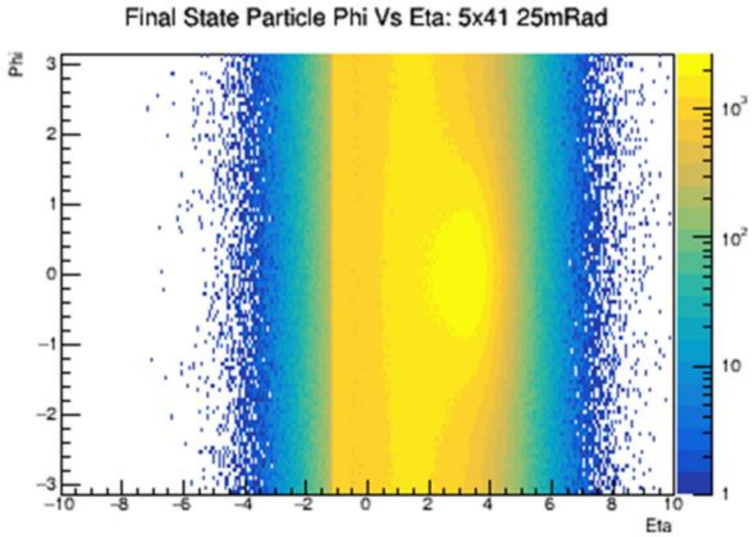
18 x 275

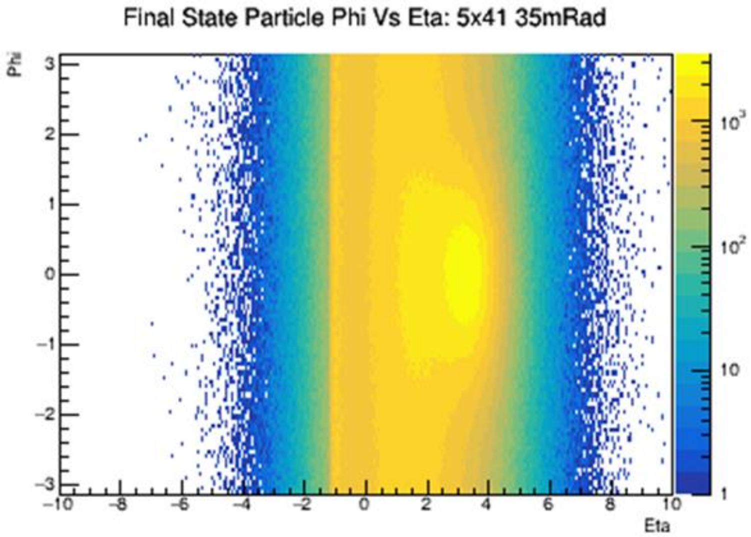


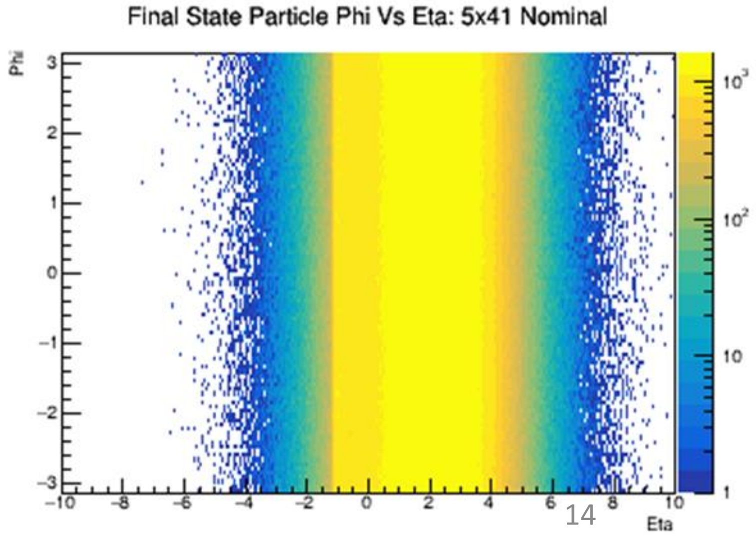




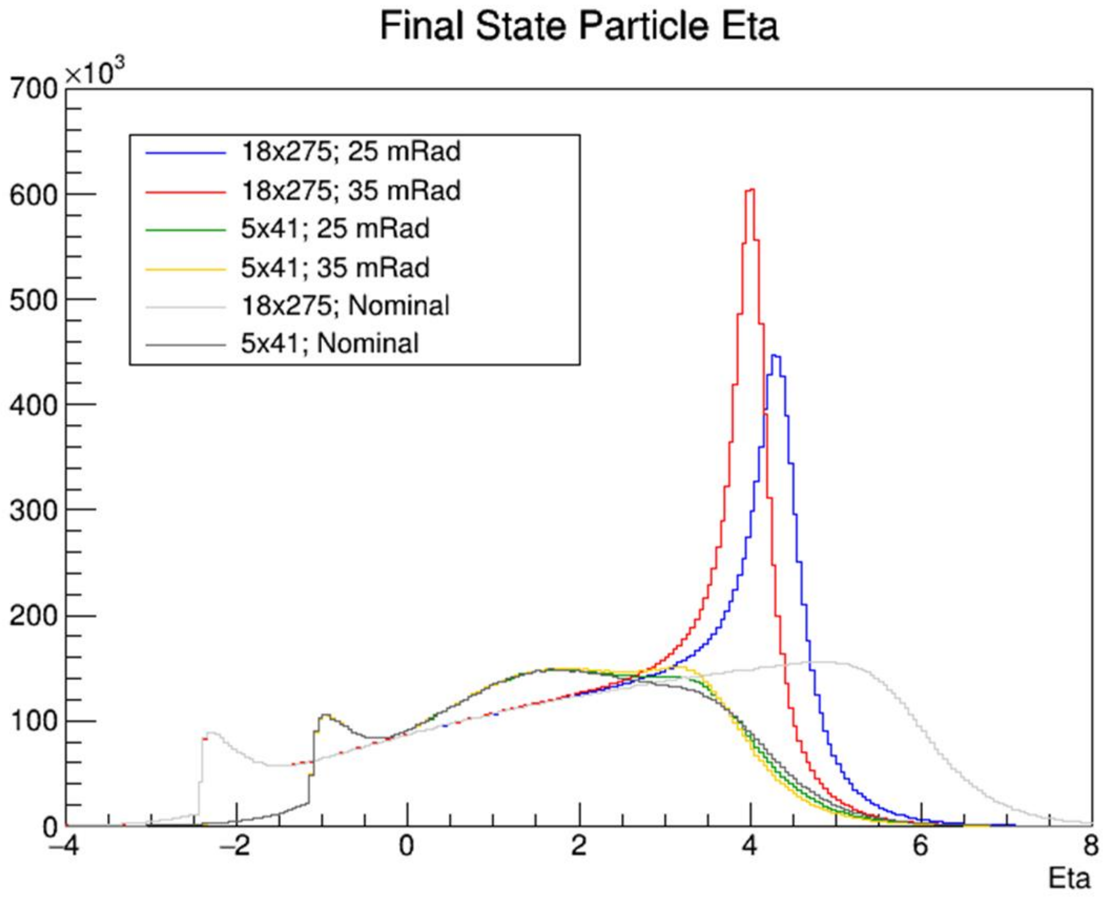
5 x 41

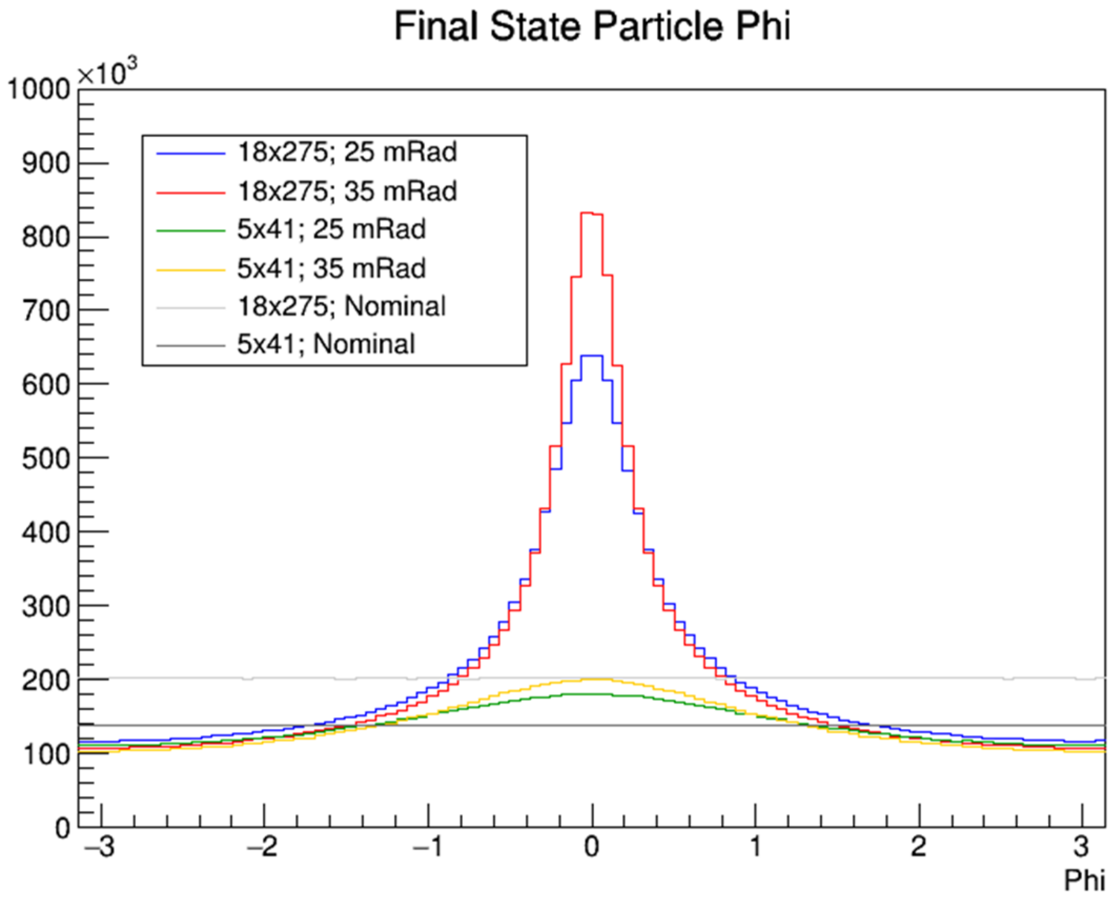






Final State Phi & Eta



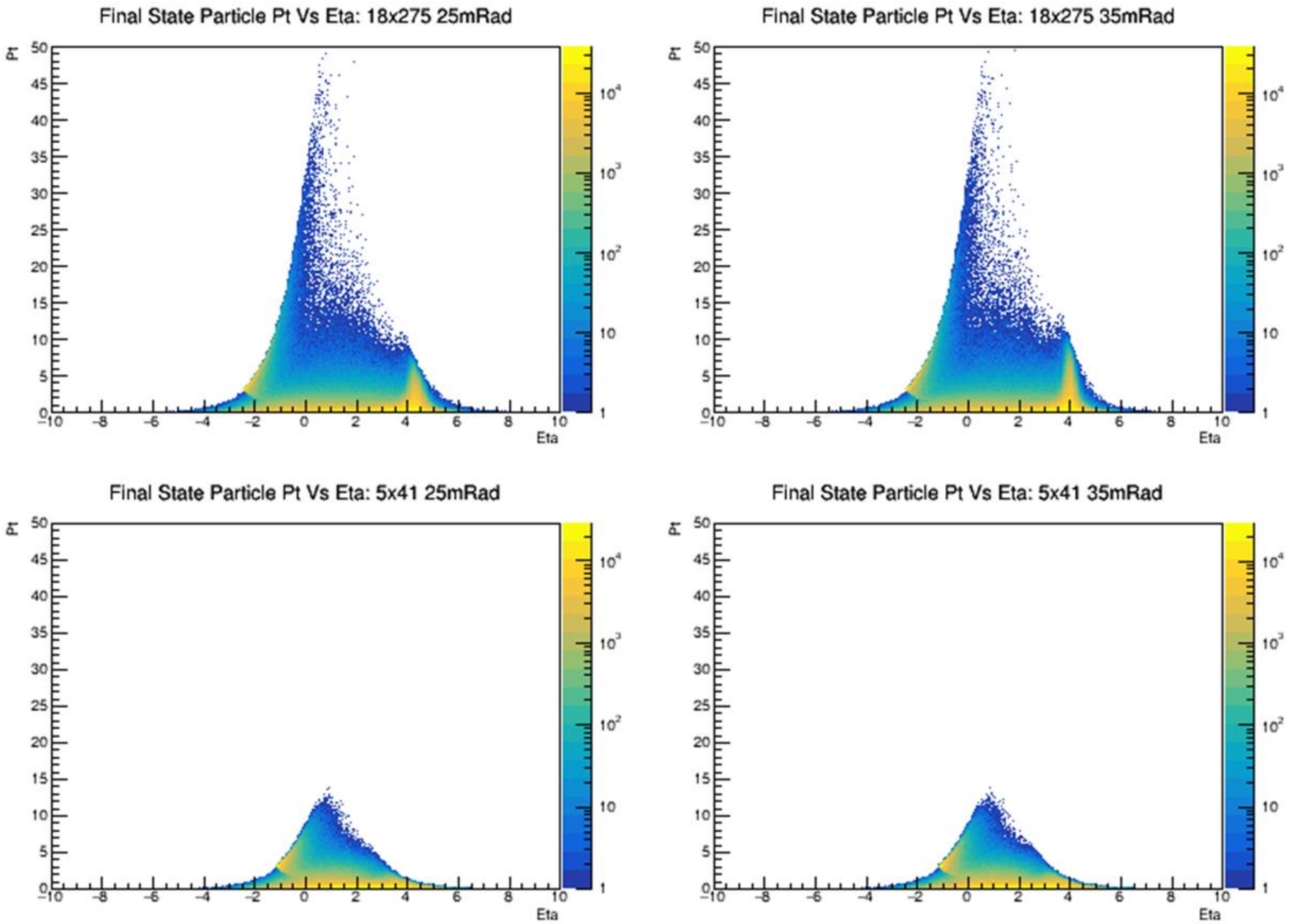


Final State P_T Vs Eta

25 mRad **35 mRad**

18 x 275

5 x 41

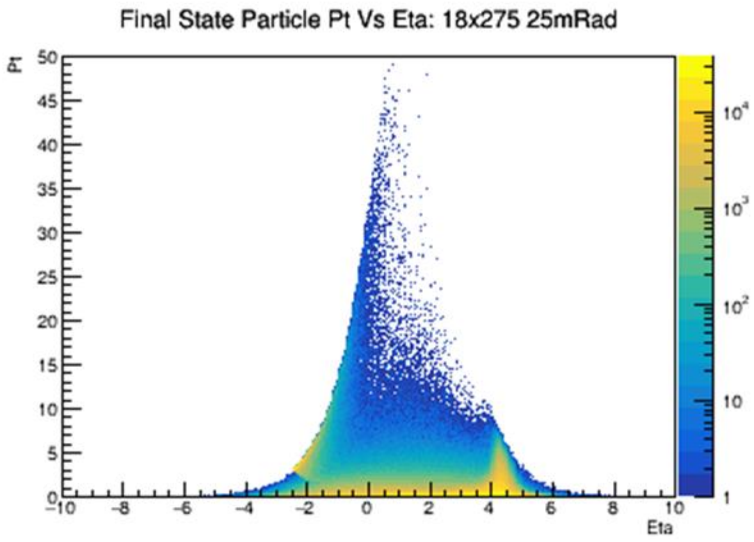


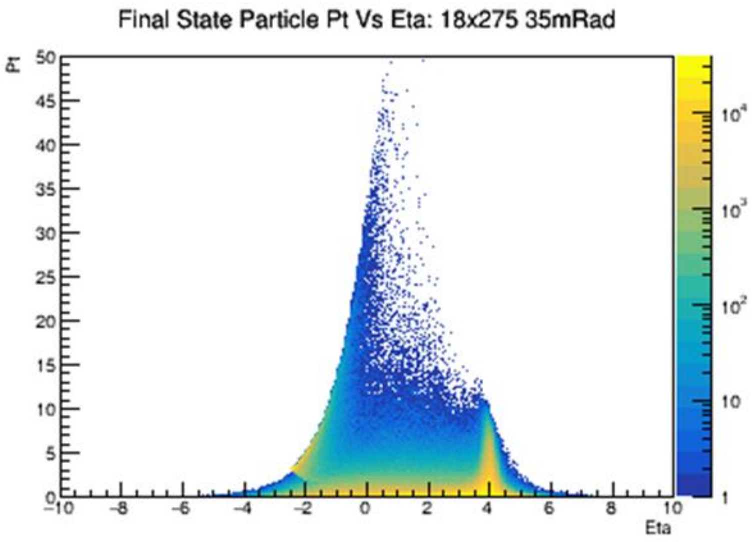
- Particles that are boosted into the peaks are also pushed to higher transverse momenta
- This is most visible for higher hadron beam momenta and a very minor effect for the lowest beam energy
- Particle distributions at backward rapidities are from the scattered beam electron which was not excluded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

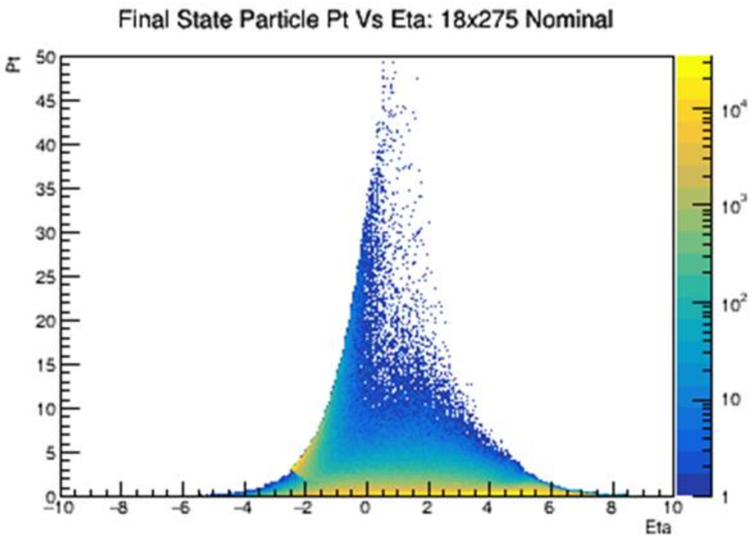
Final State P_T Vs Eta

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

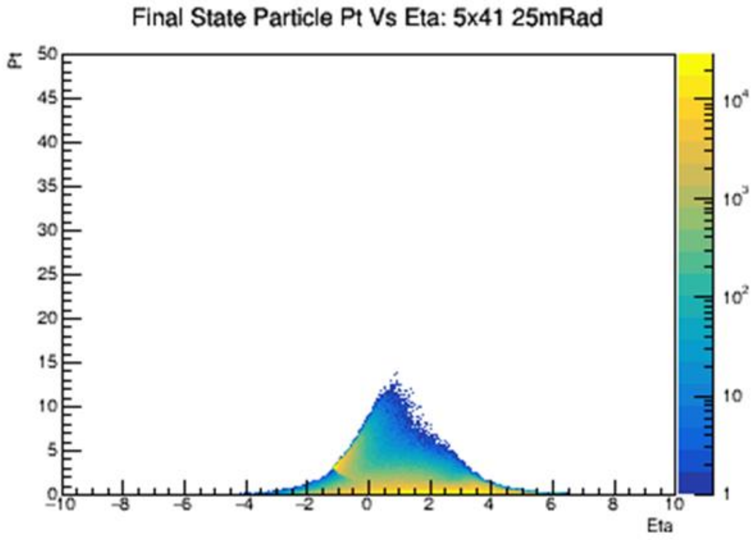
18 x 275

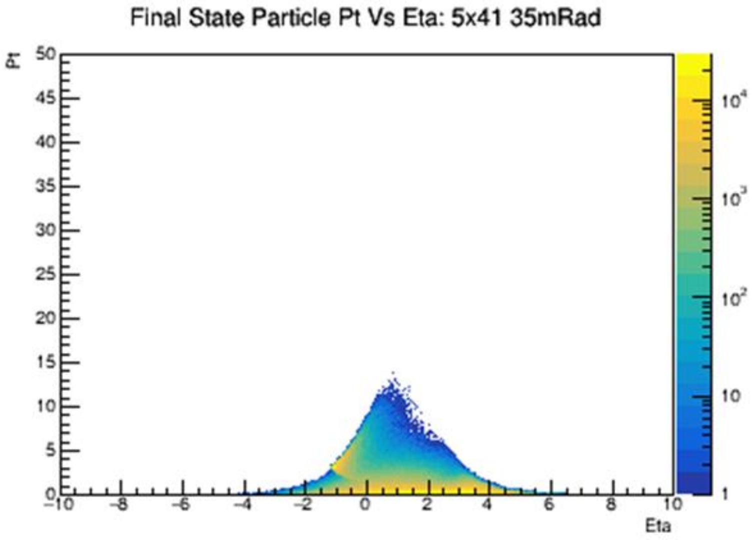


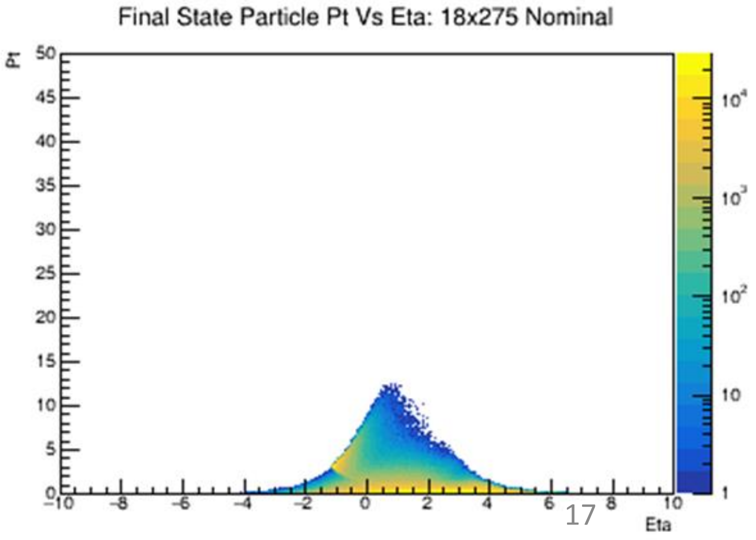




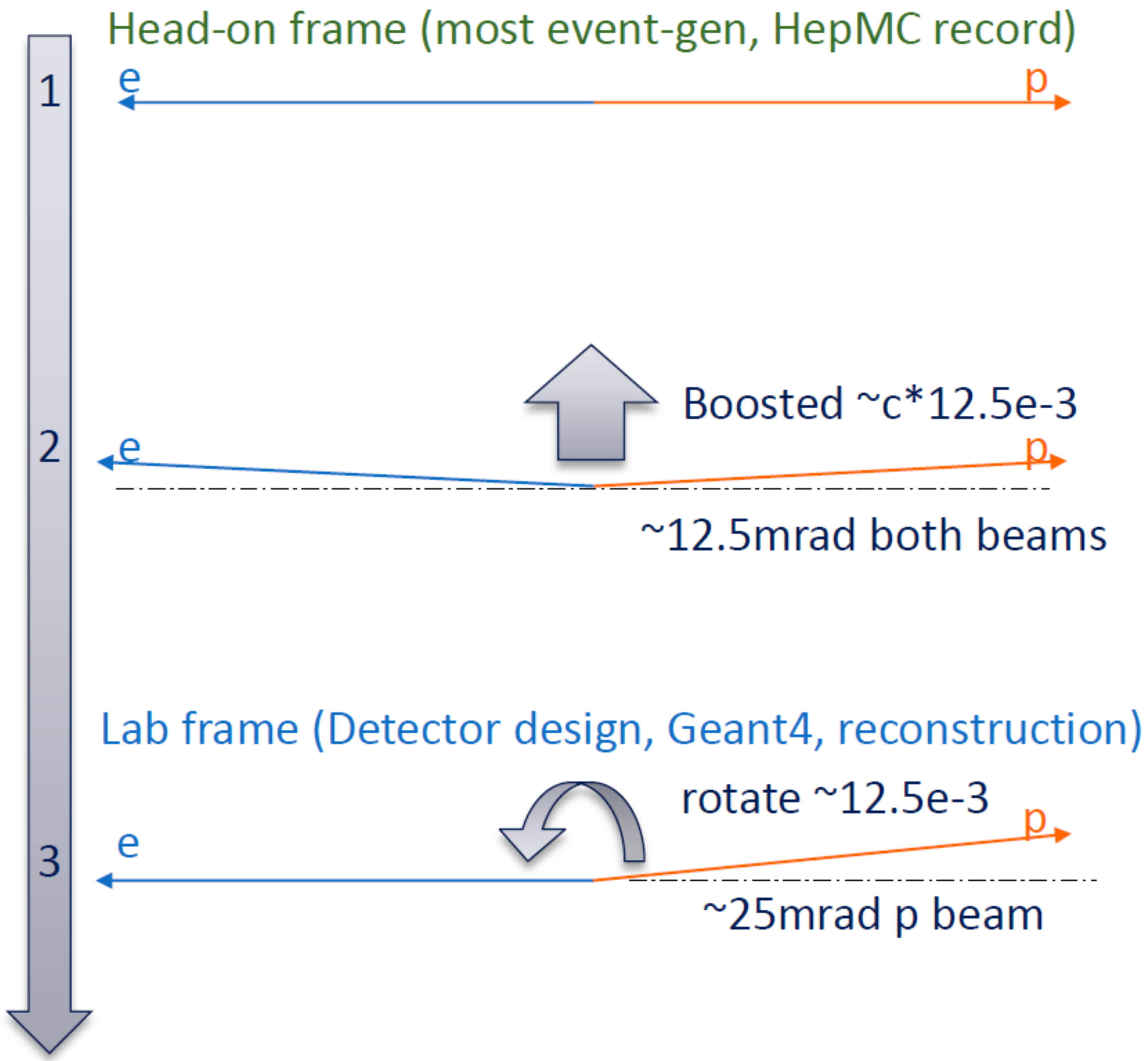
5 x 41







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.

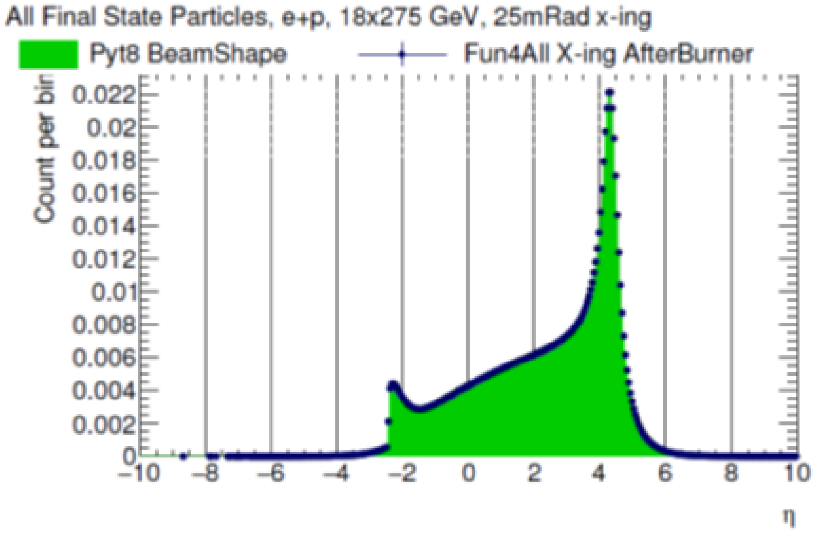
2. The head-on frame is first boosted sideways, perpendicular to the head-on colliding beam, and towards the beam crossing direction. The amplitude of the boost is $ctan(\theta_{CA}/2)$, if ignoring the beam divergence and crab-cavity kick. In the presence of these variations, the final boost direction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

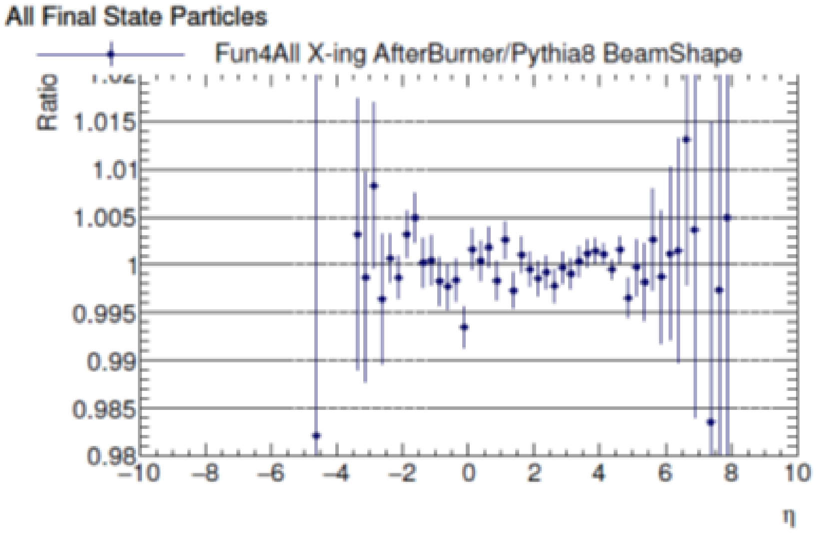
   - Note for relativistic beams, this boost is independent of the beam energy, which dramatically simplified the implementation.
   - Please also note the beam energy is not Lorentz invariant. This choice of the boost vector induces minimal changes in the beam energies of both beams between the two frames,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

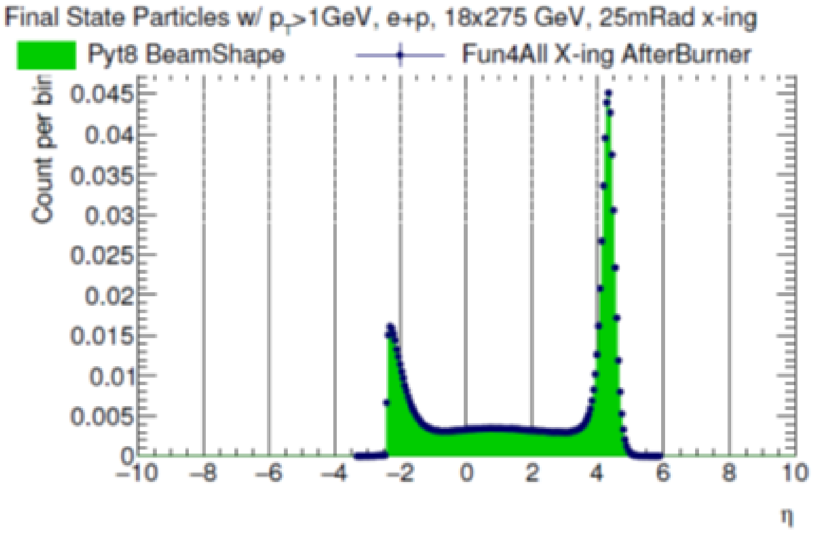
$$E_{\text{lab}} = E_{\text{head-on}}/cos(\theta_{CA}/2)$$

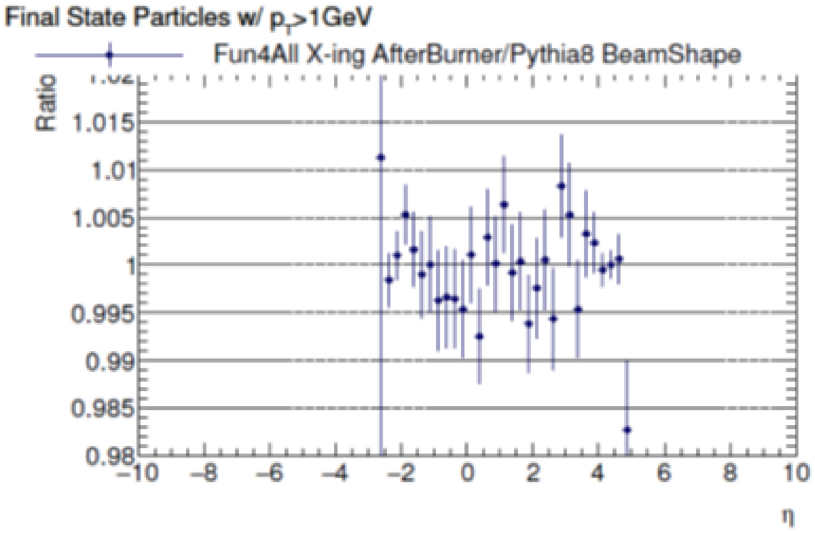
3. In the last step, a simple rotation of $\theta_{CA}/2$ around the vertical axis aligns the electron beam back to the $-z$ axis, which leaves the proton beam with the intended crossing angle of θ_{CA}. In the presence of the beam divergence and crab-cavity kick, the final rotation angle is $arccos(-\hat{p}_p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

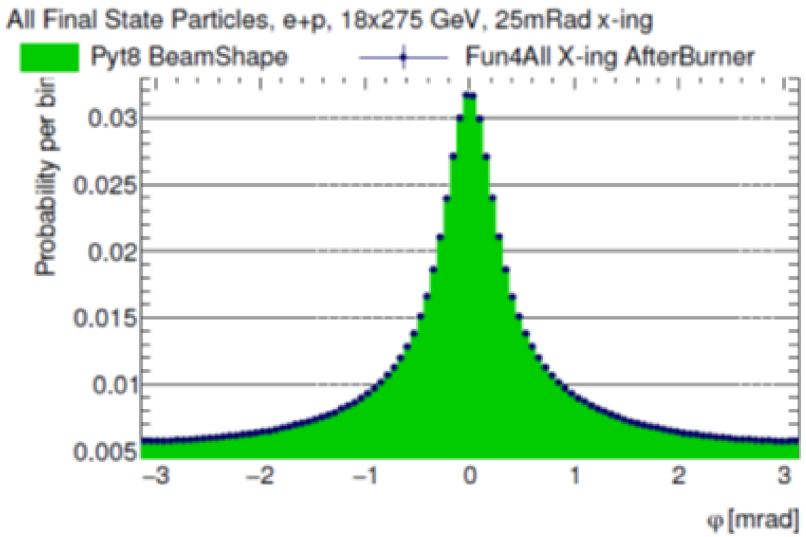


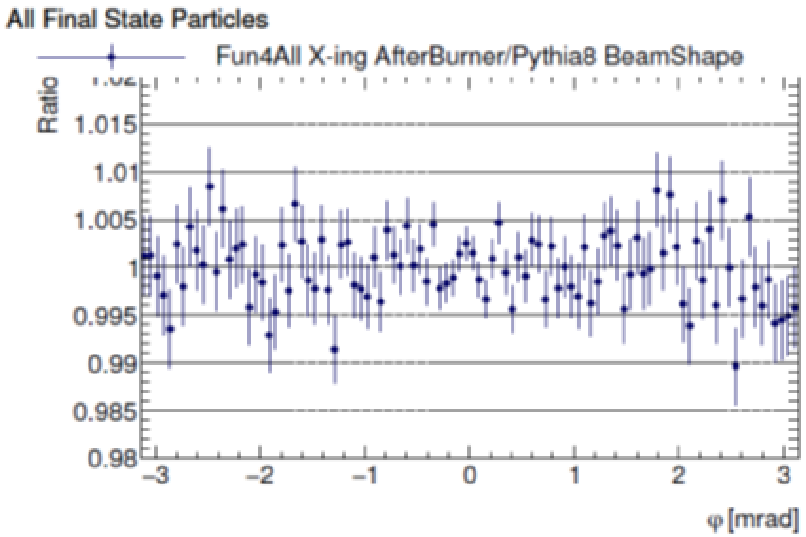


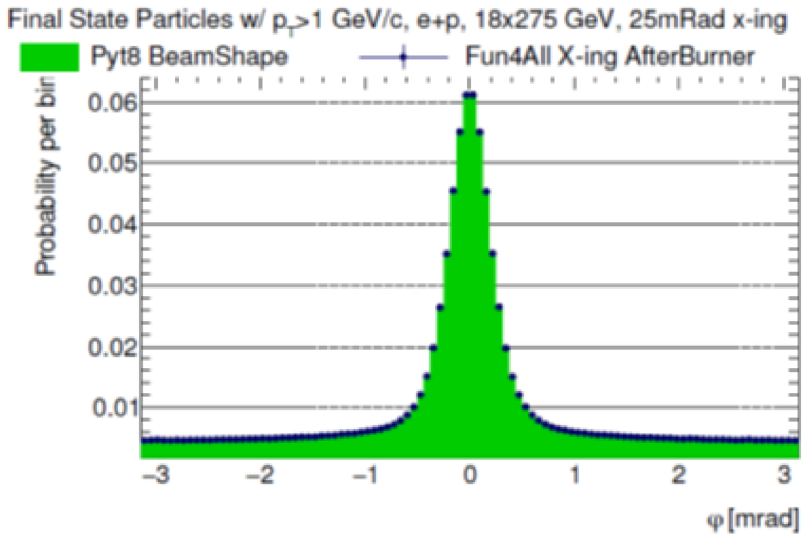


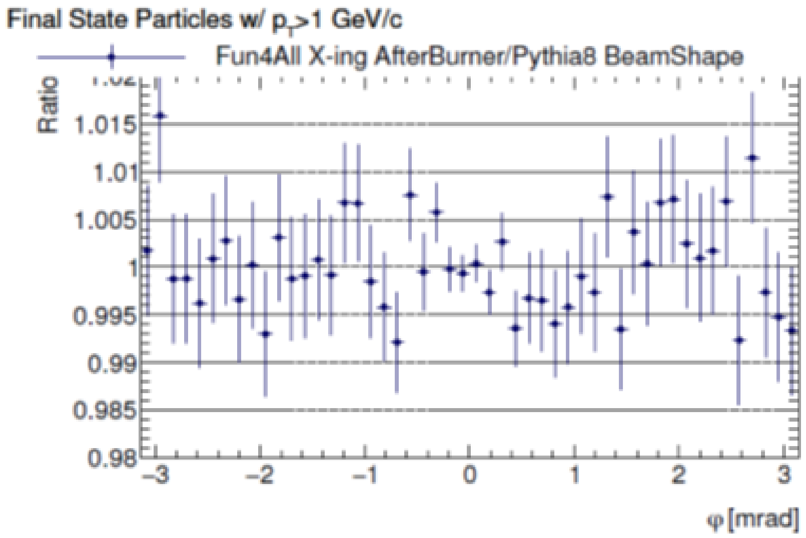


Pythia-8 Vs After-burner Comparison (Eta)









Summary

- Impact of crossing angle, beam divergence, beam energy spread, and crabbing on beam momentum, vertex, and final state particle distributions shown
- Displayed limiting cases of 18x275 and 5x41 beam energies for 25 and 35 mRad crossing angles
- Crossing angle will have large impact on distribution and momentum of final state particles in the central detector – needs to be taken into account in all analyses
- Comparisons between PYTHIA-8 and After-burner implementations show excellent agreement. Good agreement also seen between PYTHIA-8 and Transport model vertex distributions
- Detailed technical note is available to all EIC Proto-Collaborations and code is ready to be used

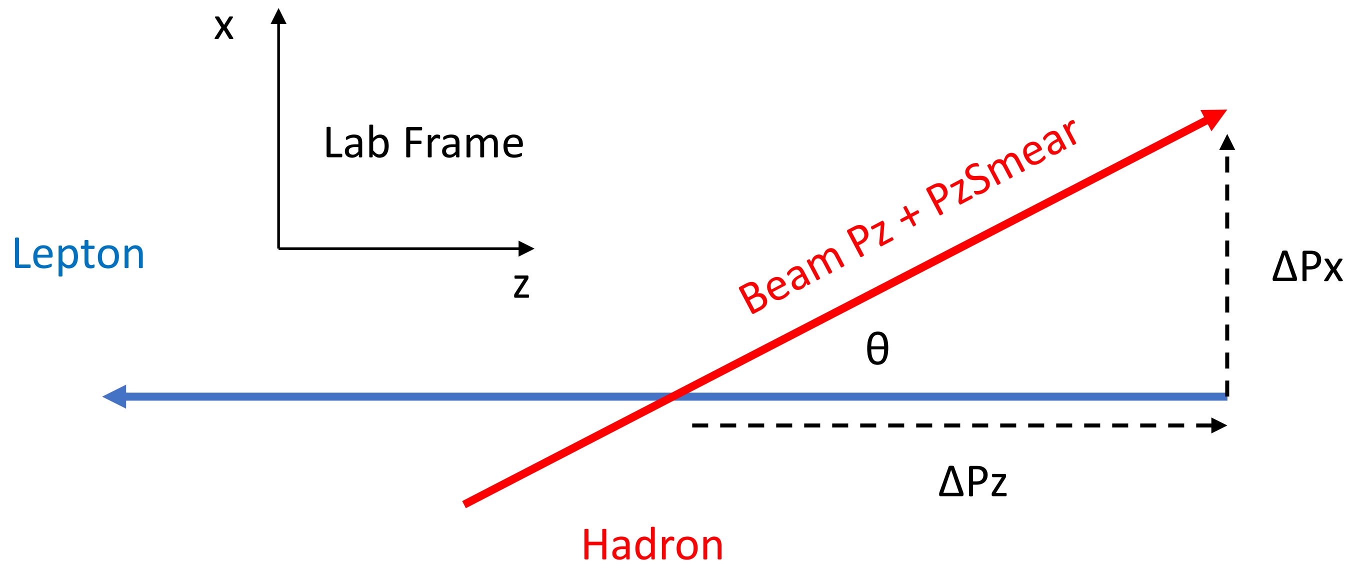
Backup Slides

Energy (Pz) Variation

- Pythia BeamShape class allows variation in z-component of beam momentum (assume change is small enough that physics processes or cross sections do not appreciably change)
- ΔPz = (Beam Pz)*sigma*randomGauss
- Sigma is taken from tables 3.3 and 3.4 in the CDR with ΔP/P on the order of 10^{-4} to 10^{-3}, depending on beam energy

Crossing Angle

- ❑ The lepton and hadron beams will cross at an angle (use 25 milliradian) w.r.t each other
- ❑ Take lepton beam as z-axis as it will align with the center of the detector and apply momentum modifications to hadron beam only
- ❑ Assume crossing angle imparts momentum kick only in x (horizontal) direction
- ❑ ΔPx = (Beam Pz + PzSmear)*Sin(Crossing Angle)
- ❑ ΔPz = (Beam Pz + PzSmear)*Cos(Crossing Angle) – (Beam Pz)   (Here PzSmear is Pz variation of the beam)



Beam Divergence

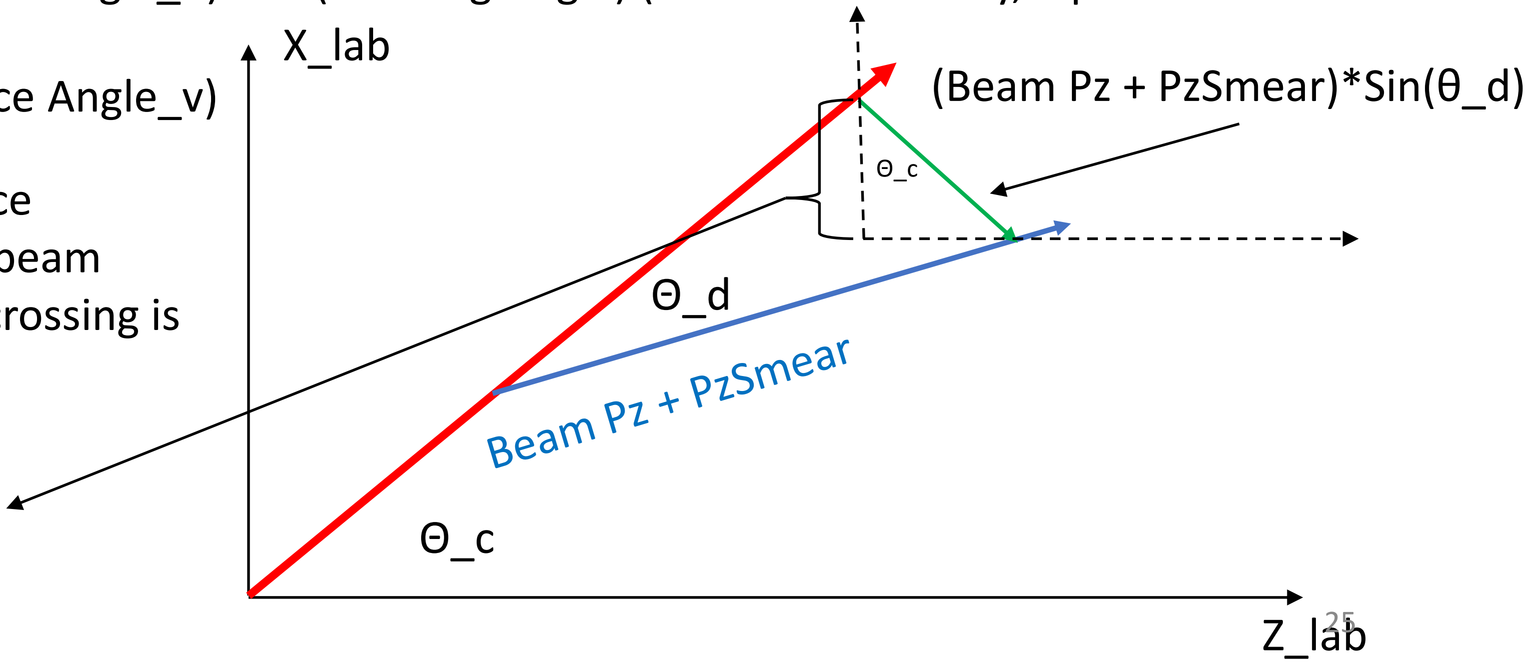
- Will get transverse momentum kicks from beam angular divergence in horizontal and vertical directions

- Use angular divergence ($\Delta\theta$) from table 3.3 in CDR: h/v 150/150 (Hadron) and 202/187 (Lepton)

- Assume that momentum kicks in the horizontal and vertical direction are with respect to the beam. The beam will be rotated in the x direction due to the crossing angle – need to translate transverse momentum kick in horizontal direction into lab frame

- ΔPx += (Beam Pz + PzSmear)*Sin(Divergence Angle_h)*Cos(Crossing Angle) (Hadron Beam only, lepton beam has no xing angle)
- ΔPy += (Beam Pz + PzSmear)*Sin(Divergence Angle_v)

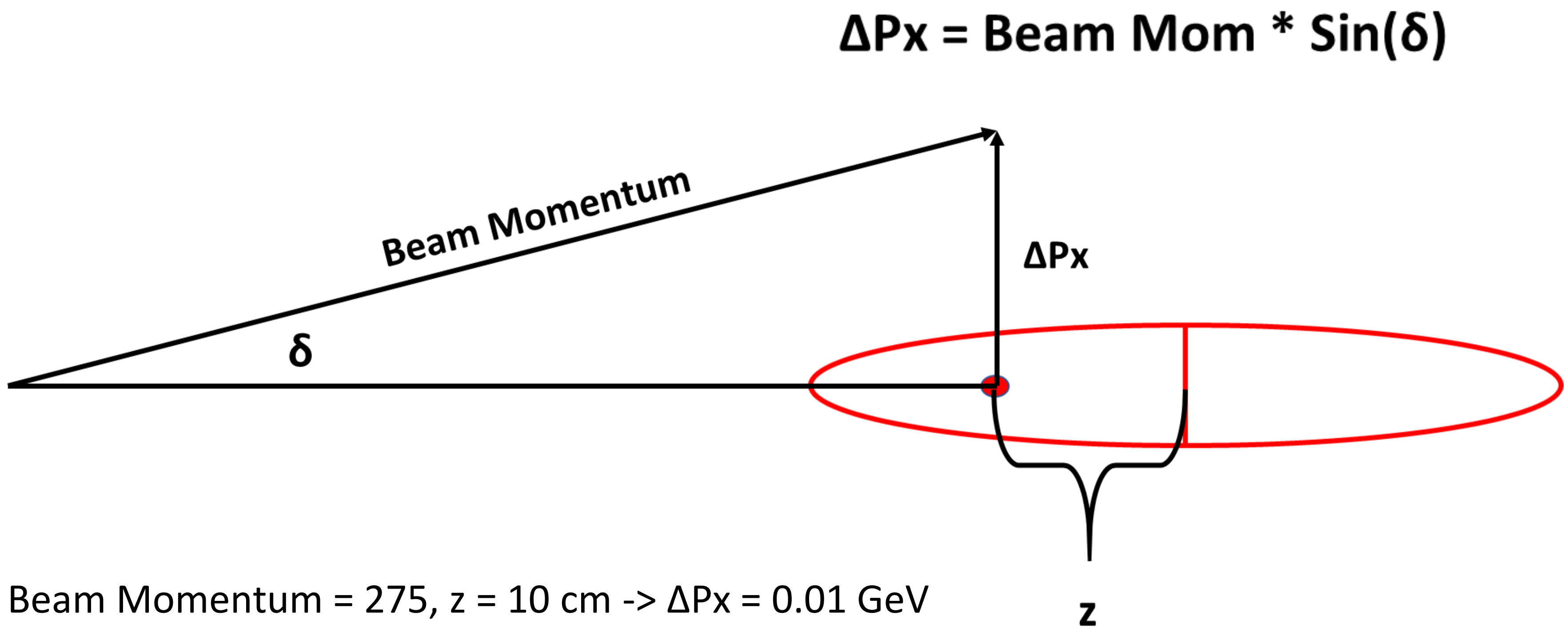
- ΔPz += (Beam Pz + PzSmear)*Sin(Divergence Angle_h)*Sin(Crossing Angle) (For hadron beam only; for horizontal (x) divergence only as crossing is purely in x direction)



Crabbing Effects on Beam Momentum

- Crabbing rotation will impart momentum kicks along the x-direction to particles within the bunch
- The size of this kick will depend on the z-position of the particle within its bunch

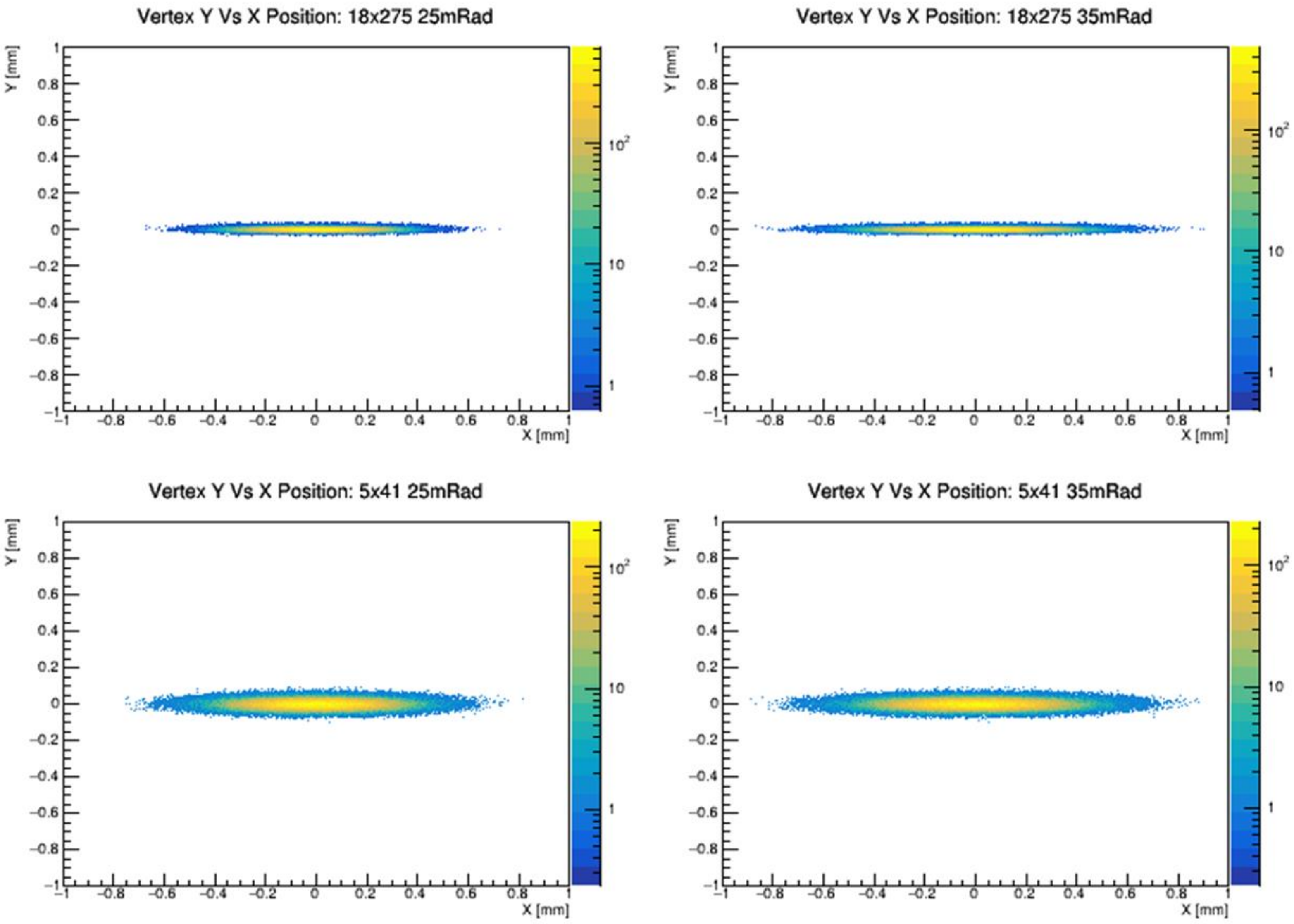
$$\delta = \frac{\frac{\theta_c}{2} z}{\sqrt{\beta_{crab}\beta^*}}$$



For Beam Momentum = 275, z = 10 cm -> ΔPx = 0.01 GeV

Rotate this into detector frame: ΔPx` = ΔPx*Cos(θ/2) and ΔPz` = -ΔPx*Sin(θ/2)

Vertex Distributions: Y vs X Interaction Vertex Position



Relevant Beam 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