EIC beam effect in simulation afterburner

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Special thanks to discussion and inputs from Aschenauer Elke-Caroline, Rolf Ent, Yulia Furletova, Alexander Jentsch, Diefenthaler Markus, Brian Page

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https://eic.github.io/resources/simulations.html

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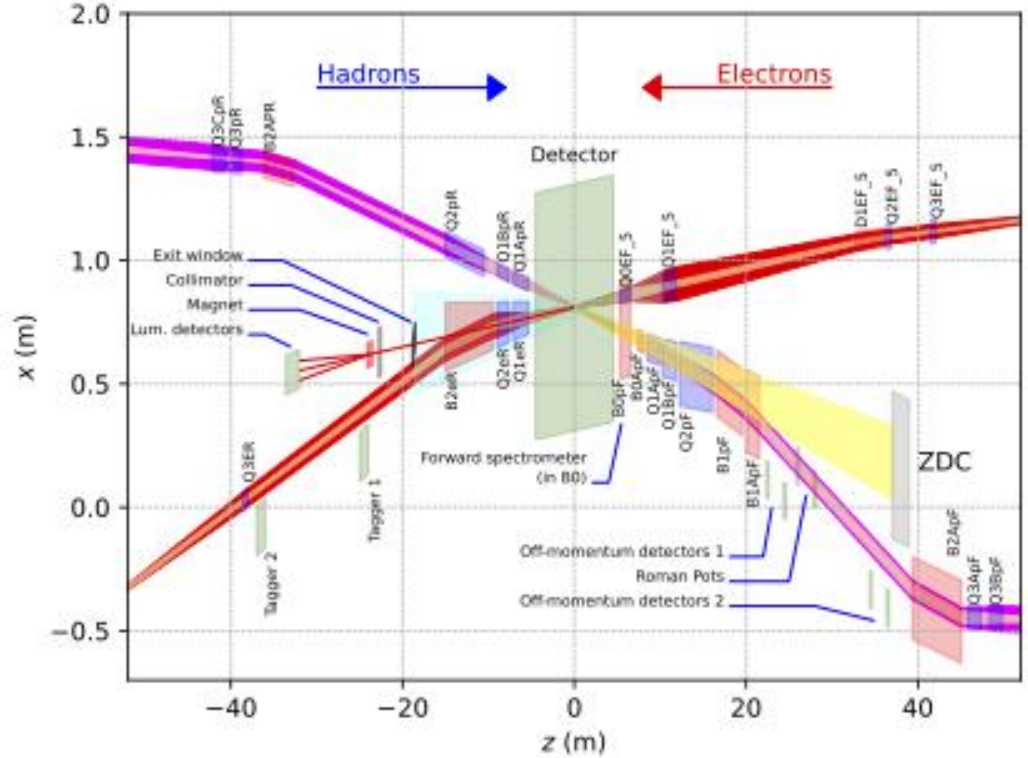
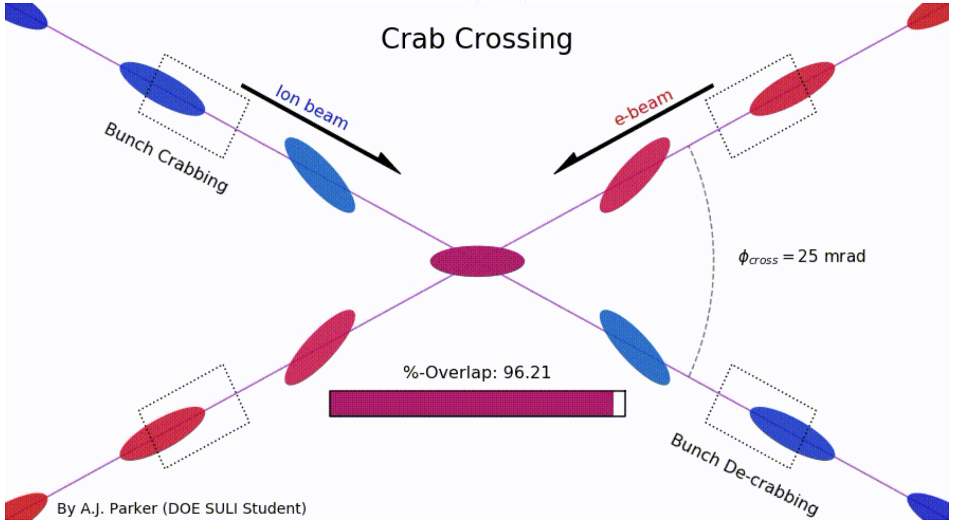
Abstract

We identify accelerator and beam conditions at the Electron-Ion Collider (EIC) that need to be included in physics and detector simulations. For our studies, we implement accelerator and beam effects in the Pythia 8 Monte Carlo event generator and examine their influence on the measurements in the central and far-forward regions of the detector. In our analysis, we demonstrate that the accelerator and beam effects can be also studied accurately by modifying the Monte Carlo input to detector simulations, without having to implement the effects directly in the event generators.

Leading EIC beam effects

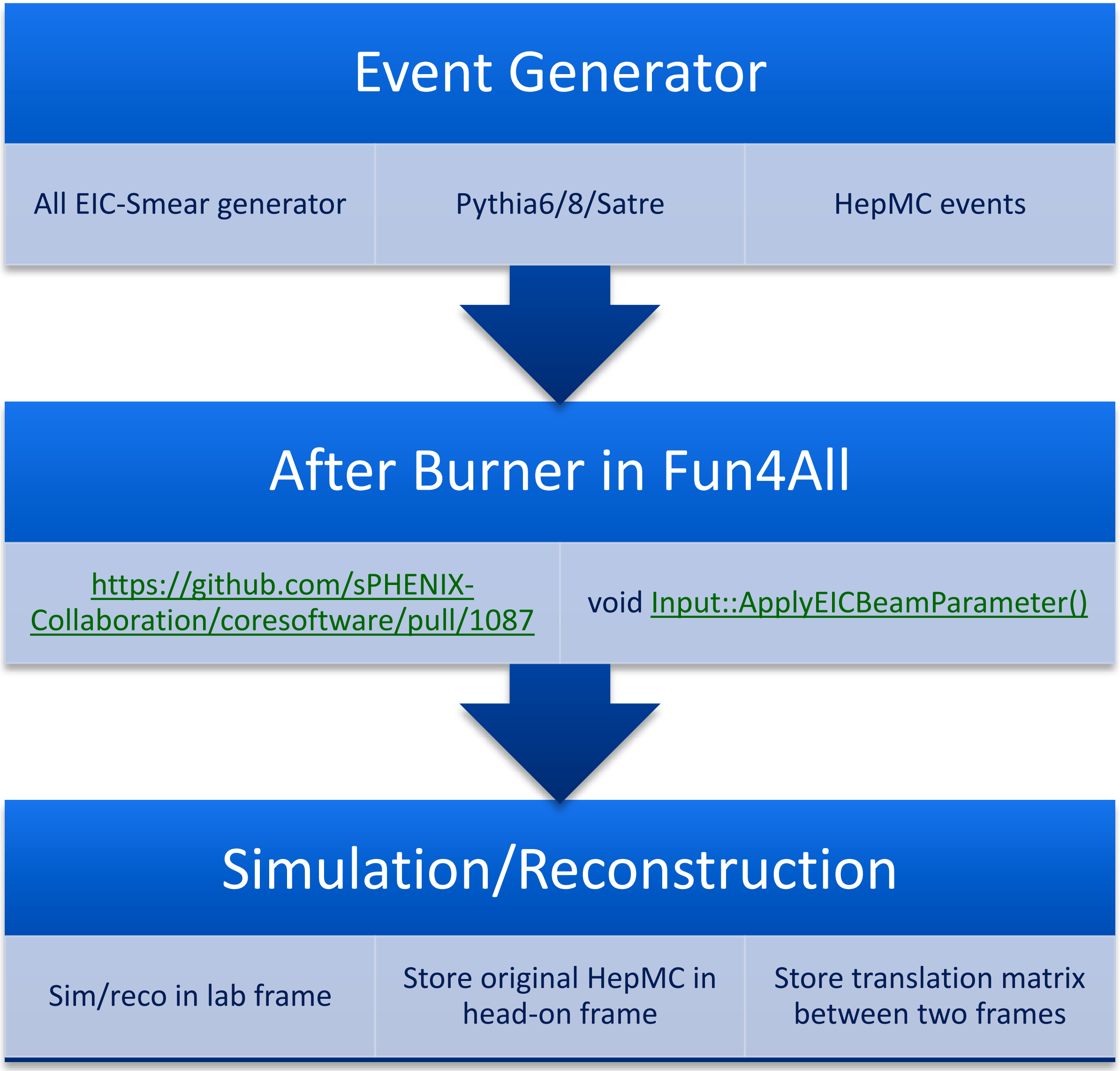
- Unique accelerator with diverse beam effect direct impact exp.
  - Beam parameter in CDR section 3.1 and tables 3.3 to 3.5 and section 3.2
- 25-35 mrad beam crossing angle
- Angular beam divergence: O(100urad)
- Crab crossing (bunch-z dependent angle smear): O(<100urad)
- Beam energy spread $O(10^{-4})$
- Beam vertex spread from 10cm h-bunch collider with 1-cm e-bunch at finite crossing angle





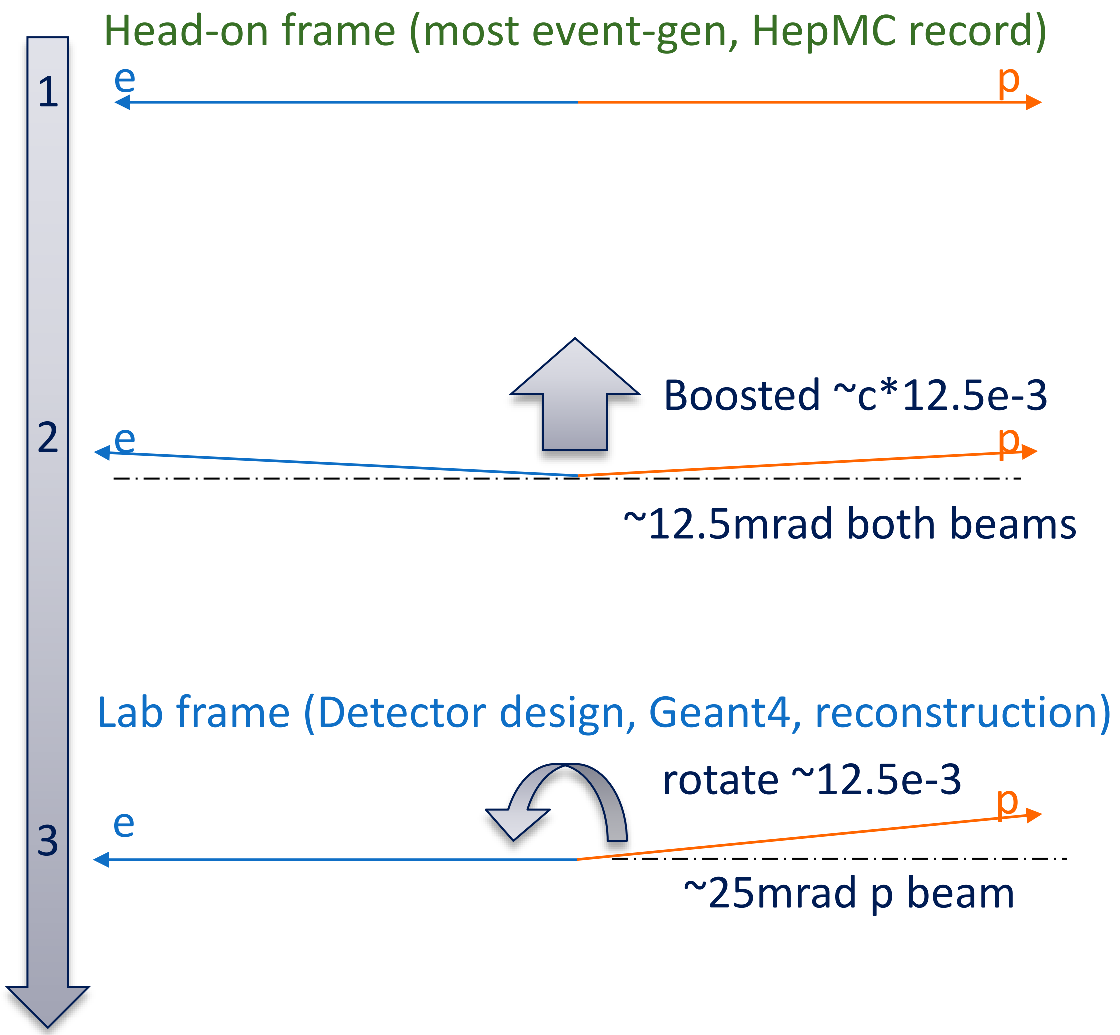
Afterburner impl. in Fun4All

- Not all event generator support beam effects while beam crossing and other effects are essential parts of EIC experiment
- After burner introduced to boost frame of any HepMC/EICSmear event of head-on collision to the lab frame with beam crossing, etc.
- Note sqrt-s is not changed in after-burner as it is boost invariant. Effect is small for most non-threshold measurement $O(10^{-4})$



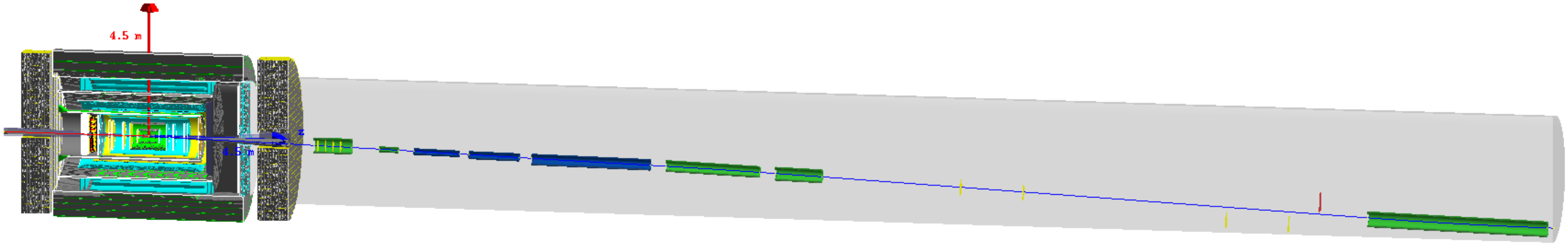
How does it work

- Input via user macro for beam angle, divergence, vertex shift in space time
- Calculate the boost-rotation-shift that is used to translate a head-on-collision event generator's record to the lab frame and use in Geant4 simulation inputs
- Apply the boost-rotation-shift from event generator to G4 simulation input
  - Simplified process on right for beam x-ing only
- Record keeping to allow analysis to reverse the translation from lab to event generator frame



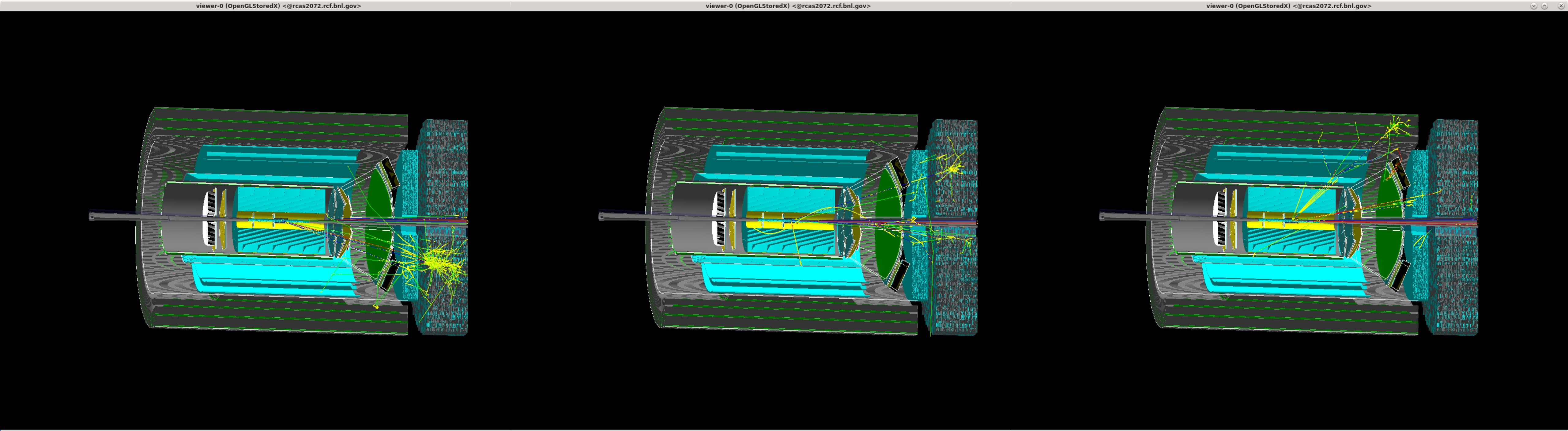
Beam transport checks

- Tested with hepMC event with proton and electron passing each other head-on
- Boost-rotated to lab frame and validate the beam propagation through ECCE and far-forward beamline
- Reference: https://github.com/ECCE-EIC/macros/pull/26



Afterburner applied to full detector events

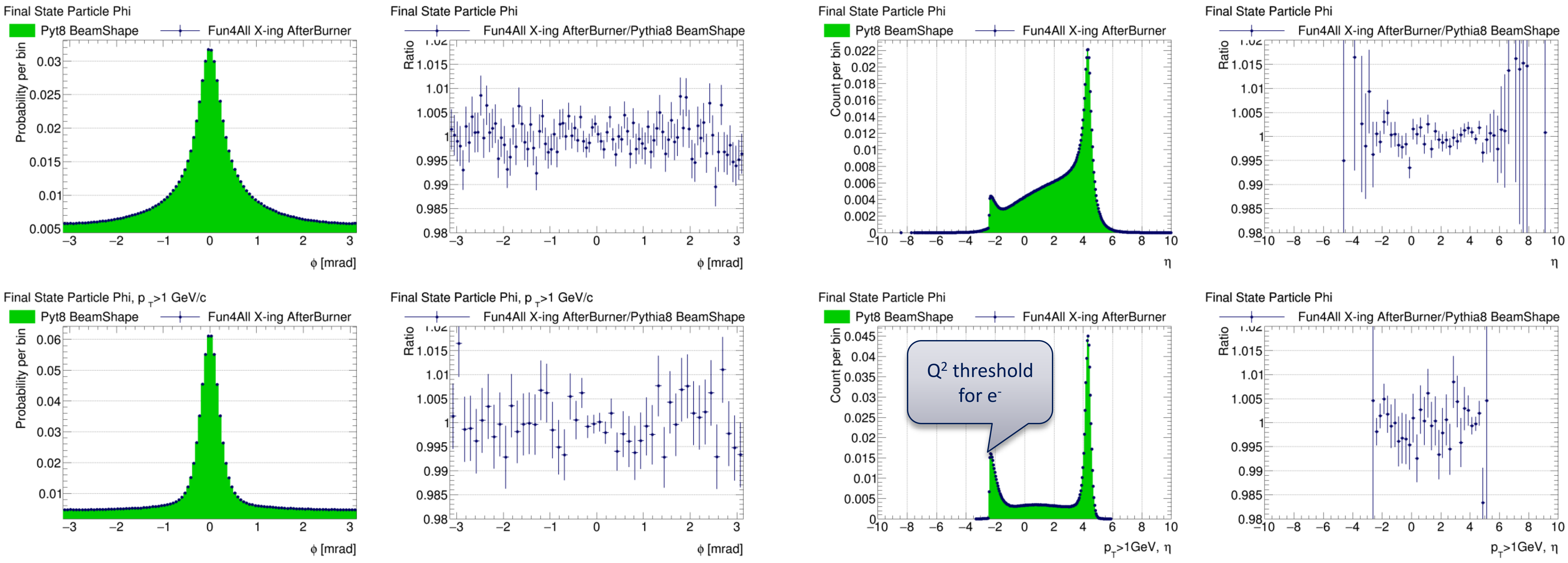
Sample	Generator	Beam Parameters	Path	Notes
"Min-Bias"	Pythia6	ep, 10 GeV x 250 GeV	/sphenix/user/cdean/ECCE/DST_files/general/pythia6_ep/	Run using internal Fun4All generator
SIDIS	Pythia6	ep, 18 GeV x 100 GeV	/sphenix/user/cdean/ECCE/DST_files/SIDIS/pythia6/ep_18x100/	EIC-smear tree input
HF & Jets	Pythia6	ep, 10 GeV x 100 GeV	/sphenix/user/cdean/ECCE/DST_files/HFandJets/pythia6/ep_10x100/	EIC-smear tree input



Generator file with head-on 10x250 ep collision: https://github.com/eic/fun4all_calibrations/blob/master/Generators/phpythia6_ep_MinPartonP20GeV.cfg

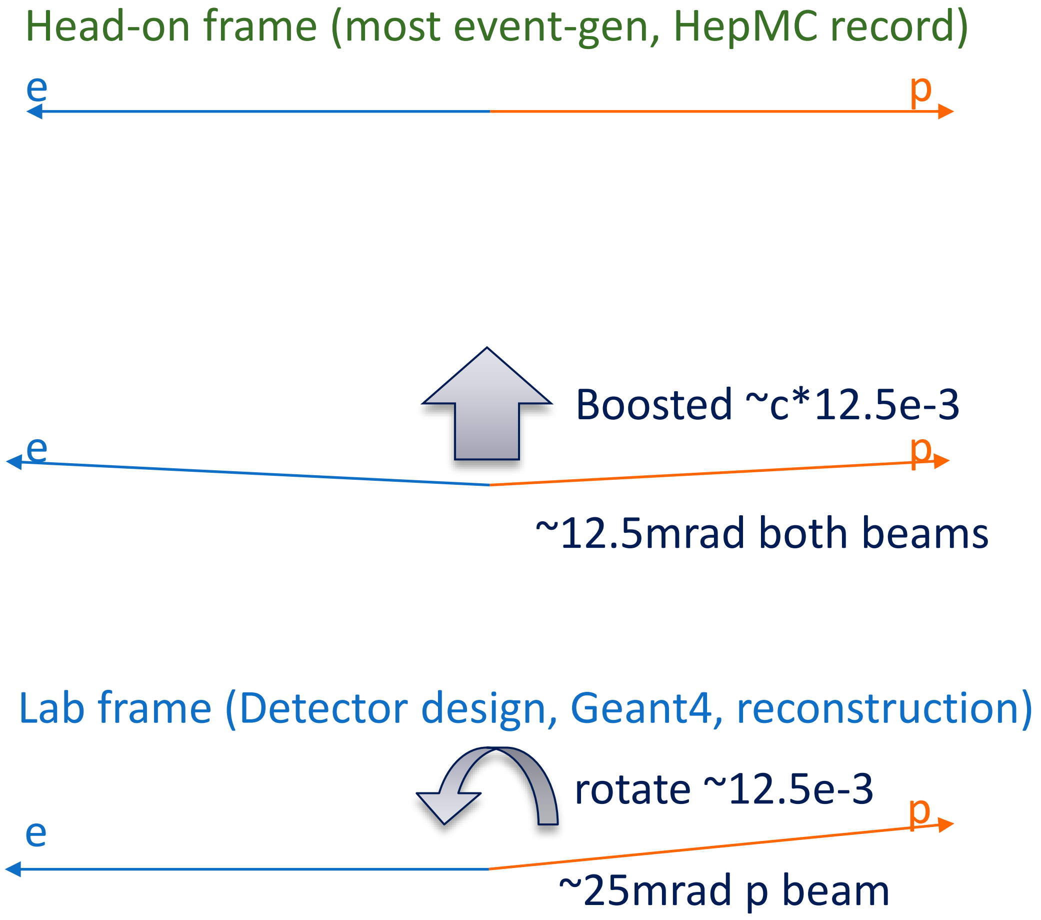
Direct comparison: Fun4all afterburner vs Pythia8

- 1M Pythia8 events -> Fun4All beam afterburner -> G4 ↔ compared to 1M Pythia8 BeamShape [link]. Also checked with IP6/8 and low-high beam configuration [link]
- Consistency well beyond the 1% stat. uncertainty provided by the test sample



Beam effect discussion 1: two frames

- Head-on frame as used in most event generator and stored in HepMCEventMap is different from
  the Lab Frame as used in Detector design, Geant4 simulation and reconstruction
- In lab frame, electron is along –z axis, i.e. along symmetric axis of exp. and no B-bending
- From head-on to lab frame, beam energy increase by
  $E_{Lab} = E_{HeadOn}/\cos(crossing\ angle/2)$

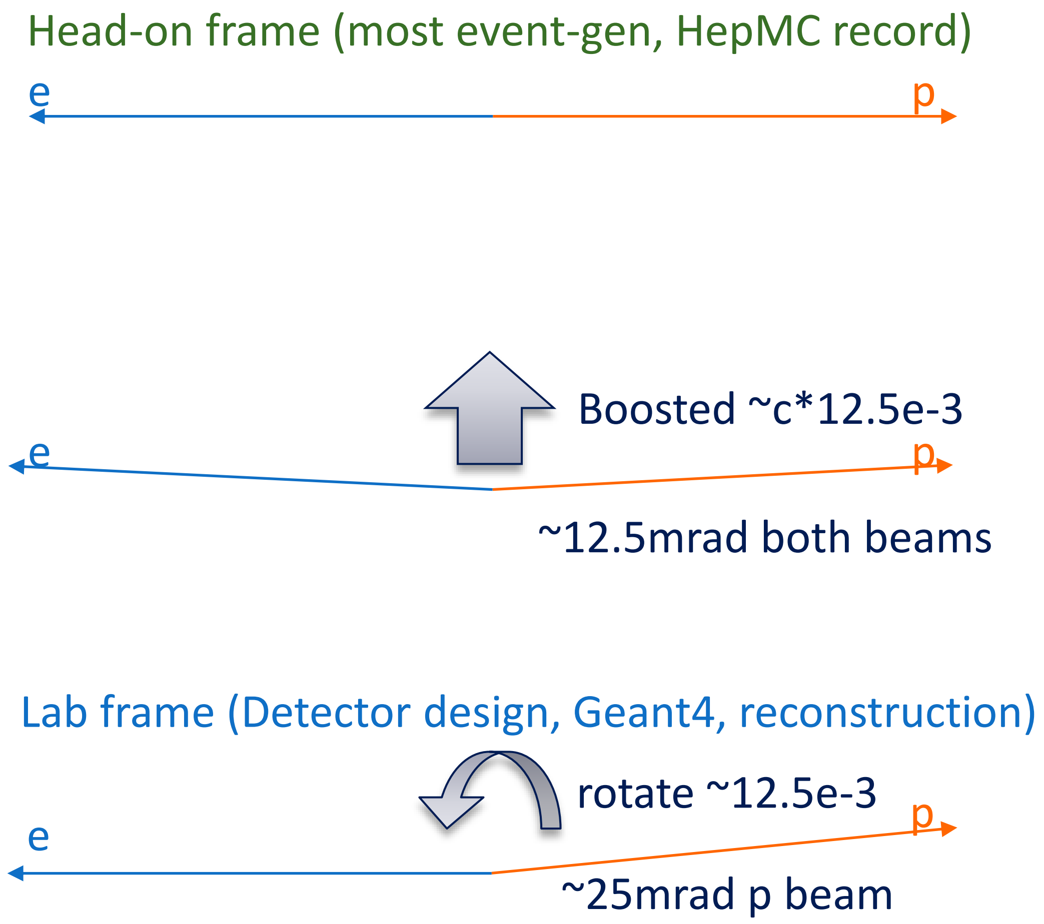


Beam effect discussion 2: reconstruction

- Beam divergence (O(100)urad) is not measured event-by-even, so in reconstruction we need to assume central beam four momentum with

$$E_{Lab} = E_{HeadOn}/\cos(crossing\ angle/2)$$

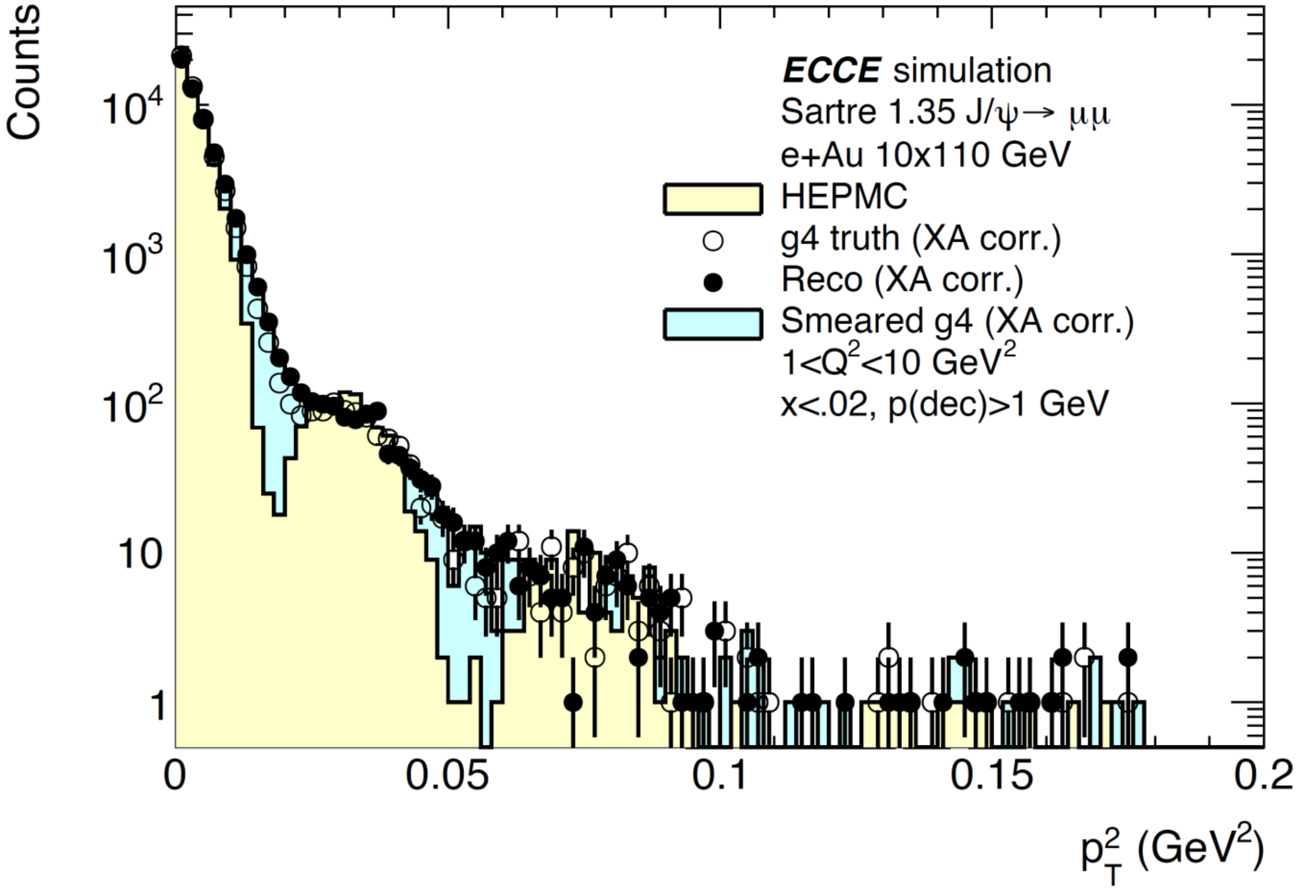
  - Electron beam four vector: (0,0,-1, 1)*E_{e_lab}
  - Proton beam Ip6, Ip8: (-sin(25mrad),0,cos(25mrad),1)*E_{p_lab}, (+sin(35mrad),0,cos(35mrad),1)*E_{p_lab}
- Lorentz invariant variable is reconstructed regardless frame, e.g. x-y-z-W-Q2-PhT
- Vectors and Lorentz variant need to be explicitly expressed with its frame, e.g. pT, angle, pseudorapidity
- In sim we know e-by-e divergence. Truth Lorentz-rotation matrix between head-on and lab frame available at :
  - CLHEP::HepLorentzRotation PHHepMCGenEvent::get_LorentzRotation_EvtGen2Lab() const
  - CLHEP::HepLorentzRotation PHHepMCGenEvent::get_LorentzRotation_Lab2EvtGen () const



Beam effect discussion 3: truth tracing service

- Truth tracing is an essential part of sim-reco software
- Separated objects storing frames of event-gen (head-on) and G4/Detector/Reco (with crossing, vertex)
- Allow user to trace and compare EventGen -> G4 truth -> best matching reco object
- Truth tracing chain and connection between objects (as in Fun4All)
  - event-gen -> PHHepMCGenEvent
  - G4 -> PHG4TruthInfoContainer (g4particle, g4vertex, truth history chain)
  - G4-Reco mapping -> PHG4Shower, `SvtxTrackEval::best_track_from(PHG4Particle * truth_particle)`, etc.

Exclusive J/Psi production: Transverse-t reco comparison with various stage of beam and detector effects
Peter Steinberg (BNL), 3rd ECCE simulation workshop [link]



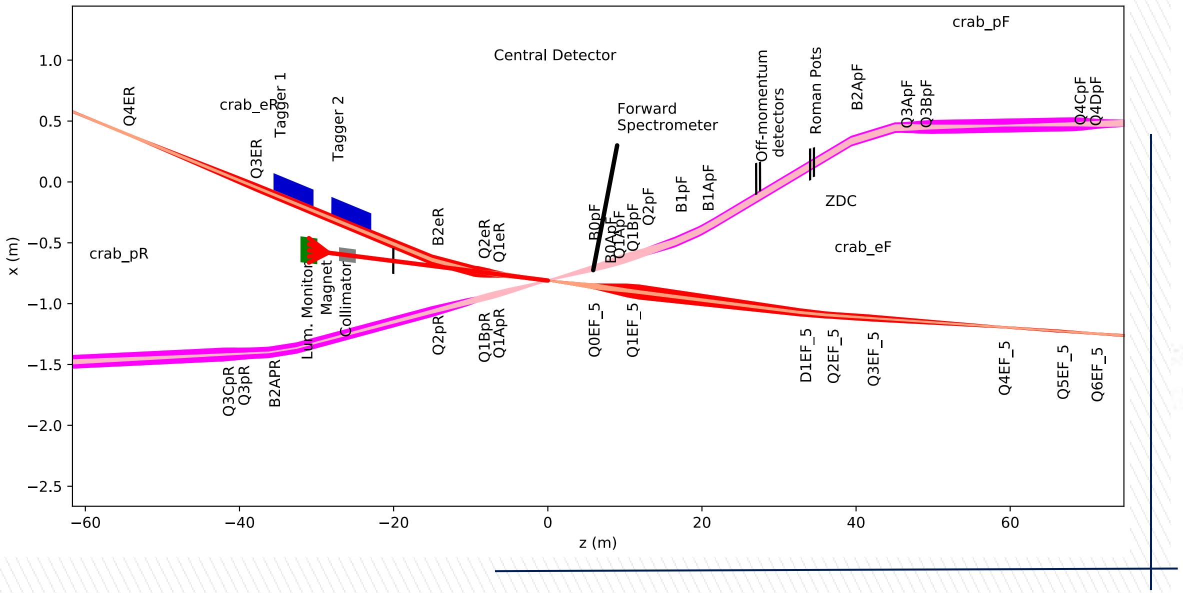
Summary

- EIC has complex beam effects: crossing angle, beam divergence, beam energy spread, and crabbing on beam momentum, vertex
- Need to take into account for all analysis in proposal stage
- Not all event generator can handle these beam effect→ beam eff. after-burner
- Most simulation can be done with
  - Event generators in head-on frame
  - Apply these beam effects via Fun4All afterburner
  - Note the limitation that CM energy would not be modified in after burner
- Analyzers need to be aware of the beam effect
  - Average beam crossing angle can be taken into analysis, e.g. e- along –z axis, proton carry full crossing angle:
    - Shift of beam energy $E_{Lab} = E_{HeadOn}/\cos(crossing\ angle/2)$
    - Electron beam four vector: (0,0,-1, 1)*E_{e_lab}
    - Proton beam Ip6, Ip8: (-sin(25mrad),0,cos(25mrad),1)*E_{p_lab}, (+sin(35mrad),0,cos(35mrad),1)*E_{p_lab}
  - Some effect are stochastic, e.g. beam divergence and the effect will be part of experimental uncertainty

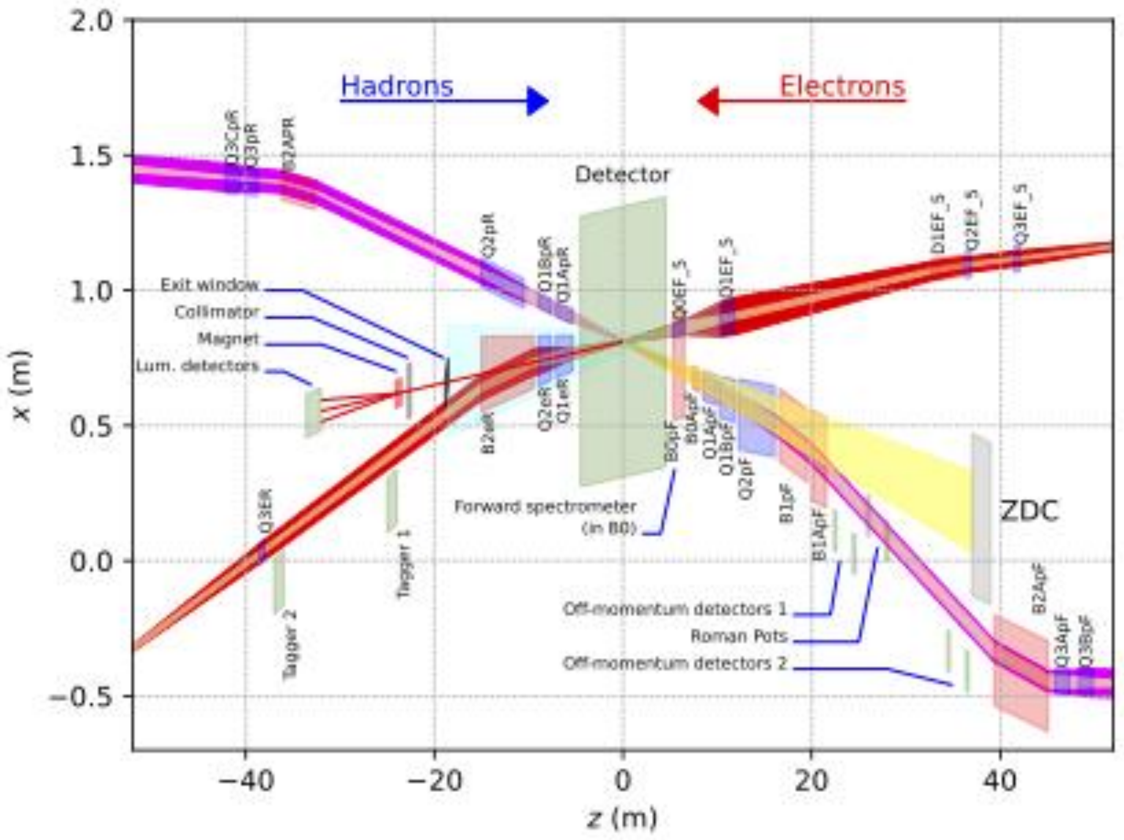
Extra information

New IP6 crossing sign convention, now default in ECCE sim-reco!

EIC CDR / YR (bottom-up view of IP6)



New convention (top-down view)

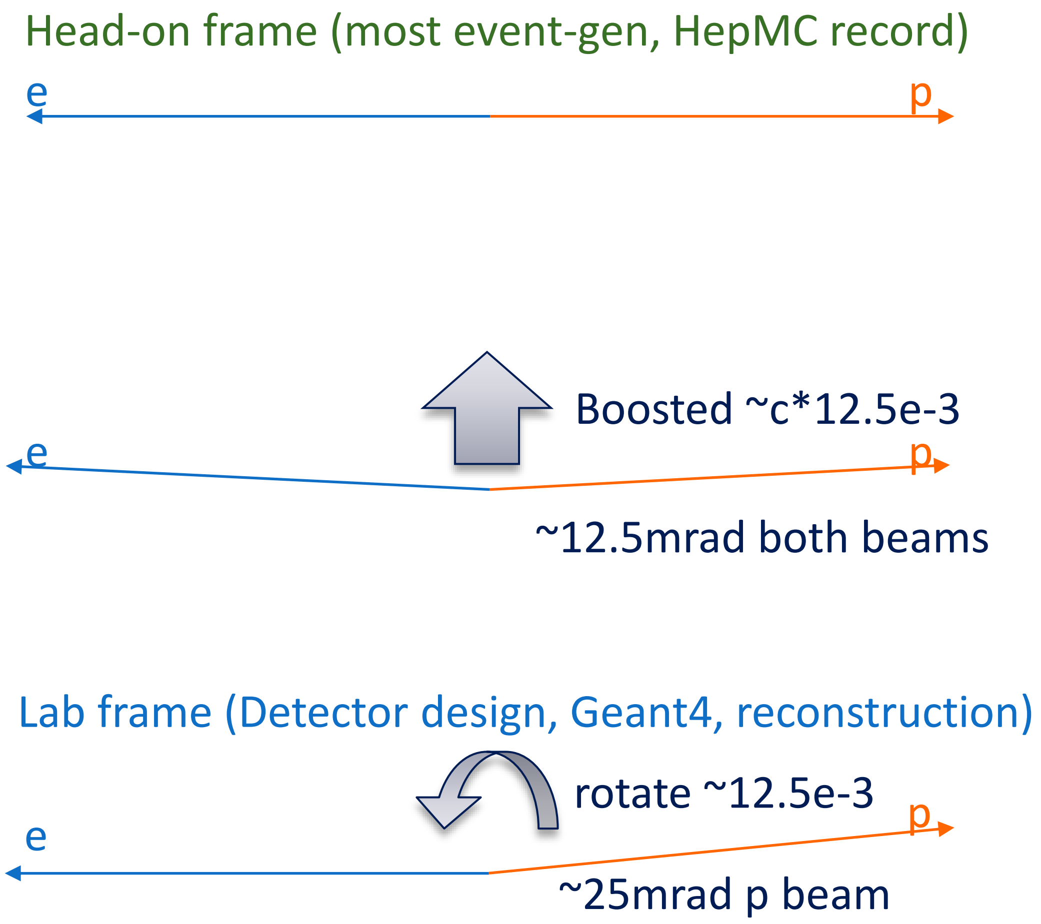


- New convention of IP6 has y-axis towards up and x-axis towards inside the ring
- Hadron beam cross towards **–x** direction
- Default of ECCE sim-reco this week(!) at PR26 [link]

Beam effect discussion 2: IP switch

- Beam effect such as x-ing angle enabled for all event generator input by default
  - https://github.com/sPHENIX-Collaboration/coresoftware/pull/1087
  - void Input::ApplyEICBeamParameter()
- Single switch being introduced to swap default IP6/IP8 crossing and beamline [link to new ECCE macro draft]:

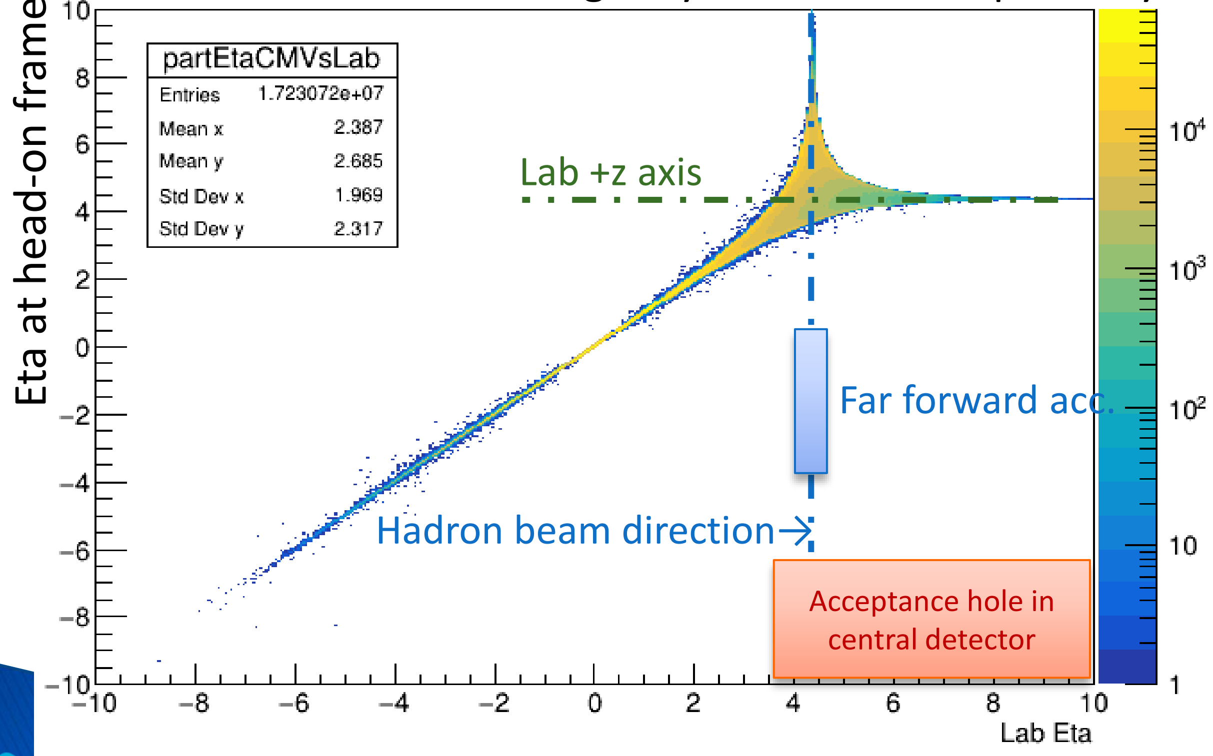
```
//===============
// Input options
//===============

// switching IPs by comment/uncommenting the following lines
// used for both beamline setting and for the event generator crossing boost
Enable::IP6 = true;
// Enable::IP8 = true;
```

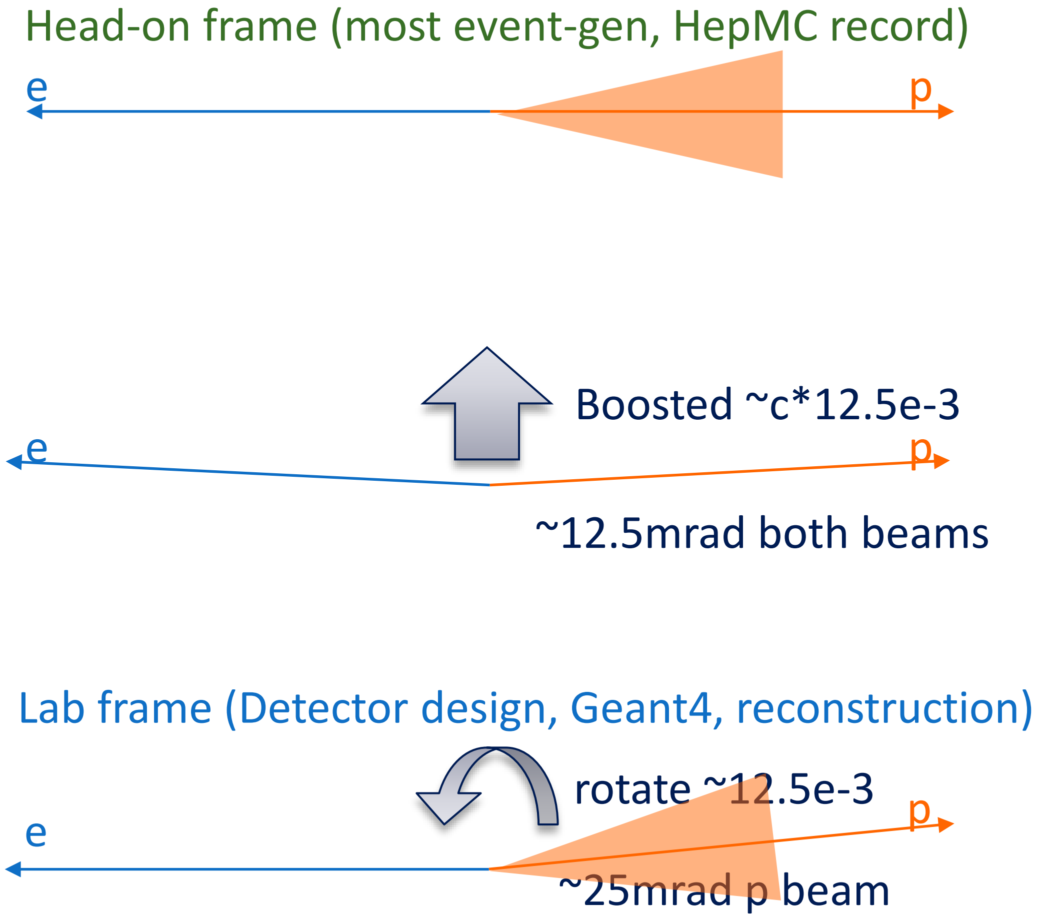


Beam effect in ECCE analysis 4: size of x-ing effect

- eta_lab>2 : eta (and pT, phi) shift significant from lab to head-on

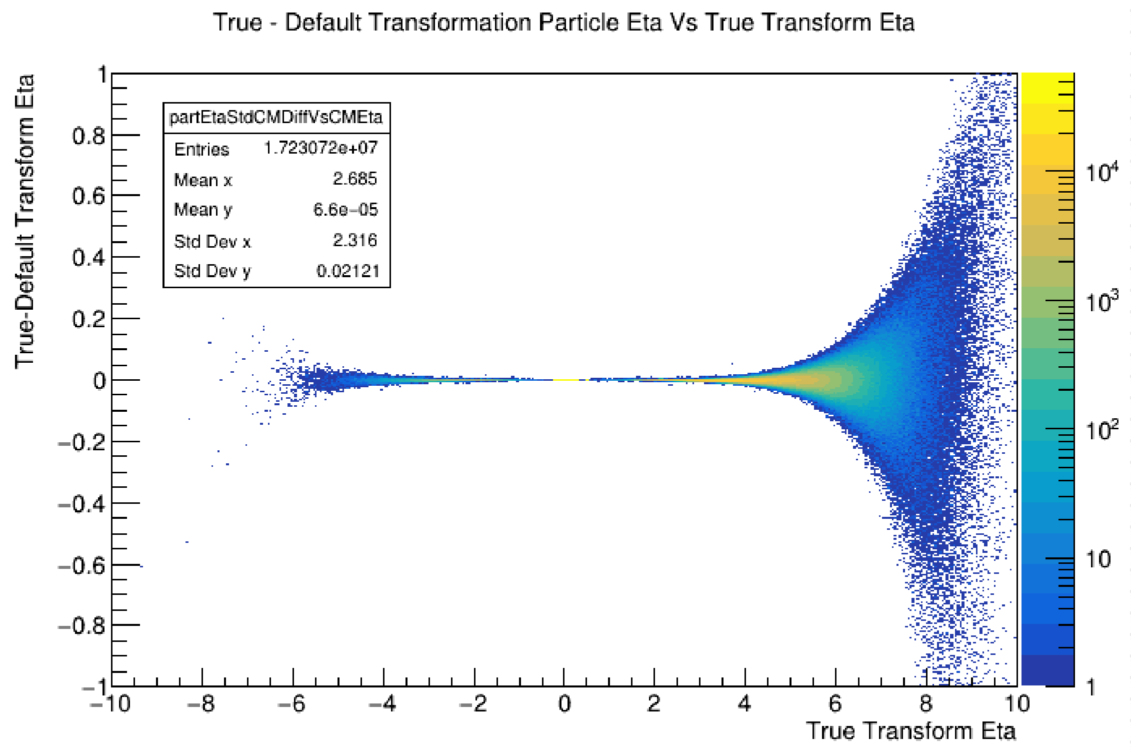
Brian Page: Pythia8 BeamShape study

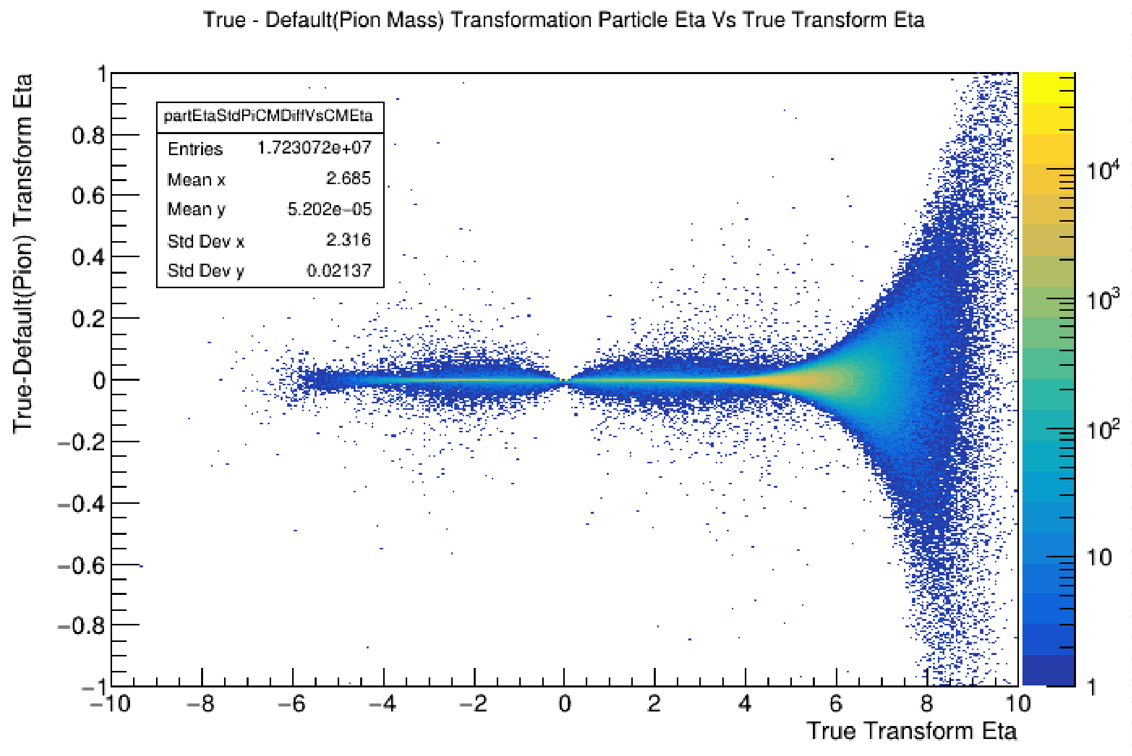




Beam effect in ECCE analysis 5: irreducible residuals

If we translate all tracks from lab frame to head-on, how much eta error we will have? Plot from Brian Page (BNL) [link]

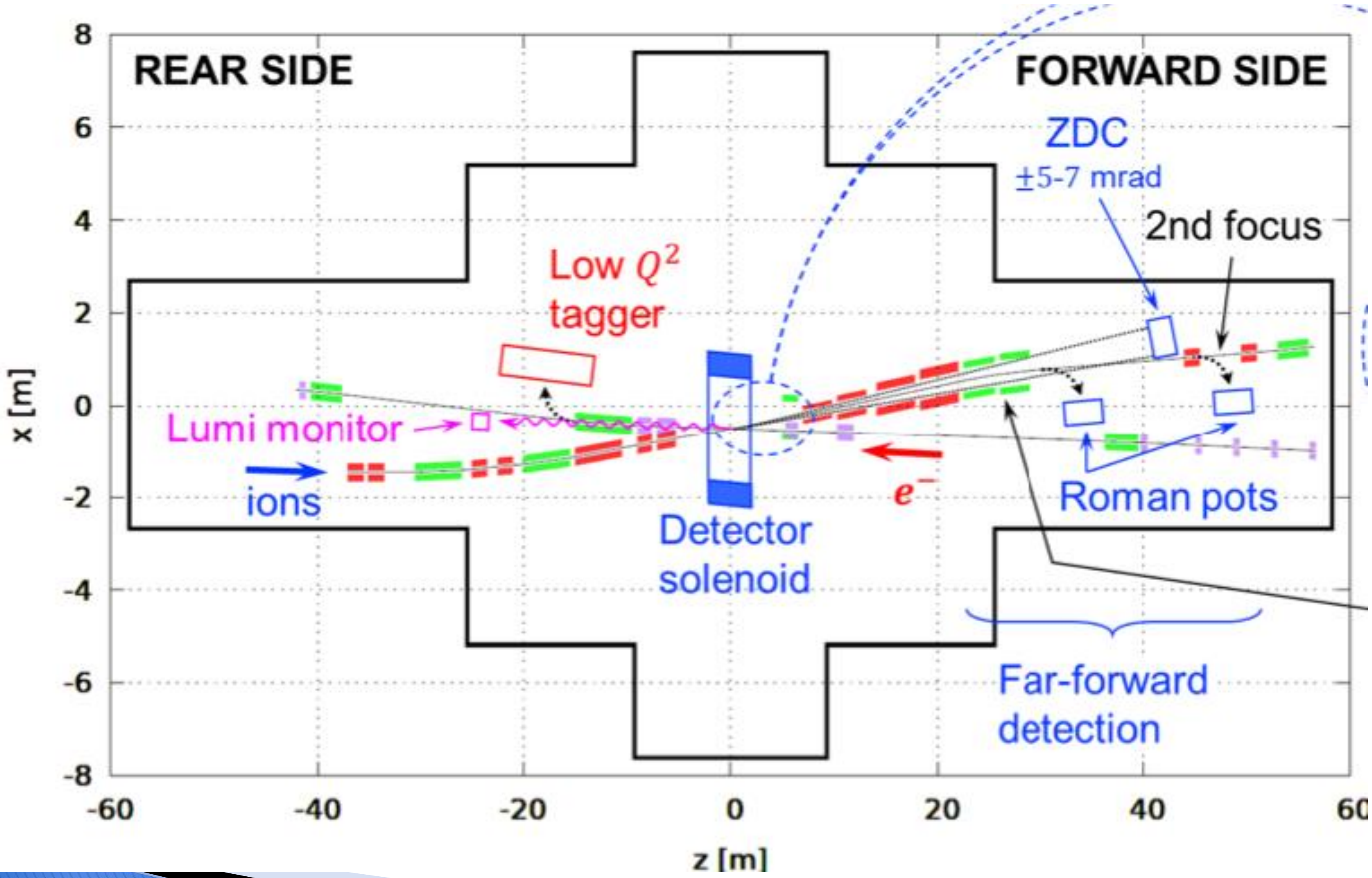




If we know PID & perfect tracking:
Left over is dominated by beam divergence

If we DO NOT know PID & perfect tracking:
Left over is imperfect boost with pi mass + divergence

IP8 crossing



Beam parameters (IP6) [CDR]

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

Test with Pythia8 input

- Thanks to Brian Page (BNL) for generating pairs of head-on VS beam-effect-on Pythia8 events for validation testing
- The head-on collision beam energy is reduced by cos(12.5mrad) to allow boost to lab frame at actual beam energy
- Works out of box: https://github.com/blackcathj/macros-1/tree/ecce-test-xing-display