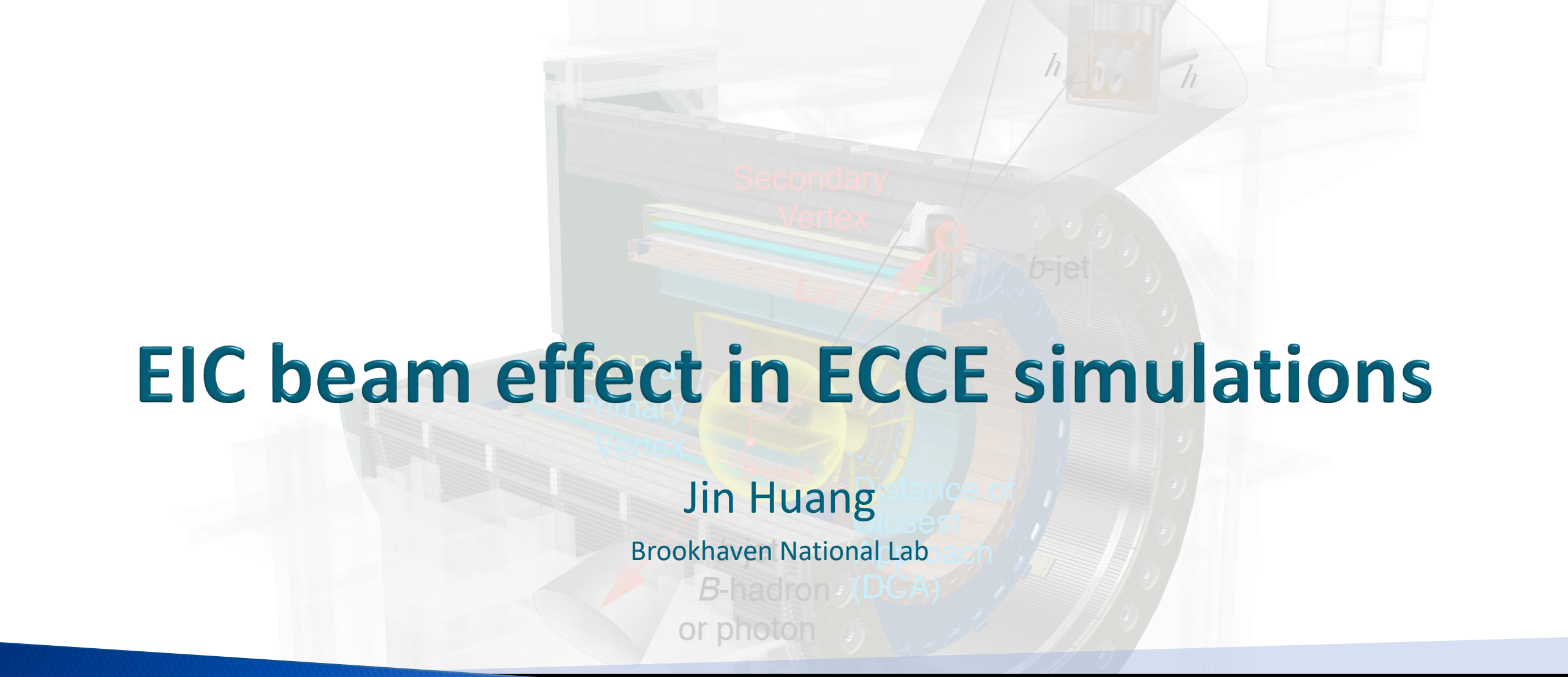

EIC beam effect in ECCE simulations

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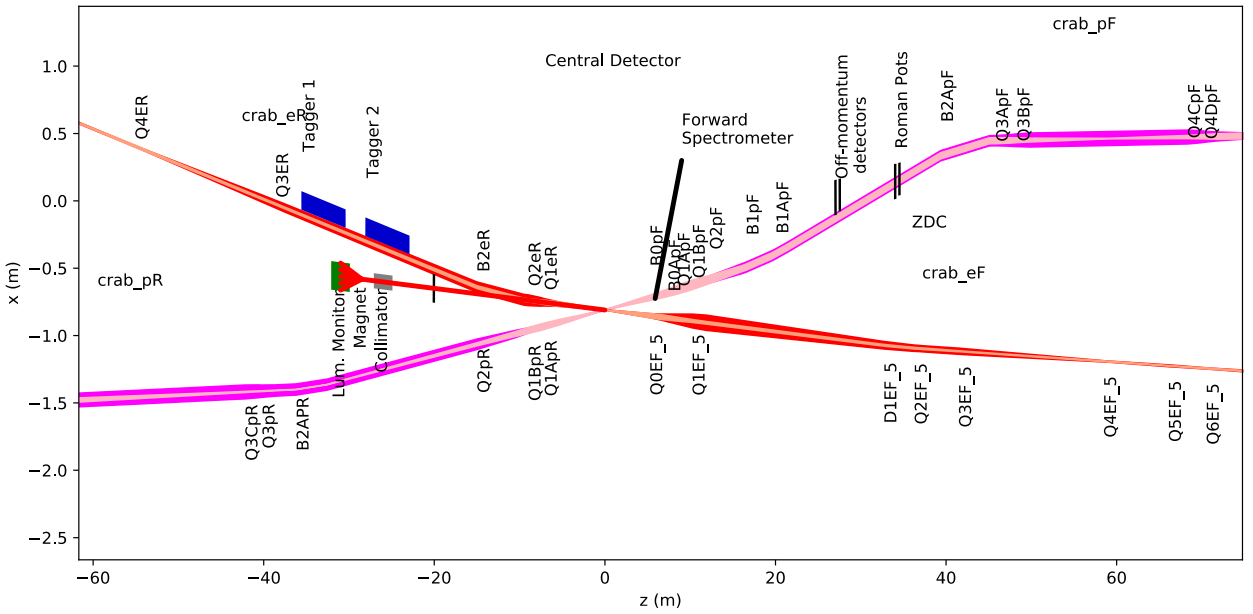
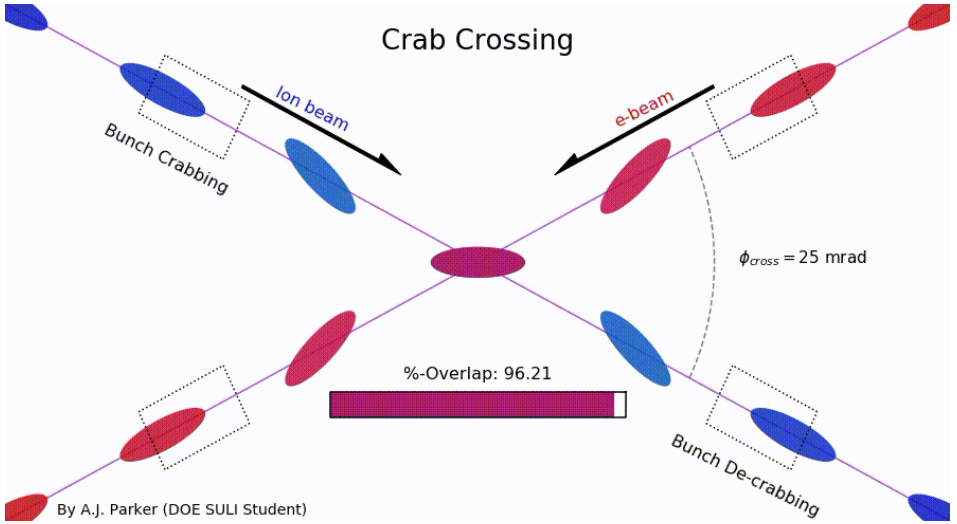
Special thanks to discussion and inputs from Aschenauer Elke-Caroline, Rolf Ent, Yulia Furletova, Alexander Jentsch, Diefenthaler Markus, Brian Page

EIC beam effects

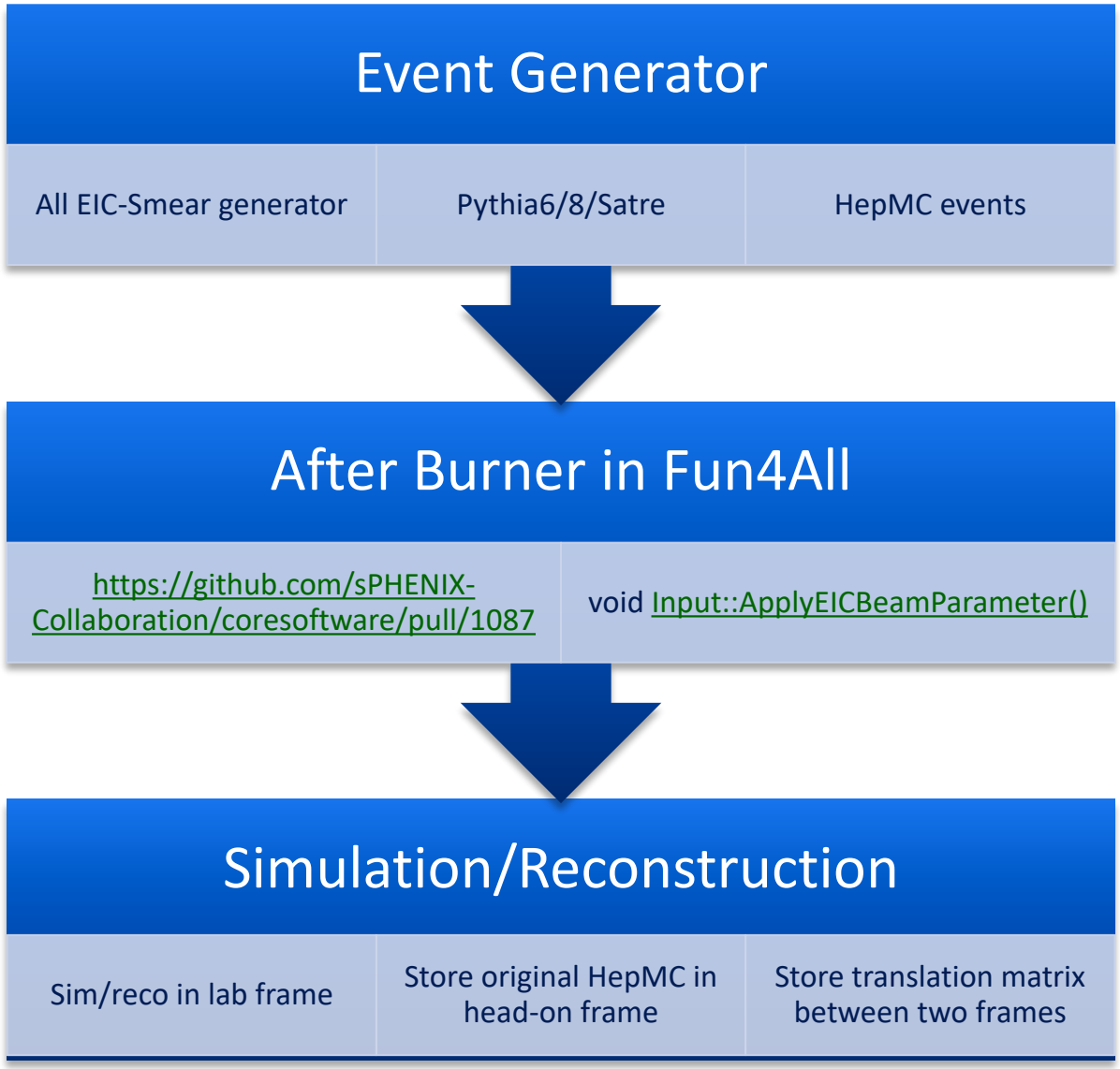
- Unique accelerator with diverse beam effect direct impact exp.
  - Beam parameter in CDR section 3.1 and tables 3.3 to 3.5 and section 3.2
- 25-35 mrad beam crossing angle
- Angular beam divergence: O(100urad)
- Crab crossing (bunch-z dependent angle smear): O(<100urad)
- Beam energy spread O(10^{-4})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





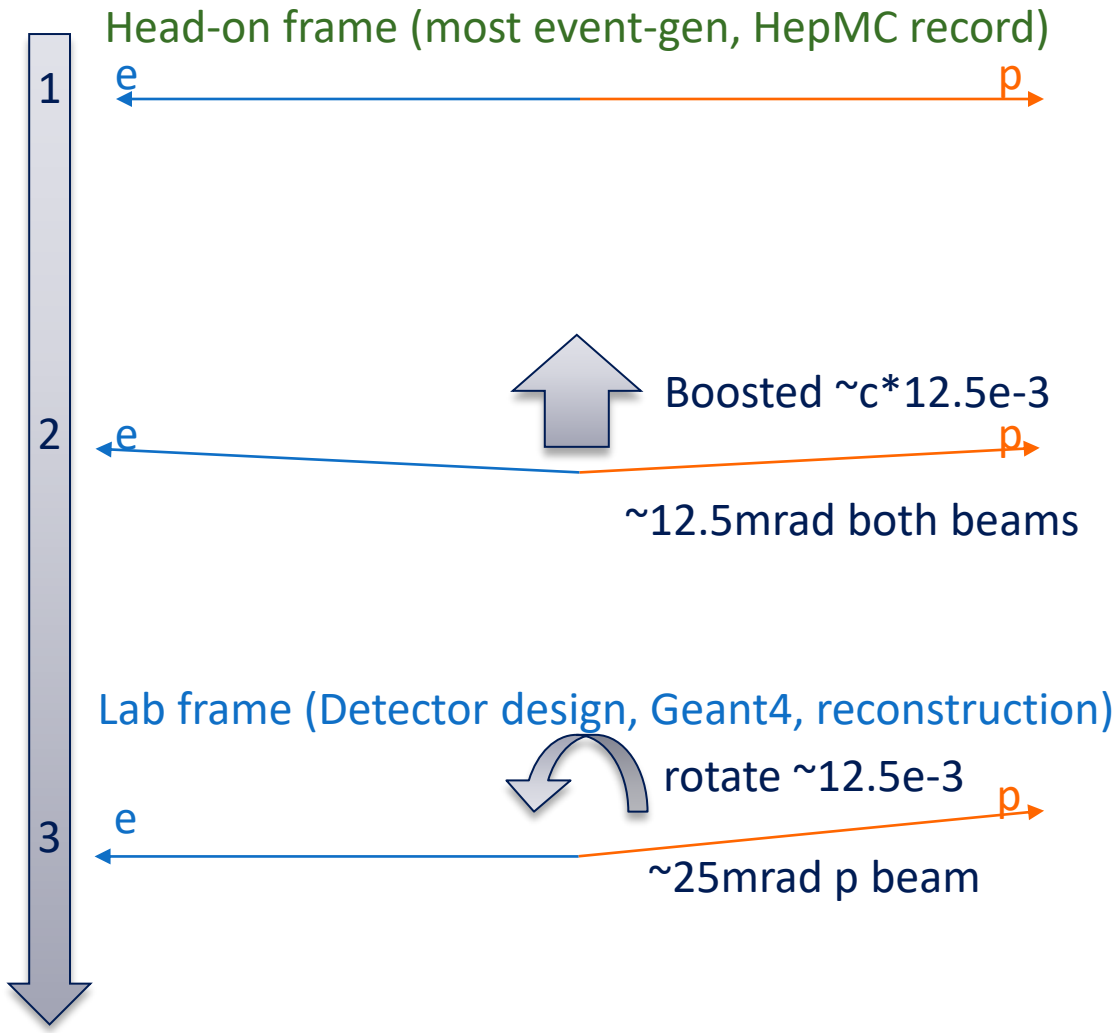
Beam effects in ECCE sim.

- 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})



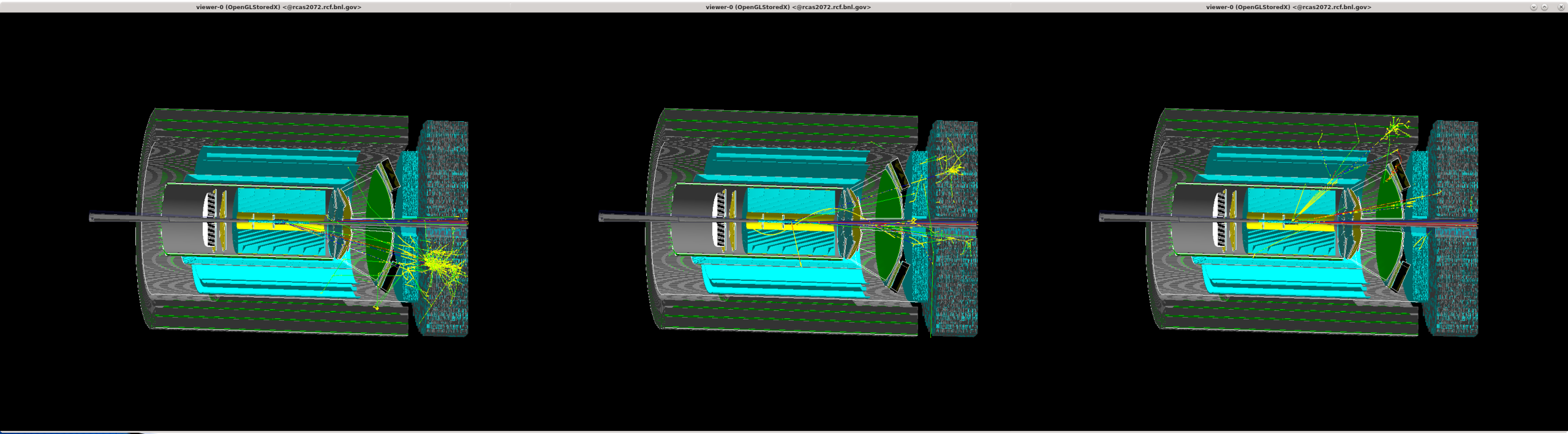
How does it work

- 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



Test sample available in sim+reco full detector data
1M events so far in each test sample

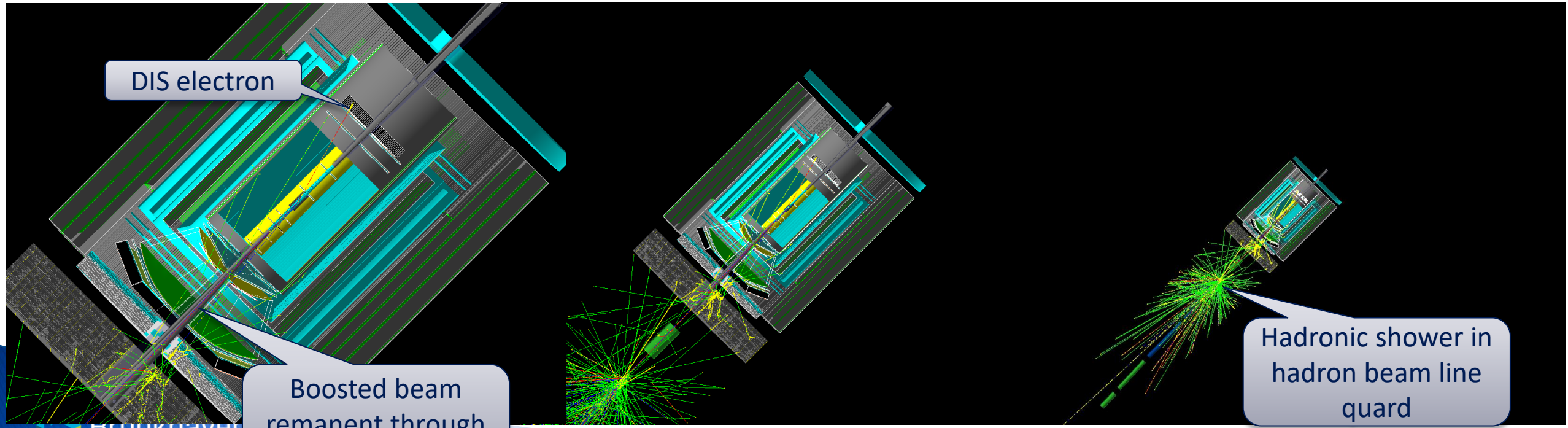
Sample	Generator	Beam Parameters	Path	Notes
"Min-Bias"	Pythia6	ep, 10 GeV x 250 GeV	/sphenix/user/cdean/ECCE/DST_files/general/pythia6_ep/	Run using internal Fun4All generator
SIDIS	Pythia6	ep, 18 GeV x 100 GeV	/sphenix/user/cdean/ECCE/DST_files/SIDIS/pythia6/ep_18x100/	EIC-smear tree input
HF & Jets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

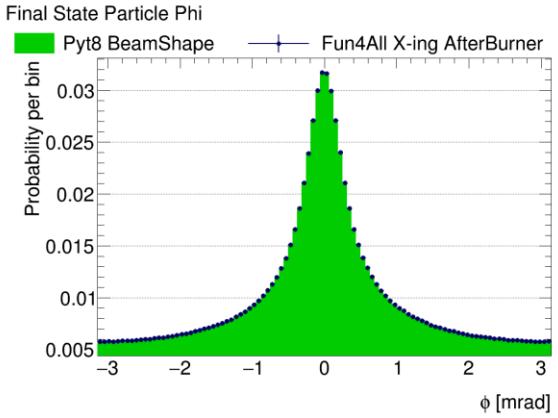
Test with Brian's Pythia8 input

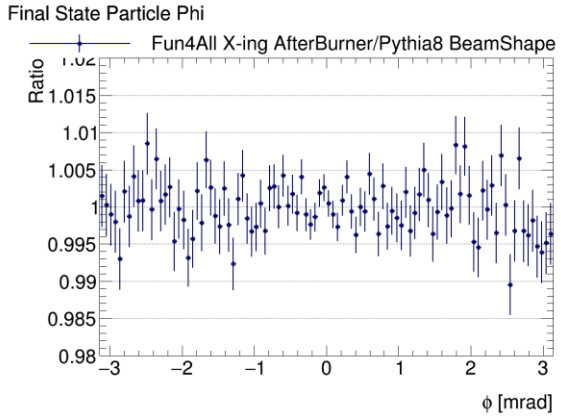
- Thanks to Brian Page (BNL) for generating pairs of head-on VS beam-effect-on Pythia8 events for validation testing
- The head-on collision beam energy is reduced by cos(12.5mrad) to allow boost to lab frame at actual beam energy
- Works out of box: https://github.com/blackcathj/macros-1/tree/ecce-test-xing-display

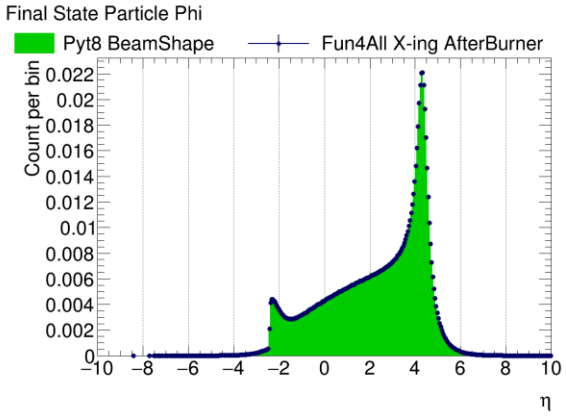


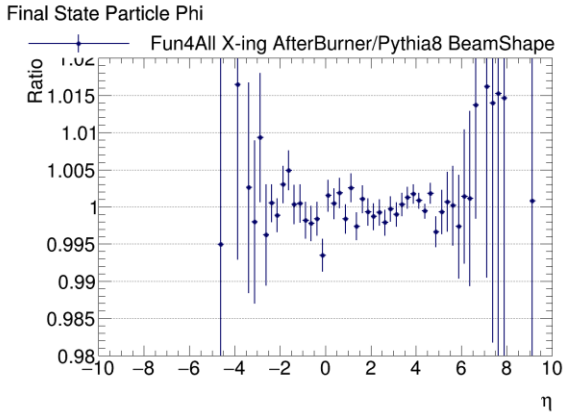
Direct comparison: Fun4all afterburner vs Pythia8

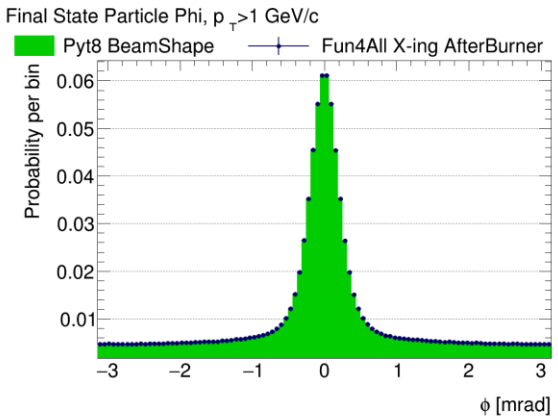
- 1M Pythia8 events -> Fun4All beam afterburner -> G4 ↔ Compare to 1M Pythia8 BeamShape [link to note]
- Consistency well beyond the 1% stat. uncertainty provided by the test sample

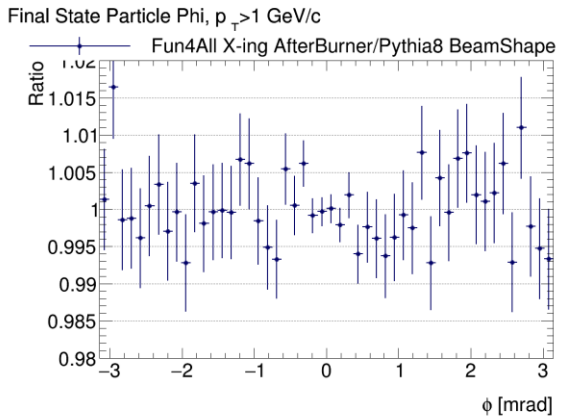


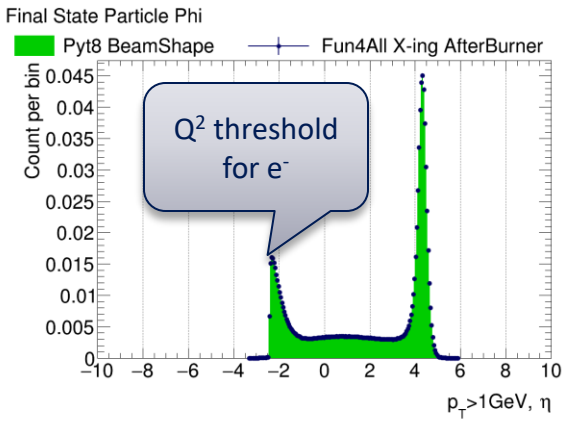


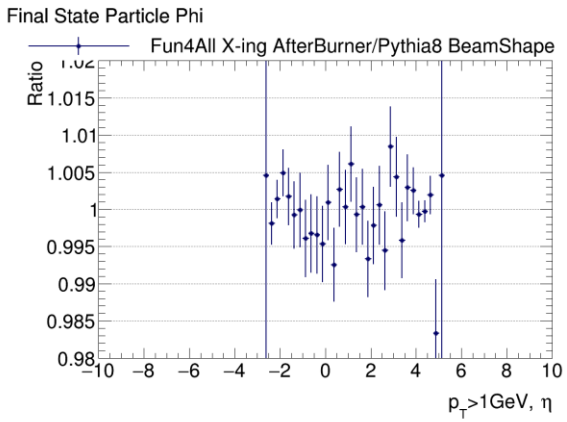






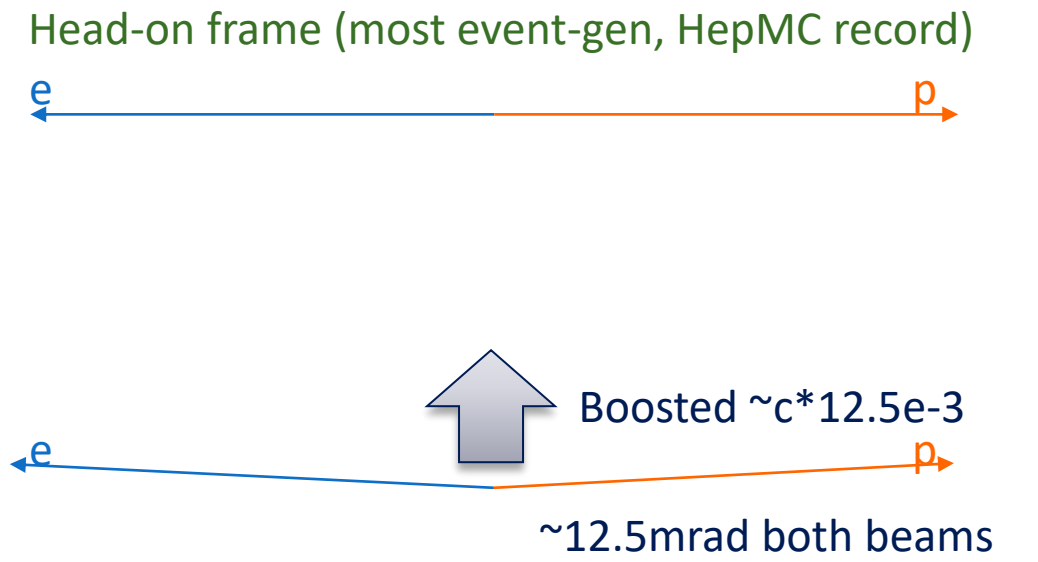






Beam effect in ECCE analysis 1: two frames

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

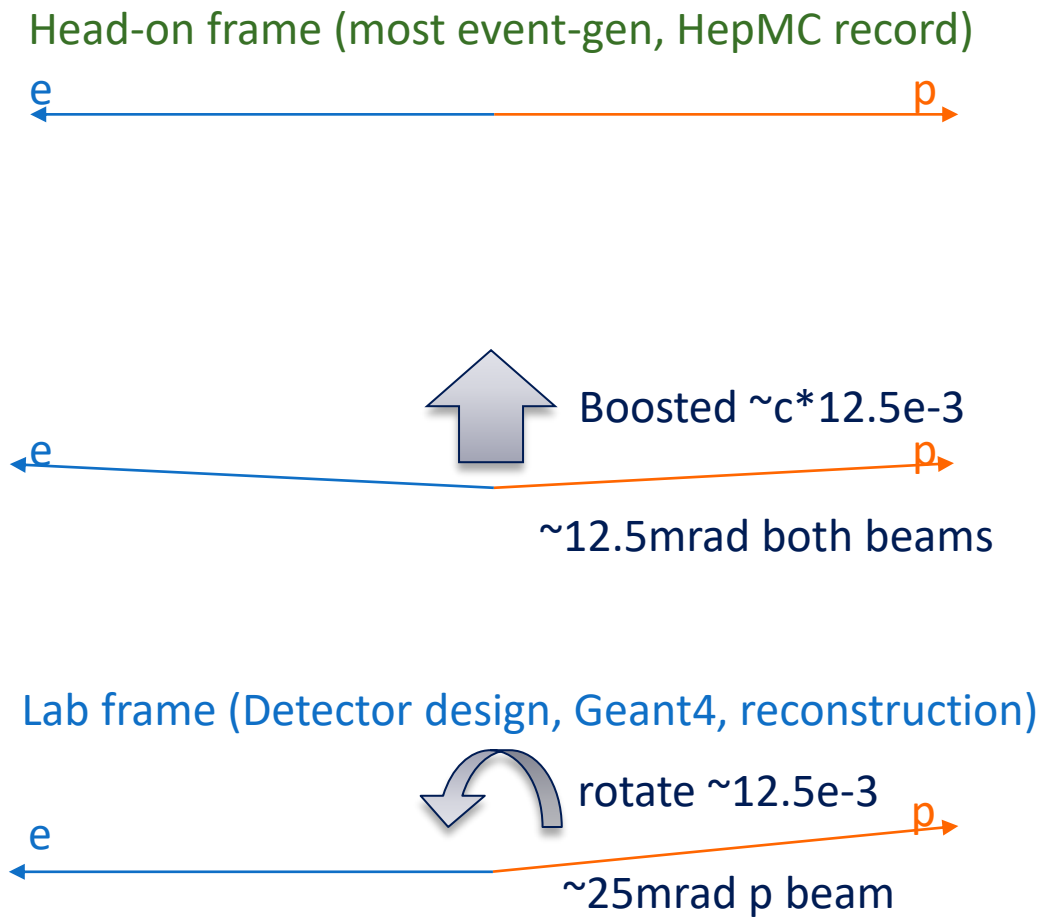


Beam effect in ECCE analysis 2: IP switch

- 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;
```

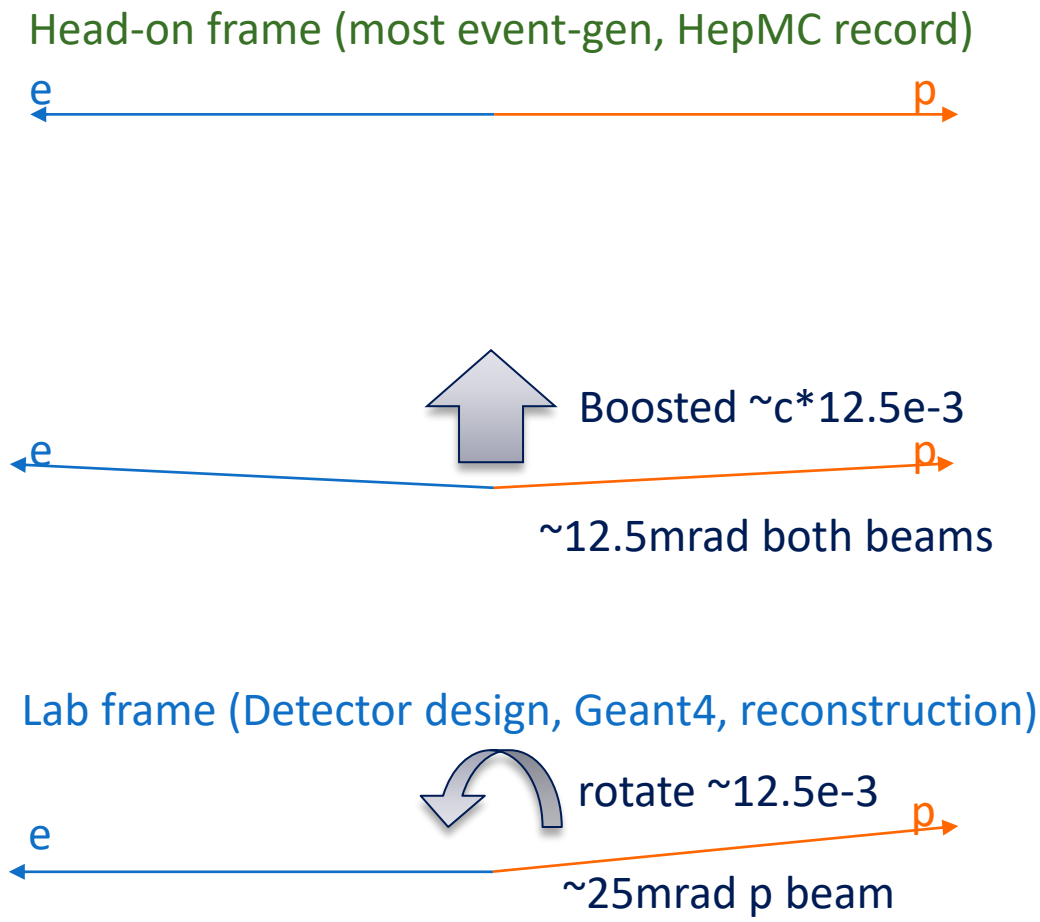


Beam effect in ECCE analysis 3: reconstruction

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

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

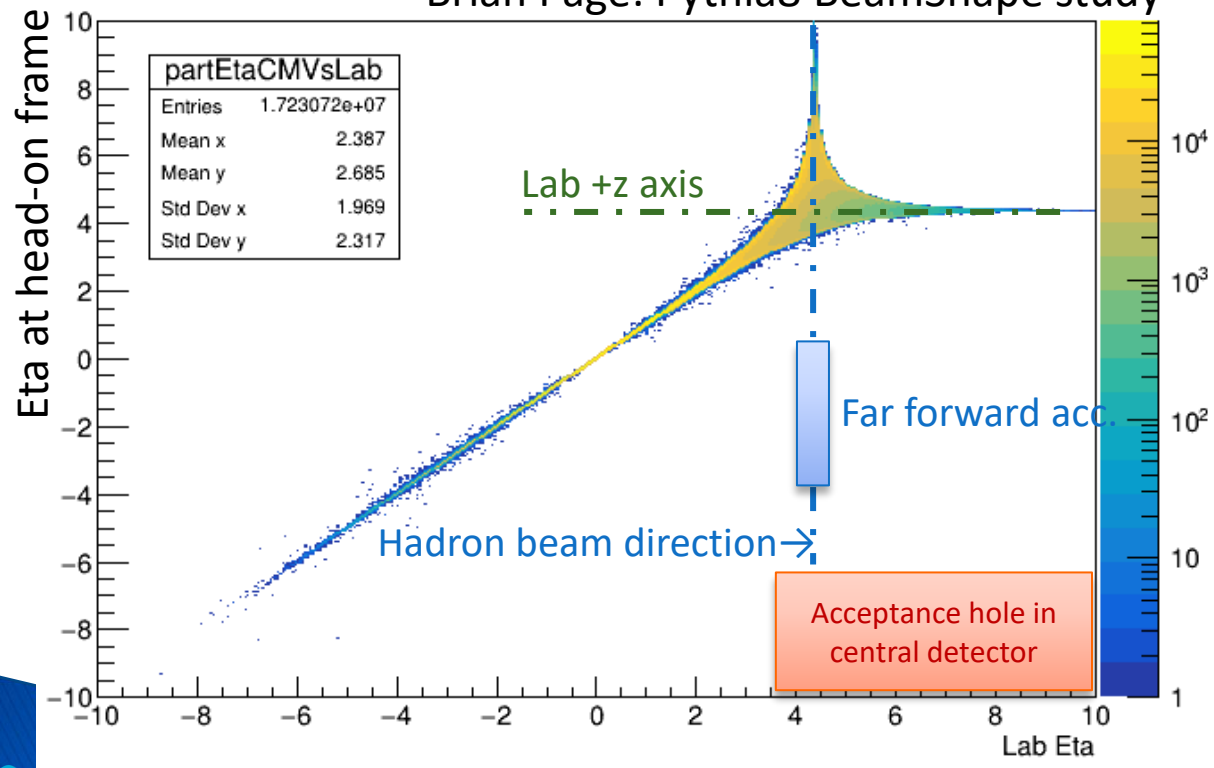
  - Electron beam four vector: (0,0,-1, 1)*E_{e_lab}
  - Proton beam four vector: (sin(25mrad),0,cos(25mrad),1)*E_{p_lab}
- Lorentz invariant variable is reconstructed regardless frame, e.g. x-y-z-W-Q2-PhT
- Vectors and Lorentz variant need to be explicitly expressed with its frame, e.g. pT, angle, pseudorapidity
- 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



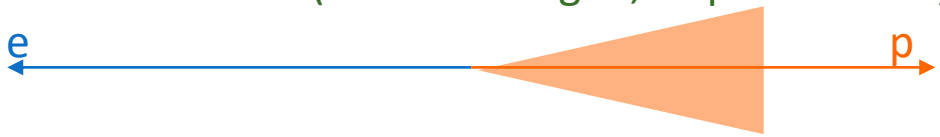
Beam effect in ECCE analysis 4: size of x-ing effect

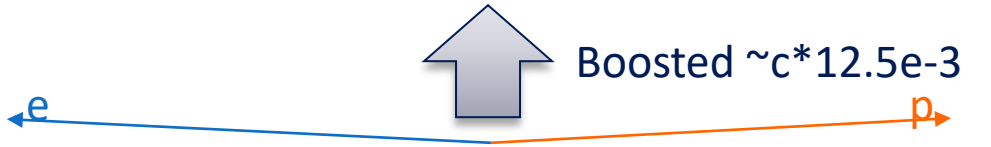
- eta_lab>2 : eta (and pT, phi) shift significant from lab to head-on

Brian Page: Pythia8 BeamShape study



Head-on frame (most event-gen, HepMC record)





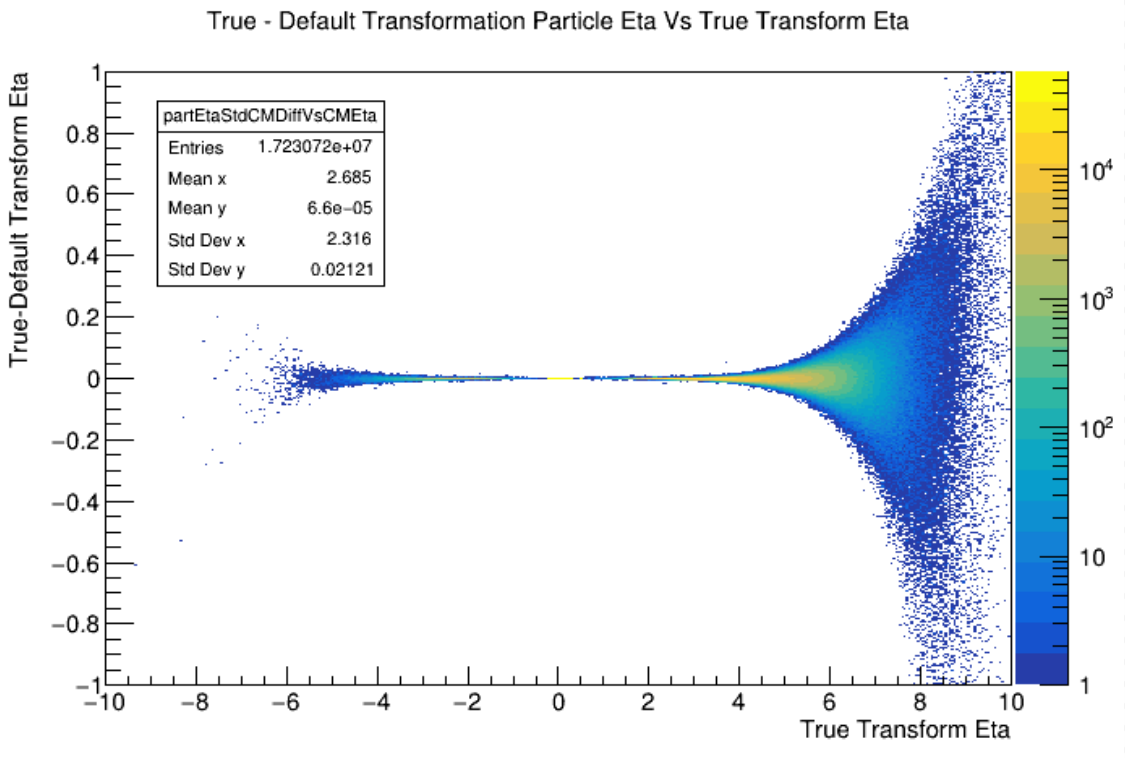
~12.5mrad both beams

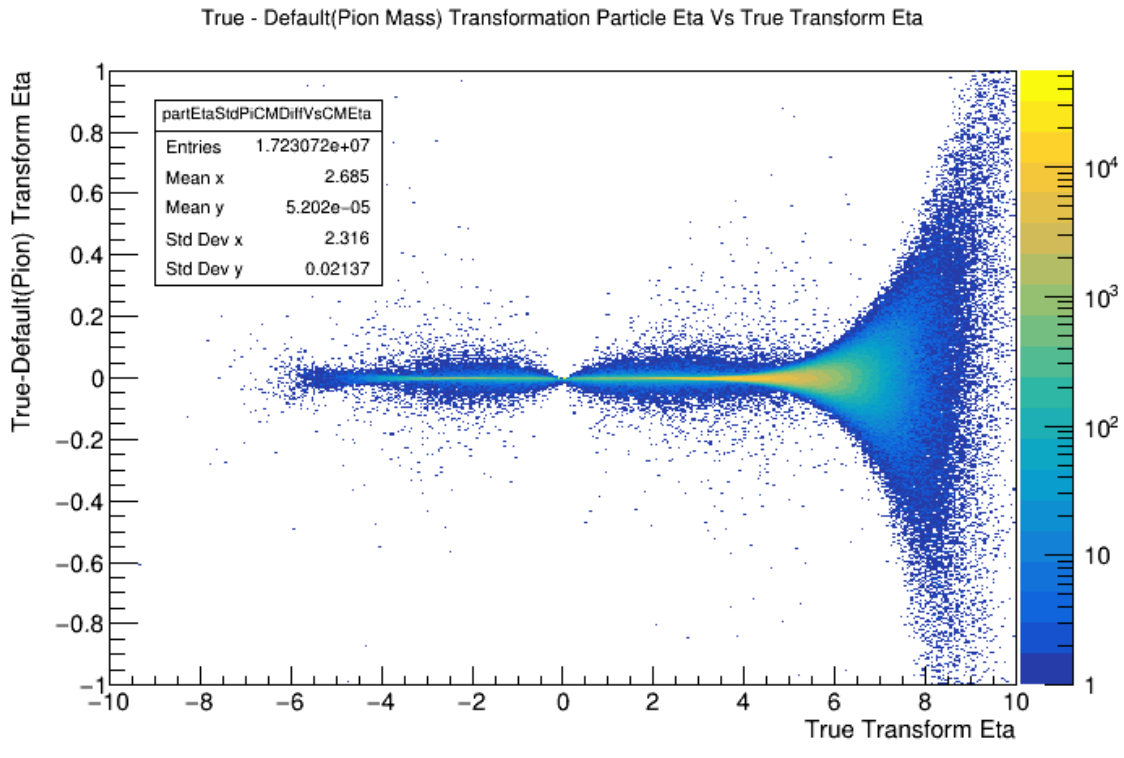
Lab frame (Detector design, Geant4, reconstruction)

~25mrad p beam

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

Summary

- EIC has complex beam effects: crossing angle, beam divergence, beam energy spread, and crabbing on beam momentum, vertex
- Need to be taken into account for all analysis in proposal stage
- Not all event generator can handle these beam effect
- ECCE simulation campaign will take
  - Event generators in head-on frame
  - Apply these beam effects via Fun4All afterburner
- Analyzer 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 $E_{Lab} = E_{HeadOn}/\cos(crossing\ angle/2)$
  - Some effect are stochastic, e.g. beam divergence and the effect will be part of experimental uncertainty