Beam Effects in Fun4All framework and ECCE status/needs

Jin Huang

Brookhaven National Lab

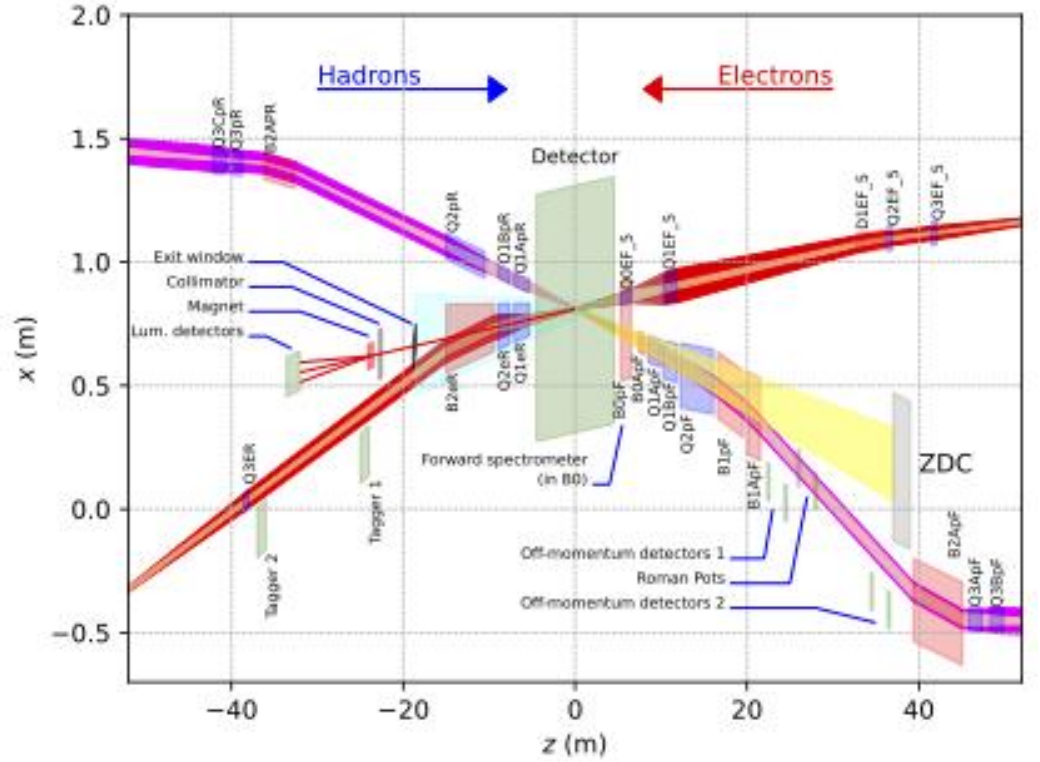
Brookhaven National Laboratory

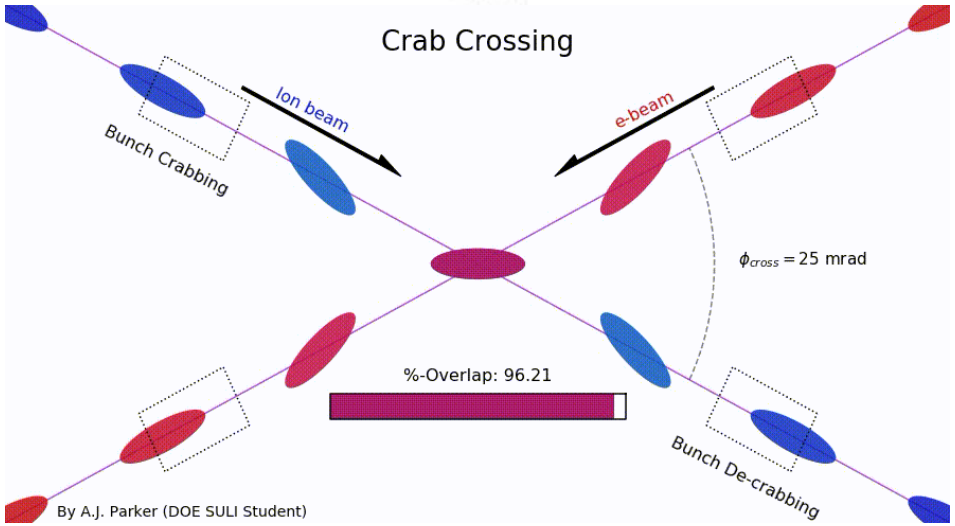
This talk is based on:

- Technote by J. Adam, E.-C.Aschenauer, M. Diefenthaler, Y. Furletova, J. Huang, A. Jentsch, B. Page, D. Romanov [Link]
- ECCE 3rd simulation workshop, July 8, 2021 [Link], in particular, work from P. Steinberg, W. Li, B. Schmookler

Leading order beam effects

- At EIC unique accelerator with diverse beam effect [ref: CDR]
  - -25 to +35 mrad beam crossing angle, both supported in ECCE setup
  - 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
- Interestingly, sPHENIX will run w/ 2mrad beam crossing angle at RHIC [ref: BUP]
  - Common interest in sim/reco./theory
  - Also use Fun4All simulation+reconstruction framework [link]

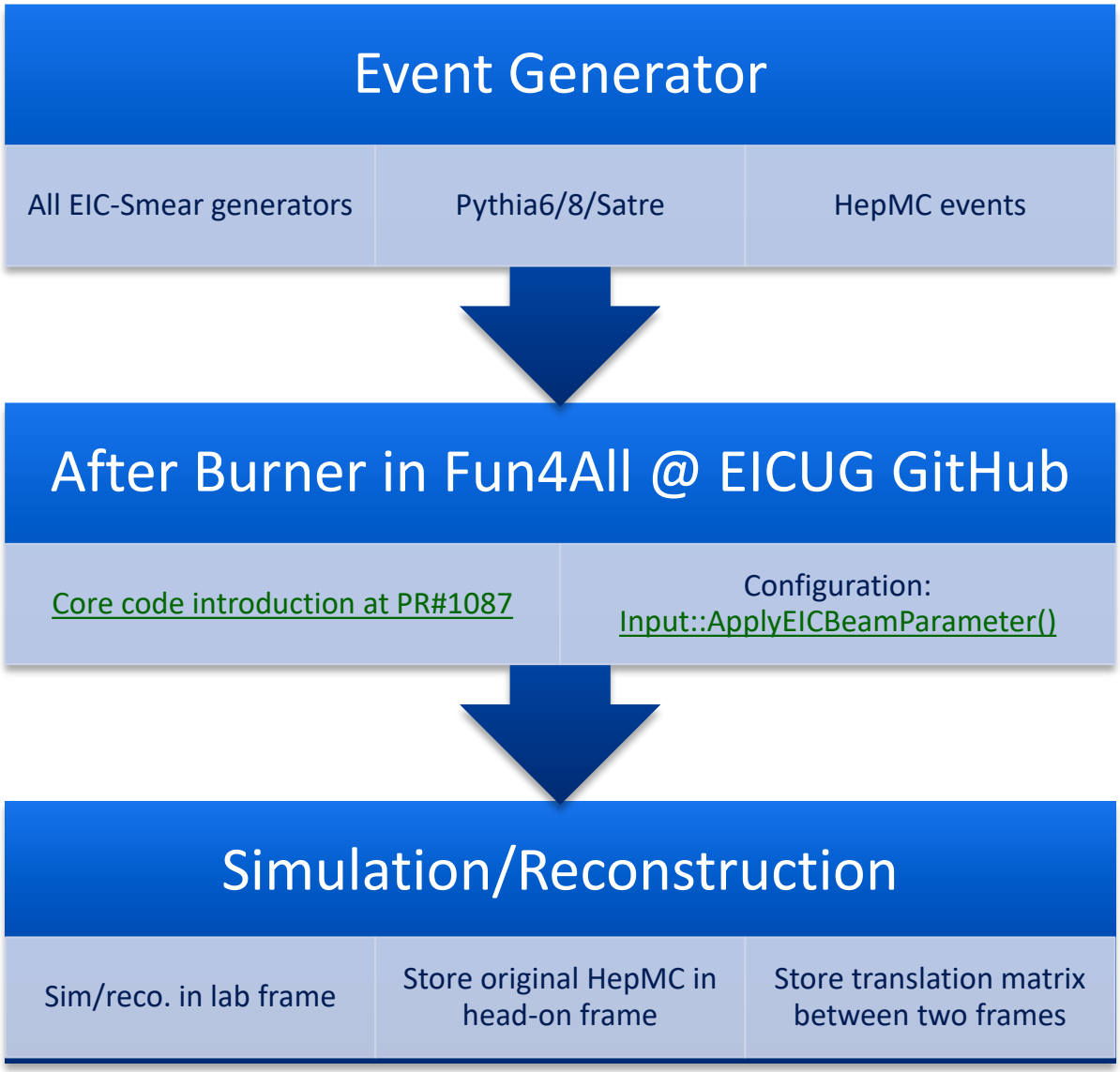




Beam Effects in Fun4All framework

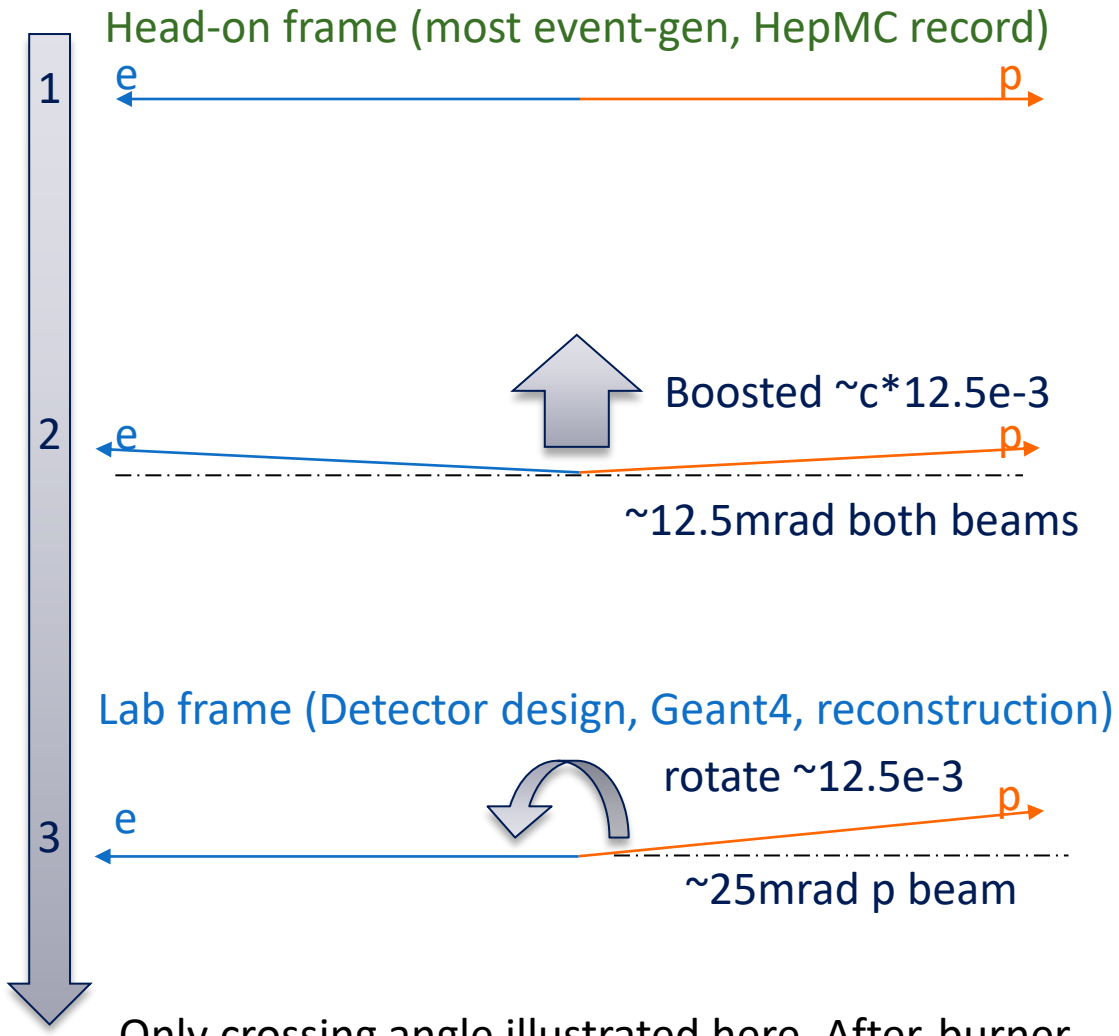
Beam effects in Fun4All sim.

- 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: $\sqrt{s_{eN}}$ is not changed in after-burner as it is boost invariant. Effect is small for most non-threshold measurement O(10^{-4})
- Book-keeping
  - Truth vertex, beam angle (variation event-by-event)
  - Truth and reco transformation matrix for reco objects → head-on frame



How does it work: the transformation

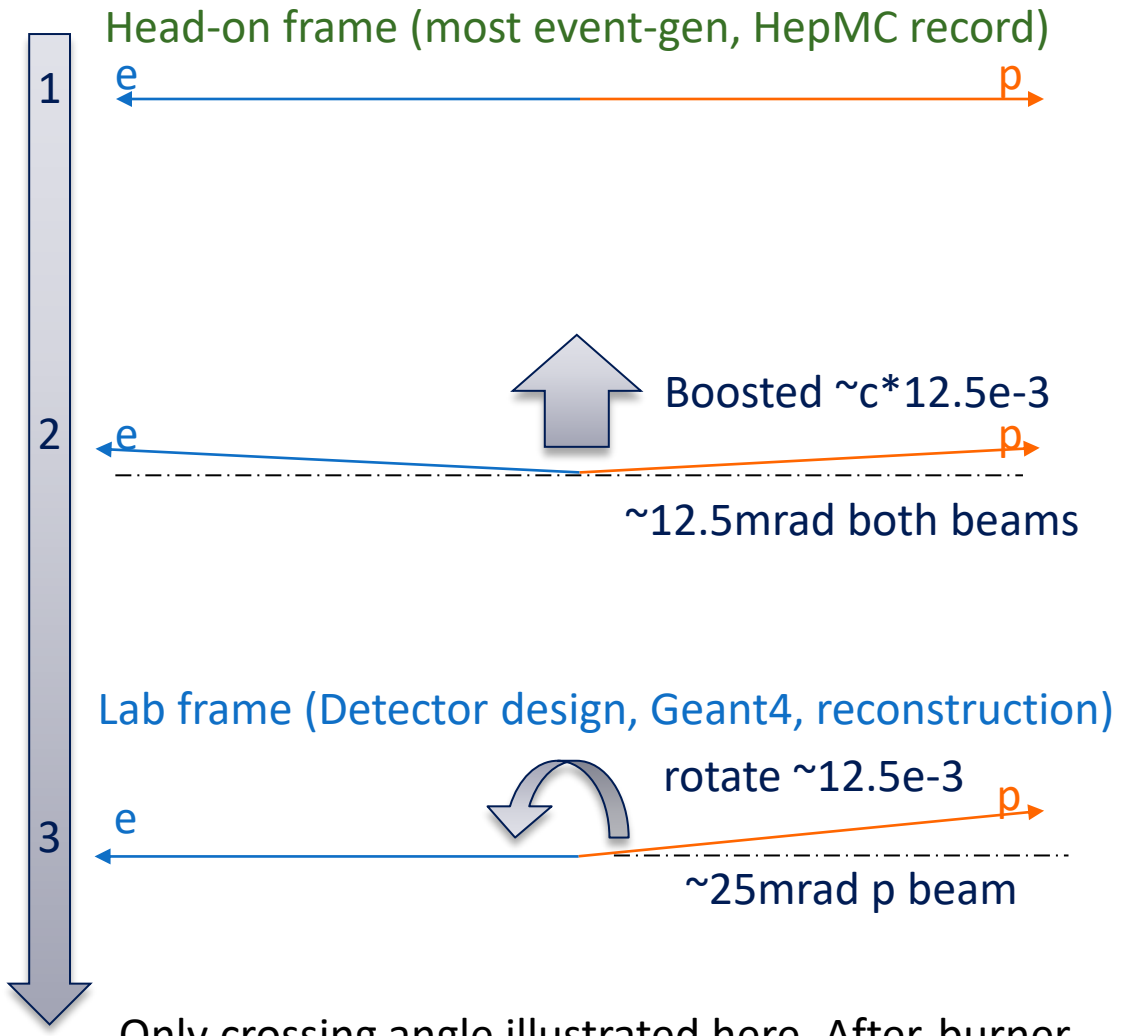
- Head-on → Lab transformation: one boost + one rotation
- Precise solution for relativistic beam
  - Minimal modification to beam energy, or RMS(Δp)
  - Significant simplify config management independent of beam specie and energy
  - Visual aid for interpretation of x-ing effects on EIC observables
- Non-relativistic beam correction
  - Correction At order $O(\theta_{Xing}\gamma_{Beam}^{-2})$ << beam divergence



Only crossing angle illustrated here. After-burner handles all beam effects [link]

How does it work: algorithm flow

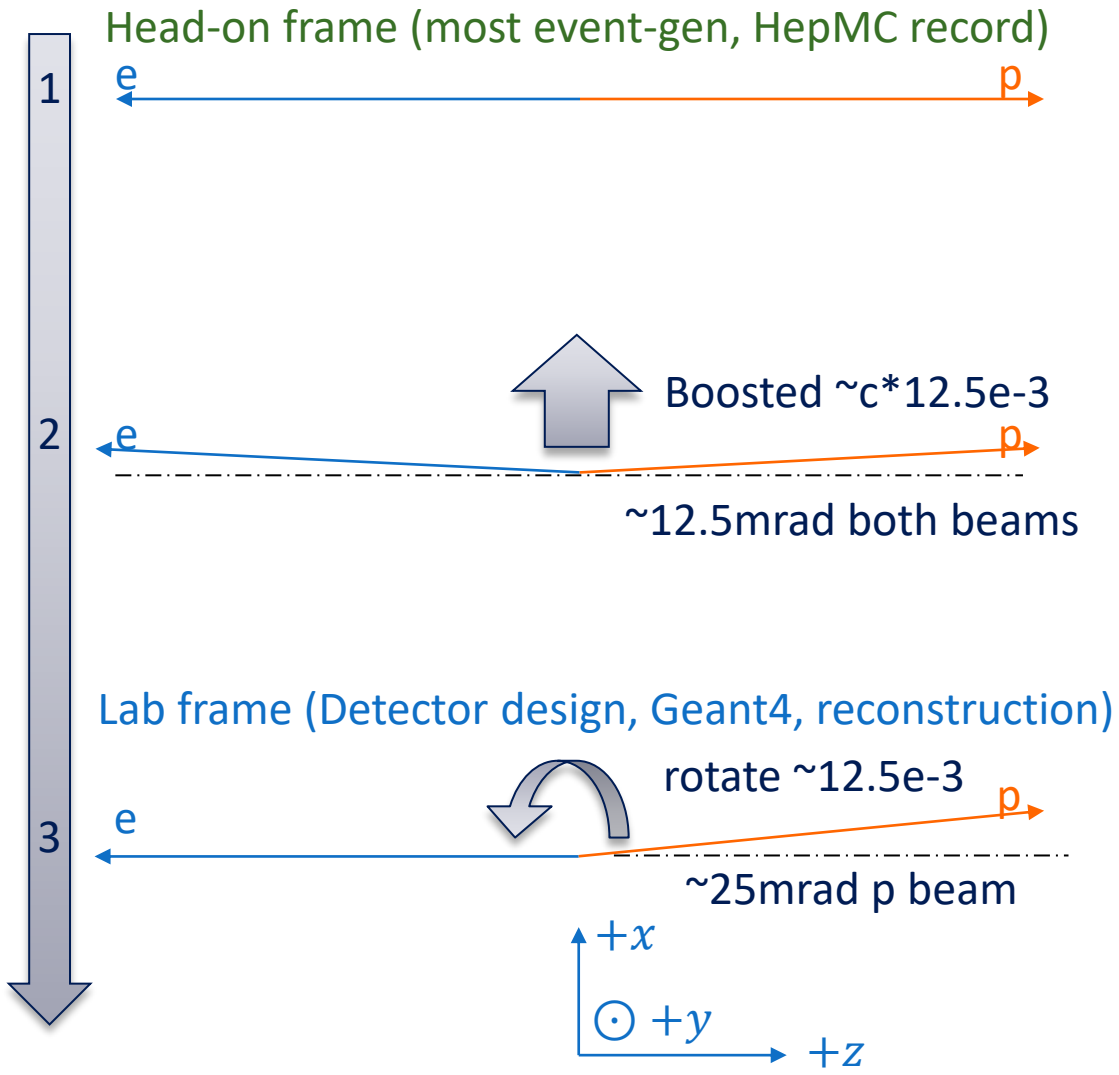
- Input via user macro [link] for beam angle, divergence, vertex shift in space time
- Calculate the boost-rotation-shift [link] that is used to translate a head-on-collision event generator's record to the lab frame and use in Geant4 simulation inputs
- Apply the boost-rotation-shift from event generator to G4 simulation input [link]
- Bookkeeping to allow analysis to reverse the transformation from lab observable to event generator frame



Only crossing angle illustrated here. After-burner handles all beam effects [link]

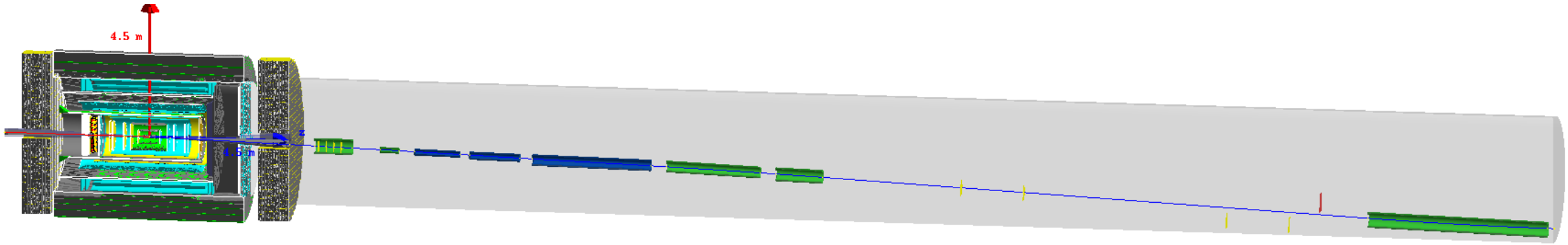
Coordinate system

- 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
  - +z axis: inverse of electron beam direction
  - +y axis: up
  - +x axis: $y \times z$, towards center of RHIC ring
- Note: from head-on to lab frame, beam energy increase by
  $E_{Lab} = E_{HeadOn}/\cos(crossing\ angle/2)$



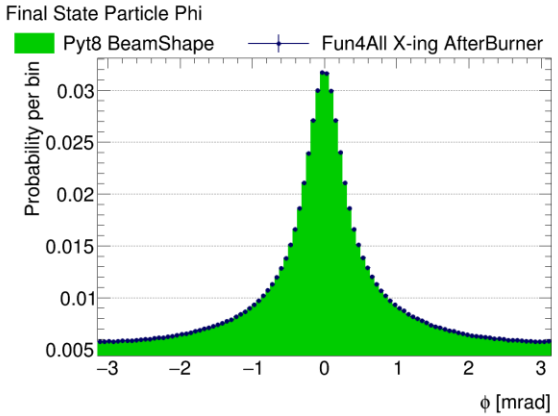
Beam transport checks

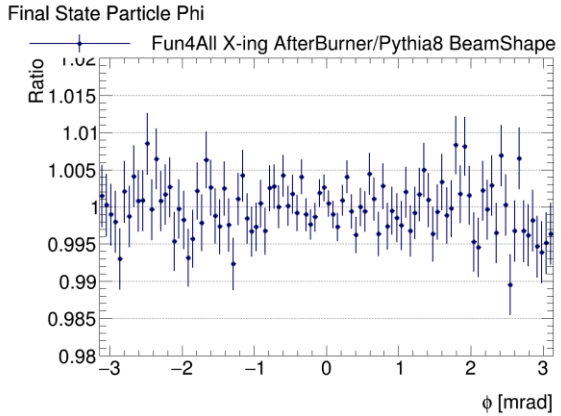
- Tested with proton and electron beam particle passing through each other in the head-on frame
- Boost-rotated to lab frame and validate the beam propagation through far-forward beamline
- Reference: https://github.com/ECCE-EIC/macros/pull/26

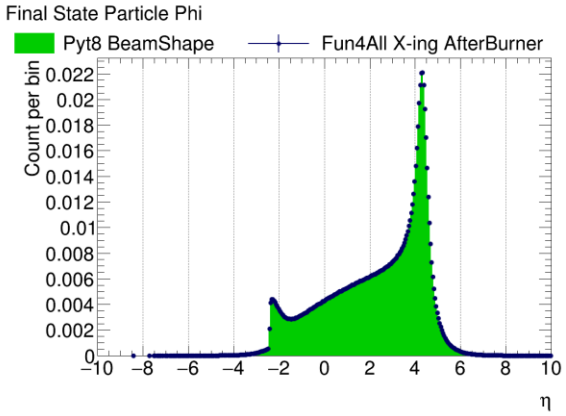


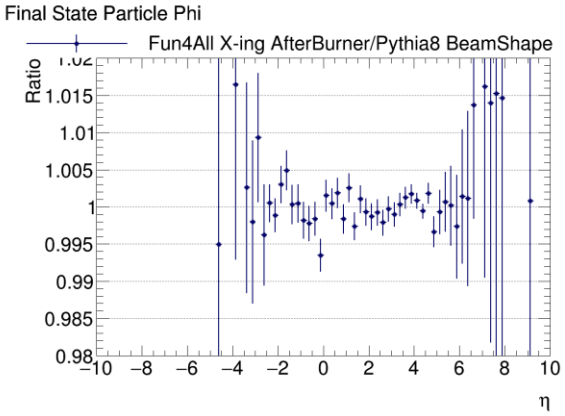
Direct comparison: Fun4all afterburner vs Pythia8

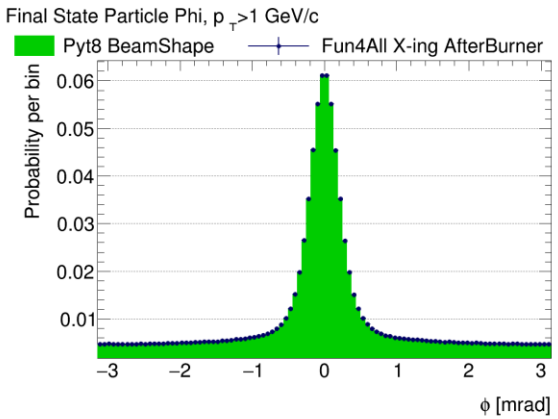
- 1M Pythia8 events -> Fun4All beam afterburner -> G4 ↔ compared to 1M Pythia8 BeamShape [link]. Also checked with IP6/8 and low-high beam configuration [link]
- Consistency well beyond the 1% stat. uncertainty provided by the test sample

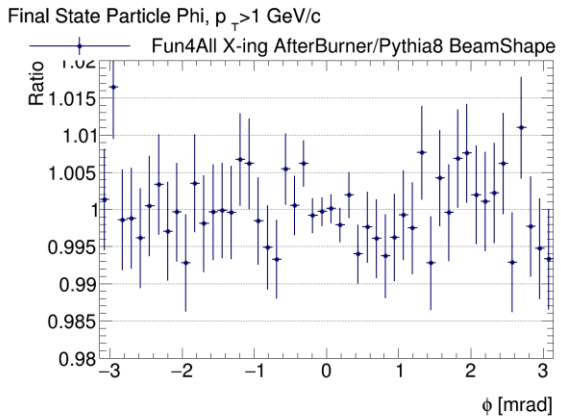


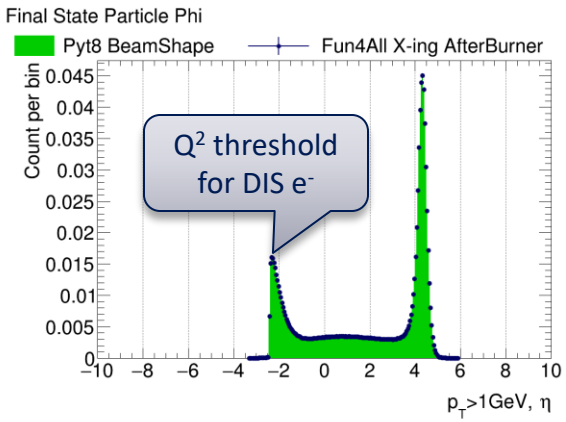


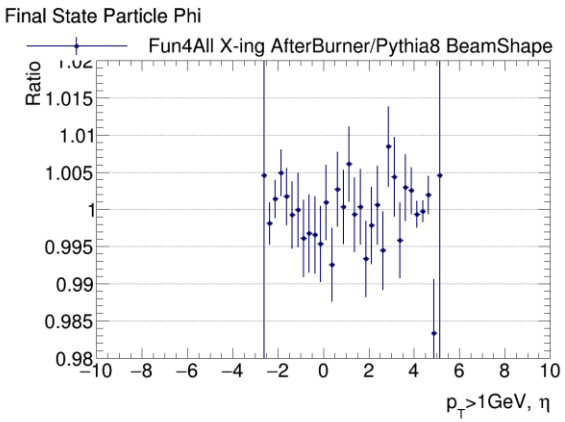










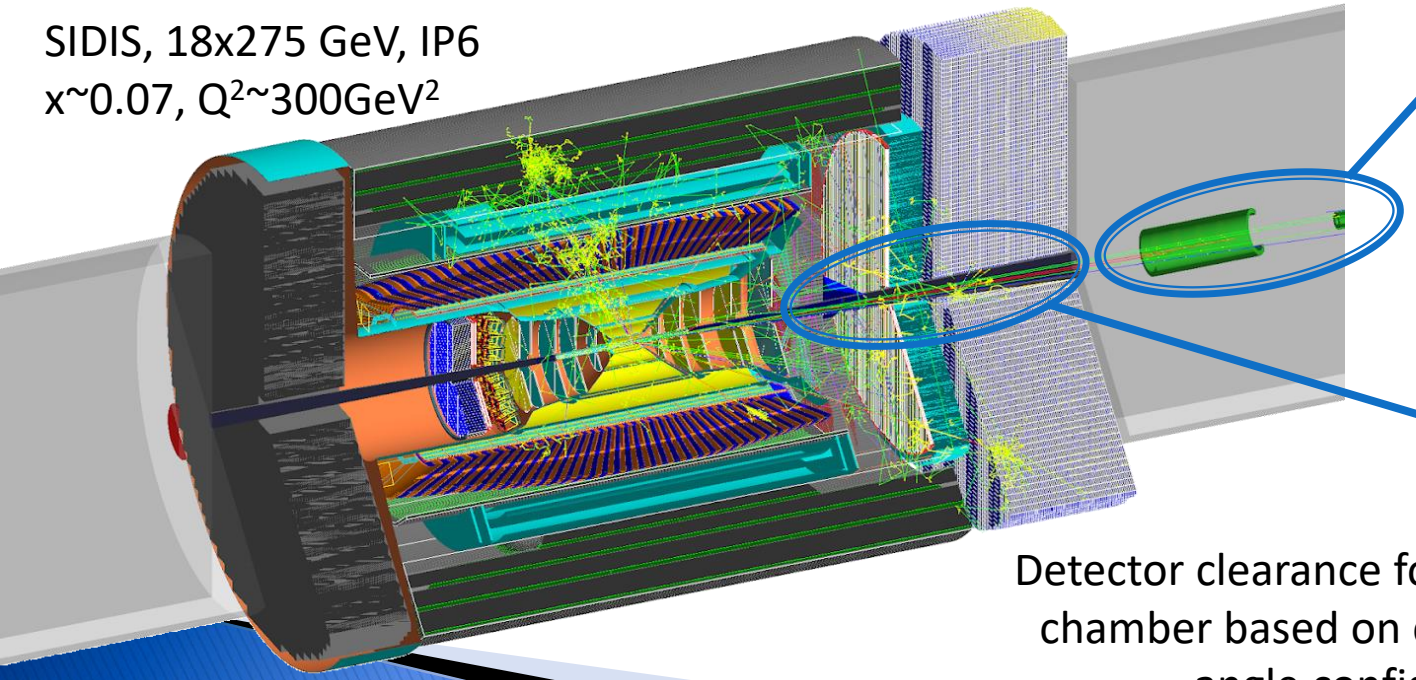


ECCE status/needs

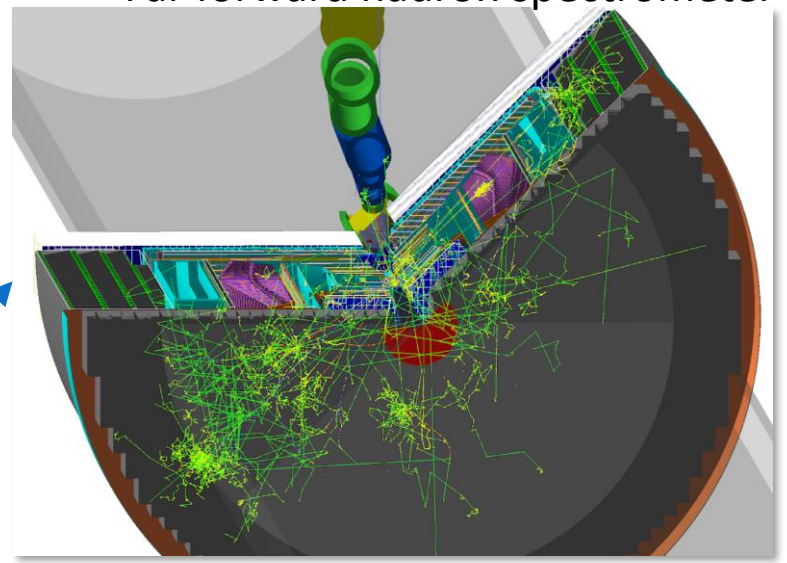
Beam chamber clearance in simulation

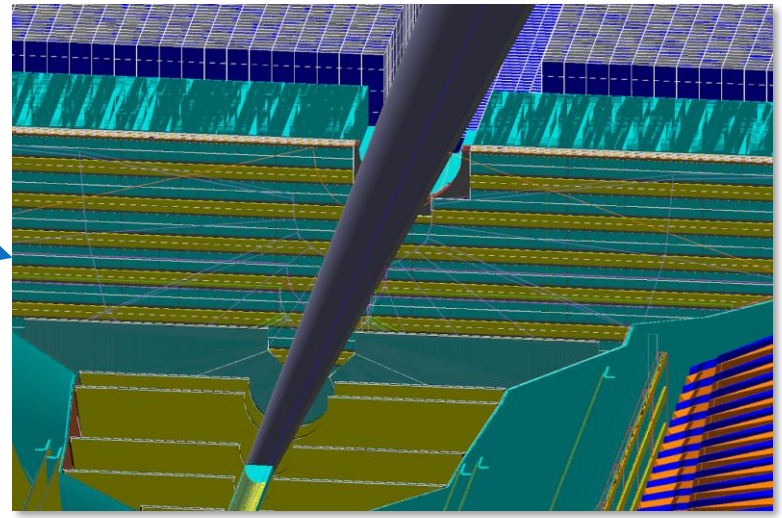
- ECCE setup support switch for IP6/IP8 beam chamber / beam line in sim-reco framework [link]

SIDIS, 18x275 GeV, IP6
$x \sim 0.07$, $Q^2 \sim 300 GeV^2$



Far forward hadron spectrometer





Detector clearance for beam chamber based on crossing angle configuration

ECCE simulation campaigns

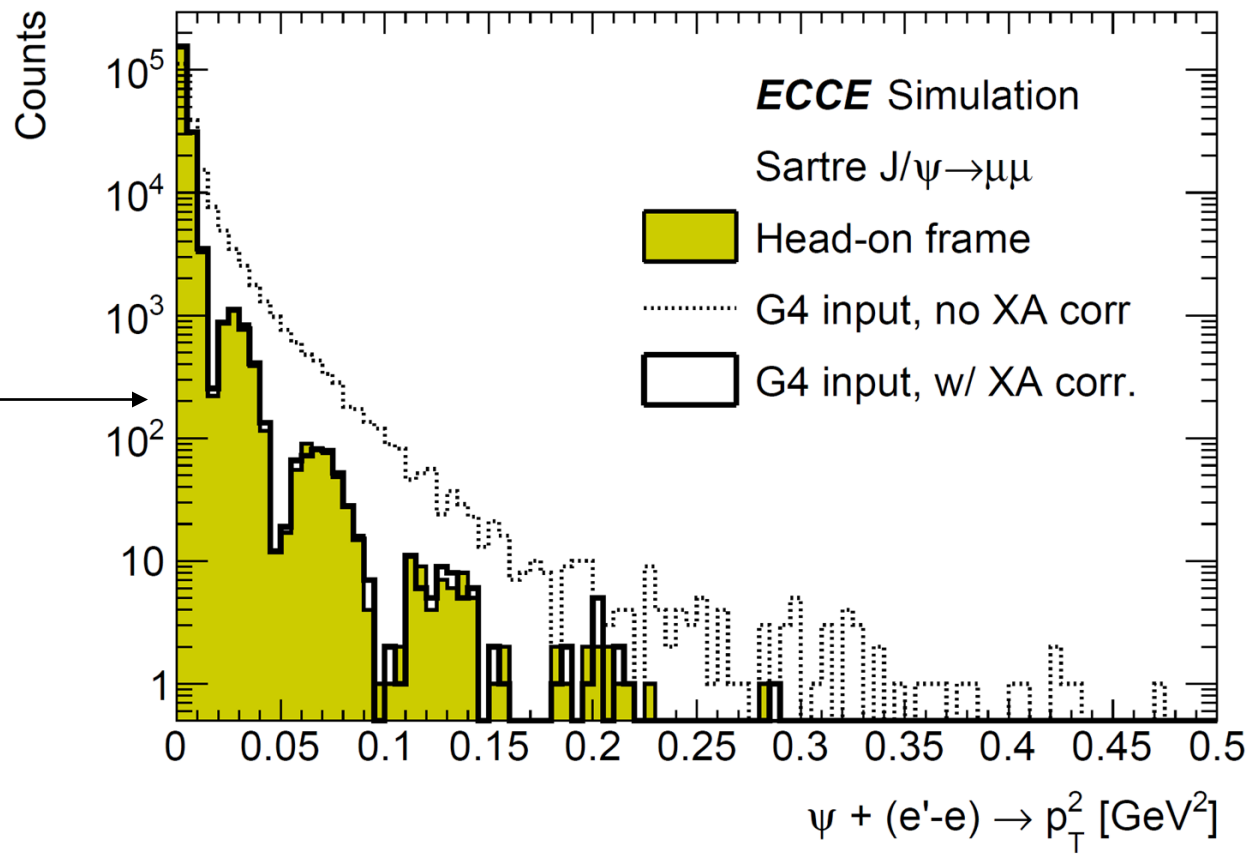
- Beam effects are built into the default macros for sim and reco.
  - Generators are run in head-on frame
  - Let Fun4All take care of application of beam effects (crossing angle, beam smearing, etc)
- Included in two ECCE simulation campaigns since June 2021
- Applied to O(100) event generator configurations [link]
- All ECCE analysis will have beam effects built in

PWG	Process	Generator	Beam Parameters	No. Events Requested	No. Events In Storage
General	Single Pions	Particle Gun	N/A	5M	4.9M
General	Single Electrons	Particle Gun	N/A	5M	4.98M
HF & Jets	HF	Pythia8	5x41 ep	5M	4.94M
HF & Jets	HF	Pythia8	10x100 ep	5M	4.87M
HF & Jets	Jets	Pythia8	18x275 ep	4M	3.81M
SIDIS	(SI)DIS	Pythia6	18x275 ep	20M	19.97M
HF & Jets	Jets	Pythia8	10x100 ep	20M	19.51M
HF & Jets	Jets	Pythia8	18x275 ep	20M	19.45M
SIDIS	(SI)DIS	Pythia6	18x100 ep	20M	14.95M
HF & Jets	Jets	Pythia8	10x100 ep	2M	1.93M
Inclusive	Neutral	Djangoh	18x166 eHe3	1M	0.98M
Inclusive	Neutral	Djangoh	5x41 ep	1M	0.982M
Inclusive	Neutral	Djangoh	10x100 ep	1M	0.978M
Electroweak	Charged	LQGENEP (Leptoquark)	18x275 ep	1M	0.975M
Electroweak	Charged	LQGENEP	18x275 ep	1M	0.95M

Discussion: reconstruction / analysis

- Lorentz invariant variable is reconstructed regardless frame, e.g. x-y-z-W-Q2-PhT
  - Native language for DIS, as γ^* always has crossing angle event in head-on frame
- Vectors and Lorentz variant need to be explicitly expressed with its frame, e.g. angle, pseudorapidity, p_T
  - In sim we know e-by-e divergence. Truth Lorentz-rotation matrix between head-on and lab frame can be used to isolate effects from divergence and vertex smearing
  - In reco, we only know average beam vector. Therefore, lab to head-on boost in reco is TLorentzRotation().RotateY(12.5e-3).Boost(sin(12.5e-3),0,0)

Plot from P. Steinberg



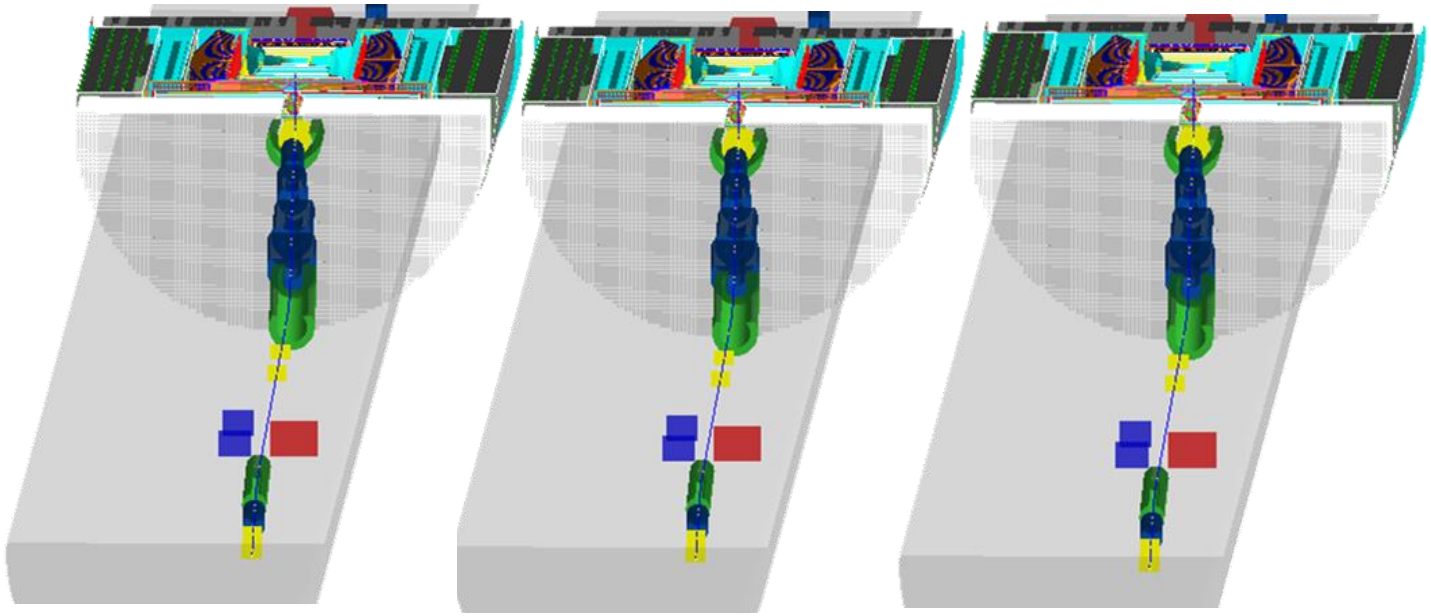
Beam steering using Fun4All (IP8)

Work by Dhevan Gangadharan (University of Houston)

Fun4all support sanmoutanous study for IP6 and IP8 in ECCE

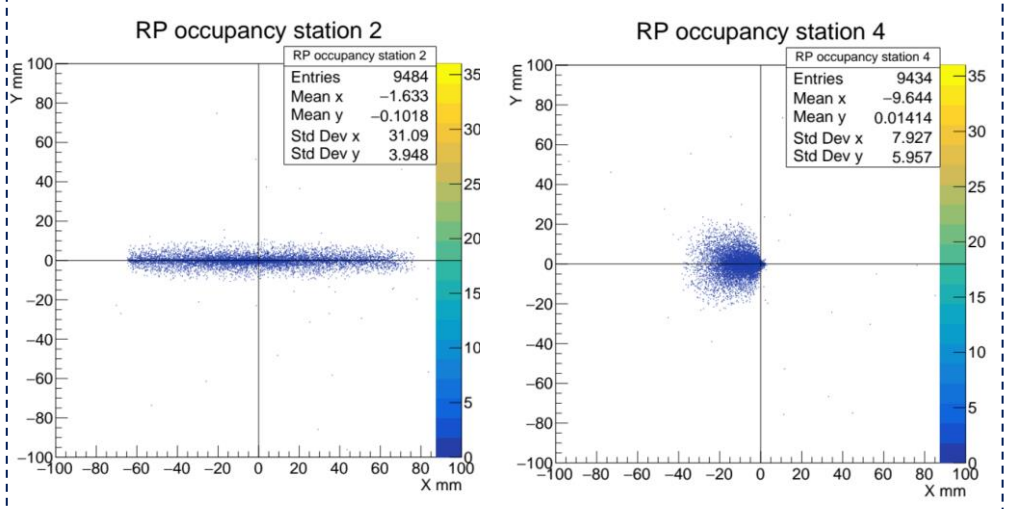
- Same event-gen file for both IPs
- Beam effect applied in Fun4All depending on the IP selection

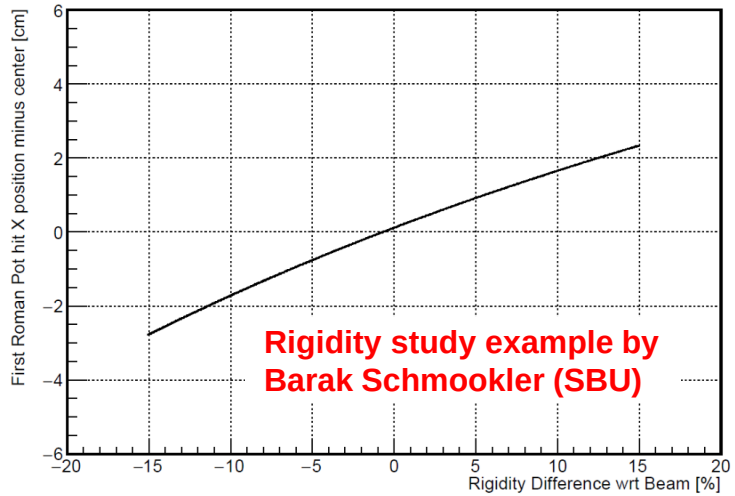
Fun4all Beam Steering Capability



IP8 41GeV proton **IP8 100GeV proton** **IP8 275GeV proton**

Occupancy before and after 2nd focus





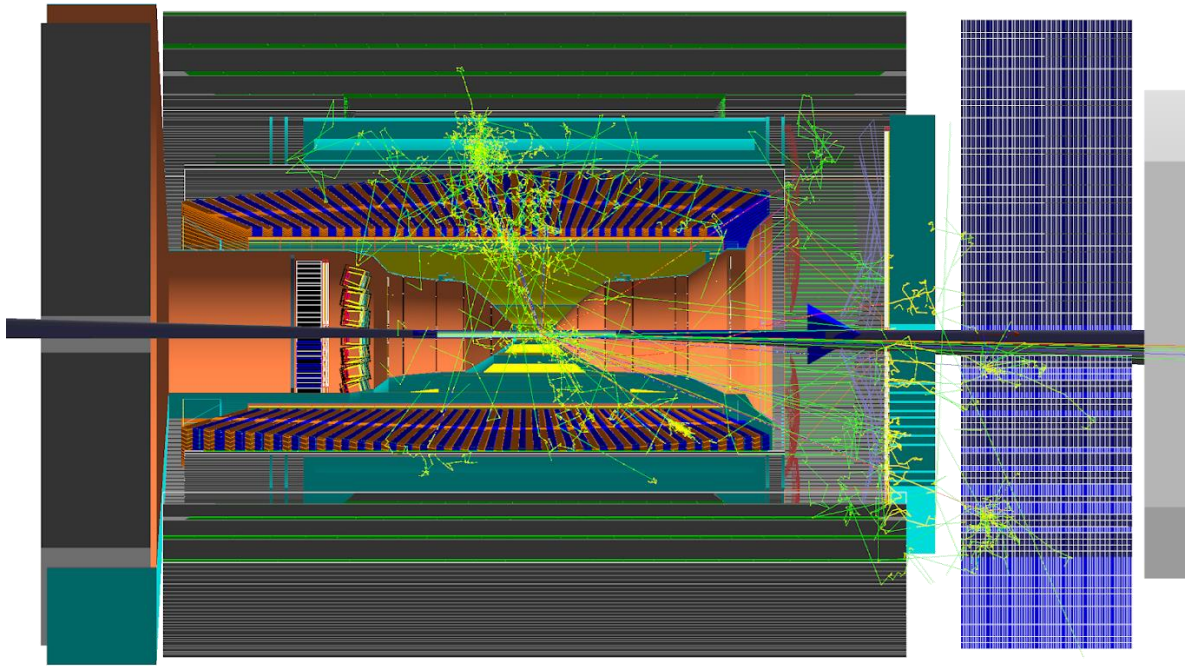
Further needs/discussions

- Near threshold production
  - Afterburner uses Lorentz transformation, which can not change boost invariants, e.g. central mass energy variation due to beam energy spread
  - Low phase space from near threshold production would make beam energy spread and small correction effects important
  - Suggest near threshold event generator support built-in beam effects, or at least beam energy spread sampling
- Treatment of beam polarization
  - L/T components of beam polarization changes at $\mathrm{O}(\theta_{Xing})$ before/after applying x-ing angle
  - Polarized event generator may need to have L/T polarization components adjusted in head-on frame to recover lab-frame beam polarization, or apply post simulation reweight

  [Thanks to Marie Boer for brining up this point during ECCE studies]

Summary

- EIC has complex beam effects: crossing angle, beam divergence, beam energy spread, and crabbing on beam momentum, vertex
- Not all event generator can handle these beam effect→ beam eff. after-burner
- ECCE simulation campaign
  - Event generators in head-on frame
  - Apply these beam effects via Fun4All afterburner
- Used in large production setting from Fun4All in past a few months, applied to O(100) event generator configurations



Extra information

Much of the work based on EICUG note

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

Jaroslav Adam[1], Elke-Caroline Aschenauer[1], Markus Diefenthaler[2], Yulia Furletova[2], Jin Huang[1], Alexander Jentsch[1], and Brian Page[1]

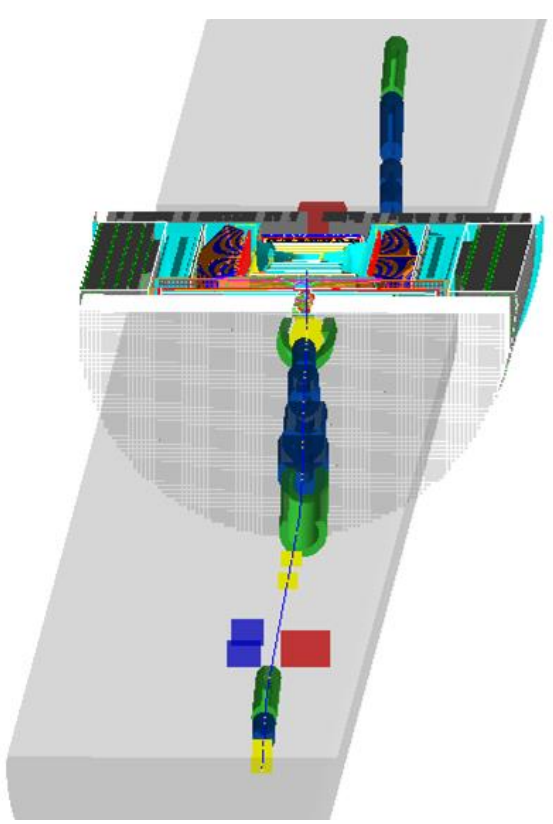
[1]Brookhaven National Laboratory, Upton, New York 11973, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA

July 8, 2021

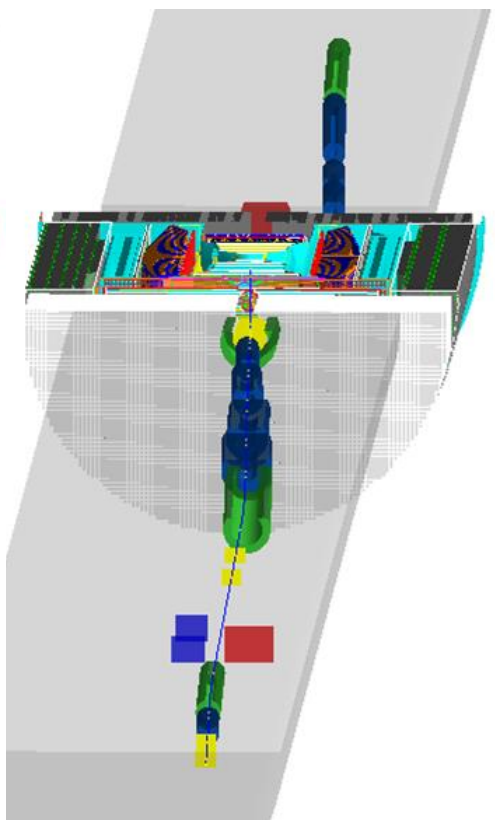
Abstract

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.

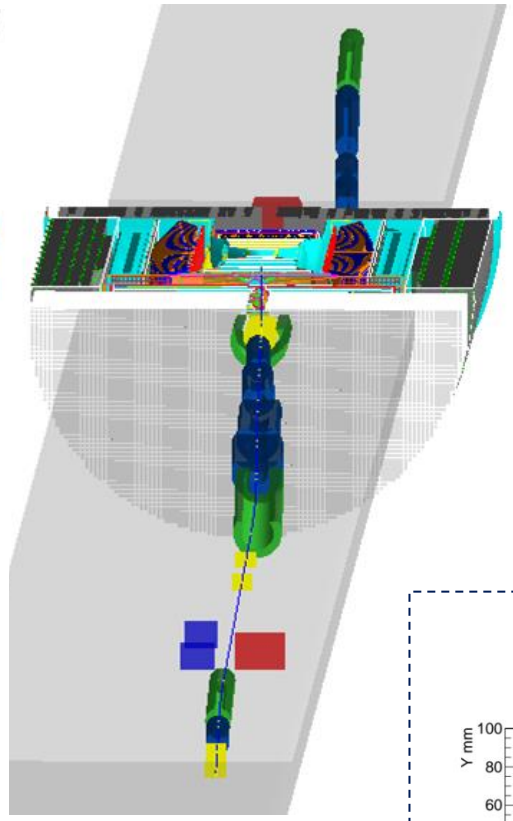
Beam steering using Fun4All (IP8)



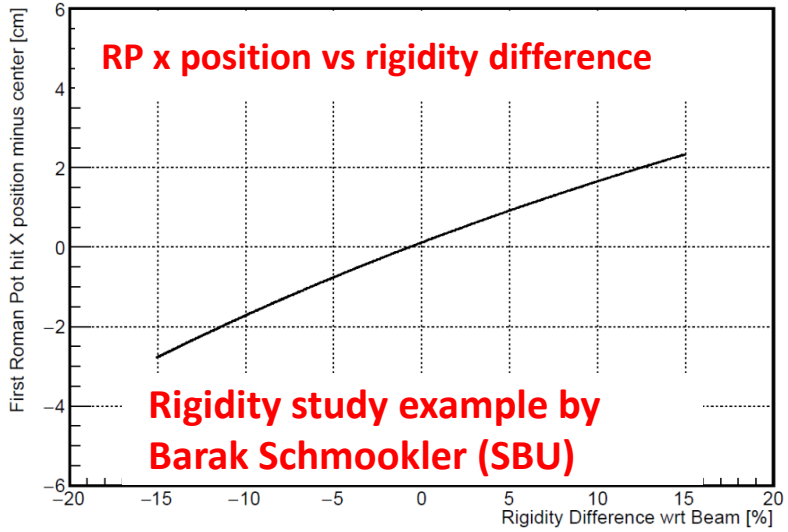
IP8 41GeV proton



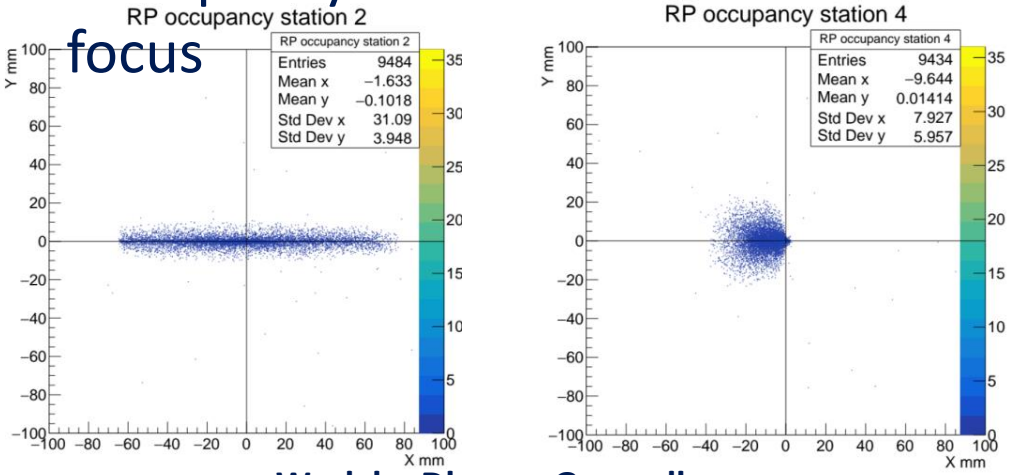
IP8 100GeV proton



IP8 275GeV proton



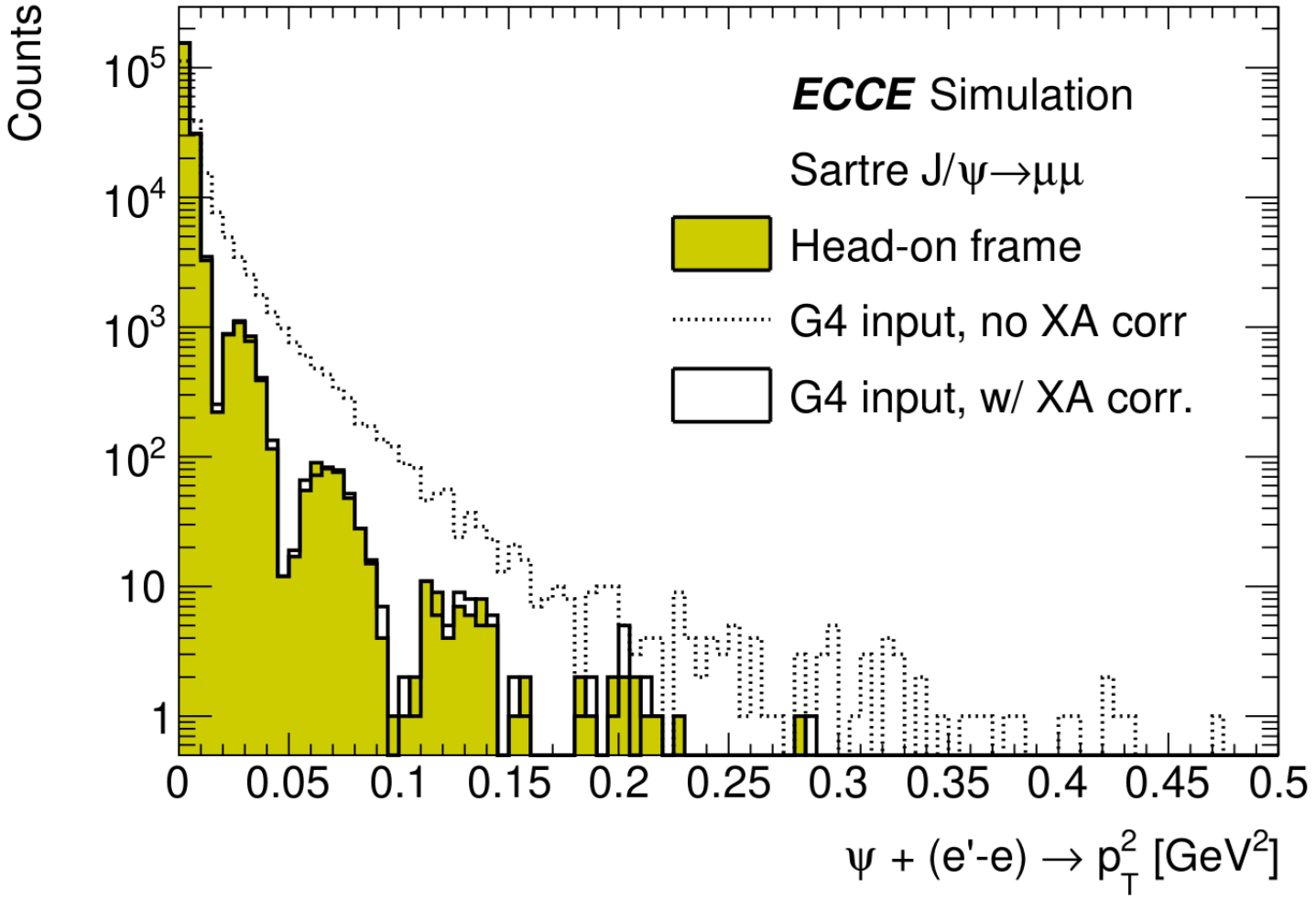
Occupancy before and after 2nd focus



Work by Dhevan Gangadharan
(University of Houston)

Fun4all Beam Steering Capability

Fun4all is Physics Ready

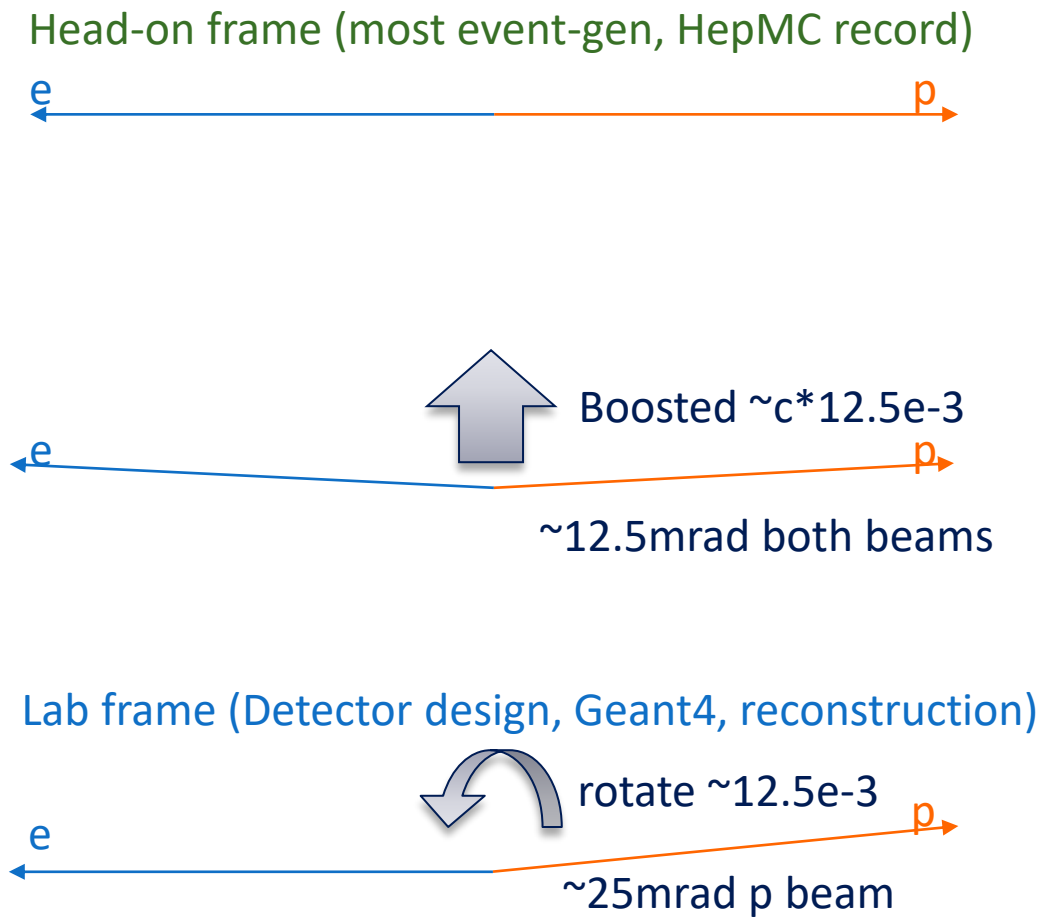


- Fun4all support sanmoutanous study for IP6 and IP8
- 2nd focus @ IP8 enhances e+A diffractive studies
- Example: eA (eZr) diffractive production of J/psi meson at IP8 by Peter Steinberg (BNL)

eA diffractive study of J/Psi production by Peter Steinberg (BNL)

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

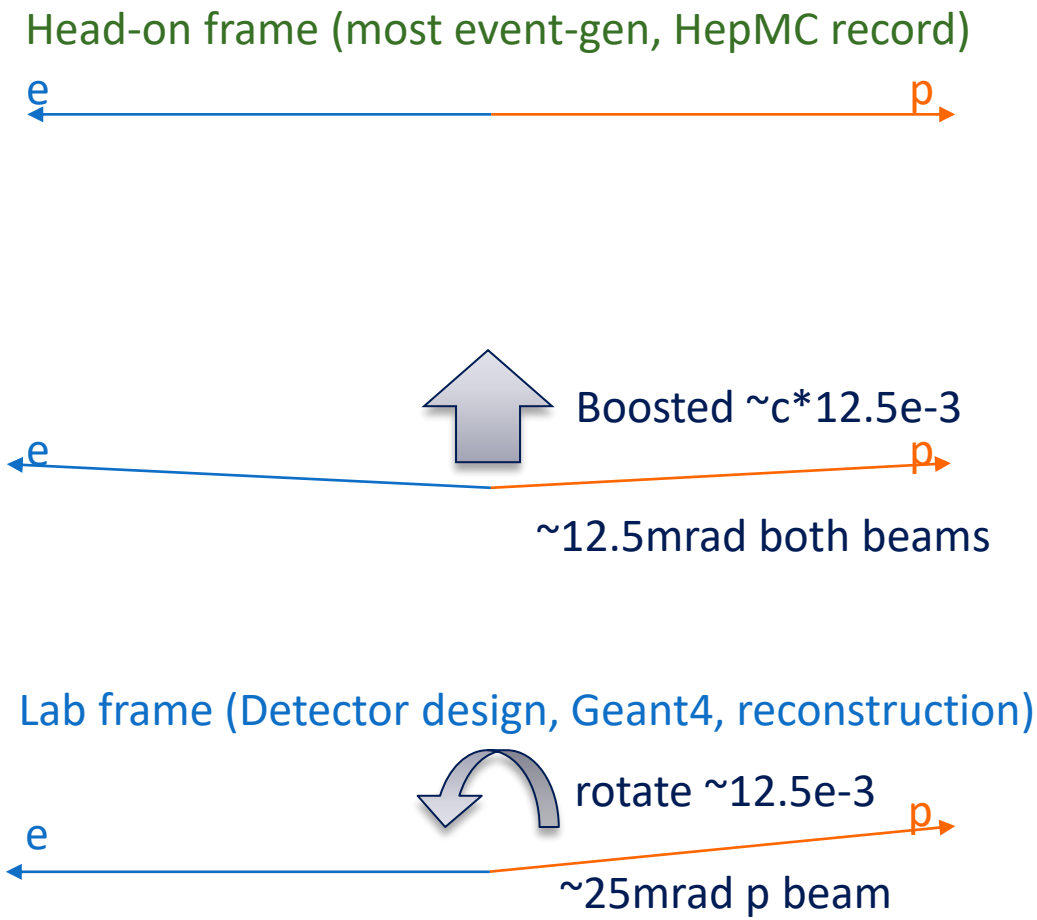


Beam effect in ECCE analysis 2: IP switch

- 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;
```

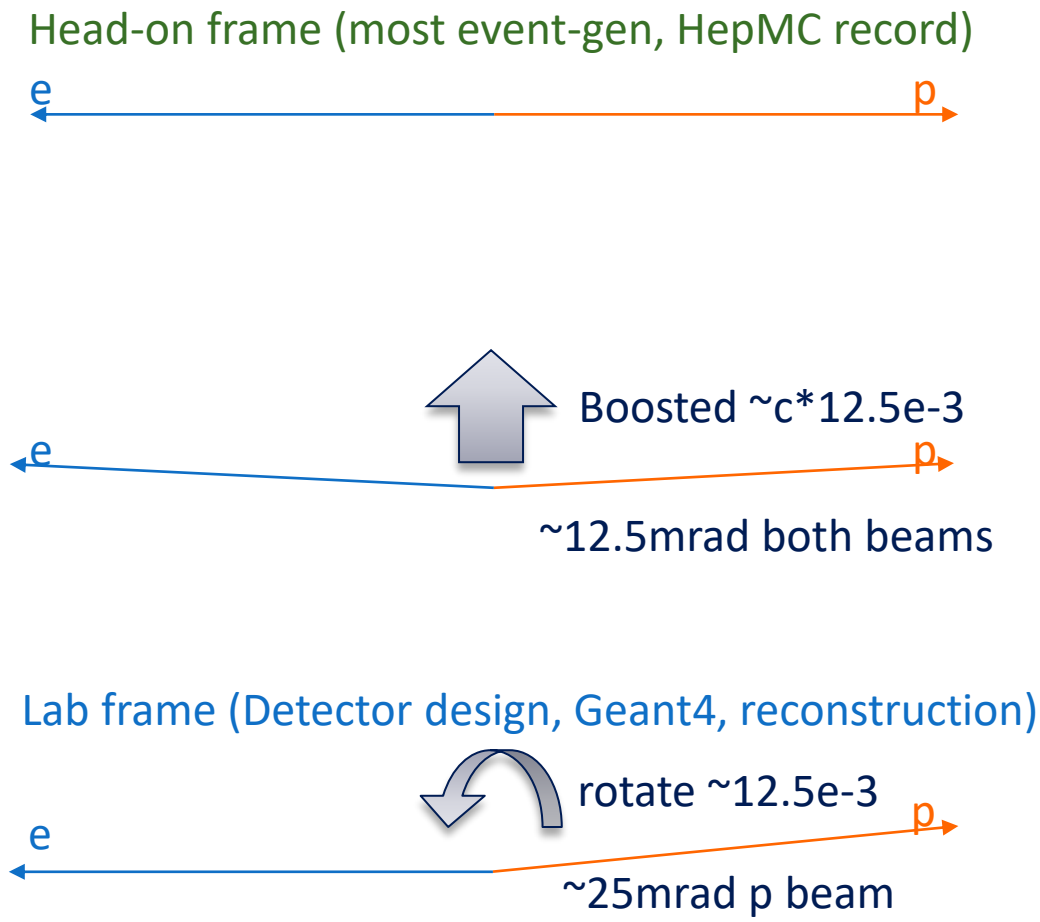


Beam effect in ECCE analysis 3: reconstruction

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

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

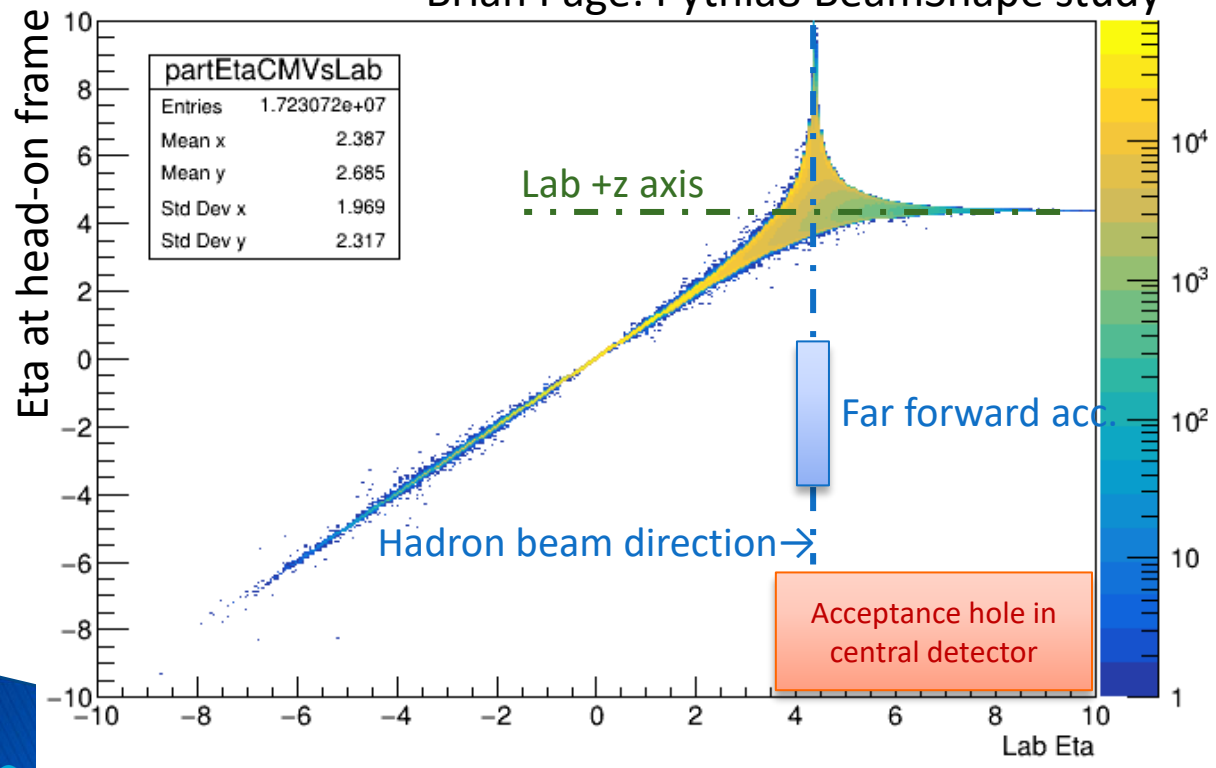
  - Electron beam four vector: (0,0,-1, 1)*E_{e_lab}
  - Proton beam Ip6, Ip8: (-sin(25mrad),0,cos(25mrad),1)*E_{p_lab}, (+sin(35mrad),0,cos(35mrad),1)*E_{p_lab}
- Lorentz invariant variable is reconstructed regardless frame, e.g. x-y-z-W-Q2-PhT
- Vectors and Lorentz variant need to be explicitly expressed 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
- In reco, we only know average beam vector. Therefore, lab to head-on boost in reco is TLorentzRotation().RotateY(12.5e-3).Boost(sin(12.5e-3),0,0)



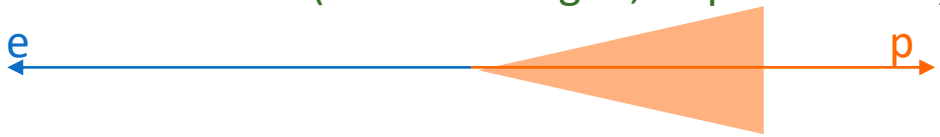
Beam effect in ECCE analysis 4: size of x-ing effect

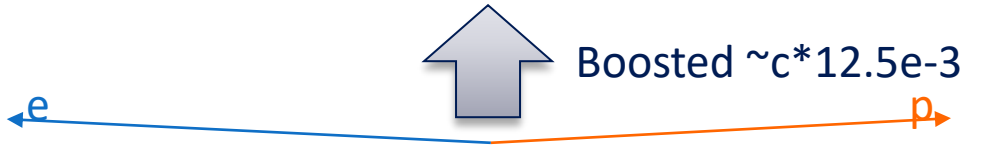
- eta_lab>2 : eta (and pT, phi) shift significant from lab to head-on

Brian Page: Pythia8 BeamShape study



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





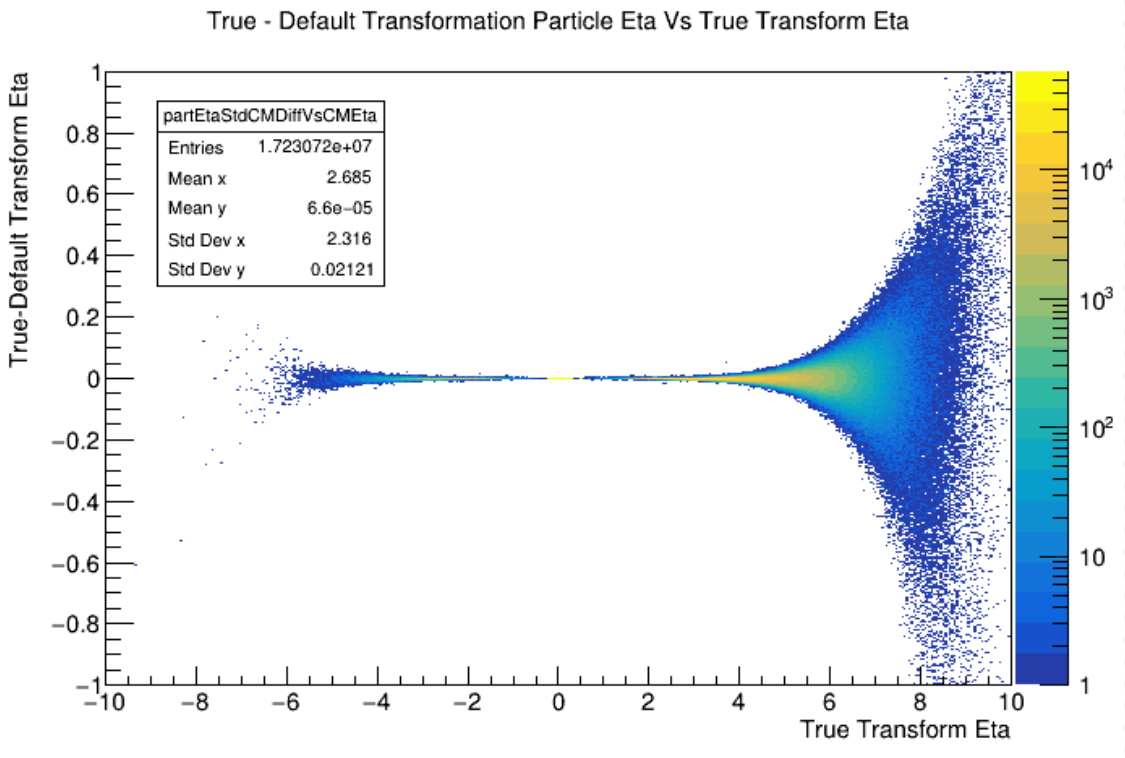
~12.5mrad both beams

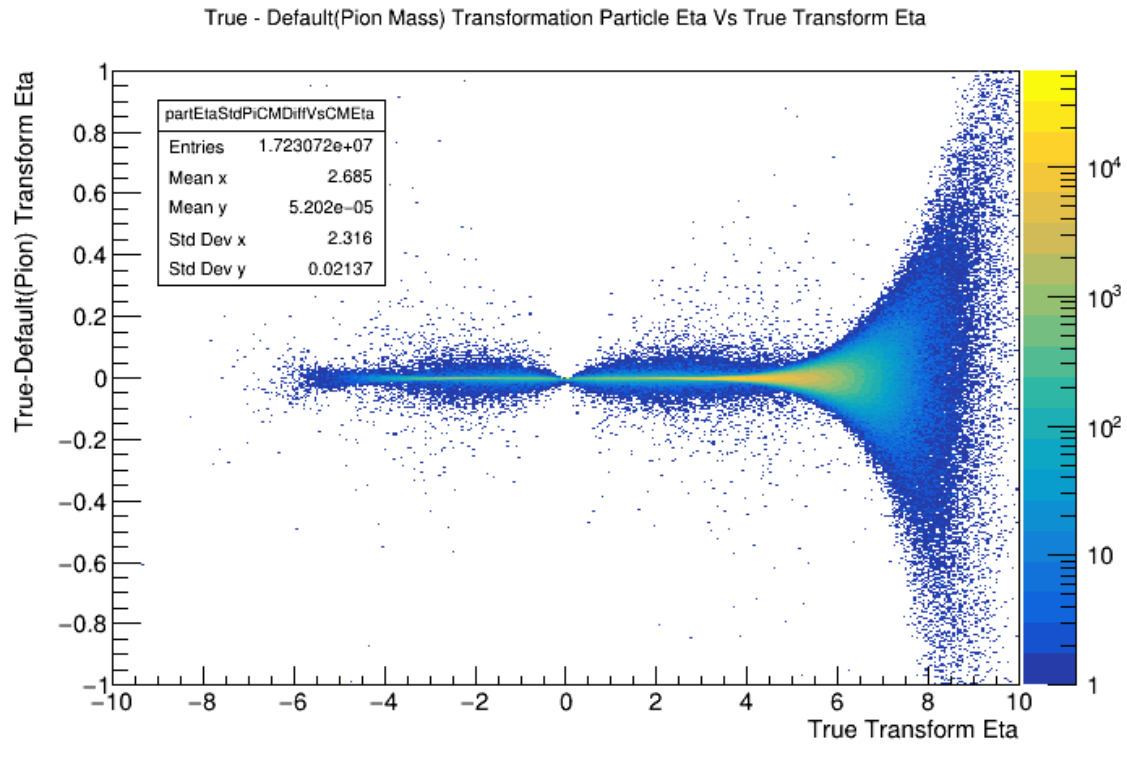
Lab frame (Detector design, Geant4, reconstruction)

~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]



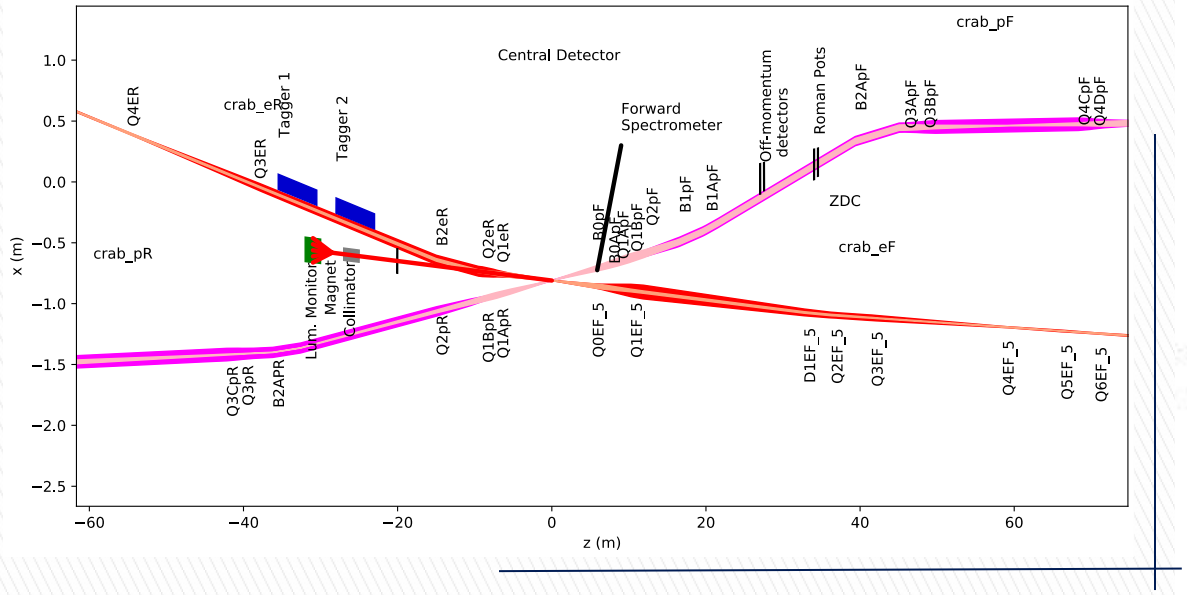


If we know PID & perfect tracking:
Left over is dominated by beam divergence

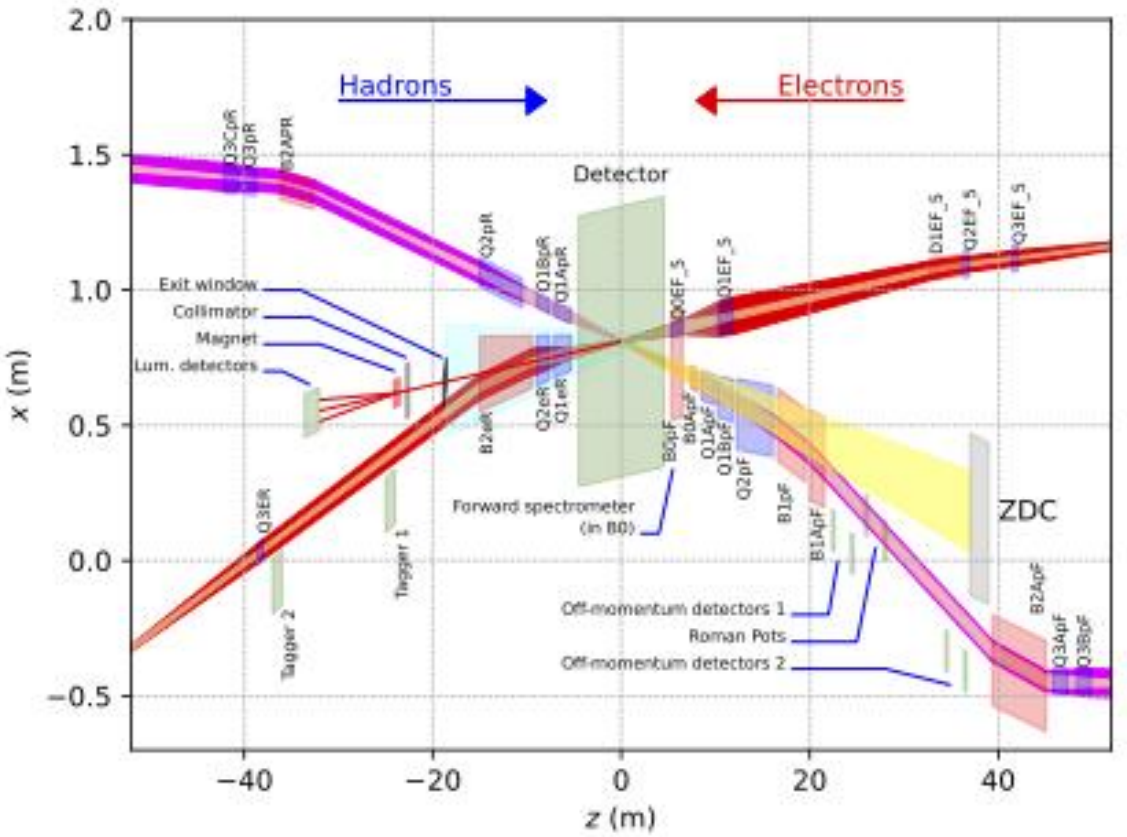
If we DO NOT know PID & perfect tracking:
Left over is imperfect boost with pi mass + divergence

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]

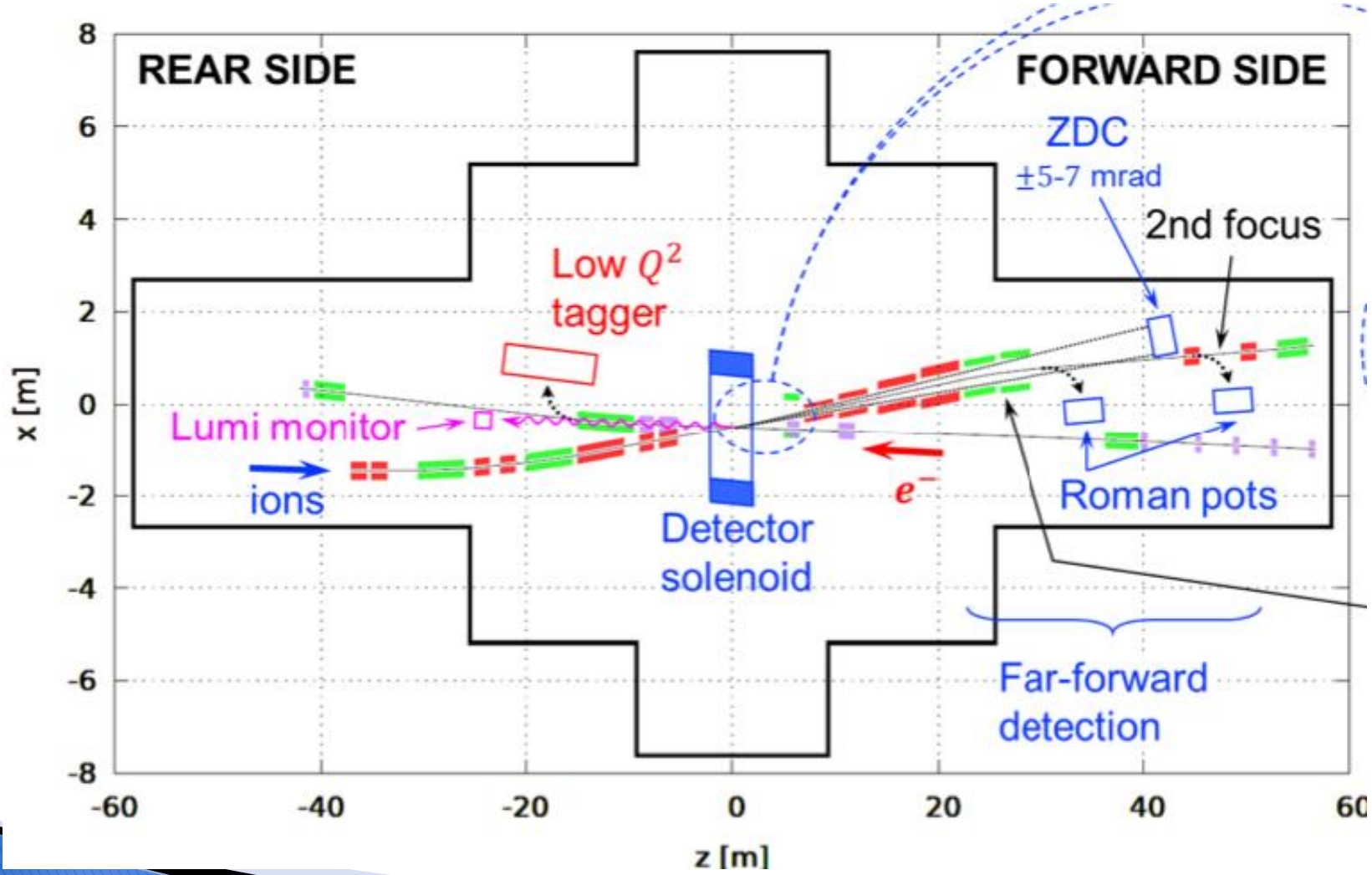
Interactive validation of reco lab->headON boost

```
root [0] TLorentzRotation l = TLorentzRotation().RotateY(12.5e-3).Boost( sin(12.5e-3),0,0) (TLorentzRotation &)
Name: TLorentzRotation Title: Lorentz transformations including boosts and rotations

root [1] (l * TLorentzVector (0,0,-1,1)).Print()
(x,y,z,t)=(0.000000,0.000000,-0.999922,0.999922) (P,eta,phi,E)=(0.999922,-100000000000.000000,0.000000,0.999922)

root [2] (l * TLorentzVector (-sin(25e-3),0,cos(25e-3),1)).Print()
(x,y,z,t)=(0.000000,0.000000,0.999922,0.999922)
(P,eta,phi,E)=(0.999922,100000000000.000000,0.000000,0.999922)
```

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