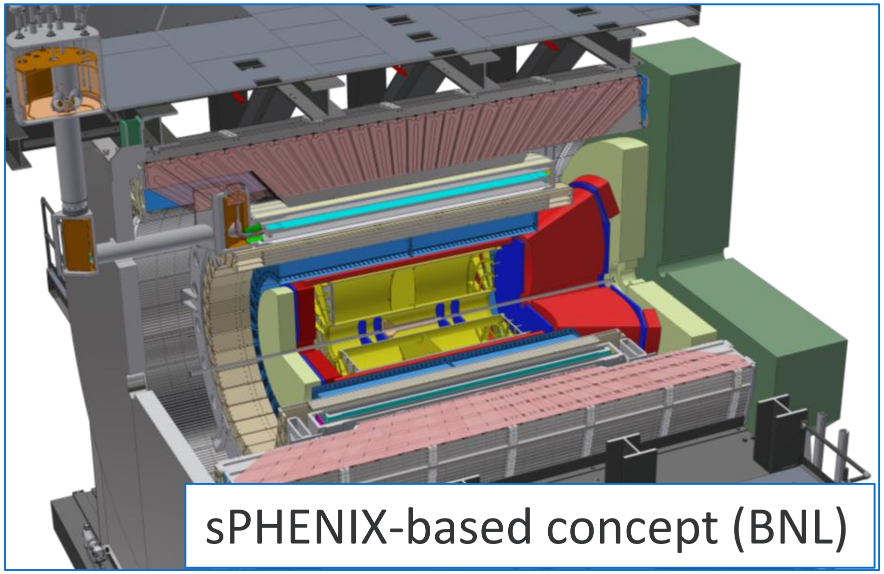
Studies of beam-gas background, neutron flux, radiation dose at an EIC

Jin Huang (BNL)

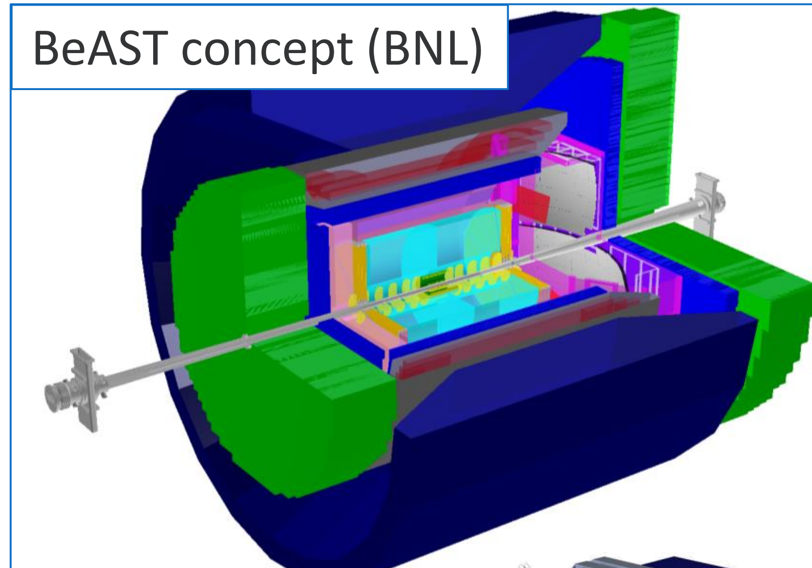
BROOKHAVEN NATIONAL LABORATORY

Thanks to the inputs from many of our colleagues!

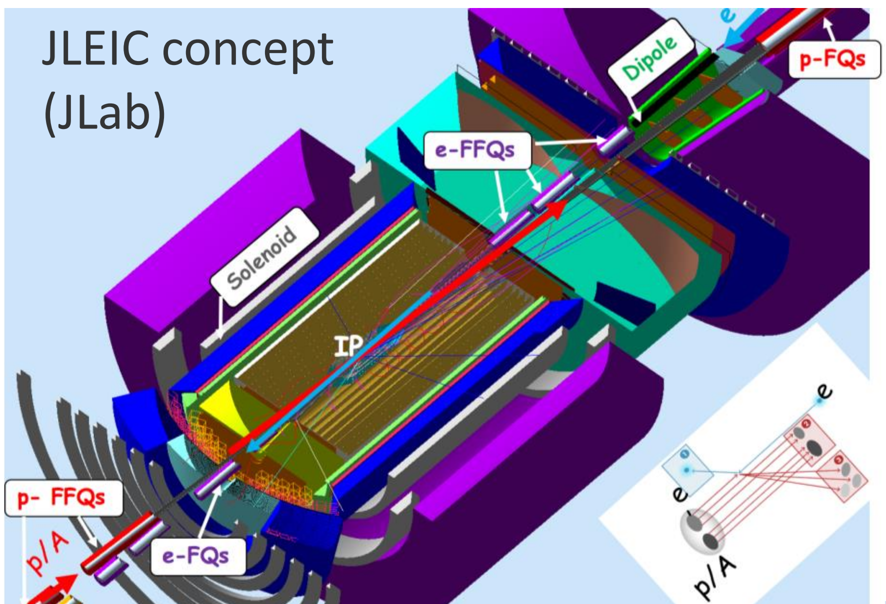
Early EIC Detector Concepts



sPHENIX-based concept (BNL)

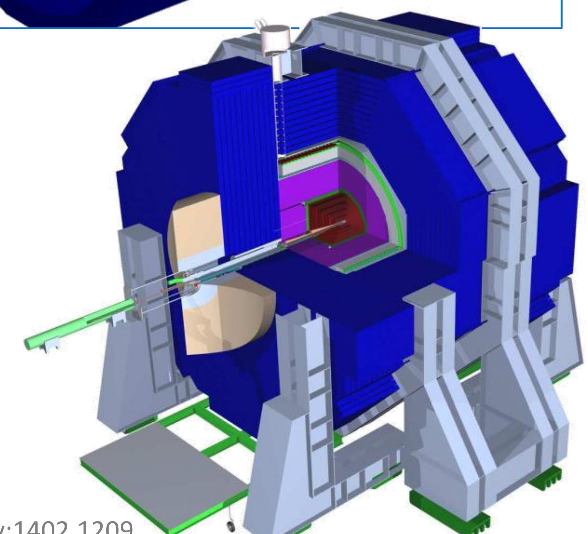


BeAST concept (BNL)



JLEIC concept (JLab)

TOPsiDE concept (ANL)



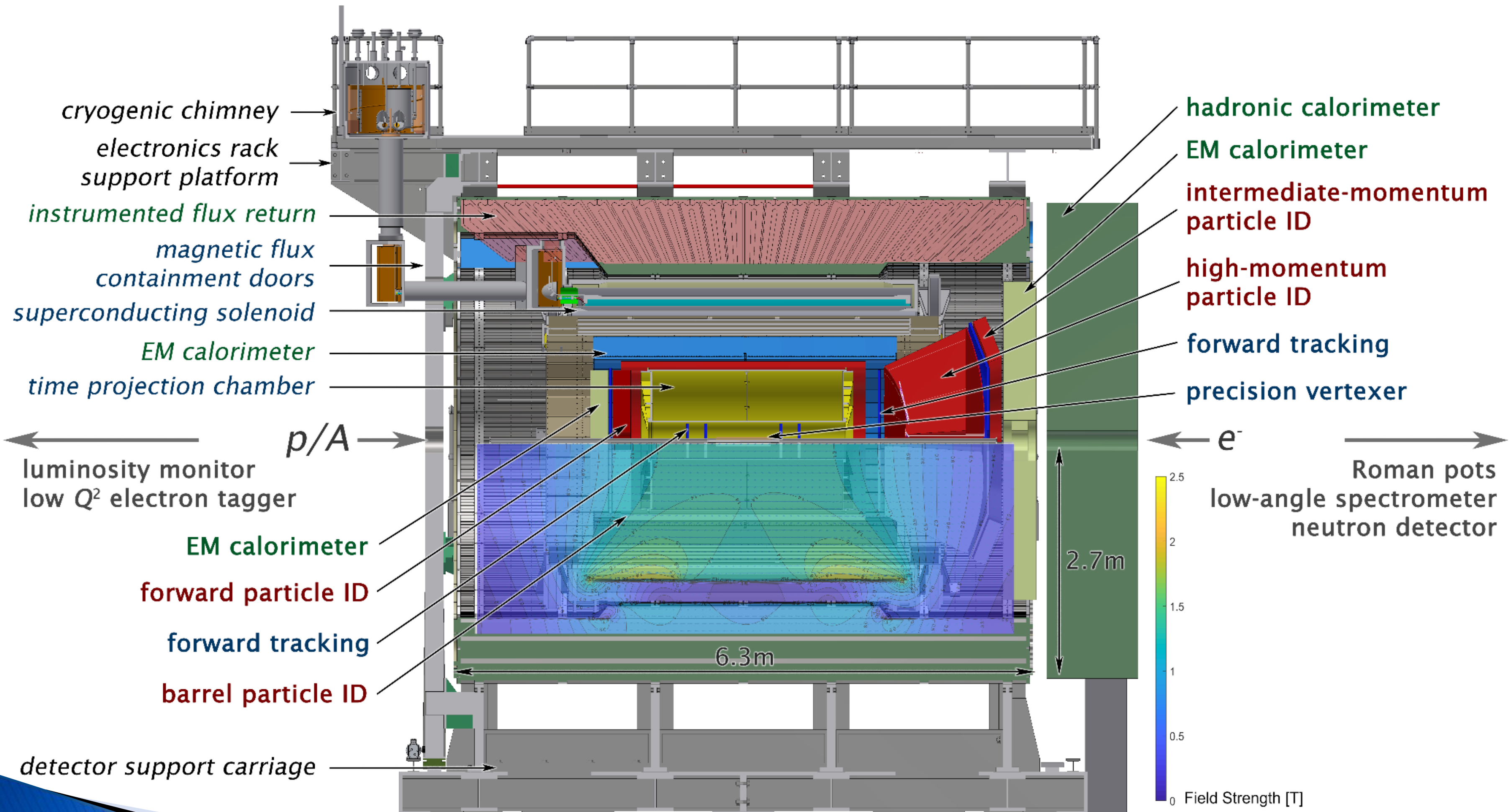
References reports :

- ePHENIX LOI: arXiv:1402.1209
- eRHIC design report, preCDR: arXiv:1409.1633
- MEIC (JLEIC) design summary: arXiv:1504.07961
- On-going development and updates

Assignment 1:
Beam gas background

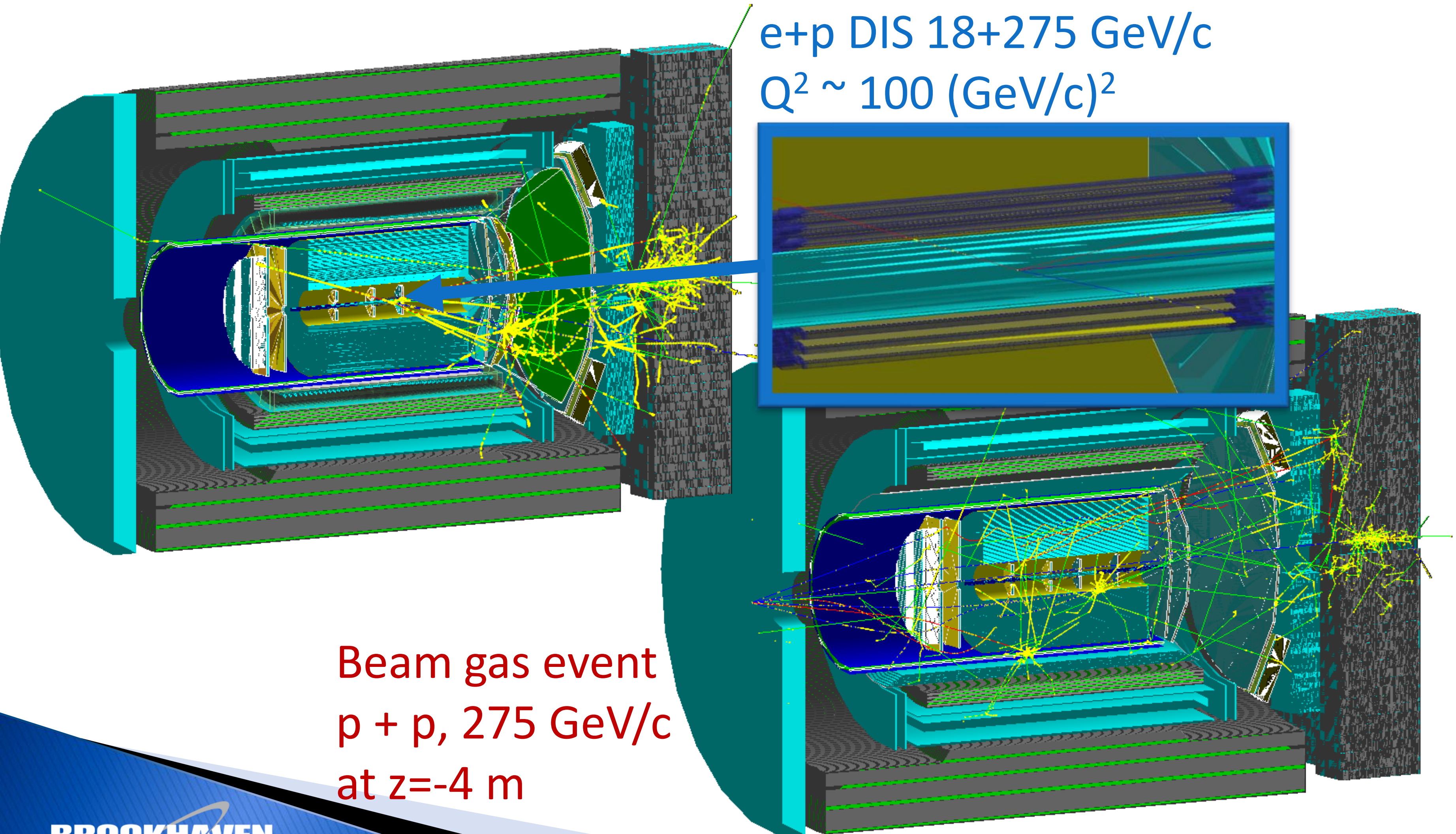
sPHENIX-EIC concept

2014 concept: arXiv:1402.1209 [nucl-ex], 2018 update: sPH-cQCD-2018-001



EIC DAQ in Geant4 simulation

Note sPH-cQCD-2018-001: https://indico.bnl.gov/event/5283/ , Simulation: https://eic-detector.github.io/



Beam-gas interactions

- p + p (beam gas) cross section ~ 40 mb @ 250 GeV
- **Beam gas interaction rate** = 2.65e10(H_2/cm^2/10m) * 2(proton/H_2) * 40e-27(40mb→cm^2) * 1(A) / 1.6e-19(C/proton)
  = **13kHz / 10m beam line < 10% EIC collision rate**
- The following estimation assumes
  - HERA inspired flat 10e-9 mbar vac in experimental region of |z|<450 cm
  - 2M M.B. Pythia-8 beam gas events simulated in Geant4 full detector

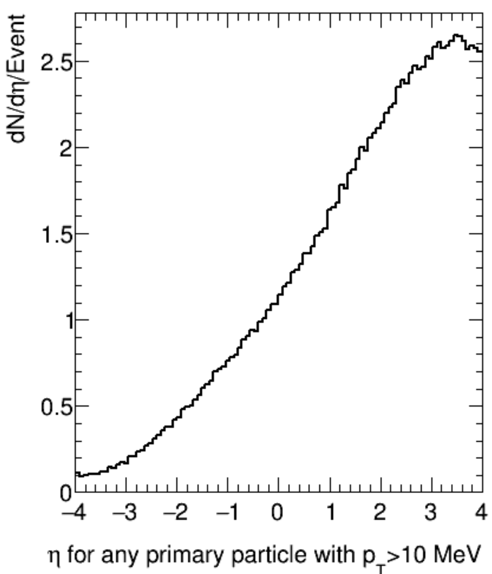
Vacuum pressure	10^{-9} mbar
Beampipe temperature	Room temperature
Average atomic weight of gas	Hydrogen (H^2)
Molecular density (for 10 m pipe)	2.65×10^{10} molecules/cm^2
Luminosity (Ring-Ring)	10.05×10^{33} cm^{-2}s^{-1}
Bunch intensity (R-R) (e/p)	15.1 / 6.0×10^{10}
Beam Current (R-R) (e/p)	2.5 / 1 A
Bunch spacing (Ring-Ring)	8.7 ns → 1320 bunches
ElectronxProton beam energy	10 GeV x 275 GeV

Courtesy: E.C. Aschenauer
eRHIC pre-CDR review

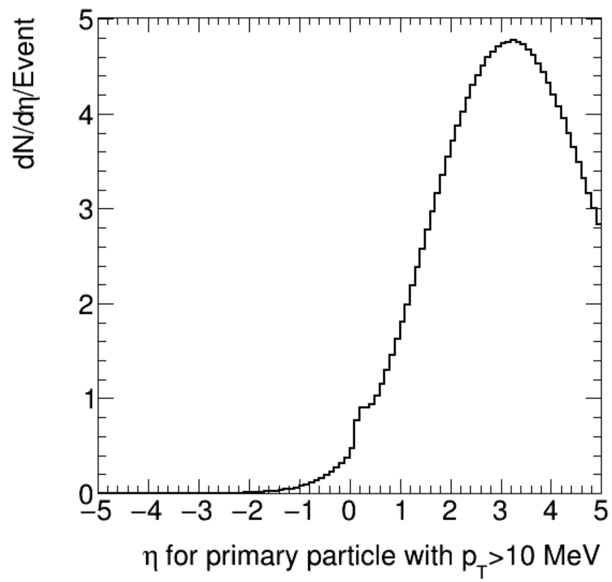
Beam gas multiplicity

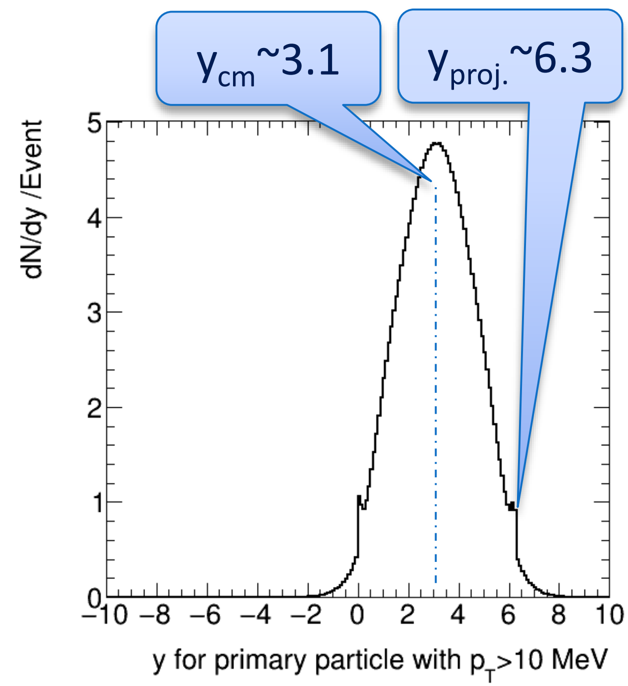
- 250 GeV/c proton beam on H_2 gas target
- C.M. rapidity~3.1, sqrt[s] ~ 22 GeV, cross section~40 mb
- Lab per-pseudorapidity multiplicity is higher than e+p, but ***not*** orders of magnitude higher

e+p, 20 + 250 GeV/c



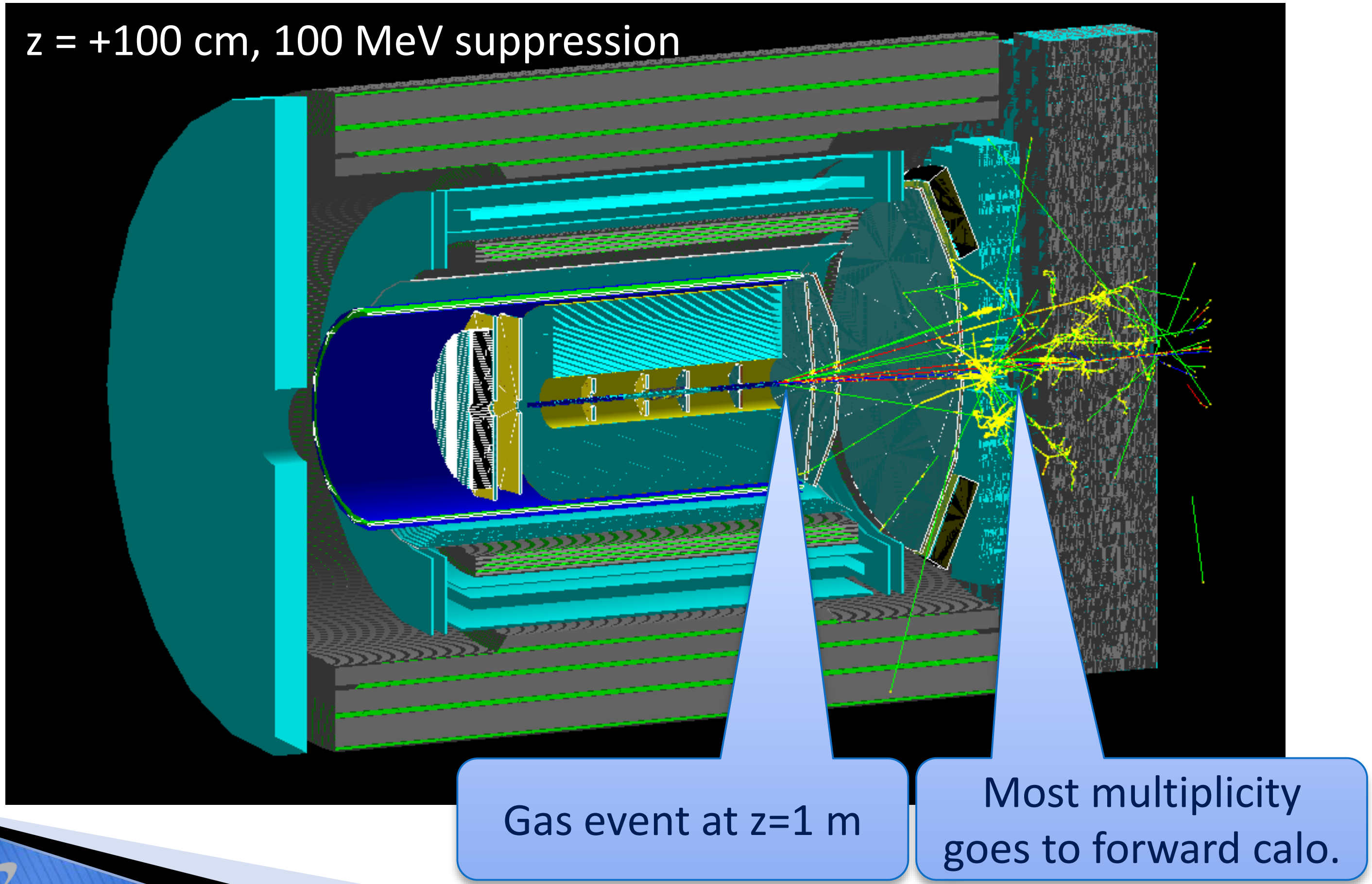
p+p (beam gas), 250 GeV/c





Beam gas event in a detector

- 250 GeV proton beam on proton beam gas, sqrt[s] ~ 22 GeV
- For this illustration, use pythia-8 very-hard interaction event (q^hat > 5 GeV/c)



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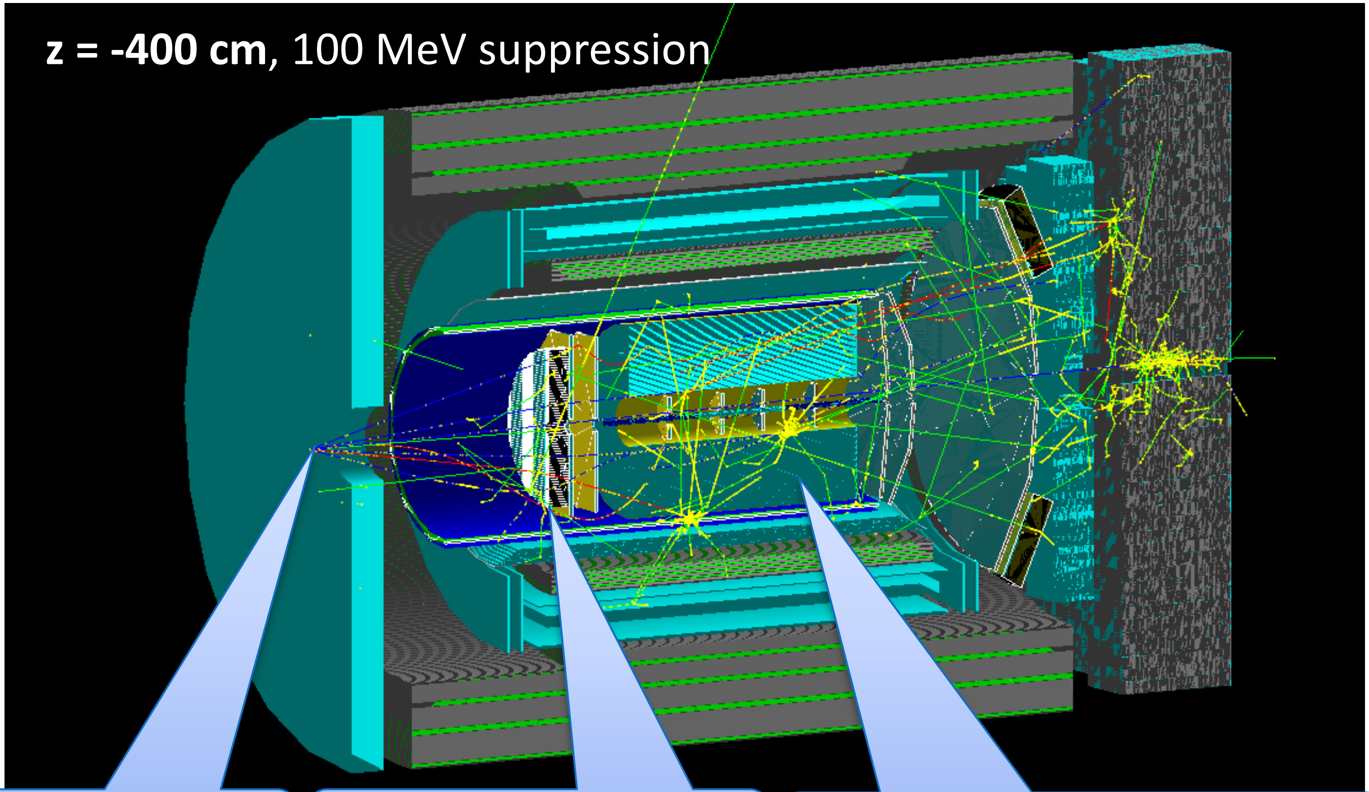


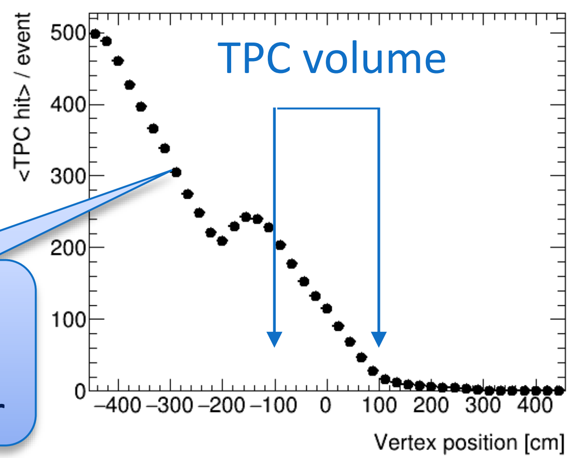
Gas event at z=-4 m

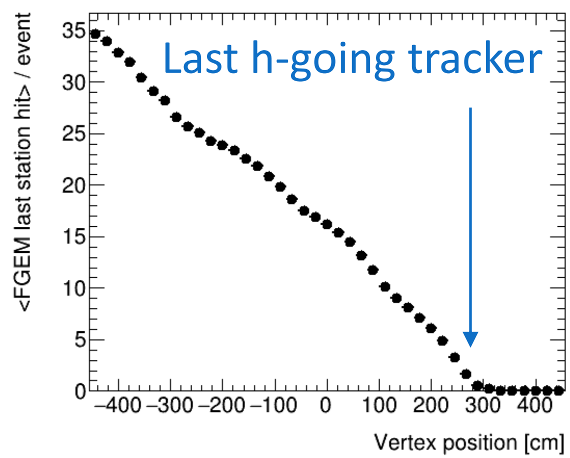
Shower starts in e-going calorimeter

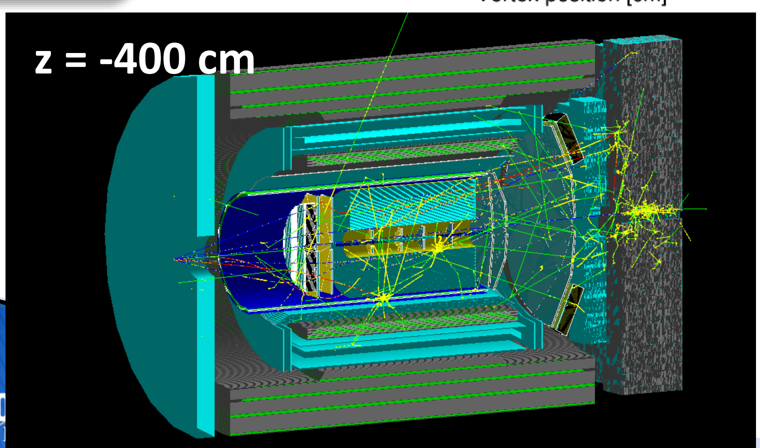
Induce multiplicity in trackers and forward calo

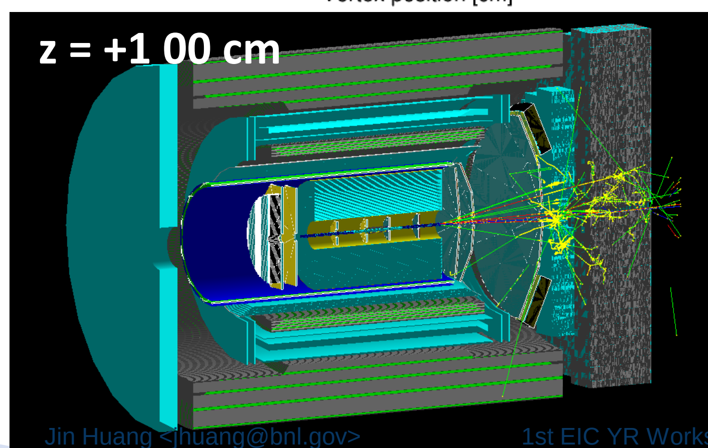
Beam gas vertex sensitivity - tracker

- Average active hit for each beam gas vertex bin
- 250 GeV proton beam on proton beam gas, Pythia-8 M.B.









Beam gas vertex sensitivity – calo.

- Average active hit for each beam gas vertex bin
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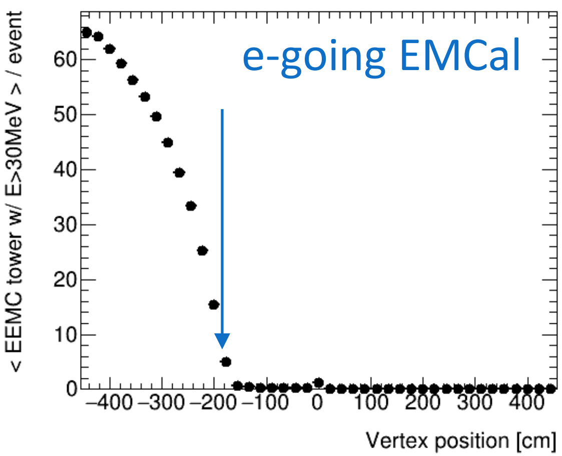
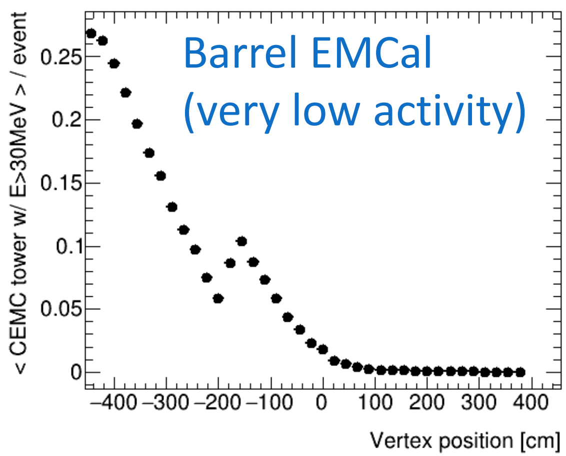
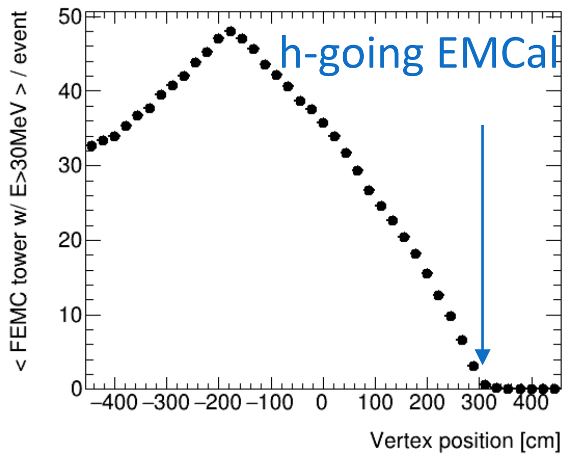
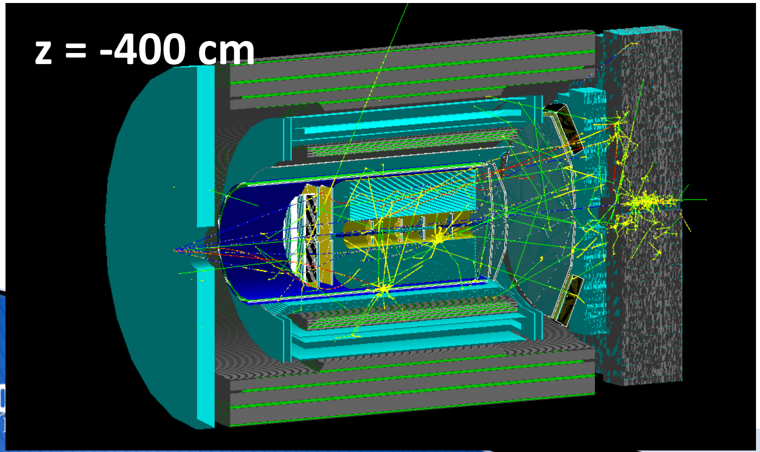
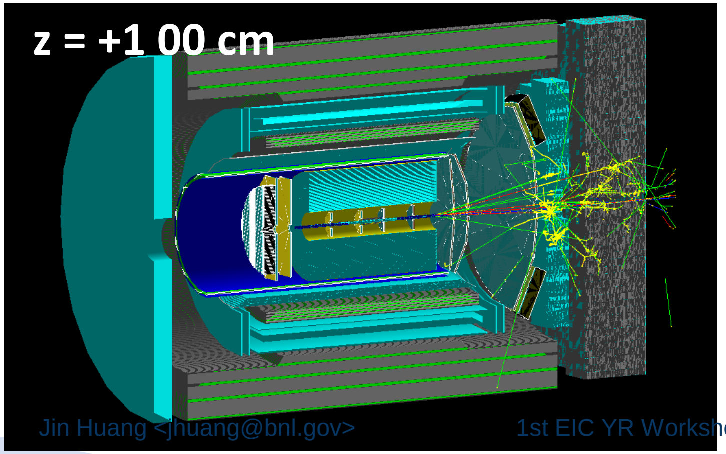




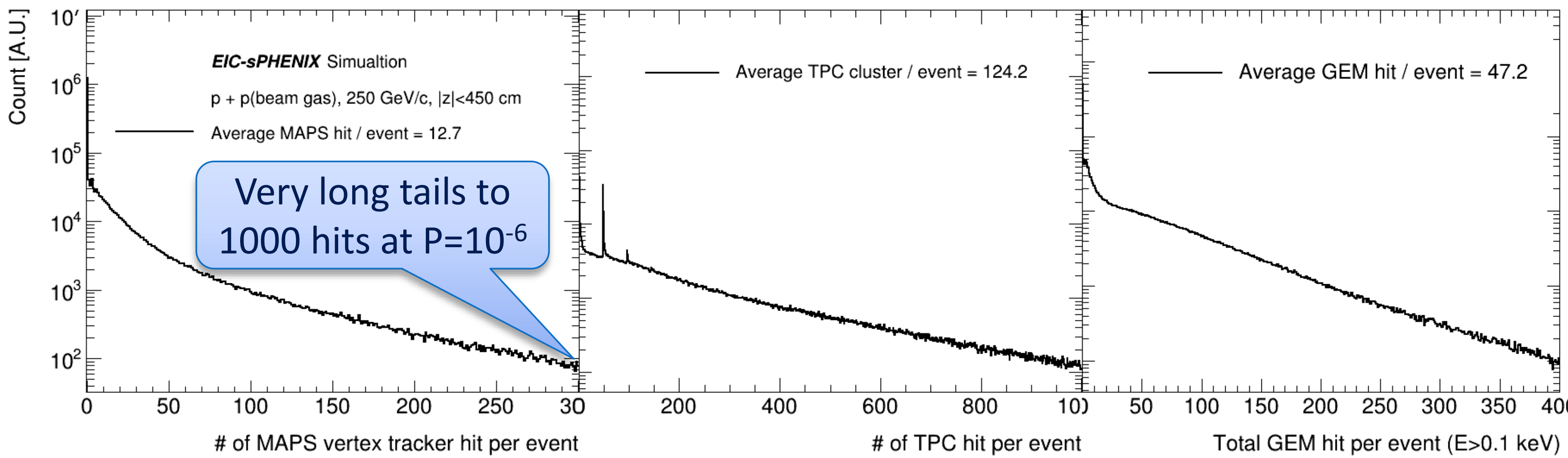






GEANT4-based detector simulation: beam gas event on tracker

Extract mean value/collision (signal data rate) and tails (relates to buffer depth requirement)



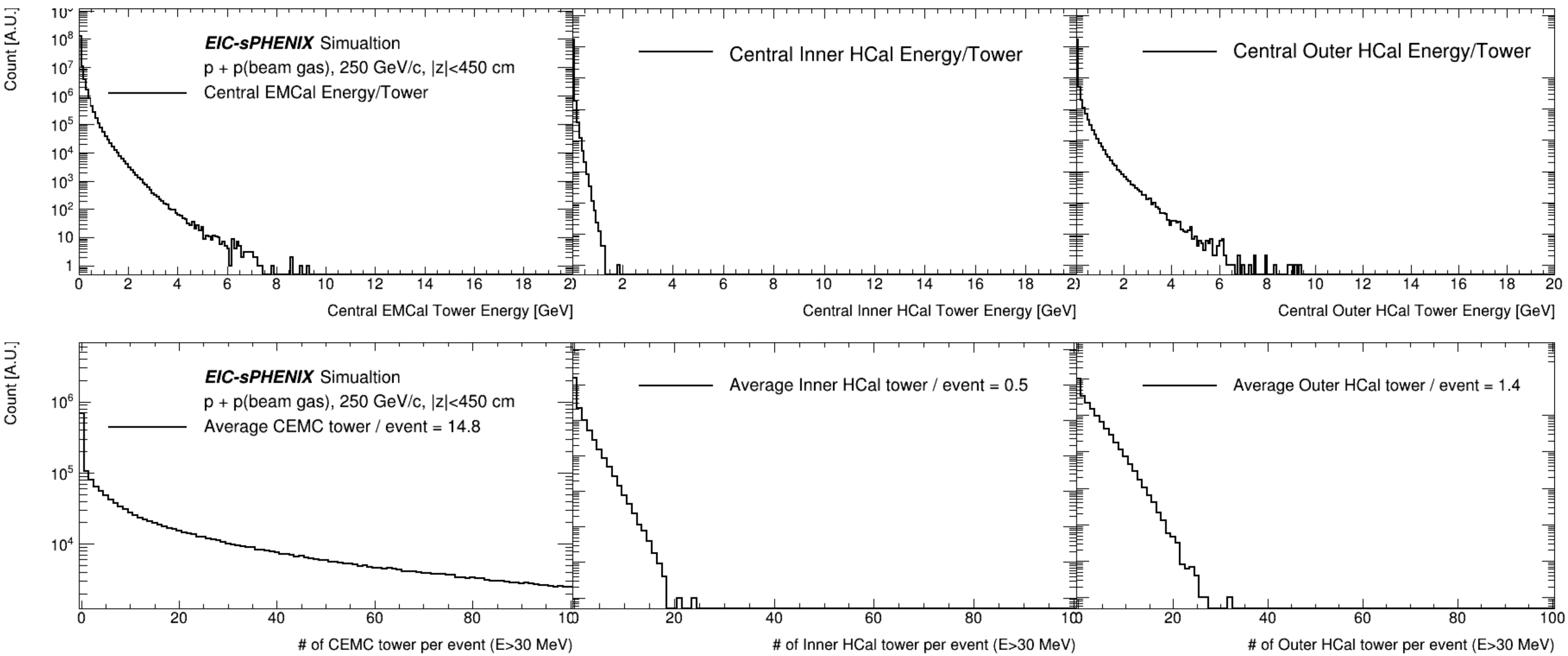
Raw data:
3 pixel x 16 bit / MAPS hit

Raw data:
3 (strip) x5(time)x 10 bit / TPC hit
+ headers (60 bits)

Raw data:
3 (strip) x5(time)x 10 bit / GEM hit
+ headers (60 bits)

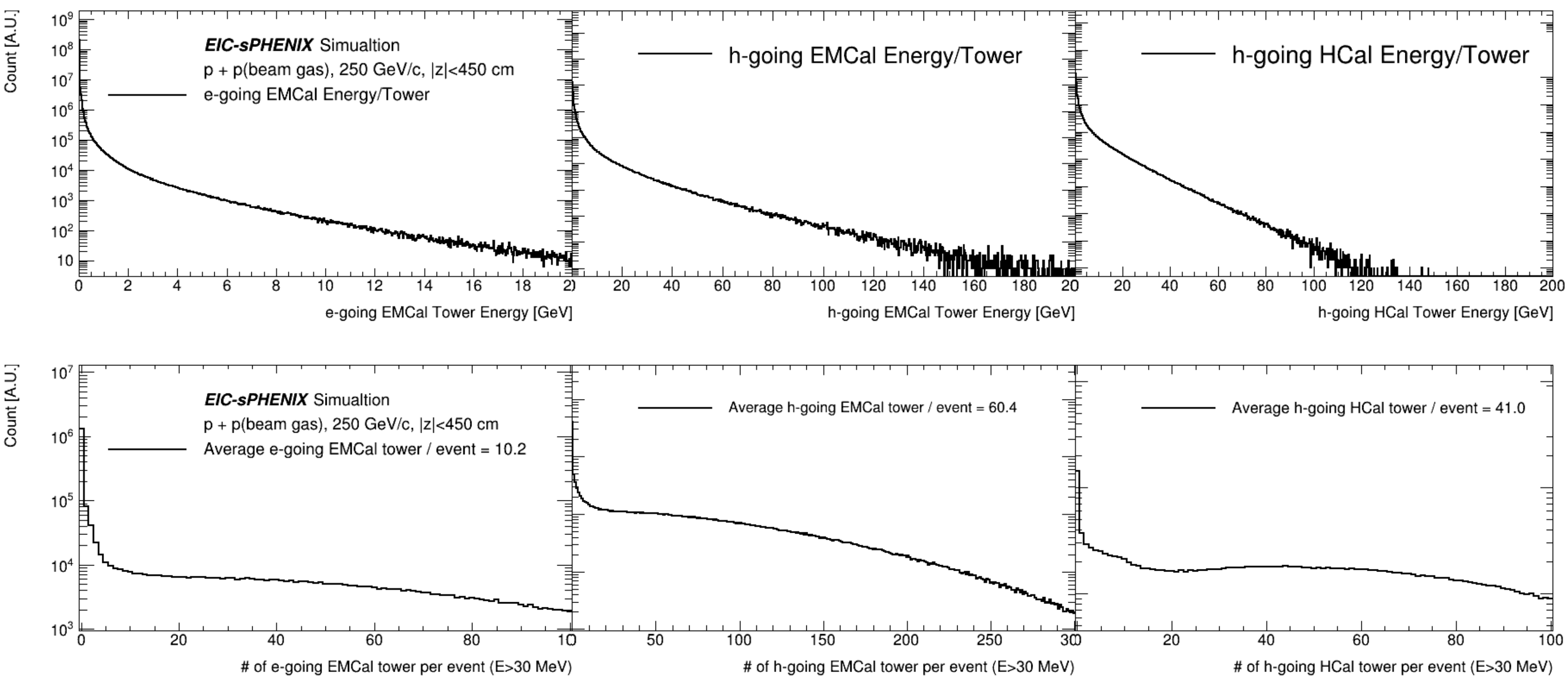
GEANT4-based detector simulation: beam gas event on central calorimeters

Raw data: 31x 14 bit / active tower +padding + headers ~ 512 bits / active tower



GEANT4-based detector simulation: beam gas event on forward calorimeters

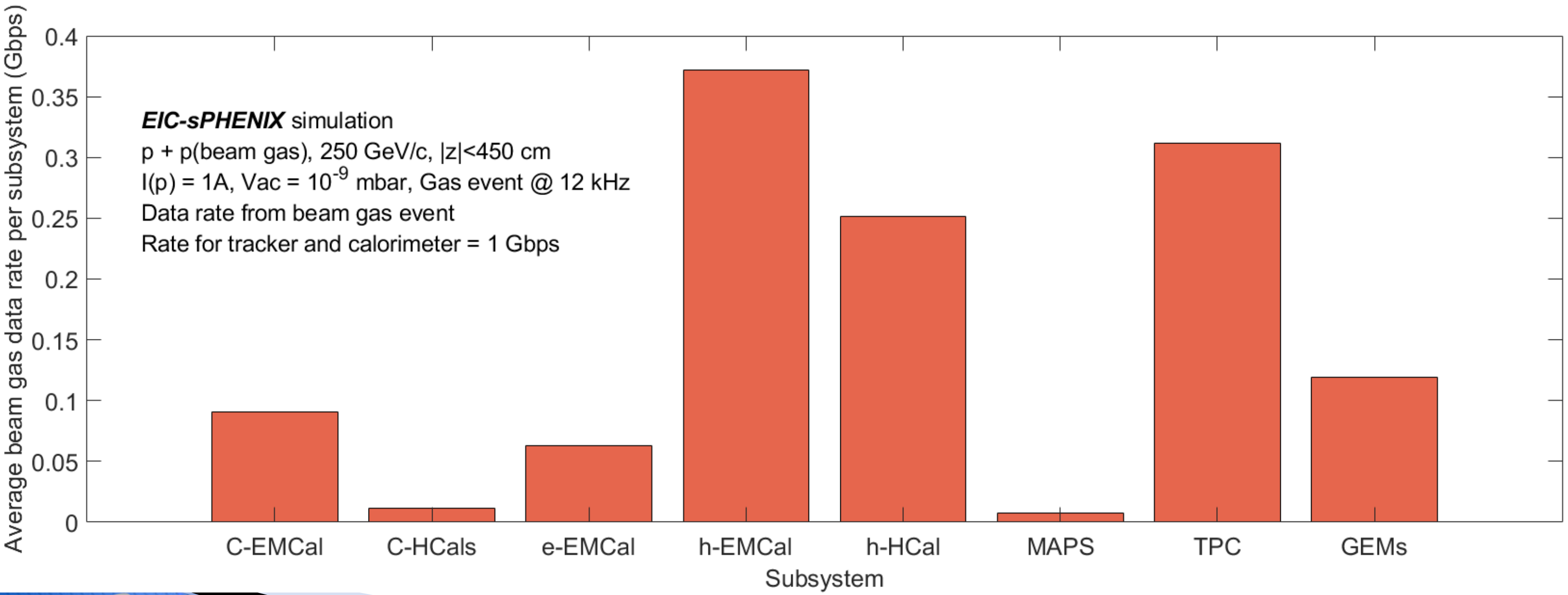
Raw data: 31x 14 bit / active tower +padding + headers ~ 512 bits / active tower



Rate summary for beam gas

- Very similar rate distribution among subsystems when compared with EIC collisions
- With an assumed vacuum profile
  - Based on HERA experience, assuming 10^{-9} mbar flat within experiment region (|z|<450 cm)

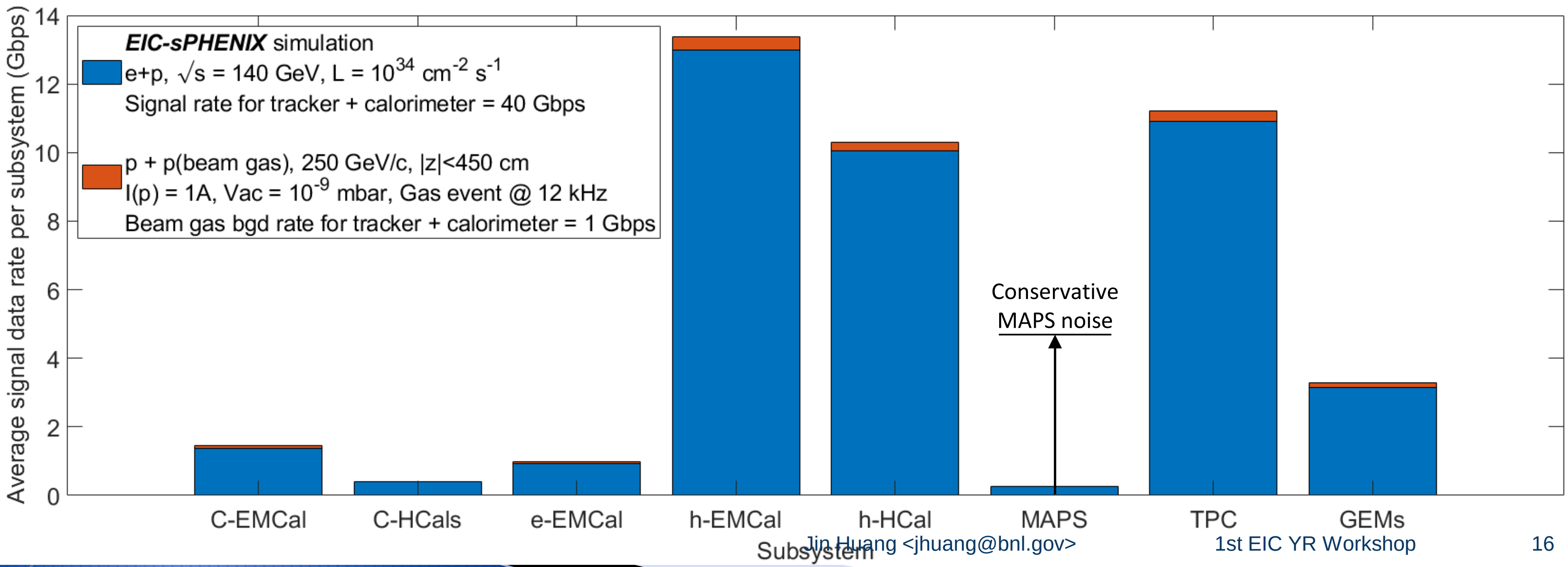
  Thanks to the discussions with E. Aschenauer, A. Kiselev, and C. Hyde
- Further investigation needed:
  - In the experimental region : Dynamic vac profile
  - Beyond experiment region: beam gas profile, possible passive shielding and active veto



Signal data rate -> DAQ strategy

Note sPH-cQCD-2018-001: https://indico.bnl.gov/event/5283/ , Simulation: https://eic-detector.github.io/

- Beam gas of overall ~ 1 Gbps @ 12kHz beam gas << EIC collision signal data rate at ~100 Gbps (details in backup)
- Collision and background rate is critical for detector and DAQ design (see my parallel talk in DAQ session this AM)
- Looking forward to working with the group in integrating other important source of background, e.g. synchrotron radiation (see talk Charles Hetzel, Latifa Elouardhiri) and far forward detectors.

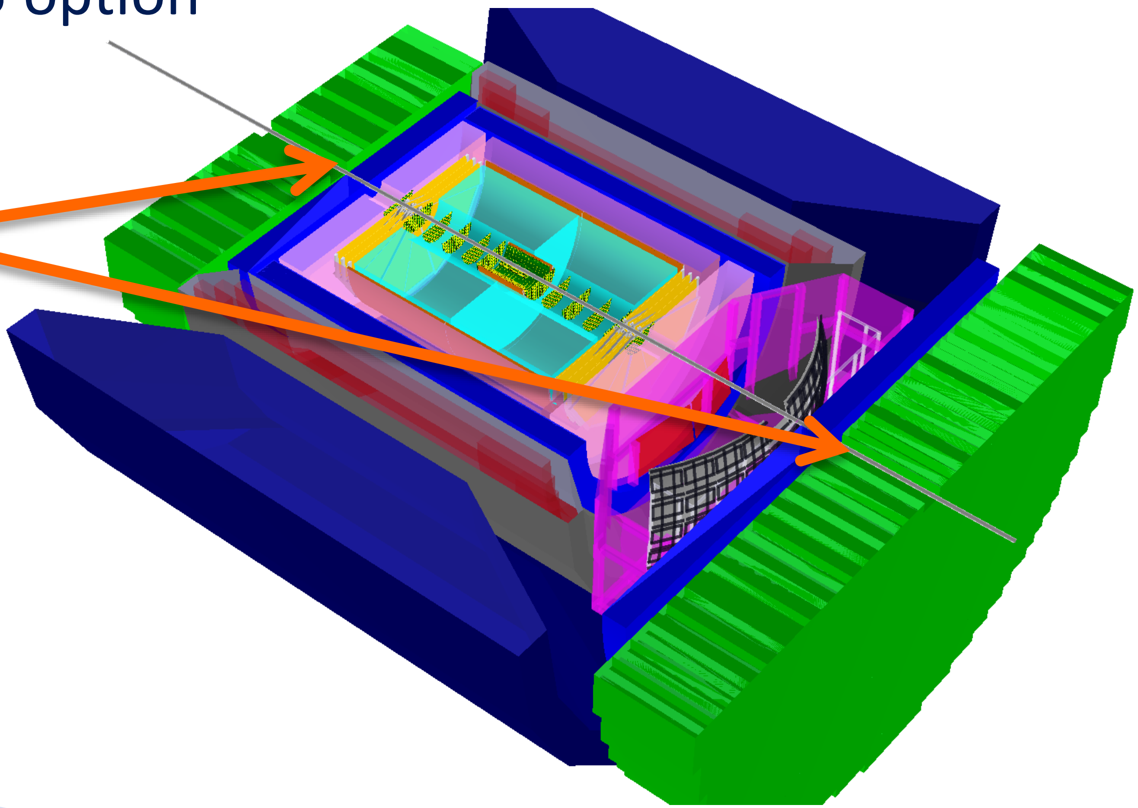


Assessment 2:
Neutron fluence and radiation dose

EICROOT & BeAST

Study performed by Alexander Kiselev

- Simulated using the BeAST geometry embedded into the STAR experimental hall (the latter is not shown)
- 100k ep events; PYTHIA, 20x250 GeV beam energies
- GEANT3 with HADR=5 option



This study:

-> focus on endcap EmCal area close to beam line

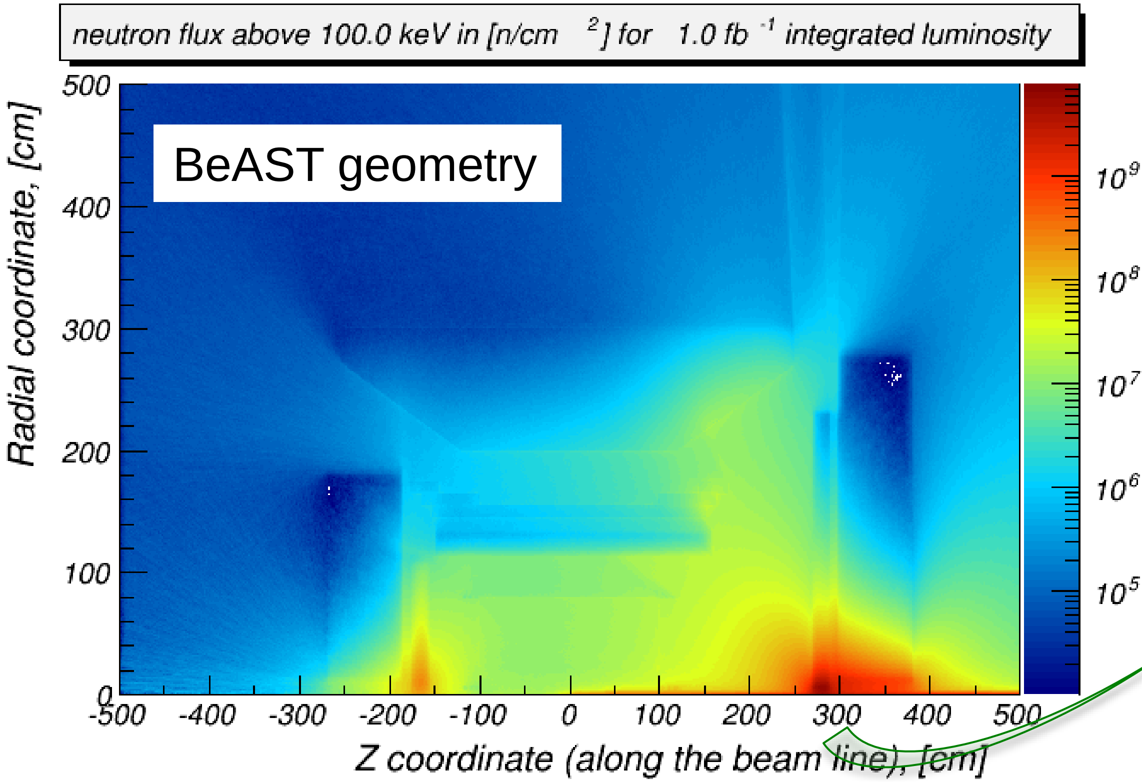
-> One of the main objective was to get some idea about the radiation dose for the crystal EmCal in the electron-going direction and the neutron fluence for the forward EmCal/HCal in the forward direction

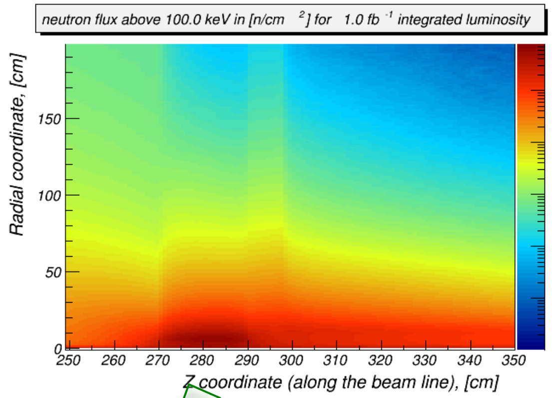
Neutron fluence

Study performed by Alexander Kiselev

<u>The quantity</u>: Fluence = "a sum of neutron path lengths"/"cell volume" for N events

-> basically use Y.Fisyak's approach (STAR BG study), also Geant4 fluence module (G4ScoringManager)





-> forward EmCal: up to ~$5*10^9$ n/cm^2 per fb^{-1} (*inside the towers*); perhaps ~5 less at the SiPM location;

NB: "standard" EIC run at ~10^{33} cm^{-2}s^{-1} luminosity is 10 fb^{-1}

- Assume azimuthally-symmetric setup -> so build {R,Z} map
- Close to beam line: ~10^{34} cm^{-2}s^{-1} over ~10 years would exceed ~10^{11} n/cm^2

Study performed by Alexander Kiselev

Neutron flux & radiation dose

So far the only modeling source of information used to question SiPM readout (integrated flux is too high) and to help justify PWO as inner crystal EmCal (integrated dose is pretty low)

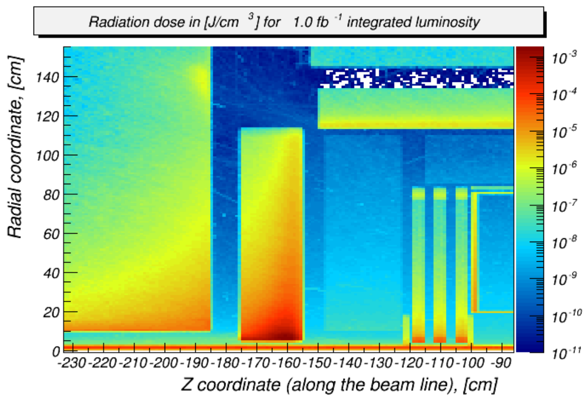
Small print:

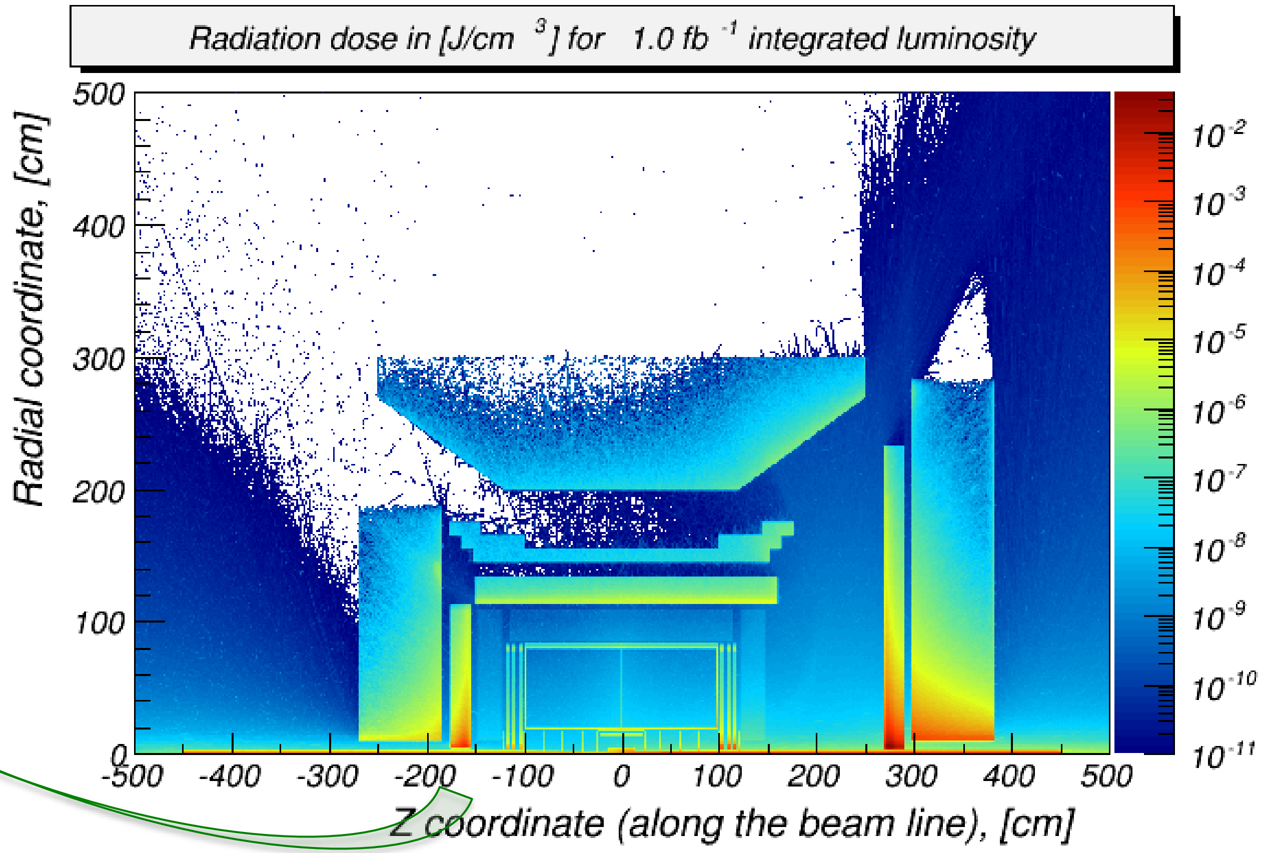
- These are the rates **from primary interaction only:**
  - No synchrotron radiation
  - No beam-gas scattering
- Neither machine elements were incorporated in that simulation nor the experimental hall material
- It is a particular detector geometry (BeAST)
- GEANT3 used; comparison against GEANT4 need to be performed
- Thermal neutrons are not accounted
- Strictly speaking, integrated neutron flux is high only close to the beam pipe

Radiation dose

Study performed by Alexander Kiselev

<u>The (primary) quantity</u>: E_{sum} = “a sum of dE/dx”/”cell volume” for N events





-> crystal EmCal: up to $\sim 2*10^{-3}$ J/cm^3 per fb^{-1} (close to beam line)

1 rad = 0.01 Gy & [Gy] = [J/kg] & PWO density ~8g/cm^3 -> ~250 rad/year

(at “WP-nominal” luminosity ~10^{33} cm^{-2} s^{-1})

Summary

- EIC has 1/1000 cross-section when compared to hadron colliders, background matters tremendously
- Beam gas background appears moderate when comparing to EIC collision via full detector Geant4 simulation
  - Assuming 10^{-9} mbar flat within experiment region ($|z|<450$ cm)
  - sPHENIX-EIC Geant4-Fun4All simulation
  - Beam gas hit rate << EIC collision data rate
  - Looking forward to detector/DAQ study with more background sources, e.g. input work from Charles Hetzel, Latifa Elouardhiri
- EIC radiation dose from main collision appears moderate via full detector Geant3 simulation
  - Benchmark to STAR background study at RHIC
  - BeAST Geant-EICROOT simulation
  - Highest radiation immediately around beam pipe: 10^{34} $cm^{-2}s^{-1}$ over ~10 years → ~10^{11} n/cm^2 , O(20) kRad

Extra information

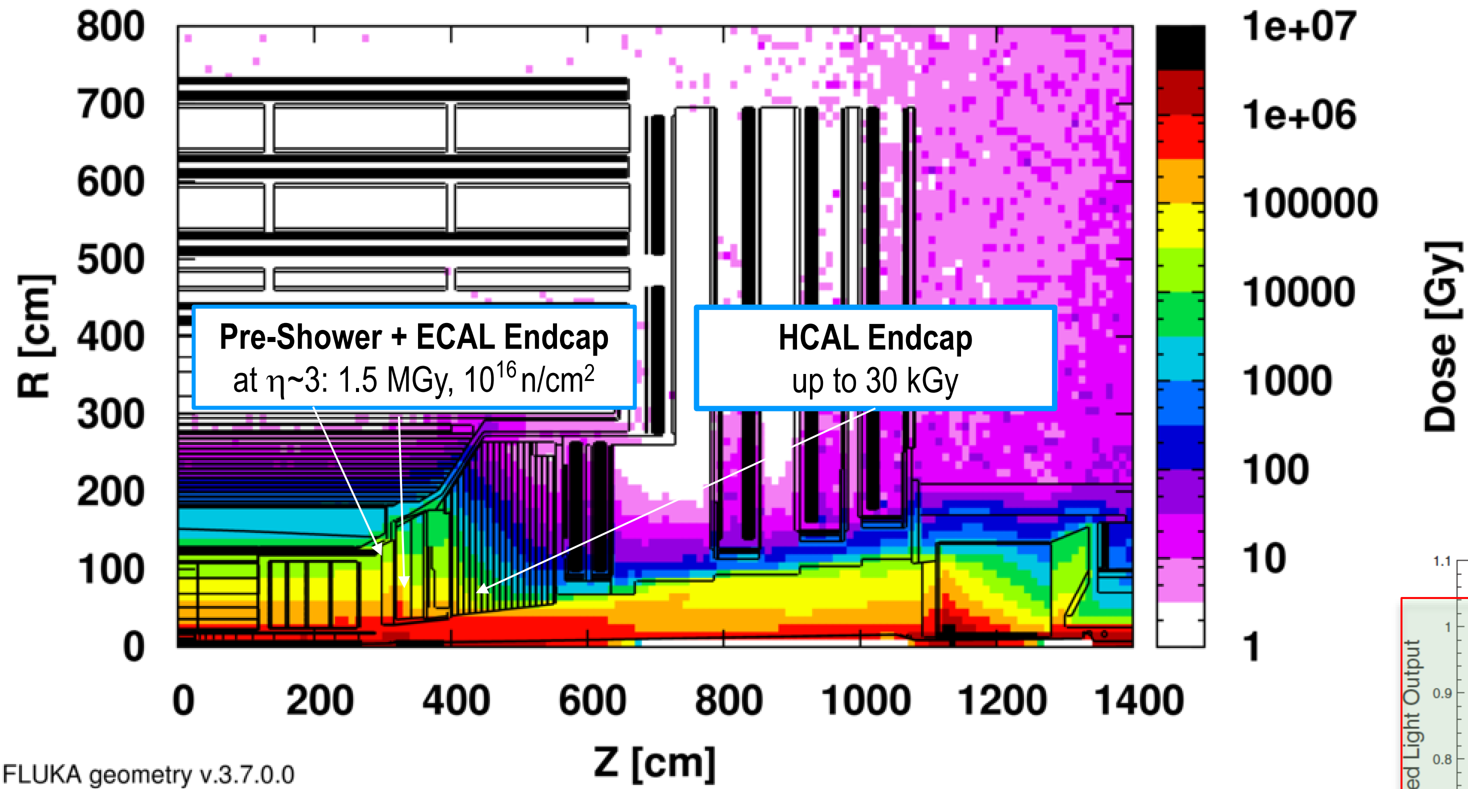
EIC: unique collider → Background is major challenge

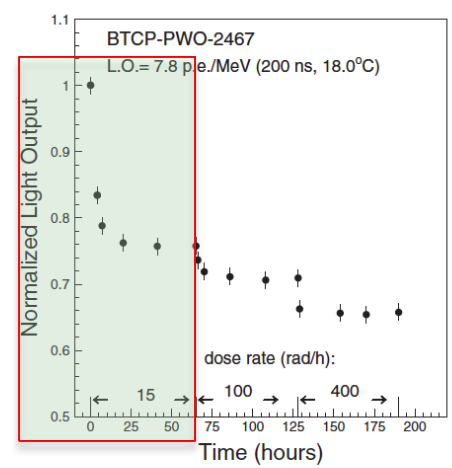
	EIC	RHIC	LHC → HL-LHC
Collision species	$\vec{e}+\vec{p}, \vec{e}+A$	$\vec{p}+\vec{p}/A, A+A$	$p+p/A, A+A$
Top x-N C.M. energy	140 GeV	510 GeV	13 TeV
Bunch spacing	10 ns	107 ns	25 ns
Peak x-N luminosity	10^{34} cm^{-2} s^{-1}	10^{32} cm^{-2} s^{-1}	10^{34} → 10^{35} cm^{-2} s^{-1}
x-N cross section	50 μb	40 mb	80 mb
Top collision rate	500 kHz	10 MHz	1-6 GHz
$dN_{ch}/d\eta$ in p+p/e+p	0.1-Few	~3	~6
Charged particle rate	4M N_{ch}/s	60M N_{ch}/s	30G+ N_{ch}/s

- EIC luminosity is high, but collision cross section is small ($\propto \alpha_{EM}^2$) → low collision rate
- But events are precious and have diverse topology. Background and systematic control is crucial

Extreme comparison (CMS)

3000 fb-1 Absolute Dose map in [Gy] simulated with MARS and FLUKA





clearly our numbers are orders of magnitude smaller

-> however integrated flux of ~10^{11} n/cm^2 is already harmful for SiPMs

-> and PWO crystals show reduction in light output at relatively small doses

Radiation dose at sPHENIX

- Many detector parts are sensitive to radiation background
  - Ionization radiation (Radiation damage, flip bits, …)
  - MeV neutron damage (Si sensor lattice damage, SiPM noise, …)
  - Dominated by AuAu dose. Expect lower but comparison dose from pp and pA systems
- Strategy
  - Geant4 physics list QGSP_BERT_HP and FTFP_BERT_HP
  - Reproduce the PHENIX Run14 AuAu Radmon data
    - Same collision system, and closest accelerator configuration
    - Raditaion sensor
  - Use the same procedure to predict sPHENIX radiation map
- Analysis interface to G4ScoringManager: https://github.com/sPHENIX-Collaboration/coresoftware/pull/465

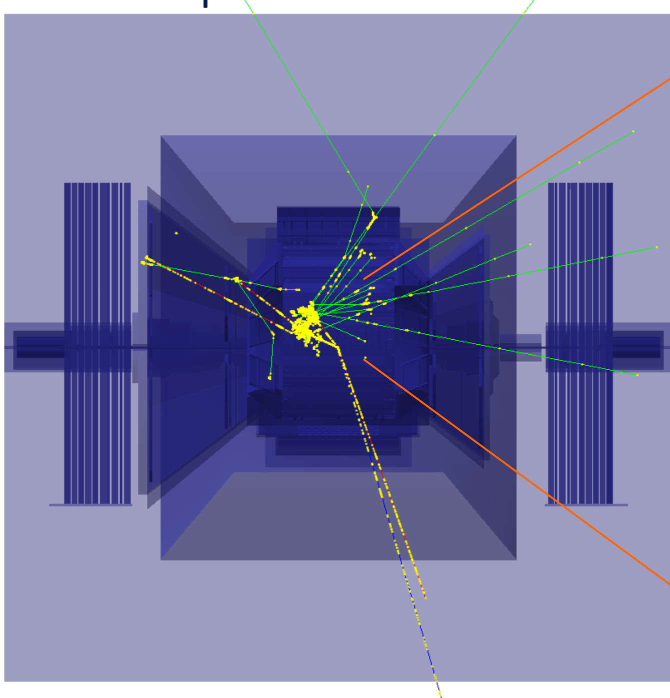
sPH-TRG-2018-001: ~20% pp collision in |z|<10cm

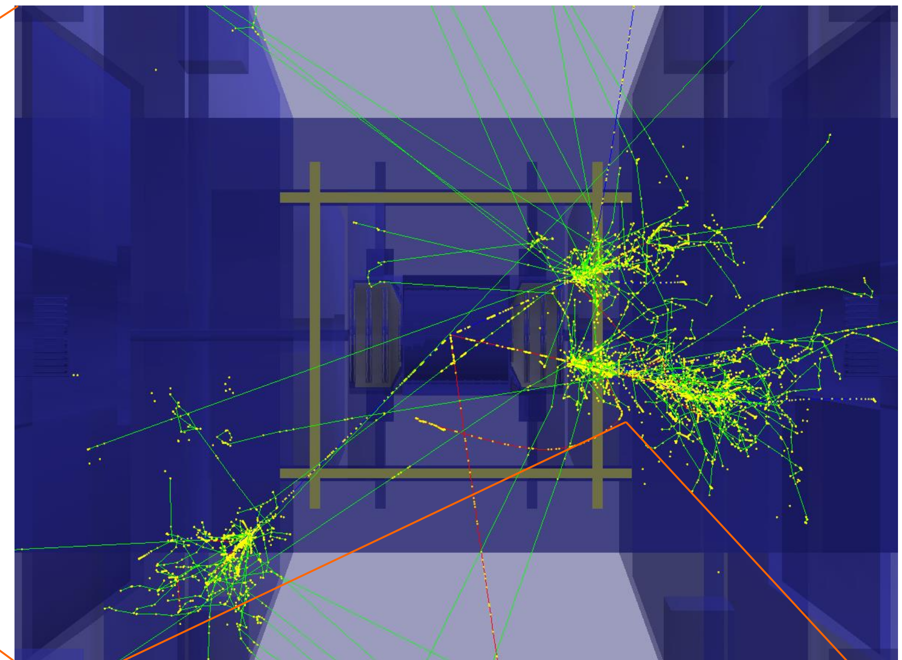
Table 2: Summary of integrated samples summed for the entire five-year scenario.

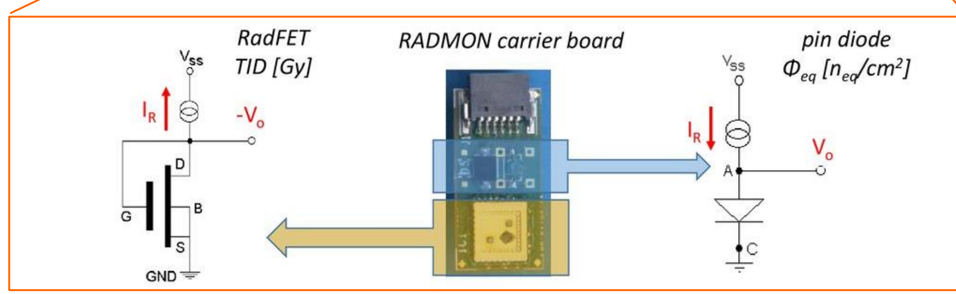
Species	Energy [GeV]	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Au+Au	200	35 nb^{-1} (239 billion)	80 nb^{-1} (550 billion)	214 nb^{-1} (1.5 trillion)
p+p	200	—	197 pb^{-1} (8.3 trillion)	1.0 fb^{-1} (44 trillion)
p+Au	200	—	0.33 pb^{-1} (0.6 trillion)	1.46 pb^{-1} (2.6 trillion)

Calibration – PHENIX data

PHENIX experiment in sPHENIX simulation

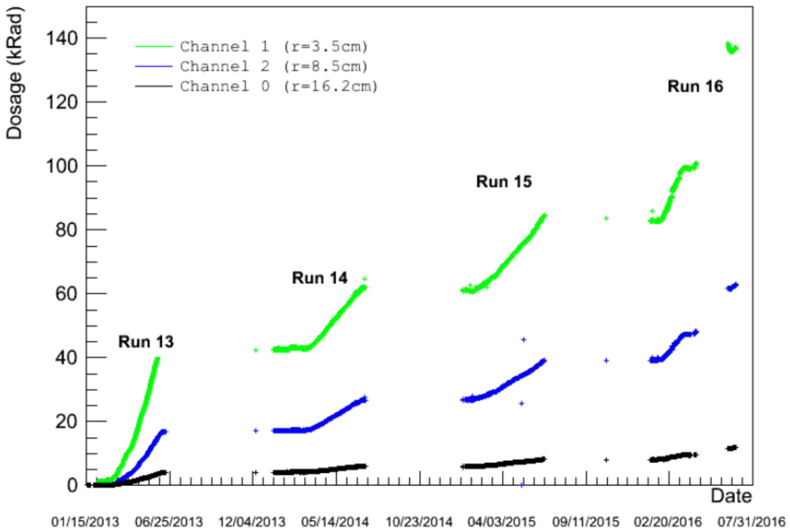


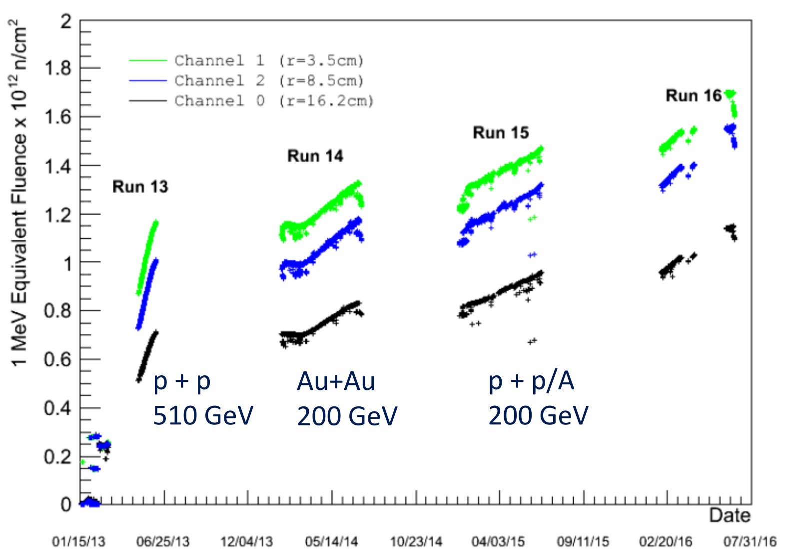




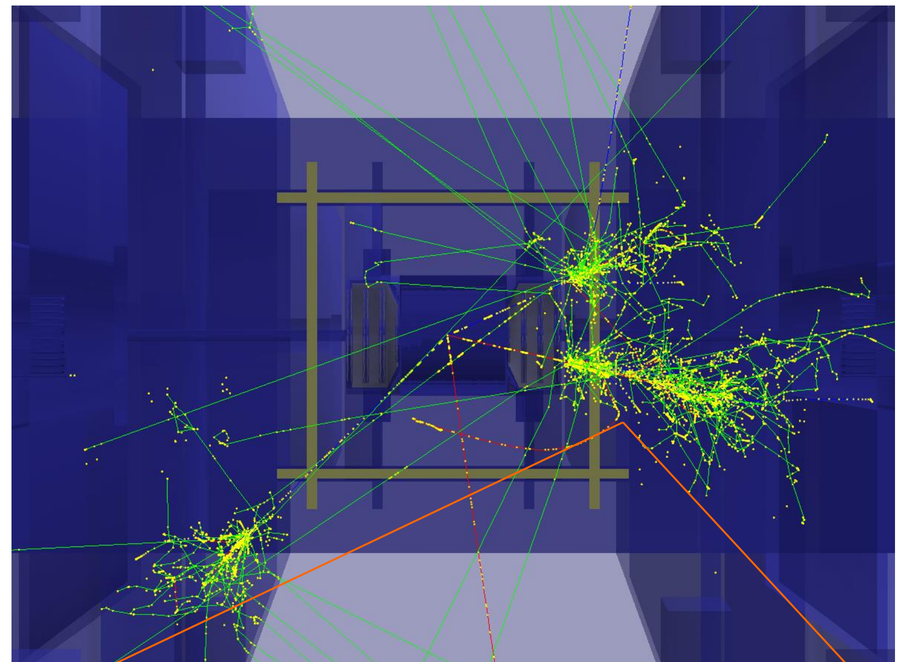
Calibration – PHENIX data

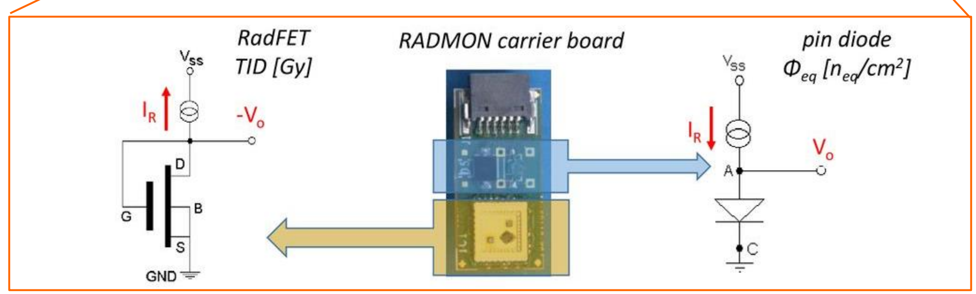
PHENIX data, from Eric Mannel





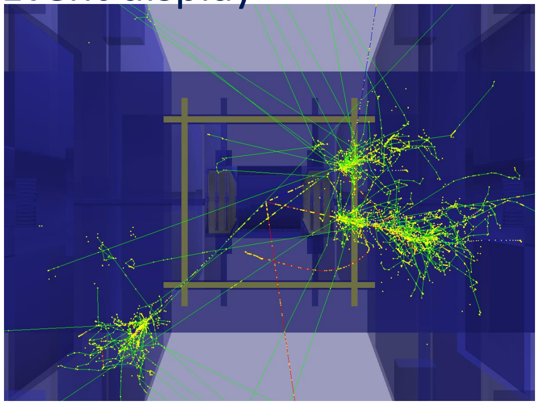
PHENIX experiment in sPHENIX simulation

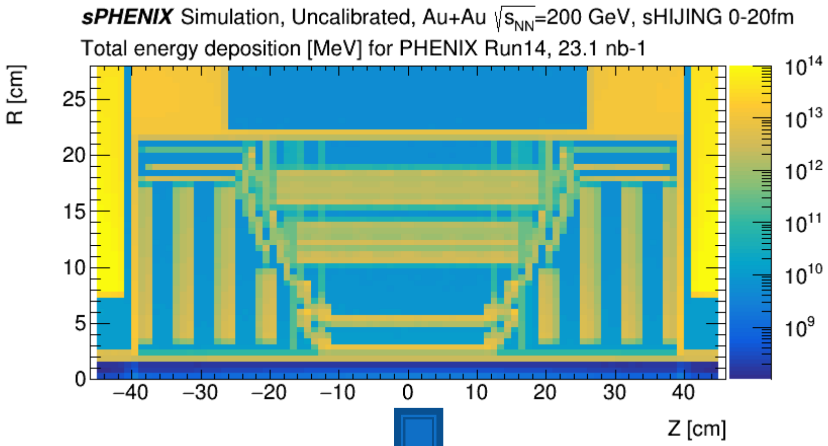




Calibration – PHENIX data

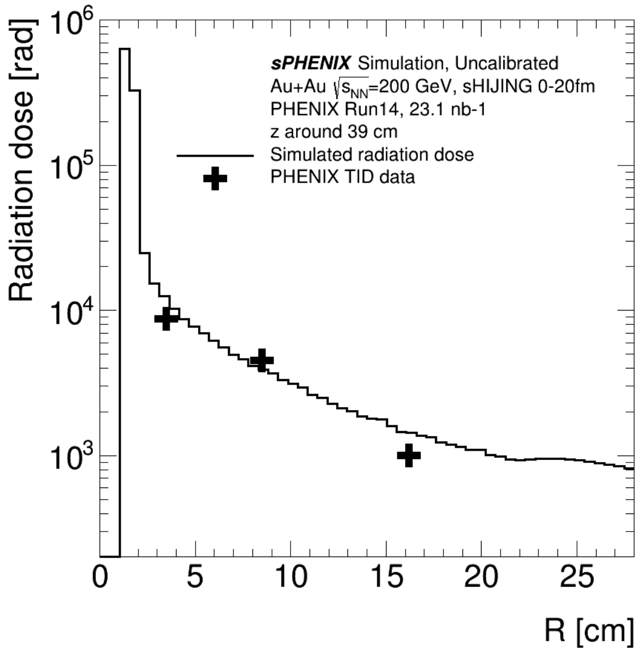
Event display

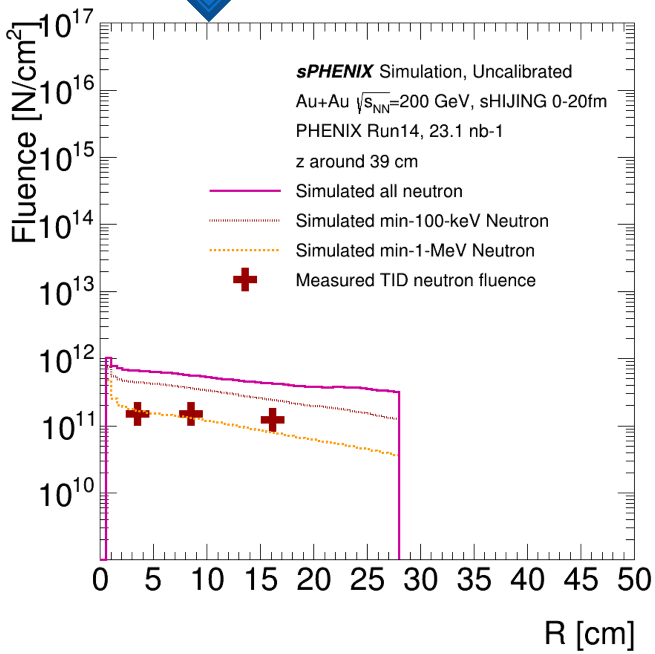




Comparison to sensor data

Reasonable agreement in x2 ranges





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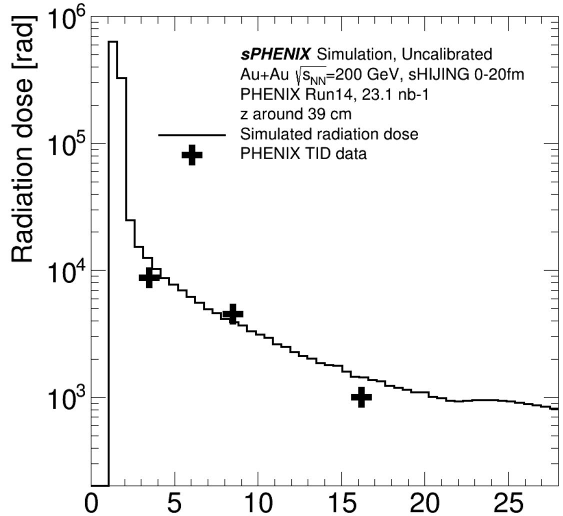
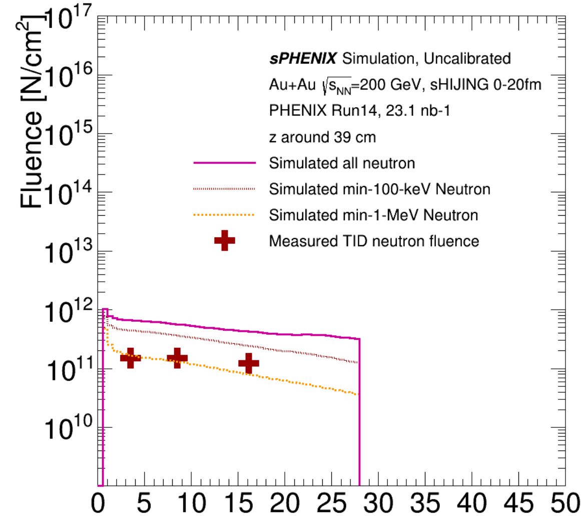
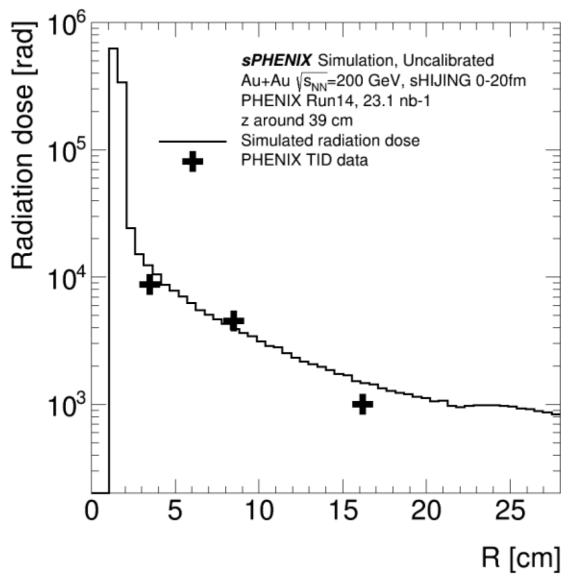
Physics list dependence is small

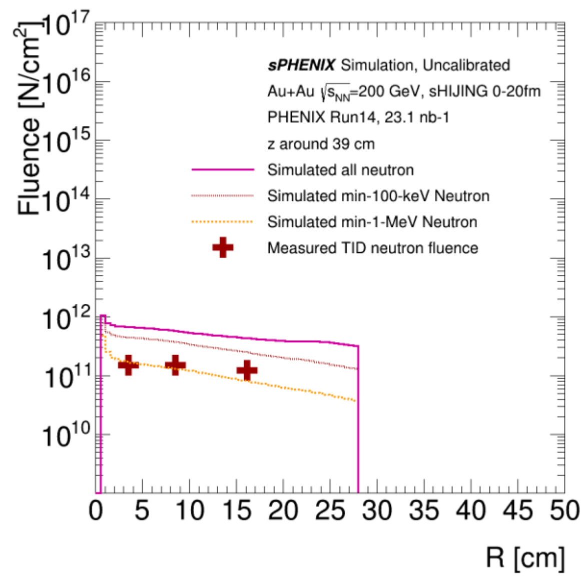
QGSP_BERT_HP



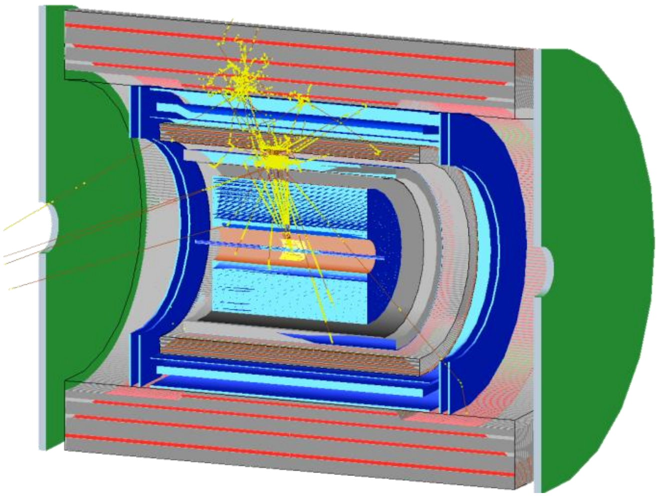


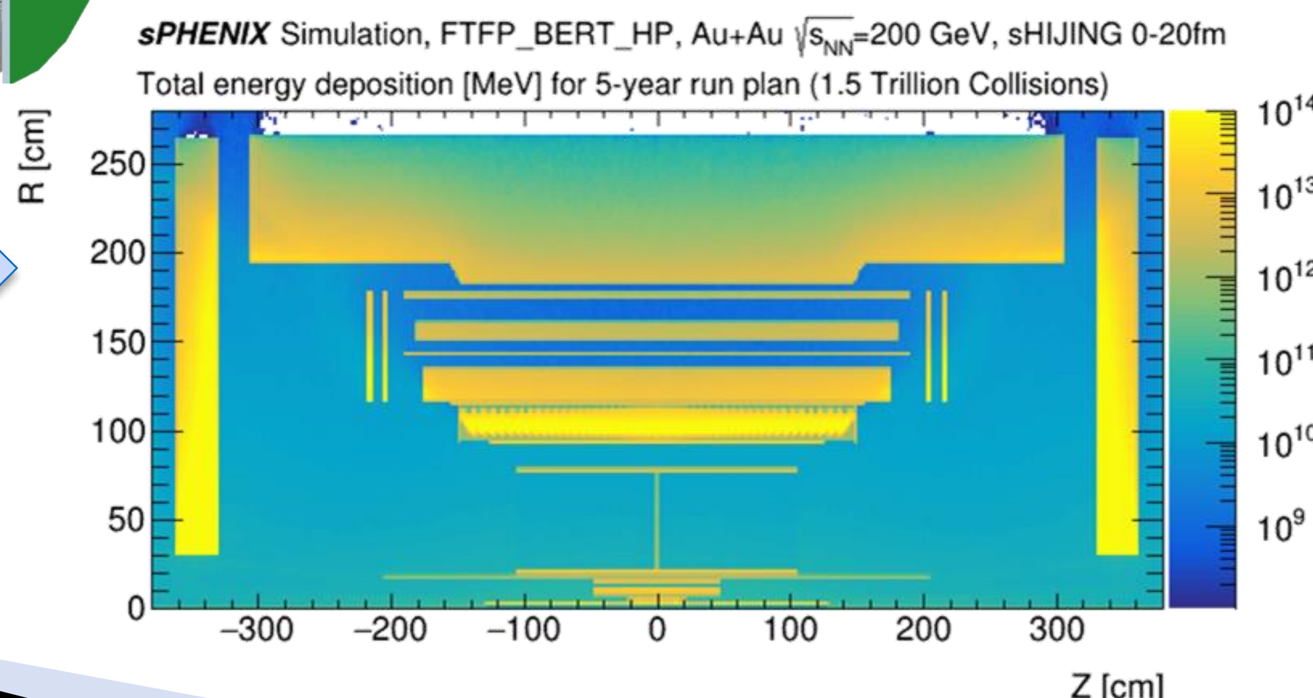
FTFP_BERT_HP
(Few % higher dose)



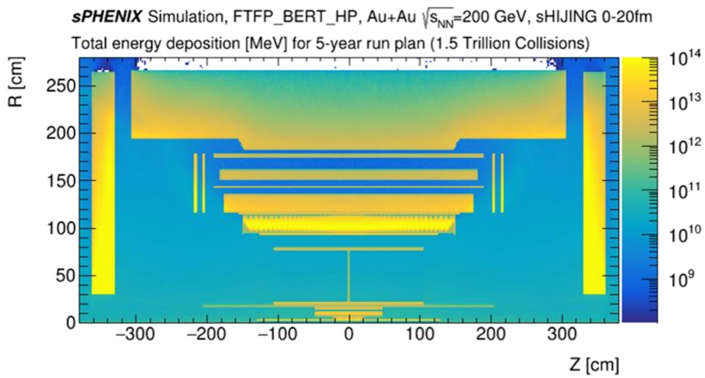


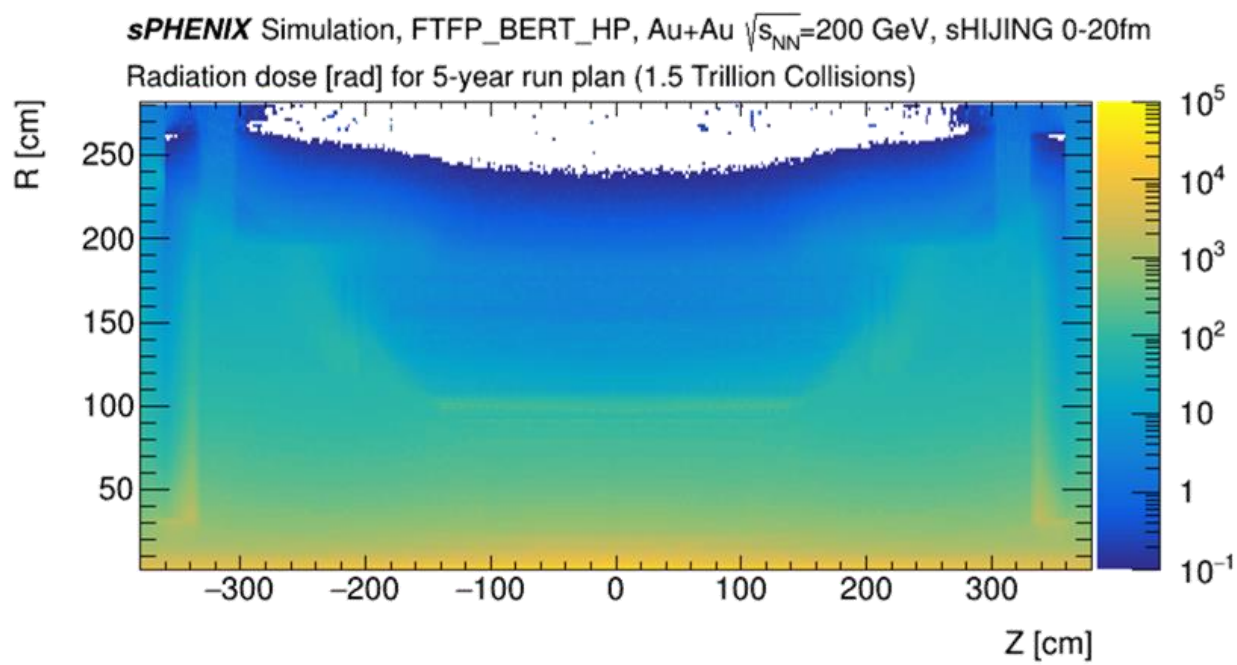
Next, apply to full sPHENIX detector



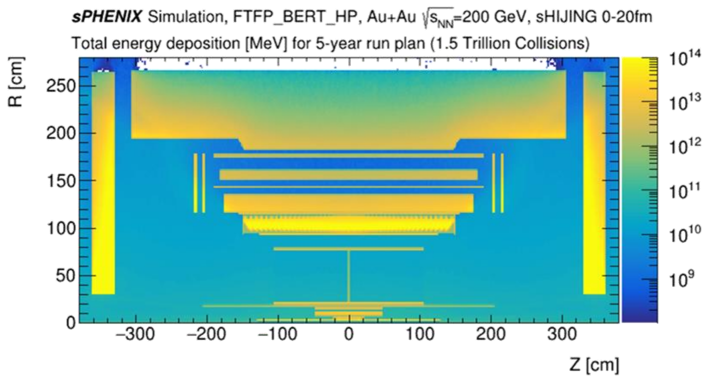


Radiation dose

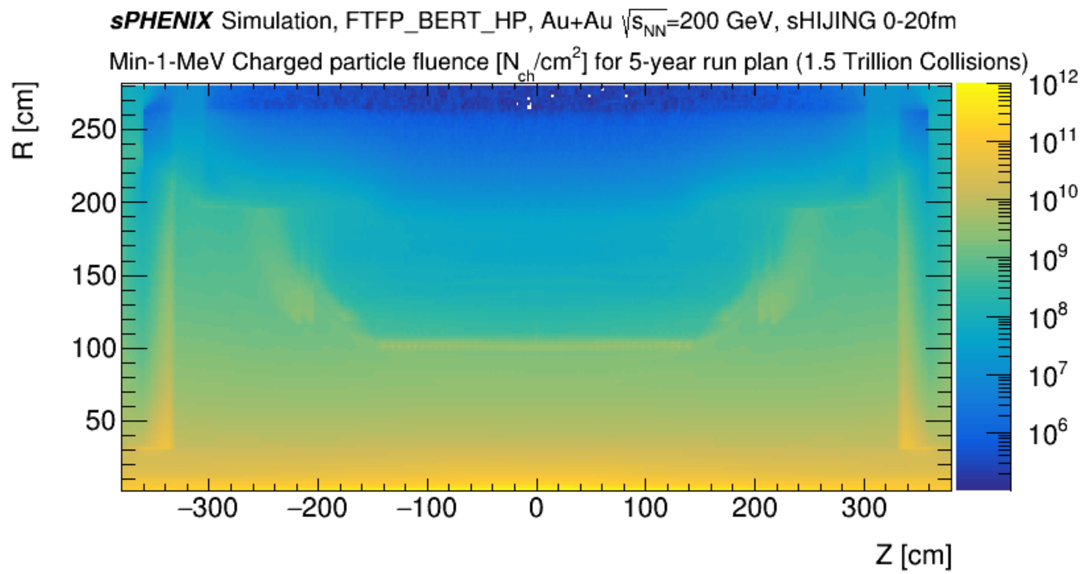




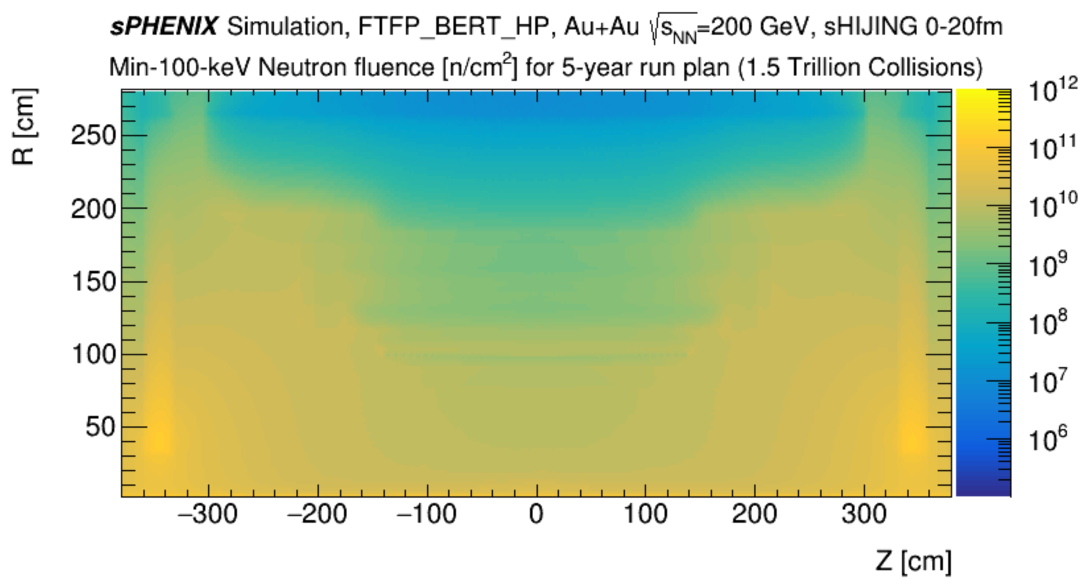
Fluence



sPHENIX Simulation, FTFP_BERT_HP, Au+Au $\sqrt{s_{NN}}$=200 GeV, sHIJING 0-20fm
Total energy deposition [MeV] for 5-year run plan (1.5 Trillion Collisions)
R [cm]
Z [cm]

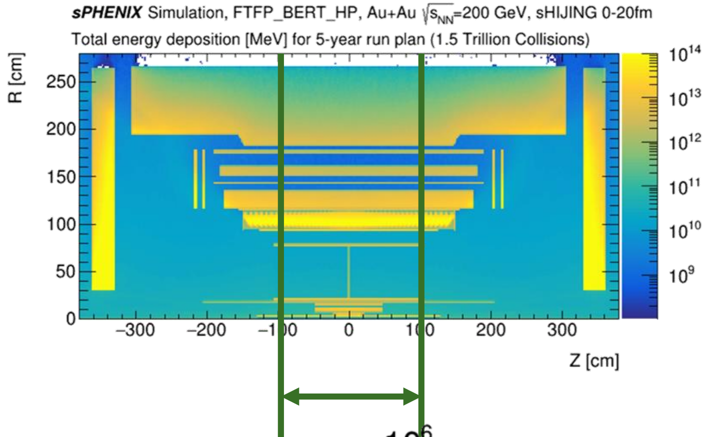


sPHENIX Simulation, FTFP_BERT_HP, Au+Au $\sqrt{s_{NN}}$=200 GeV, sHIJING 0-20fm
Min-1-MeV Charged particle fluence [N_{ch}/cm^2] for 5-year run plan (1.5 Trillion Collisions)
R [cm]
Z [cm]

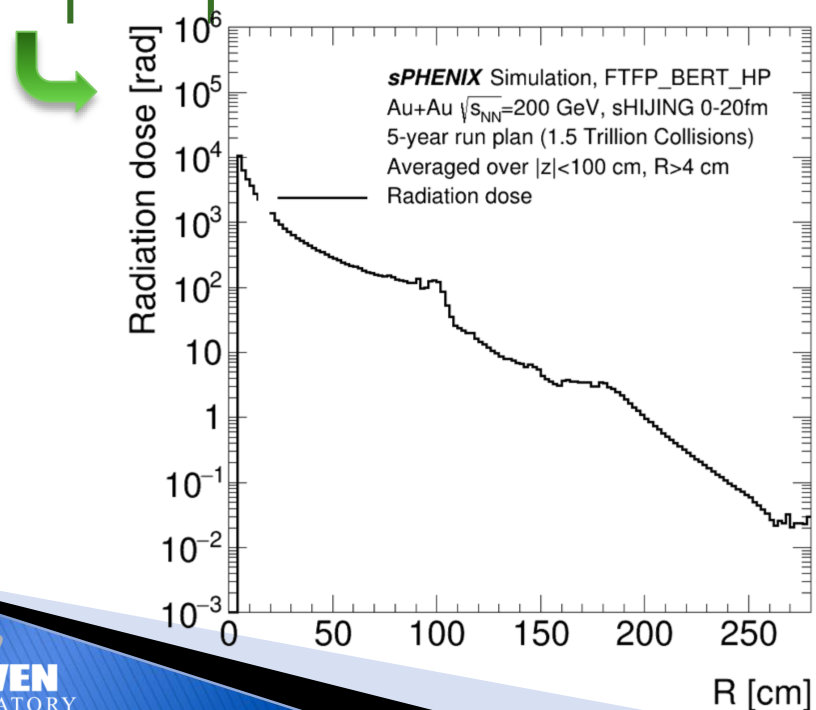


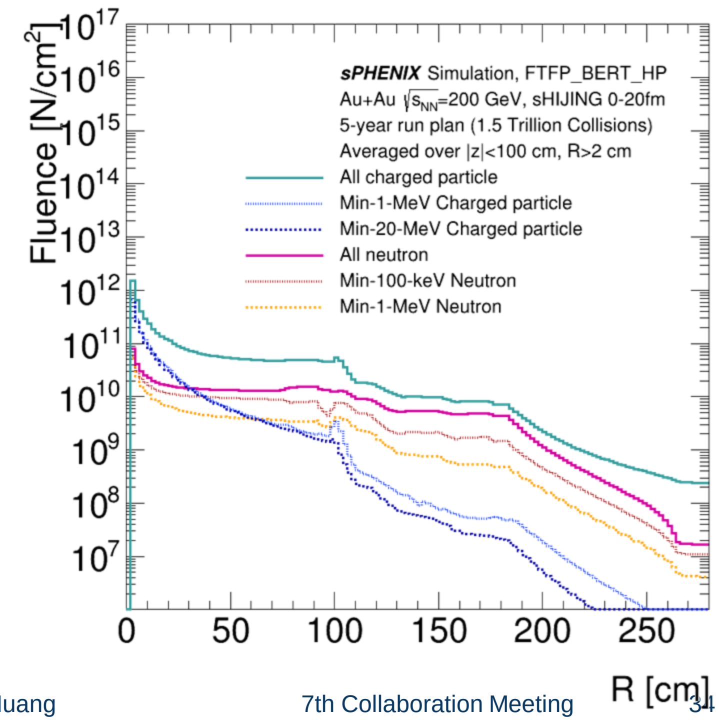
sPHENIX Simulation, FTFP_BERT_HP, Au+Au $\sqrt{s_{NN}}$=200 GeV, sHIJING 0-20fm
Min-100-keV Neutron fluence [n/cm^2] for 5-year run plan (1.5 Trillion Collisions)
R [cm]
Z [cm]

More quantitatively ...

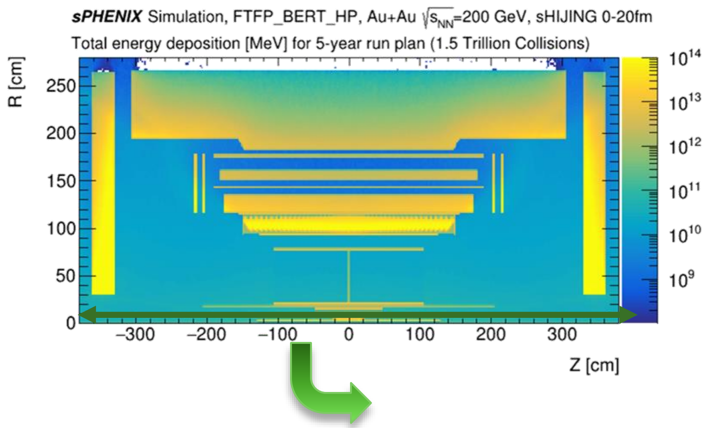


- Averaged in |z|<100 cm
- Plot against R
- Dose peaked at 10kRad
- MeV-Neutron ~ 10^{10} n/cm^2 for inner detectors

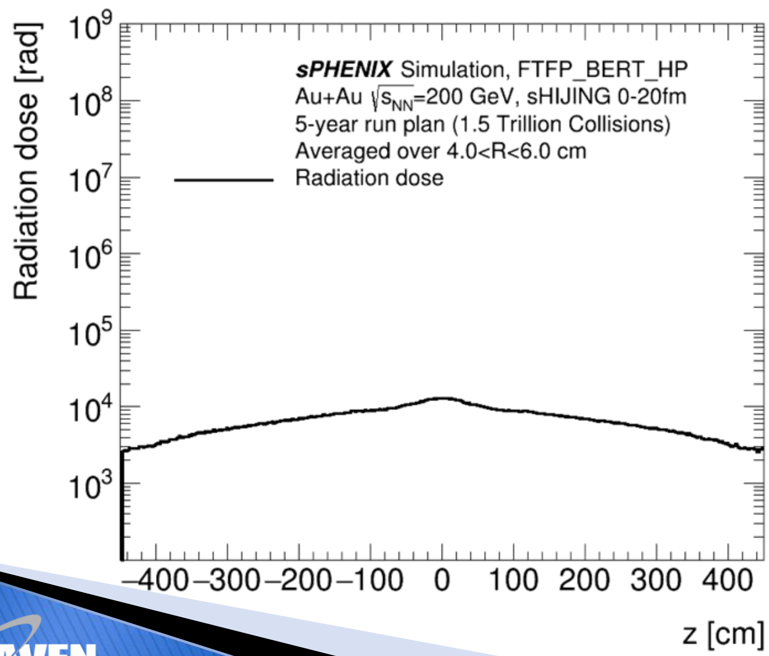


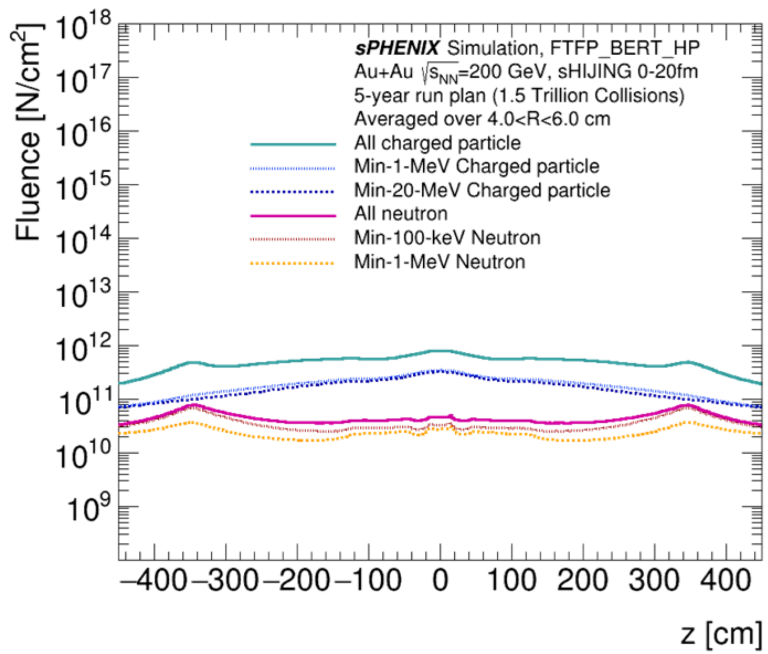


More quantitatively …



- Averaged in R~5 cm
- Plot against z
- Dose peaked at 10kRad
- MeV-Neutron ~ 10^{10} - 10^{11} n/cm^2 for inner detectors





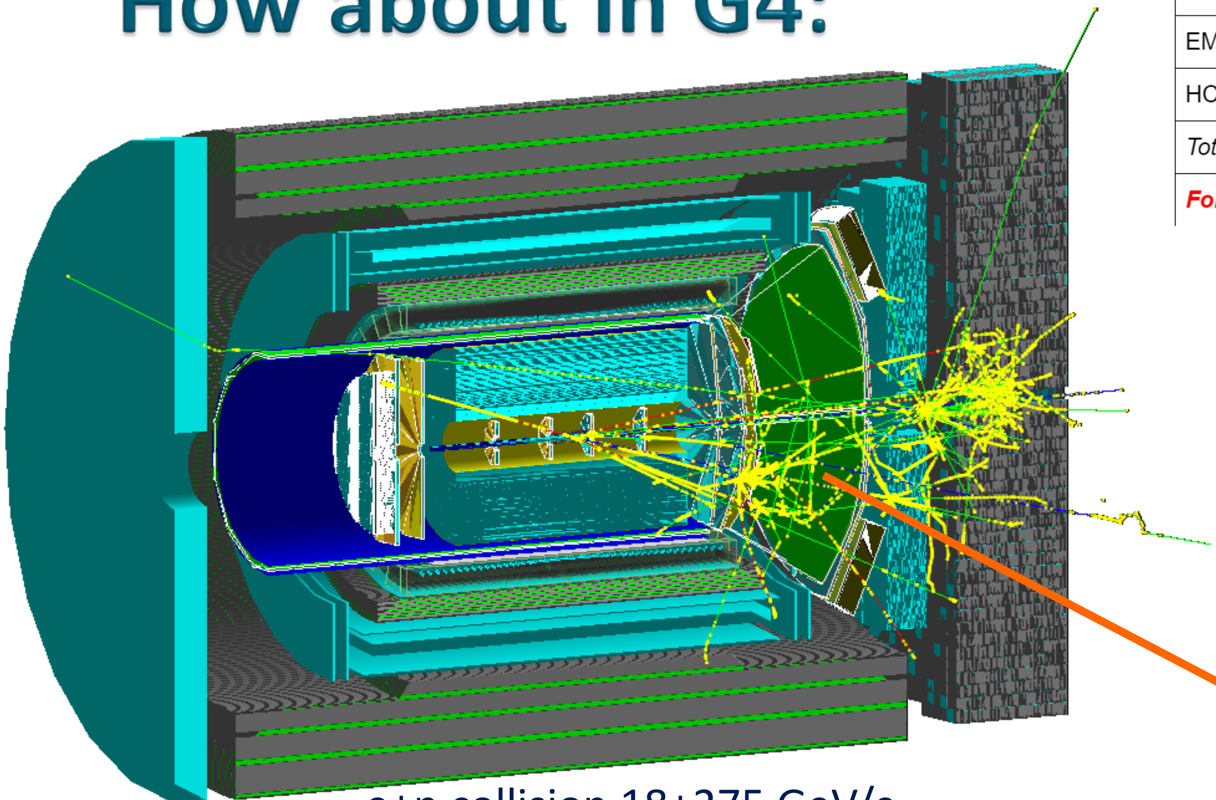
Tonko's estimation:

Signal rate = 16*8 Gbps ~ 100 Gbps @ 10^{33} cm^{-2} $s^{-1,}$ 200kHz collision

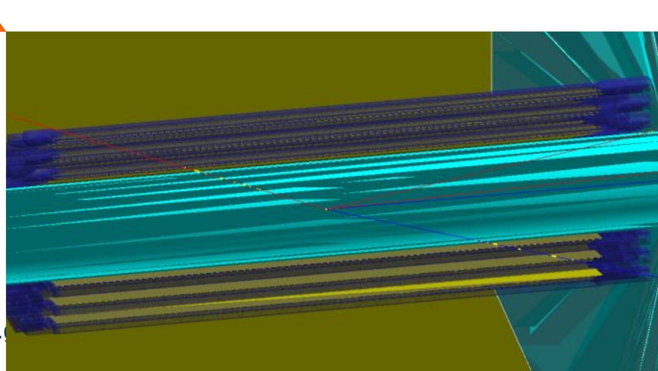
How about in G4:

Tonko's estimation (2015)
The eRHIC Detector ("BeAST") Readout Scheme

Detector	Bytes per track
TPC	100 x (80+4+4) ~ 9000
Silicon	7 x (4+4+4) ~ 90
RICH	20 x (4+4+4) ~ 250
EMCal	1 x (4+4+4) ~ 20
HCal	1 x (4+4+4) ~ 20
Total per track	*9.4 kB*
For 1.7M tracks/s	***(1.7M x 9.4 kB =) 16 GB/s***



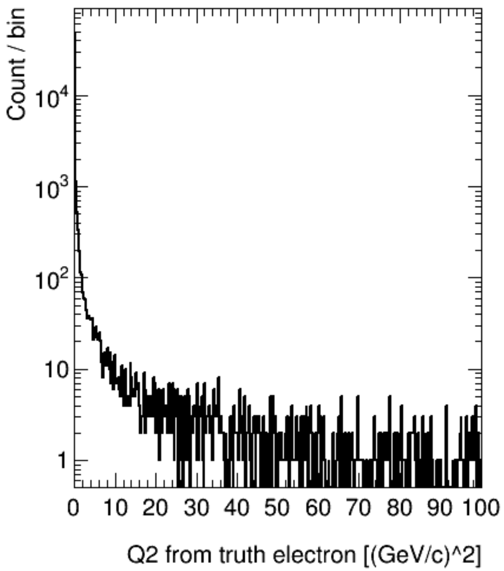
e+p collision 18+275 GeV/c
DIS @ Q^2 ~ 100 $(GeV/c)^2$

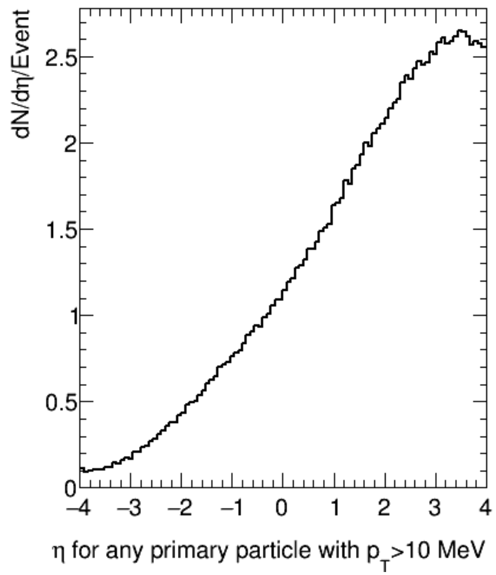


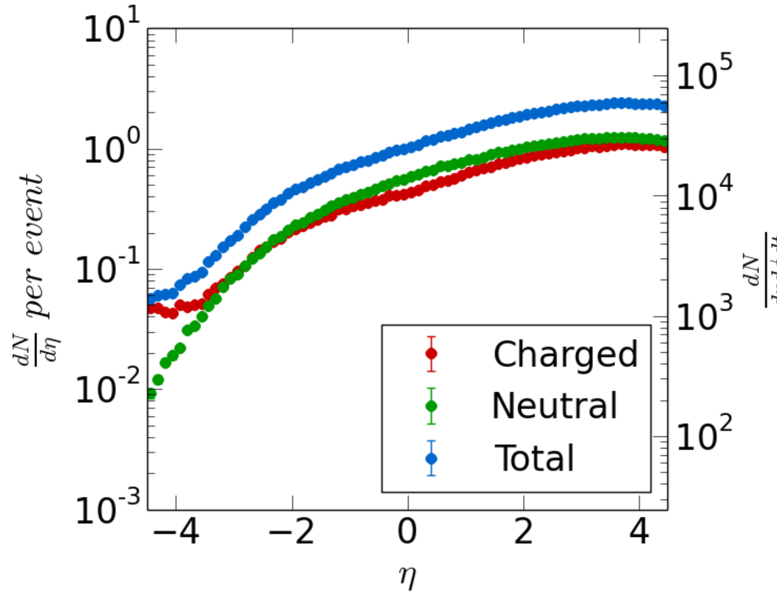
Full detector “Minimal bias” EIC events in sPHENIX framework: quick first look

Multiplicity check for all particles
Minimal bias Pythia6 e+p 20 GeV + 250 GeV
53 µb cross section

BNL EIC taskforce studies
https://wiki.bnl.gov/eic/index.php/Detector_Design_Requirements







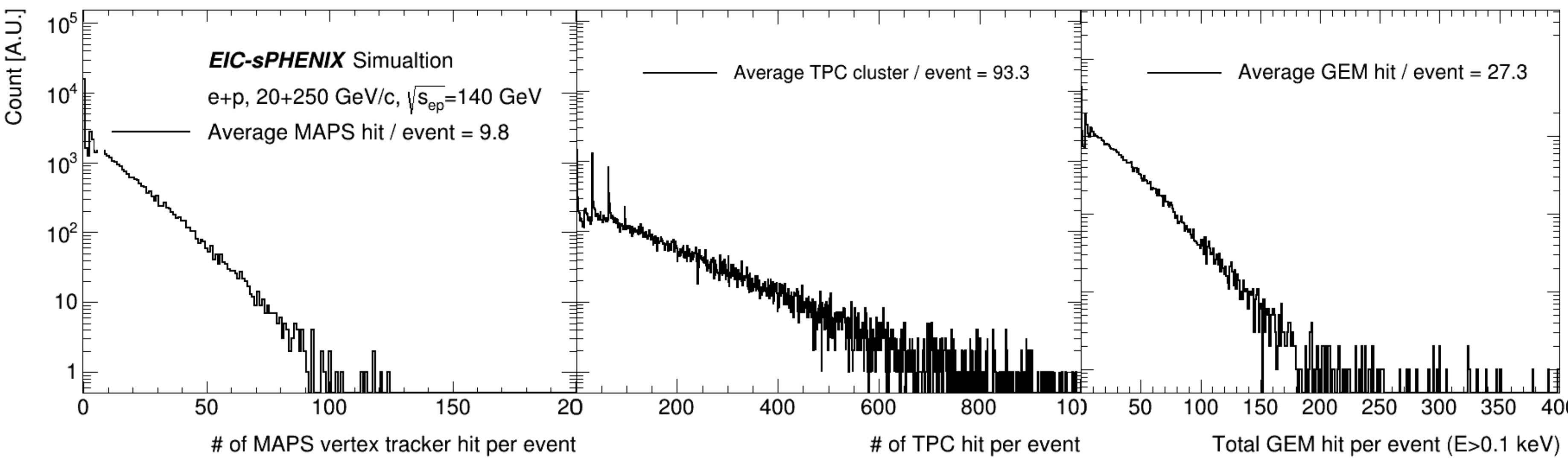
Based on BNL EIC task-force eRHIC-pythia6 55ub sample

```
pythia.ep.20x250.1Mevents.RadCor=0.root
CKIN(3)        changed from        0.00000 to        0.00000
CKIN(4)        changed from       -1.00000 to       -1.00000
```

GEANT4-based detector simulation for DAQ simulation: tracker

sPH-cQCD-2018-001, https://indico.bnl.gov/event/5283/

Extract mean value/collision that produces average signal data rate and tails that produce the buffer depth and latency requirements



Raw data: 16 bit / MAPS hit

3x10 signal hit / collision → 0.2 Gbps @10^{34} $cm^{-2}s^{-1}$

- MAPS is vulnerable to beam background see later slides
- ALPIDE MAPS noise are low, expect 10^{-6} /pixel/strobe, 200M pixel, 3us strobe → ~1Gbps

Raw data: 3x5 10 bit / TPC hit + headers (60 bits)

Raw data: 3x5 10 bit / GEM hit + headers (60 bits)

EIC collision signal data rate summary

sPH-cQCD-2018-001, https://indico.bnl.gov/event/5283/

- Tracker + calorimeter ~ 40 Gbps
  - + PID detector + 2x for noise ~ 100 Gbps
  - Similar rate to an earlier estimation T. Ljubicic for BeAST (2015)
- Unlike LHC or RHIC, signal-collision data rate of 100 Gbps seems quite manageable:
  - Smaller than sPHENIX TPC peak disk rate of 200 Gbps
- Forward spectrometer not yet included