System design considerations for EIC detectors

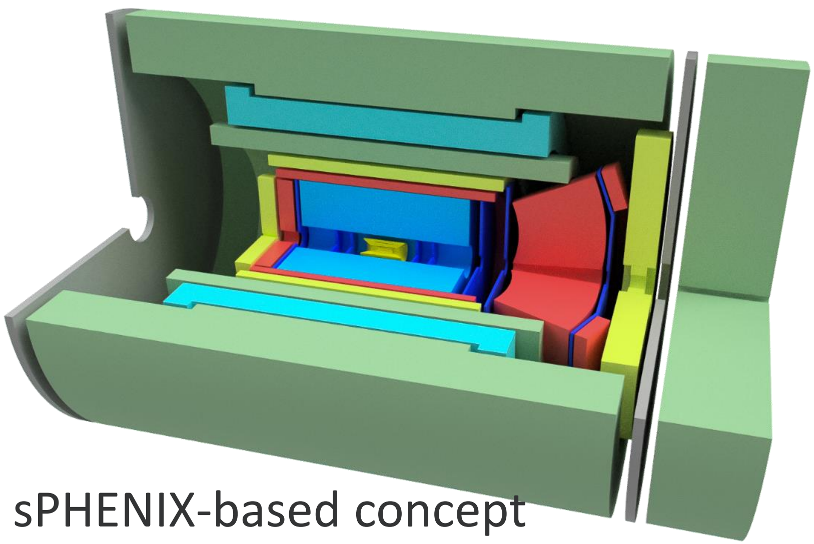
Outline: ● Design studies ● Software ● DAQ interface

Mainly based upon EIC detector design study: sPH-cQCD-2018-001

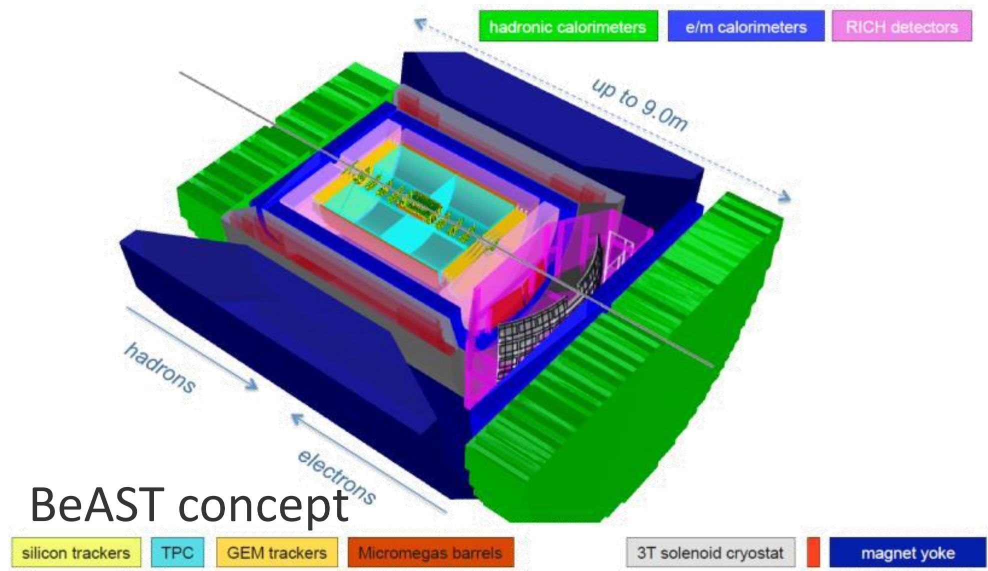
Jin Huang (BNL)

Detector concepts

See also: P. Nadel-Turonski

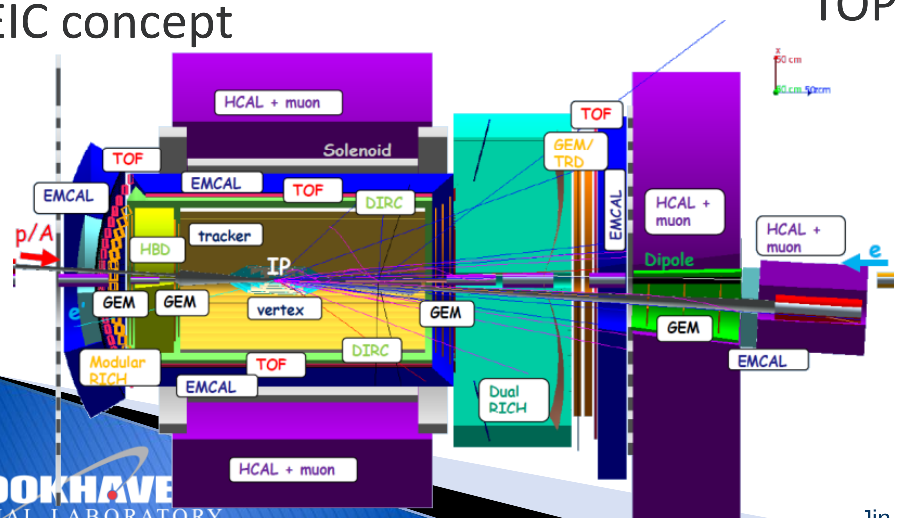


sPHENIX-based concept

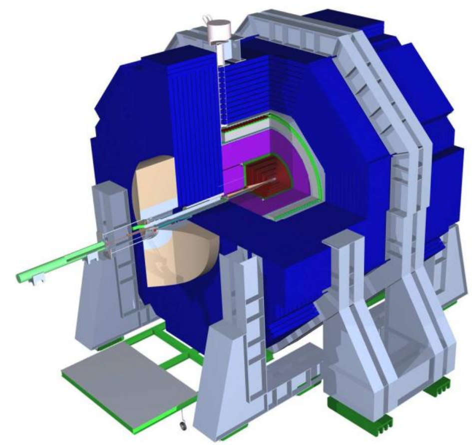


BeAST concept

JLEIC concept



TOPSiDE concept



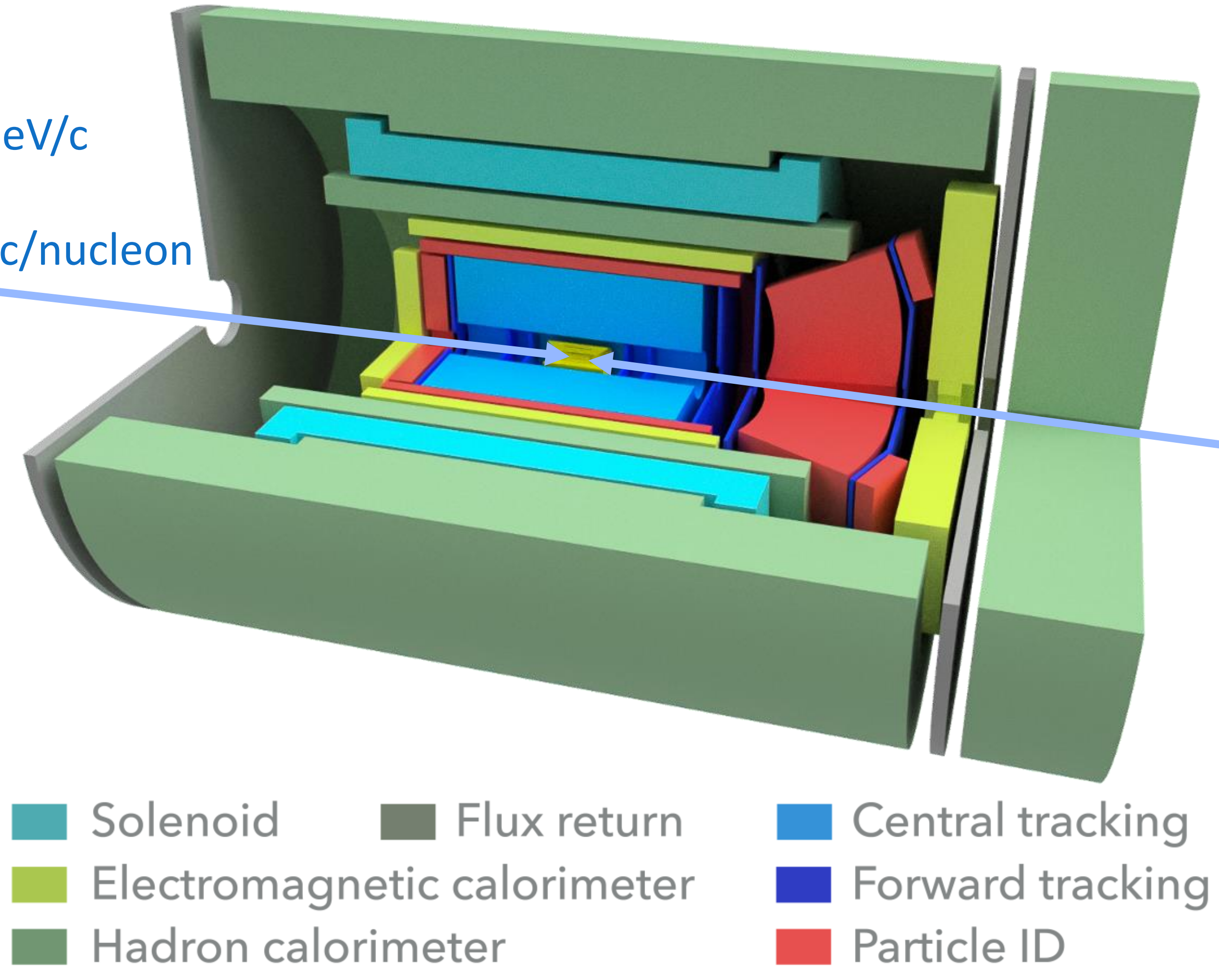
References reports :

- ePHENIX LOI: arXiv:1402.1209
- eRHIC design report, preCDR: arXiv:1409.1633
- MEIC (JLEIC) design summary: arXiv:1504.07961

sPHENIX-based EIC detector

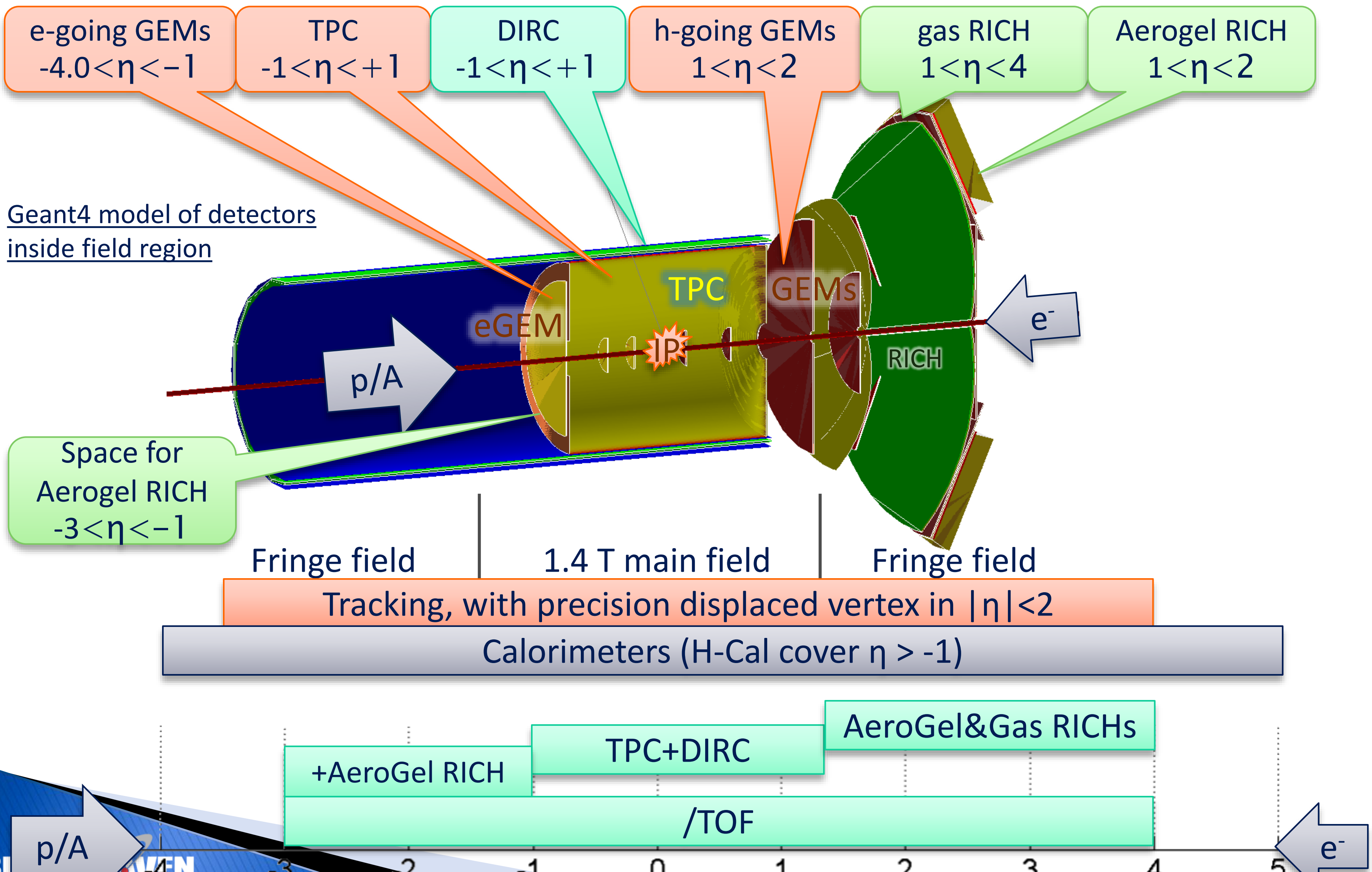
2018 update: sPH-cQCD-2018-001 https://indico.bnl.gov/event/5283/

- Proton 275 GeV/c Polarized
- Ion 100 GeV/c/nucleon

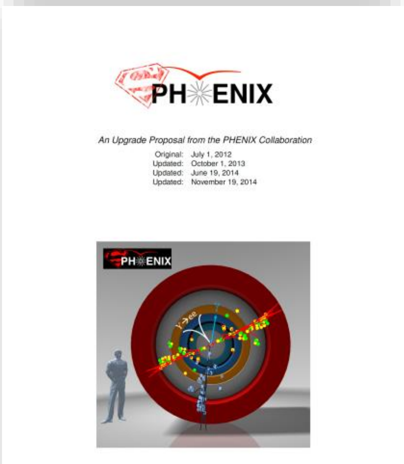


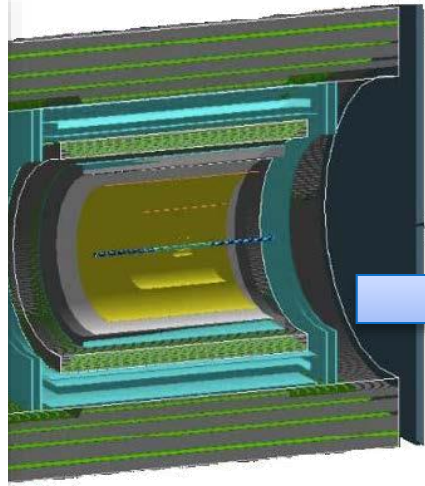
e^- 10 GeV/c Polarized

Tracking and PID detectors

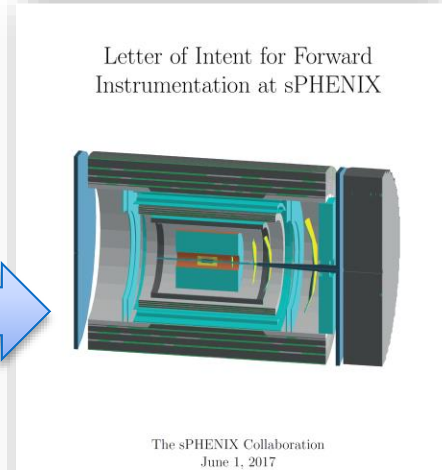


Evolving upgrade concepts

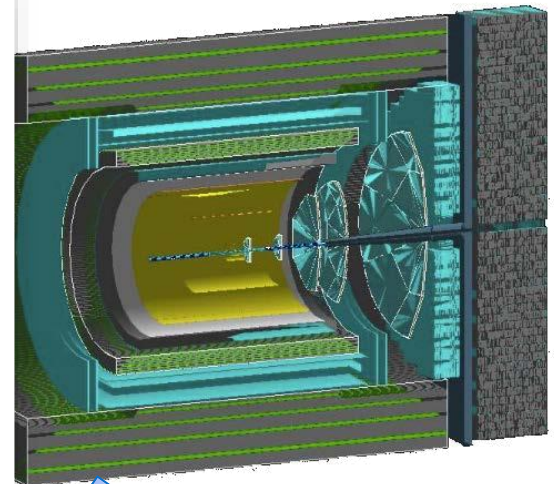




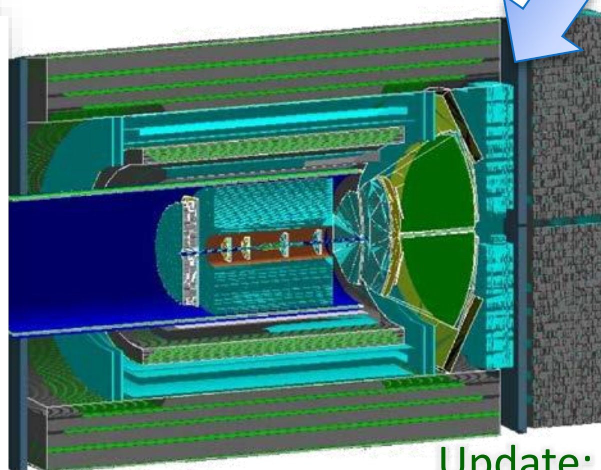
arXiv:1501.06197
CD-1 approval
Successful PD2/3 review



To RHIC PAC 2017

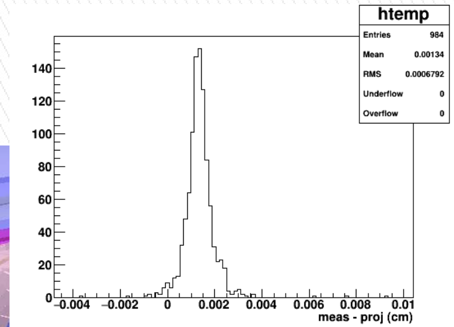


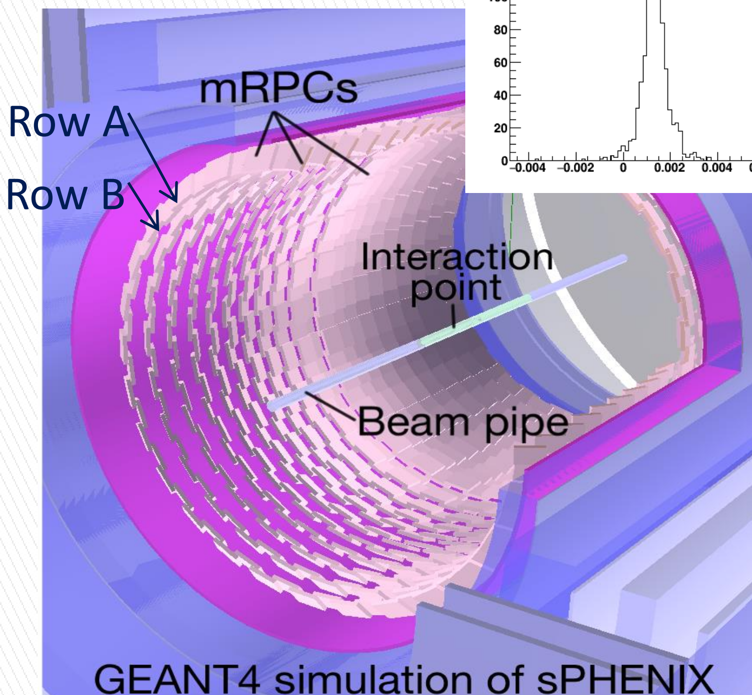
arXiv:1402.1209



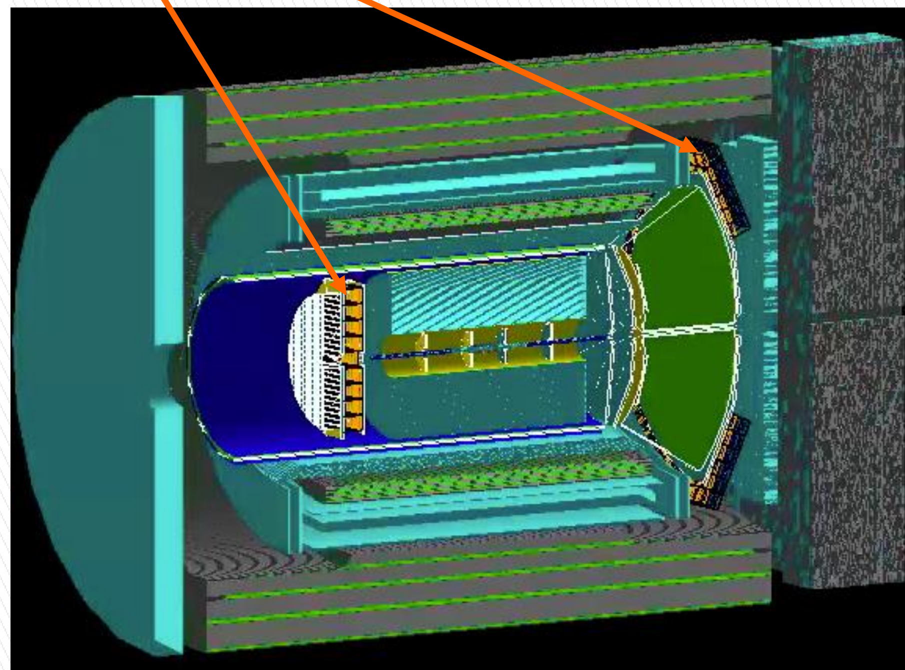
Update: sPH-cQCD-2018-001

eRD14 in sPHENIX, fsPHENIX, sPHENIX-EIC





e-going & h-going mRHIC implemented by Xu



Barrel TOF
See also, **talk M. Chui**

Forward mRHIC
See also, **talk X. He, X. Sun**

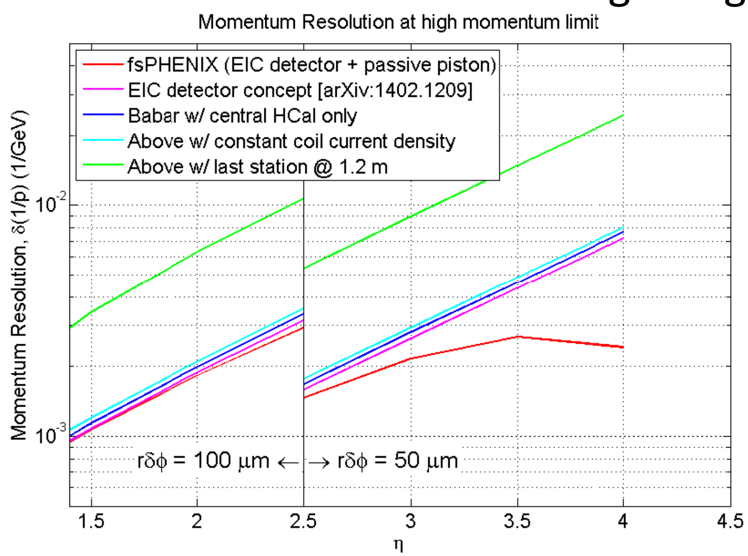
Not shown here:
gas RICH modeled with eRD6 HBD-RICH prototype, see talk **S. Torre, K. Dehmelt**

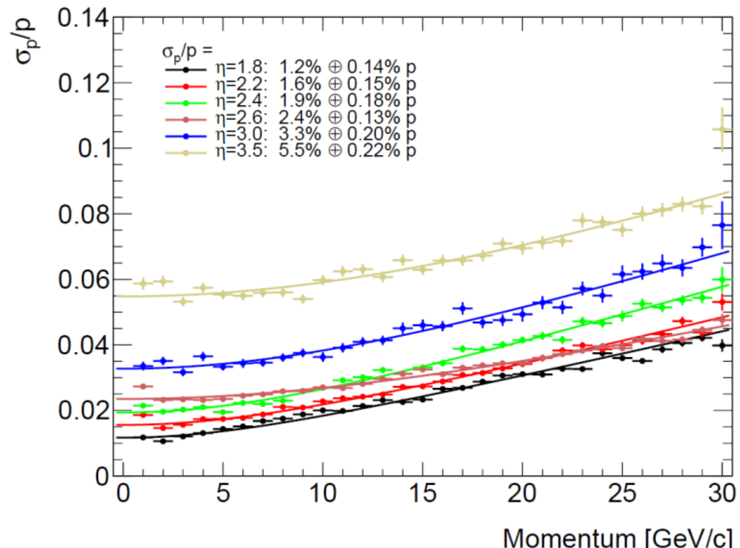
sPHENIX-EIC simulation reconstruction framework

https://github.com/sPHENIX-Collaboration/macros

- Fun4All: single frameworks integrating simulation and reconstruction
  - Built for collider experiments from simulation to reco and analysis
  - Regularly processing PBs of data and billions-of-particle simulation and analysis in sPHENIX studies
- Add your module
  - For example, it would be easy to port over the DIRC G4 simulation
  - Then you can utilize the full detector reconstruction

Numerical estimation in design stage → Full G4 + Kalman filter reco and vertexing

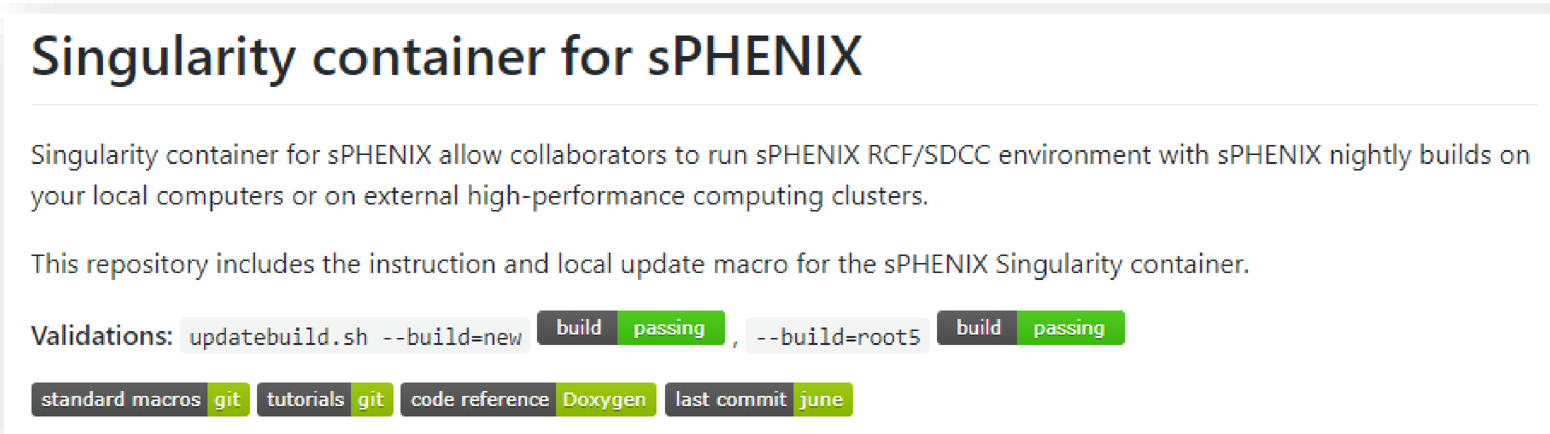




Distribution of sPHENIX-EIC simulation

- Now the sPHENIX software + tool set available via singularity container
- Distributed via CVMFS to computing centers
- And available for download to use on laptop
- Daily updates and validations

https://github.com/sPHENIX-Collaboration/Singularity



Singularity container for sPHENIX

Singularity container for sPHENIX allow collaborators to run sPHENIX RCF/SDCC environment with sPHENIX nightly builds on your local computers or on external high-performance computing clusters.

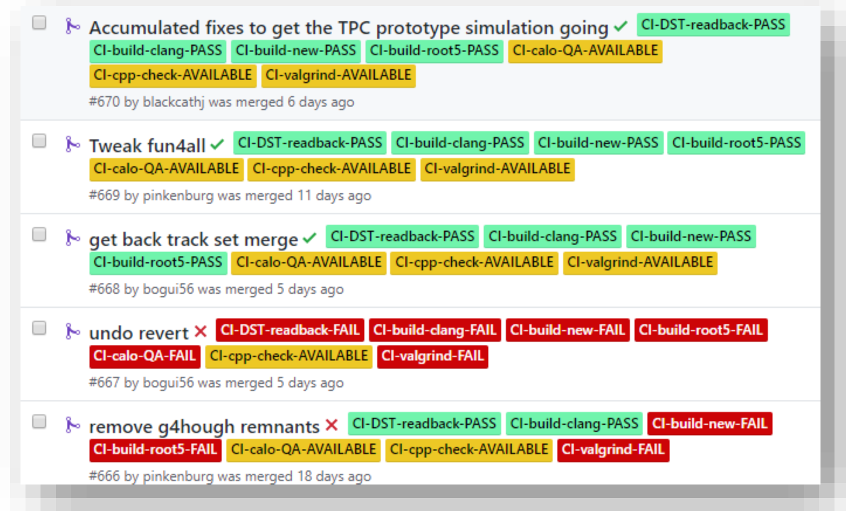
This repository includes the instruction and local update macro for the sPHENIX Singularity container.

Validations: `updatebuild.sh --build=new` build passing , `--build=root5` build passing

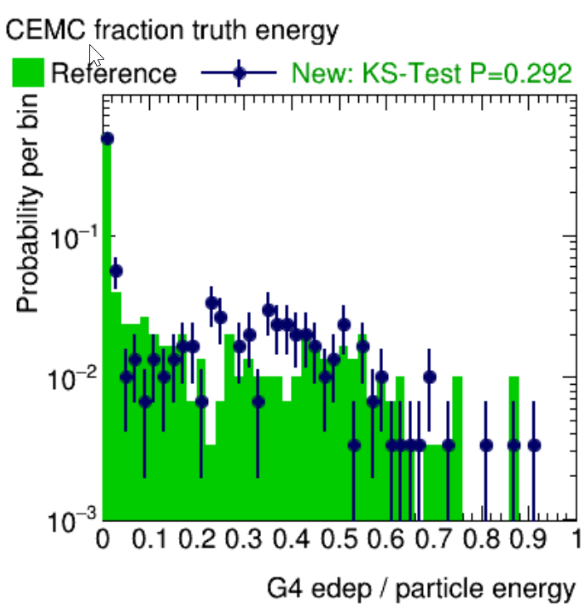
standard macros git | tutorials git | code reference Doxygen | last commit june

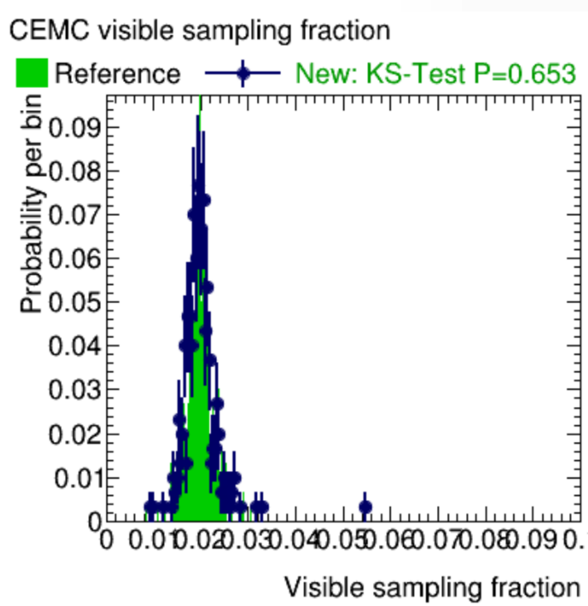
Daily QA Check

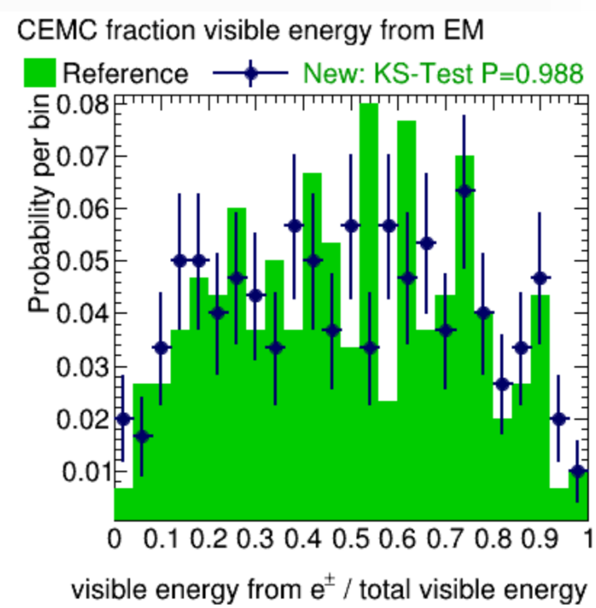
https://github.com/sPHENIX-Collaboration/coresoftware/pulls?q=is%3Apr+is%3Aclosed



- sPHENIX Continuous Integration automatically check every Pull Request and daily builds
- It will be useful to have such validation for PID detectors too
  - e.g. calorimeter is check from G4-basics to jet reconstruction

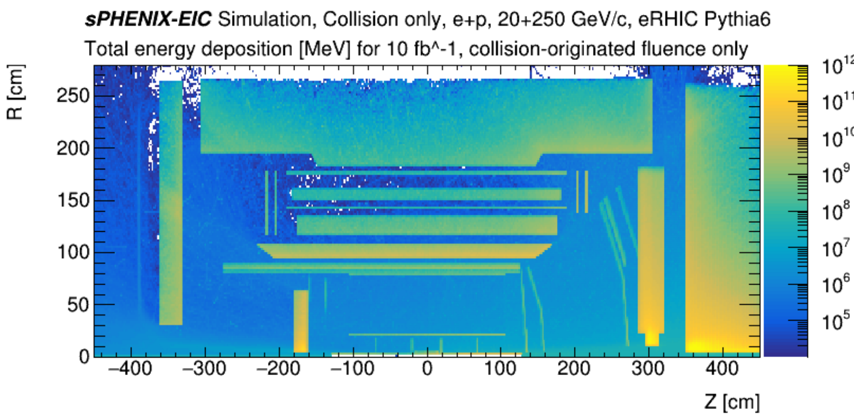


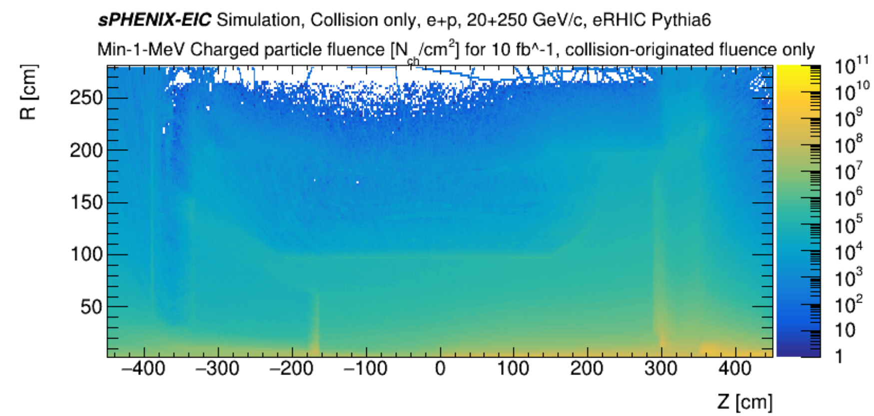


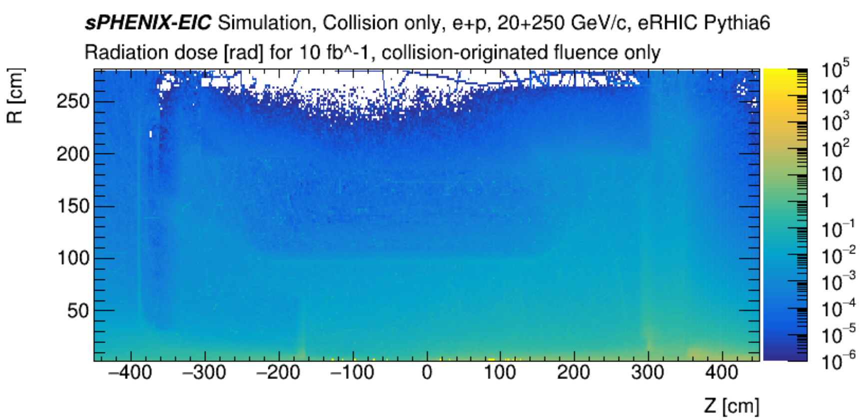


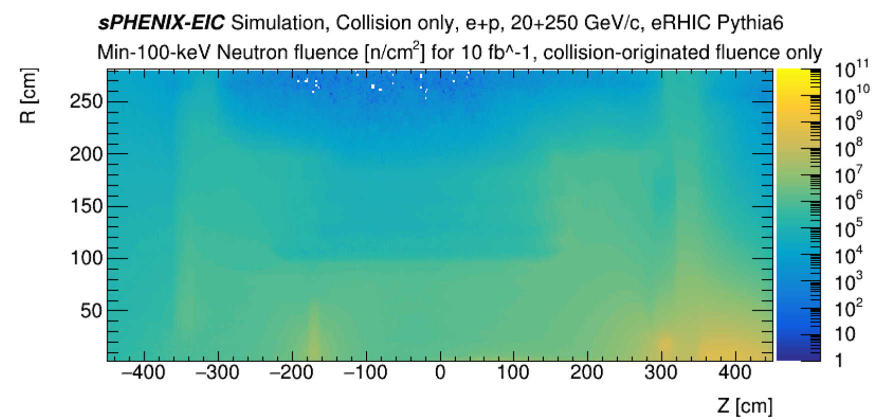
Radiation considerations

For discussion of relative radiation only. Absolute value need double check, consider very tentative







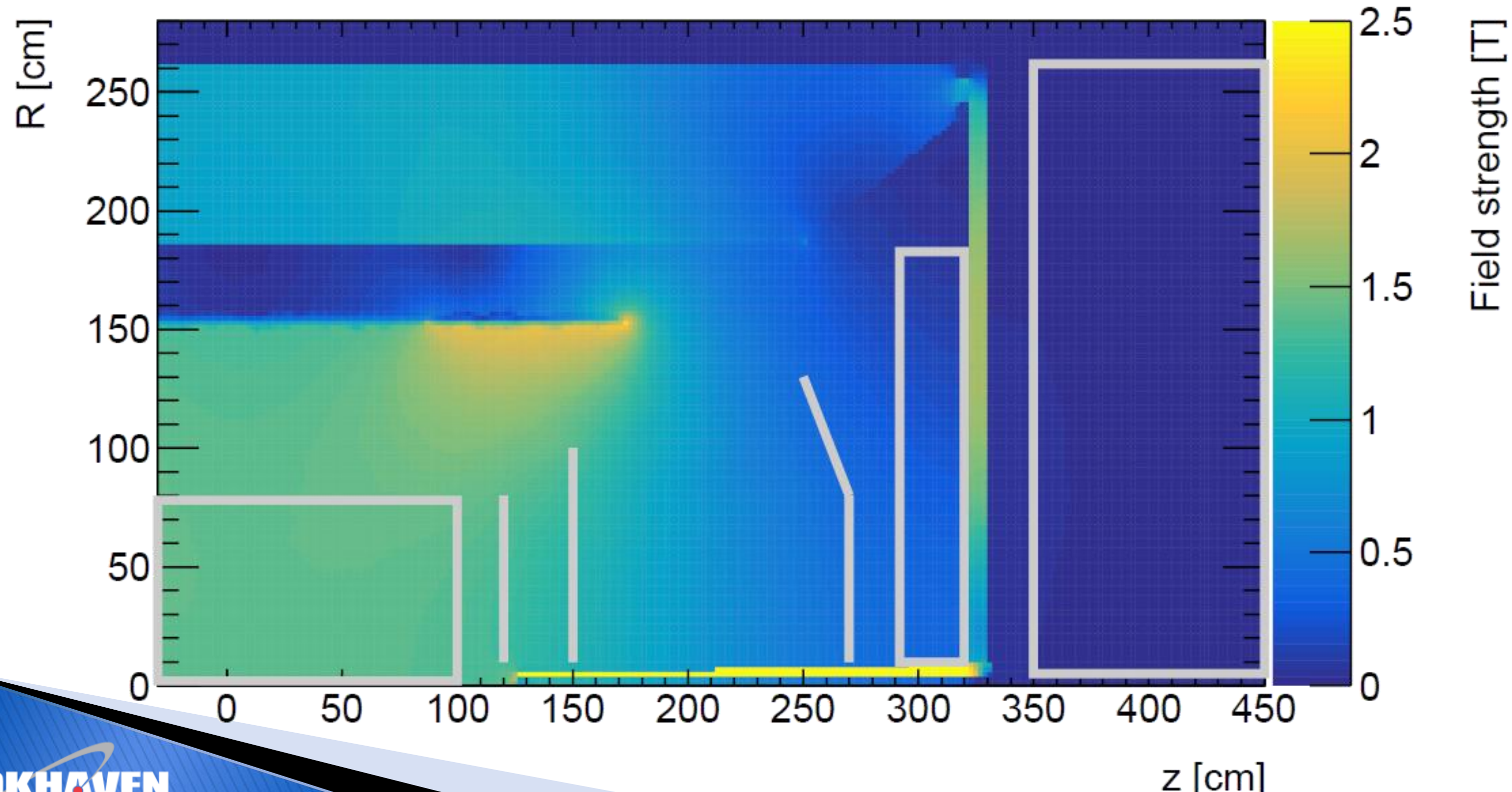


1st year radiation dose (10 fb^{-1})

Note the dose would be order-magnitude higher at $10^{34} cm^{-2}s^{-1}$

Magnetic field considerations

- Had a long talk on magnetic field optimization for tracking+RICHs in eRD14…
- Gas RICH photo sensor near field coil, which could experience strong and varying-direction field
- mRHIC is further away and could be aligned to the field direction
- Field sensitivity studies see Talk Y. Ilieva



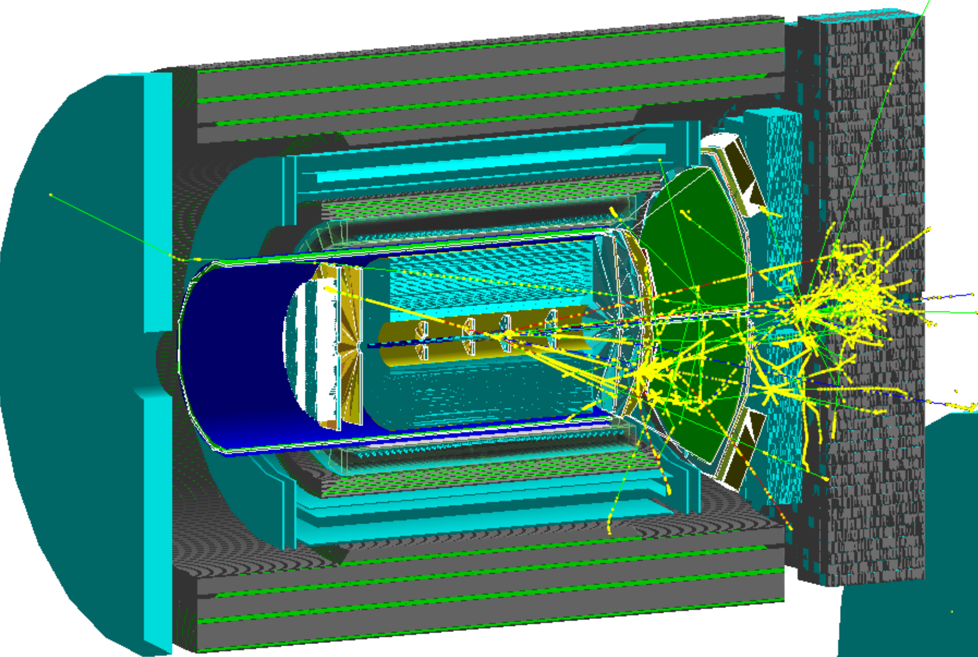
EIC: unique collider → unique real-time challenges

	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	2-10 ns	100 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

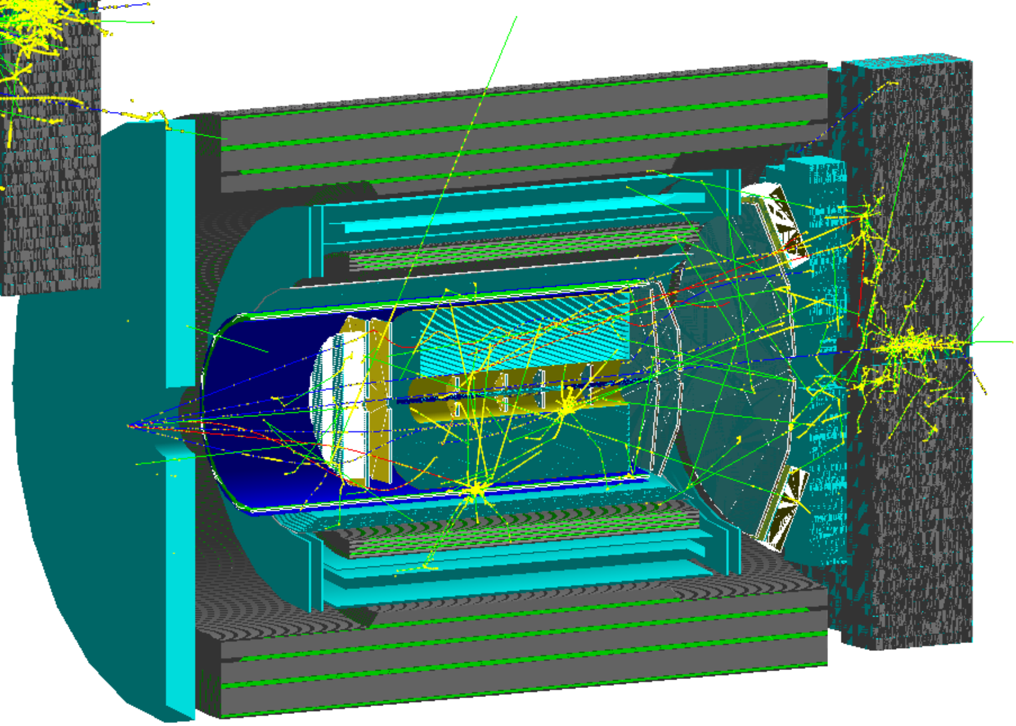
- EIC has lower collision rate and event size is small → signal data rate is low
- But events are precious and have diverse topology
- EIC luminosity is high, so background and systematic control is key

Rate in Geant4 full detector simulation Sum collision + beam gas

sPH-cQCD-2018-001: https://indico.bnl.gov/event/5283/ , Simulation: https://github.com/sPHENIX-Collaboration/singularity



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

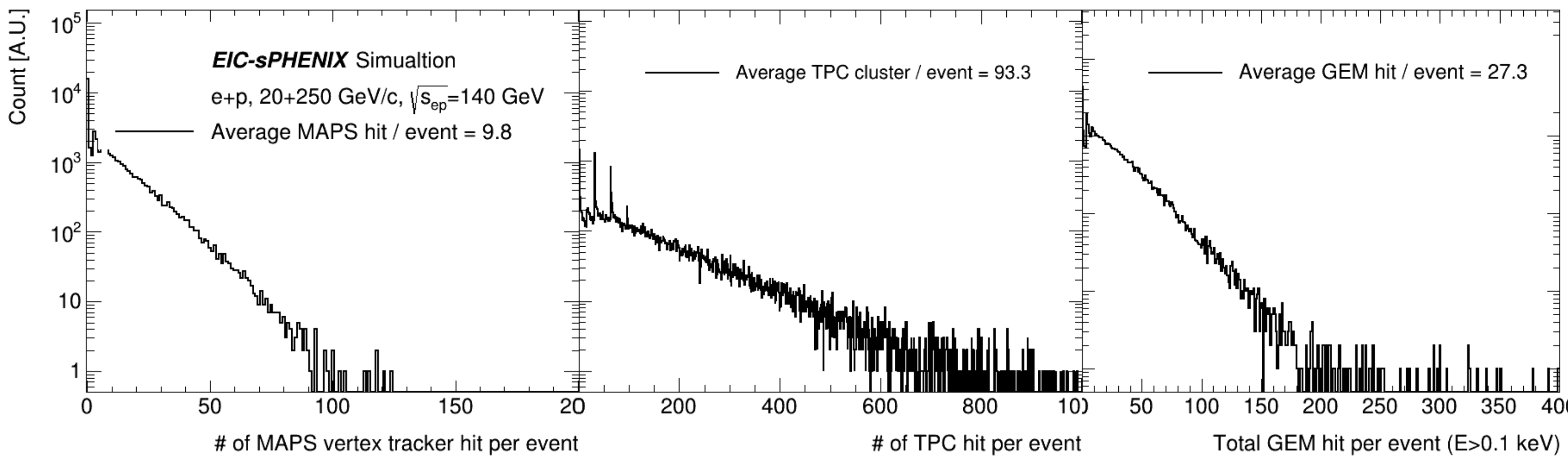


Beam gas event
p + p, 275 GeV/c
at z=-4 m

GEANT4-based detector simulation for DAQ simulation: tracker for example

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

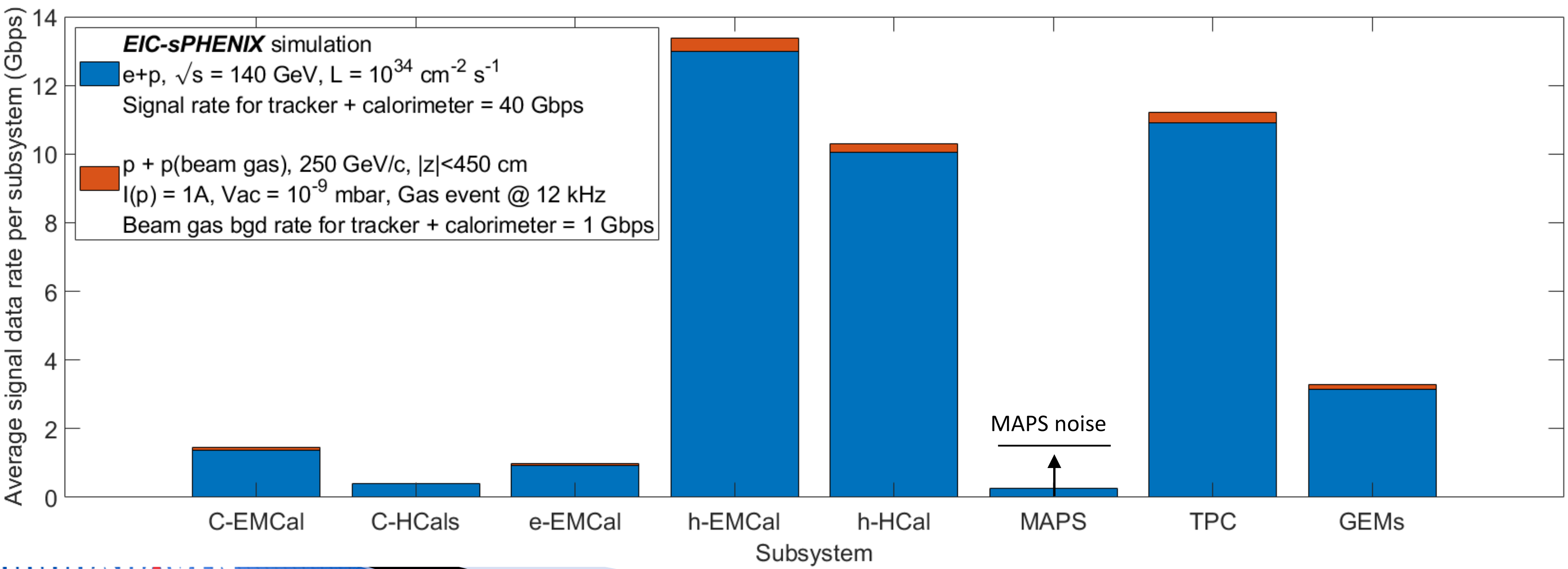
Raw data: 3x5 10 bit / TPC hit + headers (60 bits)

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

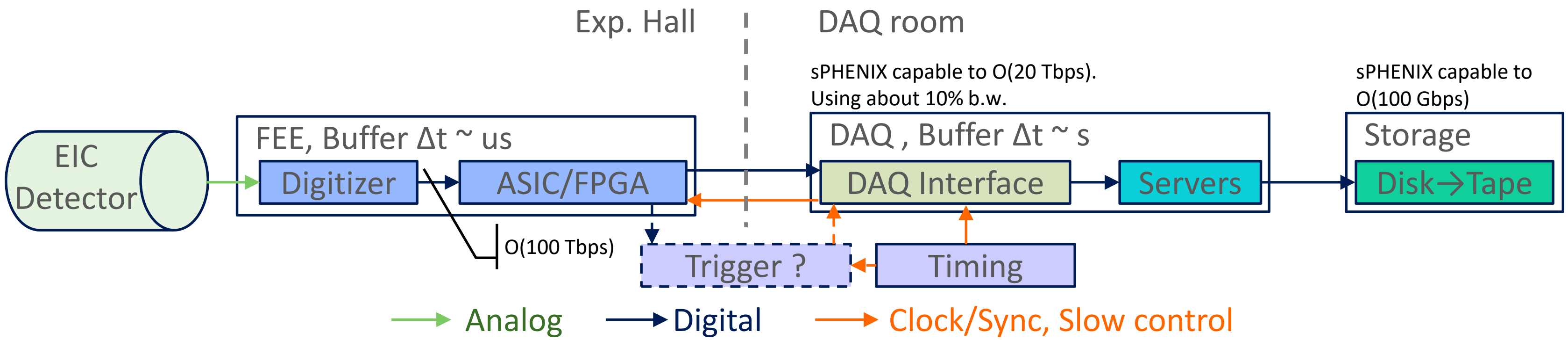
Rate in Geant4 full detector simulation Sum collision + beam gas

sPH-cQCD-2018-001: https://indico.bnl.gov/event/5283/ , Simulation: https://github.com/sPHENIX-Collaboration/singularity

- Tracker + Calo signal ~ 40 Gbps @ 10^{34} cm^{-2} s^{-1} < sPHENIX peak disk rate
- Vac profile based on HERA experience (10-9 mbar) → Overall ~ 1 Gbps @ 12kHz beam gas interaction, << EIC collision signal data rate
- Be great to include PID detectors too



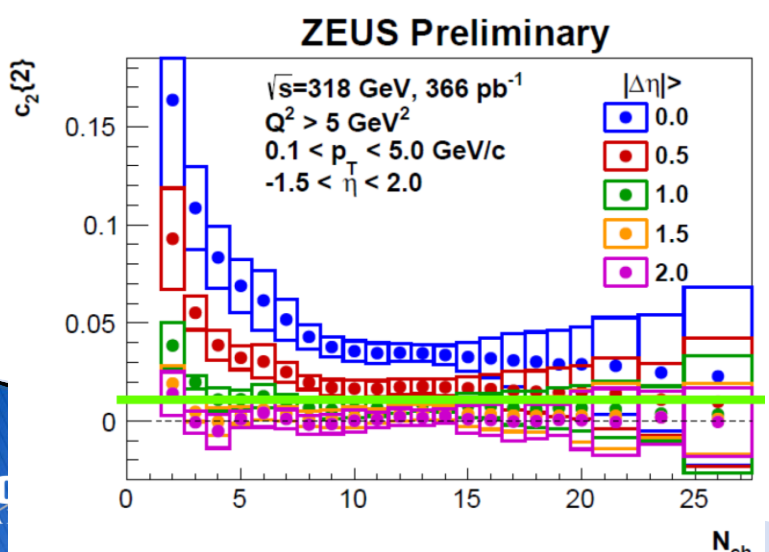
Strategy for an EIC real-time system



- For the signal data rate from EIC (100 Gbps), we can aim for filtering-out and streaming all collision in raw data without a hardware-based global triggering
  - Diversity of EIC event topology → streaming DAQ enables expected and unexpected physics
  - Streaming minimizing systematics by avoiding hardware trigger decision, keeping background and history
  - At 500kHz event rate, multi-μs-integration detectors would require streaming, e.g. TPC, MAPS
- Requirement
  - All front-end to continuously digitize data or self-triggering
    e.g. PHENIX FVTX, STAR eTOF, all sPHENIX trackers, any many prototypes in this workshop
  - Reliably synchronize all front-ends and identify faults
  - Recording all collision data (100 Gbps if raw)
  - If needed, filtering out background with low signal loss (10^{-4}?)
  - Requiring reliable data flow → control systematics:
    Low data loss rate < 10^{-4}(?) and/or loss in a deterministic manor

Streaming DAQ enables expected and unexpected physics. Example:

- In 2016, surprising evidence of collectivity in p+p collisions [CMS, PLB 2016]
- Inspired search of QGP signatures in even smaller system, in e+p [ZEUS, QM18], and e+e systems [MOD, arXiv 1906.00489]
- As HERA data is limited by statistics and the available trigger at that time, such search could be naturally conducted at EIC e+p/A
- Key requirement is to collect large amount of high multiplicity events with minimal triggering acceptance bias, including low Q2 and diffractive events
- In LHC, such data are collected with streaming/local-triggered front-end + HLT of high N_{ch} events
- In EIC, processing low-Q2 events naturally leads to streaming readout DAQ

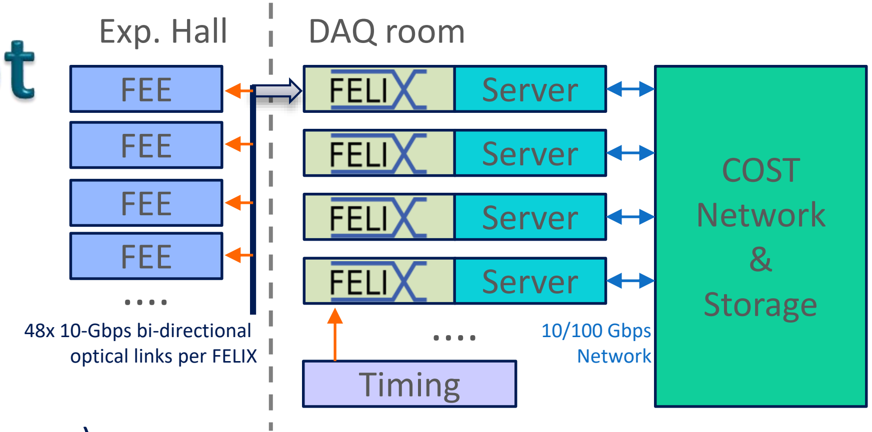


Figures/discussion courtesy Baty IS2019, ZEUS QM18

- $c_2\{2\} < 0.01$ at $N_{ch} = 15$
- implies $v_2 < 0.1$
- Room for small v2 signal
- Need more statistics

sPHENIX-EIC concept DAQ strategy

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

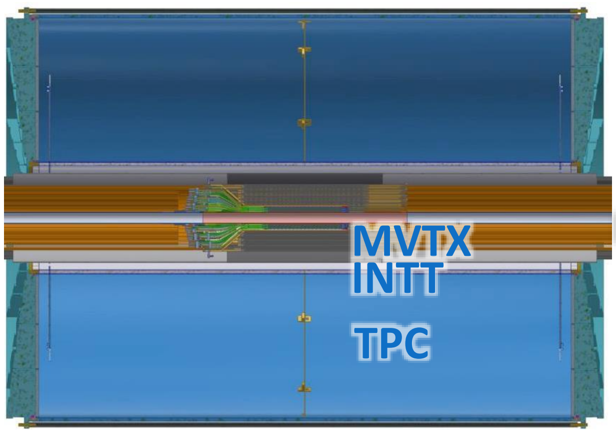


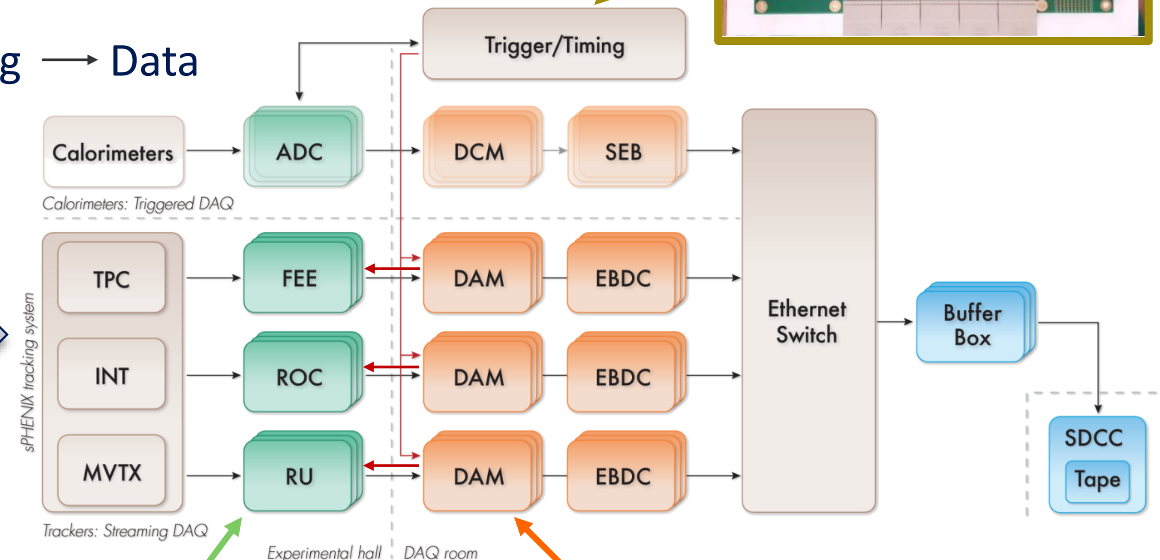
- Full streaming readout front-end (buffer length : µs)
  → DAQ interface to commodity computing via PCIe-based FPGA cards (e.g. FELIX)
  → Disk/tape storage of streaming time-framed zero-suppressed raw data (buffer length : s)
  → Collision event tagging in offline production (latency : days)
- Why time-framed streaming readout?
  - Diversity of EIC event topology. Streaming minimizing systematics by avoiding hardware trigger decision, keeping background and history
  - At 500kHz event rate, multi-µs-integration detectors would require streaming, e.g. TPC, MAPS
- Why FELIX-like DAQ interface?
  - Deterministic transmission from FEE up to server memory, buffering and busy generation
  - 0.5 Tbps x bi-direction IO, bridging µs-level FEE buffer length with ms+ DAQ network time scale
  - Interface with commodity computing via PCIe @ ~100Gbps
  - Distribute experiment timing and synchronization cross large system
  - Similar architecture have wide support in 2020+ for high throughput DAQ e.g. ATLAS, ALICE, LHCb, CBM, Proto-DUNE
- Why keep raw data?
  - EIC collision signal @ 100 Gbps < sPHENIX disk rate, it is affordable to disk-write all raw signal data
  - Allow time + special run needed for final calibration, followed by prompt reconstruction
  - Filter out noise if needed

See also discussion on eRD23: SRO Consortium

Streaming DAQ of sPHENIX trackers

Global Timing Module





MVTX RU
ASIC: ALPIDE

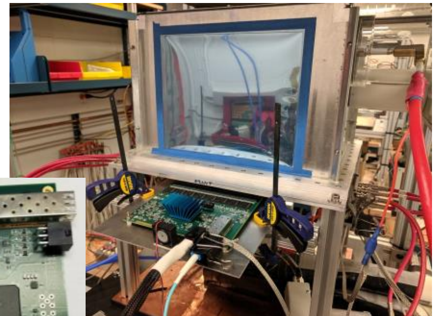
INTT ROC
FPHX

TPC FEE
SAMPA v4 → v5

BNL-712/FELIXv2 as DAM
Streaming ASIC → DAQ

Test stands: SAMPA for GEM trackers

eRD6 TPC HBD

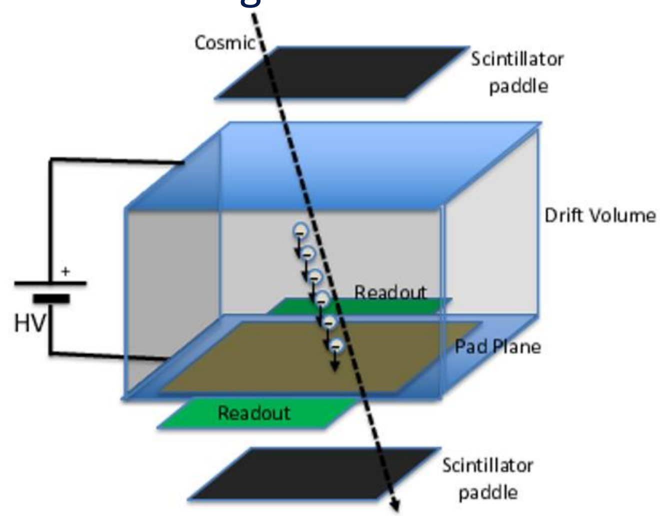


8x SAMPA FEE
256 ADC/FEE

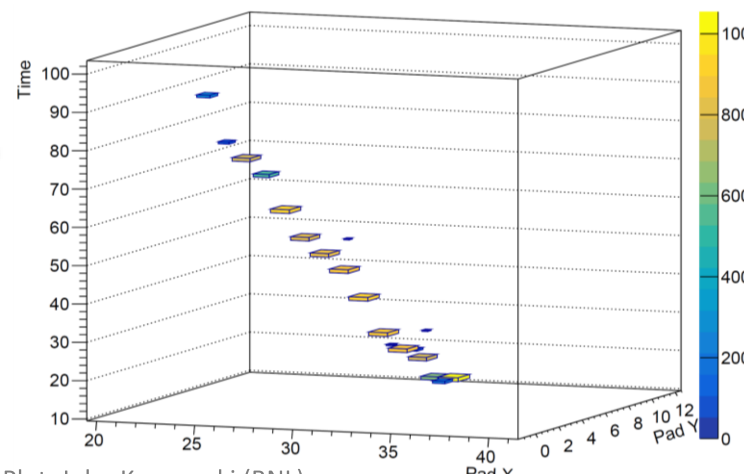
FELIX v2 DAQ interface

Commodity server

Cosmic through mini-TPC test stand

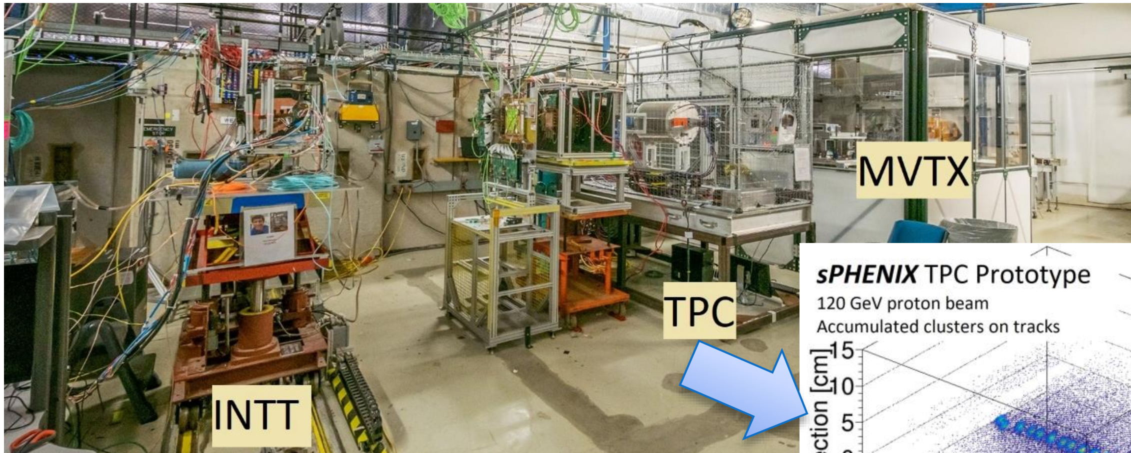


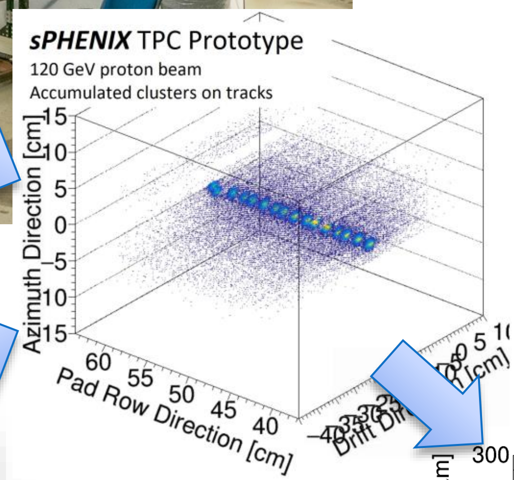
Reconstructed GEM hits from SAMPA data



Plot: John Kuczewski (BNL)

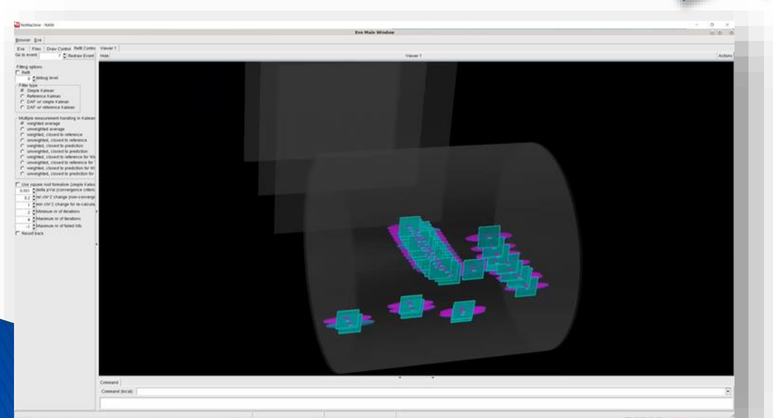
Recent test beam in June 2019



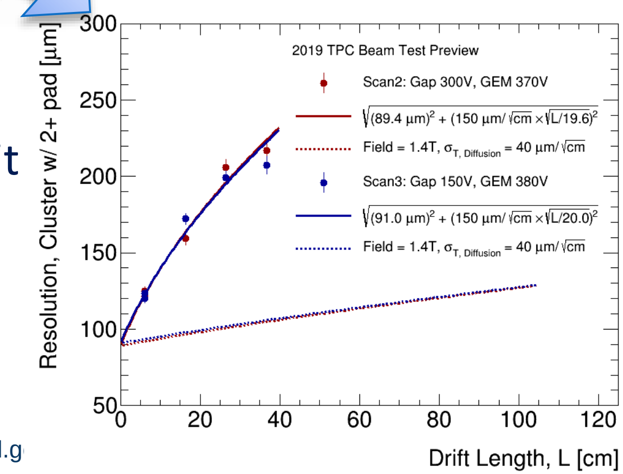


Track finding

Simulated track in Geant4



Kalman-filter fit
And resolution



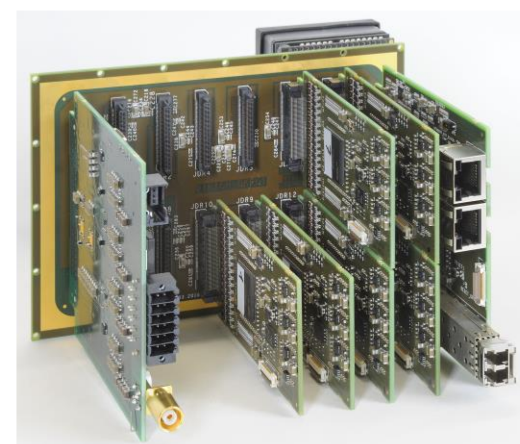
Electronics considerations for PID

- Streaming FEE choices
  - Continuous digitizing ADC (e.g. SAMPA, various calorimeter fADC)
  - Analog memory cells w/ self trigger (e.g. DRS4GLO, TargetX/SiREAD?, MAROC??)
  - Leading + trailing edge TDC (e.g. TOFPET, HADES FPGA TDC)
- Sync and distribution of clock

sPHENIX 256-ch SAMPA FEE
Applicable to MPGD Photon det.

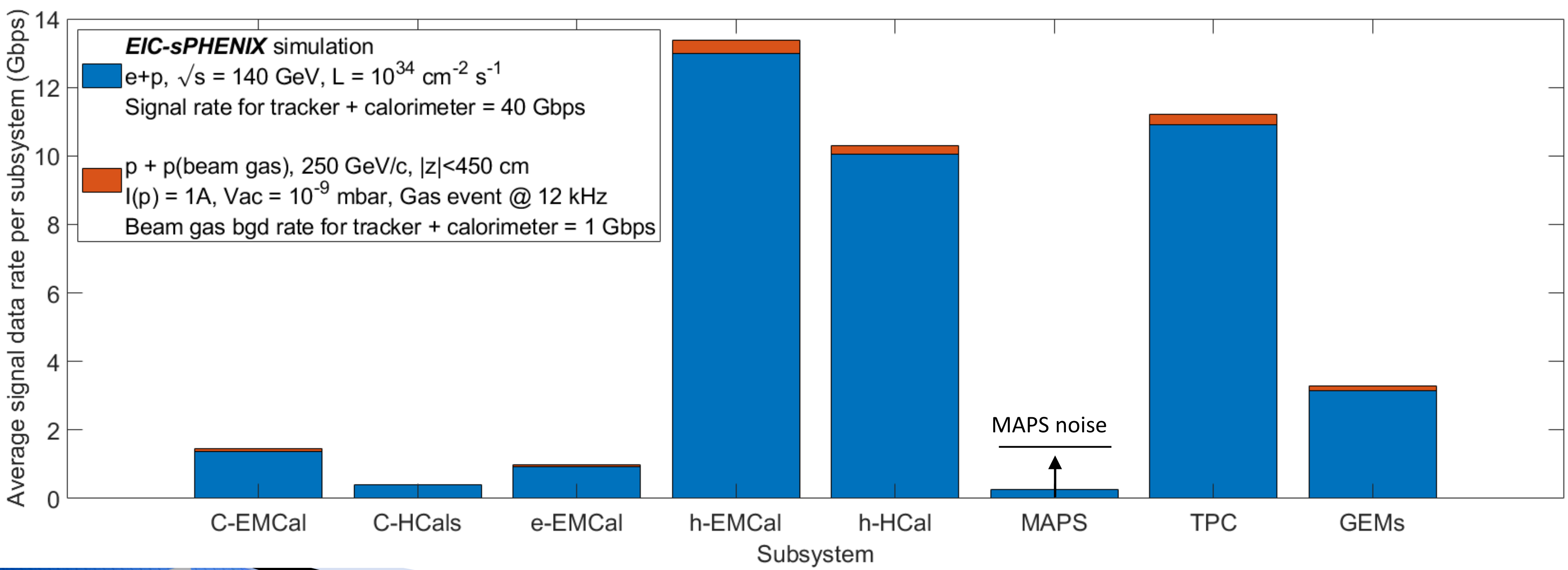
DRS4GLO

HADES RICH TDC backplane



Electronics considerations for PID

- With eRD14: it would be very useful to include actual PID detector rate in this study too.
- In streaming mode, detector noise are sensitive issue
  - e.g. Radiation damage of SiPM would be important



Ongoing R&D, BNL LDRD 19-026: Common development for Advanced DAQ

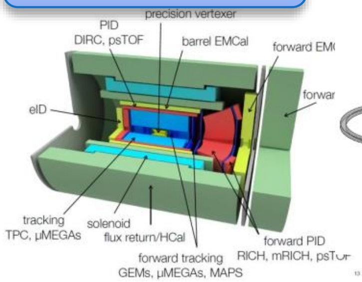
EIC detectors

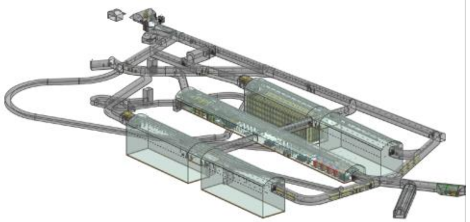
DUNE far detector

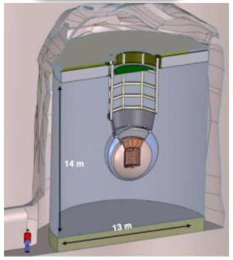
nEXO

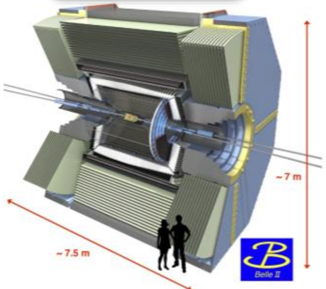
BELLE-II

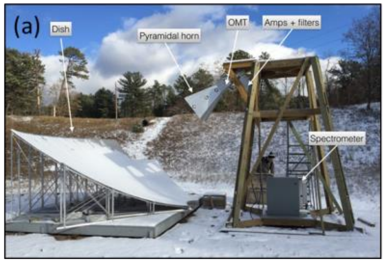
21-cm digital interferometer

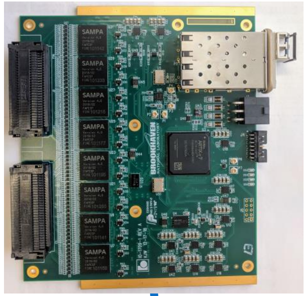


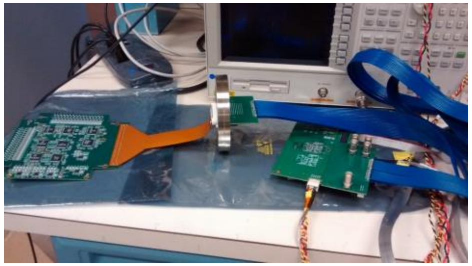


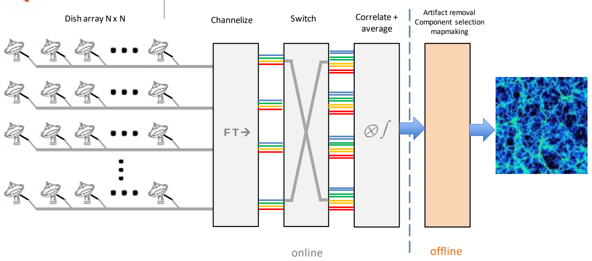












BNL 712 – series PCIe Card

Commodity Computing

We could support streaming DAQ integration R&D with eRD14 front-end too

Summaries

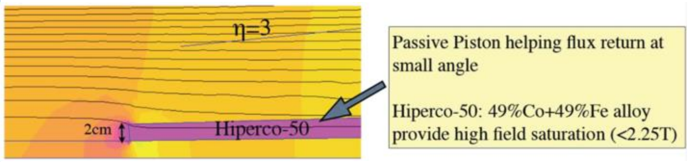
- sPHENIX-EIC detector design study updated in 2018
  - Thanks for the many contributions from eRD14
- Software framework for sPHENIX-EIC detector supports detector integration
  - Supports from simulation to reconstruction, from conceptual design to final data analysis
- A streaming DAQ fits the unique environment and physics needs at EIC
  - We could support eRD14 evaluating streaming readout FEE and how it fits into EIC data stream

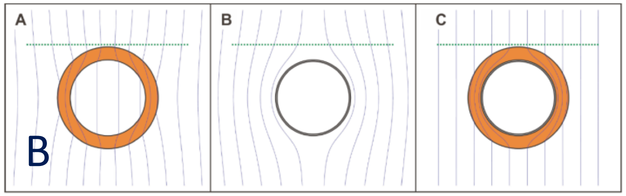
Extra Slides

What field shall we add in the forward? - Brain storm in the past few years

Design Family	Example
Piston	• Passive piston (C. L. da Silva) • Active piston (J. Huang, C. L. da Silva) • Super conducting piston (Y. Goto)
Dipole	• Forward dipole (Y. Goto, A. Deshpande, et. al.) • Redirect magnetic flux of solenoid (T. Hemmick) • Use less-magnetic material for a azimuthal portion of central H-Cal (E. Kistenev)
Toroid	• Air core toroid (E. Kistenev) • Six fold toroid (J. Huang)
Other axial symmetric Field shaper	• Large field solenoidal extension (C. L. da Silva) • Pancake field pusher (T. Hemmick)

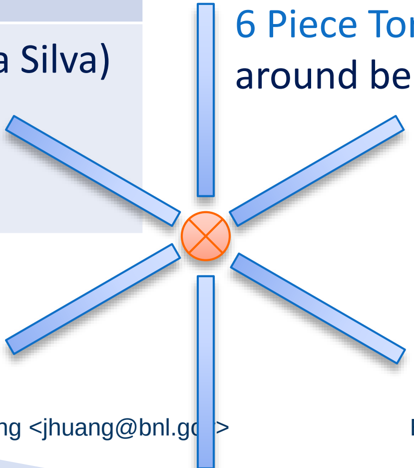
Passive piston

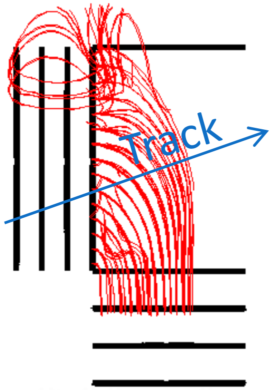




Beam line magnetic field shielding, based on superconducting pipe.

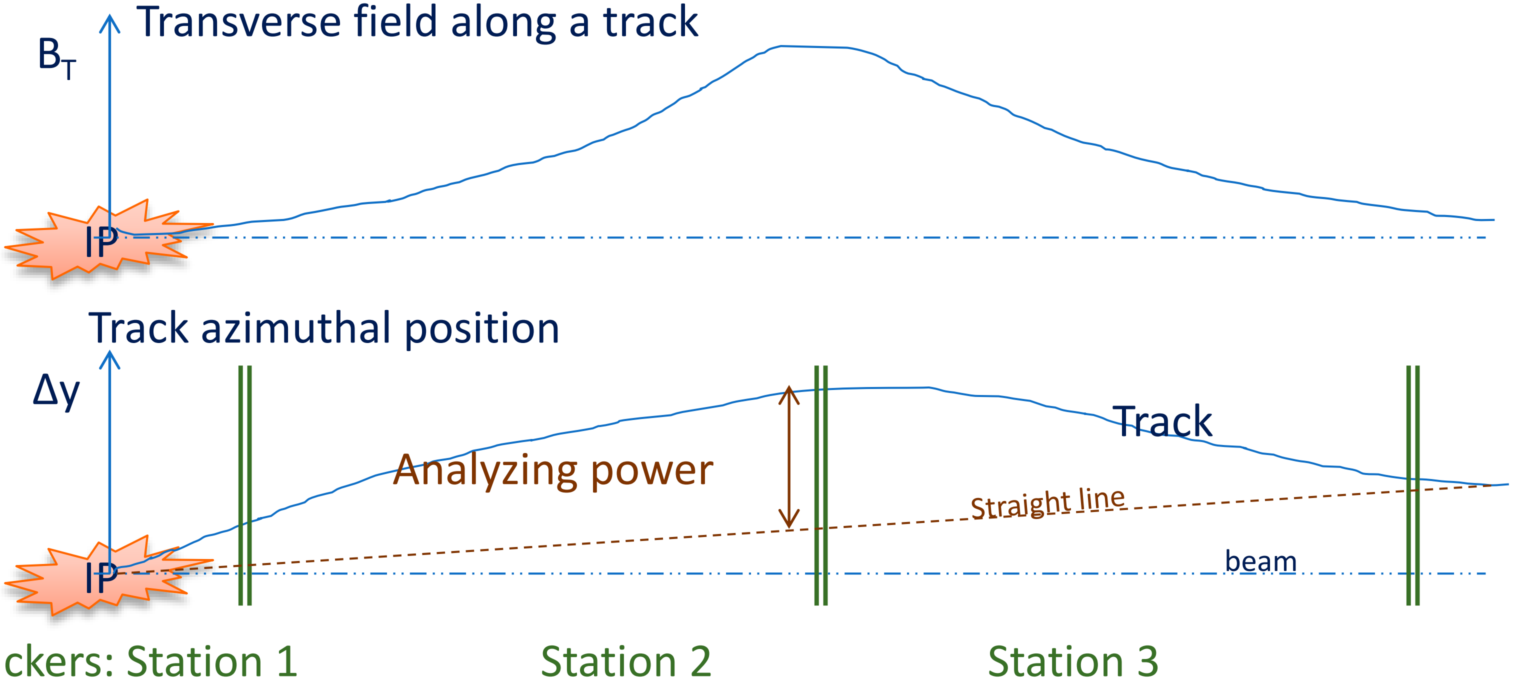
6 Piece Toroid around beam pipe





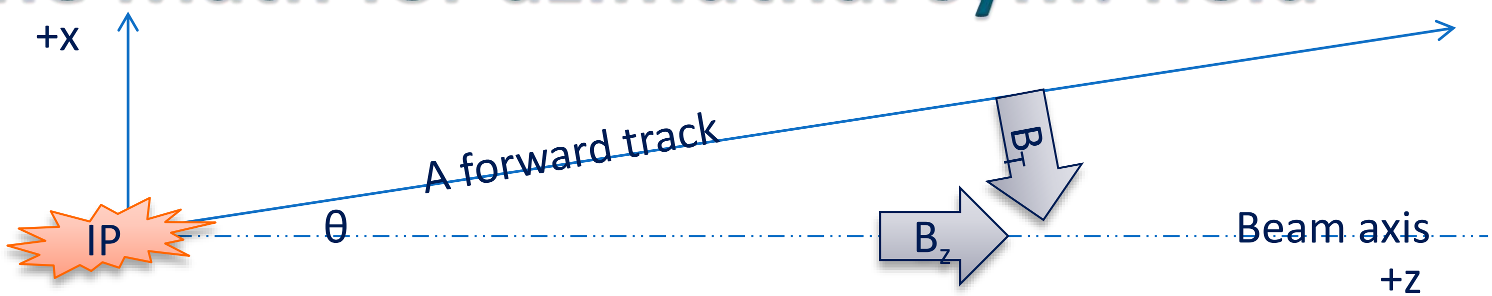
Pancake field pusher

Option of solenoidal field: What transverse field we want?



- Transverse field (B_T) provide azimuthal bending and therefore momentum resolution
- momentum resolution ∝ (tracker resolution)/(spacing between stations)
  - Want max bending (and BT) in the middle of tracking region
  - Should keep three stations as far away as possible

Option of solenoidal field: The Math for azimuthal sym. field



Transverse field is directly related to shape of central longitudinal field:

$$B_T = B_z \tan\theta + \frac{\tan\theta}{2} z \frac{\partial B_z}{\partial z} + O(\theta^2)$$

Geometry Term

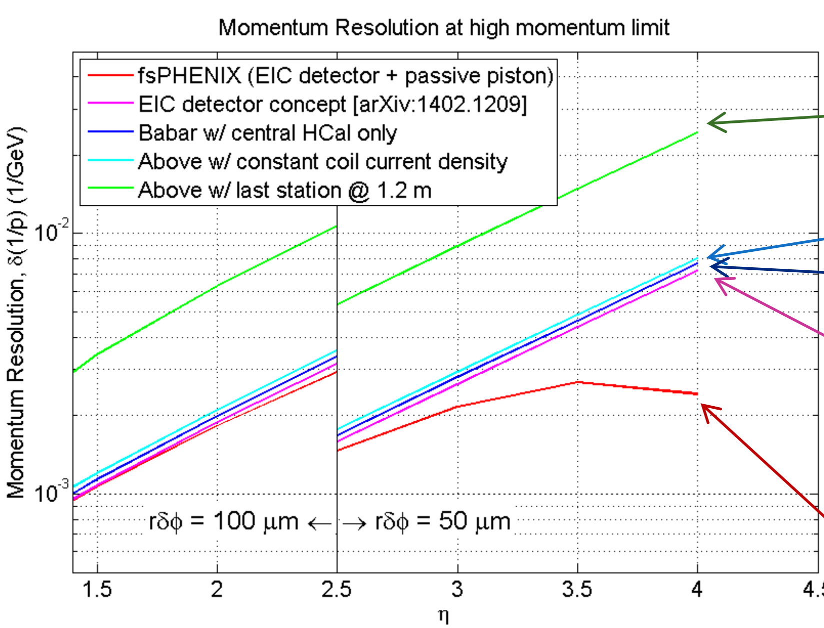
Flux Term

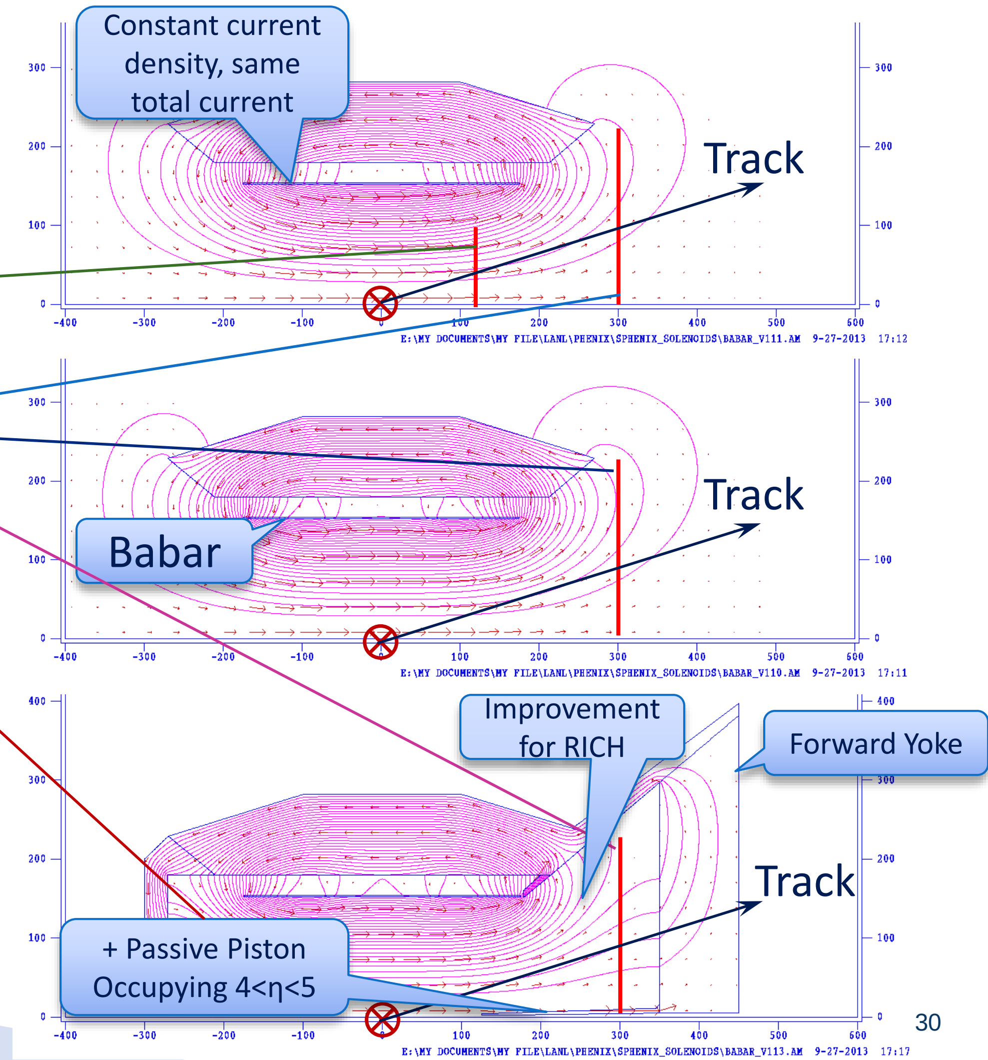
Two way to optimize transverse field, B_T

1. Maximize inward B_T at sensitive region
   - Need a sneezing coil
2. Maximize outwards B_T at sensitive region
   - Need a coil with opposite field

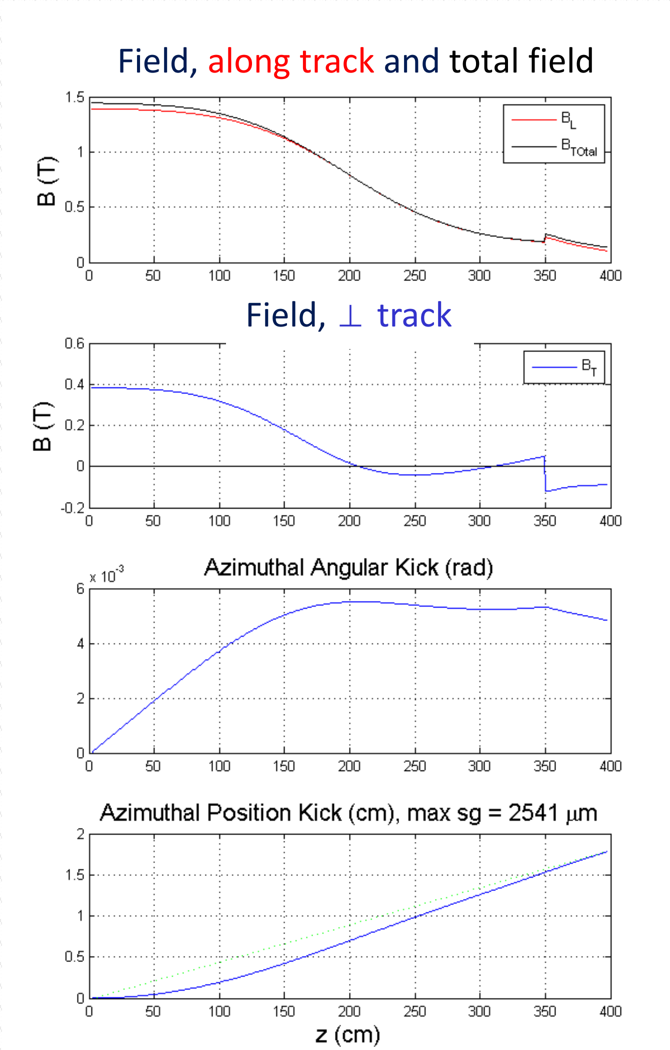
Considerations for yoke and tracking designs

- Optimal tracking configurations
  - Measure sagitta with vertex – optimal sagitta plane (not drawn) – last tracking station
  - Yoke after tracking space and conform with a |z|<4.5m limit (eRHIC machine/detector "truce" line)
- A good configuration forward tracking
  - Central + forward yoke (hadron calo.)
  - Last tracking station at z=3.0m

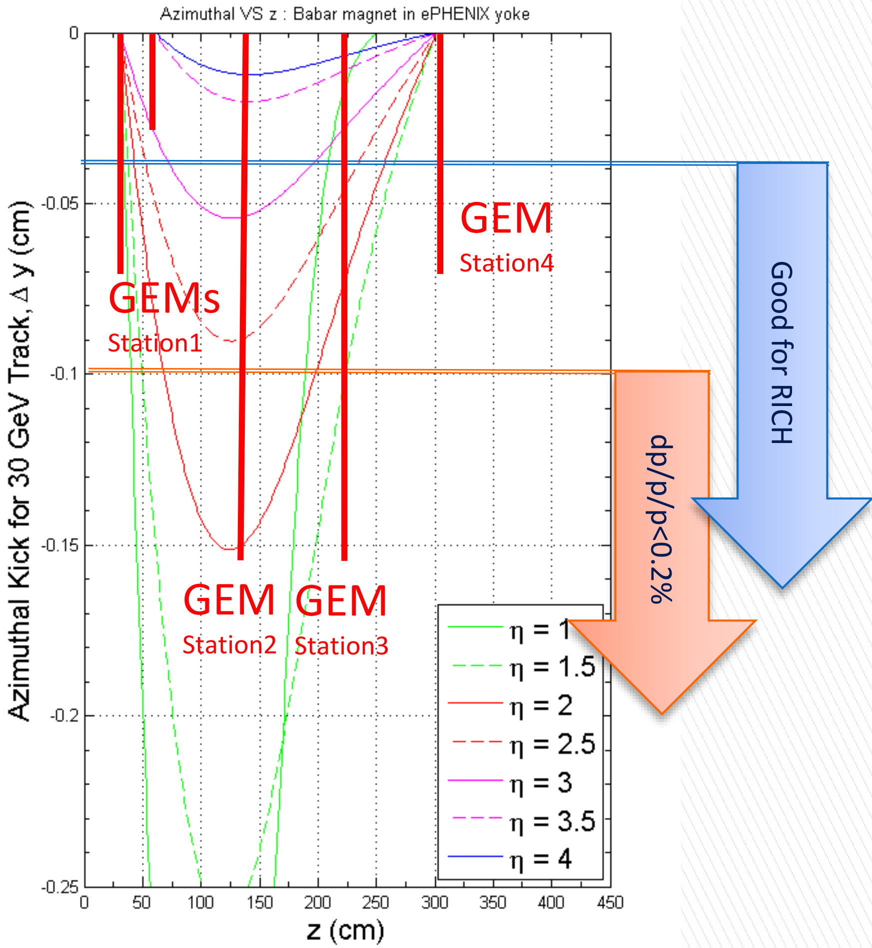




Forward tracking optimization



Using ϕ segmented GEM
with resolution of R Δϕ = 50µm

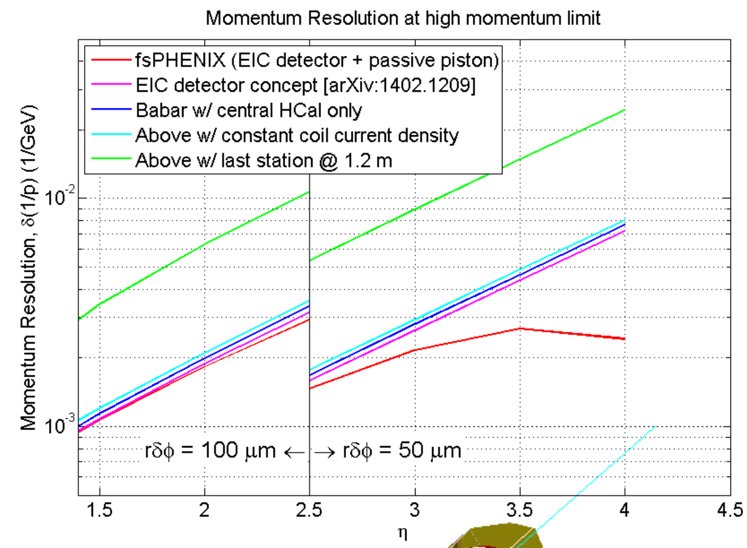


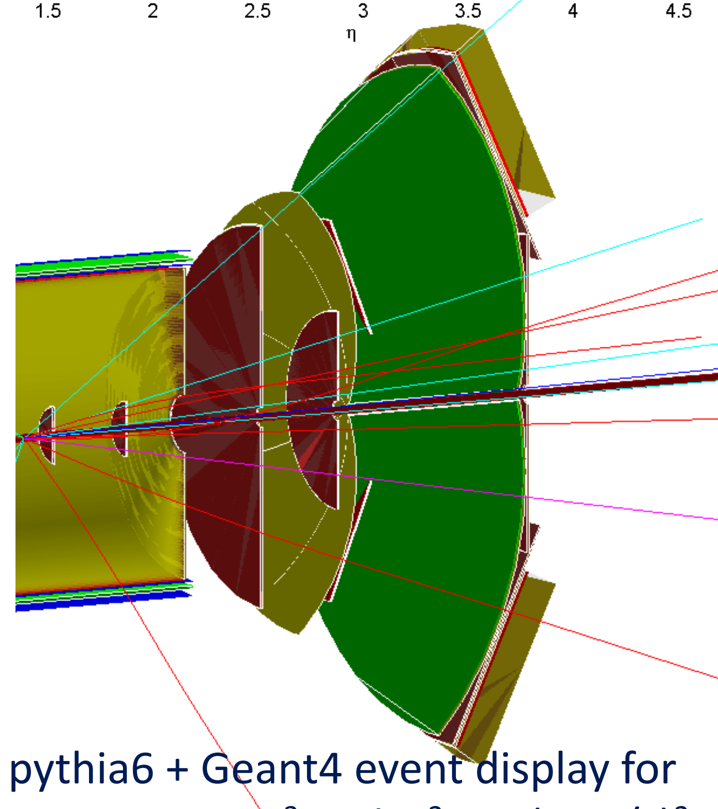
Magnetic bending
Track of η=2.0, p=30 GeV

Tracker layout for max sensitivity
Track of p=30 GeV

Forward tracking detector considerations

- Using variations of fringe magnetic field for forward tracking requires high position resolution (control linear term) and thin detector for the Sagitta plane (control the constant term)
- GEM detector is one good choice, however we are pushing it towards its limit (so far)
- MAPS type silicon sensor could work well in very forward region too, covering R~30cm disk around beam pipe

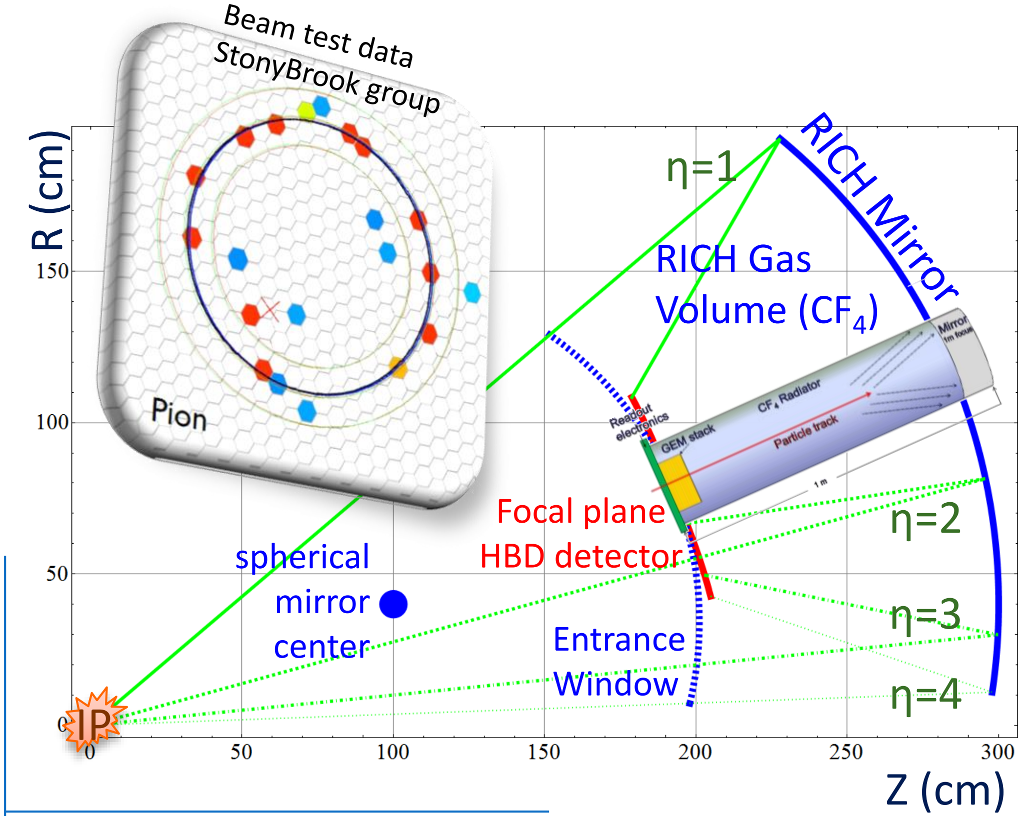




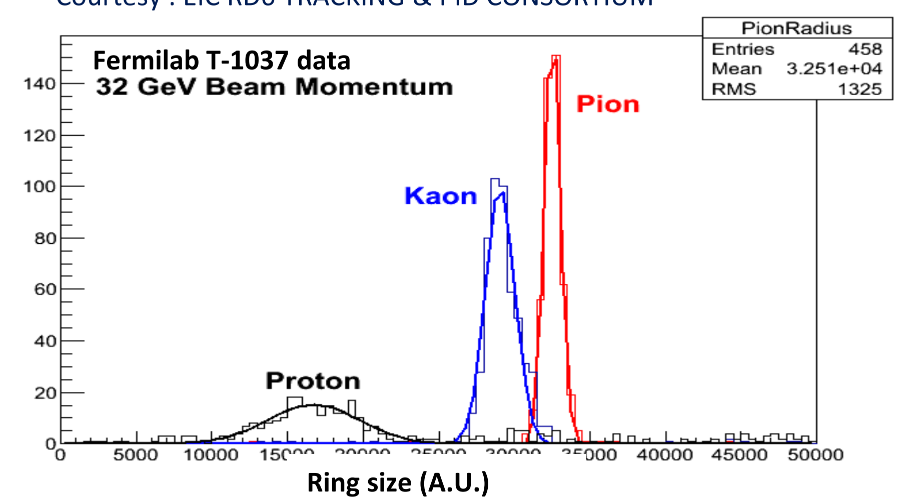
A pythia6 + Geant4 event display for SIDIS @ $x \approx 5\times10^{-3}$ and $Q^2=10\ (GeV/c)^2$

Gas RICH
- The Design

- Hadron ID for p>10GeV/c require gas Cherenkov
  - CF_4 gas used, similar to LHC_b RICH
- Beautiful optics using spherical mirrors
- Photon detection using CsI–coated GEM in hadron blind mode
  - thin and magnetic field resistant
- Active R&D:
  - Generic EIC R&D program
  - recent beam tests by the stony brook group

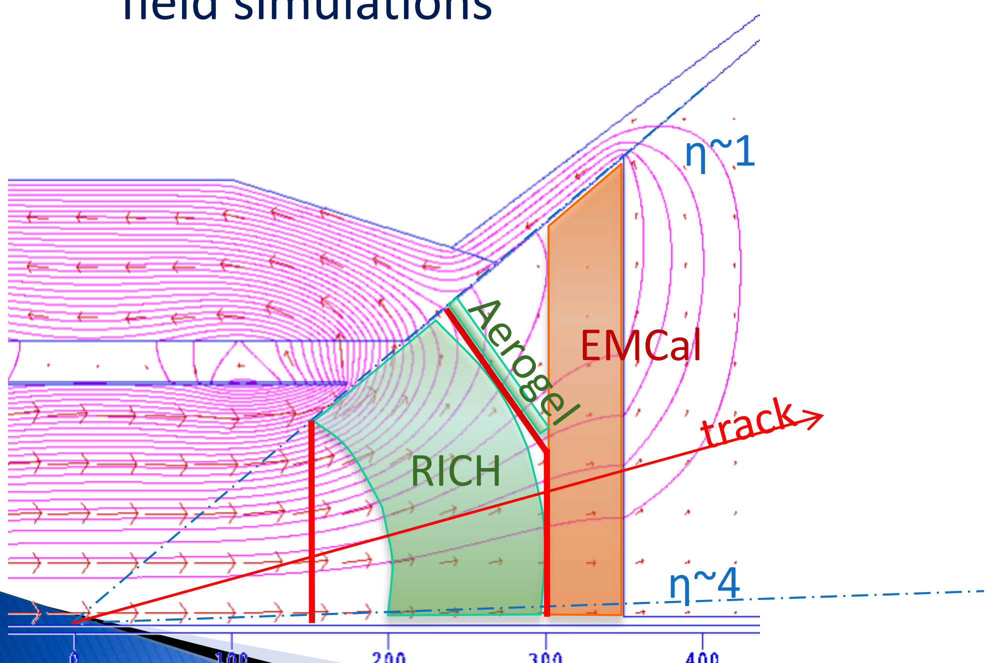


Courtesy : EIC RD6 TRACKING & PID CONSORTIUM



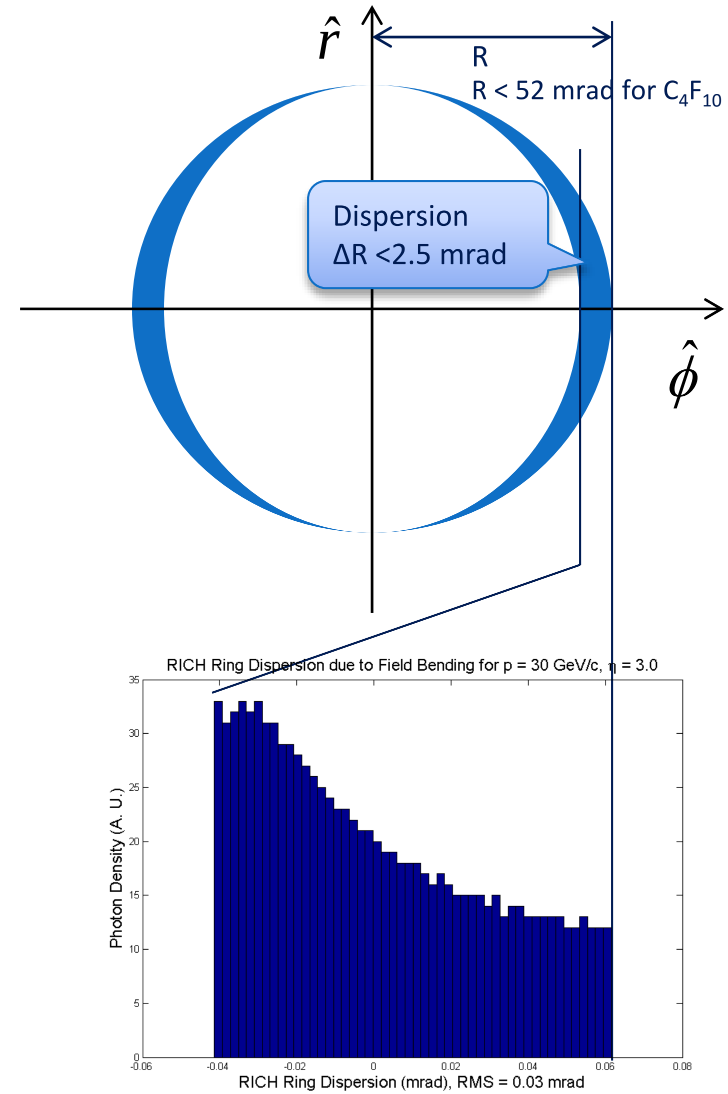
Field effect - distortion for RICH

- Field calculated numerically with field return
- Field lines mostly parallel to tracks in the RICH volume with the yoke
- We can estimate the effect through field simulations

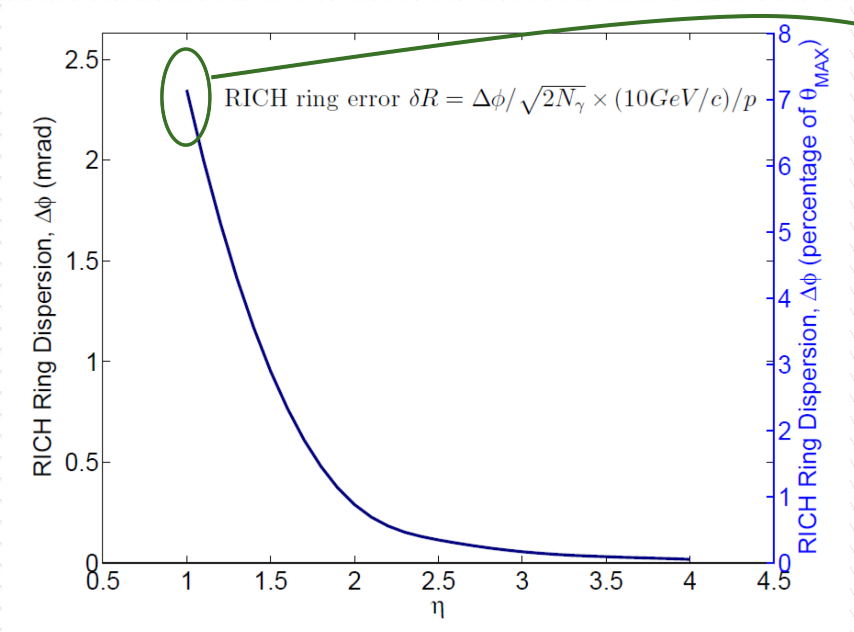


A RICH Ring:

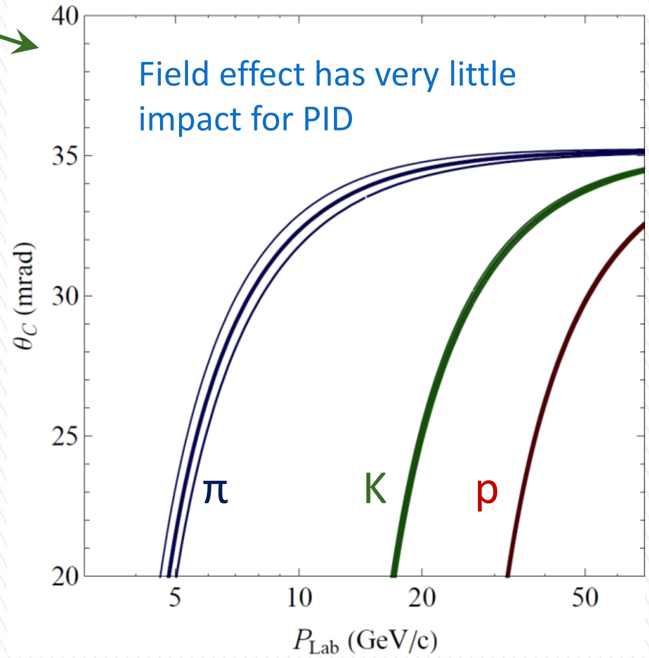
Photon distribution due to tracking bending only



Field effect –
Radius uncertianty of RICH Ring



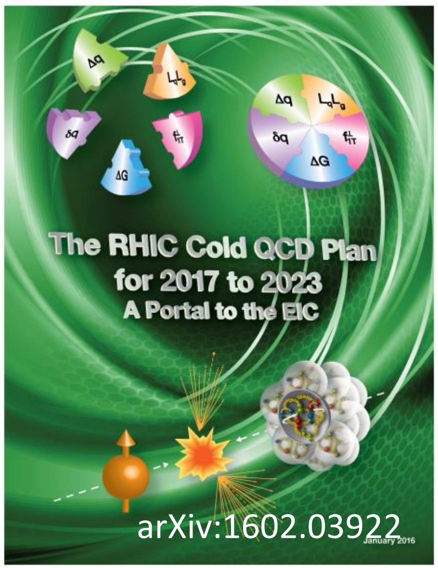
Ring radius ± 1σ field effect (for worst η=1)



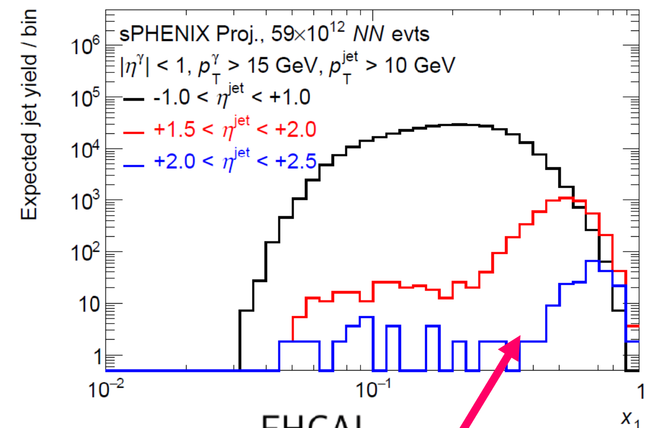
Quantify ring radius error

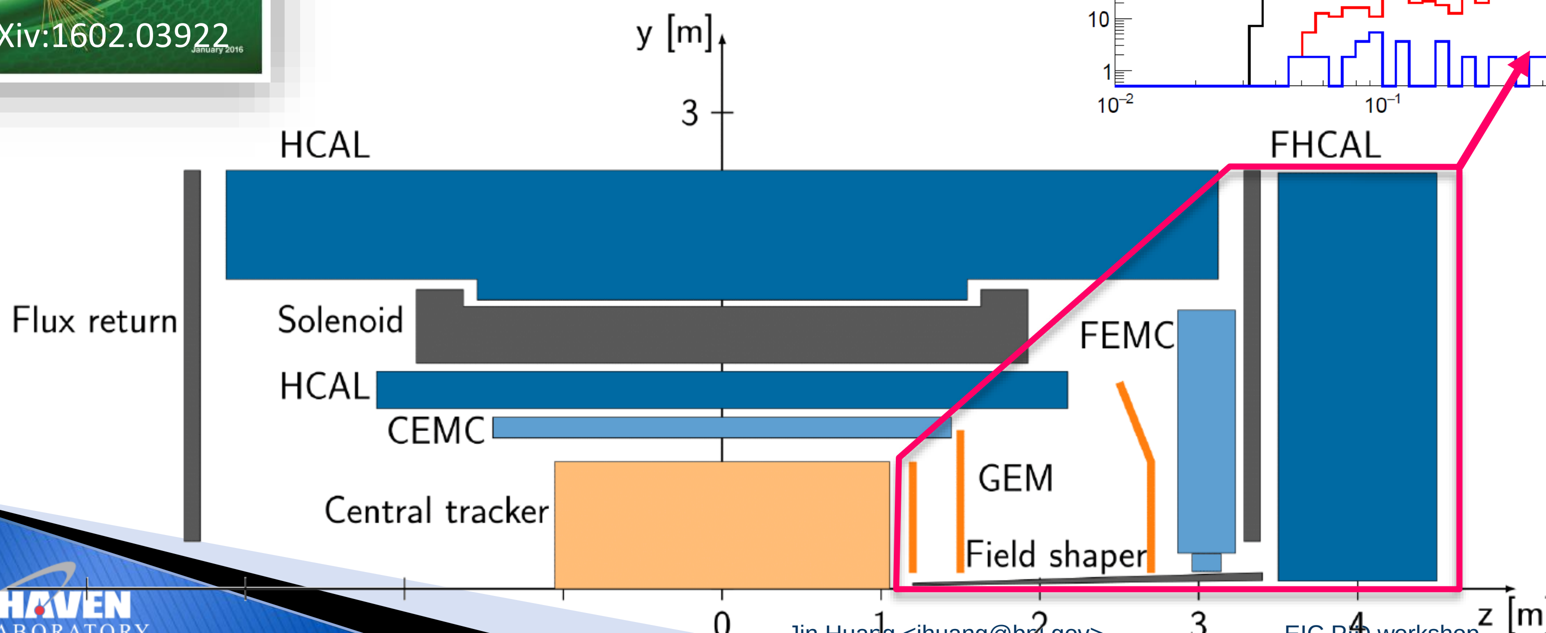
In the respect of PID: minor effect

Forward upgrade for sPHENIX



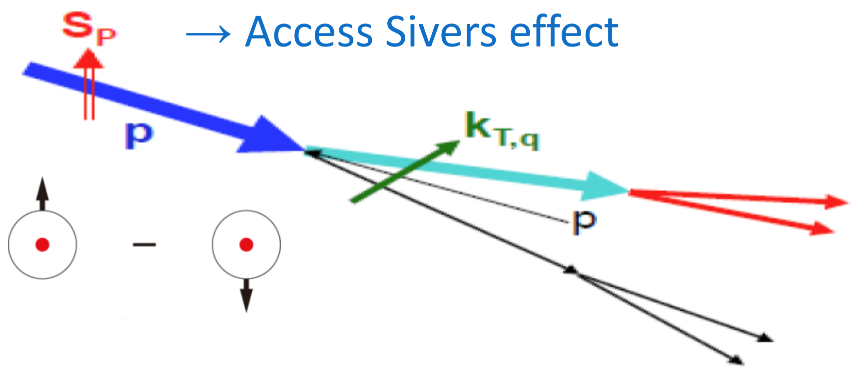
- RHIC cold-QCD community is also pushing for an forward tracking + calorimetry upgrade @ sPHENIX or STAR (J. Zhang, Tue)
- LOI for forward upgrade was submitted to RHIC PAC 2017 Tracking + Calorimetry leads to joint coverage of -1<η<4
- sPHENIX forward upgrade:
  - Transverse spin
  - Cold nuclear matter
  - Longitudinal evolution of QGP
  - And more ...



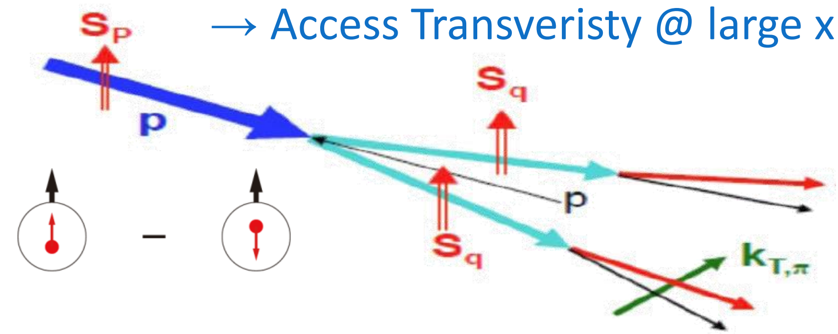


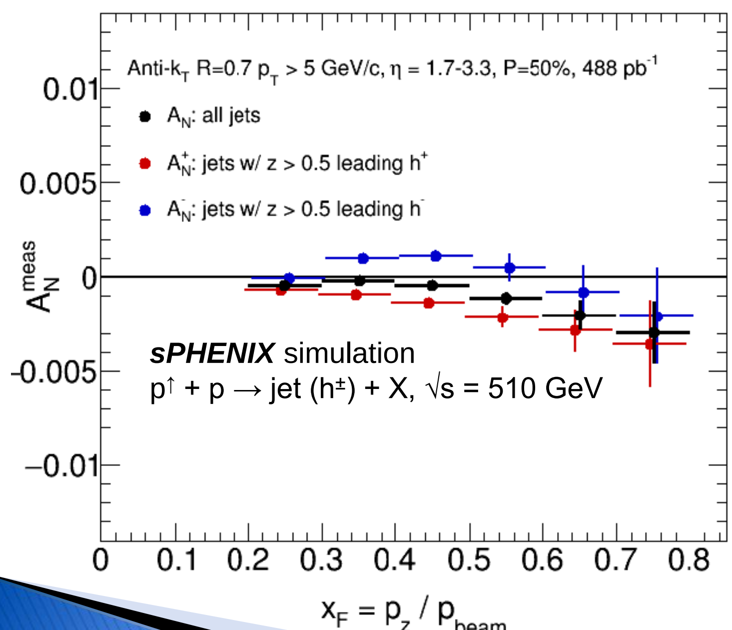
Forward jet → origin of transverse A_N

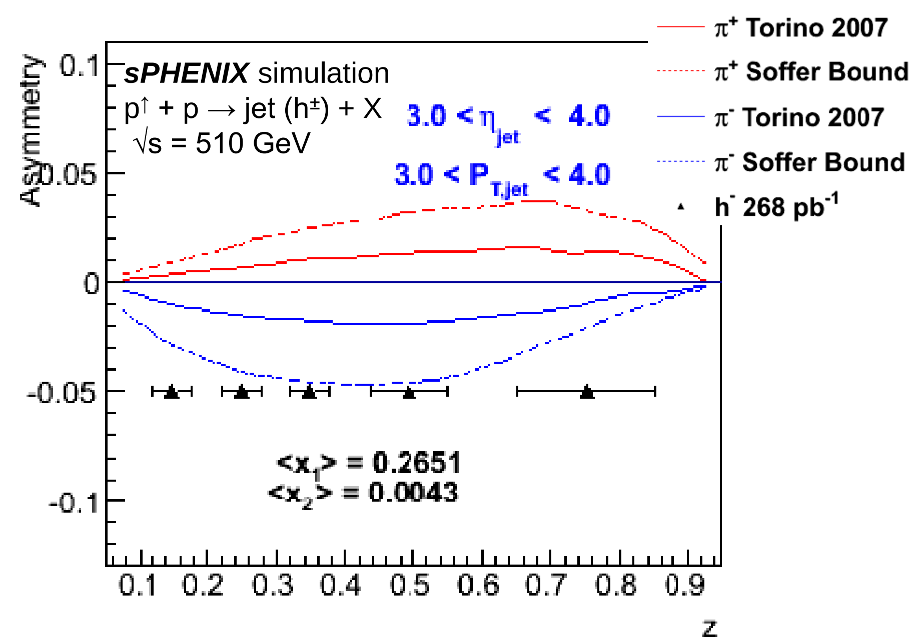
Charge-track tagged jet asymmetry
→ Access Sivers effect



Charge-track asymmetry in jet
→ Access Transveristy @ large x

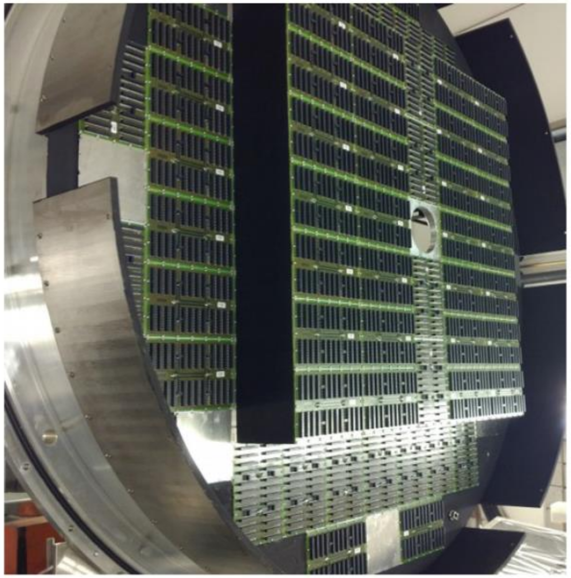




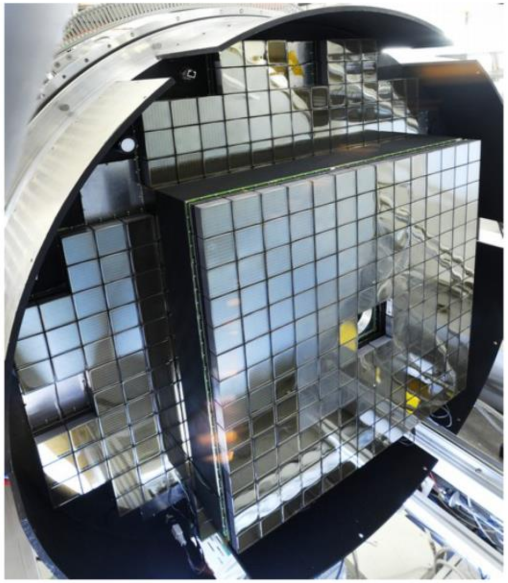


Check universality of Transversity @ SIDIS

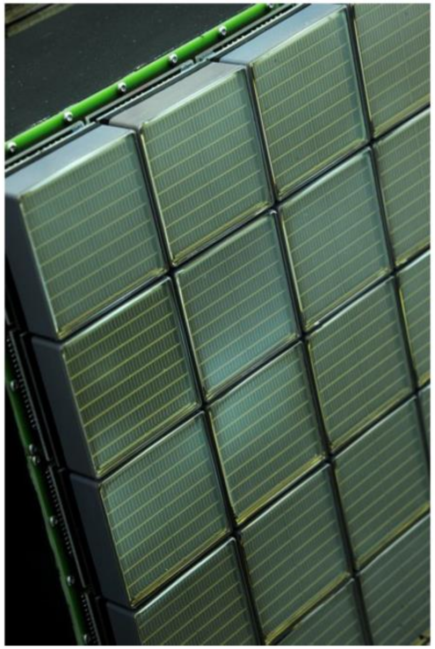
New photon detector with MAPMTs mounted



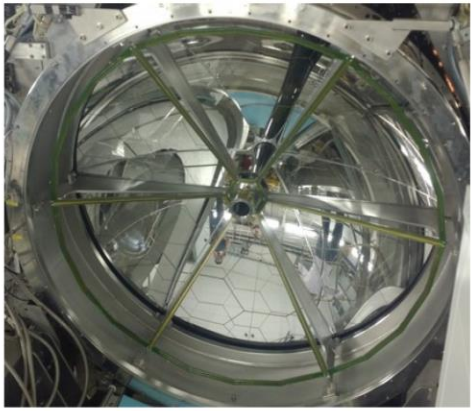
New photon detector flange
after installation of PMT backplanes



… and after installation of the
first 396 MAPMTs



Close-up of MAPMTs
mounted on backplanes

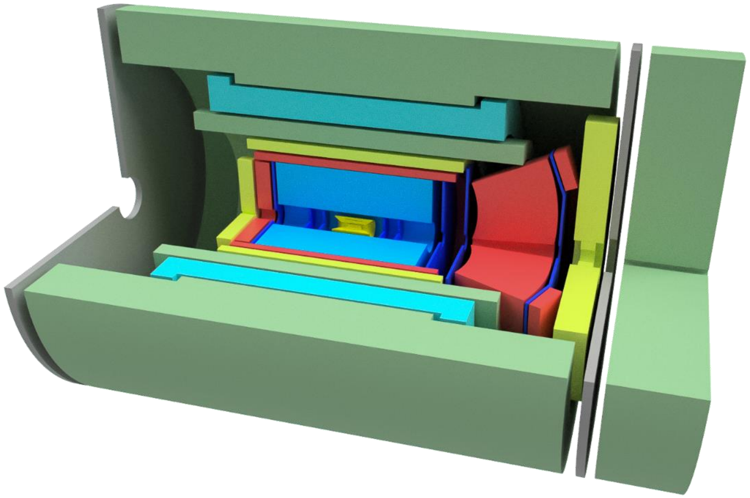


HADES RICH mirror with
CaF window in front

photos by G. Otto, GSI

BNL detector concepts

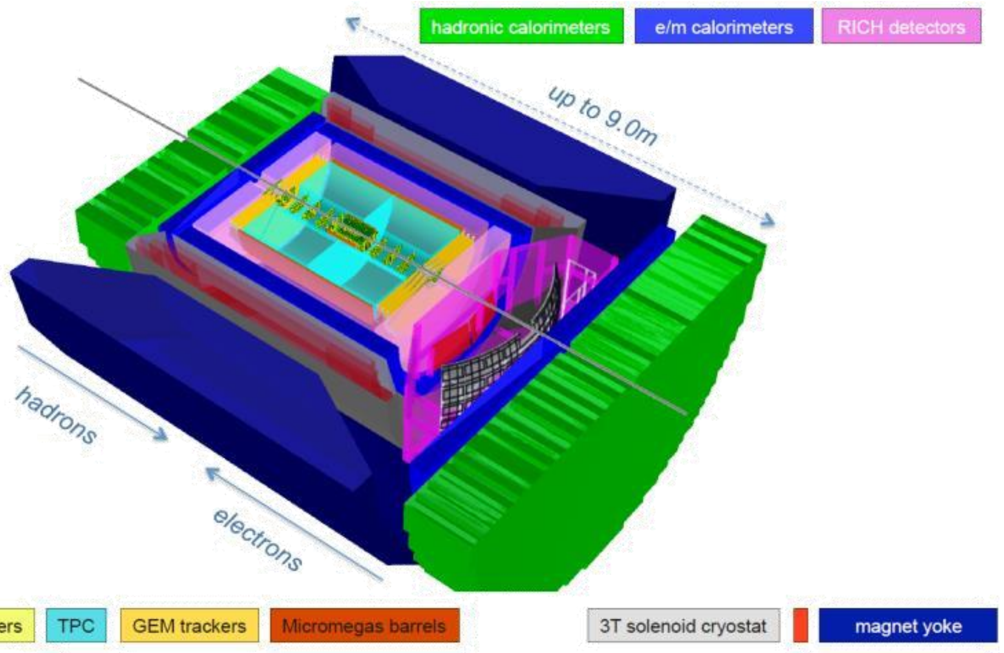
See also TOSIDE, JLEIC concepts in last two talks [Repond, Heyes]



sPHENIX-based concept

- Solenoid
- Flux return
- Central tracking
- Electromagnetic calorimeter
- Forward tracking
- Hadron calorimeter
- Particle ID

BeAST concept



References reports :

- ePHENIX LOI: arXiv:1402.1209
- eRHIC design report, preCDR: arXiv:1409.1633

EIC: unique collider → unique real-time challenges

	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	2-10 ns	100 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 has lower collision rate and event size is small → signal data rate is low
- But events are precious and have diverse topology
- EIC luminosity is high, so background and systematic control is key

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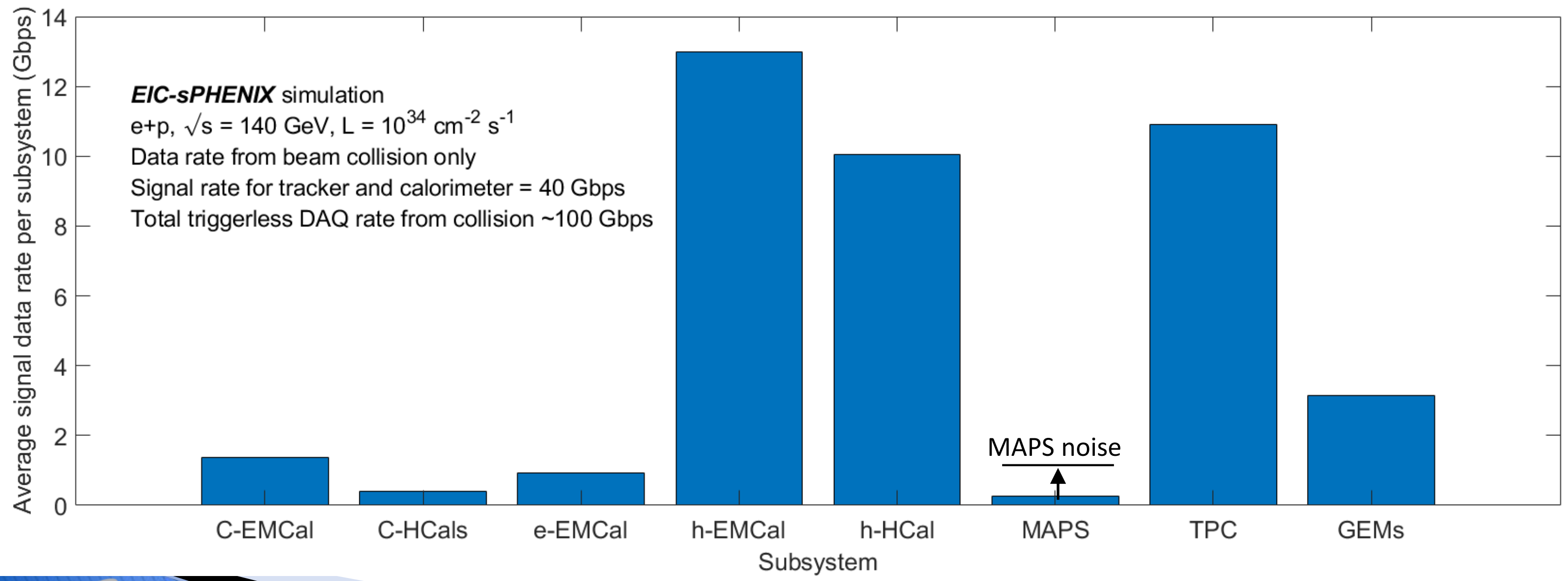
From Stream-III Workshop:

Collision signal data rate

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

- Details in simulation presented in last workshop (also in backup)
- Tracker + calorimeter ~ 40 Gbps
- + PID detector + 2x for noise ~ 100 Gbps
- Signal-collision data rate of 100 Gbps seems quite manageable,
  - < sPHENIX TPC peak disk rate of 200 Gbps



Beam-gas interactions

- As discussed in last workshop, EIC combine high luminosity and small signal x-section, and background control would be critical
- Beam gas interactions.
  - p + p (beam gas) cross section ~ 40 mb
- Beam gas interaction rate ~ 13kHz / 10m beam line < 10% EIC collision rate
- The following estimation assumes
  - HERA inspired flat 10^{-9} mbar vac in experimental region of |z|<450 cm

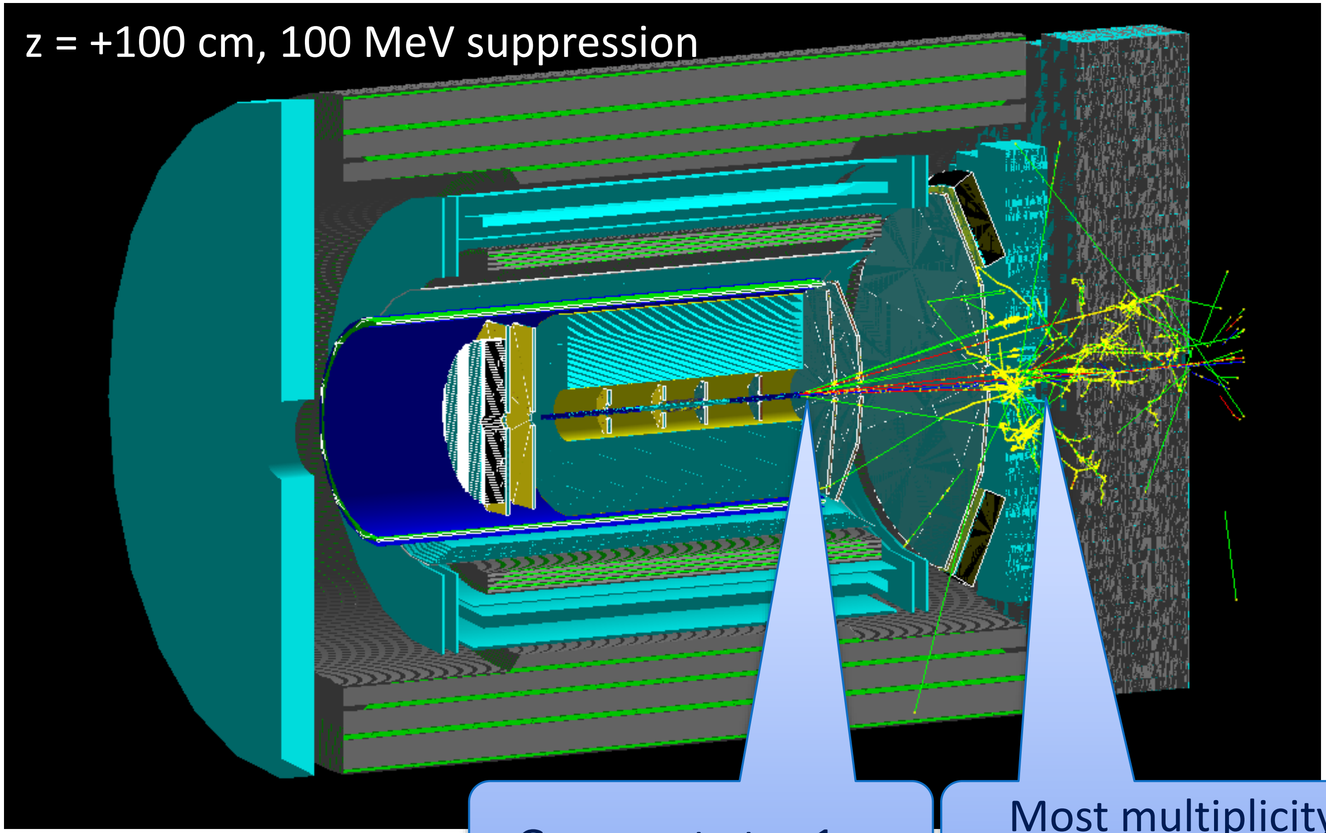
Vacuum pressure	10^{-9} mbar
Beampipe temperature	Room temperature
Average atomic weight of gas	Hydrogen (H^2)
Molecular density (for 10 m pipe)	2.65×10^{10} molecules/cm^2
Luminosity (Ring-Ring)	10.05×10^{33} cm^{-2}s^{-1}
Bunch intensity (R-R) (e/p)	15.1 / 6.0×10^{10}
Beam Current (R-R) (e/p)	2.5 / 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 event in a detector (upstream)

Simulation: https://github.com/sPHENIX-Collaboration/singularity

- 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)



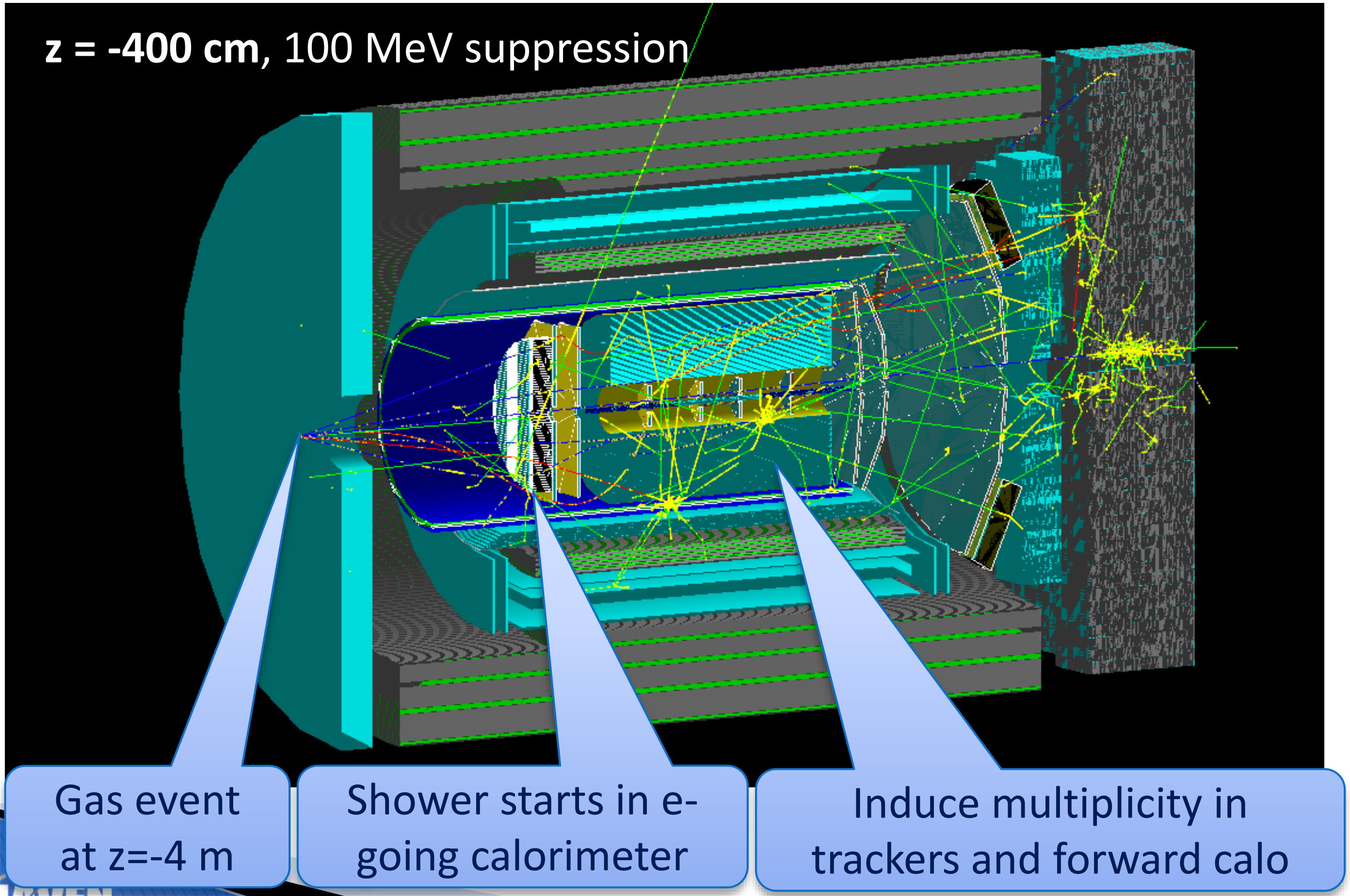
Gas event at z=1 m

Most multiplicity goes to forward calo.

Beam gas event in a detector (downstream)

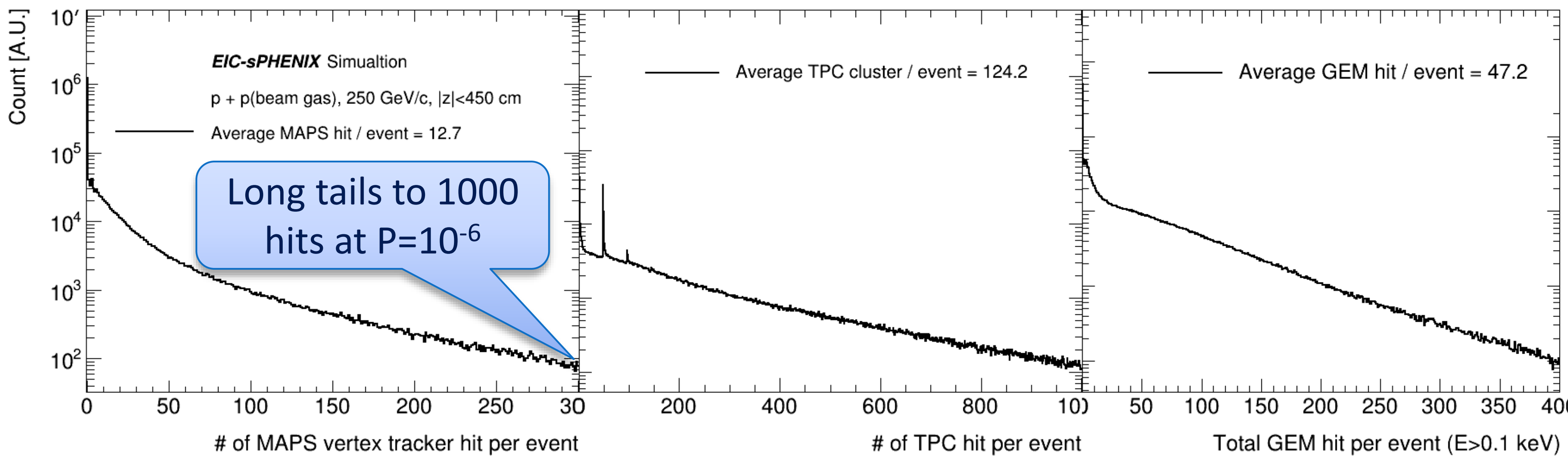
Simulation: https://github.com/sPHENIX-Collaboration/singularity

- 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)



GEANT4-based data rate simulation:
Beam gas event on tracker (more detectors in backup)

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



Raw data:
3 pixel x 16 bit / MAPS hit

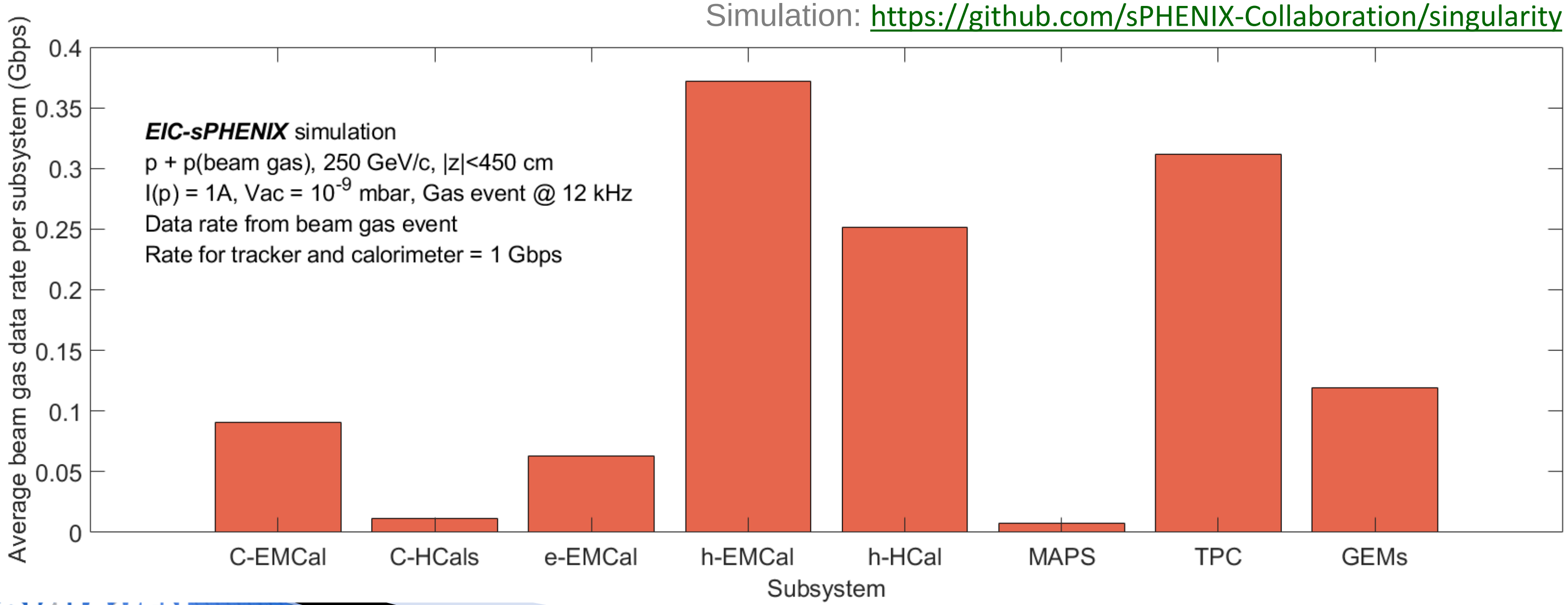
Raw data:
3 (strip) x5(time)x 10 bit / TPC hit
+ headers (60 bits)

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

Rate summary for beam gas

- Very similar rate distribution among subsystems when compared with EIC collisions
- With an assumed vacuum profile (10^{-9} mbar flat within experiment region):
  - Overall few Gbps @ 12kHz beam gas at 10^{-9} mbar in |z|<450 cm (detector region)

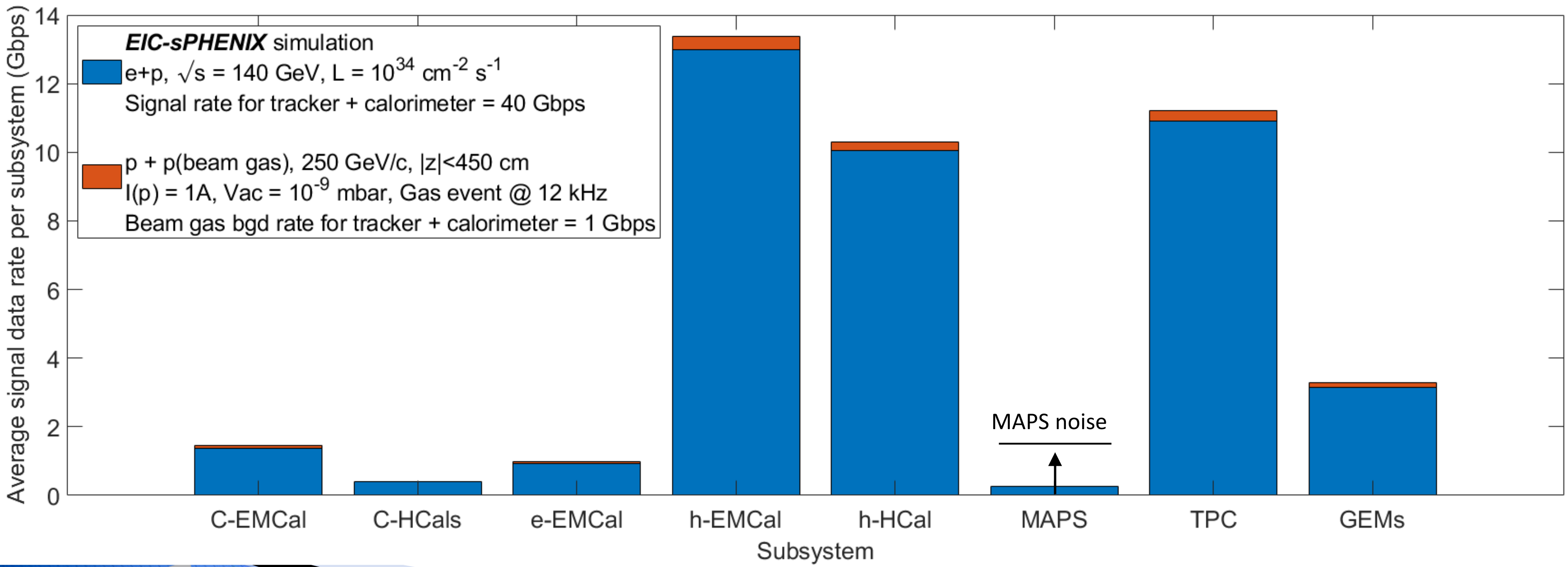
Simulation: https://github.com/sPHENIX-Collaboration/singularity



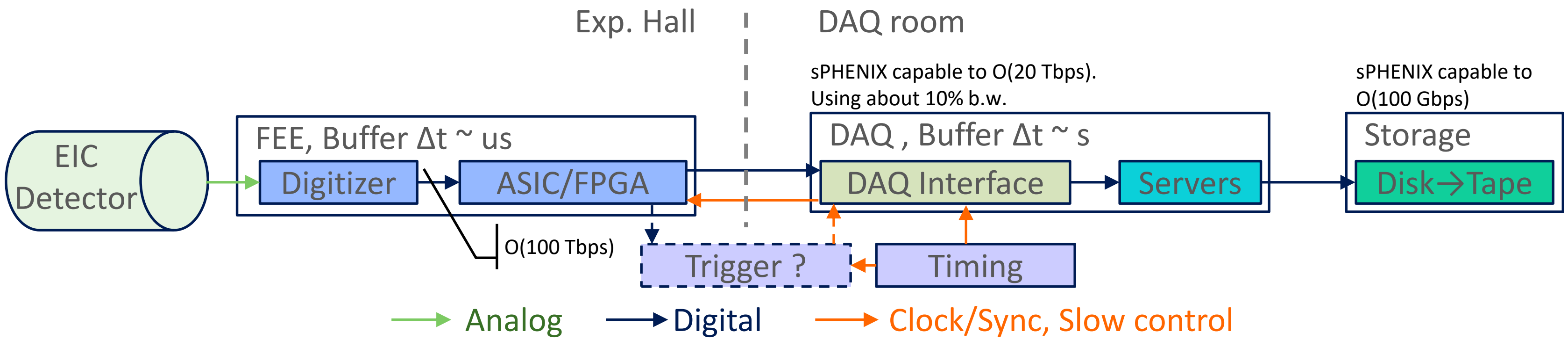
Data rate: sum together

sPH-cQCD-2018-001: https://indico.bnl.gov/event/5283/ , Simulation: https://github.com/sPHENIX-Collaboration/singularity

- Total signal ~ 100 Gbps @ 10^{34} cm^{-2} s^{-1} < sPHENIX peak disk rate
- Beam gas rate << EIC collision signal data rate



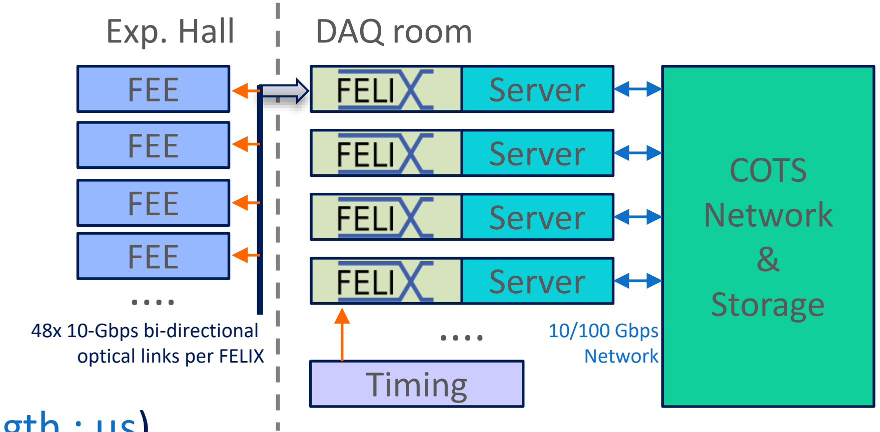
Strategy for an EIC real-time system



- For the signal data rate from EIC (100 Gbps), we can aim for filtering-out and streaming all collision in raw data without a hardware-based global triggering
  - Also consider hybrid DAQ for EIC: possibilities for distribute triggers for calibration systematics control. e.g. trigger for laser calibration pulses, pedestal
- Requirement
  - All front-end to continuously digitize data or self-triggering
    e.g. PHENIX FVTX, STAR eTOF, all sPHENIX trackers, any many prototypes in this workshop
  - Reliably synchronize all front-ends and identify faults
  - Recording all collision data (100 Gbps if raw)
  - If needed, filtering out background with low signal loss (10^{-4}?)
  - Requiring reliable data flow → control systematics:
    Low data loss rate < 10^{-4}(?) and/or loss in a deterministic manor

FELIX-based DAQ

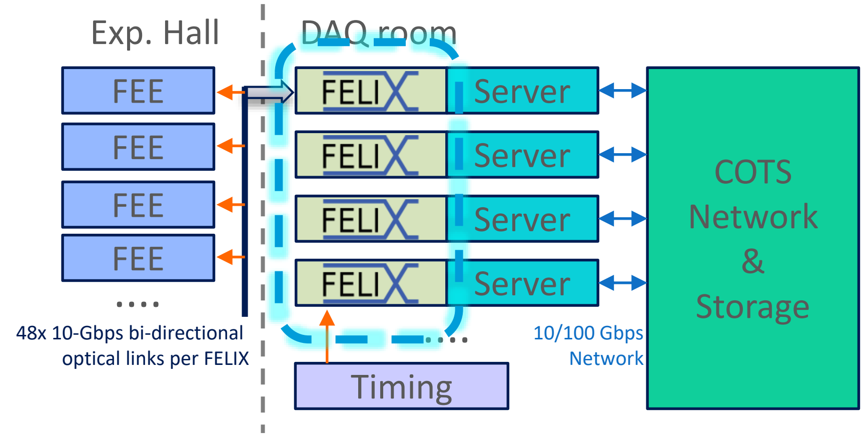
sPH-cQCD-2018-001
https://indico.bnl.gov/event/5283/



- Full streaming readout front-end (buffer length : μs)
  → DAQ interface to commodity computing via PCIe-based FPGA cards (FELIX)
  → Disk/tape storage of streaming time-framed zero-suppressed raw data (buffer length : s)
  → Collision event tagging in offline production (latency : days)
- Why time-framed streaming readout for collision data?
  - Diversity of EIC event topology. Streaming minimizing systematics by avoiding hardware trigger decision, keeping background and history
  - At 500kHz event rate, multi-μs-integration detectors would require streaming, e.g. TPC, MAPS
- Why FELIX-like DAQ interface?
  - Deterministic transmission from FEE up to server memory, buffering and busy generation
  - 0.5 Tbps x bi-direction IO, bridging μs-level FEE buffer length with ms+ DAQ network time scale
  - Interface with commodity computing via PCIe @ ~100Gbps
  - Distribute experiment timing and synchronization cross large system
- Why keep raw data?
  - EIC collision signal @ 100 Gbps < sPHENIX disk rate, it is affordable to disk-write all raw signal data
  - Allow time + special run needed for final calibration, followed by prompt reconstruction
  - Filter out noise if needed

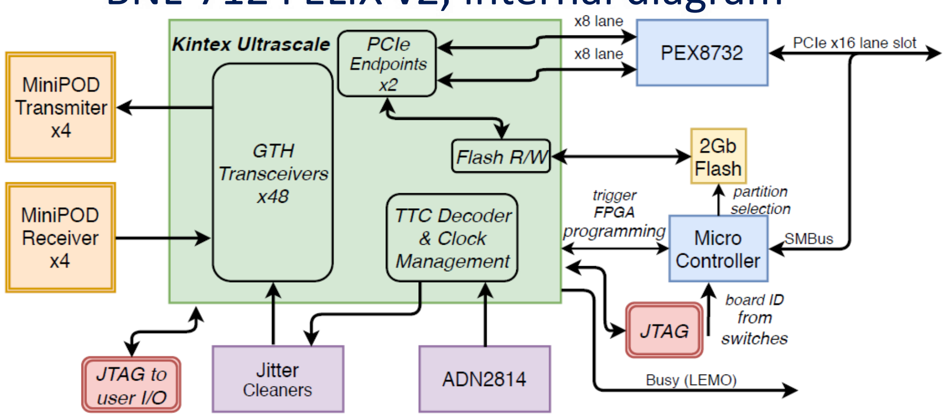
Front-End LInk eXchange (FELIX)

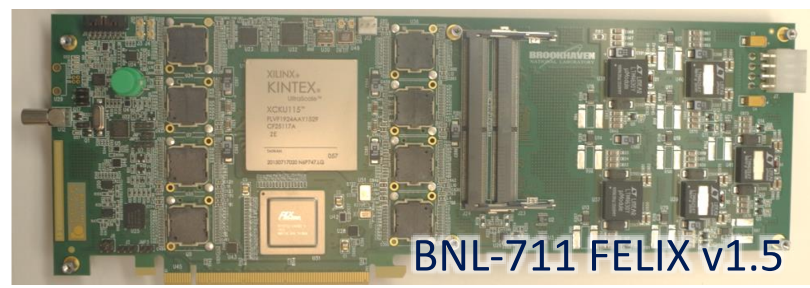
- FELIX: DAQ interface card initially developed for ATLAS Phase 1 upgrade and beyond
  - Similar architecture have wide support in 2020+ for high throughput DAQ e.g. ATLAS, ALICE, LHCb, CBM, Proto-DUNE
- Future versions concepts supporting 48x 25Gbps transceivers and PCIe Gen4



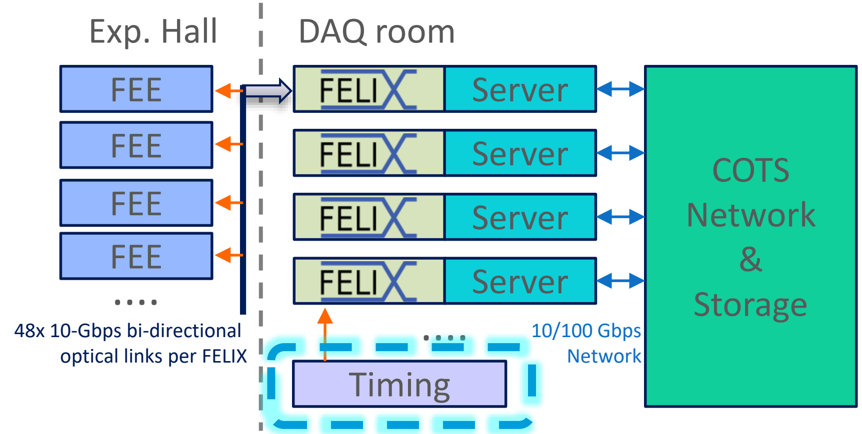
[K. Chen et al, submitted to TIM]

BNL-712 FELIX v2, internal diagram



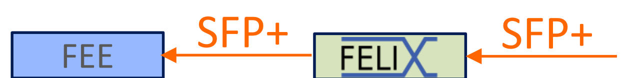


Timing

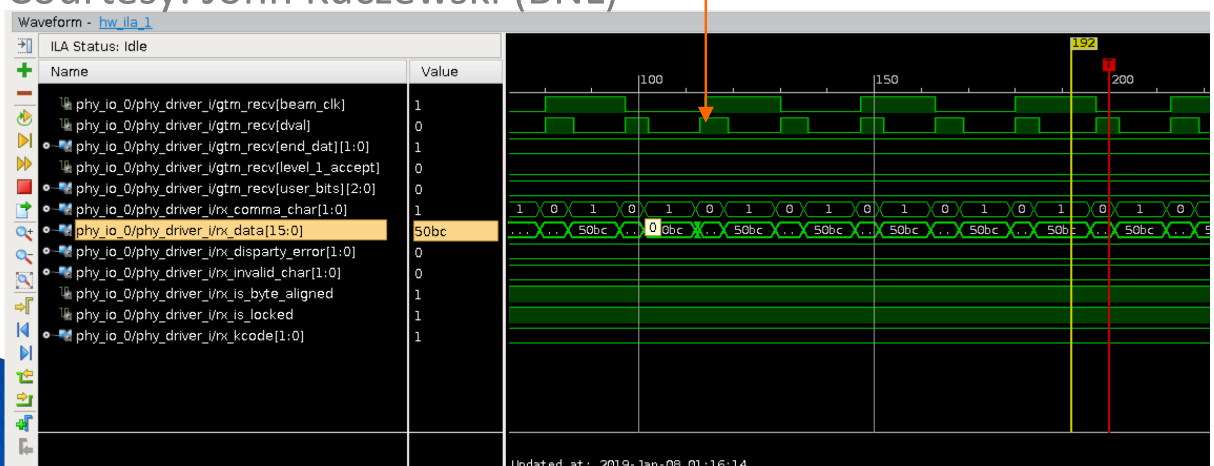


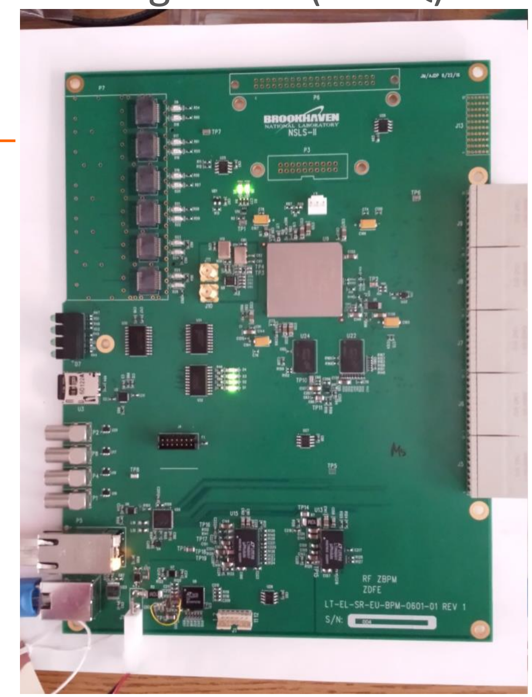
- All FEE & FELIX synchronized to collider collision clock
- Broadcast 64b-clock counter and validate synchronization
- Timing prototype
  - Zynq-based timing system board with multiple SFP+ links
  - Demonstrated SFP+ based timing link at 112.8 MHz

Timing board (ZYNQ)

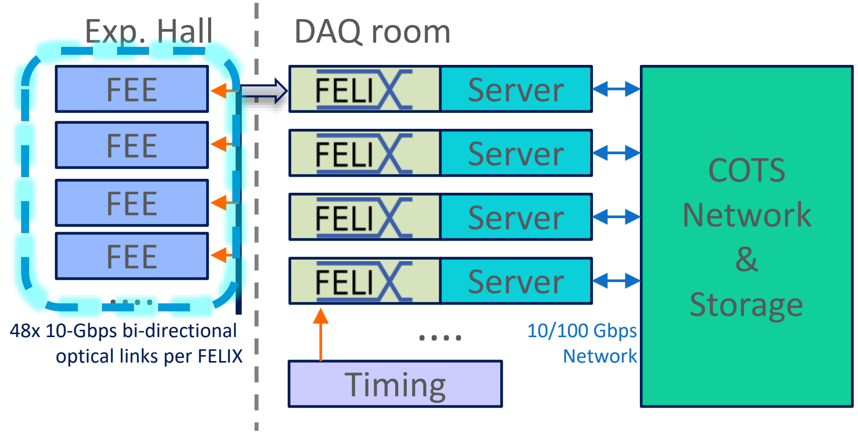


Courtesy: John Kuczewski (BNL)



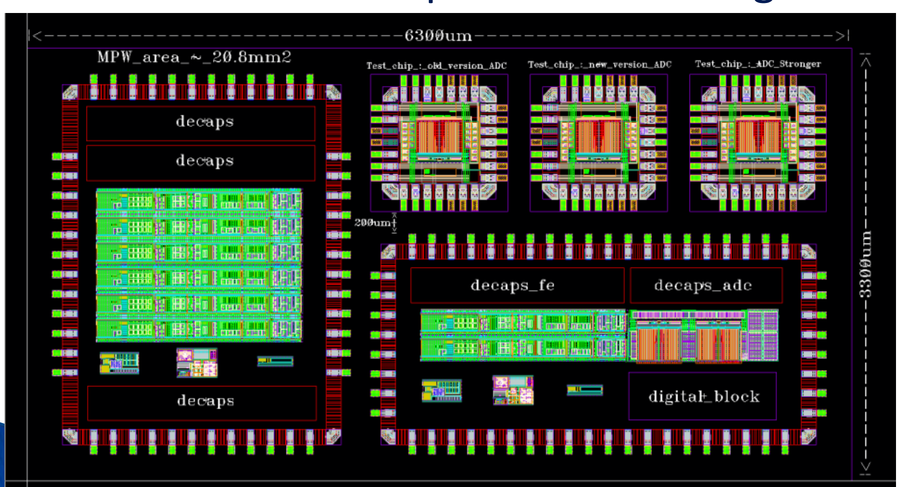


Streaming frontend

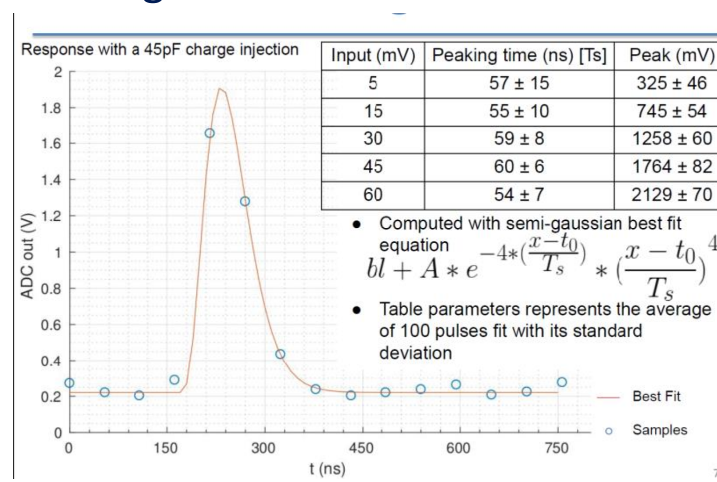


- Streaming ASIC in prototyping: ALPIDE, FPHX, SAMPA
- Generic SFP+ and Versatile link support
- sPHENIX version of SAMPA with 80ns-shaping in development
  - Based on ALICE development

80ns SAMPA components in testing



Analog + ADC data at USP



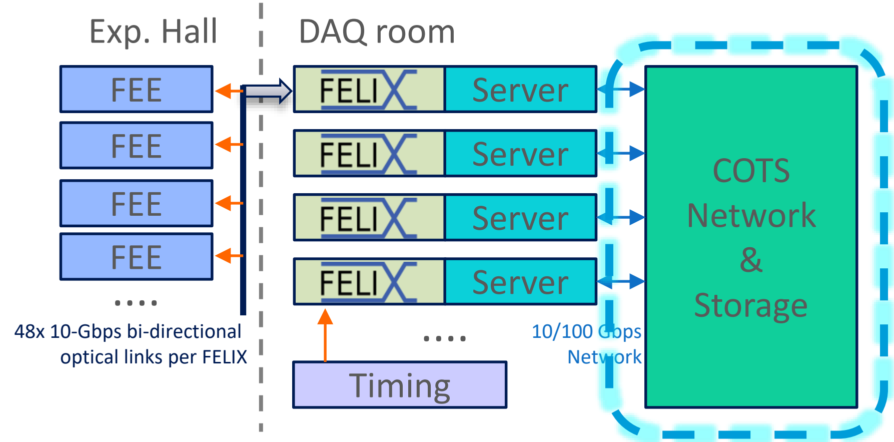
Input (mV)	Peaking time (ns) [Ts]	Peak (mV)
5	57 ± 15	325 ± 46
15	55 ± 10	745 ± 54
30	59 ± 8	1258 ± 60
45	60 ± 6	1764 ± 82
60	54 ± 7	2129 ± 70

- Computed with semi-gaussian best fit equation $bl + A * e^{-4*(\frac{x-t_0}{T_s})} * (\frac{x-t_0}{T_s})^4$
- Table parameters represents the average of 100 pulses fit with its standard deviation

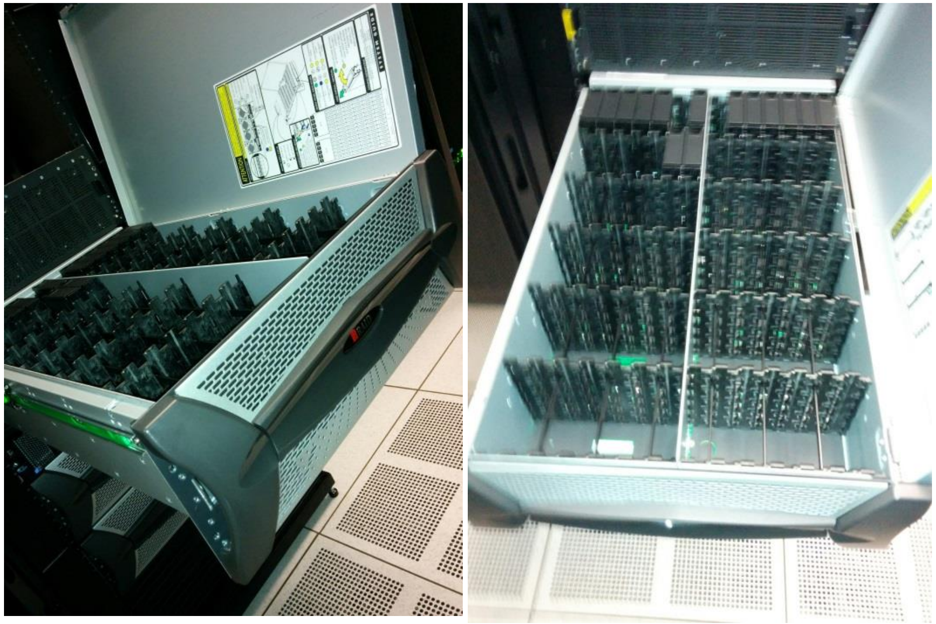
Online Storage

- Data buffer box
  - Average out data transfer: reduced rate and resilient to interruptions
  - Consist of multiple storage servers for write/transfer
- Existing server at RCF:

  Write test demonstrated ~50Gbps continuous memory → disk write-only speed for single server



COTS storage server, hosting ~100 disk slots



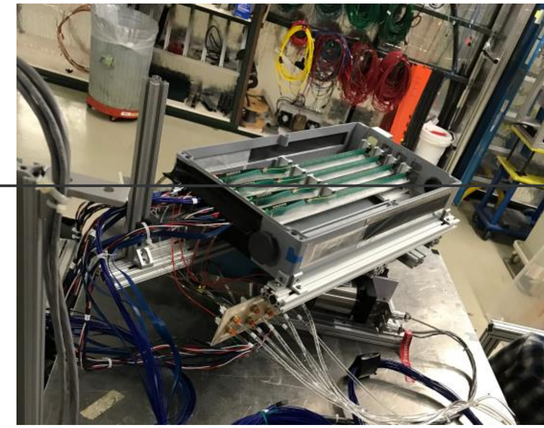
Courtesy: Martin Purschke (BNL)

Beam test: MAPS silicon tracker (on-going)

Supported by
LANL LDRD

Readout Unit
4.5M pixel/RU

ALPIDE MAPS tracker in test beam

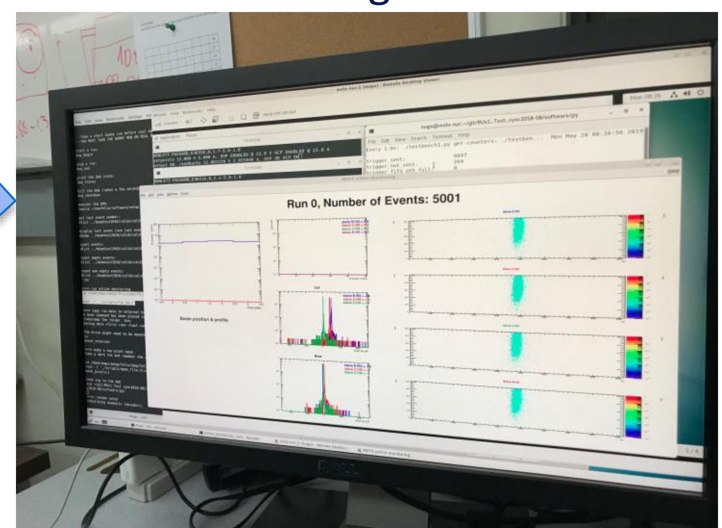


120 GeV p

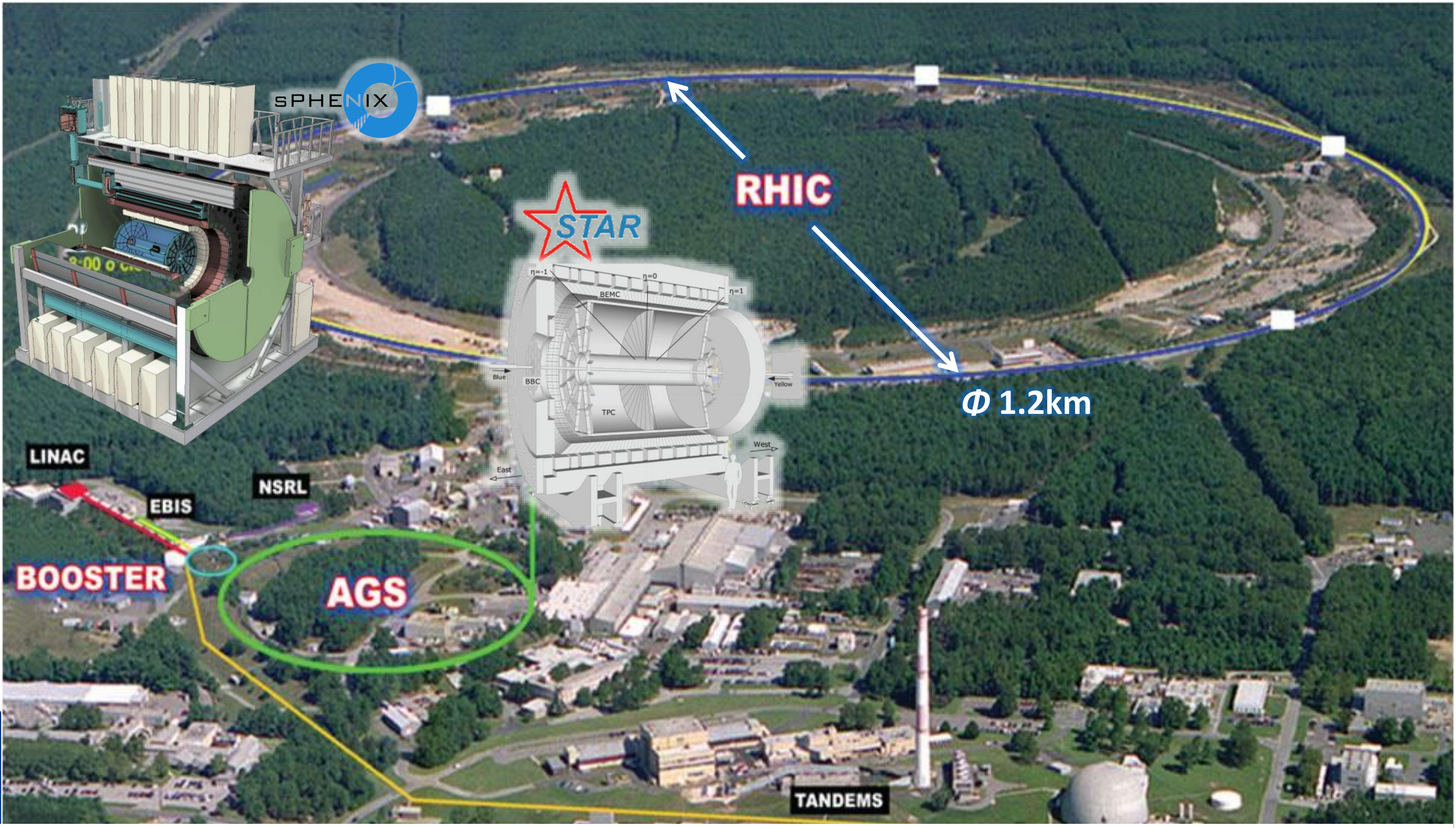
FELIX v2 DAQ interface

Commodity server

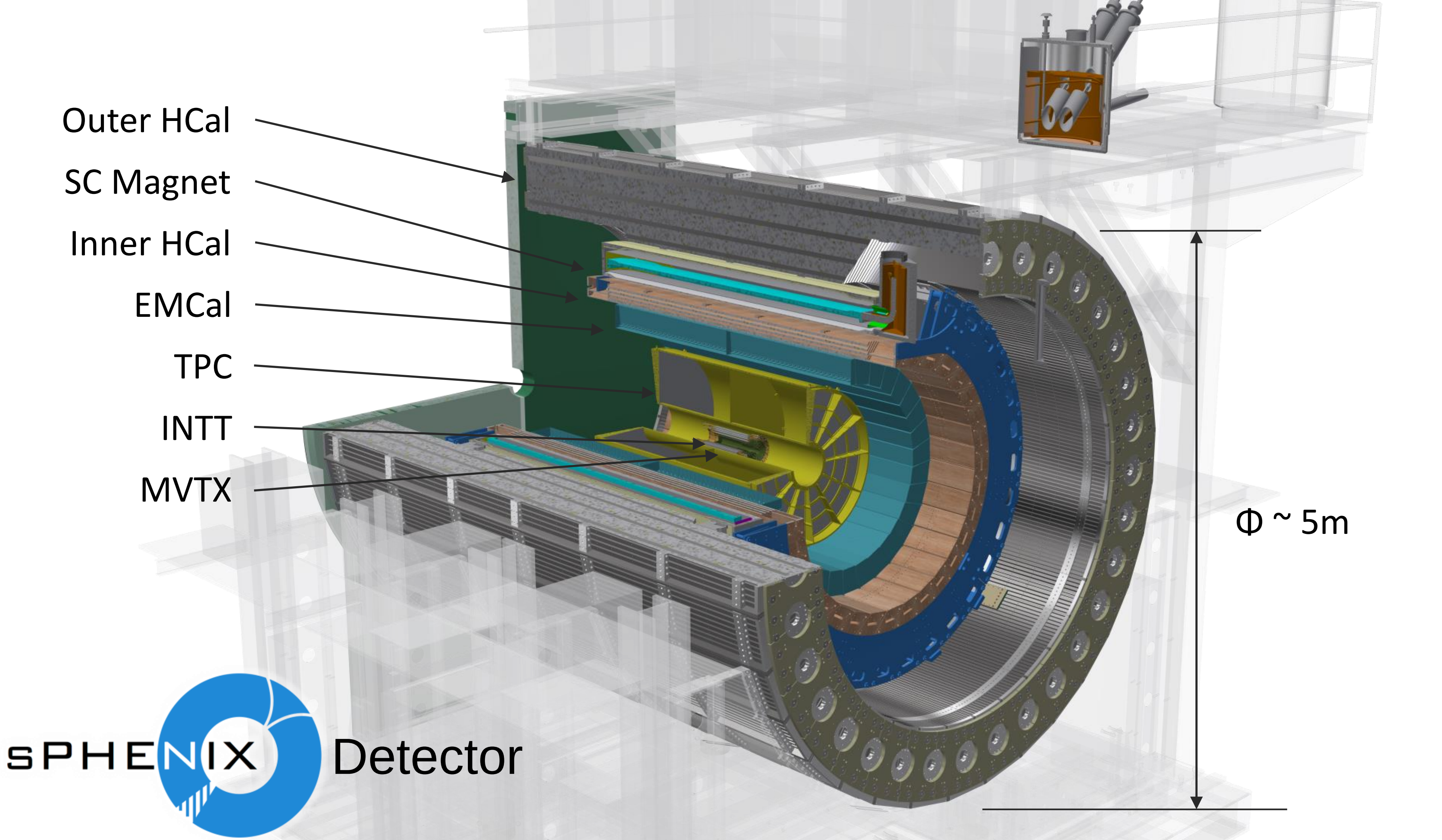
Online monitoring of silicon hits



RHIC @ mid-2020s



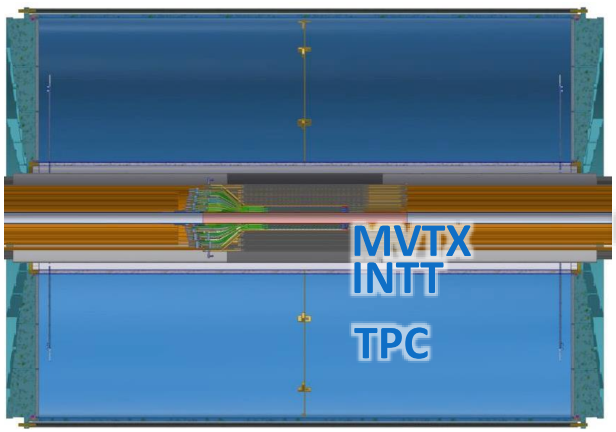
See also: PHENIX silicon tracker with streaming front end DOI:10.1016/j.nima.2014.04.017

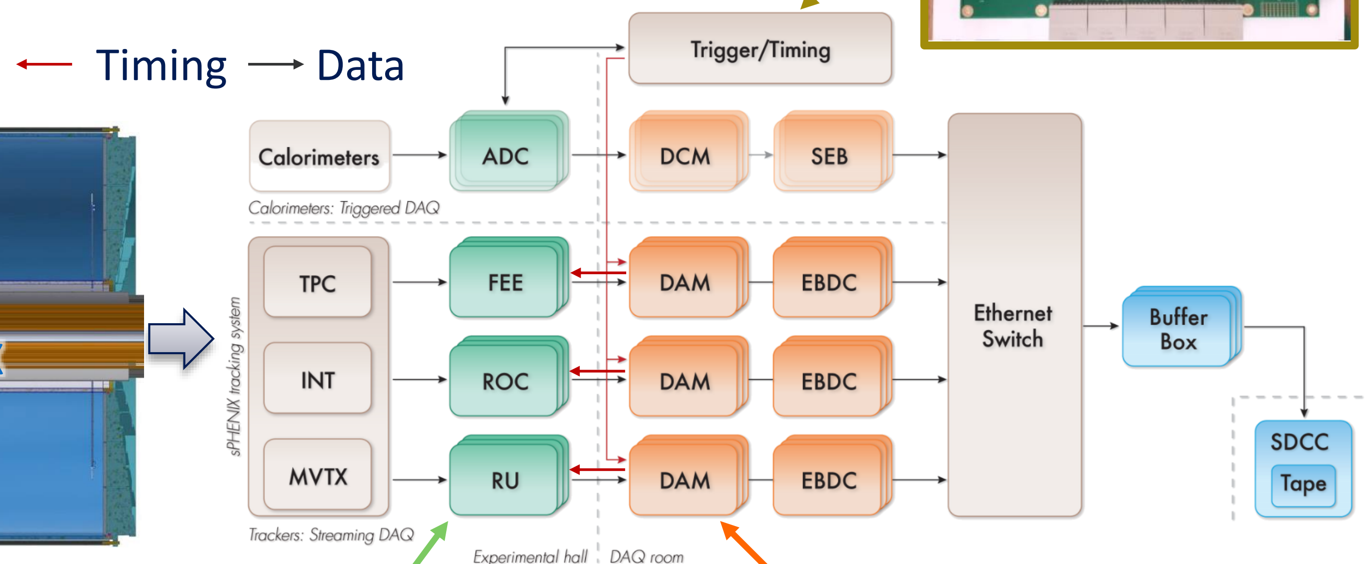


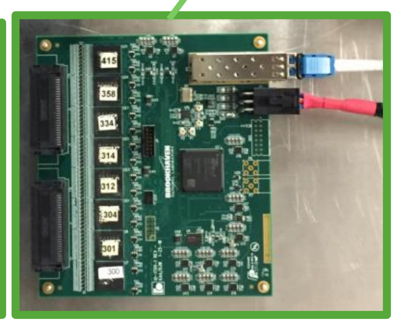
- 2018: Cost/schedule review and DOE approval for production start of long lead-time items (CD-1/3A)
- PD2/3 review next week!
- 2022 installation, 2023: First data

Streaming DAQ concept of sPHENIX trackers

Global Timing Module







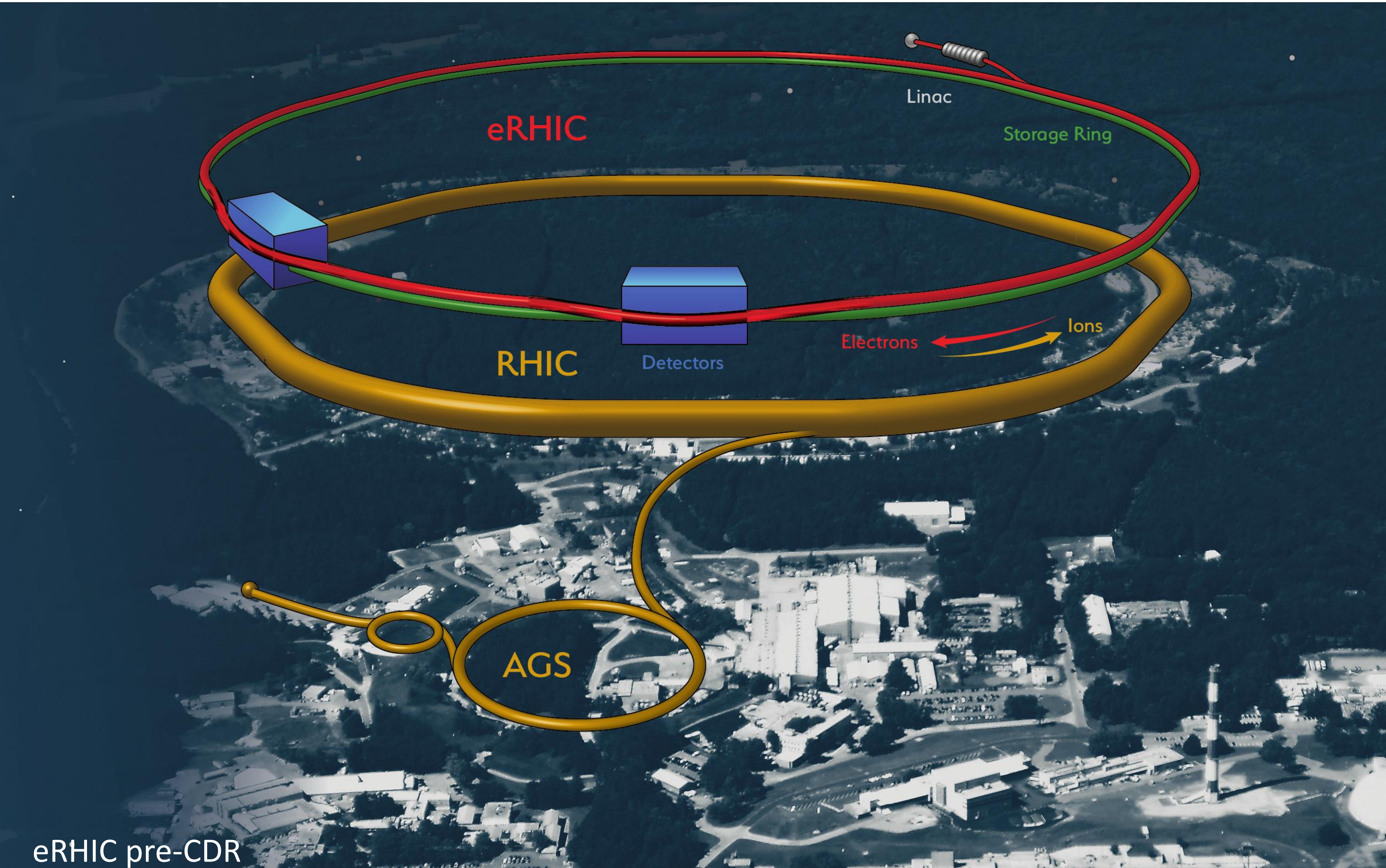
MVTX RU
ASIC: ALPIDE

INTT ROC
FPHX

TPC FEE
SAMPA v4 → v5

BNL-712/FELIXv2 as DAM
Streaming ASIC → DAQ

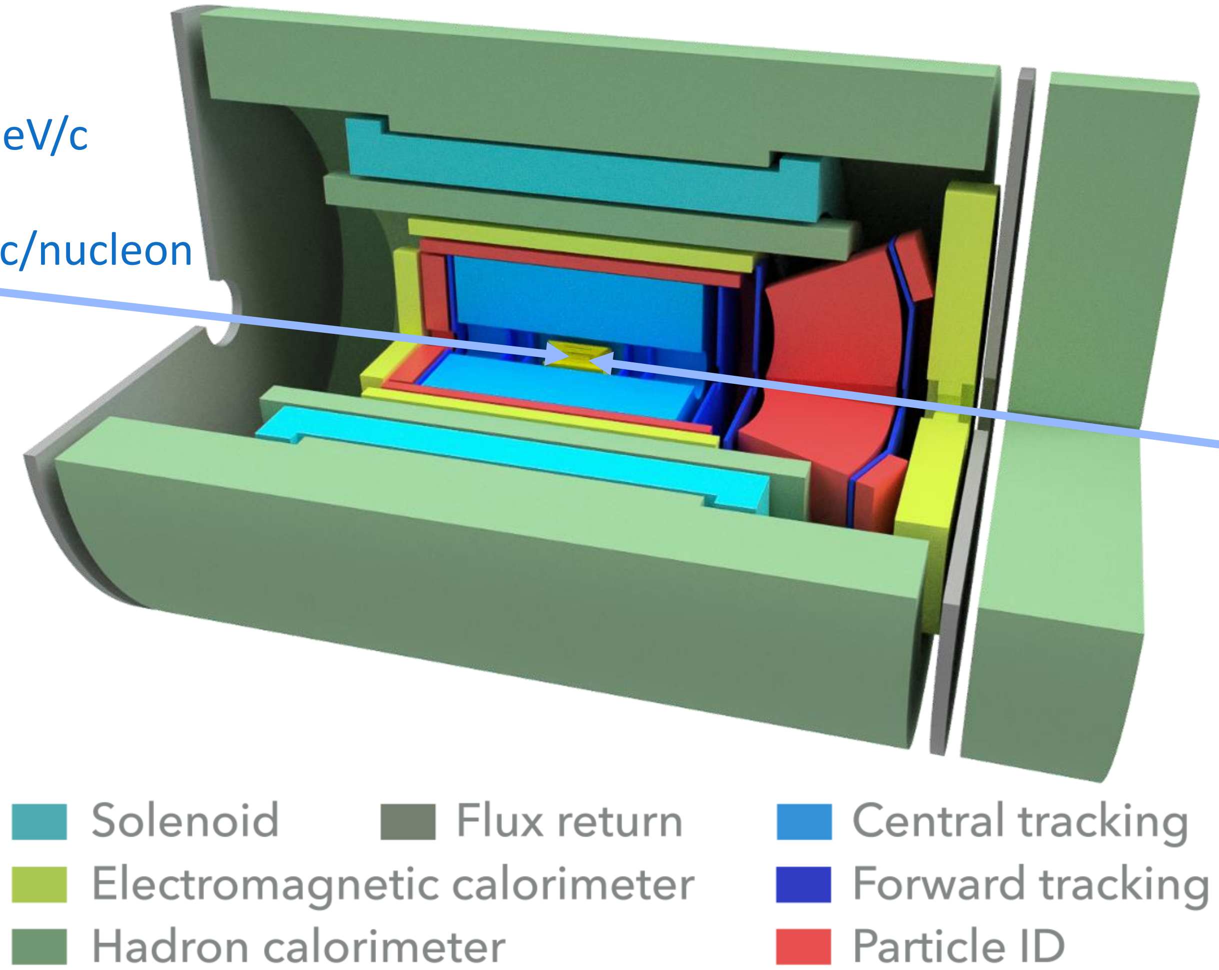
Proposed eRHIC @ end of 2020s



eRHIC pre-CDR

Example: sPHENIX-based EIC detector

- Proton 275 GeV/c Polarized
- Ion 100 GeV/c/nucleon



e^- 10 GeV/c Polarized

Tonko's estimation:

Signal rate = 16*8 Gbps ~ 100 Gbps

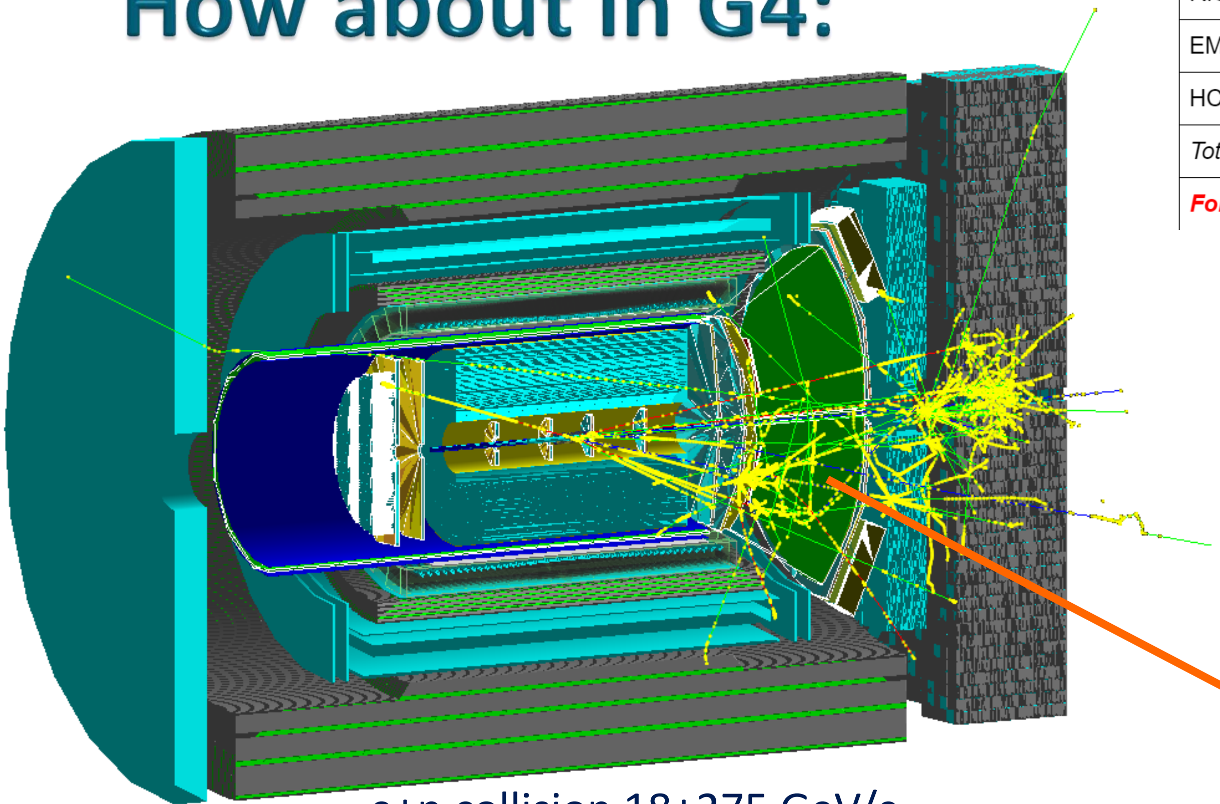
@ 10^{33} cm^{-2} s^{-1}, 200kHz collision

How about in G4:

Tonko's estimation (2015)

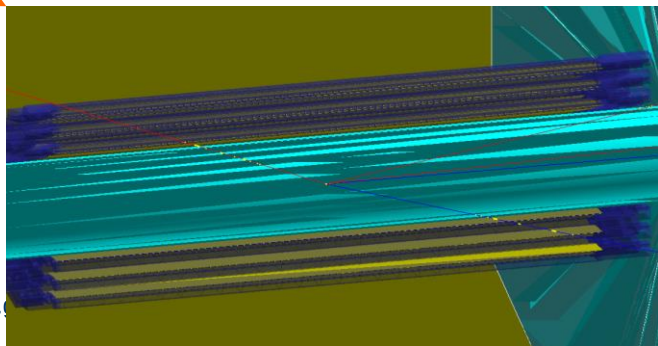
The eRHIC Detector ("BeAST") Readout Scheme

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

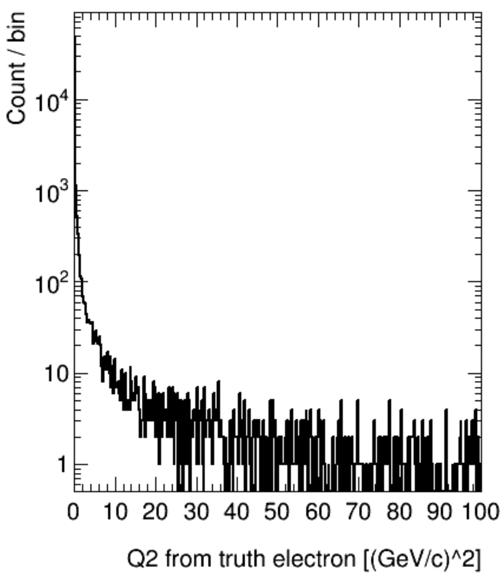
DIS @ Q^2 ~ 100 $(GeV/c)^2$

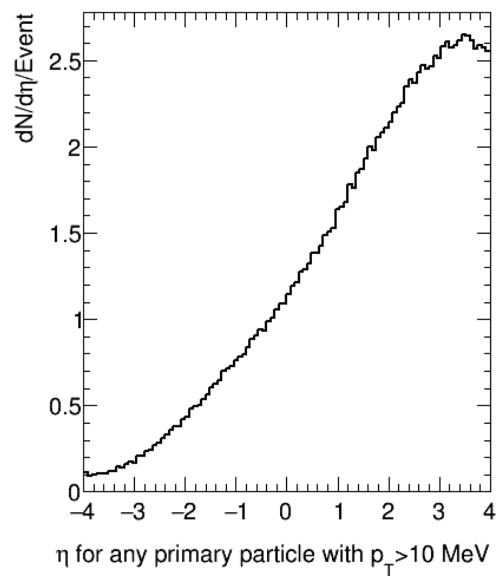


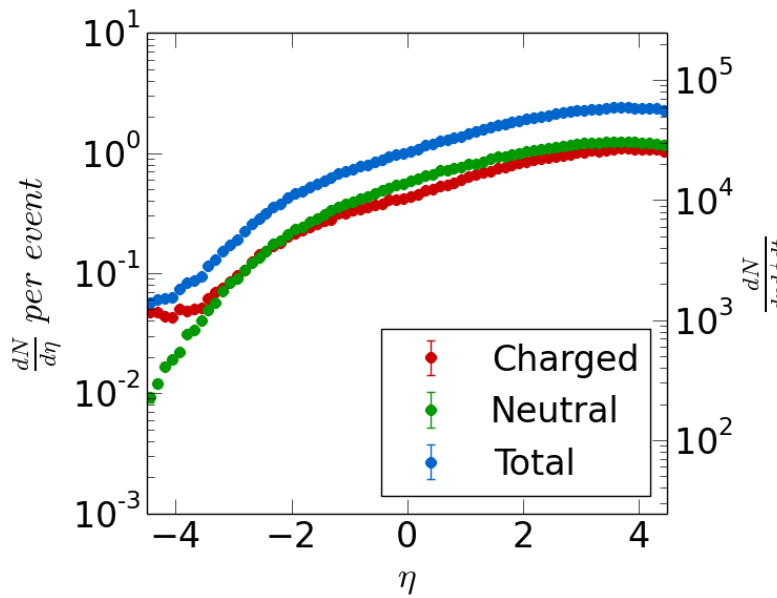
Full detector "Minimal bias" EIC events in sPHENIX framework: quick first look

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







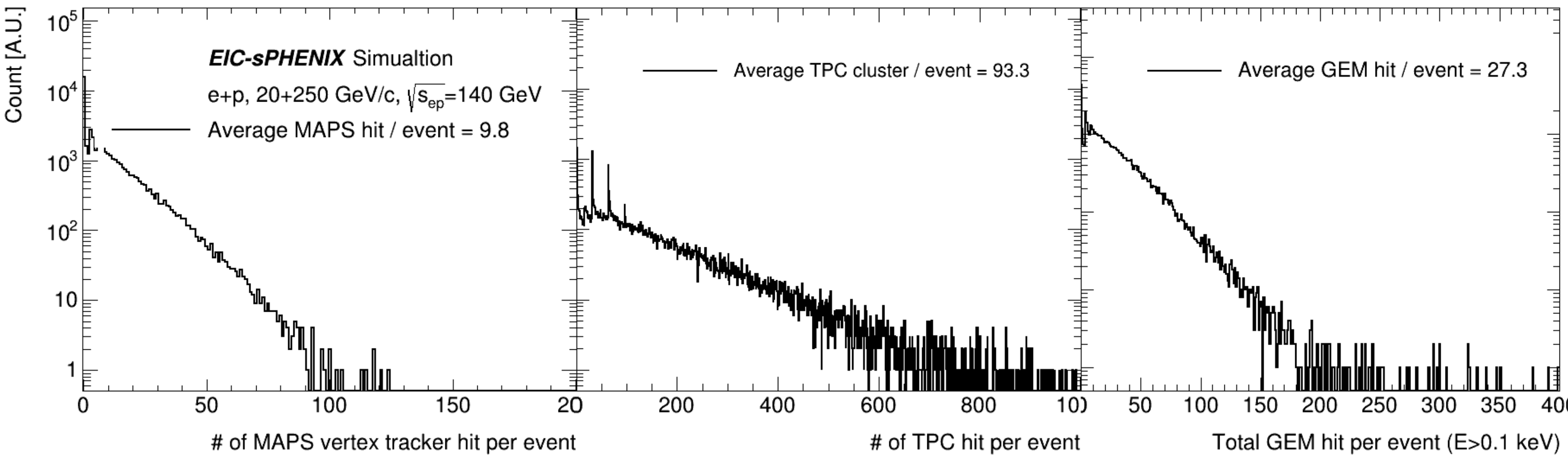
Based on BNL EIC task-force eRHIC-pythia6 55ub sample

```
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} $cm^{-2}s^{-1}$

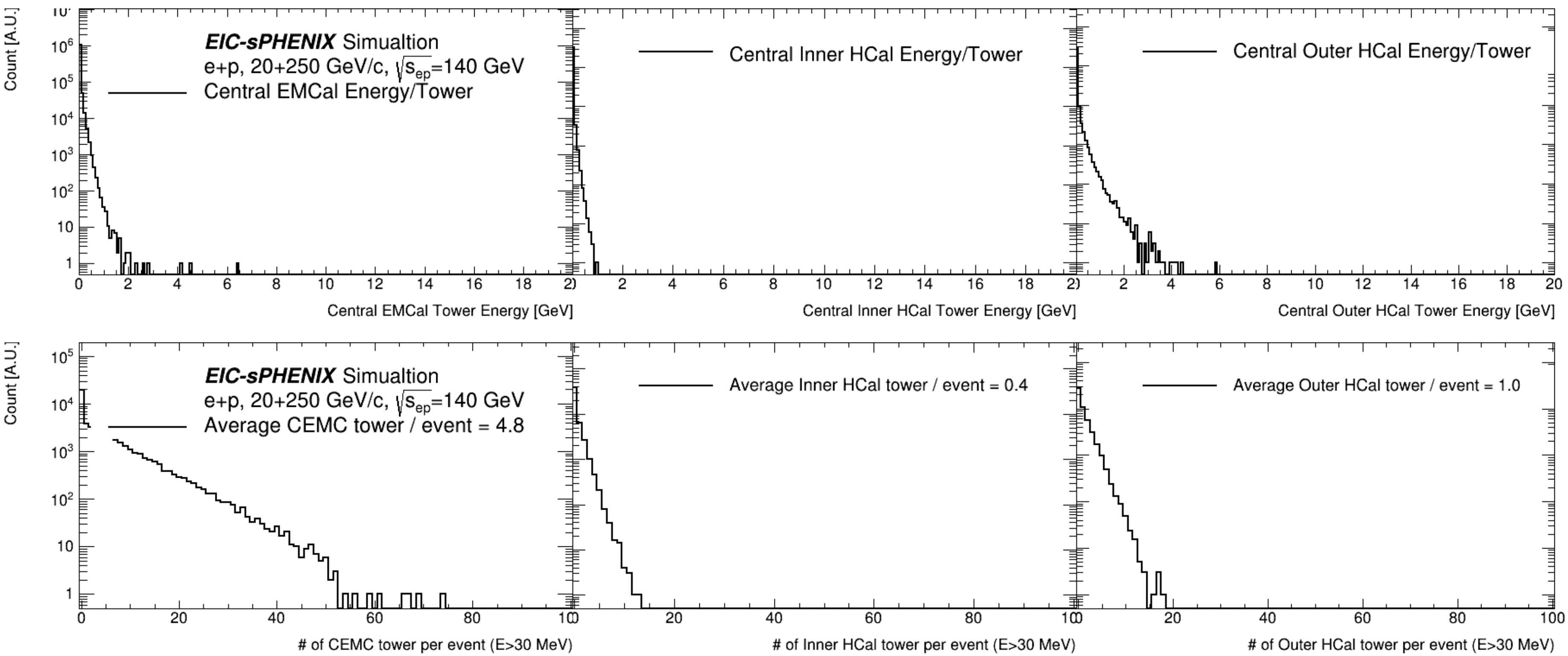
- MAPS is vulnerable to beam background see later slides
- ALPIDE MAPS noise are low, expect 10^{-6} /pixel/strobe, 200M pixel, 3us strobe → ~1Gbps

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

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

GEANT4-based detector simulation for DAQ simulation: central calorimeters

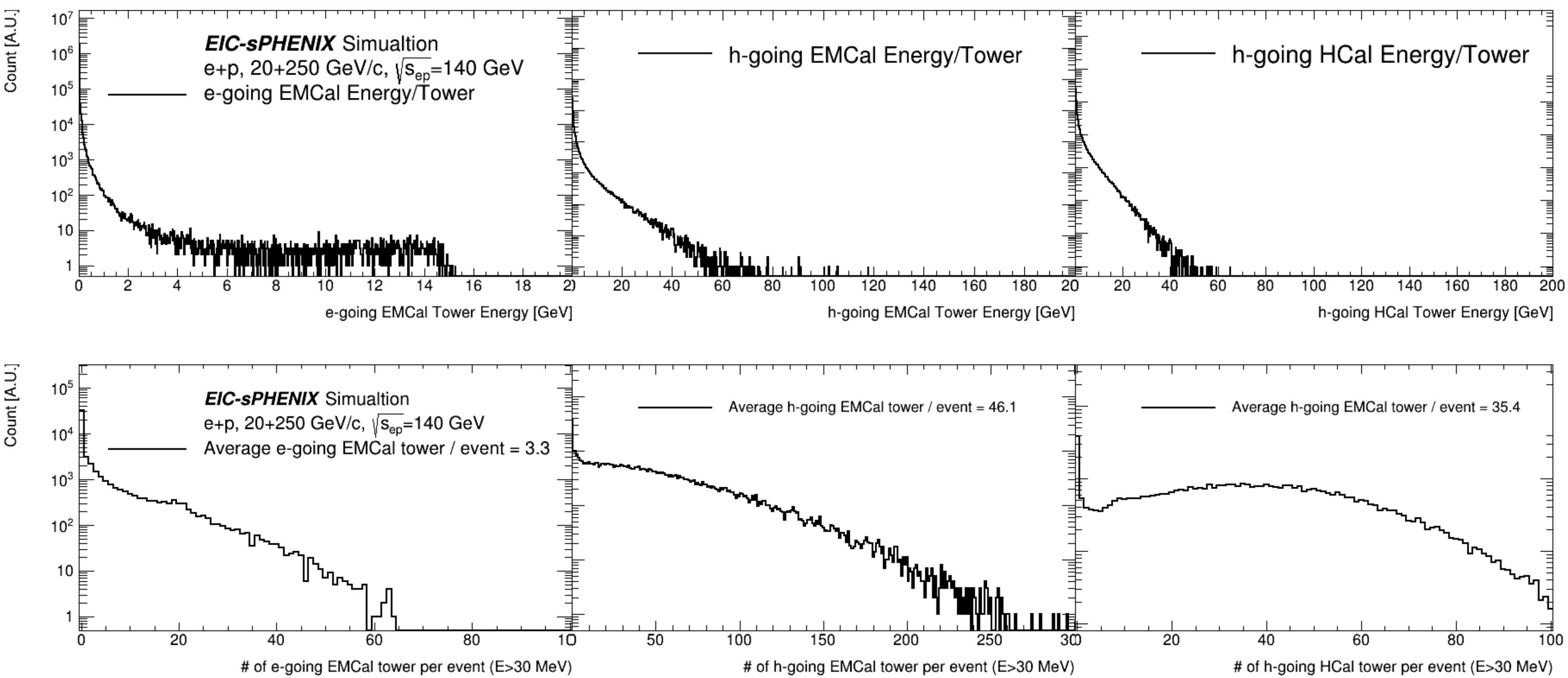
Raw data: 31x 14 bit / active tower +padding + headers ~ 512 bits / active tower



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

GEANT4-based detector simulation for DAQ simulation: forward calorimeters

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

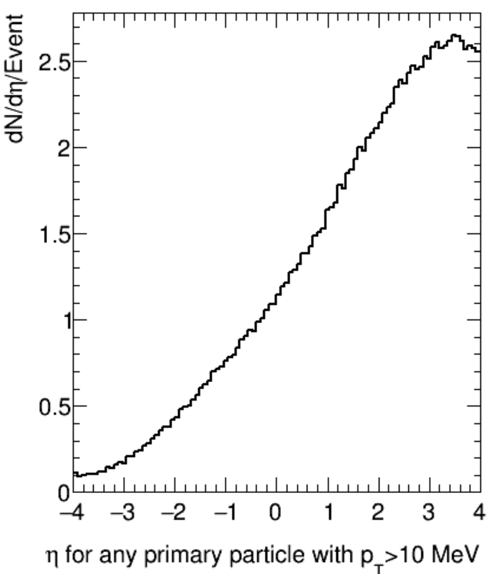


sPH-cQCD-2018-001, https://indico.bnl.gov/event/5283/

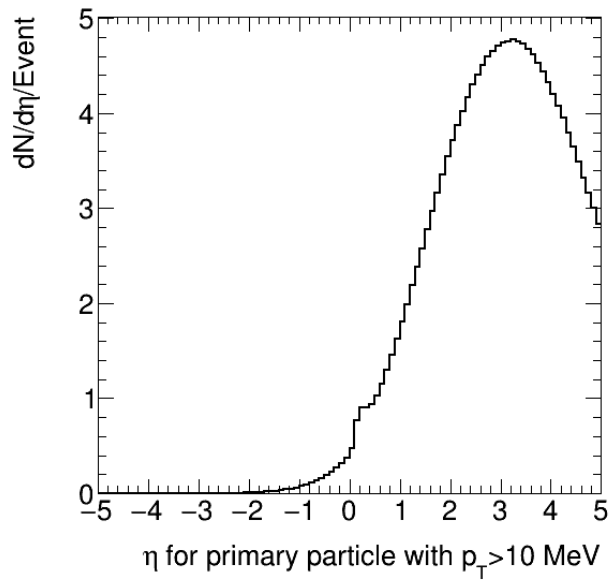
Beam gas multiplicity

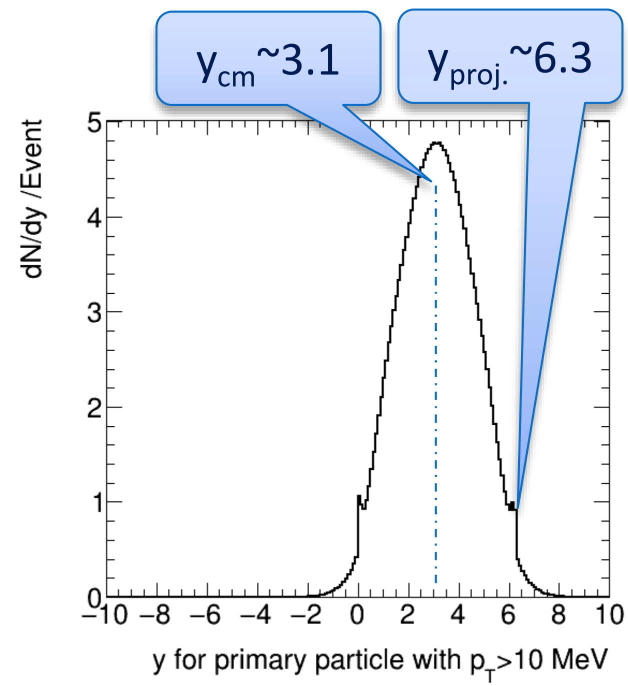
- 250 GeV/c proton beam on H_2 gas target
- C.M. rapidity~3.1, sqrt[s] ~ 22 GeV, cross section~40 mb
- Lab per-pseudorapidity multiplicity is higher than e+p, but ***not*** orders of magnitude higher

e+p, 20 + 250 GeV/c



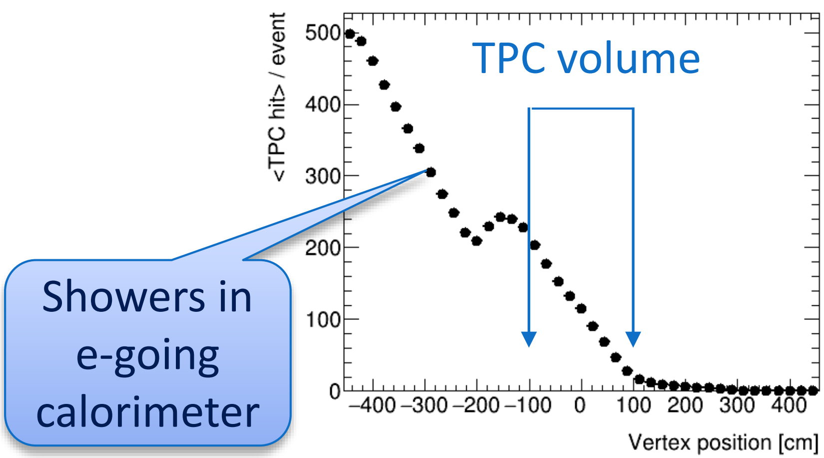
p+p (beam gas), 250 GeV/c

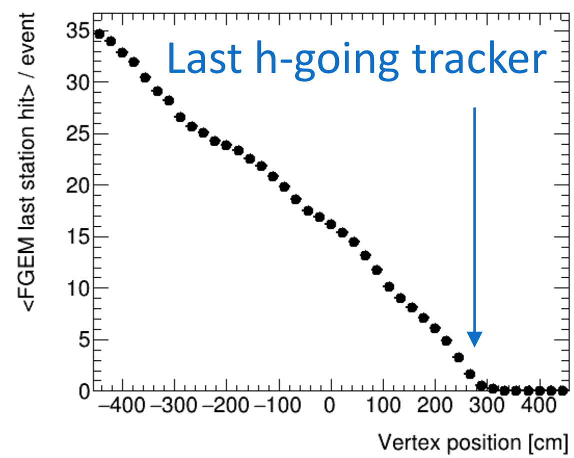


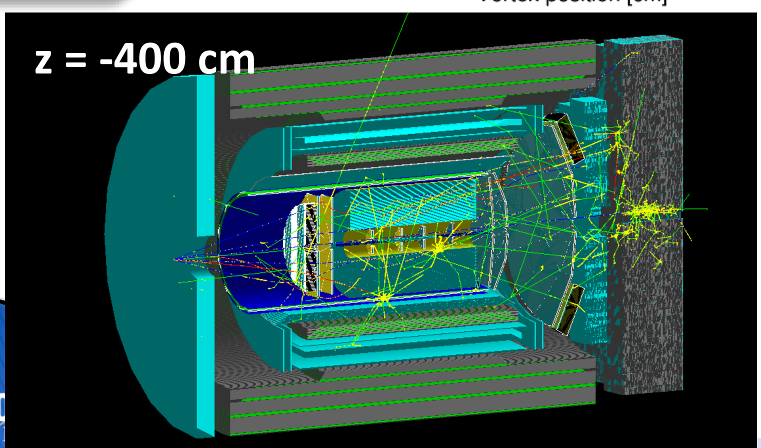


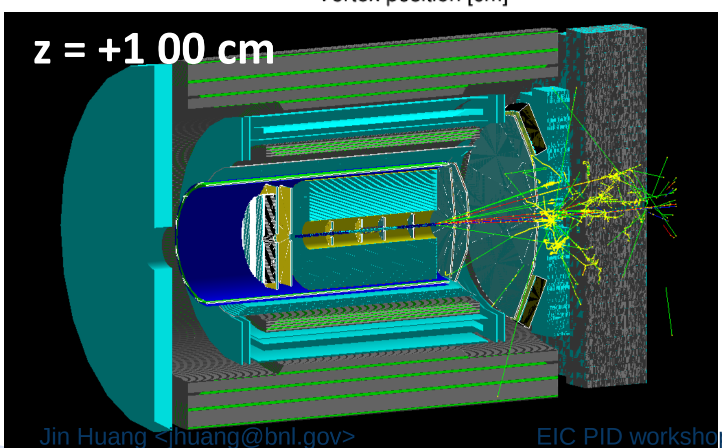
Beam gas vertex sensitivity - tracker

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



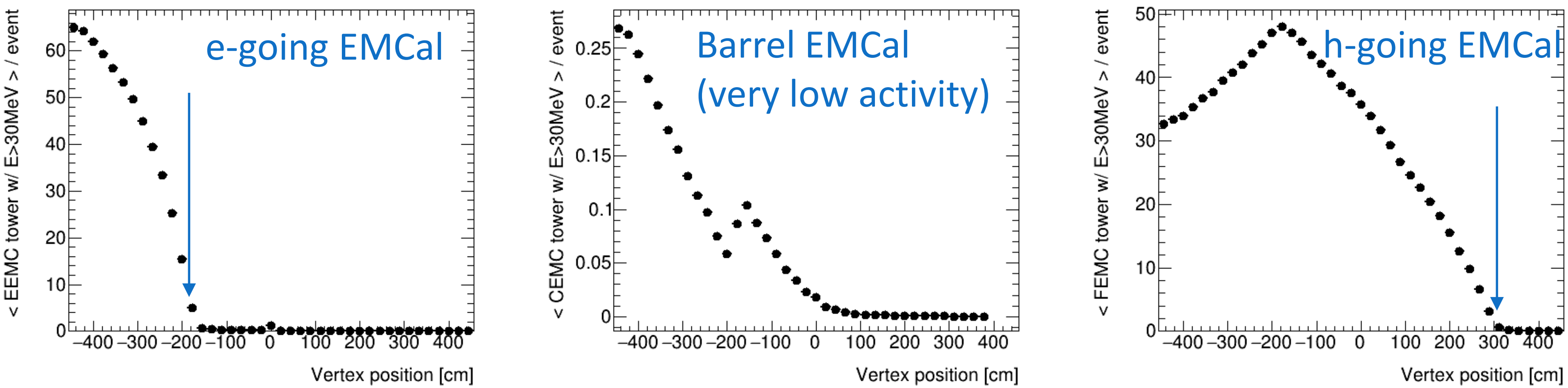


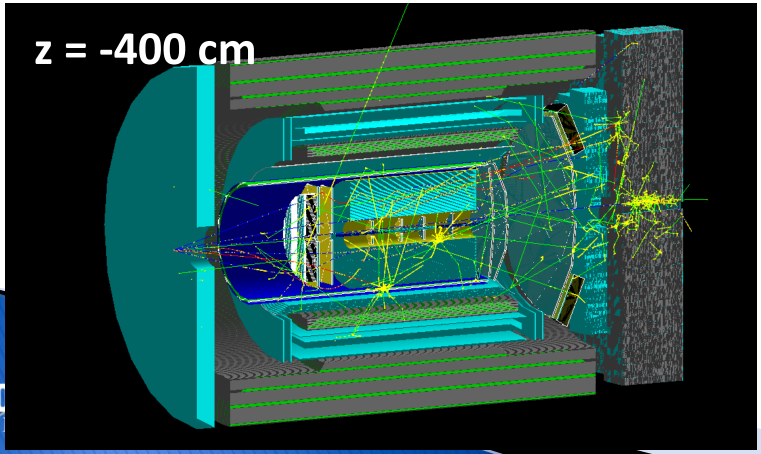


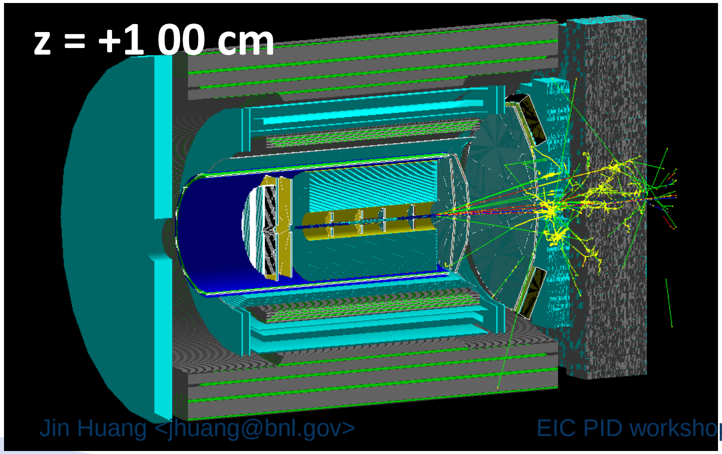


Beam gas vertex sensitivity – calo.

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

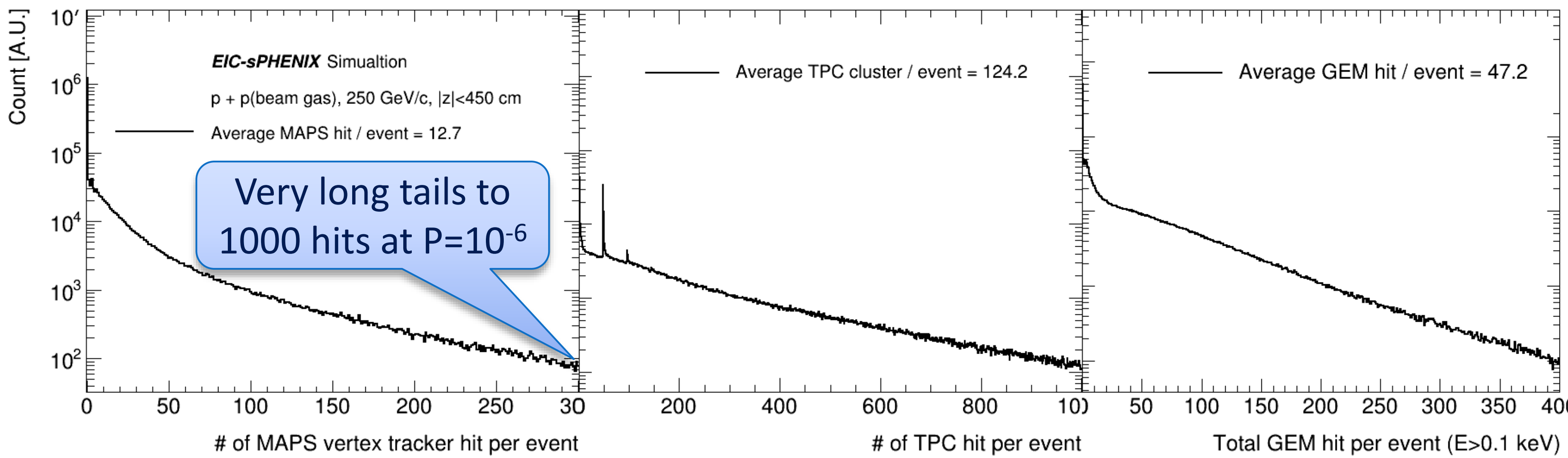






GEANT4-based detector simulation: beam gas event on tracker

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



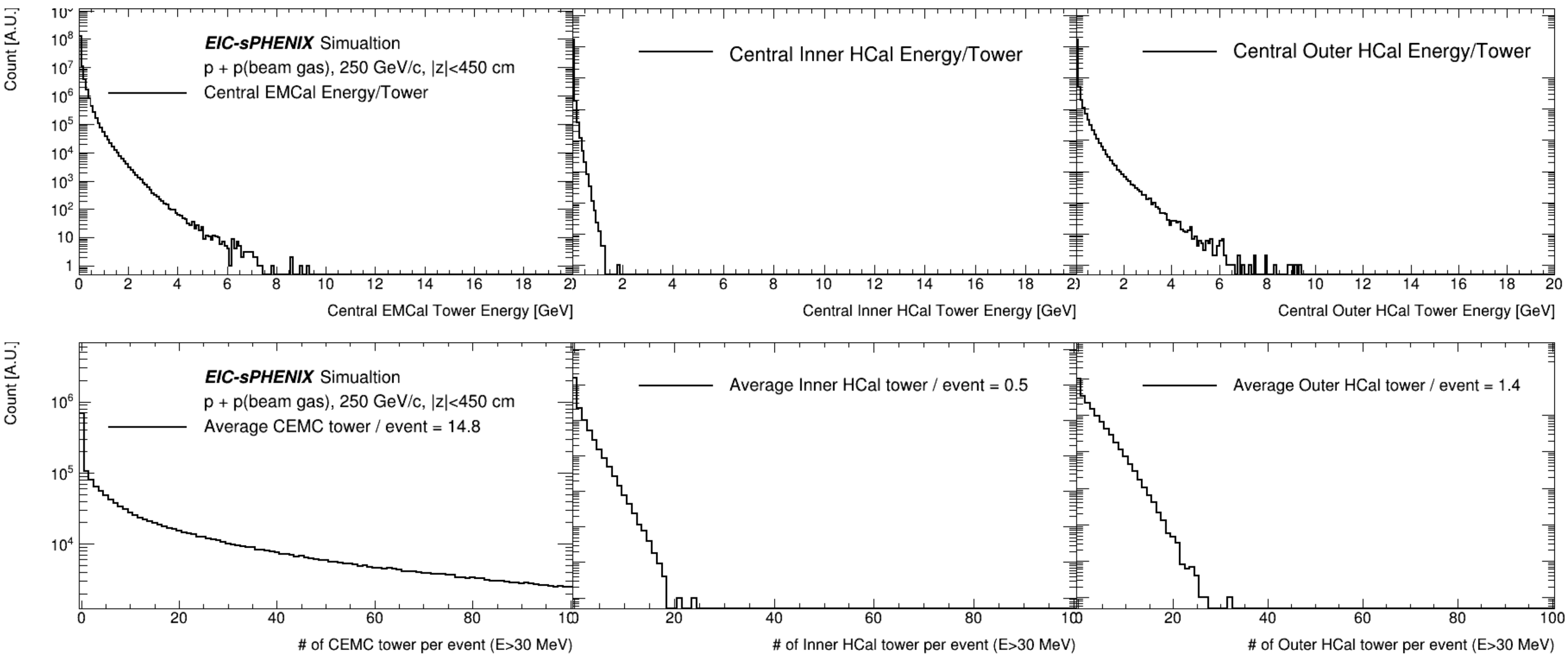
Raw data:
3 pixel x 16 bit / MAPS hit

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)

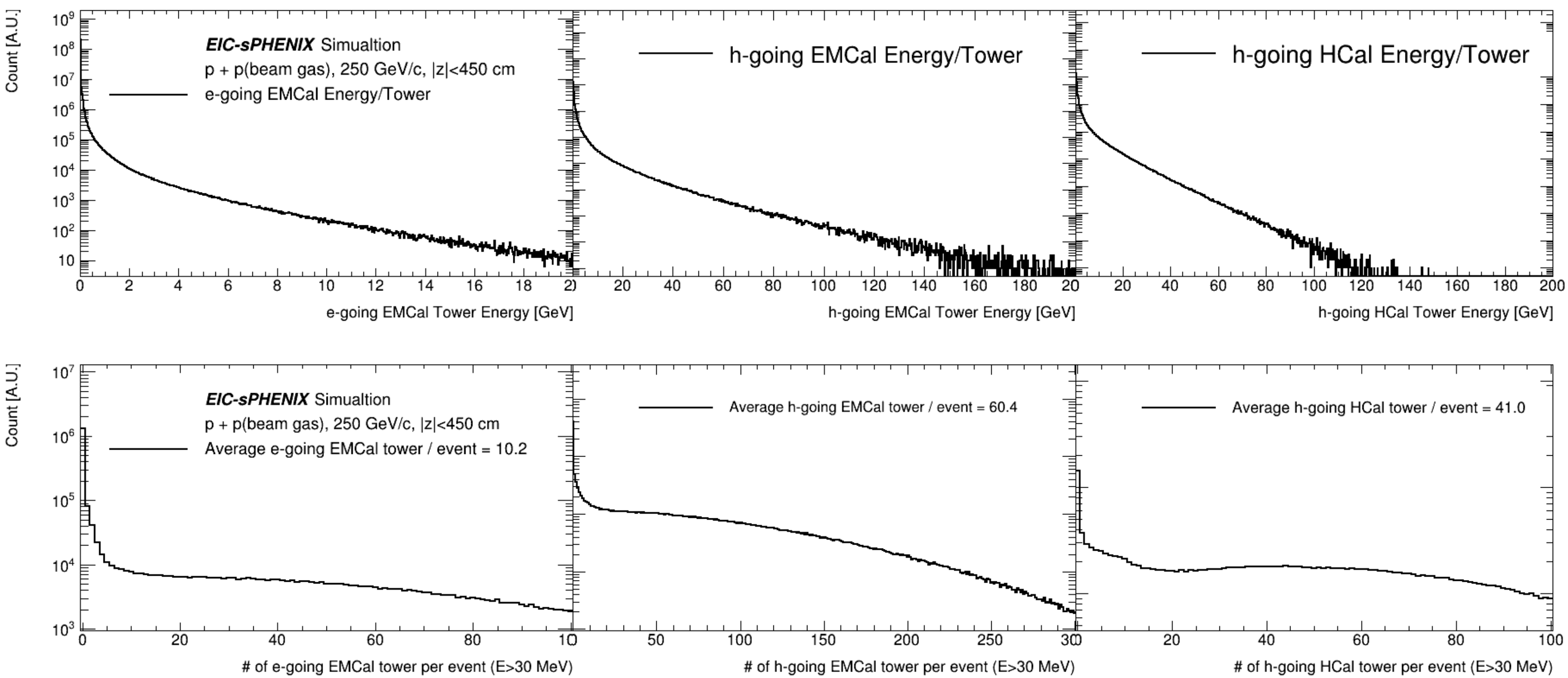
GEANT4-based detector simulation: beam gas event on central calorimeters

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



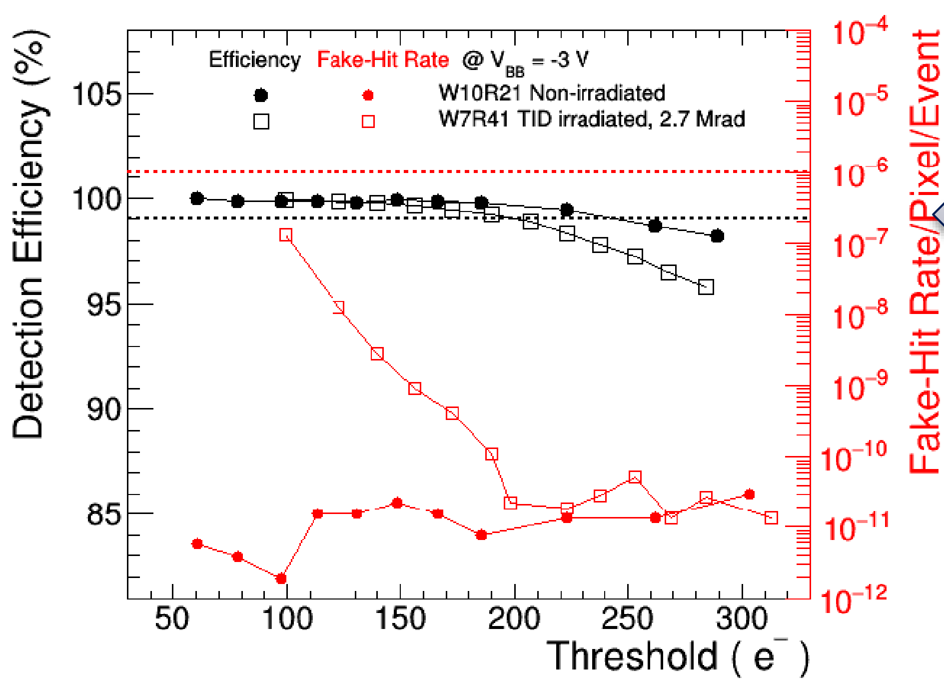
Per-strobe ALPIDE multiplicity

Four factor contributes in a MC simulation:

- Per-collision multiplicity, PDF as in last page
- Number of pile up collision, Poisson distributed
- The triggered collision, |z|<10 cm (trigger mode only)
- Number of noise, Poisson distributed

Comments received:

- Duplicated hits between strobes are not included yet (Thanks to Jo)
- UPC electron background not included (Thanks to Xin)
- Aiming for 10^{-6} noise in final detector (Many)



Bottom line: 10^{-4}

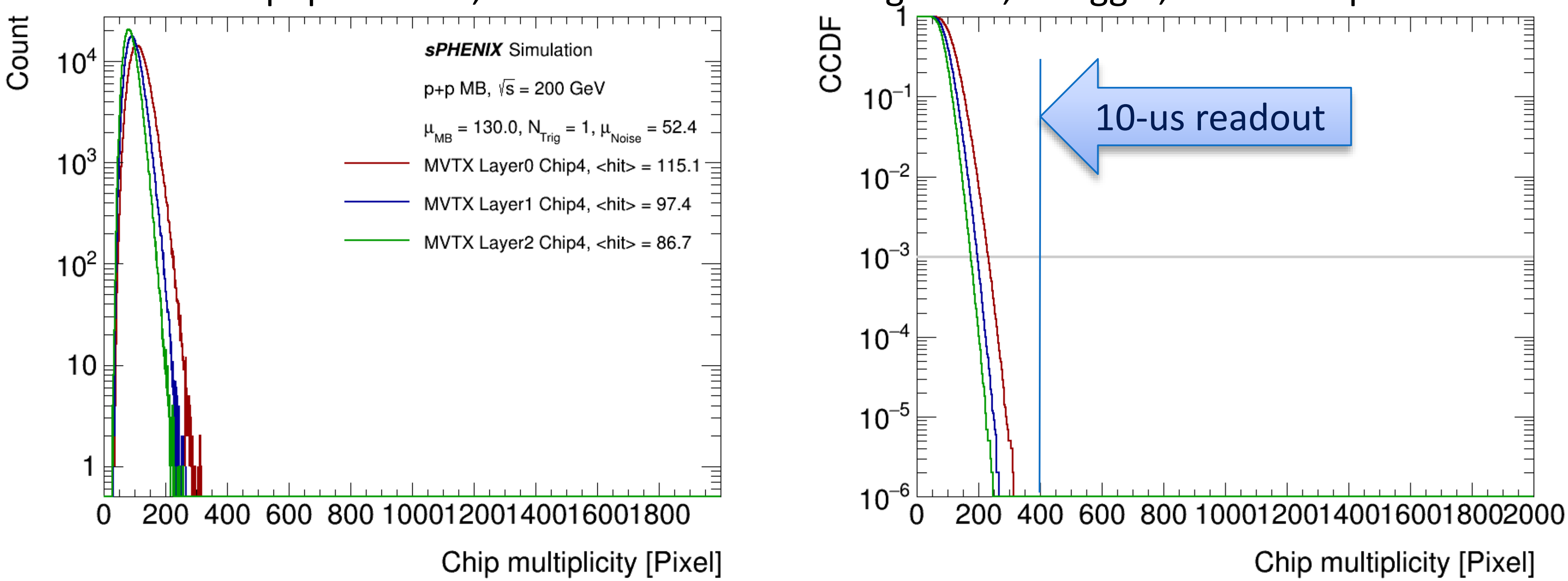
Also studied: 10^{-5}

Likely in operation: 10^{-6}

p+p multiplicity, per-strobe, chip-4

- p+p collision related data is completely dominated by pile-ups
- Central limit theorem: High number of pile up → low non-Gauss high tails
- Continuous-mode is quite safe @ 10-us strobe window

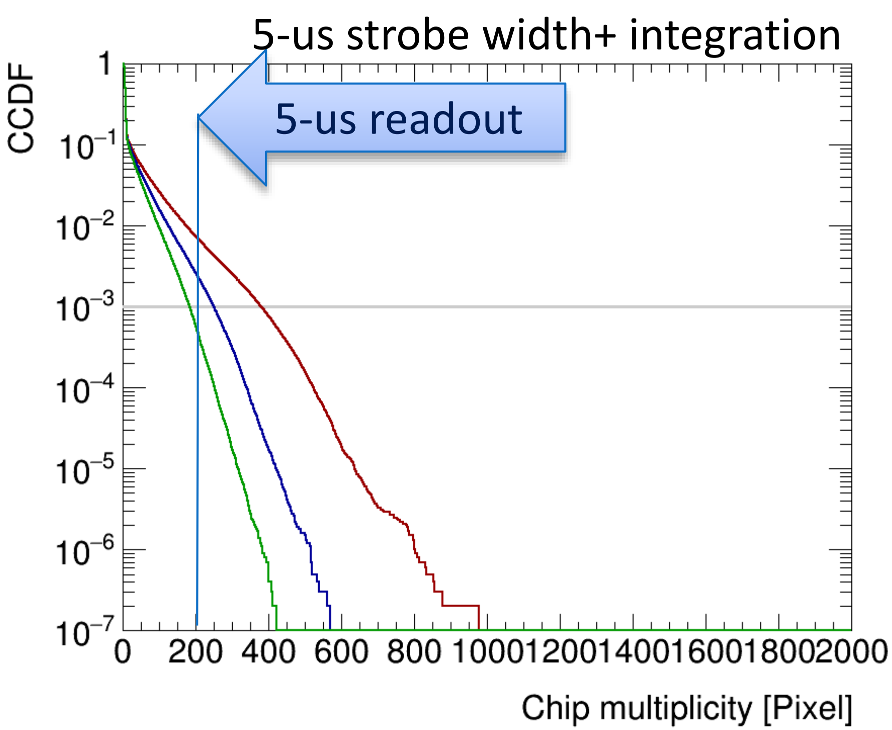
13 MHz p+p collision, 10-us strobe width+integration, 1 trigger, 10^{-4} noise per strobe

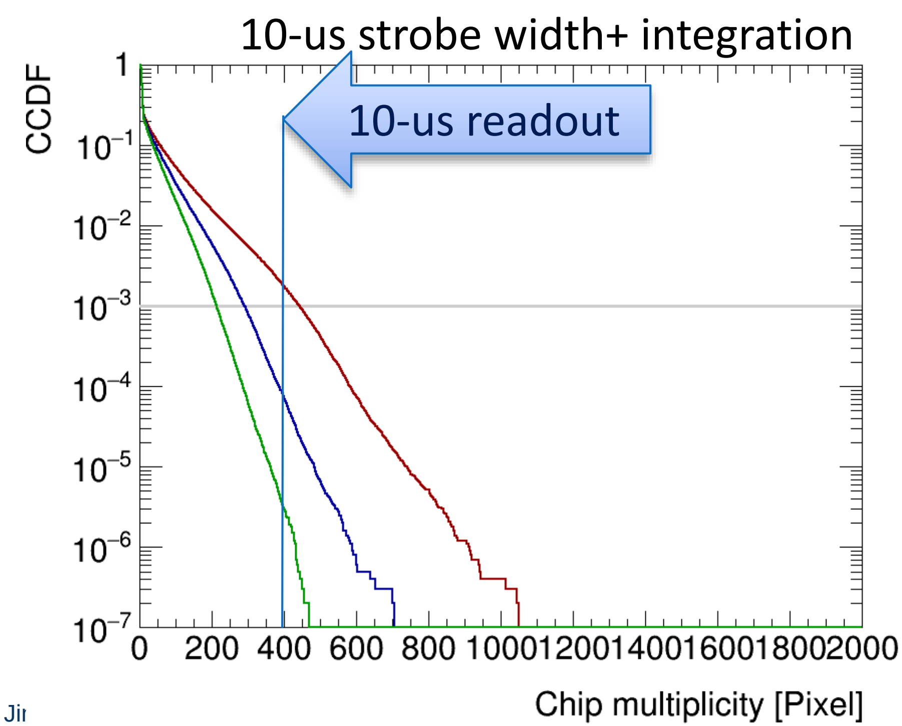


Au+Au multiplicity, per-strobe, chip-4

- Can we do better?
  - Further reducing collision rate to 50kHz by introducing a beam crossing angle
  - Reducing noise by 1/10 to 10^{-5} noise per strobe
- Still challenging for continuous , but plausible to have overflow dead-time < 0.1% further using multi-hit buffer on chip (eating the safety factor)

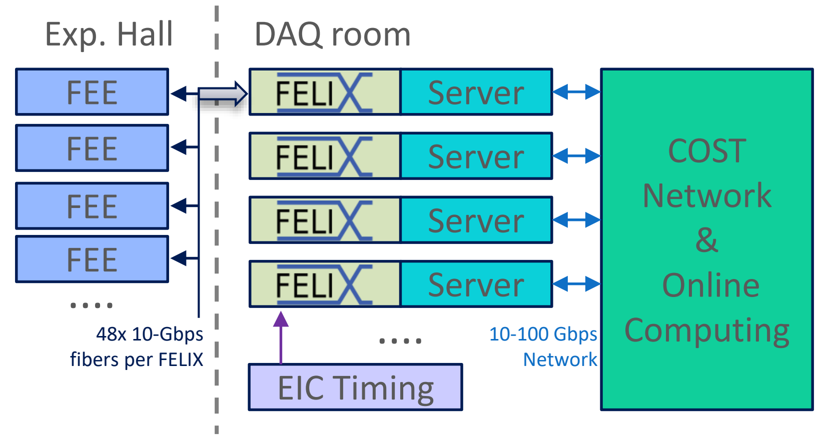
50 kHz Au+Au collision, periodic strobe, 10^{-5} noise per strobe





Timing distributions

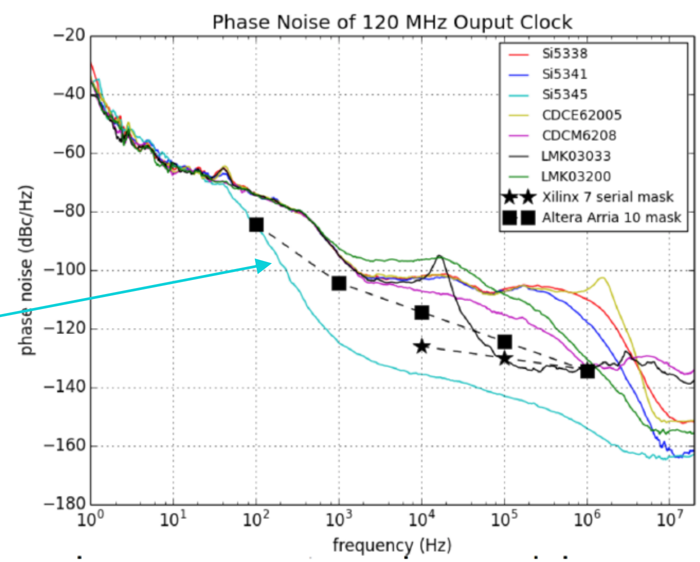
- All PHENIX/sPHENIX FEE are synced to beam clock/counter. Expecting similar for EIC detector
- BNL-712/FELIX can receive clock of multiple protocols (SPF+, White Rabbit, TTC, …) via a timing mezzanine card
- SI5345 jitter cleaner control jitter to <0.1 ps
- BNL-712/FELIX carries 48x 10 Gbps downlink fiber for control data to FEE. Beam clock and sync word can be encoded on fiber (e.g. 8b10b encoding)
- For EIC hadron beam RF, extra cautious need to be taken for hadron machine ramp from low gamma to high gamma, which leads to clock frequency variation [next slide].



timing mezzanine cards

Device	SI5338	SI5345	SI5341
Jitter (ps)	8.58	0.09	6.39
Device	CDCM6208	LMK03200	LMK03033
Jitter (ps)	2.06	5.91	2.74
Device	CDCE62005		
Jitter (ps)	8.61		

The jitter from 10 kHz to 1 MHz



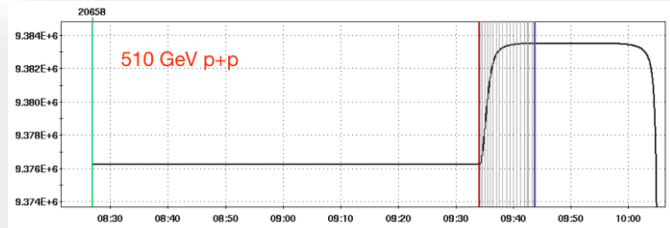
Kai Chen – FELIX Design Review

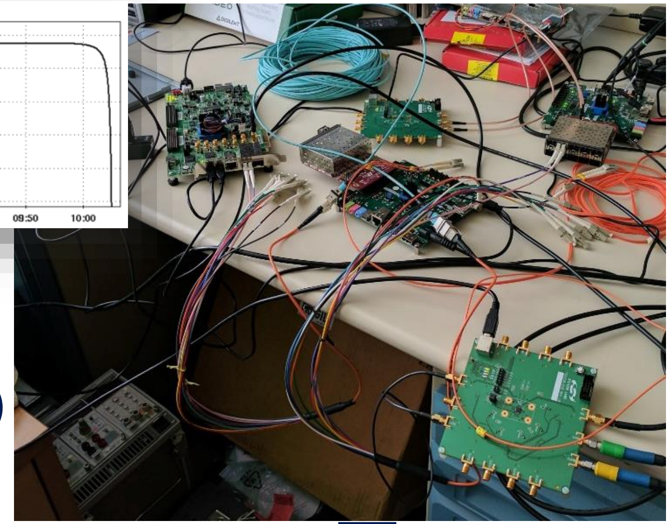
Courtesy of Kai Chen (BNL)

Embedded clock demo with variable beam clock frequency

Function generator mimic repeated RHIC clock ramping (triangle pattern)

RHIC frequency spread (due to ramp) is large, 9.362 MHz ±22 kHz





Demo FELIX
Kintex-7 Ultrascale

Downlink: 4.8 Gb/s
Multiples of RHIC clock (9.4 MHz)
Recover clock from 8b/10b

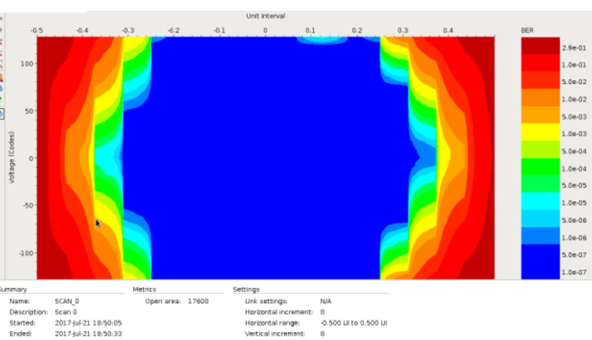
Optical Links

Demo FEE
Atrix-7

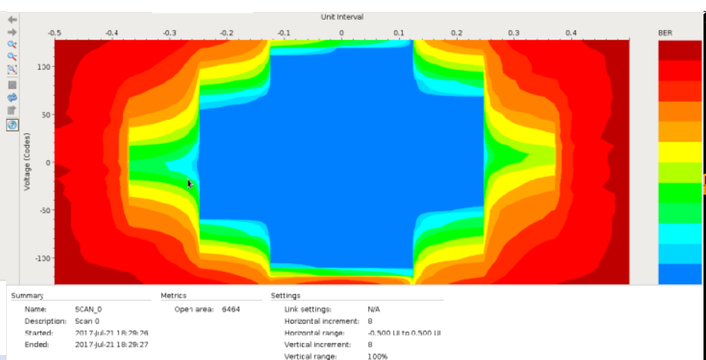
Uplink: 4.8 Gb/s, fixed clock

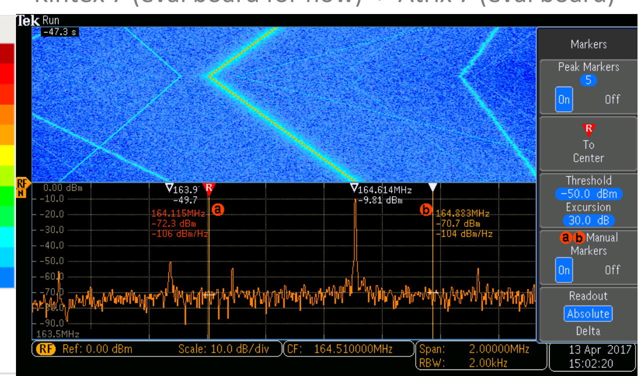
Test recovered "RHIC" clock
Kintex 7 (eval board for now) -> Atrix 7 (eval board)

Uplink iBERT @ DAM: 1.46e-13



Downlink iBERT @ FEE: 1. 023e-13

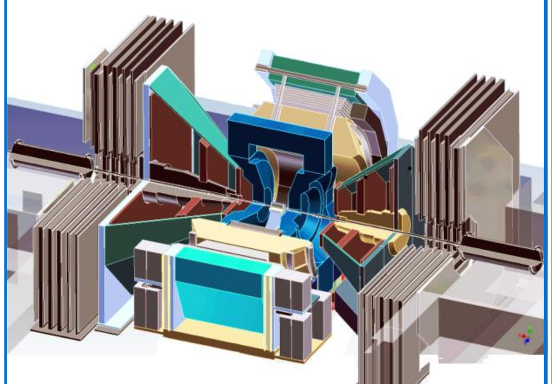




Evolution of the RHIC 1008 Interaction region

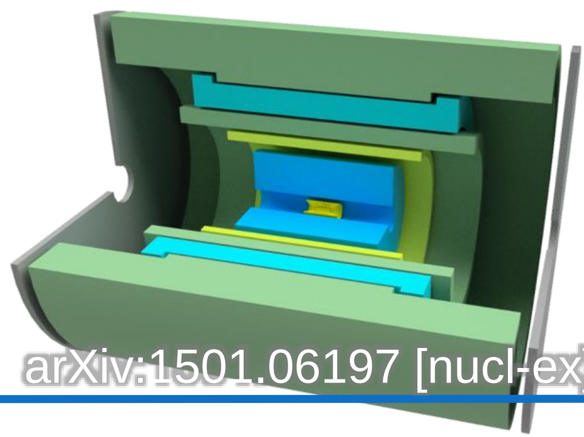
PHENIX experiment

- 16y+ operation
- Broad spectrum of physics 180+ physics papers with 25k citations
- 1.4-M channel streaming



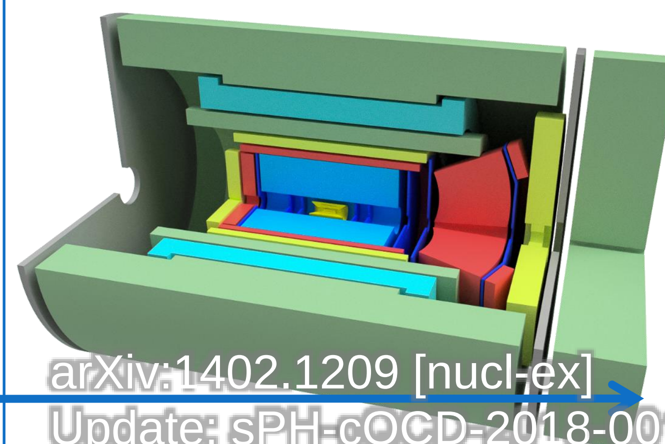
sPHENIX

- Comprehensive central upgrade base on previous BaBar magnet
- Rich jet and HF physics program
  → Microscopic nature of QGP



An EIC detector

- Path of PHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- Full streaming DAQ based on sPHENIX



~2000

2017→2023, CD-1/3A Approved

>2025

Time

RHIC: A+A, spin-polarized p+p, spin-polarized p+A

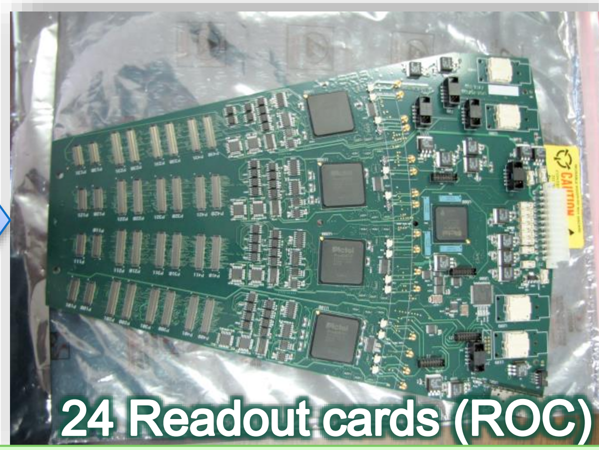
EIC: e+p, e+A

PHENIX/FVTX Streaming FEE

384 Wedges
1.4M channel 3-bit flash ADC

HDI
FPHX Chip
Ionizing Hit
Sensor

17k LVDS
3.2 Tb/s



24 Readout cards (ROC)

Flash ADC & free streaming

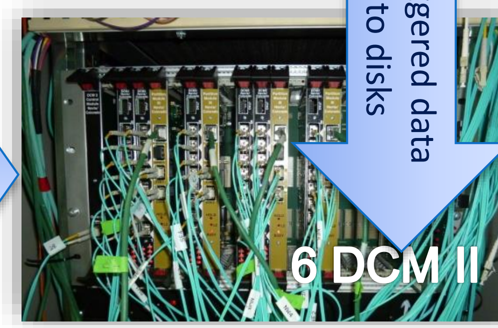
768 fibers
1.9 Tb/s

IR | DAQ Room

Streaming data processing on FPGA for b-by-b luminosity & Transverse SSA (A_N)

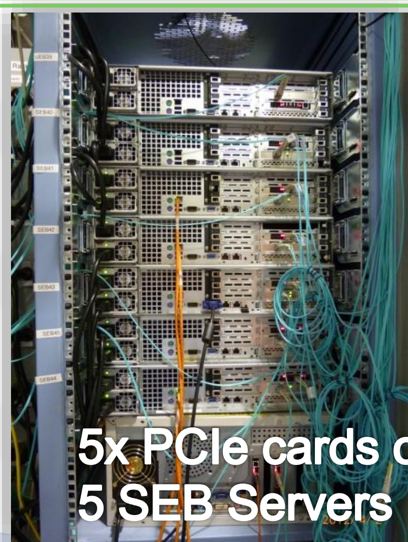
48 FEM

Triggered data to disks



6 DCM II

8 fibers



5x PCIe cards on 5 SEB Servers

PHENIX event builder / Data storage

Online display

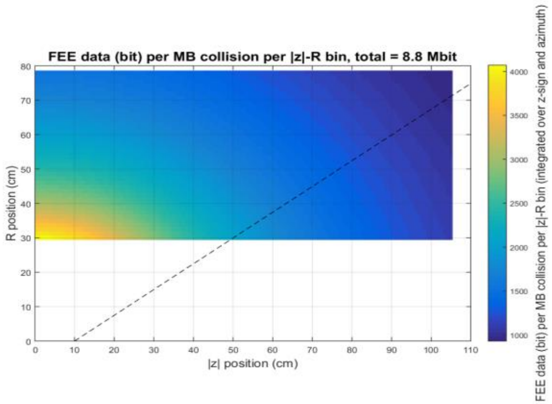
Standalone data (calibration, etc.)

Data cable/bandwidth shown on this slide only

eRHIC and JLEIC key parameters at max Lumi points

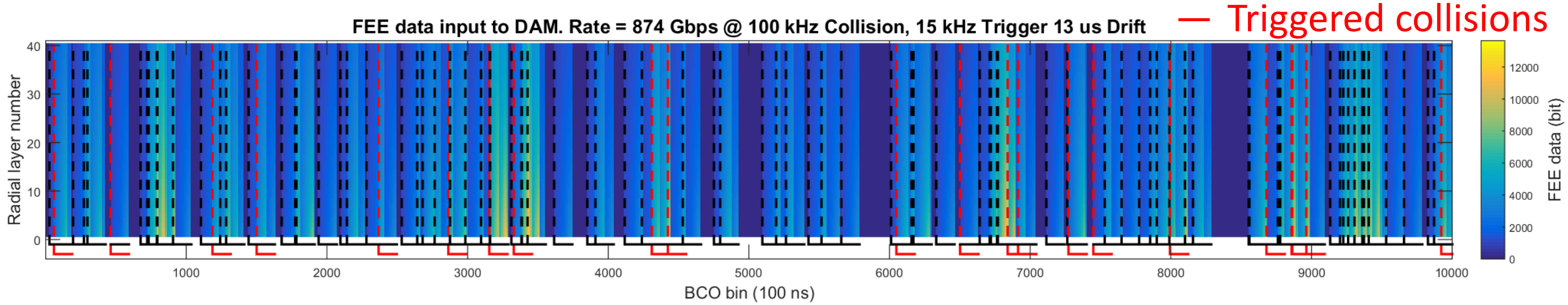
design parameter	eRHIC proton	eRHIC electron	JLEIC proton	JLEIC electron
center-of-mass energy [GeV]	105		44.7	
energy [GeV]	275	10	100	5
number of bunches	1320		3228	
particles per bunch [10^{10}]	6.0	15.1	0.98	3.7
beam current [A]	1.0	2.5	0.75	2.8
horizontal emittance [nm]	9.2	20.0	4.7	5.5
vertical emittance [nm]	1.3	1.0	0.94	1.1
β_x^* [cm]	90	42	6	5.1
β_y^* [cm]	4.0	5.0	1.2	1
tunes (Q_x, Q_y)	.315/.305	.08/.06	.081/.132	.53/.567
hor. beam-beam parameter	0.013	0.064	0.015	0.068
vert. beam-beam parameter	0.007	0.1	0.015	0.068
IBS growth time hor./long. [min]	126/120	n/a	0.7/2.3	n/a
synchrotron radiation power [MW]	n/a	9.2	n/a	2.7
bunch length [cm]	5	1.9	1	1
hourglass and crab reduction factor	0.87		0.87	
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.05		2.1	
integrated luminosity/week [fb^{-1}]	4.51		9.0	

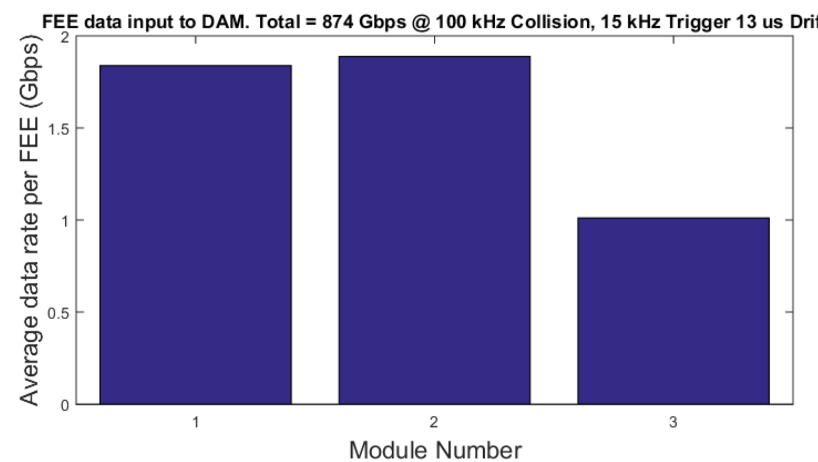
FEE data rate



100kHz collision in continuous DAQ trigger
In TPC DAQ simulation

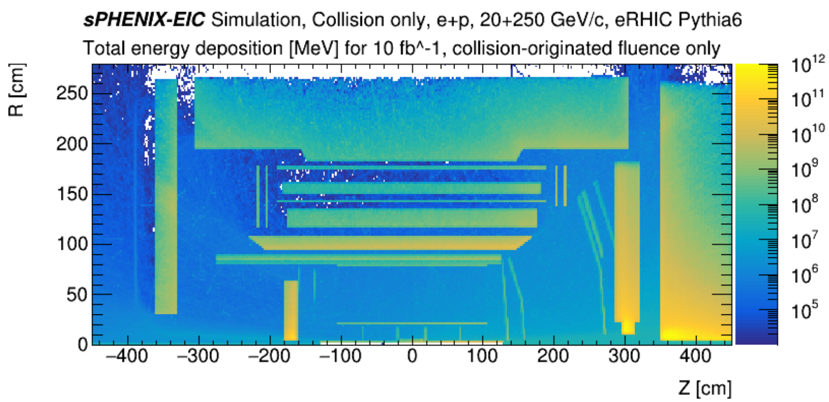
— All collisions
— Triggered collisions

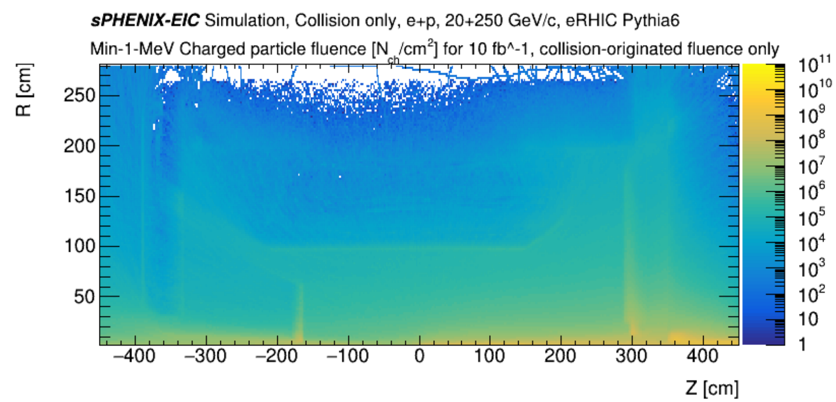


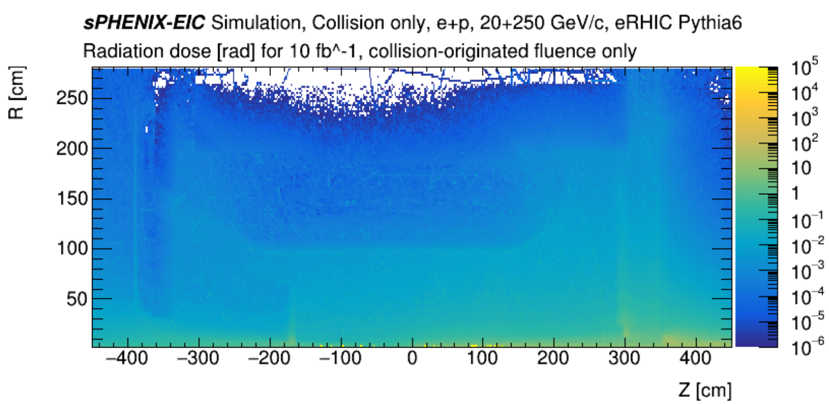


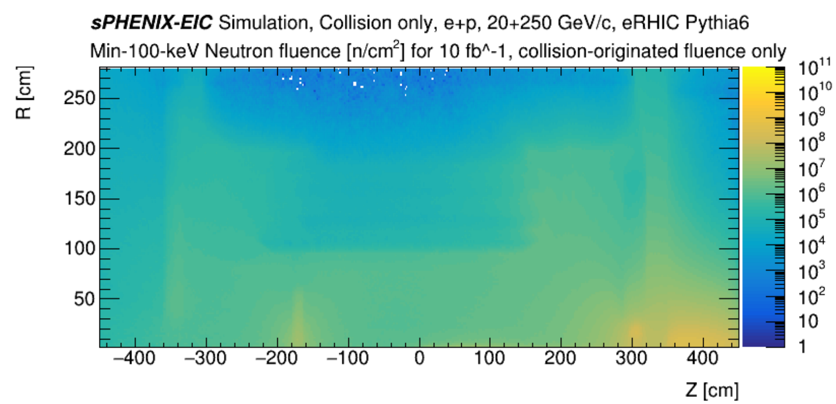
FEE -> DAM limit : 6 Gbps x 8b/10b per FEE
Reference design rate: 1.9 Gbps, far lower than limit
Max rate: 200kHz + 48 rings → max 7.2 Gbps @ module 1

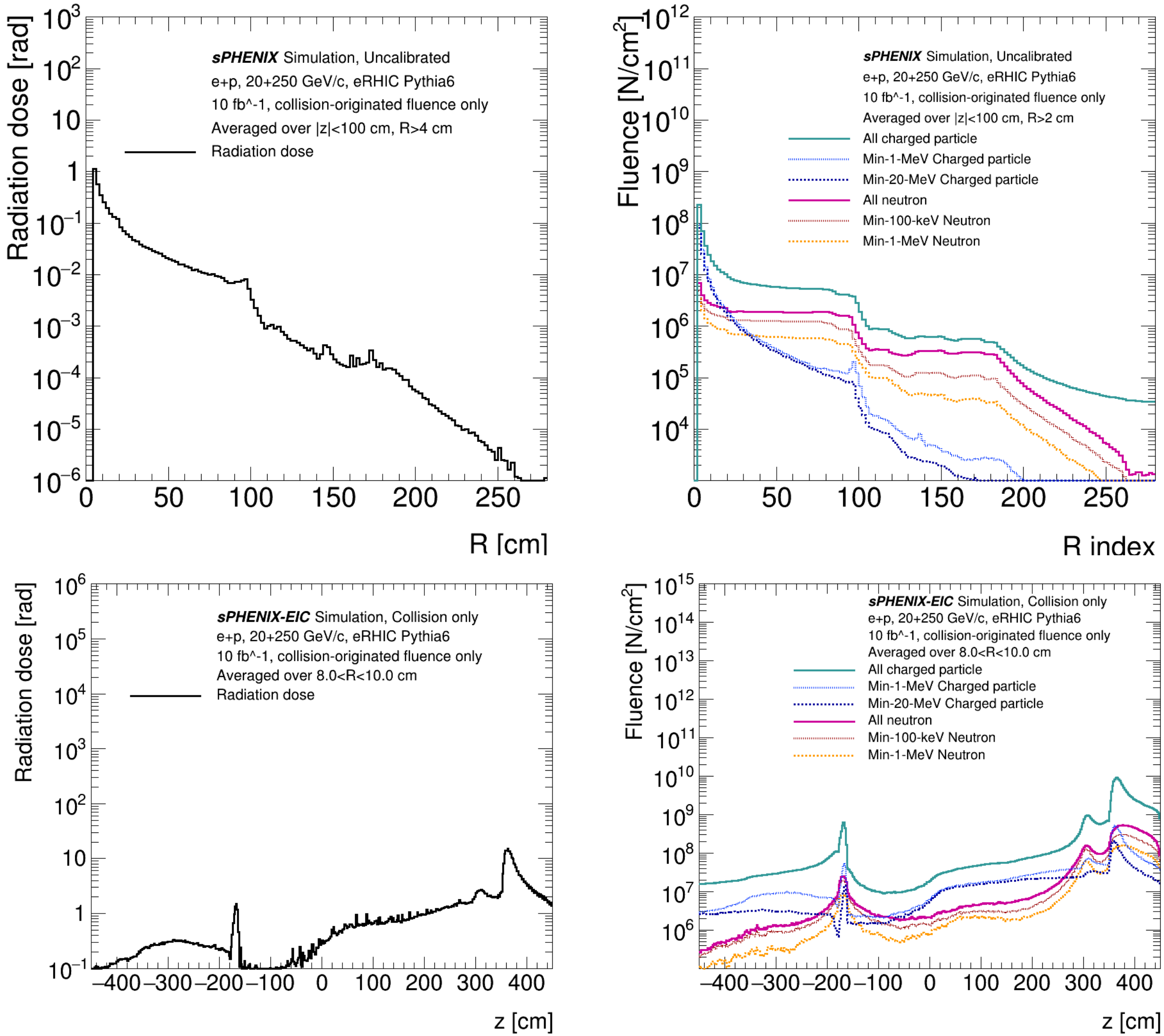
Radiation map










sPHENIX Simulation, Uncalibrated
e+p, 20+250 GeV/c, eRHIC Pythia6
10 fb^-1, collision-originated fluence only
Averaged over |z|<100 cm, R>4 cm
Radiation dose
Radiation dose [rad]
R [cm]
sPHENIX Simulation, Uncalibrated
e+p, 20+250 GeV/c, eRHIC Pythia6
10 fb^-1, collision-originated fluence only
Averaged over |z|<100 cm, R>2 cm
All charged particle
Min-1-MeV Charged particle
Min-20-MeV Charged particle
All neutron
Min-100-keV Neutron
Min-1-MeV Neutron
Fluence [N/cm²]
R index
sPHENIX-EIC Simulation, Collision only
e+p, 20+250 GeV/c, eRHIC Pythia6
10 fb^-1, collision-originated fluence only
Averaged over 8.0<R<10.0 cm
Radiation dose
Radiation dose [rad]
z [cm]
sPHENIX-EIC Simulation, Collision only
e+p, 20+250 GeV/c, eRHIC Pythia6
10 fb^-1, collision-originated fluence only
Averaged over 8.0<R<10.0 cm
All charged particle
Min-1-MeV Charged particle
Min-20-MeV Charged particle
All neutron
Min-100-keV Neutron
Min-1-MeV Neutron
Fluence [N/cm²]
z [cm]