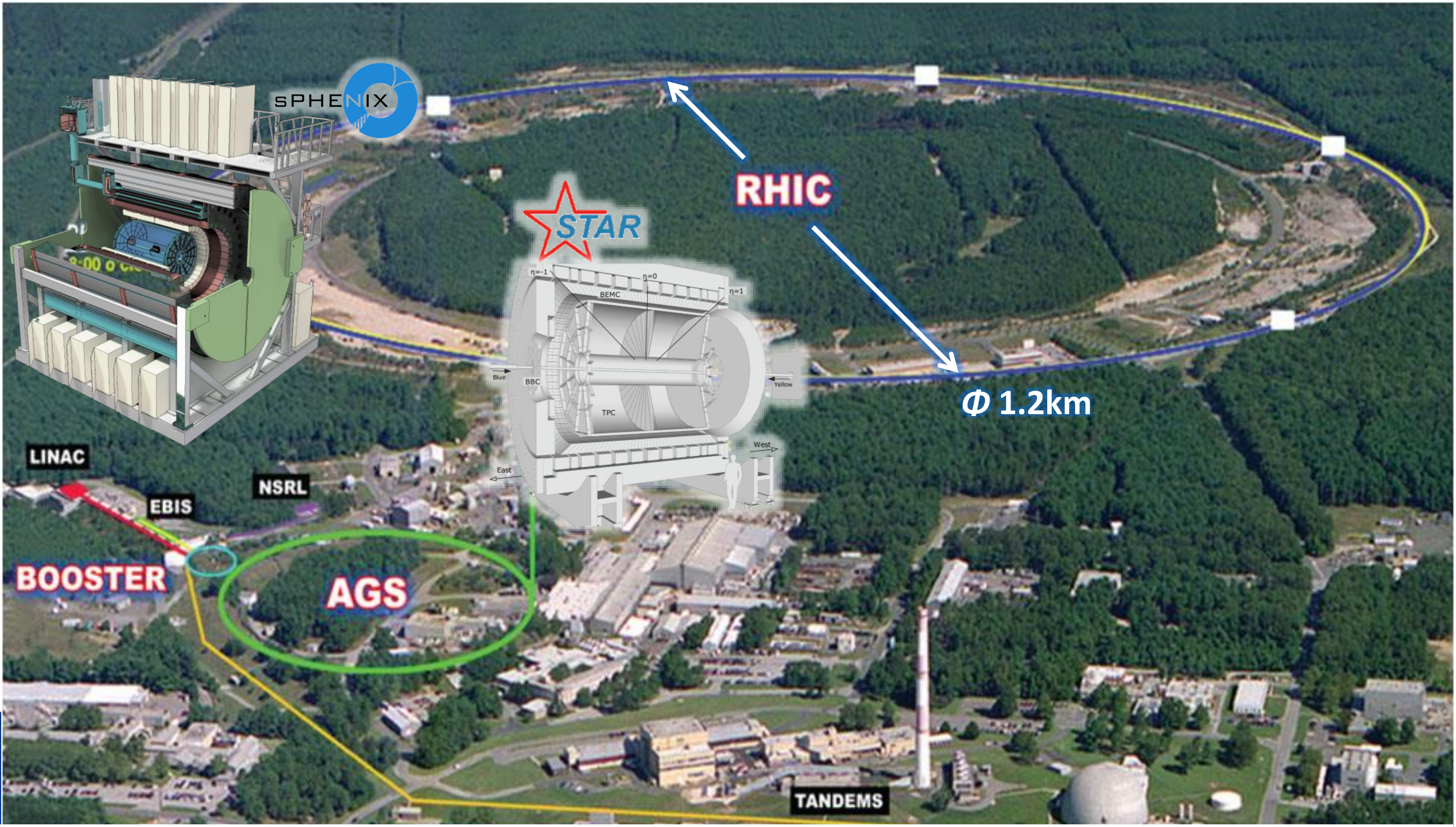
FELIX-based streaming DAQ for EIC

Outline: ● Detector concepts ● Data rate ● FELIX DAQ ● Test stands & Beam tests

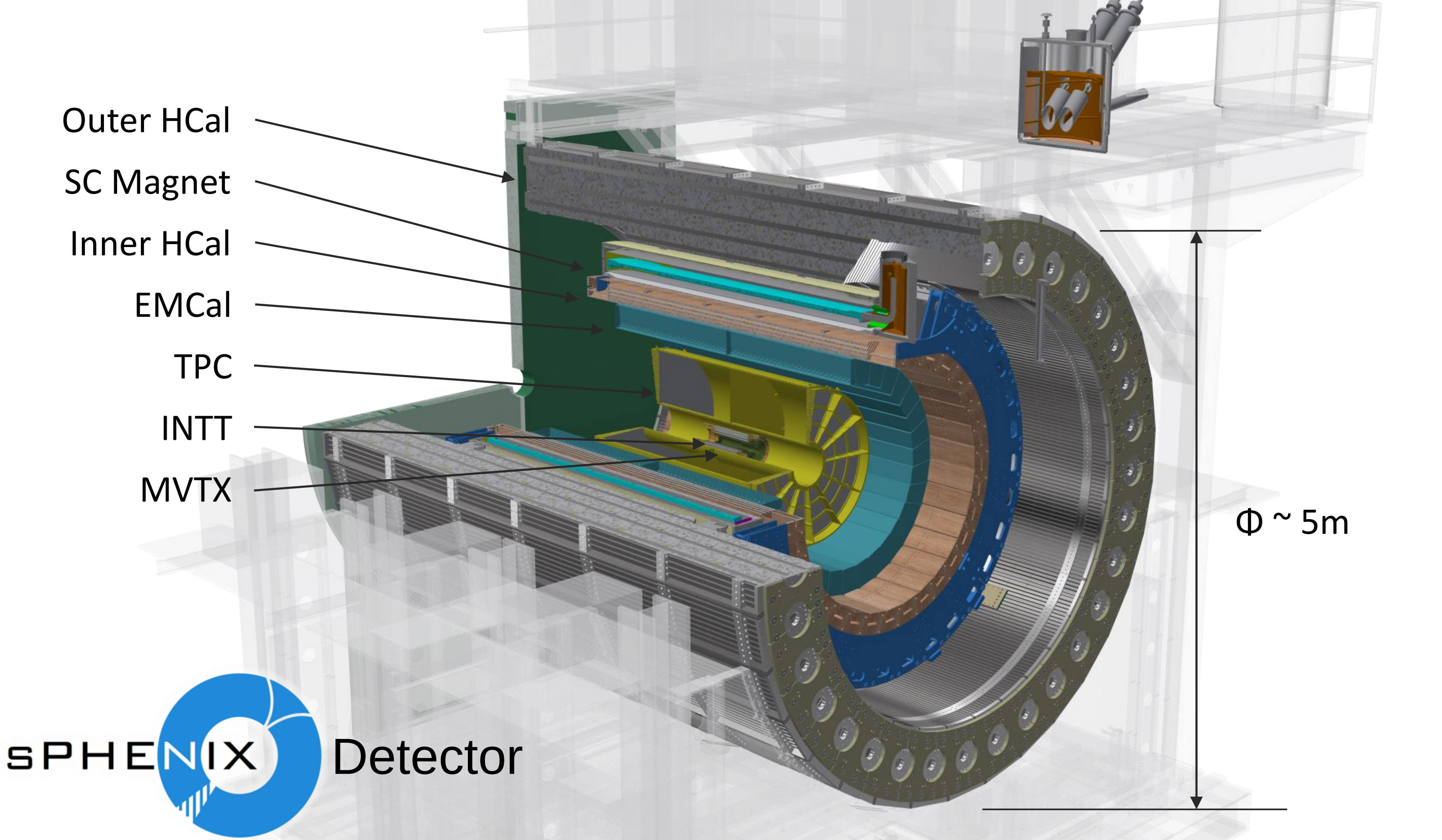
Jin Huang (BNL)

Many thanks to the inputs from
Elke **Aschenauer**, Kai **Chen**, Abhay **Deshpande**, Alexander **Kiselev**, John **Kuczewski**
Tonko **Ljubicic**, David **Morrison**, Christopher **Pinkenburg**, Martin **Purschke**

RHIC @ mid-2020s



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

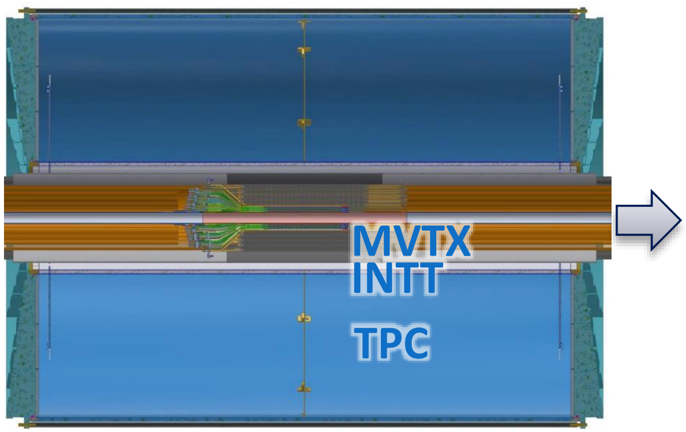


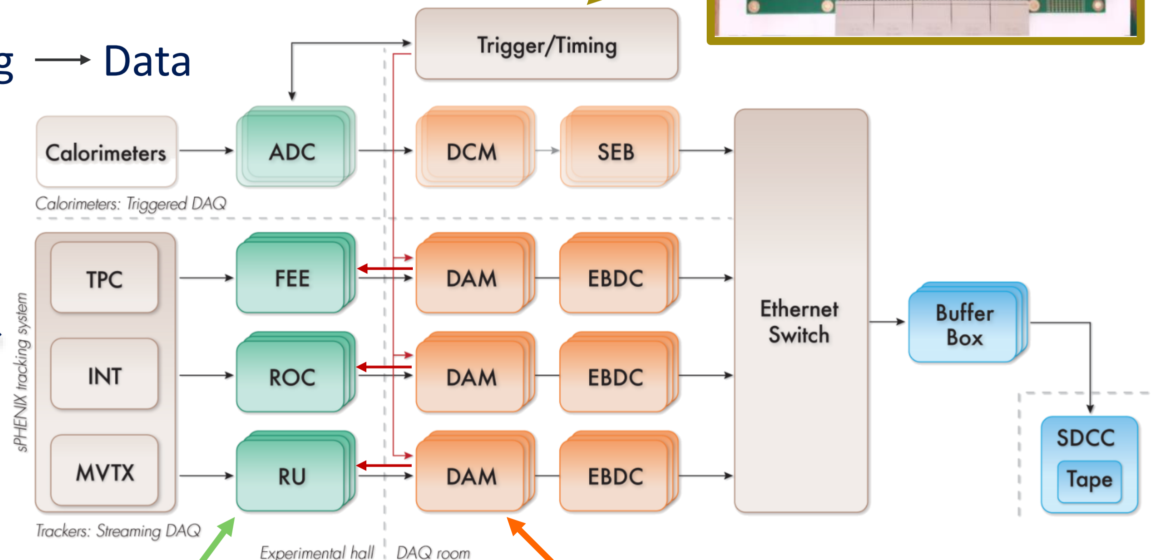
- 2018: Cost/schedule review and DOE approval for production start of long lead-time items (CD-1/3A)
- PD2/3 review next week!
- 2022 installation, 2023: First data

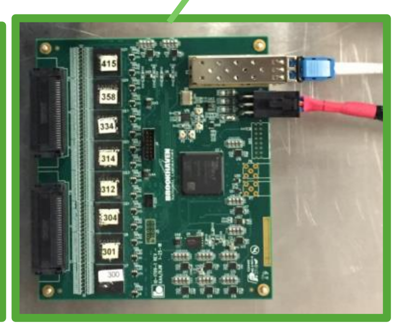
Streaming DAQ concept of sPHENIX trackers

Global Timing Module

← Timing → Data







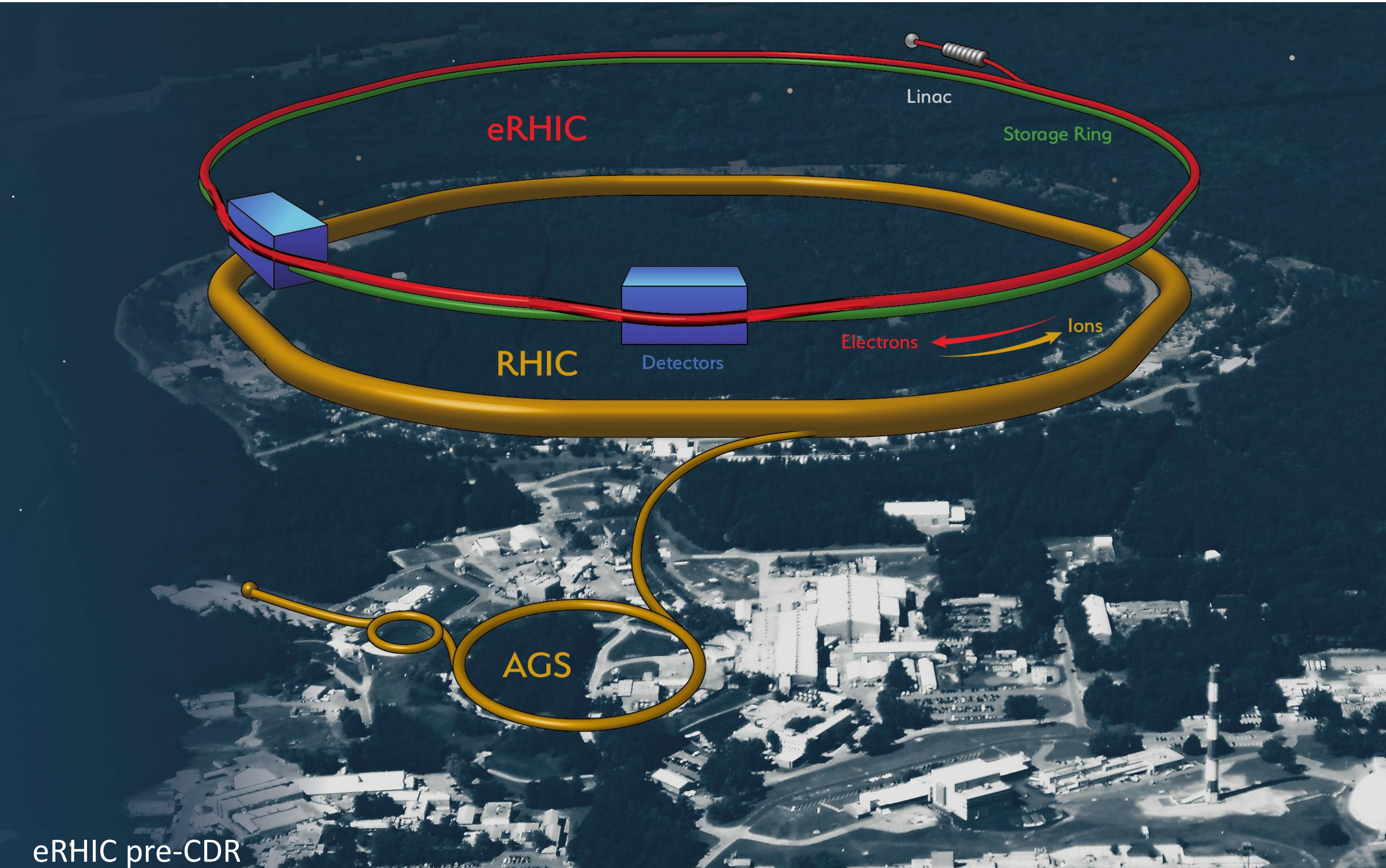
MVTX RU
ASIC: ALPIDE

INTT ROC
FPHX

TPC FEE
SAMPA v4 → v5

BNL-712/FELIXv2 as DAM
Streaming ASIC → DAQ

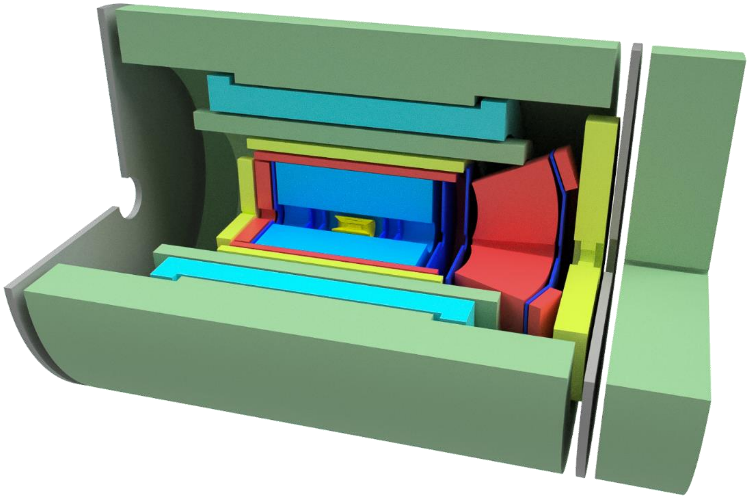
Proposed eRHIC @ end of 2020s



eRHIC pre-CDR

BNL detector concepts

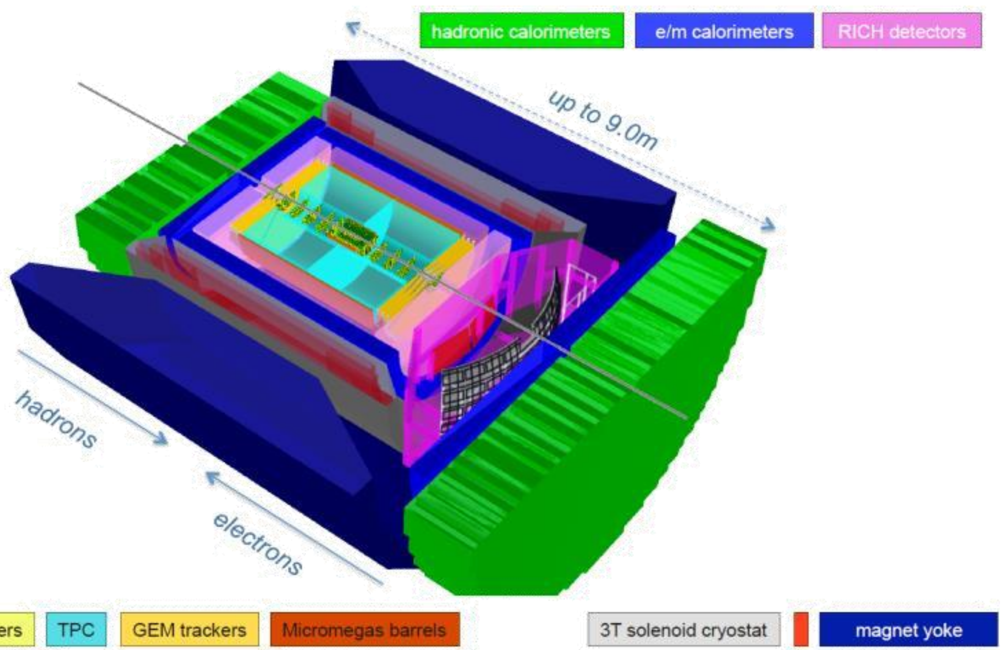
See also TOSIDE, JLEIC concepts in last two talks [Repond, Heyes]



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

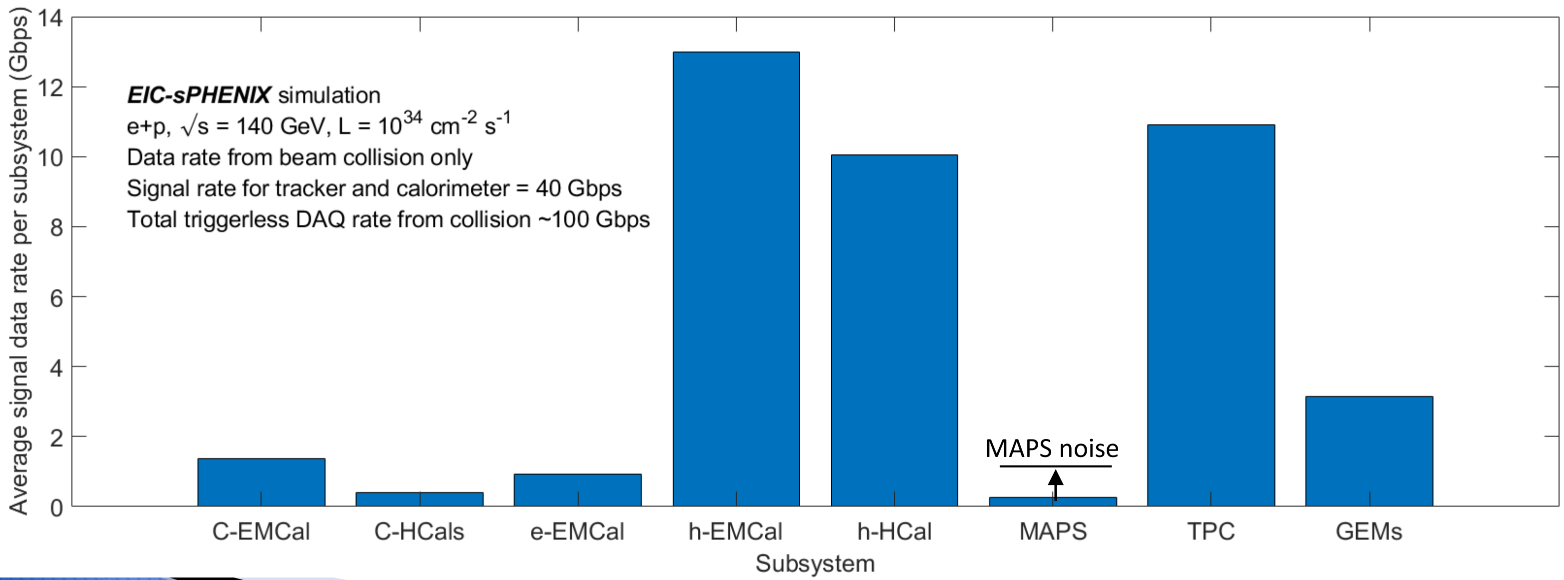
- EIC has lower collision rate and event size is small → signal data rate is low
- But events are precious and have diverse topology
- EIC luminosity is high, so background and systematic control is key

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

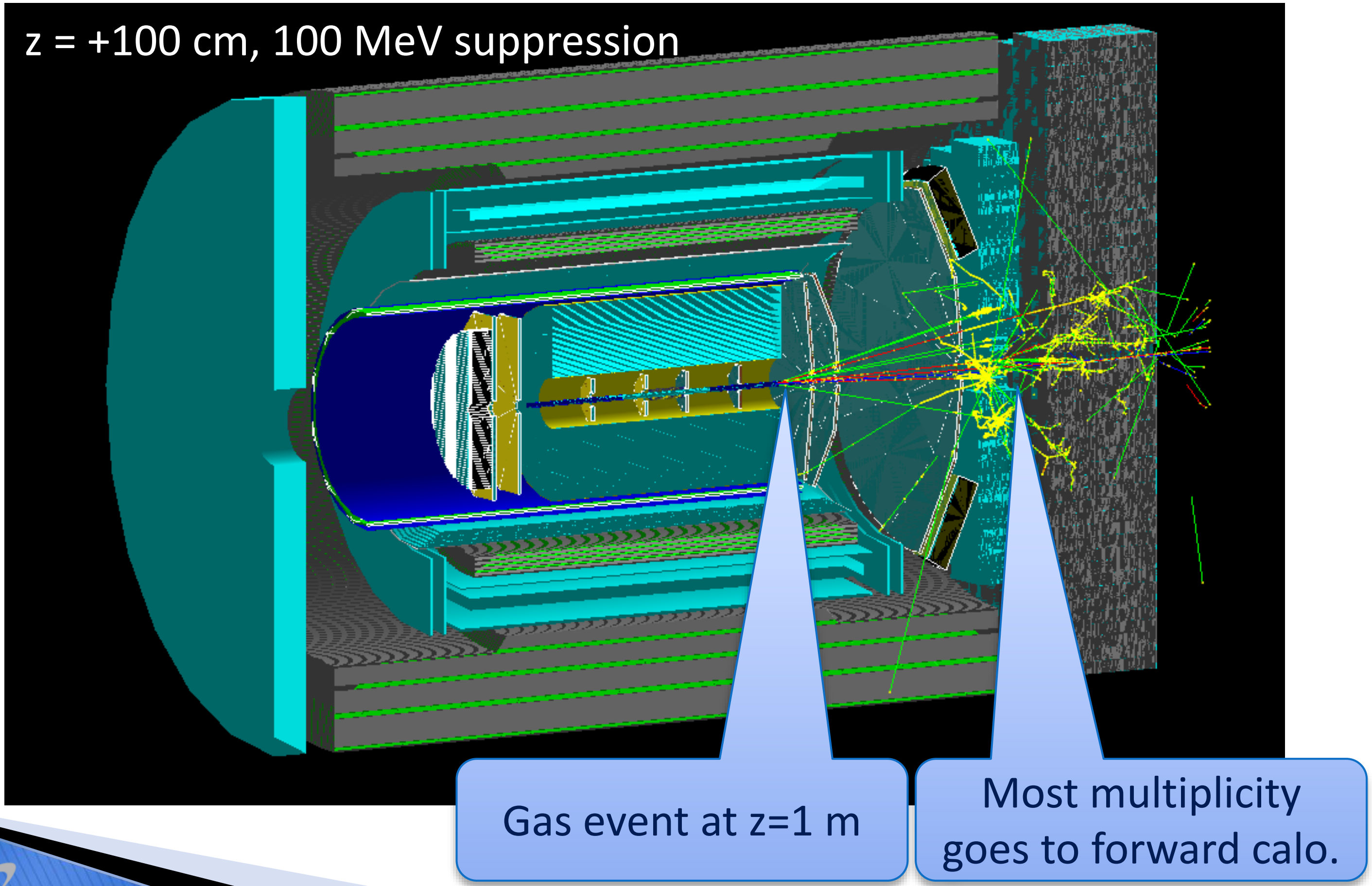
Vacuum pressure	10^{-9} mbar
Beampipe temperature	Room temperature
Average atomic weight of gas	Hydrogen (H^2)
Molecular density (for 10 m pipe)	2.65×10^{10} molecules/cm^2
Luminosity (Ring-Ring)	10.05×10^{33} cm^{-2}s^{-1}
Bunch intensity (R-R) (e/p)	15.1 / 6.0×10^{10}
Beam Current (R-R) (e/p)	2.5 /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

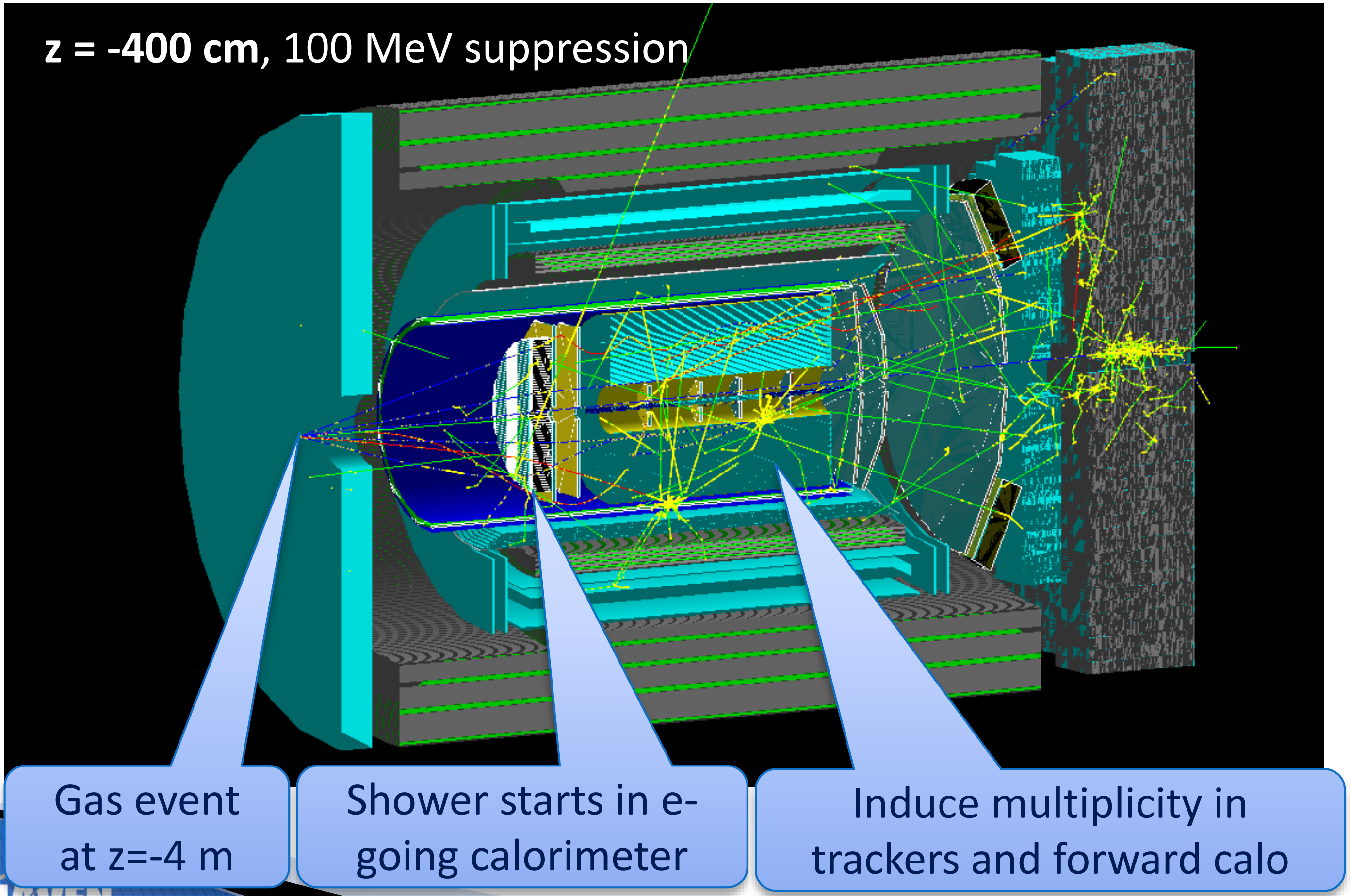
- 250 GeV proton beam on proton beam gas, sqrt[s] ~ 22 GeV
- For this illustration, use pythia-8 very-hard interaction event (q^hat > 5 GeV/c)



Beam gas event in a detector (downstream)

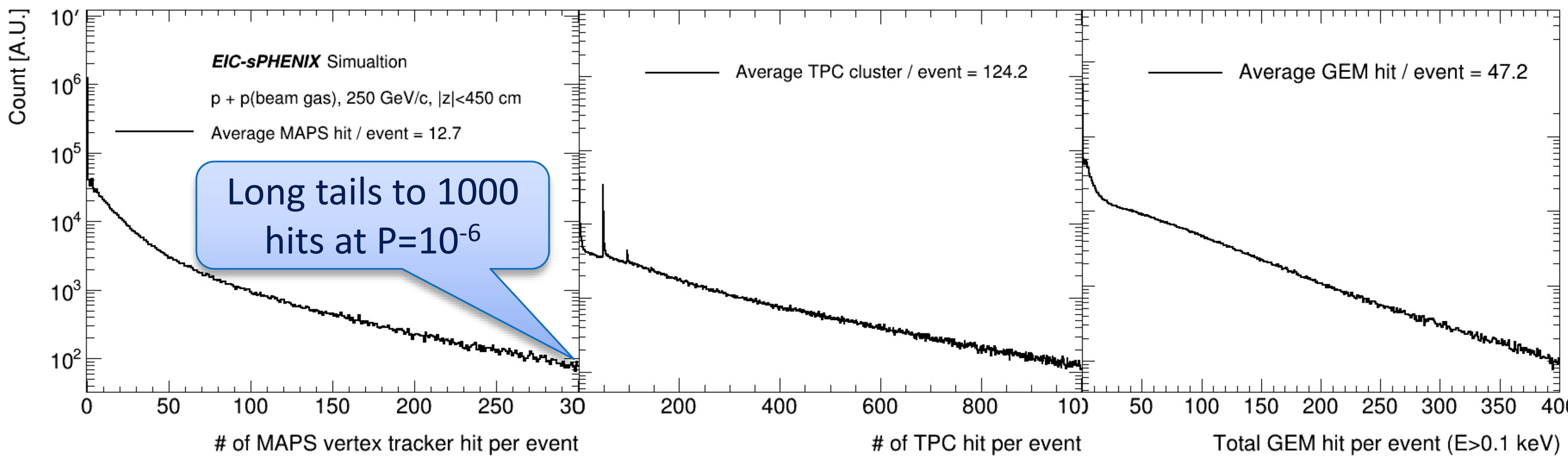
Simulation: https://github.com/sPHENIX-Collaboration/singularity

- 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

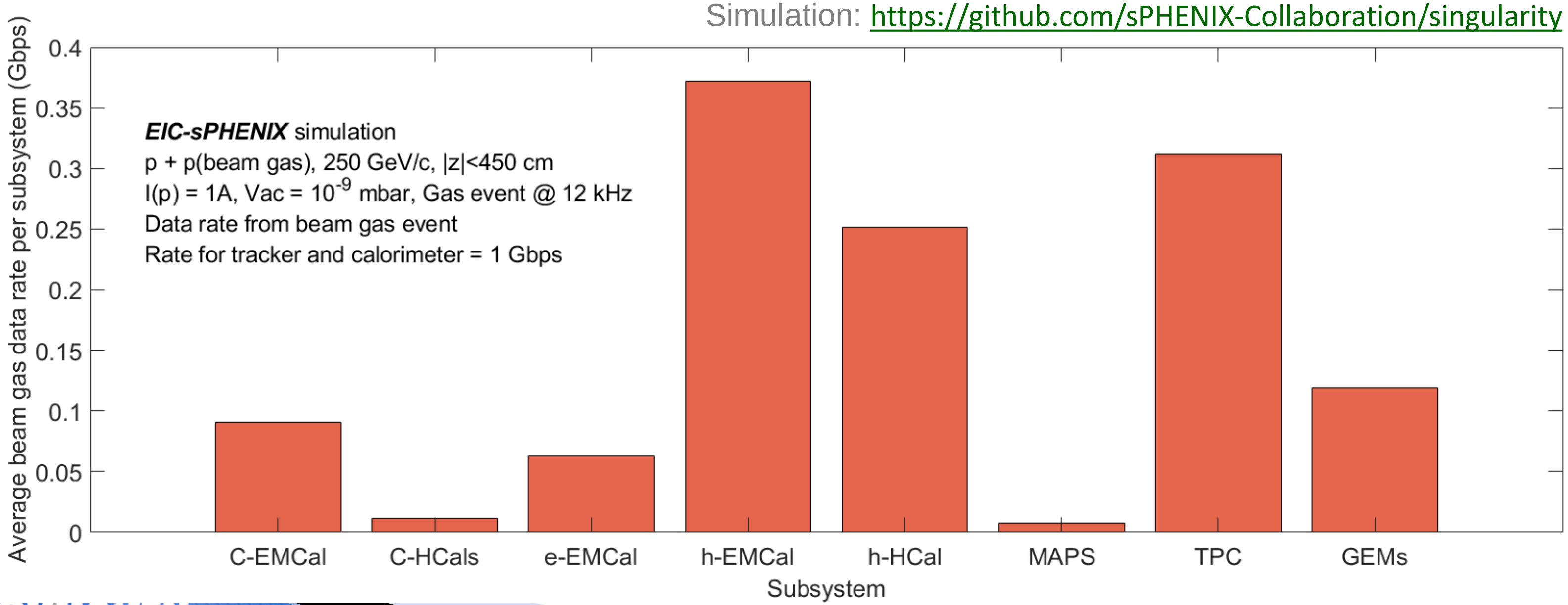
Raw data:
3 (strip) x5(time)x 10 bit / TPC hit
+ headers (60 bits)

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)

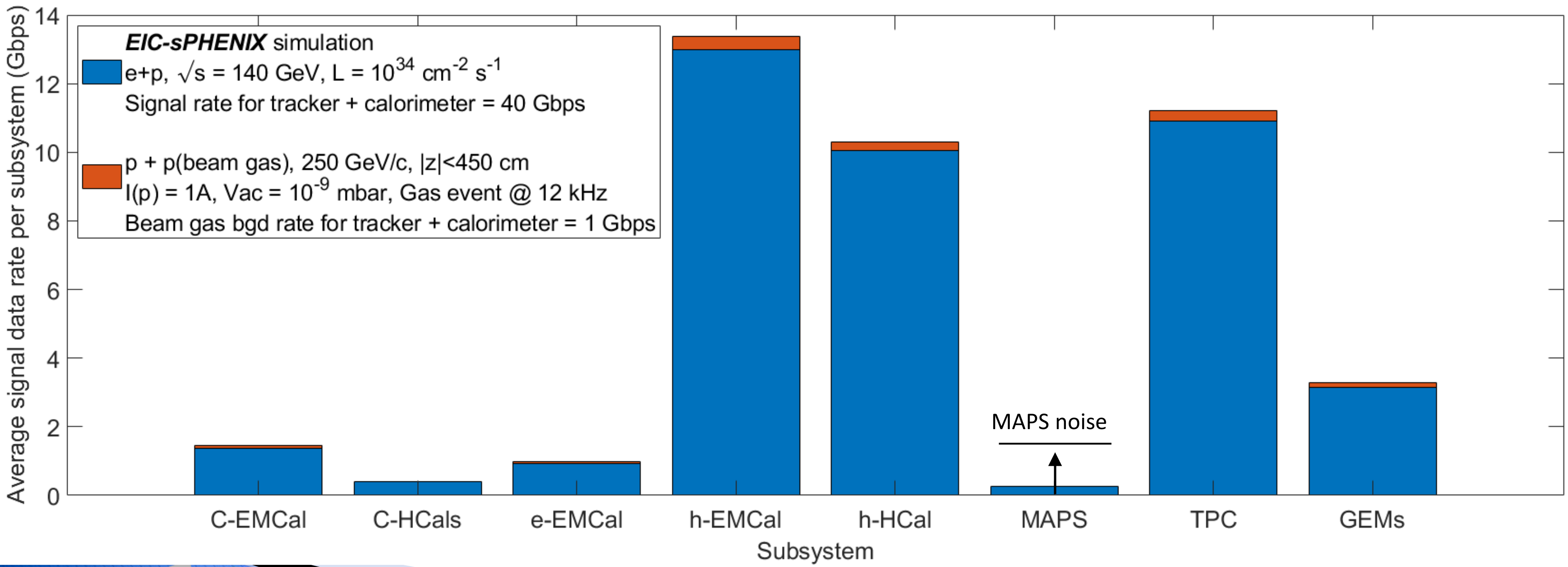
Simulation: https://github.com/sPHENIX-Collaboration/singularity



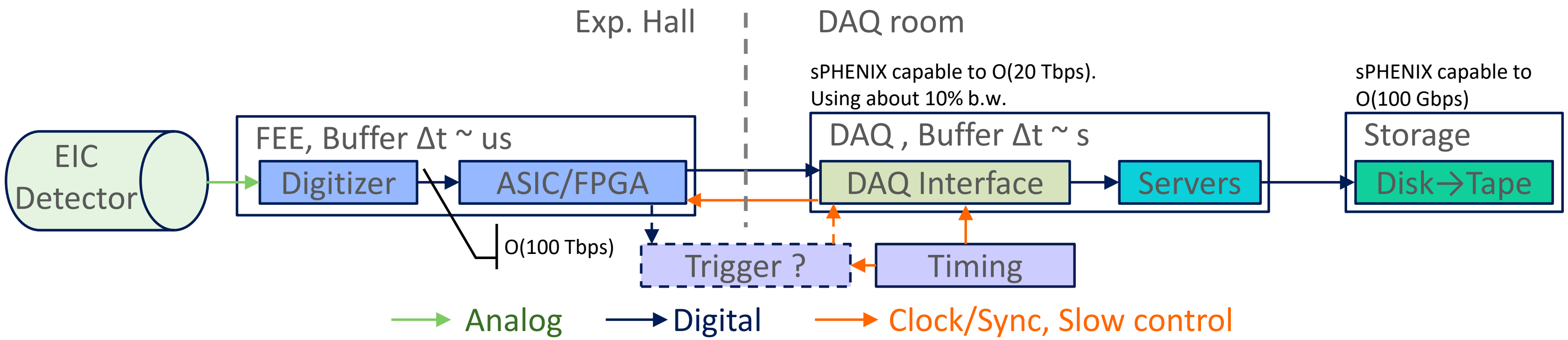
Data rate: sum together

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



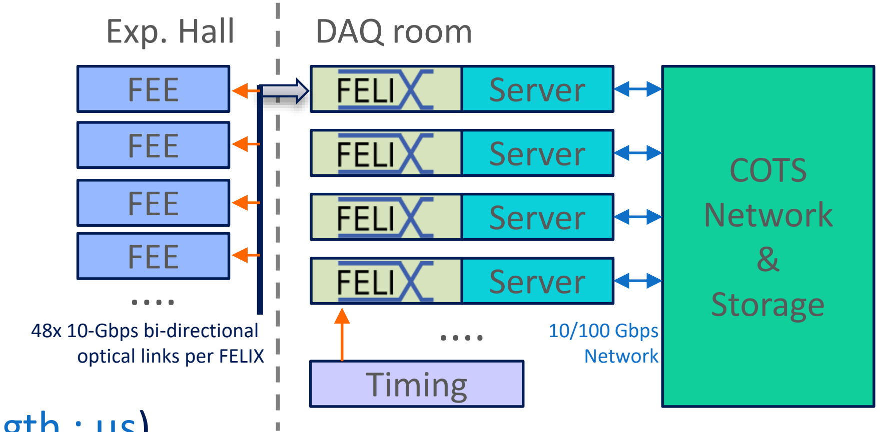
Strategy for an EIC real-time system



- 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

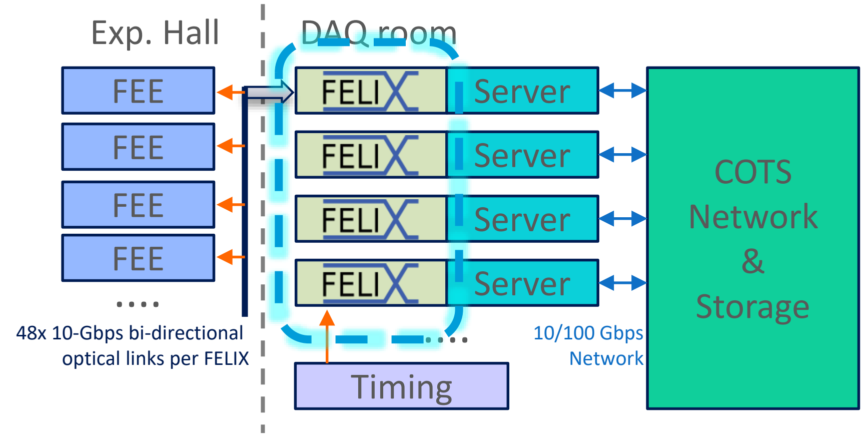
sPH-cQCD-2018-001
https://indico.bnl.gov/event/5283/



- 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

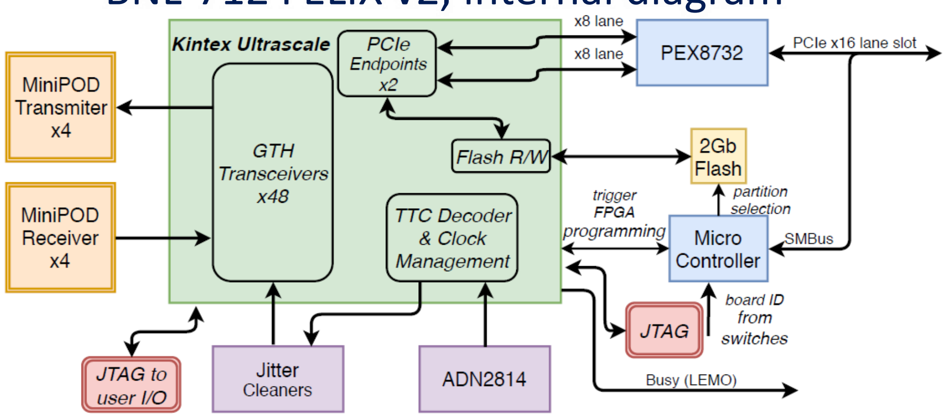
Front-End LInk eXchange (FELIX)

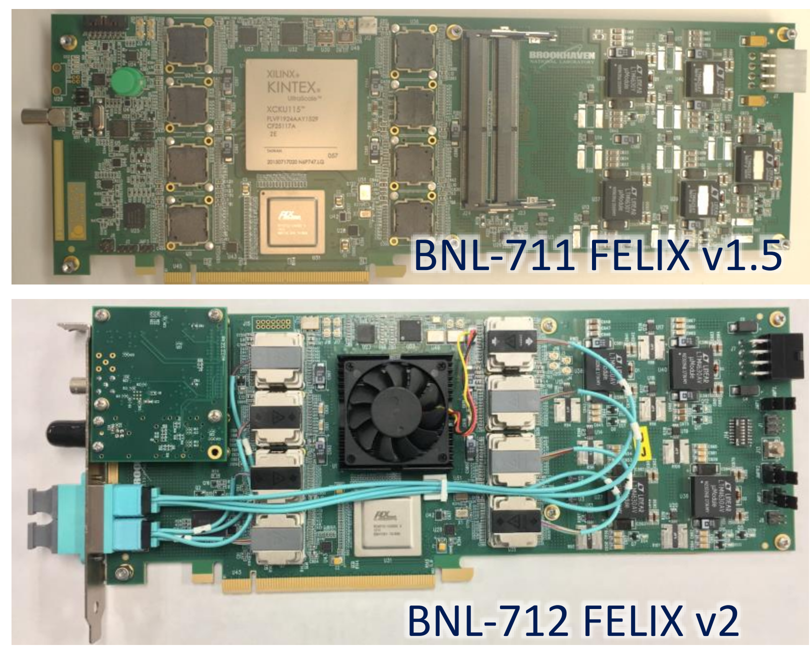
- FELIX: DAQ interface card initially developed for ATLAS Phase 1 upgrade and beyond
  - Similar architecture have wide support in 2020+ for high throughput DAQ e.g. ATLAS, ALICE, LHCb, CBM, Proto-DUNE
- Future versions concepts supporting 48x 25Gbps transceivers and PCIe Gen4



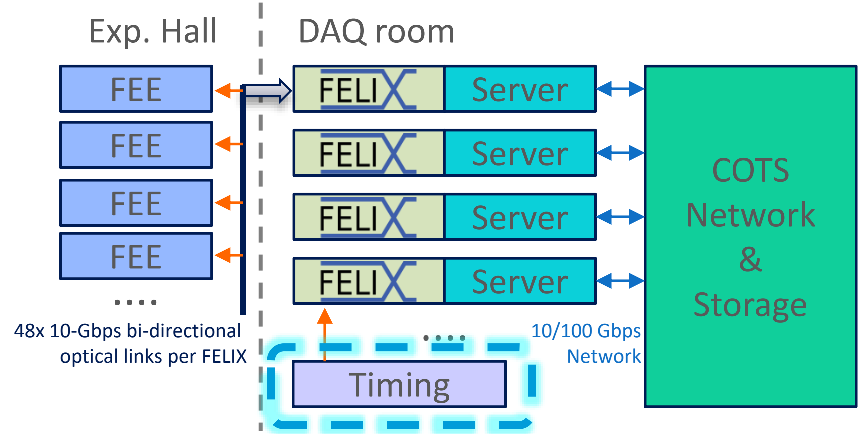
[K. Chen et al, submitted to TIM]

BNL-712 FELIX v2, internal diagram

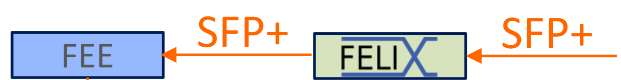




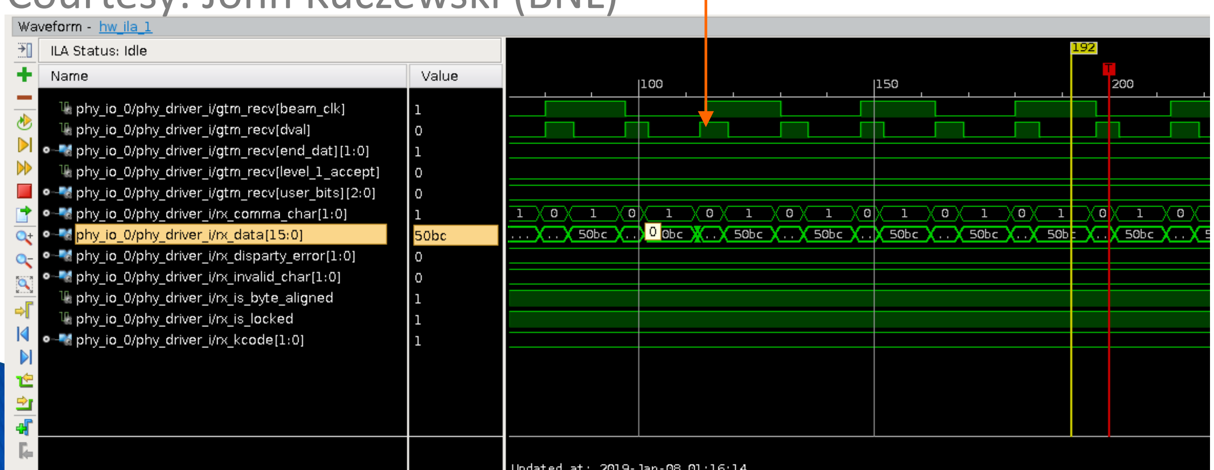
Timing



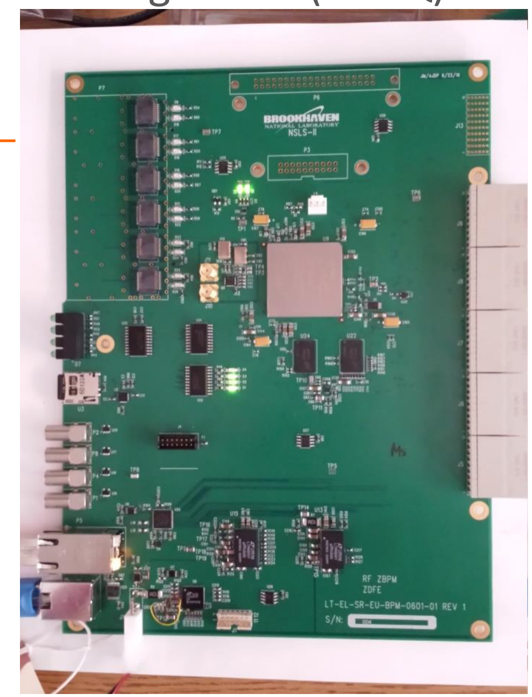
- All FEE & FELIX synchronized to collider collision clock
- Broadcast 64b-clock counter and validate synchronization
- Timing prototype
  - Zynq-based timing system board with multiple SFP+ links
  - Demonstrated SFP+ based timing link at 112.8 MHz



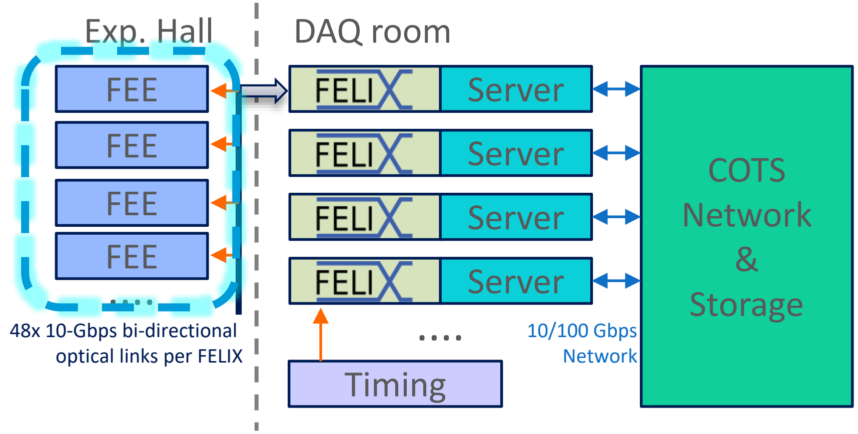
Courtesy: John Kuczewski (BNL)



Timing board (ZYNQ)

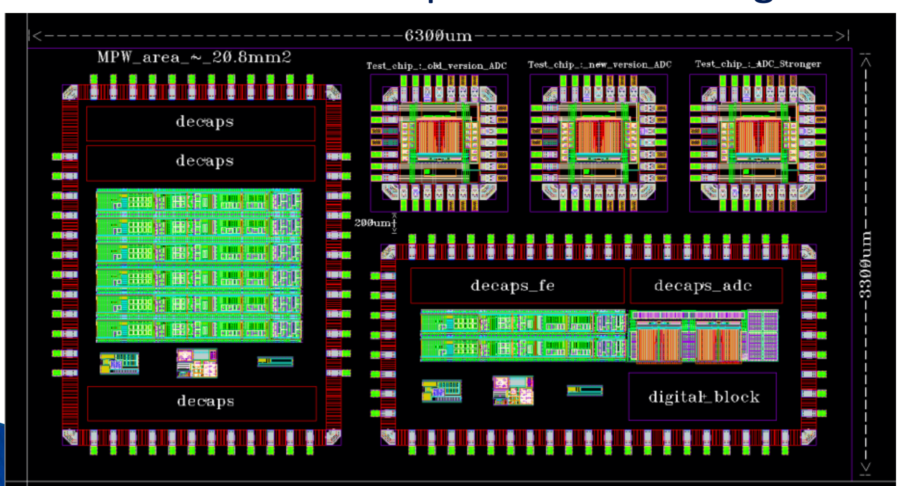


Streaming frontend

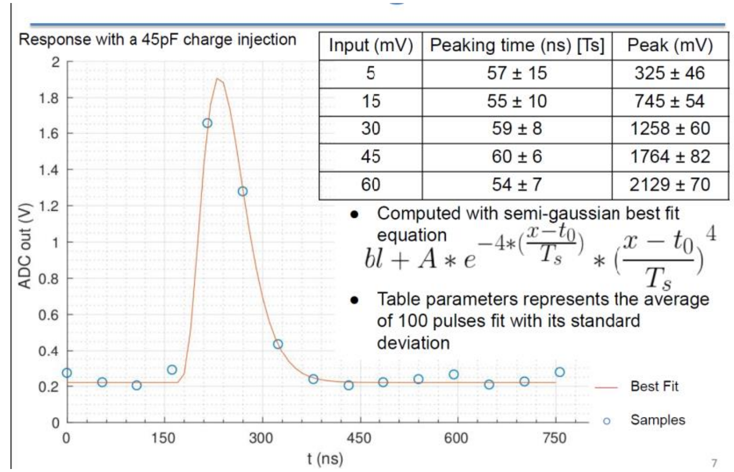


- Streaming ASIC in prototyping: ALPIDE, FPHX, SAMPA
- Generic SFP+ and Versatile link support
- sPHENIX version of SAMPA with 80ns-shaping in development
  - Based on ALICE development

80ns SAMPA components in testing



Analog + ADC data at USP



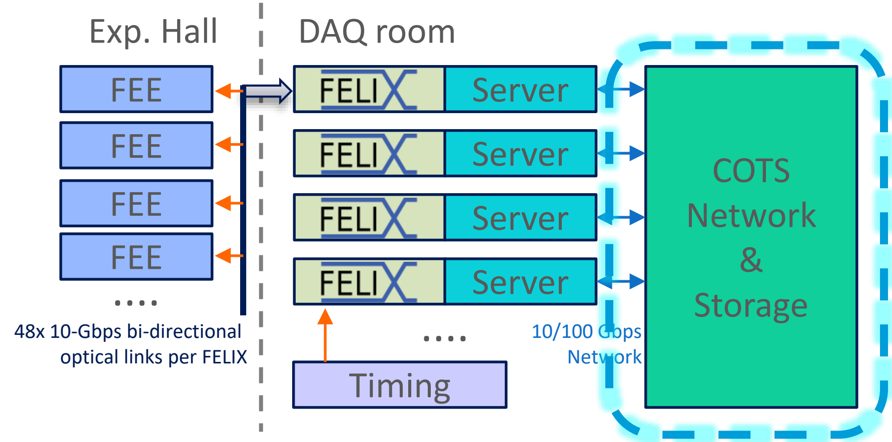
Input (mV)	Peaking time (ns) [Ts]	Peak (mV)
5	57 ± 15	325 ± 46
15	55 ± 10	745 ± 54
30	59 ± 8	1258 ± 60
45	60 ± 6	1764 ± 82
60	54 ± 7	2129 ± 70

- 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

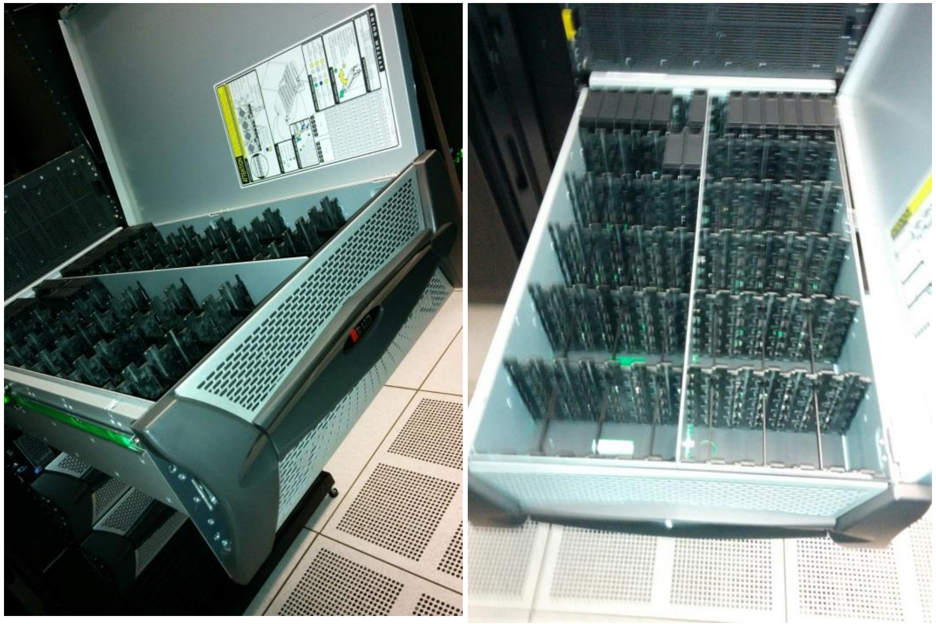
Online Storage

- 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



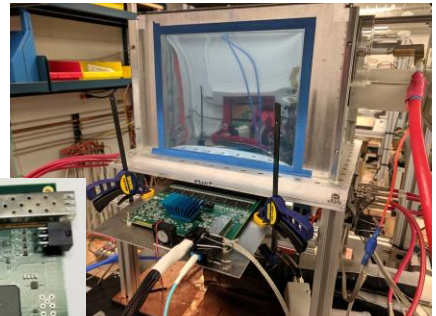
COTS storage server, hosting ~100 disk slots



Courtesy: Martin Purschke (BNL)

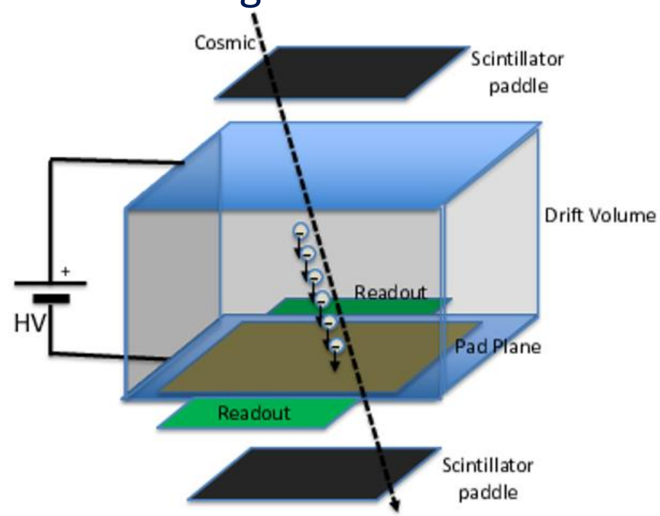
Test stands: SAMPA for EIC RD GEM tracker

eRD6 TPC HBD

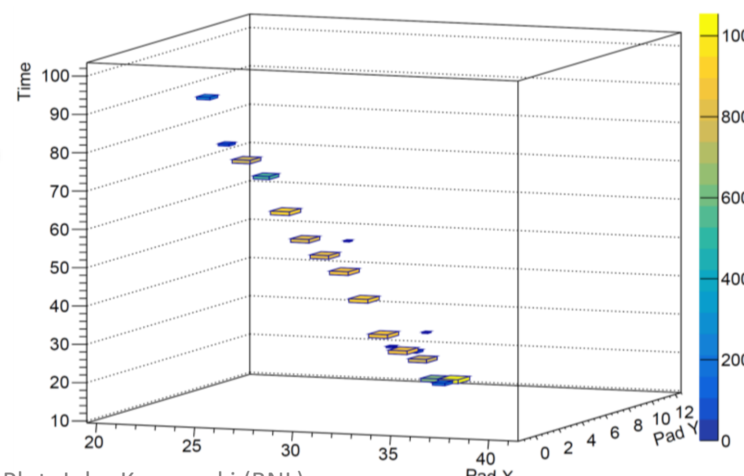


8x SAMPA FEE
256 ADC/FEE

Cosmic through mini-TPC test stand



Reconstructed GEM hits from SAMPA data



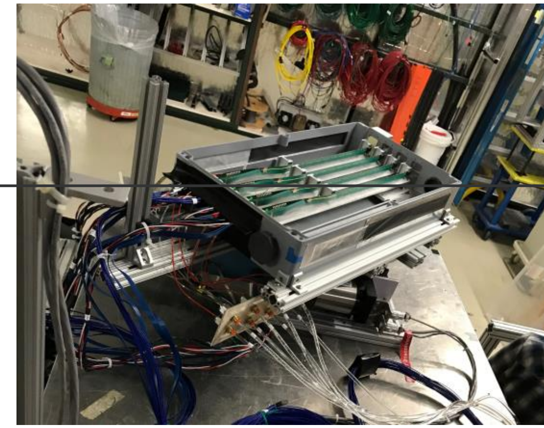
Plot: John Kuczewski (BNL)

Beam test: MAPS silicon tracker (on-going)

Supported by
LANL LDRD

Readout Unit
4.5M pixel/RU

ALPIDE MAPS tracker in test beam

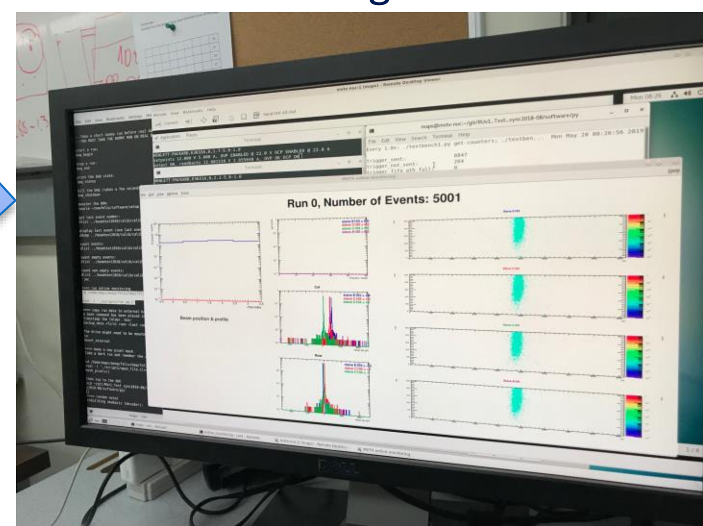


120 GeV p

FELIX v2 DAQ interface

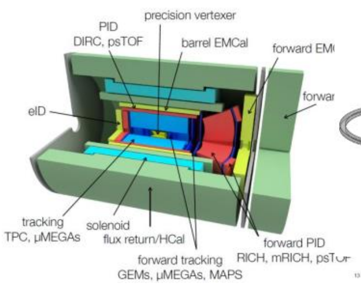
Commodity server

Online monitoring of silicon hits

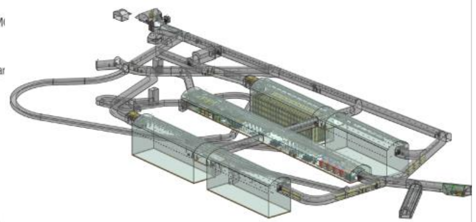


LDRD 19-028: Common development using FELIX DAQ

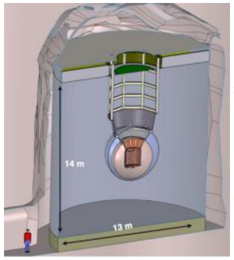
EIC detectors



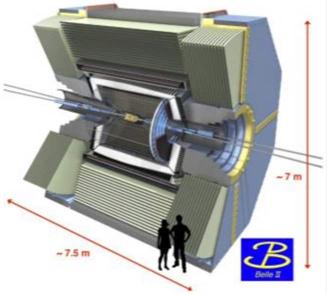
DUNE far detector



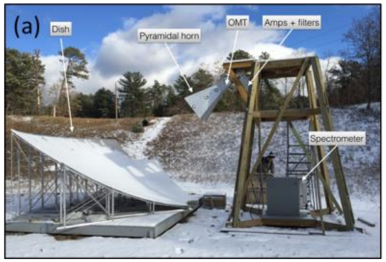
nEXO



BELLE-II



21-cm digital interferometer



- Producing FELIX cards in two productions
  - Possible to support additional EIC-oriented test stands
- Position openings for high speed DAQ developer
  - Multiple openings in senior and junior high speed DAQ developers in both Physics Department and Instrumentation Division
  - Applications and questions welcomed: https://jobs.bnl.gov/search-jobs?orgIds=3437&ac=18928

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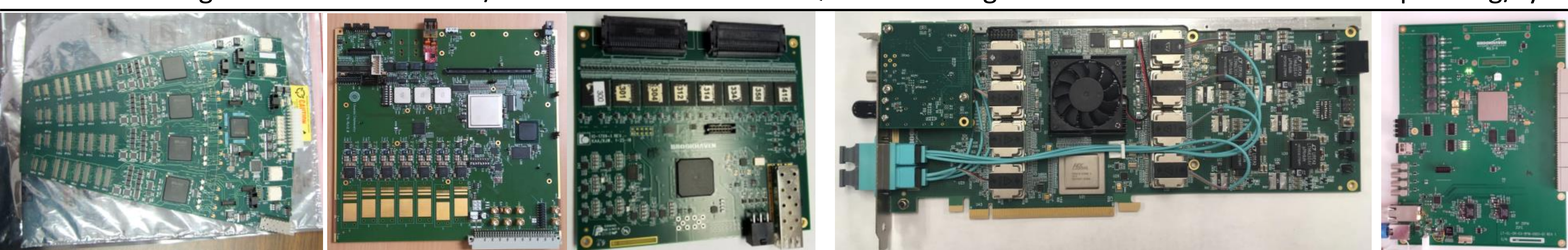
Summary

- sPHENIX will use a hybrid DAQ joining streaming tracker and triggered calorimeters
- Data rate estimated for the EIC detector, which defines the EIC DAQ strategy: at 100 Gbps collision signal rate, possible to stream record all
- FELIX-type DAQ architecture fits EIC purpose.
  - Similar architecture have wide support in 2020+ for high throughput DAQ e.g. ATLAS, ALICE, LHCb, CBM
  - Deterministically bridging custom front-end with commodity computing
- Welcome to joint R&D for EIC DAQ

FPHX streaming front-end for PHENIX/sPHENIX | FELIX DAQ chain reading out EIC GEM detectors | Exp timing/sync



Extra Slides

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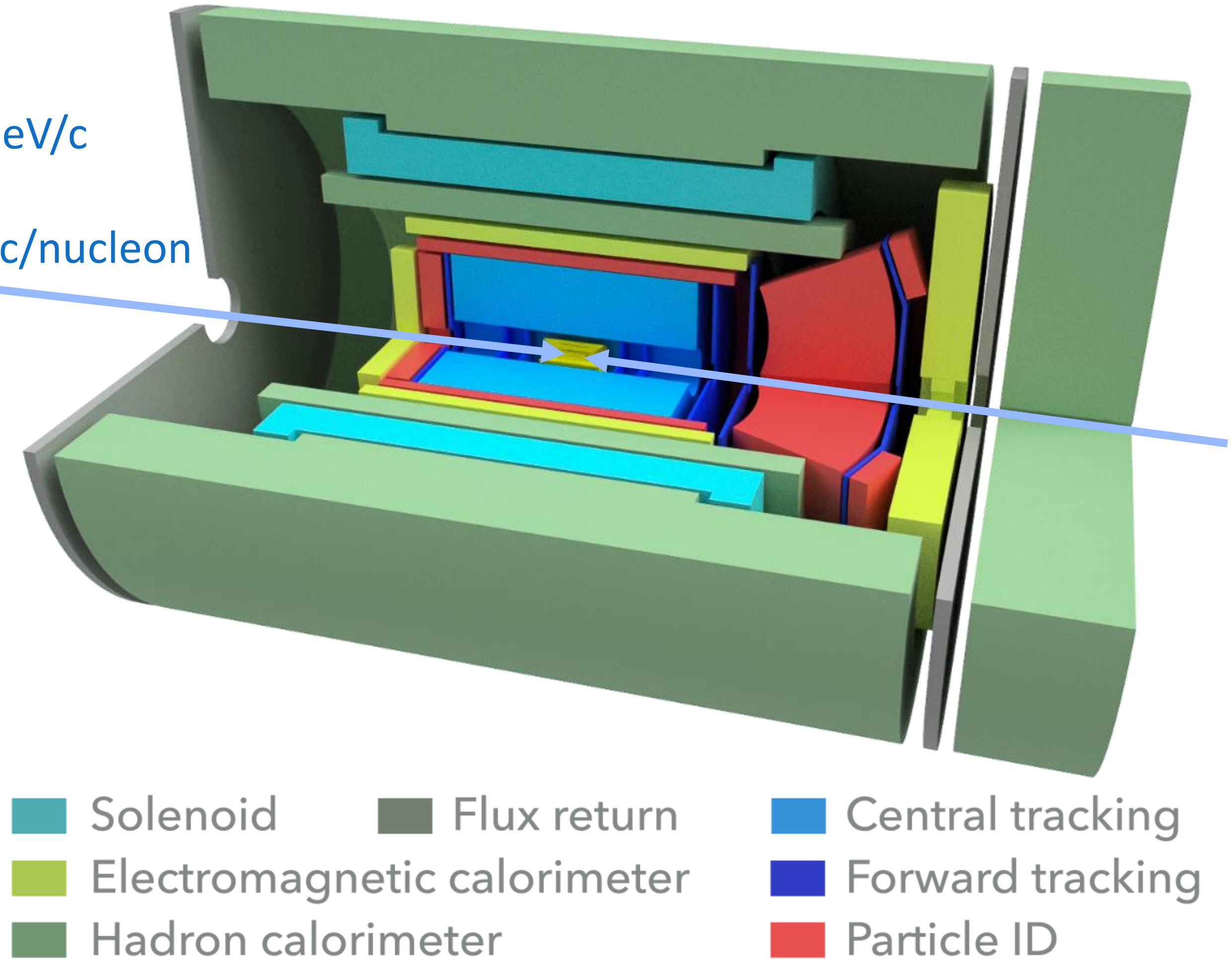
Example: sPHENIX-based EIC detector

- 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

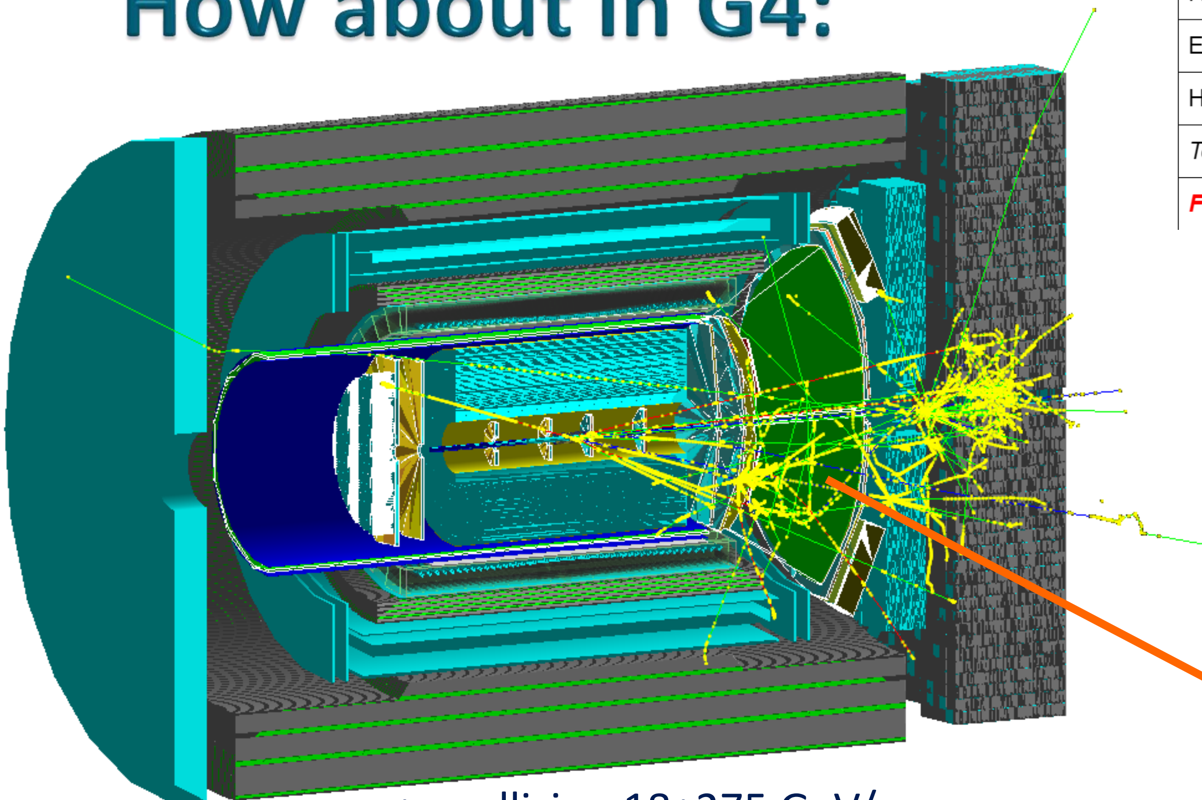
@ 10^{33} cm^{-2} s^{-1}, 200kHz collision

How about in G4:

Tonko's estimation (2015)

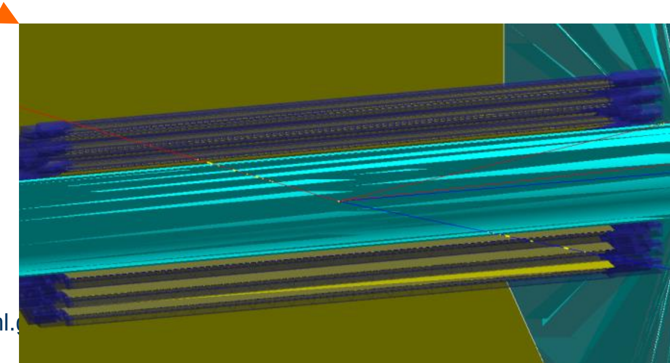
The eRHIC Detector ("BeAST") Readout Scheme

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

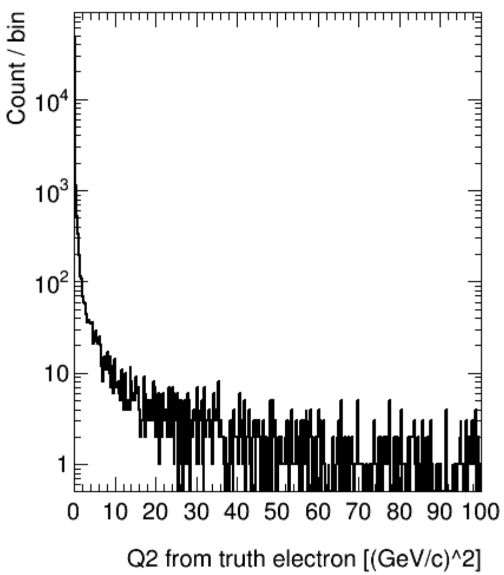
DIS @ Q^2 ~ 100 $(GeV/c)^2$

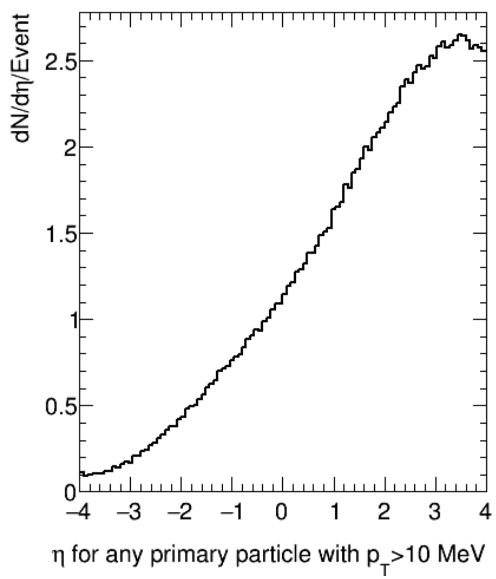


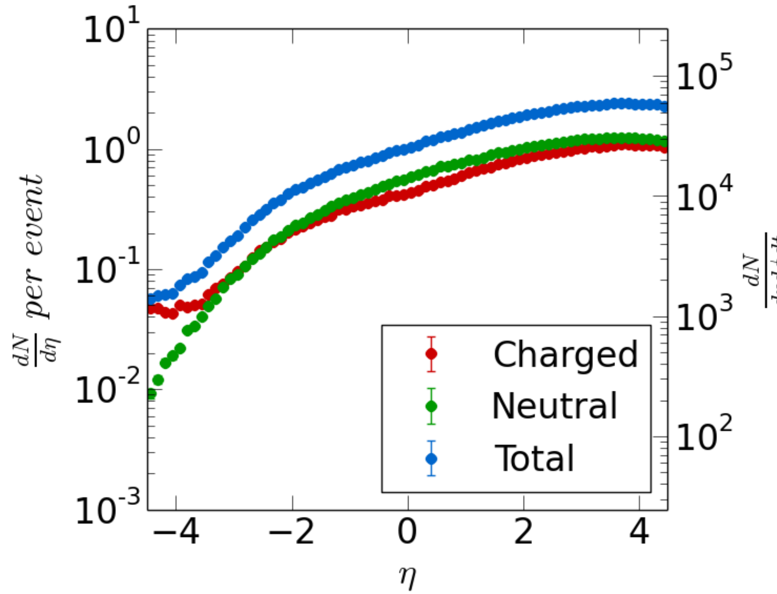
Full detector "Minimal bias" EIC events in sPHENIX framework: quick first look

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







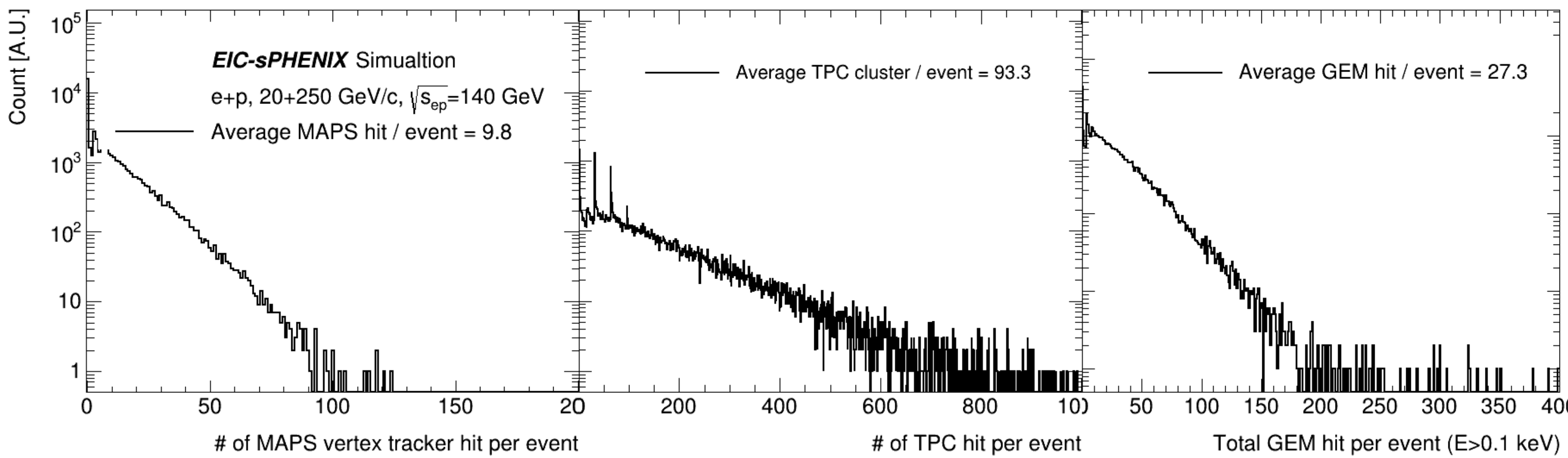
Based on BNL EIC task-force eRHIC-pythia6 55ub sample

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

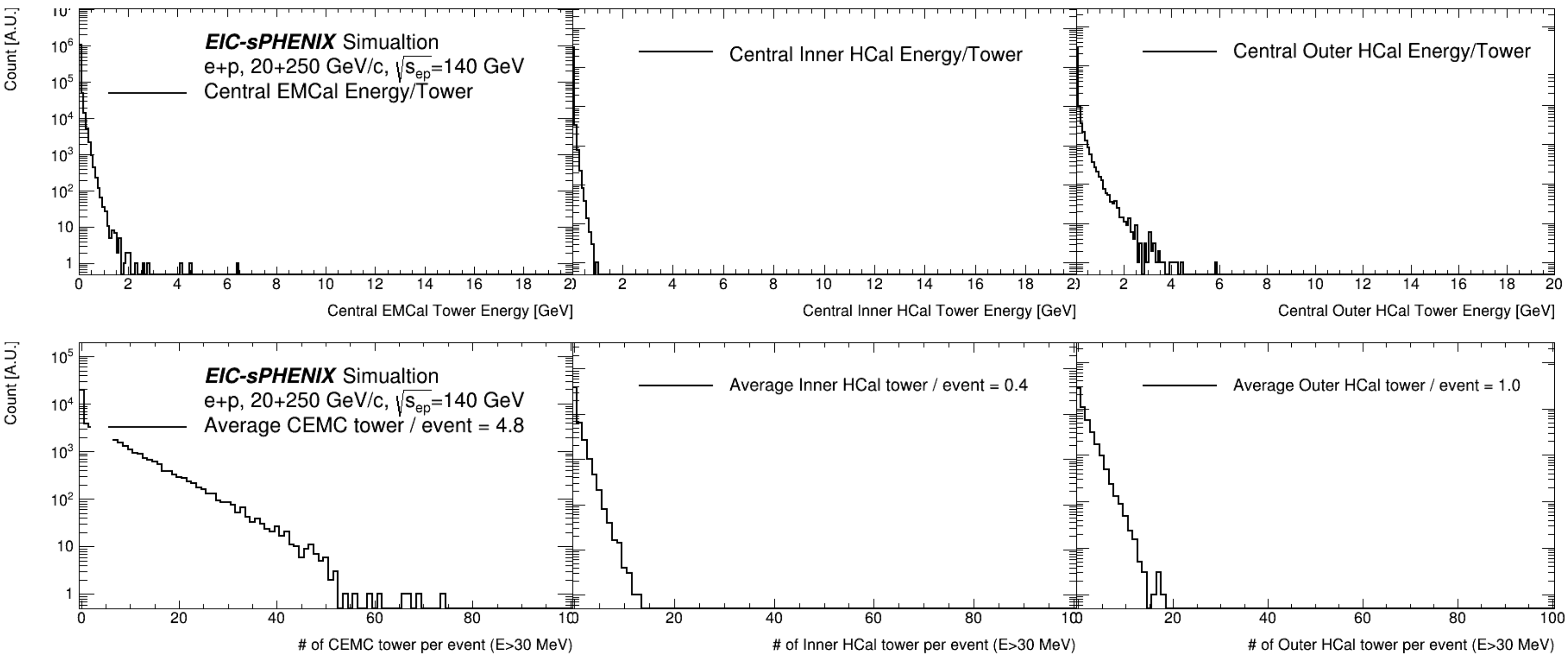
- MAPS is vulnerable to beam background see later slides
- ALPIDE MAPS noise are low, expect 10^{-6} /pixel/strobe, 200M pixel, 3us strobe → ~1Gbps

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

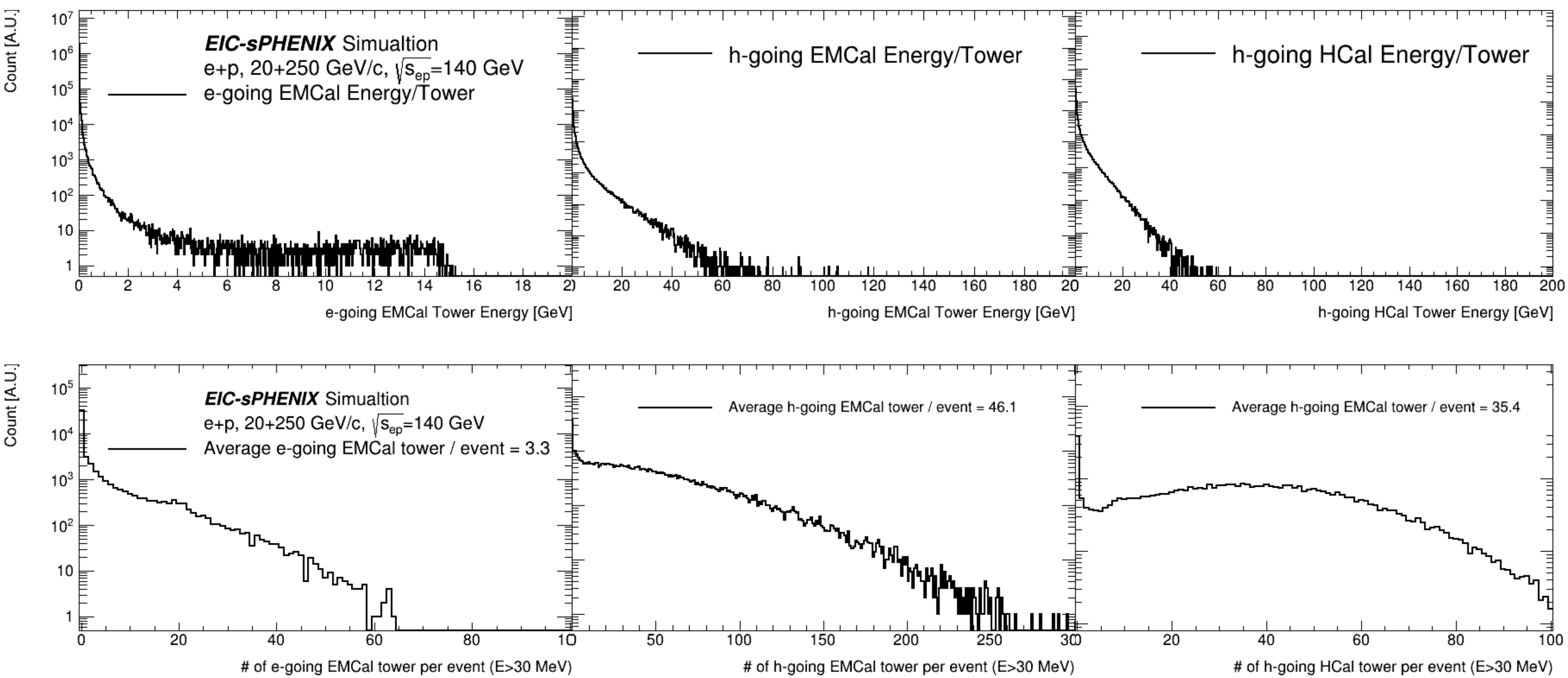
Raw data: 31x 14 bit / active tower +padding + headers ~ 512 bits / active tower



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

GEANT4-based detector simulation for DAQ simulation: forward calorimeters

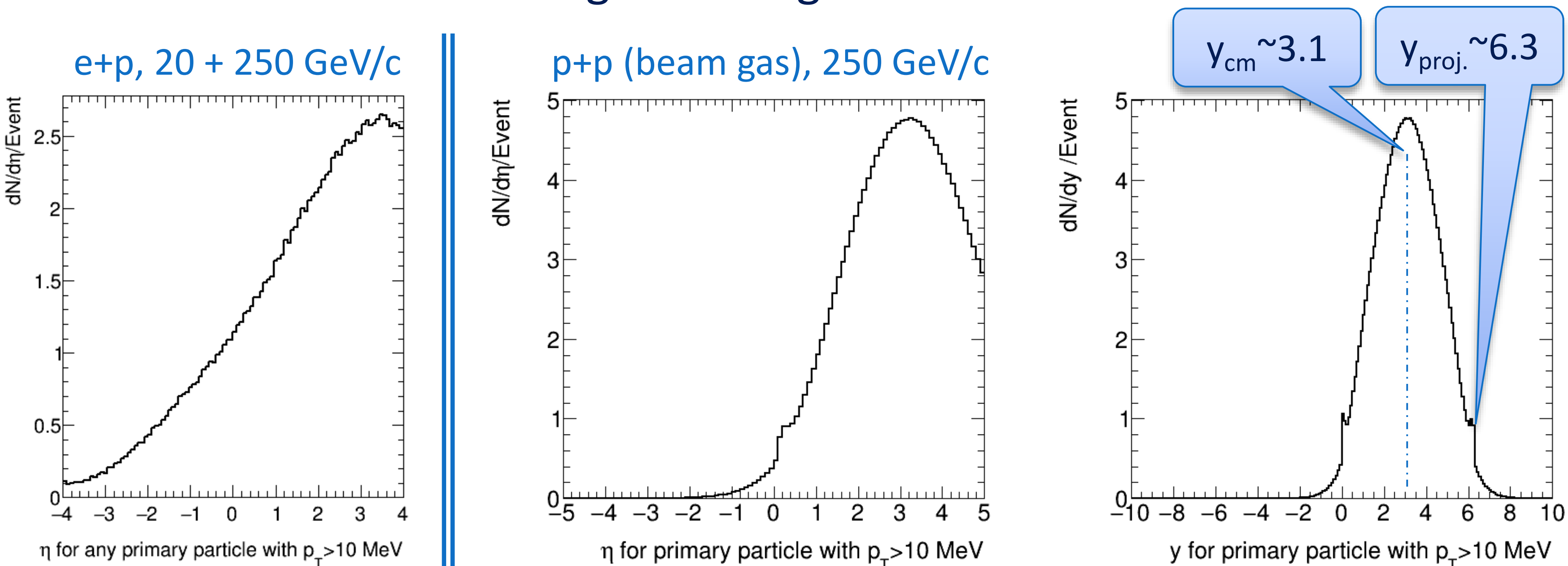
Raw data: 31x 14 bit / active tower +padding + headers ~ 512 bits / active tower



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

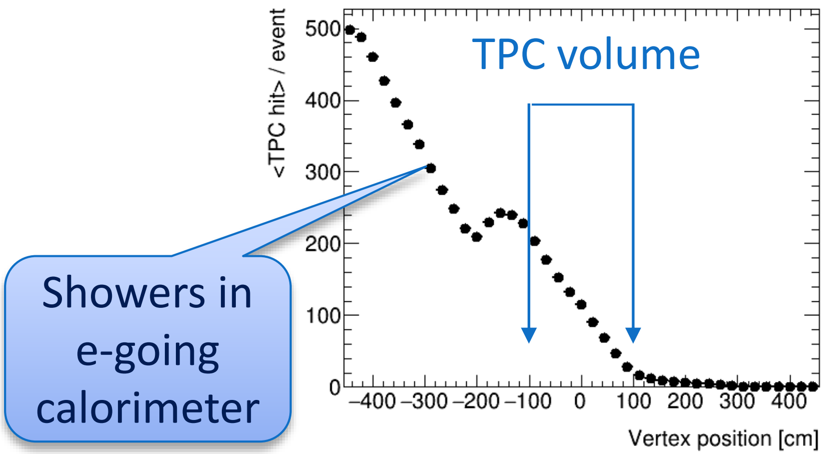
Beam gas multiplicity

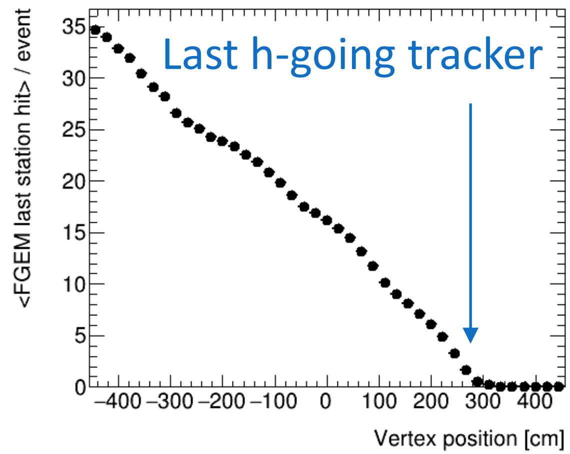
- 250 GeV/c proton beam on H_2 gas target
- C.M. rapidity~3.1, sqrt[s] ~ 22 GeV, cross section~40 mb
- Lab per-pseudorapidity multiplicity is higher than e+p, but ***not*** orders of magnitude higher

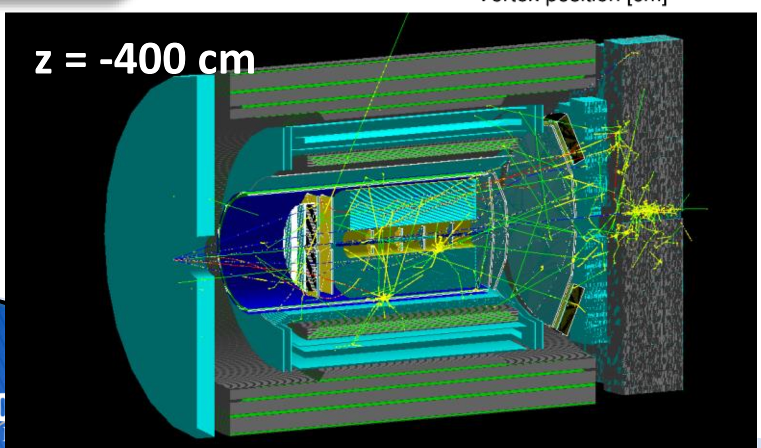


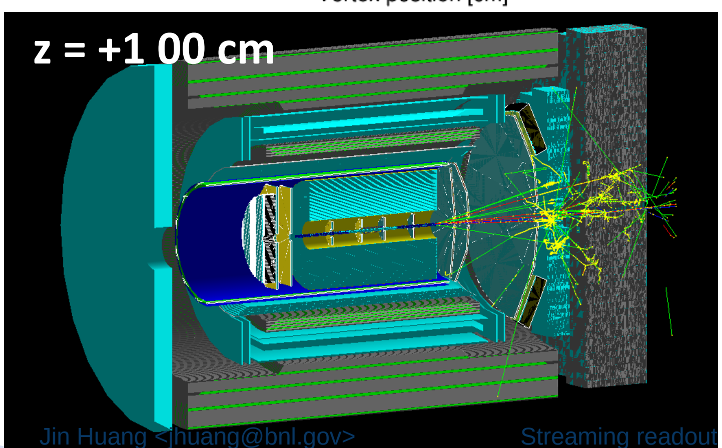
Beam gas vertex sensitivity - tracker

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



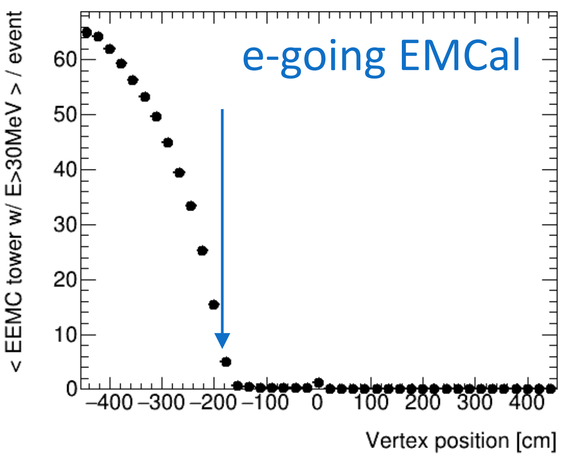


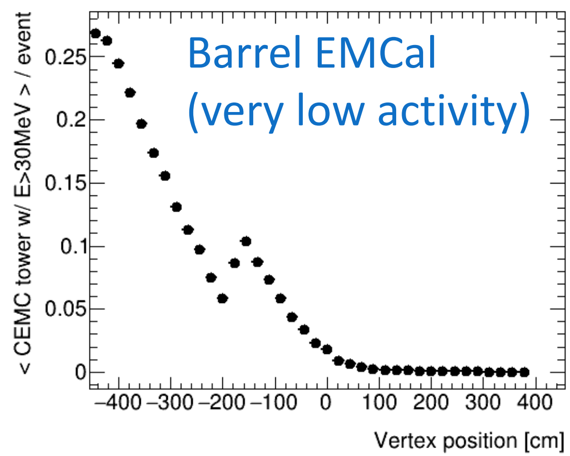


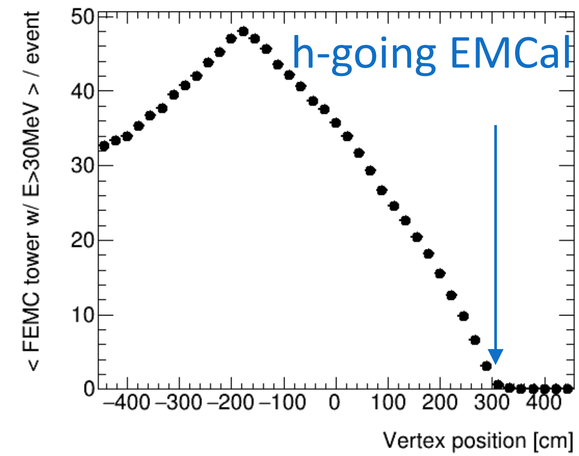


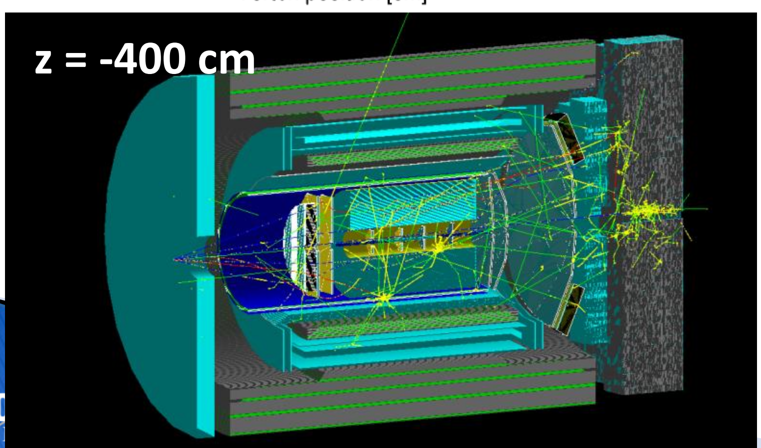
Beam gas vertex sensitivity – calo.

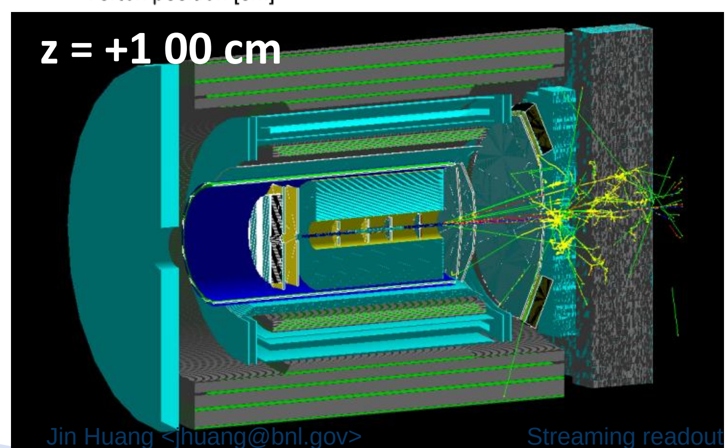
- Average active hit for each beam gas vertex bin
- 250 GeV proton beam on proton beam gas, Pythia-8 M.B.





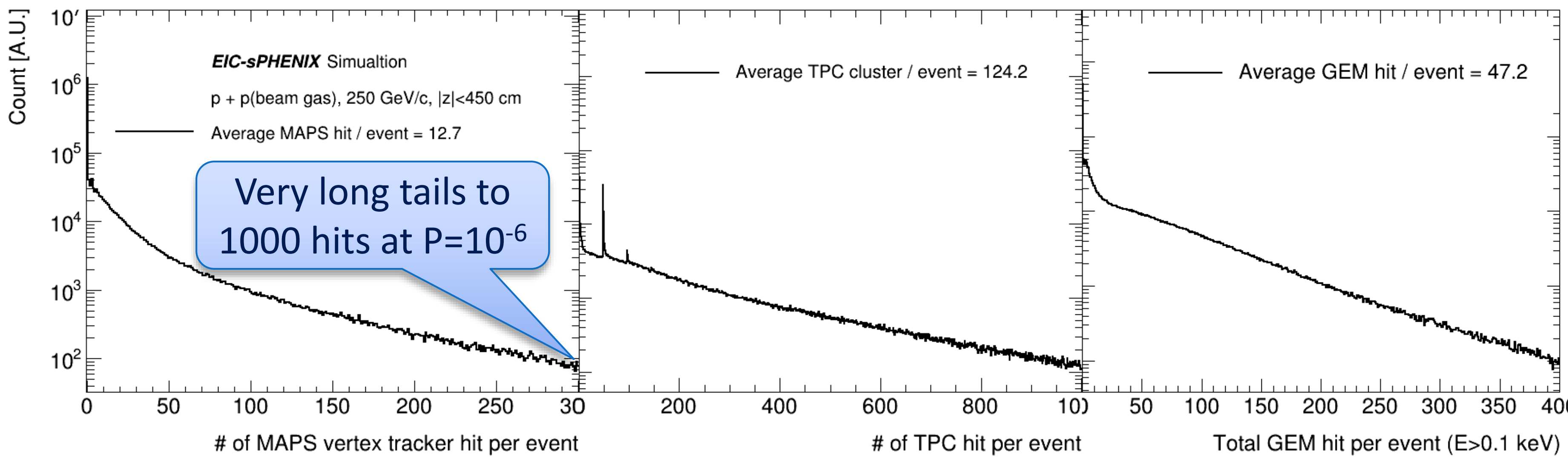






GEANT4-based detector simulation: beam gas event on tracker

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



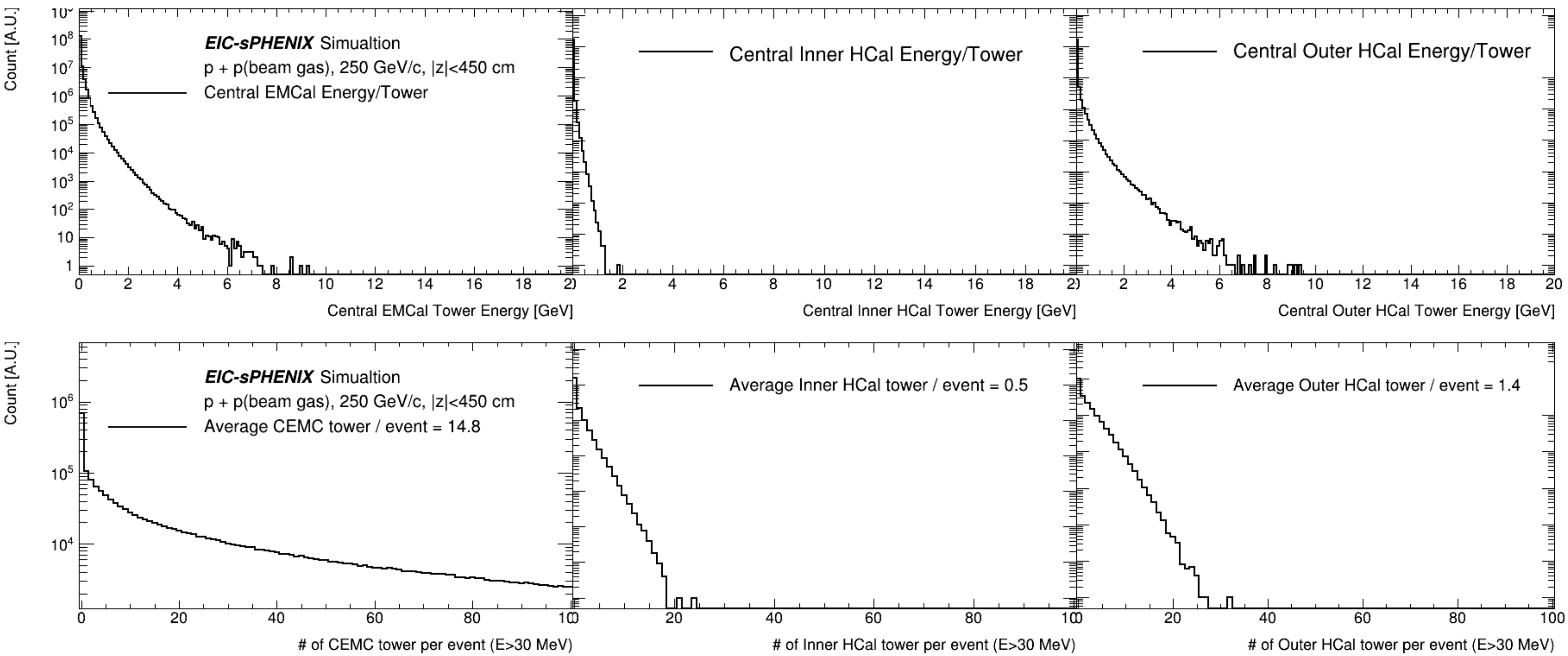
Raw data:
3 pixel x 16 bit / MAPS hit

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)

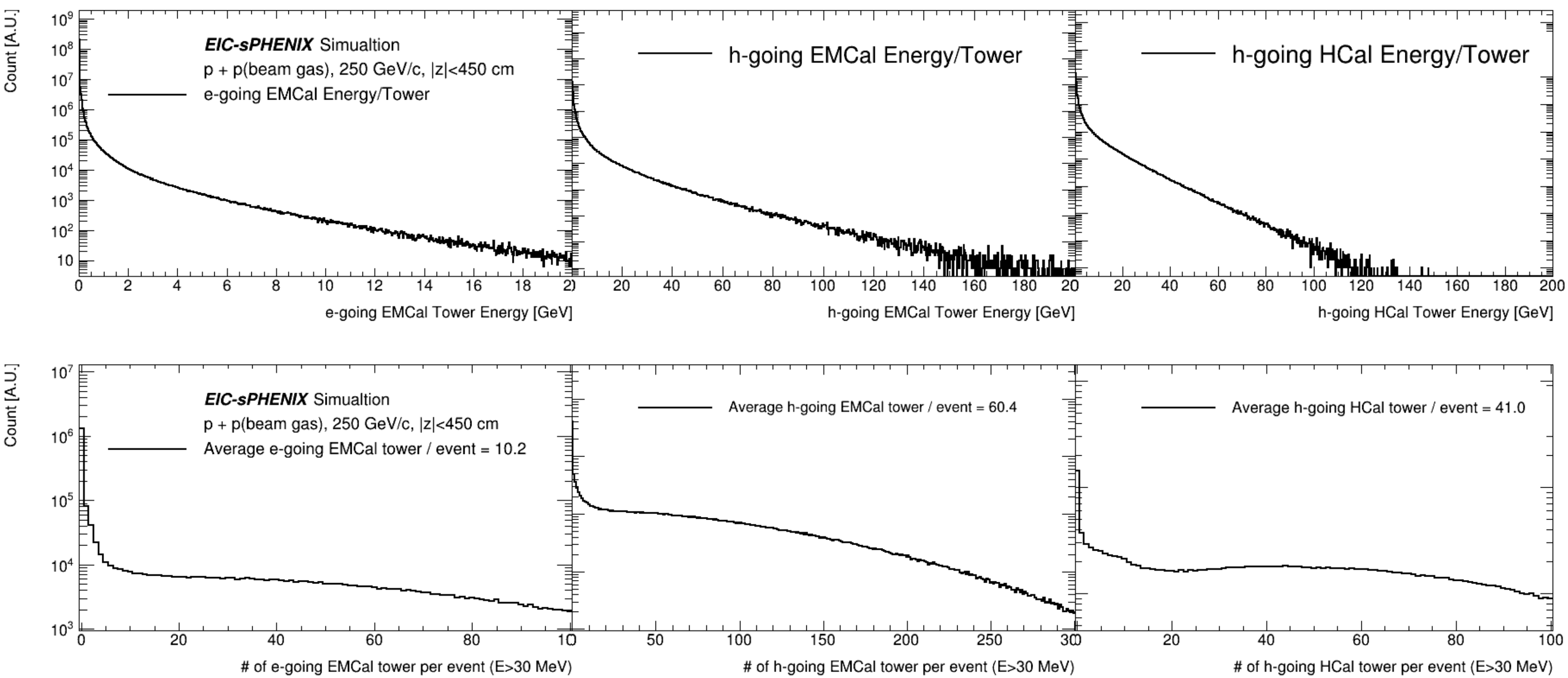
GEANT4-based detector simulation: beam gas event on central calorimeters

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



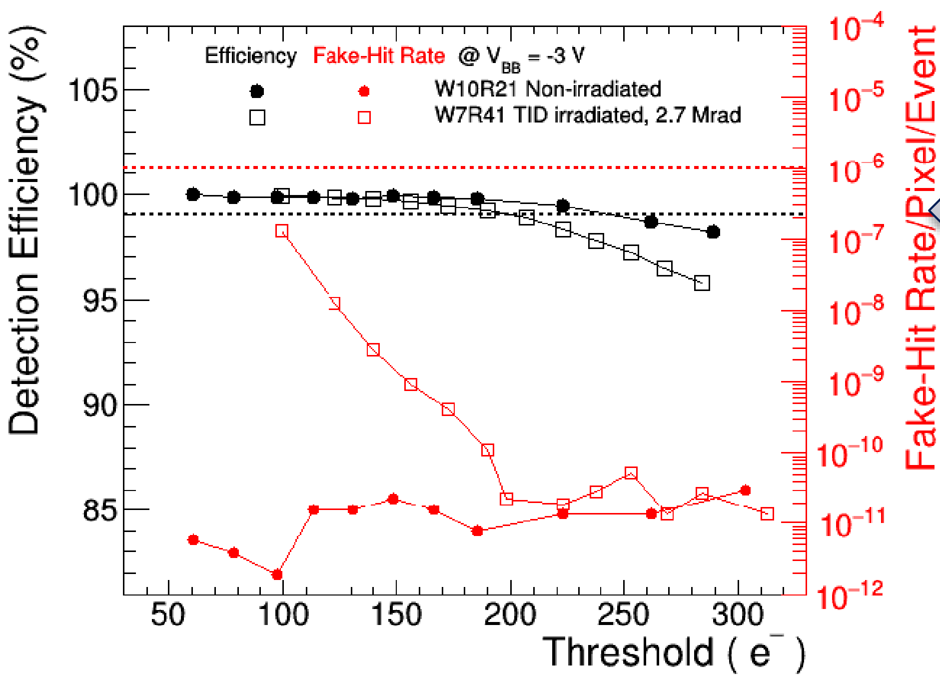
Per-strobe ALPIDE multiplicity

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}

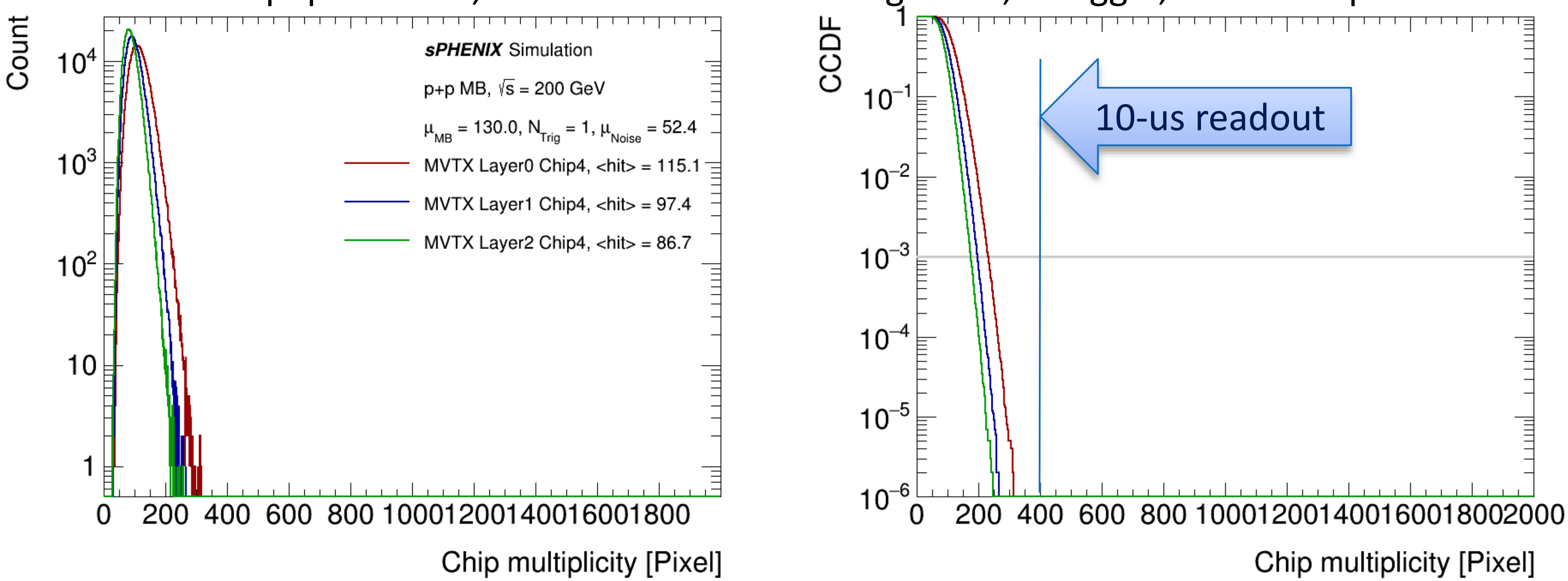
Also studied: 10^{-5}

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

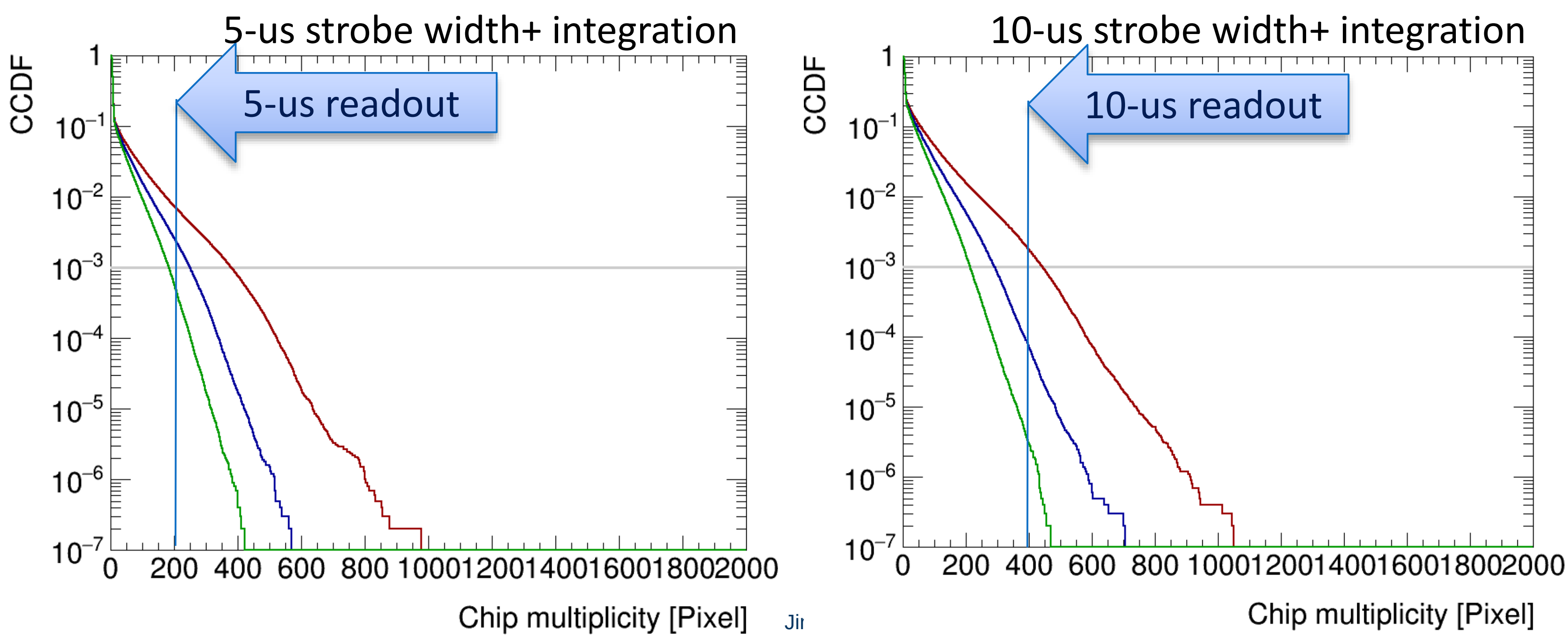
13 MHz p+p collision, 10-us strobe width+integration, 1 trigger, 10^{-4} noise per strobe



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

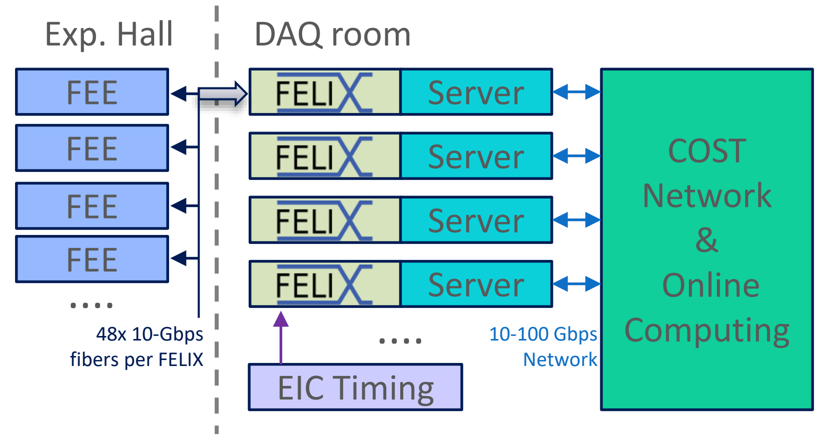
- Can we do better?
  - Further reducing collision rate to 50kHz by introducing a beam crossing angle
  - Reducing noise by 1/10 to 10^{-5} noise per strobe
- Still challenging for continuous , but plausible to have overflow dead-time < 0.1% further using multi-hit buffer on chip (eating the safety factor)

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].

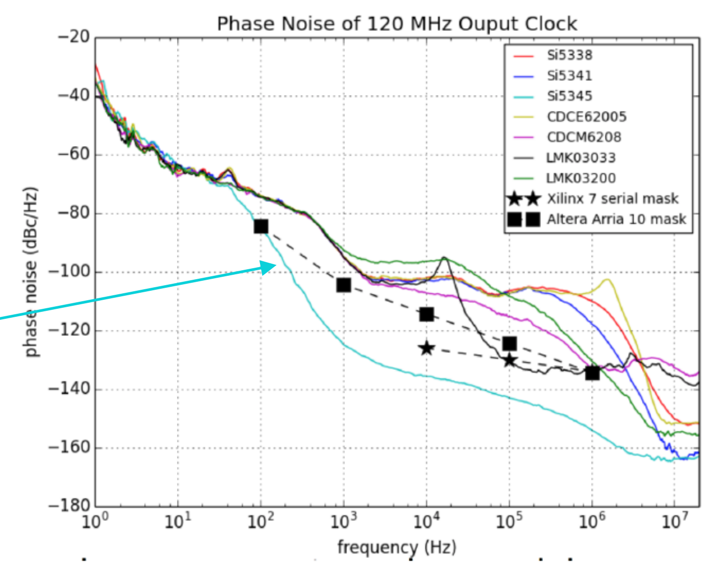


timing mezzanine cards

TTC　TTC-PON　White Rabbit

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



Courtesy of Kai Chen (BNL)

Kai Chen – FELIX Design Review

Embedded clock demo with variable beam clock frequency

Function generator mimic repeated RHIC clock ramping (triangle pattern)

Demo FELIX
Kintex-7 Ultrascale

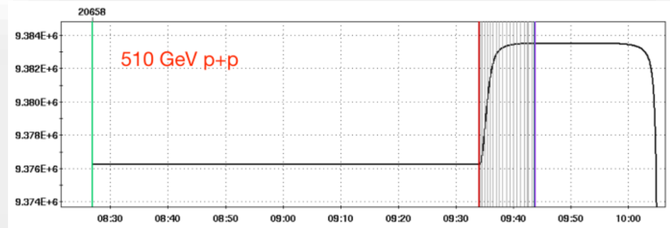
Downlink: 4.8 Gb/s
Multiples of RHIC clock (9.4 MHz)
Recover clock from 8b/10b

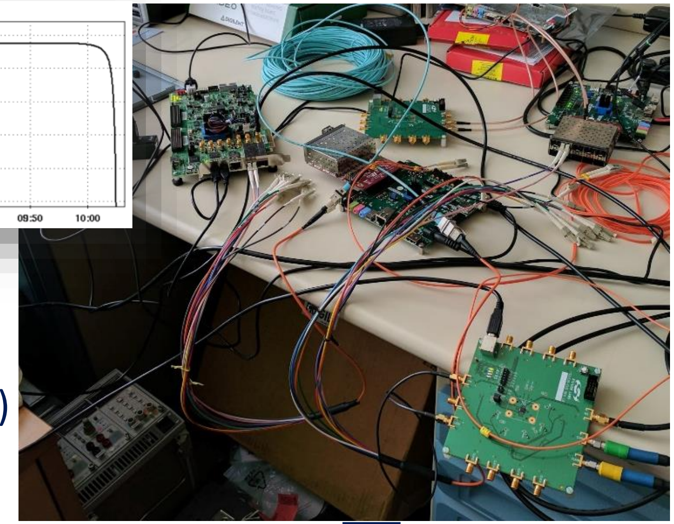
Optical Links

Demo FEE
Atrix-7

Uplink: 4.8 Gb/s, fixed clock

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

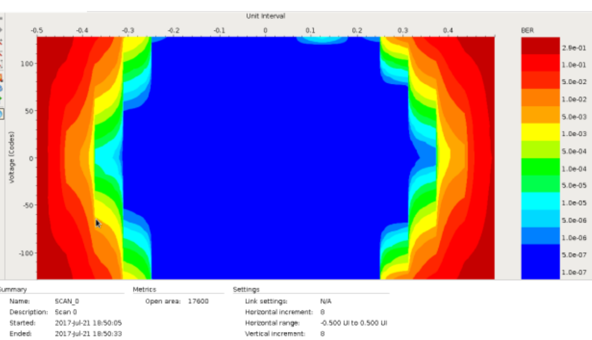




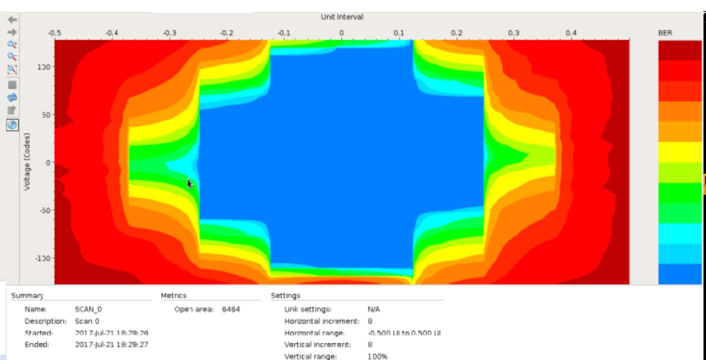
Test recovered "RHIC" clock

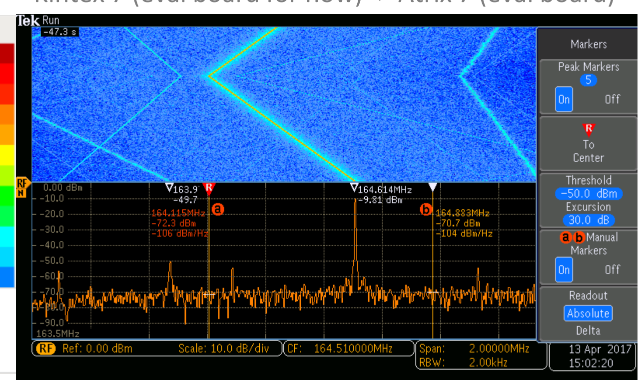
Kintex 7 (eval board for now) -> Atrix 7 (eval board)

Uplink iBERT @ DAM: 1.46e-13



Downlink iBERT @ FEE: 1. 023e-13

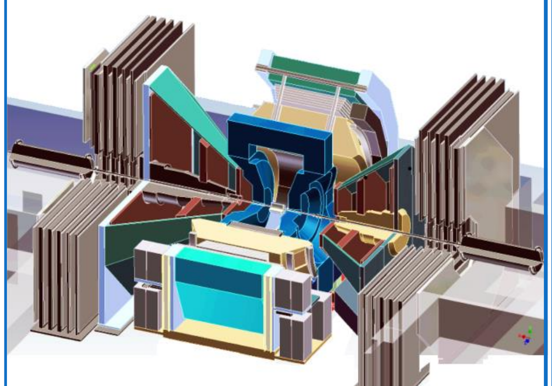




Evolution of the RHIC 1008 Interaction region

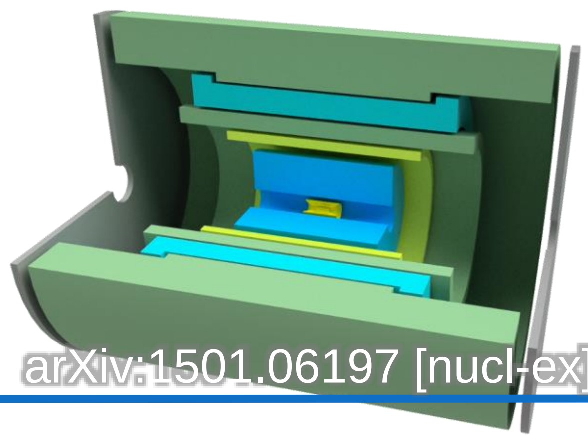
PHENIX experiment

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



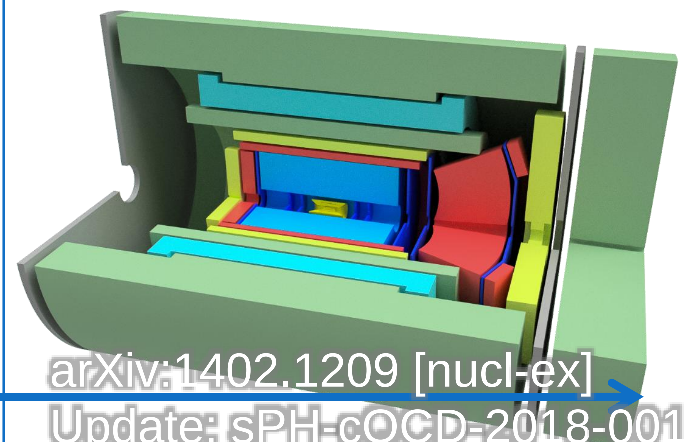
sPHENIX

- 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

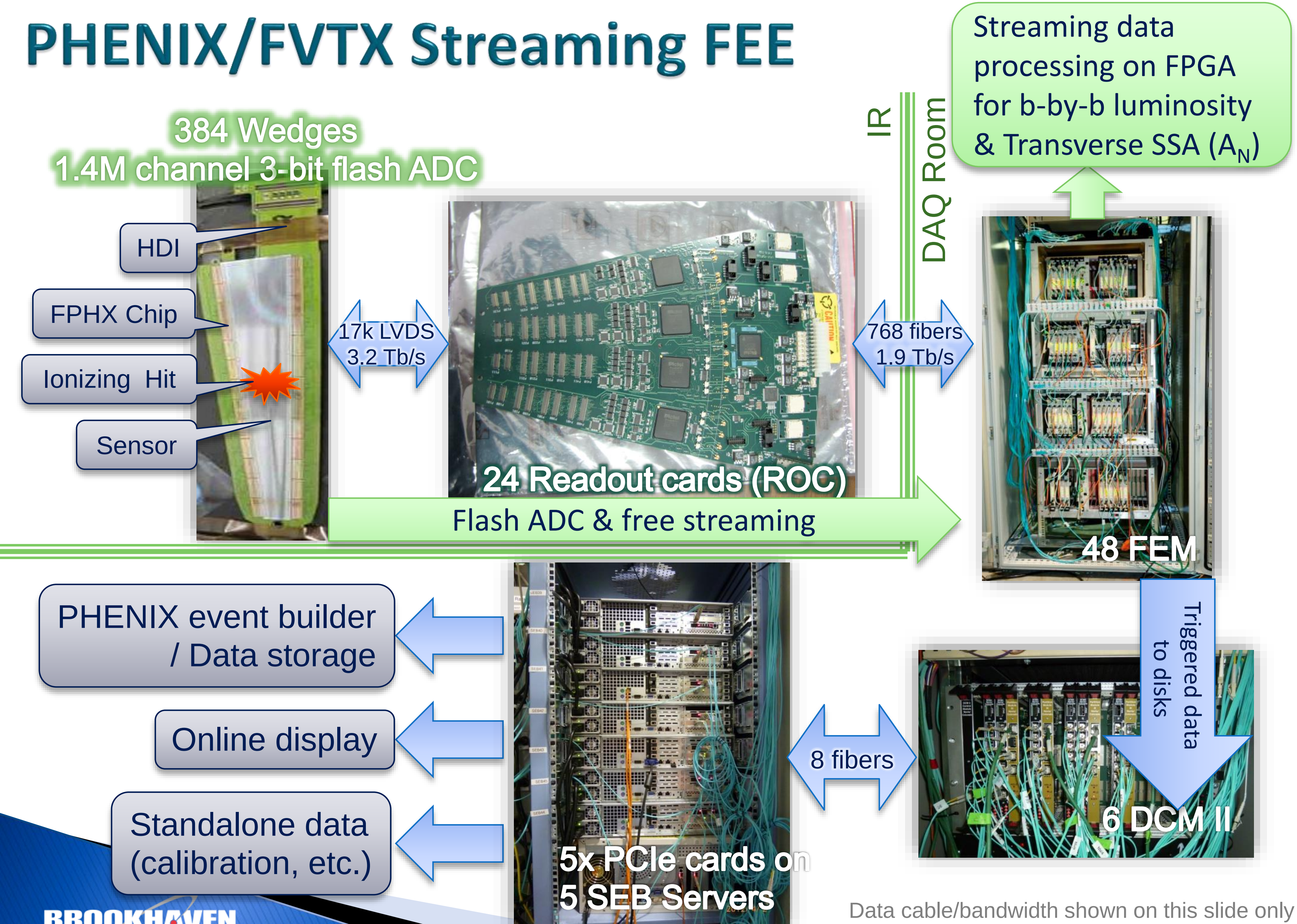


~2000 | 2017→2023, CD-1/3A Approved | >2025 | Time

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

EIC: e+p, e+A

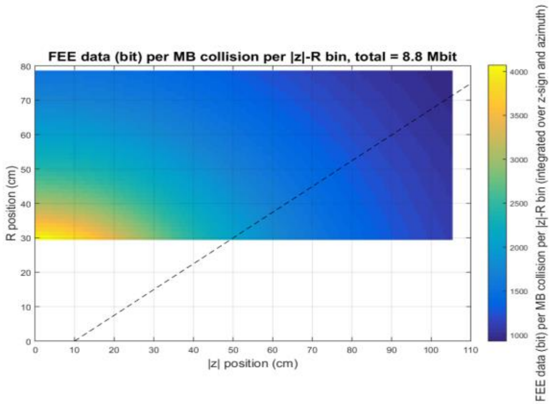
PHENIX/FVTX Streaming FEE



eRHIC and JLEIC key parameters at max Lumi points

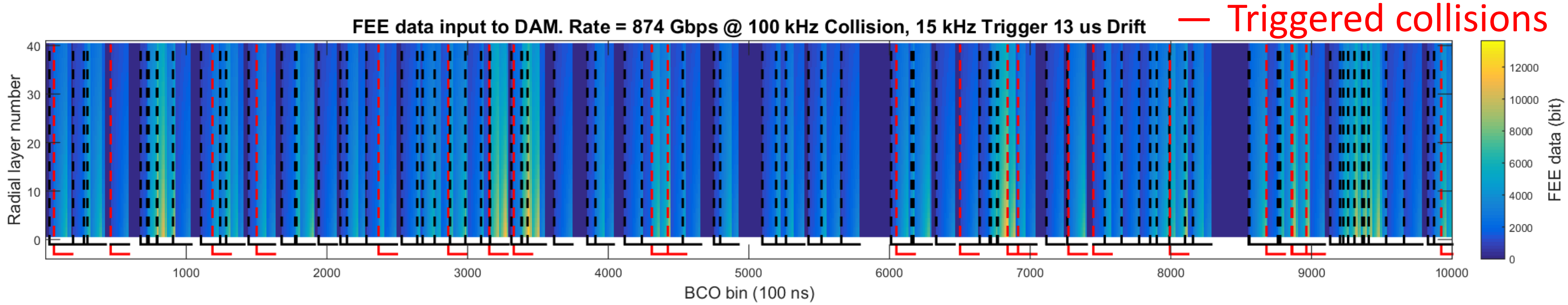
design parameter	eRHIC proton	eRHIC electron	JLEIC proton	JLEIC electron
center-of-mass energy [GeV]	105		44.7	
energy [GeV]	275	10	100	5
number of bunches	1320		3228	
particles per bunch [10^{10}]	6.0	15.1	0.98	3.7
beam current [A]	1.0	2.5	0.75	2.8
horizontal emittance [nm]	9.2	20.0	4.7	5.5
vertical 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 [$10^{34}\,\mathrm{cm^{-2}s^{-1}}$]	1.05		2.1	
integrated luminosity/week [fb^{-1}]	4.51		9.0	

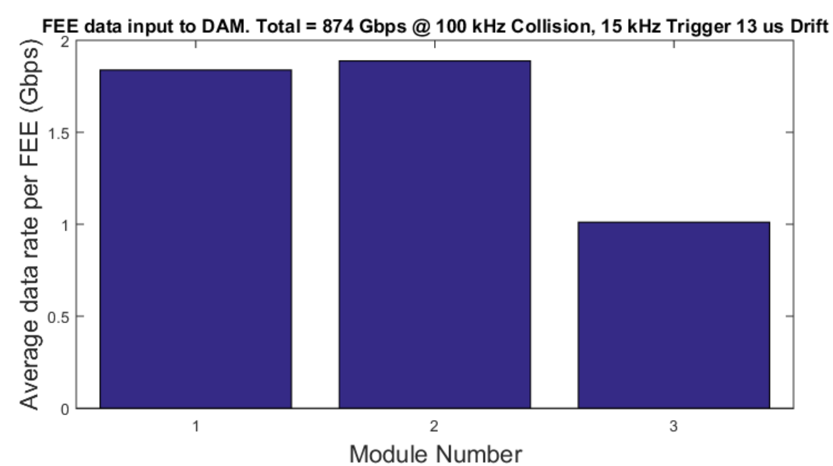
FEE data rate



100kHz collision in continuous DAQ trigger
In TPC DAQ simulation

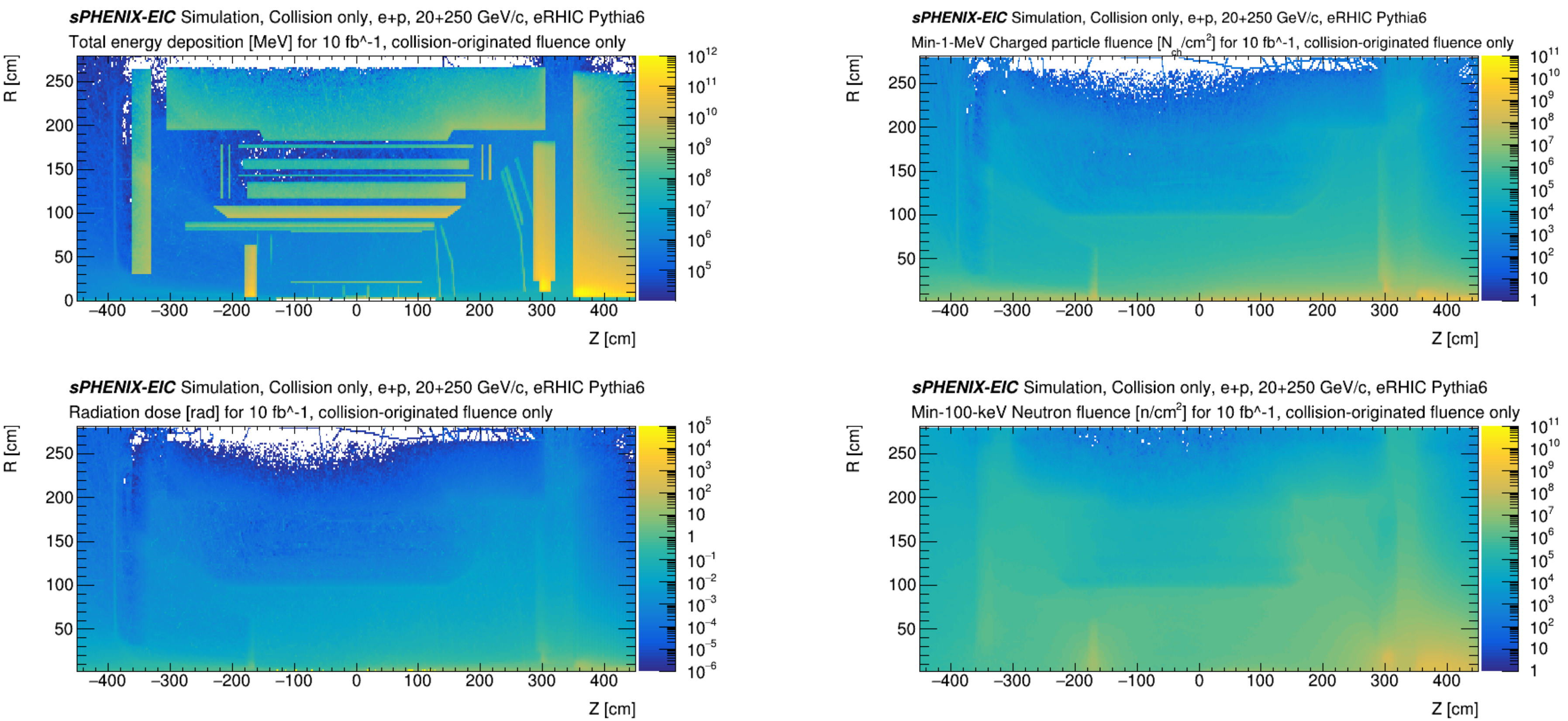
— All collisions
— Triggered collisions

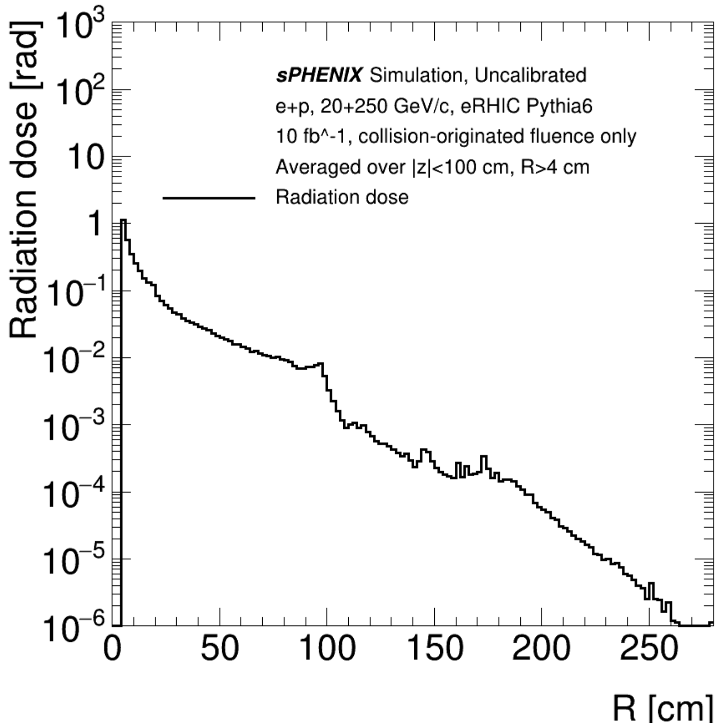


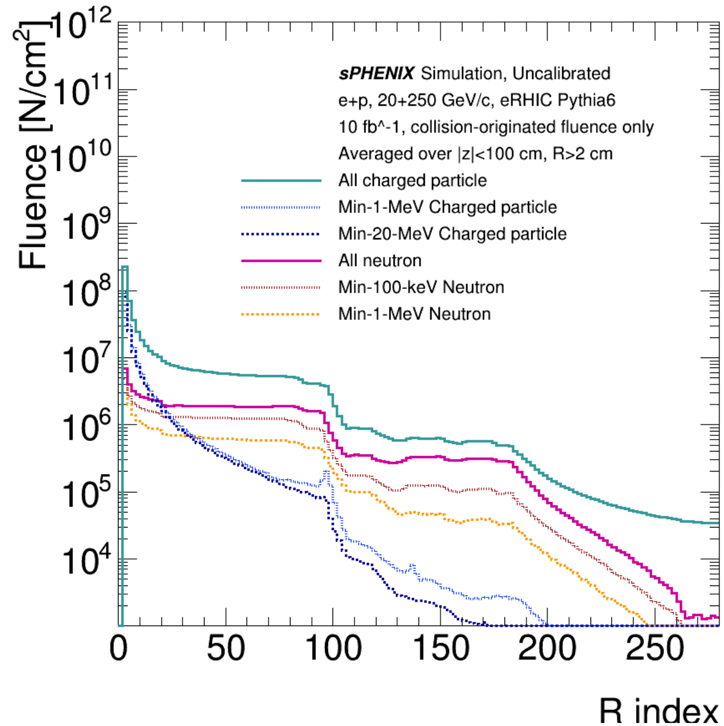


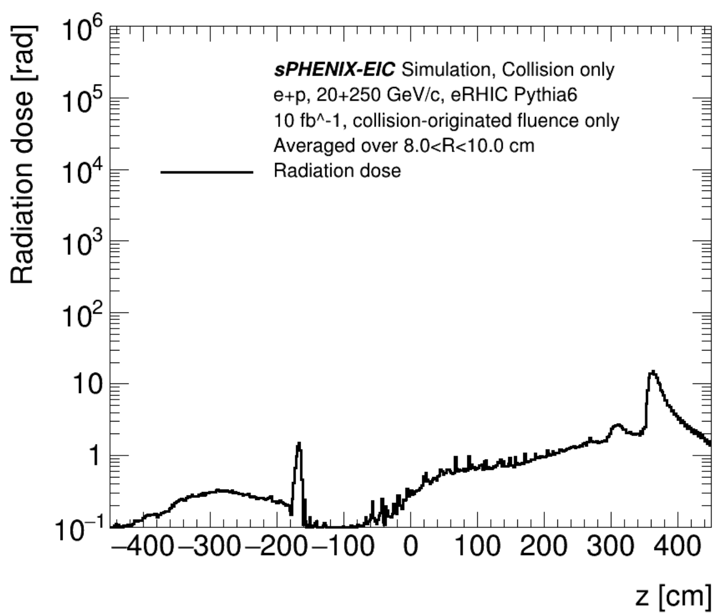
FEE -> DAM limit : 6 Gbps x 8b/10b per FEE
Reference design rate: 1.9 Gbps, far lower than limit
Max rate: 200kHz + 48 rings → max 7.2 Gbps @ module 1

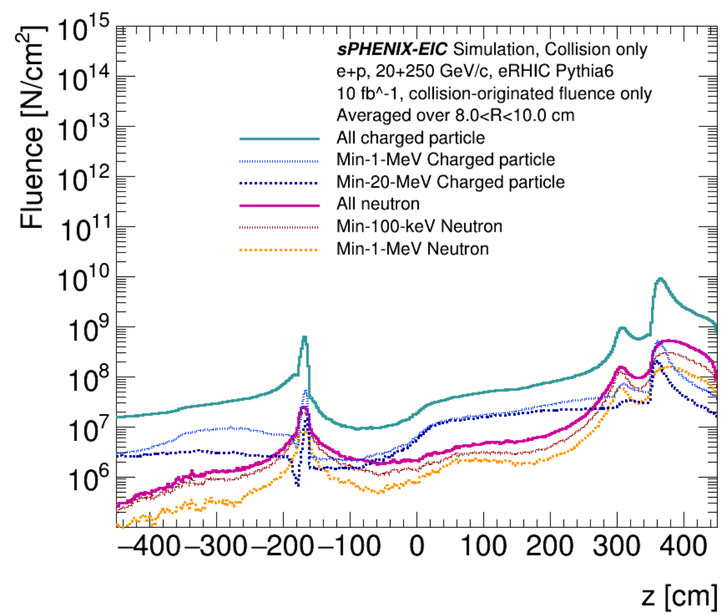
Radiation map




Radiation dose [rad]
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
R [cm]


Fluence [N/cm2]
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
R index


Radiation dose [rad]
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
z [cm]


Fluence [N/cm2]
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
z [cm]