Streaming Readout for sPHENIX and EIC

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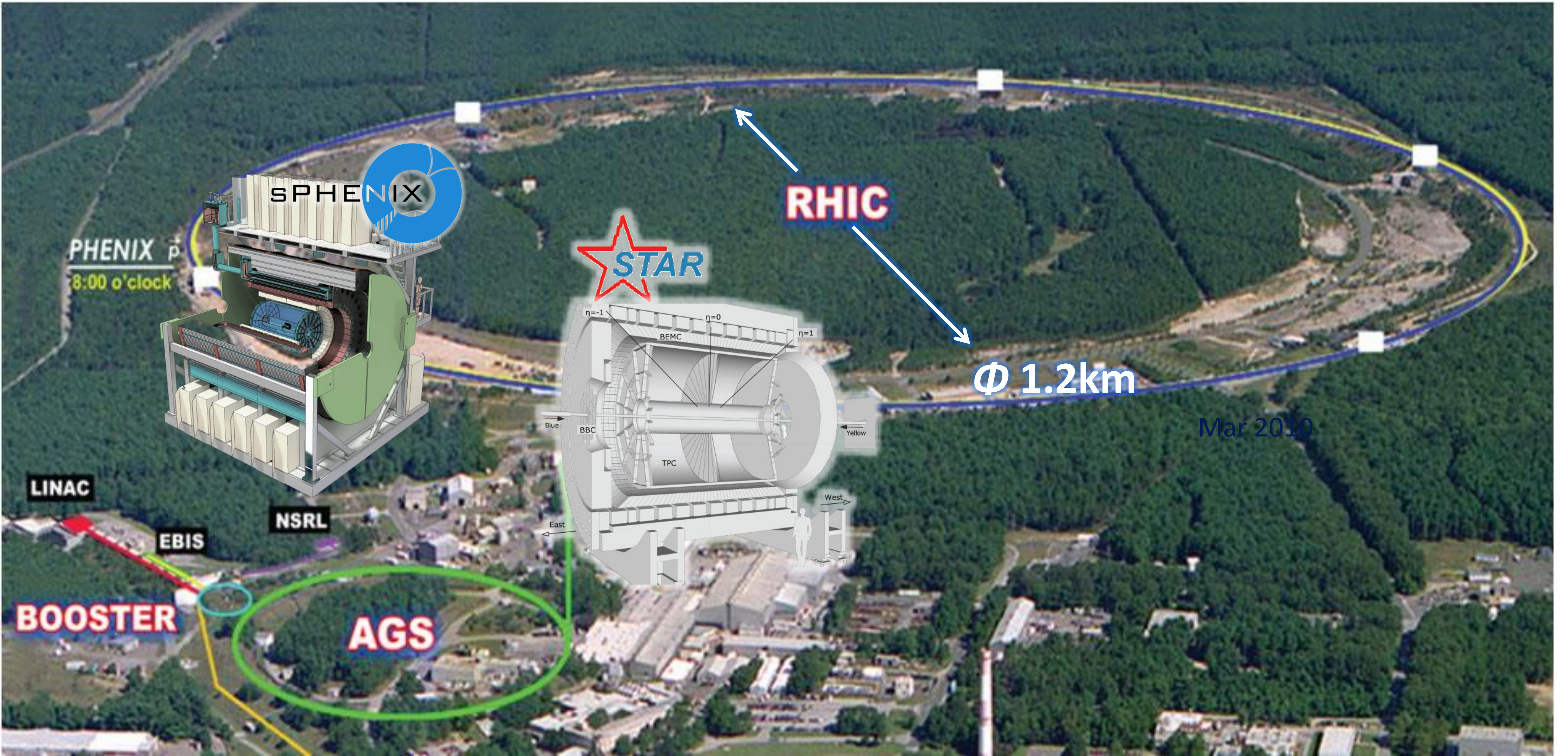
Thanks to the inputs from many colleagues!

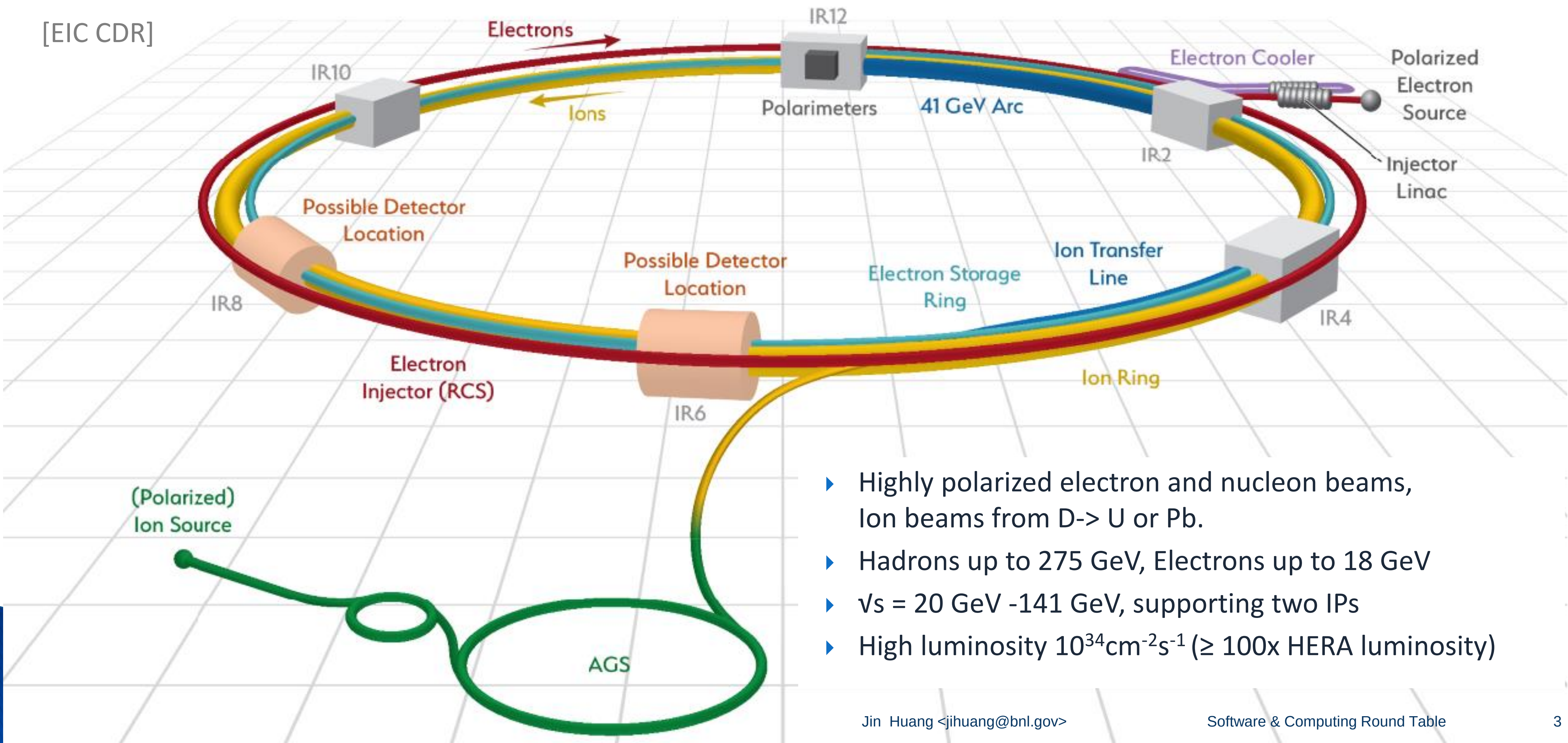
Also with reference to talks at Streaming Readout VIII and AI4EIC workshops

Relativistic Heavy Ion Collider



RHIC transition to the EIC

[EIC CDR]

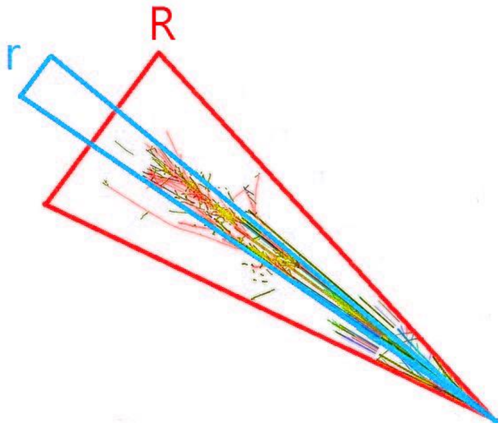


- Highly polarized electron and nucleon beams, Ion beams from D-> U or Pb.
- Hadrons up to 275 GeV, Electrons up to 18 GeV
- √s = 20 GeV -141 GeV, supporting two IPs
- High luminosity $10^{34}cm^{-2}s^{-1}$ (≥ 100x HERA luminosity)

Core physics programs

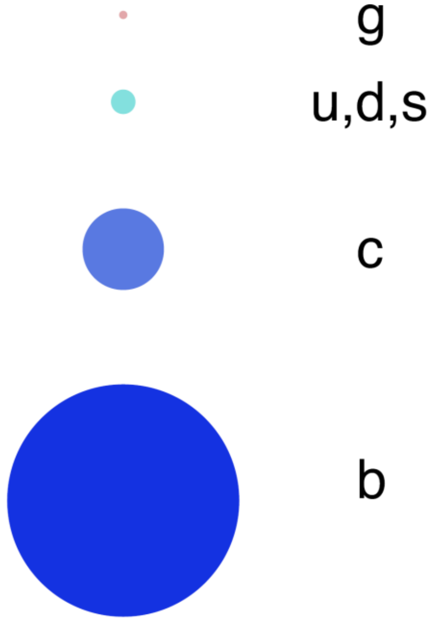
Jet cor. & substructure

Vary momentum/angular size of probe



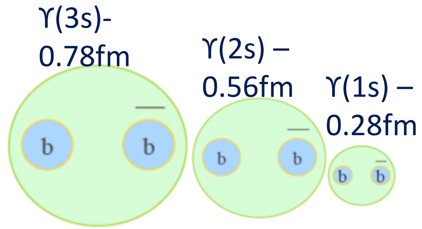
Parton energy loss

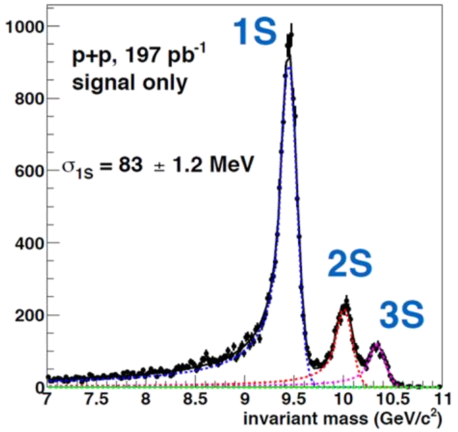
Vary mass/momentum of probe



Upsilon spectroscopy

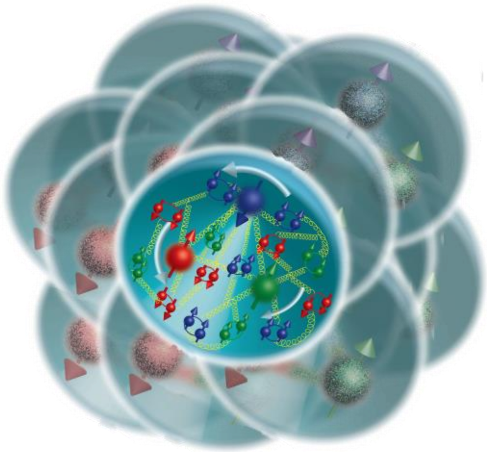
Vary size of the probe



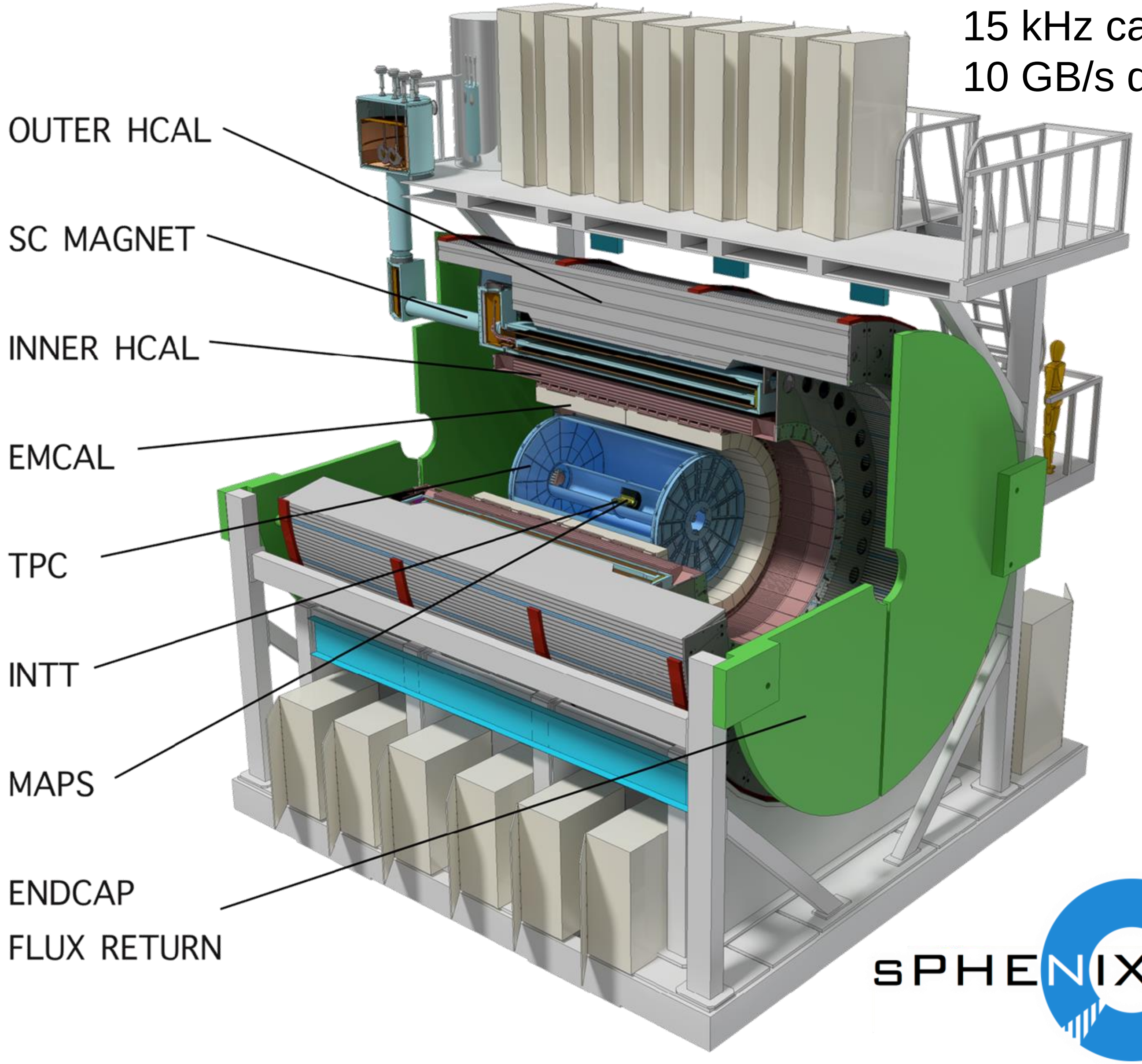


Cold QCD

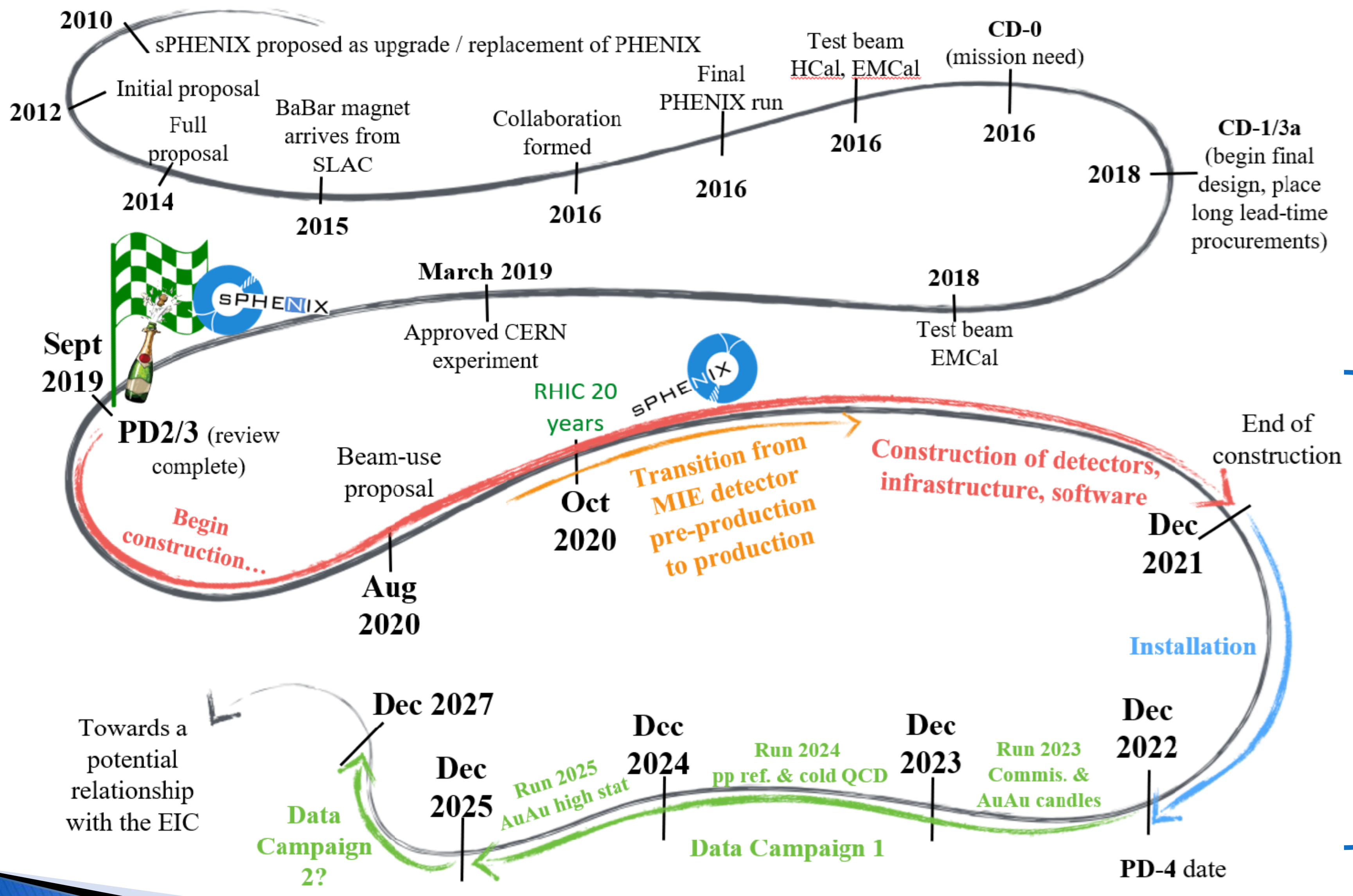
Vary temperature of QCD matter



15 kHz calo trigger + 10% streaming DAQ
10 GB/s data logging



sPHENIX Detector



~1 years !
From now to first data

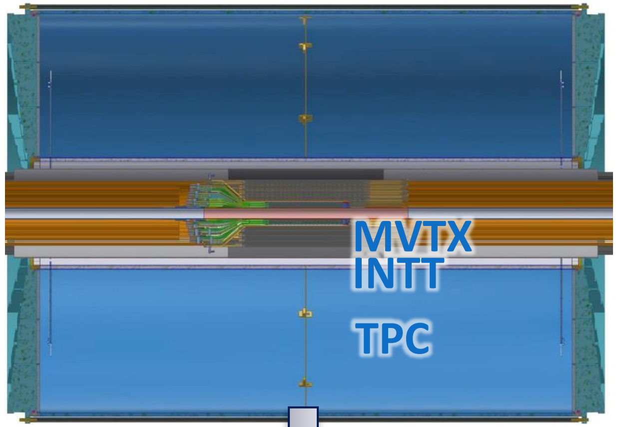

sPHENIX magnet installation
RHIC IP8 Hall, Oct 7, 2021
← 13/32 sPHENIX hadronic calorimeter sectors installed

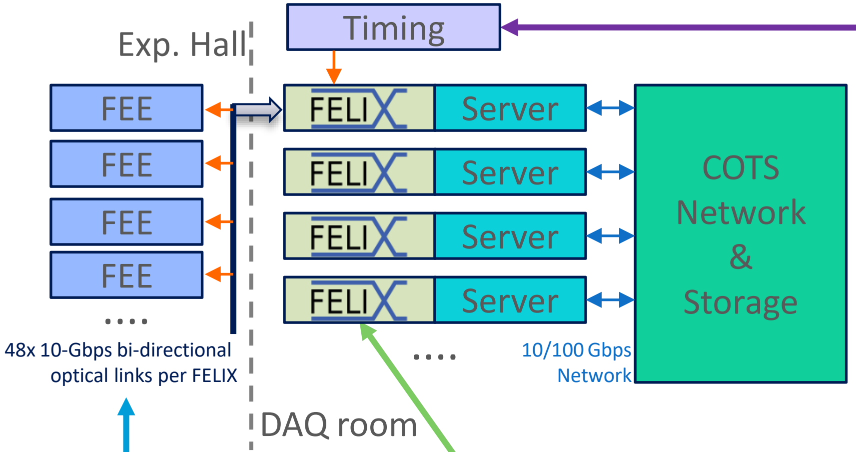
Related streaming readout electronics

Associated test projects

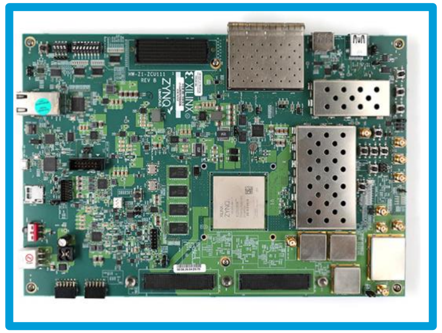
Precision timing digitizer
DRS4GIO (SBIR/LDRD)

sPHENIX streaming DAQ for tracker

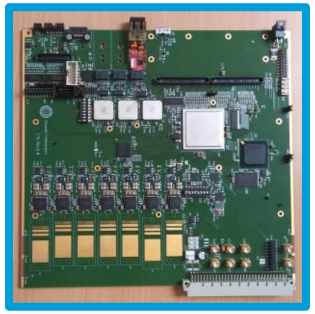




Global Timing Module (NSLS II/sPHENIX)
Receiving from RHIC RF low glitter clock source



High density multiplexer+ ADC
RFSoC Digitizer (LDRD)



MVTX RU, 200M ch

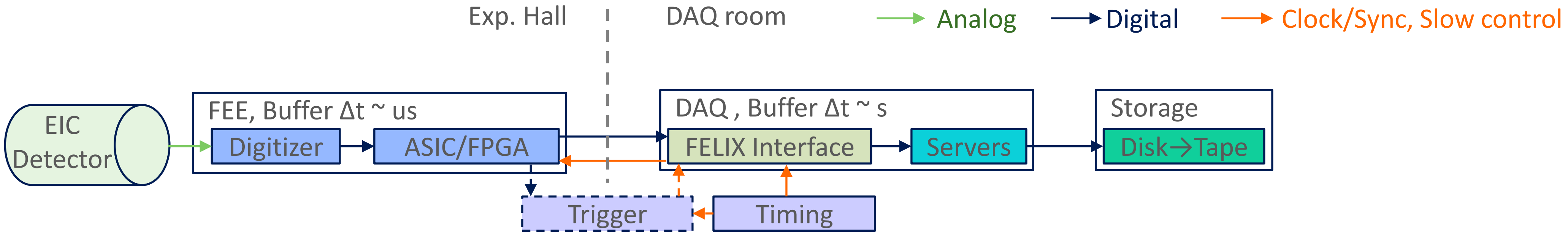
INTT ROC, 400k ch
ALPIDE (ALICE/sPHENIX), FPHX (PHENIX)

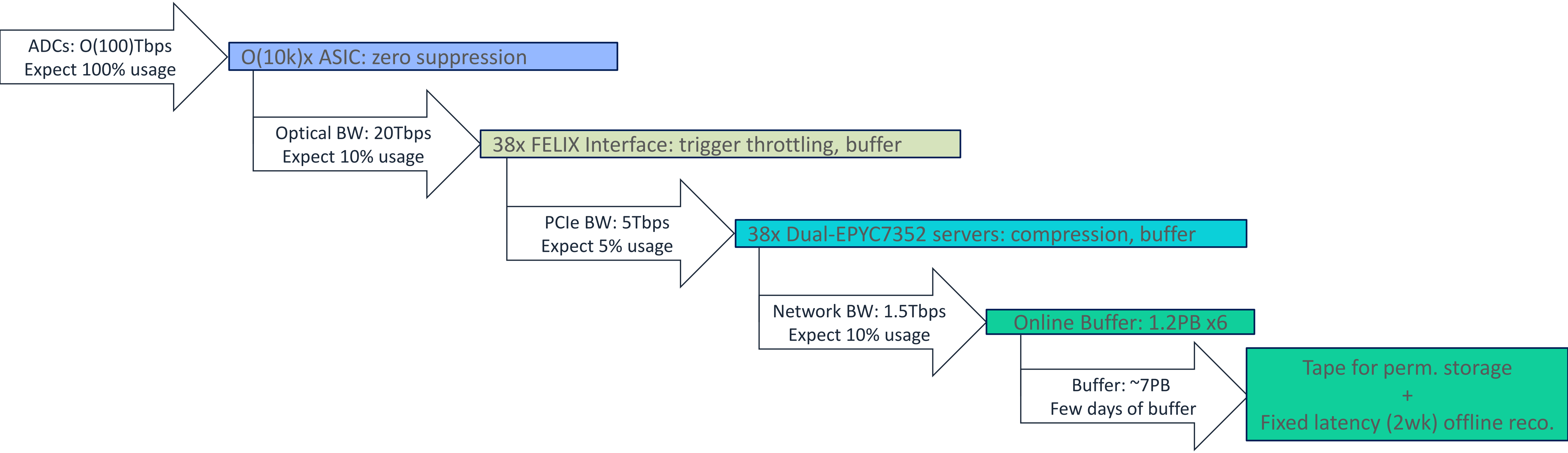
TPC FEE, 160k ch
SAMPAv5 (ALICE/sPHENIX)

BNL-712 / FELIX v2 x38 (ATLAS/sPHENIX)

FELIX Ref: 10.1109/tim.2019.2947972
Similar role as PICe40 in LHCb [R. Aaij's talk]

sPHENIX Streaming data flow





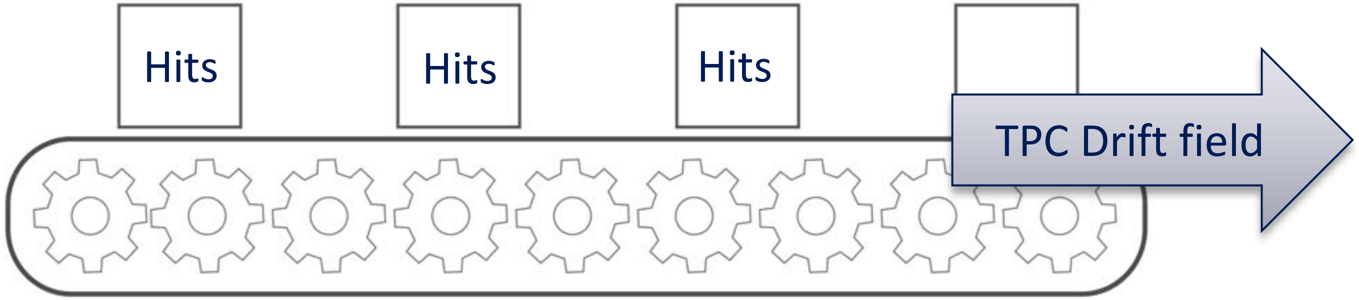
Streaming readout status at sPHENIX

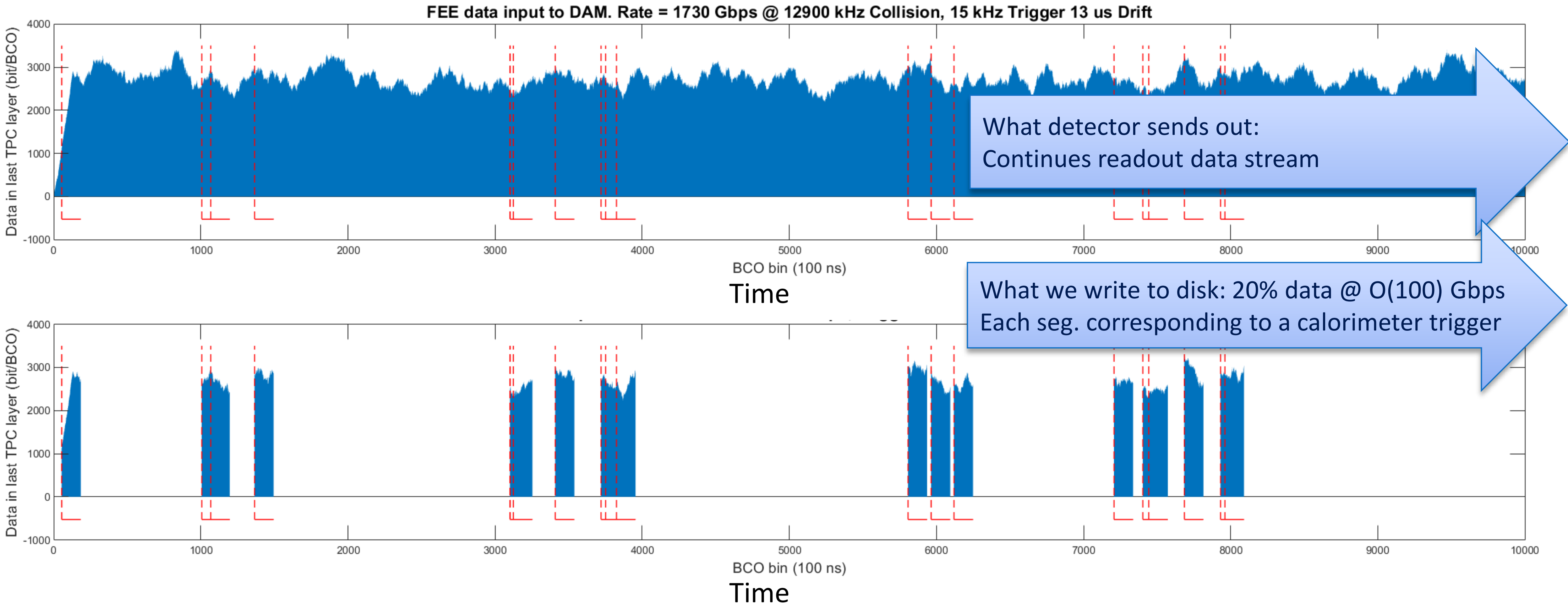
- All three sPHENIX tracking detector uses streaming readout
- Developed plan to take streaming data for heavy flavor physics program (next slides), commended by RHIC PAC.
- Completed construction of sPHENIX FELIX DAQ interface (~50) and procurement of DAQ servers, network infrastructure and online disk buffers
- Data taking start in 2023!

RHIC PAC 2020 report

> We commend sPHENIX for developing the continuous streaming readout option for the detector, which increases the amount of data that can be collected in Run-24 by orders of magnitude. In particular in the sector of open heavy flavor, this technique will give access to a set of qualitatively novel measurements that would otherwise not be accessible. Given the tight timeline for completing the RHIC physics program before construction of the EIC begins, this is a tremendous and highly welcome achievement.

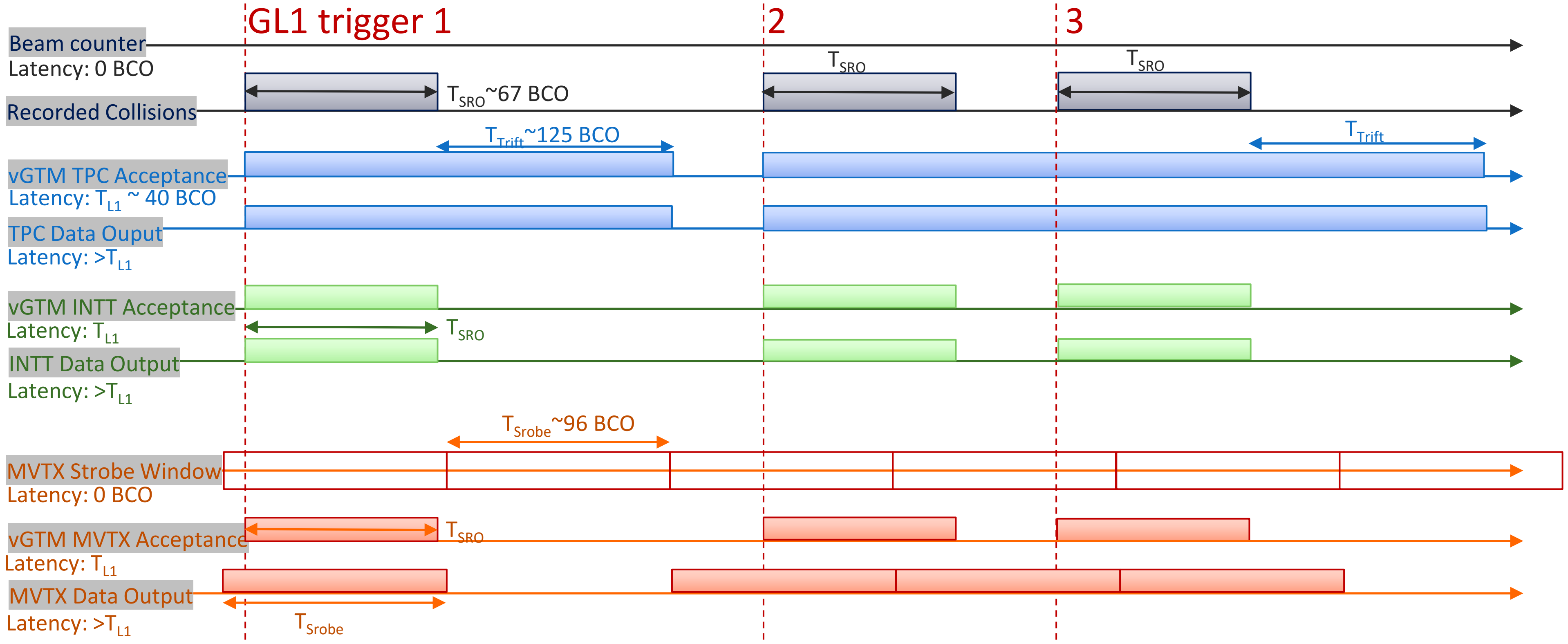
TPC data stream in sPHENIX triggered DAQ





SRO-Mode1-Simple [Recommended]

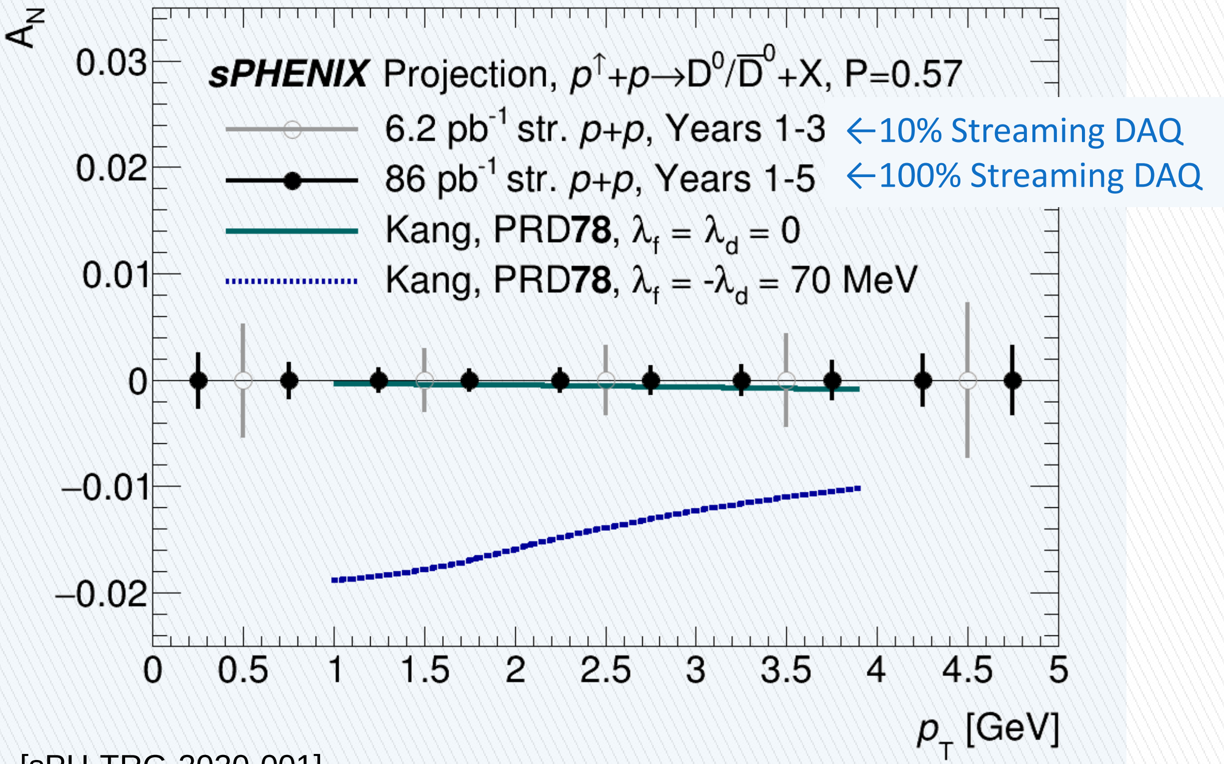
Simply prolong L1-Acceptance signal to each subsystem, from 1 BCO to T_{SRO}~67 beam crossings (~7us or 10% SRO data)
→ x500 increase of hard-to-trigger p+p sample
→ at cost only 50% increase in data vol. (by piggy back on long TPC readout window of 13us)



Streaming-DAQ enabled scientific connection: e.g. gluon dynamics via heavy flavor A_N

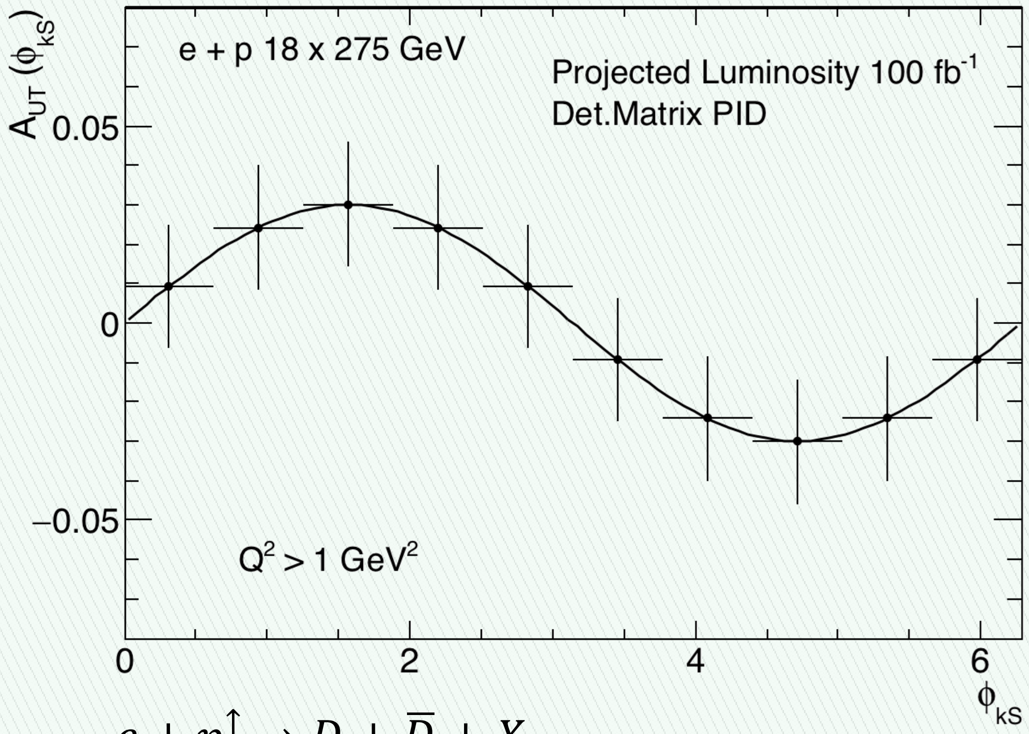
Universality test on gluon Sievers

sPHENIX D^0 trans. spin asymmetry, $A_N \rightarrow$ Gluon Sievers via tri-g cor.



[sPH-TRG-2020-001]
Model: 10.1103/PhysRevD.78.114013

EIC SIDIS D^0 transverse spin asymmetry → Gluon Sievers



$$e + p^{\uparrow} \rightarrow D + \bar{D} + X$$

[CNFS HF@EIC workshop, Nov 4-6, 2020]

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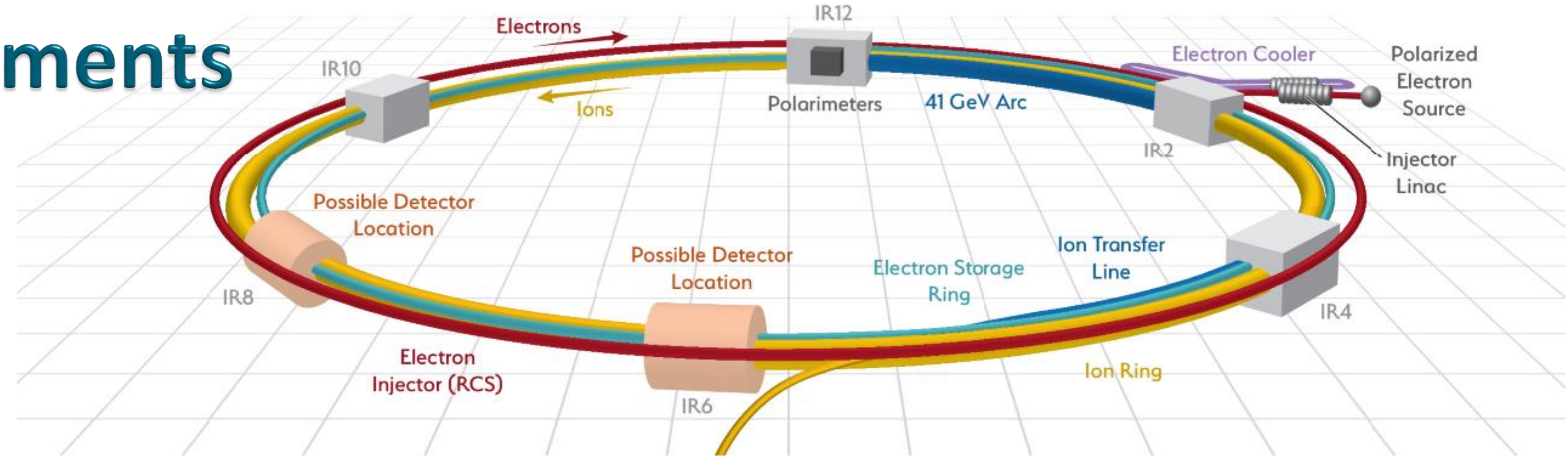
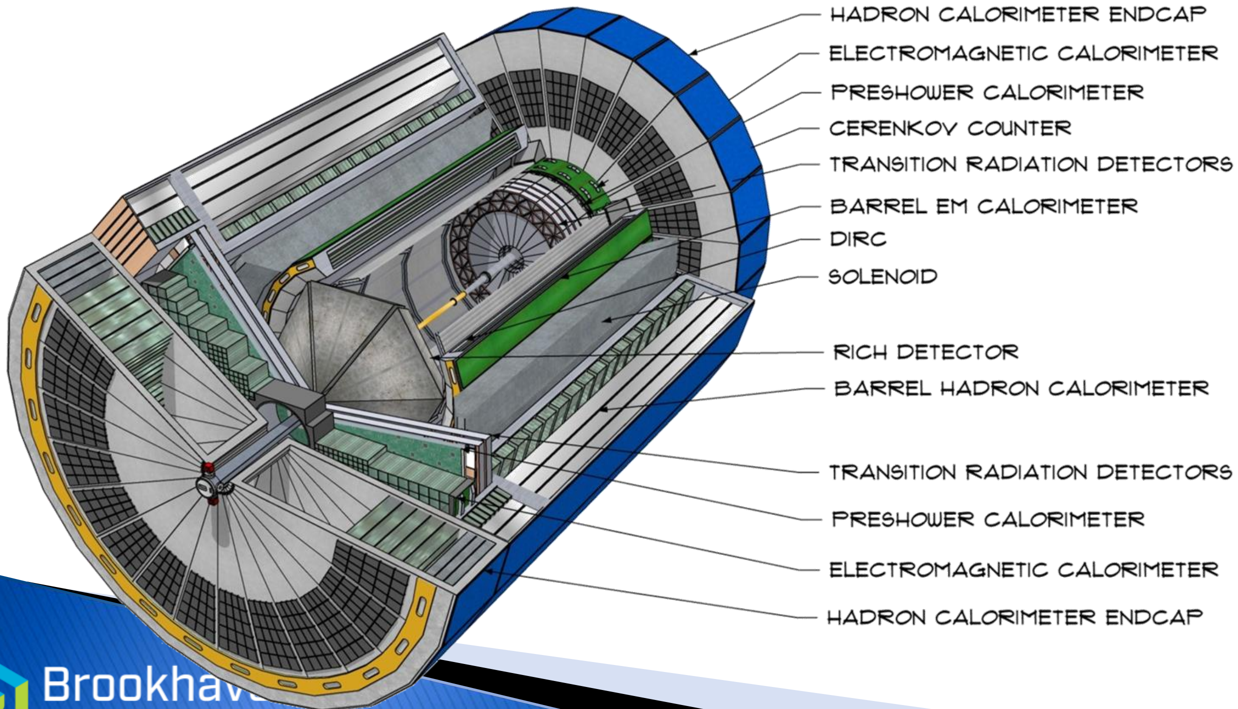
EIC experiments





Generic EIC Detector model [EIC YR]

See also: proposal detectors in development

- ATHENA: athena-eic.org
- CORE: eic.jlab.org/core
- ECCE: ecce-eic.org

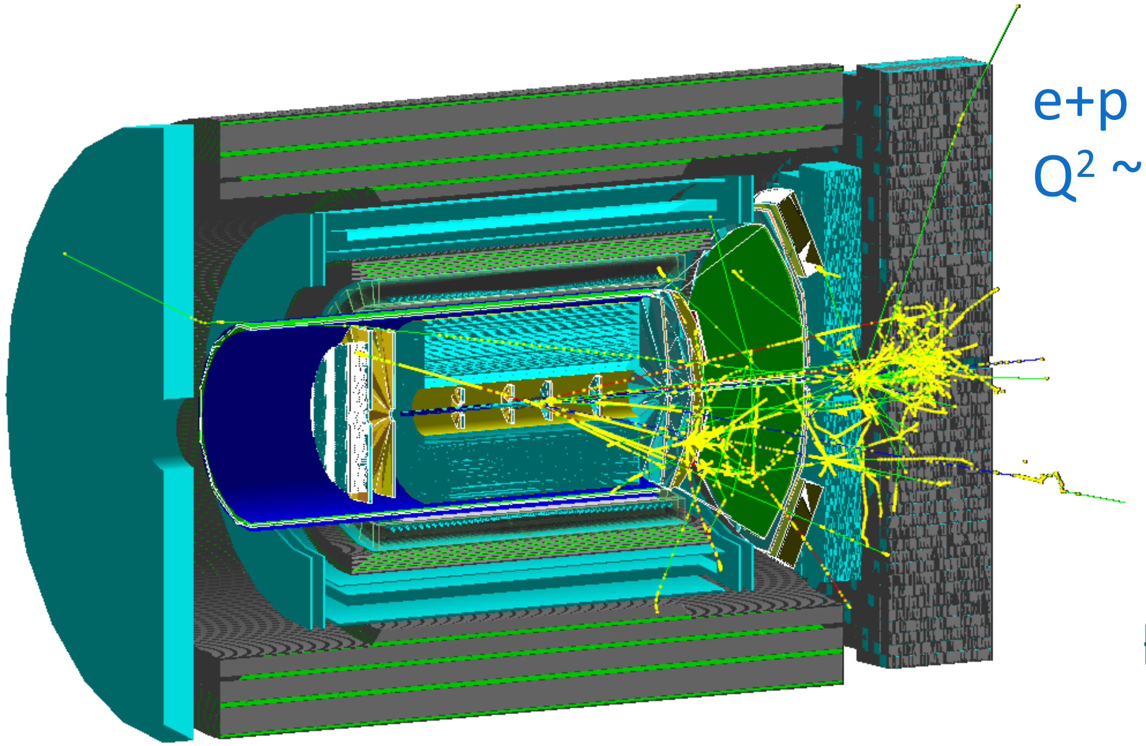
EIC: unique collider
→ unique real-time system challenges

	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	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 luminosity is high, but collision cross section is small ($\propto \alpha_{EM}^2$) → low collision rate
- But events are precious and have diverse topology → hard to trigger on all process
- Background and systematic control is crucial → avoiding a trigger bias

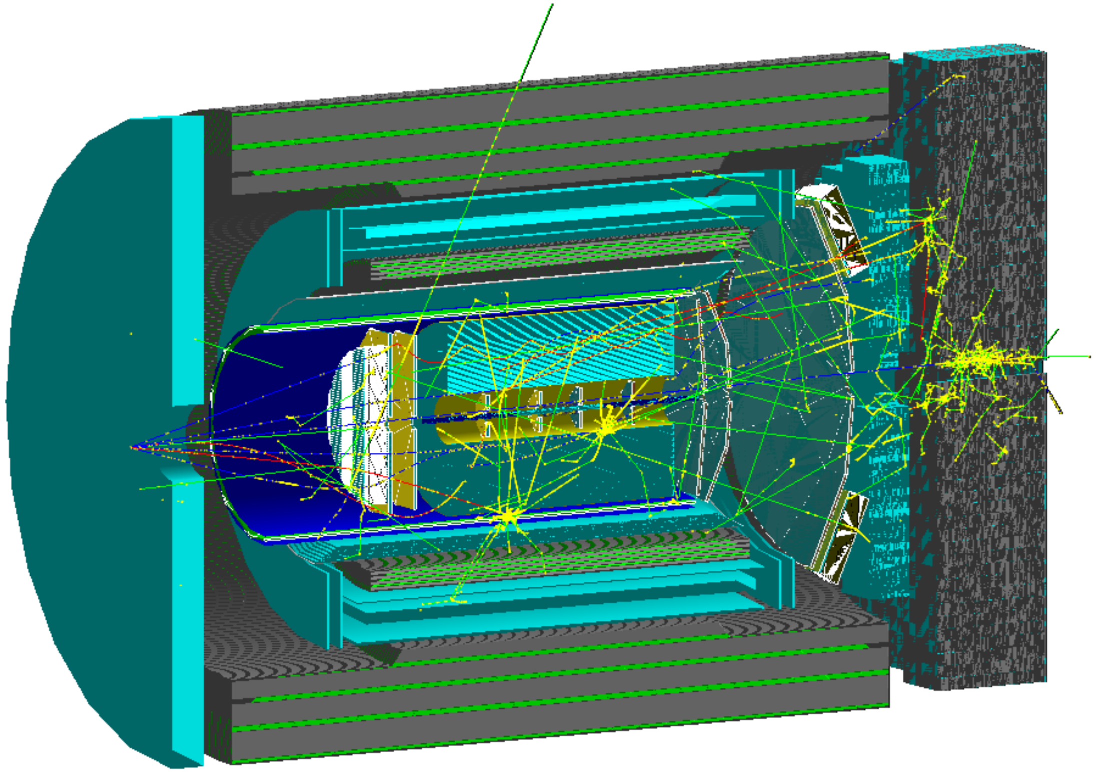
EIC DAQ in Fun4All-EIC simulation

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

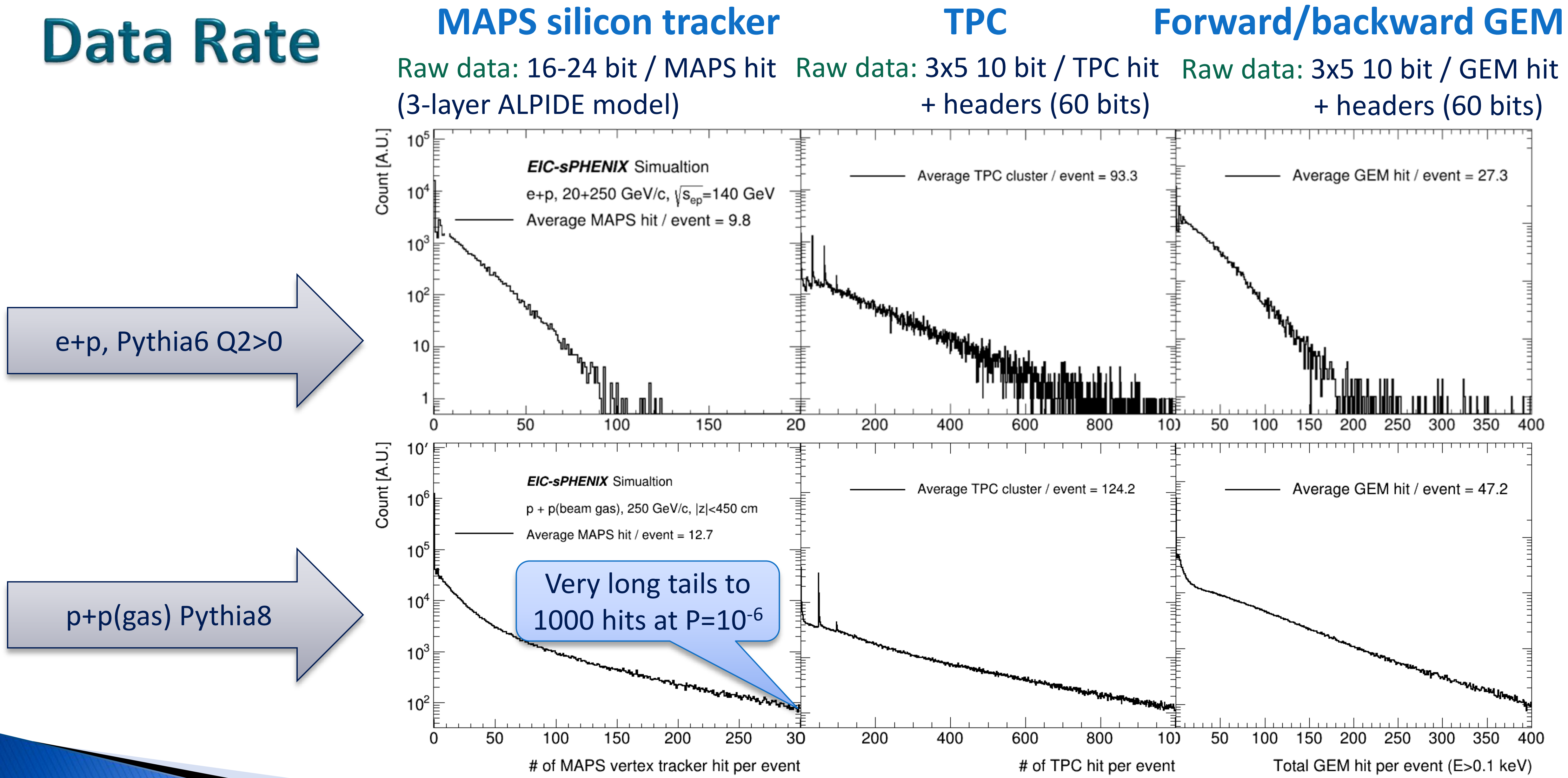


e+p DIS 18+275 GeV/c
$Q^2 \sim 100\ (\text{GeV}/c)^2$

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



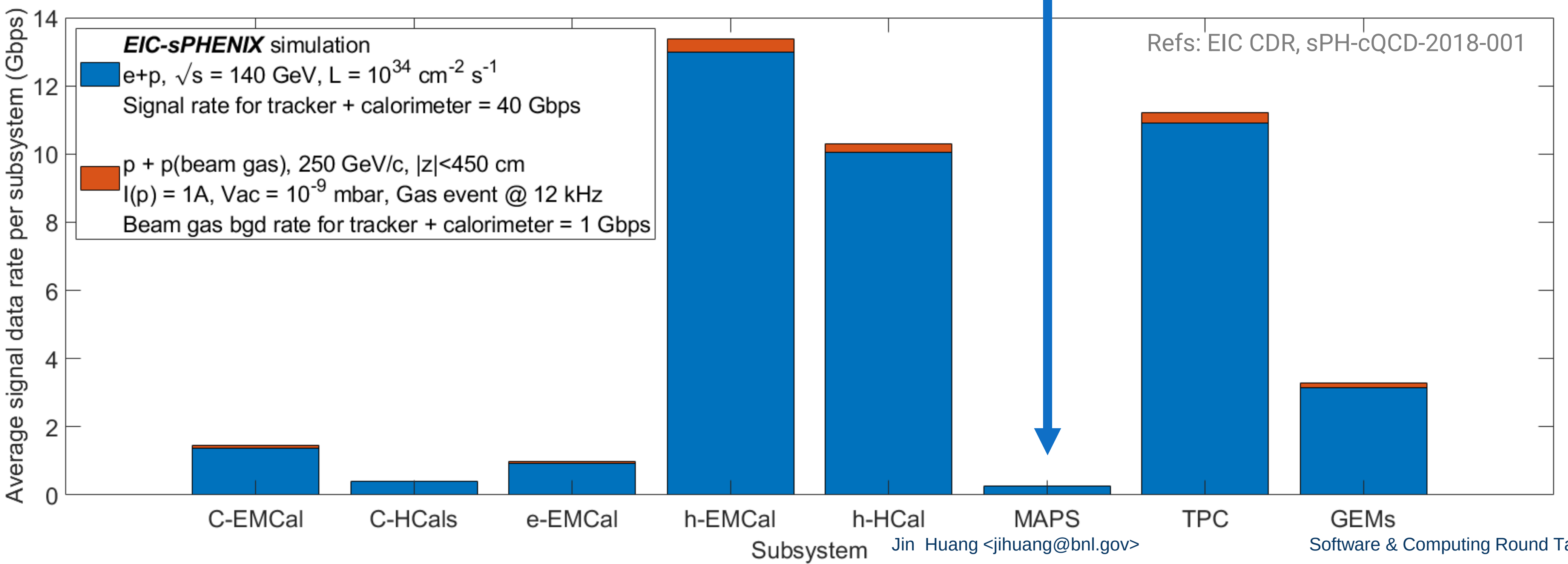
Data Rate



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

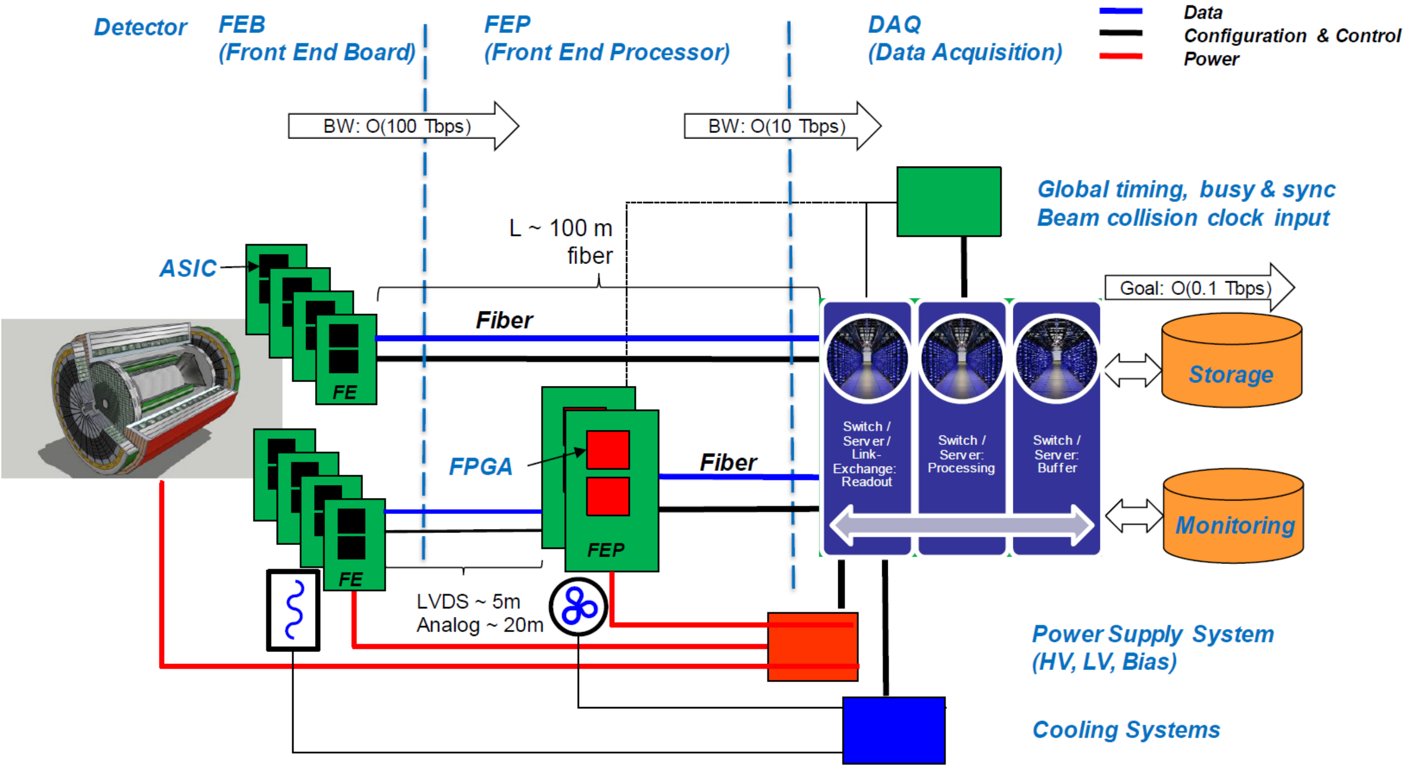
Signal data rate -> DAQ strategy

- What we want to record: total collision signal ~ 100 Gbps @ 10^{34} cm^{-2} s^{-1}
  - Assumption: sPHENIX data format, 100% noise, Less than sPHENIX peak disk rate. 10^{-4} comparing to LHC collision
- Therefore, we could choose to stream out all EIC collisions data
  - In addition, DAQ may need to filter out excessive beam background and electronics noise, if they become dominant.
  - Very different from LHC, where it is necessary to filter out uninteresting p+p collisions (CMS/ATLAS/LHCb) or highly compress collision data (ALICE)



Strategy for an EIC real-time system

- **EIC streaming DAQ**
  - → Triggerless readout front-end (buffer length : µs)
  - → DAQ interface to commodity computing (e.g. FELIX/CRU). Background filter if excessive background rate
  - → Disk/tape storage of streaming time-framed zero-suppressed raw data (buffer length : s)
  - → Online monitoring and calibration (latency : minutes)
  - → Final Collision event tagging in offline production (latency : days+)

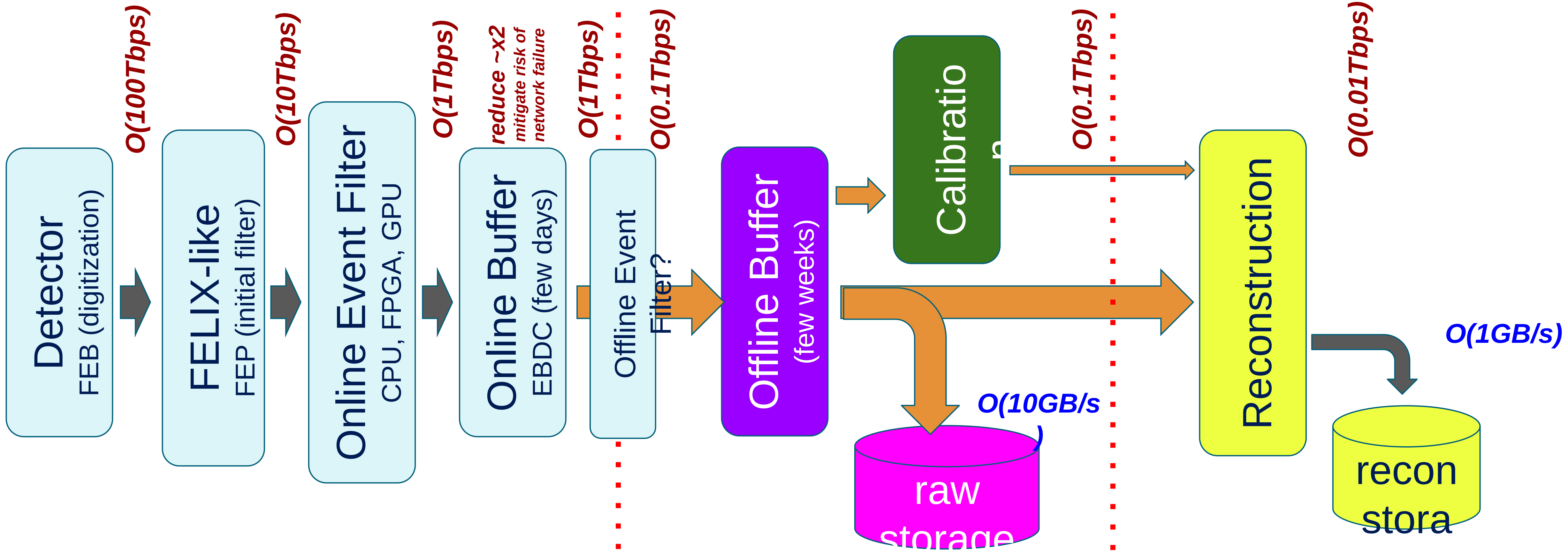


Ref: EIC-CDR

Blured boundary with offline computing

Countesy: David Lawrence
ECCE computing model [link]

See also: last talk M. Battaglieri



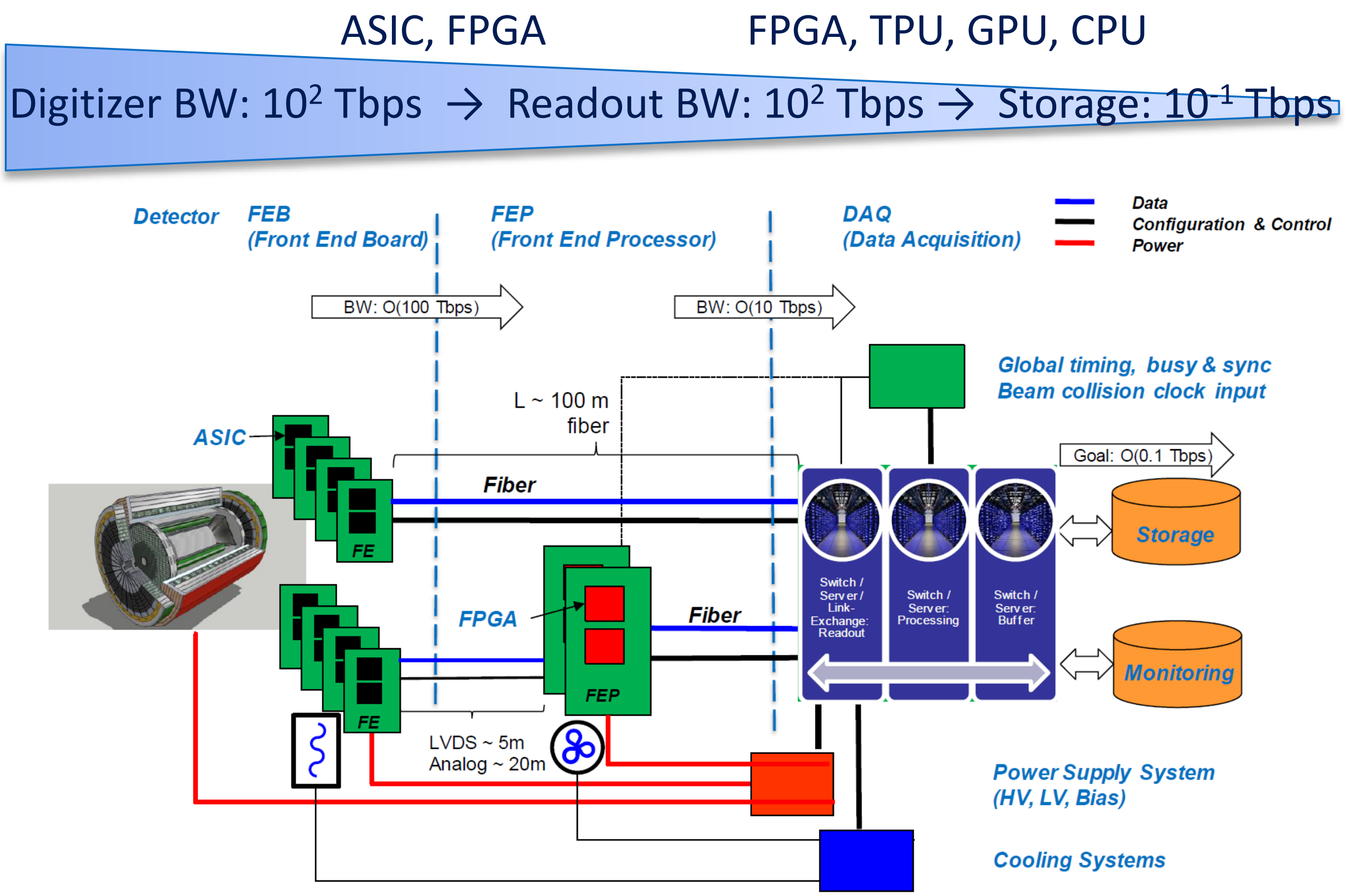
Experimental Hall and Counting House (Project Funds)

Data Center(s): SDCC [,JLab, …] (Operations Funds)

HTC Compute Facilities SDCC ,JLab, … (Operations)

Real-time computing for streaming data pipeline

- Despite low signal rate, the raw data rate can be filled with noises and background
  - Need low background & low noise detector & electronics design
- An essential job of EIC real-time computing: reliable streaming data reduction to fit permanent storage (next topics)
- And more traditional roles for online/offline server farm:
  - Online monitoring/fault det.
  - Calibration
  - Production → Initial analysis pass



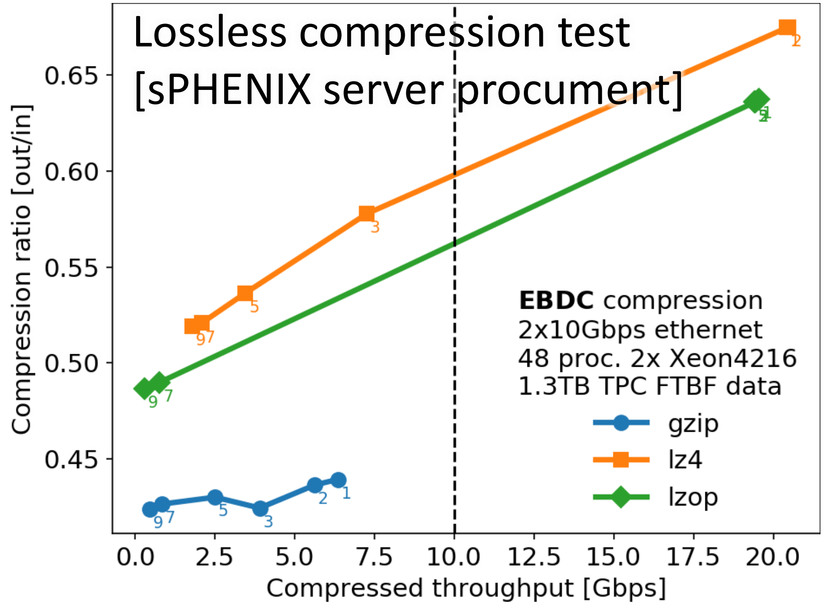
[EIC CDR]

Online computing for streaming data – trigger throttling

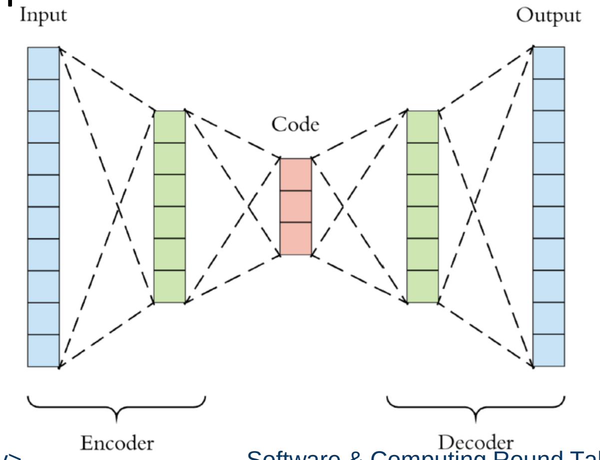
- At the beginning of the EIC operation, background & noise rate could be unpredictable and high
- A contingency method: throttling streaming data with triggering
  - Immediately reduce streaming data by orders of magnitudes
  - Widely used hardware producing trigger, fix latency or HLT (Aaji’s talk)
  - Has physics loss, added systematic uncertainty for hardware trigger efficiency
- Can utilize ML to produce more complex triggering on FPGA
  - PID trigger, e.g. ref: S. Furletov @ streaming workshop VIII [link]
  - Tracking-event topology trigger: D. Yu @ AI4EIC workshop [link]

Online computing for streaming data - compression

- Lossless compression
  - Compress by ~1/2
  - Well established fast compression algorithm
- Lossy compression
  - Opportunity for unsupervised machine learning based on data, e.g.
  - Auto-encoder on ASIC for HGCal @ CMS [link]
  - Bicephalous Convolutional Neural Encoder for zero-suppressed data (next)

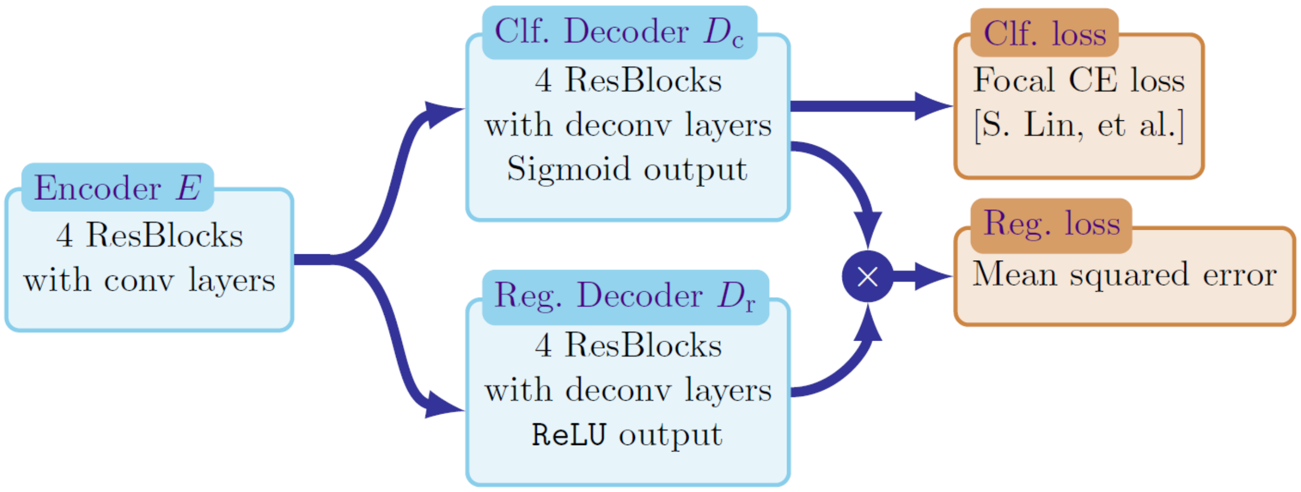


Simple auto-encode neural network

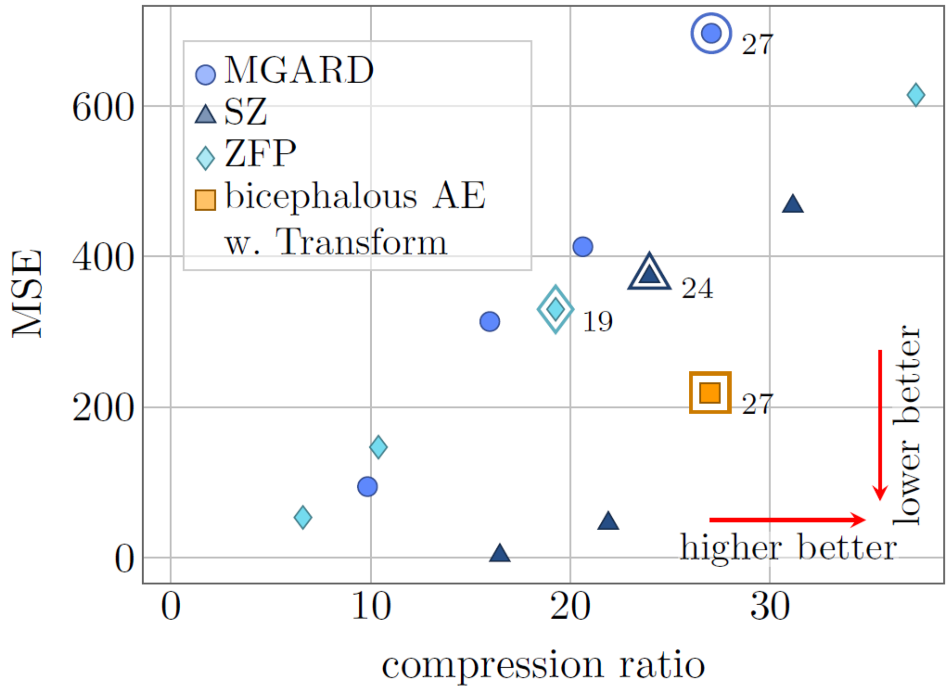


Bicephalous Convolutional Auto-Encoder for zero-suppressed data

- Some detector ADC data is challenging for Auto-Encoder, e.g. features such as zero-suppression cut off
- A dual-output auto encoder is designed to output both a region of interest and decompressed ADC. Possibility for further noise filtering
- Ref: Y. Huang @ AI4EIC workshop [link]



Compression comparison with published compressor tested on busiest sPHENIX TPC timeframes

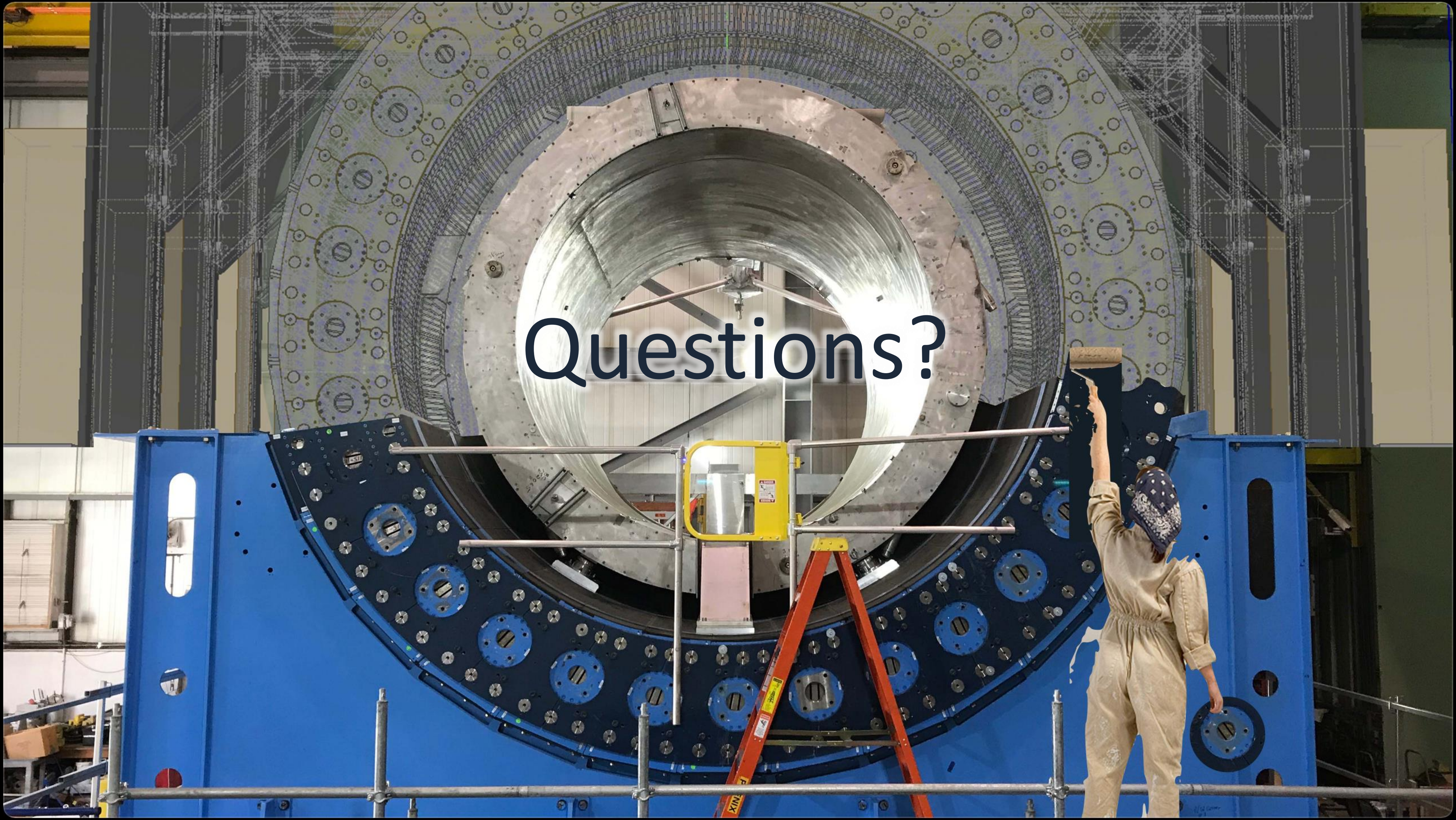


Online computing for streaming data - feature building

- Another effective way of suppressing background is feature building, e.g.
- Clustering on calorimeter
  - Effective in suppressing single tower noise
  - e.g. CLAS12 test as in M. Battaglieri's talk
- Tracklet building on tracker:
  - Effective in suppressing isolated noise, such as the synchrotron background
  - e.g. ALICE TPC streaming data [arXiv:1910.12214]. D. Yu @ AI4EIC workshop [link]
- ADC timeseries -> amplitude extraction
  - e.g. Specialized filters: C. Crawford @ Streaming readout VIII [link];
  - Neural network on ASIC: S. Miryala @ Streaming readout VIII [link]

Summary

- sPHENIX under construction for start of data taking in 2023
  - Recent development on streaming data (on top of streaming readout) for sPHENXI tracker show significant increase of physics capability
  - Strong link with EIC both technical implementation and physics program
- EIC is a unique collider with low x-section, high luminosity and stringent requirement on systematic control.
  - Streaming readout fit well, wide adoption in community [YR, CDR]
  - EIC collision signal data rate is low, but noise/background rate uncertain
  - EIC online computing: key development on reliable noise/background filtering



Remix credit: Dave Morrison

Extra information

EIC x-sec : further quantification [Courtesy E. Aschenauer]

- Inelastic e+p scattering x-sec:
  - For a luminosity of 10^{34} $cm^{-2}s^{-1}$ 50ub corresponds to **500 kHz**
- Elastic e+p cross-section:
  - For EIC central barrel, elastic cross section is **small** comparing to the inclusive QCD processes
- Beam gas interaction:
  - Beam proton – beam gas fix target inelastic interactions. The pp elastic cross section is smaller (~7 mb)
  - For a vacuum of 10^{-9} mbar in the detector volume (10m) this gives a rate of **14 kHz**

Beam [GeV]	HERA	5 x 50	10 x 100	18 x 275
$Q^2>10^{-9}$ GeV	65.6	**29.9**	**41.4**	**54.3 ub**
$Q^2>1$ GeV	1.29	0.45	0.65	0.94 ub

Beam [GeV]	HERA	5 x 50	10 x 100	18 x 275
σ [y_{Exp} >-4]	5 pb	**5 ub**	**0.7 ub**	**0.06 ub**
σ [y_{Exp} >-6]	11 ub	420 ub	100 ub	29 ub

E_p:	50 GeV	100 GeV	275 GeV	920 GeV
	38.4 mb	**38.4 mb**	**39.4 mb**	41.8 mb

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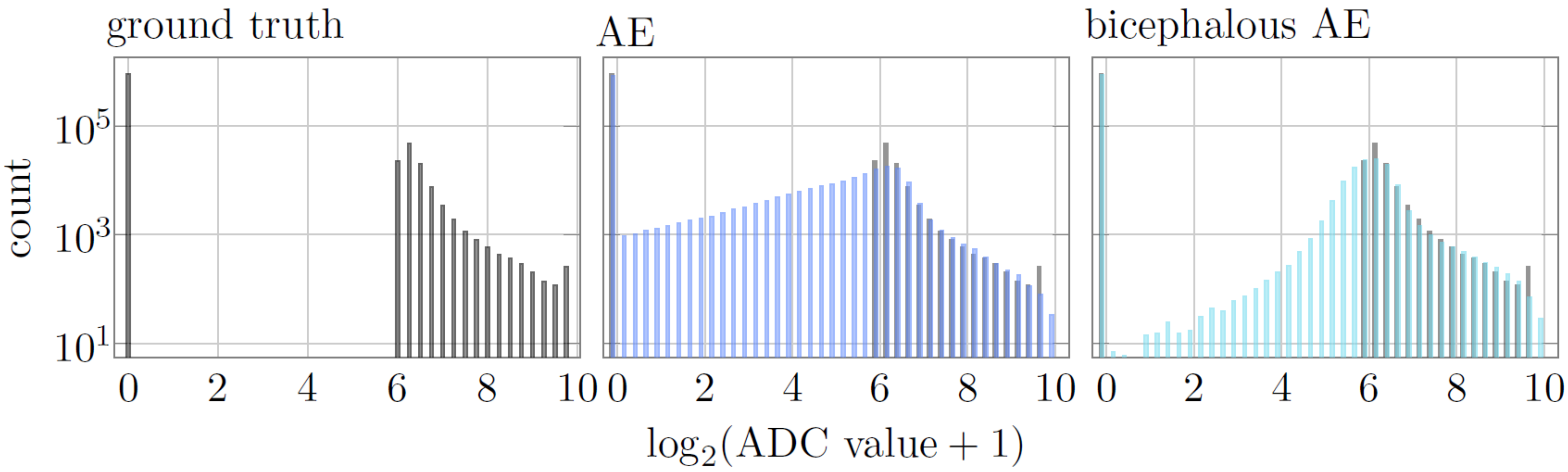
Results I: AE v.s. Bicephalous AE

Compression ratio is 1 : 27

(1 : 3 for SAMPA ASIC for this busiest event)



Result III. Ablation Study

ground truth | AE | bicephalous AE | bicephalous AE w. transform