sPHENIX TPC and Real-time AI

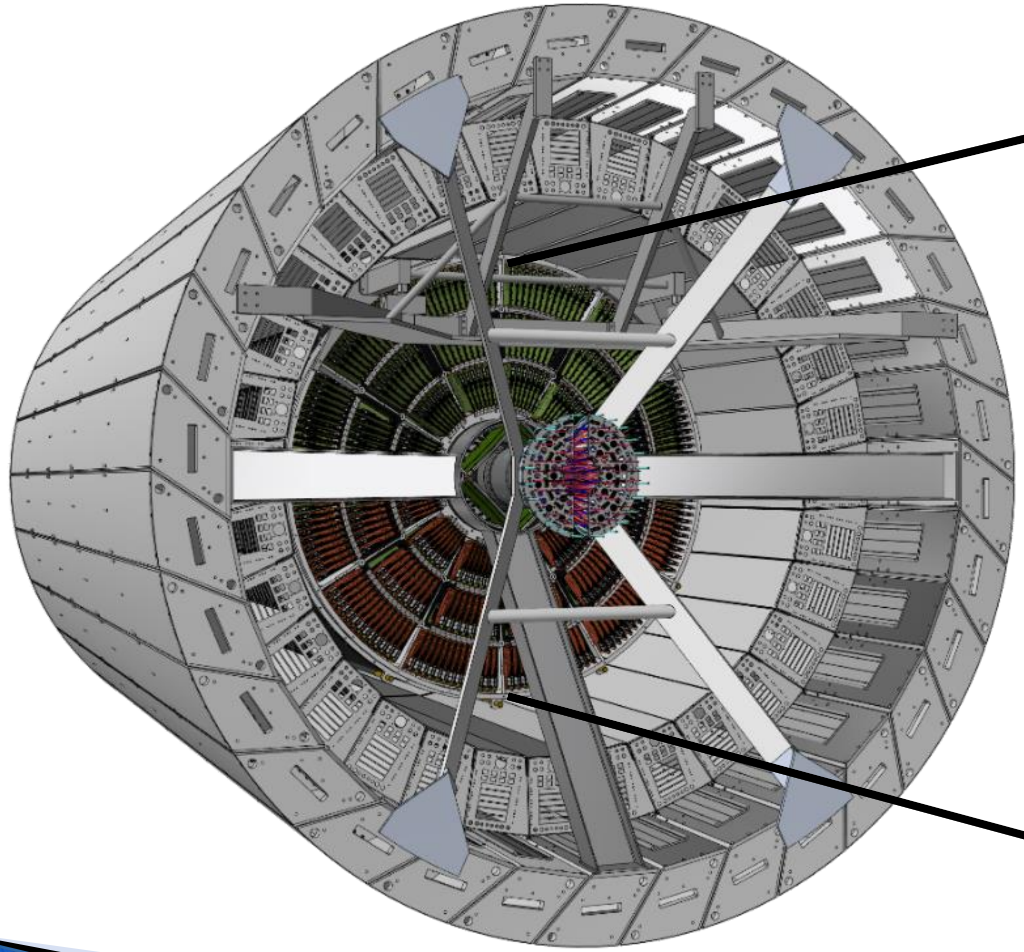
Outline: ● sPHENIX TPC Year-1 Commissioning ● Applications of Realtime AI (LDRD 23-048) ● Summary

Jin Huang

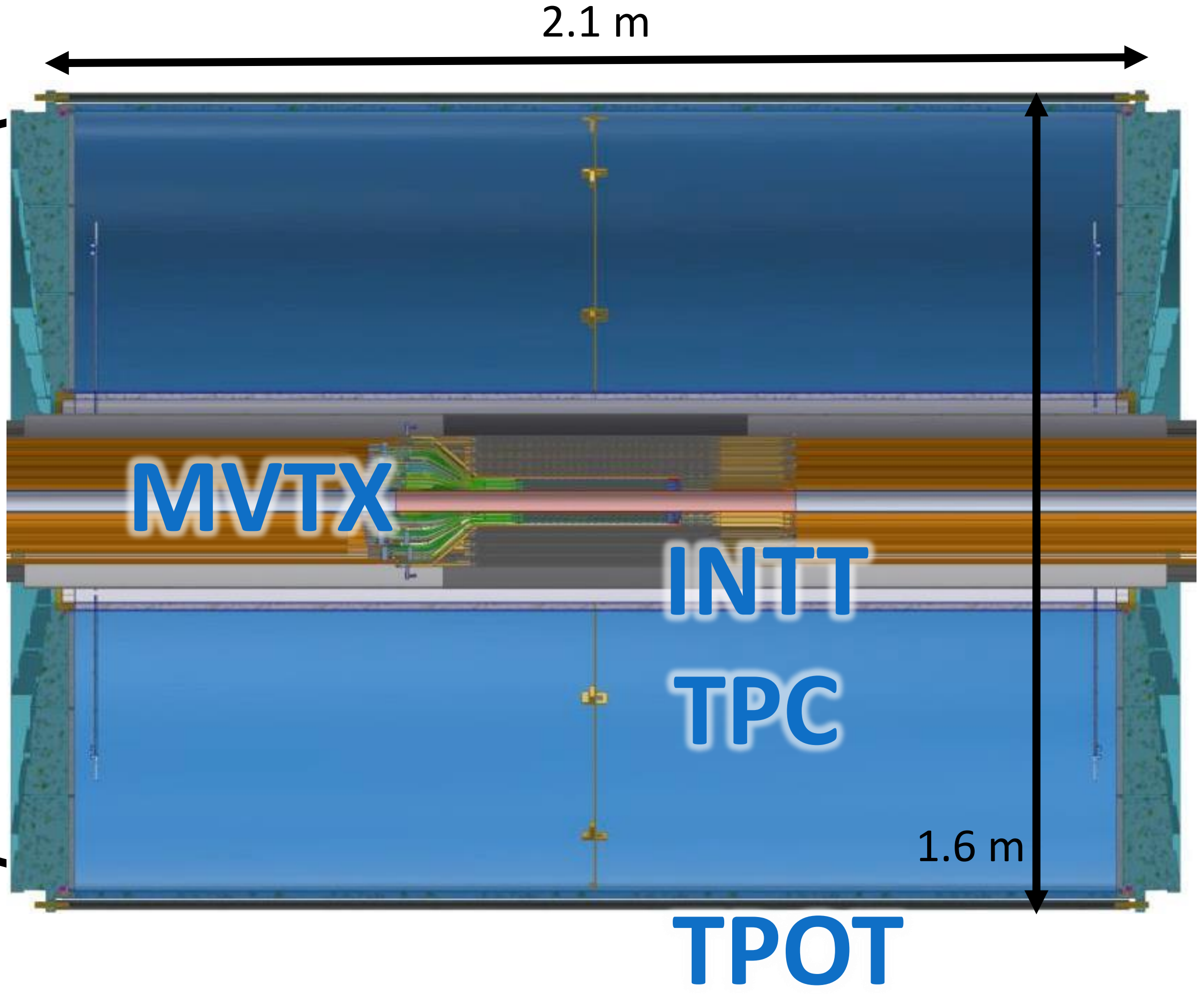
Brookhaven National Lab


sPHENIX experiment
Completed first/commissioning run in 2023!
See also: M. Purschke's talk Just now
ABLE

sPHENIX Tracking Detectors



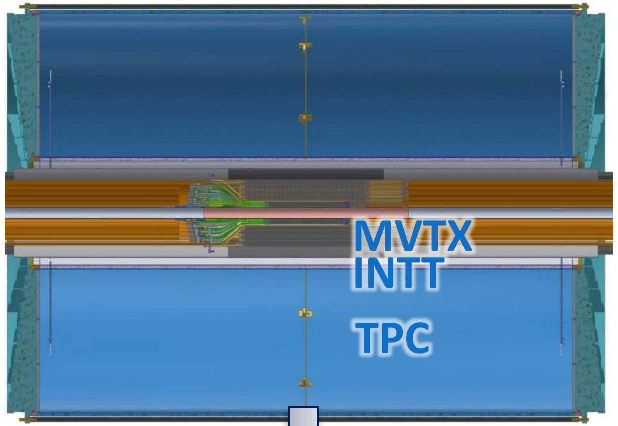
Detectors inside the magnet

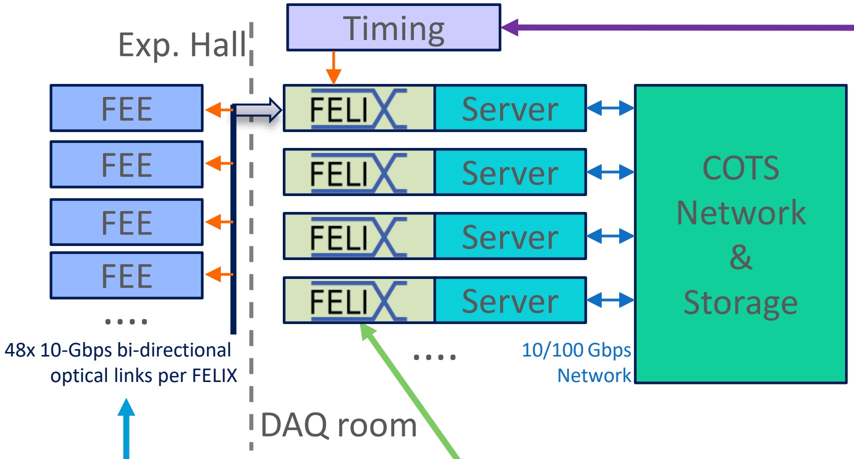


Streaming readout electronics

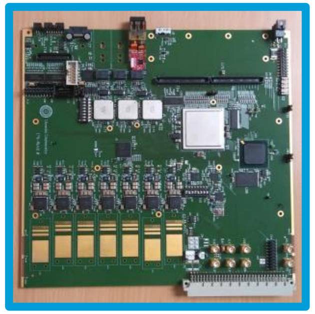
Plan to recording 10% p+p collisions in hybrid streaming DAQ
→ 2-3 orders of magnitude increase in soft-HF statistics

sPHENIX streaming DAQ for tracker





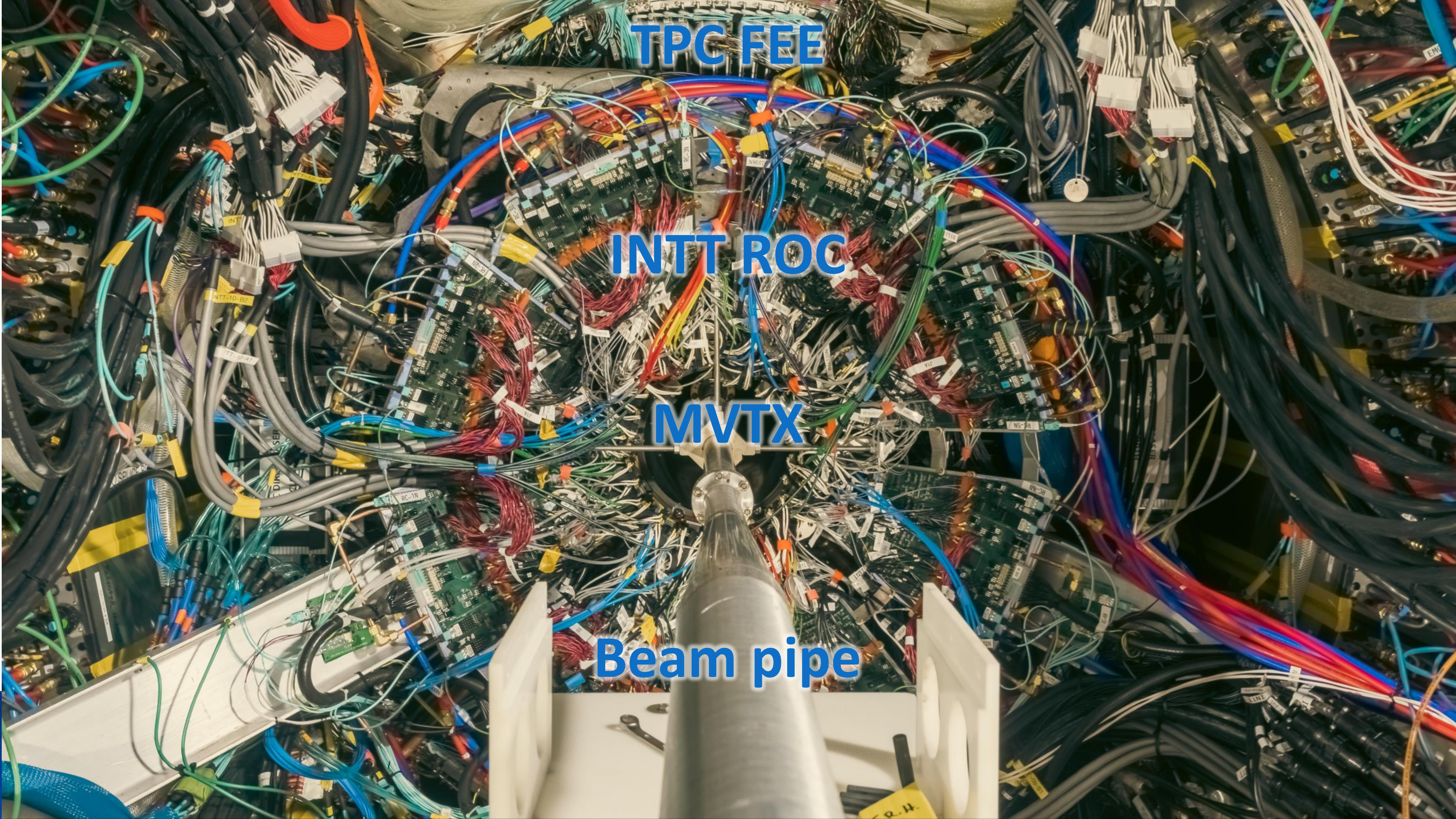
Global Timing Module (NSLS II/sPHENIX) Receiving from RHIC RF low glitter clock source



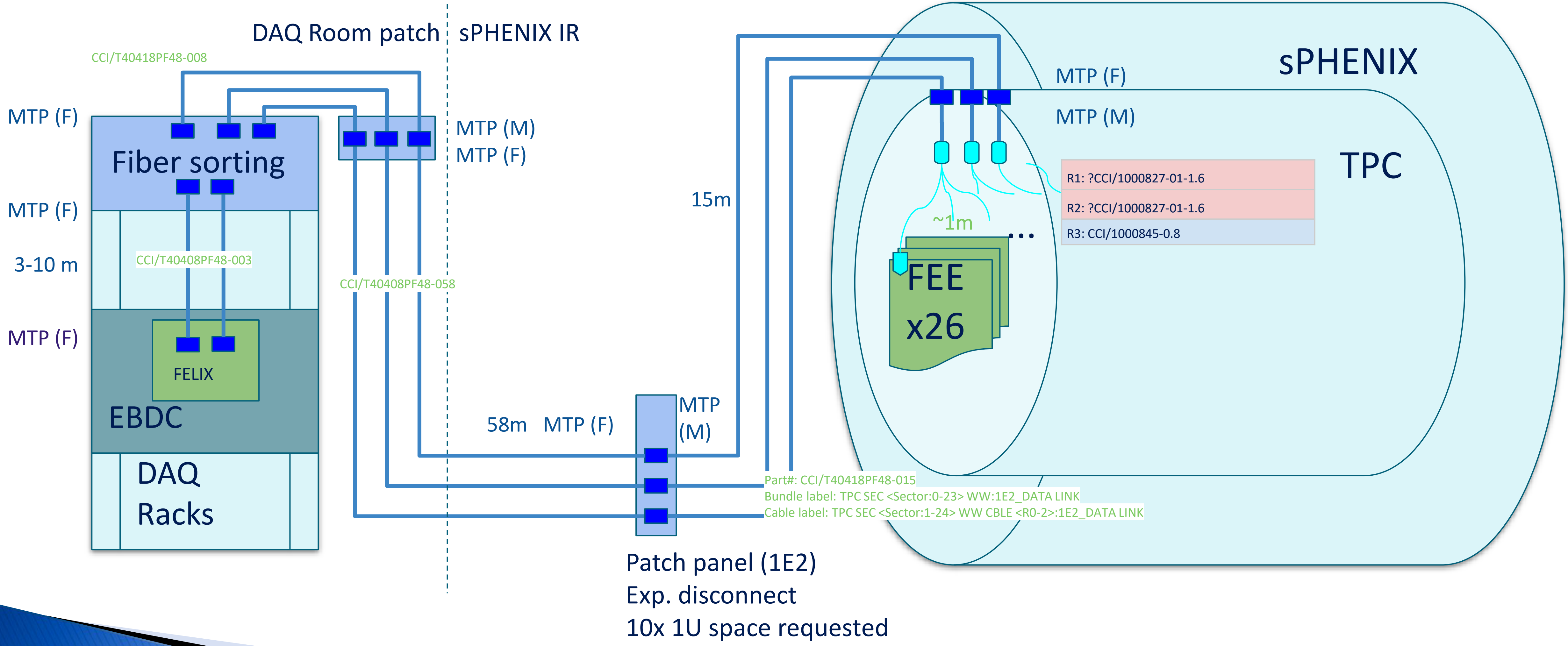
MVTX RU, 200M ch INTT ROC, 400k ch
ALPIDE (ALICE/sPHENIX), FPHX (PHENIX)

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

BNL-712 / FELIX v2 x38 (ATLAS/sPHENIX)
FELIX Ref: 10.1109/tim.2019.2947972


TPC FEE
INTT ROC
MVTX
Beam pipe

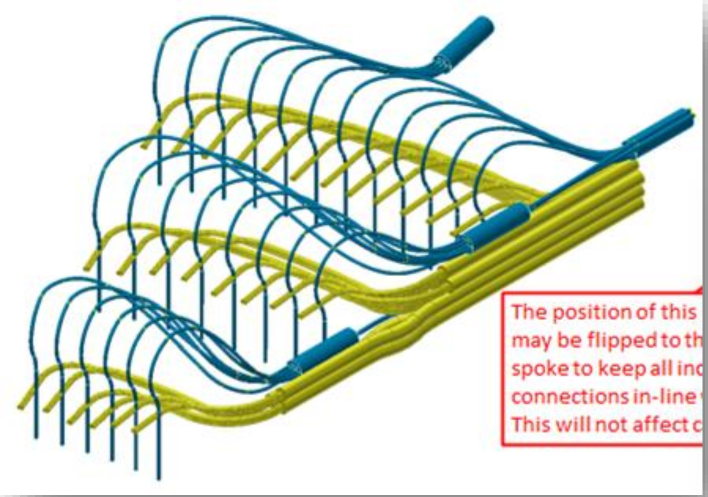
sPHENIX TPC Data Fiber Cabling Plan, 1 of 24 sectors shown



48F MTP Cable MTP coupler MTP-QSFP breakout QSFP MTP cable QSFP Transceiver

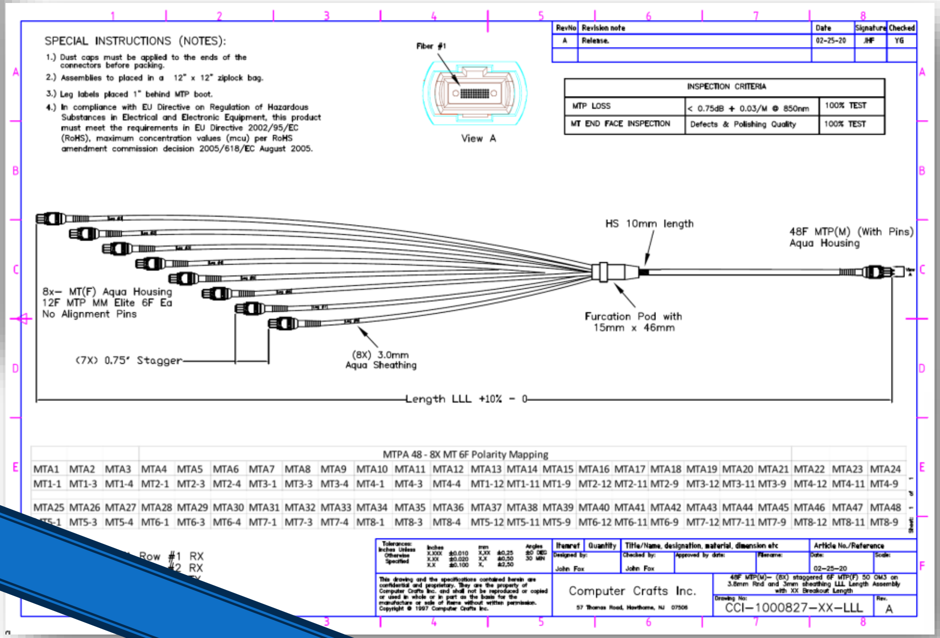
One-way optical loss: 1.5dB

Custom MTP-48 to MTP-12 breakout

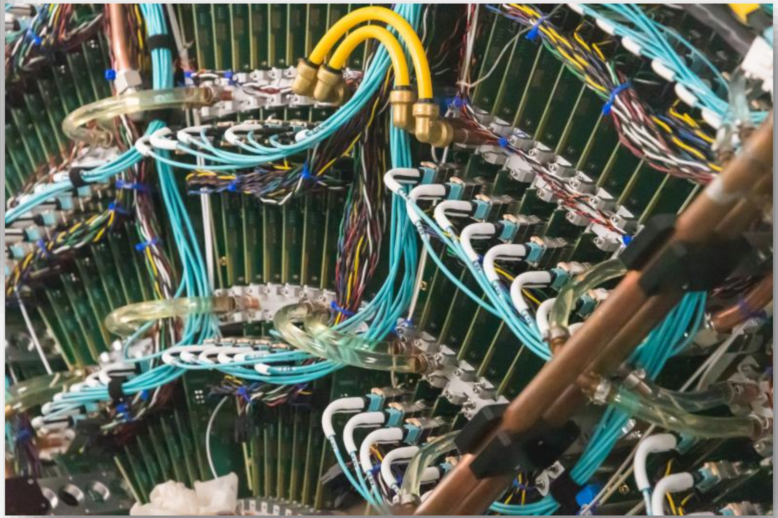


Mechanical and channel-mapping design at BNL

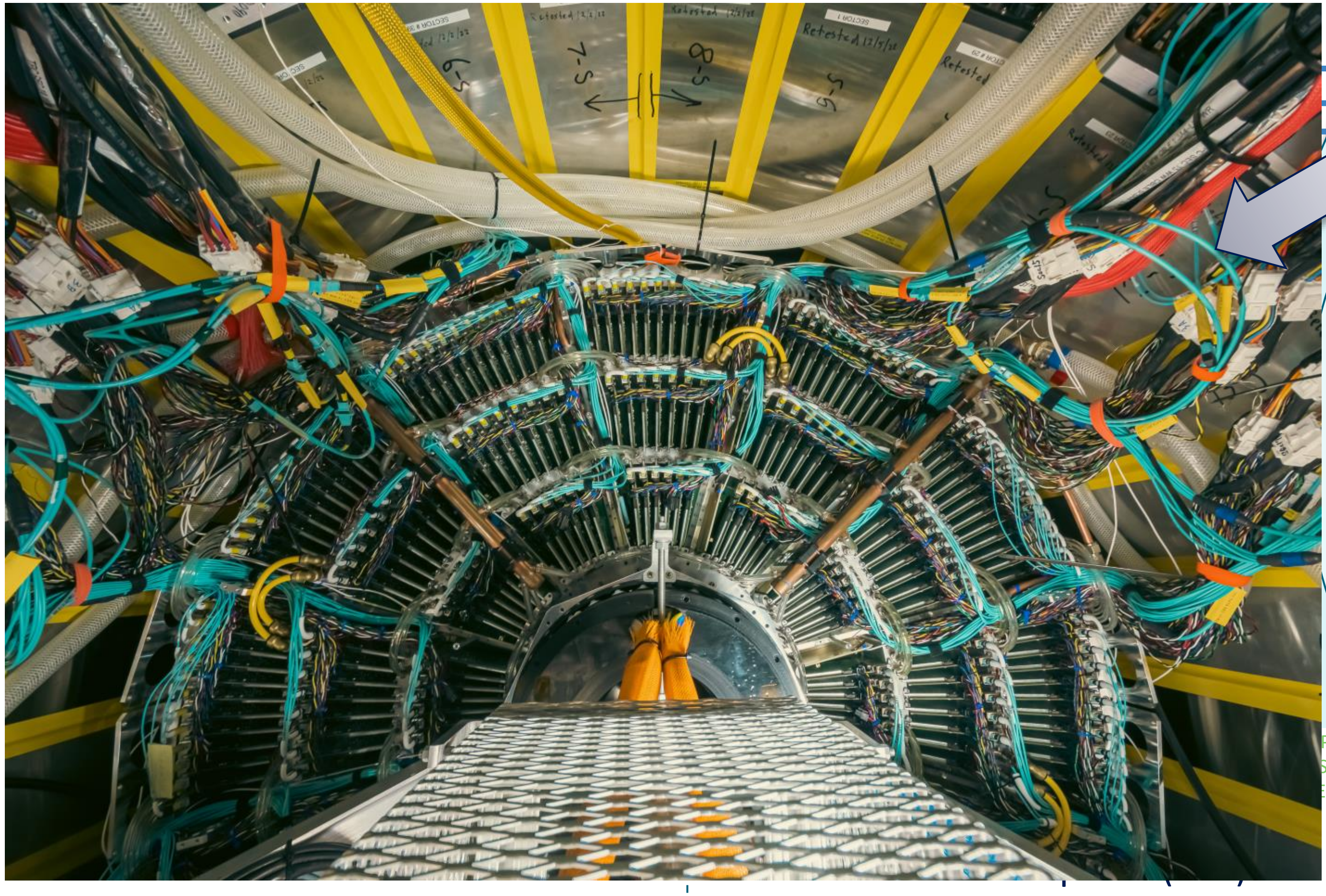
Drawing and manufacture/QA at CCI: ~$500 + 4wk LT

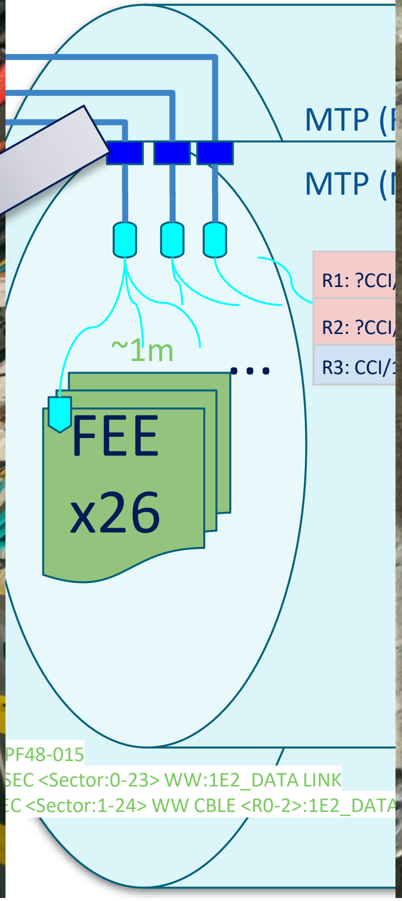


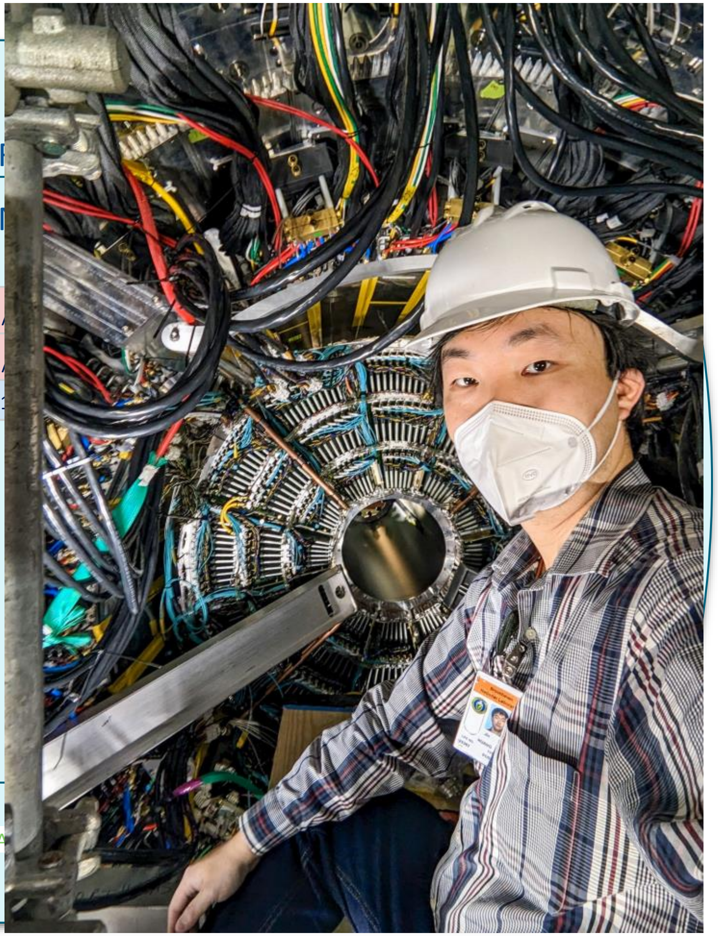
Installation at sPHENIX



sPHENIX TPC Data Fiber Cabling Plan, 1 of 24 sectors shown





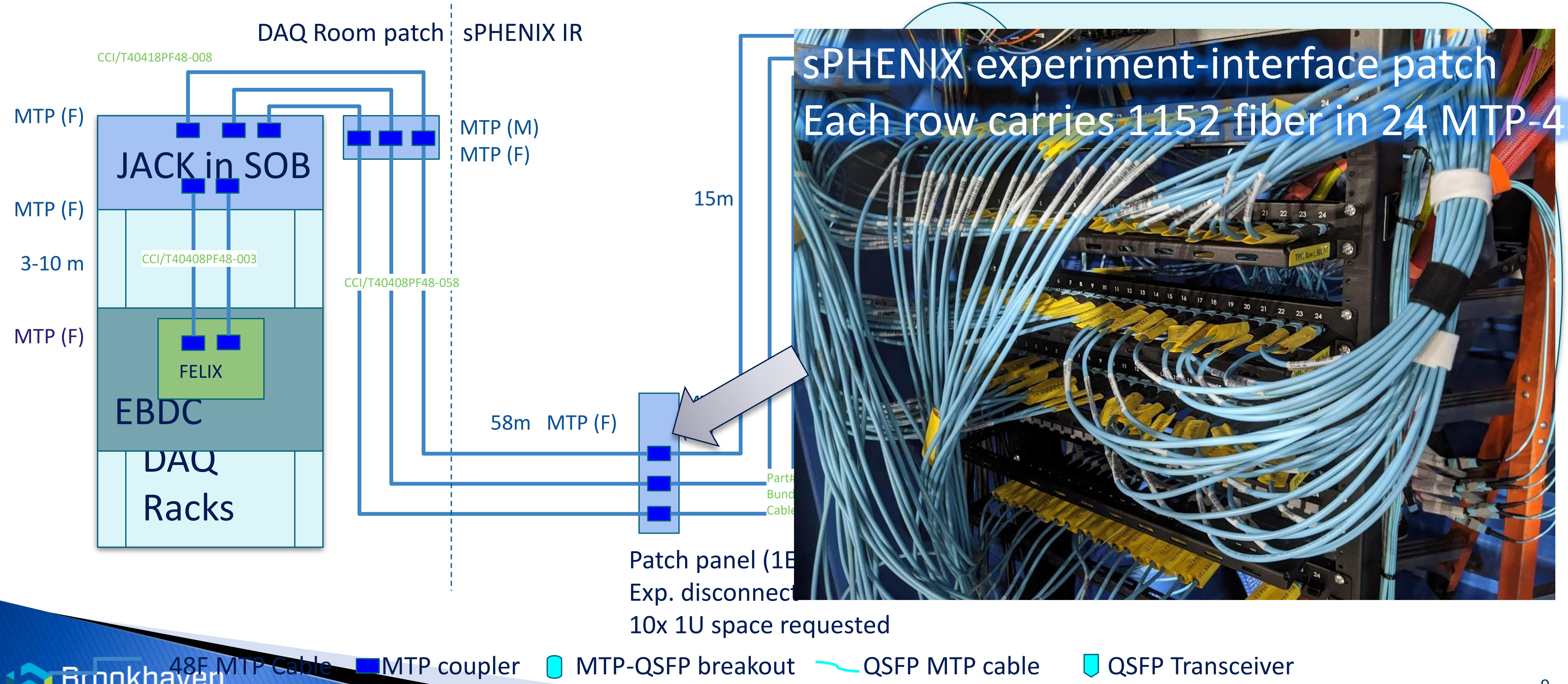


Exp. disconnect
10x 1U space requested

48F MTP Cable | MTP coupler | MTP-QSFP breakout | QSFP MTP cable | QSFP Transceiver

One-way optical loss: 1.5dB

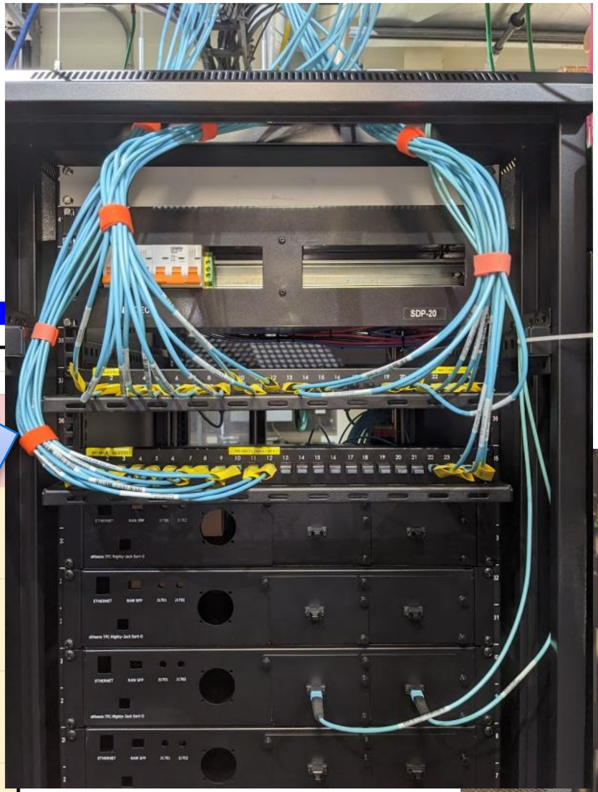
sPHENIX TPC Data Fiber Cabling Plan, 1 of 24 sectors shown

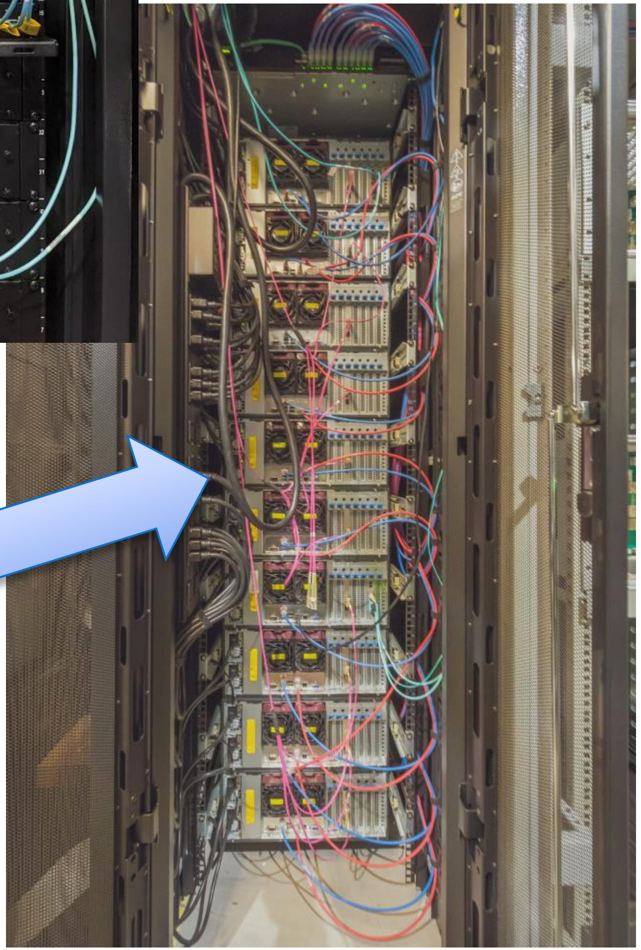


One-way optical loss: 1.5dB

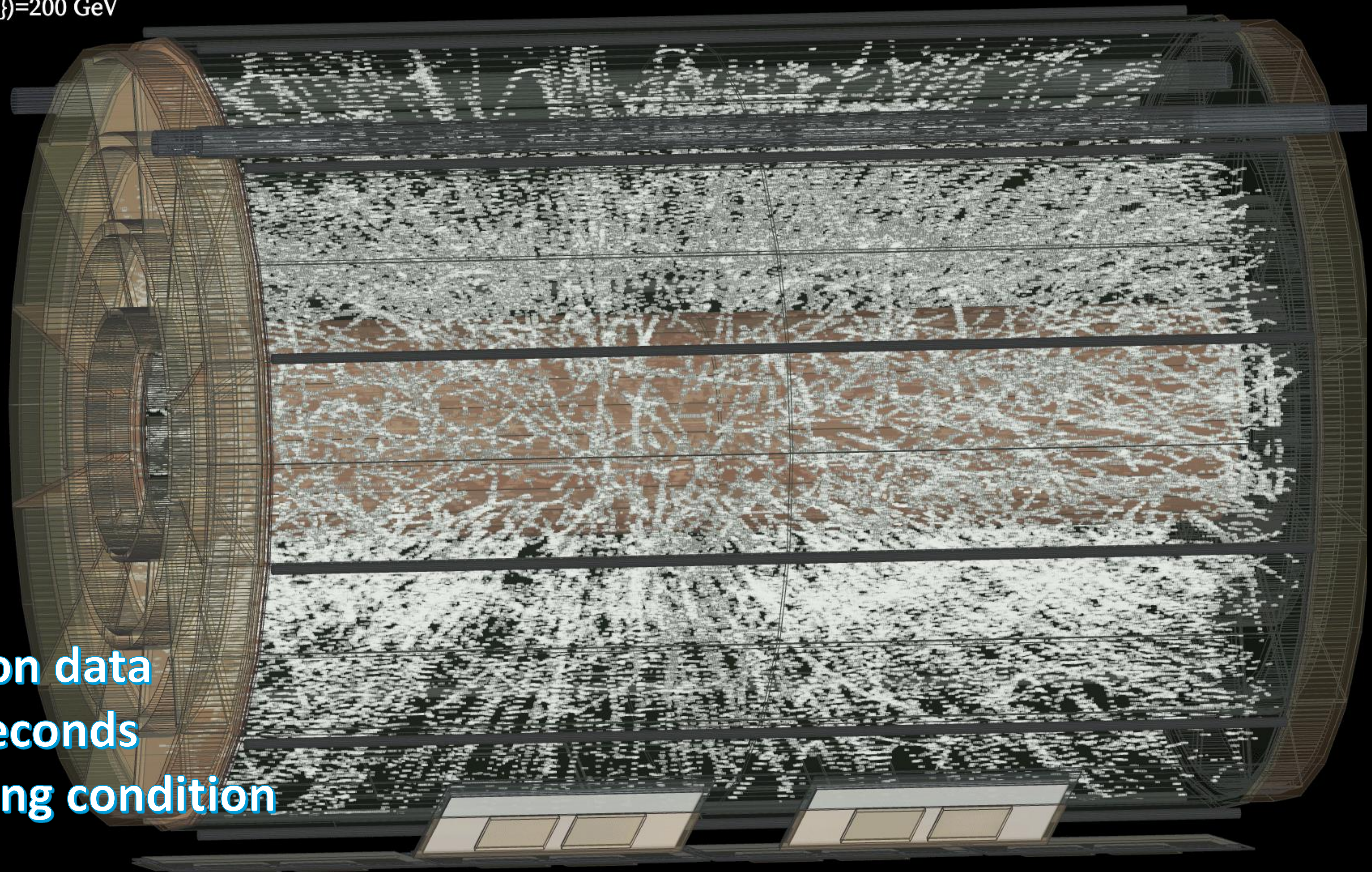
Rack room layout

Row 3, viewed outside in								
Assignment Rack	RHIC infrastructure 3.1	LL1 3.2	EBDC TPC South 3.3	Patch/ TPC SOB South 3.4	BDC TPC North/Sou 3.5	Patch/ TPC SOB North 3.6	EBDC TPC South 3.7	EBDC Other 3.8
	1	1	1	1 Fiber Patch MVTX	1	1 Fiber Patch INTT	1	1
	2	2	2	2 Fiber Patch	2	2 Fiber Patch INTT	2	2
	3	3	3	3 Fiber Patch	3	3 Fiber Patch	3	
	4	4	4 EBDC MVTX 1	4 Fiber Patch	4 EBDC TPC S5	4 Fiber Patch	4 EBD	
	5	5	5	5 Fiber Patch TPC S1-4	5	5 Fiber Patch TPC N1-		
	6	6	6	6 Fiber Patch TPC S5-8	6	6 Fiber Patch TPC N5-8		6
	7	7	7	7 Fiber Patch TPC S9-12	7	7 Fiber Patch TPC N9-12		7
	8	8	8 EBDC MVTX 2	8	8 EBDC TPC S6	8	8 EBDC TPC N4	8 EBDC INTT1
	9	9	9	9	9	9	9	9
	10	10	10	10 SOB Spare	10	10 SOB TPOT	10	10
	11	11	11	11	11	11	11	11
	12	12	12 EBDC MVTX 3	12 SOB S1	12 EBDC TPC S7	12 SOB N1	12 EBDC TPC N5	12 EBDC INTT2
	13	13	13	13	13	13	13	13
	14	14	14	14 SOB S2	14	14 SOB N2	14	14
	15	15	15	15	15	15	15	15
	16	16	16 EBDC MVTX 4	16 SOB S3	16 EBDC TPC S8	16 SOB N3	16 EBDC TPC N6	16 EBDC INTT3
	17	17	17	17	17	17	17	17
	18	18	18	18 SOB S4	18	18 SOB N4	18	18
	19	19	19	19	19	19	19	19
	20	20	20 EBDC MVTX 5	20 SOB S5	20 EBDC TPC S9	20 SOB N5	20 EBDC TPC N7	20 EBDC INTT4
	21	21	21	21	21	21	21	21
	22	22	22	22 SOB S6	22	22 SOB N6	22	22
	23	23	23	23	23	23	23	23
	24	24	24 EBDC MVTX 6	24 SOB S7	24 EBDC TPC S10	24 SOB N7	24 EBDC TPC N8	24 EBDC INTT5
	25	25	25	25	25	25	25	25
	26	26	26	26 SOB S8	26	26 SOB N8	26	26
	27	27	27	27	27	27	27	27
	28	28	28 EBDC TPC S1	28 SOB S9	28 EBDC TPC S11	28 SOB N9	28 EBDC TPC N9	28 EBDC INTT6
	29	29	29	29	29	29	29	29
	30	30	30	30 SOB S10	30	30 SOB N10	30	30
	31	31	31	31	31	31	31	31
	32	32	32 EBDC TPC S2	32 SOB S11	32 EBDC TPC S12	32 SOB N11	32 EBDC TPC N10	32 EBD
	33	33	33	33	33	33	33	
	34	34	34	34 SOB S12	34	34 SOB N12	34	
	35	35	35	35	35	35	35	
	36	36	36 EBDC TPC S3	36 SOB Spare	36 EBDC TPC N1	36 SOB Spare	36 EBDC TPC	36 EBDC INTT8
	37	37	37	37	37	37	37	37
	38	38	38	38 SOB Spare	38	38 SOB Spare	38	38
	39	39	39	39	39	39	39	39
	40	40	40 EBDC TPC S4	40	40 EBDC TPC N2	40	40 EBDC TPC N12	40 EBDC Spare
	41	41	41	41	41	41	41	41
	42	42	42	42	42	42	42	42



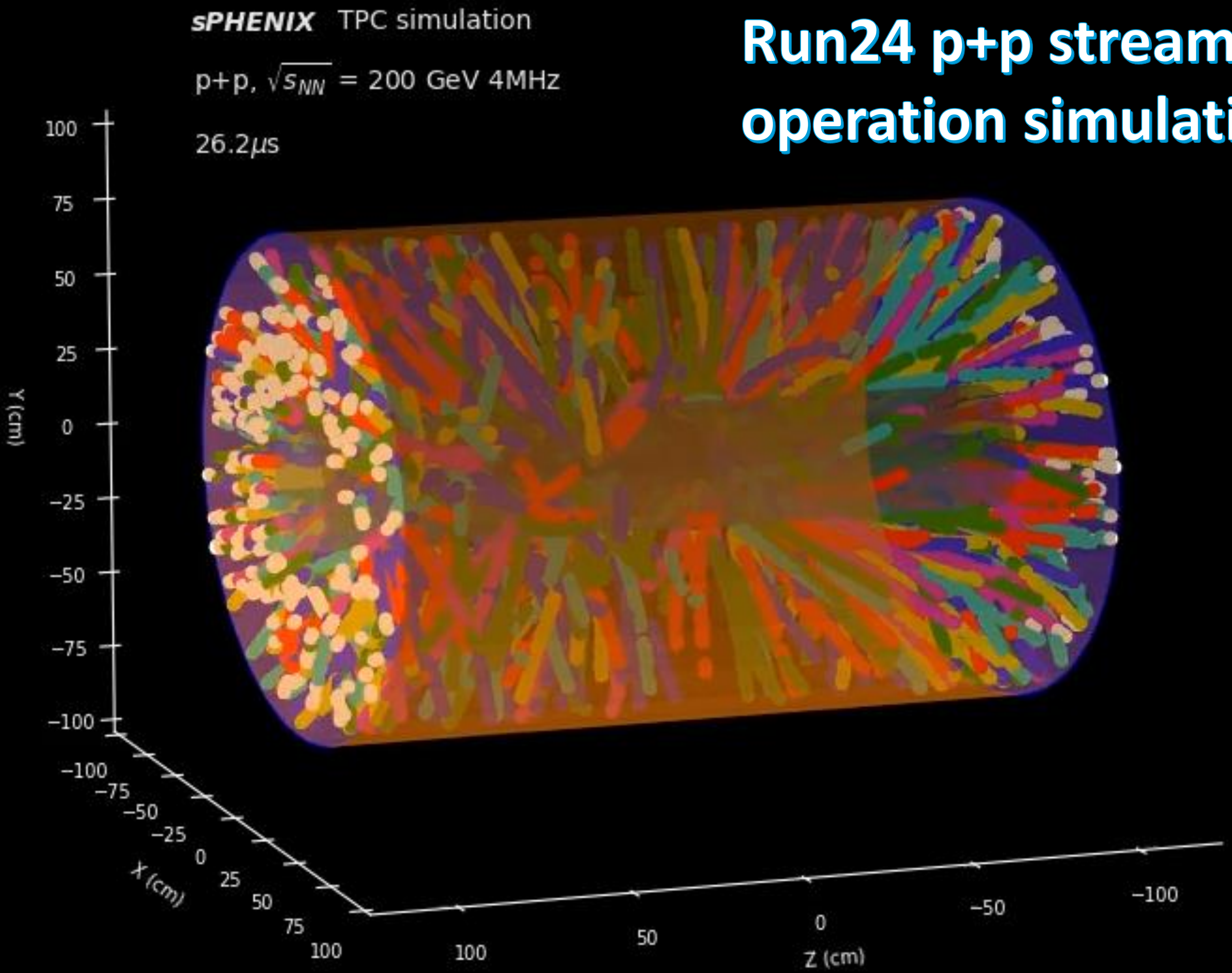


sPHENIX Time Projection Chamber
100 Hz ZDC, MBD Prescale: 2, HV: 4.45 kV GEM, 45 kV CM, X-ing Angle: 2 mrad
2023-06-23, Run 10931 - EBDC03 reference frame 43
Au+Au sqrt(s_{NN})=200 GeV



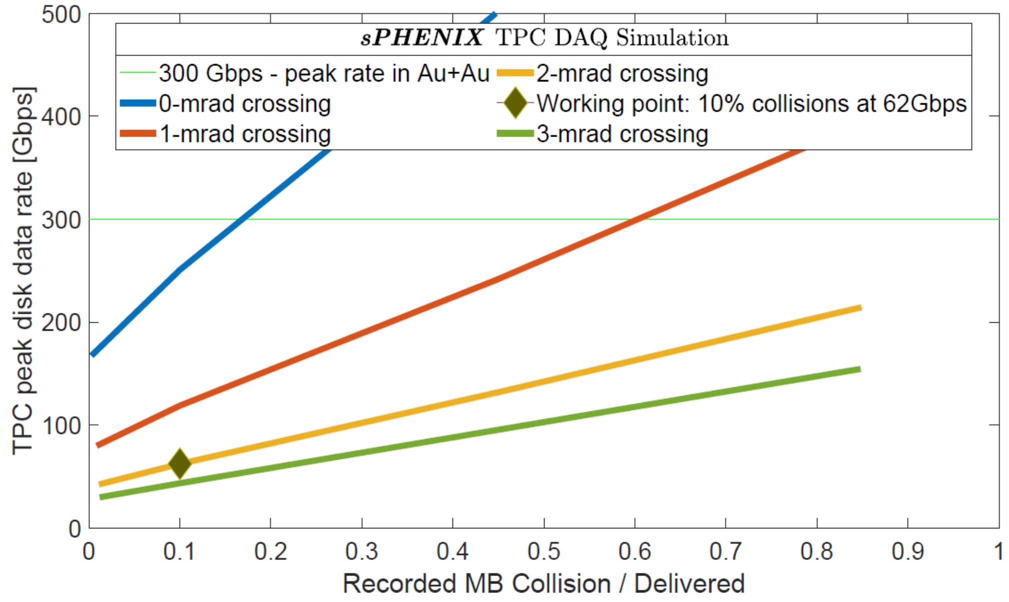
Run23 AuAu collision data
Taken in first few seconds
after TPC in operating condition

Run24 p+p streaming operation simulation



Streaming readout status at sPHENIX

- All three sPHENIX tracking detector uses streaming readout
- Developed plan to take 10% streaming data for heavy flavor physics program commended by RHIC PAC.



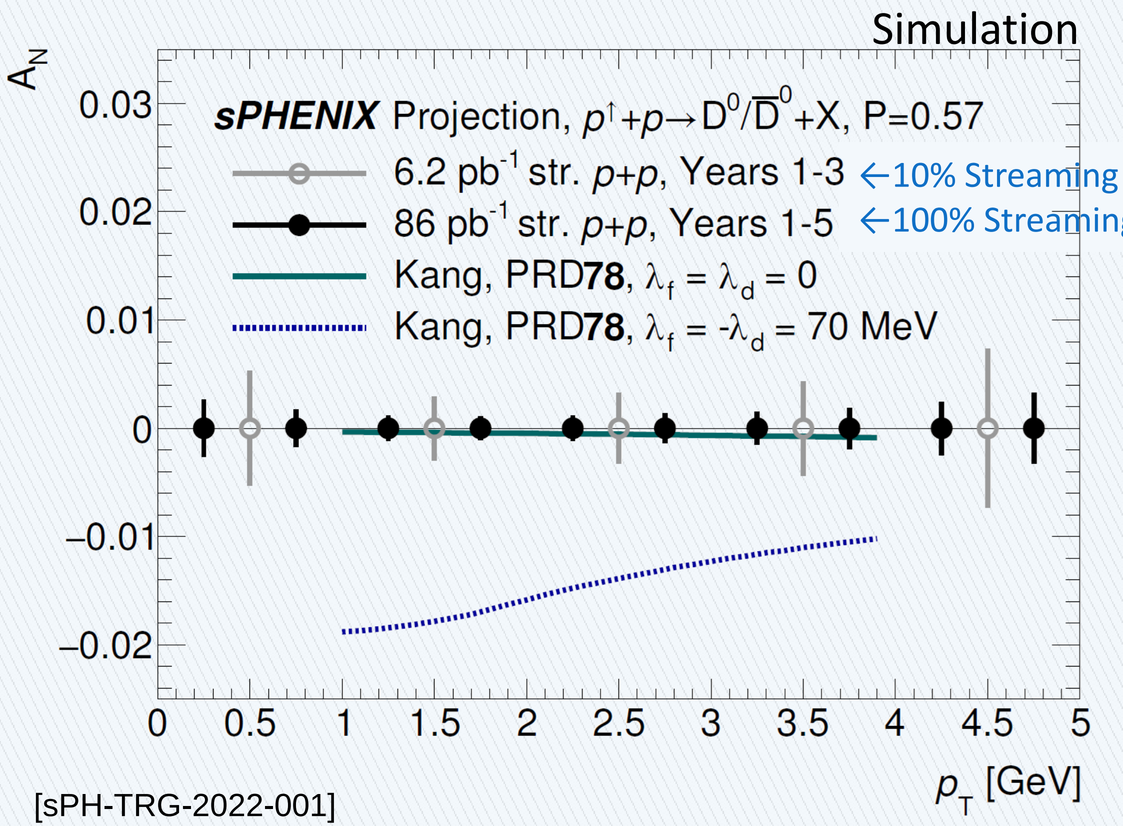
RHIC PAC 2020 report

> 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.

Streaming-DAQ enabled scientific connection: e.g. gluon dynamics via heavy flavor transverse spin asym.

Universality test on gluon Sievers

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



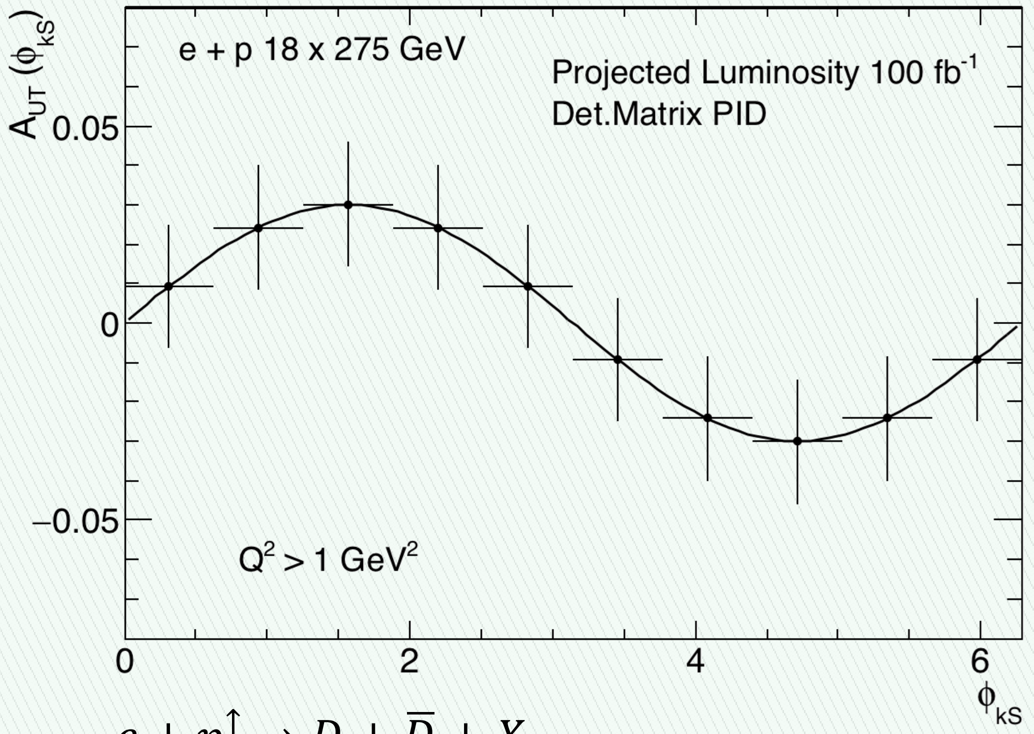
←10% Streaming DAQ

←100% Streaming DAQ

[sPH-TRG-2022-001]

Model: 10.1103/PhysRevD.78.114013

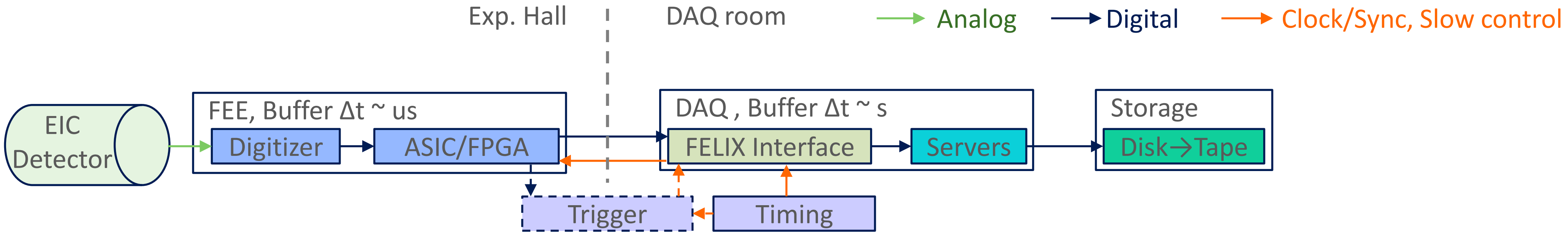
EIC SIDIS D^0 transverse spin asymmetry → Gluon Sievers

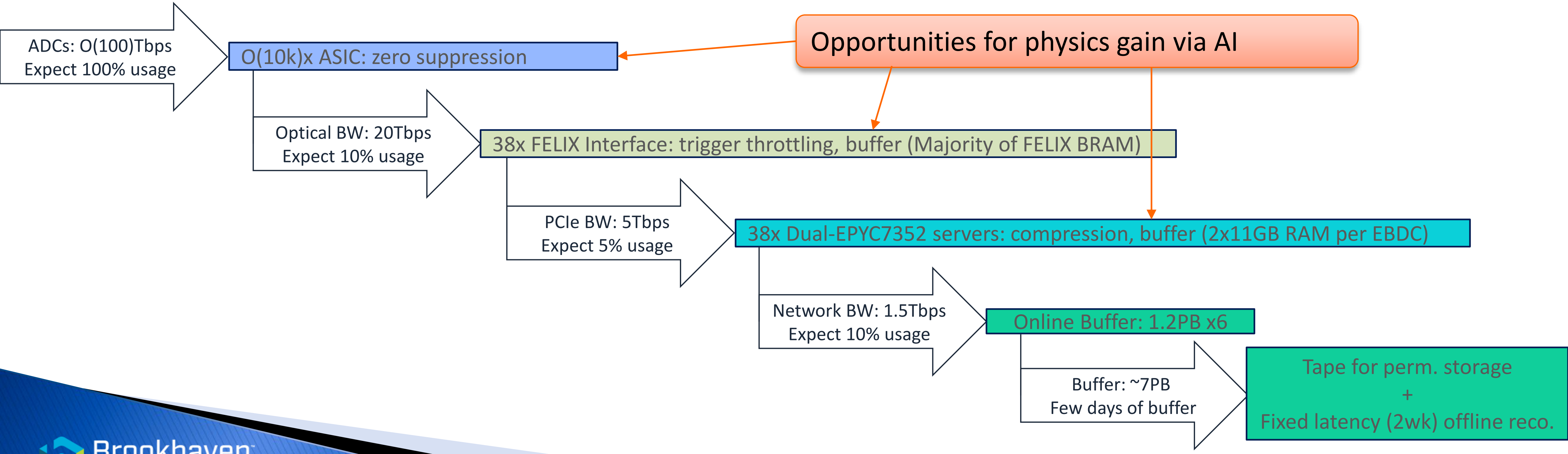


$e + p^{\uparrow} \rightarrow D + \overline{D} + X$

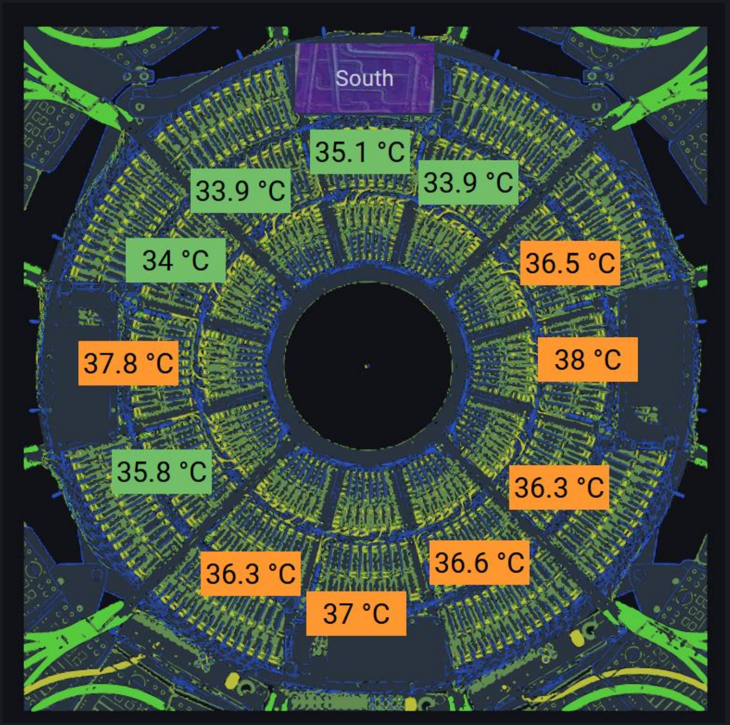
[CNFS HF@EIC workshop, Nov 4-6, 2020]

sPHENIX Streaming data flow





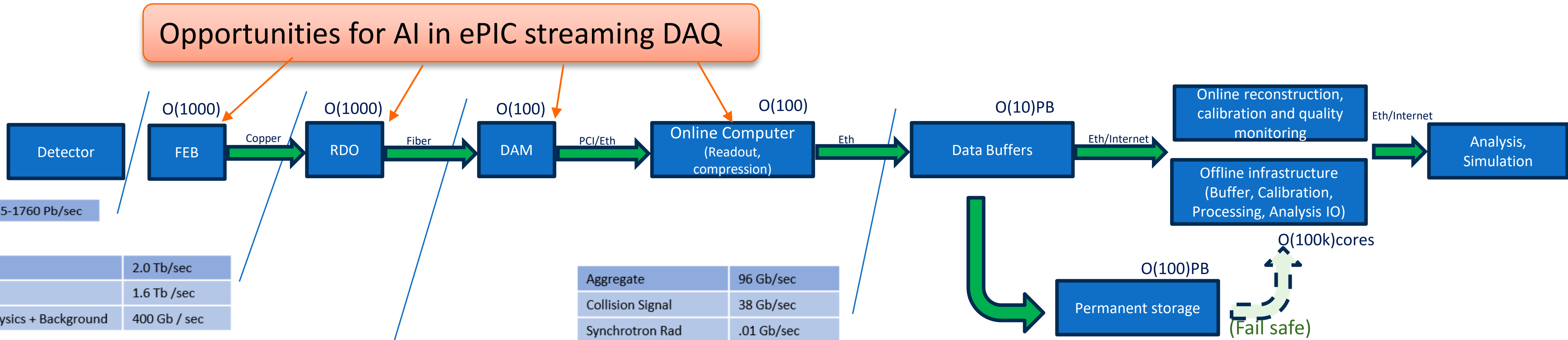
SRO pipeline monitoring via TSDB + Grafana



FEE PCB temperature during first collision data taking
Part of SRO control data stream

Data pipeline monitoring during the max throughput stress test at 7GBps for each PCIe EP
→ 2.7Tbps FEE to server memory readout (without the limit of file logging)

ePIC streaming DAQ-computing
See also: Jeff Landgraf's talk later today



100% Occupancy	27.5-1760 Pb/sec

Aggregate	2.0 Tb/sec
Noise	1.6 Tb /sec
Signal from Physics + Background	400 Gb / sec

Aggregate	2.0 Tb/sec
Per RDO (Avg)	.7 Gb/sec

Aggregate	96 Gb/sec
Collision Signal	38 Gb/sec
Synchrotron Rad	.01 Gb/sec
Electron Beam	22Gb/sec
Hadron Beam	4 Gb/sec
Noise	32 Gb/sec

Throughout the data flow: monitoring, QA, feedback towards operation

Latency :

0ns O(100)ns O(1)us O(10)us O(1)min O(1)min-O(1) day O(1)day-O(1)week

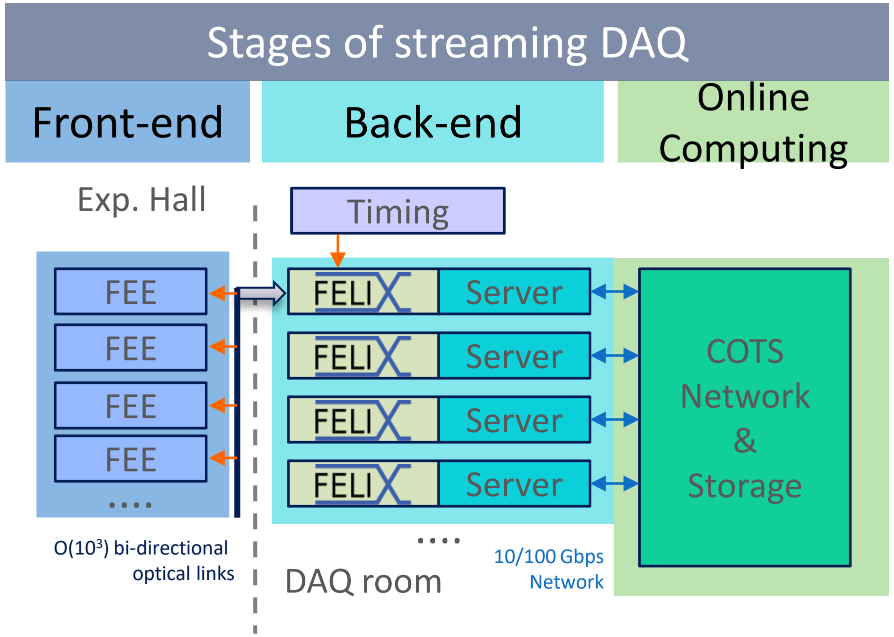
Possible facilities:

On detector On detector/rack DAQ room Host labs/Echelon 1 facility Remote resources

Reference:
- ePIC DAQ wiki: https://wiki.bnl.gov/EPIC/index.php?title=DAQ
- ECCE computing plan, *Nucl.Instrum.Meth.A* 1047 (2023) 167859

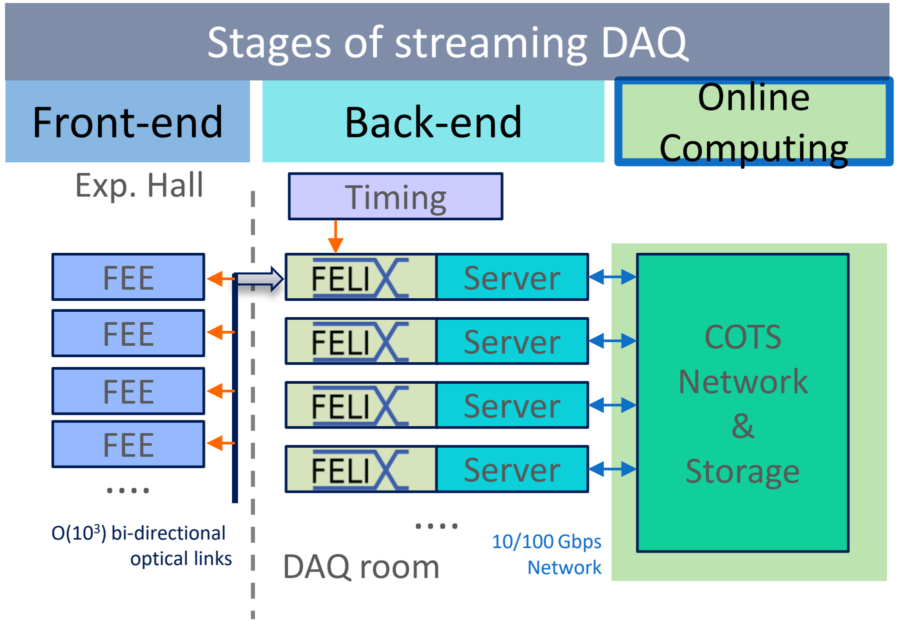
AI in streaming readout DAQ

- Main challenge: data reduction
  - Traditional DAQ: triggering was the main method of data reduction, assisted by high level triggering/reconstruction, compression
  - Streaming DAQ need to reduce data computationally: zero-suppression, feature building, lossy compression
- Opportunities for Real-time AI
  - Emphasize on reliable data reduction, applicable at each stages of streaming DAQ: Front-end electronics, Readout Back-end , Online computing
  - Data quality monitoring, fast calibration/reconstruction/ feedback
    - Has many AI application too
    - Not focus of this talk, nonetheless important for NP experiments



Streaming DAQ stage 3: Online computing

- Online computing is an integral part of streaming DAQ
  - Blending the boundary of online/offline computing
- AI opportunities:
  - Lossy compression
  - Noise and background filtering
  - Higher level reconstruction
- Target hardware:
  - Traditional computing: CPU, GPU
  - Novel AI Accelerators



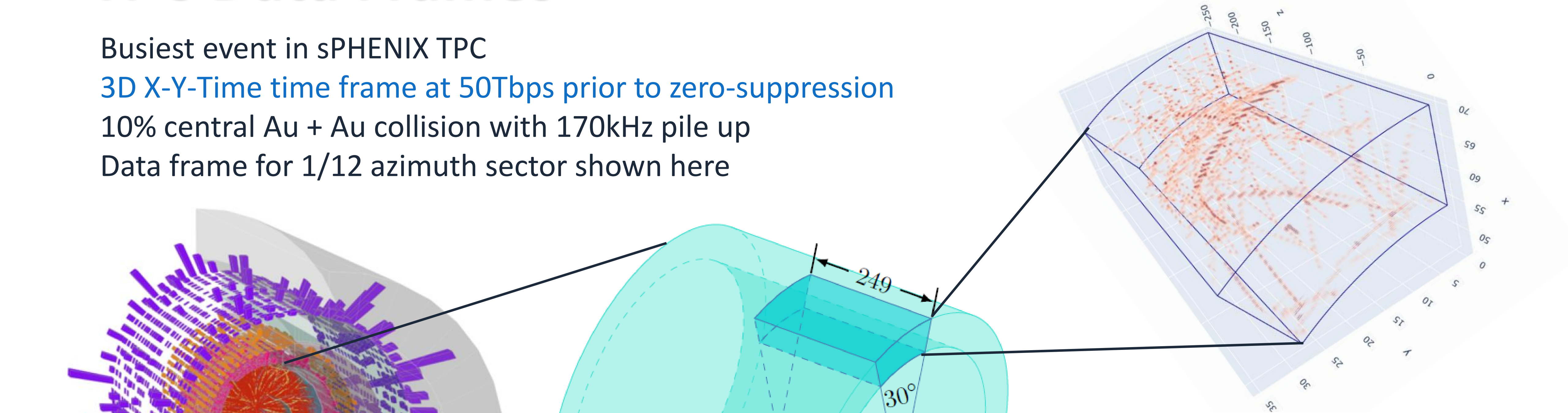
TPC Data Frames

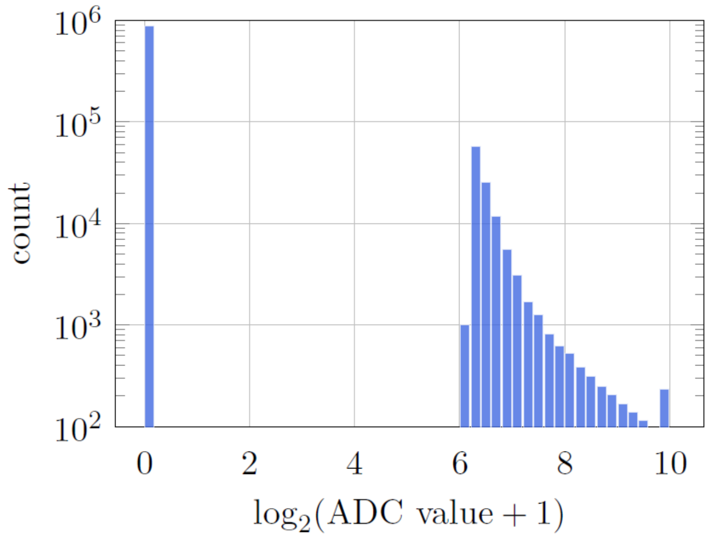
Busiest event in sPHENIX TPC

3D X-Y-Time time frame at 50Tbps prior to zero-suppression

10% central Au + Au collision with 170kHz pile up

Data frame for 1/12 azimuth sector shown here

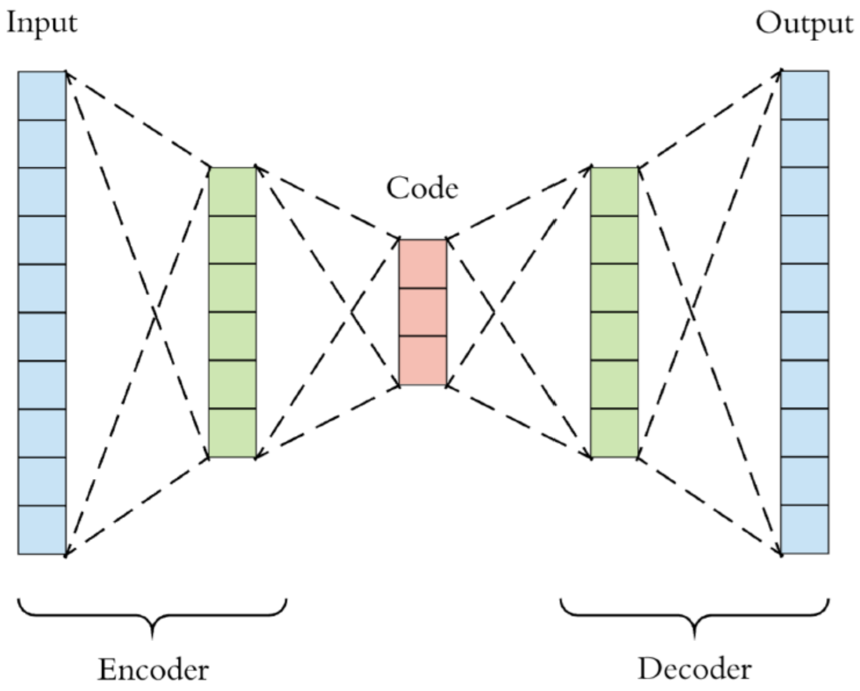




Lossy compression of data, noise filtering

Auto-encoder (AE) is a natural choice for self-supervised learning for lossy data compression and noise removal

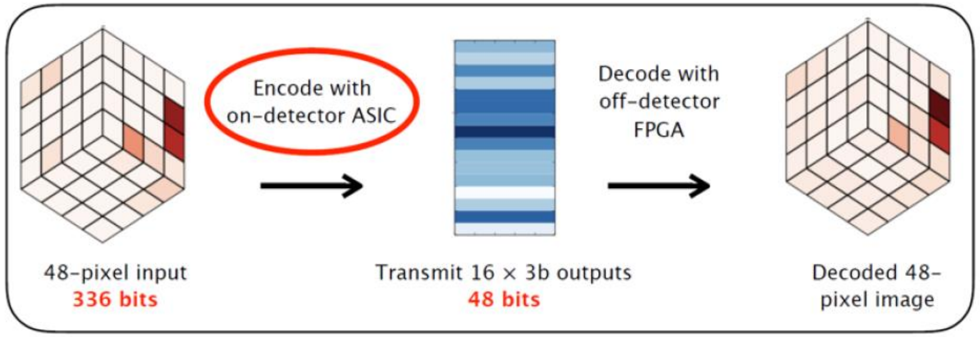
Simple auto-encode neural network



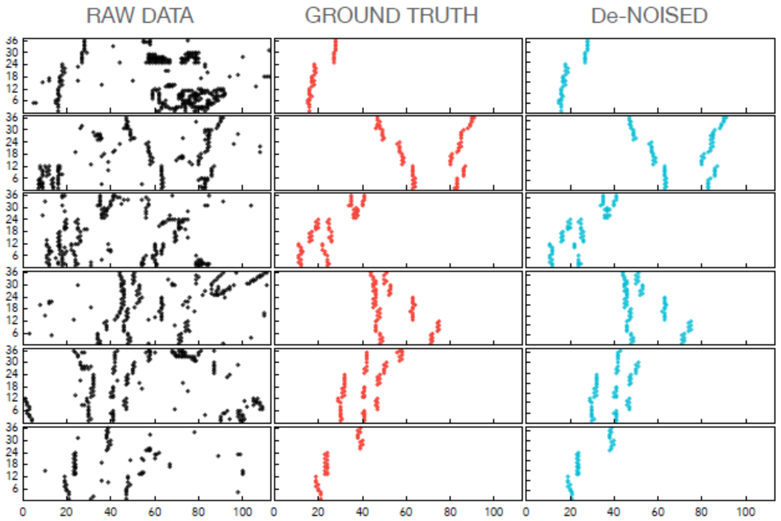
Lossy compression of data, noise filtering

- Auto-encoder (AE) is a natural choice for unsupervised learning for lossy data compression: streaming data reduction
- Same network architecture can be adopted with supervised learning to filter out noise: further data reduction, speed up reconstruction

CMS HGCal compression ASIC, [10.1109/TNS.2021.3087100 , talk by Maximilian J Swiatlowski]



CLAS12 Drift Chamber offline AE de-noise [link]
See also: talk by Diana McSpadden



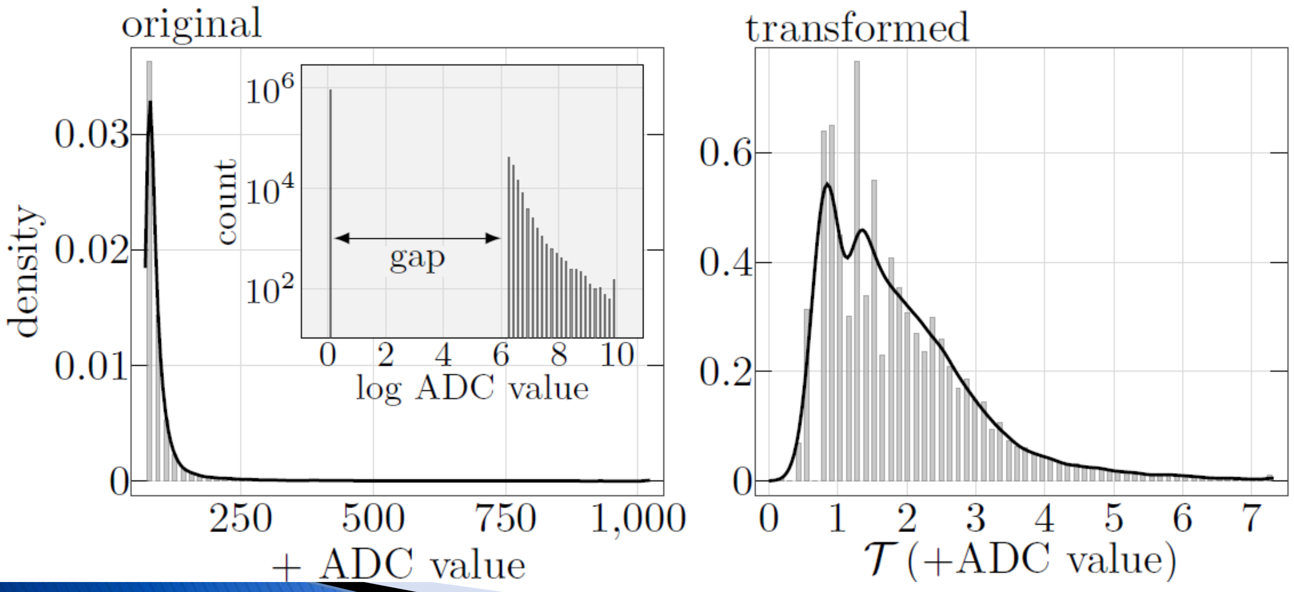
Bicephalous Convolutional Auto-Encoder (BCAE) and input transform

[Huang et al ICMLA21, DOI: 10.1109/ICMLA52953.2021.00179 arXiv:2111.05423]

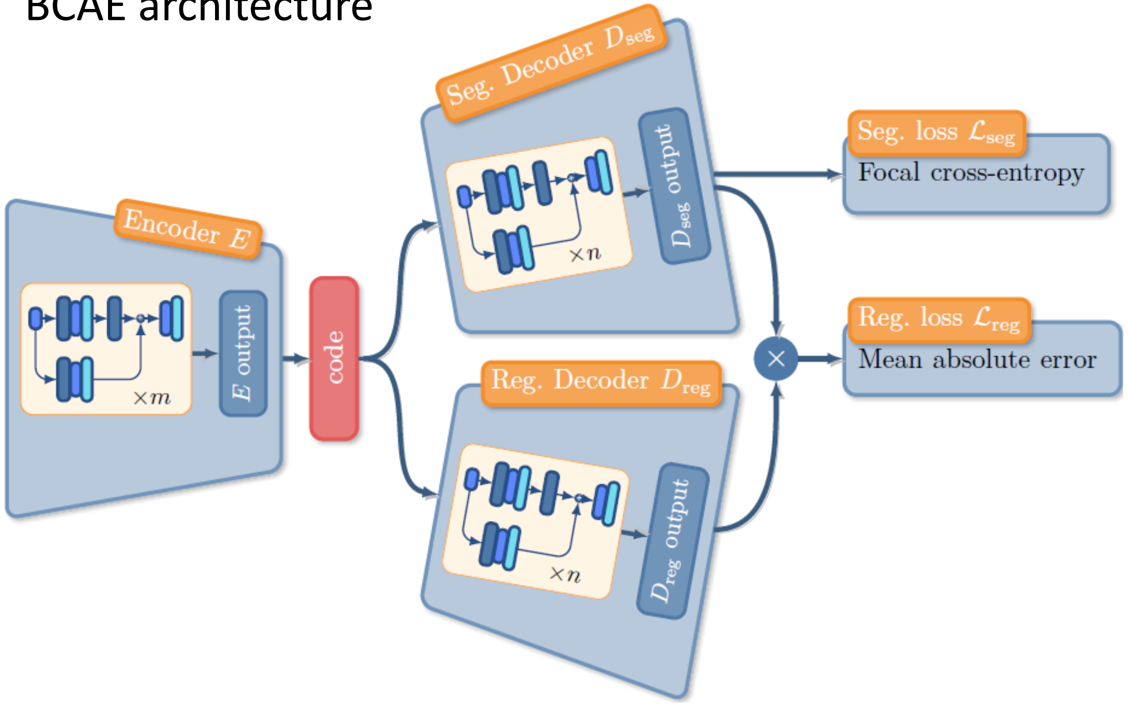
- Input transform: fill in the zero-suppression gap and make ADC distribution much less steep
- Bicephalous decoder: +classification decoder to note the zero-suppressed ADC voxels and +noise voxels in TPC

$$\text{Input transform: } \mathcal{T}(x) = \log(x - 64)/6, \qquad x > 64$$

$$\text{Inverse transform: } \mathcal{T}^{-1}(y) = 64 + \exp(6y), \qquad x \in \mathbb{R}$$

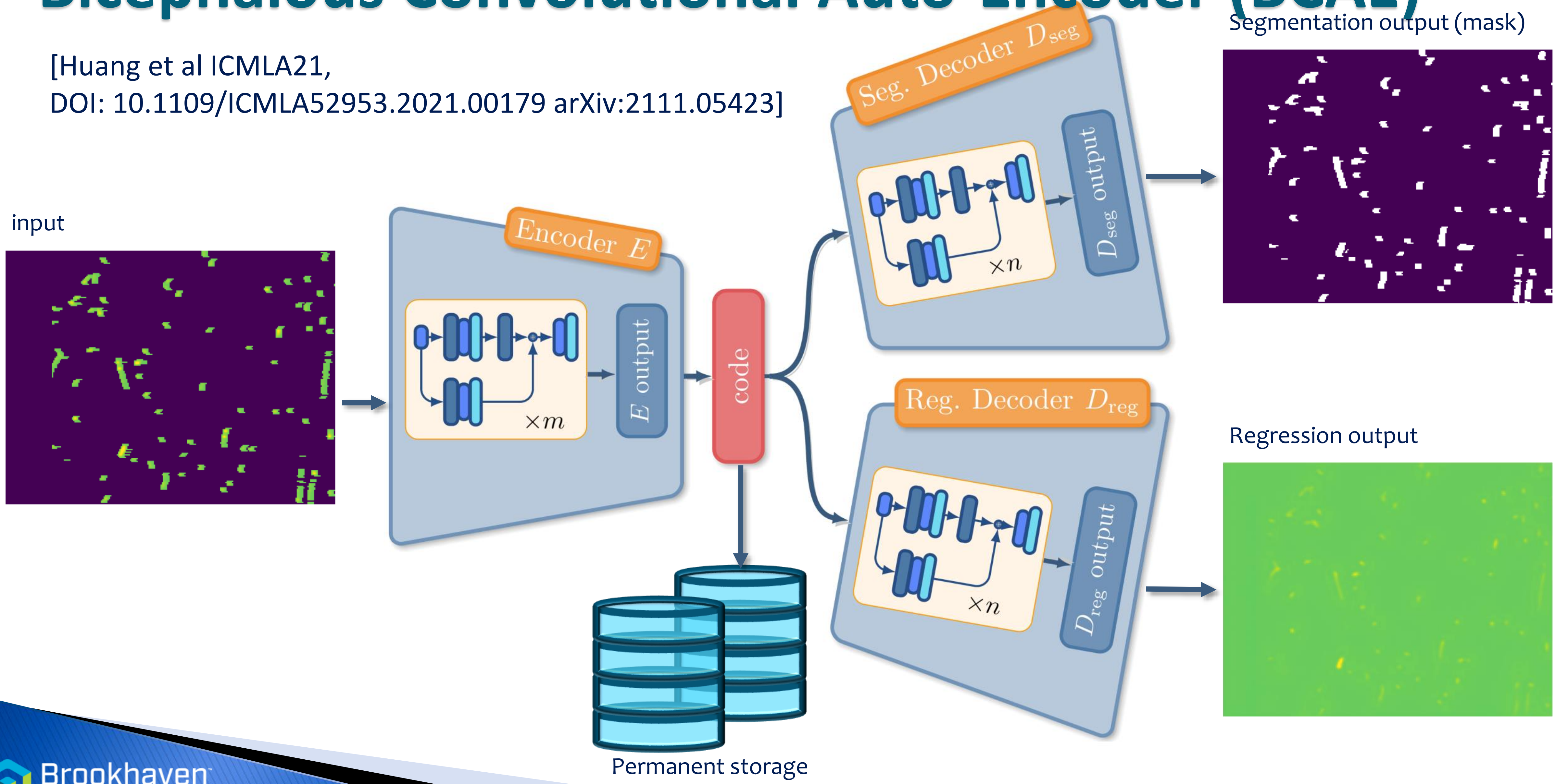


BCAE architecture



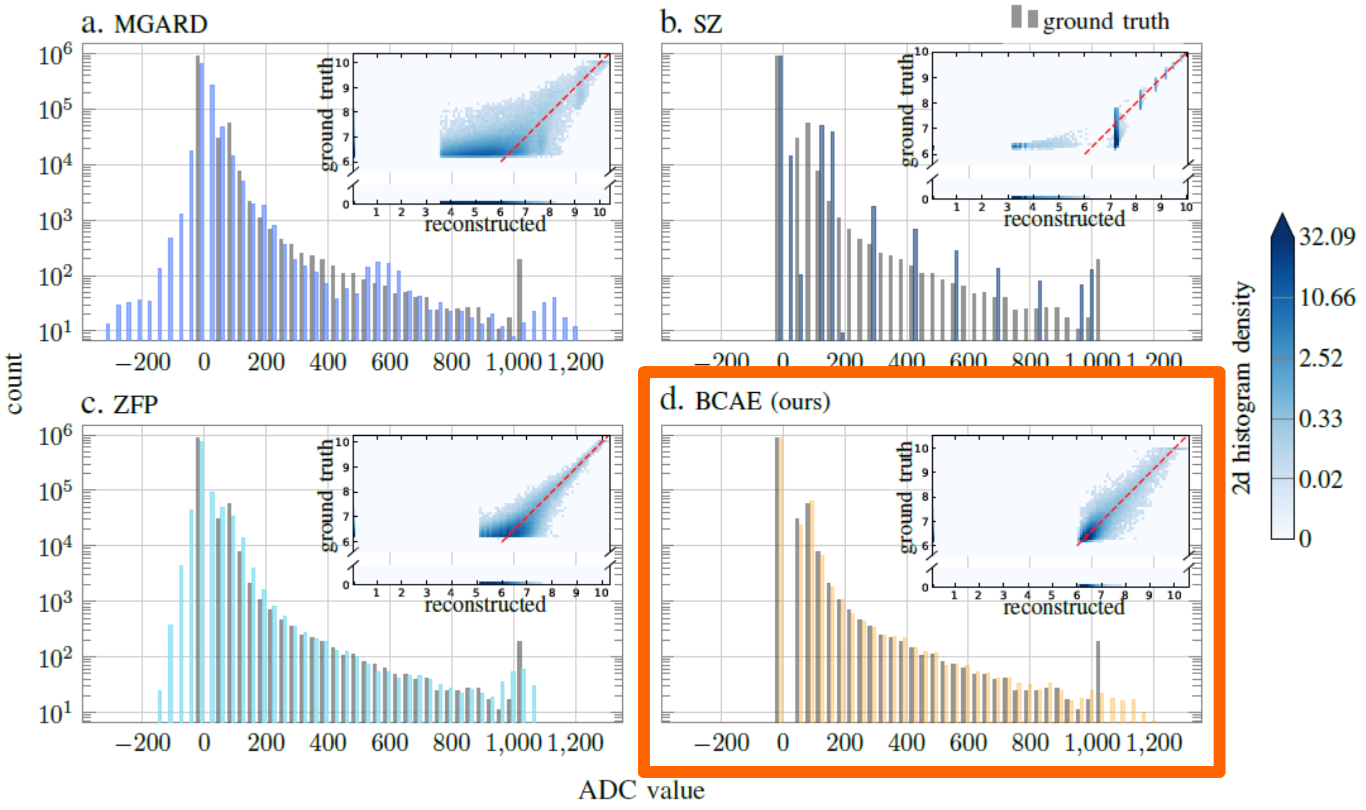
Bicephalous Convolutional Auto-Encoder (BCAE)

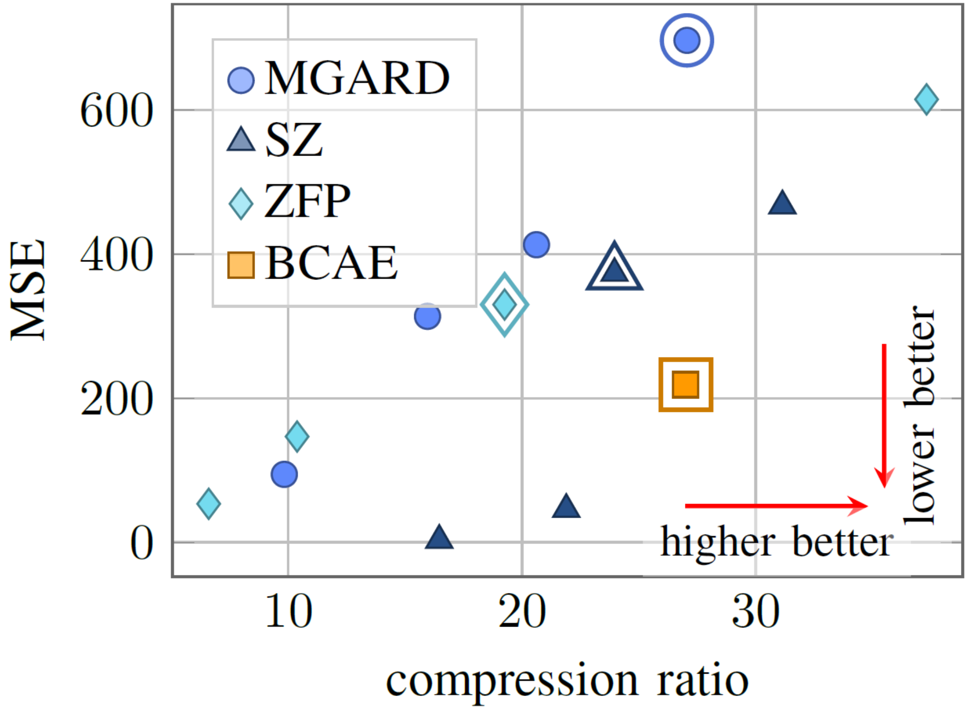
[Huang et al ICMLA21,
DOI: 10.1109/ICMLA52953.2021.00179 arXiv:2111.05423]



Comparison with existing algorithm

[Huang et al ICMLA21, DOI: 10.1109/ICMLA52953.2021.00179, arXiv:2111.05423]



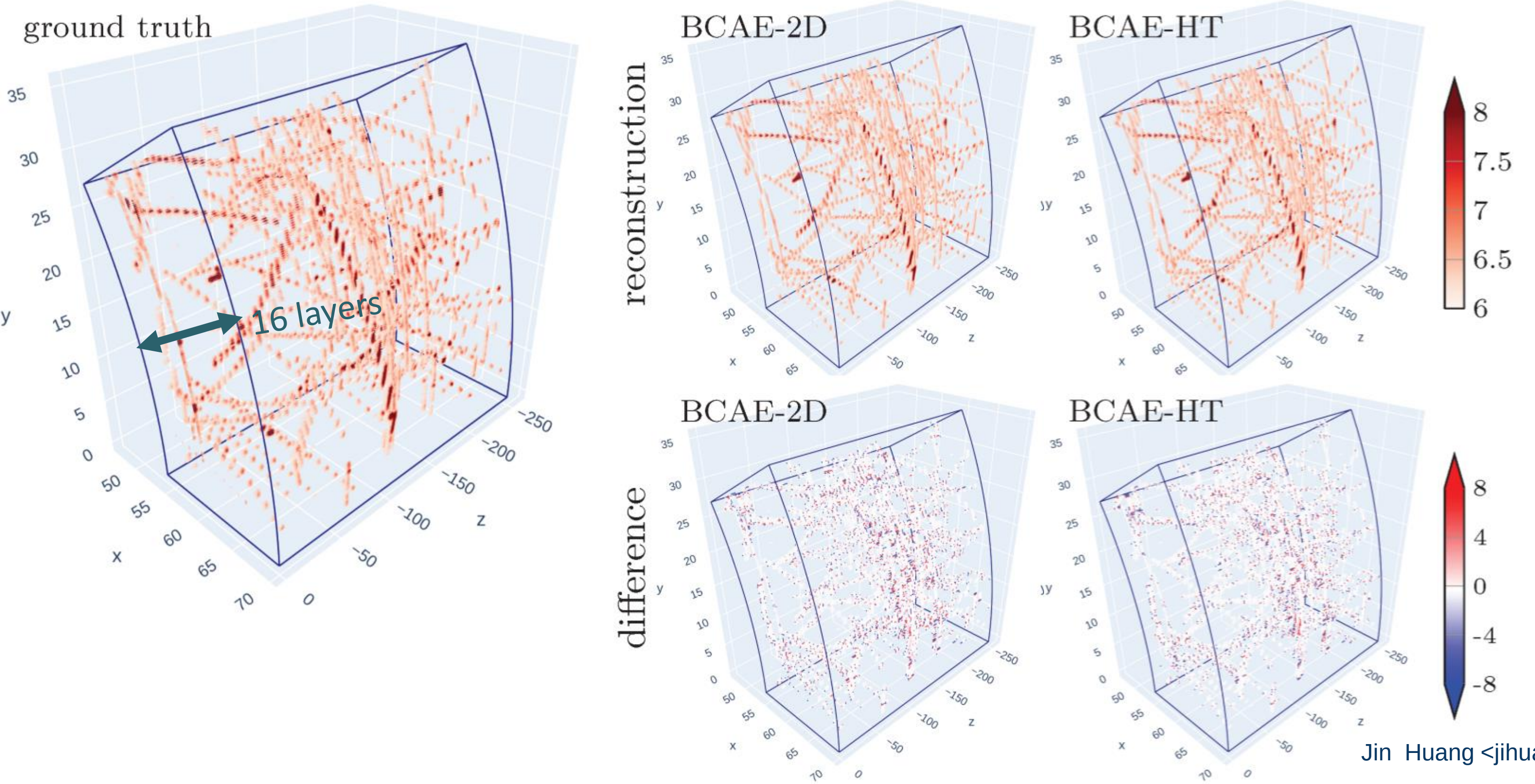


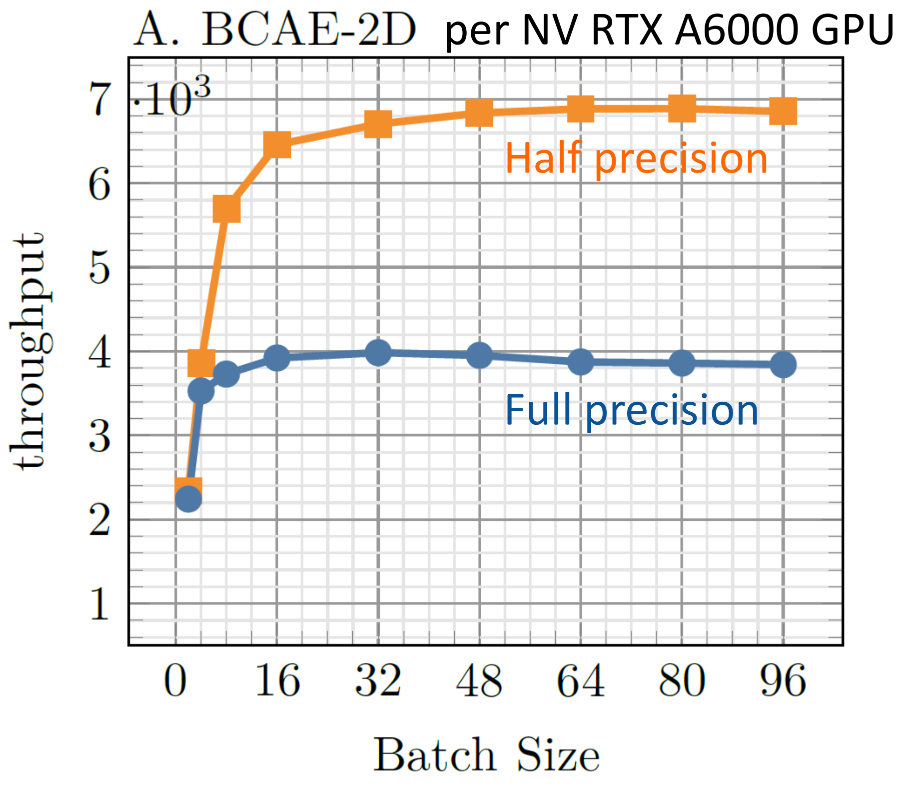
Real-time speed optimization for BCAE

[Huang et al DRBSD9@SC23, DOI: 10.1145/3624062.3625127 arXiv:2310.15026], received paper award

Optimization of inference speed of BCAE while maintaining better MAE than first version:

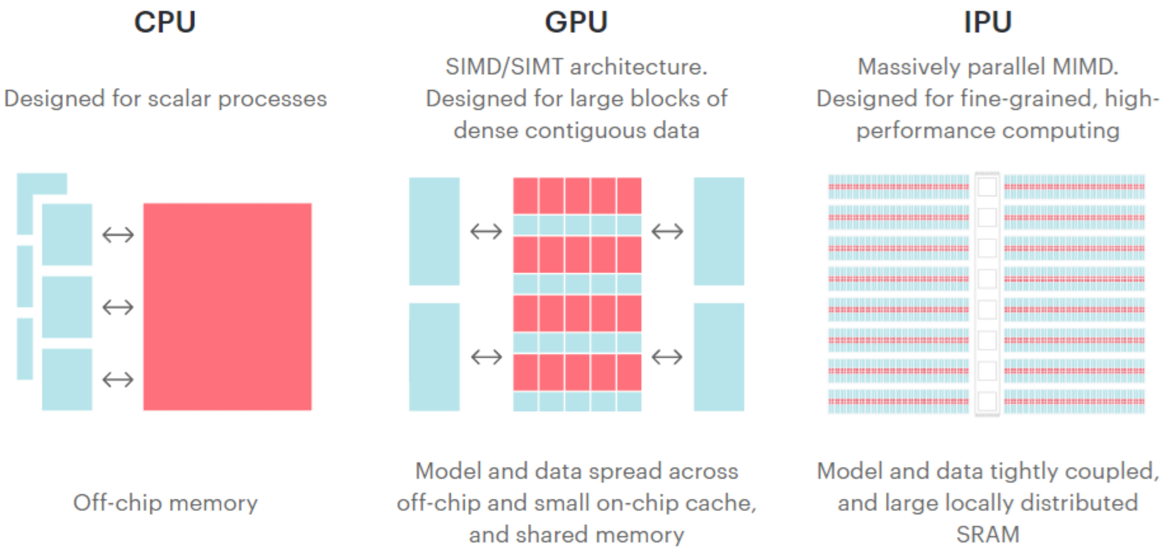
- BCAE-2D: 3D convolution -> 2D convolution with 16 color channels
- BCAE-HT: smaller intermediate output channels, 1/20 in size for encoder
- NN use of half-precision float (16bit) operations



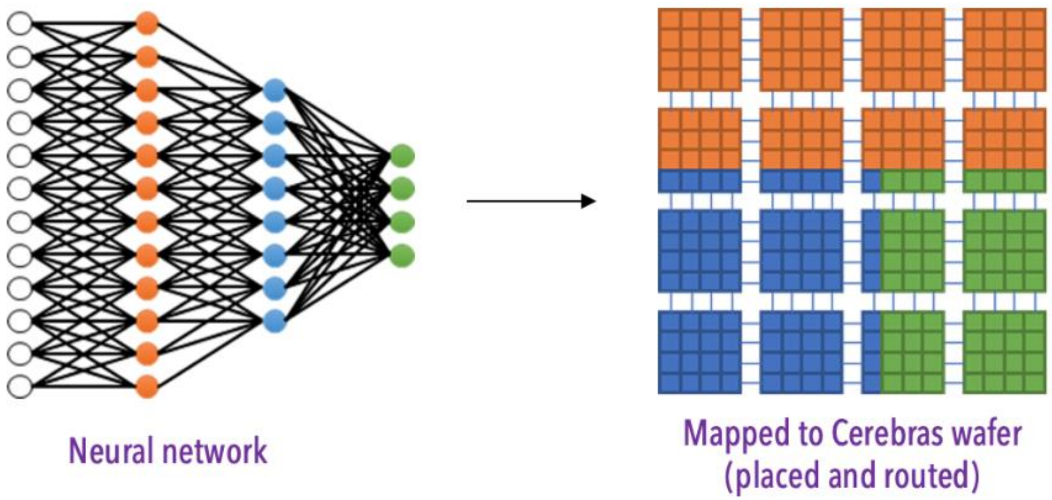


Novel AI Accelerators for streaming DAQ

- A new family of AI chips is emerging with non-von Neumann Architectures
  - Designed for NN computing, similarities to ML on FPGA
  - Massive on-chip activation/weight storage on sRAM
  - Good integration with popular AI tools
  - Energy efficient and high throughput
- Significant throughput gain with testing of BCAE on Graphcore IPUs, a Dataflow Architectures processor for AI application

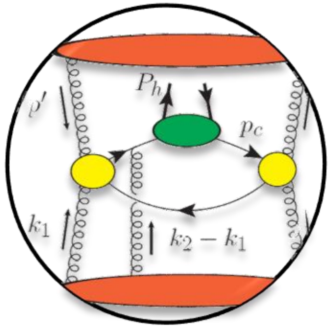


[GraphCore Web, link]



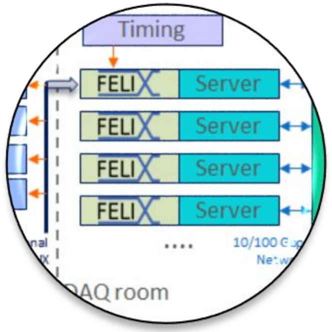
[Cerebras Compiler Docs, link]

Summary



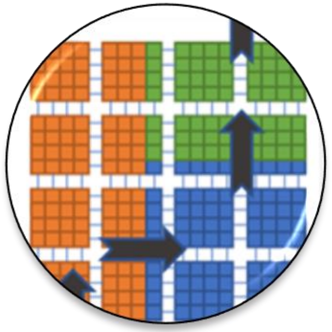
NP Physics

- Diverse topology
- Stringent sys. Ctrl
- Max data preservation



Streaming DAQ

- New physic capability accessible only via streaming DAQ
- Example: adopted for sPHENIX and EIC
- Require data reduction computationally

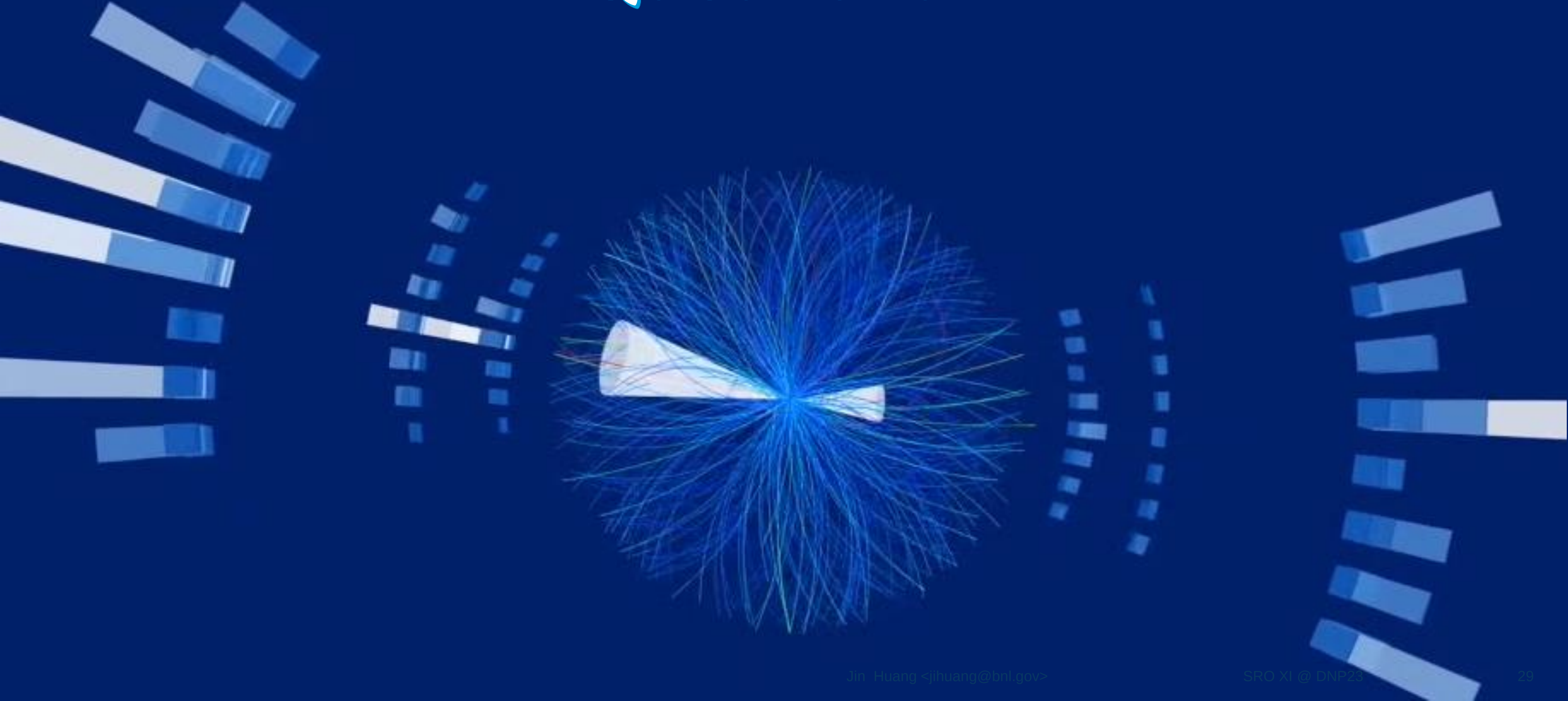


Opportunities for AI enhancement

- Specialized AI algorithm for reliable and high-performance data reduction
- Novel hardware emerging for high-throughput AI computing

Physics need → Streaming DAQ → Opportunity for real-time AI → Enhanced physics program

Questions?



Extra information

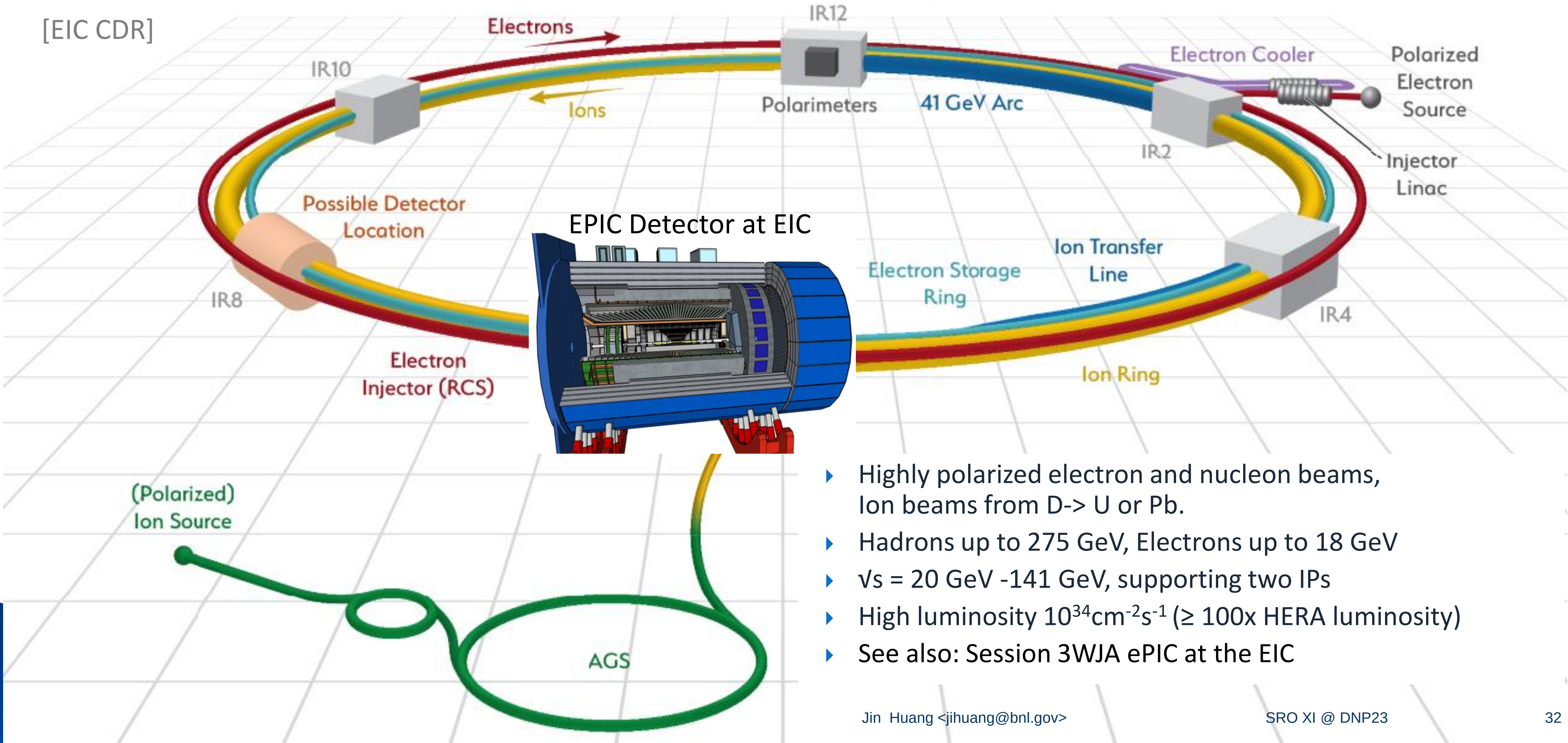
Nuclear collider experiments: unique real-time system challenges leads to streaming DAQ

	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**

- Signal data rate is moderate → possible to streaming recording all collision signal
- But events are precious and have diverse topology → hard to trigger on all process
- Background and systematic control is crucial → avoiding a trigger bias; reliable data reduction

RHIC transition to the Electron Ion Collider (EIC)
Just had a successful CD3-A review, Science Phase in 2030+

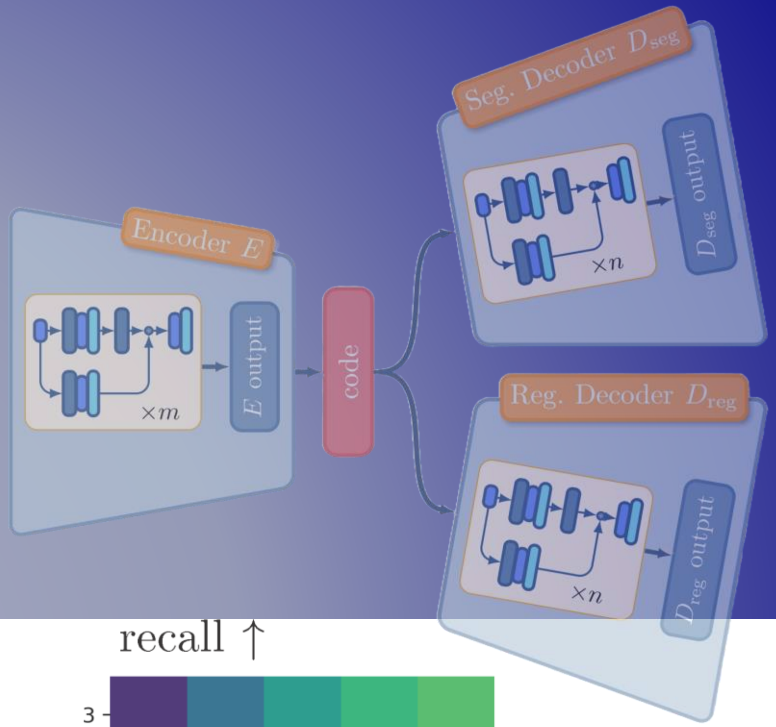
[EIC CDR]

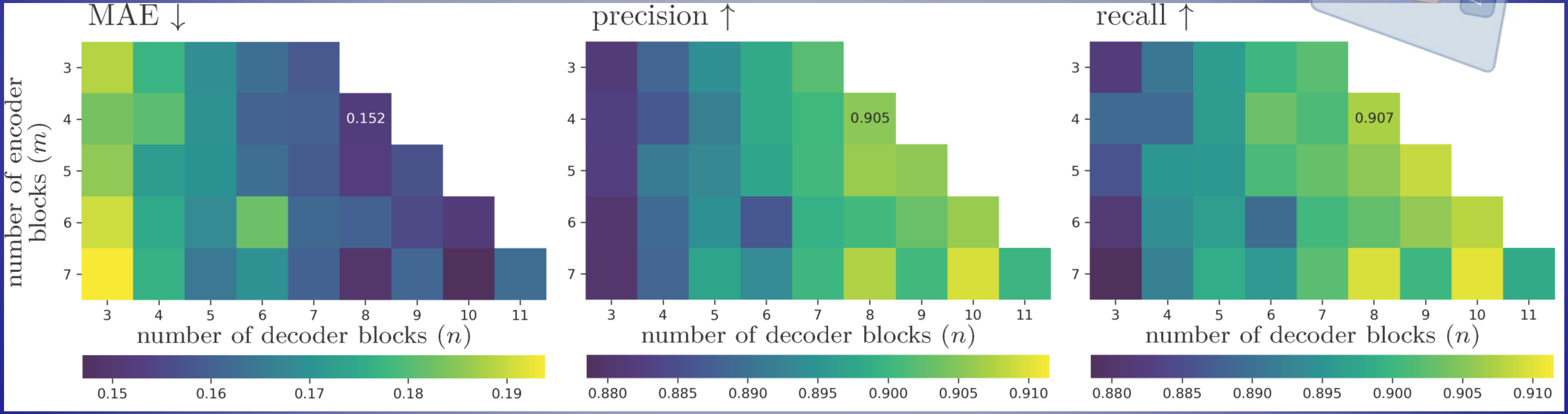


- Highly polarized electron and nucleon beams,
  Ion beams from D-> U or Pb.
- Hadrons up to 275 GeV, Electrons up to 18 GeV
- $\sqrt{s}$ = 20 GeV -141 GeV, supporting two IPs
- High luminosity $10^{34}cm^{-2}s^{-1}$ (≥ 100x HERA luminosity)
- See also: Session 3WJA ePIC at the EIC

2D Encoder and Decoder

tunable encoder decoder sizes





Performance comparison

better 3D BCAE

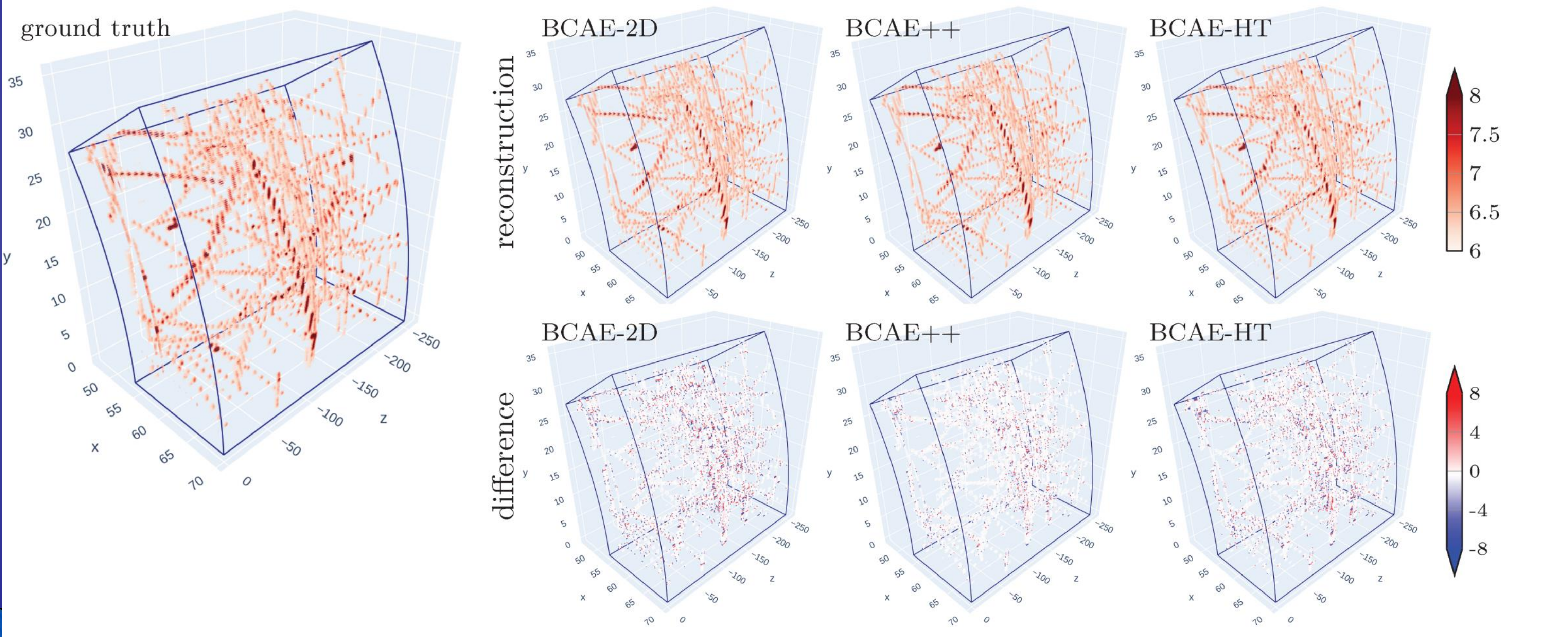
model	MAE ↓	PSNR ↑	Precision ↑	Recall ↑	Encoder size ↓	Compr. Ratio ↓
BCAE	0.198	9.923	0.878	0.861	201.7k	27.041
BCAE-2D	0.152	11.726	0.906	0.907	169.0k	31.125
BCAE++	0.112	14.325	0.934	0.936	226.2k	31.125
BCAE-HT	0.138	12.376	0.916	0.915	9.8k	31.125

From BCAE to BCAE-HT

1. 3D convolution
2. Pad (16, 192, 249) to (16, 192, 256) for easy halving and an increased compression ratio
3. Remove normalization
4. Much smaller intermediate output channels for higher throughput

- Slightly better reconstruction performance
- Super small model size
- Higher throughput

Performance comparison



Throughput comparison

two computing modes

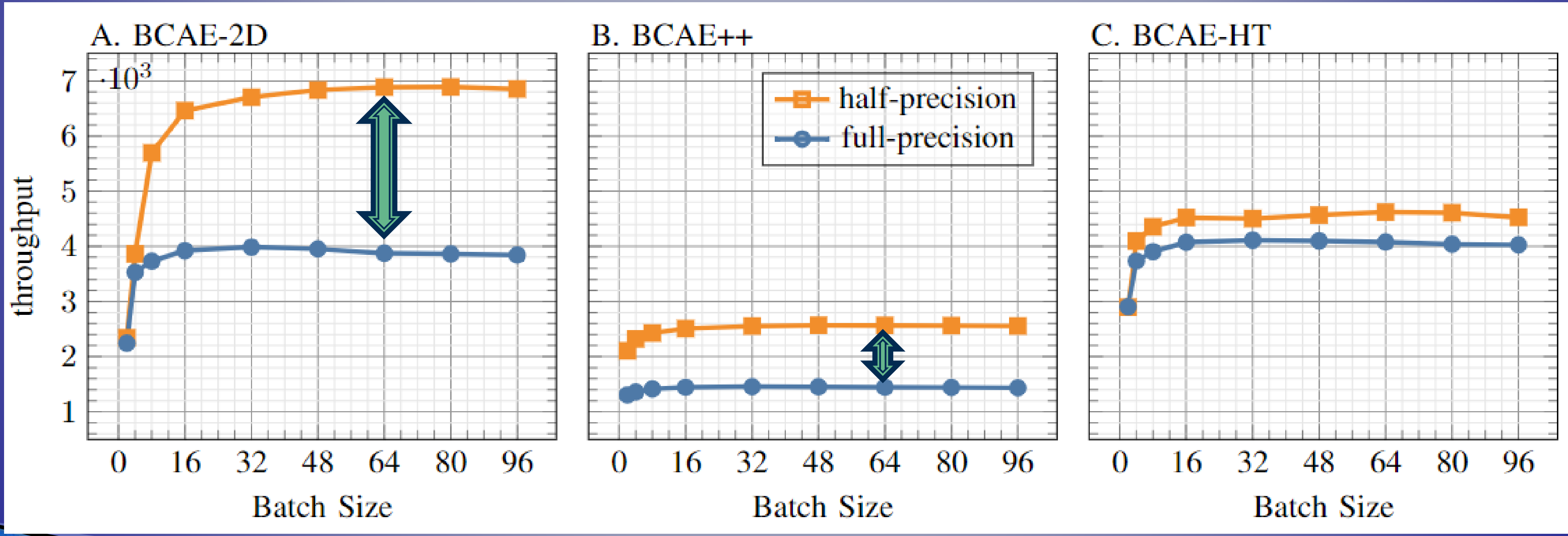
- **Full:** encode with float 32, save code as float 16, decode with float 32
- **Half:** encode with float 16, save code as float 16, decode with float 32

model	mode	MAE	precision	recall
BCAE-2D	Full	0.151937	0.905469	0.906916
	Half	0.151965	0.905326	0.907050
BCAE++	Full	0.112347	0.933817	0.935779
	Half	0.112342	0.933852	0.935741
BCAE-HT	Full	0.138443	0.915891	0.914562
	Half	0.138441	0.915780	0.914701

Throughput comparison

two computing modes

Why don't we have the same speedup here?

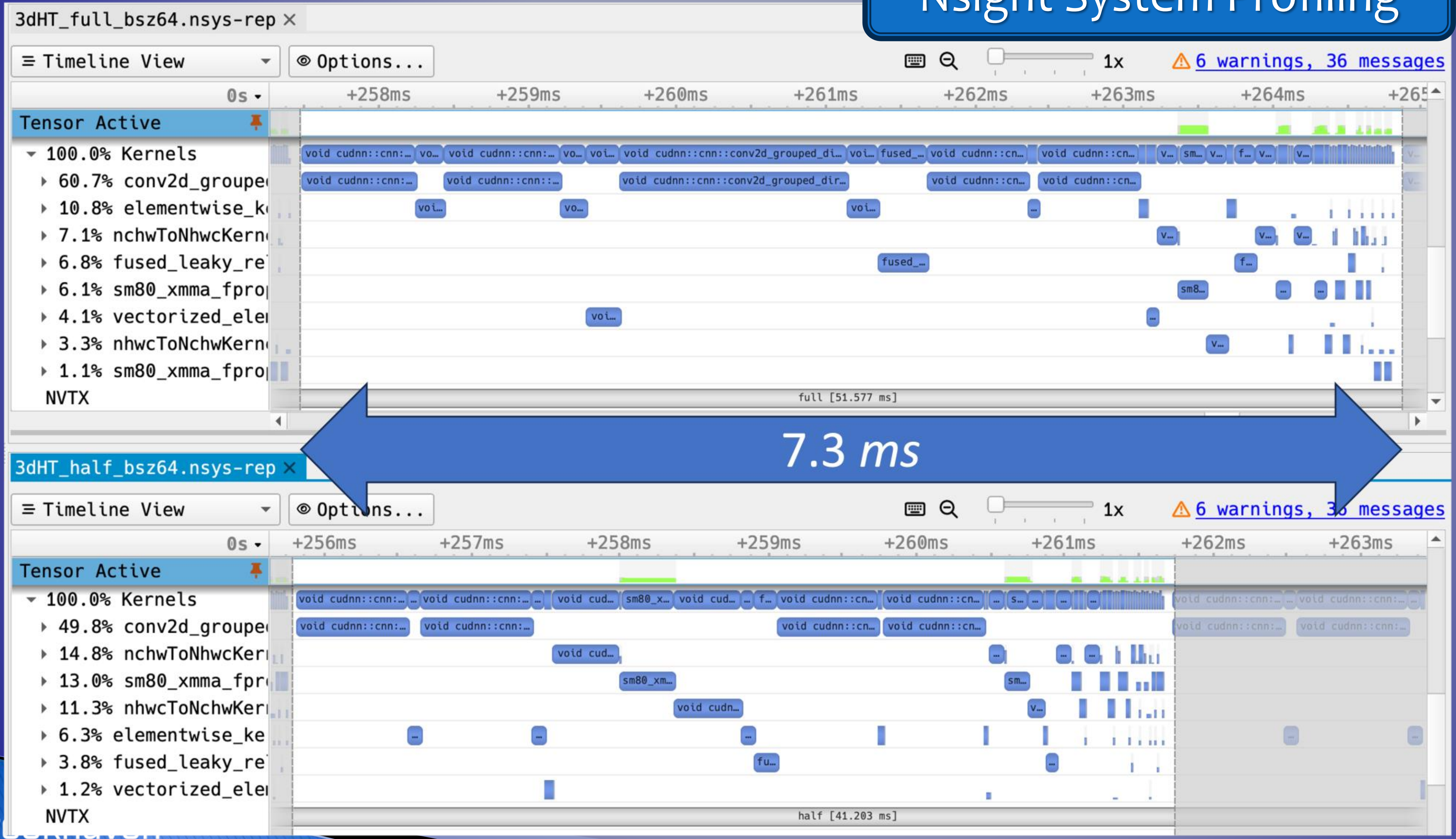


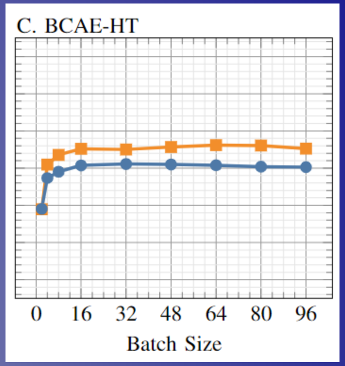
Why the Lack of Speedup

Nsight System Profiling

Full precision

Half precision





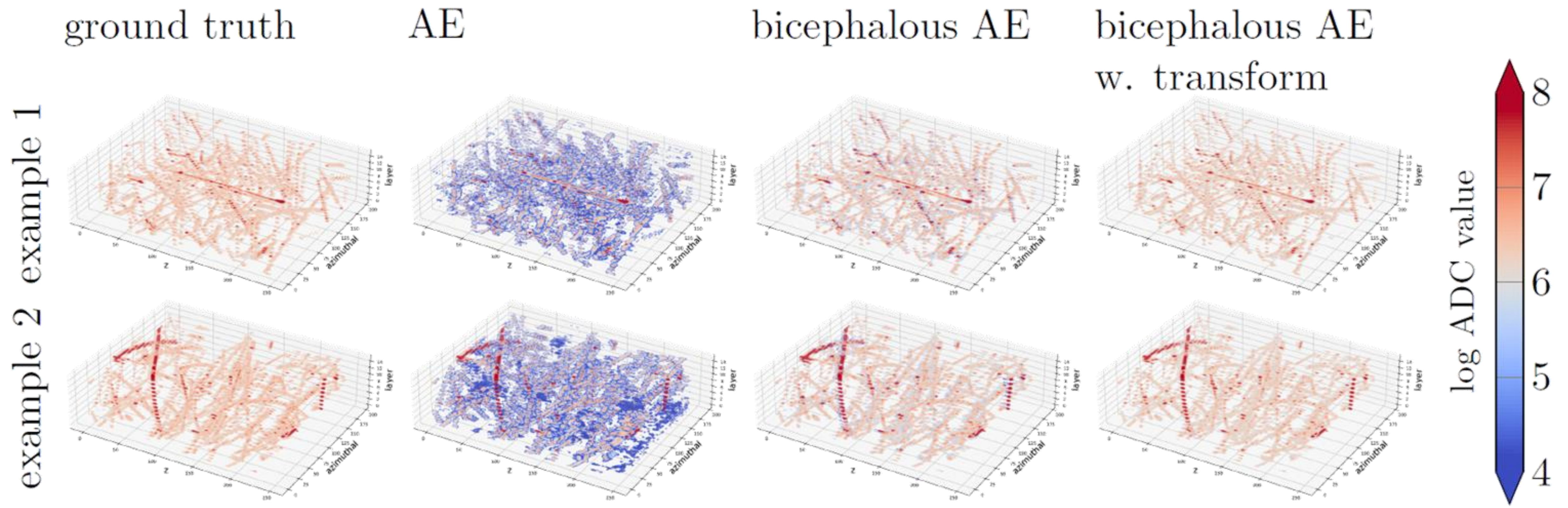
2D Encoder and Decoder

```
Algorith… ncoder_2D
Input: … blocks m,
       … of downsampling layers d
Output: A PyTorch module
Initialize network N to be an empty module list;
Append N with L_in = Conv2D (i = 16, o = 32, k = 7, p = 3)
for i ← 1 to m do
    if i ≤ d then
        Append N with AvgPool2D (k = 2, s = 2);
    Append N with two residual block
      Res (i = 32, o = 32, k = 3, p = 1);
Append N with L_out = Conv2D (i = 32, o = 16, k = 1);
return N;
```

4 convolutions per block

```
Algorith… _decoder_…
Input: …mber of blocks n, …mber of upsampling layers d,
       output activation function A
Output: A PyTorch module
# NOTE: a decoder must have the same number of
  upsampling steps as the downsampling steps in
  its corresponding encoder
Initialize network N to be an empty module list;
for i ← 1 to n do
    if i ≤ d then
        Append N with Upsample (scale_factor = 2);
    Append N with two residual block
      Res (i = 32, o = 32, k = 3, p = 1);
Append N with L_out = Conv2D (i = 32, o = 16, k = 1);
Append N with output activation function A;
return N;
```

Results from Bicephalous AE with transform [arXiv:2111.05423]



Compressibility check: thanks to suggestion from Brett!

- The lossy-compressed code is hardly compressible further losslessly