dE/dx in TPC and Electron Identification

Jin Huang (Brookhaven National Laboratory)

- Thanks to the input from Bob Azmoun, Klaus Dehmelt, Prakhar Garg John Haggerty, Tom Hemmick, Chris Pinkenburg, Martin Purschke
- And based on our last report to eRD6

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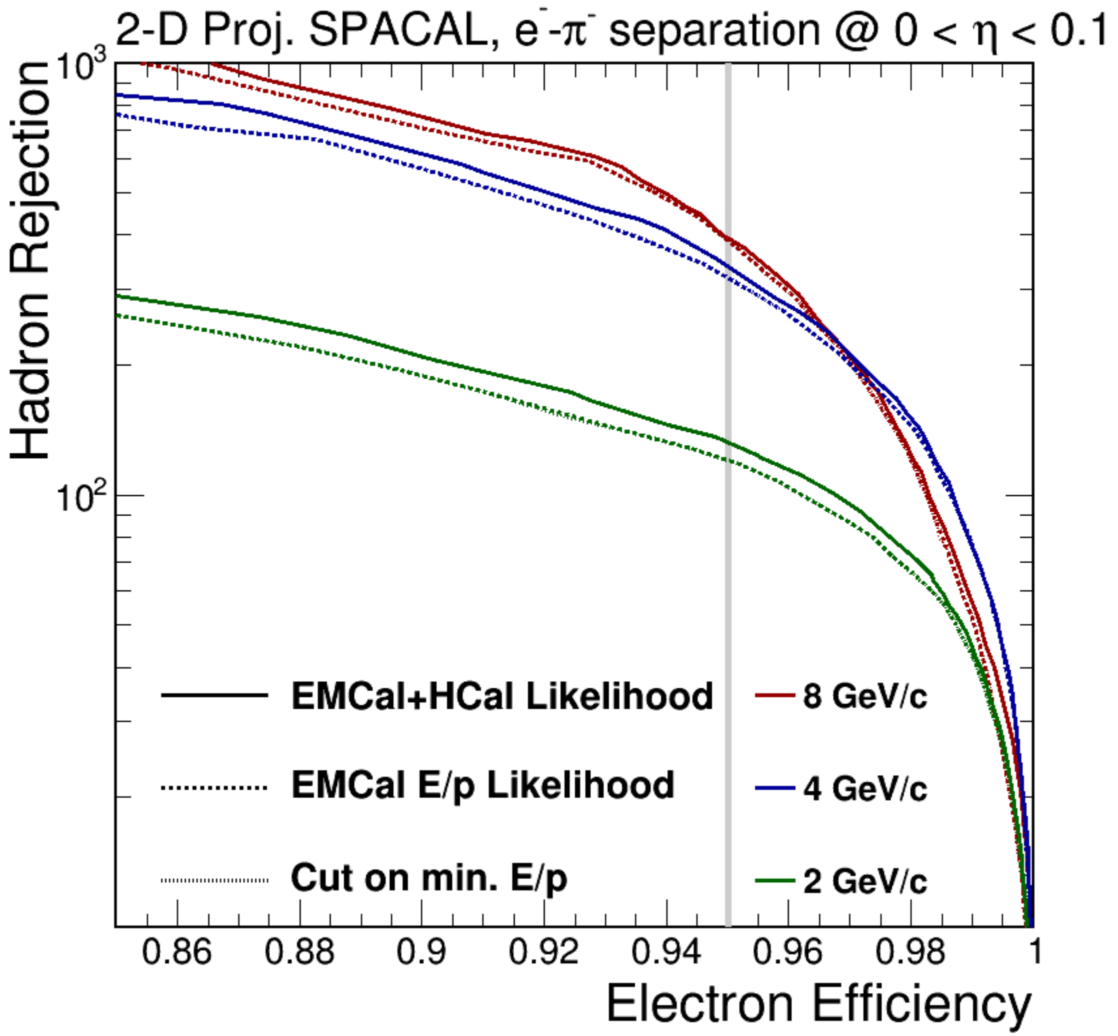
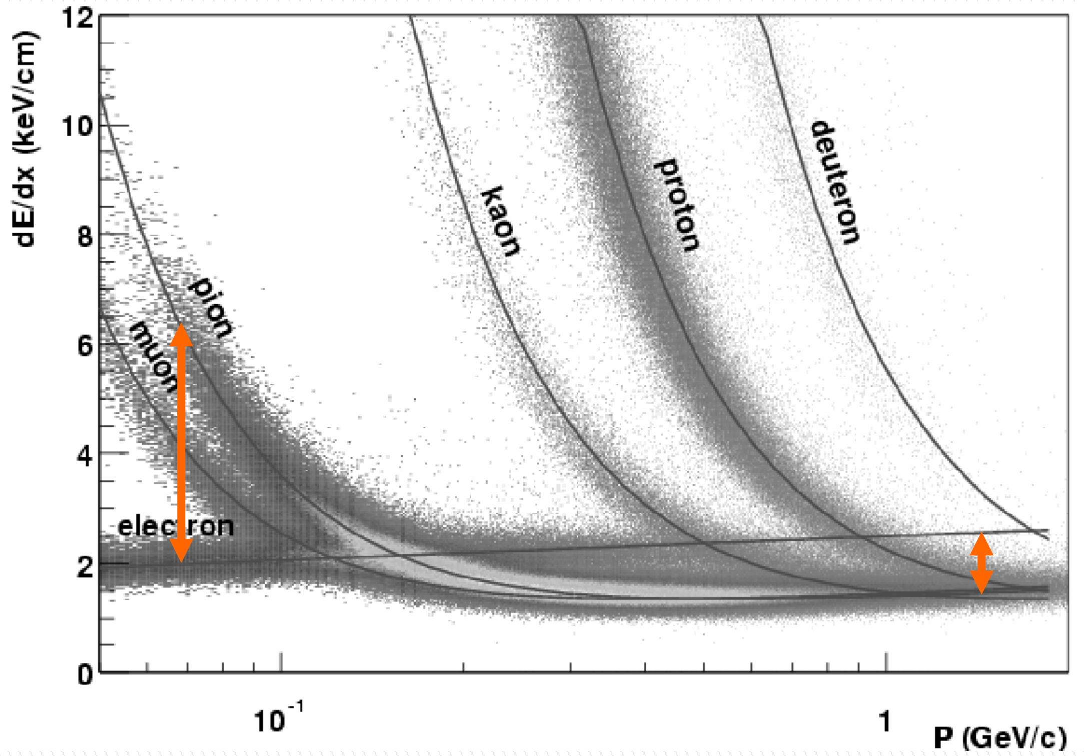
Electron ID

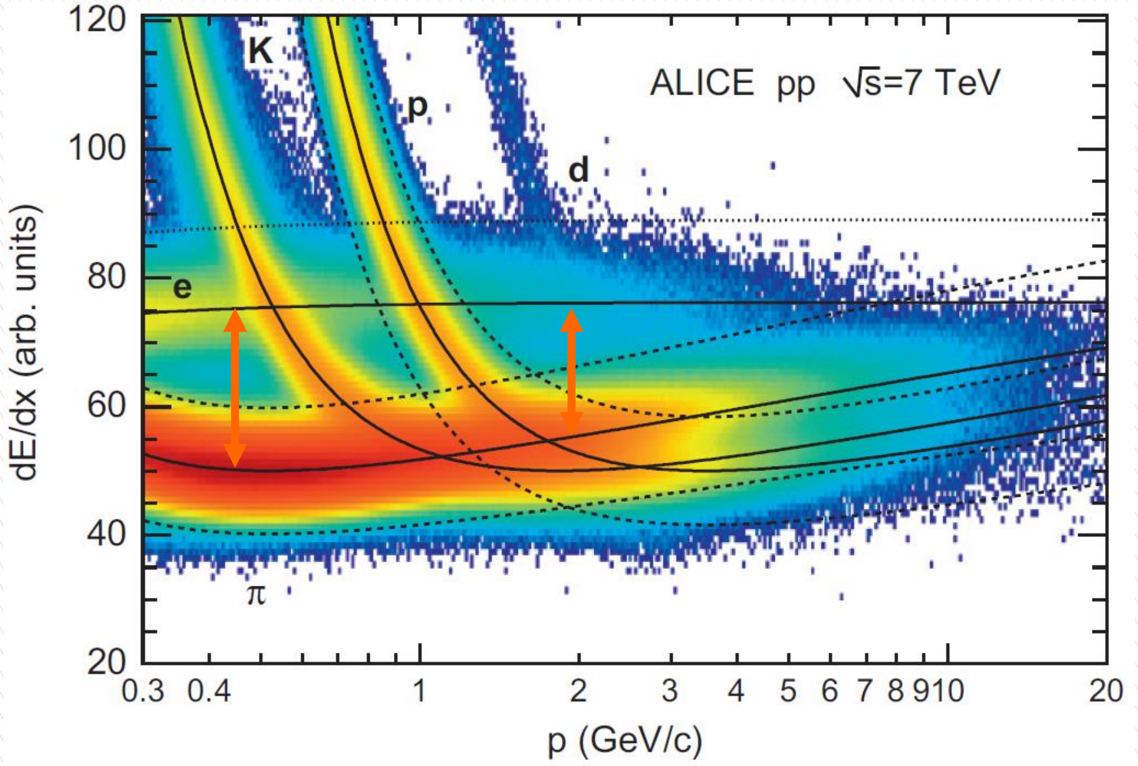
- This group: electron ID via Cherenkov
- Calo group: track-EMCal E/p matching
  - See also past sPHENIX studies
  - Usually much less effective in lower energy, e.g. 4 GeV and below.
- TRD: as in Yulia's talk
- Tracker dE/dx
  - Via dE/dx's gamma dependent
  - Could be excellent choice for low-p region
  - Usually require long-segmented dE/dx measurements to build statistics, making TPC a prime choice
  - Combined TPC-HBD Cherenkov?

sPHENIX pre-CDR study [2015], full detector simulation + reco.
EMCal: Projective W-Scint SPACAL (eRD1-based)
Track-driven clustering + optional HCal post-shower rej.



TPC dE/dx measurement :
Two success collider applications

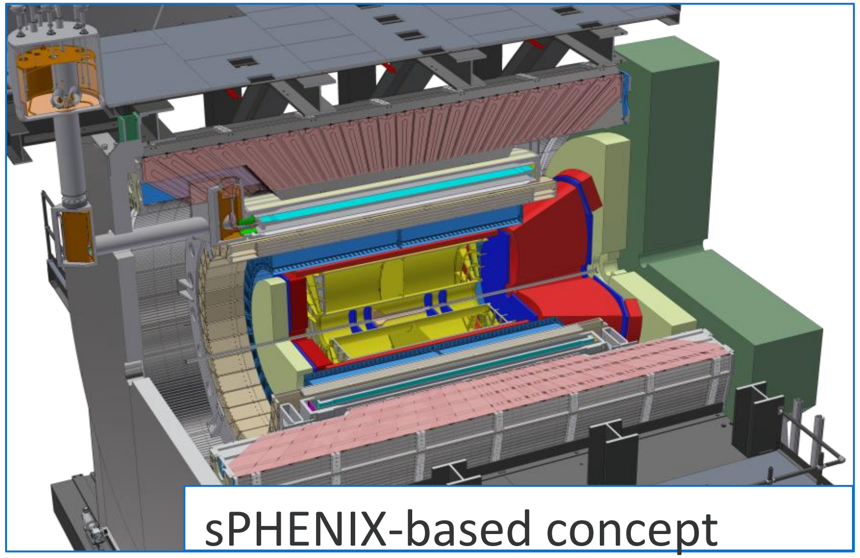




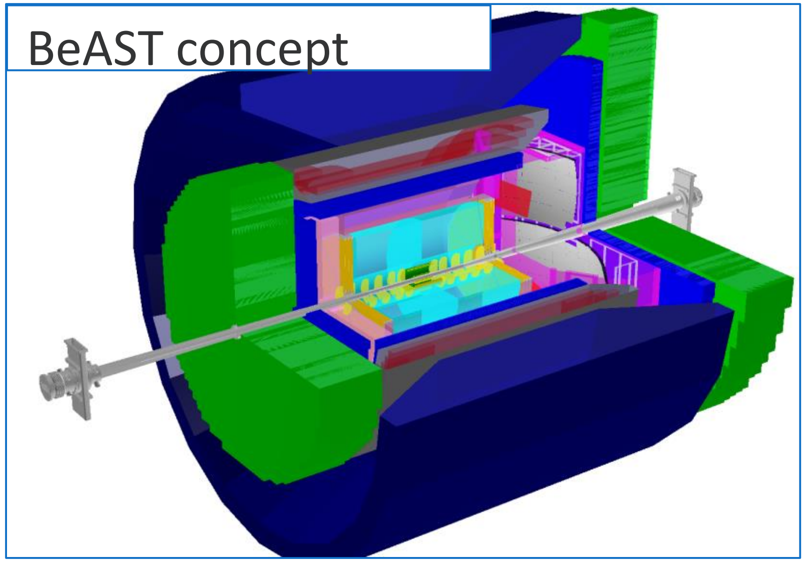
STAR (2003 NIMA):
DOI: 10.1016/S0168-9002(02)01964-2

ALICE (2013 NIMA)
DOI: 10.1016/j.nima.2012.05.022

What about PID dE/dx for EIC?



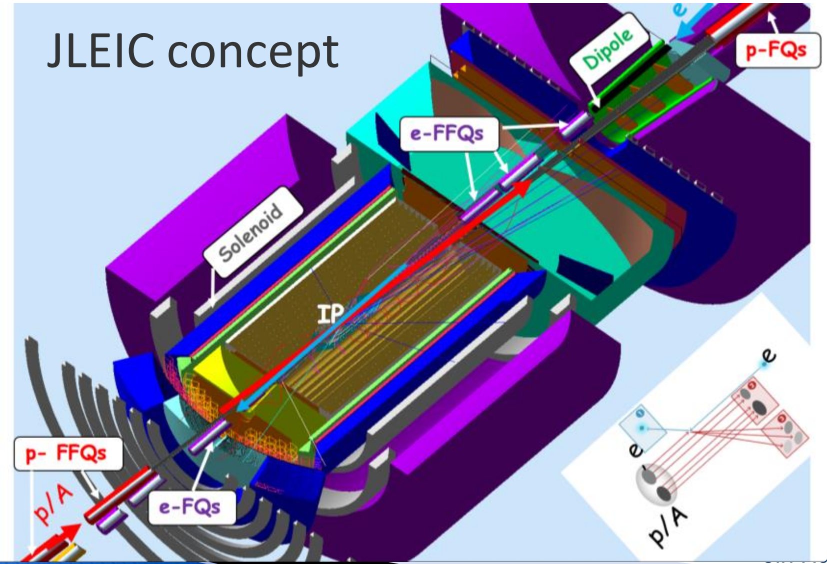
sPHENIX-based concept



BeAST concept

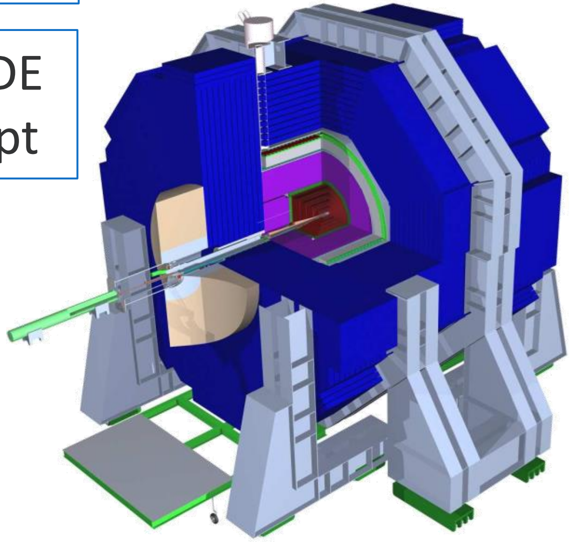
References reports :

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



JLEIC concept

TOPsiDE concept



What about PID dE/dx for EIC?

- Similar to sPHENIX, EIC TPC is very compact comparing to STAR/ALICE
  - ΔR = 50cm(sPHENIX) / 60cm(EIC R1). Compact favored for EIC detector
- sPHENIX-2019 gas is 50% CF_4 – 50% Ne
  - CF_4 is a very attractive gas for PID via dE/dx:
  - Very high in primary ionization: 51 / cm, 2x of Ar
  - Very low in Secondary ionization: $n_{total}/n_{primary}$= 2, ½ of Ar
    Low fluctuation due to Landau tail and high sensitivity per measurement
- Although not a sPHENIX req., this TPC could be a PID-capable detector

TPC	Pad rows	Gas	Radial Drift Vol. [cm]	dE/dx [keV/cm]	Primary Ionization [/cm]	Total Ionization [/cm]	Total Ionization/Initial Ionization	Integrated Primary Ionization	dE/dx resolution eta=0	Reference
STAR w/ iTPC	72	P10 - 10% methane, 90% argon	150	2.344	23.2	89.9	3.9	3,480	6.5%	RHIC S&T review 2019, Caines; iTPC proposal
ALICE 2010	160	(Ne/CO2 90/10)/N2 5% (N2 not in calculation)	161.8	1.705	14.35	47.8	3.3	2,322	5% (cosmic)	doi:10.1016/j.nima.2010.04.042
sPHENIX2019 w/ EIC R1	48	Ne/CF4 50/50	60	4.28	31.5	71.5	2.3	1,890	This study	sPHENIX TDR; arXiv:1402.1209 [nucl-ex]

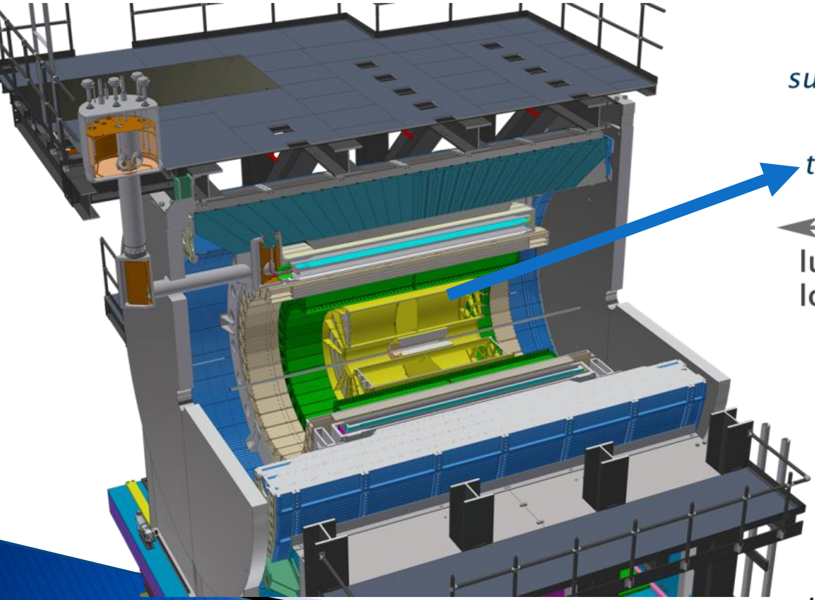
Compact size

High primary ionization

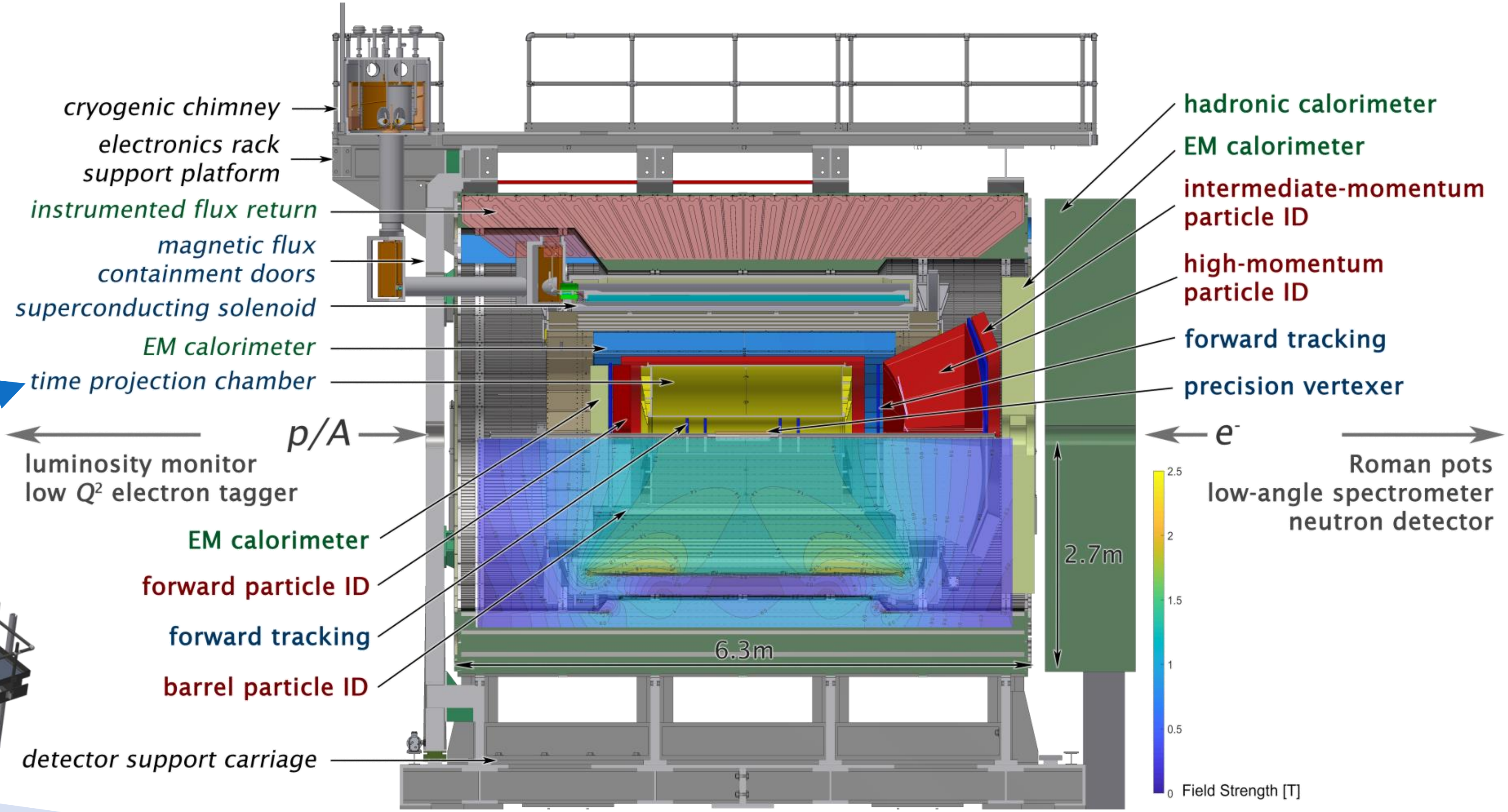
Low secondary ionization

sPHENIX TPC → sPHENIX-EIC detector concept

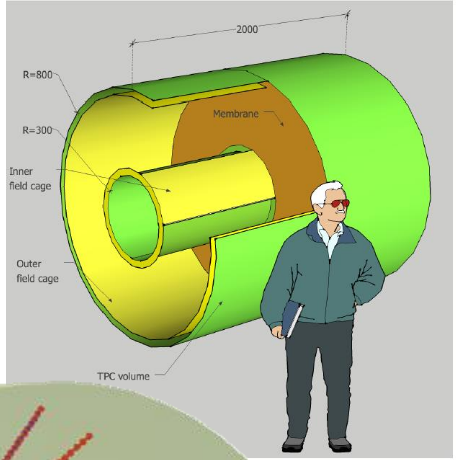
- sPHENIX:
  - Next generation RHIC detector
  - Sept 2019: Approved of construction (PD-3)



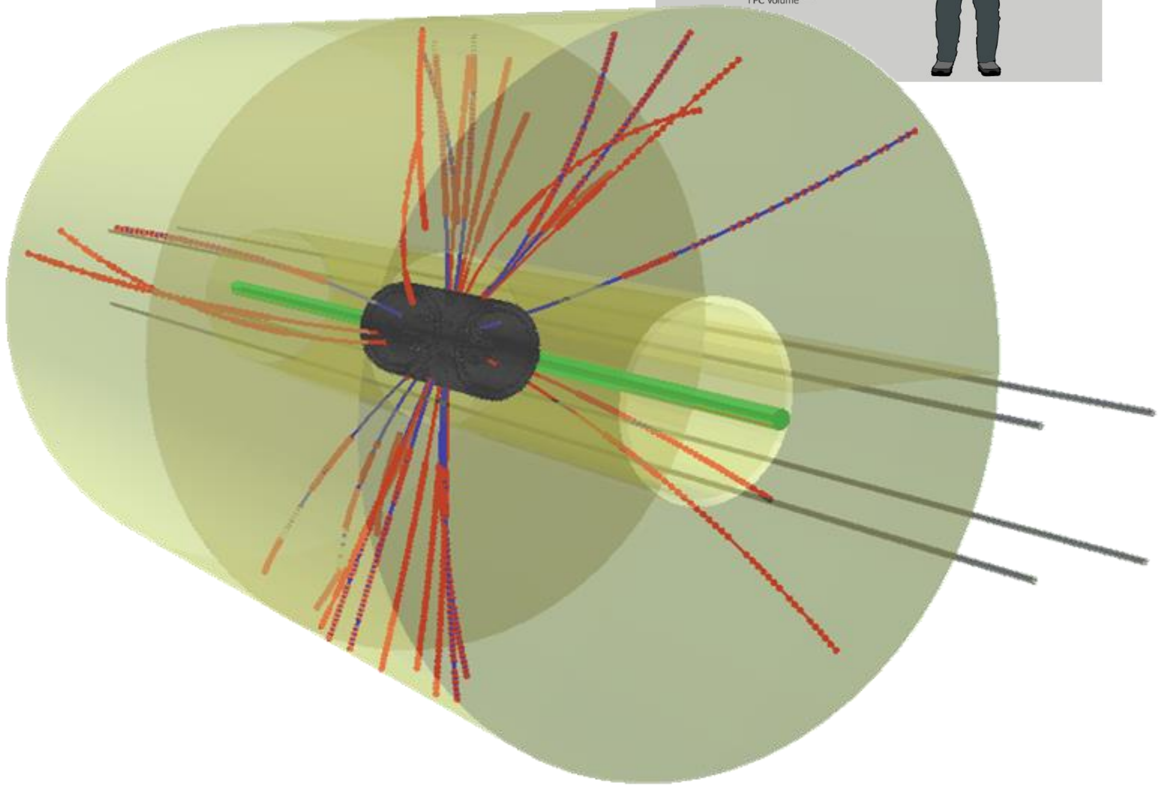
- Foundation for an EIC detector concept [arXiv:1402.1209, sPH-cQCD-2018-001]



sPHENIX Time projection chamber



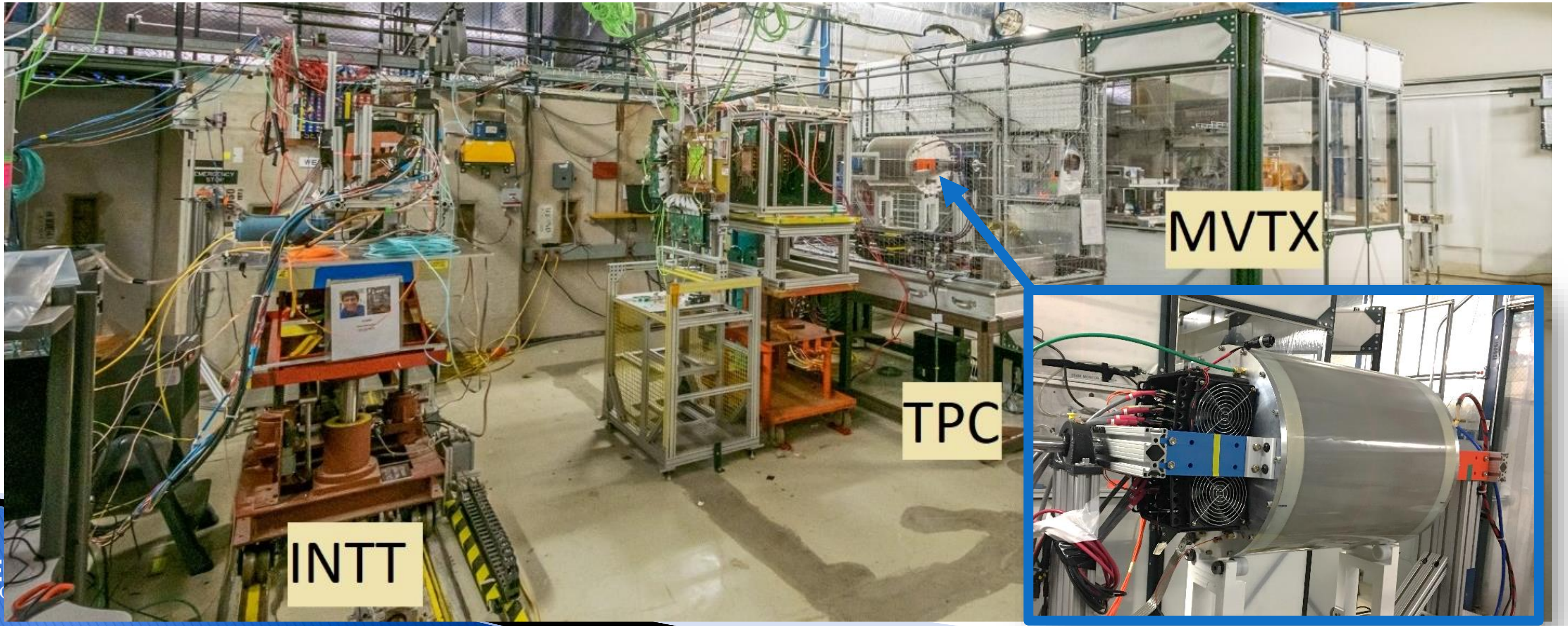
- A next-generation TPC operated in continuous readout mode using Gas-Electron Multiplier (GEM) avalanche w/ low Ion Back Flow (IBF)
  - Thin field cage: 1.5cm, 1.5% X_0
  - sPHENIX-2019 gas: Ne/CF_4 50/50
  - Drift : 400V/cm, 8 cm/μs, 13 μs drift
  - Low T-diffusion: 40um/√cm @ B=1.4T
  - GEM: Gain = 2000, IBF~1%
  - 48 pad rows in sensitive vol. R = 20-80 cm (30-80 used in sPHENIX). Zig-zag pads.
  - Shaping/FEE: 80ns/20MHz SAR ADC (SAMPAv5 ASIC), trigger-less readout
- Operation point is optimized for top multiplicity AA operation. Many can be easily adjusted for EIC application.



di-b-jet in p+p collisions √s=200 GeV, full G4 sim → Kalman filter reco display

Latest iteration test beam : 2019 @ FTBF

- GEM Framing @ BNL, tested @ Yale → Prototype field cage
  - 50/50 Ne/CF4 gas, various HV tunes to test low ion backflow
  - Readout w/ one of 24 sPHENIX R2 readout pad, 16 pad rows
- First run with SAMPA+DAM+GTM→RCDAQ (sPHENIX Chain)



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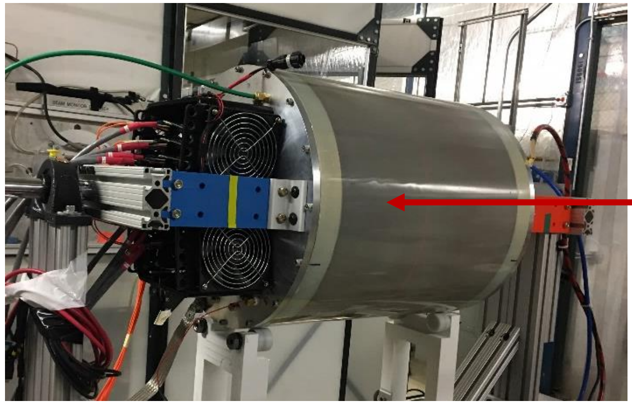
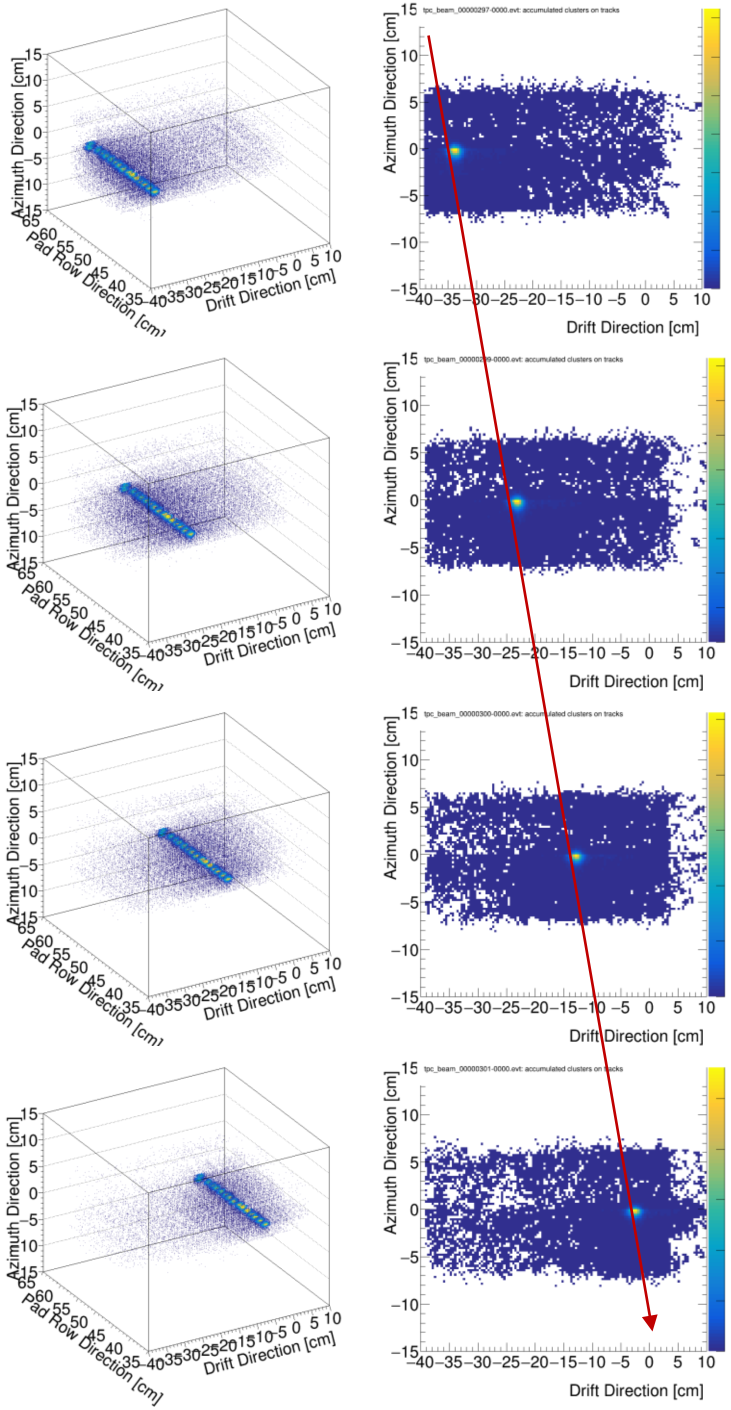
Positions scans

- Main goal is to study resolution as function of drift length
- Example, longitudinal scan with 120 GeV/c proton:

Postion (in)	Runs
6	288, 292
10	293
14	294
18	295

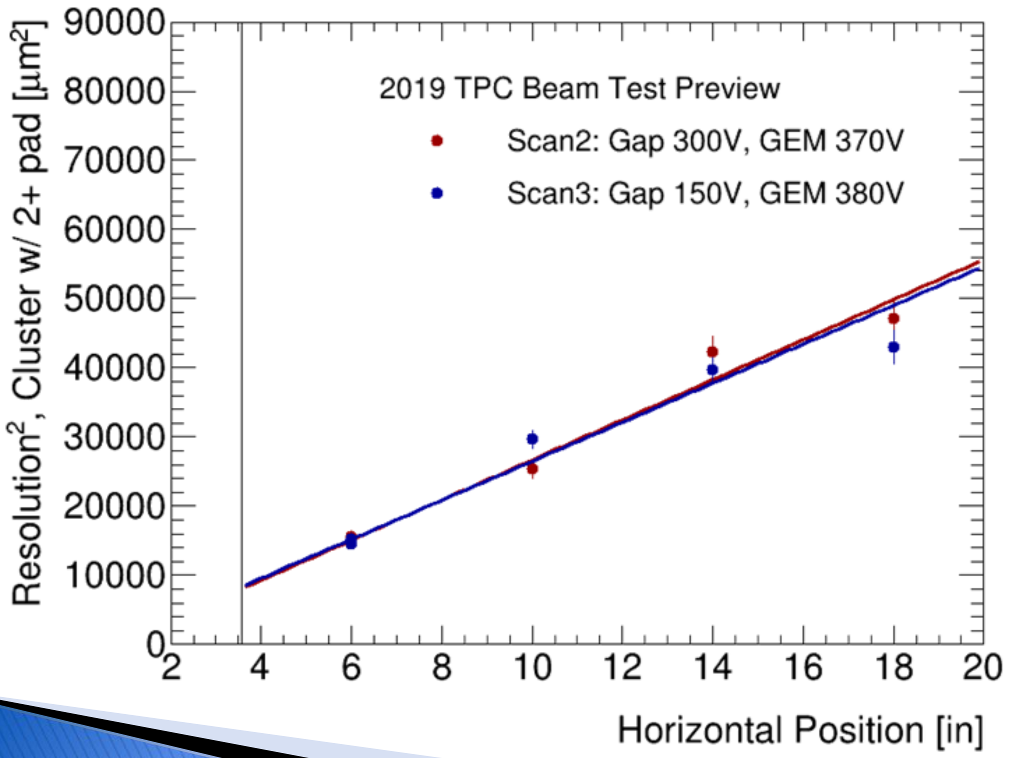


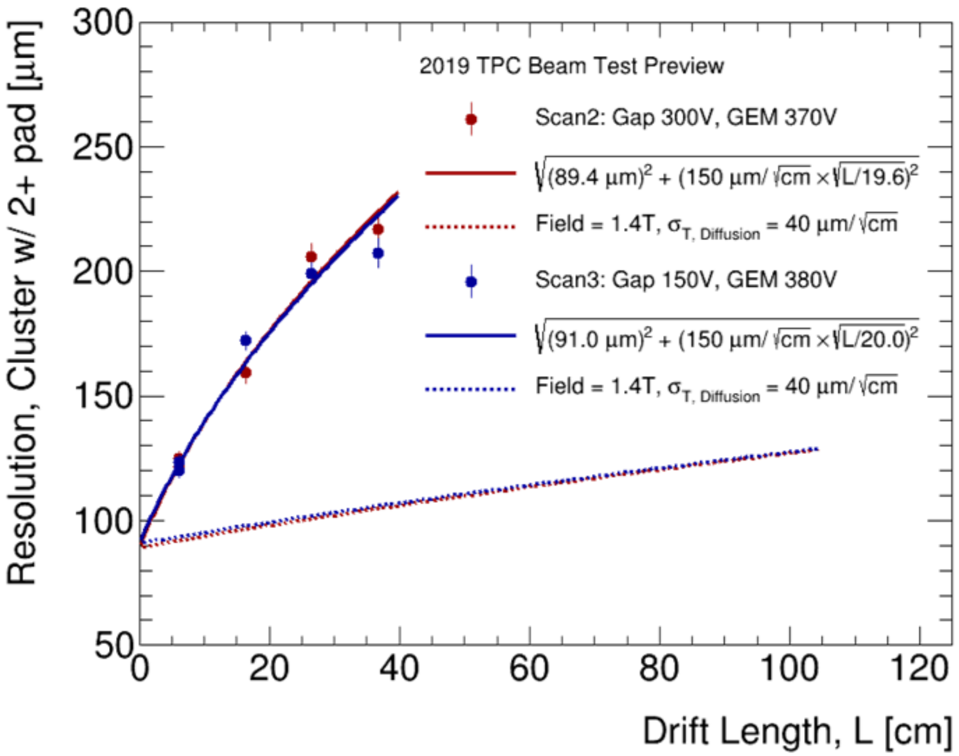
Proton
120 GeV



Very preliminary results : position resolution

- Two position scans show consistent results in position resolution
- Project to full length TPC in 1.4T magnetic field, resolution<150 um



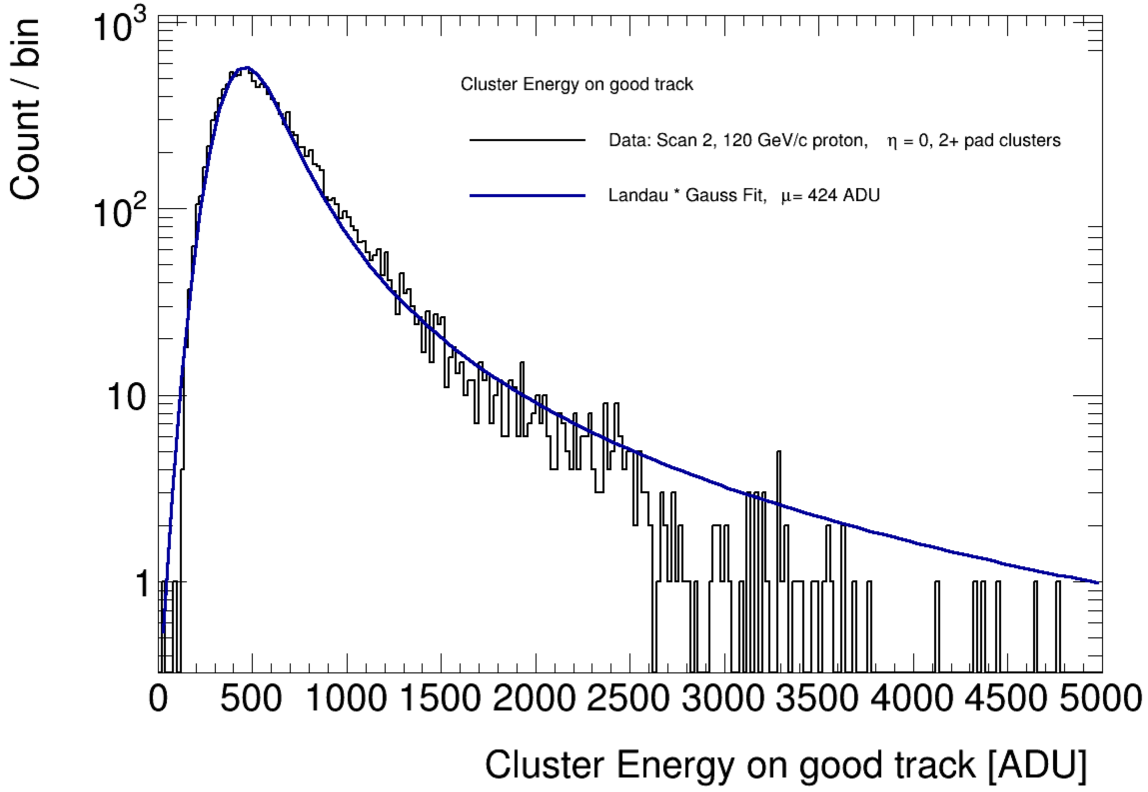


What about PID dE/dx resolution?

- sPHENIX TPC is compact comparing to STAR/ALICE
  - 48 pad row, ΔR = 50cm(sPHENIX) / 60cm(EIC R1). Compact favored for EIC detector
  - sPHENIX-2019 gas is 50% CF_4 – 50% Ne.
  - GEM gain setting: ***Not*** in low-ion feedback mode as suggested by Nikolai

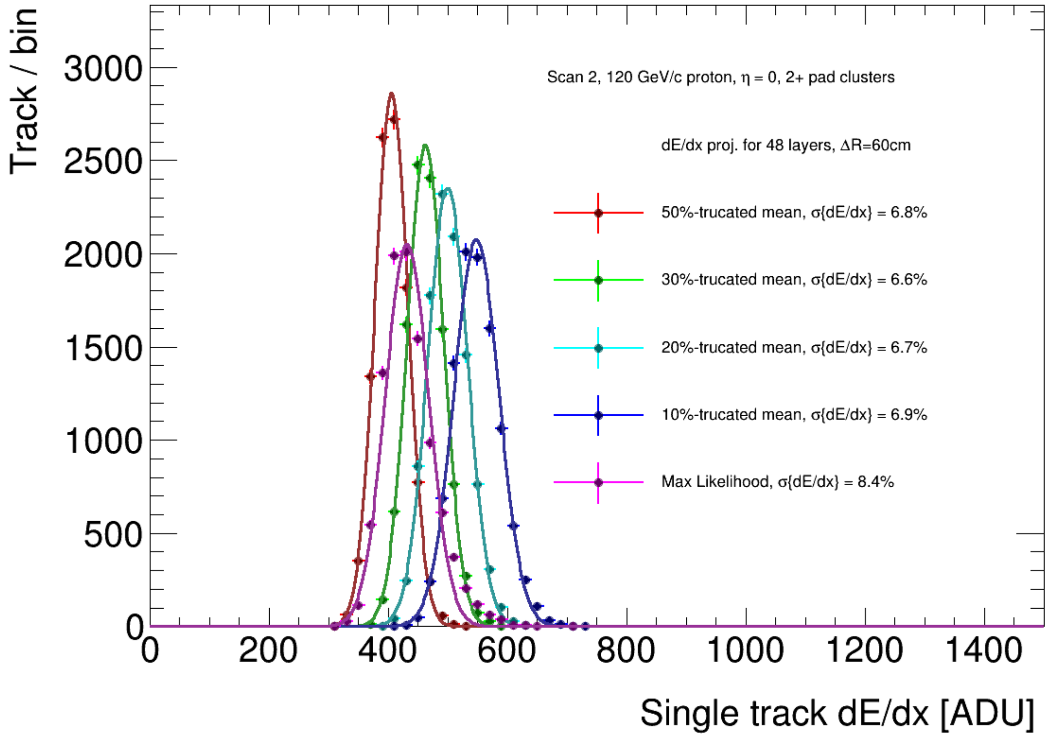
1. Measured cluster energy distribution in each of 16 layers (1.25cm/layer) prototype in 2019 test beam
2. Sample the energy distribution to project dE/dx performance to 48-layer/60cm full TPC in central rapidity
3. Performa various tail rejector to further reduce bias from 2ndary electron

2019 TPC Beam Test preview

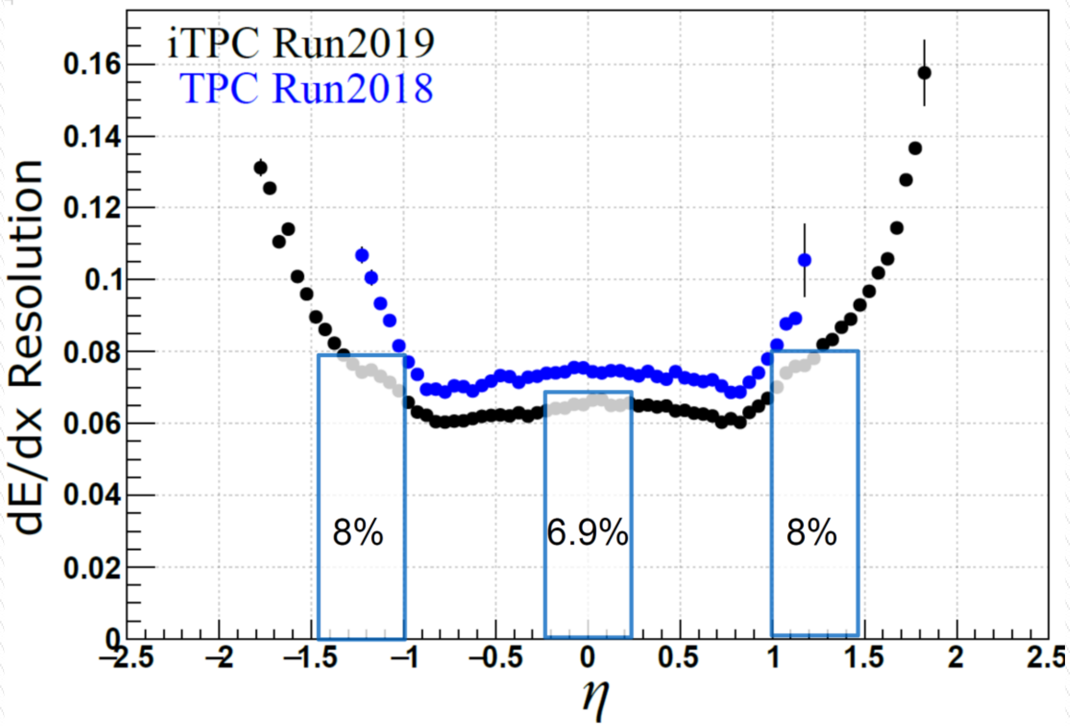


Very preliminary results : dE/dx resolution

2019 TPC Beam Test preview, projection for 48 layer



Improved dE/dx resolution



sPHENIX test beam data projected to EIC readout: resolution ≤7%

STAR iTPC upgrade
[RHIC S&T review, Caine]

More detailed note: https://nbviewer.jupyter.org/github/sPHENIX-Collaboration/analysis_tpc_prototype/blob/master/fnal_2019/dEdx/main.ipynb

Possible TPC work points for EIC operation

sPHENIX operation point

- Continuous readout mode using Gas-Electron Multiplier (GEM) avalanche w/ low Ion Back Flow (IBF)
- sPHNEIX-2019 gas: Ne/CF_4 50/50
- Drift : 400V/cm, 8 cm/μs, 13 μs drift
- Low T-diffusion: 40um/√cm @ B=1.4T
- GEM: Gain = 2000, IBF~1%
- 48 pad rows in sensitive vol. R = 30-80 cm
- Shaping/FEE: 80ns/20MHz SAR ADC (SAMPAv5 ASIC)
- Optimized for AA top multiplicity operation

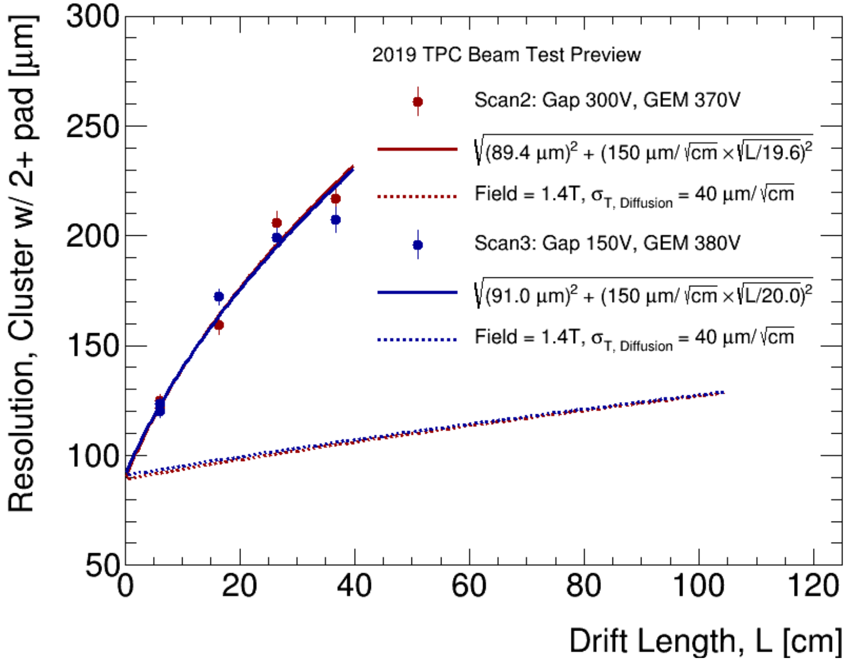
Subset of possible EIC operation points

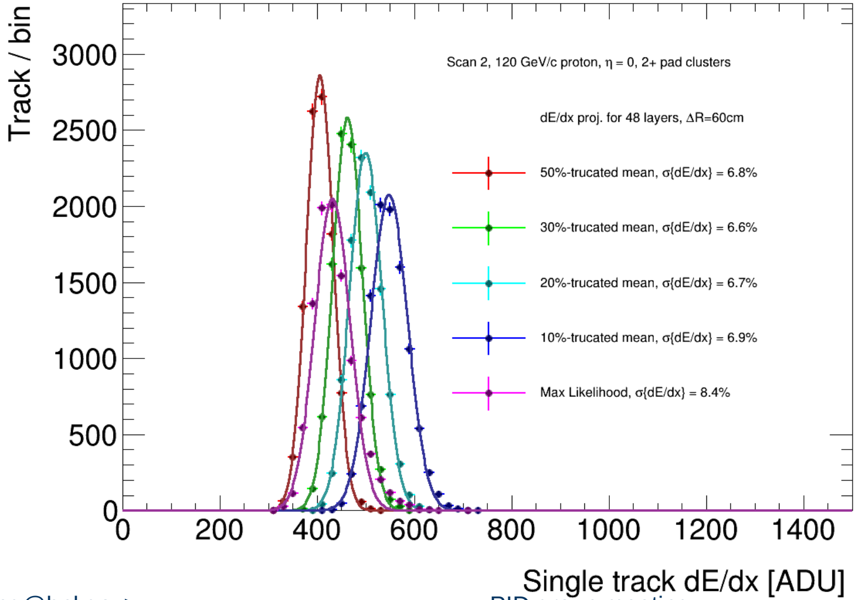
- Continuous readout mode using GEM aiming to stream record 500kHz EIC collision
- Gas: High CF_4 gas, Ar/CF_4 95/5, T2K??
- Drift : 5-10 cm/us?
- Low T-diffusion: <50um/√cm @ B=1.4-3 T
- Gain Config: IBF not as big as a concern as A+A (debatable)
- # pad rows in sensitive vol. R = 20-80 cm
- Shaping/FEE: 80-160ns/10-20MHz SAR ADC (SAMPAv5 ASIC)
- Need optimization study…
  See also tracking group discussions

Summary

- The sPHENIX TPC in EIC config is a capable detector:
  - Early results from test beam indicates: rΦ position resolution < 150um, PID via σ[dE/dx] ≤ 7%
  - High throughput trigger-less readout which fits EIC too
- This is not end of the story, but a start:
  - Work point study needed to optimize for EIC performance: Gas choice, drift field, GEM gain stack, Readout pads, Shaping time, Readout firmware
  - Need to validate details on implementation in Geant4 gas physics model and Digitization + Reco. Tuning
  - Run dedicated beam test in e/pi secondary beam
- Final dE/dx resol. can be translated to PID group's sigma separation plot

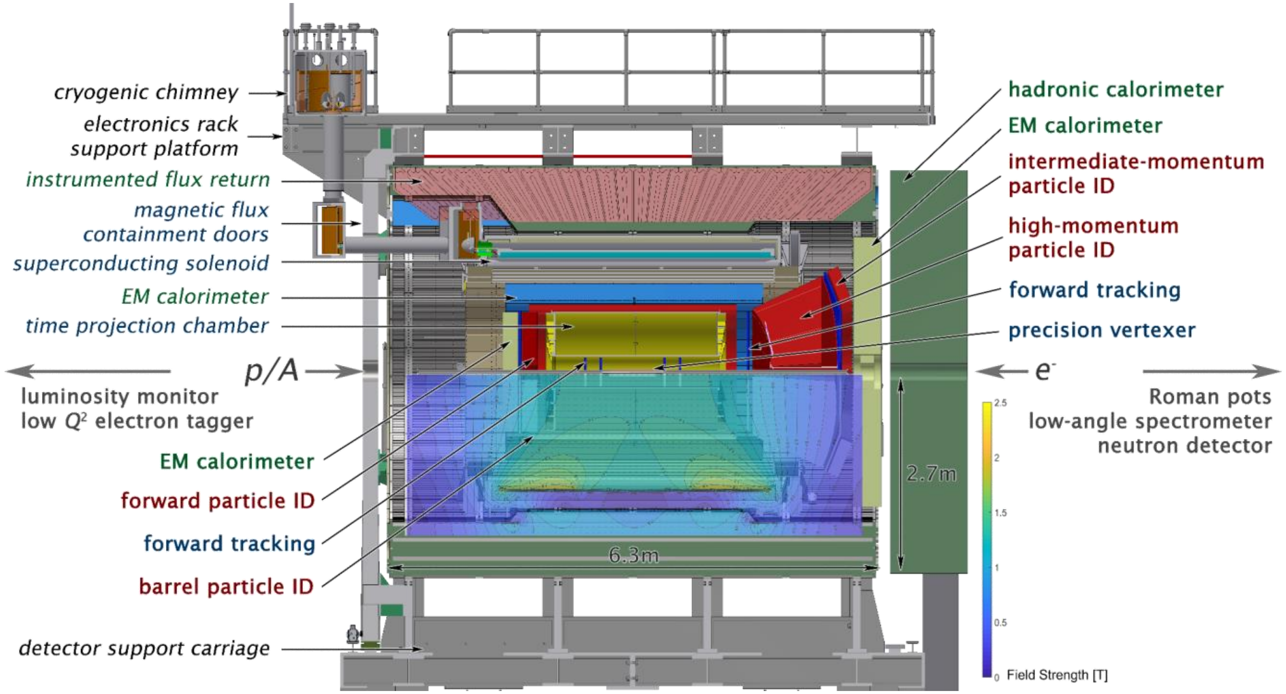
sPHENIX 2019 TPC test beam preview

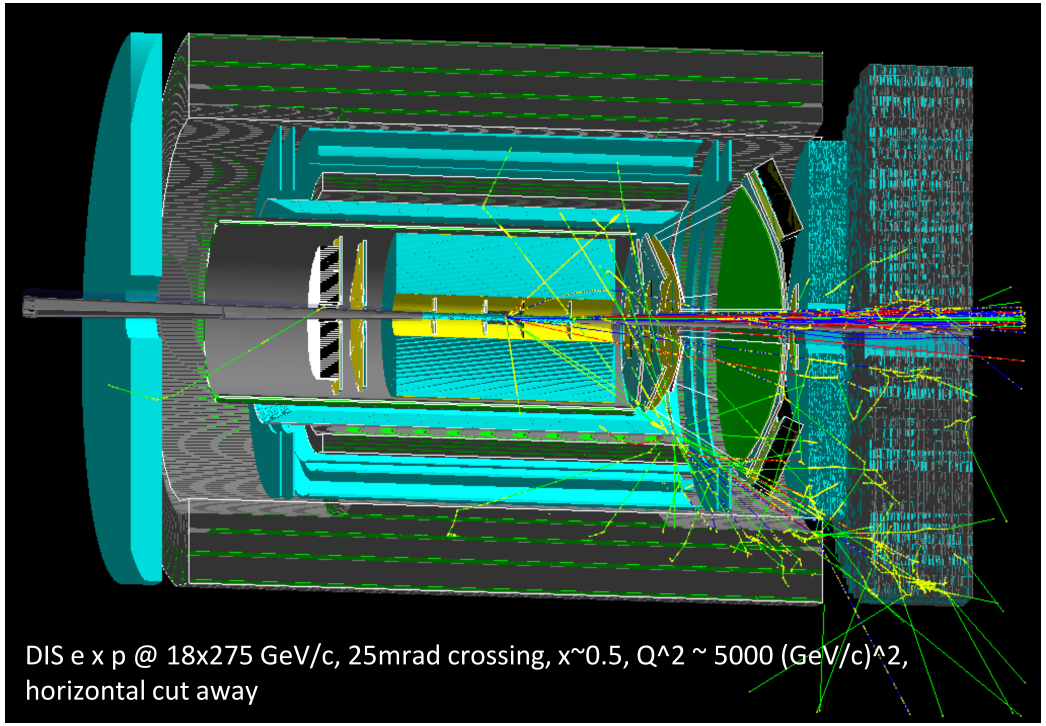




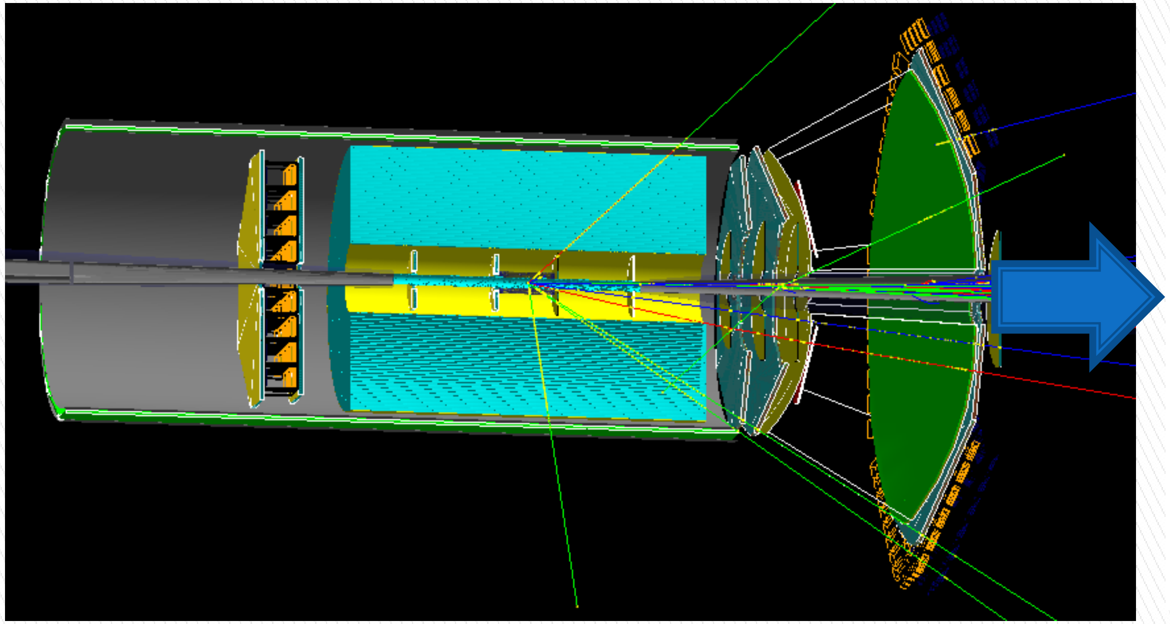
BTW: Fun4All-based simulation

- https://github.com/eic/Singularity

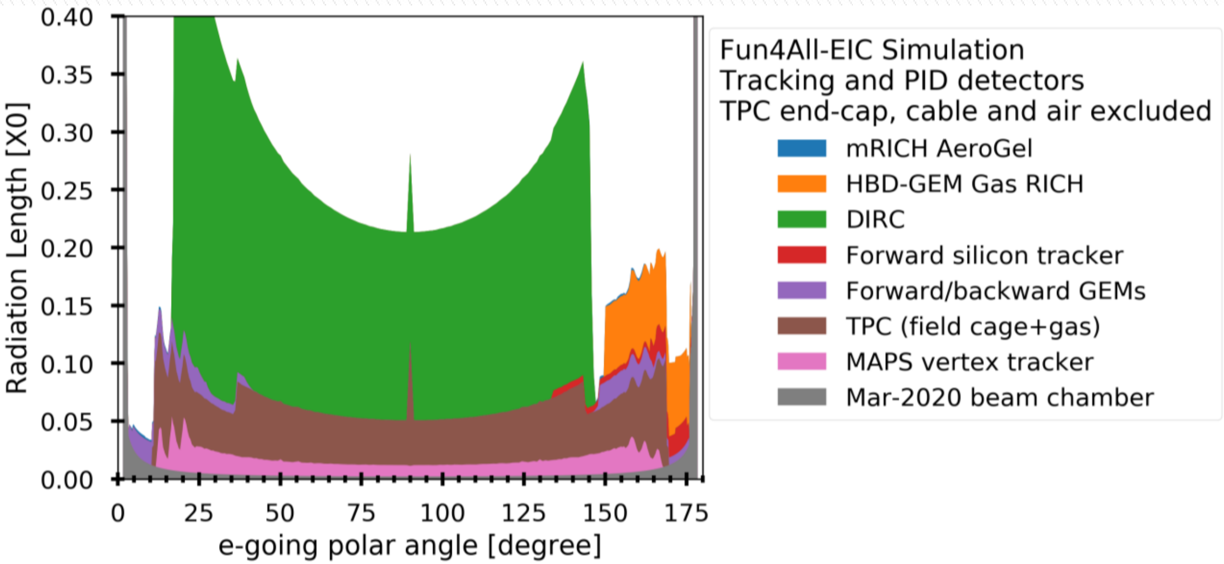




Need input from PID group



Material thickness scan as reported in 2nd EIC YR workshop



Reproduce:

https://github.com/blackcathj/macros/tree/display-EIC-BeamPipe-materialscan/macros/g4simulations

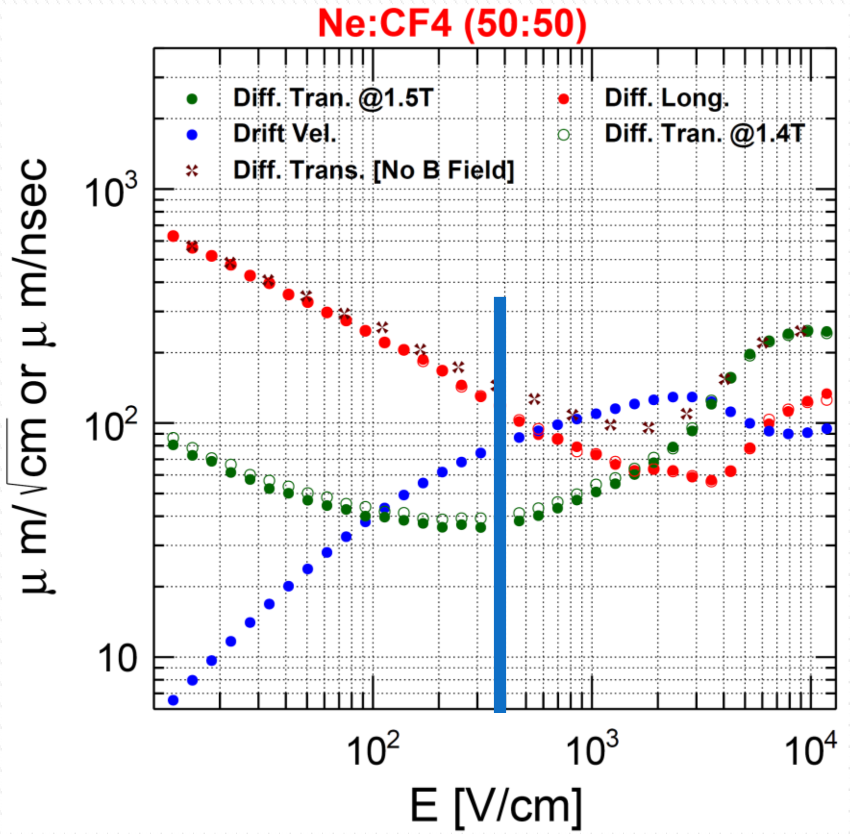
Central detectors:
mRICH, HBD-GEM gas RICH, DIRC

Material scan out of box:
Need DIRC focusing optics & mRICH support material

Extra information

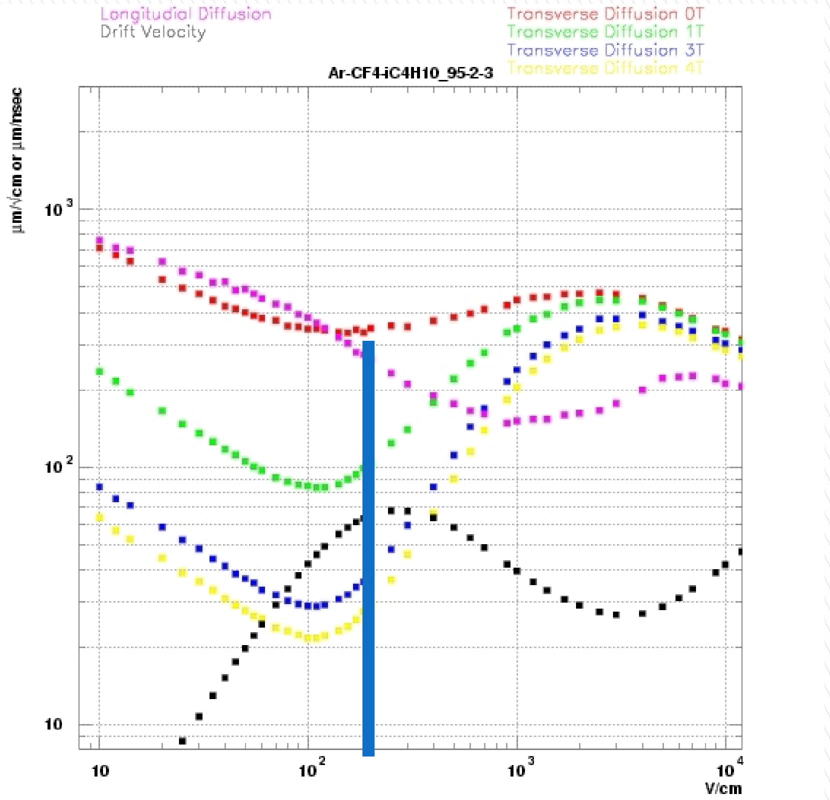
Reprehensive gas choices, Ne or Ar-based

Prakhar Garg <prakhar.garg@stonybrook.edu>



sPHENIX-2019 gas: Ne-CF_4 50-50
Drift E~ 400 V/cm, $n_{primary}$=32/cm, n_{total}=72/cm

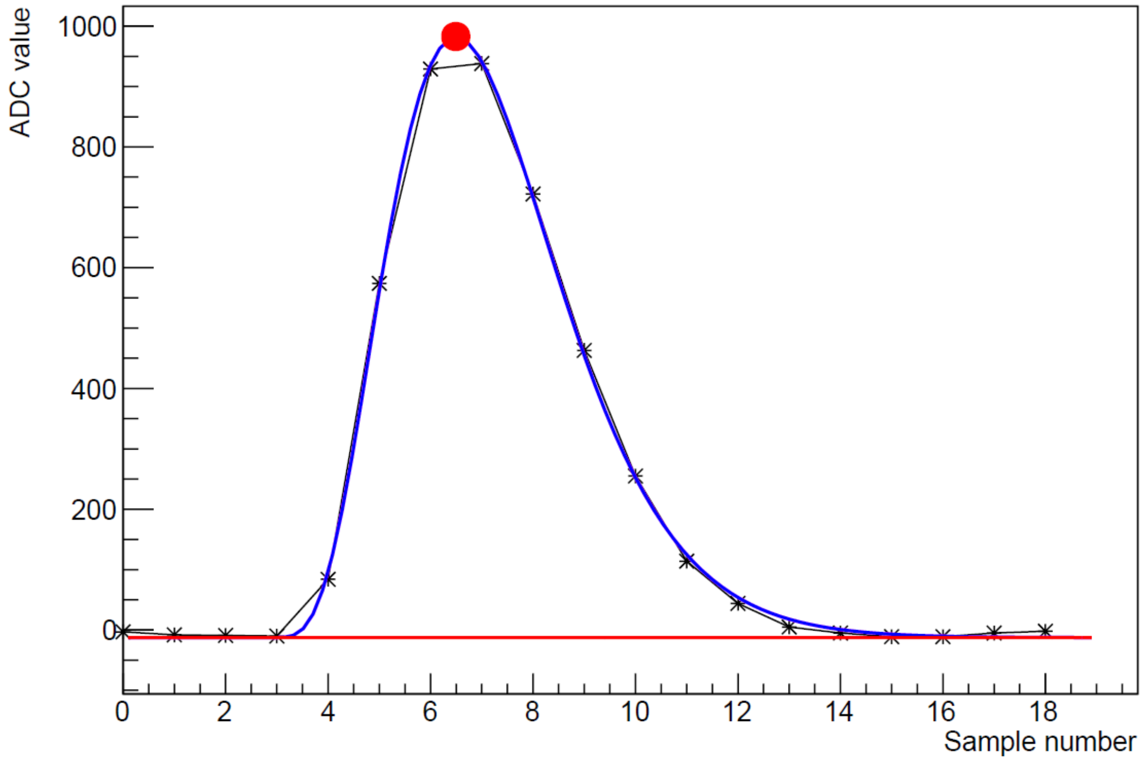
ILC, Saga University



T2K gas: Ar-CF_4-IsoButane 95-3-2
Drift E~ 200 V/cm , $n_{primary}$=25/cm , n_{total}=96/cm

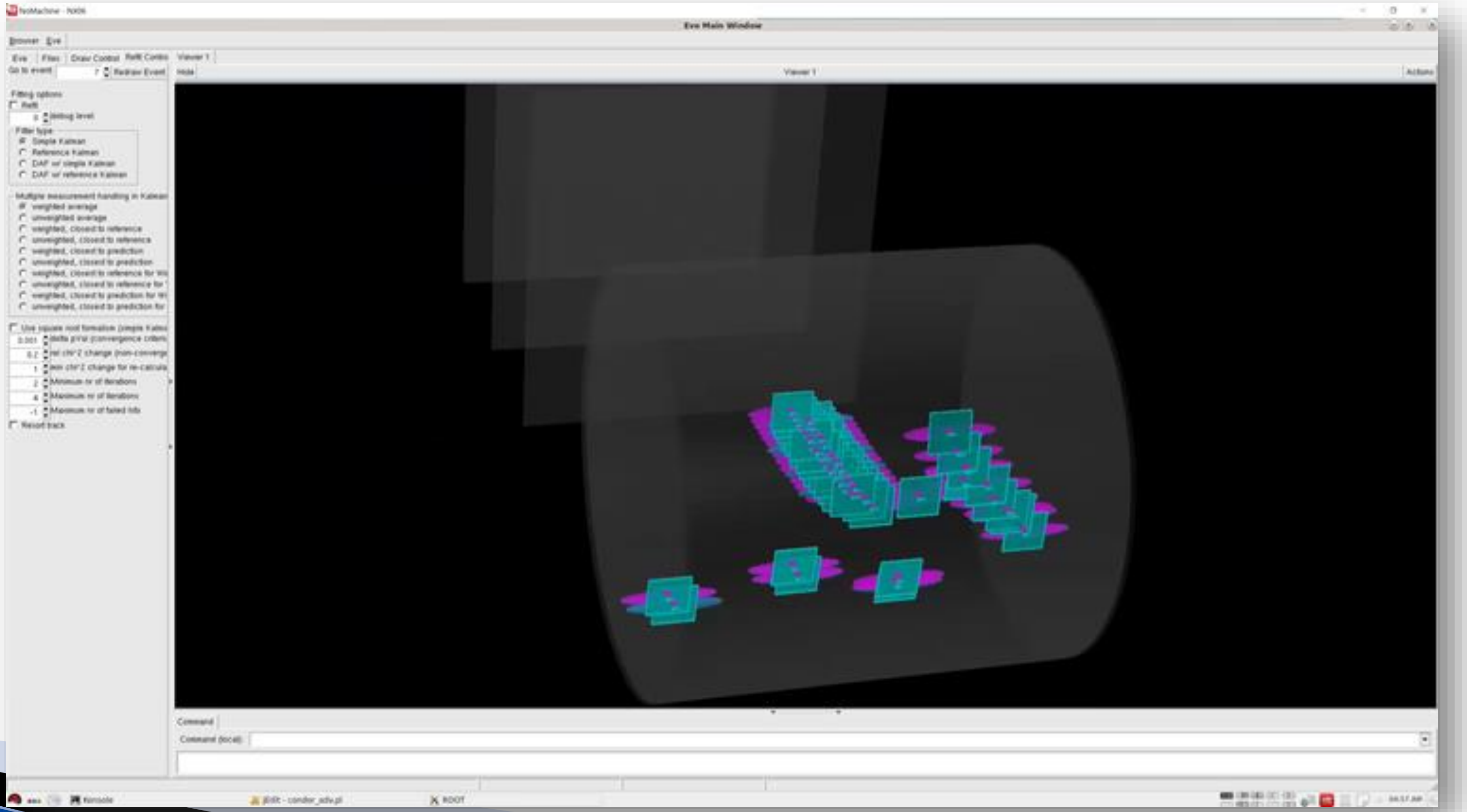
Clustering and Fit with LC-shaping function

- Reference to code: TpcPrototypeUnpacker::Clustering()
- With in each layer, clustering neighboring pads above threshold
- Fit overall cluster ADC vs Time to get signal shape with shaping function fit
- Use the constraint fit to fit each pad, and use each pad's energy to extract energy weighted cluster position



Tracking and Kalman track fitting

- Code reference: TpcPrototypeGenFitTrkFitter
- 1-removed residual: Remove the cluster in study, perform Kalman filter fit of rest clusters on track, extrapolate to cluster and calculate residual on both phi and z dimensions



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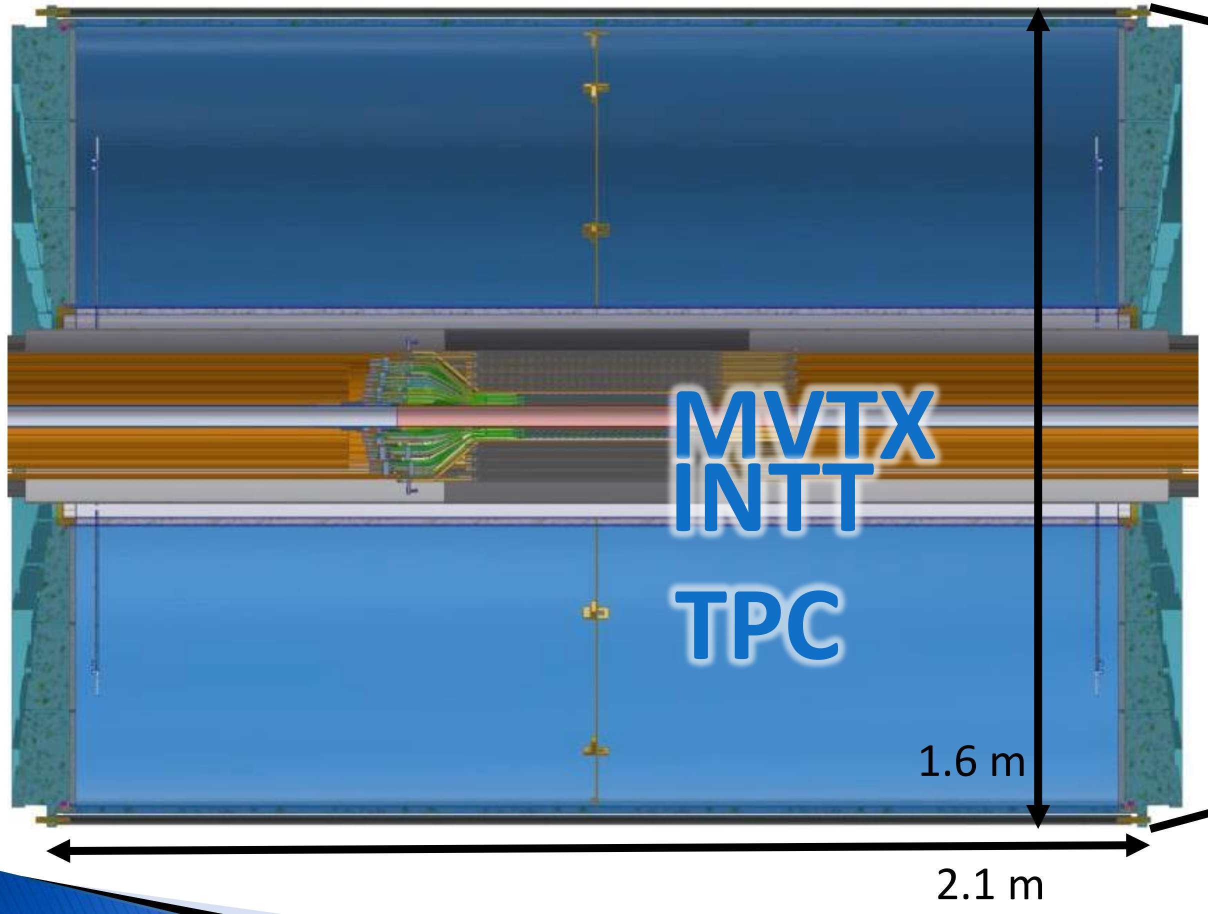
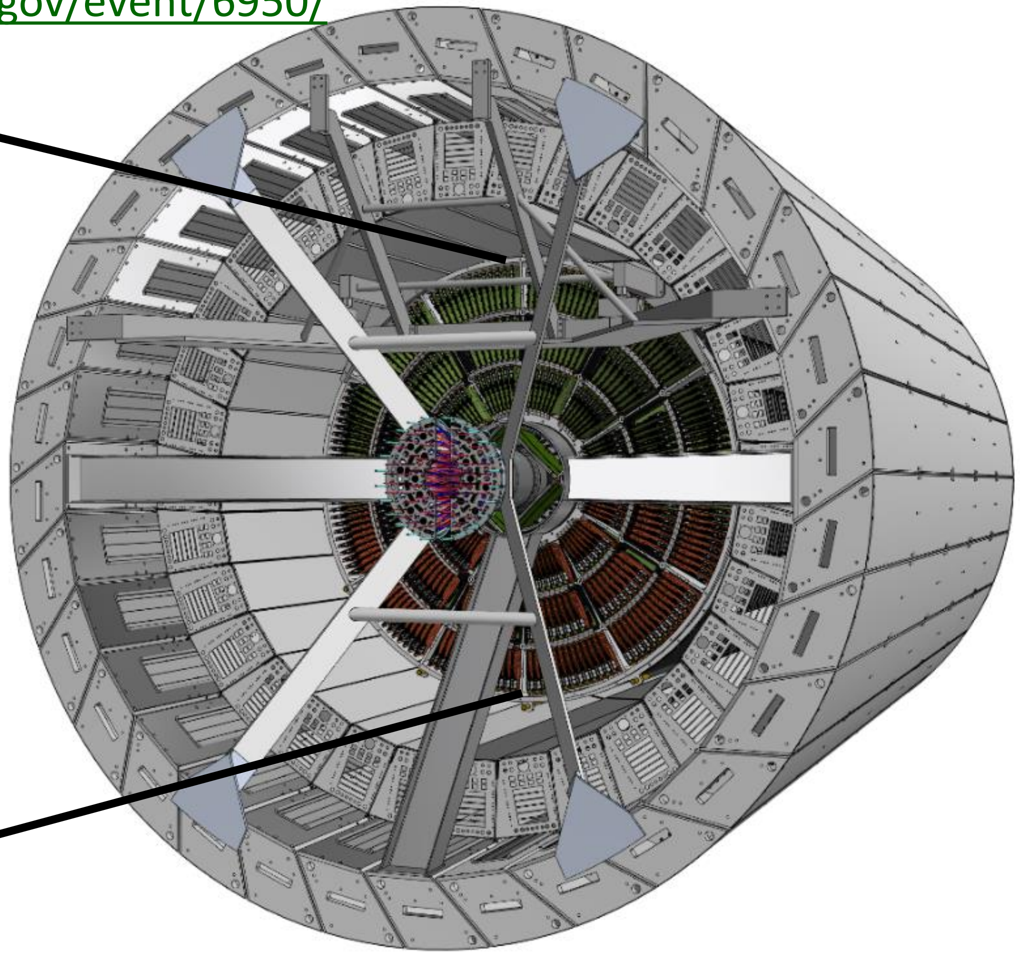
Mechanical assembly

More details: https://indico.bnl.gov/event/6662/ , https://indico.bnl.gov/event/6950/

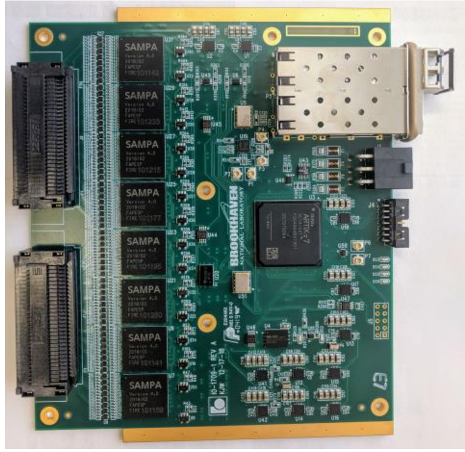




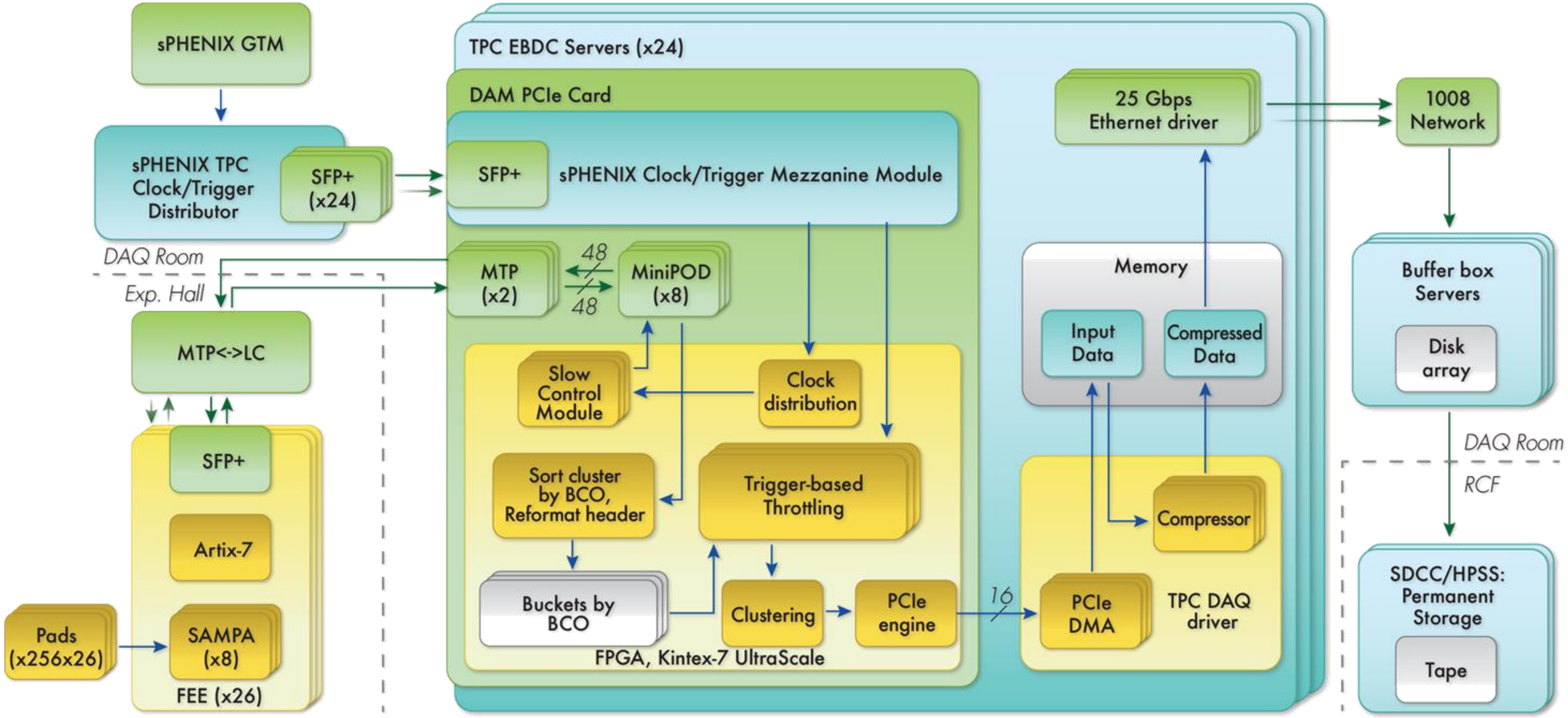
Detectors inside the magnet

Continuous readout DAQ

256ch FEE based on ALICE
to be SAMPAv5 w/ 80ns shaper



sPHENIX DAM based on ATLAS FELIX

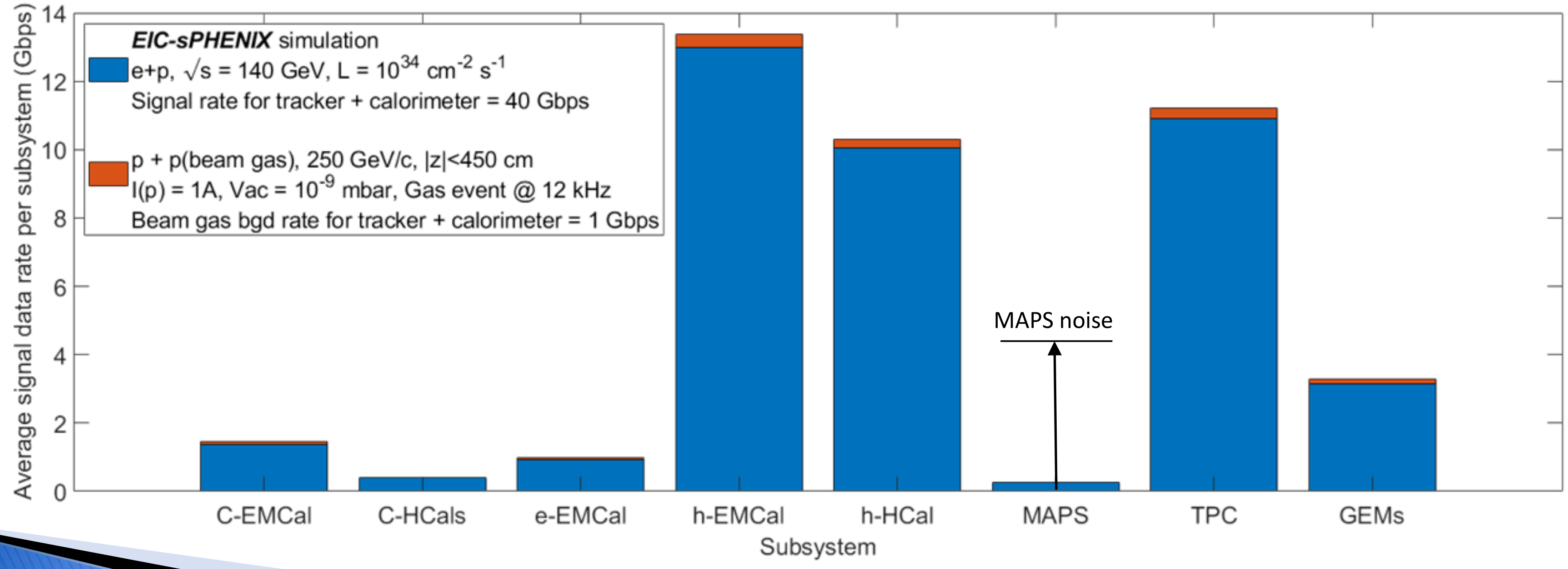


1 sector, 26 FEEs per DAM for readout
24 sectors, 160k Pads and 624 FEEs
24DAMs total

DAQ Rate in Geant4 full detector simulation

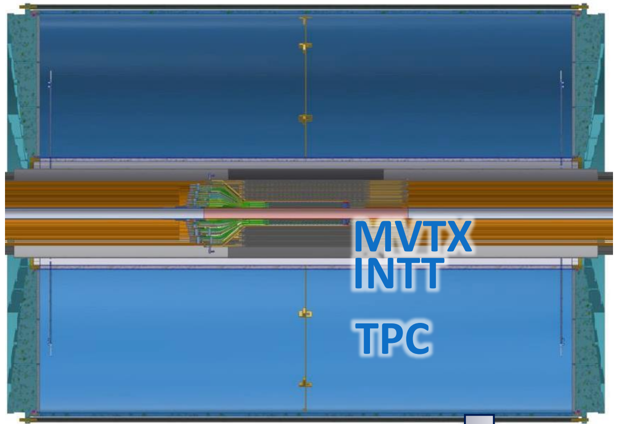
sPH-cQCD-2018-001: https://indico.bnl.gov/event/5283/ , Simulation: https://github.com/sPHENIX-Collaboration/singularity

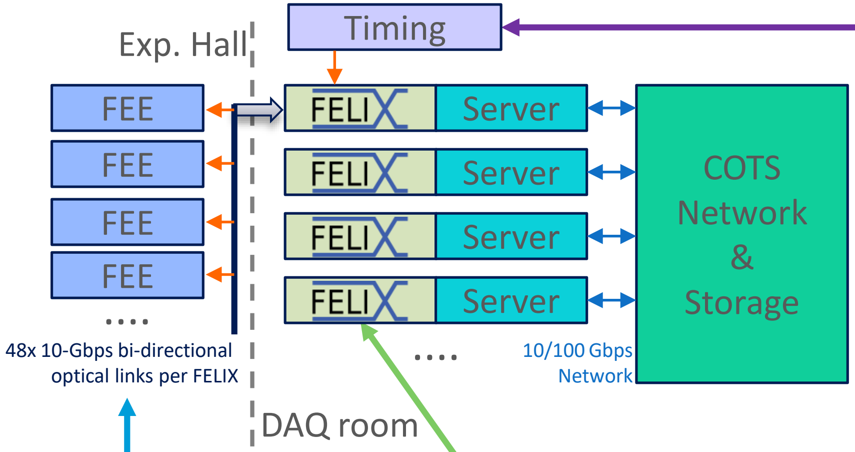
- Data we want to record: all EIC collision signal ~ 100 Gbps @ 10^{34} cm^{-2} s^{-1}, < sPHENIX peak disk rate
- Background hit rejection, if needed:
  - Vac profile based on HERA experience (10^{-9} mbar)
    → Overall ~ 1 Gbps @ 12kHz p+p(beam gas) interaction << EIC collision signal data rate
  - We will be happy to collaborate on studying other source of background and noises (e.g. synchrotron)



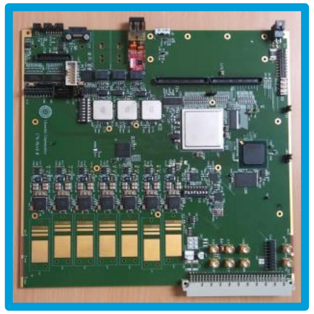
Streaming readout for sPHENIX trackers as EIC demo

- A large demo of this EIC streaming DAQ concept: sPHENIX tracking system
- Exploring EIC application with BNL LDRD19-028, EIC eRD21





Global Timing Module



MVTX RU, 200M ch
ASIC: ALPIDE

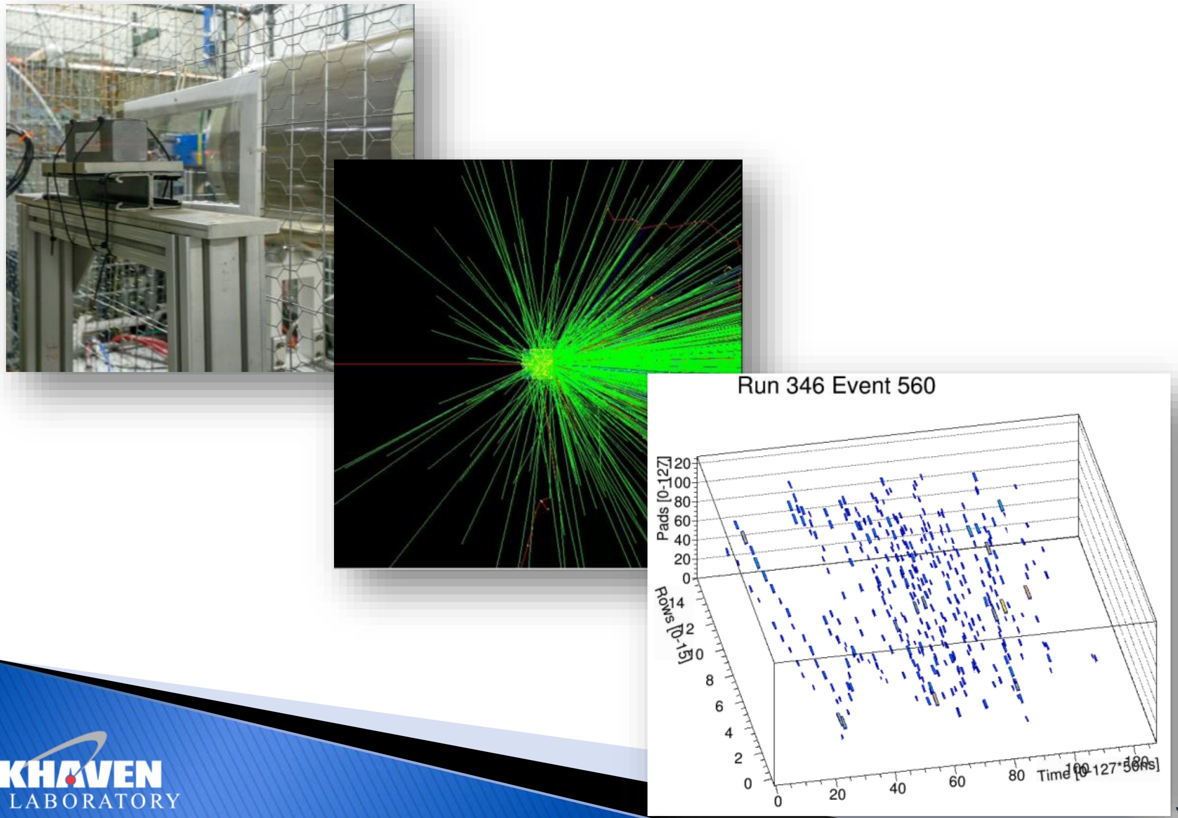
INTT ROC, 400k ch
FPHX

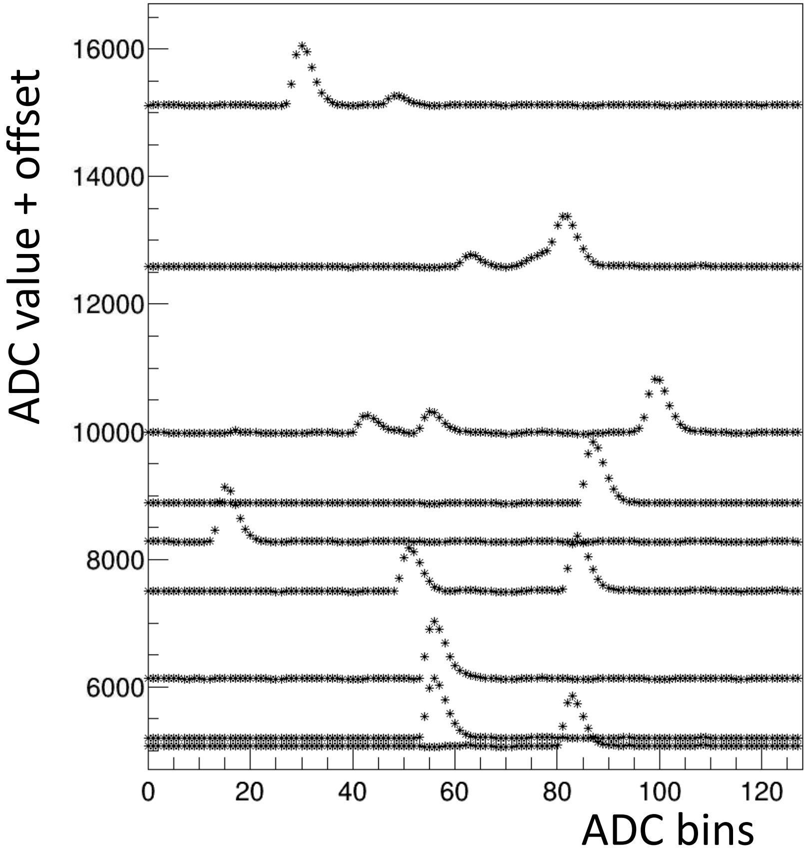
TPC FEE, 160k ch
SAMPA

BNL-712 / FELIX v2 x48
Streaming ASIC → DAQ

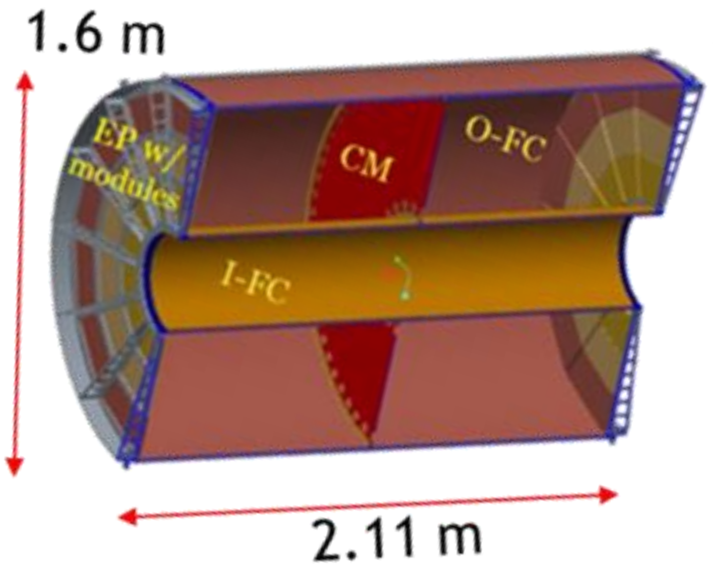
High multiplicity operation

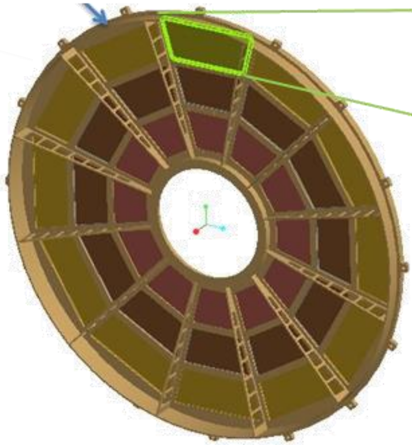
- Put a 7 radiation length EMCal block in front of TPC to induce high track density
- For pile up study, high signal recovery



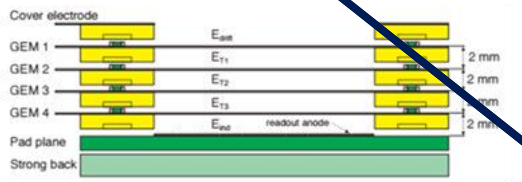


Readout components

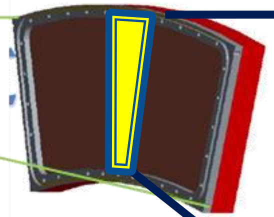


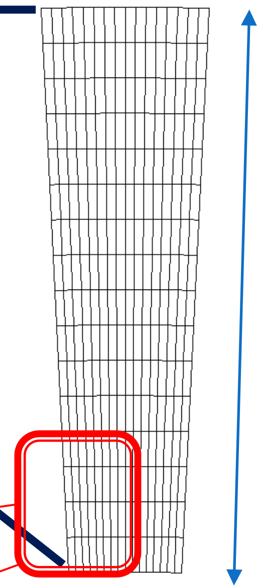


72 modules
2(z), 12(ϕ), 3(r)

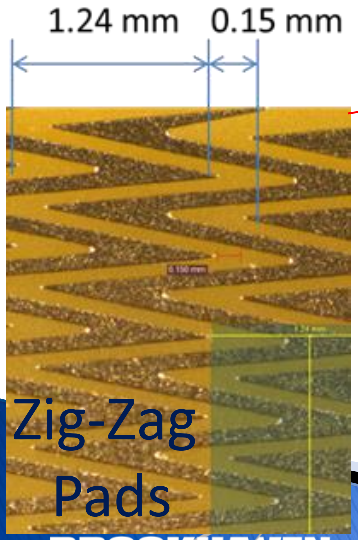


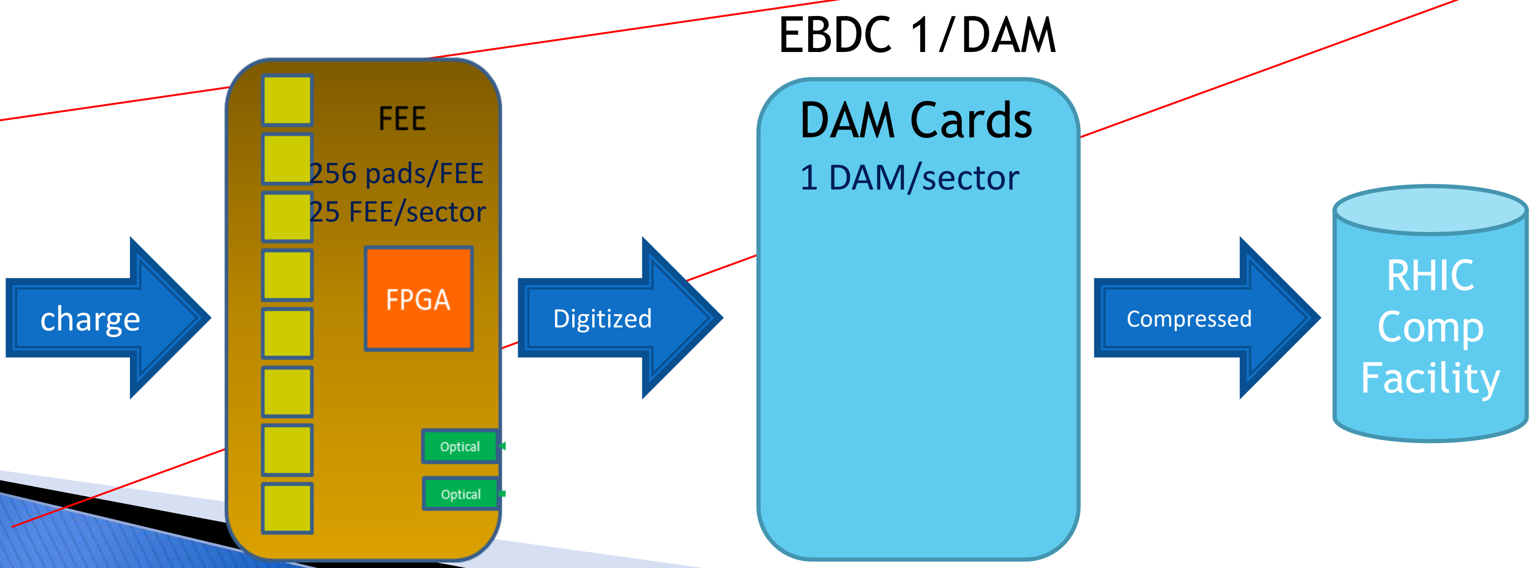
Quad-GEM Gain Stage
Operated @ low IBF





"Wedge"

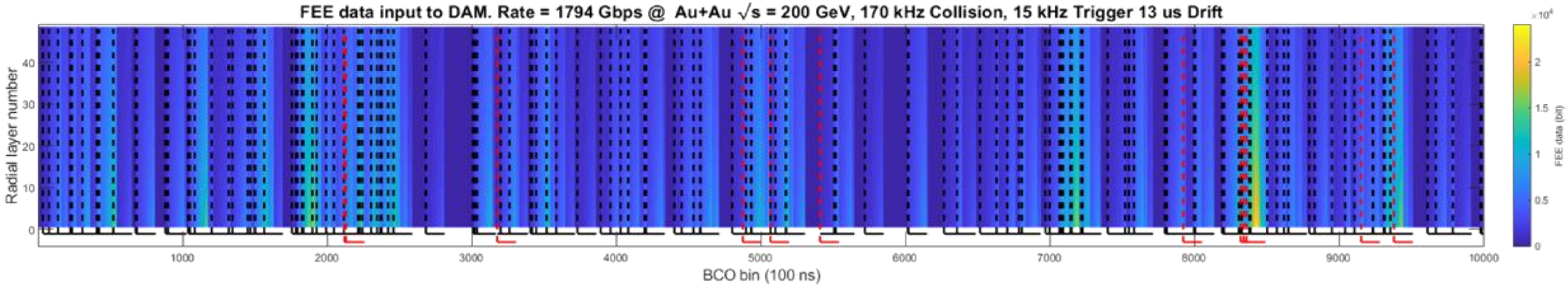


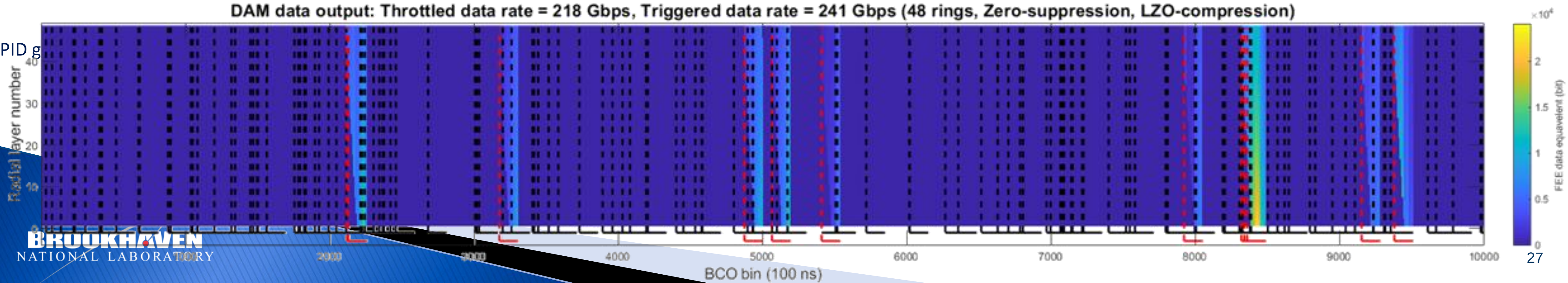


Item	Count
Field Cage	1
Modules	72
FEE	624
DAM	24
EDBC	24

Continuous readout operation

- FEE continuously digitize at 20 MHz, zero suppression in SAMPA ASIC
- DAM buffer all data in FPGA, throttle output that is corresponding to calo. trigger





PID g

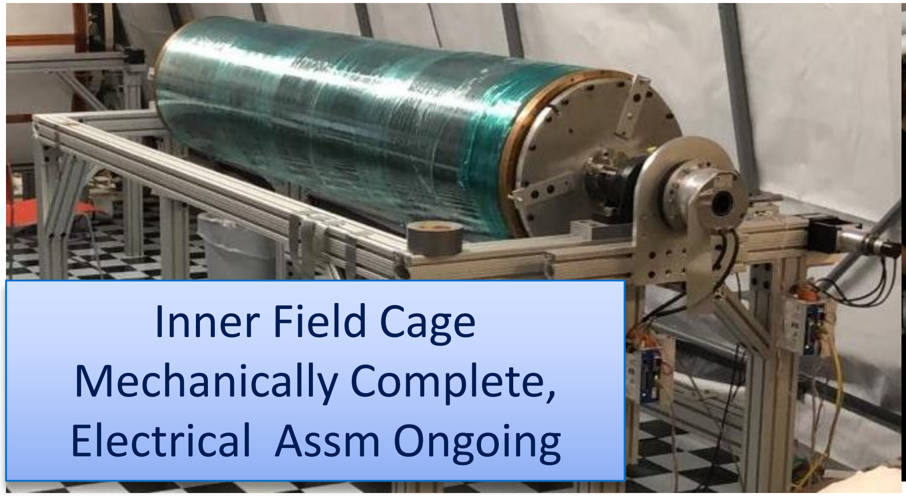
BROOKHAVEN
NATIONAL LABORATORY

sPHENIX TPC data rate?

- Instantaneous TPC data rate at a given instantaneous collisions rate
  - Au+Au TPC data rate [Gbps] ~ 70 + 1 * Collision_kHz
- sPHENIX rate capability would allow EIC operation stream recording all collision-induced data without triggering

	AuAu (Y-1)	AuAu (Y-3)	AuAu (Y-5)	pp	pA
Average collision rate [kHz]	100	140	170	12900	2800
FFE → DAM data rate [Gbps]	1100	1476	1800	1700	1470
DAM → DAQ data rate [Gbps]	170	209	240	160	133
Per-event size @ DAQ [MB/evt]	1.4	1.7	2.0	1.3	1.1

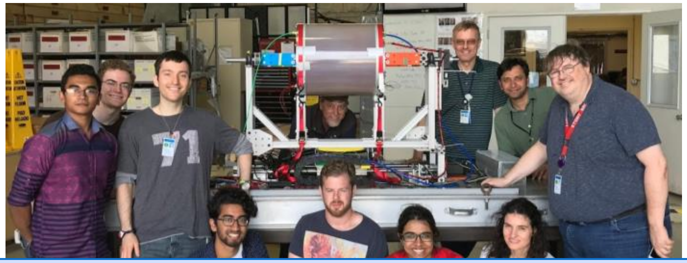
Status and Highlights



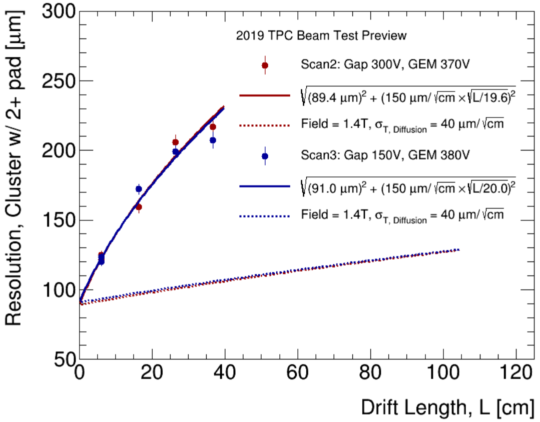
Inner Field Cage Mechanically Complete, Electrical Assm Ongoing

Large Field Cage Assm Ongoing

V1a Module



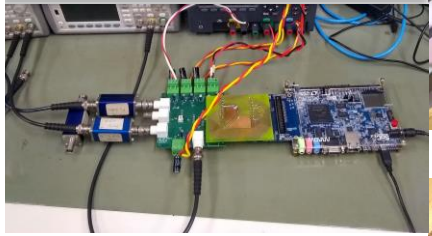
40cm-drift Prototype Test Beam

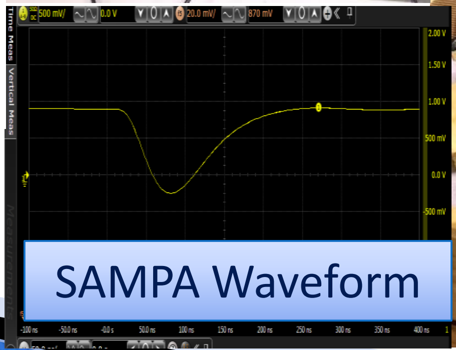


Sim <138μm>

Meas 90-130μm

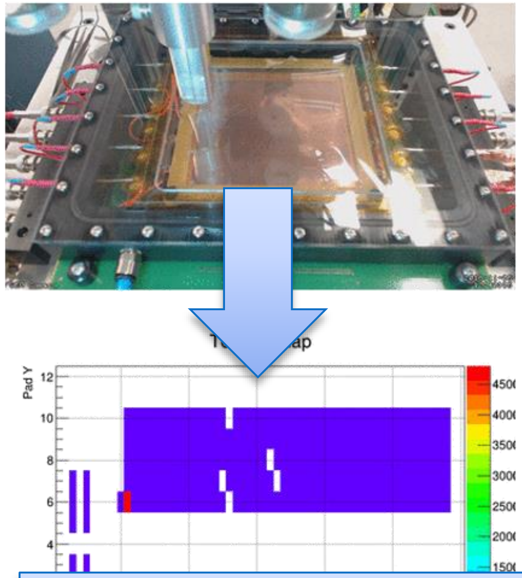
SAMPA v5





SAMPA Waveform

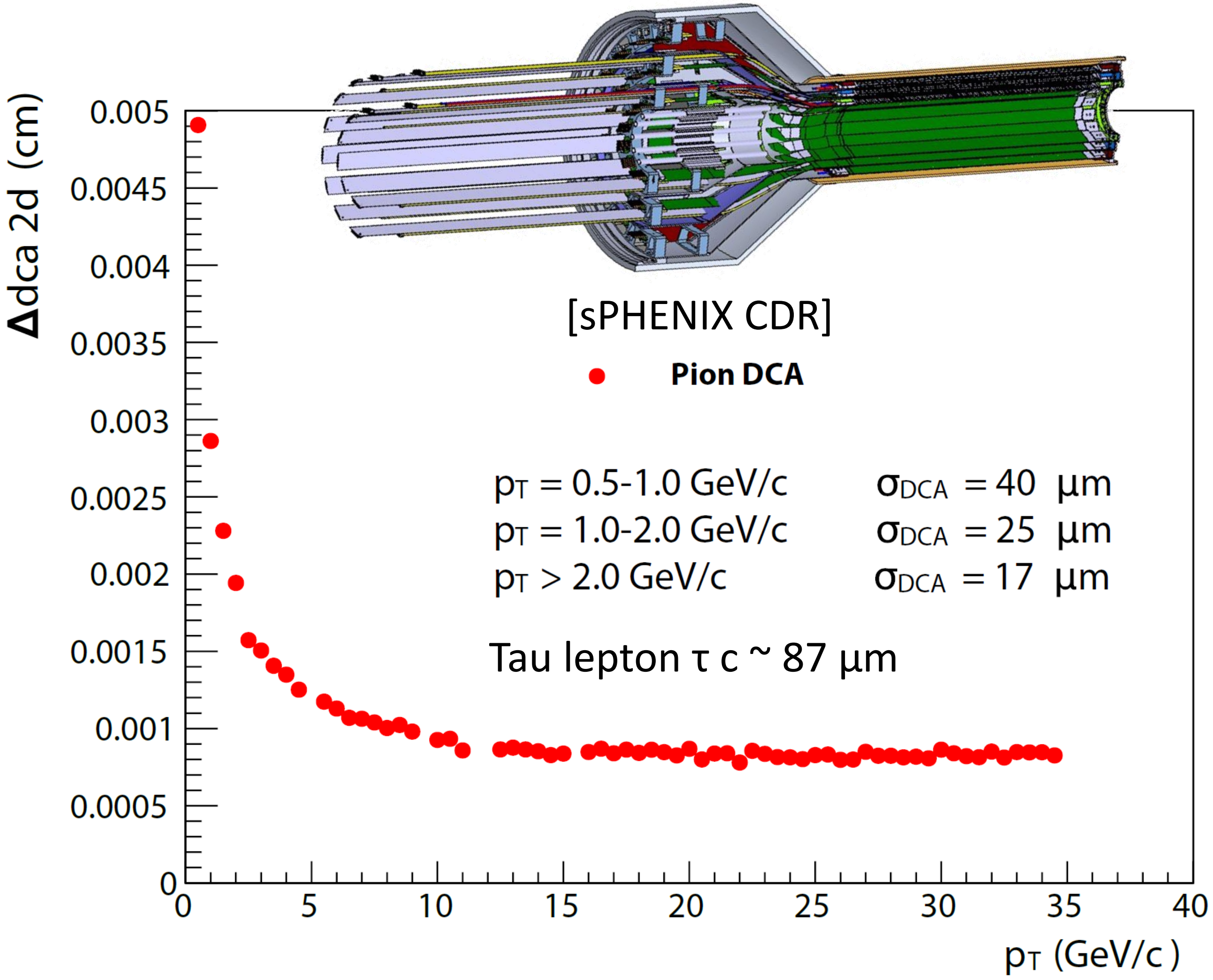
Wagon Wheels Delivered/Accepted



X-ray scan measured/analyzed through full chain

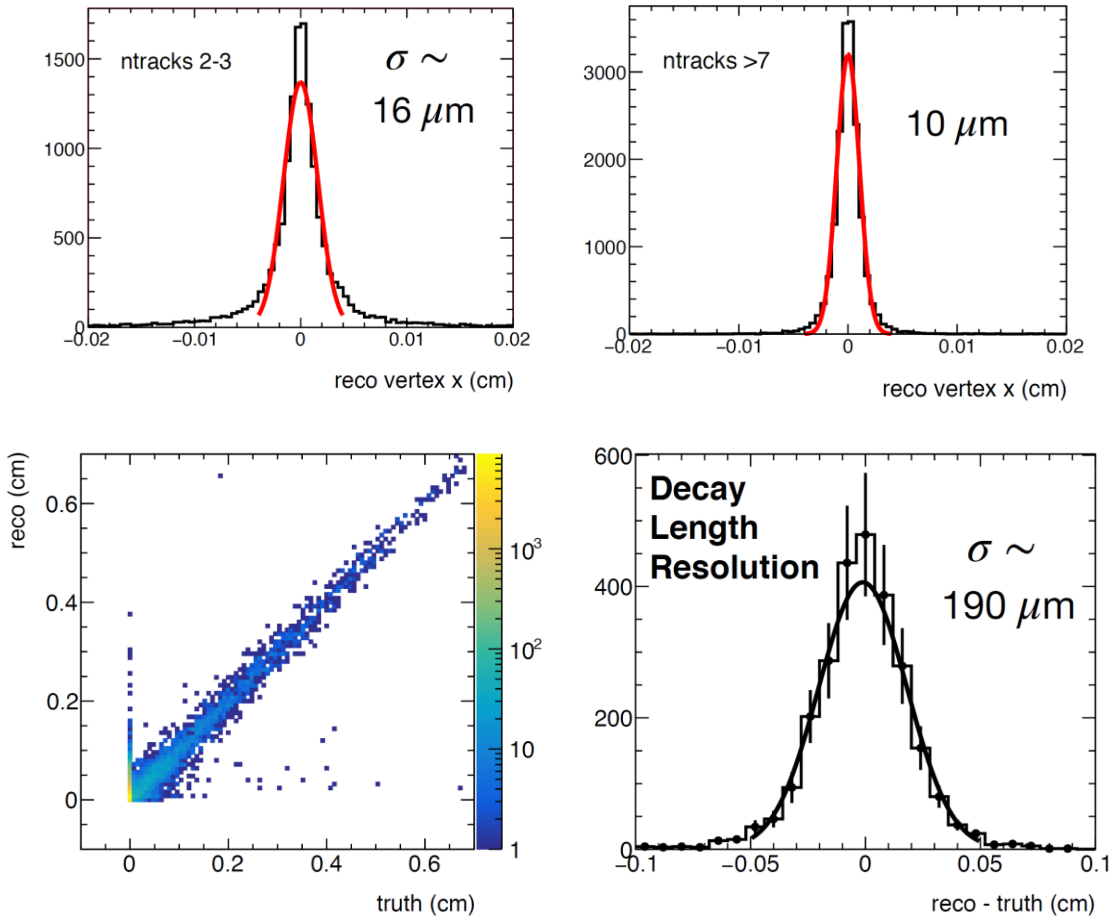
MAPS-based silicon tracker: τ ID via displaced vertex

- For initial τ-reco evaluation: sPHENIX vertex tracker
  - 30 µm ALICE Pixel MAPS pixel in three layers, total 200 M pixel channels
  - 5 um hit position resolution
  - 0.3% X_0 thickness per layer
  - R_{min} ~2cm. Note: EIC R_{min} likely ~3cm
- Simulation: full detector in Geant4
- Reconstruction: digitization→ clustering → track finding → Kalman filter → primary and 2ndary vertexing
- Run it on your laptop: https://github.com/sPHENIX-Collaboration/Singularity

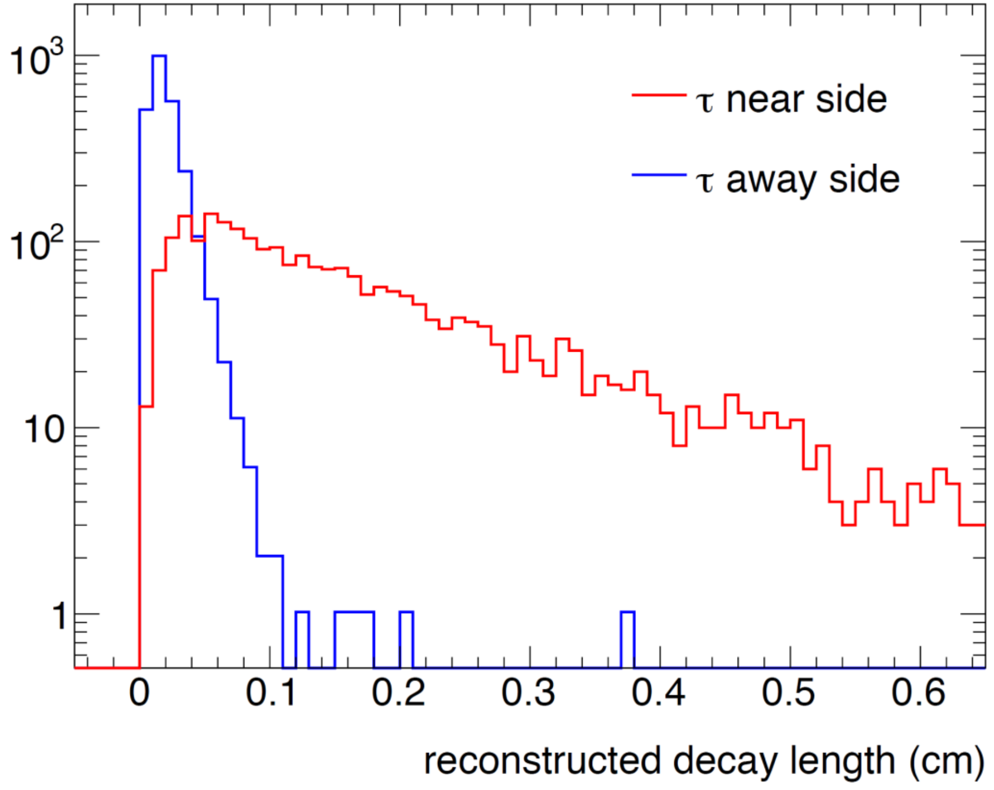


Full sim + reconstruction: secondary vertex of τ

Vertex reco. performance, Plot by Jinlong Zhang (SBU)

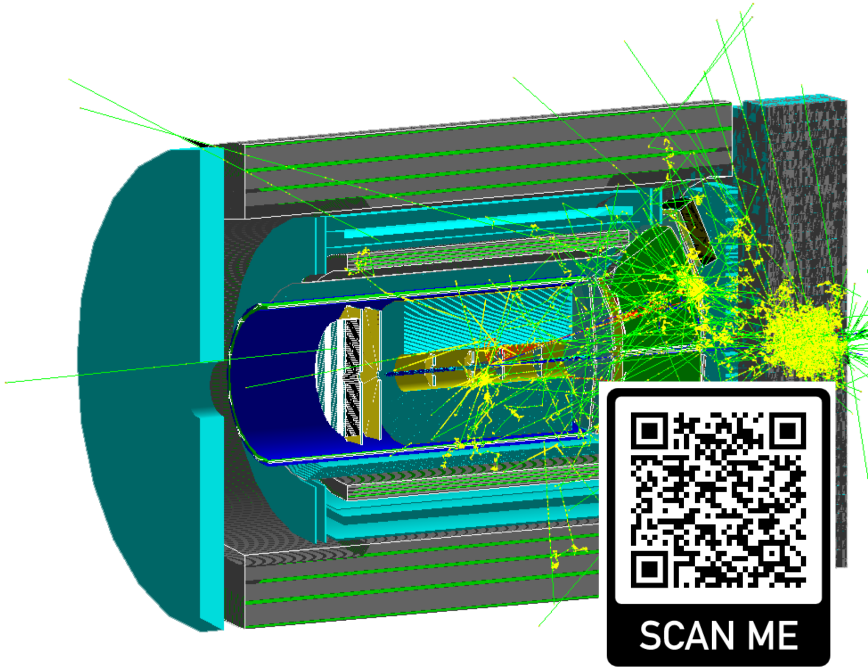


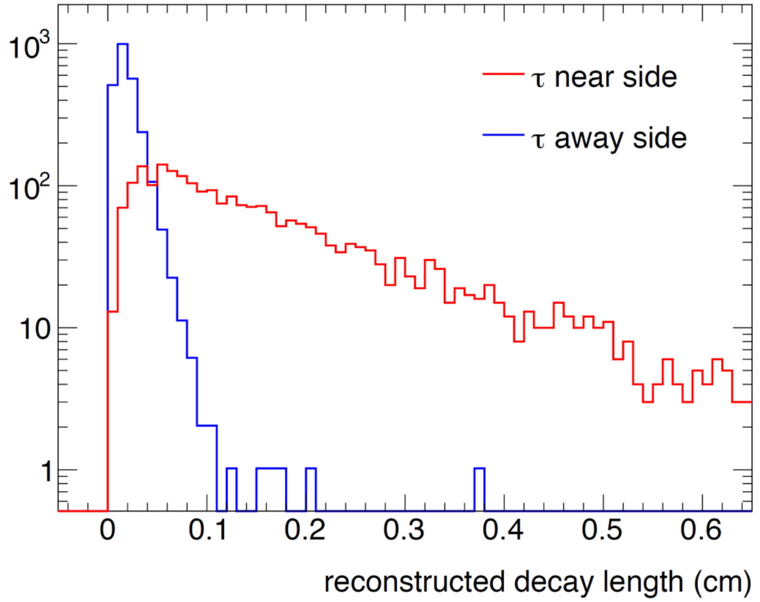
- Via realistic simulation and reco.
  - W/ sPHENIX vertex tracker configuration.
  - Updating with an EIC vertex tracker simulation
- Capable separation of τ jet from QCD jet

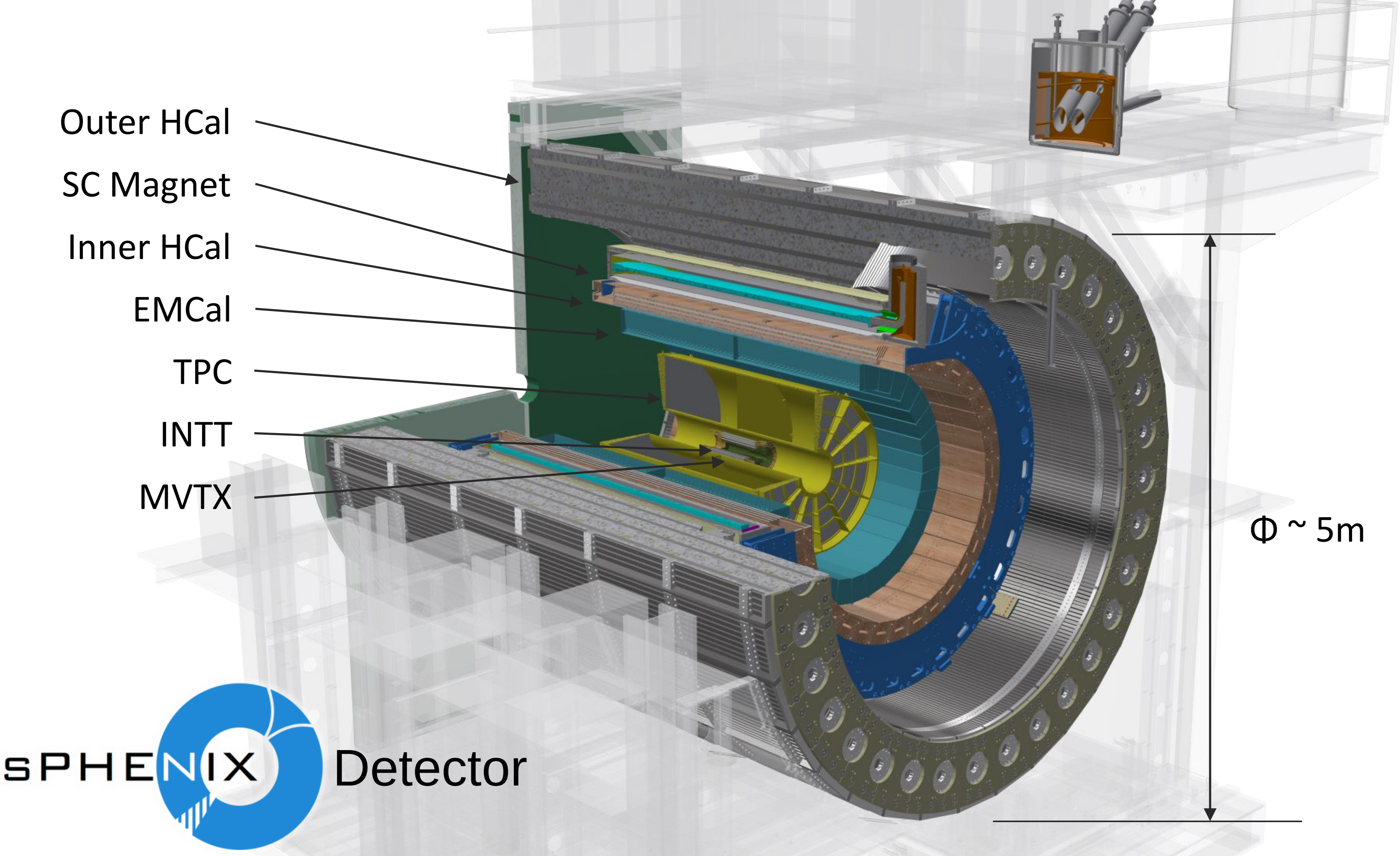


Summary

- EIC with high ($10^{34}/cm^2/s$) luminosity opens opportunities for Charged Lepton Flavor Violation search
  - Benchmarking e→τ search with Leptoquark models
- Starting an effort reexamining the potential of CLFV search with decay topological using modern precision vertex tracker and event shape analysis
  - Aiming for 0.1 fb cross-section sensitivity
  - Synergies with heavy flavor program at EIC: Talk X. Li, Y.S. Lai
- Full detector simulations and reconstruction via sPHENIX-EIC concept
  - Try it on your computers: https://github.com/sPHENIX-Collaboration/Singularity
- Next steps:
  - Completing study 3-prong τ → charged pion decay
  - Explore 1-prong ($\pi^-\pi^0$, μ^- X) possibilities





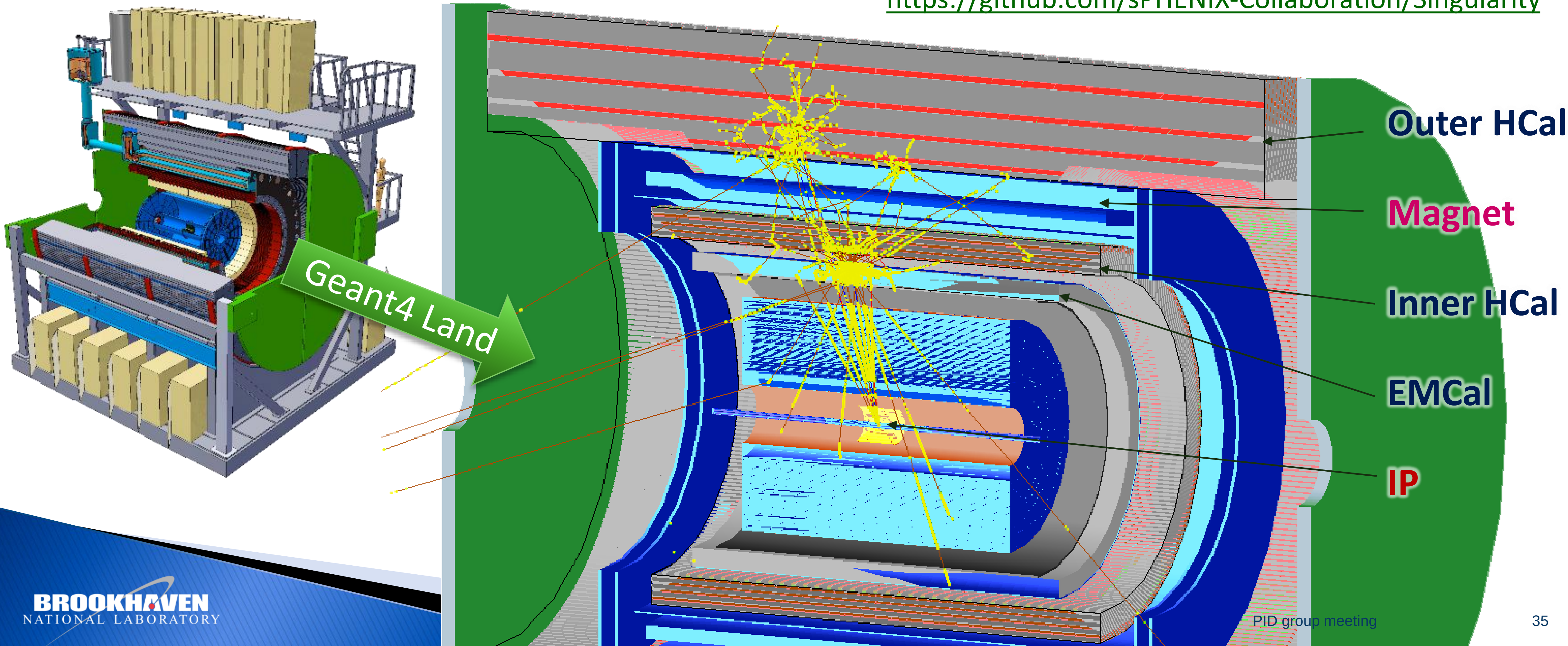


- 2018: Cost/schedule review and DOE approval for production start of long lead-time items (CD-1/3A)
- 2022: installation in RHIC 1008 Hall; 2023: First data
  - All tracker front end support streaming readout.
  - DAQ disk throughput for 9M particle/s + pile ups (> EIC ~4M particle/s)

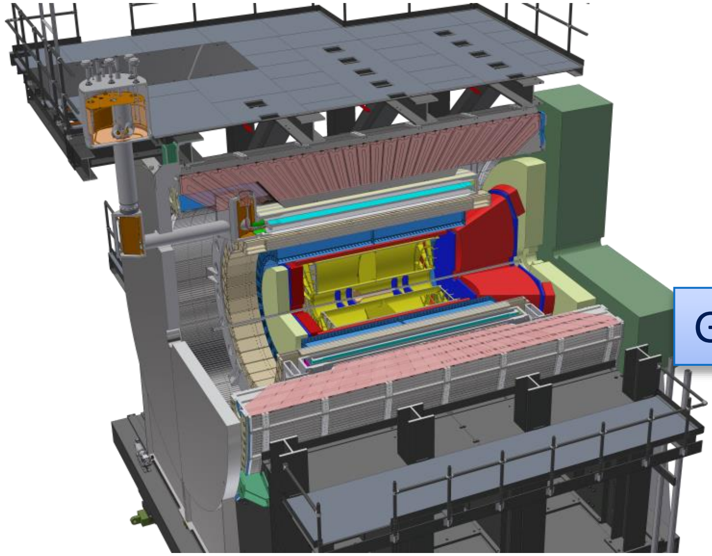
Simulation implementation

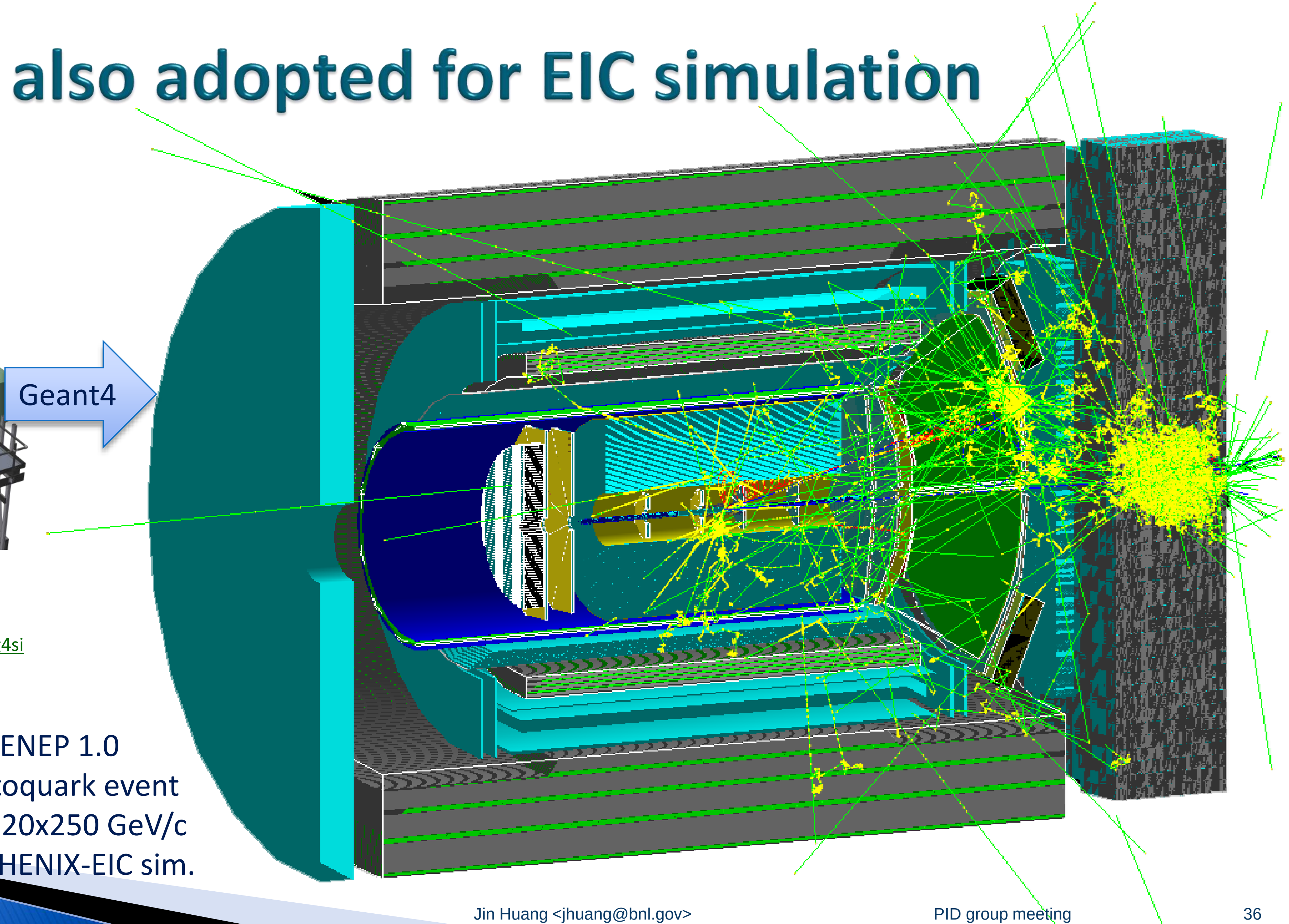
sPHENIX in simulation

- Open source on GitHub
- Try it on your laptop: https://github.com/sPHENIX-Collaboration/Singularity



Framework also adopted for EIC simulation

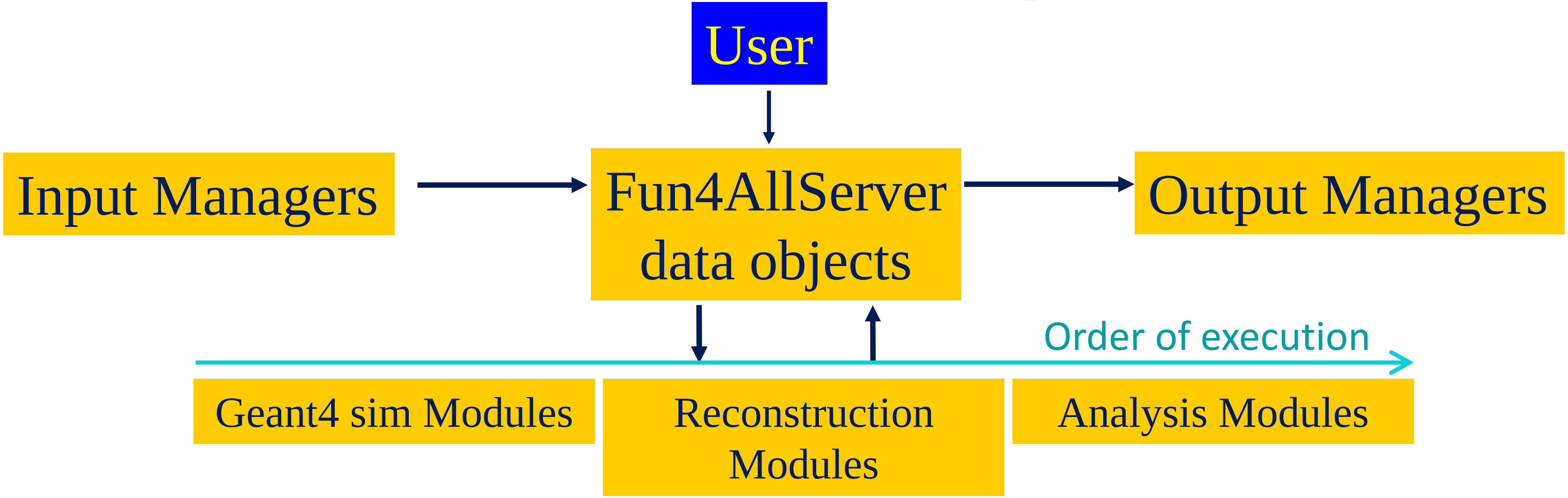




https://github.com/sPHENIX-Collaboration/macros/blob/master/macros/g4simulations/Fun4All_G4_EICDetector.C

LQGENEP 1.0
Leptoquark event
e+p 20x250 GeV/c
+ sPHENIX-EIC sim.

Simulation/reco framework integration



- Geant4 simulation and reconstruction are integrated in the sPHENIX software framework
- In production mode: run Geant4 sim in central production (CPU intensive), buffer the output file (DST) for reuse (require disk space), then run reconstruction in separated user sessions.
- Ensure same configuration and geometry are used in simulation and reconstruction → embedding
  - For example, Geometry and magnetic field configuration in Geant4 is automatically passed down to reconstruction stage for use in alignment adjustment, in tracking Kalman filter and in calorimetry geometric presentation.

Simulation chain

Event generation

- Process
  - Support pile up and embedding generations
  - Generators: Pythia6/8, HIJING, (JetScape), EIC wrapper, anything HepMC-compatible
- Storage
  - HepMC objects in DST or standalone file
  - Particle at collision and immediate decay

Detector Simulation

- Process
  - Geant4 package
  - Evaluating Intranuclear cascade physics lists
  - Detailed detector/field model
  - Store G4-particle interaction and truth-look up table
- Storage
  - Arrays of Geant4-hit objects
  - Field map configurations
  - Detailed geometry objects
  - Detector configuration parameters
  - Truth association table

Digitization

- Process
  - Convert Geant4 steps to initial ionization in gas
  - Drift ionization in gas in fast simulation. Slow sim in dev.
  - GEM amplification sim.
  - +Noises baseline
  - ADC and ASIC zero-suppression emulation
  - Maintain truth association tables
- Storage
  - Arrays of digitized hits
  - Truth association table

Reconstruction

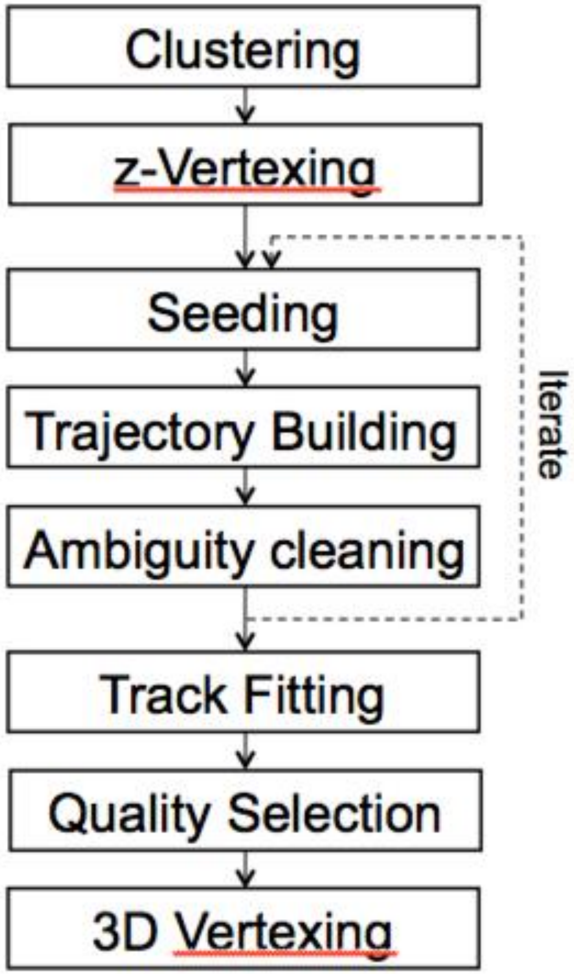
- Process
  - See the last three talks
  - Tracking, clustering, jet finding
- Storage
  - Reconstructed objects
    - See the last three talks
  - Truth association table

100 ms / ev (HIJING)	**2000 s / ev (Calo domin.)**	**500s / ev (TPC domin.)**	**See reco. slide**
1.7 MB / ev * 29%	210 MB / ev * 49%	Not saved	See reco. slide

- Above table : per-event resource for **central** Au+Au event in full sPHENIX.
- Store object optimized for fast dev, **rather for space saving yet**. Stored in ROOT file with compression ratio shown in the table.
- Rare signal probes simulated in the embedding mode (fast 10s/ev, regularly carried out 0.1-1M sample studies in the past)

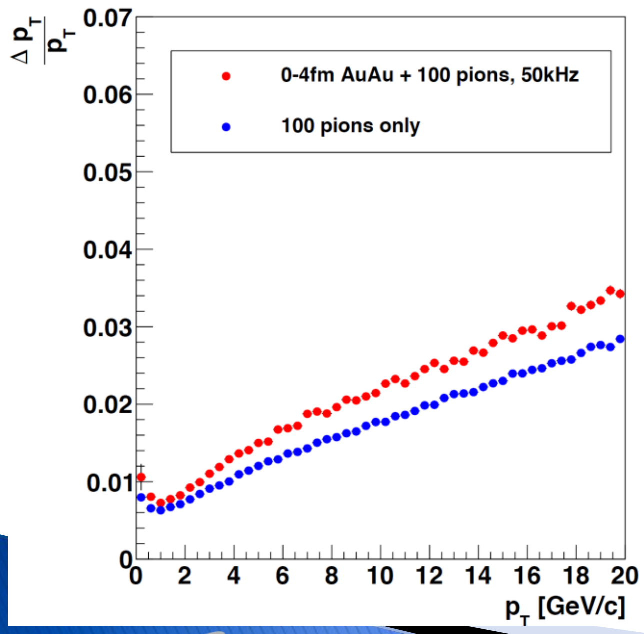
Reconstruction chain

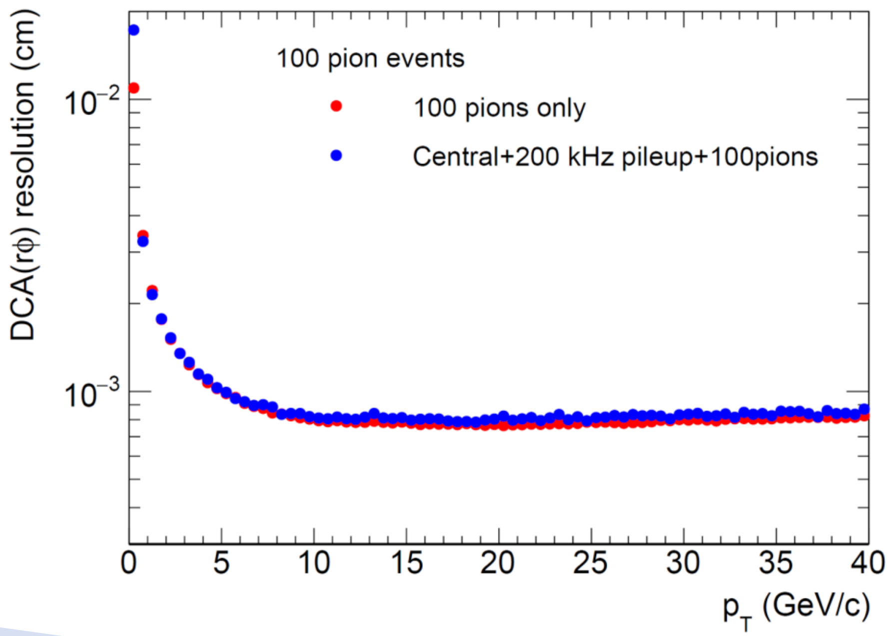
- Iterative Kalman Filter based track reconstruction package
- Hough transformation based seeding algorithm
  - Provides redundancy against missing hits
  - Outside in approach
- Track propagation and fitting based on the GenFit package
  - Open source software
  - Well tested through use in different experiments
    - E.g. PANDA, BELLE
- Iterations with hit removal and different seed constraints
  - 4 hits out of 7 layers
  - 6 hits out of 12 layers
- RAVE-based vertex finding, fitting
- Considering evolution to ACTS for speed optimization by HEP community

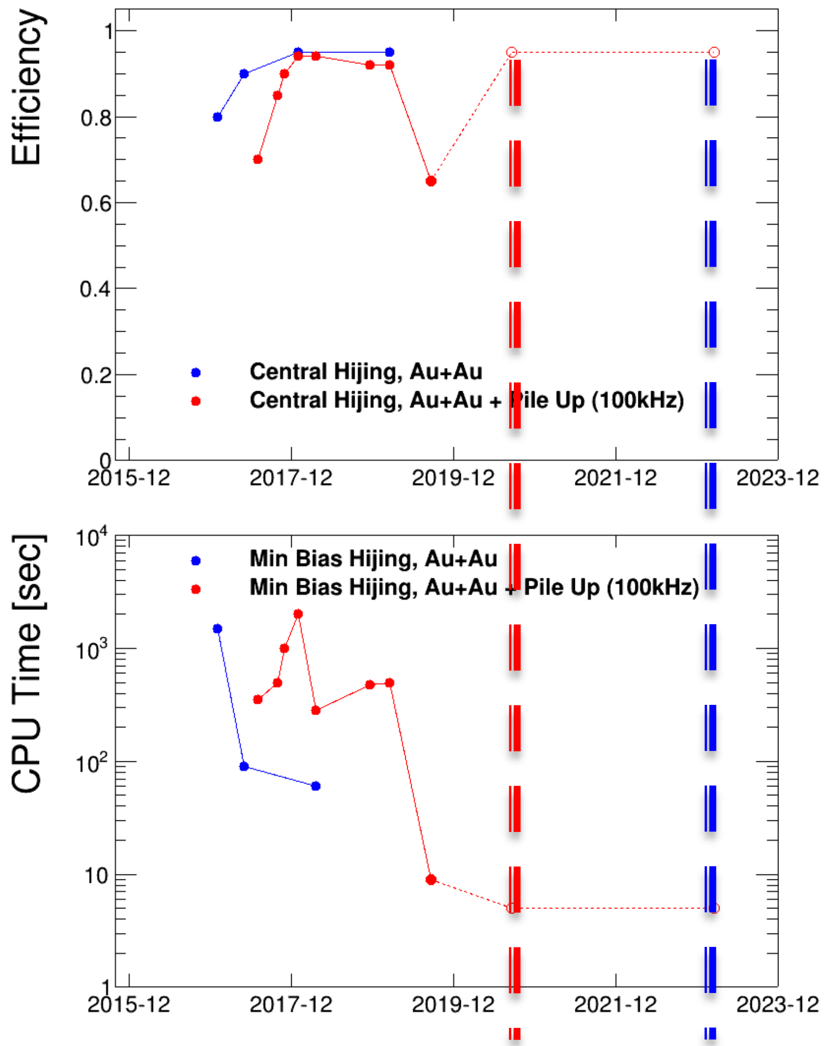


Tracking performance

- Evaluated for most challenging case of AuAu collision + pileup
- EIC multiplicity would be significantly lower
- Reference: https://indico.bnl.gov/category/85/
  - sPHENIX PD-2/3 review
  - sPHENIX computing review







Distributed computing for simulation

- Simulation are suitable for distribute for opportunistic computing offsite, e.g. OSG
- Successful experience in distributing sPHENIX simulation via Singularity container, e.g. at LLNL, Umich, …
  - A light-weight virtual environment to reproduce RCF software environment offsite
  - Validated output to be consistent with RCF

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

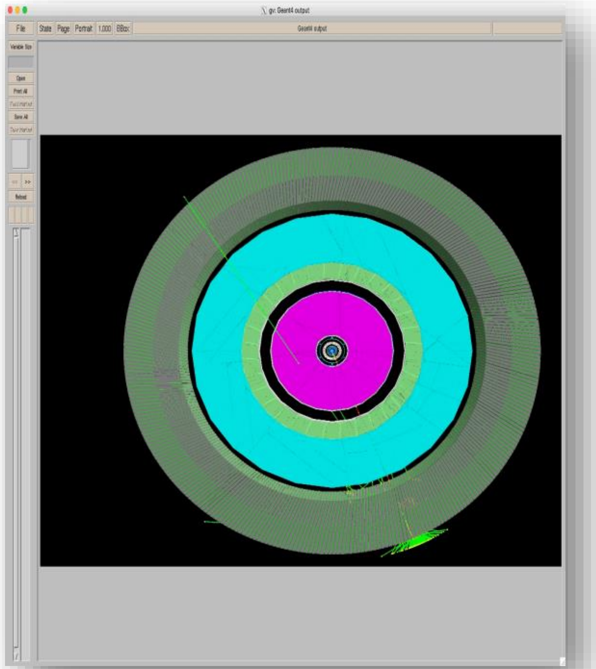
Singularity container for sPHENIX and EIC-sPHENIX

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

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

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

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



Comments on EIC evolution

sPHENIX and sPHENIX based EIC detector

LOI: arXiv:1402.1209 [nucl-ex]
Update: sPH-cQCD-2018-001 https://indico.bnl.gov/event/5283/