

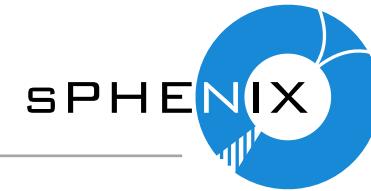
Open heavy flavor prospects at sPHENIX

Cameron Dean, on behalf of the sPHENIX collaboration,
Massachusetts Institute of Technology,
Quark Matter, Houston,
September 5th, 2023

MIT HIG group's work was supported by US DOE-NP



This talk's focus



Open Heavy Flavor

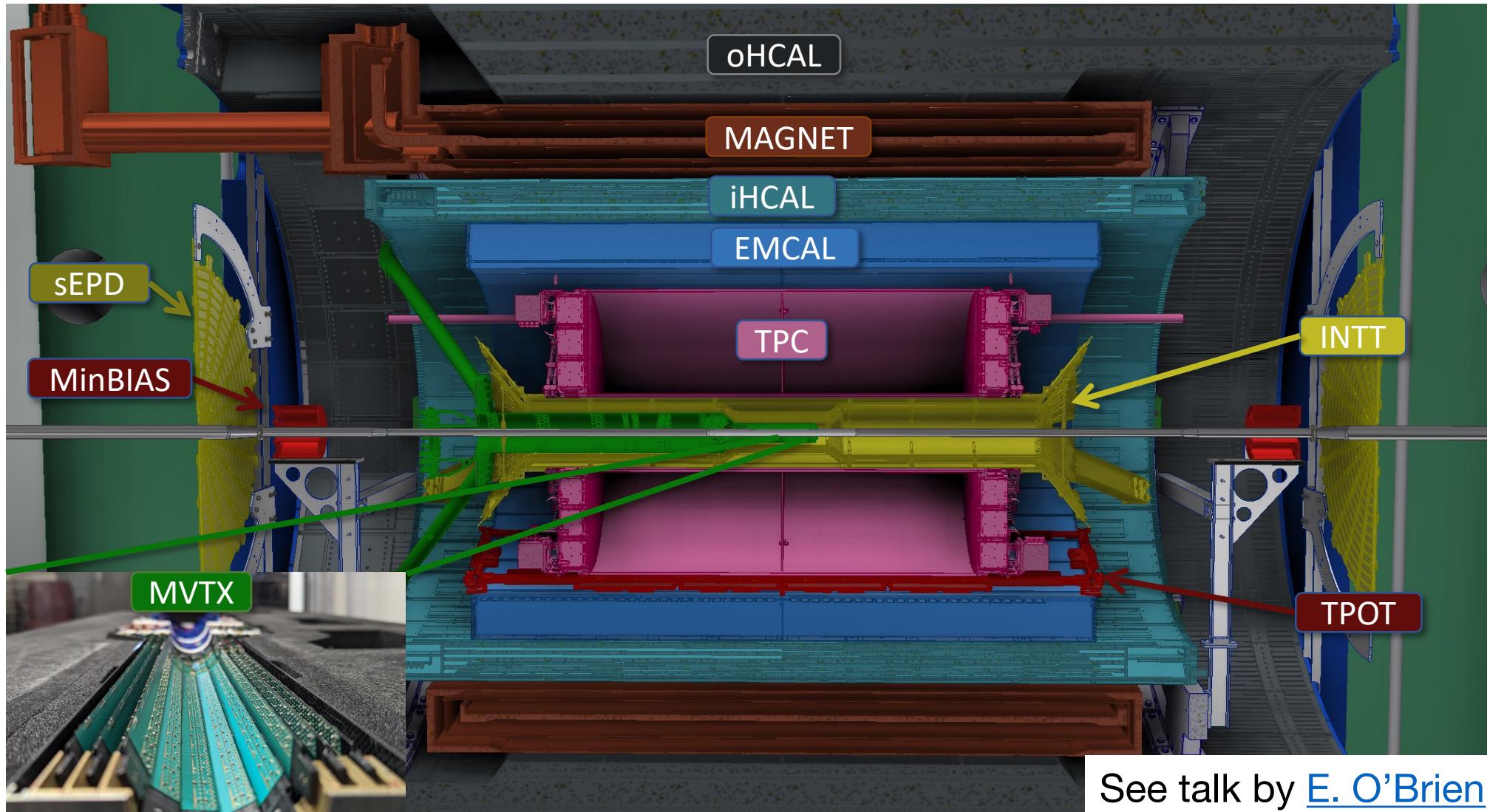
Vary mass/
momentum
of probe

• g
• u,d,s
● c

● b

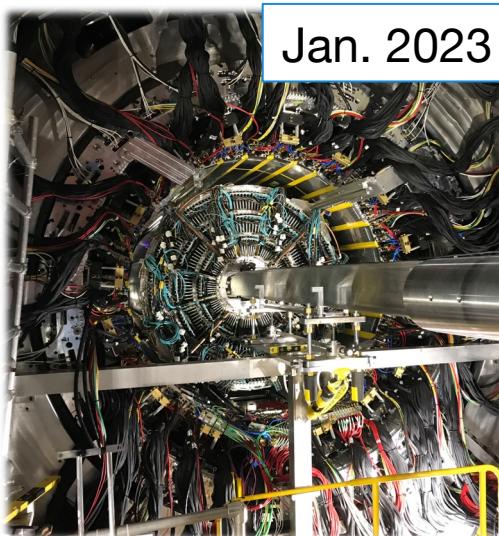
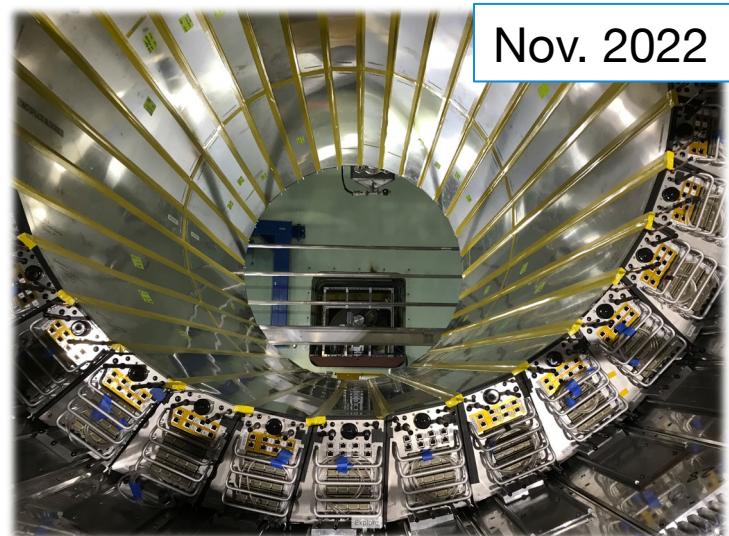
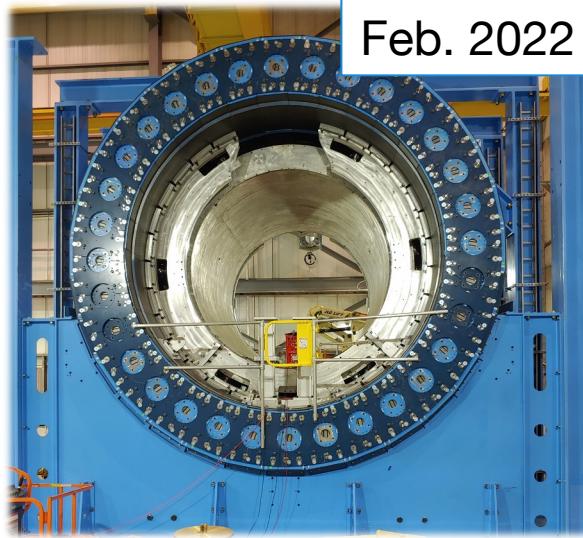
1. How is sPHENIX optimized for open heavy flavor
2. What are sPHENIX's projections for open HF observables
3. How can machine learning impact HF at RHIC and beyond

The sPHENIX detector

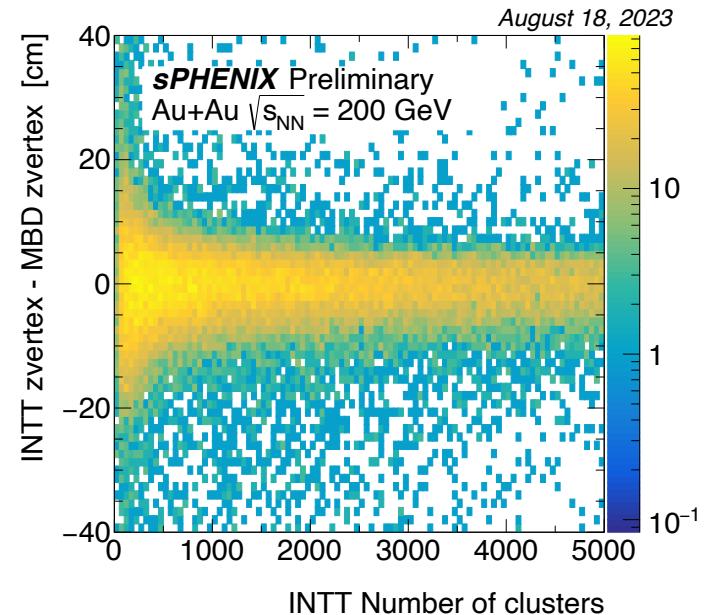
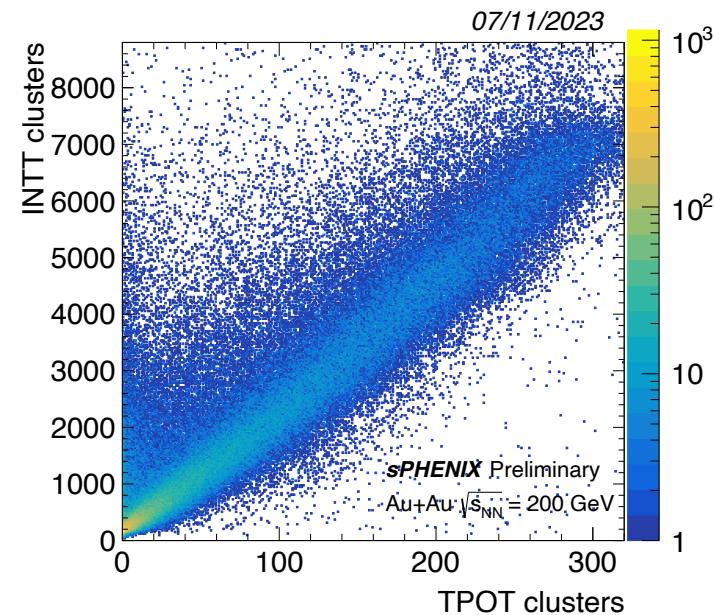
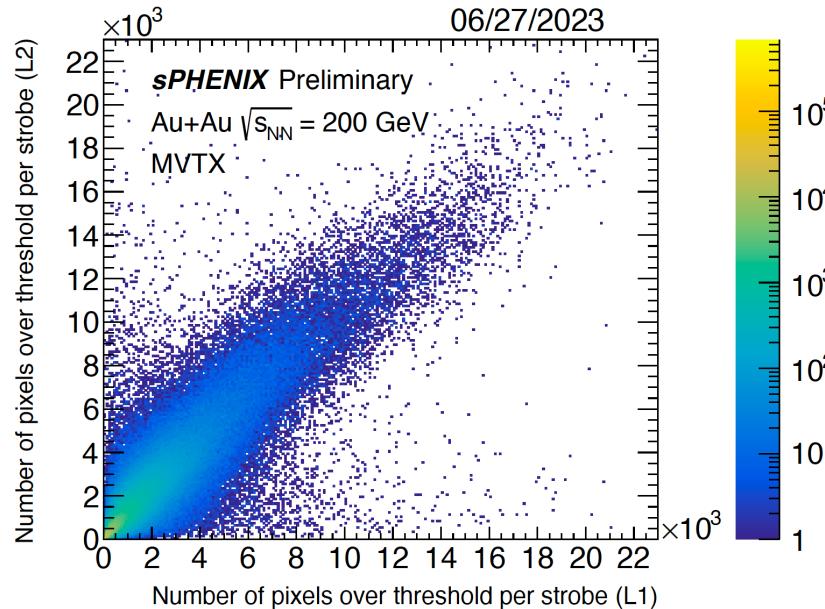


See talk by [E. O'Brien](#)

Timeline to first collisions

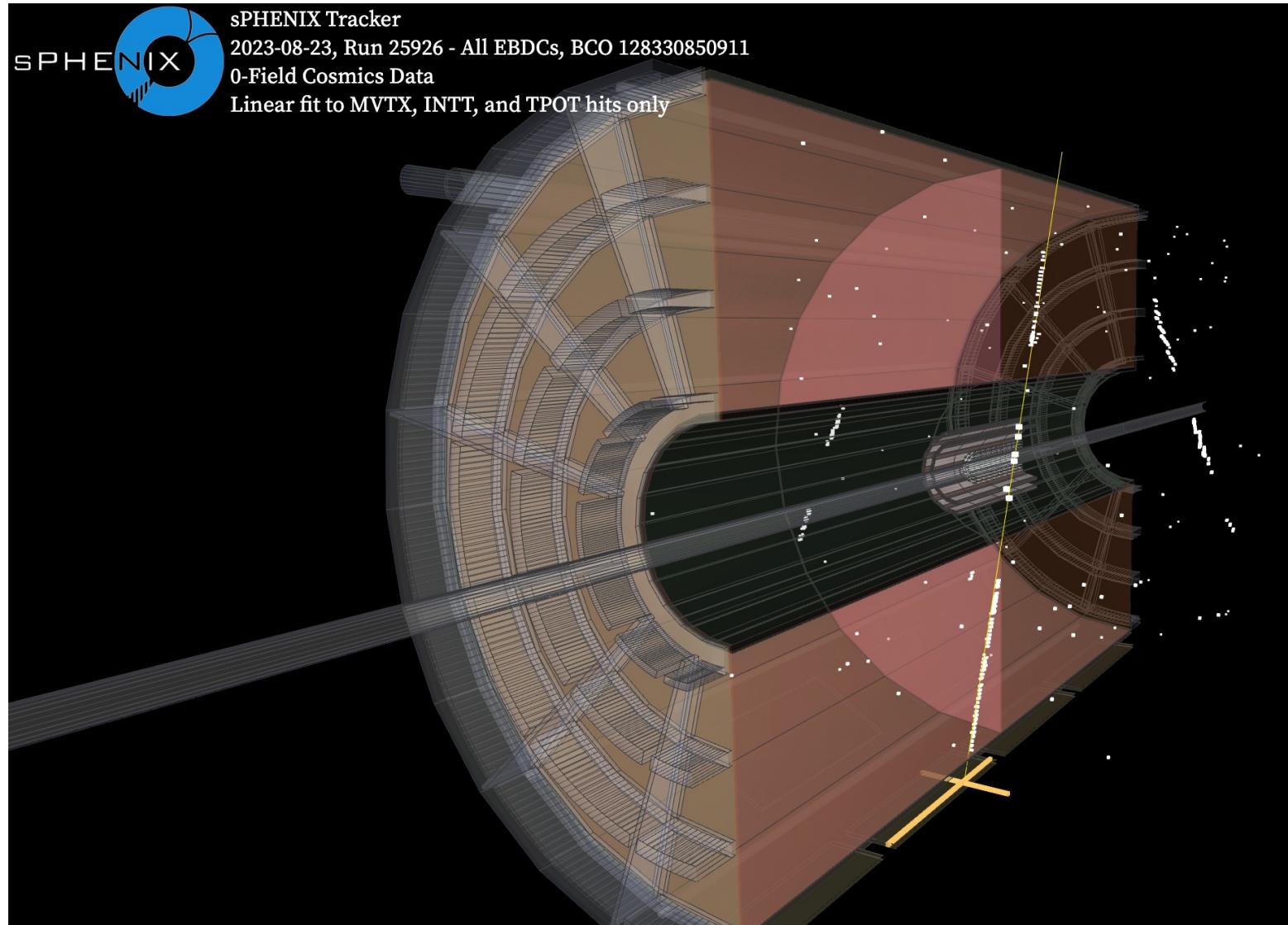


Detector commissioning

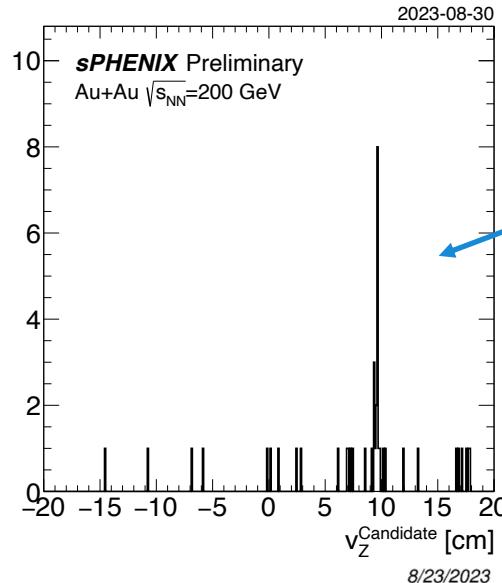


- sPHENIX AuAu commissioning was from May 18th to August 1st
- Too many performance plots to show!
(please see our collaborators for the full set)
- All detectors have demonstrated internal correlations
- All subsystems have correlated data with at least one other subsystem

Cosmic rays with all trackers

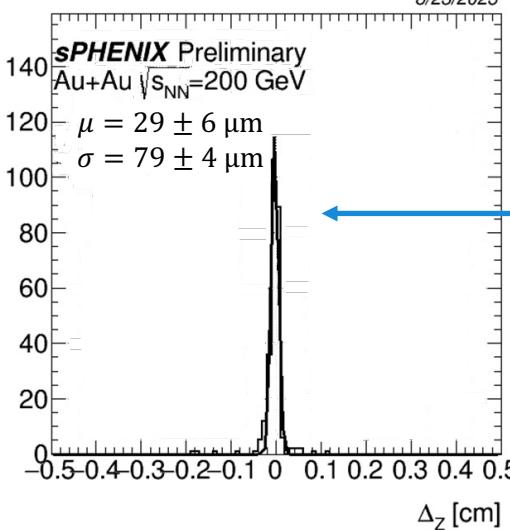


Unlocking heavy flavor



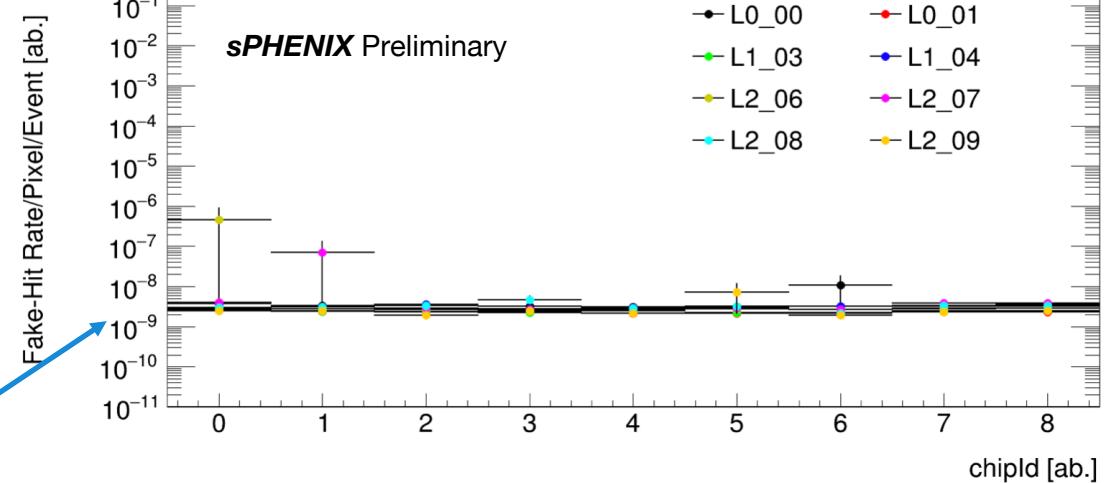
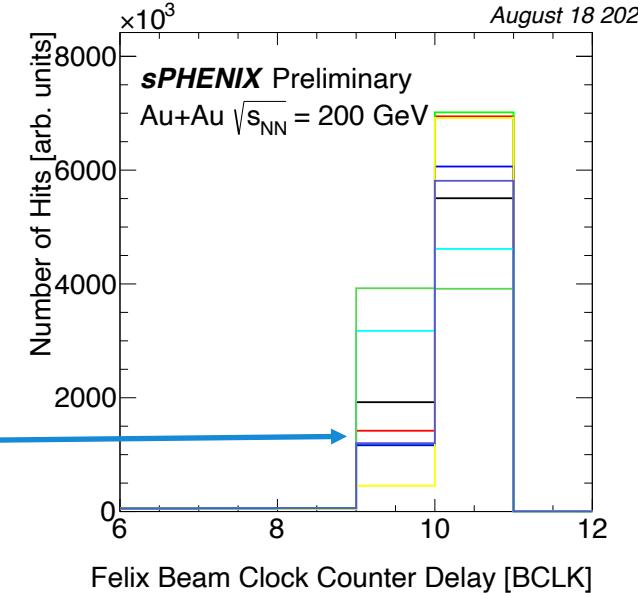
Vertex estimate from MVTX, before alignment

Collision timing for vertex separation with INTT
(1 beam clock = 106 ns)



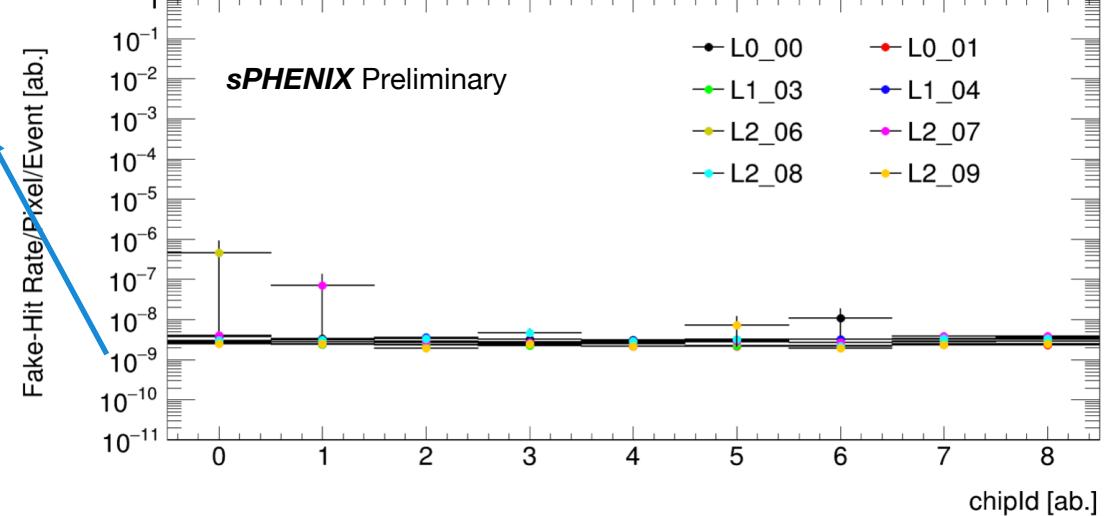
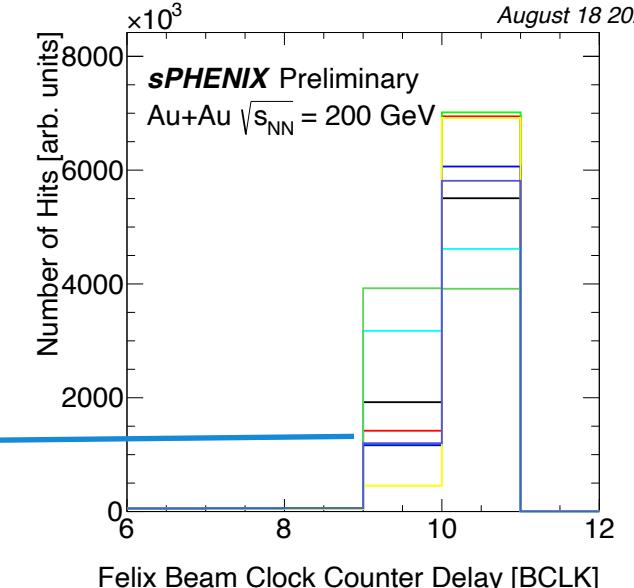
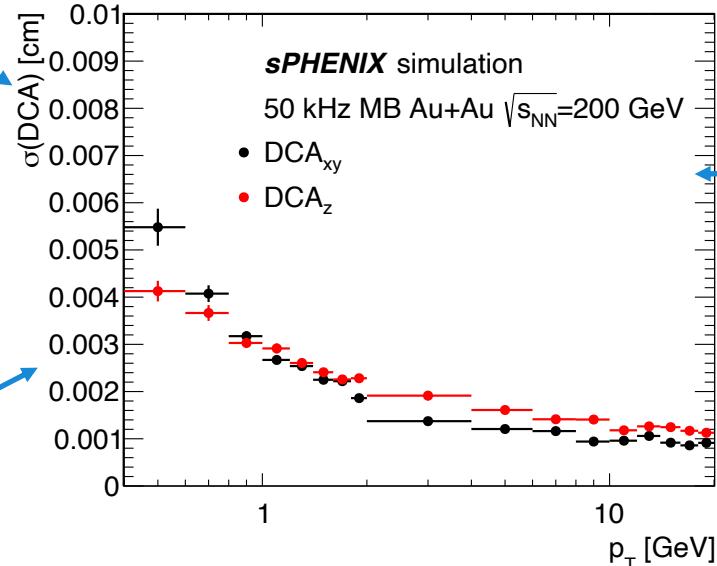
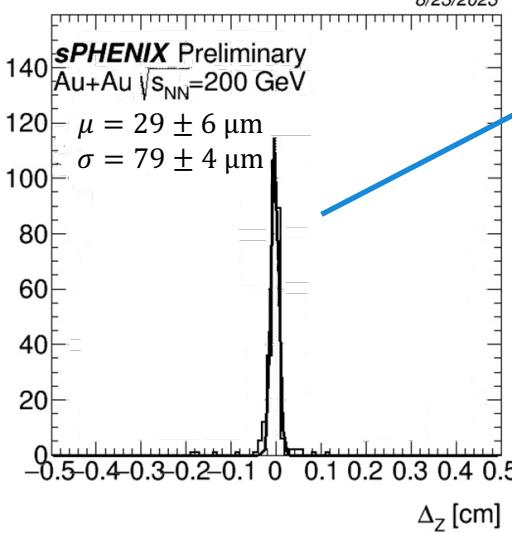
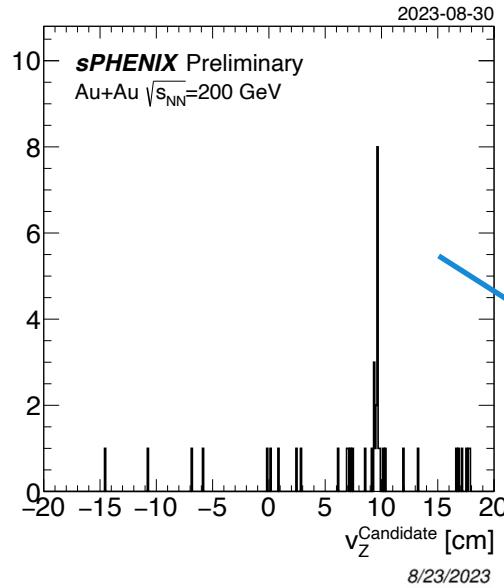
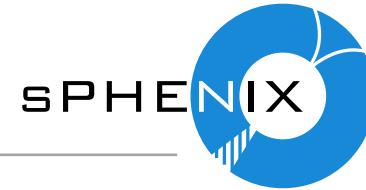
Hit residual from MVTX, before alignment

Low noise from MVTX



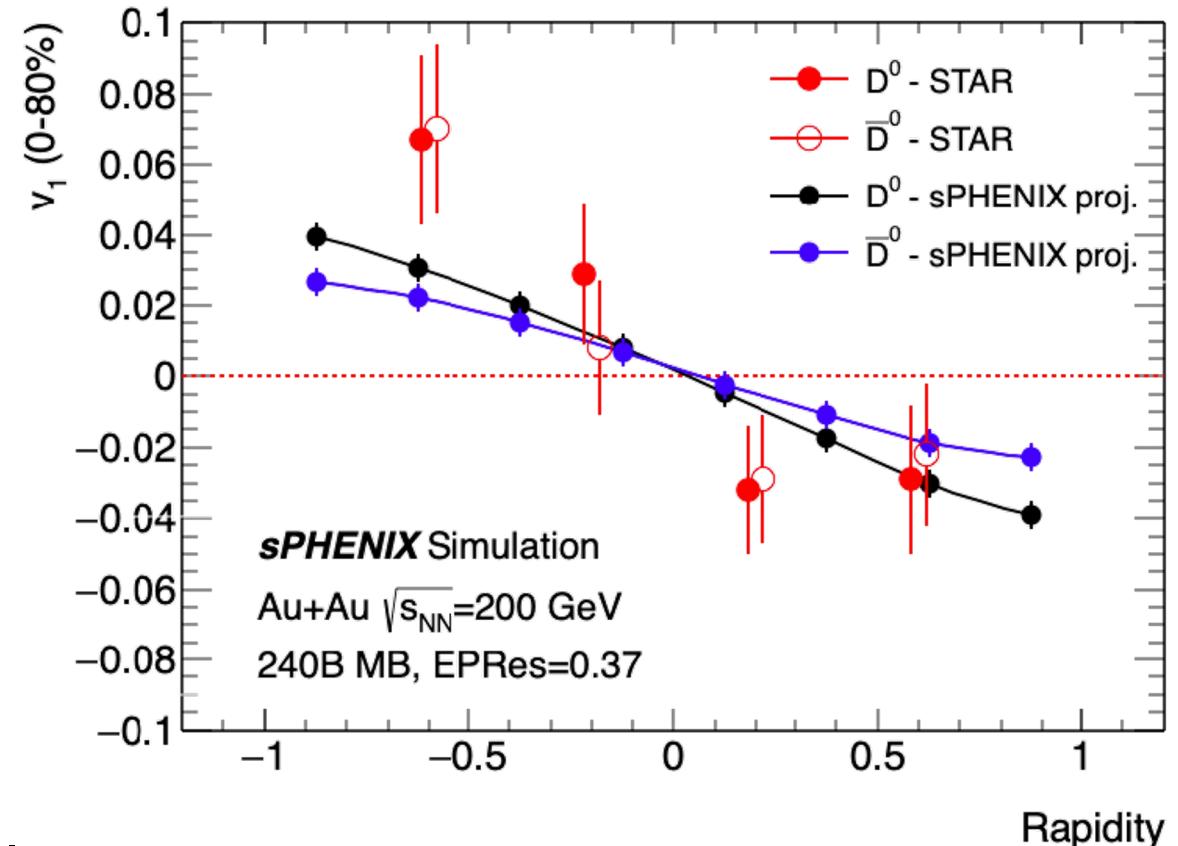
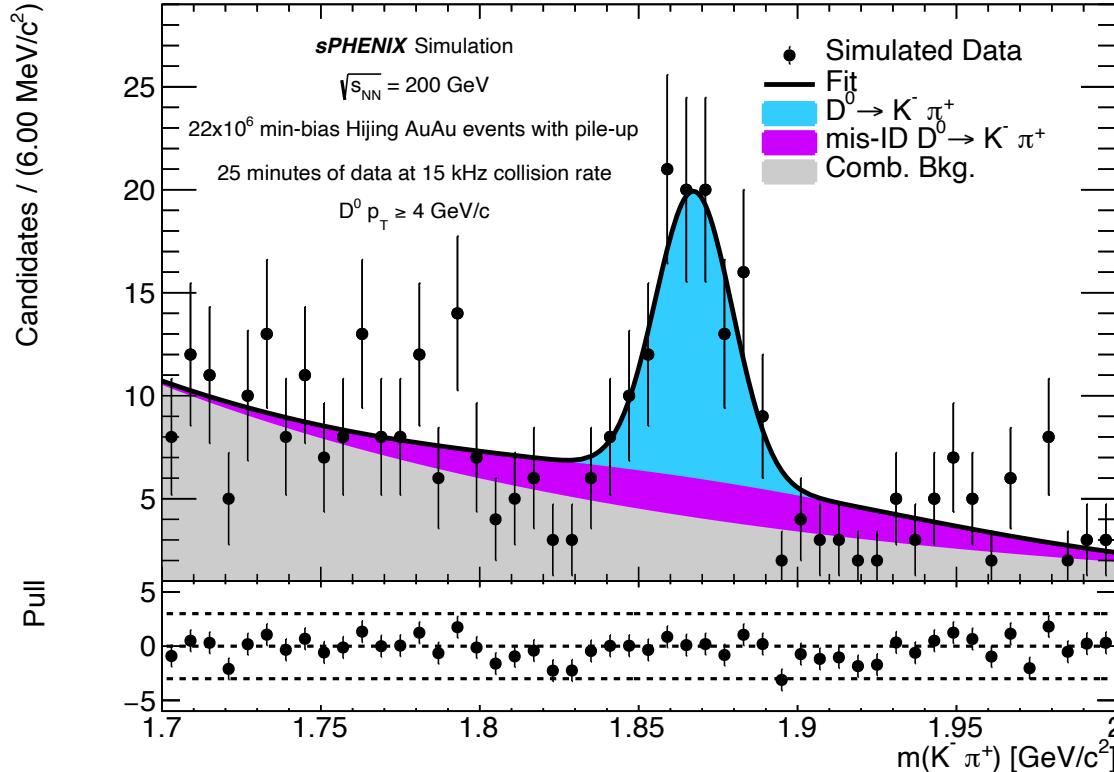
Posters by
[H-R. Jheng \(547\)](#),
[C-W. Shih \(503\)](#),
[J. Kim \(548\)](#) and
[Y. Corrales Morales \(541\)](#)

Unlocking heavy flavor



Posters by
[H-R. Jheng \(547\)](#),
[C-W. Shih \(503\)](#),
[J. Kim \(548\)](#) and
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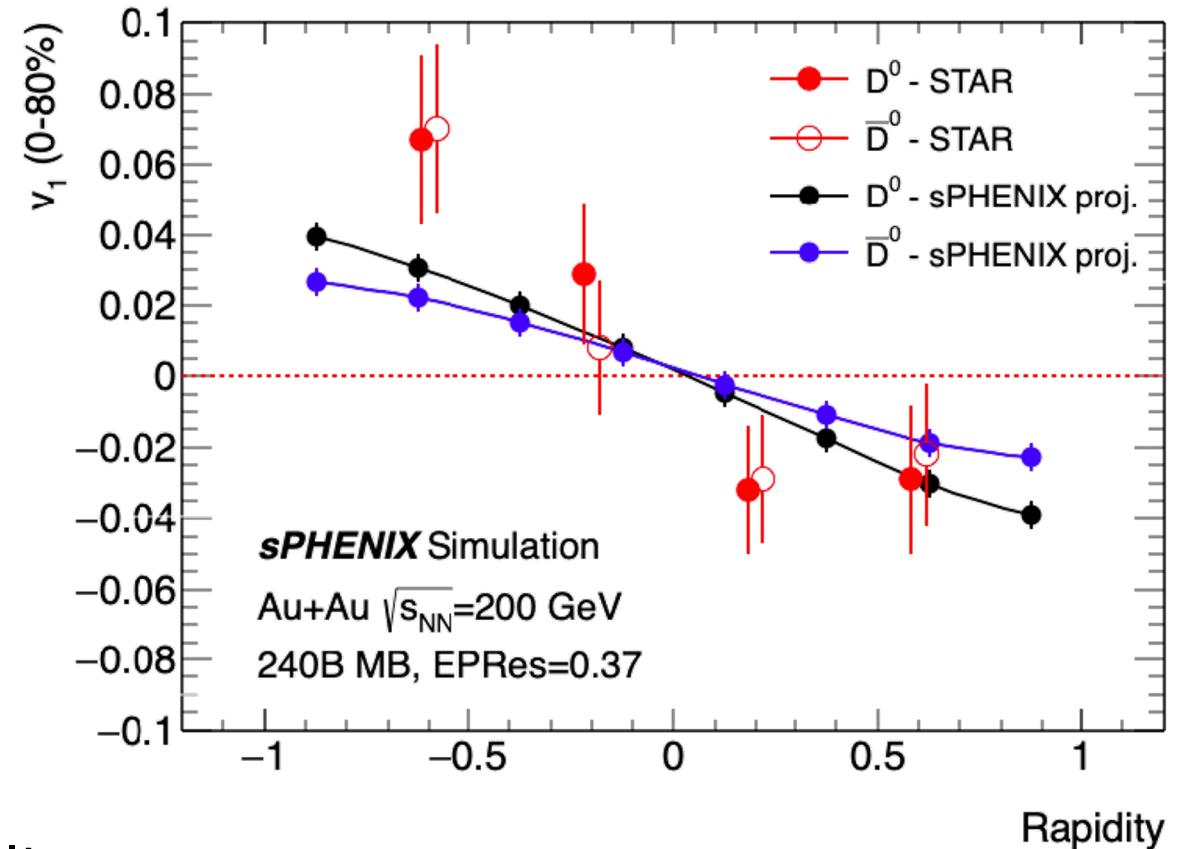
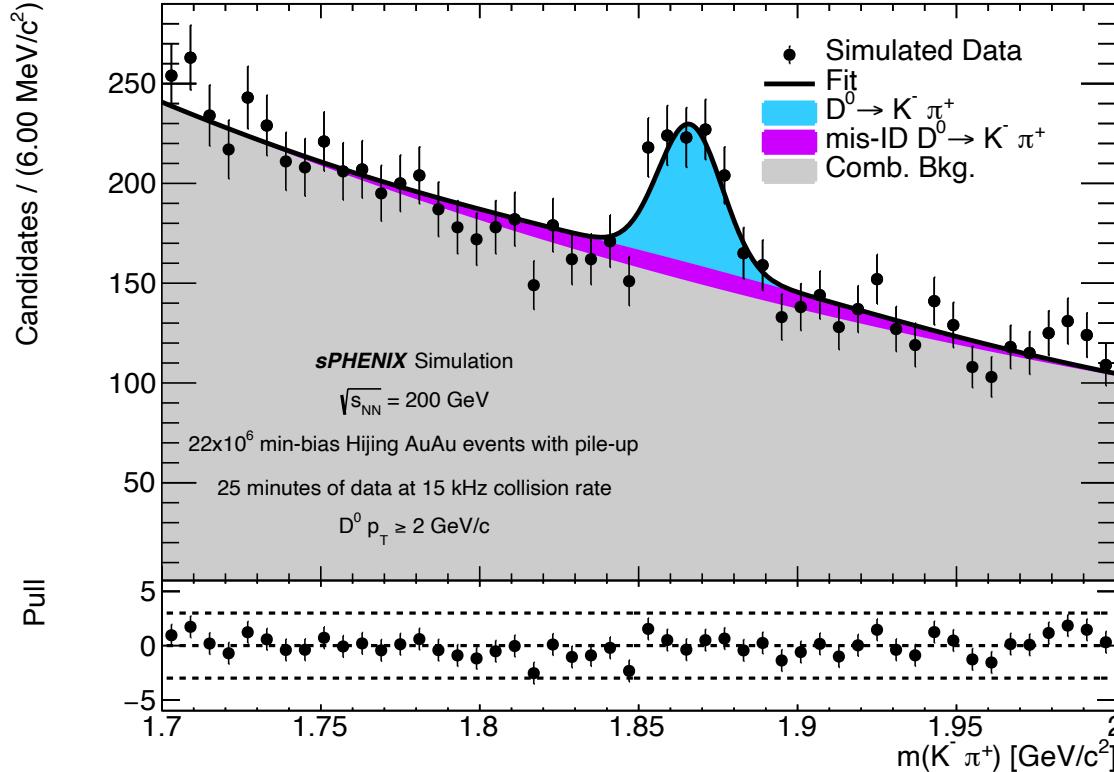
Open charm physics simulation



- Prediction that transient mag. field alters v_1
- This effect is odd under charge-conjugation, resulting in splitting
- $D^0 \rightarrow K^\mp \pi^\pm$ is mixed, requires good production knowledge

[PRL 123 \(2019\) 162301](#)
[PRL 118 \(2017\) 212301](#)

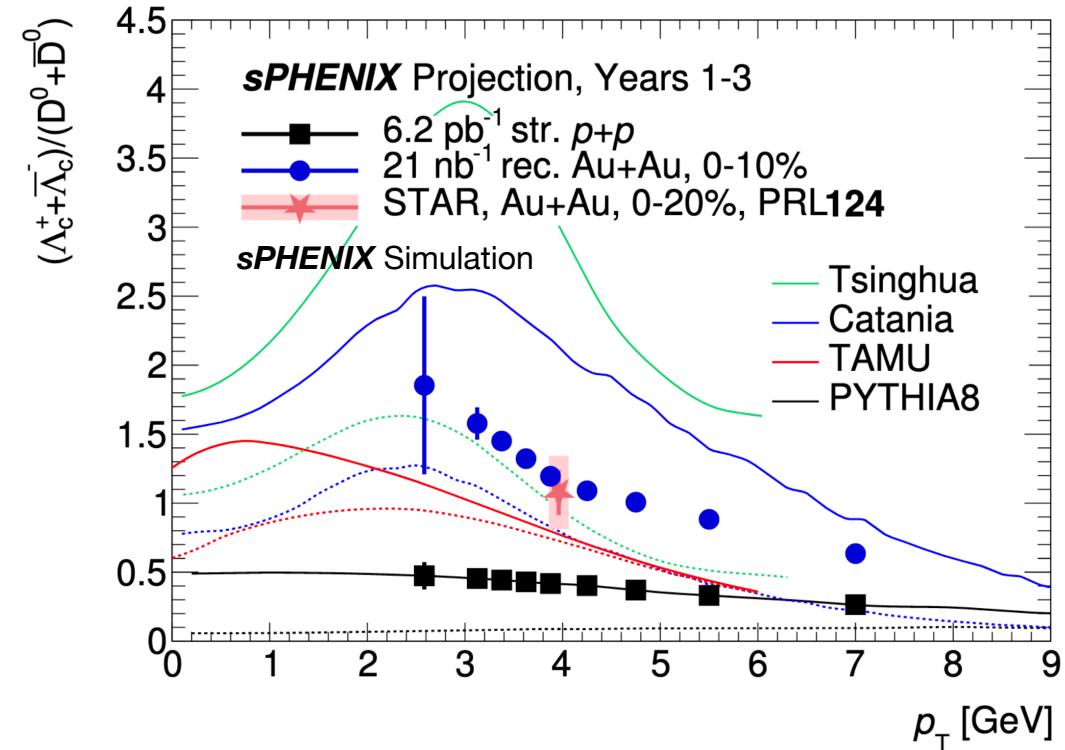
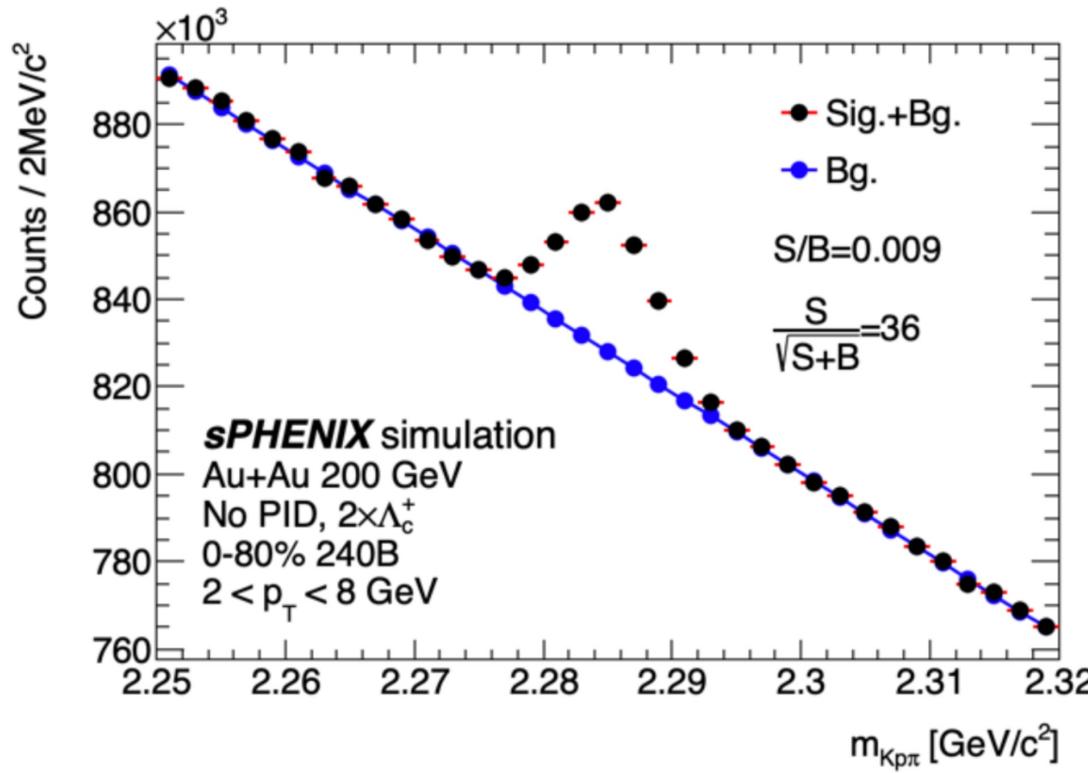
Open charm physics simulation



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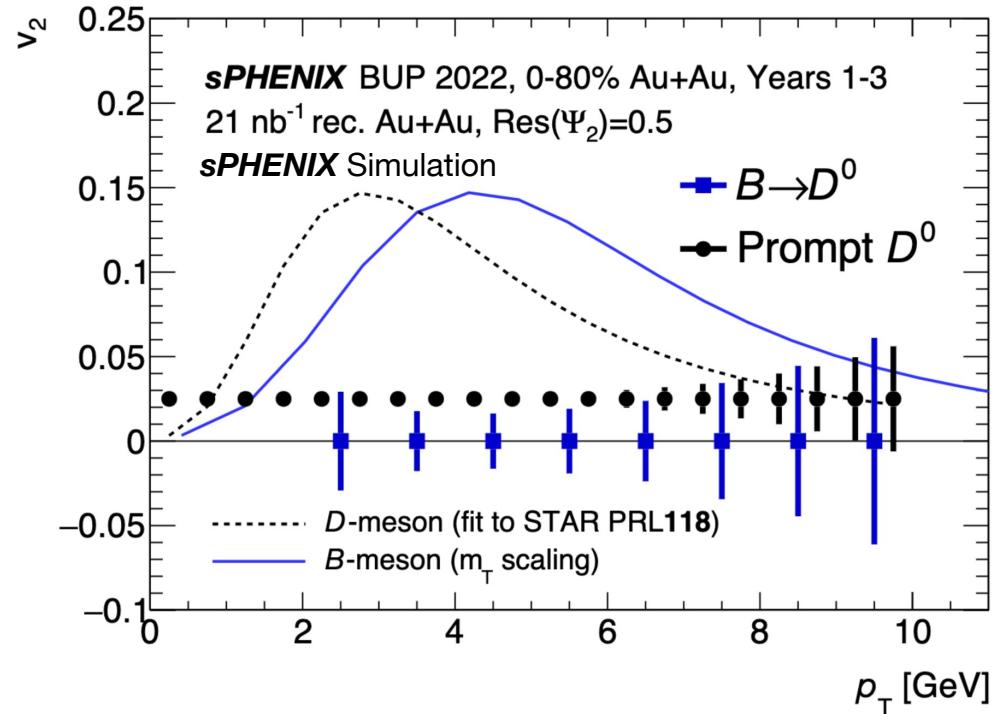
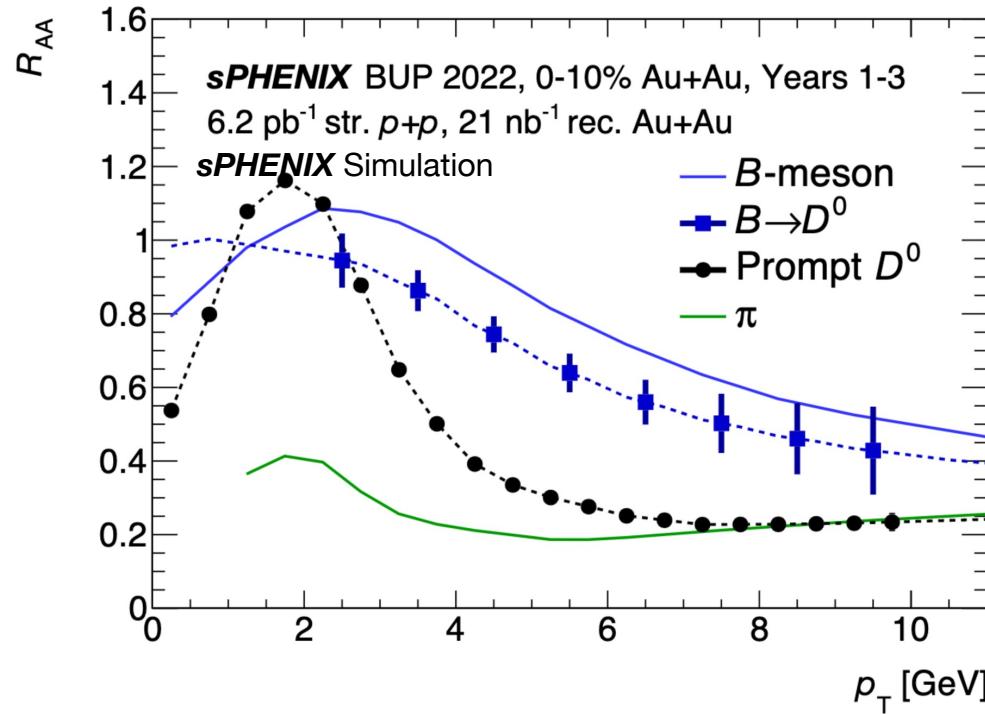
Λ_c^+ coalescence simulation



- Baryon/meson yields offer new insights in hadronization
- Models currently favor coalescence hadronization
- Low p_T region ($< 8 \text{ GeV}$) is key
- Huge benefit from streaming readout in pp

[sPH-HF-2019-001](#)
[PRL 124 \(2020\) 172301](#)

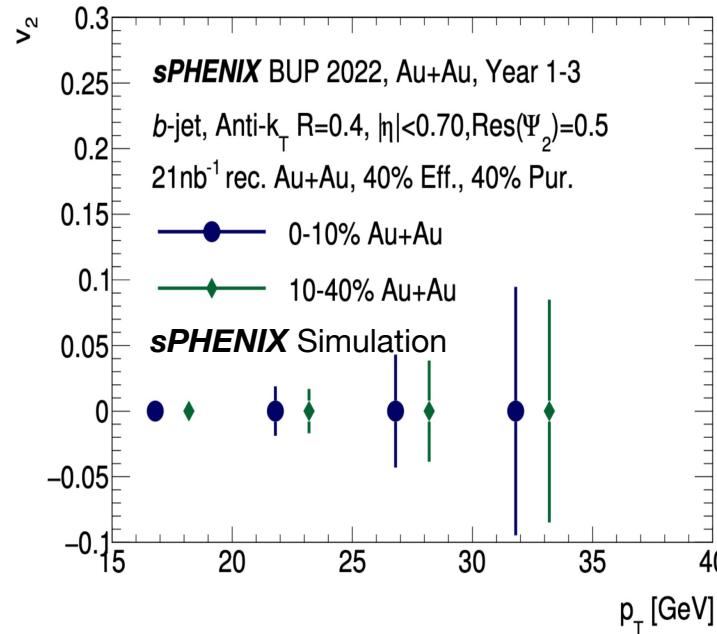
b-hadron simulation



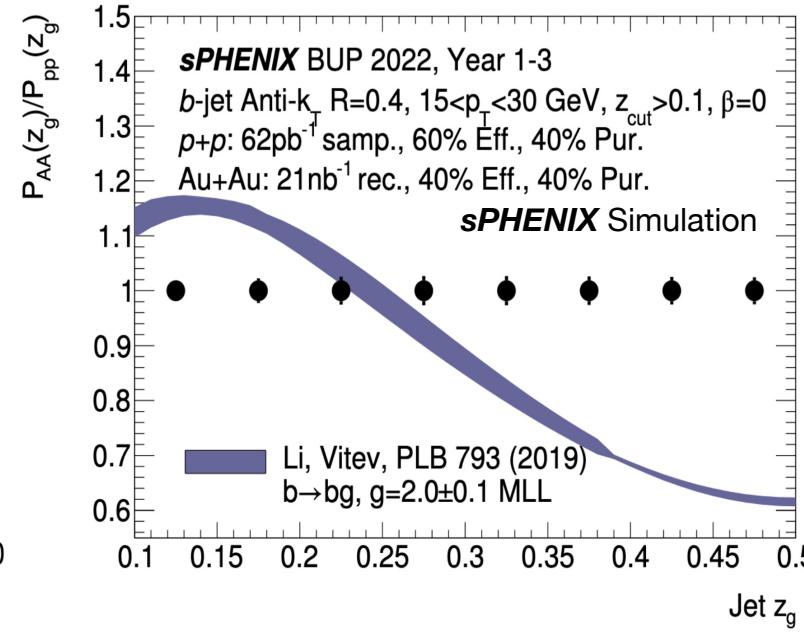
- Non-prompt D^0 reco. gives low p_T b-hadron access
- sPHENIX aims to
 - constrain heavy quark diffusion coefficients
 - Parton energy loss mechanism

PRL 118, 212301

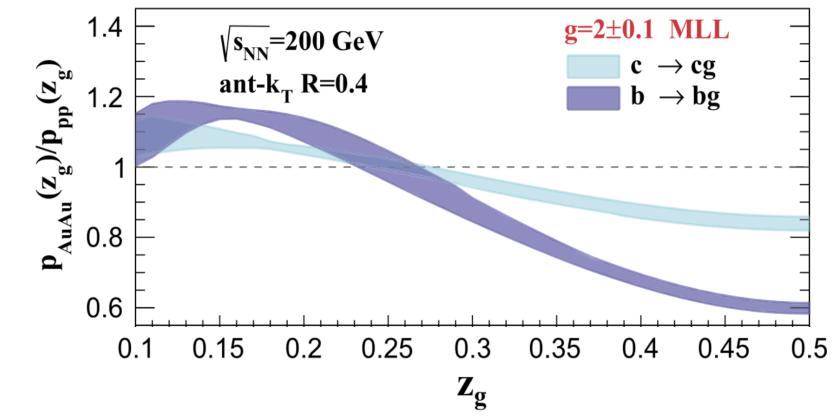
Heavy flavor jet observable simulation



b-jet elliptical flow



Predicted b-jet subjet splitting sensitivity



Model comparison of b- and c-jet subjet splitting sensitivity

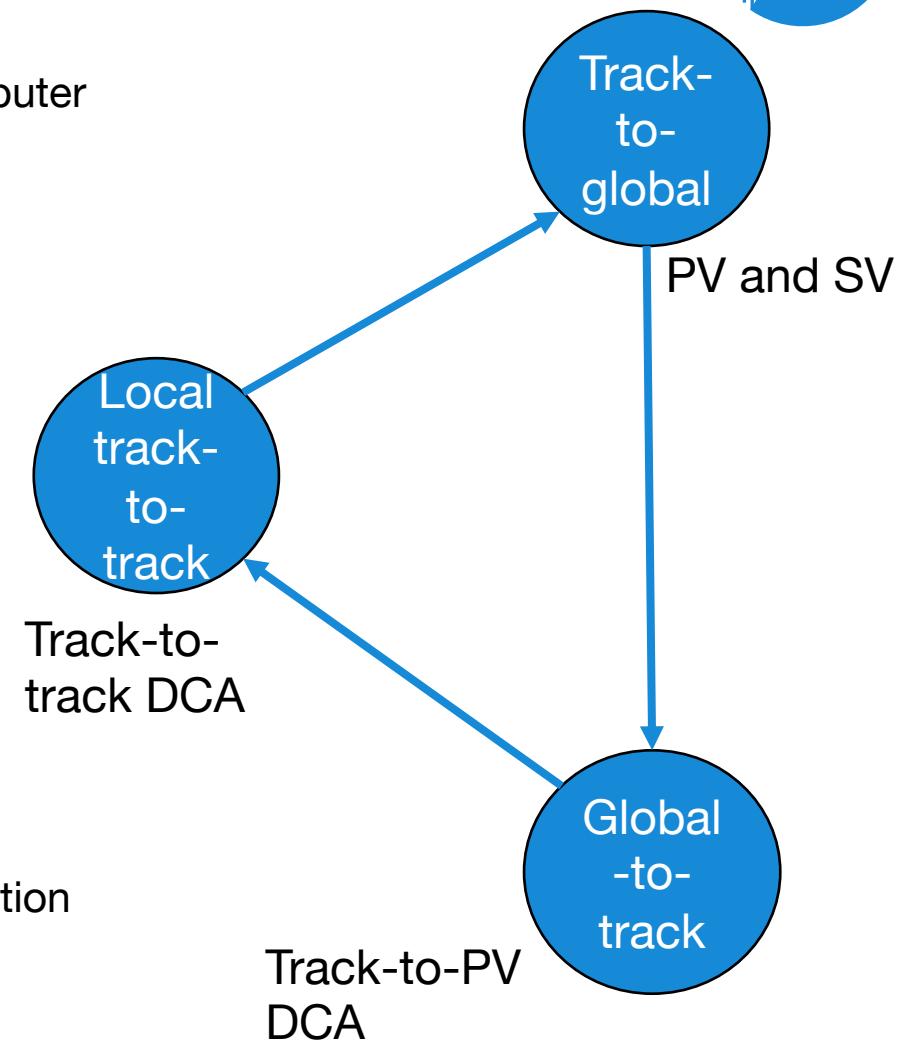
Posters by [A. da Silva \(537\)](#) and [J. Kvapil \(540\)](#)

[PLB 793 \(2019\) 259](#)

Tagging with machine learning*



- sPHENIX is benefitting from a 2020 DOE funding call
 - Cross-discipline group of sPHENIX and LHC physicists, engineers, and computer scientists working on firmware-based ML applications data selection
- RHIC pp collision rate is 3 MHz
- sPHENIX calorimeter DAQ max. rate is 15 kHz
 - Limits sPHENIX to recording 1% of triggered pp
- Trackers are all streaming readout (SRO) capable
 - TPC dominates data rate, can't save all streamed data
 - 10% trigger-enhanced SRO increases open HF MB rate ~300 kHz
 - N.B. All previous projections are with 10% trigger-enhanced SRO
- ML hardware tagging demonstrator under development with eyes to the EIC offers possible further increase in HF MB rate for sPHENIX
 - MVTX + INTT data can be combined on FPGA to perform tracklet reconstruction
 - Feed to graph neural net to tag HF candidates for TPC readout
 - Aim to sample remaining 90% of luminosity using demonstrator



* On behalf of the FastML Team

[ECML PKDD 2022, Sub 1256](#)

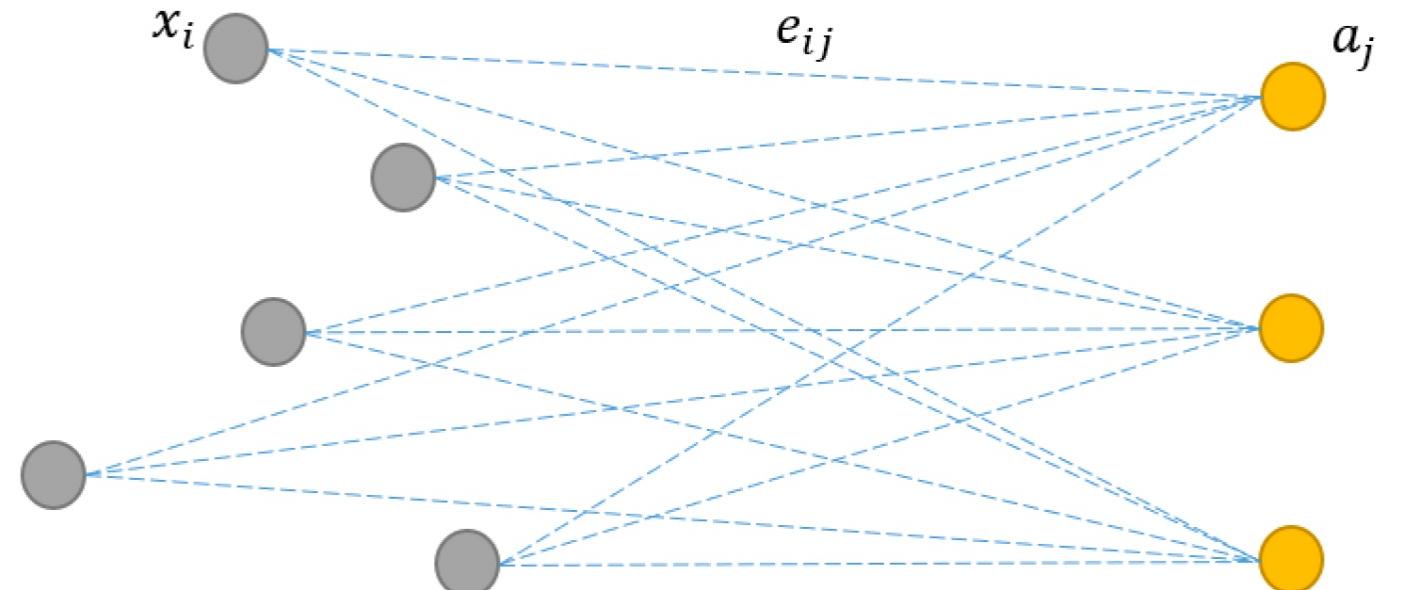
Tagging with machine learning*



Graph Neural Net design

- Track node input vectors
 1. 5 hits (MVTX + INTT)
 2. Length of each segment: $L = |\vec{x}_{i+1} - \vec{x}_i|$
 3. Angle between segments
 4. Total length of segments
- Aggregators
 1. Primary vertex
 2. Secondary vertex
- Current ML tracklet algorithm has
 - Accuracy > 91% for building tracks
 - Area under receiver-operating characteristic curve (AUC) > 97% liken to “probability of combining the correct track elements compared to incorrect elements” – random chance is 50%
 - Purity and rejection studies are underway

Track Nodes



$e_{ij} = s_{ij}x_i$ is track-aggregator messages
 s_{ij} is the weight

* On behalf of the FastML Team

[ECML PKDD 2022, Sub 1256](#)

Tagging with machine learning*



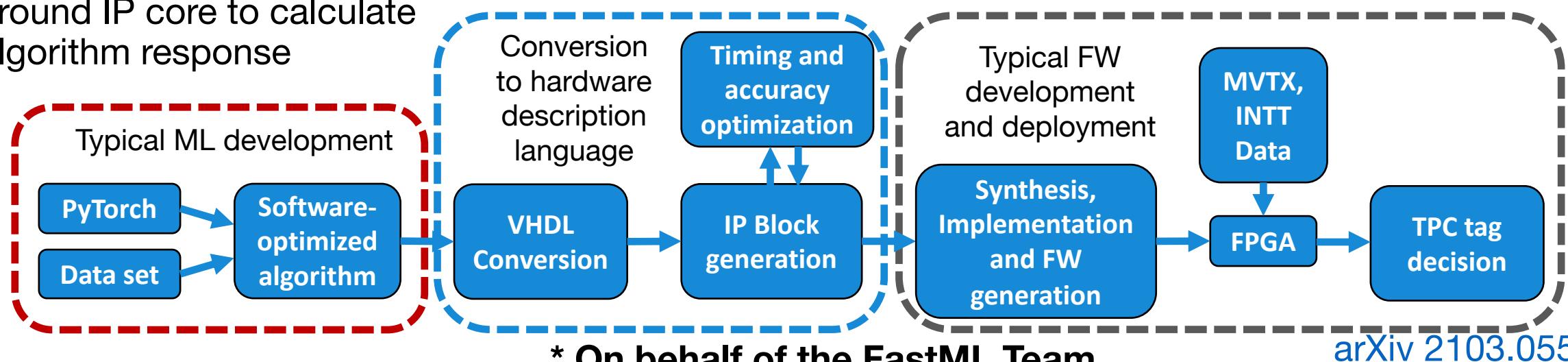
- Algorithms must have low latency and resource use
- *hls4ml* translates NN algorithms into high level synthesis
- Also generates IP cores for easy implementation
- Rest of firmware can be built around IP core to calculate algorithm response



Server for algorithm conversion and FW generation



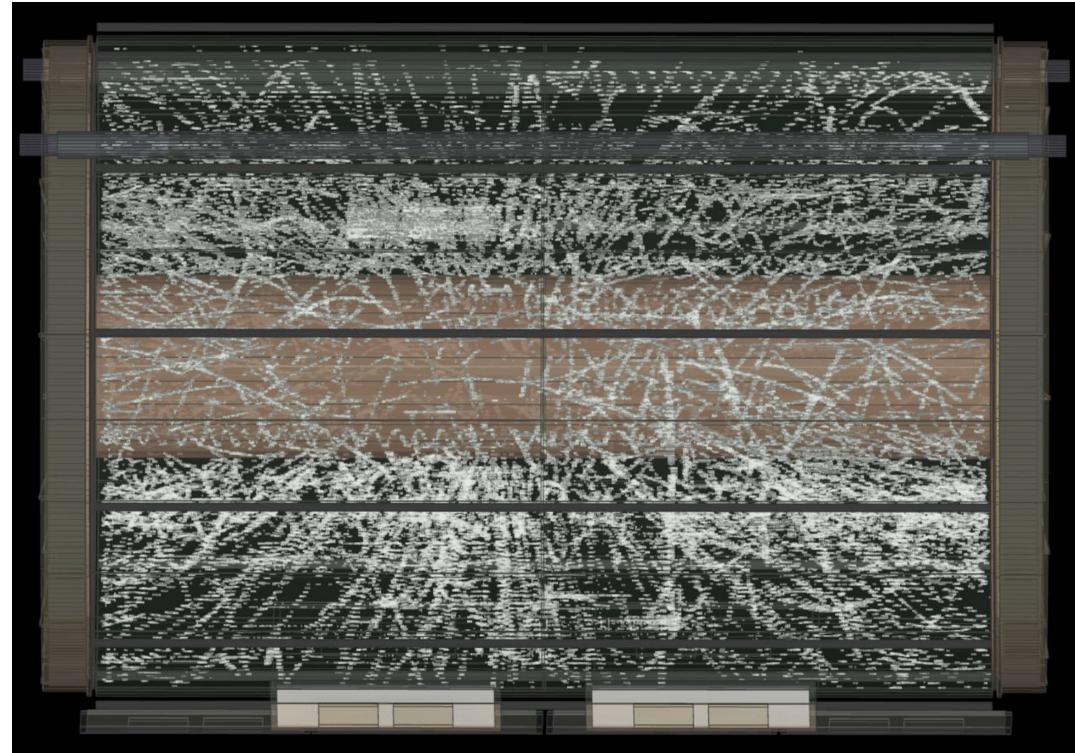
FELIX card (712) on server for FW testing



Summary and outlook



- sPHENIX commissioning run started in May 18th
- Huge collaboration effort over summer
 - All detectors installed, turned on and taking data
- Heavy flavor prospects at sPHENIX are exciting
 - First barrel HCal at RHIC for precise HF-jets
 - Largest inclusive b-hadron sample at RHIC enabled by streaming readout
- ML in firmware under study to increase HF physics sampling to full 3 MHz pp rate
- The story doesn't end, commissioning continues into next year
 - First look at data is being used to finalise offline code in preparation to physics runs



June 23rd 2023: AuAu collision seen by the TPC

sPHENIX posters



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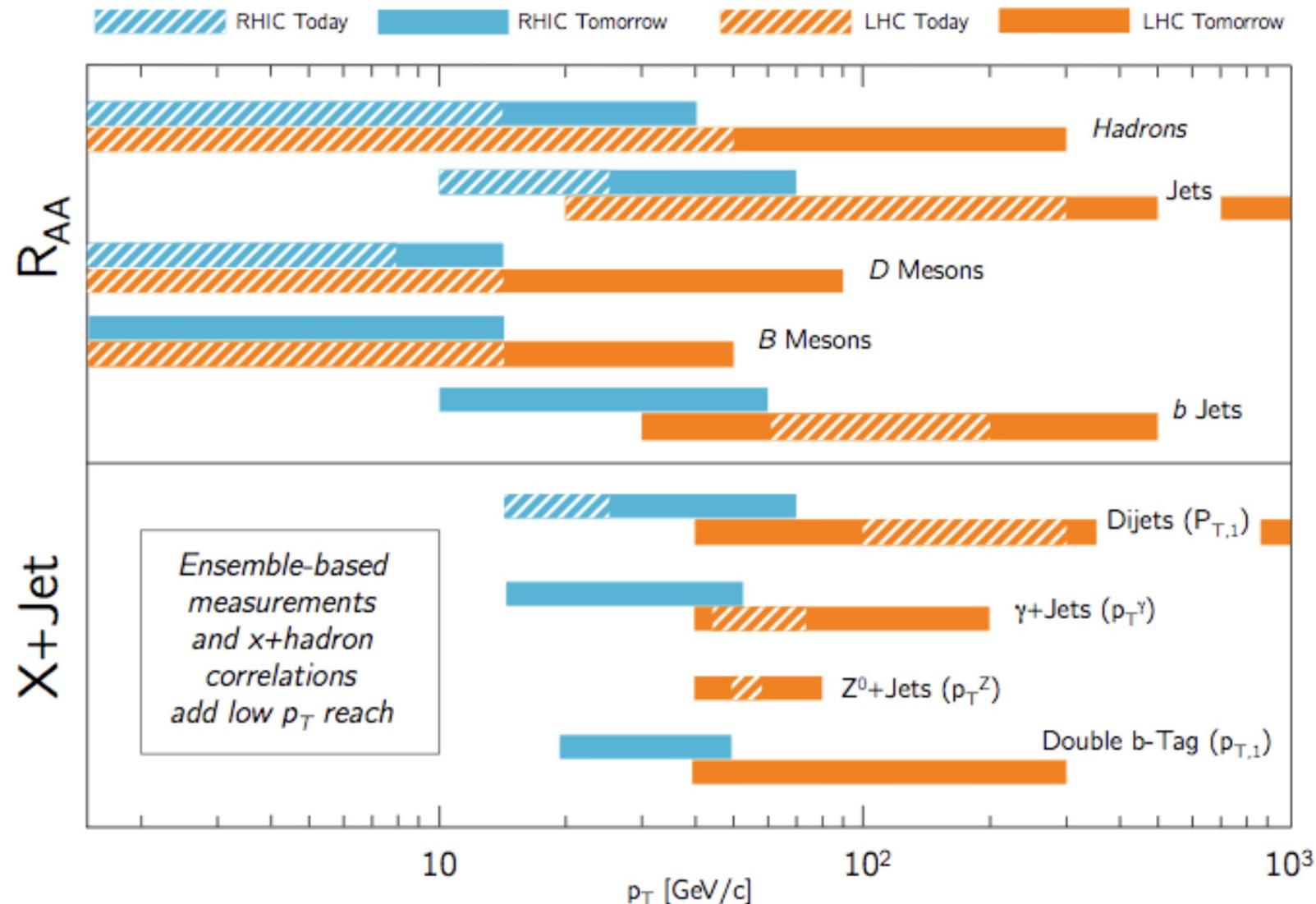
Backup

The FastML Team



- Cross-discipline group of computer scientists, engineers and physicists
- Formed in 2020 from DE-FOA-0002490
- Consists of groups from
 - Los Alamos National Laboratory
 - Massachusetts Inst. of Technology
 - New Jersey Institute of Technology
 - Fermilab
 - Oak Ridge National Laboratory
 - Stony Brook
 - Georgia Institute of Technology
 - University of North Texas
 - Central China Normal University

LHC vs RHIC



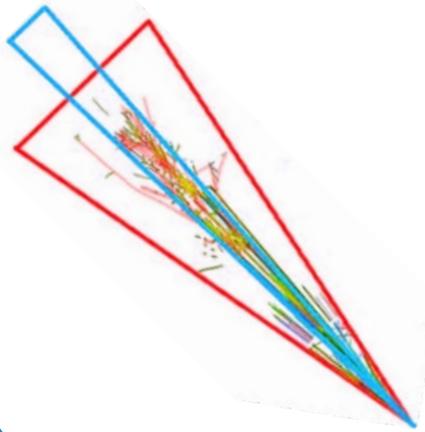
Core physics program



Jet Physics

Vary momentum/
angular size of probe

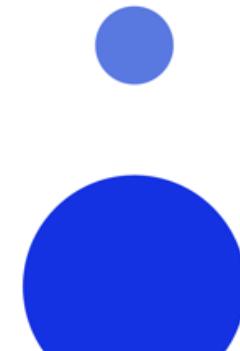
([Talk by T. Rinn](#))



Heavy Flavor

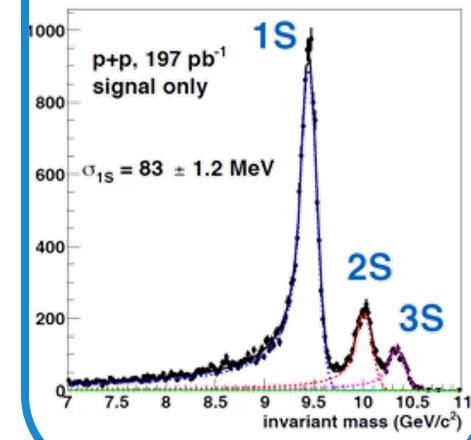
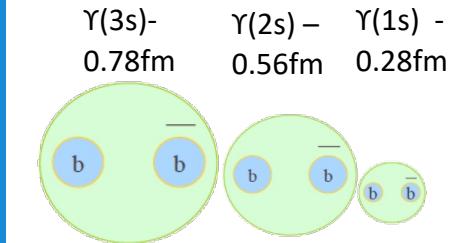
Vary mass/
momentum of probe

• g
• u,d,s
• c
• b



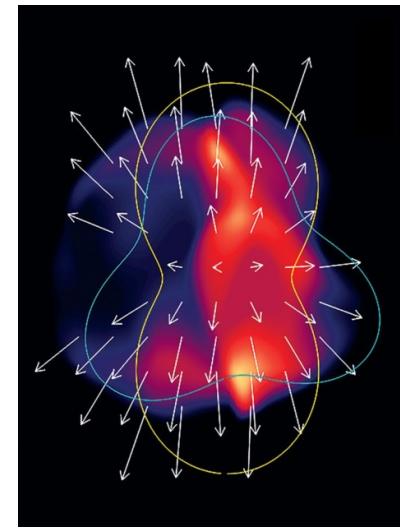
Quarkonia

Vary size of probe



Bulk

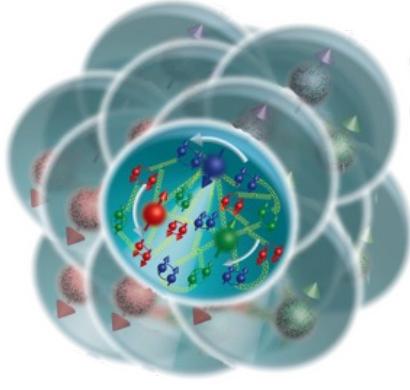
Study global/local medium properties



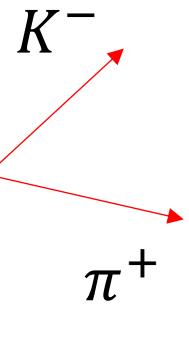
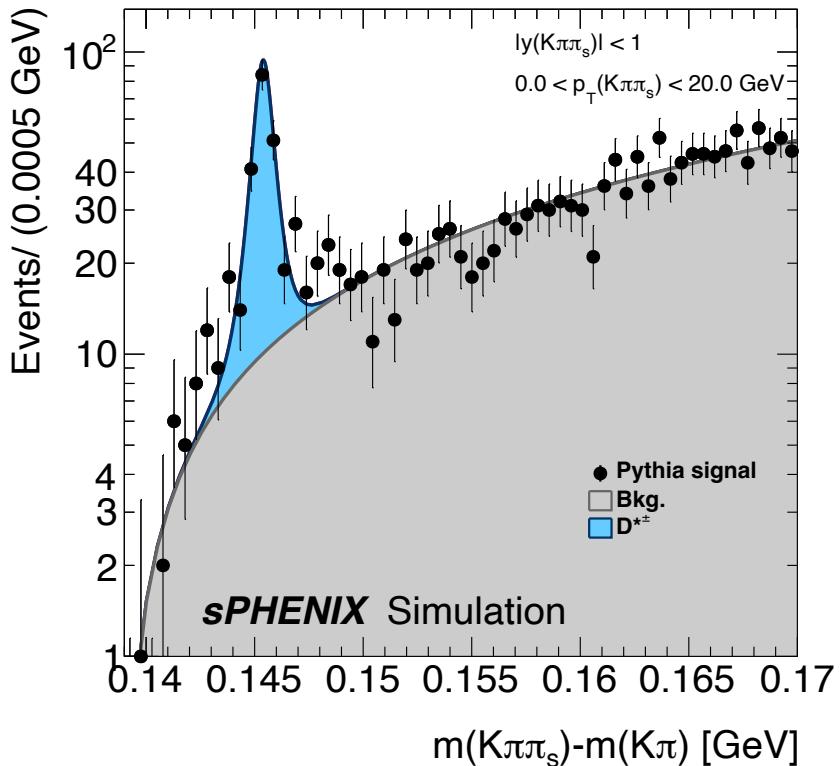
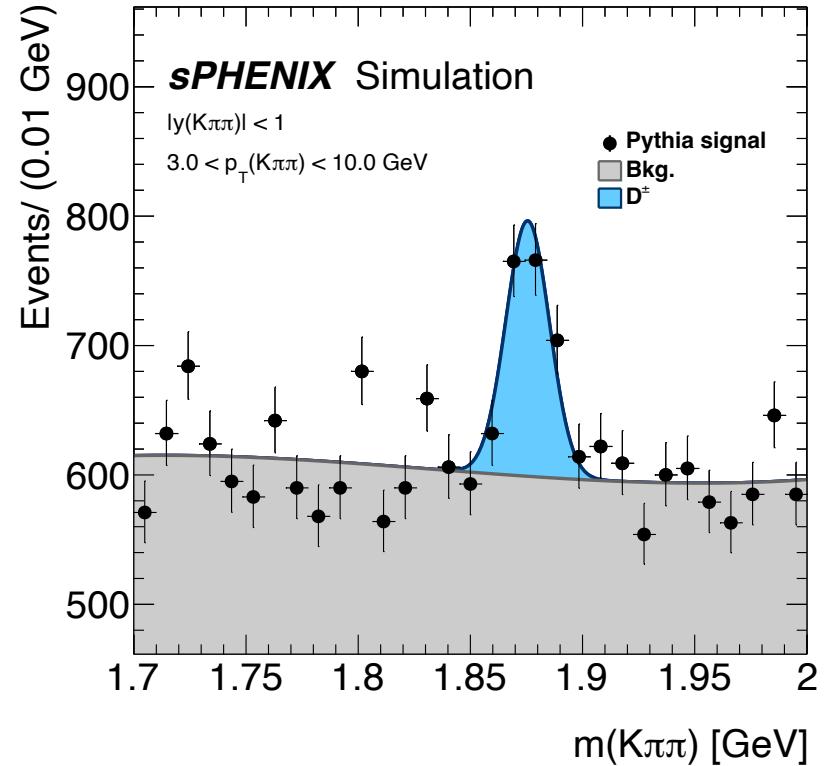
arXiv:1209.6330

Cold QCD

Study proton spin, p_T , and cold nuclear effects



$D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+) \pi_S^+$

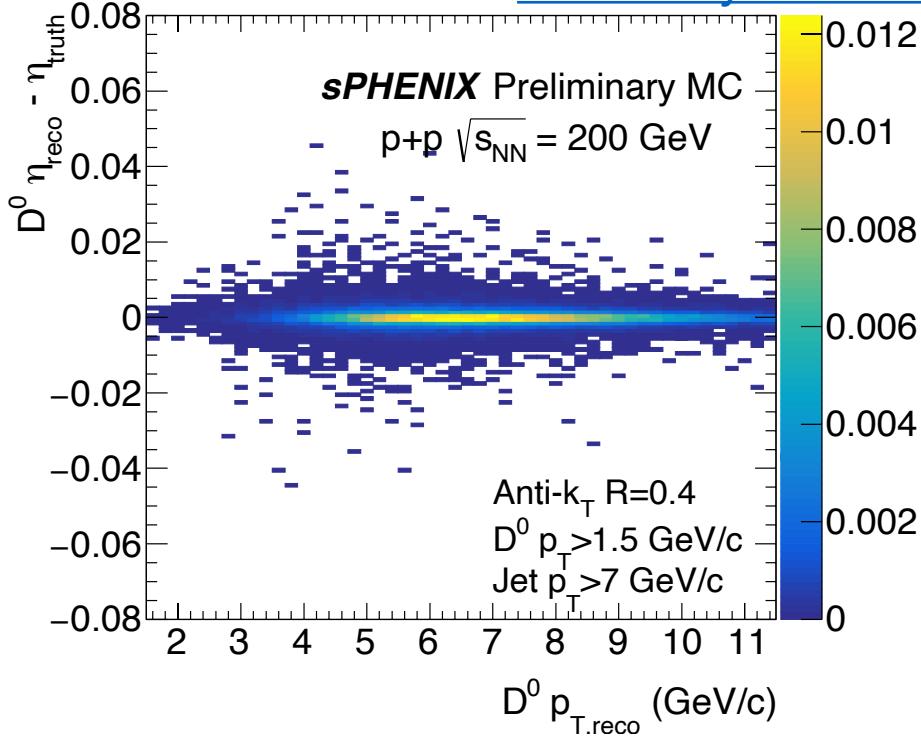
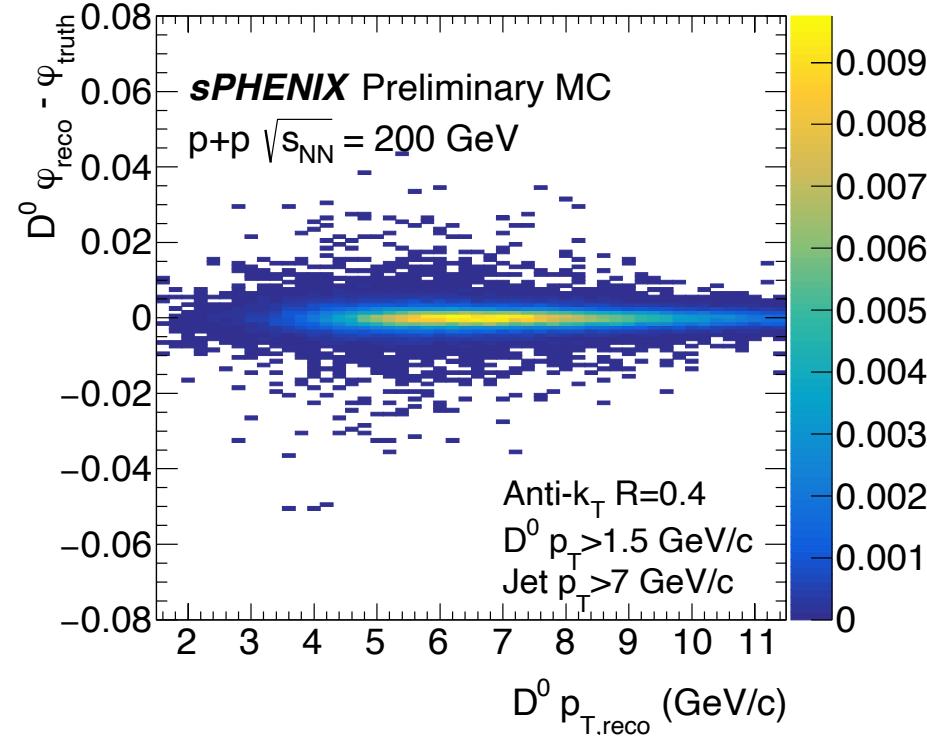


- D^{*+} decays promptly
- Requires good handle on PV, SV and tracking
- In PDG: $m(K\pi\pi_s) - m(K\pi) = 145.426(2)$
- This channel fully defines D^0 flavor at production

Particle flow and HF-tagged jet sim.



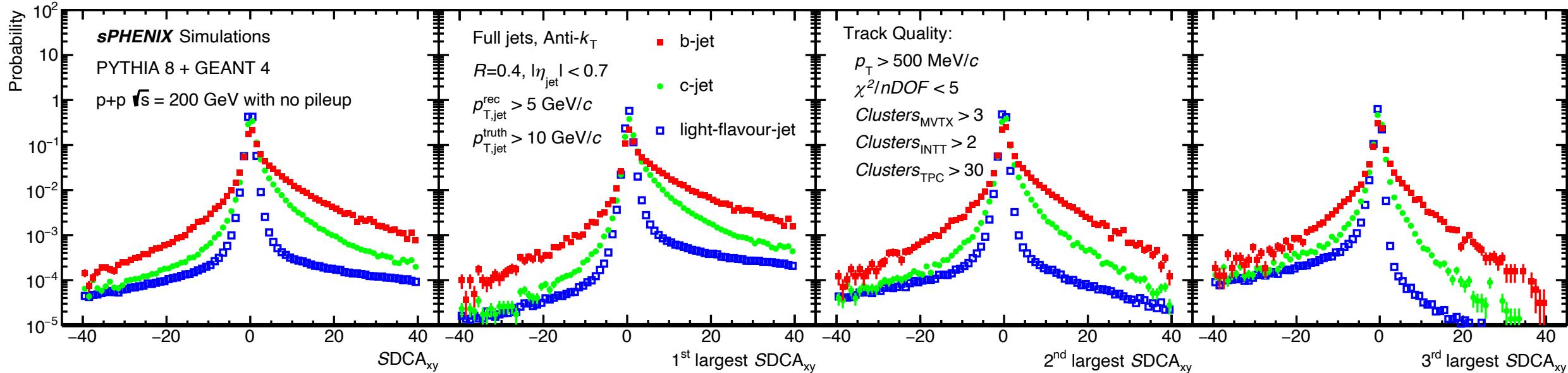
Poster by A. da Silva



- Particle Flow implementation and calibration is ongoing using tracks and topo-clusters
- Cross-working group collaboration
- Above test sample requires min. jet $p_T > 5 \text{ GeV}$ and $D^0 \rightarrow K^- \pi^+$ in each event
- Full $D^0 \rightarrow K^- \pi^+$ candidates are reconstructed, daughter tracks are then removed inside the jet and replaced with D^0 kinematics

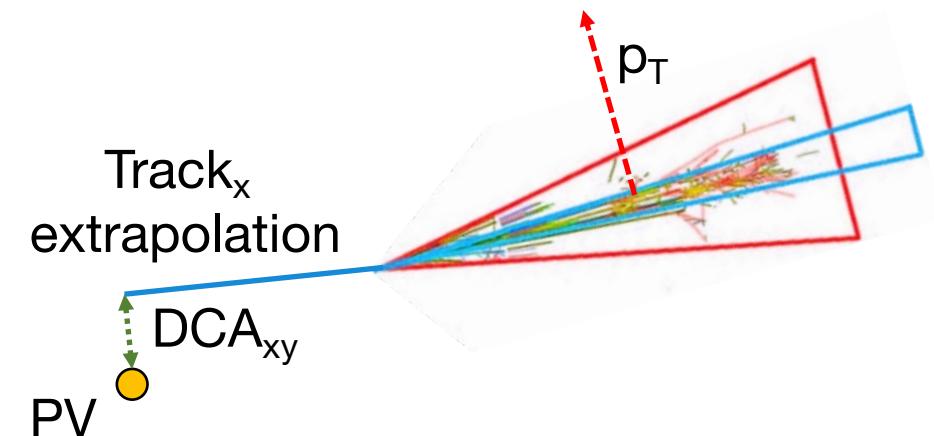
b-jet tagging sim.

[Poster by J. Kvapil](#)

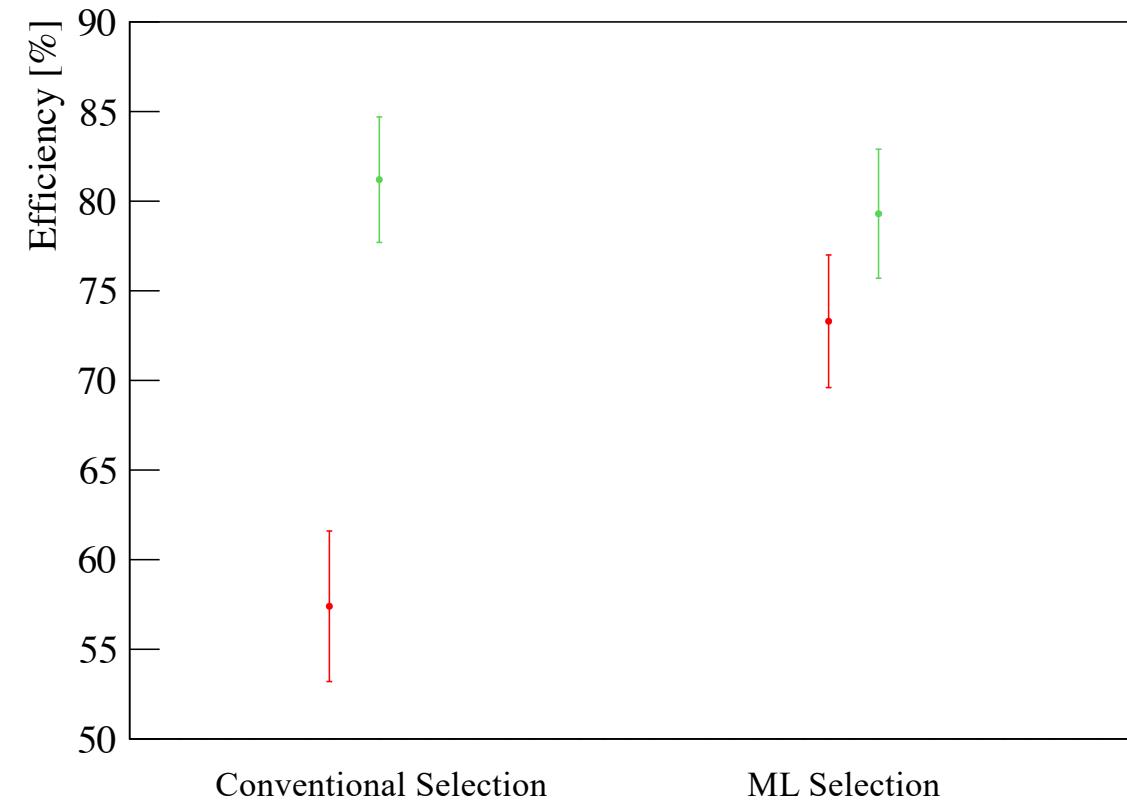
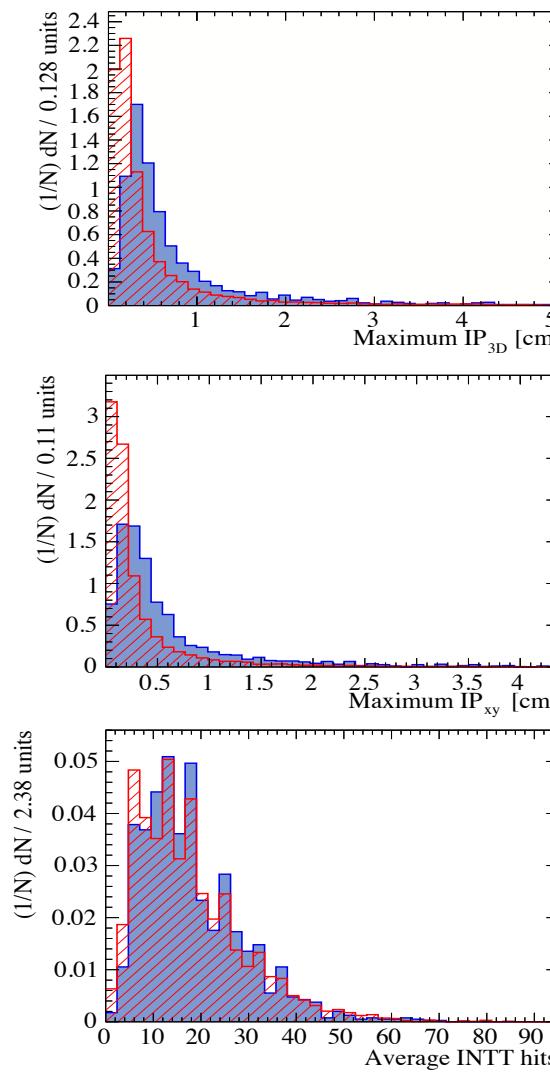
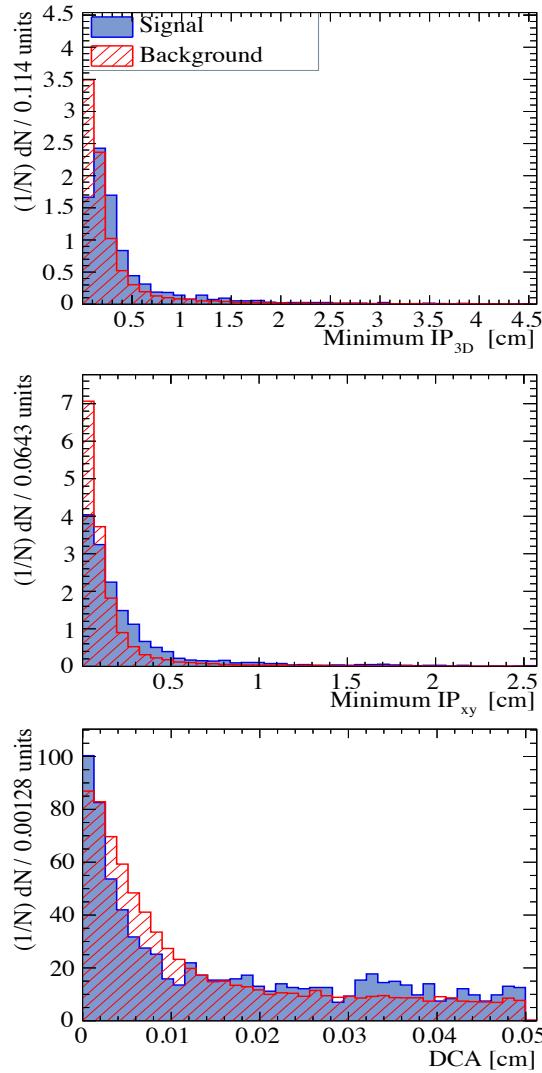


- Jet reco. with anti- k_T algorithm
- Particle flow to connect jets and tracks
- Jet type tagged using signed DCA_{xy} significance

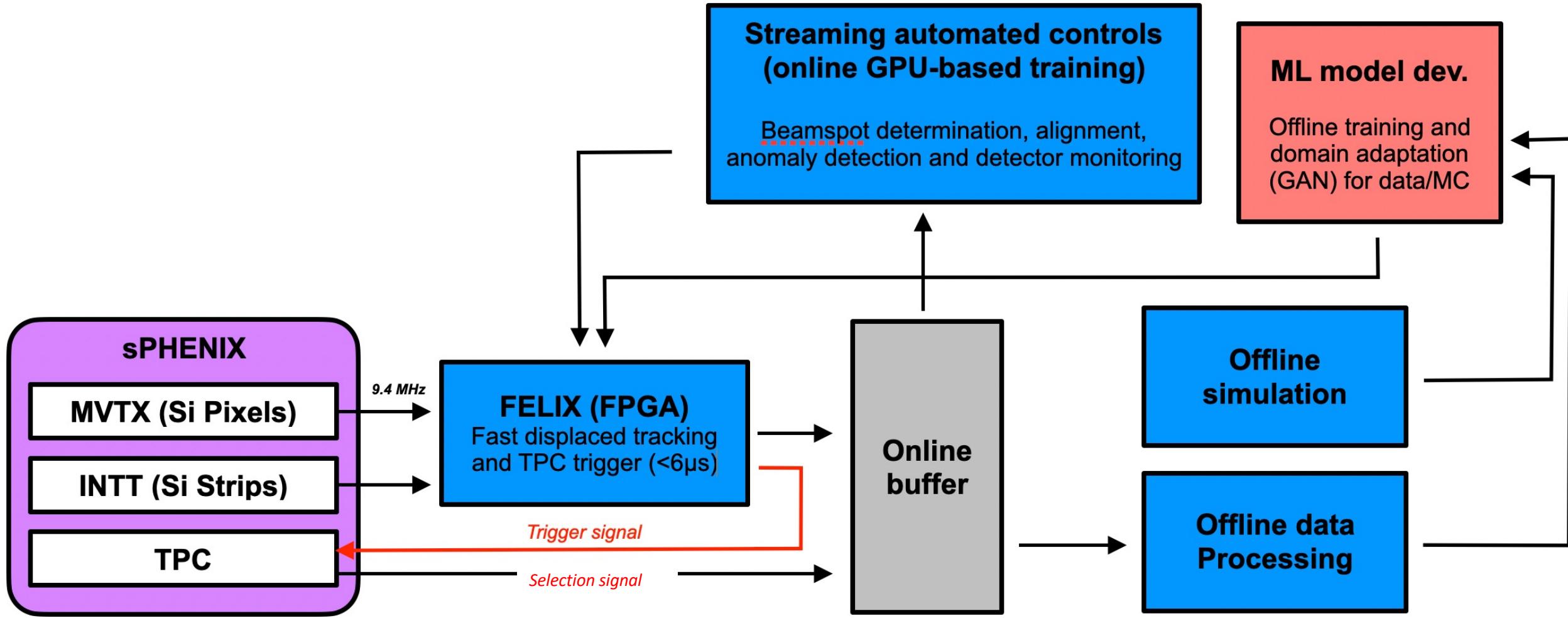
$$SDCA_{xy} = \text{sgn}(\vec{p}_T \cdot \overrightarrow{DCA}_{xy}) \times \frac{|\overrightarrow{DCA}_{xy}|}{\sigma \overrightarrow{DCA}_{xy}}$$



Vars. used for first ML trigger study

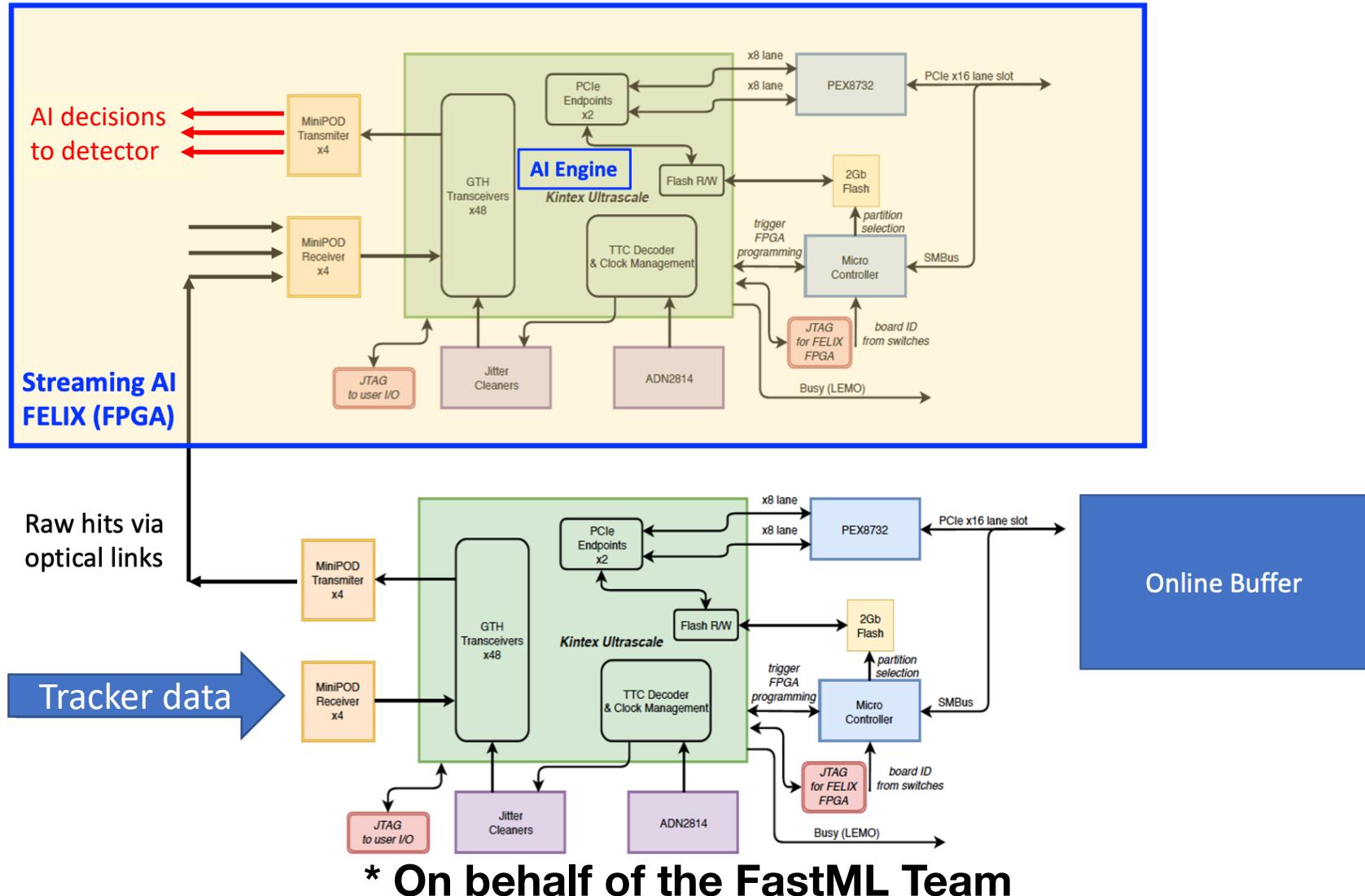


Overcoming DAQ limits with AI

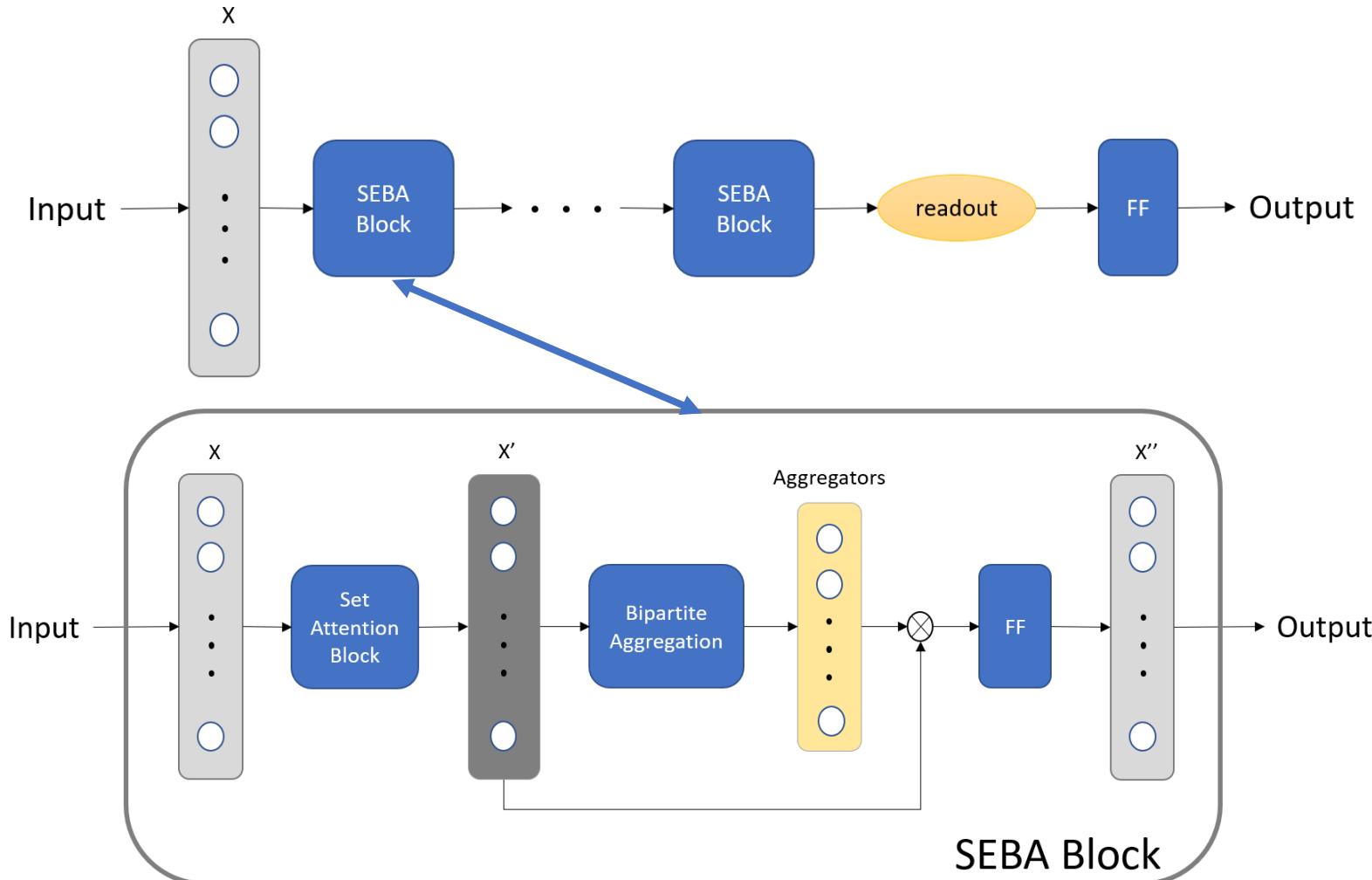
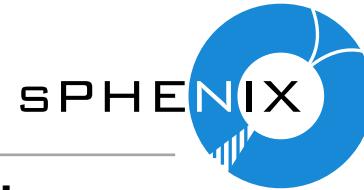


* On behalf of the FastML Team

Realizing trigger in firmware



Tagging with machine learning*



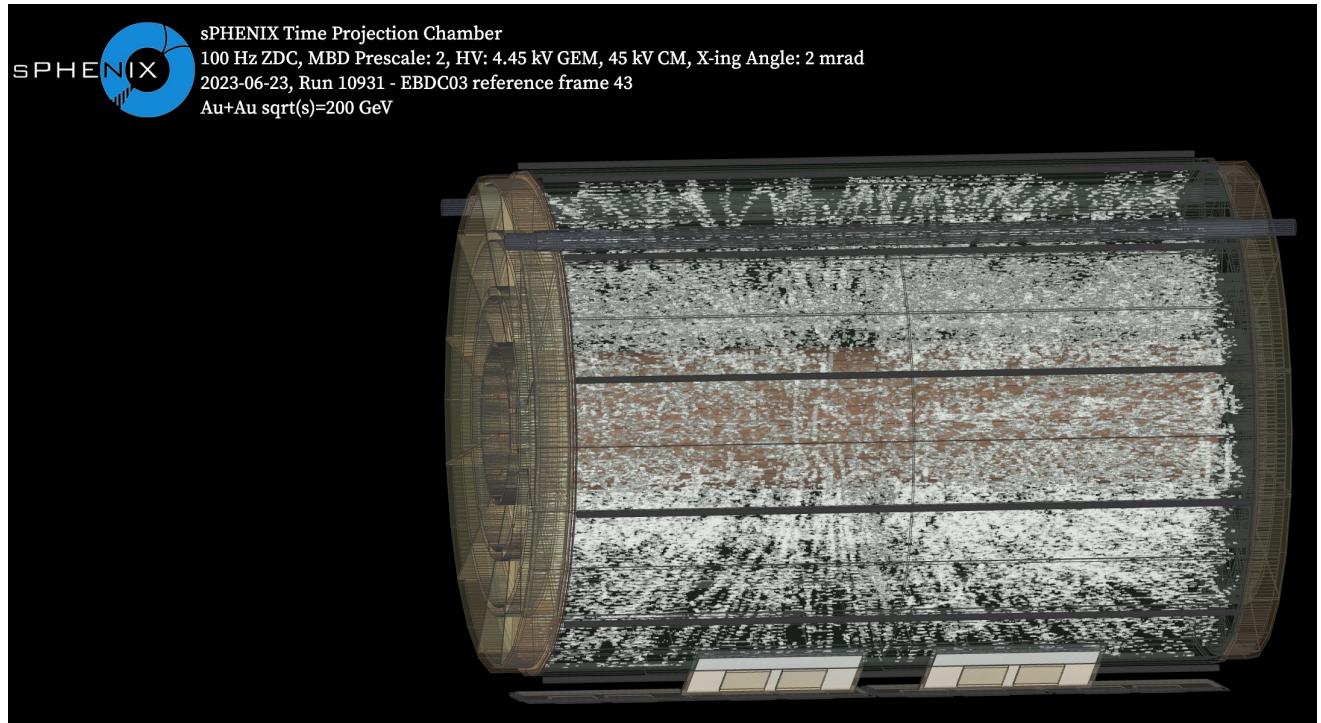
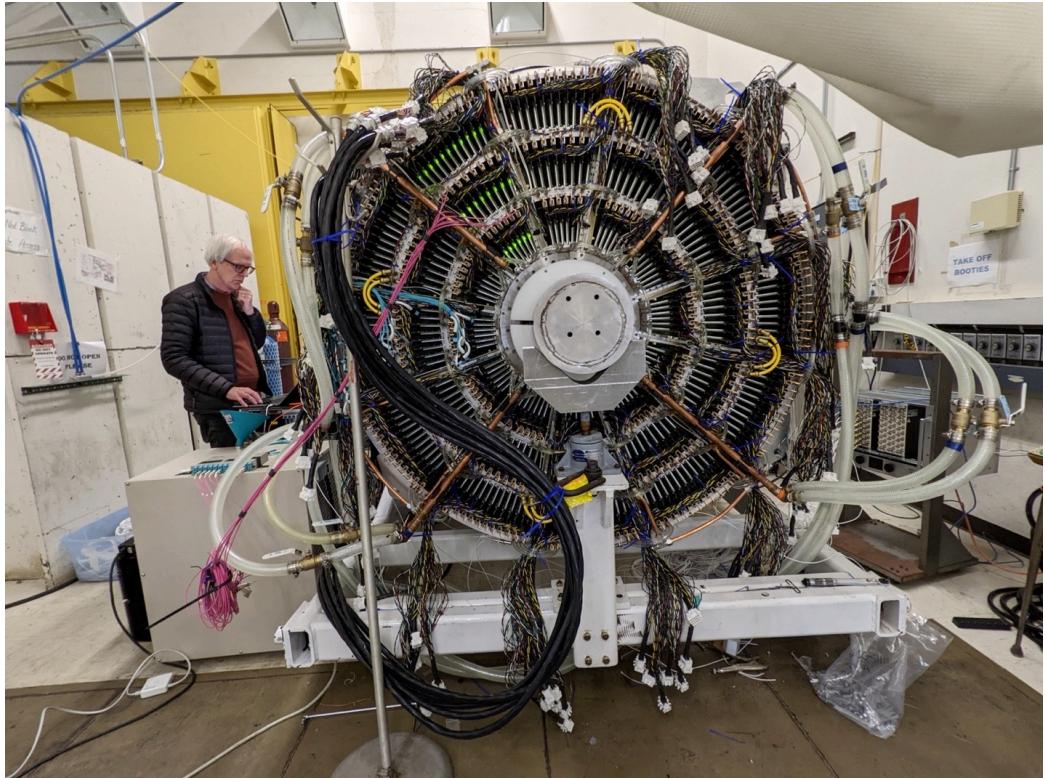
The cycle

1. Track information is initially defined
 2. This is relayed to all primary and secondary vertex information
 3. Weights are assigned to each link
 4. The PV and SV information go through a feedforward NN
 5. This updates the track information
- We aim to
 - Implement algorithm on FELIX card in October
 - Deploy for sPHENIX Run-24 as demonstrator
 - Refine for use at EIC after studying sPHENIX results
- N.B. SEBA = Set Encoder with Bipartite Aggregator

* On behalf of the FastML Team

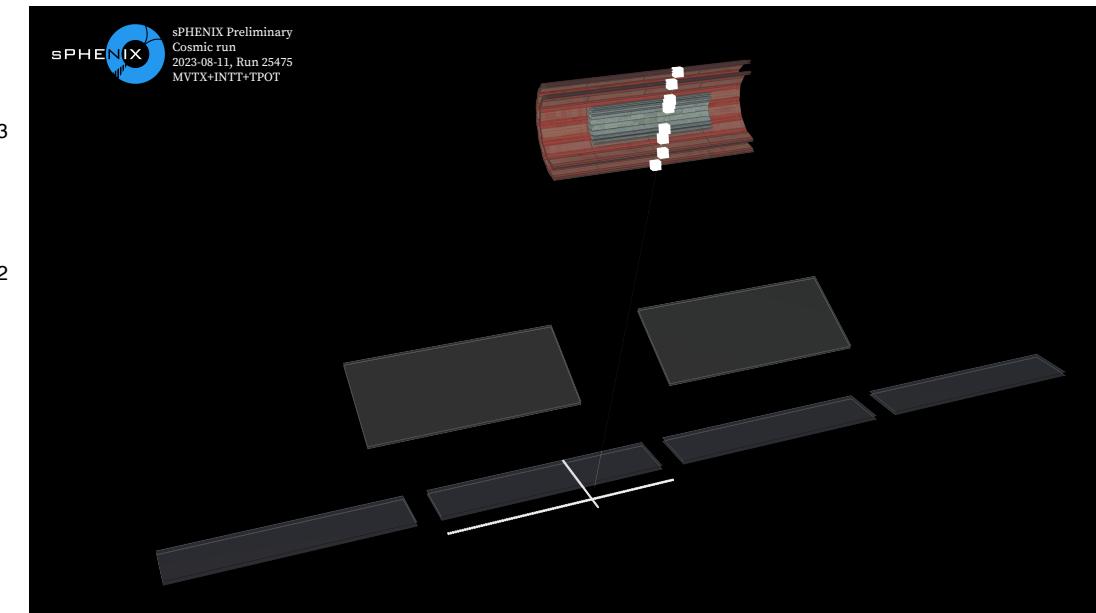
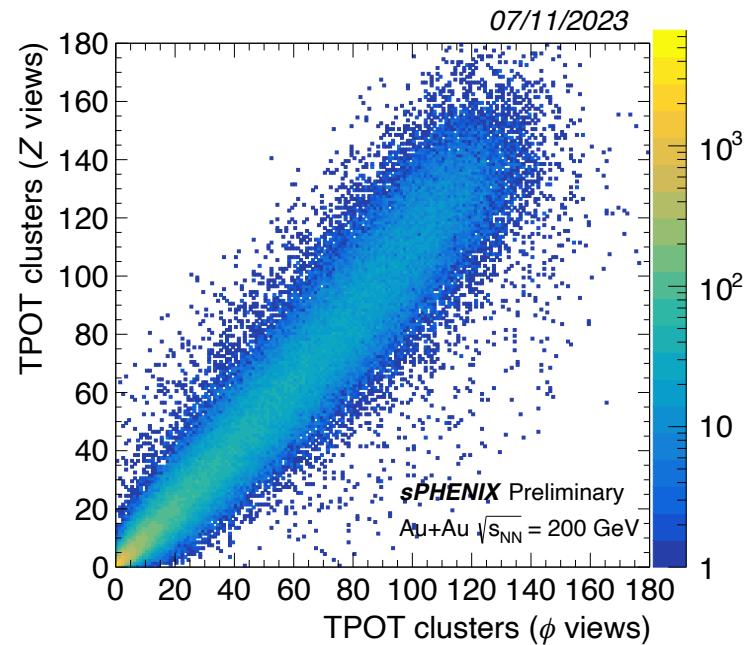
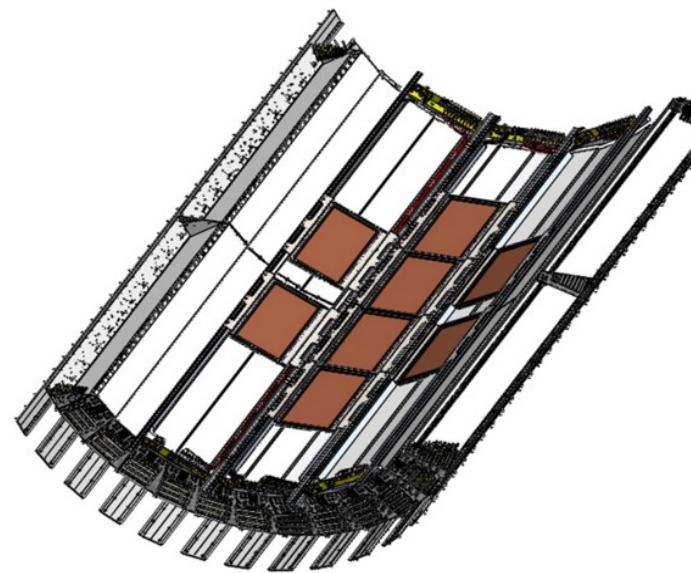
[ECML PKDD 2022, Sub 1256](#)

TPC



- Compact TPC, $20 < r \text{ [cm]} < 78$ (active volume $r > 30\text{cm}$)
- IBF is minimized, TPC is live at all times
 - IBF $< 0.5\%$ at a few kV in GEMs

- TPOT adds another hit point for tracking detectors
- Allows calibration of beam-induced space charge distortions
- Uses micromegas for detection

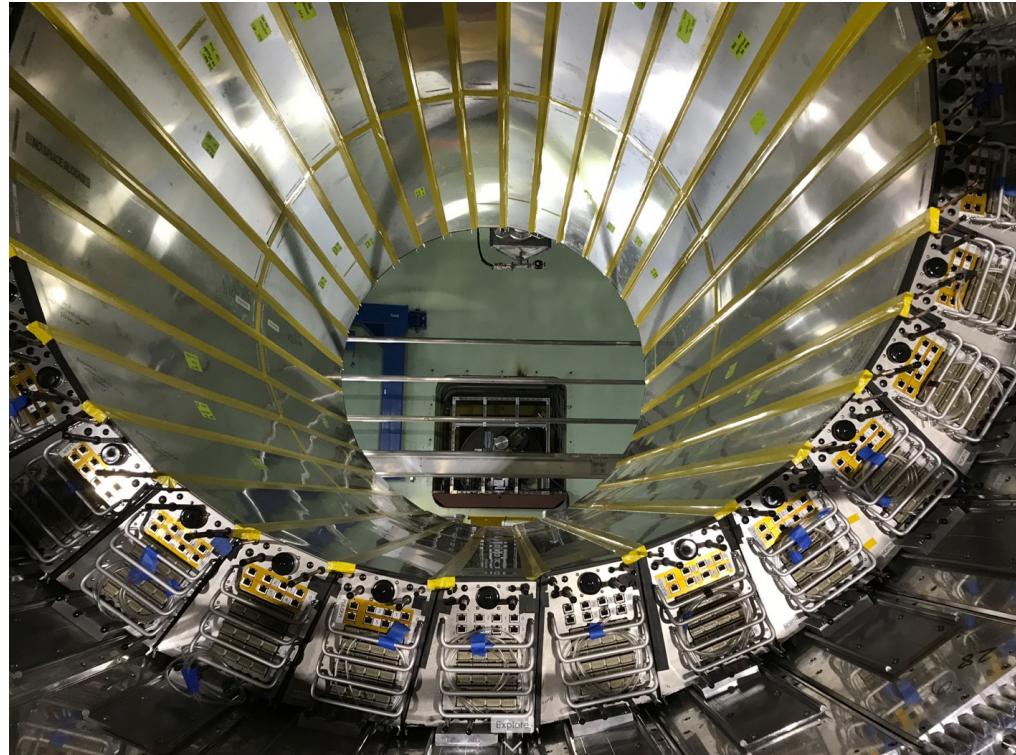


Left – TPOT drawing, center – TPOT correlations, right – cosmic seen by MVTX, INTT & TPOT

EM calorimetry



[<https://arxiv.org/abs/2003.13685>]



- Sampling EMCal, using SciFi in tungsten and epoxy
- $20.1X_0$ and $0.83\lambda_{int}$

Hadron calorimetry



- Two detectors on inside and outside of the magnet
- Alternating tiles of steel (outer) or aluminum (inner) and scintillator

Event Plane Detector



- EPD is based off STAR design
- Adapted for use in sPHENIX
- Covers $2.0 \leq |\eta| \leq 4.9$
- 2 disks, with 12 sectors and 31 tiles/sector



EPD sectors under construction

