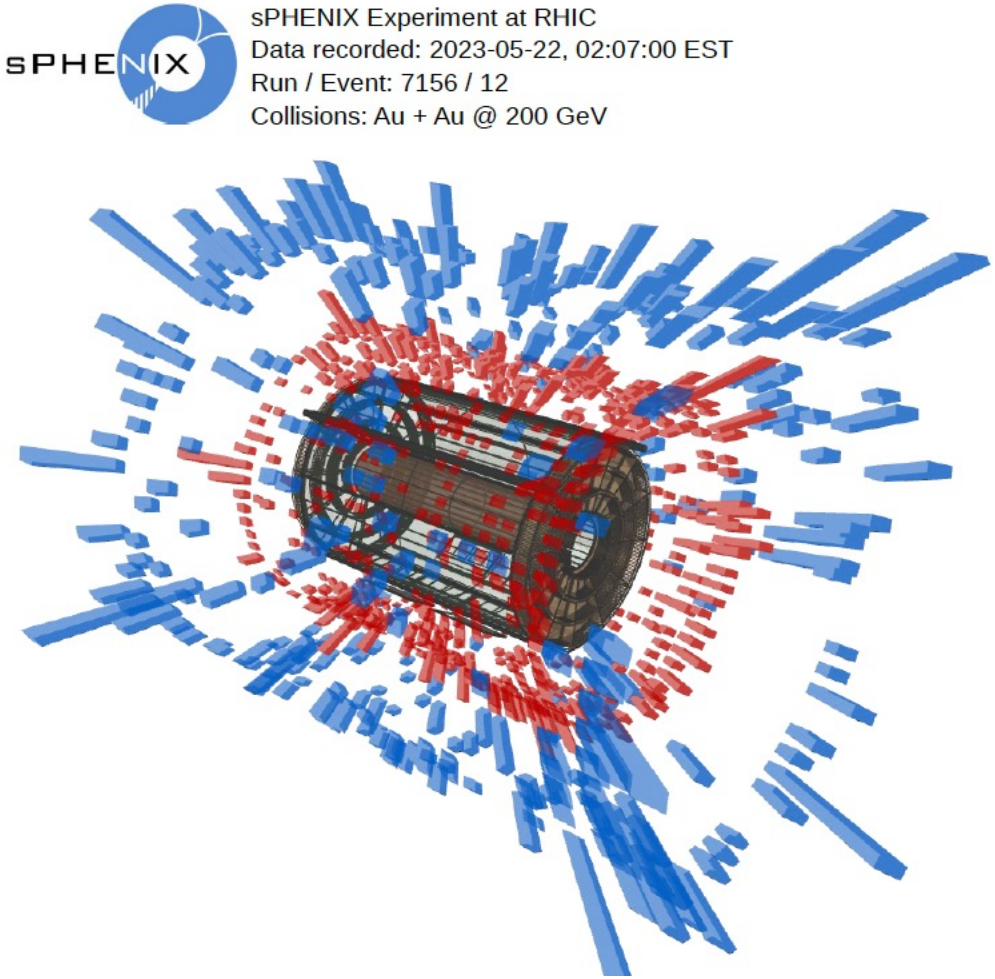


The First Days of sPHENIX

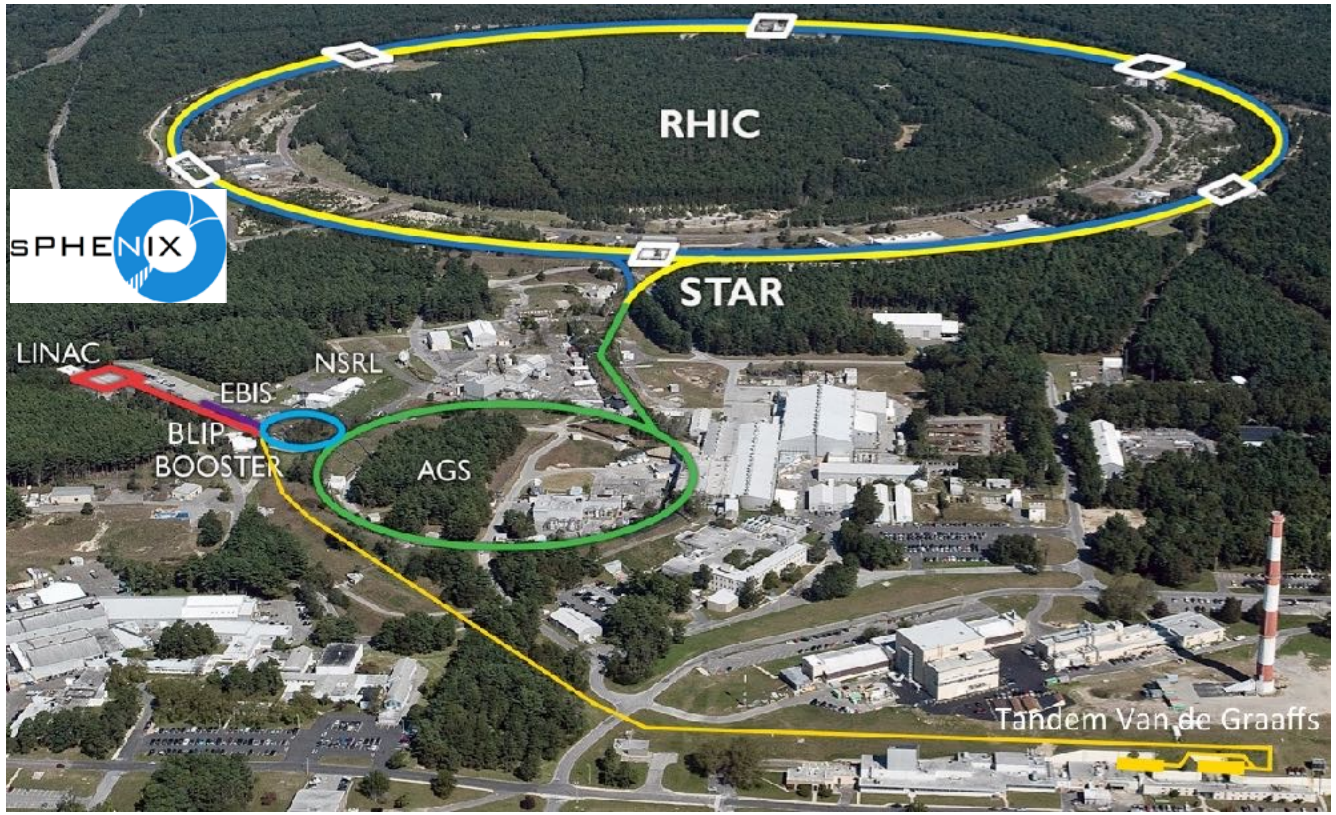
Ming Liu, Los Alamos National Lab
for the sPHENIX Collaboration

Workshop on Hadron Femtography with Hard Exclusive Reactions

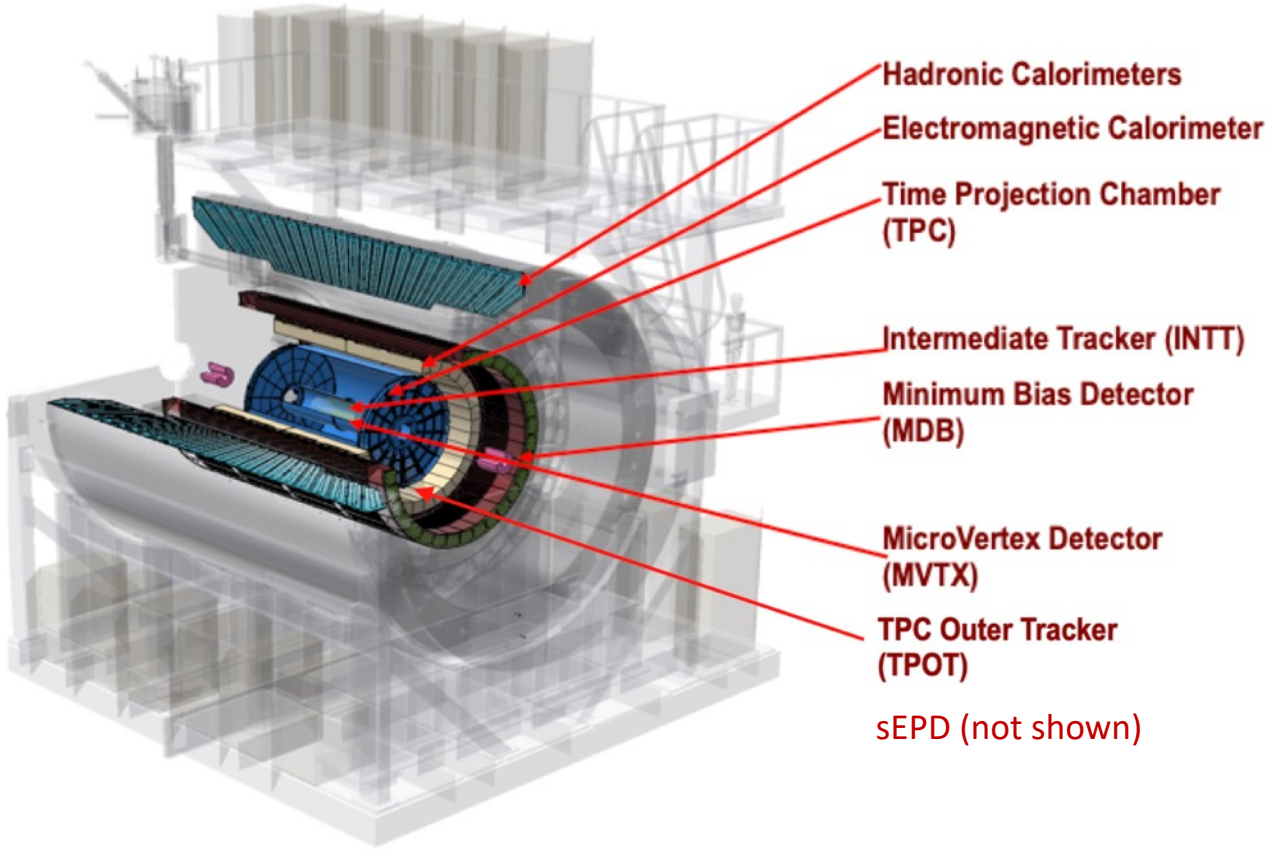
Aug. 7 – 11, 2023, JLab

Outline

- sPHENIX at RHIC
- Detector overview
- Installation and commissioning
- Initial commissioning in 2023



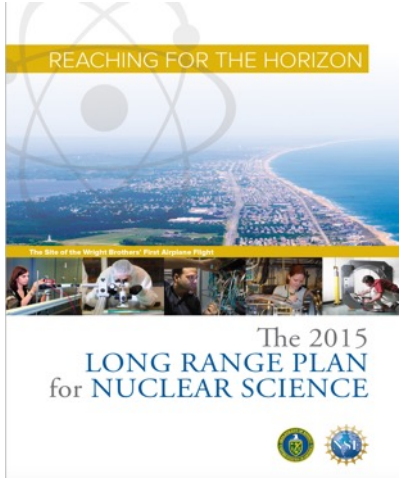
sPHENIX Experiment at RHIC



- Collaboration formed
- **2016** CD0
- **2018** CD-1/3A
- **2019** PD-2/3, construction
- **2023** End of construction; Commissioning

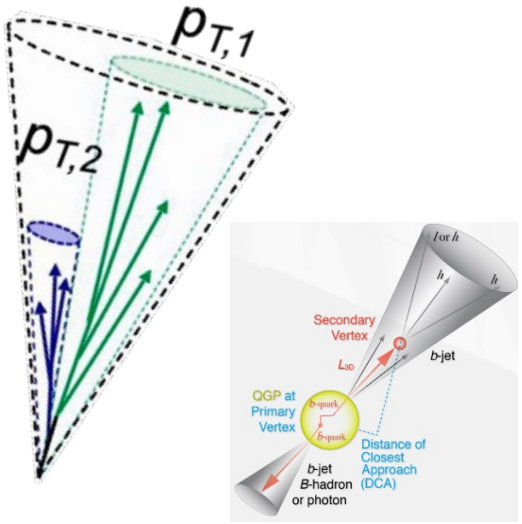
2015 NSAC Long Range Plan for Nuclear Science: sPHENIX Experiment at RHIC

- An upgrade of the PHENIX experiment
- Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales
- Complementary to LHC experiments to study relativistic heavy-ion collisions



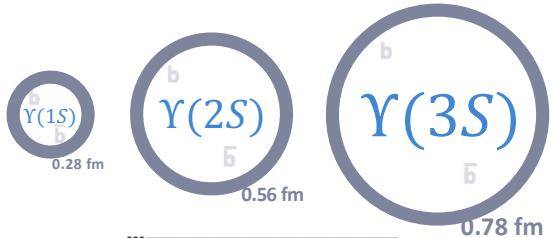
sPHENIX Physics Program

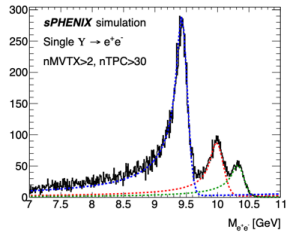
Jet Physics



- Jet correlations
- Nuclear Modification Factor
- Jet structure
- Jet flavor dependencies

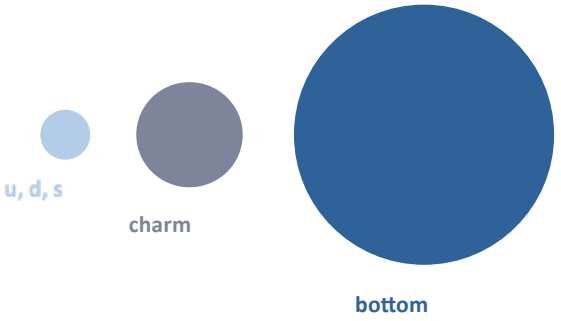
Quarkonium Spectroscopy





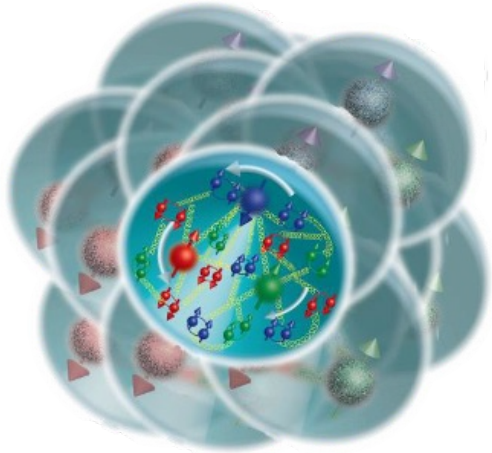
- Sequential quarkonia melting: Suppression of quarkonium depending on the state

Energy Loss in QGP



- Flavor (mass) dependence of parton energy loss in QGP

Cold-QCD

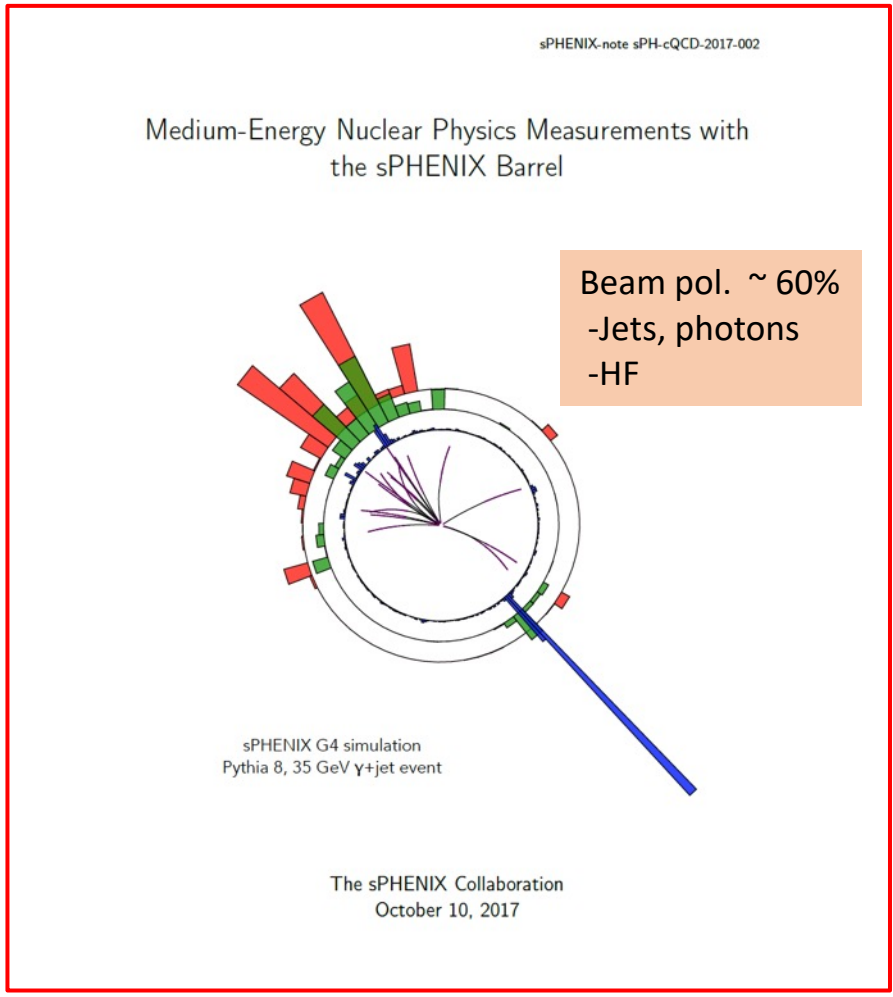


- Origin of the transverse single spin asymmetries
- Nucleon structure
- Fragmentation functions
- Nuclear effects

sPHENIX Run Plan and Cold-QCD Program

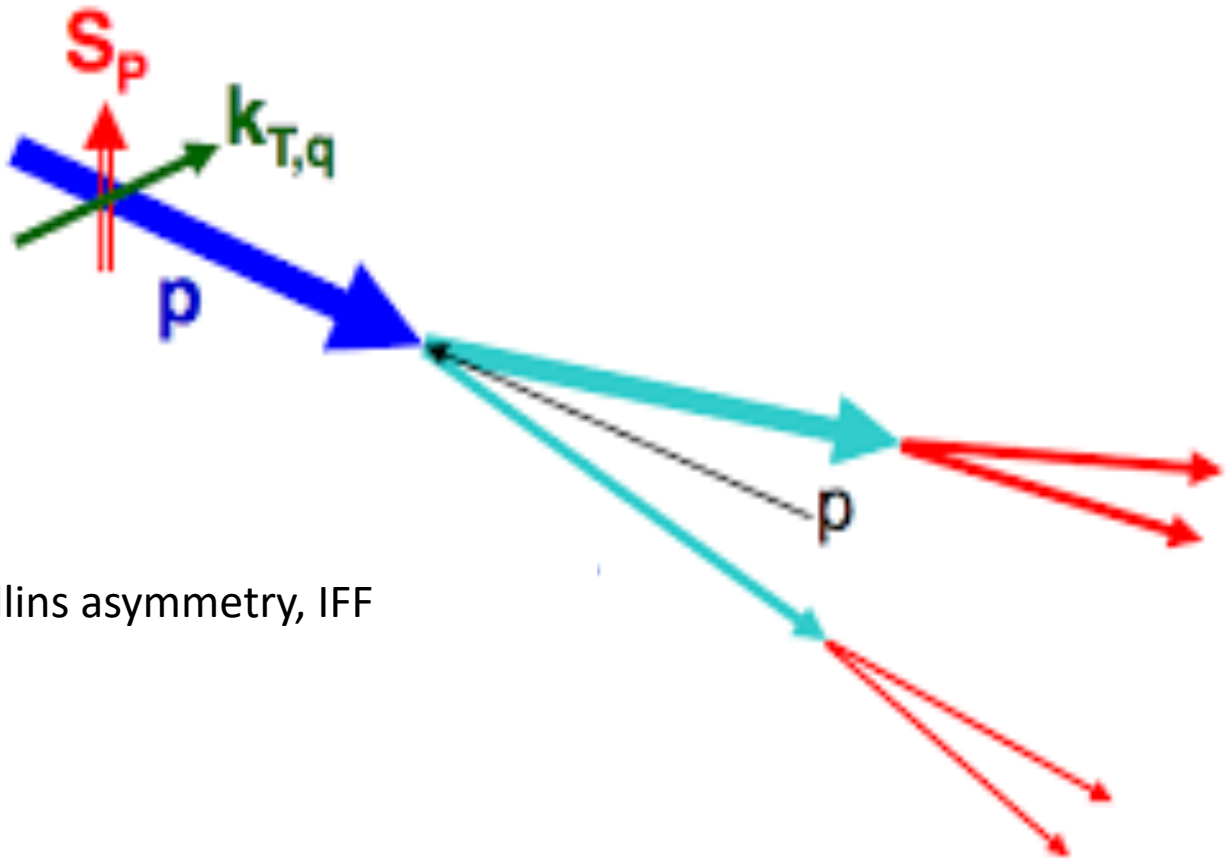
Presented to PAC 2022

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}



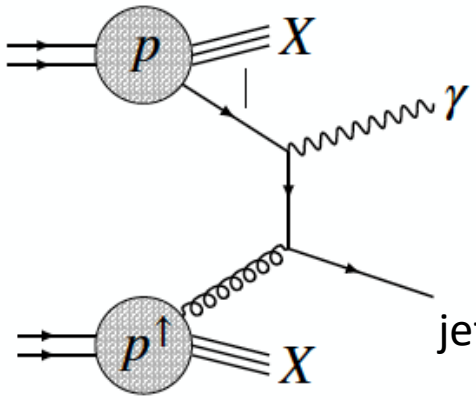
- Extensive **3-year** data taking from 2023
  - **Year-1**: commissioning and first physics in Au+Au
  - **Year-2**: p+p and p+Au runs for heavy-ion reference and cold QCD physics
  - **Year-3**: very large Au+Au dataset (141B events in total)

TMD Physics in Transversely Polarized p+p/Au: TSSA



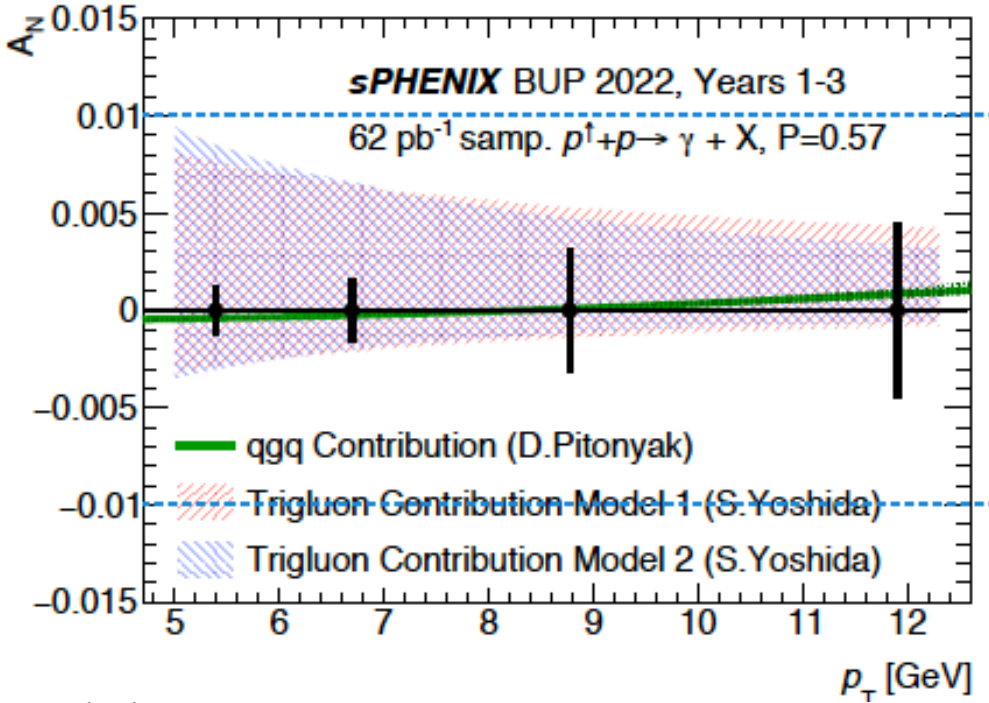
- Sivers asymmetry
- Jet structure and Collins asymmetry, IFF

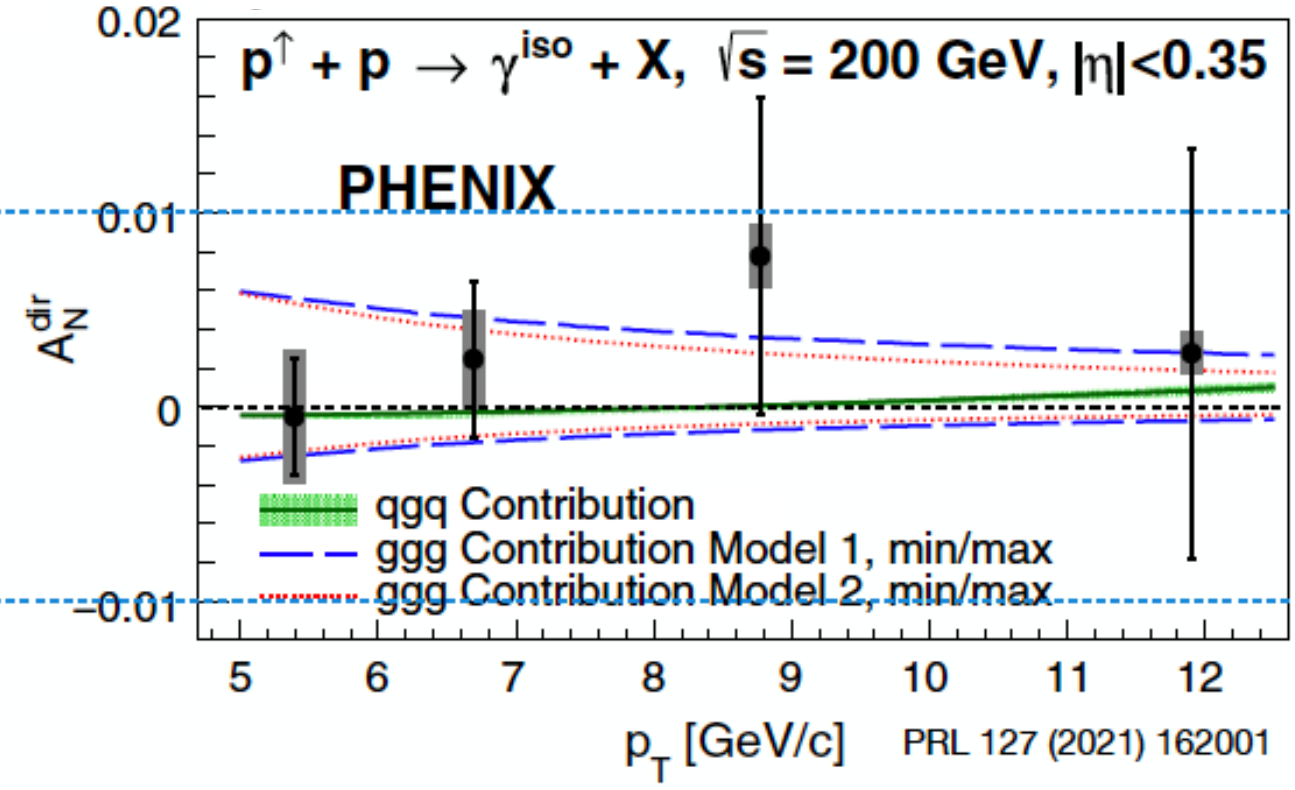
Gluon TMD with Direct photons



$$p^{\uparrow} + p \rightarrow \gamma + X$$

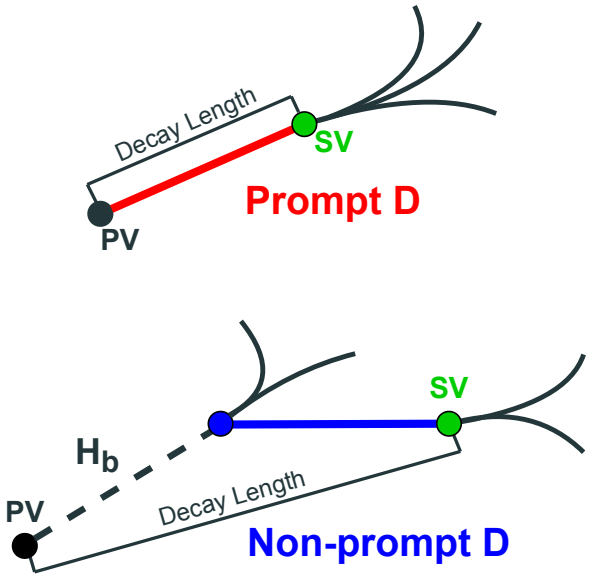
Much improved direct photon TSSA -> gluon TMD





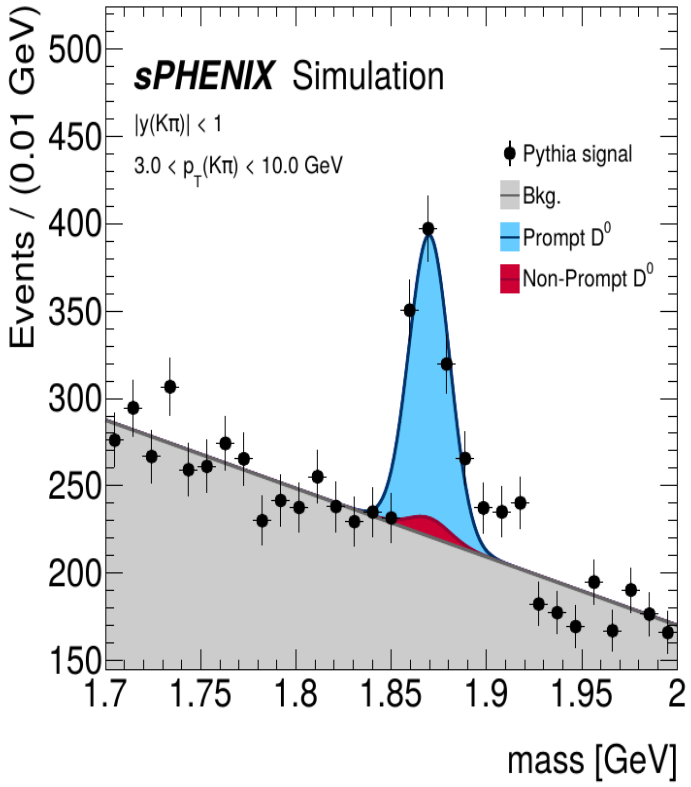
Gluon TMD with Heavy Flavor Probe: TSSA

$$p^{\uparrow} + p \rightarrow D^0/\bar{D}^0 + X$$

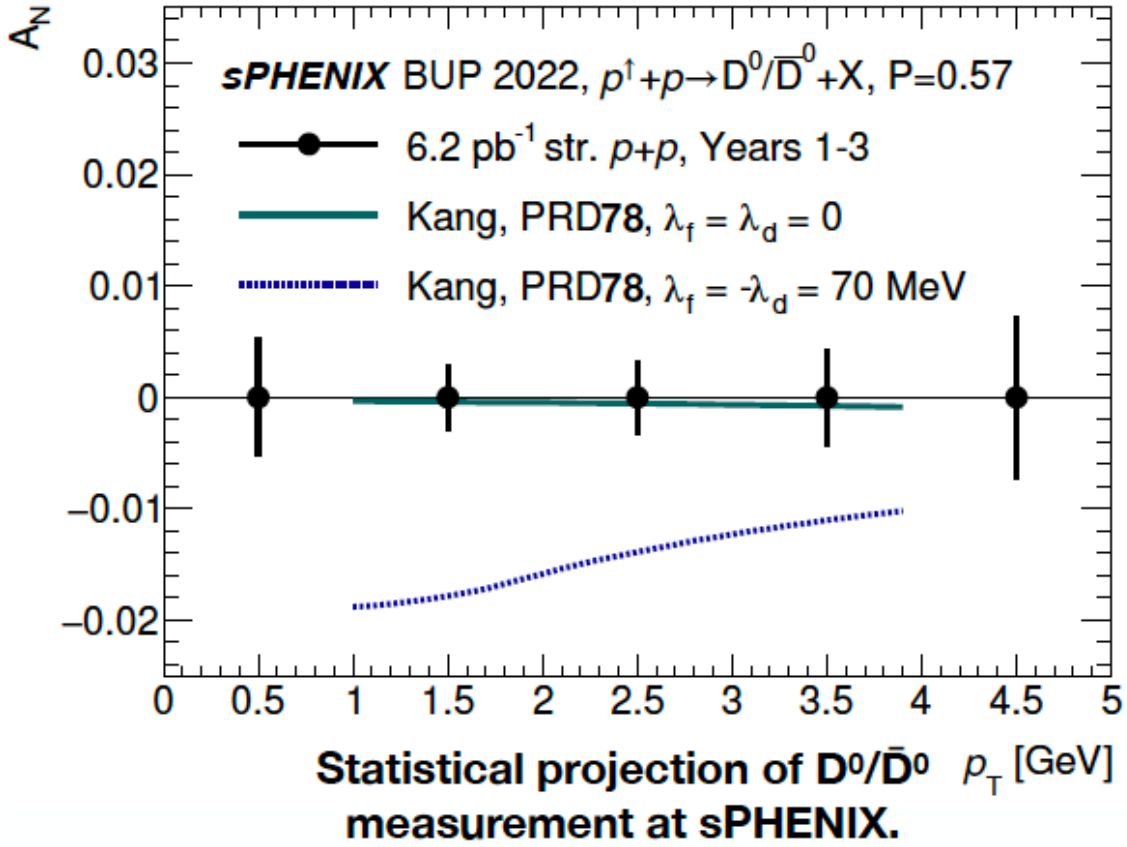


HF mostly produced by gluon-gluon interaction at RHIC

D^0 tagging



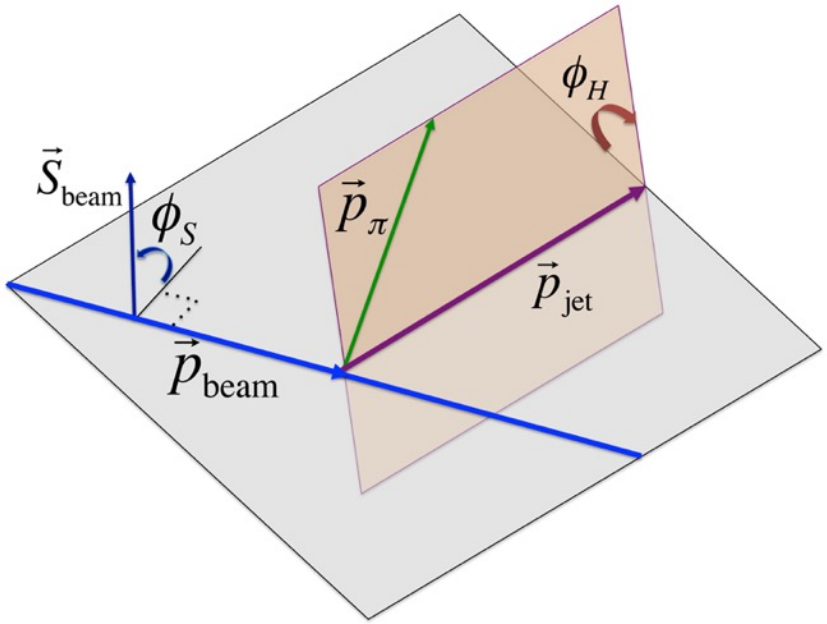
Precision open charm TSSA -> gluon TMD

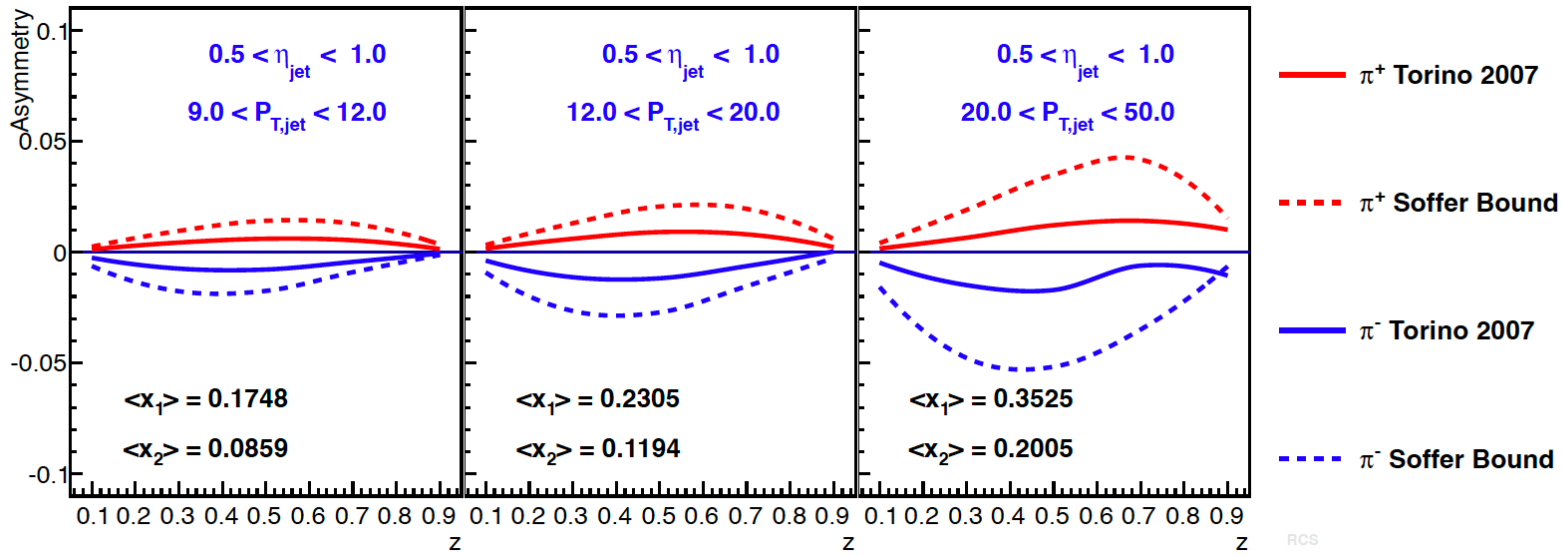


Statistical projection of $D^0/\bar{D}^0$ measurement at sPHENIX.

Hadrons in Jets – Quark Transversity and Collins FF

Collins TSSA: $A_{Collins} \sim \{\text{Transversity}\} \times \{\text{Collins FF}\}$





Explore new opportunity at hadron machines?

Single directive “di-jet”, di-photon, hadron-jet pair production in transversely polarized p + p/A?

- Large Q^2, small kT
- Forward “proton capture” detector behind MBD/sEPD + Fcal/“mini-Hcal/ZDC” like

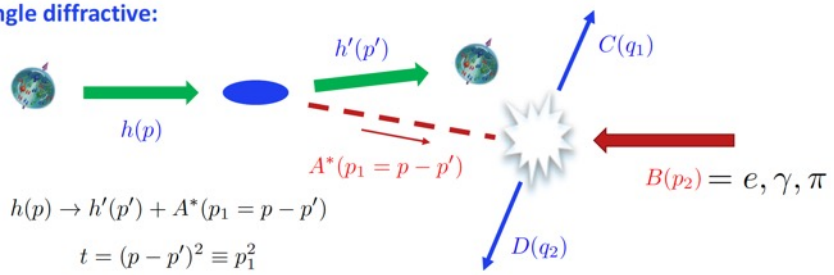
Qiu @Wed.

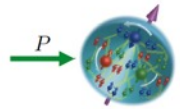
Single-Diffractive Hard Exclusive Processes (SDHEP)

❑ **Two-stage diffractive $2 \to 3$ hard exclusive processes:**

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1

- **Single diffractive:**





Probing its structure without breaking it!

$$h(p) \to h'(p') + A^*(p_1 = p - p')$$
$$t = (p - p')^2 \equiv p_1^2$$

- **Hard probe:** $2 \to 2$ **high** q_T **exclusive process**

$$A^*(p_1) + B(p_2) \to C(q_1) + D(q_2)$$
$$(p - p') \cdot n \gg \sqrt{|t|} \iff |q_{1T}| = |q_{2T}| \gg \sqrt{-t}$$

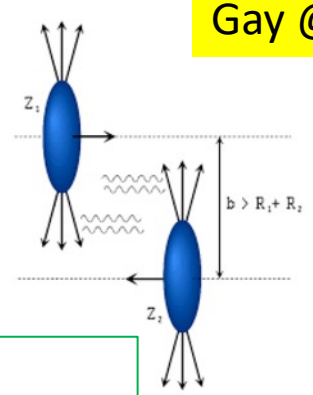
- **The single diffractive $2 \to 3$ exclusive hard processes:**

$$h(p) + B(p_2) \to h'(p') + C(q_1) + D(q_2)$$

10

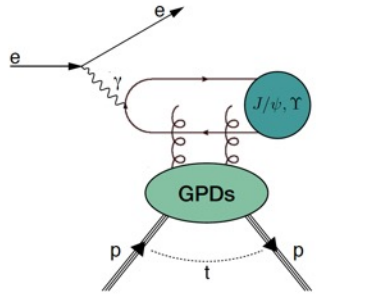
Ultraperipheral Collisions

Gay @Thur.



Experimental access to GPDs

Van Hulse @Thur.

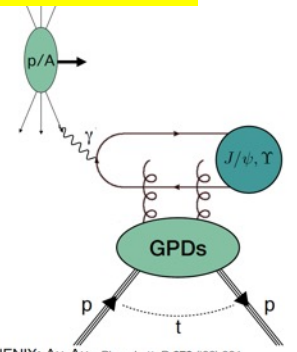


Hard scale = large charm/bottom-quark mass

H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251
ZEUS – Nucl. Phys. B 695 ('04) 3; PLB 680 ('09) 4

$W_{\gamma p} = [30, 300]$ GeV

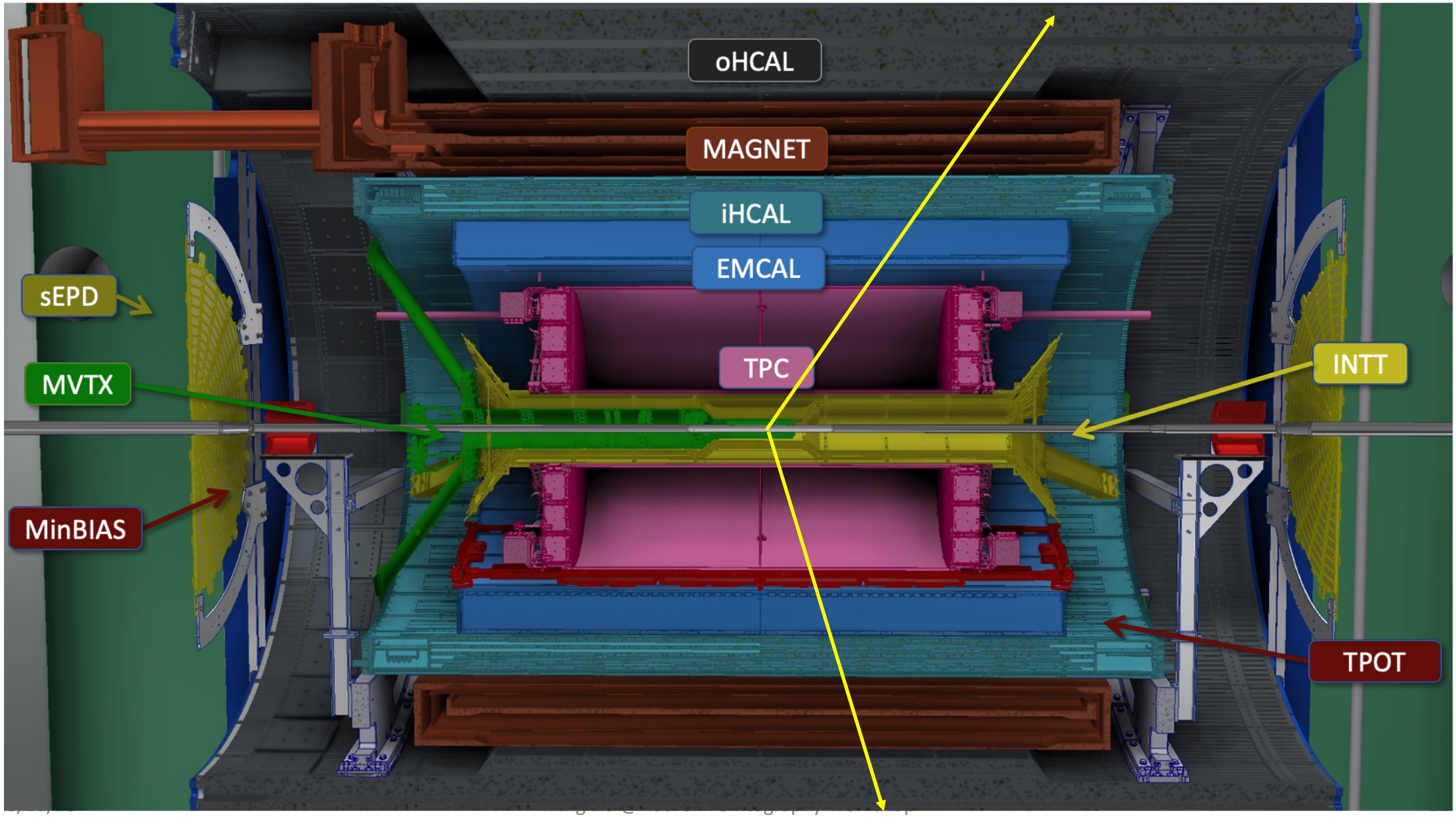
down to x_B=10^{-4}



$W_{\gamma N}^{max} = 34$ GeV
PHENIX: Au-Au – Phys. Lett. B **679** ('09) 321
CDF: p-$\bar{p}$ – Phys. Rev. Lett. **102** ('09) 242001
CMS, PbPb: Phys. Lett. B **772** ('17) 489
CMS, pPb: Eur. Phys. J. C **79** ('19) 277
ALICE: Pb-Pb – Eur. Phys. J. C **73** ('13) 2617; Phys. Lett. B **718** ('13) 1273; Phys. Lett. B **751** ('15) 358; Phys. Lett. B **798** ('19) 134926.
ALICE: p-Pb – Phys. Rev. Lett. **113** ('14) 232504; Eur. Phys. J. C **79** ('19) 402
LHCb: PbPb – CERN-LHCb-CONF-2018-003
$W_{\gamma p}^{max} = 1.5$ TeV
LHCb: pp – J. Phys. G: Nucl. Part. Phys. **40** ('13) 045001; **41** ('14) 055002; JHEP 1509 ('15) 084); JHEP10('18)167
down to x_B=10^{-6}

3

sPHENIX Detectors

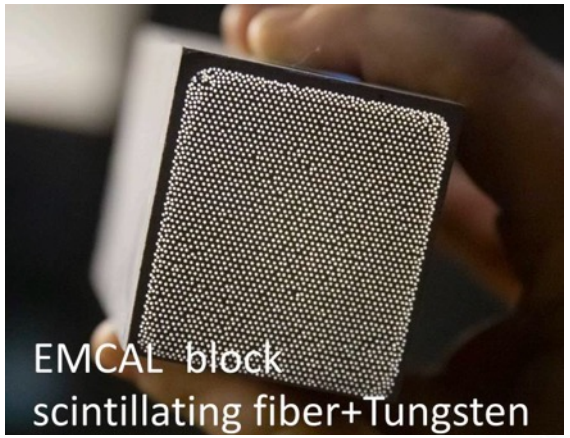


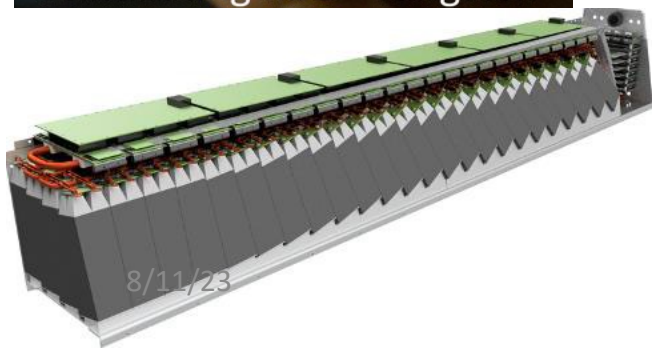
Calorimeters: EMCal, iHCal and oHCal

EMCal:
- SiFi in Tungsten powder
- SiPM readout, 4 SIPMs per tower, summed by one preAmp

$\Delta\eta \times \Delta\phi = 0.025 \times 0.025$

$\sigma_E/E = 5\% \oplus 16\%/\sqrt{E}$



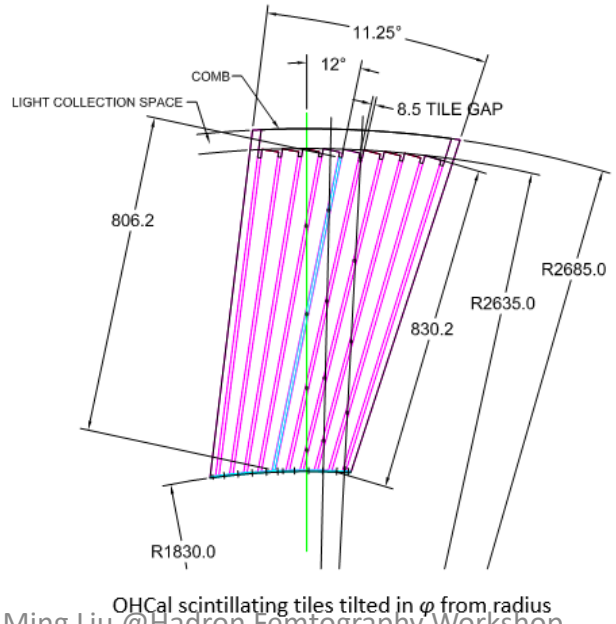


HCals:
- First mid-rapidity hadronic calorimeters at RHIC
- Al (iHCal) and steel (oHCal) absorber plates, scintillating tiles with embedded WLSF with SiPM readout

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

$\sigma_E/E \sim 14\% \oplus 81\%/\sqrt{E}$ for hadrons,

$\sigma_E/E \sim 11\% \oplus 31\%/\sqrt{E}$ for electrons.



OHCal scintillating tiles tilted in φ from radius

sPHENIX Tracking System

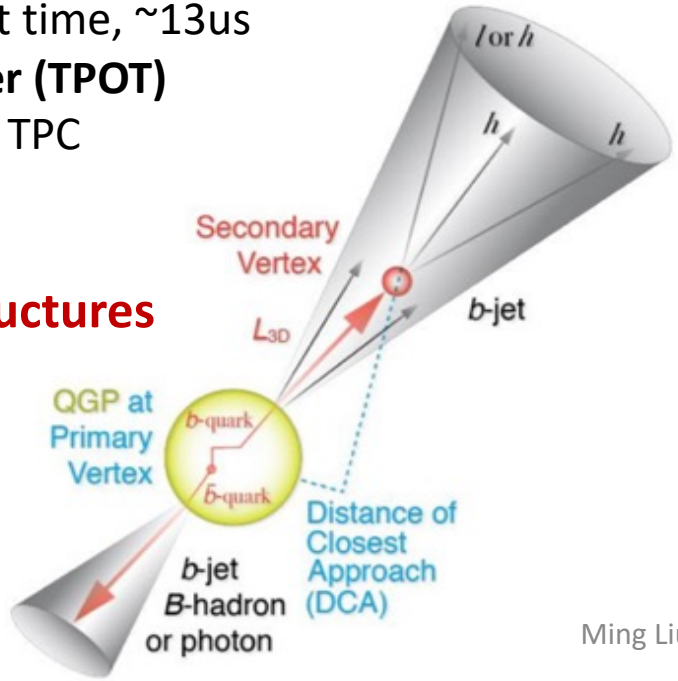
Silicon pixel detector (MVTX)
- 29 um x 27 um, pixels
- 2.5 cm < R < 4.5cm

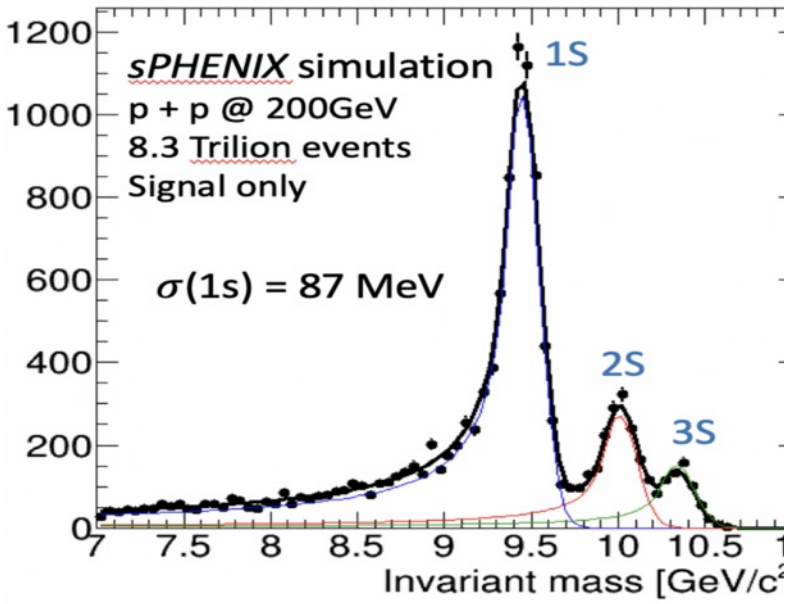
Silicon strip detector (INTT)
- 78um, strip sensors
- 7cm < R < 11cm

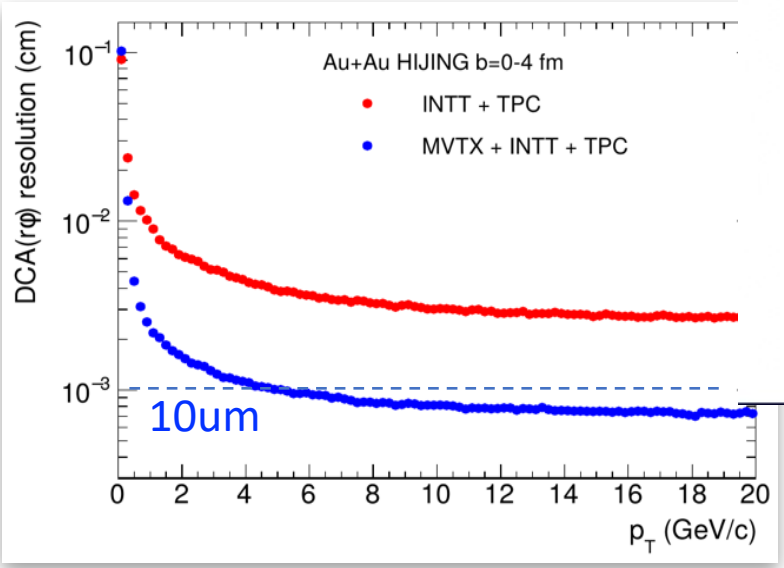
Time projection Chamber (TPC)
- 20cm < R < 78cm
- Spatial resolution, ~100um
- Long drift time, ~13us

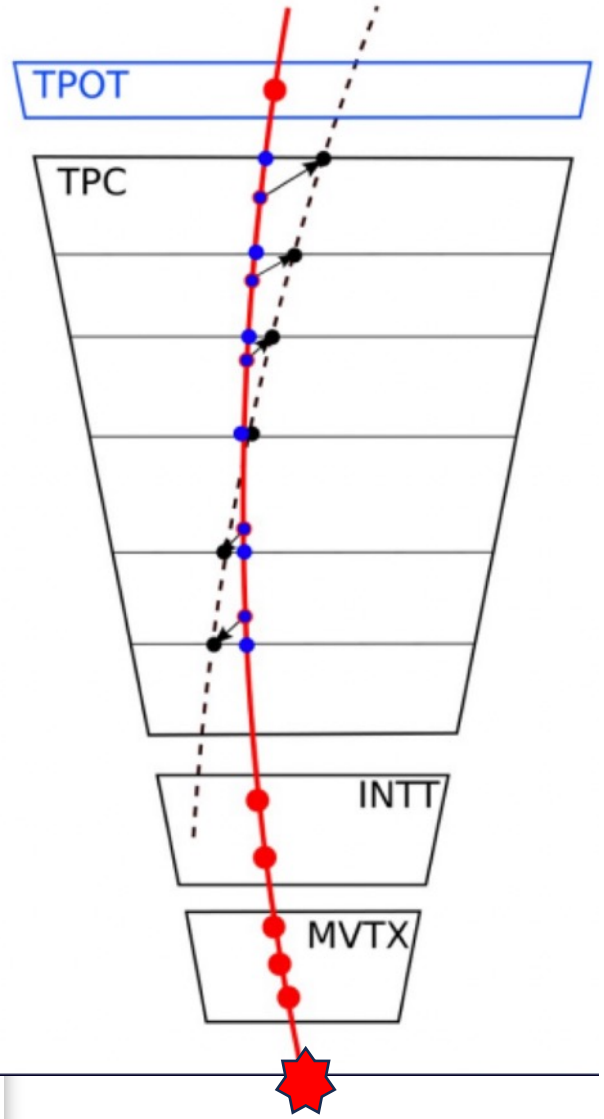
TPC Outer Tracker (TPOT)
- Calibrate TPC

Jet sub-structures







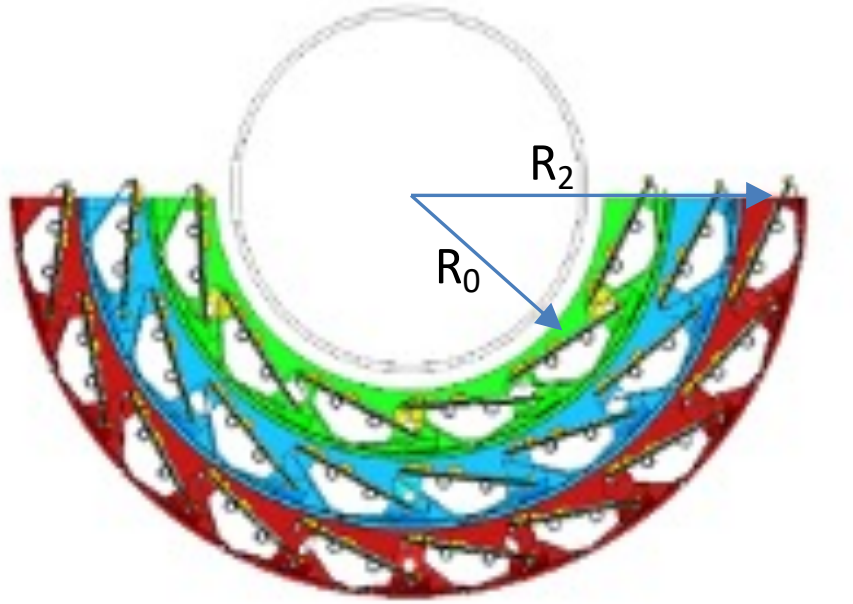


MVTX: State of the Art Silicon Pixel Detector

- **Inner most pixel detector**
  - Pixel size, 27 um x 29 um
  - Ultrathin, < 0.35% X_0
  - ~5um spatial resolution
- **Streaming readout**
  - Fast, ~5us integration time
  - **AI/ML smart HF trigger possible (on-going R&D)**

3 layers with full azimuth coverage

R (mm)	min	mid	max
Layer 0	24.61	25.23	27.93
Layer 1	31.98	33.35	36.25
Layer 2	39.93	41.48	44.26



sPHENIX Detector Installation Timeline

2021

10/2021, Magnet

03/2022, OHCal

2022

06/2022, IHCal

12/2022, EMCal

12/2022, TPOT

01/2023, TPC

03/2023, INTT

2023

03/2023, MVTX

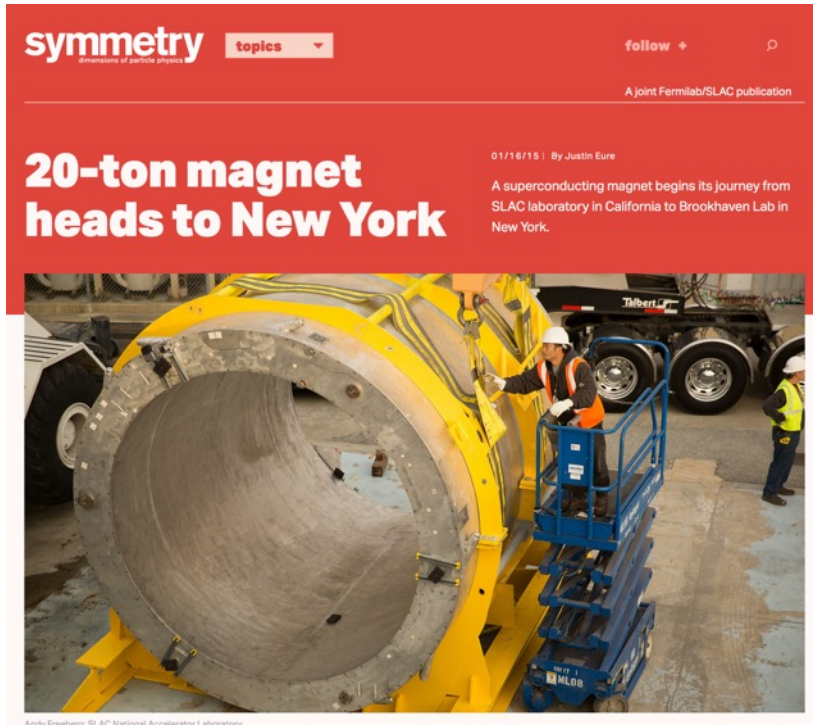
04/2023, MBD

5/18/2023, start commissioning

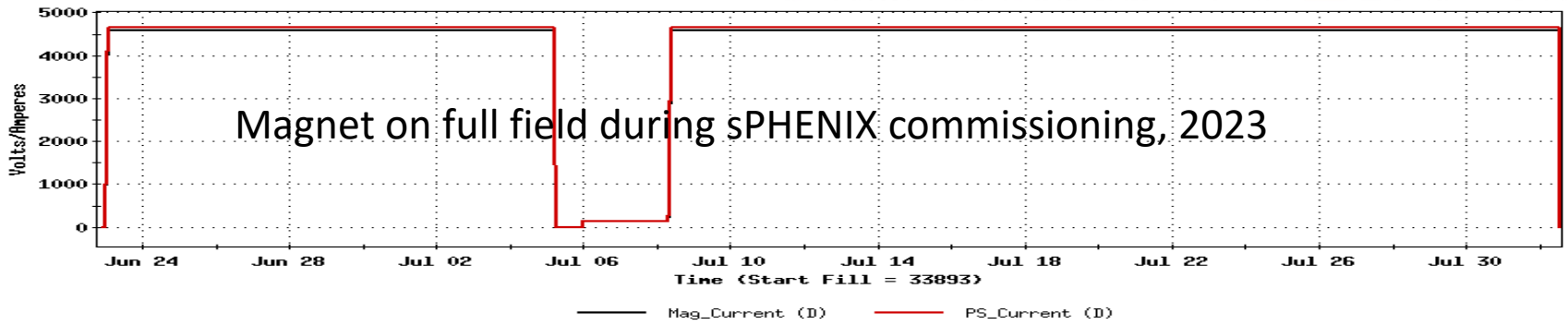
July 2023, sEPD

Today, 8/11/2023

Jan. 2015



Oct. 2021



Magnet on full field during sPHENIX commissioning, 2023

2021

10/2021, Magnet

03/2022, OHCal

2022

06/2022, IHCal

12/2022, EMCal

12/2022, TPOT

2023

01/2023, TPC

03/2023, INTT

03/2023, MVTX

04/2023, MBD

5/18/2023, start commissioning

July 2023, sEPD

Today, 8/11/2023

2021

10/2021, Magnet

03/2022, OHCal

2022

06/2022, IHCal

12/2022, EMCal

12/2022, TPOT

01/2023, TPC

03/2023, INTT

2023

03/2023, MVTX

04/2023, MBD

5/18/2023, start commis

July 2023, sEPD

Today, 8/11/2023

EMCal installed 12/2022

2021

10/2021, Magnet

03/2022, OHCal

2022

06/2022, IHCal

12/2022, EMCal

12/2022, TPOT

01/2023, TPC

03/2023, INTT

2023

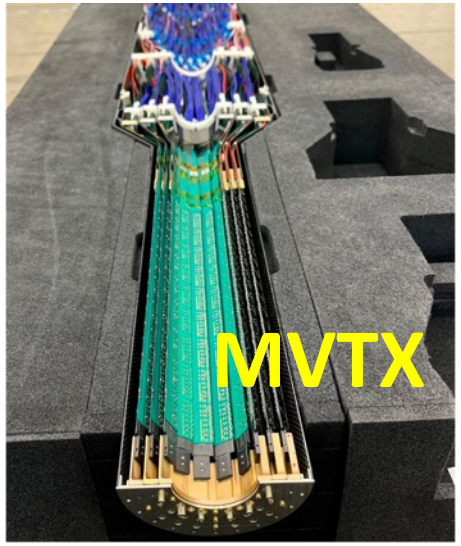
03/2023, MVTX

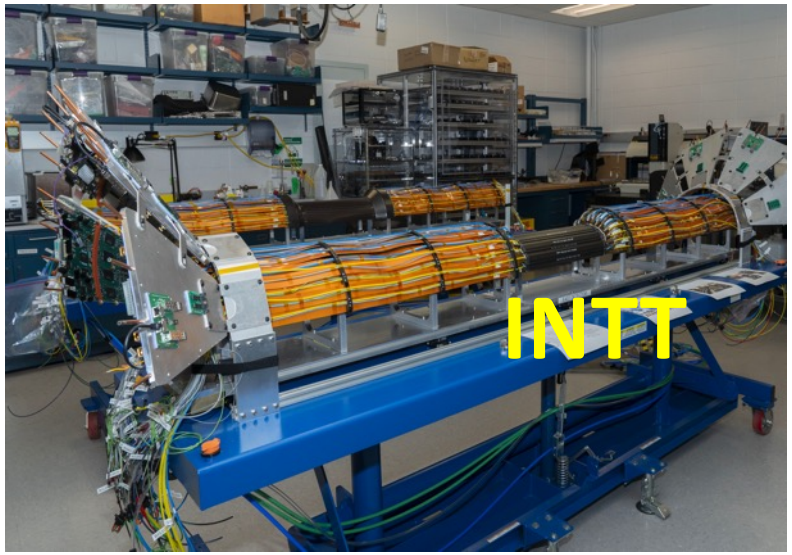
04/2023, MBD

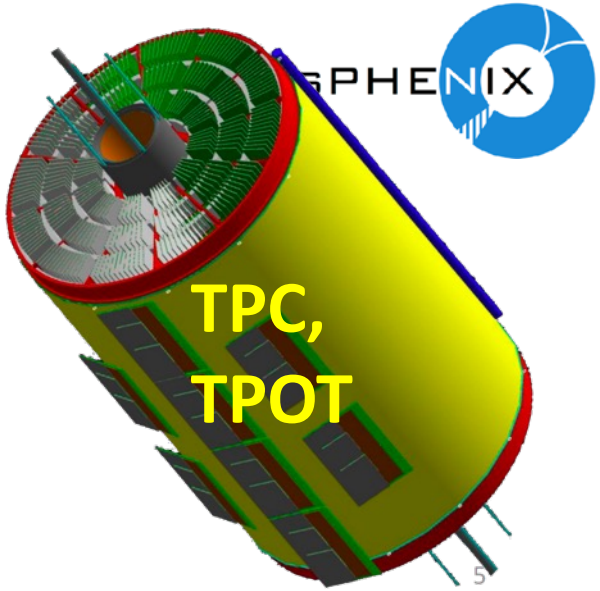
5/18/2023, start commissioning

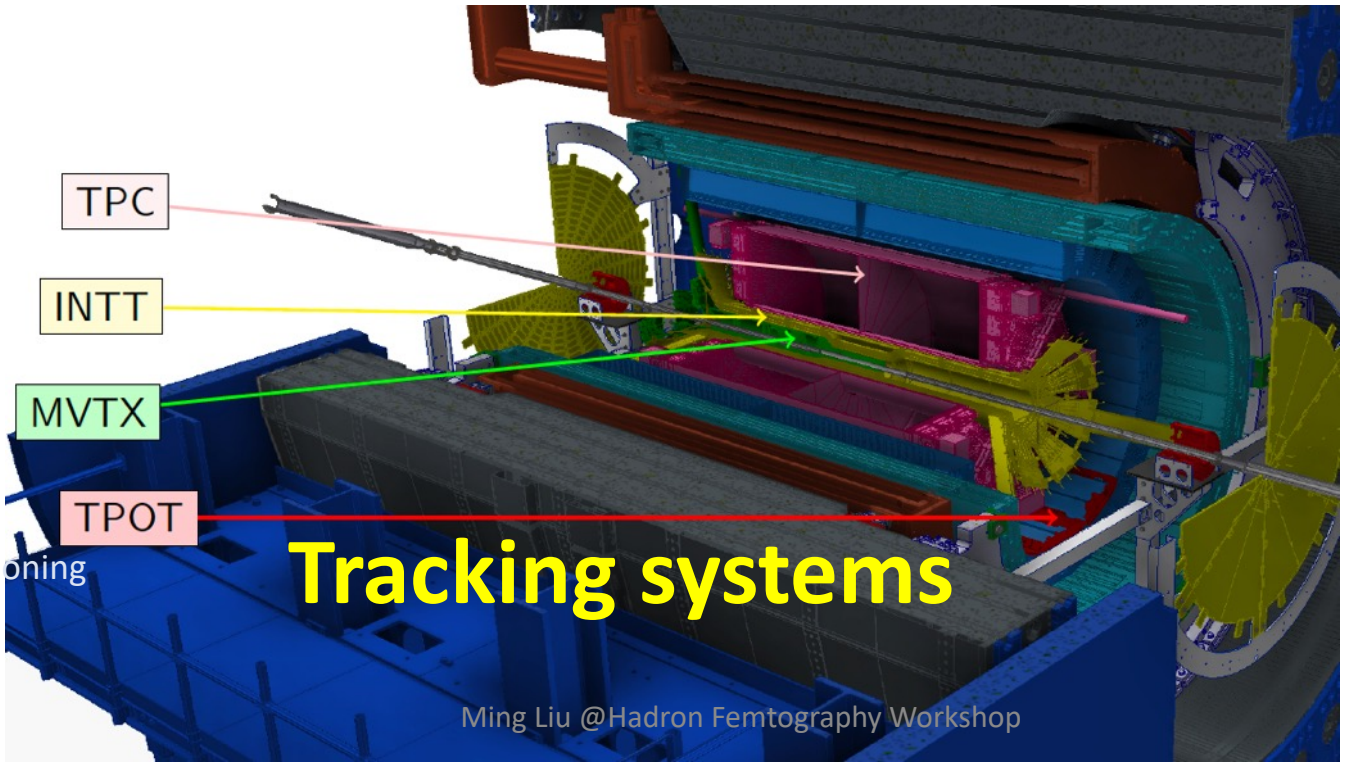
July 2023, sEPD

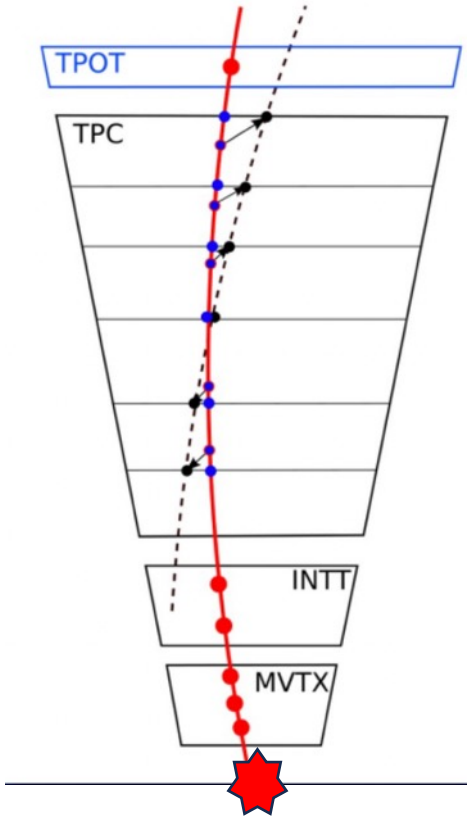
Today, 8/11/2023











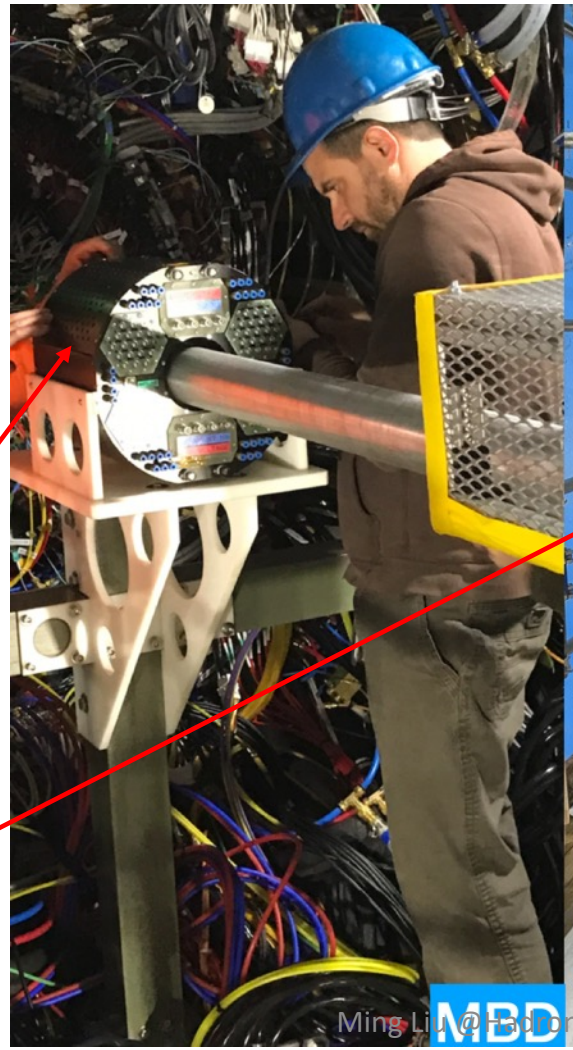
Other Trigger and Event Plane Detectors

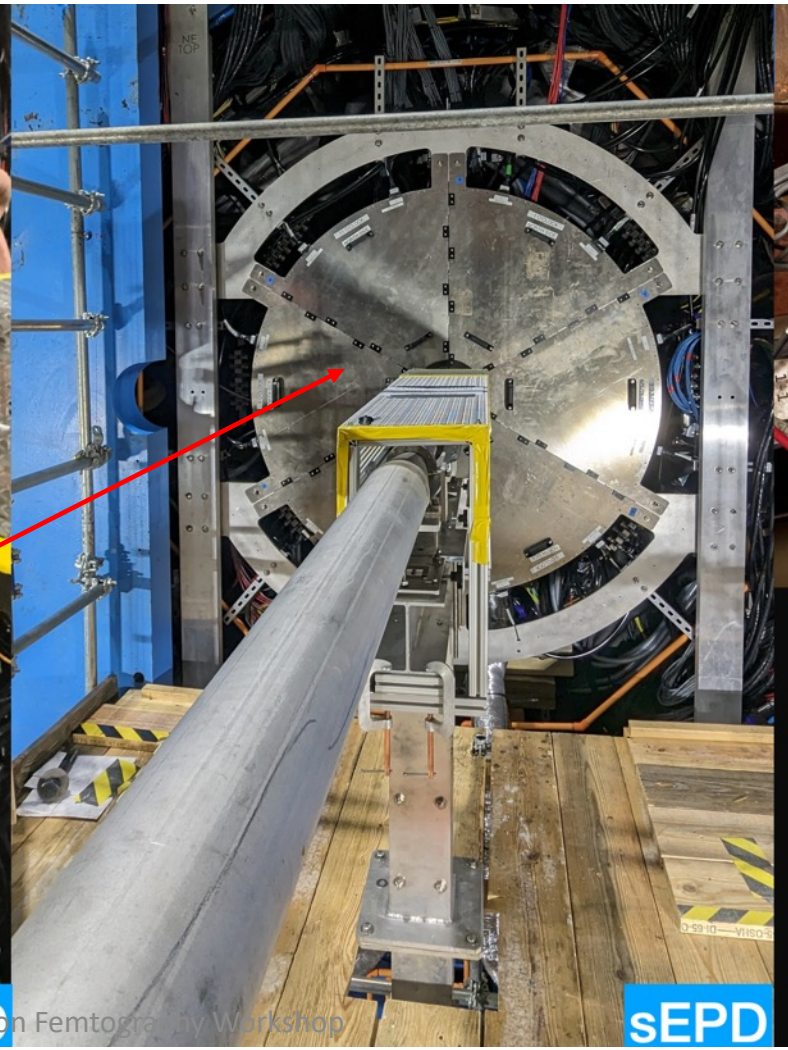
2021
- 10/2021, Magnet

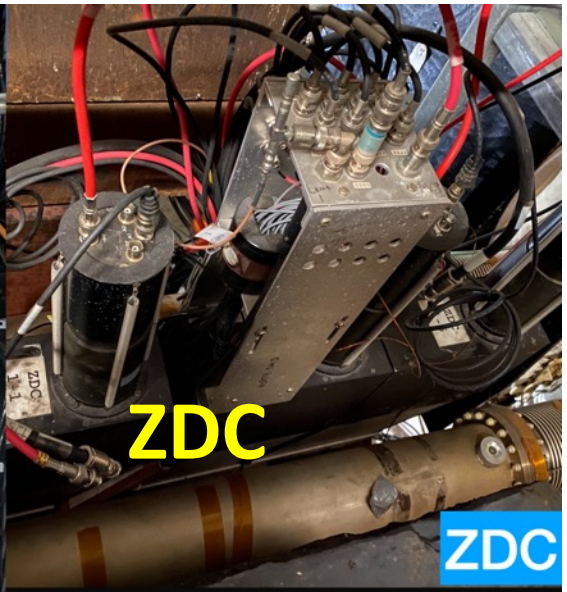
2022
- 03/2022, OHCal
- 06/2022, IHCal
- 12/2022, EMCal
- 12/2022, TPOT

2023
- 01/2023, TPC
- 03/2023, INTT
- 03/2023, MVTX
- 04/2023, MBD
- **5/18/2023, start commissioning**
- July 2023, sEPD

Today, 8/11/2023



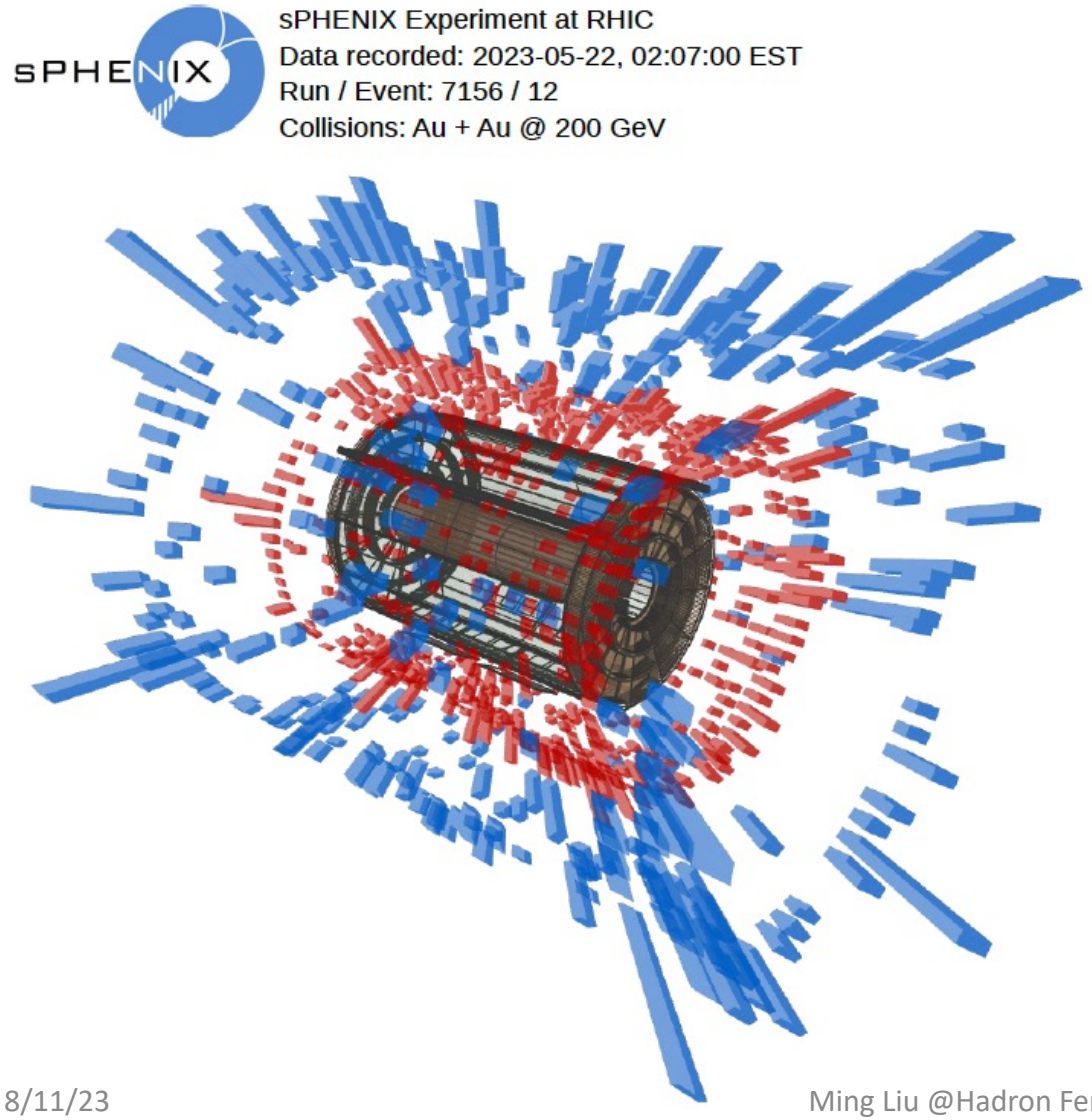




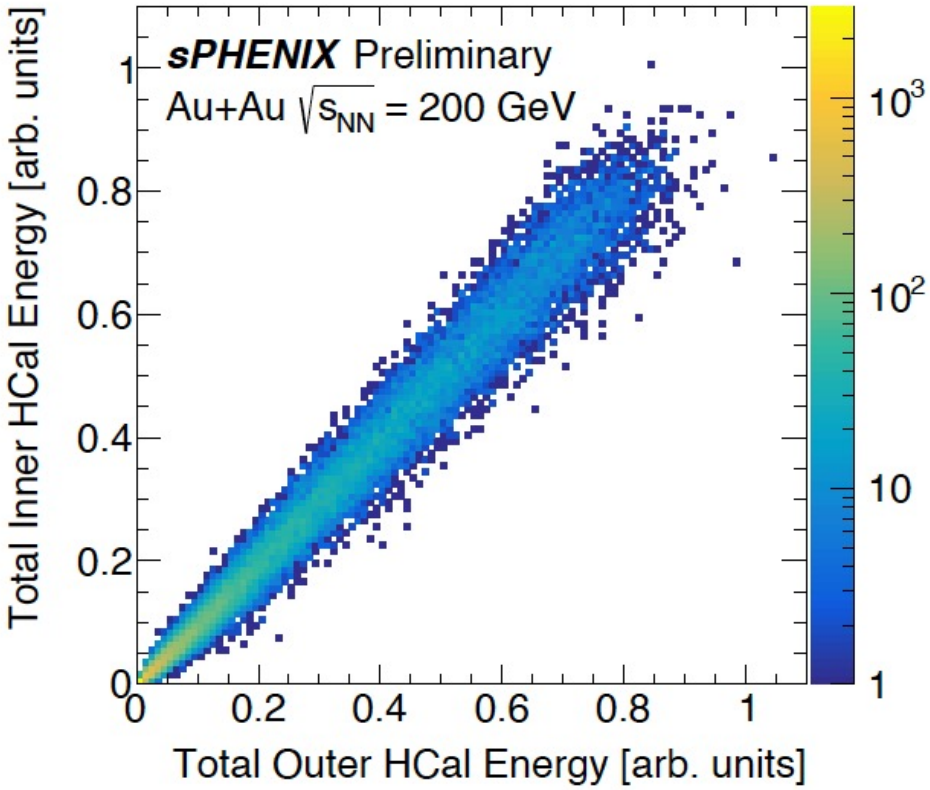
MBD: $3.5 < |\eta| < 4.6$
sEPD: $2.0 < |\eta| < 4.9$

ZDC: +/- 2 mrad
@Z = +/-18m

First Data from Commissioning: Au+Au Collisions

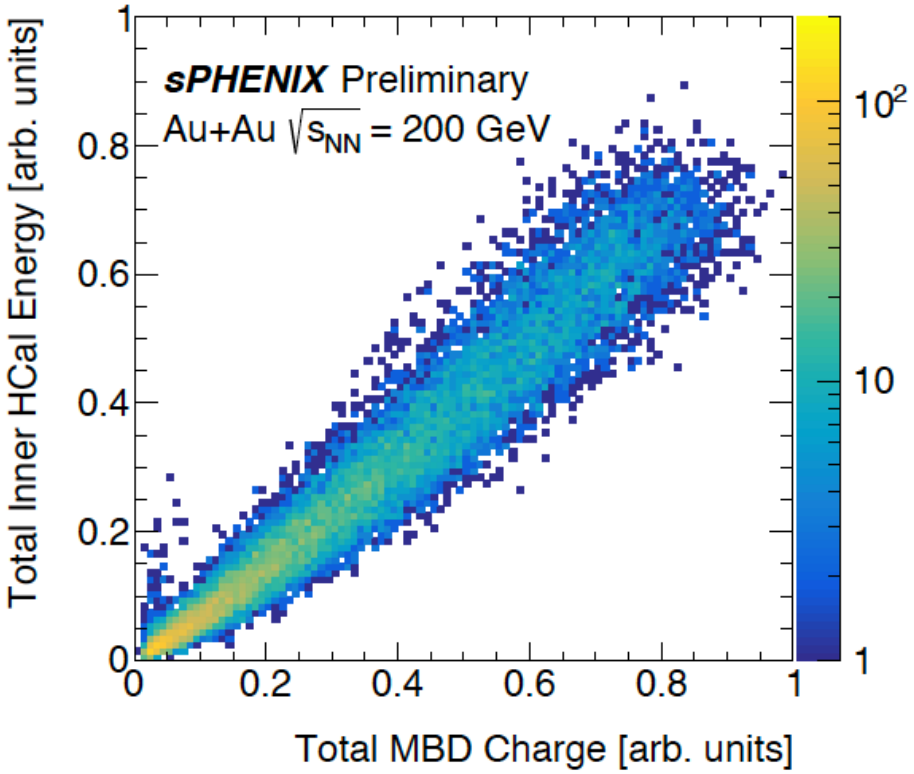


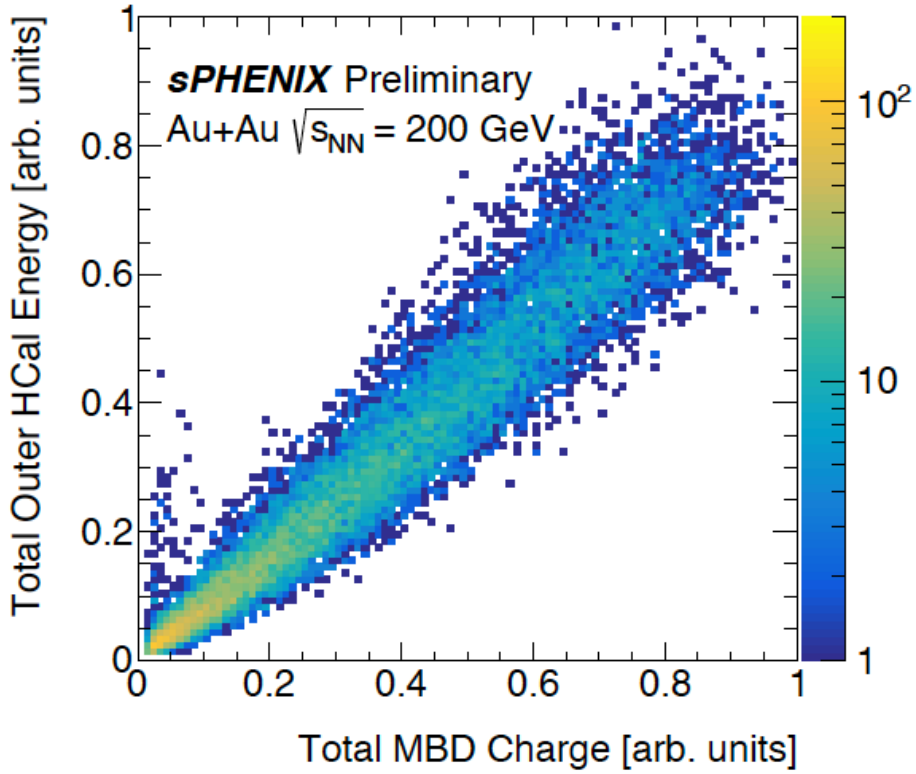
Correlation of inner and outer HCal



First Data from Commissioning: HCal and MBD

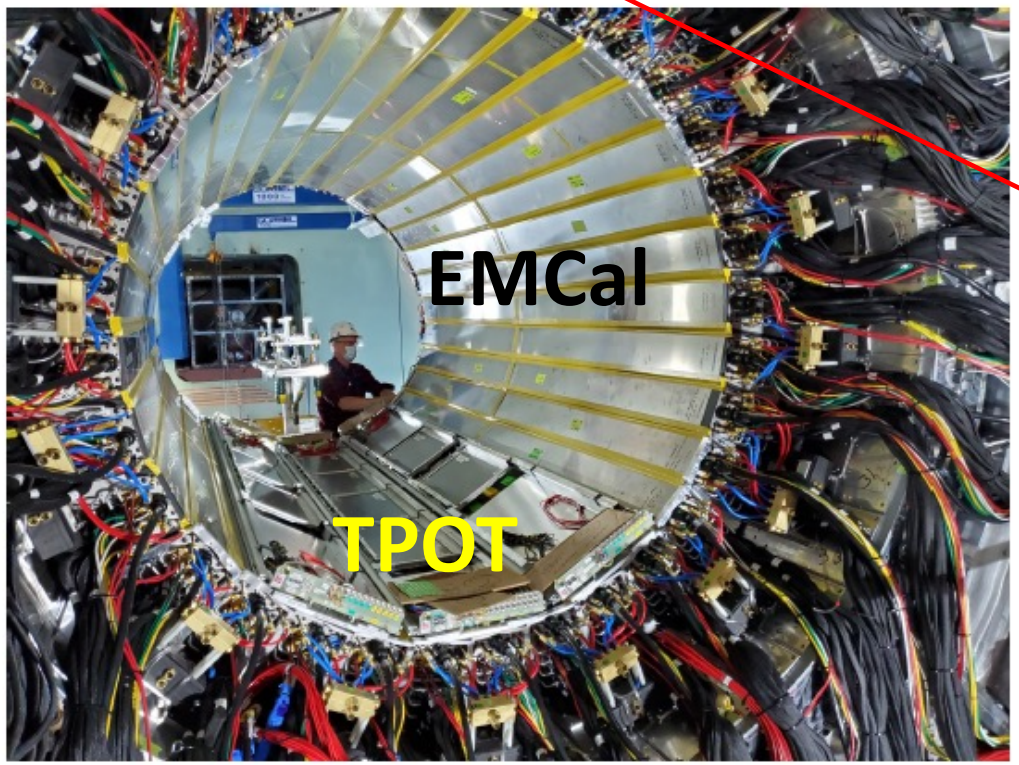
- Hit correlation of Hadronic calorimeters at mid-rapidity with MBD at the forward rapidity
- 99% of HCal channels live

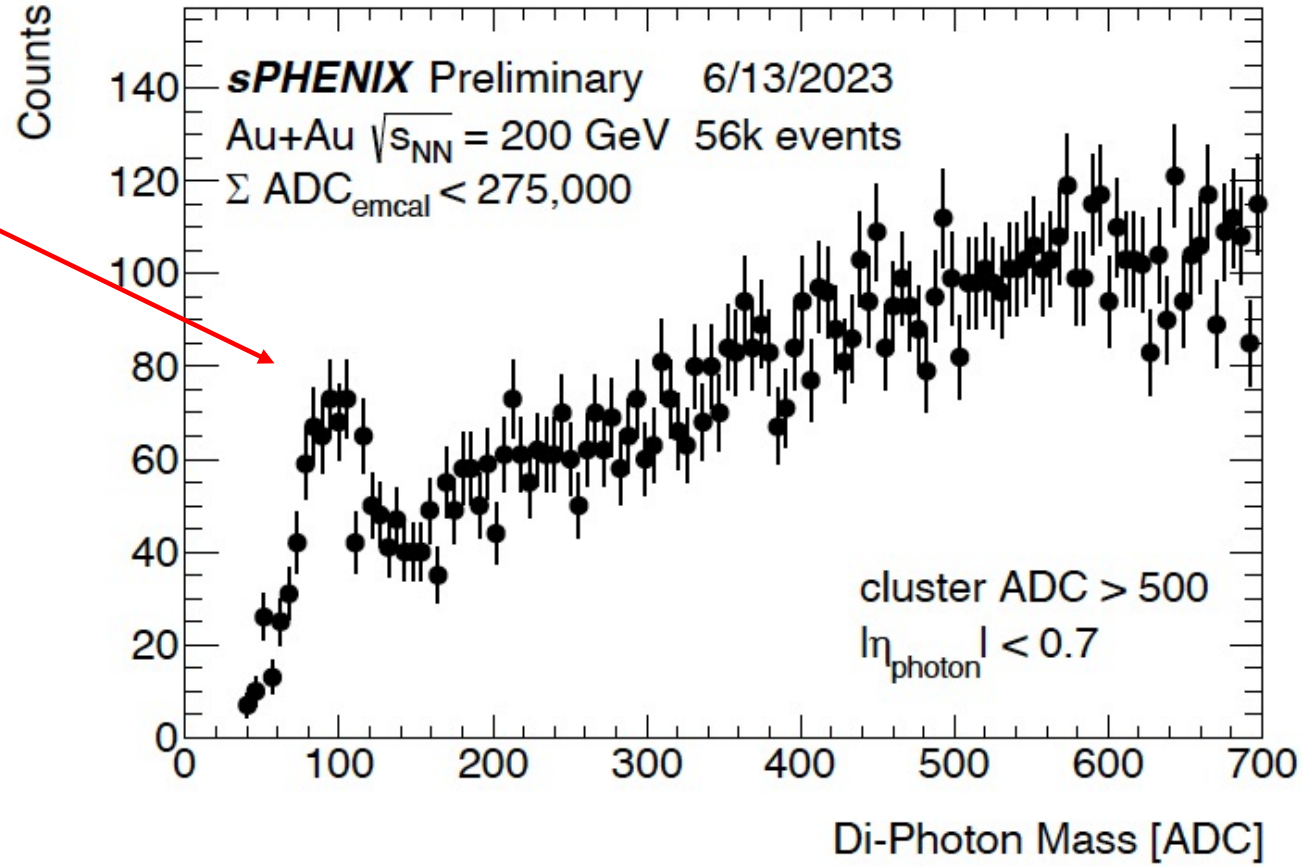




First Data from Commissioning: EMCal

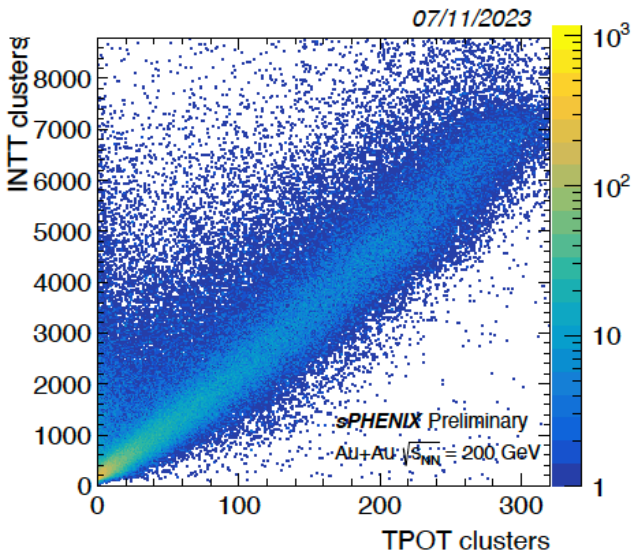
- Clear pi0 peak seen in the di-photon invariant mass spectrum

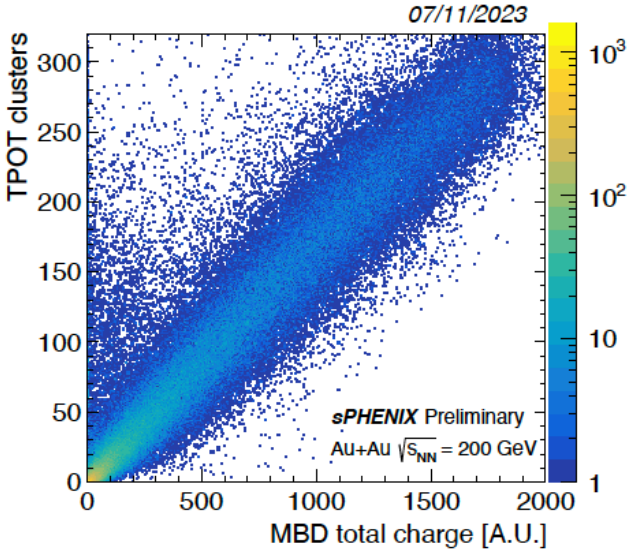


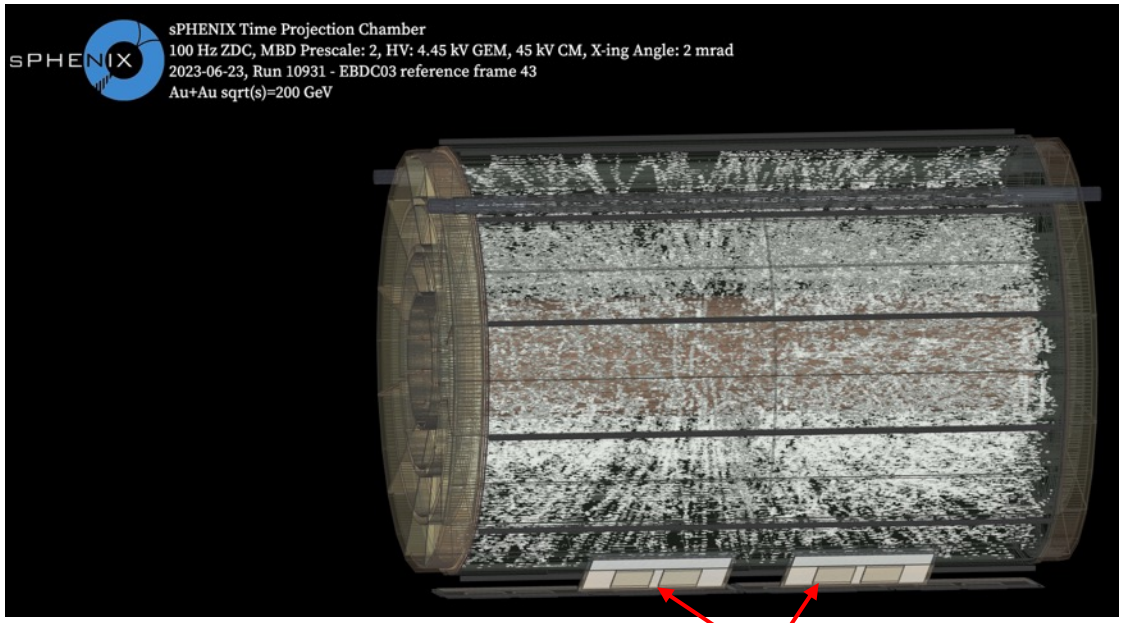


First Data from Commissioning: TPC and TPOT

- Hit correlation: TPOT vs INTT and MBD
- TPC event display of one AuAu collision



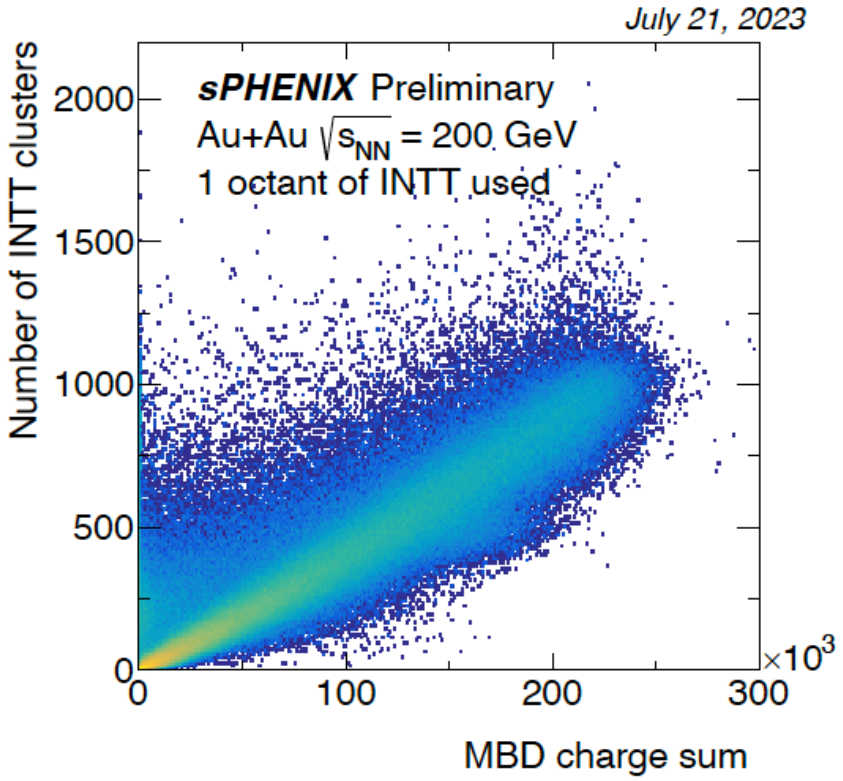


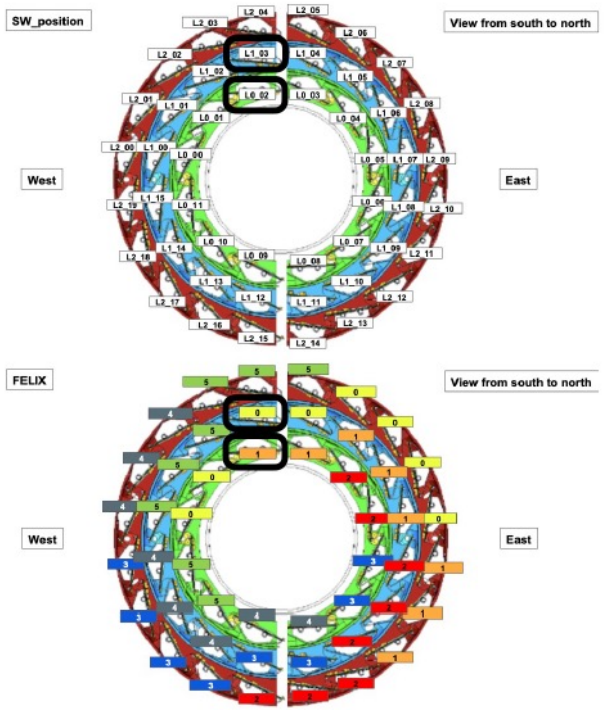


First Data from Commissioning: INTT and MVTX

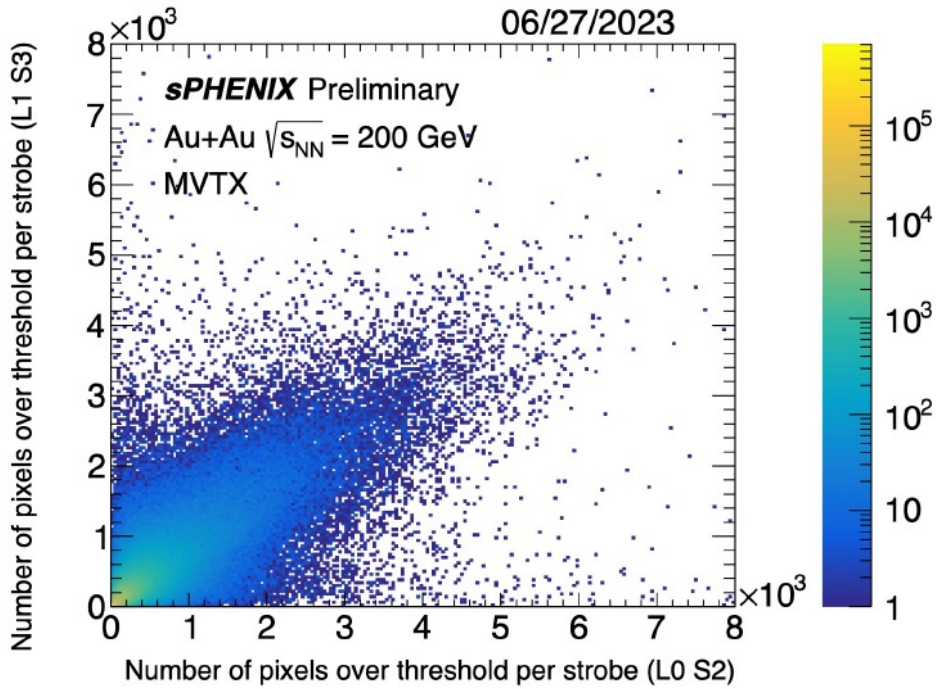
- Hit correlation: INTT and MBD
- MVTX hit correlation

INTT



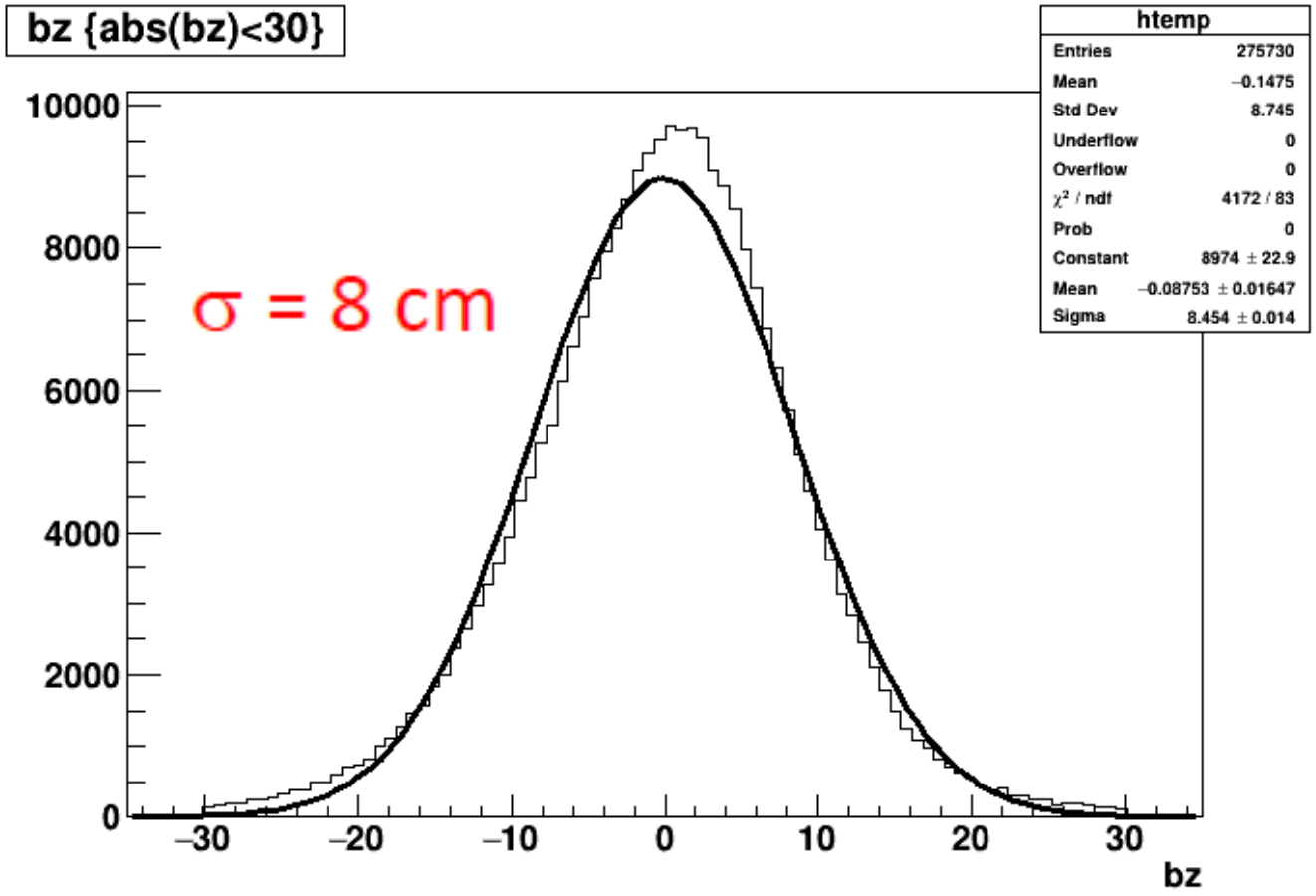


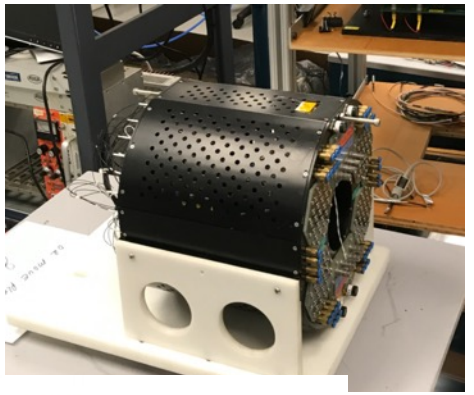
MVTX

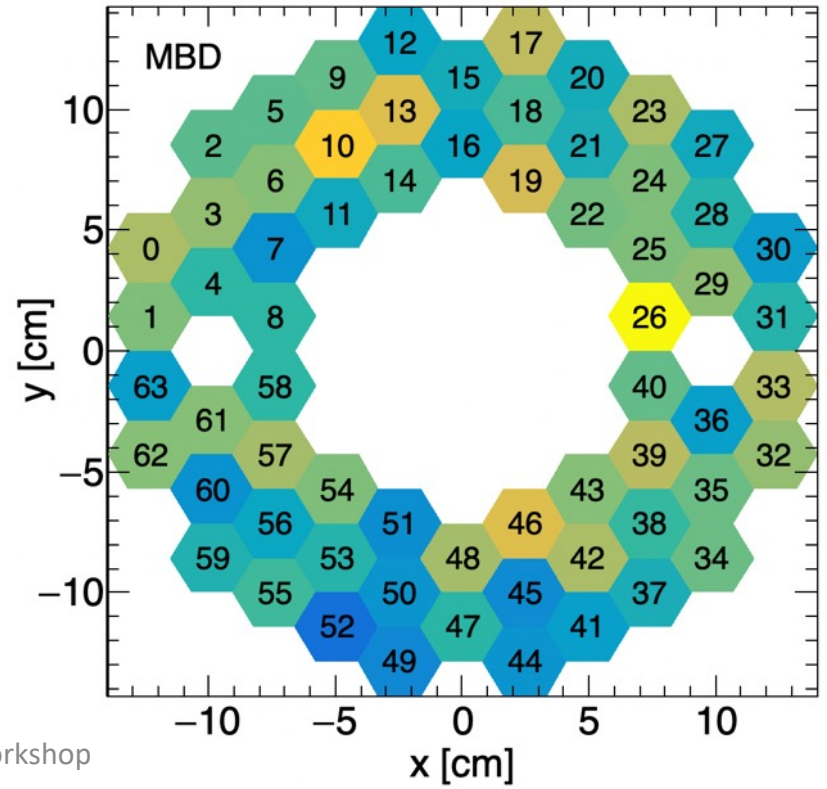


First Data from Commissioning: MBD

- **2 mrad beam crossing angle commissioned**
- Narrow event collision Z-vertex distribution







2023 Commissioning Data Taking Ended Abruptly due to Hardware Failures in RHIC Accelerator Complex

- sPHENIX continues active detector commissioning w/o beams

From BNL ALD Haiyan Gao
08/04/2023

Dear colleagues:

I am writing to update you on our plan regarding the repair of the RHIC building 1004B valve box and the plan for Run 2023.

Since my last email, we have learned that the repair will be significantly more involved than what previously we had hoped for a more optimistic scenario. The damage is more extensive than just a weld as there are multiple shorted Blue circuits, and all are in the same cryo line. The expected access to the valve box will be next Friday, August 11th. The estimate for the repair is 4 weeks or more following that. Given where we are in the calendar, it is therefore prudent that we end Run 2023 and start controlled warm-up now. This plan allows sPHENIX magnet to be cold until at least the end of next week and please work with CAD colleagues on this.

We did not come to this decision lightly and the Laboratory Director, JoAnne Hewett has been in multiple meetings concerning this plan in the last few days. We have also consulted the DOE Office of Nuclear Physics (ONP) and have their strong support for this plan. This will allow us to start the repair and the planned shutdown process so that we can start earlier with Run 2024 next year. We received the agreement from the DOE ONP to carry forward unspent FY23 funds for an expanded next year's RHIC running.

I would like to thank you all again for all the great work you have been doing and will continue to do. Our collective hard work and perseverance will prevail. Thank you also very much for your understanding.

Best wishes, Haiyan

Summary and Outlook

- **sPHENIX, the first state-of-the-art jet detector at RHIC**
  - QGP and Cold-QCD physics
  - Jets and HF probes for precision measurements

- **Excellent progress in sPHENIX detector commissioning with beams**
  - Continue commissioning without beam till early October

- **Great opportunity for Cold-QCD with new capabilities at RHIC**
  - Gluon TMD
  - Quark transversity
  - Collings FF
  - and more, UPC … hard processes for hadron femtography?

Backup slides ..

HF Trigger Challenge in p+p

– tag rare events in real time in high-rate collisions

sPHENIX experiment at RHIC: 2023 – 2025+

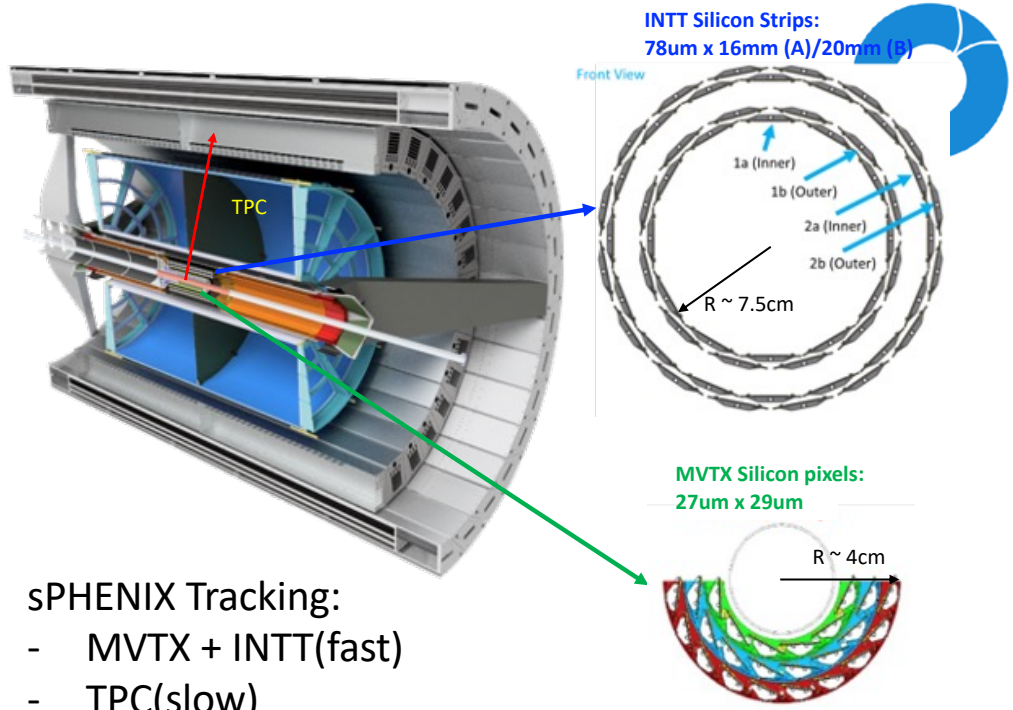
- Very high p+p collision rate: ~3MHz
  - Rare Beauty production rate: ~150Hz (or 0.005% MB)
- Limited DAQ bandwidth
  - 15 kHz (or 0.5% of p+p collisions)
- No effective conventional triggers available
- Streaming readout (SRO) -> huge data volume, high cost

Our approach:

Develop effective HF triggers for p+p with SRO and AI

- Streaming readout key detectors for high efficiency
- ML-trained algorithm for HF event selection
- AI-based beam/detector monitoring and autonomous feedback & control

Supported by a separate DOE AI/ML FOA project

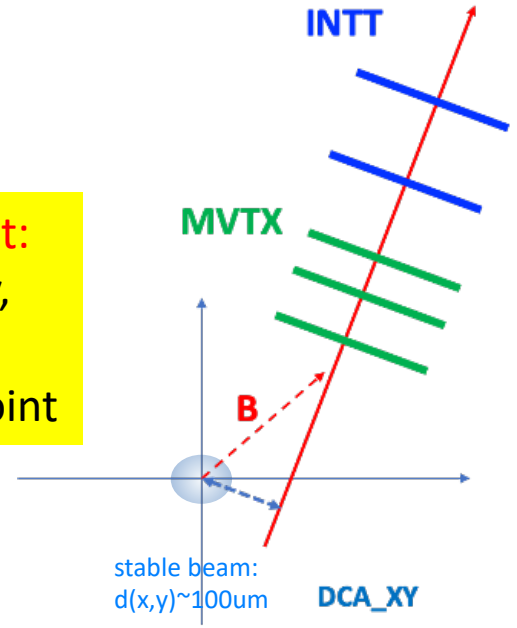


sPHENIX Tracking:

- MVTX + INTT(fast)
- TPC(slow)

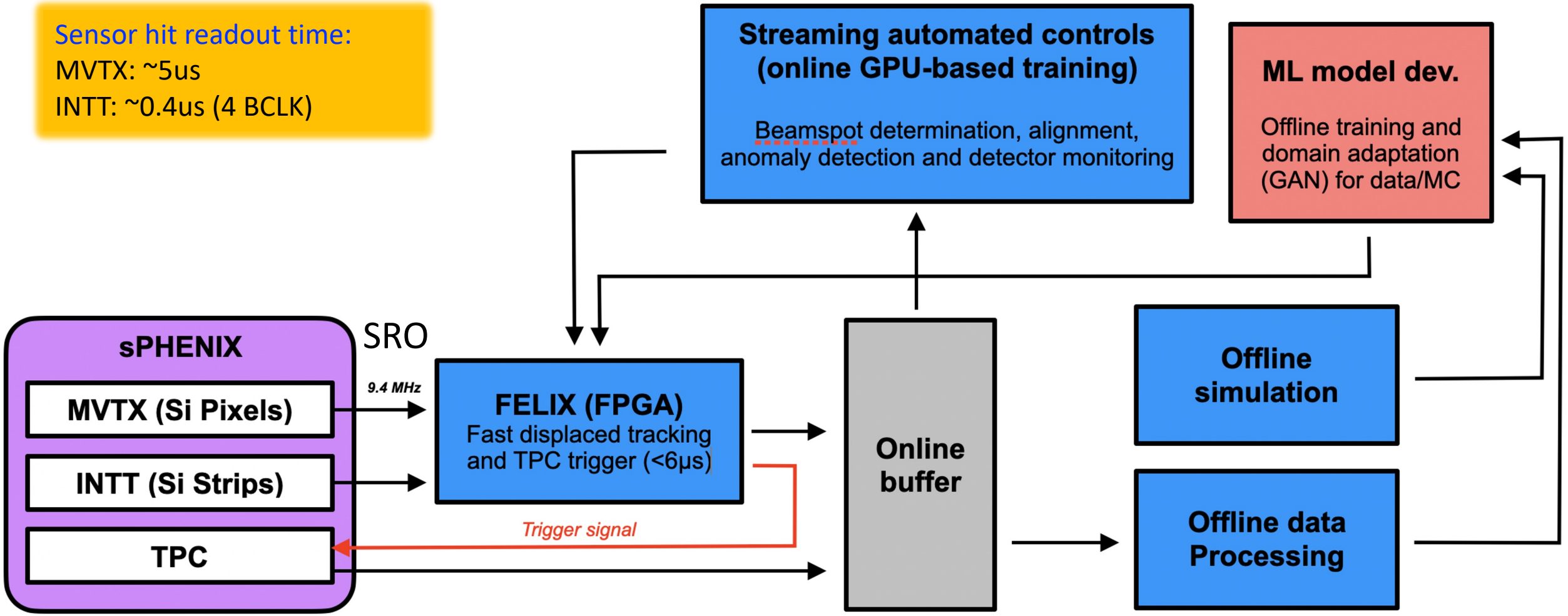
Identify B-hadron event:

- Topology of B decay, with large DCA
- Monitor collision point



HF AI Trigger: sPHENIX as a Test Ground

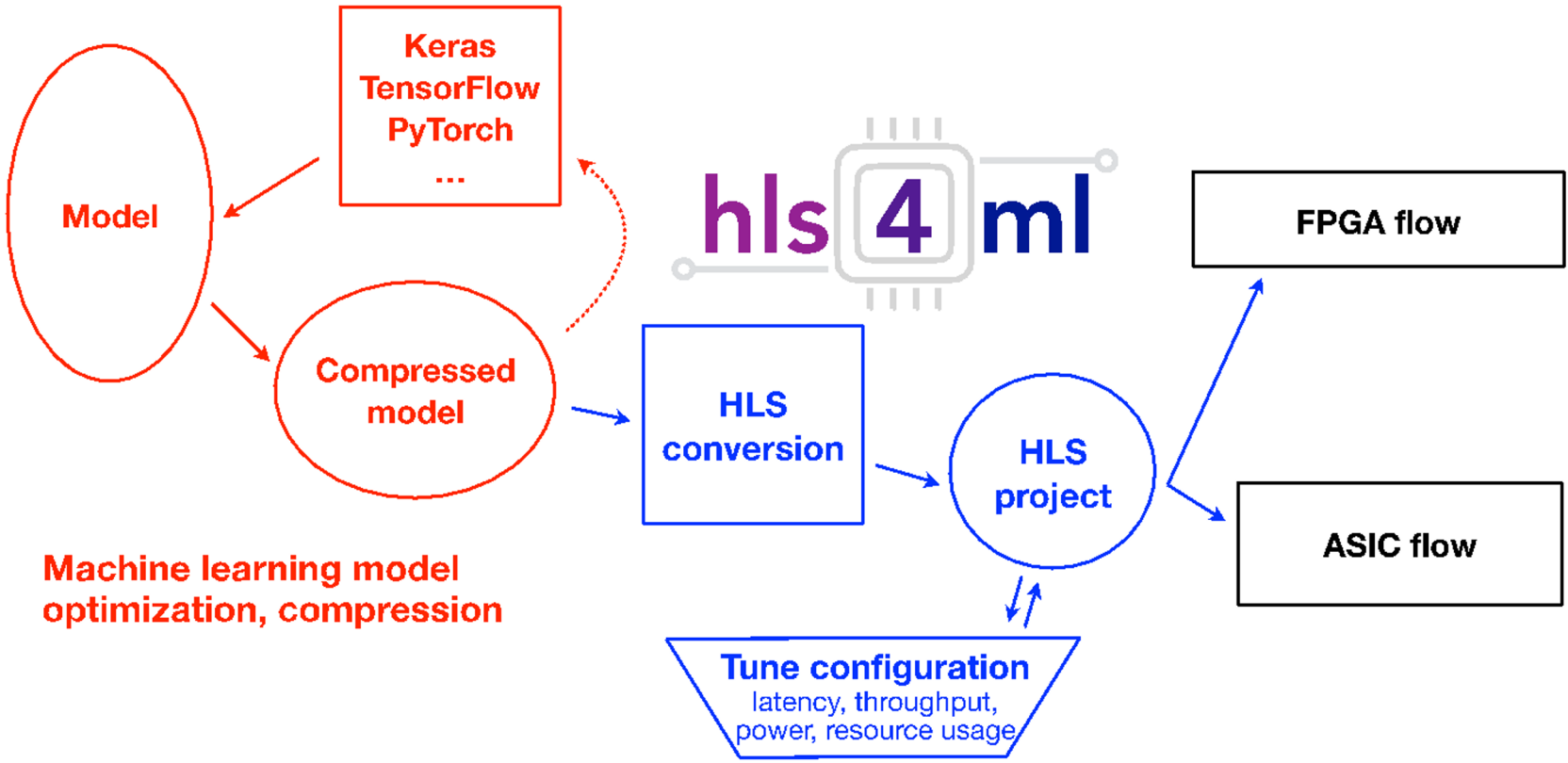
Sensor hit readout time:
MVTX: ~5us
INTT: ~0.4us (4 BCLK)



sPHENIX DAQ & Trigger integration

Translating Models into FPGA Firmware

- Algorithms must have low latency and resource usage
- **hls4ml** translates NN algorithms into high level synthesis
- Also generates IP cores for easy implementation



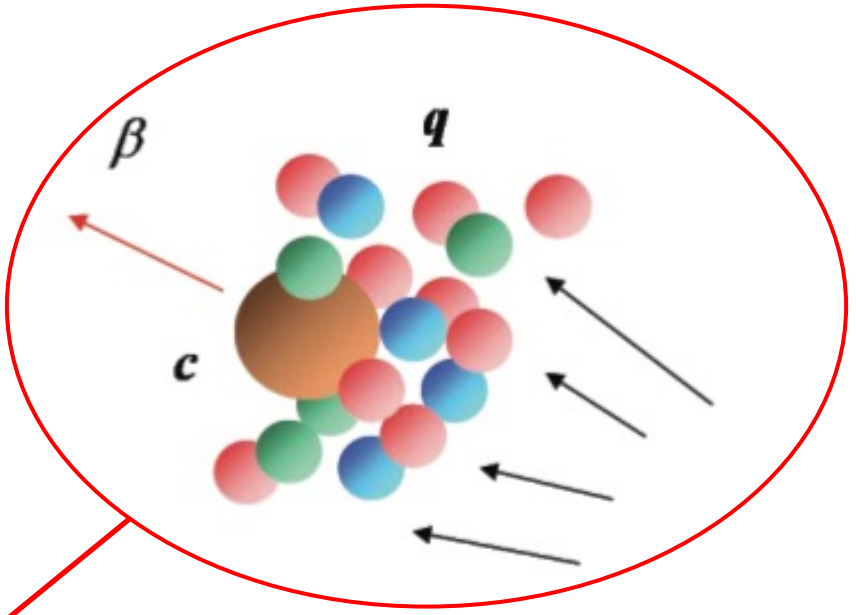
Red – typical ML algorithm development stages, Python/C++

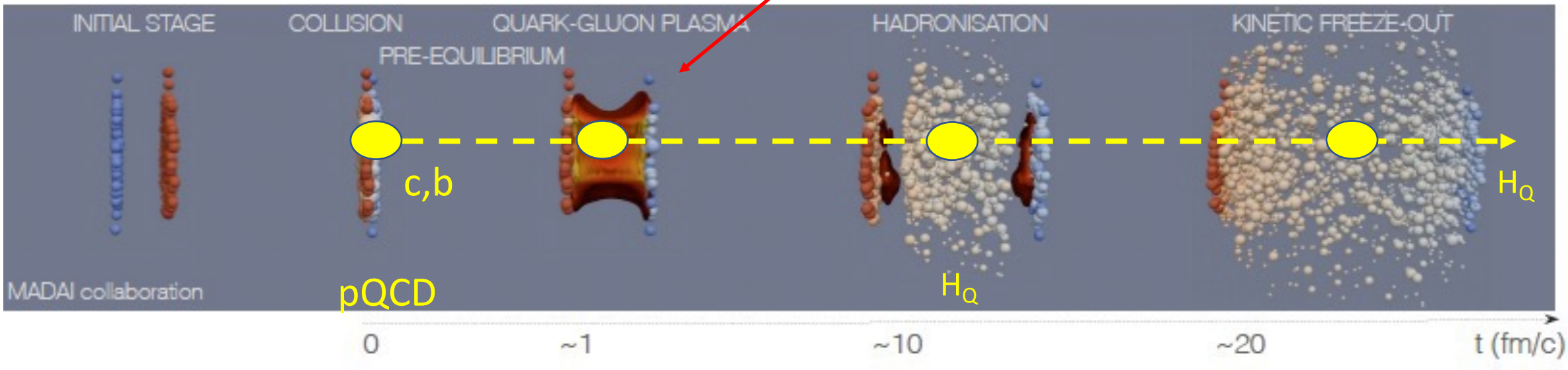
Blue – HLS conversion to FPGA IP

Black – typical implementation onto chips

Heavy Quark (HQ) to Probe QGP

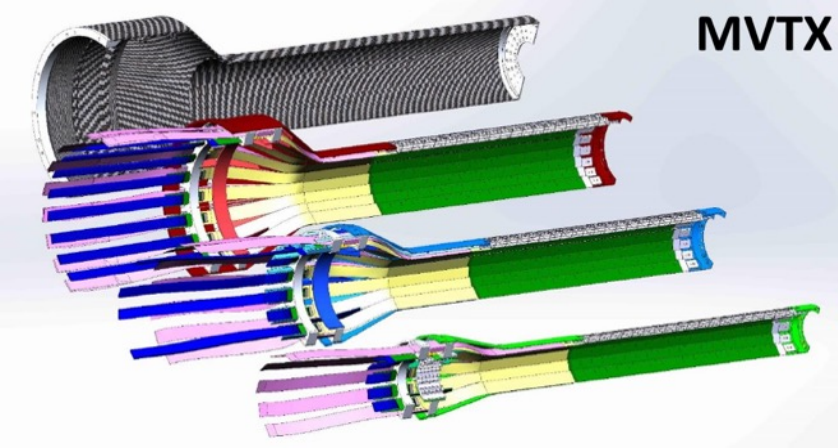
- **Quark diffusion in QGP: v_2**
  - ➢Flow, medium interactions
- **Quark energy loss in QGP: R_{AA}**
  - ➢Collisional vs radiative
  - ➢Mass dependence





Open HF Tagging with MVTX

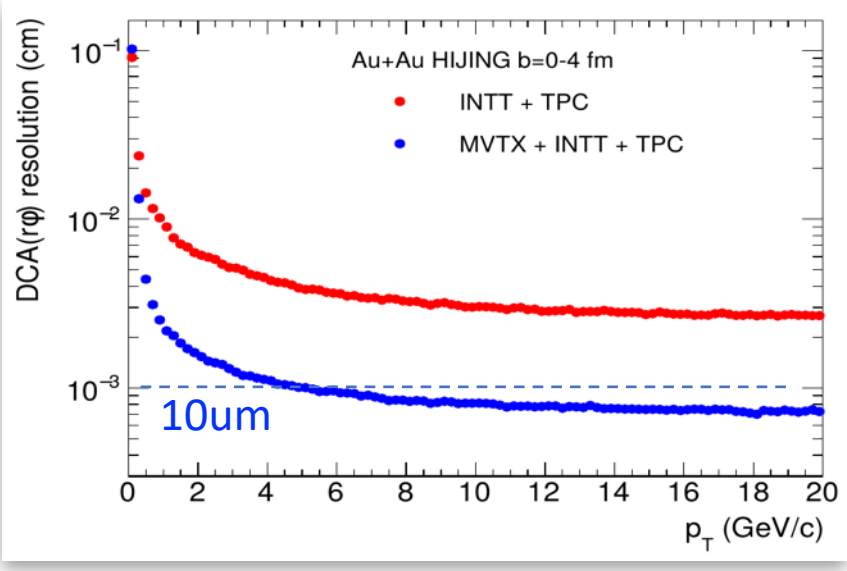
- Monolithic-active-pixel-sensor based VerTeX detector

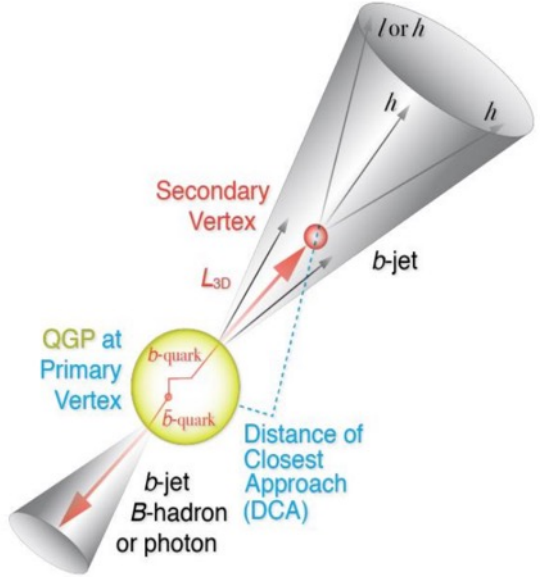


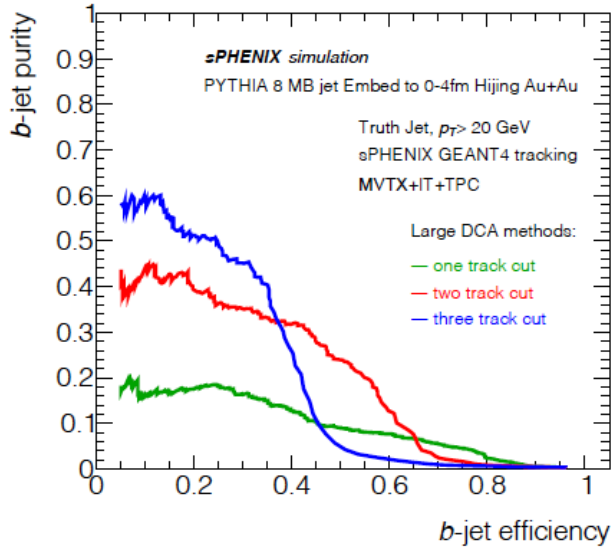
MVTX key parameters: (ALPIDE)

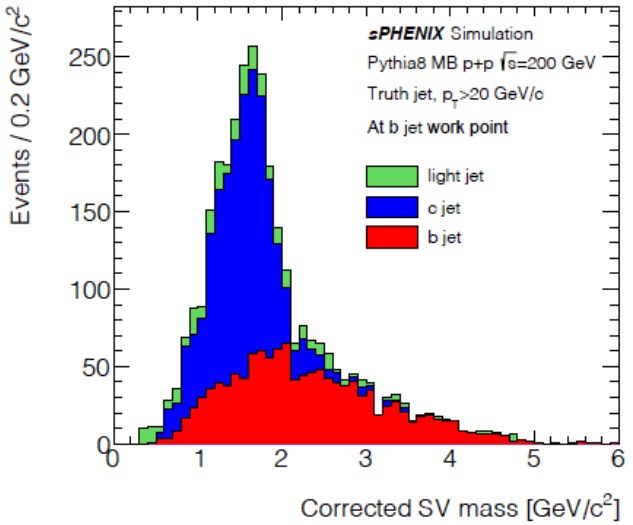
- pixel size: **27um x 29 um**
- ultra-thin stave: **0.35%X_0**
- Integration time: **~5us**

- Multi-tracks w/ large DCA
- 2nd vertex mass
- Exclusive hadron reconstruction





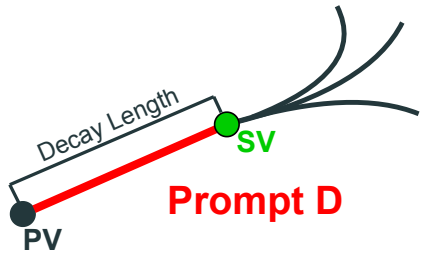


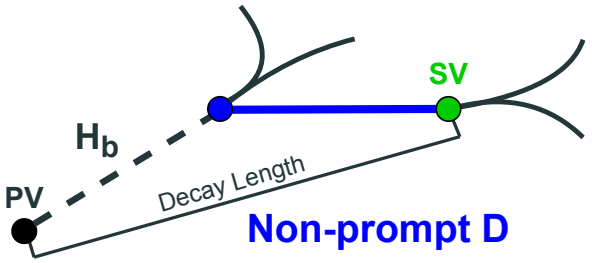


Work in Progress: from Full Monte Carlo Simulations

PYTHIA 8 p+p with full detector GEANT sim + reco

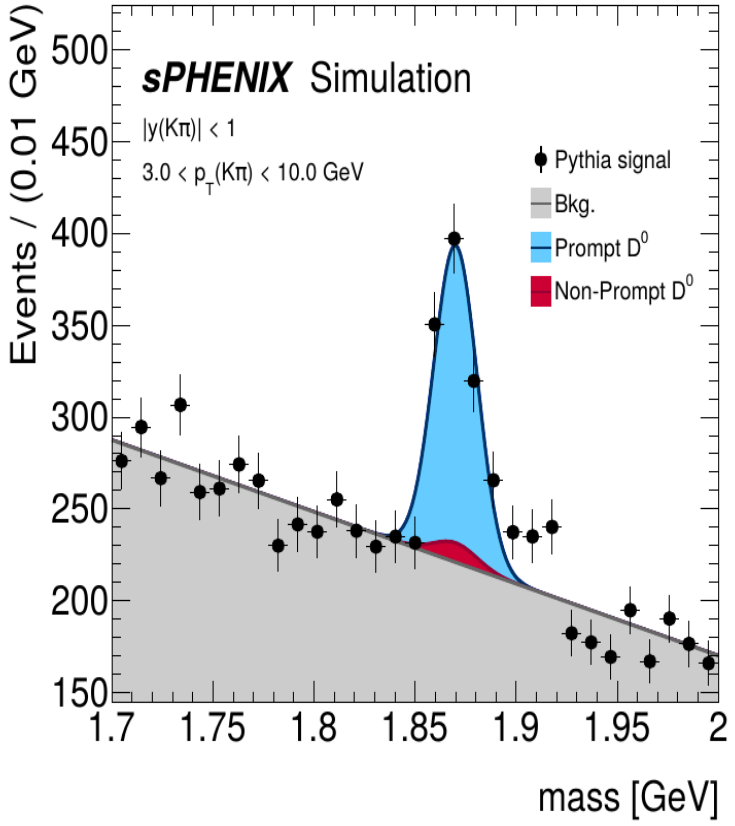
$$p + p \to D^0 + X \to (K^- \pi^+) + X$$

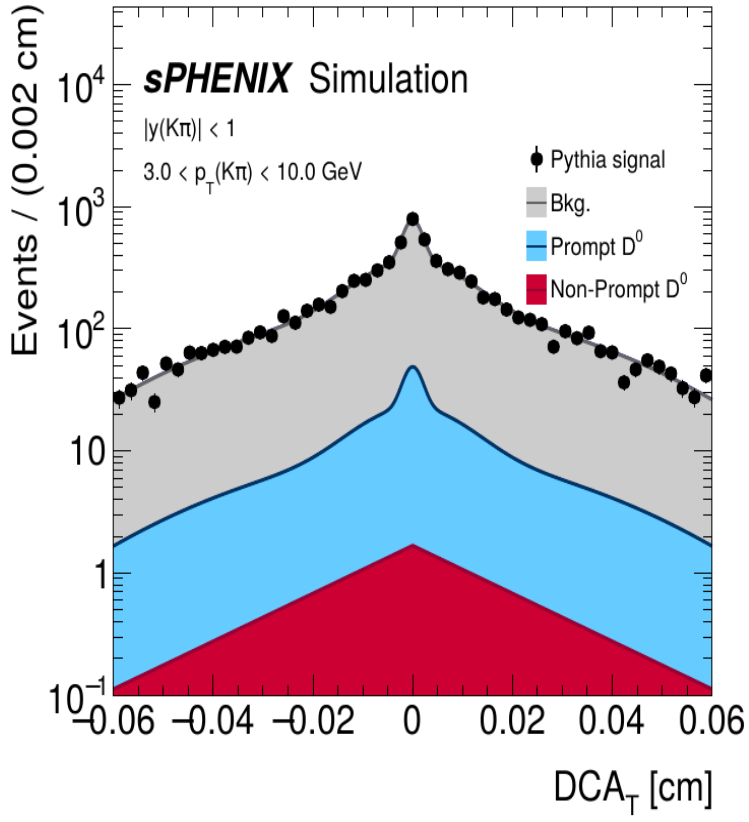




$$p + p \to H_b + X \to (D^0 + X') + X$$

KFParticle package implemented for exclusive HF hadron reconstruction



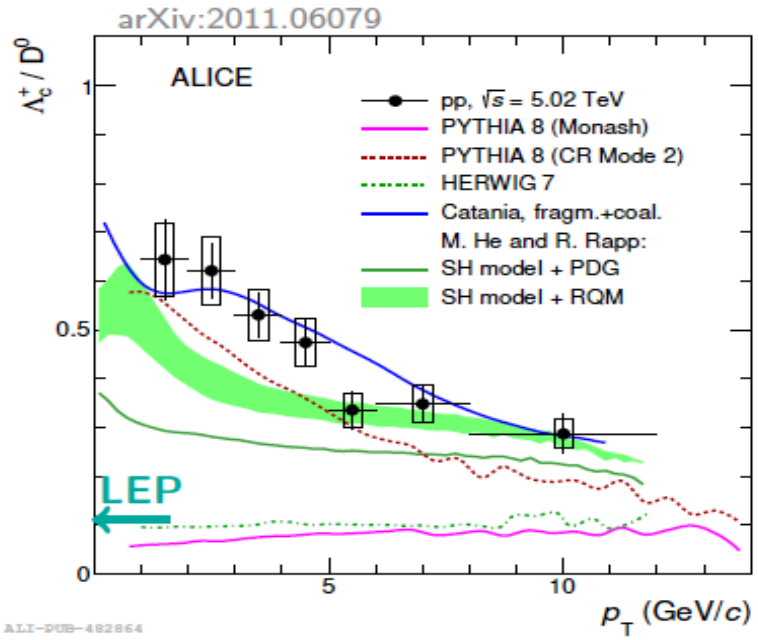


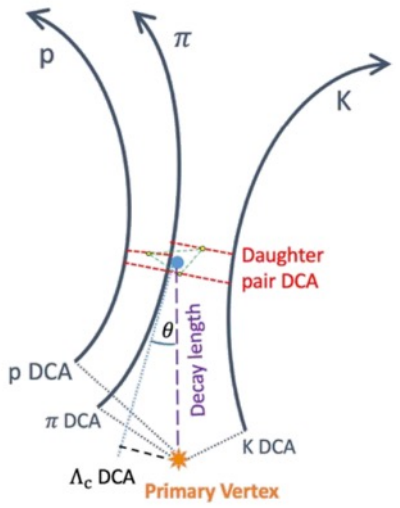
From Quark to Hadron in QGP

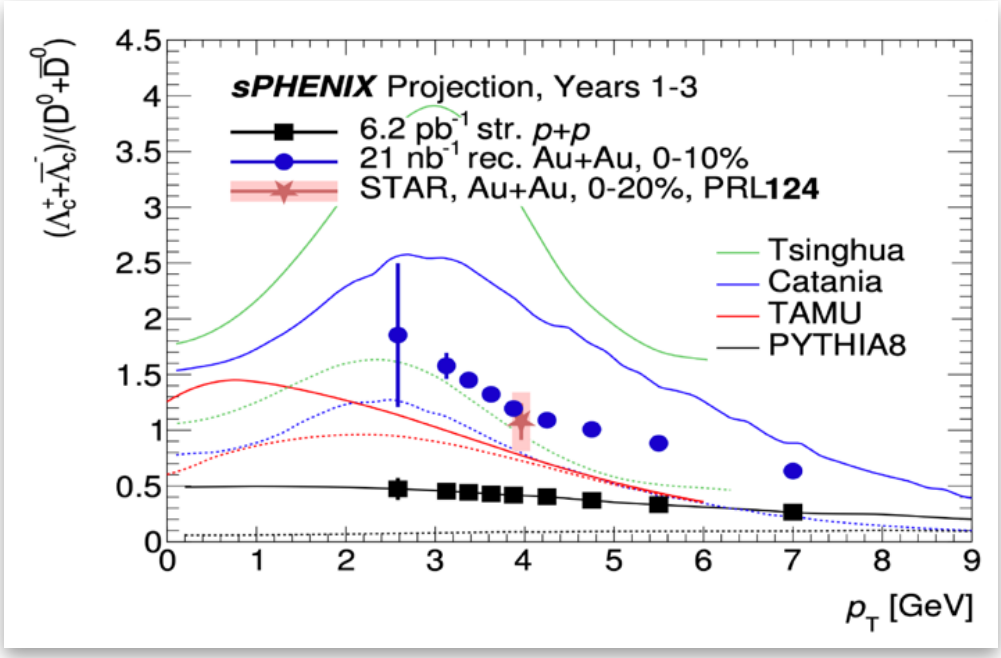
- Critical to understand the hadronization process

- **Hadron production strongly affected by the QCD environment**
  - Non-perturbative process important at low pT, coalescence etc.
  - Strong multiplicity dependence observed in p+p, pA and AA … @RHIC and LHC
  - Study the breakdown of pQCD factorization at low pT …
- **High precision measurements of HF meson and baryons in sPHENIX**

Clear pT dependence observed: e+e- vs pp







MVTX Alignment with AI Approach (**Regression fit**)

The idea - align MVTX detector geometry sensor by sensor with reconstructed good tracks

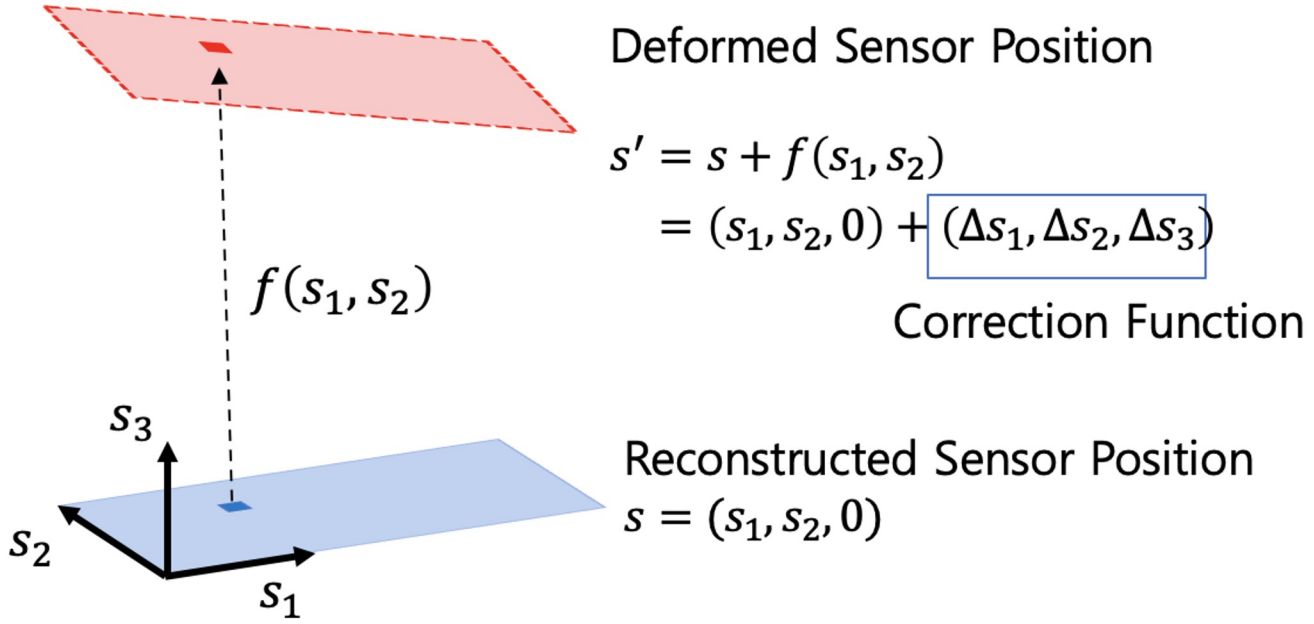
- Chip: 512[R] x 1024[C] pixels
- 9 chips per stave
- 48 staves total

Staves per layer: 12/16/20

AI/NN:

- find correction factors for each sensor (**translation/rotation/shear/expansion /contraction**)

Alignment in the sensor coordinate



s_1 : column direction, parallel to z axis
s_2 : row direction
s_3 : normal to sensor

Trigger Detectors: MBD and ZDC