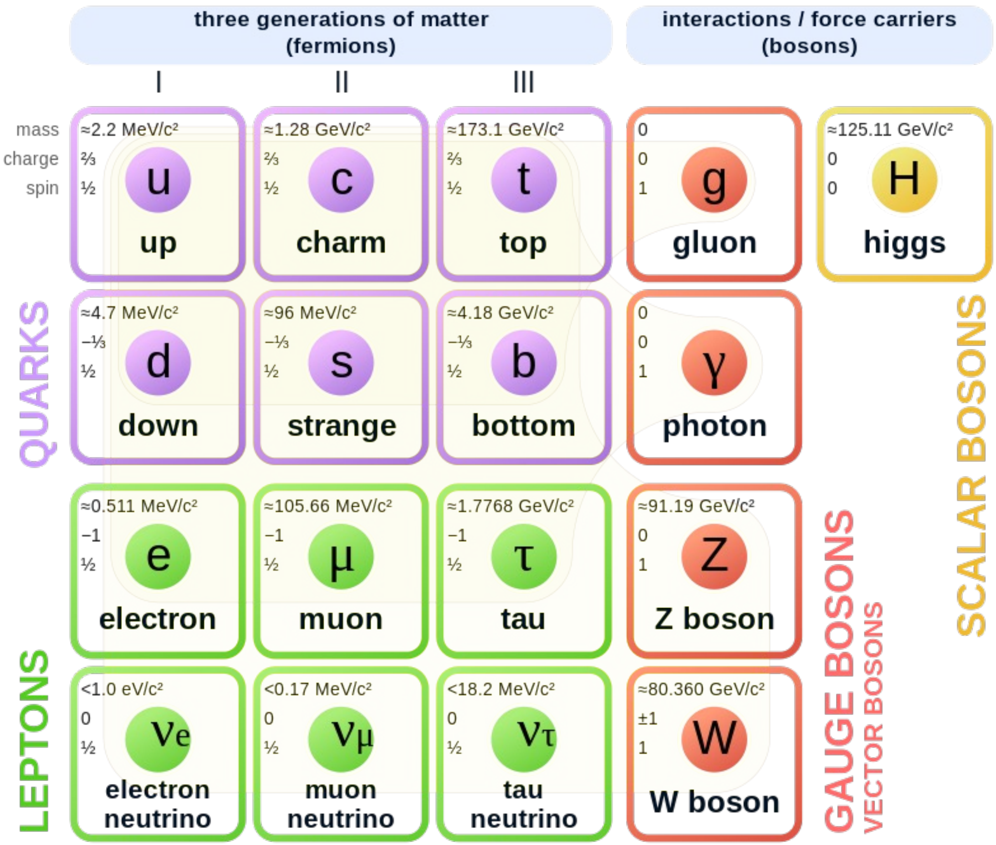
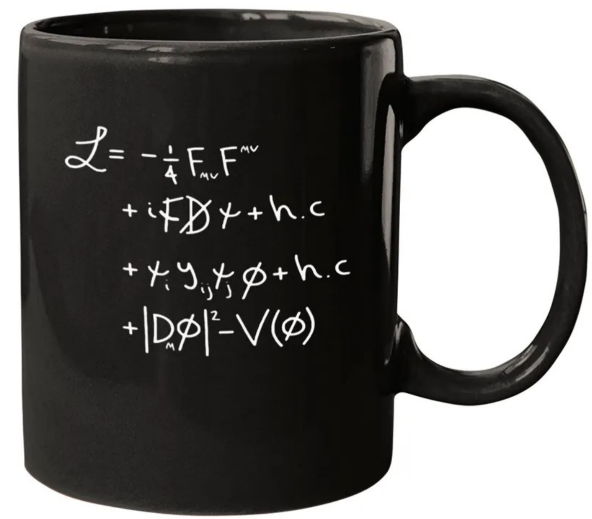
Traversing the Flavorful Universe: Insights into Heavy Quarks from Heavy Ion Collisions

Zhaozhong Shi

Los Alamos National Laboratory

Standard Model of Elementary Particle Physics





- Electromagnetic, strong, and weak interaction among elementary particles
- Elegant Gauge symmetry: $SU(3)\times SU(2)\times U(1)$

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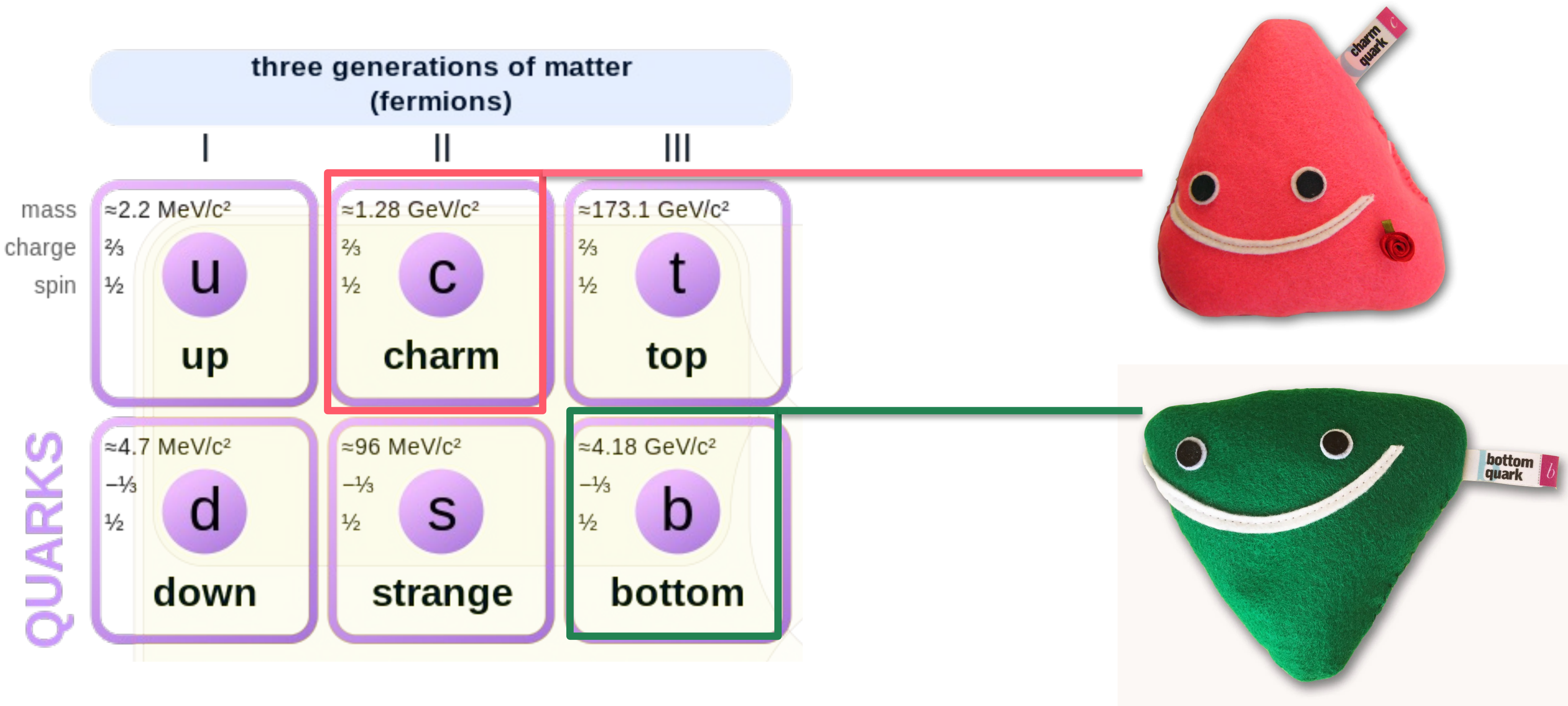
Heavy Quarks



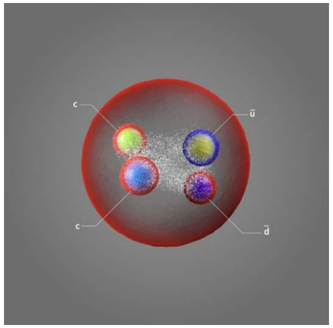
- Nature: fermion participating in strong, electromagnetic, and weak
    - Charm and bottom: hadronize and then decay
    - Carry spin and flavor
    - Excellent tools to test the Standard Model

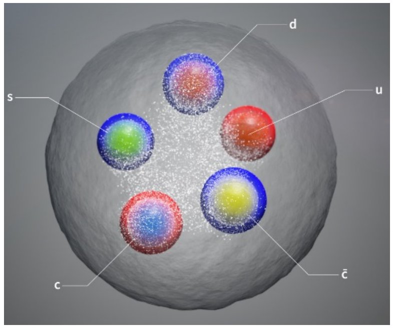
Interesting Features of Heavy Quarks

CP Violation

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

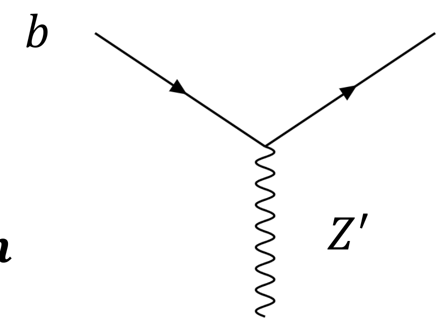
Exotic Hadrons





Above QCD Scale: Λ_{QCD}

BSM Physics: FCNC $b \rightarrow s$



Snowmass 2021

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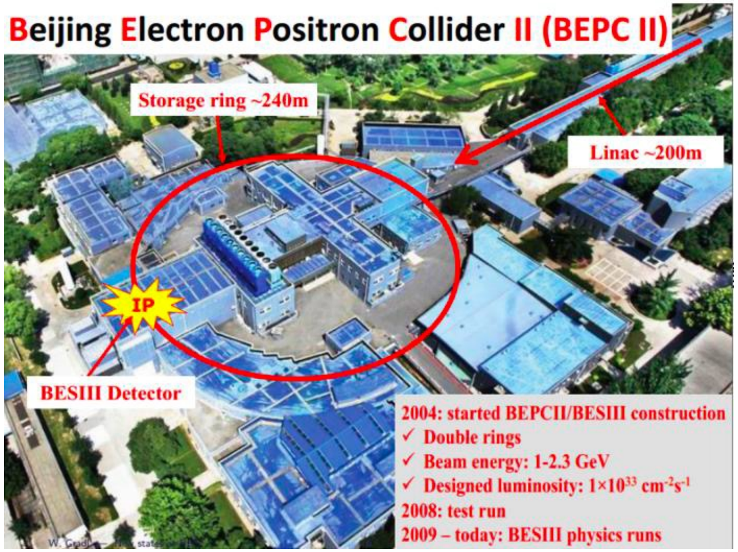
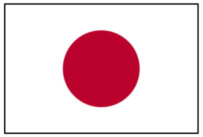
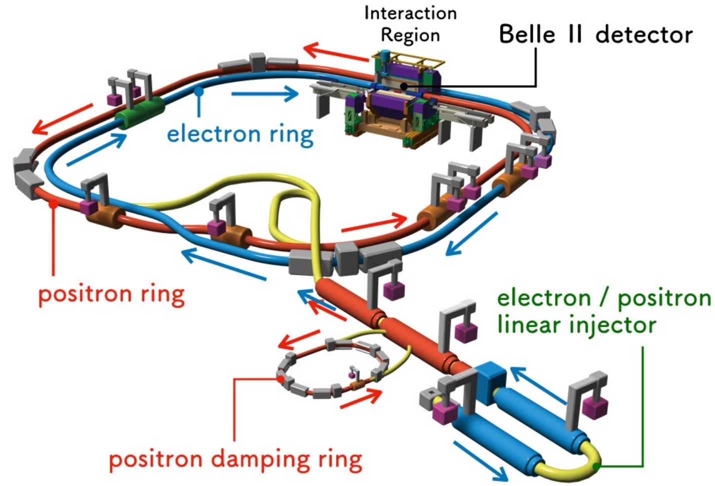
Colliders for Heavy Flavor Physics

BEPC II

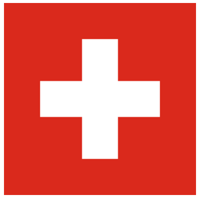


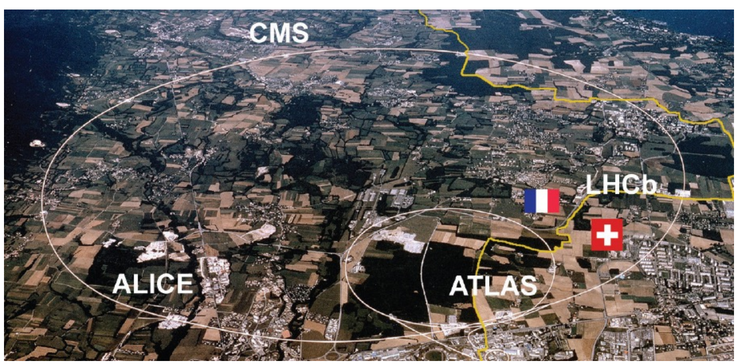
Super KEKB



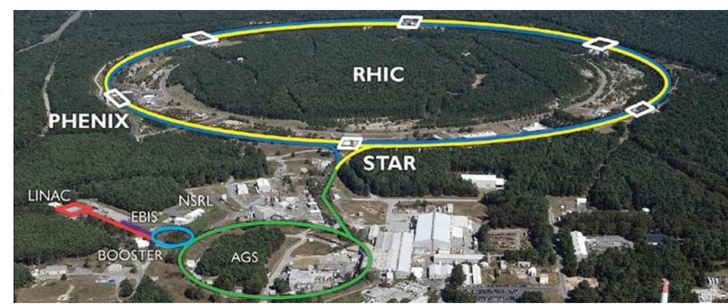


LHC





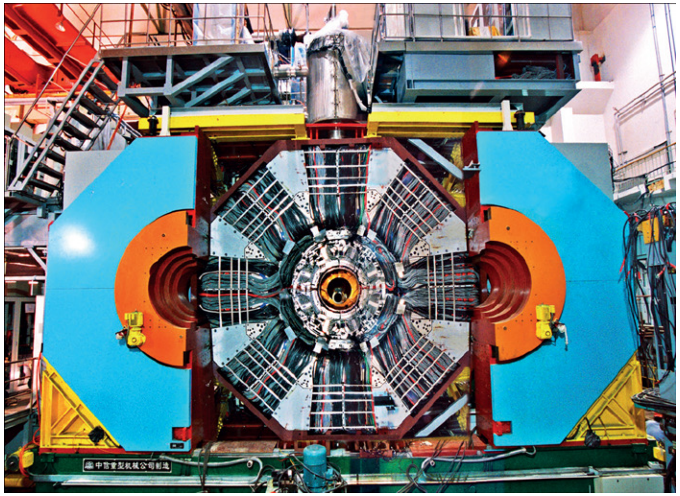
RHIC



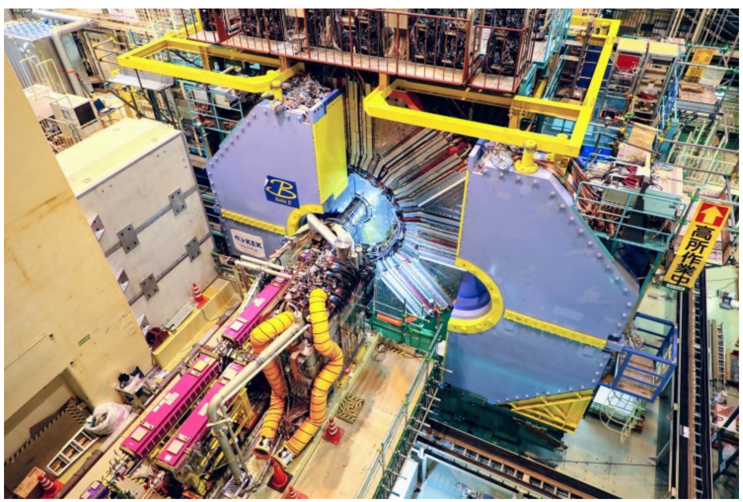
- Production of heavy quarks at high energy colliders around the world
  - Different collisions systems
  - Possible beam polarization

e^+e^- Collider Experiments

BES III

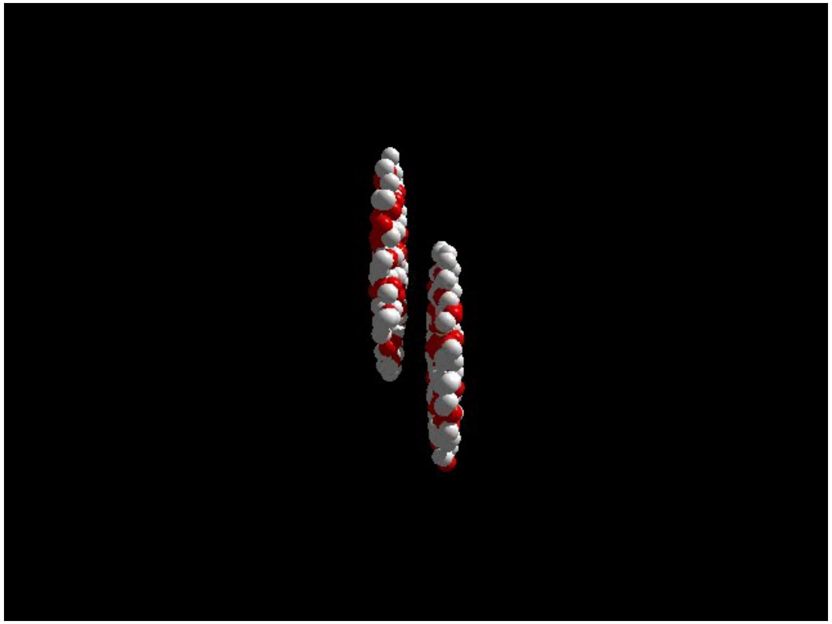


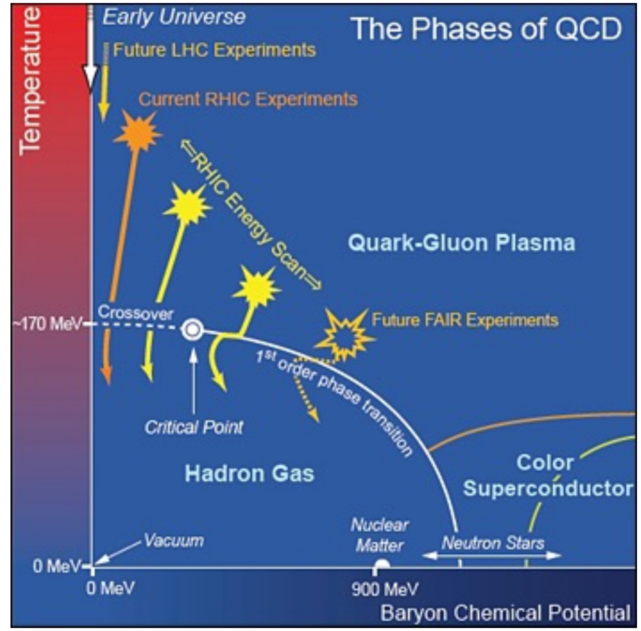
Belle II

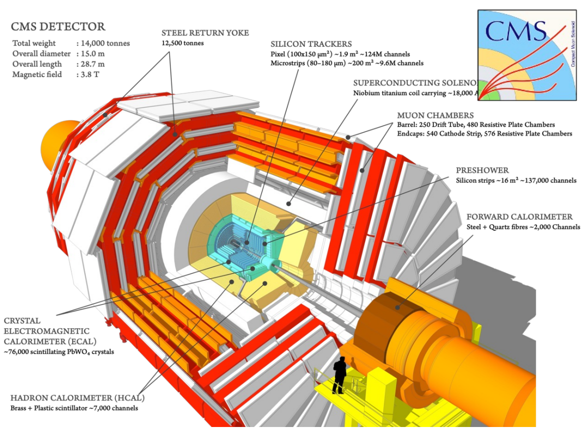


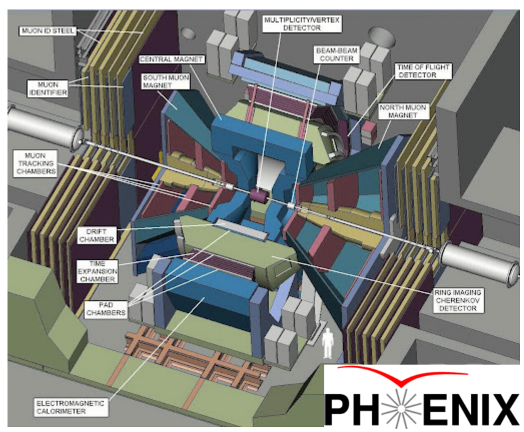
- Clean initial state: e^+e^-
- Precision studies of charm and bottom quarks physics

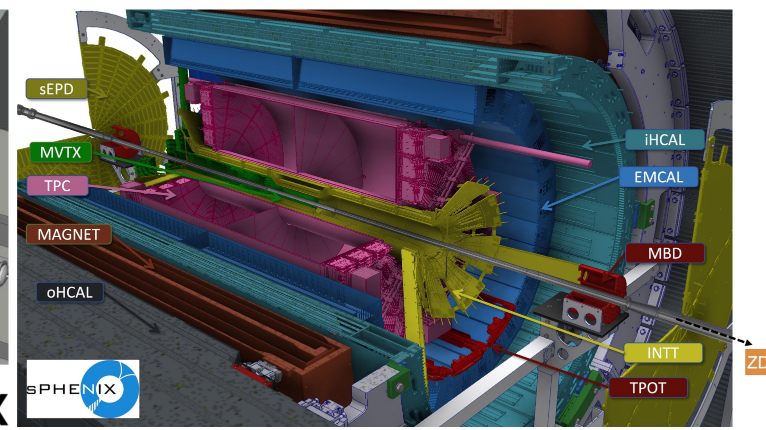
Heavy Ion Collision











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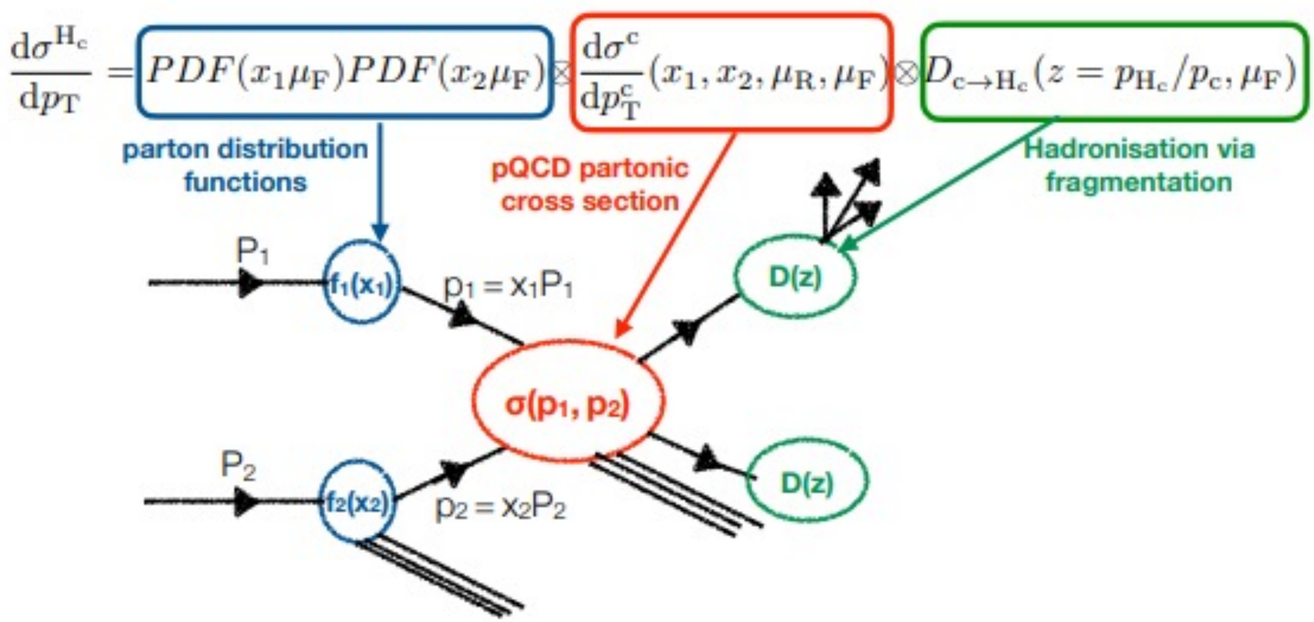
QCD Factorization Theorem

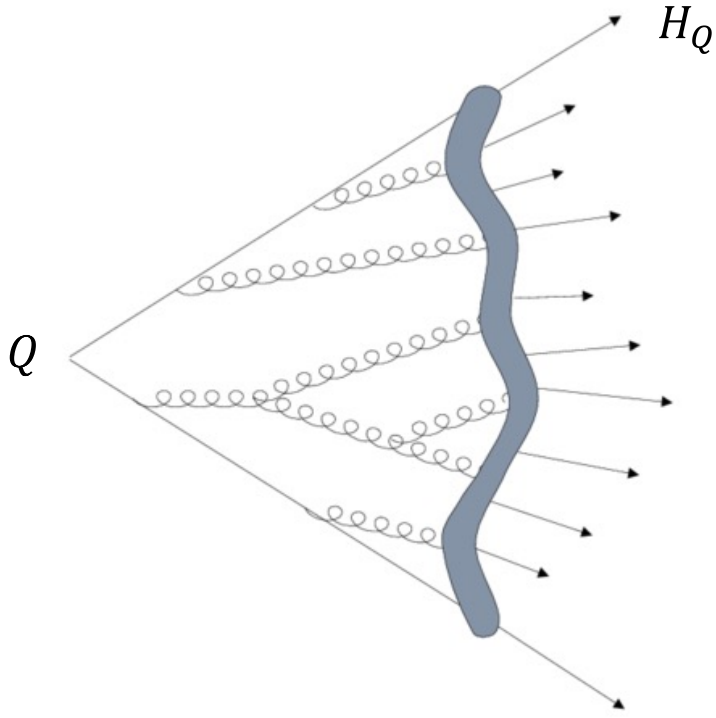


$$D_{e^+e^-}(z,\mu^2) = D_{ep}(z,\mu^2) = D_{pp}(z,\mu^2) = D(z,\mu^2)$$

- Factorization of soft and hard processes
- Hard processes: perturbatively calculable
- Soft processes: not perturbative
  - Universal in elementary collisions
  - Determined from experiments at different scales

Heavy Quark Hadronization

Fragmentation



Quarks "pop out" from vacuum

Coalescence

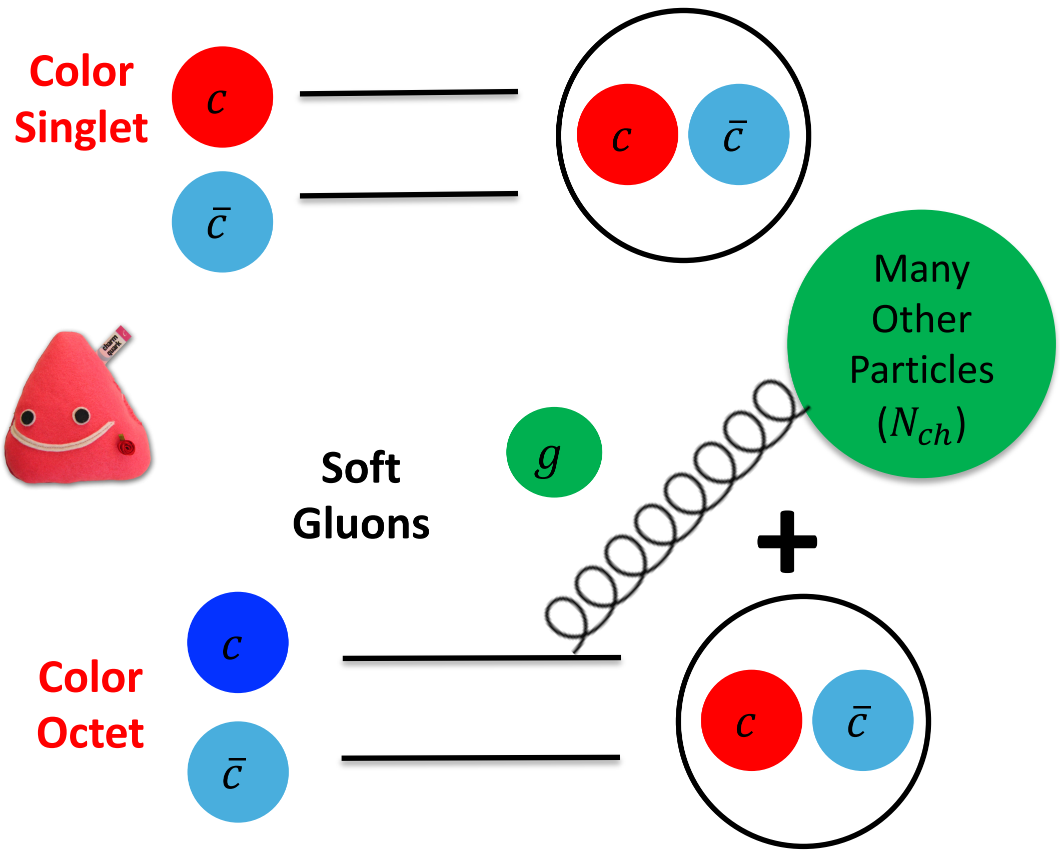
Recombining with surrounding quarks

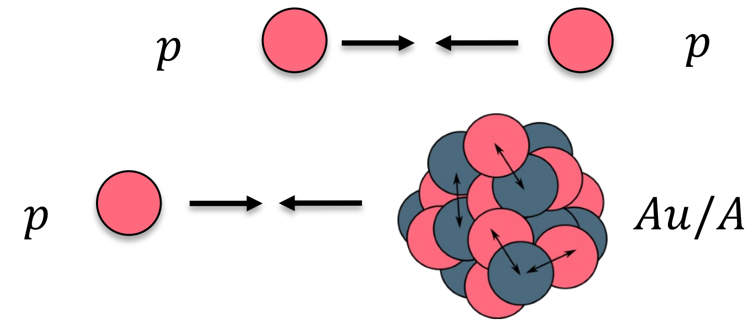
- Due to the strong nature: they confine into hadrons
- Processes: $Q \rightarrow H_Q$

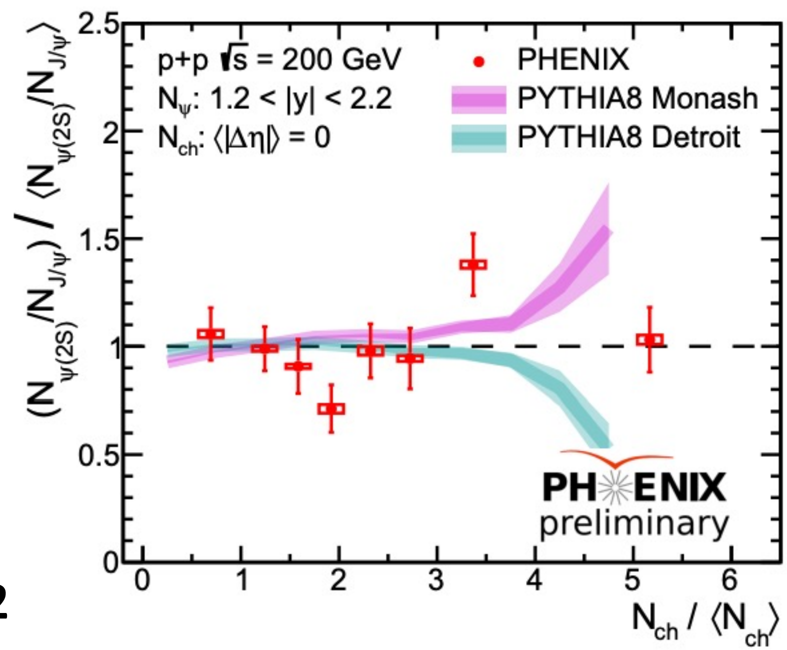
Charm Hadronization

Non-Relativistic QCD Model

$$J/\psi(1S),\ \ \psi(2S)$$

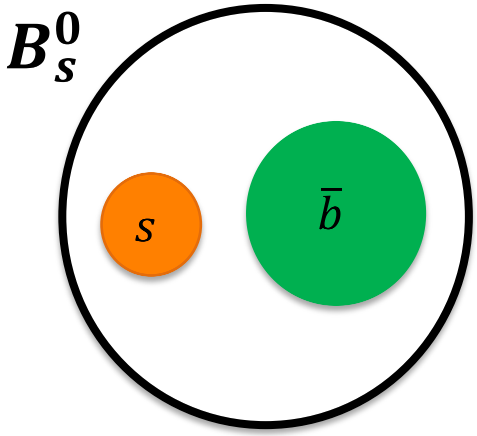


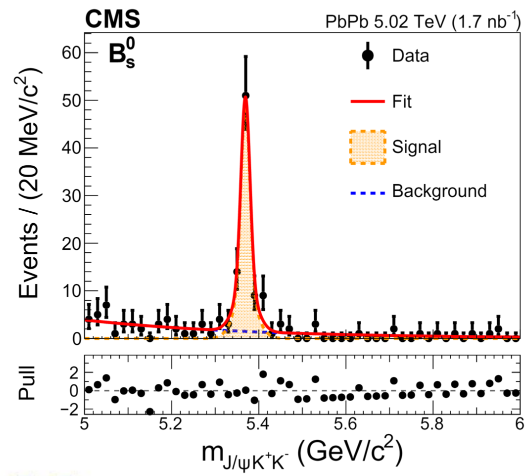


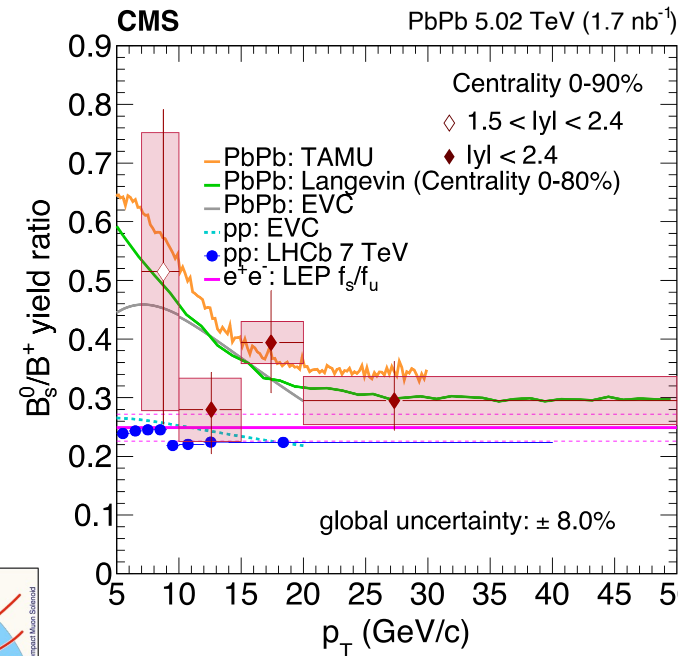


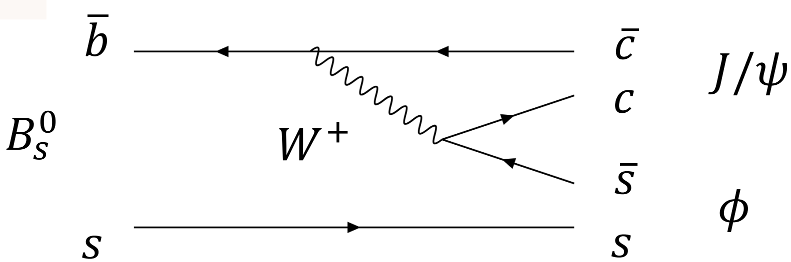
Z. Shi, Universe 2023, 9(7), 322

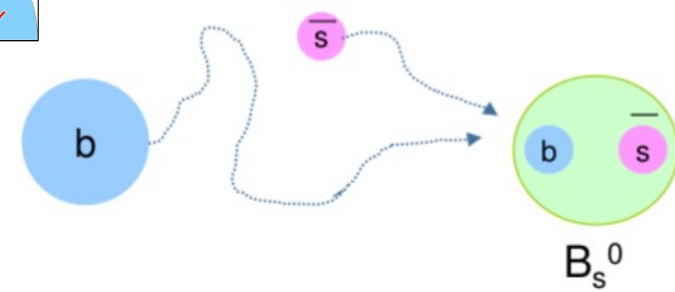
Bottom Hadronization











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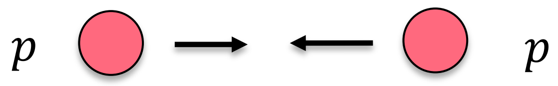
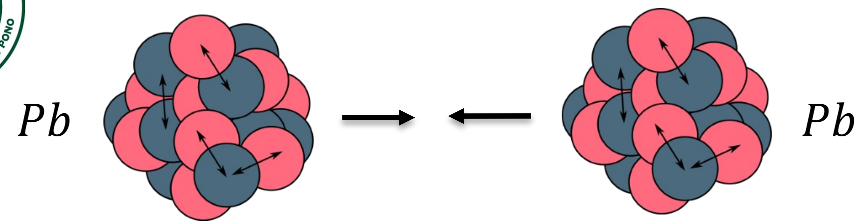
- First observation of B_s^0 with greater than 5σ in heavy-ion collisions
- Enhancement of B_s^0/B^+ in heavy-ion collisions

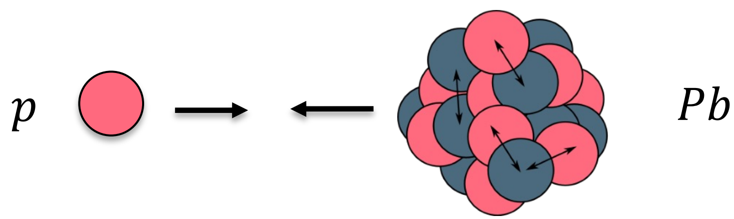
Exotic Hadron: X(3872) at the LHC

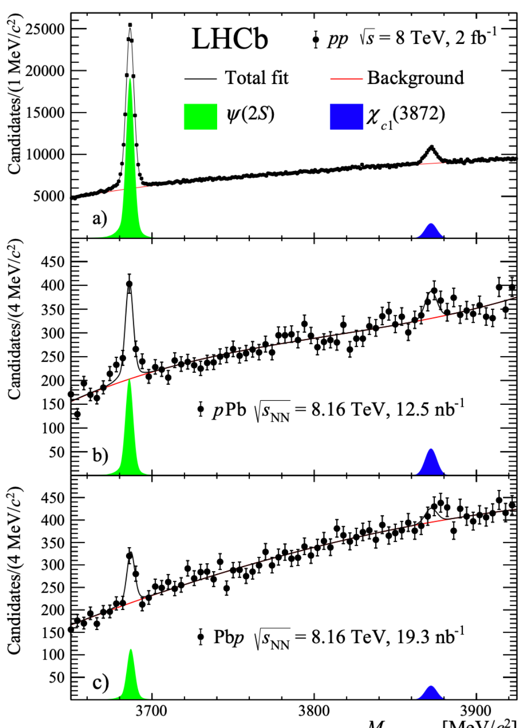
$X(3872)$

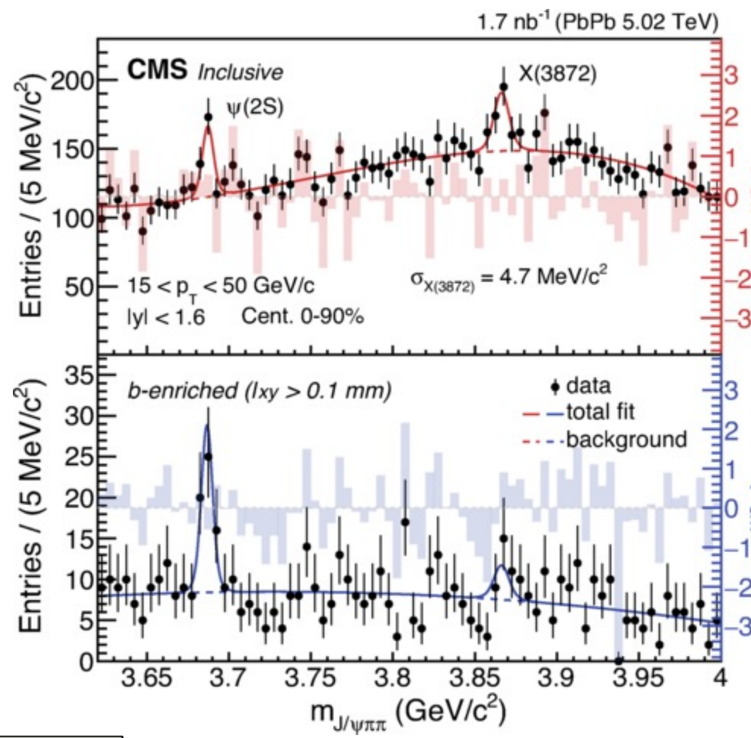
$$I^G(J^{PC}) = 0^+(1^{++})$$



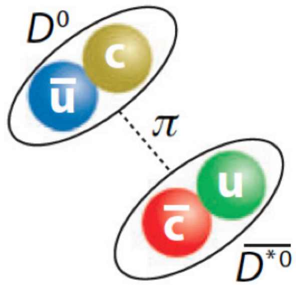




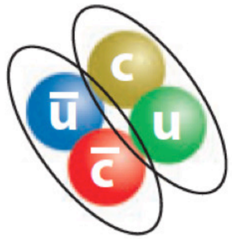




Ongoing Project: X(3872) at RHIC



D^0–$\overline{D^{*0}}$ "molecule"



Diquark–diantiquark

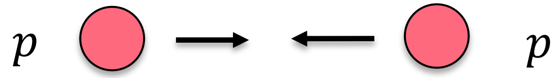
$$X(3872) \rightarrow J/\psi\rho \rightarrow e^+e^-\pi^+\pi^-$$

Xudong Yu

Peking University

Model Calculations

SCNU



Predicted $X(3872)$ Yield	Lower Bound	Upper Bound
Hadronic Molecule	1525	4727
Compact Tetraquark	163	179

- Adding a data point to study $X(3872)$ at RHIC

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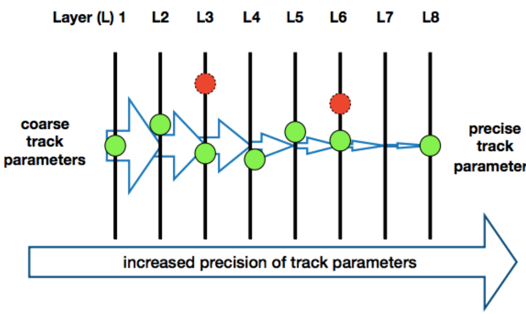
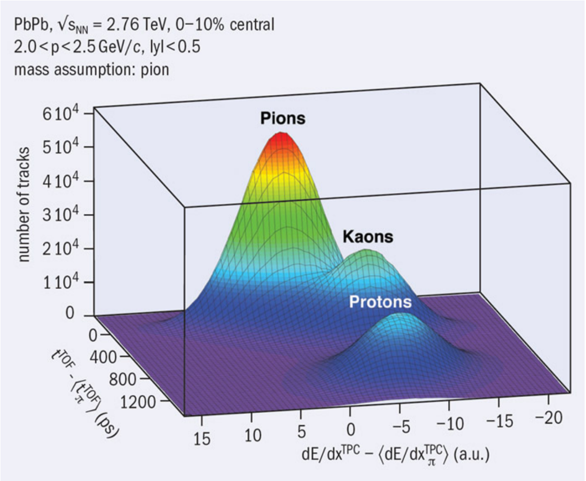
Detector Instrumentation

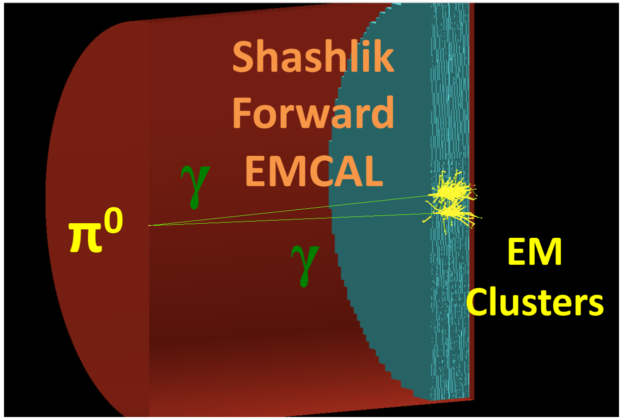
Tracking and Vertexing



Particle Identification

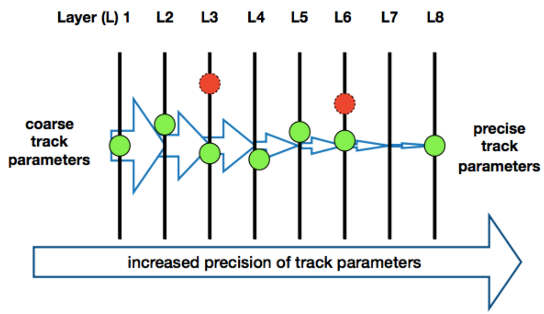


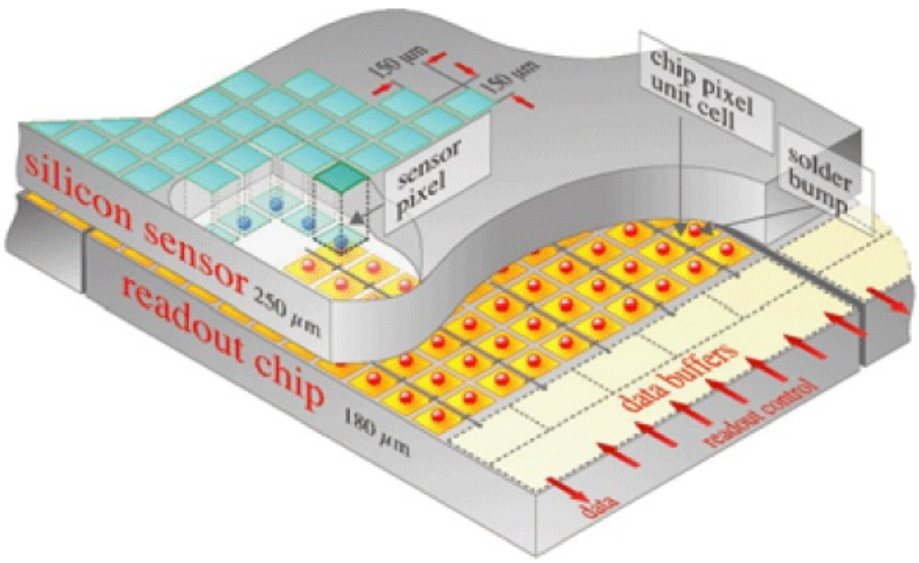
Calorimetry



Tracking and Vertexing Detector

Tracking and Vertexing

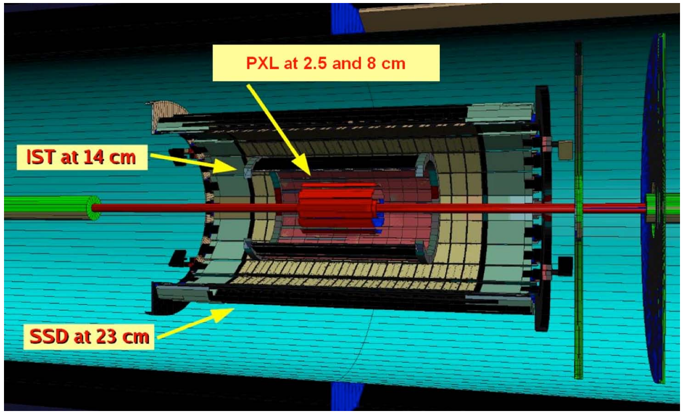




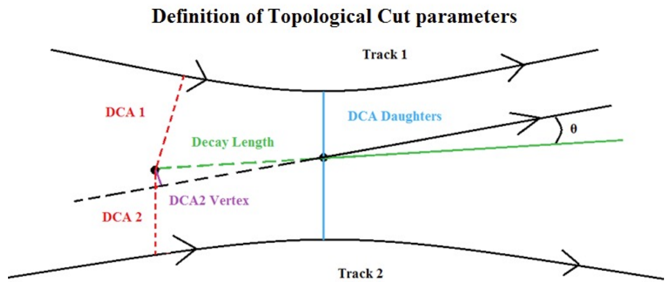
Past Experience

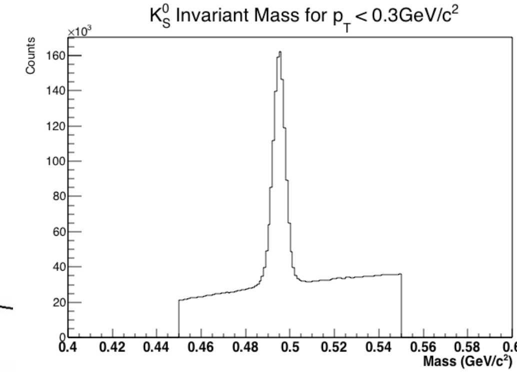
- Physics Performance
- Quality Control
- Detector Commissioning
- Readout Electronics
- Accelerator Beam Background Studies

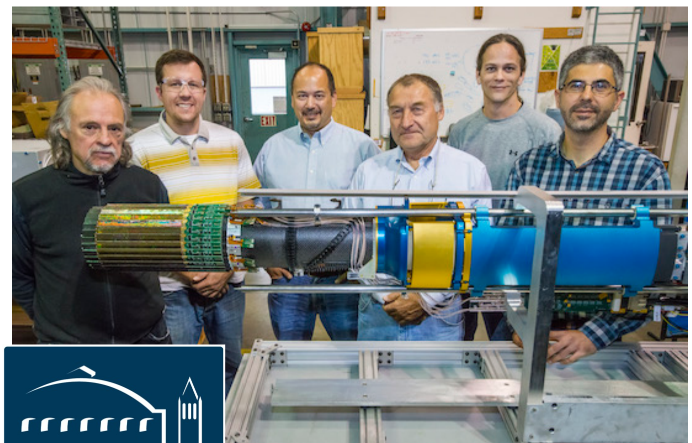
Heavy Flavor Tracker with STAR

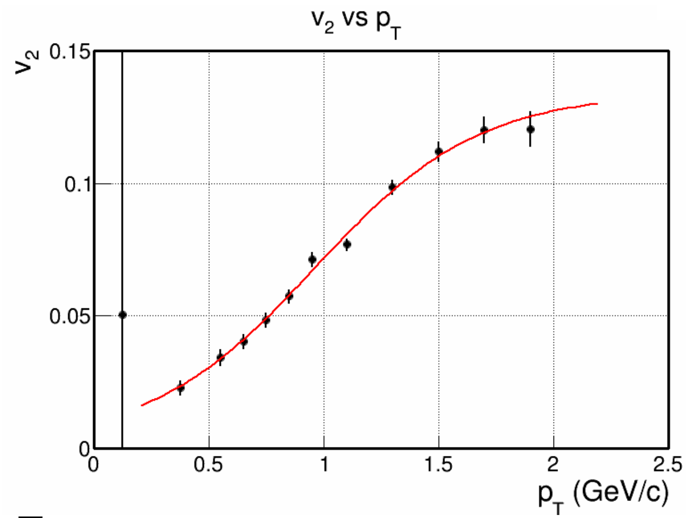


$$K_S^0 \to \pi^+\pi^-$$





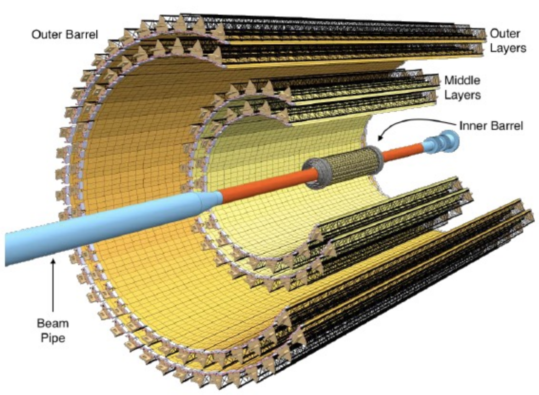


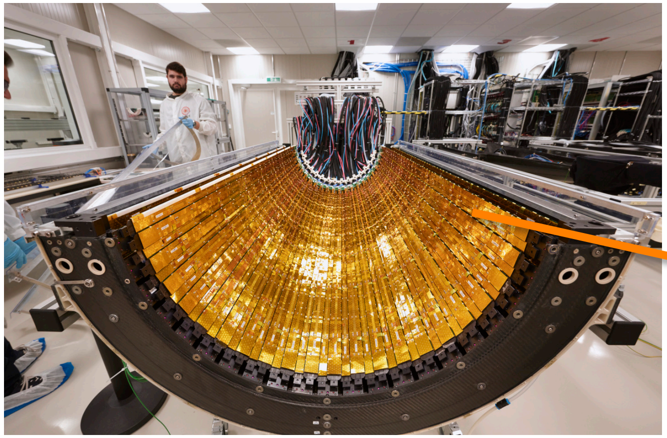


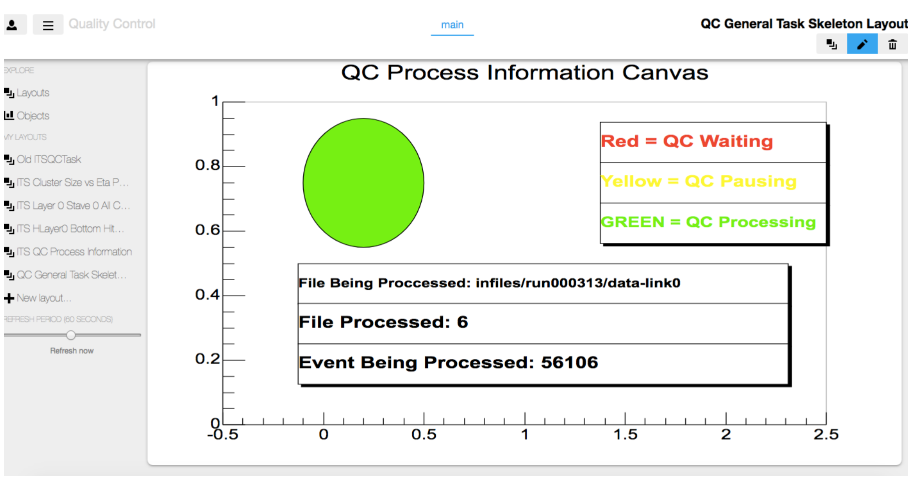
Z. Shi, Undergraduate Honors Thesis at UC Berkeley

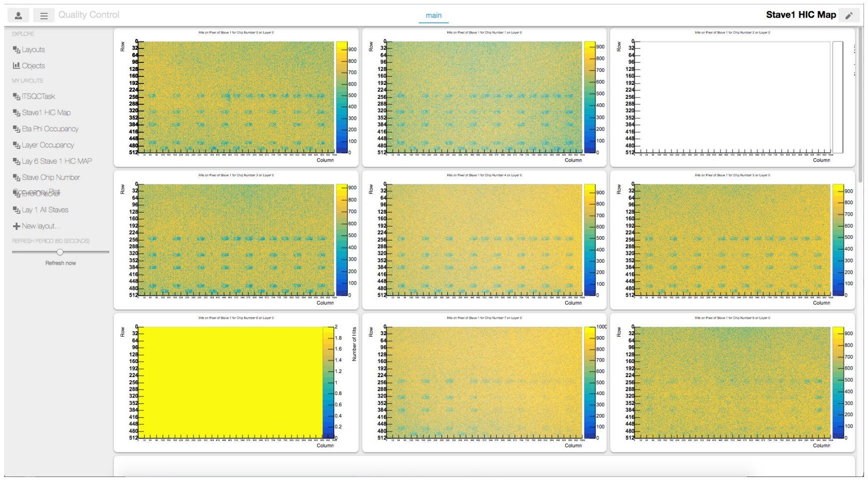
- Validation with $K_S^0 \to \pi^+\pi^-$
  - Elliptic flow: verified $n_q = 2$ through quark coalescence hadronization
- Enable heavy flavor physics program at RHIC: D^0 and Λ_c^+

ALICE Inner Tracking System (ITS)



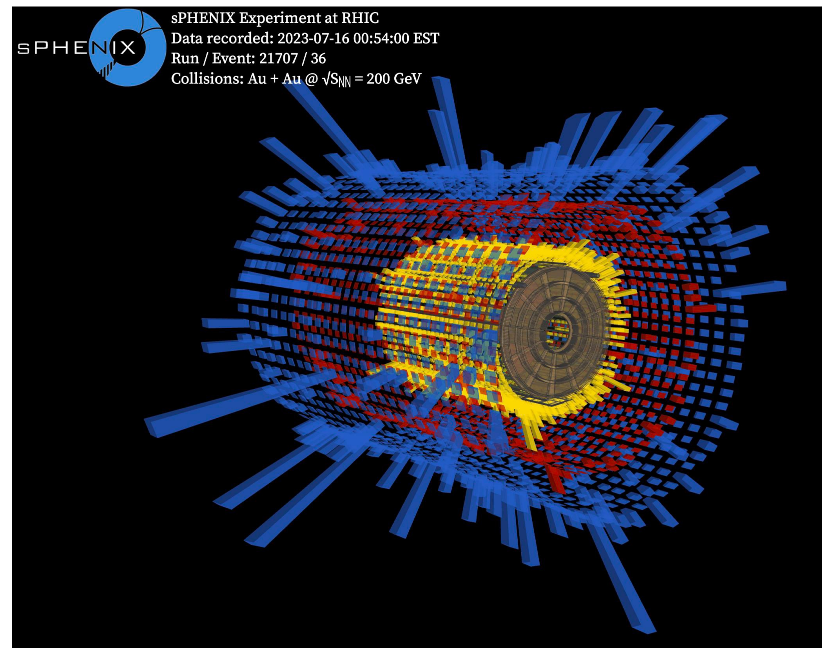


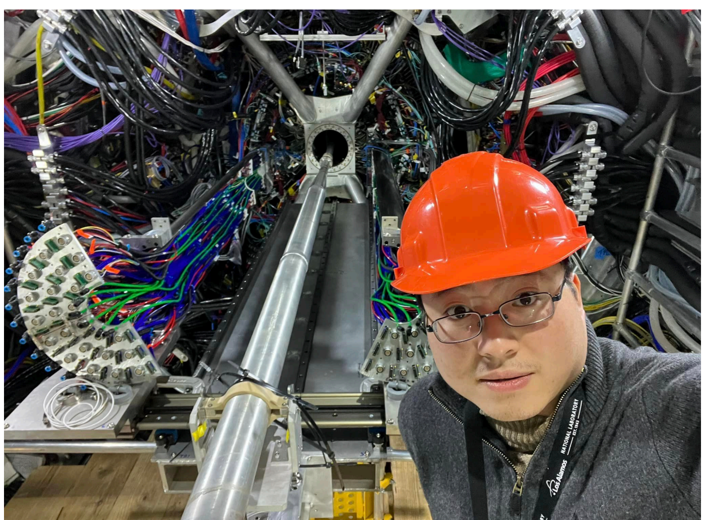




- Quality Control System and on-call expert during commissioning
- Noisy pixel calibration: masking noisy pixels with a dynamical database

The sPHENIX Experiment





sPHENIX

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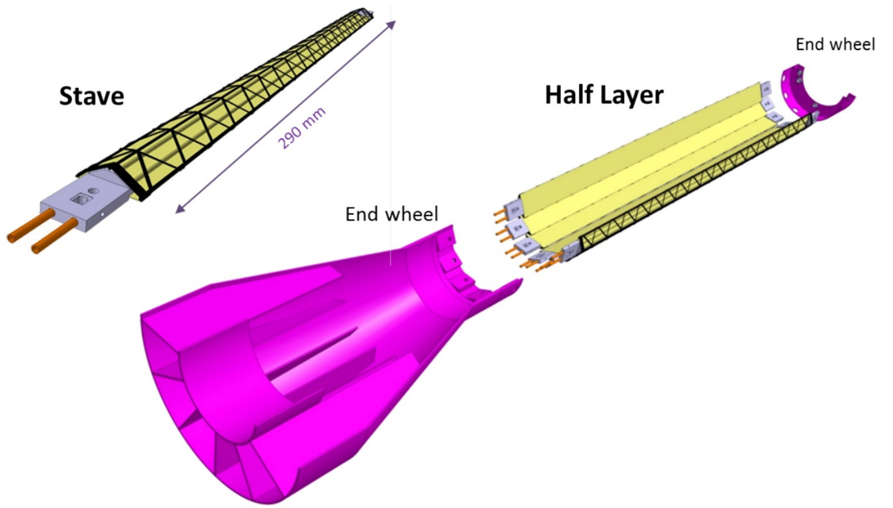
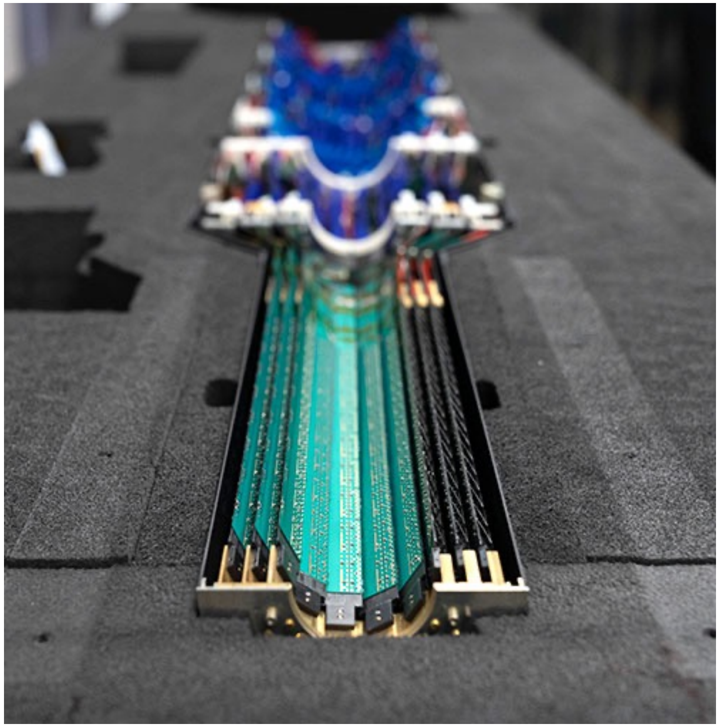
Basic Information About MVTX





- Name: Monolithic-Active-Pixel-Sensor-based Vertex Detector (MVTX)
- Adapted from ALICE ITS
- Innermost of sPHENIX: ~5 µm spatial resolution for vertexing
- Streaming and trigger readout capabilities
- Enable heavy flavor physics program in sPHENIX

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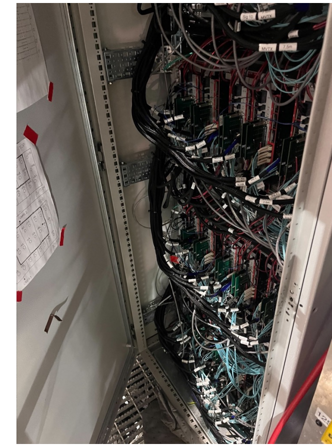
The MVTX Detector System

Front-End Readout Unit

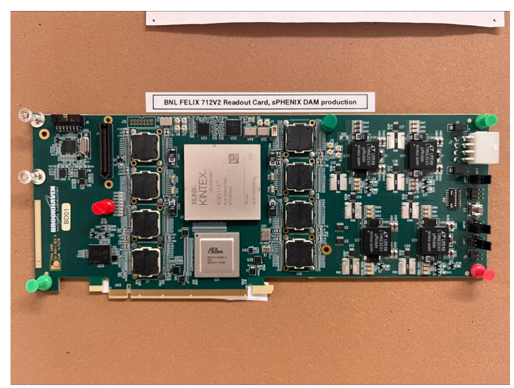
Readout Rack



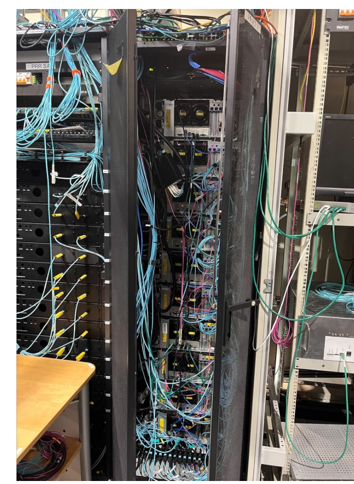
Power System

Cooling System

FELIX Card



Back-End FELIX Servers



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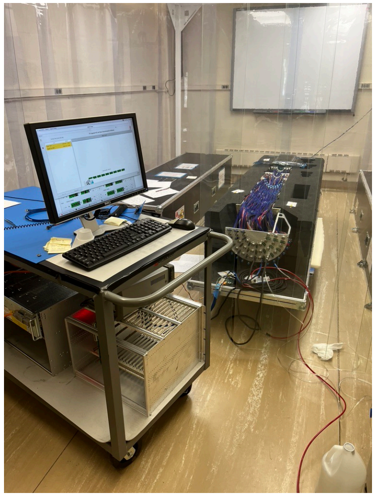
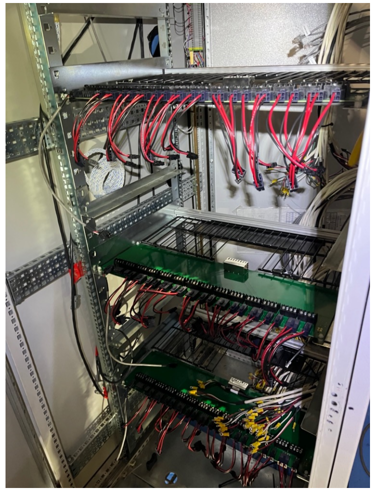
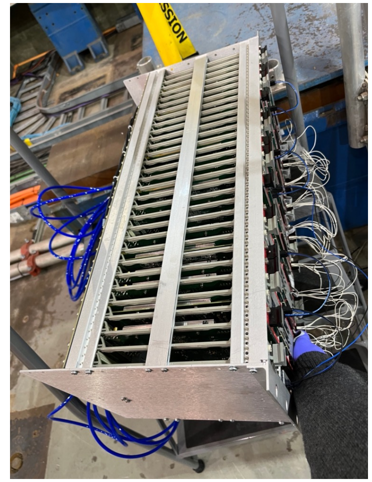
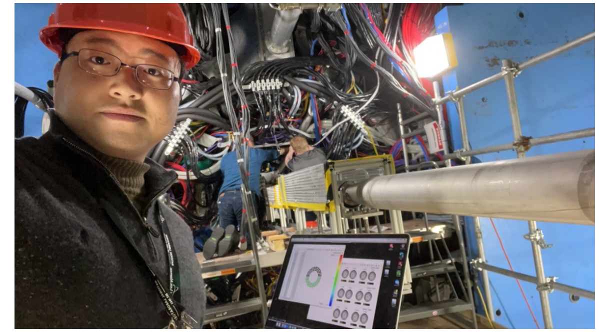
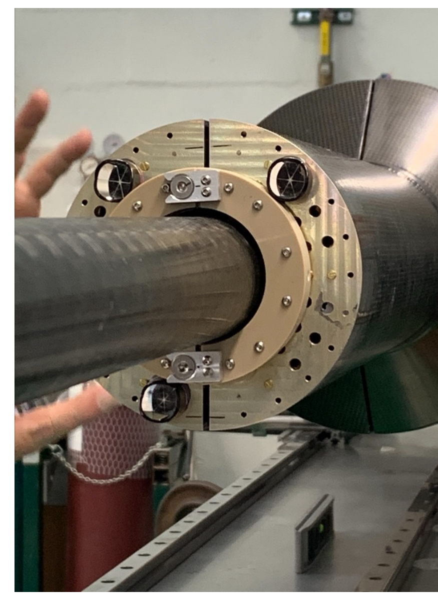
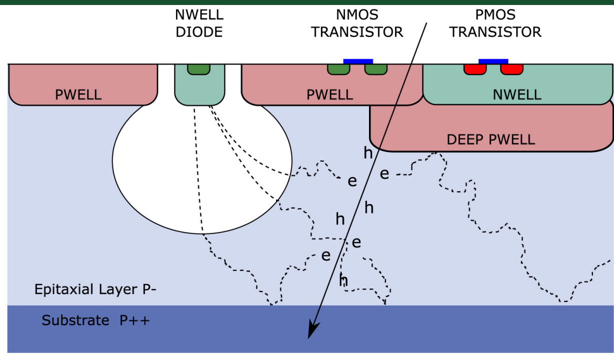
MVTX Commissioning

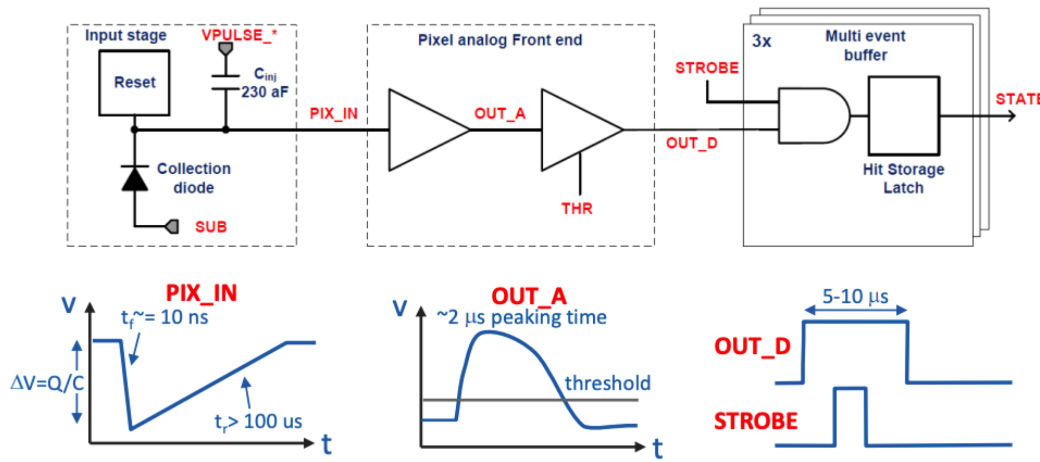





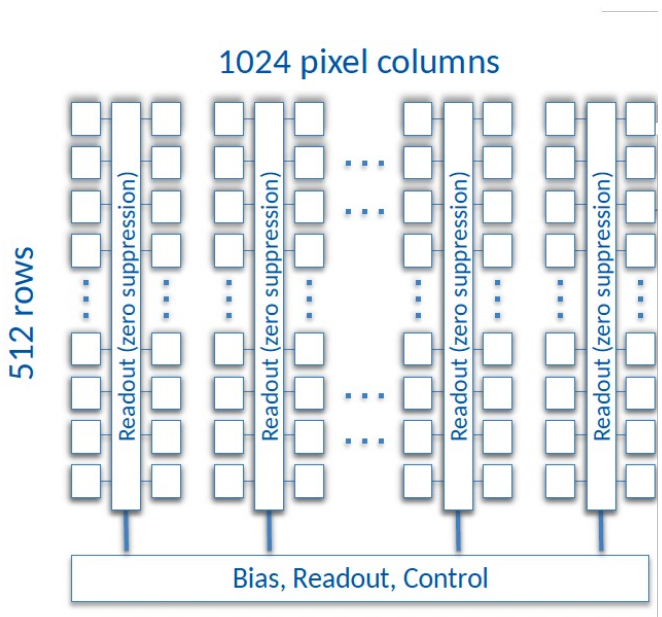



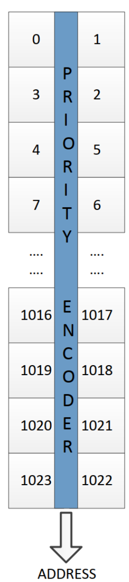
- Intense work over the past 2 years
- 2mm clearance with the beryllium beam pipe (fragile)

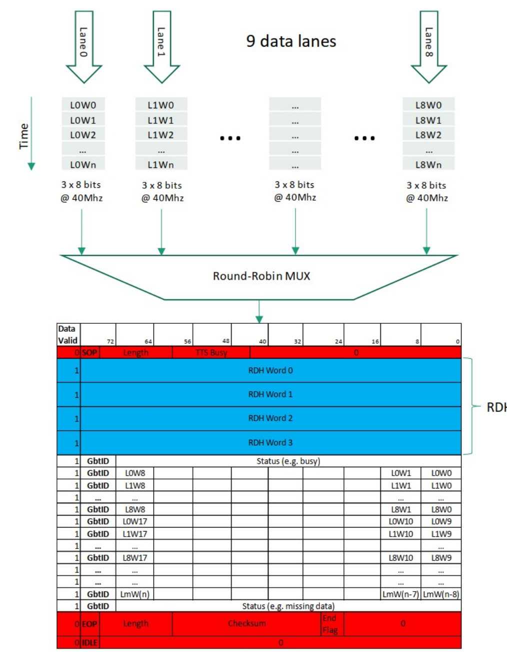
ALPIDE Silicon Chip and Signal Processing







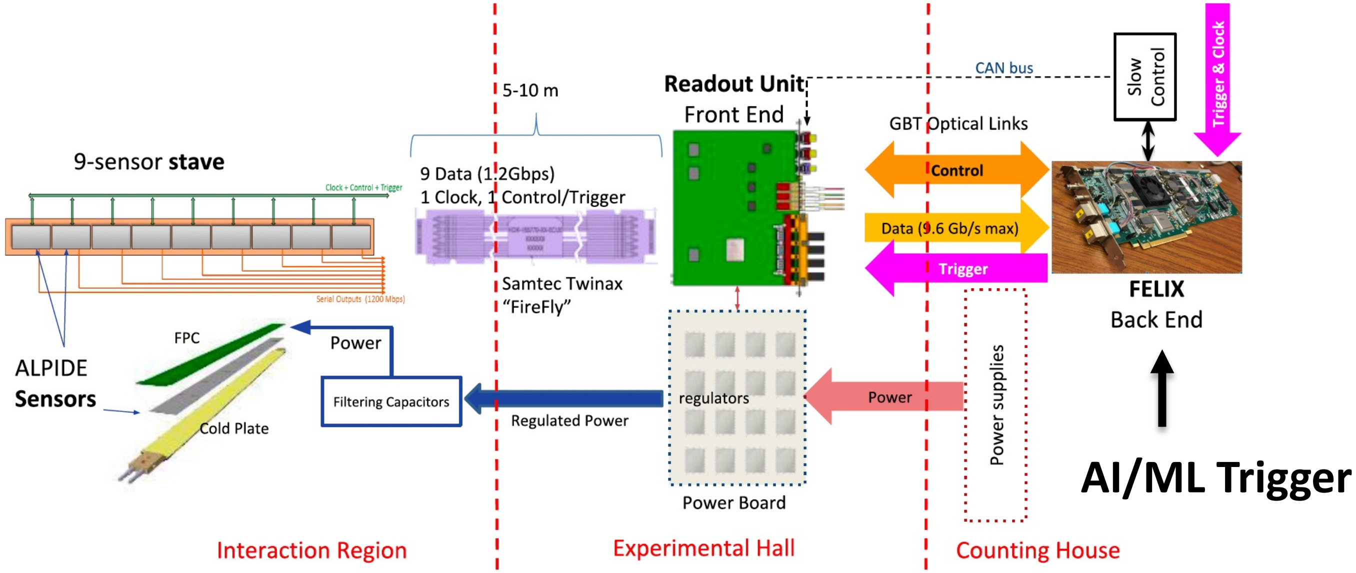




10 00 00 00 00 00 00 00 00 00
00 00 00 00 00 20 00 00 40 08 00 00 00 00 00 00 00 00 00 00 00 00 00 01 00 00 00 00 00 00
e0 00 00 00 00 00 0f ff ff ff
e8 00 00 00 00 00 00 00 00 00
22 00 00 b0 07 2a 2c cd 00 a2
24 00 00 b0 07 ec 30 dc 00 a4
f0 01 00 00 00 00 00 00 00 00
20 00 00 00 00 00 00 00 00 00

Readout Systems

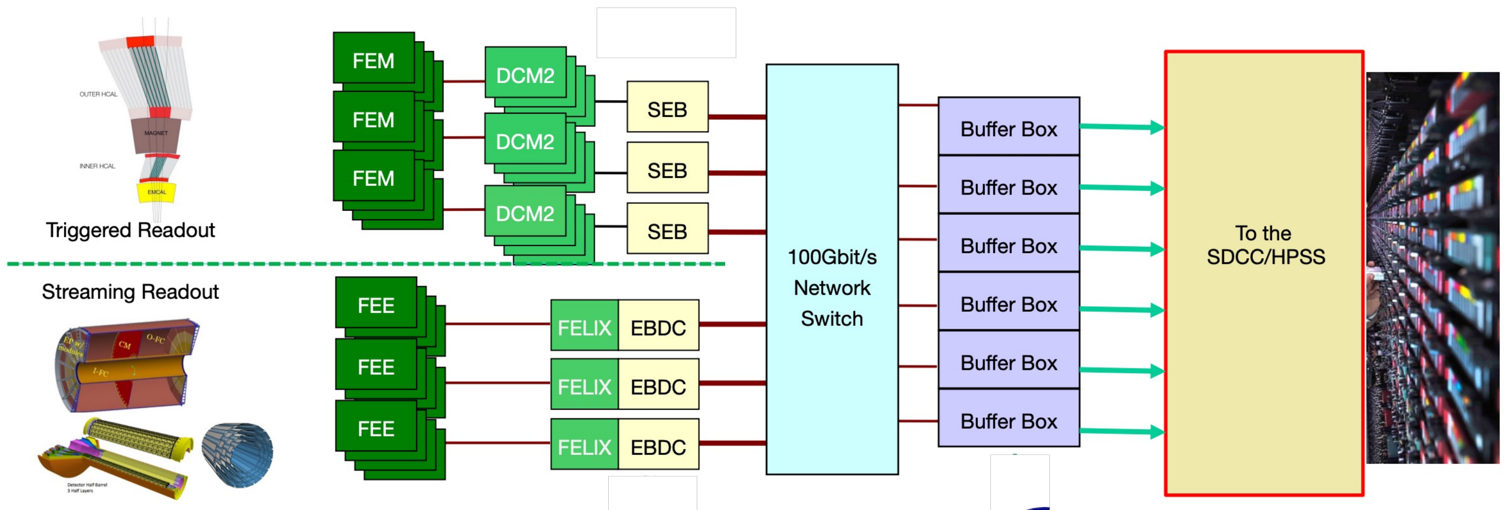
MVTX Electronic Readout System



MVTX Detector Electronics consists of three parts

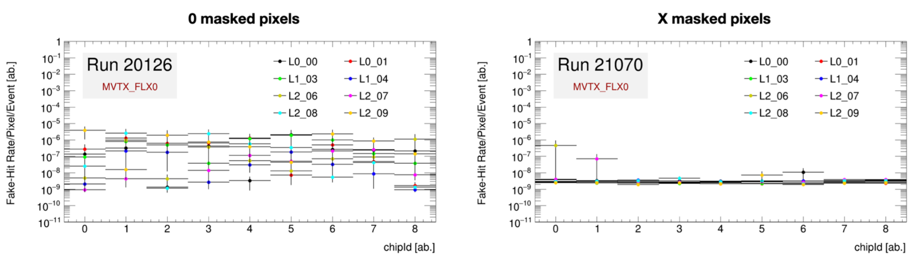
Sensor-Stave (9 ALPIDE chips) | **Front End**-Readout Unit | **Back End**-FELIX

sPHENIX Readout System ~15kHz



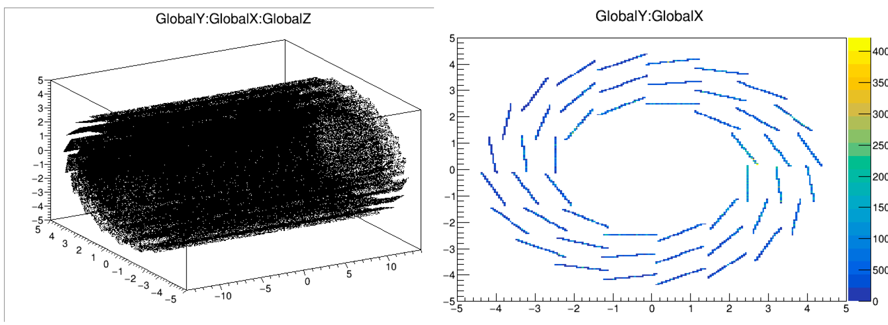
sPHENIX MVTX Data Analysis

Low Noise Level



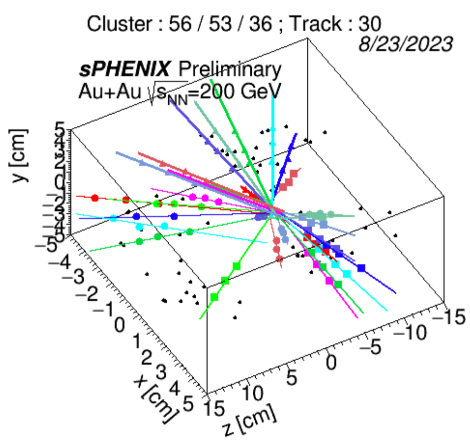
Low noise level after noisy pixel masking

3D Channel Mapping



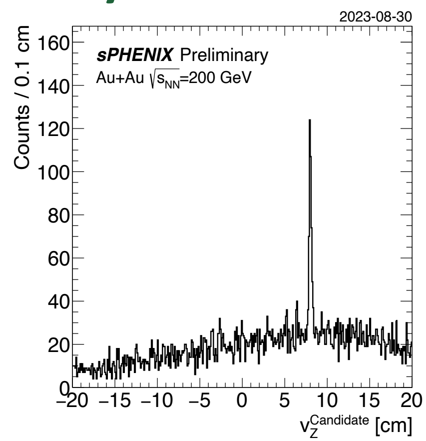
All MVTX hits in AuAu Collisions

Tracklet Reconstruction



Reconstruction tracklets with MVTX

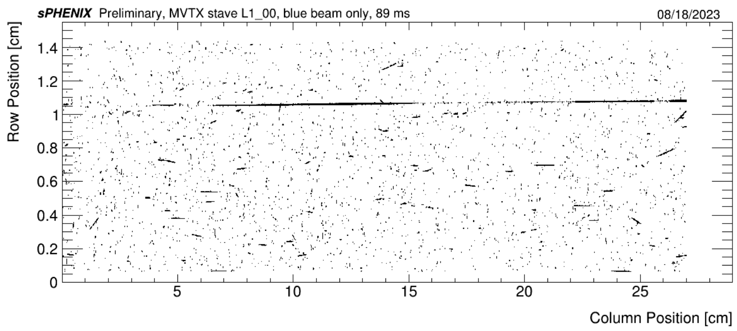
Offline Analysis Vertex Determination

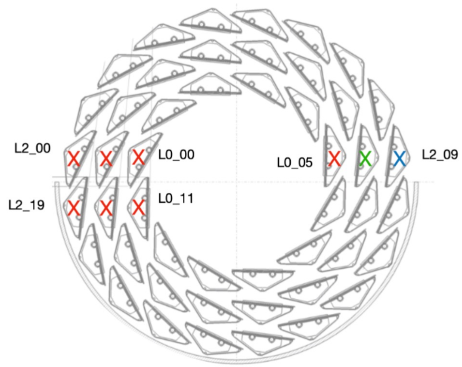


Reconstruction vertex with MVTX

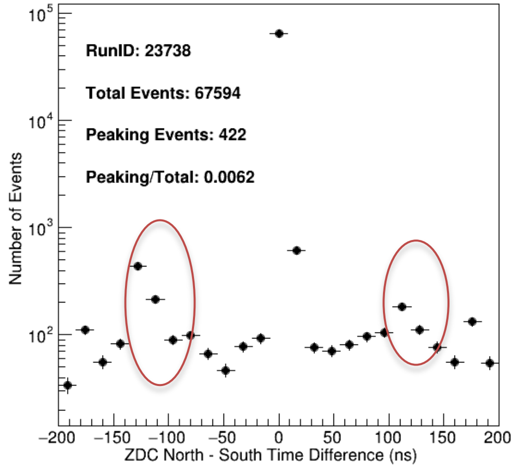
Beam Background at RHIC and the LHC

sPHENIX MVTX at RHIC





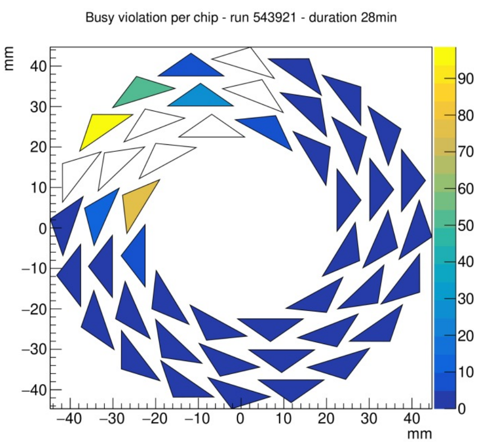
sPHENIX ZDC



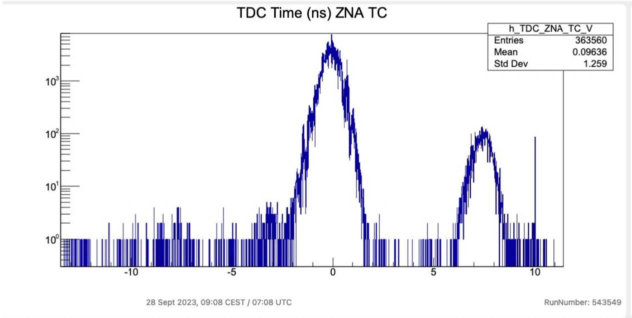
- Beam halo effect?
- Beam gas interaction

Additional peaks seen at ± 120 ns

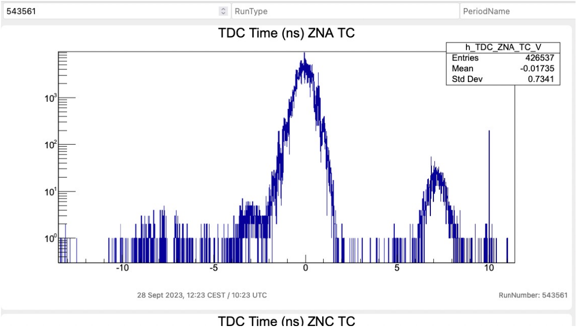
ALICE ITS at the LHC



ALICE ZDC

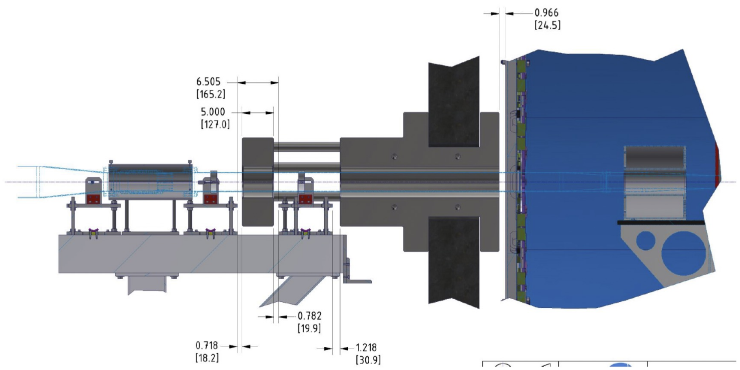


After mitigation by LHC Collider Department

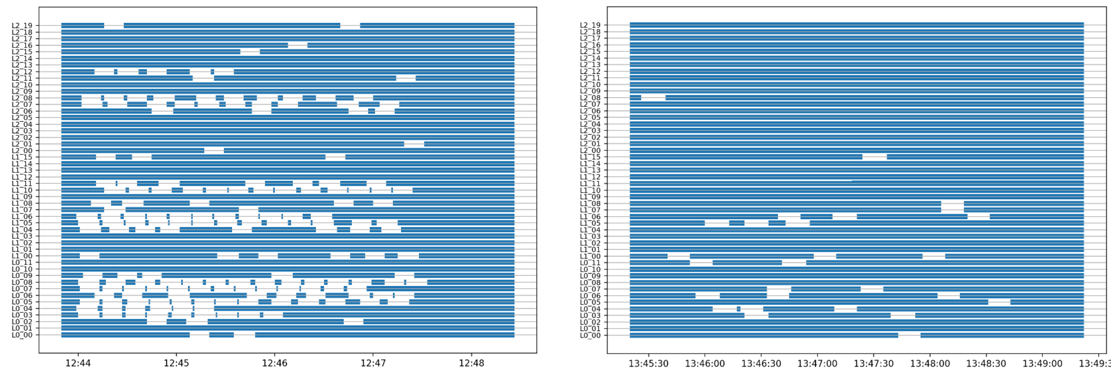


Solutions

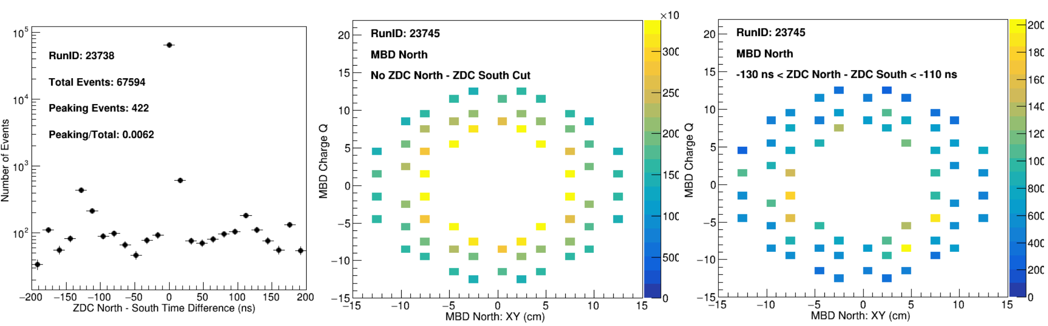
Absorber Shielding



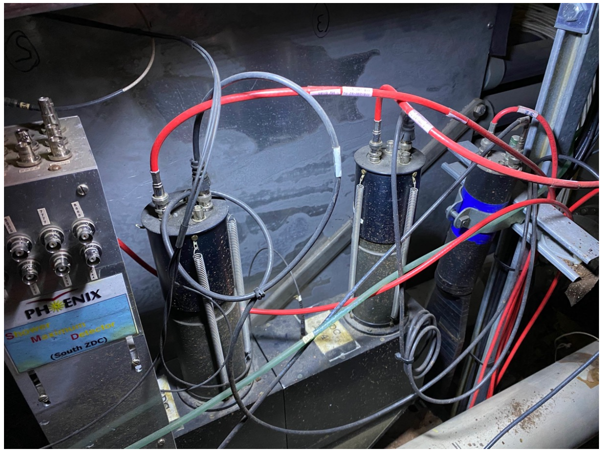
Fast Auto Recovery



MBD + ZDC Trigger Veto



Beam Background Particles



No Show Max Detector Readout in Run 23

BEAST II: Beam Background Commissioning Detector

SuperKEKB Commissioning Detector
BEAST II
Belle II Collaboration

UNIVERSITY OF HAWAI'I
MĀLAMALAMA
1907
UA MAU KE EA O KA 'ĀINA I KA PONO

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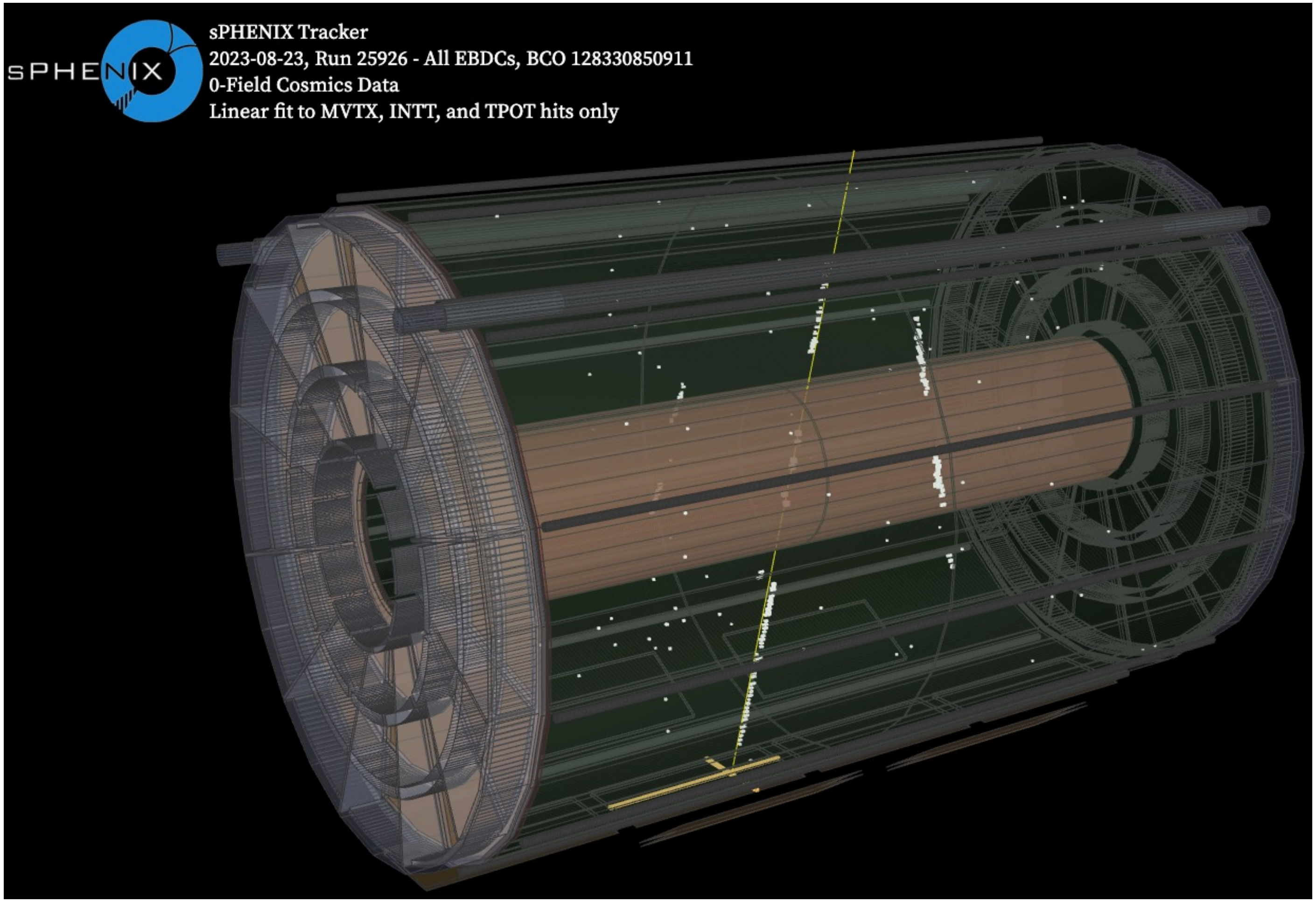
Cosmic Ray Event Display



- Cosmic muon events display of the sPHENIX tracking system without B field
- HCAL coincident trigger required
- Clear straight-line track

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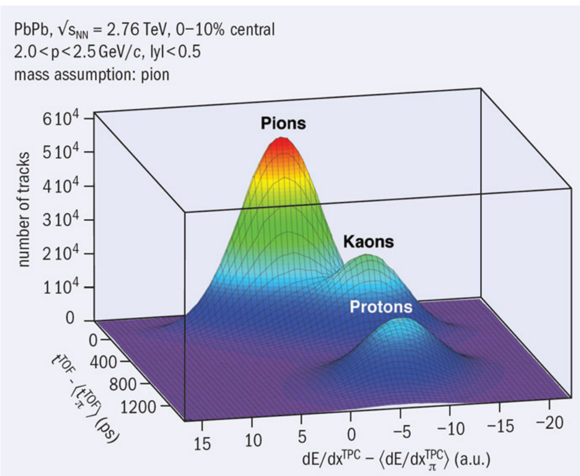
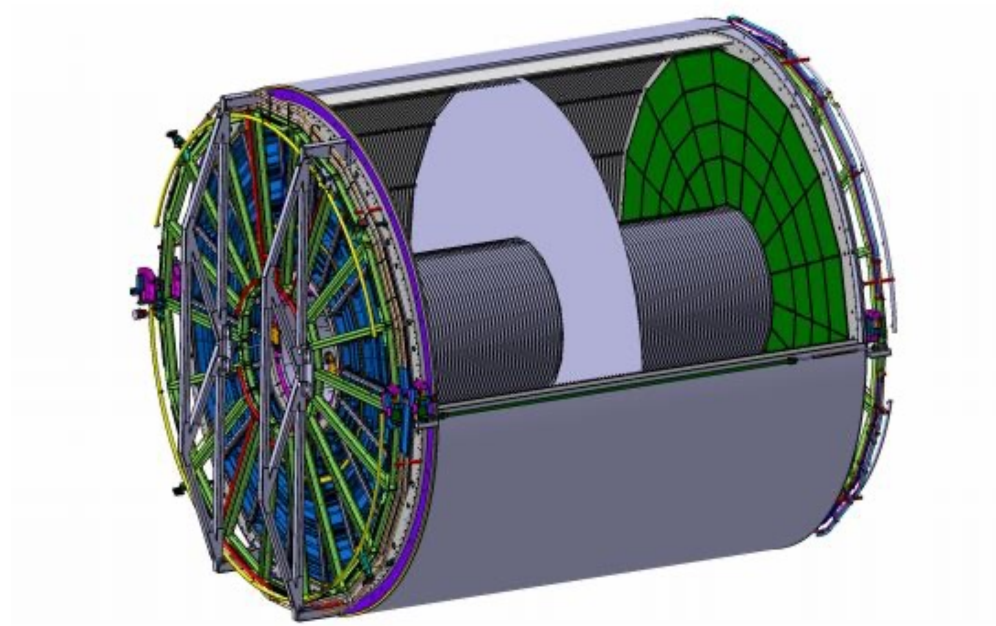
Particle Identification

Particle Identification

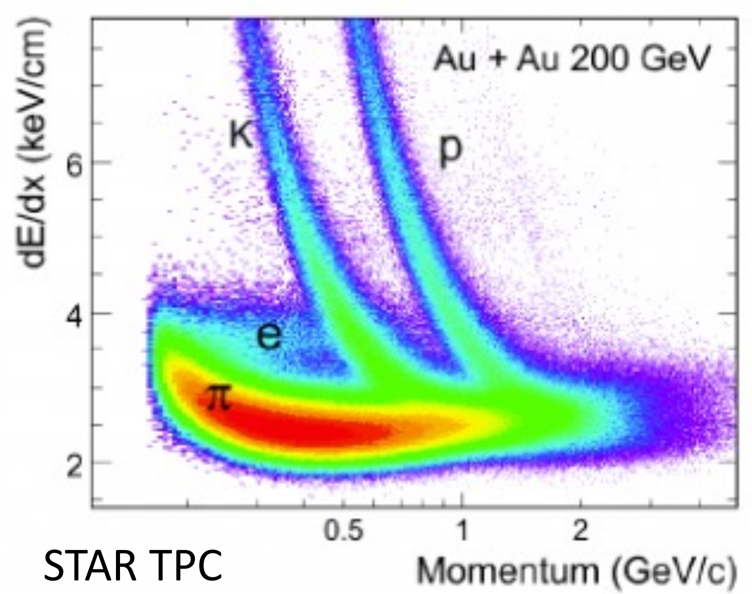




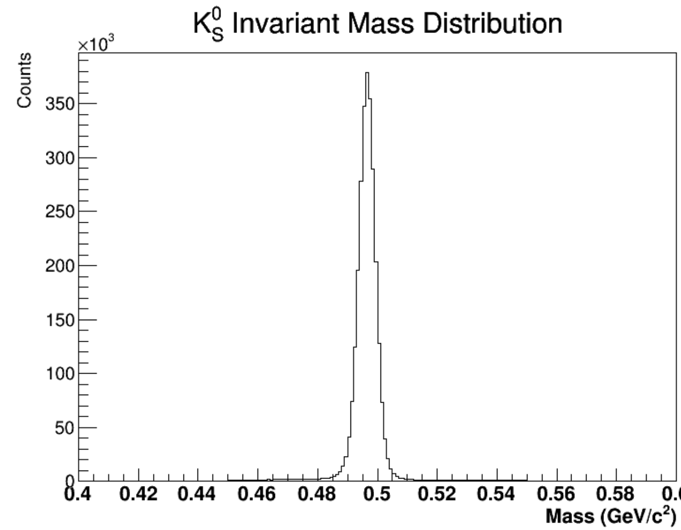
Past Experience

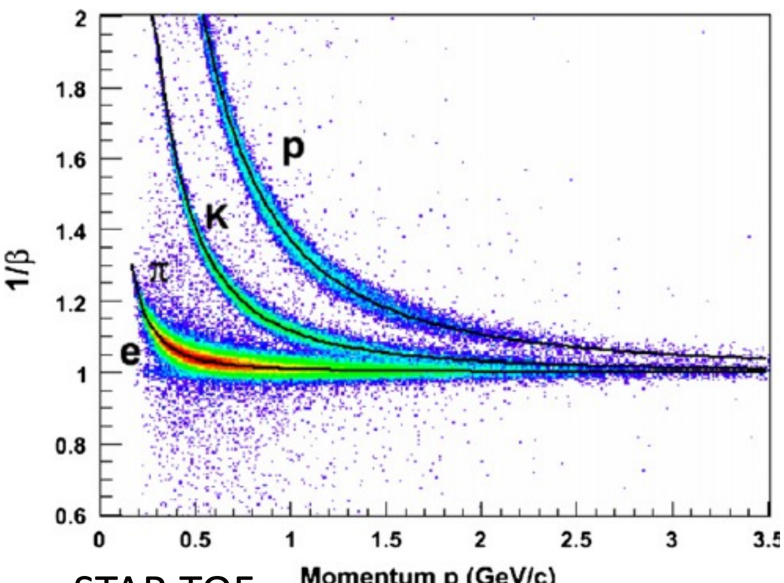
- Physics performance
- CMS Silicon Strip dE/dx Calibration

PID Performance with STAR TPC and TOF



STAR TPC





STAR TOF

- Excellent separation of charged particles: e, π, K, p
- Crucial for heavy ion physics studies
- Reconstruct $K_S^0 \rightarrow \pi^+\pi^-$

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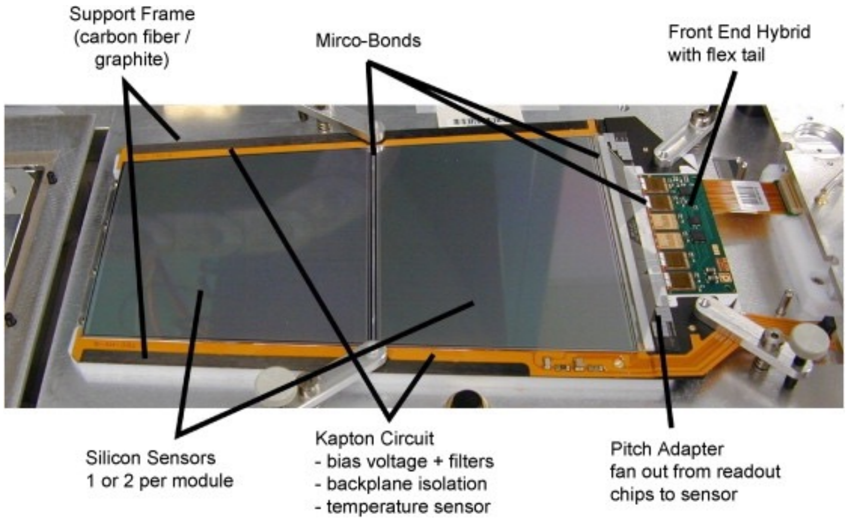
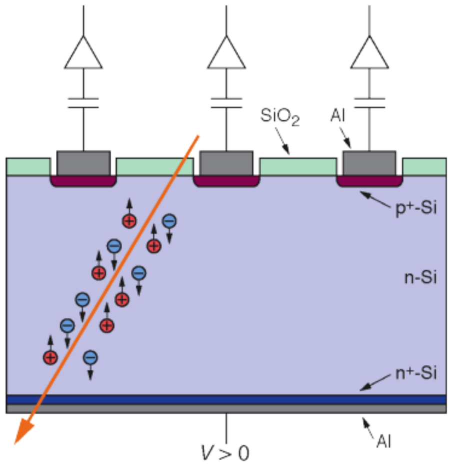
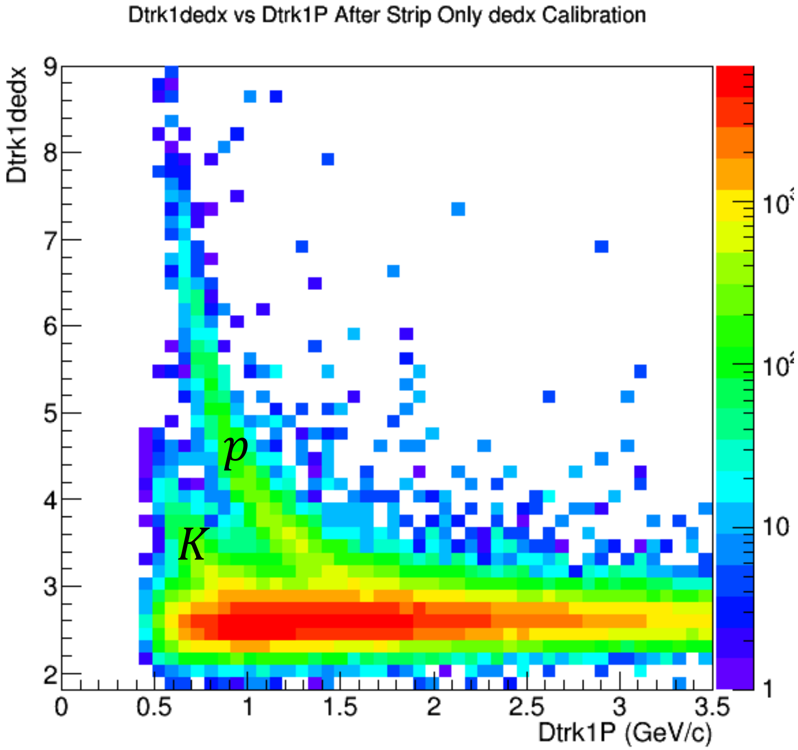
CMS Silicon Detector dE/dx Calibration







- Possible separation of protons but not pions from kaons
- Limited hadron PID capabilities of the CMS silicon tracker

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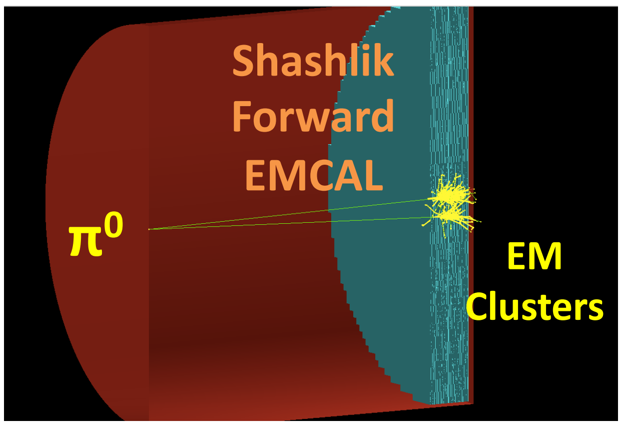
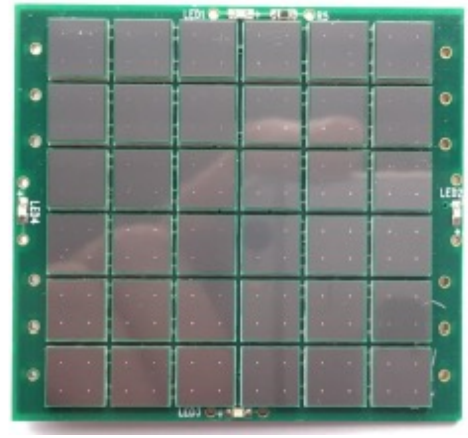
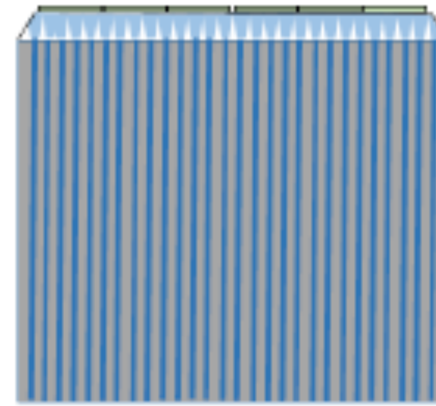
Calorimetry

Calorimetry

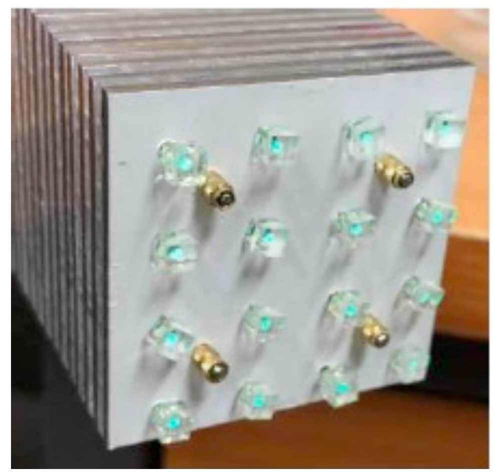


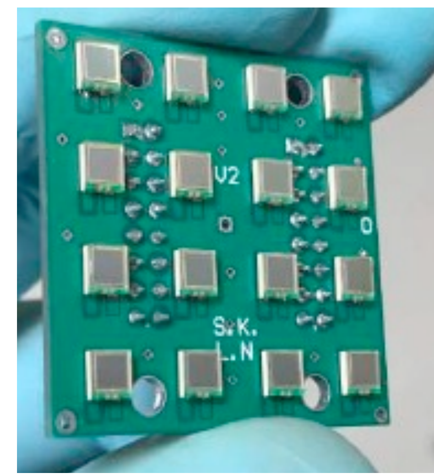
W/SciFi SPECAL Design





Shashlik Design

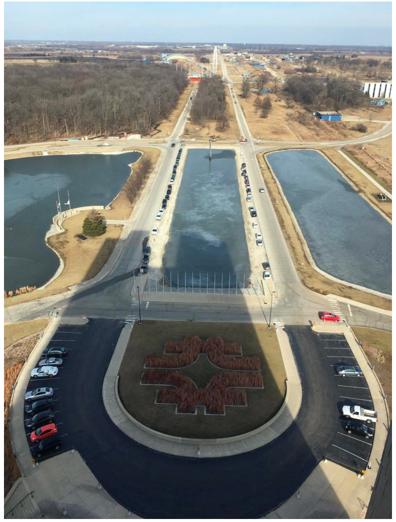




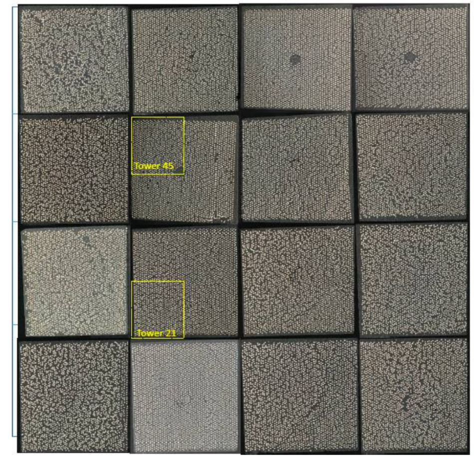
Past Experience

- Fermilab Test Beam Studies of sPHENIX EMCAL
- EIC Forward EMCAL R&D

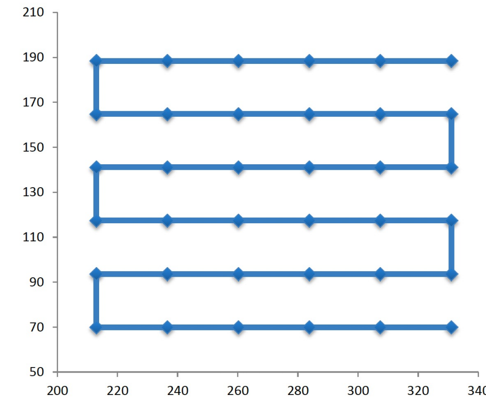
sPHENIX EMCAL Test Beam at Fermilab



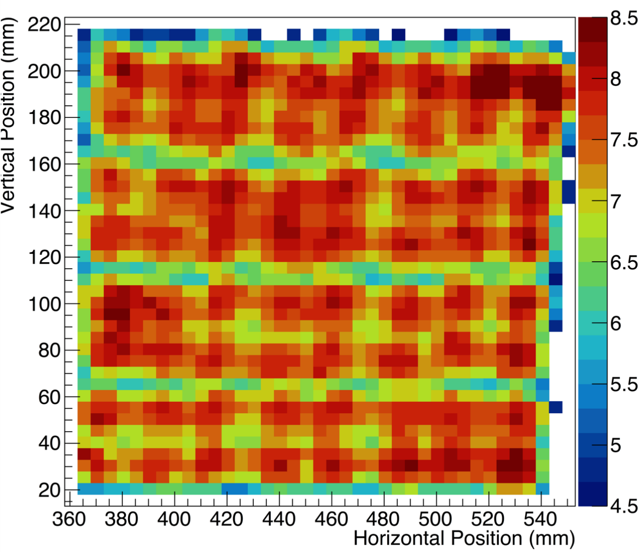
16 EMCAL Block structure



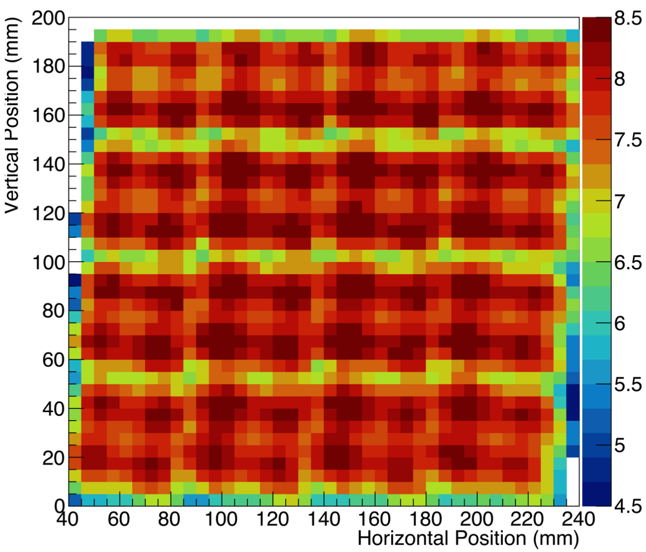
Position Scan Path



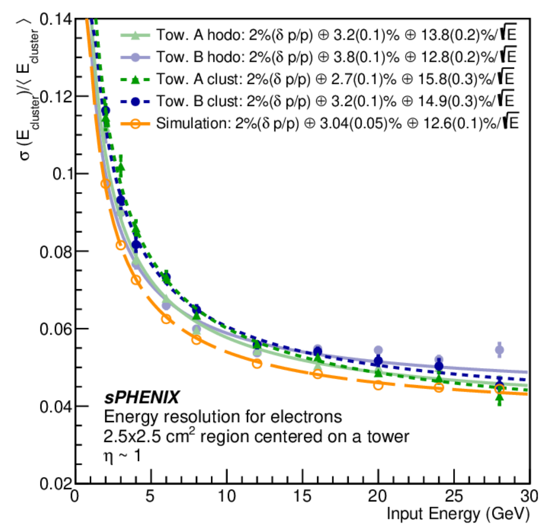
Data



Simulation



Energy Resolution



IEEE Trans. Nucl. Sci, (No. TNS-00239-2020.)

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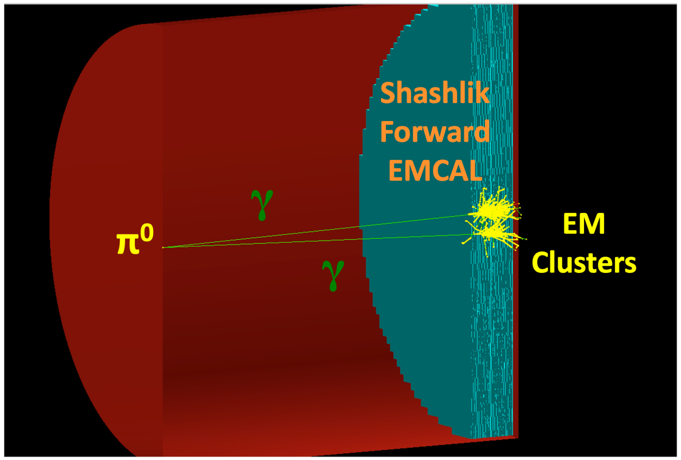
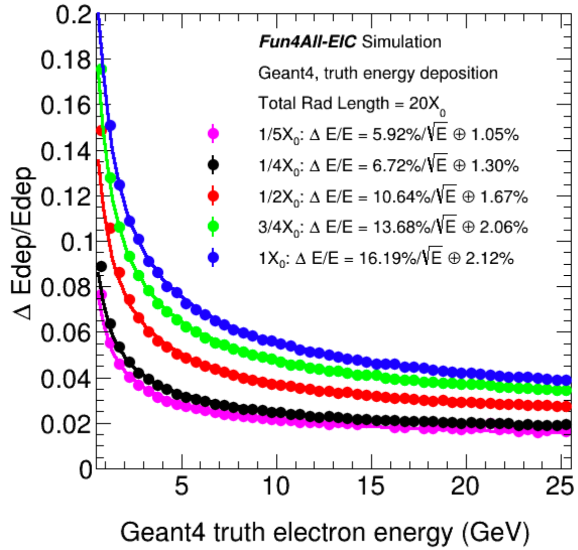
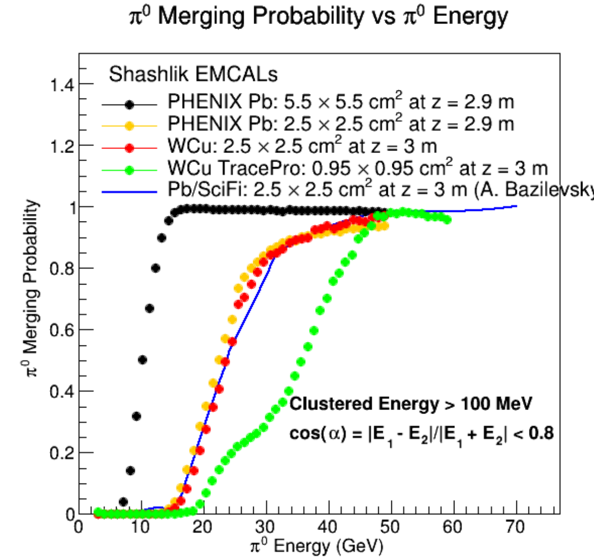
EIC Forward Shashlik EMCAL R&D

EIC Hadron-Going Direction



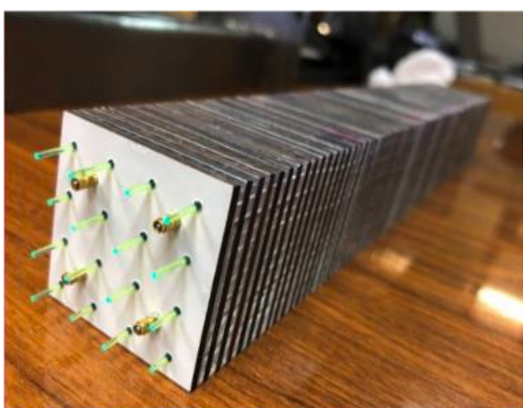


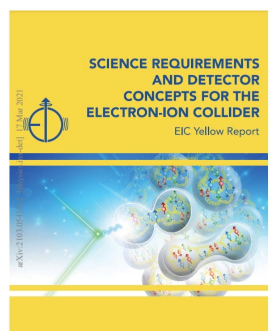


EIC Yellow Report Nucl. Phys. A 1026 (2022) 122447

Z.Shi, J. Lajoie, C. Woody, and I. Delk, EPJ Web Conf. 276 (2023) 05001

Shashlik Tower Design





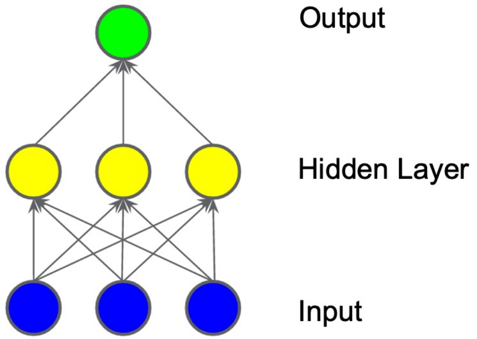
U.S. DEPARTMENT OF ENERGY

Office of Science

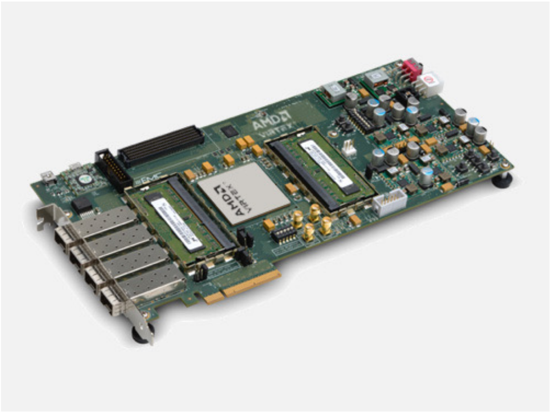
Office of Science Graduate Student Research (SCGSR) Program

Cutting-Edge Technologies

Machine Learning (ML)



Field Programming Gate Array (FPGA) Integrated Circuit



High Performance Computing (HPC)

- Application of the latest technologies to achieve physics goals
  - Obtain better results in a shorter time

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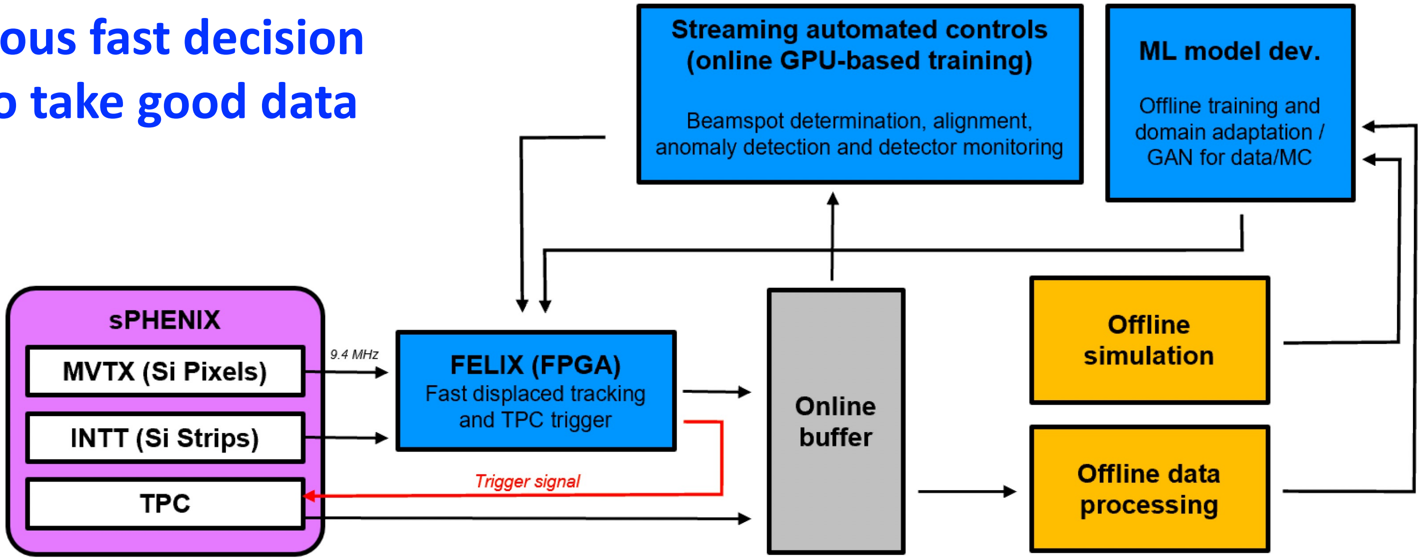
Fast ML Trigger Development

Autonomous fast decision making to take good data



2021 — Project Started

2022

2023 — First AuAu Data Taking

2024 — Deployed for pp Taking

2025 — Last year of Large AuAu Data Taking

2030+ — Deploy AI Device

Phase I: sPHENIX at RHIC

Phase II: EIC

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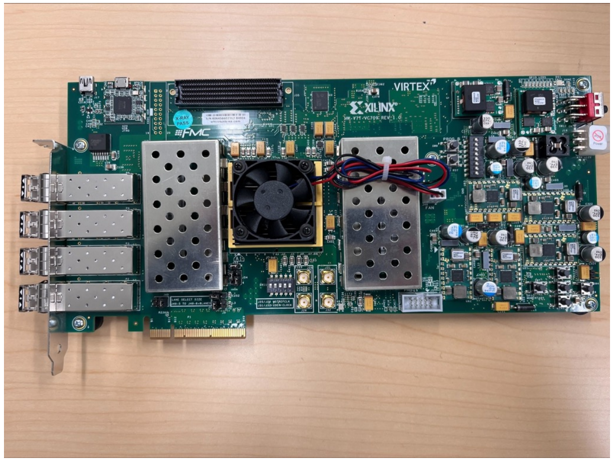
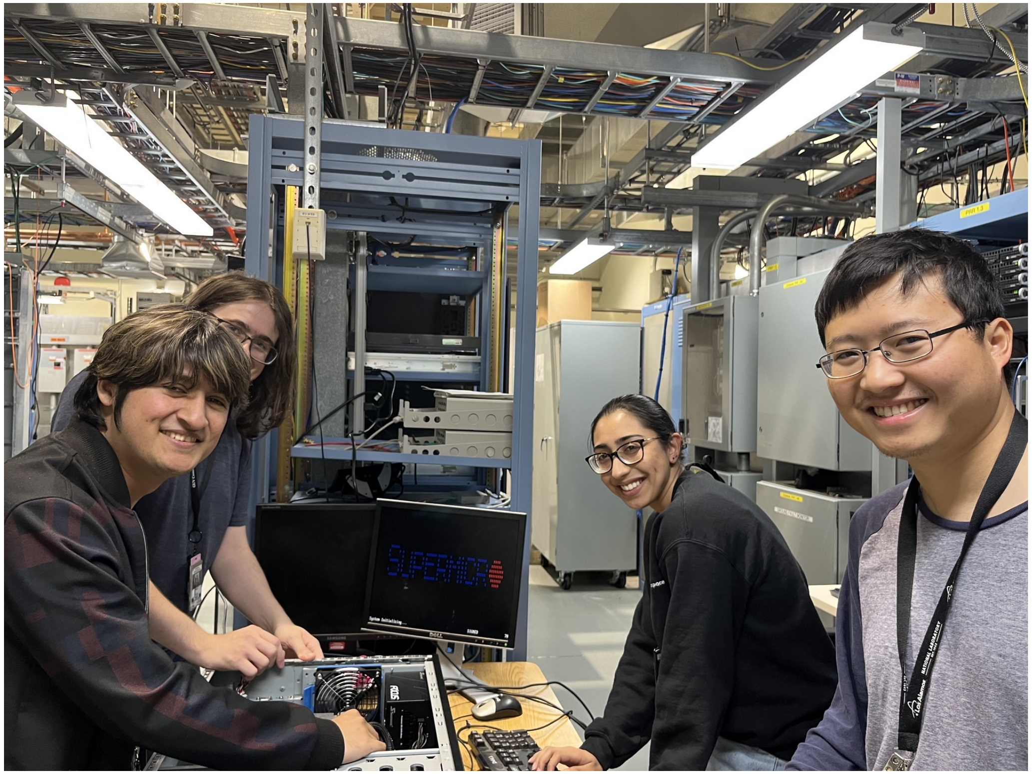
Field Programming Gate Array (FPGA)

FPGA Evaluation Board



Mentor 3 UConn Students at BNL



LABORATORY DIRECTED RESEARCH & DEVELOPMENT

- Secured LANL LDRD grant to purchase a FPGA evaluate board hardware
- Supervised with 3 UConn students to install the setup at BNL

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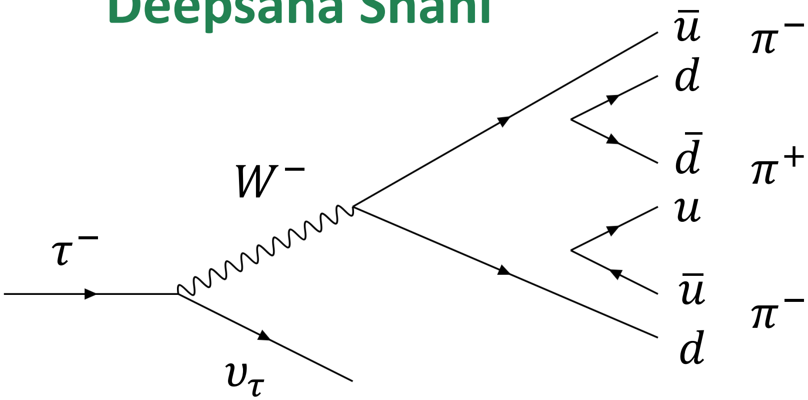
High Performance Computing

THE UNIVERSITY OF ARIZONA

Deepsana Shahi

Hadronic Tau Decay, for instance,
$\boldsymbol{\tau^- \rightarrow \upsilon_\tau \pi^- \pi^+ \pi^-}$



- Principal Investigator: LANL Tier_1 high performance computing resources: Chicoma/CPU and Chicoma/Rome GPU
- Created guest account for my Physics PhD student Deepsana Shahi from the University of Arizona for machine learning model development

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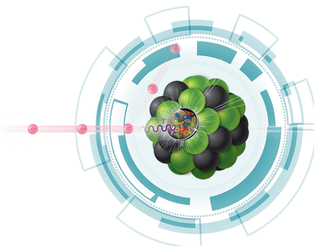
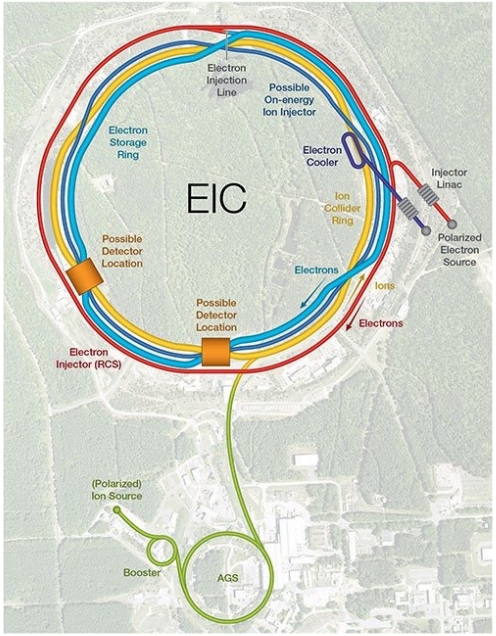
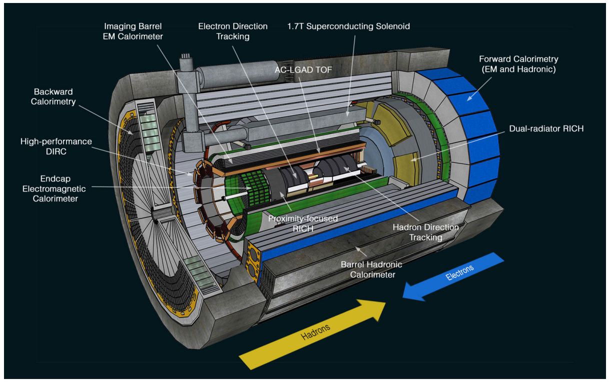
Future Opportunities

Electron-Ion Collider



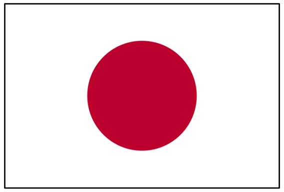
ePIC

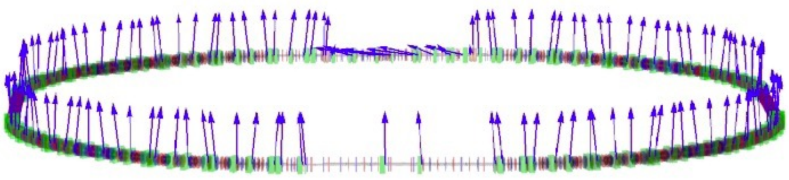




- High luminosity and highly polarized beams

SuperKEKB Upgrade





Snowmass 2021 White Paper
Upgrading SuperKEKB with a Polarized Electron Beam:
Discovery Potential and Proposed Implementation

April 13, 2022

US Belle II Group [1]
and
Belle II/SuperKEKB e- Polarization Upgrade Working Group [2]

Snowmass 2021

Belle II++

Credit: Francesco Forti, Virginia Tech

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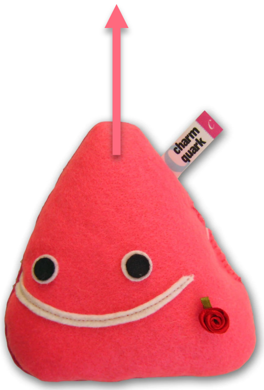
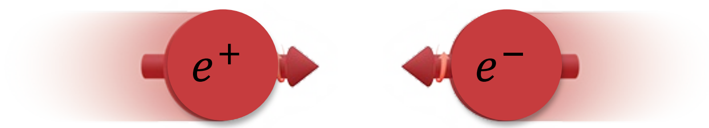
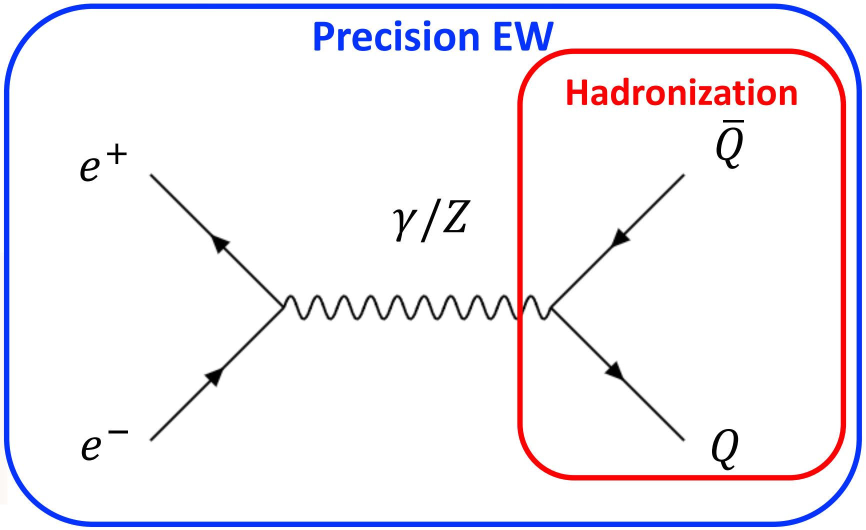
Spin Degree of Freedom

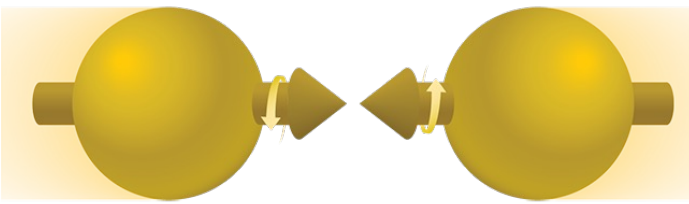


Polarized SuperKEKB

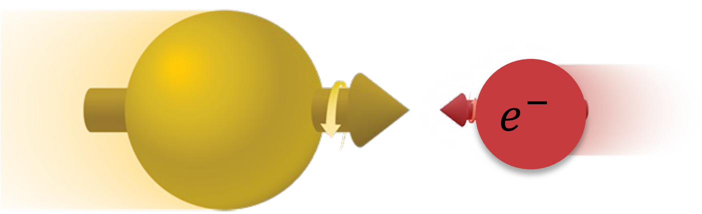


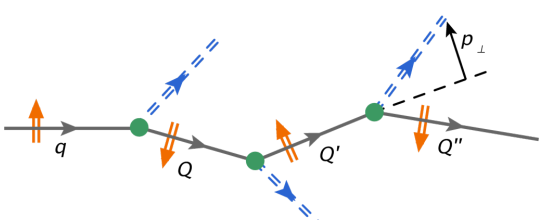


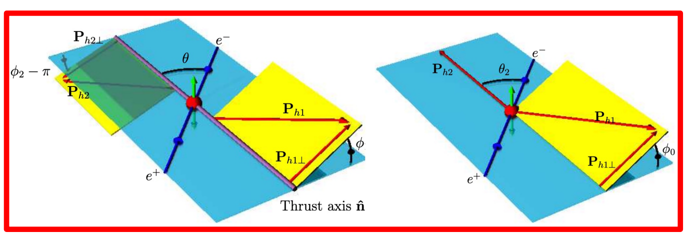
RHIC: $p^{\uparrow}p^{\uparrow}$



EIC: ep







$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Spin studies through polarization of the beams

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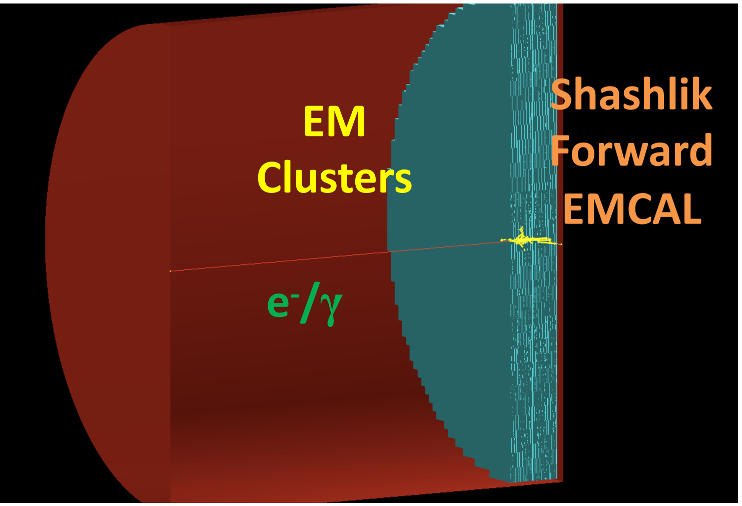
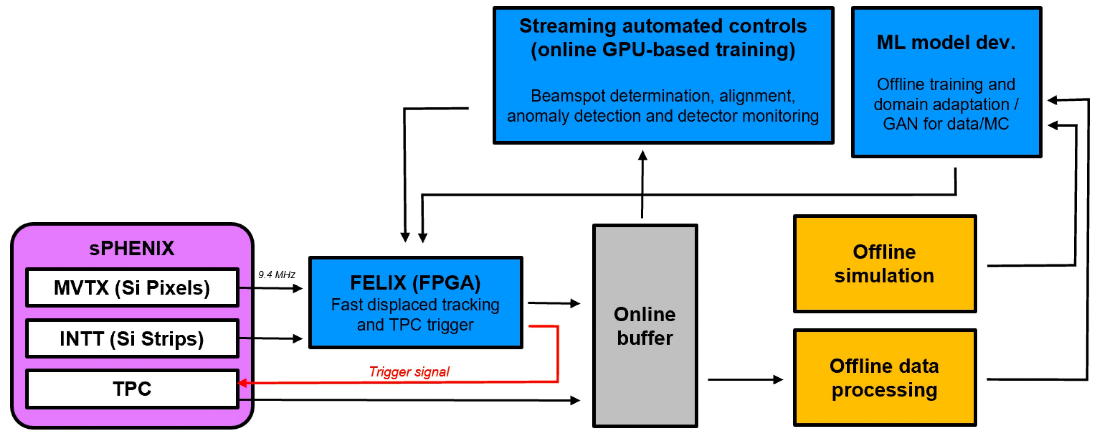
Future Detector Projects for the EIC

EIC Forward EMCAL



Fast ML for the EIC



- Many future detector R&D opportunities at the EIC with the application of latest technologies including ML, FPGA, and HPC

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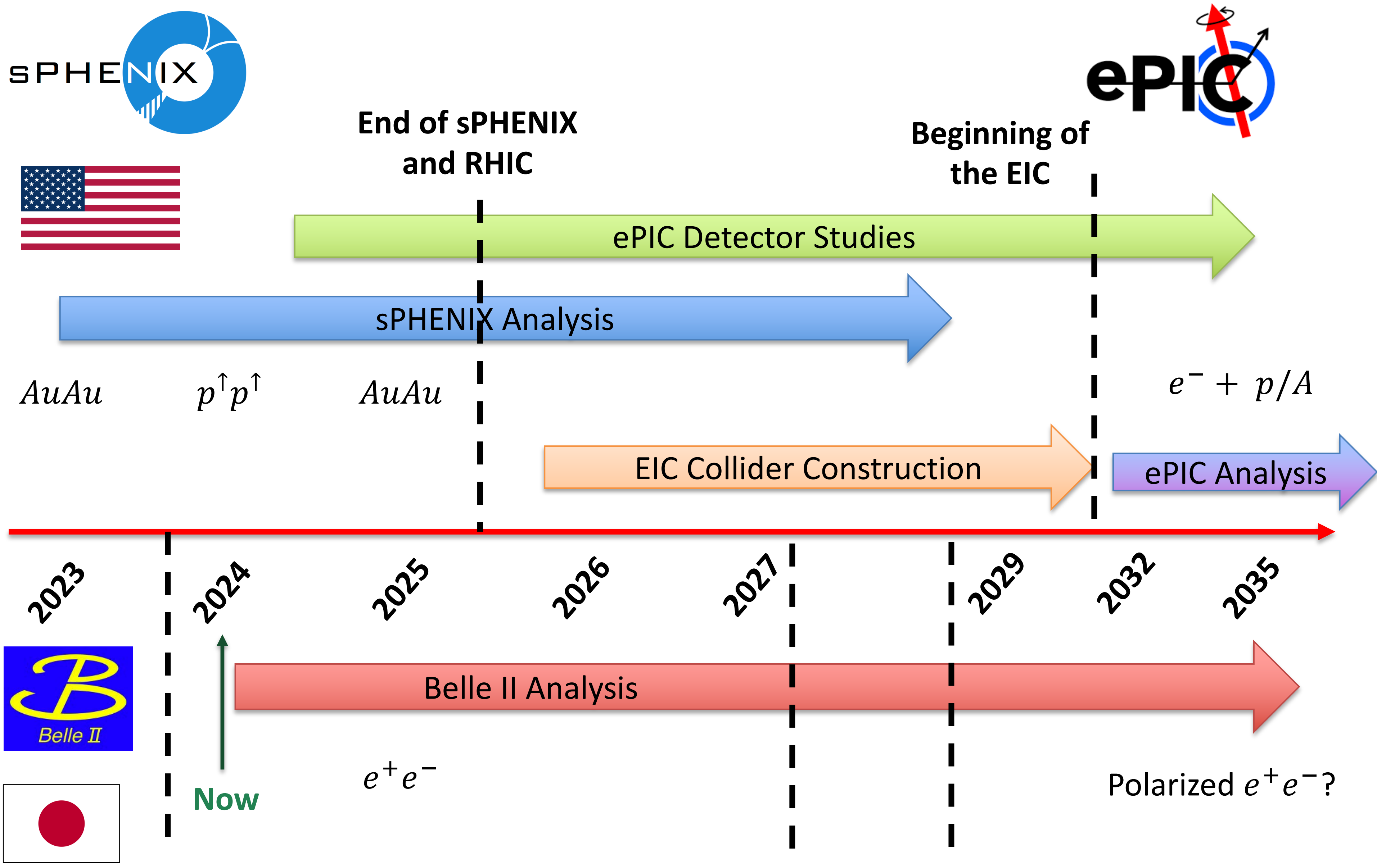
Timeline



sPHENIX
End of sPHENIX and RHIC
Beginning of the EIC
ePIC
ePIC Detector Studies
sPHENIX Analysis
$AuAu$
$p^{\uparrow}p^{\uparrow}$
$AuAu$
$e^{-} + p/A$
EIC Collider Construction
ePIC Analysis
2023
2024
2025
2026
2027
2029
2032
2035
Belle II
Belle II Analysis
Now
$e^{+}e^{-}$
Polarized $e^{+}e^{-}$?
LS1
LS2

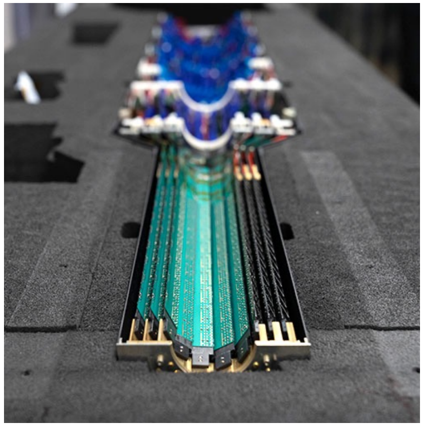
Summary

Heavy Flavor Physics

- Fascinating features: CP violation, exotic hadron, and above Λ_{QCD}, potential BSM physics
- Studies at high energy colliders from e^+e^- to AA

Instrumentation

- Detector technologies: tracking, PID, calorimeters
- Accelerator studies: beam background issues at RHIC and LHC
- Cutting-edge technologies: ML, FPGA, and HPC



Future Opportunities

- EIC in the U.S. and SuperKEKB upgrade in Japan
- Physics related to spin polarization
- Detector R&D projects with ML and FPGA
- Synergy between physics and electrical engineering

ePIC

Belle II

Many exciting opportunities in the high luminosity and highly polarized beam era to explore in the flavorful universe in the next decades!

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Thank You

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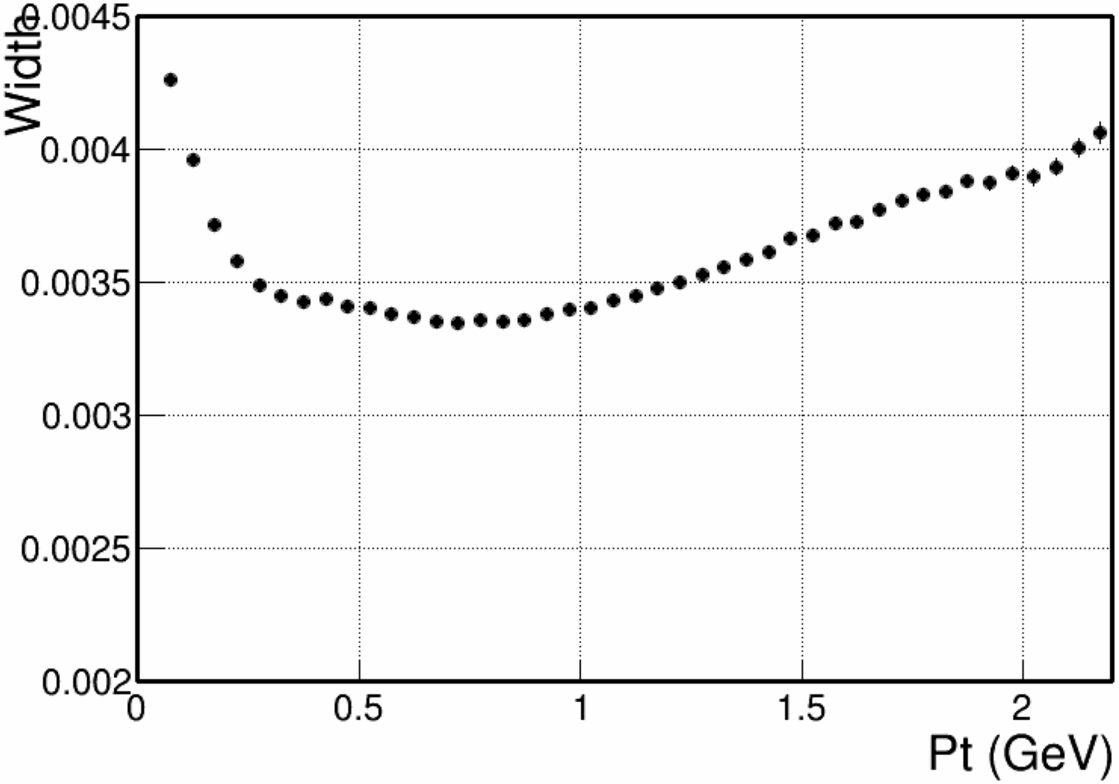
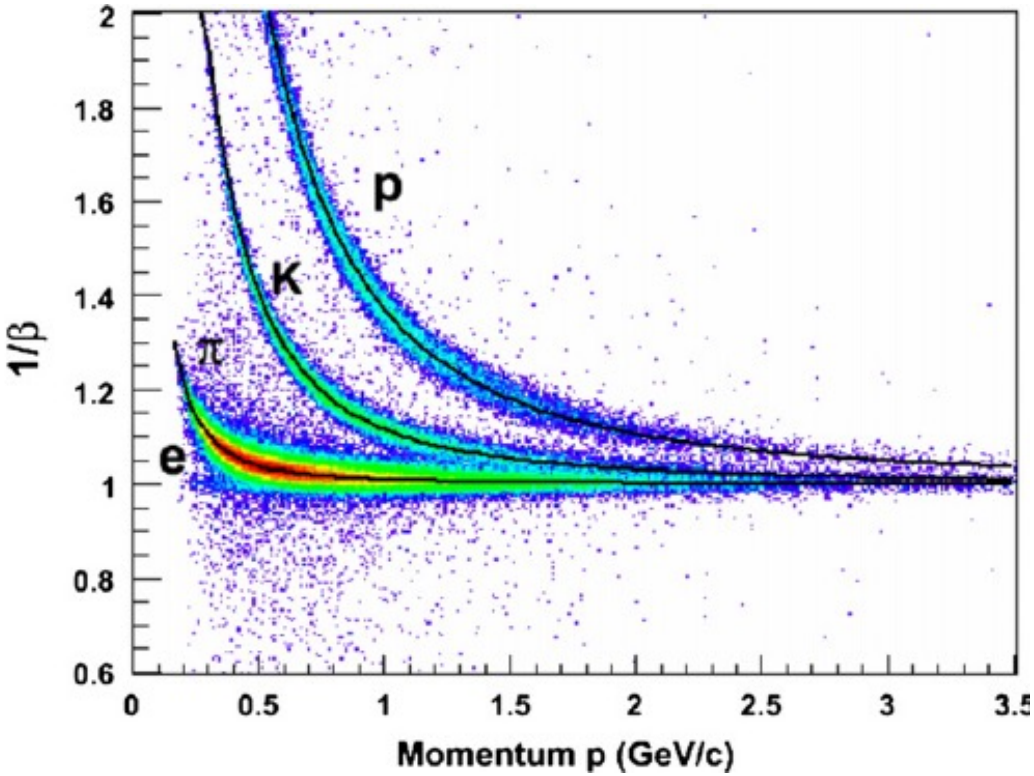
Back Up

STAR Tracking Performance



- Excellent momentum resolution for reconstructed K_S^0 in the level of 5 MeV
- Track Quality Selection in the K_S^0 analysis:
  - TPC Fit Points ≥ 20
  - At least 1 hit per HFT layer
  - DCA to primary vertex > 0.1 cm

PID Performance



- Excellent π, K, p separation performance for the STAR TOF
- In the K_S^0 analysis, we apply
  - $\left|\frac{1}{\beta} - \frac{1}{\beta_\pi}\right| < 0.04$ if β > 0
  - If no physical β, then $|n\sigma_\pi|$< 3

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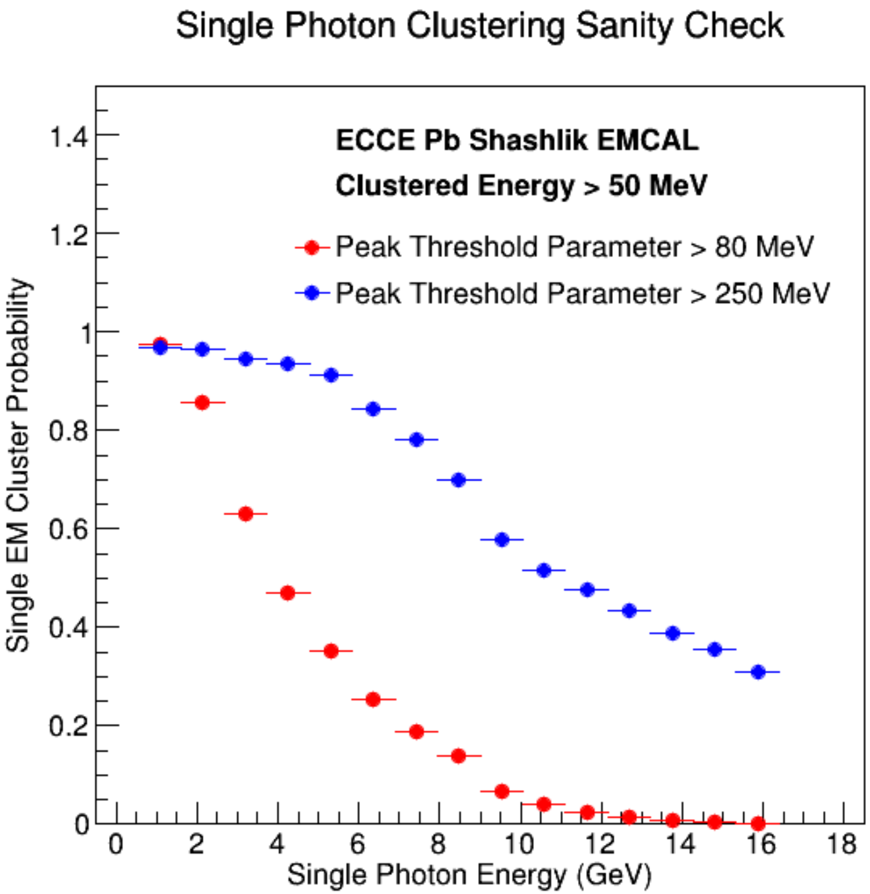
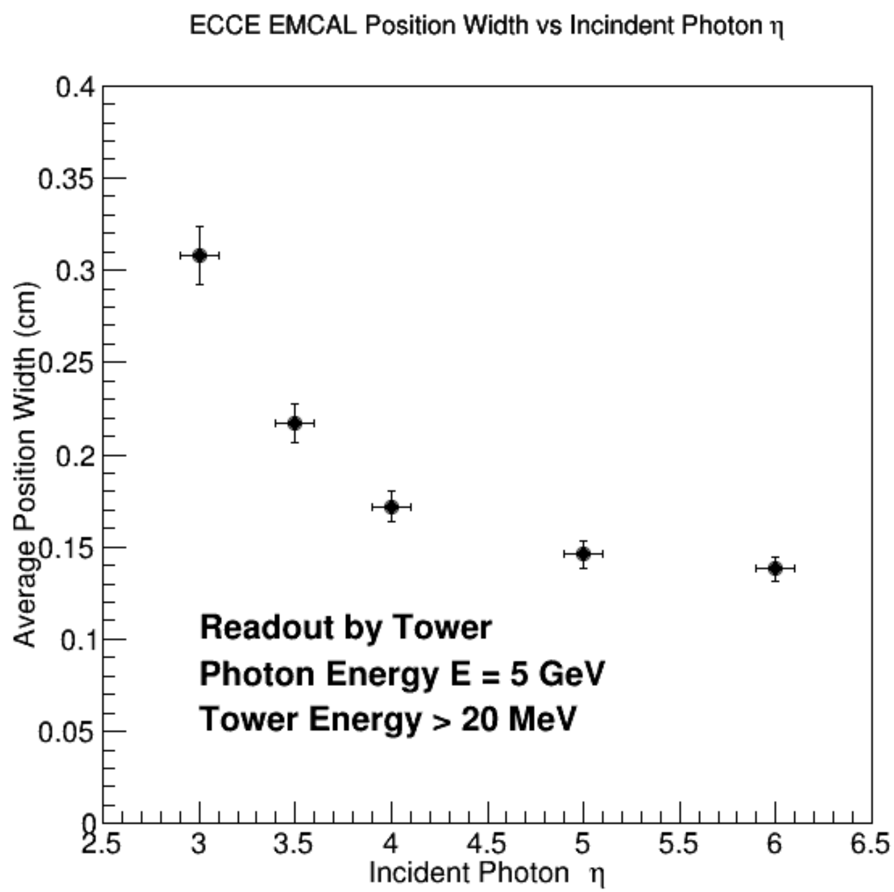
Further Improvement for the EIC

Clustering Algorithm



2D Projective Design



- Application of machine learning to optimize clustering algorithm
- Potential benefit with a projective tower design even for the EIC hadron-going direction

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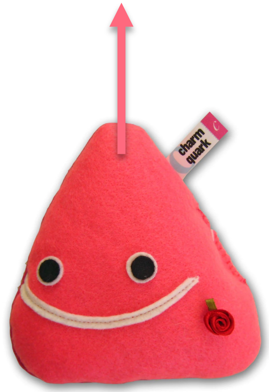
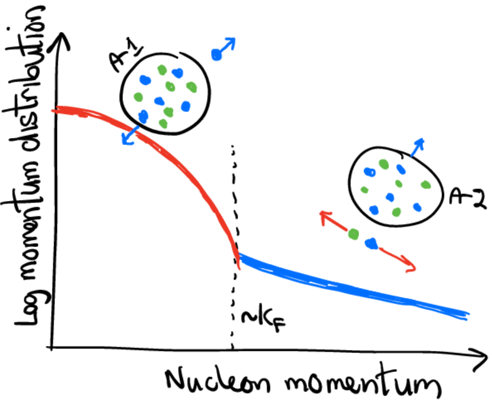
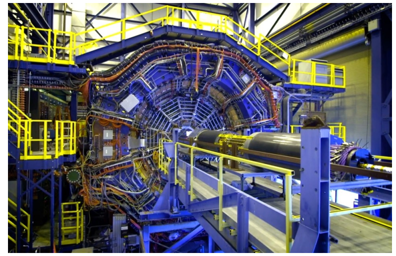
Spin Degree of Freedom

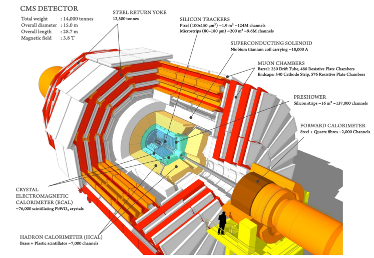


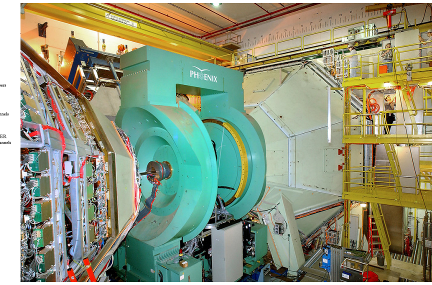
- Quarks as spin 1/2 fermion carry spin and will evolve
- Spin evolution from initial to final state is also interesting
  - $|S_Q(t_0)\rangle \rightarrow |S_Q(t_1)\rangle$
- Can determine
- Interesting phenomena like Collin's effect related to quark spin
- *EvtGen* implementation of hadron interaction with detector
  - Existing implementation of heavy flavor decay with sPHENIX
  - Further integration of spin polarization effect

Heavy Ion Physics

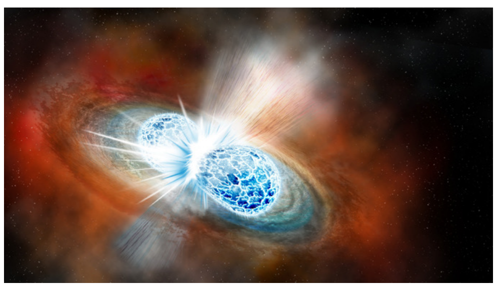


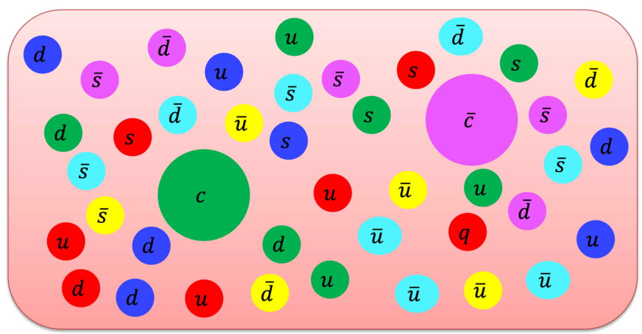


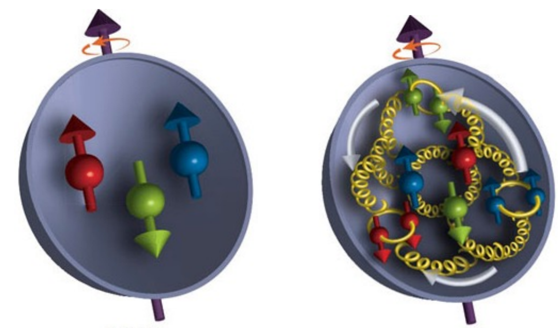




Neutron Star **Quark-Gluon Plasma** **Proton**







1980s now

- Main purpose to use heavy quarks to study complex QCD systems
  - Traversing the flavorful universe: a journey from isospin to bottomness
  - Eventually understand how phenomena like as small as nucleons and as large as neutron star arise from QCD
- Alternative it can contribute to heavy quark physics?

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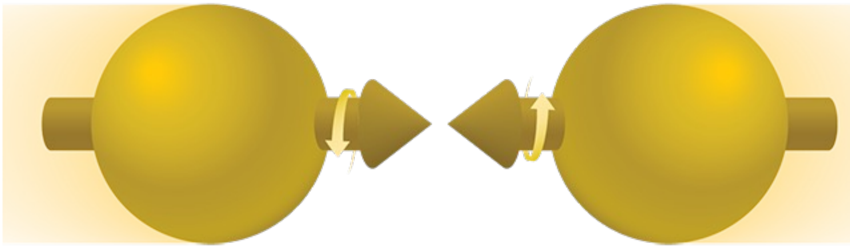
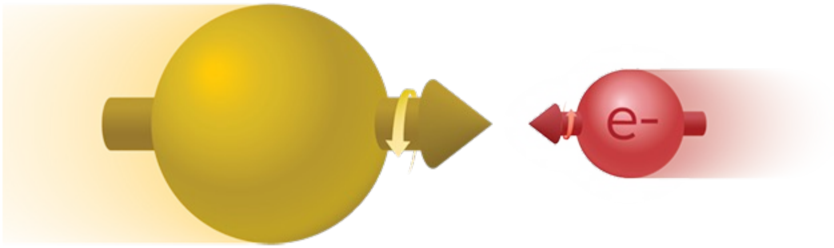
Polarized Colliders

BEPC and KEKB

RHIC: $p^{\uparrow}p^{\uparrow}$



EIC: ep



$$|S_e\rangle = \alpha|L\rangle + \beta|R\rangle$$

$$|\alpha|^2 + |\beta|^2 = 1$$

$$|S_Q\rangle = \gamma|L\rangle + \delta|R\rangle$$

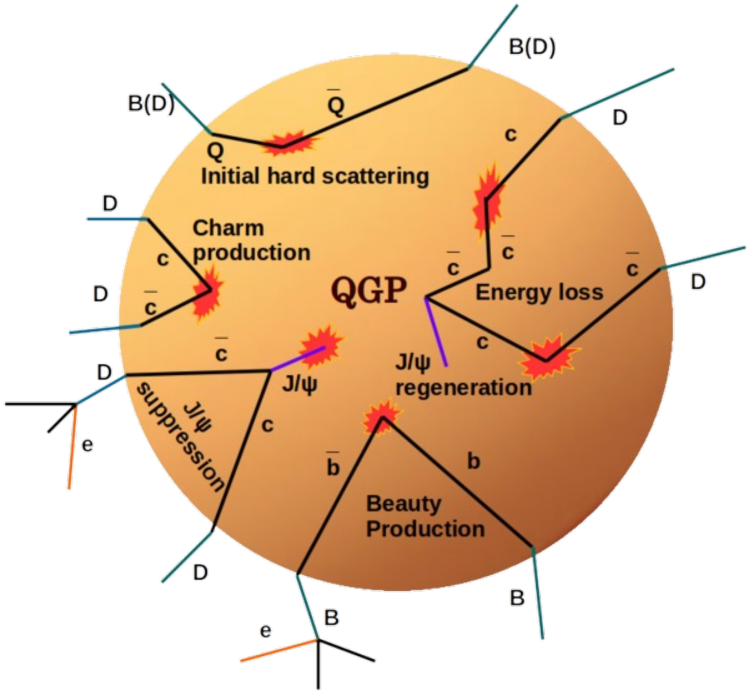
Single Spin Asymmetry (TSSA)

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

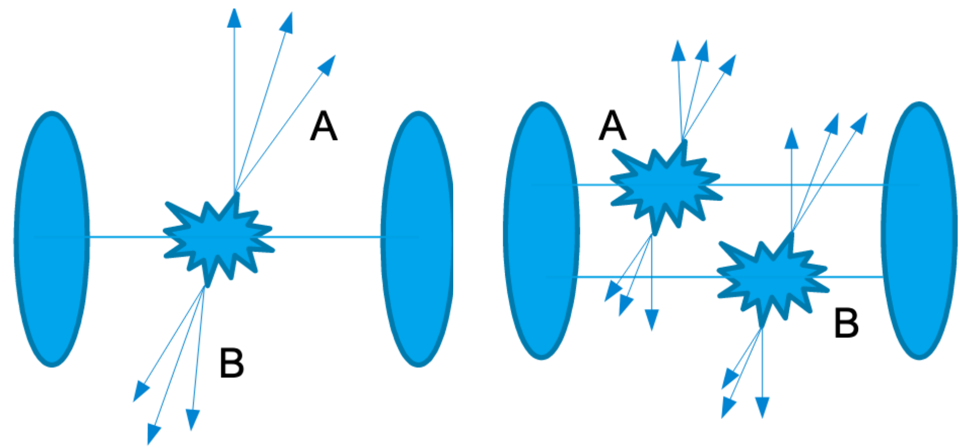
- Polarization: fix α and β to determine the outgoing quark spin state
- Chiral Belle: Belle II polarization: precision electroweak studies in e^+e^-
- Polarized RHIC ($p^{\uparrow}p^{\uparrow}$) and EIC (ep/eA): spin structure of hadrons

Heavy Quark in Heavy Ion Collisions

Probe the Transport Properties of QGP



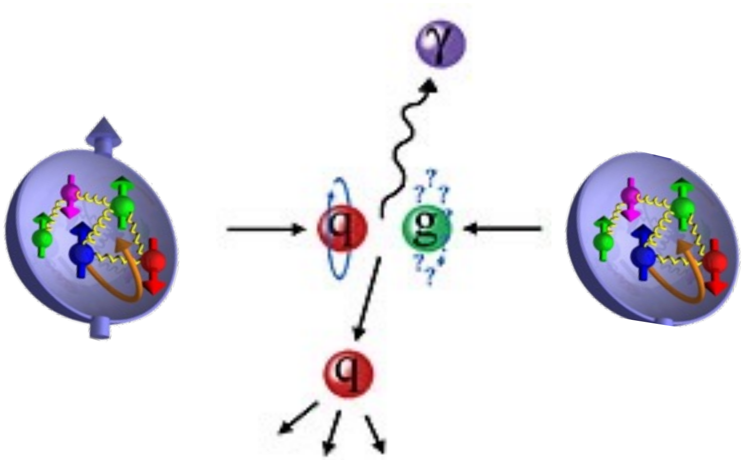
Multiparton Interaction (MPI)



- Controlled probes for QCD system
  - Initial spectral is perturbatively calculable
  - Flavor tagging: interact with QCD system before decay

Experimental Observable

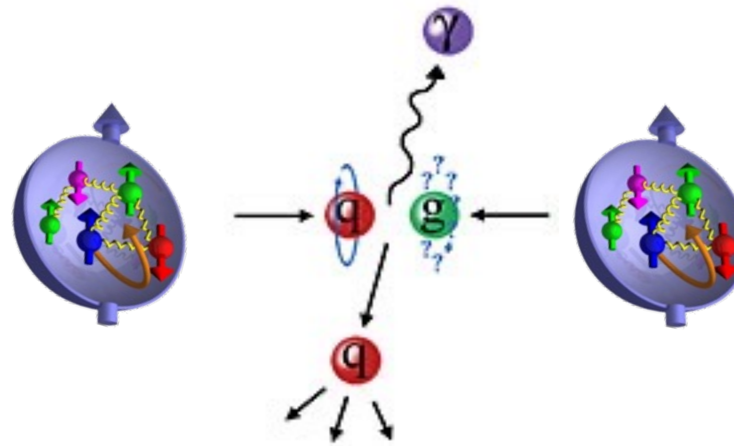
$p^{\uparrow}p$



Transverse Single Spin Asymmetry (TSSA)

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$p^{\uparrow}p^{\uparrow}$

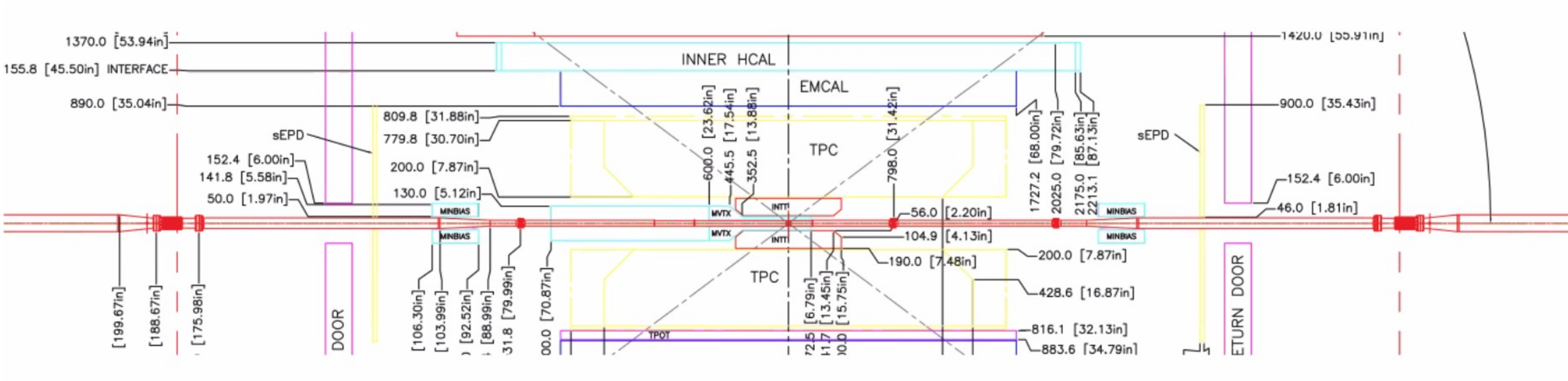


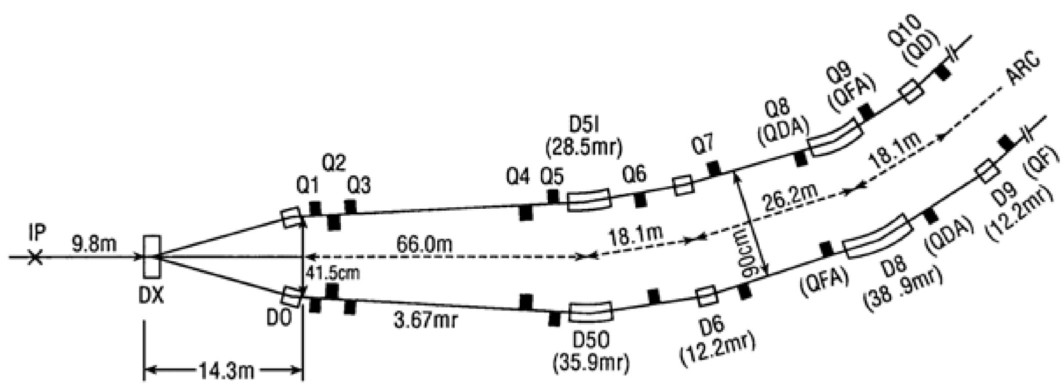
Double Spin Asymmetry

$$A_{TT} = \frac{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow} - \sigma^{\uparrow\downarrow} - \sigma^{\downarrow\uparrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow} + \sigma^{\uparrow\downarrow} + \sigma^{\downarrow\uparrow}}$$

- Extract underlying physics mechanism for specified processes

Understand from Accelerator





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