Experimental Overview of ePIC for BSM

Michael Nycz

Uncovering New Laws of Nature at the EIC

November 20-22 2024

Thank you to the many people I borrowed / adapted slides from

Introductory Remarks

- What this talk won't be: an exhaustive list of the BSM possibilities at the future EIC with ePIC
- Will hope to give a (broad) overview and capabilities of the ePIC detector that may be helpful in future studies

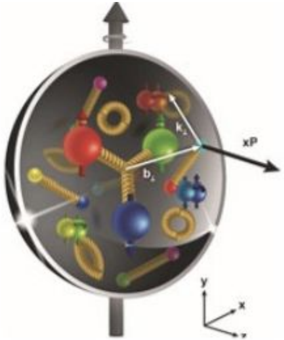
My apologies if I missed something critical or overlooked a topic you had hoped to see

The Electron-Ion Collider Physics

"The Electron-Ion Collider (EIC) will address some of the most fundamental questions in science regarding the visible world, including"

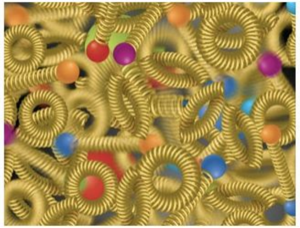
Origin of nucleon spin

Origin of nucleon mass



How are quark & gluons distributed in momentum and space

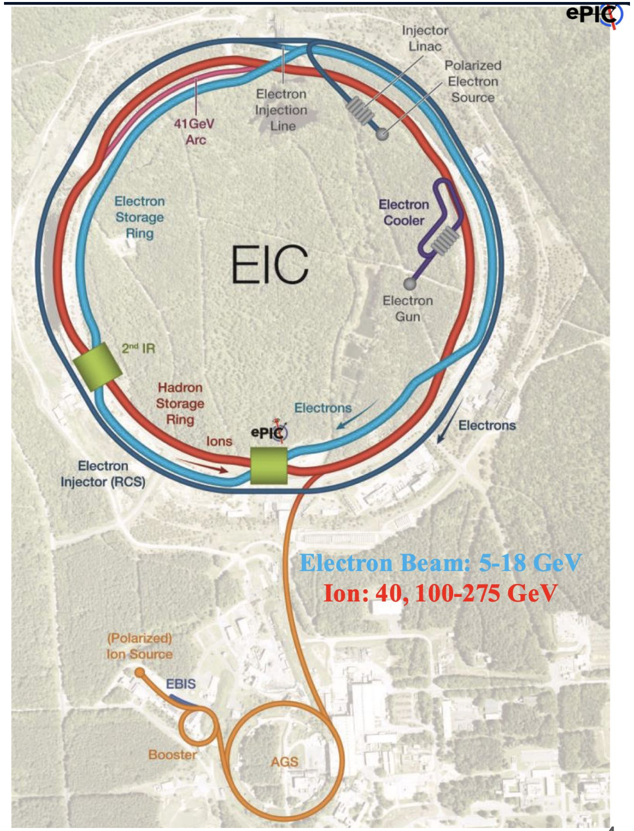
How do quarks and gluons interact with nuclear medium



What are the emergent properties of dense system of gluons

The Electron-Ion Collider

- High luminosity machine
  - (10^{33} - 10^{34} cm^{-2} s^{-1})
- Large center-of-mass energy range
  - √21-140 GeV
- Polarized e^-, protons and light ions beams
  - ≥70%
- Ions beam from deuteron to heavier nuclei
  - Gold, lead, or uranium



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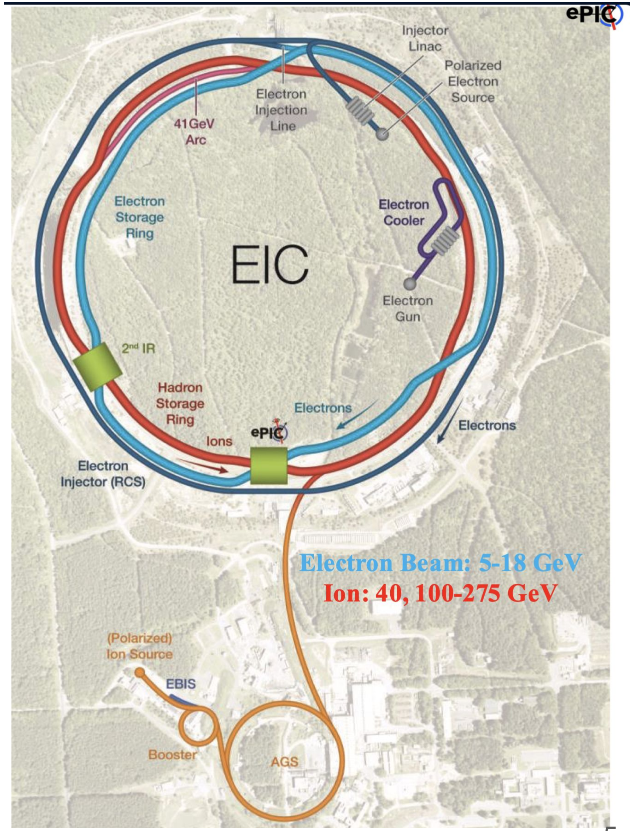
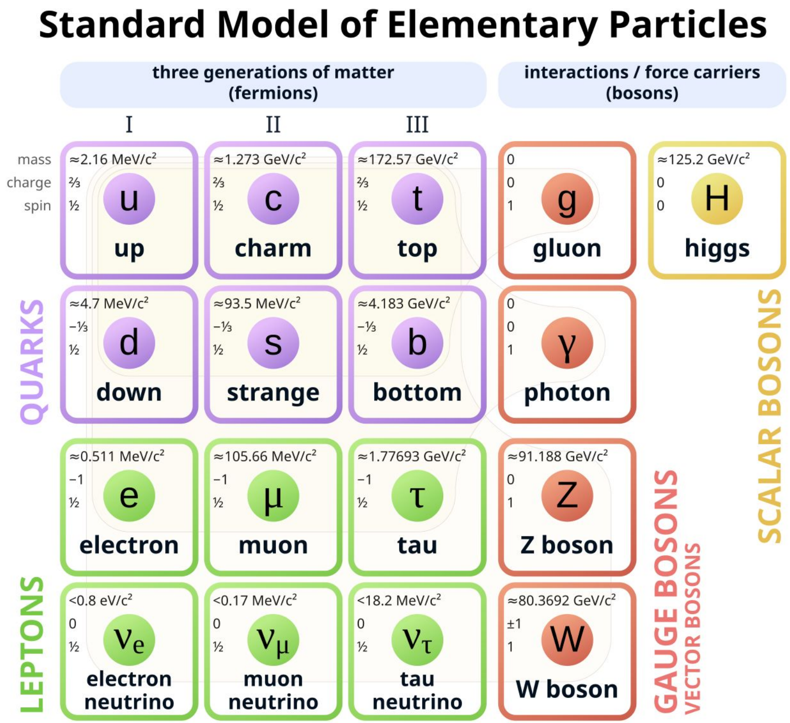
Complement a BSM (and Electroweak) physics program



The Standard Model

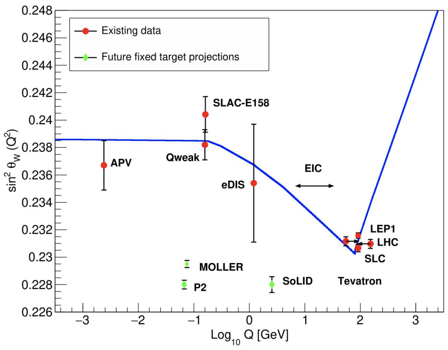


Puzzles

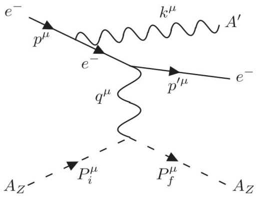
- Neutrino Flavor Oscillations
  - $m_\nu \neq 0$
- Baryon Asymmetry
- Dark Energy
- Dark Matter
- Higgs Mass Hierarchy Problem

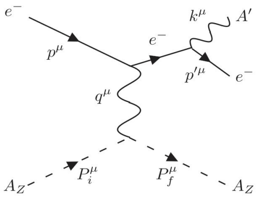
Testing The Standard Model

Precision measurements (***PVES*** / muon g-2)

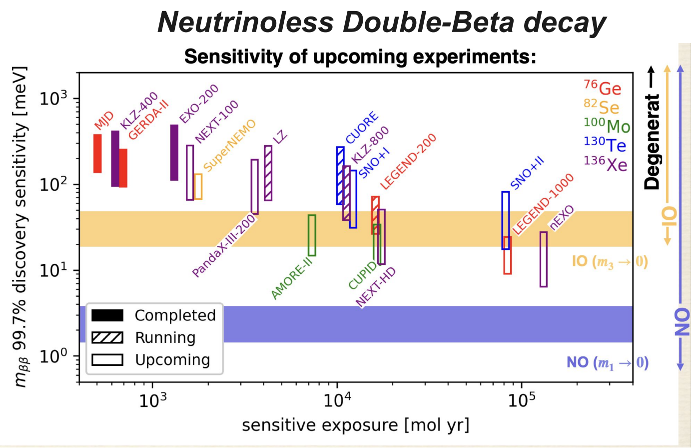


Searches of light & weakly coupled particles



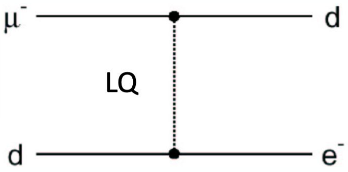


Rare / forbidden processes



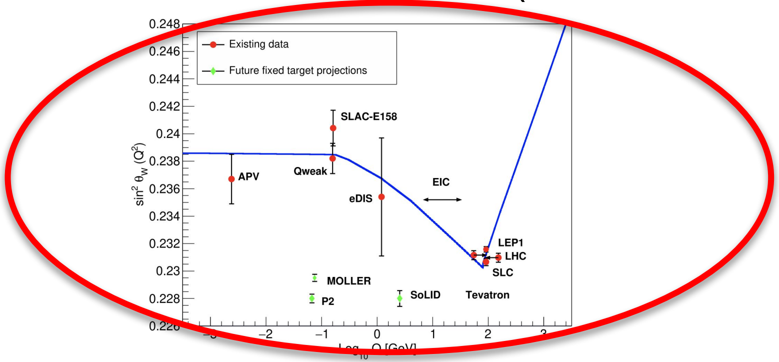
Leptoquarks

CLFV

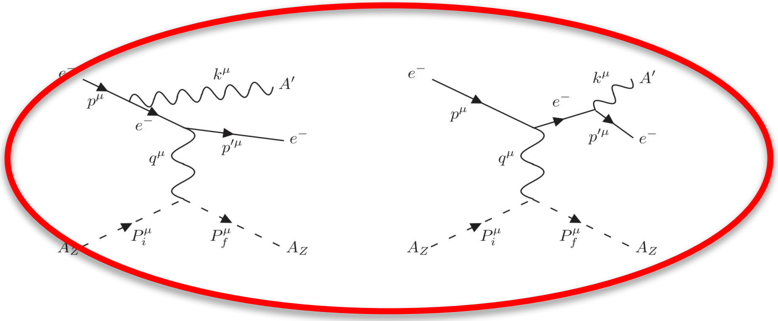


Testing The Standard Model

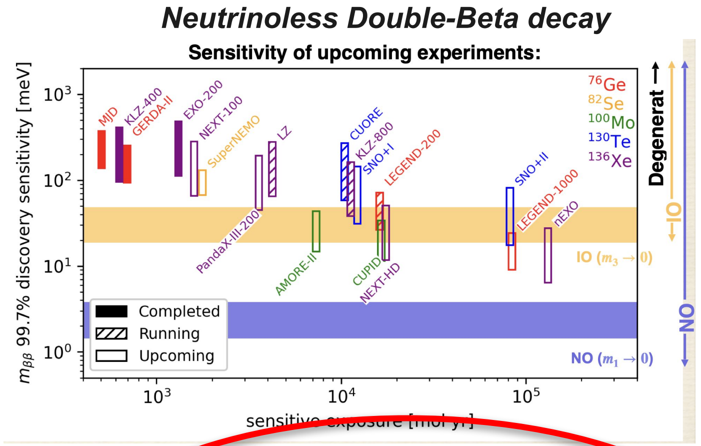
Precision measurements (***PVES*** / muon g-2)



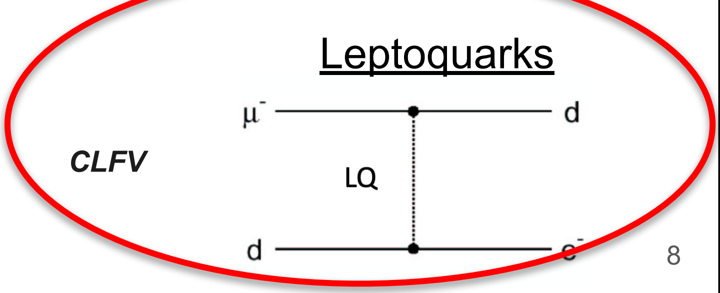
Searches of light & weakly coupled particles



Rare / forbidden processes



Leptoquarks



The ePIC **Detector**

hadronic calorimeters

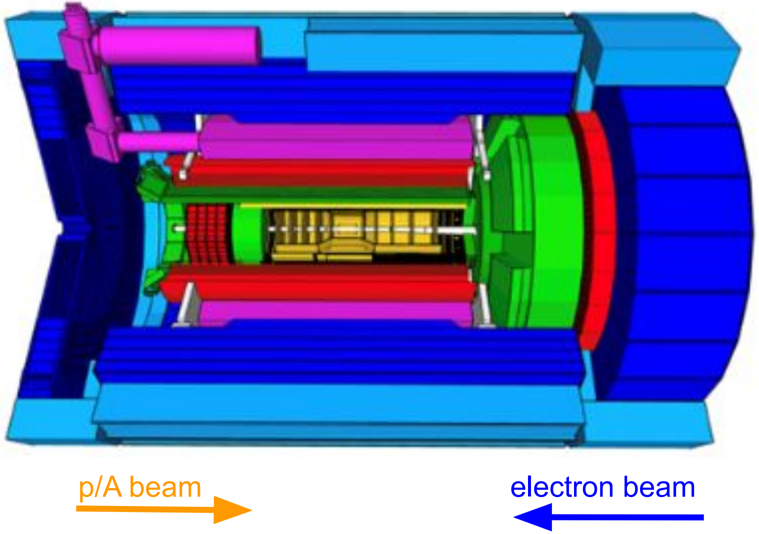
Solenoid Magnet

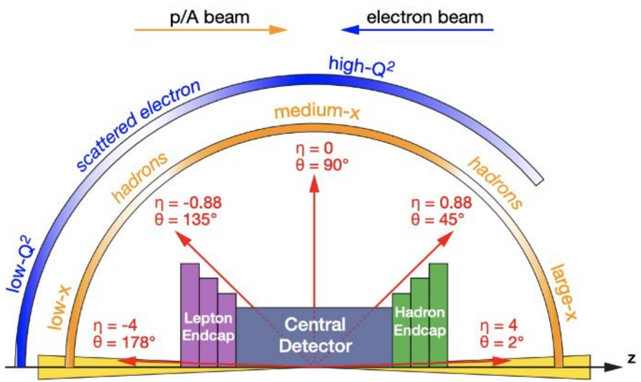
e/m calorimeters (Ecal)

Time of Flight
DIRC
Rich Detectors

MPGD trackers

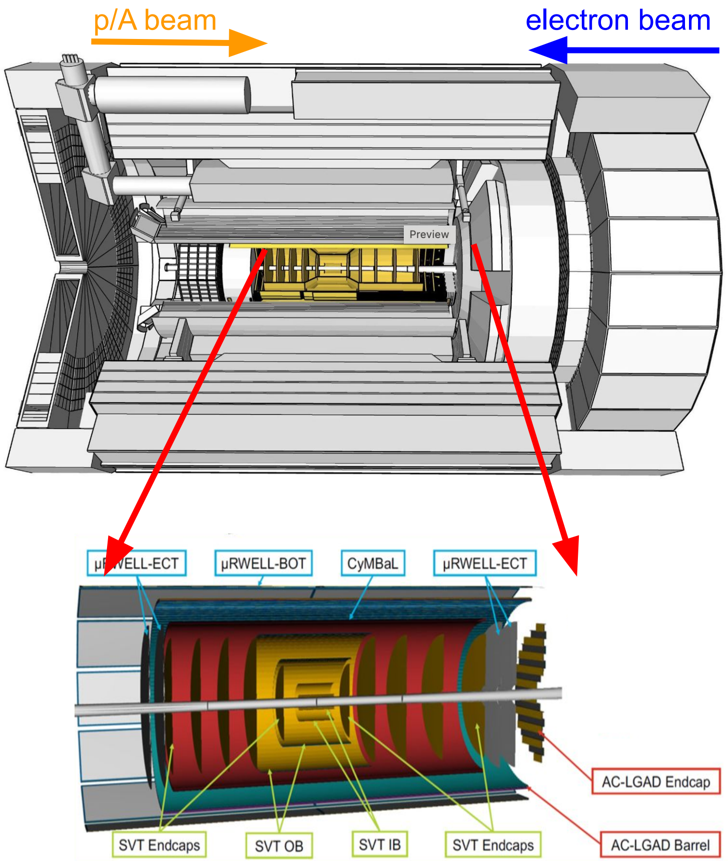
MAPS tracker





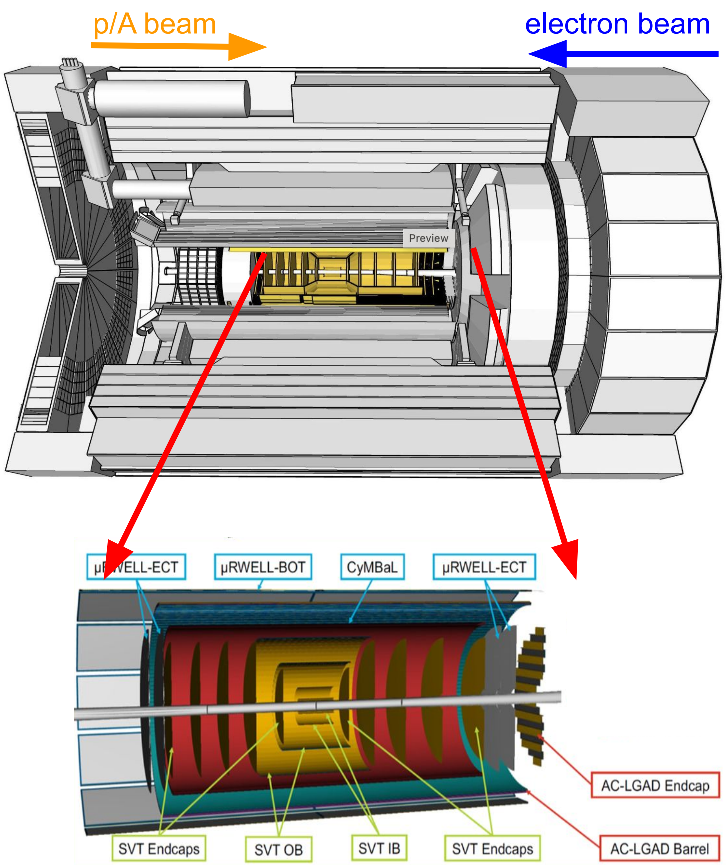
- ➔ Large η coverage ($-3.5 < \eta < 3.5$)
- ➔ High precision silicon detectors for tracking
- ➔ Excellent calorimeters for measuring energy of EM particle showers
- ➔ Extended PID for hadron ID

The ePIC Detector: **Tracking**



- High precision low mass tracking
- High spatial-resolution & efficiency and large-area coverage
- High pixel granularity
- Low material budget at large η

The ePIC Detector: **Tracking**



Silicon Vertex Tracker (SVT)

- ~6 μm point resolution
- 3 Inner Barrels: ITS3-curved wafer-scale sensor, 0.05% X/X0
- 2 Outer Barrels: ITS3-based sensors (EIC-LAS), 0.25/0.55% X/X0
- 5 disks (forward/backward), EIC-LAS, 0.25% X/X0

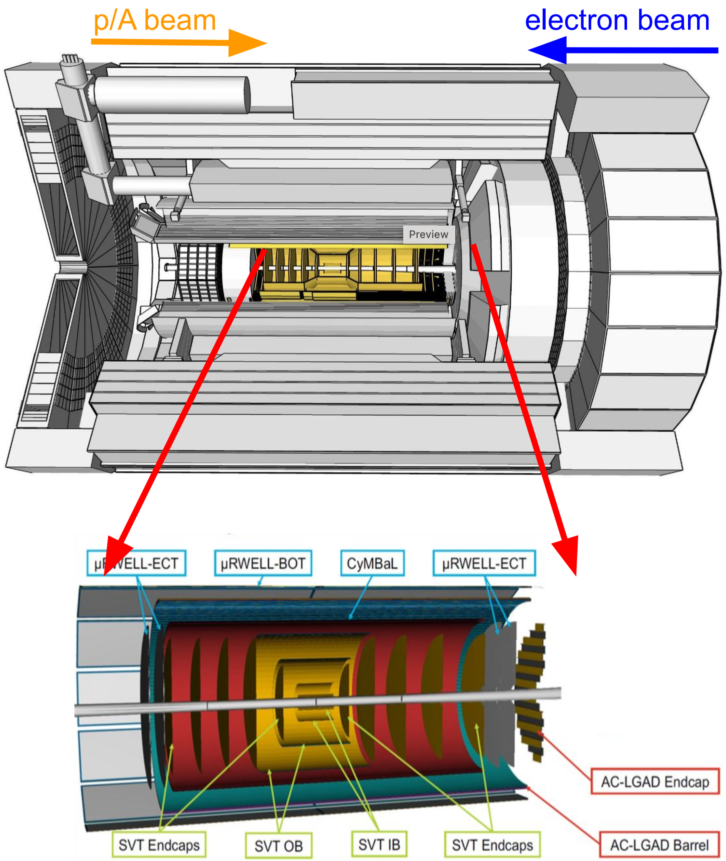
AC-coupled Low Gain Avalanche Diode (AC-LGAD)

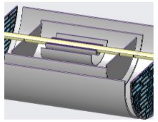
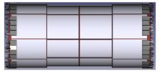
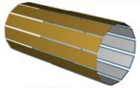
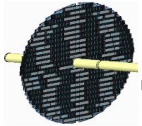
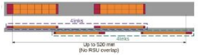
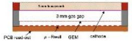
- 30 μm + 30 ps resolutions
- Barrel TOF 0.05 x 1 cm strip, 1% X/X0
- Forward TOF: 0.05 x 0.05 cm pixel, 5% X/X0

Micro Pattern Gas Detectors (MPGD)

- 10 ns & 150 μm resolutions
- 2 GEM-μRWELL (hybrid) - Endcaps
- 1 Cylindrical Micromegas - Inner Barrel
- 1 Thin-gap GEM-μRWELL (hybrid) - Outer Barrel

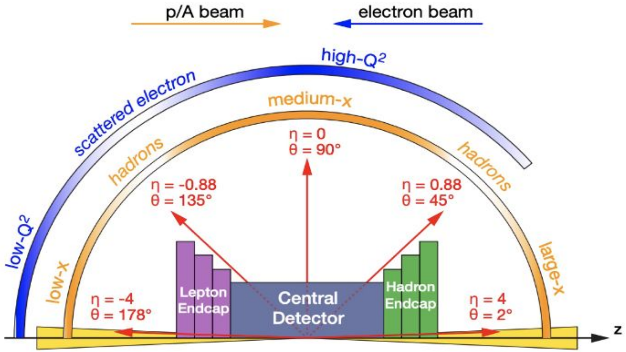
The ePIC Detector: **Tracking**



	µVertex Tracker	Barrel Tracker	Outer Barrel MPGD Tracker		EndcapTracker	
			 MicroMegas Tracker	 µRWELL Tracker	 MAPS Disks	 µRWELL Disks
Main Function	Excellent momentum 0.05%pT⊕0.5% and spatial resolution 20µm/pT⊕ 5µm Displaced vertex reconstruction		Provide redundancy and pattern recognition for tracking	Tracking close to hpDIRC detector to improve angular and space point resolution. Redundancy and pattern recognition for tracking	Excellent momentum 0.05 (0.10)% pT⊕1.0 (2.0)% and spatial resolution 30µm/pT⊕ (20 – 40) µm	Provide redundancy and pattern recognition for tracking
Proven Technology	Monolithic Active Pixel Sensor → ALICE ITS3 MOSAIX sensor (65 nm) small pixels (~18 mm) and power consumption (<20 mW/cm^2)	EIC Large Area Sensor (LAS), modification of ITS3 sensor with 5 or 6 RSU forming staves as the basic building elements for the Barrel 	Cylindrical resistive Micromegas technology Used: ATLAS NSW, CLAS12, SPHENIX, MINOS& T2K TPC	world's first atePIC 24 planar Thin-gap & double amplification (GEM & µRWELL) modules & 2D-strip readout	EIC Large Area Sensor (LAS), staves as the basic building elements for the MAPS disks	GEM- µRwell hybrid configuration with increased gain 

The ePIC Detector: **Tracking Requirements**

η range	Momentum Resolution	Spatial Resolution
Backward (-3.5 to 2.5)	~0.10% × p ⊕ 2.0%	~30/pT μm ⊕ 40 μm
Backward (-2.5 to -1.0)	~0.05% × p ⊕ 1.0%	~30/pT μm ⊕ 20 μm
Barrel (-1.0 to 1.0)	~0.05% × p ⊕ 0.5%	~20/pT μm ⊕ 5 μm
Forward (1.0 to 2.5)	~0.05% × p ⊕ 1.0%	~30/pT μm ⊕ 20 μm
Forward (2.5 to 3.5)	~0.10% × p ⊕ 2.0%	~30/pT μm ⊕ 40 μm



The ePIC Detector: PID

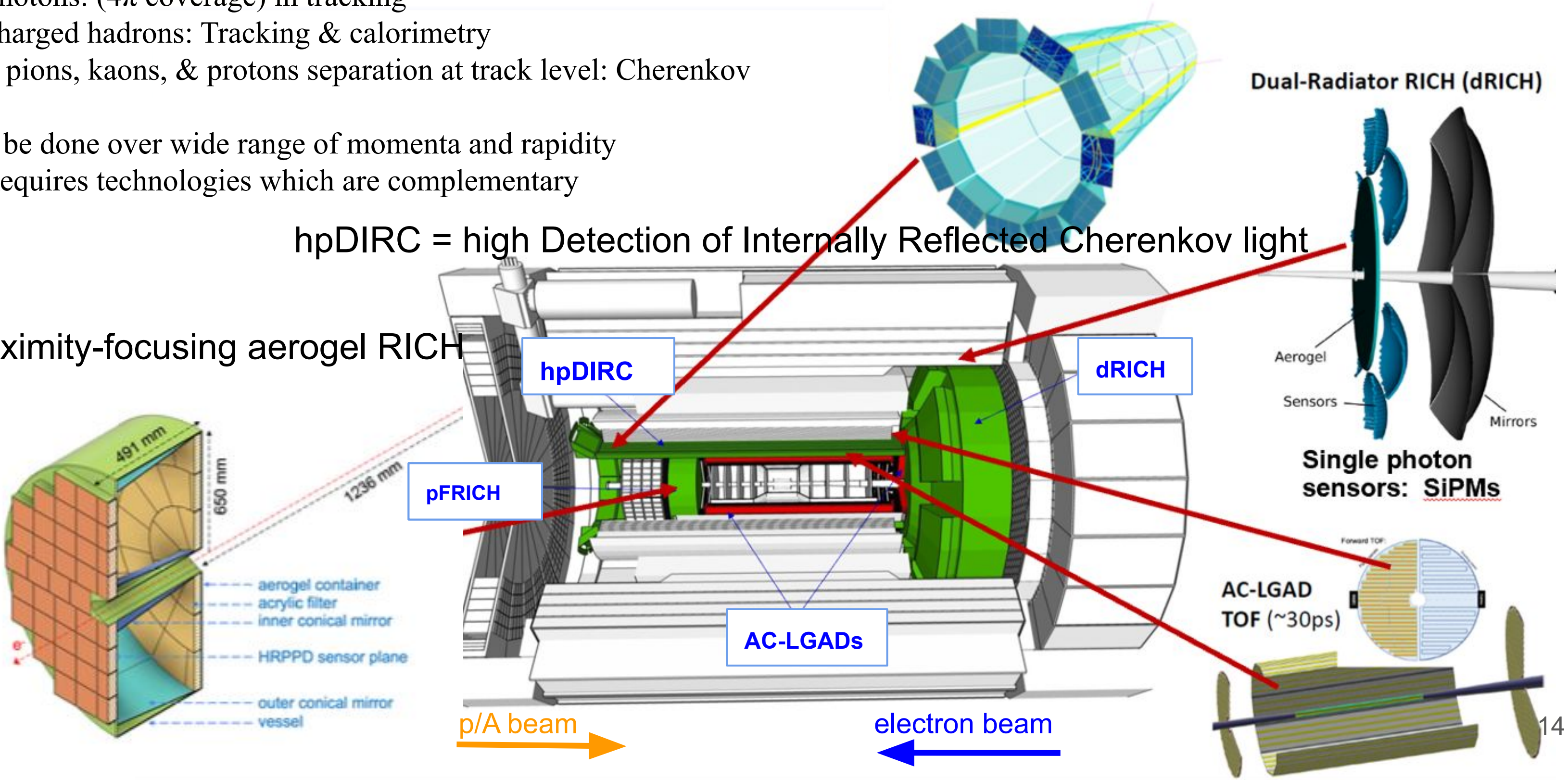
PID Requirements

- ➔ e^- from photons: (4π coverage) in tracking
- ➔ e^- from charged hadrons: Tracking & calorimetry
- ➔ Charged pions, kaons, & protons separation at track level: Cherenkov

- ❖ Needs to be done over wide range of momenta and rapidity
  - ➢ Requires technologies which are complementary

hpDIRC = high Detection of Internally Reflected Cherenkov light

pFRICH = proximity-focusing aerogel RICH



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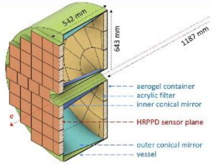
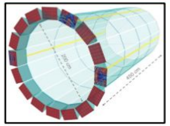
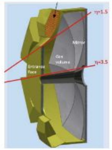
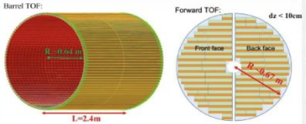


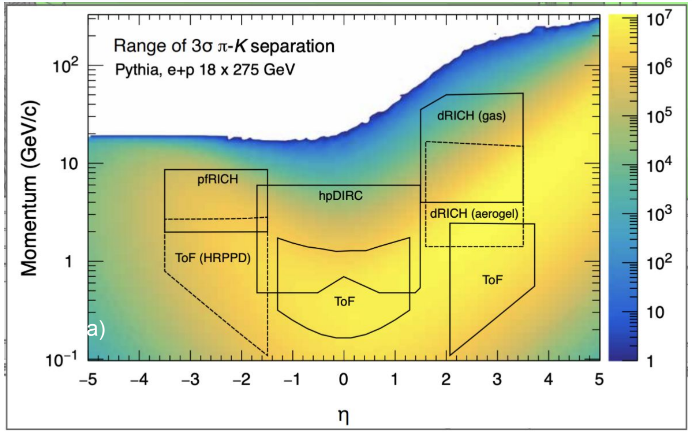


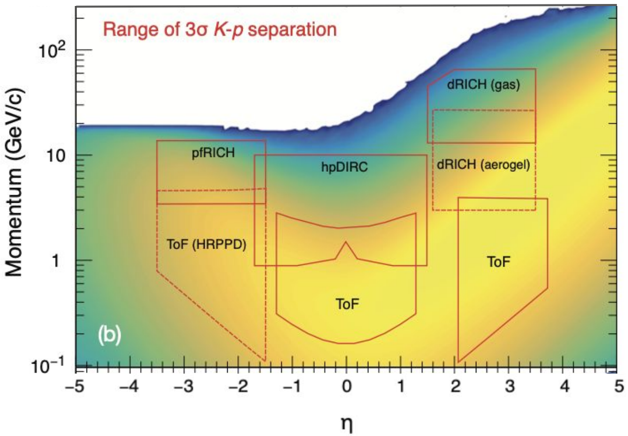


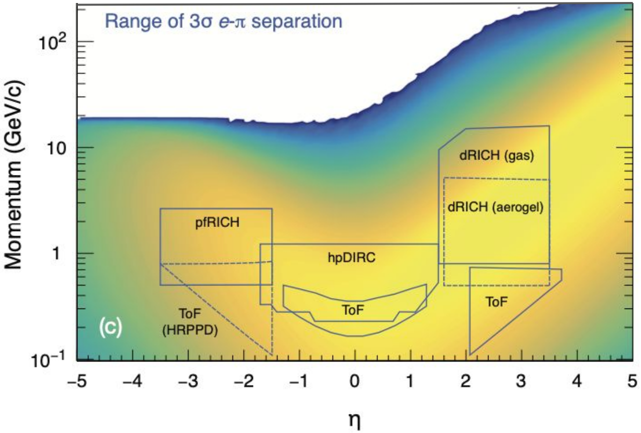


Backward RICH	Barrel DIRC	Forward RICH	Time-of-Flight (Barrel, Forward)
Main Function			
▪ e, π, K, p separation → π/K 3σ sep. up to 9 GeV/c and 10-20 ps timing → ToF	▪ e, π, K, p separation → π/K 3σ sep. at 6 GeV/c	▪ e, π, K, p separation → π/K 3σ sep. up to 50 GeV/c	▪ e, π, K, p separation through 20-35 ps ToF Barrel: $0.15 < p_T < 1.5$ GeV/c Forward: $0.15 < p_T < 2.5$ GeV/c ▪ Accurate space point for tracking
Proven Technology			
Classical single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)	High Performance DIRC ▪ Quartz bar radiator → Reuse of BaBAR DIRC bars ▪ light detection with MCP-PMTs ▪ Fully focused	Dual Radiator RICH ▪ Aerogel and C_2F_6 gas ▪ Spherical Mirrors (6 Azimuthal Sectors) ▪ Photon-Sensors tiled on spheres	
world's first atePIC			
Photonsensors: HRPPDs for Time-of-Flight 		First use of SiPMs as Photonsensors in a RICH	First time use of AC-LGAD (Low Gain Avalanche Detector) in collider detector

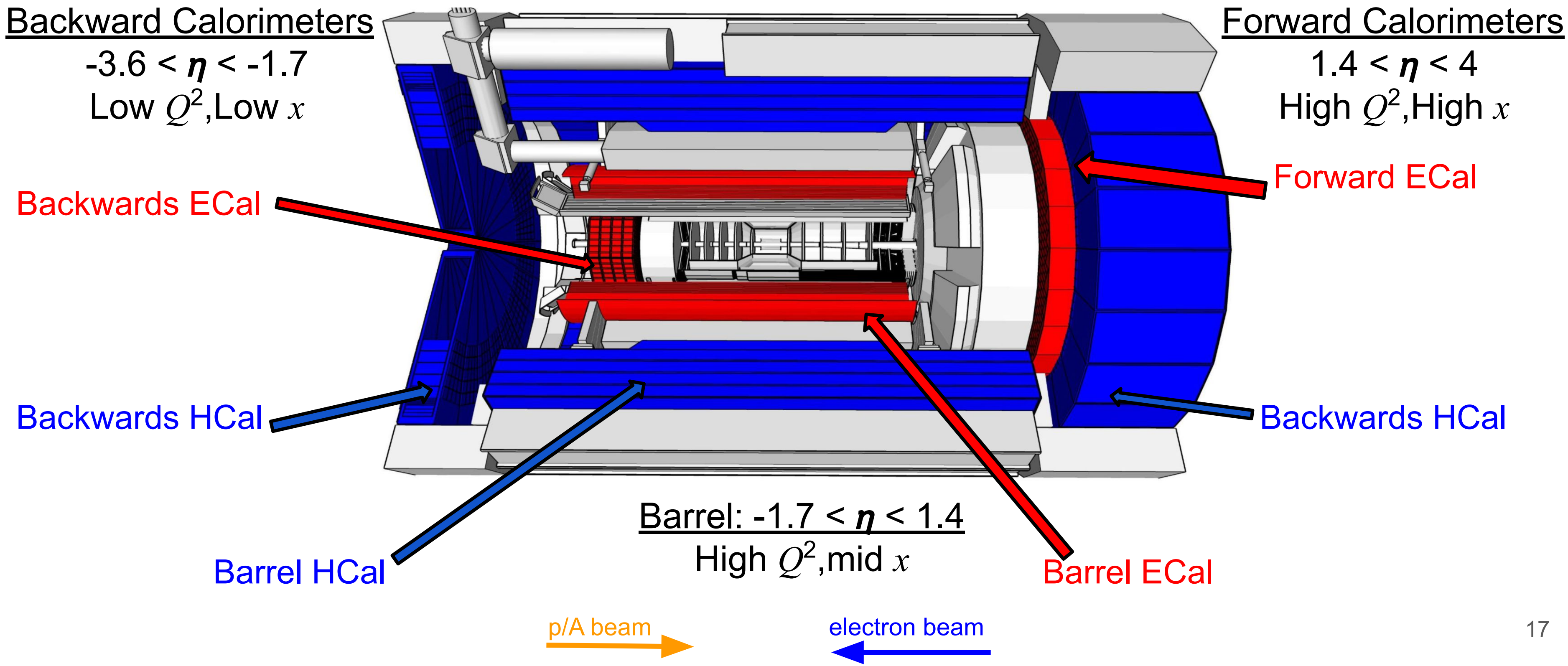
The ePIC Detector: **PID**







The ePIC Detector: **Calorimetry**



The ePIC Detector: **Calorimetry**

Backward Calorimeters

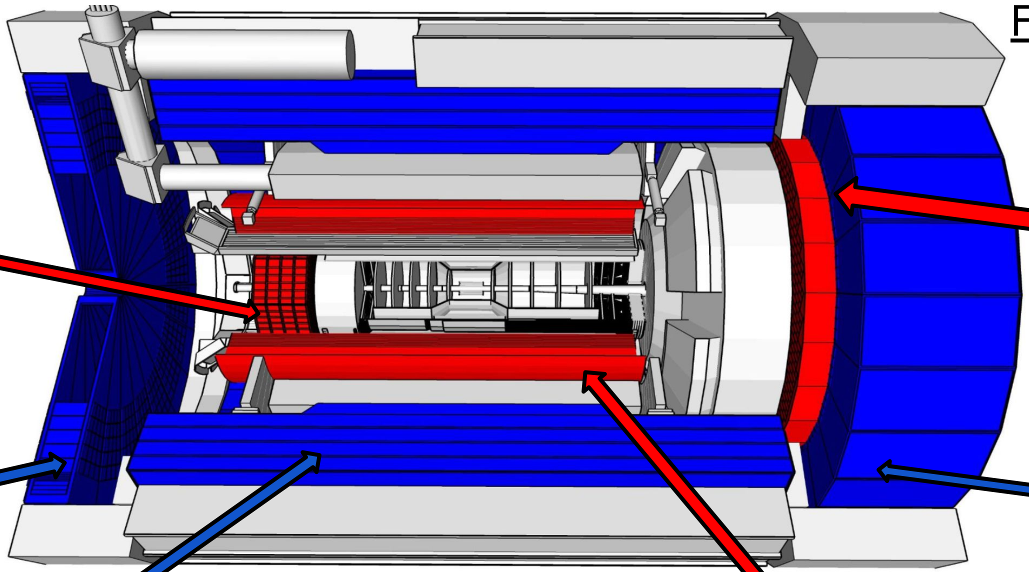
$-3.6 < \eta < -1.7$

Low Q^2,Low x

Forward Calorimeters

$1.4 < \eta < 4$

High Q^2,High x



Backwards ECal

$\frac{\sigma_E}{E} \sim \frac{2-3\%}{\sqrt{E}} \oplus 1-2\%$

Forward ECal

$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 2-3\%$

Backwards HCal

$\frac{\sigma_E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 10\%$

Backwards HCal

$\frac{\sigma_E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 10\%$

Barrel: $-1.7 < \eta < 1.4$

High Q^2,mid x

Barrel HCal

$\frac{\sigma_E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 10\%$

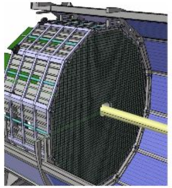
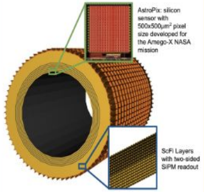
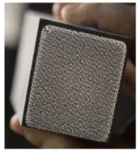
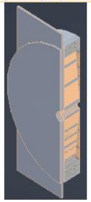
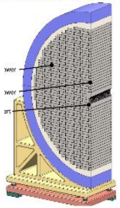
Barrel ECal

$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 2-3\%$

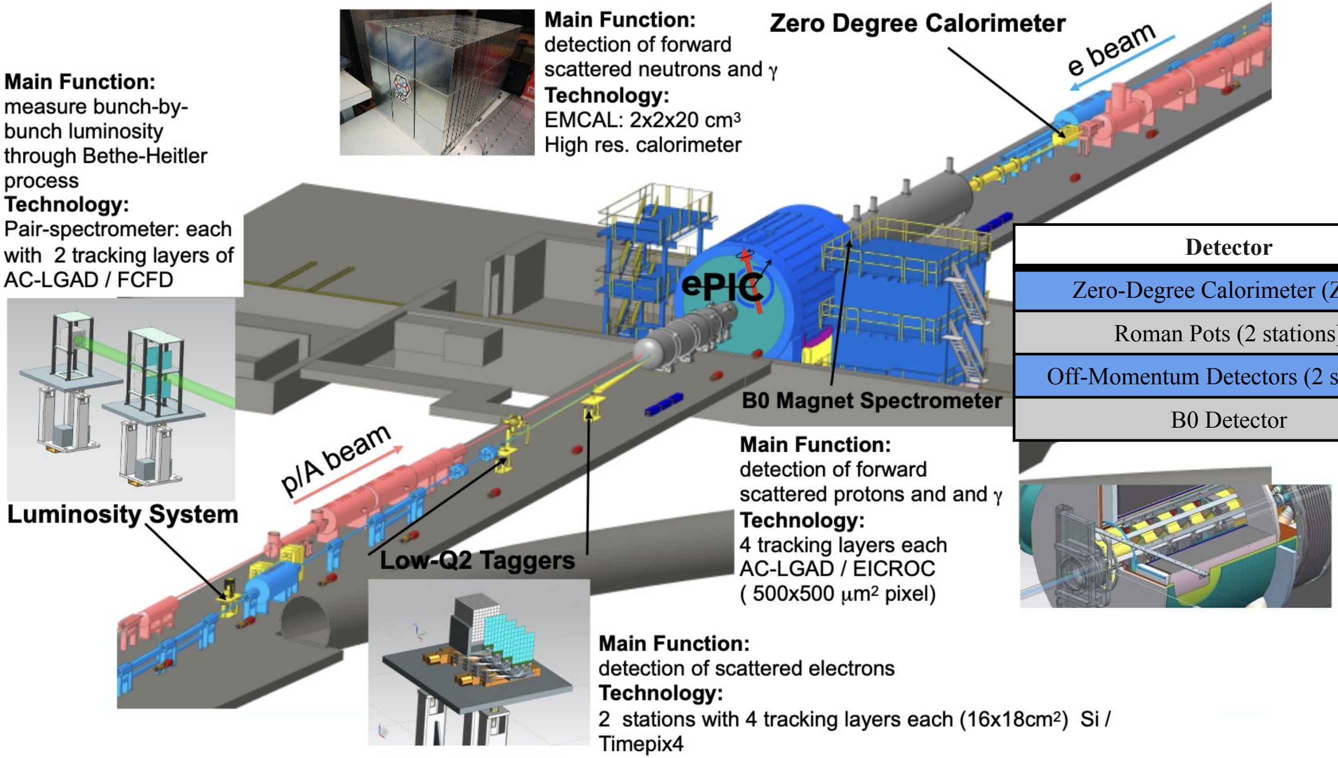
p/A beam

electron beam

The ePIC Detector: **Calorimetry**

Backward ECal	Barrel ECal	Forward ECal	Backward HCal	Barrel HCal	Forward HCal
					
Main Function					
scattered lepton detection → very high-precision	scattered lepton and γ detection, hadronic final state characterization	lepton and γ detection, hadronic final state characterization → π^0, γ separation	muon and neutral detection → improved jet Energy reconstruction	muon and neutral detection → improved jet Energy reconstruction	particle-flow measurements
Proven Technology					
PbWO4 – crystals → long lead procurement	Pb/SciFi sampling part using SiPMs combined with imaging section (6 layers) interleaving Pb/SciFi with ASTROPIX	Tungsten-powder + SciFi SPACAL design Developed through EIC R&D and applied successfully in sPHENIX	Steel + Scintillator SiPM-on-tile	Steel + Scintillator design re-used from sPHENIX	longitudinal segmented Steel + Scintillator SiPM-on-tile Pioneered by CALICE analog HCal High resolution insert next to beam-pipe
world's first at ePIC					
SiPM as Photonsensors	Use of ASTROPIX in Calorimetry				first-time full-size CALICE like calorimeter in collider experiment

The ePIC Detector: **Far Forward and Far Backward**



Main Function:
detection of forward scattered neutrons and γ
Technology:
EMCAL: 2x2x20 cm³
High res. calorimeter

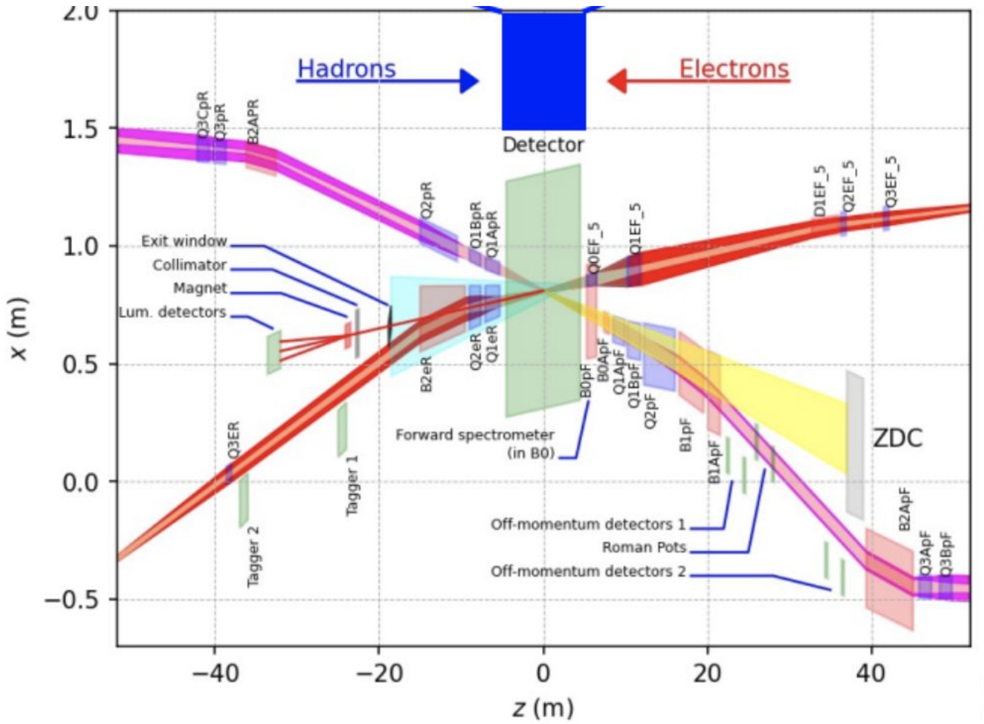
Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with 2 tracking layers of AC-LGAD / FCFD

Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$\theta < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \theta < 20.0$ mrad ($4.6 < \eta < 5.9$)

Main Function:
detection of forward scattered protons and and γ
Technology:
4 tracking layers each AC-LGAD / EICROC
(500x500 μm² pixel)

Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm²) Si / Timepix4

The ePIC Detector: **Far Forward and Far Backward**



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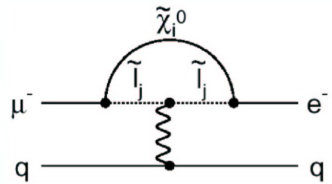
Zero-Degree Calorimeter (ZDC)	$\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$\boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \boldsymbol{\theta} < 20.0$ mrad ($4.6 < \eta < 5.9$)

Potential BSM Physics: **Charged Lepton Flavor Violation**

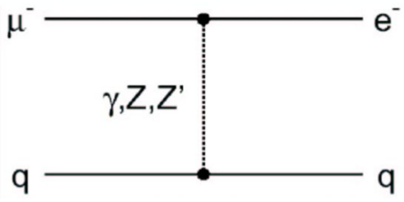
- ❖ Neutrino oscillations
  - ➢ Provided evidence for lepton flavor violation
- ❖ No experimental evidence for flavor violation in charged lepton sector
- ❖ Predicted CLFV branching ratio
  - ➢ $Br(\mu \rightarrow e\gamma) < 10^{-54}$
- ❖ Example: Supersymmetry prediction
  - ➢ $Br(\mu \rightarrow e\gamma) \sim 10^{-15}$
- ❖ $Br(\mu \rightarrow e\gamma) < 10^{-13}$: Current limit (MEG experiment)
  - ➢ [Baldini, A.M., Bao, Y., Baracchini, E. et al. Eur. Phys. J. C 76, 434](#)
- ❖ $e \rightarrow \tau$ transition constraints - much weaker
  - ➢ $Br(e \rightarrow \tau Y) \sim 10^{-8}$

<u>Leptoquarks</u>
- Color triplet particles
- Couple to leptons & quarks
- Mediate CLFV processes at tree-level

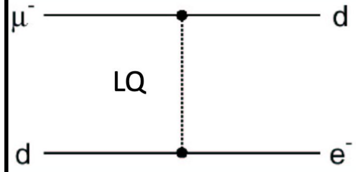
<u>Supersymmetry</u>



<u>Heavy Z</u>



<u>Leptoquarks</u>



BSM models that predict CLFV

Charged Lepton Flavor Violation: **Decay Channel(s)**

1 Prong

$$\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$$

1. Larger branching ratio ~ 17%
2. Suppression of SM background
3. Needs (good) μ identification

3 Prong (from $e \rightarrow \tau$)

$$\tau \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$$

1. Identification is easier than 1 prong channel

Charged Lepton Flavor Violation: **1 Prong Decay Channel**

1 Prong

$$\tau \rightarrow \mu \bar{\nu}_{\mu} \nu_{\tau}$$

1. Larger branching ratio ~ 17%
2. Suppression of SM background

on

μ channel

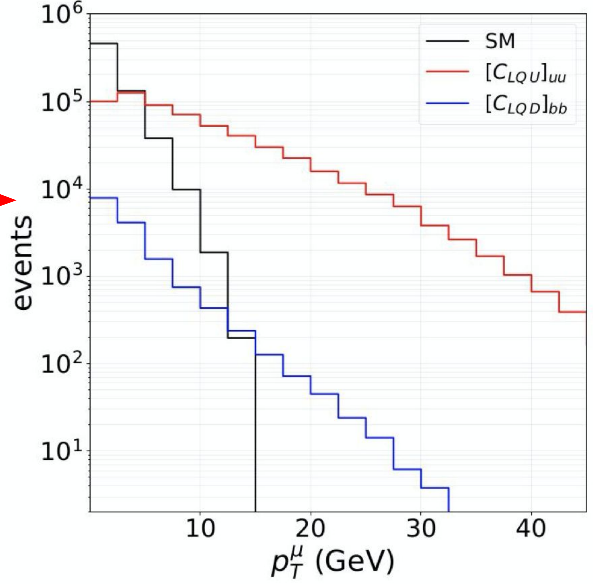


*Image courtesy of Emanuele Mereghetti

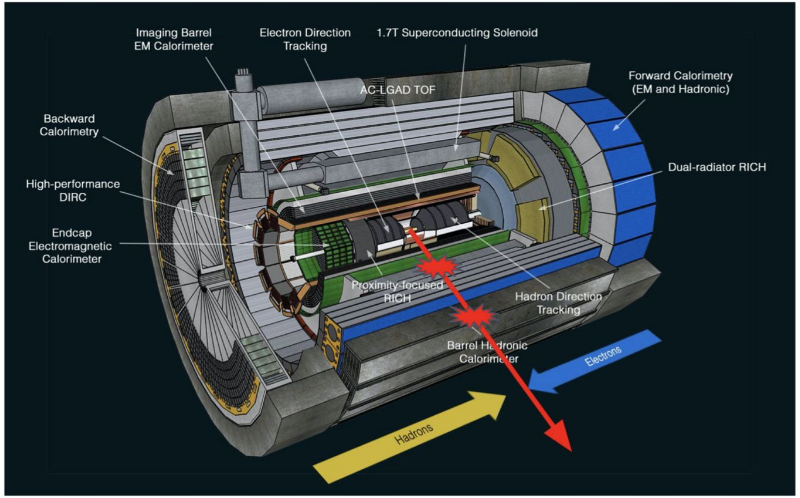
[Charged Lepton Flavor Violation at the EIC]

Charged Lepton Flavor Violation: **1 Prong Decay Channel**

<u>1 Prong</u>

$$\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$$

1. Larger branching ratio ~ 17%
2. Suppression of SM background
3. Needs (good) μ identification



Preliminary **(Andrew Hurley)**

- No dedicated muon detector
  - Limit tracks to those MIPs in calorimerter
- Utilize E/p in both barrel calorimeters

Charged Lepton Flavor Violation: **1 Prong Decay Channel**

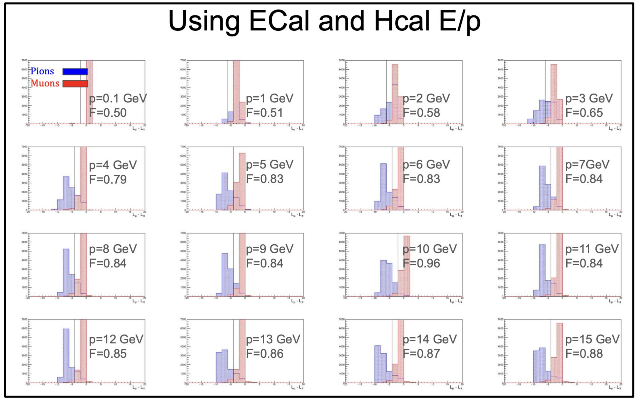
1 Prong

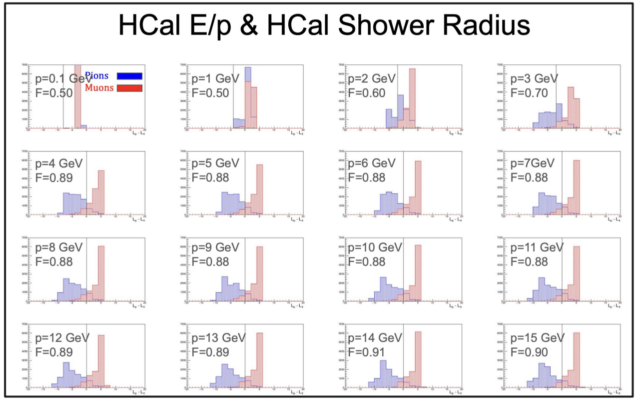
$$\tau \rightarrow \mu \bar{\nu}_{\mu} \nu_{\tau}$$

1. Larger branching ratio ~ 17% ➔ Momentum scan @ θ =90
2. Suppression of SM background ➔ Focus for $e \rightarrow \tau$
   - ◆ |p|>10 GeV
3. Needs (good) μ identification ➔ Log-likelihood method

Preliminary **(Andrew Hurley)**

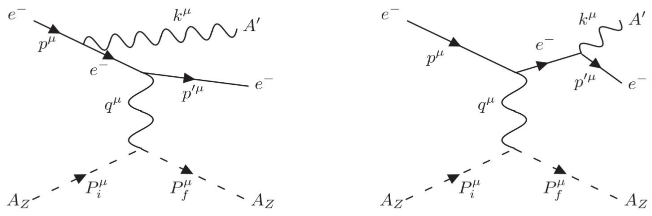
- No dedicated muon detector
  - Limit tracks to those MIPs in calorimerter
- Utilize E/p in both barrel calorimeters

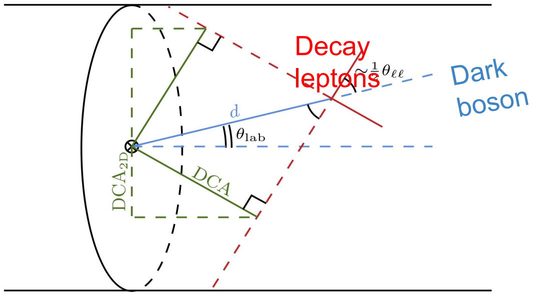


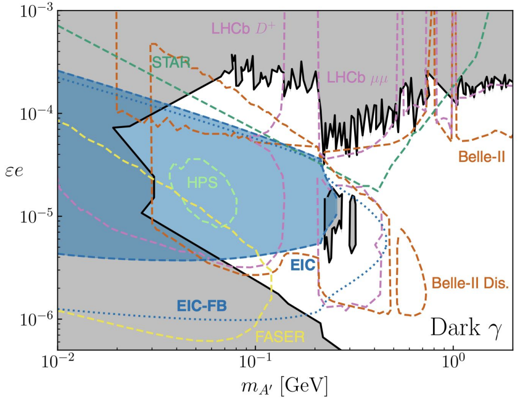


Displace Hidden Vectors

- Production of massive light vector boson A'
  - $e^- A_Z \rightarrow e^- A_Z A'$
- Assumed zero background
  - Background in Far Background needs to estimated



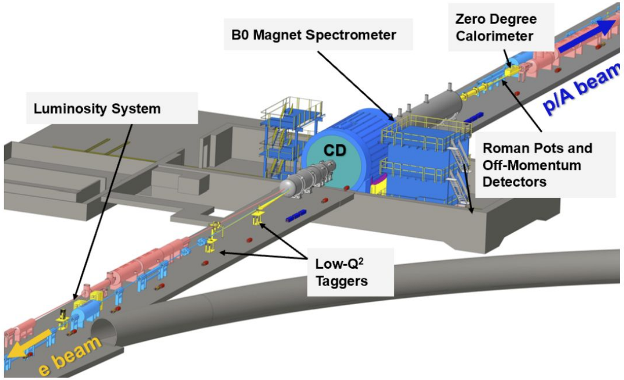


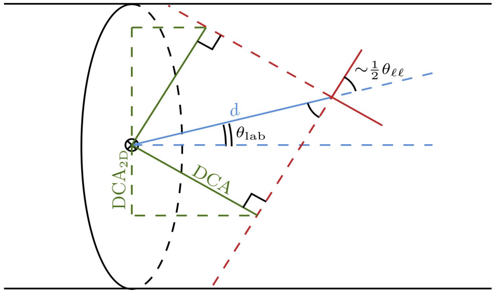


Hooman Davoudiasl, Roman Marcarelli, and Ethan T. Neil

Backwards physics - B0 is in the wrong place!

- eA collisions can be leveraged to significantly improve the chances to observe BSM effects (Z^2 scaling)
- Better estimations are needed for DCAs with/without tracking for ePIC
- Evaluation of backgrounds in the backwards region will be critical to ensure we can make this measurement





From Ciprian Gal Workshop Summary

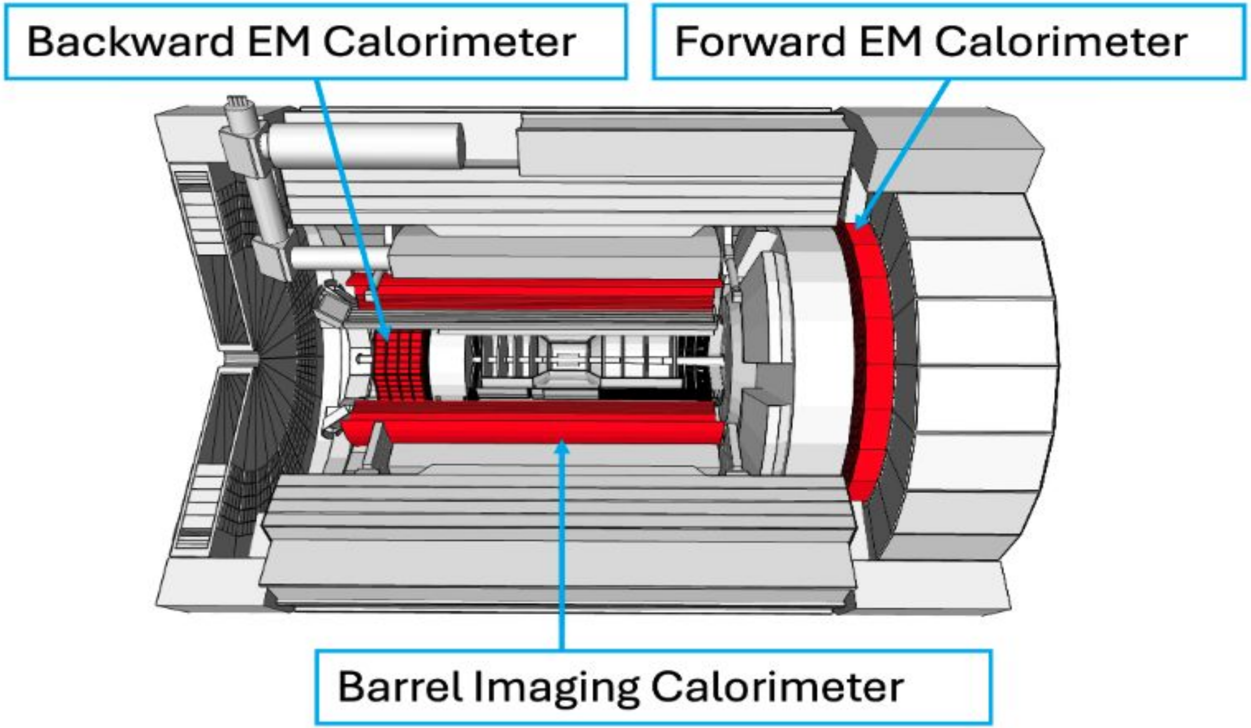
INT Workshop EW and BSM physics at the EIC (2024)

Displace Hidden Vectors

- ➔ There are many interesting BSM physics topics to explore for the future EIC!
- ➔ The ePIC detector is designed to maximize its physics reach
- ➔ Many completed and ongoing BSM impact studies with ePIC
  - R. Boughezal et al., Neutral-current electroweak physics and SMEFT studies at the EIC, Phys. Rev. D
  - J. Zhang et. al, Charged Lepton Flavor Violation Study at the EIC, in Electroweak and BSM physics at the EIC
  - R. Boughezal, D. de Florian, F. Petriello, and W. Vogelsang, Transverse spin asymmetries at the EIC as a probe of anomalous electric and magnetic dipole moments, Phys. Rev. D 107, 075028 (2023)
  - Hooman Davoudiasl, Roman Marcarelli, and Ethan T. Neil , Displaced signals of hidden vectors at the Electron-Ion Collider
- ➔ Future work
  -
- ➔ Interested in Electroweak & BSM physics at the EIC
  - Electroweak & BSM working group (Ciprian Gal and Juliette Mammei)
  - eic-projdet-inclusive-l@lists.bnl.gov & eic-projdet-bsmew-l@lists.bnl.gov

Thank You

The ePIC Detector: **EM Calorimeter Detectors**



The ePIC Detector: **Hadron Calorimeter Detectors**