A practical guide to the light-ion physics at the Electron-Ion Collider

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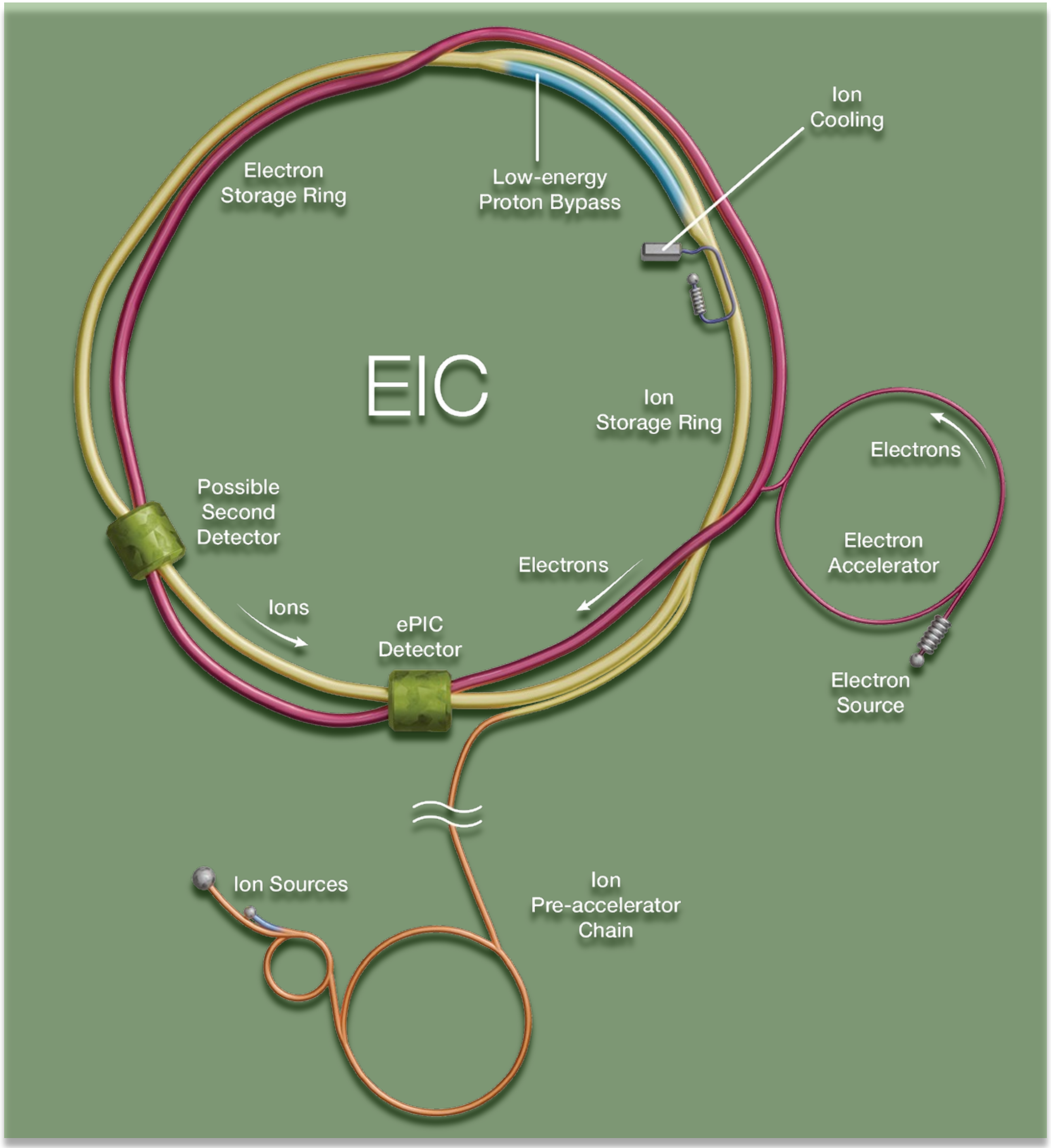
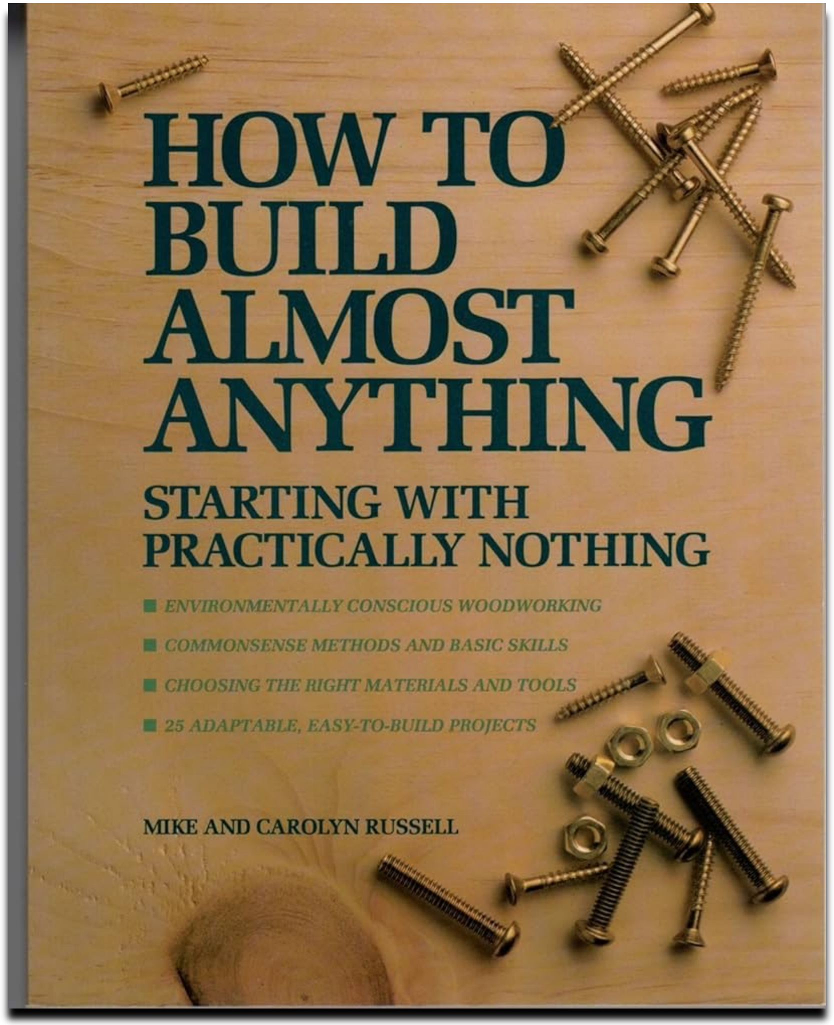
BNL/SBU

06/23/2025



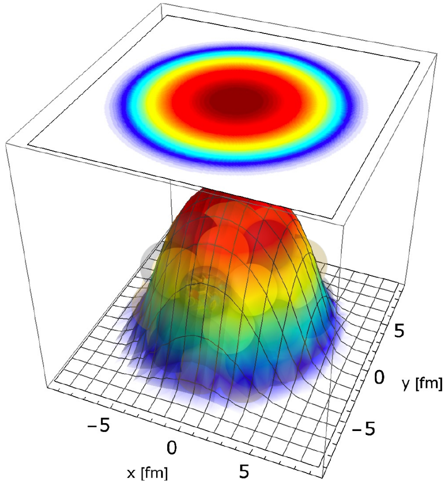
Outline of this practical guide:

- Section 1 (mostly me talking + you ask questions):
  - DIS physics processes on light-ions
  - What light ions?
  - What can be accelerated at the EIC?
  - the ePIC detector
  - Detection principle in the forward region.
  - MC Models
  - Analysis with light ions.
- Section 2 (you working/discussing):
  - Hands-on experience of doing a light-ion pseudo-analysis.



Exercise – *“What are we running?”*

- (1-2) theory + (2-1) experiment students **form a team (<=3 persons)**; the team will perform a pseudo-analysis in ePIC.
  - **Given:** a fully processed simulation sample that mixes coherent and incoherent contributions, but the ion species and Vector-Meson (daughters are K+K-) are unknown. The process is e+A→V+A’
  - **Goal:** a pseudo-analysis on the Vector-Meson production to produce an **image of the light ion**; *The question is to figure out what ion is used and what is its (gluonic) radius?*
  - **Software need:** only ROOT should be sufficient.



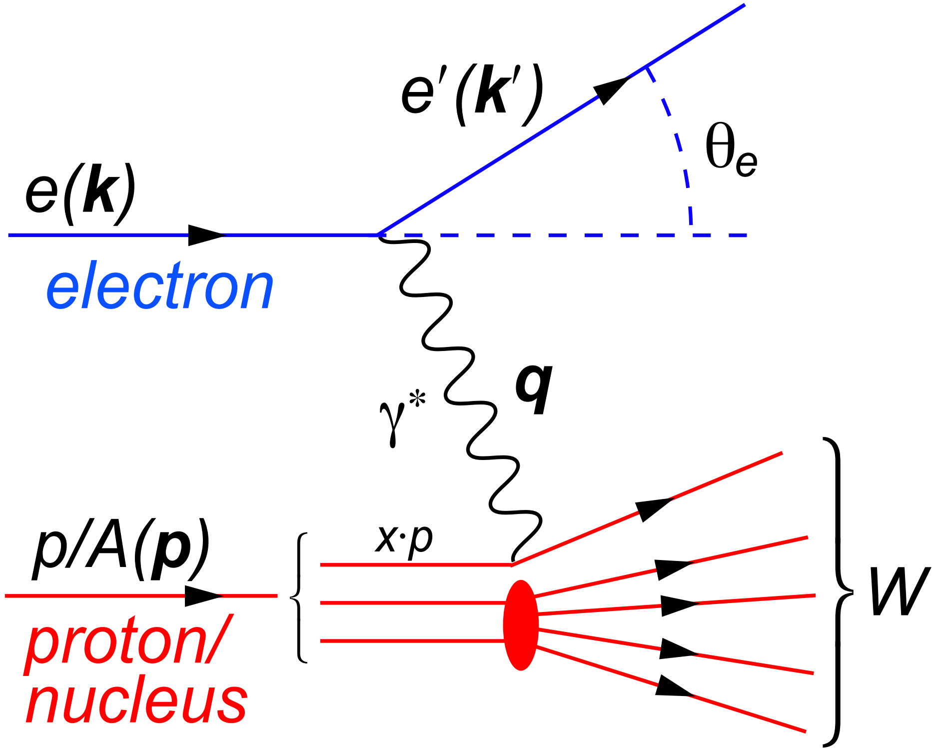
Award (if finish by the end of today at 5:30pm)

(places are subject to change if too crowded.)

- **Teams that figure out (not just guess) the ion will get (a starter + a main + a drink).**
- **Teams that figure out (not just guess) the coherent t distribution will get a main**
- **Teams that figure out (not just guess) the VM will get a drink.**

Let’s get started!

DIS physics/kinematics recap



1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

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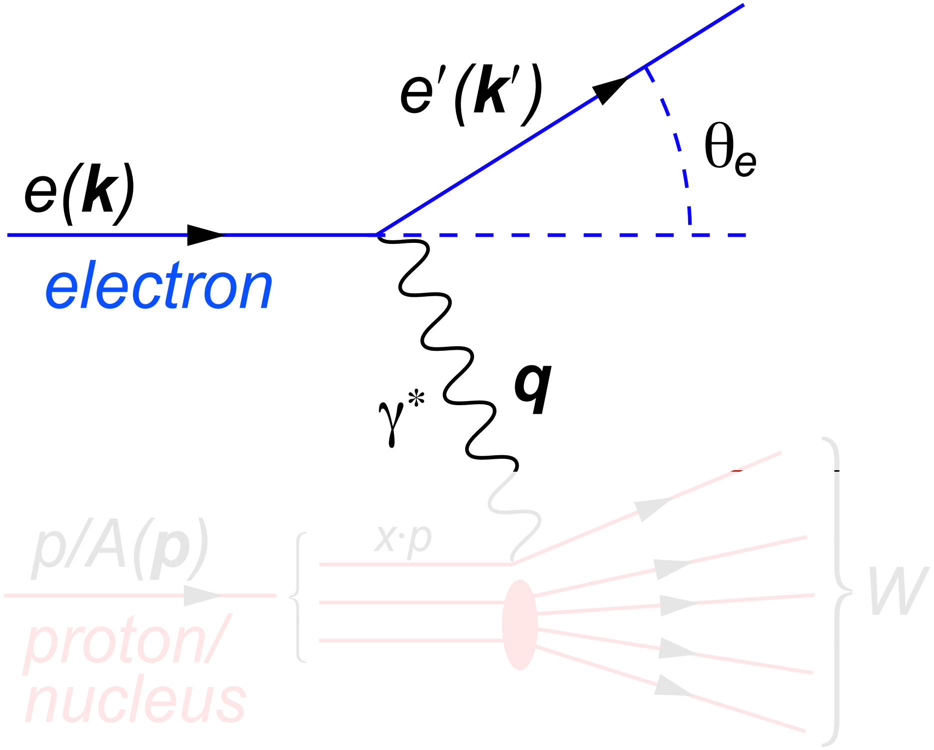

- ep/A collisions.
  - **Inclusive reactions**
  - semi-inclusive reactions
  - Exclusive reactions

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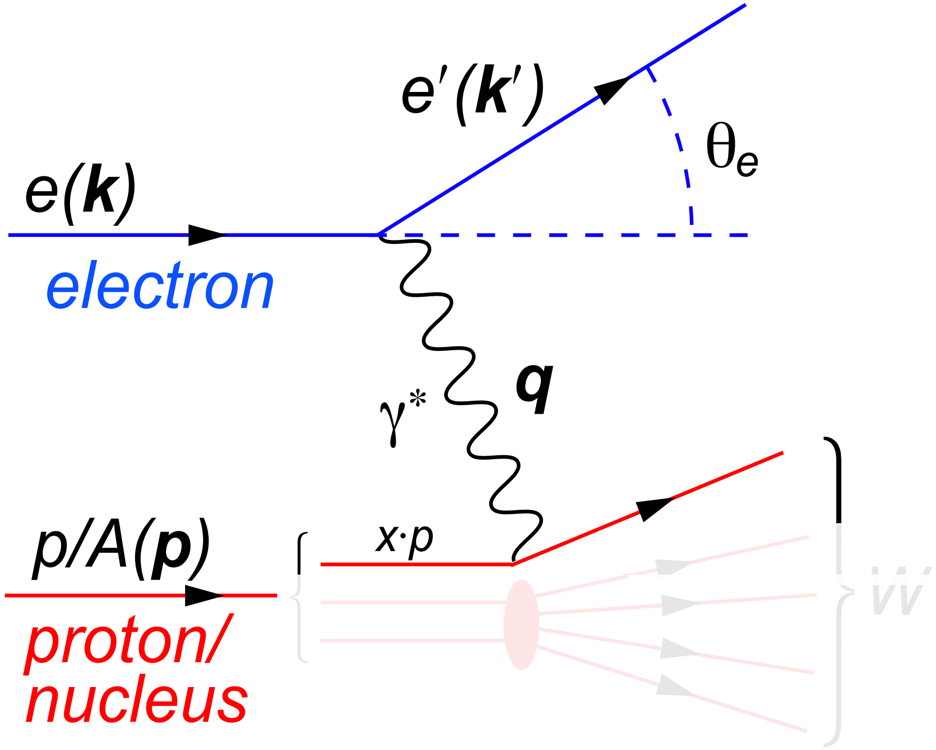

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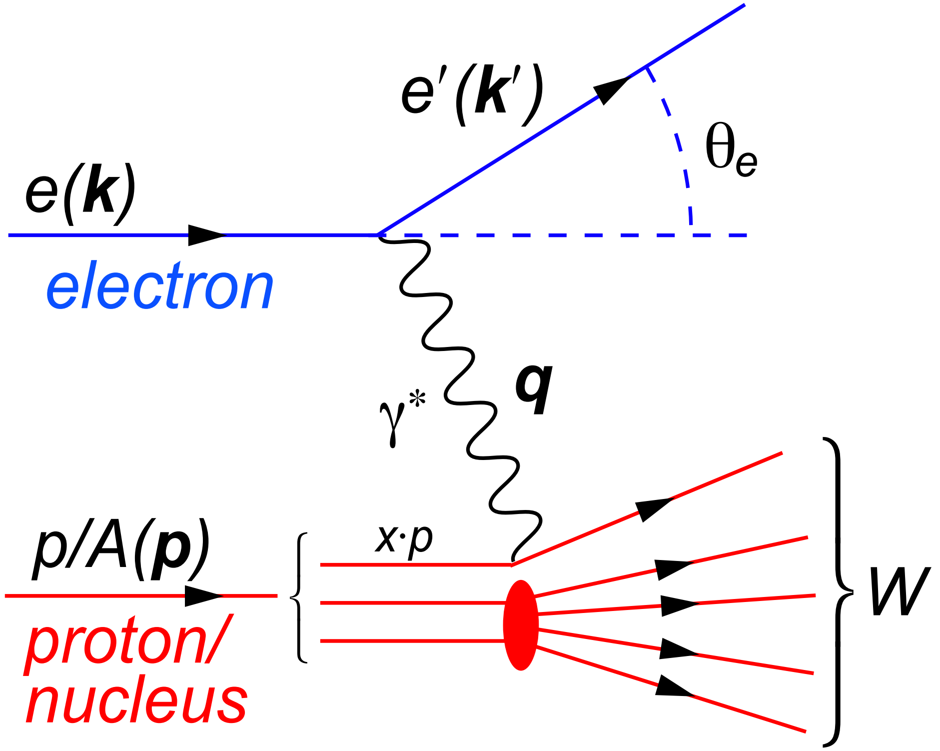

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  - Inclusive reactions
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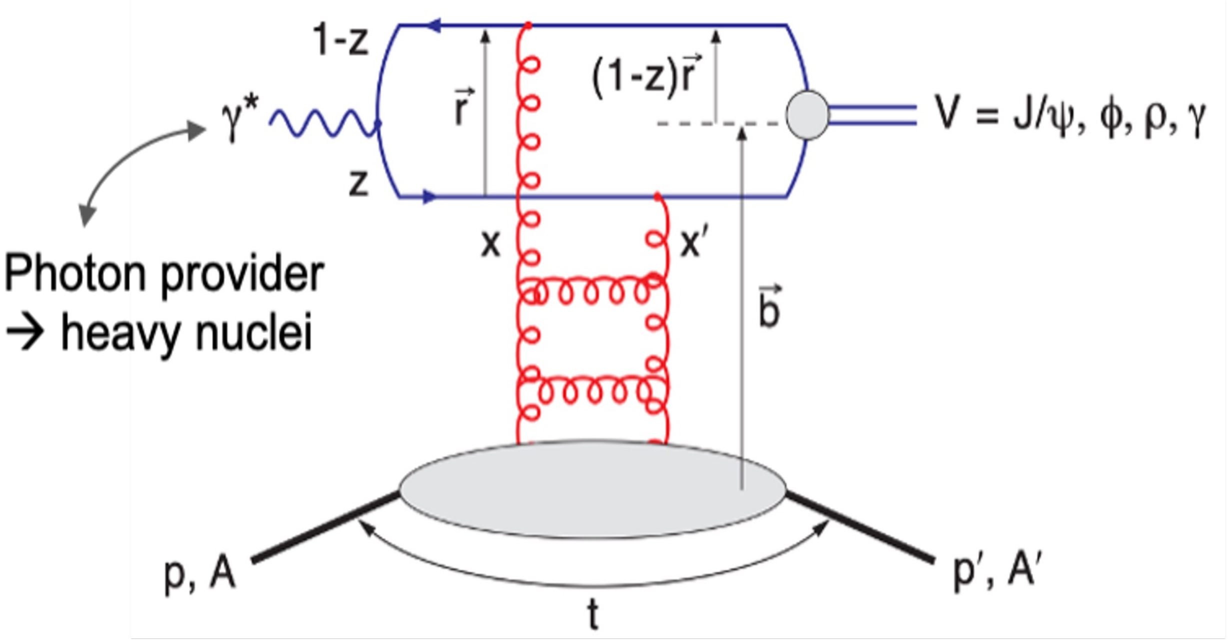
  - **Exclusive reactions**

  limited number of final-states

DIS physics/kinematics recap



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  Only one final-state particle

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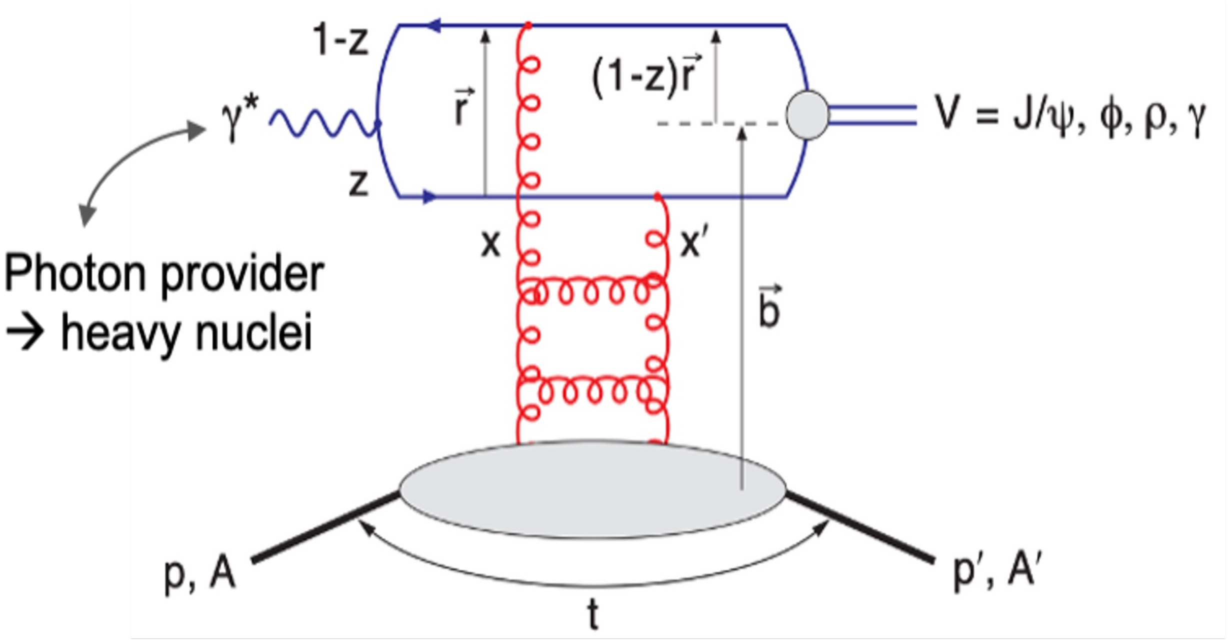

- ep/A collisions.
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  Only one final-state particle

  And the target can:

  - *Stay intact – coherent*
  - *Breaks up - incoherent*

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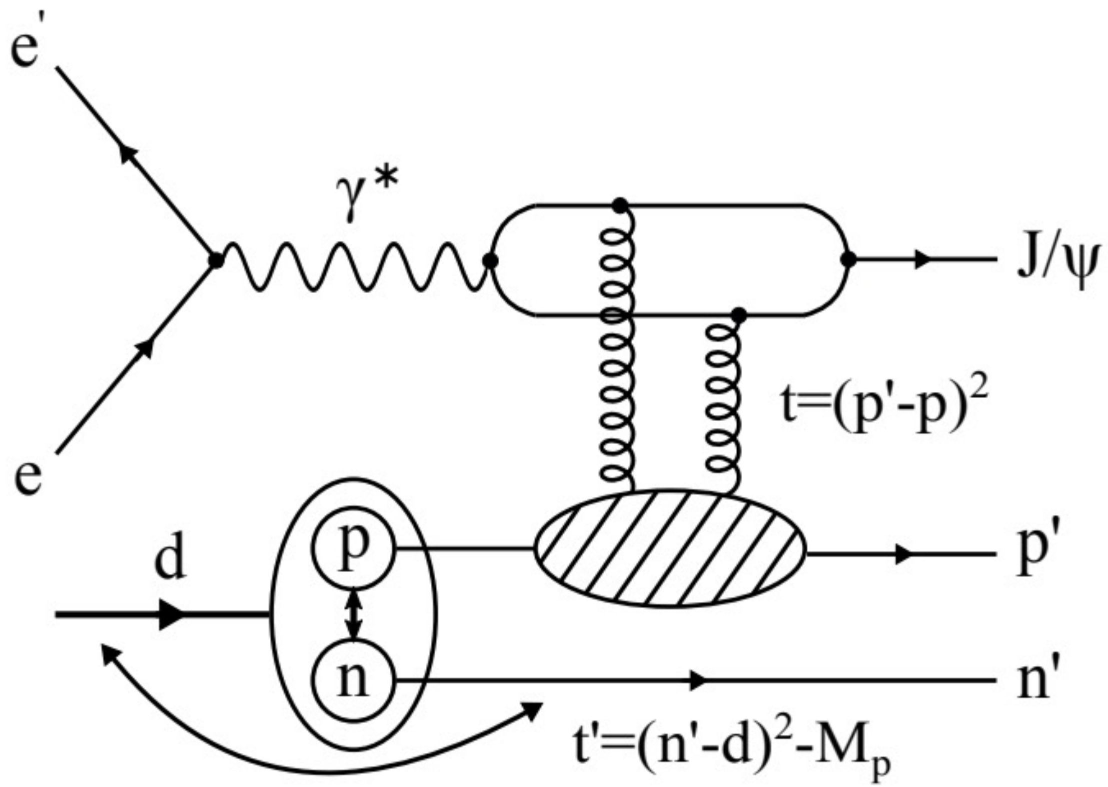

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  Only one final-state particle
  And the target can:
  - *Stay intact – coherent*
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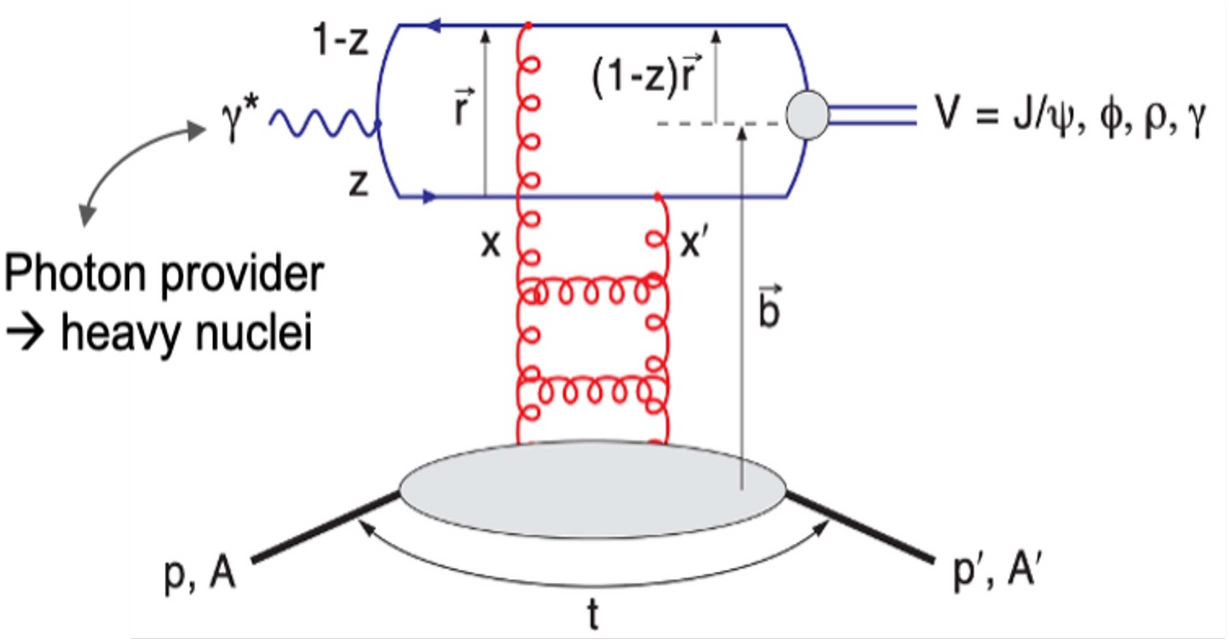
- **Tagged reactions**, which can co-exist with all above.

DIS physics/kinematics recap



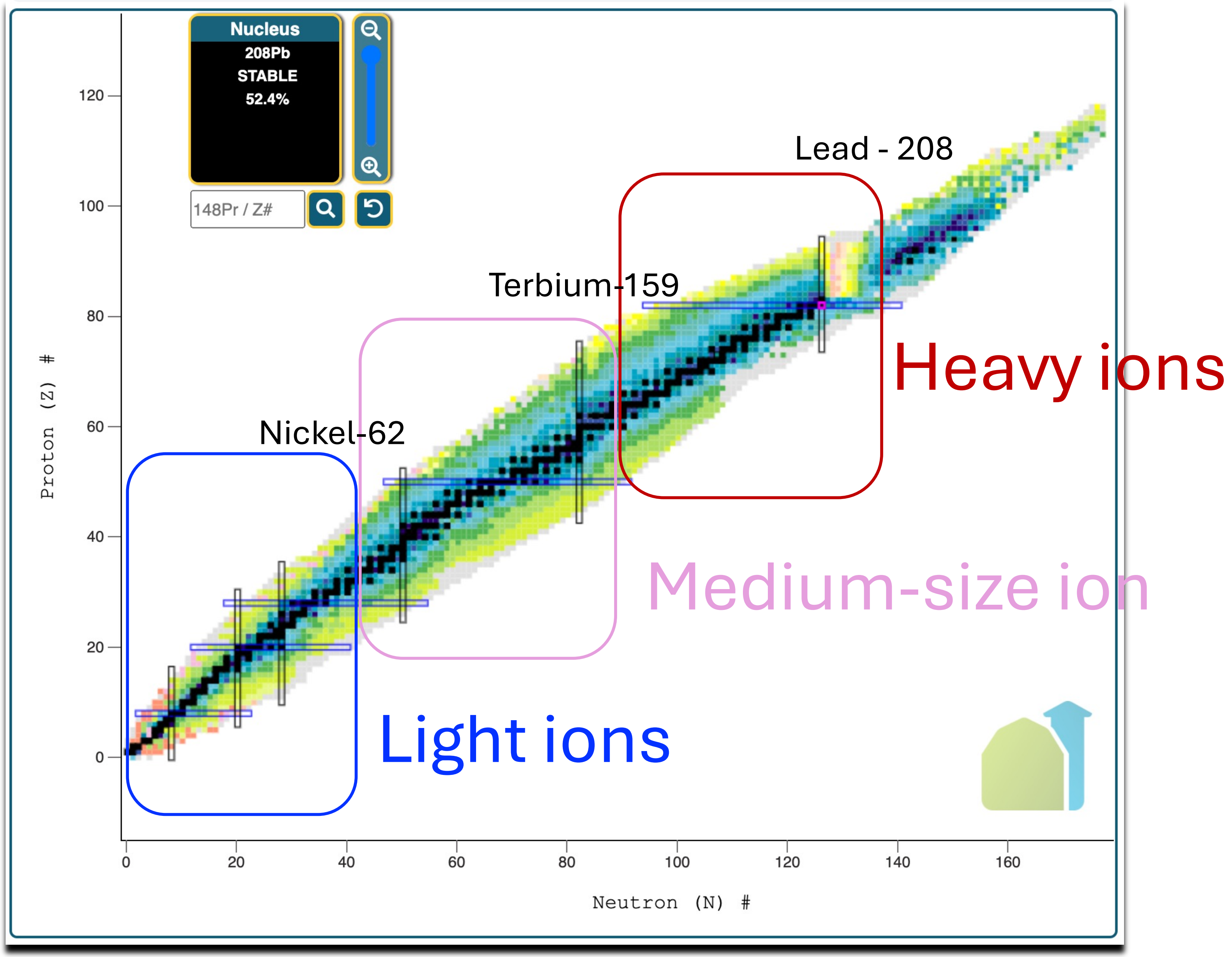
- ep/A collisions.
  - Inclusive reactions
  - semi-inclusive reactions
  - **Exclusive reactions**
  - ➢ **Tagged reactions**

For this lecture, what will be focused on is the **exclusive and tagged reactions**

What ions are light ions?

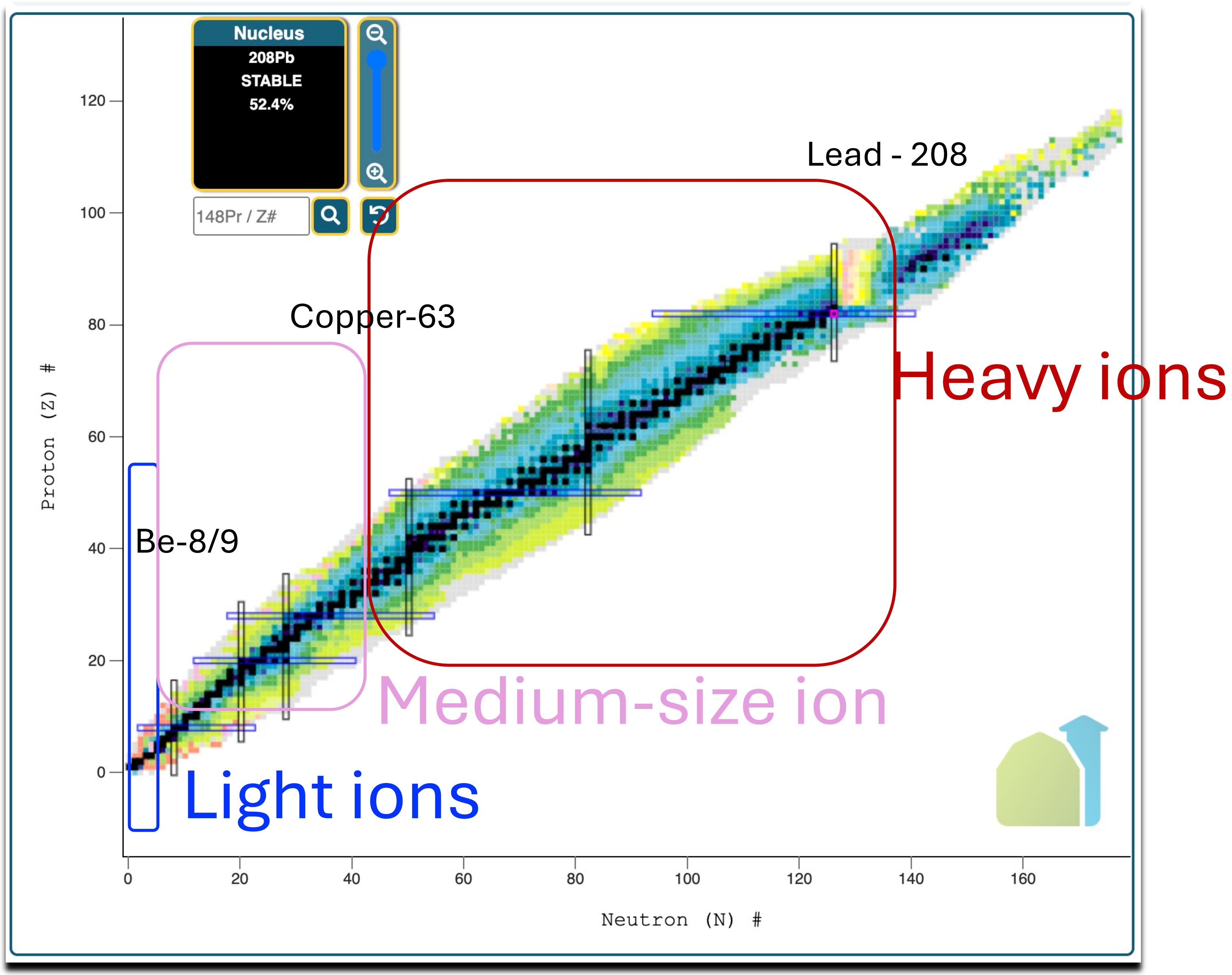
What are light ions?

- My nomenclature about separating light (A<62), medium (62<A<160), and heavy nuclei (A>160)



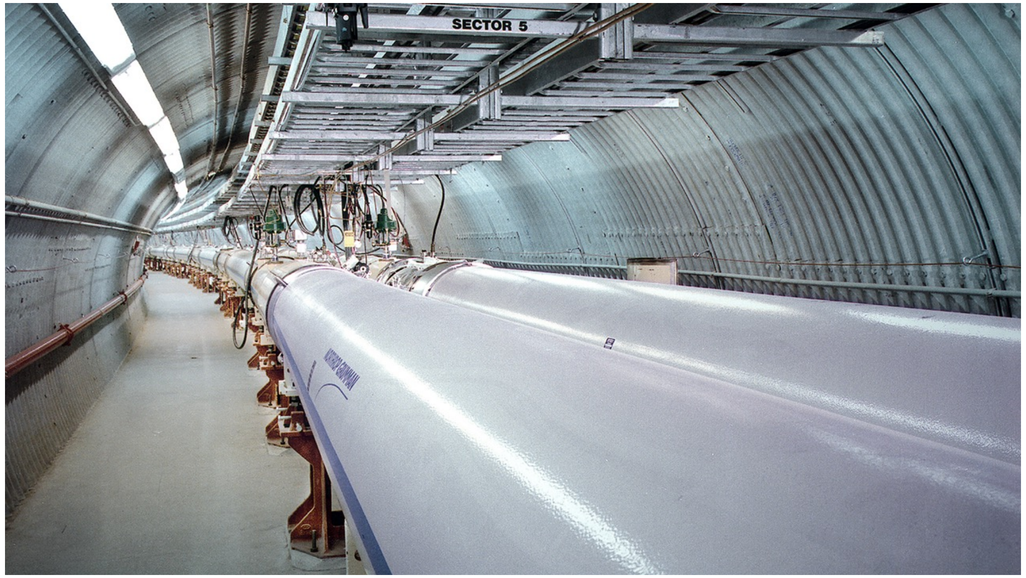
What are light ions?

- My nomenclature, if based on **saturation scale (~$A^{1/3}$)** about separating light (1-2), medium (3-4), and heavy nuclei (5-6)



Accelerating ions

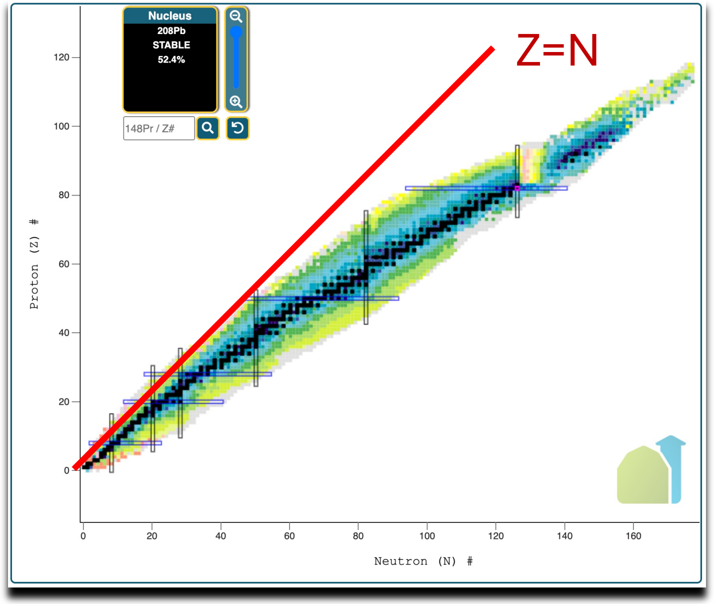
- Accelerator magnets are now optimized for a few configurations with **(i)** top energy on electron-proton at 18x275 GeV, and **(ii)** the lowest energy at 5x41 GeV.
- The simple way to see the top energy for ions is to scale them with Z/A, where the Z is the charge and A is the mass number. For example, Ru-96 has 44 protons, and the scaling factor is 44/96 = 0.46. Therefore, the top energy for **Ru-96 is 126.5 GeV.**
- **All ion energy is per nucleon.**



Combining energy and nuclear size together

- Although this is a pocket formula for saturation physics, it is relevant in kinematics in general - $Q_s^2 \sim (A/x)^{1/3}$
- x_{bj} scales inversely with beam momentum $1/E_{p/n}$ (proton energy, but the same as nucleon energy in nuclei as we denote all energies as per nucleon energy)
- Now, let's plugin the number:

$$Qs^2 \sim (A/x)^{1/3} \sim (AE_{p/n})^{1/3} \sim (A\,Z/A)^{1/3} \sim Z^{1/3}$$

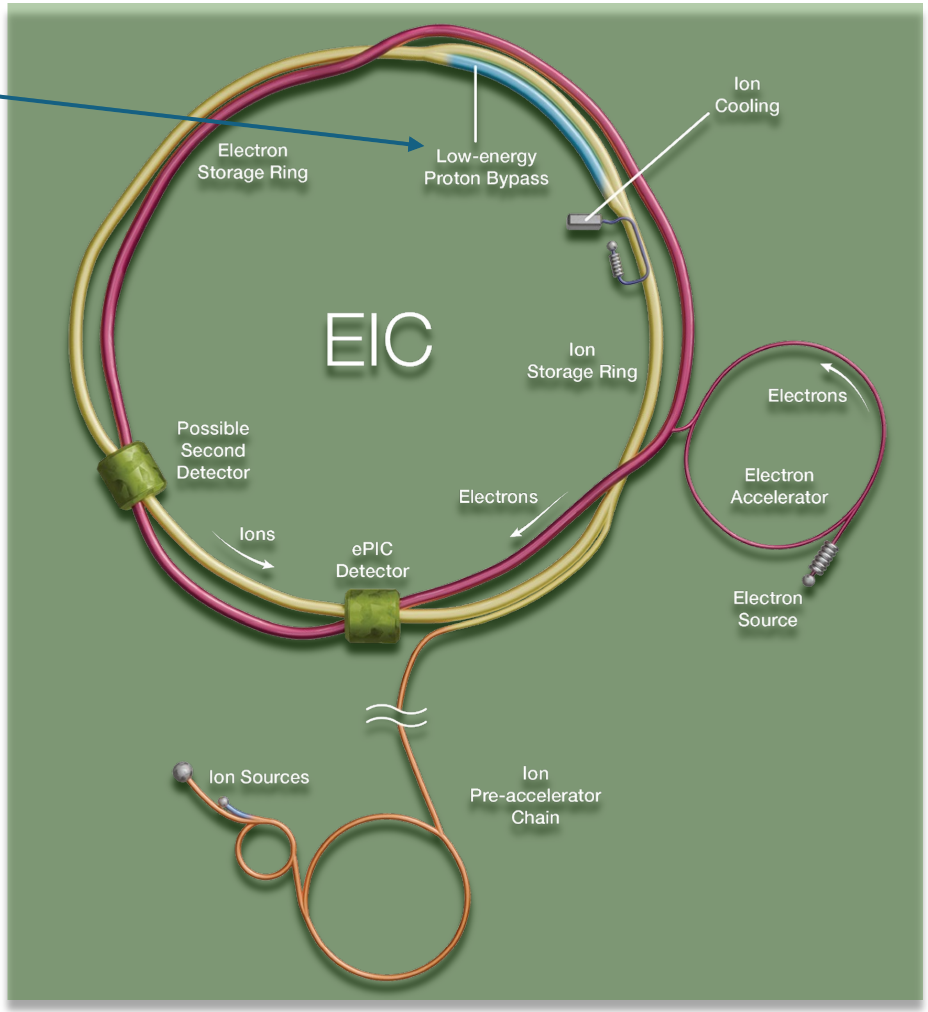


Conclusion:

Highest Z will give you the most nuclear effect.

What about lowest ion energy?

- That's still **5x41** GeV/n
- The reason is not based on magnet power but to sync the two beams at the interaction point; basically the ion beam cannot be too *slow*.
- Ion energy range: 41 GeV, 100 GeV – top energy



Pop Quiz

What's the lowest and highest running energy at the EIC for **Hafnium-176**☺?

Pop Quiz

What’s the lowest and highest running energy at the EIC for **Hafnium-176**☺?

41 GeV/n and 112.5 GeV/n, respectively.

Phase 1 EIC for ePIC (first 5 years starting 2034)

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

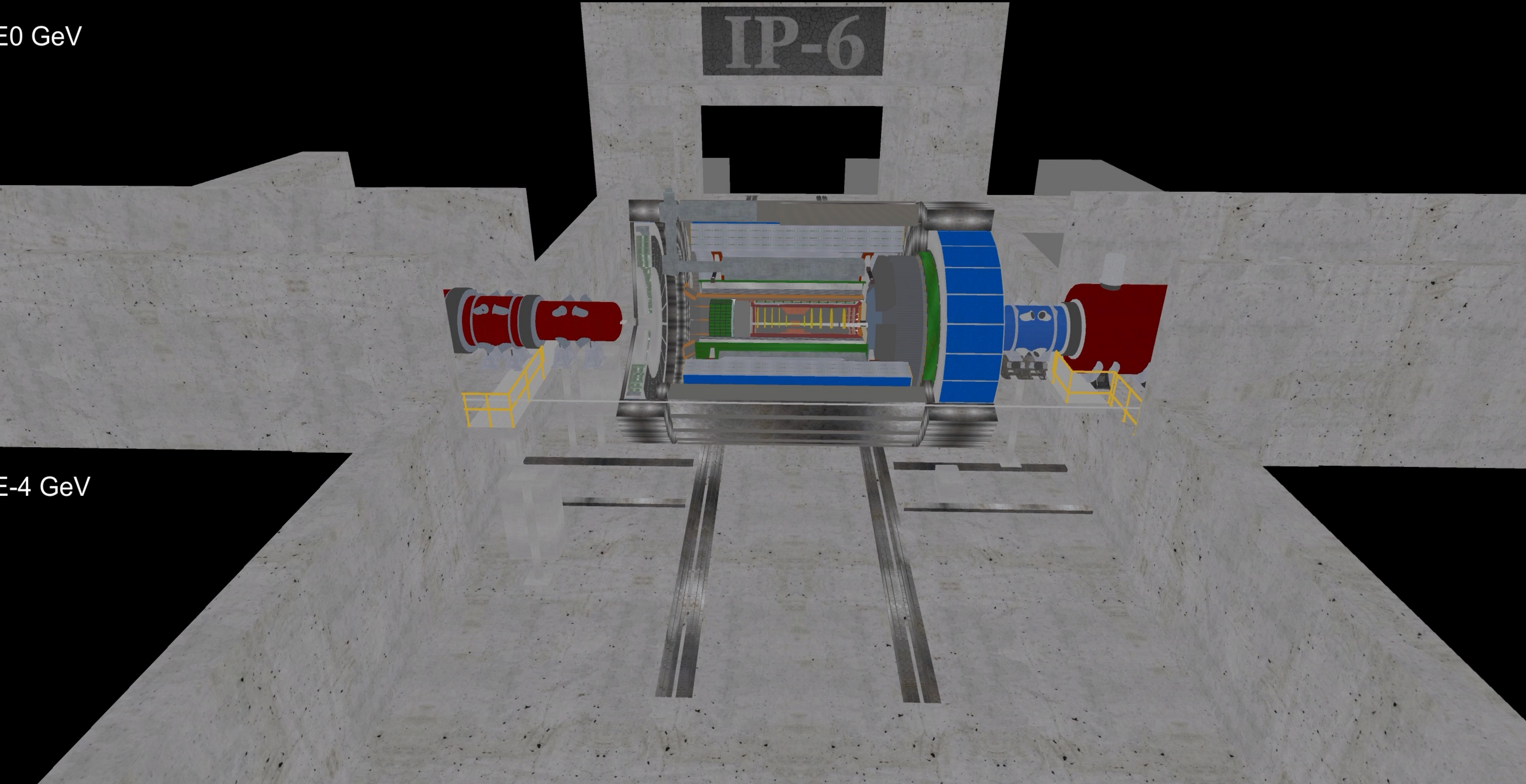
See the recent workshop, https://indico.cfnssbu.physics.sunysb.edu/event/410/overview

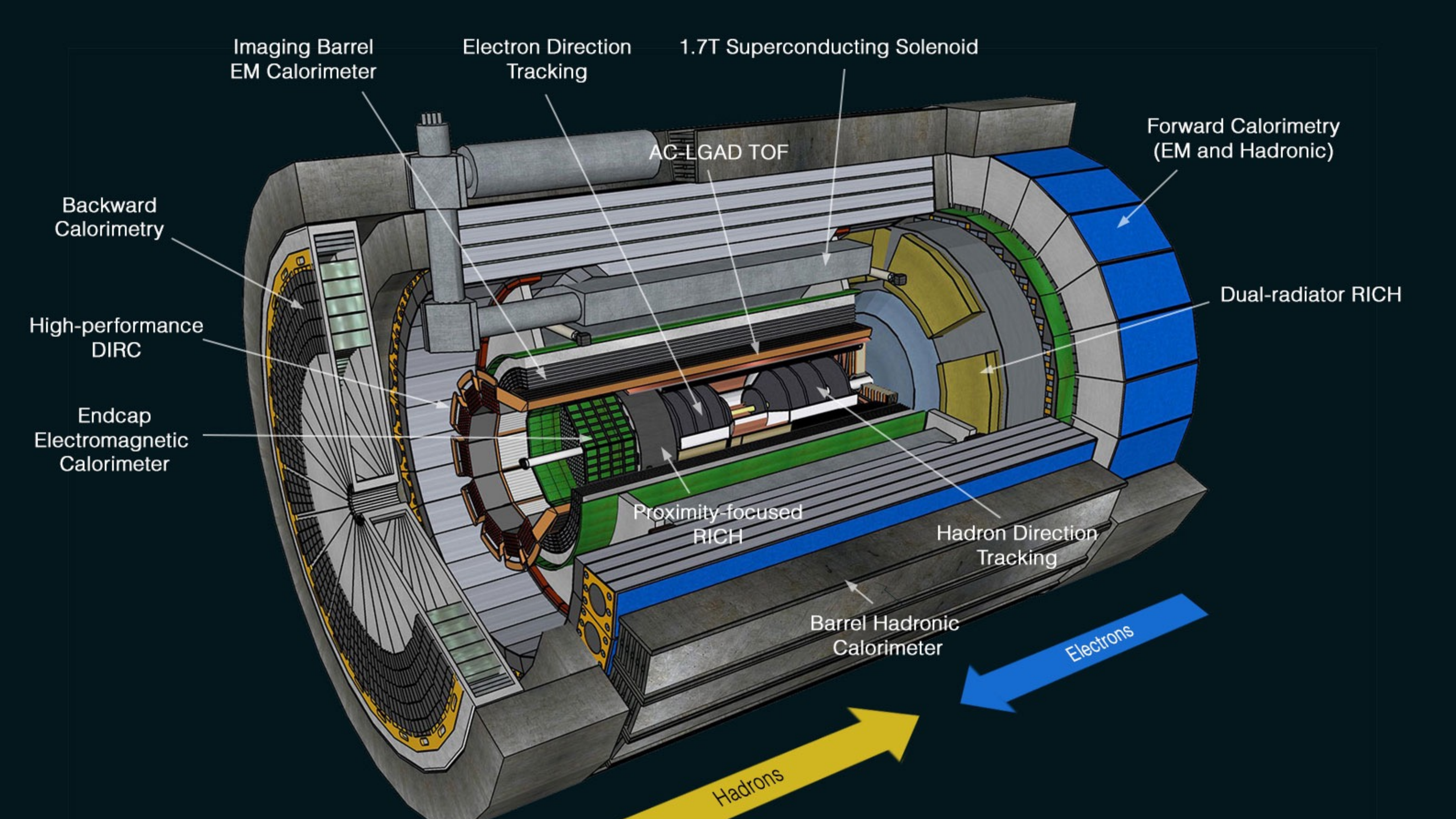
What does the EIC experiment look like?

PIC 18x275 ep Event #17

E0 GeV

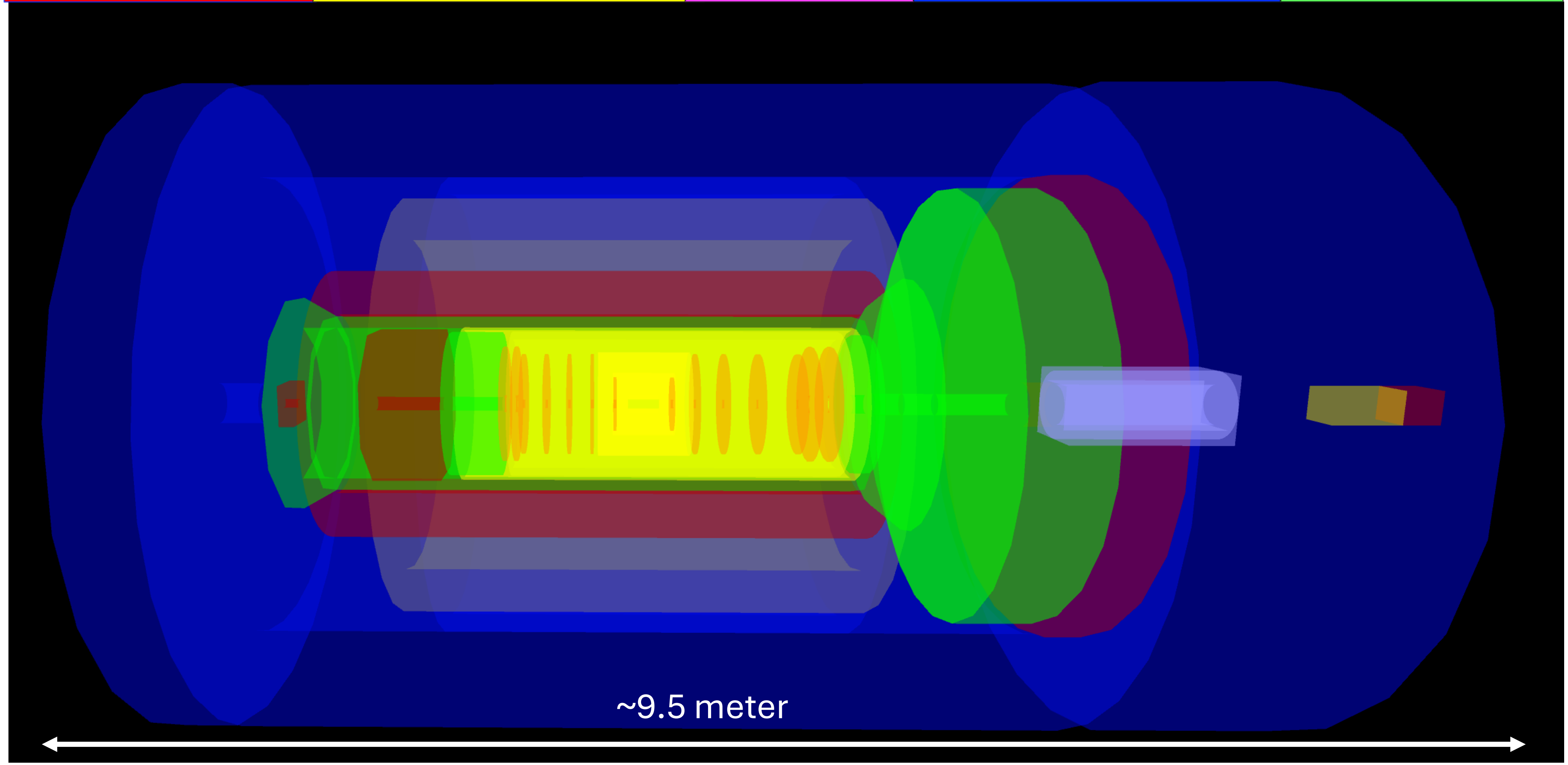
E-4 GeV




Imaging Barrel
EM Calorimeter
Electron Direction
Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry
(EM and Hadronic)
Backward
Calorimetry
High-performance
DIRC
Dual-radiator RICH
Endcap
Electromagnetic
Calorimeter
Proximity-focused
RICH
Hadron Direction
Tracking
Barrel Hadronic
Calorimeter
Electrons
Hadrons

ePIC detector subsystem overview

e/m calorimeters	MAPS & MPGD trackers	solenoid coils	hadronic calorimeters	PID detectors

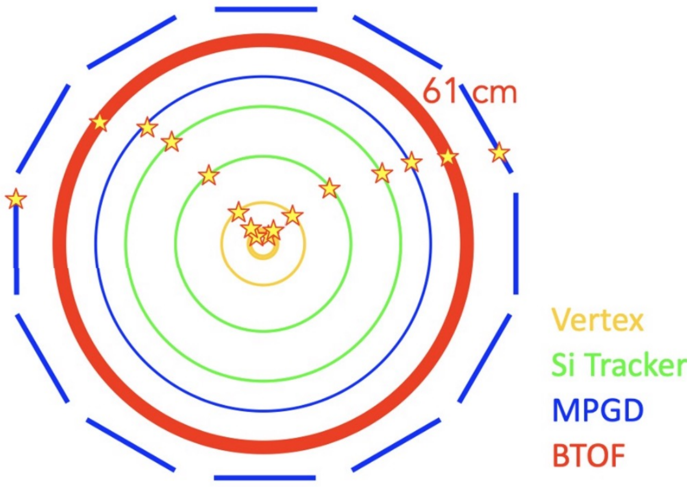


1.7 T solenoid magnet

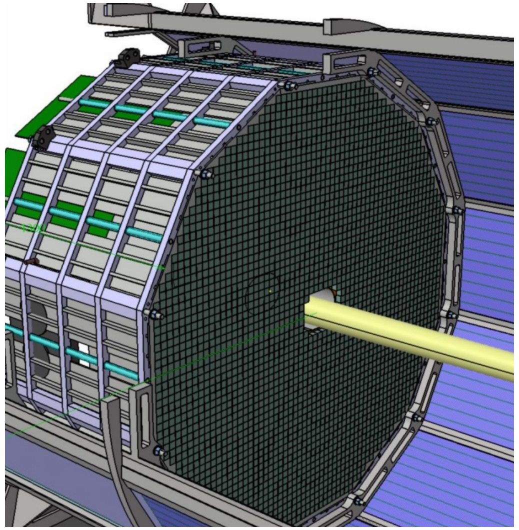
A basic idea of the main ePIC detector

ePIC has full coverage for tracking, calorimetry, and PID from **-3.5 < eta < 3.5**:

- Charged particle tracking with 1.7 T field:
  - pt > ~ 0.5 GeV/c;
  - Different technologies in 8 layers;
- Backward Calo/PID (-3.5 < eta < -1.5):
  - Crystal EM calorimeter mostly detect **scattered electron** with great energy resolution (e.g., Q2 ~ 1 – 10 GeV2)
  - pfRICH can separate pi/k/p up to 9 GeV/c in momentum.
- Central Calo/PID (-1.5 < eta < 1.5) :
  - Imaging calorimeter with 6 layers of silicon interleaved with 5 SciFi/Pb layers
  - hpDIRC and AC-LGAD (T.O.F) for PID
- Forward Calo/PID: (1.5 < eta < 3.5):
  - Forward EM and Hadronic calorimeters are available.
  - dRICH can separate pi/k/p up to 50 GeV/c.

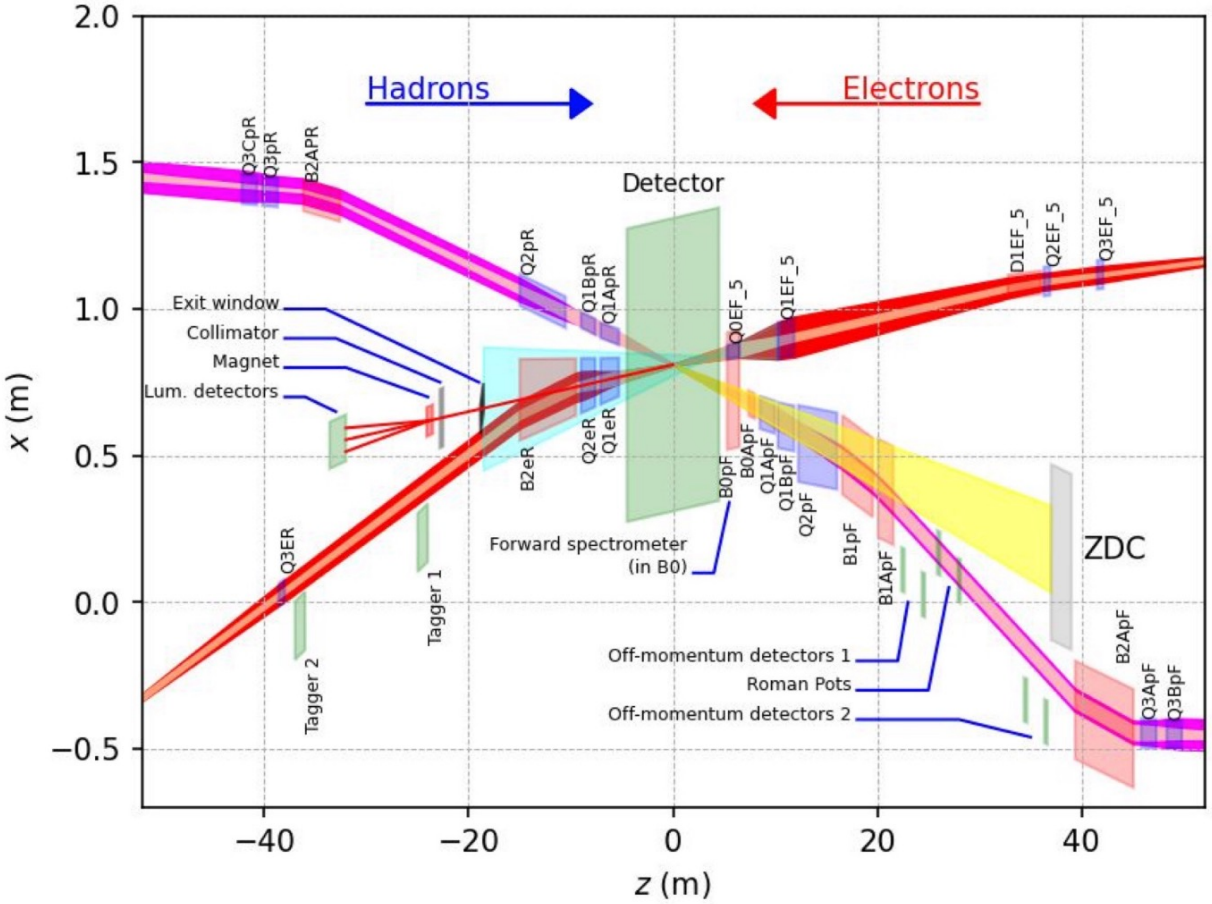


The tracking system from inside out: vertex, Si Tracker, MPGD, BTOF



Backward EM cal (e.g., scattered electron)

Far-forward and far-backward system



Far-forward: Detect particles from nuclear breakup and exclusive processes

- B0 tracker/Calorimeter
- Roman pots
- off-momentum detector
- Zero-degree calorimeter

Far-backward:

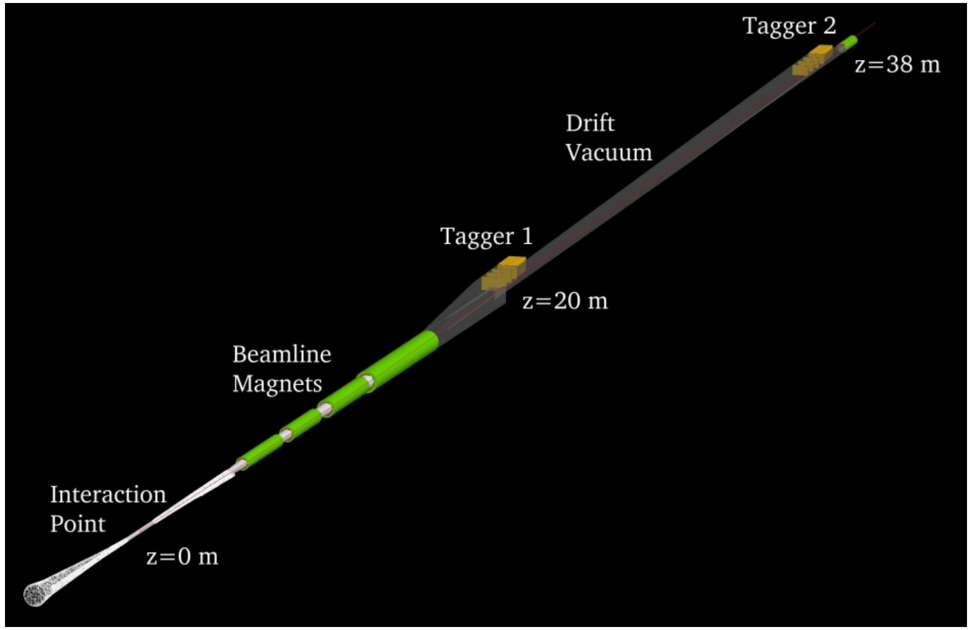
- Two low Q^2 electron taggers
- luminosity monitor

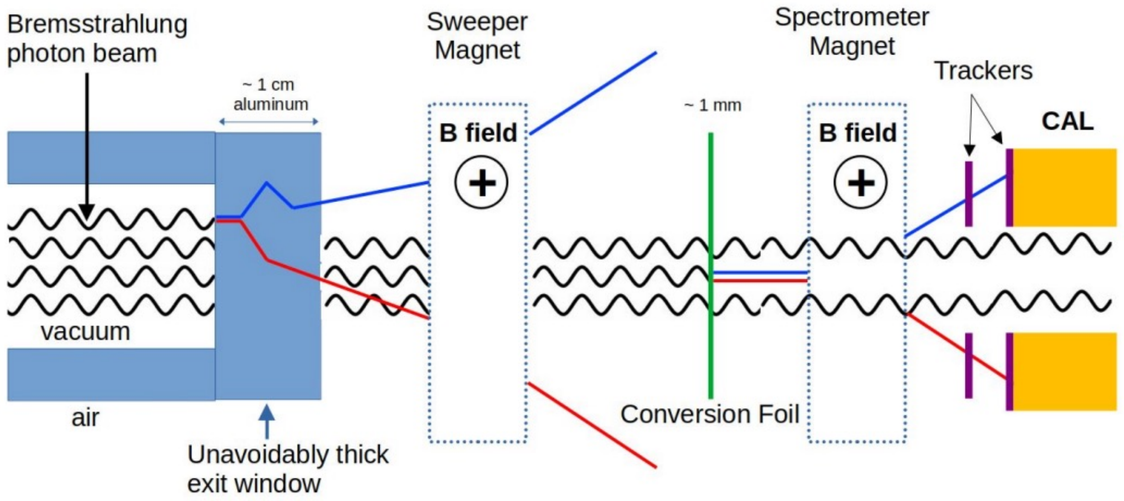
Far-backward detectors

- **Low Q^2 taggers:**
  - ✓ Pixel-based 4 trackers (Timepix4), with rate capability of > 10 tracks per bunch
  - ✓ Calorimeters (for calibration)
- Challenges: high, non-uniform Brem. background

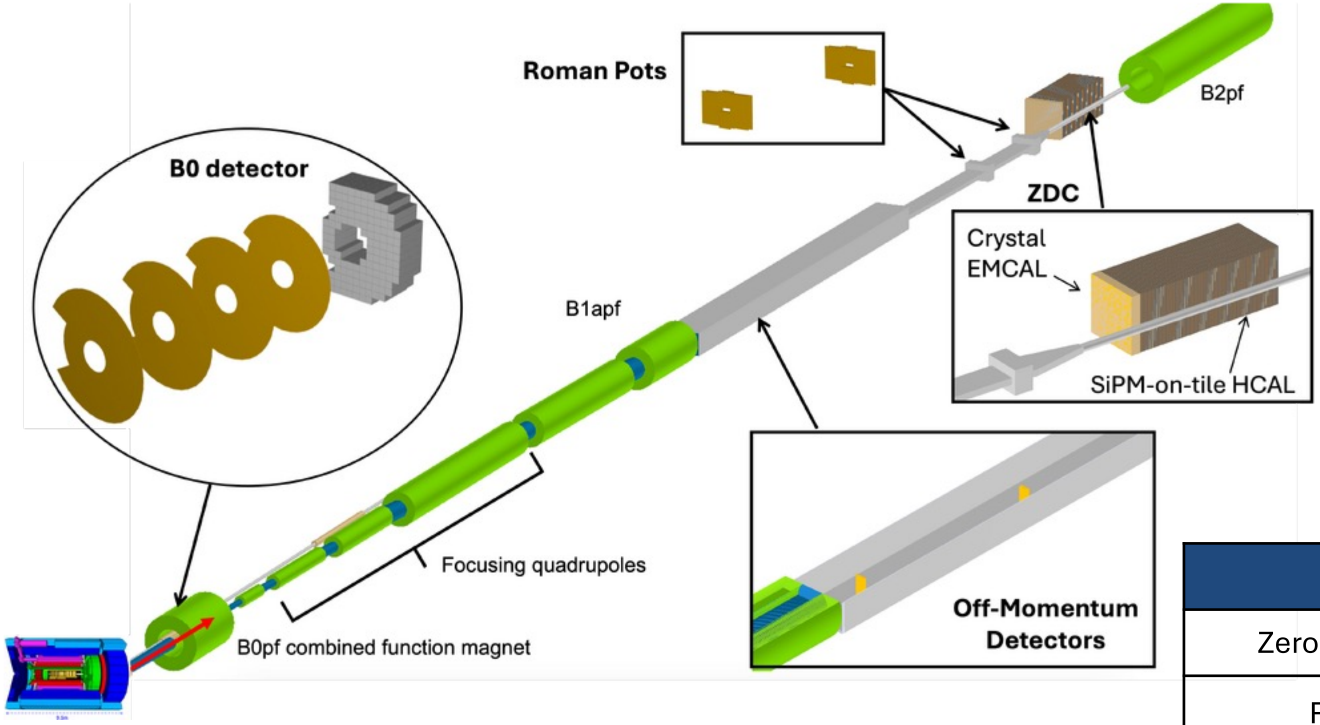
Luminosity monitor:
Precise luminosity determination (<1%), from Bremsstrahlung processes ($ep \rightarrow e\gamma p$)

- ✓ Tracker: AC-LGAD strips with 20um resolution
- ✓ Calorimeter: Scintillating Fiber, $23X_0$





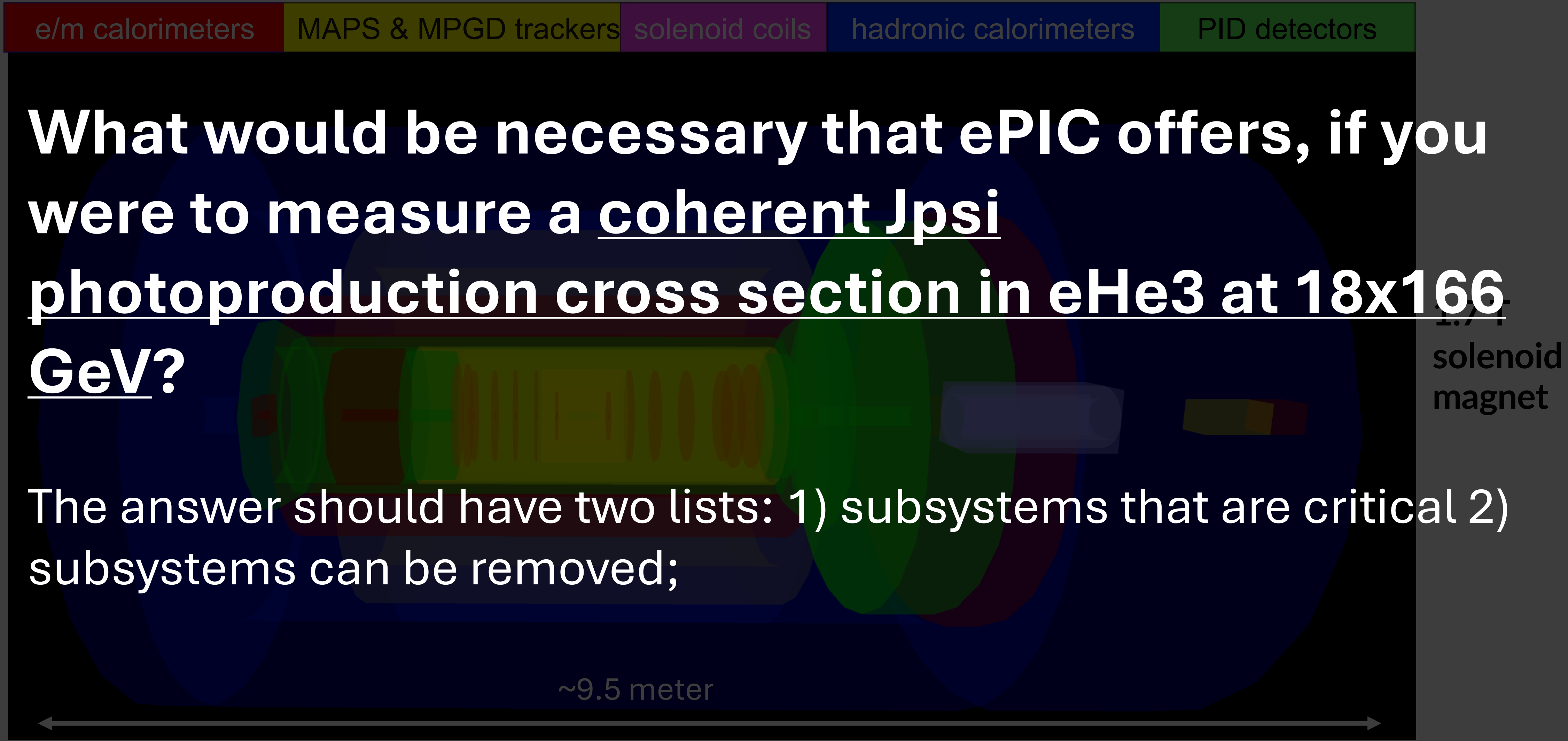
Far-forward detectors



Detector	Acceptance
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)	$0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \boldsymbol{\theta} < 20$ mrad ($4.6 < \eta < 5.9$)

Terminology: coherent (vs incoherent) means the ion has the same (vs different) initial and final state

ePIC detector subsystem overview



What would be necessary that ePIC offers, if you were to measure a <u>coherent Jpsi photoproduction cross section in eHe3 at 18x166 GeV</u>?

The answer should have two lists: 1) subsystems that are critical 2) subsystems can be removed;

What would be your answers?

My answers are (its not a unique solution):

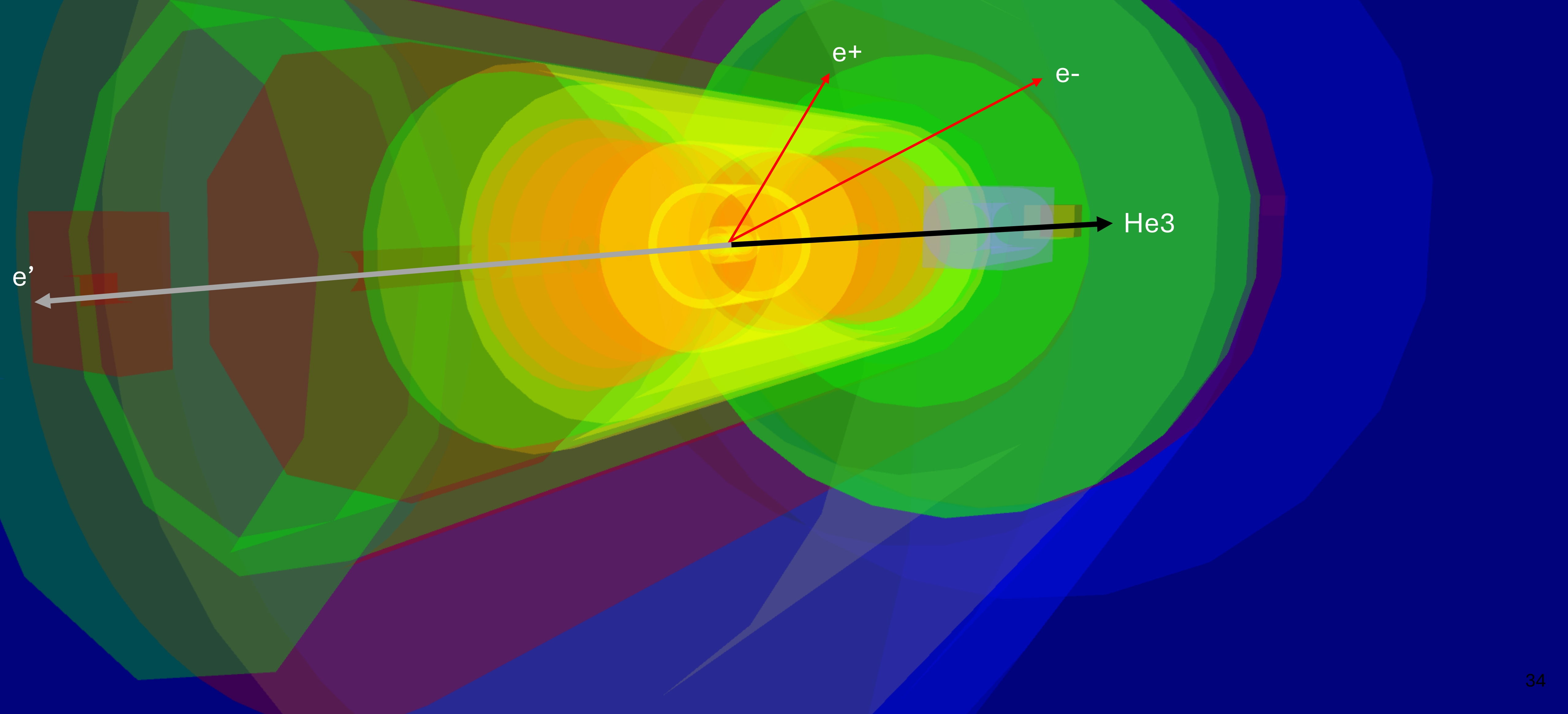
The analysis would need:

1. Magnet
2. All tracking detectors
3. All EM calorimeters (for scattered electrons and decay electrons)
4. Far-forward detectors
5. Low-Q2 taggers
6. Luminosity monitor

The analysis would NOT need:

1. Hcal
2. PID (would be helpful but not needed)

eHe3 coherent Jpsi pseudo event display



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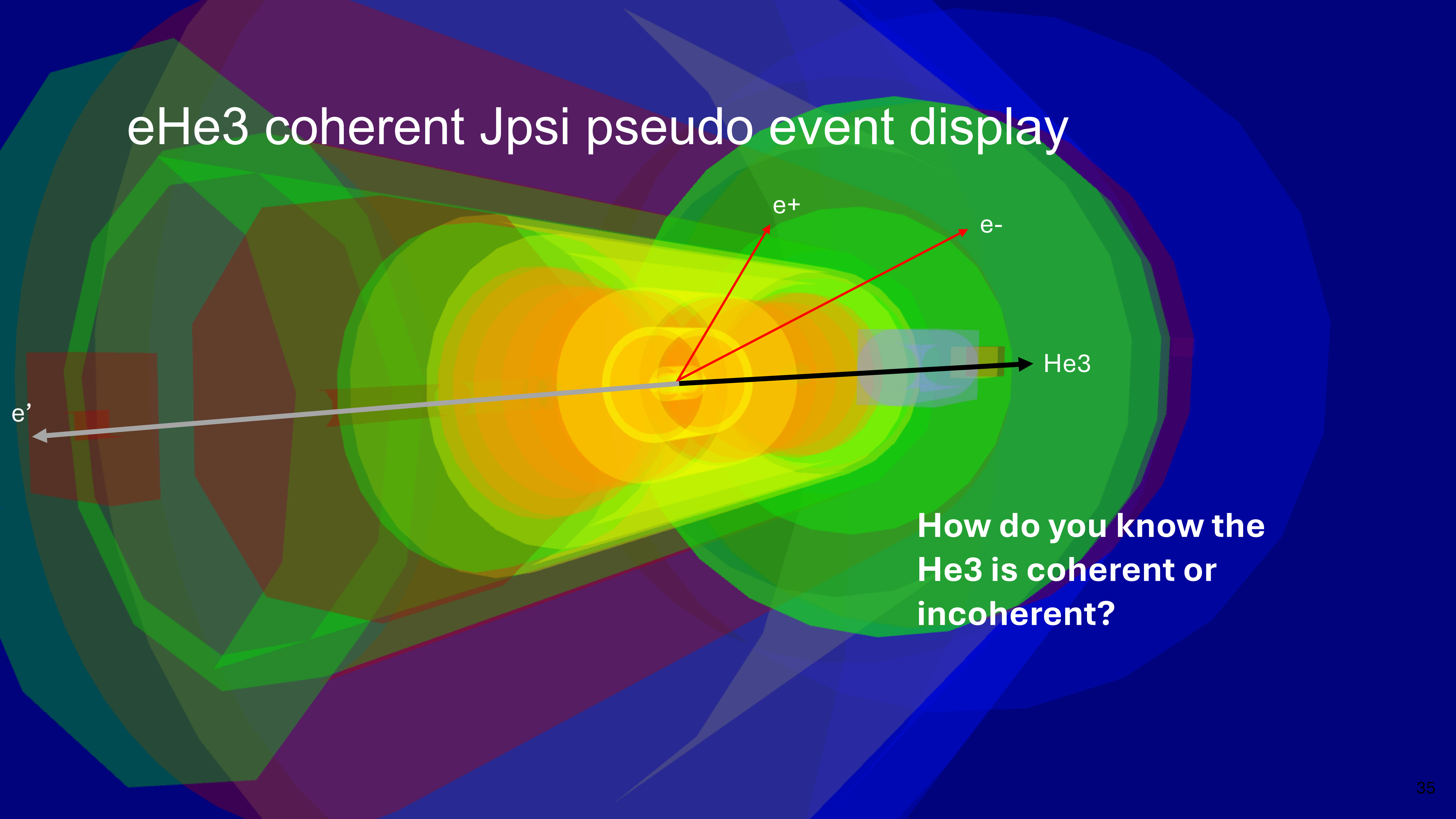
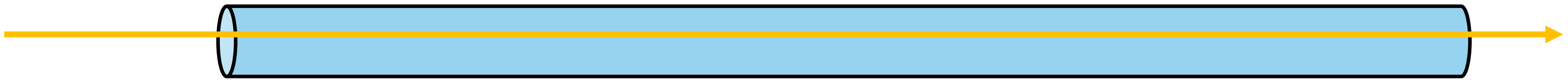


How do you know the He3 is coherent or incoherent?

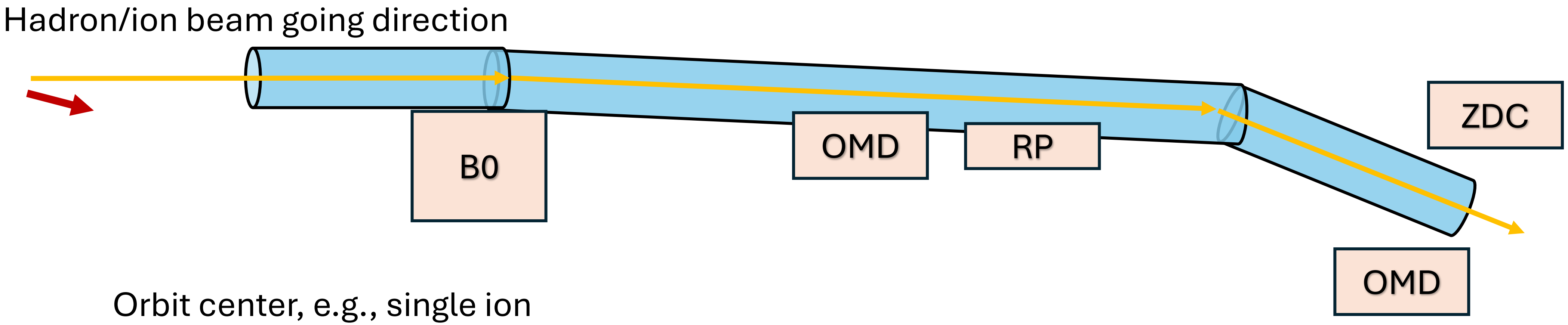
Far-forward detector systems and principles

Hadron/ion beam going direction



Orbit center, e.g., single ion beam without interaction circulating in the ring

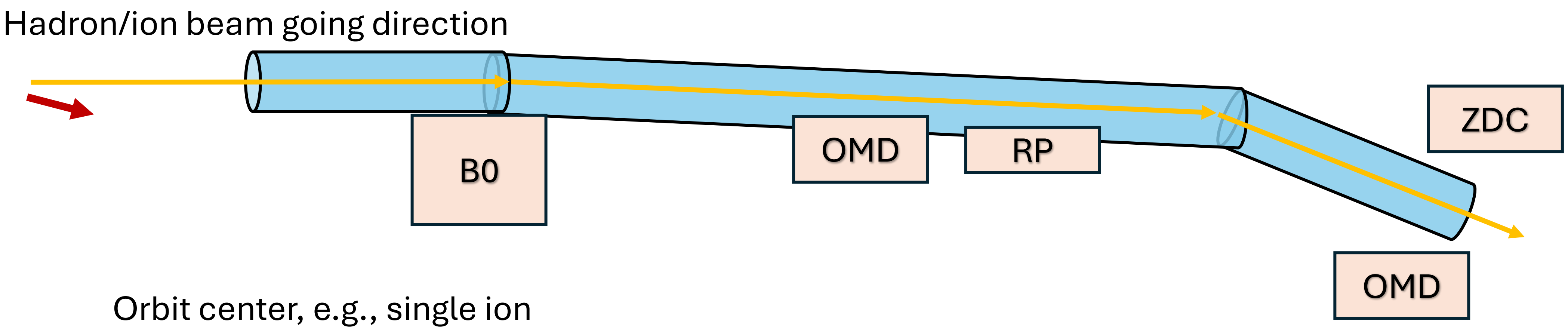
Far-forward detector systems and principles



Orbit center, e.g., single ion beam without interaction circulating in the ring

After interaction (momentum transfer), the ion has a transverse kick (pT) and longitudinal momentum loss (1-xL)

Far-forward detector systems and principles

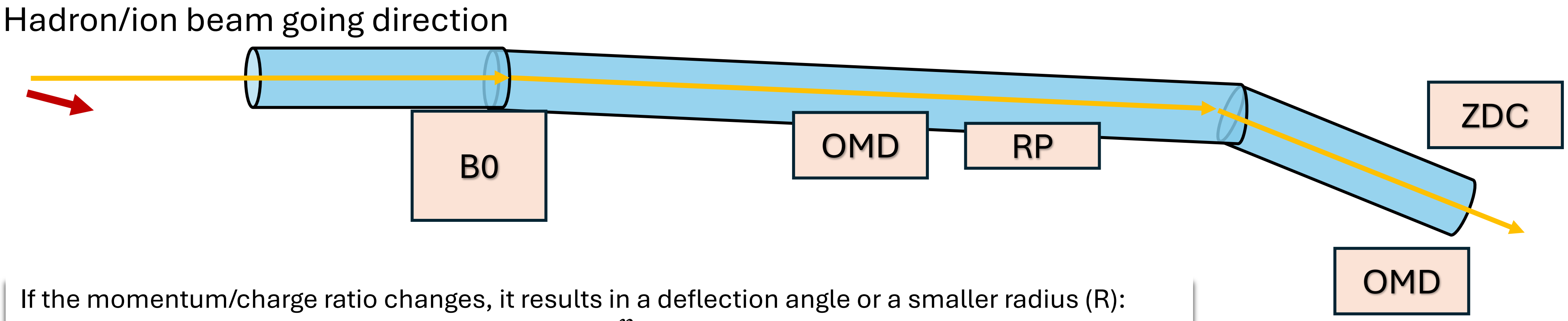


Orbit center, e.g., single ion beam without interaction circulating in the ring

After interaction (momentum transfer), the ion has a transverse kick (pT) and longitudinal momentum loss (1-xL)

Question: so how can RP and OMD detect particles down to zero angle?

Far-forward detector systems and principles



If the momentum/charge ratio changes, it results in a deflection angle or a smaller radius (R):

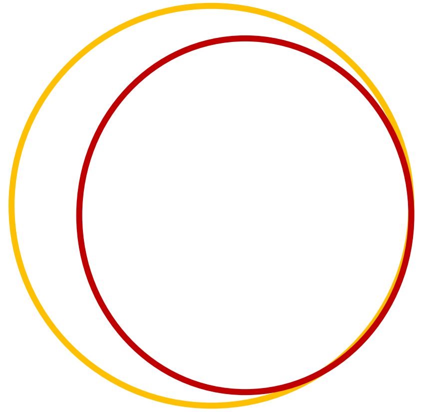
$$R = \frac{p}{qB}$$

This can be a change in a breakup process (deuteron breaks up into proton + neutron), then the change is proportional to $\Delta\frac{p}{q} \sim \Delta\frac{A}{Z}$; For example, this is how **OMD** detects the breakup particles.

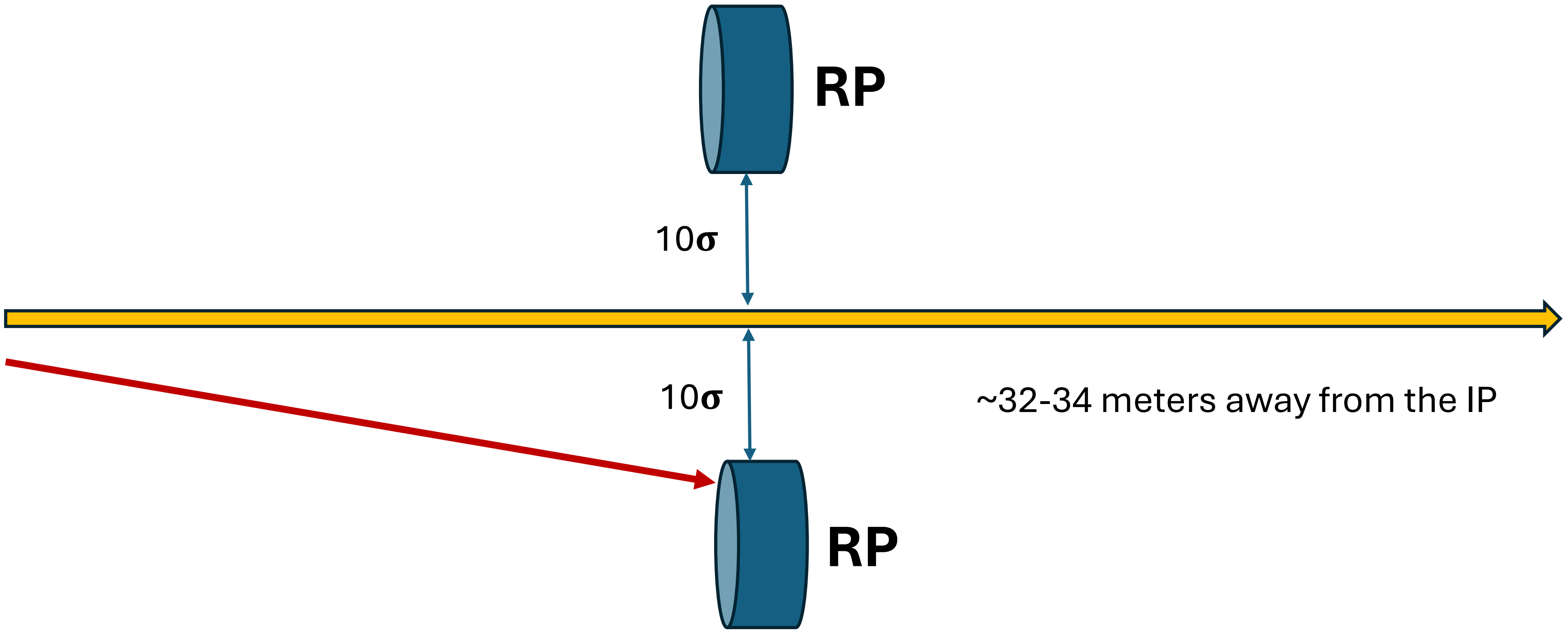
If there is only loss of momentum, the radius of the circle becomes smaller; or in terms of relative angular deflection:

$$\Delta\theta \sim \left(\frac{\Delta p}{p}\right)$$

This is how **RP** detects particles with small pT kick. The results are similar between a dipole and a quadruple, meaning a loss in momentum → a deflection angle.

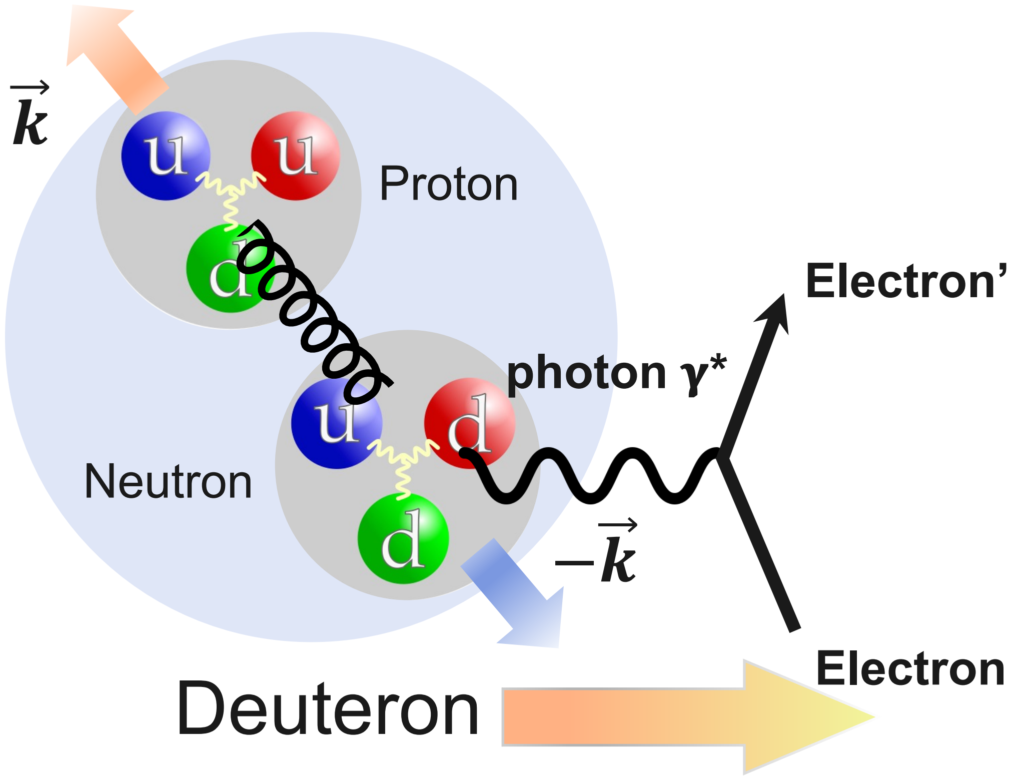


For Roman Pots: they are placed 10$\boldsymbol{\sigma}$ away from the beam ($\boldsymbol{\sigma}$ is the width of the beam)



Therefore, the RP acceptance will never be 100% - it depends on angle and momentum loss.

For OMD – it enables the spectator tagging



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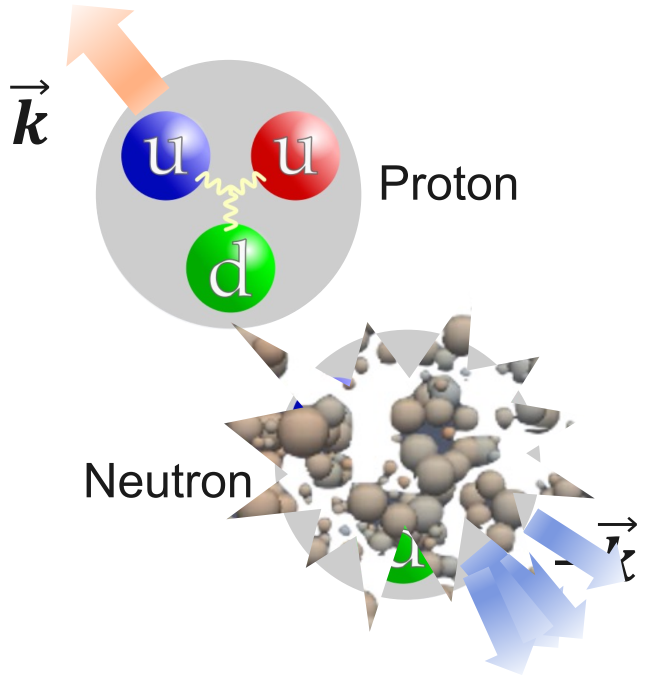
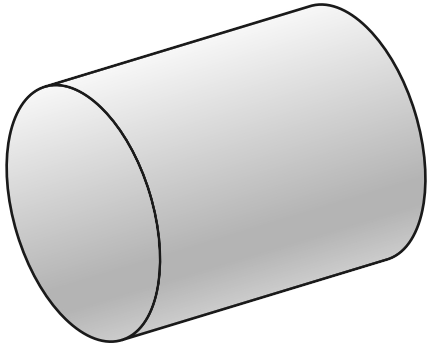
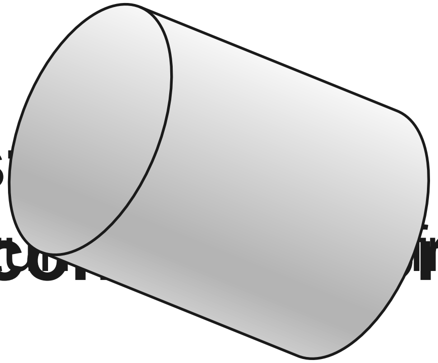


Spectator



OMD (rigidity change from 2 to 1)

Reconstruct momentum **p** + Lorentz Boost
= internal nucleon momemtum $\vec{\mathbf{k}}$



Active nucleon breaks up
But was with momentum $-\vec{\mathbf{k}}$

The beauty of collider kinematics:
Boost the detector measurement of zero momentum frame!

Fully recons
Initial-state co in

Neutron detector

Back to the question:
How can we know if a process is coherent or incoherent

- Two approaches:
  - Detect the coherent outgoing particle but nothing else
  - Or tag (veto) all events with breakup products.

Quiz:

For coherent Jpsi photoproduction (ep vs eHe3):

If a proton is scattered coherently, and the scattering angle ~ 0, with momentum loss about 10% (xbj=0.1), it just hits the edge of the RP acceptance.

At what xbj value in a coherent event can a He3 hit the same spot (or just make it in the RP acceptance)?

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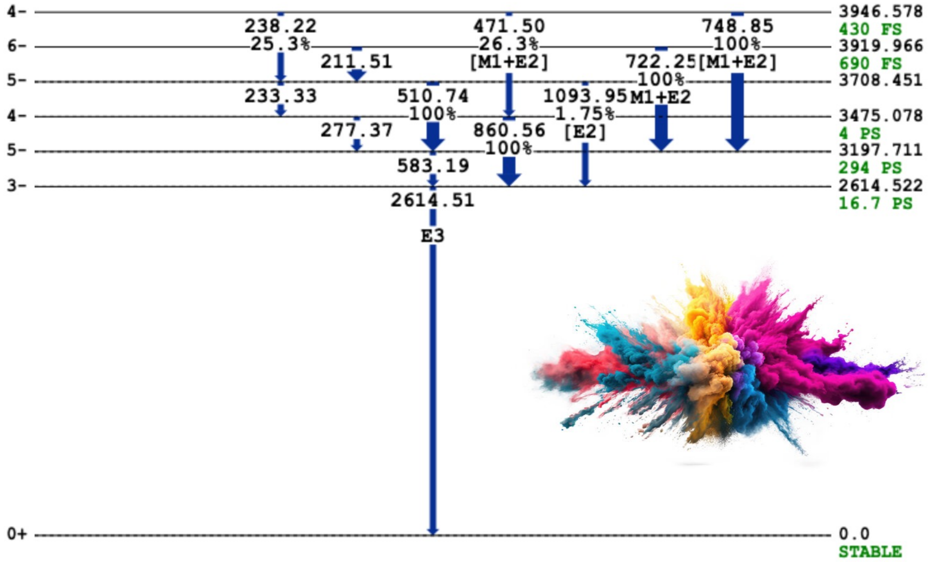
At what xbj value in a coherent event can a He3 hit the same spot (or just make it in the RP acceptance)?

Answer: xbj ~ 0.3

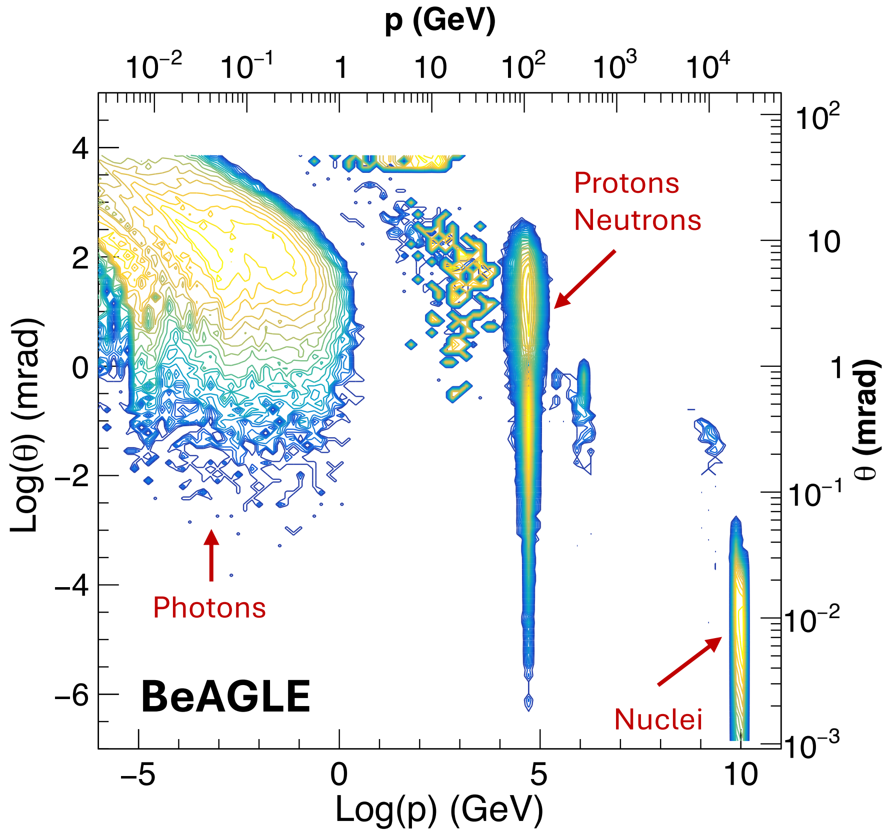
(one can immediately see the problem with larger ions)

Second approach – vetoing

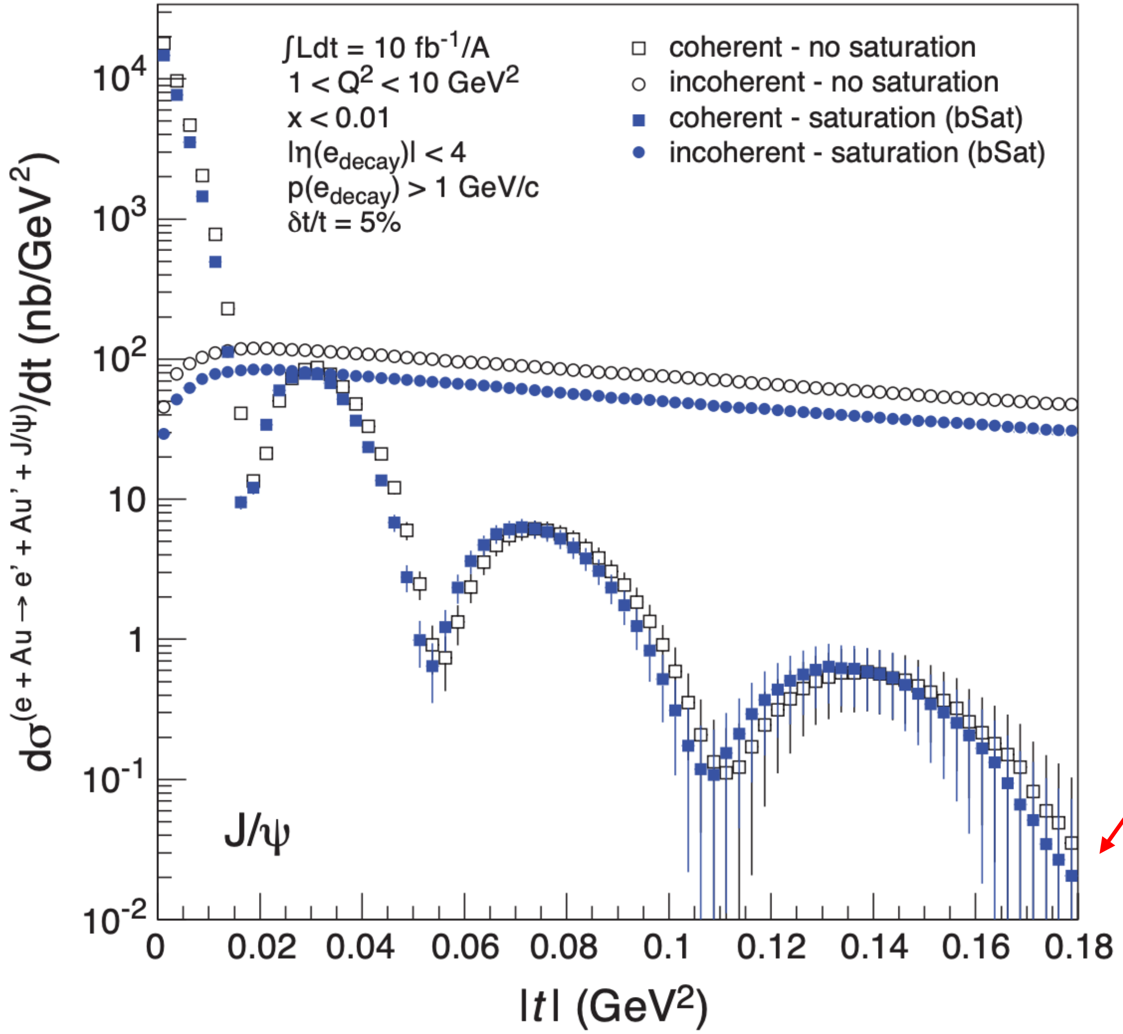
Pb 208 level scheme

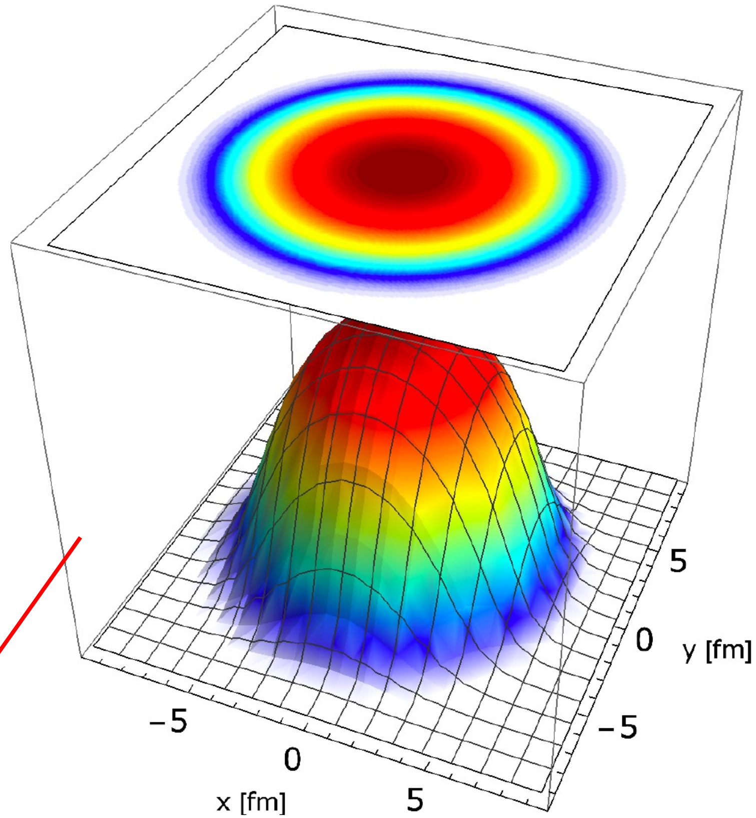


https://www.nndc.bnl.gov/nudat3/

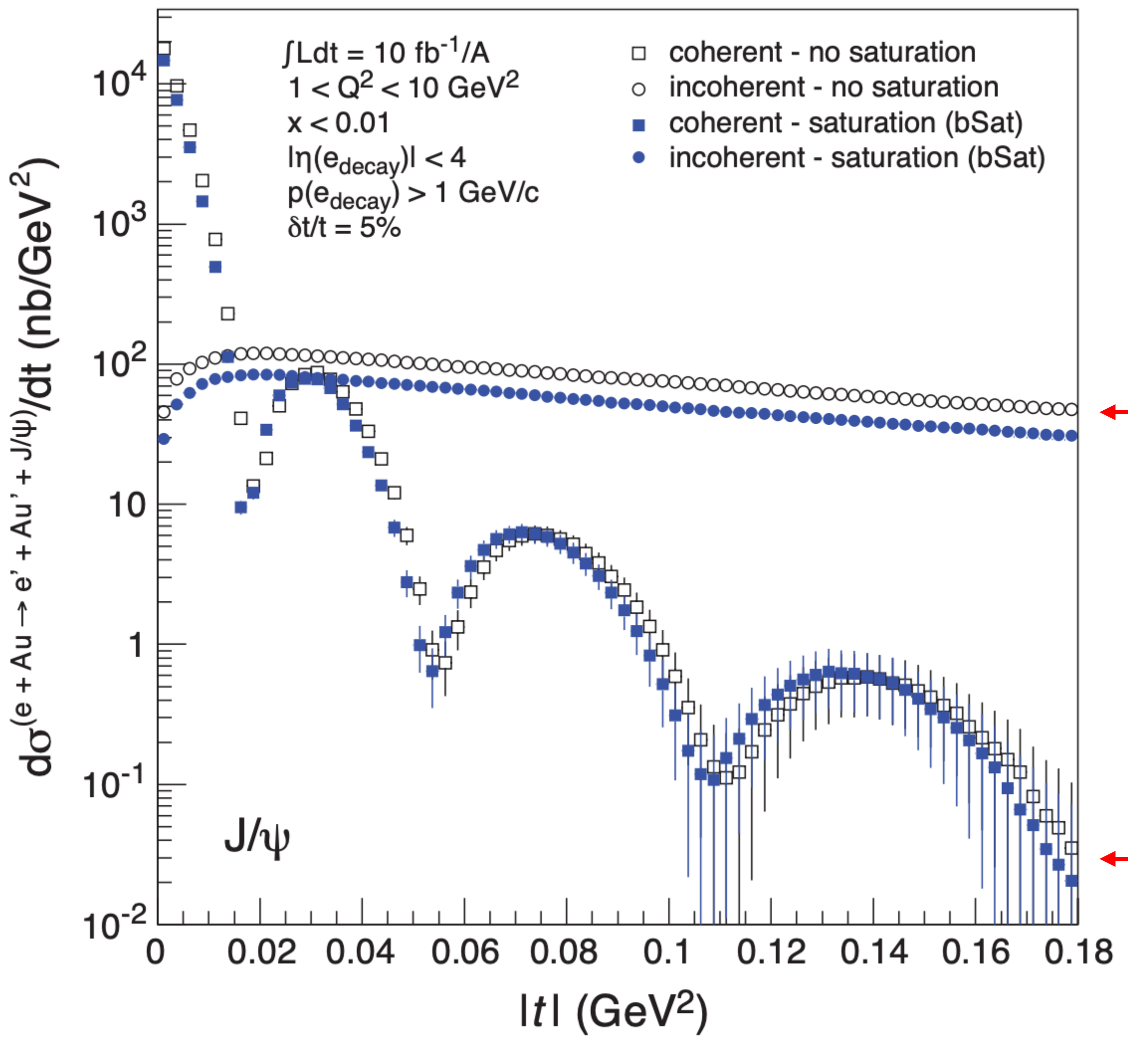


Example: Imaging heavy nuclei at the EIC





Example: Imaging heavy nuclei at the EIC

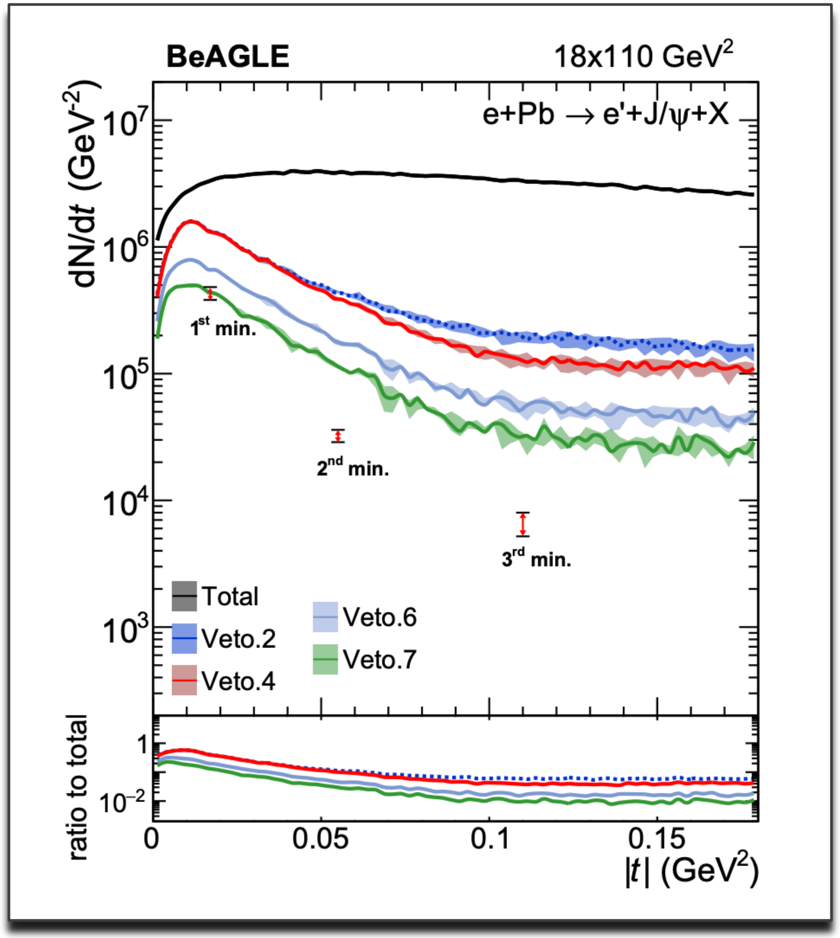


← Can far forward detectors veto those incoherent productions?

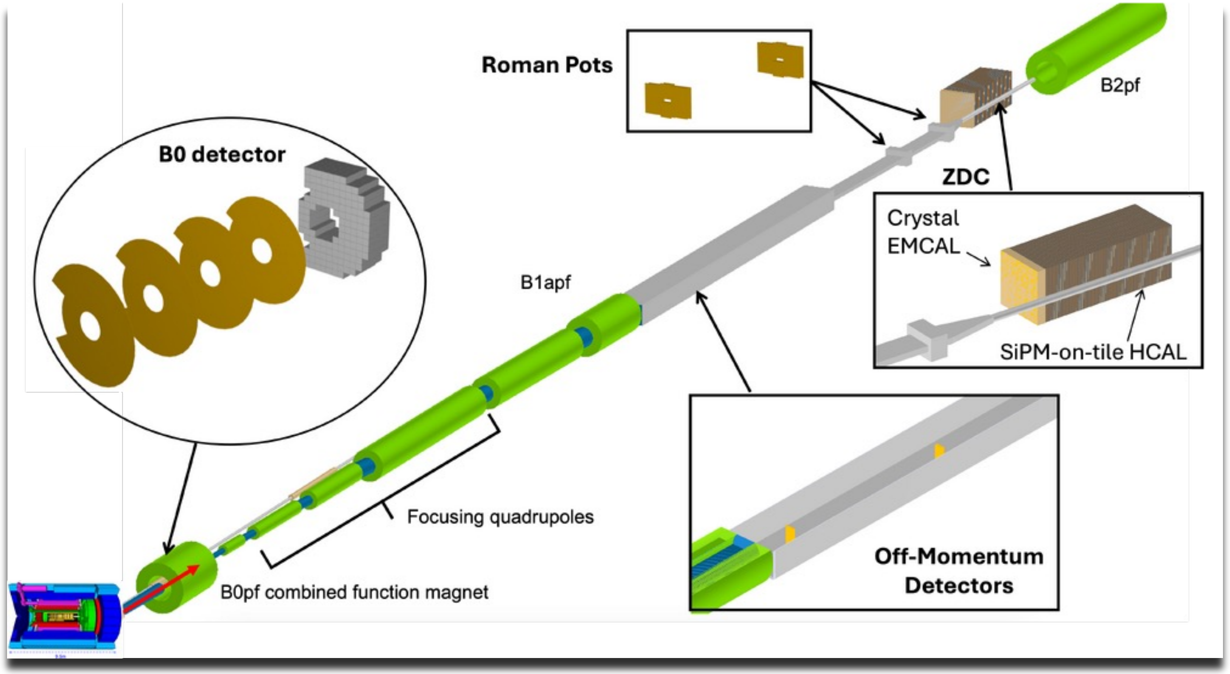
← Coherent is what we want, where *t* is a Fourier Transform of the *b (position distribution of gluons)*

Initial results for the heavy nuclei vetoing at the EIC

IR6



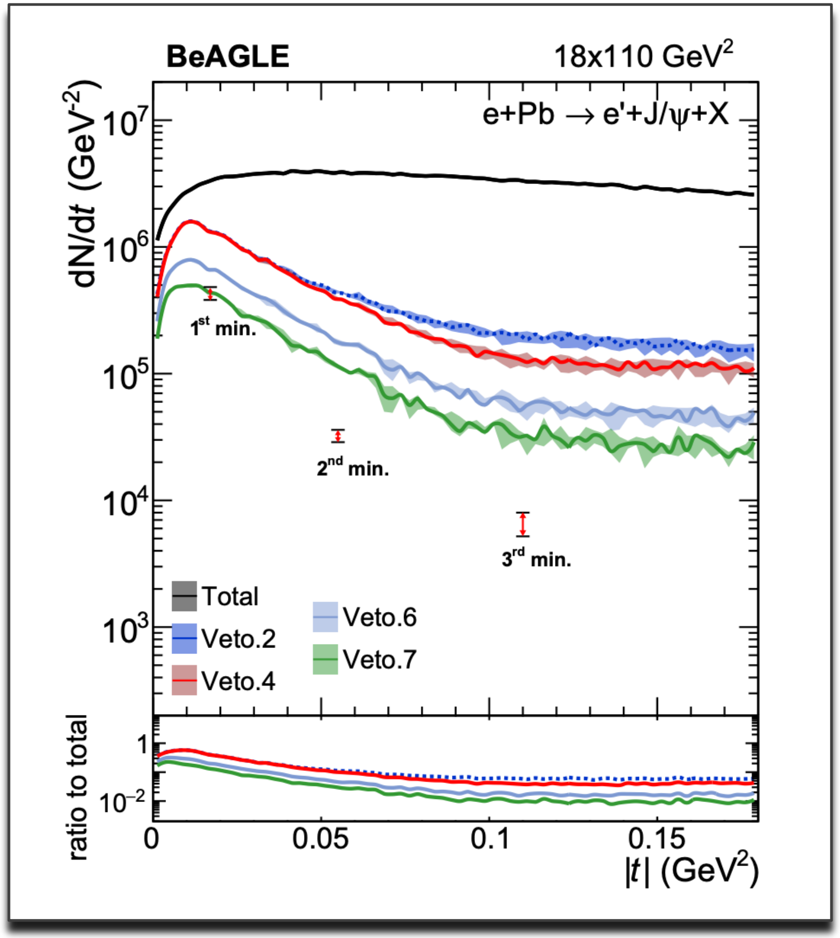
(Phys. Rev. D 104 (2021) 11, 114030)



Any particles/activities in these detectors, we can tag or veto.

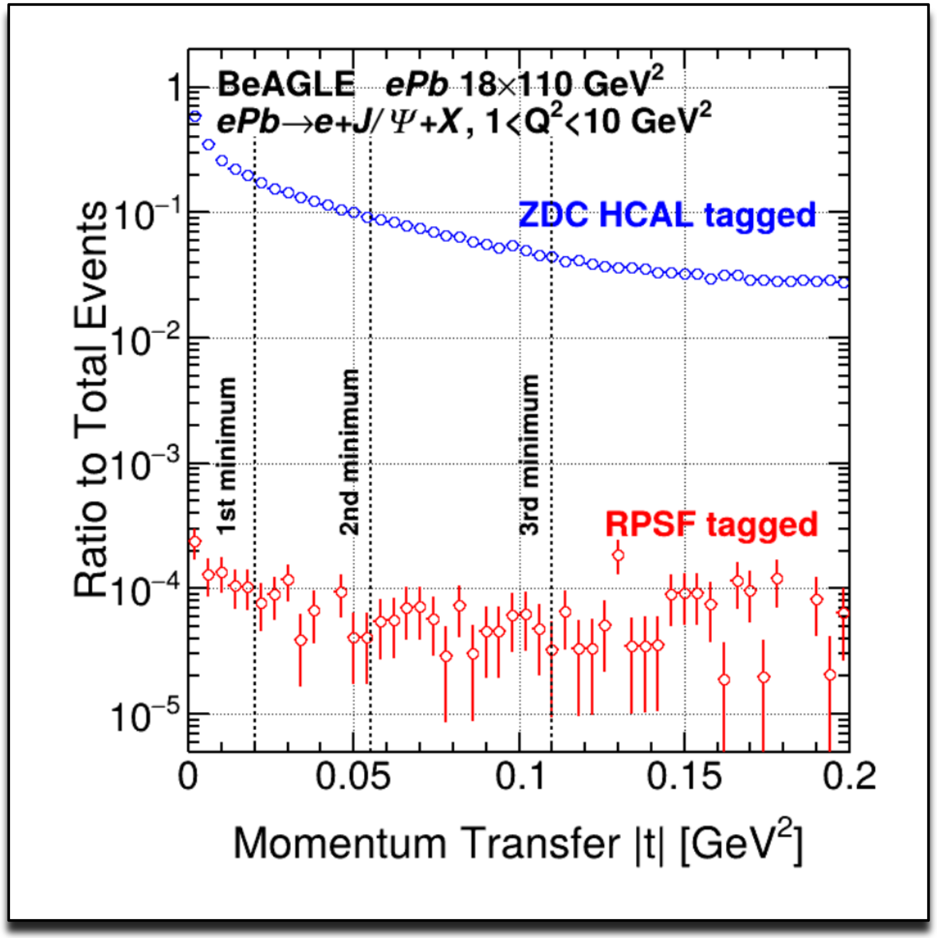
Initial results for the heavy nuclei vetoing at the EIC

IR6



(Phys. Rev. D 104 (2021) 11, 114030)

IR8

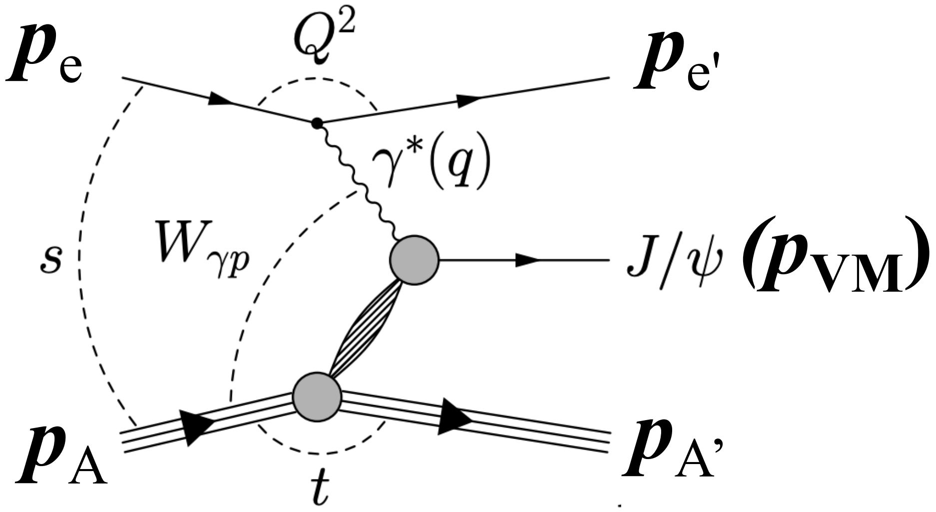


NEW: arXiv:2501.12410

Reconstructions of t variable

- Method Exact (E): $-t = -(\boldsymbol{p}_{\mathrm{e}} - \boldsymbol{p}_{\mathrm{e'}} - \boldsymbol{p}_{\mathrm{VM}})^2 = -(\boldsymbol{p}_{\mathrm{A'}} - \boldsymbol{p}_{\mathrm{A}})^2$
- Method Approximate (A) (UPCs) $-t = (\overrightarrow{p_{\mathrm{T,e'}}} + \overrightarrow{p_{\mathrm{T,VM}}})^2$
- Improved Method E: Method L $-t = -(\boldsymbol{p}_{\mathrm{A',corr}} - \boldsymbol{p}_{\mathrm{A}})^2$,

where $\boldsymbol{p}_{\mathrm{A',corr}}$ is constrained by exclusive reaction.

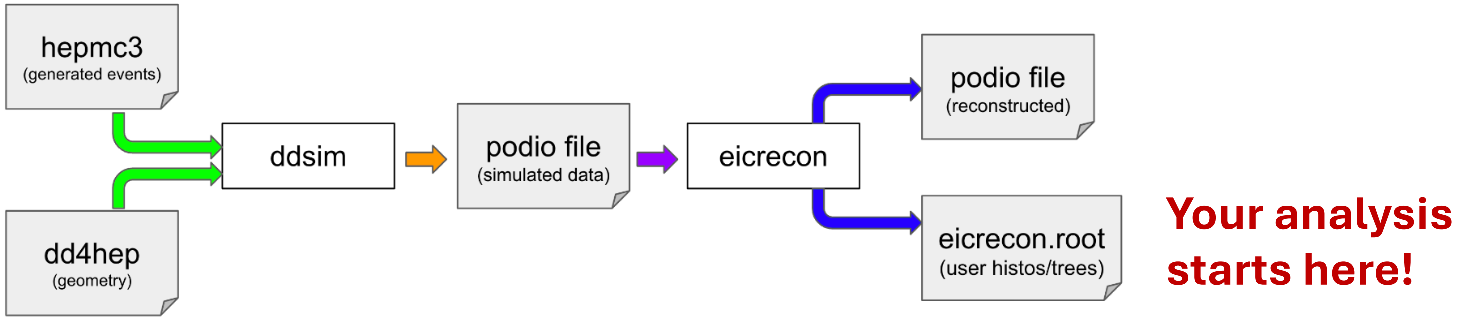


Best method concluded from the EIC Yellow Report – **Method L**

- Insensitive to beam effects, e.g., angular divergence and momentum spread.
- More precise than Method A for electroproduction

ePIC simulation workflow

1. Start at the landing page, https://eic.github.io/documentation/landingpage.html for info and especially the tutorials
2. Prepare your MC samples in the format that ePIC accepts (hepmc3), implement beam effects/crossing angles if not already done.
3. Submit to the production team, but what they do is the following:



- dd4hep detector geometry description (see EPIC detector, https://github.com/eic/epic)
- ddsim for simulation/digitization
- edm4eic data structure defined with podio and edm4hep (https://github.com/eic/EDM4eic)
- EICrecon reconstruction framework based on JANA (https://github.com/eic/EICrecon)

Example: coherent diffractive Jpsi in eAu

Step 1: event selection

- Only scattered electron and the Jpsi decay products (ee) in the main detector

Step 2: reconstruct Jpsi (invariant mass peak)

Step 3: veto incoherent production in the Far Forward region

Step 4: reconstruct *t* variable (corrections are needed in real data)

Step 5: Fourier Transform to perform the imaging.

The details are for you to figure out!

Thank you!

The exercise is next page

Exercise – *“What are we running?”*

- Form groups: 2-3 student groups;

- Github repo for this exercise:

(will send out via email this afternoon)

- Pseudo data:

https://drive.google.com/file/d/1ofgtVJOQZuD-fsEqRfIrLZhoGxKIj9dp/view

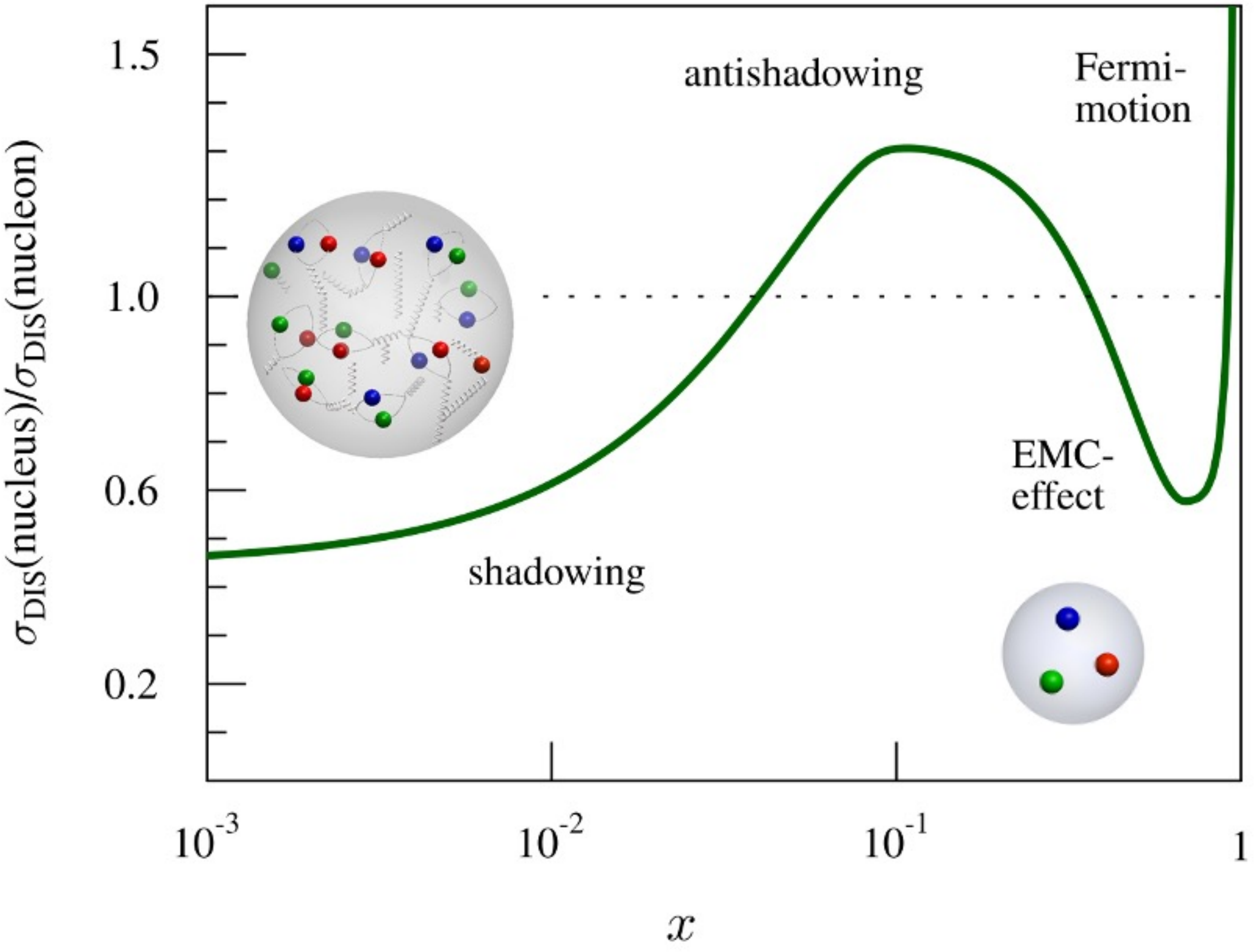
Acknowledgement

Big thanks to Sakib Rahman, Alex Jentsch, Arjun Kumar, and Rojae Mighty for helping me on preparing this!

Backup

Why study ions?

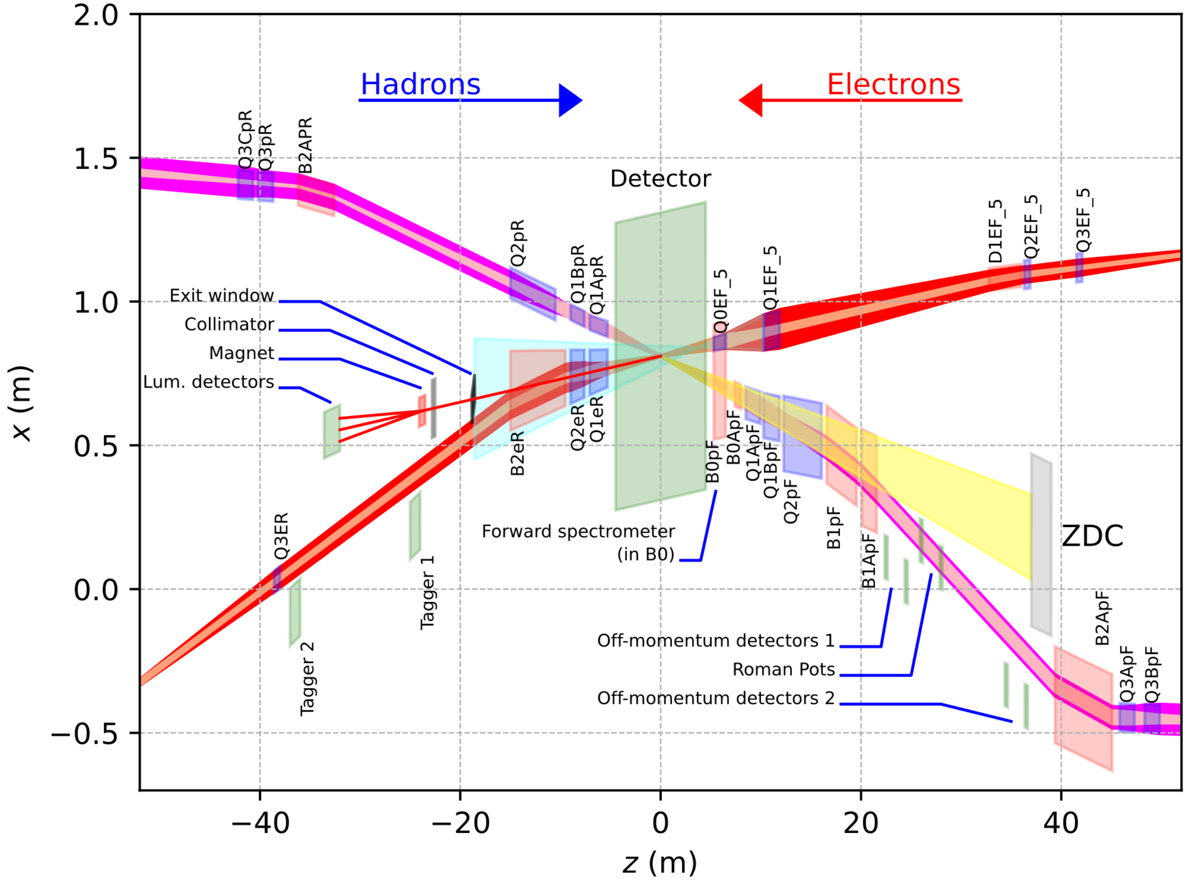
Understanding the QCD in nuclei and how they get modified (partonic degree of freedom and interactions).



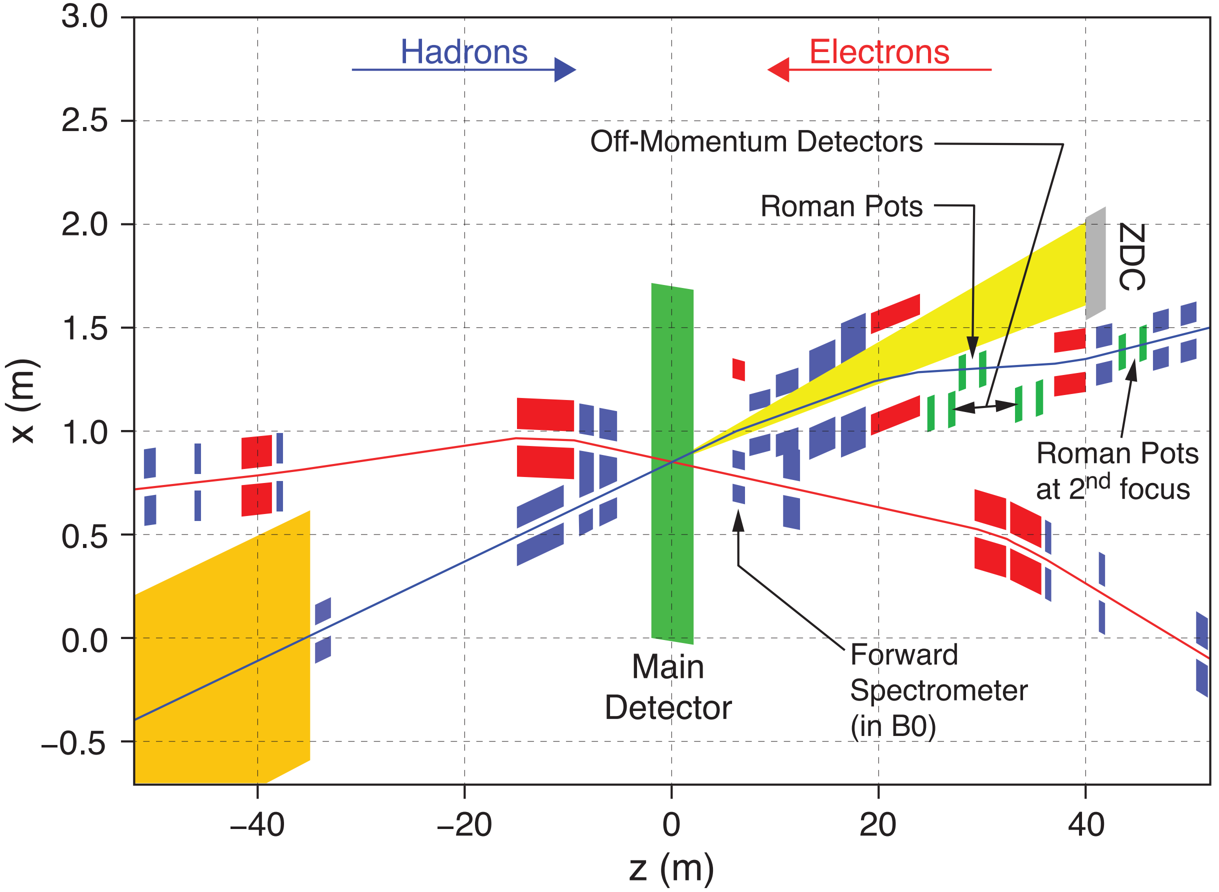
If one thinks about it, not only quarks and gluons don't exist by themselves (confinement problem)), but also almost no proton and neutron exist by themselves either…

Two IR regions

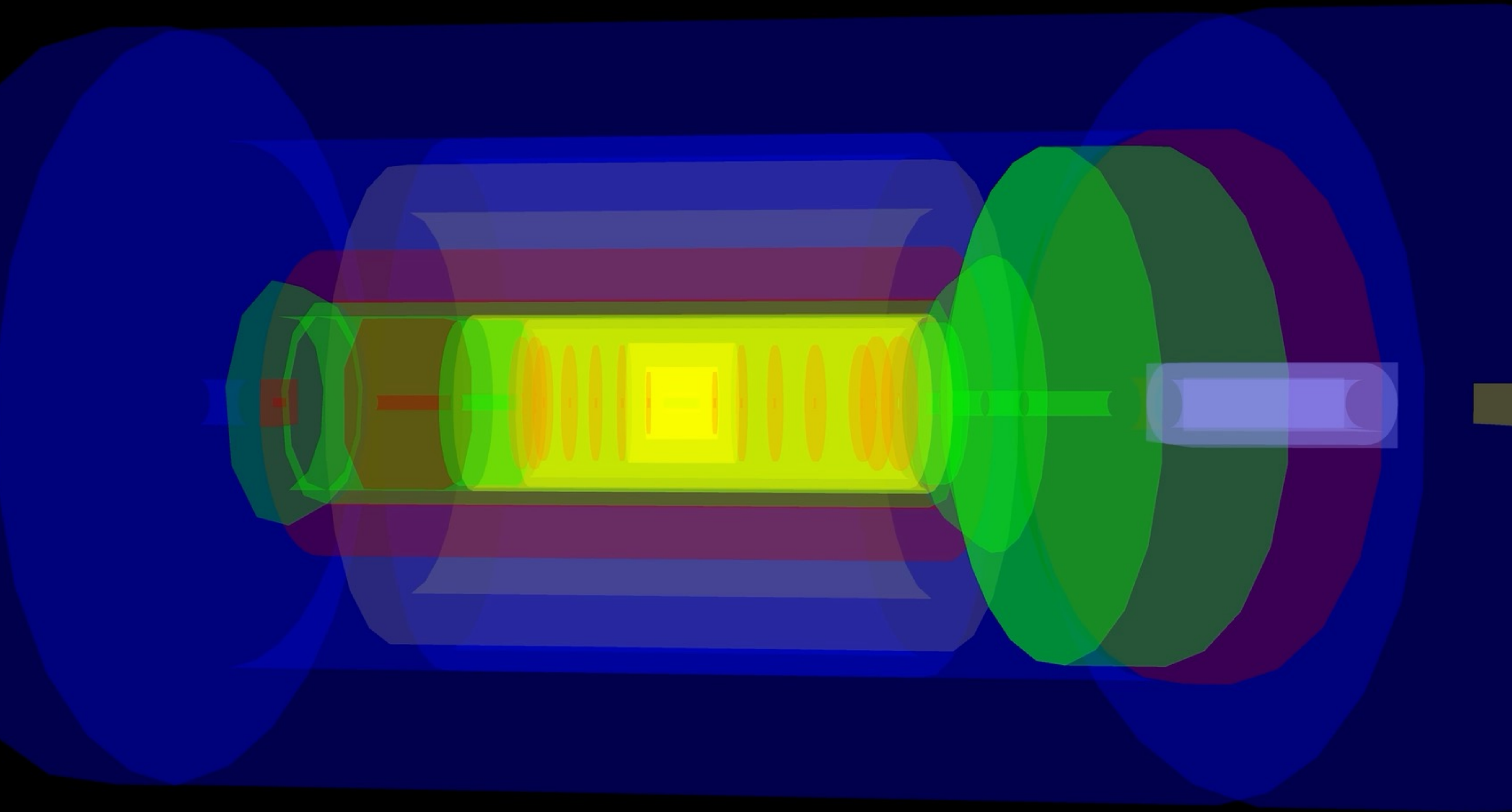
Amazing potential from IR 8, even larger acceptance. see **J. Kim's DIS talk** for details



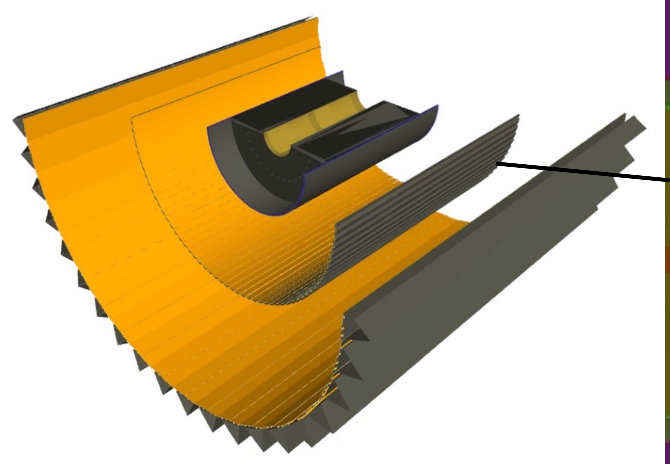
IP6

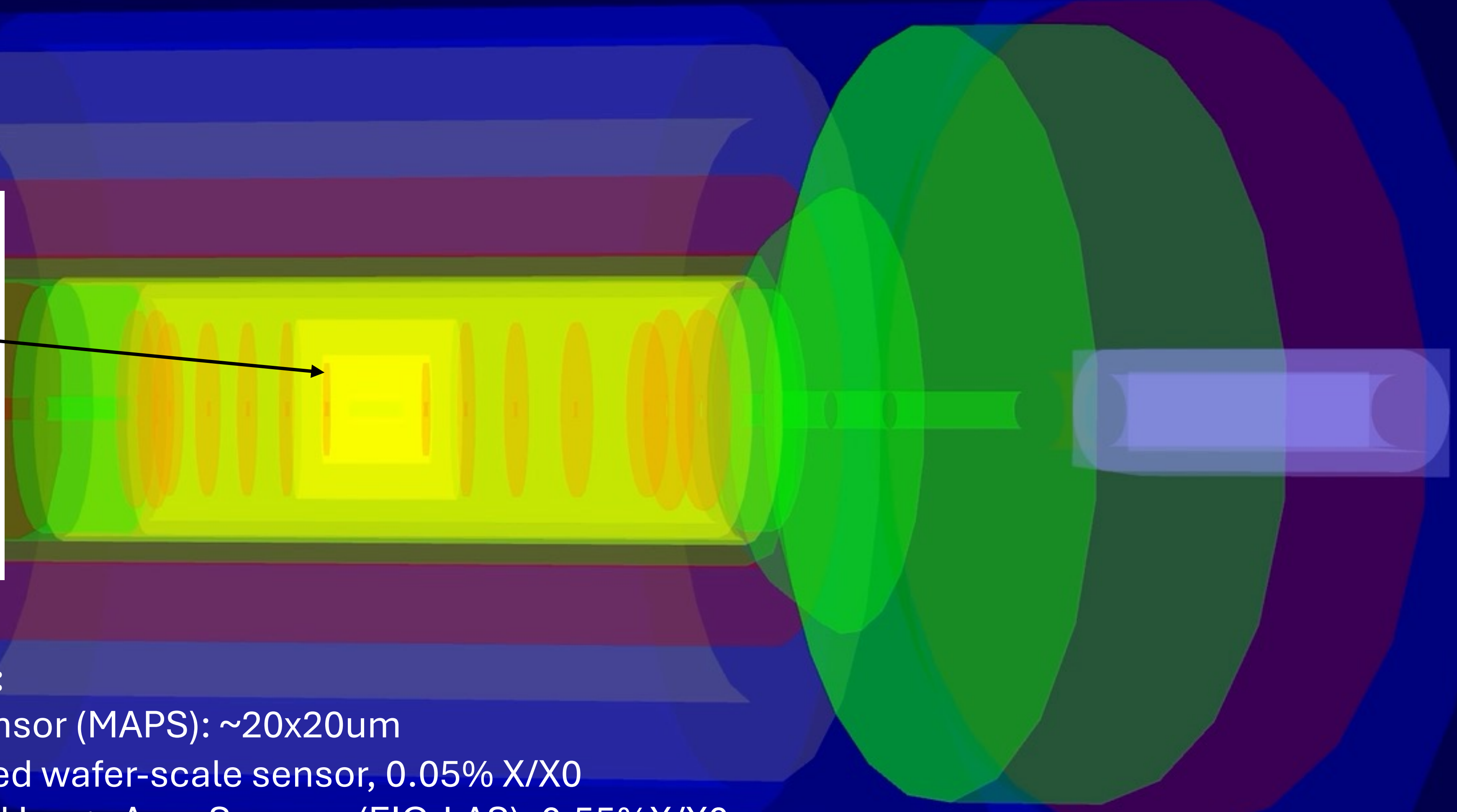


IP8



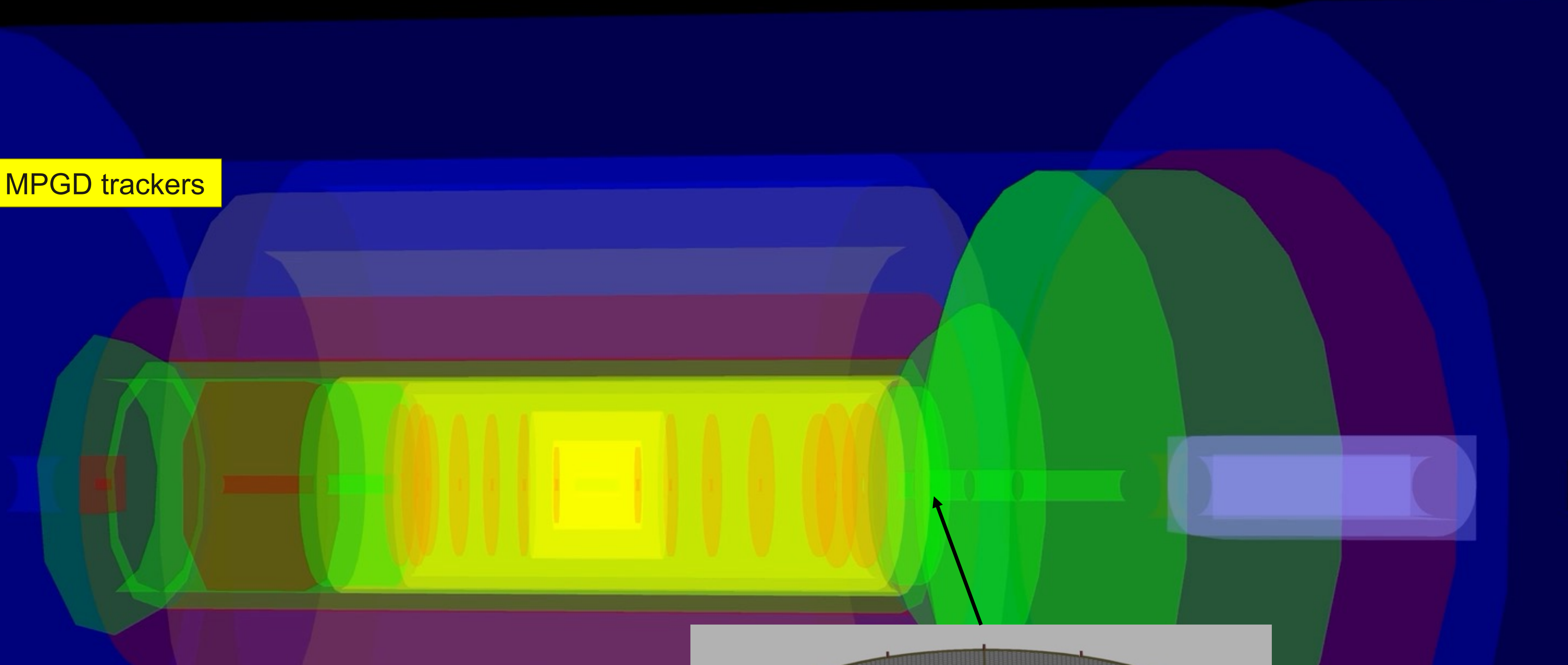
MAPS and MPGD trackers





Silicon Vertex Tracker (SVT):

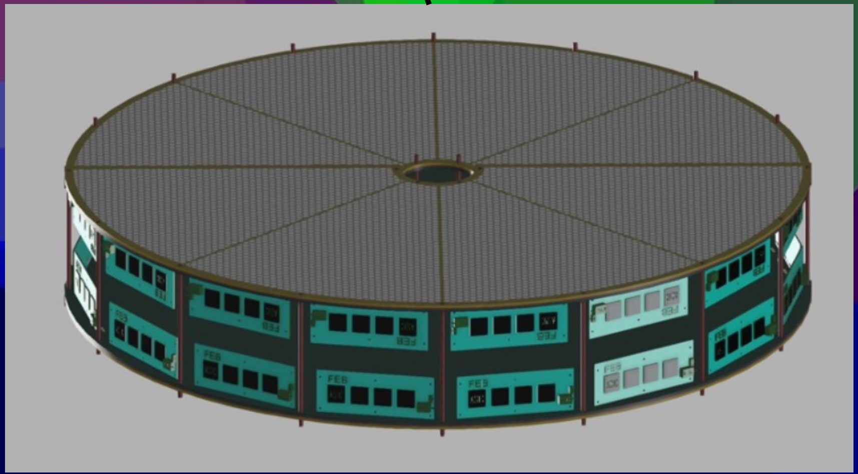
- Monolithic Active Pixel Sensor (MAPS): ~20x20um
- 3 vertex barrels: ITS3 curved wafer-scale sensor, 0.05% X/X0
- 2 outer barrels: ITS3 based Large Area Sensors (EIC-LAS), 0.55%X/X0
- 5 disks (forward/backward), EIC-LAS, 0.25% X/X0



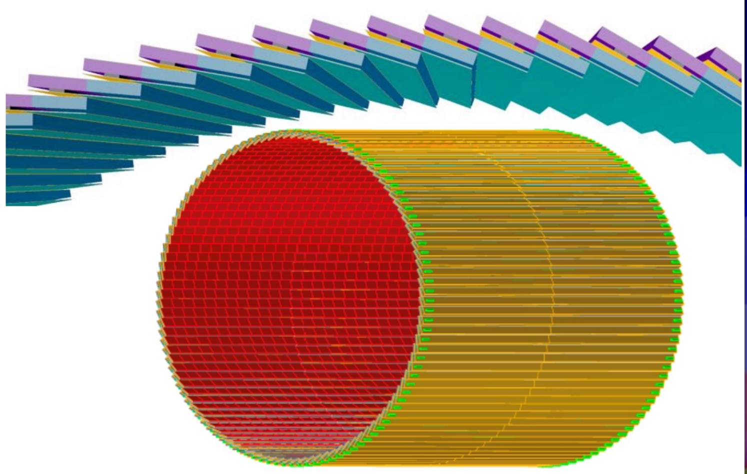
Multi Pattern Gas Detectors (MPGD):

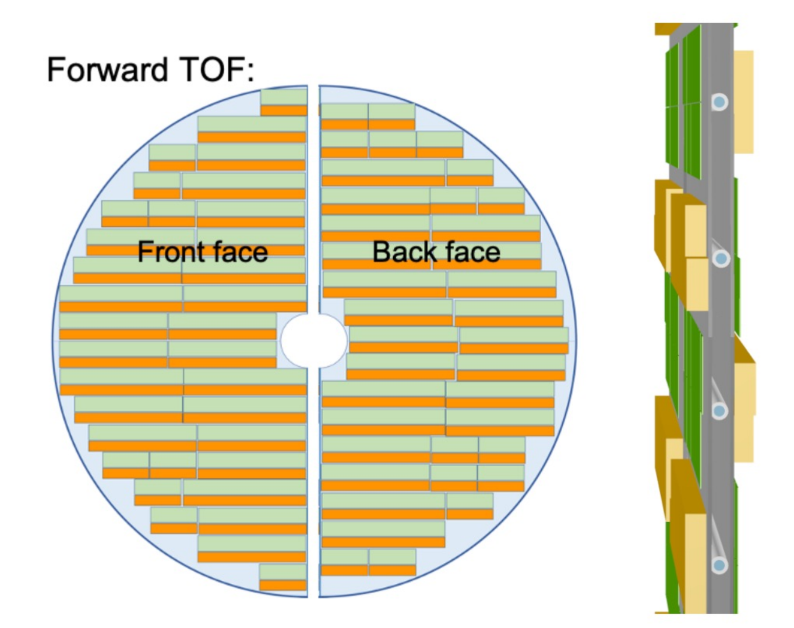
10 ns time resolution,150 um spatial resolution

- 2 GEM-microRwell endcaps (forward/backward) with 1-2% X/X0.
- Inner Micromegas barrel with 0.05% X/X0.
- Outer GEM-microRwell planar layer



AC-LGAD TOF
barrel and
forward endcap



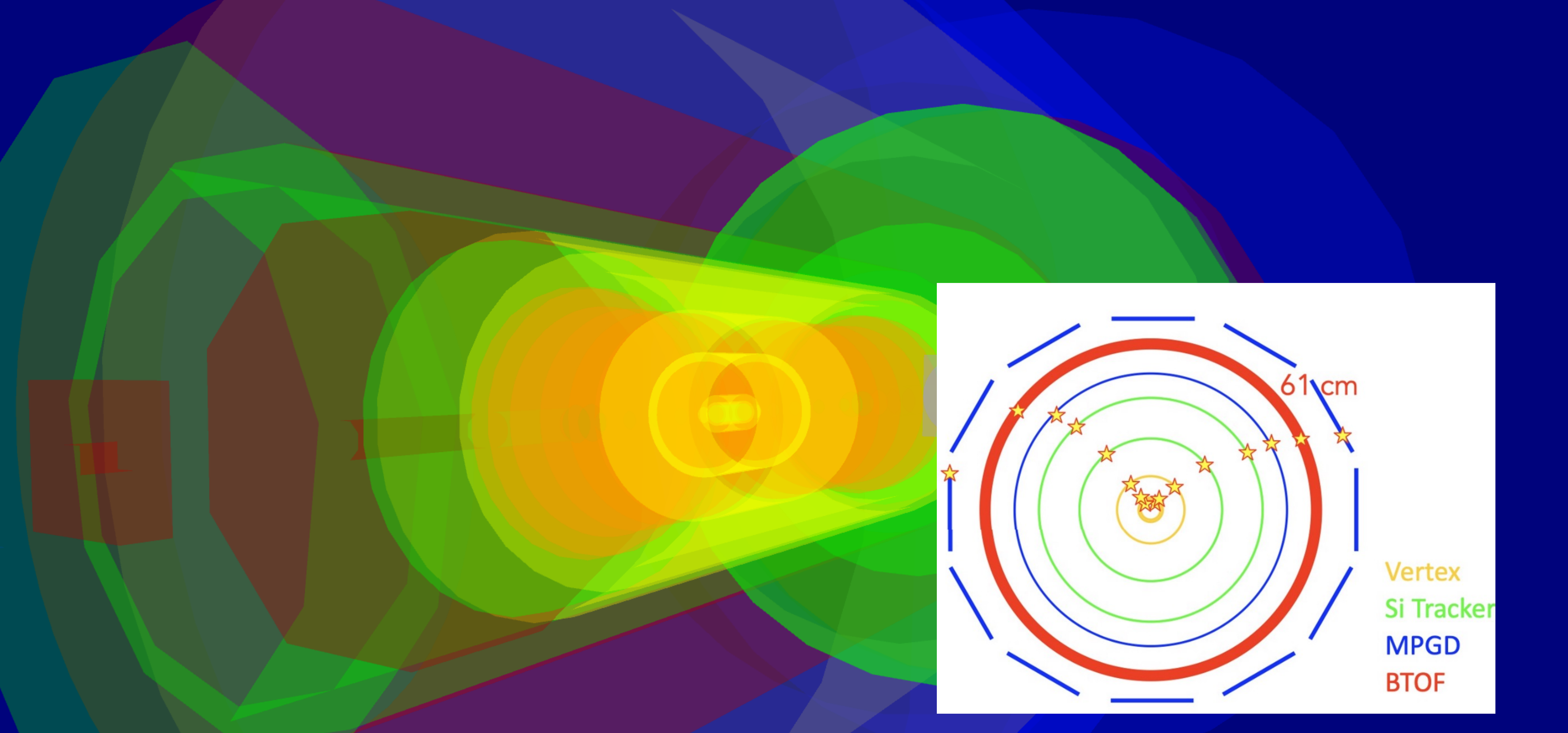


AC-coupled Low Gain Avalanche Diode (AC-LGAD)

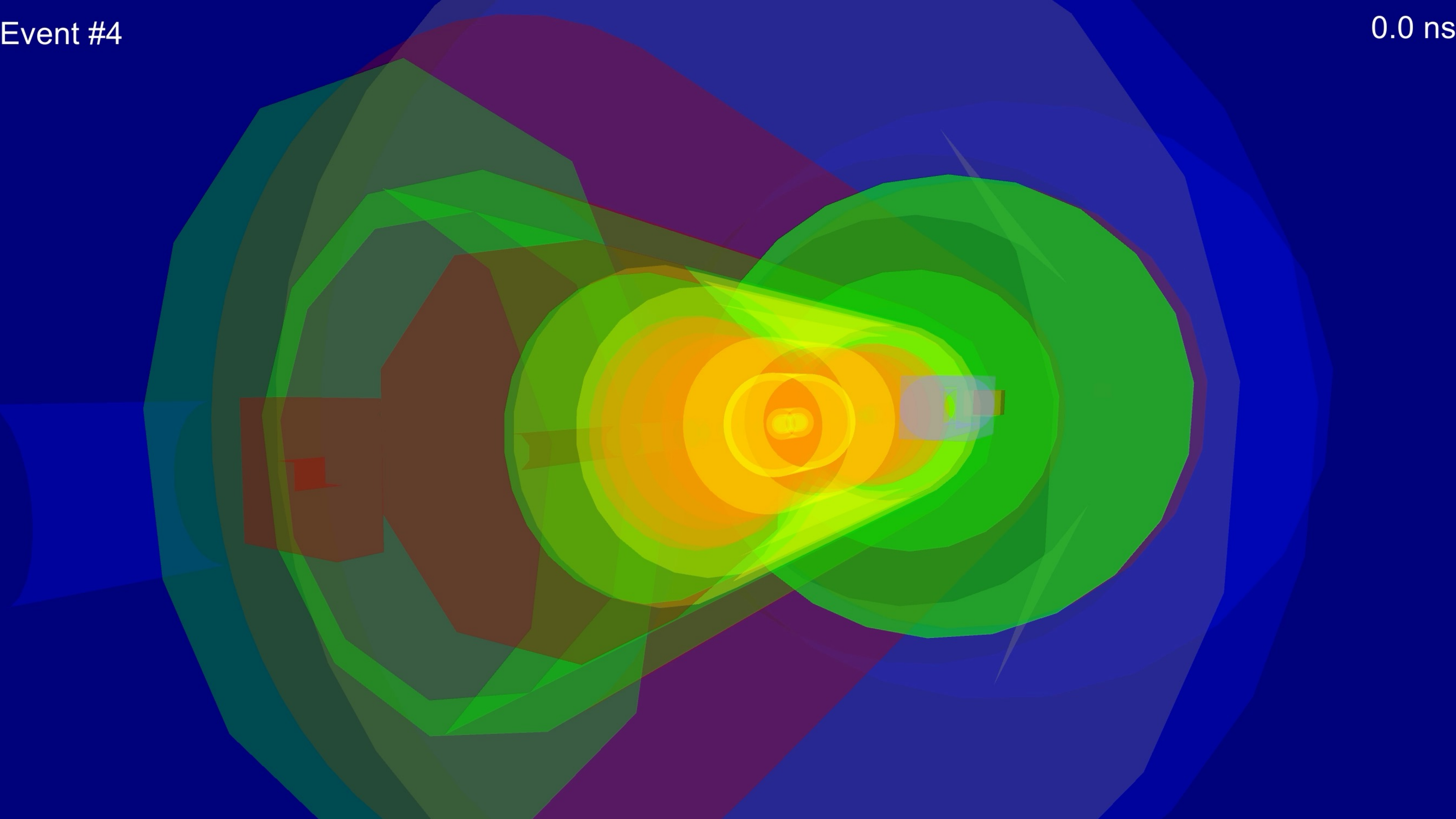
- A PID Time of Flight detectors to cover PID at low pT
- Also provide time and spatial info for tracking
- Resolution: ~30 ps, 30 um (with charge sharing)

Barrel (BTOF): 0.05 x 1 cm strip, 1% X/X0

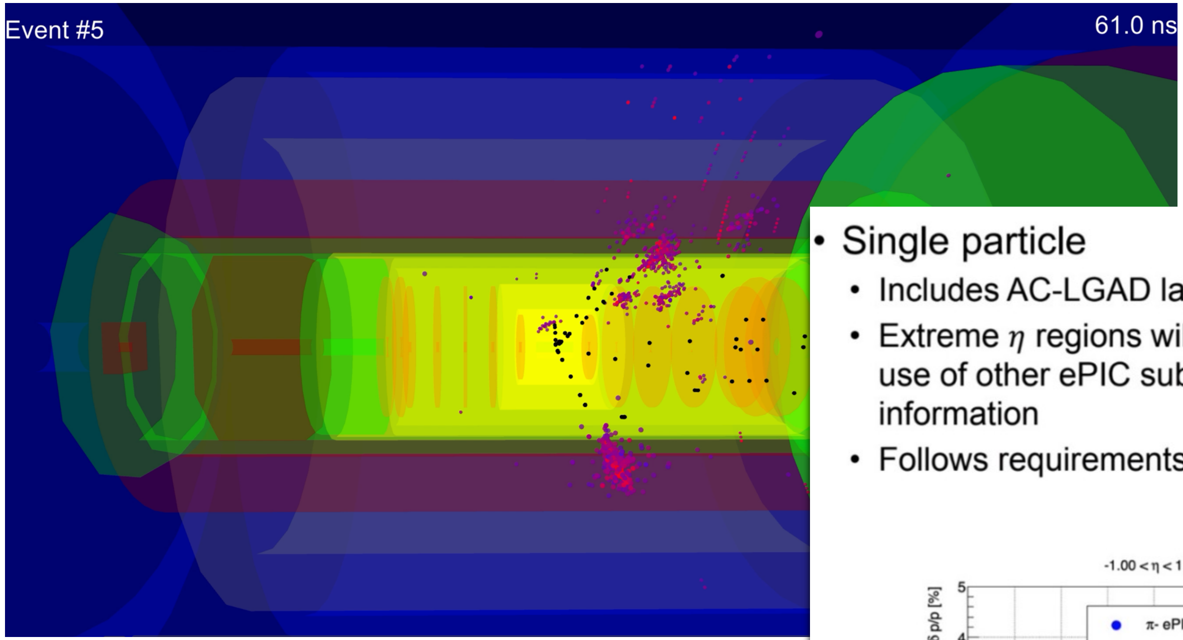
Forward disk (FTOF) : 0.05 x 0.05 cm pixel, 2.5% X/X0



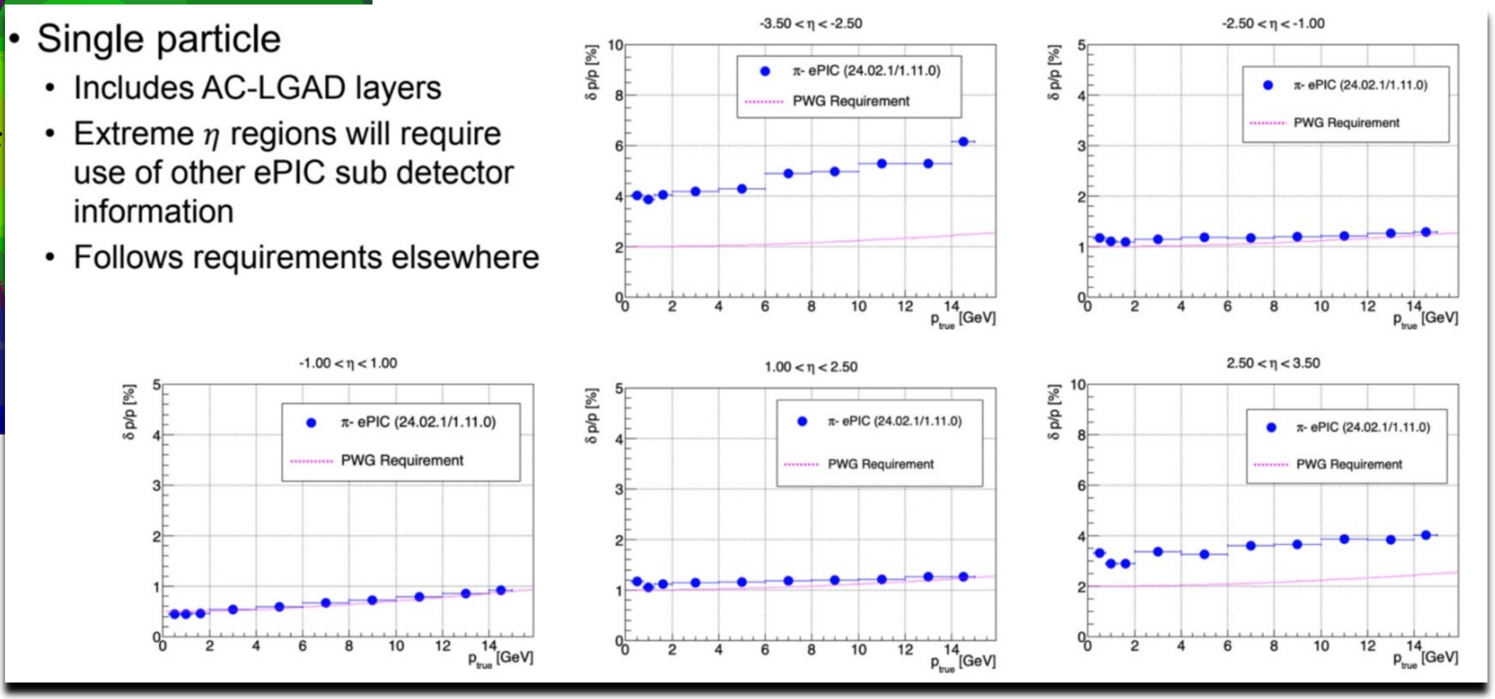
The tracking system from inside out: vertex, Si Tracker, MPGD, BTOF


Event #4
0.0 ns

Tracking is the core of ePIC

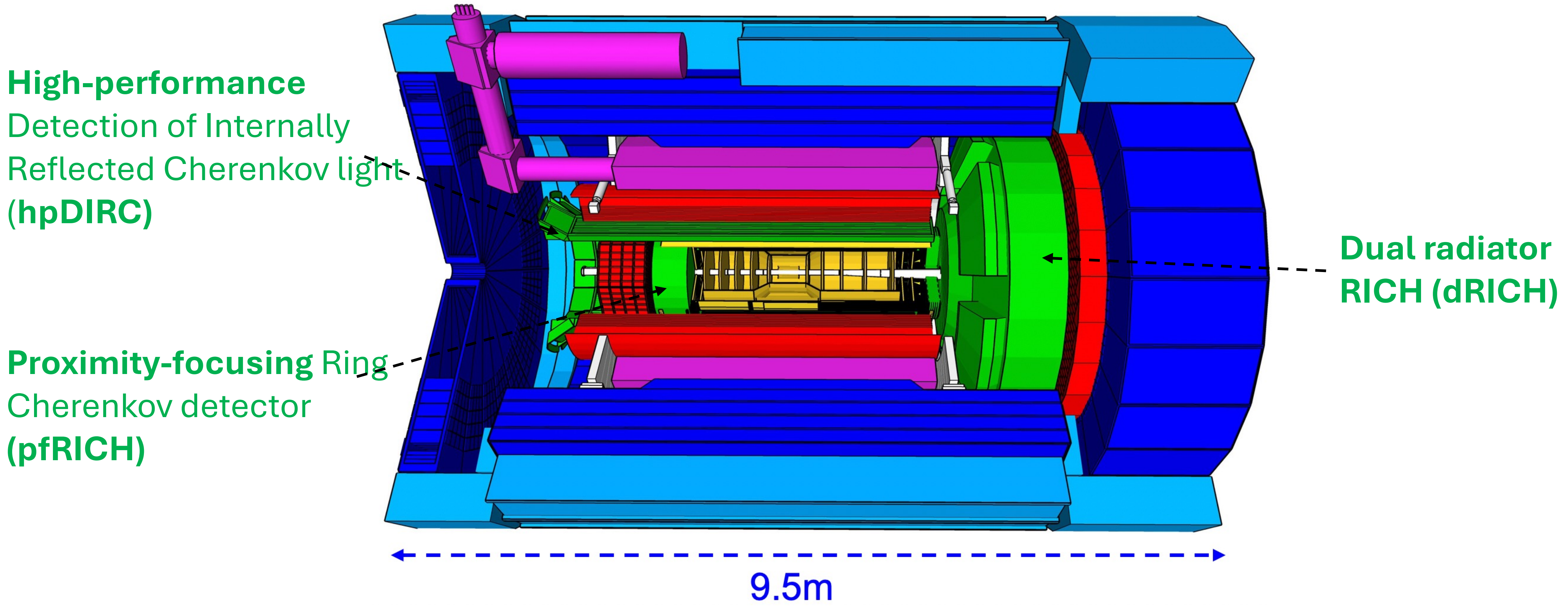


Tracking performance based on single particle studies

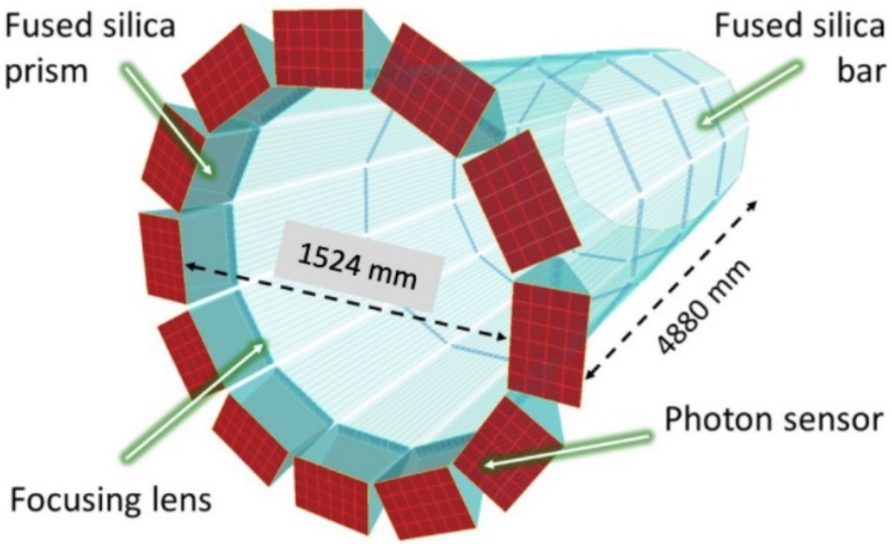


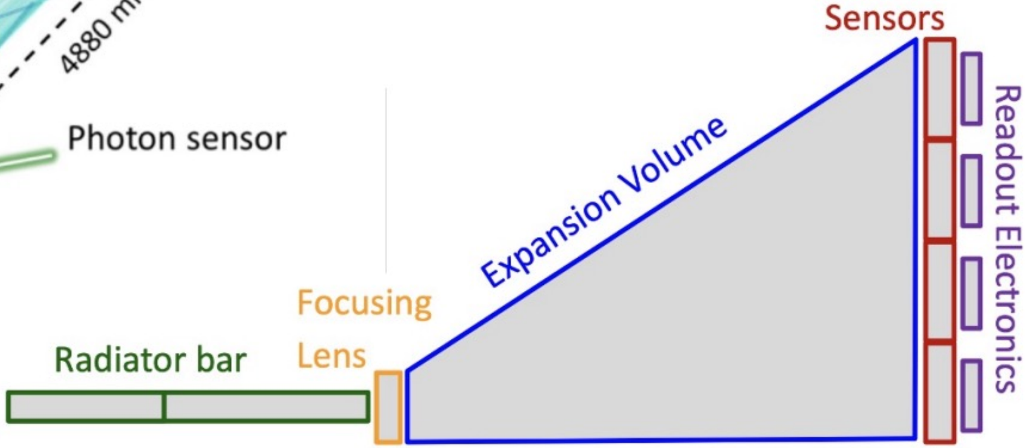
Forward and backward regions are challenging to meet the requirement alone by tracking; will need help from other subsystems.

Particle Identification Detectors in ePIC



Barrel PID detector - hpDIRC

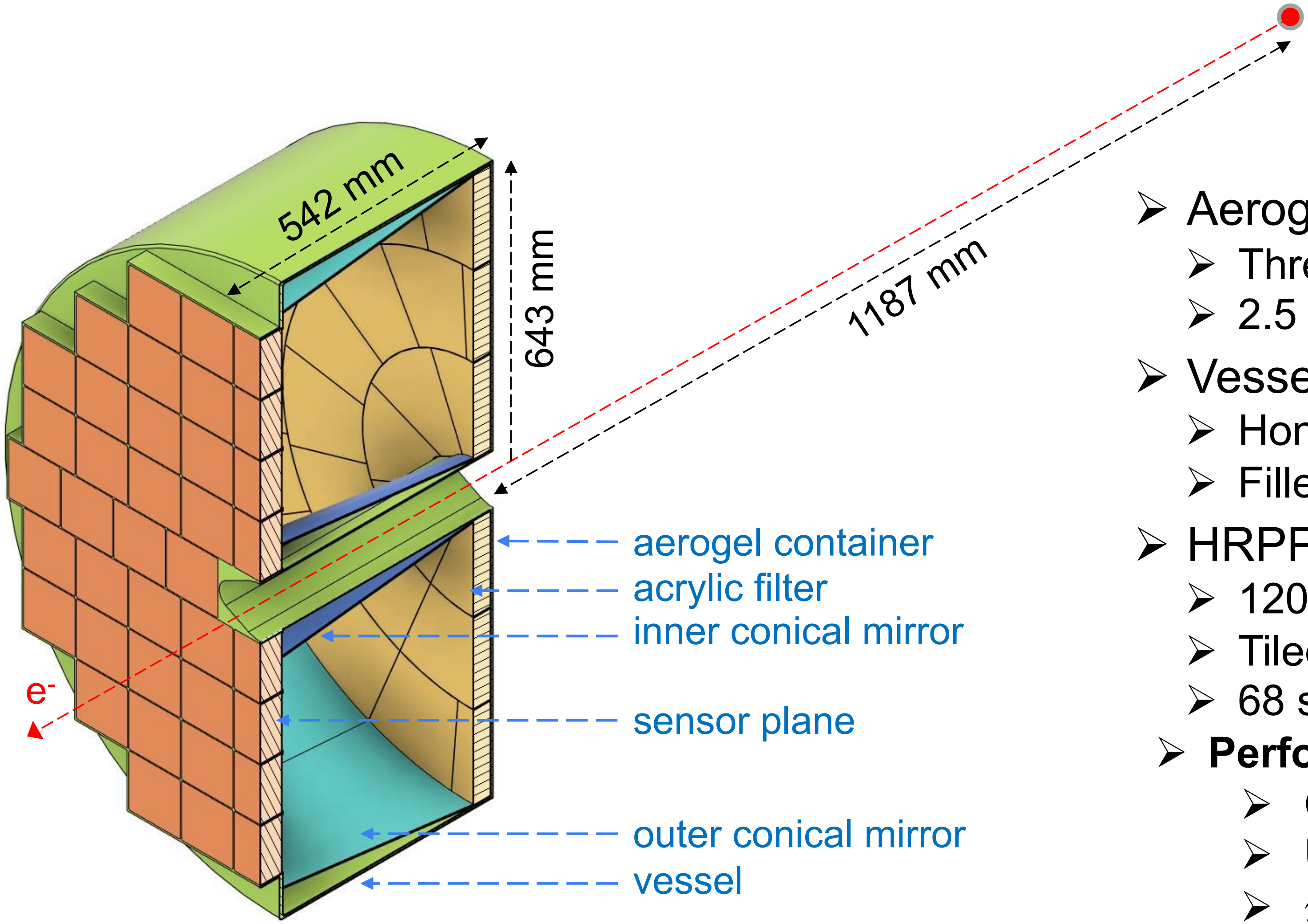




hpDIRC

- 10 long bars
- flat mirrors on far end
- MCP-PMT Sensors
- Reconstruction based on geometrical and/or time info (TOF from AC-LGAD)
- >3sigma pi/k separation power

Backward electron-going PID detector - pfRICH

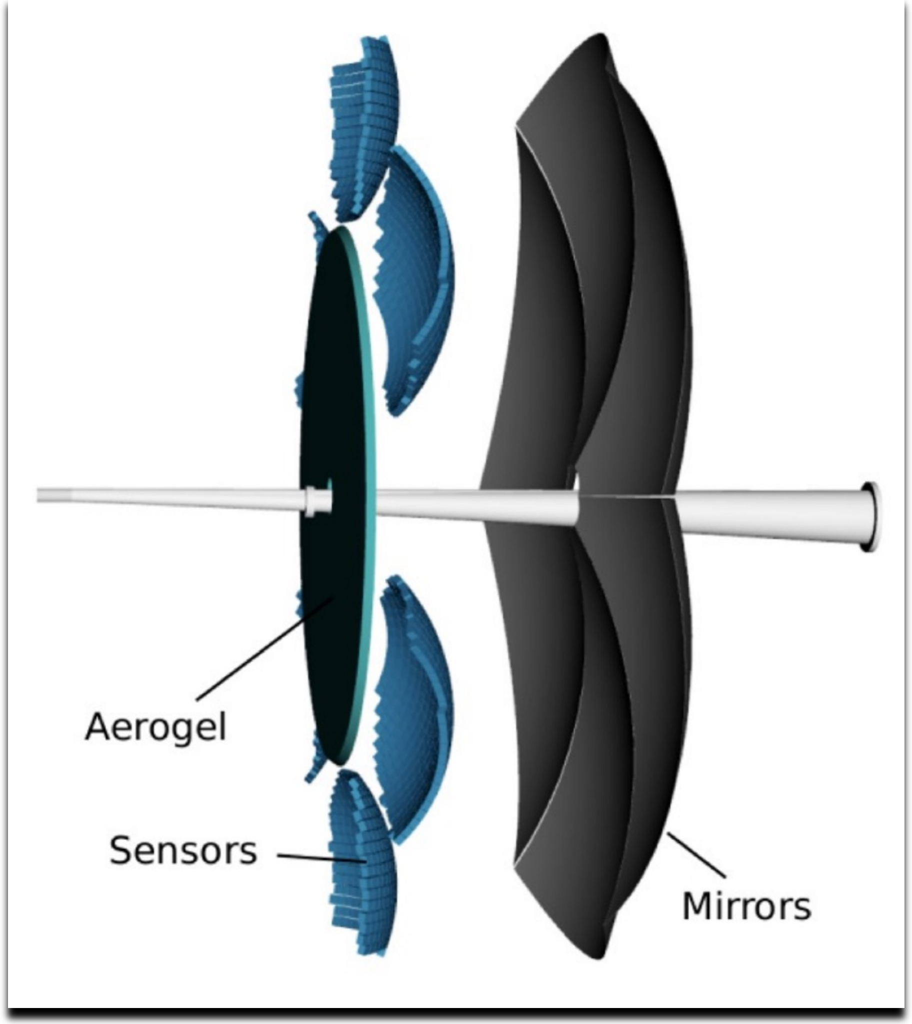


- Aerogel
  - Three radial bands; Opaque dividers
  - 2.5 cm thick, 42 tiles total
- Vessel
  - Honeycomb carbon fiber sandwich
  - Filled with nitrogen
- HRPPD photosensors with timing capability
  - 120 mm size
  - Tiled with a 1.5mm gap
  - 68 sensors total
- **Performance:**
  - Coverage: $-3.5 < \eta < -1.5$
  - Uniform performance in $\{\eta,\phi\}$ range
  - π/K separation: above 3σ up to 9.0 GeV/c

Forward hadron-going PID detector - dRICH

dRICH:

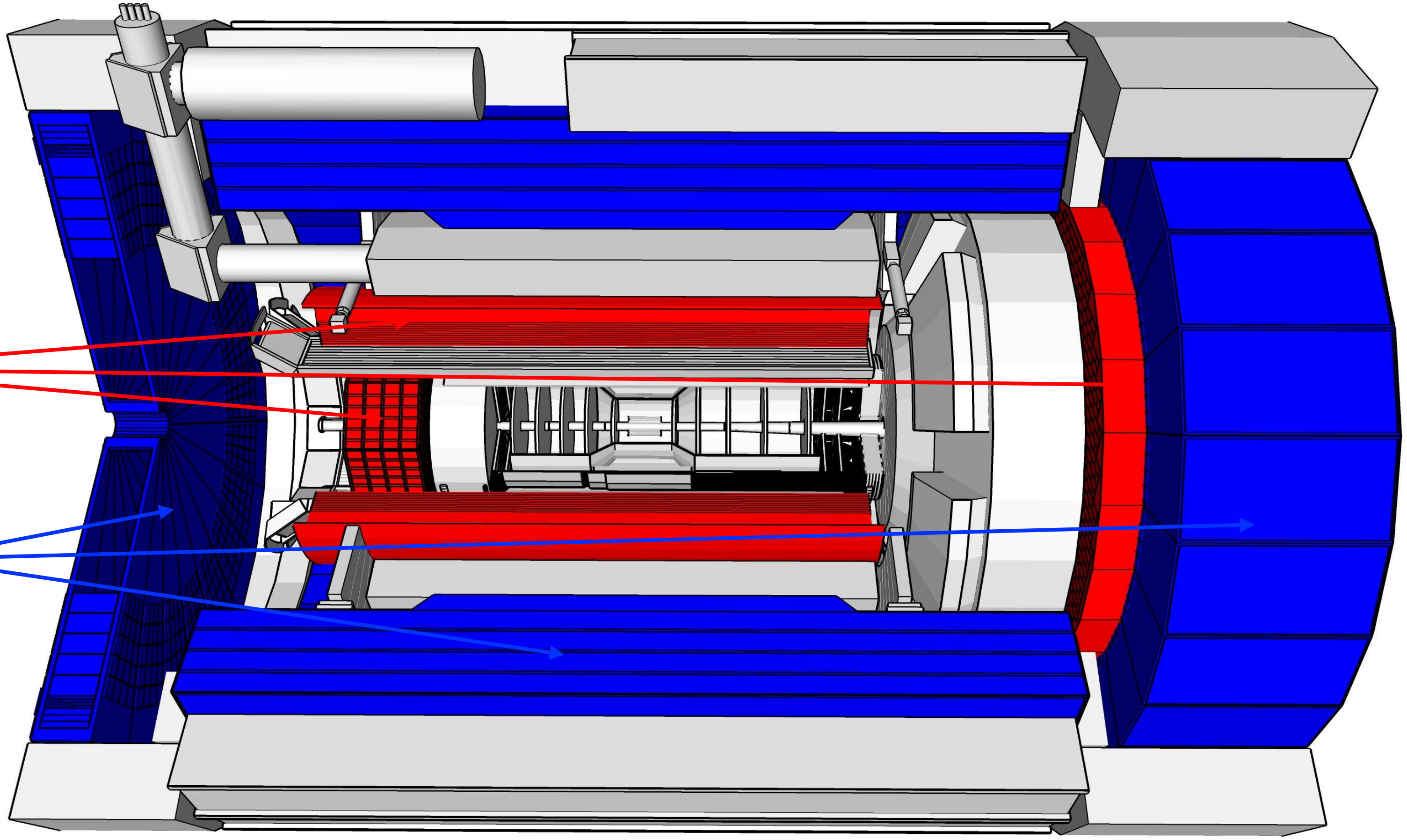
- for high momentum PID at forward region ~ 50 GeV/c for pi/K separation.
- $1.5 < \eta < 3.5$ coverage
- 4cm aerogel + C2F6 gas
- 6 spherical mirrors to focalize photons
- SiPM based sensors for photon detection



Calorimeter

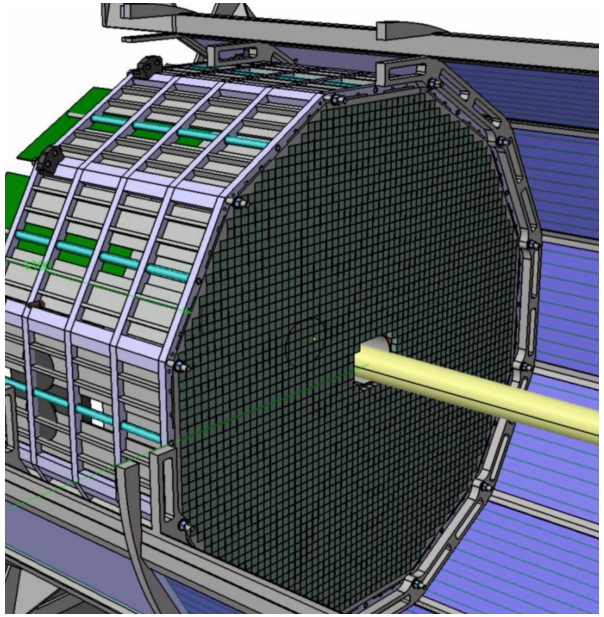
Calorimeters with wide range of acceptances(**backward, barrel, forward**) and different technologies:

- **Electromagnetic Calorimeter.**
- **Hadronic Calorimeter.**



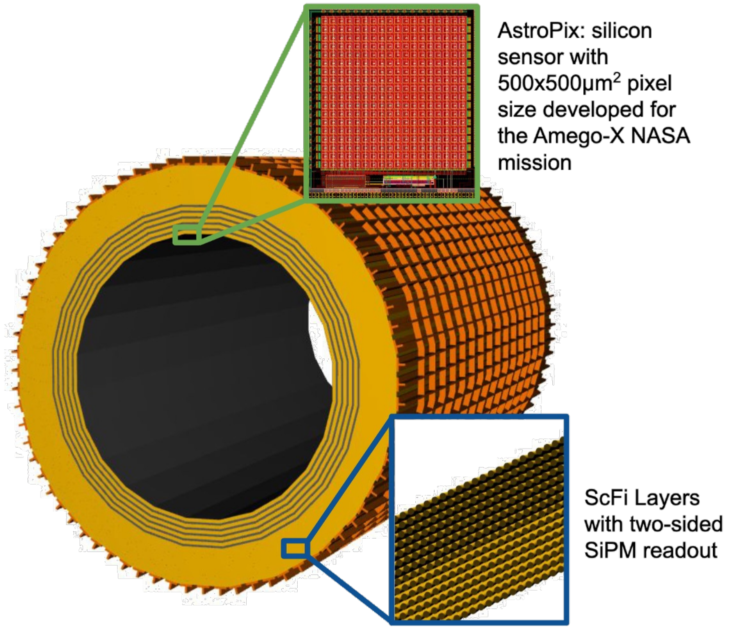
EM Calorimeter

Backward



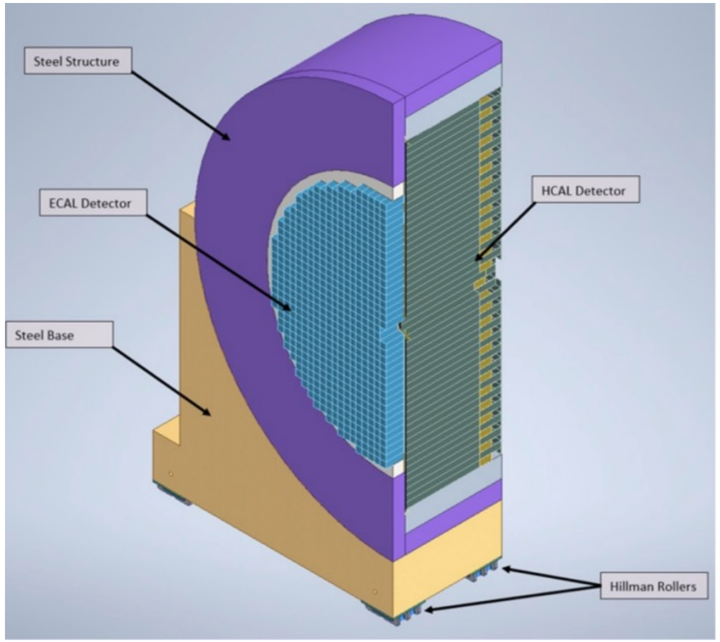
- PbWO4 crystals
- excellent energy resolution and high pion suppression for electron reconstruction

Barrel



- 6 layers of imaging Si sensors (AstroPix) interleaved with 5 SciFi/Pb layer
- Followed by a large section of SciFi/Pb

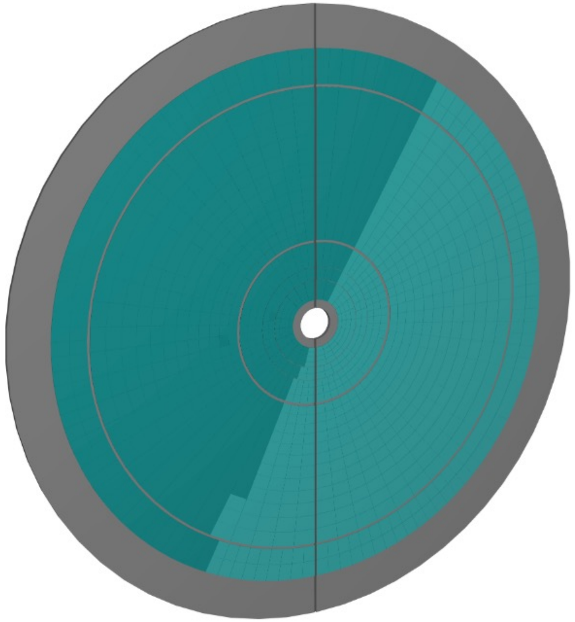
Forward



- W/ScFi blocks beehive with fiber good pi/gamma separation
- Tracking+pECal+LFHCAL for optimized HF jets
- SiPMs as photonsensors

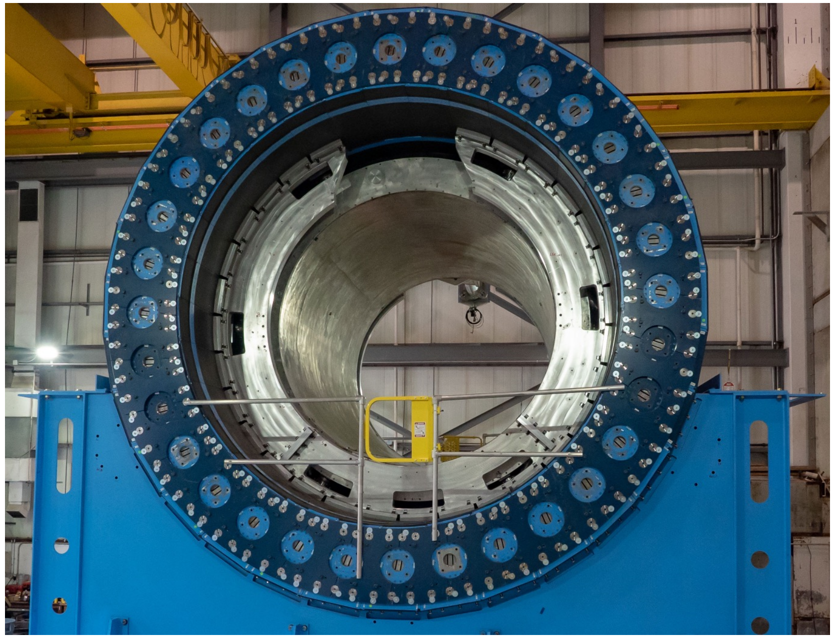
Hadronic Calorimeter

Backward



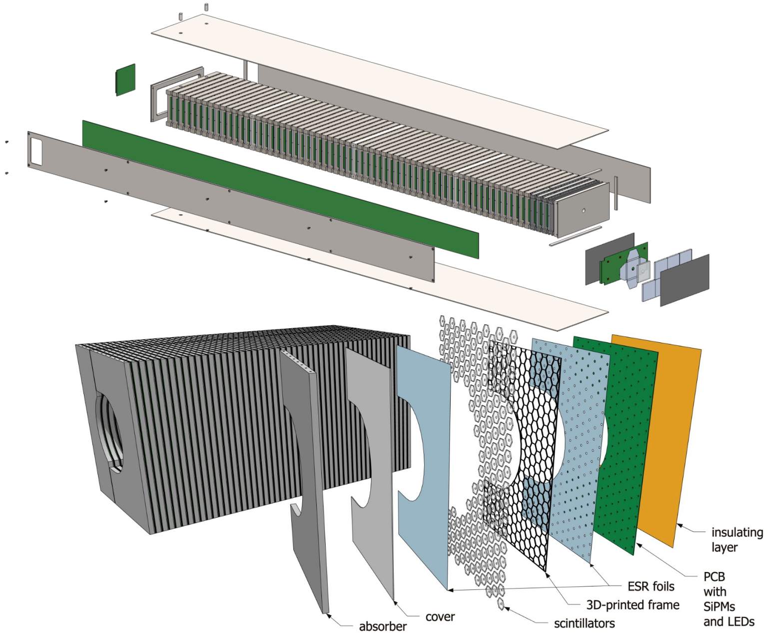
- Low-x hadronic final state important for gluon saturation, typically backward-going
- Exact design still in progress

Barrel



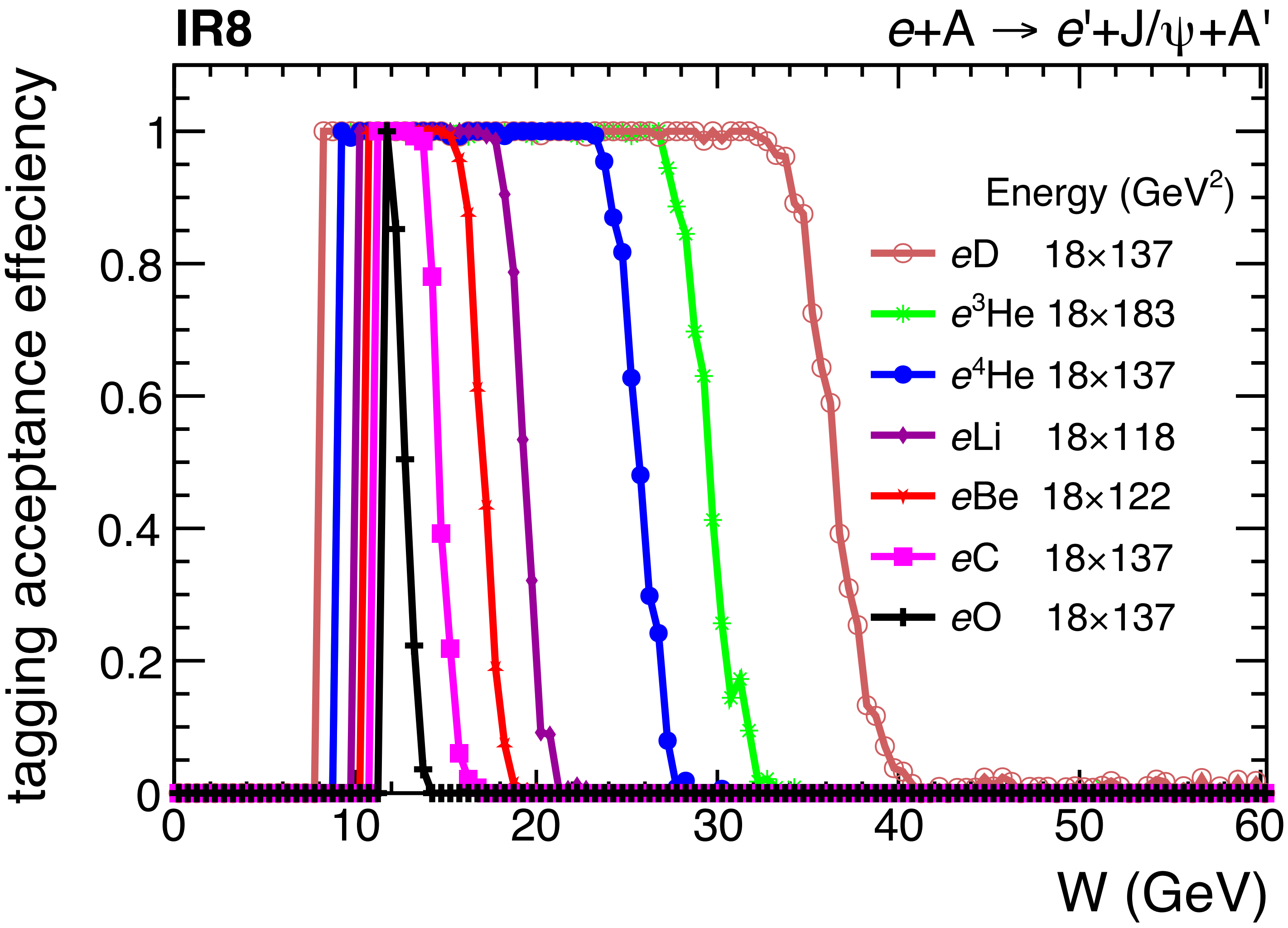
- **Reuse from sPHENIX**
- Upgrade electronics to HGCROC
- Increase segmentation by reading out each tile individually

Forward



- Forward Hcal: Steel + Scintillator SiPM-on-tile
- Forward insert calorimeter to further improve acceptance ($3.2 < \eta < 4$)

Coherent tagging efficiency



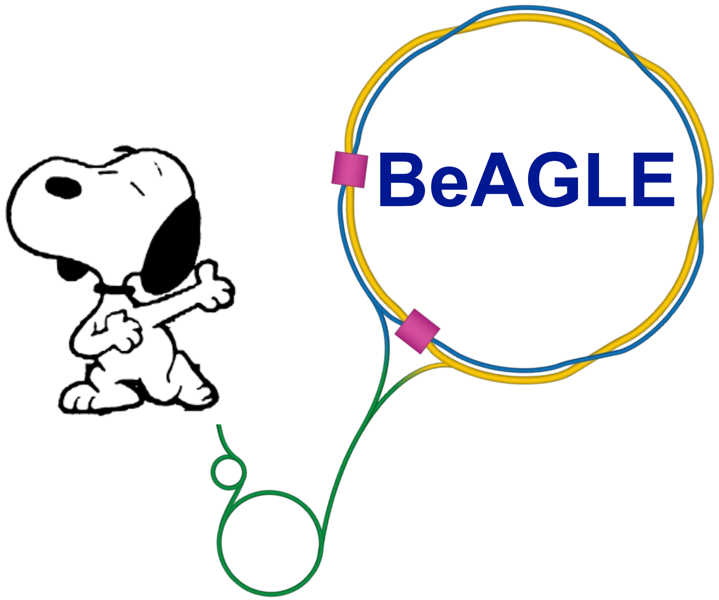
MC model from eSTARLight

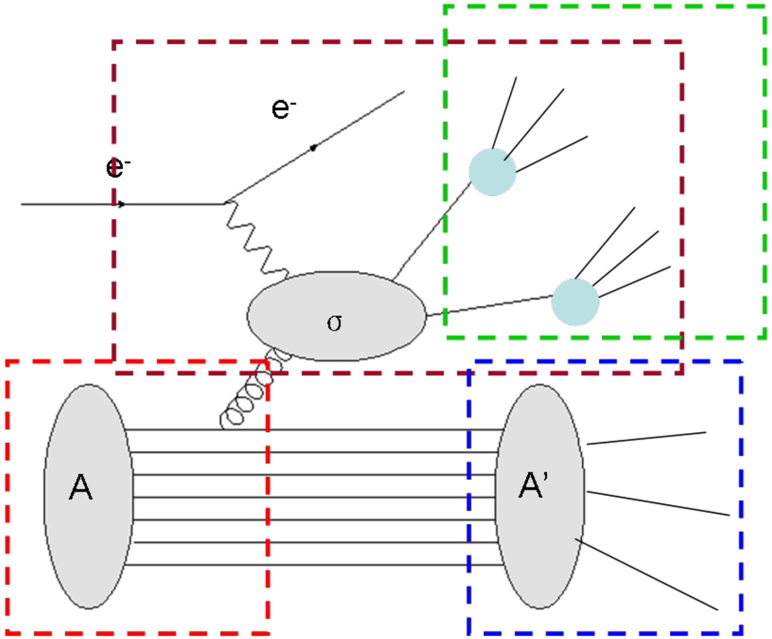
Models that support ions at the EIC

- BeAGLE - general purpose eA MC generator
- Sartre – exclusive VM and inclusive diffraction generator
- eSTARLight – exclusive VM and dilepton MC generator
- PYTHIA 8 – Angantyr model (mainly for heavy-ion collisions)
- …

BeAGLE – a hybrid model

https://eic.github.io/software/beagle.html





A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed in PYTHIA.

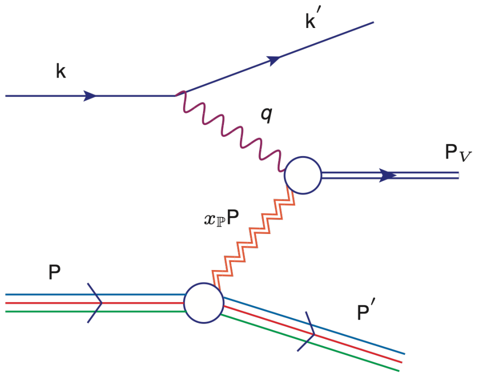
Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

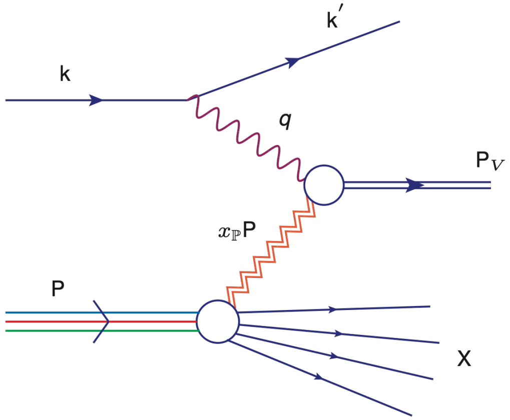
Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

BeAGLE can do everything but coherent scattering on ions

Sartre – exclusive Vector Meson model

DIFFRACTIVE VECTOR MESON PRODUCTION WITH SARTRE





Coherent diffraction

- ★ *Proton remains intact*
- ★ *Sensitive to average gluon distribution in the proton*

Incoherent diffraction

- ★ *Proton breaks up*
- ★ *Sensitive to fluctuations of gluon distribution*

Good, Walker 1960, Miettinen, Pumplin 1978

$$\mathscr{A}^{\gamma^* p \to Vp}_{T,L}(x, Q^2, \Delta) \simeq \int d^2r \int d^2b \int dz \times (\Psi^* \Psi_V)_{T,L}(Q^2, r, z) \times e^{-ib.\Delta} \times N(b, r, x, \Omega)$$

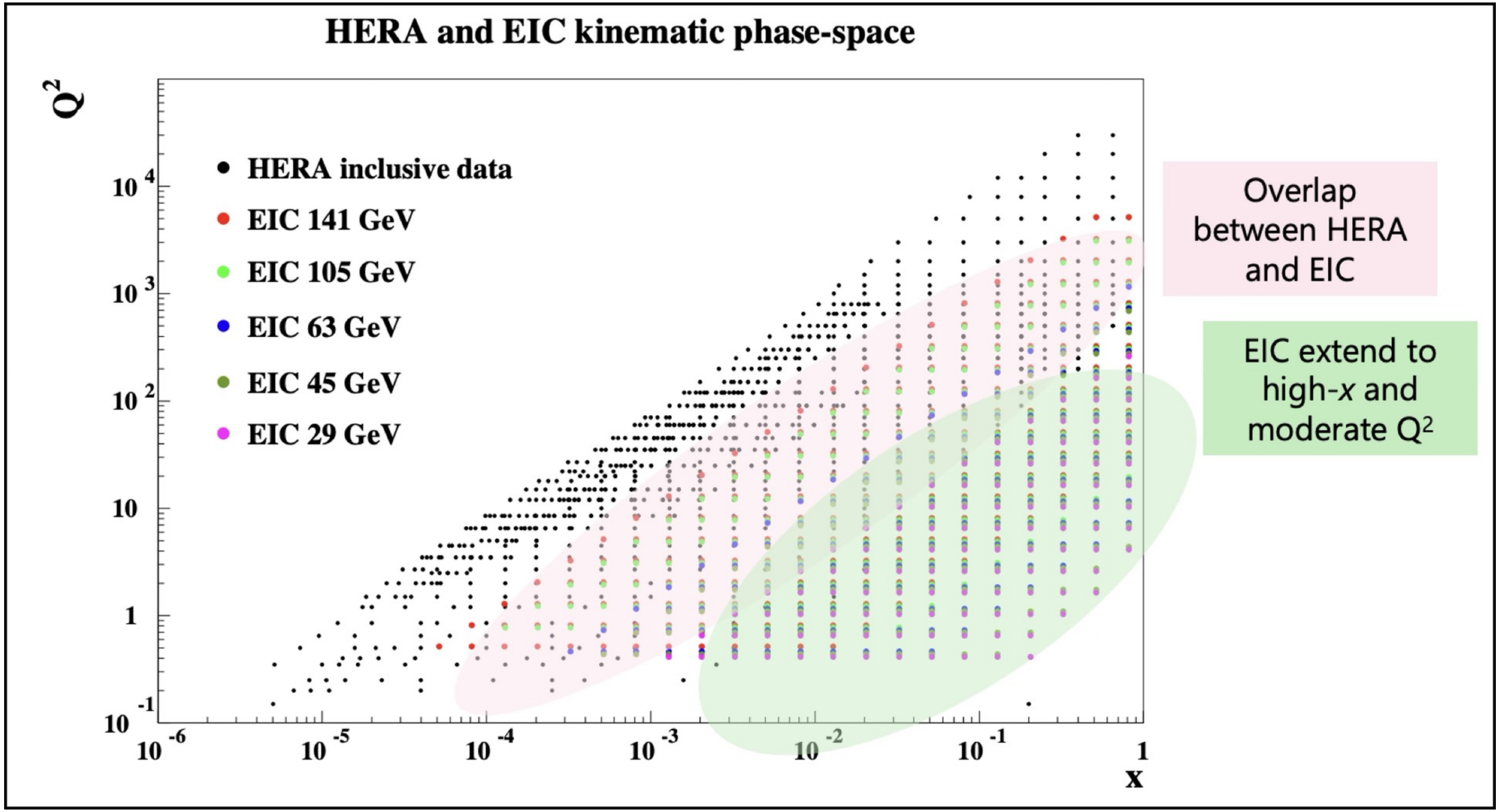
$$\sigma_{tot} \propto | < \mathscr{A} >_\Omega |^2 + (< |\mathscr{A}|^2 >_\Omega - | < \mathscr{A} >_\Omega |^2)$$

Coherent   Incoherent

X

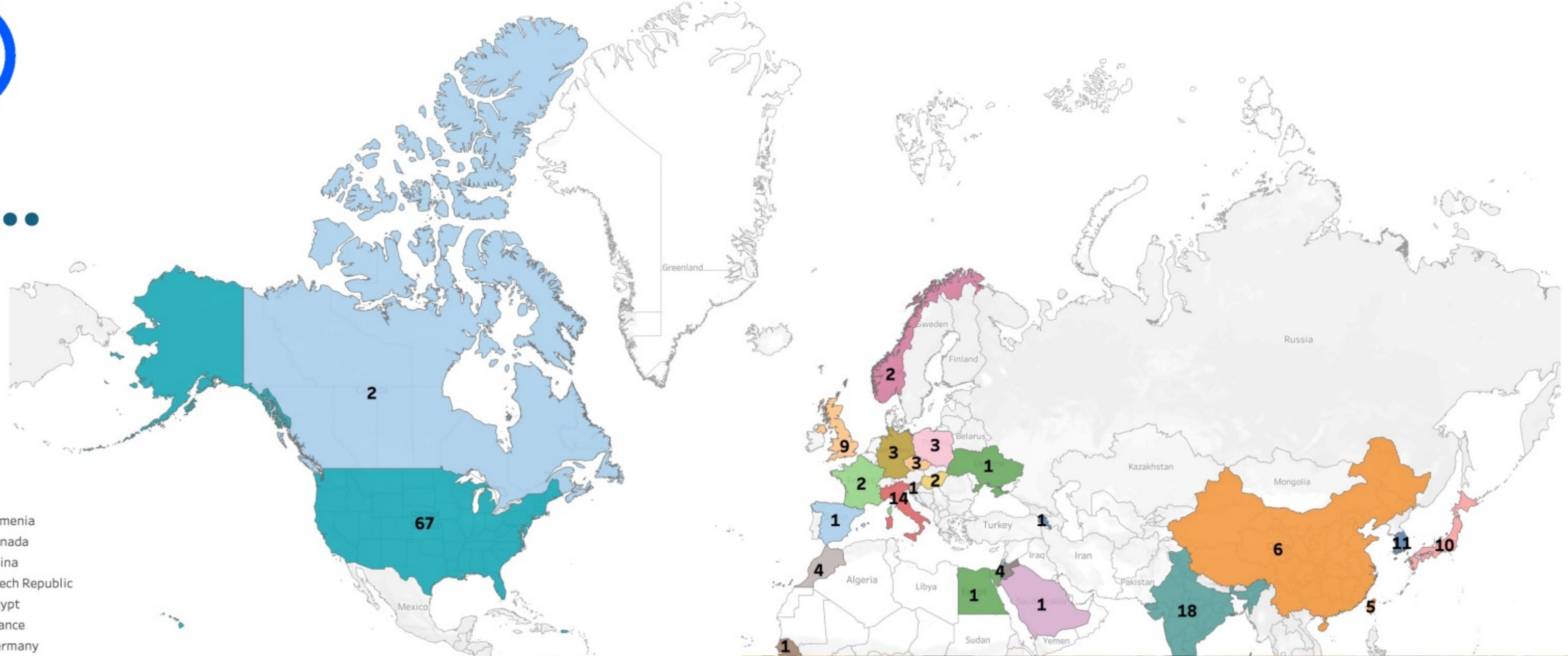
see S.Klein 2301.01408 for challenges to Good-Walker paradigm

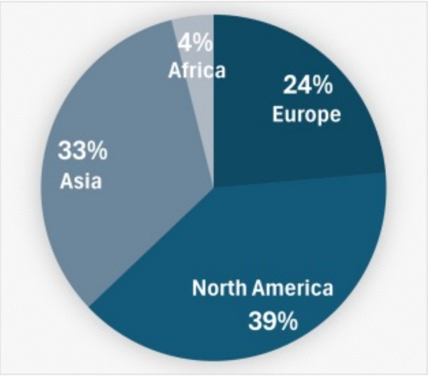
EIC and HERA kinematics



By the numbers…

Currently: >1000 collaborators (from 2025 Institutional Survey)





Frascati – January 2025