

CFNS Summer Lecture: Introduction to the forward physics at the Electron Ion Collider

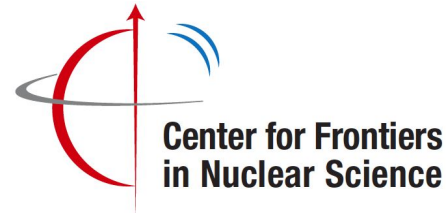
Day 2

Wenliang (Bill) Li
Assistant Professor, Mississippi State University

June/5/2026

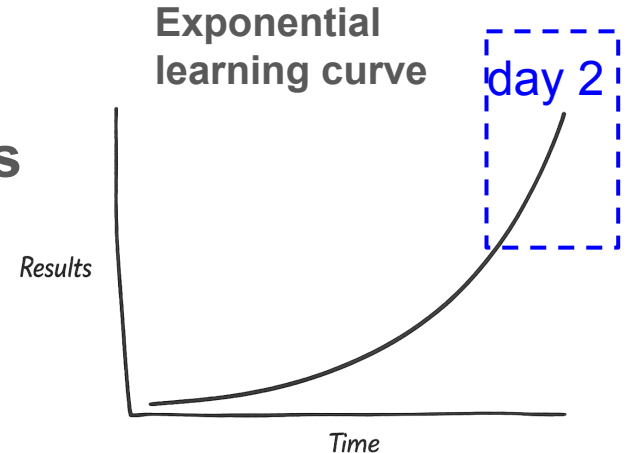


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Content for Day 2

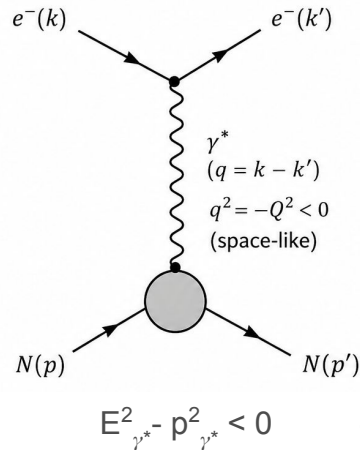
- ePIC Physics “forward” physics goals
- ePIC Far forward instrumentations
- “Forward” Physics examples
- Construction and operating challenges
- Conclusive remarks



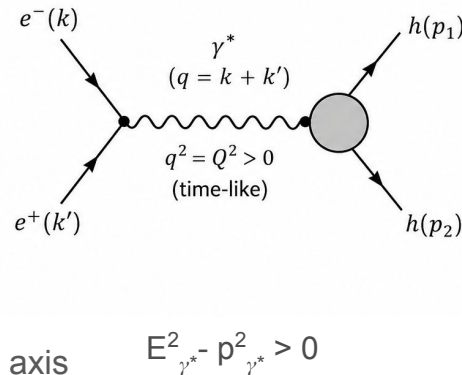
Is it possible to have a timelike-virtual photon?

- Recall from the lecture, EIC and JLab scattering experiment always involves a spacelike virtual photon.
- From Last night's discussion: Is it possible to have a timelike-virtual photon?
 - Answer: Yes, but directly induced from the incoming and scattered electron.

(a) Space-like virtual photon



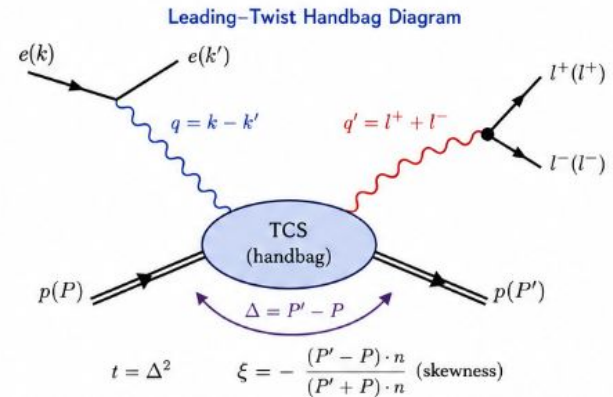
(b) Time-like virtual photon



Time axis

Time Like Compton Scattering

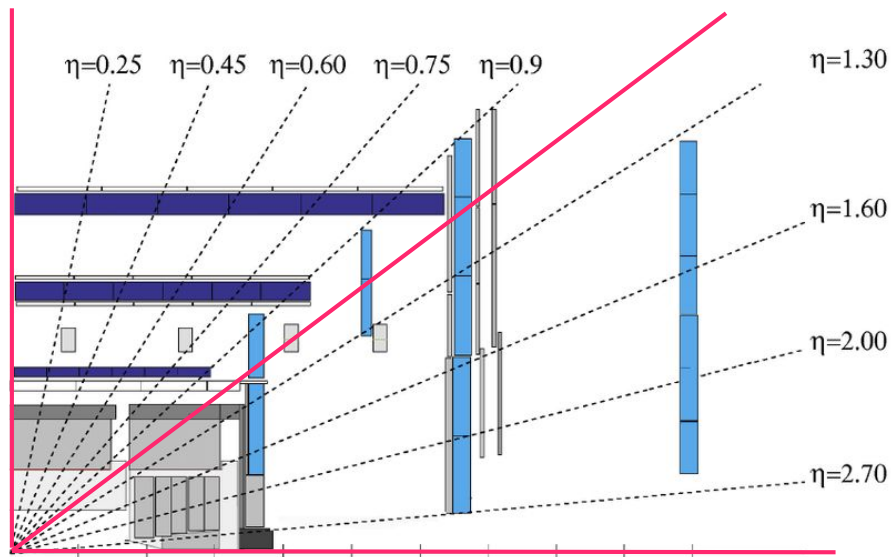
$$e + p \rightarrow e' + p' + \gamma^*, \quad (\gamma^* \rightarrow e^+ e^-)$$



Pseudorapidity In EIC and ePIC

$\eta = 0, \theta = 90^\circ$

$\eta=0.88$ ~~$\eta=1.0$~~ , $\theta = 45^\circ$



$\eta \sim \infty, \theta = 0^\circ$

CMS detector schematics
is used as an example

Pseudorapidity is easy at the EIC!

- Defined with respect to the proton beam
- $\eta=0$ when particle is at $\theta = 90^\circ$
- $\eta=1$ when particle is at $\theta = 45^\circ$
- $\eta \sim \infty$ when particle is at $\theta = 0^\circ$
- Easy to remember!

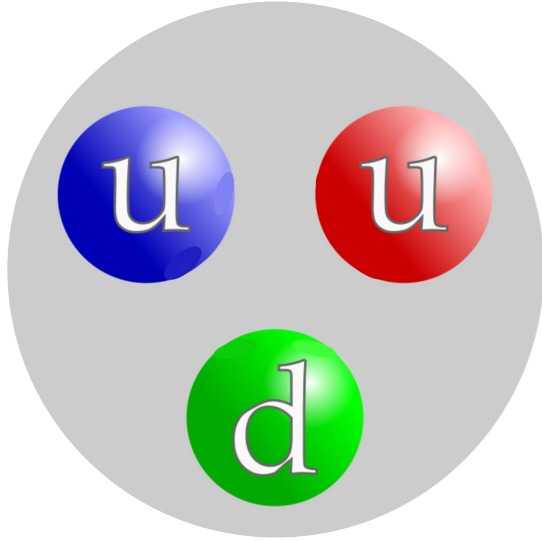
Now read the ePIC detector coverage again:

- Central detector: $\eta \leq |3.5|$
- Forward endcap: $+1.5 \leq \eta \leq +3.5$
- Backward endcap: $-3.5 \leq \eta \leq 1.5$
- Far-forward/far-backward systems: $|\eta| > 6$

Forbidden question:

- Why ePIC is not designed to use $\eta \sim 1$ ($\theta = 45^\circ$) as detector system boundary.

Fundamental Properties of Proton

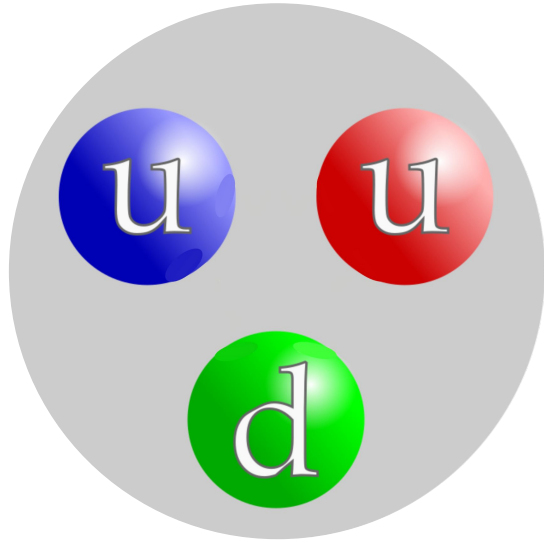


	Property
Mass	938.272 MeV
Spin	$\frac{1}{2}$
Charge	+1
Baryon Number	+1

What do my field study?

- Answer: Properties of proton
- **Question:** we knew these 30 years ago, why are you still studying this?

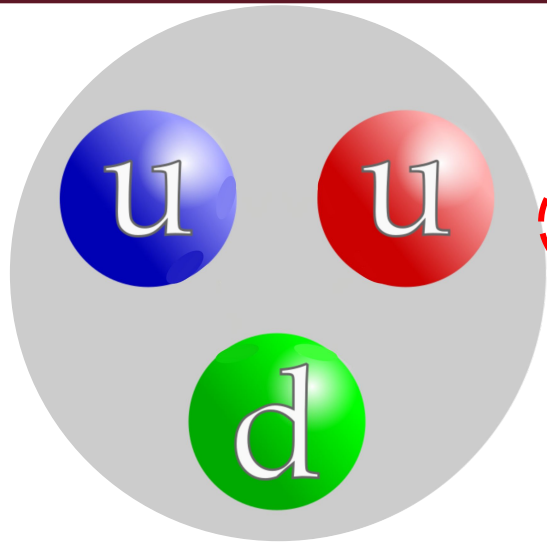
Fundamental Properties of Proton



	Property	Structure
Mass	938.272 MeV	Fractionally carried by quarks and gluons
Spin	$\frac{1}{2}$	Fractionally carried by quarks and gluons
Charge	+1	Fractionally carried by quarks
Baryon Number	+1	Big Puzzles

- Past 30 years was dedicated to to study the dynamic nature of proton structure.
- **Gluon plays a significant role in nucleon structure. (this talk)**
- The effect of QCD confinement is nonlocal (beyond this talk).

Fundamental Properties of Proton

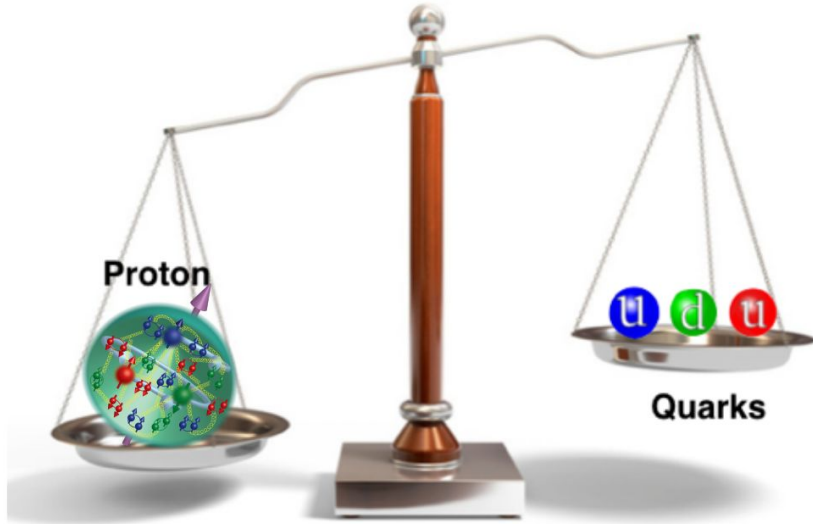


	Property	Structure
Mass	938.272 MeV	Fractionally carried by quarks and gluons
Spin	$\frac{1}{2}$	Fractionally carried by quarks and gluons
Charge	+1	Fractionally carried by quarks

Proton mass = u mass (330 MeV) + u mass (330 MeV) + d mass (330 MeV) ? (Mass puzzle) **No!**

Proton spin = u spin + u spin + d spin = $+\frac{1}{2} - \frac{1}{2} + \frac{1}{2}$? (Spin puzzle) **No!**

Proton Mass Puzzle



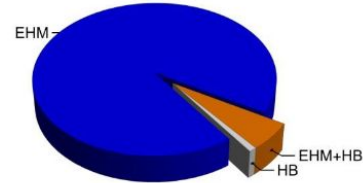
Proton mass:
~ 1000 MeV

Mass of 3 "free" quarks:
~ 10 MeV

- See a problem here?
 - "Free" quarks contributes to <1% of the proton mass

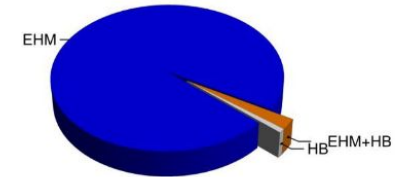
Blue: Gluon
Orange: Higgs+gluon
Grey: Higgs

A Proton Mass Budget

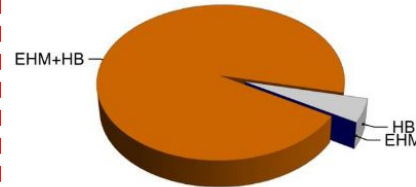


Prof. EI Fassi at MSU

B ρ Meson Mass Budget

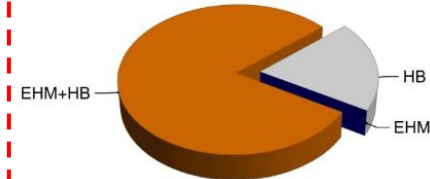


C π Meson Mass Budget



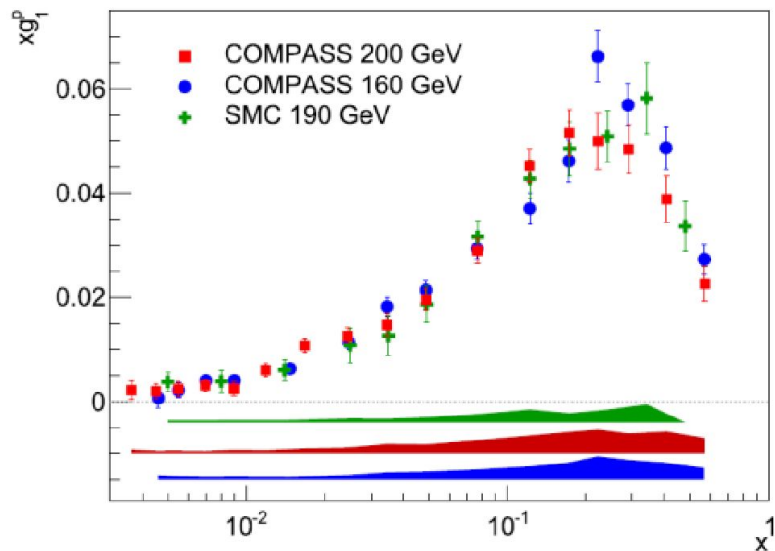
Prof. Dutta at MSU

D K Meson Mass Budget



Plots by Graig Robert

Proton Spin Crisis Puzzle



$$g_1^p(x) = \frac{4}{9}\Delta u(x) + \frac{4}{9}\Delta\bar{u}(x) + \frac{1}{9}\Delta d(x) + \frac{1}{9}\Delta\bar{d}(x) + \frac{1}{9}\Delta s(x) + \frac{1}{9}\Delta\bar{s}(x)$$

$$\int_0^1 g_1^p(x) dx = 0.176 \pm 0.006$$

Expectation: 0.25!

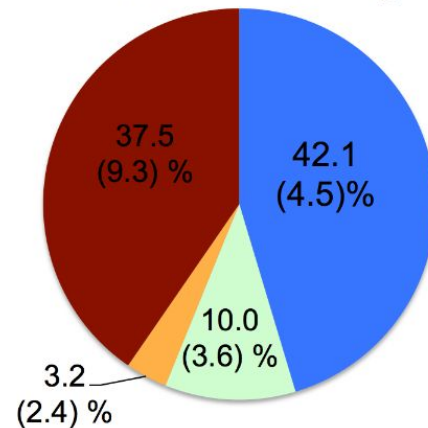
Frame-independent spin sum rule

(Ji)

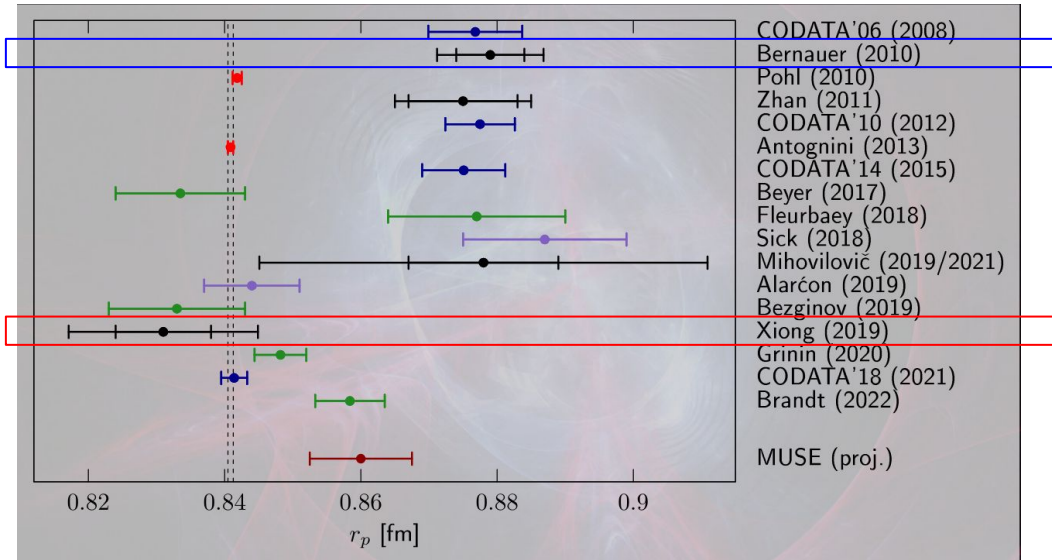
$$\frac{1}{2}\Delta\Sigma + L_q^z + J_g = \frac{\hbar}{2}$$

- $\Delta\Sigma/2$ and L_q^z (sum to J_q) are the quark helicity and OAM, respectively;
- Quark and gluon contributions J_q and J_g can be obtained from GPD moments;
- The sum rule also works for the transverse angular momentum in the IMF.

■ J_u ■ J_d ■ J_s ■ J_g



Proton Radius Puzzle

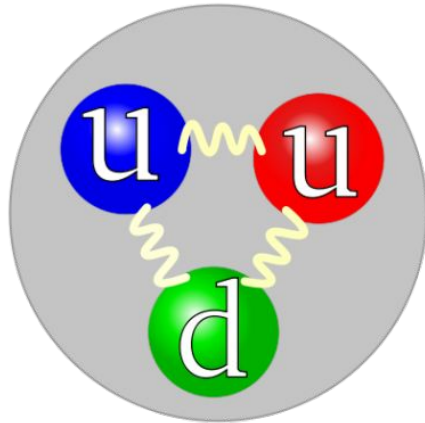


Proton radius:

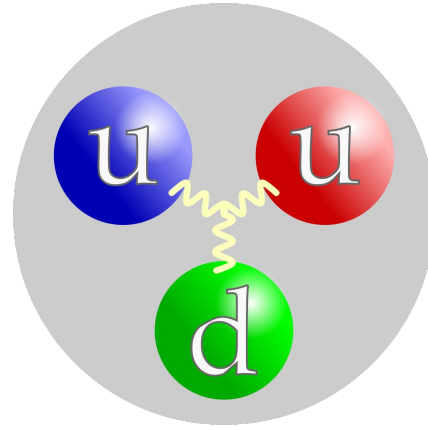
- Before 2010: 0.88 fm
- After 2010: 0.84 fm
 - But we don't know.
 - An unsettled issue
 - Mainz ep data disagree with JLab ep data, what is going on?
- Another good example of being curious instead of listening to your supervisor :D

Puzzle #4: Proton's Identity Puzzle (New one)

- Proton internal structure: **which of the following picture is correct?**



A



B

Does Google know the answer?

The screenshot shows a Google search for "proton quark". The search bar at the top contains the text "proton quark". Below the search bar, there are several tabs for related topics: Atom, Neutron, Electron, Diagram, Model, Molecule, Sea, Spin, Gluon, Quanta magazine, and Charm quark. The search results are displayed in a grid format, featuring various images and snippets of text. The images include diagrams of quarks (up and down) and gluons, as well as articles from sources like Medium, Quanta Magazine, and Physics.org. The snippets provide brief information about the proton's structure and the quark model. A "Related searches" section is visible at the bottom left, listing terms like "what are quarks made of", "neutron quarks", and "atoms quarks".

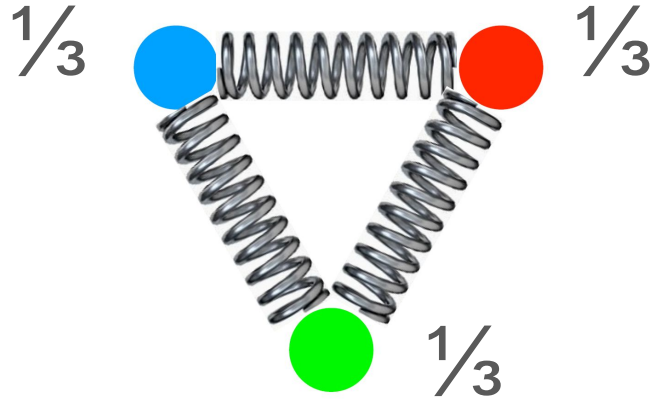


As you can see
google is unsure.

Proton Image by Frank Wilczek

If A is correct:

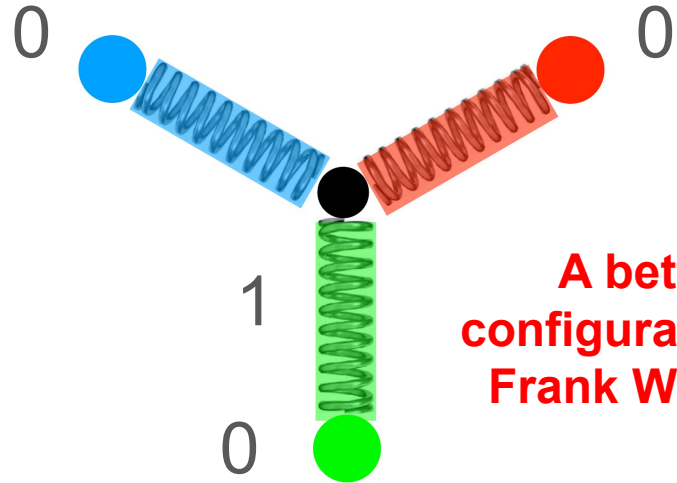
To put back the “3” in color SU(3), we can use $U(1) \times U(1) \times U(1)$ with an appropriate charge spectrum:



$(1, -1, 0) \& (-1, 0, 1) \& (0, 1, -1)$

If B is correct (Ver-ton):

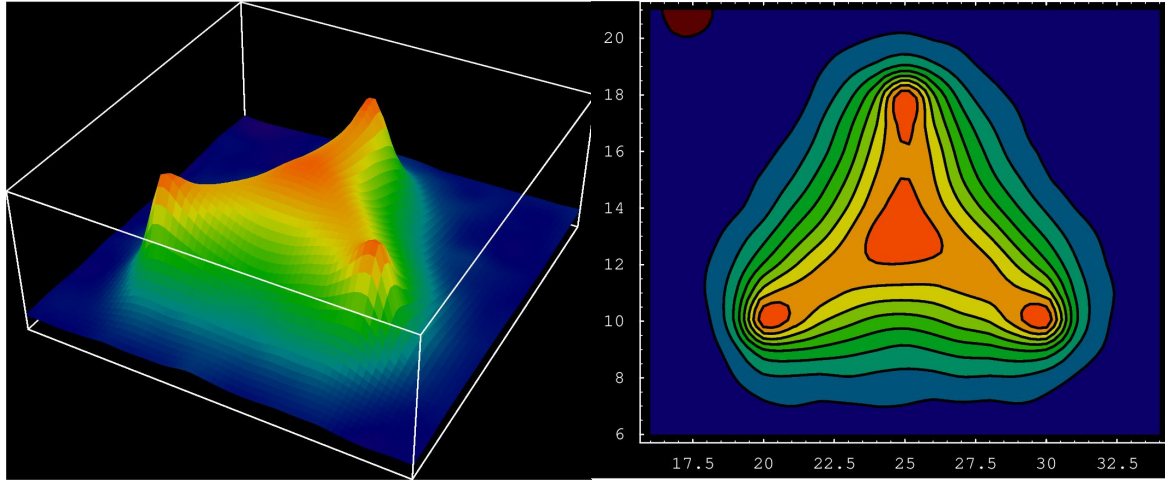
Or, likely best of all in this vein: just $U(1)$, unit charged quarks and a charge -3 ver-ton.



A better configuration by Frank Wilczek

$(1, 0, 0) \& (0, 1, 0) \& (0, 0, 1) + \text{ver-ton } (-1, -1, -1)$

Insights on baryon junction



Lattice QCD Study on proton wavefunction

Hideo Suganuma, Toru T. Takahashi, Fumiko Okiharu, Hiroko Ichie, [arXiv:hep-lat/0412026](https://arxiv.org/abs/hep-lat/0412026), 2004

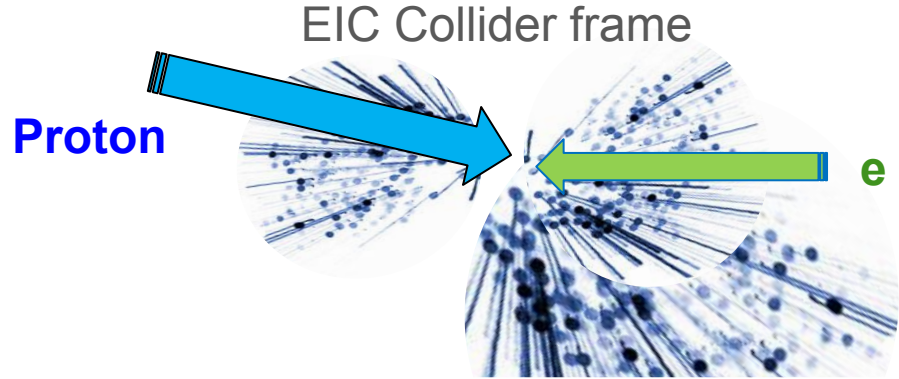
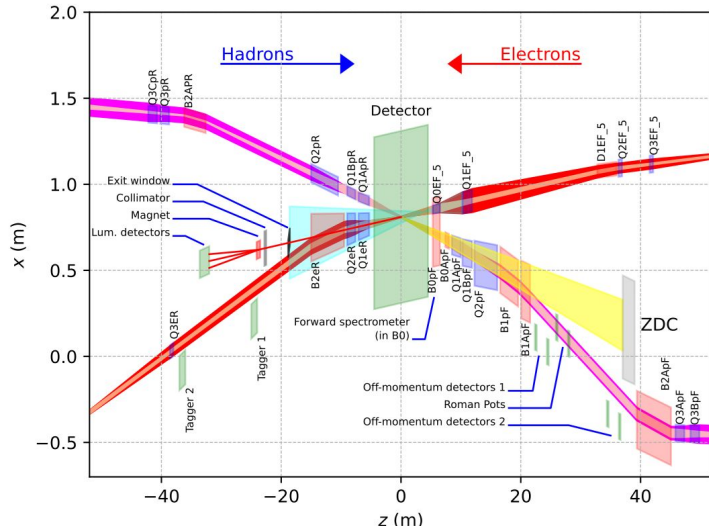
- Baryon Junction was predicted by local gauge invariance of the baryon wave function (1977)
 - ([G.C. Rossi, G. Veneziano, Nuclear Physics B, Volume 123, Issue 3, 1977](#))
- The lattice results of a “baryon junction” inside proton – a purely gluonic field configuration that represents entanglement among the quarks and carries baryon number! (2004)
- D. Kharzeev argued the transport of baryon number in high energy pp collision (1996)
 - [arXiv:nucl-th/9602027](https://arxiv.org/abs/nucl-th/9602027)

Science Mission/Pillars of the EIC

EIC Science Pillar	Core Question	Key Observables / Channels
Proton Spin	How do quarks, gluons, and orbital motion make the proton spin?	Polarized DIS/SIDIS, jets, heavy flavor, spin asymmetries
3D Nucleon Imaging	Where are quarks and gluons in position and momentum space?	TMDs, GPDs, DVCS, exclusive mesons, SIDIS
Mass & Confinement	How does QCD generate nucleon mass and internal forces?	Gluon structure, energy-momentum tensor, quarkonium, exclusive reactions
Dense Gluon Matter	Do gluons saturate at small x , especially in nuclei?	e+A DIS, diffraction, forward particles, dijets, heavy flavor
Hadronization in Nuclei	How do colored partons become hadrons inside nuclear matter?	SIDIS on nuclei, identified hadrons, jets, charm, nuclear modification

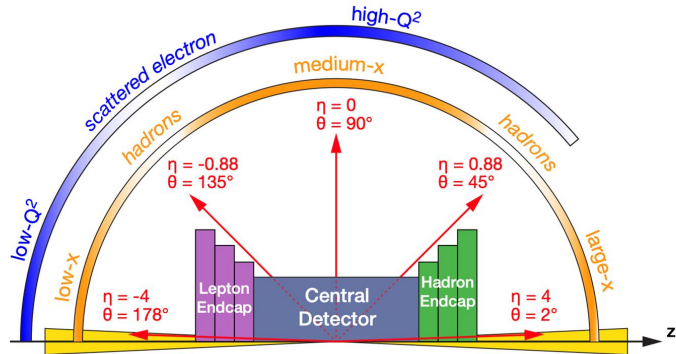
**Forward
Physics**

ePIC Detector Detail

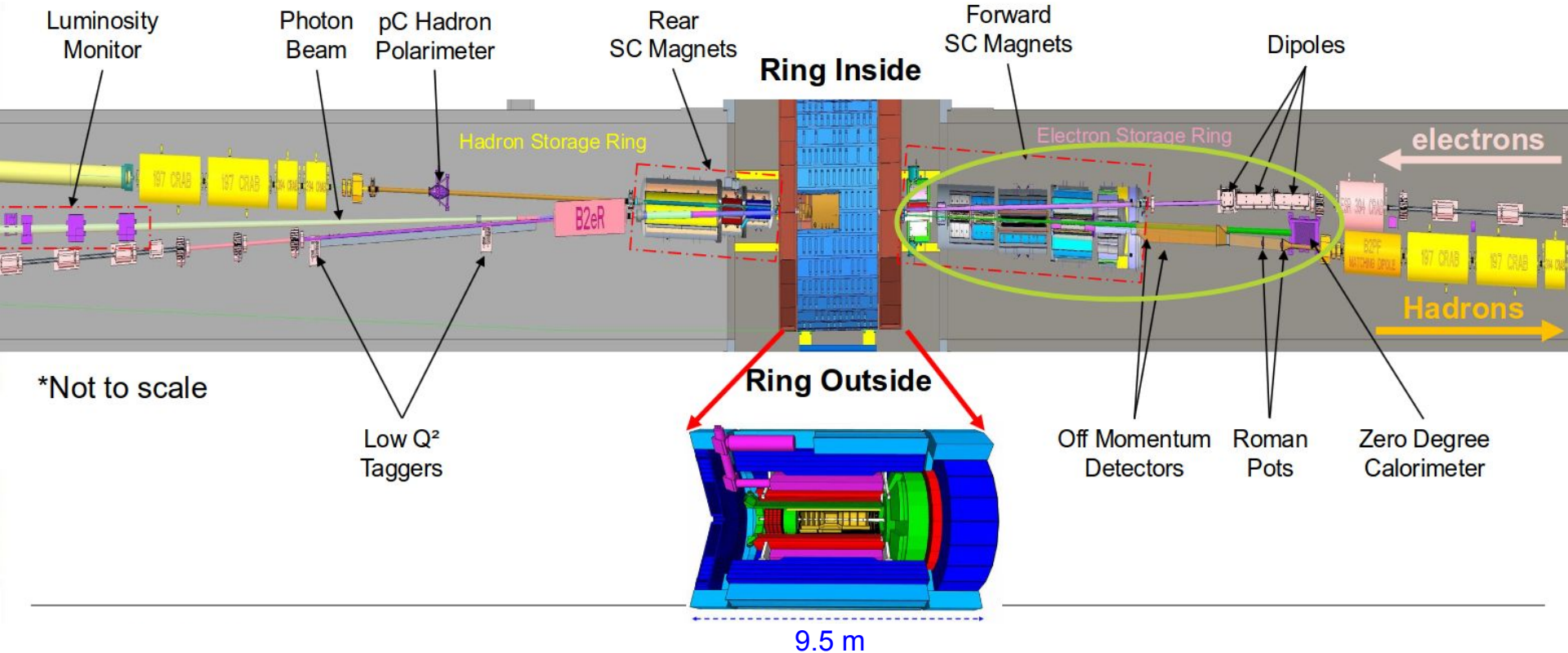


ePIC detector features:

- A hermetic detector stack (almost 4π coverage)
- Asymmetrical collision frames (highly boosted in favors of proton)
- 25 mRad crossing angle: accessing $\eta \sim 6$ for charged particles, $\eta \sim \infty$ for neutral particles (Accessing small $-t$ or p_T).

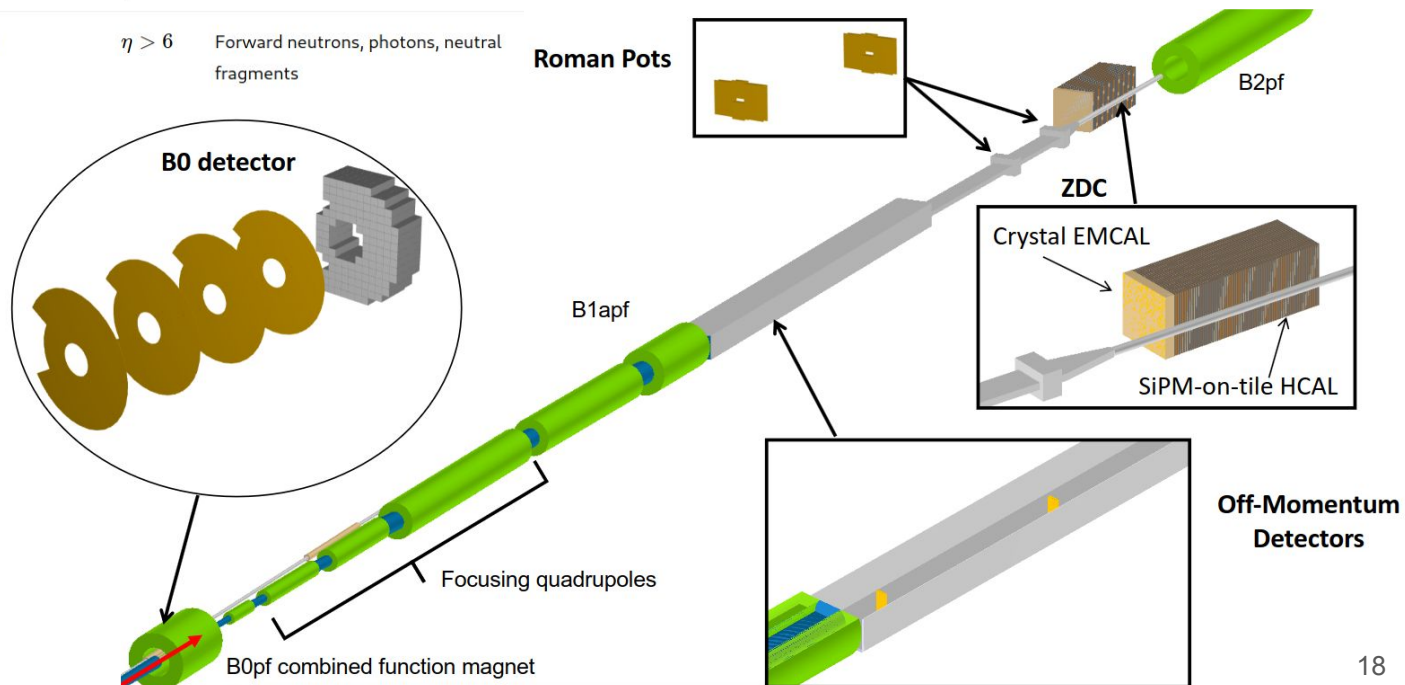


Full ePIC Stack



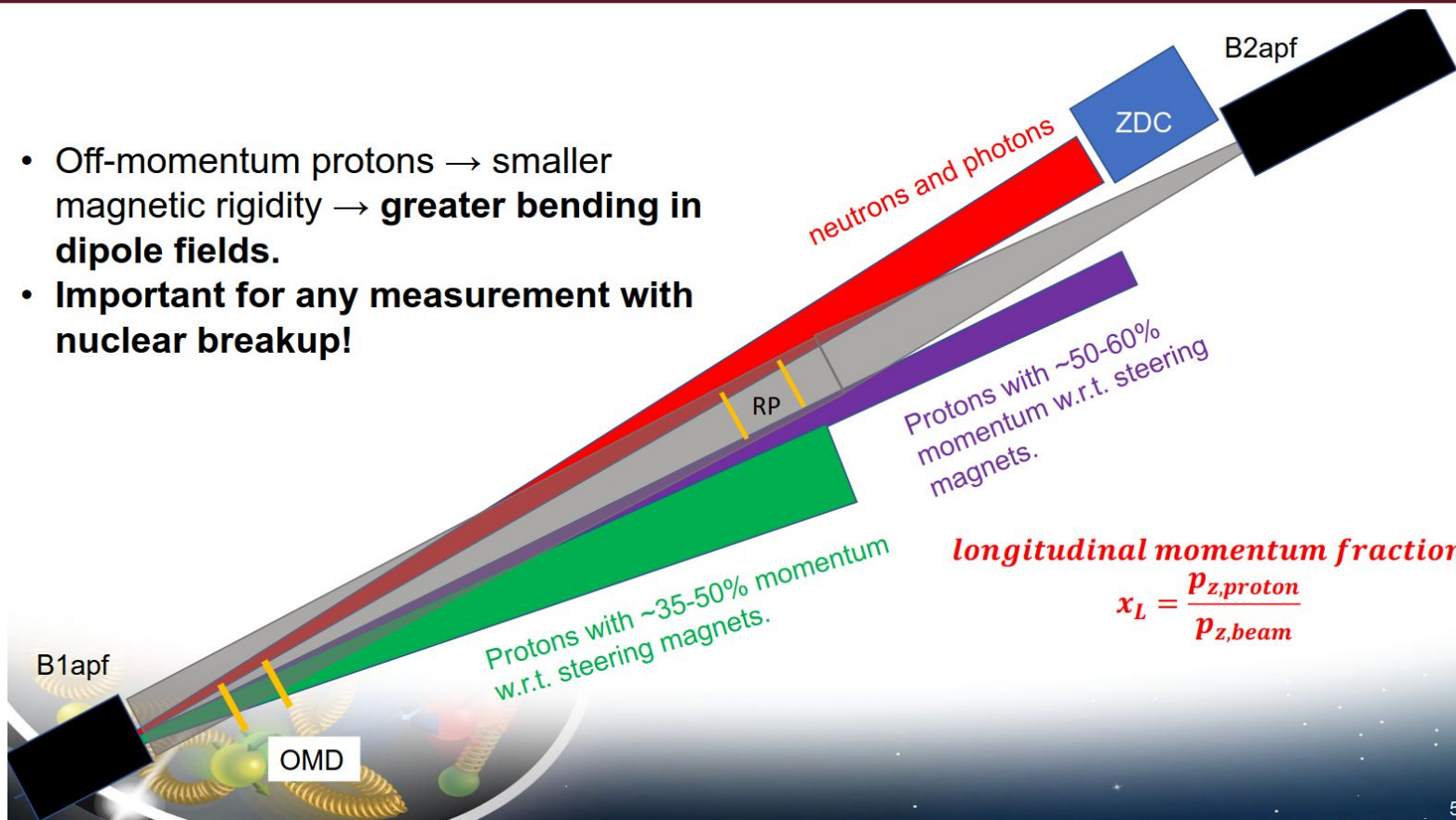
Far Forward Detector Layout

	Angular coverage	η coverage	Main role
B0 tracker + B0 EMCal	$5.5 < \theta < 20$ mrad	$4.6 < \eta < 5.9$	Forward charged particles + photons
Roman Pots	$0 < \theta < 5$ mrad	$\eta > 6$	Leading protons / intact fragments
Off-momentum detectors	$\theta < 5$ mrad	$\eta > 6$	Low-rigidity charged fragments
ZDC	$\theta < 5.5$ mrad	$\eta > 6$	Forward neutrons, photons, neutral fragments

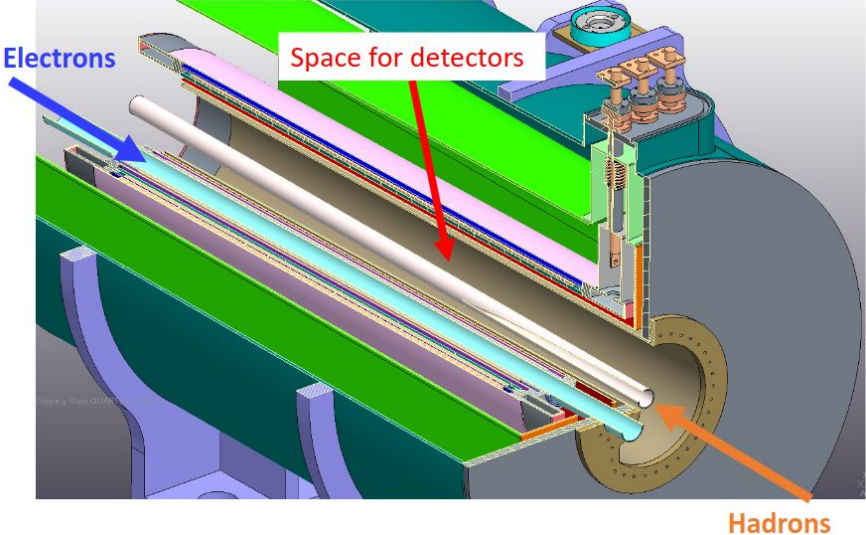
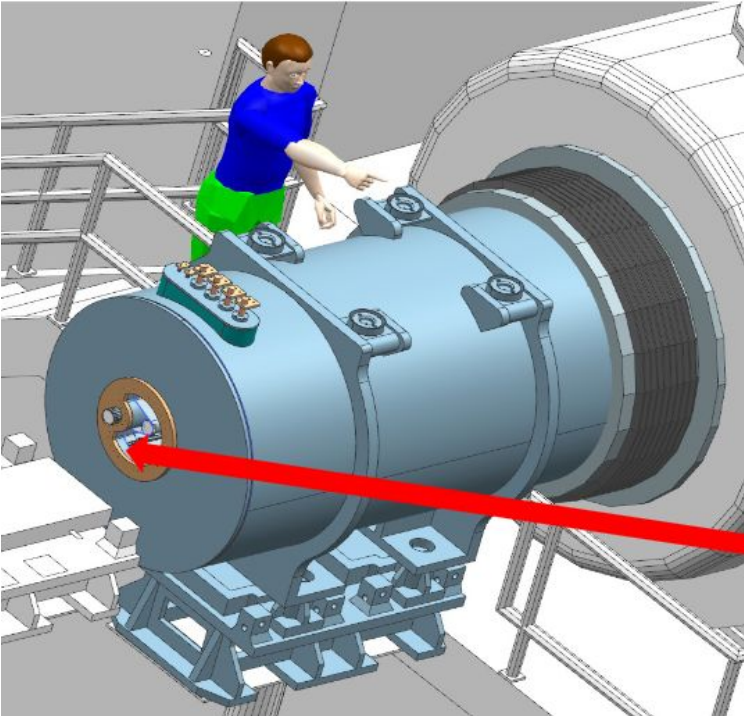


Where Does Particle Go After the Interaction?

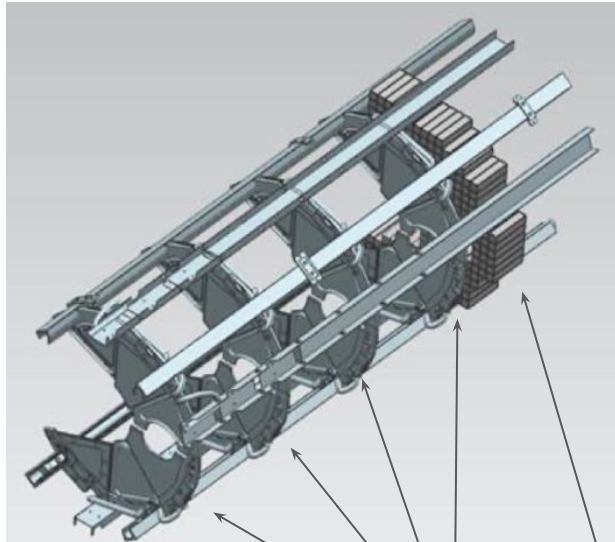
- Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields.**
- **Important for any measurement with nuclear breakup!**



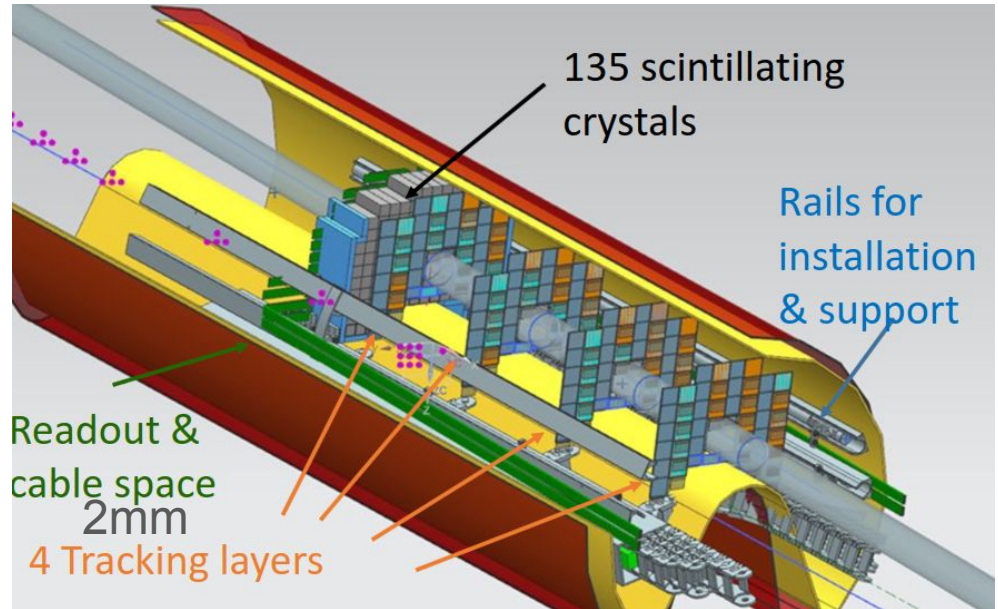
Integrated B0 Magnetic/Detector Stack



Integrated B0 Magnetic/Detector Stack



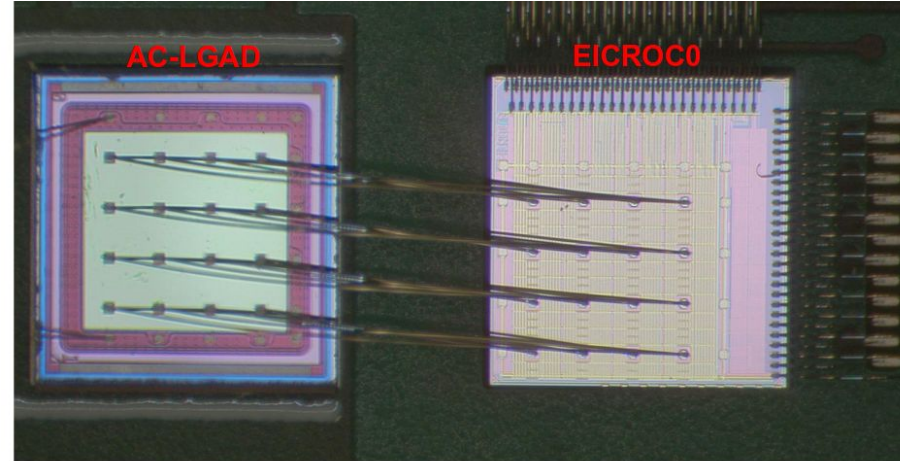
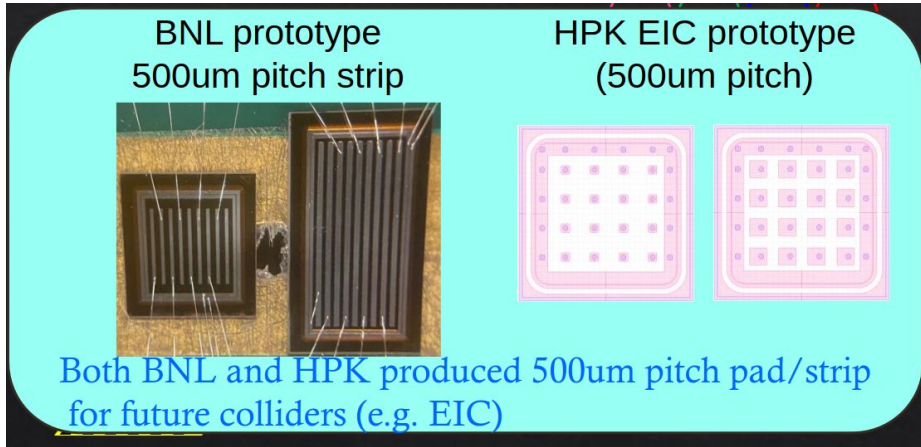
AC-LGAD Tracker



LYSO Calorimeter ~ 6-7% energy resolution

What do we need calorimeter there?

AC-LGAD Solution as Tracker



- **AC-Low Gain Avalanche Detector (LGAD)**

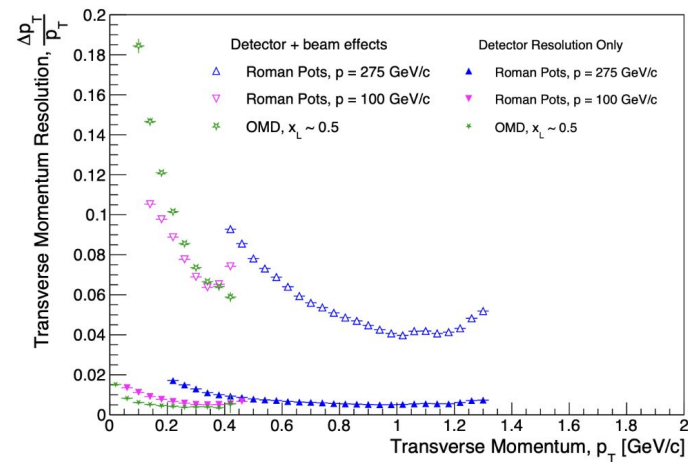
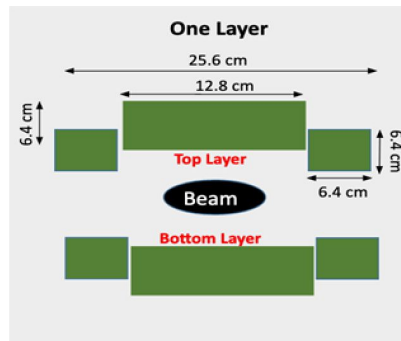
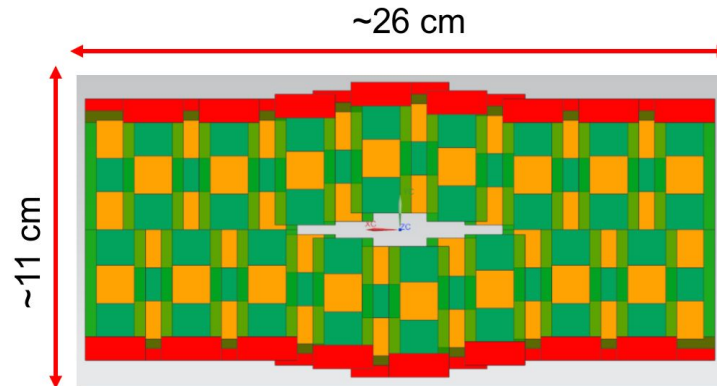
- Low material budget
- Fast timing
- High spatial resolution
- New tracking technology

- **Hamamatsu ACLGAD pixel sensor of $2 \times 2 \text{ mm}^2$ used in prototyping and quote pixel-sensor performance around **20 ps timing** and **$\sim 20 \mu\text{m}$ spatial resolution.****

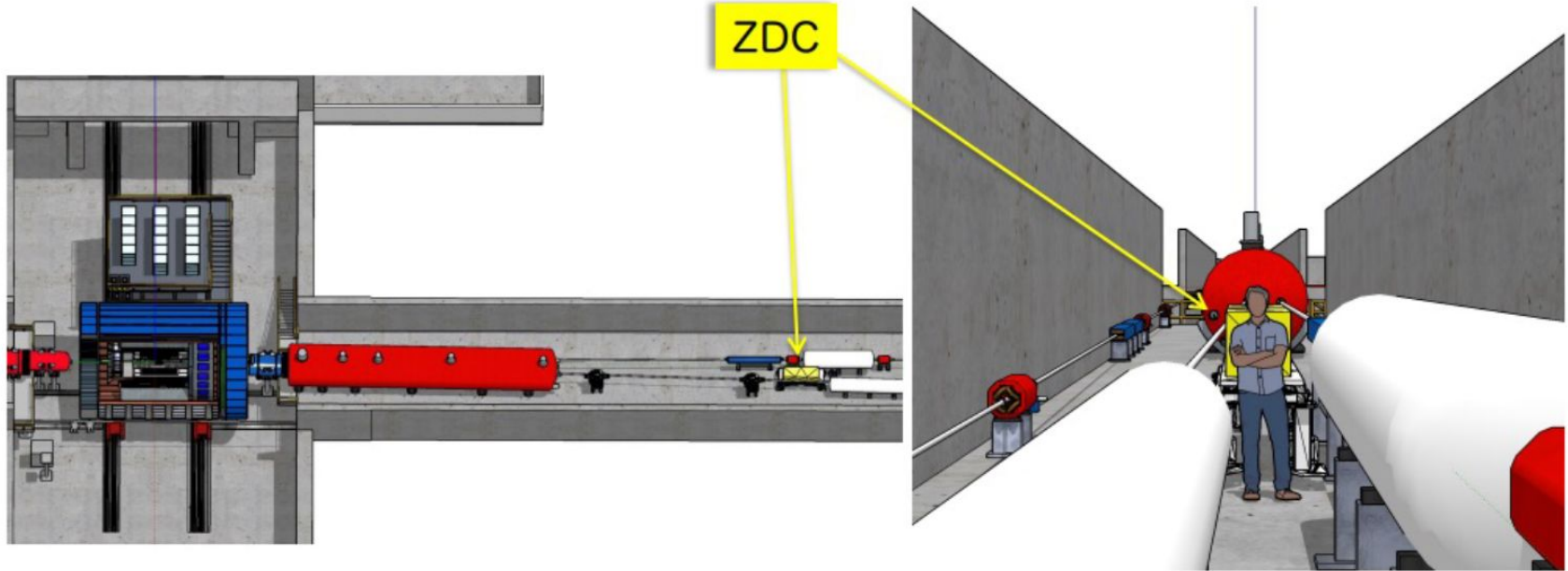
BNL AC-LGAD:

- $500 \times 500 \text{ um}^2$ pixel pitch
- $100 \times 100 \text{ um}^2$ metal electrode
- 30um active thickness

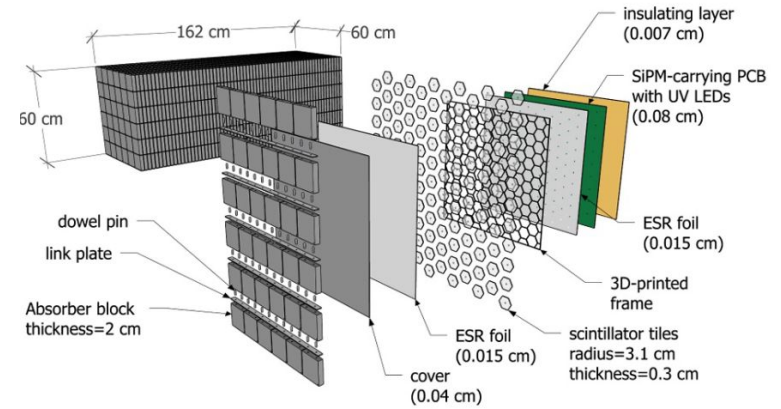
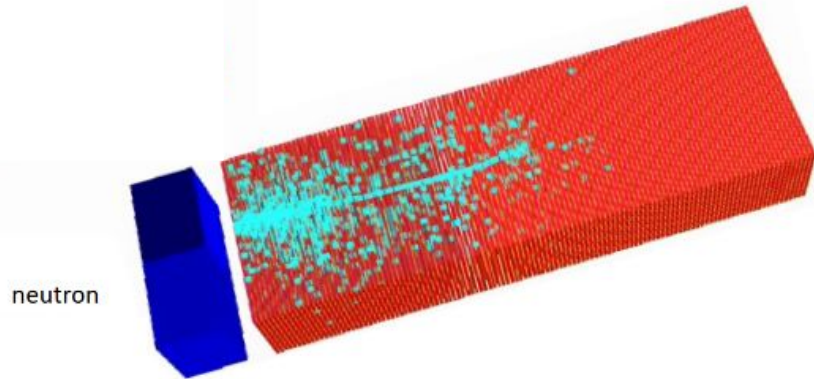
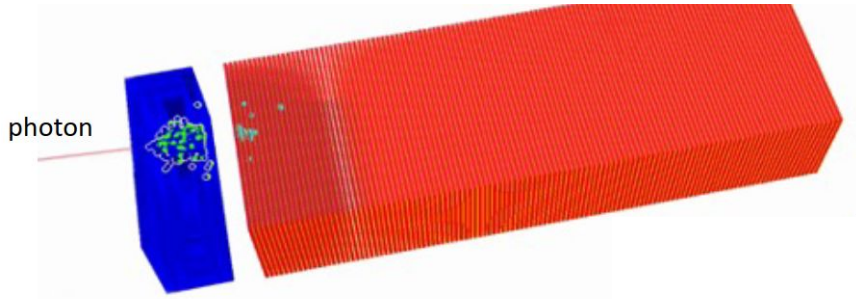
Roman Pot (RP) and Off-Momentum Detector



Zero Degree Calorimeter (ZDC)

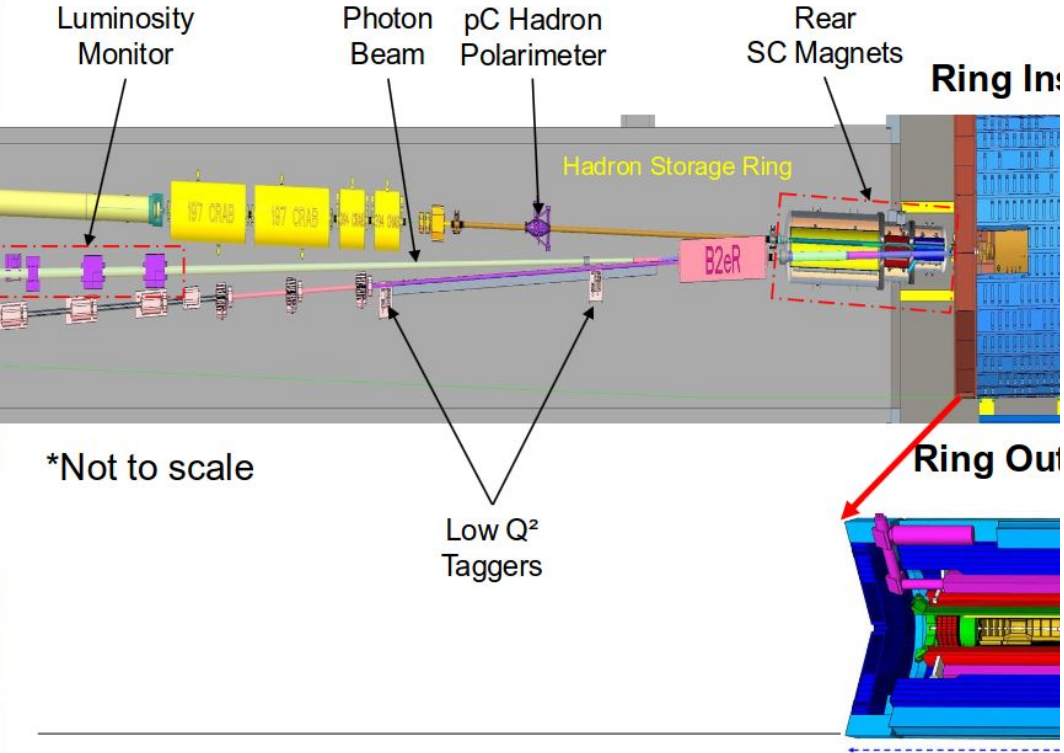


Zero Degree Calorimeter (ZDC)



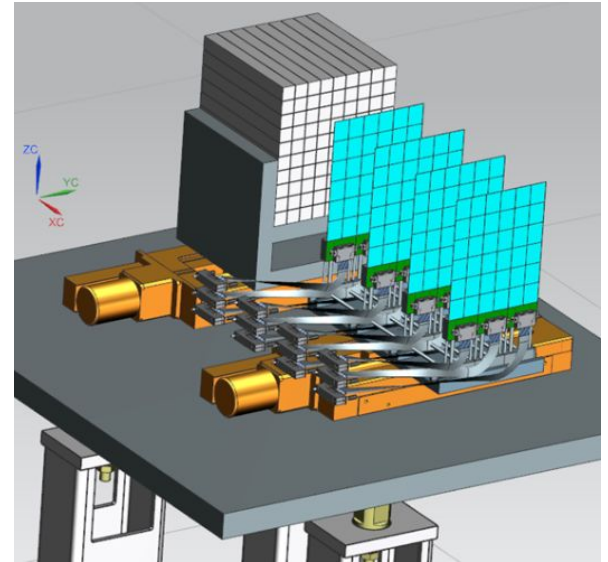
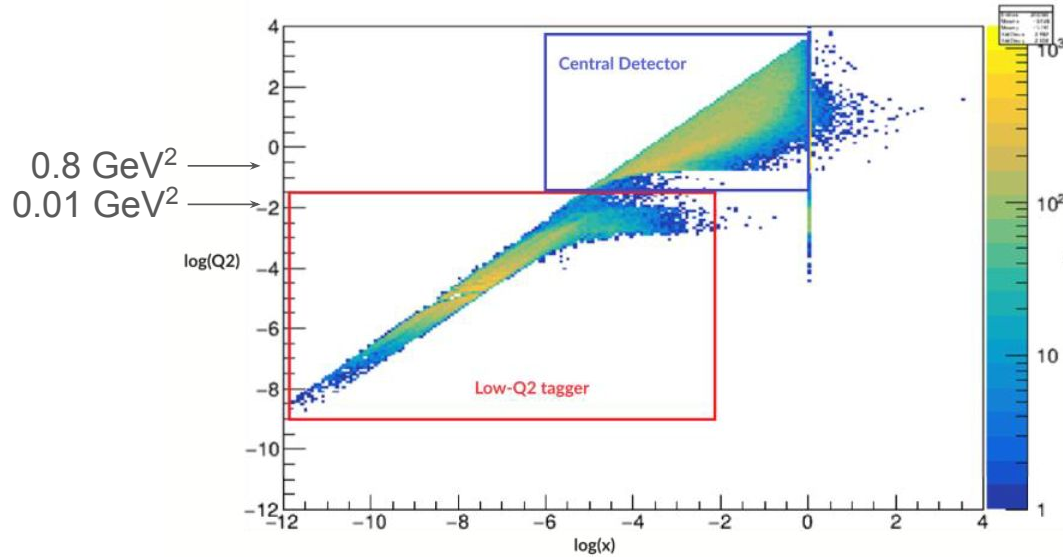
- ZDC
 - LYSO Layer + Hadron Calorimeter layer
 - Photon and Neutron detection
 - Photon energy resolution: 6-7%
 - Hadron energy resolution: 20%

Low Q^2 Tagger (far backward region)



- **Low Q^2 target:**
 - Main purpose: e tagger at ultra low Q^2

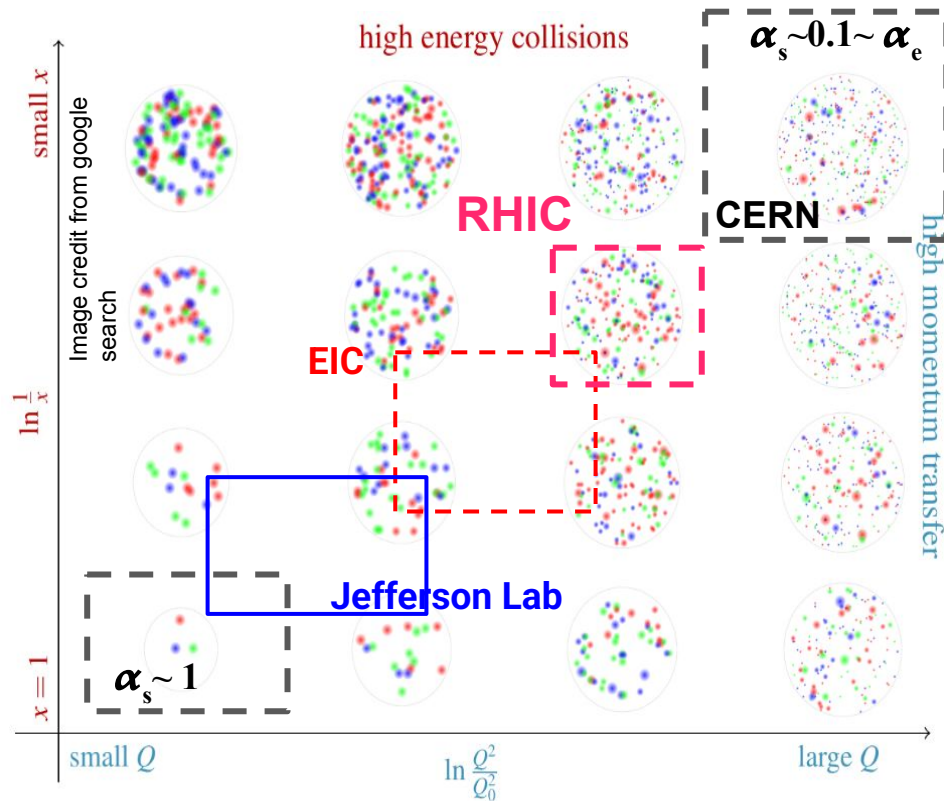
Hole in the Q^2 Coverage



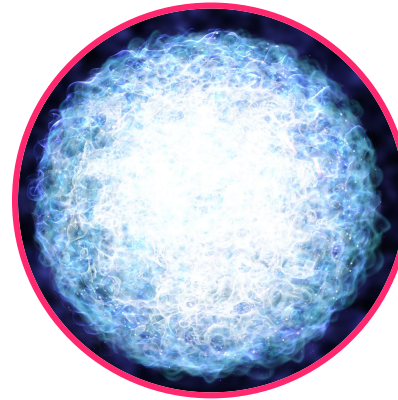
Two tagger stations covering different energy ranges.

- Tracker consisting of 4 layers of Timepix4 detectors, pitch 55 μ m
- tungsten-powder + scintillating-fiber SPACAL / spaghetti calorimeter, derived from the far-backward luminosity-system calorimeter design.
- Ultra high rate 70k/pixel
- EM resolution $\sigma E/E \sim 12\%/E \oplus 2\%$

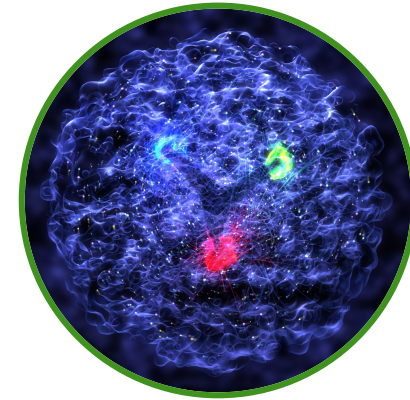
Image of a proton (via Virtualized art)



Dynamic structure of proton



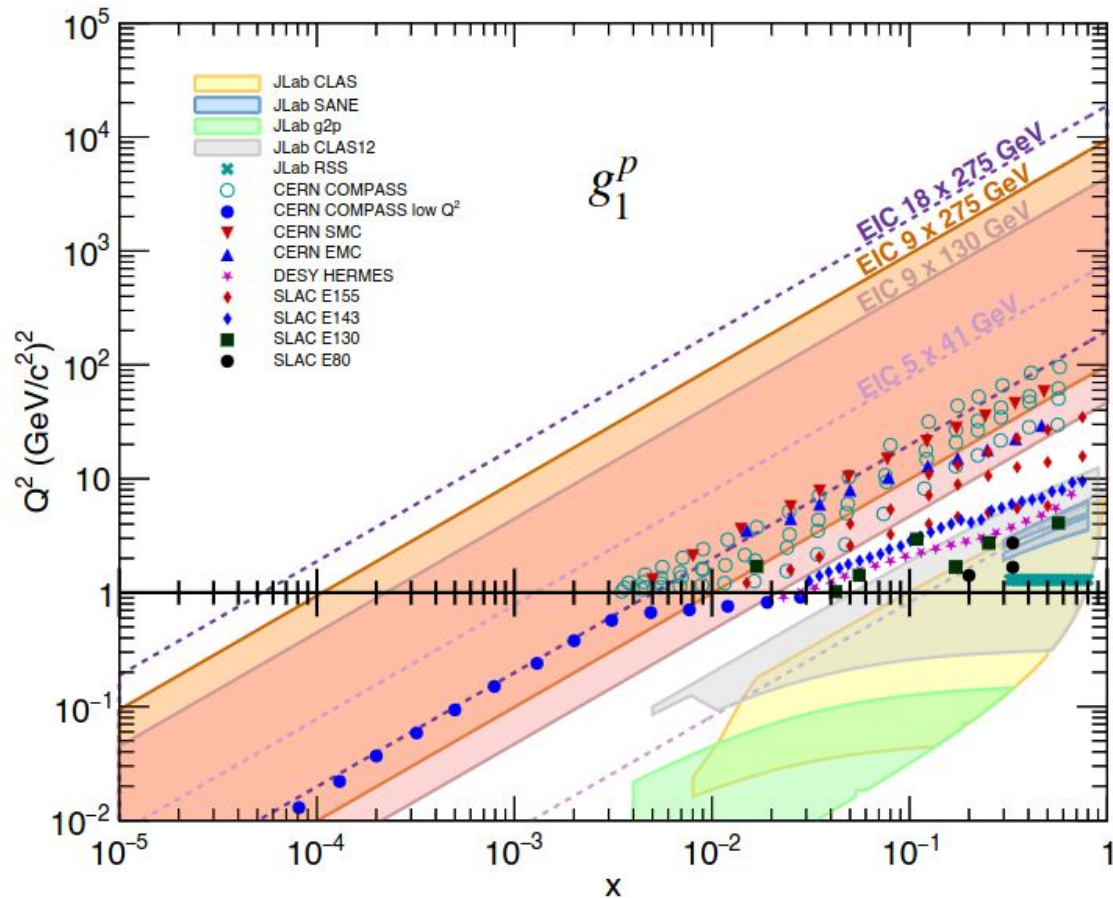
Proton image at CERN



Proton image at Jefferson Lab

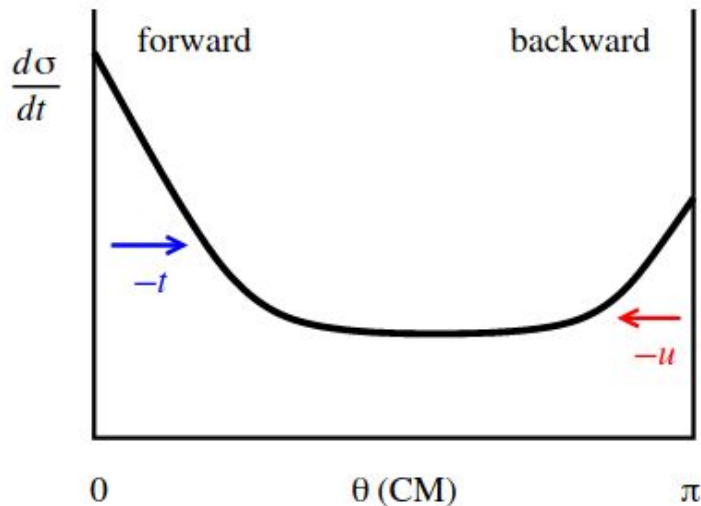
Image credit to JLab and MIT:
[Full video available on YouTube](#)

Kinematics Phasespace of the EIC

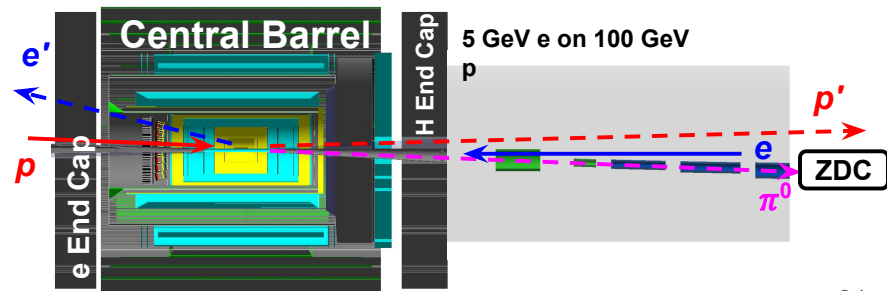
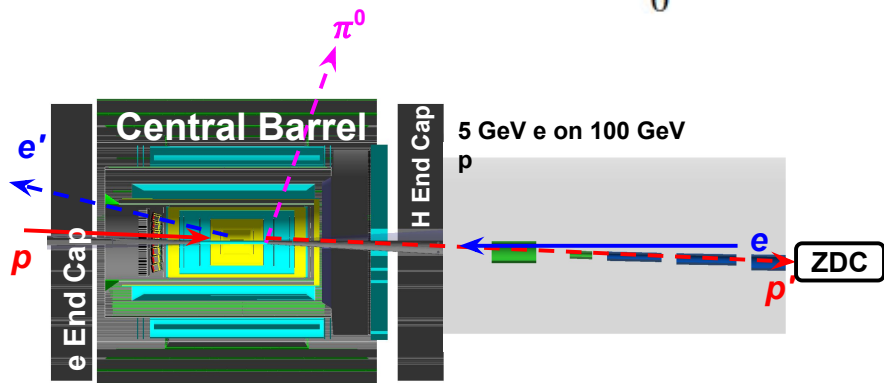


Forward and Backward π^0 electroproduction at EIC

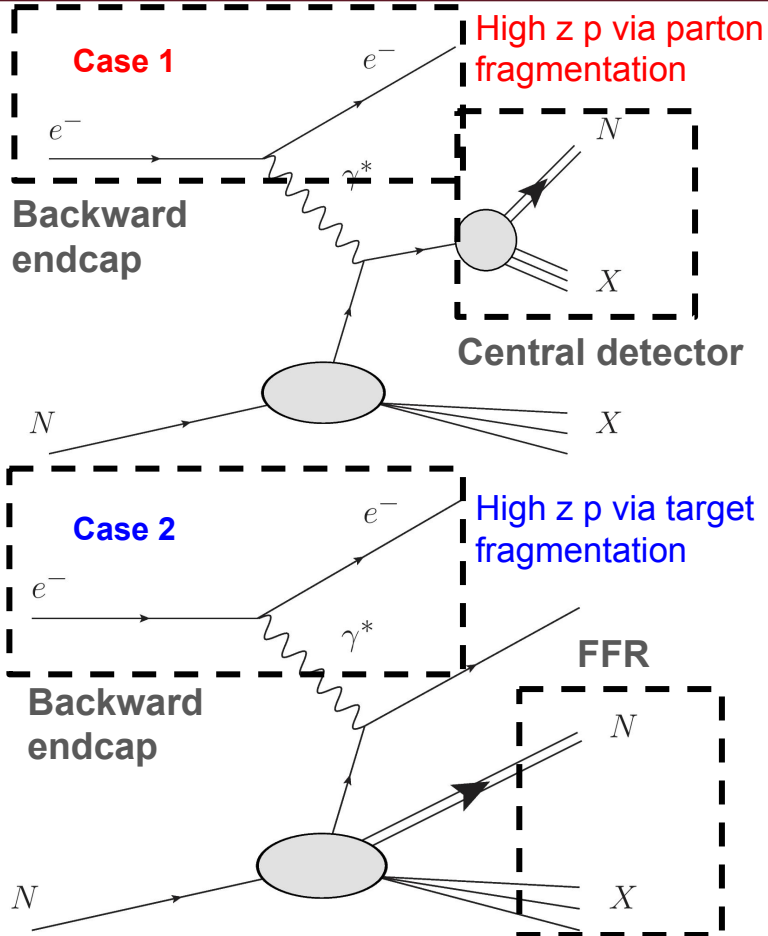
t-Channel forward scattering



u-Channel backward scattering



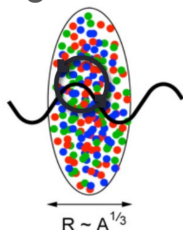
Semi-inclusive scattering (inspired by Alessandro Bacchetta)



- **Where is the high-z proton coming from?**
- **Two possibilities**
 - Case 1: From the fragmented parton region, which can be described by proton fragmentation function (can be integrated into the TMD formalism)
 - Case 2: From the target fragmentation region, collinear factorization approach. Fracture function.
- **PDF vs Fragmentation Function (FF) vs Fracture Function**
 - **PDF:** what parton is struck?
 - **FF:** how does the struck quark hadronize?
 - **Fracture function:** what parton is struck while the spectator remnant produces a tagged baryon? (L. Trentadue and G. Veneziano, *Fracture functions*, *Phys. Lett. B* 323, 201–211 (1994).)
- **Misconception:** George Sterman (with W. Vogelsang and D. De Florian) derived the fragmentation probability for high momentum proton production 30 years ago.
 - True for case 1
 - George Sterman: Case 2 is where he study stopped, “target fragmentation” is a new problem requires new theoretical and experimental approach, perhaps at the future EIC.
- **No Hadron Calorimeter in B0 area to capitalize this opportunity**

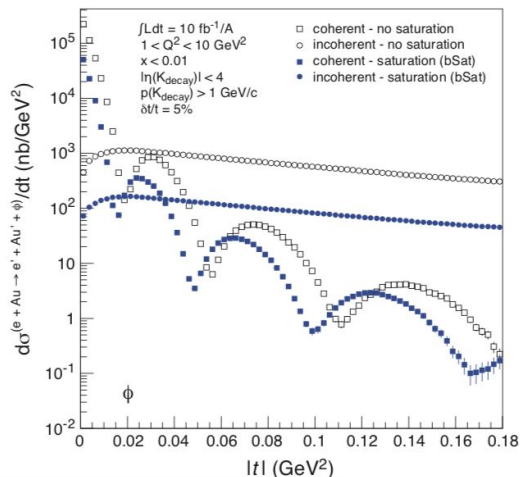
Diffractive Vector Meson Production via eA Scattering

Accessing the gluon saturation regime



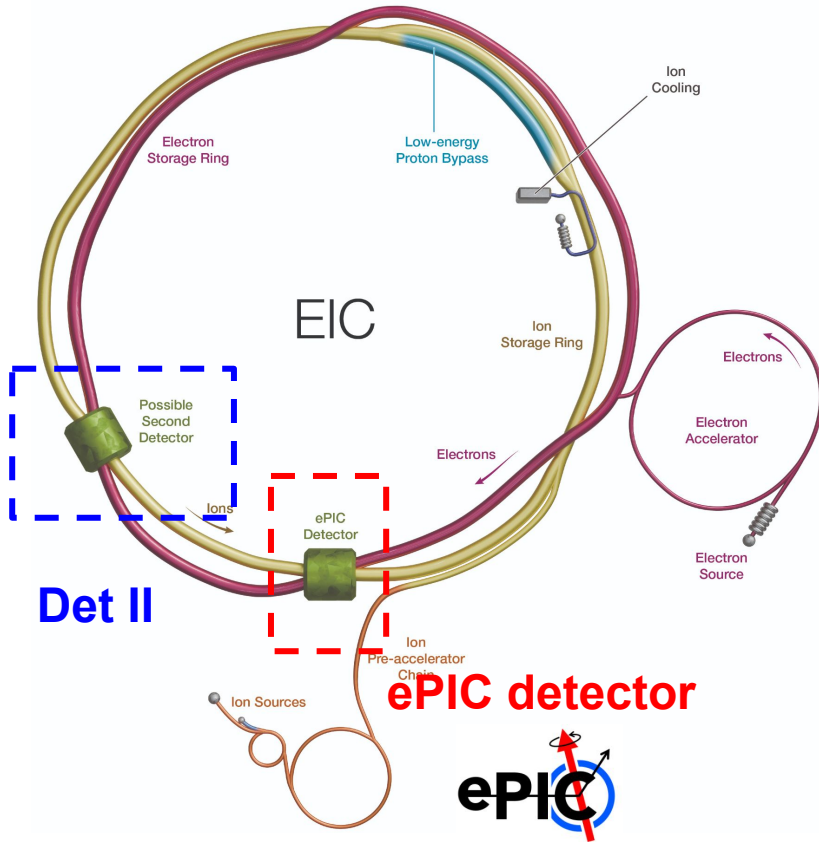
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x} \right]^{1/3}$$

Saturation scale



- Very similar Ultra-Peripheral collision at LHC
 - No color exchange
- **Incoherent Scattering:** Scattering from individual constituents, with the target often breaking up or being left in an unobserved excited/remnant state
- **Coherent Scattering:** Scattering where amplitudes from the whole target add coherently and the target remains intact
 - sensitive to the “slumpiness” of gluon inside of the nuclei
- First observation of a quantum collective gluonic system
 - Precision comparison of experiment and “Color Glass Condensate” (CGC) as a theoretical model of the gluon saturation

2nd Detector at EIC? Do we need it?



- Good cases and examples were made for both nuclear and particle physics experiments
 - CMS & ATLAS
 - ZEUS & H1
 - CDF & D0
 - BELLE & BaBar
- Opinion by P. Grannis and H. Montgomery

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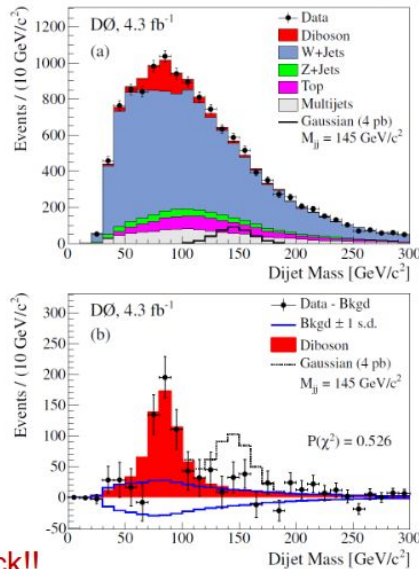
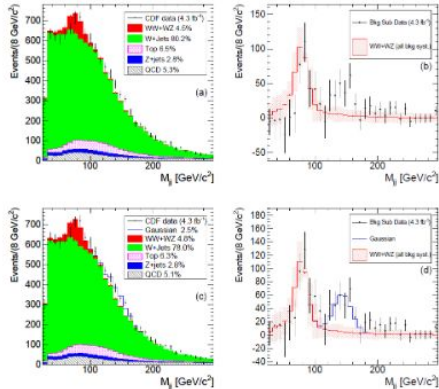
Motivation for Two Detectors at a Particle Physics Collider

Paul D. Grannis* and Hugh E. Montgomery†
(Dated: March 27, 2023)

It is generally accepted that it is preferable to build two general purpose detectors at any given collider facility. We reinforce this point by discussing a number of aspects and particular instances in which this has been important. The examples are taken mainly, but not exclusively, from experience at the Tevatron collider.

Prime Example of Cross Checking Power

144 GeV Resonance? No!



- 2011 CDF study of dijet mass distributions in W + jets measurement.
- Statistically significant (p -value $7.6 \cdot 10^{-4}$, 3.2σ) excess
- Fit to extra Gaussian with width scaled to dijet resolution \rightarrow mass 144 ± 5 GeV, $\sigma \cdot BR = 4$ pb.

Crosscheck!!

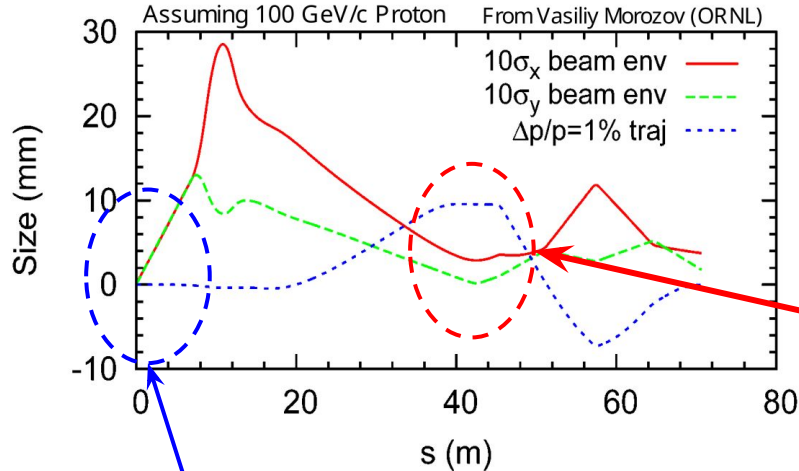
- 2011 DØ study gives no excess, with likelihood of 145 GeV resonance of $\sigma \cdot BR = 4$ pb of $8 \cdot 10^{-6}$ Rejection 4.3σ , 95% CL UL 1.9 pb

- A slide stolen from Mont's talk at EICUG 2023 on vetoing false signal:

<https://indico.cern.ch/event/1238718/sessions/495759/>

- Result verification
 - Mass determination
 - Veto false signals
- My personal take: EIC carries the potential for discovery level physics: **would anyone believe our results without a cross-check?**

Implementation of the **Second Focus** at Detector II



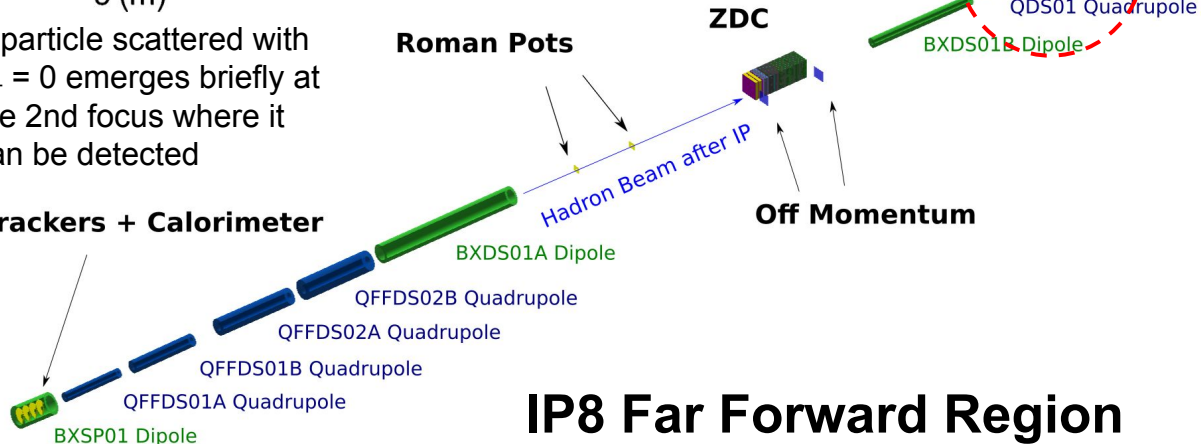
- **Beam squeezed twice**

- First at the IP (flat beams for max luminosity)
- Then at ~ 45 m downstream of the IP (weaker 2nd focus for optimal detection in the RPs)
- 10σ beam envelope at 2nd focus in x is 4 mm (10σ beam envelope size at ePIC RP ~ 8 cm)

A particle scattered with $p_T = 0$ emerges briefly at the 2nd focus where it can be detected

B0 Trackers + Calorimeter

IR
✕



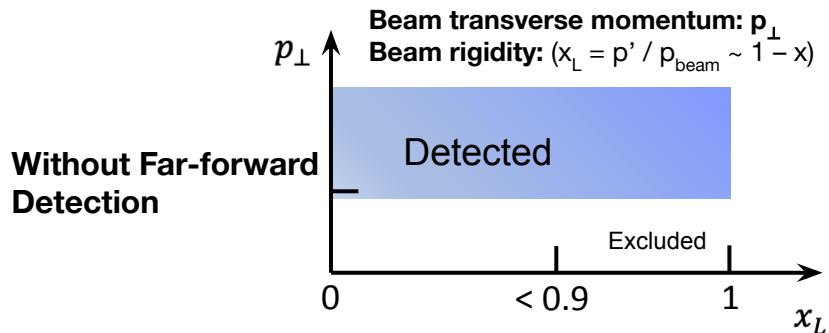
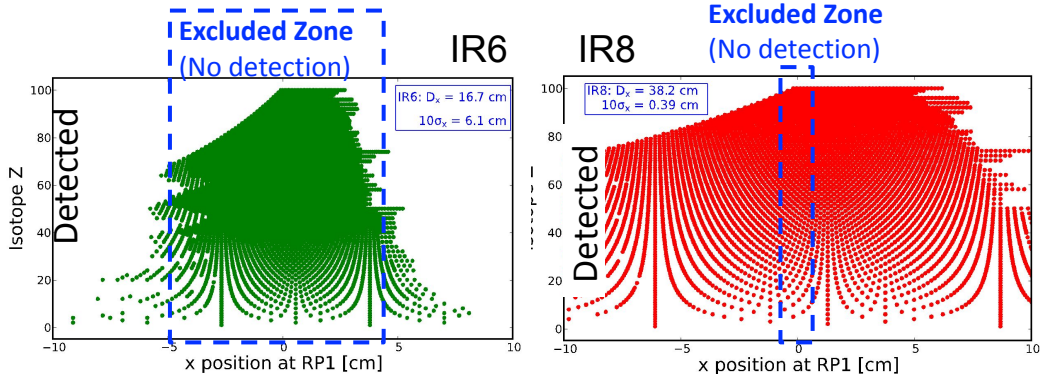
IP8 Far Forward Region

Opportunities from the **Second Focus** at Detector II

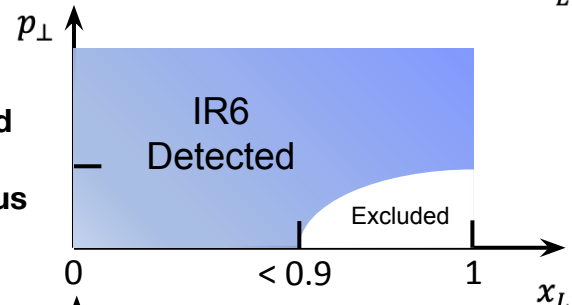
Much improved near-beam detection at Detector II:

- Low- x / low- p_T proton acceptance
- Detection of light nuclei (coherent processes)
- Vetoing breakup of heavier nuclei (diffraction)
- Tagging a wide range of spectator nuclei
 - Including A-1 for studying the bound nucleon
- Properties of the nuclear final state
 - Hypernuclei, Rare isotopes, etc

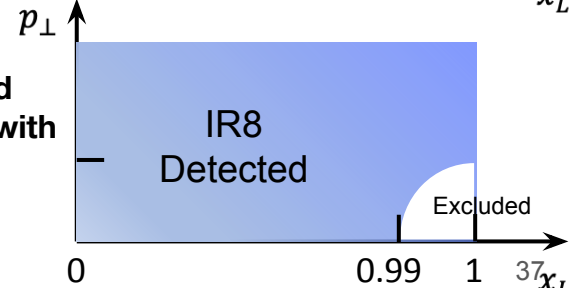
Isotope fragments from ^{238}U , Brynna Moran, *et. al.*



With Far-forward Detection (RP), without 2nd focus



With Far-forward Detection (RP), with 2nd focus



Questions?

Far Forward Region

