Electron-Ion Collider

Matthew Nguyen
Conseil Scientifique LLR
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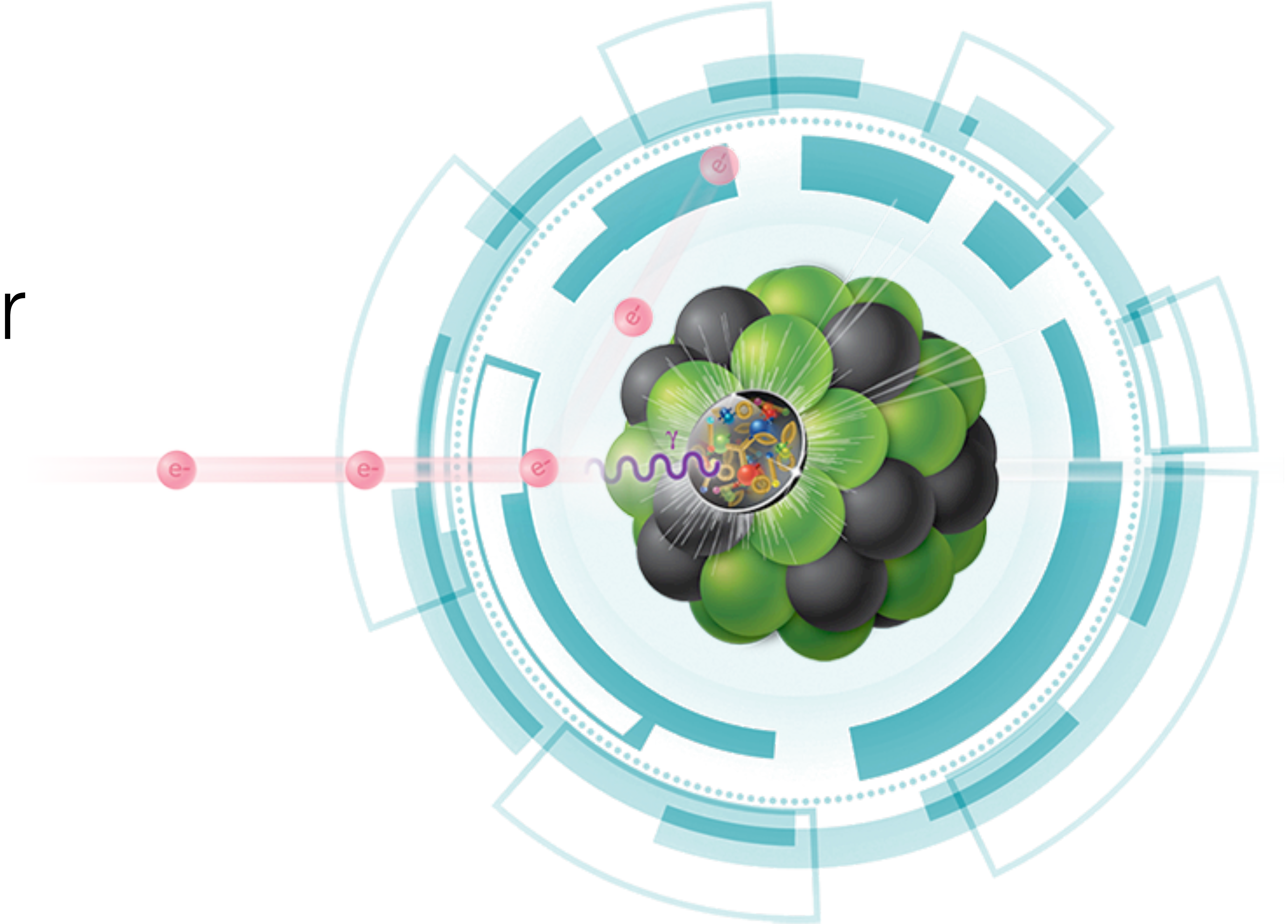
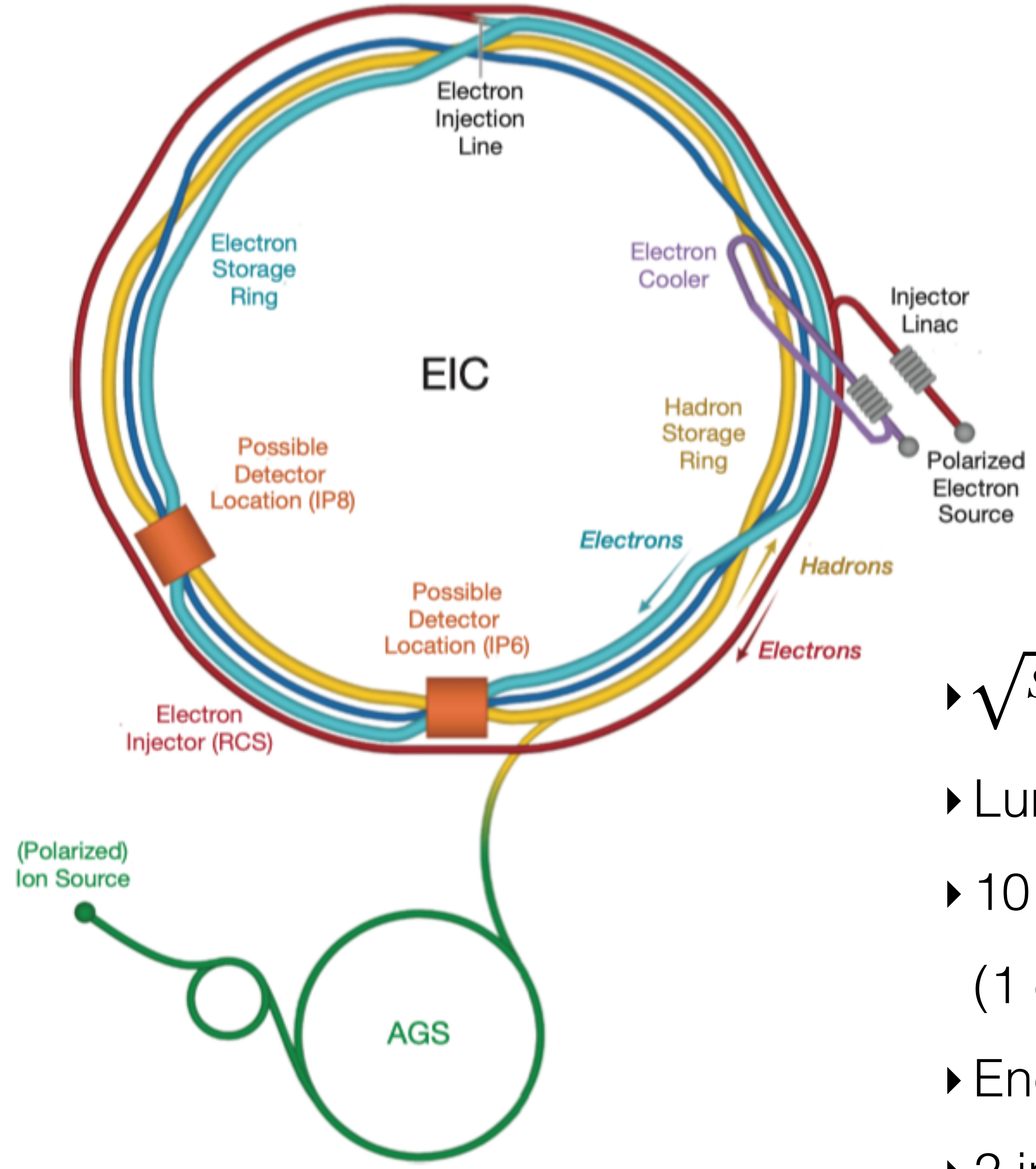
Overview

- Physics goals of the electron-ion collider
- The ePIC detector & backward ECAL
- ASIC for readout of the backward ECAL



What is the electron-ion collider?

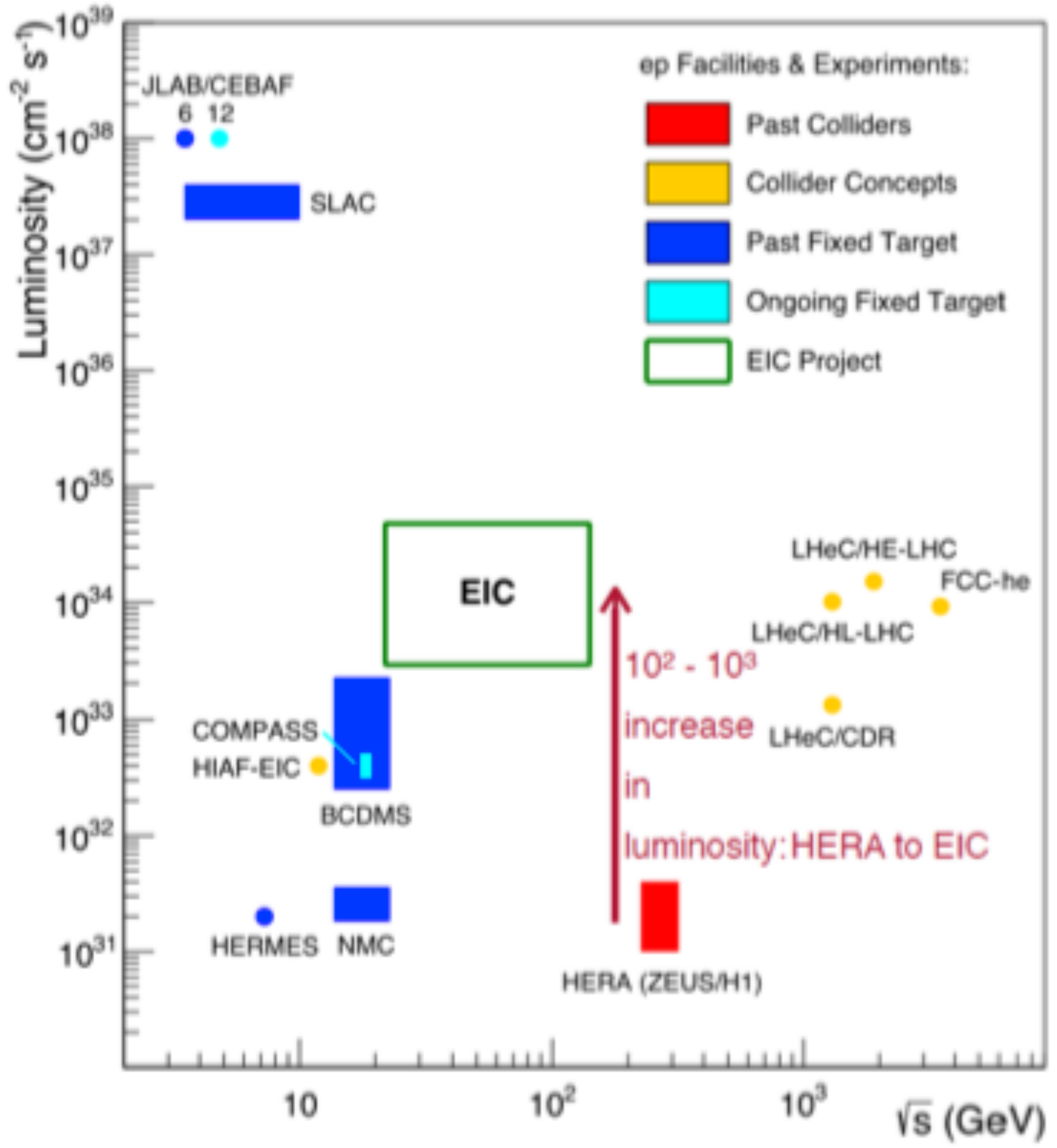


A new collider based on existing proton (500 GeV) and ion (e.g., Au @ 200 GeV) rings at BNL

➡Features polarized (>70%) DIS with e-p

➡Large variety of colliding nuclei up to uranium

- $\sqrt{s_{\mathrm{NN}}}$ = 29 — 140 GeV
- Luminosity = $10^{33\text{-}34}$ /cm^2/s, 10-100 /fb/year
- 10 ns bunch spacing w/ 500 kHz integration rate (1 collision per 200 BX)
- Energy recovery linac w/ hadron beam cooling
- 2 interaction points with detector caverns



Why does the world need an EIC?

EIC YELLOW REPORT
Volume I: Executive Summary

EIC YELLOW REPORT
Volume II: Physics

EIC YELLOW REPORT
Volume III: Detector

~900 pages, ~400 authors including CEA, IJCLab, CPHT

The EIC as a (polarized) electron-proton collider

Origin of nucleon spin

Proton spin has 3 possible components

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_{Q+G}(\mu)$$

quarks gluons OAM

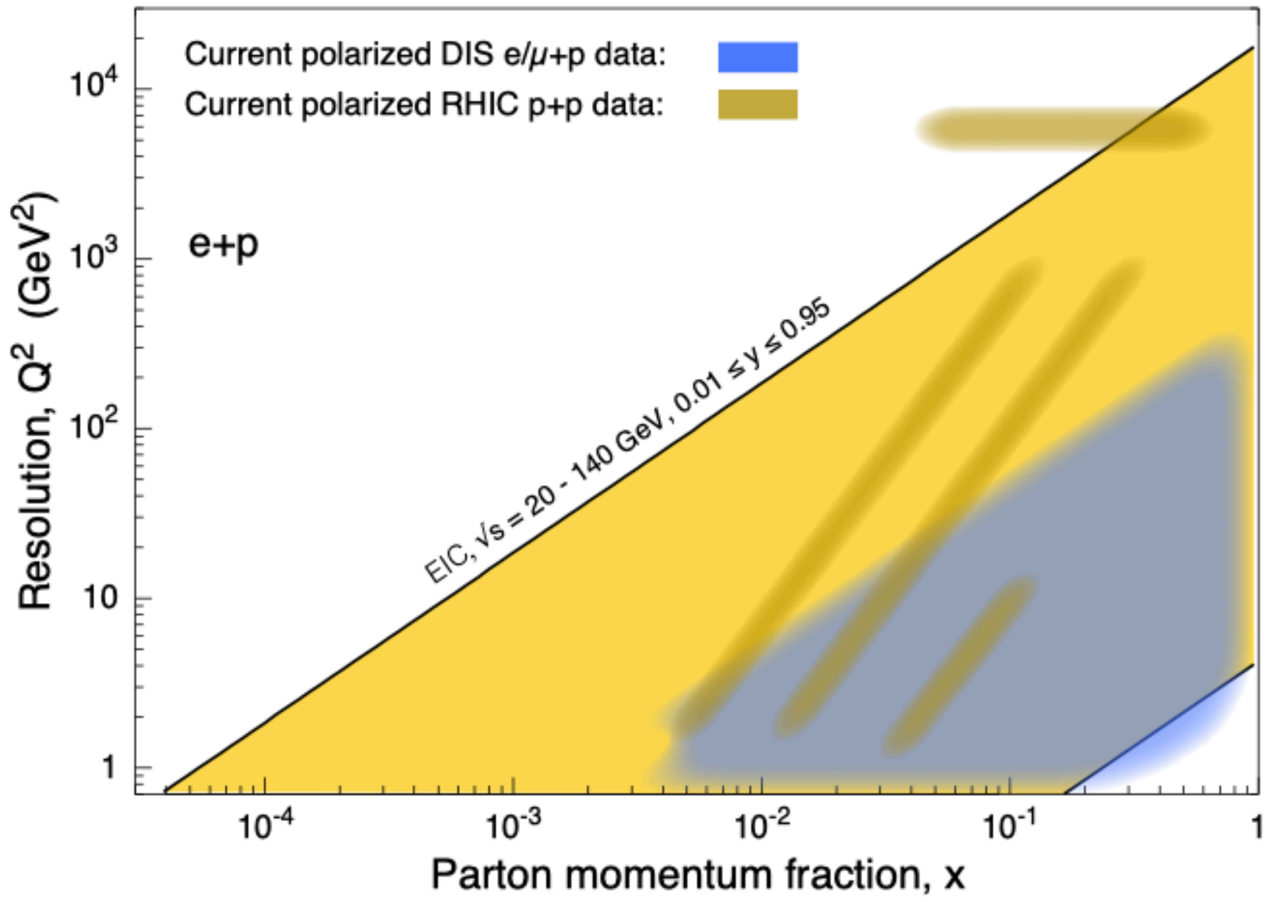
Current constraints:

- EMC polarized DIS data —> quarks are not enough
- RHIC polarized p-p data —> gluons may not be either

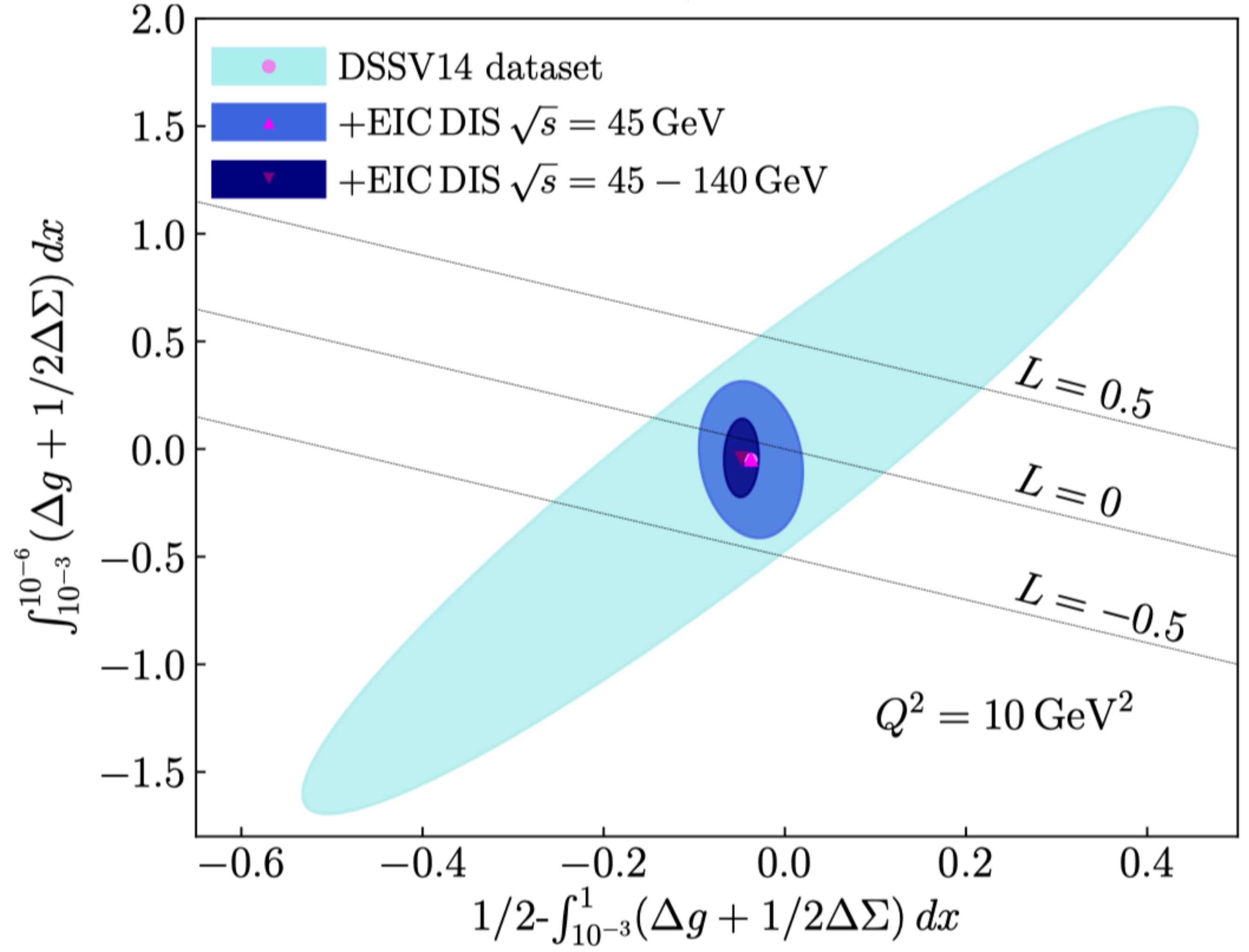
➡The origin of the nucleon spin poorly known!

- Crux of the problem: No helicity constraints below x < 0.005
- Excellent EIC potential thanks to large longitudinal polarization of e and p
- Constraints from EIC on ΔG will indirectly constrain orbital ang. mom. (L)
- Requires excellent energy resolution in ECALs, particularly in backward (i.e., electron-going) direction

Kinematic reach of EIC vs previous polarized collisions



Projected constraints on nucleon spin



Origin of nucleon mass

- 99% of the visible mass of the universe from nuclei
- Higgs mechanism accounts for 1% of it, the rest is dynamically generated by QCD
- What can the EIC tell us about the origin of mass?

1) Measure q and g contributions to energy-momentum tensor

Unknown term is the gluon contribution to the trace anomaly, the “gluon condensate”

➡Probed by exclusive threshold quarkonium production

2)Measurements sensitive to Dynamical Chiral Symmetry Breaking

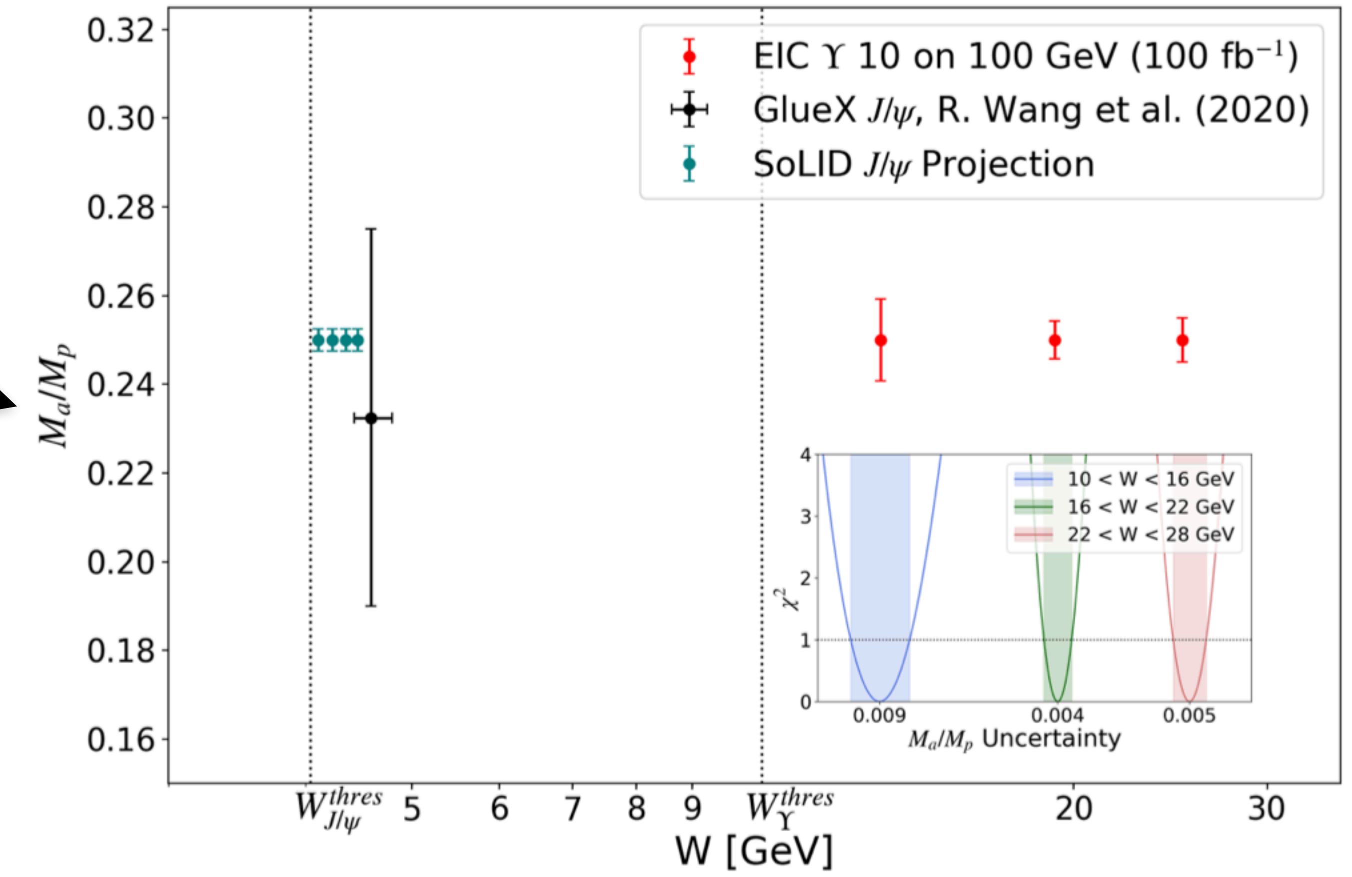
Pion mass from QCD, while kaons have a Higgs contribution

➡Probed by comparing the pion and kaon form factors

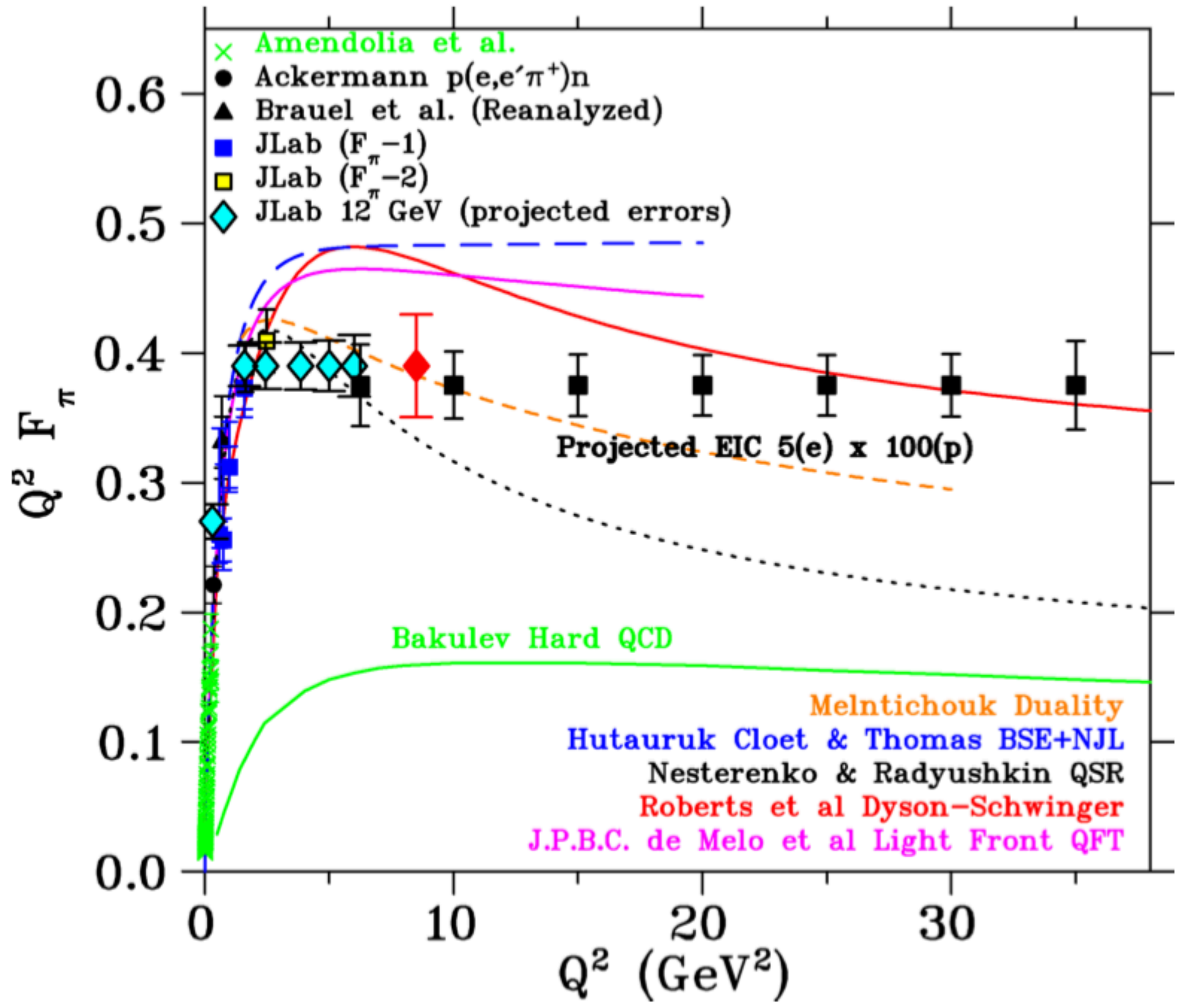
Requires measurement of recoil protons at very forward rapidity

Projections for Υ photoproduction

trace anomaly contribution to the proton mass



Projection for the pion form factor



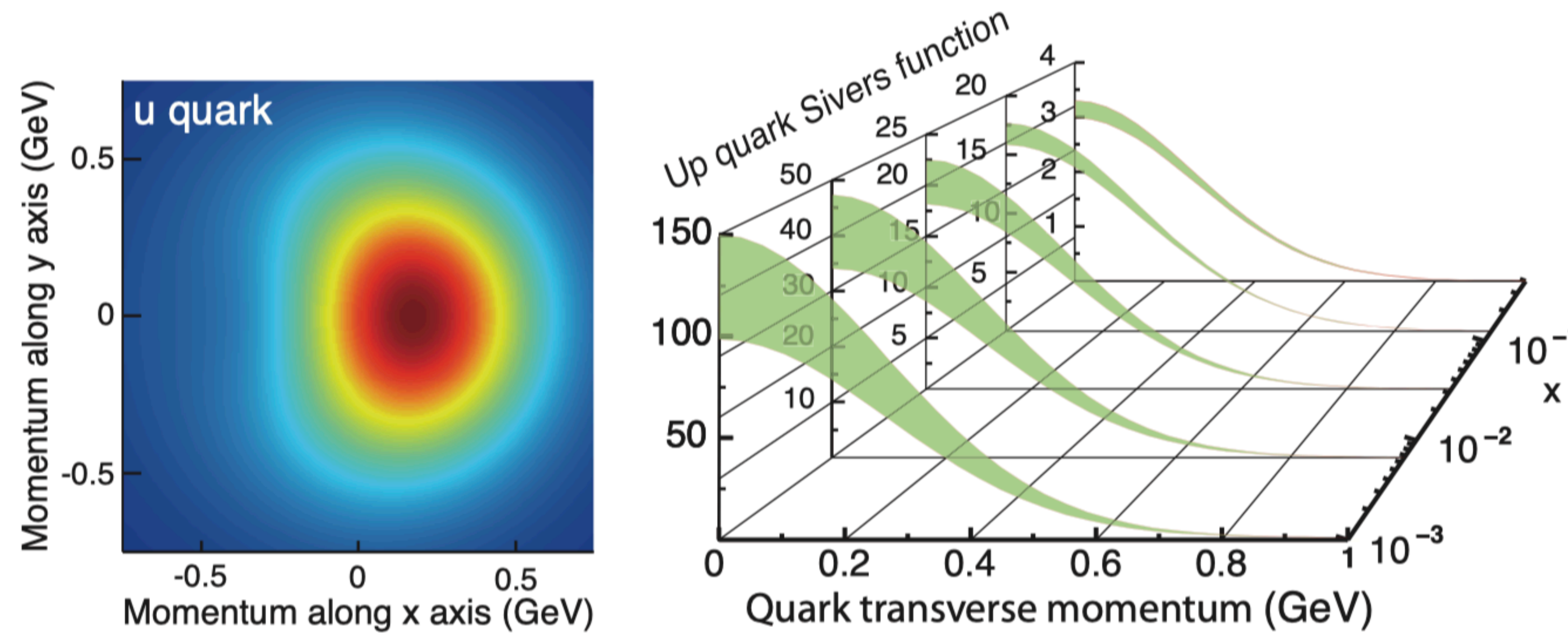
Multi-dimensional imaging of the nucleon

- Standard DIS give you 1D (longitudinal) parton momentum
- Due to confinement partons also have transverse momentum
- EIC can measure the poorly known 3D structure of the nucleon

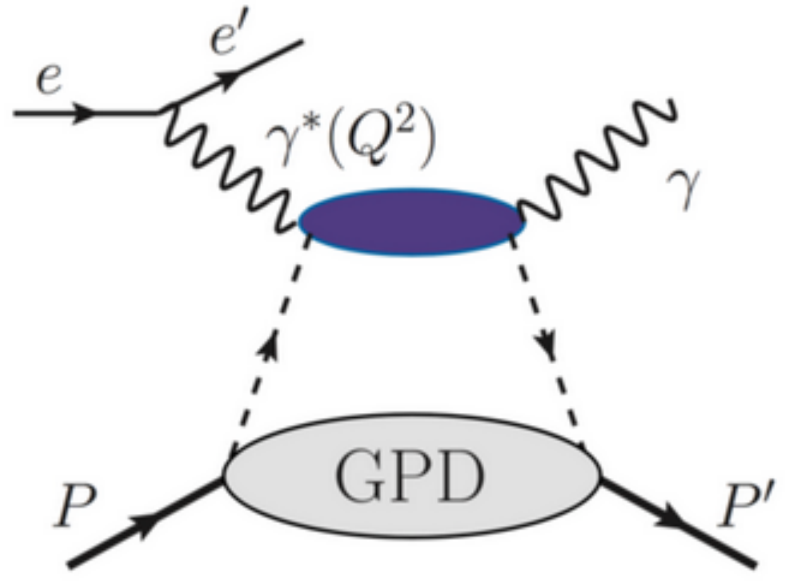
- TMDs sensitive to 3D structure of nucleon via spin-orbit coupling
- TMDs can be measured in semi-inclusive DIS, w/ transversely polarized proton
  - Large Q^2 range of EIC probes evolution of TMDs, more complex than PDFs
  - Gluon TMDs sensitive to long distance structure of QCD, completely unknown
  - ➡ can be measured with dijets and/or heavy flavor
- Requires good PID (π/K/p) & d or ^{3}He polarized beams for flavor dependence

- Transverse spatial distribution also accessible (Generalized Parton Distribution)
- Measured via exclusive reactions, i.e., DVCS & deeply virtual meson production
- Requires forward proton detection & careful choice of accelerator configuration

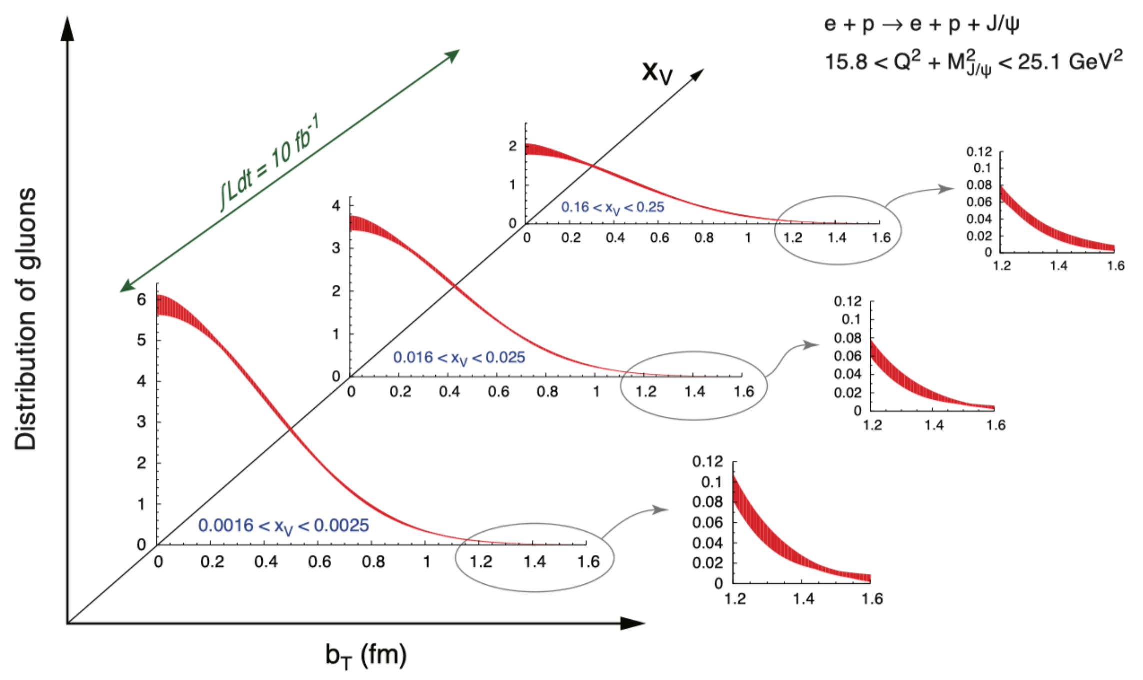
Transverse momentum distribution of up quark w/ x = 0.1in y-polarized p



Deeply Virtual Compton Scattering



Projection of gluon transverse spatial distribution from exclusive J/ψ

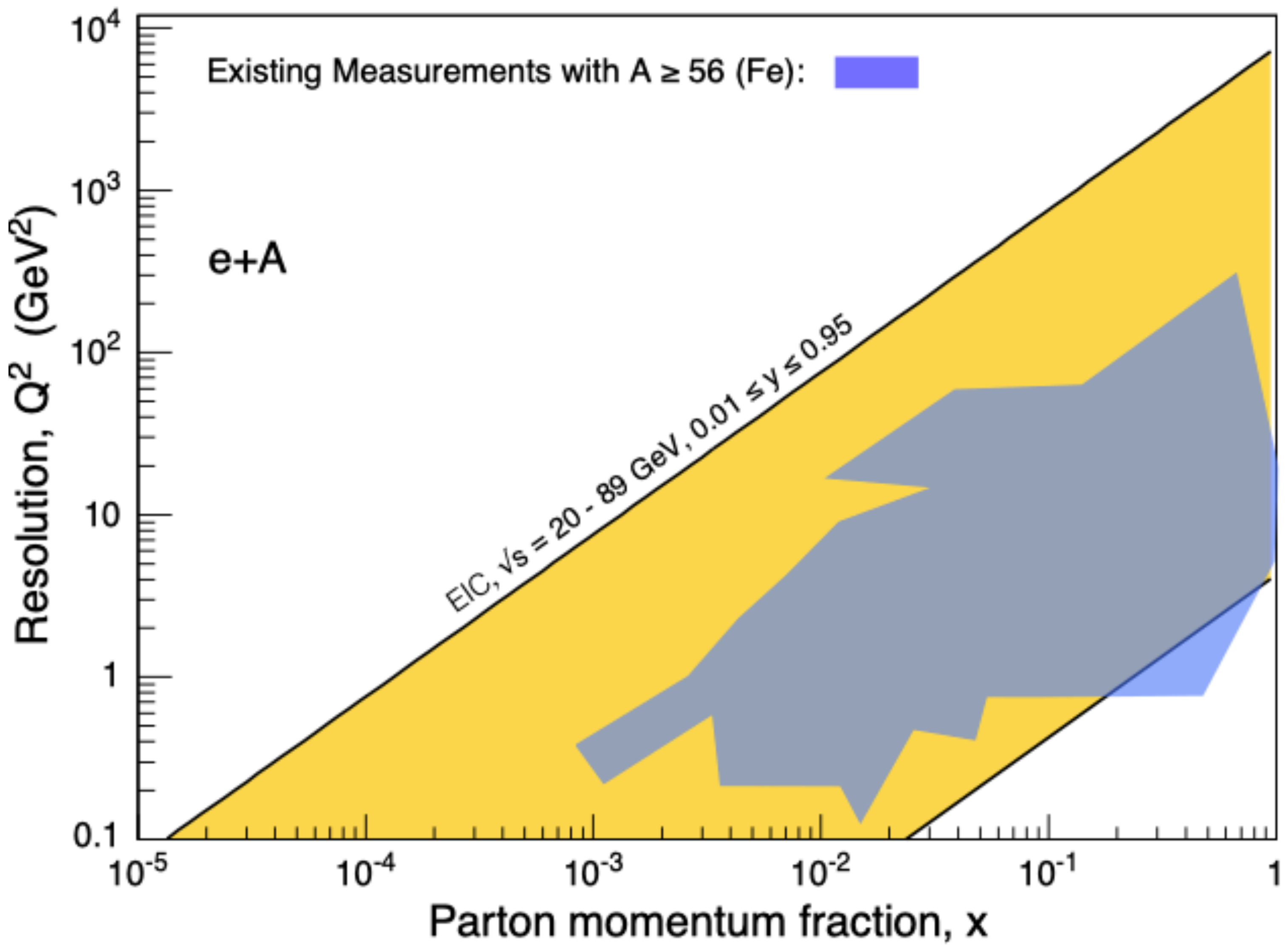


Using heavy ion beams @ the EIC

Nuclear modification to the PDFs

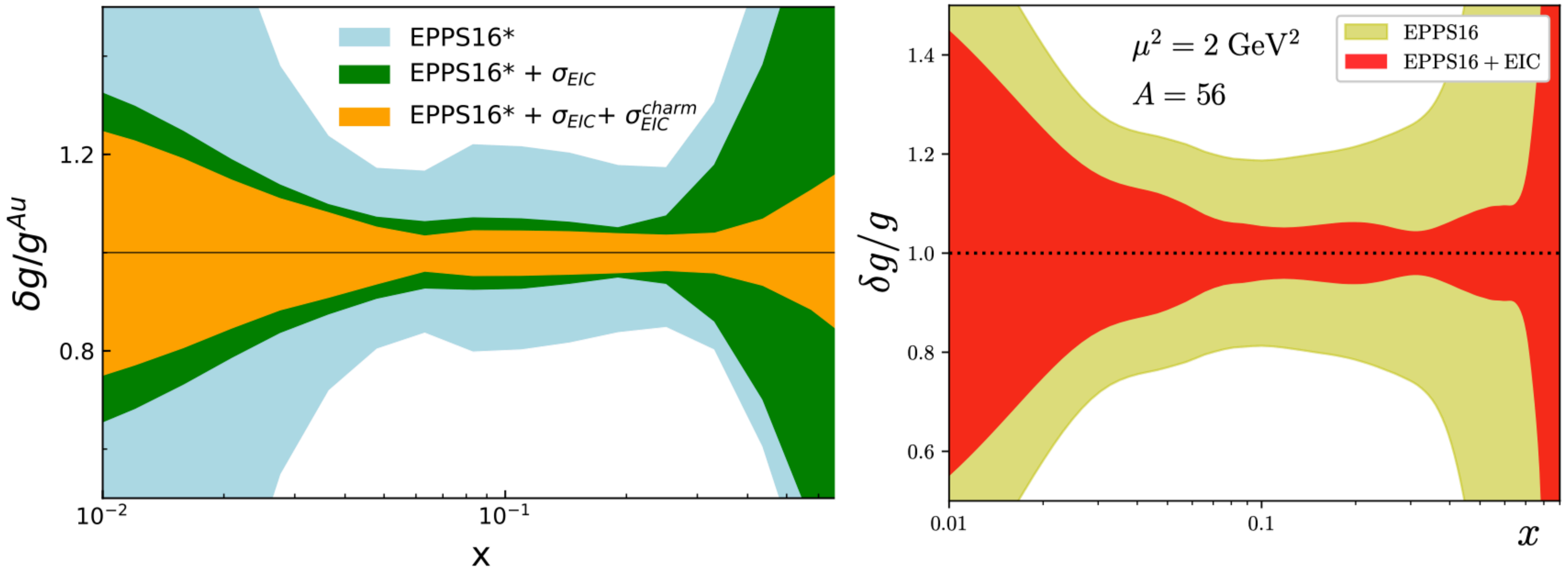
- Parton distributions are modified inside nuclei
- Precision nPDFs essential for interpretation of heavy ion data
- Cleaner than data from hadron colliders
- Large kinematic range compared to previous DIS
- Incorporate A dependence in a single global fit

Kinematic reach of inclusive DIS in e-A



- Strong constraint on high-x gluons from $c\bar{c}$, produced mainly by photon-gluon fusion
- Requires excellent impact parameter resolution

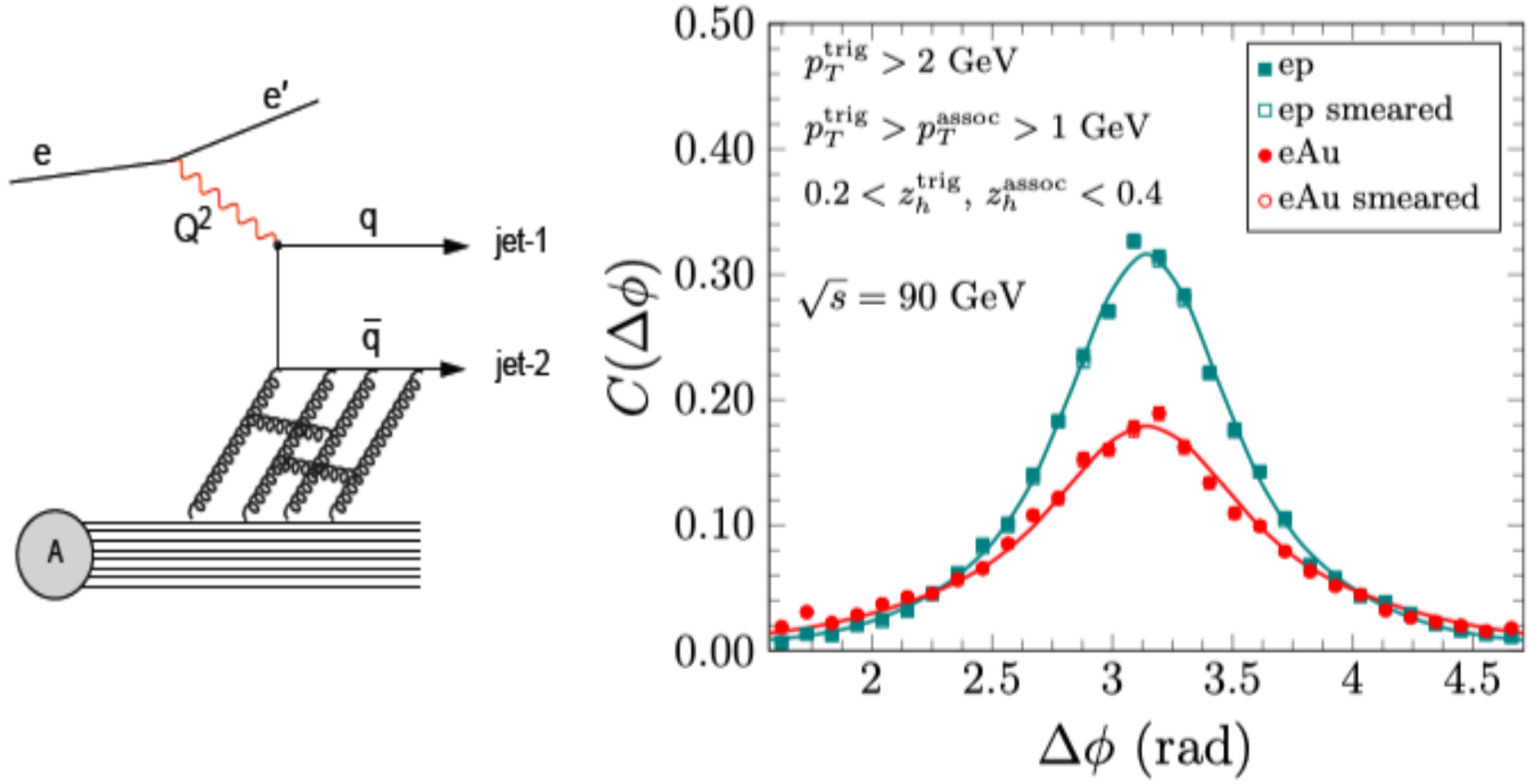
Impact of inclusive DIS and charm



Gluon saturation

- Saturation of gluon distribution is inevitable, but difficult to measure unambiguously
- When saturation scale $Q_s > \Lambda_{QCD}$, gluon dynamics calculable in effective field theory
- $Q_s \sim A^{1/3}$ —> e-A collisions are the idea probe of saturation
- Crucial to understand dependence on nuclear target thickness

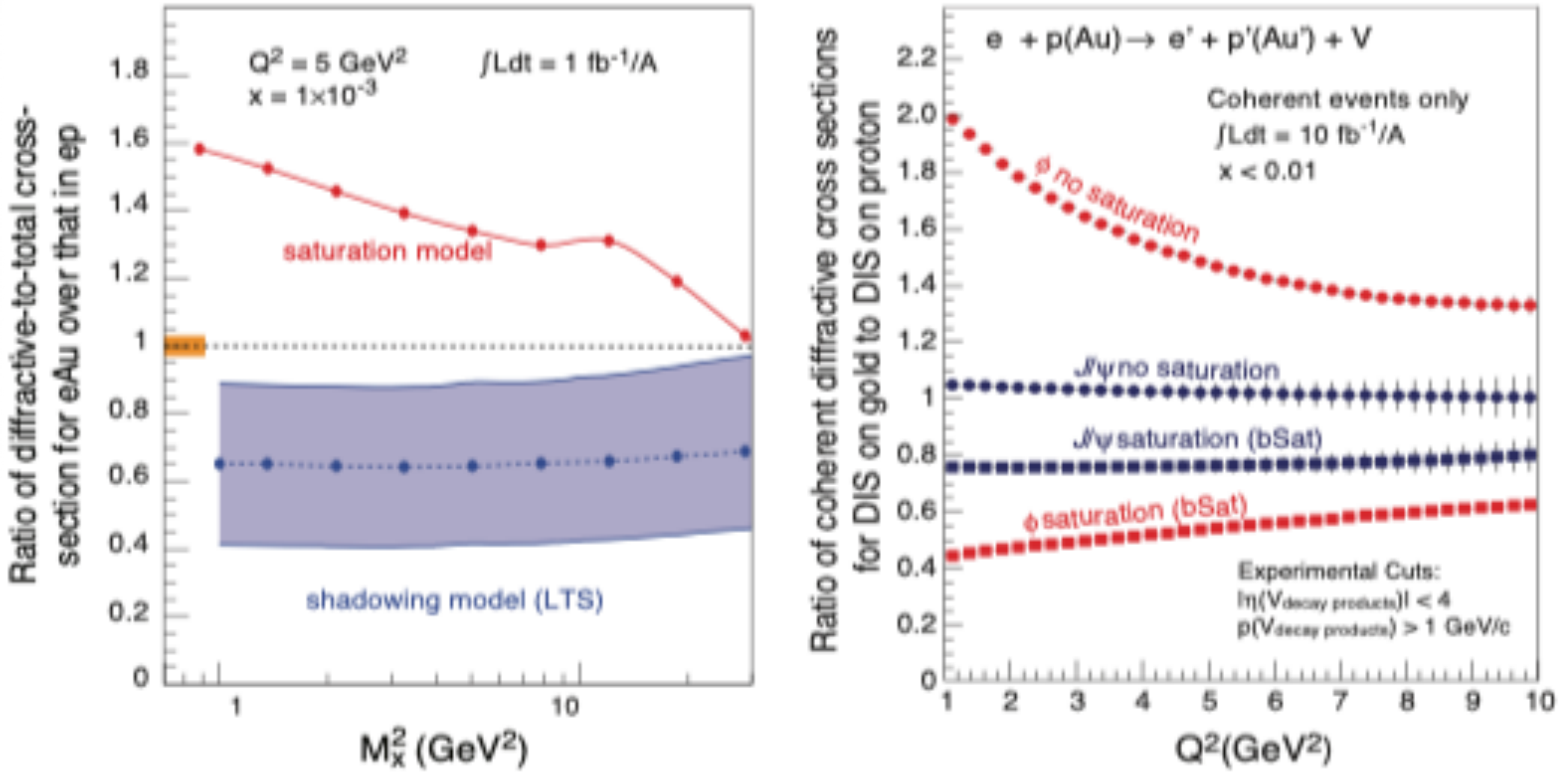
Suppression of back-to-back correlations in e-A



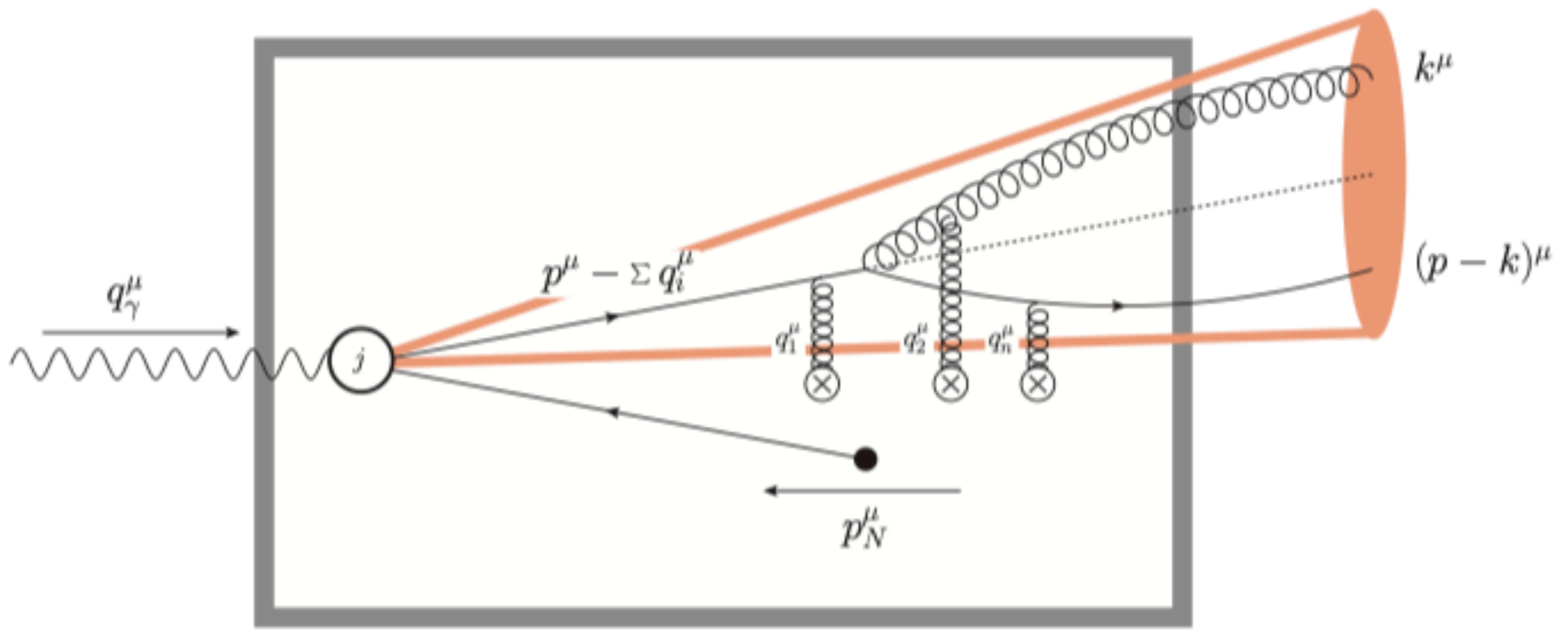
Key signatures

- Suppression of back-to-back correlations
- Large diffractive cross-section at EIC, characterized by events w/ rapidity gap
  - Since x-section ~ (gluon PDF)^2 sensitive to onset of saturation
  - Color-dipole-moment-dependent suppression of vector mesons

Sensitivity of diffraction in e-A to saturation

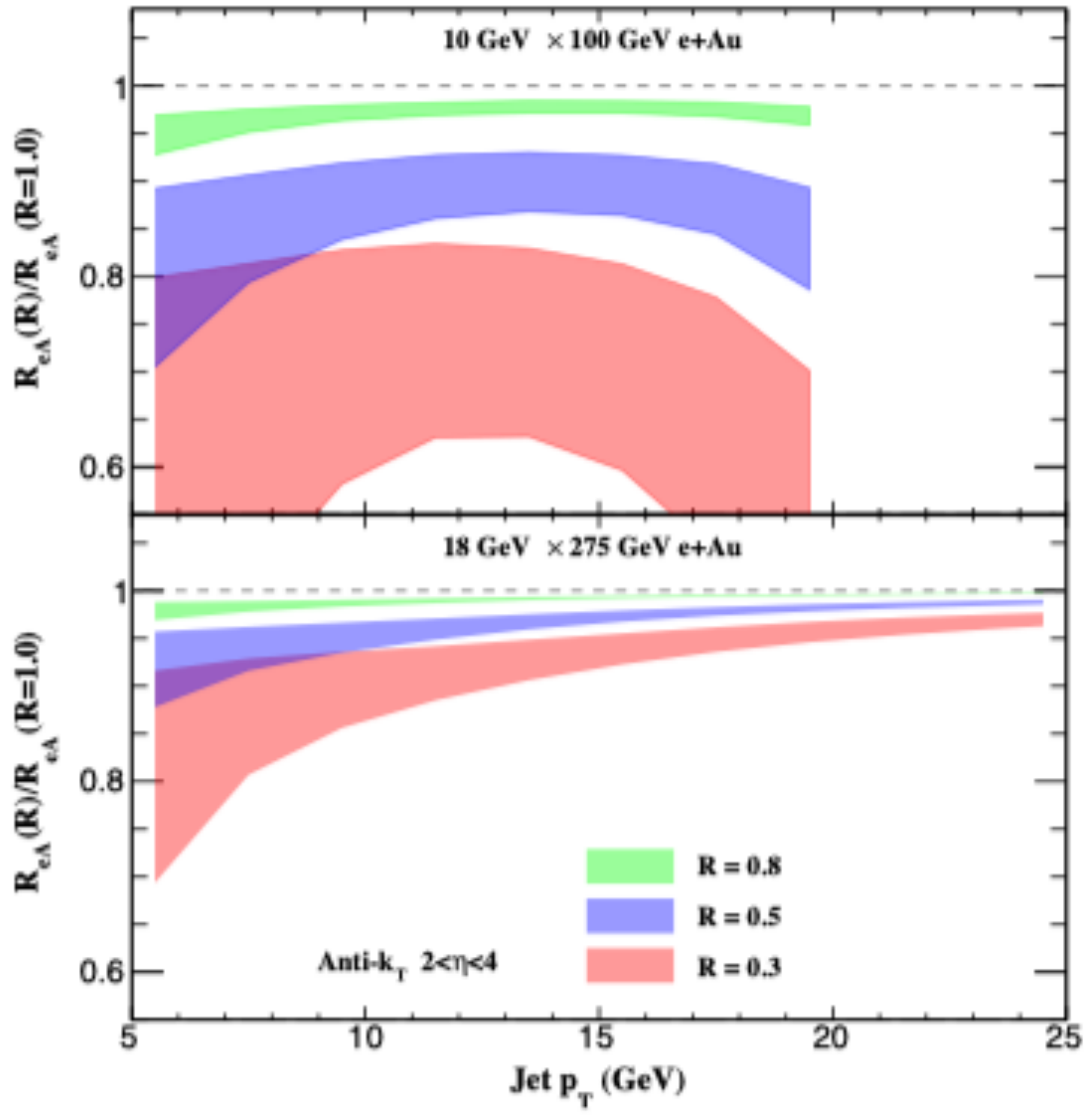


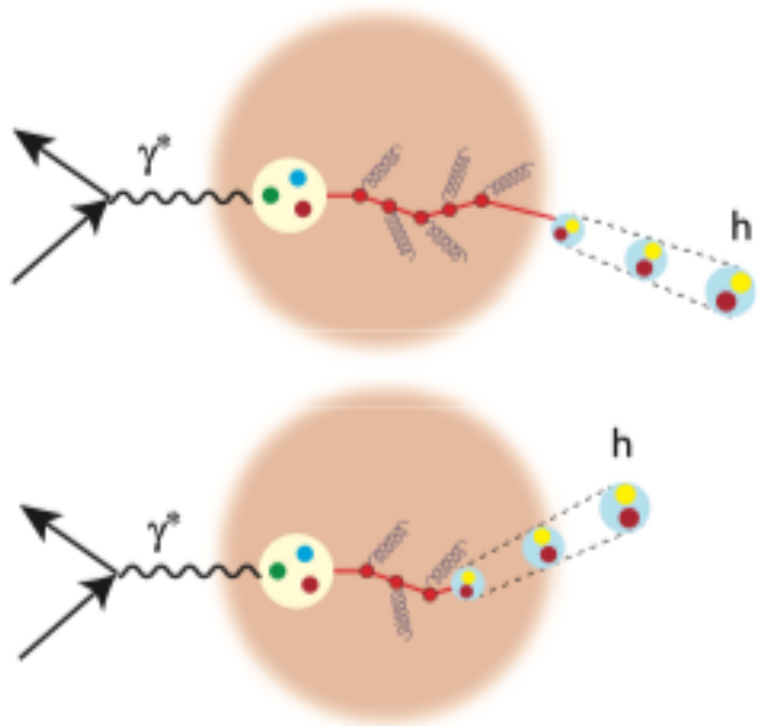
QCD in cold nuclear matter



- Parton energy loss in cold nuclear matter is poorly constrained (0.02 < $\hat{q}$ < 0.014 GeV^2/fm)
  - Should exhibit strong energy dependence
  - Separate from final state effects by looking at jet radius dependence

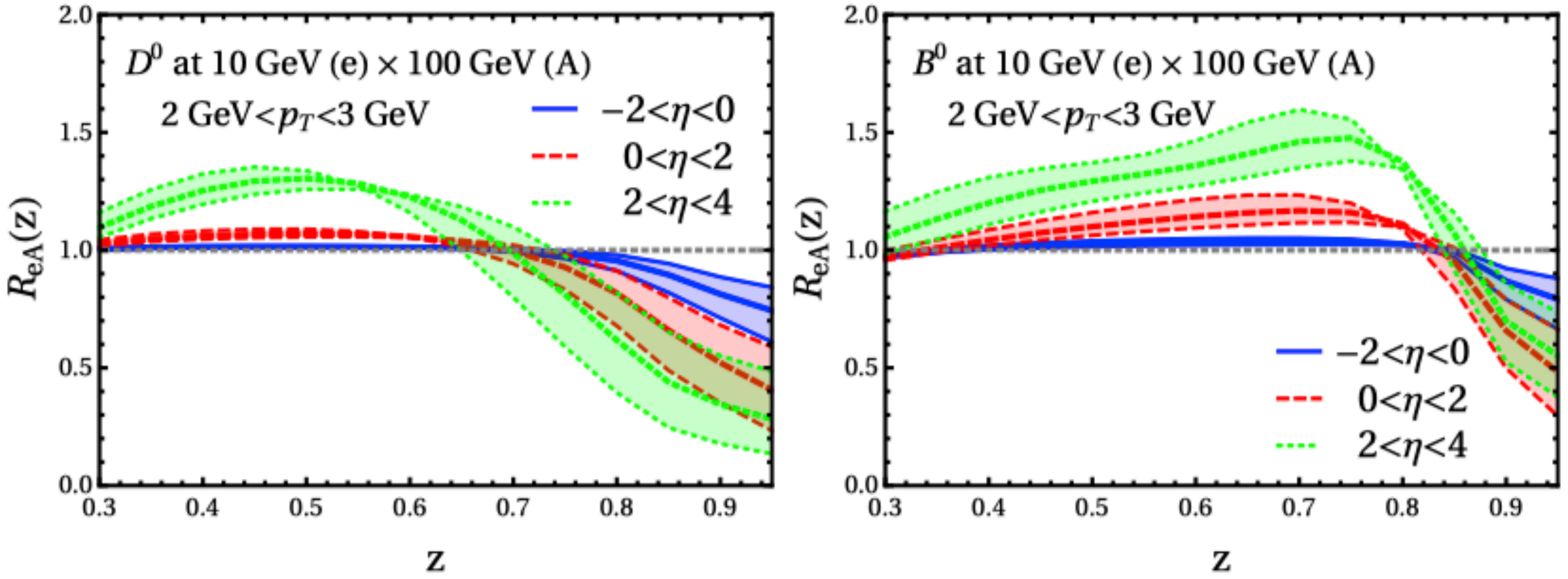
Jet suppression in e-A



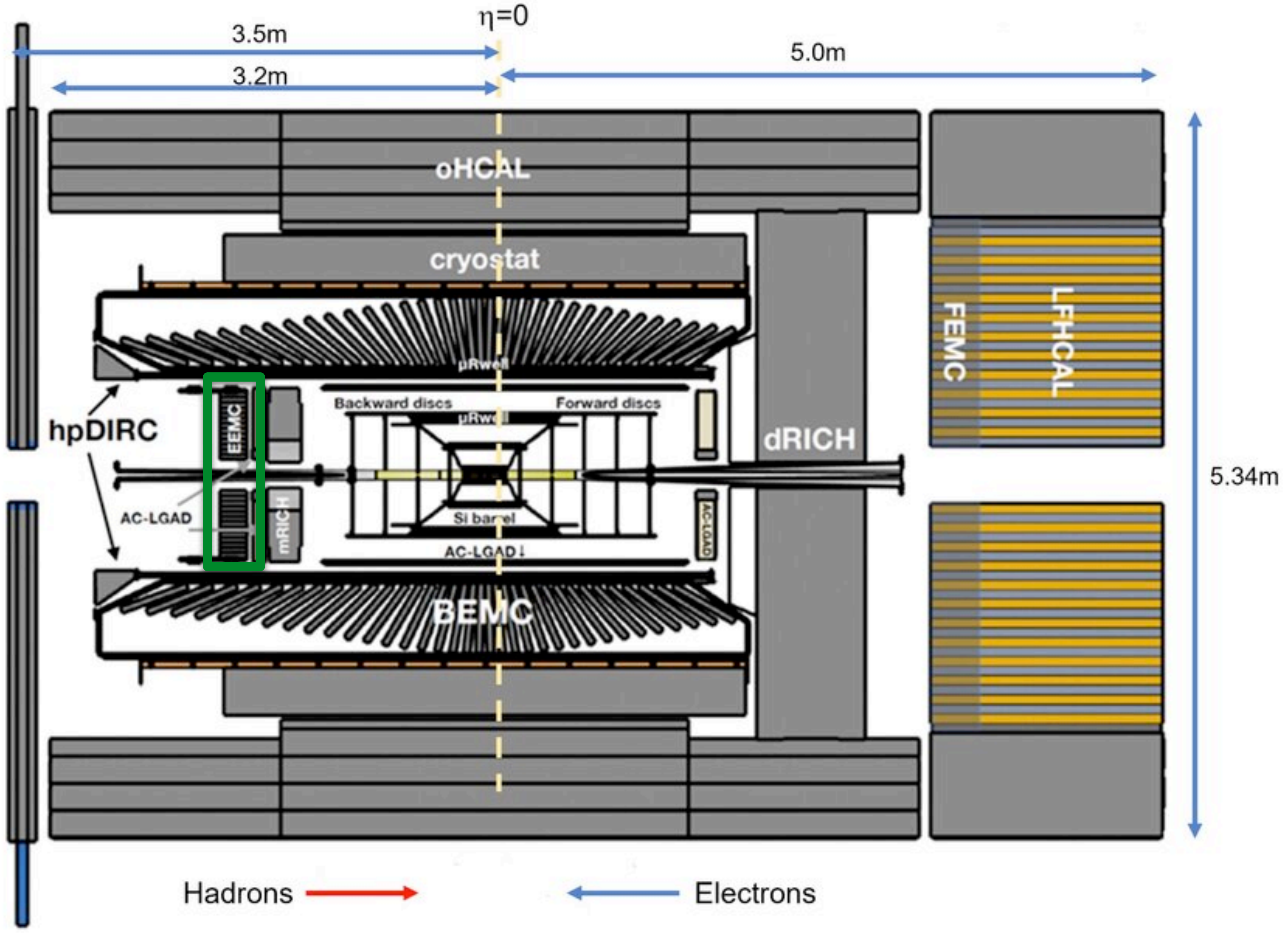


- Understanding hadronization
  - Pre-bound state of heavy flavor hadrons expected to form in-medium
  - Expect large rapidity dependence of nuclear modification factor

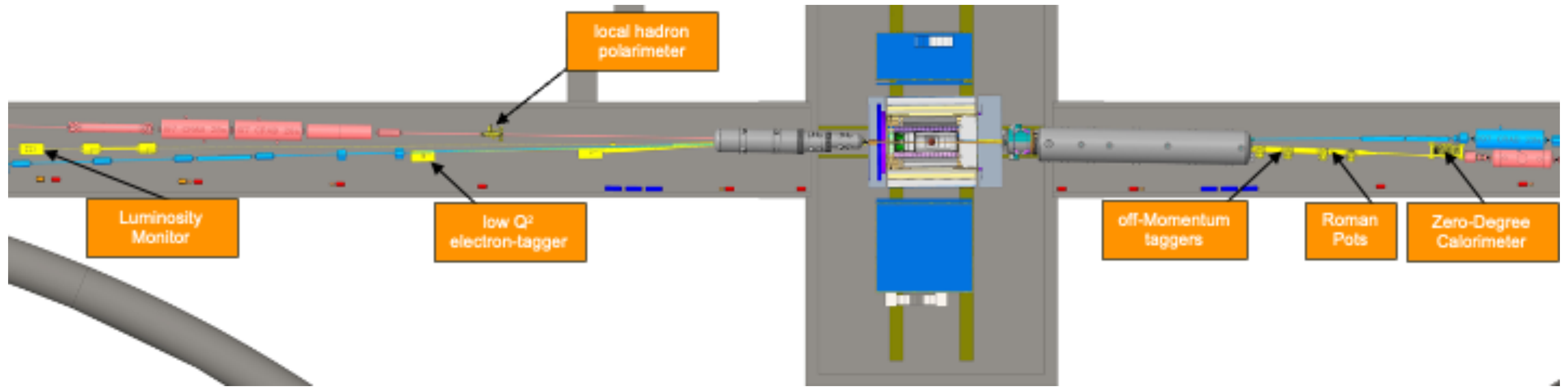
Nuclear modification to heavy quark hadrons in e-A



ePIC detector



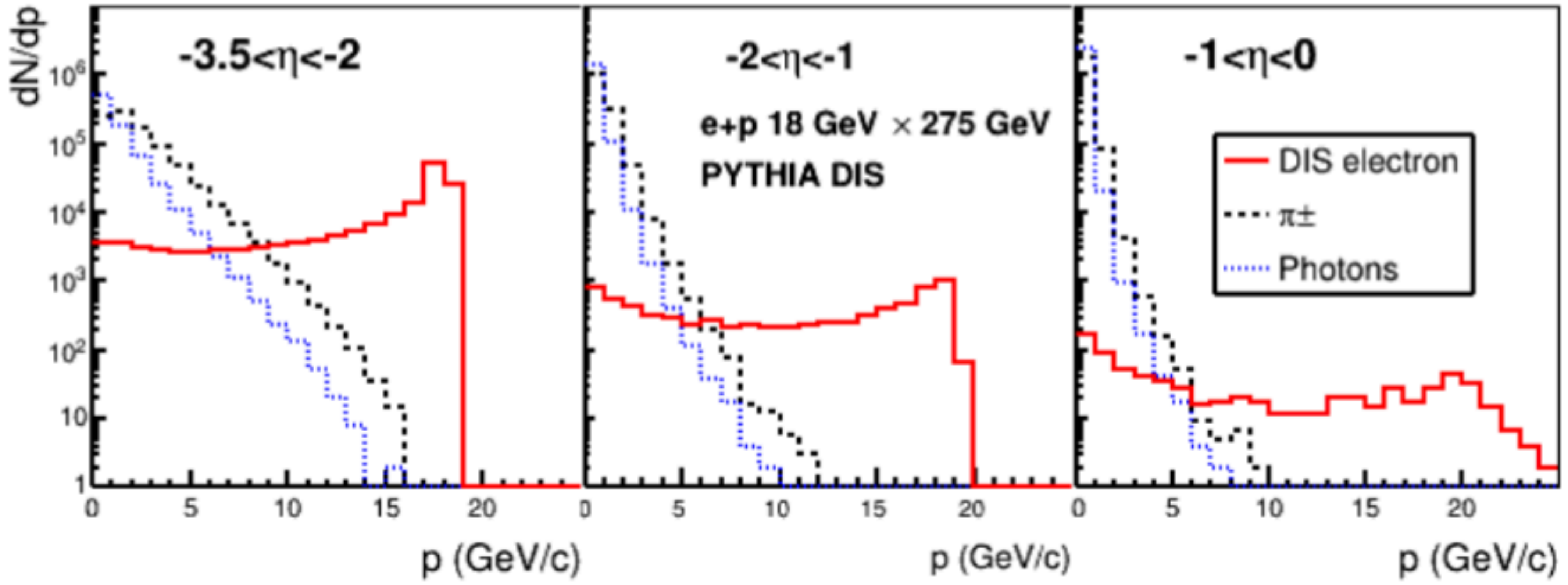
- Tracking
  - 1.7 T solenoid
  - MAPS tracker based on ALICE ITS3
  - + MPGD (e.g., micromegas)
- Full coverage PID
  - TOF at low p (AC-LGAD, 30 ps)
  - Various Cherenkov solutions at high p
- Calorimeters
  - SciGlass or imaging barrel ECAL
  - sPHENIX barrel HCAL
  - High segmentation ECAL + HCAL in forward direction
  - High resolution ECAL in backward direction
  - Backward HCAL (tail catcher) ?



+ very forward: ZDC, roman pots, charge particle tracking, etc.
+ very backward: calo for luminosity monitoring & low Q^2 tagging

NB: ePIC is continuous (streaming) readout detector, there is no triggering

The electron-going ECAL (EEEMCal)



Requires excellent energy resolution & low energy threshold for determining event kinematics, particularly for inclusive DIS

$2\% / \sqrt{E} \oplus 1\%$
particle E: ~ 0.05-15 GeV

Low occupancy & radiation compared to a hadron collider

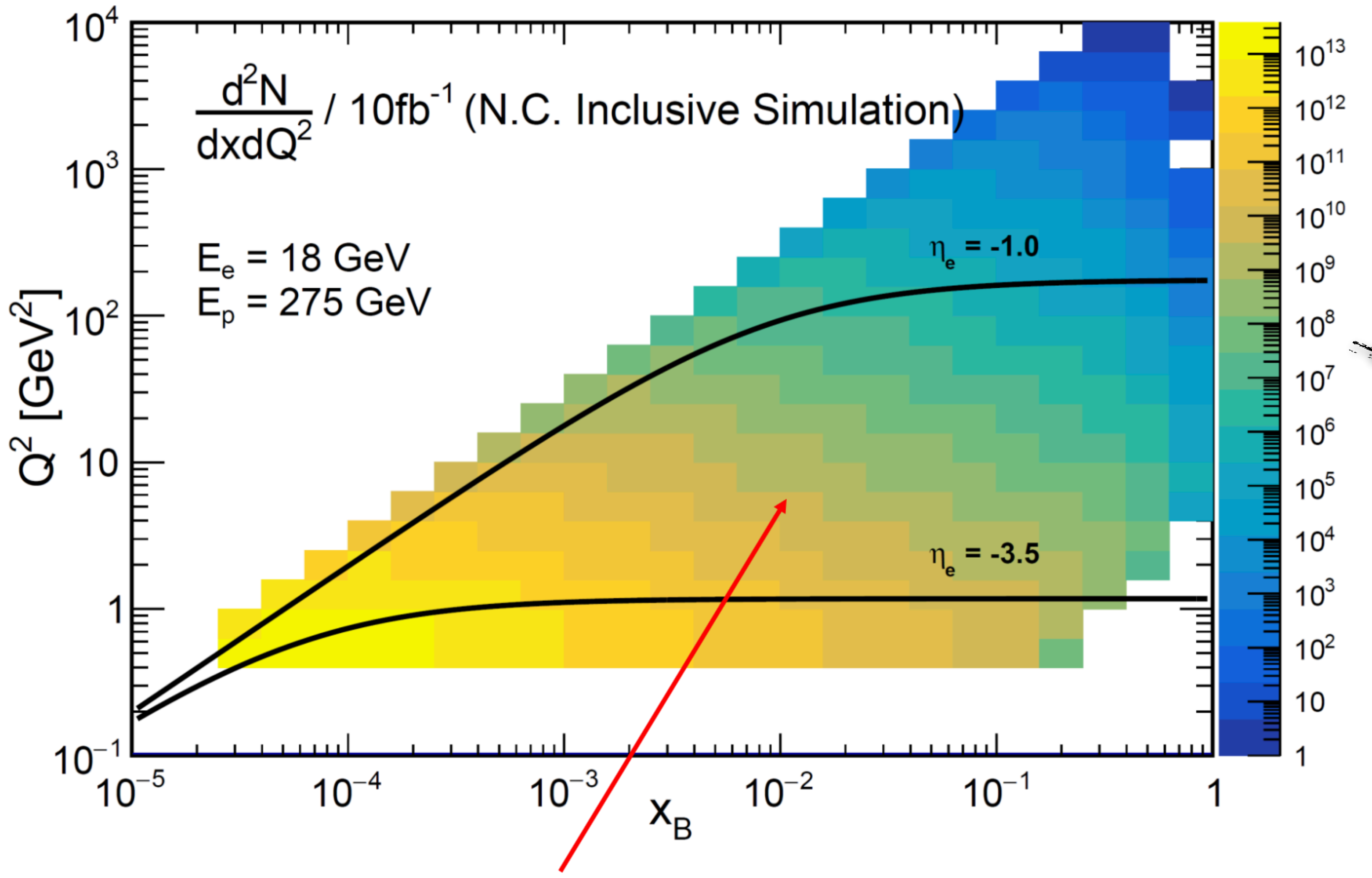
Crucial role! Measure:

- Scattered e⁻ from DIS
- Direct γ from DVCS

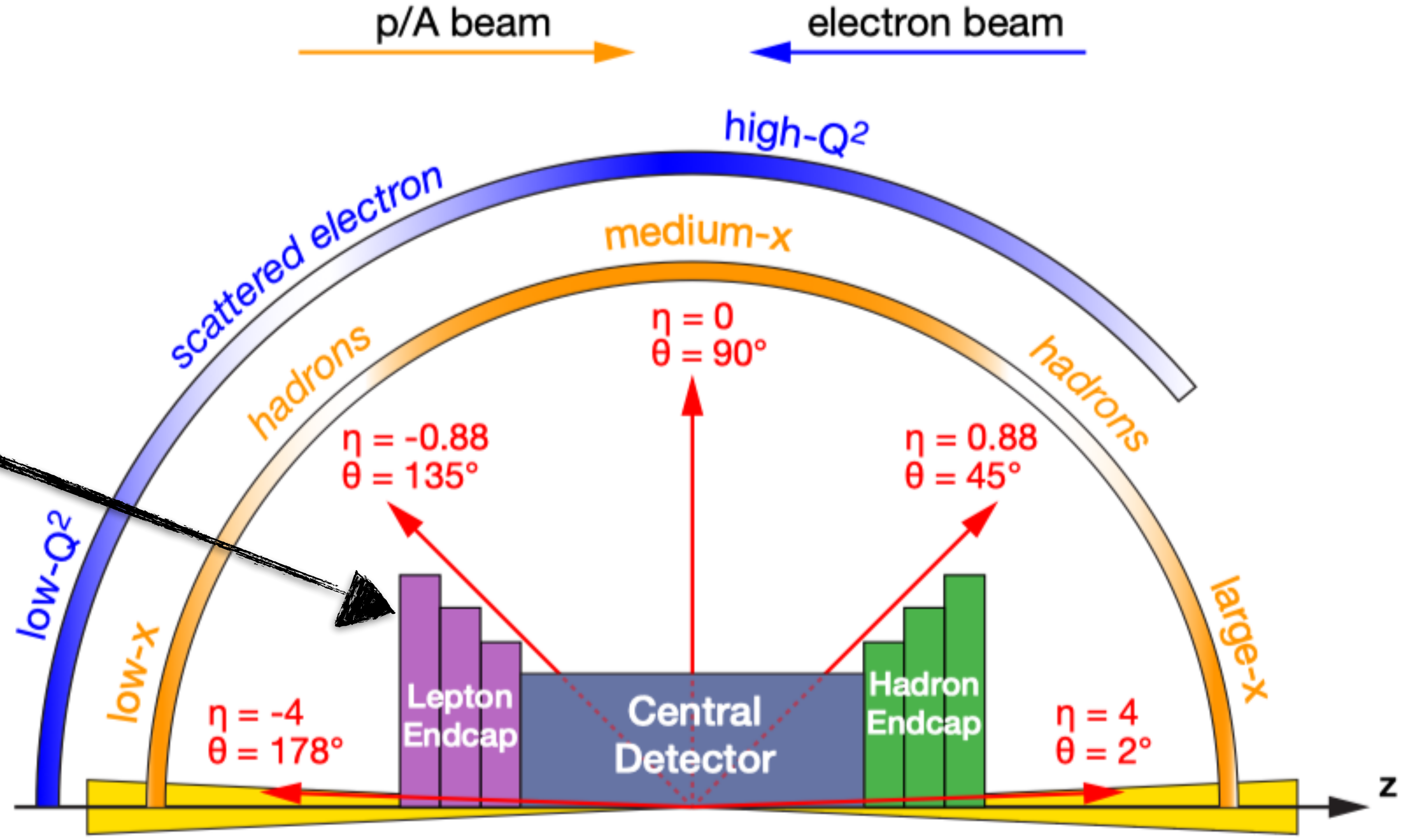
Needs to:

- distinguish e⁻ from $\pi^{+/-}$
- collect bremsstrahlung γ's
- reject photons from π^0

Scattered electrons have to be detected in the Lepton Endcap (-3.5 < η < -1.0)



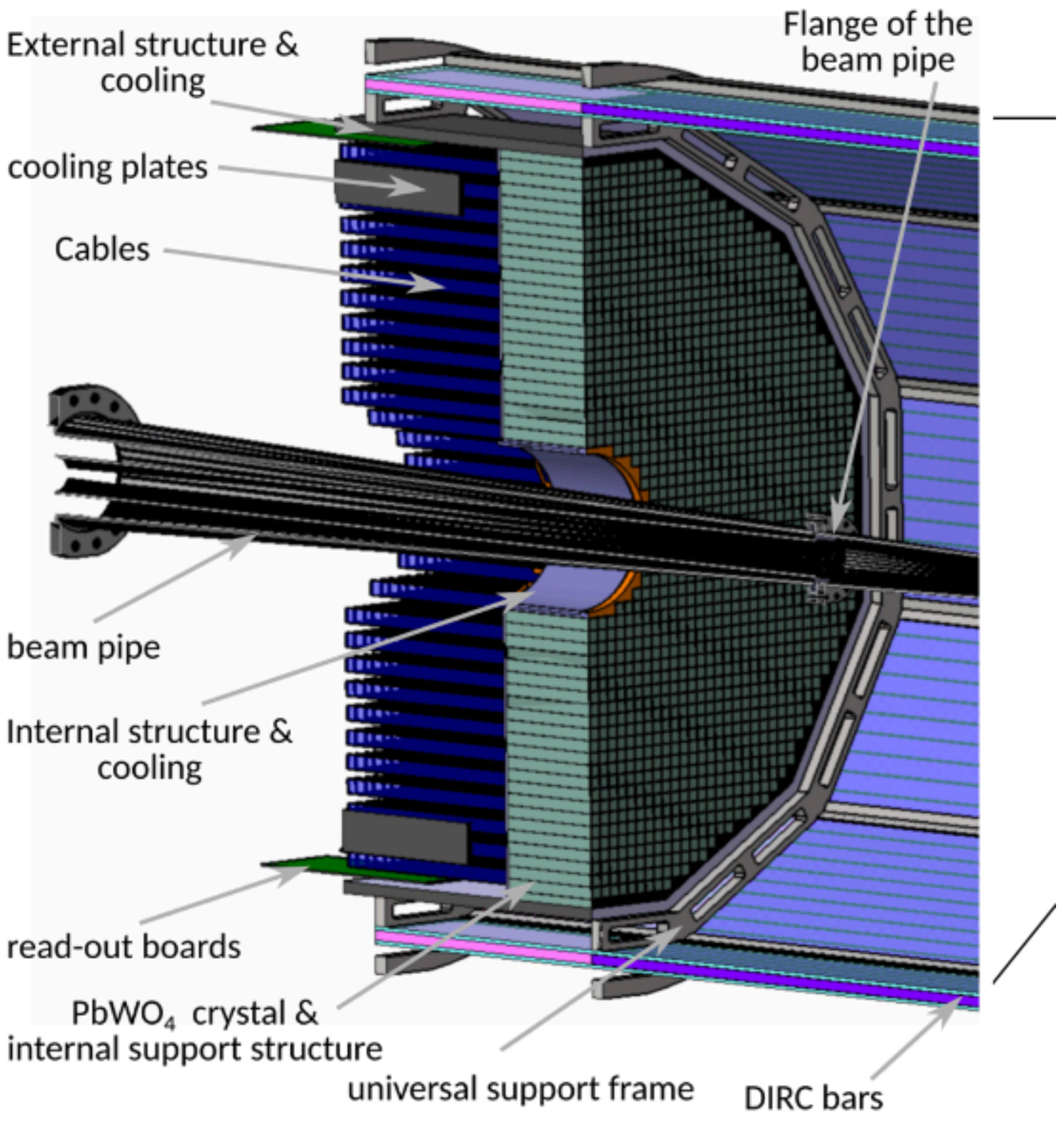
Region of physics enabled by the EEEMCal



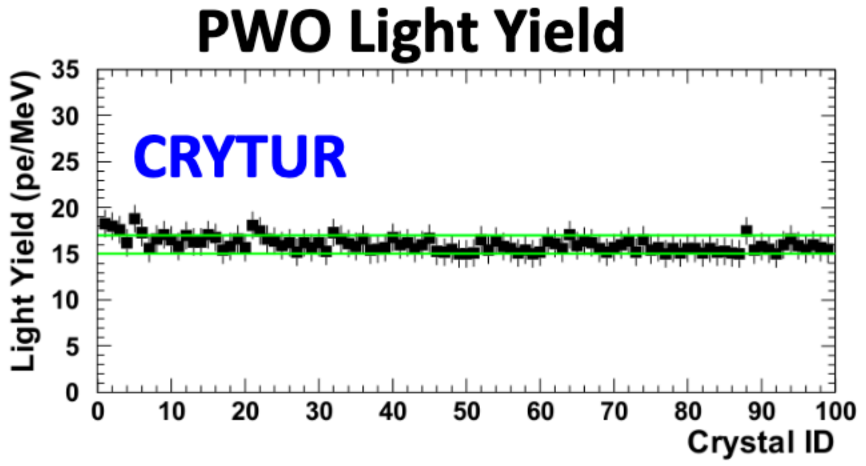
EEEMCal design

Excellent energy resolution requires a homogenous calorimeter

State of the art is PbWO4, e.g., CMS ECAL



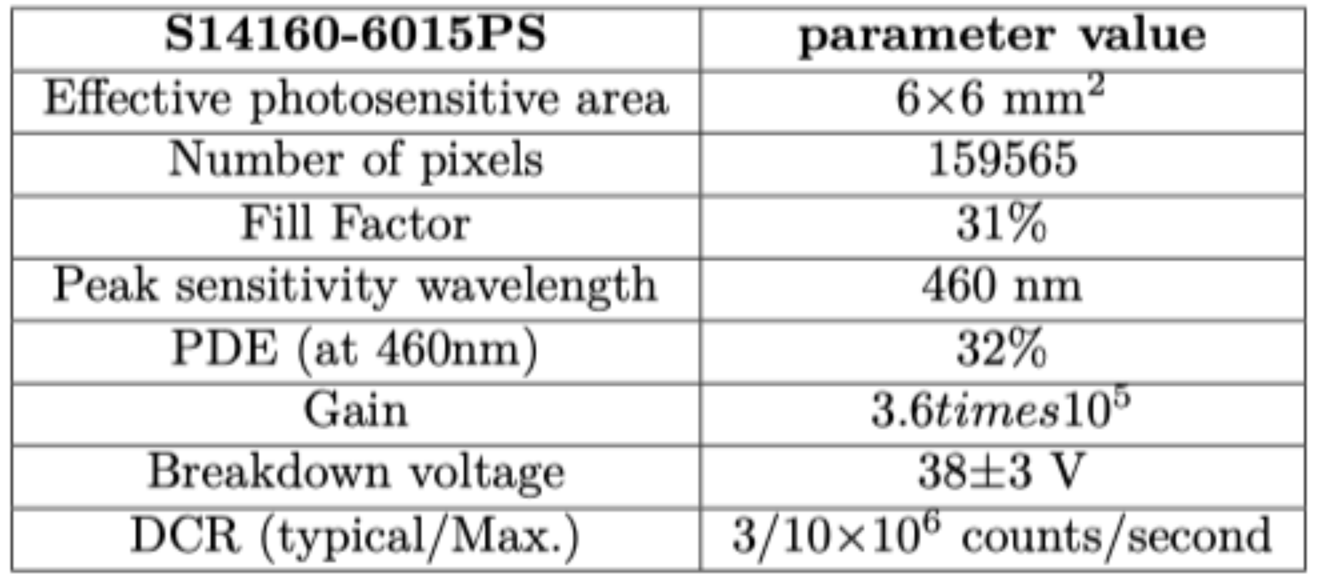
Mechanical design by IJCLab



Active material

- ~ 3000 PWO crystals
- 20 cm long —> 22 X_0
- 2 cm Molière radius (2x2 cm crystals)
- Produced by CRYTUR (Czechia)
- PWO-II —> 50% more p.e. than PWO

current option under consideration



S14160-6015PS	parameter value
Effective photosensitive area	6×6 mm^2
Number of pixels	159565
Fill Factor	31%
Peak sensitivity wavelength	460 nm
PDE (at 460nm)	32%
Gain	$3.6times10^5$
Breakdown voltage	38±3 V
DCR (typical/Max.)	$3/10\times10^6$ counts/second

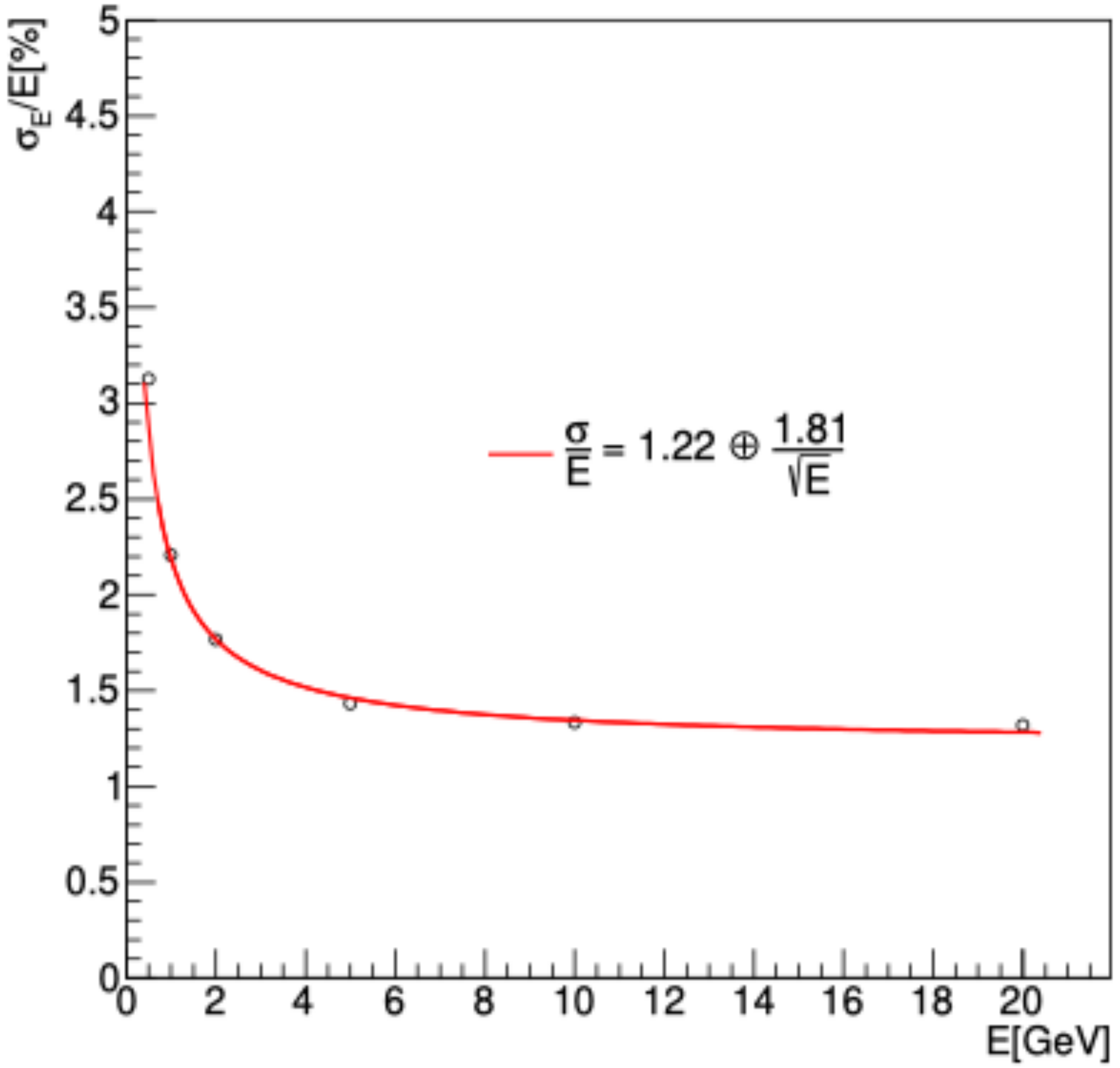
Signal detection

Readout by SiPM

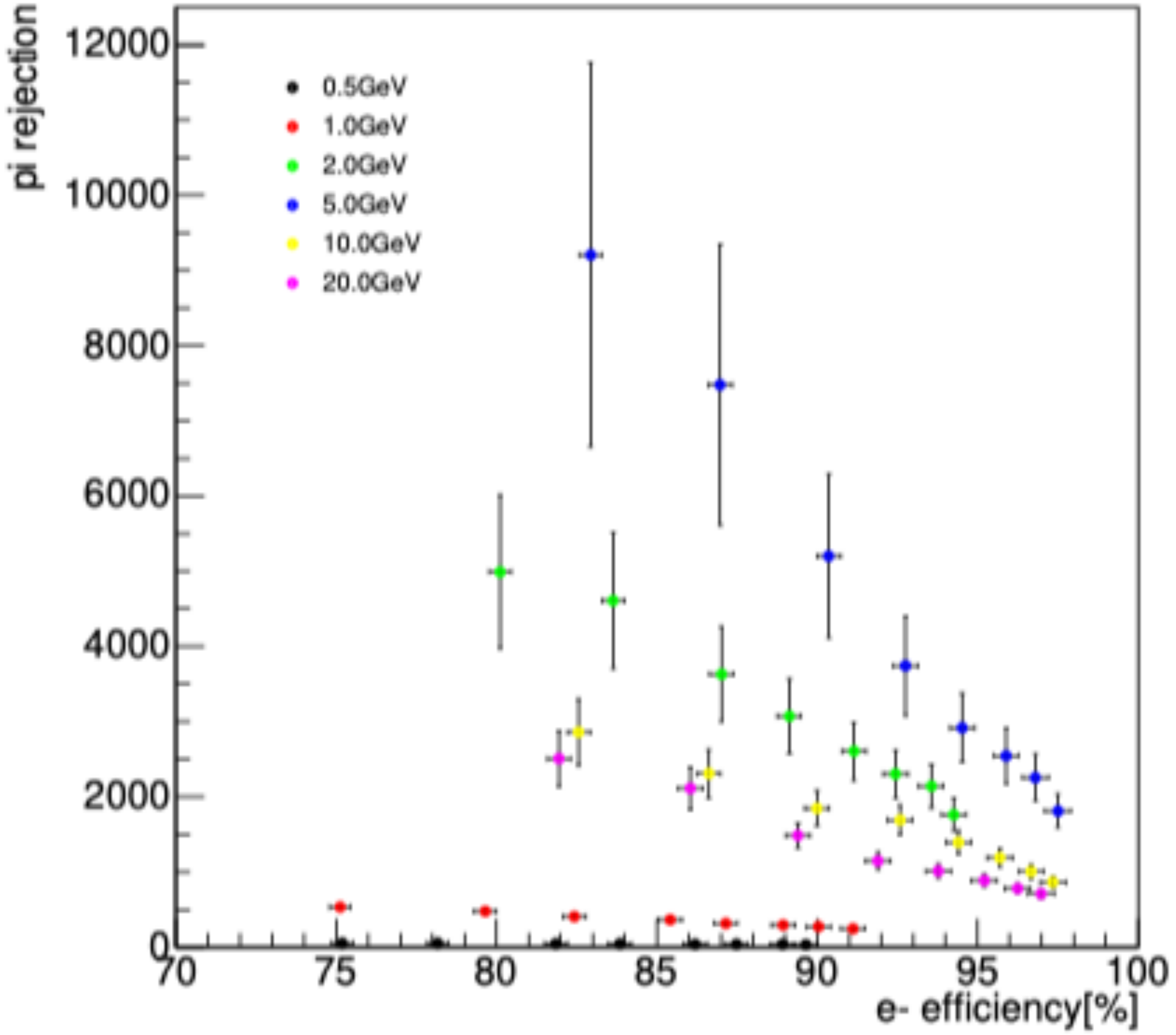
2x2 array per crystal

EEMCal in simulation

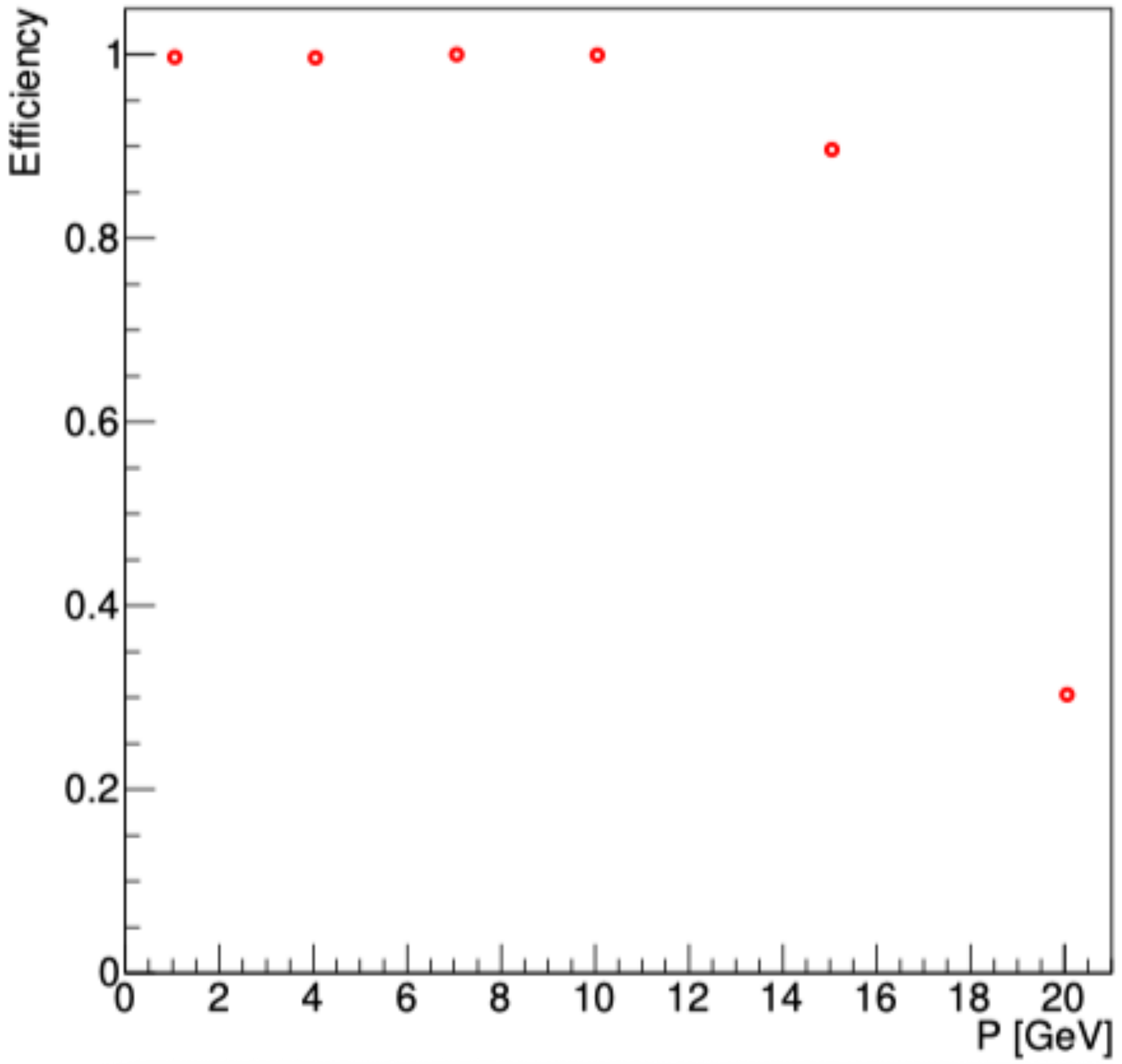
Energy resolution



Charged pion rejection



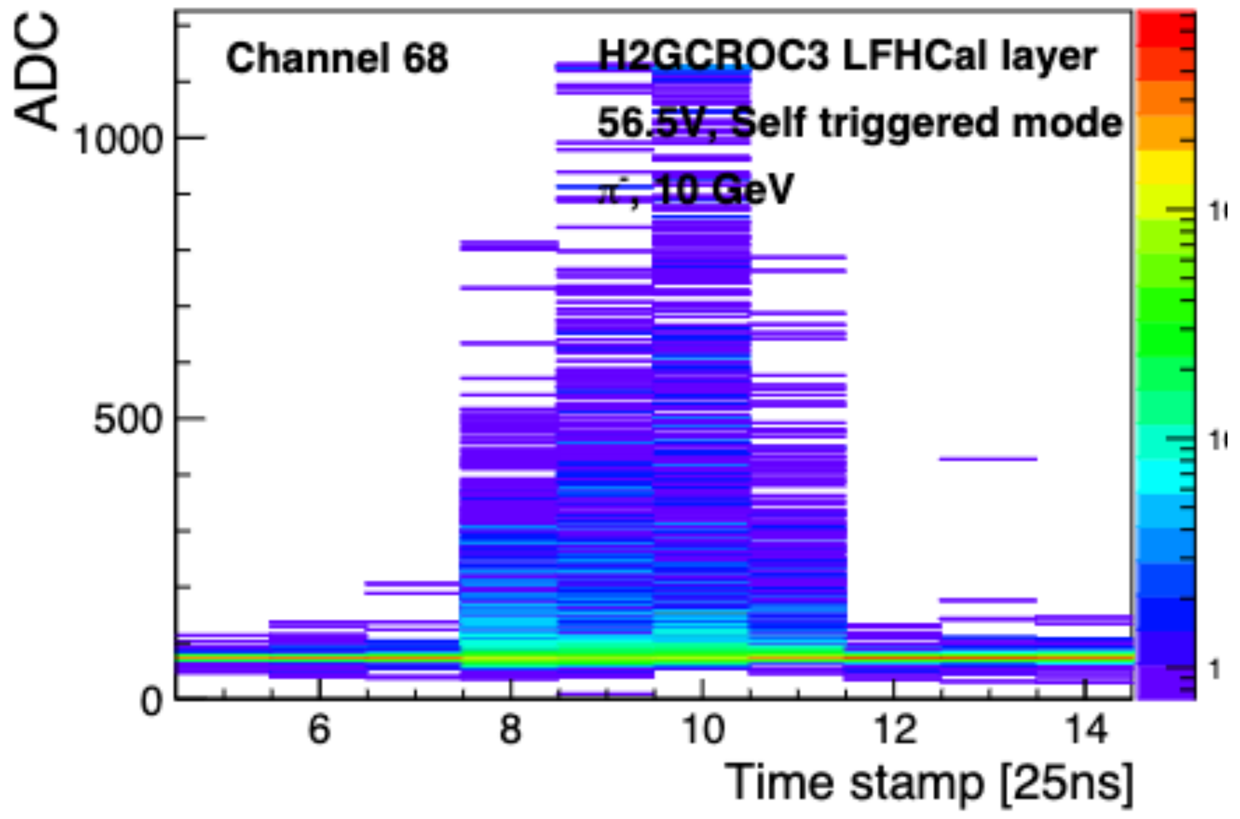
π^0 photon seperation efficiency



Geant4 simulations w/ particle guns
Electronics & SiPM not yet included
PhD thesis of Pu-Kai Wang (IJCLab)

Calorimeter readout at ePIC

HCALs will use a variant of the CMS HGCROC
Already first beam test results for forward HCAL



Material from N. Novitsky (ORNL)

SiPMs of the various ePIC calorimeters

	Insert Calorimeter	Forward HCal	Forward ECal	Barrel HCal	Barrel ECal	Backward ECal	Backward HCal
SiPM Size	1.3x1.3 mm Or 3x3 mm	1.3x1.3 mm And 3x3 mm	6x6 mm2	3x3 mm		6x6 mm2	1.3x1.3 mm Or 3x3 mm
Voltage	38-45 V	50-53 V	33-47 V	38 V		40-46 V	50-53 V
Array of SiPM (summing)	-	5 or 10	2x2 Parallel	-		2x2	5 or 10
Capacitance/ channel	320pF or 1280 pF	1.6-3.2 nF And 6.4-12.8 nF	10 nF	320 pF		2.5 nF	1.6-3.2 nF Or 6.4-12.8 nF
Pixel/channel	7.3k Or 38k	13k-26k And 72k-144k	638k	40k		160-360k	13k-26k Or 72k-144k
Dynamic range	TBD	TBD	0.29pC-5.8 nC	TBD		10-10,000pC	0.1pC-320 pC

We would like to use the same ROC for EEEMCal
“Flash ADC”/FPGA alternative planned for barrel ECal
➡ requires much more power, cooling

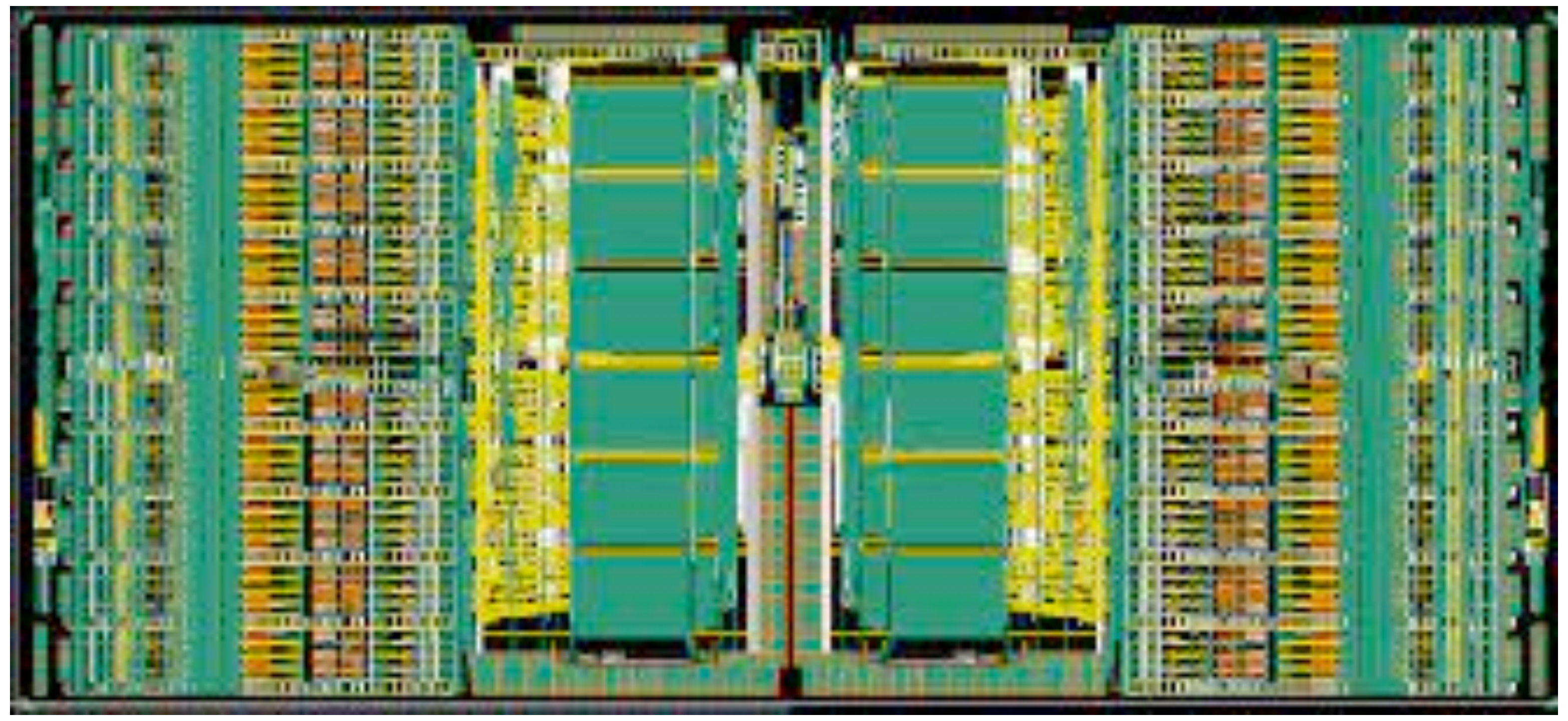
Beyond design considerations HGCROC has obvious advantages
- Builds HGCAL experience, infrastructure, etc.
- Proximity & cooperation w/ OMEGA beneficial for ePIC calo effort

Goal: Convince ePIC that ASIC solution meets requirements (resolution, stability, linearity)

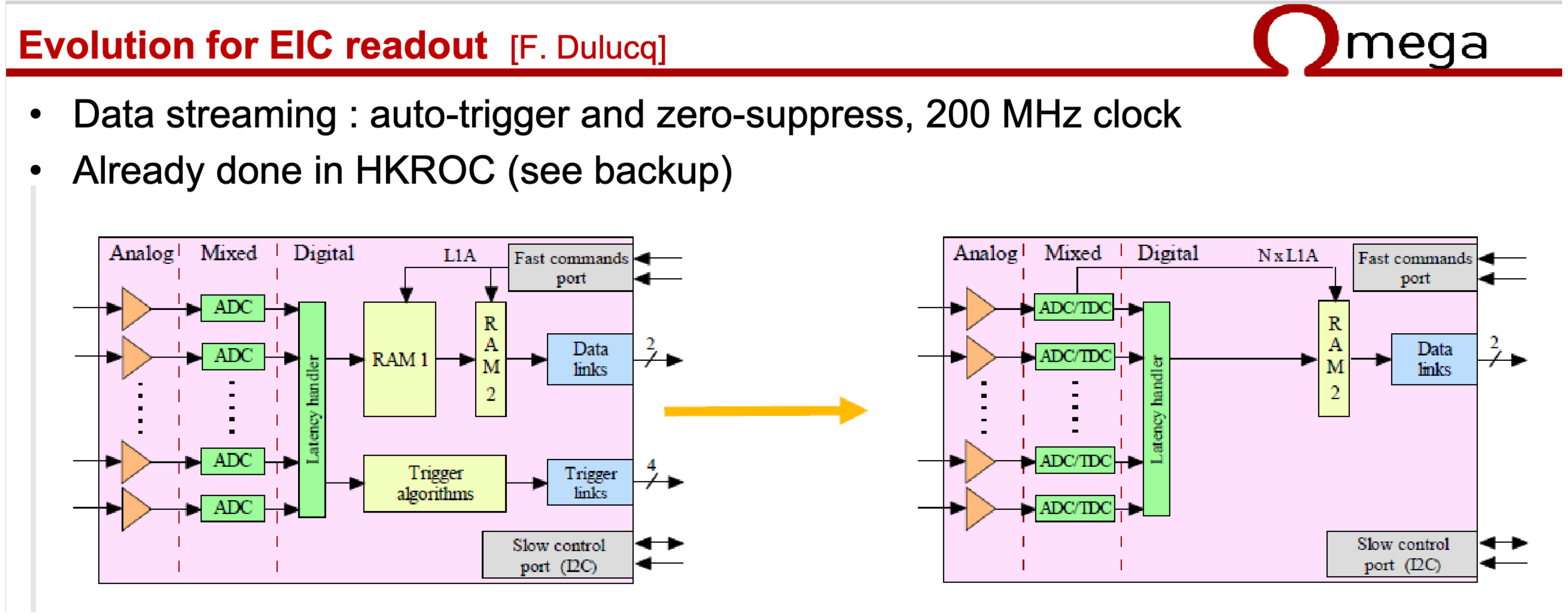
HGCROC

“H2GCROC” version (SiPM)

- 72 channels per card
- Large dynamic range, from MIPs to ~TeV (CMS)
- Measures
  - ADC: 10 bit, 0.4fC resolution
  - TOT: 12 bit, 2.5fC resolution
- Low power consumption
- Linearity better than 1% over full range
- Fast shaping time (~20 ns)
- Radiation hard
- Input capacitance: 100 - 2.5 nF, 10 nF grouping under study



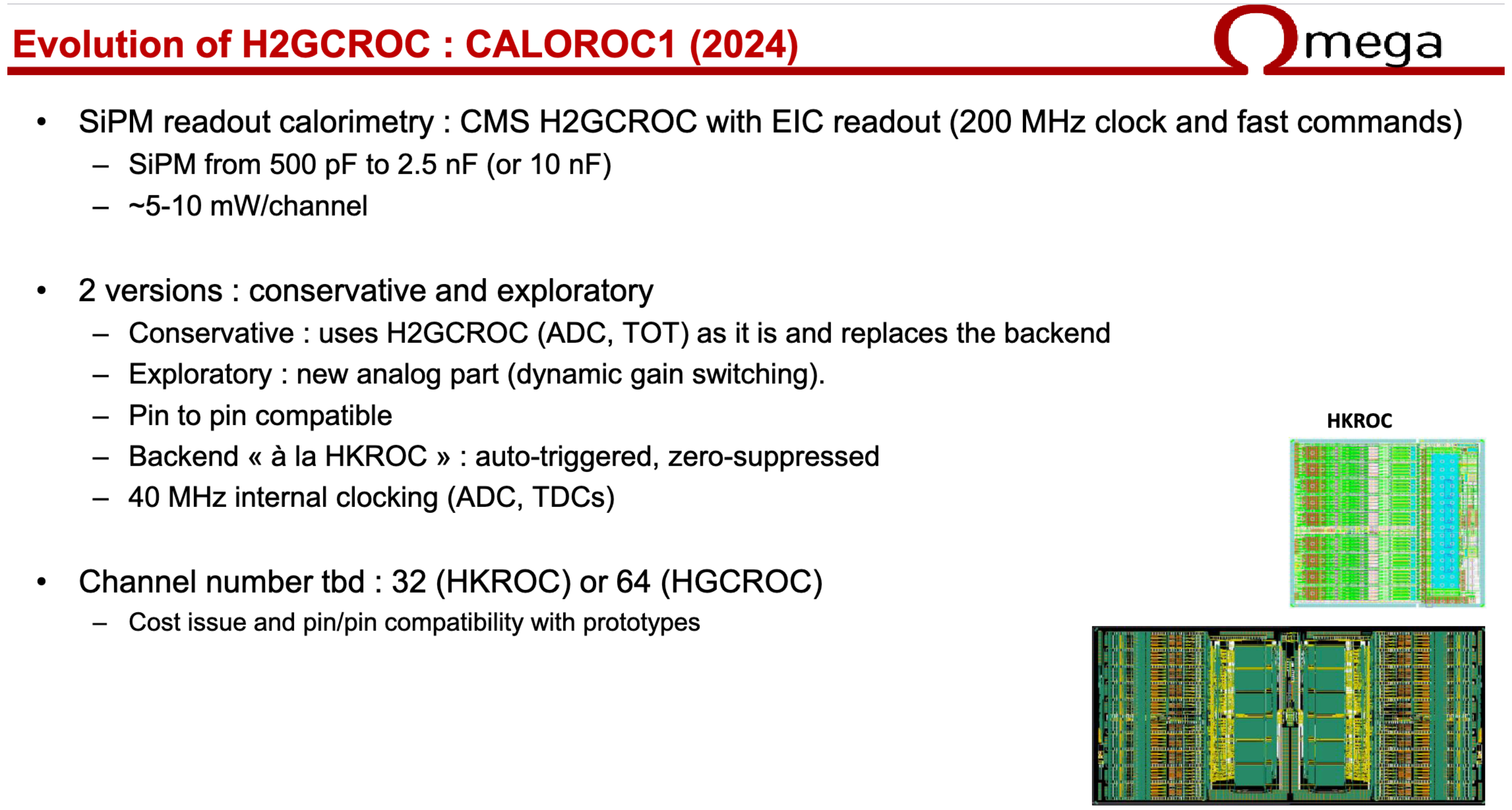
“CALOROC” for EIC



Evolution for EIC readout [F. Dulucq]

Ωmega

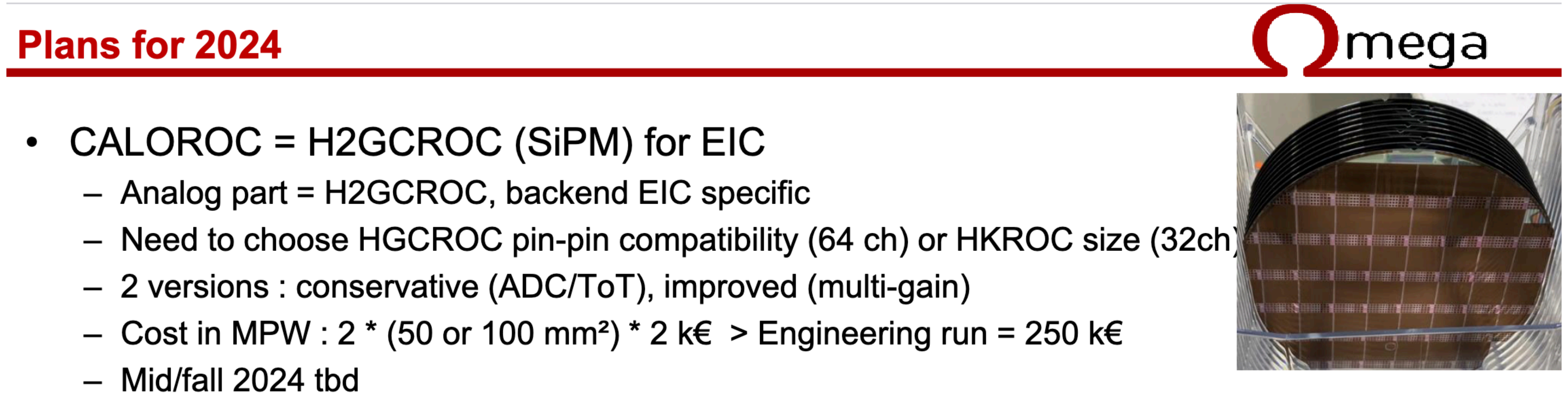
- Data streaming : auto-trigger and zero-suppress, 200 MHz clock
- Already done in HKROC (see backup)



Evolution of H2GCROC : CALOROC1 (2024)

Ωmega

- SiPM readout calorimetry : CMS H2GCROC with EIC readout (200 MHz clock and fast commands)
  - SiPM from 500 pF to 2.5 nF (or 10 nF)
  - ~5-10 mW/channel
- 2 versions : conservative and exploratory
  - Conservative : uses H2GCROC (ADC, TOT) as it is and replaces the backend
  - Exploratory : new analog part (dynamic gain switching).
  - Pin to pin compatible
  - Backend « à la HKROC » : auto-triggered, zero-suppressed
  - 40 MHz internal clocking (ADC, TDCs)
- Channel number tbd : 32 (HKROC) or 64 (HGCROC)
  - Cost issue and pin/pin compatibility with prototypes



Plans for 2024

Ωmega

- CALOROC = H2GCROC (SiPM) for EIC
  - Analog part = H2GCROC, backend EIC specific
  - Need to choose HGCROC pin-pin compatibility (64 ch) or HKROC size (32ch)
  - 2 versions : conservative (ADC/ToT), improved (multi-gain)
  - Cost in MPW : 2 * (50 or 100 mm²) * 2 k€ > Engineering run = 250 k€
  - Mid/fall 2024 tbd

Backend being redesigned for EIC clock and self-triggering
Considering swapping TOT for additional ADC resolution
“dynamic gain switching”

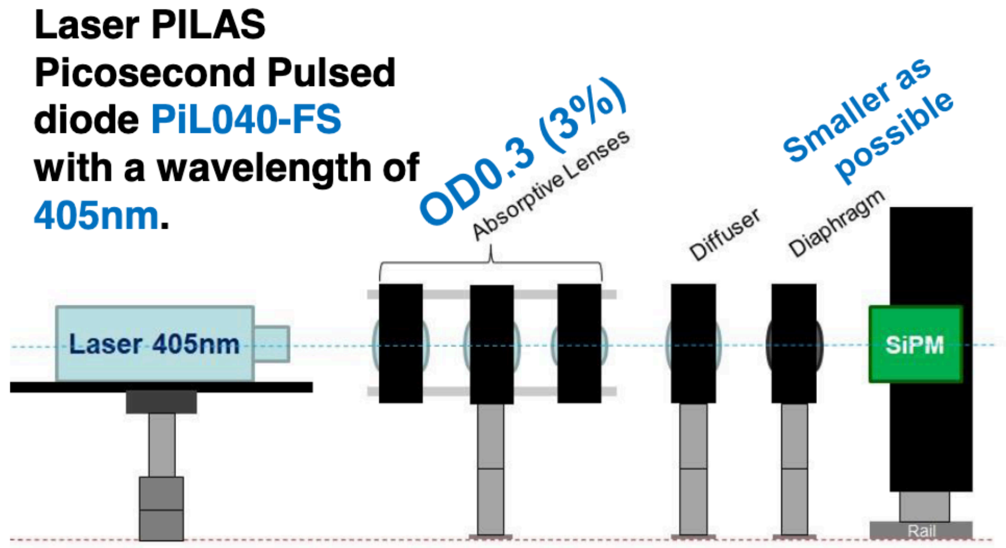
Local “CaloROC” workforce

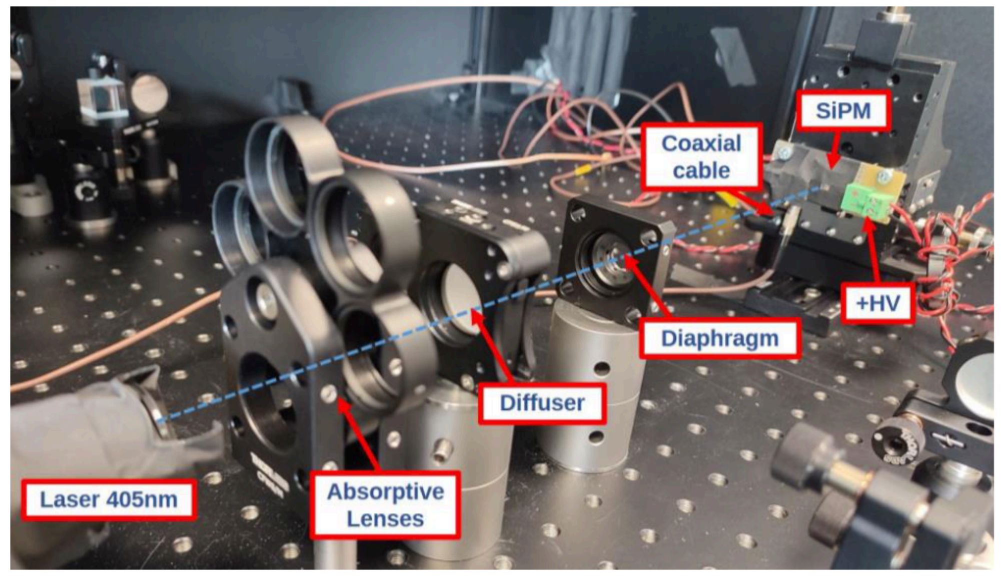
We are meeting bi-weekly with the OMEGA team & IJCLab colleagues
LLR: Le Dortz, Gastaldi, Kalipoliti, Nguyen
OMEGA: El Berni, Dulucq, Dumas, Gonzales, de la Taille, Thienpont
IJCLab: Munoz, Pilleux

LLR added to IN2P3 “master project”, which can be used, e.g., to purchase small equipment

Signal injection tests

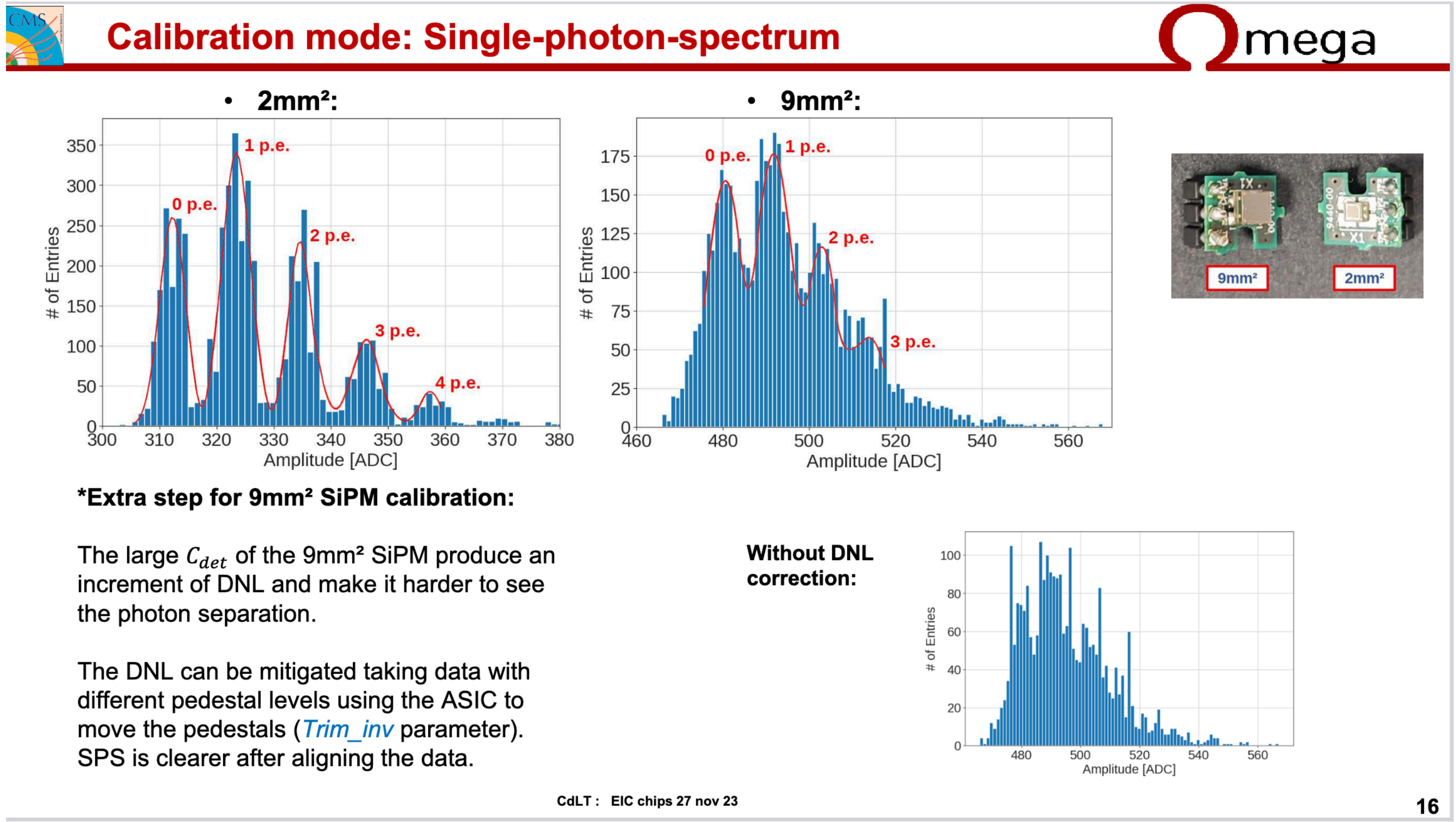
laser darkbox setup @ OMEGA





- Single photo-electron peaks measurable in small SiPMs
- Already difficult to see in a 9mm² SiPM (CMS-version)
- Requires dedicated (high-gain) HGCROC calibration mode, as well as various tricks to see the peaks

- **2 typical gains**
  - Low gain (Physics mode): **44 fC/ADC gain, 50 fC noise (1.25 ADCu)**
  - High gain (Calibration mode): **10 fC/ADC gain, 20 fC noise (2 ADCu)**



Calibration mode: Single-photon-spectrum

- **2mm²:**
- **9mm²:**

***Extra step for 9mm² SiPM calibration:**

The large C_{det} of the 9mm² SiPM produce an increment of DNL and make it harder to see the photon separation.

The DNL can be mitigated taking data with different pedestal levels using the ASIC to move the pedestals (*Trim_inv* parameter). SPS is clearer after aligning the data.

Without DNL correction:

CdLT : EIC chips 27 nov 23

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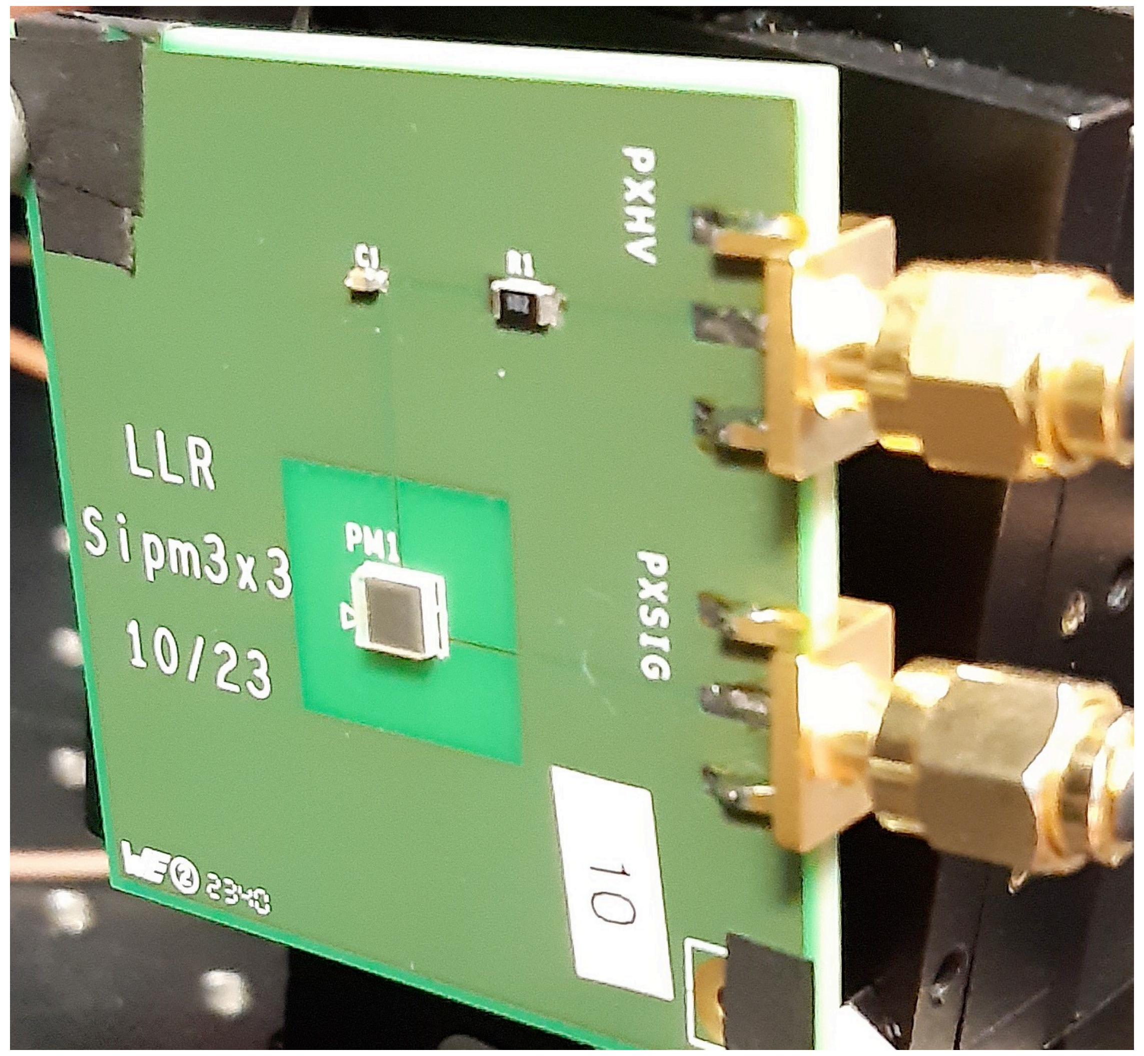
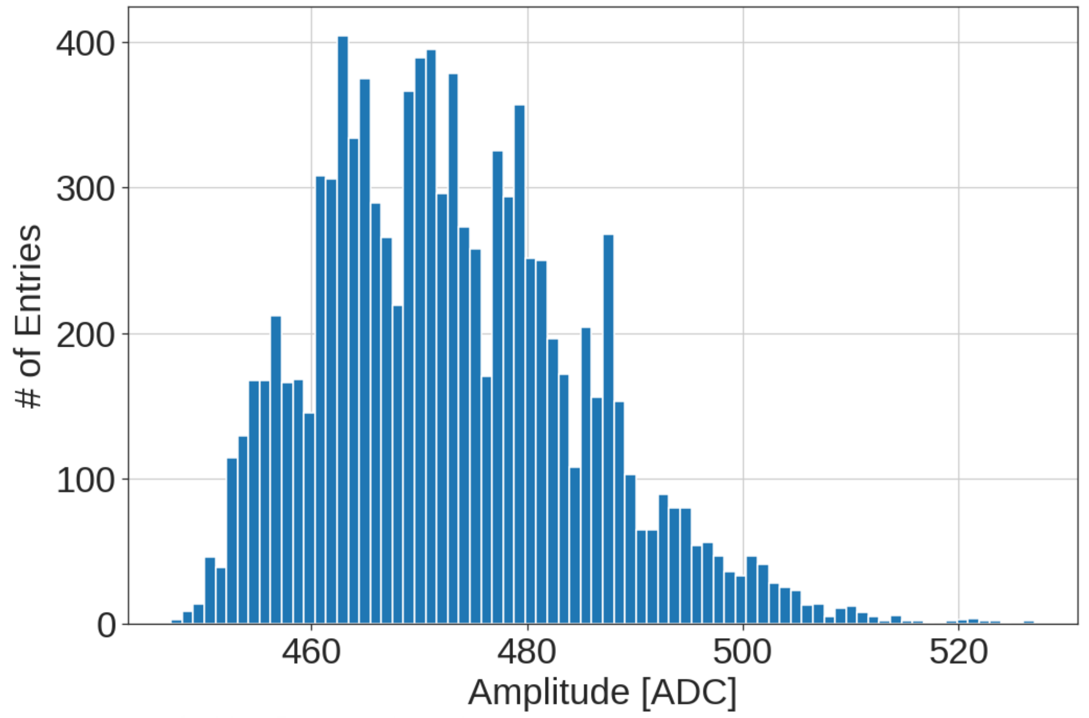
Testing EIC SiPMs

Testing SiPMs at OMEGA, we had issues w/ reproducibility
Decided to mount SiPM in a PCB to improve the robustness



Credit: Le Dortz

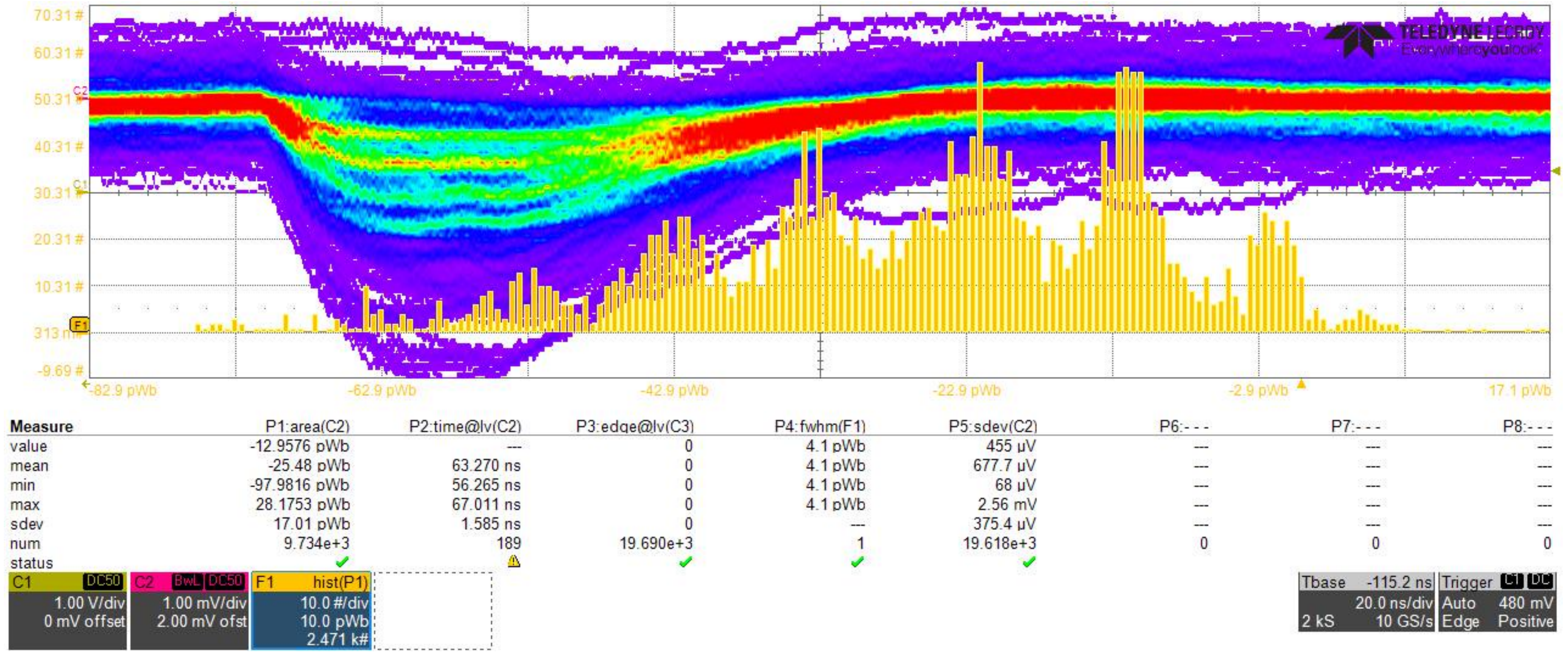


- We readout 4 SiPMs through the HGCROC: (9mm2, 36mm2) x (10μm, 15μm)

✓ We see the signal through all four

Cannot see single p.e.'s in 36 mm^2 SiPMs, 9mm^2 seems to be the limit

Not a limitation of the HGCROC, also cannot see p.e.'s directly on scope



Measure	P1:area(C2)	P2:time@lv(C2)	P3:edge@lv(C3)	P4:fwhm(F1)	P5:sdev(C2)	P6:- - -	P7:- - -	P8:- - -
value	-12.9576 pWb	---	0	4.1 pWb	455 µV	---	---	---
mean	-25.48 pWb	63.270 ns	0	4.1 pWb	677.7 µV	---	---	---
min	-97.9816 pWb	56.265 ns	0	4.1 pWb	68 µV	---	---	---
max	28.1753 pWb	67.011 ns	0	4.1 pWb	2.56 mV	---	---	---
sdev	17.01 pWb	1.585 ns	0	---	375.4 µV	---	---	---
num	9.734e+3	189	19.690e+3	1	19.618e+3	0	0	0
status	✓	⚠	✓	✓	✓			

SiPM measurements

1 Experimental setup

Hamatsu SiPMs models S14160 - 3010,3015 and 6010 are tested. They can be read in two ways: either directly with a short coaxial cable or using a PCB matrix. The PCB matrix links the cathode to an HV entry with a resistor and capacitance and the anode to a readout connector to which a resistor was added a posteriori. It is shown in Fig. 1. Four samples are available:

- 3×3 mm^2 with 10 μm pixels (3010) read with the direct connection with a short coaxial cable
- 3×3 mm^2 with 15 μm pixels (3015) read with the direct connection with a short coaxial cable
- 3×3 mm^2 with 15 μm pixels (3015) read with a PCB matrix
- 6×6 mm^2 with 10 μm pixels (6010) read with a PCB matrix

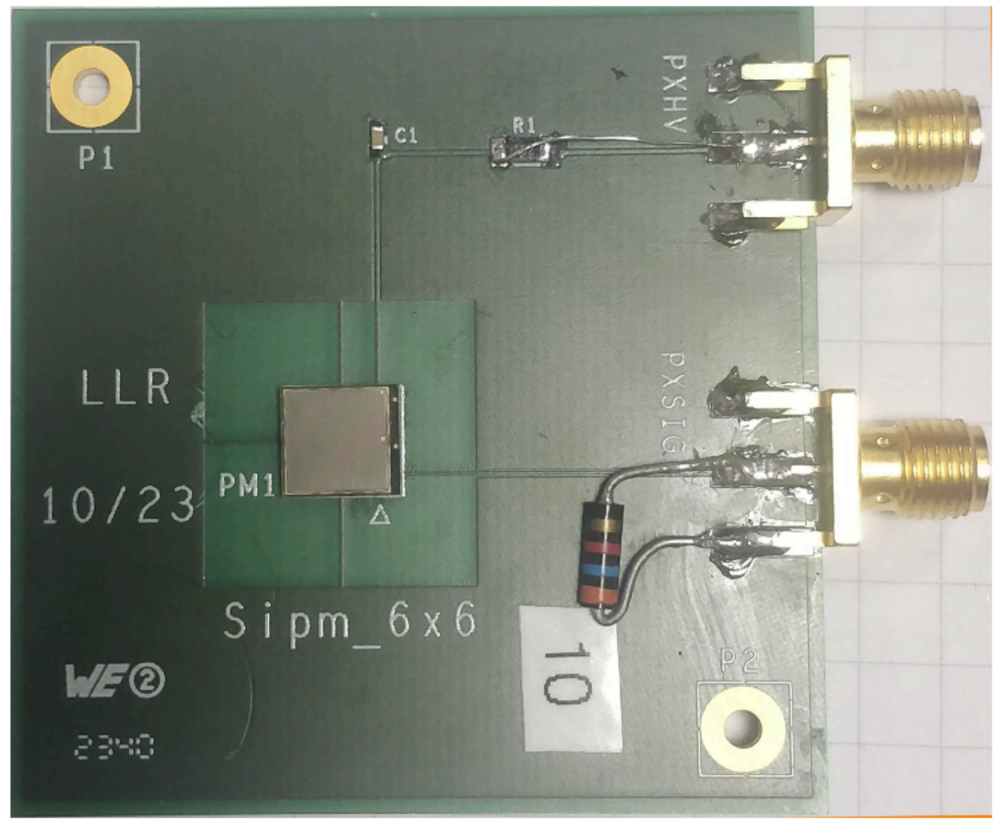


Figure 1: PCB matrix holding a 36 mm^2 SiPM. A resistor is added on the readout side.

Dark current for different SiPMs

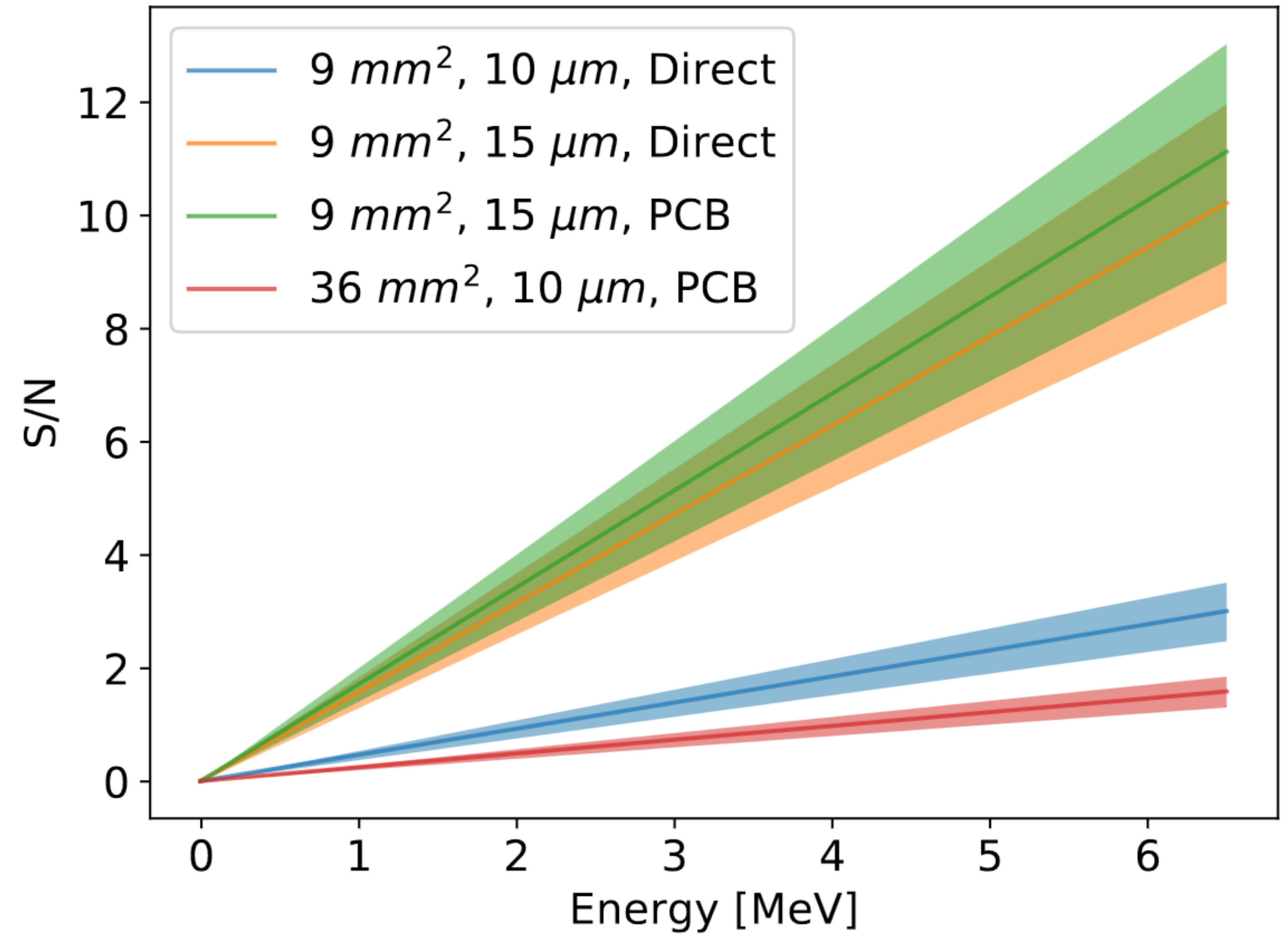
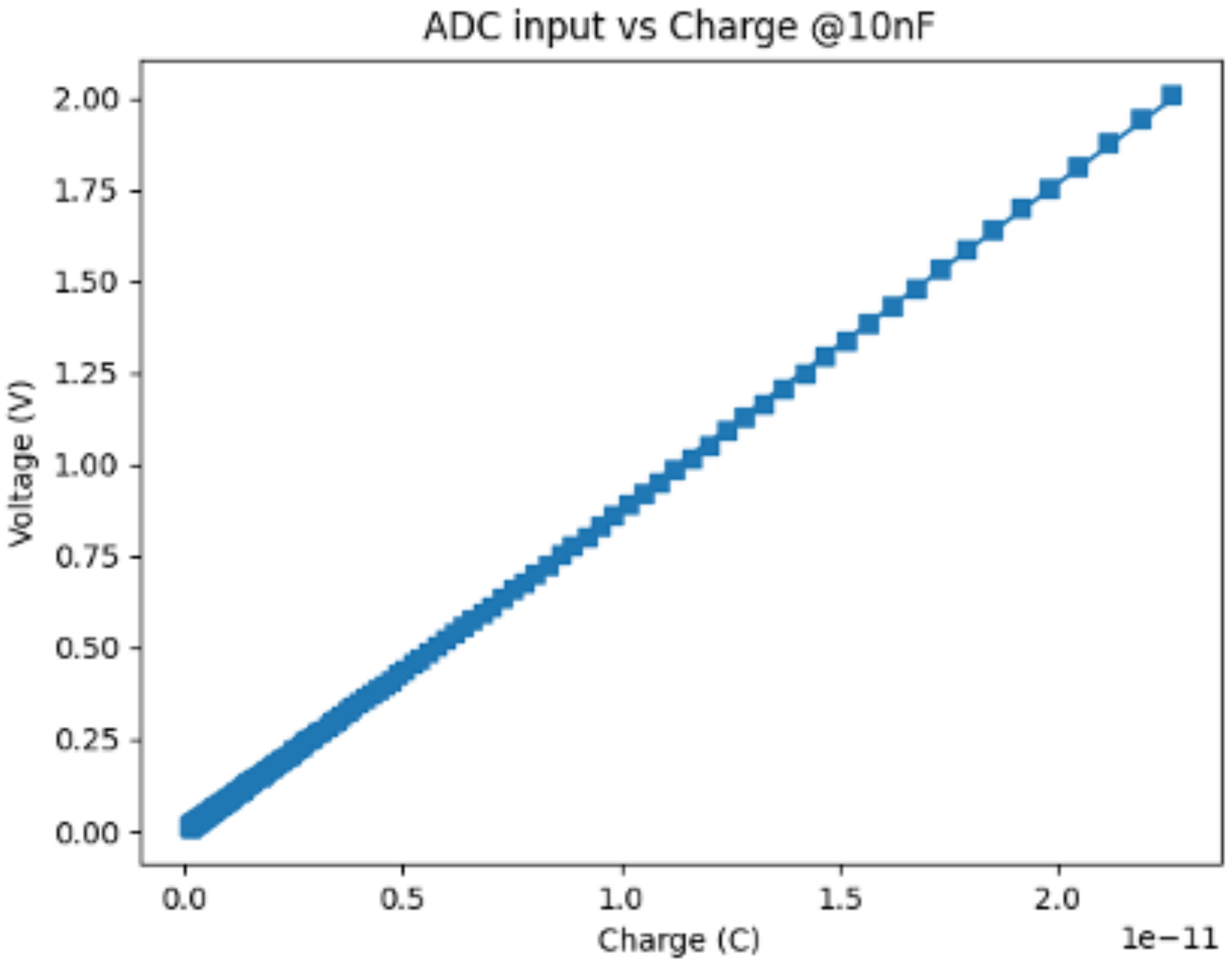


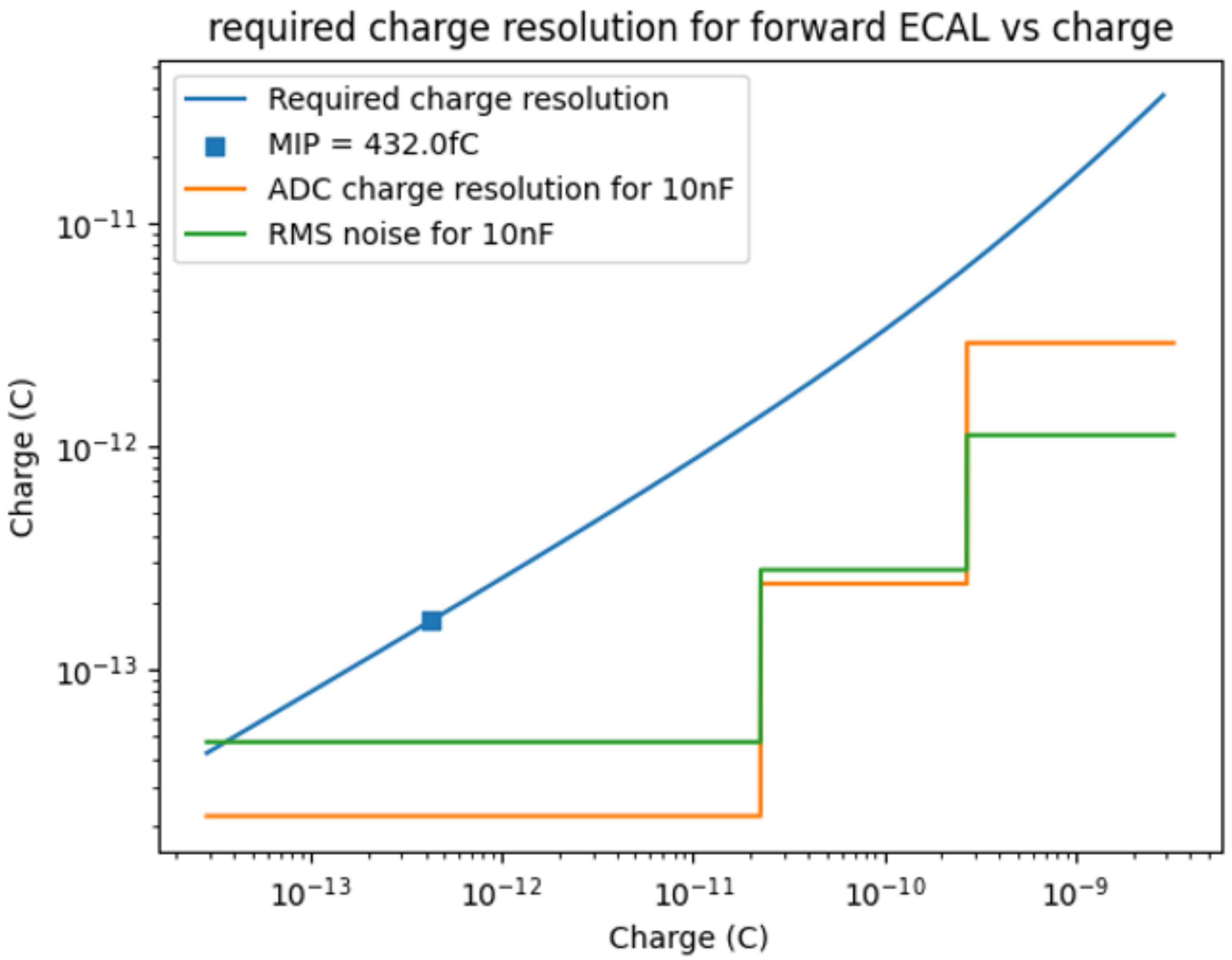
Figure 3: S/N ratio as a function of the incident energy.

Stand-alone SiPM measurements being done @ IJCLab (Pilleux)

HGCROC+SiPM simulations



Linearity within 0.5%
studied for various gains & input capacitance



Charge resolution is within specifications

Simulations by P. Dumas (OMEGA)

HGCROC outlook

- Test SiPMs arrays w/ different configurations (serial vs. parallel)

➡An 4x4 array of 9mm^2 SiPMs will arrive next week

- Set up laser or LED dark box at LLR
- Aiming for beam tests with a minimal crystal + SiPM array in 2024, using DAQ developed for forward HCAL
- Needs dedicated person-power to converge,

➡ postdoc will take the lead & also contribute to HGCAL effort

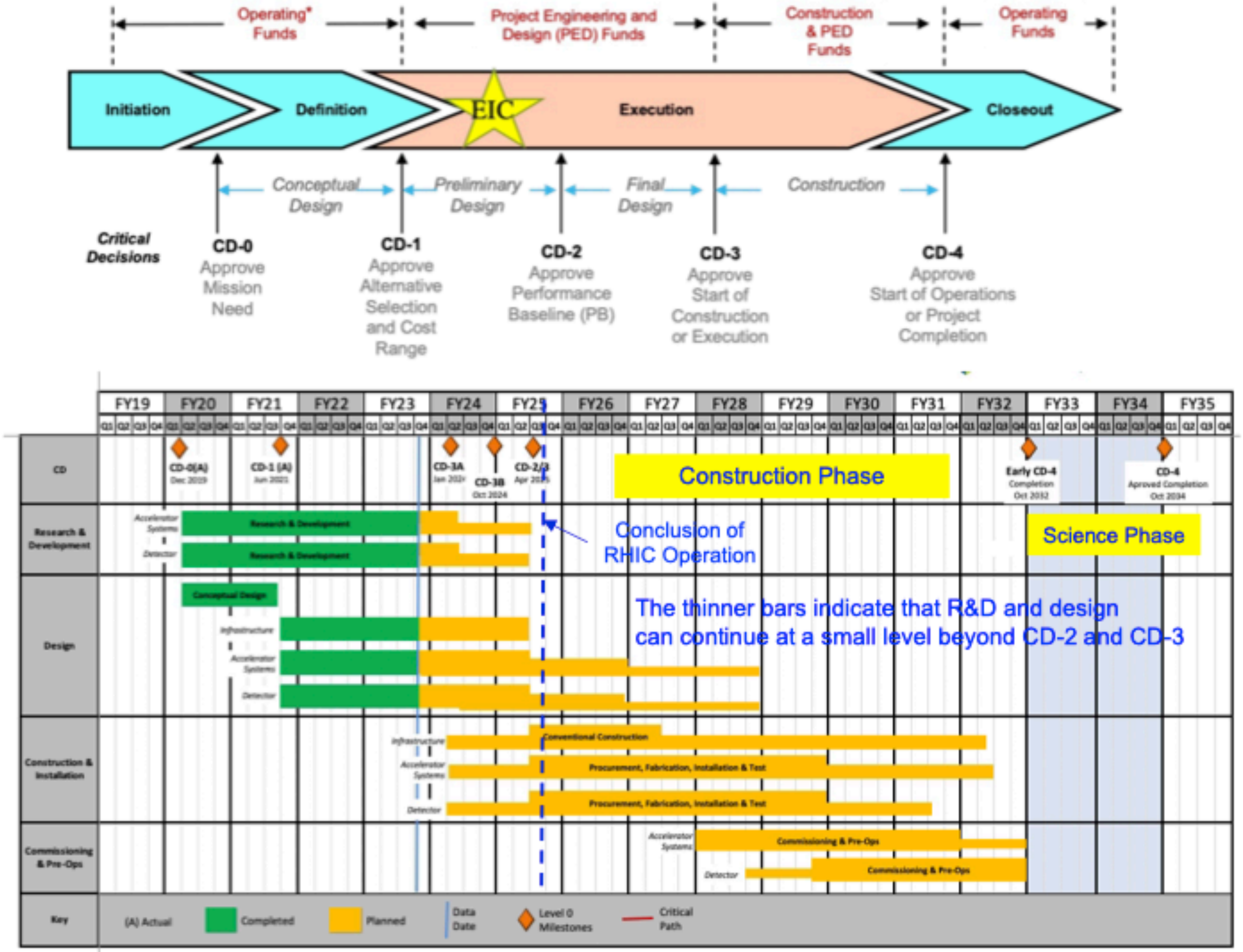
EIC Schedule

EIC Critical Decision Plan

CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	January 2024
CD-3B	**October 2024**
CD-2/3	**April 2025**
early CD-4	October 2032
CD-4	**October 2034**

CD-2:
Approve preliminary design for all subdetectors
Design Maturity: >60%
Need “pre-”TDR
Baseline project in scope, cost, schedule

CD-3:
Approve final design for all subdetectors
Design Maturity: ~90%
Need full TDR



Construction Phase

Conclusion of RHIC Operation

Science Phase

The thinner bars indicate that R&D and design can continue at a small level beyond CD-2 and CD-3

Electron-Ion Collider

ePIC Collaboration Meeting, January 9-13, 2024

E.C. Aschenauer & R. Ent

Take Away:

- Solenoid and Barrel HCal need to be ready by Jan 2029
- all other subdetectors need to be ready between 06/29 to 06/30 depending on their location in the detector

Summary

- EIC: Interesting & varied physics program for the ‘30s
- LLR has the opportunity to get in on the ground floor
- EEEMCal seems an appropriate entry point
  - ECAL technology we know very well
  - Maintain our expertise in exploiting ASICs from OMEGA
- LLR has prioritized my request for an IN2P3 post-doc to support the HGCROC effort, ensuring overlap w/ Lida (defending in ’25)

Backup

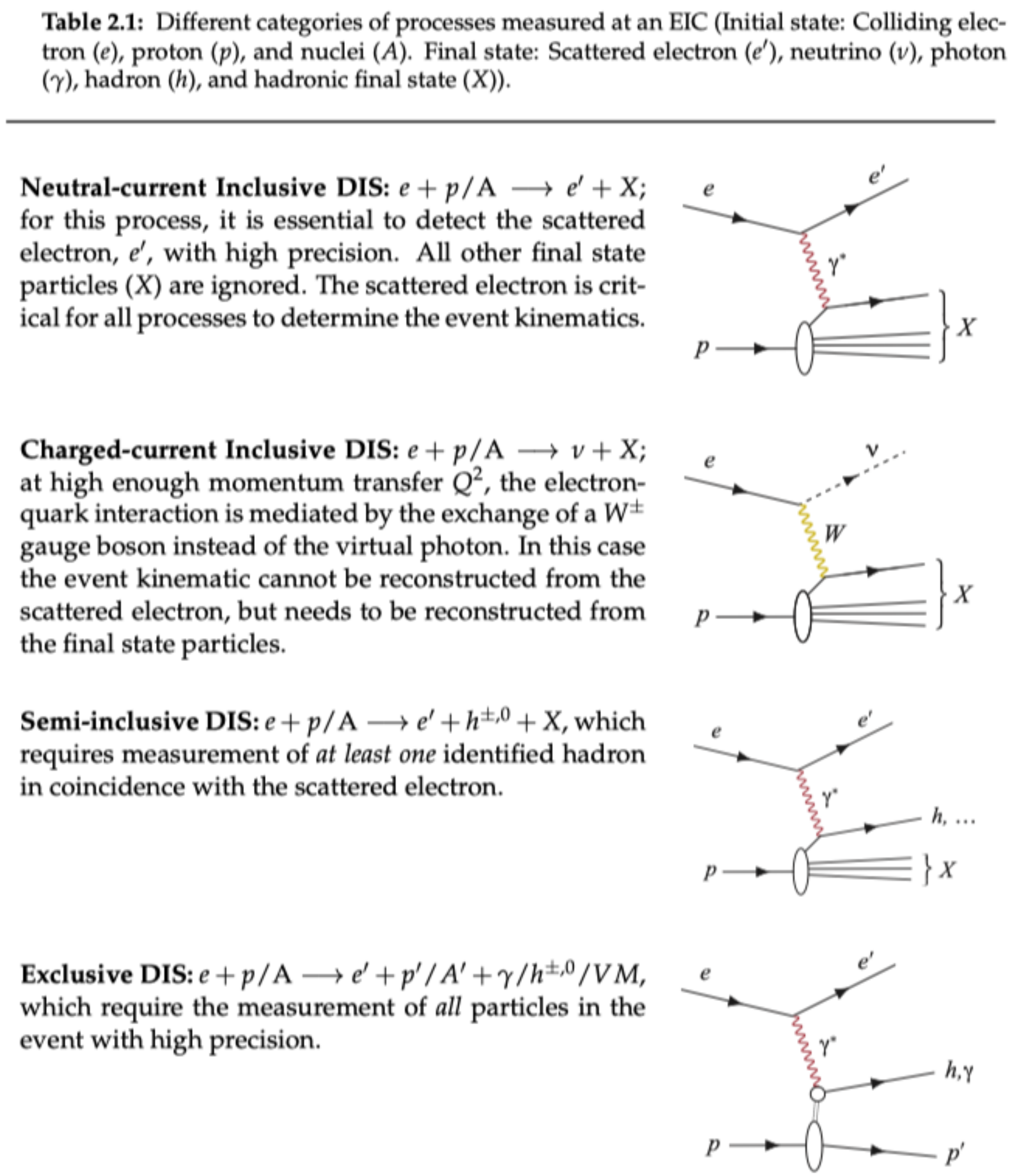


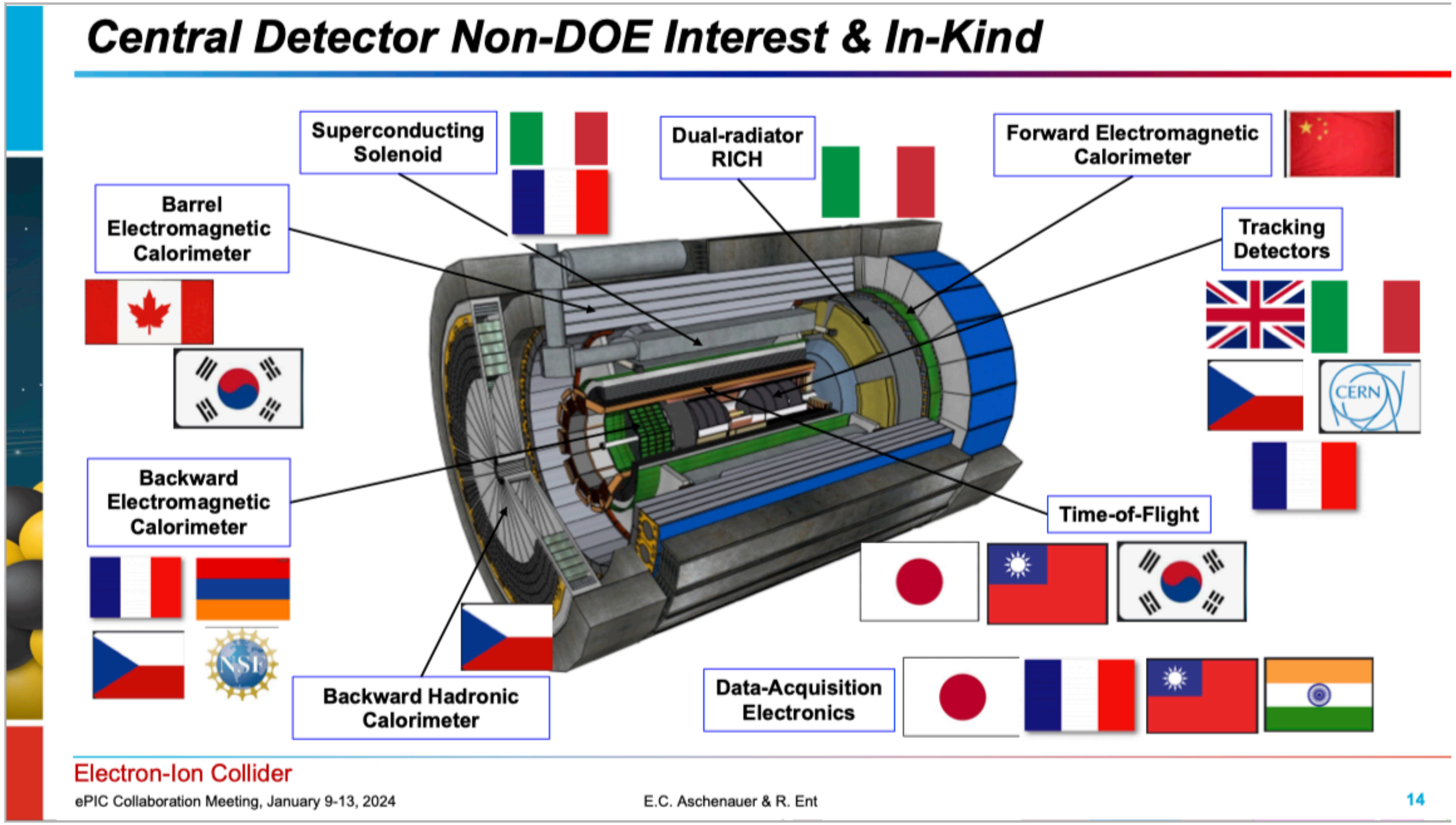
Table 2.1: Different categories of processes measured at an EIC (Initial state: Colliding electron (e), proton (p), and nuclei (A). Final state: Scattered electron (e'), neutrino (ν), photon (γ), hadron (h), and hadronic final state (X)).

Neutral-current Inclusive DIS: $e + p/\mathrm{A} \longrightarrow e' + \mathrm{X}$; for this process, it is essential to detect the scattered electron, e', with high precision. All other final state particles (X) are ignored. The scattered electron is critical for all processes to determine the event kinematics.

Charged-current Inclusive DIS: $e + p/\mathrm{A} \longrightarrow \nu + \mathrm{X}$; at high enough momentum transfer Q^2, the electron-quark interaction is mediated by the exchange of a $W^{\pm}$ gauge boson instead of the virtual photon. In this case the event kinematic cannot be reconstructed from the scattered electron, but needs to be reconstructed from the final state particles.

Semi-inclusive DIS: $e + p/\mathrm{A} \longrightarrow e' + h^{\pm,0} + \mathrm{X}$, which requires measurement of *at least one* identified hadron in coincidence with the scattered electron.

Exclusive DIS: $e + p/\mathrm{A} \longrightarrow e' + p'/A' + \gamma/h^{\pm,0}/VM$, which require the measurement of *all* particles in the event with high precision.



Central Detector Non-DOE Interest & In-Kind

Electron-Ion Collider

ePIC Collaboration Meeting, January 9-13, 2024

E.C. Aschenauer & R. Ent

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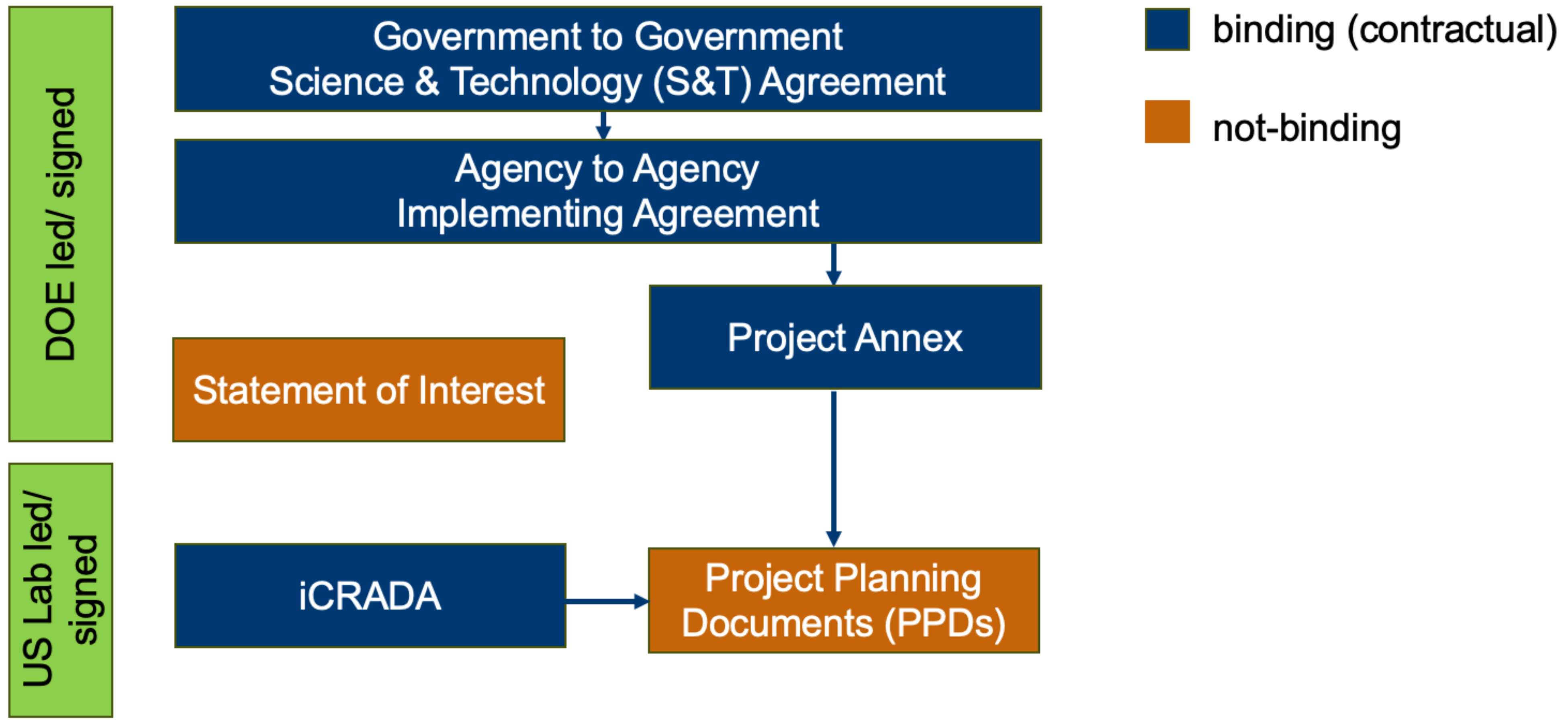
1st Wave of Milestones for Detector IKC

Agency	Milestone	Target Date
Italy-INFN	Outcome on detector solenoid funding (CD-3A scope)	December 2023
US-NSF	Outcome on MSRI funding (CD-3A scope)	January 2024
UK	UKRI outcome on funding proposal	January 2024
Italy-INFN	JLab iCRADA draft on magnet	February 2024
Italy-INFN	BNL iCRADA draft on magnet	March 2024
Italy-INFN	iCRADAs on magnet signed	May 2024
France-IN2P3	PPD draft	May 2024
France-CEA	PPD draft	June 2024
UK	PPD draft	August 2024
Italy-INFN	JLab iCRADA signed (excluding magnet scope)	August 2024
Italy-INFN	PPD draft / excluding magnet scope	August 2024
France-IN2P3	JLab iCRADA and BNL iCRADA signed (draft in Jun/Jul)	September 2024
France-CEA	JLab iCRADA signed (draft in Jun/Jul)	September 2024
UK	JLab iCRADA signed (draft in Jun/Jul)	September 2024
	CD-2/CD-3 Director's Review / All PPDs signed	**November 2024**
	CD-2/3 OPA review	**January 2025**
	CD-2/3 ESAAB	**April 2025**


DOE led/ signed

Government to Government Science & Technology (S&T) Agreement

Agency to Agency Implementing Agreement

Project Annex

Statement of Interest

US Lab led/ signed

iCRADA

Project Planning Documents (PPDs)

🟦 binding (contractual)

🟧 not-binding