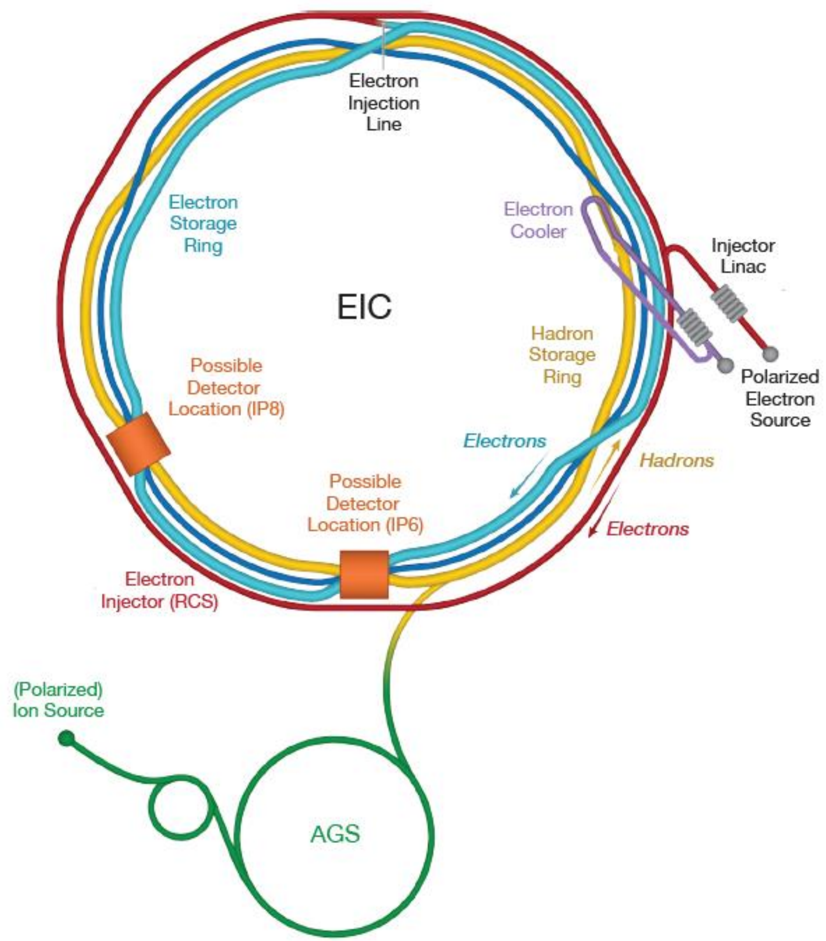
EIC Physics and Detector-1 overview

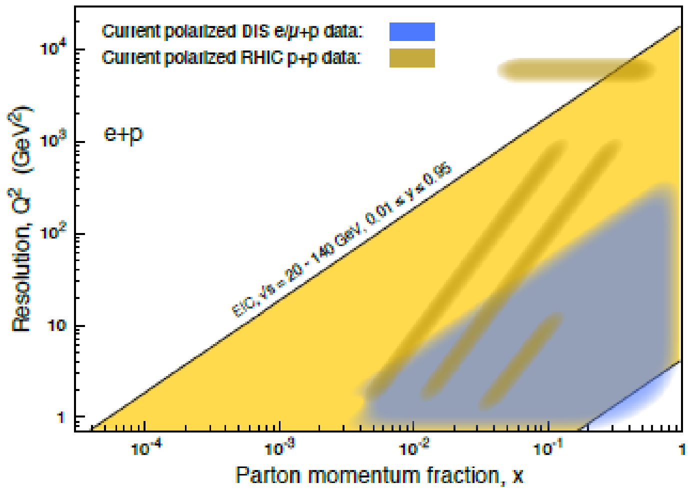
Barak Schmookler

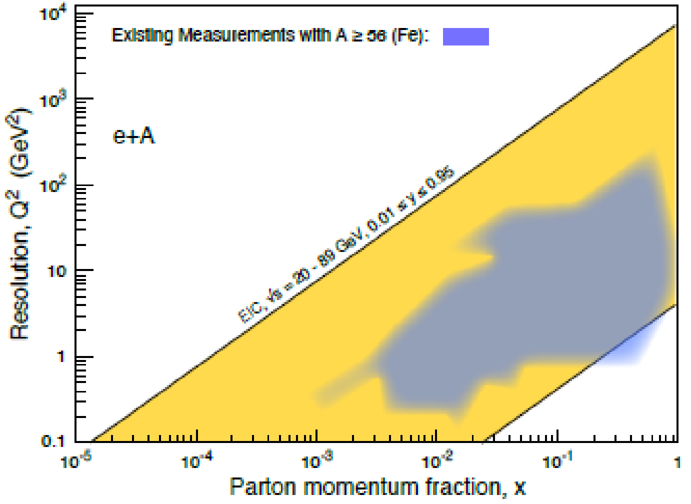
Outline

- ❑Short introduction to EIC physics goals
- ❑Key detector requirements and associated challenges
- ❑Overview of recent detector proposals and DPAP decision
- ❑Plans for *Detector 1* collaboration

The EIC will make extremely important contributions to our understanding of nucleon structure



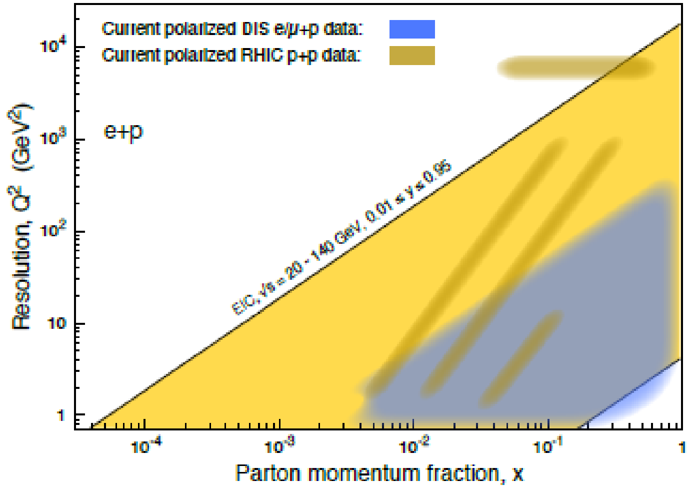


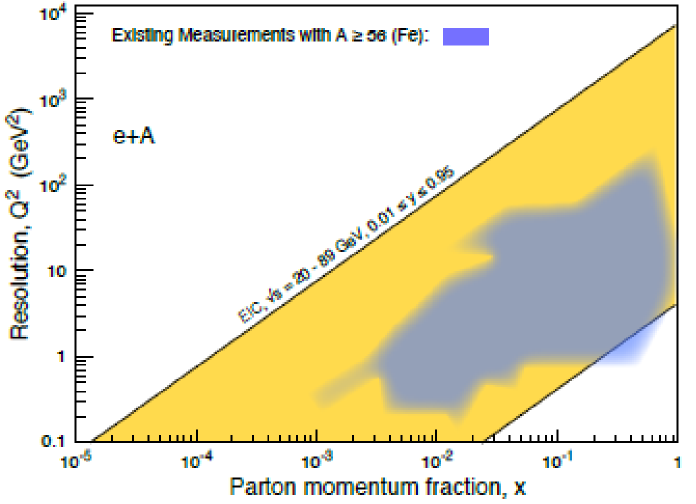


The EIC will make extremely important contributions to our understanding of nucleon structure

<u>Main physics topics to be explored at the EIC:</u>

- Nucleon structure – full three-dimensional momentum and spatial structure, as well as spin structure
- Origin of nucleon (hadron) mass – how is the nucleon's mass generated by the underlying internal partonic interactions
- Gluon saturation – at the smallest momentum fractions, the parton density can grow so large that their interactions enter a non-linear regime
- Science beyond the 2018 National Academies of Science (NAS) report

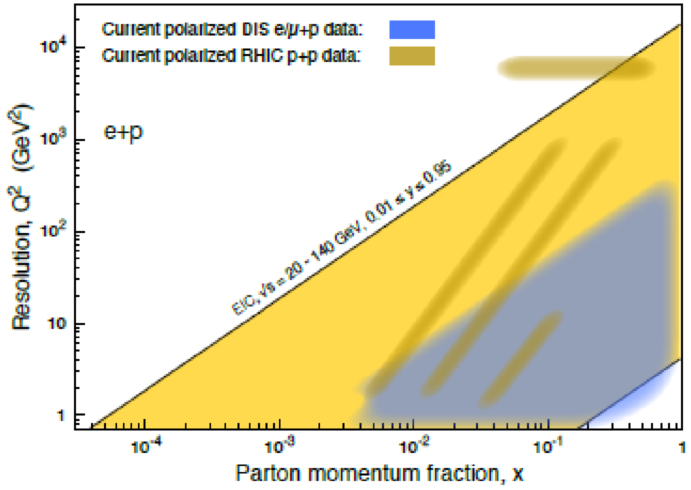


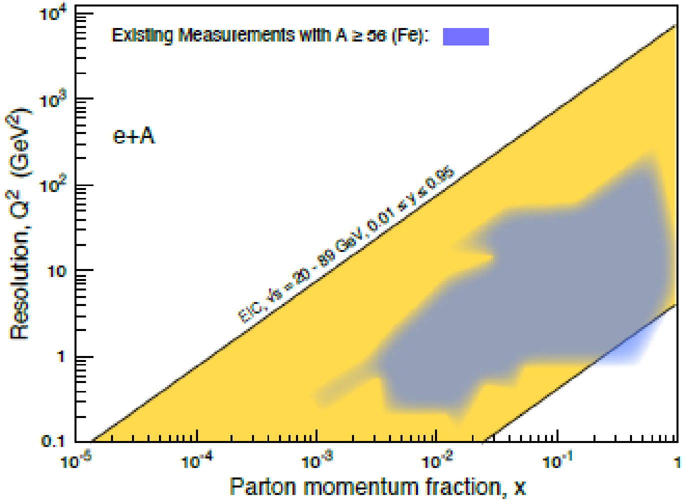


The EIC will make extremely important contributions to our understanding of nucleon structure

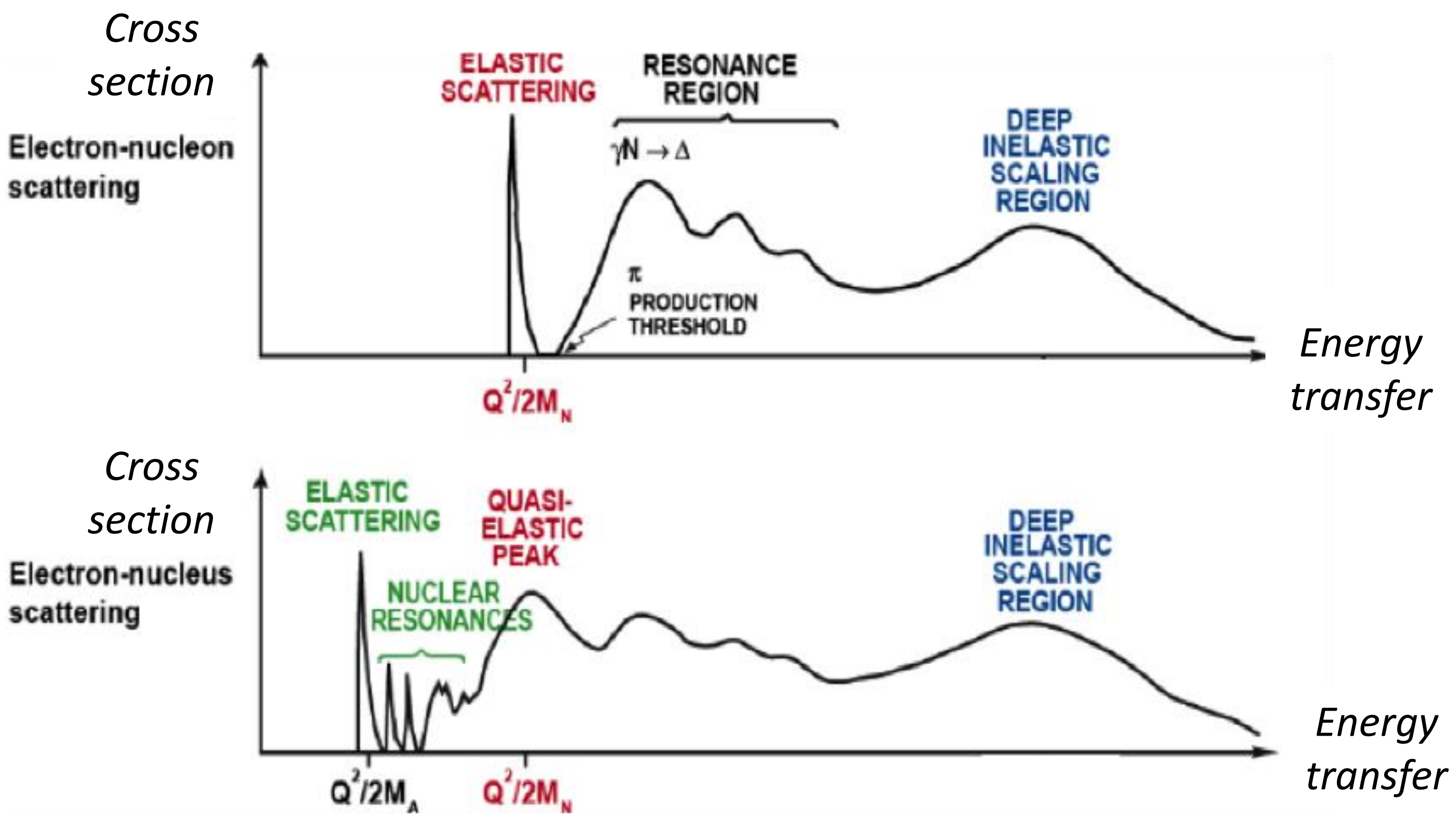
<u>Where to find more information:</u>

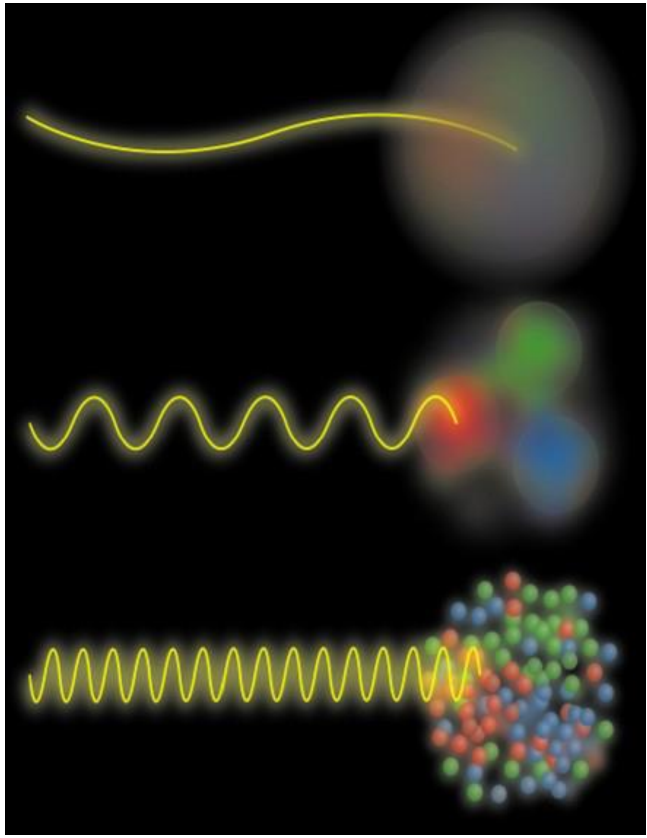
- EIC White Paper
- 2018 NAS Report
- EIC Yellow Report





Why use electrons – physics depends on the resolution of the probe





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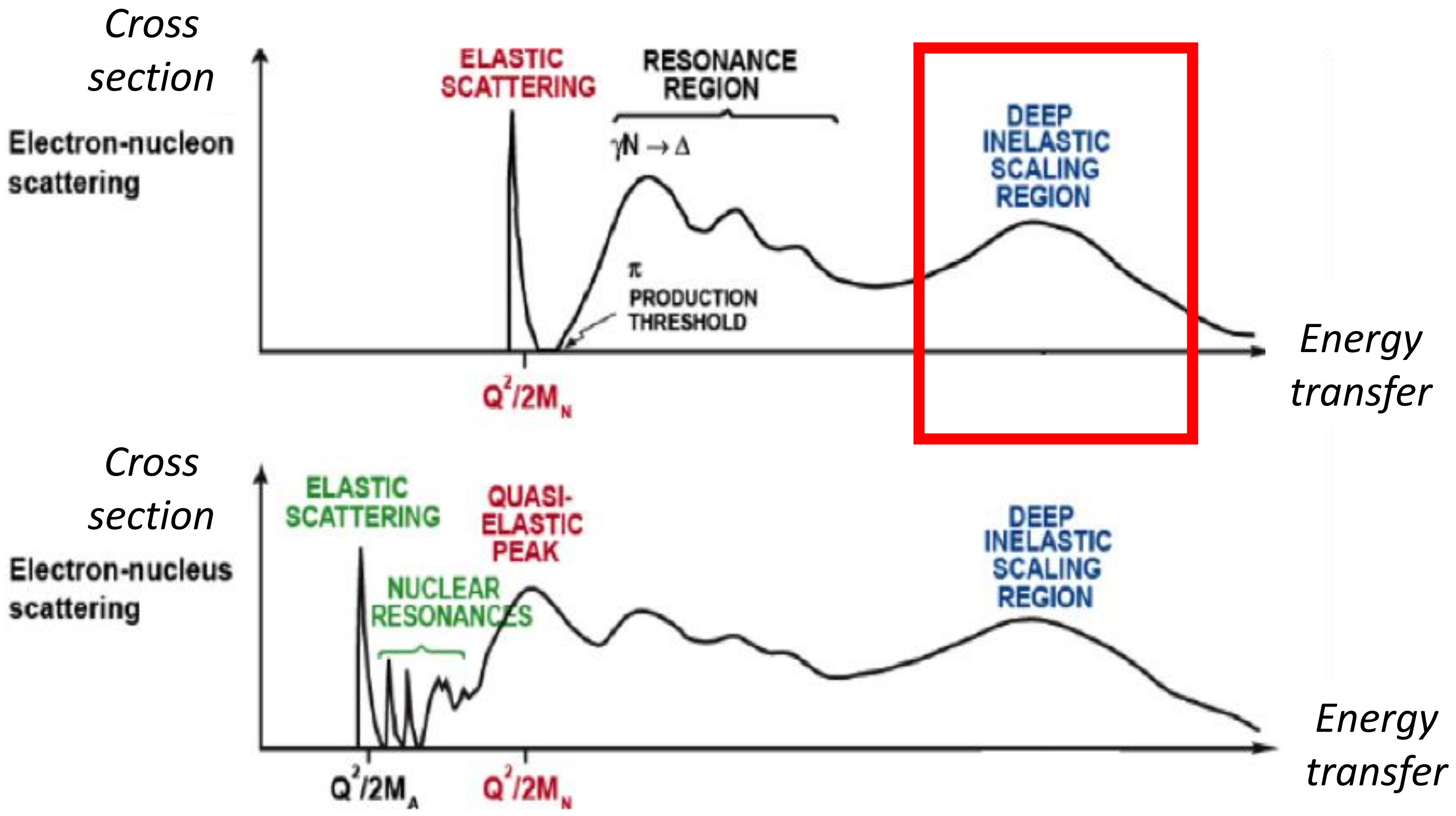
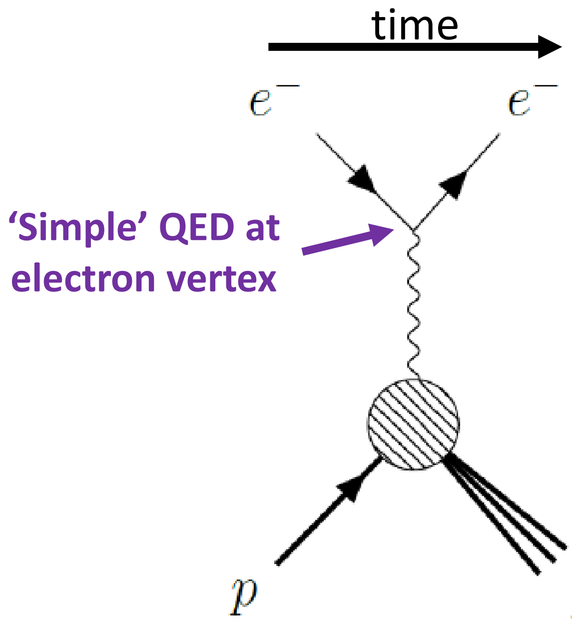




Deep Inelastic Scattering (DIS): Provides information on underlying partonic structure of the protons and neutrons

Why use electrons – can determine probe's resolution (and other important quantities) by measuring outgoing electron

$$Q^2 = -q^2 = -(e - e')^2$$

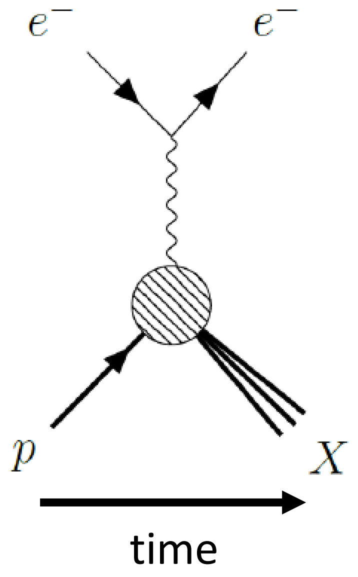
Probe resolution

$$x = \frac{Q^2}{2p \cdot q}$$

Momentum fraction of struck parton

$$y = \frac{p \cdot q}{p \cdot e}$$

Event 'inelasticity' – related to polarization of the probe



Deep Inelastic Scattering (DIS)

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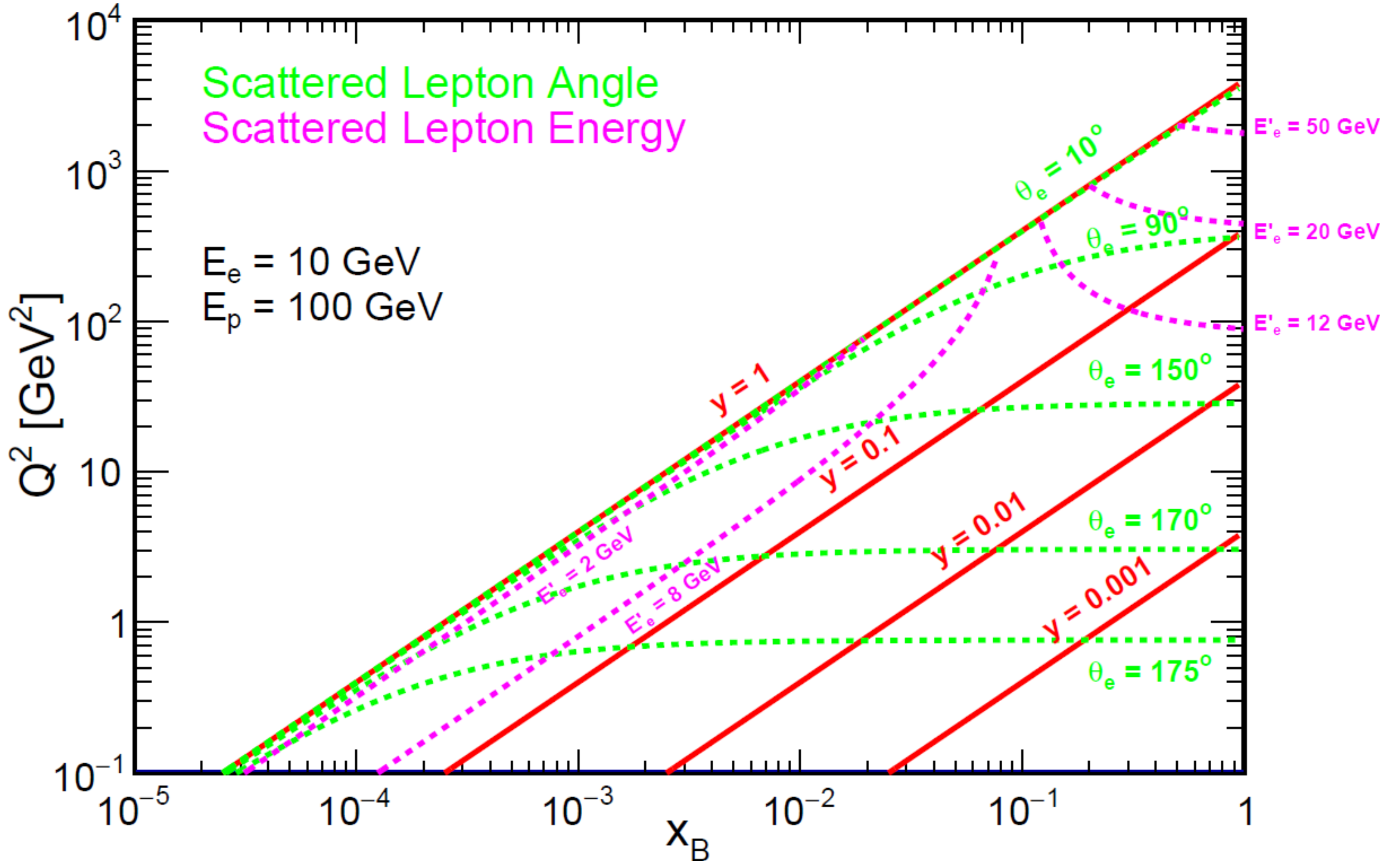
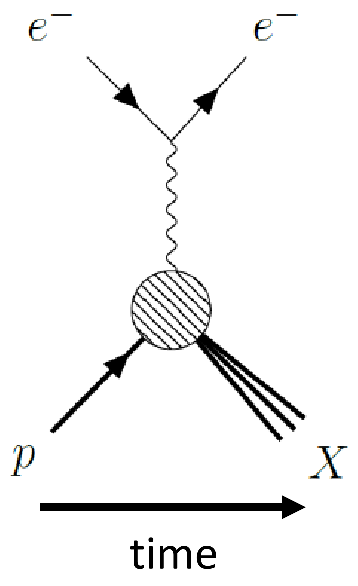


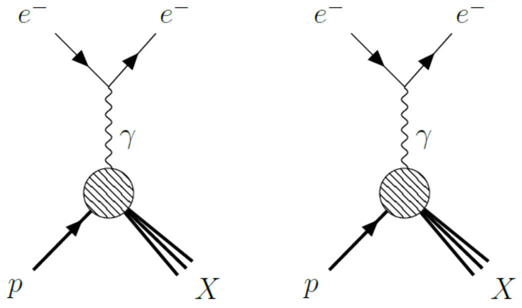


Deep Inelastic Scattering (DIS)

Physics example – Nuclear PDFs and gluon saturation

Inclusive scattering formalism

$\sigma_{NC} \propto$



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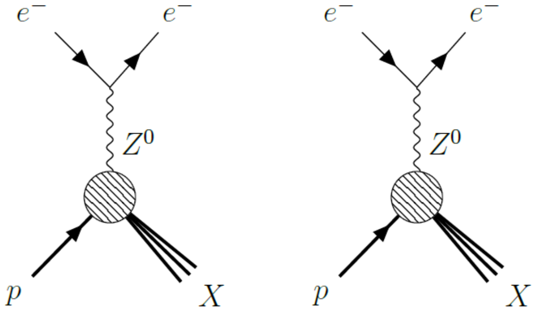

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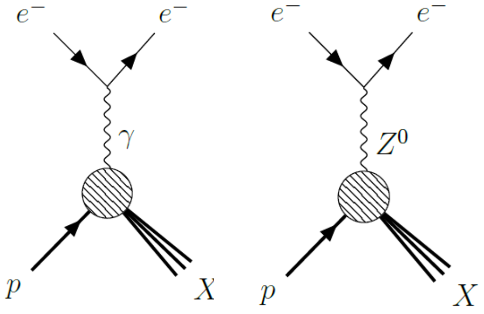
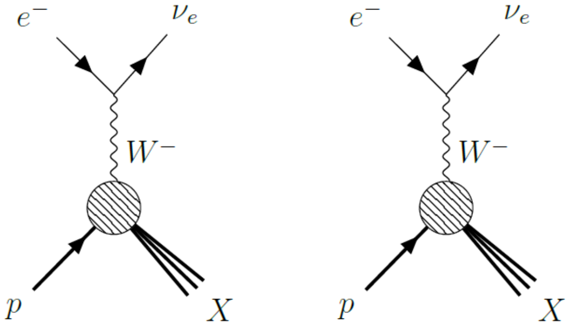


$\sigma_{CC} \propto$



Neutral Current (NC) inclusive scattering cross section

<u>For an unpolarized proton (nucleus):</u>

$$\sigma_{r,NC}^{e^\pm p \to e^\pm X} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \times \frac{d^2\sigma_{NC}^{e^\pm p \to e^\pm X}}{dx dQ^2} = F_2 + \frac{Y_-}{Y_+} x F_3 - \frac{y^2}{Y_+} F_L$$

$$F_L = F_2 - 2xF_1 \qquad Y_\pm = 1 \pm (1-y)^2$$

NC Structure Functions

$$F_{1,2}^{\pm} = F_{1,2}^{\gamma} + \eta_z \left(-g_v^e \mp \langle\lambda\rangle g_A^e\right) F_{1,2}^{\gamma z} + \eta_z^2 \left[\left(g_v^e\right)^2 + \left(g_A^e\right)^2 \pm 2\langle\lambda\rangle g_A^e g_v^e\right] F_{1,2}^{z}$$

$$xF_3^{\pm} = \eta_z \left(\pm g_A^e + \langle\lambda\rangle g_v^e\right) xF_3^{\gamma z} + \eta_z^2 \left[\mp 2 g_v^e g_A^e - \langle\lambda\rangle \left(\left(g_v^e\right)^2 + \left(g_A^e\right)^2\right)\right] xF_3^{z}$$

$\langle\lambda\rangle$: Polarization of Electron Beam [-1,1]

$$\eta_z = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2 + M_Z^2}\right)$$

$$g_v^e = -\frac{1}{2} + 2\sin^2\theta_w \approx -0.05$$

$$g_A^e = -\frac{1}{2}$$

NC Structure Functions in the Quark-Parton model

$$[F_2^\gamma, F_2^{\gamma z}, F_2^z] = x \sum_q \left[e_q^2, 2e_q g_v^q, (g_v^q)^2 + \left(g_A^q\right)^2\right](q + \bar{q})$$

$$[F_3^\gamma, F_3^{\gamma z}, F_3^z] = \sum_q [0, 2e_q g_A^q, 2g_v^q g_A^q](q - \bar{q})$$

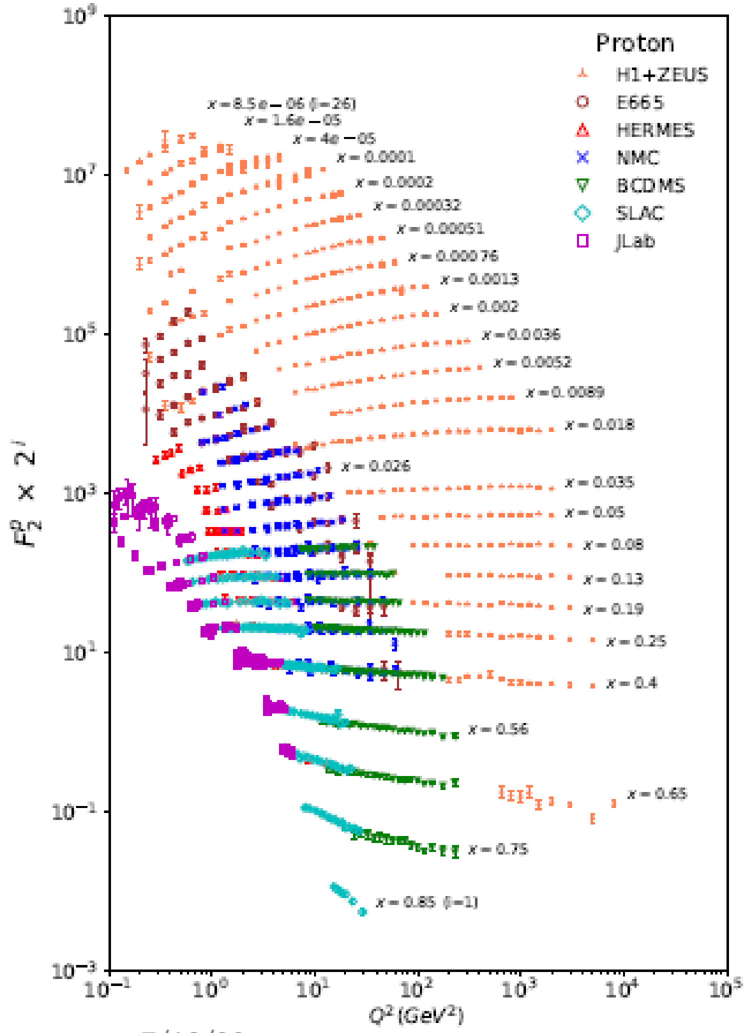
Different linear combinations of quark pdfs

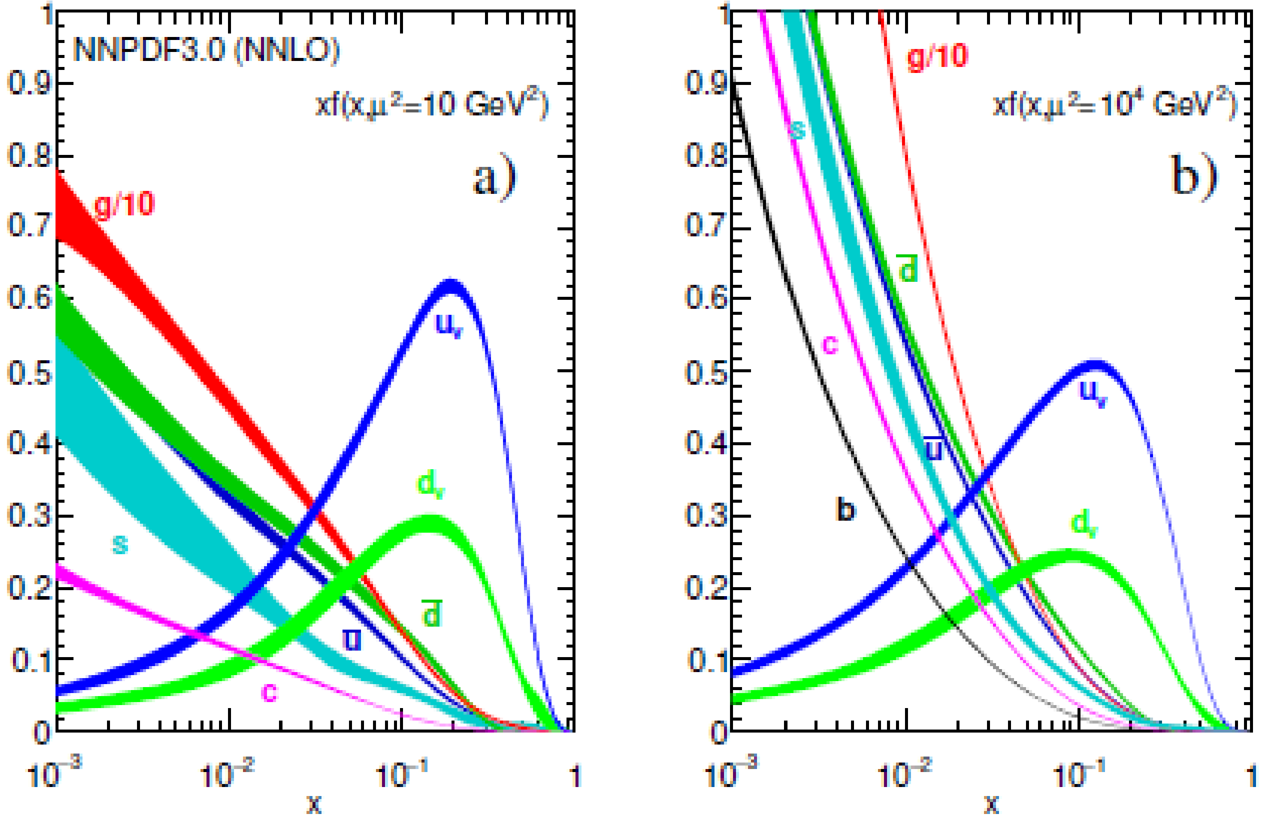
$$g_v^q = \pm\frac{1}{2} - 2e_q \sin^2\theta_w$$

$F_L = F_2 - 2xF_1$ = 0 in quark-parton model

$$g_A^q = \pm\frac{1}{2}$$

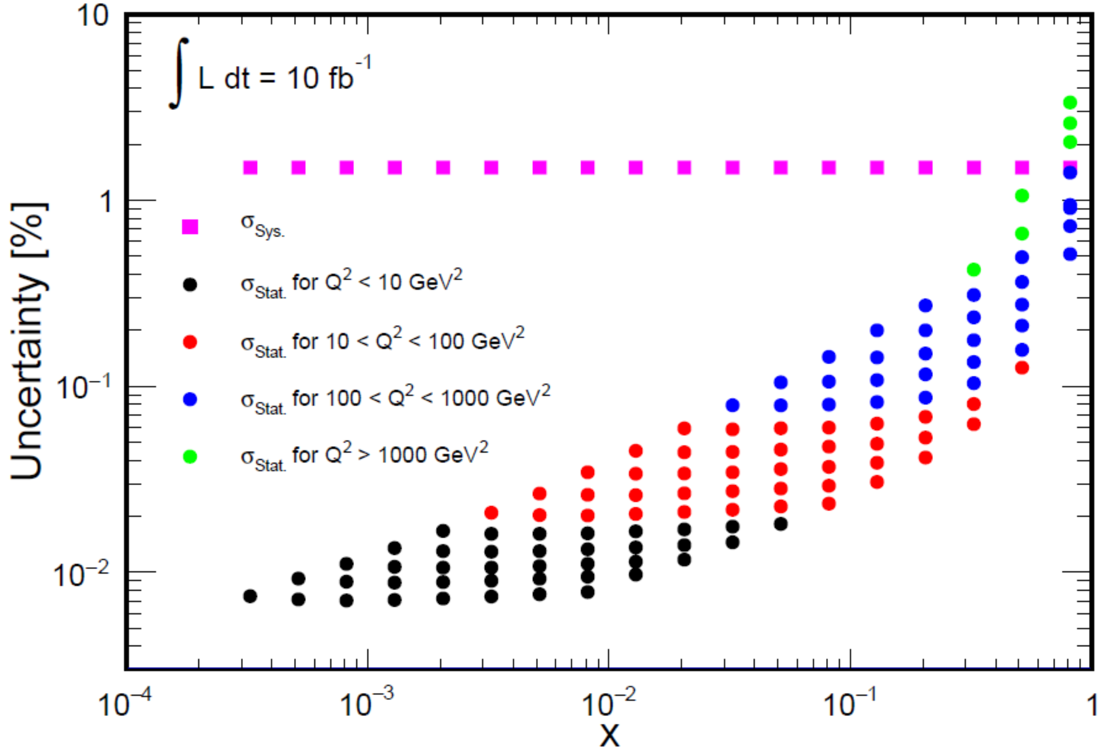
Unpolarized nucleon PDFs

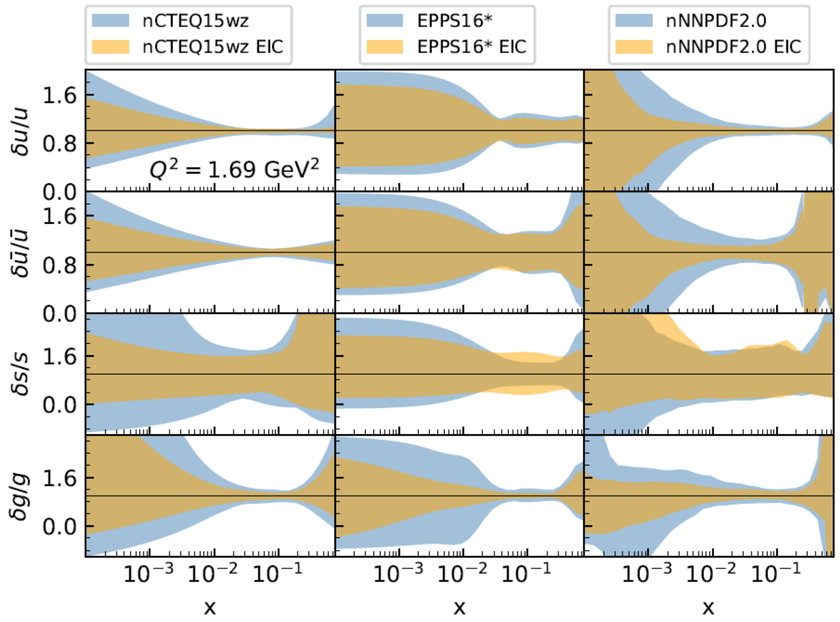


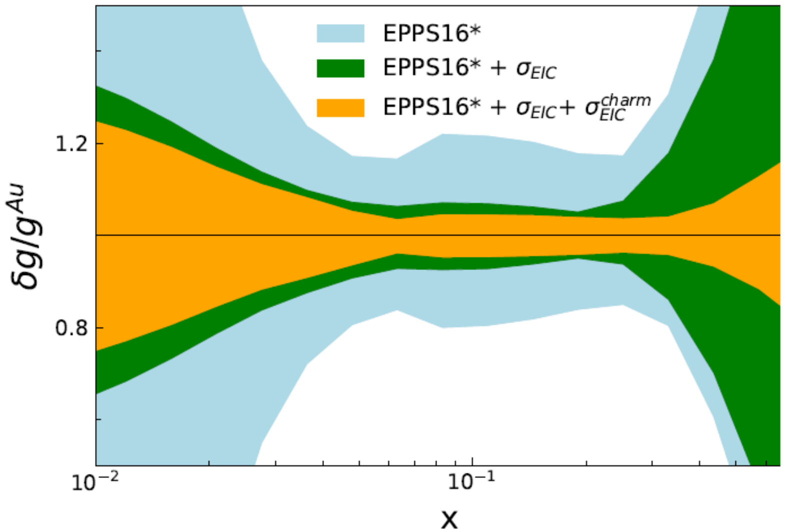


Unpolarized nuclear PDFs at the EIC

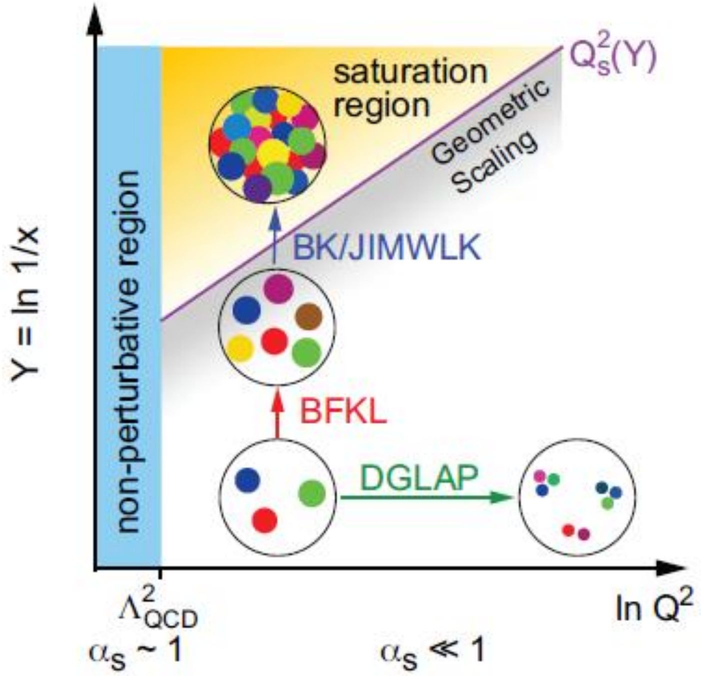
e-Au NC at $\sqrt{s}$ = 89 GeV (18x110 GeV)

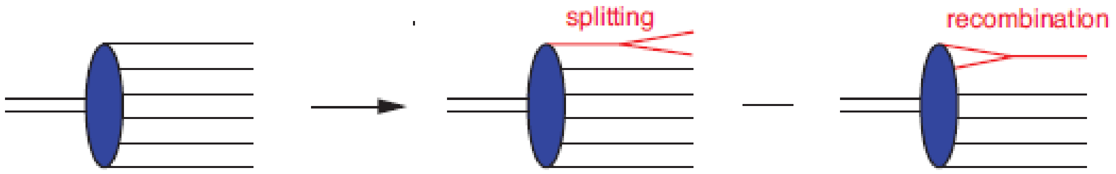




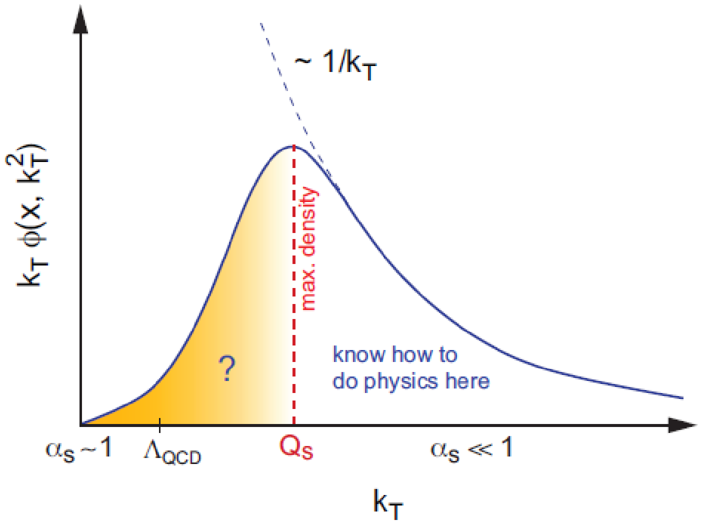


Gluon saturation at high energies (low x)





$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T) - \alpha_s [N(x, r_T)]^2$$



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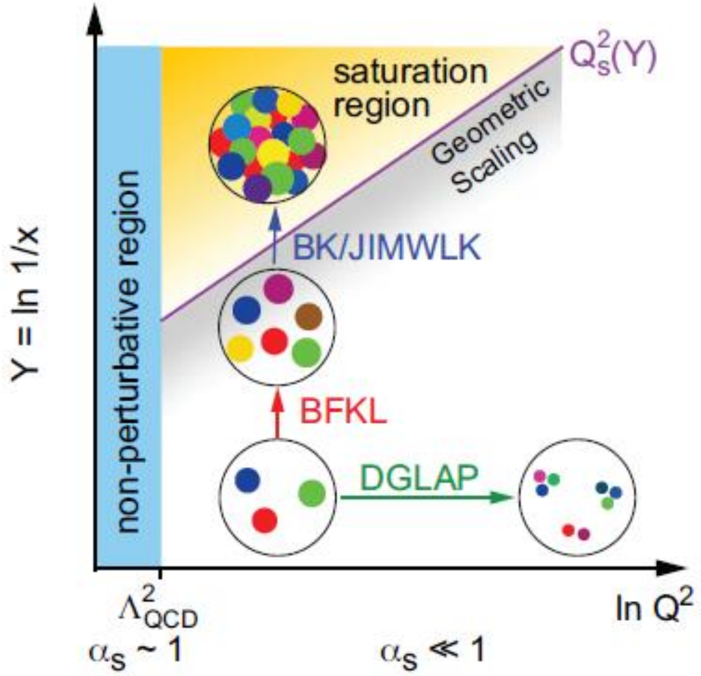

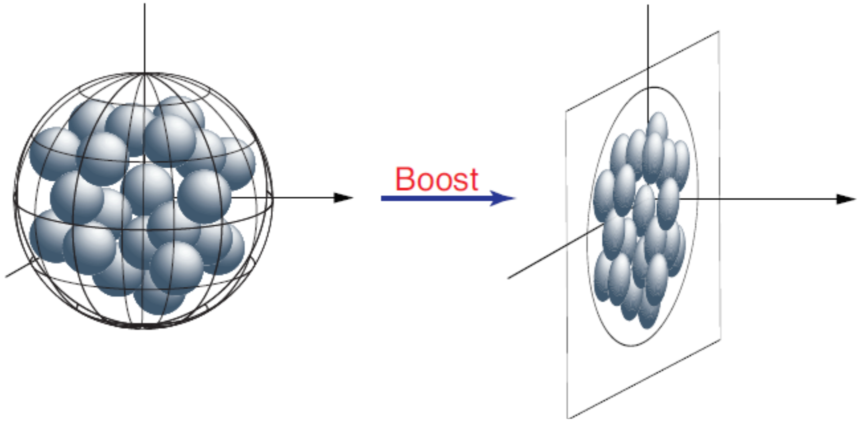

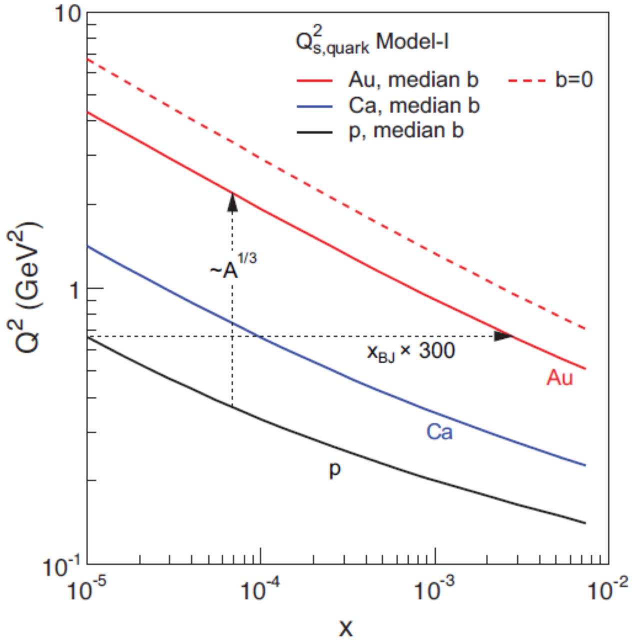

$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$

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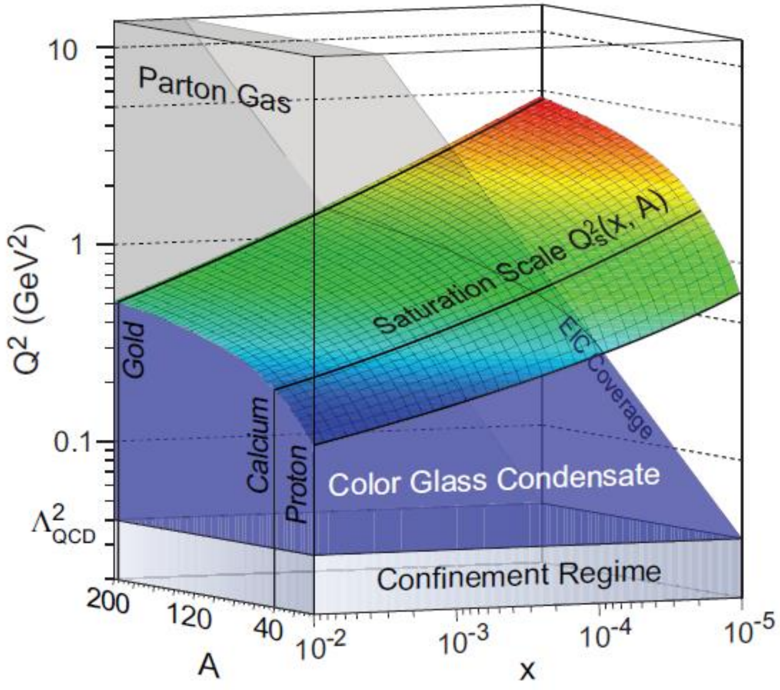

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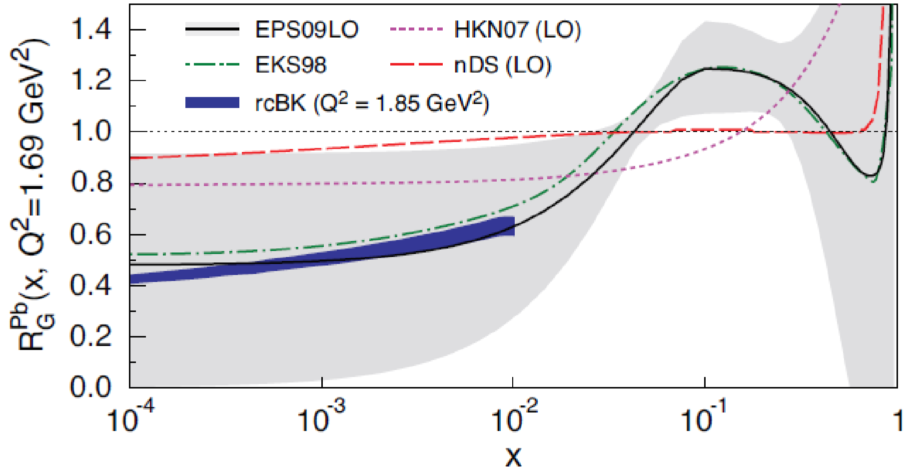
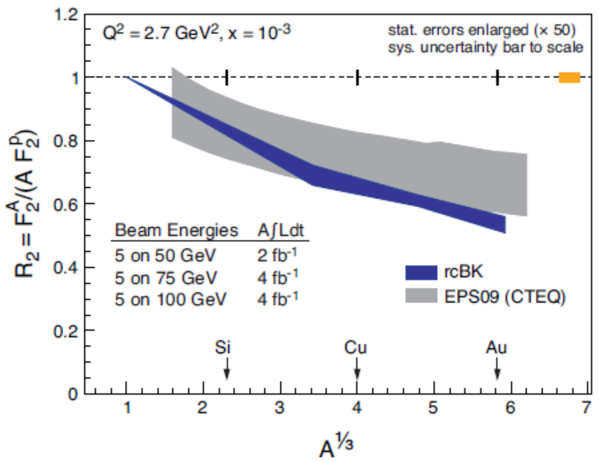
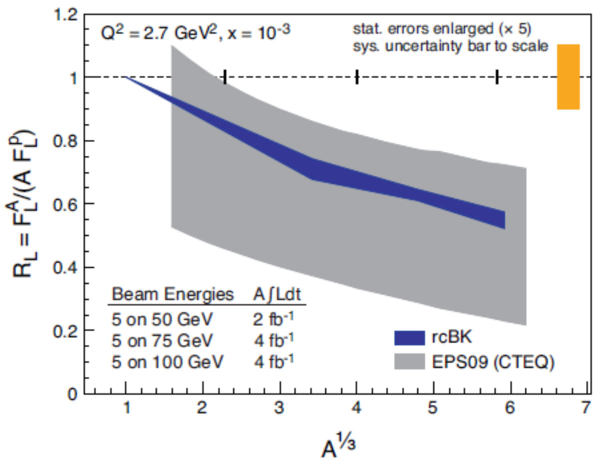
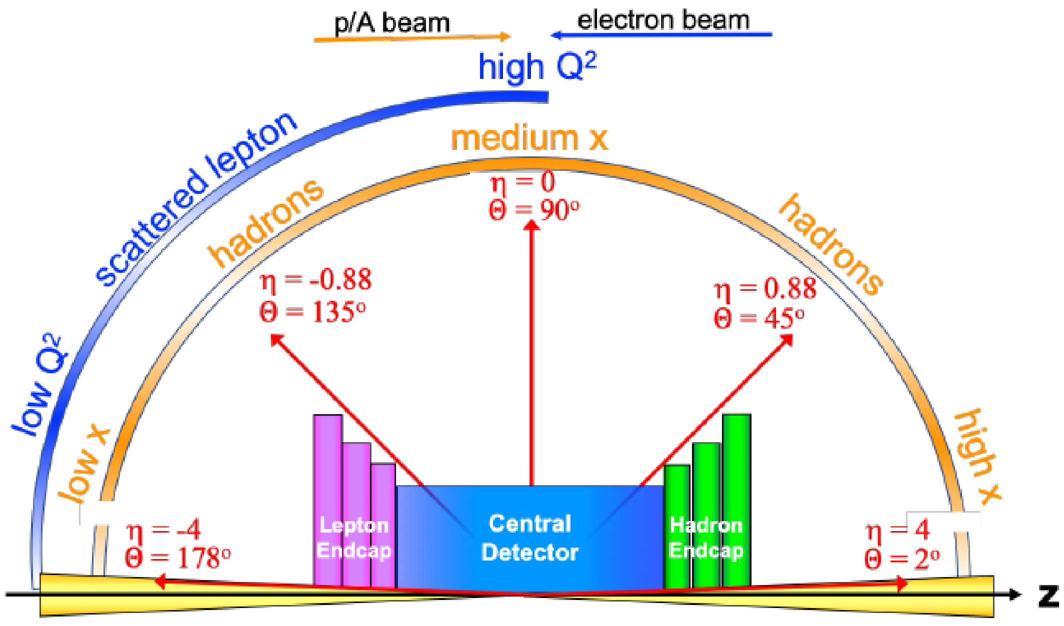






Detector requirements and associated detector design challenges



Detector requirements from EIC Yellow report

η	Nomenclature			Tracking: Min p_T	Tracking: Resolution	Tracking: Allowed X/X_0	Tracking: Si-Vertex	Electrons and Photons: Min E	Electrons and Photons: Resolution σ_E/E	Electrons and Photons: PID	π/K/p PID: p-Range (GeV/c)	π/K/p PID: Separation	HCAL: Min E	HCAL: Resolution σ_E/E	Muons
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q² tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV²										
...															
-4.5 — -4.0			Instrumentation to separate charged particles from γ						2%/√E+(1-3)%						
-4.0 — -3.5				100 MeV π 135 MeV K				50 MeV						~50%/√E+6%	
-3.5 — -3.0		Central Detector	Backwards Detectors		$\sigma_p/p \sim 0.1\% \times p + 2.0\%$	~5% or less				π suppression up to 1:10⁴	≤ 7 GeV/c	≥ 3σ	~500 MeV	~45%/√E+6%	Useful for bkg, improve resolution
-3.0 — -2.5							$\sigma_{xy} \sim 30 \mu m/p_T + 40 \mu m$								
-2.5 — -2.0					$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30 \mu m/p_T + 20 \mu m$								
-2.0 — -1.5									7%/√E+(1-3)%						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p + 0.5\%$		$\sigma_{xyz} \sim 20$ μm, $d_0(z) \sim d_0(r\varphi) \sim 20/p_T$ GeV μm + 5 μm		(10-12)%/√E+(1-3)%		≤ 10 GeV/c			~85%/√E+7%	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30 \mu m/p_T + 20 \mu m$			3σ e/π	≤ 30 GeV/c			~35%/√E	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					$\sigma_p/p \sim 0.1\% \times p + 2.0\%$		$\sigma_{xy} \sim 30 \mu m/p_T + 40 \mu m$				≤ 30 GeV/c				
3.0 — 3.5							$\sigma_{xy} \sim 30 \mu m/p_T + 60 \mu m$				≤ 45 GeV/c				
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from γ												
4.0 — 4.5															
...															
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\lvert t \rvert)/\lvert t \rvert < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c										

Detector requirements and associated detector design challenges

- ➢ Hermetic coverage for scattered electron – leave no gaps in EMcal coverage while also incorporating PID readout
- ➢ Particle momentum resolution in the forward and backward direction – design trackers to optimize momentum resolution when the particle has a large component parallel to the solenoid field
- ➢ Scattered electron purity in the backwards direction and barrel – high-precision EMcals and additional detectors for low momentum
- ➢ Barrel PID for *π/K/p* separation down to very low momenta – DIRC only covers down to ~600 MeV/c
- ➢ Forward calorimetry and PID – want good jet energy resolution; space is constrained for PID detector placement

Detector requirements from EIC Yellow report

<table>
<tr><th rowspan="2">η</th><th rowspan="2" colspan="3">Nomenclature</th><th colspan="4">Tracking</th><th colspan="3">Electrons and Photons</th><th colspan="2">π/K/p PID</th><th colspan="2">HCAL</th><th rowspan="2">Muons</th></tr>
<tr><th>Min p_T</th><th>Resolution</th><th>Allowed X/X_0</th><th>Si-Vertex</th><th>Min E</th><th>Resolution σ_E/E</th><th>PID</th><th>p-Range (GeV/c)</th><th>Separation</th><th>Min E</th><th>Resolution σ_E/E</th></tr>
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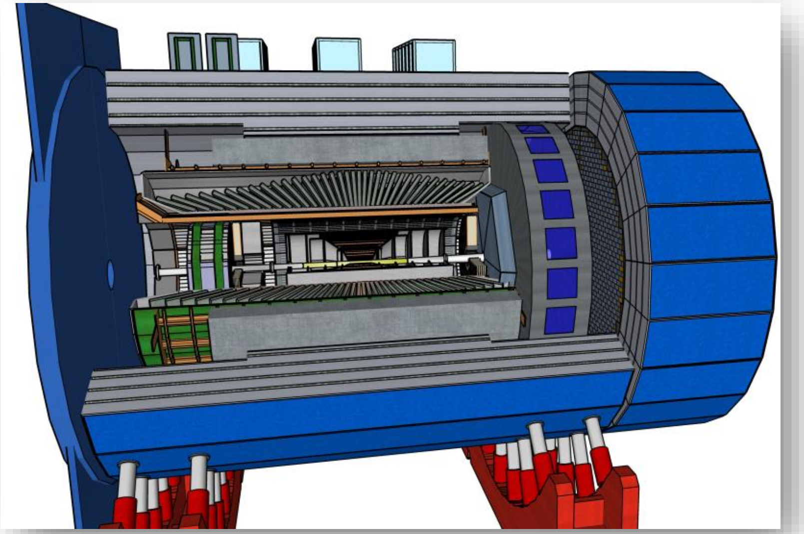
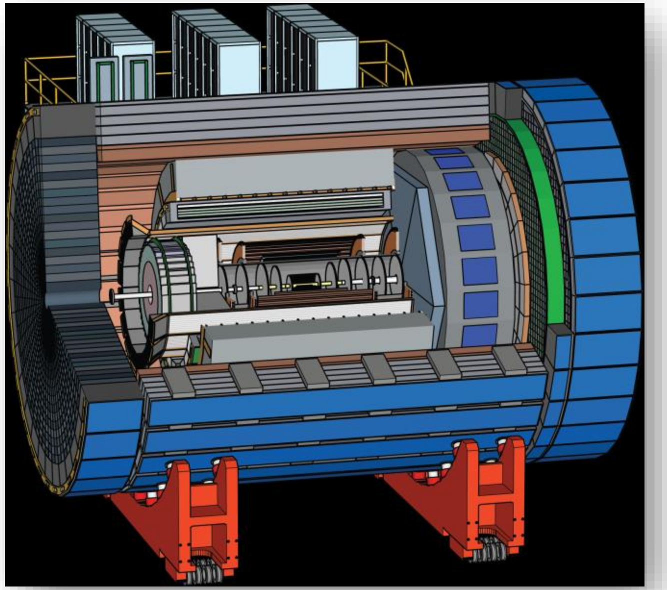
EIC detector proposals

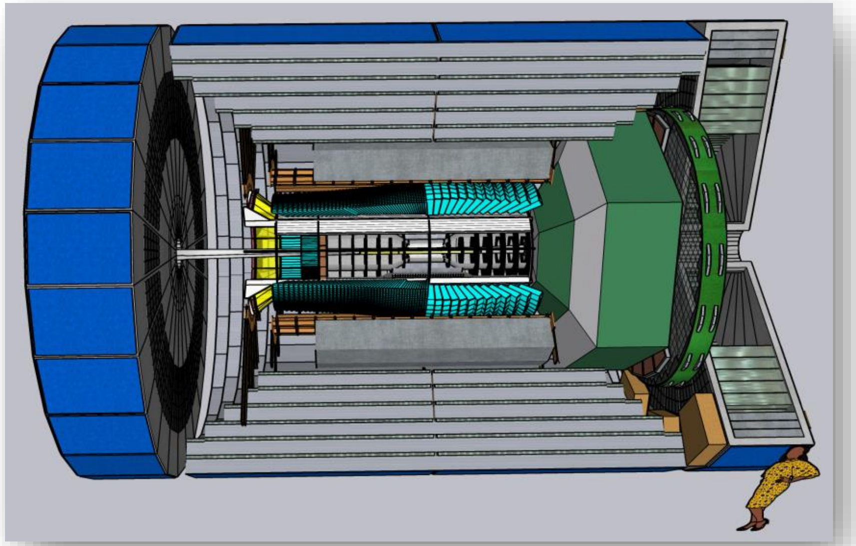
ECCE – EIC Comprehensive Chromodynamics Experiment



ATHENA – A Totally Hermetic Electron-Nucleus Apparatus

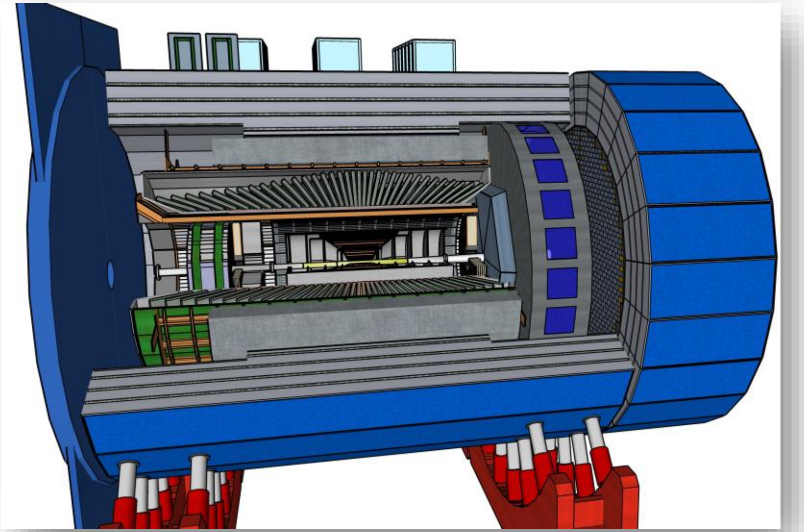


CORE – a COmpact detectoR for the EIC

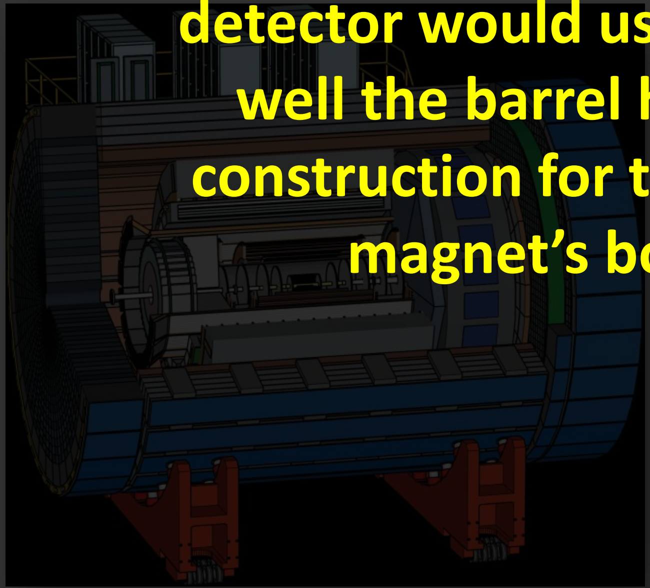


EIC detector proposals

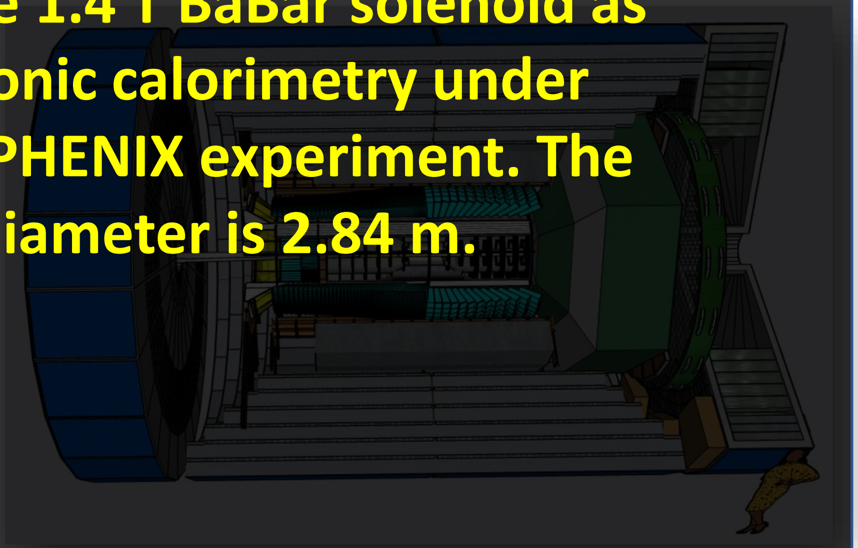
ECCE – EIC Comprehensive Chromodynamics Experiment



ATHENA – A Totally Hermetic Electron-Nucleus Apparatus



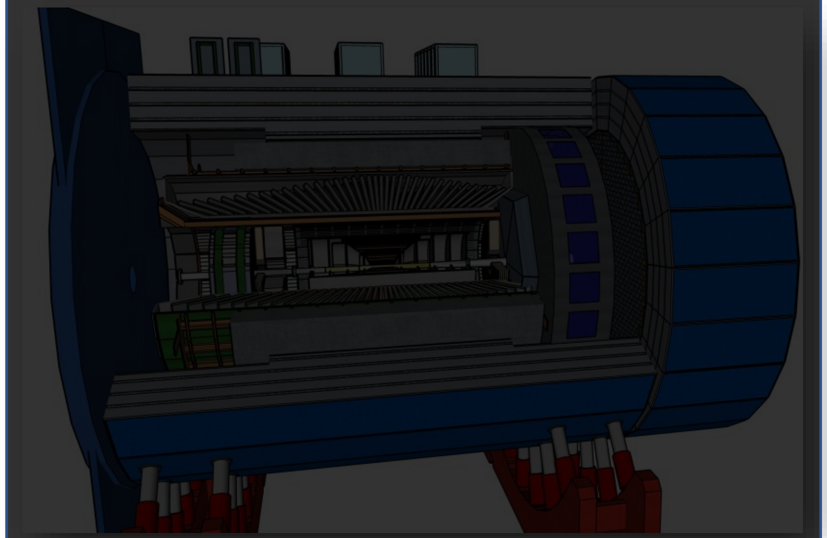
CORE – a COmpact detectoR for the EIC



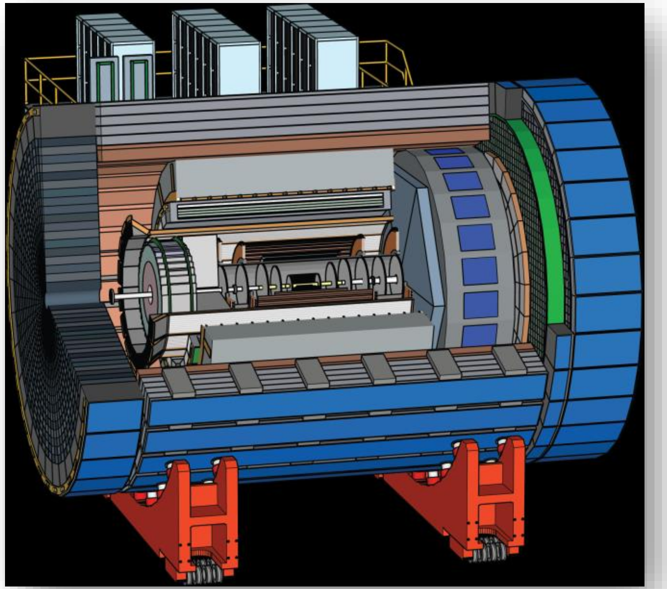
ECCE is a proposal for the first EIC detector. The detector would use the 1.4 T BaBar solenoid as well the barrel hadronic calorimetry under construction for the sPHENIX experiment. The magnet's bore diameter is 2.84 m.

EIC detector proposals

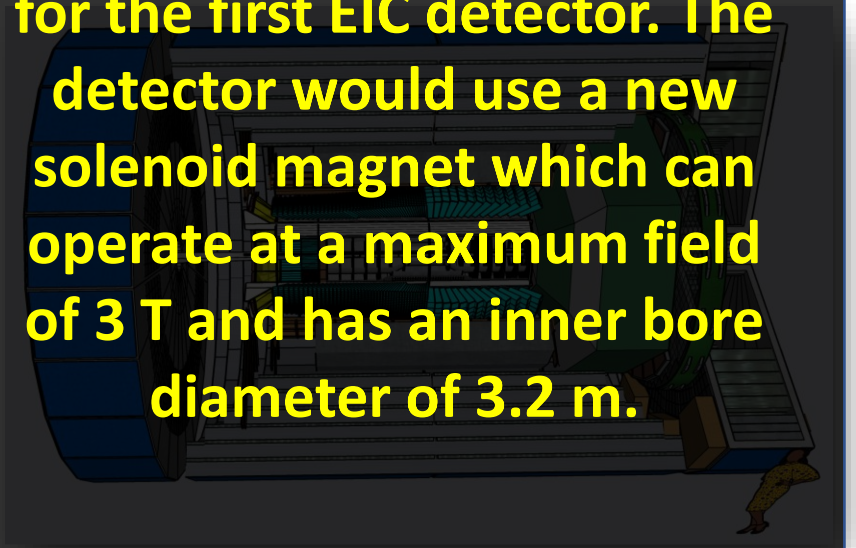
ECCE – EIC Comprehensive Chromodynamics Experiment



ATHENA – A Totally Hermetic Electron-Nucleus Apparatus



CORE – a COmpact detectoR for the EIC

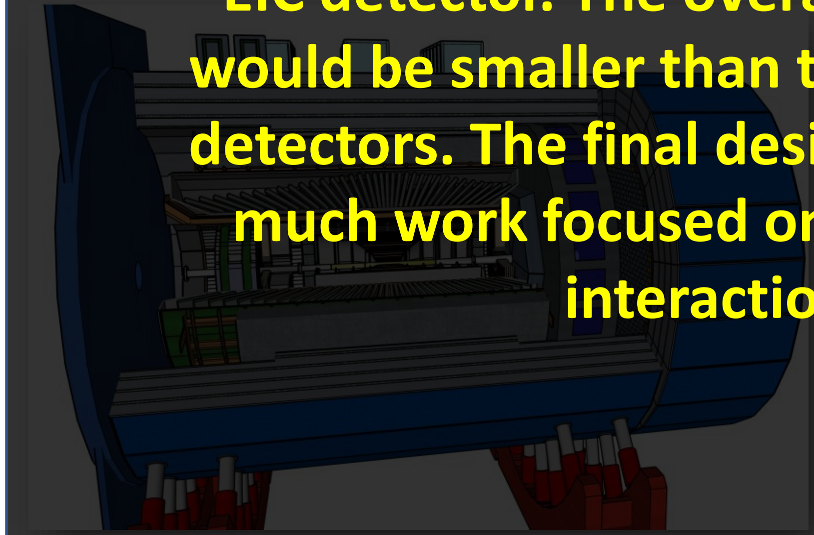


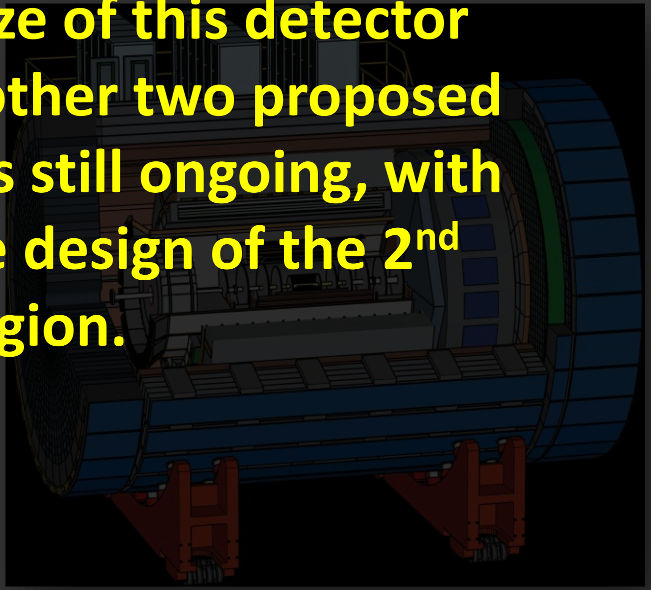
ATHENA is also a proposal for the first EIC detector. The detector would use a new solenoid magnet which can operate at a maximum field of 3 T and has an inner bore diameter of 3.2 m.

EIC detector proposals

ECCE – EIC Comprehensive Chromodynamics Experiment

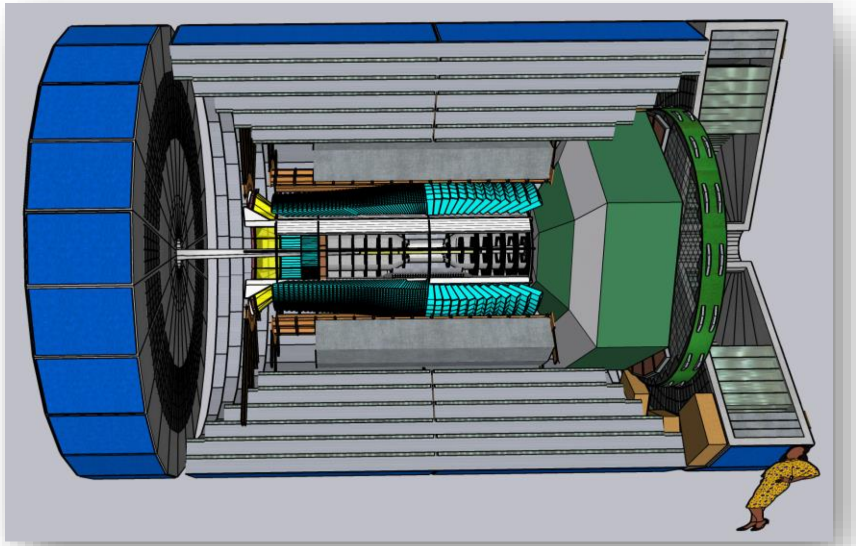
ATHENA – A Totally Hermetic Electron-Nucleus Apparatus



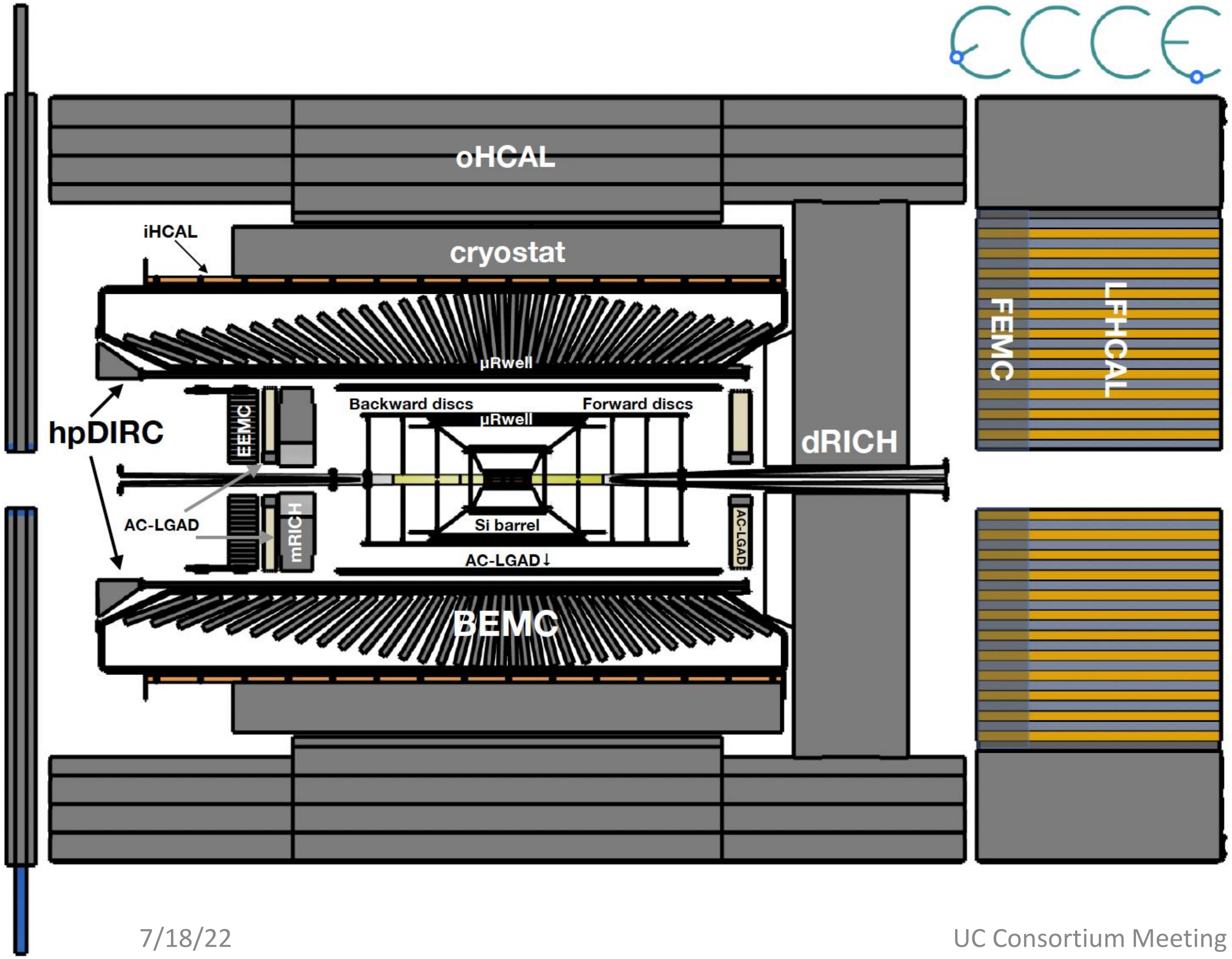


CORE is a proposal for either the 1st or the 2nd EIC detector. The overall size of this detector would be smaller than the other two proposed detectors. The final design is still ongoing, with much work focused on the design of the 2nd interaction region.

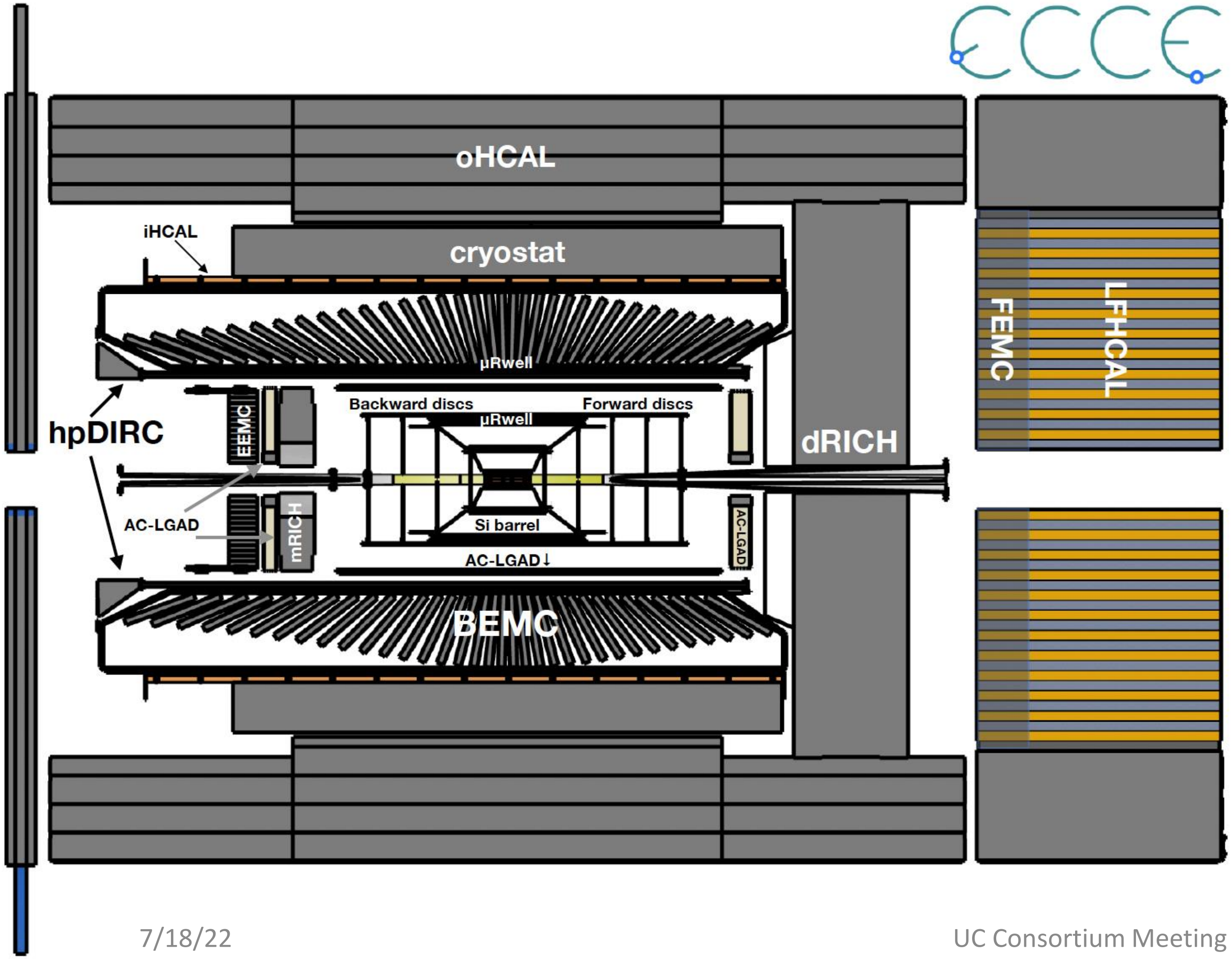
CORE – a COmpact detectoR for the EIC



Details of ECCE detector



Details of ECCE detector



Backward

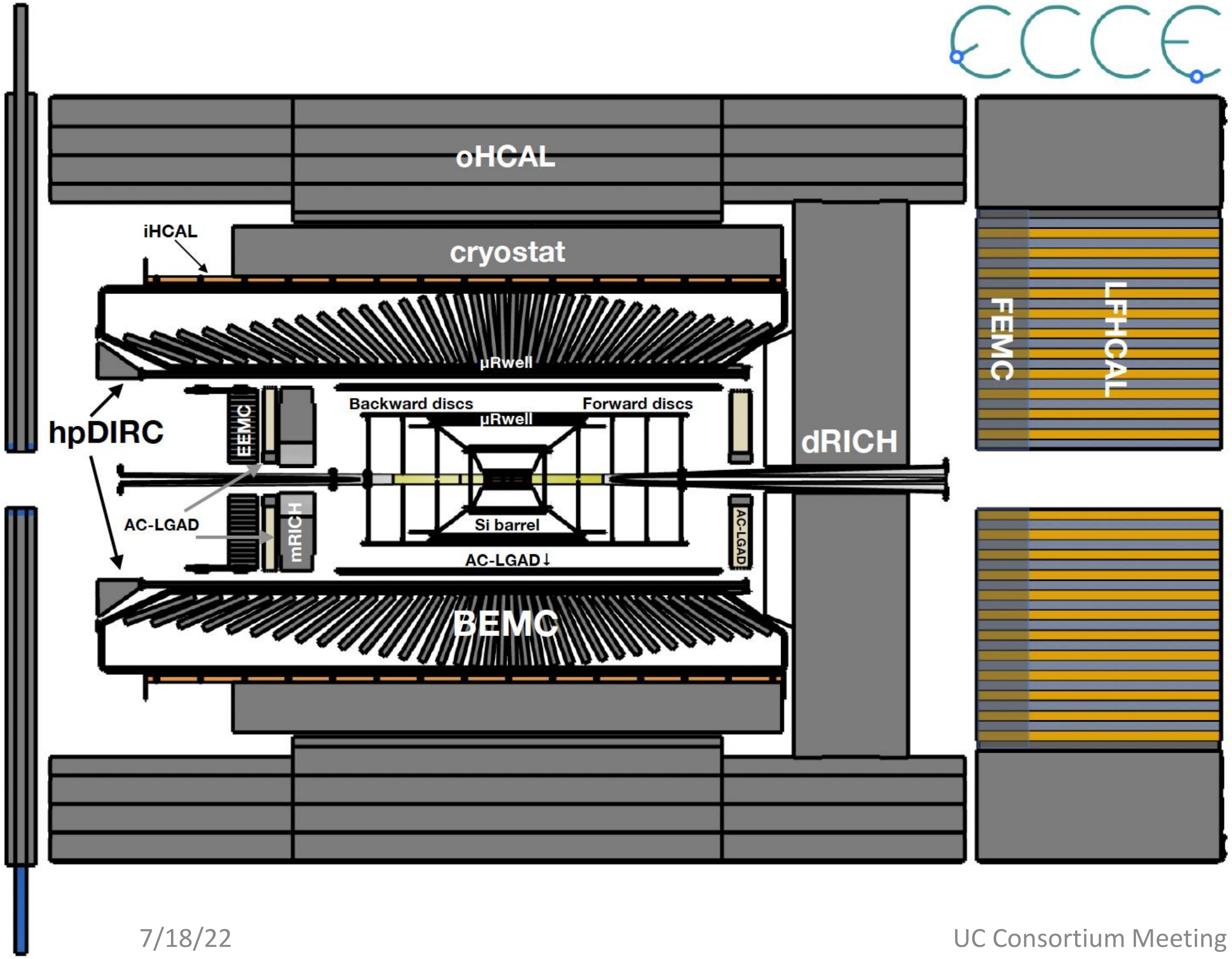
Tracking:

- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:

- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

Details of ECCE detector



Backward

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

Barrel

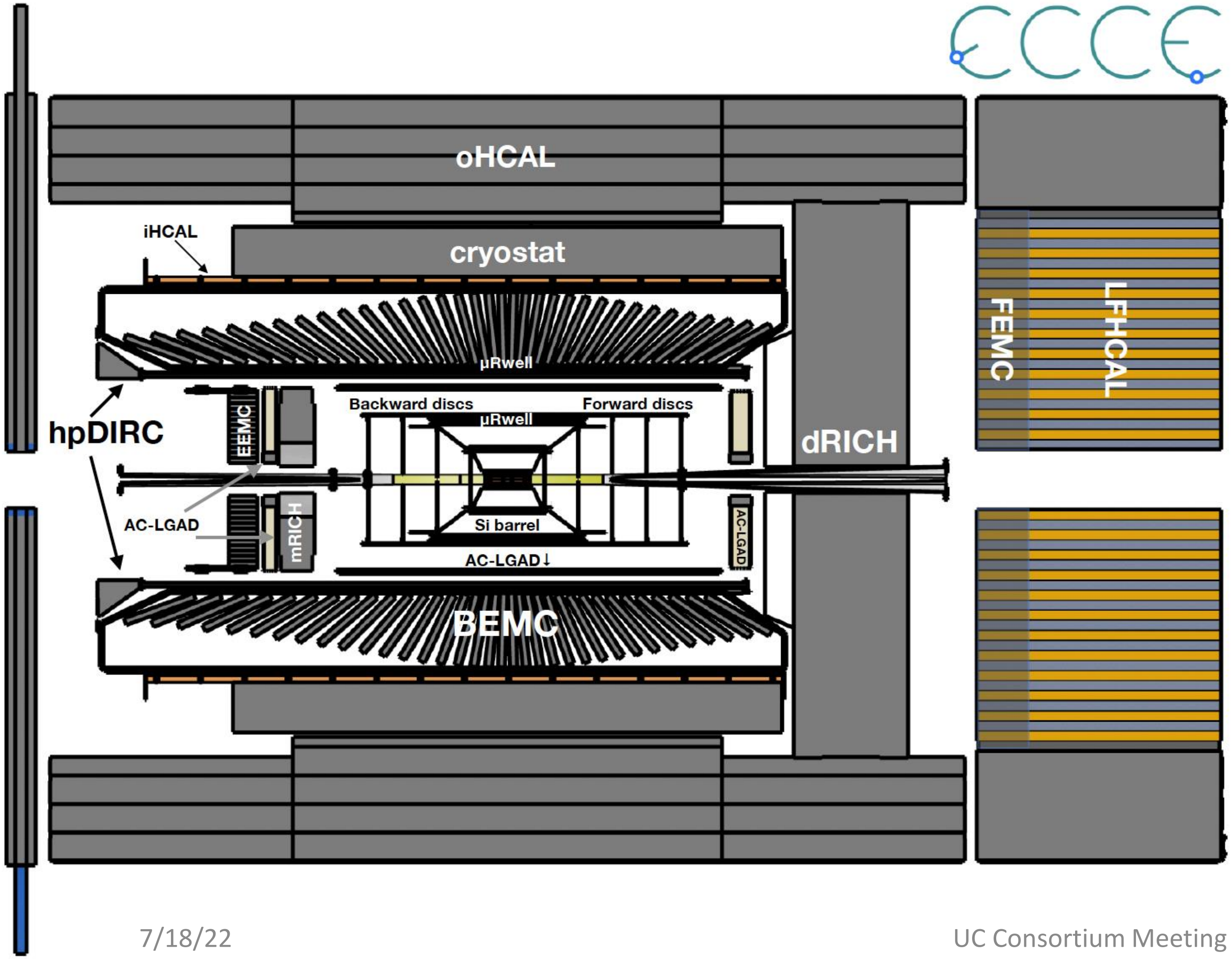
Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)

Details of ECCE detector



Backward

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)

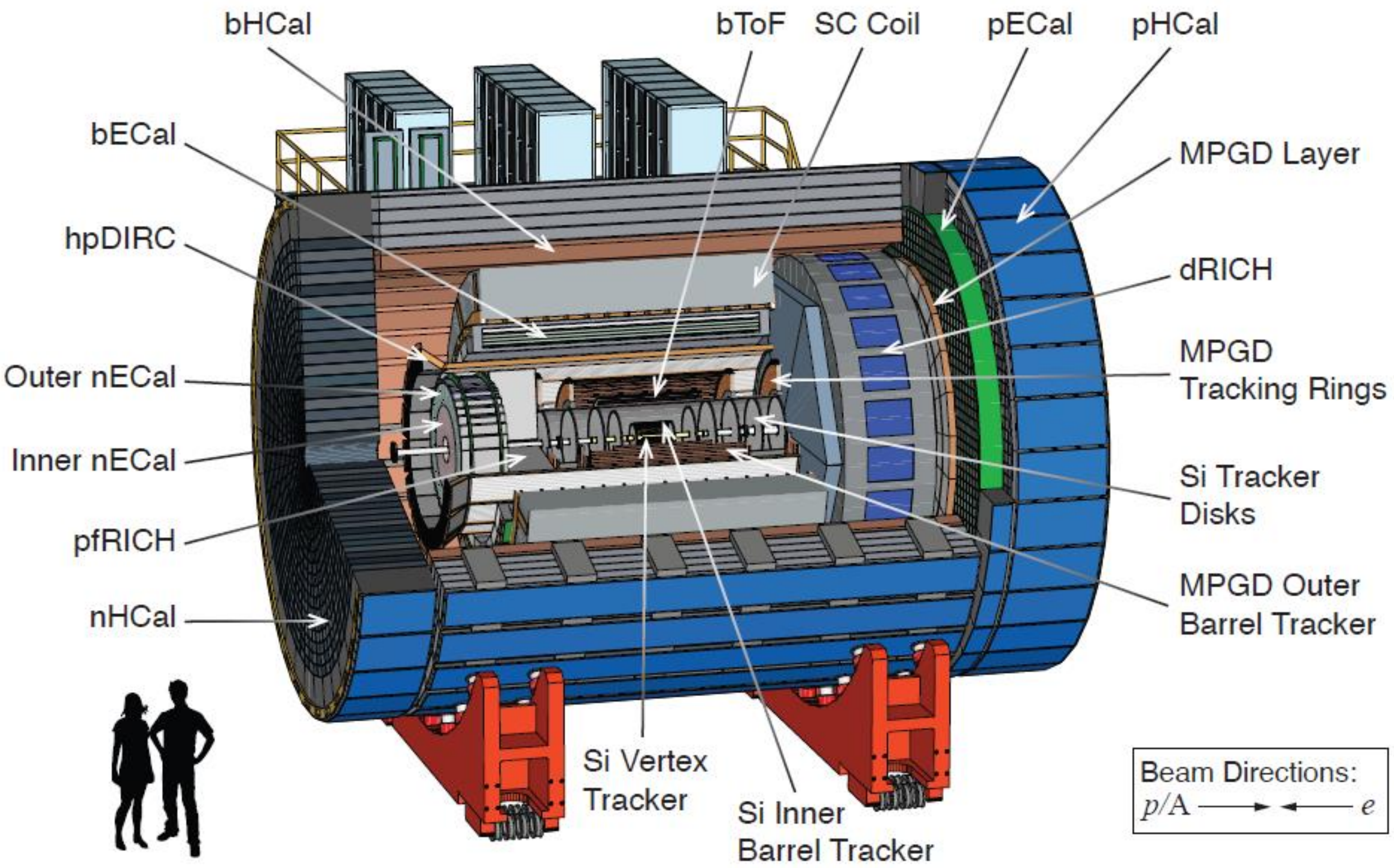
Forward

Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

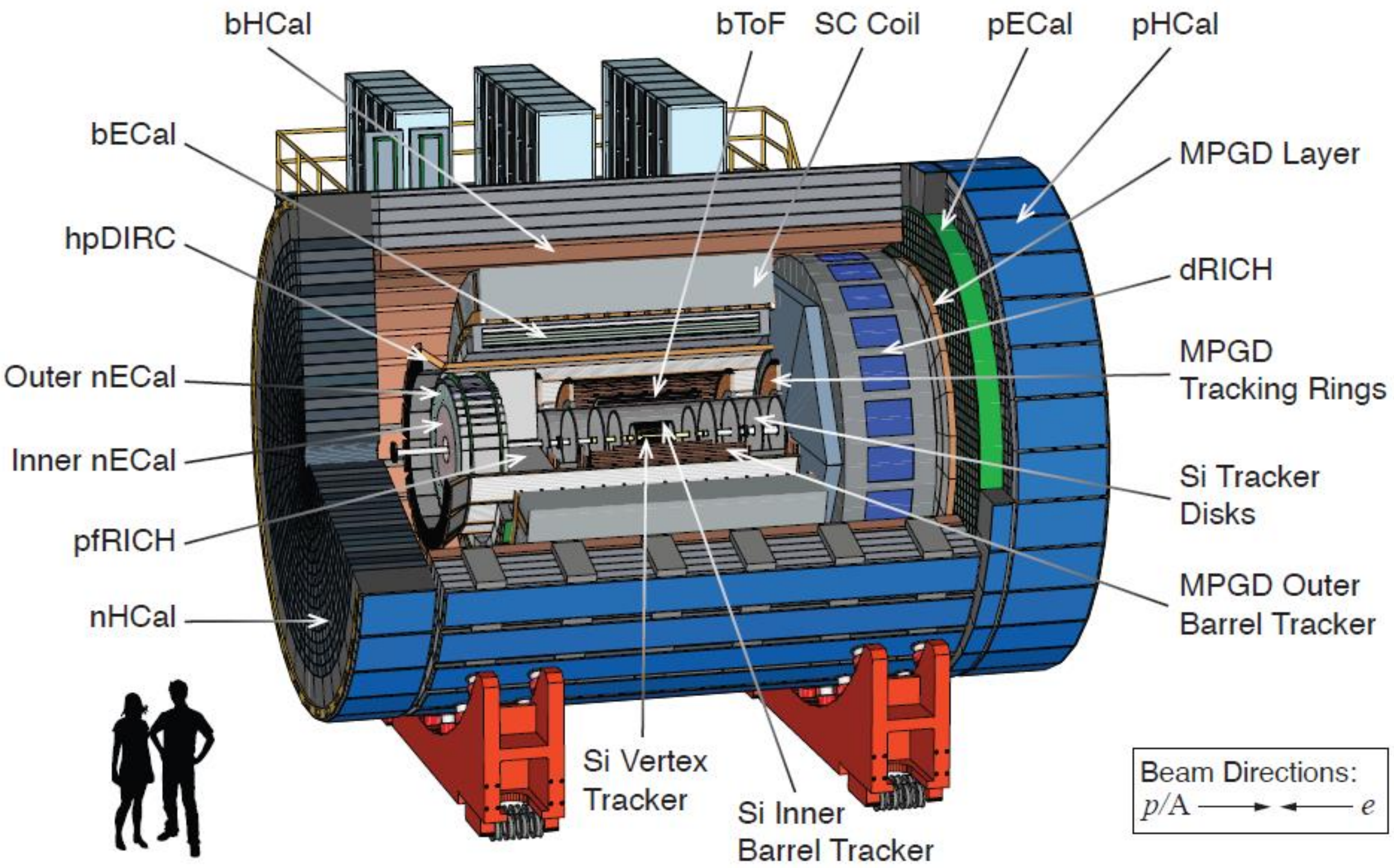
PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LFHCAL)

Details of ATHENA detector



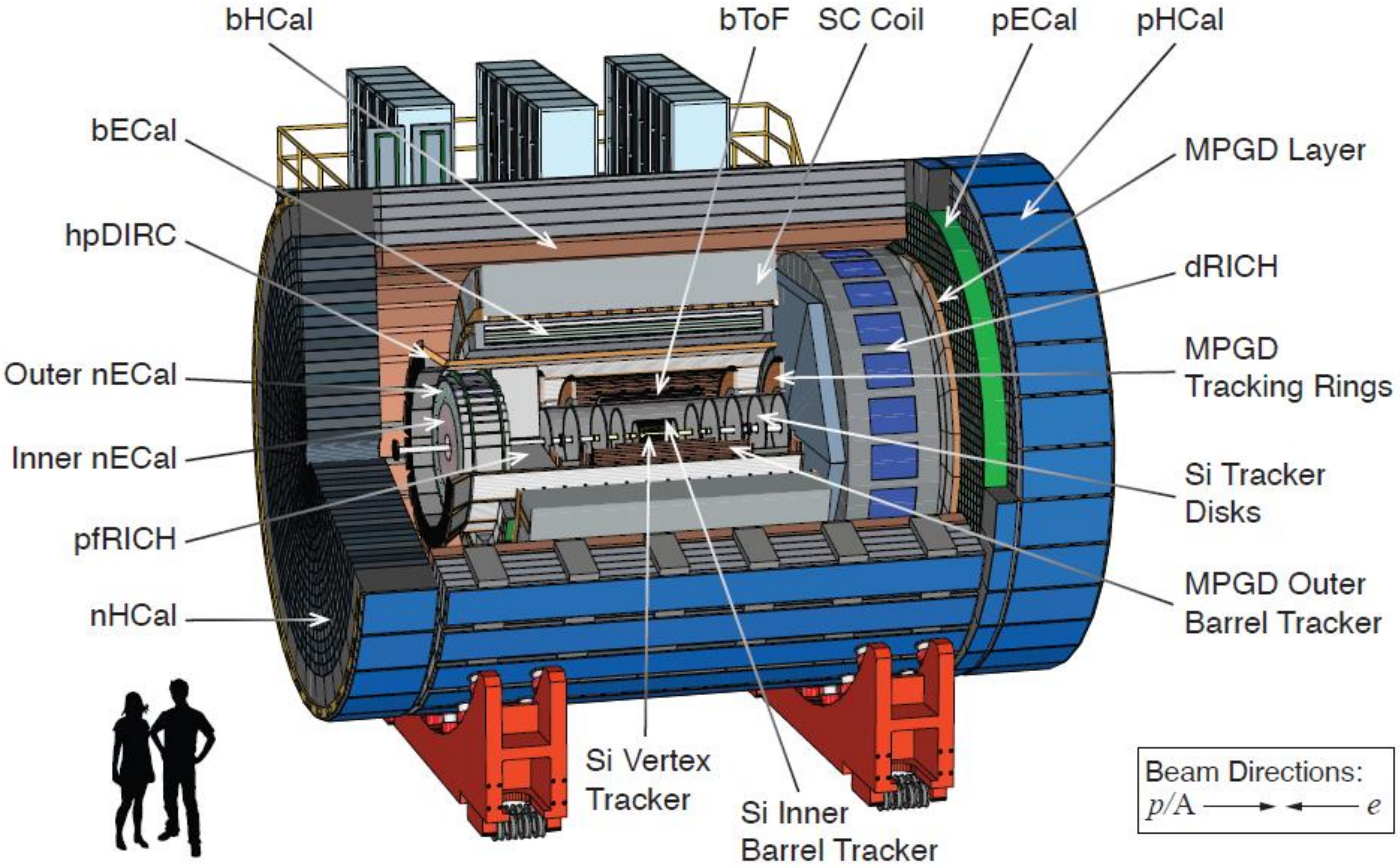
Details of ATHENA detector



Backward

Si-Tracker Disks	Tracking	5 disks of MAPS
Tracking Rings (MPGD)	Tracking	Planar GEMs with annular shape surrounding the Si-disks
pfRICH	PID	Proximity focusing RICH with aerogel
Inner nECal	e/m Calorimetry	$PbWO_4$
Outer nECal	e/m Calorimetry	SciGlass
nHCal	Hadron Calorimetry	Fe/Sci sandwich

Details of ATHENA detector



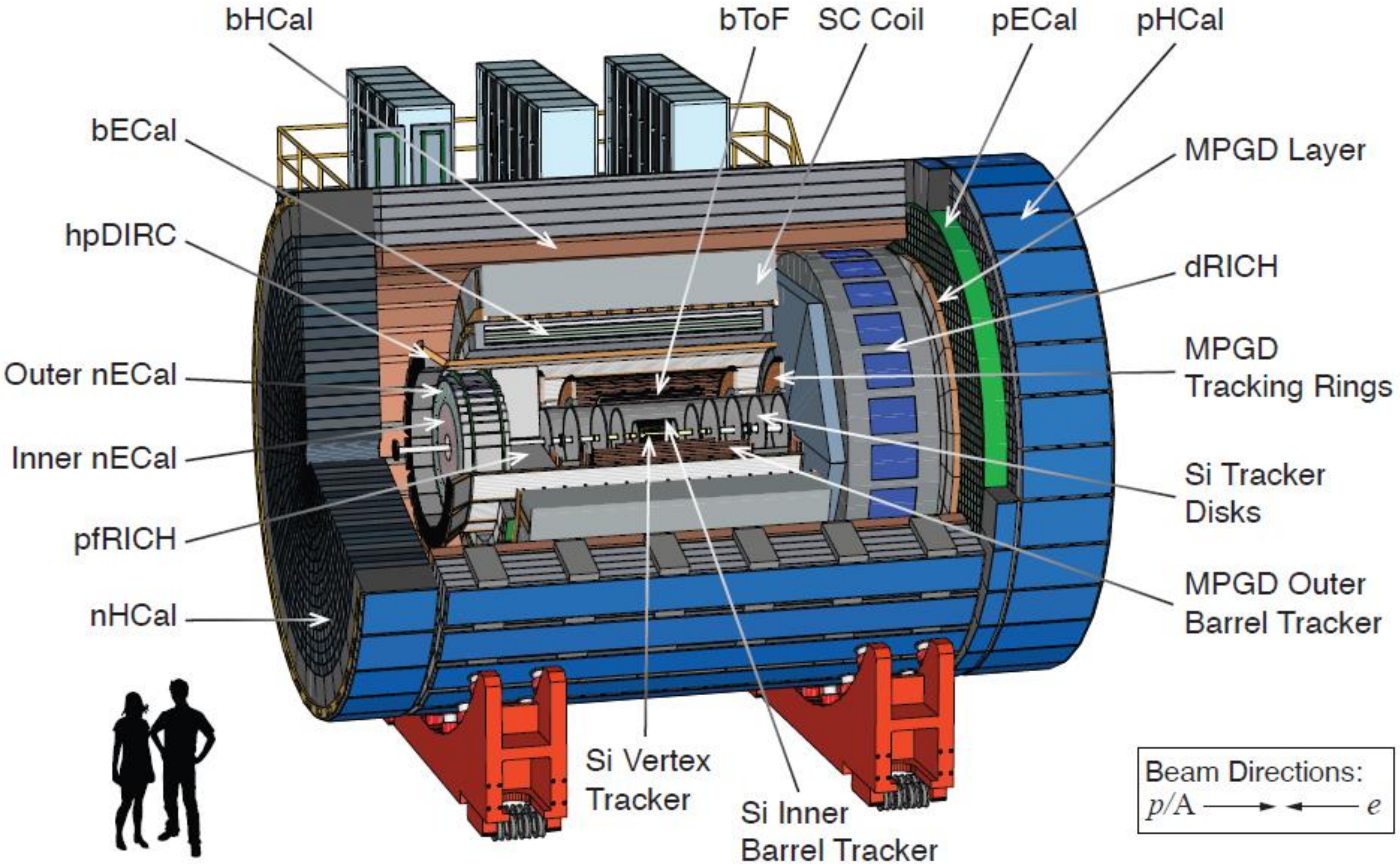
Backward

Si-Tracker Disks	Tracking	5 disks of MAPS
Tracking Rings (MPGD)	Tracking	Planar GEMs with annular shape surrounding the Si-disks
pfRICH	PID	Proximity focusing RICH with aerogel
Inner nECal	e/m Calorimetry	$PbWO_4$
Outer nECal	e/m Calorimetry	SciGlass
nHCal	Hadron Calorimetry	Fe/Sci sandwich

Barrel

Si Vertex-Tracker	Tracking and Vertexing	3-layer MAPS
Si Barrel-Tracker	Tracking	2-layer MAPS
bToF	PID and Tracking	AC-LGAD
Barrel Tracker (MPGD)	Tracking	4 (2+2) layer cylindrical Micromegas
hpDIRC	PID	DIRC with focusing elements and fine pixel readout
bECal	e/m Calorimetry & Tracking	Hybrid with Astropix imaging layers alternated with Pb/SciFi layers followed by a set of Pb/SciFi layers
bHCal	Hadron Calorimetry	Fe/Sci sandwich

Details of ATHENA detector



Backward

Si-Tracker Disks	Tracking	5 disks of MAPS
Tracking Rings (MPGD)	Tracking	Planar GEMs with annular shape surrounding the Si-disks
pfRICH	PID	Proximity focusing RICH with aerogel
Inner nECal	e/m Calorimetry	$PbWO_4$
Outer nECal	e/m Calorimetry	SciGlass
nHCal	Hadron Calorimetry	Fe/Sci sandwich

Barrel

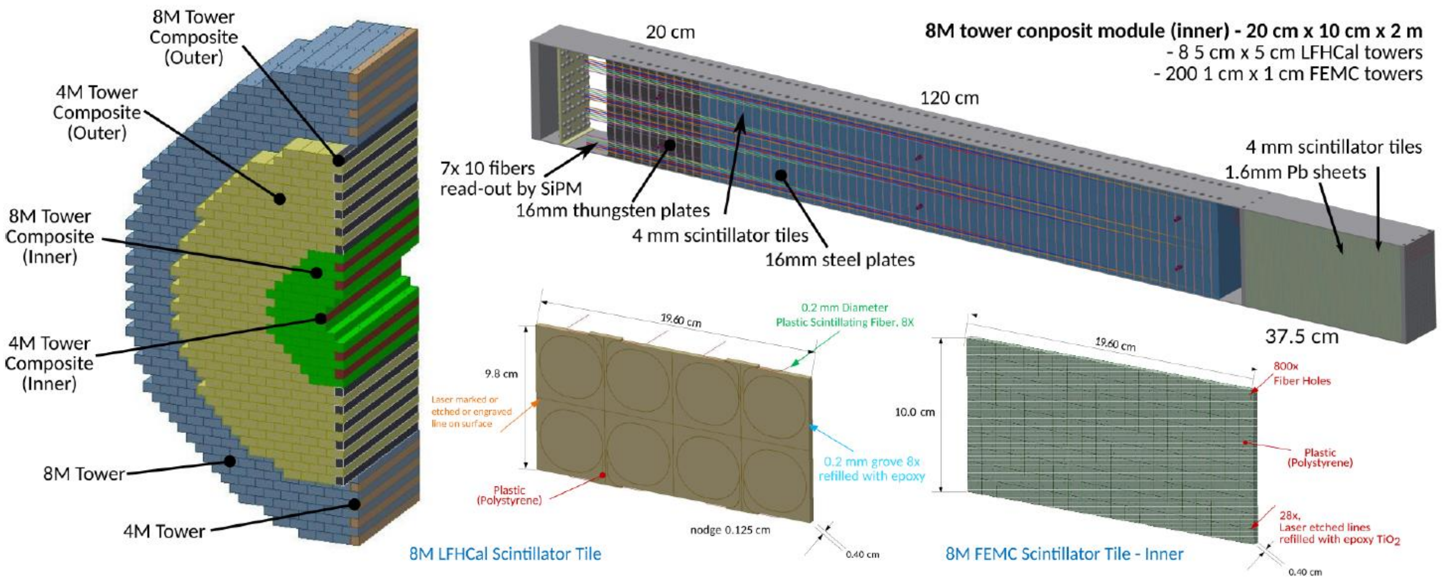
Si Vertex-Tracker	Tracking and Vertexing	3-layer MAPS
Si Barrel-Tracker	Tracking	2-layer MAPS
bToF	PID and Tracking	AC-LGAD
Barrel Tracker (MPGD)	Tracking	4 (2+2) layer cylindrical Micromegas
hpDIRC	PID	DIRC with focusing elements and fine pixel readout
bECal	e/m Calorimetry & Tracking	Hybrid with Astropix imaging layers alternated with Pb/SciFi layers followed by a set of Pb/SciFi layers
bHCal	Hadron Calorimetry	Fe/Sci sandwich

Forward

Si-Tracker Disks	Tracking	6 disks of MAPS
Tracking Rings (MPGD)	Tracking	Planar GEMs with annular shape surrounding the Si-disks
dRICH	PID	Dual RICH with aerogel and gas
MPGD Layer	Tracking	Planar μRWell disk
pECal	e/m Calorimetry	W-Powder/SciFi calorimeter
pHCal	Hadron Calorimetry	Fe/Sci sandwich

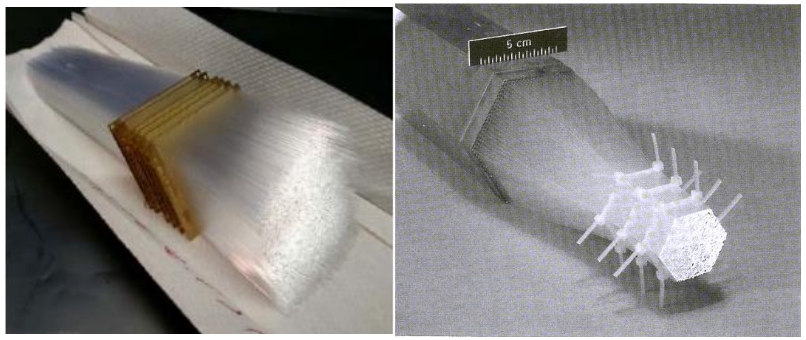
ECCE and ATHENA comparison – forward calorimetry

ECCE design



	EMcal	Hcal
ECCE	Pb/Shashlik	Fe/W/Scint (longitudinally segmented)
ATHENA	W/SciFi (similar to sPHENIX)	Fe/Scint (similar to STAR FCS)

SciFi calorimeter



EIC Detector Proposal Advisory Panel (DPAP) report

- The three detector proposals were submitted in December 2021. The DPAP report was then issued in March 2022.
- The main conclusions from the report are as follows:

  “The panel finds that ECCE and ATHENA fulfill all requirements for a Detector 1. ECCE has several advantages, in particular reduced risk and cost, and qualifies best for Detector 1. CORE presented a more conceptual design...The panel unanimously recommends ECCE as Detector 1. The proto-collaboration is urged to openly accept additional collaborators and quickly consolidate its design so that the Project Detector can advance to CD2/3a in a timely way.”

  “The panel supports the case for a second EIC detector, however, given the current funding and available resources, the committee finds that a decision on Detector 2 should be delayed until the resources and schedule for the Project detector (Detector 1) are more fully realized.”

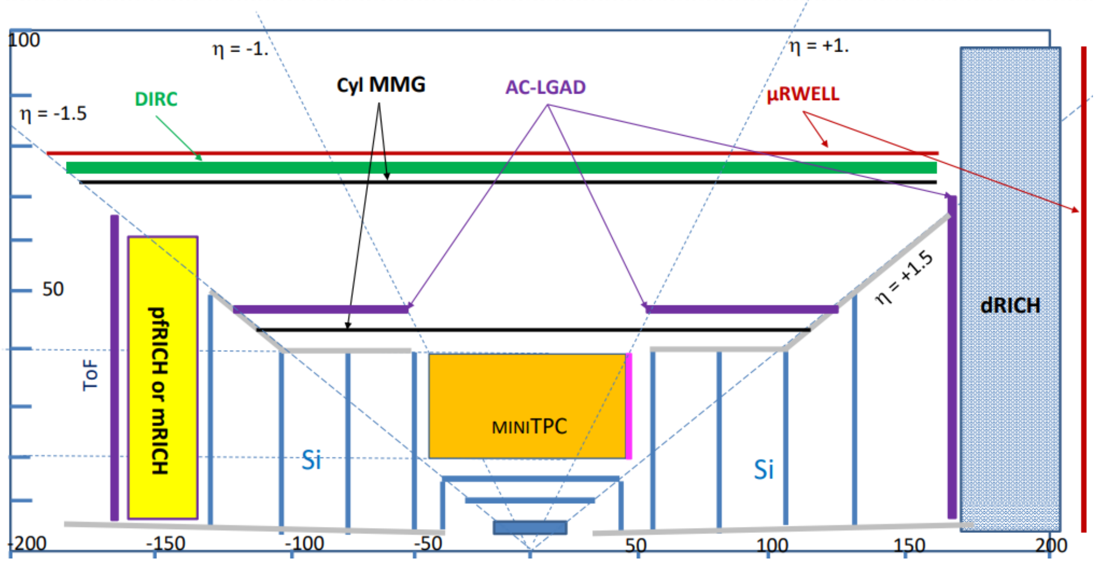
Towards the first EIC detector

- Following the DPAP report, the ECCE and ATHENA ‘collaborations’ have merged into a single *Detector 1* effort, and joint detector and physics working groups have now been formed.
- “The overall goal of the detector WG’s is to optimize the ECCE reference design towards a technical design…”.
- The physics working groups should “[w]ork with the Detector Working Groups to perform constant validation of the performances for physics observables.”
- The upshot of the above is that certain parts of the *Detector 1* design – such as the use of the BaBar solenoid – have been set. Other aspects, such as the final detector subsystem decisions are being discussed by the working groups.

Examples – tracking and calorimetry

- Much discussion on how to optimize tracker design. For example, the option below was presented at last week's tracking WG meeting.

EIC detector 1 Barrel Tracker: The eRD108 mini-TPC option



	EMcal	Hcal
ECCE	Pb/Shashlik	Fe/W/Scint (longitudinally segmented)
ATHENA	W/SciFi (similar to sPHENIX)	Fe/Scint (similar to STAR FCS)
Detector 1 (Recommended)	ATHENA	ECCE?

- Ease of construction
- Less space needed for W/SciFi
- Better shower containment
- Comparable costs

How to get involved

- Sign up for the *Detector 1* mailing lists and attend some of the WG meetings.
- Software information:
  - Try to run some of the EIC event generators. See this tutorial.
  - For the detector geometry, the decision seems to be to move towards using DD4HEP. See this repository for ATHENA based examples.
  - Not sure what the plan is for the reconstruction software (*eJana*?).

Summary

- The EIC will make very important contributions to nuclear physics. The presentations today and tomorrow will cover a wide variety of topics.
- In order to make the best possible measurements at the EIC, a given detector needs to fulfill many requirements, which together present significant technical challenges.
- Following the DPAP process, a new *Detector 1* ‘collaboration’ has formed and is working towards designing a comprehensive, general-purpose EIC detector.