Quarkonia at the Electron-Ion Collider

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Quarkonia as Tools

Aussois – 12th January 2023

Electron-Ion Collider

World's first polarized electron-proton/light ion and electron-Nucleus collider.

For e-N collisions at the EIC:

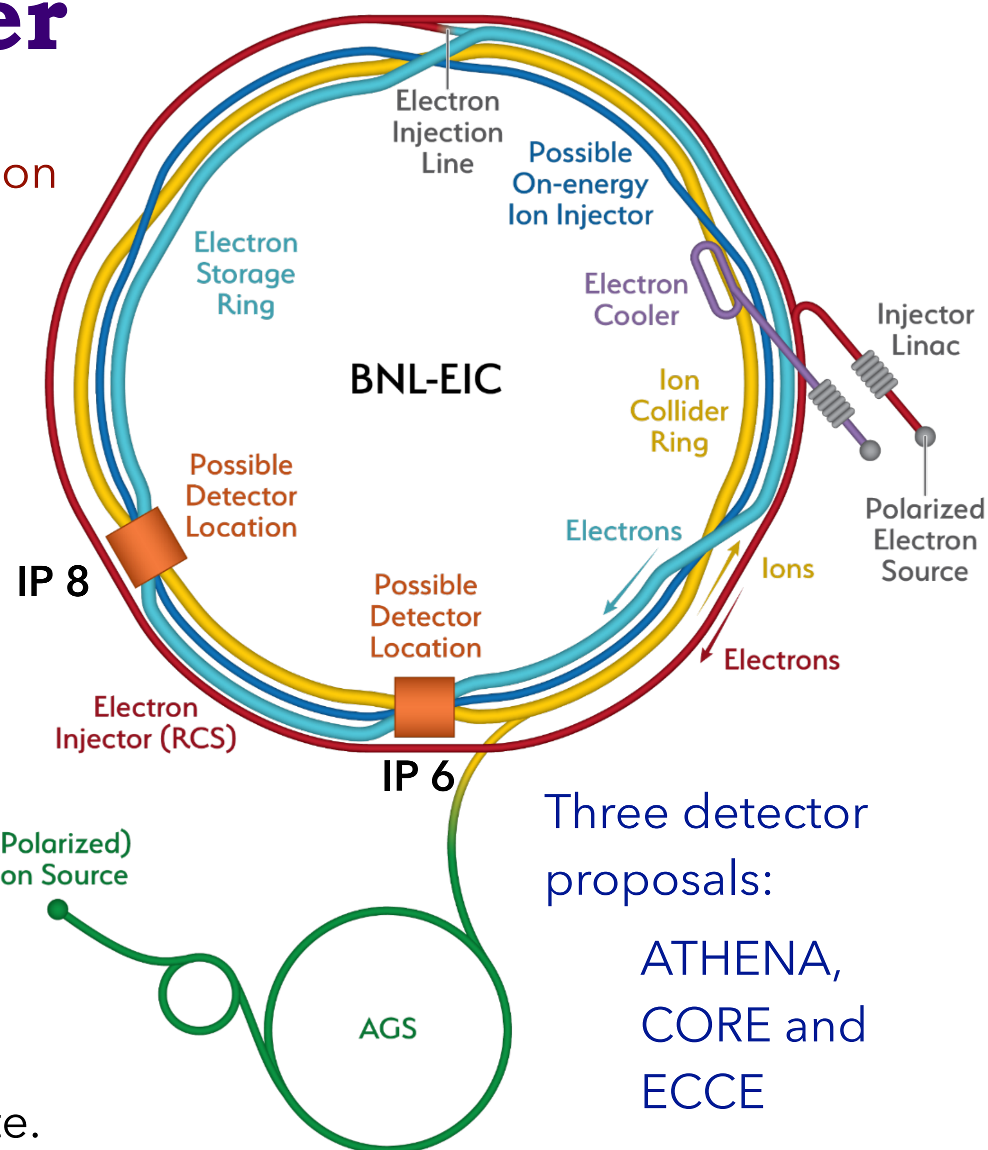
- ✓ Polarized beams (70%): e, p, d/^{3}He
- ✓ e beam 3 - 10 (18) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}s^{-1}
- ✓ 20 - 100 (140) GeV Variable CoM

For e-A collisions at the EIC:

- ✓ Wide range of nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable centre of mass energy

Brookhaven National Lab selected as the site.

Expected start of operations: early 2030s.



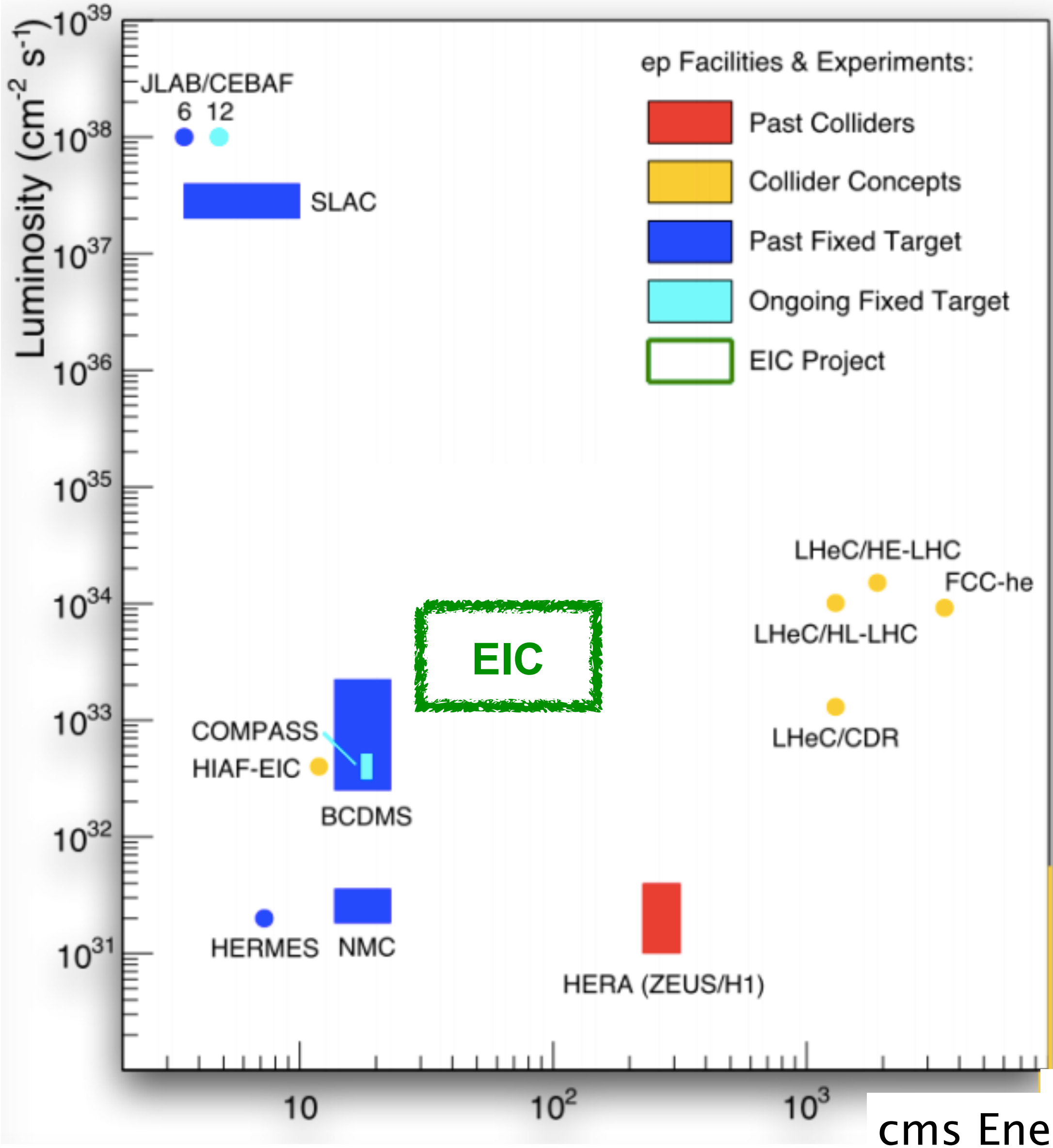
arXiv:1409.1633

Three detector proposals:

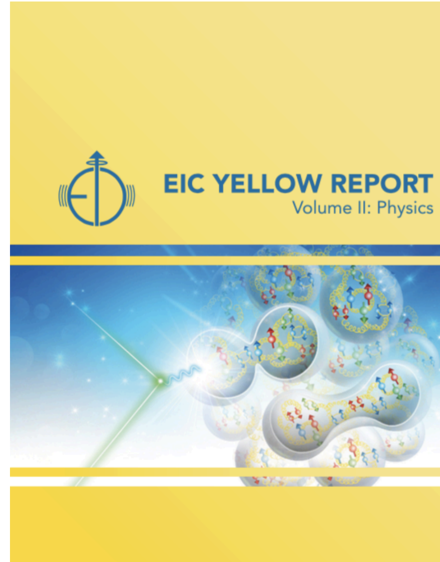
ATHENA, CORE and ECCE

First detector at IP 6

EIC landscape

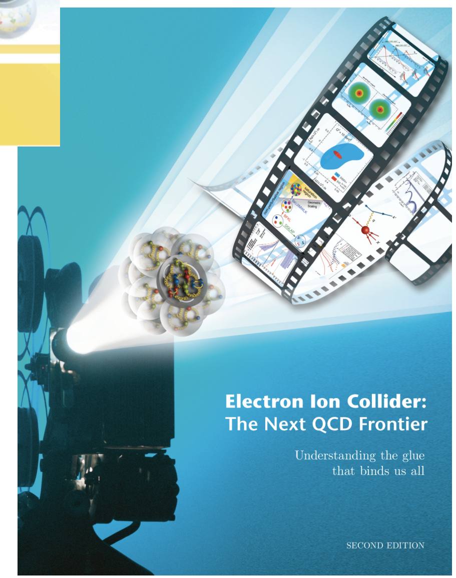


cms Energy



2020 EIC Yellow Report,
Nuc. Phys. A 1026, 122447 (2022)

Dedicated studies of EIC physics and design



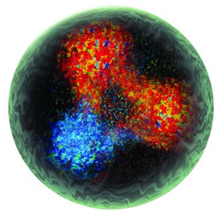
2012 EIC White Paper,
Eur. Phy. J. A 52, 9 (2016)

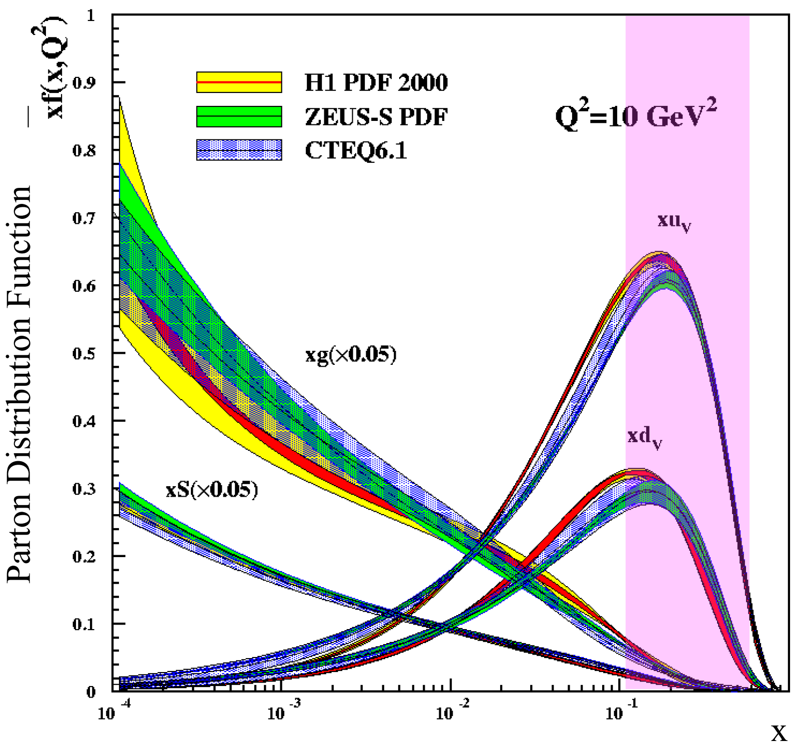
Nucleon at different scales

Valence quarks

Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$





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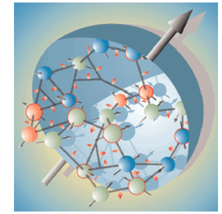

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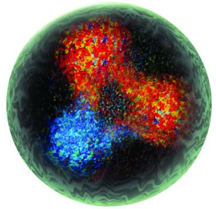
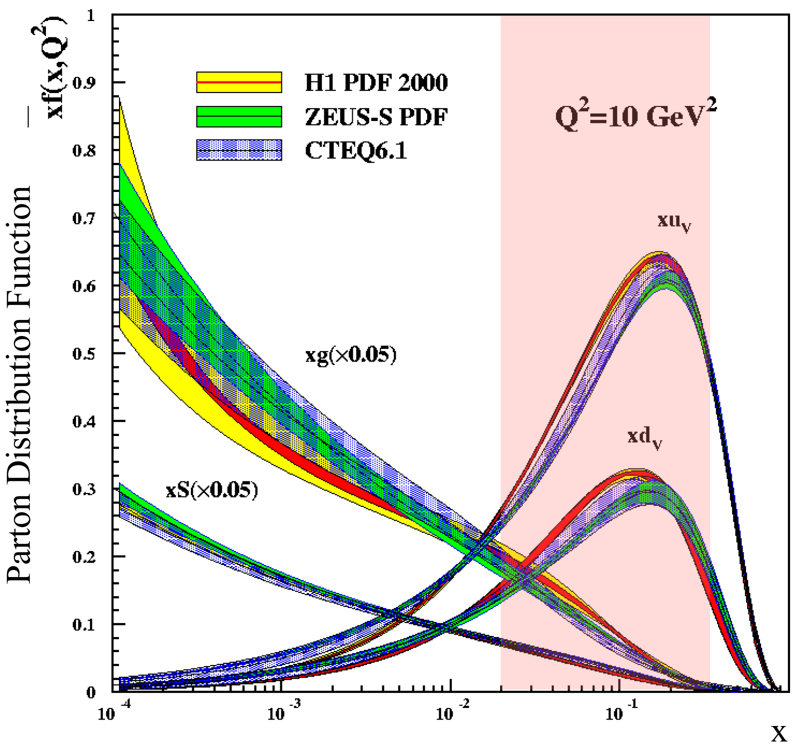


Sea quarks

HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$



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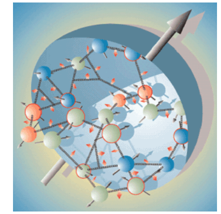

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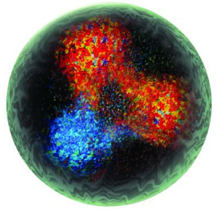

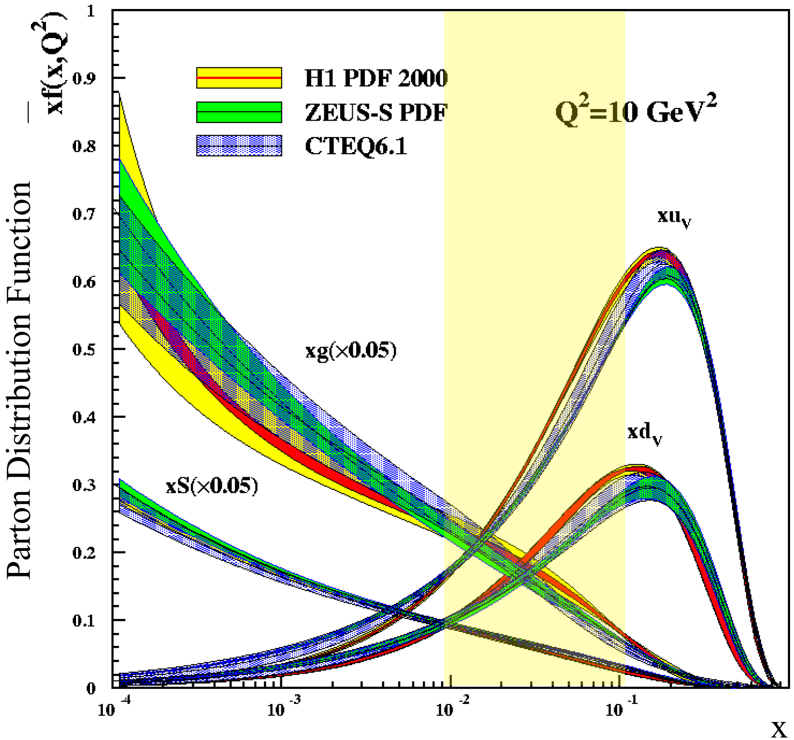

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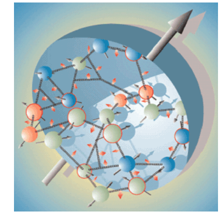
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

COMPASS: fixed-target muon scattering

$0.01 < x_B < 0.1$

Nucleon at different scales



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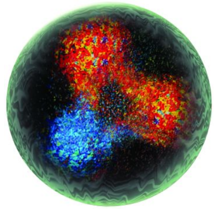

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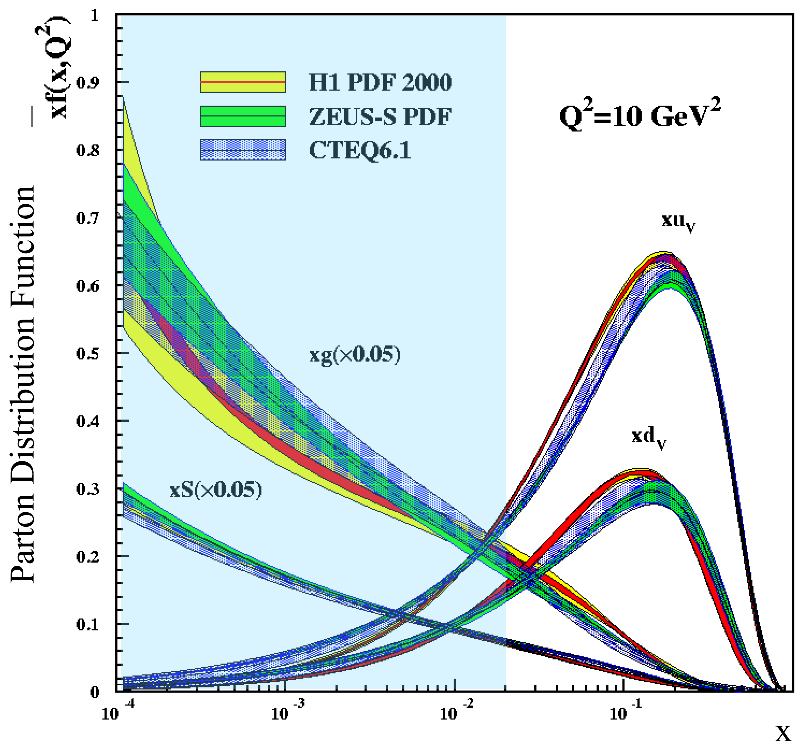
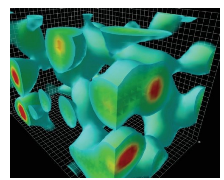


The glue

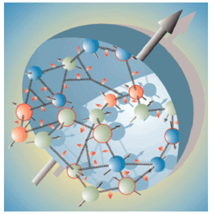


Derek Leinweber

ZEUS/H1: electron/ positron-proton collider

$10^{-4} < x_B < 0.02$

Nucleon at different scales



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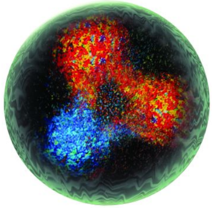
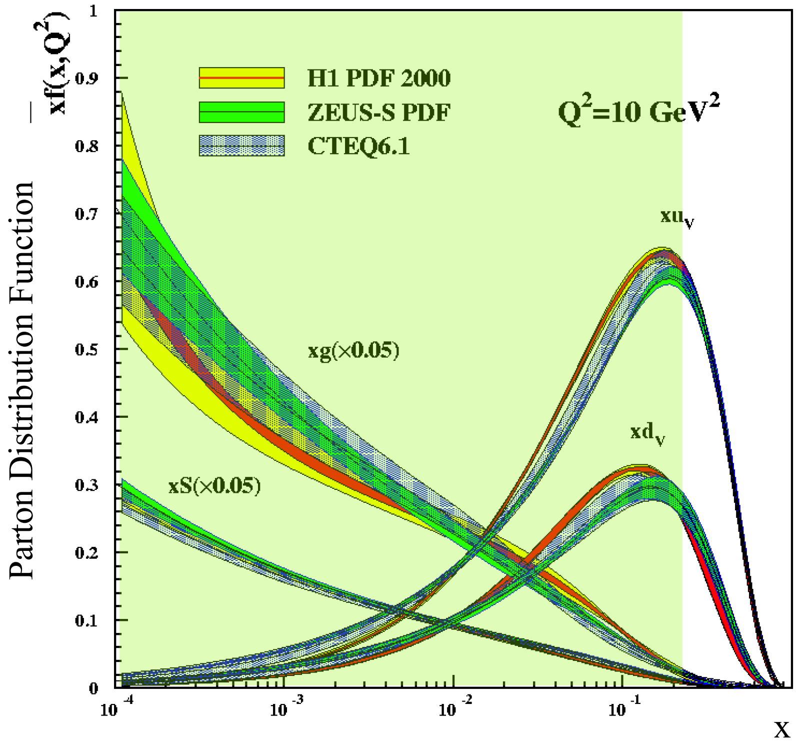


Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$



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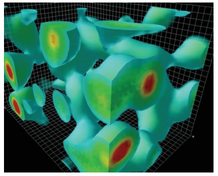


Derek Leinweber

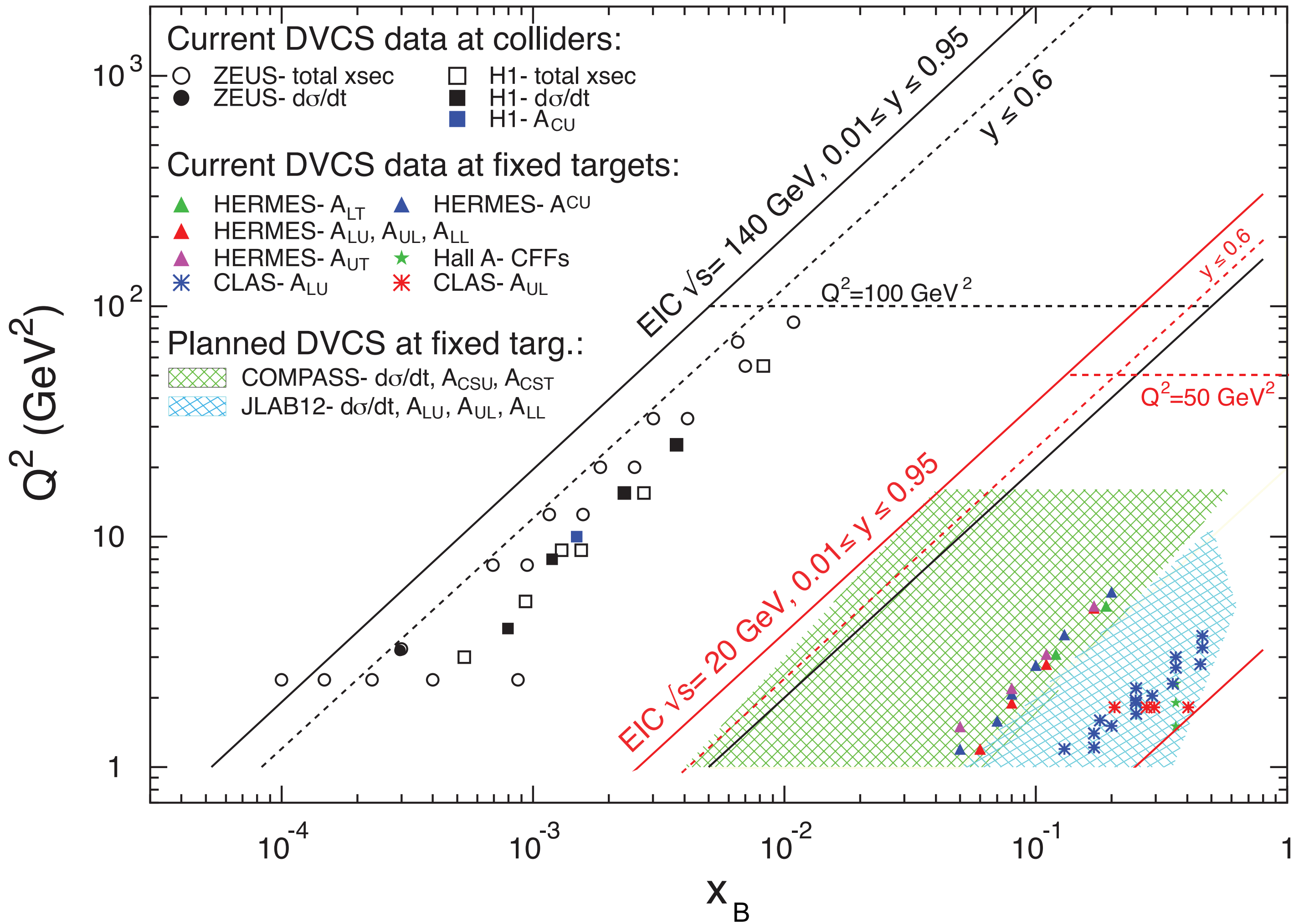
ZEUS/H1: electron/ positron-proton collider

$10^{-4} < x_B < 0.02$

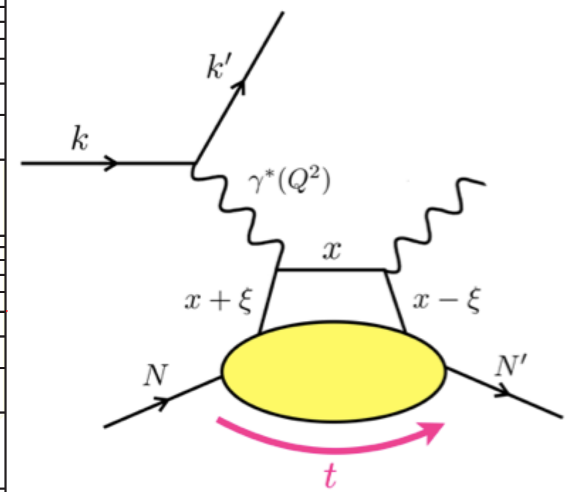
EIC: $10^{-4} < x_B < 0.2$

Luminosity 100 - 1000 times that of HERA

EIC kinematic reach



DVCS:
deeply virtual
Compton scattering



$$Q^2 = -(\mathbf{k} - \mathbf{k}')^2$$

y: inelasticity

$$x_B = \frac{Q^2}{2N \cdot q}$$

Bjorken-x

https://arxiv.org/abs/2103.05419

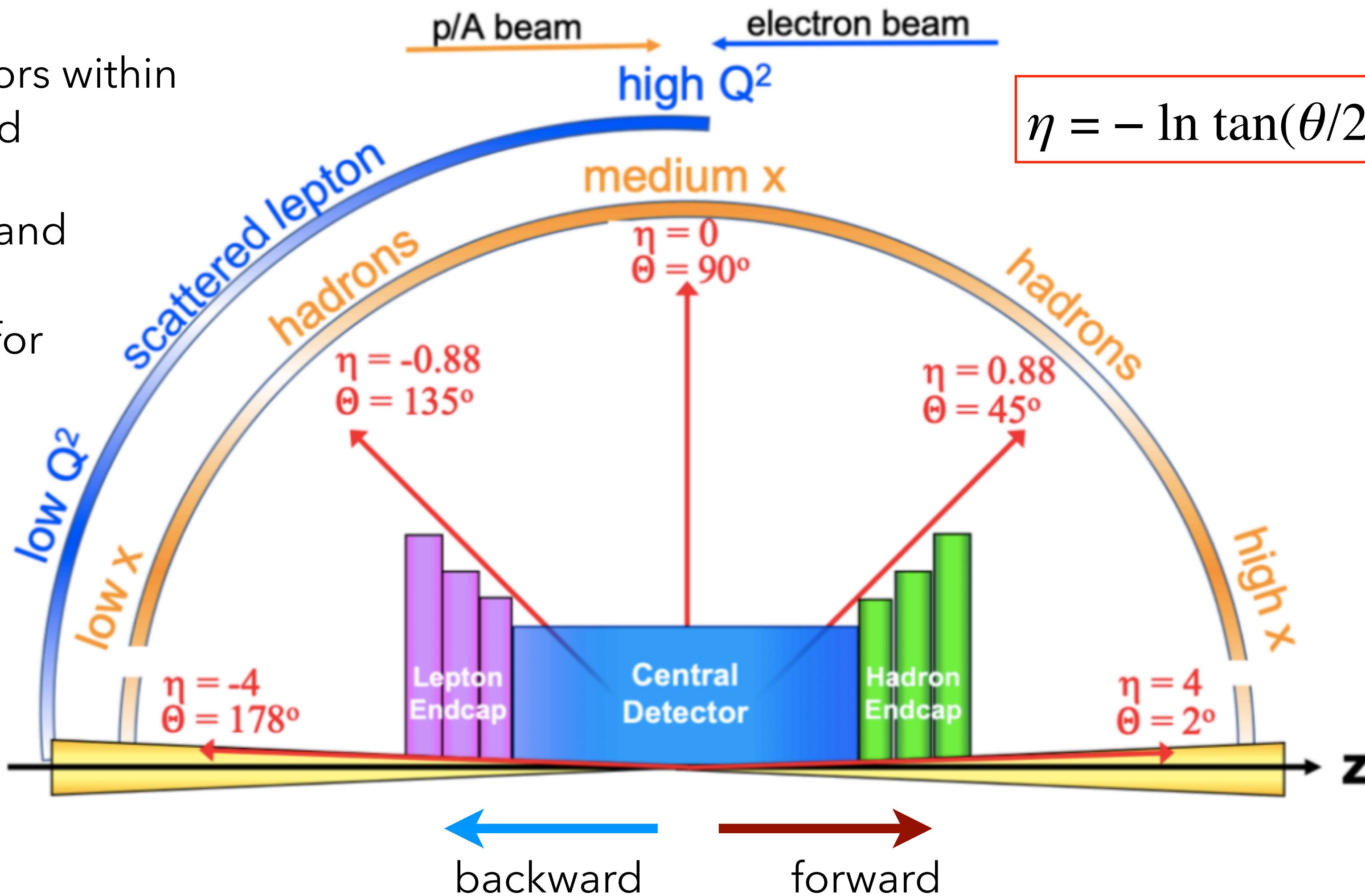
Detector configuration

Very asymmetric beams

Hermetic detectors within a central solenoid

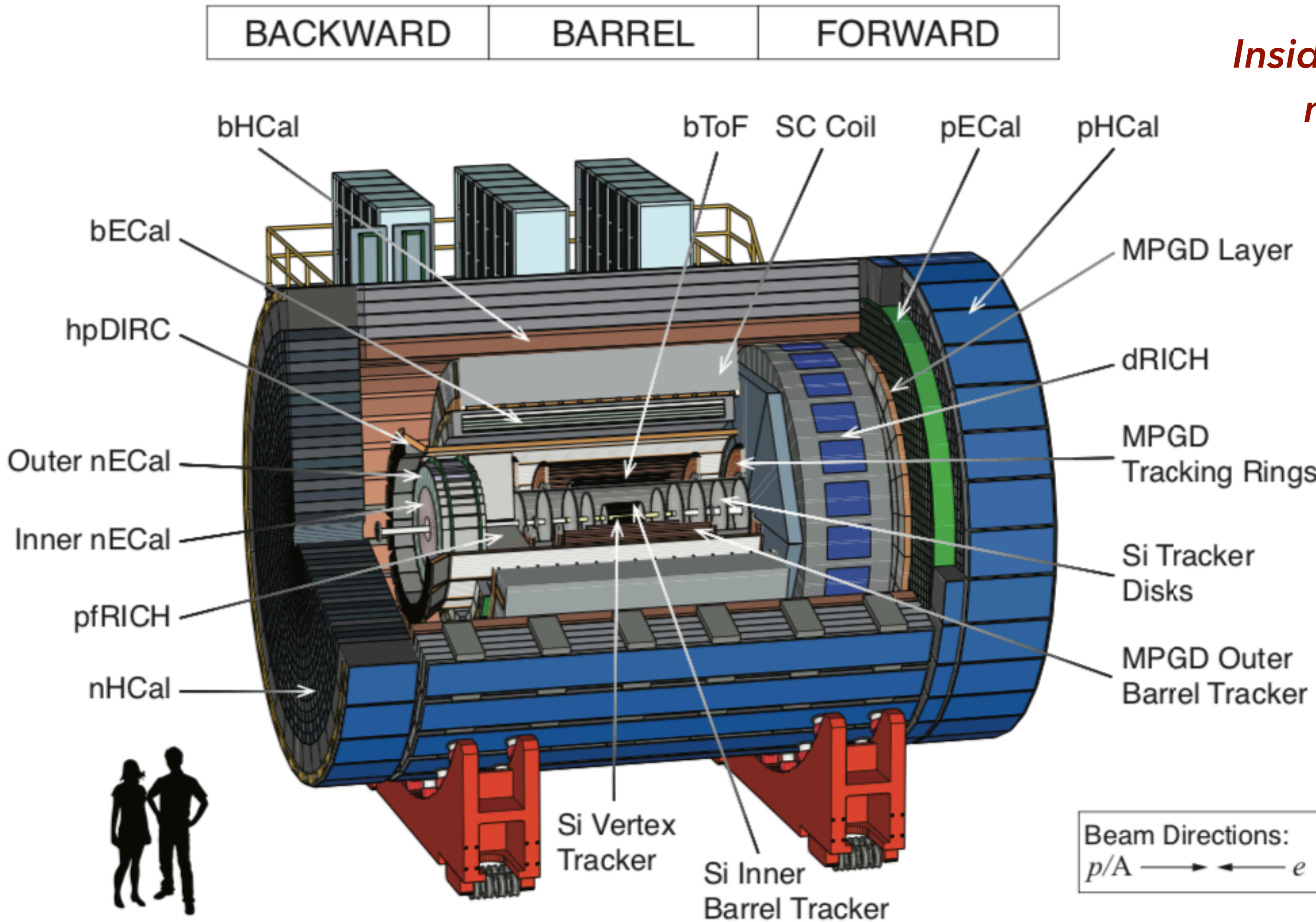
Very far-forward and far-backward instrumentation for lowest scattering angles.

$$\eta = -\ln \tan(\theta/2)$$



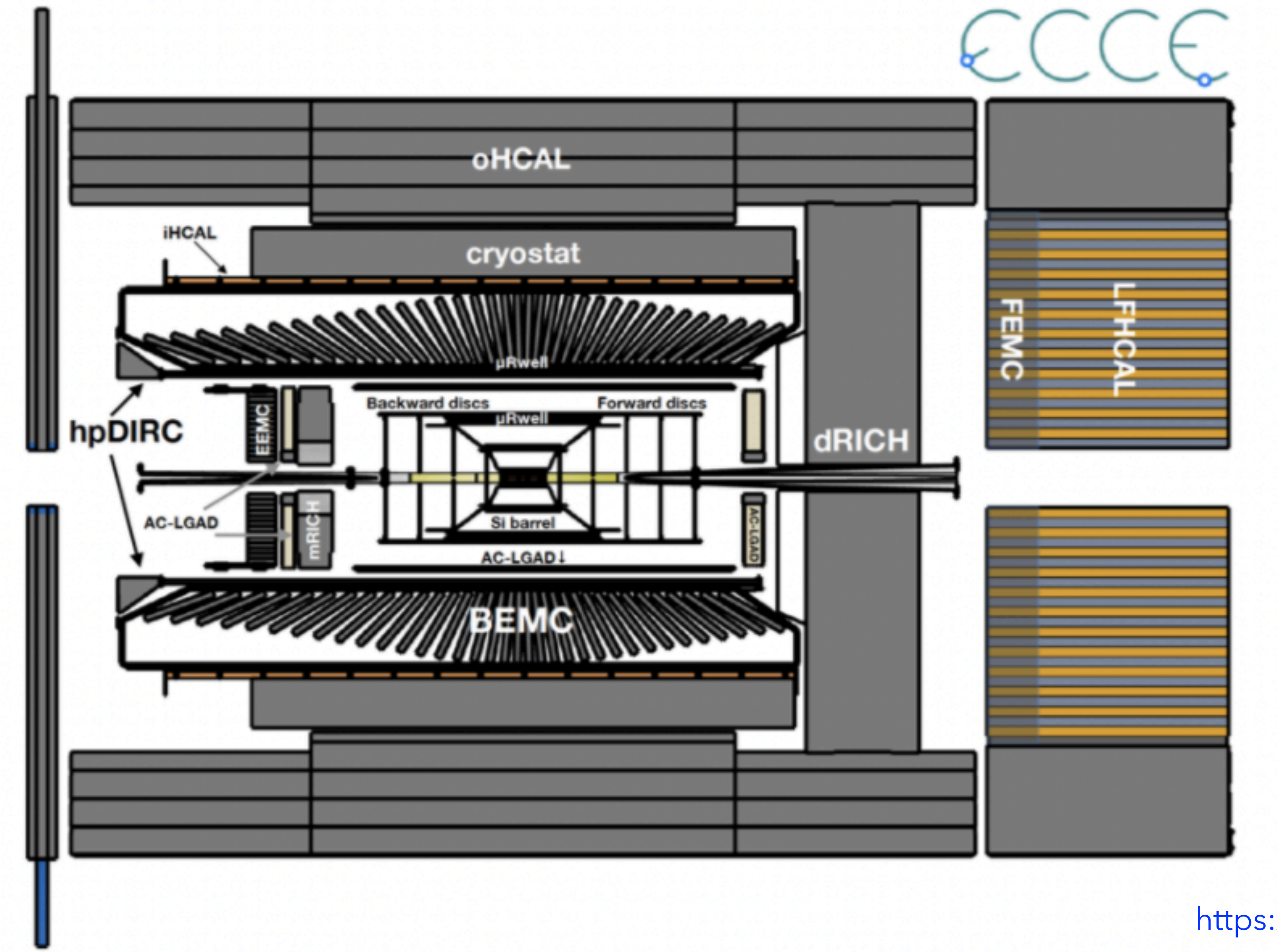
ATHENA:
A Totally Hermetic Electron Nucleus Apparatus

Inside a new 3T magnet



https://sites.temple.edu/eicatip6/

ECCE: EIC Comprehensive Chromodynamics Experiment



Reusing the 1.4T BaBaR solenoid magnet

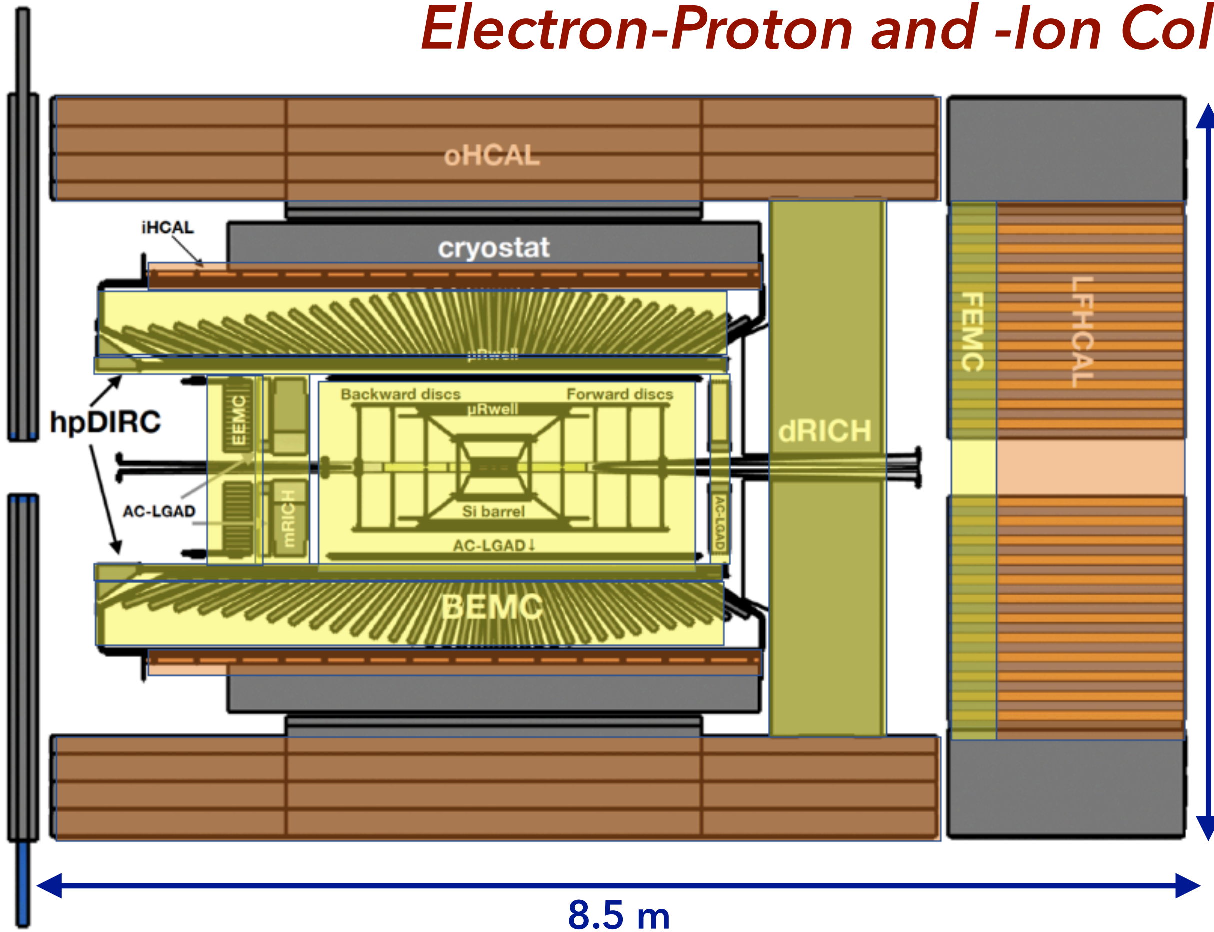
https://www.ecce-eic.org

The ePIC detector

Electron-Proton and -Ion Collider detector

Result of the merging of ECCE and ATHENA collaborations.

The "project detector" to be constructed at IP 6



Calorimetry:

Range of EM and hadron calorimeters.

Particle ID (PID):

High time-resolution Si (AC-LGAD), Cherenkov detectors: RICH, DIRC.

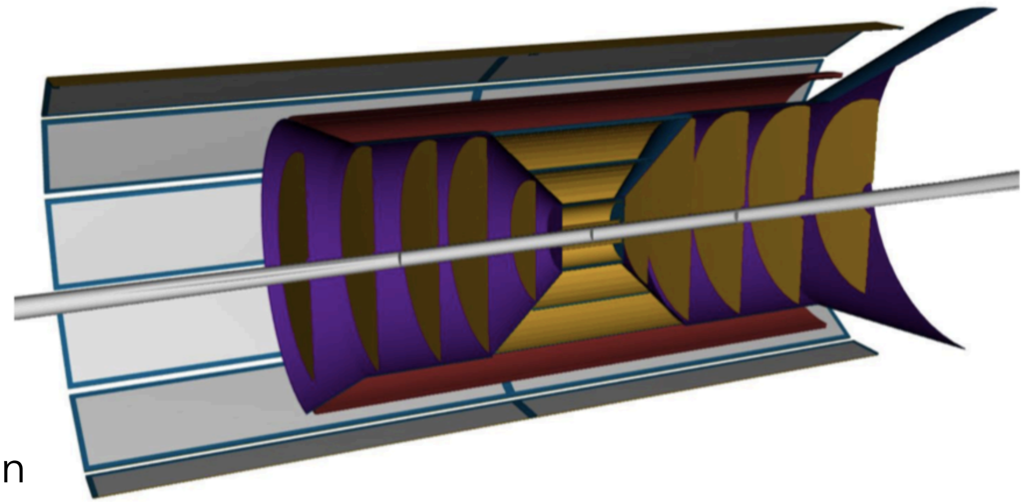
Tracking: New 1.7 T magnet (MARCO)

Light-weight Si tracking (65nm MAPS), micro-pattern gaseous detectors (MPGDs).

ePIC Tracking

Current design:

- 5 barrel layers of Si: 3 vertex layers, 2 sagitta layers.
- 5 Si endcap disks at each end.
- One or two (under discussion) MPGD layer outside the Si: mainly to improve pattern recognition.
- 1 AC-LGAD ToF barrel layer and a hadron endcap disk.



Technologies:

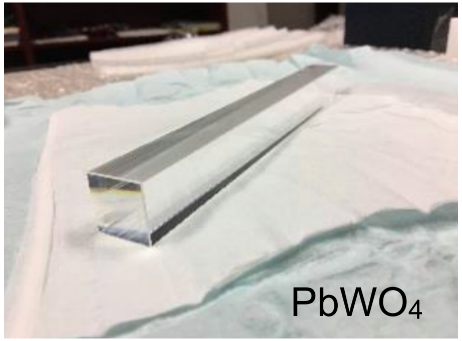
- Si tracking: 65nm technology MAPS, based on ALICE ITS3 upgrade development.
- MPGD: Cylindrical Micromegas, backup technology: μRWELL.

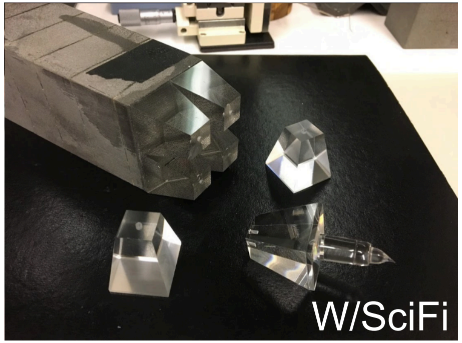
Momentum resolution requirement: 0.5 - 1% (depending on momentum).

ePIC Calorimetry

EM Calorimeter

- Detection of photons, electron ID
- Barrel: Pb/SciFi + either imaging calorimeter (6 layers of Si sensors (AstroPix) + 5 SciFi/Pb layers, inner SciFi/Pb section) or Scintillating glass
- Forward endcap: W/SciFi spacial
- Backward endcap: $PbWO_4$ crystals

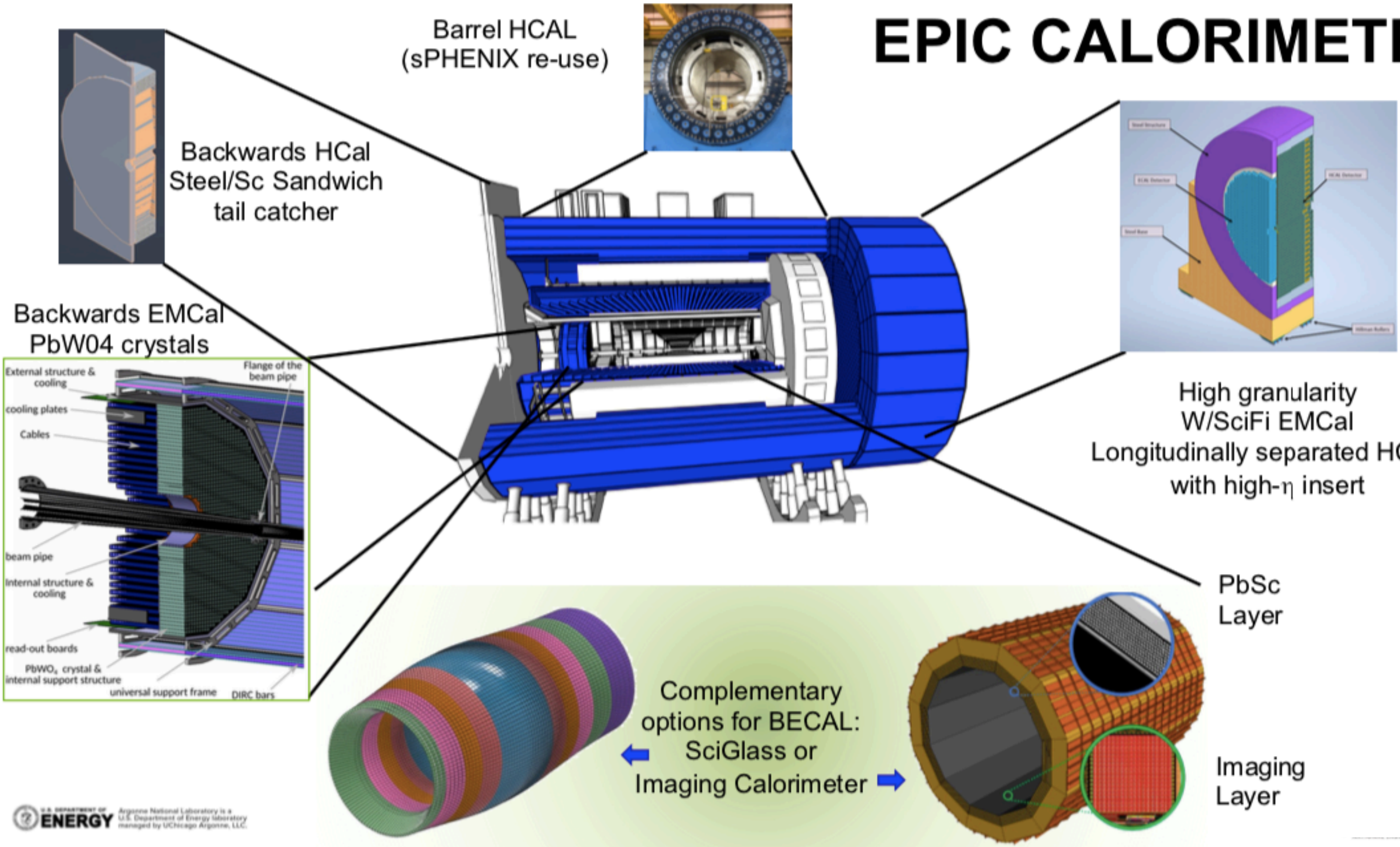




Hadron Calorimeter

- Charged hadrons, neutrons, K_L^0
- Fe/Sc sandwich: backward and barrel (outside solenoid).
- Fe/Sc and W/Sc: forward endcap.
- Forward endcap inset: Sci/ Fe+W sampling calorimeter.

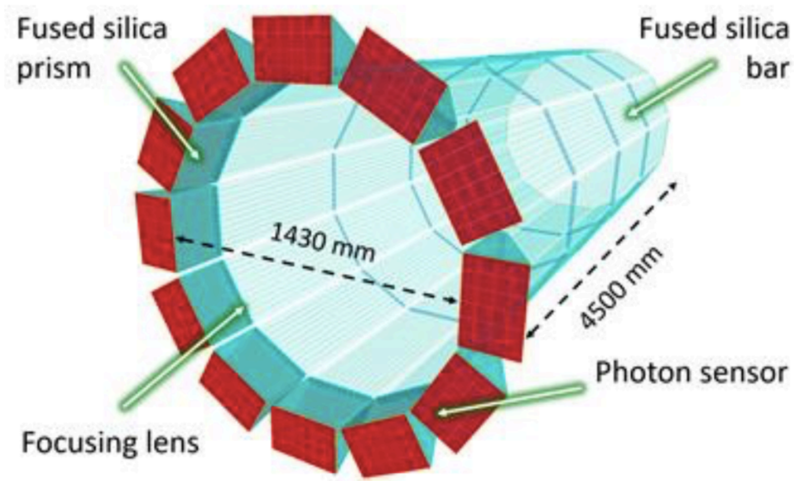
EPIC CALORIMETRY

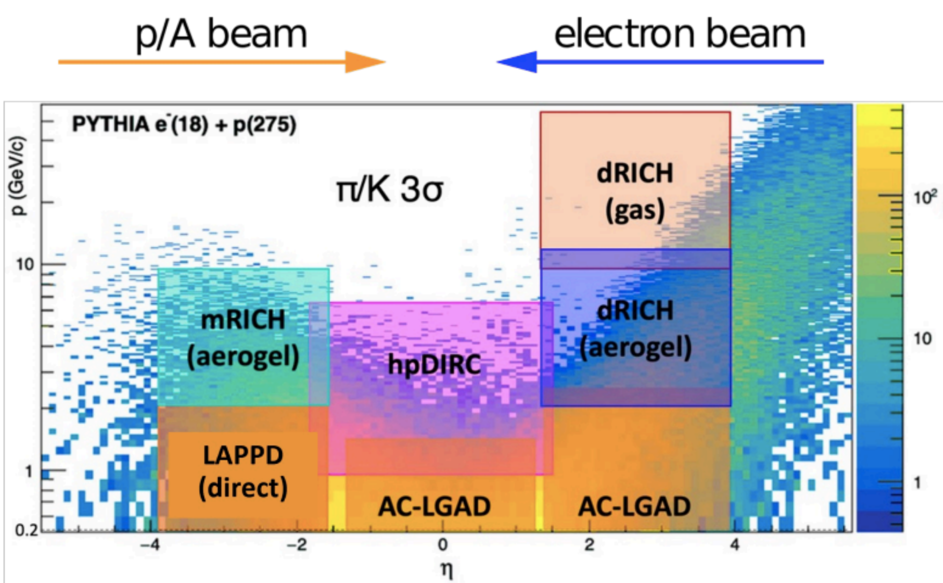


slide from E.C. Aschenauer

Cerenkov and AC-LGAD ToF PID

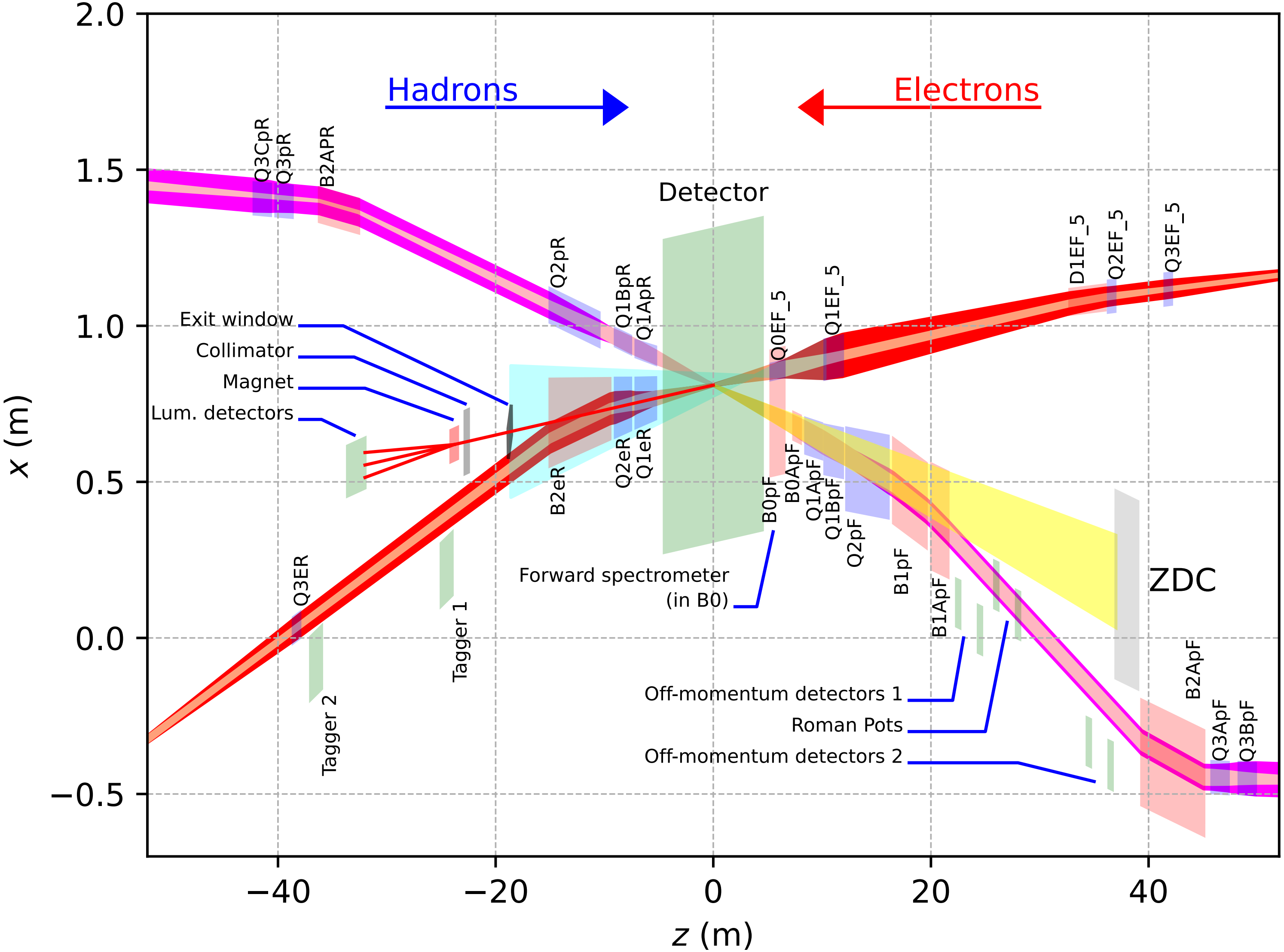
- Barrel: hpDIRC (high-performance DIRC), fused-silica radiator, 3σ π/K separation up to ~6 GeV
- Forward endcap: dRICH (dual-RICH): aerogel + C_2F_6 gas
- Backward endcap (both using aerogel):
    - mRICH (modular RICH): uses aerogel or
    - pfRICH (proximity-focussing RICH), 3σ π/K separation up to ~7 GeV or better





- Barrel and Forward AC-LGAD ToF: improves tracking resolution when a hit in a Si layer is missing

The Interaction Region @ IP6



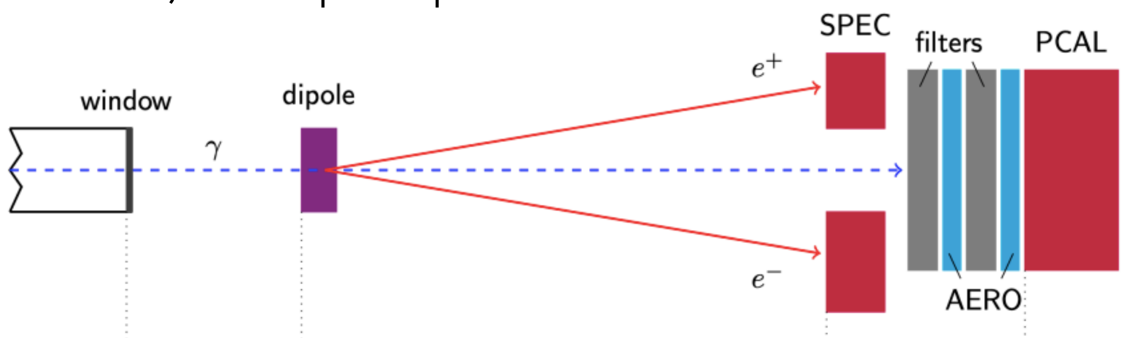
Crossing angle for the beams: 25 mrad.

Far-backward detectors

Luminosity Monitors:

- Use Bremsstrahlung
- Accuracy of 1% or better than 10^{-4} precision on relative luminosity of different bunch crossings.
- Direct photon detector (calorimeter) and a pair-spectrometer

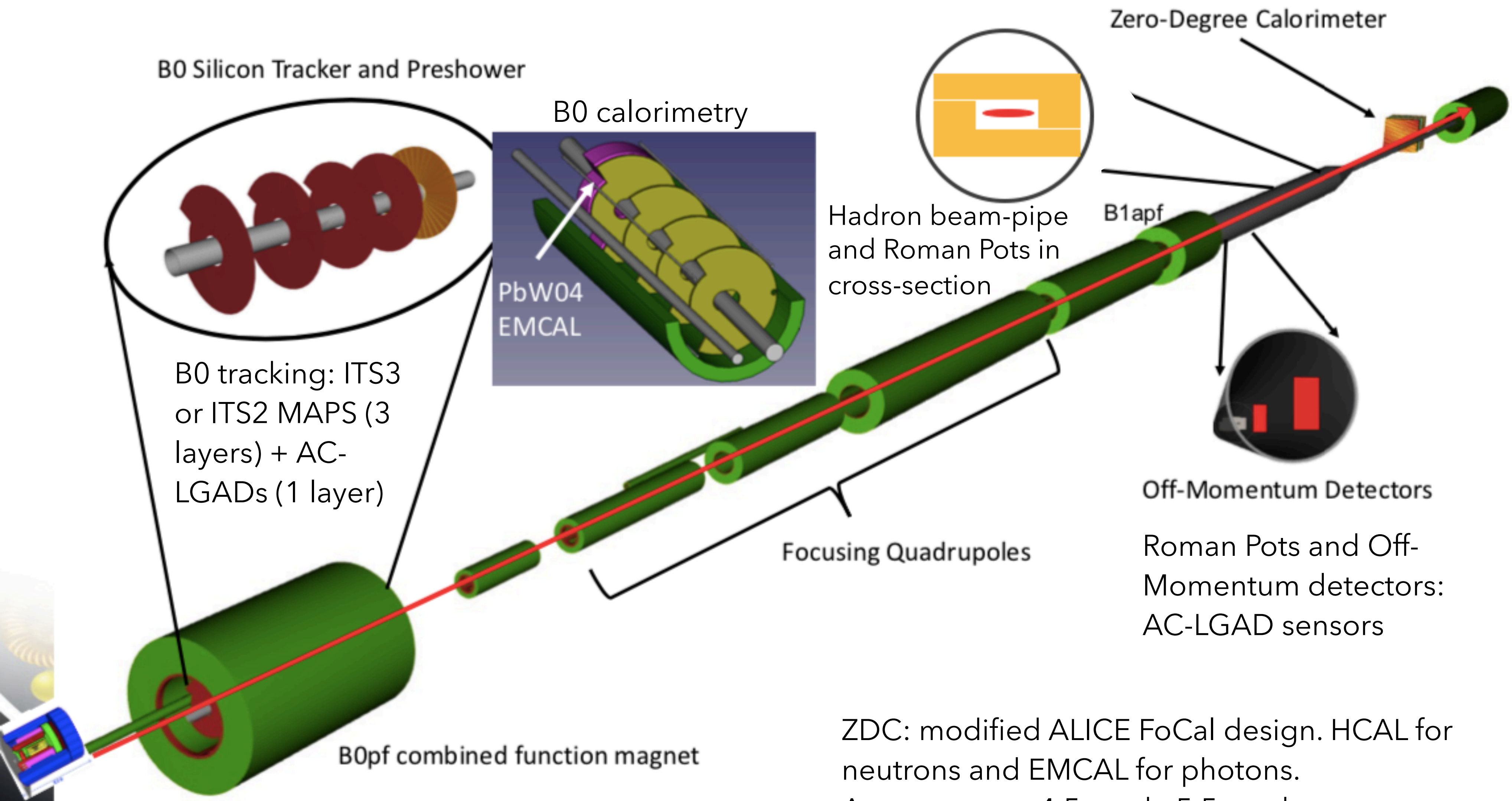
Modification of the HERA II design:



Low-Q2 Taggers:

- Two Tagger stations, in the primary vacuum (θ_e < 10 mrad)
- Each tagger: tracking layers (MAPS or AC-LGAD sensors, Timepix4 + i-LGAD)
- Calorimeter under consideration for the taggers: PbWO4, sampling W/SciFi, quartz fibres or W-Si.

Far-forward detectors



B0 tracking: ITS3 or ITS2 MAPS (3 layers) + AC-LGADs (1 layer)

Roman Pots and Off-Momentum detectors: AC-LGAD sensors

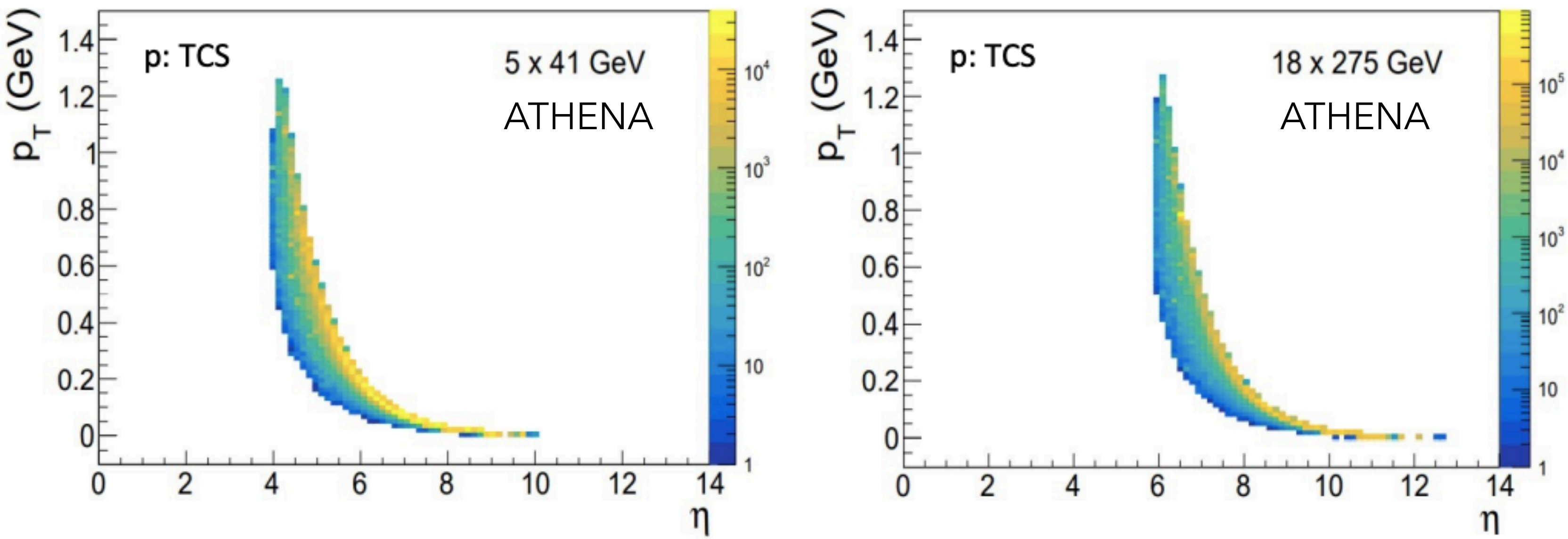
ZDC: modified ALICE FoCal design. HCAL for neutrons and EMCAL for photons. Acceptance: +4.5mrad, -5.5mrad.

Recoil protons in *ep*

- The impact parameter information in many exclusive processes is encoded in *t*, via a Fourier Transform. Require accurate measurement of *t* from as close to zero as possible and across a wide range in *ep and e(light-A)* collisions.

$$t = (p' - p)^2$$

- Scattered protons / light ions detected in Roman Pots (for the lowest values of *t*) and in the B0 spectrometers (for higher values). Eg: recoil in Timelike Compton Scattering:



Note: produced particle collinear, carries off most longitudinal momentum. So almost all t corresponds to a transverse kick of the proton / ion.

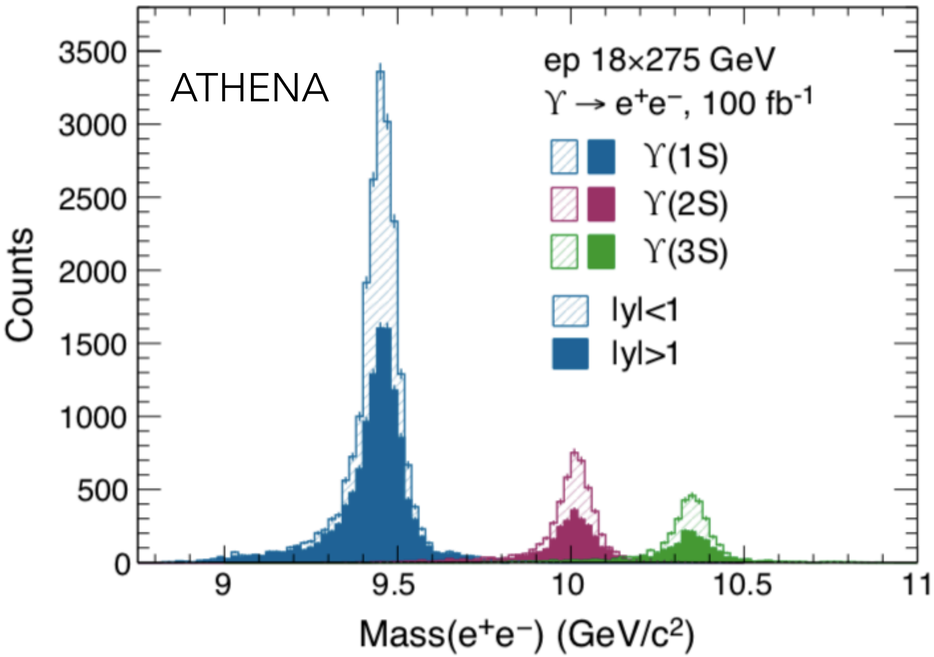
Quarkonium production

- Sensitivity to 3D gluon distributions (via Generalised Parton Distributions)

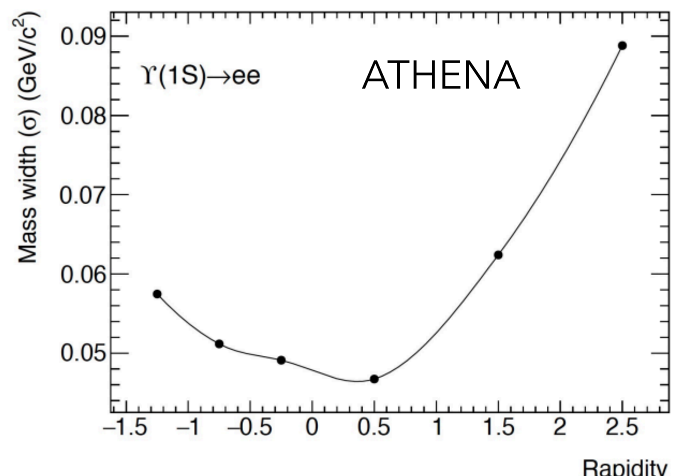
Near-threshold production in particular:

- Information on colour correlations
- Quarkonium-proton scattering lengths
- May act as a saturation probe (in eA)
- Sensitivity to the composition of proton mass via the trace anomaly.
- Photoproduction: sensitivity to gravitational form-factor? Perhaps not directly:

PRD 101 (11) (2020)114004, PRD 103 096010 (2021), PLB 822:10(2021), 136655



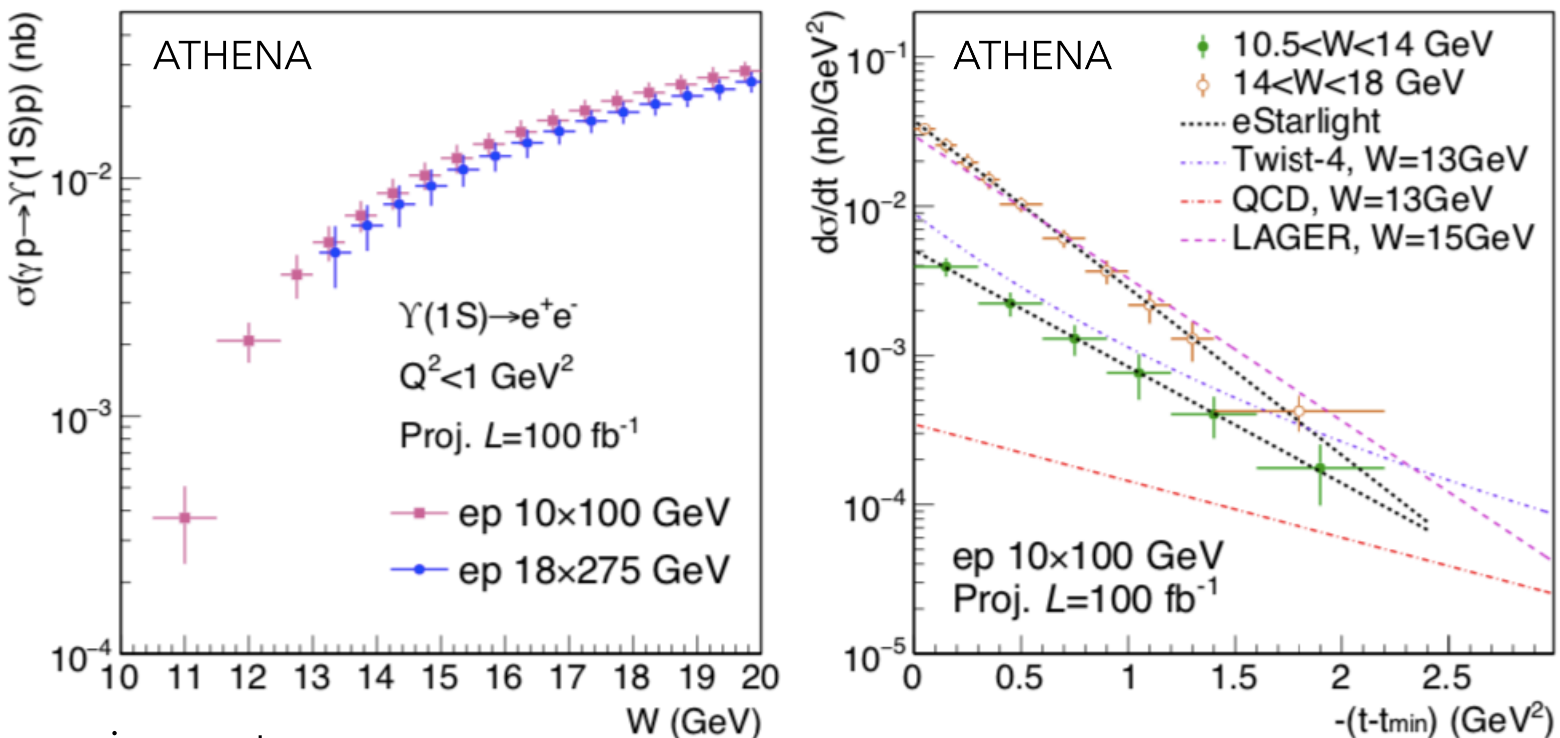
- Measurement requires good mass resolution (< 100 MeV) to separate Upsilon states.



Yuangjing Ji, Spencer Klein (LBNL)

At-threshold Upsilon photo-production

- Upsilon near-threshold production is little-known, twist-4 effects contribute significantly.

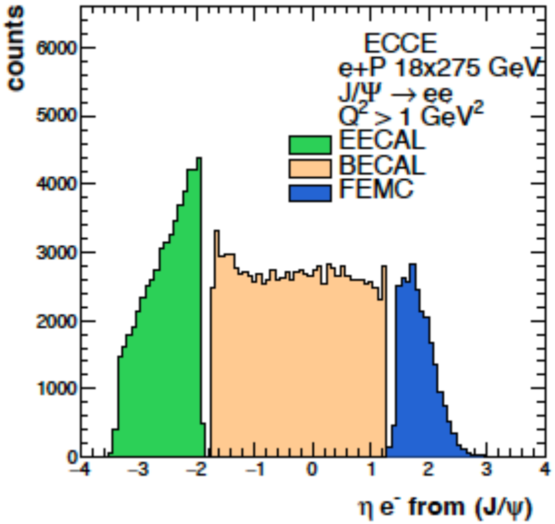


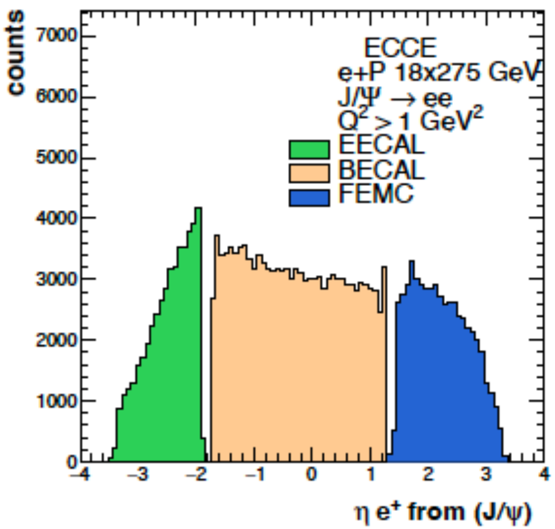
Detector requirements:

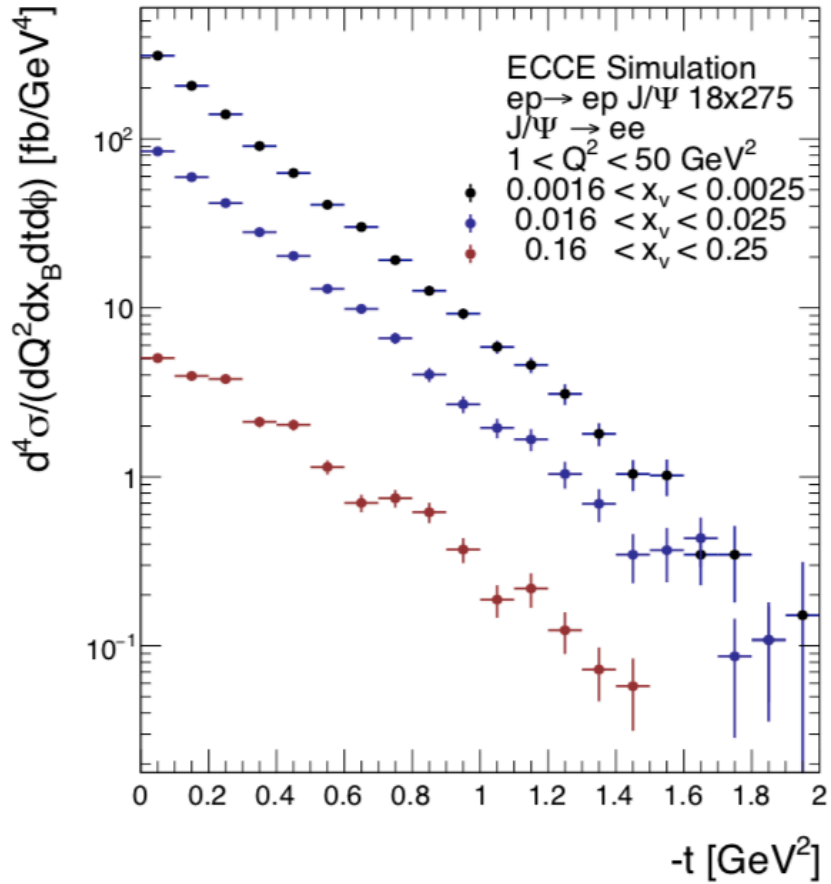
- Good t resolution.
- Good PID and momentum resolution to reject continuum (background suppression).
- Good rapidity coverage to reject events with other particles in final state.

Twist-4 : PLB 822:10(2021), 136655
QCD (GPD factorization) : PRD 103, 096010 (2021)
LARGER: PRD 102, 014016 (2020)

J/Psi production



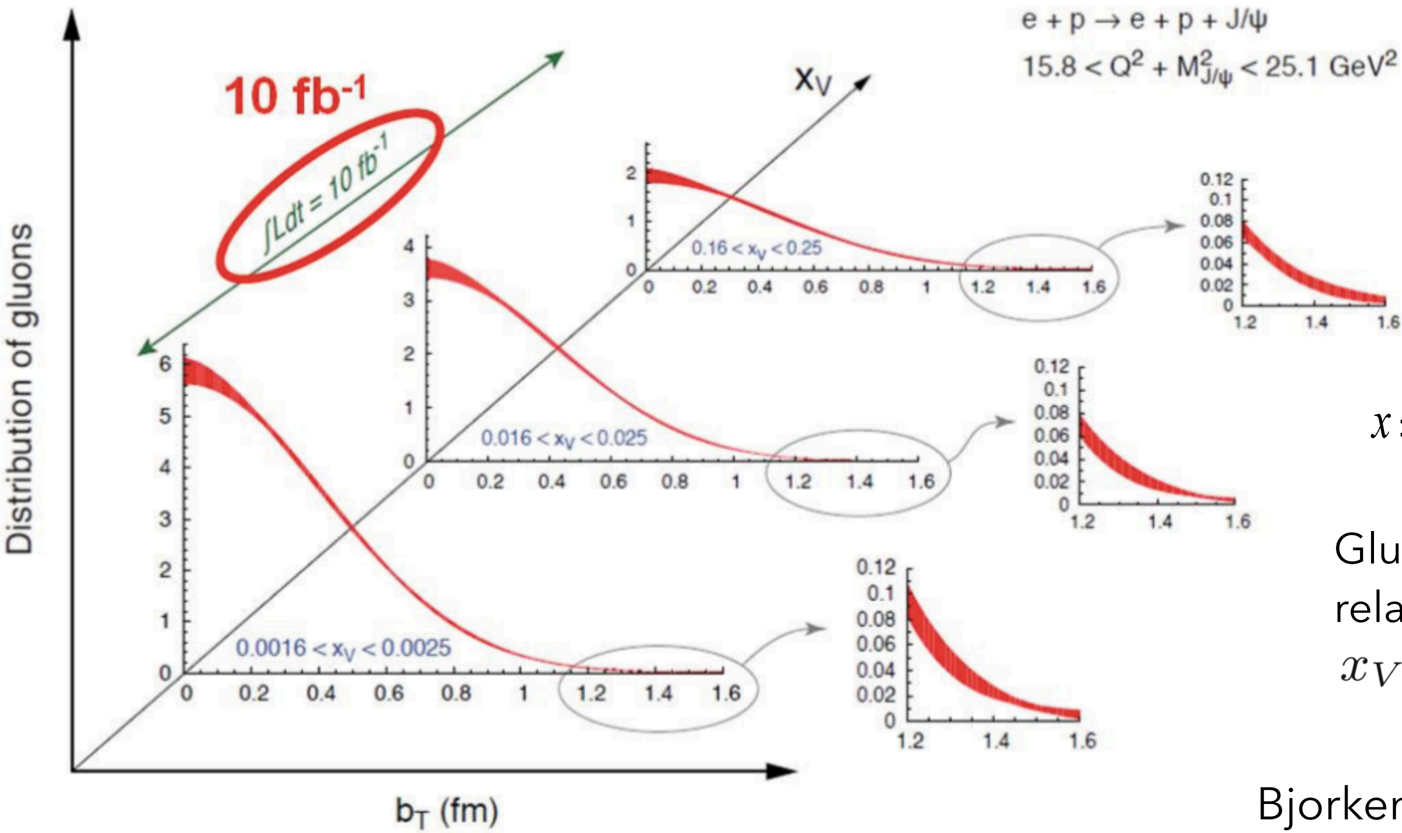


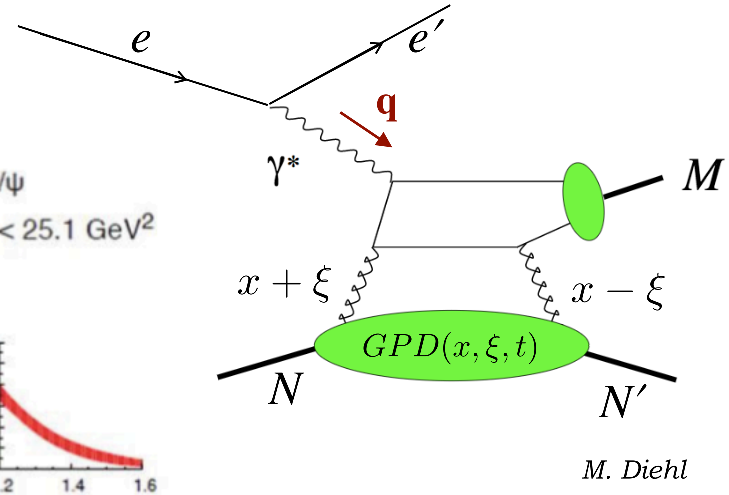


- Excellent acceptance coverage for J/Psi decay leptons
- Multi-dimensional binning possible

Nucleon tomography: imaging glue

- Gluon GPDs can be accessed through deeply virtual meson production (DVMP), eg: J/Ψ
- Access to spatial distributions of gluons at different longitudinal momentum fractions:





$x \pm \xi$ longitudinal momentum fractions of the struck parton

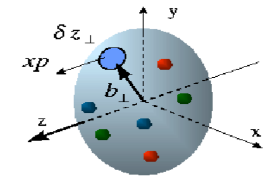
Gluon momentum fraction related to:

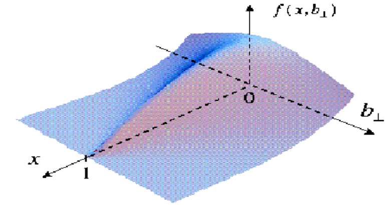
$$x_V = x_B(1 + M^2_{J/\Psi}/Q^2)$$

Bjorken variable $x_B = \dfrac{Q^2}{2\mathbf{p_n} \cdot \mathbf{q}}$

EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

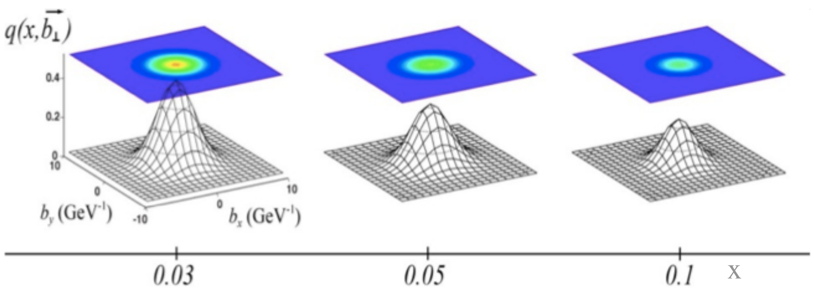
Generalised Parton Distributions





- proposed by Müller (1994), Radyushkin, Ji (1997).
- can be interpreted as relating, in the infinite momentum frame, transverse position of partons (impact parameter $b_\perp$) to longitudinal momentum fraction (x).

* **Tomography** of the nucleon: transverse spatial distributions of quarks and gluons in longitudinal momentum space.



* Information on the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.

$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

Ji's relation:

GPDs

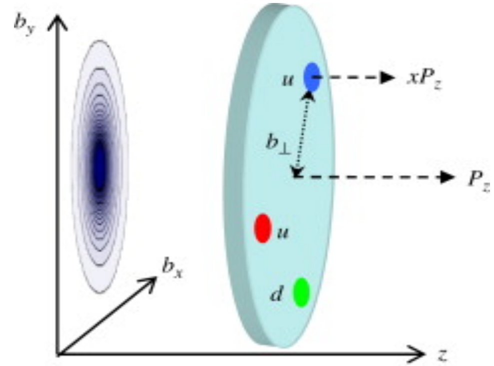
$$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x\,dx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$

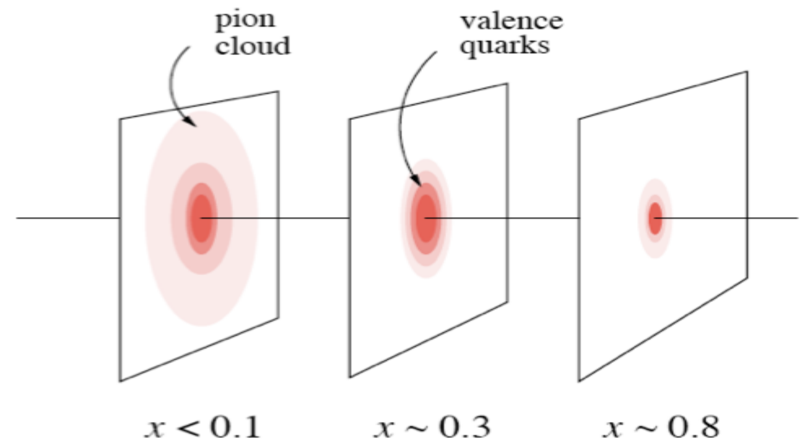
* Indirect access to mechanical properties of the nucleon: possibilities of extracting **pressure distributions** within the nucleon.

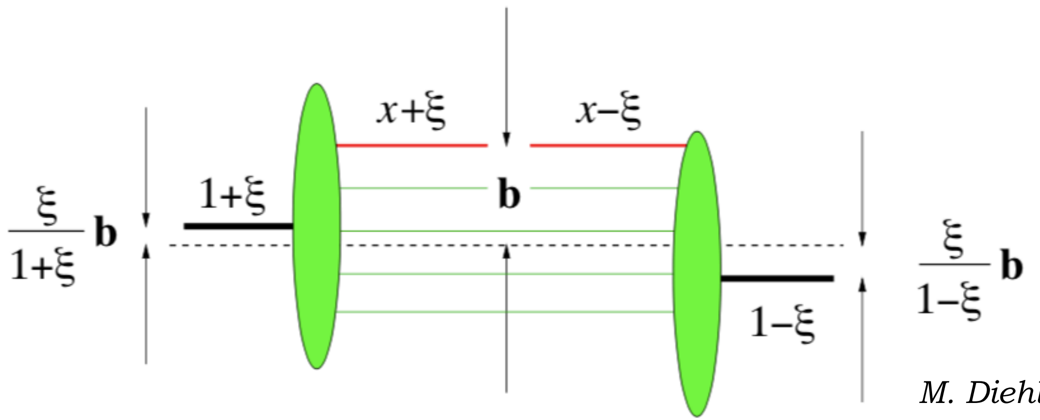
* Combine with TMDs to access **spin-orbit correlations** of quarks and gluons, study non-perturbative interactions of partons.

Nucleon Tomography from GPDs

At a fixed Q^2, x_B and ξ=0 slope of GPD with t is related, via a Fourier Transform, to the transverse spatial distribution.







M. Diehl

Formally, the radial separation, **b**, *between the struck parton and the centre of momentum of the remaining spectators.*

Experimentally, look for the t-dependence of structure functions (from meson-production) or Compton Form Factors (from DVCS/TCS).

Spin and pressure in the nucleon

- GPDs also provide indirect access to mechanical properties of the nucleon (encoded in the gravitational form factors, GFFs, of the energy-momentum tensor).

  X. D. Ji, PR**D 55**, 7114-7125 (1997)
  M. Polyakov, PL**B 555**, 57-62 (2016)

- Three scalar GFFs, functions of *t*: encode pressure and shear forces ($d_1(t)$), mass ($M_2(t)$) and angular momentum distributions ($J(t)$).

- Can be related to GPDs via sum rules: $$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,\mathrm{d}x = 2J(t)$$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

(Ji's relation)

$$J_N = \frac{1}{2} = \frac{1}{2}\Sigma_q + L_q + J_g$$

- $d_1(t)$ (D-term) "last unknown global property of the nucleon" – can be accessed via the $\mathcal{Re}$ and $\mathcal{Im}\ \mathcal{H}$:

Dispersion relation: $$\mathrm{Re}\mathcal{H}(\xi,t) = \int_{-1}^{1}\left(\frac{1}{\xi-x}-\frac{1}{\xi+x}\right)\mathrm{Im}\mathcal{H}(\xi,t)\ dx + \Delta(t).$$

Assuming double-distribution parametrisation: $\Delta(t) \propto d_1(t)$

Trace anomaly

Composition of proton mass: quark energy, gluon energy, quark mass and **trace anomaly:**

$$M_a = \frac{1}{4}(1 - b) M_N$$

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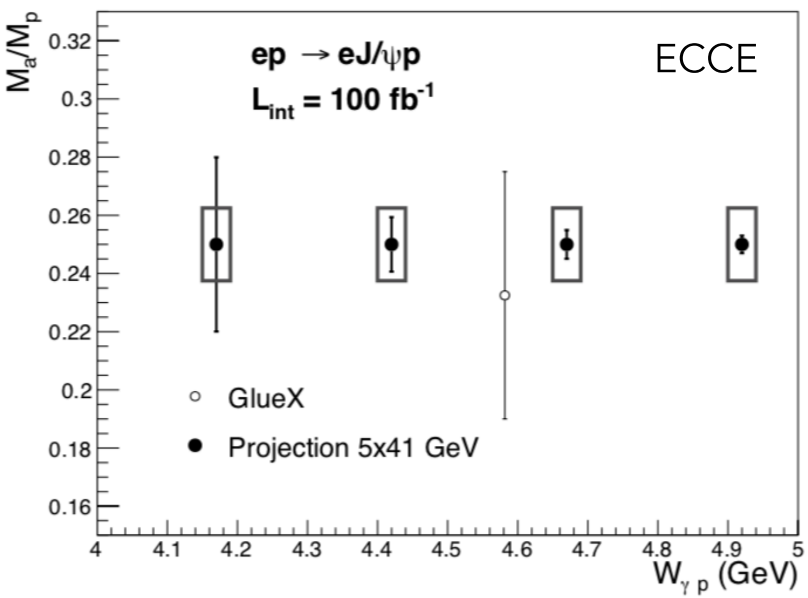
Assuming Vector Dominance Model:

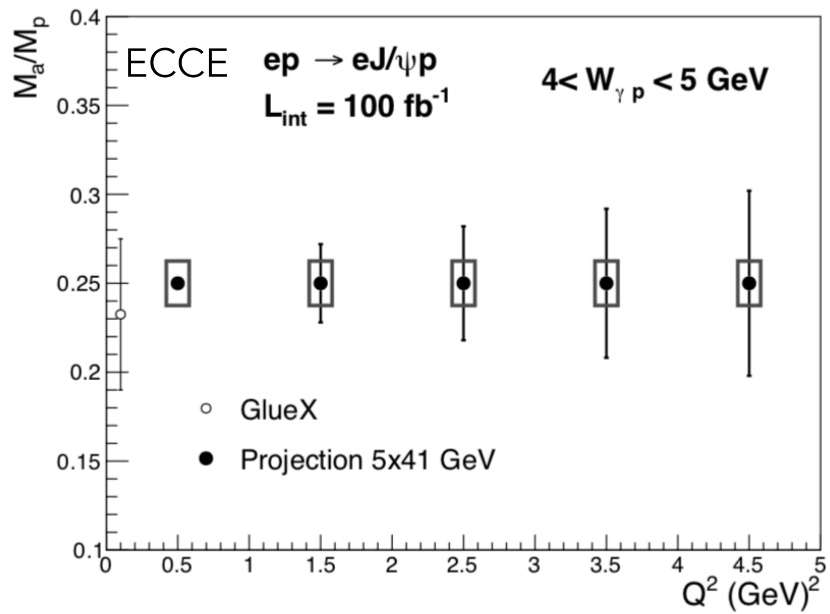
$$\left.\frac{d\sigma_{J/\Psi N \to J/\Psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi}\frac{1}{m^2_{J/\Psi}(\lambda^2 - m^2_N)}\left|F_{J/\Psi N}\right|^2$$

nucleon energy in charmonium rest-frame

At low energy:

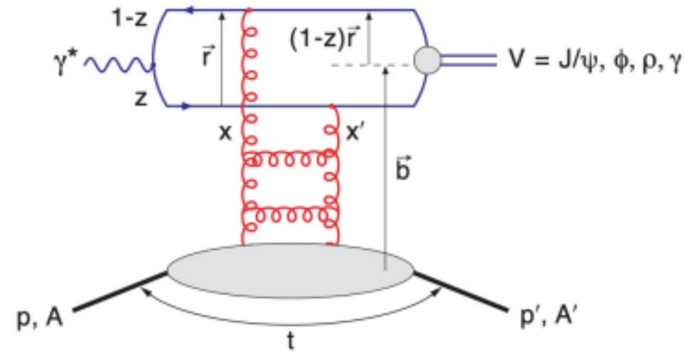
$$F_{J/\Psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2(1-b)$$



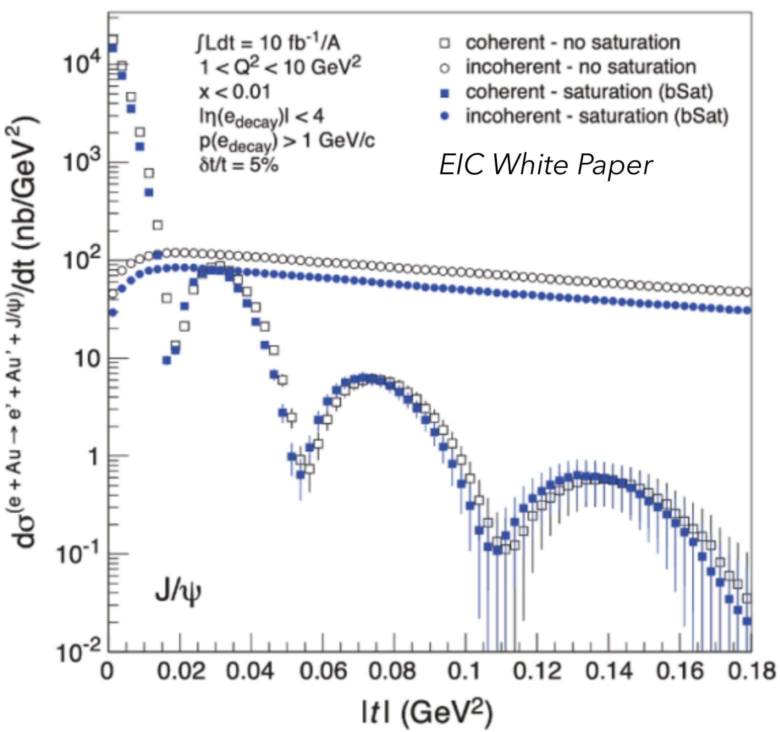


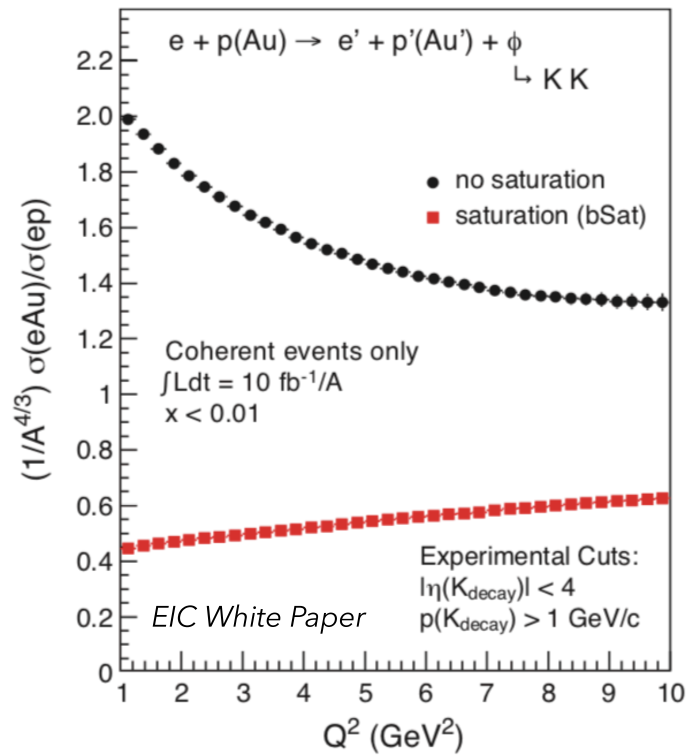
Coherent VM production in eA

- Gluon distributions in nuclei and a probe of gluon saturation.
- Detector challenge: reconstruct *t* from leptons and mesons, not from nuclei (these escape undetected): resolution is crucial to identify *t* minima.
- Incoherent backgrounds dominate greatly at anything other than the lowest *t*:



t ~ momentum transfer (kicks)

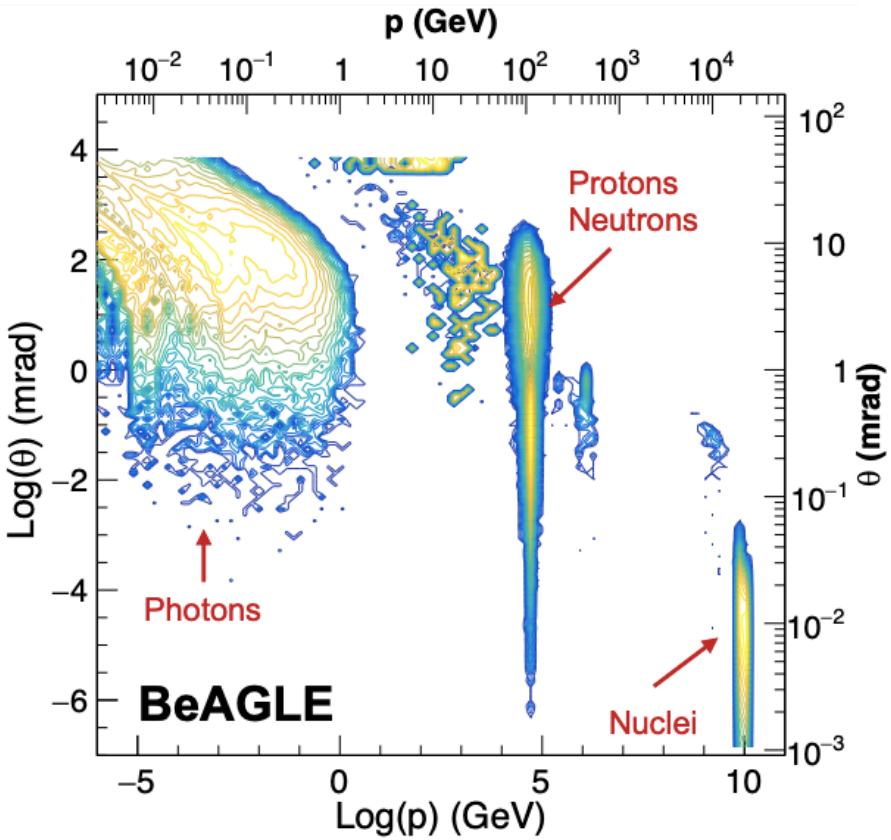


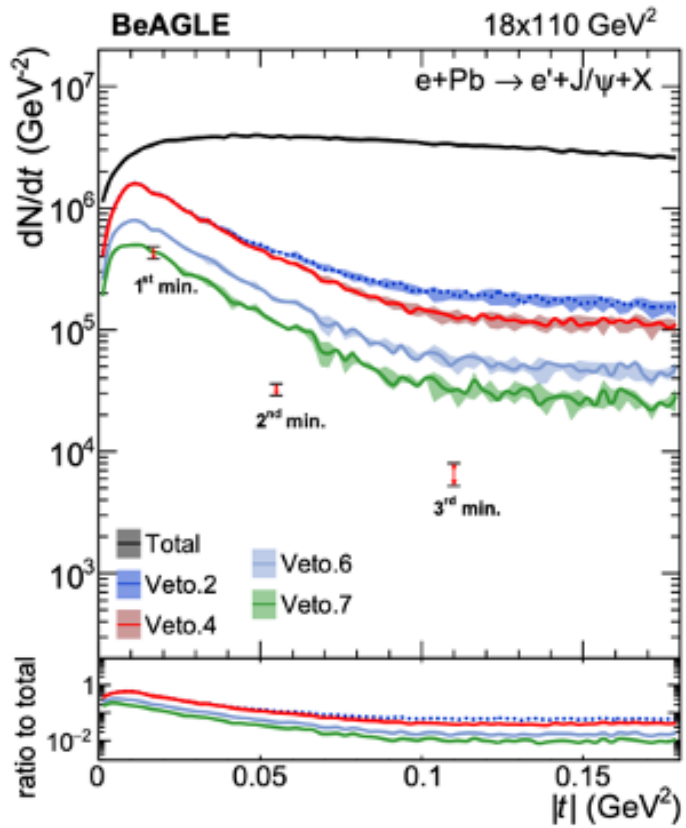


Incoherent backgrounds in eA

- Suppression of incoherent background by vetoing nuclear break-up in Far-Forward detectors:

Incoherent backgrounds:





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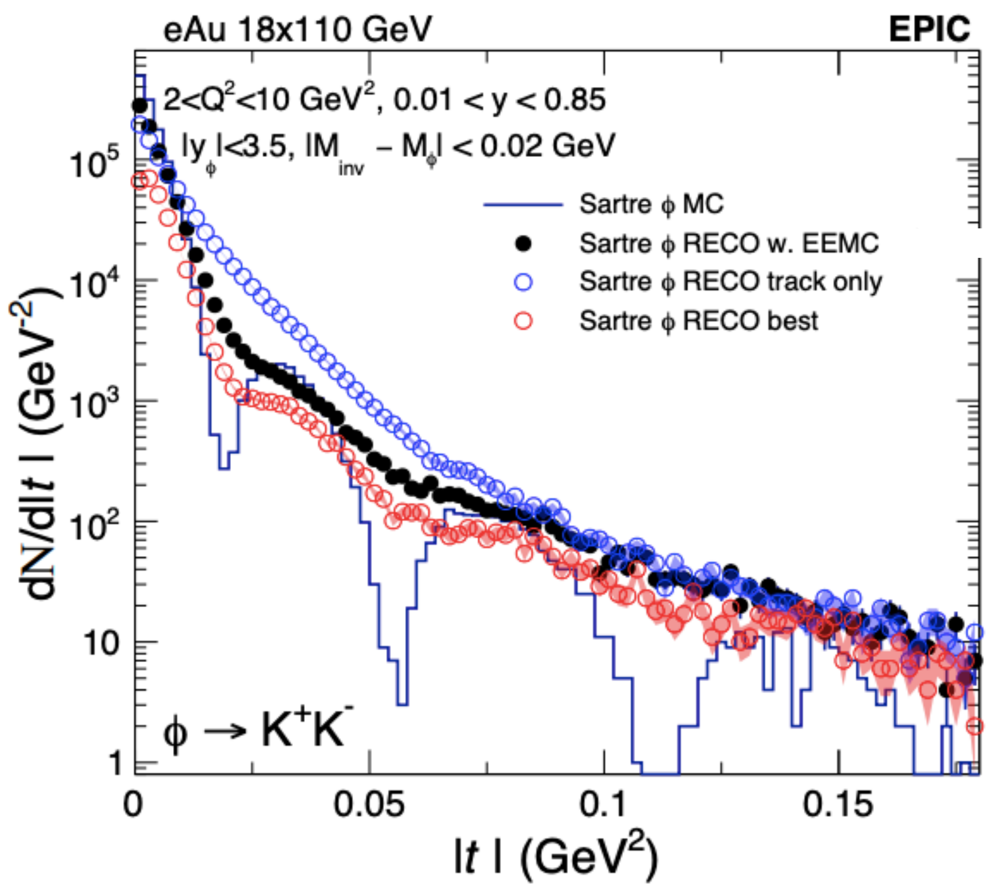
Coherent production of φ in eAu

- First simulations out of ePIC, on φ in eAu. Gradual improvements in the reconstruction: these are only the first steps!

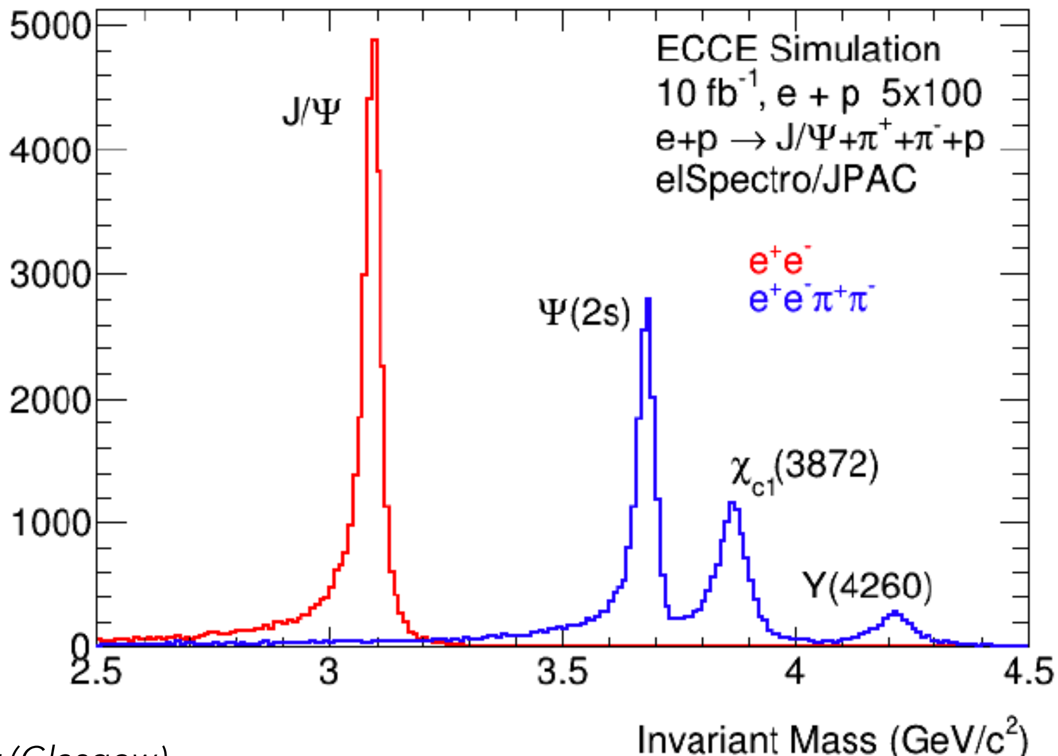


Similar challenges for J/Ψ and Upsilon…

Kong Tu (BNL)

Charmonium as a tool for XYZ Spectroscopy

- XYZ Spectroscopy, spectroscopy of mesons with charm quarks, search for exotics.
- New XYZ states have unexpectedly narrow widths inconsistent with quark model predictions.
- Low-Q2 tagger will enable fully exclusive reconstruction of photoproduction in part of the kinematics.
- Resolution sufficient to separate states:



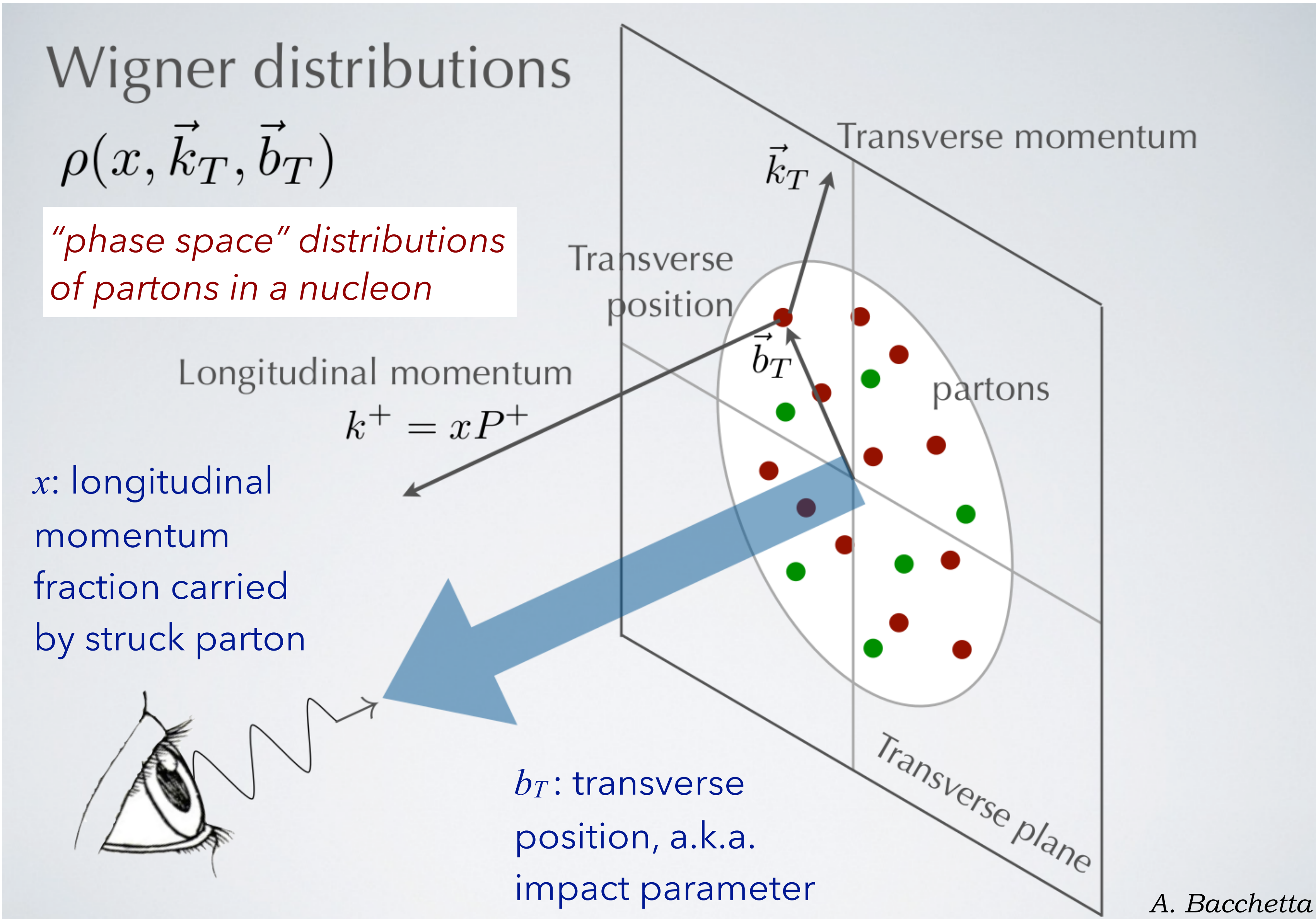
Concluding remarks

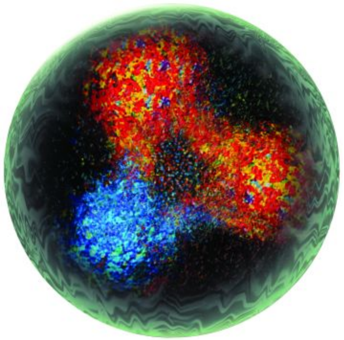
- EIC for the moment is the only (imminent) facility to provide collisions of polarised ions and polarised electrons – expect first data in ~2032.
- EIC is the only facility to be built purely for the study of QCD!
- Wide CoM energy range, high luminosity, hermetic multi-purpose detectors, triggerless data acquisition, possibility of jet reconstruction: wealth of opportunities for quarkonia production and reconstruction, from inclusive to fully exclusive processes, in electro- and photoproduction.
- Discussed ePIC – but a second detector is also intended.
- Possibilities of extracting gluon GPDs (gluon tomography, spin and pressure composition), accessing the trace anomaly for the composition of nucleon mass, probing gluon saturation, searching for exotics and much much more!

Join us! We have working groups for (almost) everything :-)


Thank you!
Any questions?

A constructivist view of the nucleon

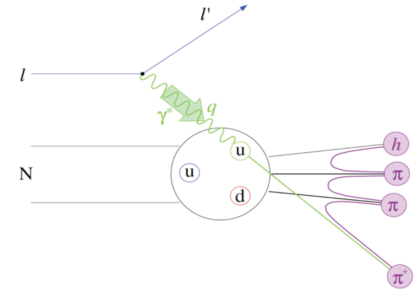




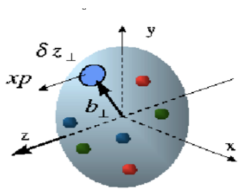
Wigner function: full phase space parton distribution of the nucleon

Generalised Transverse Momentum Distributions (GTMDs)

Possible access via exclusive di-jet production or exclusive π⁰-production at high Q^2.

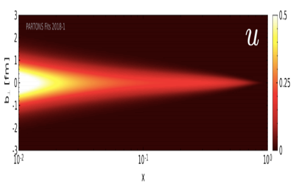


$$\int d^2k_T$$

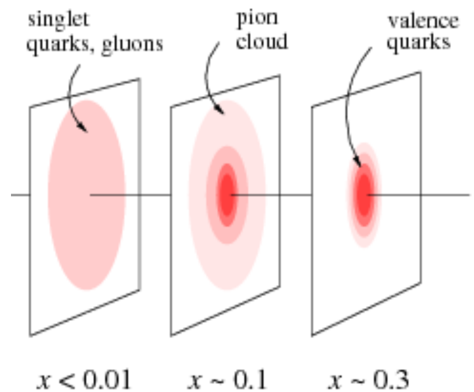


Generalised Parton Distributions (GPDs)

Exclusive processes



$$\int d^2b_T$$

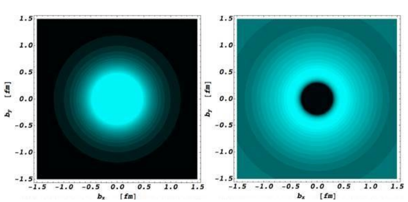


Transverse Momentum-Dependent distributions (TMDs)

Semi-inclusive DIS (SIDIS)

$$\int dx$$

$$\int d^2k_T$$

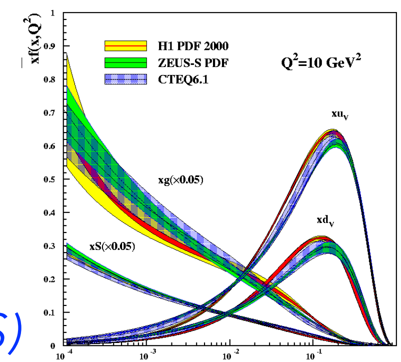


Form Factors

Elastic scattering

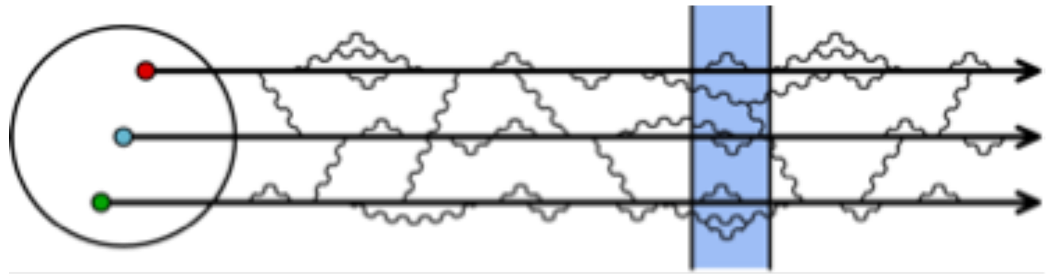
Parton Distribution Functions (PDFs)

Deep Inelastic Scattering (DIS)

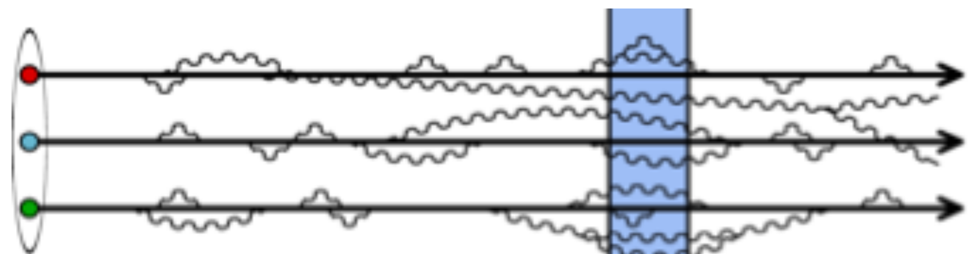


Runaway glue

* Nucleon probed at low Q^2, high x.



* Nucleon probed at large Q^2, low x.



Courtesy of A. Deshpande

* Gluons are charged under colour: can generate (and absorb) other gluons.

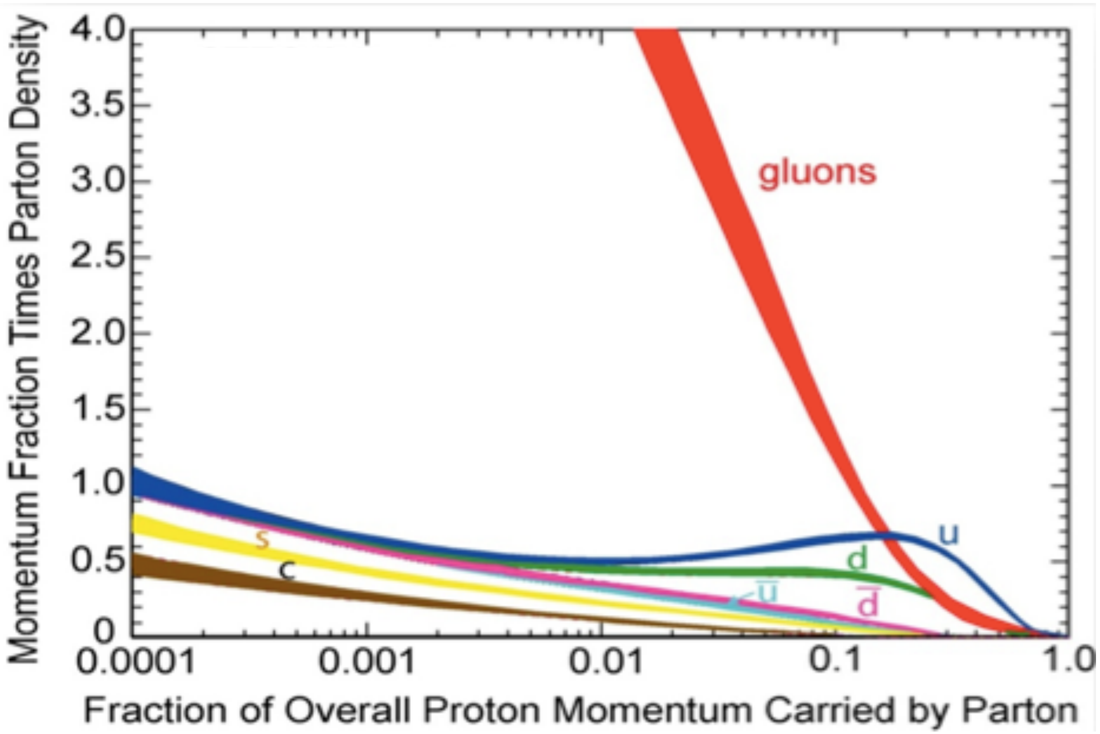
* Nucleon probed at high energies, time dilation of strong interaction processes: gluons appear to live longer, emitting more and more gluons. Runaway growth! Runaway growth?

Saturation of gluon density

* Runaway growth of glue at low-x:

“…A small color charge in isolation builds up a big color thundercloud….”

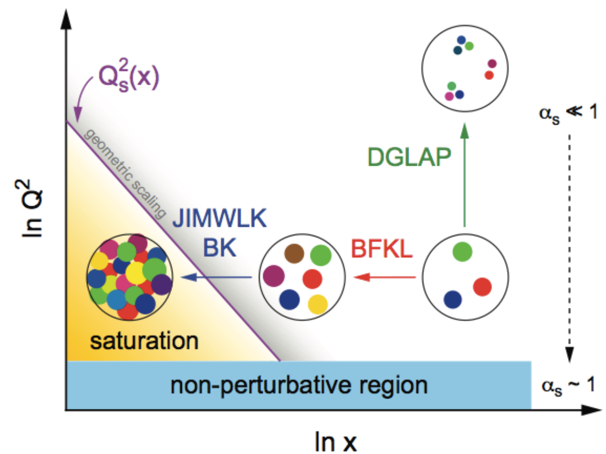
F. Wilczek, in “Origin of Mass”
Nobel Prize, 2004



But somewhere it must saturate…

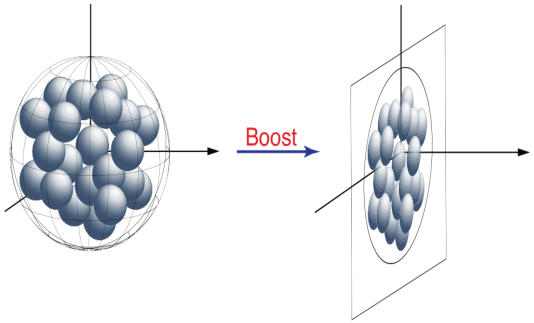
rate of  = rate of 

Recombination of gluons leads to saturation of gluon densities. Possible effective theory: Colour Glass Condensate.

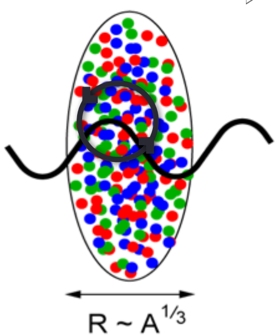


Courtesy of A. Deshpande

Can we reach saturation at EIC?



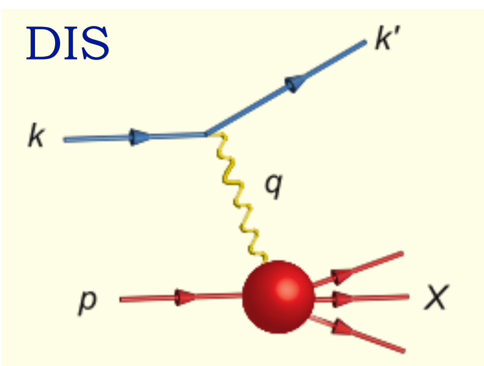
Saturation regime would be accessible at much lower energy in *e-A* collisions than *e-p*. You do not need a TeV collider!



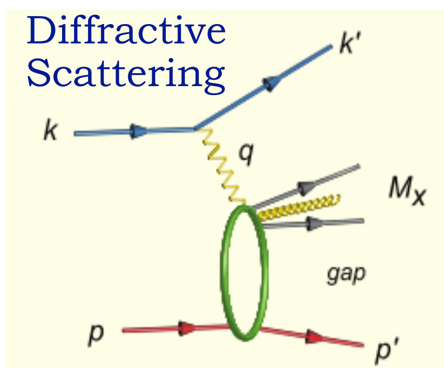
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

saturation scale

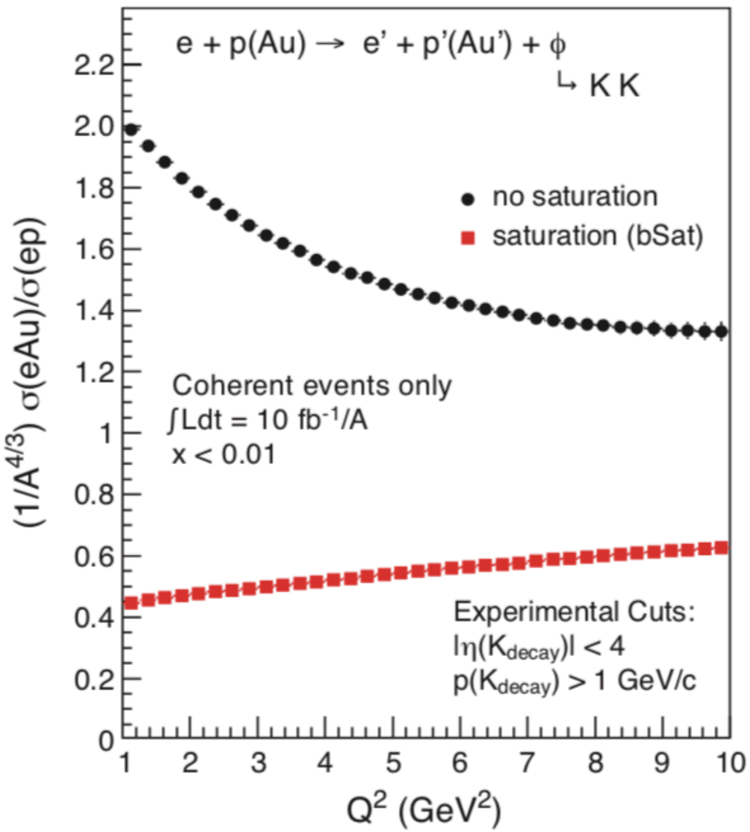
A powerful signature is diffractive cross-sections:



Saw ~10% diffractive events at HERA.

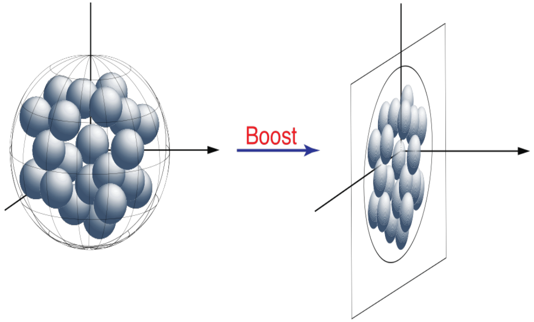


$$\sigma_{\rm diff} \propto [g(x, Q^2)]^2$$



EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Can we reach saturation at EIC?



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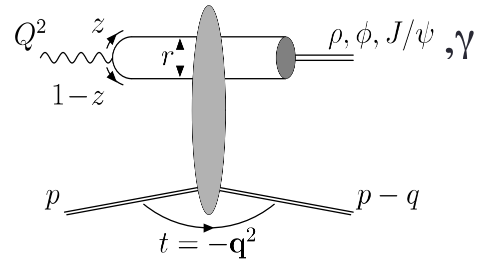

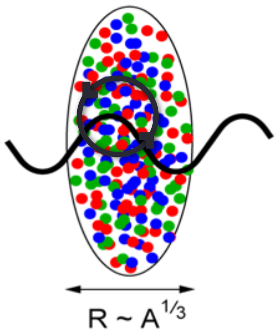

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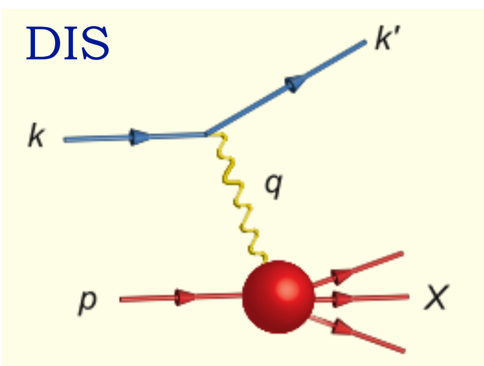

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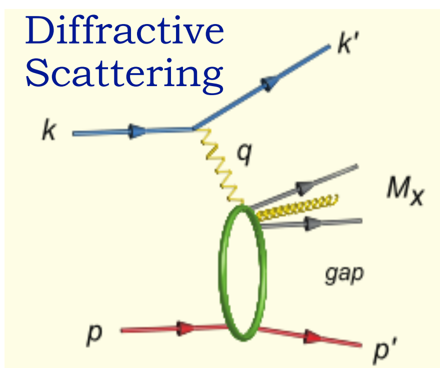

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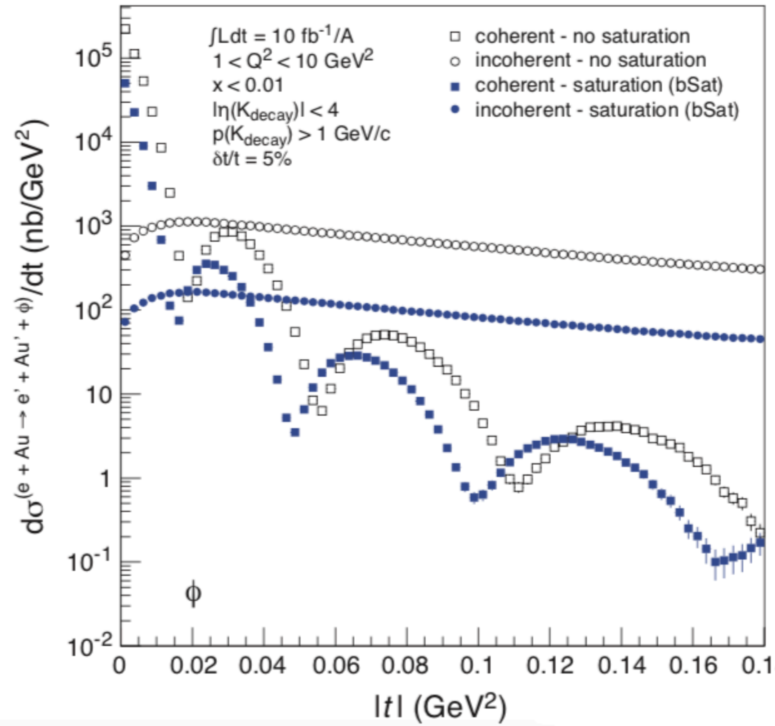
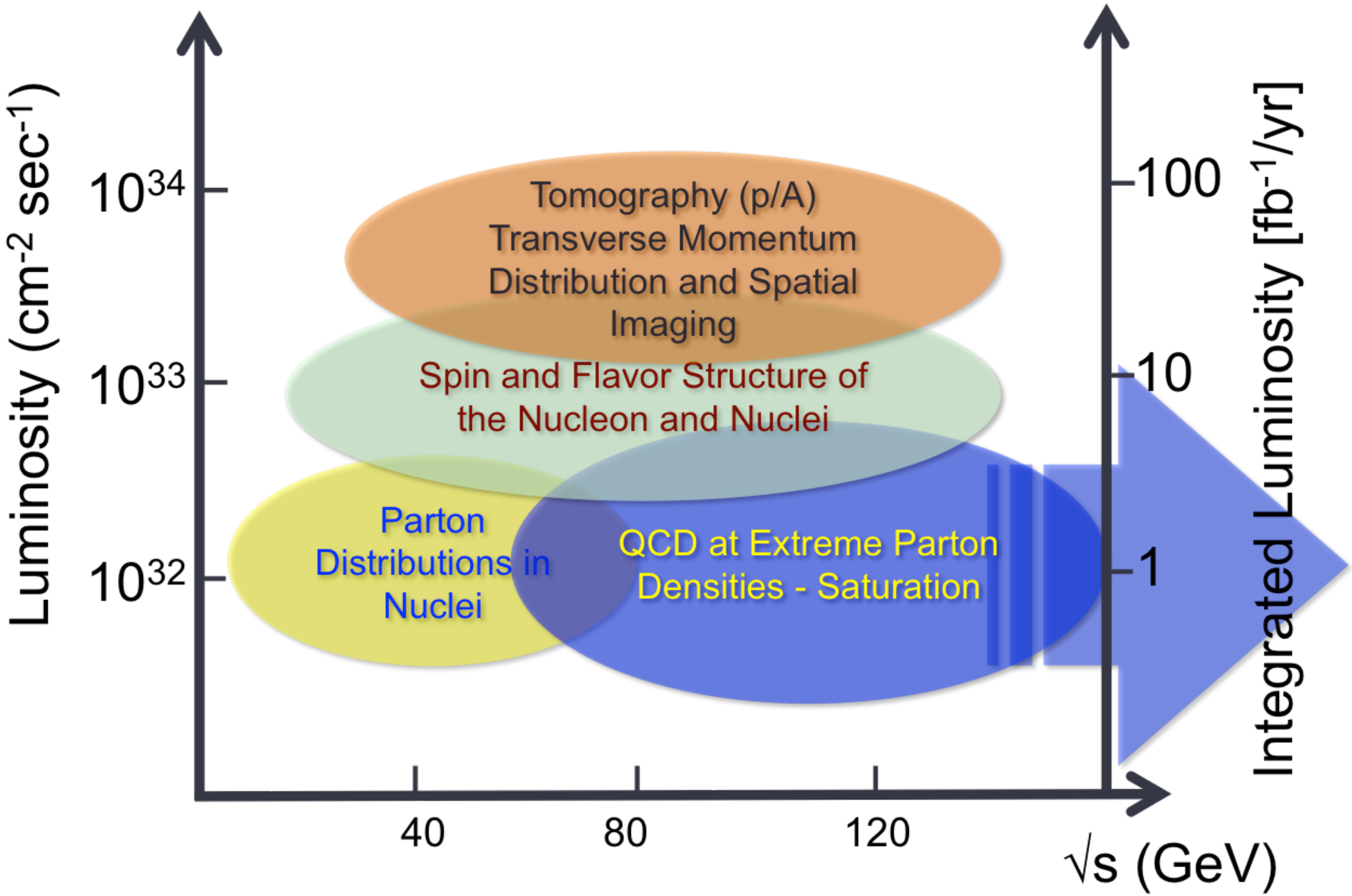


EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

Physics reach of the EIC

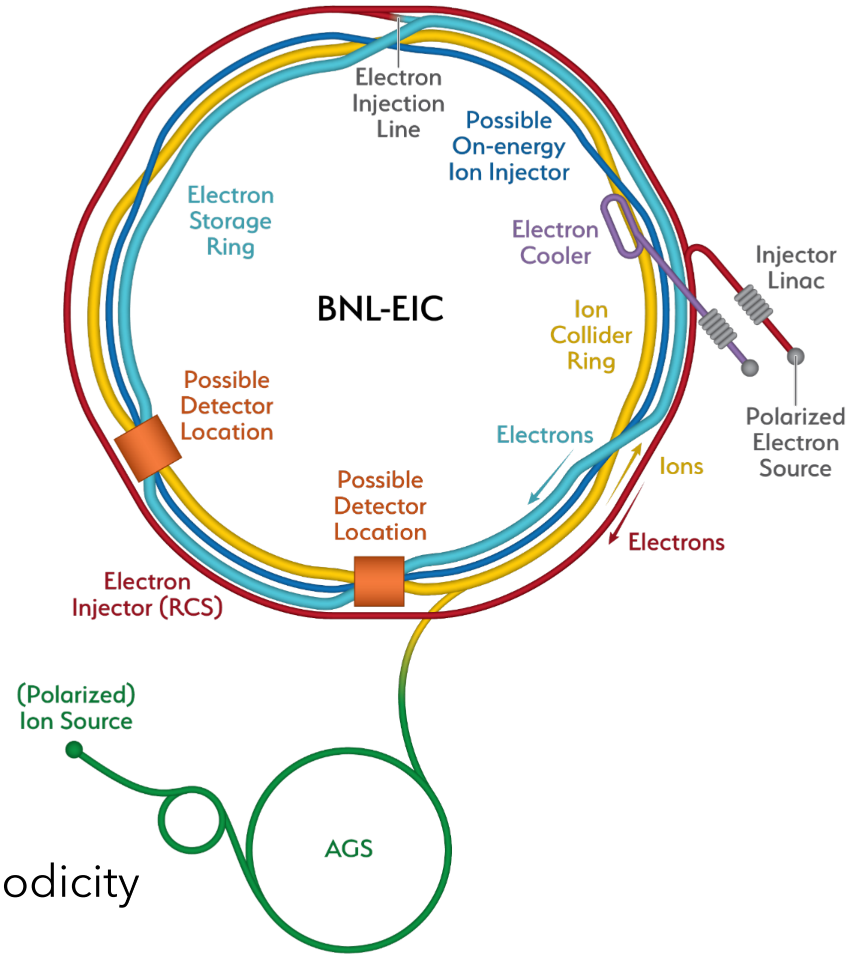


year $=10^7$ sec

EIC accelerator

Hadron storage ring (HSR): 41-275 GeV (based on RHIC)

- up to 1160 bunches, 1A beam current (3x RHIC)
- bright vertical beam emittance (1.5 nm)
- strong cooling (coherent electron cooling, ERL)



Electron storage ring (ESR): 2.5–18 GeV (new)

- up to 1160 bunches
- high polarization by continual reinjection from RCS
- large beam current (2.5 A) ➔ 9 MW SR power
- superconducting RF cavities

Rapid cycling synchrotron (RCS): 0.4-18 GeV (new)

- 2 bunches at 1 Hz; spin transparent due to high periodicity

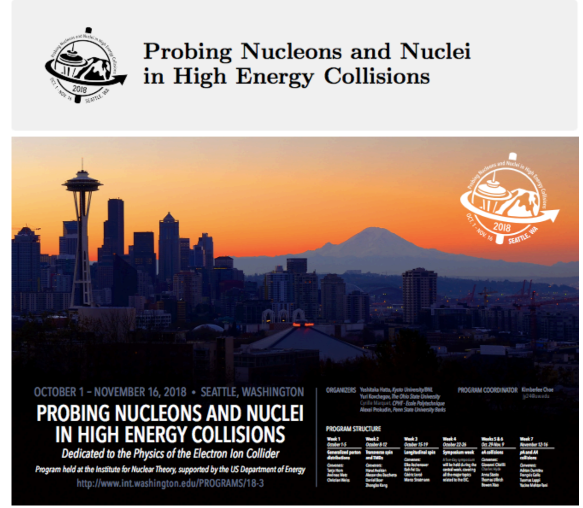
High luminosity interaction region(s) (new)

- L = 10^{34} cm^{-2}s^{-1}
- superconducting magnets
- 25 mrad crossing angle with crab cavities
- spin rotators (produce longitudinal spin at IP)

EIC in the making

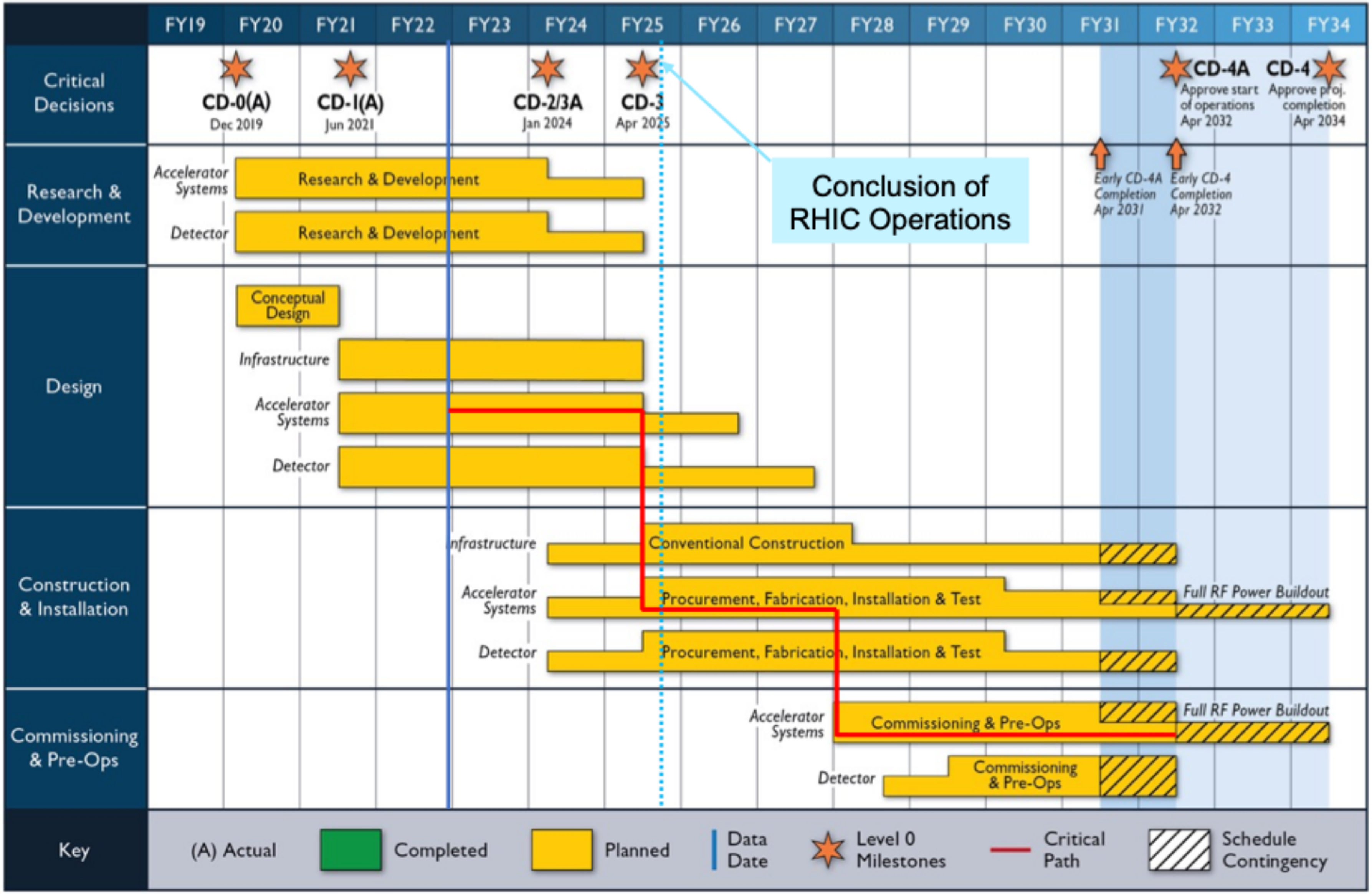
- **2007 Nuclear Physics Long Range Plan** "*The EIC is embodying the vision of reaching the next QCD frontier*"
- **2011:** US DOE starts to fund generic R&D (**eRD programme**)
- **2012:** EIC White Paper
- **2015 Nuclear Physics Long Range Plan** "*high-energy, high-luminosity polarised EIC as the highest priority for new facility construction following completion of FRIB*"
- **2016: Users Group** acquires formal charter / elected board of representatives (eicug.org)
- **2017-18 National Academies of Science (NAS) Review:** "*the science questions that an [EIC] would answer are central to completing our understanding of atomic nuclei… An EIC can* ***uniquely*** *address three profound questions about nucleons … and how they are assembled to form the nuclei of atoms*"

EIC in the making



- ✦ **2018: "Probing Nucleons and Nuclei in High Energy Collisions"**: 7-week workshop programme at INT, Seattle. https://arxiv.org/abs/2002.12333
- ✦ **2019:** DOE **Independent Cost review Exercise**, DOE-led meetings with international funding agencies / government representatives.
- ✦ **Dec 2019: CD0 (Critical Decision 0) status granted by US DoE**: establishes "mission need" & formal launch of project. Funding envelope: $1.6 - $2.6 billion.
- ✦ **2020:** **EIC Yellow Report**
- ✦ **2020: Expressions of Interest** from the international community
- ✦ **2021:** Development of detector proposals: **ATHENA, ECCE, CORE**
- ✦ **2021:** **Conceptual Design Report**
- ✦ **June 2021: CD1 status granted by DOE:** "approve alternative selection and cost range"
- ✦ **2022:** Formation of the **ePIC Collaboration**, design of the "project detector" (detector 1).

EIC Reference Schedule - V3



Slide: Rolf Ent