Inclusive DIS Measurements at the EIC

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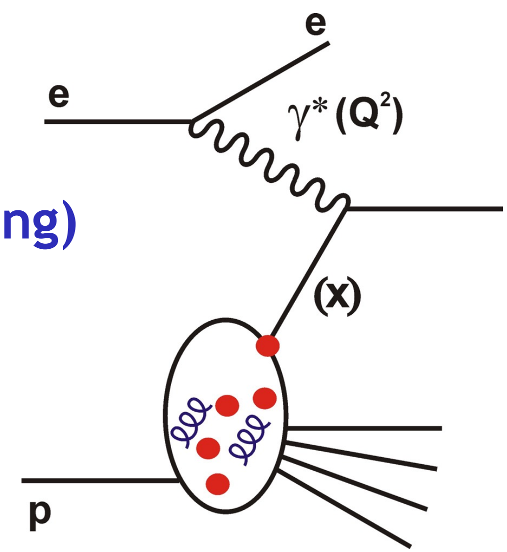
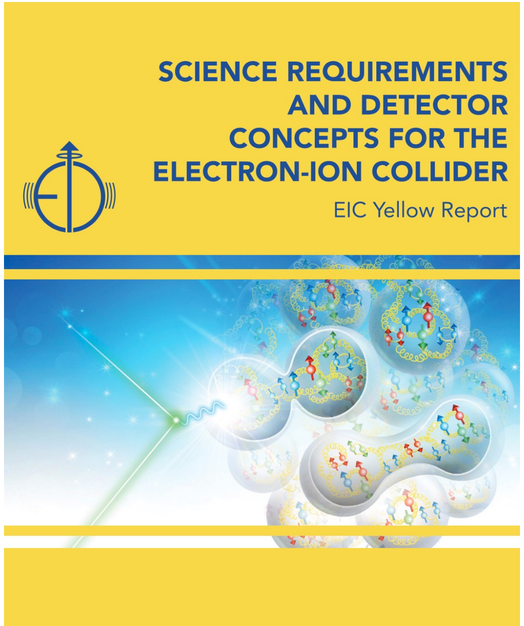
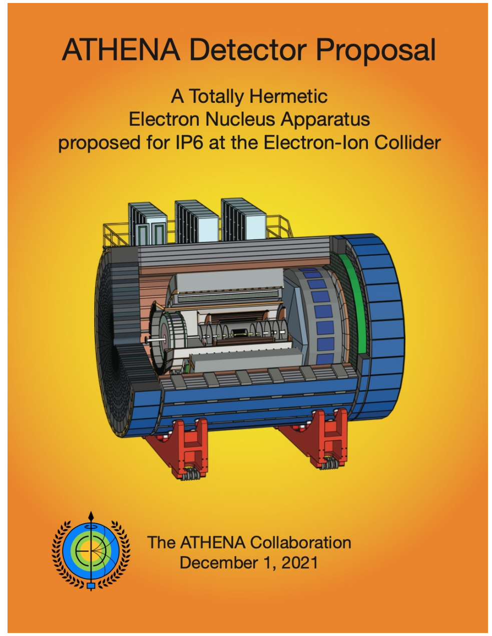
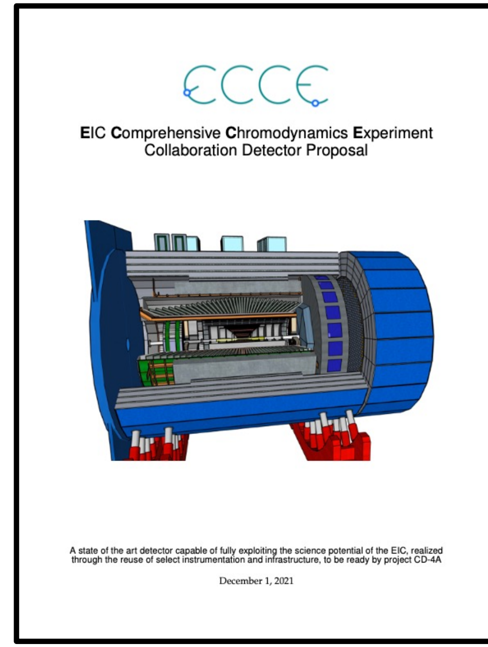


1) Current snapshot experimental status
2) Experimental issues → precision
3) Early EIC performance simulations
4) Early simulated EIC data
5) Some thoughts on MCs

Current EIC Experimental Status







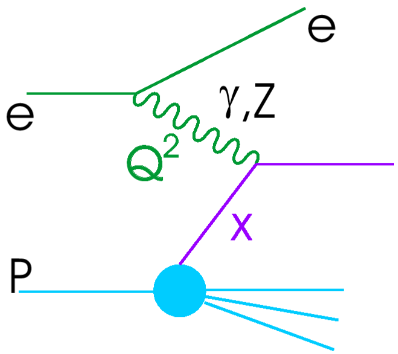
- Following Yellow Report (arXiv:arXiv:2103.05419), three detailed detector proposals (ATHENA, ECCE, CORE) emerged.

- ECCE chosen as reference design. Realignment of community in `EPIC' collaboration. Currently building a detailed design and simulation framework

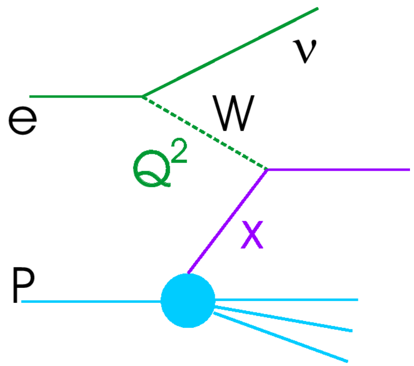
- Ongoing work towards a second, complementary detector.

Most results shown here are taken from ATHENA / ECCE proposals

Inclusive Scattering Observables



Neutral Current:
ep → eX



Charged Current:
ep → νX

`Inclusive' refers to anything we can measure starting from the inclusive neutral and charged current processes

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

$$y = \frac{p \cdot q}{p \cdot e} \qquad Q^2 \simeq sxy.$$

$$W^2 = (q + p)^2.$$

- x, Q^2 (via y, Q^2) can be reconstructed from any two of $E_e, \theta_e, E_h, \theta_h$

- Hadronic final state understanding also important for background rejection

… starting point is electron identification & reconstruction, plus inclusive hadronic final state measurement.

Inclusive Scattering Derived Measurements

At the world's first: eA collider;
High luminosity ep collider;
Polarised target collider;
… inclusive measurements lead to a long list of underlying physics quantities…

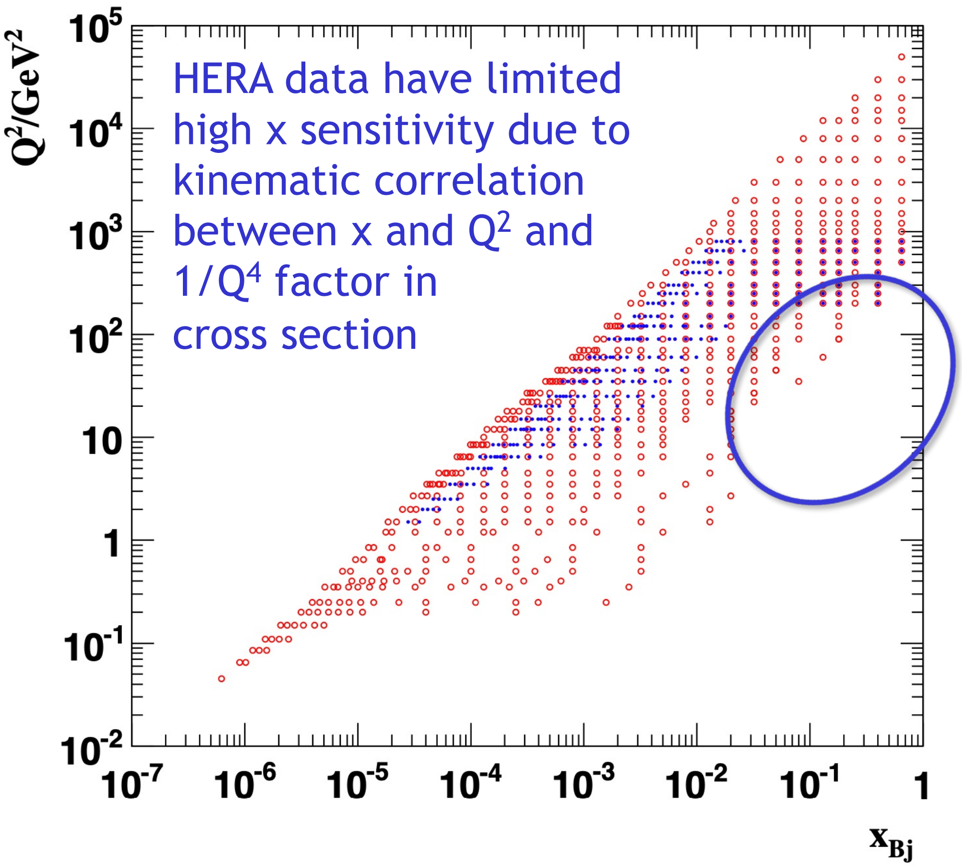
Measurement	Physics Topic/goal
$\boldsymbol{\sigma}_{red,NC(CC)}(x,Q^2) \rightarrow F_2, F_L$	Proton PDFs $q(x,Q^2)$, $g(x, Q^2)$
$\boldsymbol{\sigma}_{red,NC(CC)}(x,Q^2) \rightarrow F_2, F_L$	Nuclear PDFs $q(x,Q^2)$, $g(x, Q^2)$ Non-linear QCD dynamics
Inclusive $A_{\|\|}$ / $A_{\perp}$ for proton, deuterium, ^{3}He	Gluon & Quark Helicity $\Delta g(x,Q^2)$, Δu^+, Δd^+

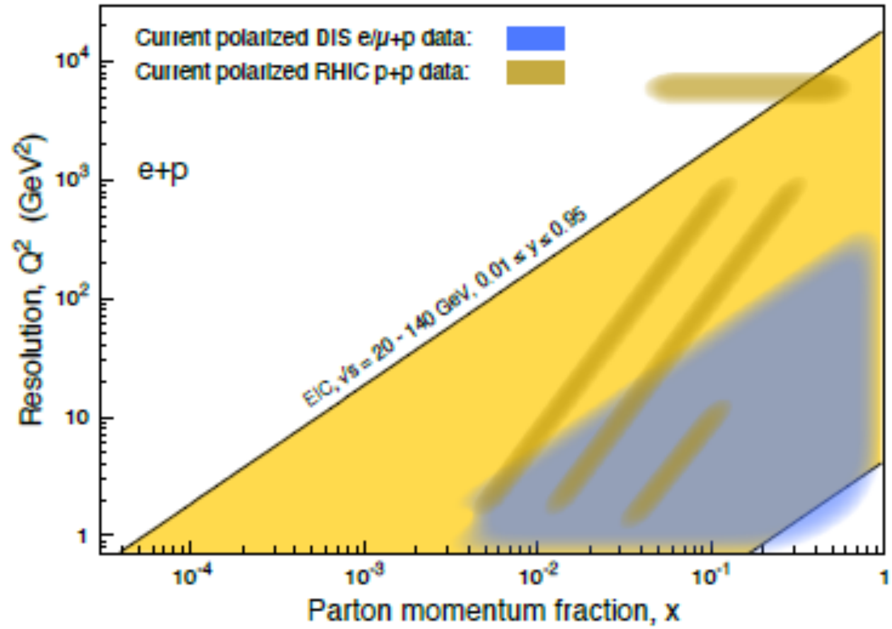
Also
- Neutron PDFs from deuterium studies
- Also electroweak parameters ($\sin^2\theta_W$, M_W, g_A^F, g_V^F)
- Exotic searches (leptoquarks, excited leptons, compositeness …)

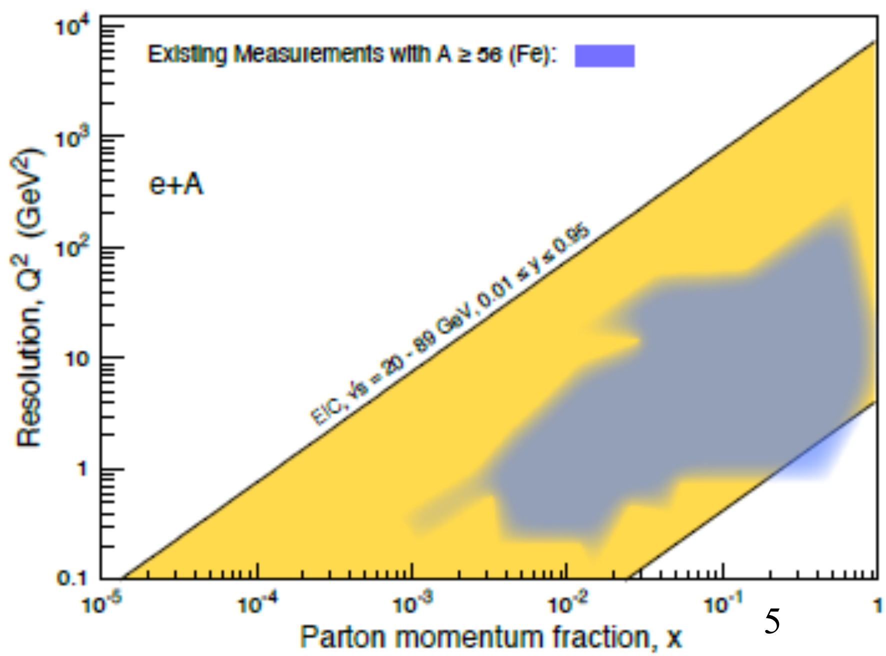
Kinematic Coverage v Existing Data

- ~2 new orders of magnitude for polarised ep and eA

- Precision in large x unpolarised ep beyond the fixed target region.





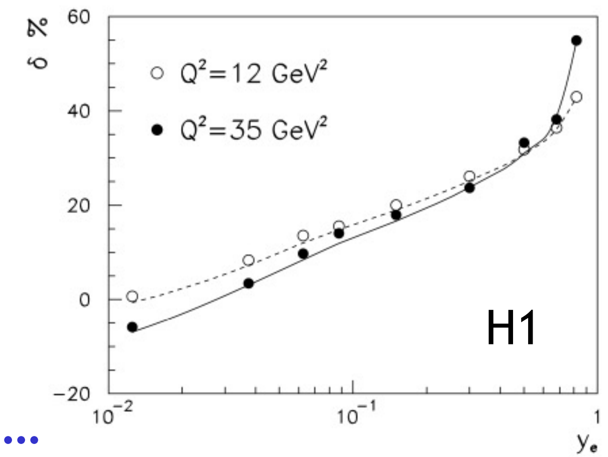


Reconstructing the Kinematics

- Use electron only where possible (E_e', θ_e usually very well measured)

... BUT ... resolution degrades as 1/y
[E_e' large, towards the 'kinematic peak']
→ limitation on measurements at low y,
i.e. high x (central part of EIC programme!)

$$y_e = 1 - \frac{E_e'}{E_e}\sin^2\frac{\theta}{2}$$



... AND ... initial state radiation corrections
(and uncertainties) grow as y→1 (i.e. at low x)

- Some methods used at HERA / under study for EIC ...

1) Electron only method (NC working horse)
2) Hadron only method (CC)
3) Double Angle methods (θ_e, θ_h)
   → insensitive to calorimeter energy resolution
4) Sigma methods ($E_e', \theta_e, (E - p_z)_h$)
   → insensitive to forward hadronic losses & ISR

Choice depends on kinematic region and details of detector performance.

Detector Calibration

- The redundancy in NC kinematic variable reconstruction lies at the heart of the detector calibration methods used in DIS.

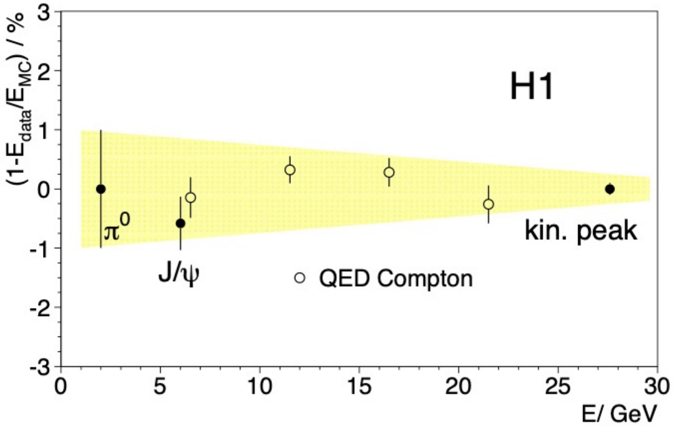
<u>**Typical approach:**</u>

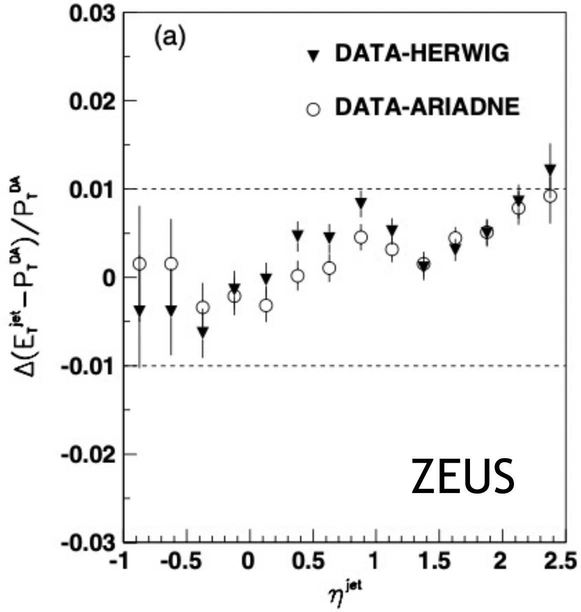
1) Electron calibration from 'known' resonances / kinematic peak
2) Hadronic final state from pT and E-pz balance relative to electron

… <0.5% on electrons and <1% on hadronic energy scale achieved at HERA.

- EIC will improve, particularly at low p_T, by using 21st century calibration techniques.

- Requires high statistics, high quality HFS reconstruction, high quality MC modelling

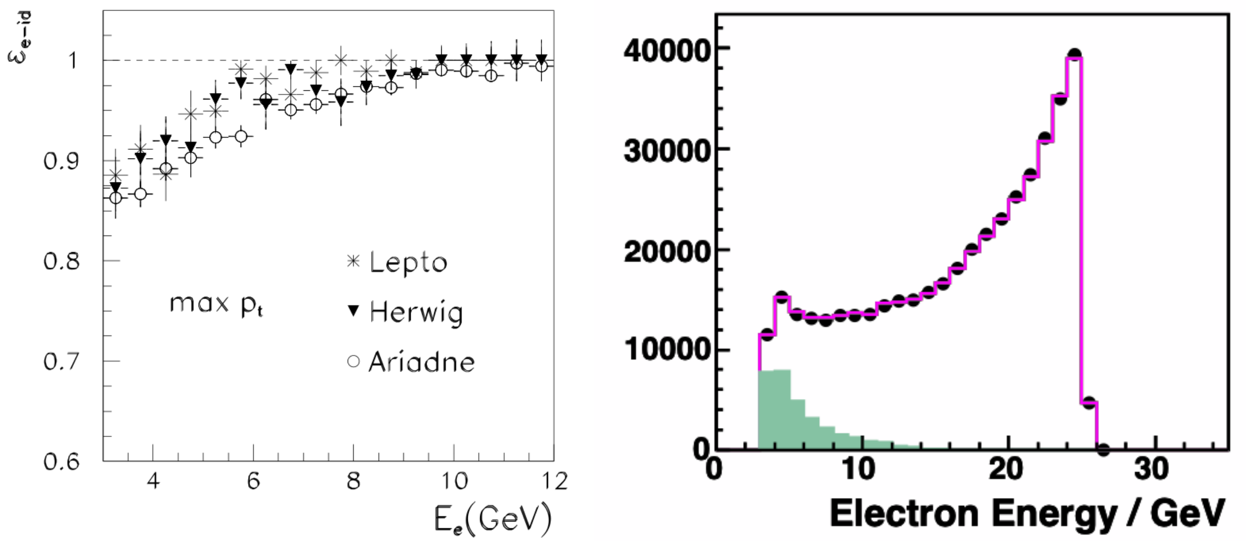




Scattered Electron Identification

- For high electron energies, choosing highest energy or highest p_T electromagnetic calo cluster is already efficient and almost background free

- At smaller energies, misidentification and 'photoproduction' background become important.

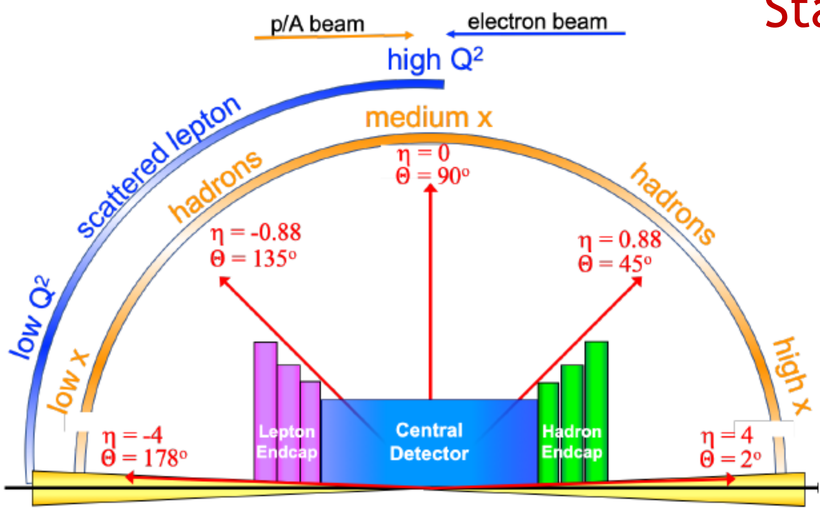


[Example HERA Plots from inclusive measurements focused on high y (low Ee, low x)]

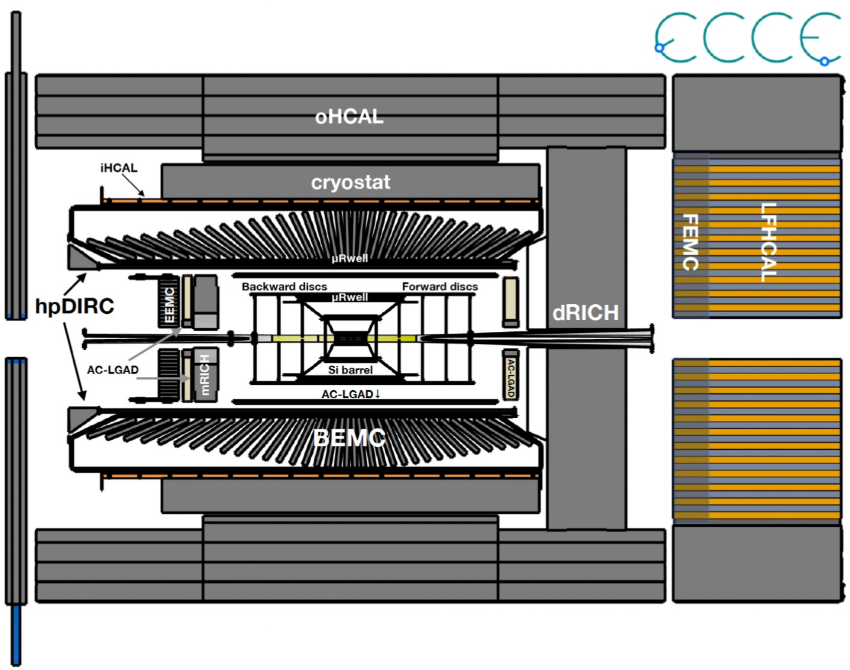
- Particle ID at HERA was very limited (basically only dE/dx of tracker)

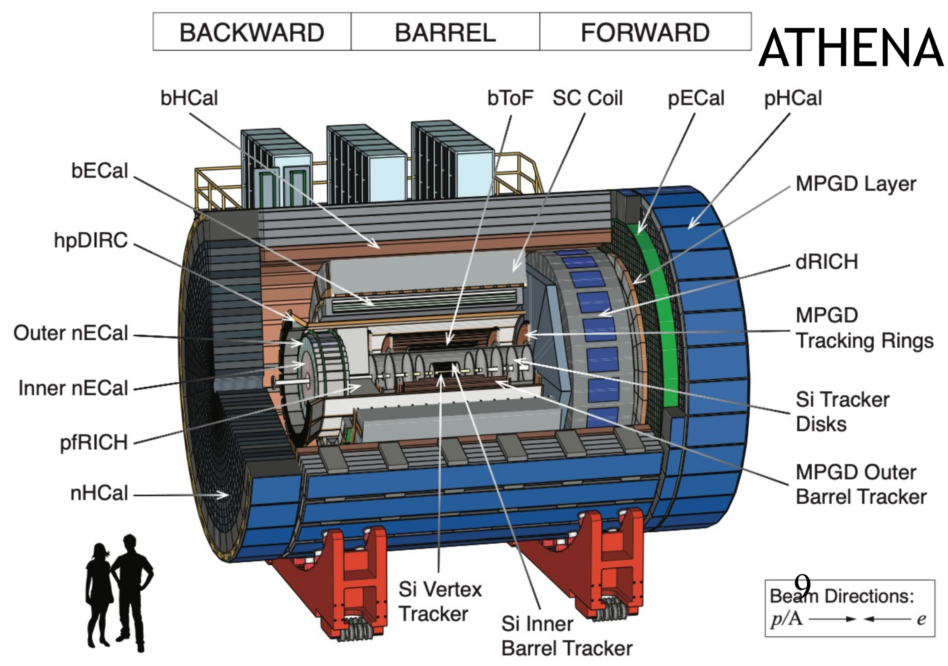
- Measurements down to E_e ~ 3 GeV (1/10 beam energy) were made, but with ever-increasing systematics

EIC will be transformationally different



State-of-the-art detectors with:
- Hermetic e, h coverage to |η|~4
- High tracking resolution (MAPS silicon)
- High precision ECAL (and HCAL)
- Stong emphasis on particle ID
- Strong emphasis on Forward / Backward beamline instrumentation

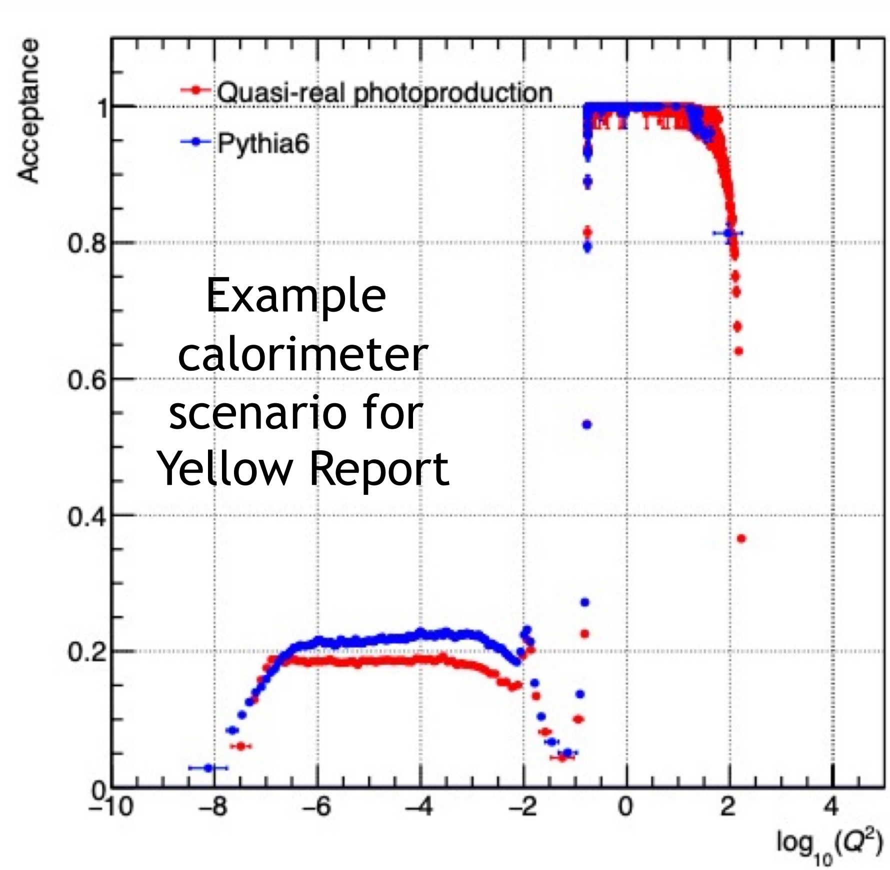


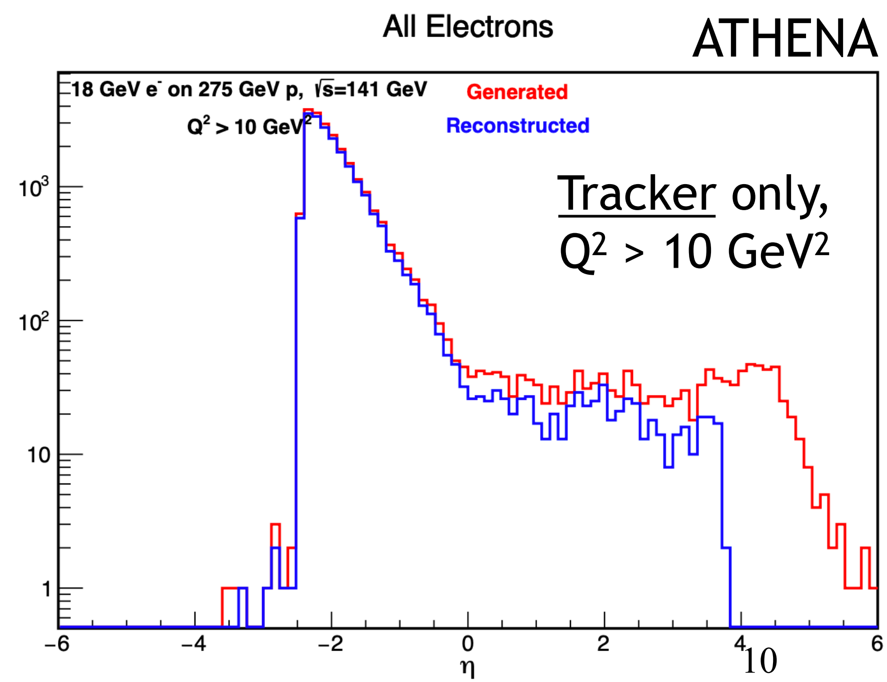


Early Performance Studies: electron acceptance

- Acceptance for calorimeter and tracker in main detector extends to $\eta\sim-4$ ($Q^2 \sim 1$ GeV^2)

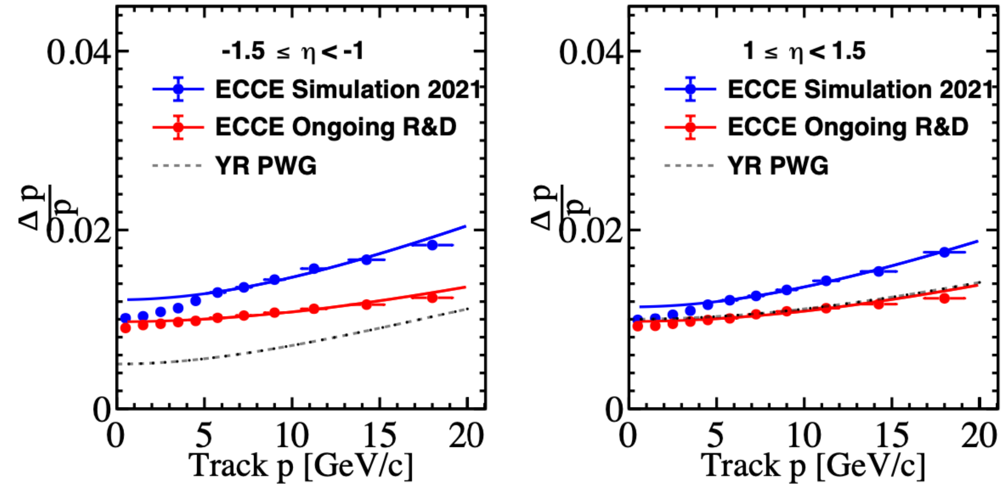
- Beamline instrumentation adds partial acceptance over broad region at $Q^2 < 1$ GeV^2 → "photoproduction"

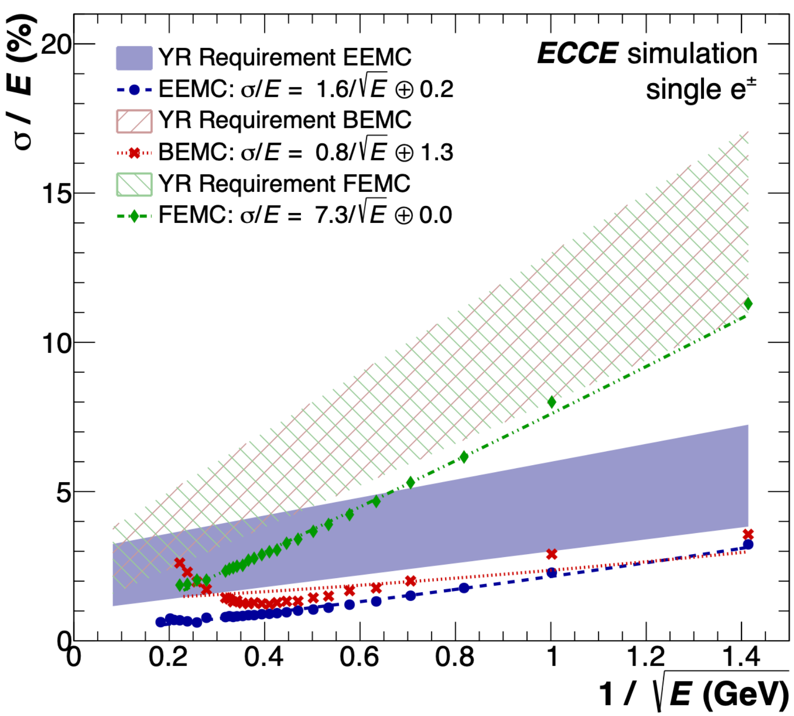


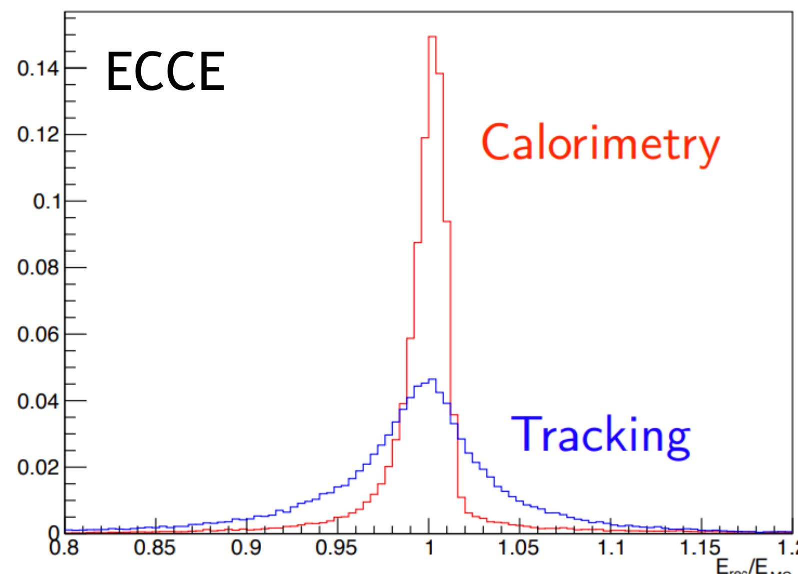


Early Performance Studies: electron energy measurement

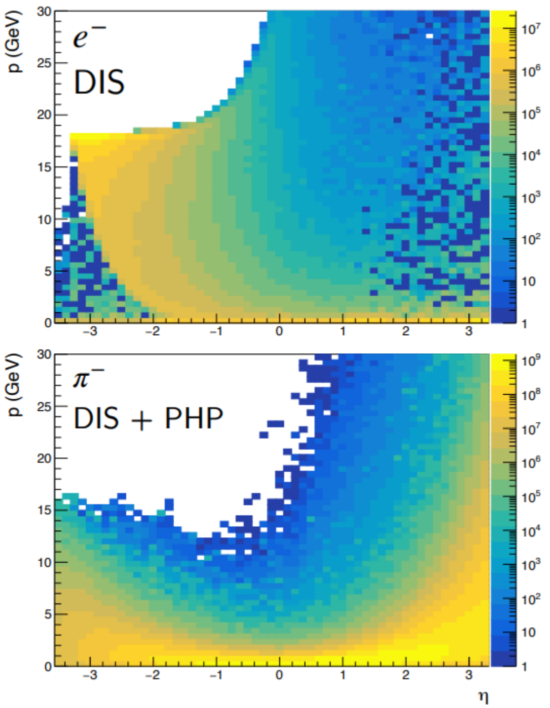
Electron energy measurement with either tracker (low p_T) or ECAL (high p_T) is at ~1% level throughout measured range



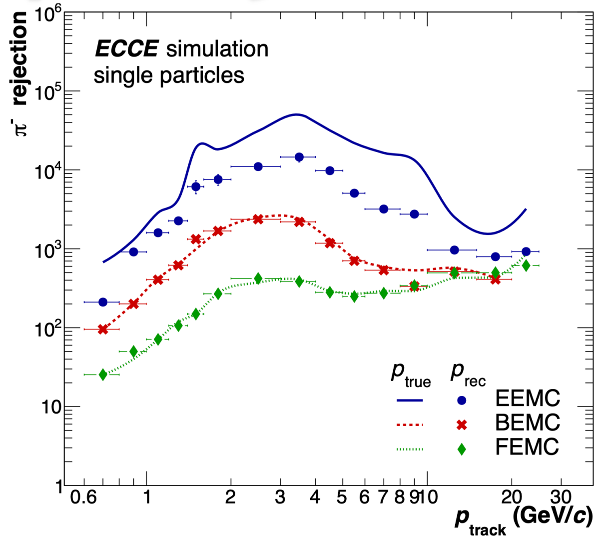


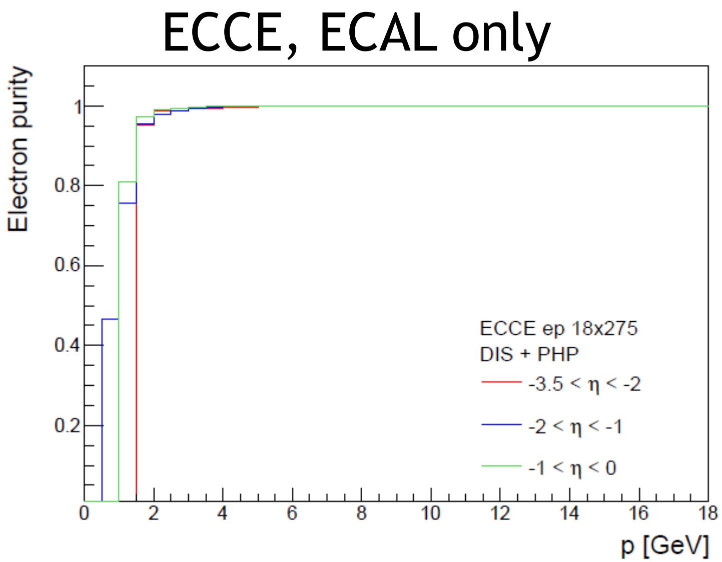


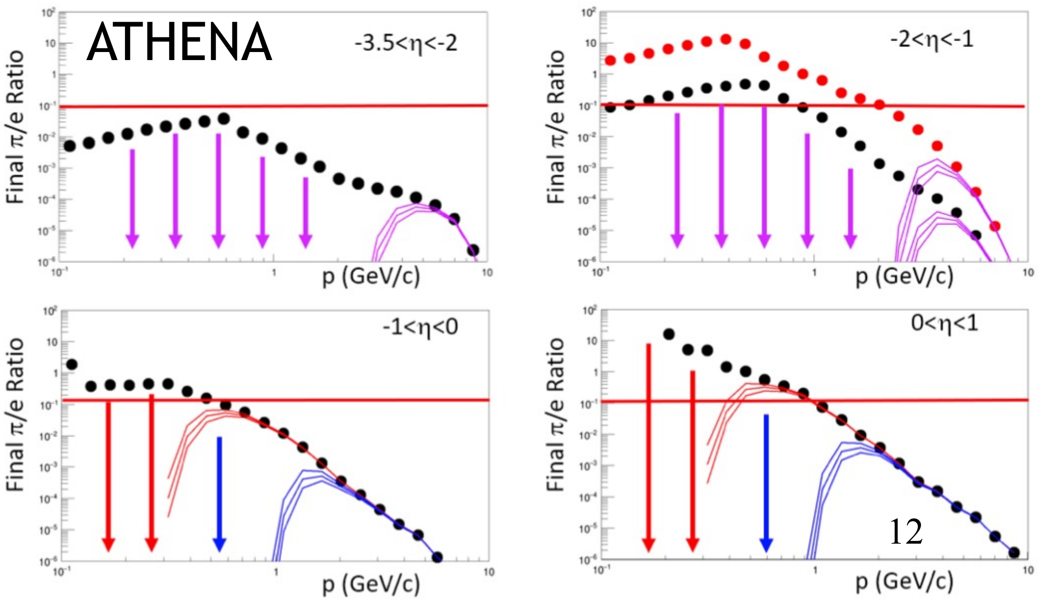
Early Performance Studies: electron purity



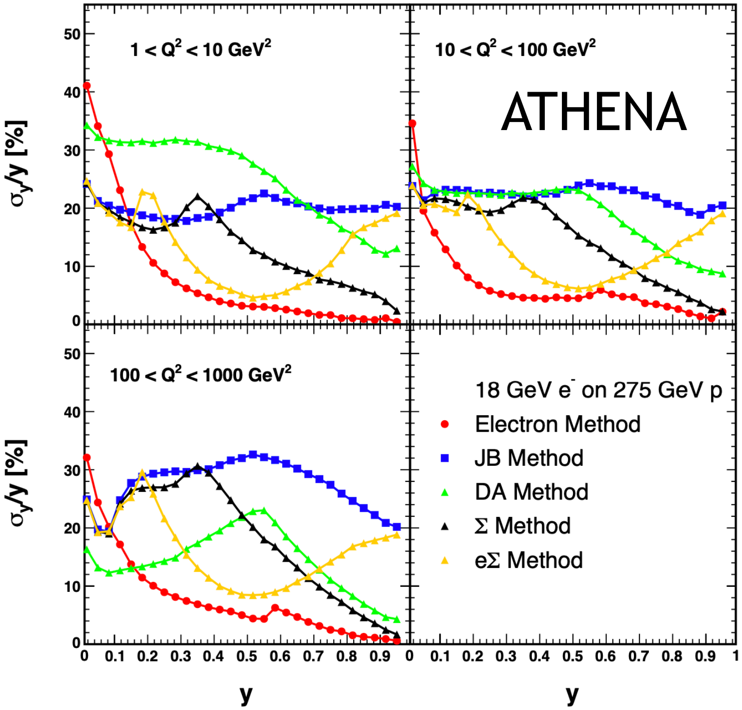
Photoproduction background to electron ID (from π) can be suppressed to < few% level using calorimeter alone, and to completely negligible levels when also including particle ID detectors.

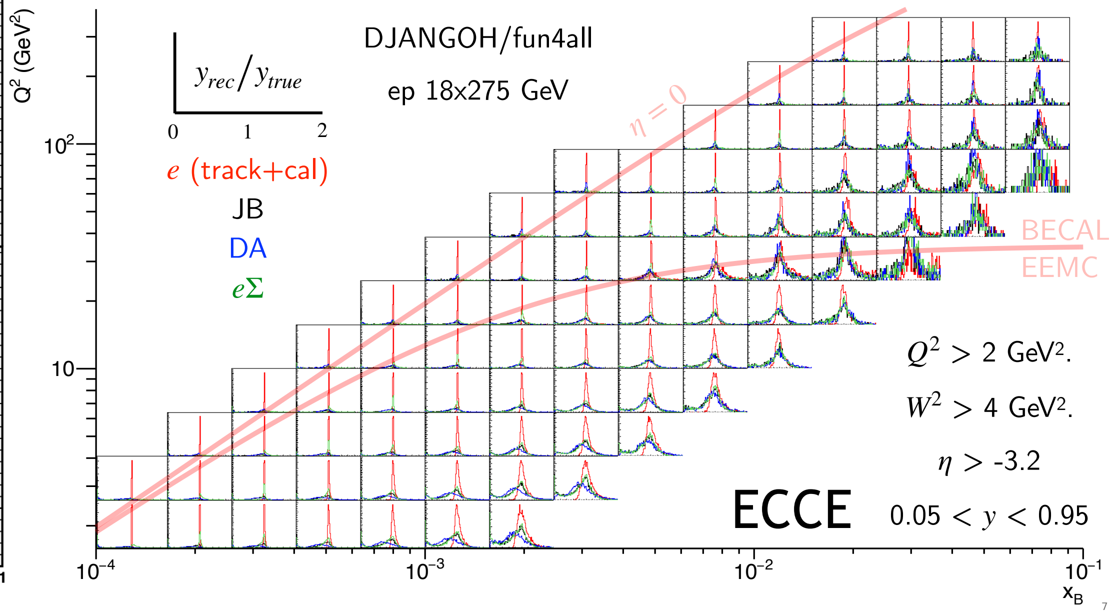






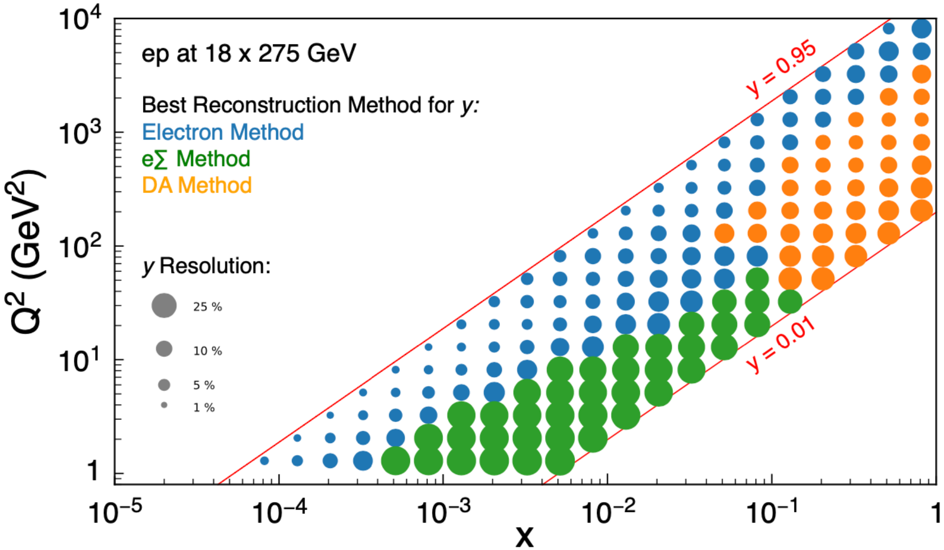
Early Performance Studies: Kinematic Resolution from MC with first approximation to particle flow algorithm



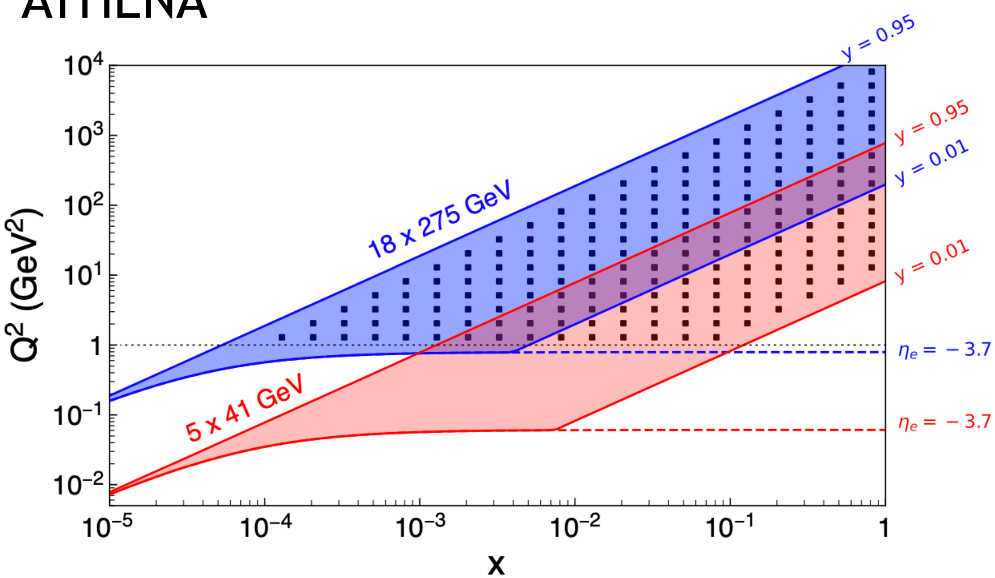


- First detailed assessment of relative performance of reconstruction methods throughout measured phase space
- Ongoing work on modernised methods in which all measurements are used simultaneously (machine learning / kinematic fitting)

Possible Neutral Current Measurement Strategy



ATHENA



- Kinematic coverage driven by e and h acceptance: $Q^2 > 1$ GeV^2, $0.01 < y < 0.95$, $W > 3$ GeV

- Choose reconstruction methods to optimise resolutions throughout phase-space
→ 5 bins per decade in x and Q^2

- Lower y accessible in principle, but easier to rely on overlaps between data at different $\sqrt{s}$

- Highest x bin centre at x=0.815

Estimating Experimental Precision

- With projected luminosities, inclusive measurements expected to be limited by systematic uncertainties at all but the very highest Q^2 values (maybe different for some asymmetry measurements).

- Systematic precision estimated based on experience from HERA, knowledge of EIC detector performance, and guesswork

(ongoing process, not yet fully based on MC simulations)

- Dominant sources at HERA were:
  - Electron energy scale (intermediate y)
  - Photoproduction background (high y)
  - Hadronic energy scale / noise (low y)

- EIC will improve in all areas (see previous slides)

- Current (conservative?) assumption on EPIC systematic precision (compatible with assumptions in **Yellow report)** …

→ 1.5-2.5% point-to-point uncorrelated
→ 2.5% normalisation (uncorrelated between different $\sqrt{s}$)

EIC sim's and expected impact (ATHENA)

- Neutral current ep pseudodata with current estimates of integrated luminosities at different $\sqrt{s}$

e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

- Charged current also included at highest $\sqrt{s}$

Similar approach for eA … per-nucleon integrated luminosities:

5 x 41GeV: 4.4 fb^{-1} 10 x 110GeV: 79 fb^{-1} 18 x 110GeV: 79 fb^{-1}

Fitting procedure for impact on PDF sets

1) Get prediction from PDF set for each EIC pseudodata (x-Q^2) point

2) Smear pseudodata with uncorrelated uncertainties point-by-point

3) Smear pseudodata with normalisation systematic uncertainty at each $\sqrt{s}$

4) Perform fit with standard input data plus EIC data

5) Compare uncertainties with those from fit without EIC data

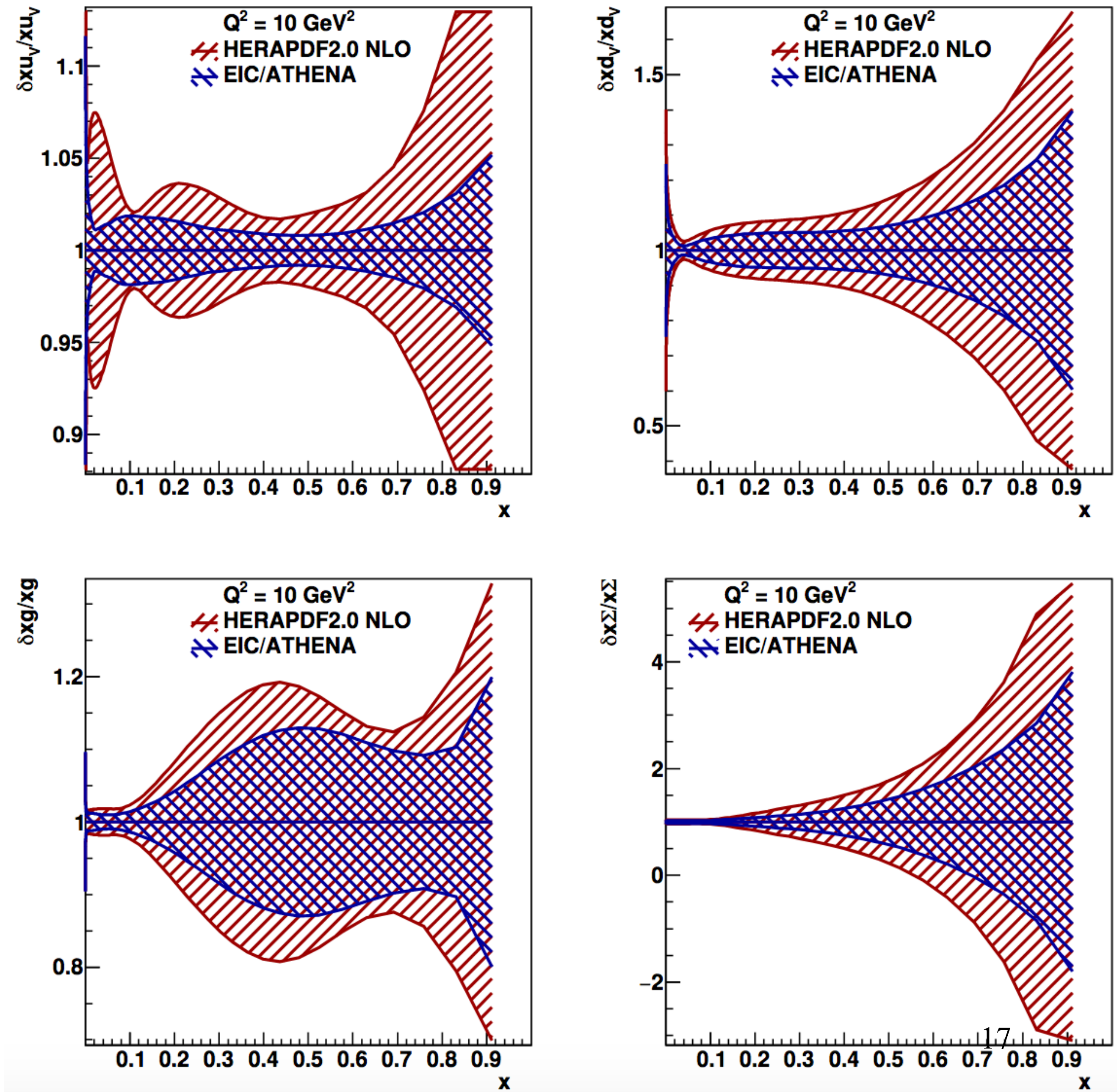
Impact of EIC/ATHENA on HERAPDF2.0

HERAPDF2.0 obtained from final combined HERA data only

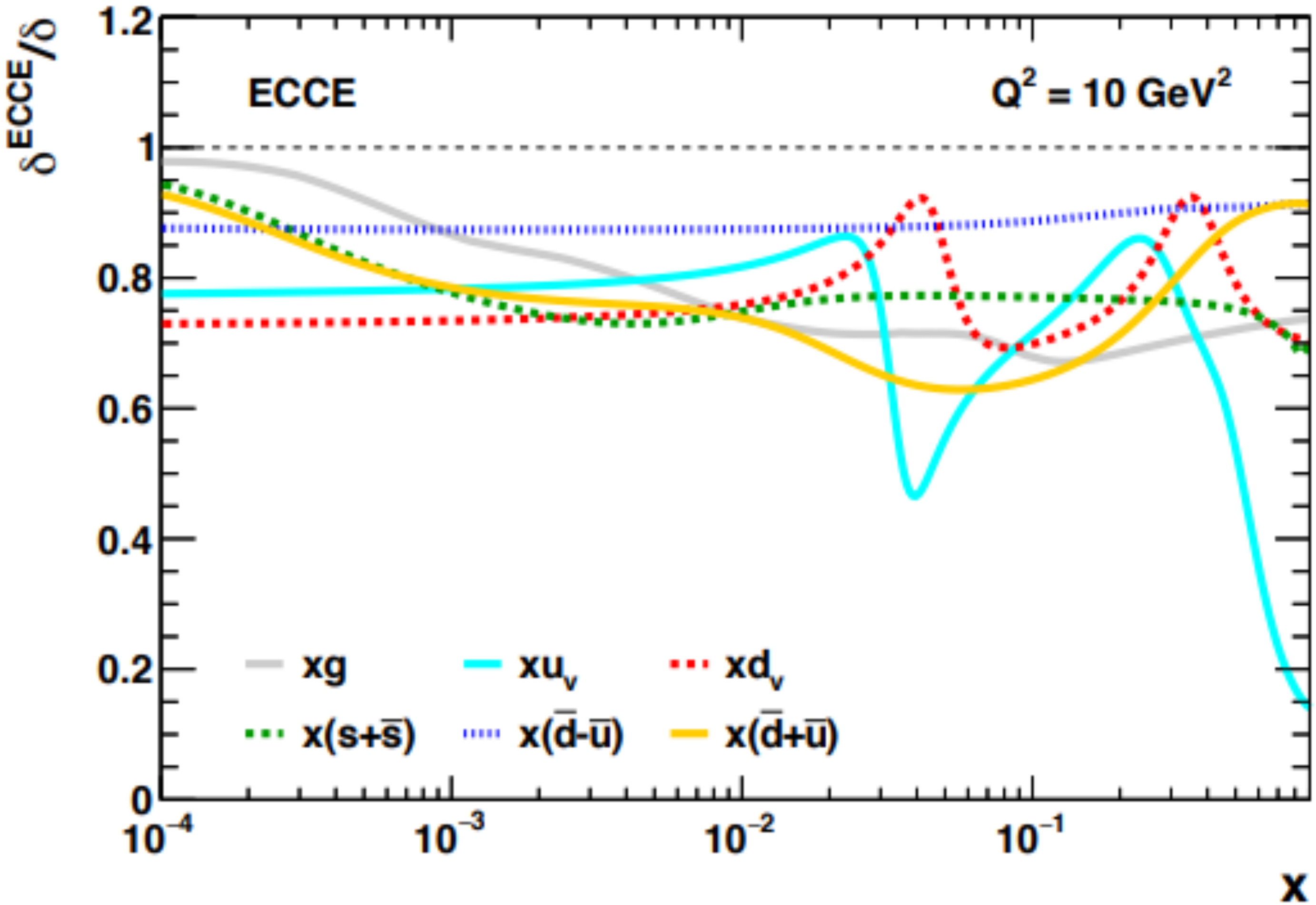
Fractional total uncertainties with / without EIC / ATHENA data included along with HERA

(linear x scale)

… EIC will bring significant reduction in uncertainties for all parton species at large x



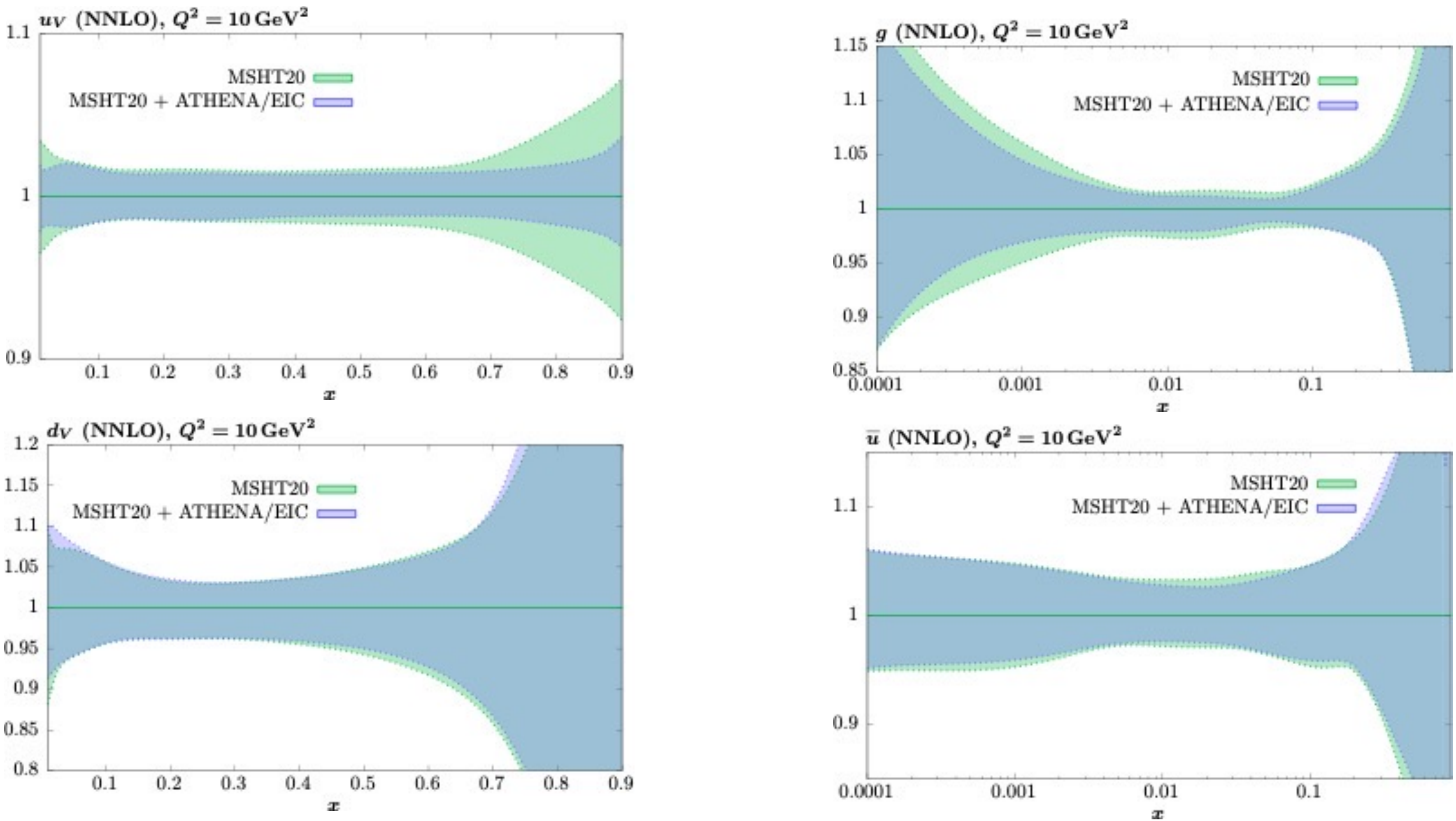
The ECCE Equivalent (log x scale)



- Impact of simulated ECCE data on PDFs relative to HERAPDF2.0
- Results broadly compatible with ATHENA

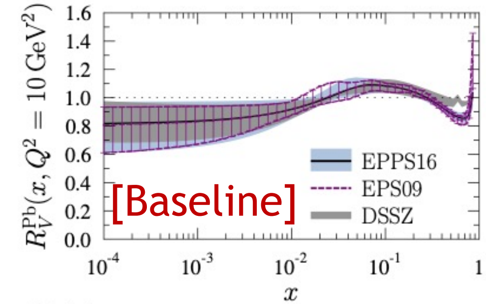
Impact relative to 'Global' Fit (i.e. also including LHC and FT): MSHT20 NNLO

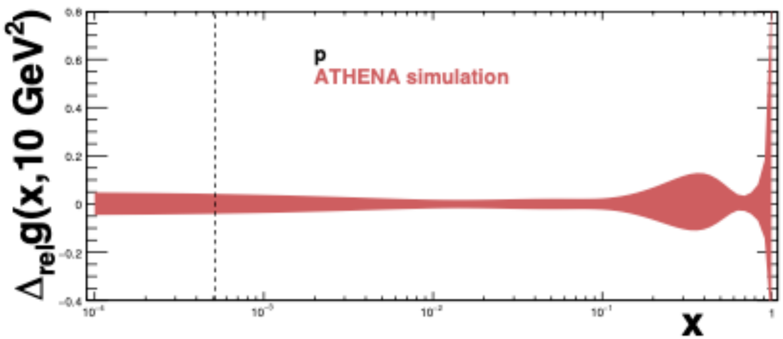
- Including LHC / FT data in global fits has large impact on PDFs at large x
- EIC pseudodata still improves u density precision (charge-squared weight)
- Small, but valuable improvements in gluon / all other parton species



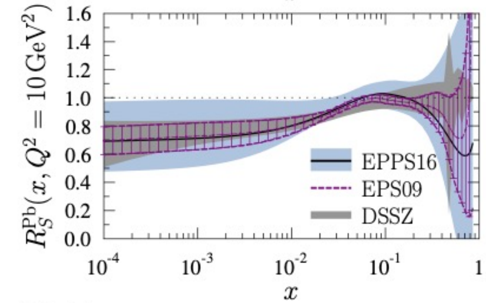
EIC and nuclear PDFs

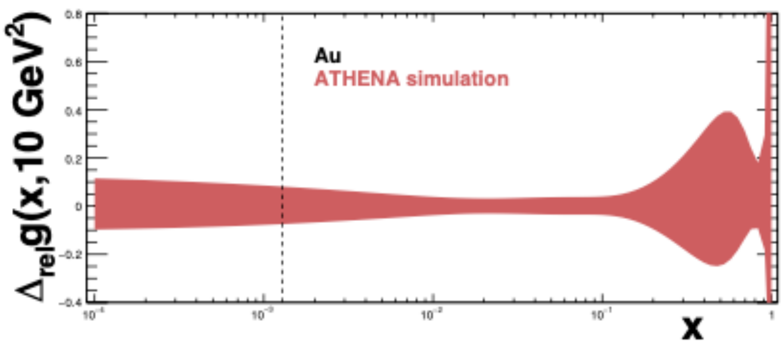
EIC will have revolutionary impact on eA phase space
Studies to assess sensitivity relative to EPPS16 …



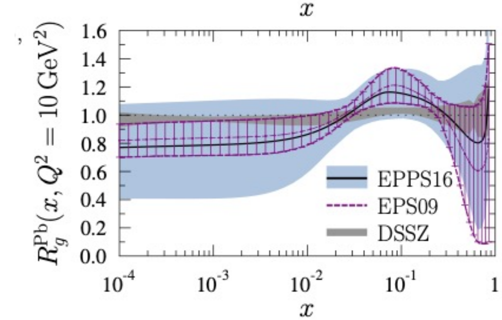


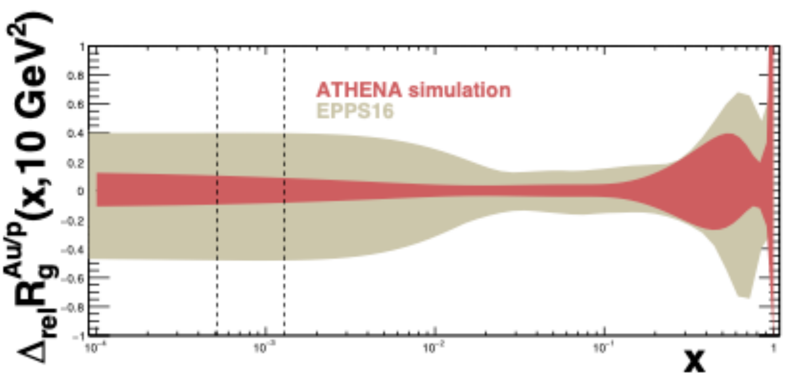
Projected uncertainty on gluon density of proton from EIC-only fit





Projected uncertainty on gluon density of (gold) nucleus from EIC-only fit → ~10%



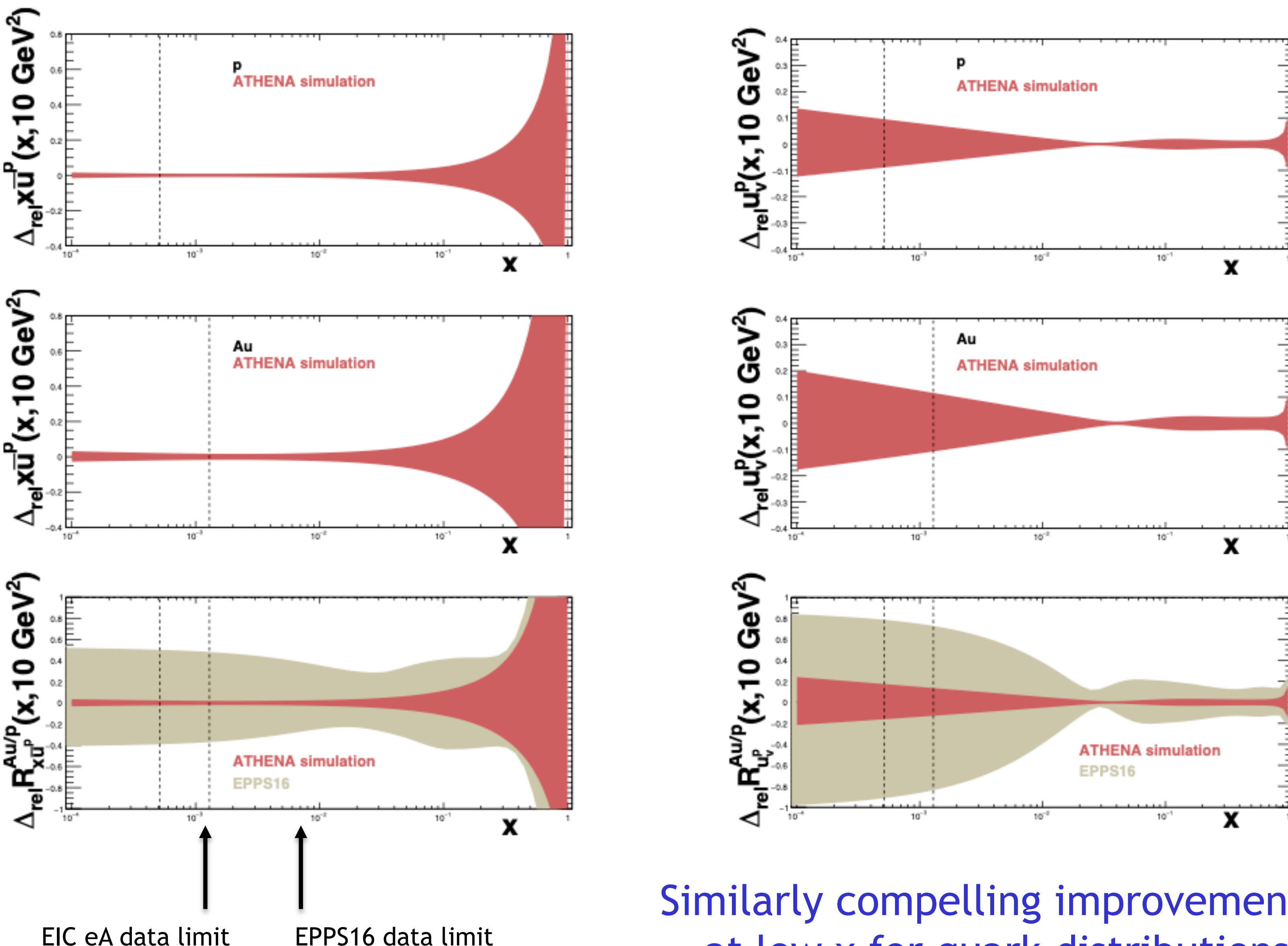


Projected uncertainty on gluon nuclear modification factor, EIC-only v EPPS'16

→ Factor ~ 2 improvement at x~0.1

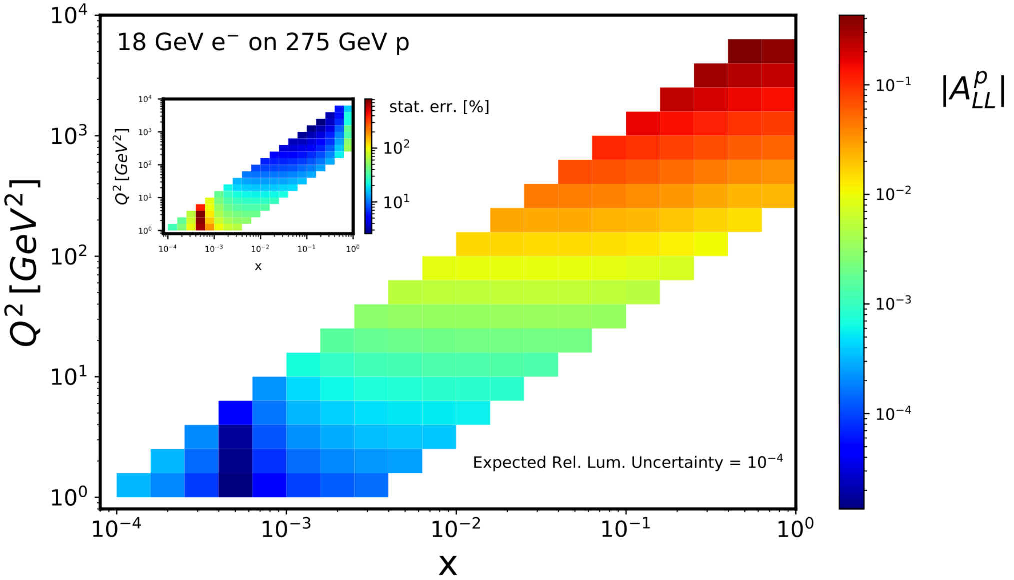
→ Very substantial improvement in newly accessed low x region

Impact on Nuclear PDFs: ubar and u_v



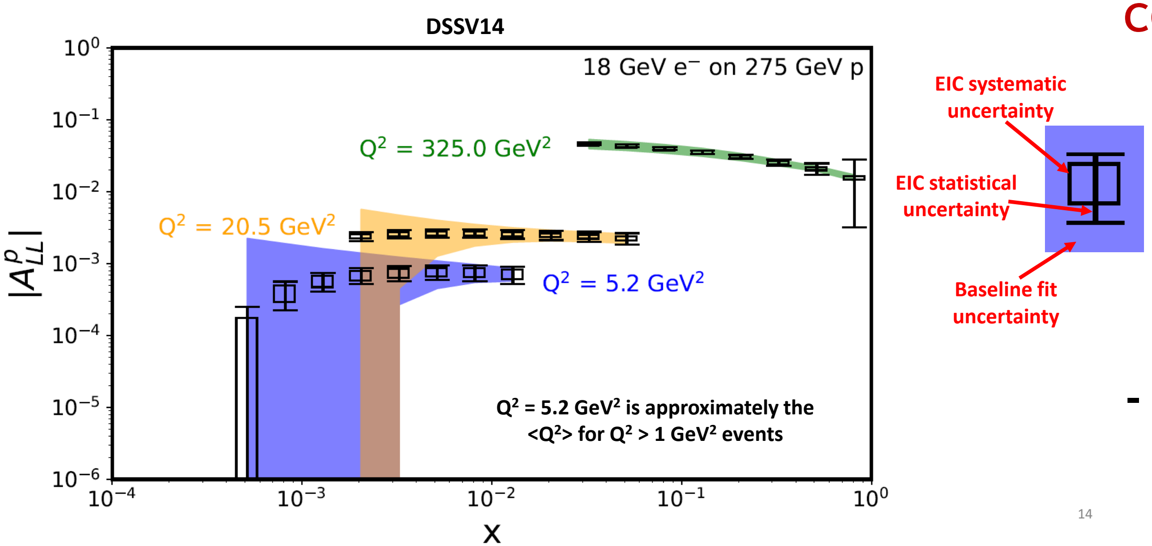
Similarly compelling improvements at low x for quark distributions

Spin: Impact on A_{LL} (ATHENA / DSSV)



- Study for integrated luminosity 15fb^{-1}, and 70% e,p polarization

- EIC measures down to x~10^{-3} with statistical precision better than the projected size of the asymmetry and systematics controlable



- Similar results with JAM

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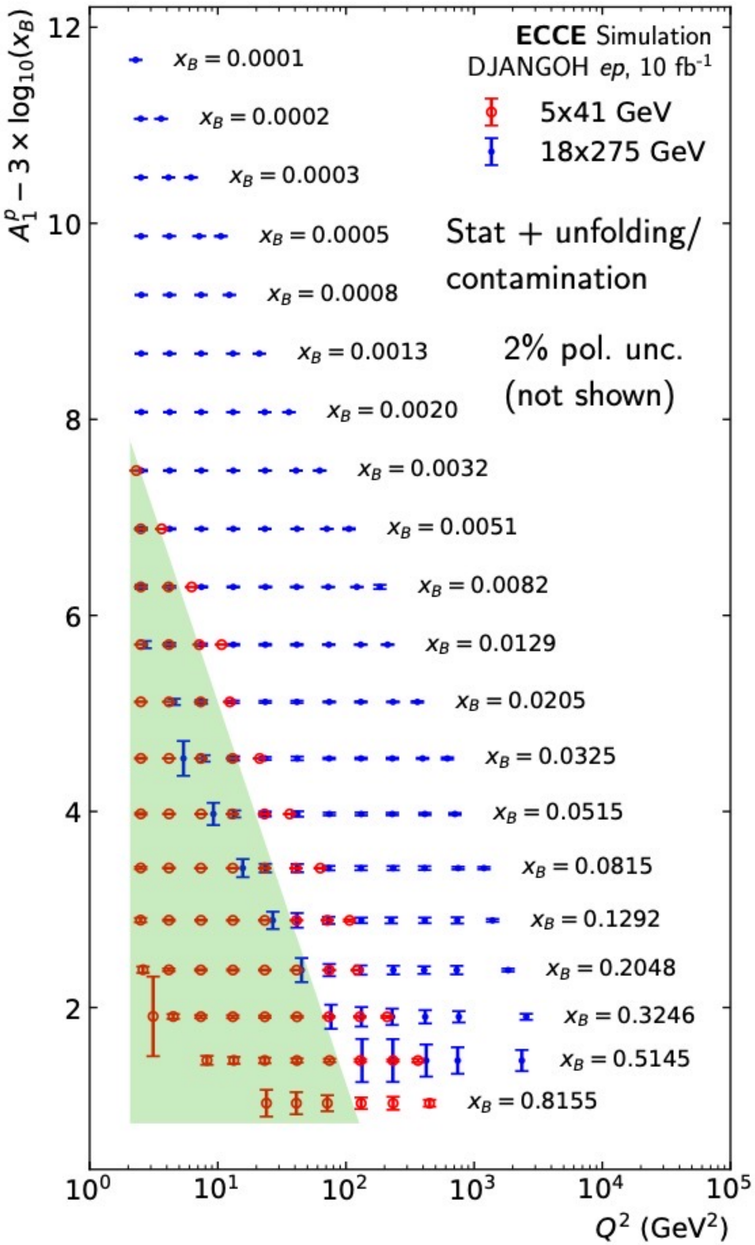
Spin: Virtual γ Asymmetry, A_1^p (ECCE)



$$A_{\parallel} = \frac{\sigma^{\leftrightarrows} - \sigma^{\rightrightarrows}}{\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows}} \quad \text{and} \quad A_{\perp} = \frac{\sigma^{\rightarrow\uparrow} - \sigma^{\rightarrow\downarrow}}{\sigma^{\rightarrow\uparrow} + \sigma^{\rightarrow\downarrow}}$$

$$\rightarrow A_1(x) \approx g_1(x)/F_1(x)$$

… measures the quark and antiquark helicity distributions …

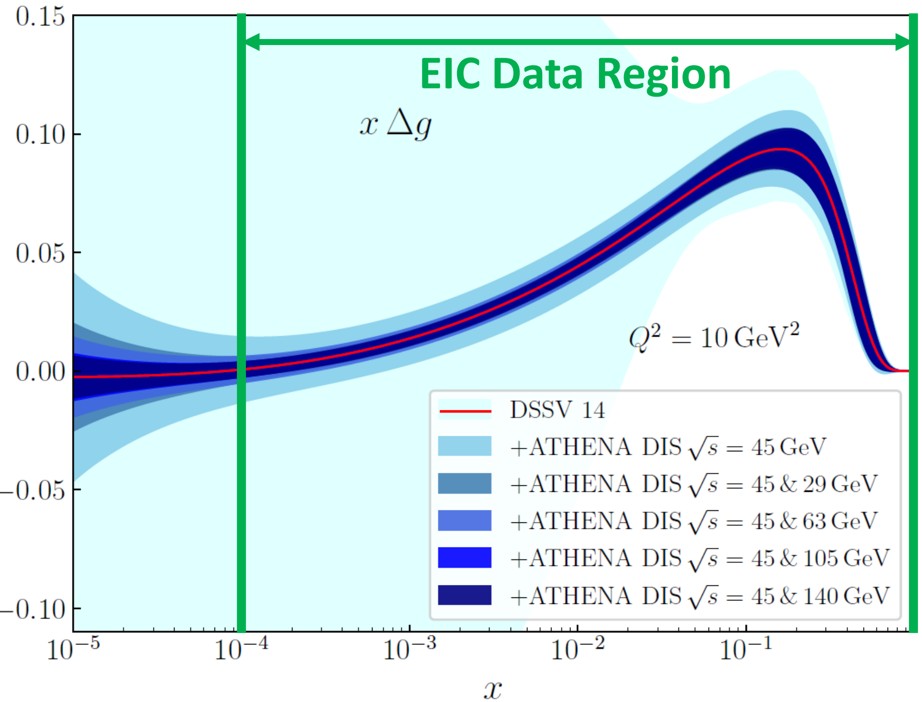
$$g_1(x) = \sum \left(\Delta q(x) + \Delta\bar{q}(x)\right)$$

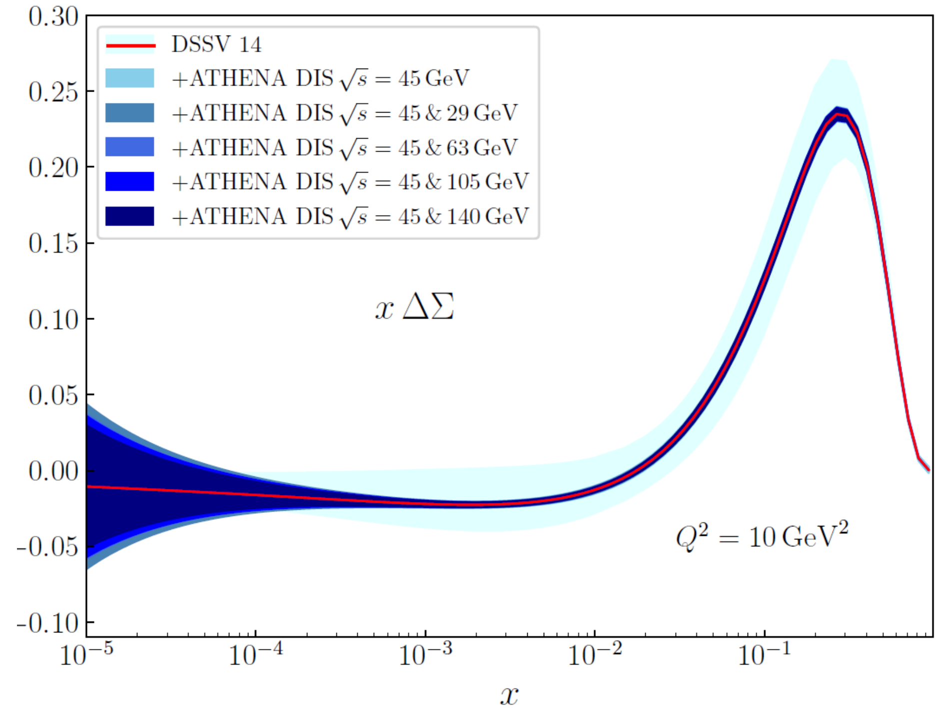
… with gluon sensitivity from Q^2 dependence

- EIC measures down to x ~ 5 x 10^{-3} for 1 < Q^2 < 100 GeV^2

- cf previously measured region (in green)

Impact on Helicity Distributions (Study in DSSV framework)





Very significant impact on polarised gluon and quark densities using only inclusive polarised ep data

Some thoughts on Monte Carlos

MC is / will be used everywhere in EIC

- Basic detector design / comparing layouts & characterising performance
- Acceptances, resolutions, backgrounds, systematics in physics studies
- Modelling cross sections / estimating event yields for pseudodata
- (Soon) full MC simulations of measurement chains
- (Ultimately) unfolding / correcting real data and comparing with models

Neutral (and Charged) Current at large Q^2

- ECCE mainly used DJANGO, ATHENA mainly used PYTHIA8. Others exist.
- Hadronic final state and ISR modelling are vital ingredients
- Lots of experience from HERA, but that was 15+ years ago

… attention to details and more benchmarking to be done?

The $Q^2 \rightarrow 0$ limit

- Essential for understanding 'photoproduction' background in DIS
- Interesting in its own right → $\sigma^{\gamma^{(*)}p}(x, Q^2 \rightarrow 0)$ and its decomposition
- So far both ECCE and ATHENA used PYTHIA6 (in DIS or γp modes)
- HERA used PHOJET, but not maintained. Now PYTHIA8, SHERPA, DJANGO …
- Modelling of resolved photon structure has large uncertainties (has HERA data been fully exploited in constraining that?)

… opportunities for basic development?

Summary

- Increasingly detailed simulations of inclusive EIC physics, including performance understanding and main sources of systematics

- No doubt as to potential impact on inclusive proton and nuclear PDFs, and understanding of spin structure

- Ongoing work / main current questions:

- What level of performance can be obtained in overall hadronic final state reconstruction (via energy flow algorithms)

- How much can we improve on NC kinematic reconstruction by trying novel machine learning or kinematic fitting methods

- Do we have ISR completely under control?

- What can be done to better understand photoproduction regime?

→ fully simulate an inclusive measurement using MC, event-by-event