FIRST INTERNATIONAL SCHOOL OF HADRON FEMTOGRAPHY

Jefferson Lab | September 16 - 25, 2024

Experimental Methods

Sep 21st 2024

F.-X. Girod

Lecture 4

with Charles Hyde

EIC Kinematics and the QCD Landscape

The Science Pillars at the EIC

as outlined in the NAS NSAC

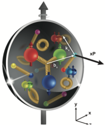
SPIN is one of the fundamental properties of matter.
All elementary particles, but the Higgs carry spin.
Spin cannot be explained by a static picture of the proton
It is the interplay between the intrinsic properties and interactions of quarks and gluons

The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum.

Does the mass of visible matter emerge from quark-gluon interactions?

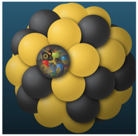
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

For the proton the EIC will determine an important term contributing to the proton mass, the so-called “QCD trace anomaly



How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?

How do the nucleon properties emerge from them and their interactions?
How can we understand their dynamical origin in QCD?
What is the relation to Confinement

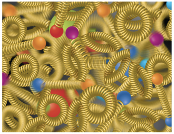


Is the structure of a free and bound nucleon the same?

How do quarks and gluons, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

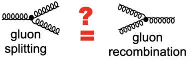
How do the quark-gluon interactions create nuclear binding?



How many gluons can fit in a proton?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy?

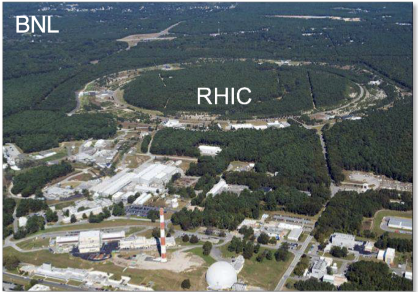


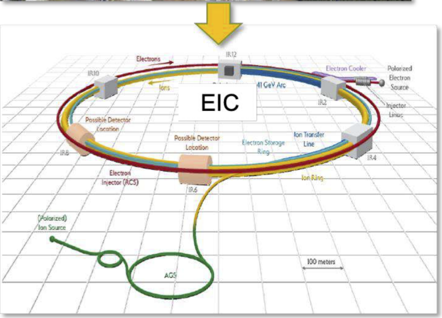
EIC Design Overview

- Existing RHIC complex at BNL
- superconducting magnets
  275 GeV polarized protons
- Add an electron accelerator
  in the same tunnel
- 25 mrad crossing angle with crab cavities
- IP6 (location of STAR)
- Forward Hadron instrumentation

e^-:	5 - 18 GeV
p:	41 - 275 GeV
$\sqrt{s}$:	**30 - 140 GeV**
$\mathcal{L}$	up to 10^{34} cm^{-2}s^{-1}

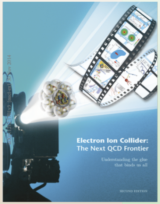
Full luminosity achieved in phases

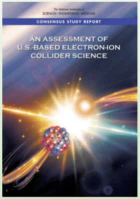


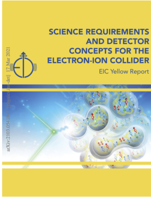


Legacy and the place of the EIC

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	15 - 20	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	2×10^{-3}	1×10^{-4}
ion	p	p, Pb, ...	p - U	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	3×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	Upgrade to HIAF	> 2031







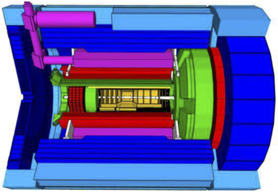
The ePIC detector collaboration

The ePIC collaboration is formed a year ago.

ePIC is now 171 (+) institutions

Representing 24 countries and 500+ participants

ePIC Spokesperson: John Lajoie (Iowa State)
ePIC Deputy Spokesperson: Silvia Dalla Torre (INFN Trieste)



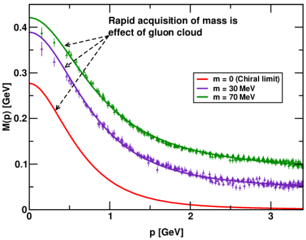
Interlude: my opinion on known unknowns

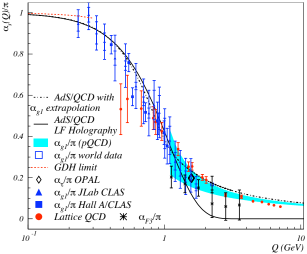
Yuri L. Dokshitzer, (CERN-Dubna School Pylos August 2002)

In the late 1970s one could say "QED was 30 years old".
In 2003 we cannot but state that "QCD is 30 years young".

Confinement Mechanism(s?)

Hadrons are singlets under $SU(3)_{color}$: No net color charge in asymptotic particle states



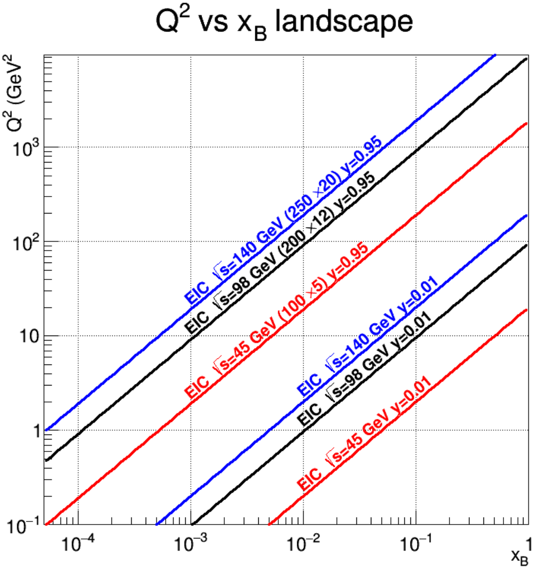


- **Linear growth of the static quark-antiquark pair**
  Area-law falloff for the Wilson loop
- **Gribov Confinement for light quarks**
  Analytical properties of the propagators in the infrared
  Instability of the vacuum above a supercritical charge

$$\alpha_{\text{QED}}^{\text{crit}} = 137 \text{ for a point-like nucleus}$$
$$\approx 180 \text{ for a finite size nucleus}$$
$$\frac{\alpha_{\text{QCD}}^{\text{crit}}}{\pi} = C_F^{-1}\left[1-\sqrt{\frac{2}{3}}\right] \approx 0.137$$

- **Light-Front AdS/QCD**
  quark and gluon chiral condensates confined!
  →condensates contribution to the cosmological constant already included in hadron mass
- Mass-Gap Millenium problem and Yang-Mills existence
  $1M from the Clay Mathematical Institute

Collider Energy Scenarios



Build on knowledge from

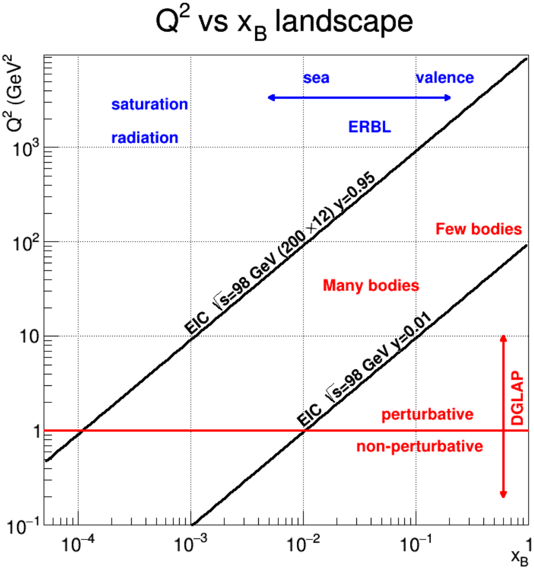
other colliders
HERA, RHIC, LHC

Fixed targets
SLAC, HERMES, COMPASS, JLab

Crucial ingredients:
polarizations
luminosity

Complementarity of energy runs

Kinematic reach and QCD Landscape



Rich physics program

Position, Spin, Energy, Momentum distributions of quarks and gluons

Origin Mass, Confinement, χSM
QCD and Gravity

Gluon saturation, jet radiophysics
QCD Bremsstrahlung

Nuclear Modifications
EMC Effect, SRC

Kinematics reconstruction strategies at the EIC

U. Bassler and G. Bernardi, NIM A361 (1995) 197.

$$\Sigma = \sum_h (E_h - p_{z,h}) \qquad T = \sqrt{(\sum_h p_{x,h})^2 + (\sum_h p_{y,h})^2} \qquad \tan\frac{\gamma}{2} = \frac{\Sigma}{T}$$

	method	y	Q^2	x
Electron method:	e	$1-\frac{E}{E^e}\sin^2\frac{\theta}{2}$	$4E^e E\cos^2\frac{\theta}{2}$	Q^2/ys
Jacquet-Blondel:	h	$\frac{\Sigma}{2E^e}$	$\frac{T^2}{1-y_h}$	Q^2/ys
Mixed:	m	y_h	Q_e^2	Q^2/ys
Double-angle:	DA	$\frac{\tan\gamma/2}{\tan\gamma/2+\tan\theta/2}$	$4E^{e2}\frac{\cot\theta/2}{\tan\gamma/2+\tan\theta/2}$	Q^2/ys
Sigma:	Σ	$\frac{\Sigma}{\Sigma+E(1-\cos\theta)}$	$\frac{E^2\sin^2\theta}{1-y_\Sigma}$	Q^2/ys

*

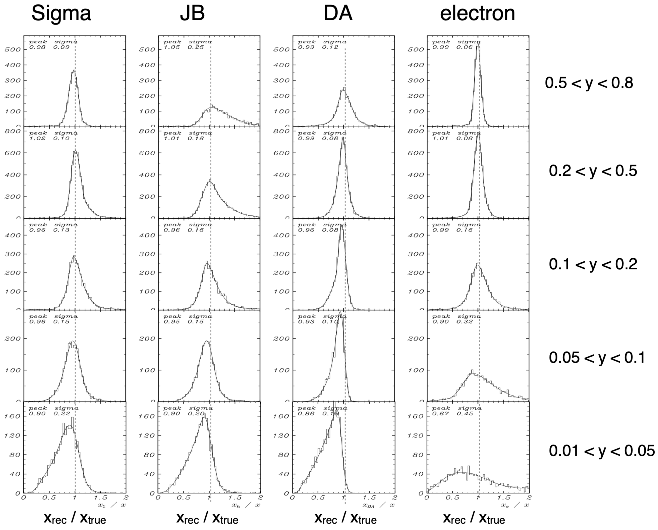
Resolutions for these different strategies

U. Bassler and G. Bernardi, NIM A361 (1995) 197:

Electron method works very well at high-y; degrades as 1/y

Jacquet-Blondel degrades at high-y, but works well for y < ~0.2,

Double-Angle does not depend on absolute energy calibrations; accurate at high Q^2, degrades at small-x and small Q^2



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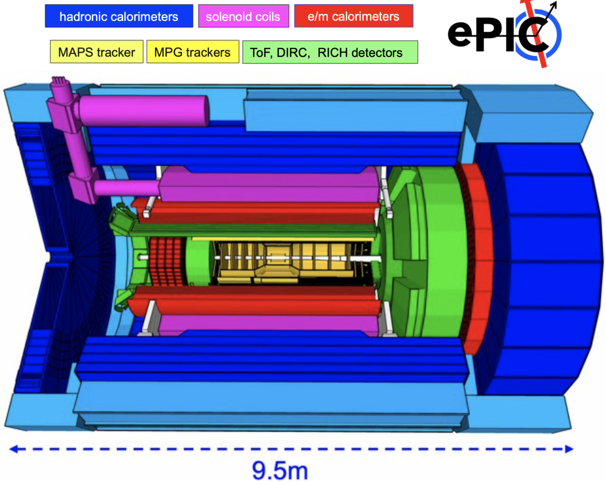
Exclusive Reactions at the EIC
A brief overview of the detector design

Conceptual Design of a detector package for EIC

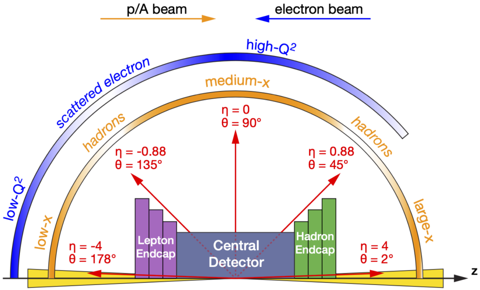


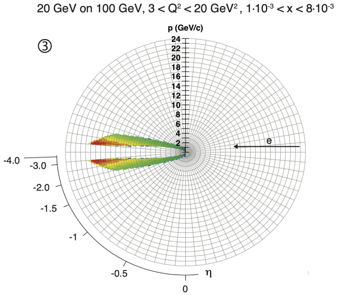
Large acceptance package:
Ideally "100% acceptance"
1.7 T solenoid magnet

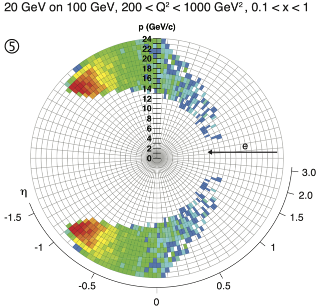
Notion of <u>rapidity</u>
related to the polar angle
$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$

Notion of <u>diffractive event</u>
Rapidity gap between jets and recoil target
Pomeron exchange in Regge theory

Kinematical coverage in terms of rapidity

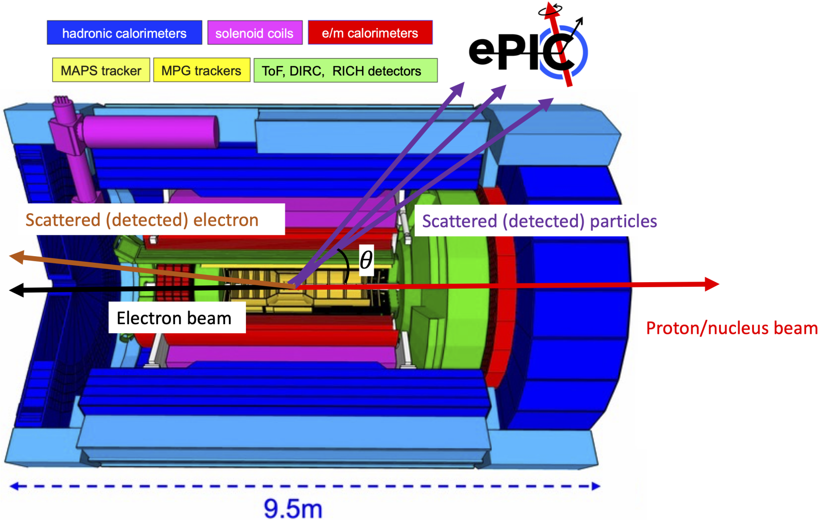




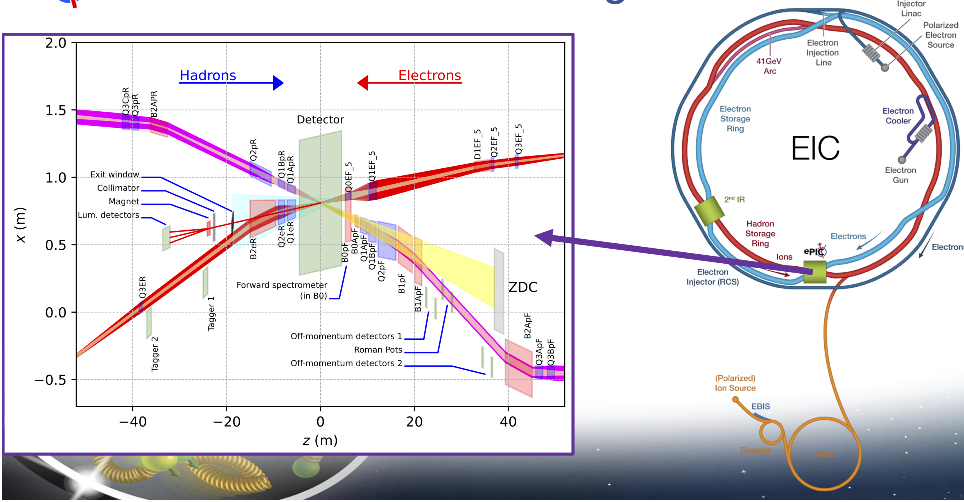


- The DIS cross section falls-off as $\sim 1/Q^4$
- High momenta are associated with high x_B processes
- In general correlation between p and η

Typical topology of a diffractive event



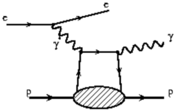
and the full interaction region!



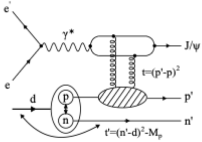
- Additional detectors in the far-forward and far-backward regions at $\pm$ 40 m
- Crossing angle provides beam separation and space for detectors
- Operation over large range of energies and luminosities
- Design integrated into the beamline!

Some Far Forward Processes at the EIC

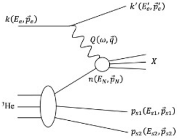
e+p DVCS



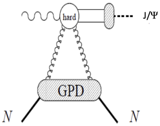
e+d exclusive J/Psi with p/n tagging



e+He3 spectator tagging

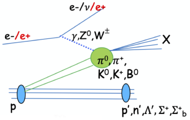


coherent/incoherent J/ψ production in e+A

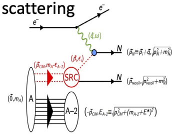


Meson structure:

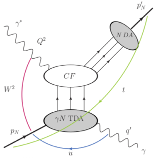
- ep→ (π) →e' n X
- $\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$



Quasi-elastic electron scattering

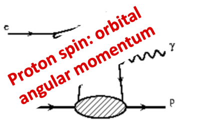


u-channel backward exclusive electroproduction

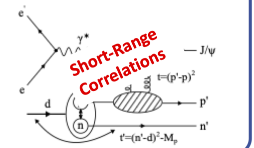


Some Far Forward Physics at the EIC

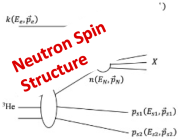
e+p DVCS



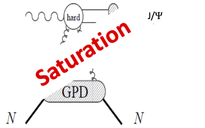
e+d exclusive J/Psi with p/n tagging



e+He3 spectator tagging

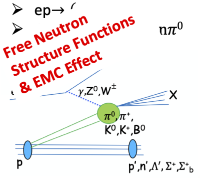


coherent/incoherent J/ψ production in e+A

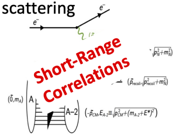


Meson structu

- ep→
-

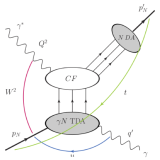


Quasi-elastic electron scattering



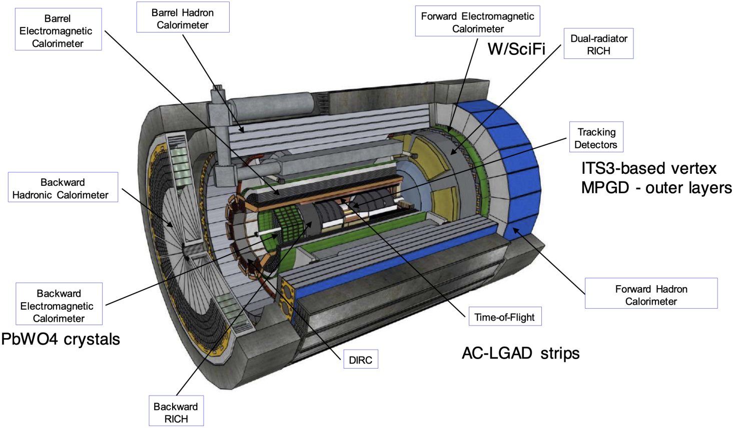
[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, A. Jentsch, J.H. Lee, Z. Tu, Z. Yin, and L.Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104**, 065205, (2021) **(Editor's Suggestion)**

u-channel backward exclusive electroproduction



Central Detector Overview

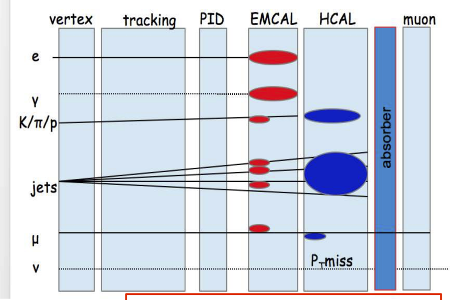
General purpose detector
Coverage: -4< η<4
PID: DIRC, dual-radiator RICH,pfRICH



How to design a general purpose spectrometer

Limited number of "stable" final state particles: only 13 have cτ > 500μm

- Electrons
- Photons/Gammas
- Jet/Jets
- Individual hadrons ($\pi \pm$, K$\pm$,p)
- Muons (absorber and muon chamber)
- Neutrinos (missing PT in EM+HCAL)
- Neutral hadrons (n,K^0_L) (HCAL)



- Electrons: EMCAL cluster + track pointing to cluster
- Gammas (γ): EMCAL cluster, no track pointing to cluster
- Neutrinos (ν): missing P_T
- Muons: track, min. energy in EMCAL, min. energy in HCAL, track in muon det.(if any)

For all particles emerging in the collision we would like to measure:

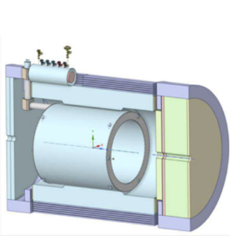
- Momentum (px,py,pz) , charge
- Origination (vertex)
- Energy (E)
- Type of the particle: PID (Mass)

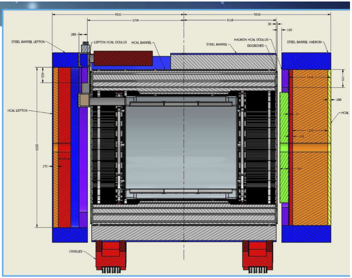
18

New EIC solenoid

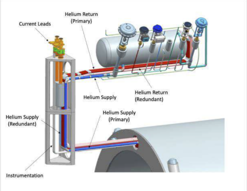
Superconducting Detector Solenoid

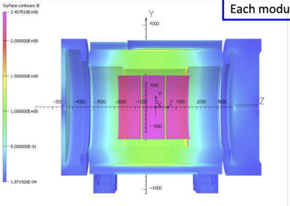
- 3.5 m long coil, 2.84 m room temperature bore diameter
- 2 T on-axis field
- Operating Temperature 4.5 K
- Conductor: Copper Cladded, Rutherford Cable made with NbTi superconducting strands





Coil is divided in 3 module
Each module has 6 layers



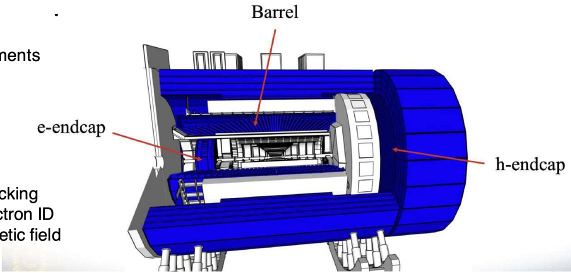


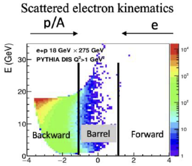
JLab, BNL
CEA, Saclay

Calorimeter Design Requirements

✓ fully hermetic (but different requirements for energy resolution)
✓ Placement in barrel:
EMCAL - inside the solenoid
HCAL- outside

✓ Highest resolution EMCal in the most backward region (due to degraded tracking mom. res.) Key role of EMCal for electron ID
✓ Photosensors and FEE tolerate magnetic field





	σ_E/E	E range, GeV	$\pi^{\pm}$ suppression (In combination with other subsystems)	$\pi 0/\gamma$ discr.
e-endcap	$\frac{(2-3)\%}{\sqrt{E}} \oplus (1-2)\%$	0.05–18 GeV	Up to 10^4	Up to 7 GeV/c
Barrel	$\frac{(7-10)\%}{\sqrt{E}} \oplus (1-3)\%$	0.05–50 GeV	Up to 10^4	Up to 10 GeV/c
h-endcap	$\frac{(10-12)\%}{\sqrt{E}} \oplus (1-3)\%$	0.1–100 GeV	Up to 10^4	Up to 50 GeV/c

Generalities on EM Shower: e vs γ

Notation: scale variables
$t = x/X_0$, $y = E/E_c$
distance in units of R.L.
energy in units of critical e.

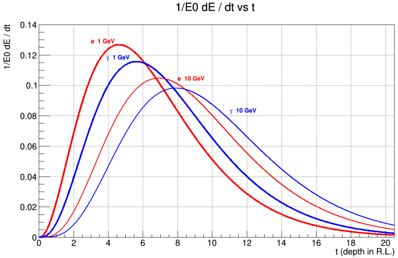
ref: sect. 34.5 PDG 2020

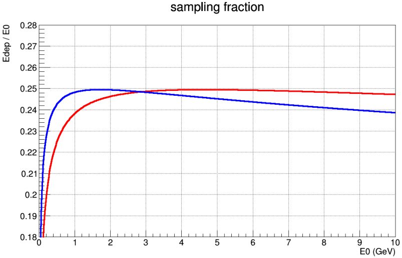
Longitudinal profile of e. dep.

$$\frac{1}{E_0}\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{b}{\Gamma(a)}\,(bt)^{a-1}\,\mathrm{e}^{-bt}$$

Parameters given by:
$b \approx 0.5$ (above Fe)
$\frac{a-1}{b} = \ln y \pm 0.5$

Toy Sampling Fraction:
integrate profile over (arbitrary?) samples
N.B: for illustration of e vs γ only
not meant as a serious estimate





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Longitudinal profile of e. dep.

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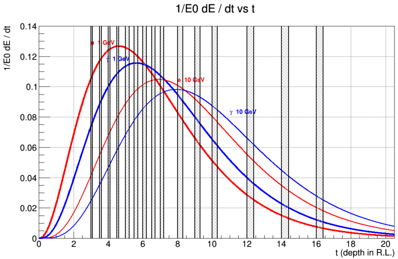
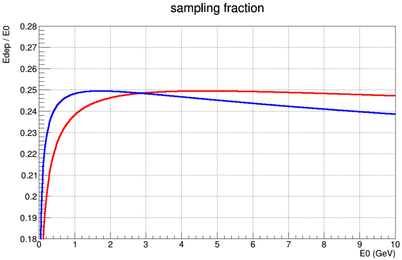
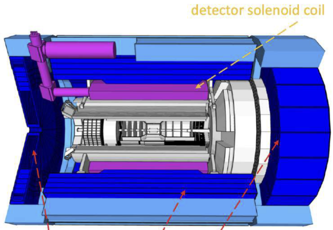
N.B: for illustration of e vs γ only
not meant as a serious estimate





Hadronic Calorimeters



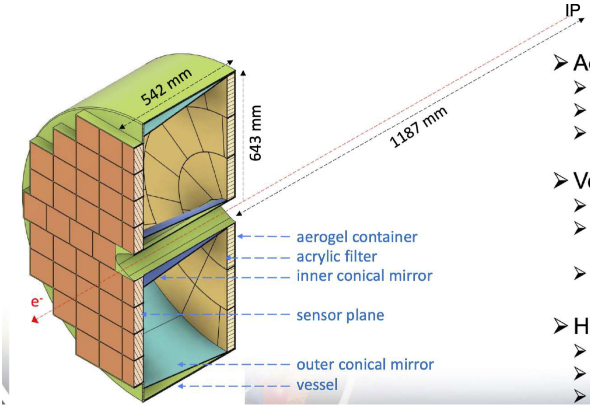
- Jet energy measurement
  - Tag jets with a neutral component
- DIS kinematics reconstruction
  - Hadronic method

- Solenoid flux return
- Additional capability: muon ID

Barrel HCal	Refurbished sPHENIX barrel calorimeter
Backward HCal	Scintillator recycled from STAR endcap EmCal
Forward HCal	Brand new design

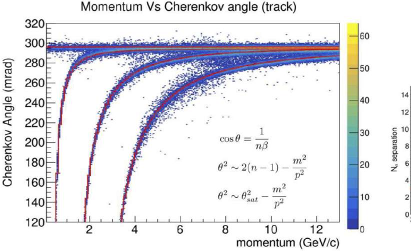
	"Ideal" configuration		Acceptable configuration	
η	σ_E/E, %	E_{min}, MeV	σ_E/E, %	E_{min}, MeV
-3.5 to -1.0	$45/\sqrt{E}+7$	500	$50/\sqrt{E}+10$	500
-1.0 to +1.0	$85/\sqrt{E}+7$	500	$100/\sqrt{E}+10$	500
+1.0 to +3.5	$35/\sqrt{E}$	500	$50/\sqrt{E}+10$	500

Proximity Focusing RICH

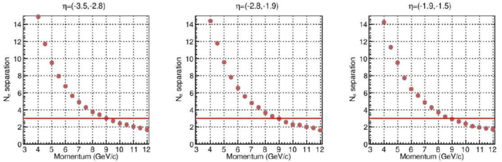


- Aerogel
  - Three radial bands
  - Opaque dividers
  - 2.5 cm thick, 42 tiles total
- Vessel
  - Lightweight structure
  - Reinforced carbon fiber and 3D printed materials
  - Filled with nitrogen
- HRPPD photosensors
  - 120 mm size
  - Tiled with a 1.5mm gap
  - 68 sensors total

pfRICH PID and $e/\pi/K/p$ separation



e/π/K/p response integrated over the whole η acceptance

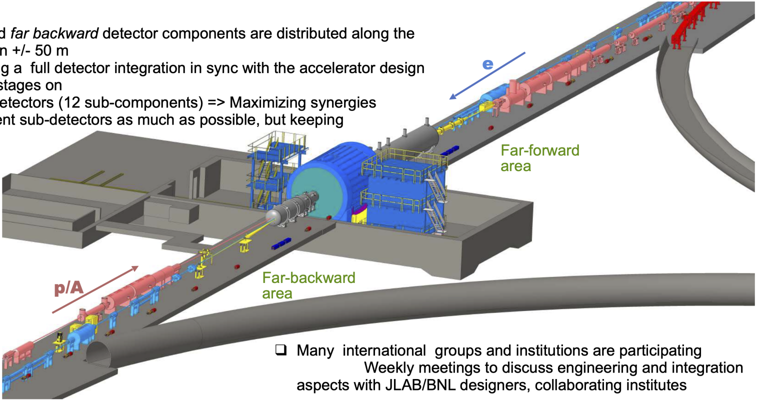


π/K N_σ separation in η bins

- ➢ Comfortably reach 7+ GeV/c momentum range with a higher than 3σ π/K separation level

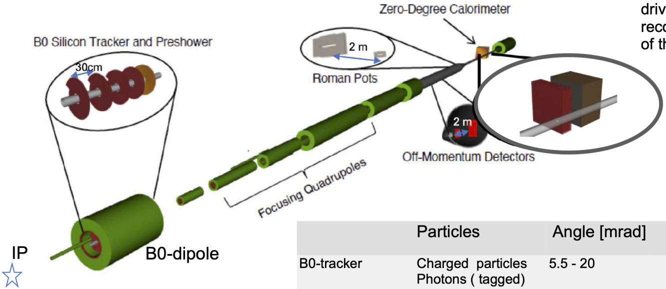
Far- Forward/Backward Instrumentation

- F*ar forward* and *far backward* detector components are distributed along the beam line within +/- 50 m
- We are keeping a full detector integration in sync with the accelerator design from the early stages on
- In total 7 sub-detectors (12 sub-components) => Maximizing synergies between different sub-detectors as much as possible, but keeping performance

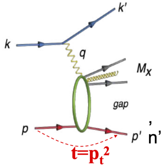


- Many international groups and institutions are participating Weekly meetings to discuss engineering and integration aspects with JLAB/BNL designers, collaborating institutes

Far-Forward Detectors



Exclusive /diffractive reactions driving the design of FF area -> reconstruction of particles outside of the central detector acceptance



✓protons at wide range of p_T^2
✓protons with **different rigidity**
✓**neutrons and photons**

	Particles	Angle [mrad]		Distance from IP
B0-tracker	Charged particles Photons (tagged)	5.5 - 20		ca 6-7 m
Off-momentum	Charged particles	0-5.0	0.4< xL< 0.65	ca 23-25 m
Roman Pots	Protons Light nuclei	0*-5.0	0.6 < xL< 0.95	ca 27-30 m
ZDC	Neutrons Photons	0-4.0 (5.5)		ca 35 m

Streaming DAQ

Triggerless streaming architecture gives much more flexibility to do physics

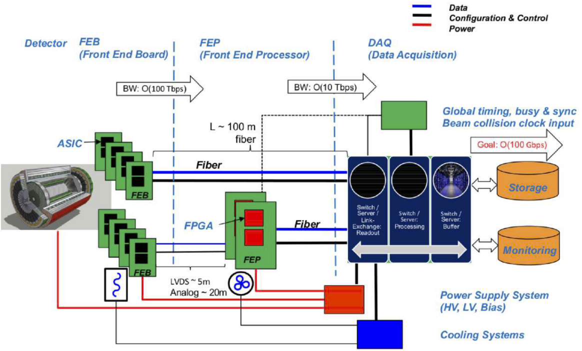
Allows to integrate AI/ML as close as possible to subdetectors

Event selection with data from all detectors

Data volume is reduced as much as possible at each stage

Expectation for O(100) PB per run, feasible to store for analysis

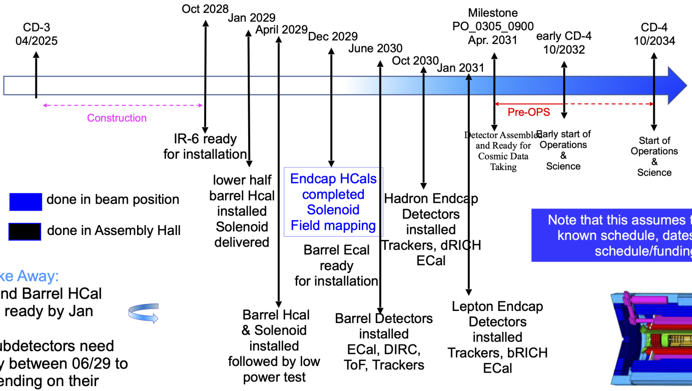
RF clock is used to make a physics synchronization with beam bunches



10GB/s ~ 2-3 DVD movies (DVD ~ 4.7 Gigabytes) per second

72

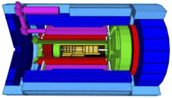
Installation Schedule



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

Note that this assumes the present best-known schedule, dates may shift with schedule/funding actuals



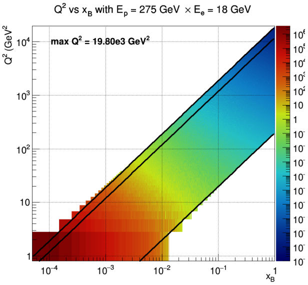
with the understanding that this is an evolving, current draft

CFF local Fits at EIC

EIC proton DVCS Observables

	$\int \mathcal{L}$	Observables	$A_{e,p}$		
unpolarized	200 fb^{-1}	σ	A_{LU}		
L polarized	100 fb^{-1}	A_{UL}	A_{LL}		
T polarized	100 fb^{-1}	A_{UTx}	A_{UTy}	A_{LTx}	A_{LTy}
e^+	100 fb^{-1}	A^C	A^C_{LU}		

$$N_{events} = \int \mathcal{L} \times \sigma \times KPS$$
$$KPS = \Delta x_B \Delta Q^2 \Delta t \Delta \phi$$



$$\frac{\Delta\sigma}{\sigma} = \frac{1}{\sqrt{N_{events}}} \oplus 5\%$$

$$\Delta A_{LU} = \frac{1}{P_e}\sqrt{\frac{1-P_e^2 A_{LU}^2}{N}} \oplus 3\%_{relative} \qquad P_e = 70\%$$

$$\Delta A_{UL} = \frac{1}{P_p}\sqrt{\frac{1-P_p^2 A_{UL}^2}{N}} \oplus 3\%_{relative} \qquad P_p = 70\%$$

$$\Delta A_{LL} = \frac{1}{P_e P_p}\sqrt{\frac{1-P_e^2 P_p^2 A_{LL}^2}{N}} \oplus 3\%_{relative} \oplus 3\%_{relative}$$

$$\Delta A_C = \sqrt{\frac{1-A_C^2}{N}} \oplus 3\%_{relative}$$

$$\Delta A_{LC} = \frac{1}{P_{e+}}\sqrt{\frac{1-P_{e+}^2 A_{LC}^2}{N}} \oplus 3\%_{relative} \qquad P_{e+} = 70\%$$

N.B. assumption on the luminosity

$$1 \text{ year} = 365 \text{ days} \times 24 \text{ hours/day} \times 3600 \text{ s/hour} = 3.15 \times 10^7 \text{ s} \approx \frac{1}{3} \times 10^8 \text{ s}$$

$$\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} = 10^{38} \text{ m}^{-2}\text{s}^{-1}$$

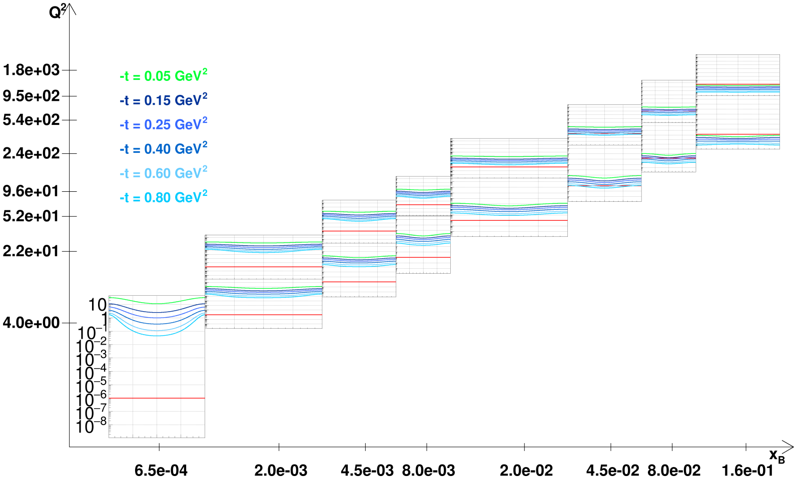
$$\int \mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \times 1 \text{ year} \approx \frac{1}{3} \times 10^{46} \text{ m}^{-2}$$

$$\begin{aligned} 1 \text{ barn} &= 10^{-28} \text{ m}^2 \\ 1 \text{ fb} &= 10^{-43} \text{ m}^2 \\ 1 \text{ fb}^{-1} &= 10^{43} \text{ m}^{-2} \\ 100 \text{ fb}^{-1} &= 10^{45} \text{ m}^{-2} \end{aligned}$$

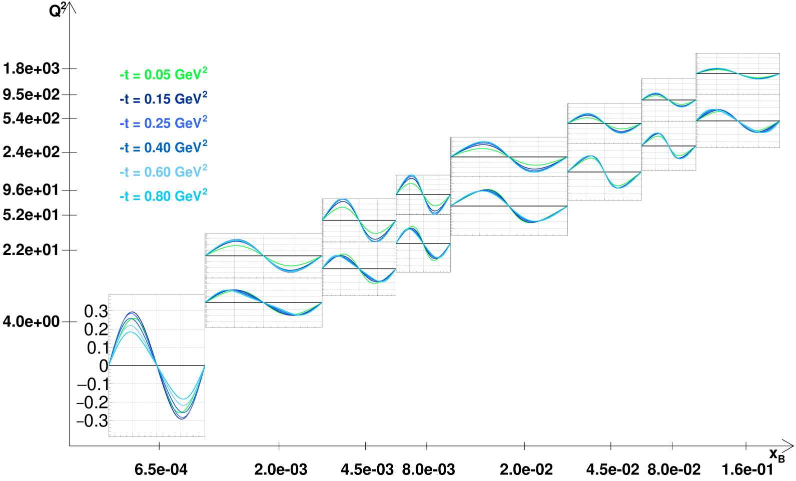
$$\begin{aligned} 100 \text{ fb}^{-1} \quad &\Longleftrightarrow \quad 1 \text{ year at } 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ with contingency } (\approx 3) \\ &\Longleftrightarrow \quad 10 \text{ years at } 10^{33} \text{ cm}^{-2}\text{s}^{-1} \end{aligned}$$

<u>Luminosity is a potential challenge for exclusive reactions</u>

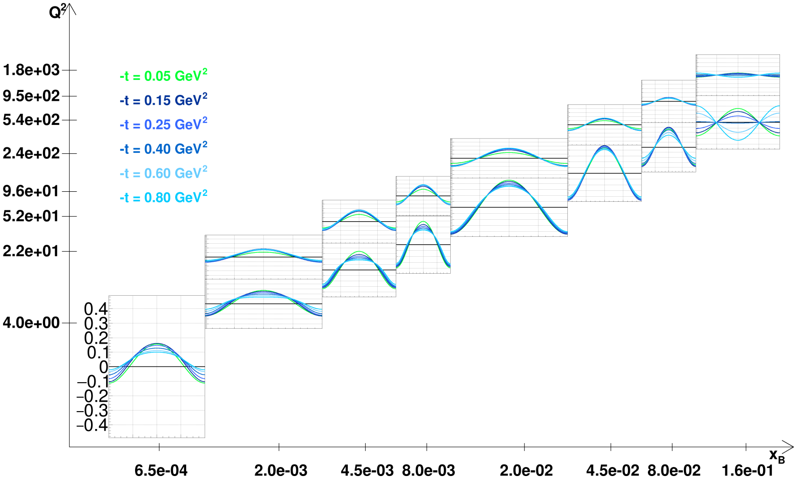
275 GeV × 18 GeV σ



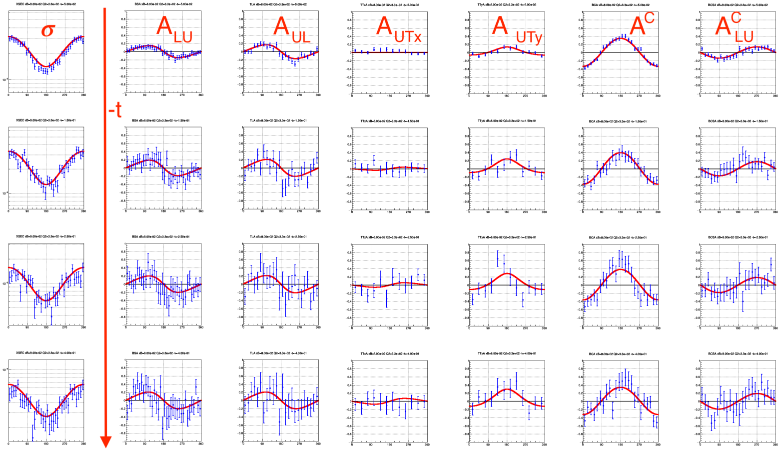
275 GeV × 18 GeV A_{LU}



275 GeV × 18 GeV A^C

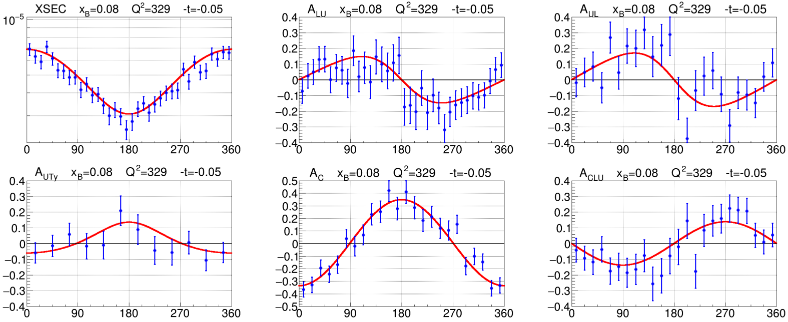


275 **GeV** × 18 **GeV** $x_B = 0.08 \pm 0.02$ $Q^2 = 329 \pm 175$ **GeV**^{2}



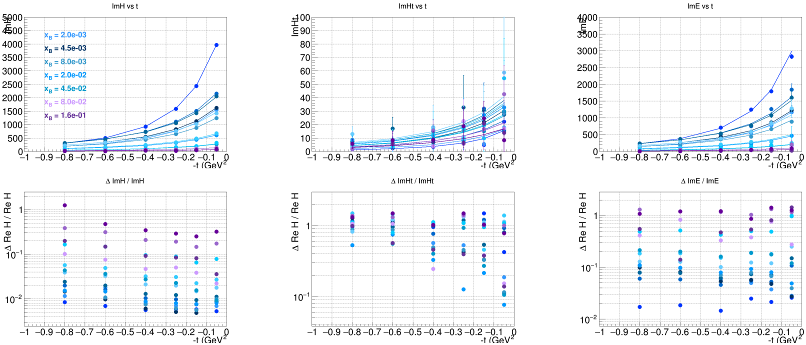
Not shown here: A_{LL} A_{LTx} A_{LTy} are small

275 **GeV** $\times$ 18 **GeV** $x_B = 0.08 \pm 0.02$ $Q^2 = 329 \pm 175$ **GeV**^{2} $-t = 0.05 \pm 0.05$ **GeV**^{2}

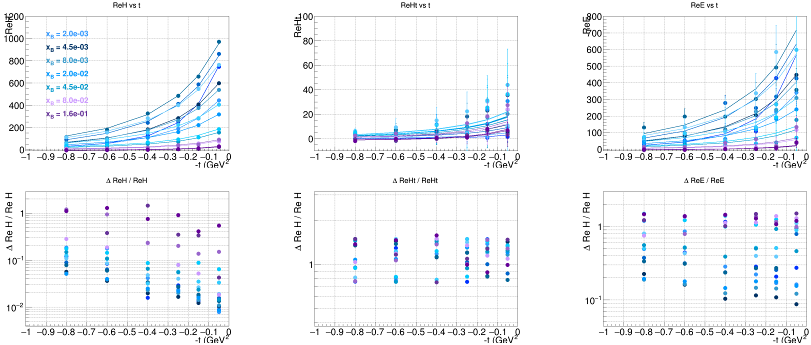


note: statistics and systematics included

Locally extracted Im CFF 275×18 GeV^2



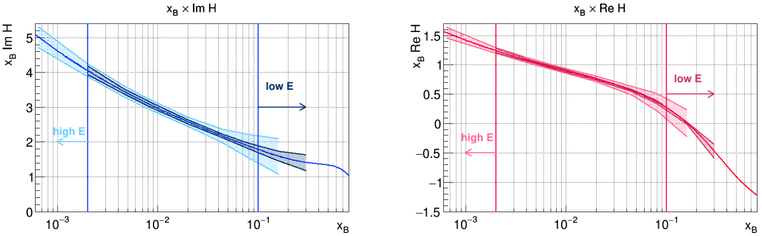
Locally extracted Re CFF 275×18 GeV^2



High and Low energies runs

Kinematical coverage complementarity

Local extraction results:



Better Strategy:

global fit using DR and parameterizations for $\mathcal{I}m\mathcal{H}$ and $D(t)$

note: subtraction constant: same for $\mathcal{H}$ and $\mathcal{E}$, none for $\tilde{\mathcal{H}}$ and $\tilde{\mathcal{E}}$

Towards Ji's sum rule

$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

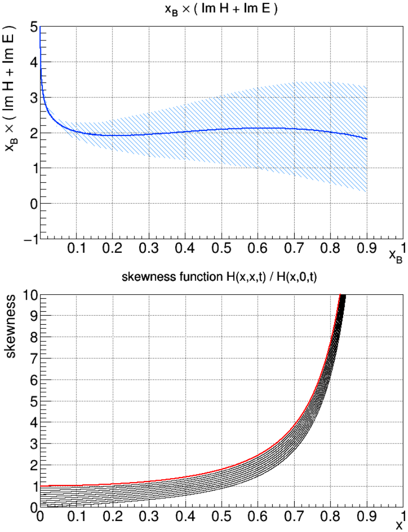
independent of ξ but at fixed ξ

DVCS measures

$$\mathcal{I}m\mathcal{H}(\xi,t) = \pi H(\xi,\xi,t)$$

need another process to access the skewness
→ especially crucial at large x_B

DDVCS?
JLab 12 luminosity upgrade?

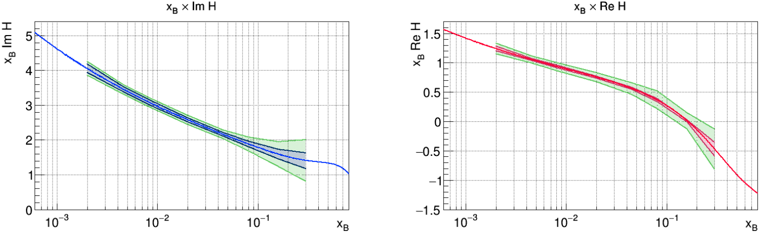


Impact of the positron beam

Enhanced sentivity to the Real part of the amplitude

Local extraction results:

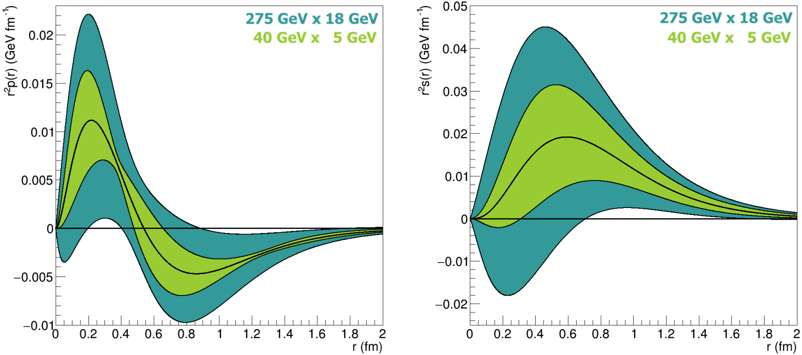
low E: 40 GeV $\times$ 5 GeV



Improved sensitivity, and systematic checks
Also, in general opens up access to new physics ($\cdots$)

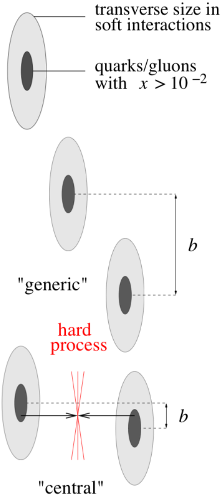
Pressure and Shear Sensitivities

Propagate uncertainties estimated with local fits using dispersion relation

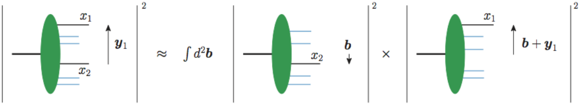


Relevance of the large x_B region to the dispersion analysis

Nucleon structure for hadron-hadron colliders



- MultiParton Interaction first suggested in 1975 (Landshoff & Polkinghorne)
- Evidence in :
  - high p_T at the CERN/ISR and Tevatron
  - intermediate p_T : underlying event in Dijet and Drell-Yann at CFD Run I and II, and at CMS
  - Found to be necessary to tune low p_T Pythia and Herwig
- MPI more important at LHC is expected to challenge many new physics search
- MPI can also be better studied at LHC for itself !



C. Weiss, L. Frankfurt, M. Strikman, Ann.Rev.Nucl.Part.Sci. 55 (2005) 403-465
Diehl, Ostermeier, Schäfer, "Elements of MPI in QCD", DESY 11-196

Summary / Outlook

- Rich physics program envisioned at the future EIC
- Today: just a sample in the school context, and with my personal biais
- Many aspects we did not discuss: computing, AI, accelerator physics...
- Synergy between:
  - Fixed target experiments at JLab
  - Future EIC at BNL
  - Hadron hadron colliders
- Exciting opportunities for you!