Outlook to future electron–proton colliders

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University of Warsaw

Workshop on Challenges in Photon Induced Interactions

Cracow, 8 .IX. 2017

> “New **directions** in science are **launched** by **new tools** much more often than by new concepts.”
>
> *Freeman Dyson*

(Theorist, mathematician; IAS, Princeton)

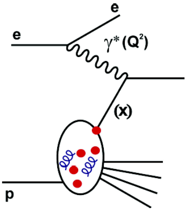
About...

- **EIC:** Electron–Ion Collider, BNL or JLab (alternatives: eRHIC/MEIC) ☺
- **LHeC:** Large Hadron–electron Collider, CERN (also: FCC-ep: Future Circular Collider-ep) ☹
- **VHEeP:** Very High Energy electron–Proton (collider), CERN ?

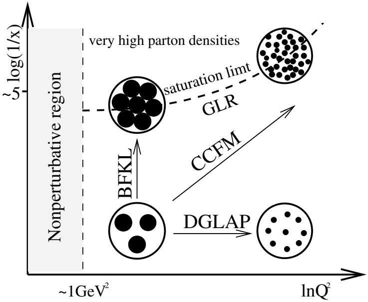
Physics areas in QCD

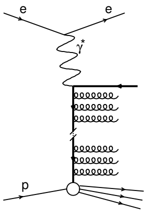
QCD: richest of Standard Model Gauge Field Theories

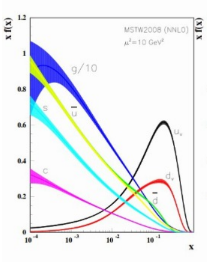
- Deep Inelastic Scattering (DIS) and parton distribution functions (pdfs),
- proton spin puzzle; proton "tomography"
- low-x and saturation,
- total γ-p and γ^*-p cross section,
- (exclusive) vector meson production,
- diffraction -> pdfs,
- α_s measurement,
- jet measurements,
- heavy flavours production,
- F_L measurement,
- eA scattering,
- quark structure,
- compositeness (leptoquarks),
- standard tests,
- ....



Physics domains in (x, Q^2) plane: "Kwieciński plot"







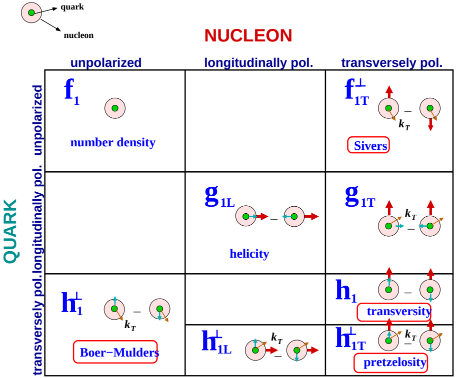
BFKL: $[\alpha_s \ln(1/x)]^n$

DGLAP: $[\alpha_s \ln(Q^2)]^n$

- At low x, energy in the γ^*p cms is large (large gluon cascades): $W^2_{\gamma^* p} = Q^2(1-x)/x$.
- Contributions from large $\alpha_s \ln(1/x)$ terms $\Rightarrow$ new evolution equations: BFKL, CCFM.
- At low x: strong increase of gluon density with decreasing x (cf. HERA data) $\Rightarrow$ gluon recombination (saturation).
- At $Q^2 \gg Q^2_{sat}$ nonlinear effects of parton evolution must be considered.
- Low x effects particularly visible in $g_1^{\rm ns} \Longrightarrow \ln^2(1/x)$ terms

Partonic structure of the nucleon; distribution functions

- In LT and considering k_{T}, 8 PDF describe the nucleon
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T} only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY by measuring azimuthal asymmetries
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\mathrm{Sivers}} \propto$ PDF$^{\mathrm{beam}} \otimes$ PDF$^{\mathrm{target}}$

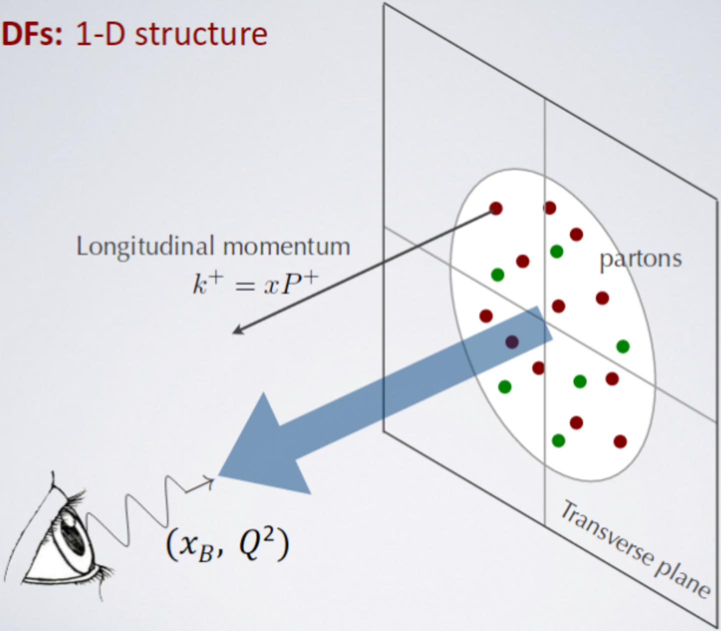


- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

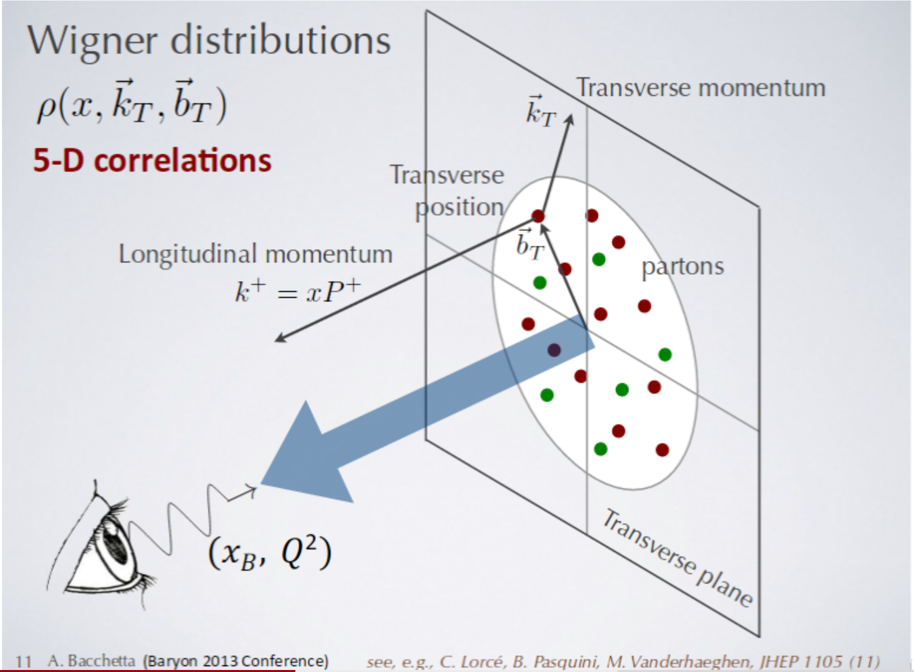
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

- OBS! transversity PDF is chiral-odd (may only be measured with another chiral-odd partner, e.g. fragmentation function.
- Boer-Mulders, Sivers and transversity $(h_1^{\perp}, f_{1\mathrm{T}}^{\perp}, h_1)$ will be measured in COMPASS II

PDFs: 1-D structure

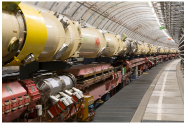
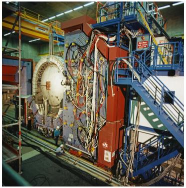
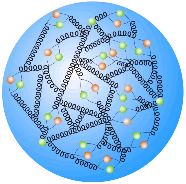
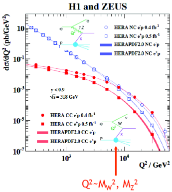


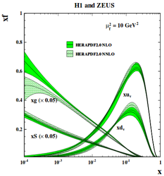
11 A. Bacchetta (Baryon 2013 Conference)


Wigner distributions
$\rho(x, \vec{k}_T, \vec{b}_T)$
5-D correlations
Transverse momentum
$\vec{k}_T$
Transverse position
$\vec{b}_T$
partons
Longitudinal momentum
$k^+ = xP^+$
(x_B, Q^2)
Transverse plane
11 A. Bacchetta (Baryon 2013 Conference)
see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

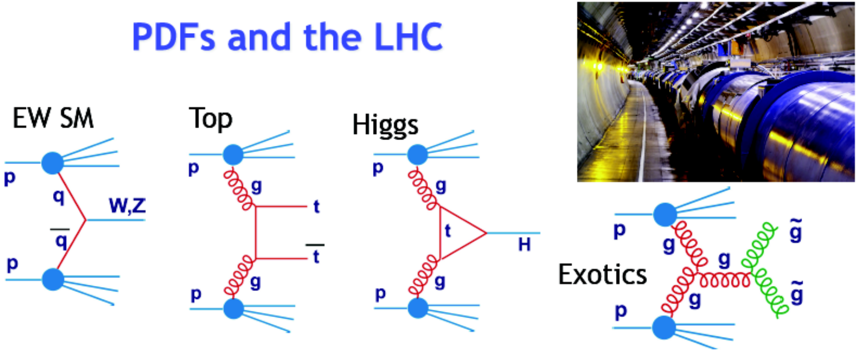
HadronElectronRing Accelerator (1990–2007) legacy 300 authors, 70 institutions

- A collider of protons and electrons (positrons); $\sqrt{s} \sim$ 300 GeV; $\sim$0.5 fb $^{-1}$/exp.
- 6.3-kilometre superconducting p ring; separate (normalcond.) for e$^+$/e$^-$;
  2 intersection points, detectors: ZEUS and H1
- Most precise picture of inner proton dynamics (without spin) $\Longrightarrow$ QCD (-> NNLO)
- Unification of electromagnetic and weak forces at high energies
- Joint ZEUS+H1 set of DIS data: HERAPDF2.0 (LO, NLO, NNLO)
- Tension between the data and QCD at $Q^2 \lesssim 15$ GeV^2
- No deviations from SM $> 2.5\sigma$; compositeness: $R_q < 0.43 \cdot 10^{-18}$m



Eur.Phys.J. C75(2015) 580



Example: largest sources of uncertainty in the Higgs X-section

$\longrightarrow$ pdfs (1.9%)
$\longrightarrow$ α_s (2.6%)
$\longrightarrow$ non-availability of N^{3}LO pdfs (1.2%)

P. Newman, DIS2016

HERA's Non-Legacy

Some of HERA's Limitations ...

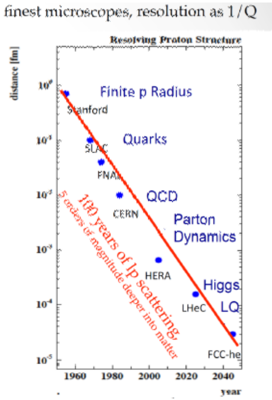
- Insufficient lumi for high x precision or searches
- Lack of Q^2 lever-arm restricts precision on low x for gluon
- Limited quark flavour info (no deuterons to separate u and d)
- Protons not polarised except HERMES
  (no access to spin, transverse structure at low x)
- No nuclear targets

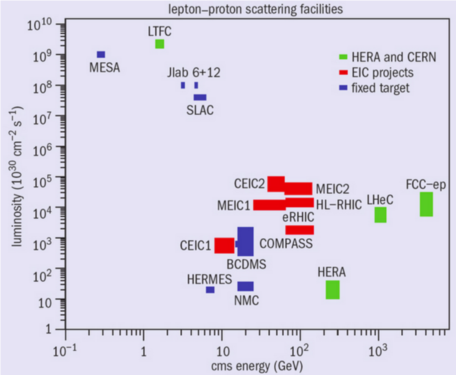
ALL of these limitations are addressed by currently proposed future DIS projects in the USA and at CERN.

Needs strong support from the DIS community to have a chance of success (HERA was ~1000 at its peak).

P. Newman, DIS2016

Past, presence and future of DIS





EIC

medium energy $\sqrt{s} \simeq 20 - 100$ GeV

high luminosity 10^{34} cm^{-2}s^{-1}

wide range of nuclei from deuteron to heaviest(uranium/lead)

polarization of electron and nucleon beams

LHeC FCC-ep

high energy $\sqrt{s} \simeq 1 - 5$ TeV

high luminosity 10^{34} cm^{-2}s^{-1}

electron ion scattering on lead

VHEeP

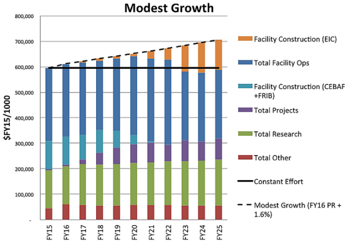
very high energy, $\sqrt{s}$ ~9 TeV
low luminosity, 10–100 pb^{-1}
electron–proton scattering

A.M. Cooper-Sarkar, Poetic7,2016; A. Stasto, Poetic7,2016; http://cerncourier.com/cws/article/cern/57304

Status of the new machines

EIC: The White Paper (arXiv:1212.1701),
EIC Users Group http://www.eicug.org;
construction recommendation NSAC LRP2015

- end 2017: acceptation by DOE
- 2020: site selection
- 2023: start construction
- 2028: physics operation



igure 10.4: DOE budget in FY 2015 dollars for the Modest Growth scenario.

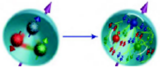
LHeC: CDR (J. Phys. G39 (2012) 075001, arXiv:1206.2913), http://lhec.web.cern.ch;
ongoing CERN-sponsored working group;
European Strategy for Partice Physics: no recommendation for R&D

- end 2018: update CDR2012
- pursue ERF (PERLE)

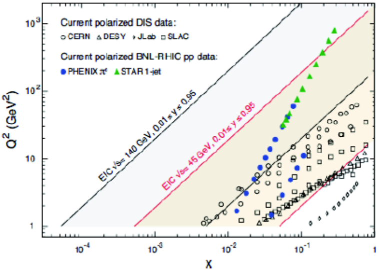
VHEeP: e.g. arXiv:1606.00783v2, first meeting of physics community in VI. 2017.
proton-driven wakefield acceleration achieved XII.2016! Exp. AWAKE @ CERN

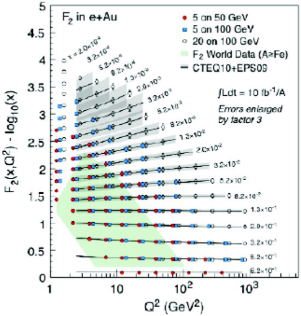
In a nut shell...

EIC Physics



Polarised hadrons → DIS spin puzzle and 2+1D proton structure tackled in unprecedented low x regime





Wide range of ions and large step in eA kinematic range
→ Nuclear parton densities
→ Potential access to low x sat'n
→ Struck partons in cold nuclear matter

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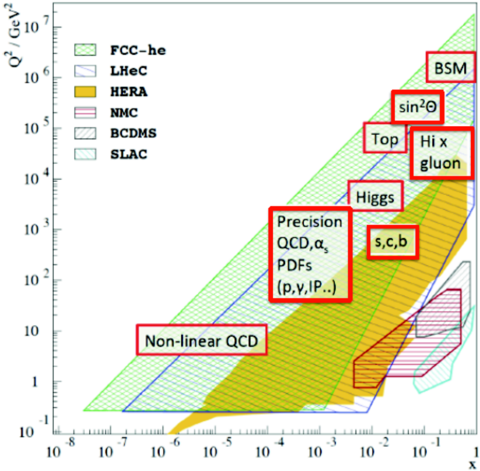
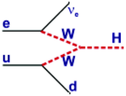
P. Newman, DIS2016

In a nut shell...

LHeC Physics





- Substantial Higgs programme

- Revolutionary p PDF (& α_s) precision improves LHC sensitivity to Higgs and new physics

- Elucidates low x dynamics in ep & eA

- 4 orders of mag. in kinematic range of nuclear structure

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P. Newman, DIS2016

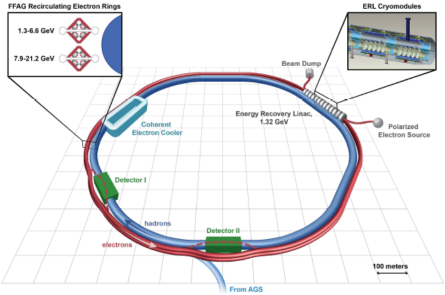
EIC

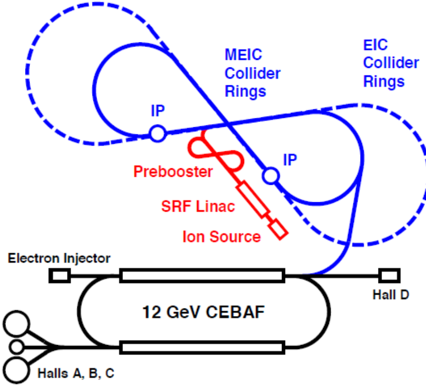
US EIC at BNL or JLab

BNL (eRHIC) | JLab (MEIC)

Add energy recovery LINAC (inside RHIC tunnel)

Add hadron rings “8” to CEBAF (external)



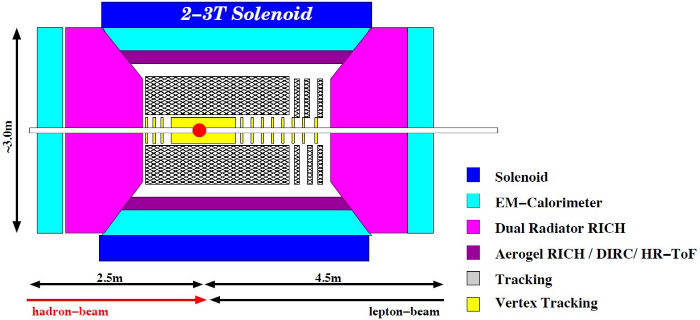


The White Paper, arXiv:1212.1701

EIC: main features

- Highly polarised ($\sim$ 70%) e, N beams
- ions from deuteron to uranium (lead ?)
- variable $\sqrt{s}$ from $\sim$ 20 GeV to $\sim$ 100 (150) GeV
- high luminosity: $\sim 10^{33-34}$ cm^{-2} s^{-1} (cooling of hadronic beam !)
- more than one interaction region
- limits of current technology $\Longrightarrow$ R & D!
- staged realisation; first stage: $\sqrt{s}$ = 60 - 100 GeV and high luminosity.

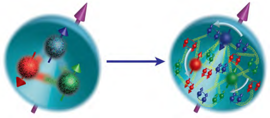
A dedicated EIC detector



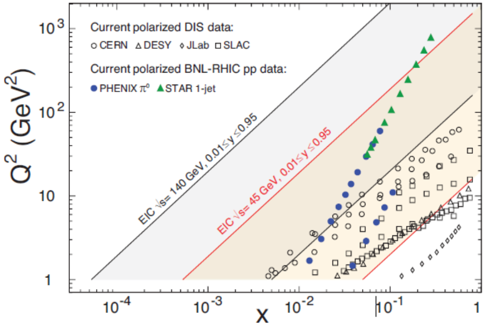
- Acceptance -5 $< \eta <$ 5 (large, comparable to CMS forward)
- PID: π, K, p, leptons
- Low material density (minimal multiple scattering and bremsstrahlung)
- Hadron beams: proton to lead

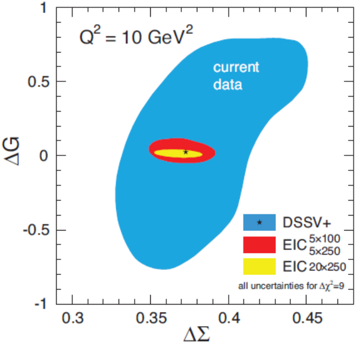
From “White paper”, arXiv:1212.1701

Nucleon spin “puzzle” at EIC



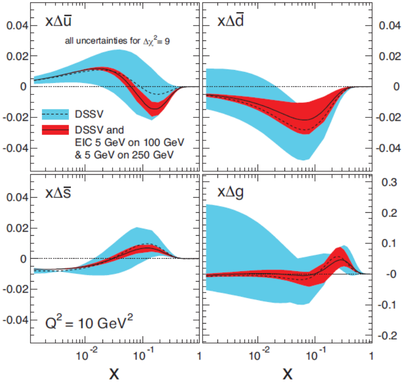
$$\frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark spins}} + \underbrace{\Delta G}_{\text{gluon spins}} + \underbrace{L_z}_{\text{quark\&gluon orbital motion}}$$





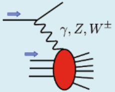
From “White paper”, arXiv:1212.1701

Parton separation at EIC pseudo-data (inclusive and semi-inclusive)



- $\Delta g(x)$ from scaling violation
- $\Delta\bar{u}, \Delta\bar{d}, \Delta s$ from SIDIS
- Flavor separation at high Q² via CC DIS:

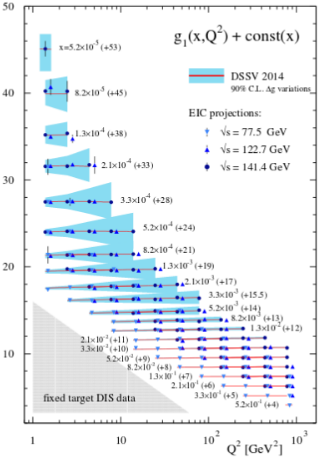
$$g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta\bar{c} + \Delta s$$
$$g_1^{W^-} = \Delta u + \Delta\bar{d} + \Delta c + \Delta\bar{s}$$
$$g_5^{W^+} = \Delta\bar{u} - \Delta d + \Delta\bar{c} - \Delta s$$
$$g_5^{W^-} = -\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}$$

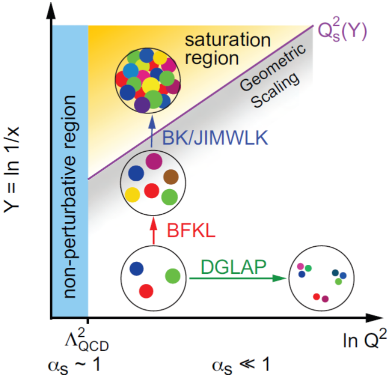


From "White paper", arXiv:1212.1701

E. Aschenauer, SPIN2016

Inclusive $g_1(x, Q^2)$ at EIC (pseudo-data)





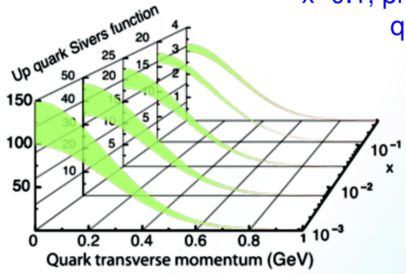
Errors statistical (EIC: expected, modest parameters); bands: from gluon helicity uncertainty

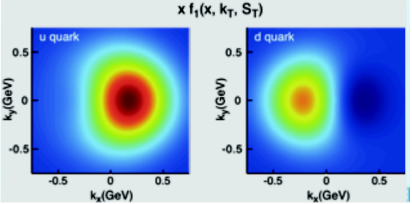
arXiv:1509.06489

"White paper", arXiv:1212.1701

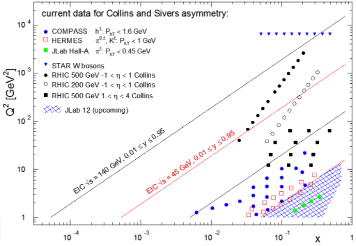
Sivers function at EIC

x=0.1, proton ⊥ polarised along y, moving along z
quark “flow” in a nucleon





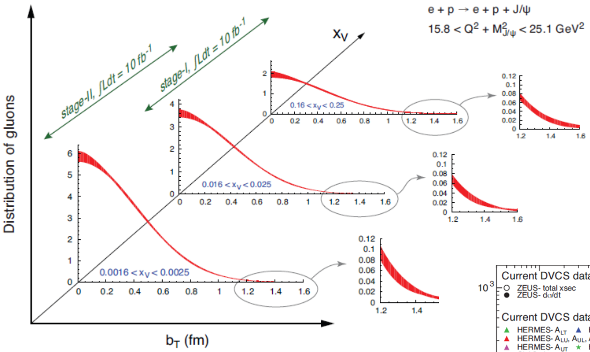
From “White paper”, arXiv:1212.1701



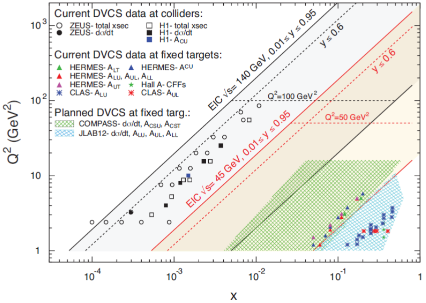
⟸ EIC acceptance for Sivers meas.

O. Eyser, SPIN2016

3D picturing of nucleon (or GPDs) at EIC



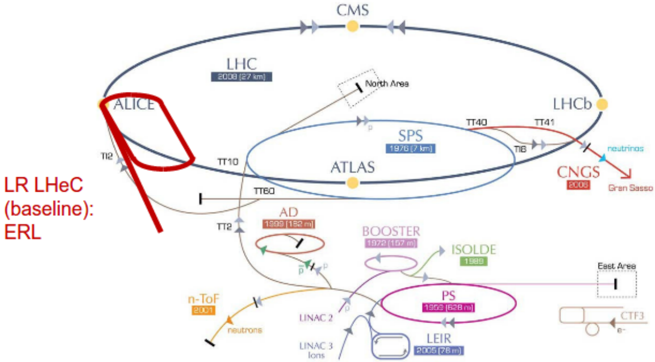
$$x_V = x\left(1 + \frac{M^2_{J/\Psi}}{Q^2}\right)$$



From “White paper”, arXiv:1212.1701

LHeC

LHeC options: RR and LR

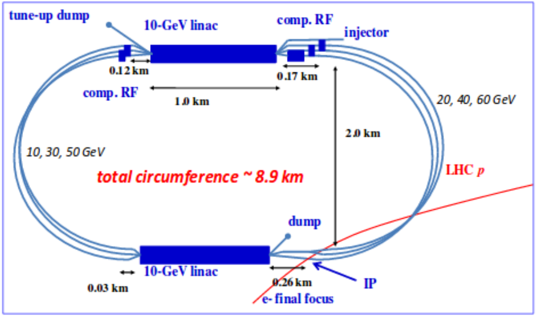


Study team provided CDR:
Ring-ring option, feasible but impact LHC operation during installation
Linac-ring option, the baseline
A solution exists, will now have to find the best solution
Already have a baseline and alternatives for some components

17 Juni 2014 IPAC '14, Dresden Erk Jensen: ERL Test Facility IPAC14 8

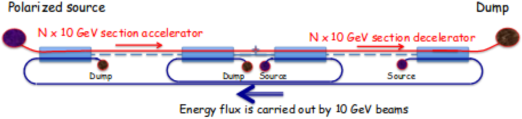
Default Electron Accelerator Concept

Conceptual Design Report: arXiv:1206.2913



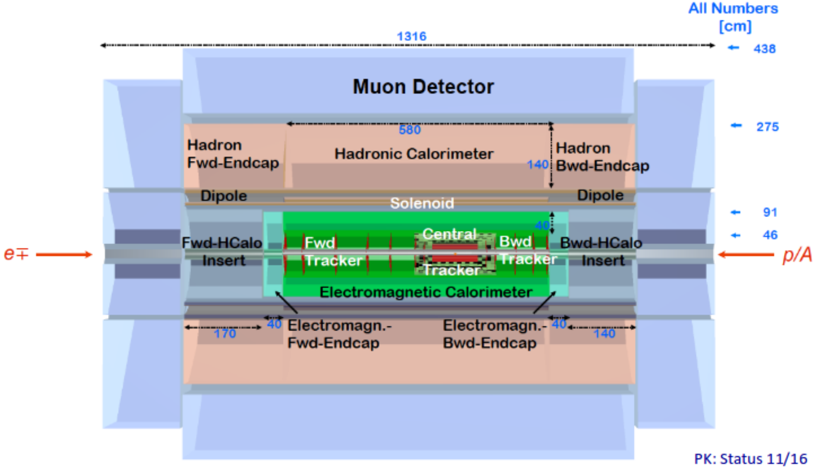
LHeC: 60 GeV off 7 TeV, L(ep) $=10^{34}\ cm^{-2}\ s^{-1}$ (1000 x HERA) in synchronous ep+pp operation

Non default: An expensive generalisation to achieve E_e= 500 GeV or more



V Litvinenko

LHeC Detector



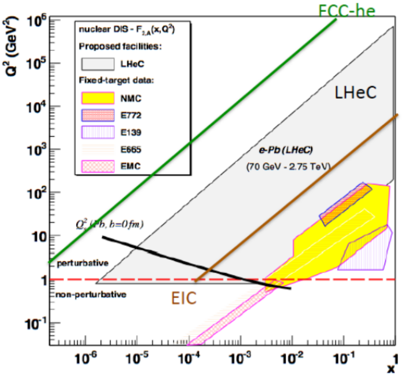
PK: Status 11/16

Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =13x9m^2 [CMS 21 x 15m^2, ATLAS 45 x 25 m^2]
Taggers at -62m (e), 100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

E. Jensen, IPAC, 2014

A Large Hadron Electron Collider (LHeC) at CERN

- Symposium on the European Strategy for Partice Physics, Cracow, 2012 arXiv:1211.4831
- Two options: ring–ring (RR) and linac–ring (LR). Basic beam design:



electron beam 60 GeV	Ring	Linac
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	6	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.59, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	100	6.6
energy recovery efficiency [%]	–	94
proton beam 7 TeV		
protons per bunch N_p [10^{11}]	1.7	1.7
transverse emittance $\gamma\epsilon^p_{x,y}$ [μm]	3.75	3.75
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing [ns]	25	25
rms beam spot size $\sigma_{x,y}$ [μm]	45, 22	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\ L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.45	1

- The “Strategy” has not recommended a continuation of R&D for LHeC!

The LHeC Physics Programme

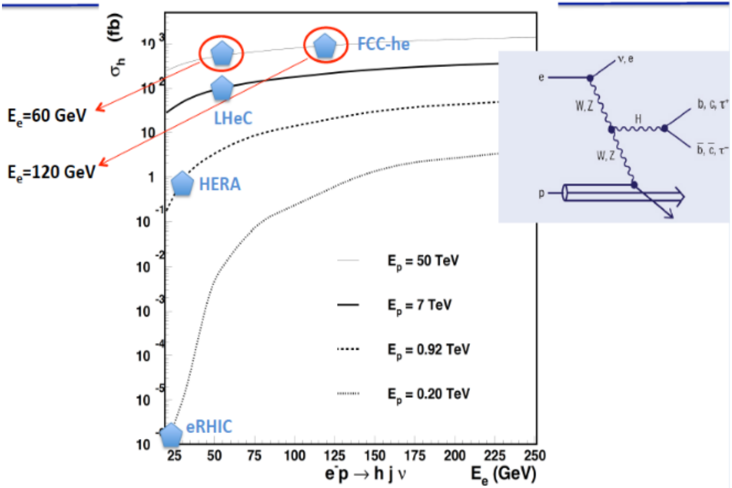
arXiv:1206.2913 (CDR) 1211.4831 and 5102

QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H? leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution Precision DIS	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure Quark Distributions QCD	Proton, Deuteron, Neutron, Ions, Photon valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top N^3LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron Heavy Ions Modified Partons	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing initial QGP, nPDFs, hadronization inside media, black limit, saturation PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity

M. Klein, Poetic7,2016

SM Higgs in ep → ν/e H X



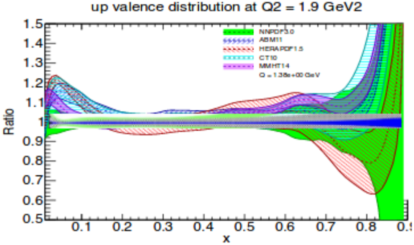
LHeC / FCC-he: Sizeable charged current DIS unpolarised **ep cross sections**

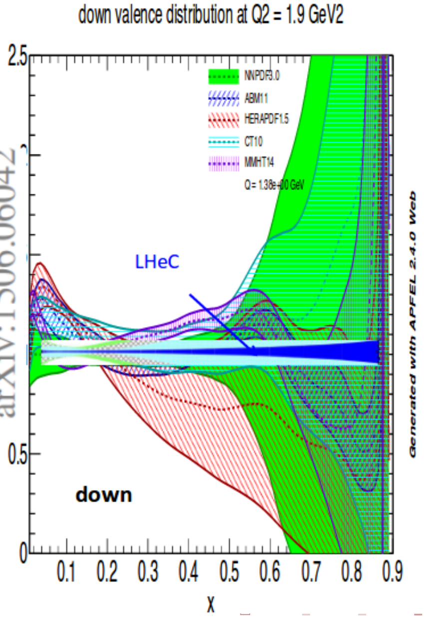
Uta Klein, Future ep/eA Colliders 26

Valence quarks

High x crucial for HL LHC searches
Related to DrellYan , W mass etc
d/u → 1 a classic question, still there

up



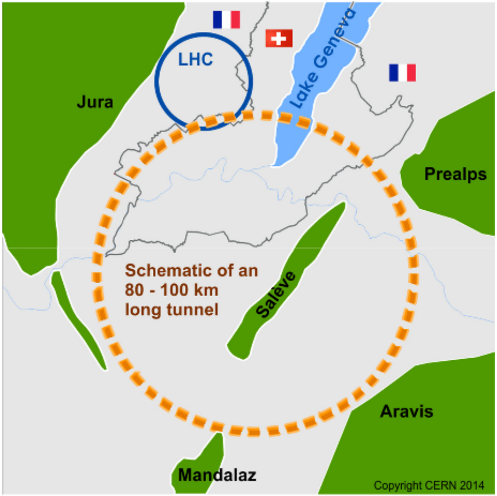


M. Klein, Poetic7,2016

FCC-he

- 80-100 km tunnel infrastructure in Geneva area
- *pp*-collider (*FCC-hh*) defining the infrastructure requirements
- *e⁺e⁻* collider (*FCC-ee*) as potential intermed. step
- **p-e (*FCC-he*)** option
- international collaboration hosted by CERN

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km



FCC-he

- 80-100 km tunnel infrastructure in Geneva area
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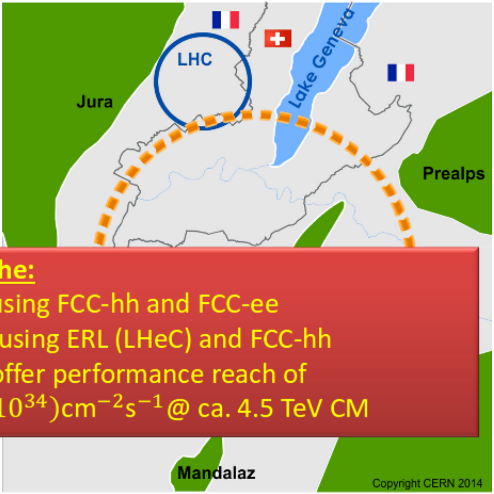
- *e^+e^-* collider (*FCC-ee*) as potenti
- ***p-e* (*F***
- interna hosted



Two Options for FCC-he:

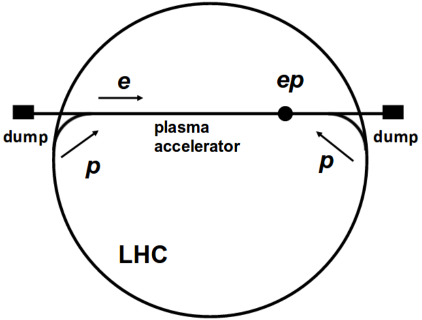
- Ring-Ring collider using FCC-hh and FCC-ee
- Linac-Ring collider using ERL (LHeC) and FCC-hh

Both options offer performance reach of
$\mathcal{L} = (10^{33} \div 10^{34})\mathrm{cm}^{-2}\mathrm{s}^{-1}$@ ca. 4.5 TeV CM

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

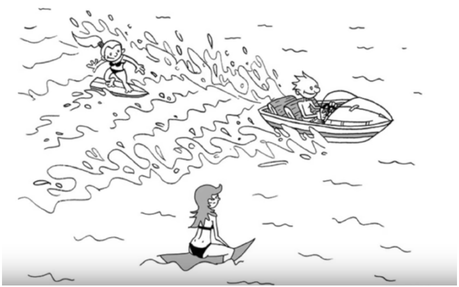
VHEeP

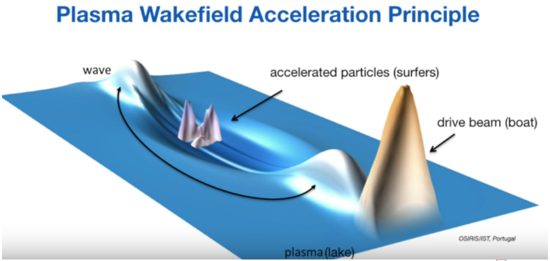
A very high energy electron–proton collider



hep-ex/1606.00783v2

Principle of plasma acceleration E. Gschwendtner, TEDxCERN, 2015





AWAKE @ CERN

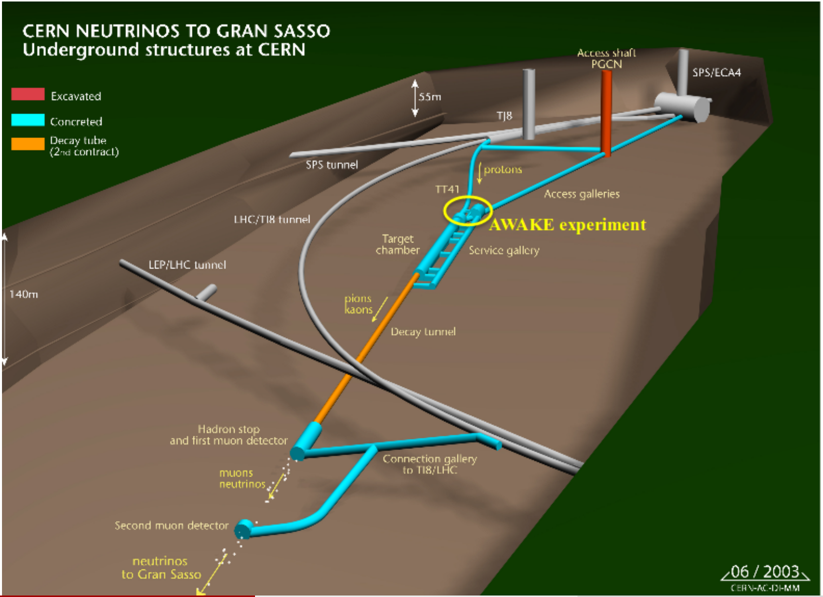
The Advanced Proton Driven Plasma Wakefield Acceleration Experiment.

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) aims at studying plasma wakefield generation and electron acceleration driven by proton bunches. It is a proof-of-principle R&D experiment at CERN and the world´s first proton driven plasma wakefield acceleration experiment. The AWAKE experiment will be installed in the former CNGS facility and uses the 400 GeV/c proton beam bunches from the SPS. The first experiments will focus on the self-modulation instability of the long
(rms ~12 cm) proton bunch in the plasma. These experiments are planned for the end of 2016. Later, in 2017/2018, low energy (~15 MeV) electrons will be externally injected into the sample wakefields and be accelerated beyond 1 GeV.

AWAKE is a proof-of-concept acceleration experiment with the aim to inform a design for high energy frontier particle accelerators and is currently being built at CERN. The AWAKE experiment is the world´s first proton driven plasma wakefield acceleration experiment, which will use a high-energy proton bunch to drive a plasma wakefield for electron beam acceleration. A 400 GeV/c proton beam will be extracted from the CERN Super Proton Synchrotron, SPS, and utilized as a drive beam for wakefields in a 10 m long plasma cell to accelerate electrons with amplitudes up to the GV/m

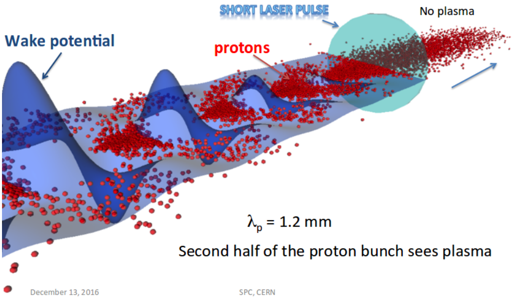
AWAKE @ CERN... cont'd

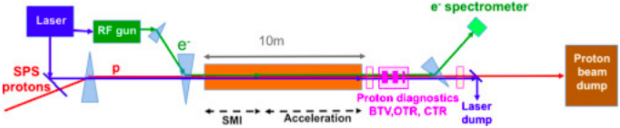
A. Caldwell, SPC CERN, 13.XII.2016



AWAKE @ CERN... cont'd

A. Caldwell, SPC CERN, 13.XII.2016





Drivers:
PW lasers today, ~40 J/Pulse

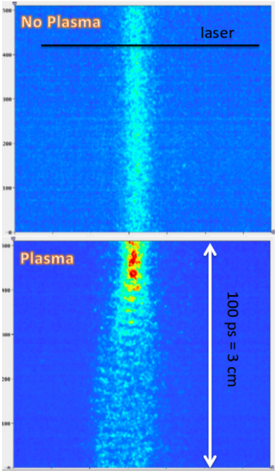
FACET, 30J/bunch

SPS 20kJ/bunch
LHC 300 kJ/bunch

Witness:
10^{10} particles @ 1 TeV ≈ few kJ

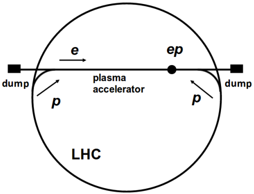
- Accelerating power up to 1 GV/m ($\sim$ 1000$\times$ more than present)

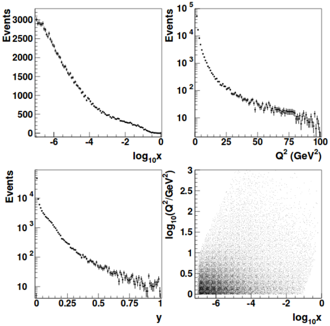
Phase I $\Longrightarrow$ SUCCESS! (Dec. 2016)



VHEeP kinematics and basic parameters

- ep cms energy: 3 TeV (e) + 7 TeV (p, LHC) $\Longrightarrow \sqrt{s} \sim 9$ TeV (6$\times$ higher than proposed for LHeC; 30$\times$ higher than HERA)
- luminosity: $\sim$ 10 – 100 pb^{-1} over lifetime (1000 – 100 $\times$ less than HERA) lower OK for low x physics; higher needed for BSM (typically @ high Q^2)
- plasma accelerator must be $\lesssim$ 4 km long
- ARIADNE MC for $Q^2 >$ 1 GeV^2, $W^2 >$ 5 GeV^2, $x > 10^{-7}$, 0.01 pb^{-1}





x_{min} : $1000\times$ less than @ HERA!

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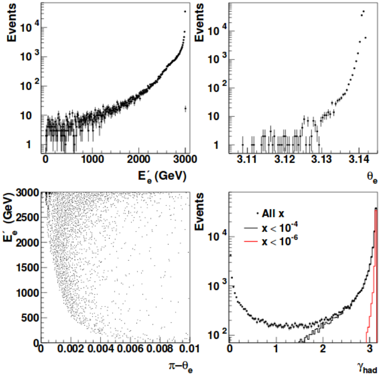
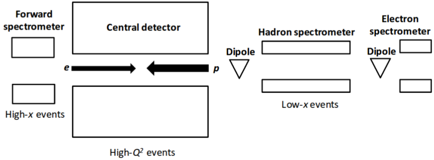
VHEeP kinematics and basic detector design



Same simulation parameters and conditions as before



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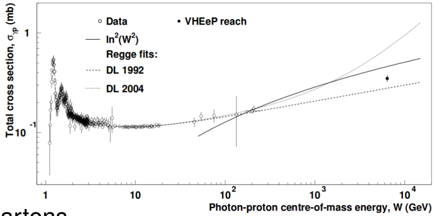
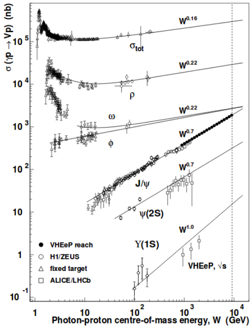
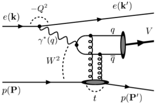
QCD physics at VHEeP

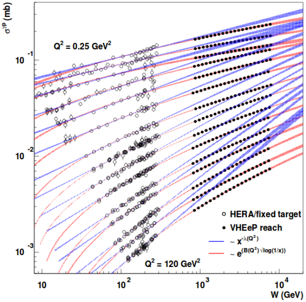
- **Total $\gamma{-}$p cross section:** resolving models, constrain cosmic-ray simulations



- **Vector meson production:** particularly sensitive to saturation of partons







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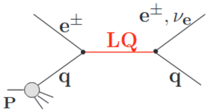
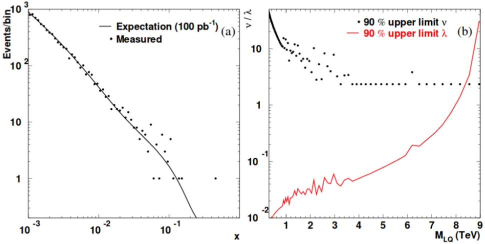
- Quark substructure

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{\rm SM}}{dQ^2}\left(1 - \frac{R_e^2}{6}Q^2\right)^2\left(1 - \frac{R_q^2}{6}Q^2\right)^2$$

Simulation at $10^5 < Q^2 < 10^7$ GeV^2, 68% CL: $R_q \leq 1 \cdot 10^{-19}$ m
HERA recent, $Q^2 < 3 \cdot 10^4$ GeV^2, 95% CL: $R_q \leq 4 \cdot 10^{-19}$ m PL B757 (2016) 468

- Leptoquark production





BRW model:

$$\sigma^{\rm NWA} = (J+1)\frac{\pi}{4s}\lambda^2 q(x_0, M_{\rm LQ}^2)$$

$x_0 = M_{\rm LQ}^2/s$ sensitivity on $M_{\rm LQ}^2$ up to ∼9 TeV (HERA: 1 TeV, LHC: 1–2 TeV)

hep-ex/1606.00783v2

Take-away menu

New e–p machine(s) planned to develop QCD, e.g. (in increasing $\sqrt{s}$ order):

- **EIC:** Electron–Ion Collider, BNL or JLab ☺
  (alternatives: eRHIC/MEIC)
  Polarised beams, high lumi, heavy ions, as good as approved, operational 2028
- **LHeC:** Large Hadron–electron Collider, CERN ☹
  (also: FCC-ep: Future Circular Collider-ep)
  Unpolarised beams, high luminosity, some ions, not very probable
- **VHEeP:** Very High Energy electron–Proton (collider), CERN ?
  VERY attractive technology, unprecedented kinematic reach, unpolarised beams, low luminosity