Progress and Challenges in Proton Structure: From HERA to Future Colliders EIC/LHeC

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Outline

- Deep Inelastic Scattering (DIS) at HERA - lessons learned and future prospects
- The LHC precision era
- LHeC: Electroweak and Strong Interactions
- What will we learn from EIC?
- Summary and Closing Words

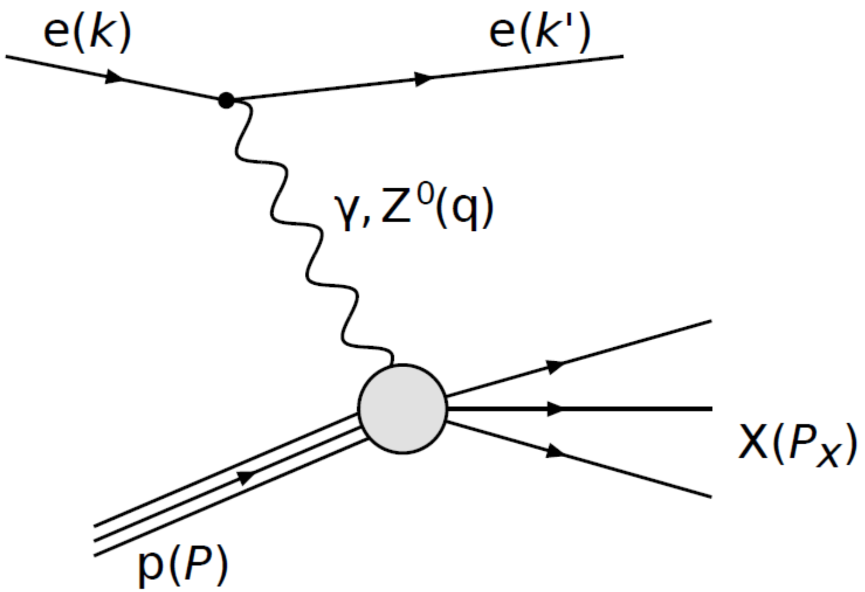
Deep Inelastic Scattering (DIS) at HERA

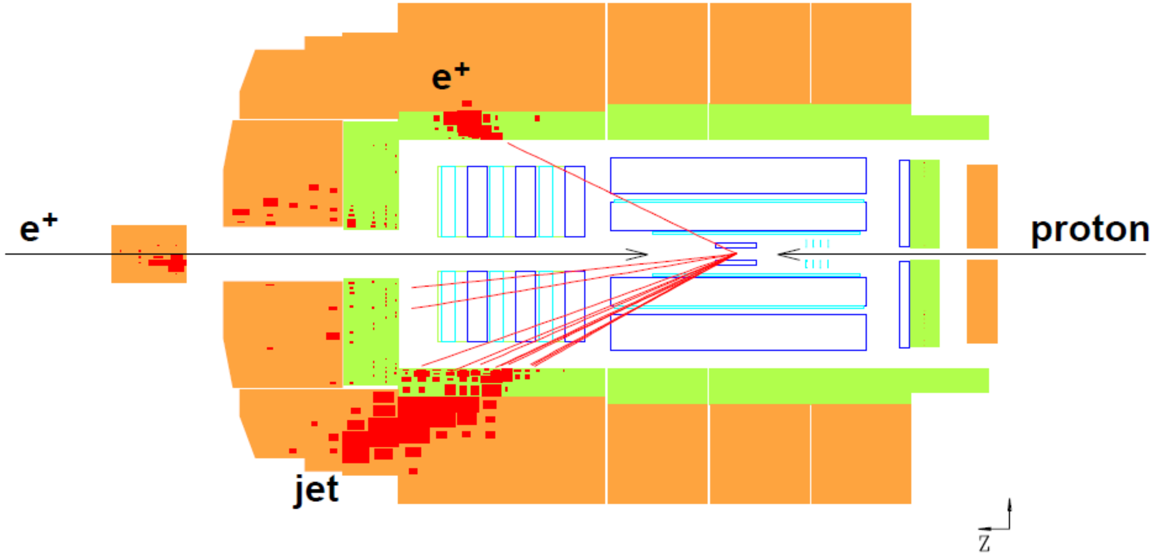
Deep Inelastic Scattering (DIS)

- This process can be mediated by charged ($W^{\pm}$) or neutral (γ^*, Z^0) exchange.
- Deep inelastic scattering (DIS) is a powerful tool to study the parton densities in the nucleon.

$$e(k) + p(P) \rightarrow e(k') + X(P_X)$$

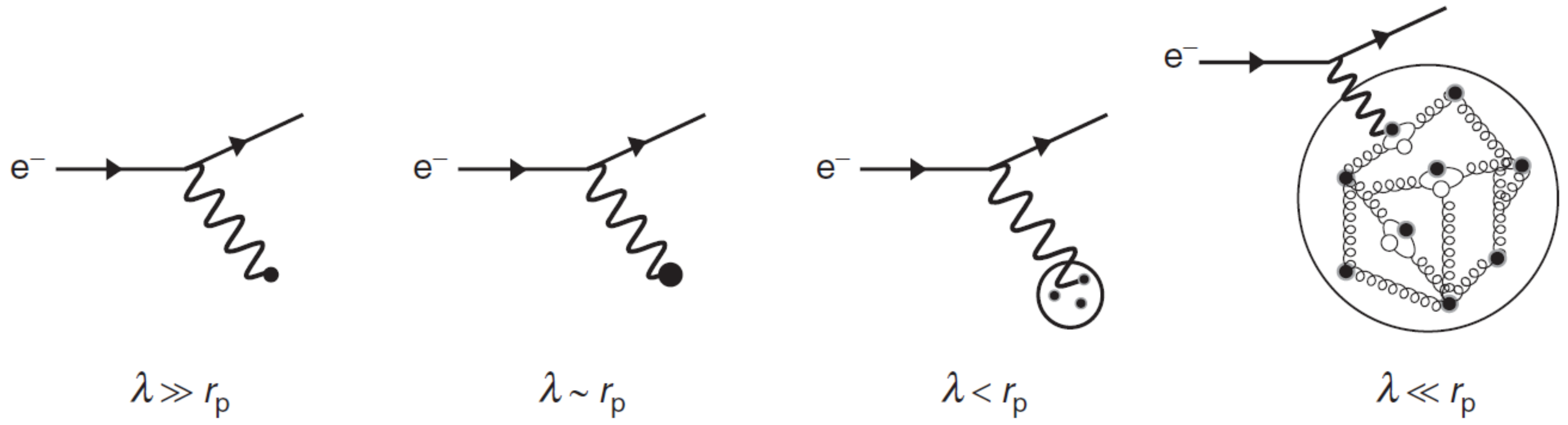
Feynman diagram for DIS





Probing the structure of the proton

- Electron-proton scattering provides a powerful tool for probing the structure of the proton. At low energies, the dominant process is elastic scattering where the proton remains intact. Elastic scattering is described by the interaction of a virtual photon with the proton as a whole, and thus provides a probe of the global properties of the proton, such as its charge radius.
- At high energies, the dominant process is Deep Inelastic Scattering, where the proton breaks up. Here the underlying process is the elastic scattering of the electron from one of the quarks within the proton. Consequently, DIS provides a probe of the momentum distribution of the quarks.



The nature of e^-p scattering depending on the wavelength of the virtual photon.

Inclusive DIS kinematics

- The Bjorken scaling variable which can be interpreted within parton model as the proton momentum fraction entering to the hard subprocess, *x*.

$$x = \left(\frac{Q^2}{2p \cdot q}\right) \qquad 0 \leq x \leq 1.$$

- The virtuality of the exchanging photon, Q^2.

$$Q^2 = -q^2$$

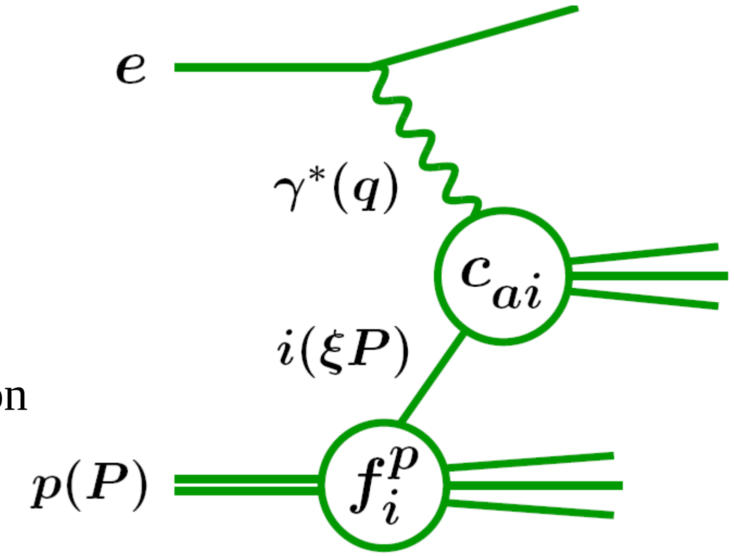
The Quark Parton Model

- The basic idea of the QPM is that in the DIS process, $ep \to eX$, the virtual proton interacts with one of the quark constituents of the proton.
- As a result, the *ep* interaction may be written as a sum (of probabilities) of scattering from single free quarks.

$$\frac{d\sigma}{dx dQ^2} = \sum_q \int_0^1 d\xi \; f_q(\xi) \left(\frac{d\hat{\sigma}_{eq}}{dx dQ^2} \right)$$

$f_q(\xi)$ is the probability of finding the quark q in the proton carrying a fraction ξ of its momentum

electron-quark cross section



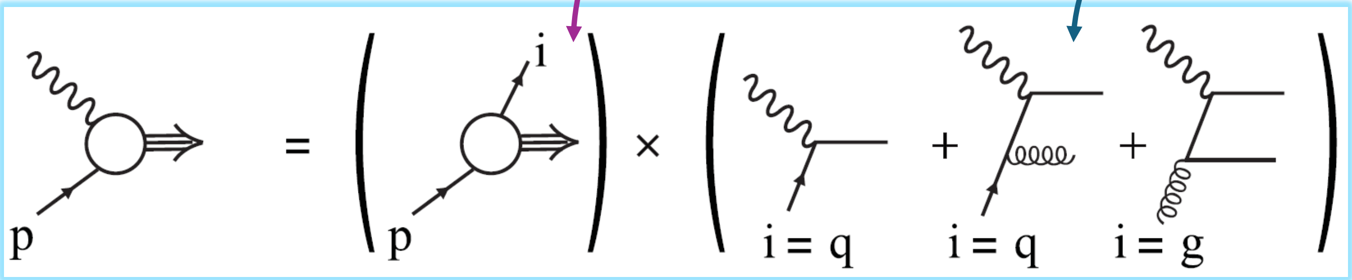
Inclusive DIS structure functions

- The structure functions F_a as a physical observables describe the DIS processes.
- For the structure functions F_a, describing the deep inelastic processes $\ell+p \longrightarrow \ell'+X$, the factorization formula has the following form:

$$F_a(x, Q^2) = \sum_{i=q,\bar{q},g} \int_0^1 \frac{dy}{y} f_i(y, Q^2)\, C_{a,i}\left(\frac{x}{y}, \alpha_s(Q^2)\right)$$

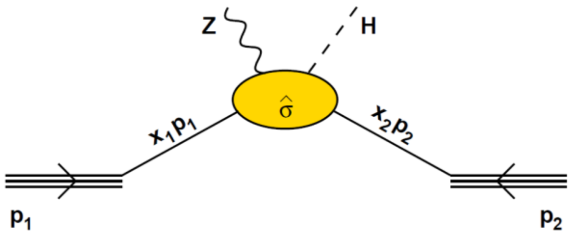
Universal parton densities (of the proton). They cannot be calculated in perturbative QCD, but their Q^2 dependence is calculable using the DGLAP evolution equations

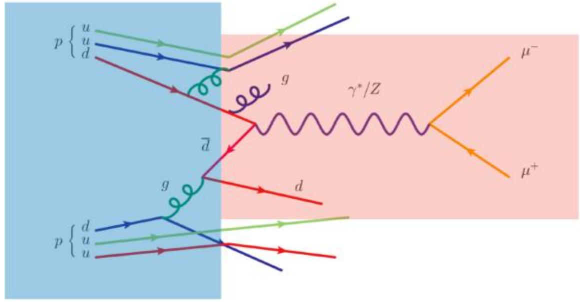
Coefficient functions. They are calculable from perturbative QCD as a power series in α_s, but are unique to the particular observable, F_a.

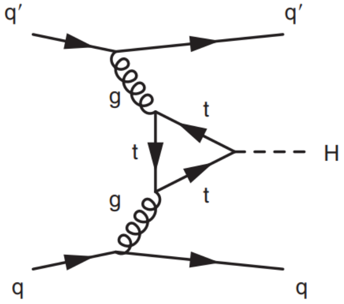


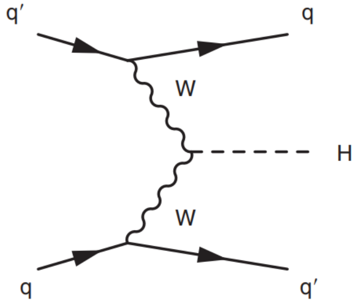
Parton Distribution Functions (PDFs)

- A PDFs is defined as the probability density for finding a particle with a certain longitudinal momentum fraction x at momentum transfer Q^2.
- Provide fundamental information regarding nucleon and nuclear structure.
- Knowledge of the interaction initial state, and hence the PDFs, is critical to precision measurements at hadron colliders (LHC).
- Measure total cross sections $\leftrightarrow$ need to know PDFs.
- Hadron-hadron collisions is complex because of two incoming partons.









$$\sigma_{\mathrm{LHC}} = \sum_{ij} C_{ij}\left(x, \alpha_s(Q^2)\right) \otimes q_i(x, Q^2) \otimes q_j(x, Q^2)$$

DGLAP Evolution Equations

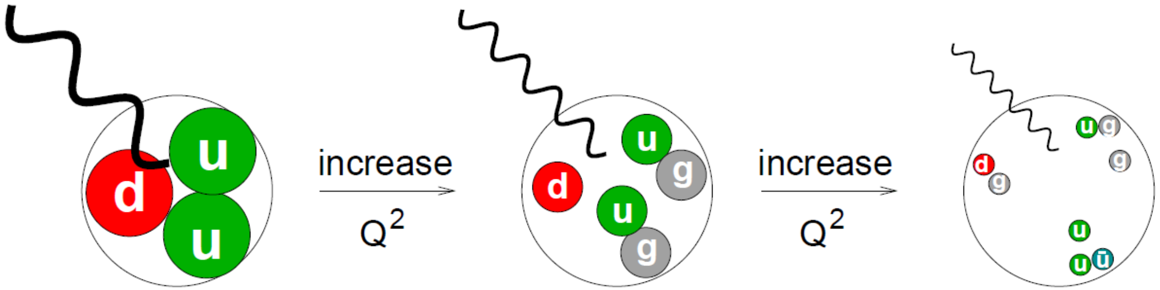
- These equations allow to calculate PDFs at arbitrary scale Q^2 from knowledge of PDFs at the initial scale Q_0^2

$$\frac{\partial q(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left(P_{qq}\otimes q \; + \; P_{qg}\otimes g\right)$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left(\sum_i P_{gq}\otimes (q_i+\bar{q}_i) \; + \; P_{gg}\otimes g\right)$$

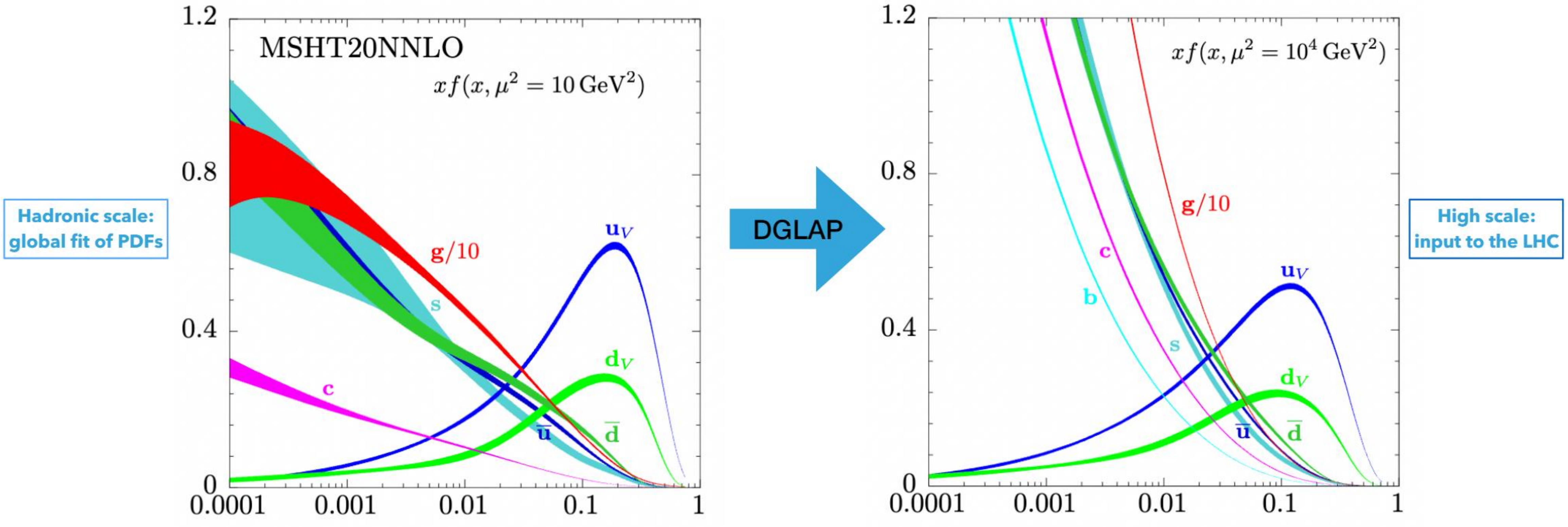
- In general, the splitting functions can be expressed as a power series in α_s

$$P_{ab}(\alpha_s, z) \; = \; P_{ab}^{\mathrm{LO}}(z) + \alpha_s P_{ab}^{\mathrm{NLO}}(z) + \alpha_s^2 P_{ab}^{\mathrm{NNLO}}(z) + \ldots$$



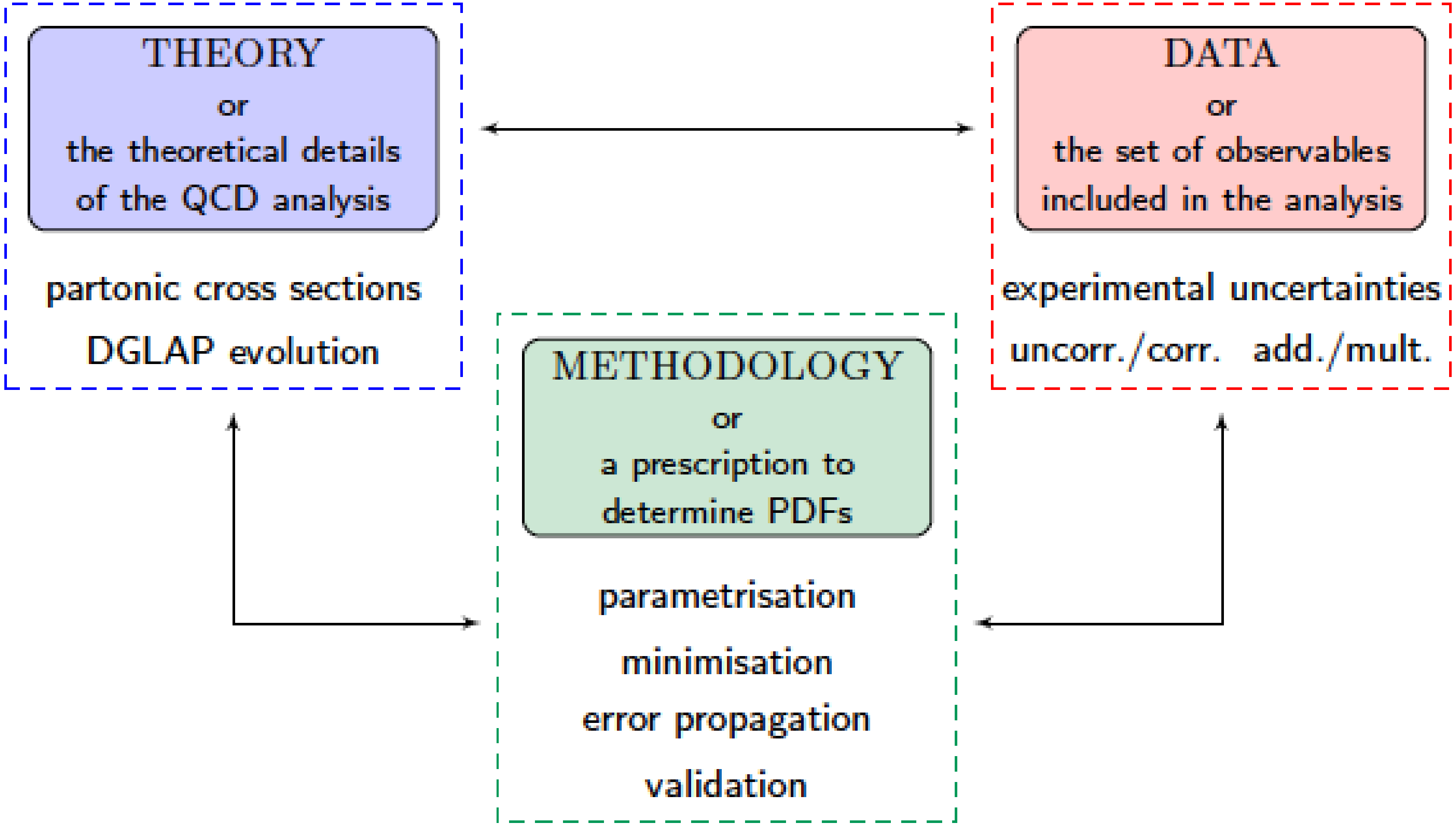
PDFs → Input to the LHC

- Global fit of PDFs → evolution up to a typical LHC scale → input for the LHC phenomenology



The effect of the DGLAP evolution in the MSHT20NNLO PDFs, from low scale of $Q^2 = 10\ \mathrm{GeV}^2$ (left) with the same PDFs evolved up to a typical LHC scale of $Q^2 = 10^4\ \mathrm{GeV}^2$ (right plot).

Determination of PDFs



Global QCD Analysis

Basic idea is simple: $\text{Data} = \text{PDF} \otimes \sigma_H$ but many ingredients enter! Three key areas:

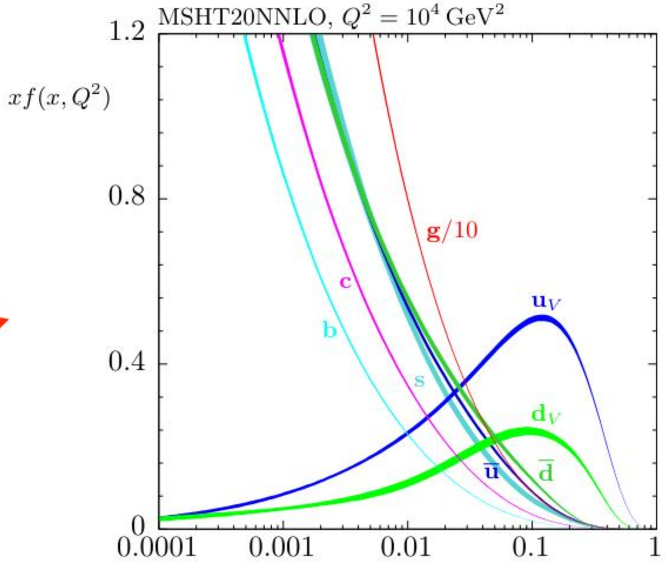
measure **fit** **predict**

Methodology

PDF parameterisation, uncertainty prescription…

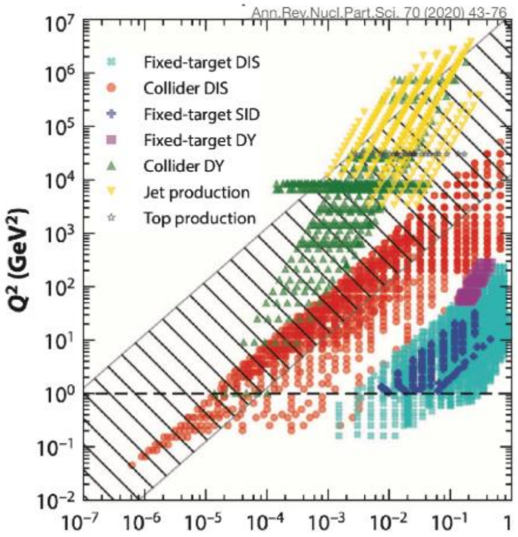
Theory

High precision: NNLO QCD + NLO EW the standard



Data

- From fixed target, to HERA DIS and collider. LHC data increasingly important.



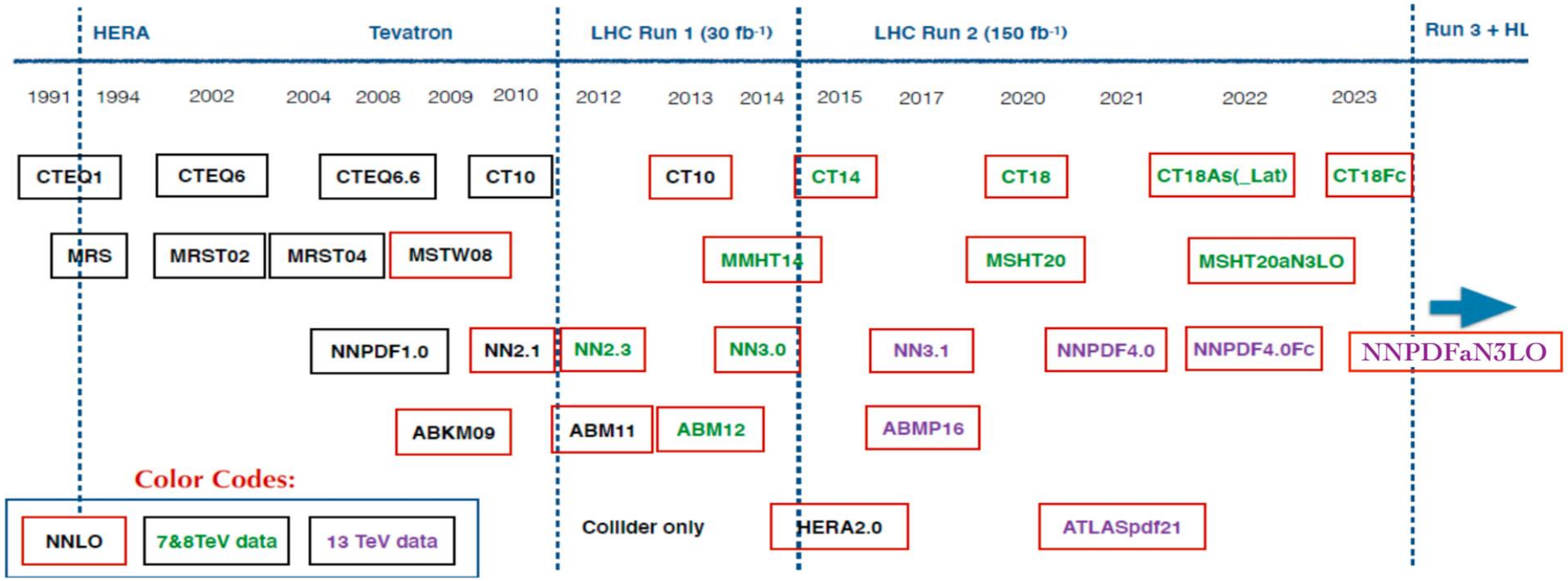
Aim: high precison theory + wide range of data $\longrightarrow$ **precise** + **accurate** PDFs

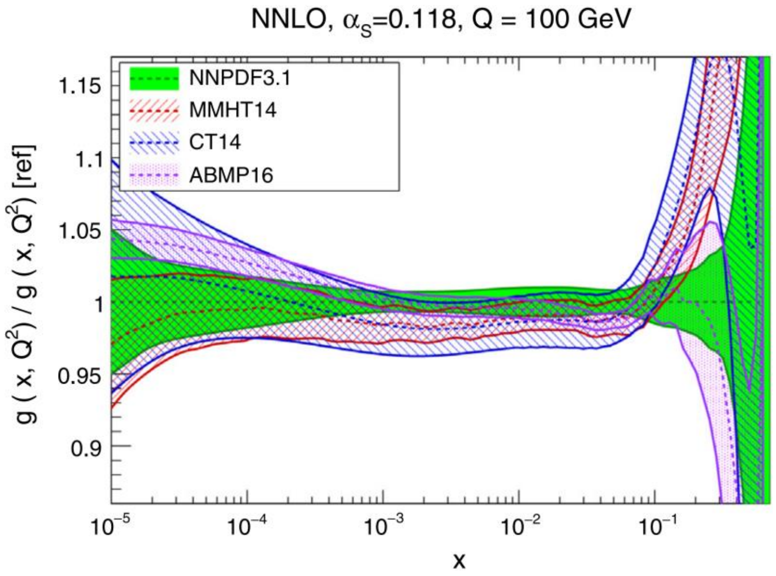
L. Harland-Lang @ DIS 2024

Available PDF Analyses

- Multiple PDF analyses, with different methodogies and datasets.

- **HERA** → **TEVATRON** → **LHC** → **(HL)LHC** → Future Colliders **EIC**/**LHeC**/**FCC**

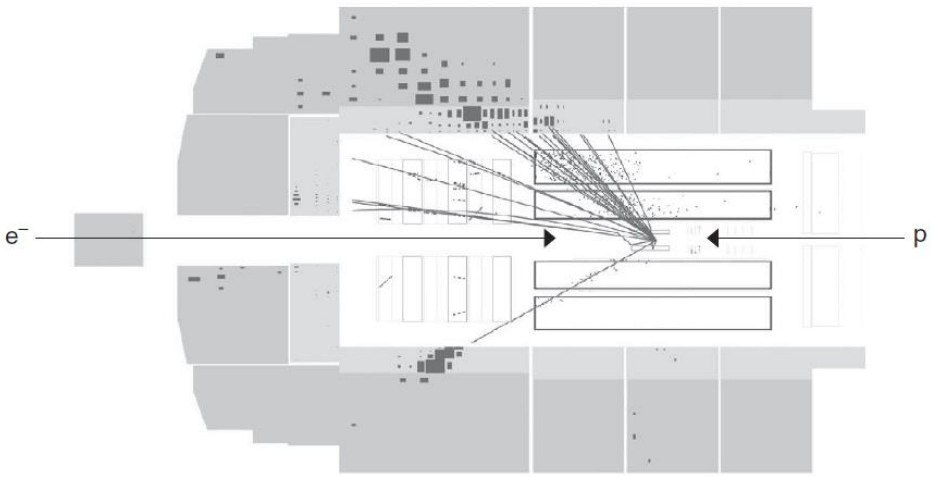




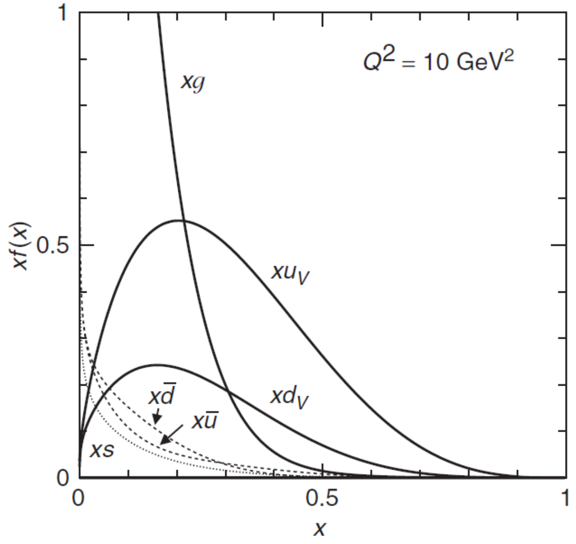
The gluon PDF at Q = 100 GeV comparing the ABMP16, CT14, MMHT14, and NNPDF3.1 NNLO sets with α_S = 0.118. The results are normalized to the central value of NNPDF3.1.

Electron-proton scattering at the HERA collider

- The studies of DIS at very high Q^2 and at very low x were amongst the main goals of the HERA electron-proton collider that operated from 1991 to 2007 at the DESY (Deutsches Elektronen-Synchrotron) laboratory in Hamburg, Germany. It consisted of a 3 km circumference ring where 27.5 GeV electrons (or positrons) were collided with 820 GeV or 920 GeV protons.
- Two large experiments, H1 and ZEUS, were located at opposite sides of the ring.



A high-energy electron-proton collision in the H1 detector at HERA.



The proton PDFs.

H1 and ZEUS Collaborations: Inclusive DIS $e^{\pm}$ p scattering cross sections

Eur. Phys. J. C 75 (2015) 580

- The two collaborations, H1 and ZEUS, have explored a large phase space in Bjorken x, and negative four-momentum-transfer squared, Q^2.

- Cross sections for neutral current (NC) interactions have been published for $0.045 \leq Q^2 \leq 50000$ GeV^2 and $6 \times 10^{-7} \leq x \leq 0.65$ at values of the inelasticity, $y = Q^2/(s\,x)$, between 0.005 and 0.95.

- Cross sections for charged current (CC) interactions have been published for $200 \leq Q^2 \leq 50000$ GeV^2 and $1.3 \times 10^{-2} \leq x \leq 0.40$.

- Consistency with old fixed-target data & HERA covers five orders of magnitude in x and Q^2

- H1 and ZEUS combined datasets are crucial input to the PDF fits.

The QCD analysis by HERAPDF

- In the approach of HERAPDF, the PDFs of the proton, $xf(x)$, are generically parameterised at the starting scale Q_0^2 as,

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2),$$

- The central parameterization of HERAPDF is

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{uv}}(1-x)^{C_{uv}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{dv}}(1-x)^{C_{dv}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}$$

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The HERAPDF2.0

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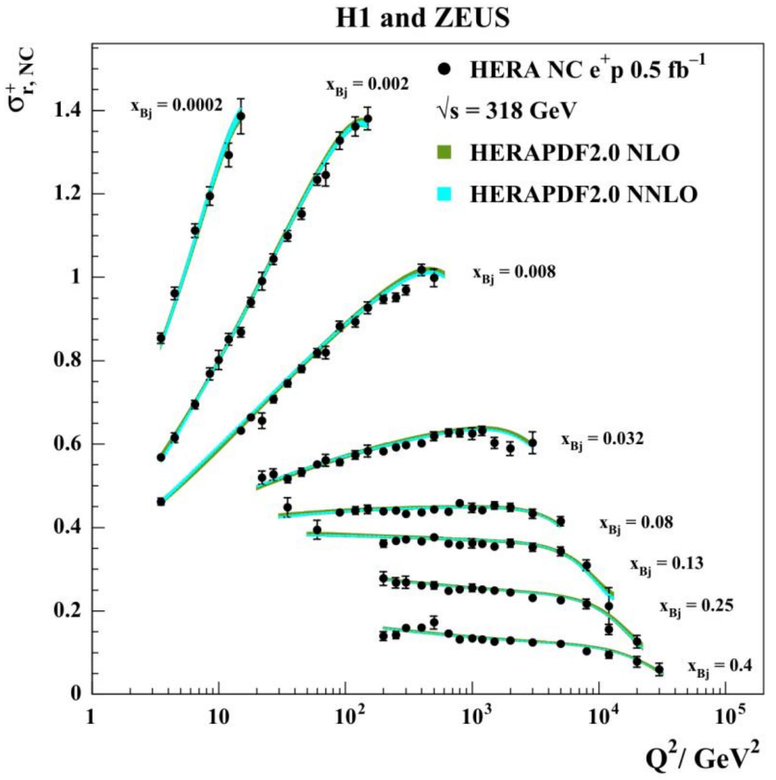
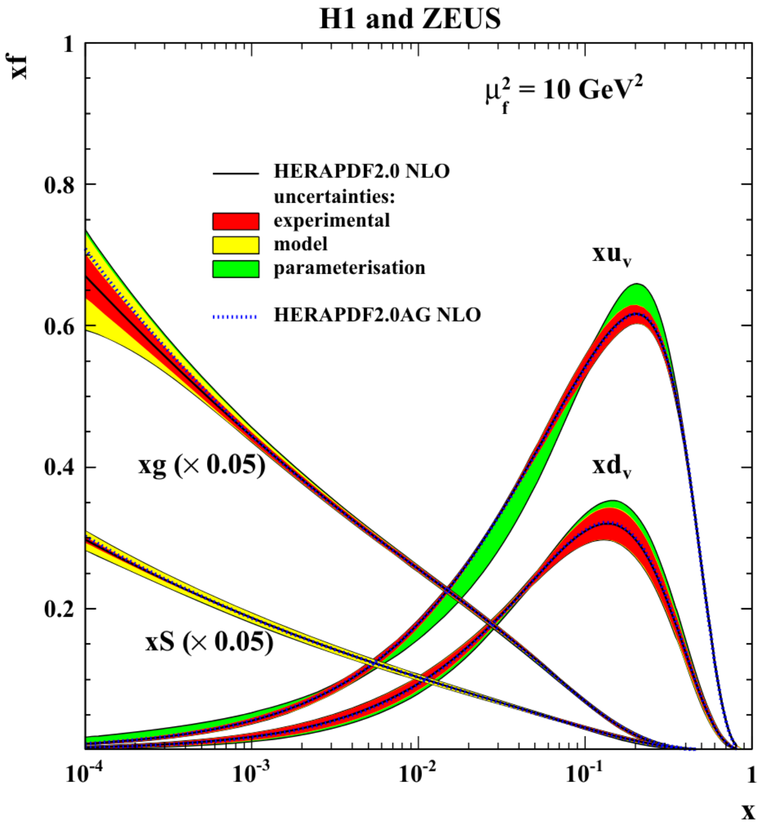


The combined HERA inclusive NC e+ p reduced cross sections & predictions of HERAPDF2.0 NLO and NNLO.



The HERAPDF2.0 at NLO accuracy.

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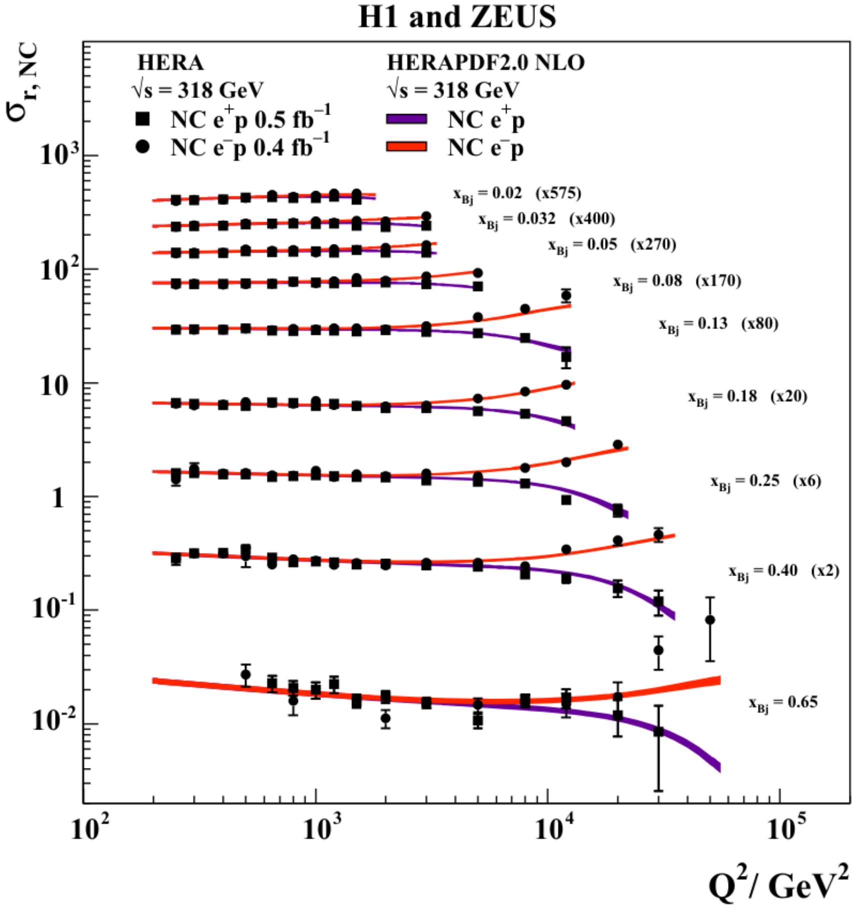
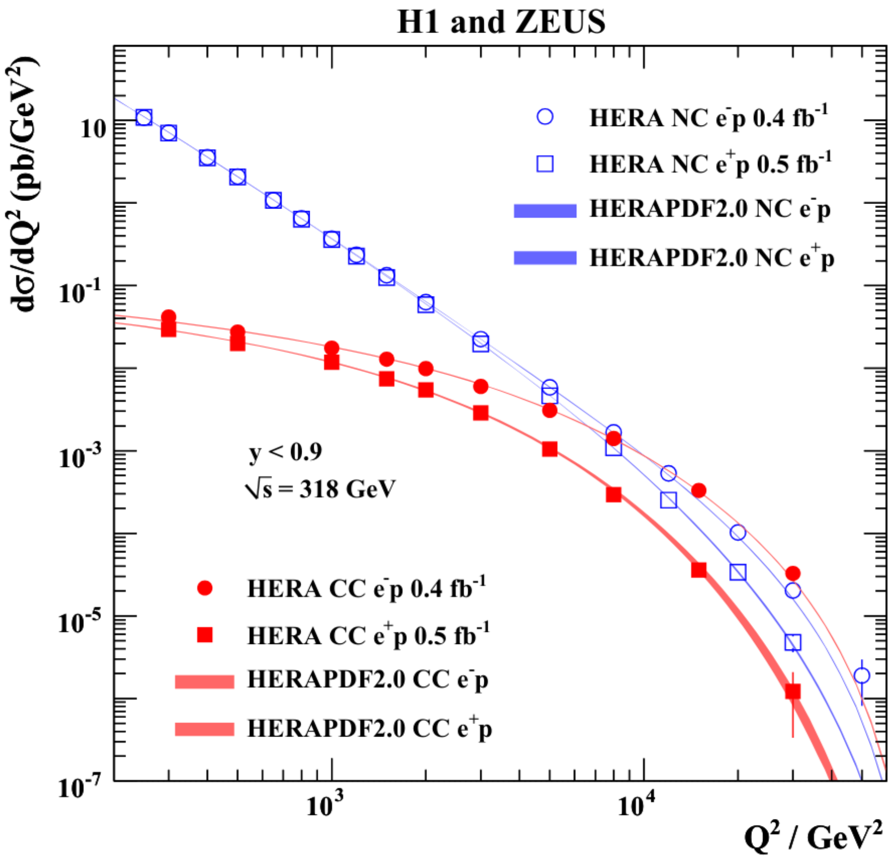


The combined HERA data predictions of HERAPDF2.0 NNLO.



The combined HERA NC and CC cross sections, $\frac{d\sigma}{dQ^2}$, together with predictions from HERAPDF2.0 NLO.

The LHC precision era

The structure of the proton in the LHC precision era

- The determination of the quark and gluon structure of the proton is a central component of the precision phenomenology program at the LHC.

- The global QCD analysis program involves combining the most PDF-sensitive data (+ LHC data) and the highest precision QCD and electroweak calculations.

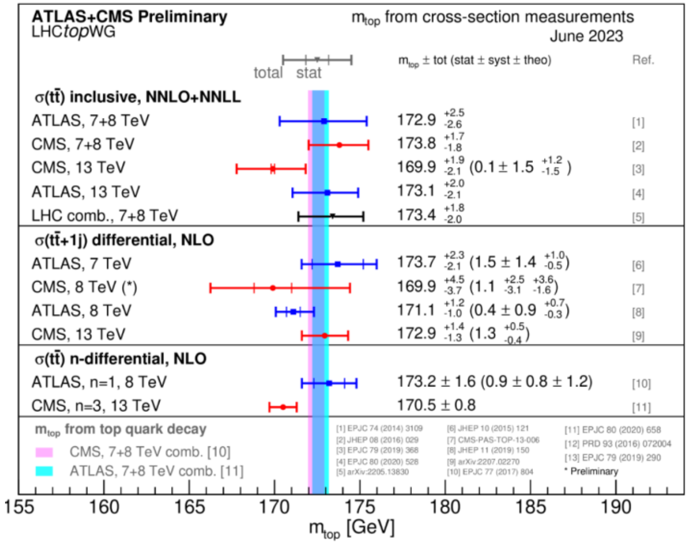
- One of the main motivations: PDFs and their associated uncertainties play a decisive role in several LHC applications [Phys. Rept. 742 (2018) 1-121].

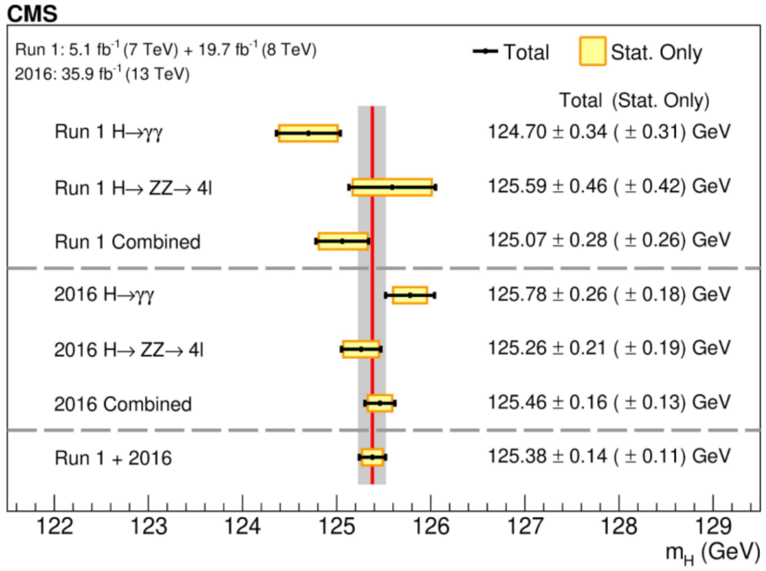
- LHC is a Higgs factory: The dominant theoretical uncertainties for the determination of the Higgs boson couplings [1610.07922 [hep-ph]].

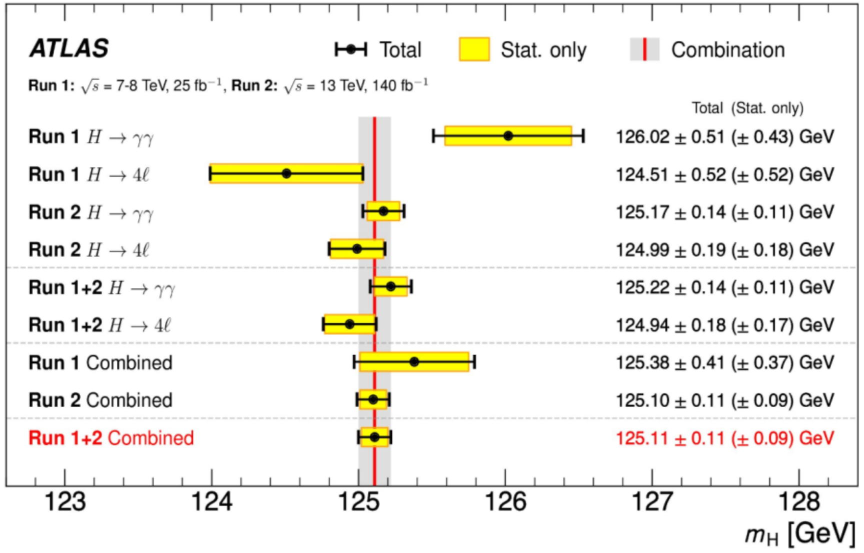
- LHC is a SM precision machine: The measurement of precision SM parameters at hadron colliders, such as the W mass [Phys. Rev. D 91 (11) (2015) 113005] or the strong coupling constant [Eur. Phys. J. C 75 (6) (2015) 288].

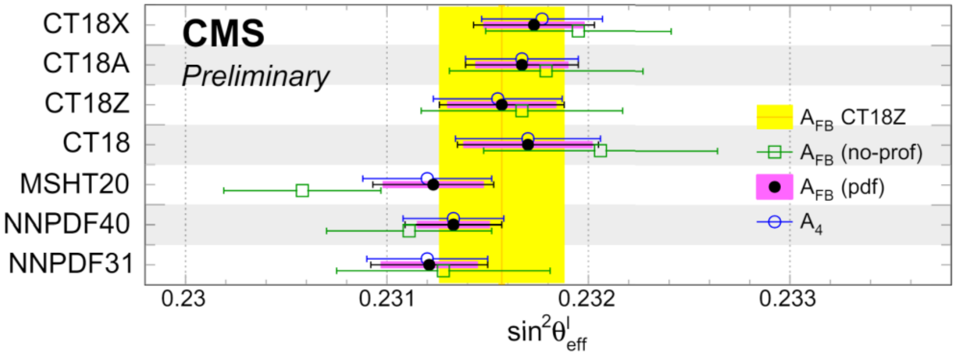
Why do we care about PDFs for the LHC phenomenology?

- The LHC is SM precision machine, top quark/Higgs boson factory, and a BSM search machine.









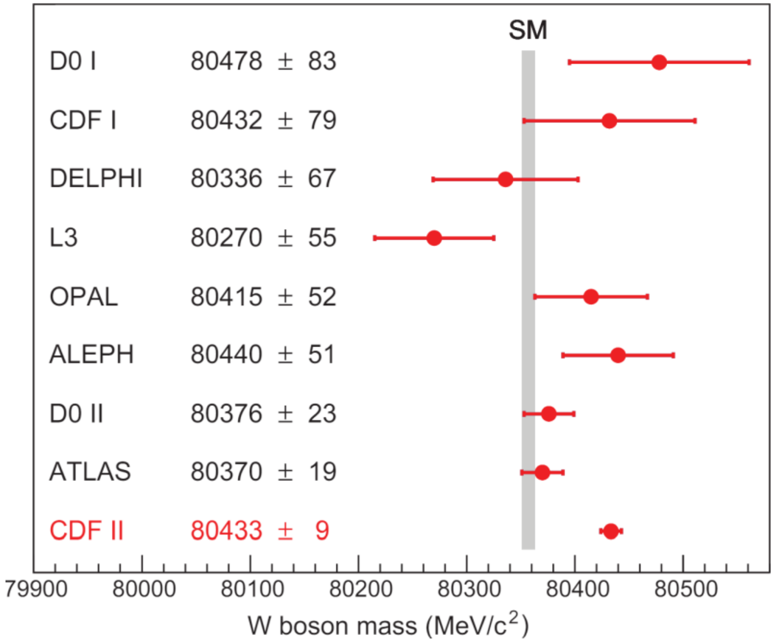
A precise measurement of the effective leptonic electroweak mixing angle [CMS-PAS-SMP-22-010]

Using the CT18Z set of parton densities, the result is:

$$\sin^2\theta^{\ell}_{\rm eff} = 0.23157 \pm 0.00010\,({\rm stat}) \pm 0.00015\,({\rm syst}) \pm 0.00009\,({\rm theo}) \pm 0.00027({\rm PDF})$$

The total uncertainty, dominated by the PDF term=0.00031

$$\sigma_{\rm PDF} \sim \sigma_{\rm tot}$$



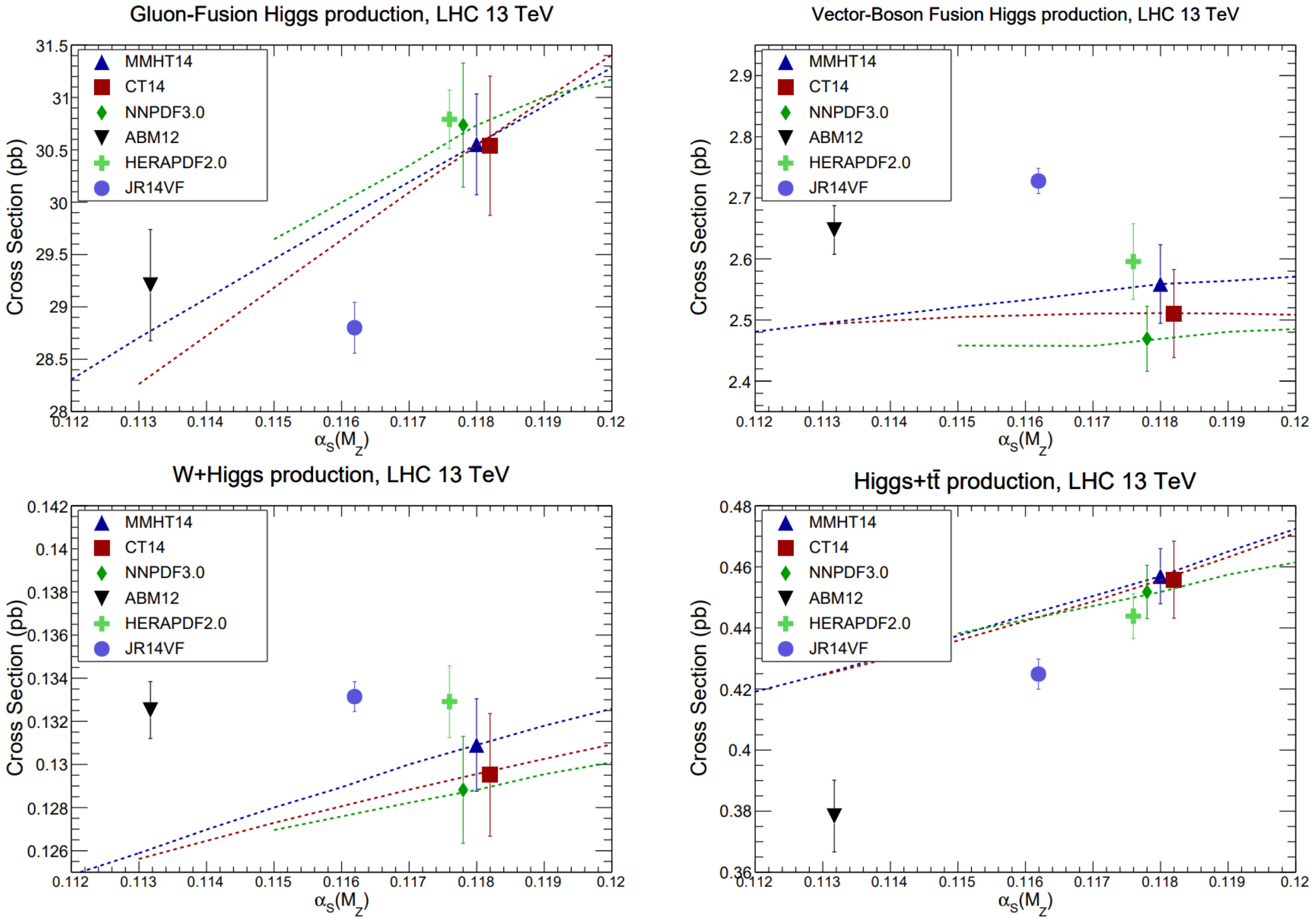
High-precision measurement of the W boson mass with the CDF II detector [*Science* 376 (2022) 6589, 170-176].

Set	$\sigma_{\rm PDF,base}$ [MeV]	$\sigma_{\rm PDF,\alpha_s}$ [MeV]	$\sigma_{\rm PDF}$ [MeV]
NNPDF3.1	8.3	2.4	8.6
CT18	11.5	1.4	11.6
MSHT20	6.5	2.1	6.8

Measurement of the W boson mass [The LHCb collaboration, JHEP 01 (2022) 036]

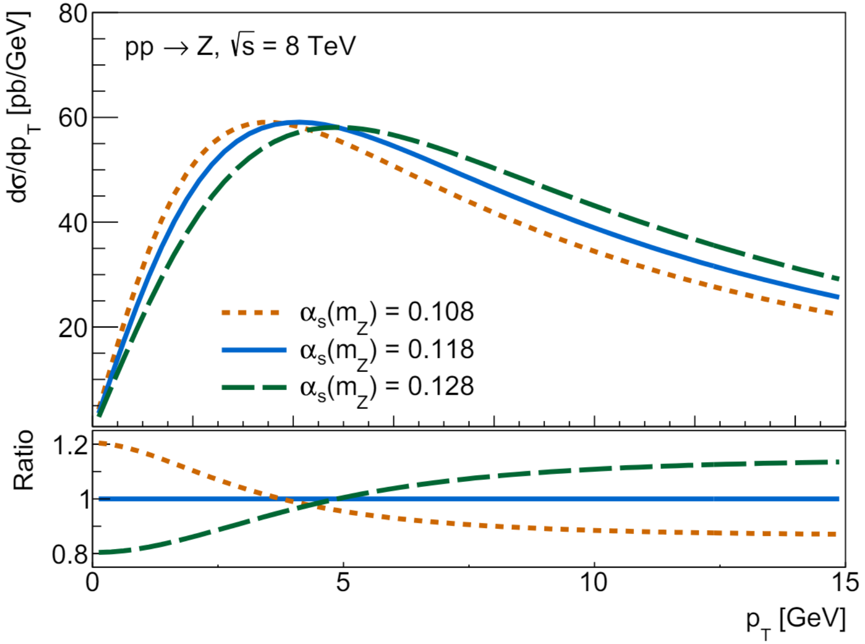
$$m_W = 80354 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 9_{\rm PDF}\ {\rm MeV}$$

Uncertainty due to the choice of $\alpha_S(M_Z)$

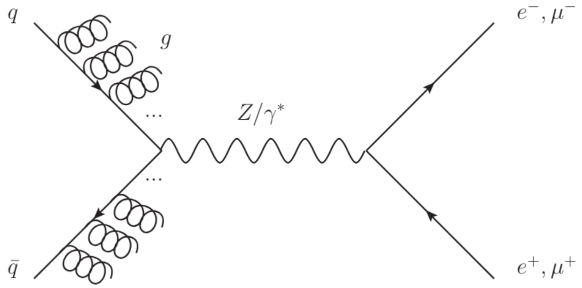


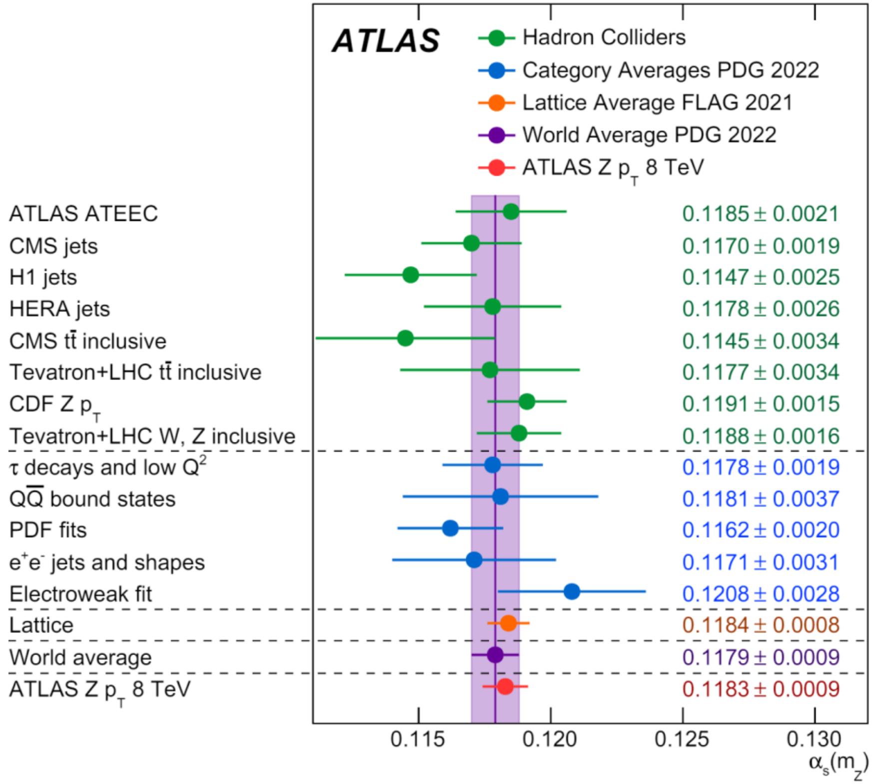
Dependence of the total inclusive cross-sections for Higgs boson production at 13 TeV in different production channel on the value of the strong coupling.

Handbook of LHC Higgs cross sections, arXiv:1610.07922



Transverse-momentum distribution of Z bosons at different values of $\alpha_s(m_Z)$, using the MSHT20 PDF set.





ATLAS Collaboration, arXiv:2309.12986

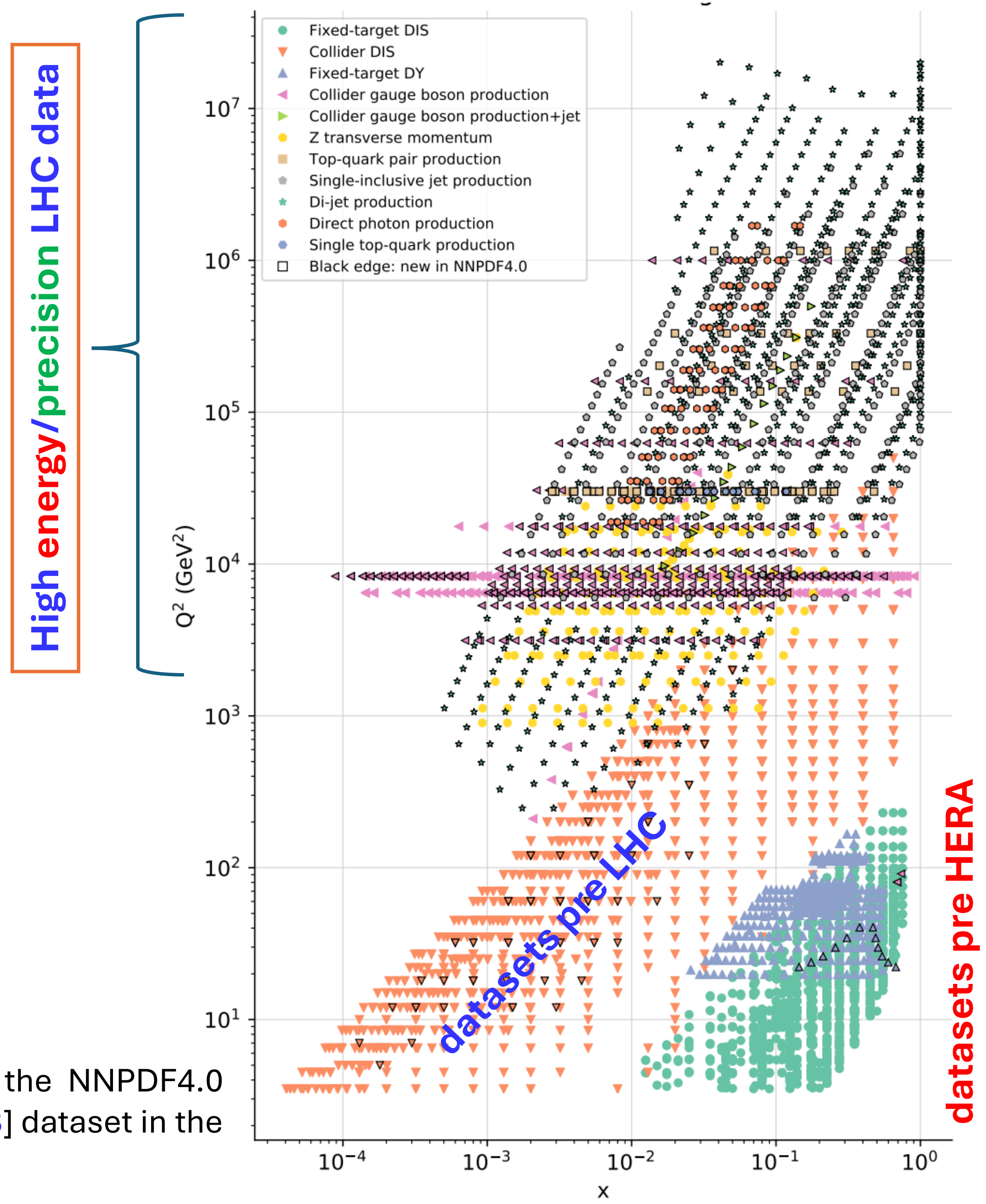
Impact of LHC data

- HERA data crucial to constrain quark valence (up and to less extent down valence) across intermediate to small *x* and gluon at small *x*.

- LHC high energy data crucial to provide additional constraints to PDFs, in particular in medium- to large-*x* gluon and quarks.

- Impressive range of precise cross section measurements & huge progress in theoretical calculations → Precise determination of proton PDFs.

- NNPDF4.0: About 30% of input data are LHC data!



The kinematic coverage of the NNPDF4.0 [Eur. Phys. J. C 82 (2022) 428] dataset in the (x, Q^2) plan.

LHC experimental constraints on PDFs: flavour decomposition

	Process	Subprocess	Partons	x range
Fixed Target	$\ell^\pm \{p,n\} \to \ell^\pm + X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm + X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu})N \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^-\mu^+ + X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+\mu^- + X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
Collider DIS	$e^\pm p \to e^\pm + X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} + X$	$W^+ \{d, s\} \to \{u, c\}$	d, s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c} + X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to e^\pm b\bar{b} + X$	$\gamma^* b \to b, \gamma^* g \to b\bar{b}$	b, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
Tevatron	$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm \nu) + X$	$ud \to W^+, \bar{u}\bar{d} \to W^-$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-) + X$	$uu, dd \to Z$	u, d	$x \gtrsim 0.05$
	$p\bar{p} \to t\bar{t} + X$	$qq \to t\bar{t}$	q	$x \gtrsim 0.1$
LHC	$pp \to \text{jet} + X$	$gg, qg, q\bar{q} \to 2j$	g, q	$0.001 \lesssim x \lesssim 0.5$
	$pp \to (W^\pm \to \ell^\pm \nu) + X$	$u\bar{d} \to W^+, d\bar{u} \to W^-$	$u, d, \bar{u}, \bar{d}, g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X$	$q\bar{q} \to Z$	$q, \bar{q}, g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X, p_\perp$	$gq(\bar{q}) \to Zq(\bar{q})$	$g, q, \bar{q}$	$x \gtrsim 0.01$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, Low mass	$q\bar{q} \to \gamma^*$	$q, \bar{q}, g$	$x \gtrsim 10^{-4}$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, High mass	$q\bar{q} \to \gamma^*$	$\bar{q}$	$x \gtrsim 0.1$
	$pp \to W^+\bar{c}, W^-c$	$sg \to W^+c, \bar{s}g \to W^-\bar{c}$	$s, \bar{s}$	$x \sim 0.01$
	$pp \to t\bar{t} + X$	$gg \to t\bar{t}$	g	$x \gtrsim 0.01$
	$pp \to D, B + X$	$gg \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to J/\psi, \Upsilon + pp$	$\gamma^*(gg) \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to \gamma + X$	$gq(\bar{q}) \to \gamma q(\bar{q})$	g	$x \gtrsim 0.005$

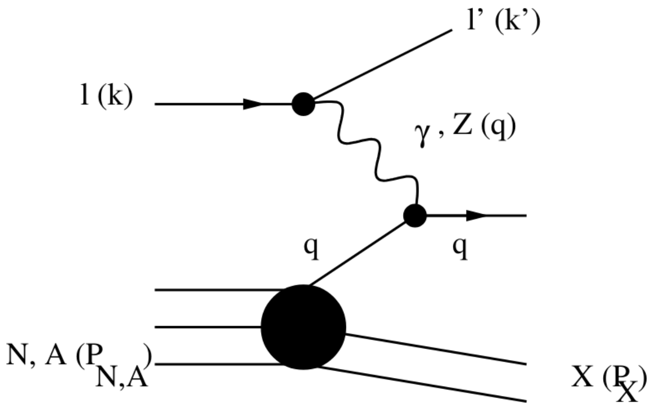
High energy/precision LHC data

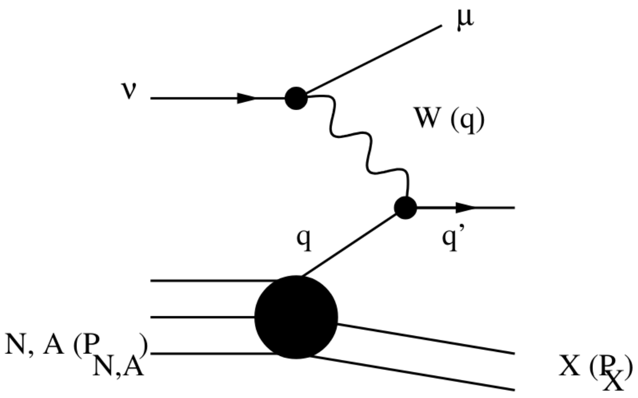
Overview of the various hard-scattering processes which are used to constrain PDFs in a global analysis.

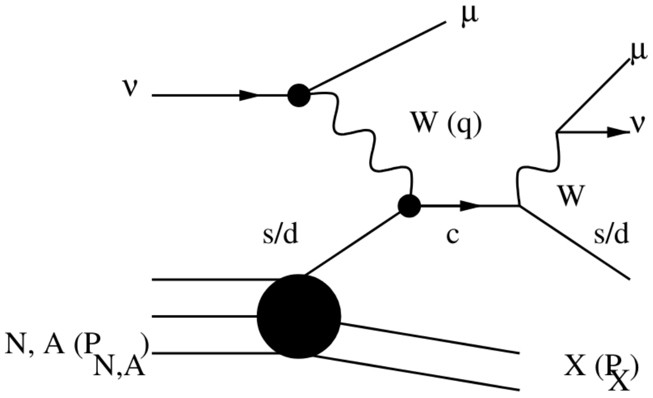
Nuclear PDFs after the first decade of LHC Data

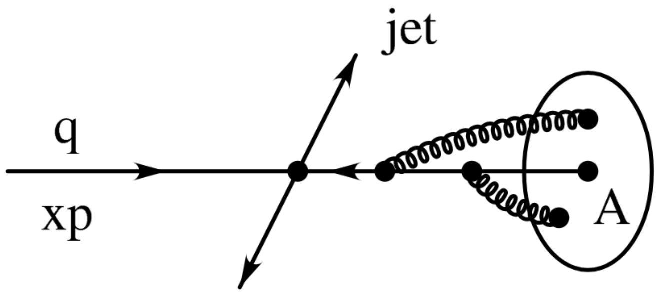
Nuclear DIS and nuclear PDFs

○ Nuclear Deep-Inelastic Scattering (DIS) & Hadronic collisions









M. Klasen @ DIS 2024

Nuclear structure function(s) in nuclear DIS

- Nuclear structure function(s) in nuclear DIS:

$$F_2^A(x, Q^2) = \sum_i f_i^{(A,Z)}(x, Q^2) \otimes C_{2,i}(x, Q^2)$$

Nuclear PDFs

Proton PDFs

$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q)$$

Nuclear Modification Factor

- QCD factorization theorem, Wilson coefficients, …

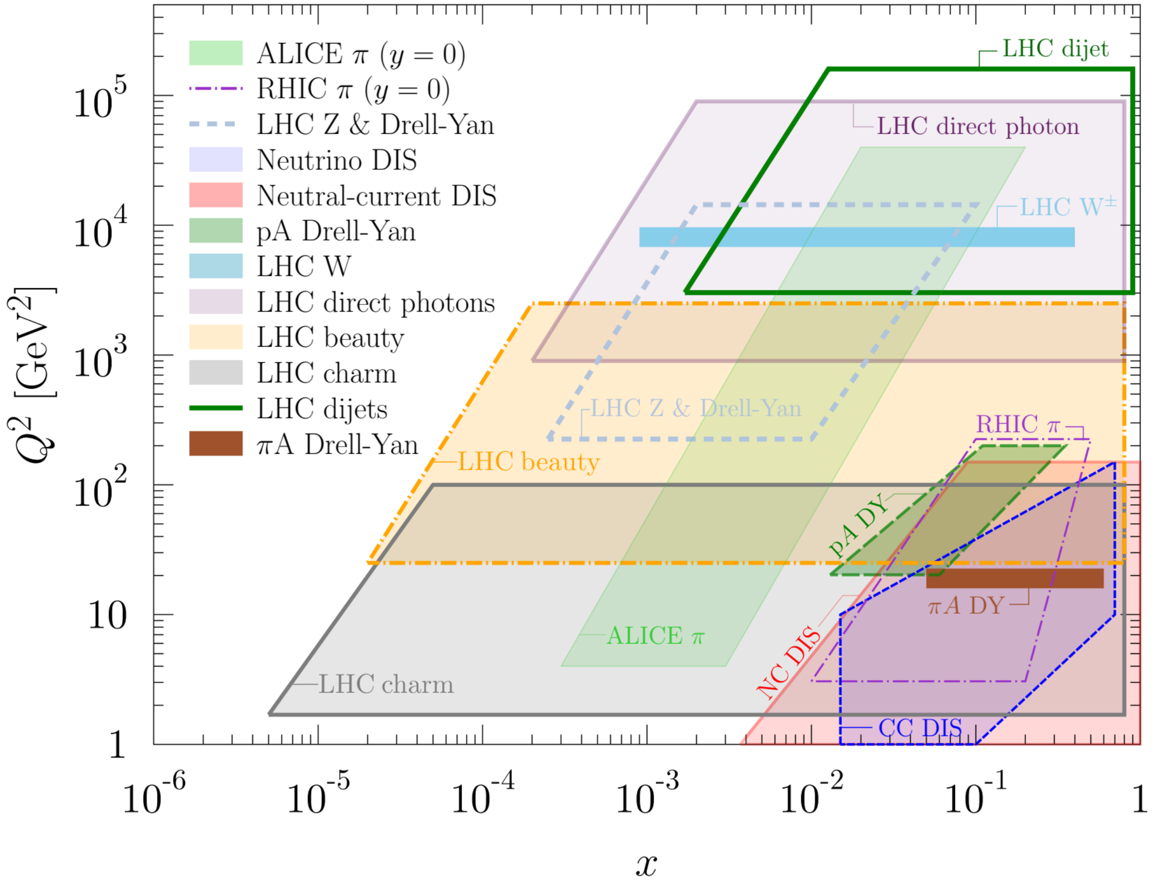
- Nuclear parton density functions (nPDFs): $f_i^{(A,Z)}(x, Q^2) = \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2)$

- DGLAP evolution equations: $\frac{\partial f_i(x, Q^2)}{\partial \log Q^2} = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) f_j(z, Q^2)$

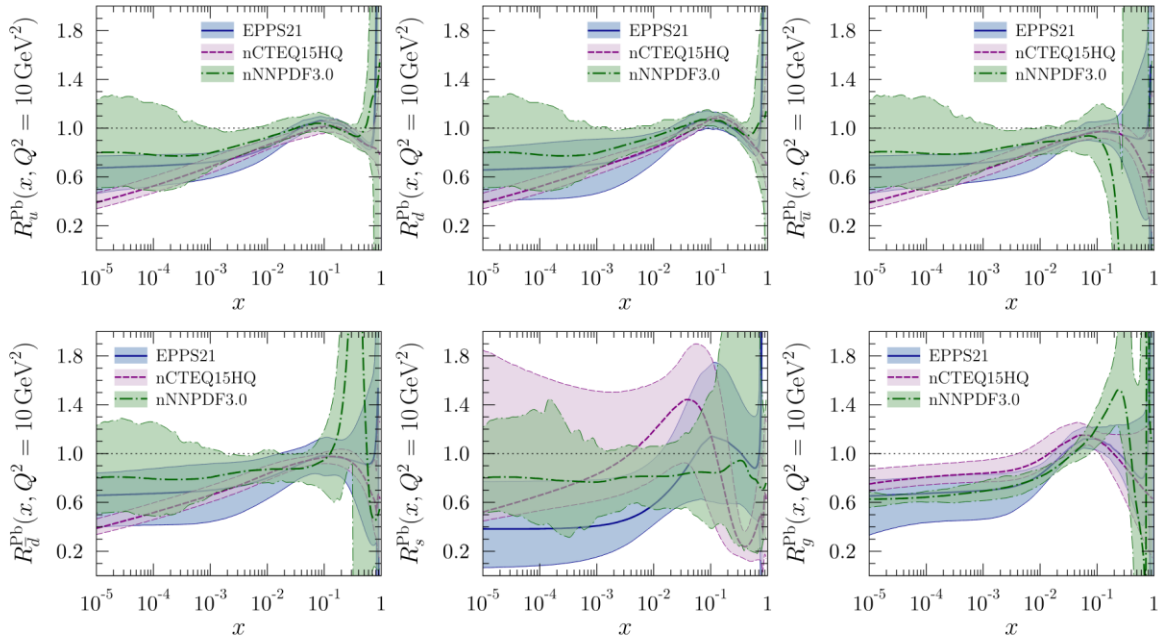
Theoretical input and experimental data

Analysis	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KSASG20
Theoretical input:					
Perturbative order	NLO	NLO	NLO	NNLO	NNLO
Heavy-quark scheme	SACOT$-\chi$	SACOT$-\chi$	FONLL	FONLL	FONLL
Data points	1484	2077	2188	2410	4353
Independent flavors	5	6	6	4	3
Free parameters	19	24	256	16	18
Error analysis	Hessian	Hessian	Monte Carlo	Hessian	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 33$	N/A	$\Delta\chi^2 = 50$	$\Delta\chi^2 = 20$
Proton PDF	∼CTEQ6.1	CT18A	∼NNPDF4.0	∼HERAPDF2.0	CT18
Deuteron corrections	(✓)[a,b]	✓[c]	✓	✓	✓
Fixed-target data:					
SLAC/EMC/NMC NC DIS	✓	✓	✓	✓	✓
– Cut on Q^2	4 GeV^2	1.69 GeV^2	3.5 GeV^2	3.5 GeV^2	1.2 GeV^2
– Cut on W^2	12.25 GeV^2	3.24 GeV^2	12.5 GeV^2	12.0 GeV^2	
JLab NC DIS	(✓)[a]	✓			✓
CHORUS/CDHSW CC DIS	(✓/-)[b]	✓/-	✓/-	✓/✓	✓/✓
NuTeV/CCFR 2μ CC DIS	(✓/✓)[b]		✓/-		
pA DY	✓	✓	✓		✓
Collider data:					
Z bosons	✓	✓	✓	✓	
$W^{\pm}$ bosons	✓	✓	✓	✓	
Light hadrons	✓	✓[d]			
Jets		✓	✓		
Prompt photons			✓		
Prompt D^0	✓	✓	✓[e]		
Quarkonia (J/ψ, ψ', Υ)	✓				

Nuclear PDFs after the first decade of LHC Data



An illustration of the x and Q^2 regions probed by the current lepton-A, pion-A and proton-A data included in the global analyses of nuclear PDFs.



MK, H. Paukkunen, Nuclear PDFs after 10 years of LHC data, Ann. Rev. Nucl. Part. Sci. (2024) [2311.00450]

LHeC: A post HERA collider !?

The Large Hadron-Electron Collider (LHeC)

- The LHeC is designed to move the field of DIS to the energy and intensity frontier of particle physics & LHeC Luminosity ≈ **1000** × HERA

- It collides electron beam with a proton or ion beam from the High Luminosity–Large Hadron Collider (HL-LHC).

- It extends the accessible kinematic range in lepton-nucleon and lepton-nucleus scattering by several orders of magnitude.

- Due to enhanced luminosity, large energy and the clean hadronic final states, the LHeC has a strong Higgs physics program and its own discovery potential for New Physics & Very powerful lab for Electroweak Physics ⇉ LHeC is NOT just a DIS super-collider.

The Large Hadron-Electron Collider at the HL-LHC, arXiv:2007.14491 [hep-ex], J. Phys. G 48 (2021) 110501.

Electron-Proton Collisions at the LHeC/EIC/FCC-eh

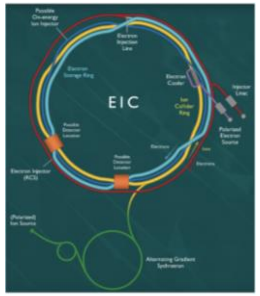
- Another DIS option is studied as part of the possible Future Circular Collider (FCC) at CERN, the FCC-eh [Eur. Phys. J. C 79 (2019) 474], and will reach center-of-mass energies still higher than at the LHeC.

- At Brookhaven, the EIC is under development to perform DIS measurements at lower energies but with higher luminosities than were achieved at HERA [Nuclear Physics A 1026 (2022) 122447].

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23	8	15

Summary of luminosity parameter values for the LHeC and FCC-eh.

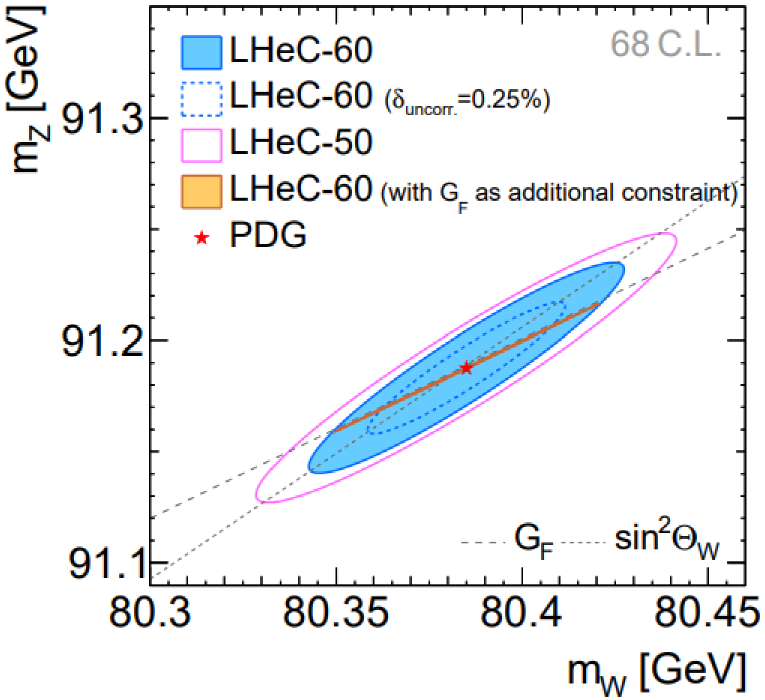
arXiv:1206.2913, J. Phys. G 39 (2012) 075001.
arXiv:2007.14491 [hep-ex], J. Phys. G 48 (2021) 110501.

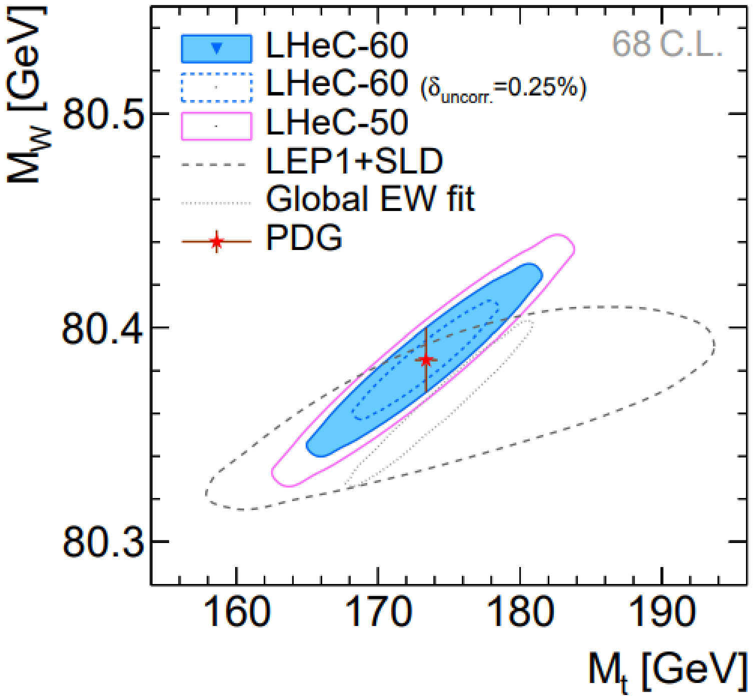


Electroweak Physics at the LHeC

- With LHeC inclusive NC and CC DIS data, unique measurements of electroweak parameters can be performed with highest precision.

Eur Phys J C 80 (2020) 831



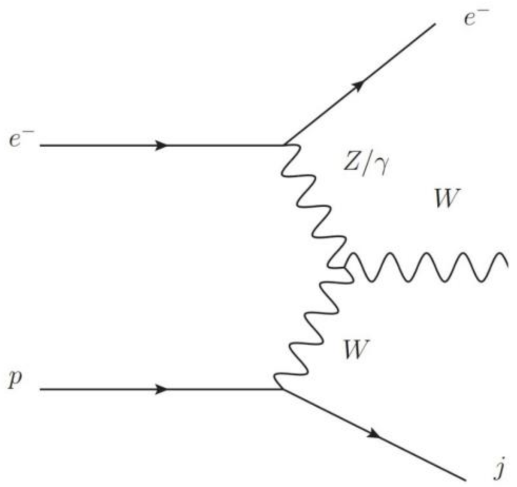


Simultaneous determination of the top-quark mass and W-boson mass from LHeC60 or LHeC-50 data (right).
Simultaneous determination of the W-boson and Z-boson masses from LHeC60 or LHeC-50 data (left).

Direct W and Z Production at the LHeC

- The direct W or Z production in electron-proton collisions can be classified into five processes

Process	$E_e = 50$ GeV, $E_p = 7$ TeV $p_T^e > 10$ GeV	$E_e = 60$ GeV, $E_p = 7$ TeV $p_T^e > 10$ GeV	$E_e = 60$ GeV, $E_p = 7$ TeV $p_T^e > 5$ GeV
$e^- W^+ j$	1.00 pb	1.18 pb	1.60 pb
$e^- W^- j$	0.930 pb	1.11 pb	1.41 pb
$\nu_e^- W^- j$	0.796 pb	0.956 pb	0.956 pb
$\nu_e^- Z j$	0.412 pb	0.502 pb	0.502 pb
$e^- Z j$	0.177 pb	0.204 pb	0.242 pb



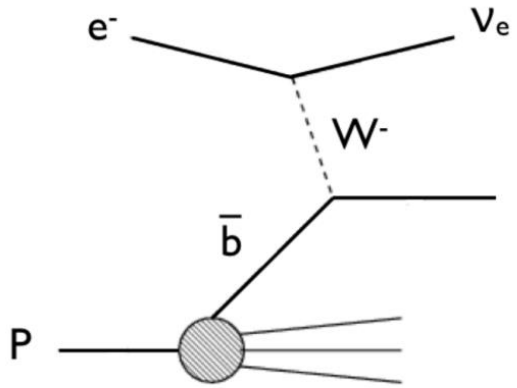
- Study of Tripe Gauge Couplings (TGCs), *e.g.* $WW\gamma$ and WWZ couplings.

Top Quark Physics at the LHeC

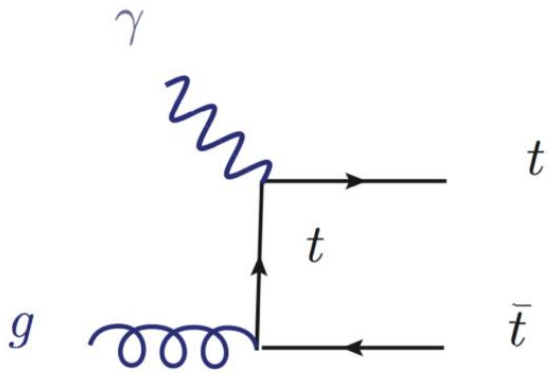
- SM top quark production at a future LHeC collider is dominated by single top quark production, mainly via CC DIS production.

- The total cross section for single top quark production is 1.89 pb at the LHeC and a center-of-mass energy of 1.3 TeV, i.e. with an electron beam energy of 60 GeV and an LHC proton beam of 7 TeV.

- The second important production mode for top quarks at the LHeC is photoproduction of top-antitop quark pairs ($t\bar{t}$), where a total cross section of 0.05 pb is expected at the LHeC.



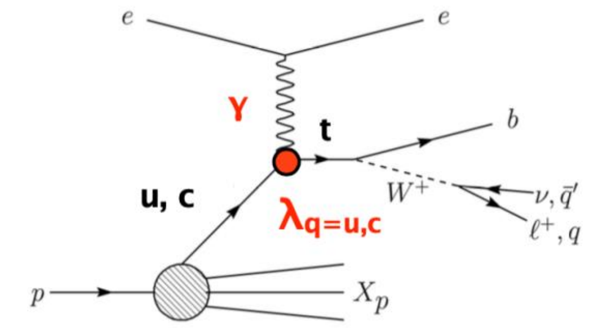
top quark production in CC DIS



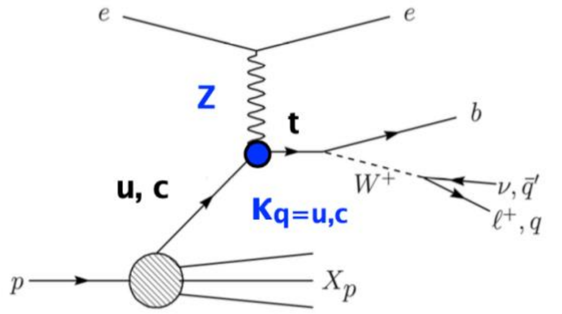
$t\bar{t}$ photoproduction

Top Quark FCNC at the LHeC

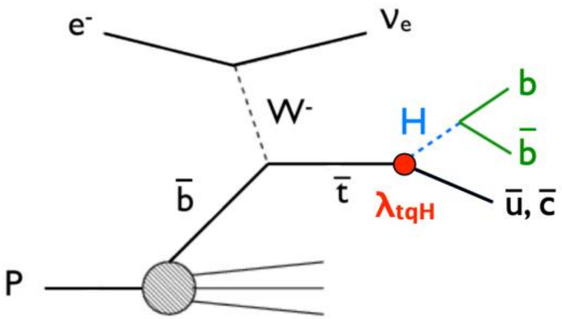
- The top quark Flavour Changing Neutral Currents (FCNCs) interactions are also extremely suppressed in the SM, which renders them a good test of New Physics.



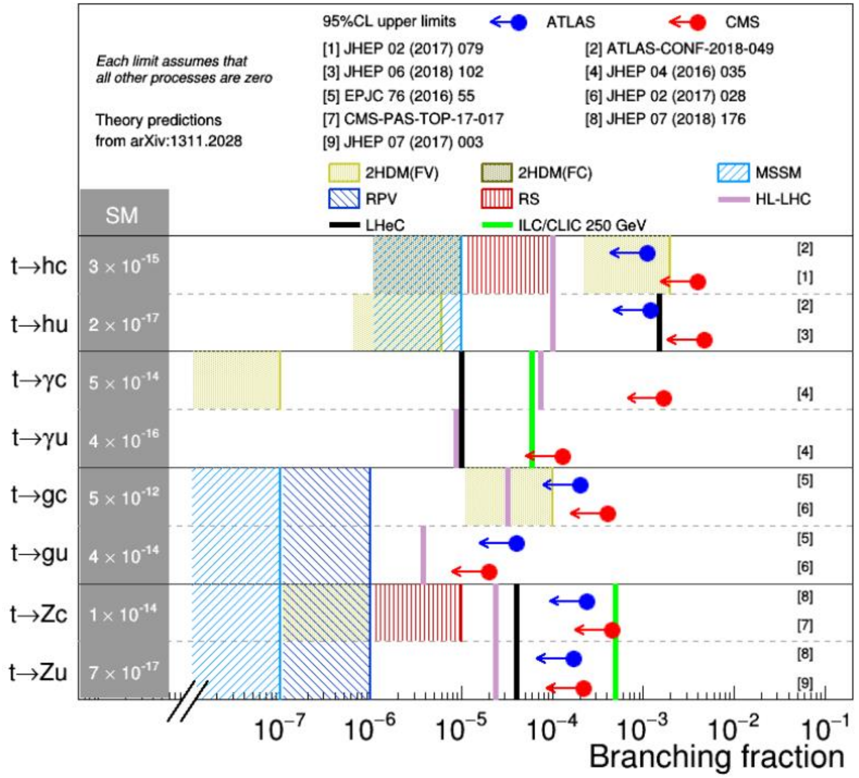
$tq\gamma$



tqZ



tqH

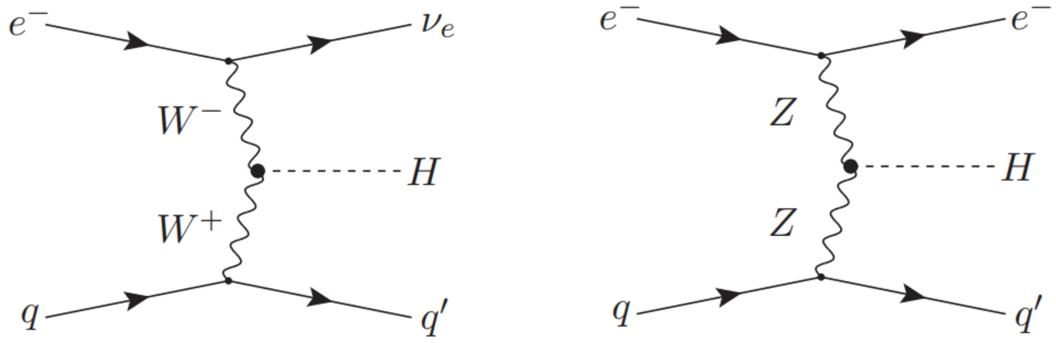


Summary of 95% C.L. limits on top FCNC tqH, tqZ and $tq\gamma$ at the LHeC.

Higgs Physics at the LHeC

- In deep inelastic electron-proton scattering, the Higgs boson is predominantly produced through WW fusion in charged current DIS (CC) scattering.

- The next large Higgs production mode in *ep* is fusion in neutral current DIS (NC) scattering, which has a smaller but still sizable cross section.



Higgs boson production in charged (left) and neutral (right) current DIS

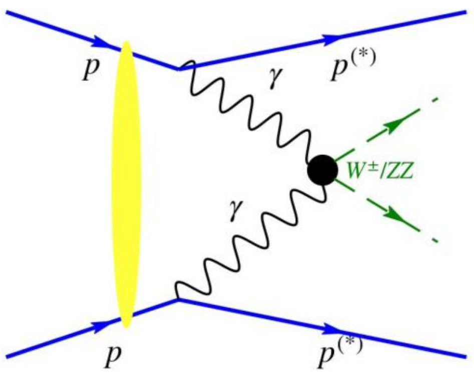
Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46
σ_{CC}	fb	110	206	289	577
σ_{NC}	fb	20	41	64	127

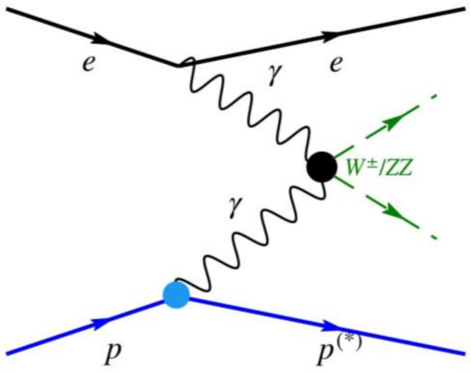
The cross sections for Higgs production in CC and NC DIS electron-proton scattering of a 60 GeV electron beam with protons at three different energies, for LHeC, HE-LHeC and FCC-eh.

High energy $\gamma\gamma$ interactions at the LHeC

K. Piotrzkowski, and Y. Yamazaki, PoS (EPS-HEP2021) 486

- Very high ep luminosity & Clean experimental environment.
- Comprehensive survey of studies of high energy photon-photon interactions at the LHeC, for the $\gamma\gamma$ center-of-mass energy of up to 1 TeV.
- Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC, including in particular the exclusive production of lepton pairs, W and Z bosons as well as pairs of charged supersymmetric particles.
- Very high statistics of these processes are expected to achieved at the LHeC.





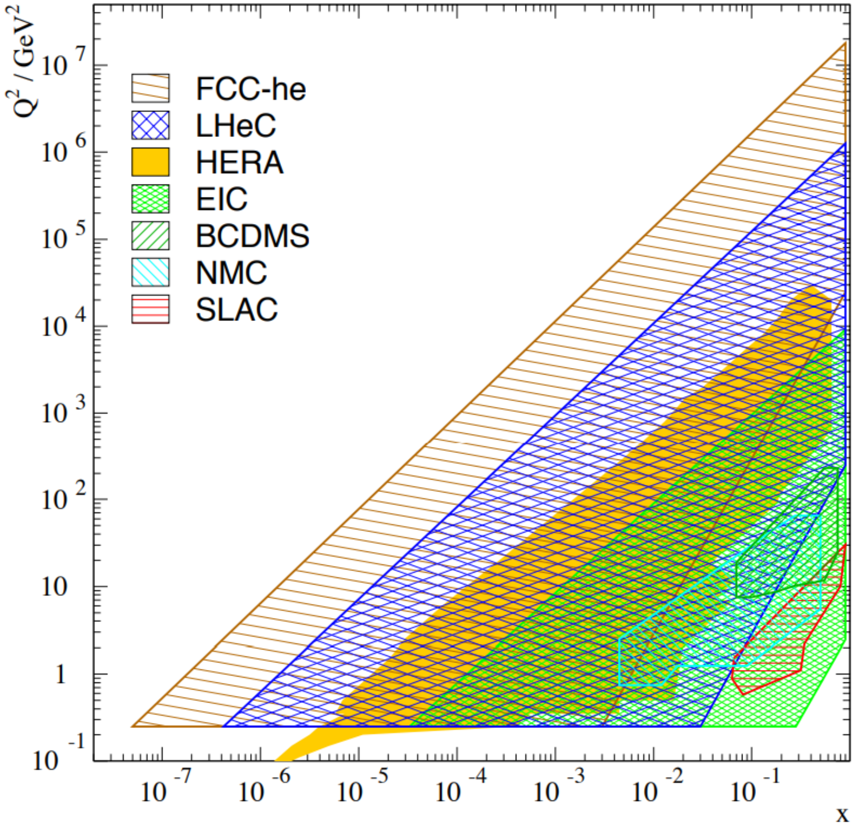
The exclusive W- and Z-boson pair production via photon-photon fusion at the LHC (left) and future LHeC (right).

Extensive DIS and QCD program at the LHeC

- DIS stands to enter a golden age with the prospect of precision programs at the EIC and LHeC.
- Clarification of the parton interaction dynamics at very small and large Bjorken x.
- Precision DIS for HEP at the LHeC
- LHeC → Highly constraining datasets for PDFs fits

arXiv:2202.08286, J. Phys. G: Nucl. Part. Phys. 48 (2021) 110501

Coverage of the kinematic plane in deep inelastic lepton-proton scattering.



Simulated LHeC data & PDFs

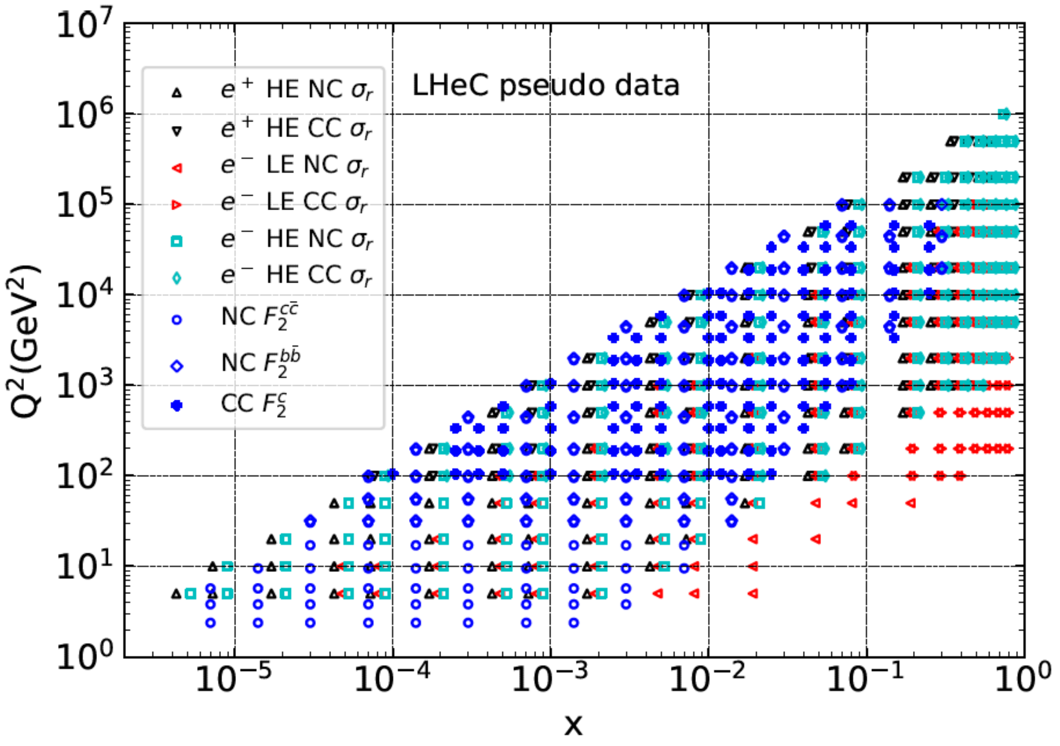
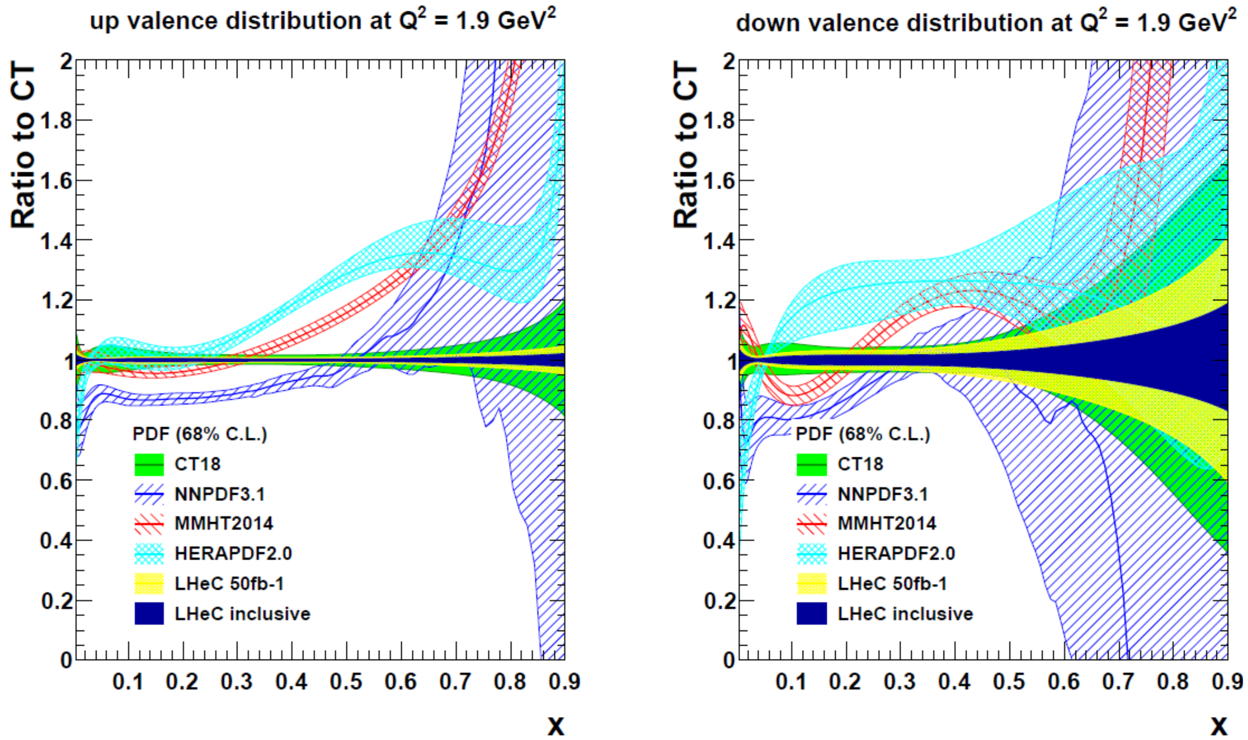


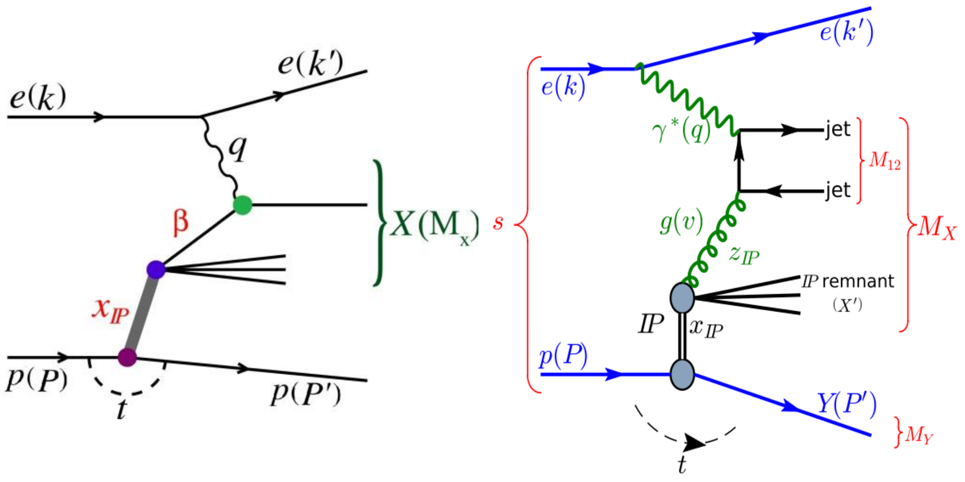
Illustration of the x and Q^2 values of simulated cross section and heavy quark density data used in LHeC studies.



Valence quark distributions at Q^2= 1.9 GeV^2 as a function of x, presented as the ratio to the CT18 central values.

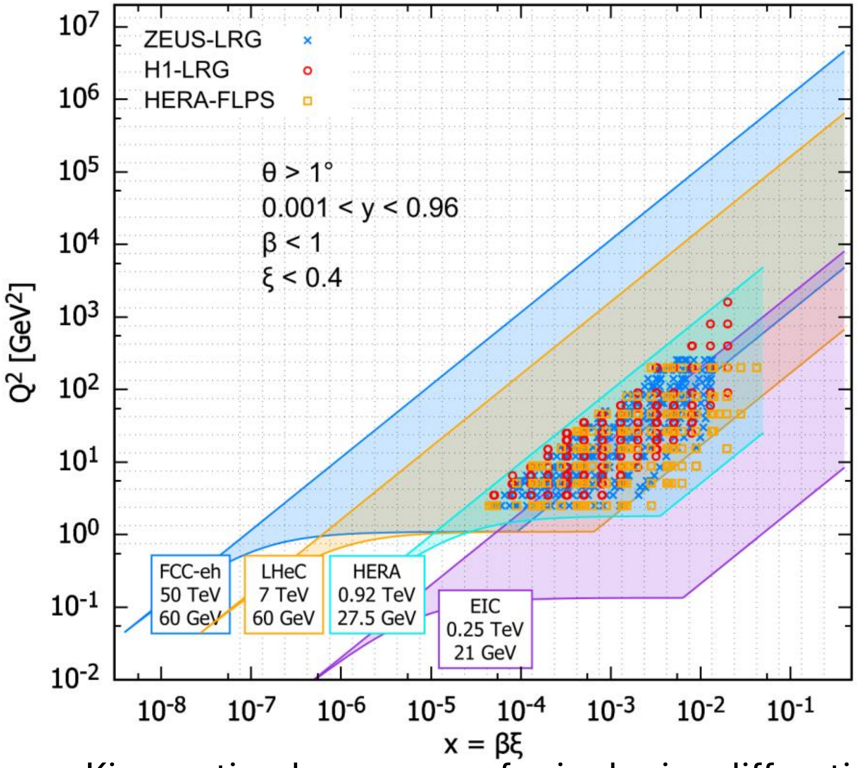
Diffractive DIS at the LHeC

- Seminal potential for diffractive DIS at LHeC.



Diffractive DIS (left) and dijet (right) production at LHeC.

2206.13788 [hep-ph]; 2301.10284 [hep-ph].

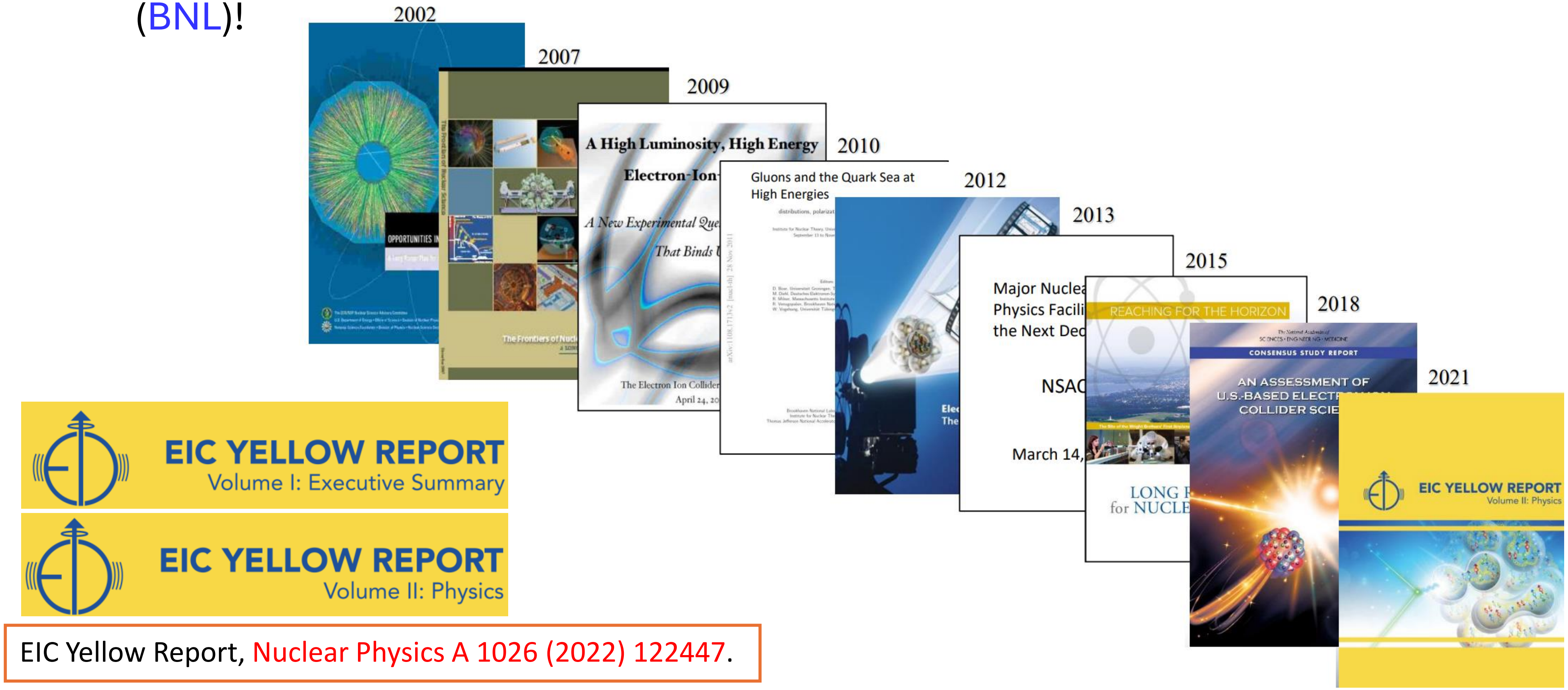


Kinematic phase space for inclusive diffraction in (x, Q^2) for the EIC, the LHeC, and the FCC-eh as compared with the HERA data.

What will we learn from EIC?

Future High-Luminosity Electron-Ion Collider (EIC)

- A unique high-energy and high-luminosity polarized collider that will be one of the most challenging and exciting accelerator complexes ever built! Brookhaven National Laboratory (BNL)!



EIC Yellow Report, Nuclear Physics A 1026 (2022) 122447.

Key science questions that the EIC will address

- How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?
- How are partons inside the nucleon distributed in both momentum and position space?
- Precision QCD?
- Multi-dimensional nucleon tomography and the 3D parton structure (GPDs)?
- Challenges and opportunities via exclusive production of lepton pairs ($\mu^{\pm}$ & $\tau^{\pm}$) at EIC.
- Specific machine parameters and detector requirements needed to address them!

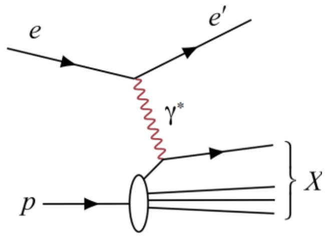
EIC Yellow Report, Nuclear Physics A 1026 (2022) 122447.

Why EIC is unique among other DIS Facilities ?

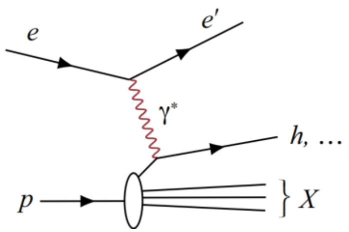
- Four different categories of processes at EIC

- Inclusive DIS: high-precison measurement of scattered electron.
- Diffraction in the ep or e⁺A collisions.
- Exclusive processes (diffraction) - all particles are identified.
- The best place to study diffraction in 21th century.
- Polarized lepton & hadron beams & (polarized) nuclear beams.
- Polarized beams will allow to study spin-dependent SF.
- e⁺A DIS will allow to directly measure modifications to the nucleon SF.

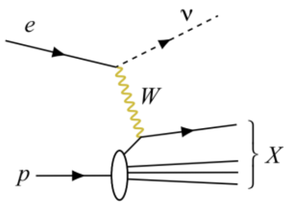
Neutral-current Inclusive DIS: $e + p/A \longrightarrow e' + X$; for this process, it is essential to detect the scattered electron, e', with high precision. All other final state particles (X) are ignored. The scattered electron is critical for all processes to determine the event kinematics.



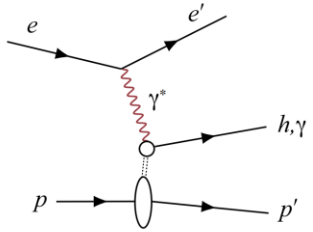
Semi-inclusive DIS: $e + p/A \longrightarrow e' + h^{\pm,0} + X$, which requires measurement of *at least one* identified hadron in coincidence with the scattered electron.



Charged-current Inclusive DIS: $e + p/A \longrightarrow \nu + X$; at high enough momentum transfer Q^2, the electron-quark interaction is mediated by the exchange of a $W^{\pm}$ gauge boson instead of the virtual photon. In this case the event kinematic cannot be reconstructed from the scattered electron, but needs to be reconstructed from the final state particles.

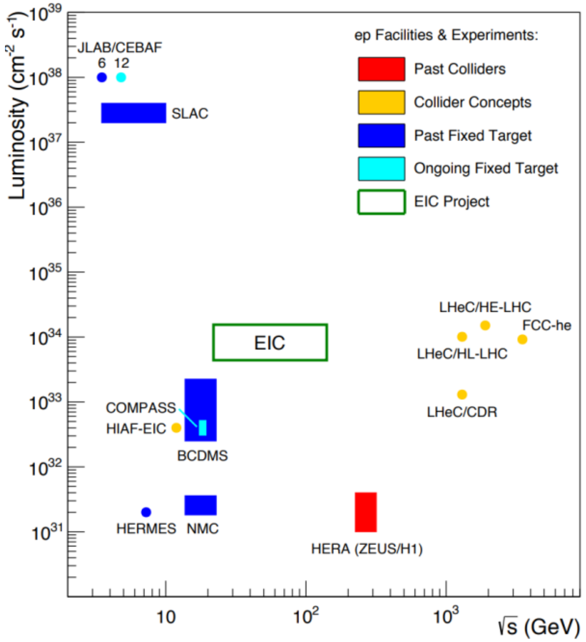


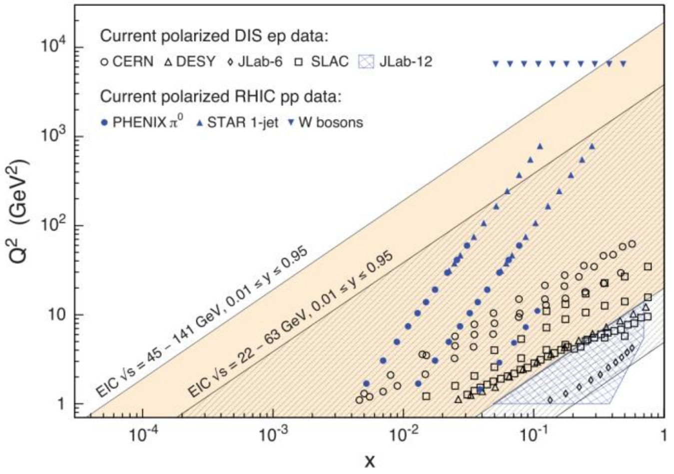
Exclusive DIS: $e + p/A \longrightarrow e' + p'/A' + \gamma/h^{\pm,0}/VM$, which require the measurement of *all* particles in the event with high precision.

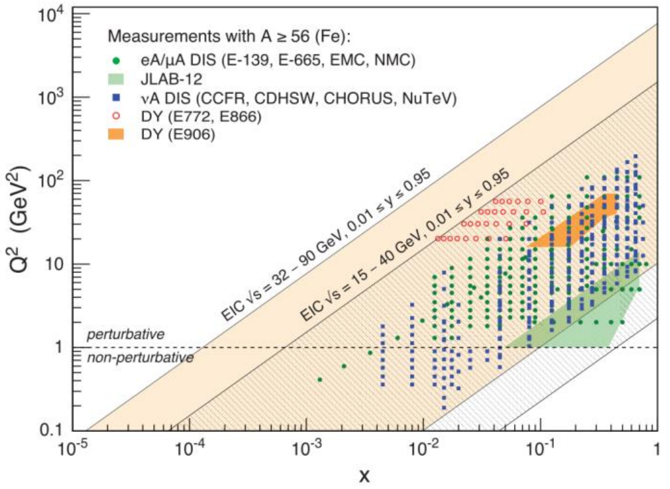


Energy settings and total integrated luminosity

- Two energy settings of the EIC:
- ✓ EIC 1 (electron beam energy E_e = 10 GeV and proton beam energy E_p = 100 GeV)
- ✓ EIC 2 (E_e = 18 GeV and E_p = 275 GeV)
- Total integrated luminosity of the order of 1000 fb^{-1} is expected at the EIC.
- To ensure a wide kinematic reach and a large coverage of phase space, the EIC requires a variable center-of-mass energy in the range of ~ 20 – 100 GeV, upgradable to 140 GeV.
- An energy of 140 GeV is needed to provide sufficient kinematic reach into the gluon dominated regime.
- The lower center-of-mass energy limit is driven by the ability to measure transverse quantities well, which are of the order of 10-100 MeV.
- One of the key detector requirements at low x refers to the precision measurement of the scattered electron's energy (E) demanding good electromagnetic calorimetry.



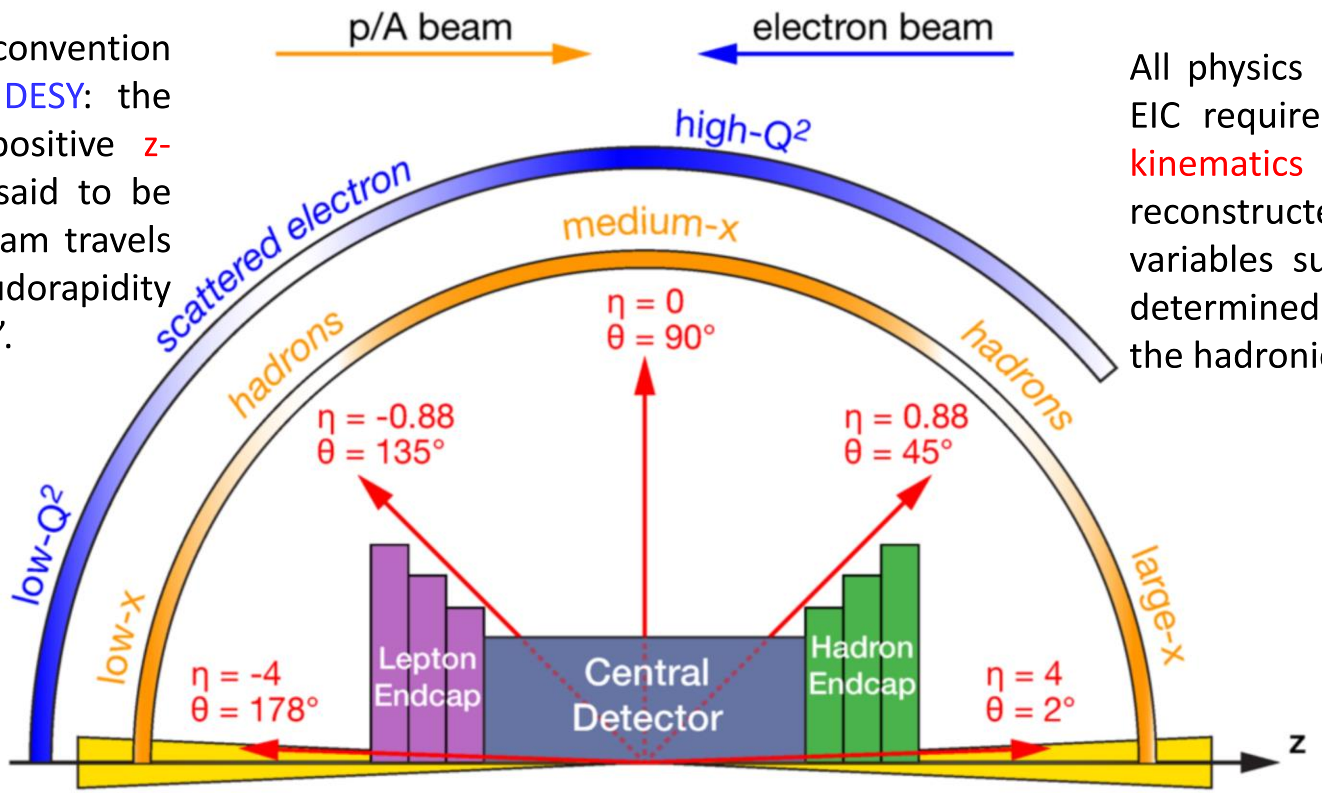




More on the EIC detector concepts: **Mariusz Przybycień**, Zderzacz Elektronowo-Jonowy Nowe narzędzie dla fizyki wysokich energii, Seminarium WFiIS, **27.11.2020**.

Detector Requirements

The beams' directions follow the convention used at the HERA collider at DESY: the hadron beam travels in the positive z-direction/pseudorapidity and is said to be going "forward." The electron beam travels in the negative z-direction/pseudorapidity and is said to be going "backward".



All physics processes to be measured at an EIC require having the event and particle kinematics (x, Q^2, y, W, pT, z, ϕ, θ) reconstructed with high precision. Kinematic variables such as x, Q^2 , y, and W can be determined from the scattered electron or the hadronic final state.

Correlation between polar angle (θ) and pseudorapidity ($\eta = -\ln\tan(\theta/2)$) and the $x - Q^2$ phase space for the EIC physics program.

EIC Yellow Report, Nuclear Physics A 1026 (2022) 122447.

Mariusz Przybycień, Zderzacz Elektronowo-Jonowy Nowe narzędzie dla fizyki wysokich energii, Seminarium WFiIS, 27.11.2020

EIC accessible kinematics (*x*, *y*, and Q^2)

- The quantities x, y, and Q^2 are obtained from measurements of energies and angles of final state objects, *i.e.* the scattered electron, the hadronic final-state or a combination of both.

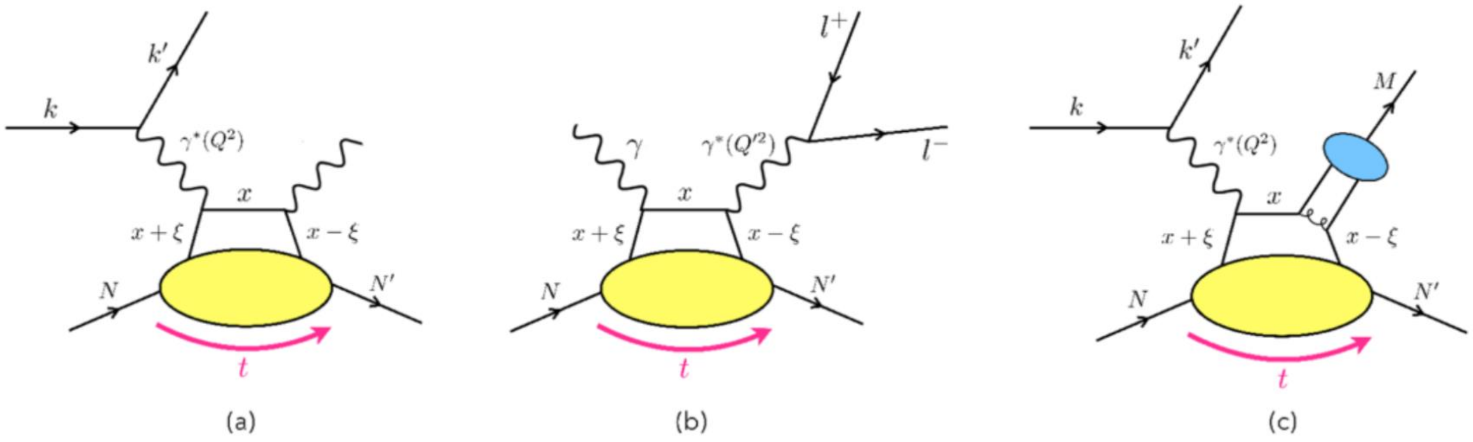
- The EIC will allow in both collider modes an important overlap with present and past experiments. In addition, the EIC will provide access to entirely new regions in both x and Q^2 in a polarized e^+p collider and e^+A collider mode, such as the low-*x* region, providing critical information about the gluon-dominated regime.

- High energy electron-nucleus collisions at the EIC will enable measurements of nuclear PDFs over a broad and continuous range in Q^2 , all the way from photo-production ($Q^2 \sim 0$) to high Q^2 in the perturbative Regime.

- Ion beams of heavy nuclei (Gold, Lead, or Uranium) combined with the highest center-of-mass energy, will provide access to the highest gluon densities. Nuclear PDFs are determined through global fits to existing inclusive DIS data off nuclei.

Multi-Dimensional Imaging of the Nucleon (GPDs)

- The key challenge of nuclear physics is the tomographic imaging of the nucleon, encoded in the Generalized Parton Distributions (GPDs).
- They provide a connection between ordinary PDFs and form factors and hence can describe the correlations between the longitudinal momentum of quarks and gluons and their position in the transverse spatial plane in a nucleon.



Illustrations of three main processes which are sensitive to GPDs: (a) exclusive electroproduction of a real photon (DVCS), (b) Timelike Compton Scattering (TCS) and (c) exclusive electroproduction of a meson (DVMP).

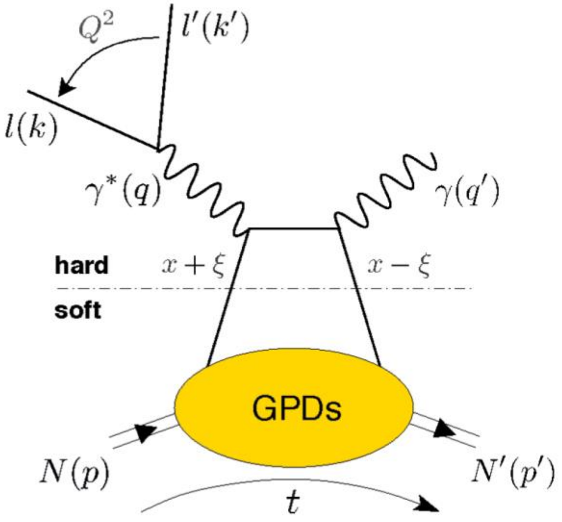
3D structure of nucleon

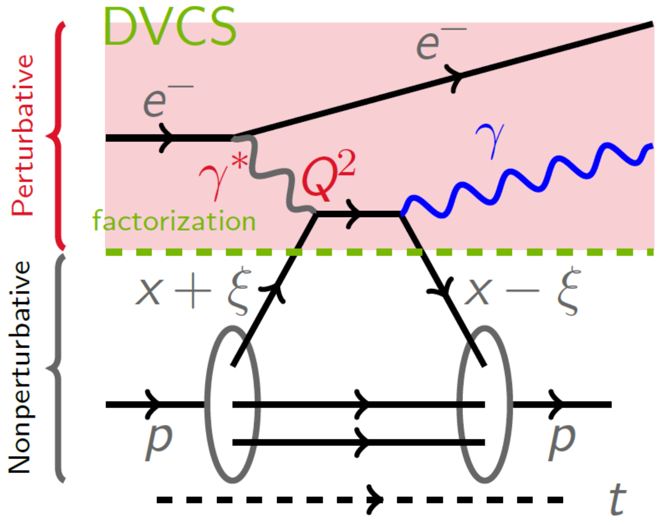
- Three-dimensional (3D) structure of the nucleon has been investigated by generalized parton distributions (GPDs).

✓ Framework for the extraction of 3D parton distributions.

✓ QCD Phenomenology of 3D parton distribution and factorization theorem.

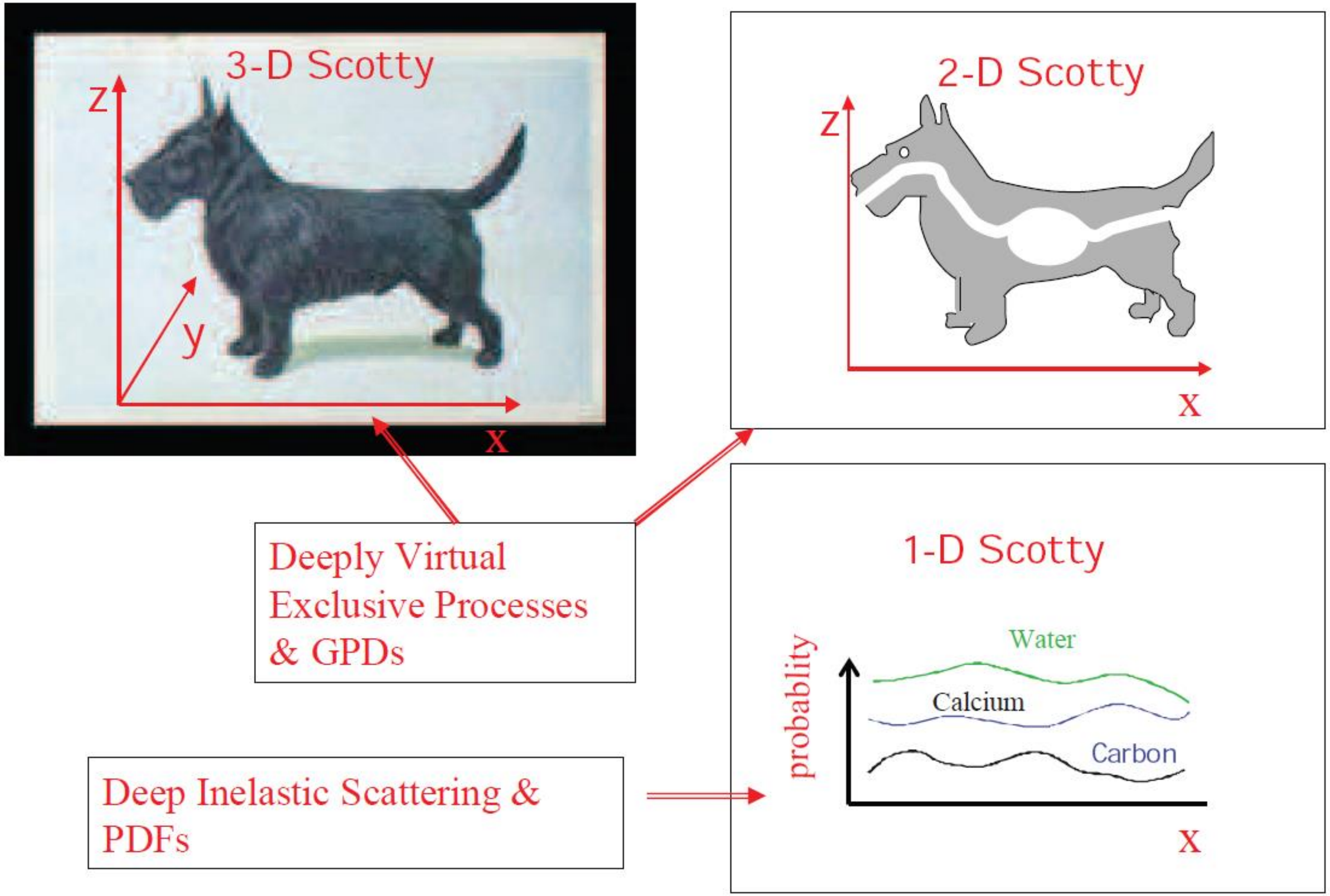
✓ MC generators for global analysis of GPDs.



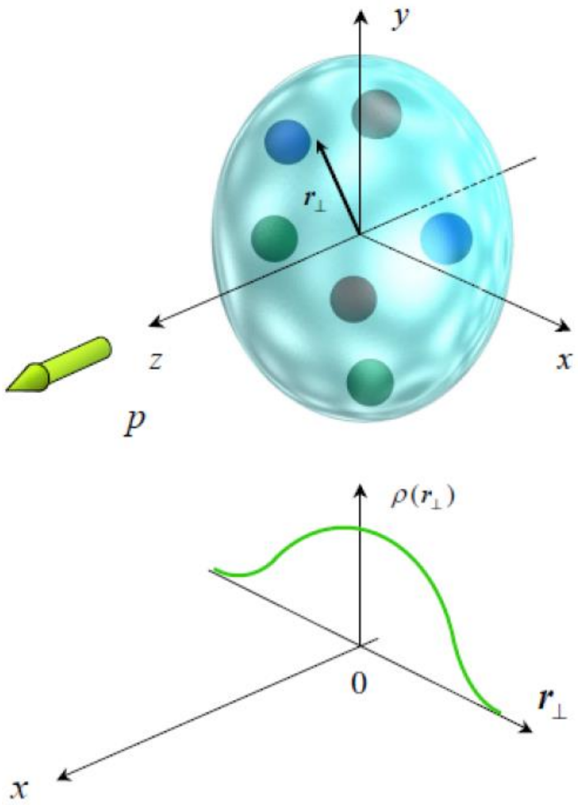


$$\mathcal{H}(\xi, t, Q^2) = \int_{-1}^{1} \frac{\mathrm{d}x}{\xi} \times \boldsymbol{C}(x/\xi, Q^2/\mu^2, \alpha_s(\mu)) H(x, \eta = \xi, t, \mu^2)$$

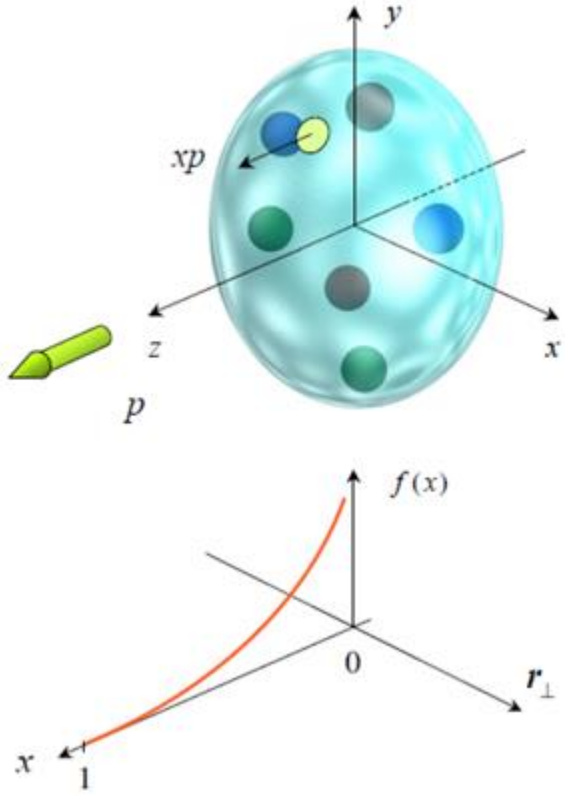
3D structure of hadron I



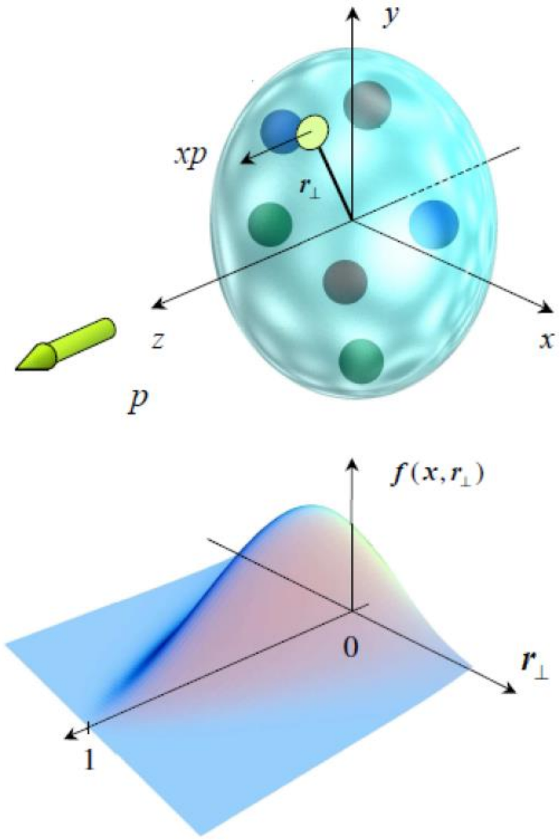
3D structure of hadron II



Elastic Scattering (ES)



Deep Inelastic Scattering (DIS)



Deeply virtual Compton Scattering (DVCS)

Exclusive production of lepton pairs ($\mu^{\pm}$ & $\tau^{\pm}$)

- The two-photon exclusive production of lepton pairs at the EIC will open interesting research directions thanks to a very high luminosity and clean experimental conditions.

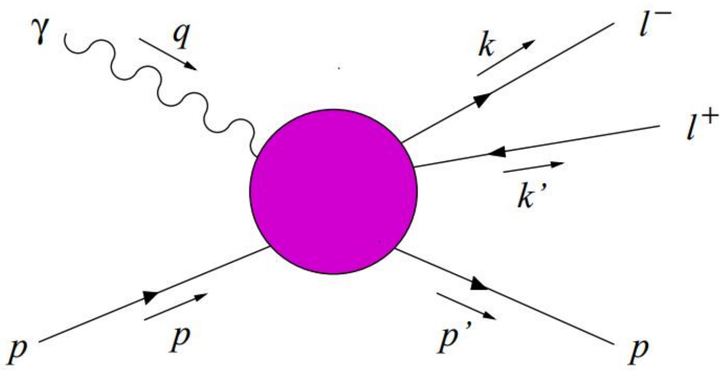
- Two-photon exclusive (Bethe-Heitler) production of lepton pairs in *ep* collisions is usually studied as the main source of background in TCS [CLAS Collaboration; Phys. Rev. Lett. 127 (2021) 262501].

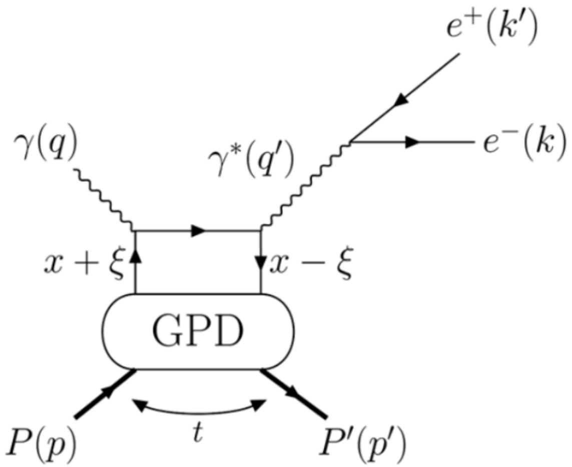
- Thanks to huge *ep* luminosity at the EIC a very large exclusive lepton pair event statistics can be acquired.

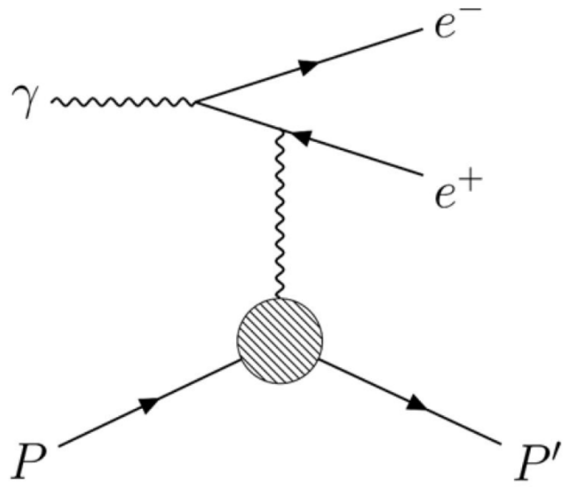
- This will allow to carry out original and very interesting research in which profit from high polarizations of both electron and proton beams as well.

Dilepton production at EIC

- First Measurement of Timelike Compton Scattering, CLAS12 detector at Jefferson Lab [Phys. Rev. Lett. 127, 262501].







(Left) Real photon-proton scattering into a lepton pair and a proton, (Middle) handbag diagram of the TCS process, and (Right) diagram of the BH process.

- Far forward and far backward detectors at EIC will measure hadrons and electrons, respectively, scattered at very small angles - and will allow for selection of pure samples of fully exclusive events.

Precision QCD phenomenology at the EIC

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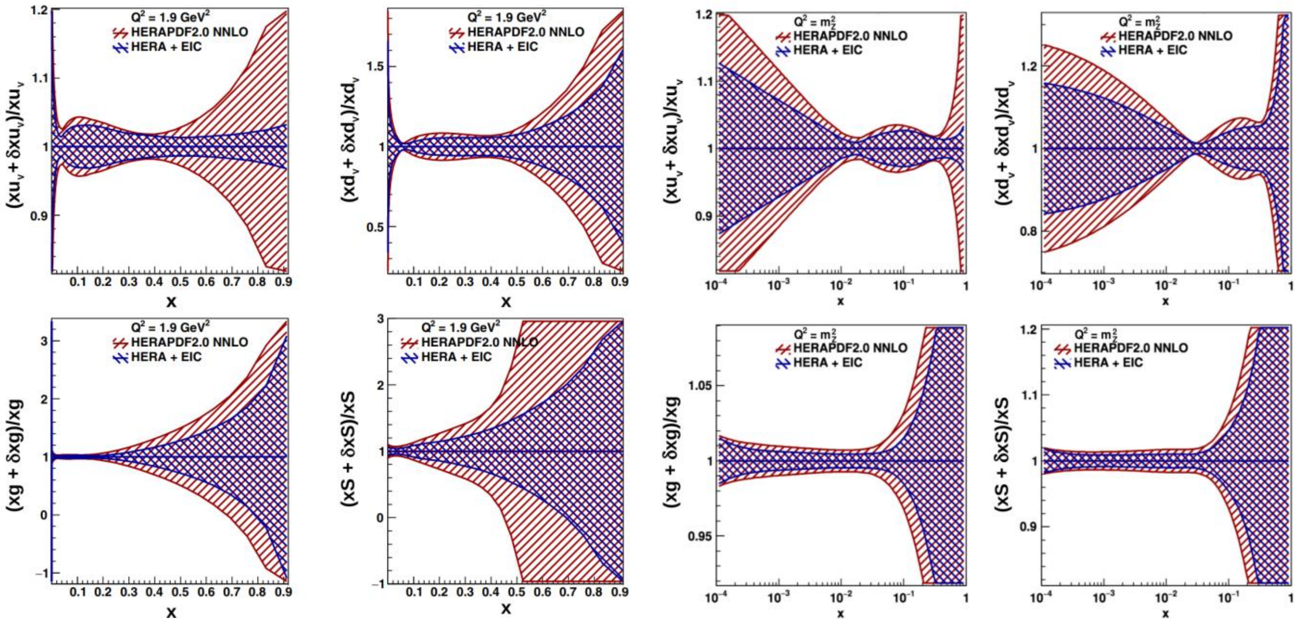
- Precise determination of proton (nuclear) PDFs?
- Precise determination of Strong Coupling Constant?



Impact of inclusive EIC data on proton PDFs

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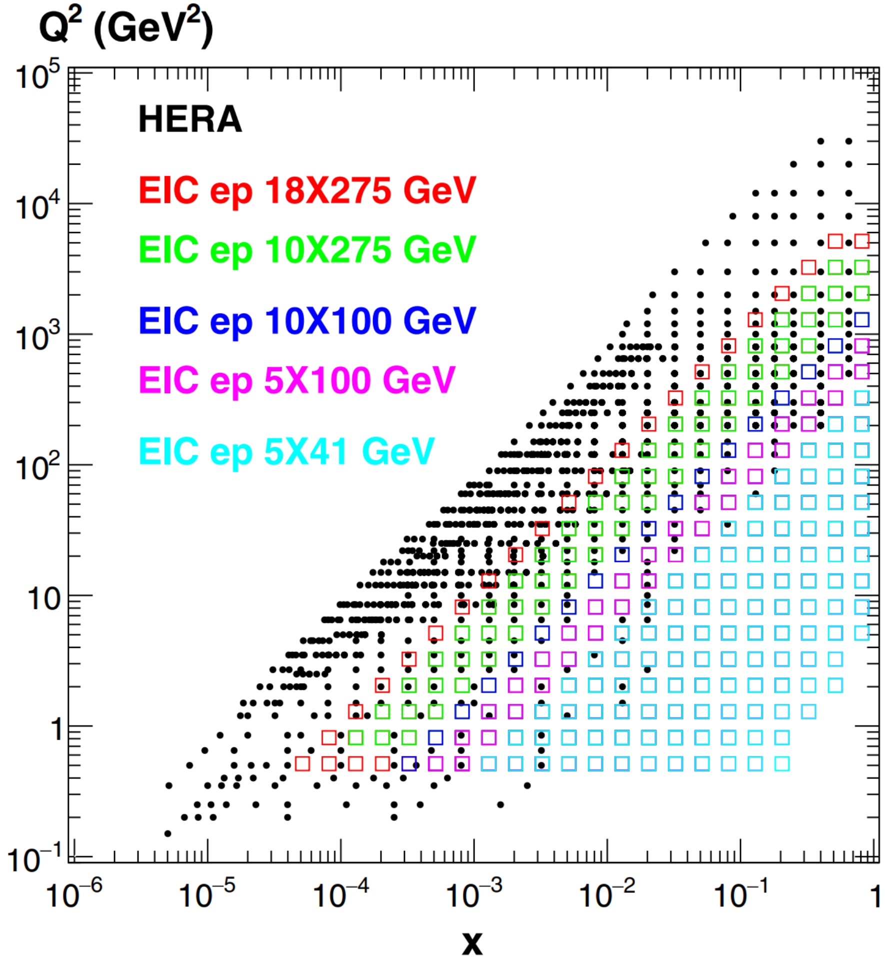
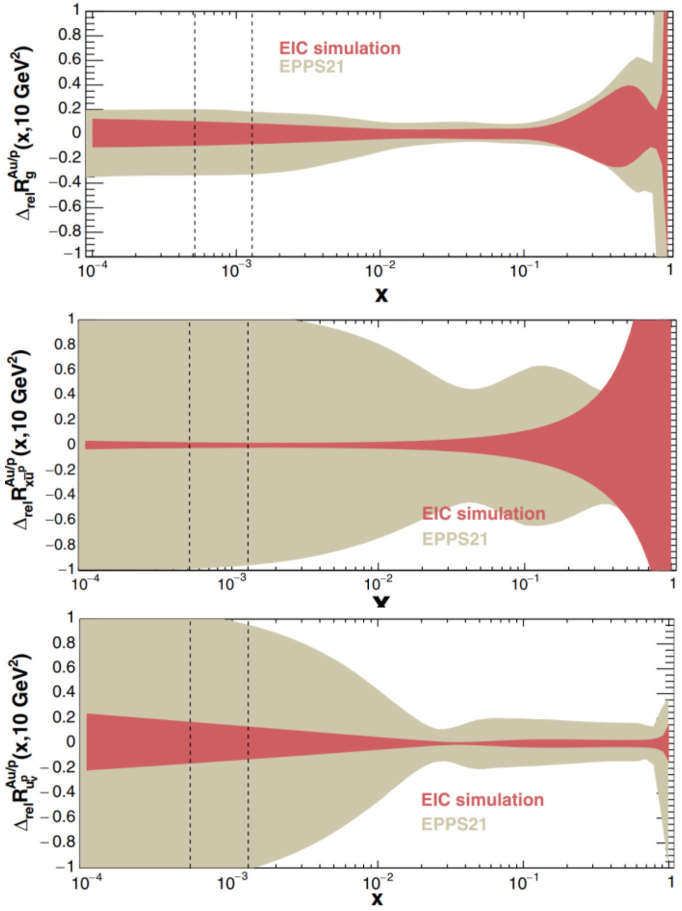
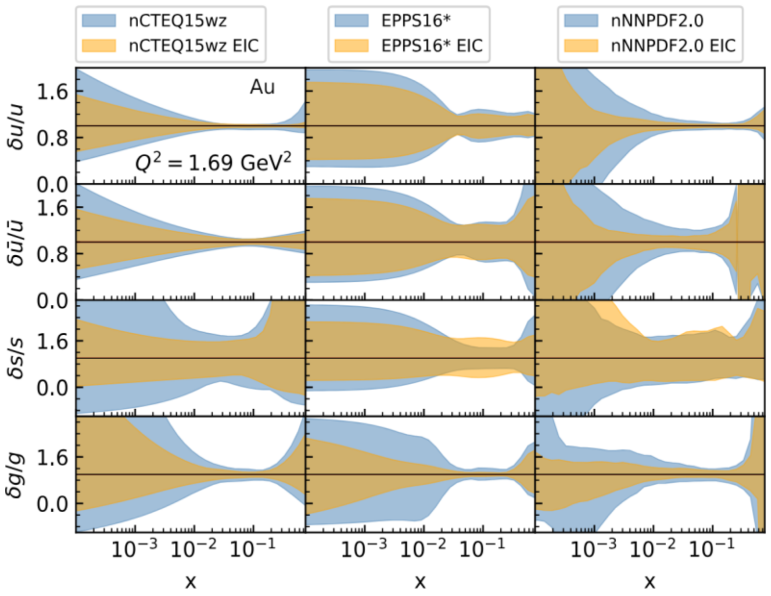


The locations in the (x, Q^2) plane of the HERA and EIC neutral current inclusive DIS data points included in the analysis

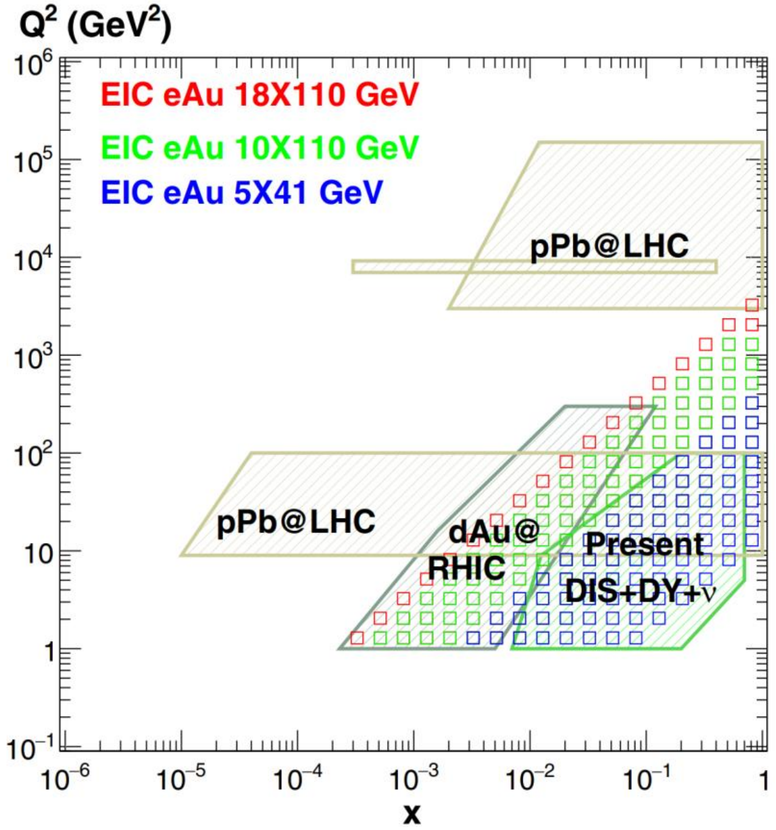
Impact of inclusive EIC data on nuclear PDFs



Impact of EIC data on the of the EPPS21 nuclear PDFs.



Impact of EIC data on the of the nCTEQ nuclear PDFs.



The locations in the (x; Q^2) plane of the eAu EIC neutral current inclusive DIS data points.

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Strong Coupling Constant at EIC?

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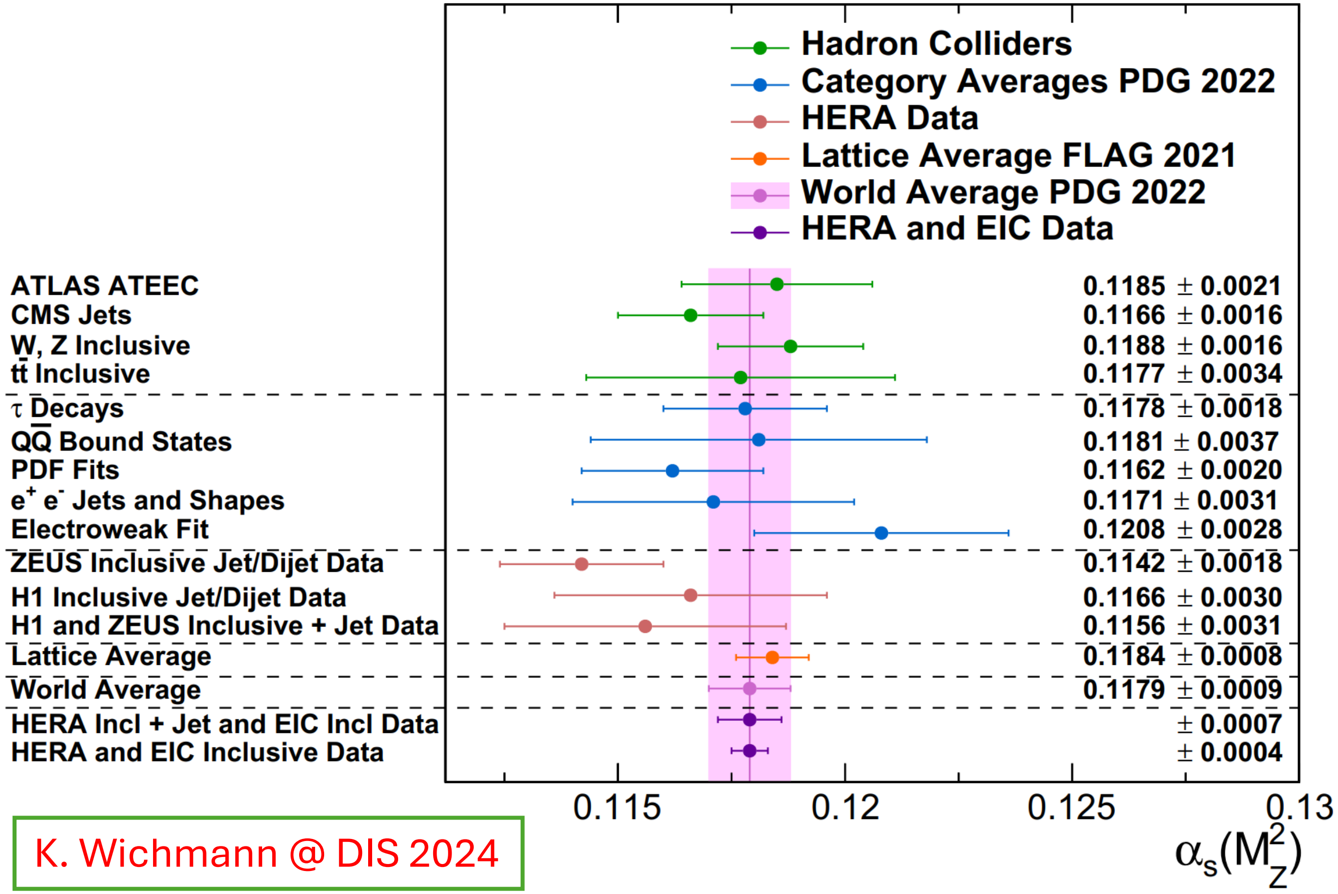
- The strong coupling extracted from the simultaneous fit for the PDFs and $\alpha_S(M_Z^2)$, using the full set of EIC pseudodata together with the HERA inclusive data, is

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004 \text{ (exp) } {}^{+0.0002}_{-0.0001} \text{ (model + parameterisation)},$$

- Stunning improvement!

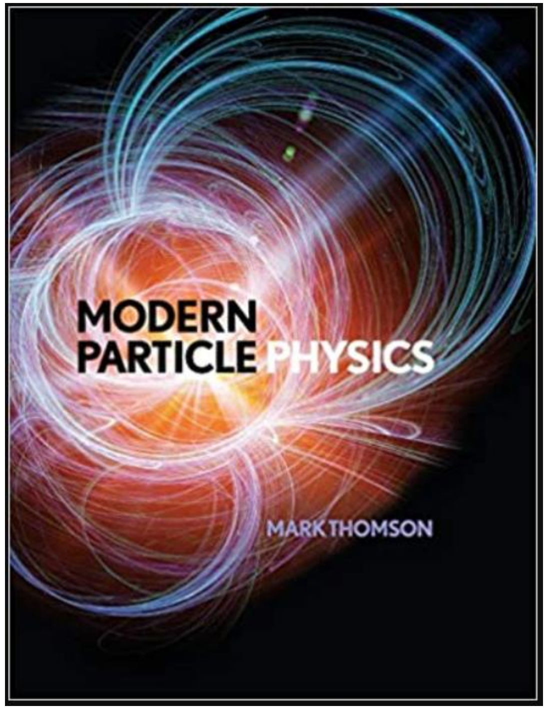


K. Wichmann @ DIS 2024

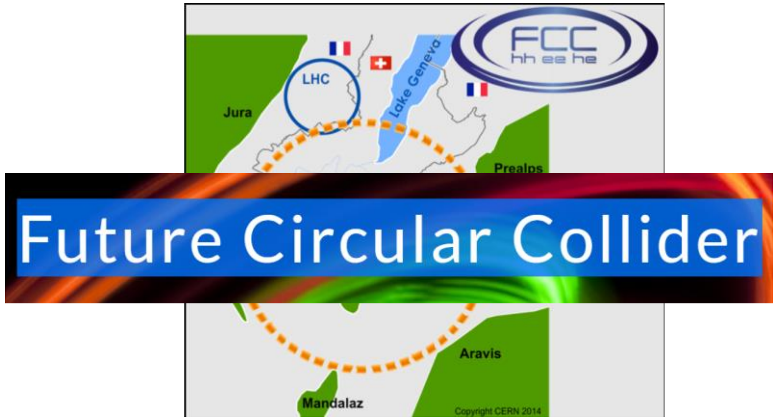
Projected total uncertainties on the strong coupling constant estimated using HERA and simulated EIC data

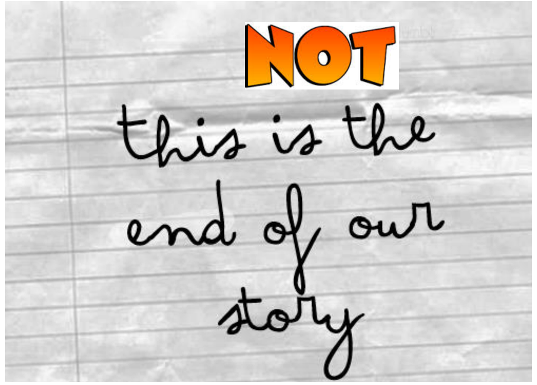
Summary and Closing Words

Despite it success, it should not be forgotten that the Standard Model is not the end of the story; there are just too many loose ends. The coming years will see the high-luminosity operation of the LHC at a centre-of-mass energy close to 14 TeV. In addition, a new generation of experiments will search for signatures for physics beyond the Standard Model. We may be standing at the threshold of new and potentially revolutionary discoveries. Only time will tell whether this will be the direct detection of dark matter, the demonstration that neutrinos are Majorana particles, the discovery of supersymmetry, or quite possibly something completely unexpected. The only certain thing is that interesting times lie ahead of us.



Modern Particle Physics, Prof. Mark Thomson, Cambridge University Press, September 2013, *Page 510*.






Thank you!