Probing the Partonic Content of Nucleons and Nuclei at LHC and Future Colliders

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Outline

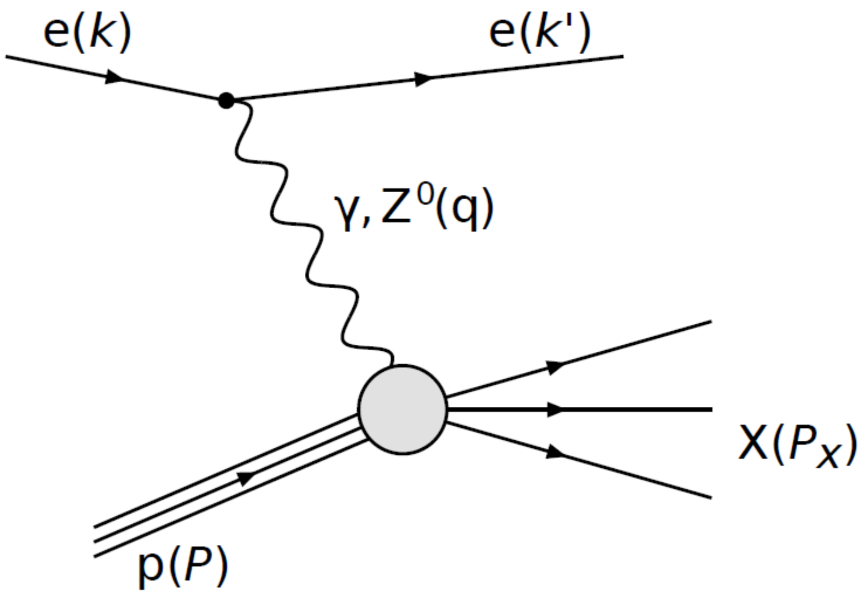
- High-energy hadronic scattering in perturbative Quantum Chromodynamics (QCD).
- The current status of PDFs determinations for unpolarized and longitudinally polarized protons and for unpolarized nuclei.
- The theoretical framework, the experimental information, and the methodological aspects inherent to any modern PDF extraction.
- Global QCD analysis.
- Present knowledge of PDFs, discussion of their limitations in both accuracy and precision relevant to advance our understanding of QCD proton substructure and pursue our quest for precision in the Standard Model and beyond.
- The role of future high-energy colliders, FCC-hh, he, LHeC, EIC, etc.
- Future directions

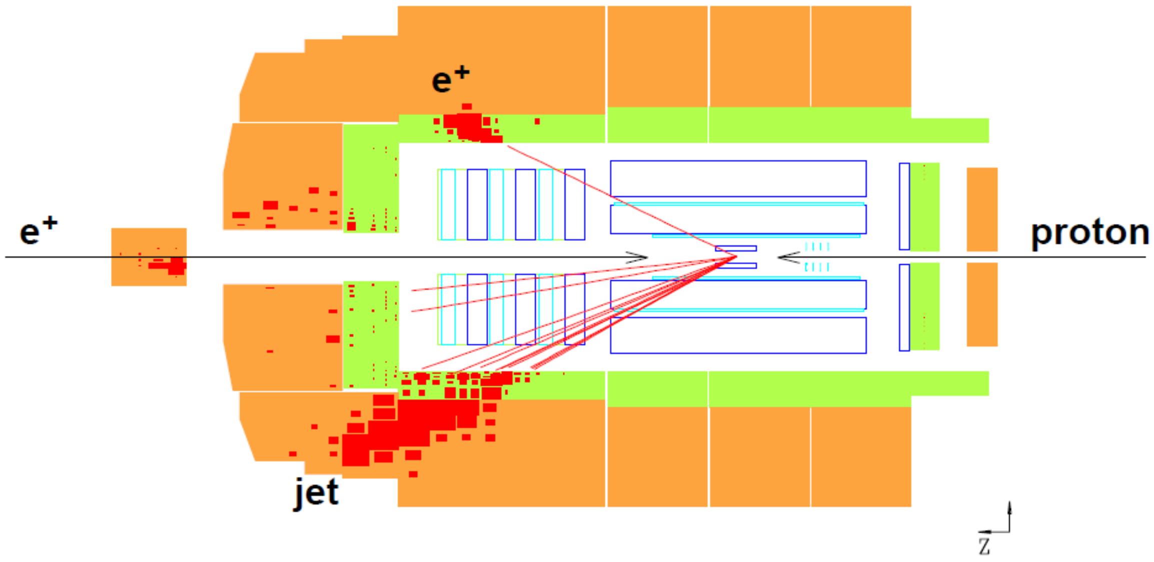
Deep inelastic scattering (DIS) - I

- This process can be mediated by charged ($W^{\pm}$) or neutral (γ^{*}, Z^{0}) exchange.
- Nucleons are probed by high-energy scattering a beam of leptons or protons/antiprotons from them in large-momentum-transfer processes.

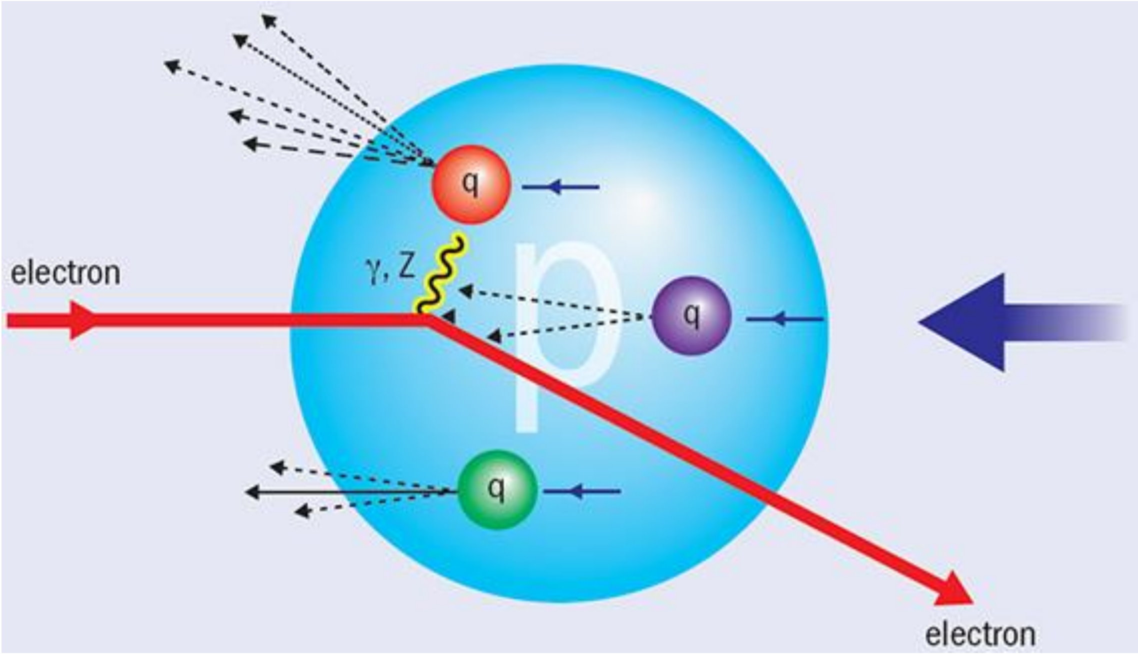
$$e(k) + p(P) \to e(k') + X(P_X)$$

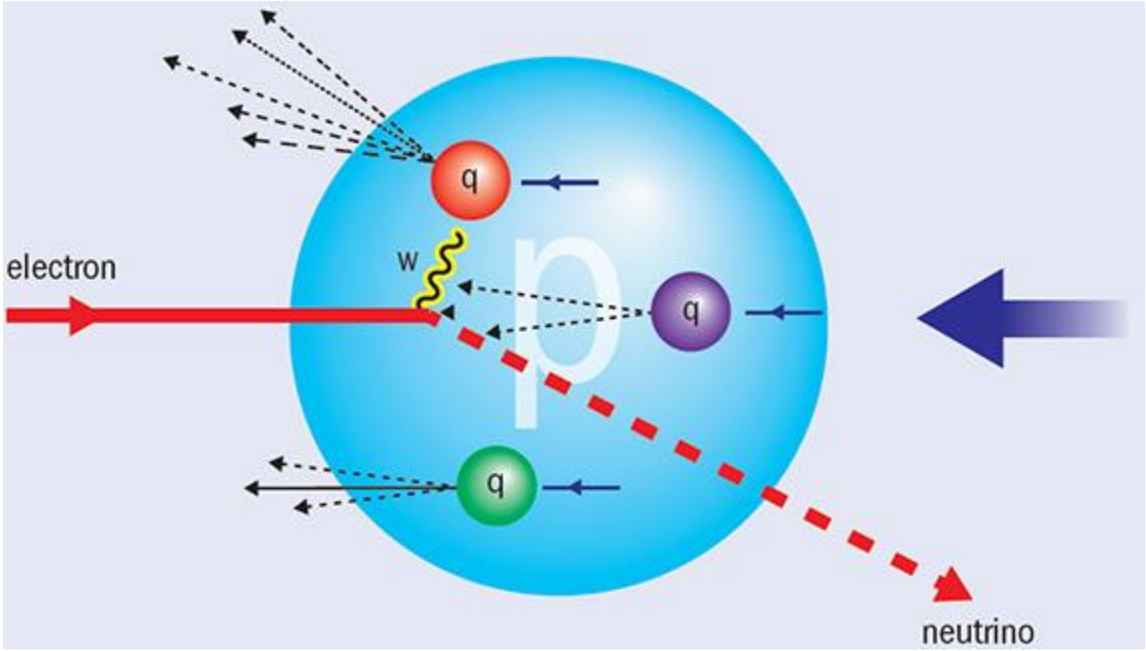
Feynman diagram for DIS





Deep inelastic scattering (DIS) - II





Unpolarized (polarized) DIS cross sections

- The unpolarized (polarized) DIS cross sections for neutral current (NC) interactions involving a photon or Z^0-boson exchange, and for charged current (CC) interactions given by a $W^{\pm}$-boson exchange, can be written as

$$\frac{d^2\sigma^i}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\eta^i\left[Y_+F_2^i \mp Y_-xF_3^i - y^2F_L^i\right] ,$$

$$\frac{d^2\Delta\sigma^i}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\eta^i\left[-Y_+g_4^i - \lambda_\ell Y_-2xg_1^i + y^2g_L^i\right]$$

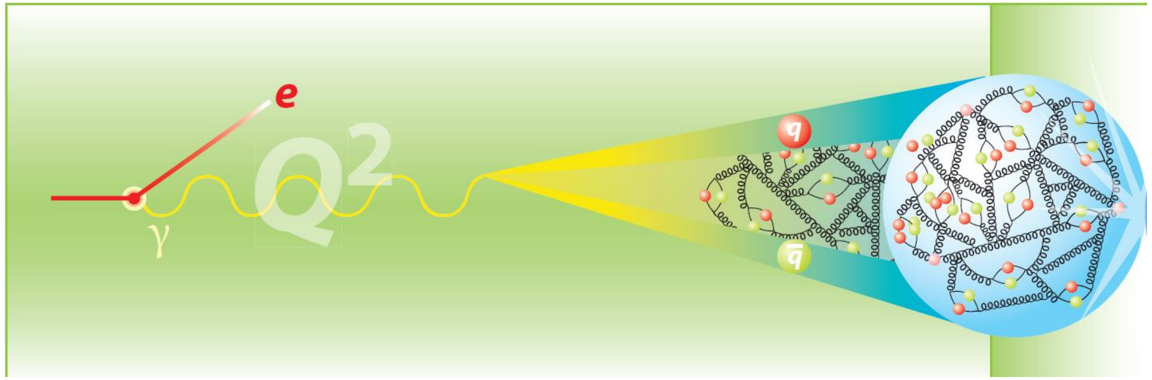
Inclusive DIS kinematics

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

$$x = \left(\frac{Q^2}{2p \cdot q}\right)$$

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

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



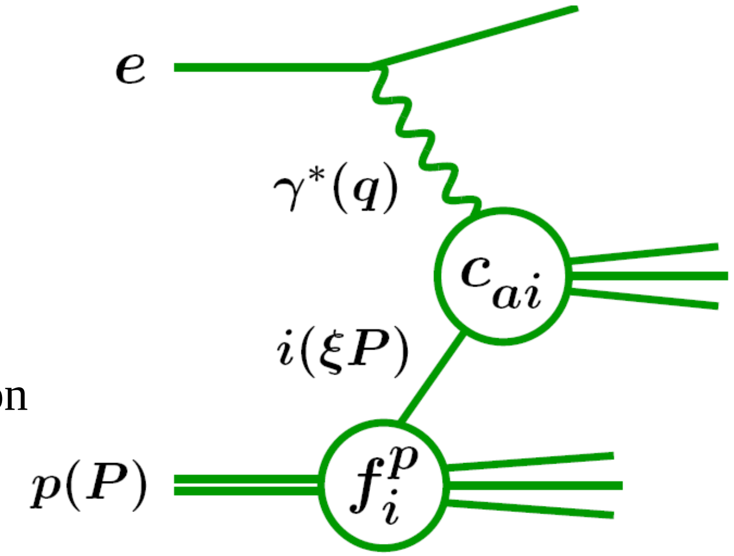
The Quark Parton Model

- The basic idea of the QPM is that in the DIS process, *ep*→*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.

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

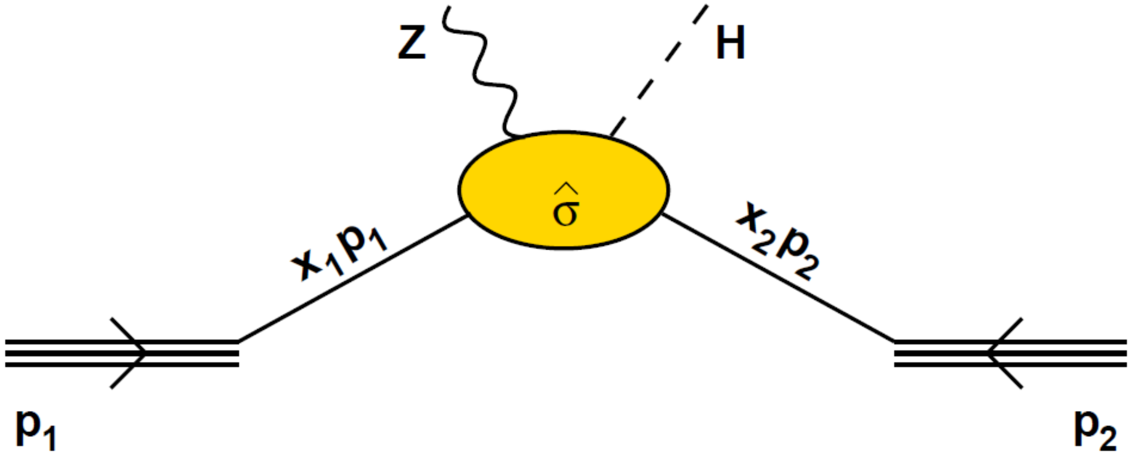
$f_q(\xi)$ is the probability of finding the quark q in the proton carrying a fraction ξ of its momentum

electron-quark cross section



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.
- Measure total cross section ↔ need to know PDFs.
- Hadron-hadron collisions is complex because of two incoming partons.



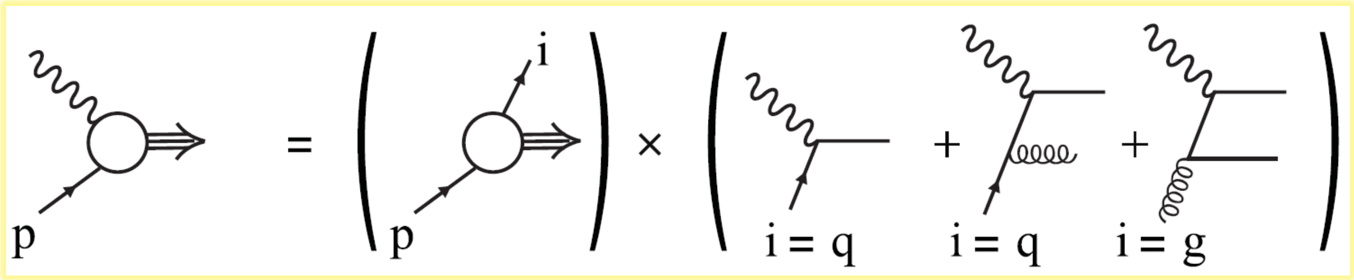
Inclusive DIS structure functions

- The structure functions F_a as a physical observables describe the DIS processes.
- For the structure functions F_a, describing the deep inelastic processes $\ell + p \to \ell' + X$, 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.



DGLAP evolution equations

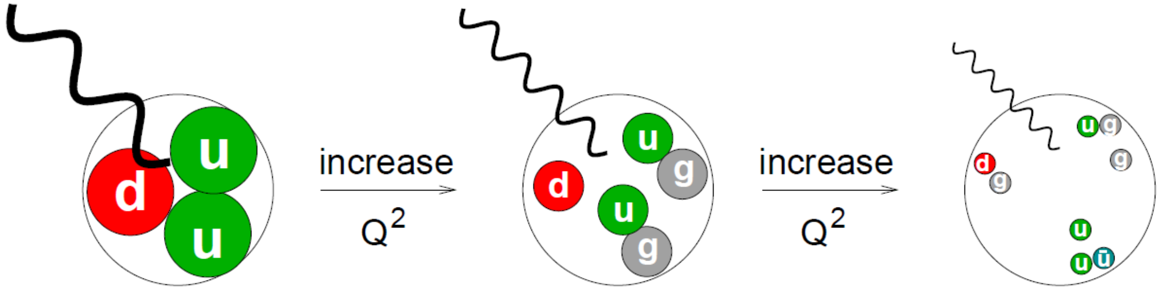
- These equations allow to calculate PDFs at arbitrary scale Q^2 from knowledge of PDFs at the initial scale Q_0^2

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

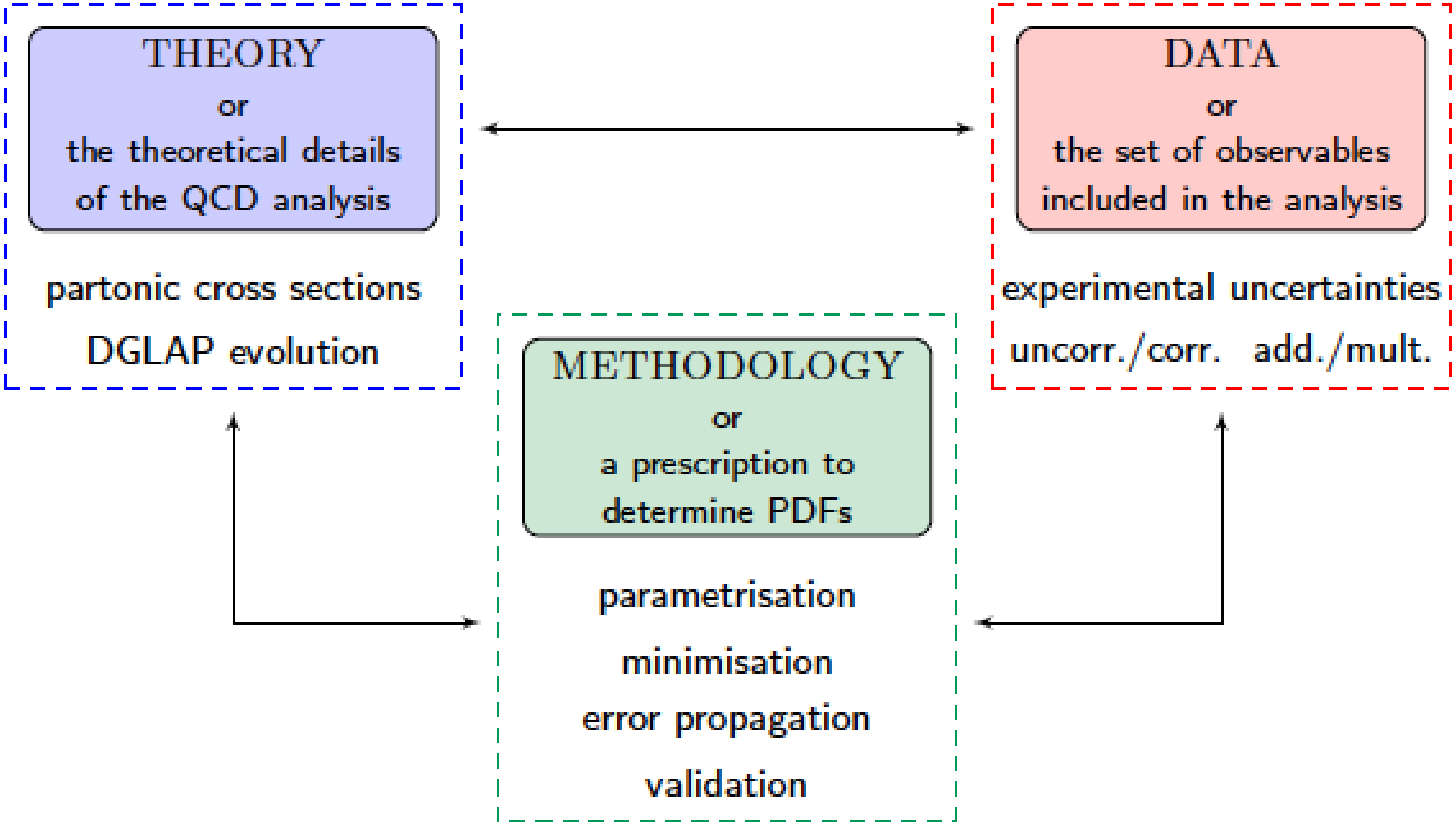
$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi} \left(\sum_i P_{gq} \otimes (q_i + \bar{q}_i) + P_{gg} \otimes g\right)$$

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

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



Global QCD analysis



Experimental input

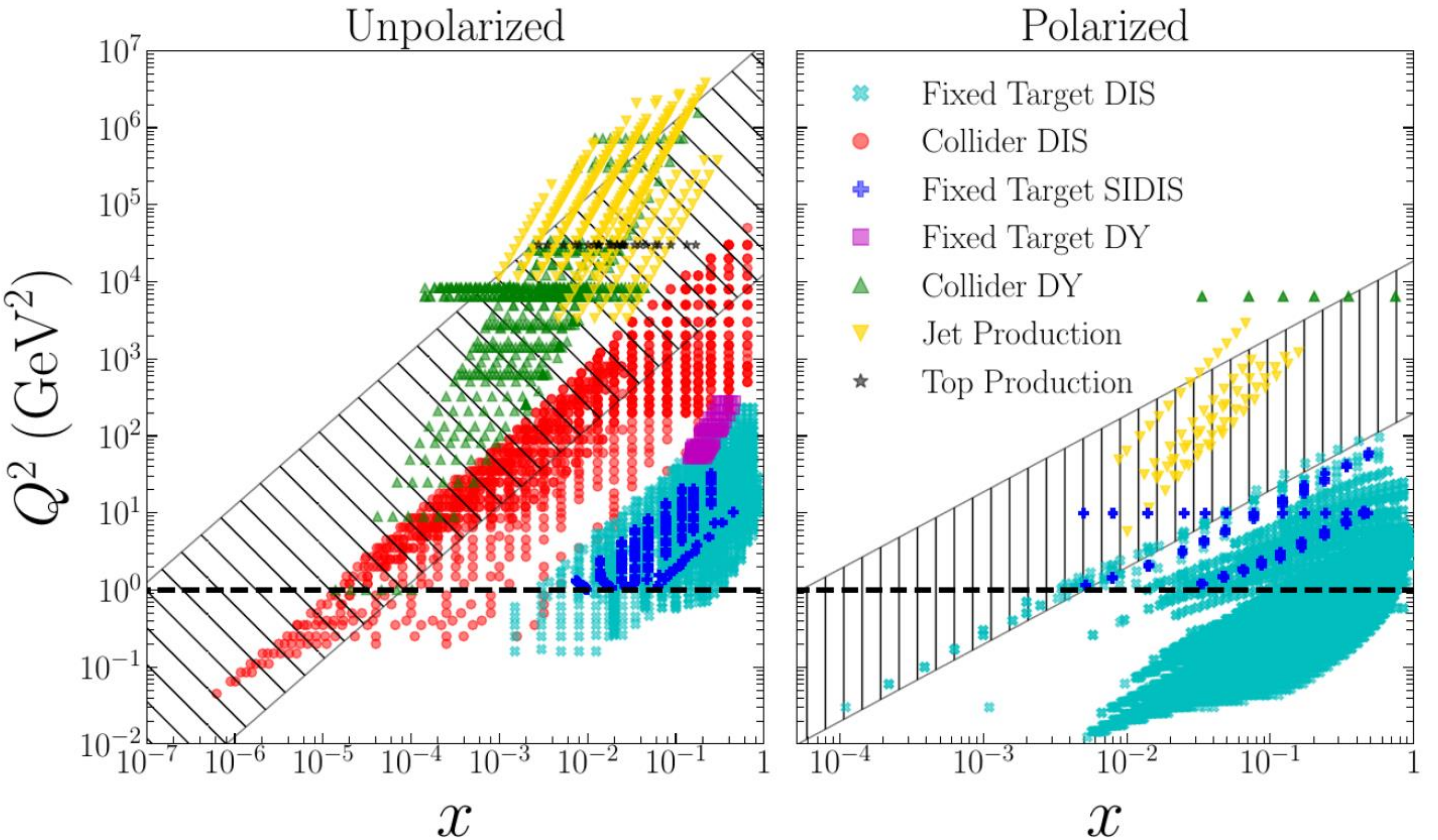
- Theoretical predictions for hadronic cross sections, obtained by the formalism discussed in previous slides, must be compared to the experimental data in order to determine PDFs.

- Fixed target DIS; Collider DIS, Fixed target SIDIS, Fixed target Drell Yan (DY), Collider DY, Jet and hadron production, and top-quark production (LHC).

The main hadronic processes commonly used to determine PDFs. For each reaction, the leading partonic process, the probed partons, and whether available data exists in the unpolarized (U), polarized (P), and nuclear (N) cases is indicated.

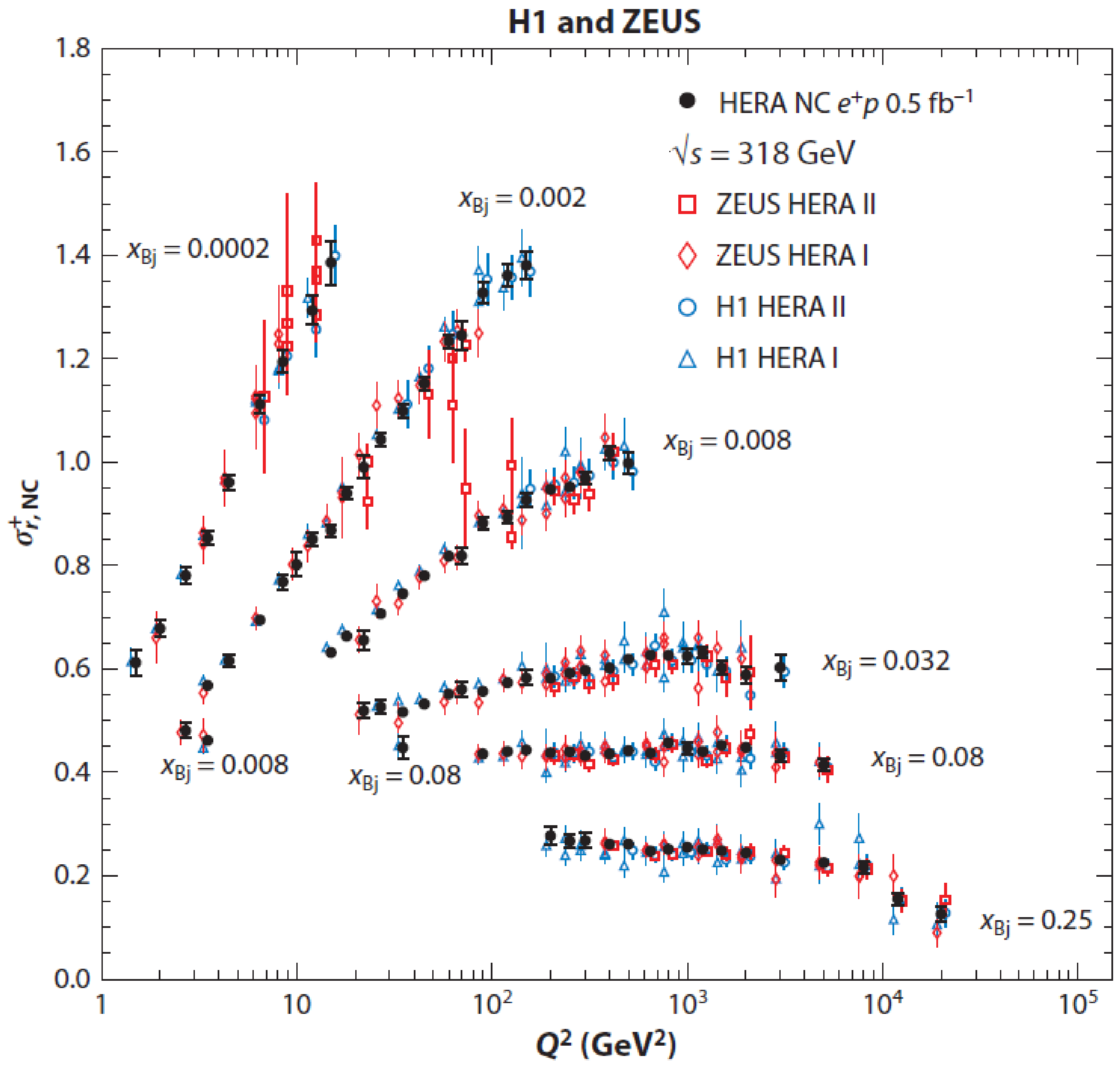
Hadronic Process	Partonic Process	Probed Partons	U	P	N
Fixed Target DIS					
$\ell^{\pm}\{p,n\} \to \ell^{\pm} + X$	$\gamma^* q \to q$	$\mathrm{q}^+, \mathrm{q}, \bar{\mathrm{q}}, \mathrm{g}$	✓	✓	✓
$\ell^{\pm}\{n,A\}/p \to \ell^{\pm} + X$	$\gamma^* d/u \to d/u$	d/u	✓		✓
$\nu(\bar{\nu})A \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$\mathrm{q}, \bar{\mathrm{q}}$	✓		✓
$\nu A \to \mu^-\mu^+ + X$	$W^* s \to c$	s	✓		✓
$\bar{\nu} A \to \mu^+\mu^- + X$	$W^* \bar{s} \to \bar{c}$	$\bar{\mathrm{s}}$	✓		✓
Collider DIS					
$e^{\pm}p \to e^{\pm} + X$	$\gamma^* q \to q$	$\mathrm{g}, \mathrm{q}, \bar{\mathrm{q}}$	✓		
$e^{+}p \to \bar{\nu} + X$	$W^+\{d,s\} \to \{u,c\}$	d, s	✓		
$e^{\pm}p \to e^{\pm} c\bar{c} + X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	✓		
$e^{\pm}p \to$ (di−)jet(s) $+ X$	$\gamma^* g \to q\bar{q}$	g	✓		
Fixed Target SIDIS					
$\ell^{\pm}\{p,d\} \to \ell^{\pm} + h + X$	$\gamma^* q \to q$	$\mathrm{u}, \bar{\mathrm{u}}, \mathrm{d}, \bar{\mathrm{d}}, \mathrm{g}$	✓	✓	
$\ell^{\pm}\{p,d\} \to \ell^{\pm} c\bar{c} \to \ell^{\pm} D + X$	$\gamma^* g \to c\bar{c}$	g		✓	
Fixed Target DY					
$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{\mathrm{q}}$	✓		
$p\{n,A\}/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{\mathrm{d}}/\bar{\mathrm{u}}$	✓		✓
Collider DY					
$p\bar{p} \to (W^{\pm} \to \ell^{\pm}\nu) + X$	$ud \to W^+, \bar{u}\bar{d} \to W^-$	$\mathrm{u}, \mathrm{d}, \bar{\mathrm{u}}, \bar{\mathrm{d}}$	✓		
$p\{p,A\} \to (W^{\pm} \to \ell^{\pm}\nu) + X$	$u\bar{d} \to W^+, d\bar{u} \to W^-$	$\mathrm{u}, \mathrm{d}, \bar{\mathrm{u}}, \bar{\mathrm{d}}$	✓	✓	✓
$p\bar{p}(p\{p,A\}) \to (Z \to \ell^+\ell^-) + X$	$uu, dd(u\bar{u}, d\bar{d}) \to Z$	u, d, g	✓	✓	✓
$pp \to (W + c) + X$	$gs \to W^- c, g\bar{s} \to W^+ \bar{c}$	$\mathrm{s}, \bar{\mathrm{s}}, \mathrm{g}$	✓		
$pp \to (\gamma^* \to \ell^+\ell^-)X$	$u\bar{u}, d\bar{d} \to \gamma^*, u\gamma, d\gamma \to \gamma^*$	$\bar{\mathrm{q}}, \mathrm{g}, \gamma$	✓		
Jet and hadron production					
$p\bar{p}(p\{p,A\}) \to$ (di−)jet(s) $+ X$	$gg, qg, qq \to$ jet(s)	g, q	✓	✓	✓
$p\bar{p}(pp) \to h + X$	$gg, qg, qq \to \pi, K, D$	g, q	✓	✓	
Top Production					
$pp \to t\bar{t} + X$	$gg \to t\bar{t}$	g	✓		
$pp \to t + X$	$W^* q \to q'$	$\mathrm{q}, \bar{\mathrm{q}}$	✓		

arXiv:2001.07722 [hep-ph]



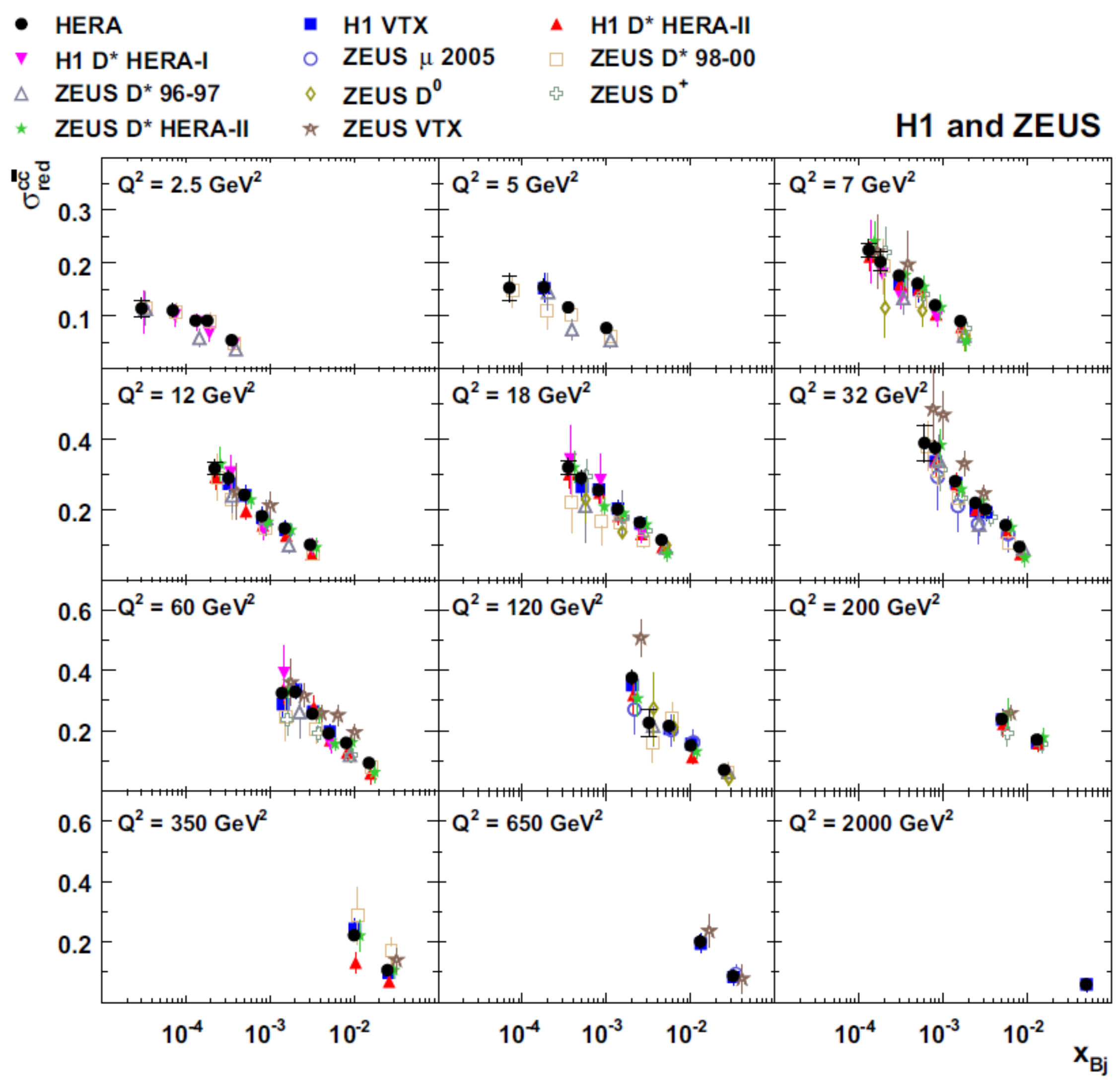
The kinematic coverage, in the (x; Q^2) plane, of the hadronic cross section data for the processes commonly included in global QCD analyses of PDFs.

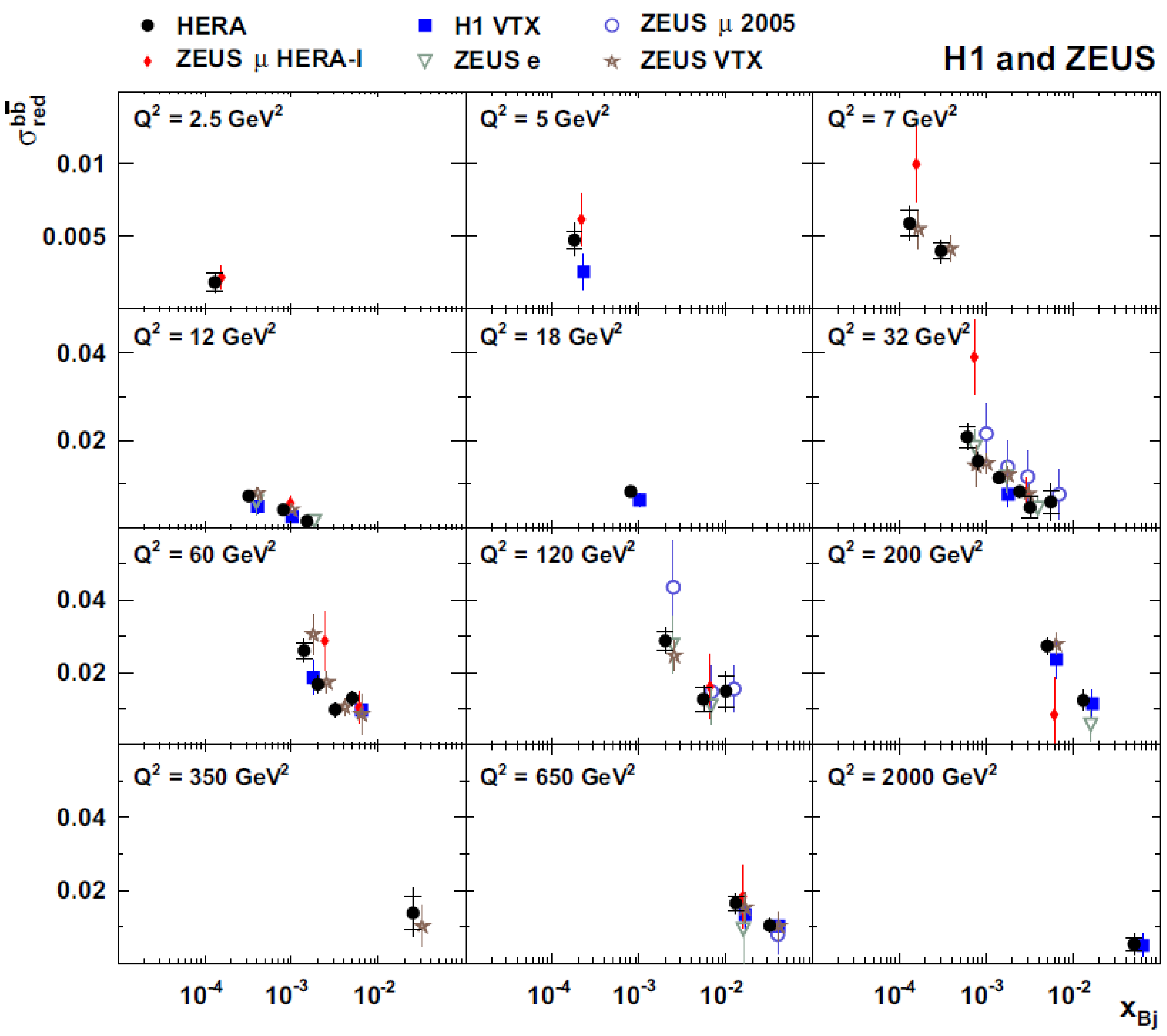
arXiv:2001.07722 [hep-ph]



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

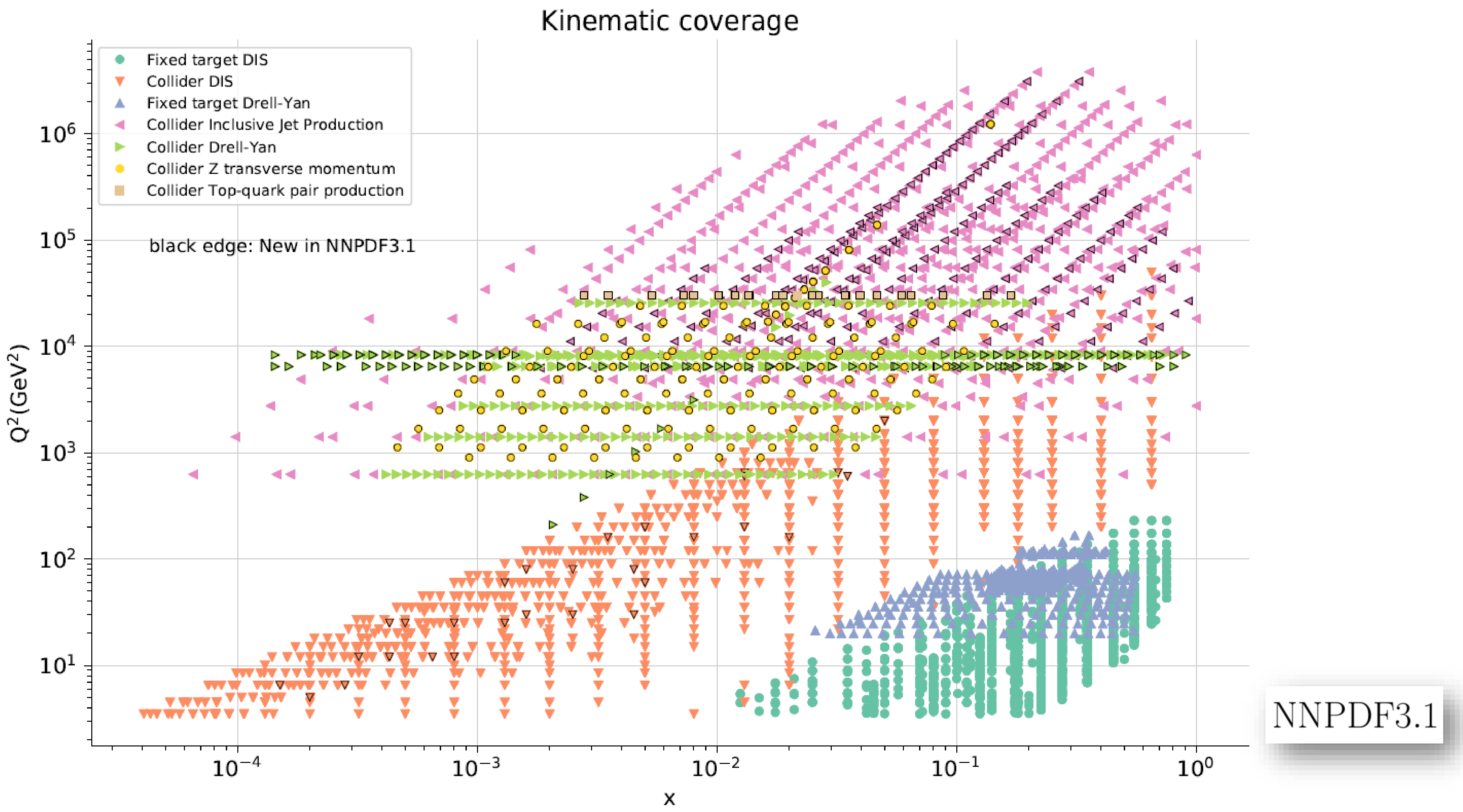
The combined HERA data for the inclusive neutral-current (NC) reduced cross sections as a function of Q^2.





Eur. Phys. J. C 78 (2018) 473

Combined measurements of the reduced charm and bottom production cross sections.



Typical kinematical coverage in the (x; Q^2) plane for the datasets included in a global analysis. The various datasets are clustered into families of related processes.

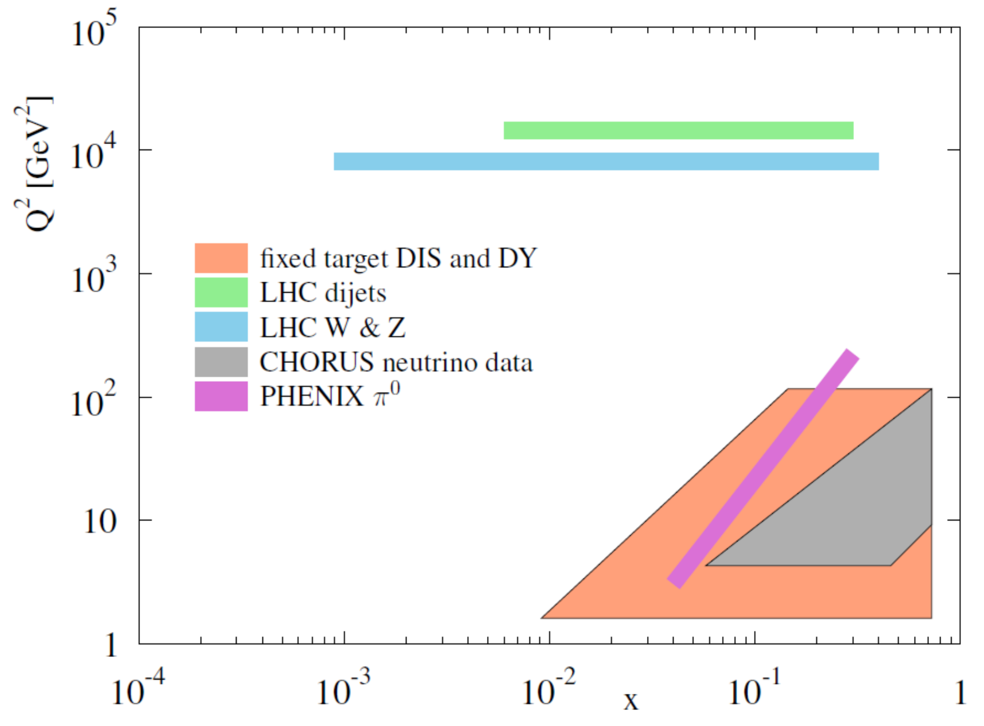
	Process	Subprocess	Partons	x range
Fixed Target	$\ell^{\pm}\{p,n\} \to \ell^{\pm} + X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^{\pm} n/p \to \ell^{\pm} + X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu}) N \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^- \mu^+ + X$	$W^* s \to c$	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	$x \gtrsim 0.005$

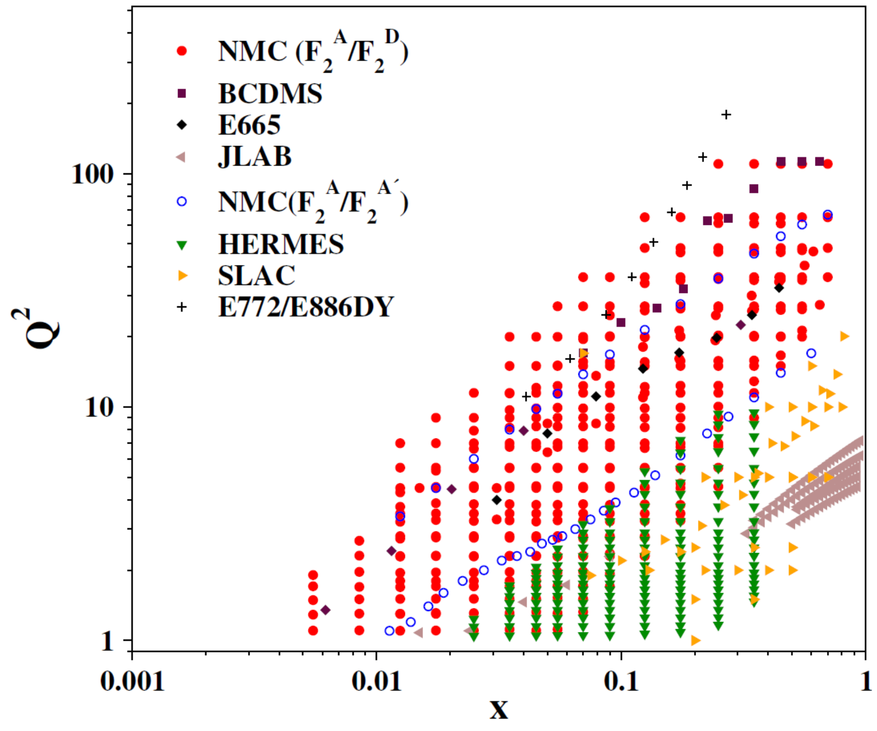
NNPDF3.1

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

Charged-lepton scattering of the nuclei and nuclear PDFs

- These data do not have the power to constrain all of the nuclear PDFs components.
- The LHC data opens a previously unexplored kinematic region.

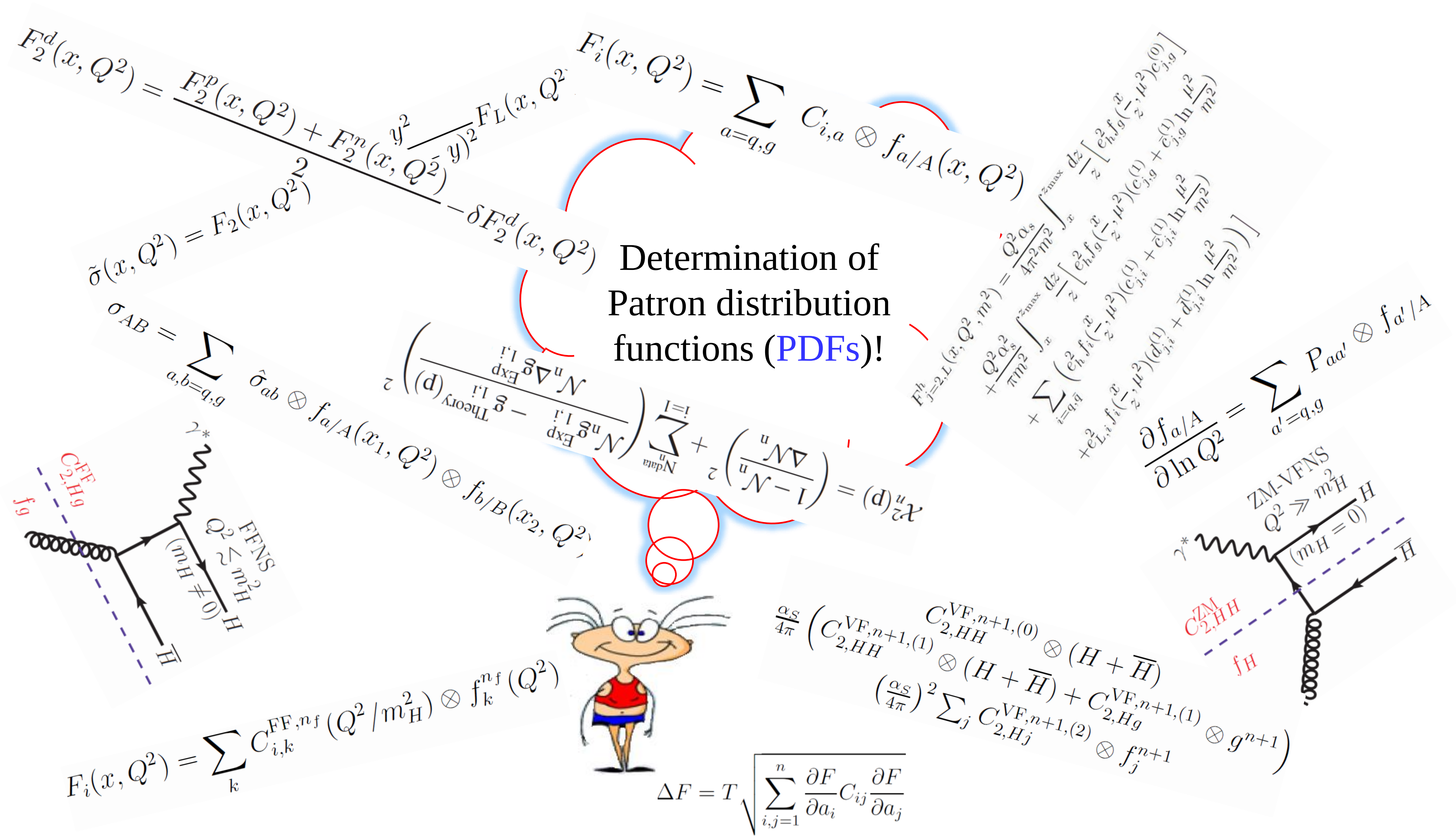




Nominal x and Q^2 coverage of nuclear DIS.

EPPS16 is the first nuclear parton distributions with LHC data [Eur. Phys. J. C77 (2017), 163].

Methodological input


Determination of
Patron distribution
functions (PDFs)!

- PDFs are determined by comparing the theoretical predictions of hadronic cross sections to the experimental data from high-energy experiments.

The process-dependent kernels that are computed perturbatively in QCD

The momentum distribution of partons that enter the elementary scattering process in terms of universal functions.

- PDFs must be modeled by a function of fit parameters and optimized by data to yield matching theoretical predictions.
- It can be classified more generally as a nonlinear regression problem.
- In the next slides, the methodological aspects to perform a global QCD analysis will be discussed, in particular the PDFs parameterization, optimization, and uncertainty estimation.

Standard definition of PDFs

- PDFs are modeled by means of some parameterization, which is then optimized by comparing the PDF-dependent predictions of one or more physical process to its actual measurement, a procedure that is called (global) QCD analysis.

- Unpolarized and polarized proton PDFs are usually parameterized for each parton *f* as,

$$\mathrm{f}^p(x, Q_0^2) = \mathcal{N} x^{\alpha_\mathrm{f}} (1-x)^{\beta_\mathrm{f}} \mathcal{I}(x; \boldsymbol{a})$$

$$\mathcal{I}(x) = (1 + \gamma\sqrt{x} + \delta x + \ldots)$$

Standard definition of nuclear PDFs

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

Nuclear modifications

Free proton baseline

$$d\sigma = \sum_{i,j} f_i^{p}(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j^{Pb}(Q_f^2)$$

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

- Nuclear Modification at large *x* poorly constrained by present data

Optimization

- Once the parameterization is set at an input scale Q_0^2, the PDFs can be evolved to the scale of the data Q by means of the DGLAP equations.

- Then PDFs convoluted with the partonic cross sections to obtain theoretical predictions for the hadronic cross sections at a given perturbative order (LO, NLO and NNLO).

- The optimal PDF parameters are then found by optimizing a suitable figure of merit, commonly taken as the log-likelihood χ^2.

- The extracted PDFs can then be used to describe any other process that depends on them due to their universal property.

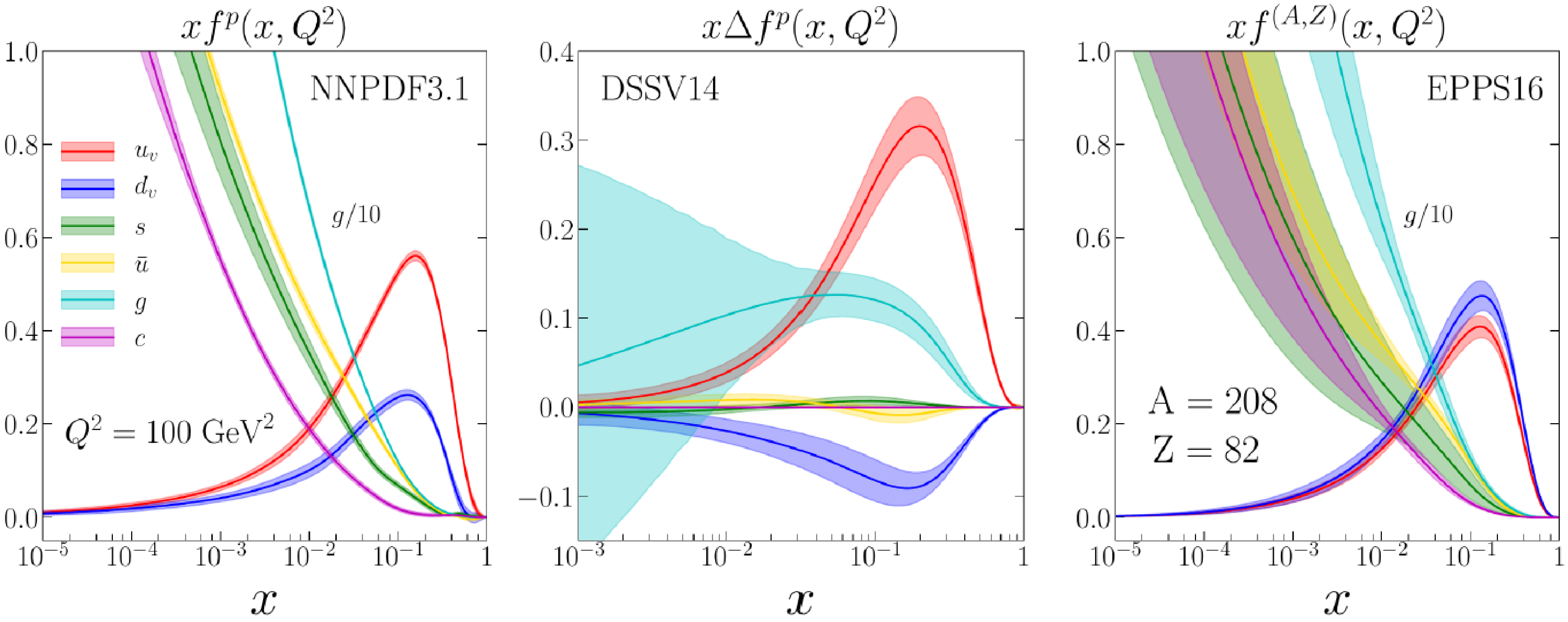
Covariance matrix

$$\chi^2(\boldsymbol{a}) = \sum_{i,j}^{N_{\rm dat}} [D_i - T_i(\boldsymbol{a})]\, {\rm cov}_{ij}^{-1}\, [D_j - T_j(\boldsymbol{a})] \ ,$$

Theoretical predictions

Measurements

CERN program MINUIT: Comput. Phys. Commun. 10, 343 (1975); CERN-D506.



A representative snapshot of unpolarized and polarized proton PDFs, and on nuclear (lead) PDFs

The PDF fitting landscape

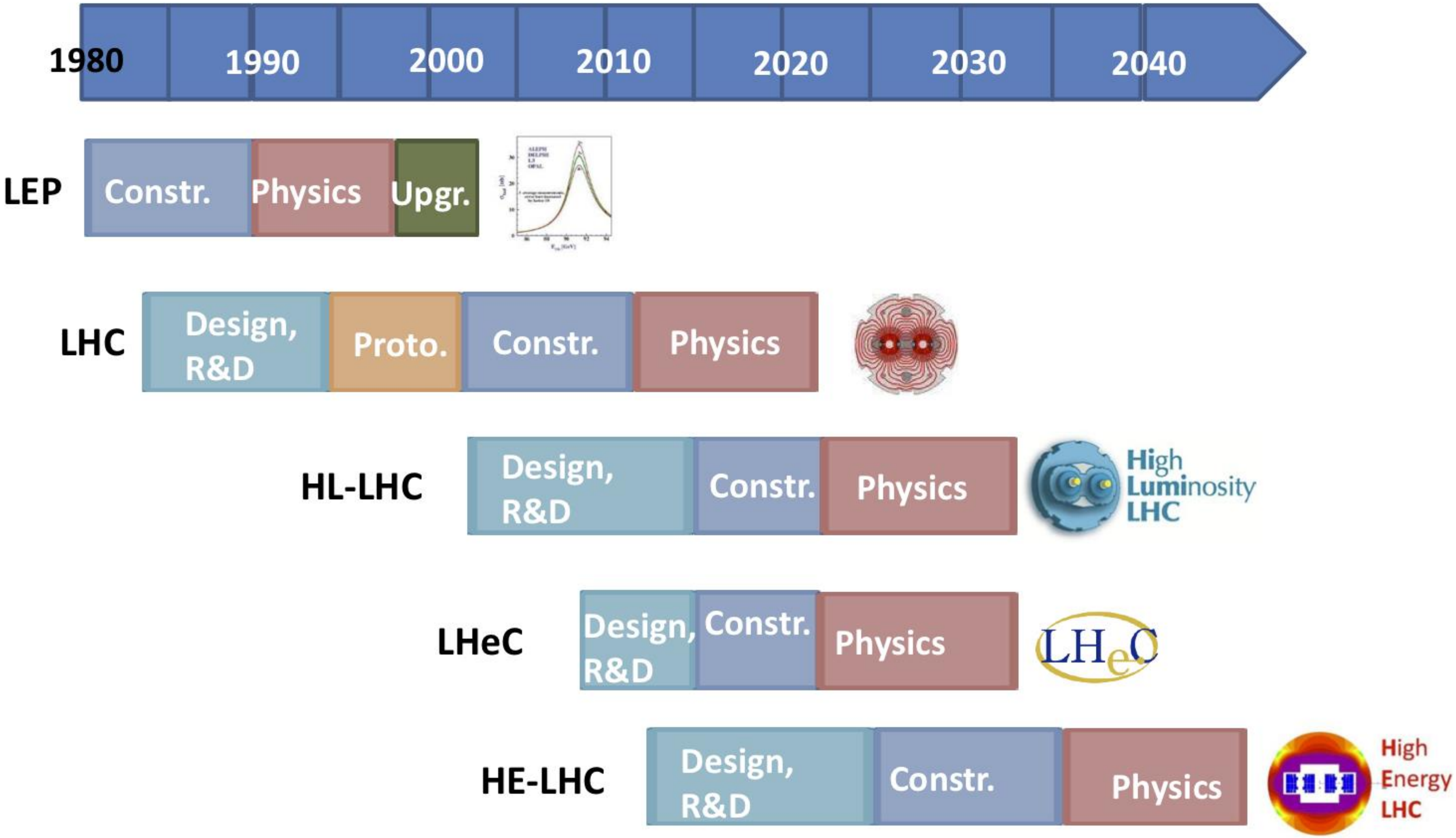
April 2017	NNPDF3.0	MMHT2014	CT14	HERAPDF2.0	CJ15	ABMP16
Fixed Target DIS	✔	✔	✔	✘	✔	✔
JLAB	✘	✘	✘	✘	✔	✘
HERA I+II	✔	✔	✔	✔	✔	✔
HERA jets	✘	✔	✘	✘	✘	✘
Fixed Target DY	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔	✔	✘	✔	✔
Tevatron jets	✔	✔	✔	✘	✔	✘
LHC jets	✔	✔	✔	✘	✘	✘
LHC vector boson	✔	✔	✔	✘	✘	✔
LHC top	✔	✘	✘	✘	✘	✔
Stat. treatment	Monte Carlo	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2=1$	Hessian $\Delta\chi^2=1.645$	Hessian $\Delta\chi^2=1$
Parametrization	Neural Networks (259 pars)	Chebyshev (37 pars)	Bernstein (30-35 pars)	Polynomial (14 pars)	Polynomial (24 pars)	Polynomial (15 pars)
HQ scheme	FONLL	TR'	ACOT-χ	TR'	ACOT-χ	FFN (+BMST)
Order	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO	NLO/NNLO

nCTEQ

NNPDF

DESY

The role of future high-energy colliders


1980
1990
2000
2010
2020
2030
2040
LEP
Constr.
Physics
Upgr.
LHC
Design, R&D
Proto.
Constr.
Physics
HL-LHC
Design, R&D
Constr.
Physics
High Luminosity LHC
LHeC
Design, R&D
Constr.
Physics
LHeC
HE-LHC
Design, R&D
Constr.
Physics
High Energy LHC

- Several new accelerator upgrades and designs are being planned that will improve much of the PDFs statuses.

- The LHC is currently upgrading to its high luminosity (HL-LHC) phase, where various observables will be measured with significantly increased statistical precision.

- HL-LHC will extend the LHC physics output for another decade, providing rich precision measurements of SM parameters such as the Higgs couplings and the W-boson mass.

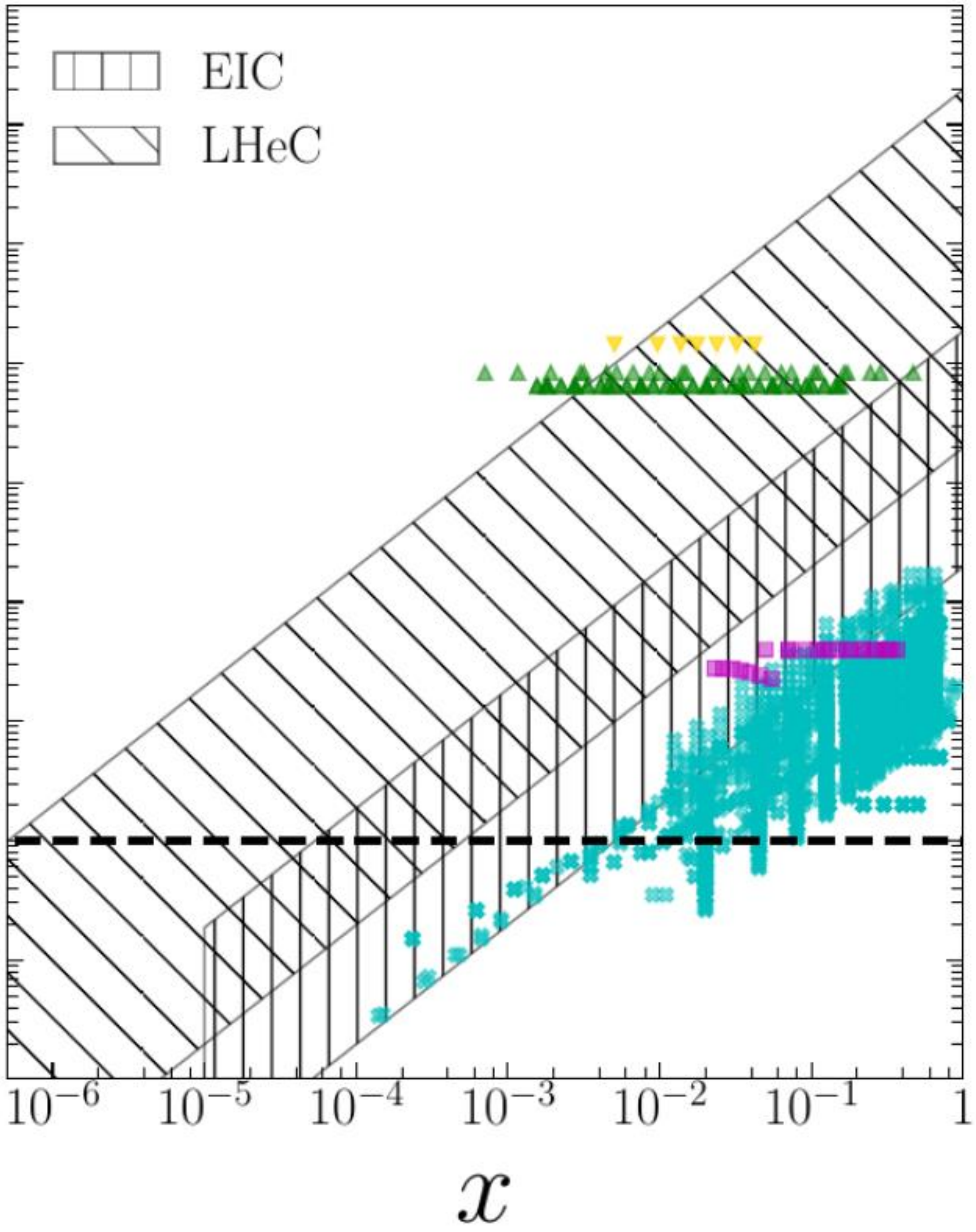
- At lower energies, the JLab has just completed its upgrade to 12 GeV, which will allow for a careful investigation of aspects related to the non-perturbative structure of the unpolarized and polarized proton.

- Electron-proton collider at the LHC (LHeC), which intends to inject roughly 60 GeV electron beams into the LHC proton collider.

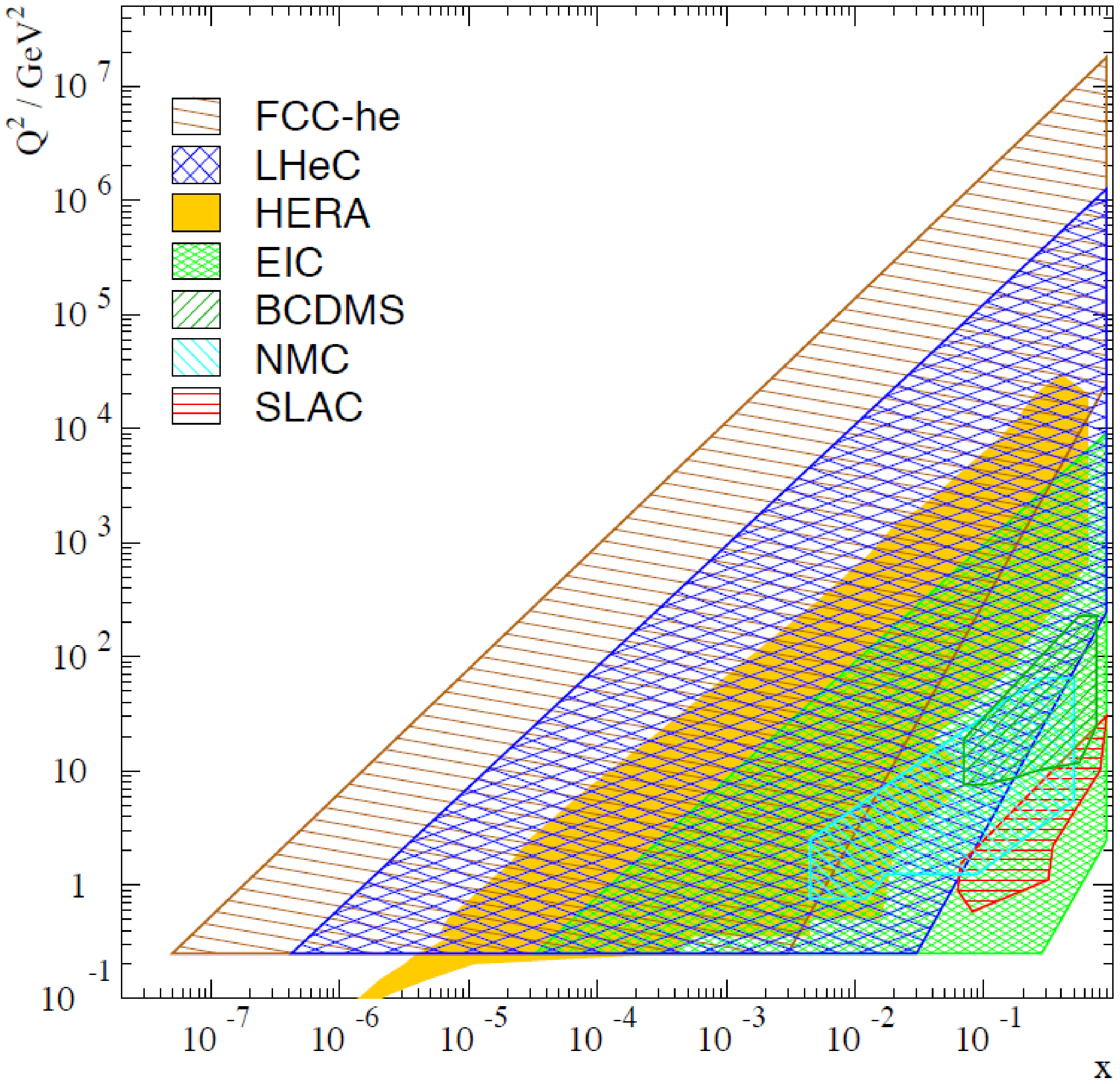
- With the point-like nature of the electron probe and the energies of the LHC, high precision DIS measurements will be achieved for Bjorken-*x* down to 10^{-6}, a kinematic region that has yet to be explored.

- Electron-ion collider (EIC) planned to be built on the current site of RHIC, with medium energies of up to 90 GeV. The aim of the EIC is to study with high precision the three-dimensional structure of nucleons and nuclei.

- EIC will be able to provide high precision DIS measurements for nuclear PDFs determination down to to 10^{-4}.



The extended kinematic ranges attained by the LHeC and the EIC.



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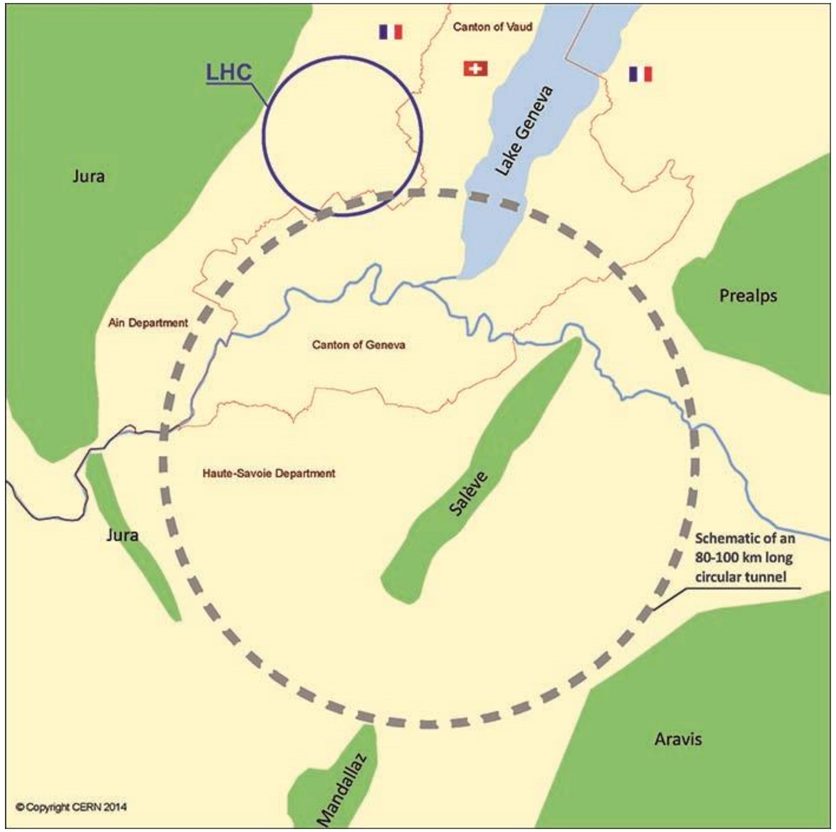
Coverage of the kinematic plane in deep inelastic lepton-proton scattering by some initial fixed target experiments, with electrons (SLAC) and muons (NMS, BCDMS), and by the ep colliders: the EIC (green), HERA (yellow), the LHeC (blue) and the FCC-eh (brown).

Future Circular Collider (FCC)

- The goal of the FCC is to greatly push the energy and intensity frontiers of particle colliders, with the aim of reaching collision energies of 100 TeV, in the search for new physics.
- The FCC Study, hosted by CERN, is an international collaboration of more than 150 universities, research institutes and industrial partners from all over the world.

The phenomenology of PDFs at such extreme energies is very rich: such as top quark PDFs and ... lots of fun!!!

Growing consensus that the next big machine more suitable to explore the energy frontier should be a 100 TeV hadron collider, possibly with also e^+e^-, ep and pp operation modes.



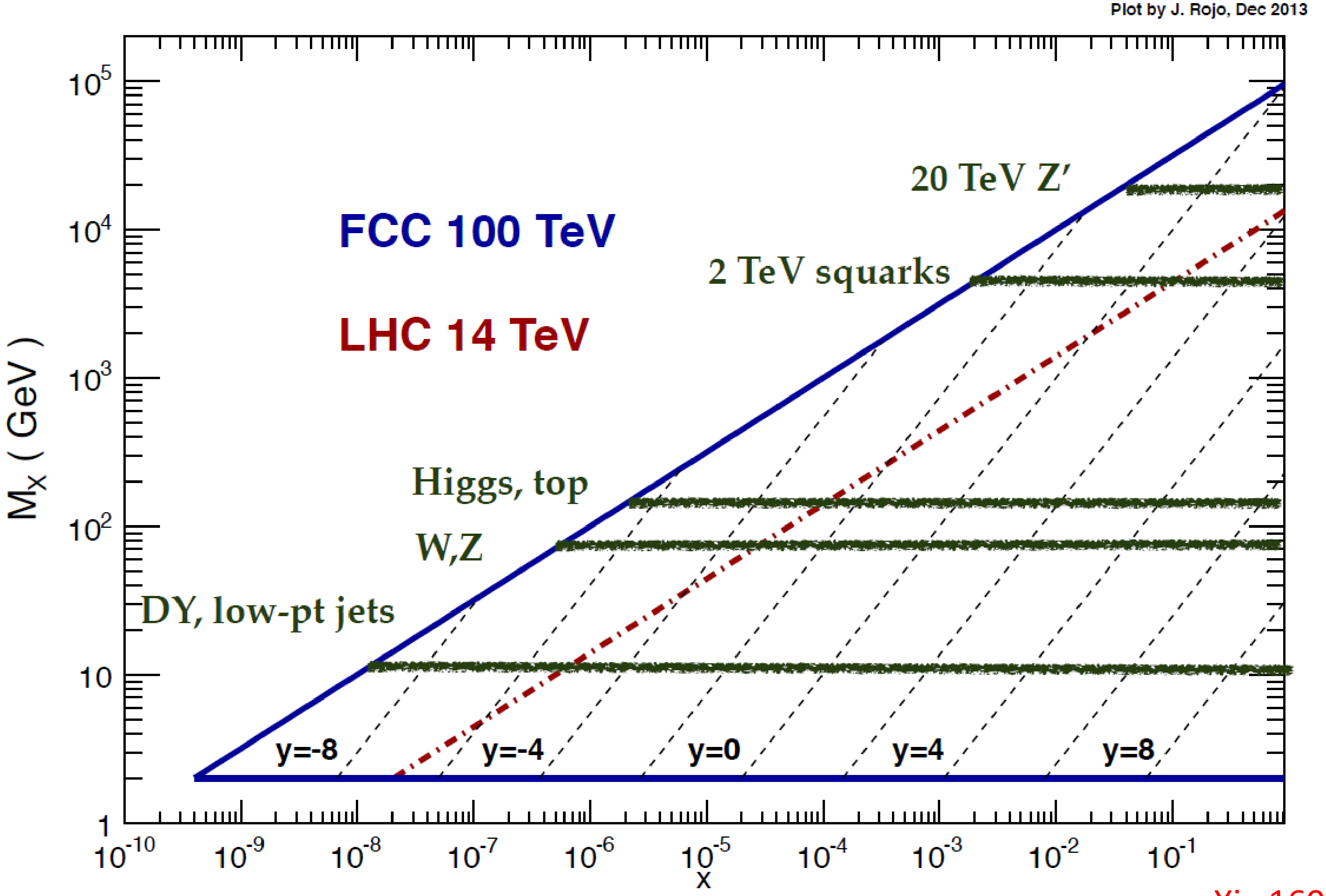
Eur. Phys. J. C 79 (2019) 474

Particle physicists update strategy for the future of the field in Europe

The CERN Council today announced that it has updated the strategy that will guide the future of particle physics in Europe

19 JUNE, 2020

Kinematics of a 100 TeV FCC



arXiv:1605.08302 [hep-ph]

Kinematic coverage in the (x; M_X) plane of a 100 TeV hadron collider compared with the corresponding coverage of the LHC at 14 TeV.

Summary

- An overview of the most important recent developments in PDF determination, with emphasis on their implications for the LHC phenomenology has been presented.

- Global QCD analyses of PDFs continue to be an active field in particle and hadronic physics.

- Now that PDFs are entering a new precision era, they will be critical for calculations of signal and background events in physics searches beyond the SM.

- Further colliders, such as LHeC, EIC, FCC, etc. could offer unique possibilities to reach the ultimate precision in PDFs determinations by probing kinematic regions which are far from the reach of current experiments.

It is my honor to thank: The organizers of 27th IPM Physics spring conference, and your attentions!