Measuring the unobservable: quarks and gluons in the proton

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HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

Jefferson Lab

Selected reviews and references:

- Jimenez-Delgado, Melnitchouk, Owens,
  "Momentum and helicity distributions in the nucleon"
  J.Phys. G40 (2013) 093102
- Gao, Harland-Lang, Rojo,
  "The Structure of the Proton in the LHC Precision Era"
  Phys.Rept. 742 (2018) 1-121
- Kovarik, Nadolsky, Soper
  "Hadron structure in high-energy collisions"
  arXiv:1905.06957
- Accardi et al.
  "A Critical Appraisal and Evaluation of Modern PDFs"
  Eur.Phys.J. C76 (2016) no.8, 471
- Butterworth et al.
  "PDF4LHC recommendations for LHC Run II"
  J.Phys. G43 (2016) 023001
- Accardi et al. [CTEQ-JLab collab.]
  "Constraints on large-x PDFs from new weak boson production and DIS data"
  Phys.Rev. D93 (2016) no.11, 114017

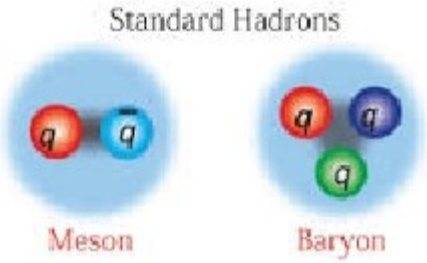
also spin PDFs,
JLab physics

*S*tart from here,
if you wish

Confinement: Quarks and gluons in hiding

- **Quantum Chromo Dynamics**
  - Strong interactions in terms of "colored" quarks and gluons

- **But "color confinement"**
  - No detector has ever interacted with a quark or gluon



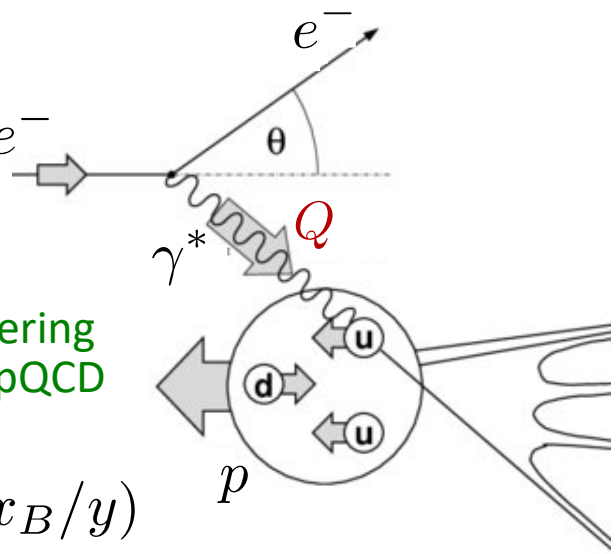
  - Quarks and gluons are "confined" inside color neutral hadrons

- **Quarks and gluons are not observable!**
  - Yet they are the basic QCD degrees of freedom
  - And are responsible for the inner life of protons & C.
  - **How can one measure these?**

Hard probes of the proton's structure

- **Scattering processes with large momentum transfer *Q*:**
  - Coupling constant decreases with *Q* → perturbation theory
  - Separation of fast partonic dynamics & slow hadronic structure
  - Unobservable hadronic structure in terms of quark (and gluon) "quantum correlation functions"

$$\phi_q(x) = \int d\xi\, e^{ixP^+\xi^-} \langle P|\bar{\psi}_q(\xi^-)\tfrac{\gamma^+}{2}\psi_q(0)|P\rangle$$



- Example: **Deep Inelastic Scattering**

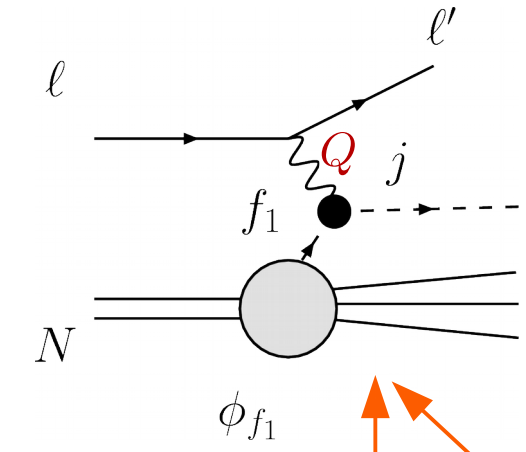
$$\frac{d\sigma^{e+p\to e+X}}{dx_B dQ^2} = \sum_q \int_{x_B}^1 dy\, \phi_q(y,Q^2)\, \hat{\sigma}^{\gamma^*+q\to q}(x_B/y) + O(1/Q^2)$$

Parton scattering calculable in pQCD

Parton Distribution Fns (PDF) of the proton

Power-suppressed, Improvable approx. (incl. multi-parton corr. fns.)

Factorization and universality



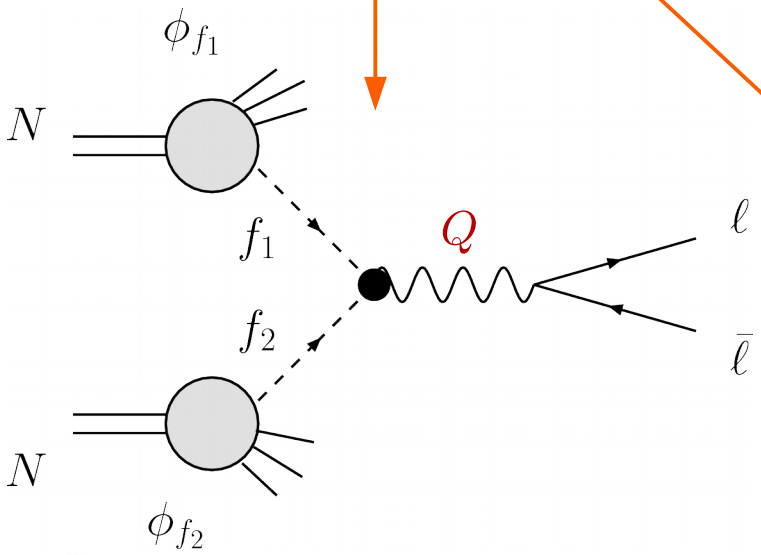
- **perturbative QCD factorization** of short and long distance physics

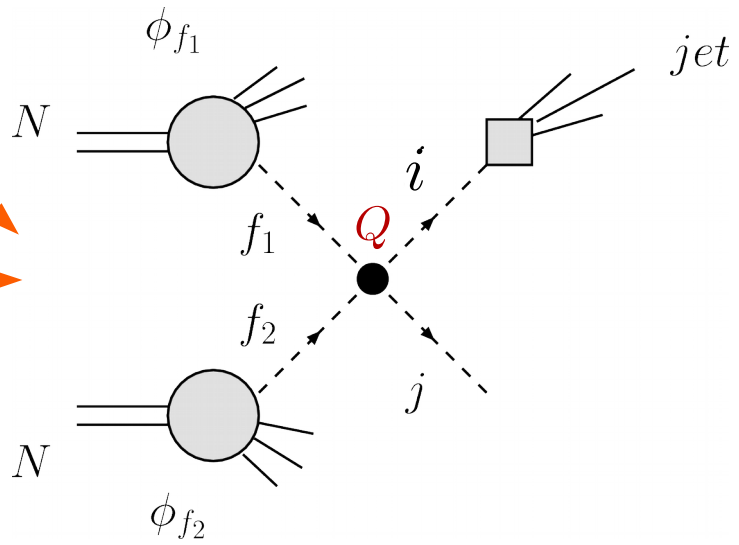
$$d\sigma_{\text{hadron}} = \sum_{f_1,f_2,i,j} \phi_{f_1} \otimes \hat{\sigma}^{f_1 f_2 \to ij}_{\text{parton}} \otimes \phi_{f_2}$$

Parton Distribution Fns

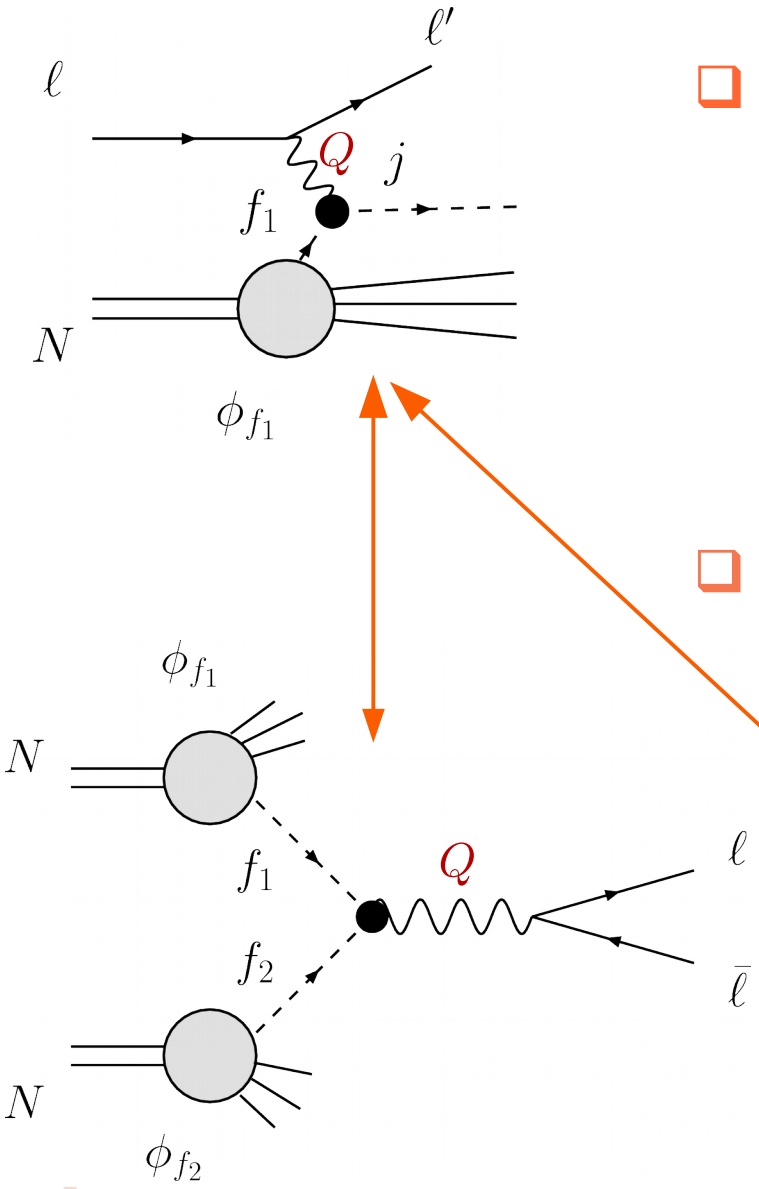
pQCD cross section

- **Universality:** PDF from DIS describe also DY, jets, ...





Factorization and universality



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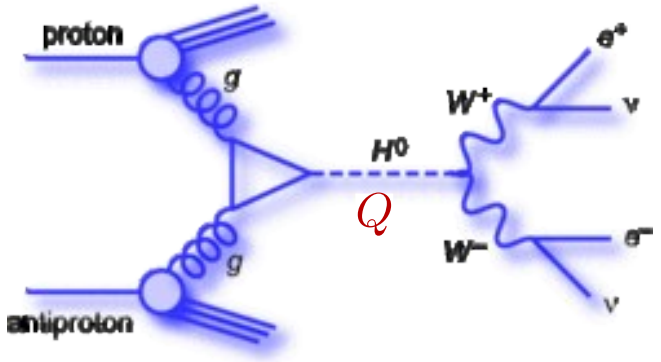
Parton Distribution Fns

pQCD cross section

- **Universality:** PDF from DIS describe also DY, jets, Higgs,
  Beyond Standard Model physics, ...



Global QCD analysis

- **Need**: a set of PDFs in order to, for example,
  - Calculate a particular hard-scattering process (old or new physics)
  - Discover new particles
  - Investigate proton structure, nature of confinement forces
  - Test new theoretical ideas
    - are heavy charm quarks part of the proton's "DNA",
    - can "sea quarks" differ from "sea anti-quarks", …
  - Investigate nuclear dynamics → use Deuteron, heavier nuclei

- **Solution**:

HOW ??

Global QCD analysis of Parton Distribution Functions

Different kinds of experimental data

Rigorous, controllable calculations

Unobservable, but theoretically well defined

Global QCD analysis

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- **Inverse problem**

$$\sigma_i^{\exp} = \phi \otimes \hat{\sigma}_i^{\text{th}}$$

INPUT: *O*(5000) *measurements*

OUPUT: *∞–dimensional functional space*

Global QCD analysis: the standard workflow

data

- DIS: p, d
- p+p(pbar) $\rightarrow l^+l^-$, $W^{\pm}$, Z
- p+p(pbar) $\rightarrow$ jets, γ+jet

theory

- Perturbative QCD
- Factorization & universality
- Large-x, low-Q^2, nuclear corr.

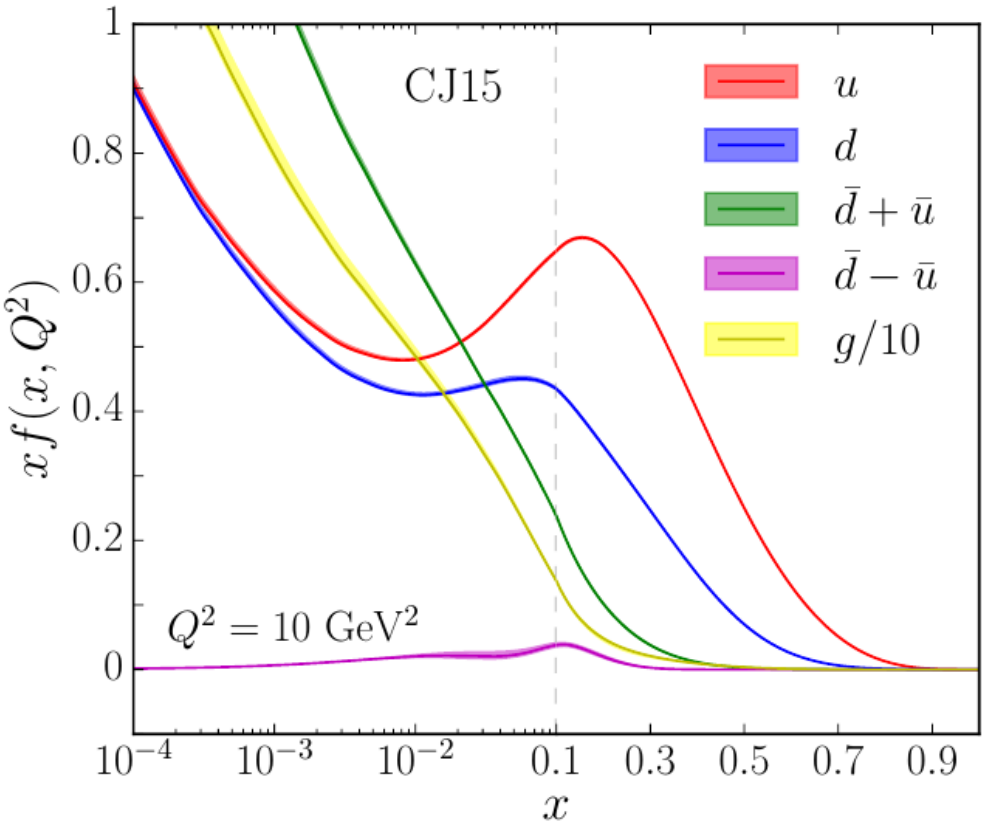
fits

- Parametrize PDF at Q_0, evolve to Q
- Calculate cross sections
- Minimize χ^2

PDFs

F_2(n)
W, Z / W',Z', Higgs
(or any other "hard" observable)

CTEQ-JLab collaboration: "CJ15" PDFs



- Fitted with $\chi^2/\mathrm{datum} = 1.04$
- Hessian error analysis
- Error bands displayed for

$$\Delta\chi^2 = 2.71$$

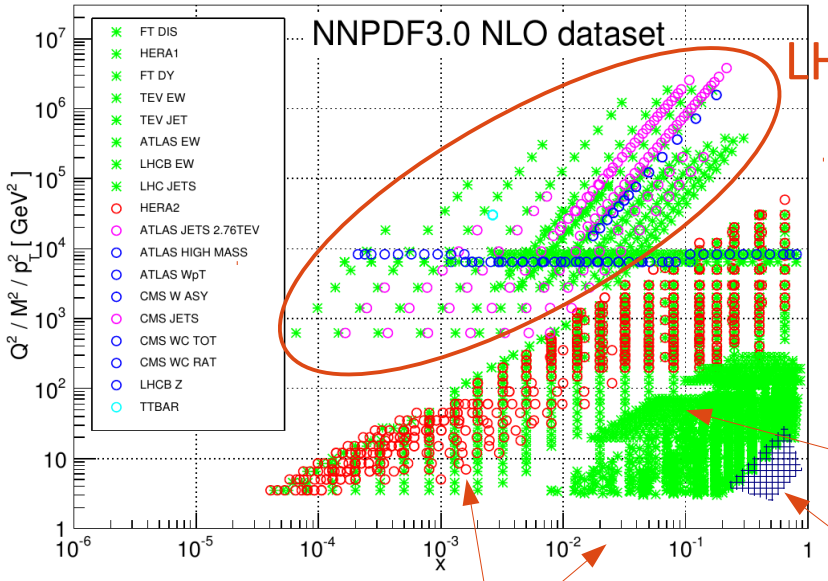
(= 90% confidence level
in a perfect, Gaussian world)

35+ years of unpolarized global PDF fits

	Choice of data						Large-*x* theory			
	JLab & BONUS	HER MES	HERA I+II	Tevatron new W,Z	LHC	ν+A di-μ	Nucl.	HT TMC	Flex *d*	low-W DIS
CJ15 *	✓	✓	✓	✓	*in prog.*	✗	✓✓	✓	✓	✓
CT18			✓	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.1			✓		✓	✓		TMC only		
JR14	✓				✓	✓	✓	✓		
ABMP16/17 **				✓ ¤¤	✓	✓	✓✓	✓		✓
HERAPDF2.0			✓	¤						

* NLO only ** No jet data ¤ see 1503.05221 ¤¤¤ see 1508.06621 ¤¤ no reconstructed W

Data coverage for PDF fits



LHC data

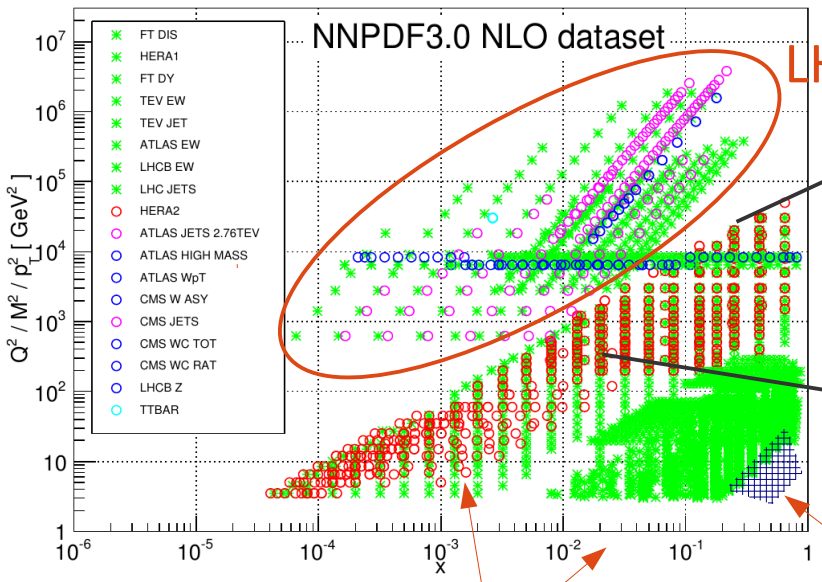
W and Z production in p+p (or anti-p)

Dilepton production in p+p or p+d

SLAC, JLab

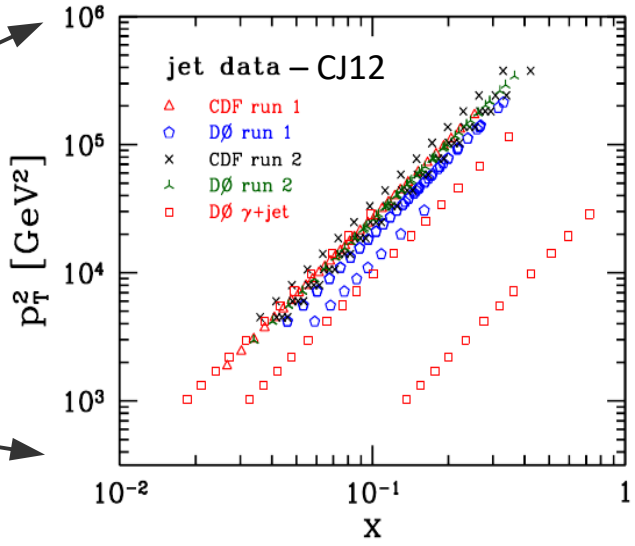
DIS (on p, d)

Data coverage for PDF fits



LHC data

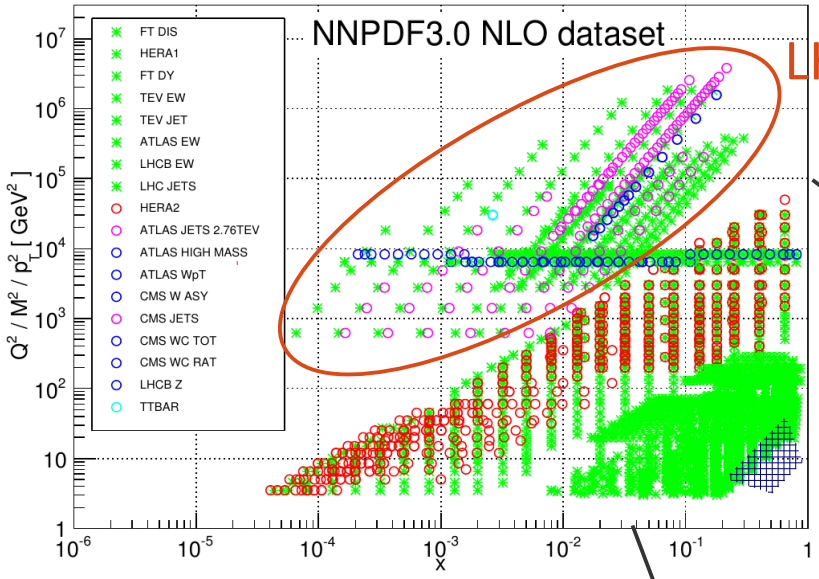
Tevatron Jets



SLAC, JLab

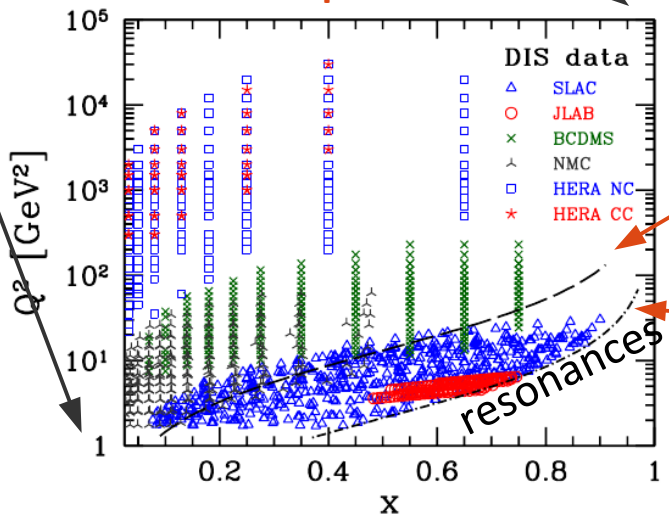
DIS (on p, d)

Data coverage for PDF fits



LHC data

DIS – prot. & deut.



standard cut

$W^2 \gtrsim 14$ GeV^2

CJ15

$W^2 \gtrsim 3.5$ GeV^2

Challenges…

- **Sheer number of data points**
  - Needed for quark flavor separation, kinematic coverage

- **Computational time**
  - (Next-to)-Next-to-Leading order theory for precision
  - Monte-Carlo generators to map onto experimental cuts & details
  - Computational cost grows with every convolution
    - 1 in DIS
    - 2 in nuclear DIS, p+p collisions, SIDIS (e+p → h+X)
    - 3 in p+p → h + X

- **Compatibility of data sets**
  - Different sources, cannot be directly compared experimentally
  - Experiments with different results for same cross section

Challenges…

- **"Faithful" representation** of
  - Experimental uncertainties
  - Theoretical systematics

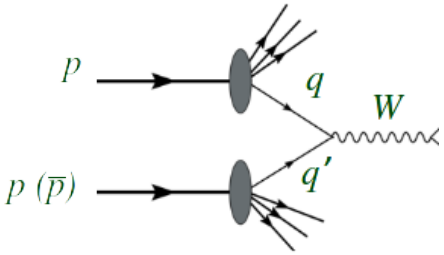
- **Comparison, combination of different QCD analysis**

- **Universal fits:**
  - Simultaneous fitting of different kinds correlation functions
    - polarized & unpolarized
    - fragmentation functions
    - in protons and nuclei, …
  - **All of the above challenges non-linearly compounded!**

- …and a few more…

…and opportunities

W asymmetry



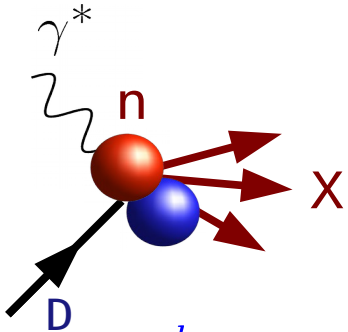
$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$

d/u

&

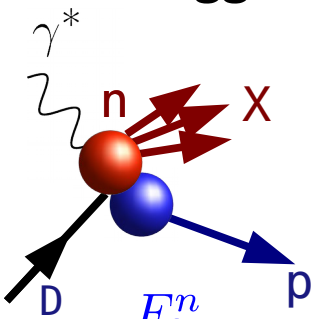
nuclear dynamics

Deep inelastic deuterium



$$F_2^d \propto \mathcal{S}_D \otimes \left[x u_{\text{off}}(x) + x d_{\text{off}}(x)\right]$$

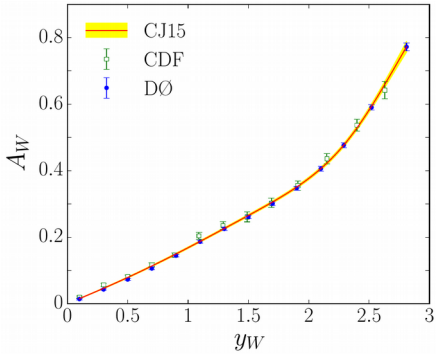
"BONuS" tagged neutron target



$$\frac{F_2^n}{F_2^d} \propto xu(x) + 4xd(x)$$

…and opportunities

Tevatron (also RHIC, LHC)



W asymmetry

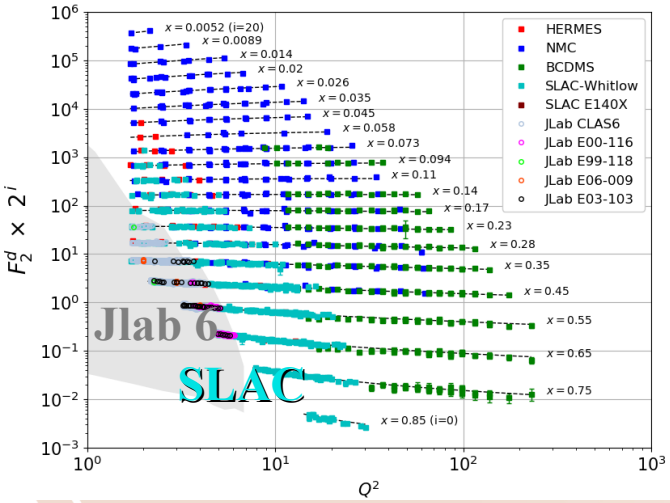
d/u

&

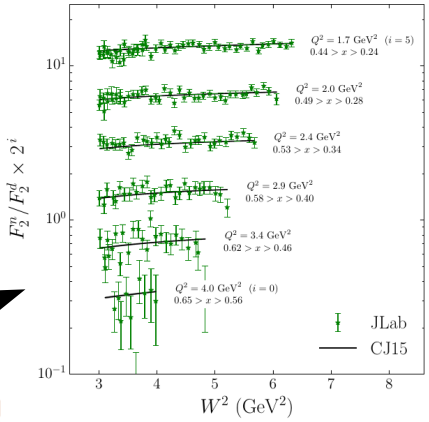
nuclear dynamics

d-quark at largest x
on proton targets

Deep inelastic deuterium



“BONuS” tagged neutron target



& much more at Jlab 12 GeV

Summary

- **Proton structure:** in terms of
  - "unobservable" quarks & gluons
    - but theoretically wel defined
  - Global fits $\leftrightarrow$ inverse problem

- **Many challenges & opportunities**

- **AI to the rescue:**
  - Improve efficiency & reach of global/universal QCD analysis
  - New approaches, **new shared opportunities**