Overview of Parton Distribution Functions

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Outline

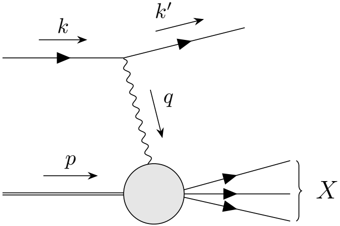
- Introduce parton distributions as necessary to describe sub-nucleon dynamics.
- Motivate nuclear modifications of the PDFs — nPDFs.
- Explain how to gain sensitivity to various types of partons.
- Explore the determination of nPDF sets.

Introduction: PDFs and the Proton Structure

Consider the reaction

$$\ell(k) + N(p) \to \ell'(k') + X(p')$$

- *Momentum exchange*: $Q^2 \equiv -q^2$
- *Inelasticity*: $y \equiv \frac{p \cdot q}{p \cdot k} = 1 - \frac{E'}{E}$
- *Bjorken-x*: $x \equiv \frac{Q^2}{2p \cdot q}$



Pick *two* kinematic variables to describe *inelastic* scattering.

For example, compute the cross section

$$\frac{d^2\sigma}{dx\,dQ^2} \propto \frac{1}{Q^4} L^{\mu\nu} W_{\mu\nu}$$

Where

- The Leptonic Tensor $L^{\mu\nu}$ can be computed perturbatively:

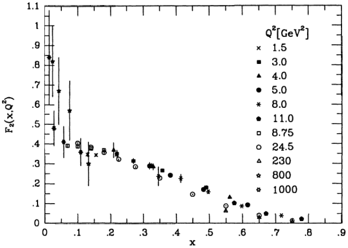
$$L^{\mu\nu} = 4\,e^2\big[(k')^\mu k^\nu + (k')^\nu k^\mu - g^{\mu\nu}(k \cdot k')\big]$$

- The Hadronic Tensor $W^{\mu\nu}$ must be parameterized,

$$W^{\mu\nu} = F_1(Q^2, x)\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) + \frac{2x}{Q^2} F_2(Q^2, x)\left(p^\mu - \frac{p \cdot q}{q^2} q^\mu\right)\left(p^\nu - \frac{p \cdot q}{q^2} q^\nu\right)$$

Measure the structure functions

- Bjorken Scaling: $F_i(x, Q^2) \xrightarrow[Q^2 \to \infty]{} F_i(x)$.
- Understand Q^2 as a momentum scale $\Leftrightarrow$ Spatial Resolution.
- Proton structure independent of resolution.



This suggests a picture of nucleons as composed by point-like constituents — Called *partons*.

Cross-section parameterization

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^4}{Q^4}\left\{\left[1+(1-y)^2\right]F_1 + \frac{1-y}{x}\left[F_2 - 2x\,F_1\right]\right\} =$$

$$= \frac{4\pi\alpha^2}{Q^4}\left[1+(1-y)^2\right]\frac{F_2(x,Q^2)}{2x}$$

Due to the *Callan-Gross relation*

$$F_2(x) = 2x\,F_1(x)$$

Compare with point-like *fermion* cross-section

$$\left(\frac{d\sigma}{dQ^2}\right)_{\text{point}} = \frac{2\pi\alpha^2}{Q^4}\,e_q^2\left[1+(1-y)^2\right]$$

This suggests that partons have spin 1/2!

Model: $F_2(x) = x\sum_i e_i^2 f_i(x)$

Parton Model

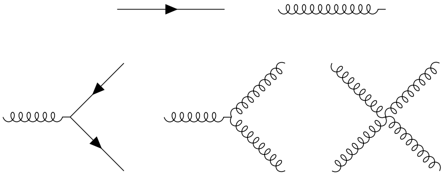
$$F_2(x) = x \sum_i e_i^2 f_i(x)$$

- Bjorken-x as momentum fraction: $(\xi p + q)^2 = 0 \iff \xi = \frac{-q^2}{2p \cdot q} \equiv x$.
- $f_i(x) \equiv$ Probability of finding parton i with momentum fraction x .
- For non-interacting partons, $f_i(x) \sim \delta(x - \xi)$.

Since the structure functions $\mathbf{F_i}$(x) are clearly more complicated, we must describe *parton dynamics*.

- One chooses QCD — SU(3) gauge theory — to describe parton dynamics.
- As a bonus, this predicts the breaking of Bjorken Scaling: $F_i(x) \to F_i(x, Q^2)$.
- This is done by computing the parton evolution (DGLAP):

$$\frac{df_b(x, \mu_F^2)}{d\ln(\mu_F^2)} = \frac{\alpha(\mu_F^2)}{2\pi} \sum_a \int_x^1 \frac{dz}{z} P_{ba}(z) f_a(x/z, \mu_F^2)$$



The Proton Structure

Parton Dynamics

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Sum rules constrain the PDFs

$$\int_0^1 dx \left\{ f_i(x) - \overline{f}_i(x) \right\} = N_i$$

$$\int_0^1 dx\, x \sum_i f_i(x) = 1$$

The Proton Structure

Measuring Parton Distributions

- From the parton model, we have $f_q(x)$, $\overline{f}_q(x)$, $f_g(x)$
- These must be measured from the structure functions of many experiments.
- Isospin symmetry is very useful:

$$f_u^p(x) = f_d^n(x)$$
$$f_d^p(x) = f_u^n(x)$$

Charge	1^{st} Gen.	2^{nd} Gen.	3^{rd} Gen.
$+2/3$	u	c	t
-1/3	d	s	b

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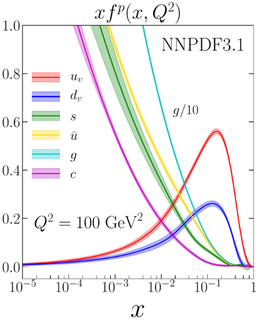
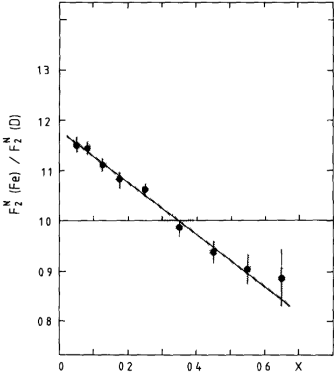


Generally, *u* and *d* are included as *valence quarks*, and $\overline{u}$, $\overline{d}$, $\overline{s}$ as *sea quarks*, while the *gluons* are fixed by the sum rules.

- Consider the structure functions for bound and free nucleons.
- Bjorken-x dependence reveals nuclear modification of PDFs.



This is the EMC effect – revealing the need for nPDFs.

W Production in Ion Collisions

W Boson Production in Ion Collisions

Motivation and Details

- Aim to study $p + Pb \to W\,X \to \mu\,\nu_\mu$ events.

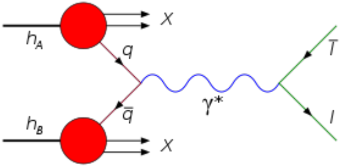
- This probes nuclear modifications as well as sea quarks.

- The predictions of nuclear effects are given by EPPS16 — which we'll discuss later.

W Boson Production in Ion Collisions

Event Selection and Background Removal

- Reducible background — Drell-Yan and μ from multi-jet events — can be tagged and removed.
- Demand that, for a given cone around the lepton, the total energy not exceed 15% of the lepton's.
- Irreducible background — $\bar{t}t$ events, or $\tau \to \mu \nu_\mu$ decays.



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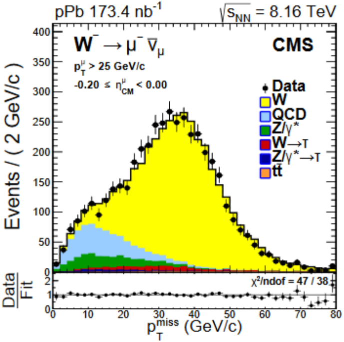
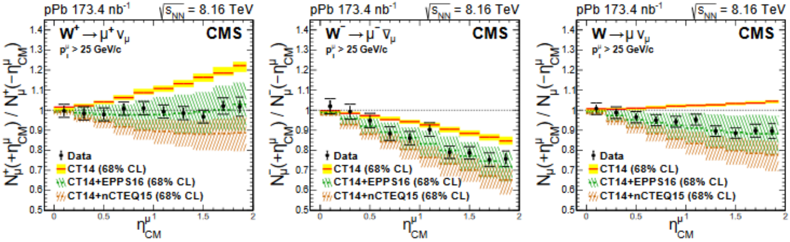


While reducible contributions can be tagged by identifying isolated particles, irreducible contributions must be estimated and subtracted.

- Define the ratios $R_{\mathrm{FB}}^{\pm} = \frac{N^{\pm}(+\eta_{\mathrm{CM}})}{N^{\pm}(-\eta_{\mathrm{CM}})}$, and $R_{\mathrm{FB}} = \frac{N(+\eta_{\mathrm{CM}})}{N(-\eta_{\mathrm{CM}})}$.

- High rapidity $\rightarrow$ small-x. Hence, the sea quark nuclear modifications can be probed.

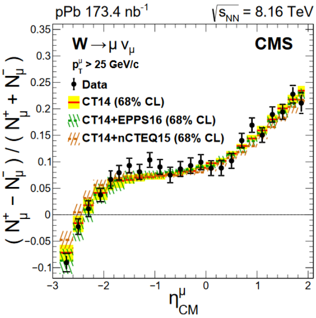
- The data seem to prefer one of the nPDF sets.



W Boson Production in Ion Collisions

Charge Asymmetries

- Define the muon charge-asymmetry
$$\mathcal{A} = \frac{N_\mu^+ - N_\mu^-}{N_\mu^+ + N_\mu^-}.$$
- Because the channels in question are $u\bar{d} \to W^+$ and $d\bar{u} \to W^-$, this observable probes flavor asymmetries in the nPDFs.
- The data seems to agree with both sets on this issue.



Nuclear Parton Distributions

Determination of Nuclear PDFs

Motivation and Details

- As we've seen, nuclear modification of PDFs is a necessity.
- From the EMC effect, there should be some depletion for large-x.
- A careful determination requires multiple data sets.

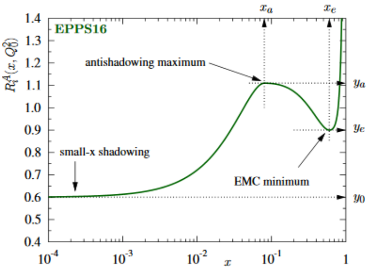
Modification:

$$f_i^{h/A}(x, Q^2) = R_i^A(x, Q^2)\, f_i^h(x, Q^2)\,.$$

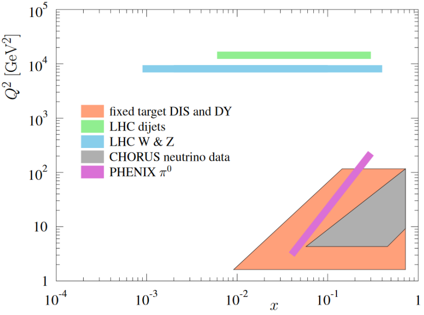
- As expected, one sees shadowing/anti-shadowing regions.

- The flavor independence is combined with isospin symmetries:

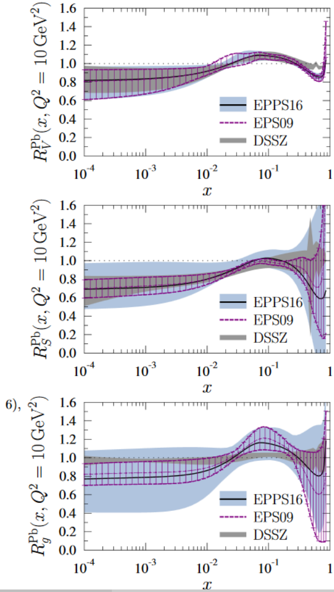
$$f_{u,\bar{u}}^{p/A} = f_{d,\bar{d}}^{n/A}\,,$$
$$f_{d,\bar{d}}^{p/A} = f_{u,\bar{u}}^{n/A}\,,$$
$$f_i^{p/A} = f_i^{n/A}\,, \quad \text{for other flavors.}$$



- Multiple data sets must be used: neutrino DIS, Drell-Yan, LHC data...
- Notice the coverage of the (x, Q^2) plane.
- Small-x physics presents itself as the frontier in these studies.



- Consider nuclear modifications for valence and sea quarks, and gluons
- EPPS16 presents a significant improvement w.r.t. the uncertainties.
- This is explained by the independence of $\overline{u}$, $\overline{d}$ from the remaining sea quarks.



Summary

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- PDFs provide a picture of the proton, with the cost of being non-perturbative objects.
- Nuclear modifications are necessary to explain the EMC effect.
- W production in pPb collisions can probe these modifications as well as the sea quark distributions.
- Good determination of the PDF sets requires careful parameterization and wide kinematic coverage.