First Pion Parton Distribution Function at High- and Low-x

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Jefferson Lab Angular Momentum (JAM) Collaboration

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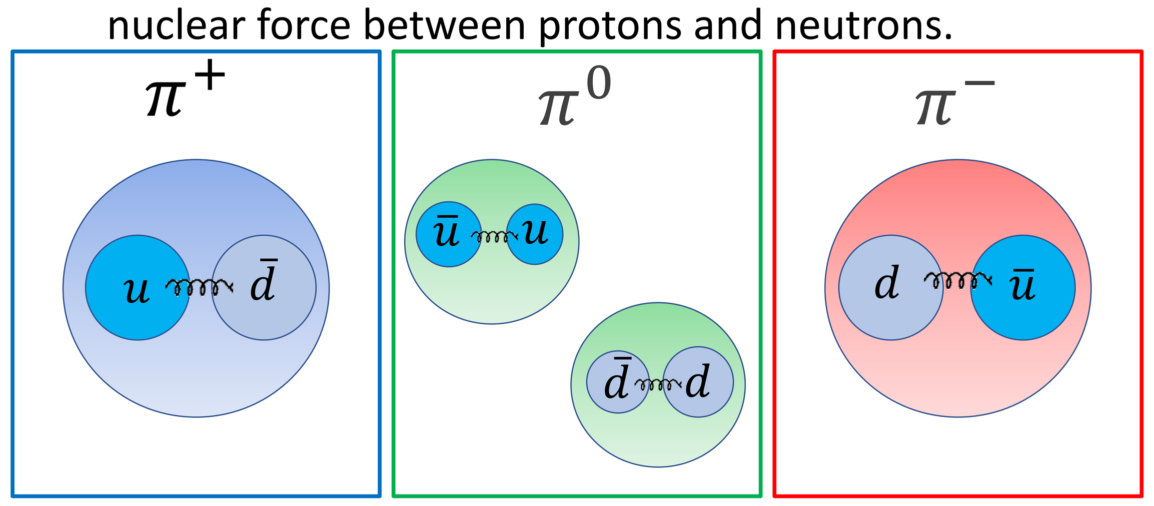
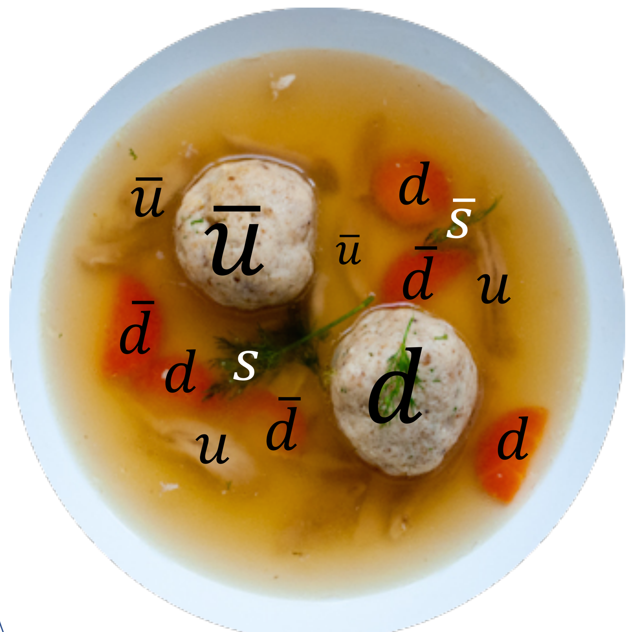
1. Introduction

Pions are known for being the mediator of the strong nuclear force between protons and neutrons.



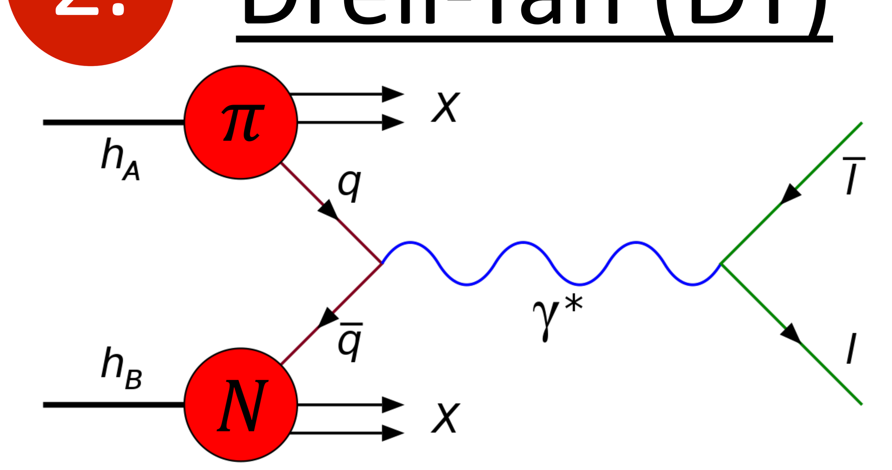
Pions are made of a quark/antiquark pair.



Pions are like **matzo ball soup**, made up of different "ingredients" other than just the matzo balls.

The **valence quarks** (matzo balls) make up the majority of the mass, the **sea quarks** (carrots, chicken and parsley) make up a portion of the total mass, and the **gluons** (broth) hold everything together.

2. Drell-Yan (DY)



The DY process has a pion beam incident on a nucleus, including experiments such as E615 from Fermilab and NA10 from CERN.

One hadron donates a quark, the other an antiquark, which annihilate into a virtual photon, which creates a dilepton pair.

$$\frac{d^2\sigma}{dQ^2 dY} = \frac{4\pi\alpha^2}{9Q^2 S}\sum_{i,j}\int_{x_\pi}^{1}\frac{d\hat{x}_\pi}{\hat{x}_\pi}\int_{x_A}^{1}\frac{d\hat{x}_A}{\hat{x}_A} \times C_{ij}(\hat{x}_\pi, \hat{x}_A, x_\pi, x_A, Q/\mu) f_i^\pi(\hat{x}_\pi,\mu) f_j^A(\hat{x}_A,\mu)$$

Differential cross-section of dilepton pair

C_{ij} is the hard-scattering kernel, and $f(\hat{x},\mu)$ are the parton distribution functions (PDFs), which are functions of the momentum fraction of the hadron, $\hat{x}$, and energy scale μ.

3. Leading Neutron (LN)

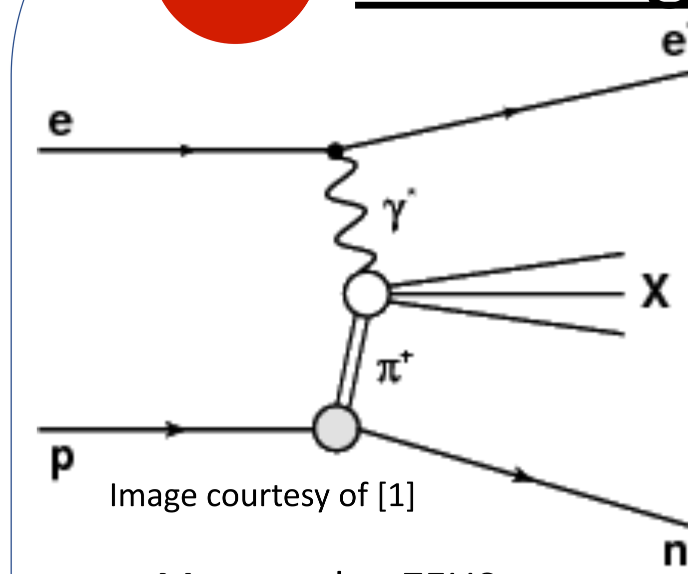


Image courtesy of [1]

Electron (e), incident on a proton (p), which splits into a π^+ and a neutron (n).

The neutron carries the majority of the longitudinal momentum of the proton, x_L.

Experiments from HERA at DESY such as H1 and ZEUS measure LN electro-production.

Measured at ZEUS

$$r(x, Q^2, x_L) = 2 f_N(y)\frac{F_2^\pi(x_\pi, Q^2)}{F_2^p(x, Q^2)}\Delta x_L$$

Measured at H1

$$F_2^{\mathrm{LN}(3)} = 2 f_{\pi N}(x_L) F_2^\pi(x_\pi, Q^2)$$

$F_2^{p,\pi}$ - structure function of the proton or pion (made up of PDFs).

πN splitting function:

$$f_{\pi N}(x_L) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \times \int dk_\perp^2 \frac{[k_\perp^2 + (1-x_L)^2 M^2]}{D_{\pi N}^2}|\mathcal{F}|^2$$

Need regulator $\mathcal{F}$ to save logarithmic divergence – associated with the finite size of the nucleon. This creates 5 models to test.

$$D_{\pi N} \equiv t - m_\pi^2 = -[k_\perp^2 + (1-x_L)^2 M^2 + x_L m_\pi^2]/x_L$$

4. Fitting Procedure

Nested Sampling

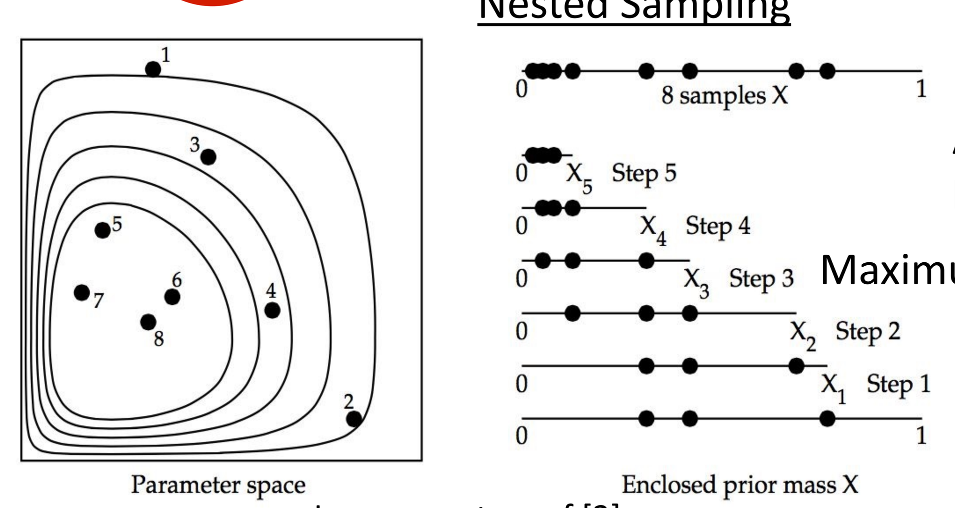


Image courtesy of [2]

As X decreases, Likelihood, $\mathcal{L}$ increases.

Maximum $\mathcal{L}$ is the minimum χ^2.

Rigorous determination of uncertainties.

General form for PDF

Fit parameters: N, α, β

$$f_\pi(x_\pi, Q^2; \boldsymbol{a}) = \frac{N}{B(1+\alpha, 1+\beta)} x_\pi^\alpha (1-x_\pi)^\beta$$

We determine the valence PDF, q_v^π, the sea quark, q_s^π, and the gluon, g^π.

5. Data & Theory Comparison

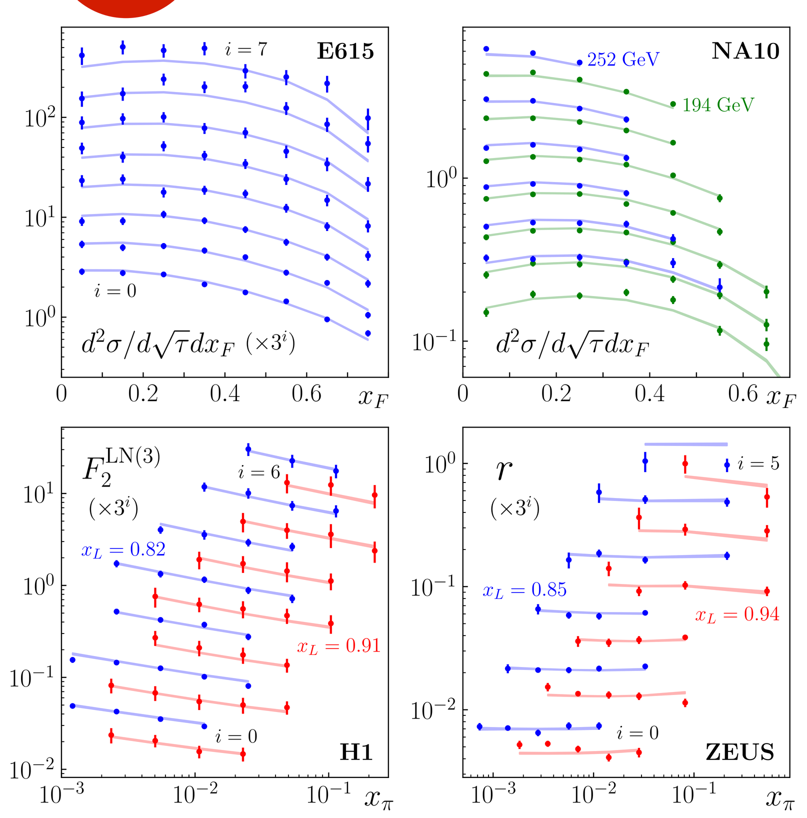
Good fit ($\chi^2_{npts} \sim 1$) among models.

s-dep. exponential gives best χ^2.

Model ($\mathcal{F}$)	χ^2_{npts}
s-dep. exponential	0.979
Regge	1.051
t-dep. monopole	1.064
t-dep. exponential	1.071
Pauli-Villars	1.095

Also good fit to only DY data (not shown here) ($\chi^2_{npts} = 0.972$).

5. Data & Theory Comparison



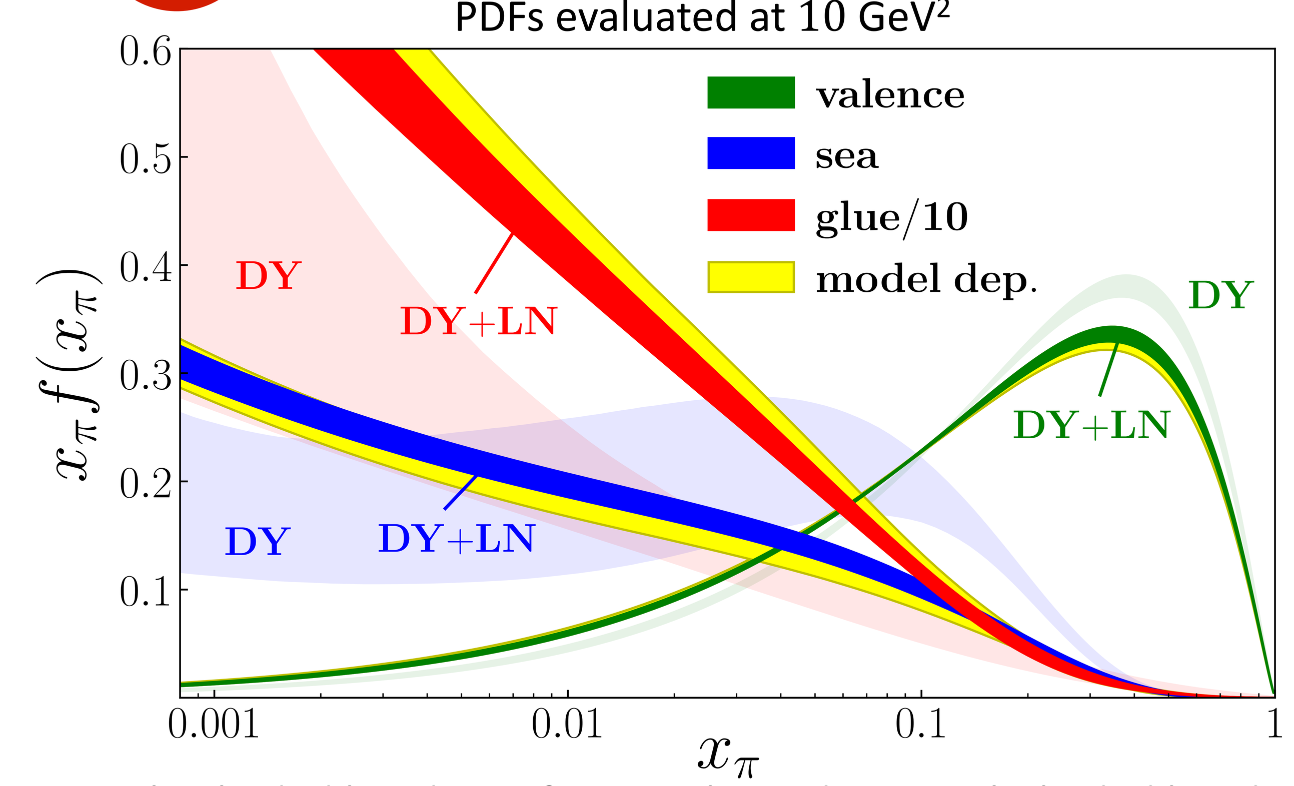
Data (points) and theory calculations (curves) for all of the data sets.

s-dep. exponential breakdown by individual data set.

Data set	# data points	χ^2
E615	72	81.82
NA10 (194 GeV)	44	41.52
NA10 (252 GeV)	26	28.85
H1	58	21.98
ZEUS	50	70.62

6. PDF Result

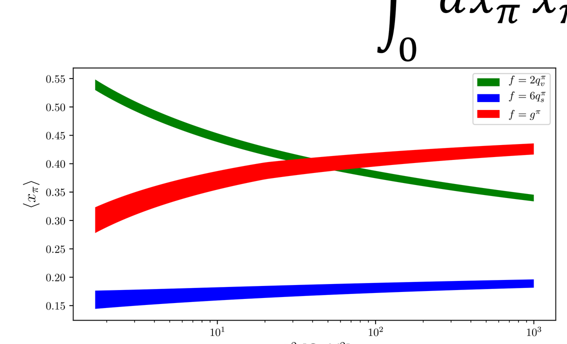
PDFs evaluated at 10 GeV²



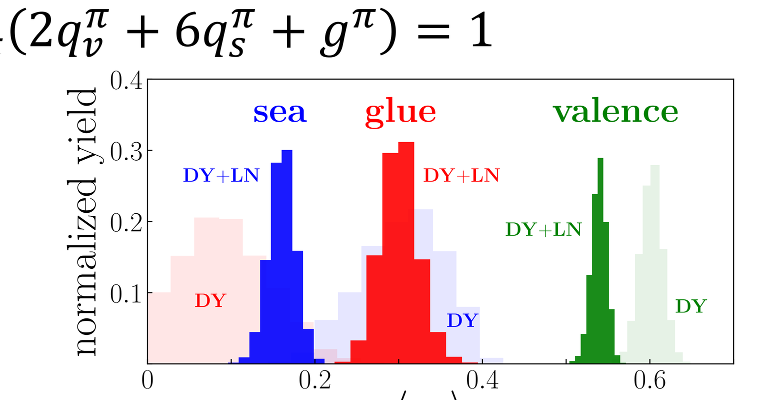
Light shaded bands are fits to only DY data. Dark shaded bands are fits to DY+LN data using s-dep. exponential model. Yellow bands represent spread from all model dependence.

7. Momentum Sum Rule

$$\int_0^1 dx_\pi\, x_\pi (2q_v^\pi + 6q_s^\pi + g^\pi) = 1$$



Q^2 dependence on $\langle x_\pi \rangle$.



Distribution of momenta evaluated at $Q^2 = m_c^2$.

flavor	JAM	GRS	MRS (10% sea)	MRS (15% sea)	MRS (20% sea)
$\langle x_\pi \rangle_v$	0.445	0.365	0.438	0.438	0.438
$\langle x_\pi \rangle_s$	0.171	0.178	0.111	0.156	0.202
$\langle x_\pi \rangle_g$	0.371	0.456	0.441	0.398	0.355

Comparison of JAM momenta vs GRS [3] and MRS [4] momenta, evaluated at $Q^2 \sim 10$ GeV².

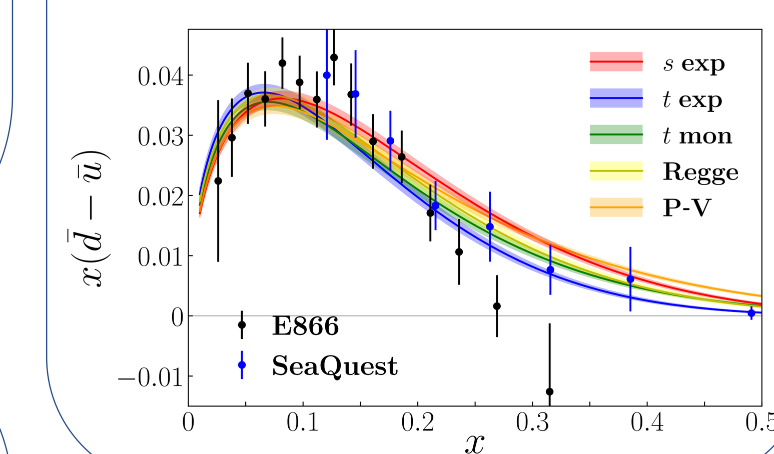
8. $\bar{d} - \bar{u}$ Asymmetry

$$\bar{d} - \bar{u} = \left(f_{\pi^+ n} - \frac{2}{3} f_{\pi^- \Delta^{++}}\right) \otimes q_v^\pi$$

The $\otimes$ symbol indicates a convolution.

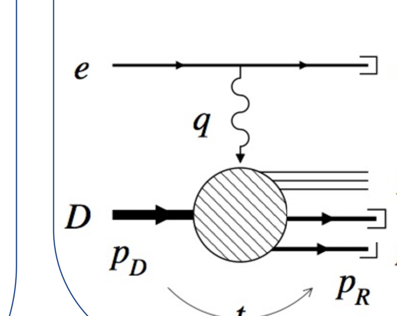
The splitting function $f_{\pi^-\Delta^{++}}$ is shown in [5].

Assuming that all the $\bar{d} - \bar{u}$ asymmetry in the proton is due to the pion, we get the following fit to the DY+LN+E866 data (SeaQuest data is preliminary):



9. Future Work

Determine the high-x_π behavior more accurately using soft collinear effective theory (SCET) and investigate higher-twist effects.



Look at future experiments, such as TDIS (shown to the left) at Jefferson Lab.

10. Conclusions

This analysis provides the first pion PDF determined at both high- (using DY data) and low-x_π (using LN data) regions.

We also use nested sampling for the first time in global pion QCD analysis at next-to-leading order in the strong coupling constant α_S.

We learn that at the input scale, the gluon carries a significantly larger momentum than inferred by only the DY data, while the sea quark carries a slightly lower momentum.

References: [1] Buniatyan, Armen, Proceedings of Science (2010).
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A submission of this work to Physical Review Letters is coming soon.

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