

First combined analysis of (un)polarized PDFs and FFs and beyond

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DNP, Hadron Structure

Hawaii, 2018



Motivations

Mapping the parton structure of the nucleon

■ Challenges:

- + **Quantitative** limits of $x, Q^2, z, \dots$ where factorization theorems are applicable
- + Universality of non perturbative objects
→ **predictive power**
- + QCD analysis framework that extracts **simultaneously** all non-perturbative objects (including TMDs)
- + Framework with the same theory assumptions

Mapping the parton structure of the nucleon

■ Need for a **reliable** Bayesian likelihood analysis:

- + Retire maximum likelihood methods that can lead to biased results (CT, MMHT, DSSV, ...)
- + Embrace likelihood analysis via MC methods (JAM, NNPDF)
- + Faithful representation of uncertainties consistent with Bayes' theorem

Bayesian likelihood analysis

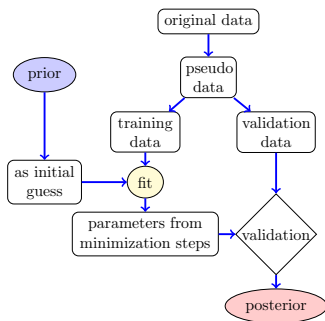
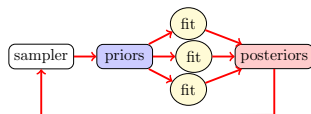
■ Inclusion of modern data analysis techniques

+ Bayesian theorem

$$\mathcal{P}(f|\text{data}) = \mathcal{L}(\text{data}, f)\pi(f)$$

+ Estimation of expectation values and variances:

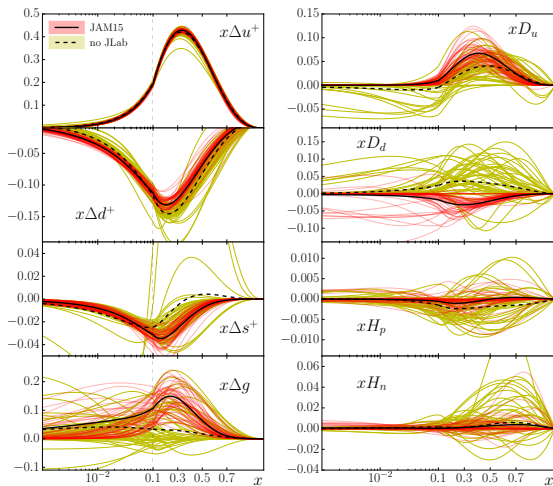
- data resampling
- partition and cross validation
- iterative Monte Carlo (IMC)
- nested sampling



History

JAM15: Δ PDFs

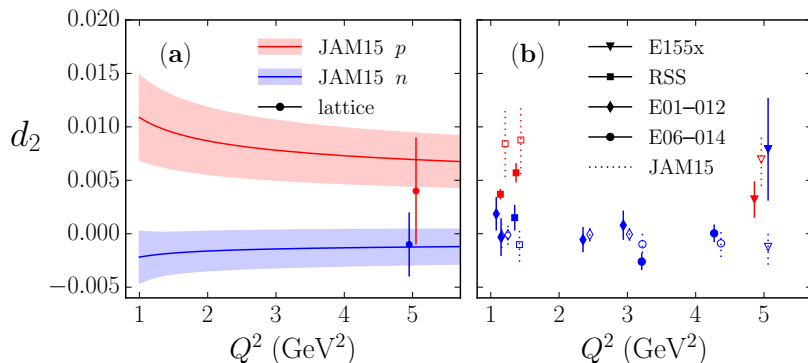
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



- Inclusion of all JLab 6 GeV data $\rightarrow 0.1 < x < 0.7$
- Non vanishing twist 3 quark distributions
- Residual twist 4 contributions consistent with zero

JAM15: d_2 matrix element

NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)

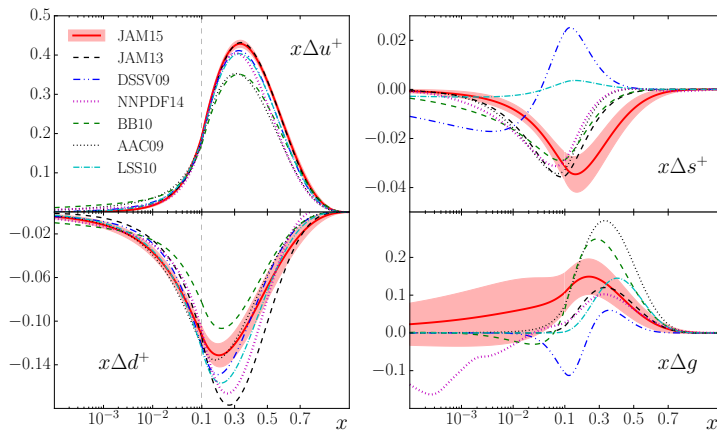


- Existing measurements of d_2 are in the resonance region
→ quark-hadron duality

$$d_2(Q^2) \equiv \int_0^1 dx x^2 \left[2g_1^{\tau^3}(x, Q^2) + 3g_2^{\tau^3}(x, Q^2) \right]$$

JAM15: Δ PDFs

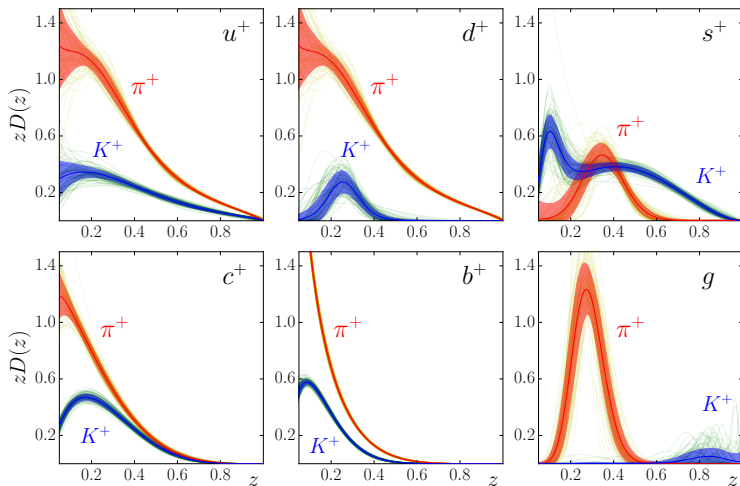
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



- SU2, SU3 constraints imposed
- What determines the sign of Δs^+ ?

JAM16: FFs

NS, Ethier, Melnitchouk, Hirai, Kumano, Accardi (PRD)

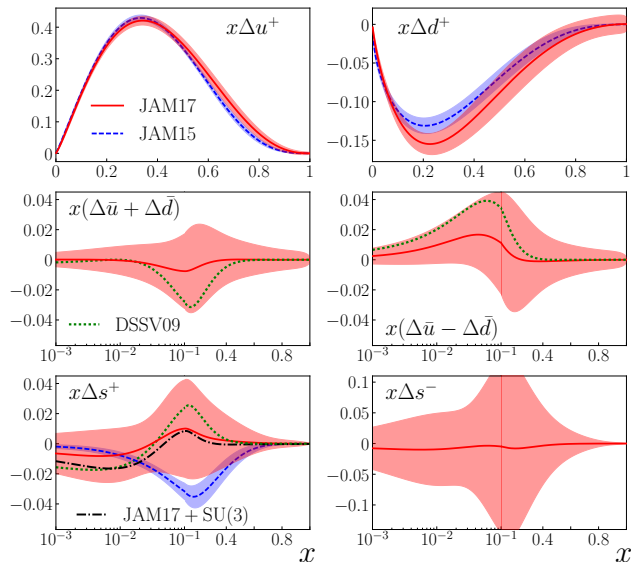


■ π and K Belle, BaBar up to LEP energies

■ JAM and DSS $D_{s^+}^K$ **consistent**

JAM17: $\Delta\text{PDF} + \text{FF}$

Ethier, NS, Melnitchouk (PRL)



■ No SU(3) constraints

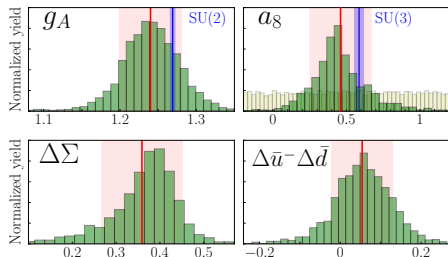
■ Sea polarization consistent with zero

■ Precision of ΔSIDIS is not sufficient to determine sea polarization

JAM17: Δ PDF +FF

Ethier, NS, Melnitchouk (PRL)

- **Flat priors** that gives flat a_8 in order to have an unbiased extraction of a_8
- Data prefers smaller values for $a_8 \rightarrow 25\%$ larger total spin carried by quarks.
- a_3 which is in a good agreement with values from β decays **within 2%**.



obs.	JAM15	JAM17
g_A	1.269(3)	1.24(4)
g_8	0.586(31)	0.46(21)
$\Delta\Sigma$	0.28(4)	0.36(9)
$\Delta\bar{u} - \Delta\bar{d}$	0	0.05(8)

Present

JAM18: Universal analysis (preliminary)

Andres, Ethier, Melnitchouk, NS, Rogers

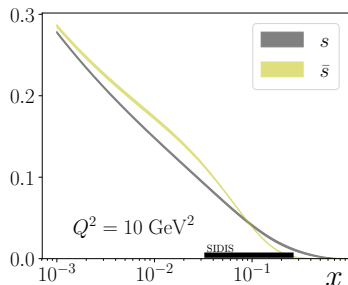
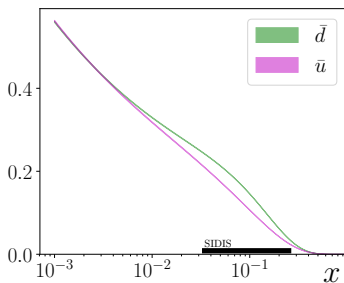
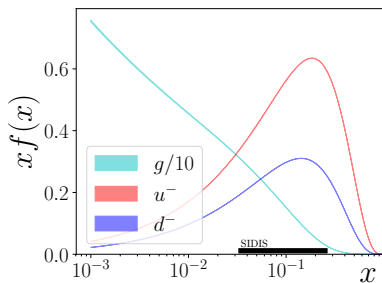
■ Goals

- + Extract PDFs, Δ PDFs and FFs **simultaneously**
 - DIS, SIDIS(π, K), DY
 - Δ DIS, Δ SIDIS(π, K)
 - $e^+e^- (\pi, K)$
- + Consistent extraction of s and Δs

■ Likelihood analysis (first steps)

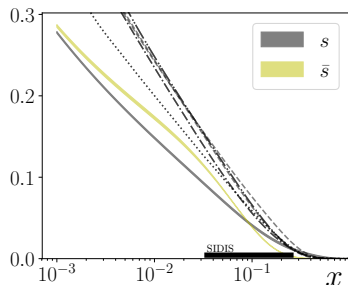
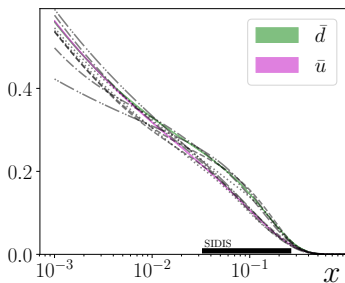
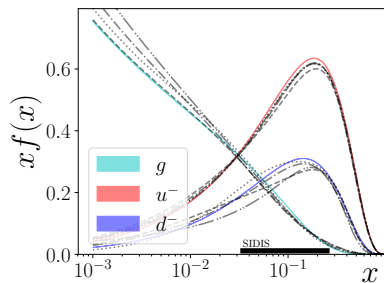
- + Use maximum likelihood to find a candidate solution
- + Use resampling to **check for stability** and estimate uncertainties
- + 80 shape parameters and 91 data normalization parameters:
171 dimensional space

JAM18: PDFs (preliminary)



- $\bar{d} - \bar{u}$ constrained mainly by DY
- SIDIS is in agreement with DY's $\bar{d} - \bar{u}$
- $s - \bar{s} \neq 0$

JAM18: PDFs (preliminary)

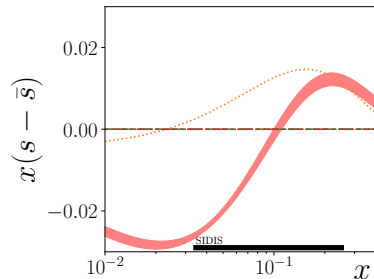
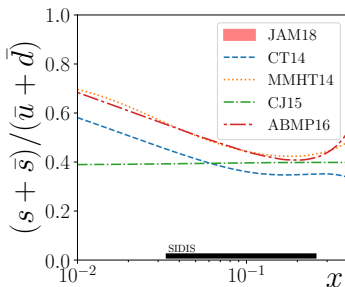
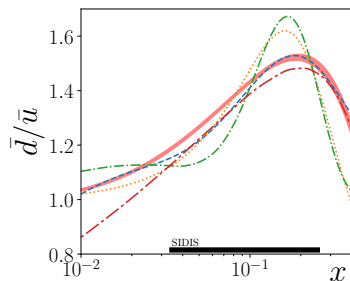


■ Comparison with other groups

- + dashed: MMHT14
- + dashed-dotted: CT14
- + dotted: CJ15
- + dot-dot-dash: ABMP16

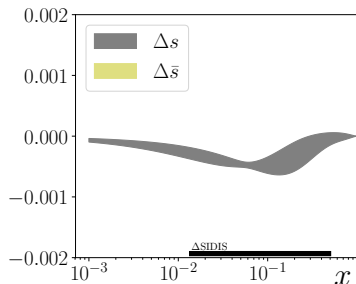
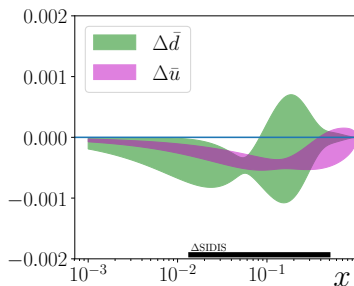
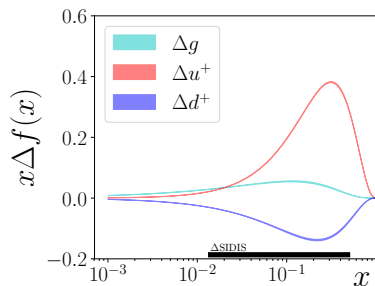
■ Big differences for $s, \bar{s}$ distributions

JAM18: upolarized sea (preliminary)



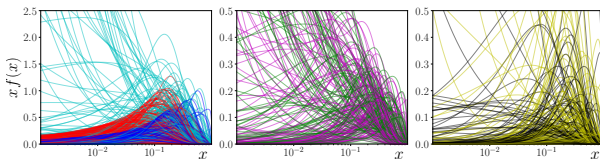
- For CJ and CT, $s = \bar{s}$
- MMHT uses neutrino DIS
- SIDIS favors a strange suppression
- and a larger $s, \bar{s}$ asymmetry

JAM18: Δ PDFs (preliminary)

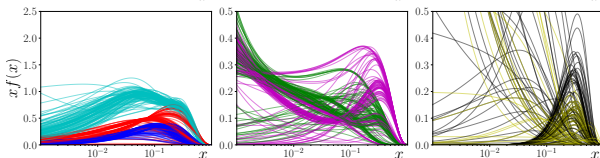


- Recall no SU2,SU3 imposed
- $\Delta s, \Delta \bar{u}, \Delta \bar{d}$ are much better known than $\Delta \bar{s}$
- It means, most of the uncertainty on Δs^+ is from $\Delta \bar{s}$

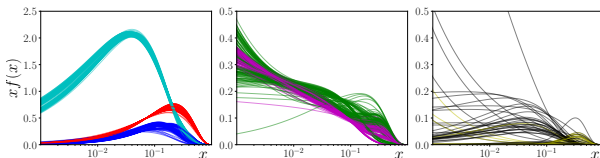
JAM18: IMC runs (preliminary)



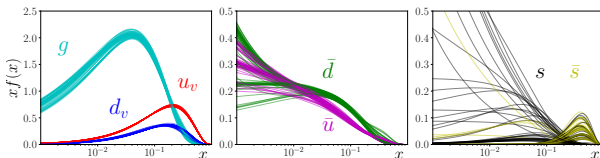
← flat priors



← DIS no HERA



← DIS with HERA

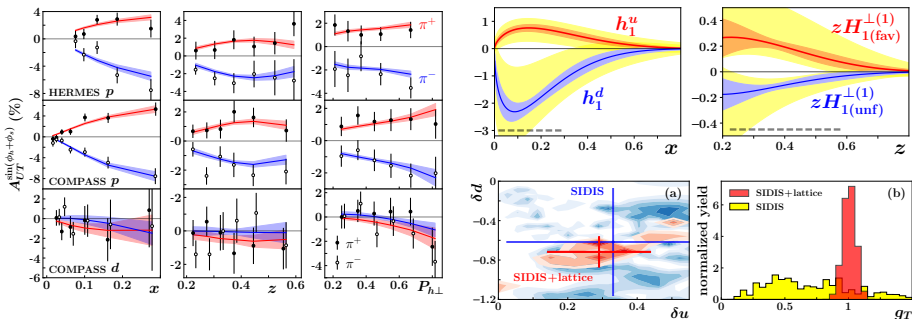


← DIS with HERA + DY

... and beyond

SIDIS+Lattice analysis of nucleon tensor charge

Lin, Melnitchouk, Prokudin, NS, Shows (PRL)



- Extraction of transversity and Collins FFs from SIDIS A_{UT} +Lattice g_T

- In the absence of Lattice, SIDIS has no significant constraints on g_T

(See talk by W. Melnitchouk)

First global Monte Carlo analysis of pion PDFs

Barry, NS, Melnitchouk, Ji (PRL)



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First Monte Carlo Global QCD Analysis of Pion Parton Distributions

Overview of attention for article published in Physical Review Letters, October 2018



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**physicsworld** **Gluons account for much more pion momentum than previously thought - Physics World**
physicsworld.com, 19 Oct 2018
Gluons contribute around 30% to the total momentum of energetic pions, which is about three times more than previously estimated.

**Researchers discover more gluons in the pion**
Phys.org, 12 Oct 2018
Home Physics General

**Synopsis: More Gluons in the Pion**
American Physical Society
A combined analysis of collider data finds that the gluon contribution to the pion is 3 times larger than earlier estimates.



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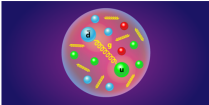
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Synopsis: More Gluons in the Pion

October 10, 2018

A combined analysis of collider data finds that the gluon contribution to the pion is 3 times larger than earlier estimates.



APS News Distribution

First Monte Carlo Global QCD Analysis of Pion Parton Distributions
P. C. Barry, N. Sato, W. Melnitchouk, and Chueng-Boyang Ji (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. Lett. 121, 152001 (2018)
Published October 10, 2018

Features
Arts & Culture: Poetry Takes on Quantum Physics
Poet Amy Catanzano hopes that poetry can help physicists develop a more effective and accurate language to describe the complex ideas of

First global Monte Carlo analysis of pion PDFs

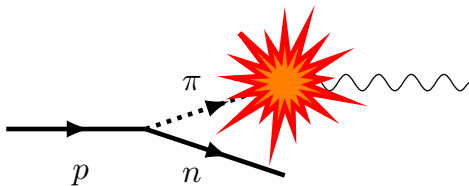
Barry, NS, Melnitchouk, Ji (PRL)

■ How to probe pion structure

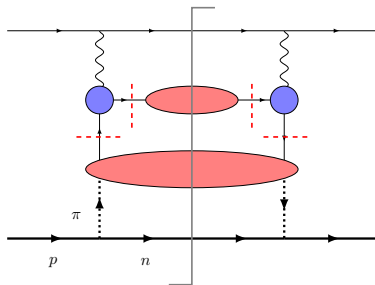
+ $\pi + A \rightarrow l\bar{l} + X$ (Drell-Yan)

+ $\pi + A \rightarrow \gamma + X$ (prompt photons)

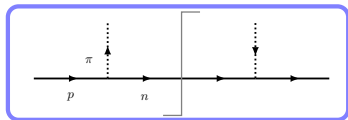
+ $e + p \rightarrow e' + n + X$ (SIDIS) $\rightarrow$ small x_π gluon PDF



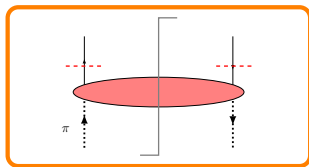
Factorization setup



χ EFT



pQCD



$$\frac{d\sigma}{dx dQ^2 dy} \sim f_{p \rightarrow \pi+n}(y) \times \sum_q \int_{x/y}^1 \frac{d\xi}{\xi} C(\xi) q\left(\frac{x/y}{\xi}, Q^2\right)$$

- The splitting function ($y = k^+/p^+ = x/x_\pi$)

$$f_{p \rightarrow \pi+n}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \frac{y(k_\perp^2 + y^2 M^2)}{(1-y)^2 D_{\pi N}^2} |F|^2$$

- UV regulators used in the literature

$F = \begin{cases}$	$\left[1 - \frac{(t-m_\pi^2)^2}{(t-\Lambda^2)^2}\right]^{1/2}$	Pauli-Villars
$\begin{cases}$	$(\Lambda^2 - m_\pi^2)/(\Lambda^2 - t)$	t -dependent monopole
$\begin{cases}$	$\exp[(t - m_\pi^2)/\Lambda^2]$	t -dependent exponential
$\begin{cases}$	$\exp[(M^2 - s)/\Lambda^2]$	s -dependent exponential
$\begin{cases}$	$y^{-\alpha_\pi(t)} \exp[(t - m_\pi^2)/\Lambda^2]$	Regge exponential,

pQCD setup

- $\pi^- + W \rightarrow l\bar{l} + X$ (Drell-Yan)

$$\frac{d\sigma}{dx_F dQ^2} = \sum_{a,b} \int d\xi d\zeta C_{a,b}(\xi, \zeta) f_{a/\pi^-}(\xi) f_{b/W}(\zeta)$$

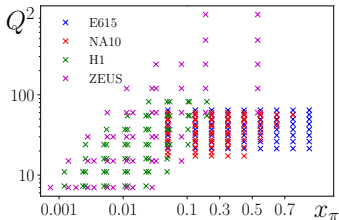
- $e + p \rightarrow e' + n + X$ (LN)

$$\frac{d\sigma}{dx dQ^2 dy} \sim f_{p \rightarrow \pi+n}(y) \times \sum_q \int_{x/y}^1 \frac{d\xi}{\xi} C(\xi) f_{q/\pi^+}\left(\frac{x/y}{\xi}\right)$$

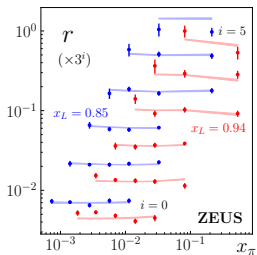
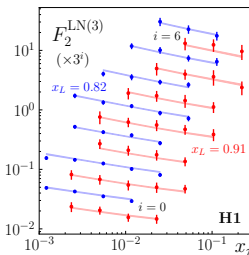
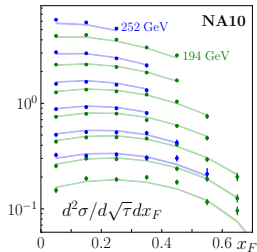
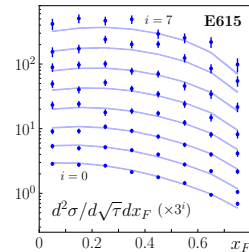
- We parametrize PDFs in π^-

- + Valence: $\bar{u}_v = d_v$
- + Sea: $u = \bar{d} = s = \bar{s}$
- + Gluon: g

Results



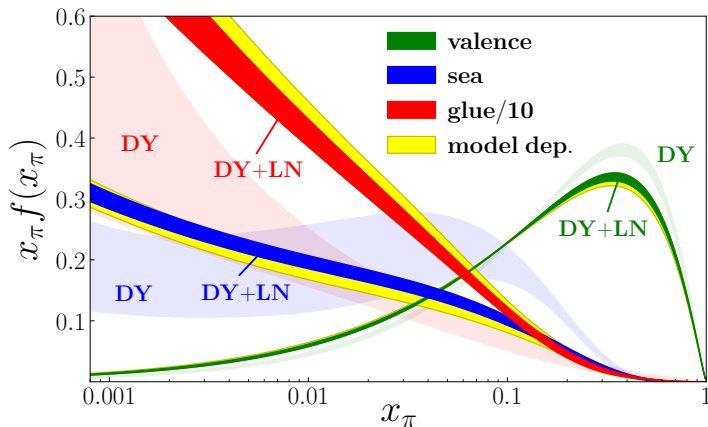
- Our new analysis extends previous pion PDF analysis down to $x \sim 0.001$
- The OPE+pQCD can describe the HERA data **simultaneously** with the DY data



$$F_2^{LN(3)}(x, Q^2, y) = 2f_{p \rightarrow \pi+n}(y)F_2^\pi(x_\pi, Q^2)$$

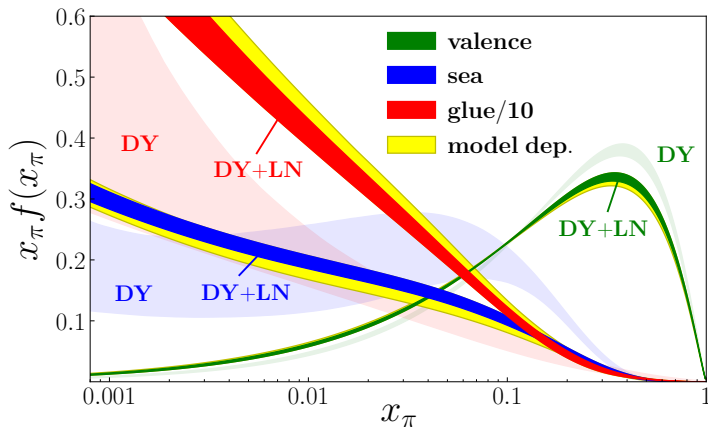
$$r(x, Q^2, y) = \frac{d^3 \sigma^{LN} / dx dQ^2 dy}{d^2 \sigma^{inc} / dx dQ^2} \Delta y$$

Results



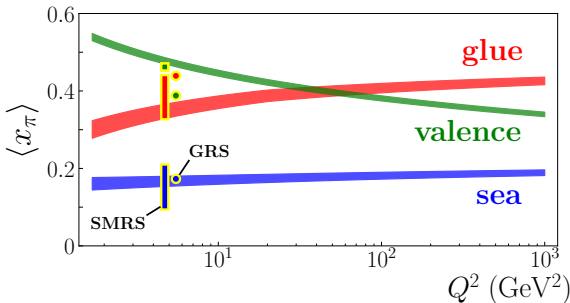
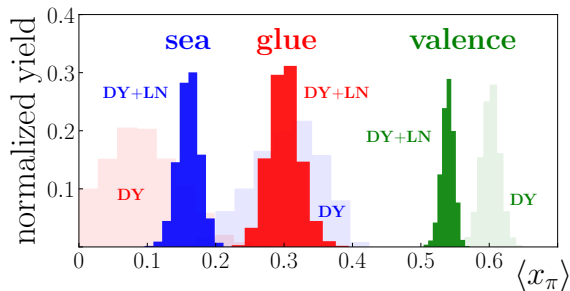
- Significant reduction of the uncertainties
- Non-overlapping uncertainties $\rightarrow$ tensions among the data
- Accuracy will be improved with future TDIS (JLab12/EIC)

Results



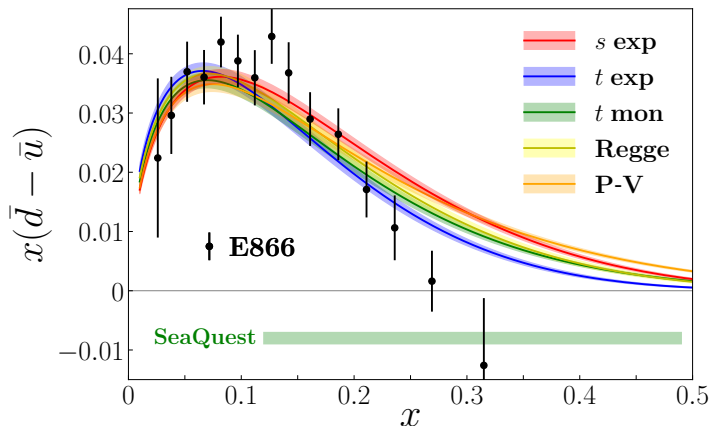
- Model dependence in LN is comparable to statistical uncertainties
- DY+LN cannot discriminate among the OPE models

Results



- Constraints from HERA significantly increase $\langle x_\pi^g \rangle$.
The role of the glue is more important than suggested by DY alone
- In contrast, the strength of the sea is reduced
- Due to momentum sum rule $\langle x_\pi^{\text{valence}} \rangle$ decreases

Results



- We performed an additional analysis of LN+DY+E866
→ good description of E866 data except for large x

Summary and outlook

