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

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Motivations

Mapping the parton strucure of the nucleon

- **Challenges:**

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

Mapping the parton strucure 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

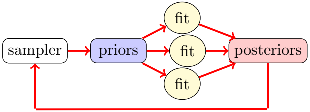
- **Inclusion of modern data analysis techniques**

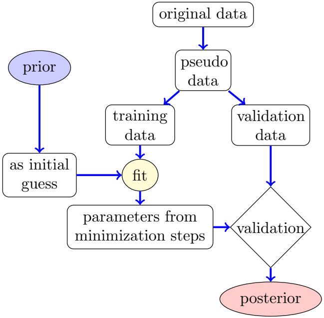
  + Bayesian theorm

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

  + Estimation of expectation values and variances:

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

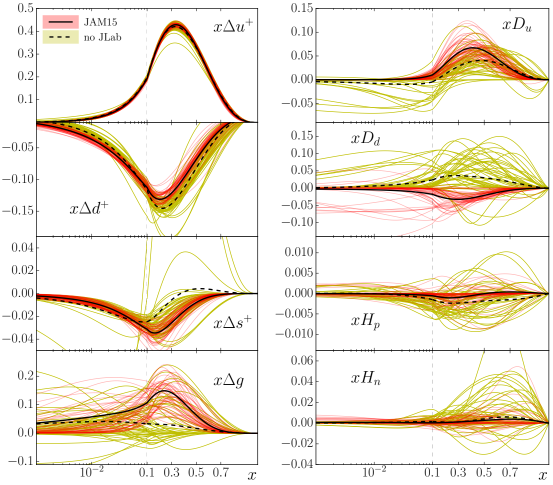




History

JAM15: $\triangle$PDFs

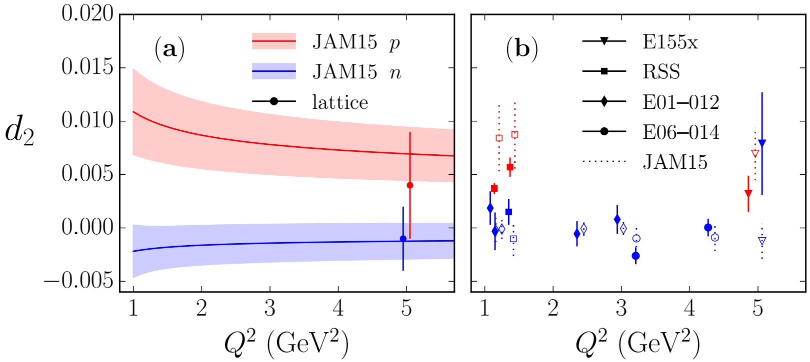
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



- 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)

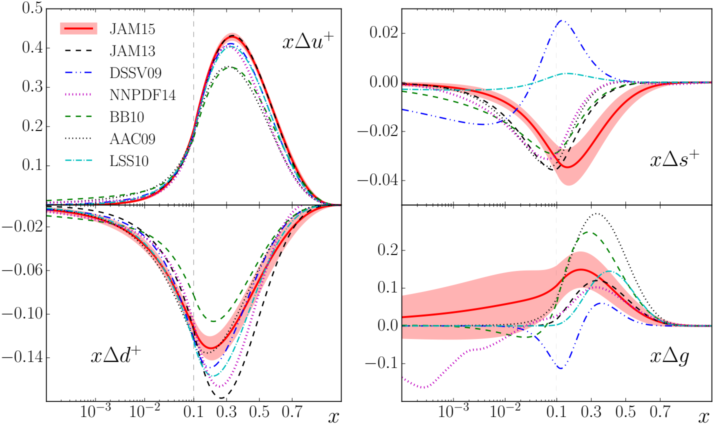


- Existing measurements of d_2 are in the resonance region
  $\rightarrow$ quark-hadron duality

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

JAM15: ΔPDFs

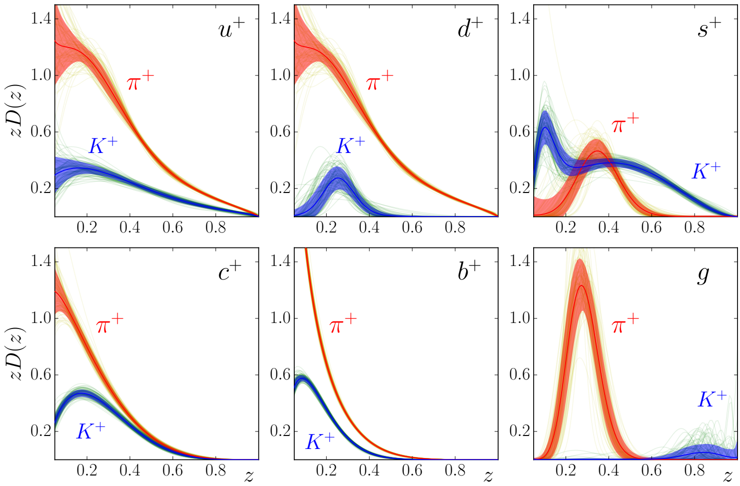
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



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

JAM16: FFs

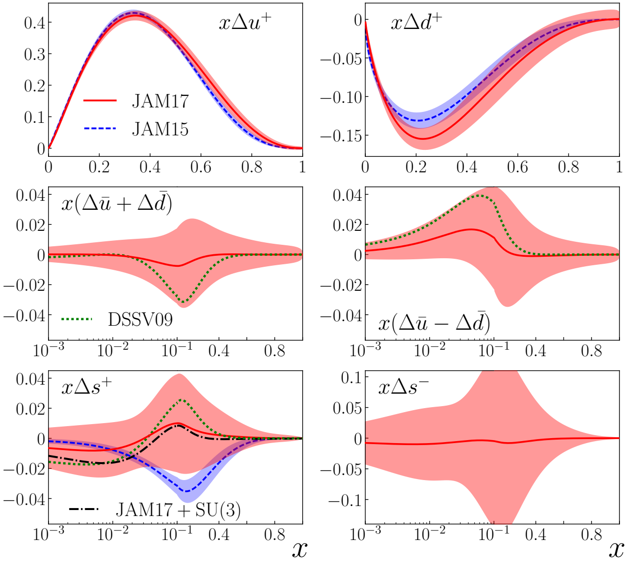
NS, Ethier, Melnitchouk, Hirai, Kumano, Accardi (PRD)



- π and K Belle, BaBar up to LEP energies
- JAM and DSS $D_{s^+}^K$ **consistent**

JAM17: ΔPDF +FF

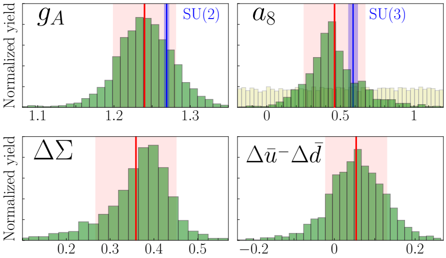
Ethier, NS, Melnitchouk (PRL)



- No SU(3) constraints
- Sea polarization consistent with zero
- Precision of ΔSIDIS is not sufficient to determine sea polarization

JAM17: ΔPDF +FF

Ethier, NS, Melnitchouk (PRL)



- **Flat priors** that gives flat a_8 in order to have an unbias 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

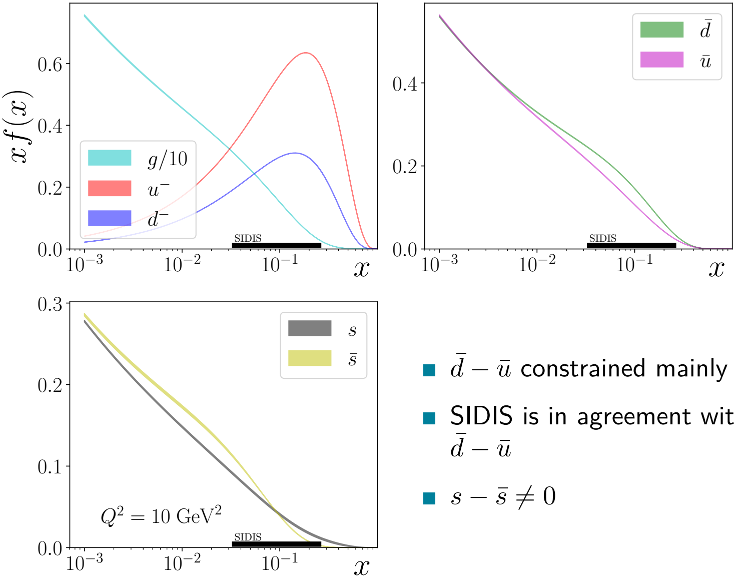
JAM18: Universal analysis (preliminary)

Andres, Ethier, Melnitchouk, NS, Rogers

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

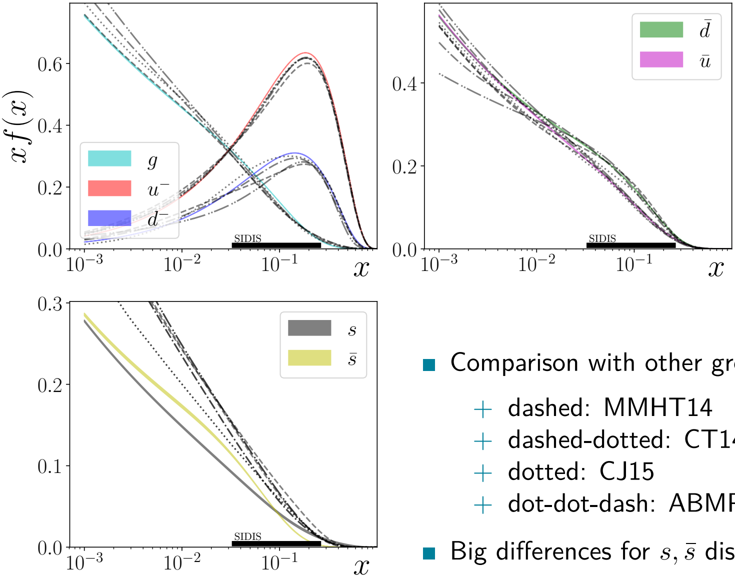
- **Likelihood analysis (first steps)**
  - Use maximum likelihood to find a candidate solution
  - Use resampling to **check for stability** and estimate uncertainties
  - 80 shape parameters and 91 data normalization parameters: **171 dimensional space**

JAM18: PDFs (preliminary)



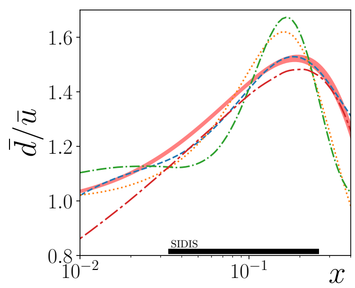
- $\bar{d} - \bar{u}$ constrained mainly by DY
- SIDIS is in agreement with DY's $\bar{d} - \bar{u}$
- $s - \bar{s} \neq 0$

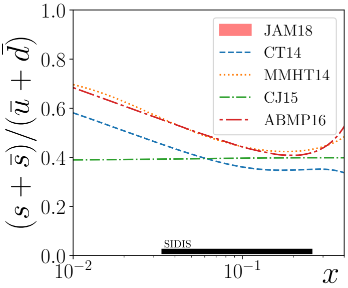
JAM18: PDFs (preliminary)

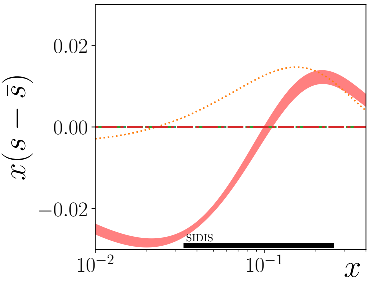


- Comparison with other groups
  - dashed: MMHT14
  - dashed-dotted: CT14
  - dotted: CJ15
  - dot-dot-dash: ABMP16
- Big differences for $s, \bar{s}$ distributions

JAM18: upolarized sea (preliminary)

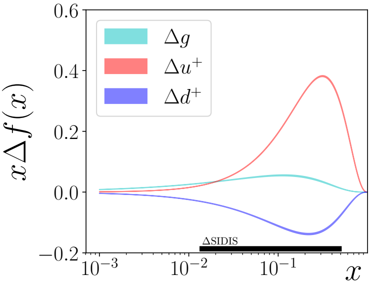


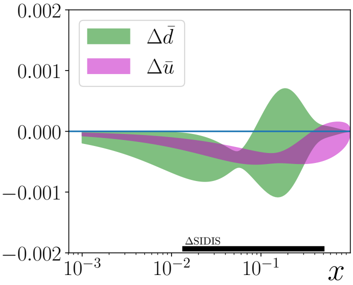


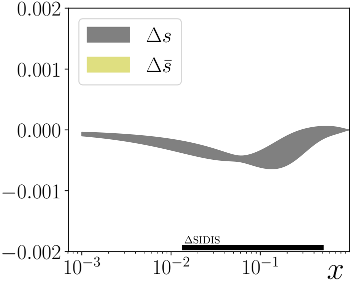


- For CJ and CT, $s = \bar{s}$
- MMHT uses neutrino DIS
- SIDIS favors a strange suppression
- and a larger s, $\bar{s}$ asymmetry

JAM18: ΔPDFs (preliminary)

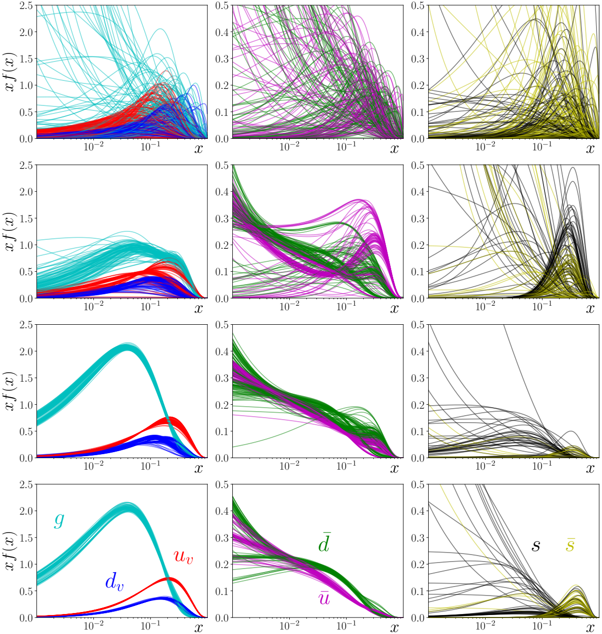






- Recall no SU2,SU3 imposed
- $\Delta s, \Delta\bar{u}, \Delta\bar{d}$ are much better known than $\Delta\bar{s}$
- It means, most of the uncertainty on Δs^+ is from $\Delta\bar{s}$

JAM18: IMC runs (preliminary)



← flat priors

← DIS no HERA

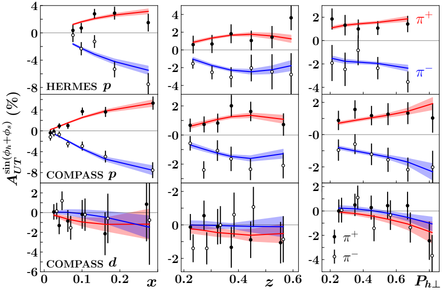
← DIS with HERA

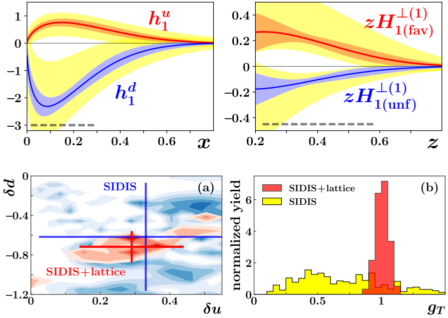
← DIS with HERA + DY

… and beyond

SIDIS+Lattice analysis of nucleon tensor charge

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



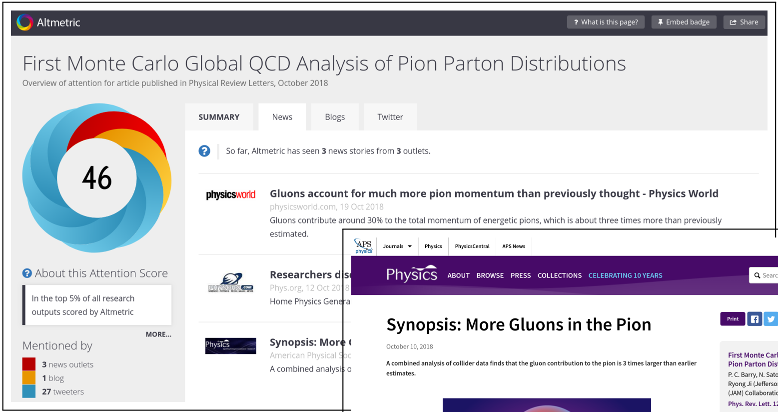


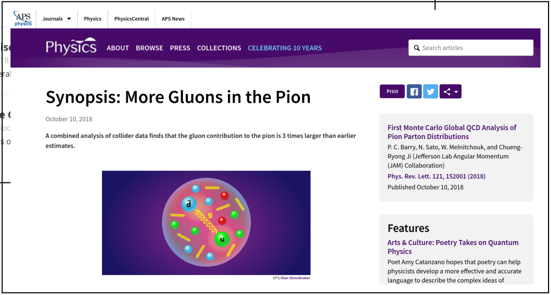
- Extraction of transversity and Collins FFs from SIDIS A_{UT}+Lattice g_T
- In the absence of Lattice, SIDIS has no significant constraints on g_T

(See talk by W. Melnitchouk)

First global Monte Carlo analysis of pion PDFs

Barry, NS, Melnitchouk, Ji (PRL)

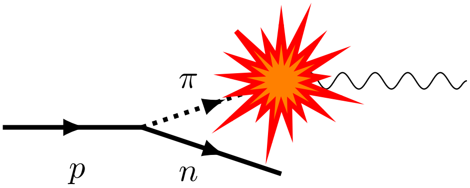




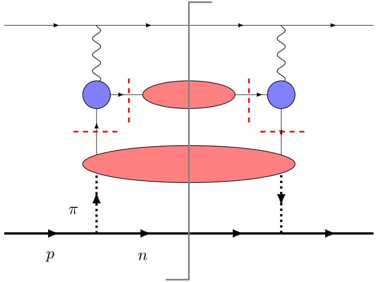
First global Monte Carlo analysis of pion PDFs

Barry, NS, Melnitchouk, Ji (PRL)

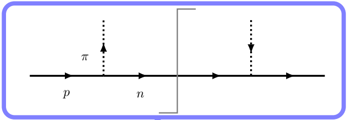
- **How to probe pion structure**
  - $\pi + A \to l\bar{l} + X$ **(Drell-Yan)**
  - $\pi + A \to \gamma + X$ (prompt photons)
  - $e + p \to e' + n + X$ **(SIDIS)** $\to$ small x_π gluon PDF



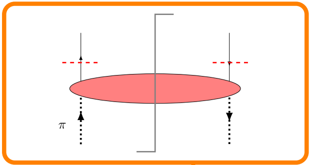
Factorization setup



χEFT



pQCD



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

χEFT setup

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

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

- UV regulators used in the literature

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

pQCD setup

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

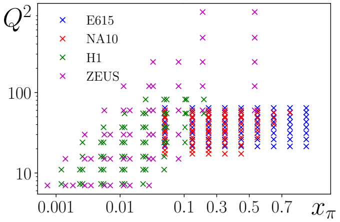
$$\frac{d\sigma}{dx_F dQ^2} = \sum_{a,b} \int d\xi d\zeta \; C_{a,b}(\xi,\zeta) f_{a/\pi^-}(\xi) f_{b/W}(\zeta)$$

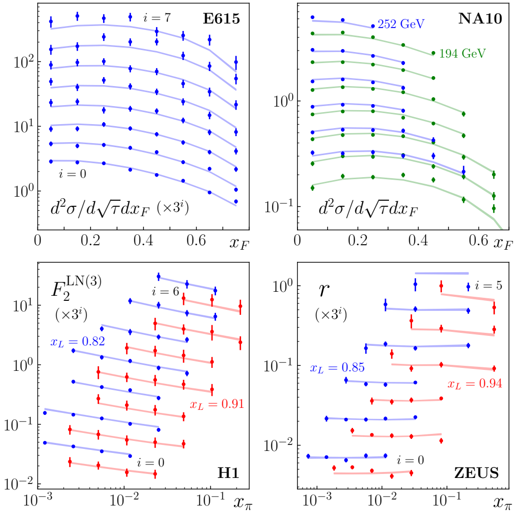
- $e + p \to e' + n + X$ (LN)

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

- We parametrize PDFs in π^-
  - Valence: $\bar{u}_v = d_v$
  - Sea: $u = \bar{d} = s = \bar{s}$
  - Gluon: g

Results



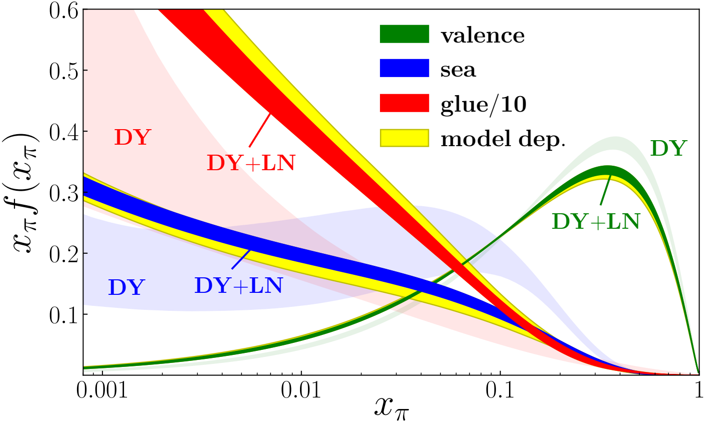


- Our new analysis extends previous pion PDF analysis down to $x \sim 0.001$
- The OPE+pQCD can describe the HERA data **simultaneously** with the DY data

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

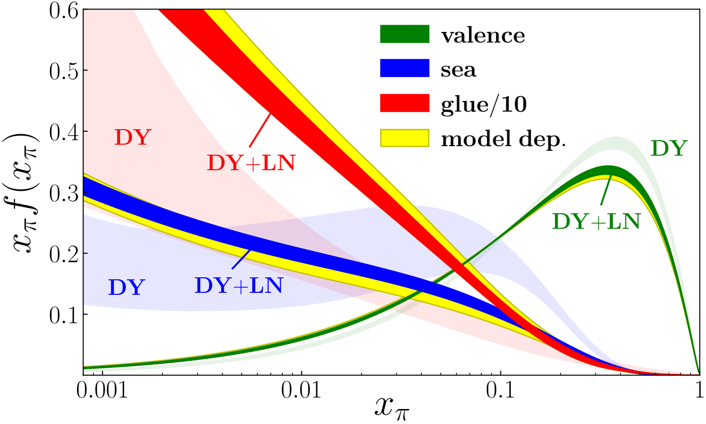
$$r(x, Q^2, y) = \frac{d^3\sigma^{LN}/dx dQ^2 dy}{d^2\sigma^{inc}/dx dQ^2} \Delta y$$

Results



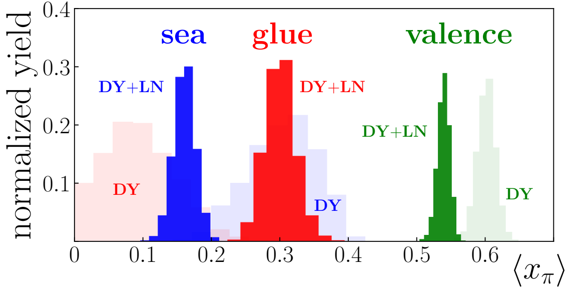
- Significant reduction of the uncertainties
- Non-overlapping uncertainties $\rightarrow$ tensions among the data
- Accuracy will be improved with future TDIS (JLab12/EIC)

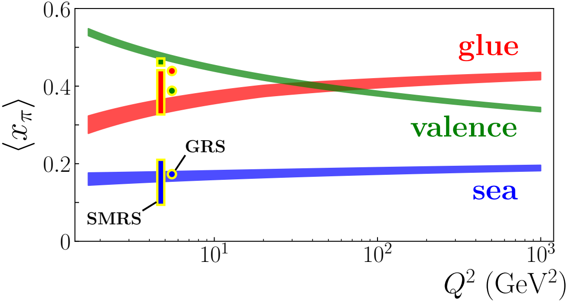
Results



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

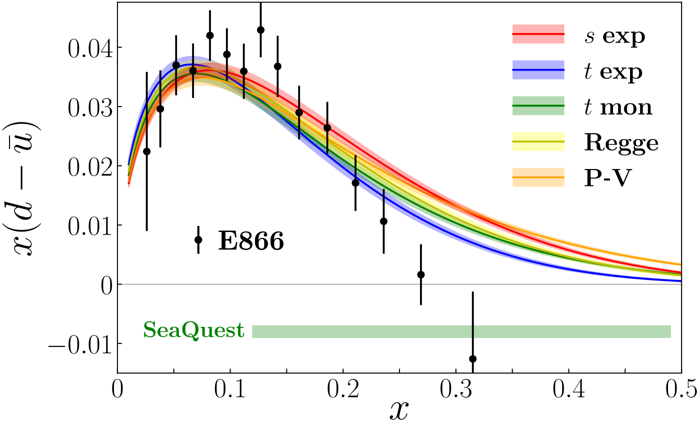
Results





- 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 $\left\langle x_\pi^{\text{valence}} \right\rangle$ decreases

Results



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

Summary and outlook