Simultaneous Global Analysis of Polarized and Unpolarized PDFs and Fragmentation Functions

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CTEQ Workshop
Parton Distributions as a Bridge from Low to High Energies
Jefferson Lab, 2018

Motivations

Mapping the parton strucure of the nucleon

- **Challenges:**

  + **Quantitative** limits of $x, Q^2, z, \ldots$ 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, CJ, MMHT, DSSV, ...)
  - + Embrace likelihood analysis via MC methods (JAM, NNPDF)
  - + Faithful representation of uncertainties consistent with Bayes' theorem

Bayesian likelihood analysis

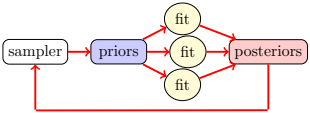
- **Inclusion of modern data analysis techniques**

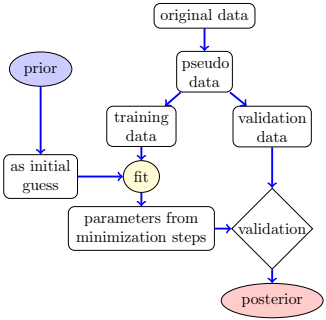
  + Bayesian theorm

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

  + Estimation of expectation values and variances:

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

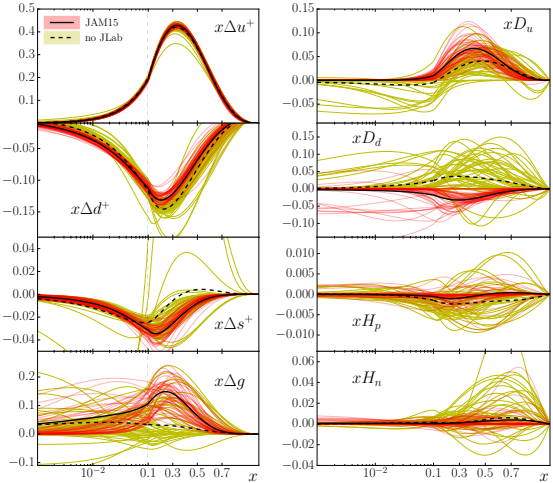




History

JAM15: ΔPDFs

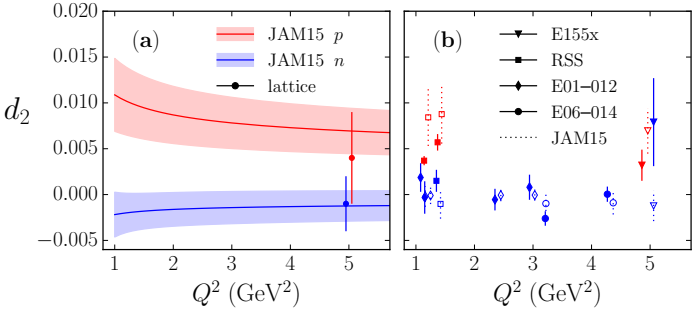
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



- 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)

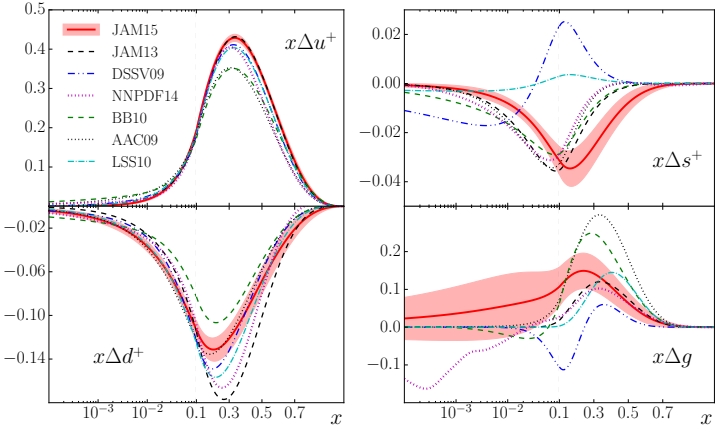


- Existing measurements of d_2 are in the resonance region $\rightarrow$ **quark-hadron duality**

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

JAM15: ΔPDFs

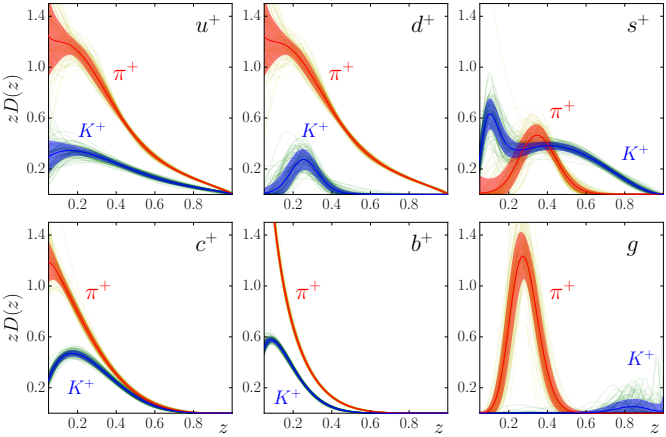
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



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

JAM16: FFs

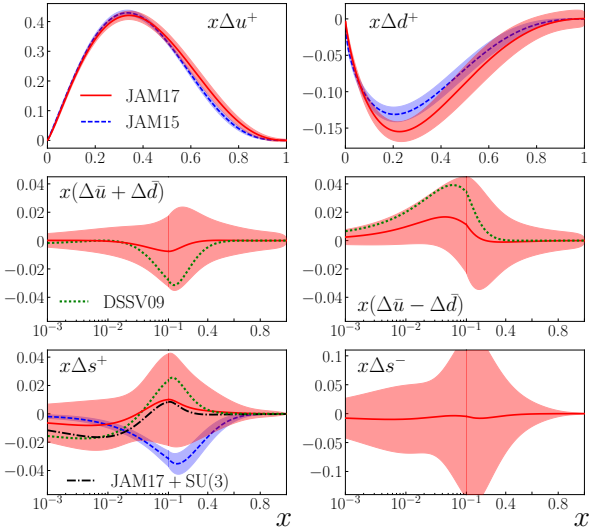
NS, Ethier, Melnitchouk, Hirai, Kumano, Accardi (PRD)



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

JAM17: ΔPDF +FF

Ethier, NS, Melnitchouk (PRL)

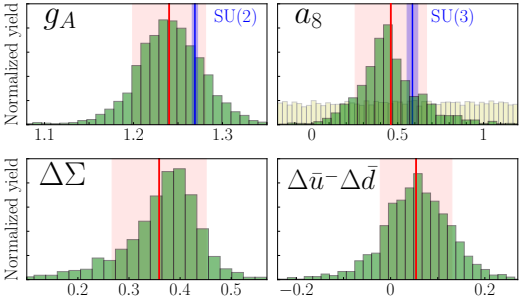


- No SU(3) constraints
- Sea polarization consistent with zero
- Precision of ΔSIDIS is not sufficient to determine sea polarization

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 $a_8 \to 25\%$ 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

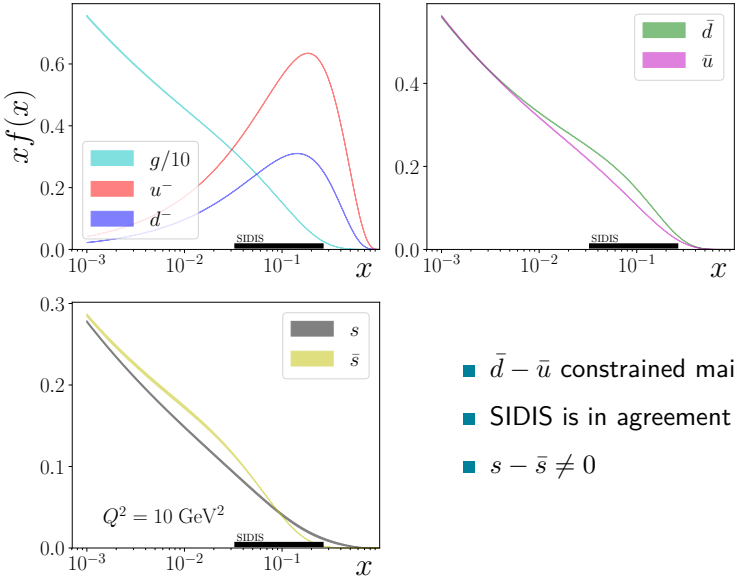
JAM18: Universal analysis (preliminary)

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

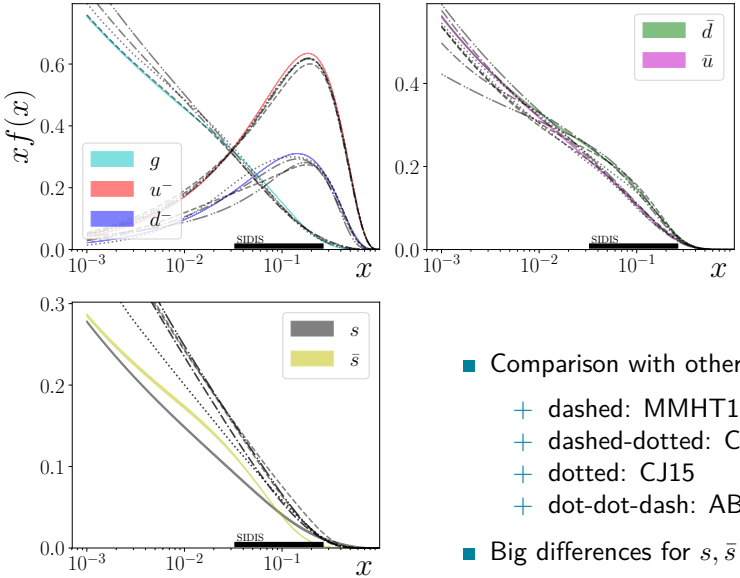
- **Likelihood analysis (first steps)**
  - Use maximum likelihood to find a candidate solution
  - Use resampling to **check for stability** and estimate uncertainties
  - 80 shape parameters and 91 data normalization parameters:
    171 dimensional space

JAM18: PDFs (preliminary)



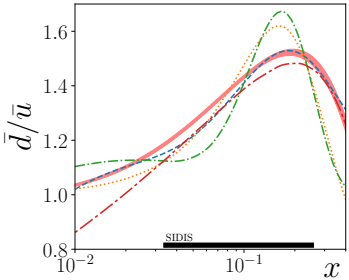
- $\bar{d} - \bar{u}$ constrained mainly by DY
- SIDIS is in agreement with DY's $\bar{d} - \bar{u}$
- $s - \bar{s} \neq 0$

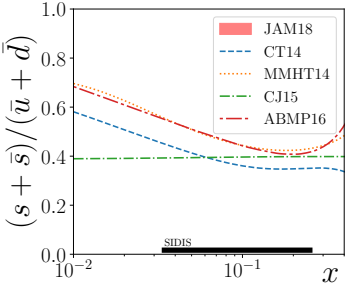
JAM18: PDFs (preliminary)

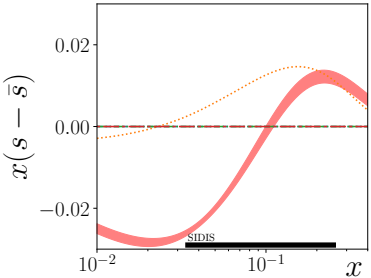


- Comparison with other groups
  - dashed: MMHT14
  - dashed-dotted: CT14
  - dotted: CJ15
  - dot-dot-dash: ABMP16
- Big differences for $s, \bar{s}$ distributions

JAM18: upolarized sea (preliminary)

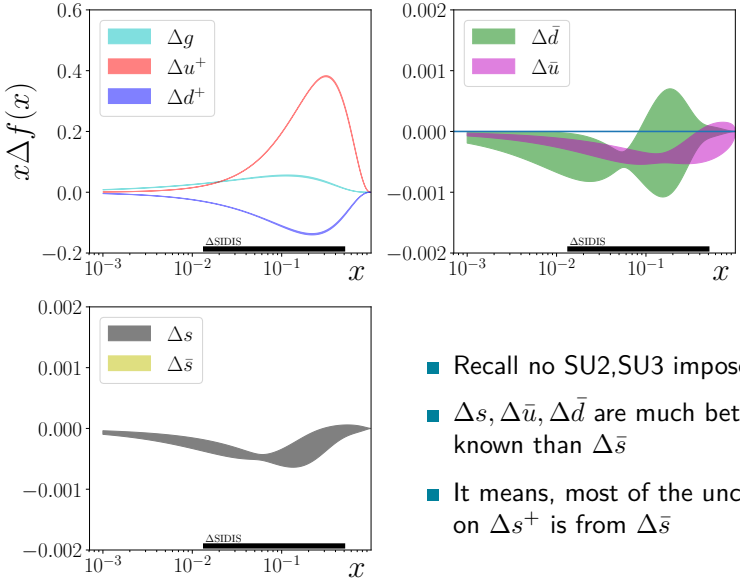






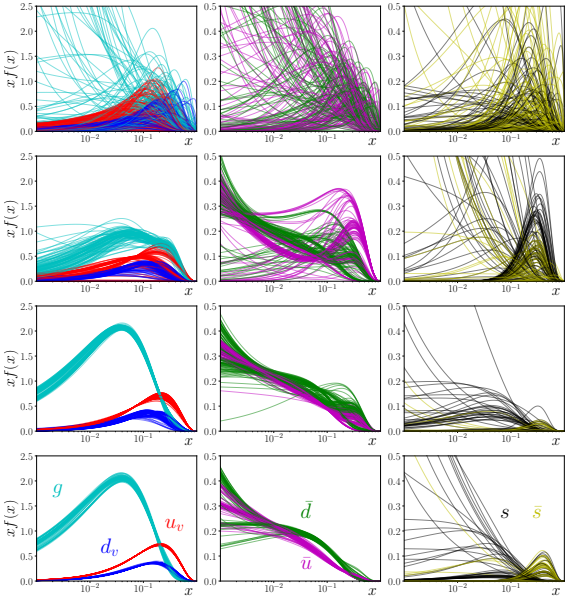
- For CJ and CT, $s = \bar{s}$
- MMHT uses neutrino DIS
- SIDIS favors a strange suppression
- and a larger s, $\bar{s}$ asymmetry

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

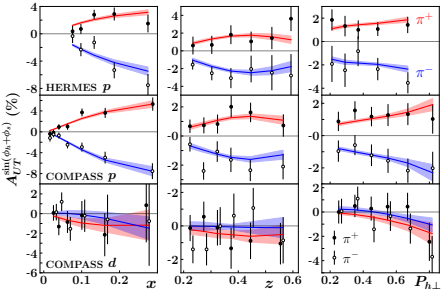
← DIS with HERA

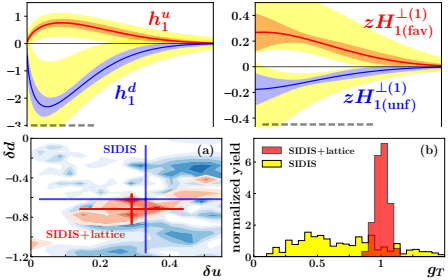
← DIS with HERA + DY

... and beyond

SIDIS+Lattice analysis of nucleon tensor charge

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

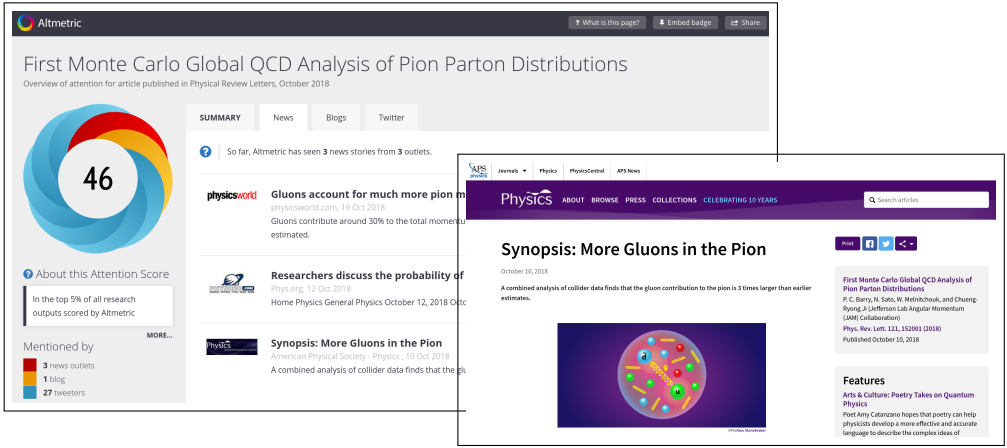




- Extraction of transversity and Collins FFs from SIDIS A_{UT}+Lattice g_T
- In the absence of Lattice, SIDIS has no significant constraints on g_T

First global Monte Carlo analysis of pion PDFs

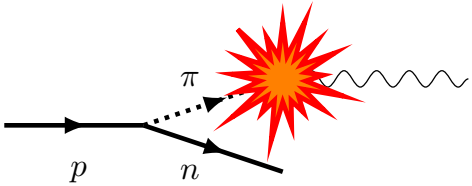
Barry, NS, Melnitchouk, Ji (PRL)



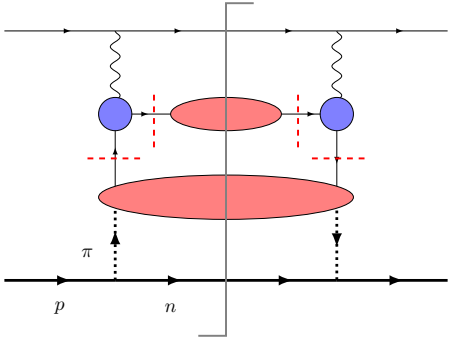
First global Monte Carlo analysis of pion PDFs

Barry, NS, Melnitchouk, Ji (PRL)

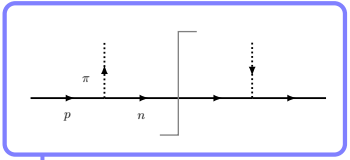
- **How to probe pion structure**
  - $+$ $\pi + A \to l\bar{l} + X$ **(Drell-Yan)**
  - $+$ $\pi + A \to \gamma + X$ (prompt photons)
  - $+$ $e + p \to e' + n + X$ **(SIDIS)** $\to$ small x_π gluon PDF



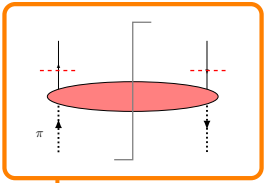
First global Monte Carlo analysis of pion PDFs



χEFT

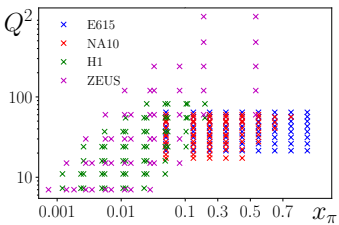


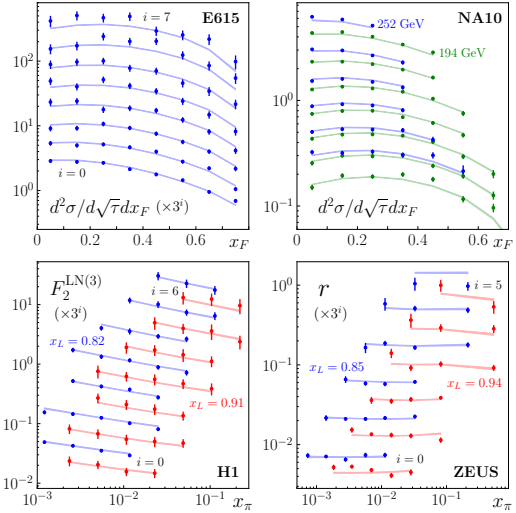
pQCD



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

First global Monte Carlo analysis of pion PDFs



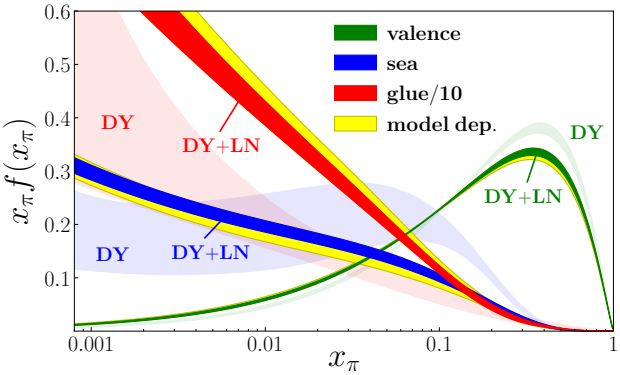


- Our new analysis extends previous pion PDF analysis down to $x \sim 0.001$
- The OPE+pQCD can describe the HERA data **simultaneously** with the DY data

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

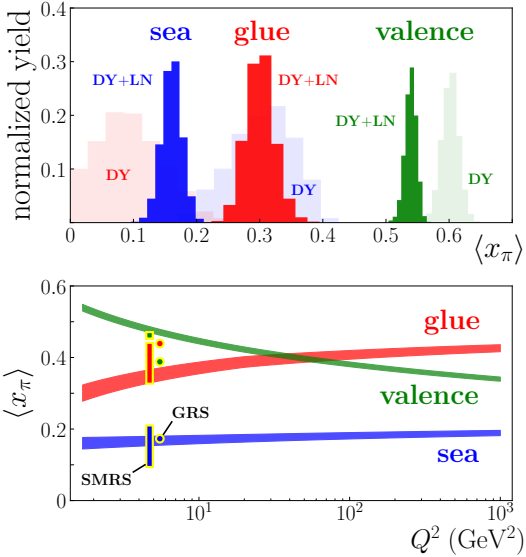
$$r(x, Q^2, y) = \frac{d^3\sigma^{LN}/dxdQ^2dy}{d^2\sigma^{inc}/dxdQ^2}\Delta y$$

First global Monte Carlo analysis of pion PDFs



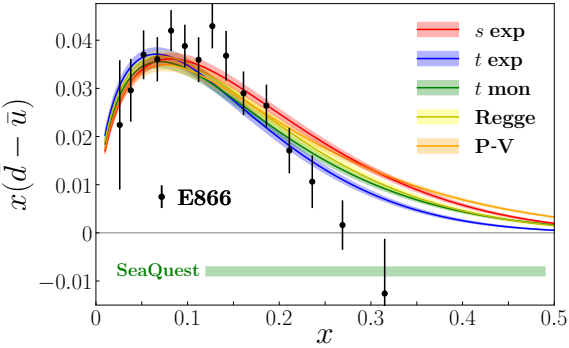
- Significant reduction of the uncertainties
- Non-overlapping uncertainties $\rightarrow$ tensions among the data
- Accuracy will be improved with future TDIS (JLab12/EIC)

First global Monte Carlo analysis of pion PDFs



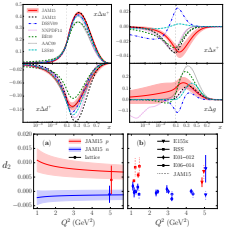
- Constraints from HERA significantly increase $\langle x_\pi^g \rangle$.
  The role of the glue is more important than suggested by DY alone
- In contrast, the strength of the sea is reduced
- Due to momentum sum rule $\langle x_\pi^{\text{valence}} \rangle$ decreases

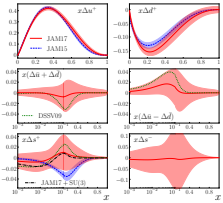
First global Monte Carlo analysis of pion PDFs

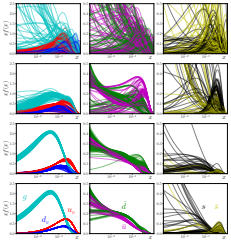


- We performed an additional analysis of LN+DY+E866
  $\rightarrow$ good description of E866 data except for large x

Summary and outlook







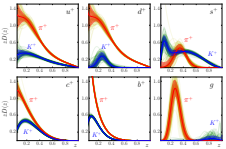
webfitter

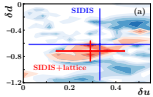
RHIC data

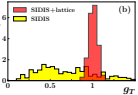
TMDs

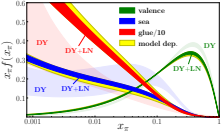
2015 2016 2017 2018 2019 2020

EIC









Jefferson Lab Angular Momentum Collaboration

Backup

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