Polarized and unpolarized PDFs and FFs

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Longitudinal spin
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Jefferson Lab Angular Momentum Collaboration

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Motivations

Motivations

- **SIDIS data from JLab 12 brings new 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

Motivations

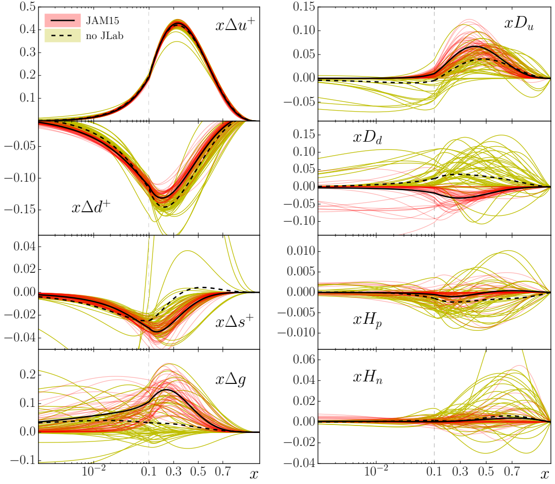
- **Inclusion of modern data analysis techniques**
  - Bayesian likelihood analysis

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

  - Estimation of expectation values and variances:
    - maximum likelihood + Hessian (+tolerance)
    - maximum likelihood + Lagrange multipliers
    - data resampling
    - partition and cross validation
    - iterative Monte Carlo (IMC)
    - nested sampling

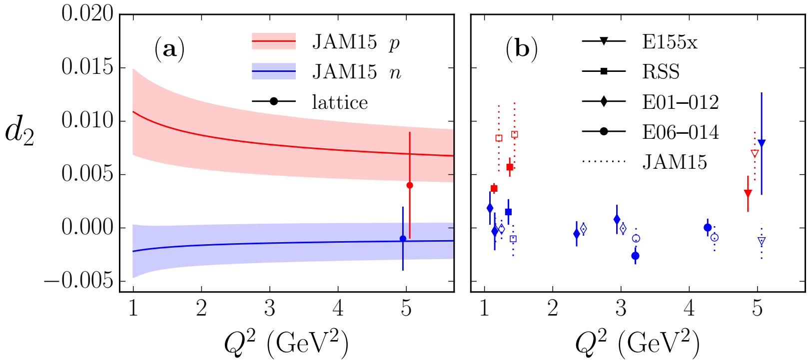
History

JAM15: ΔPDFs (NS, Melnitchouk, Kuhn, Ethier, Accardi)



- 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

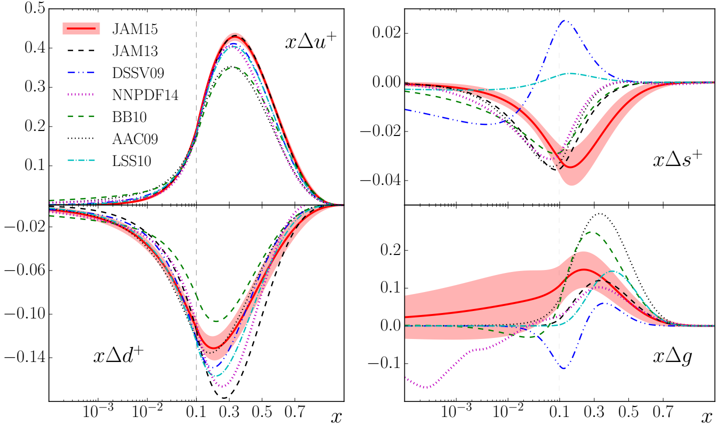
JAM15: d_2 matrix element



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

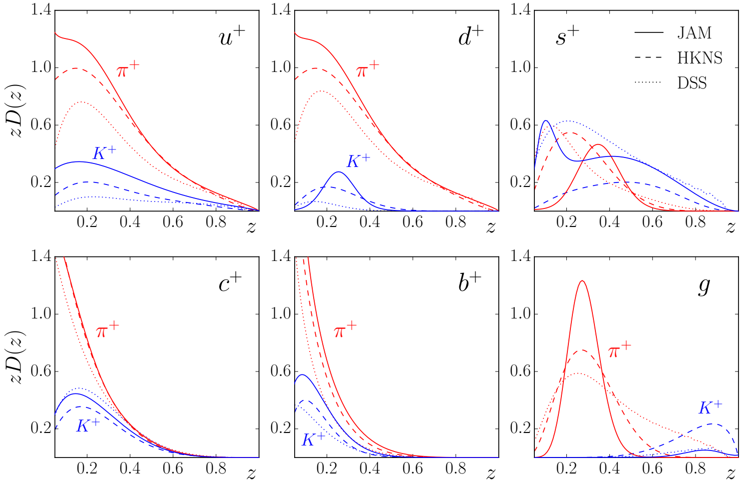
$$d_2(Q^2) \equiv \int_0^1 dx x^2 \left[2g_1^{\tau 3}(x, Q^2) + 3g_2^{\tau 3}(x, Q^2) \right]$$

JAM15: ΔPDFs (NS, Melnitchouk, Kuhn, Ethier, Accardi)



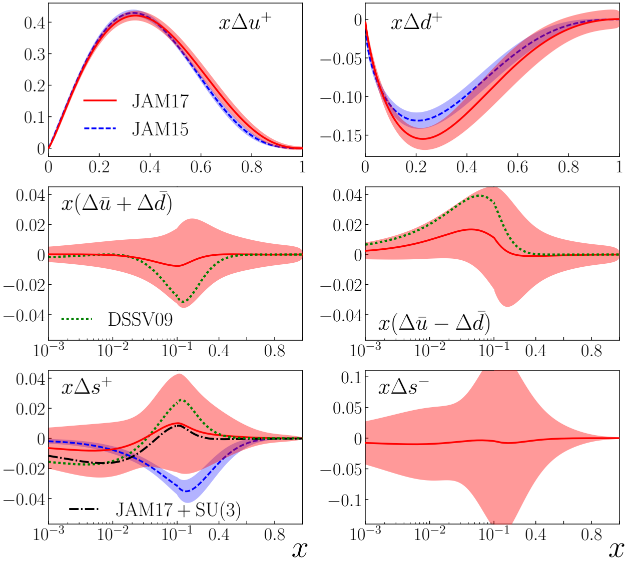
- SU2, SU3 constraints imposed
- DSSV and JAM Δs^+ is **inconsistent**

JAM16: FFs (NS, Ethier, Melnitchouk, Hirai, Kumano, Accardi)



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

JAM17: $\triangle$PDF +FF (Ethier, NS, Melnitchouk)

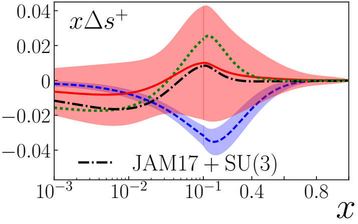


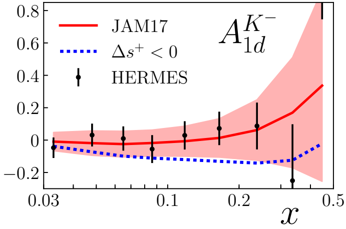
- No SU(3) constraints
- Sea polarization consistent with zero
- Precision of ΔSIDIS is not sufficient to determine sea polarization

What determines the sign of Δs^+?

- **case 1**
  - ~ 5 COMPASS d data points at $x < 0.002$ favor small $\Delta s^+(x)$
  - To generate $\Delta s^{+(1)}(Q_0^2) \sim -0.1$ a peak at $x \sim 0.1$ is generated
- **case 2**
  - In the absence of $x < 0.002$ data, the negative $\Delta s^{+(1)}(Q_0^2) \sim -0.1$ is mostly generated at small x.
  - No need for negative $\Delta s^+(x)$ at $x \sim 0.1$
- **case 3**
  - $\Delta s^+(x \sim 0.1) < 0$ disfavored by HERMES $A_{1d}^{K^-}$
  - Smaller $\Delta s^{+(1)}(Q_0^2)$ but larger uncertainties

case	data	sign change	$\Delta s^{+(1)}(Q_0^2)$
1	ΔDIS+SU(3)	No	-0.1
2	ΔDIS+SU(3) ($x > 0.02$)	Possible	-0.1
3	ΔDIS+ΔSIDIS+FF	Possible	$-0.03(10)$



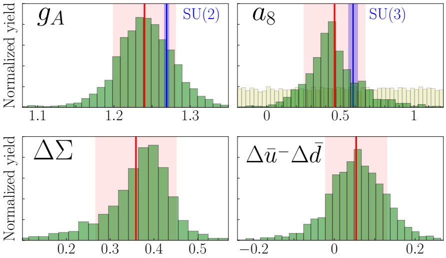


Updates on the moments

- **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.

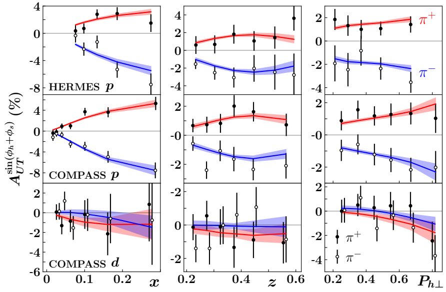
- a_3 which is in a good agreement with values from β decays **within** 2%.

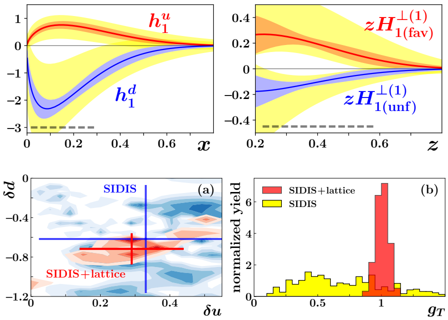


obs.	JAM15	JAM17
g_A	$1.269(3)$	$1.24(4)$
g_8	$0.586(31)$	$0.46(21)$
$\Delta\Sigma$	$0.28(4)$	$0.36(9)$
$\Delta\bar{u} - \Delta\bar{d}$	0	0.05(8)

SIDIS+Lattice analysis of nucleon tensor charge

Lin, Melnitchouk, Prokudin, NS, Shows





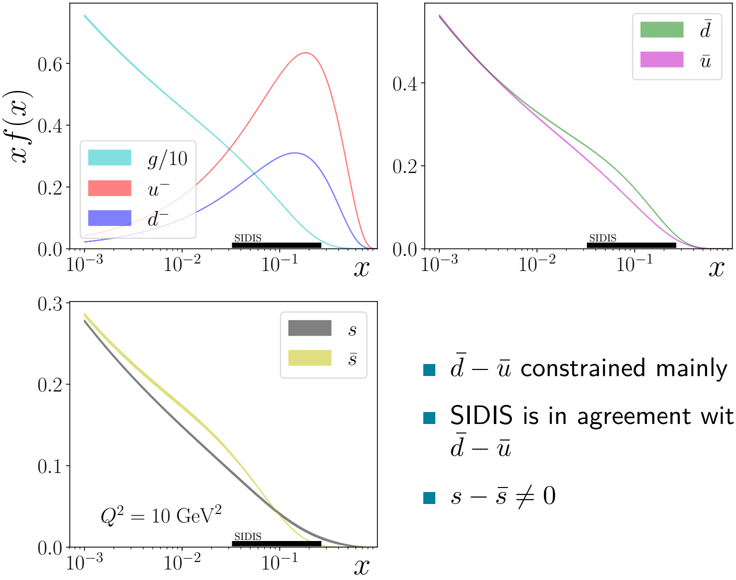
- Extraction of transversity and Collins FFs from SIDIS A_{UT}+Lattice g_T
- In the absence of Lattice, SIDIS has no significant constraints on g_T

Present

JAM18: Universal analysis (preliminary)

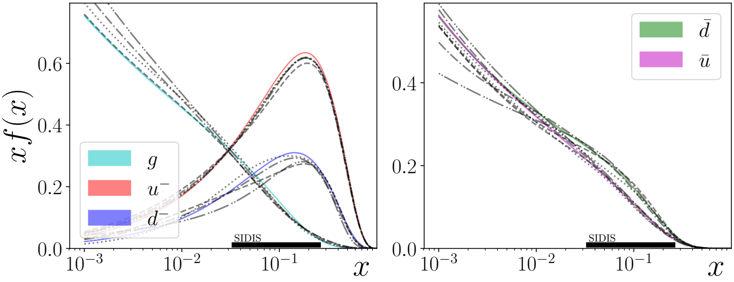
- **Data sets**
  + DIS, SIDIS(π, K), DY
  + ΔDIS, ΔSIDIS(π, K)
  + $e^+e^-(\pi, K)$
- **Theory setup**
  + Observables computed at **NLO in pQCD**
  + DIS structure functions only at **leading twist** $(W^2 > 10 \text{ GeV}^2)$
- **Likelihood analysis (first steps)**
  + Use maximum likelihood to find a candidate solution
  + Use resampling to **check for stability** and estimate uncertainties
  + 80 shape parameters and 91 data normalization parameters: **171 dimensional space**
  + Sampling to be extended with IMC/Nested Sampling

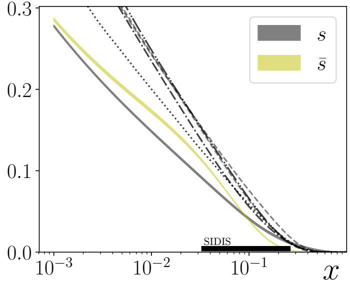
JAM18: PDFs (preliminary)



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

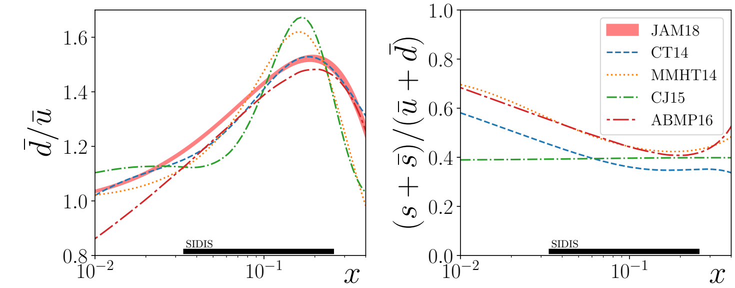
JAM18: PDFs (preliminary)

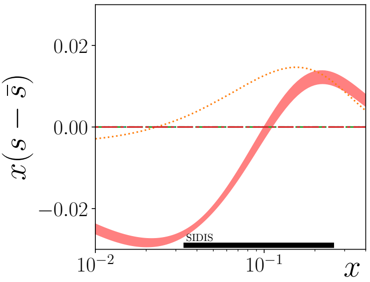




- Comparison with other groups
  - dashed: MMHT14
  - dashed-dotted: CT14
  - dotted: CJ15
  - dot-dot-dash: ABMP16
- Big differences for $s, \bar{s}$ distributions

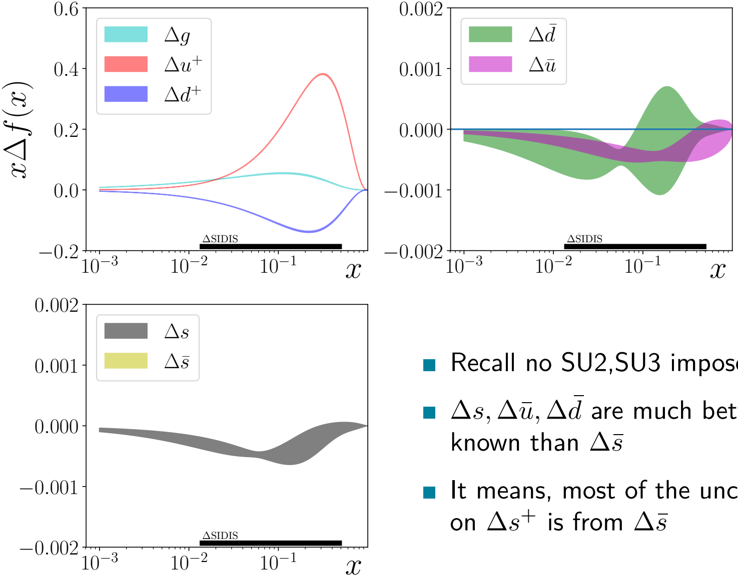
JAM18: upolarized sea (preliminary)





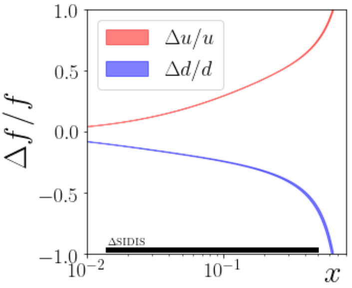
- For CJ and CT, $s = \bar{s}$
- MMHT uses neutrino DIS
- SIDIS favors a strange suppression
- and a larger s, $\bar{s}$ asymmetry

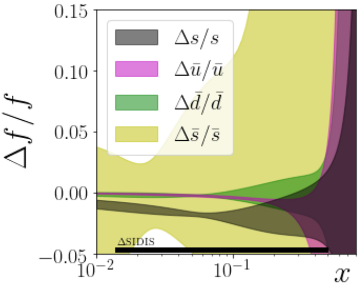
JAM18: ΔPDFs (preliminary)

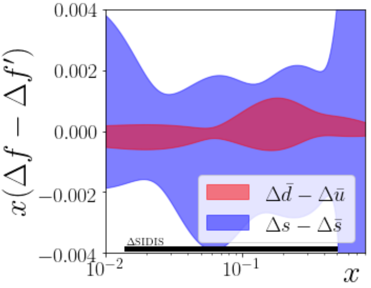


- Recall no SU2,SU3 imposed
- $\Delta s, \Delta\bar{u}, \Delta\bar{d}$ are much better known than $\Delta\bar{s}$
- It means, most of the uncertainty on Δs^+ is from $\Delta\bar{s}$

JAM18: polarized sea (preliminary)

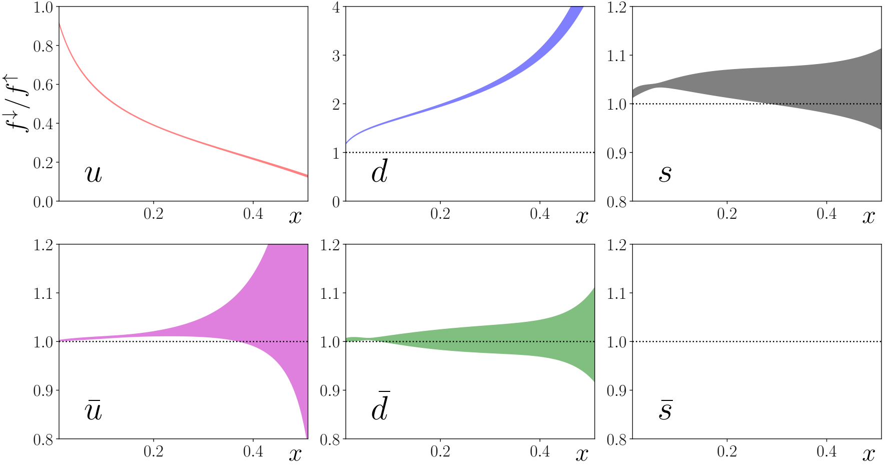






- $\Delta f/f \to 1$ only realized for u
- Polarized sea asymmetry is consistent with zero

JAM18: helicity PDFs (preliminary)



- Helicity distributions seems to be the same for the sea

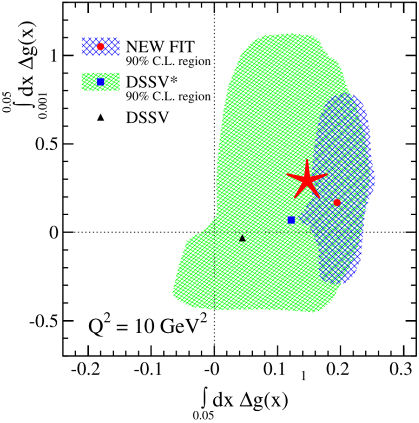
JAM18: moments (preliminary)

obs.	JAM15	JAM17	JAM18	JAM18 [truncated]
g_A	1.269(3)	1.24(4)	1.163(5)	1.107(5)
g_8	0.59(3)	0.4(2)	0.5(4)	0.39(2)
$\Delta\Sigma$	0.28(4)	0.36(9)	0.3(2)	0.386(7)
$\Delta\bar{u} - \Delta\bar{d}$	0	0.05(8)	0.0002(6)	−0.0001(5)
Δg	1(15)	–	0.22(1)	0.172(9)

- Large uncertainties on the full $\Delta\Sigma$ stem from
- JAM18 [truncated] means integration over ΔDIS and ΔSIDIS kinematics $\Delta\bar{s}$

JAM18: Δg (preliminary)

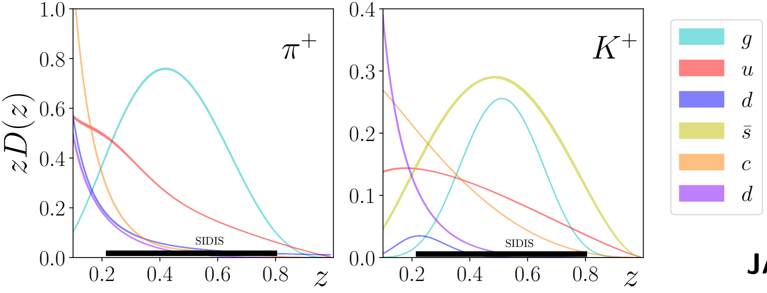
DSSV14



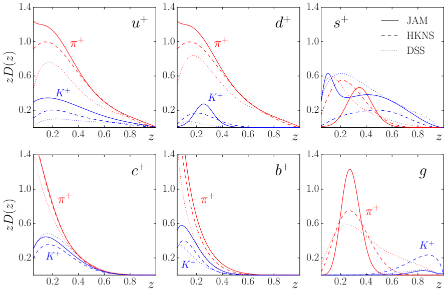
JAM18

- $\int_{0.05}^{1} dx \Delta g(x) = 0.145(5)$
- $\int_{0.001}^{0.05} dx \Delta g(x) = 0.229(9)$
- Not so bad for a prediction

JAM18: FFs (preliminary)



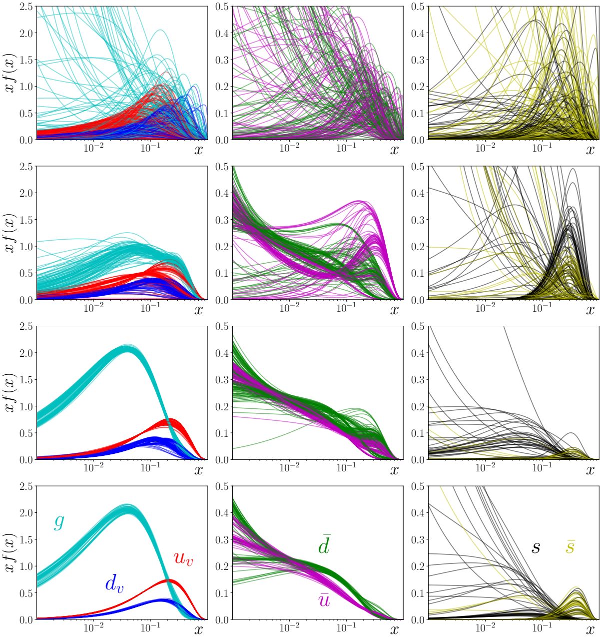
JAM16



- gluon FFs are significantly affected by SIDIS
- This feature is key for p_{T} differential SIDIS $\rightarrow$ see my talk "3D Structure of the Nucleon: TMDs"

IMC runs...

JAM18: IMC runs



← flat priors

← DIS no HERA

← DIS with HERA

← DIS with HERA + DY

Summary and outlook

- First **universal** analysis of PDFs, ΔPDF and FFs
  - + New insights on nucleon sea distributions ($s, \bar{s}$ asymmetry)
  - + π and K gluon FFs are required by SIDIS to peak at larger z
    $\rightarrow$ relevant for TMD physics
  - + The universal analysis will to be extend to TMD analysis
- Next steps
  - + Perform additional checks using IMC and Nested Sampling
  - + Make predictions to high energy observables and check the genuine predictive power of the universal analysis

Backup

Polarized DIS

Asymmetries

$$A_{||} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\downarrow\Downarrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\downarrow\Downarrow}} = D(A_1 + \eta A_2)$$

$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}} = d(A_2 - \xi A_1)$$

$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \qquad A_2 = \gamma \frac{(g_1 + g_2)}{F_1} \qquad \gamma^2 = \frac{4M^2x^2}{Q^2}$$

Theory

$$g_1(x,Q^2) = g_1^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, \ldots) + g_1^{\mathrm{T3+TMC}}(D_u, D_d) + g_1^{\mathrm{T4}}(H_{p,n})$$

$$g_2(x,Q^2) = g_2^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, \ldots) + g_2^{\mathrm{T3+TMC}}(D_u, D_d)$$

Polarized DIS

$\rightarrow \xi = \frac{2x}{1+(1+4\mu^2x^2)^{1/2}}$
$\rightarrow \mu^2 = M^2/Q^2$

Leading twist structure functions:

$$g_1^{\mathrm{LT+TMC}}(x,Q^2) = \frac{x}{\xi}\frac{g_1^{\mathrm{LT}}(\xi)}{(1+4\mu^2x^2)^{3/2}} + 4\mu^2x^2\frac{x+\xi}{\xi(1+4\mu^2x^2)^2}\int_\xi^1 \frac{dz}{z} g_1^{\mathrm{LT}}(z) - 4\mu^2x^2\frac{2-4\mu^2x^2}{2(1+4\mu^2x^2)^{5/2}}\int_\xi^1\frac{dz}{z}\int_{z'}^1\frac{dz'}{z'}g_1^{\mathrm{LT}}(z')$$

$$g_2^{\mathrm{LT+TMC}}(x,Q^2) = -\frac{x}{\xi}\frac{g_1^{\mathrm{LT}}(\xi)}{(1+4\mu^2x^2)^{3/2}} + \frac{x}{\xi}\frac{(1-4\mu^2x\xi)}{(1+4\mu^2x^2)^2}\int_\xi^1 \frac{dz}{z} g_1^{\mathrm{LT}}(z) + \frac{3}{2}\frac{4\mu^2x^2}{(1+4\mu^2x^2)^{5/2}}\int_\xi^1\frac{dz}{z}\int_{z'}^1\frac{dz'}{z'}g_1^{\mathrm{LT}}(z')$$

Leading twist quark distributions:

$$g_1^{\mathrm{LT}}(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta C_{qq}\otimes\Delta q(x) + \Delta C_{qg}\otimes\Delta g(x)\right]$$

Polarized DIS

Twist-3 structure functions:

$$g_1^{\mathrm{T3+TMC}}(x,Q^2) = 4\mu^2x^2 \frac{D(\xi)}{(1+4\mu^2x^2)^{3/2}} - 4\mu^2x^2 \frac{3}{(1+4\mu^2x^2)^2} \int_\xi^1 \frac{dz}{z} D(z) + 4\mu^2x^2 \frac{2-4\mu^2x^2}{(1+4\mu^2x^2)^{5/2}} \int_\xi^1 \frac{dz}{z} \int_{z'}^1 \frac{dz'}{z'} D(z')$$

$$g_2^{\mathrm{T3+TMC}}(x,Q^2) = \frac{D(\xi)}{(1+4\mu^2x^2)^{3/2}} - \frac{1-8\mu^2x^2}{(1+4\mu^2x^2)^2} \int_\xi^1 \frac{dz}{z} D(z) - \frac{12\mu^2x^2}{(1+4\mu^2x^2)^{5/2}} \int_\xi^1 \frac{dz}{z} \int_{z'}^1 \frac{dz'}{z'} D(z')$$

Twist-3 quark distributions:

$$D(x,Q^2) = \frac{4}{9} D_u(x,Q^2) + \frac{1}{9} D_d(x,Q^2)$$

Polarized DIS

Twist-4 structure function:

$$g_1^{\mathrm{T4(p,n)}}(x, Q^2) = H^{(p,n)}(x)/Q^2$$