Review of the JAM global QCD analysis framework

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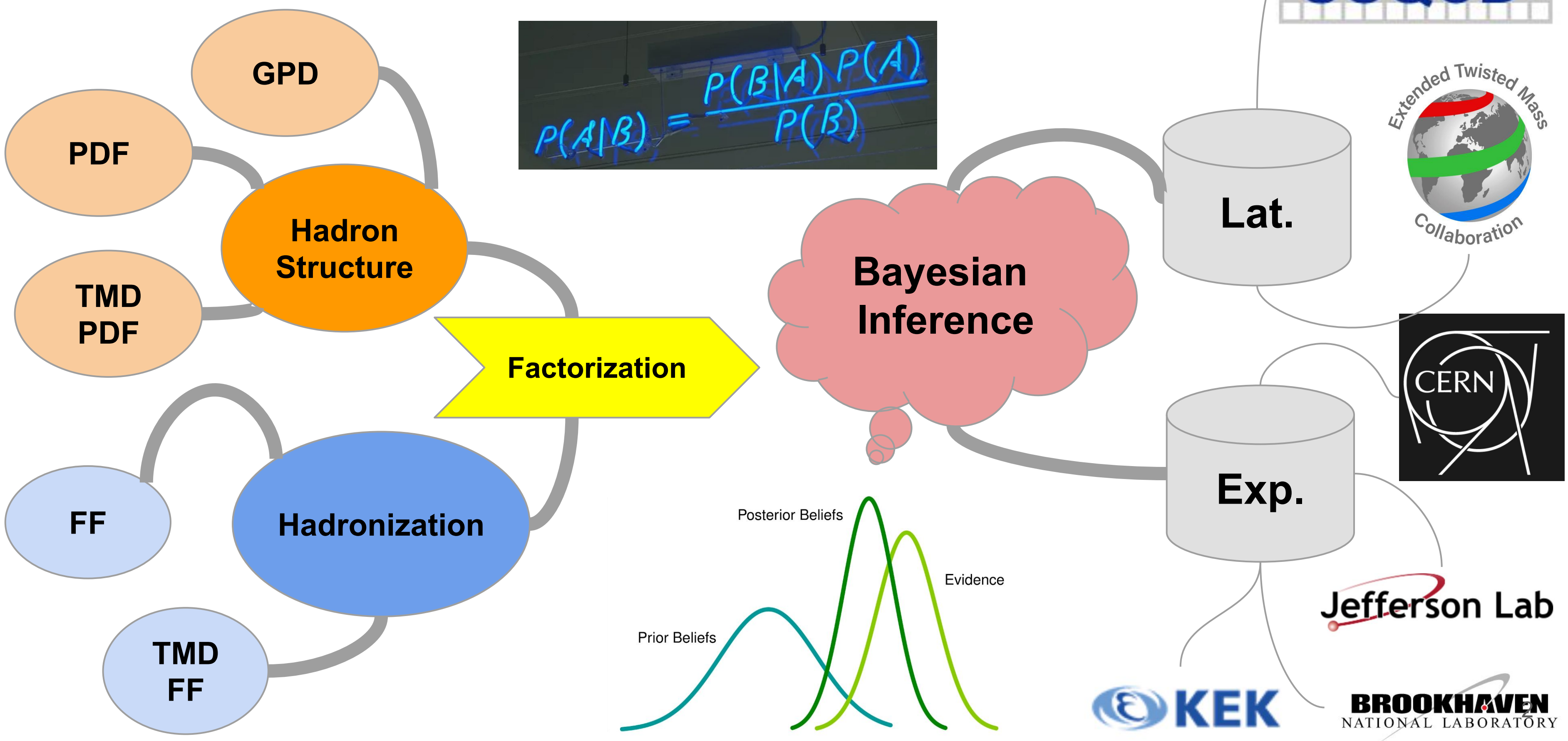
Pol He3 A1n/d2n Collaboration Meeting

Jefferson Lab

The QCD global analysis paradigm



The Bayesian inference

Experiments = theory + errors

$$d\sigma_{\mathrm{DIS}} = \sum_i H_i^{\mathrm{DIS}} \otimes f_i$$

$$d\sigma_{\mathrm{DY}} = \sum_{ij} H_{ij}^{\mathrm{DY}} \otimes f_i \otimes f_j$$

$$d\sigma_{\mathrm{SIA}} = \sum_i H_i^{\mathrm{SIA}} \otimes d_i$$

$$d\sigma_{\mathrm{SIDIS}} = \sum_{ij} H_{ij}^{\mathrm{SIDIS}} \otimes f_i \otimes d_j$$

Hadron Structure

Hadronization

$$f_i(\xi, \mu_0^2) = N_i \xi^{a_i} (1-\xi)^{b_i} (1 + \ldots)$$

$$d_i(\zeta, \mu_0^2) = N_i \zeta^{a_i} (1-\zeta)^{b_i} (1 + \ldots)$$

$$\mathbf{a} = (N_i, a_i, b_i, \ldots)$$

Posterior distribution

Prior distribution

$$\rho(\mathbf{a}|\mathrm{data}) \sim \mathcal{L}(\mathbf{a}, \mathrm{data}) \pi(\mathbf{a})$$

Likelihood

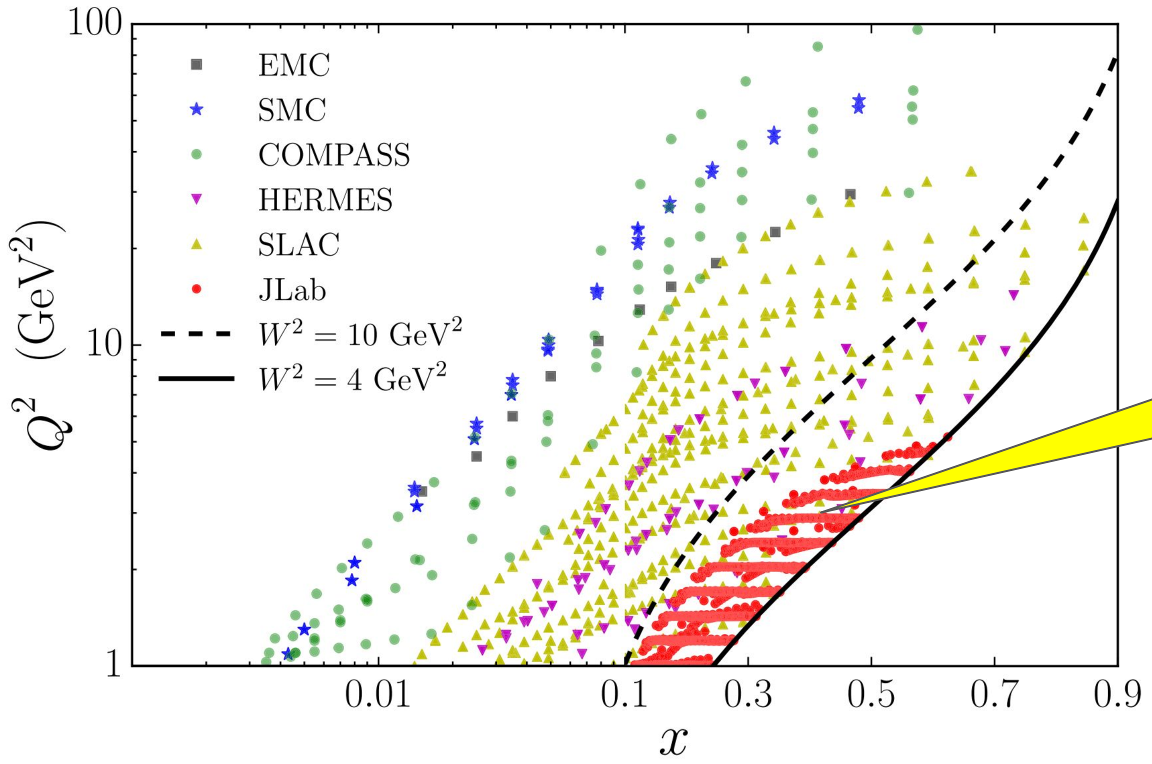
$$\mathrm{E}[f_i(\xi, \mu^2)] = \int d^n\mathbf{a}\, \rho(\mathbf{a}|\mathrm{data}) f_i(\xi, \mu^2; \mathbf{a})$$

$$\mathrm{V}[f_i(\xi, \mu^2)] = \int d^n\mathbf{a}\, \rho(\mathbf{a}|\mathrm{data}) \left[f_i(\xi, \mu^2; \mathbf{a}) - \mathrm{E}[f_i(\xi, \mu^2)]\right]^2$$

JAM15

NS, Melnitchouk, Kuhn, Ethier, Accardi

https://arxiv.org/abs/1601.07782



Inclusion of all JLab 6 GeV data

Theory framework

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

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

$$\Rightarrow$$

$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1}$$

$$A_2 = \gamma \frac{(g_1 + g_2)}{F_1}$$

$$\Downarrow$$

$$g_1 = g_1^{(\tau 2)} + g_1^{(\tau 3)} + g_1^{(\tau 4)}$$

$$g_2 = g_2^{(\tau 2)} + g_2^{(\tau 3)}$$

$$\gamma^2 = 4M^2x^2/Q^2,$$

Collinear factorization + TMCs

$$g_1 = \boxed{g_1^{(\tau 2)}} + g_1^{(\tau 3)} + g_1^{(\tau 4)}$$
$$g_2 = g_2^{(\tau 2)} + g_2^{(\tau 3)}$$

$$g_1^{(\tau 2)}(x, Q^2) = \frac{1}{2}\sum_q e_q^2[(\Delta C_q \otimes \Delta q^+)(x, Q^2) + (\Delta C_g \otimes \Delta g)(x, Q^2)],$$

$$\rho^2 = 1 + \gamma^2.$$

$$g_1^{(\tau 2+\mathrm{TMC})}(x, Q^2) = \frac{x}{\xi\rho^3} g_1^{(\tau 2)}(\xi, Q^2) + \frac{(\rho^2 - 1)}{\rho^4} \times \int_\xi^1 \frac{dz}{z}\left[\frac{(x+\xi)}{\xi} - \frac{(3-\rho^2)}{2\rho}\ln\frac{z}{\xi}\right] g_1^{(\tau 2)}(z, Q^2),$$

Not justified in standard collinear factorizaion

TMC using OPE only justified for integer moments

WW approximation/assumption

$$g_1 = g_1^{(\tau 2)} + g_1^{(\tau 3)} + g_1^{(\tau 4)}$$
$$g_2 = \boxed{g_2^{(\tau 2)}} + g_2^{(\tau 3)}$$

$$g_2^{(\tau 2+\mathrm{TMC})}(x,Q^2) = -\frac{x}{\xi\rho^3} g_1^{(\tau 2)}(\xi,Q^2) + \frac{1}{\rho^4}\int_\xi^1 \frac{dz}{z}\left[\frac{x}{\xi} - (\rho^2-1) + \frac{3(\rho^2-1)}{2\rho}\ln\frac{z}{\xi}\right] g_1^{(\tau 2)}(z,Q^2).$$

WW approximation

Theory based assumption

Twist 3 (within WW assumption)

$$g_1 = g_1^{(\tau 2)} + \boxed{g_1^{(\tau 3)}} + g_1^{(\tau 4)}$$
$$g_2 = g_2^{(\tau 2)} + \boxed{g_2^{(\tau 3)}}$$

$$\rho^2 = 1 + \gamma^2.$$

$$g_1^{(\tau 3+\mathrm{TMC})}(x, Q^2) = \frac{(\rho^2 - 1)}{\rho^3} D(\xi, Q^2) - \frac{(\rho^2 - 1)}{\rho^4} \int_\xi^1 \frac{dz}{z} \left[3 - \frac{(3 - \rho^2)}{\rho} \ln \frac{z}{\xi}\right] \times D(z, Q^2),$$

$$g_2^{(\tau 3+\mathrm{TMC})}(x, Q^2) = \frac{1}{\rho^3} D(\xi, Q^2) - \frac{1}{\rho^4} \int_\xi^1 \frac{dz}{z} \times \left[3 - 2\rho^2 + \frac{3(\rho^2 - 1)}{\rho} \ln \frac{z}{\xi}\right] D(z, Q^2).$$

Nuclear structure functions

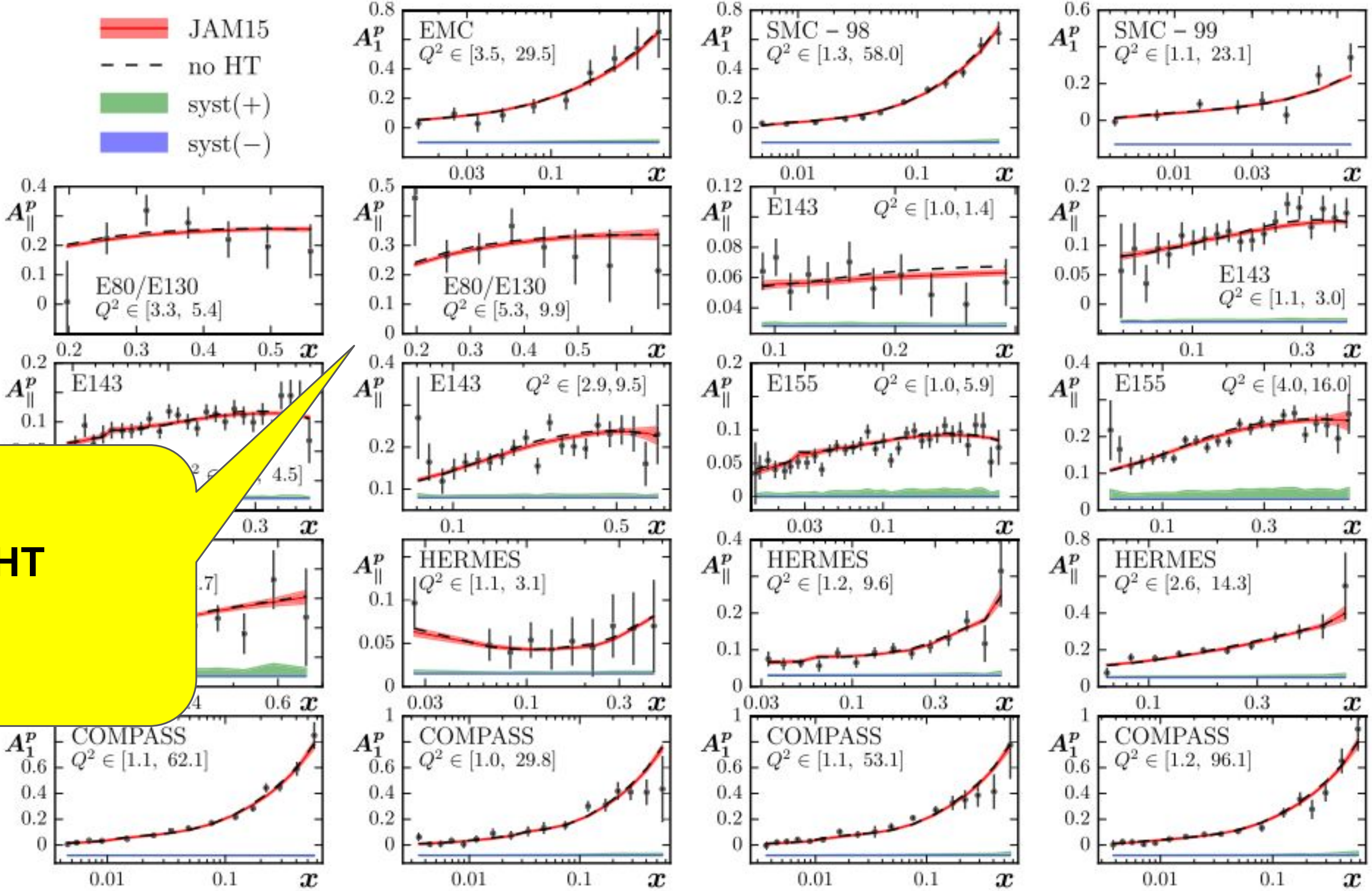
TMCs applied at the nucleon level

$$g_i^A(x, Q^2) = \sum_{\tau=p,n} \int_x^A \frac{dz}{z} f_{ij}^{\tau/A}(z, \rho) g_j^\tau\left(\frac{x}{z}, Q^2\right)$$

Only nuclear smearing

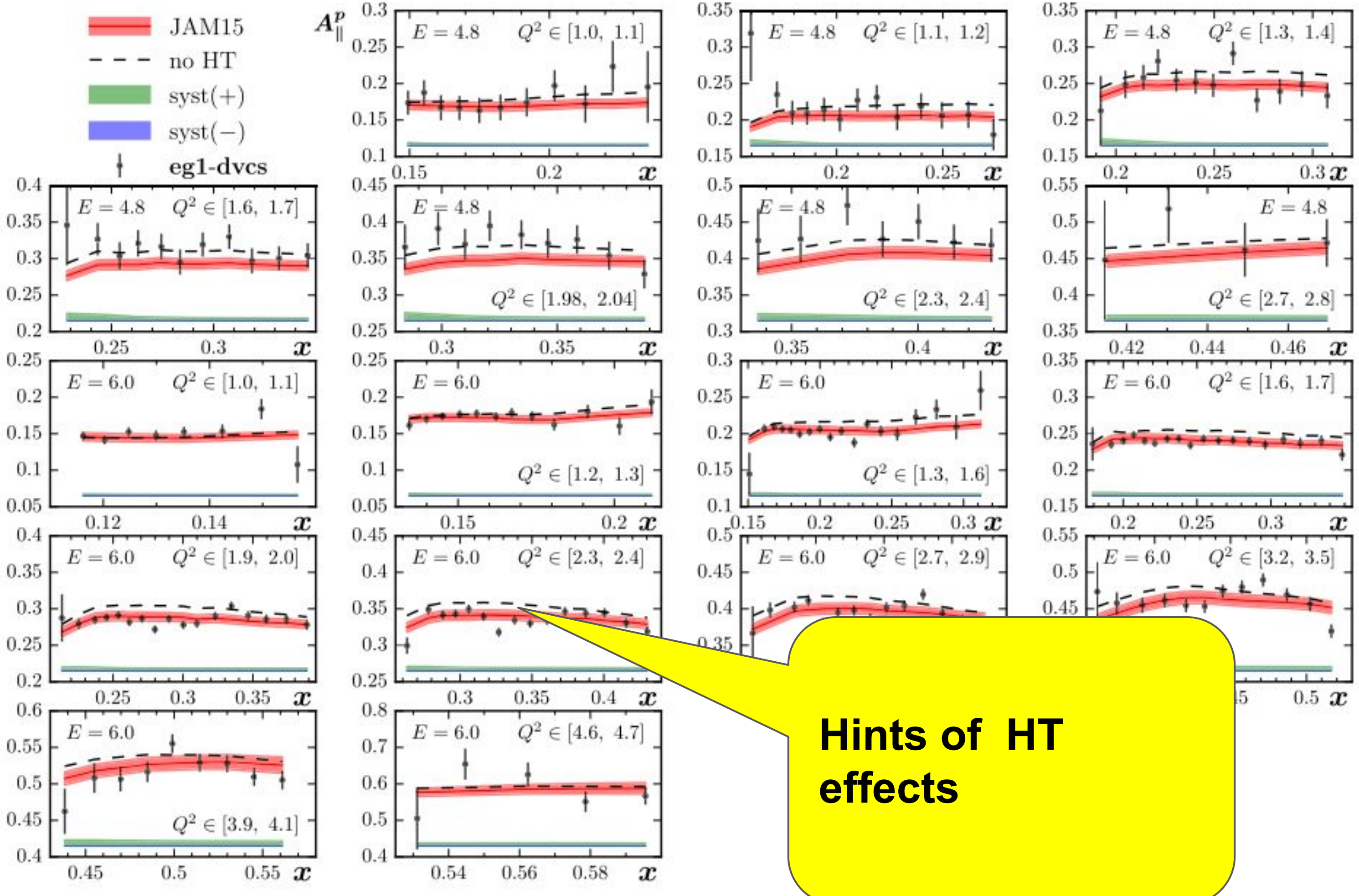
- No offshell effects
- No non-nucleonic effects
- No (anti) shadowing

Proton



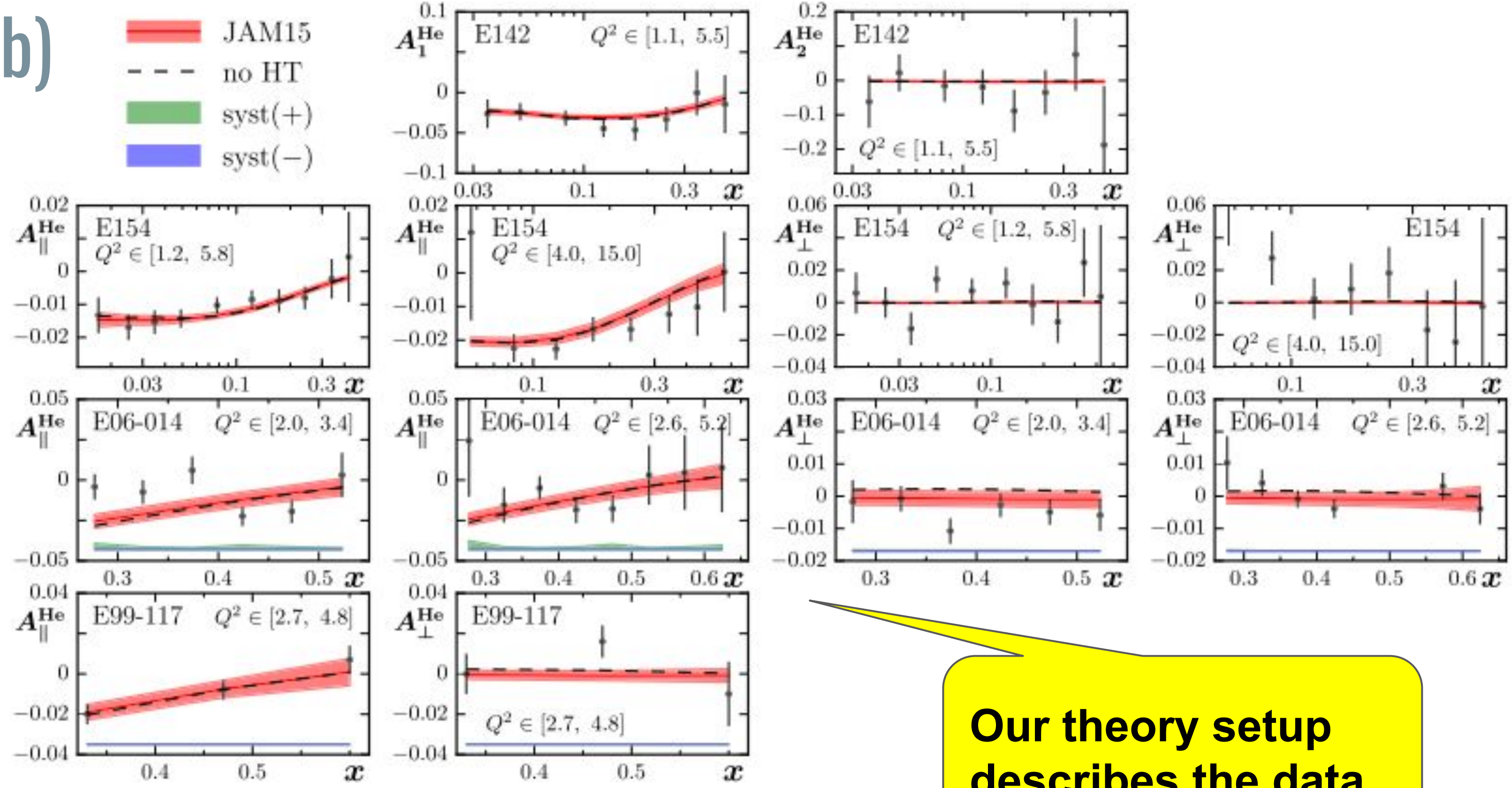
No visible HT effects

Proton (JLab)



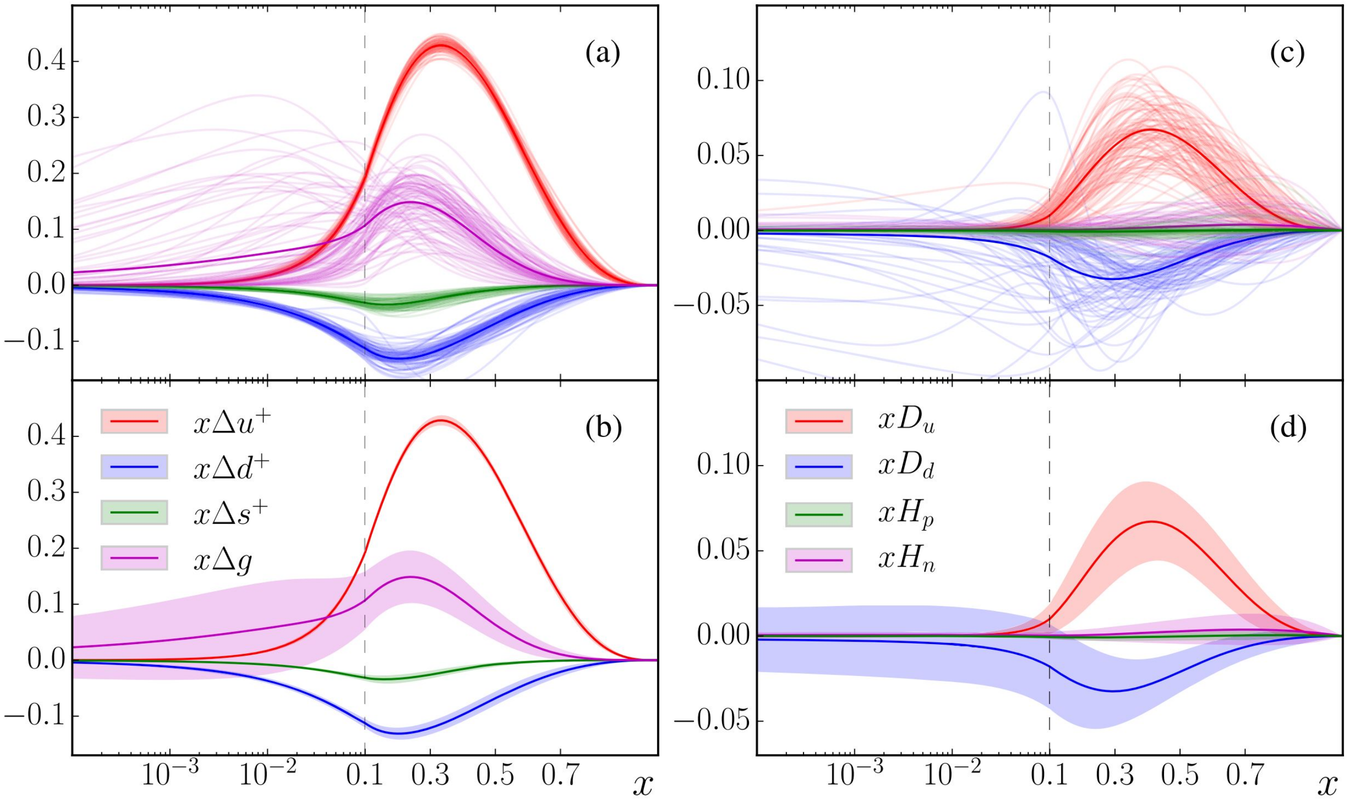
Hints of HT effects

3He (JLab)



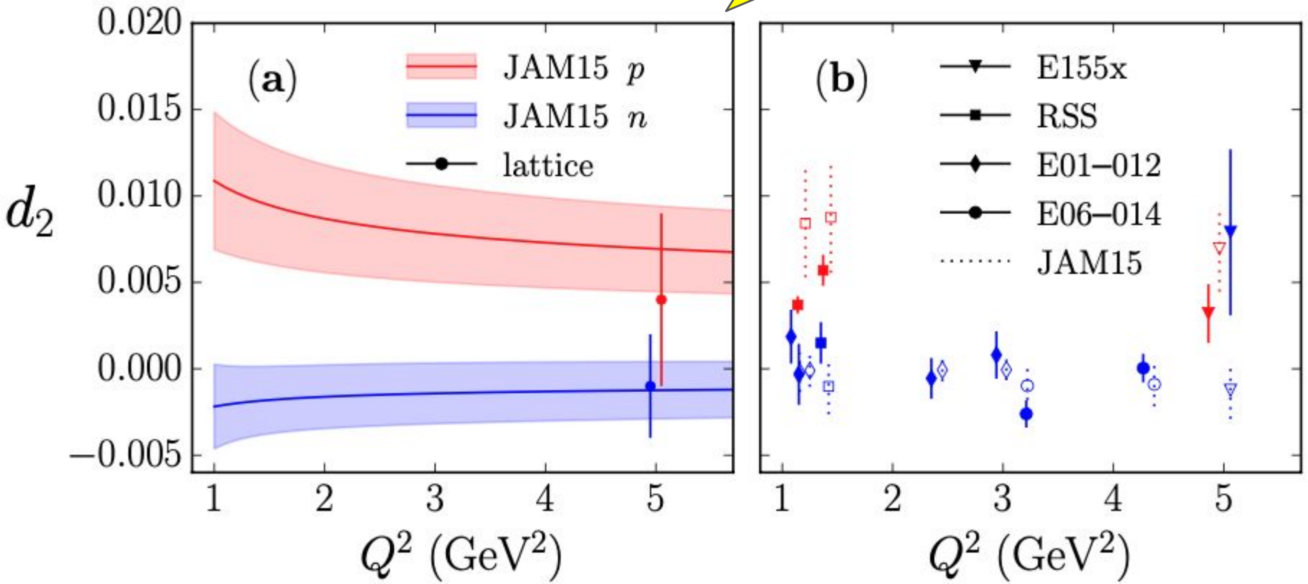
Our theory setup describes the data

Parton densities



Twist 3 effects

Corrected from original JAM15 paper

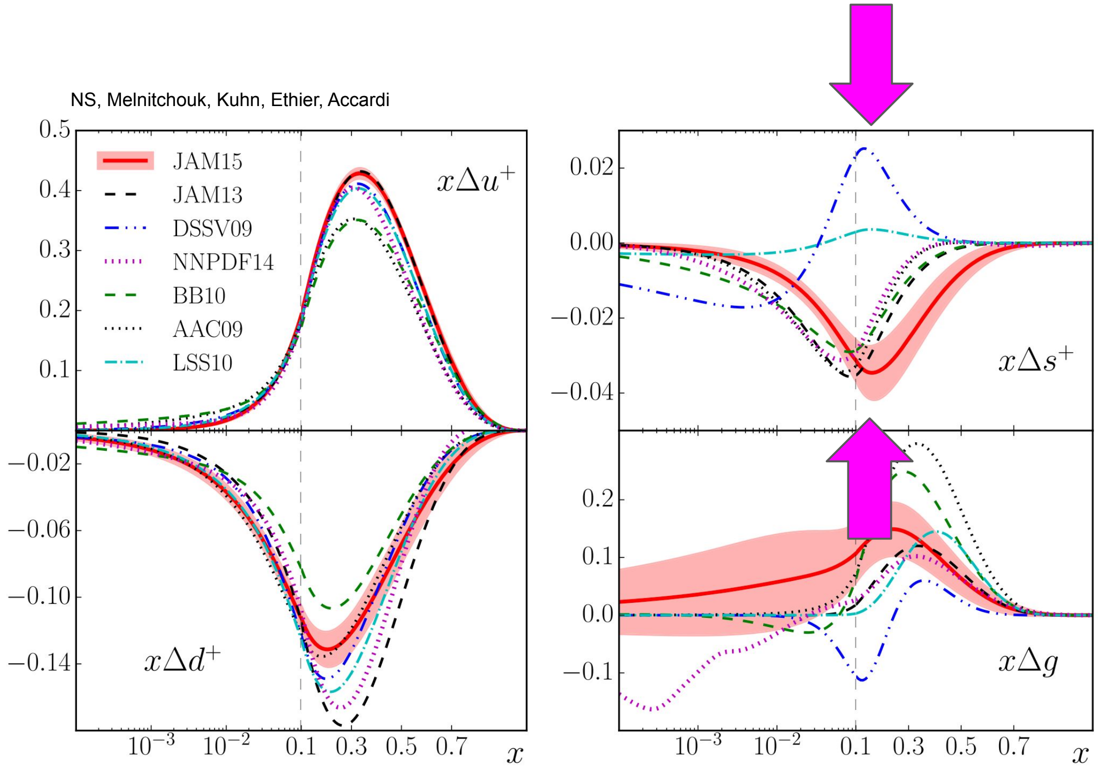


$$d_2(Q^2) \equiv \int_0^1 dx x^2 \left[2g_1^{\tau 3}(x, Q^2) + 3g_2^{\tau 3}(x, Q^2)\right]$$

https://arxiv.org/abs/1103.5979

Strange puzzle

NS, Melnitchouk, Kuhn, Ethier, Accardi



A Possible Resolution of the Strange Quark Polarization Puzzle ?

Elliot Leader, Alexander V. Sidorov, Dimiter B. Stamenov

The strange quark polarization puzzle, i.e. the contradiction between the negative polarized strange quark density obtained from analyses of inclusive DIS data and the positive values obtained from combined analyses of inclusive and semi-inclusive SIDIS data using de Florian et. al. (DSS) fragmentation functions, is discussed. To this end the results of a new combined NLO QCD analysis of the polarized inclusive and semi-inclusive DIS data, using the Hirai et. al. (HKNS) fragmentation functions, are presented. It is demonstrated that the polarized strange quark density is very sensitive to the kaon fragmentation functions, and if the set of HKNS fragmentation functions is used, the polarized strange quark density obtained from the combined analysis turns out to be negative and well consistent with values obtained from the pure DIS analyses.

"...It is demonstrated that the polarized strange quark density is very sensitive to Kaon FF."

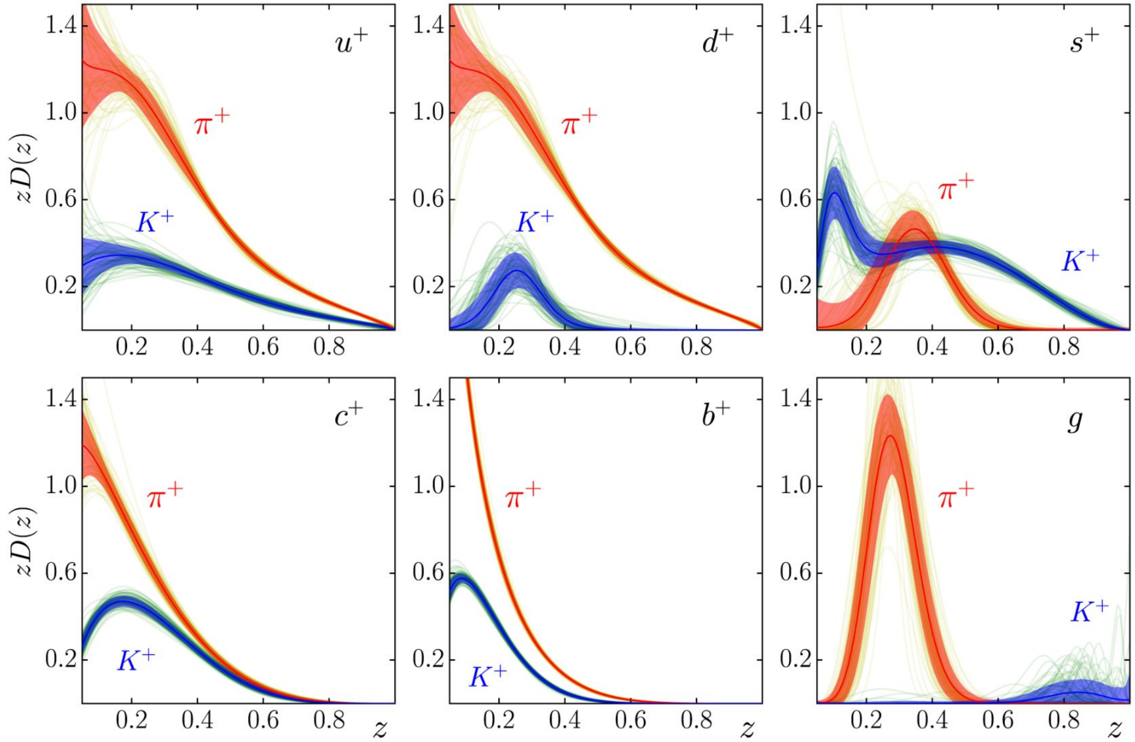
SU(3) constraints:

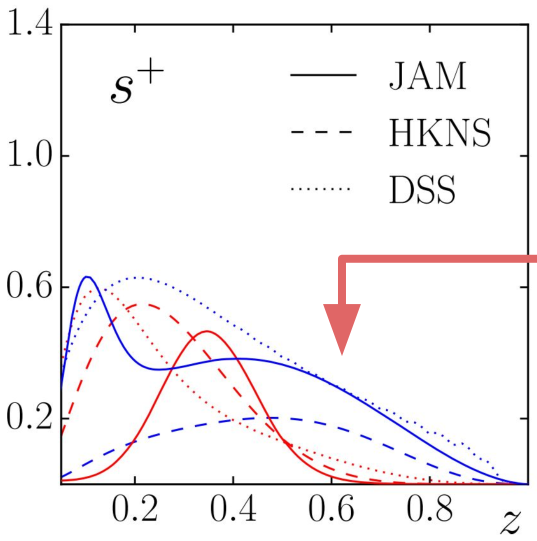
$$\Delta u^+(1,Q^2) + \Delta d^+(1,Q^2) - 2\Delta s^+(1,Q^2) = a_8,$$

Role of SIDIS and SIA ?

JAM'16 (1D FFs)

NS, Ethier, Melnitchouk, Hirai, Kumano

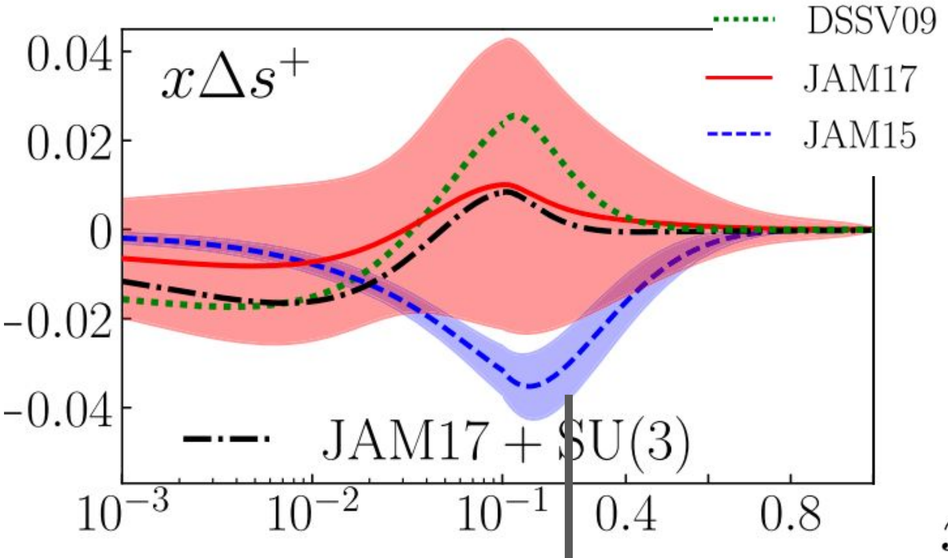




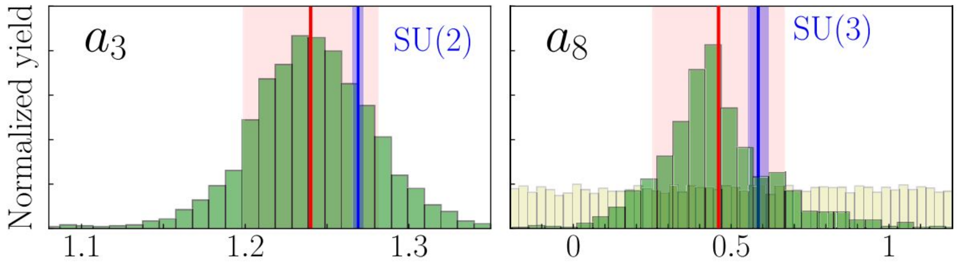
FF kaon:
JAM closer to DSS at large z

JAM'17 (towards more data-driven analysis)

Ethier, NS, Melnitchouk
https://arxiv.org/abs/1705.05889

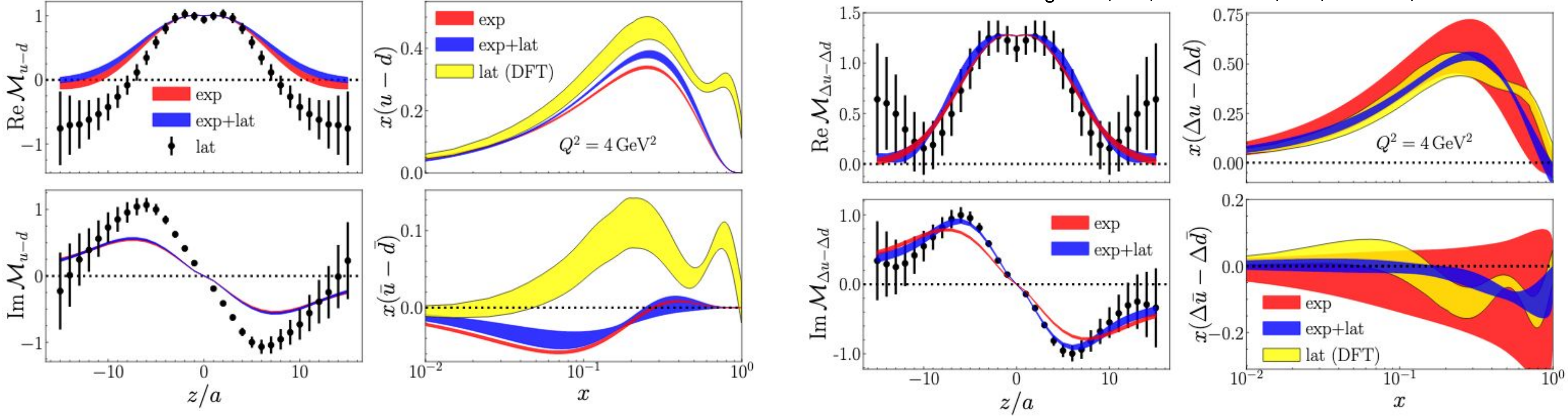


- Use of pol. **DIS, SIDIS and SIA**
- No SU(2) or SU(3) constraints
- Empirical evidence of g_3 ~ g_A 2%
- **No strange puzzle - need more data!**



JAM’20 (1D experiment + lattice QCD: quasi-PDFs)

Bringewatt, NS, Melnitchouk, Qiu, Steffens, Constantinou



$$\mathcal{M}_q(z,\mu) = \int_{-\infty}^{\infty} dx\, e^{-ixP_3 z} \int_{-1}^{1} \frac{d\xi}{|\xi|} C_q\left(\frac{x}{\xi}, \frac{\mu}{\xi P_3}\right) f_q(\xi,\mu)$$

$$\mathcal{M}_{\Delta q}(z,\mu) = \int_{-\infty}^{\infty} dx\, e^{-ixP_3 z} \int_{-1}^{1} \frac{d\xi}{|\xi|} C_{\Delta q}\left(\frac{x}{\xi}, \frac{\mu}{\xi P_3}\right) \Delta f_q(\xi,\mu)$$

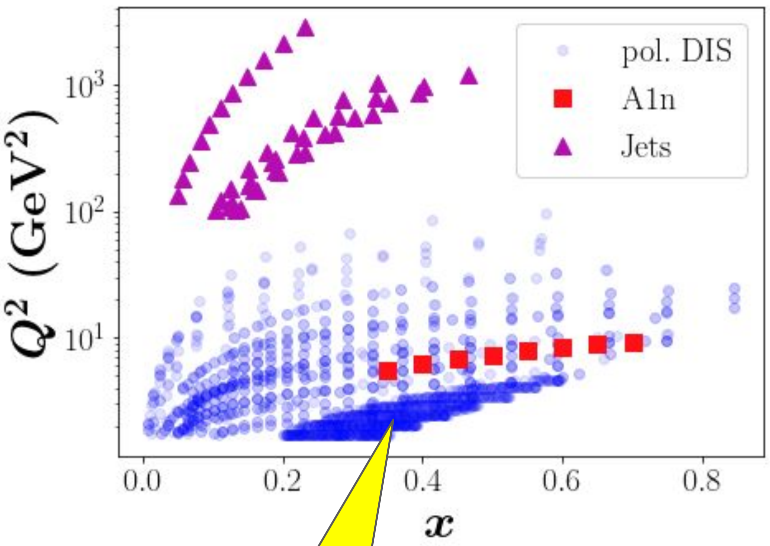
C. Cocuzza

Temple University

Y. Zhou

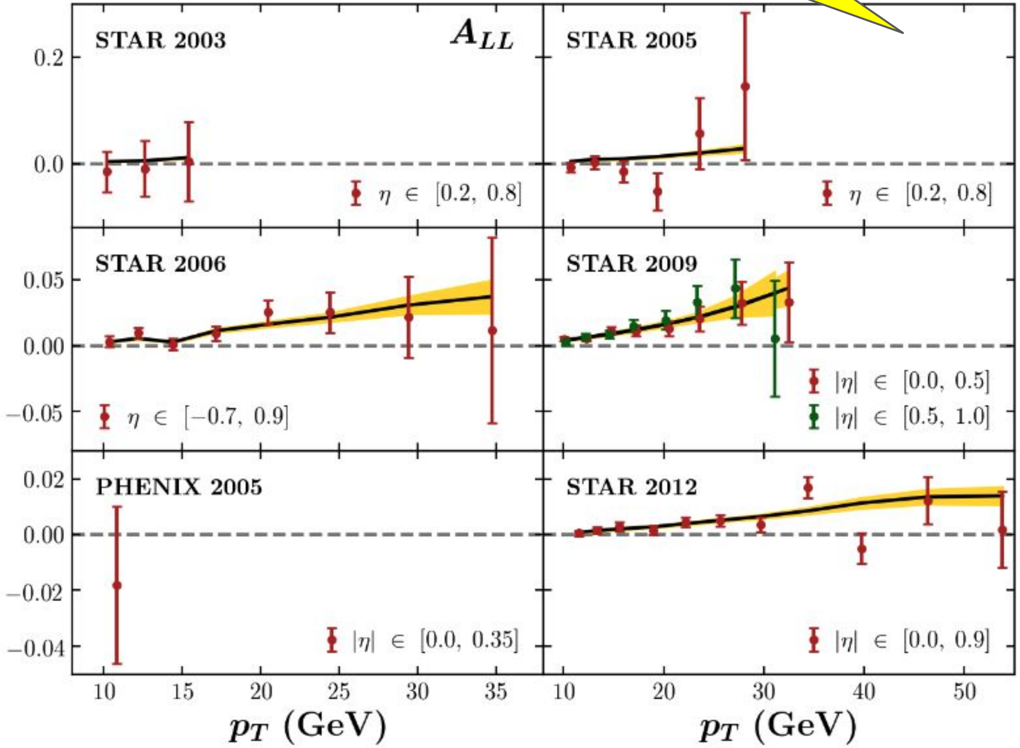
William & Mary

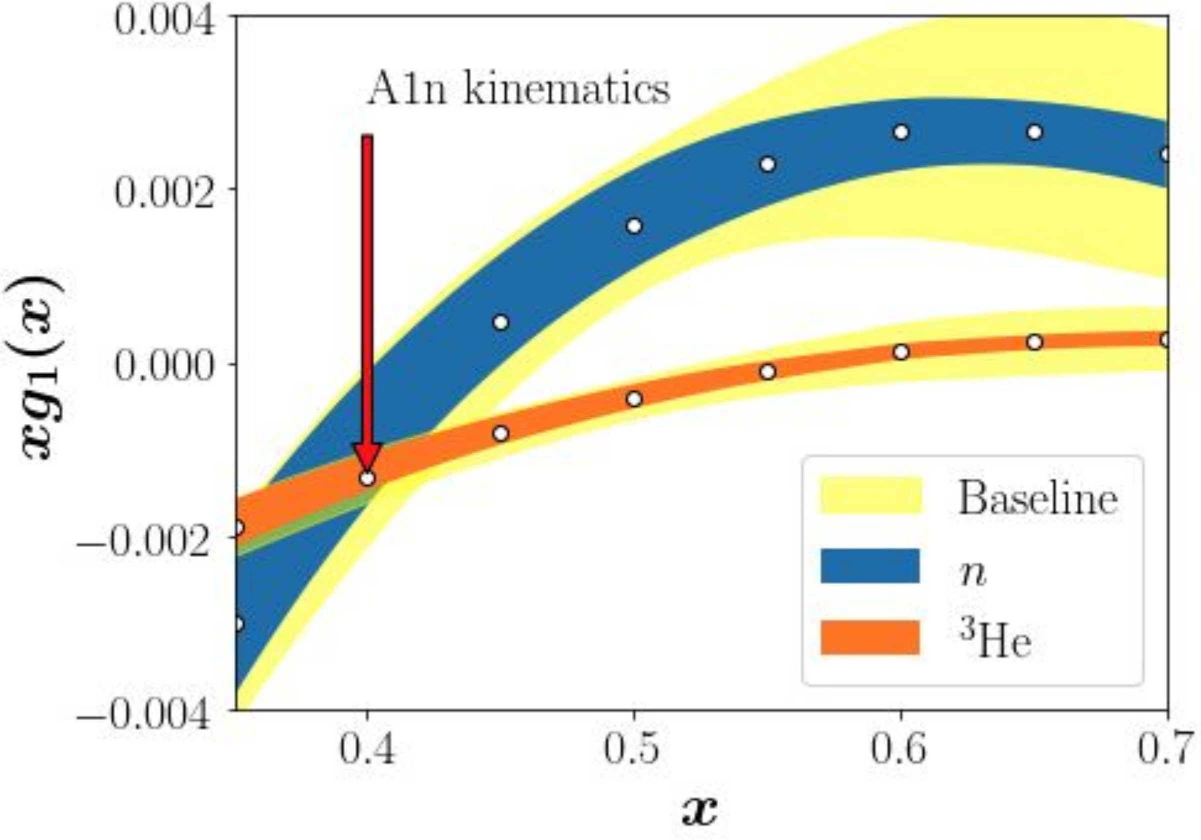
Impact of JLab12 data



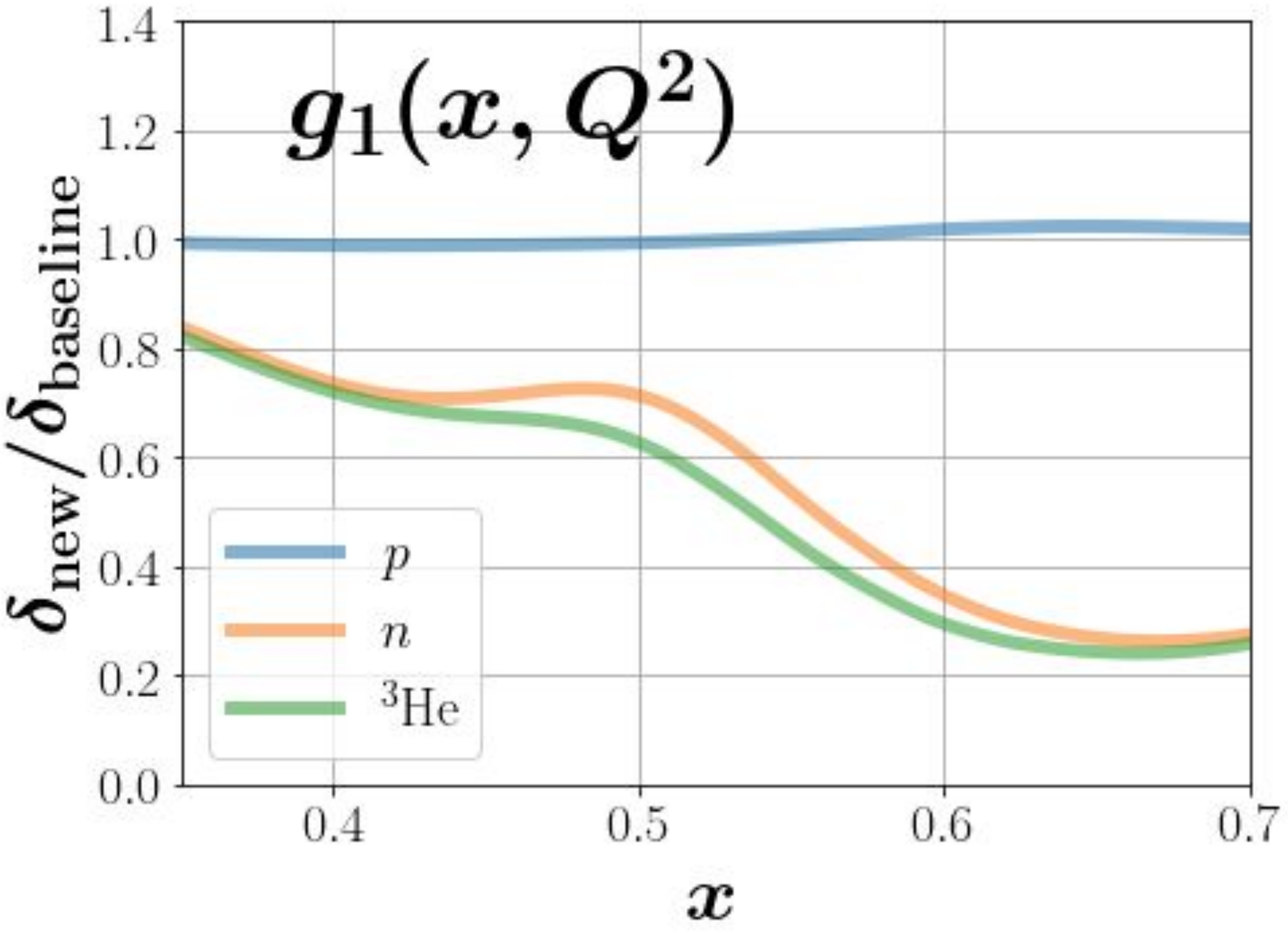
JLab 12 pseudodata

Included in the baseline fits





0.004
0.002
0.000
−0.002
−0.004
0.4
0.5
0.6
0.7
$xg_1(x)$
x
A1n kinematics
Baseline
n
^{3}He


$g_1(x, Q^2)$
$\delta_{\mathrm{new}}/\delta_{\mathrm{baseline}}$
x
p
n
^{3}He
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.4
0.5
0.6
0.7

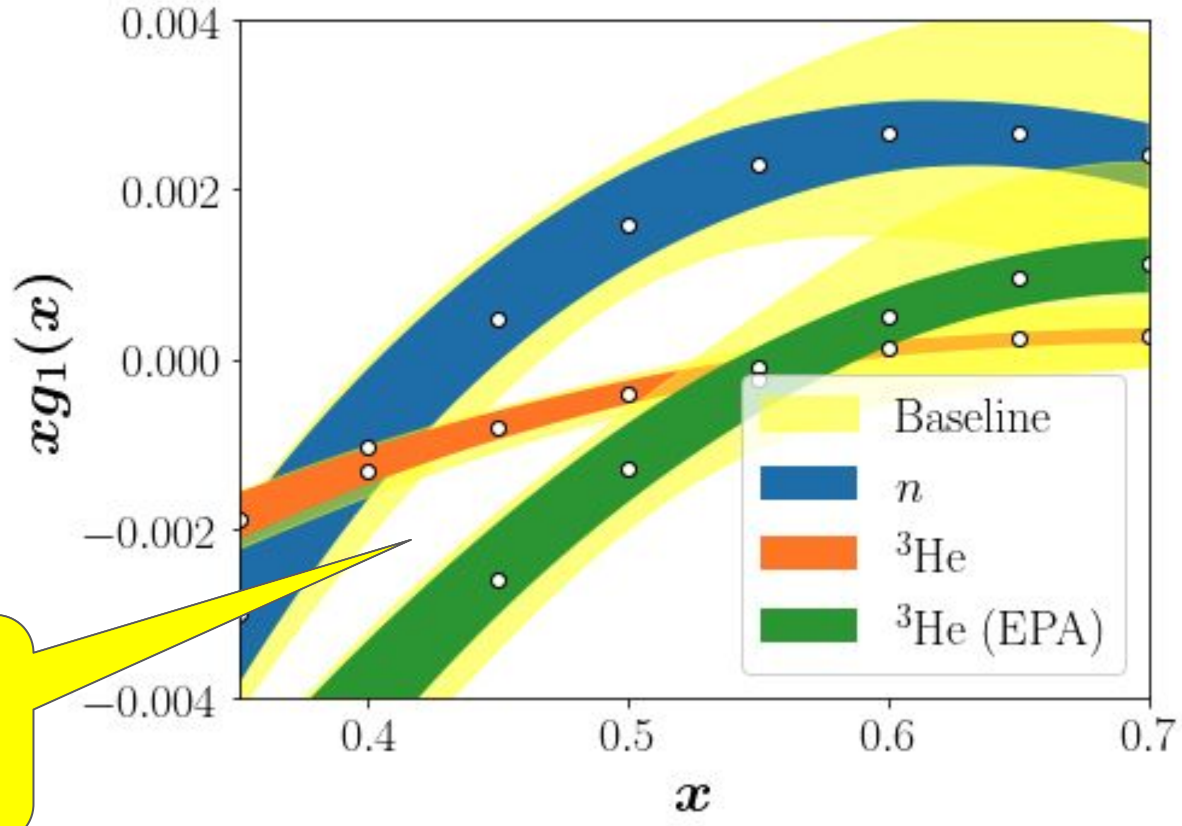
Effective polarization version

$$g_i^{^3\mathrm{He}}(x, Q^2) = \int \frac{dy}{y}\left[2 f_{ij}^p(y, \gamma)\, g_j^p\left(\frac{x}{y}, Q^2\right) + f_{ij}^n(y, \gamma)\, g_j^n\left(\frac{x}{y}, Q^2\right)\right]$$

$$P_i^N = \int dy\, f_{ii}^N(y, \gamma = 1),$$

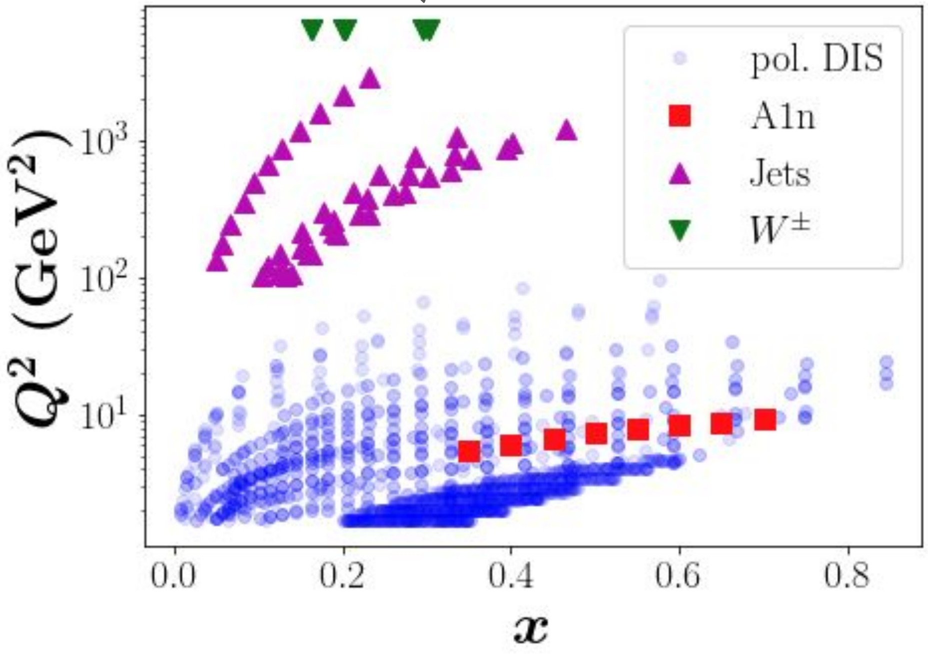
$$g_i^{^3\mathrm{He}}(x, Q^2) = 2P_i^p\, g_i^p(x, Q^2) + P_i^n\, g_i^n(x, Q^2).$$

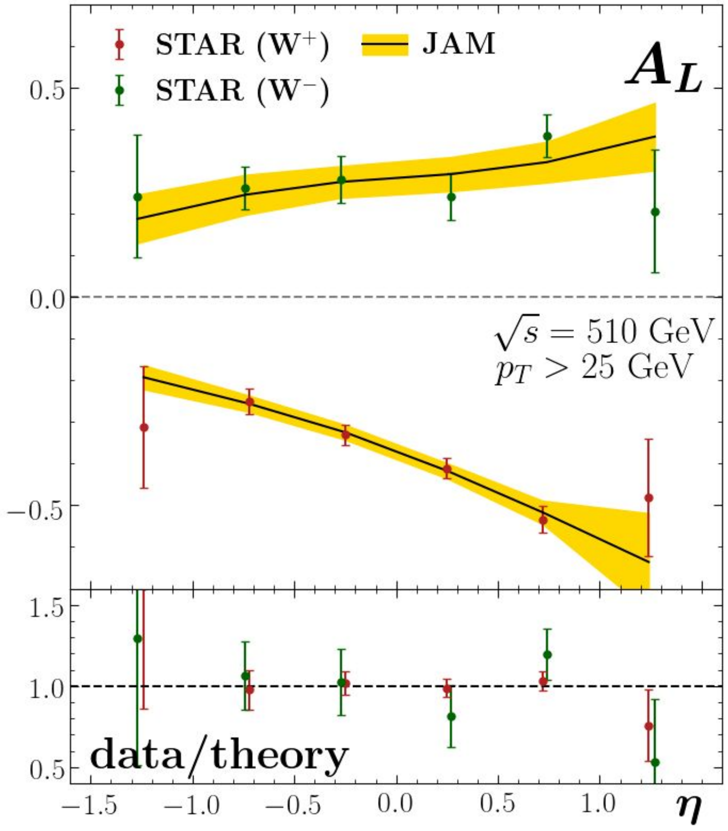
Effective polarization version

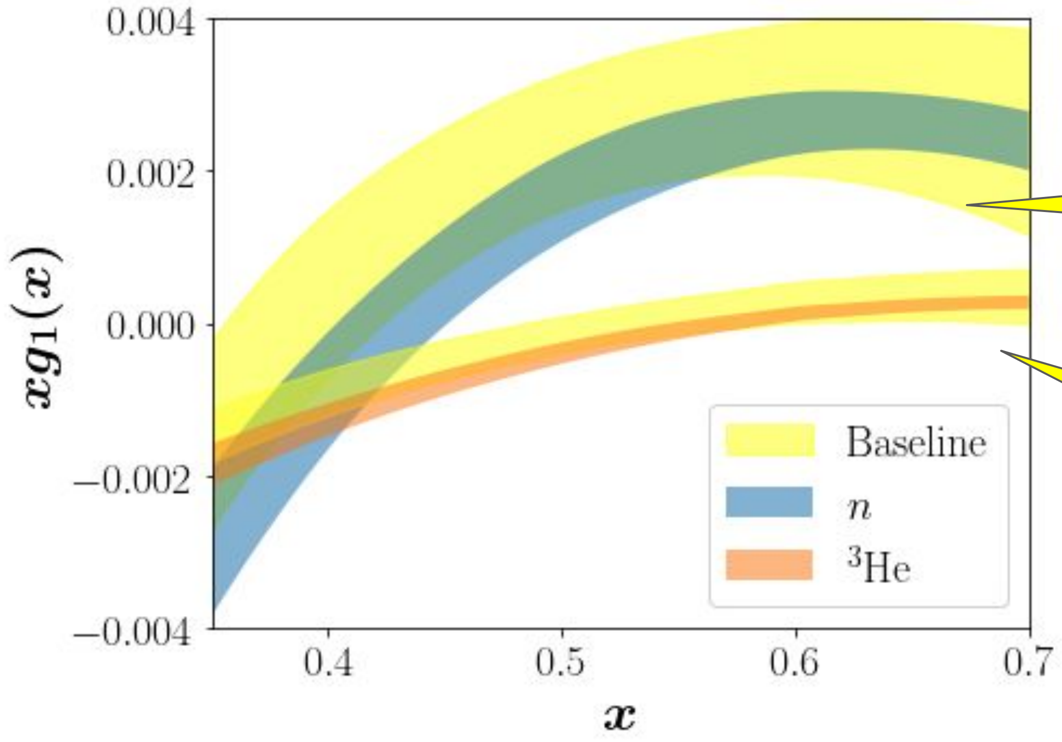


Significant differences using EPA only

Baseline with W data



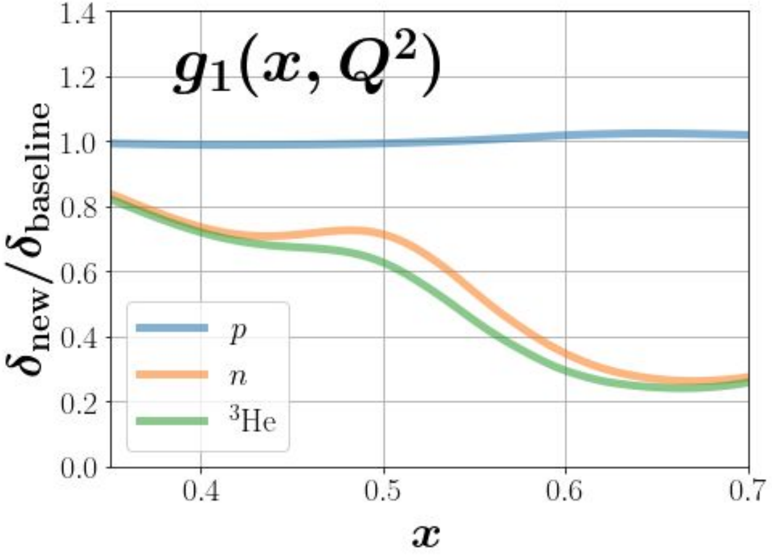




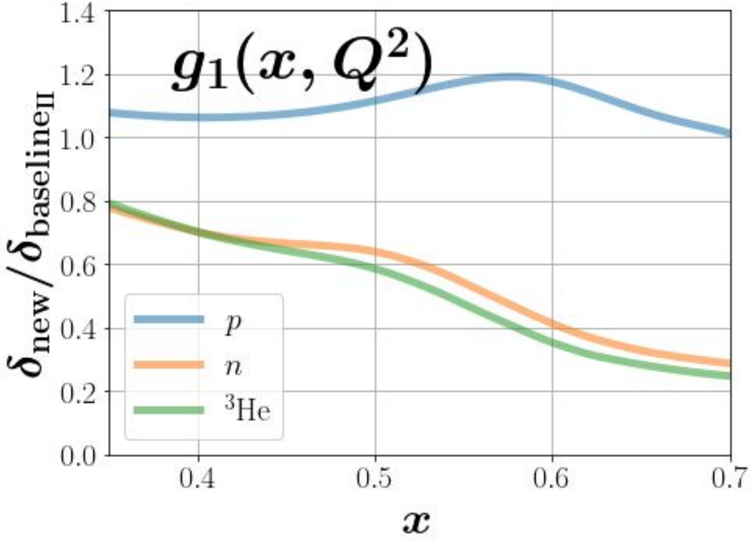
The impact was done using the DIS+jets baseline

Still, A1n JLab data will constrain significantly g1n

DIS+Jets



DIS+Jets+W



Comments on TMCs

Freedom at moderate energies: Masses in color dynamics*

Howard Georgi† and H. David Politzer†
Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138
(Received 2 February 1976)

$$\frac{\nu W_2(Q^2,x)}{m_p} = \frac{1}{2\pi i}\int_{-i\infty}^{i\infty} dn\, x^{-n+1}\sum_{j=0}^{\infty}\left(\frac{m_p^2}{Q^2}\right)^j \frac{1}{j!}\,\frac{\Gamma(n+j+1)}{\Gamma(n-1)} \times \frac{A_{n+2j}}{(n+2j)(n+2j-1)}.$$

OPE

Only valid for integer moments

Requires techniques of analytic continuation

$$\nu W_2(Q^2,x)/m_p = \frac{x^2}{(1+4x^2m_p^2/Q^2)^{3/2}}F(\xi) + 6\frac{m_p^2}{Q^2}\frac{x^3}{(1+4x^2m_p^2/Q^2)^2}\int_\xi^1 d\xi'\,F(\xi')$$
$$+12\frac{m_p^4}{Q^4}\frac{x^4}{(1+4x^2m_p^2/Q^2)^{5/2}}\int_\xi^1 d\xi'\int_{\xi'}^1 d\xi''\,F(\xi'').$$

Comments on TMCs

UNRAVELLING HIGHER TWISTS

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Received 21 June 1982

$$f(x, k_T^2) = \frac{1}{\pi M^2}\Phi\left(\frac{2P\dot{k}}{M^2}\right)\theta((P-\dot{k})^2)$$

?

$$= \frac{1}{\pi M^2}\Phi\left(x + \frac{k_T^2}{xM^2}\right)\theta(x(1-x)M^2 - k_T^2)\,.$$

The transverse momentum is bounded to be of order M^2.

???

Comments on TMCs

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Received 21 June 1982

2. Factorization

As discussed in sect. 1, the final formula is a power series expansion in $1/Q^2$. The coefficients in this series vary logarithmically with Q^2. Since the aim of this paper is to formulate a diagrammatic scheme to derive the *power* expansion, we will postpone the question of logarithmic radiative corrections. These effects are calculable and give slow logarithmic variations on top of the power-law behaviour discussed here. In our gauge the calculation of logarithmic variations (anomalous

Modern factorization **does not postpone** evolution.

https://arxiv.org/abs/1901.09016

A new perspective on TMCs

Moffat, Rogers, Melnitchouk, NS, Steffens

$$F_1\left(x_{\mathrm{Bj}}(x_{\mathrm{N}}, M^2/Q^2), Q^2\right) = \int_{x_{\mathrm{N}}}^{1} \frac{\mathrm{d}\xi}{\xi} \widehat{\mathcal{F}}_1(x_{\mathrm{N}}/\xi, Q^2)\, f(\xi) + O\left(m^2/Q^2\right)$$

$$F_2\left(x_{\mathrm{Bj}}(x_{\mathrm{N}}, M^2/Q^2), Q^2\right) = \frac{Q^2\left(Q^2 - M^2 x_{\mathrm{N}}^2\right)}{\left(Q^2 + M^2 x_{\mathrm{N}}^2\right)^2} \int_{x_{\mathrm{N}}}^{1} \mathrm{d}\xi\, \widehat{\mathcal{F}}_2(x_{\mathrm{N}}/\xi, Q^2)\, f(\xi) + O\left(m^2/Q^2\right)$$

- TMCs fully justified in collinear factorization
- No need to use OPE
- Universal corrections to all twists

Summary and Outlook