Polarized PDFs (hPDF): JAM perspective

In collaboration with
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Recent developments

Sign of gluon polarization

Zhou, NS, Melnitchouk '22
Karpie, Whitehill, Melnitchouk, Monahan, Orginos, Qiu, Richards, NS, Zafeiropoulos '23
de Florian, Forte, Vogelsang `24
Hunt-Smith, Cocuzza, Melnitchouk, NS, Thomas, White '24

Small x formalism for hPDF global analysis

Adamiak, Kovchegov, Melnitchouk, Pitonyak, NS, Sievert '21
Adamiak, Baldonado, Kovchegov, Melnitchouk, Pitonyak, NS, Sievert, Tarasov, Tawabutr `23
Adamiak, Baldonado, Kovchegov, Li, Melnitchouk, Pitonyak, NS, Sievert, Tarasov, Tawabutr `25

Approximate NNLO hPDF global analysis

Borsa, Stratmann, Vogelsang, de Florian, Sassot, '25
Cruz-Martinez, Hasenack, Hekhorn, Magni, Nocera, Rabemananjara, Rojo, Sharma, van Seeventer `25
Bertone, Chiefs, Nocera `24

Transverse Momentum

Bacchetta, Bongallino, Cerutti, Radici, Rossi, '24

hPDFs at high x

Cocuzza, Hunt-Smith, Melnitchouk, NS, Thomas,

Hadron structure

Polarized sea, sea asymmetries, gluon polarization, spin puzzle, Higher twist effects, high x asymptotics, intrinsic transverse momentum

Formalisms

Higher order corrections, dipole formalism, target mass corrections

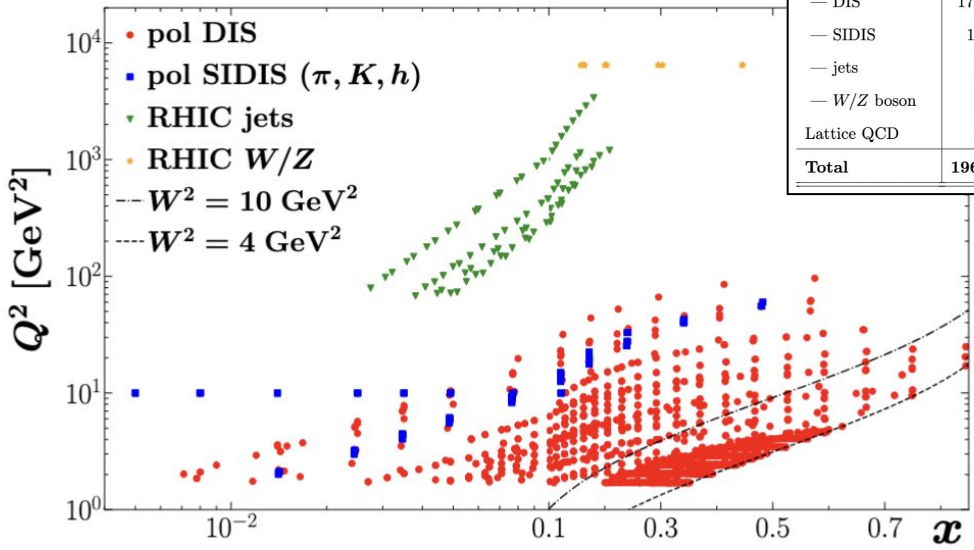
Methodologies

MC based approach, ANN, simultaneous extraction framework (key observables SIDIS), LQCD input

hPDFs at High x

Cocuzza, Hunt-Smith, Melnitchouk, NS, Thomas, (in prep.)

Data	N_{dat}
Polarized	1912†
— DIS	1735†
— SIDIS	124
— jets	83
— W/Z boson	18
Lattice QCD	48
Total	**1960†**



Motivations

Reconstruction of hPDFs at very high x
Simultaneous reconstruction of PDFs, hPDFs and FFs
Constrain subleading power corrections in DIS
Inclusion of LQCD

Ingredients

Perturbative accuracy: NLO, ZMVFS (NLL for PDFs and alphaS)
TMC corrections using AOT
Nuclear smearing for 3He
NP modeling for power corrections

Methodology

Traditional parametrization
Mellin space techniques: no K factor approach
Ensemble approach for UQ
Multi-step strategy

Theory setup for pol. inclusive DIS

Leading Twist Collinear factorization

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

Target Mass corrections

Moffat, Roger, Melnitchouk NS, Steffens '19

$$g_1^{\mathrm{TMC}}(x,Q^2) = \frac{1}{\rho^2} g_1^{\mathrm{LT}}(x_N,Q^2) + \frac{2(\rho-1)}{\rho^2}\int_{x_N}^1 \frac{dz}{z} g_1^{\mathrm{LT}}(z,Q^2)$$

$$g_2^{\mathrm{TMC}}(x,Q^2) = -\frac{1}{\rho^2} g_1^{\mathrm{LT}}(x_N,Q^2) + \frac{2}{(1+\rho)\rho^2}\int_{x_N}^1 \frac{dz}{z} g_1^{\mathrm{LT}}(z,Q^2)$$

$$\rho^2 = 1 + \frac{4M^2x^2}{Q^2}$$

Higher Twist effects

$$g_1^{\mathrm{HT}} = \frac{c_1^{\mathrm{HT}}}{Q^2} \qquad g_2^{\mathrm{HT}} = c_2^{\mathrm{HT}}$$

Final expressions

$$g_i = g_i^{\mathrm{TMC}} + g_i^{\mathrm{HT}} \qquad i = 1,2$$

For Light nuclei DIS

$$g_i^A(x,Q^2) = \sum_N \left[\Delta f_{ij}^{N/A} \otimes g_j^N\right](x,Q^2)$$

Parametrization & optimization

$$T(x,\mu^2) = \frac{N}{\mathcal{M}} x^{\alpha}(1-x)^{\beta}(1+\gamma\sqrt{x}+\eta x)$$

Input hpdfs + power corrections

$$\Delta u = \Delta u_v + \Delta \bar{u}$$
$$\Delta d = \Delta d_v + \Delta \bar{d}$$
$$\Delta \bar{u} = \Delta S + \delta \bar{u}$$
$$\Delta \bar{d} = \Delta S + \delta \bar{d}$$
$$\Delta s = \Delta \bar{s} = \Delta S$$
$$c_i^{\mathrm{HT}}$$

\+ Input pdfs + power corrections

\+ Input pion FFs

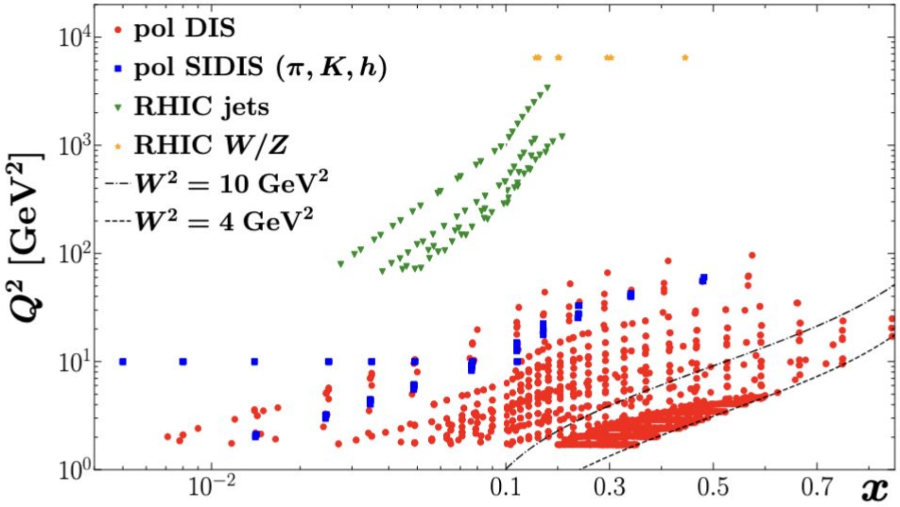
\+ Input Kaon FFs

Ensemble approach: data resampling + optimization
Multi-step strategy: sequential prior-posterior loops with increasing data aggregation
Quality metrics: reduced chi2 + Z scores based on chi2 distribution

Sensitivity on DIS cuts

$W^2_{\min}$ (GeV^2)	3.5	**4**	5	6	10
N_{dat}	2002	**1735**	1287	1008	689
χ^2_{red}	1.10	**1.02**	0.97	1.00	1.00
Z-score	+3.11	**+0.60**	−0.84	+0.02	+0.00

Multiple analysis with different W2min cuts
W2min~4 is the minimum we can push to obtain stable results
Increase in chi2 for W2min~3.5 due to proximity to resonance region



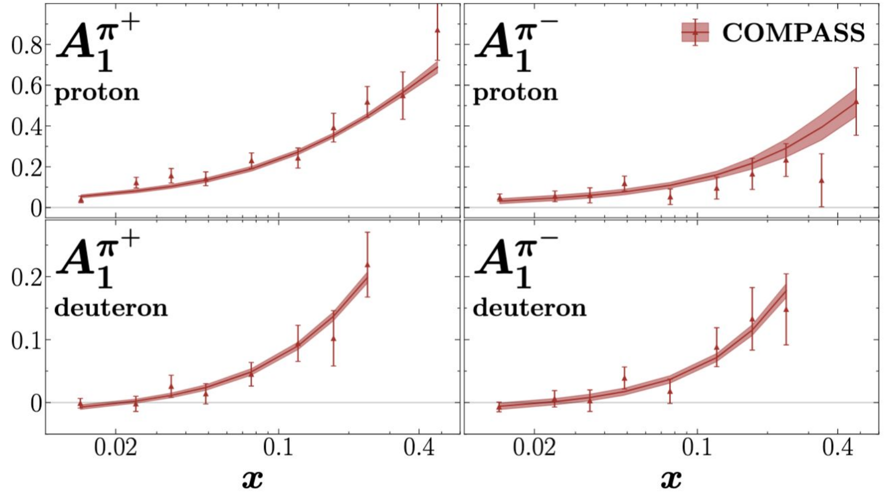
Role of HT effects

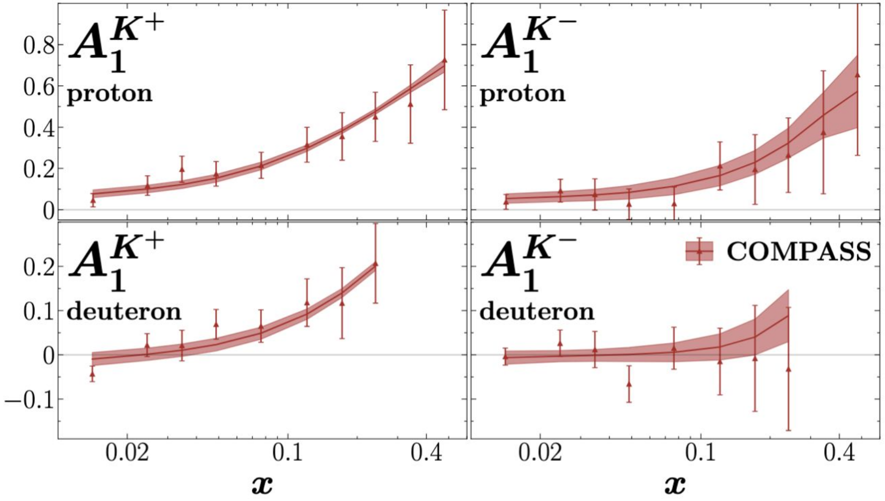
χ^2_{red} (Z-score)				
Data	N_{dat}	$W^2 > 10$ GeV^2 (no HT)	$W^2 > 4$ GeV^2 (no HT)	$W^2 > 4$ GeV^2 (with HT)
Polarized	1912†	0.86 (−3.13)	1.01 (+0.63)	0.98 (−0.61)
— DIS	1735†	1.01 (+0.28)	1.04 (+1.15)	1.03 (+0.79)
— SIDIS	124	0.82 (−1.51)	0.85 (−1.21)	0.77 (−1.95)
— jets	83	0.83 (−1.08)	0.84 (−1.06)	0.83 (−1.08)
— W/Z boson	18	0.78 (−0.61)	0.82 (−0.47)	0.67 (−1.03)
Lattice QCD	48	0.61 (−2.15)	0.57 (−2.44)	0.58 (−2.40)
Total	**1960**†	**0.93** (−1.54)	**1.01** (+0.20)	**0.99** (−0.35)

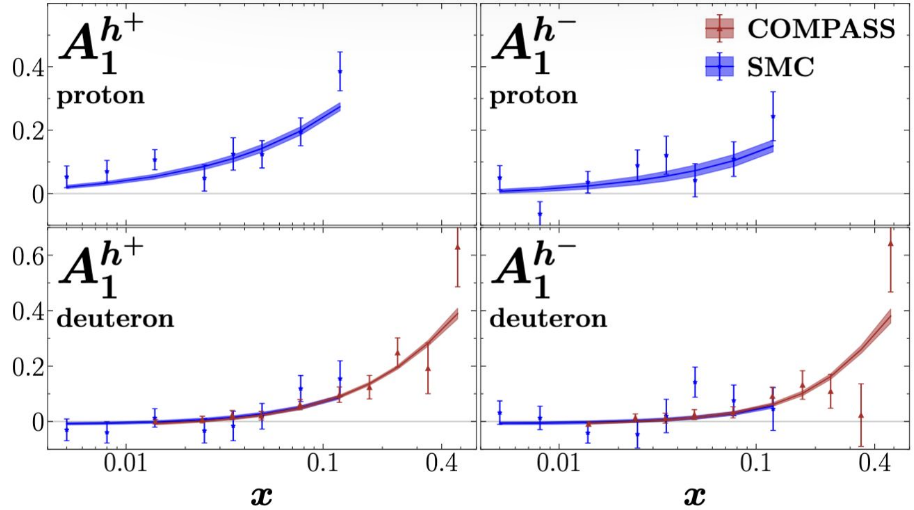
Stable global agreement when lowering W2min
Inclusion of HT effects gives marginal difference with the quality metrics
At present, we see no strong evidence to support sizable HT effects


pol. DIS data
proton target
$A_{\parallel} (+i)$
HERMES
SLAC
E143
E155
E80/E130
JLab Hall B eg1 DVCS
E4.8
E6.0
JLab Hall B
eg1b (E4.2)
eg1b (E5.7)
deuteron target
$A_1 (+i)$
COMPASS
SMC
$A_2 (+i)$
SANE
E4.7
E5.9
$A_{\perp} (+i)$
$\tilde{A}_{\perp} (+i)$
SLAC E29
E32
$\theta = 2.75$
$\theta = 5.50$
$\theta = 10.5$
egl DVCS
eg1b (E4.2)
eg1b (E5.7)
^{3}He/n target
A_1
HERMES n
SLAC (E142) ^{3}He
^{3}He target
SLAC (E154)
JLab (E06-014)
JLab (E99-117)
A_2
SLAC (E142)
x

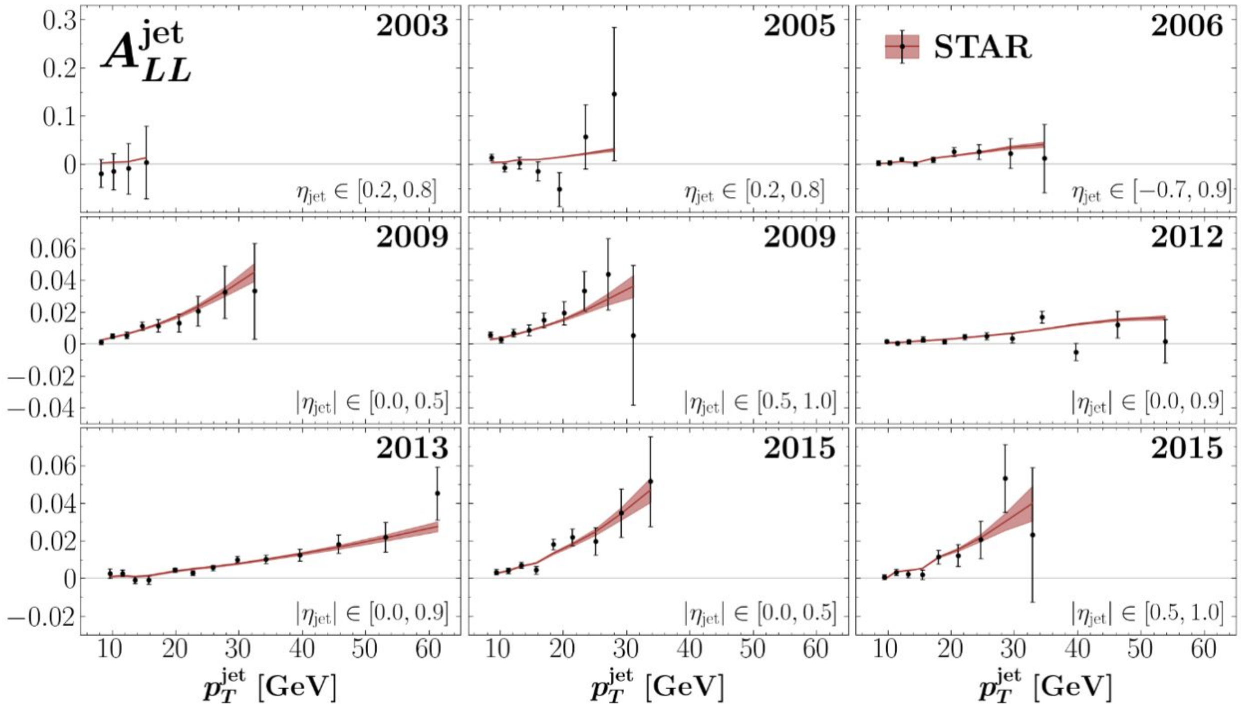
pol. SIDIS data







pol pp Jets



χ^2_{red} (Z-score)

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Polarized	1912†	1.01 (+0.63)
— DIS	1735†	1.04 (+1.15)
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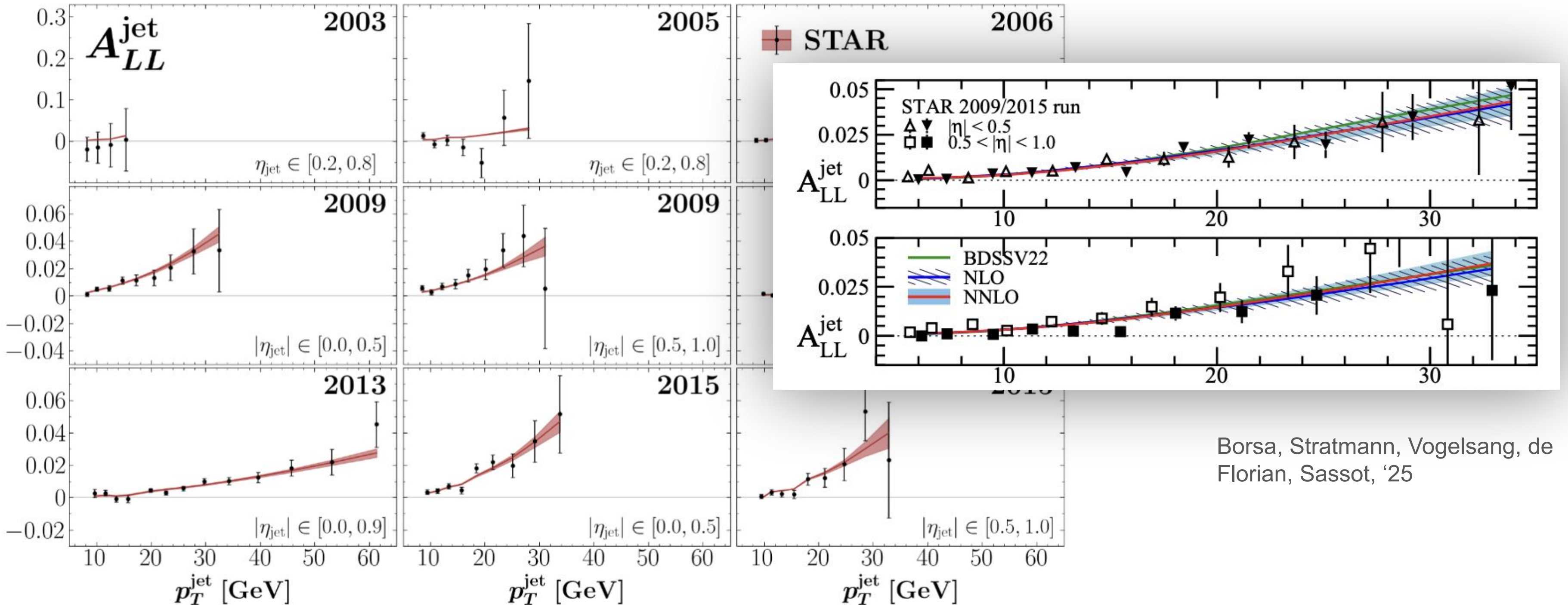
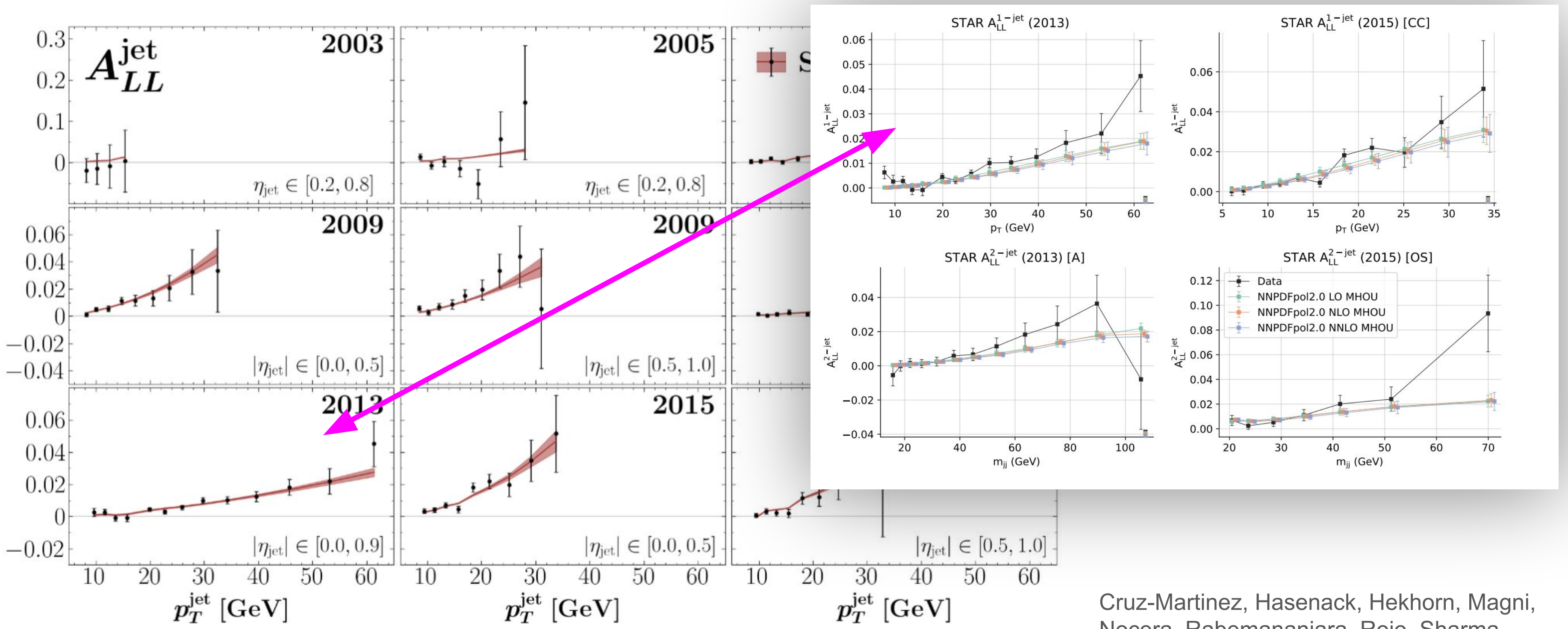
pol pp Jets



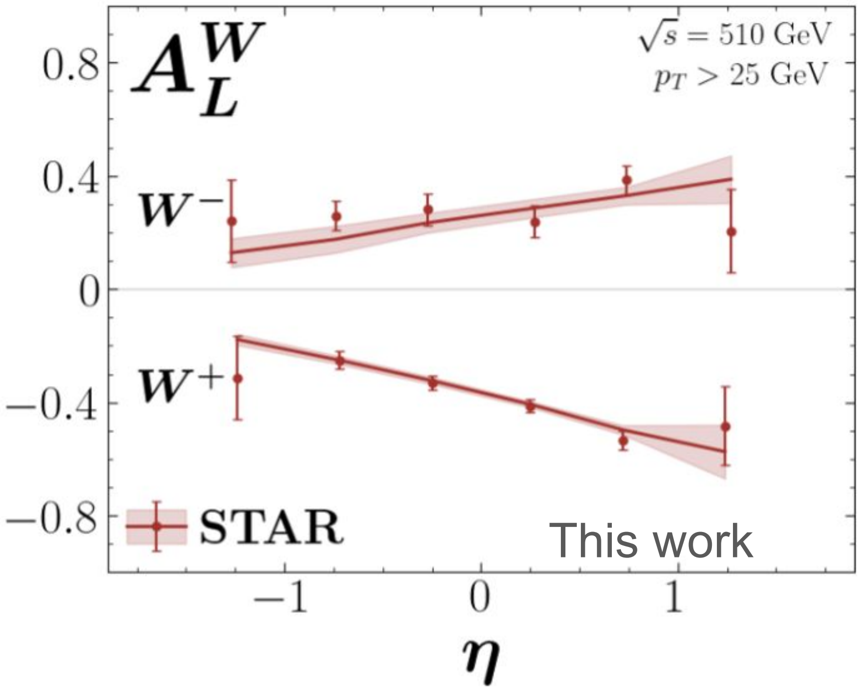
Borsa, Stratmann, Vogelsang, de Florian, Sassot, ‘25

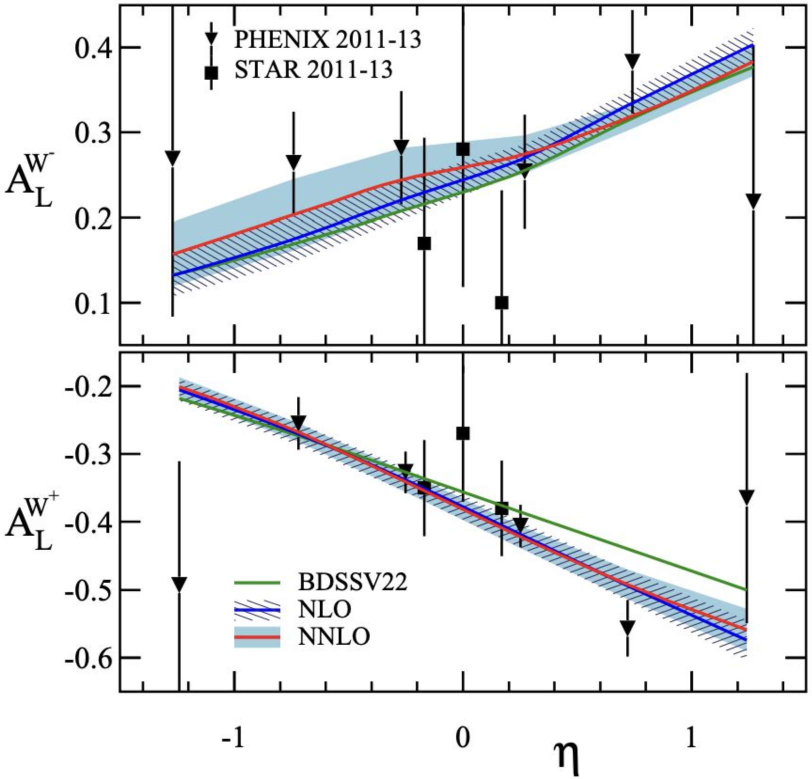
pol pp Jets



Cruz-Martinez, Hasenack, Hekhorn, Magni, Nocera, Rabemananjara, Rojo, Sharma, van Seeventer `25

pol W+/W-





Borsa, Stratmann, Vogelsang, de Florian, Sassot, ‘25

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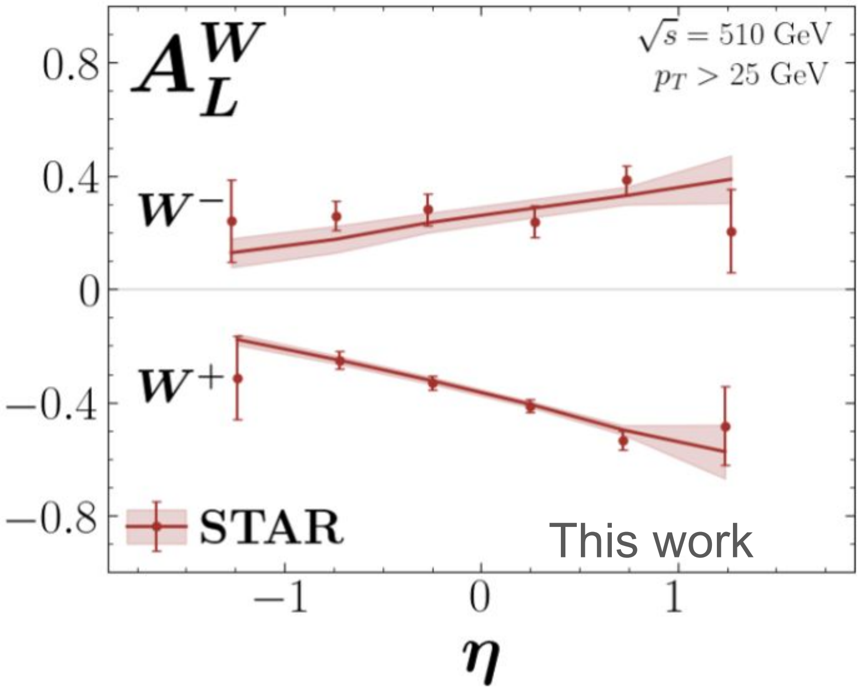
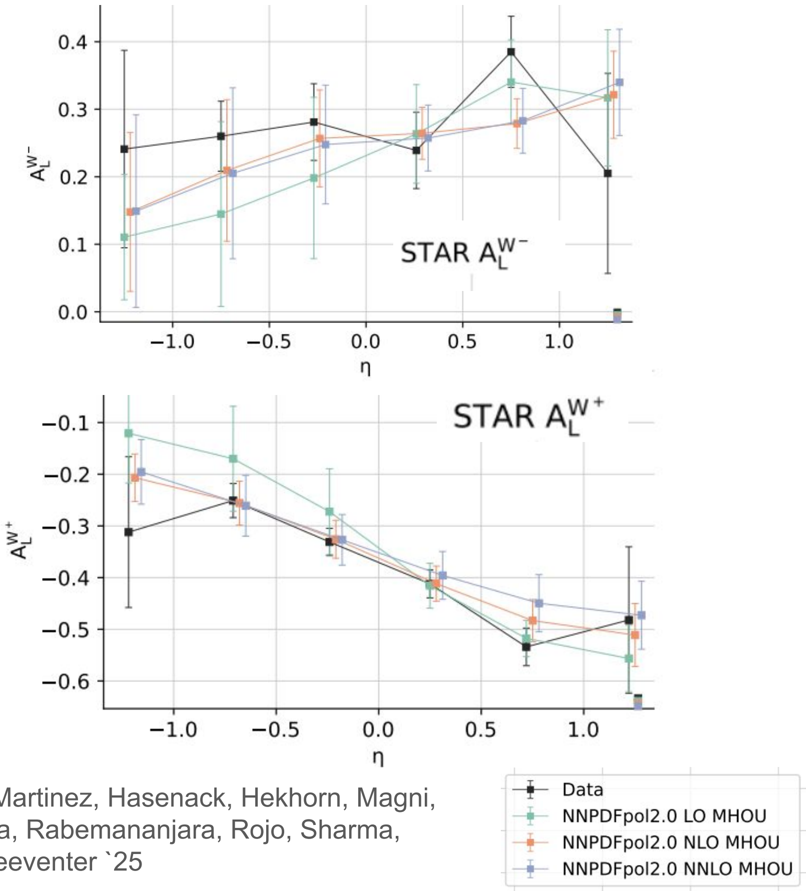
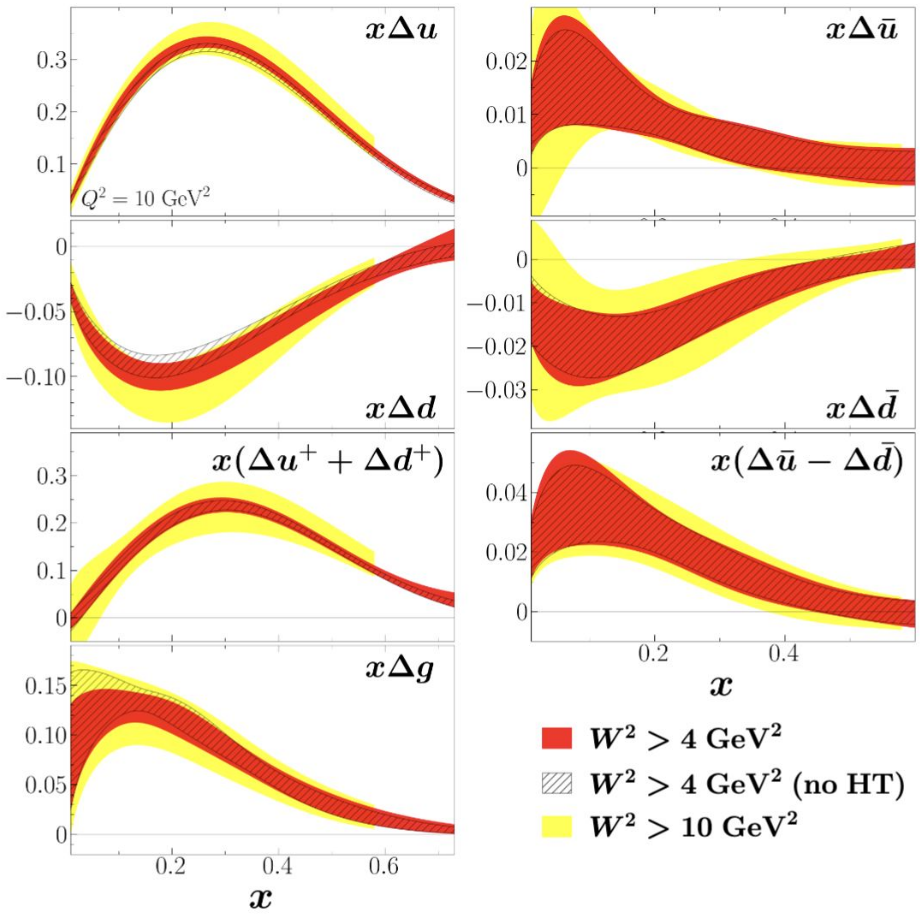
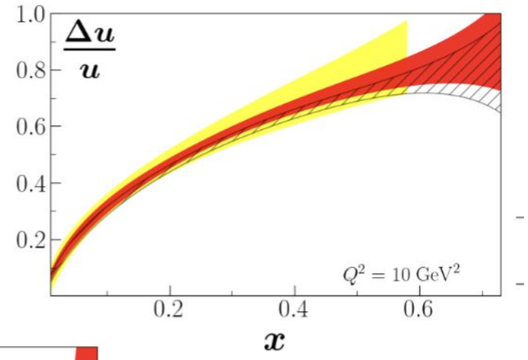


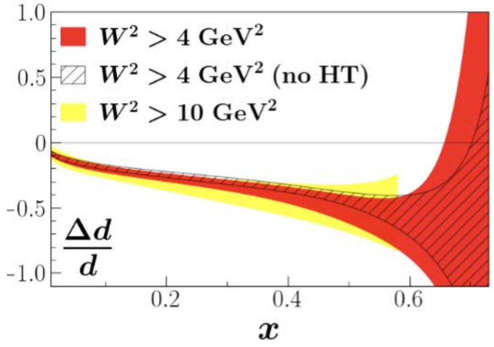


Cruz-Martinez, Hasenack, Hekhorn, Magni, Nocera, Rabemananjara, Rojo, Sharma, van Seeventer `25

Reconstructed hPDFs





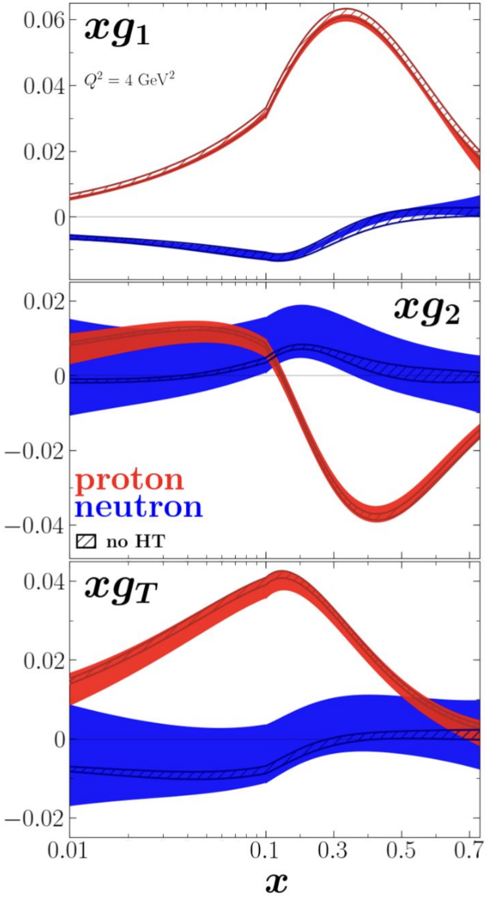


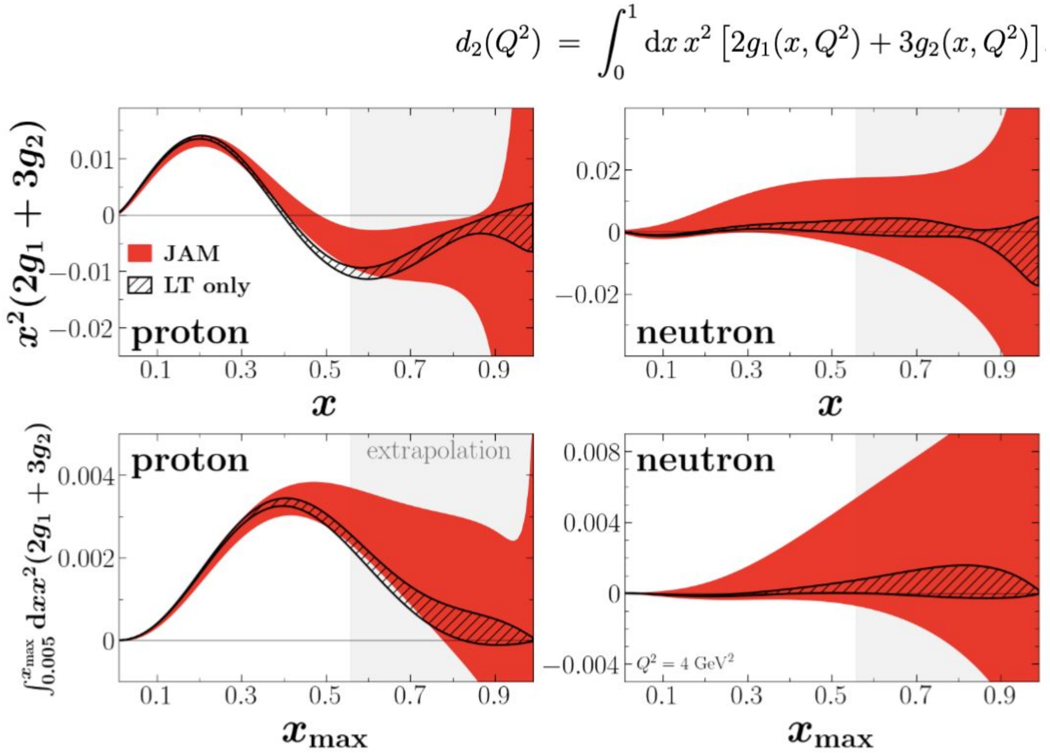
$$\lim_{x\to 1} \frac{\Delta u}{u}, \frac{\Delta d}{d} \to 1$$

Brodsky, Farrar `73

Inclusion of high x DIS data reduces significantly the uncertainties on hPDF
Reconstruction of hPDFs is stable regardless of HT effects
Sign change of delta d/d at high x is still not confirmed empirically

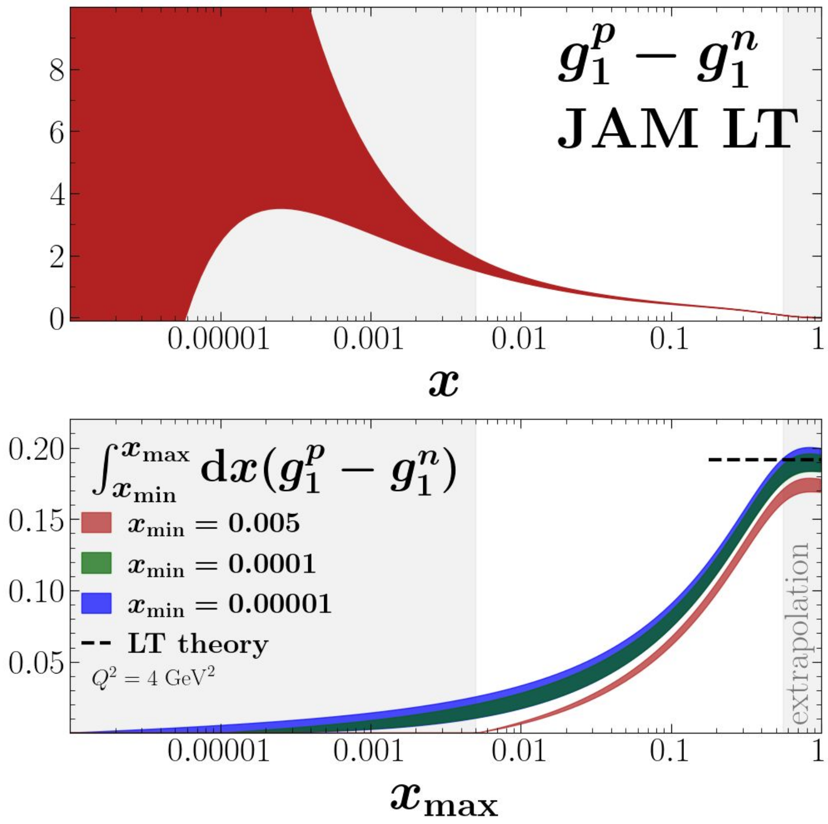
d2 matrix element (twist 3)





The present data constraints HT effects up to x~0.5.
Beyond this, large uncertainties are present preventing to elucidate the genuine twist 3 effects.
Neutron d2 is even less constrained and more data at high x in 3He is needed

Bjorken sum rule (BJSR)



$$\int_0^1 dx \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] = \frac{g_A}{6}\left(1 - \frac{\alpha_S(Q^2)}{\pi}\right)$$

The approximated reconstruction of BJSR is very close to analytic results at NLO.
Current uncertainties are still too large to be competitive to extract alphaS.
Constraining g1p and g1n at smaller values x (eg EIC) has the potential to offer competitive constraints on alphaS.

Summary & outlook

Performed a comprehensive QCD global analysis by simultaneously extracting PDFs, hPDFs, FFs, and DIS HT effects.

Based on stability of the results, it is possible to lower the W2cuts down to 4 GeV^2.

HT in protons are found to be negligible within uncertainties. For neutrons, the uncertainties are still too large to make any conclusions.

New estimates of BJSR has been provided. Compatible with analytic results, uncertainties still large to be competitive for constraining alphaS, need more data at small x (EIC)