QUARK-GLUON-QUARK INTERFERENCE WITHIN THE PROTON

Guillermo Portela Maller

In collaboration with *A. Vladimirov* and *S. Rodini*
A presentation of our work arXiv:2511.04294 with insights from a new extraction

14 May 2026

QCD Evolution 2026, El Escorial

VNiVERSiDAD D SALAMANCA
CAMPUS DE EXCELENCIA INTERNACIONAL

MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

What have we done?

We have determined for the *FIRST TIME* genuine twist-three Parton Distribution Functions –PDFs-

What does this mean?

We have obtained a significative signal from the interference of quark-gluon-quark states within the proton. A purely quantum process.

The twist-three interpretation

Remember twist-two PDFs?

$$\langle p,s|\bar{q}(zn)[zn,0]\,\Gamma\,q(0)|p,s\rangle \sim \int_{-1}^{1} dx\, e^{izxp^+} f^{\text{tw-2}}(x)$$

$$\Gamma = \{\gamma^+, \gamma^+\gamma^5, i\sigma^{\mu+}\gamma^5\}$$

$$f^{\text{tw-2}}(x) = \{f_1(x), g_1(x), h_1(x)\}$$

Infinite Mom. Frame + Axial gauge:

$$f^{\text{tw-2}}(x) \sim \int_{-1}^{1} dz\, e^{-izxp^+} \langle p,s|\bar{q}(zn)\Gamma\, q(0)|p,s\rangle$$

$$f_1(x) \sim \begin{cases} \left|\hat{a}^\dagger(xp)|p,s\rangle\right|^2 & x>0 \\ \left|\hat{a}(xp)|p,s\rangle\right|^2 & x<0 \end{cases}$$

Twist-2:
Density of partons inside the proton:
Parton Distribution Functions (PDFs)

The twist-three interpretation

Twist-three PDFs generalize twist-two PDFs:

- **Quark-gluon-quark:** $g\langle p,s|\bar{q}(z_1 n)[z_1 n, z_2 n]F^{\mu+}(z_2 n)\,\Gamma\,[z_2 n, z_3 n]q(z_3 n)|p,s\rangle \sim \int [dx] e^{-i(x\cdot z)p^+} f_{qgq}^{\text{tw-3}}(x_1,x_2,x_3)$
- **Gluon-gluon-gluon:** $g\langle p,s|F^{\mu+}(z_1 n)[z_1 n, z_2 n]F^{\nu+}(z_2 n)[z_2 n, z_3 n]F^{\tau+}(z_2 n)|p,s\rangle \sim \int [dx] e^{-i(x\cdot z)p^+} f_{ggg}^{\text{tw-3}}(x_1,x_2,x_3)$

We worked with the fundamental set of genuine twist-three PDFs:

- **Built from genuine (not dynamical: ~1/Q) twist-three operators**
- **Closed under QCD evolution.**
- **All twist-three observables are built from them**

$$\{T_q, \Delta T_q, T_{3F}^{\pm}\}$$

Dynamical vs Genuine twist: The quickest guide

Dynamical twist

Associated with observables

Suppression in inverse Powers of Q

Used to describe forces, orbital momentum from a partonic lense

$$g_2, g_T, h_2, e, e_T, \cdots$$

Genuine twist

In the conformal sense

Associated to operators $\tau_\phi = d_\phi - s_\phi$

Natural to PDFs, TMDs, etc: $\{T_q, \Delta T_q, T_{3F}^{\pm}\}$

Block diagonalization of RG:

$$\frac{\partial \vec{T}(x_1, x_2, x_3; \mu)}{\partial \ln \mu} = [\mathbf{H} \otimes \vec{T}](x_1, x_2, x_3; \mu)$$

The twist-three interpretation

qgq PDFs build all relevant twist-three observables. **Our main focus.**

$$\langle p,s|g\bar{q}(z_1 n)F^{\mu+}(z_2 n)\gamma^+ q(z_3 n)|p,s\rangle = 2\epsilon_T^{\mu\nu} s_\nu (p^+)^2 M \int [dx] e^{-ip^+\sum_i z_i x_i} T_q(x_1,x_2,x_3)$$

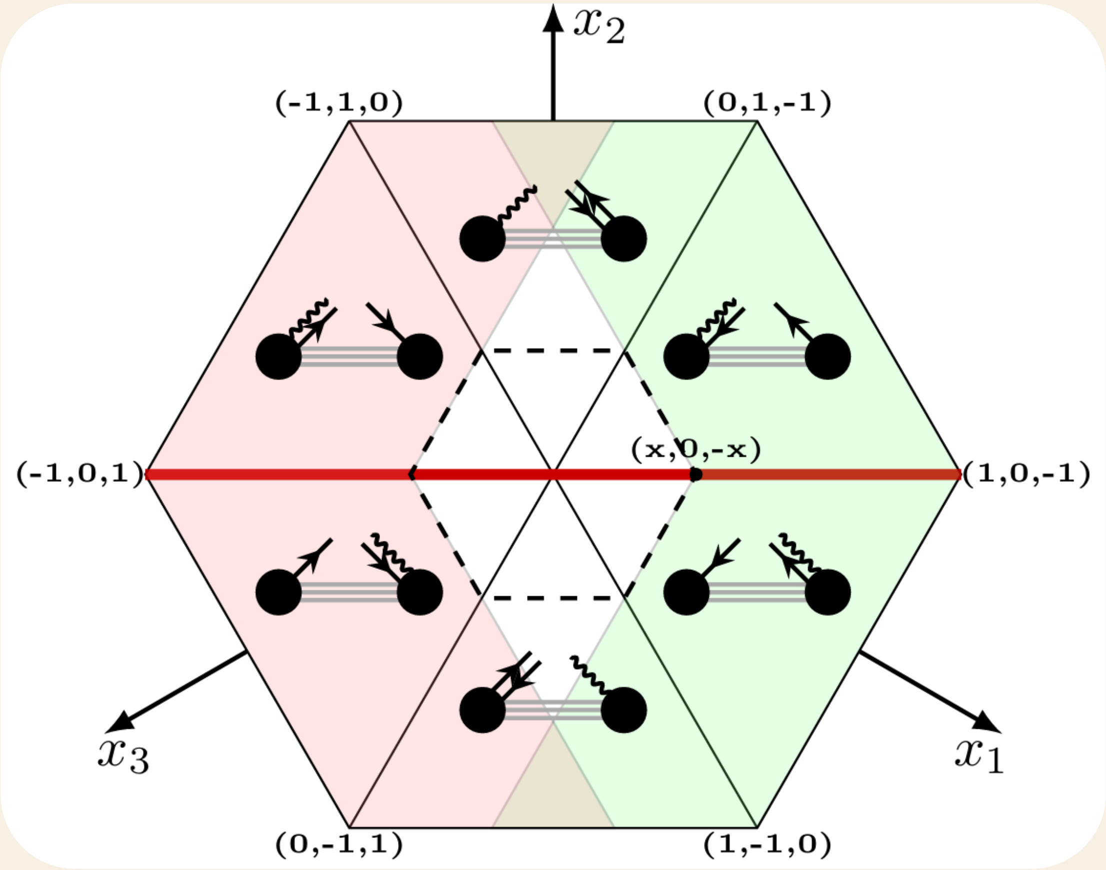
$$\langle p,s|g\bar{q}(z_1 n)F^{\mu+}(z_2 n)\gamma^+\gamma^5 q(z_3 n)|p,s\rangle = -s_T^{\mu}(p^+)^2 M \int [dx] e^{-ip^+\sum_i z_i x_i} \Delta T_q(x_1,x_2,x_3)$$

Same setting as in the parton model: Inf. Mom + Axial Gauge

$$\int [dz]\, e^{ip^+(\sum_i z_i x_i)} \langle p,s|g\bar{q}(z_1 n)F^{\mu+}(z_2 n)\gamma^+ q(z_3 n)|p,s\rangle \sim \begin{cases} \left(\langle p,s|\hat{c}^\dagger_{|x_3|}\right)\left(\hat{b}_{|x_2|}\hat{c}_{|x_1|}|p,s\rangle\right) & (x_1>0, x_2>0, x_3<0) \\ \left(\langle p,s|\hat{a}^\dagger_{|x_1|}\hat{c}^\dagger_{|x_3|}\right)\left(\hat{b}_{|x_2|}|p,s\rangle\right) & (x_1<0, x_2>0, x_3<0) \\ \left(\langle p,s|\hat{a}^\dagger_{|x_1|}\right)\left(\hat{b}_{|x_2|}\hat{a}_{|x_3|}|p,s\rangle\right) & (x_1<0, x_2>0, x_3>0) \\ \dots & \\ \langle p,s|\dots|p,s\rangle^\dagger & (x_1,x_2,x_3)\to-(x_3,x_2,x_1) \end{cases}$$

The twist-three interpretation

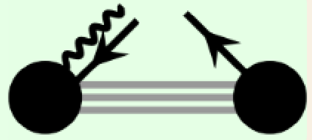
Domain of twist-three PDFs



Each sector of the hexagon represents a different interference process within the proton

Example:

$$\left(\langle p, s|\hat{c}^{\dagger}_{|x_3|}\right)\left(\hat{b}_{|x_2|}\hat{c}_{|x_1|}|p, s\rangle\right) =$$



PDFs defined in the first sector represent the interference between a proton state emmiting a gluon-antiquark, and a state absorbing an antiquark.

Twist-three physics. Observables

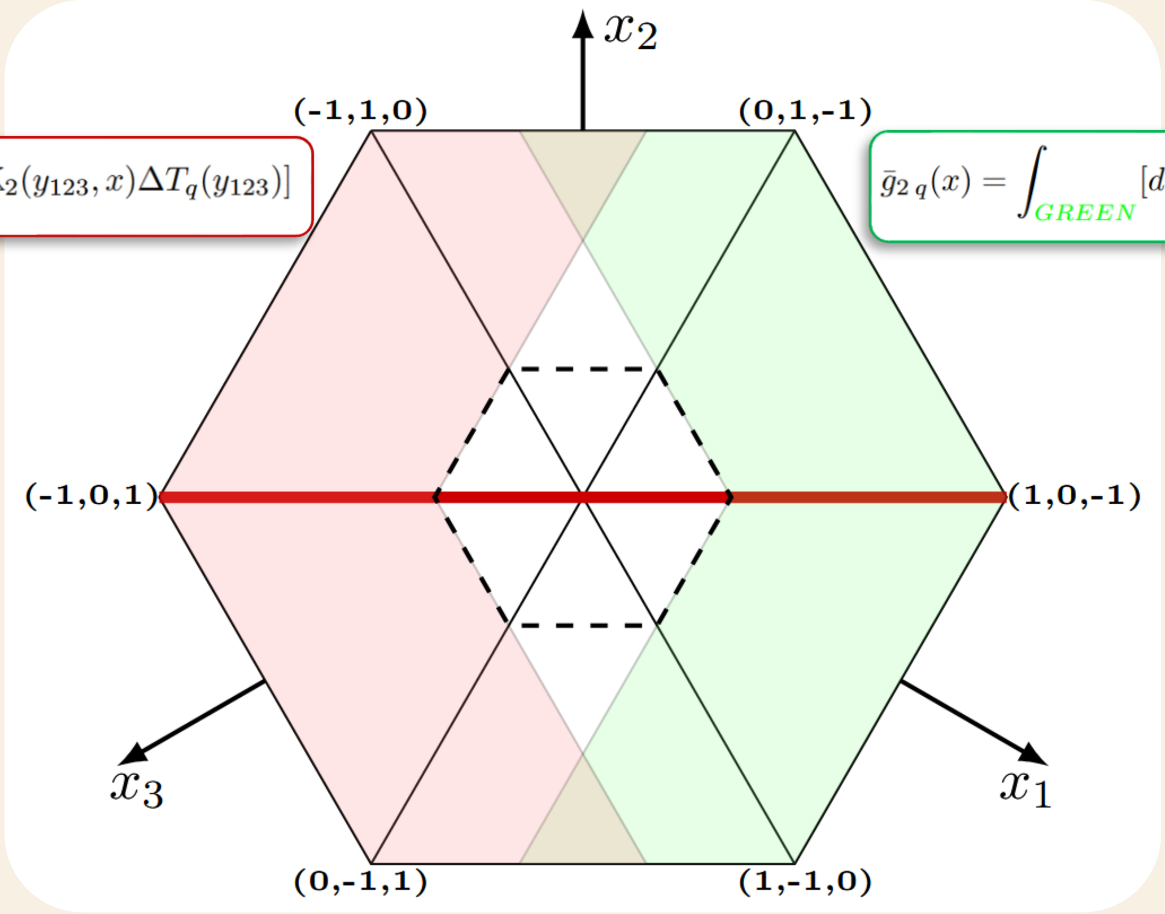
Important: All twist-three observables relevant in QCD are defined through the functions $\{T_q, \Delta T_q\}$ over a region of the hexagon.

DIS

$$\bar{g}_{2\,\bar{q}}(x) = \int_{RED} [dy]\, [\mathbb{K}_1(y_{123}, x)\, T_q(y_{123}) + \mathbb{K}_2(y_{123}, x) \Delta T_q(y_{123})]$$

DIS

$$\bar{g}_{2\,q}(x) = \int_{GREEN} [dy]\, [\mathbb{K}_1(y_{123}, x)\, T_q(y_{123}) + \mathbb{K}_2(y_{123}, x) \Delta T_q(y_{123})]$$



Twist-three physics. Observables

Important: All twist-three observables relevant in QCD are defined through the functions $\{T_q, \Delta T_q\}$ over a region of the hexagon.

DIS

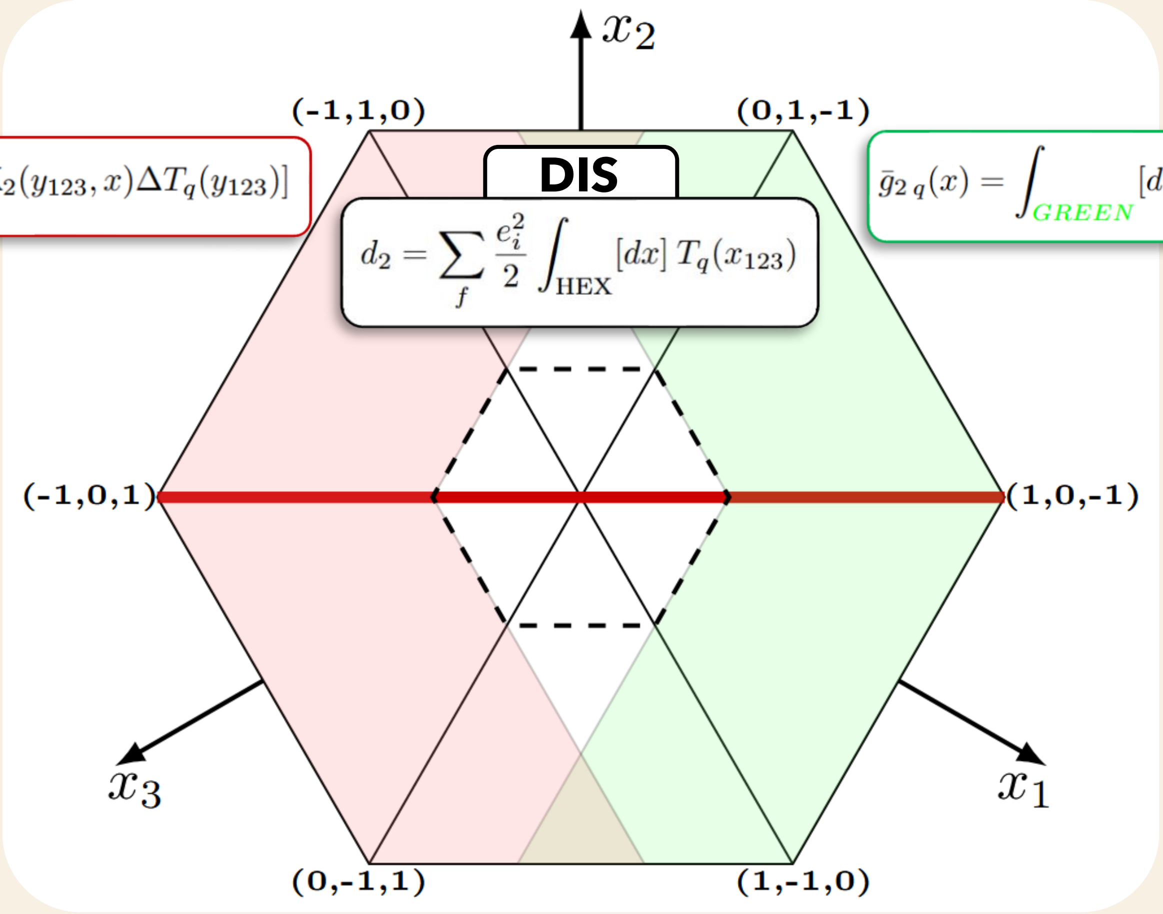
$$\bar{g}_{2\,\bar{q}}(x) = \int_{RED} [dy]\,[\mathbb{K}_1(y_{123}, x)\, T_q(y_{123}) + \mathbb{K}_2(y_{123}, x) \Delta T_q(y_{123})]$$

DIS

$$d_2 = \sum_f \frac{e_i^2}{2} \int_{\text{HEX}} [dx]\, T_q(x_{123})$$

DIS

$$\bar{g}_{2\,q}(x) = \int_{GREEN} [dy]\,[\mathbb{K}_1(y_{123}, x)\, T_q(y_{123}) + \mathbb{K}_2(y_{123}, x) \Delta T_q(y_{123})]$$



Twist-three physics. Observables

Important: All twist-three observables relevant in QCD are defined through the functions $\{T_q, \Delta T_q\}$ over a region of the hexagon.

DIS

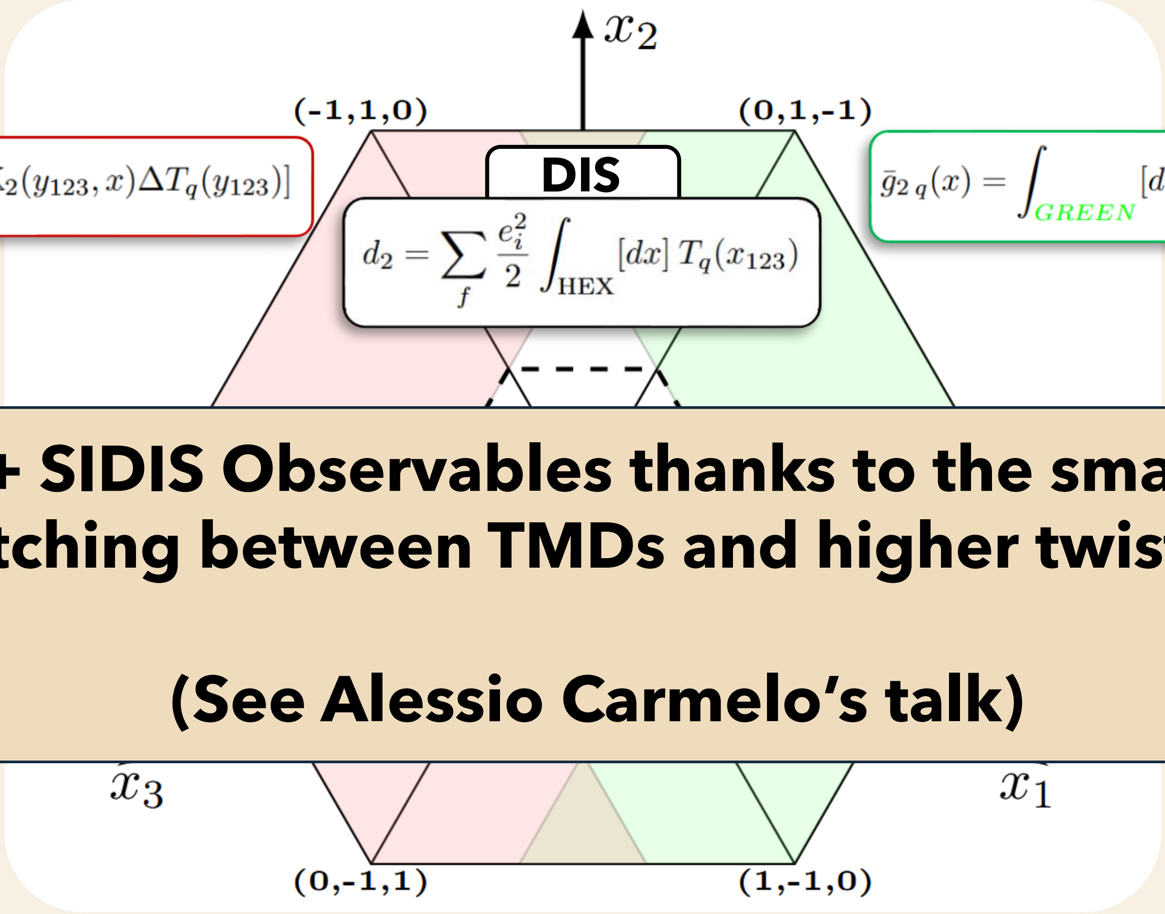
$$\bar{g}_{2\,\bar{q}}(x) = \int_{RED} [dy]\,[\mathbb{K}_1(y_{123},x)\,T_q(y_{123}) + \mathbb{K}_2(y_{123},x)\Delta T_q(y_{123})]$$

DIS

$$d_2 = \sum_f \frac{e_i^2}{2}\int_{\mathrm{HEX}} [dx]\,T_q(x_{123})$$

DIS

$$\bar{g}_{2\,q}(x) = \int_{GREEN} [dy]\,[\mathbb{K}_1(y_{123},x)\,T_q(y_{123}) + \mathbb{K}_2(y_{123},x)\Delta T_q(y_{123})]$$

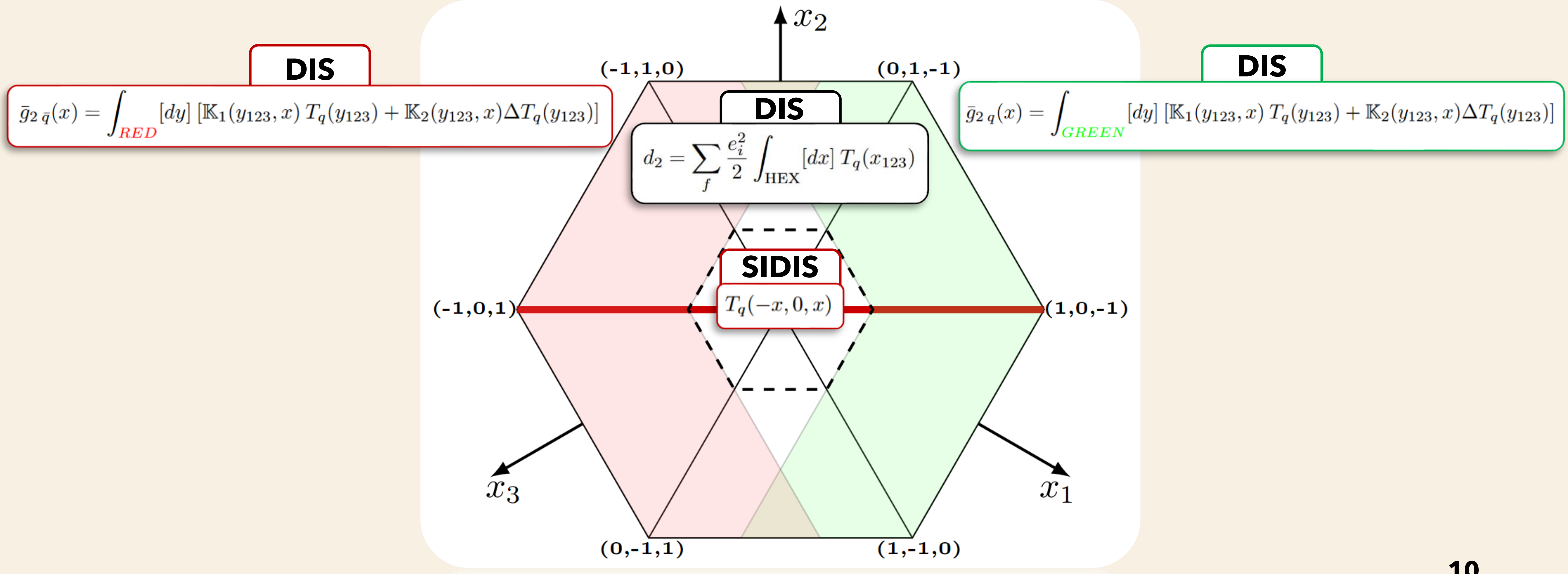


+ SIDIS Observables thanks to the small b matching between TMDs and higher twist PDFs

(See Alessio Carmelo's talk)

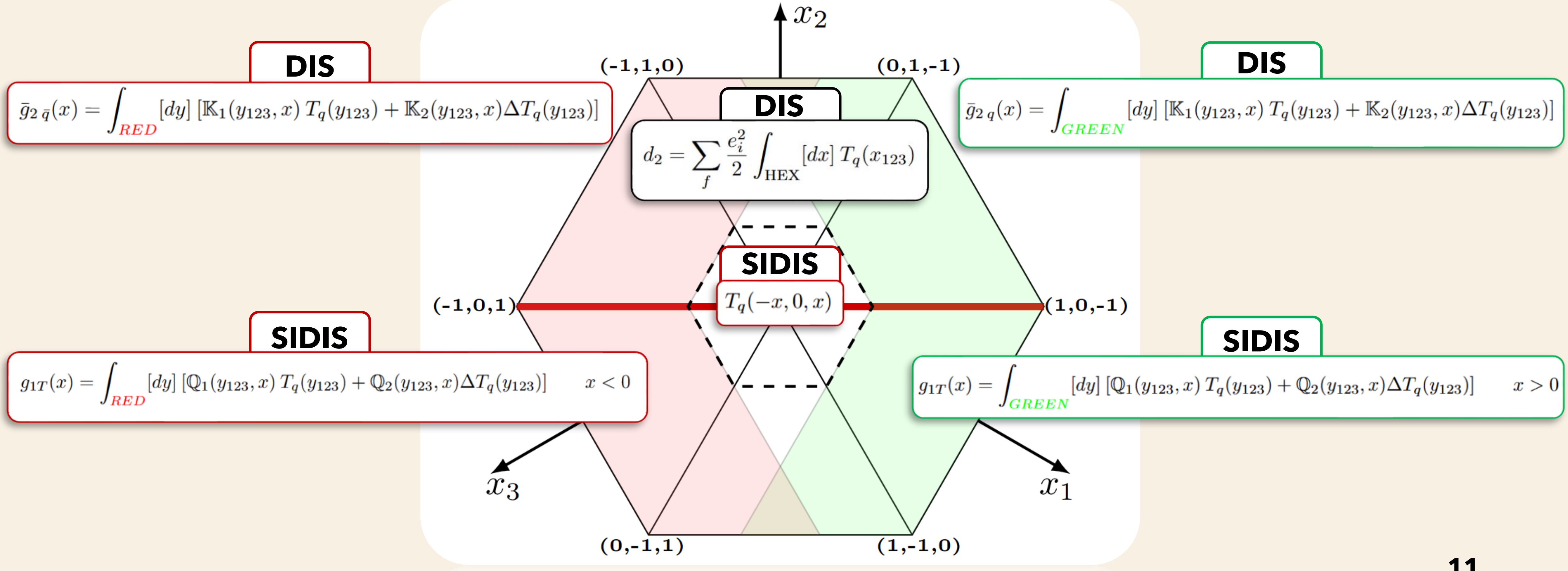
Twist-three physics. Observables

Important: All twist-three observables relevant in QCD are defined through the functions $\{T_q, \Delta T_q\}$ over a region of the hexagon.



Twist-three physics. Observables

Important: All twist-three observables relevant in QCD are defined through the functions $\{T_q, \Delta T_q\}$ over a region of the hexagon.



Extraction of twist-three PDFs

Twist-three physics= broad and important
(polarized hadron structure, forces, spin asymmetries, etc)

→ **Many pheno[...]nological studies** ✗

Why? **Virtually none !!**

- **Twist-three PDFS = 2D objects = COMPLICATED STRUCTURE**
- **Observables fix sub-regions/ integral of sub-regions = NO WAY TO UNDERSTAND GLOBAL PDFs SHAPE**
- **Some even have twist-two contributions. Overshadow twist-three physics: g2 and W.G -T**

CONCLUSSION: INDIVIDUAL MEASUREMENTS DON'T FIX MUCH

Extraction of twist-three PDFs

SOLUTION: JOINT ANALYSIS OF ALL OBSERVABLES + COMPLETE QCD EVOLUTION

Known at LO (1 Loop):

[Braun, Manashov, Pirnay, Phys.Rev. D 80, 114002 (2009)]
[Bukhvostov, Frolov, Lipatov, Kuraev, Nucl. Phys. B 258, 601 (1985)]

Why is this better?

- **Observables fix different parts of PDFs**

- **Evolution: relates behaviour over the hexagon → Brings all parts together to produce one output**

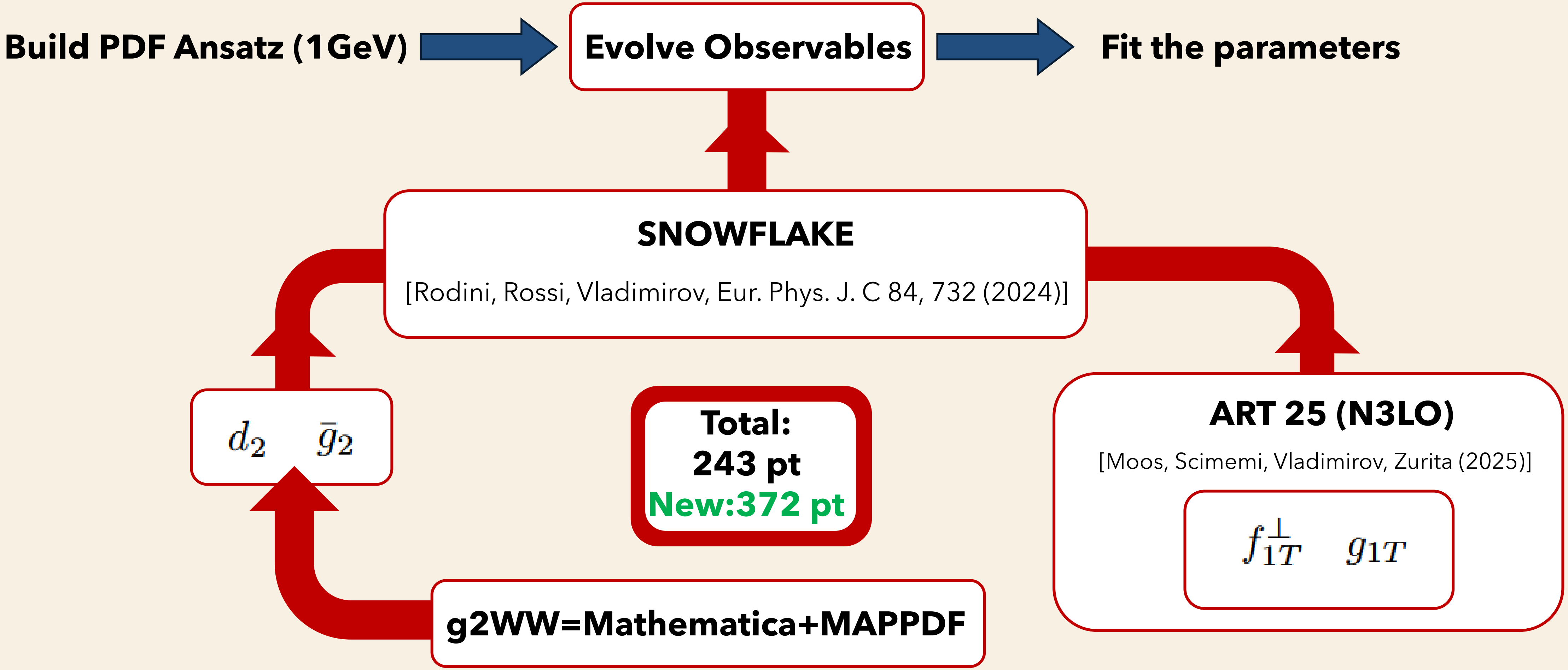
KEY

$$\frac{\partial \vec{T}(x_1, x_2, x_3; \mu)}{\partial \ln \mu} = [\mathbf{H} \otimes \vec{T}](x_1, x_2, x_3; \mu)$$

$$\vec{T} = (T, \Delta T, T^+_{3F}, T^-_{3F})$$

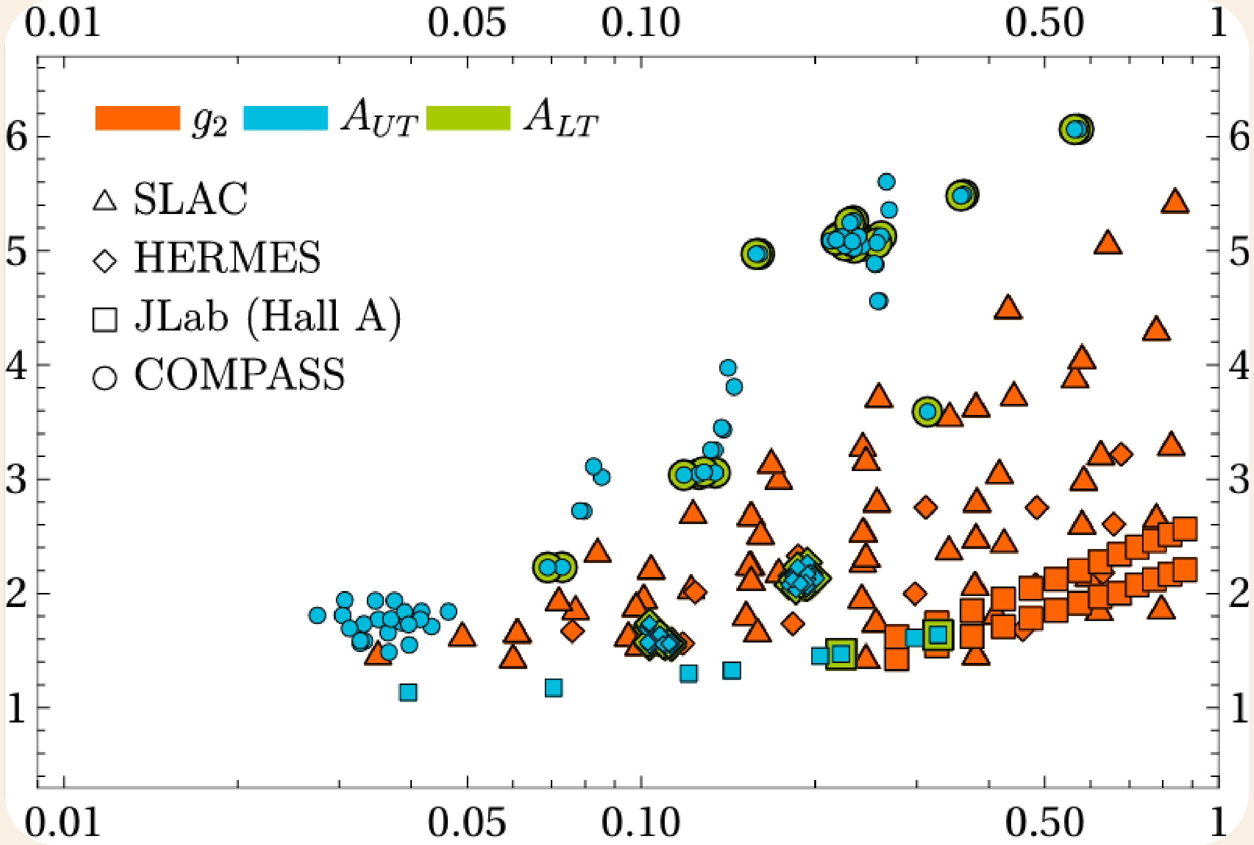
Extraction of twist-three PDFs

How?



Experimental data

Data in (x,Q) coordinates:



Detailed Data :

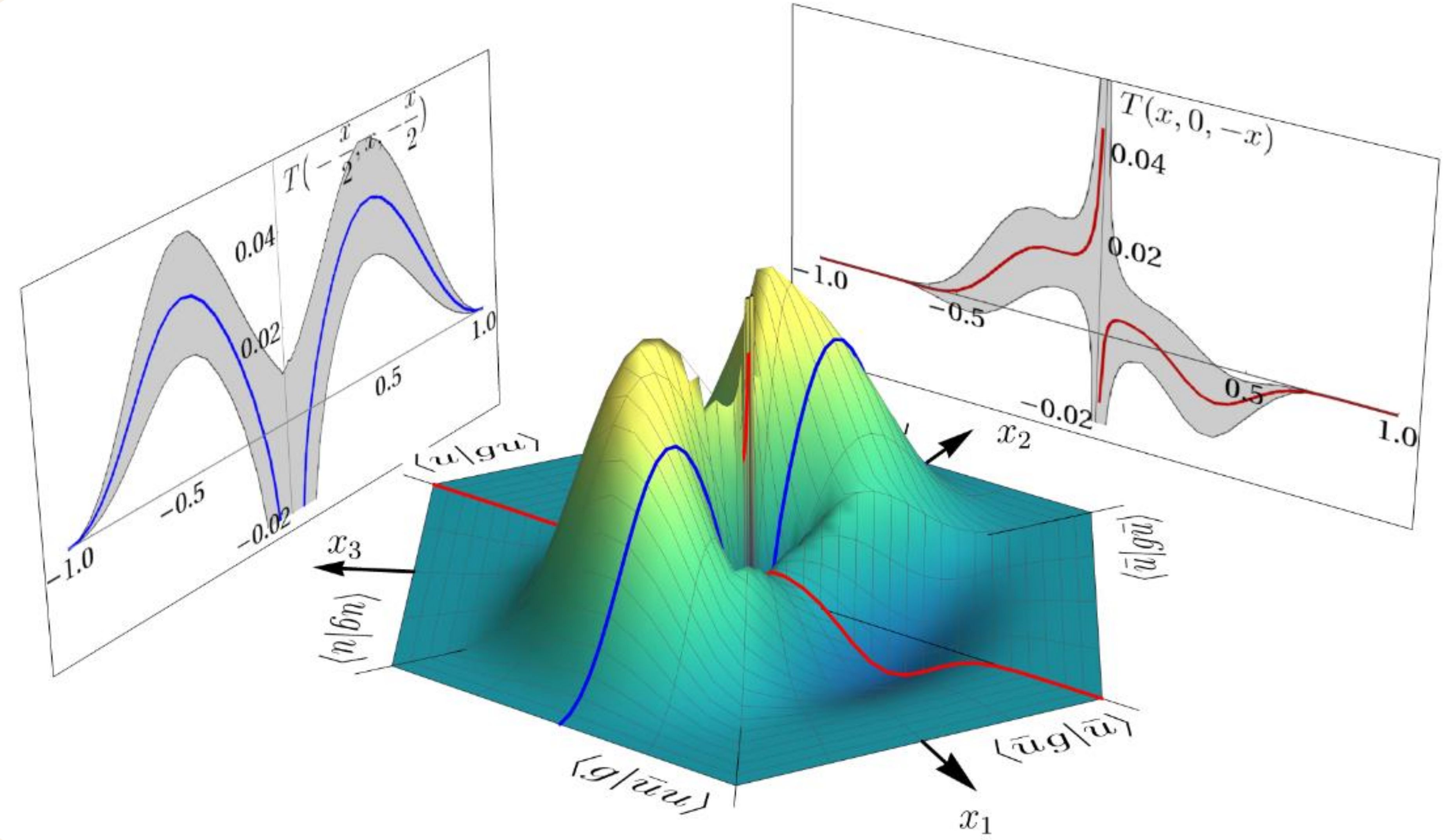
d_2	g_2	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$
HERMES	HERMES	HERMES	HERMES
COMPASS	-	COMPASS	COMPASS
JLab	JLab	JLab	JLab
-	SLAC	-	-
SANE	-	-	-
RQCD	-	-	-
$N_p(2025) = 7$	$N_p(2025) = 103$	$N_p(2025) = 63$	$N_p(2025) = 70$
$N_p(2026) = 13$	$N_p(2026) = 168$	$N_p(2026) = 117$	$N_p(2026) = 74$

Data cuts for fact. theorem:

$$Q^2 > 2\text{GeV}^2, \qquad \frac{p_\perp^2}{z^2 Q^2} < 0.35.$$

Results of the extraction: The fit

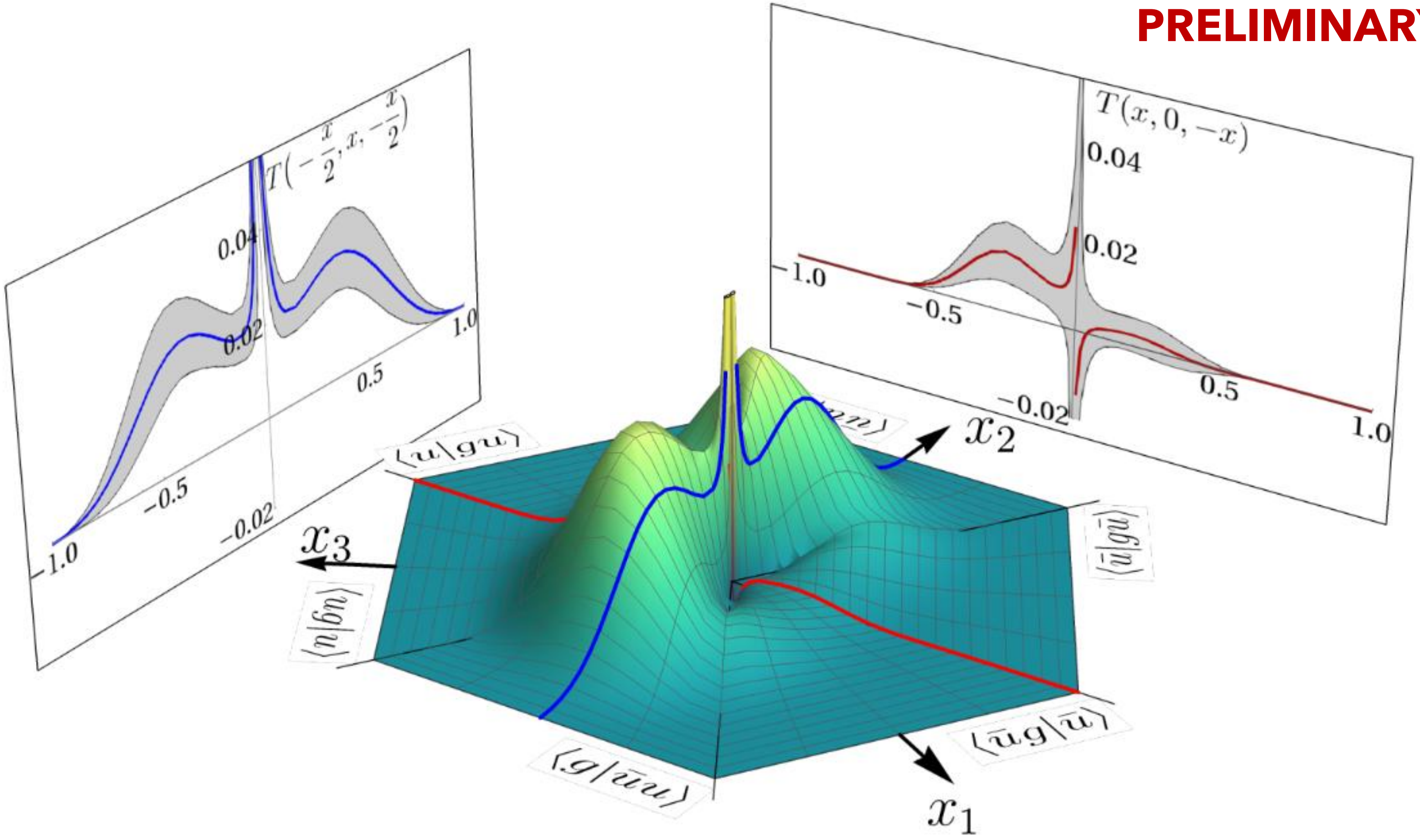
Fig: Mean value for Tu PDF at 4GeV (2025)



Results of the extraction: The fit

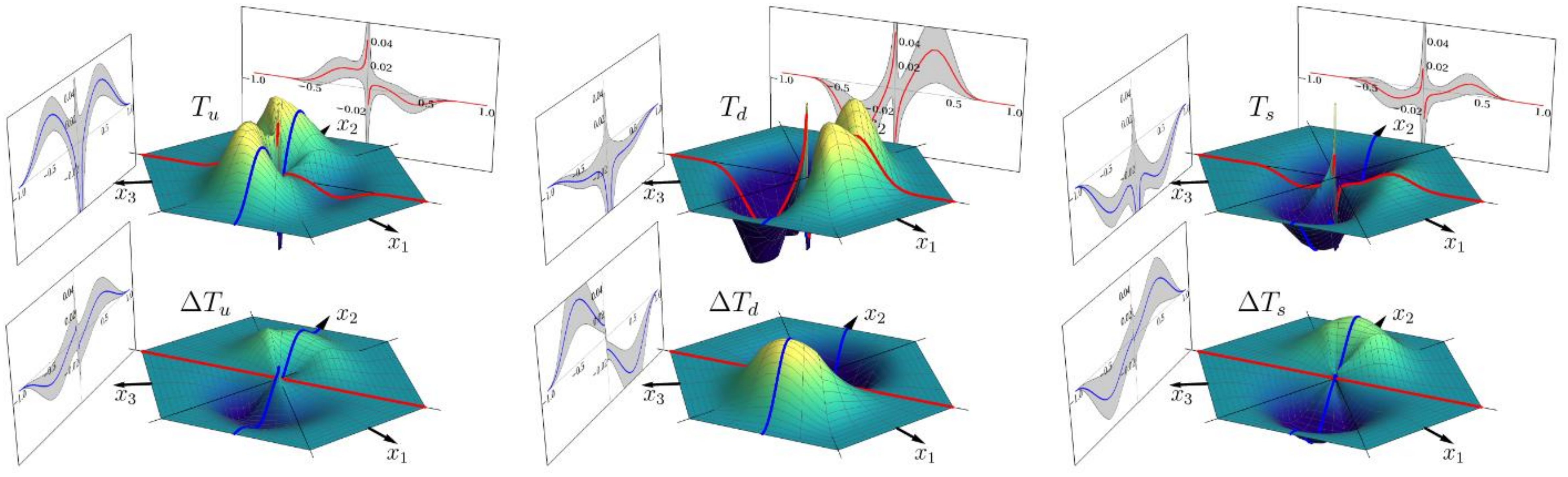
Fig: Mean value for Tu PDF at 4GeV (2026)

PRELIMINARY



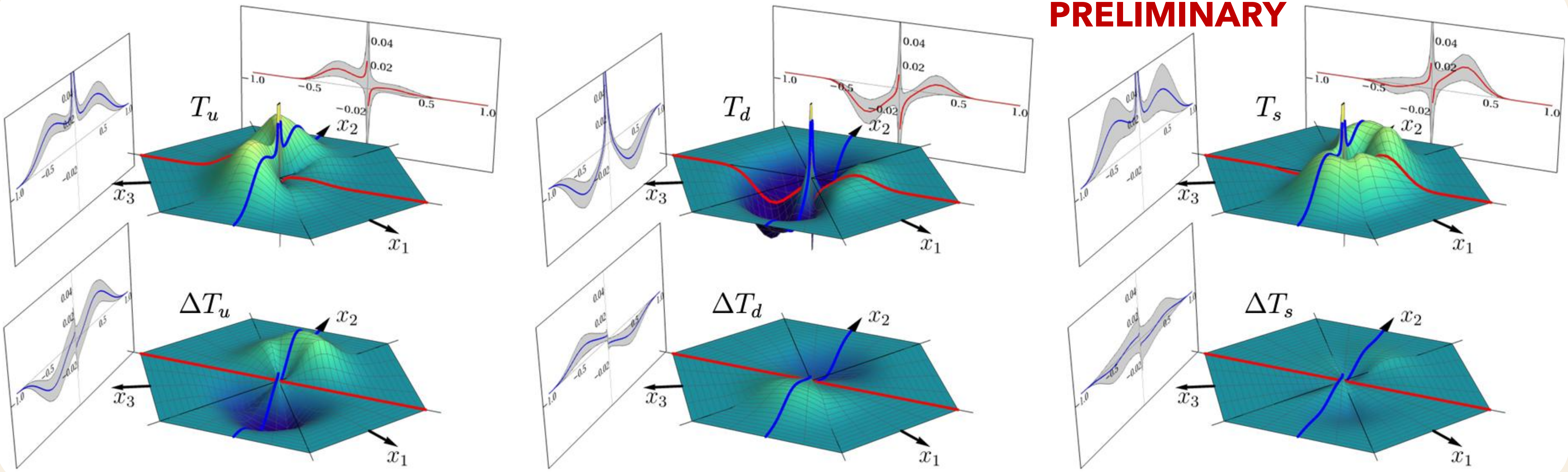
Results of the extraction: The fit

Fig: Mean value for PDFs at 4GeV (2025)



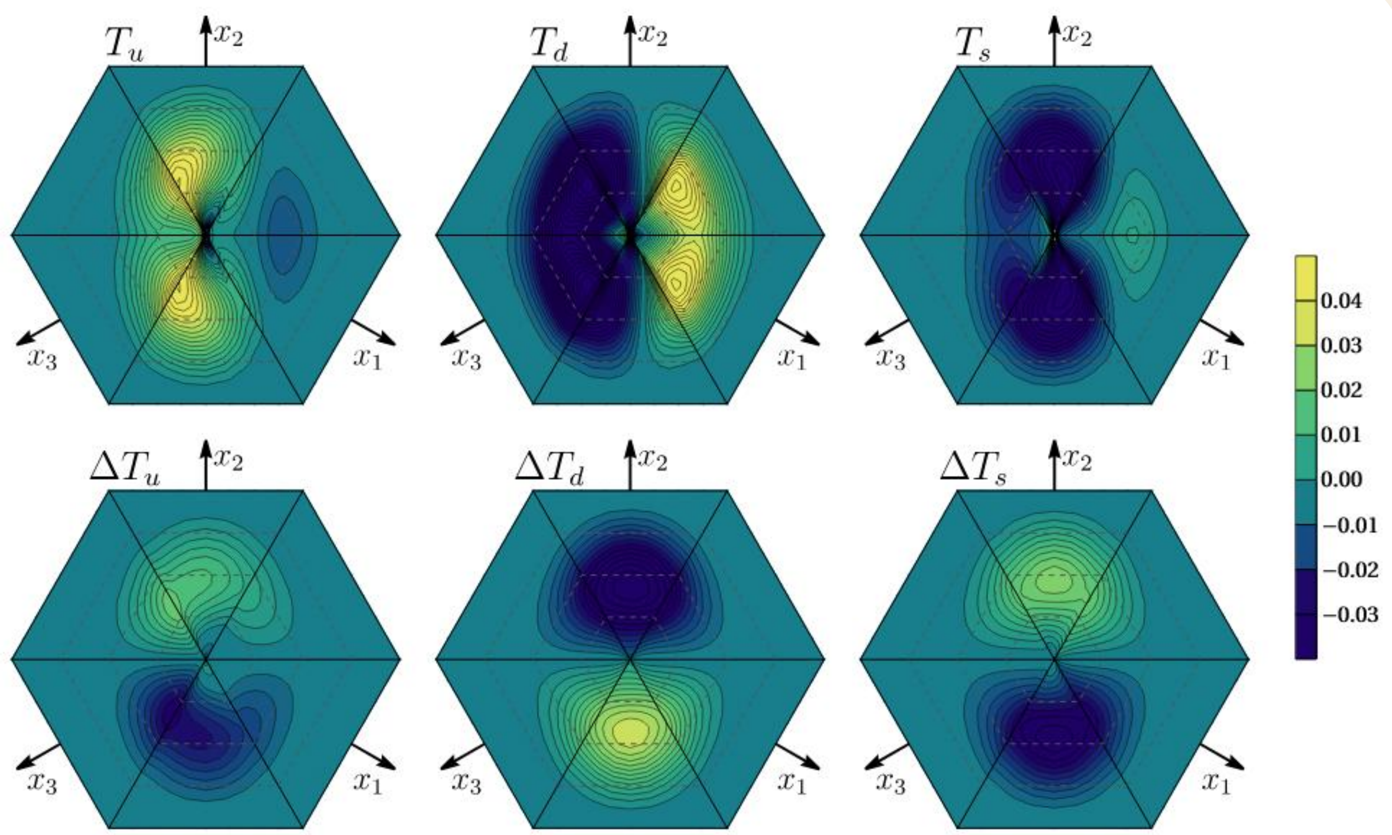
Results of the extraction: The fit

Fig: Mean value for PDFs at 4GeV (2026)



Results of the extraction: What it reveals

Fig: Mean value for PDFs at 4GeV



Observations:

Magnitude: (0.02-0.05)

- 2 OM less than unpol PDFs
- 1 OM less than helicity valence quark PDFs
- Same order as helicity sea quark PDFs

All flavours same magnitude

- Interference DOES NOT distinguish between light sea and valence quarks

Some symmetry

- The ug and dg interference terms are of opposite sign.

Results of the extraction: What it reveals

Average Transverse Momentum of quarks inside the proton

Theoretical description:

$$\langle k_\perp^i \rangle_q = -\frac{1}{2} M \epsilon_\perp^{ij} S^j \int_{-1}^{1} dx\, T_q(x,0,-x)$$

Numerical estimations (x-comp):

$$\langle k_\perp^{\mathrm{x}} \rangle_u = 9.5^{+6.9}_{-7.1}\ \mathrm{MeV}$$
$$\langle k_\perp^{\mathrm{x}} \rangle_d = -18.7^{+18.1}_{-17.5}\ \mathrm{MeV}$$

Average Transverse Force acting on quarks inside the proton

Theoretical description:

$$\langle f_\perp^i \rangle_q = -P^+ \epsilon_\perp^{ij} S^j \int_{\mathrm{Hex}} [dx]\, T_q(x_{123})$$

Numerical estimations (x-comp):

$$\langle f_\perp^{\mathrm{x}} \rangle_u = -22.89.5^{+8.2}_{-8.1}\ \mathrm{MeV/fm}$$
$$\langle f_\perp^{\mathrm{x}} \rangle_d = 54.7.5^{+17.9}_{-17.9}\ \mathrm{MeV/fm}$$

Conclusion

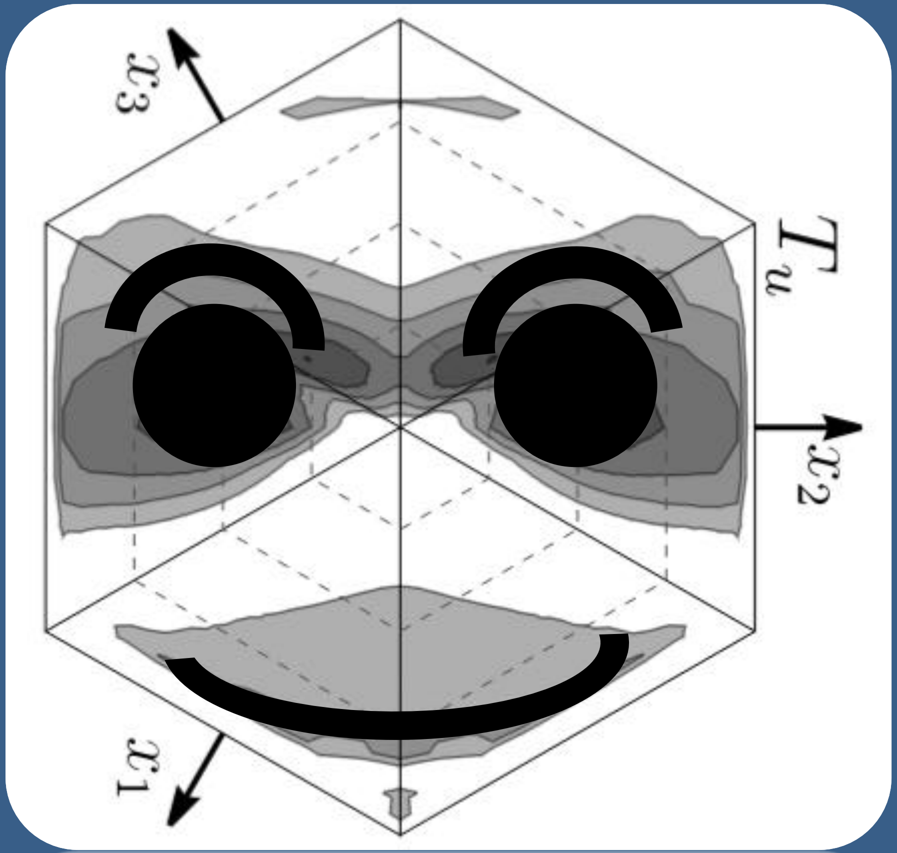
We have obtained the global shape of **twist-three PDFs** which are the key to a new kind of physics

FIRST EVER analysis implementing the correct **complete evolution at LO**

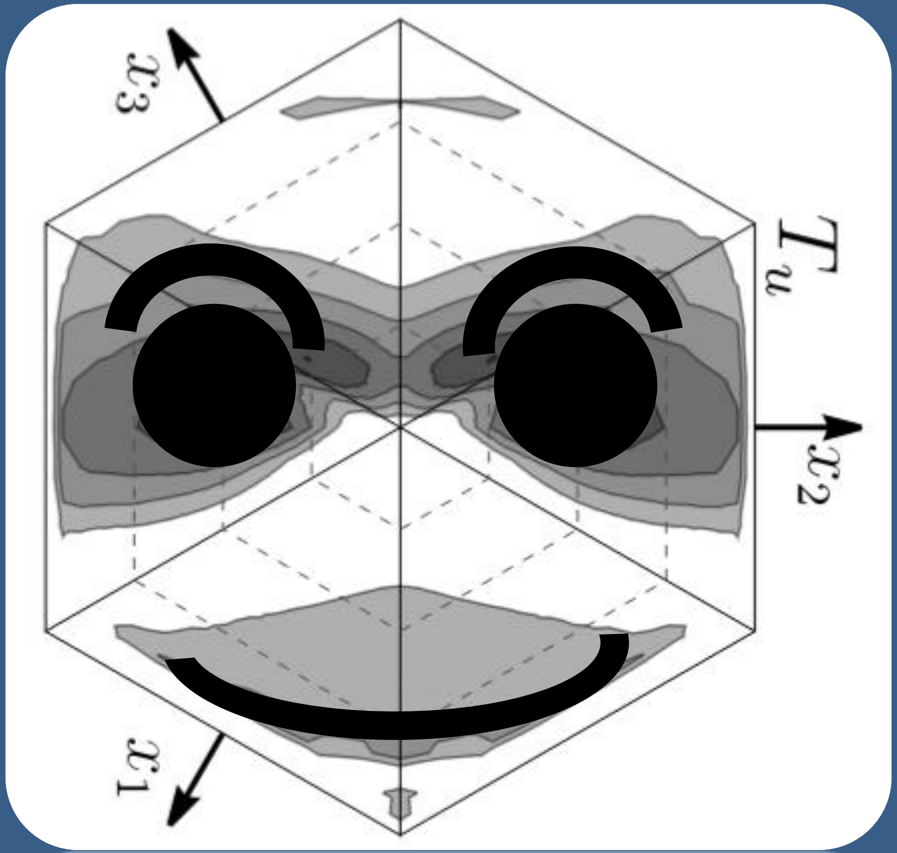
We can access new aspects of hadron structure: In prep. (Sum rules, momentum shift, OAM, etc)

Big step in the unification of high-energy physics (multiple polarized experiments and one output)

THANK YOU!

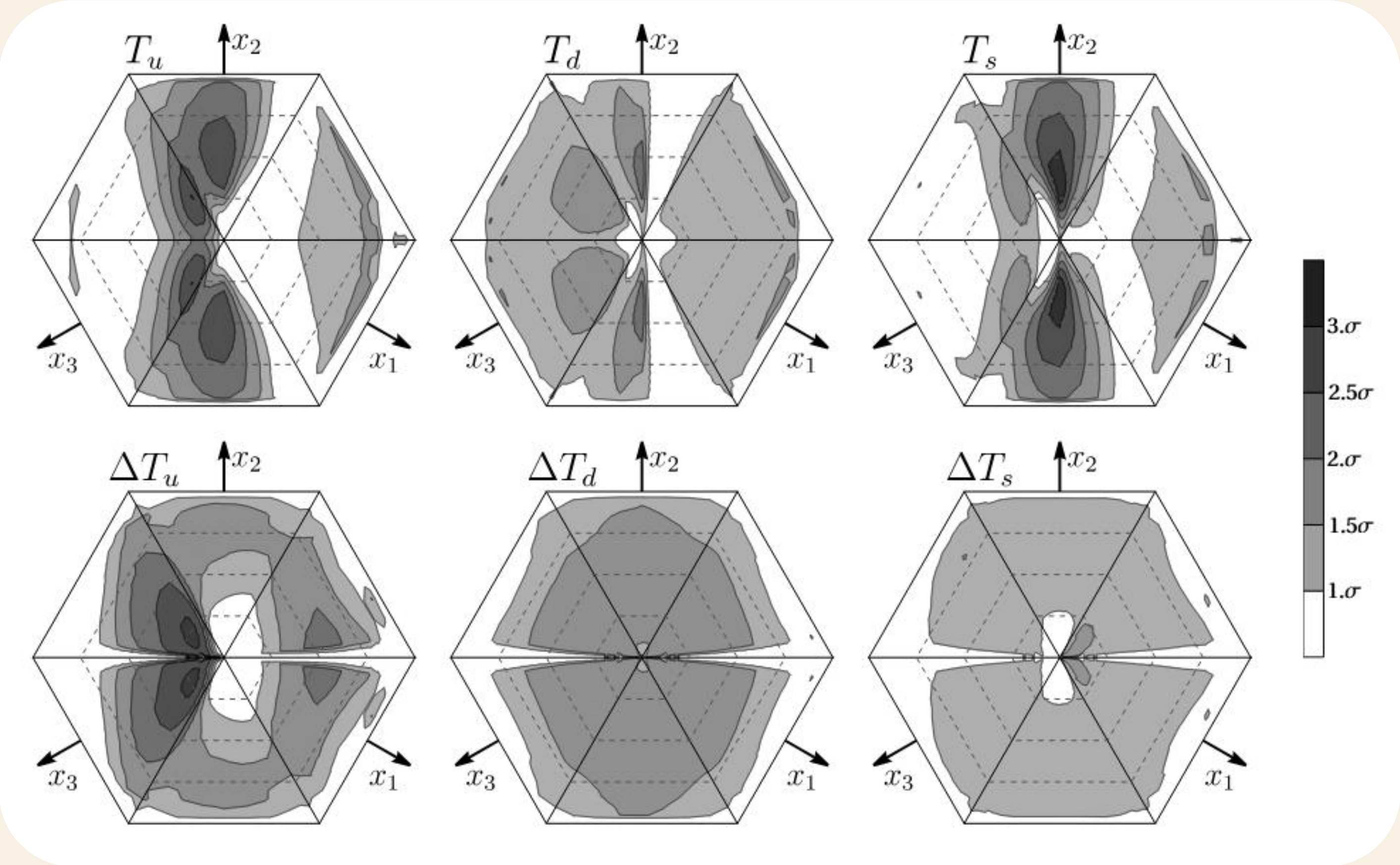


Additional slides



Results of the extraction: How reliable is it?

Fig: Significance of the signals at 4GeV



Signal:

- Very clear
- Reaches 2σ-3σ
- Similar for all PDFs

Reliability: $\frac{\chi^2}{N_{\text{pt}}} = 1{,}0$

- Discard Null-Hypothesis globally:

Within sets: $\frac{\chi^2}{N_{\text{pt}}} > 1$

$\frac{\chi^2}{N_{\text{pt}}} = 1{,}72$

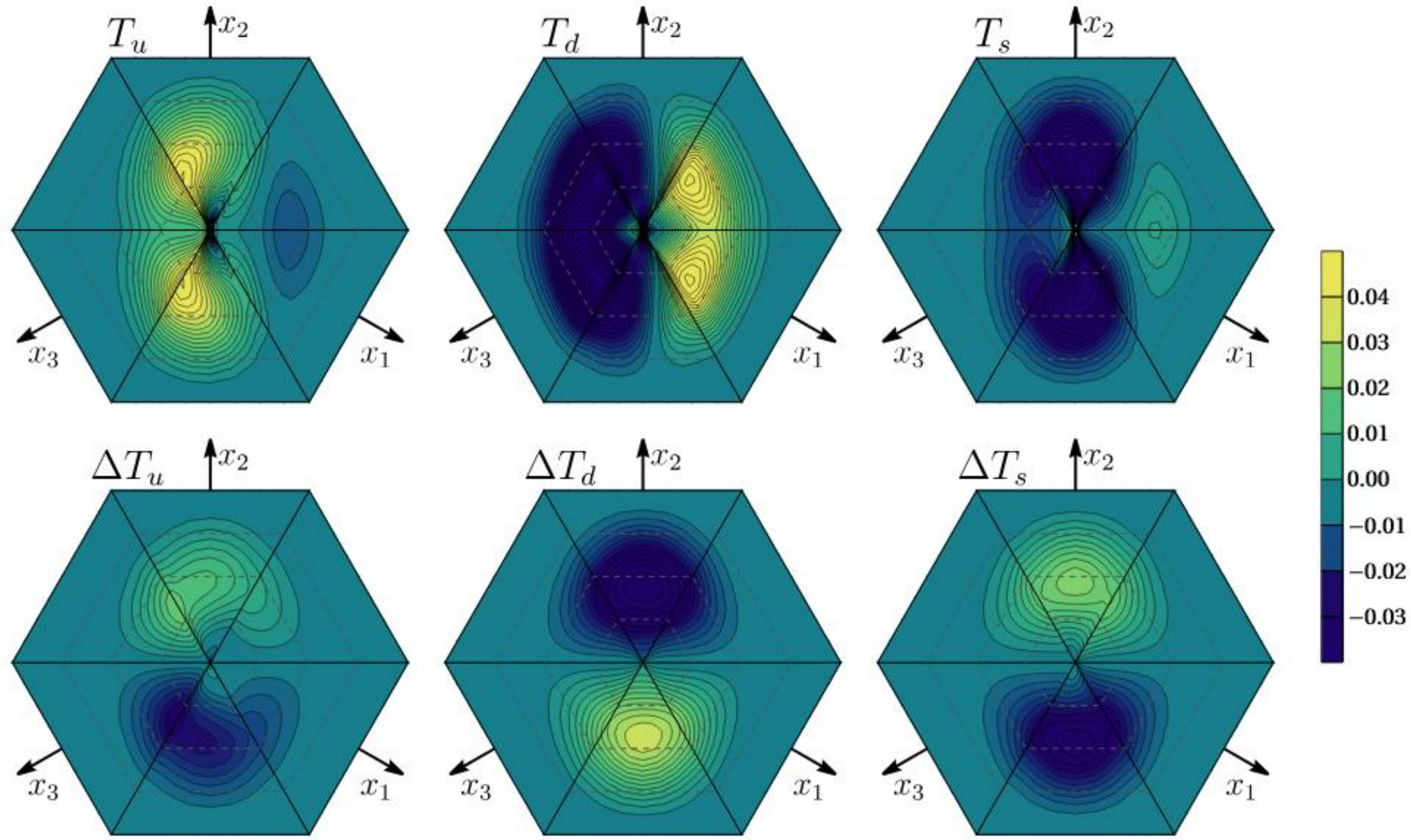
No tw-3

$\frac{\chi^2}{N_{\text{pt}}} = 1{,}23$

With tw-3

Results of the extraction

Fig: Mean value for PDFs at 4GeV



The Ansatz

2025 original ansatz

Common enveloping function:

$$h(x_1,x_2,x_3)=\frac{(1-x_1^2)^a(1-x_2^2)^b(1-x_3^2)^a}{(x_1^2+x_2^2+x_3^2)^c}$$

qgq PDFs:

$$T_f(x_1,x_2,x_3)=h(x_1,x_2,x_3)\times\left[\alpha_1^f+\alpha_2^f(x_1-x_3)+\alpha_2^f x_1x_3\right]$$

$$\Delta T_f(x_1,x_2,x_3)=h(x_1,x_2,x_3)\alpha_4^f x_2$$

ggg PDFs:

$$T_{3F}^+(x_1,x_2,x_3)=\beta_1(x_1-x_3)h(x_1,x_2,x_3)$$

$$T_{3F}^-(x_1,x_2,x_3)=\beta_2 h(x_1,x_2,x_3)$$

2026 updated ansatz

Common enveloping function:

$$h(x_{123})=\frac{(1-x_1^2)^{a_1}(1-x_2^2)^{a_2}(1-x_3^2)^{a_3}}{(x_1^2+x_2^2+x_3^2)^{a_0}}$$

qgq PDFs:

$$\mathfrak{S}_f^+(x_{123})=h(x_{123})\left(\alpha_0^f+\alpha_{11}^f x_1^2+\alpha_{13}^f x_1x_3+\alpha_{33}^f x_3^2\right)$$

$$\mathfrak{S}_f^-(x_{123})=h(x_{123})\left(\alpha_1^f x_1+\alpha_3^f x_3\right)$$

ggg PDFs:

$$T_{3F}^+(x_{123})=h_g(x_{123})\beta_1(x_1-x_3)$$

$$T_{3F}^-(x_{123})=h_g(x_{123})\beta_0$$

The Integral Measure

Restricts distributions to the conf. space (hexagon)

$$\int_{\text{Hex}} [dx] := \int_{-1}^{1} dx_1 \int_{-1}^{1} dx_2 \int_{-1}^{1} dx_3 \;\; \delta(x_1 + x_2 + x_3)$$