QUARK-GLUON-QUARK INTERFERENCE WITHIN THE PROTON

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A presentation of our work: arXiv:2511.04294

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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:**

$$g\langle p,s|\bar{q}(z_1n)[z_1n,z_2n]F^{\mu+}(z_2n)\,\Gamma\,[z_2n,z_3n]q(z_3n)|p,s\rangle \sim \int [dx]e^{-i(x\cdot z)p^+}\,f^{\text{tw-3}}_{qgq}(x_1,x_2,x_3)$$

- **Gluon-gluon-gluon:**

$$g\langle p,s|F^{\mu+}(z_1n)[z_1n,z_2n]F^{\nu+}(z_2n)[z_2n,z_3n]F^{\tau+}(z_2n)|p,s\rangle \sim \int [dx]e^{-i(x\cdot z)p^+}\,f^{\text{tw-3}}_{ggg}(x_1,x_2,x_3)$$

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

- **Built from genuine twist-three operators**
- **Closed under QCD evolution.**
- **All twist-three observables are built from them**

$$\{T_q, \Delta T_q, T^{\pm}_{3F}\}$$

The twist-three interpretation

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

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

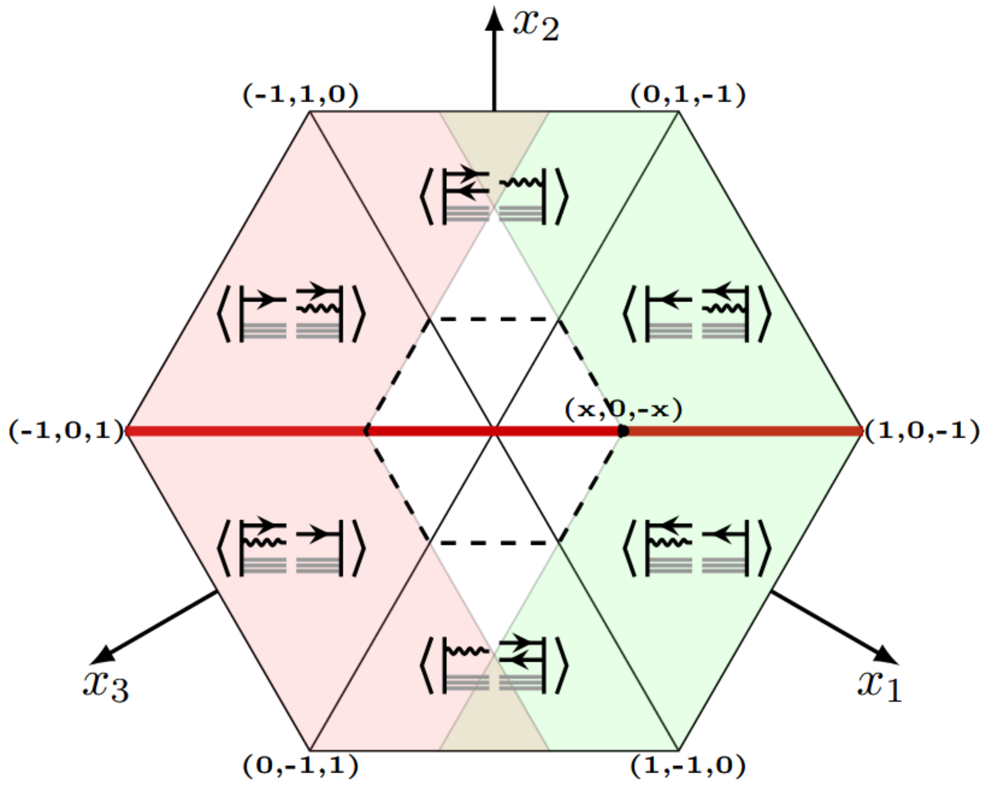
$$\langle p,s|g\bar{q}(z_1 n)F^{\mu+}(z_2 n)\gamma^+\gamma^5 q(z_3 n)|p,s\rangle = -s_T^{\mu}(p^+)^2 M\int [dx]e^{-ip^+\sum_i z_i x_i}\Delta T_q(x_1,x_2,x_3)$$

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

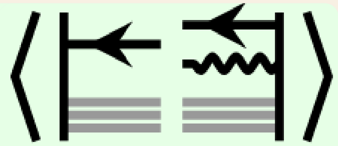
Domain of twist-three PDFs



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

Example:

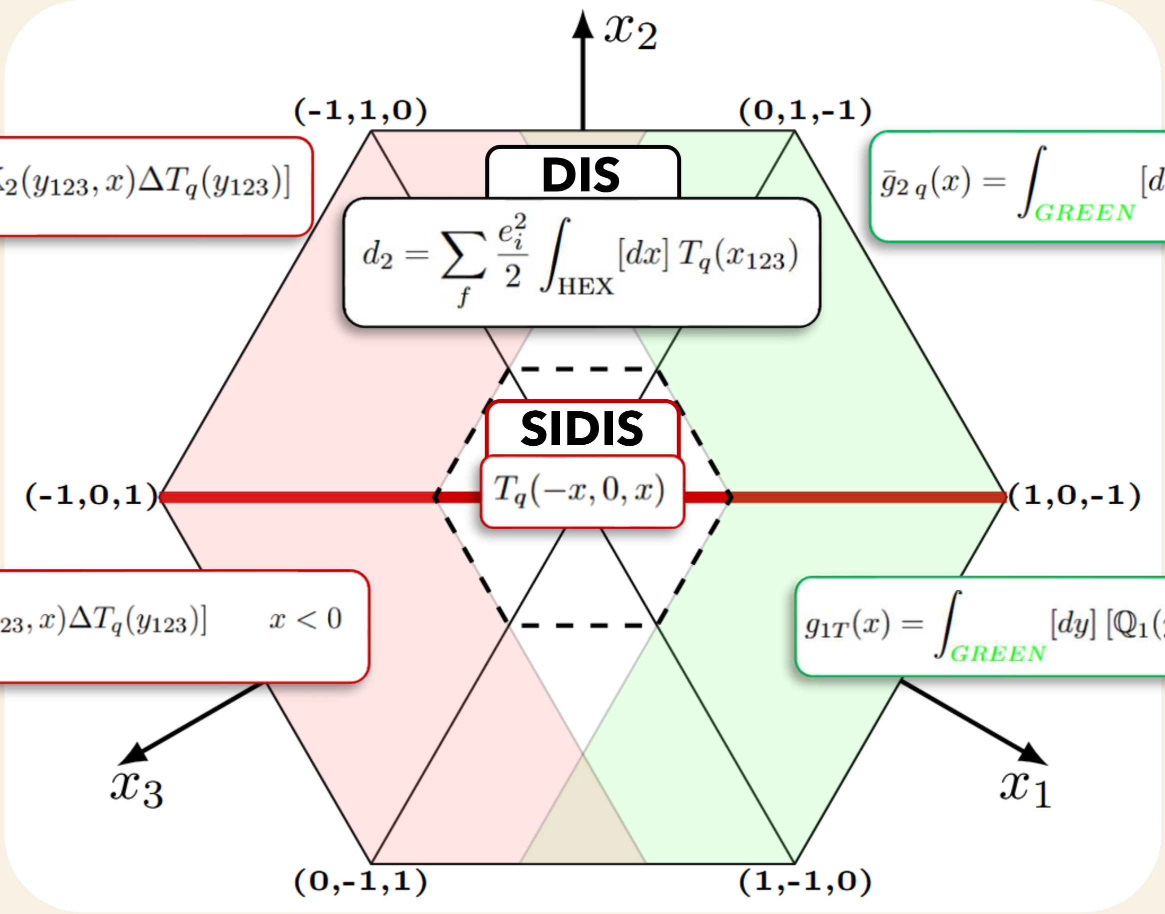
$$\left(\langle p, s|\hat{c}^{\dagger}_{|x_3|}\right)\left(\hat{b}_{|x_2|}\hat{c}_{|x_1|}|p, s\rangle\right) =$$



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

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

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

$$T_q(-x, 0, x)$$

SIDIS

$$g_{1T}(x) = \int_{RED} [dy]\, [\mathbb{Q}_1(y_{123}, x)\, T_q(y_{123}) + \mathbb{Q}_2(y_{123}, x)\Delta T_q(y_{123})] \qquad x < 0$$

SIDIS

$$g_{1T}(x) = \int_{GREEN} [dy]\, [\mathbb{Q}_1(y_{123}, x)\, T_q(y_{123}) + \mathbb{Q}_2(y_{123}, x)\Delta T_q(y_{123})] \qquad x > 0$$

Extraction of twist-three PDFs

Twist-three physics= broad and important → Many phenomenological 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:

[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**

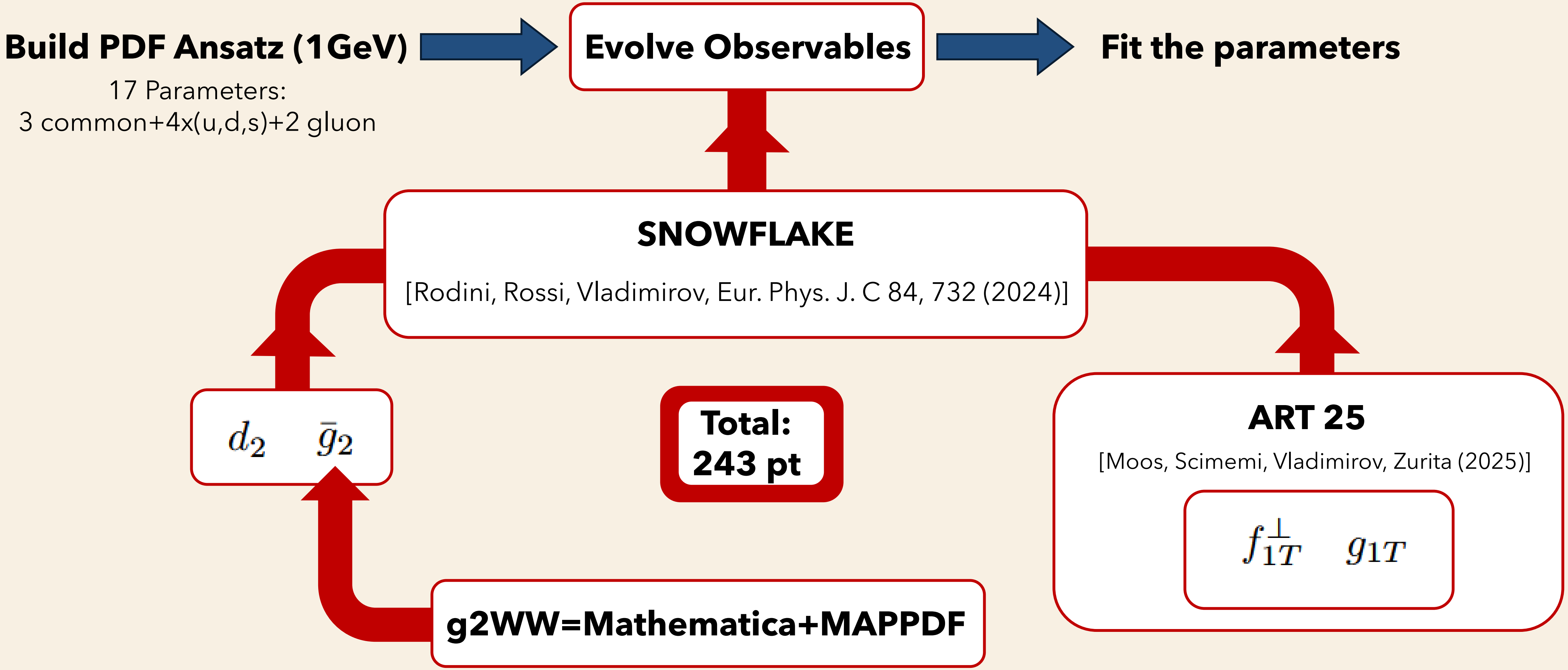
KEY

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

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

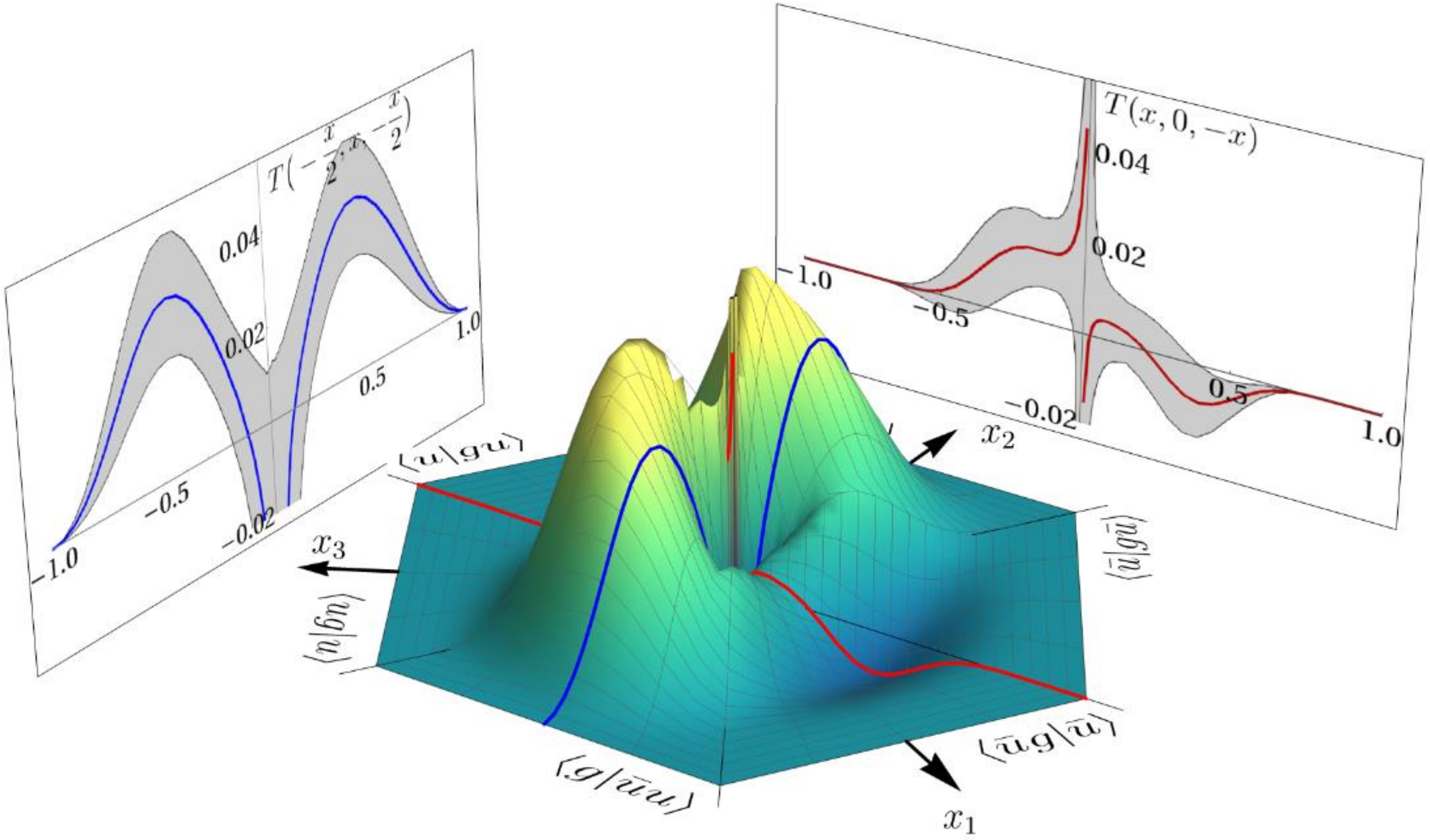
Extraction of twist-three PDFs

How?



Results of the extraction

Fig: Mean value for Tu PDF at 4GeV



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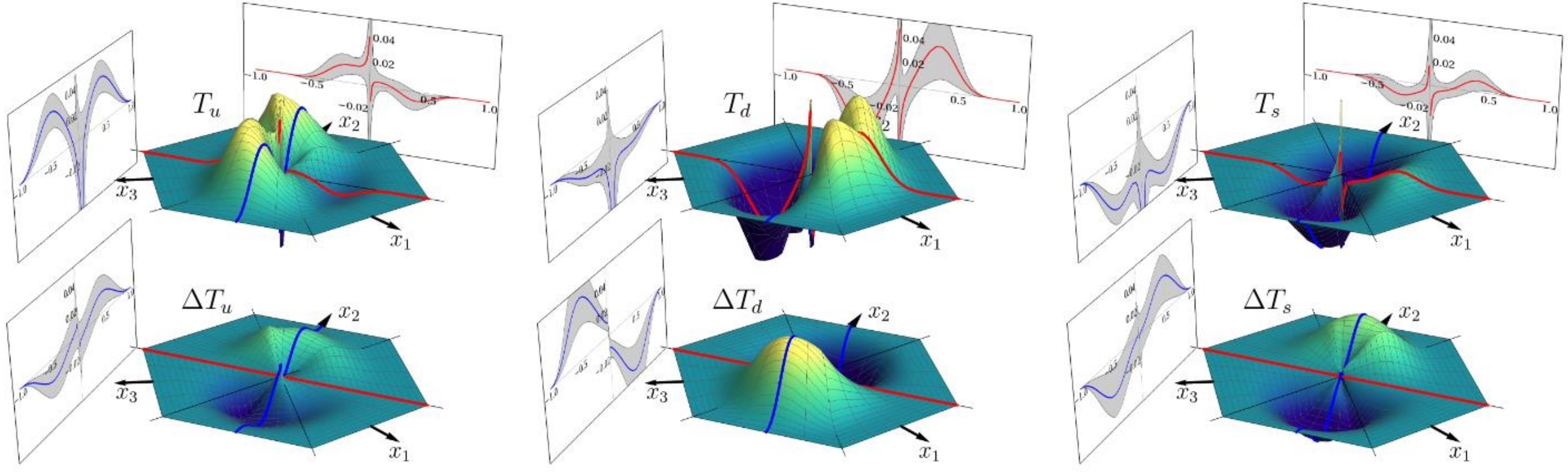
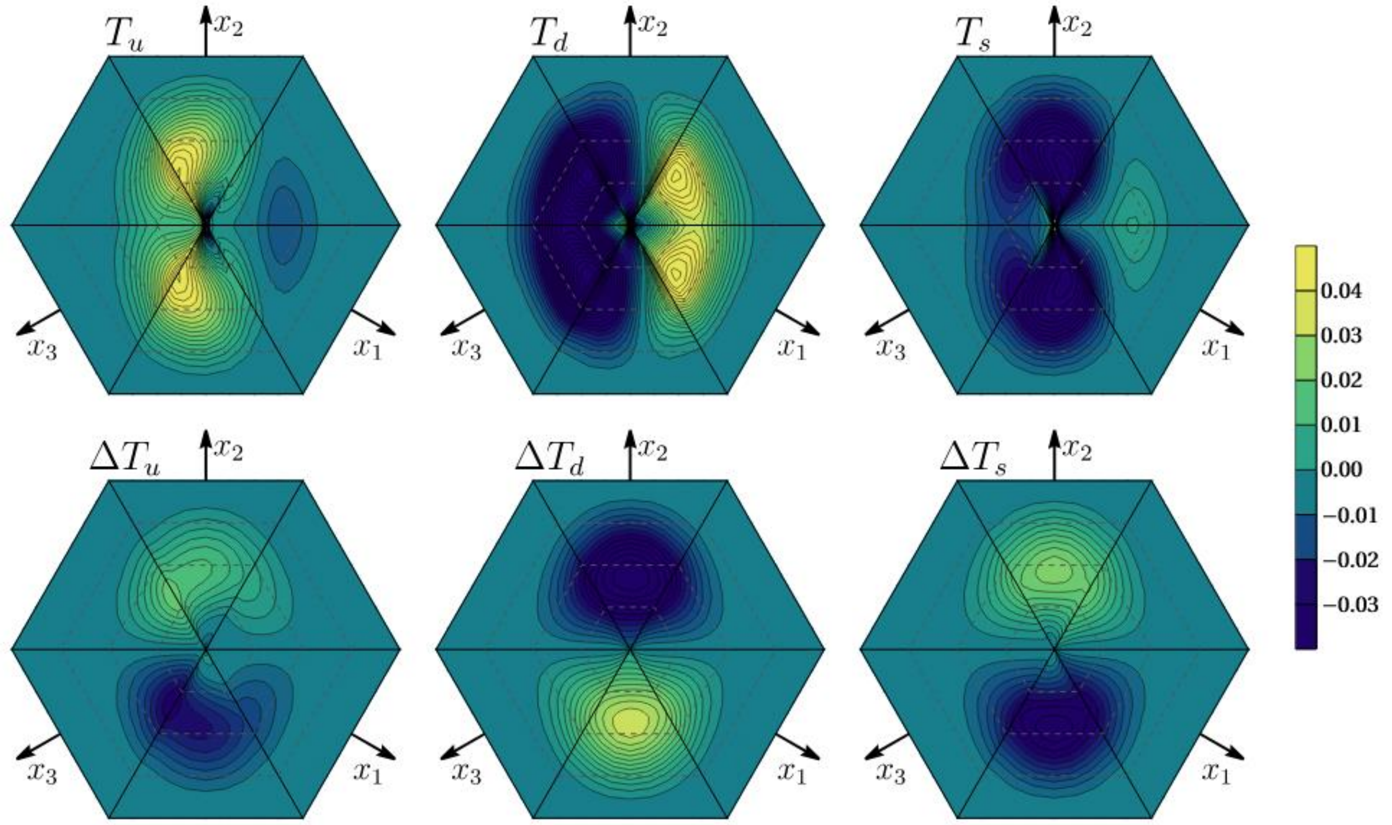


Results of the extraction

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

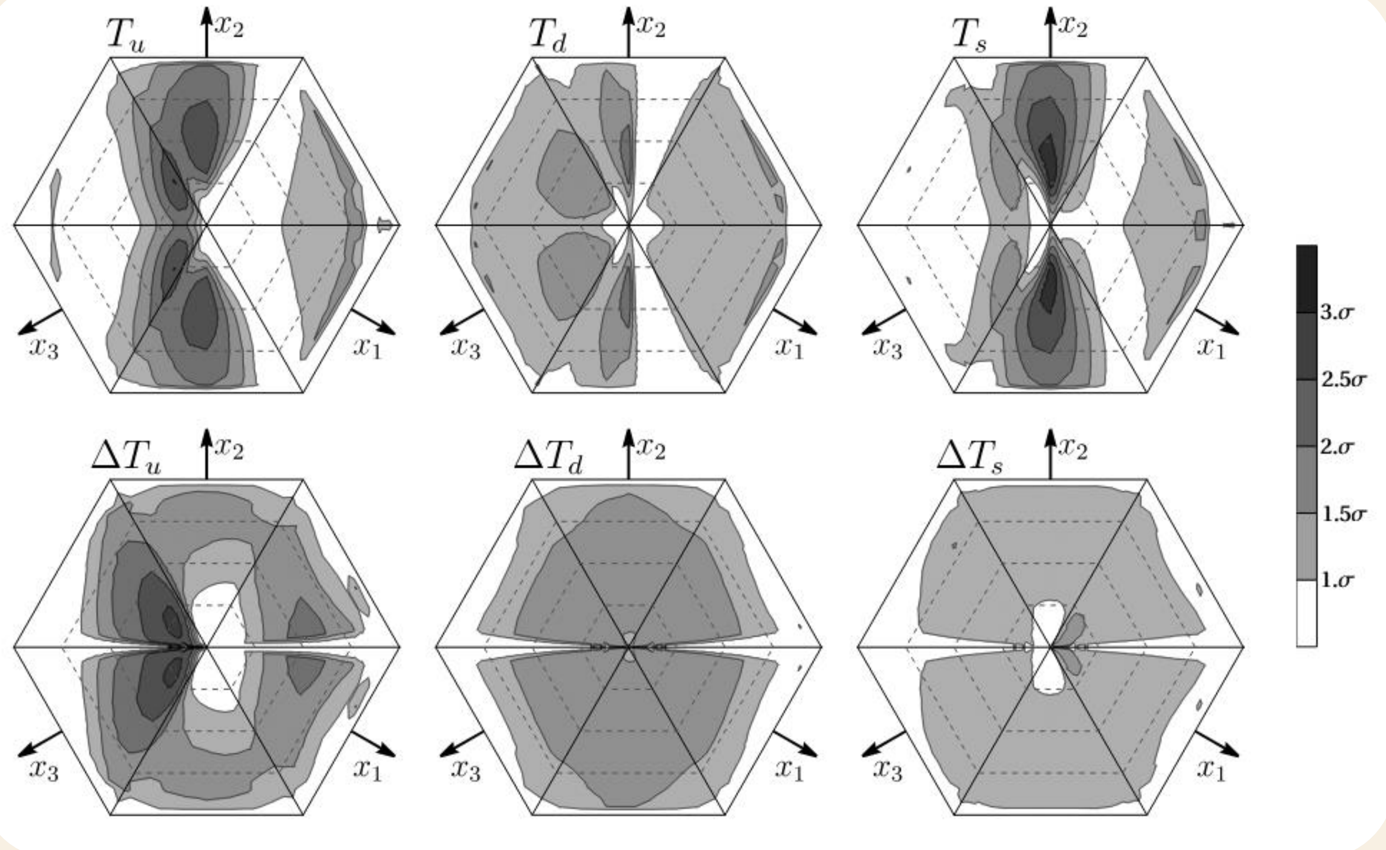
- Interference DOES NOT distinguish between light sea and valence quarks

Some symmetry

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

Results of the extraction

Fig: Significance of the signals at 4GeV



Signal:

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

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

- Discard Null-Hypothesis globally:

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

$\frac{\chi^2}{N_{pt}} = 1{,}72$ **No tw-3**

$\frac{\chi^2}{N_{pt}} = 1{,}23$ **With tw-3**

Results of the extraction. Numerical estimations

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

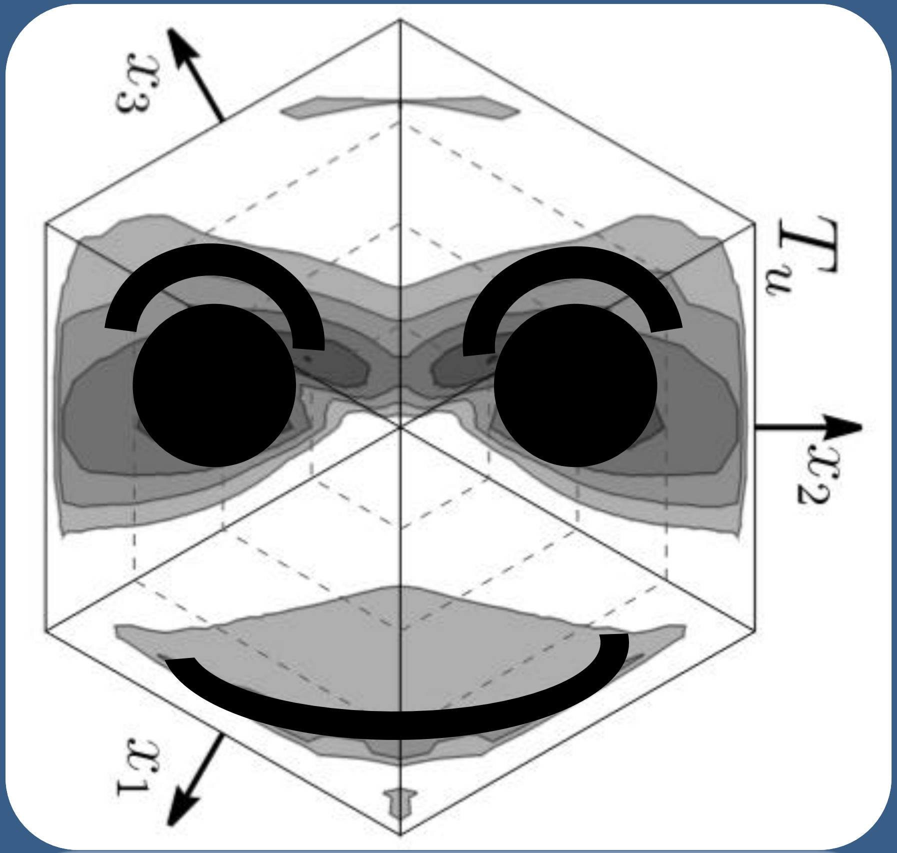
We have obtained a statistically significant signal for twist-three PDFs discarding the Null Hypothesis

FIRST EVER analysis implementing the correct complete evolution at LO

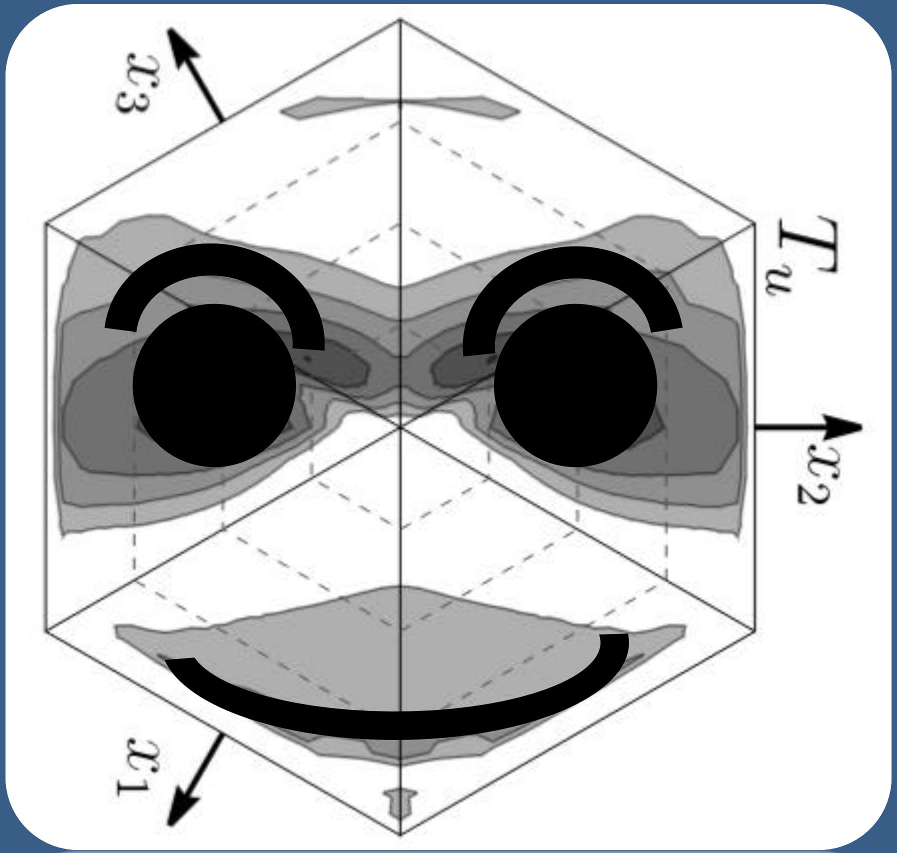
Implement more observables:
Transverse spin assymmetry (in the works!), etc.

Big step in the unification of high-energy physics

THANK YOU!



Additional slides



The 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:

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

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

ggg PDFs:

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

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

Results of the fit:

$$a = 6{,}0^{+0{,}3}_{-0{,}4}, \quad b = 1{,}03^{+0{,}03}_{-0{,}03}, \quad c = -1{,}48^{+0{,}09}_{-0{,}05},$$

$$\alpha_1^u = 1{,}2^{+0{,}2}_{-0{,}3}, \qquad \alpha_2^u = 0{,}58^{+0{,}57}_{-0{,}62},$$

$$\alpha_3^u = 8{,}3^{+0{,}6}_{-2{,}4}, \qquad \alpha_4^u = 3{,}0^{+0{,}5}_{-0{,}9},$$

$$\alpha_1^d = -0{,}54^{+0{,}08}_{-0{,}07}, \qquad \alpha_2^d = 1{,}3^{+0{,}5}_{-1{,}1},$$

$$\alpha_3^d = -10.^{+4.}_{-2.}, \qquad \alpha_4^d = -22.^{+6.}_{-3.},$$

$$\alpha_1^s = -1{,}3^{+0{,}3}_{-0{,}1}, \qquad \alpha_2^s = -8{,}9^{+3{,}1}_{-0{,}9},$$

$$\alpha_3^s = 4{,}1^{+0{,}4}_{-1{,}7}, \qquad \alpha_4^s = 1{,}2^{+0{,}4}_{-1{,}1},$$

$$\beta_1 = -2{,}7^{+1{,}4}_{-1{,}0}, \qquad \beta_2 = 2{,}1^{+0{,}8}_{-1{,}7}.$$

The Integral Measure

Restricts distributions to the conf. space (hexagon)

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