GPDs at EIC Meeting

# QCD Theory Overview

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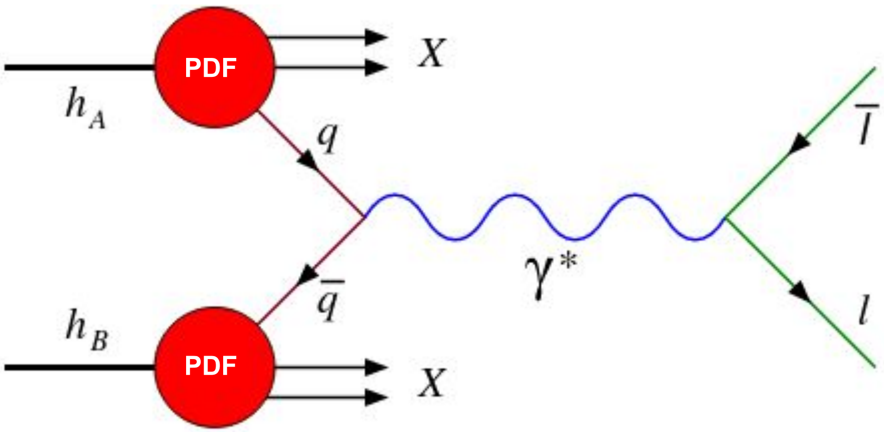
2022 LHC Days in Split
6 Oct 2022

# LHC studies and QCD

We rely on separation of short-distance (non-perturbative) and long-distance (perturbative) physics:

Drell-Yan scattering

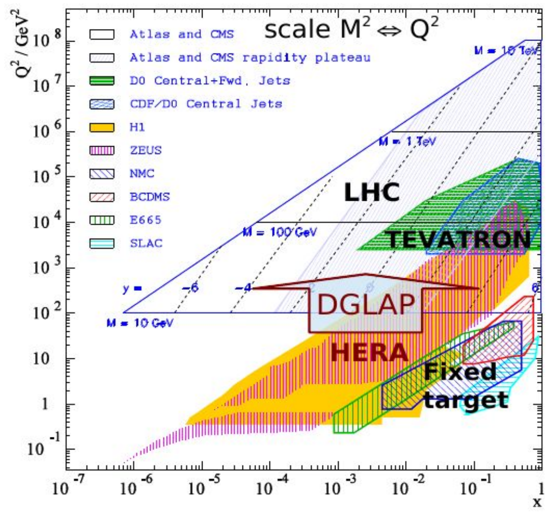


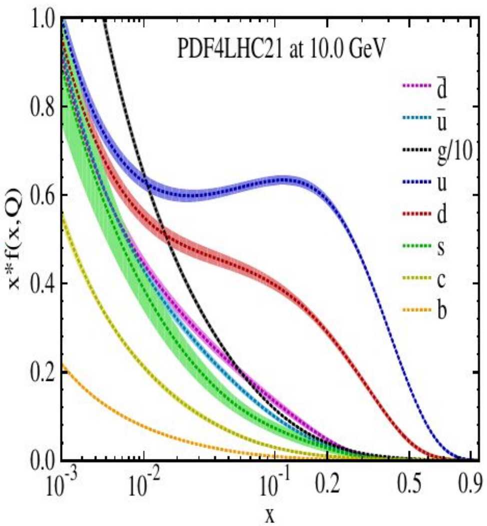

$$Q^4 \frac{d\sigma}{dQ^2} = \sum_{ab} \int dx_a dx_b \, f_a(x_a, \mu) \, f_b(x_b, \mu) \, \omega_{ab} \left( z = \frac{Q^2}{\hat{s}}, \alpha_s(\mu), \frac{Q}{\mu} \right) + \ldots$$

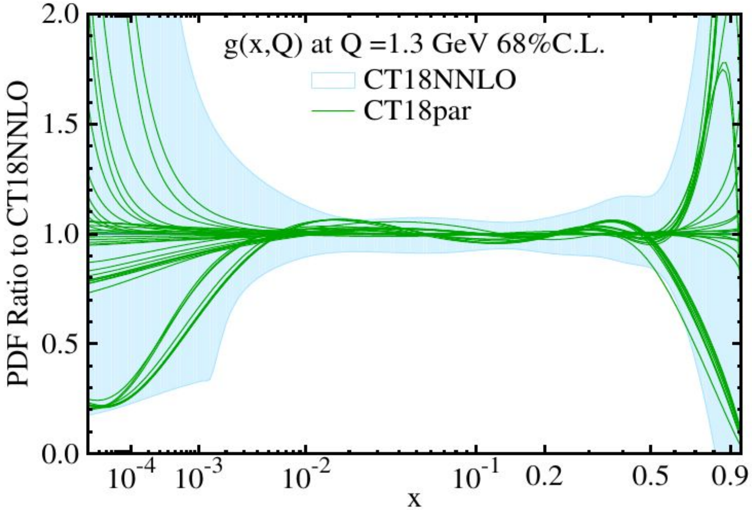
universal pdfs

partonic hard scatt.
perturbative QCD

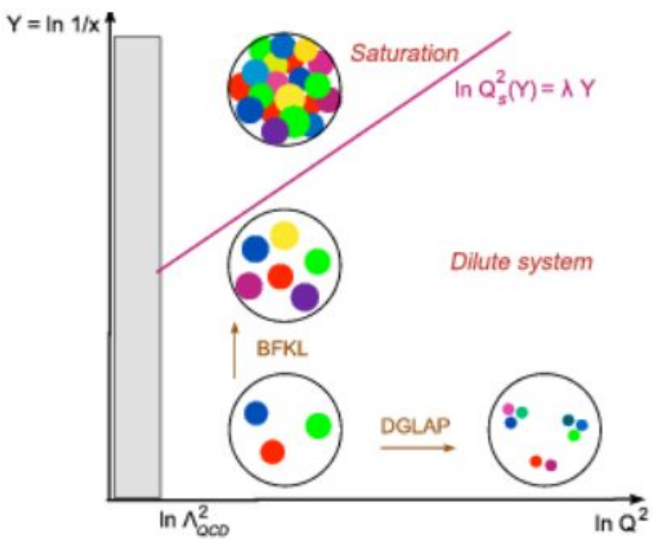
# PDFs are essential for any LHC prediction



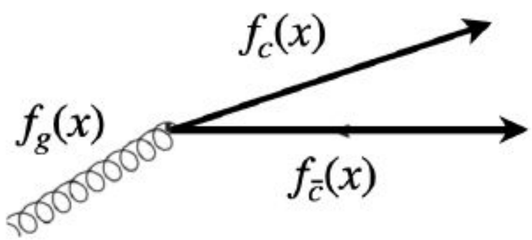



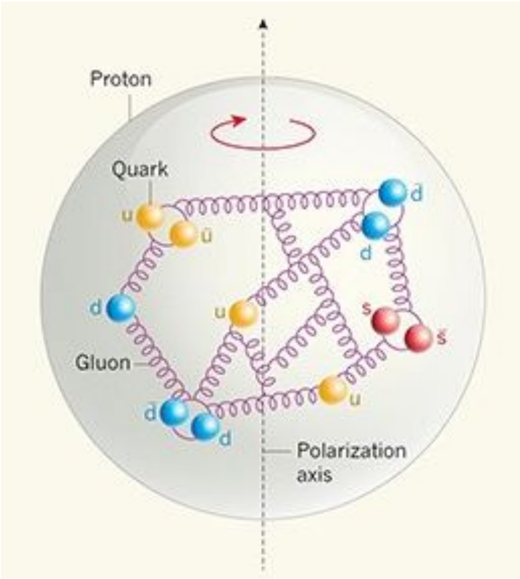

[1905.06957]



# Intrinsic charm in the proton

PDF of charm quark:




$$c^{(n_f=4)}(x,Q) \simeq c_{\text{(pert)}}^{(n_f=4)}(x,Q) + c_{\text{(intr)}}^{(n_f=4)}(x,Q)$$

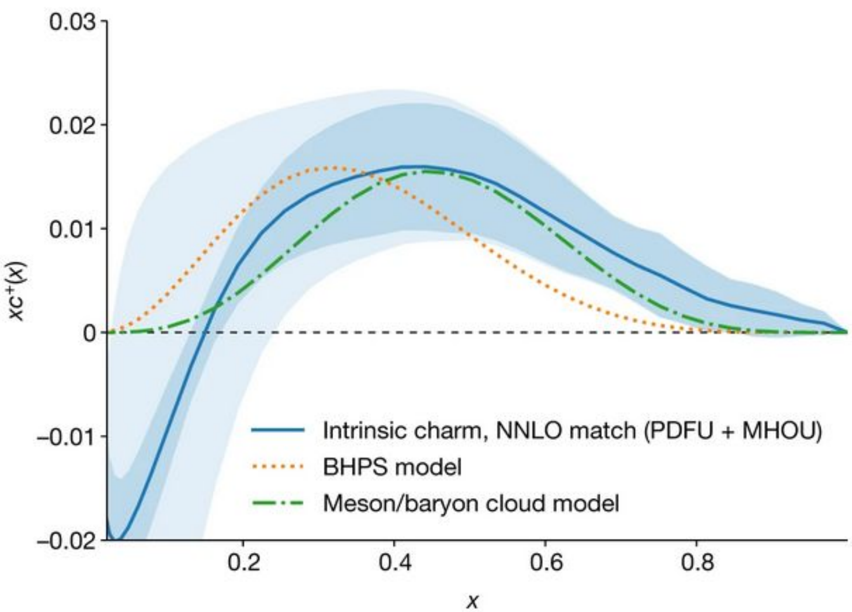
***Extracted phenomenologically from data***

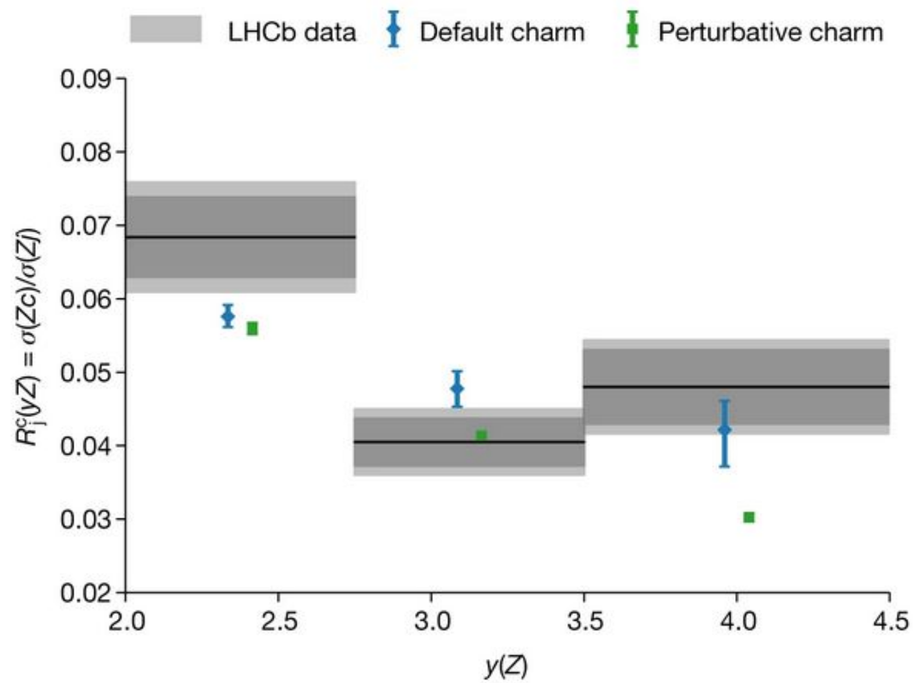
***from QCD evolution and matching***

***from intrinsic component*** $c_{\text{(intr)}}^{(n_f=3)}(x) \neq 0$

[J. Rojo, EIC4LHC]

# Intrinsic charm in the proton




- The NNPDF Collaboration

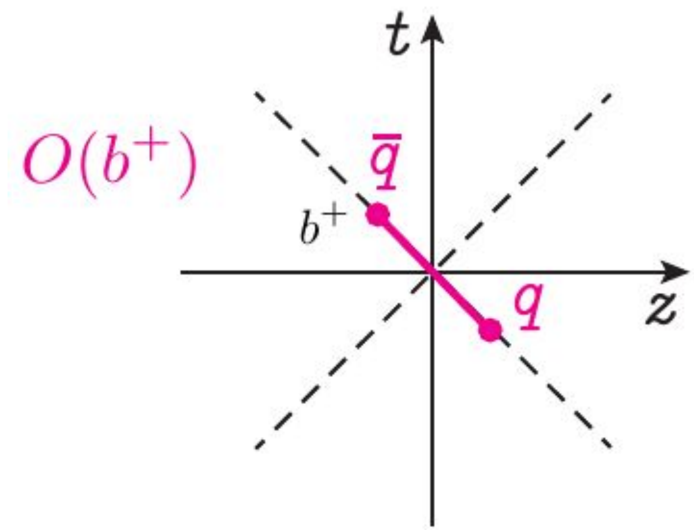
*Nature* **volume 608**, pages 483–487 (2022)

# Can PDFs be calculated in lattice QCD?

Not directly since Euclidean lattice can work only with space-like operators.

**PDF:**

$$f_{q/P}(x) = \int \frac{db^+}{4\pi} e^{-\frac{i}{2}b^+ x P^-} \langle P | O(b^+) | P \rangle$$



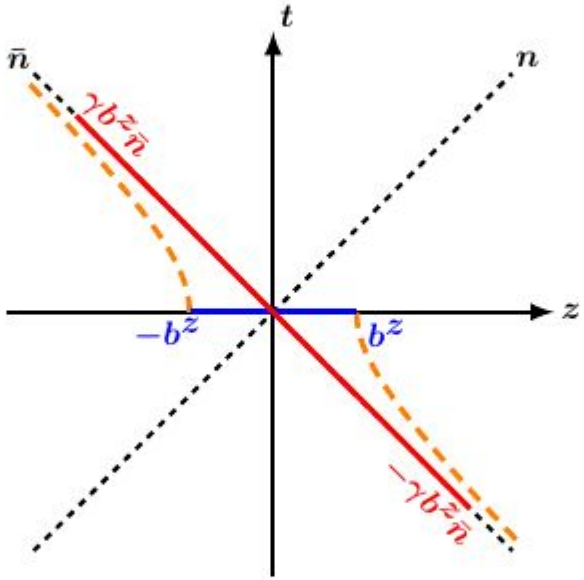

[Figs. by I. Stewart]

# Can PDFs be calculated in lattice QCD?

[X. Ji, A. Radyushkin]

$$\tilde{f}_q(x, P^z, \epsilon) = \int \frac{db^z}{4\pi} e^{ib^z x P^z} \langle p(P) | \bar{q}(b^z) W_z(b^z, 0) \gamma^0 q(0) | p(P) \rangle$$

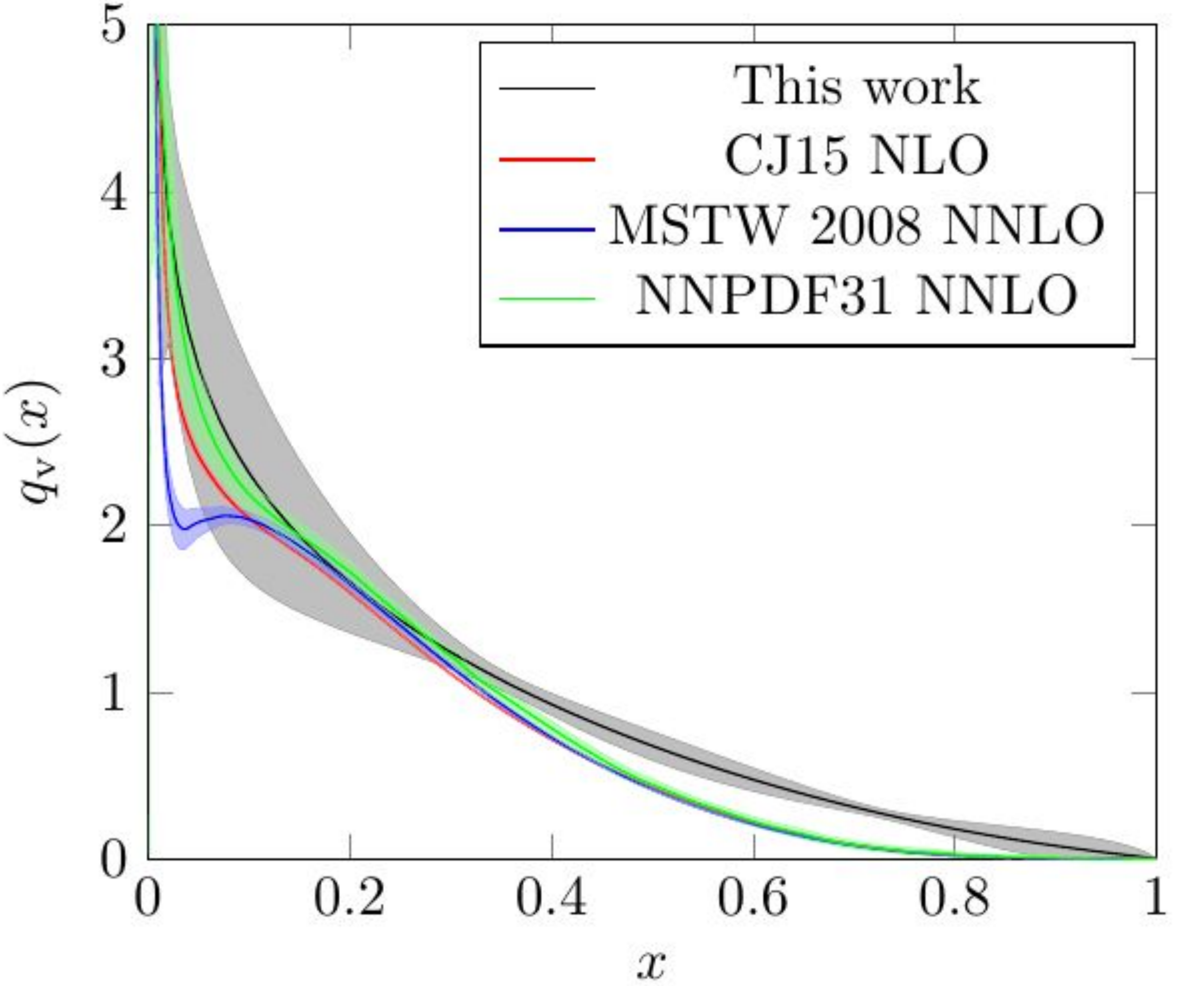
**quasi-PDF**




IR properties should be same as for PDFs, UV properties can be perturbatively matched.

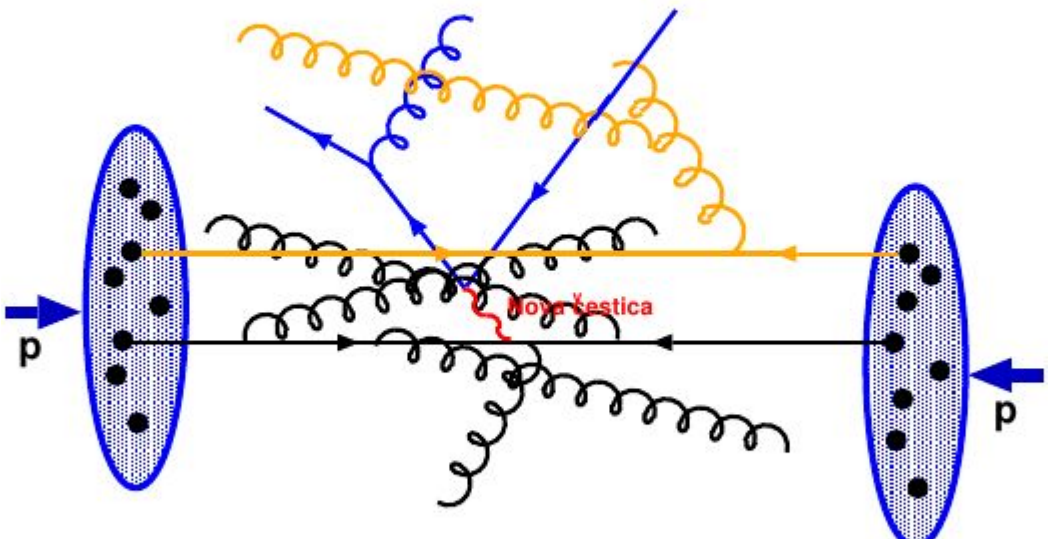
# PDFs calculated from the lattice pseudo-PDFs

[Joo et al., PRL 125 (2020) 23, arXiv:2004.01687]

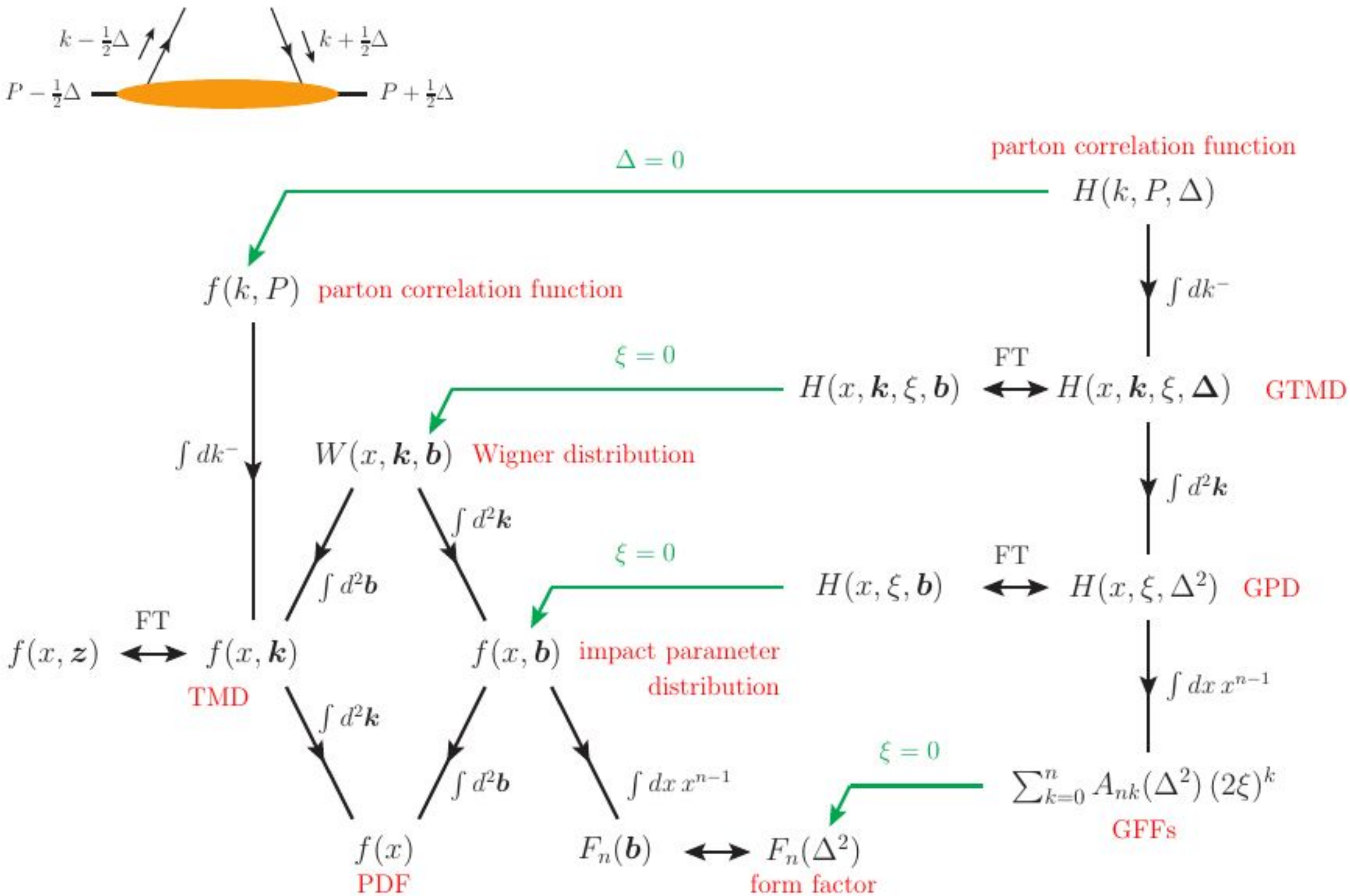


# Longitudinal structure (PDFs) is not the whole story

- lot of gluons at small x → overlap (in phase space) → gluon fusion → saturation (implies considerations in transversal direction)
- multi-parton scatterings (again, transversal shape is important)

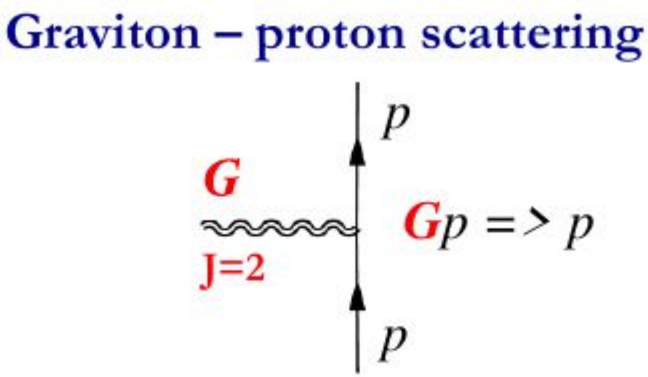


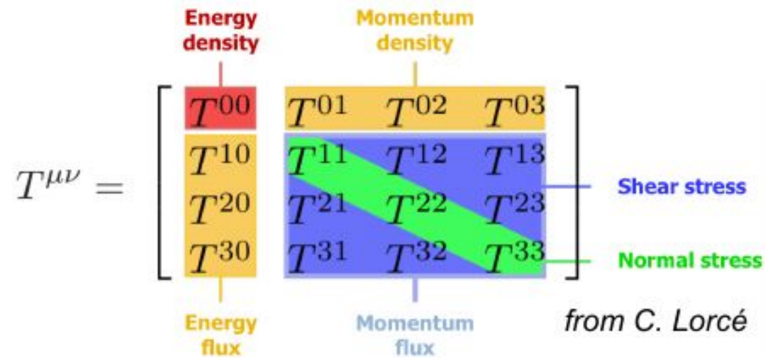
# Family tree of hadron structure functions




[Fig. by Markus Diehl]

# Graviton scattering off proton




$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

[Figs. by V. Burkert]

[Okun, Kobzarev, Pagels]

$$\langle p'|T^a_{\mu\nu}(0)|p\rangle = \bar{u}'\left[A^a(t)\,\frac{P_\mu P_\nu}{M_N} + J^a(t)\,\frac{i\,P_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{2M_N} + D^a(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4M_N} + M_N\,\bar{c}^a(t)g_{\mu\nu}\right]u$$

$A^a(t)$ ↔ $\delta g^{00}$ ↔ Mass: $\sum_a A^a(0) = 1$

$J^a(t)$ ↔ $\delta g^{0i}$ ↔ Spin: $\sum_a J^a(0) = \frac{1}{2}$

$D^a(t)$ ↔ $\delta g^{ij}$ ↔ deformation of space = elastic properties of $N$

$\bar{c}^a(t)$ ↔ non – conservation of EMT pieces ↔ $\sum_a \bar{c}^a(t) = 0$

# quasi-PDFs

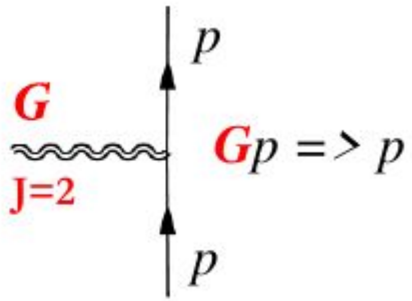
| | | | | | | |
|---|---|---|---|---|---|---|
| **em:** | $\partial_\mu J^\mu_{\rm em} = 0$ *vector* | $\langle N'\|J^\mu_{\rm em}\|N\rangle$ | $\longrightarrow$ | $Q_{\rm prot}$ | $=$ | $1.602176487(40)\times 10^{-19}$C |
| | | | | $\mu_{\rm prot}$ | $=$ | $2.792847356(23)\mu_N$ |
| **weak:** | PCAC *axial* | $\langle N'\|J^\mu_{\rm weak}\|N\rangle$ | $\longrightarrow$ | $g_A$ | $=$ | $1.2694(28)$ |
| | | | | $g_p$ | $=$ | $8.06(0.55)$ |
| **gravity:** | $\partial_\mu T^{\mu\nu}_{\rm grav} = 0$ *tensor* | $\langle N'\|T^{\mu\nu}_{\rm grav}\|N\rangle$ | $\longrightarrow$ | $M_{\rm prot}$ | $=$ | $938.272013(23)\,{\rm MeV}/c^2$ |
| | | | | $J$ | $=$ | $\frac{1}{2}$ |
| | | | | $D$ | $=$ | ? |

*P. Schweitzer et al., arXiv:1612.0672, 2016.*

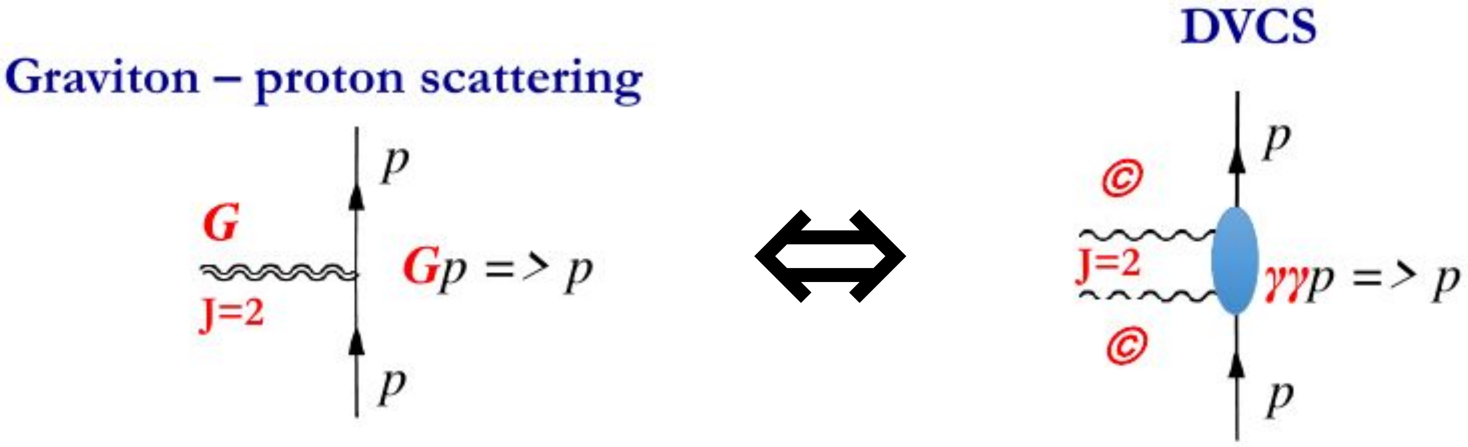
**The D-term is the "last unknown global property" of the nucleon**

# Impossible to measure?

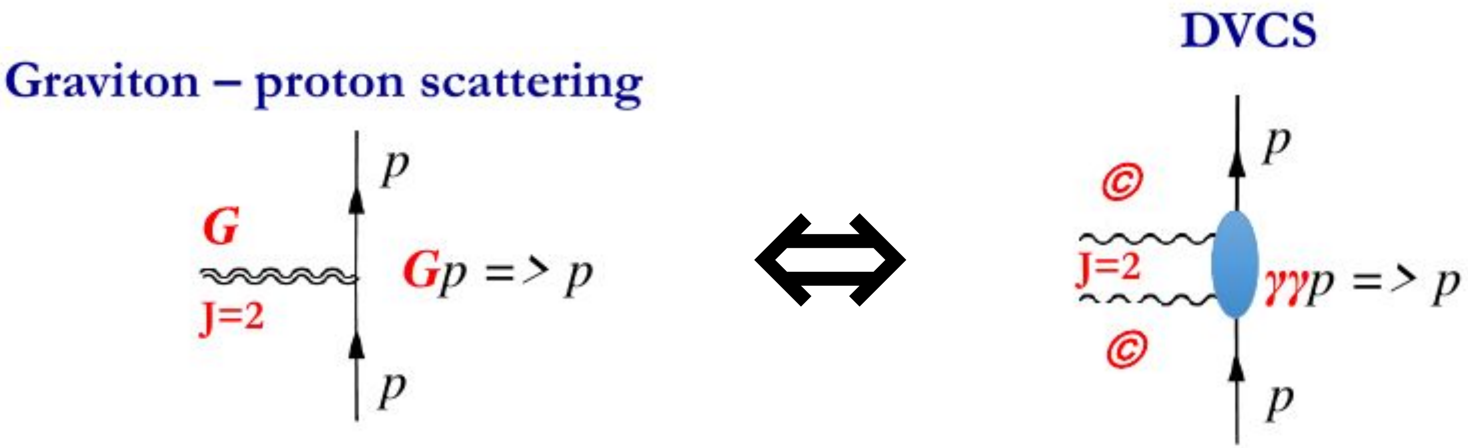
**Graviton – proton scattering**



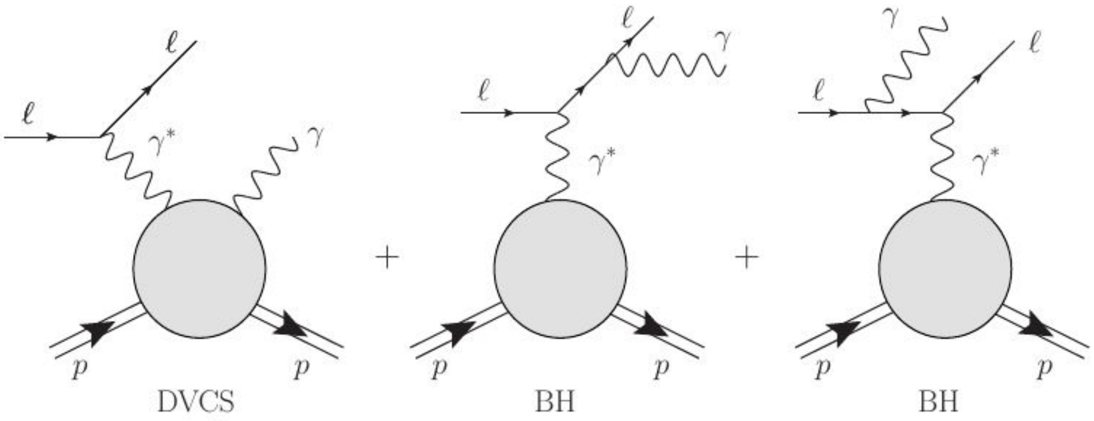
# Impossible to measure?



# Impossible to measure?




- DVCS is measured via leptoproduction of a photon



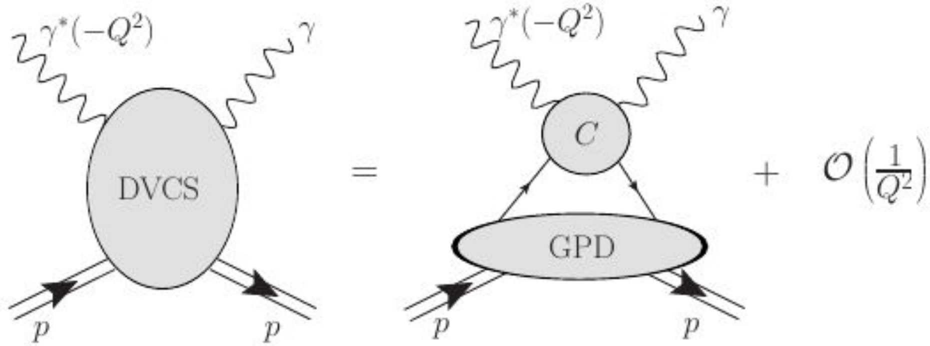

- Interference with Bethe-Heitler process gives unique access to both real and imaginary part of DVCS amplitude.

- At leading order DVCS cross-section depends on four complex

**Compton form factors (CFFs)**

$$\mathcal{H}(\xi, t, Q^2), \quad \mathcal{E}(\xi, t, Q^2), \quad \widetilde{\mathcal{H}}(\xi, t, Q^2), \quad \widetilde{\mathcal{E}}(\xi, t, Q^2)$$

- [Collins et al. '98]




- CFFs are convolution:

$$^{a}\mathcal{H}(\xi, t, Q^2) = \int \mathrm{d}x \; C^a(x, \xi, \frac{Q^2}{Q_0^2}) \; H^a(x, \eta = \xi, t, Q_0^2)$$

$a = q, G$

- $H^a(x, \eta, t, Q_0^2)$ — Generalized parton distribution (GPD)
  [Müller '92, et al. '94, Ji, Radyushkin '96]

# Three classical objectives of GPD studies

- Both meanings are valid:
  - "classical" = well known, venerable
  - "classical" = understandable from non-quantum viewpoint

❶ Ji's "sum rule"

$$J_z^a = \frac{1}{2}\int_{-1}^{1} dx\, x \Big[ H^a(x,\xi,t) + E^a(x,\xi,t) \Big]_{t\to 0}$$ [Ji '96]

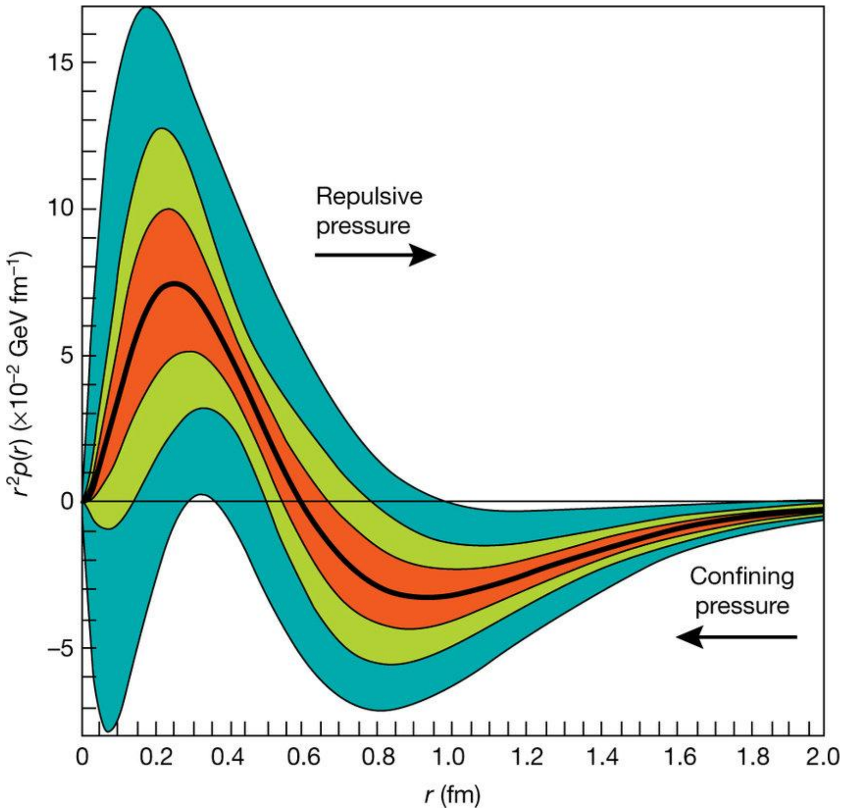
❷ 3D tomography

$$\rho(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} H(x, 0, -\vec{\Delta}_\perp^2)$$ [Burkardt '00]

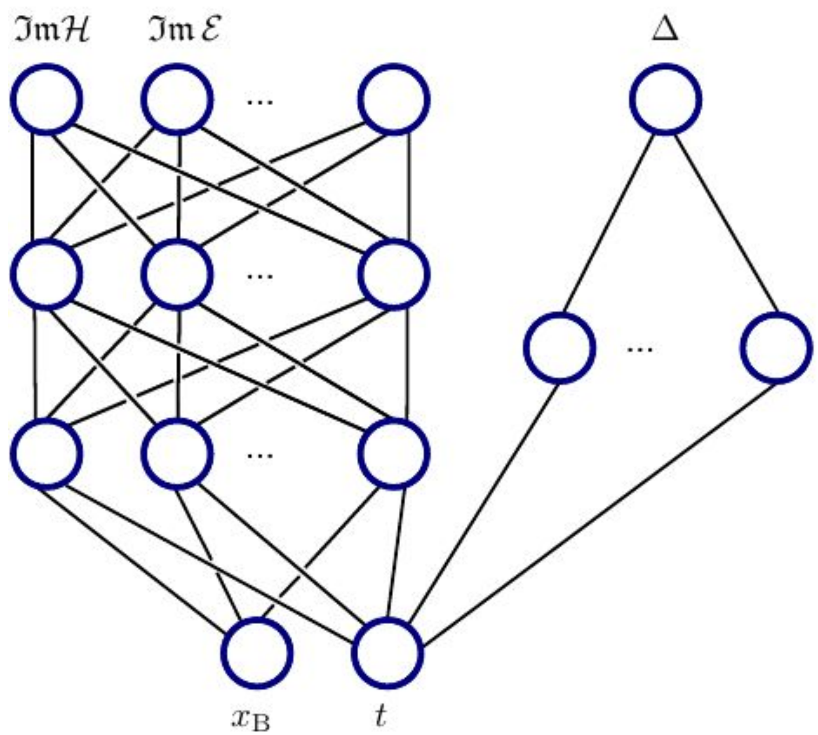
❸ Pressure distribution in the nucleon — directly related to subtraction constant $\Delta(t)$ of CFF dispersion relation — directly related to GPD "D-term" [Polyakov '03, Teryaev '05]

$$\Delta(t) = \mathfrak{Re}\,\mathcal{H}(\xi,t) - \frac{1}{\pi}\mathrm{P.V.}\int_0^1 dx \frac{2x}{\xi^2 - x^2}\,\mathfrak{Im}\,\mathcal{H}(x,t)$$

# Results on pressure distribution in the proton



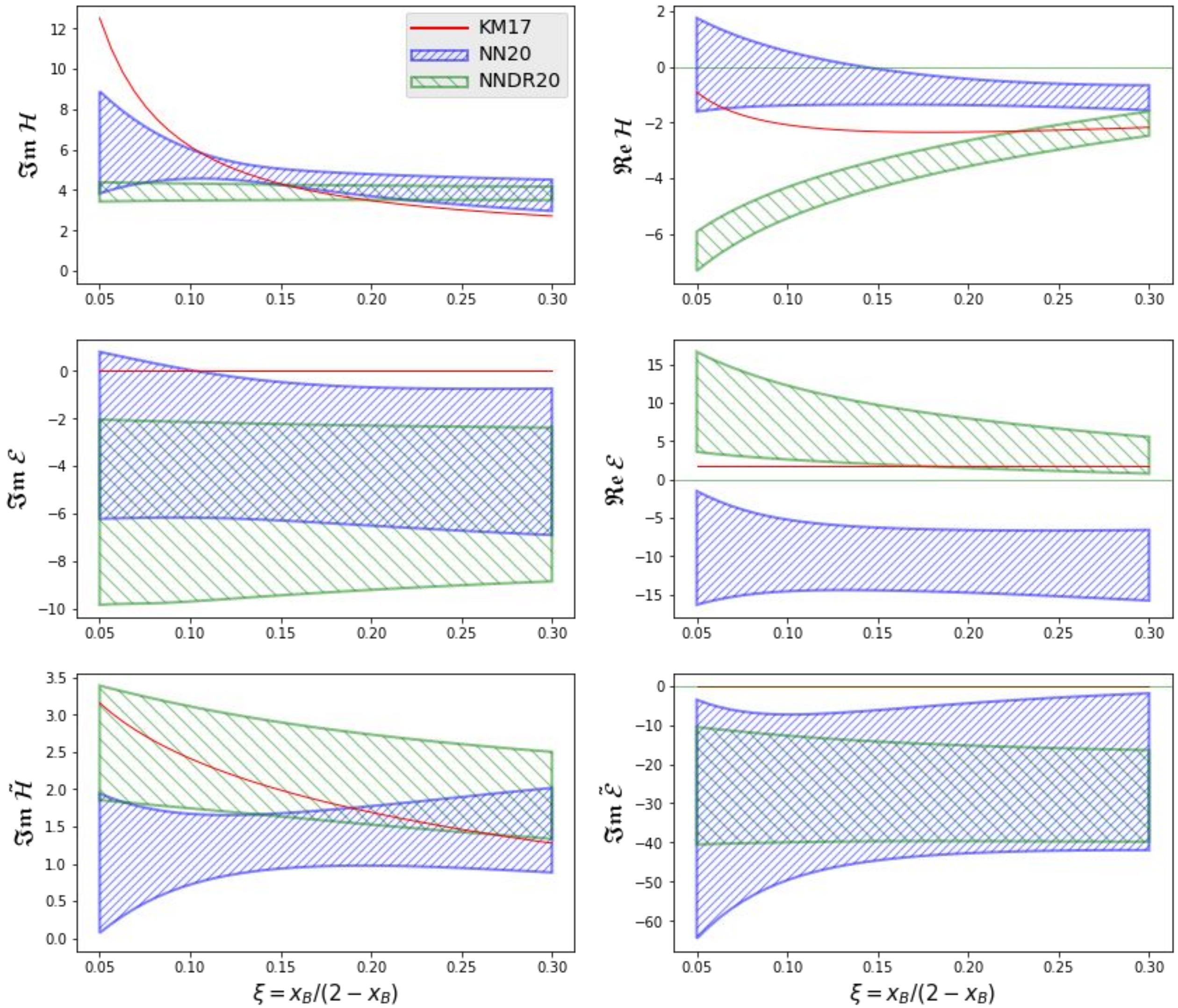

[Burkert et. al, Nature 2018]




Model-independent extraction by neural networks consistent with zero.

[K.K., Nature 2019]

# Extraction of form factors from DVCS data:




[Čuić et al. 2021]

# Combining DVCS on neutron and on proton:

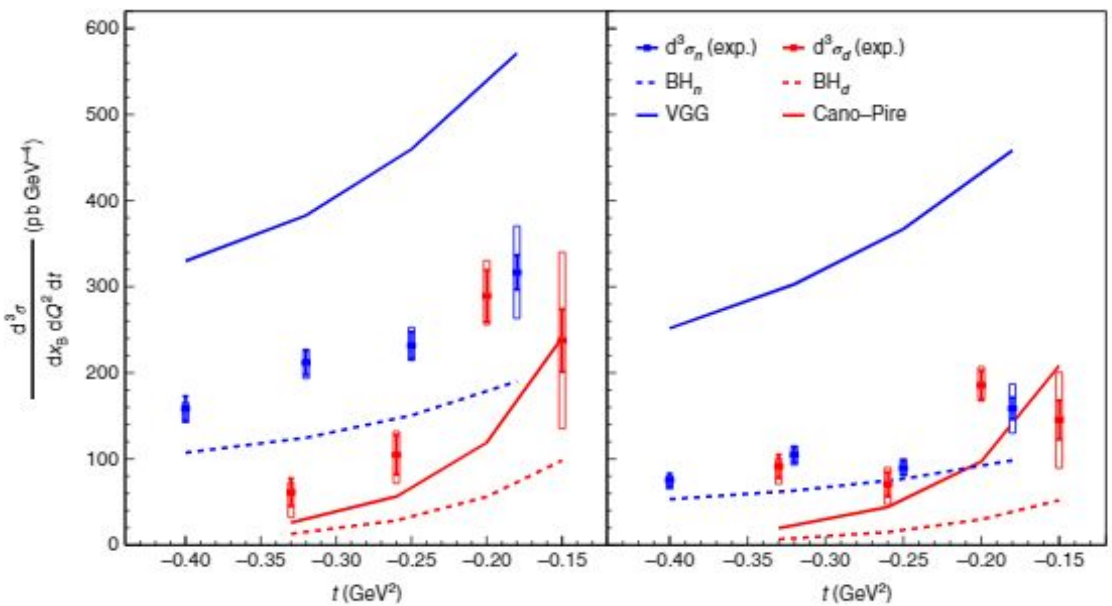
nature physics

ARTICLES

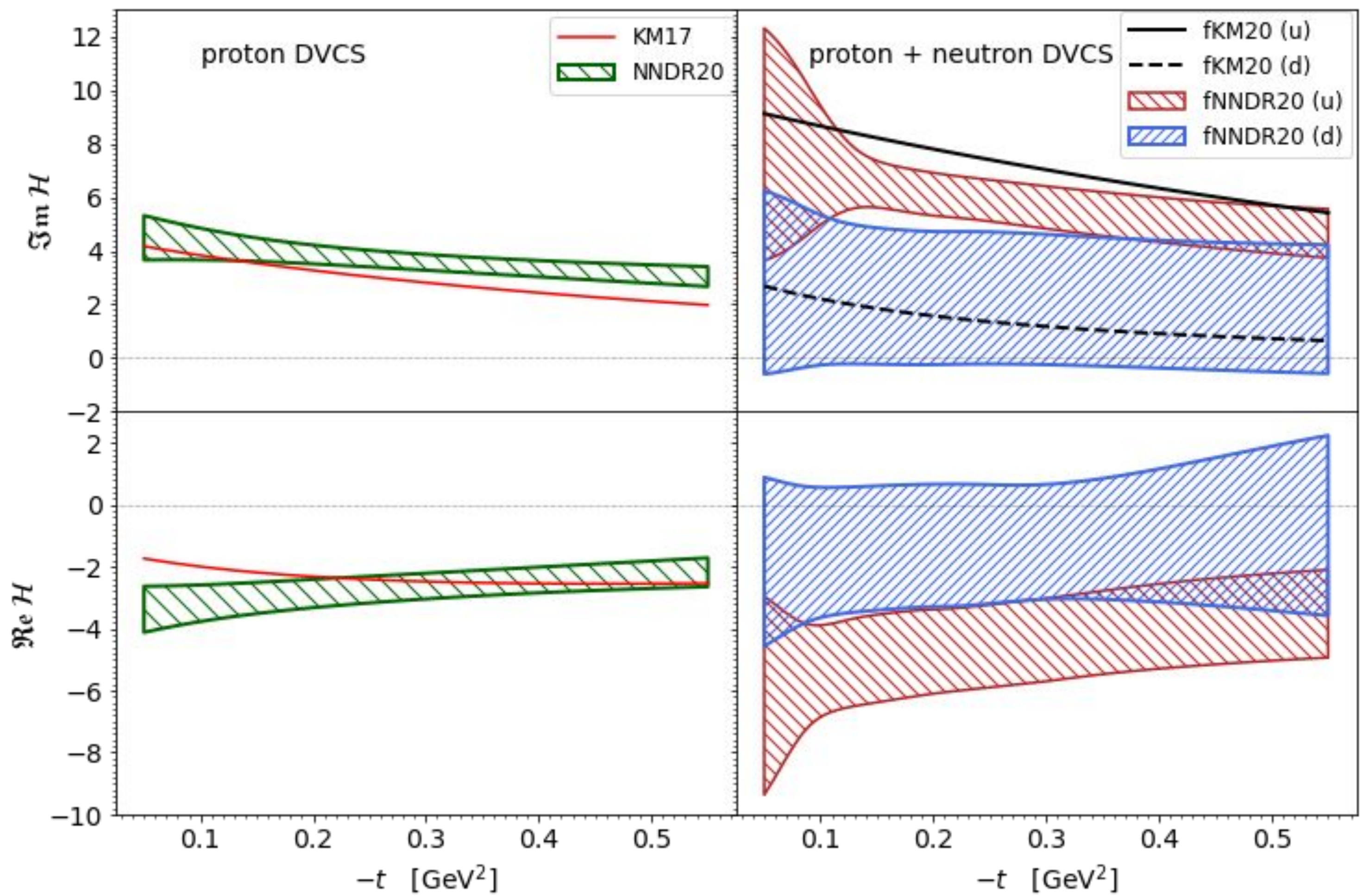
https://doi.org/10.1038/s41567-019-0774-3

## Deeply virtual Compton scattering off the neutron

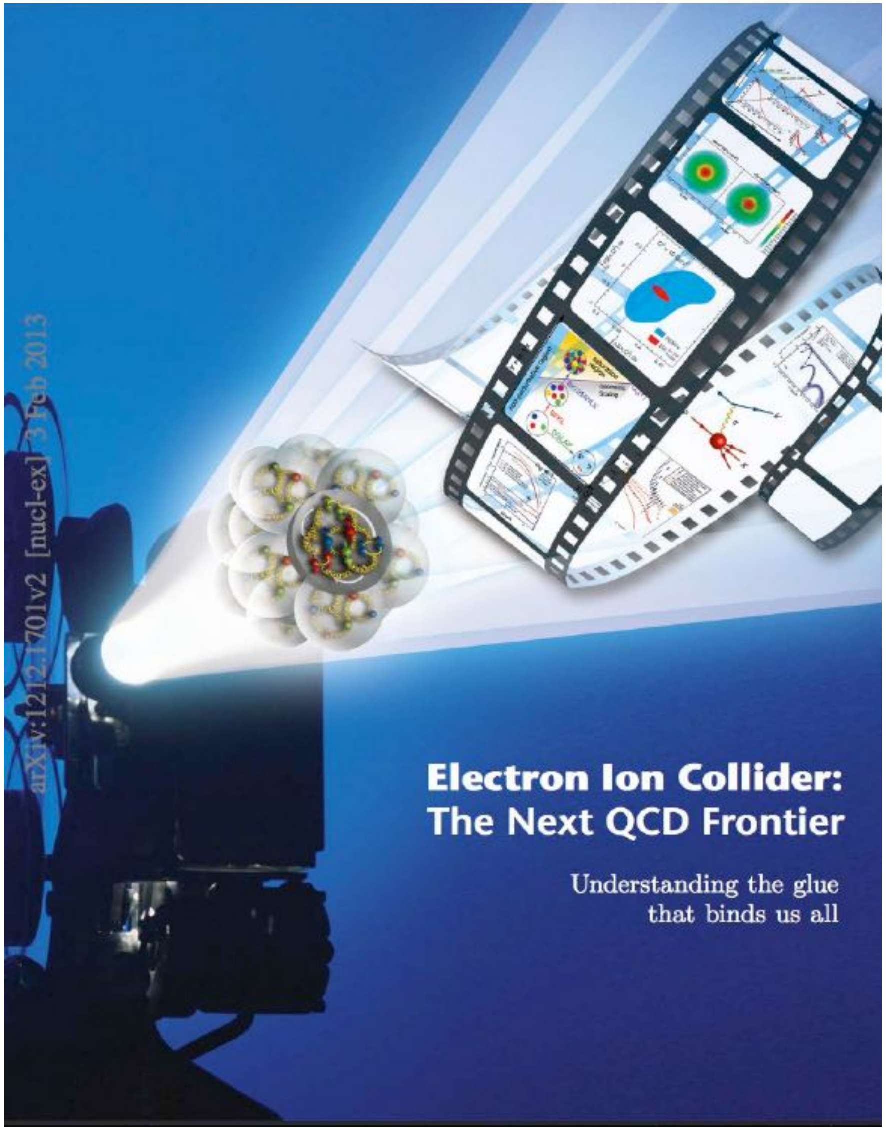
M. Benali[1,2*], C. Desnault[3], M. Mazouz[1], Z. Ahmed[4], H. Albataineh[5], K. Allada[6], K. A. Aniol[7], V. Bellini[8], W. Boeglin[9], P. Bertin[2,10], M. Brossard[2], A. Camsonne[10], M. Canan[11], S. Chandavar[12], C. Chen[13], J.-P. Chen[10], M. Defurne[14], C. W. de Jager[10,42], R. de Leo[15], A. Deur[10], L. El Fassi[16,17],



# Separation of flavors: CFFs $\mathbf{H_u}$ (red) and $\mathbf{H_d}$ (blue)

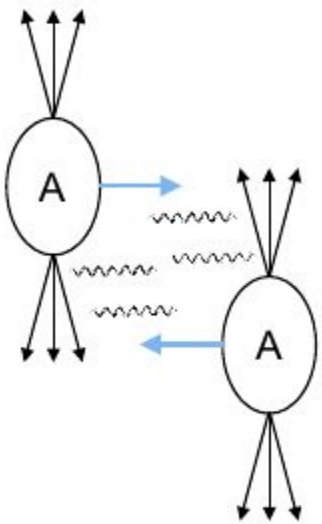


# New collider in USA to study 3D structure: EIC




[arXiv:1212.1701]

# Can we study this at LHC?




**UPC**
*Ultra Peripheral Collisions*

- pA collisions - enhancement by Z^2

- There is also an LHeC proposal arXiv:2007.14491

ECFA 80 / 42
17 March 1980
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*Report of the*
***ELECTRON PROTON WORKING GROUP of ECFA***

# STUDY ON THE PROTON-ELECTRON STORAGE RING PROJECT HERA

...

such a machine provides a unique opening on new phenomena, particularly in the field of weak interactions: new charged intermediate bosons, right-handed weak currents, new leptons, subquarks, etc.

"LHC is a beautiful QCD machine, they just don't know it yet."

-- Dieter Mueller (inventor of GPDs), circa 2010