Proton structure...

...what hides inside nucleons and how to measure it?

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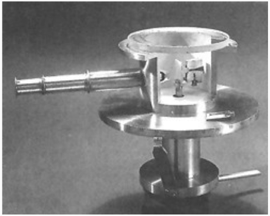
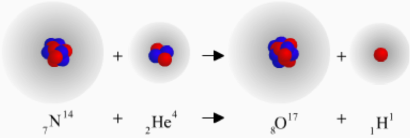
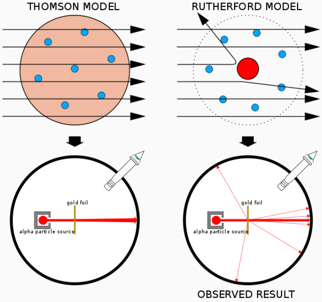
Rutherford scattering - probing atoms

- Scattering of α particles on a gold foil
- Small scattering angles expected
  $\rightarrow$ large angles observed
- Positive charge and most of the mass are concentrated in the centre of the atom in a small volume
  $\rightarrow$ nucleus
- Proton discovered in further experiments.







$$e(k) + A \to e(k') + A; \qquad k - k' = Q^2$$

- Measurements of the charge distribution of nuclei.
- Modification of point-like scattering cross section

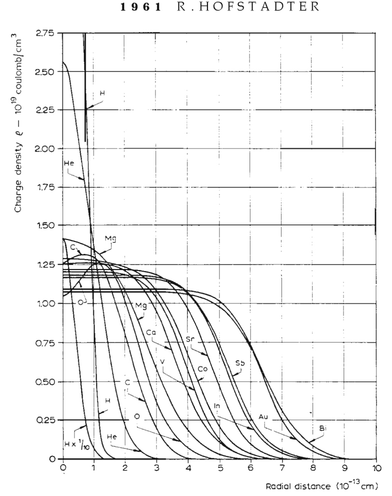
$$\frac{\mathrm{d}\sigma}{d\Omega} = |F(Q^2)|^2 \left(\frac{\mathrm{d}\sigma}{d\Omega}\right)_{\mathrm{point}}$$

$\to F(q)$ is a Fourrier transform of charge density $\rho(r)$ – **form factor**.

- Parametrization of the size of nuclei

$$r = r_0 A^{1/3}\ [\mathrm{fm}]$$

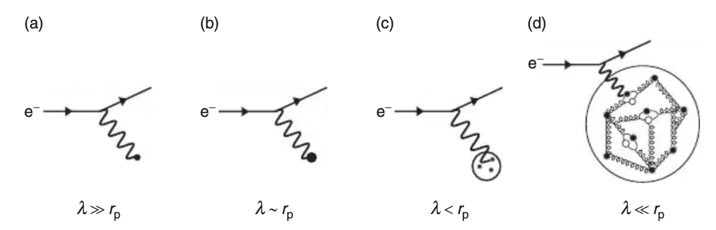
- Size of the proton $r_p \approx 1\ \mathrm{fm}$



Deep inelastic scattering (DIS) - probing nucleons

$$e(k) + p \to e(k') + X$$

- In order to see smaller structures, one needs highly energetic probe
- With high Q^2 photons, one can distinguish structure at sub-nucleonic scale



M. Thomson – Modern Particle Physics, Cambridge Uni. Press, 2013

Deep inelastic scattering

- DIS cross section

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[y^2 F_1(x, Q^2) + (1-y)\frac{F_2(x, Q^2)}{x}\right]$$

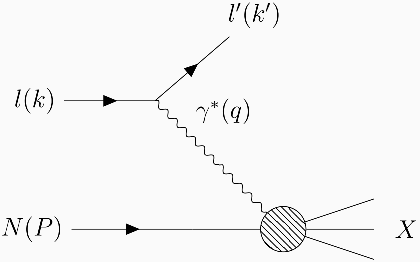
- $F_1,\ F_2$ – structure functions, include photon-proton interaction.

$$W^2_{\gamma^* p} = (P+q)^2$$

$$Q^2 = -q^2 = -(k-k')^2$$

$$x = \frac{Q^2}{2P\cdot q}$$

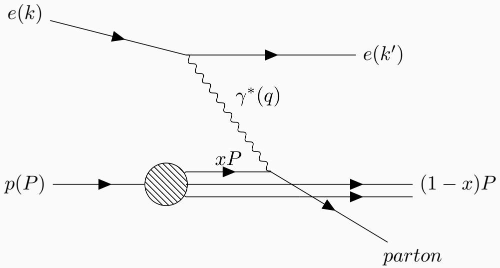
$$y = \frac{P\cdot Q}{P\cdot k}$$



DIS in Feynmann's parton model picture

- Scattering of γ^* on one of the constituent partons.
- Infinite momentum frame - incoming particles carry only longitudinal momentum.
- Partons carry fraction x of the proton momentum P.
- Electron-parton scattering cross section

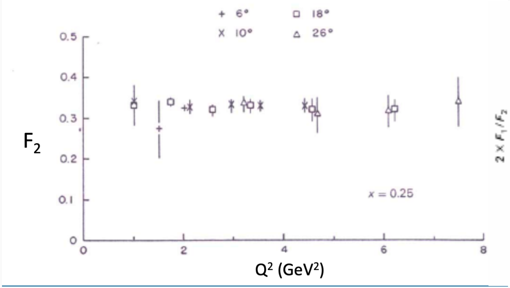
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)+\frac{y^2}{2}\right]\sum_i e_i^2 f_i(x)$$

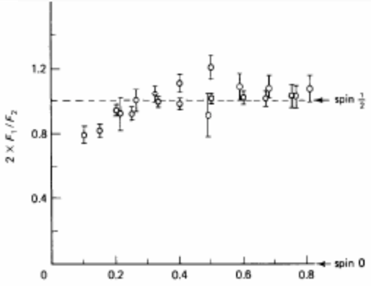


- Functions $f_i(x)$ give a probability to find a parton of kind i and with longitudinal momentum fraction x inside the proton.
- Bjorken scaling - PDFs don't depend on Q^2 of the probing photon.
- Partons are fermions – relations between PDFs and structure functions

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 f_i(x) \qquad F_2(x) = \sum_i e_i^2 x f_i(x)$$

$\rightarrow F_2(x) = 2xF_1(x)$ – Callan-Gross relation

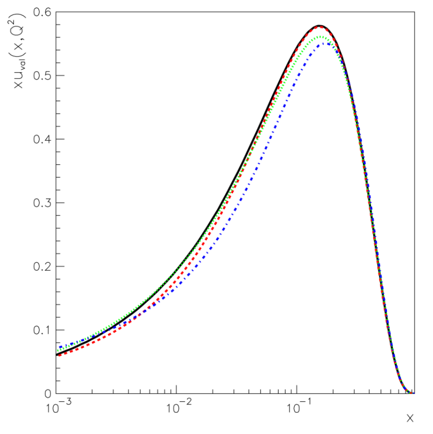


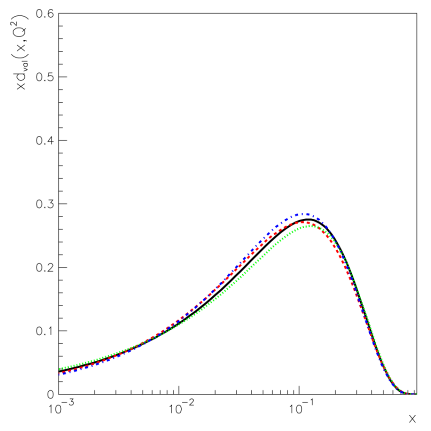


Ann. Rev: Nucl. Sci. 22,203 (1972)

Are there only valence quarks?

Something is clearly missing here! :(





Chýla - Quarks, partons and QCD; CERN PDFLIB

Let's add sea quarks

- proton $= u_v + u_v + d_v + (u_s + \bar{u}_s) + (d_s + \bar{d}_s) + (s_s + \bar{s}_s)$ [1]

$$\frac{F_2^{ep}(x)}{x} = \frac{4}{9}\left[u^p(x) + \bar{u}^p(x)\right] + \frac{1}{9}\left[d^p(x) + \bar{d}^p(x)\right] + \frac{1}{9}\left[s^p(x) + \bar{s}^p(x)\right] \quad (1)$$

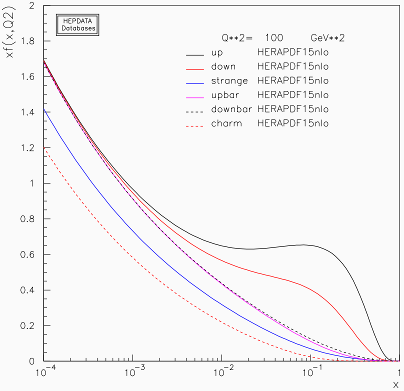
- Sum rules

$$\int_0^1 u_v(x)\mathrm{d}x = 2$$

$$\int_0^1 d_v(x)\mathrm{d}x = 1$$

$$\int_0^1 \left[q_s(x) - \bar{q}_s(x)\right]\mathrm{d}x = 0$$

This looks better. :)



Is that all?

- Fraction of the proton momentum carried by all q and $\bar{q}$ together

$$\int_0^1 x\Sigma(x)\mathrm{d}x = \frac{18}{5}\int_0^1 F_2^{eN}(x)\mathrm{d}x$$

- Naive expectation

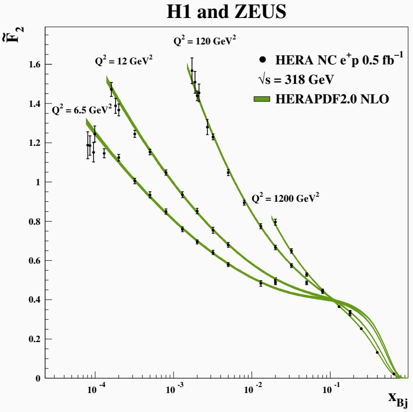
$$\int_0^1 x\Sigma(x)\mathrm{d}x = 1$$

- Experimental value

$$\int_0^1 x\Sigma(x)\mathrm{d}x \approx 0.5$$

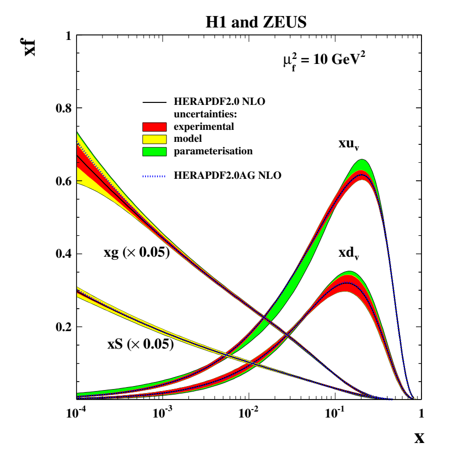
- Other, electrically neutral partons in proton → **gluons**

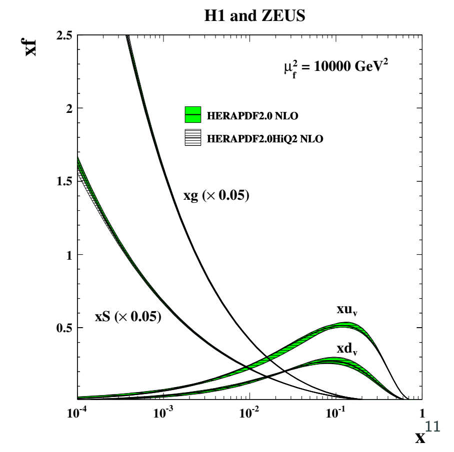
Also Bjorken scaling violation observed!



Evolution of proton structure

- Composition of the proton changes with x and Q^2.
- At low energies proton dominated by valence quarks.
- At large energies gluons dominate.
- Parton distributions functions (PDF) are universal.





Are gluon densities growing to infinity?

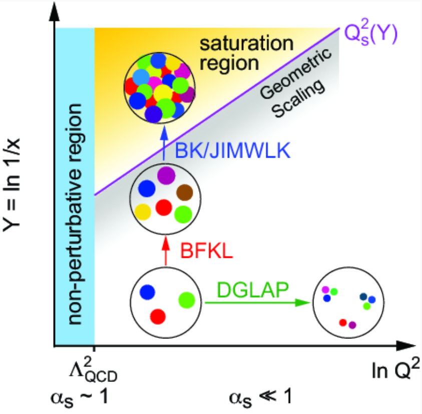


Figure 1: Diagram picturing the QCD evolution of the partonic structure of the proton.

C. Marquet, Nucl.Phys. A904-905 (2013) 294c-301c.

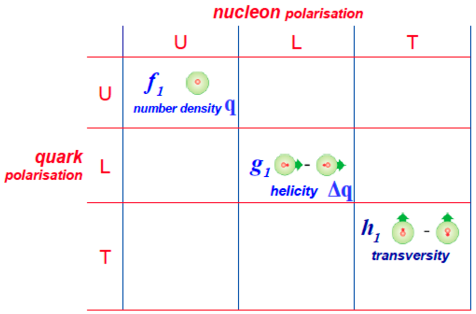
- Evolution with increasing Q^2 described by DGLAP equations.
- By fixing the scale of the process, one can fix the position in $\ln Q^2$.
- Going to smaller x, one can reach the saturation scale $Q_S^2(x)$
  - Below $Q_S^2(x) \to$ dilute regime, linear evolution of the gluon density (BFKL).
  - Above $Q_S^2(x) \to$ dense regime, non-linear evolution of the gluon density (JIMWLK, BK).

Polarized PDFs

- f_1 – regular PDFs
- $g_{1i} = q_i^+(x) - q_i^-(x) = \Delta q(x)$ – helicity

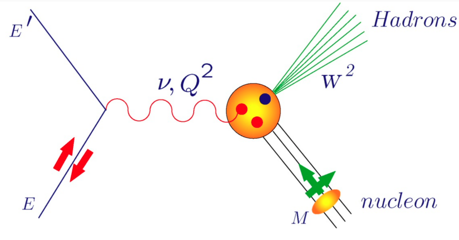
  $\rightarrow$ difference in probabilities to find quarks with their spin aligned or antialigned to the spin of longitudinally polarized nucleon
- h_1 – transversity

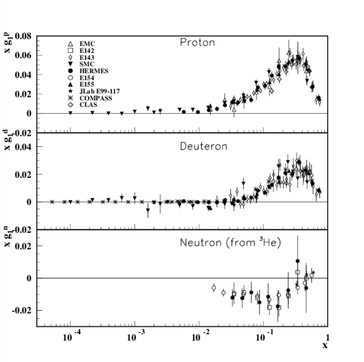
  $\rightarrow$ correlation between the transversally aligned spins of the quark and nucleon



Measurement of polarized PDFs

- Polarized PDFs give complete description of the nucleon structure in terms of x and spins.
- Measurement through polarized deep inelastic scattering
  $\rightarrow$ longitudinally polarized leptons
  $\rightarrow$ longitudinally/transversally polarized nucleons



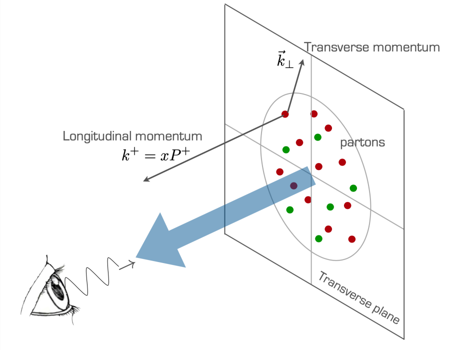


Adding transverse degree of freedom in momentum space

- In addiction to longitudinal momenta of partons, we consider also their intrinsic transverse momenta k_x, k_y
- The simplest transverse momentum distribution – unpolarized PDF with $\vec{k}_T$-dependence

$$f_1^q(x, \vec{k}_T)$$

- PDF obtained back by integrating over $\vec{k}_T$: $\int \mathrm{d}\vec{k}_T f_1^q(x, \vec{k}_T) = f_1^q(x)$

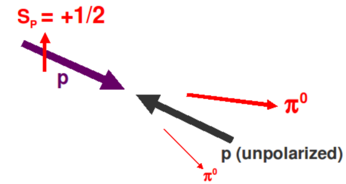


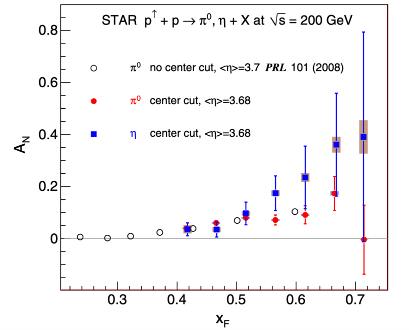
A. Bacchetta – talk given at EINN2017

How do we know partons carry transverse momentum?

- For a fast moving proton $k_T << xP$
- One can use transverse spin – can correlate with parton's $\vec{k}_T$ – as a probe.
- Single transverse spin asymmetry (SSA)
  - "Left-right" asymmetry of produced particles from the hadronic scattering of transversaly polarized protons by an unpolarized proton.
  - Should vanish if partons have only longitudinal momenta.

$$A_N = \frac{L - R}{L + R} = \frac{\sigma^{\uparrow} - \sigma}{\sigma^{\uparrow} + \sigma}$$



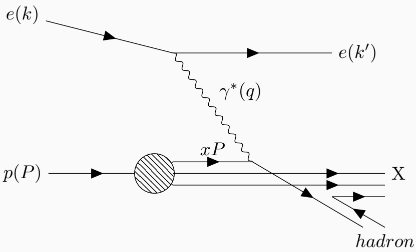


STAR Collaboration, Phys. Rev. D 86, 051101

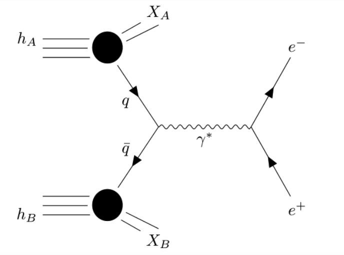
Processes suitable for measuring TMDs

- TMDs are not universal (unlike PDFs) $\rightarrow$ process dependent

  $\rightarrow$ however universality can be restored
- Several available processes
  - Semi-inclusive deep inelastic scattering ($e + p \rightarrow e' + h + X$)
    COMPASS (SPS - CERN), HERMES (DESY), JLab, EIC
  - Drell-Yan process ($h_A + h_B \rightarrow l^+ + l^-$) – PANDA (FAIR), COMPASS
  - Diffractive dijet production ($p + A \rightarrow dijets + X$)
  - $e^+ + e^- \rightarrow$ pions – BELLE, BaBar
- Final-state transverse momentum $<<$ hardest scale in the process.

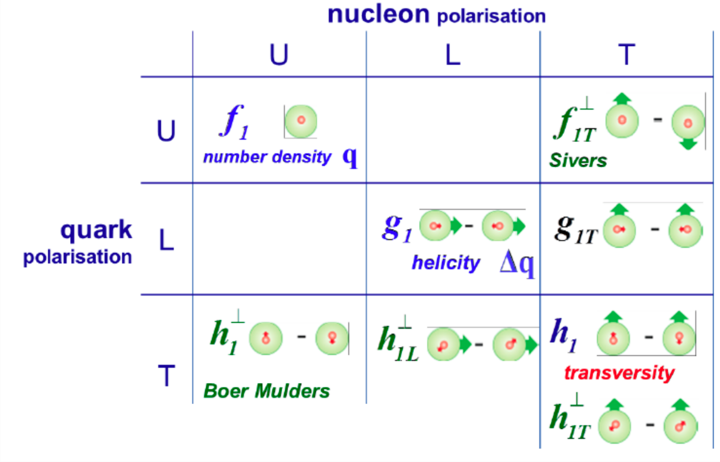


SIDIS (TMDs convoluted with fragmentation functions)



Drell-Yan (direct acces to TMDs)

- At LO, 8 TMDs are needed for full description of nucleon structure
- 5 new distributions – vanish when integrating over $\vec{k}_T$.
- 3 PDFs are the only TMDs which survive integration over $\vec{k}_T$.

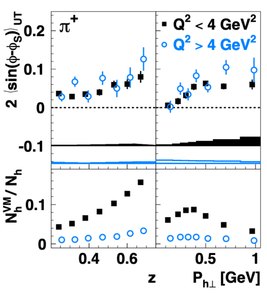


Sivers function

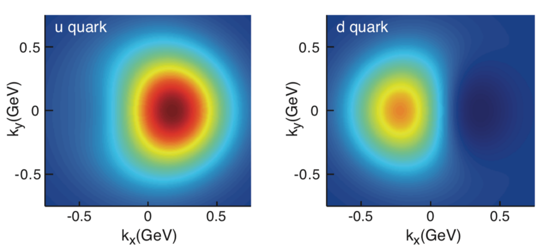
- Sivers function - unpolarized quark distribution in a transversely polarized proton.
- Introduced by D. Sivers to describe SSA measured in inclusive hadron production in pp
- Due to the presence of non-zero phase, the time reversal causes

$$f_{1T}^{\perp q}(SIDIS) = -f_{1T}^{\perp q}(DY)$$

- Measurement of the Sivers function in SIDIS – separation of $f_{1T}^{\perp q}$ through angular dependence



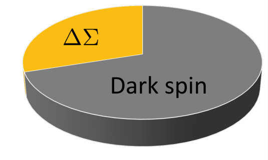
HERMES Collaboration, Phys. Rev. Lett 103, 152002



A. Accardi et al., Eur. Phys. J. A52, no. 9, 268 (2016)

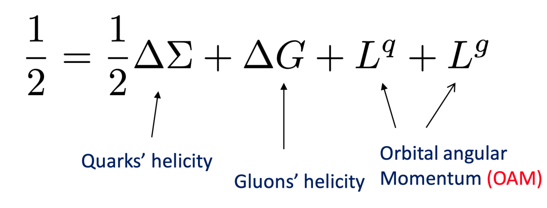
Proton spin puzzle

- From naive quark model – spins of valence quarks sum up to nucleon spin
- "Spin crisis" in 1987
  - EMC experiment (CERN) announced an unexpected small value of quark contribution to the proton spin $\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$
  - Today $\Delta\Sigma \approx 30\%$

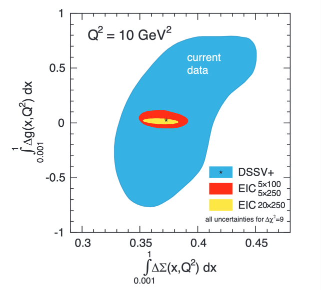


Decomposition of the proton spin:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$



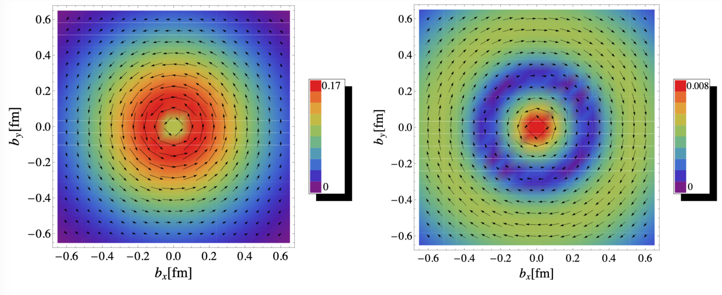
Y. Hatta, lecture given at CFNS Summer School 2019



A. Accardi et al., Eur. Phys. J. A52, no. 9, 268 (2016)

Orbital angular momentum (OAM) of partons

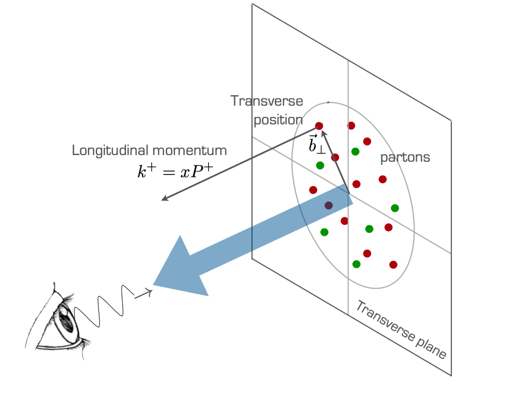
- Should contribute to the proton spin.
- TMDs provide correlations of transverse motion with quark spin and orbital motion
- Off-diagonal TMDs would vanish for zero orbital angular momentum of partons.
- Experimentally unexplored area – proposed measurements with SoLID in JLab



C. Lorcé, B. Pasquini, X. Xiong, and F. Yuan, Phys. Rev. D 85, 114006

Adding transverse degree of freedom in position space

- In addiction to longitudinal momenta of partons, we consider also their intrinsic transverse positions b_x, b_y
- Described by impact-parameter distributions $f(x, \vec{b})$
- Impact parameter $\vec{b}$ is a Fourier conjugate variable to $\vec{\Delta}$, where $\vec{\Delta}^2 = -t = -(P - P')^2$



Generalized parton distributions (GPD)

- Transformation $\vec{b} \to \vec{\Delta}^2$ and non-zero ξ (longitudinal momentum fraction).
- Unification of the concepts of parton distributions and hadronic form factors.
- Special case for zero ξ, t – "standard" collinear PDFs

$$H^q(x, \xi = 0, t = 0) = q(x)$$

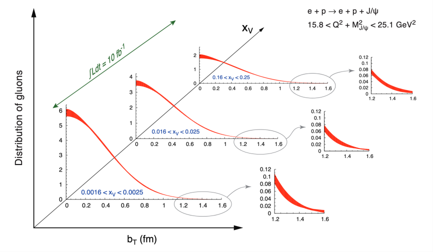
$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

- Also related to elastic form factors $F_1(t), F_2(t)$ (integration over x).
- In the simplest approach, there are 6 GPDs.
- GPDs are also connected to the orbital angular momentum of partons.

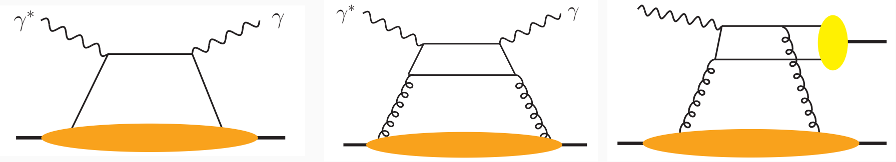
	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$

Measuring GPD's

- Invariant momentum transfer $\Delta^2 <<$ at the proton vertex hard scale Q^2
- Suitable processes:
  - Deep virtual Compton scattering $(e + p \to e' + \gamma + p)$
  - Exclusive processes (e.g. vector meson production $\gamma + p \to VM + p$)
- Competing processes – e.g. interference of DVCS with Bethe-Heitler
- Experiments: COMPASS, PANDA, JLab, EIC,



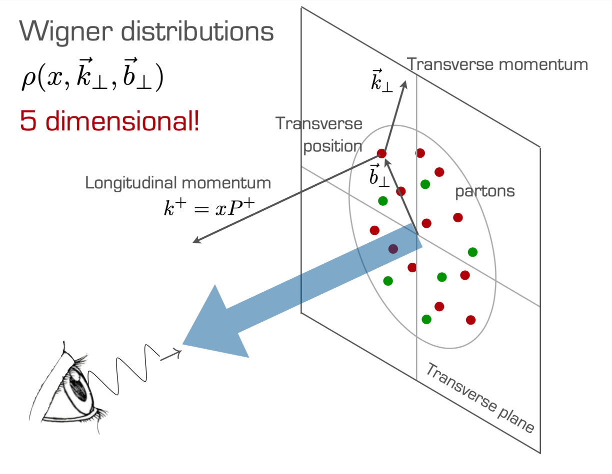
A. Accardi et al., Eur. Phys. J. A52, no. 9, 268 (2016)



M. Diehl, arXiv:1512.01382

Wigner distributions - "mother distribution function"

- Unifies both aspects – momentum and position – of the transverse structure of the proton → phase space distribution of partons
- One can derive GPDs and TMDs from it.



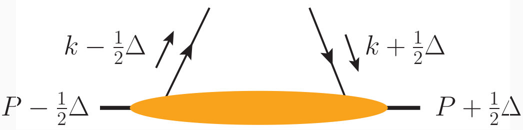
Parton correlation function

- 2-parton correlation function for quarks

$$H(k, P, \Delta) = \frac{1}{(2\pi)^4} \int \mathrm{d}^4 z e^{izk} \left\langle p\left(P + \frac{\Delta}{2}\right) \left| \bar{q}\left(-\frac{z}{2}\right) \Gamma q\left(\frac{z}{2}\right) \right| p\left(P - \frac{\Delta}{2}\right) \right\rangle$$

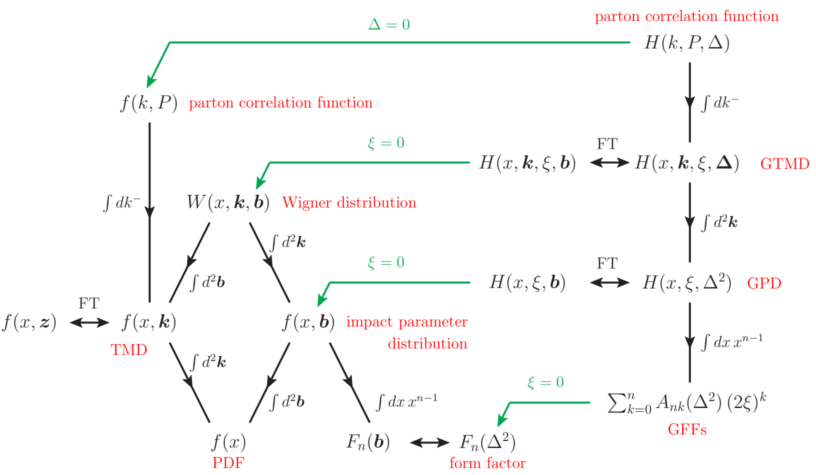
  $\rightarrow$ matrix element of the quark field operator between the proton states

- In physical observables, $H(k, P, \Delta)$ is usually integrated over one or more components of k, or they are Fourier transformed to other variables



M. Diehl, arXiv:1512.01382

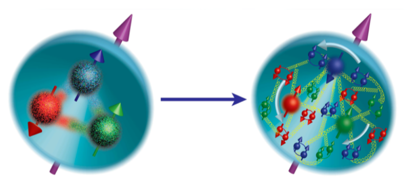
How to not get lost in all the distributions...



M. Diehl, arXiv:1512.01382

Conclusions

- Various observables and effects can be quantified using a specific parton distribution(s).
- The distributions can provide information on partonic structure of the proton from different views – tomography of the proton structure
  - Momentum - How do the partons move inside? How is the total momentum distributed among them?
  - Positions - Where are the partons located?
  - Orbital movements - Do they carry orbital angular momentum?
- Origin of the measured properties of nucleons from their partonic content?
- Wide experimental efforts and plans to untangle these puzzles
  - Past and current: CERN (EMC, COMPASS), JLab, BNL, DESY (H1, ZEUS, HERMES)
  - Future: EIC, FAIR (PANDA)



A. Accardi et al., Eur. Phys. J. A52, no. 9, 268 (2016)