# From quarks and gluons to hadrons (through exclusive hard reactions)

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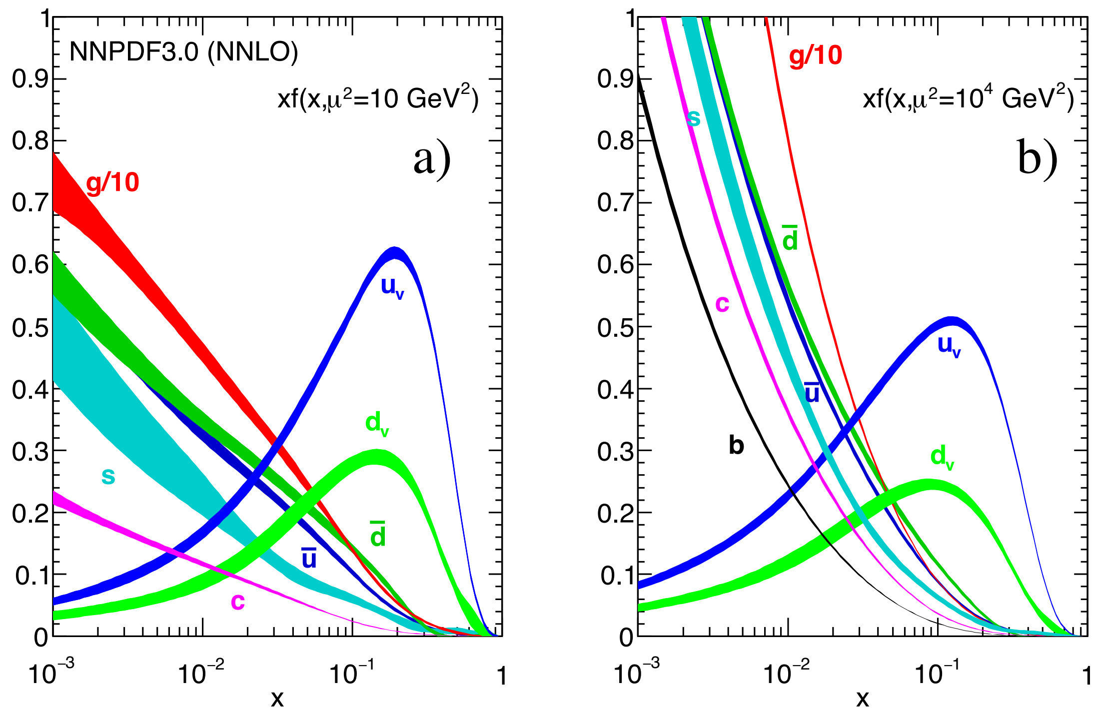
# Plan

- ➩ **Quark and gluon content of nucleons**
  - * measured but not understood
- ➩ **QCD factorization for exclusive reactions**
  - * Success in DVCS at JLab, HERMES, HERA $\rightarrow$ JLab 12
- ➩ **GPD properties** $\rightarrow$ Nucleon femtography
  - $\rightarrow$ from GPDs to GDAs and TDA
- ➩ **EIC program**

# Parton distributions

➪ **Extract quark and gluon content of nucleon**



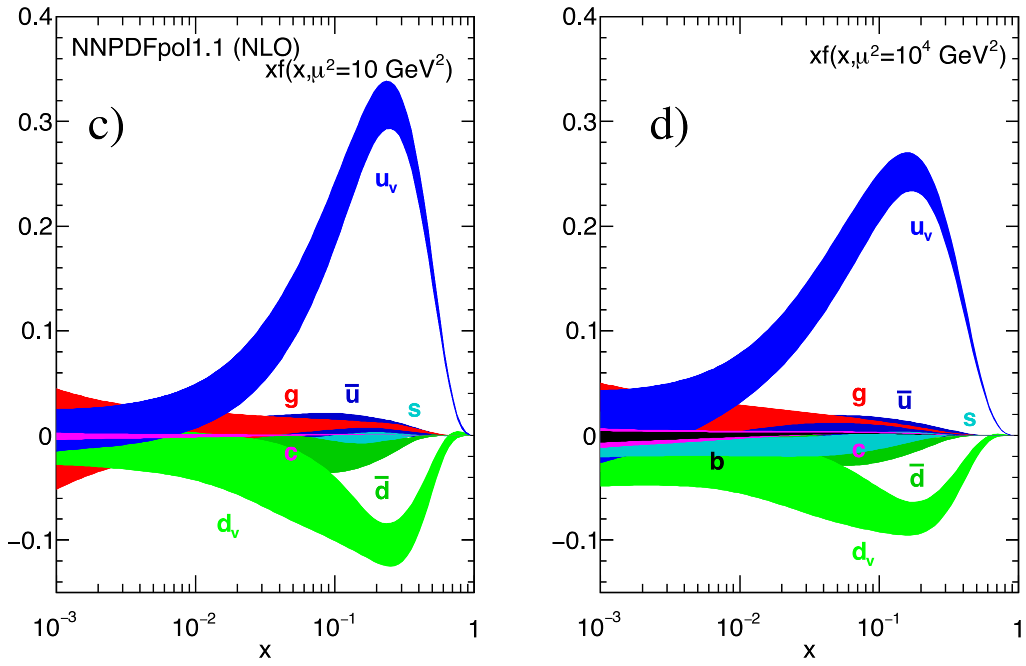

**PDF = Fourier Transform of matrix elements**

$$\langle N(p,\lambda)|\bar{\psi}(-z/2)_\alpha[-z/2;z/2]\psi(z/2)_\beta|N(p,\lambda)\rangle\Big|_{z^+=0,\,z_T=0}$$

**ON THE LIGHT CONE $z^2 = 0$**

# Polarized Parton distributions

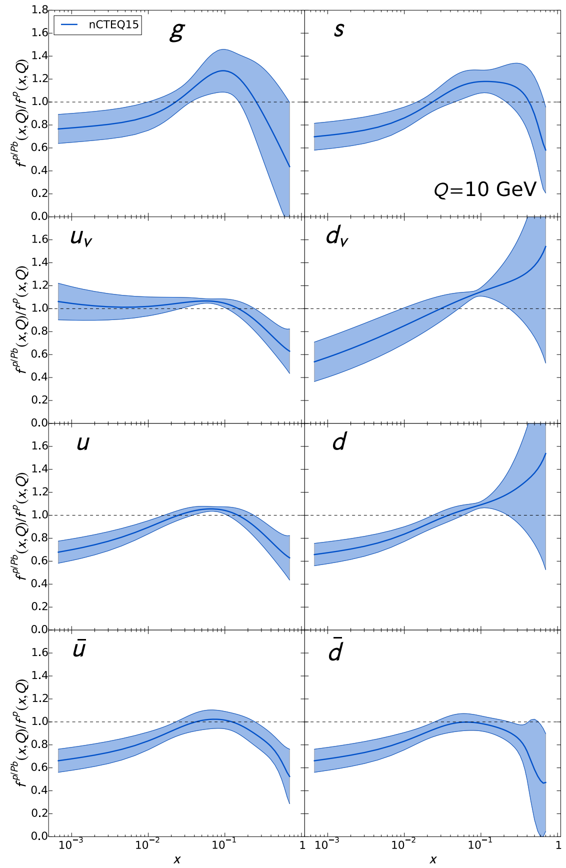
➩ **Extract how much quark and gluon remember the spin of the nucleon**




➩ **understand $\mu^2$ dependence** **but not initial value**

# Parton distributions in nuclei

➯ Partons in a bound nucleon are different than in a free one




ratio of PDF for nucleon in lead / free nucleon

➯ not really understood !

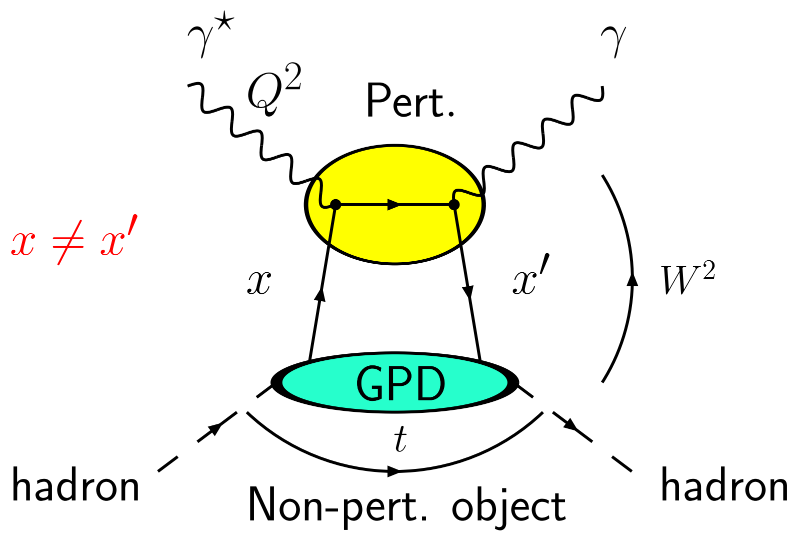
## $\boxed{\text{New tools}}$

**GPDs, TMDs, GDAs ....**

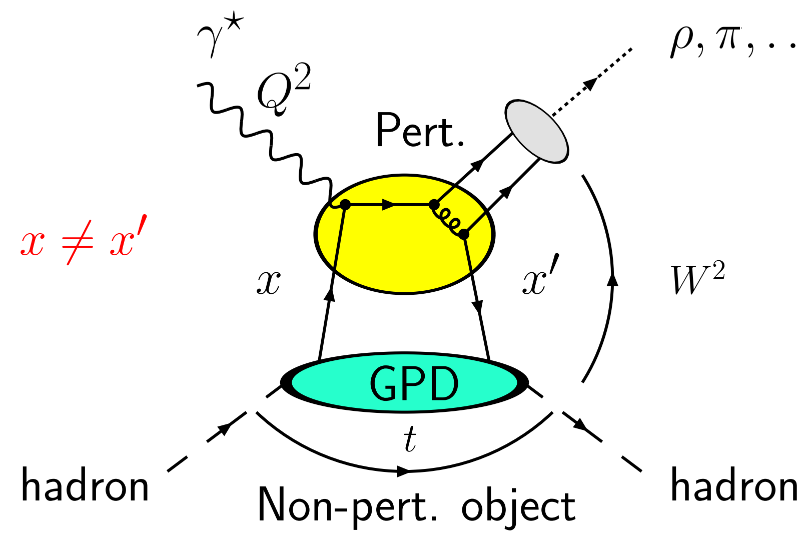
➩ **from now on ... very biased examples !**

# QCD factorization in Exclusive processes

## DVCS




## Meson Production



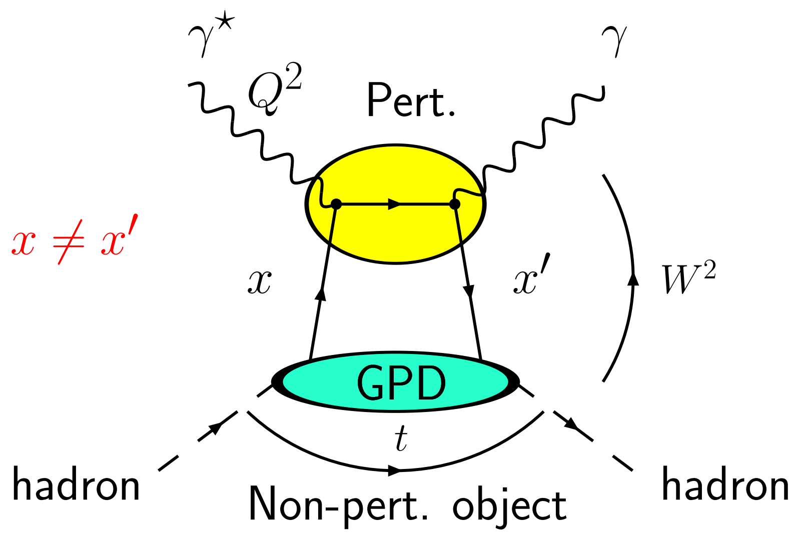

➯ Factorisation between a hard part (perturbatively calculable) and a soft part (non-perturbative) *Generalized Parton Distribution* demonstrated for

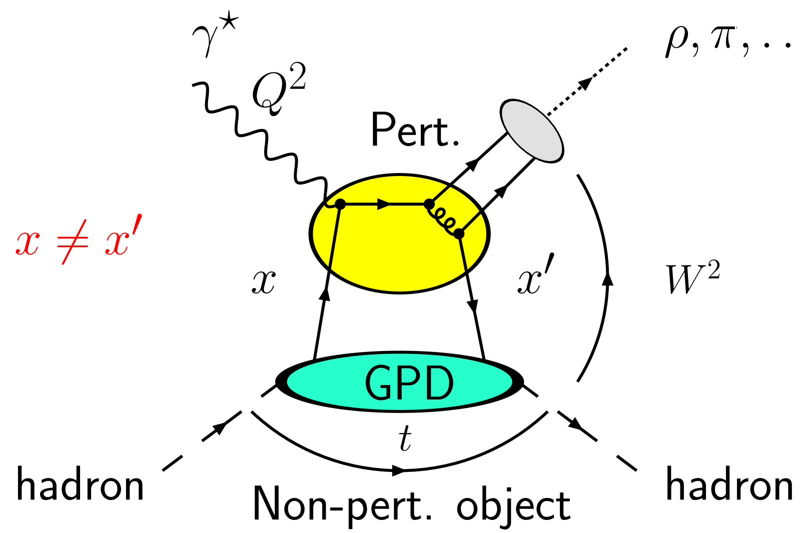
$$Q^2 \to \infty,\ x_B = \frac{Q^2}{Q^2+W^2} \text{ fixed and } t \ll \text{ fixed}$$

D. Muller *et al.* , Ji, Radyushkin, Collins *et al.* , '94, '96,'98

# Generalised Parton Distributions

**Non-Local operators (as in DIS) and non diagonal matrix elements**
**= soft part of the amplitude for exclusive reactions**




**GPD = Fourier Transform of matrix elements**

$$\langle N(p',\lambda')|\bar{\psi}(-z/2)_\alpha[-z/2;z/2]\psi(z/2)_\beta|N(p,\lambda)\rangle\Big|_{z^+=0,\, z_T=0}$$

**ON THE LIGHT CONE $z^2 = 0$**

$p' - p = \Delta$ $\qquad \Delta^2 = t$ $\qquad \Delta^+ = -\xi(p+p')^+$ $\qquad x - x' = 2\xi$

# Impact picture Representation

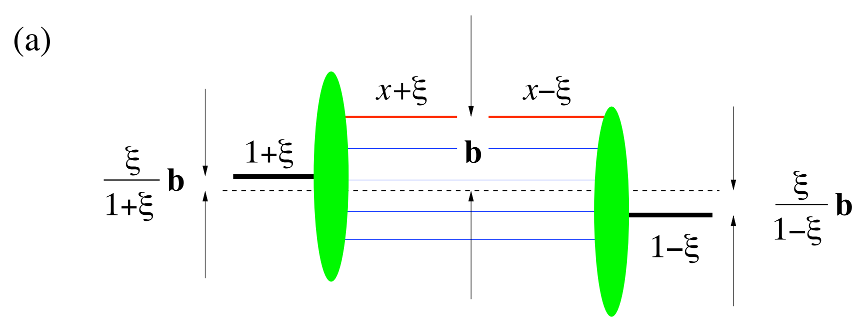
$t$ dependence of GPDs maps transverse position $b_T$ of quarks.

Fourier transform GPD at zero skewedness

$q(x, b_T) = (2\pi)^{-2} \int d^2\Delta_T e^{i\Delta_T . b_T} H(x, \xi = 0, t)$ probability

Generalize at $\xi \neq 0 \rightarrow$ Quantum femtophotography.

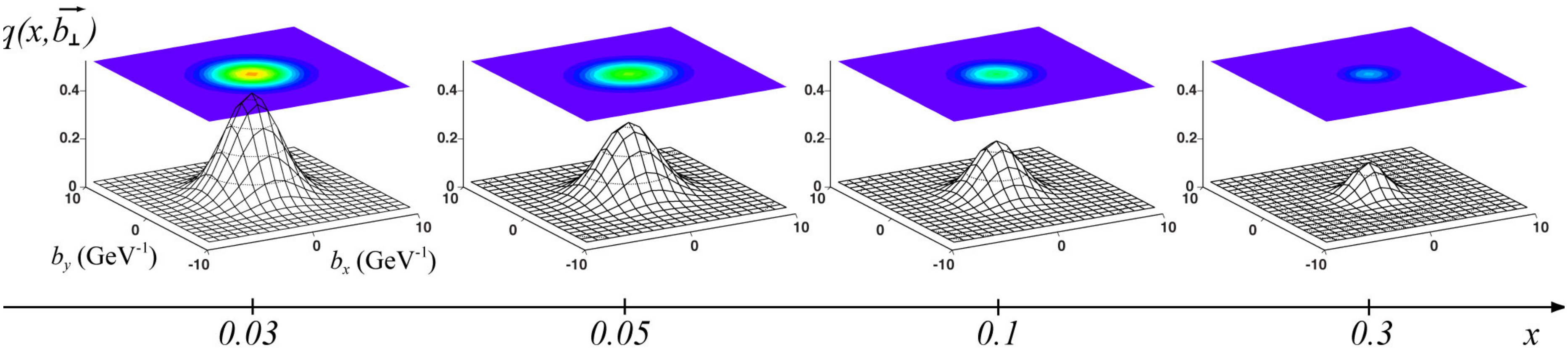
The $t-$dependence of dVCS localizes transversally the quark or the gluon in the proton




Femtophotography of quark or gluon in the proton

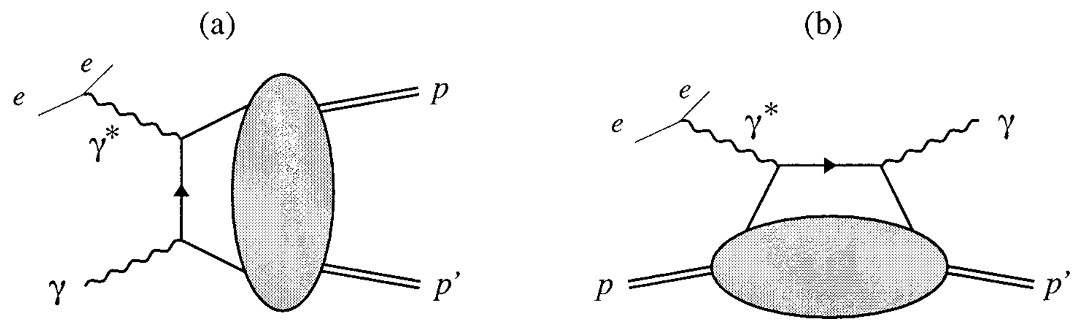
# Impact picture Representation

## Parton imaging with an EIC



# Other tools for QCD understanding of hadrons

## $\gamma^*\gamma$ vs DVCS




s - t crossing

**Generalized Distribution Amplitude $\leftrightarrow$ Generalized Parton distribution**

Muller et al, Fortsch.Phys. 42,101 ; Diehl et al, Phys Rev Lett 81, 1782

## GDA = Fourier Transform of matrix elements

$$\langle A(p_1)B(p_2)|\bar{\psi}(-z/2)_\alpha[-z/2;z/2]\psi(z/2)_\beta|0\rangle\Big|_{z^+=0,\,z_T=0}$$

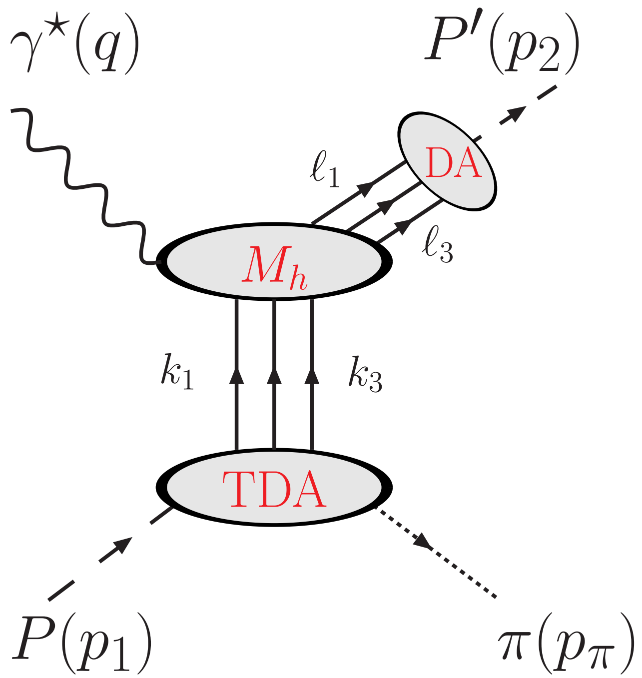
**ON THE LIGHT CONE $z^2=0$**

# 3 quark operators : DA $\rightarrow$ TDA

**In backward meson electroproduction, one may factorize a non-perturbative part describing baryon to meson transition.**

L.L.Frankfurt et al, PRD60(1999)

BP, L. Szymanowski, PRD 71 ; PLB 622 (2005)




**Kinematics (light-cone vectors p, n)**

$$p_1 = (1+\xi)p + \frac{M^2}{1+\xi}n$$

$$p_\pi = (1-\xi)p + \frac{m^2-\Delta_T^2}{1-\xi}n + \Delta_T$$

$$u = (p_1 - p_\pi)^2 \ll Q^2 \sim O(W^2)$$

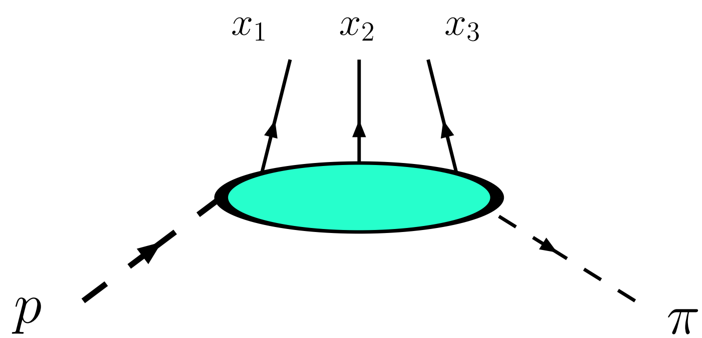
**skewness parameter :** $\xi = \frac{Q^2}{2W^2-Q^2}$

# Factorization

**The perturbative part describes the $\gamma^* qqq \to qqq$ transition.**

**The non-perturbative part describes the proton-meson transition.**

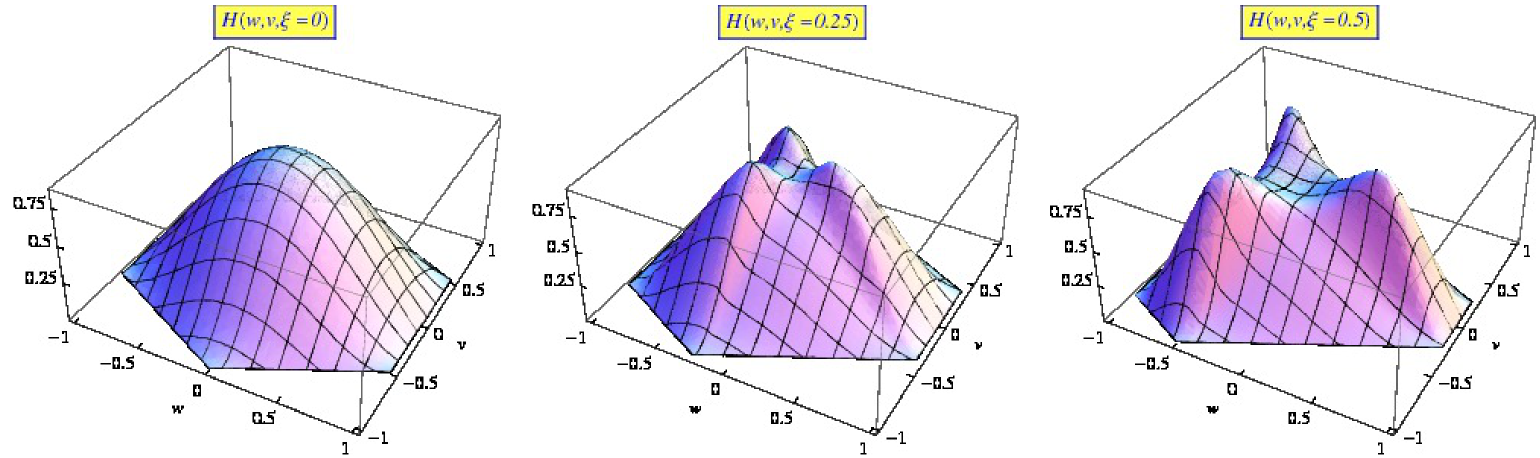
$$\langle \pi(p_\pi)|\, \epsilon^{ijk} u^i_\alpha(z_1\, n) u^j_\beta(z_2\, n) d^k_\gamma(z_3\, n)\, |p(p,s)\rangle \Big|_{n^2=0}$$




**Recall nucleon DA describing valence content of nucleon**

$$\langle 0|\, \epsilon^{ijk} u^i_\alpha(z_1\, n) u^j_\beta(z_2\, n) d^k_\gamma(z_3\, n)\, |p(p,s)\rangle \Big|_{n^2=0}$$

# TDA modeling




example from BP, L.Szymanowski, Kirill Semenov-Tian-Shansky, PRD82 (2010)

➩ generalize nucleon exchange to a well-defined QCD description

➩ 8 leading twist TDAs for $N \to \pi$

➩ difficult to access experimentally

➩ lattice calculations ?

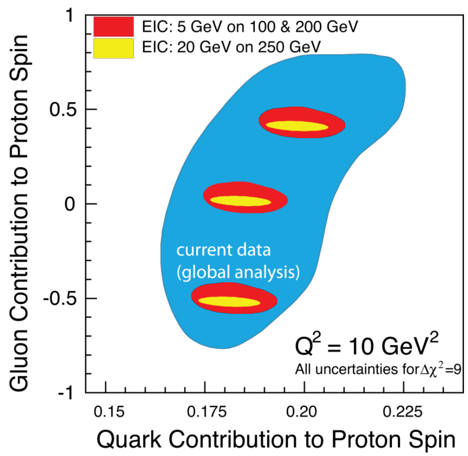
## less biased

➩ Gluon saturation at small x and dense QCD approaches

➩ Transverse momentum dependent (TMDs) structure and fragmentation functions

* new phenomenology of semi inclusive processes

➩ Obvious progresses in lattice QCD calculations



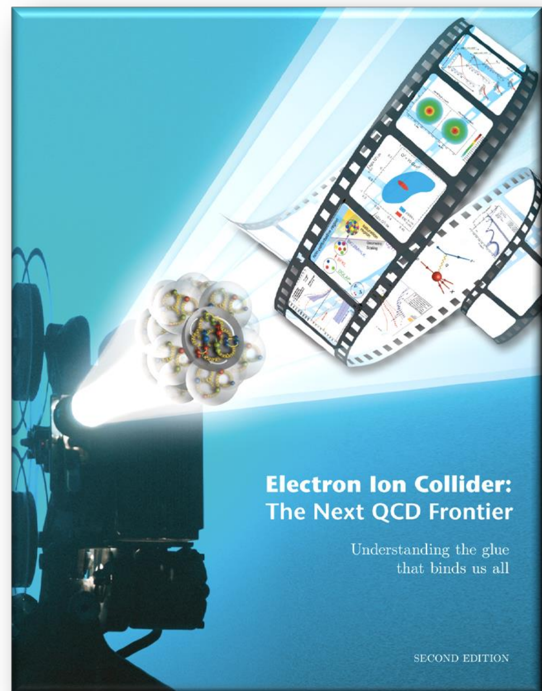

➩ EIC program

EIC

## Electron Ion Collider Design Parameters

**Electron Nucleus(p, d, … ) Collider**

Collider Energy 20 – ~100 GeV
High Luminosity → $10^{33}$ - $10^{34}$ $cm^2 s^{-1}$
Low x regime x → 0.0001
High polarizations 70%
Ion beams up to U or PB




CONCLUSION : We need new permanent positions

Thank you !