# Recent Developments in Nuclear Science (for EIC)

(I will use a broad definition of “recent”.
Perhaps also of “nuclear”.)

1. Nucleons in the language of partons
2. The game of translation: jets, diffraction and nuclei

December 15, 2020
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**Selection of topics and figures relies extensively on the judgement of summary talks at the IVth EIC Yellow Report Workshop by (on):**

**Barbara Pasquini (global properties)**

**Anselm Vossen (imaging nucleons, nuclei & mesons)**

**Spenser Klein (nuclei)**

**Ivan Vitev (hadronization)**

**Also thanks to Abhay Deshpande and Volker Burhart for their attempts at guidance.**

**Time will only allow brief sketches of a selection of broad topics, undoubtedly missing some important ones.**

# 1. Nucleons in the Language of Partons

**What is a proton? A quantum mechanical state: | 4-mtm,spin,isospin >**

- **In its own terms, a nucleon is simply a stationary state of H_{QCD}, effectively "forever" (lifetime at least 10^19 or so times the current age of the universe.)**
    - **But at the same time (literally), in terms of H_{QCD} a nucleon is a beehive of activity as seen by H_{Strong-EW}. This is the proton in the language of partons.**
- **This information is accessible through electroweak interactions, and is a central aim of the EIC. The method of electron-hadron collisions is "how we know". Scattering is reinterpreted as a series of measurements.**

**The nucleon is the ground state of the hamiltonian of the strong interactions, with baryon number = 1 and definite spin, isospin etc. Up to 1970, $\mathbf{H}_{\textbf{strong}}$ was unknown. This milestone of 20th century physics was originally found from using:**

- $\mathbf{H}_{\textbf{Nucleon}} = \mathbf{H}_{\textbf{Pure Strong}} + \mathbf{H}_{\textbf{Strong-EW}}$

**and assuming the locality of the hadronic EM current:**

- $\mathbf{H}_{\textbf{Strong-EW}} = \mathbf{J}^{\textbf{had}}{}_{\textbf{EM}} \cdot \mathbf{A}_{\textbf{EM}}$

**with $\mathbf{A}_{\textbf{EM}}$ the photon field (eventually photons and W, Z.)**
**By probing nucleons through DIS :**

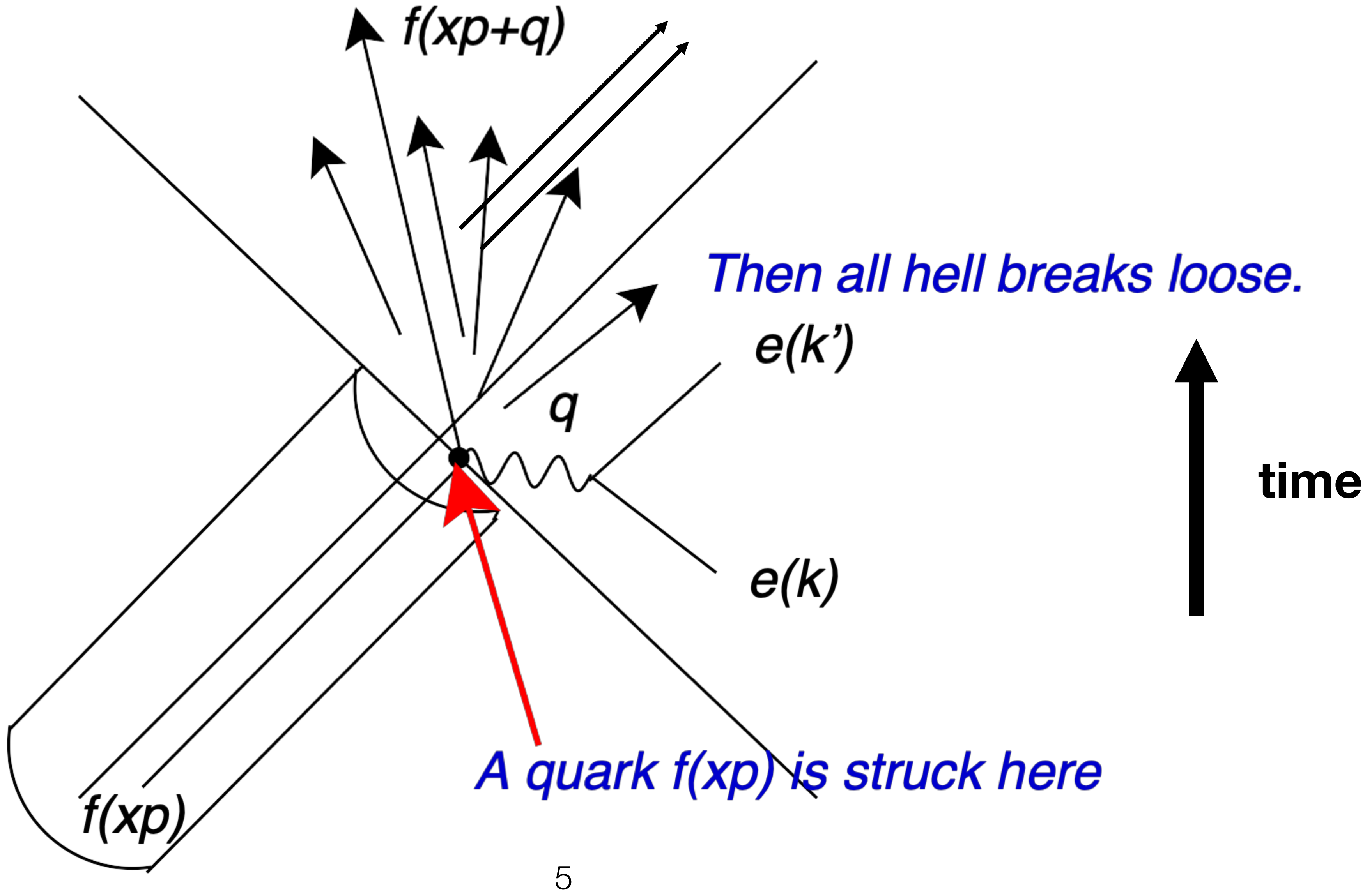
- $(\mathbf{J}^{\textbf{had}}{}_{\textbf{EM}})^{\mu} = \Sigma_{q=u,d,s\ldots}\ e_q\, \underline{\mathbf{q}}\, \gamma^{\mu}\, \mathbf{q}$

**(with charges $e_q$ that miraculously matched those of quark model.)**

# How was this done?
**(Recalling the method leads us to contemporary developments)**
**Through the magic of Inclusive Deep Inelastic Scattering**

**Picturing a typical “deep inelastic” ep event, in the usual variables**

**Sum over ALL states**
**at fixed $Q^2$ and $x$=Q^2/2p.q**



*Then all hell breaks loose.*

**time**

*A quark f(xp) is struck here*

**Proton momentum p**

**Because of the sum over states**

**Unitarity in quantum mechanics gives**

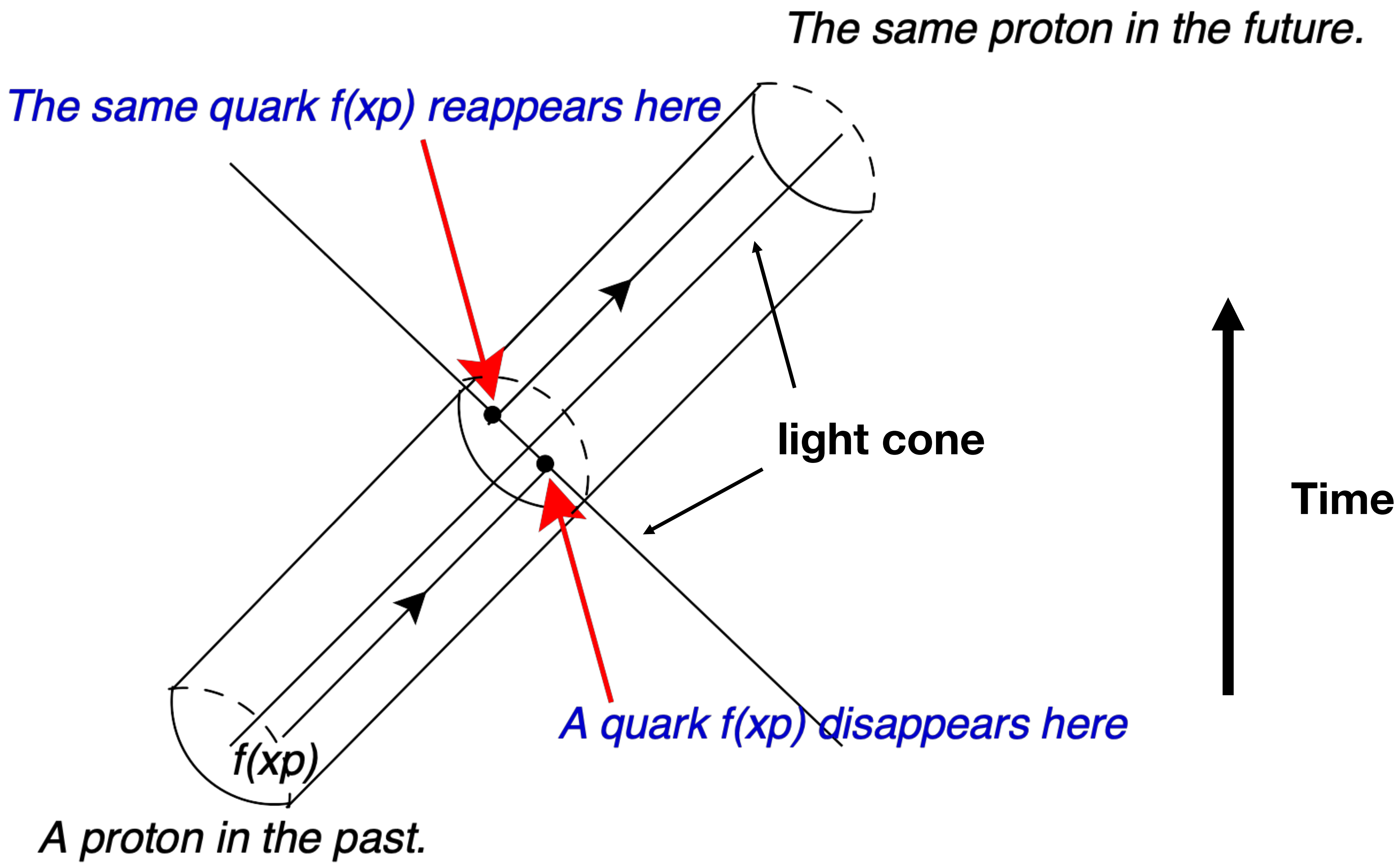
**factorized DIS in terms of pdfs**

$$\frac{d\sigma^{(lh)}}{dx\,dy} = N^{lV}\left[\frac{y^2}{2}2xF_1^{(Vh)} + \left(1-y-\frac{m_h x y}{2E}\right)F_2^{(Vh)} + \delta_V\left(y-\frac{y^2}{2}\right)xF_3^{(Vh)}\right],$$

$$F_i(x,Q^2) \quad = \quad \sum_a \int_x^1 d\xi\, C_{i,a}\left(\frac{\xi}{x},\frac{Q^2}{\mu^2}\right) \boxed{f_a(\xi,\mu)}$$

## Parton distribution as a matrix element for two measurements:

$$f_q(\xi) \quad = \quad \int d\lambda e^{-i\lambda\xi p^+} \; \left\langle p \left| \bar{q}_\beta(\lambda n^\mu)\gamma^+_{\beta\alpha} q_\alpha(0) \right| p \right\rangle$$



*The same proton in the future.*

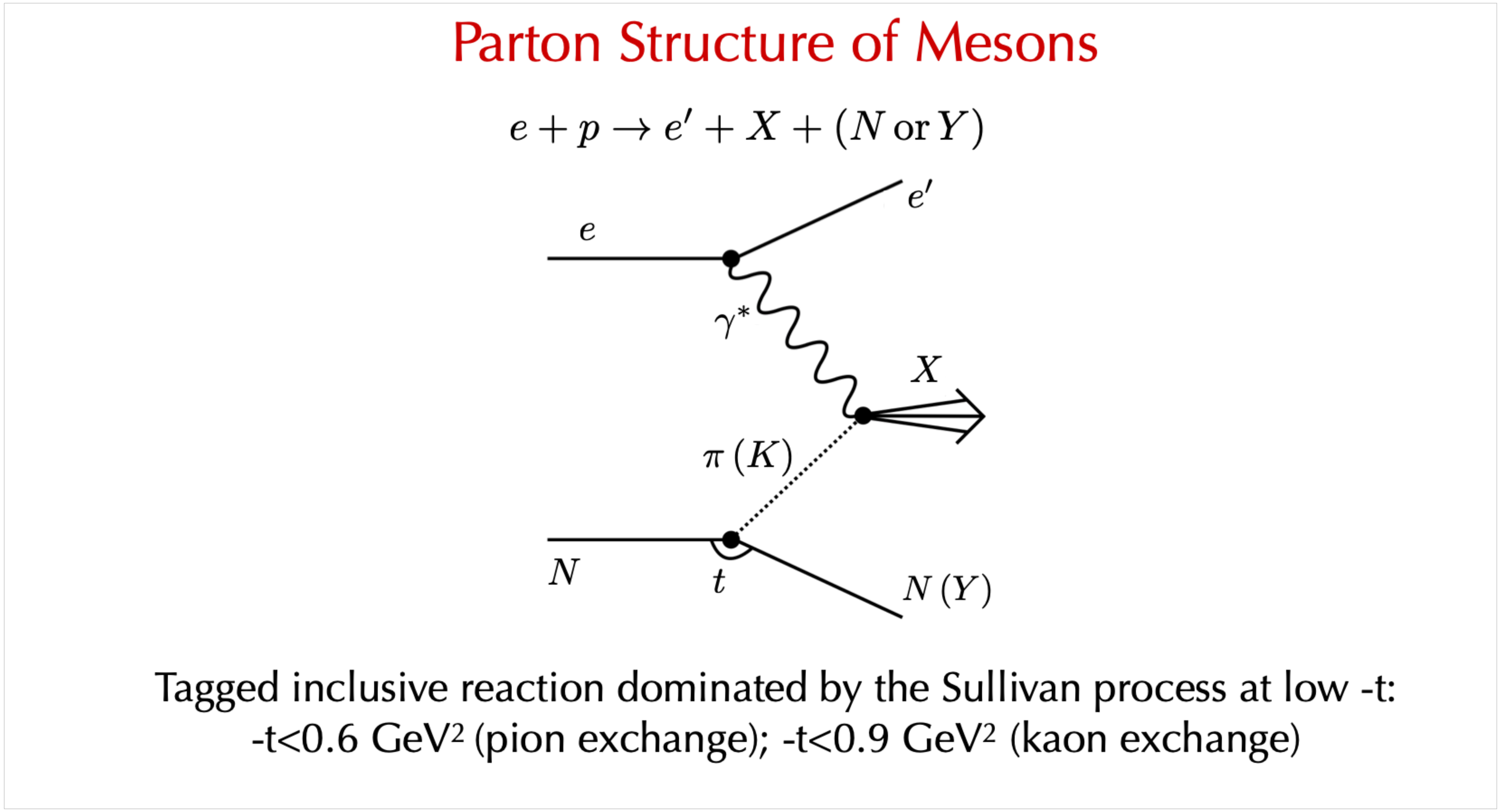
*The same quark f(xp) reappears here*

*A quark f(xp) disappears here*

*A proton in the past.*

**And also . . .**

**Because the proton is surrounded by virtual mesons, it can be used as a source of mesons.**



## Parton Structure of Mesons

$$e + p \to e' + X + (N \,\mathrm{or}\, Y)$$

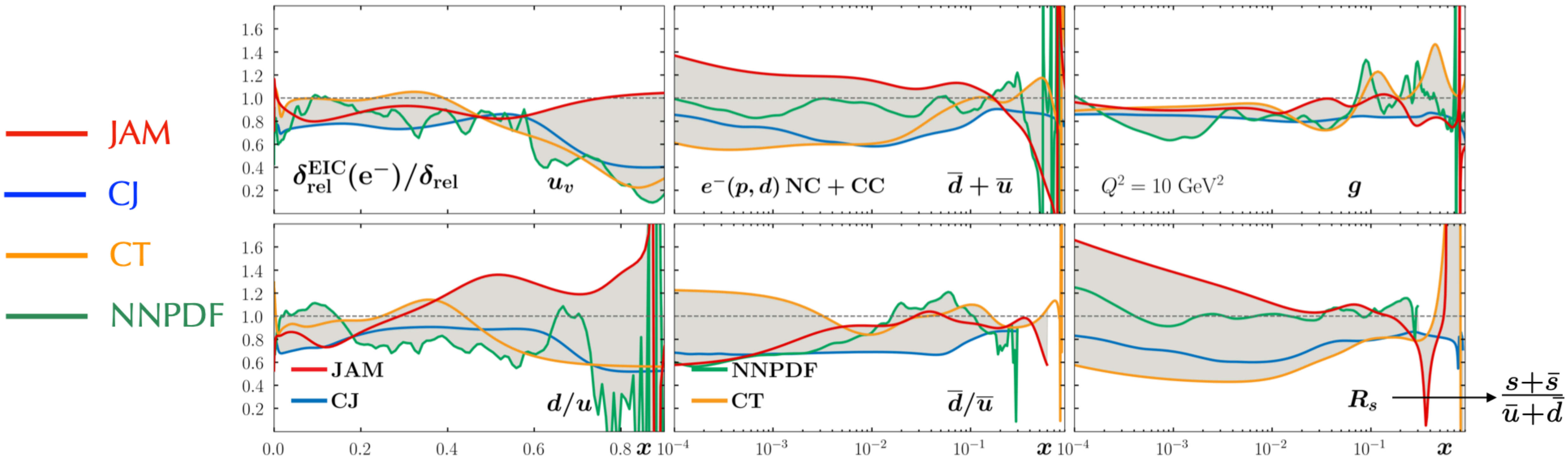
Tagged inclusive reaction dominated by the Sullivan process at low -t:
$-t<0.6$ GeV$^2$ (pion exchange); $-t<0.9$ GeV$^2$ (kaon exchange)

**(fig. BP)**

# The kind of improvements we might expect . . .

Flavor separation of x f(x)

relative uncertainties after EIC / relative uncertainties pre EIC (only e- p data sets)



e- p: $\sqrt{s}$ = 28.6, 44.7, 63.3, 140.7 GeV for NC and 140.7 for CC; proton beam $\mathcal{L}$=100 fb$^{-1}$

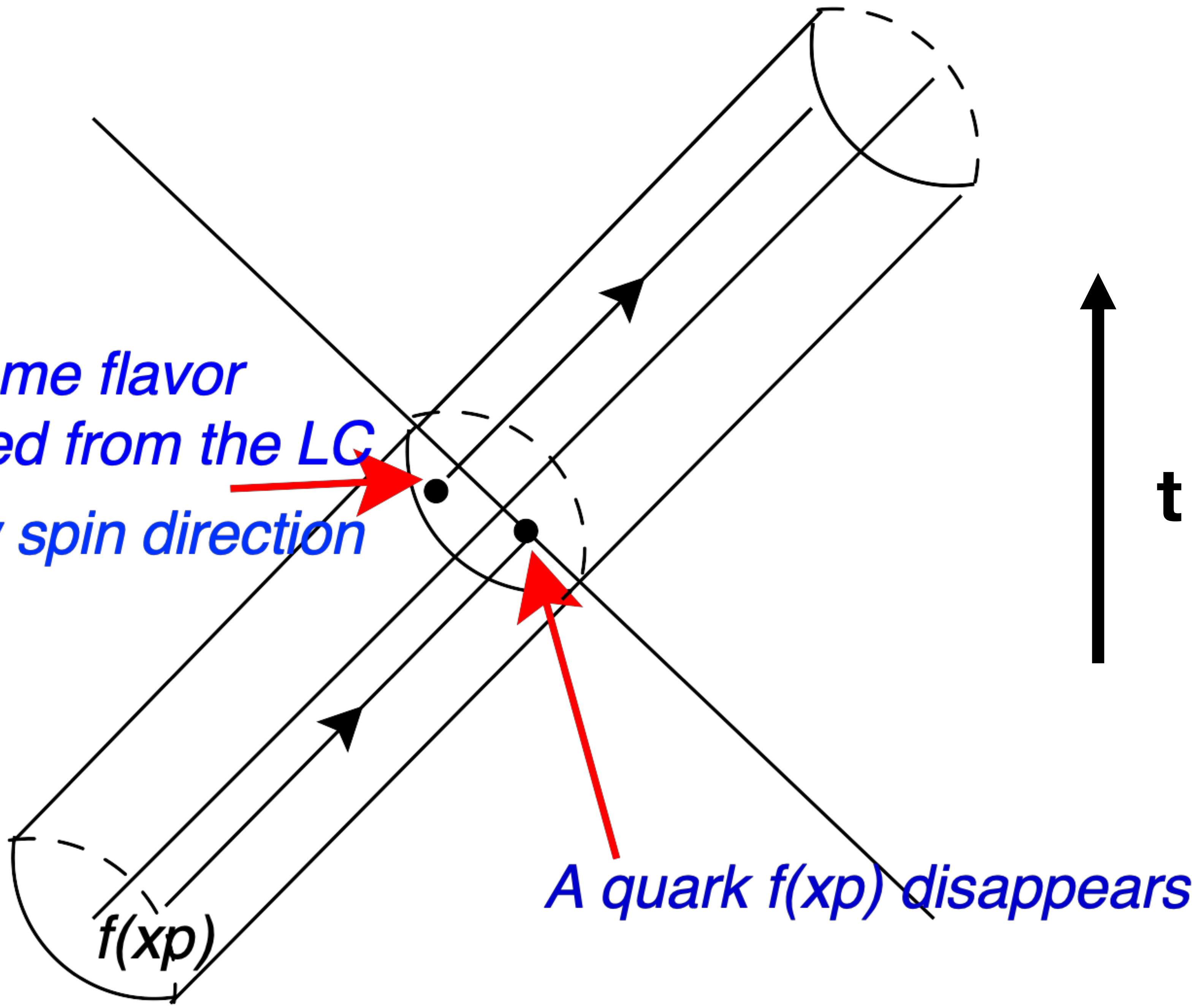
e- d: $\sqrt{s}$ = 28.6, 63.3, 89.0 GeV for NC only ; deuteron beam $\mathcal{L}$=10 fb$^{-1}$

Strong impact (80%) on the valence sector and d/u ratio at large x

Good impact (50%) on the sea sector at low x

**(slide: BP)**

**There are many more measurements for EIC to make on the nucleon state: polarized PDFs & factorizing TMDs with spin**



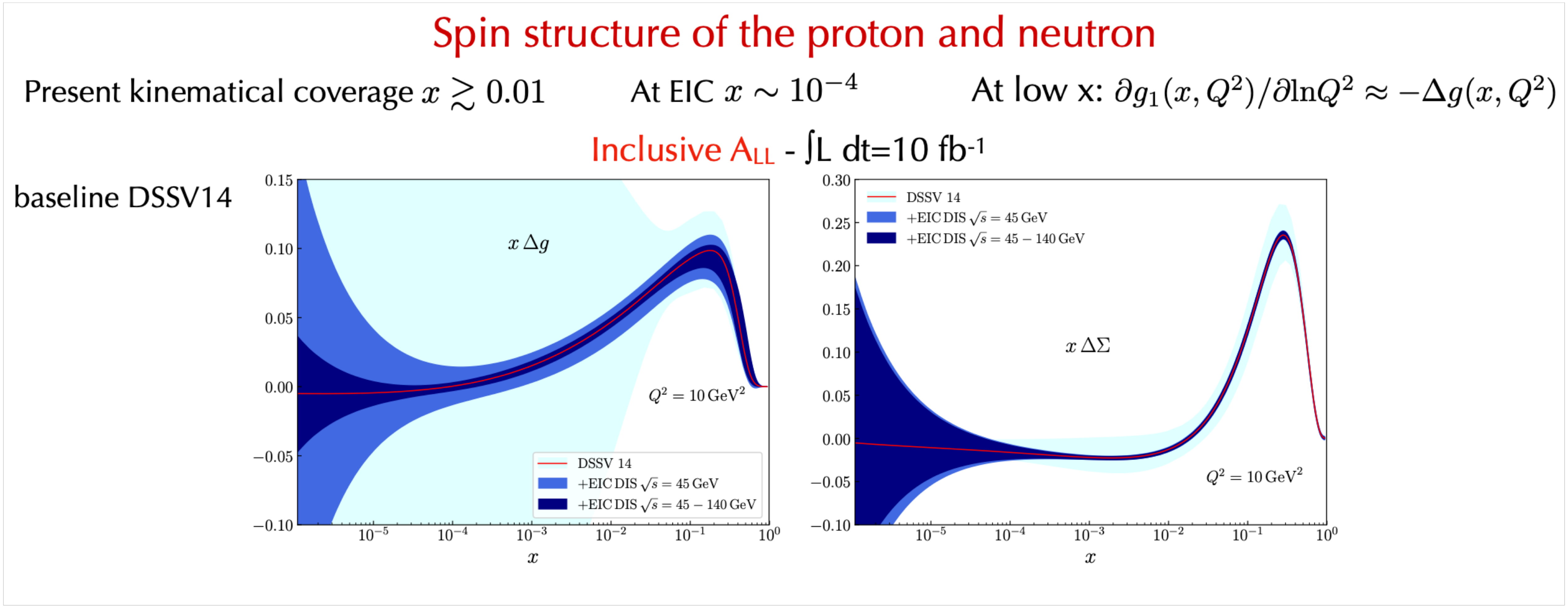
*The same proton in the future.*

*The same flavor dispaced from the LC w/ new spin direction*

*A quark f(xp) disappears here*

*A proton in the past.*

# A window to gluon contributions to nucleon spin



## Spin structure of the proton and neutron

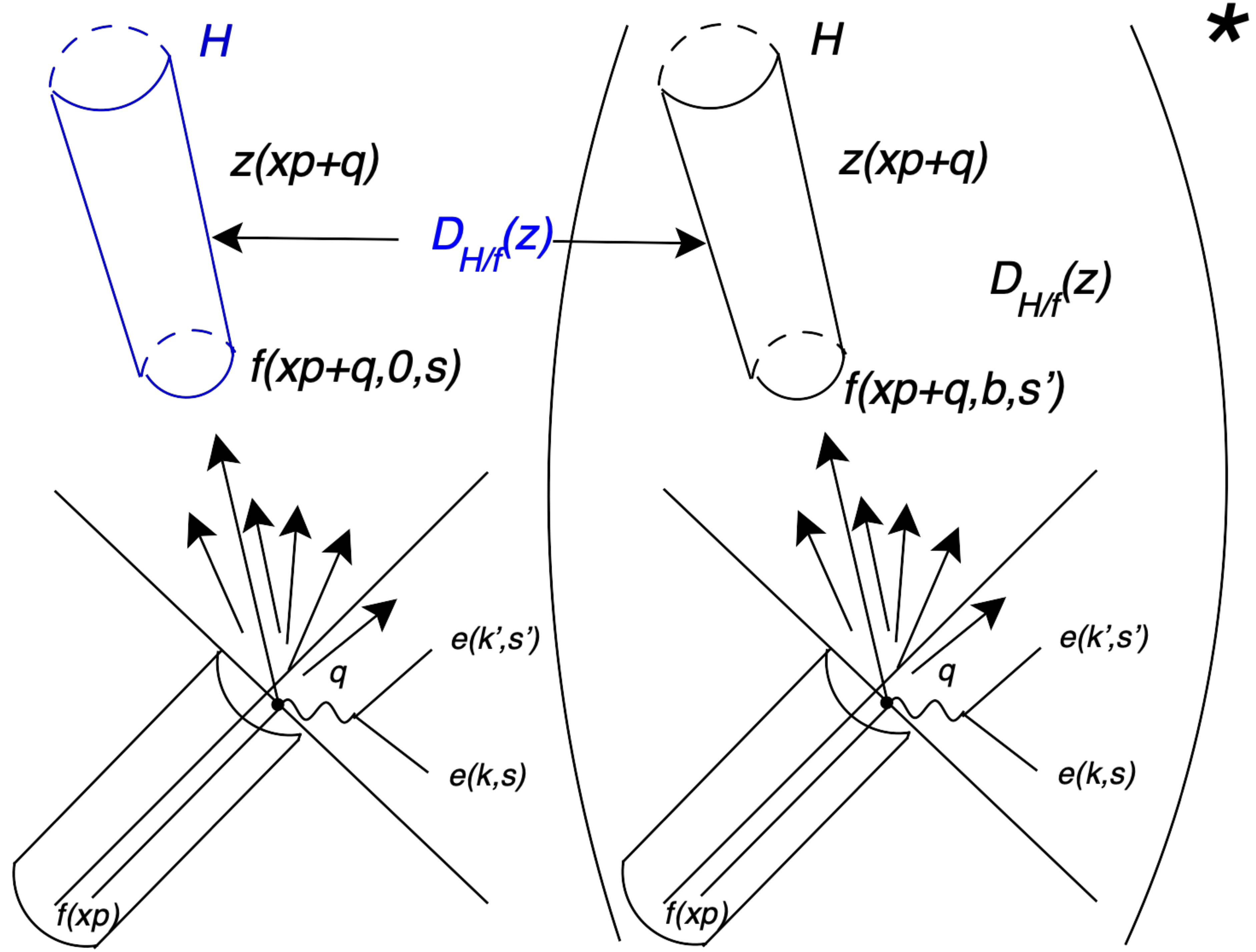
Present kinematical coverage $x \gtrsim 0.01$ At EIC $x \sim 10^{-4}$ At low x: $\partial g_1(x,Q^2)/\partial \ln Q^2 \approx -\Delta g(x,Q^2)$

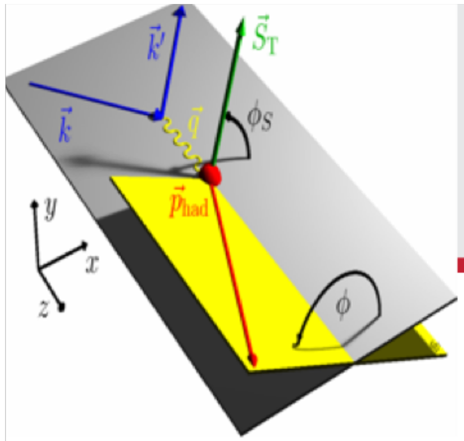
Inclusive $A_{LL}$ - $\int L\, dt = 10\ \mathrm{fb}^{-1}$

baseline DSSV14

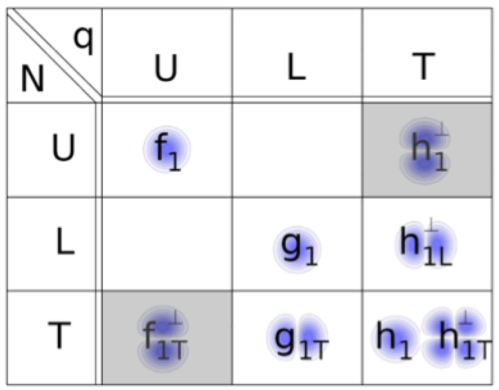
**(Slide: BP)**

## These are accessible through single inclusive DIS, with factorizing fragmentation functions D:

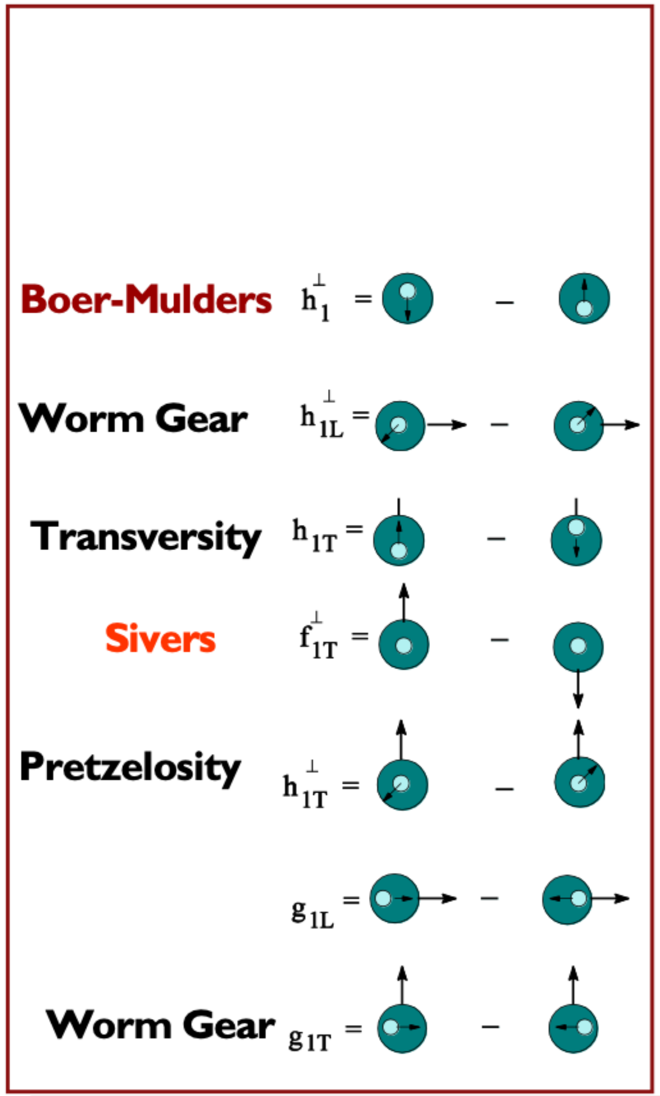




# TMD PDFs from SIDIS



| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ |  | $h_1^{\perp}$ |
| L |  | $g_1$ | $h_{1L}^{\perp}$ |
| T | $f_{1T}^{\perp}$ | $g_{1T}$ | $h_1$ $h_{1T}^{\perp}$ |



**Boer-Mulders** $h_1^{\perp} =$ −

**Worm Gear** $h_{1L}^{\perp} =$ −

**Transversity** $h_{1T} =$ −

**Sivers** $f_{1T}^{\perp} =$ −

**Pretzelosity** $h_{1T}^{\perp} =$ −

$g_{1L} =$ −

**Worm Gear** $g_{1T} =$ −

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+(1-y)\frac{P_{h\perp}^{2^2}}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

Polarized target

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

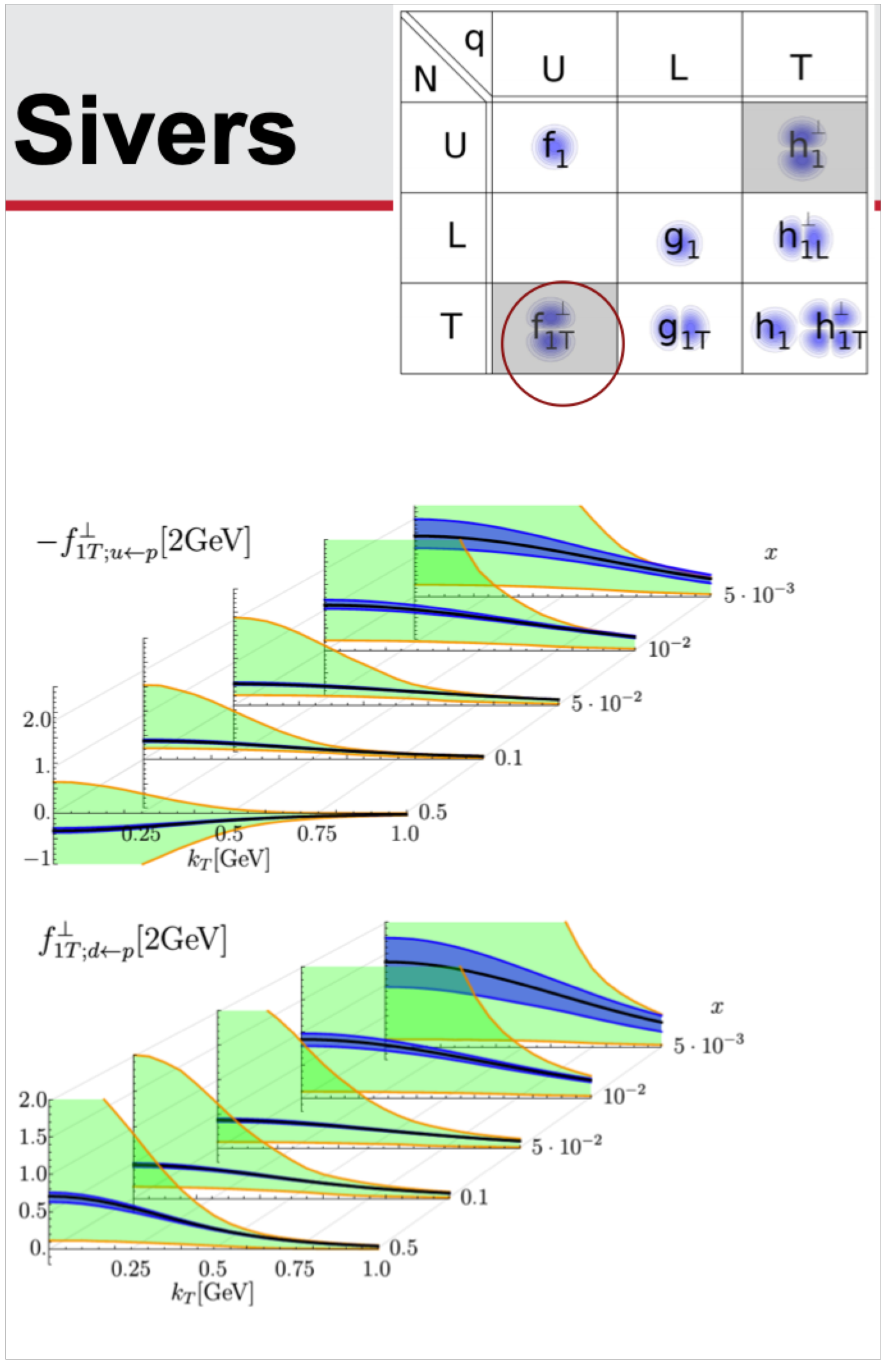
Polarzied beam and target

$S_L$ and $S_T$: Target Polarizations; $\lambda$e: Beam Polarization

x: momentum fraction carried by struck quark, z: fractional energy of hadron

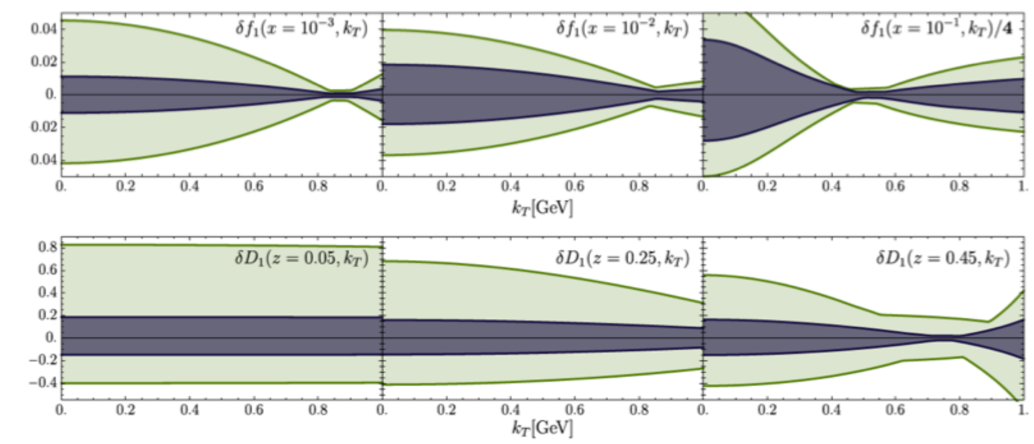
(Fig. AV)

**Projected improvements, with and without spin.**



**Sivers**

| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_1$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ $h_{1T}^\perp$ |



TMD PDF $f^u$(top) and FF $D^{\pi^+}$ (bottom)

**(Figs: AV)**

# What can be done with developing theory: the Sivers function at N$^3$LO

## Bury, Produkin, Vladimirov 2012.11125

$$\frac{d\sigma}{d\mathcal{PS}} = \sigma_0 \left\{ F_{UU,T} + |S_\perp| \sin(\phi_h-\phi_S) F_{UT,T}^{\sin(\phi_h-\phi_S)} \right\}$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} \equiv \frac{F_{UT,T}^{\sin(\phi_h-\phi_S)}}{F_{UU,T}} = -M \frac{\mathcal{B}_1^{\text{SIDIS}}\left[f_{1T}^\perp D_1\right]}{\mathcal{B}_0^{\text{SIDIS}}\left[f_1 D_1\right]}$$

where $M$ is the mass of the nucleon $h_1$, and

$$\mathcal{B}_n^{\text{SIDIS}}[fD] \equiv \sum_q e_q^2 \int_0^\infty \frac{bdb}{2\pi} b^n J_n\left(\frac{b|P_{hT}|}{z}\right) \times f_{q\leftarrow h_1}(x,b;\mu,\zeta_1) D_{q\to h_2}(z,b;\mu,\zeta_2)$$

$$f_{1T,q\leftarrow h}^\perp(x,b;\mu,\zeta) = \left(\frac{\zeta}{\zeta_\mu(b)}\right)^{-\mathcal{D}(b,\mu)} f_{1T,q\leftarrow h}^\perp(x,b)$$

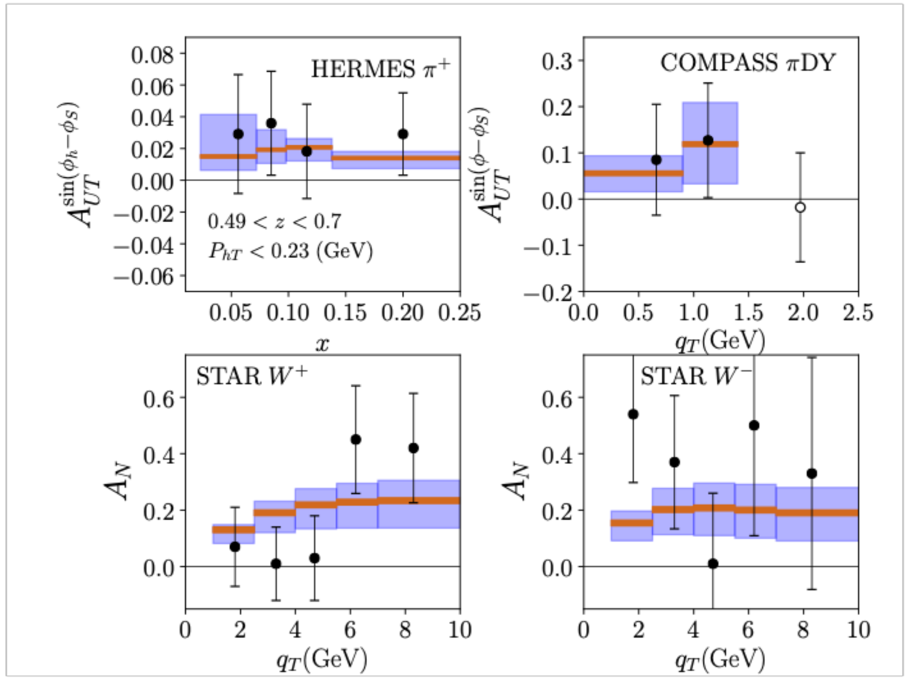
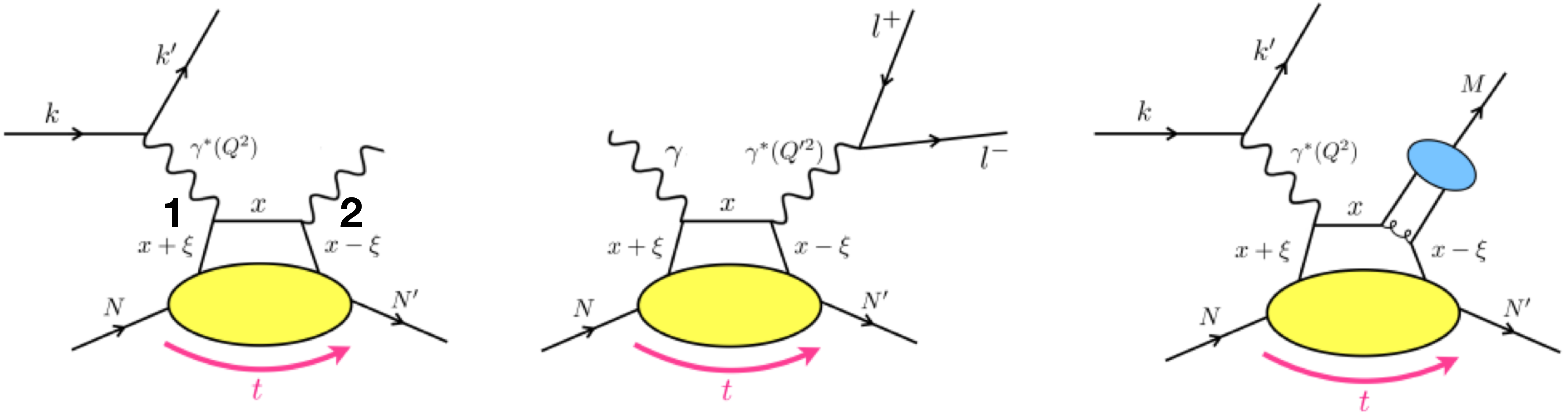


FIG. 1. Examples of data description of SIDIS+DY N$^3$LO fit for HERMES SIDIS [60], COMPASS pion-induced DY [48] and STAR $W^\pm/Z$ data [49]. Open symbols: data not used in the fit. Orange line is the CF and the blue box is 68%CI.



(a) DVCS

(b) TCS

(c) MESON

**What's going on.**

**IF the quark propagates between 1 and 2 without disturbing other partons: "factorization"**

**IN THIS CASE, we have universal generalized PDFs in convolution with perturbative quark Compton scattering**

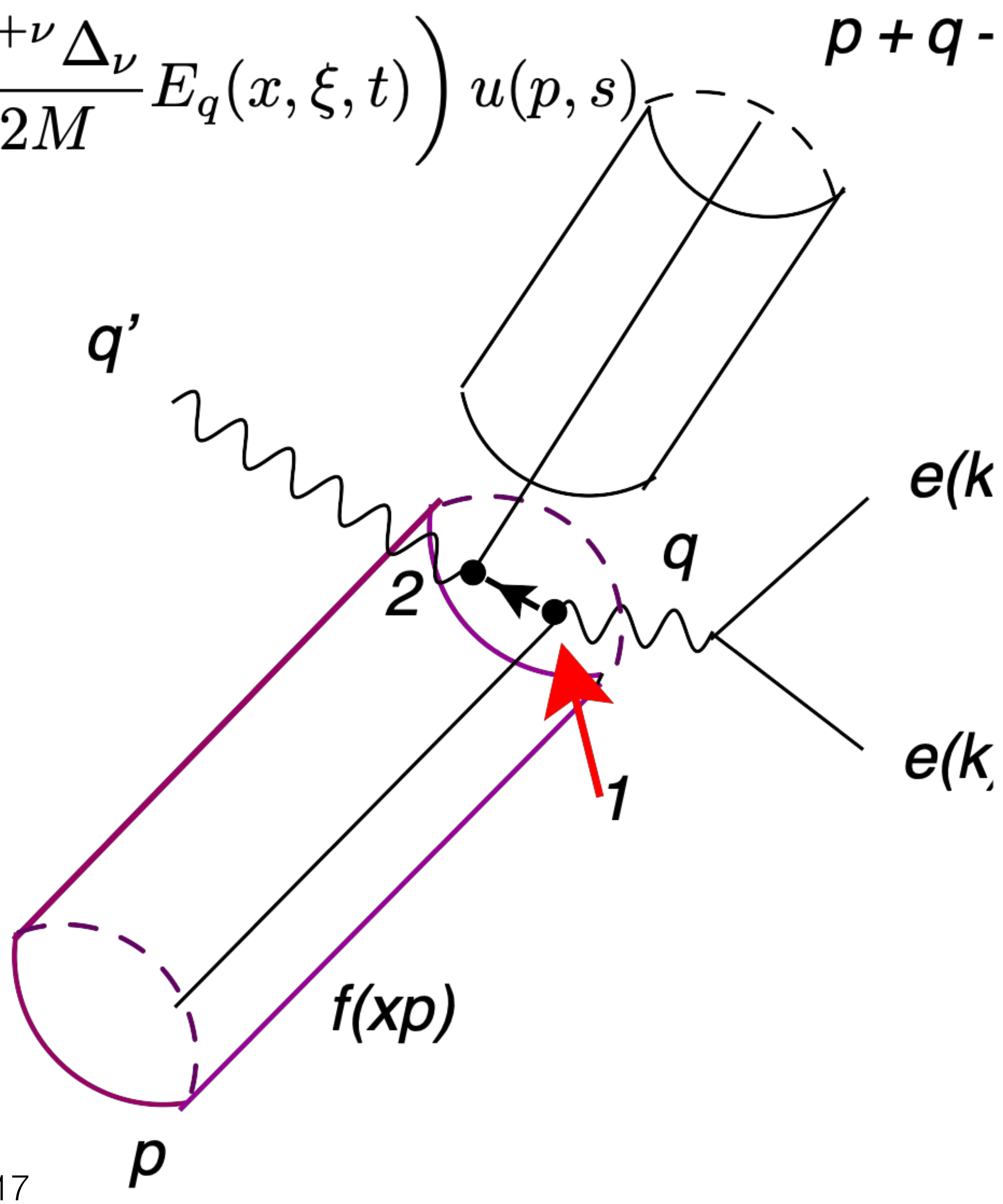
**The target can be a light nucleus, for example. (Funcini, Rinaldi, Scopetta, 2010.12212)**

**More measurements are available directly from exclusive processes, without the intermediation of unitarity.**
**Generalized parton distributions.**

$$\int \frac{dx^-}{4\pi} \langle P', S' | \bar{q}(-\frac{x^-}{2}, \mathbf{0}_\perp) \gamma^+ q(\frac{x^-}{2}, \mathbf{0}_\perp) | P, S \rangle e^{ix\bar{p}^+ x^-}$$

$$= \frac{1}{2\bar{p}^+} \bar{u}(p', s') \left( \gamma^+ H_q(x, \xi, t) + i \frac{\sigma^{+\nu} \Delta_\nu}{2M} E_q(x, \xi, t) \right) u(p, s)$$

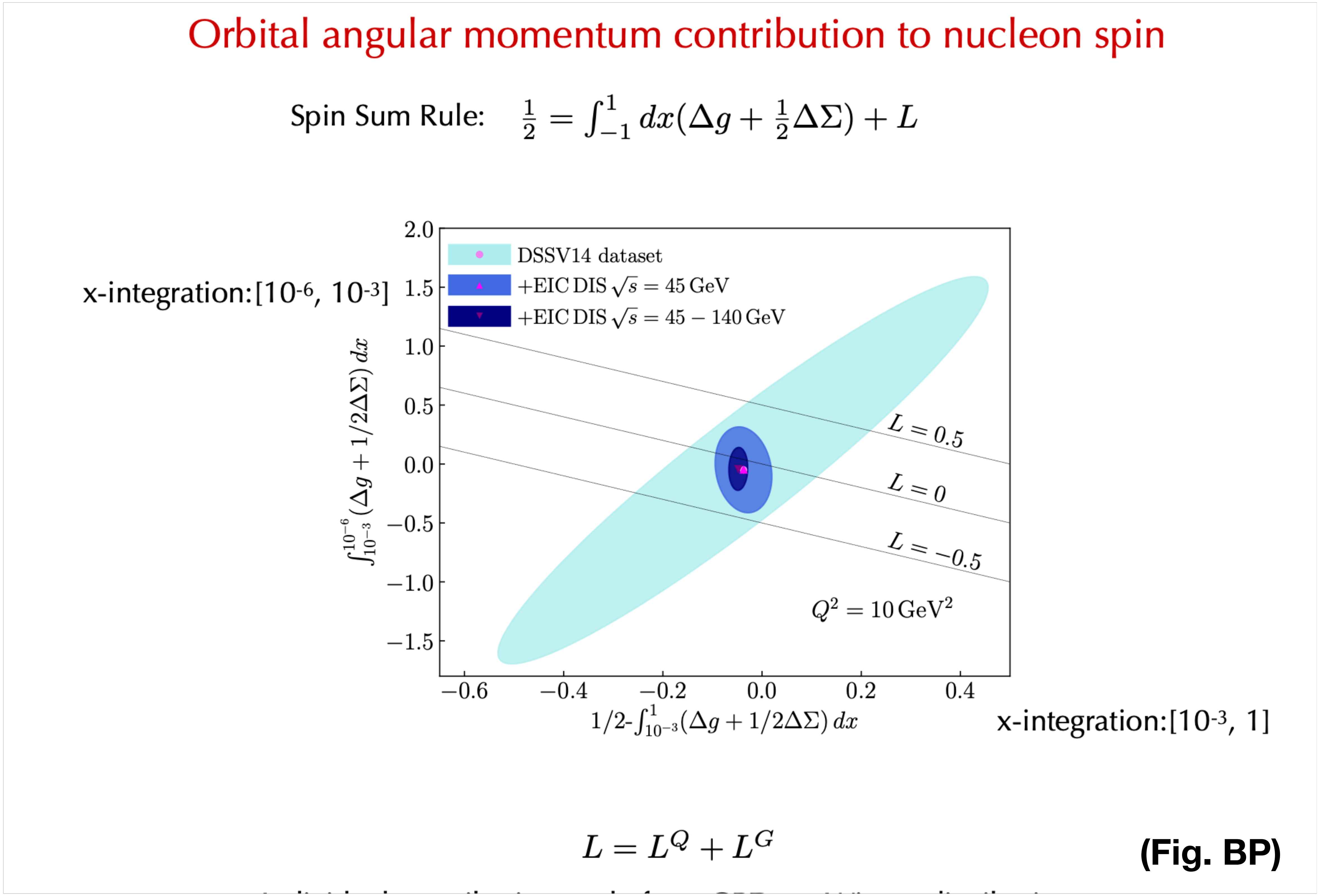
**Proton p emerges**



**At (1) a quark absorbs photon q. It travels to point 2 and emits photon q' (DVCS). If the travel is (almost) free the amplitude factorizes.**

**Proton p enters the process**

**This is famously the window into orbital angular momentum.**



## Orbital angular momentum contribution to nucleon spin

Spin Sum Rule: $\frac{1}{2} = \int_{-1}^{1} dx(\Delta g + \frac{1}{2}\Delta\Sigma) + L$

x-integration:[$10^{-6}$, $10^{-3}$]

x-integration:[$10^{-3}$, 1]

$$L = L^Q + L^G$$

**(Fig. BP)**

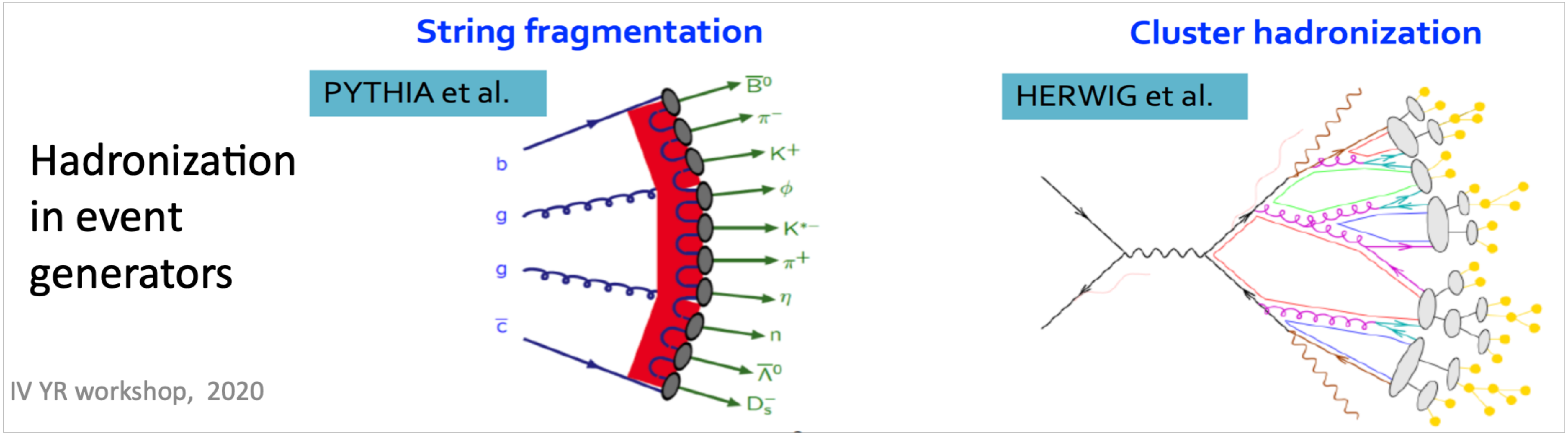
# 2. The game of translation: jets, diffraction. and propagation in nuclei

The scattered quark is a parton. How do hadrons emerge in
this and other QCD processes?

- At high energy, a jet of hadrons emerges in the direction of the quark.

- The EIC variable energy opens unprecedented opportunity to study this process.

**High statistics can make possible the clarification of hadronization/fragmentation**



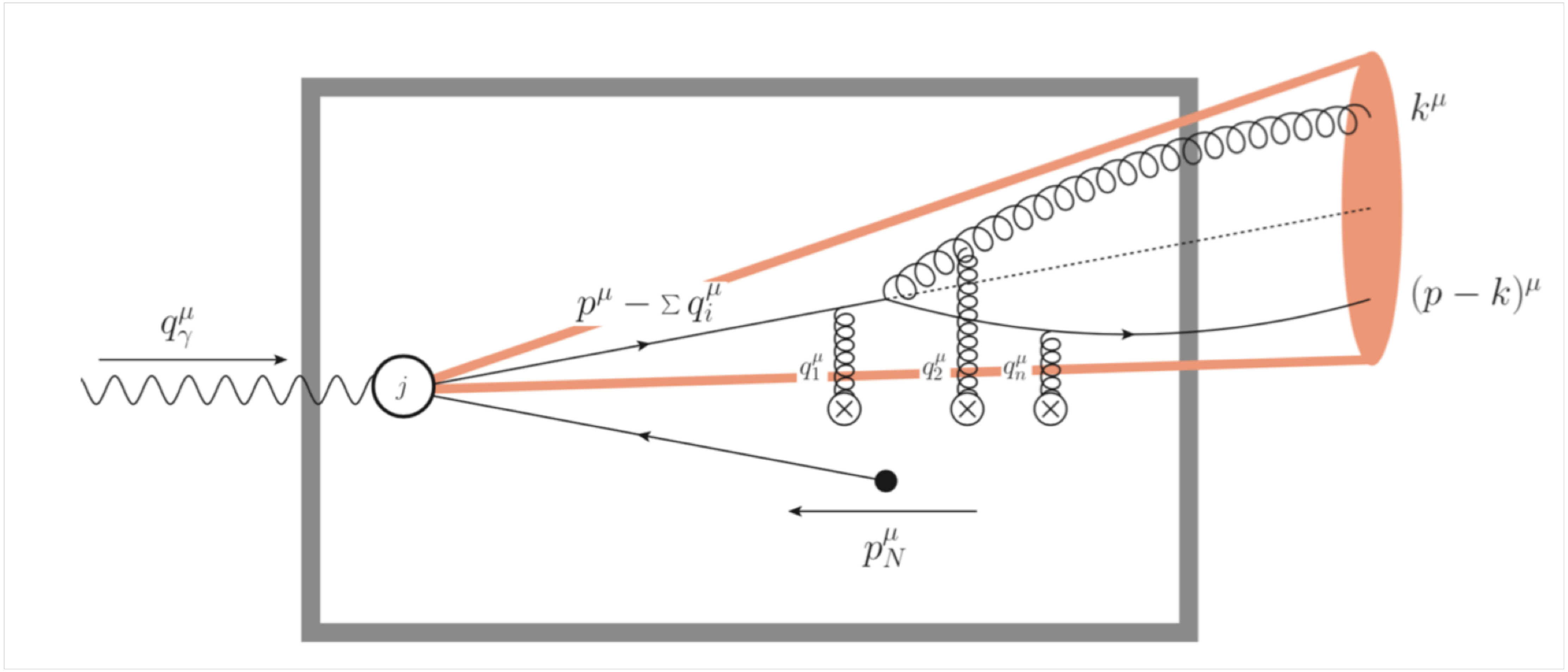
Hadronization in event generators

IV YR workshop, 2020

**The adolescence of hadrons:
The search for observables sensitive to this evolution.**

**(Fig. IV)**

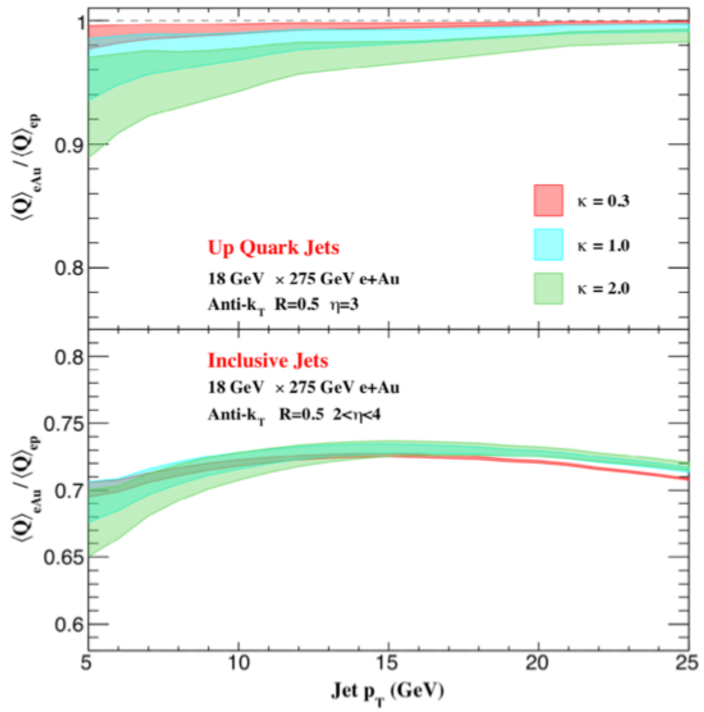
**A source that will be made possible by the EIC**
**One source of information from**
**jets in cold nuclear matter.**



**(Fig. SK)**

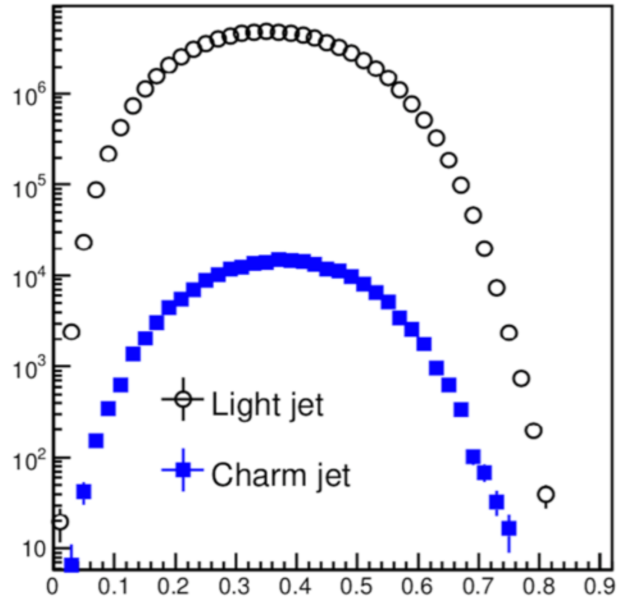
## Examples of observables with the flow of charge as well as momentum flow.

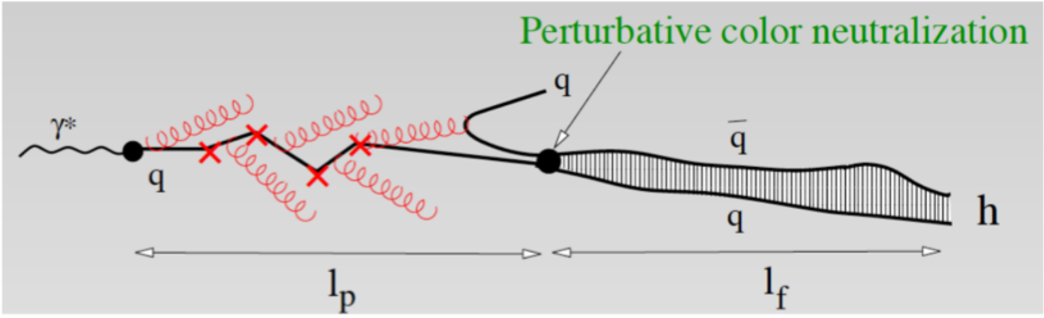
$$Q_{\kappa,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^{\kappa}} \sum_{i\in\text{jet}} Q_i \left(p_T^i\right)^{\kappa}, \quad \kappa > 0$$



**(Fig. SK)**

Jet angularity $\tau_a$ (a = 1)



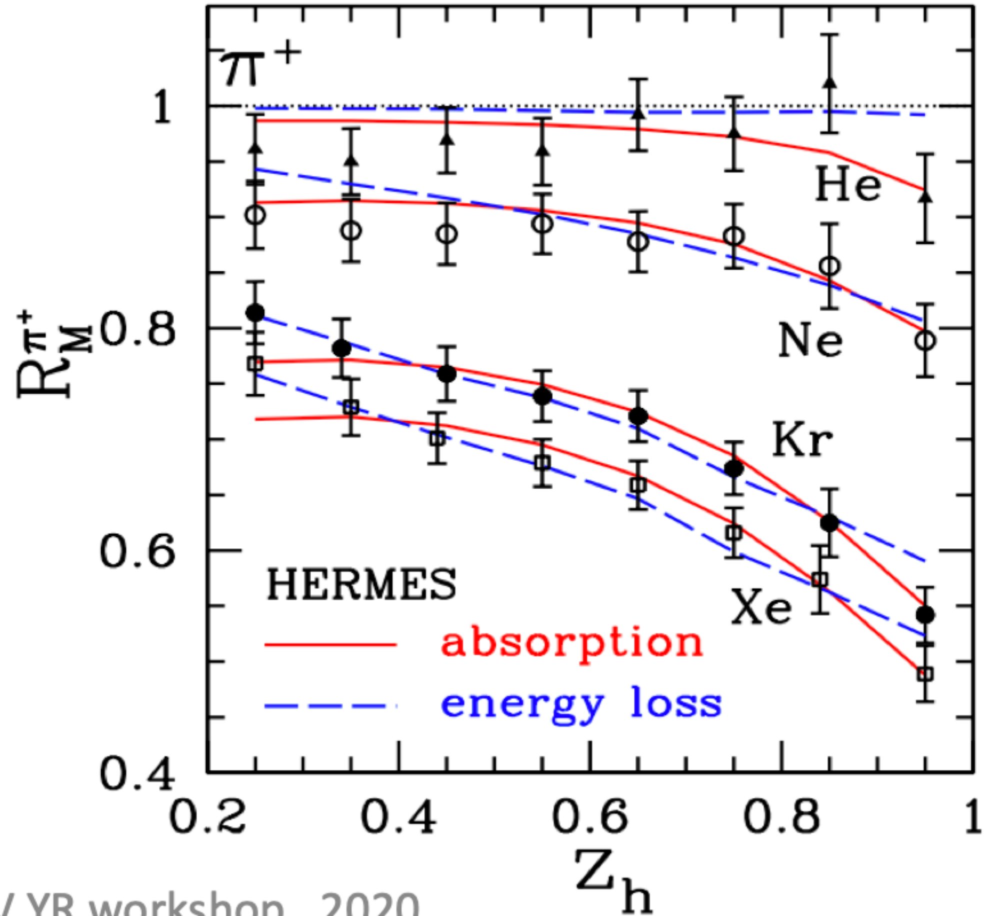


*A. Accardi et al. 2009*

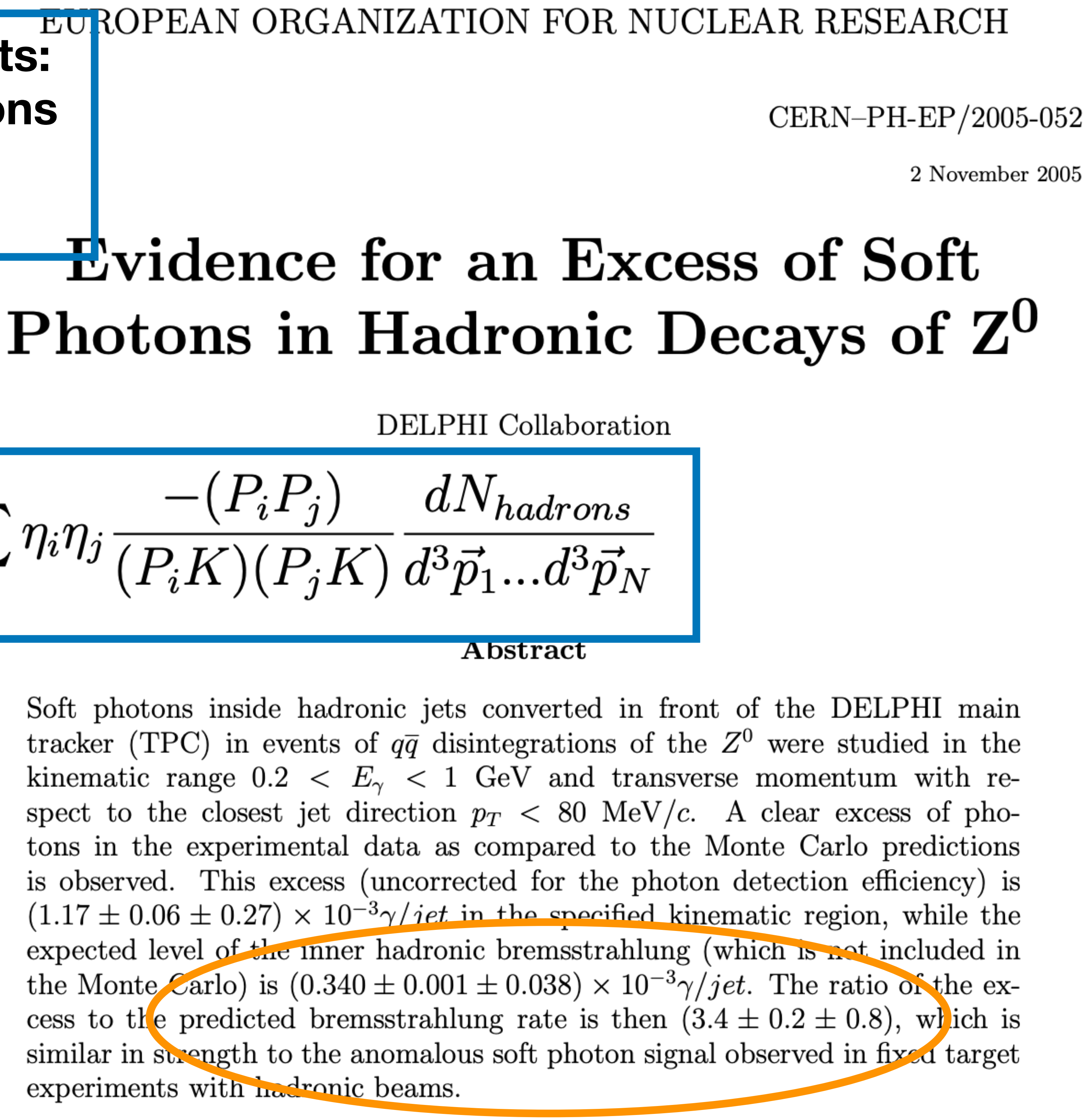
- The space-time picture of hadronization
- Competing physics explanations based on energy loss and absorption

**(Fig. IV)**

*Light hadron measurements cannot differentiate between competing mechanisms*



**Bremmstrahlung I: high-statistics jets: the excess in bremsstrahlung photons relative to expectations from asymptotic hadrons**


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PH-EP/2005-052

2 November 2005

# Evidence for an Excess of Soft Photons in Hadronic Decays of $Z^0$

DELPHI Collaboration

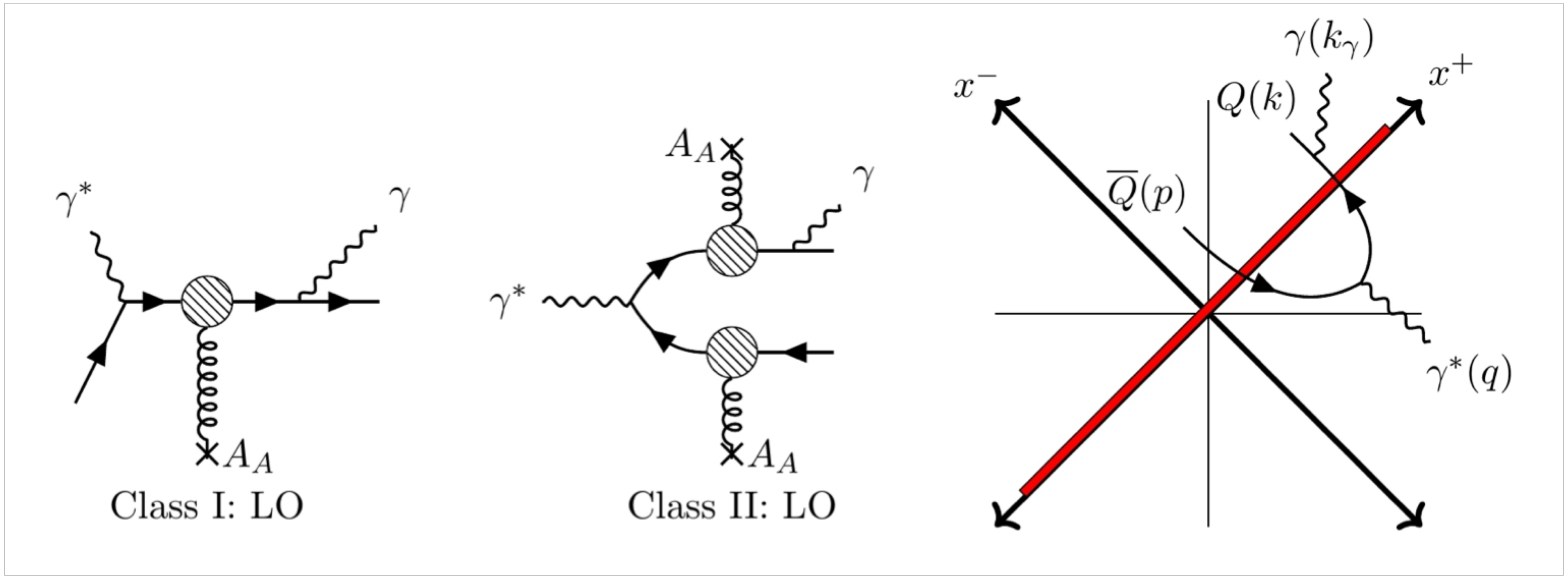
## Abstract

Soft photons inside hadronic jets converted in front of the DELPHI main tracker (TPC) in events of $q\bar{q}$ disintegrations of the $Z^0$ were studied in the kinematic range $0.2 < E_\gamma < 1$ GeV and transverse momentum with respect to the closest jet direction $p_T < 80$ MeV/$c$. A clear excess of photons in the experimental data as compared to the Monte Carlo predictions is observed. This excess (uncorrected for the photon detection efficiency) is $(1.17 \pm 0.06 \pm 0.27) \times 10^{-3}\gamma/jet$ in the specified kinematic region, while the expected level of the inner hadronic bremsstrahlung (which is not included in the Monte Carlo) is $(0.340 \pm 0.001 \pm 0.038) \times 10^{-3}\gamma/jet$. The ratio of the excess to the predicted bremsstrahlung rate is then $(3.4 \pm 0.2 \pm 0.8)$, which is similar in strength to the anomalous soft photon signal observed in fixed target experiments with hadronic beams.

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{1}{E_\gamma}\int d^3\vec{p}_1 ... d^3\vec{p}_N \sum_{i,j}\eta_i\eta_j\frac{-(P_iP_j)}{(P_iK)(P_jK)}\frac{dN_{hadrons}}{d^3\vec{p}_1 ... d^3\vec{p}_N}$$

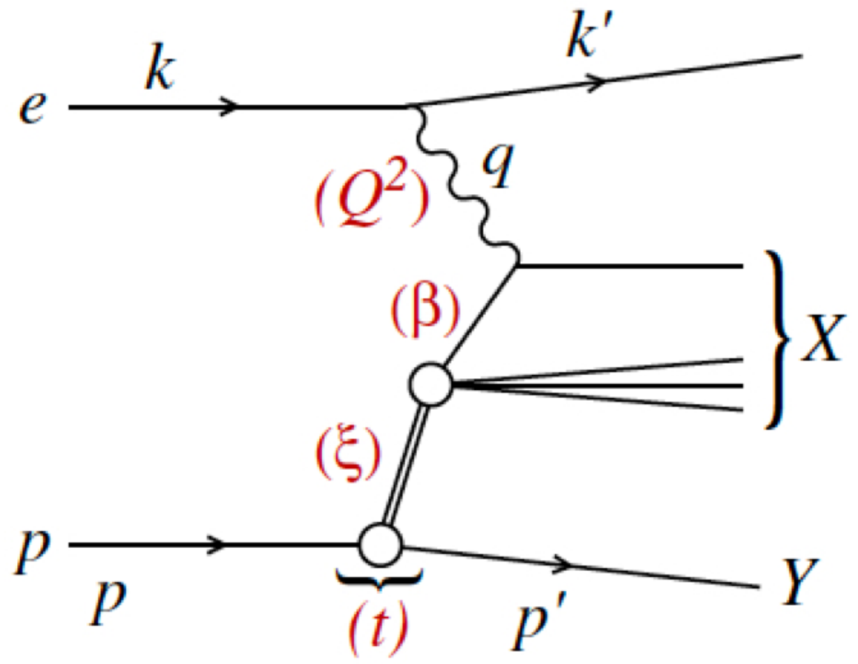
**What does the non-asymptotic source of photons say about dynamics? (Kharzeev, Loshaj (2013))**

# Bremmstrahlung II: small-x for large nuclei. Photon presents a “color dipole”.



**(Roy & Venugoplana 2018)**

# Inclusive Diffraction $e + p \rightarrow e' + X + Y$



$$\xi \equiv x_{\mathbb{P}} = \frac{Q^2+M_X^2-t}{Q^2+W^2}$$

momentum fraction
of the diffractive exchange
w.r.t. hadron

$$t = (p - p')^2$$

momentum transferred
at the proton vertex

$$\beta = \frac{Q^2}{Q^2+M_X^2-t}$$

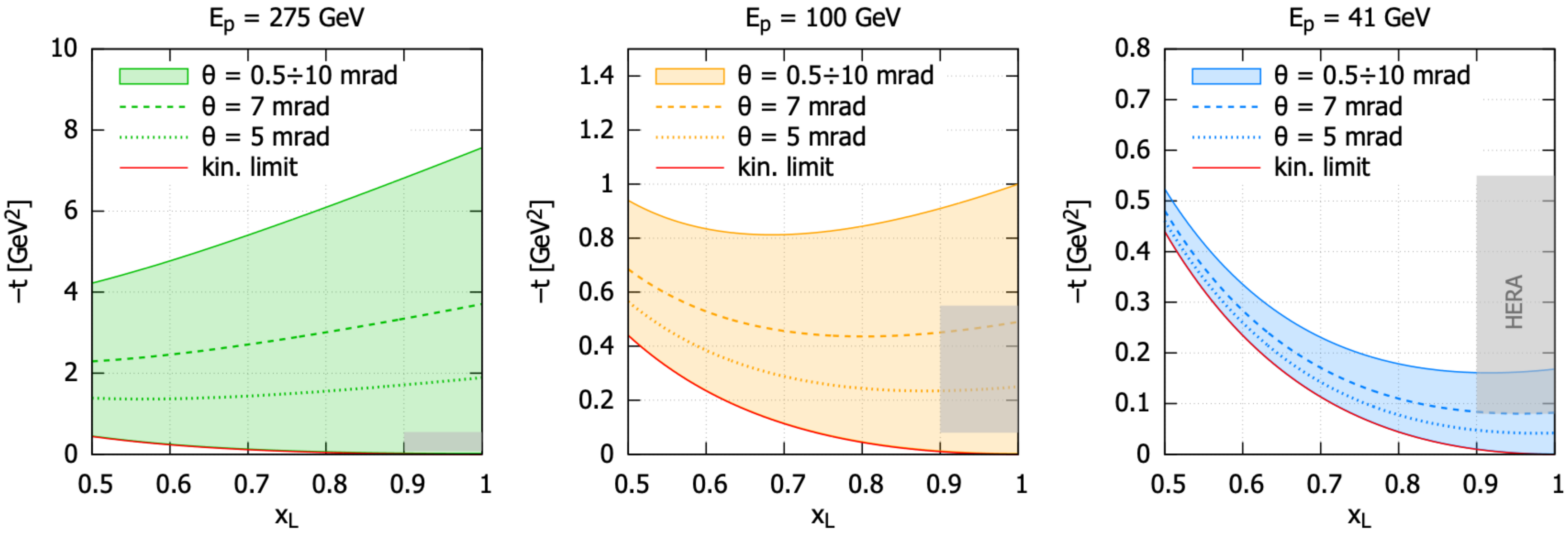
momentum fraction of the
parton w.r.t. the diffractive exchange

$$x = \beta\xi$$

Bjorken variable

**The “pomeron” is often seen as a like a particle,**
**but is really a process. Diffraction probes the “gluonic edge” of nucleons.**

Kinematics range of t and $x_L$



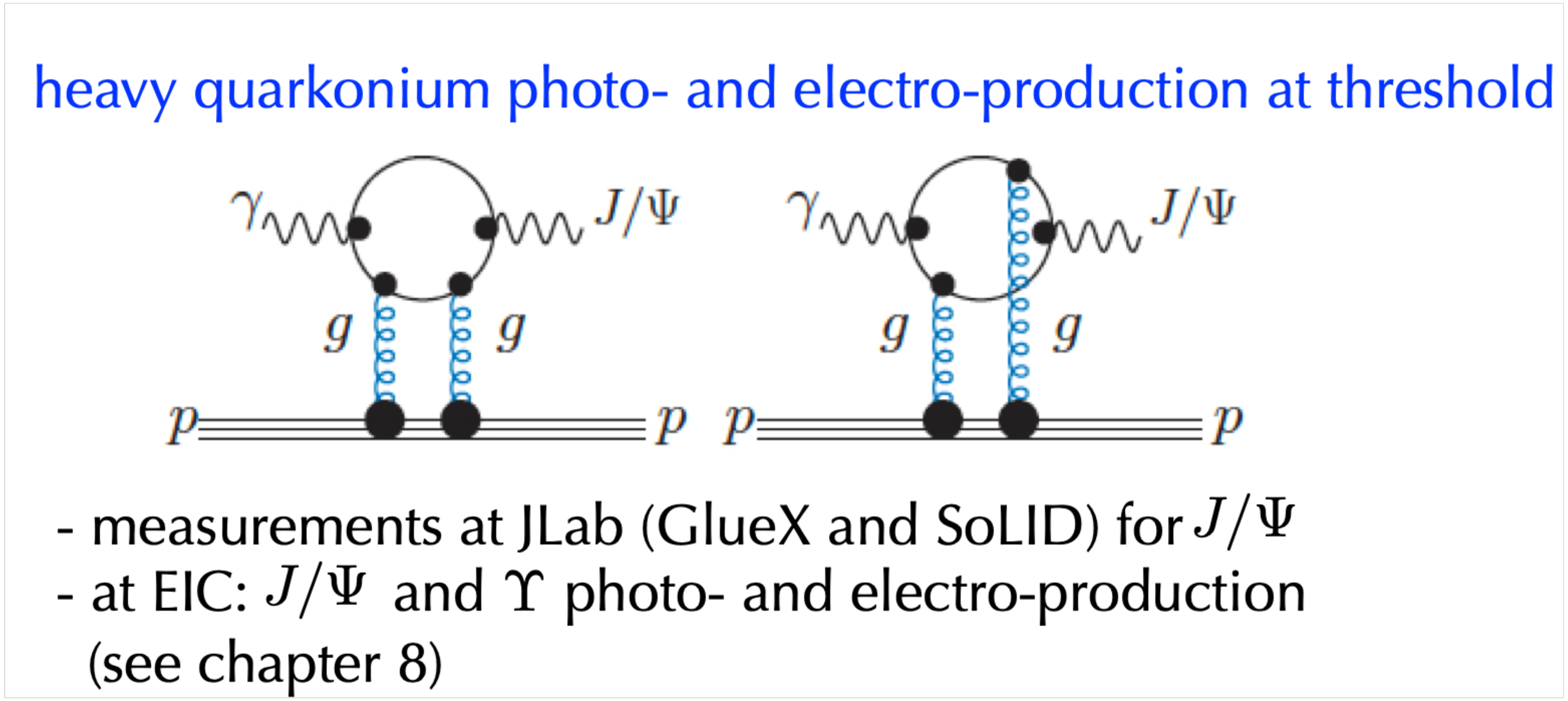
**(Fig. BP)**

$x_L = p'^+/p^+$

▨ HERA range

# Using heavy quarkonia to probe the proton mass.

$$\langle P|T^{\mu\nu}_{q,G}(0)|P\rangle = 2P^\mu P^\nu A_{q,G}(0) + 2M^2 g^{\mu\nu}\bar{C}_{q,G}(0)$$



heavy quarkonium photo- and electro-production at threshold

- measurements at JLab (GlueX and SoLID) for $J/\Psi$
- at EIC: $J/\Psi$ and $\Upsilon$ photo- and electro-production (see chapter 8)

**(Fig. BP)**

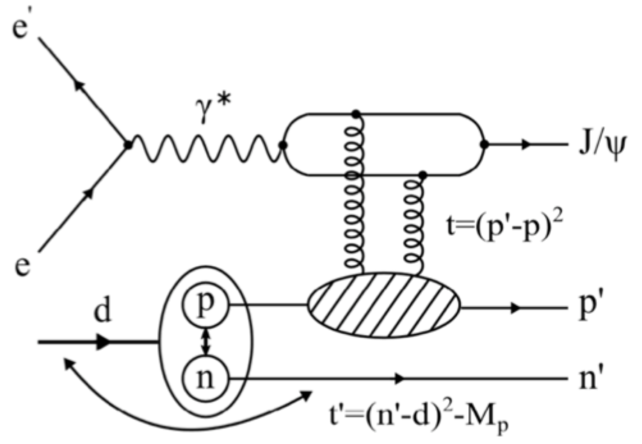
## The same gluon probes for “short-range correlations” within nuclei

Short-range nucleon-nucleon correlations (SRCs) may be responsible for the EMC effect

- What role do gluons play in SRCs?

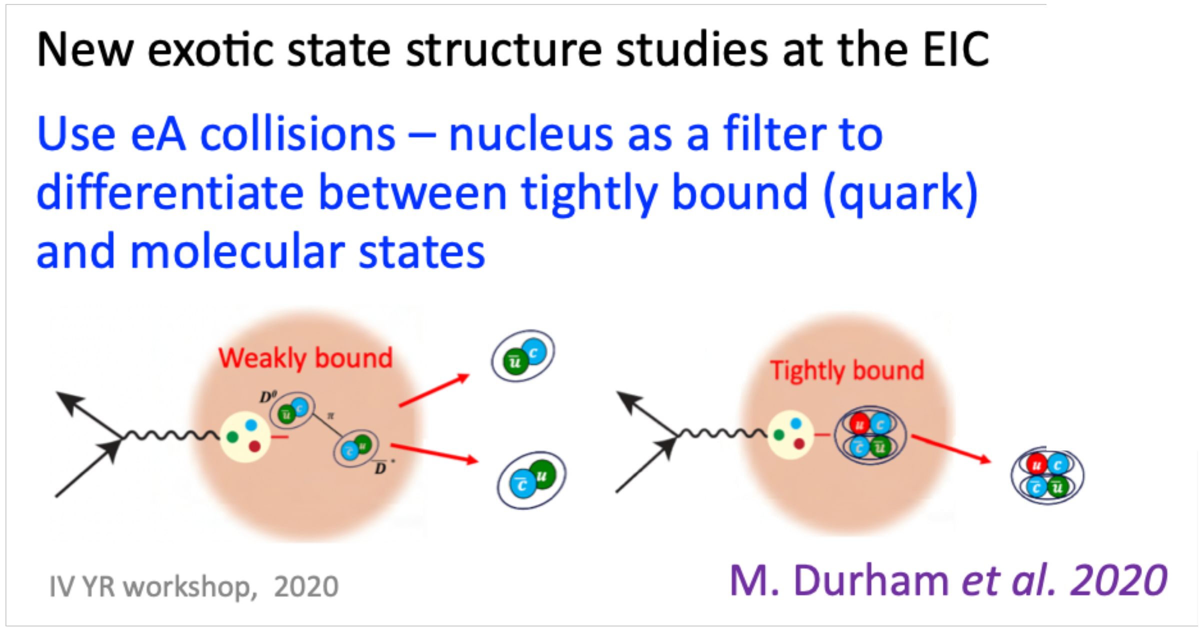
Small nuclear separation -> high relative momentum

- Nuclear momentum leads to partons with x>1



(Fig. SK)

**Heavy quarks and their newly-discovered states beyond the baryon-meson quark model.**
**A new class of probes.**

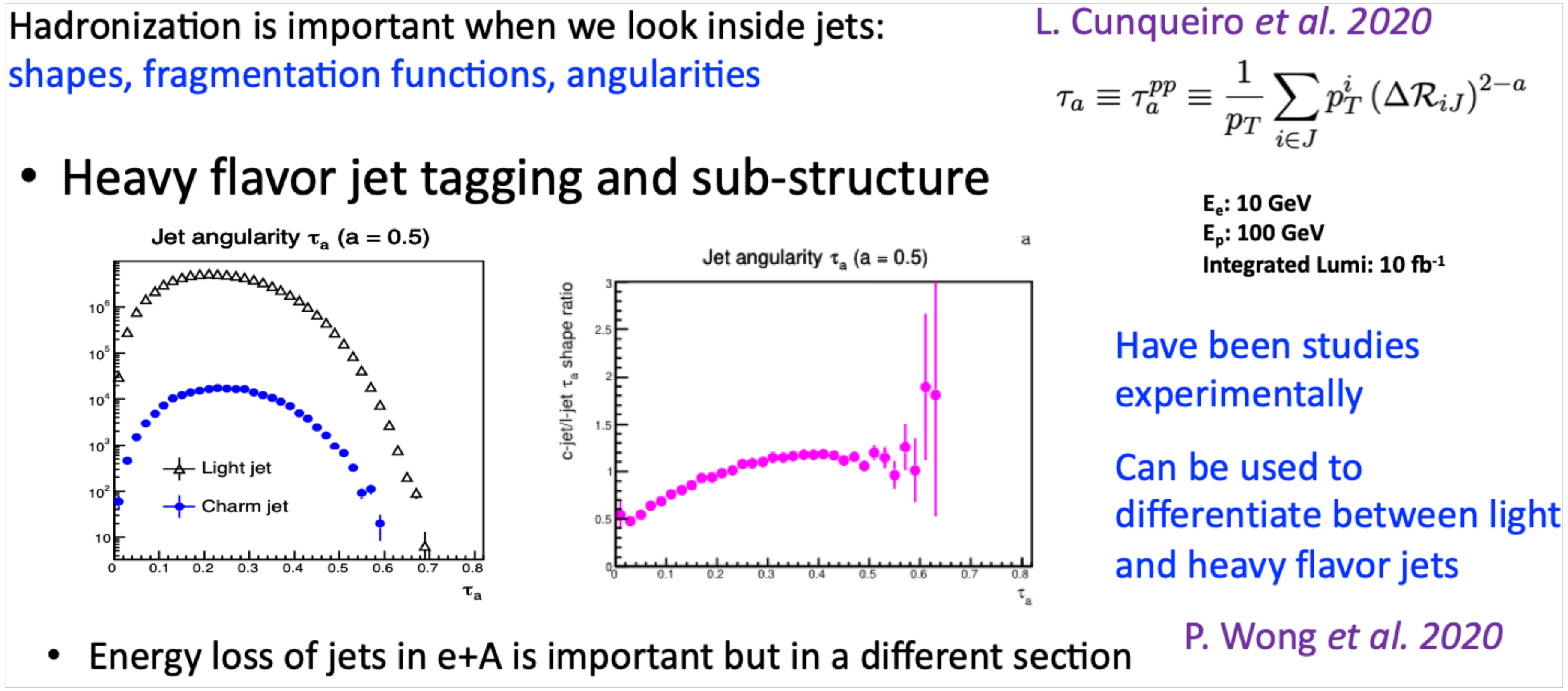


New exotic state structure studies at the EIC

Use eA collisions – nucleus as a filter to differentiate between tightly bound (quark) and molecular states

IV YR workshop, 2020

M. Durham *et al. 2020*



Hadronization is important when we look inside jets:
shapes, fragmentation functions, angularities

L. Cunqueiro *et al. 2020*

$$\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T}\sum_{i\in J} p_T^i \left(\Delta\mathcal{R}_{iJ}\right)^{2-a}$$

- Heavy flavor jet tagging and sub-structure

$E_e$: 10 GeV
$E_p$: 100 GeV
Integrated Lumi: 10 $fb^{-1}$

Have been studies experimentally

Can be used to differentiate between light and heavy flavor jets

P. Wong *et al. 2020*

- Energy loss of jets in e+A is important but in a different section

**(Figs. IV)**

**This was only a personal selection of topics**

**The advent of an Electron-Ion collider at high luminosity opens the door to qualitatively new studies of parsonic substructure and the evolution of parsonic to hadronic degrees of freedom.**