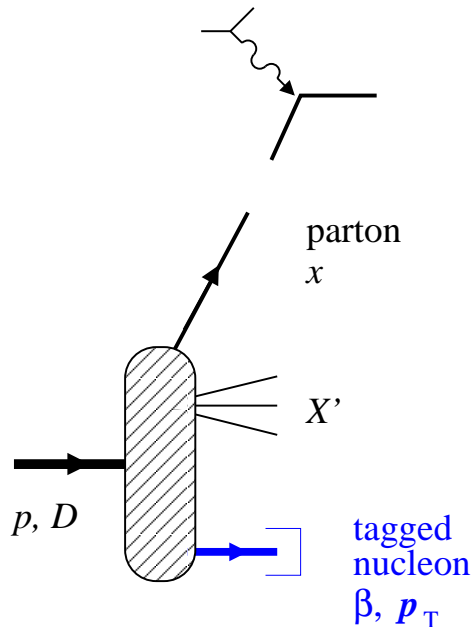


Exploring partonic structure with nucleon tagging

C. Weiss (JLab), Tagged Structure Functions Workshop, JLab, 16–Jan–14



- Target fragmentation in QCD
 - Inclusive DIS and PDFs
 - Identified hadrons and conditional PDFs
 - Interpretation at small/large x

- Proton target

Diffractive DIS $\gamma^* p \rightarrow p + \text{gap} + X$

“Pomeron”

Charge exchange $\gamma^* p \rightarrow n + X$

“Pion”

- Deuteron target $\gamma^* D \rightarrow p + X$

Free neutron from on-shell extrapolation

- Future facilities

JLab CLAS12 BoNuS, Hall A proposal

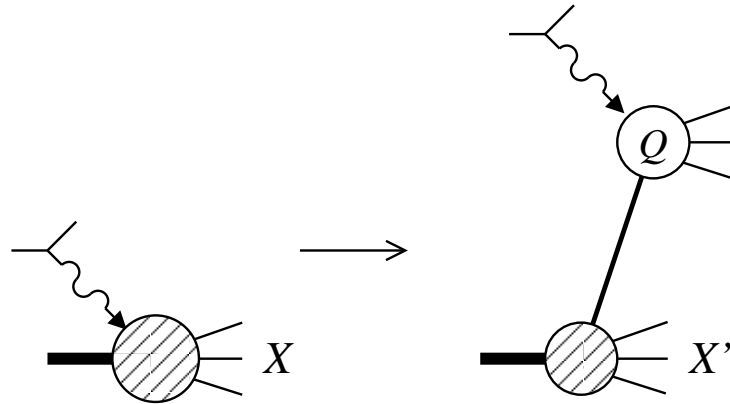
Forward tagging with EIC

Conditional parton density

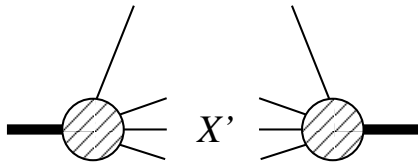
Objective definition

Dynamical interpretation:
Regge/hadron exchange,
nucleon breakup

DIS: Inclusive cross section



$$\sigma = f(x) \times \sigma_{\text{hard}}(x, Q^2)$$



$$f(x) = \sum_{X'} \int d^2 k_T \langle P | a^\dagger | X' \rangle \langle X' | a | P \rangle_{k^+ = xP^+}$$

- Factorization

Interaction decreases at short distances:
Asymptotic freedom

Separate scales $Q^2 \gg \mu_{\text{had}}^2$

σ_{hard} calculable in pQCD

- Parton distribution PDF

Light-cone momentum density in target,
probabilistic interpretation

Alt: Light-ray operator $\psi(0) \dots \psi(z)_{z^2=0}$

QCD radiation: $\log Q^2$ dependence,
DGLAP evolution

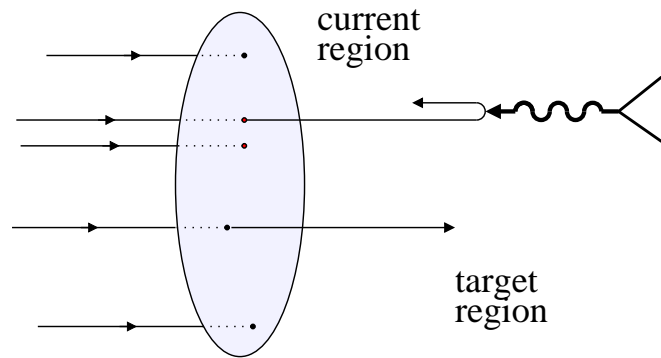
- Universality

PDF independent of hard process

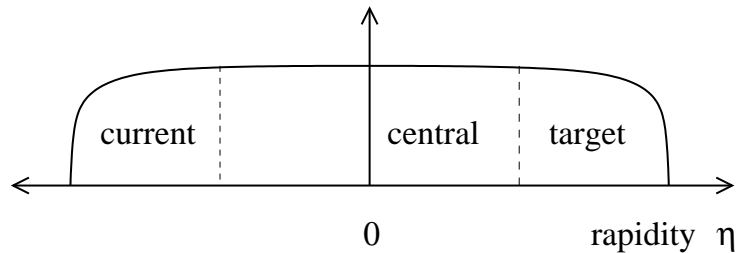
Same in $\nu N \rightarrow X$,

$NN \rightarrow X + \text{jets, dileptons}$ → Talk Reimer

DIS: Final state



$\gamma^* N$ center-of-mass frame



$$\eta = \frac{1}{2} \log \frac{E + p^z}{E - p^z} \quad \text{rapidity}$$

- Hadron production regions

Current fragmentation:
Decay of struck quark

Target fragmentation:
Breakup of target $\Delta\eta \approx 2$

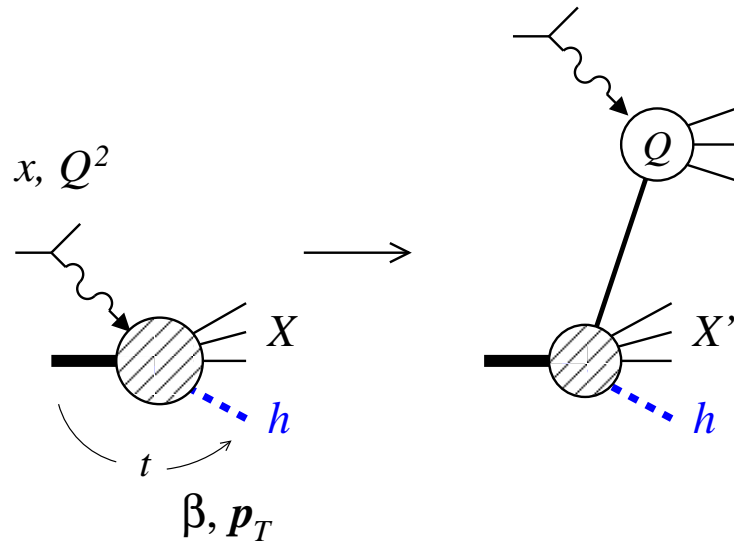
Central region:
QCD radiation, slow partons

- Different variables/definitions

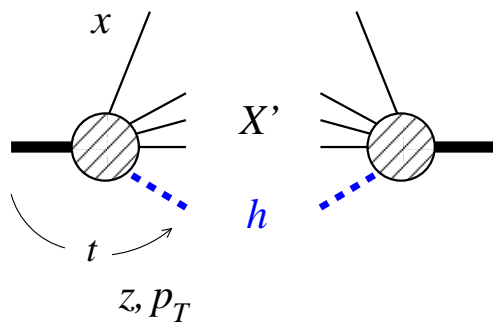
Rapidity, Breit frame, x_F , . . .

Actual distributions depend
on Q^2 , W , p_T

DIS: Target fragmentation



$$\sigma = f_h(x; \beta, t) \times \sigma_{\text{hard}}(x, Q^2)$$



$$f_h(x; \beta, t) = \sum_{X'} \int d^2 k_T \langle P | a^\dagger | h X' \rangle \langle h X' | a | P \rangle_{k^+ = x P^+}$$

- Factorization [Trentadue, Veneziano 94; Collins 98](#)

σ_{hard} same as in inclusive

Q^2 scaling for fixed $\beta, p_T \ll Q$
 Empirical tests \rightarrow [Talk Strikman, discussion](#)

- Conditional parton distribution cPDF
 Alt. [Fracture function](#)

Probability to find hadron with z, p_T after removing parton with x

$\beta = p_h^+ / (1 - x) P^+$ LC mom. fraction

p_T hadron transverse momentum

$t(\beta, p_T)$ invariant momentum transfer

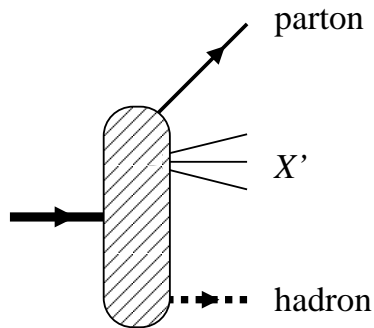
- Properties

cPDF independent of hard process, expresses structure of target

Momentum sum rule for $\sum_h f_h$
 cf. [fragmentation functions](#)

DGLAP evolution [same as PDFs](#)

DIS: Interpretation of conditional PDF



- cPDF is object in itself

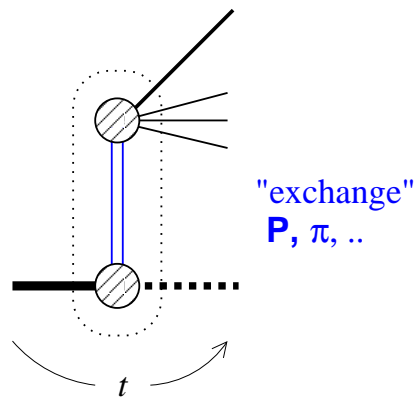
Defined through factorization theorem, universal

Can be extracted from data

- Interpretation at $x \ll 1$

Partonic content of "exchange:"
Regge trajectory, single hadron,
multihadron state...

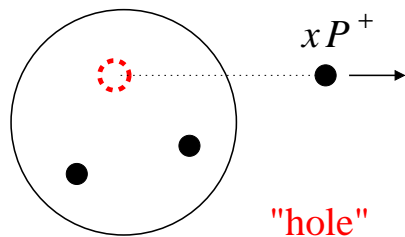
Identified through t -dependence,
 β -dependence, quantum numbers



- Interpretation at larger x

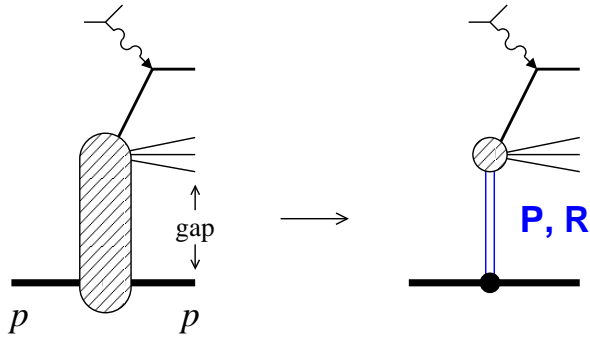
Hadronization of nucleon with
"hole" in LC wave function

Non-perturbative interactions:
 χ SB fields in QCD vacuum,
color confinement



Nucleon/hadron structure: Spin, flavor

Proton: Diffractive DIS



- Diffractive DIS $\gamma^* p \rightarrow p + \text{gap} + X$

Extensively studied at HERA $x < 10^{-2}$
 → Talk Loehr

Diffractive PDFs: DGLAP evolution,
 global fits w. DIS, jets, heavy flavors

- Interpretation

Partonic content of pomeron/reggeon
 cf. soft hadronic interactions

$$f_{j/p}(x, x_P, t) = f_{j/P}(x/x_P) f_{P/p}(x_P, t)$$

$$f_{P/p}(x_P, t) = F(t) x_P^{-2\alpha_P+2} \quad \text{pomeron flux}$$

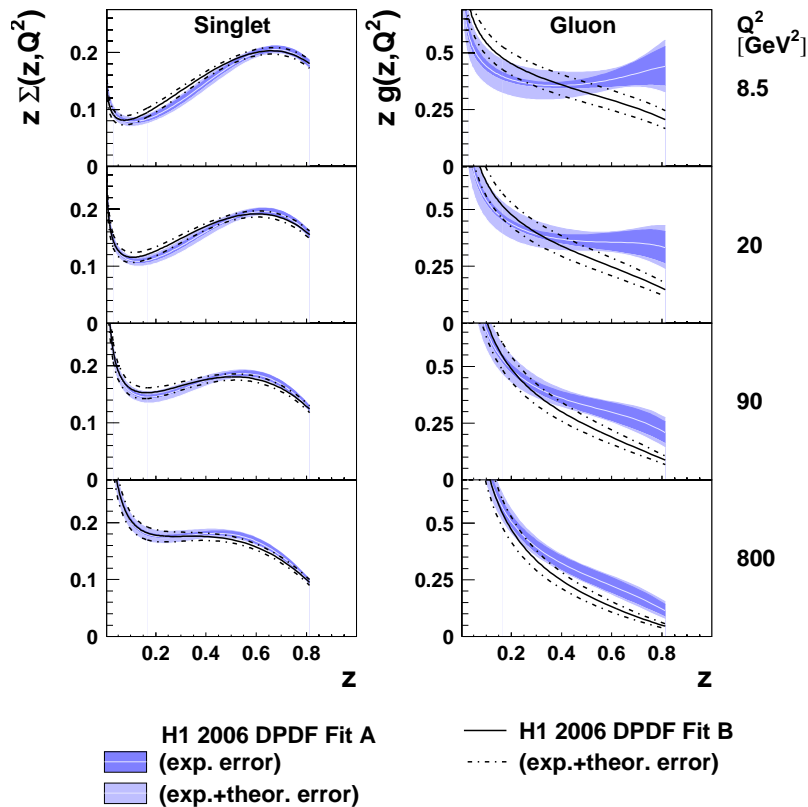
Supported by data

- Results/questions

Gluons \gg quarks in pomeron!

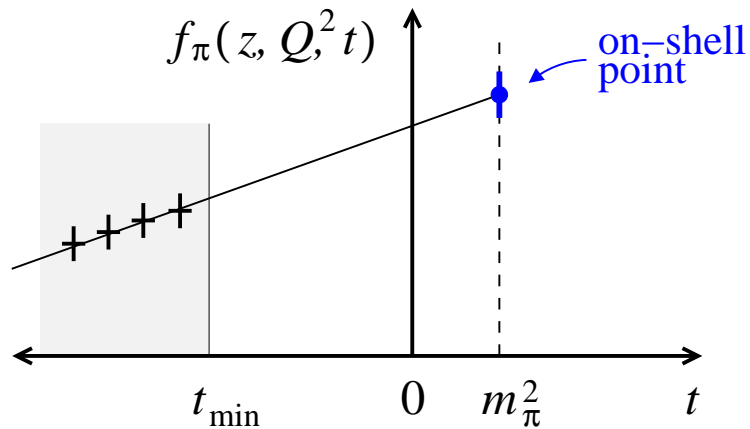
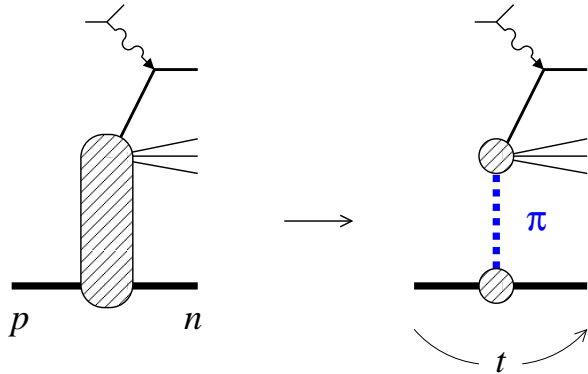
Deviations from Regge $\alpha_P = \alpha_P(Q^2)$?

Non-singlet diffractive PDFs?



$$z = x/x_P$$

Proton: Charge-exchange DIS



$$t_{\min} = -\frac{x_{\pi}^2 M_N^2}{1 - x_{\pi}}, \quad x_{\pi} > x$$

- Charge-exchange DIS $\gamma^* p \rightarrow n + X$

Forward neutrons at HERA $x < 10^{-2}$

- Pion exchange contribution

→ Talk Kopeliovich

Pole at $t = M_{\pi}^2$, residue factorizes
cf. amplitude analysis

$$f_{j/p}(x, x_{\pi})_{t=M_{\pi}^2} = f_{j/\pi}(x/x_{\pi}) f_{\pi/p}(x_{\pi})$$

Away from pole $f_{j/\pi}, f_{\pi/p}$ t -dependent:
virtual pion approximation

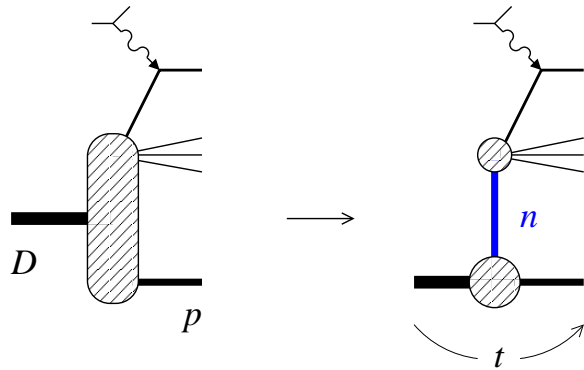
- Extrapolate to pion pole

Kinematic constraint $t < t_{\min}$

$|t_{\min}| \sim M_N^2$ for $x_{\pi} \sim 1$
Extrapolation challenging JLab 12 GeV

$|t_{\min}| \sim M_{\pi}^2$ for $x_{\pi} < M_{\pi}/M_N \sim 0.1$
Extrapolation tractable COMPASS, EIC

Deuteron: DIS with tagged nucleon



- Tagged DIS $\gamma^* D \rightarrow p + X$

Conditional parton density of D

No assumptions re nuclear structure, final-state interactions

- Neutron pole at $t = M_N^2$

Free neutron structure function from on-shell extrapolation

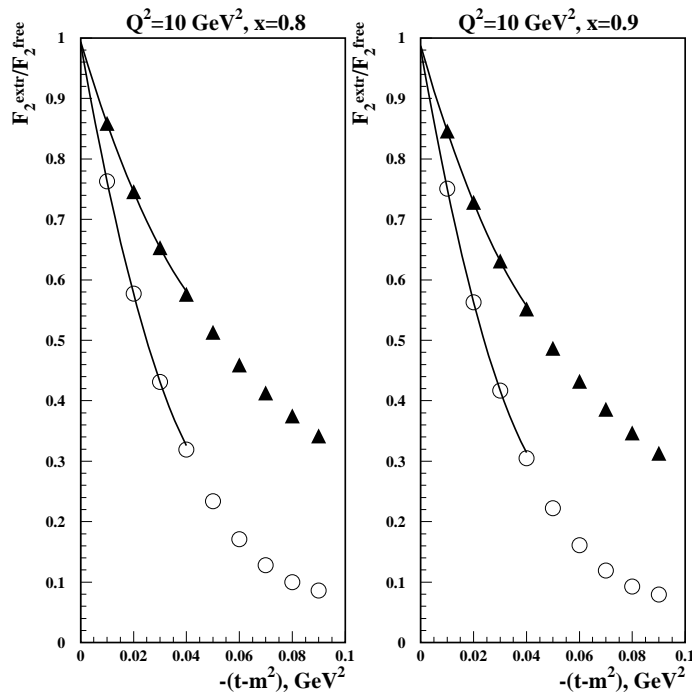
FSI does not modify leading singularity
Sargsian, Strikman 05

- Interesting applications \rightarrow Talks Sargsian, Cosyn

Model-independent extraction of neutron PDFs

Bound proton PDFs from $\gamma^* D \rightarrow n + X$, compare with free p measurement

Neutron spin structure with polarized D



$$t - M_N^2 \approx -2p_{\text{recoil}}^2 \text{ (rest frame)}$$

Experimental facilities

- HERA $e^\pm p$ collider → Talk Loehr

Diffraction DIS, jets, heavy flavors
Leading neutrons/protons

- COMPASS $\mu^\pm p / \mu^\pm D$

Measurement of conditional PDFs in original proposal – status, prospects?
Recoil p detector

- JLab 12 GeV

Semi-inclusive DIS program with CLAS12, Hall A, Hall C

CLAS12 BONuS $eD \rightarrow p + X$ → Talk Christie
Tagged $e^4\text{He} \rightarrow p + X$ → Talk Stepanyan

Hall A proposal $eD \rightarrow p + p + X$ → Talk Keppel

- Electron-Ion Collider EIC

Excellent capabilities for forward/far-forward detection of p, n
Important design goal for EIC@JLab → Talks Nadel-Turonski, Hyde

JLab 2014 LDRD project exploring physics potential of tagged DIS measurements with polarized D (also ^3He): Neutron spin, GPDs, bound nucleon PDFs, coherent scattering

Summary

- Conditional PDF as unifying concept
 - Defined through factorization theorem
 - Extracted directly from data
 - Interpreted in dynamical models
- Pion exchange contribution to $\gamma^*p \rightarrow n + X$
 - Defined rigourously through pole at $t = M_\pi^2$
 - t_{\min} large at $x \gtrsim 0.2$, extrapolation challenging!
- Physics potential of deuteron $\gamma^*D \rightarrow p + X$
 - Free neutron structure from on-shell extrapolation
 - Explore double tagging $\gamma^*D \rightarrow p + p + X$
- Need to discuss
 - Physics with double tagging at $x \gtrsim 0.2$?
 - Final-state interactions?
 - Possibility of neutron tagging $\gamma^*D \rightarrow n + X$?