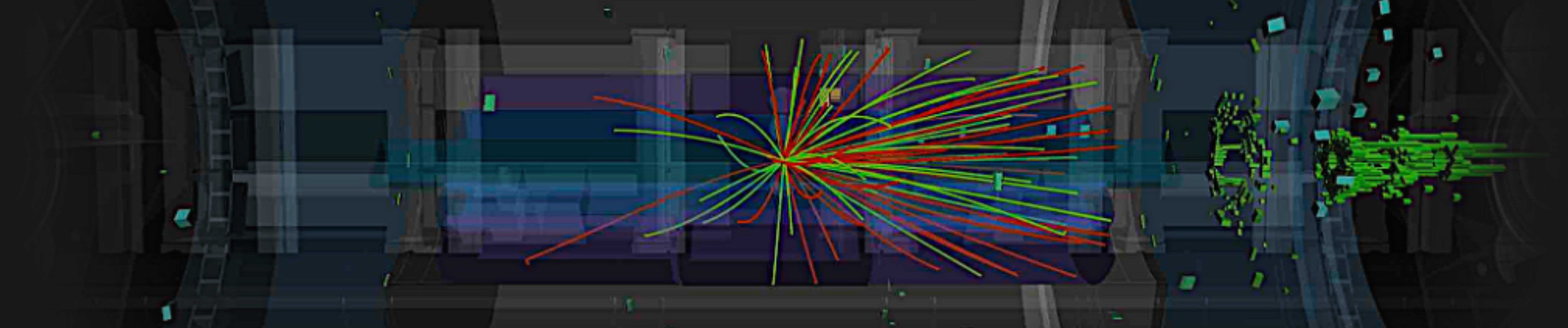
Effective Field Theory Factorization for Diffraction

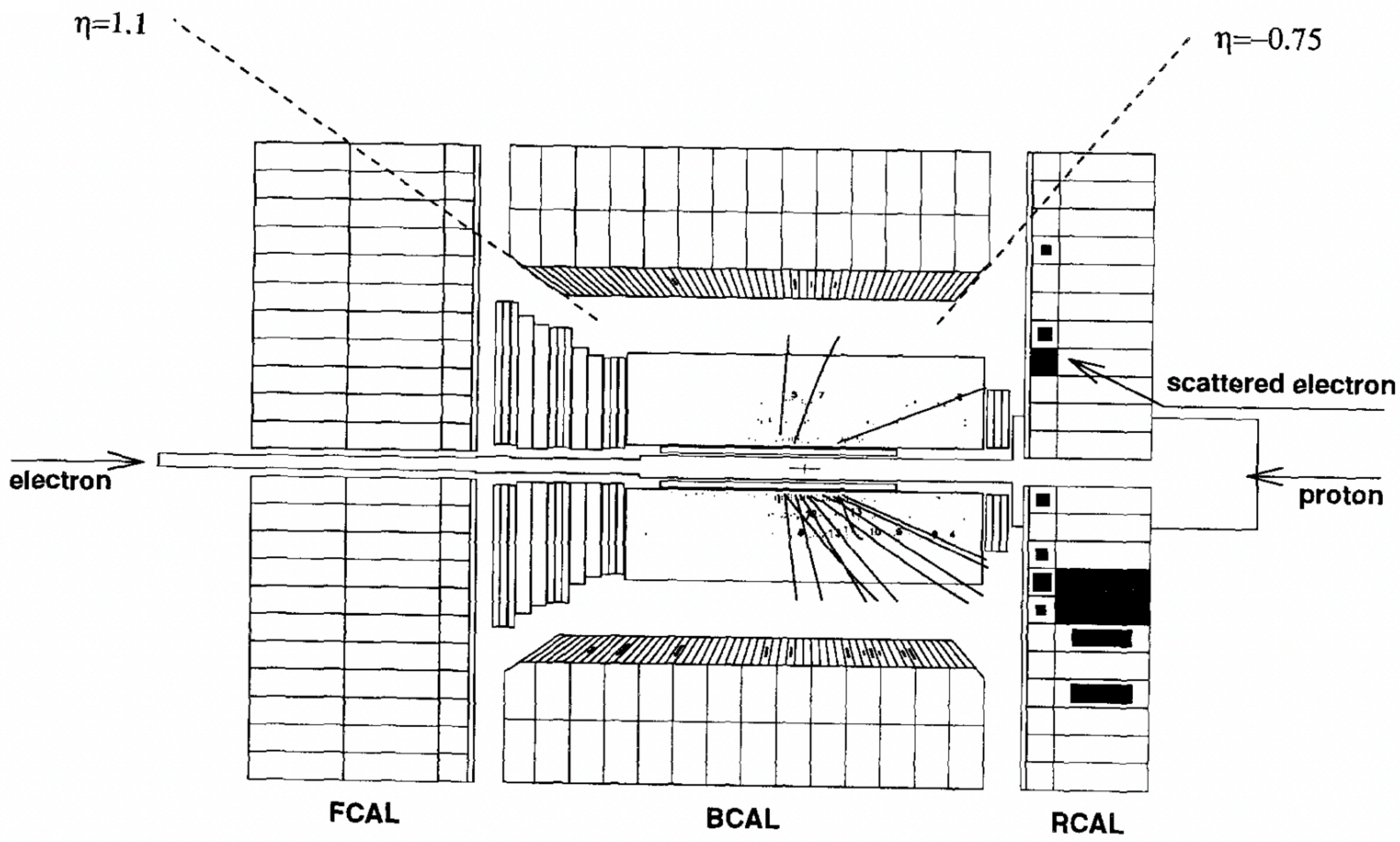


In collaboration with
Stella Schindler and Iain Stewart

Kyle Lee
CTP, MIT

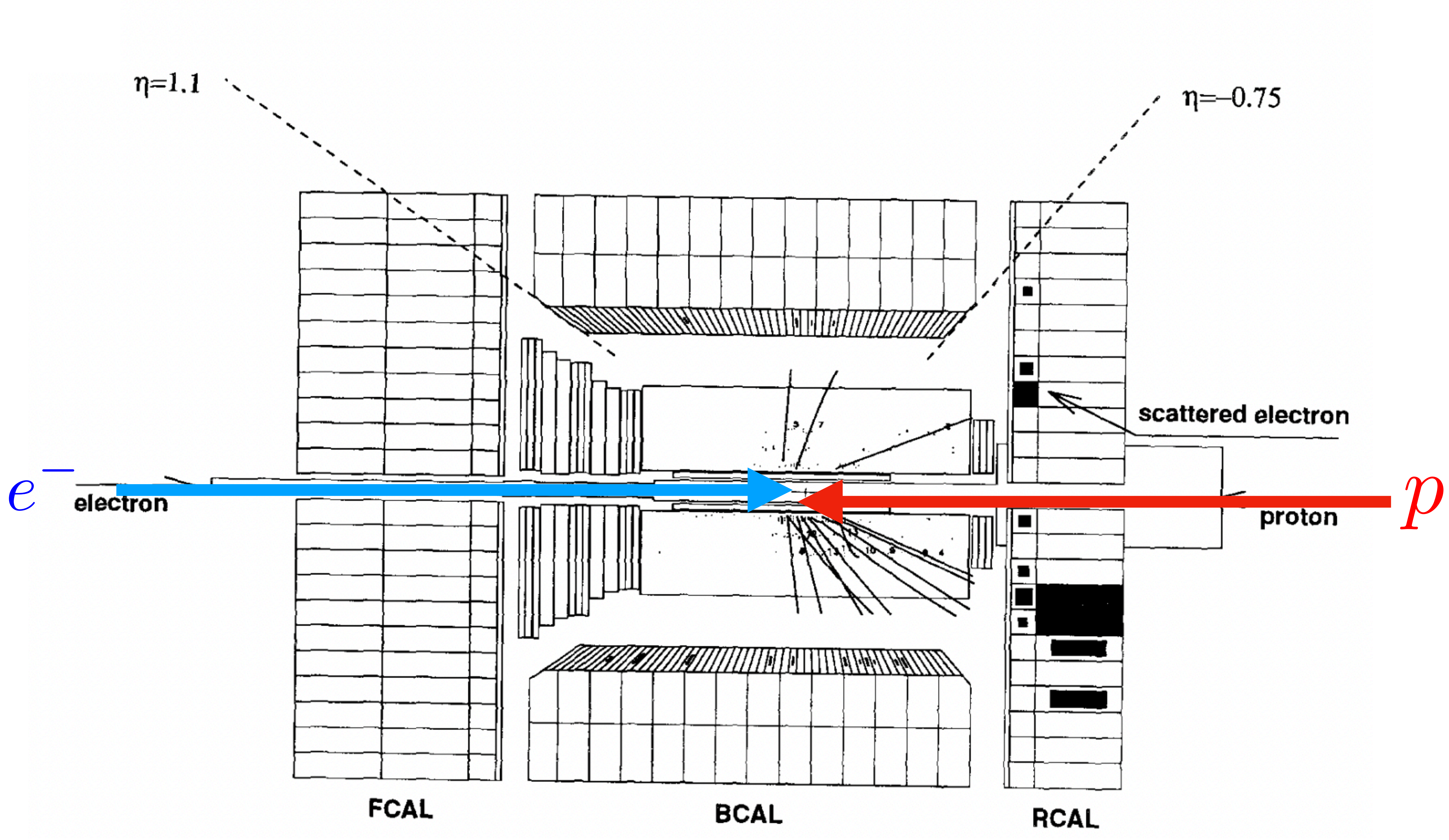
SCET 2024

INTRODUCTION



- **Diffraction describes large rapidity gap events as shown here for a HERA event (1993)**

INTRODUCTION



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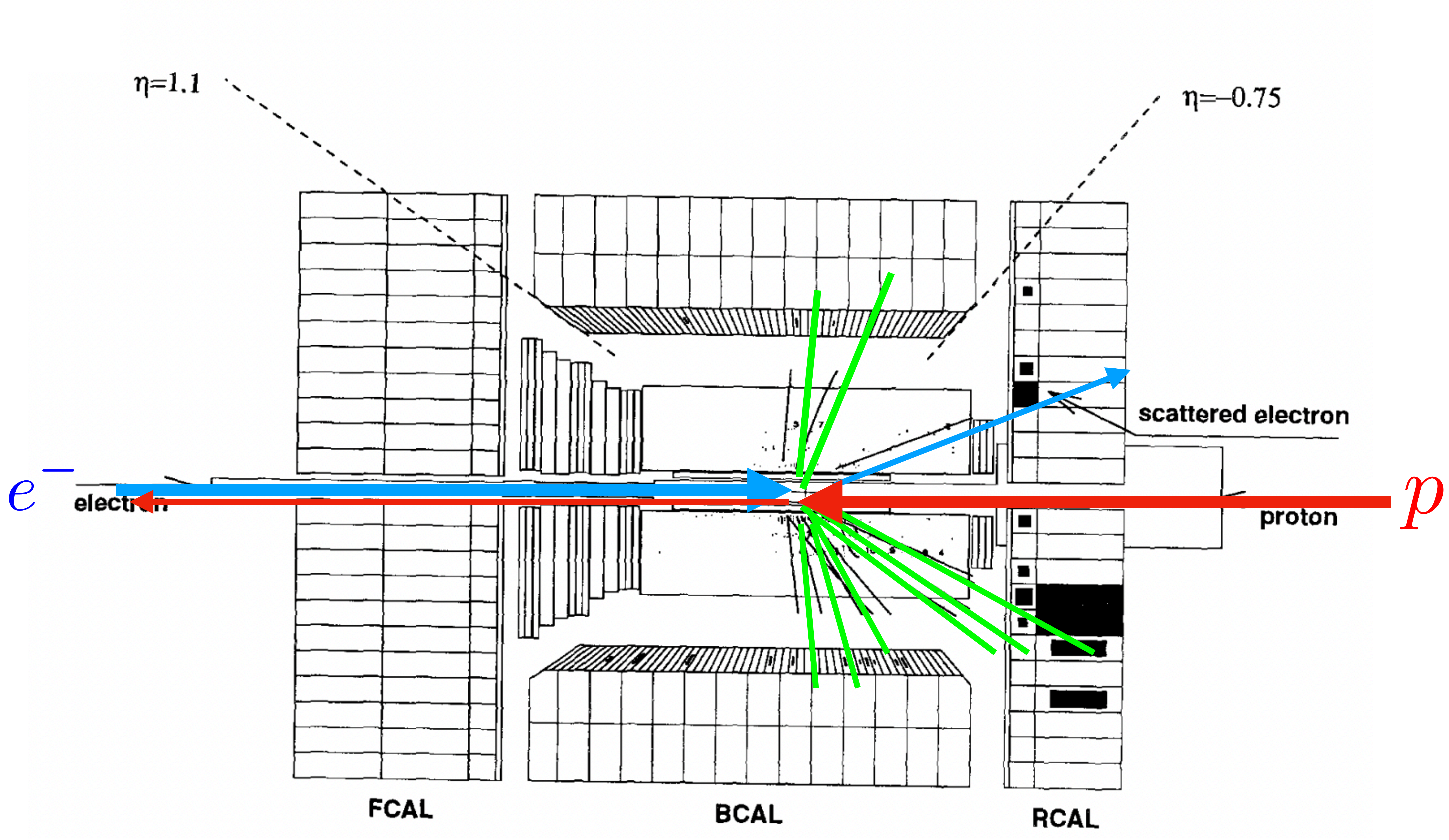
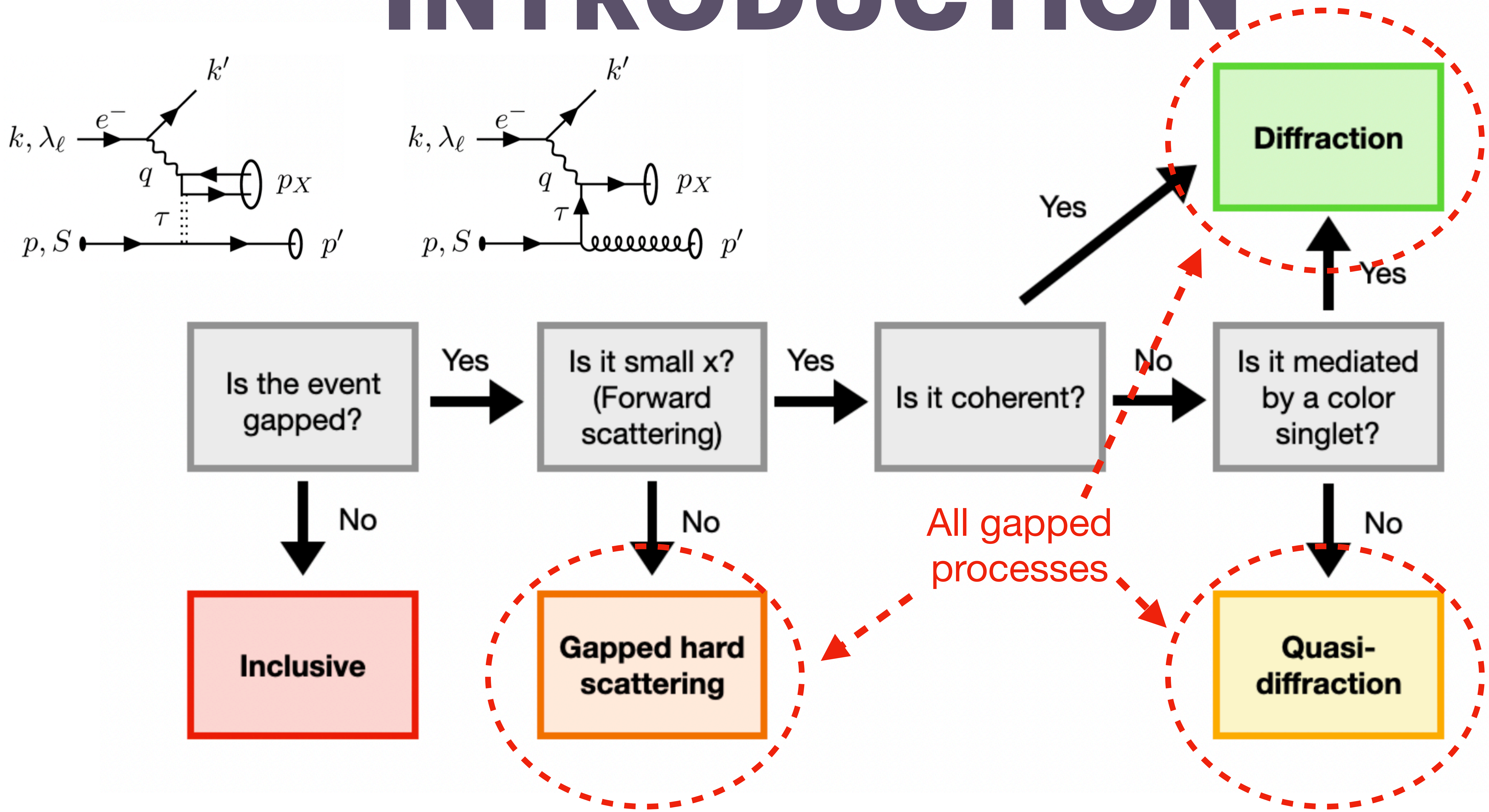
INTRODUCTION



- **Diffraction describes large rapidity gap events as shown here for a HERA event (1993)**

INTRODUCTION



Color-singlet forward scattering

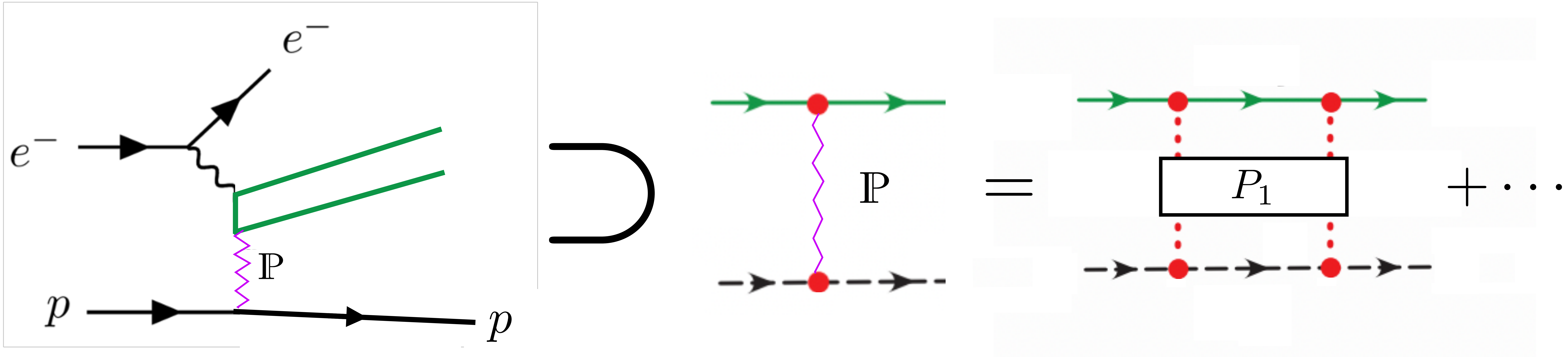
Non-singlet Important background

How large is this?

(non-small-x) DVCS(exclusive), 1-jettiness(inclusive)

- **There are varieties of gapped processes depending on the measurements. Here, we consider gapped processes with forward scattering**

WHY STUDY DIFFRACTION?

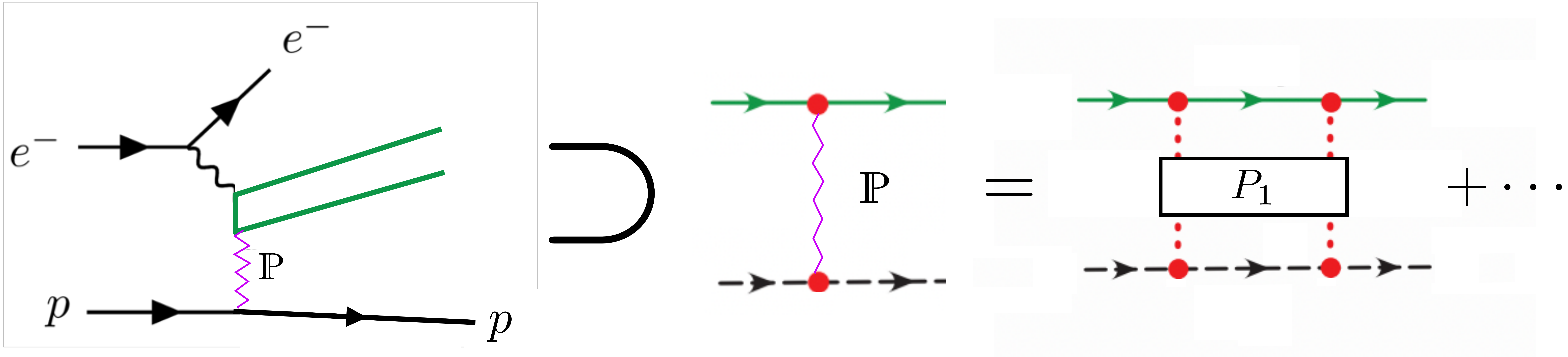


- **Observation of diffractive process imply direct and leading access to Glauber exchanges at the cross-section level!**
  - ***Nature of pomeron***
  - ***New hadron structure (GPD-like structure + more?)***
  - ***Small-x and saturation physics (BFKL and heavy-ion)***

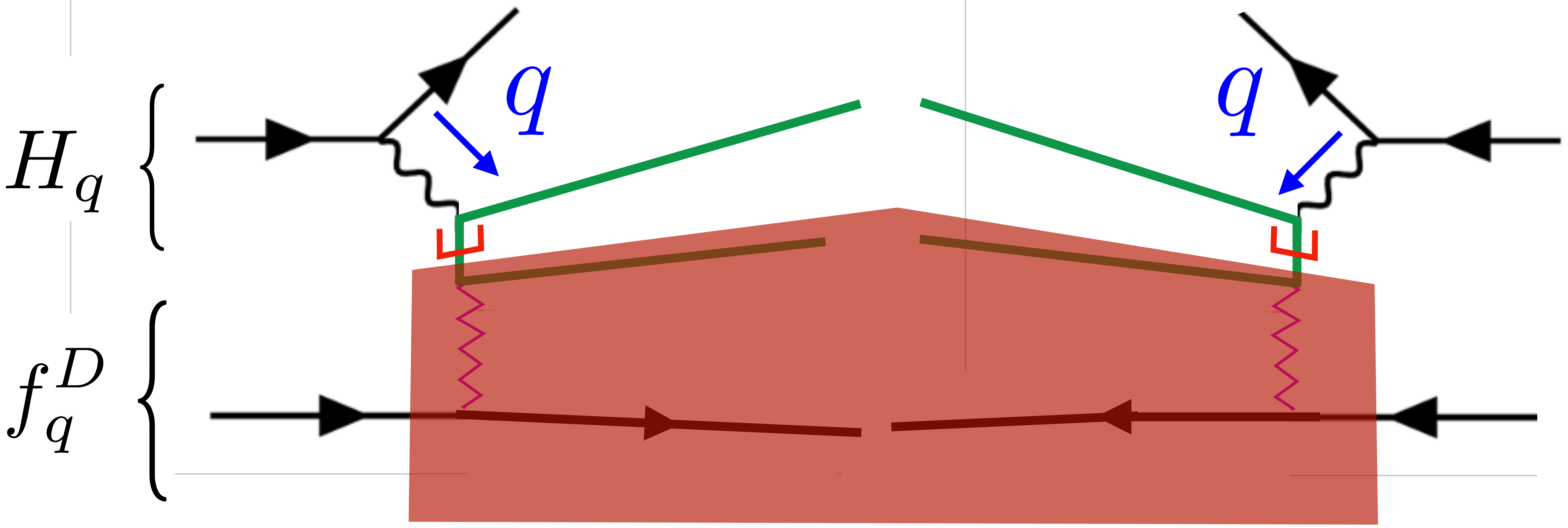
See also Hatta, Xiao, Yuan `17

- **Ample existing data and bright experimental outlook!**
  - ***10% of HERA and 20% of EIC. One of the flagship program for EIC physics!***

WHY STUDY DIFFRACTION?



- **Traditional QCD approach so far :**



Usual hard-collinear factorization for large Q^2

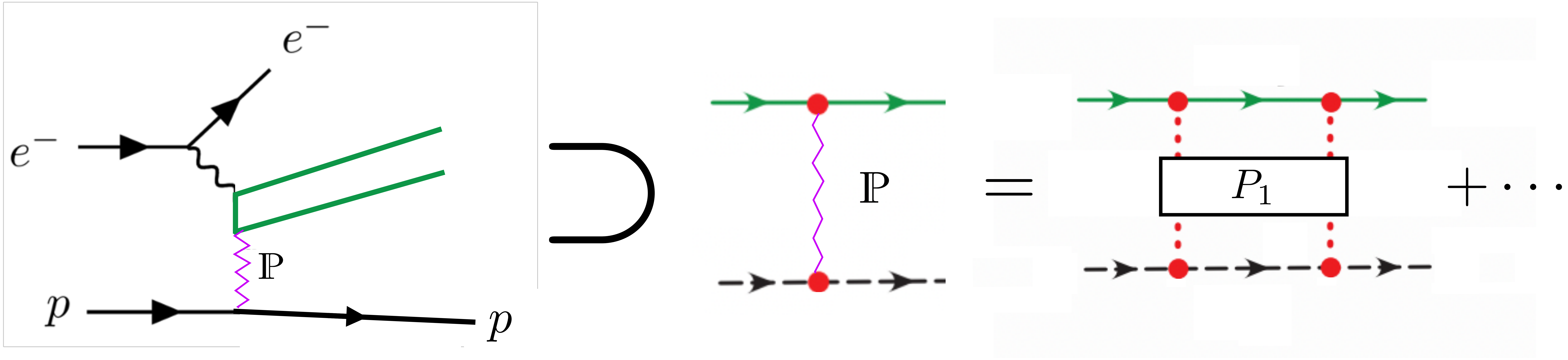
Diffractive
parton distribution functions(dpdf)

$$F_{2/L} \sim \sum_i H_i^{2/L} \otimes f_i^D$$

Collins `97, Berera, Soper `95

Also, TMD dpdf : Hatta, Yuan `22,24

WHY STUDY DIFFRACTION?



- **Traditional QCD approach so far :**

"The reader may also wonder why we don't frame the analysis in terms of the distribution of partons in the pomeron. Our excuse is ignorance. **We don't know how to relate the Regge factorization in Eq. (8) to quantum field theory.**"

Berera, Soper `95

"However, I will not at all address the separate and important question of whether **Regge factorization** is also valid.…**Unfortunately, Regge theory in the form used by Ingelman and Schlein has not been derived from QCD, and indeed is probably false**… The factorization theorem that has actually been proved, and is stated above, is somewhat different; it has **hard-scattering factorization but not Regge factorization**."

and many more…

Collins `97, `01

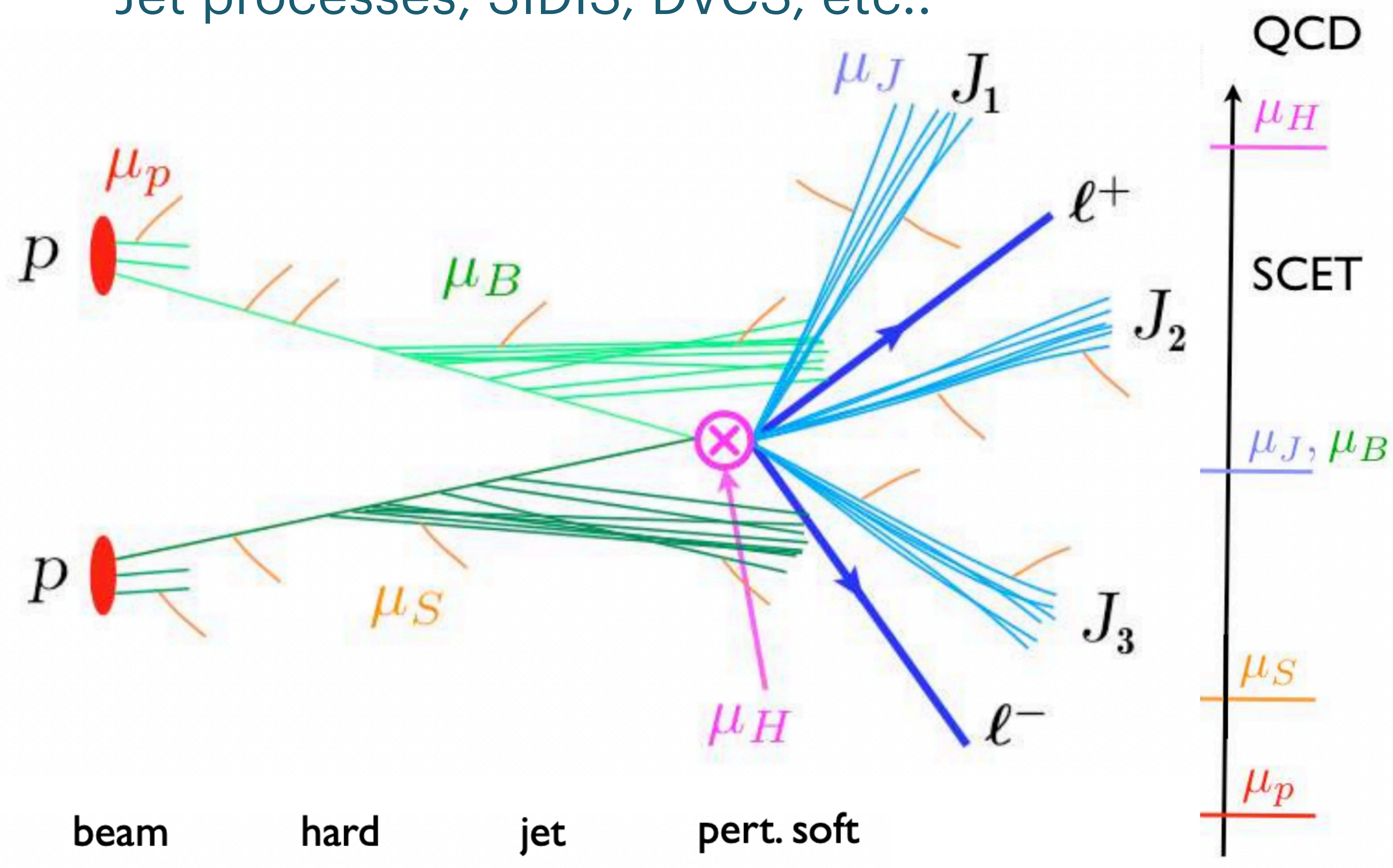
EFFECTIVE FIELD THEORY METHODS

$$\mathcal{L}^{(0)}_{\rm SCET}(\xi_{n_i}, \psi_s, A_{n_i}, A_s) = \mathcal{L}^{(0)}_h + \sum_{n_i} \mathcal{L}^{(0)}_{n_i} + \mathcal{L}^{(0)}_s + \mathcal{L}^{(0)}_{us} + \mathcal{L}^{(0)}_G$$

Bauer, Fleming, Luke, Pirjol, Stewart `00-01

- **Hard-collinear** and **soft-collinear factorization**

Jet processes, SIDIS, DVCS, etc..



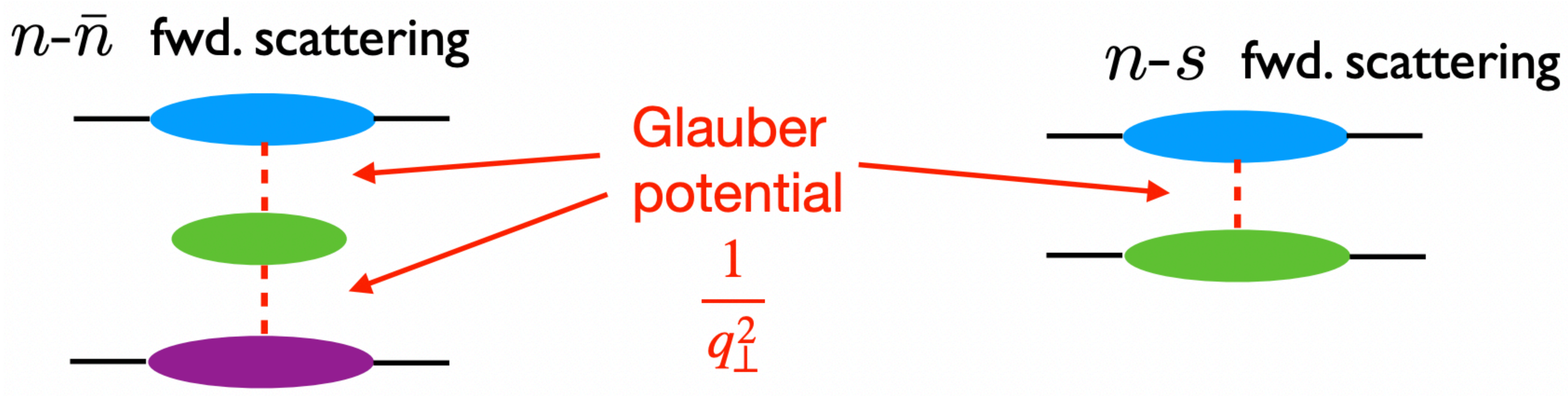
beam hard jet pert. soft

$$\hat{\sigma}_{\rm fact} = \mathcal{I}_a \mathcal{I}_b \otimes H \otimes \prod_i J_i \otimes S$$

μ_B μ_H μ_J μ_S

- **Glauber SCET** Rothstein, Stewart `16

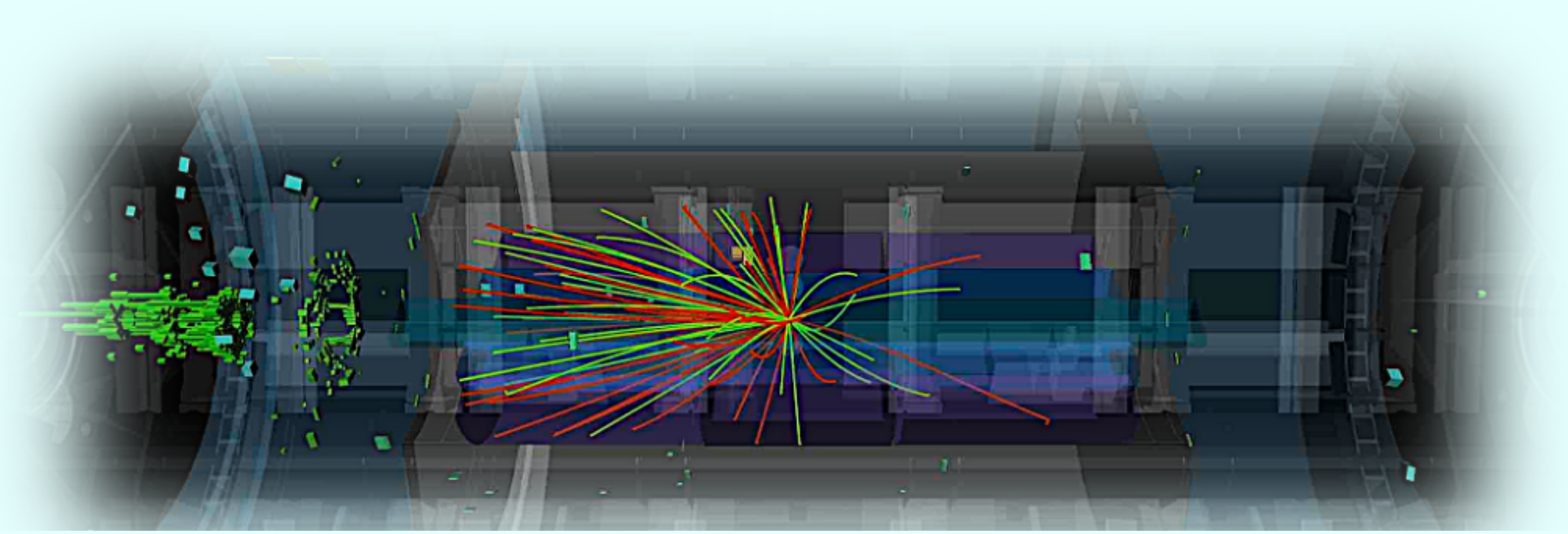
$$\mathcal{L}^{(0)}_G = \sum_{n,\bar n} \sum_{i,j=q,g} \mathcal{O}^{iB}_n \frac{1}{\mathcal{P}^2_\perp} \mathcal{O}^{BC}_s \frac{1}{\mathcal{P}^2_\perp} \mathcal{O}^{jC}_{\bar n} + \sum_n \sum_{i,j=q,g} \mathcal{O}^{iB}_n \frac{1}{\mathcal{P}^2_\perp} \mathcal{O}^{j_n B}_s$$



- Forward scattering processes
- Factorization breaking effects in hard scattering

Effective Field Theory gives powerful organization to derive a rigorous QCD factorization!

outline

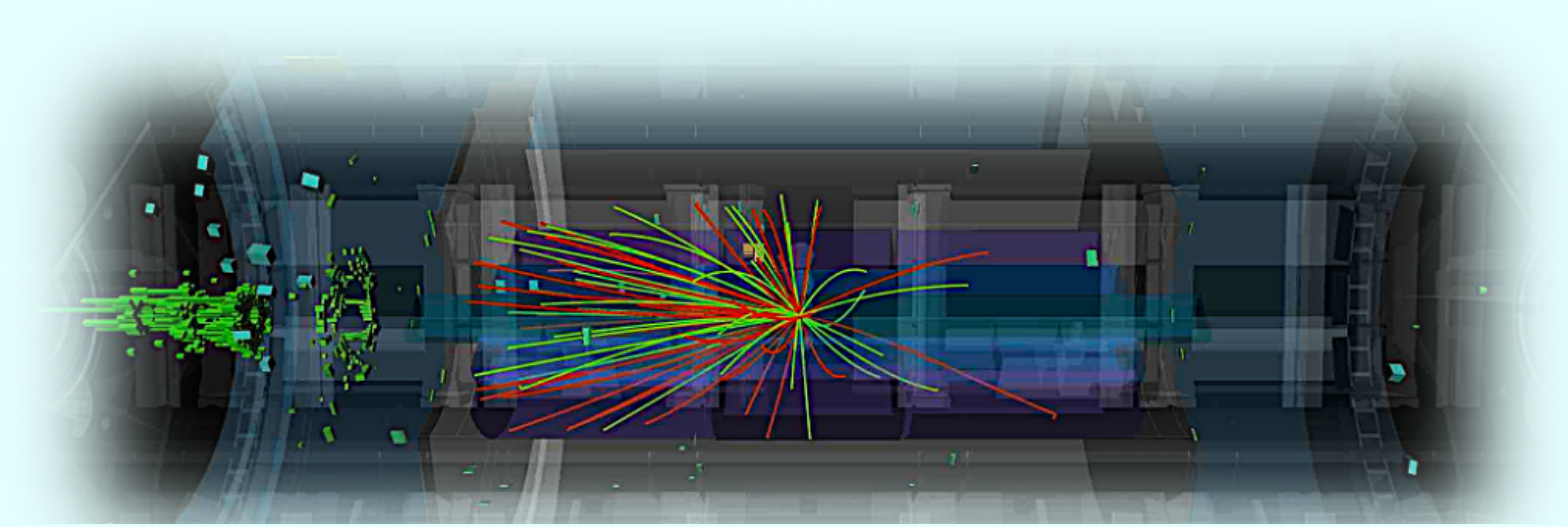


I. Kinematics and Structure Functions

II. Power-counting and Factorization

III. Phenomenology

outline



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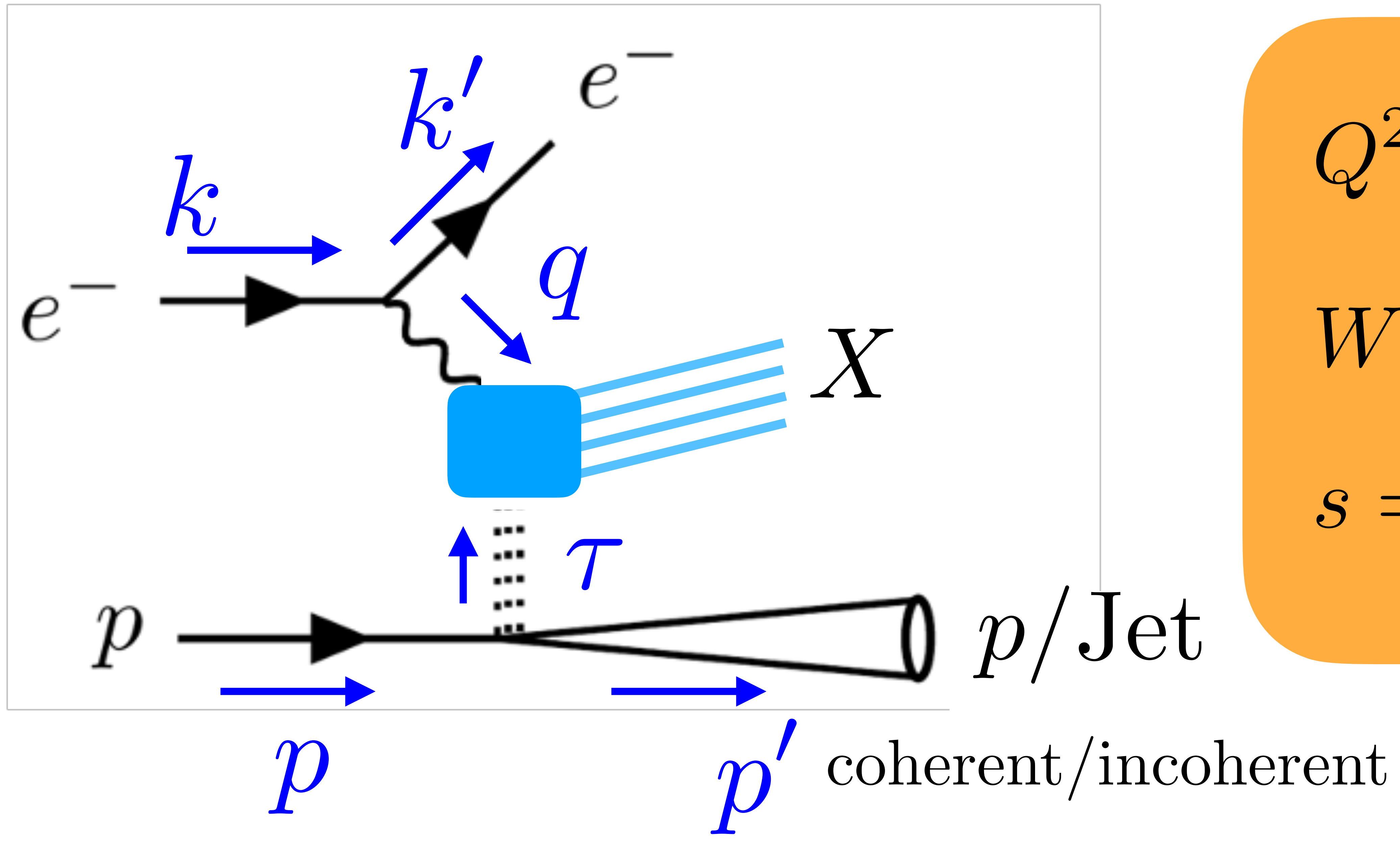
KINEMATICS



Usual DIS variables

$$Q^2 = -q^2 \quad x = \frac{Q^2}{2p \cdot q}$$

$$W^2 = (p+q)^2$$

$$s = (p+k)^2 \quad y = \frac{p \cdot q}{p \cdot k}$$

Diffraction variables

$$t = \tau^2 \quad \beta = \frac{Q^2}{2q \cdot \tau}$$

$$m_J^2 = p'^2 \quad \bar{x} = \frac{k \cdot \tau}{k \cdot p}$$

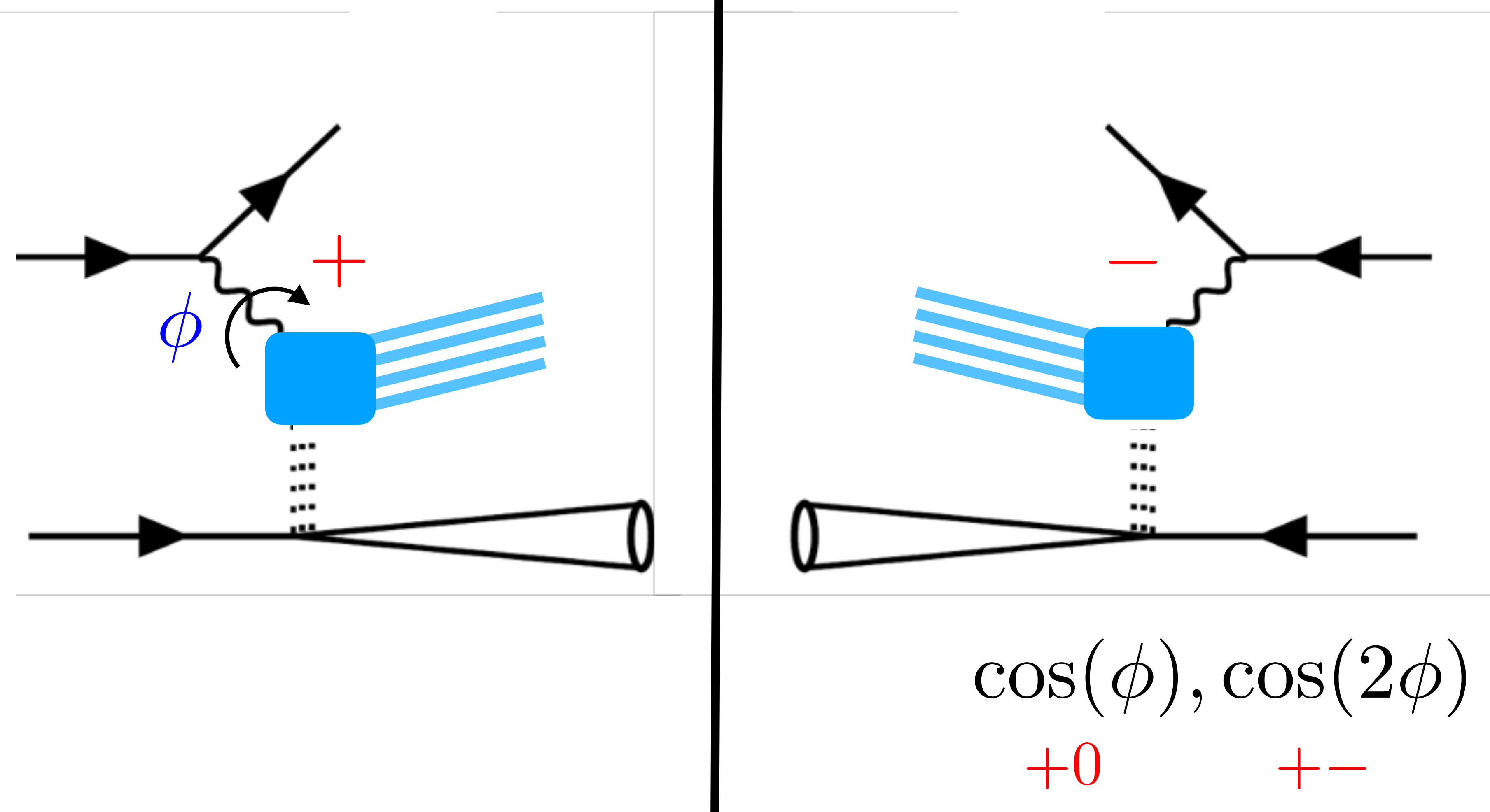
$$m_X^2 = p_X^2 \quad z = \frac{p \cdot p'}{p \cdot q}$$

- **Not all variables independent. e.g. 3 for DIS**

(in)coherent diffraction has (7) 6 independent variables :

$$\frac{d^6\sigma}{d\{x, y, \bar{x}, t, \beta, m_J^2\}}$$

STRUCTURE FUNCTION DECOMPOSITION



$$\underbrace{}_{L_{\mu\nu}}\ \underbrace{}_{W_D^{\mu\nu}}$$

$$\frac{d^6\sigma}{d\{x,y,\bar{x},t,\beta,m_J^2\}} \sim L_{\mu\nu} W_D^{\mu\nu} \sim \sum_i c_i F_i(x,Q^2,\beta,t,m_J^2)$$

$$\sim \left\{ (1-y+\frac{y^2}{2})F_2 - \frac{y^2}{2} F_L + (1-y)\cos 2\phi\, F_3 + (2-y)\sqrt{1-y}\cos\phi\, F_4 \right\}$$

- p' **dependence gives extra structure functions relative to the usual DIS** $F_i = \mathcal{P}_{i,\mu\nu}\left(\epsilon^*_{\mu,m},\epsilon_{\mu,n}\right) W^{\mu\nu}$

  FL and F2 = longitudinal and transverse photon polarization

  F3 and F4 = interference terms

  $\cos\phi = \cos\phi(\bar{x},y,\cdots)$

- y **and** $\bar{x}$ **dependence are only in the coefficients**
- **Much of the literature have missed the significance of these interference terms**

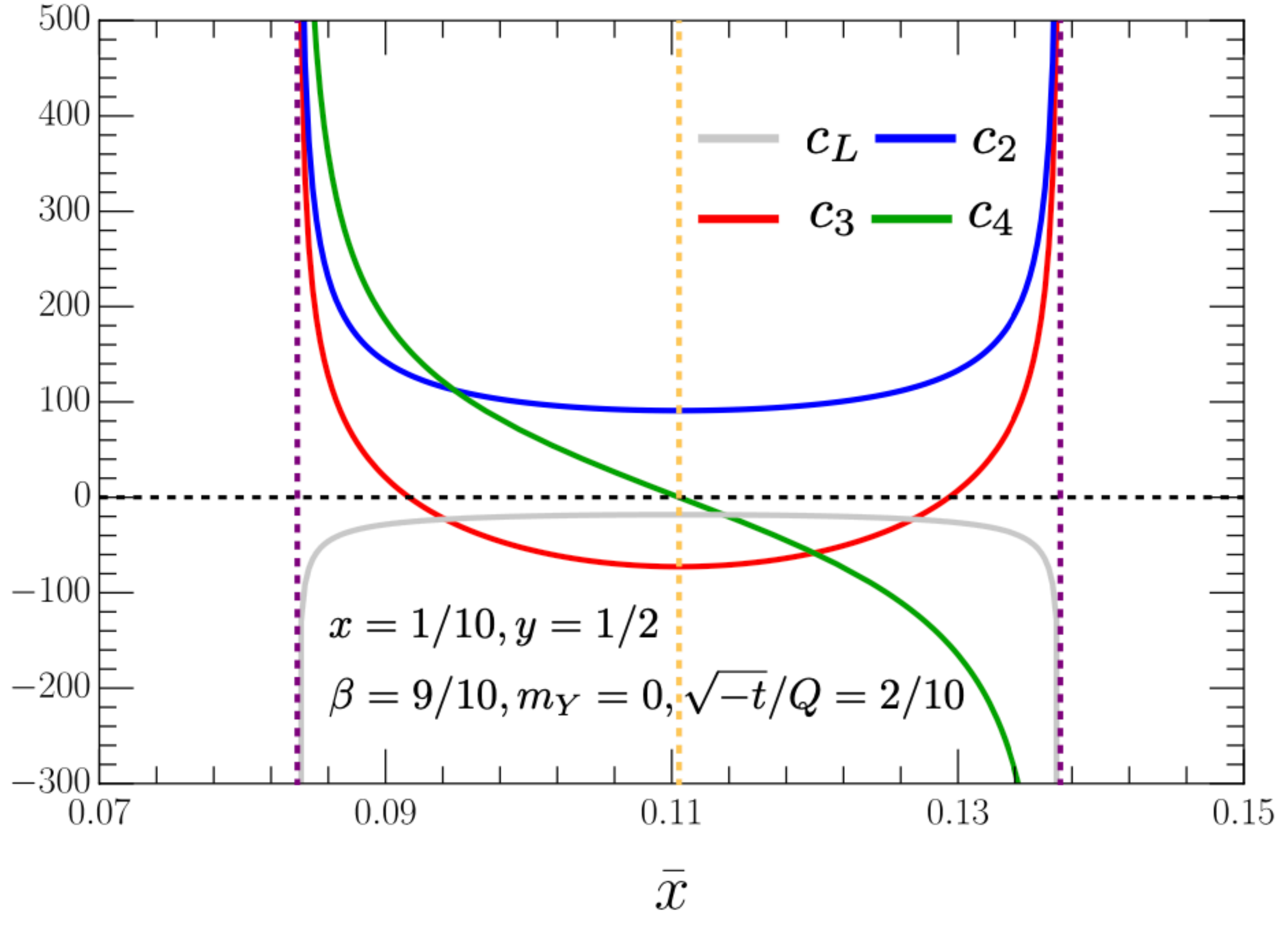
  Notable exception: *Arens, Nachtmann, Diehl, Landshoff `96, Blumlein, Robaschik `01, ZEUS `04*

STRUCTURE FUNCTION DECOMPOSITION

$$\frac{d^6\sigma}{d\{x, y, \bar{x}, t, \beta, m_J^2\}} \sim \sum_i c_i F_i(x, Q^2, \beta, t, m_J^2) \sim \Big\{(1 - y + \frac{y^2}{2})F_2 - \frac{y^2}{2}F_L + (1-y)\cos 2\phi\, F_3 + (2-y)\sqrt{1-y}\cos\phi\, F_4\Big\}$$

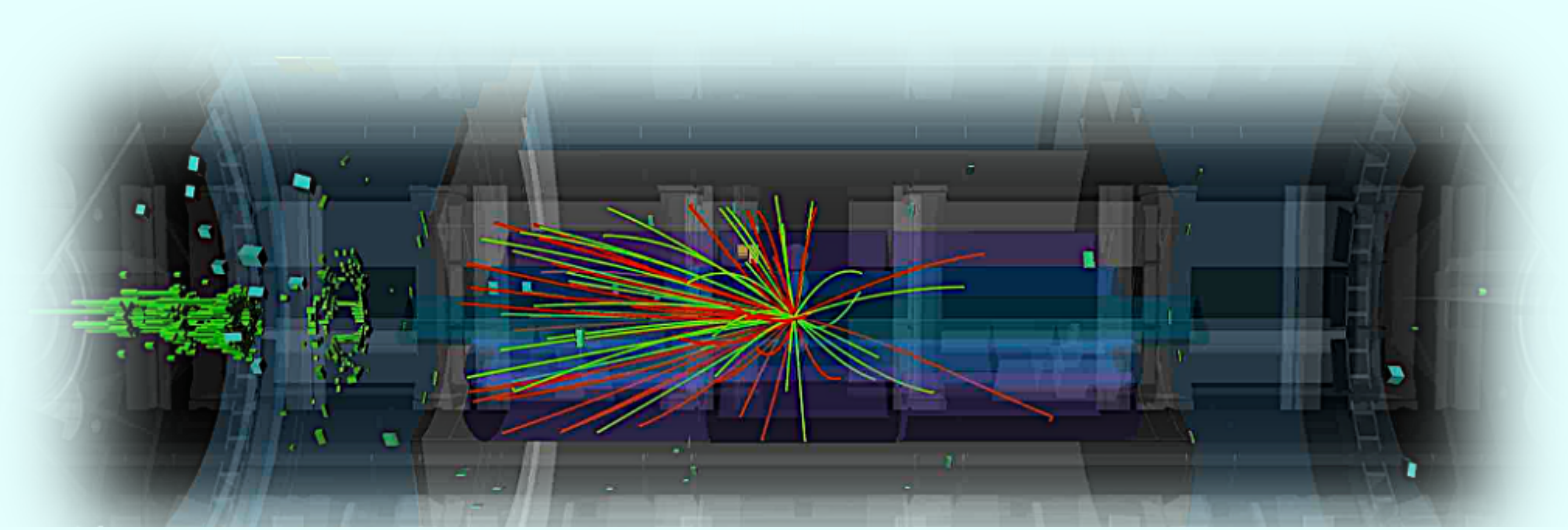
- y and $\bar{x}$ dependence are only in the coefficients

$$\cos\phi = \cos\phi(\bar{x}, y, \cdots)$$



- Much of the literature have missed the significance of these interference terms
- Great opportunities to study them!

outline



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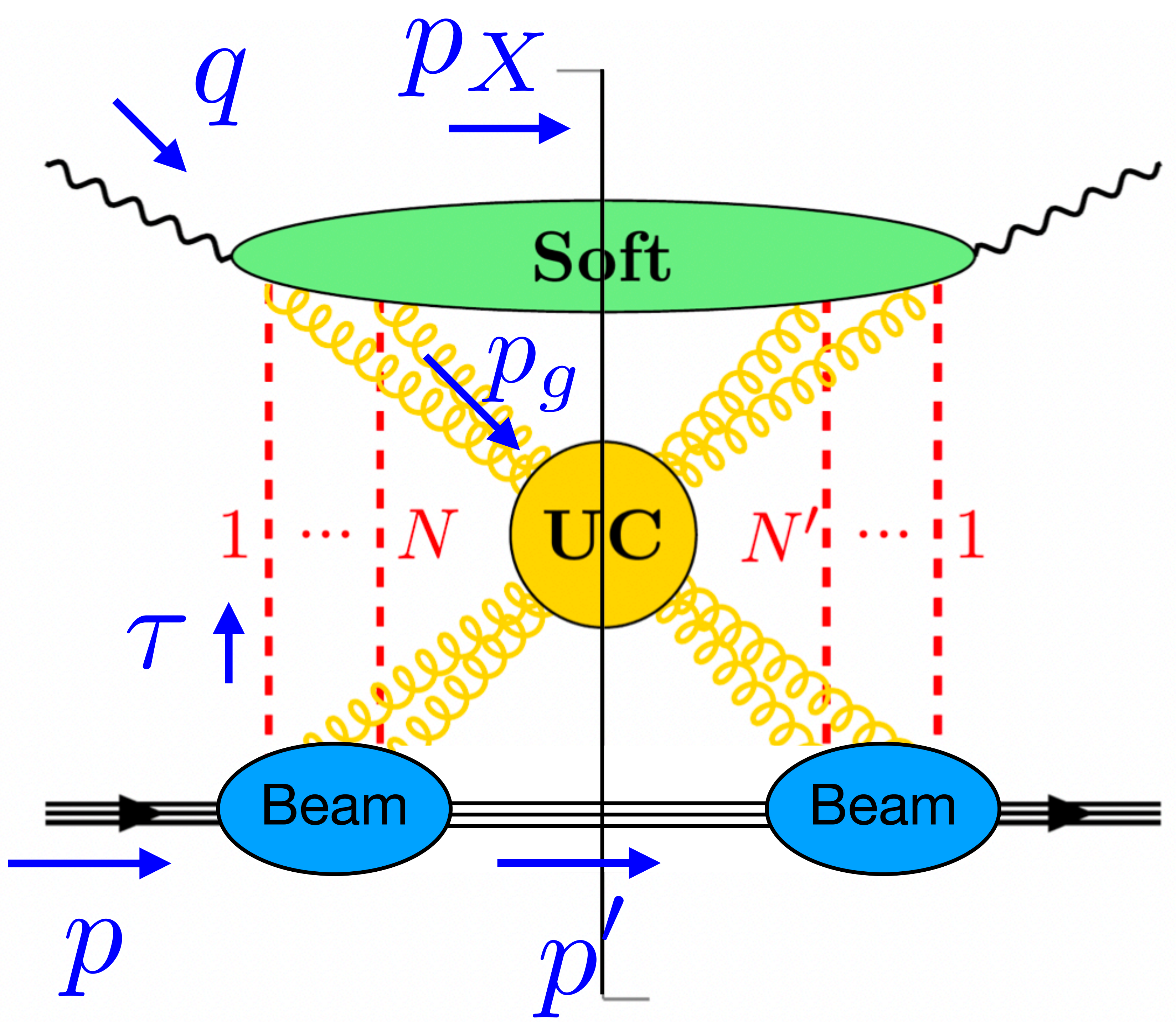
IMPOSING DIFFRACTION CONDITION



I. collimated jet conditions

$$W^2 \gg p'^2 = m_J^2, m_X^2$$

II. rapidity gap

$$\frac{p'^-}{p'^+} \gg \frac{X^-}{X^+}$$

III. Forward conditions

$$-t \ll W^2, x \ll 1$$

Ultrasoft-collinear mode:

$$p_g^\mu \sim \sqrt{s}\lambda_g^2\,(\lambda, \lambda^{-1}, 1) \sim \sqrt{s}(\lambda^3, \lambda, \lambda^2)$$

Soft mode: $q \sim \sqrt{s}(\lambda, \lambda, 0)$

$p_X \sim \sqrt{s}(\lambda, \lambda, \lambda)$

Glauber mode: $\tau \sim \sqrt{s}(\lambda^3, \lambda, \lambda)$

Collinear mode: $p' \sim \sqrt{s}(\lambda^3, \lambda^{-1}, \lambda)$

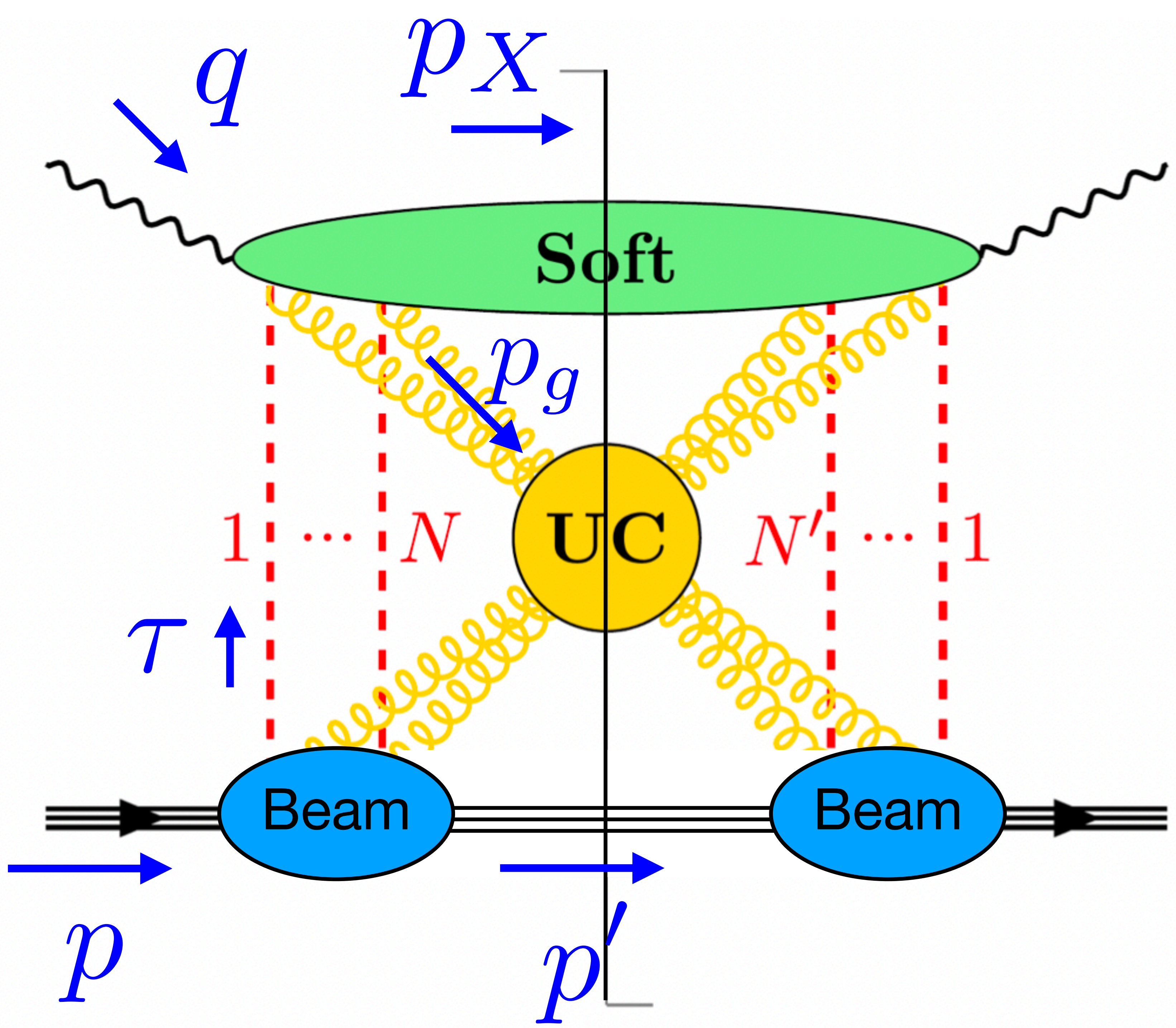
where $\lambda \sim \frac{Q}{\sqrt{s}} \sim \sqrt{x}$

In particular,

$$\tau^+\tau^- \ll \tau_\perp^2$$

i.e. glauber scaling

GLAUBER FACTORIZATION



$\lambda \sim \frac{Q}{\sqrt{s}}$

Soft mode: $q \sim \sqrt{s}(\lambda, \lambda, 0)$

$p_X \sim \sqrt{s}(\lambda, \lambda, \lambda)$

Ultrasoft-collinear mode:

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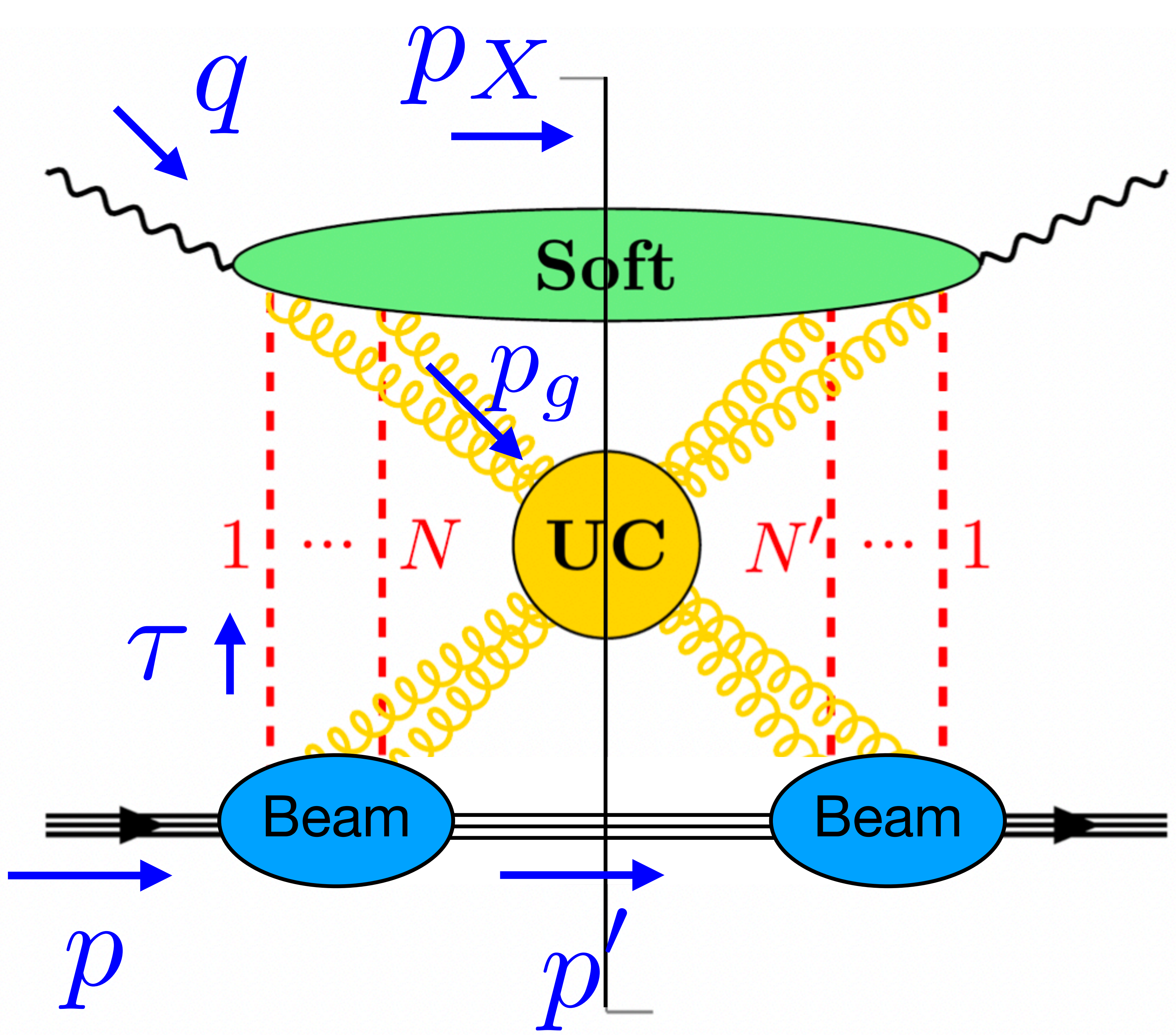
$$F_i^D = \sum_{\substack{N,N'=1\\ N+N'=\text{even}}}^{\infty} \sum_{\{R_X\}} \iint_{(N,N')}^{\perp} \int đp_n^+ đp_s^- đp_g^+ đp_g^-\, (2\pi)^2 \delta(Qz - p_n^+ - p_g^+)\,\delta(Q/\beta - p_s^- - p_g^-)$$
$$\times B^{R_A^{NN'}}_{(N,N')}(p_n^+, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, m_Y^2, \mu, \nu)\; S^{R_B^{NN'}}_{i(N,N')}(p_s^-, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \mu, \nu)$$
$$\times U^{R_A^{NN'} R_B^{NN'}}_{(N,N')}(x^{-1/2} p_g^+, x^{1/2} p_g^-, \mu).$$

Convolution structures between momentum components that are identical in size

where S and B are, respectively, vacuum and hadronic matrix elements with Glauber operators

What the QCD community wanted for decades!

GLAUBER FACTORIZATION



$$\lambda \sim \frac{Q}{\sqrt{s}}$$

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$$\times\, B_{(N,N')}^{R_A^{NN'}}\left(p_n^+, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, m_Y^2, \mu, \nu\right)\, S_{i(N,N')}^{R_B^{NN'}}\left(p_s^-, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \mu, \nu\right)$$

$$\times\, U_{(N,N')}^{R_A^{NN'} R_B^{NN'}}\left(x^{-1/2} p_g^+, x^{1/2} p_g^-, \mu\right).$$

Turns into delta function for color-singlet process

where S and B are, respectively, vacuum and hadronic matrix elements with Glauber operators

What the QCD community wanted for decades!

GENERAL POWER COUNTING

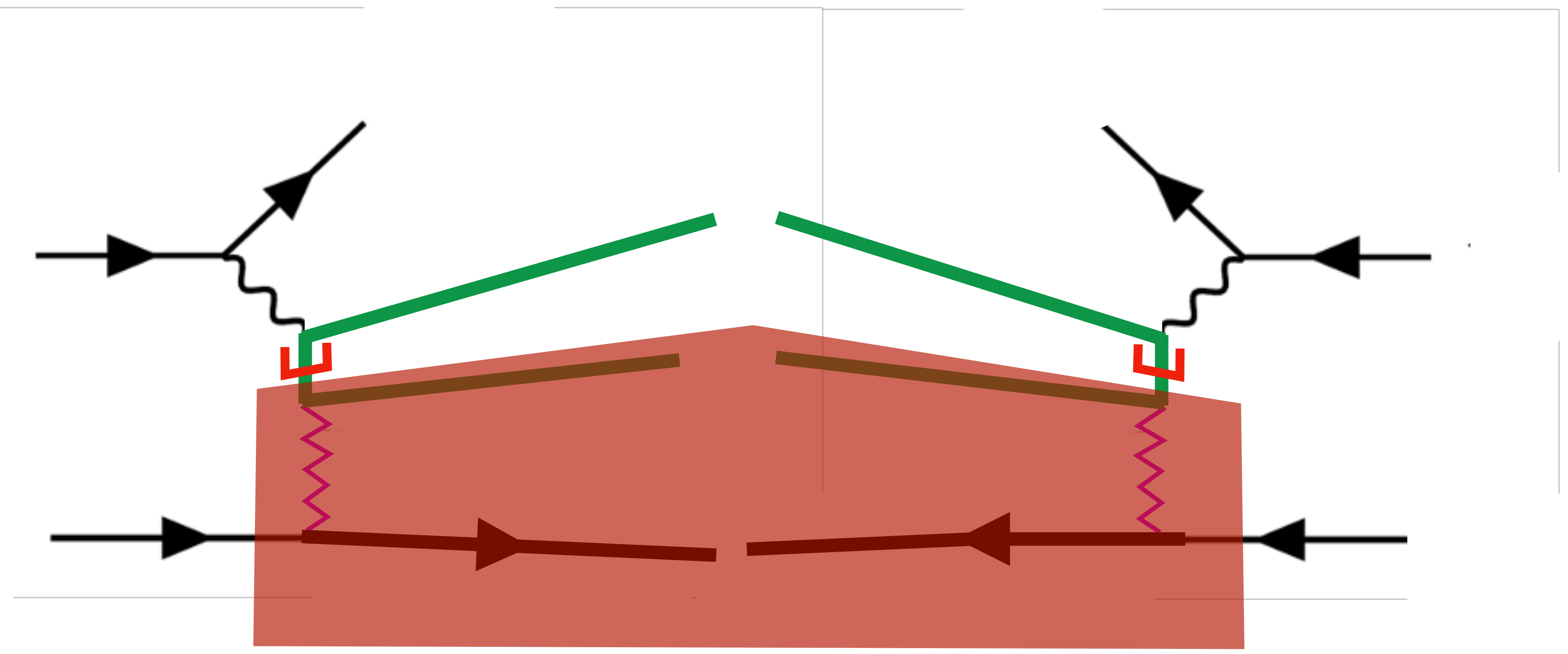
- **Diffractive process have multiple ratio of mass scales that enrich the analyses**

$$\lambda = \frac{Q}{\sqrt{s}}\,, \qquad \lambda_t = \frac{\sqrt{-t}}{Q}\,, \qquad \rho = \frac{m_J}{\sqrt{-t}}\,, \qquad \lambda_\Lambda = \frac{\Lambda_{\rm QCD}}{Q}$$

- **hard-collinear factorization**

Diffractive PDF

$$\xi = \frac{x}{\beta}$$



$$F_2 \sim \sum_\kappa \int_\beta^1 \frac{d\zeta}{\zeta} H_2^{(\kappa)}\left(\frac{\beta}{\zeta}, Q, \mu\right) f^D_{\kappa/p}\left(\zeta, \xi, t, m_J^2, \mu\right)\left(1 + \mathcal{O}\left(\lambda_t\right)\right) \longleftarrow \text{small } \lambda_t$$

Collins `97, Berera, Soper `95

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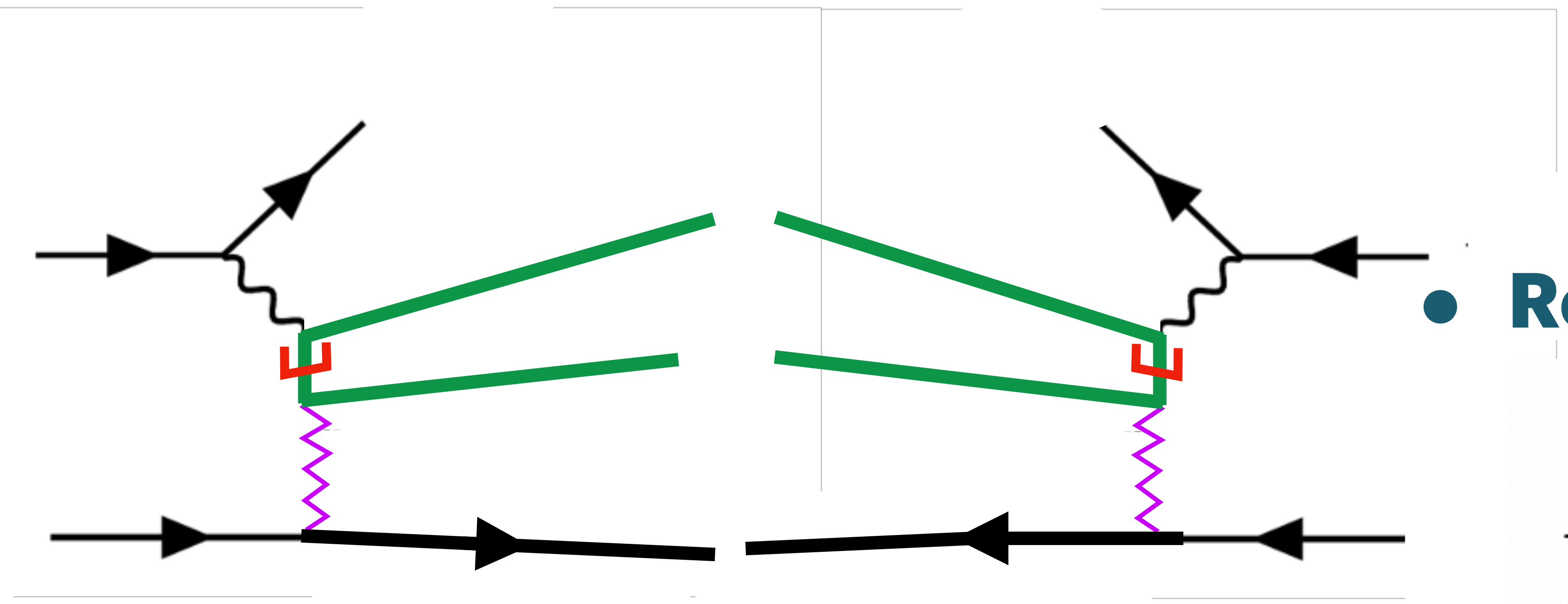

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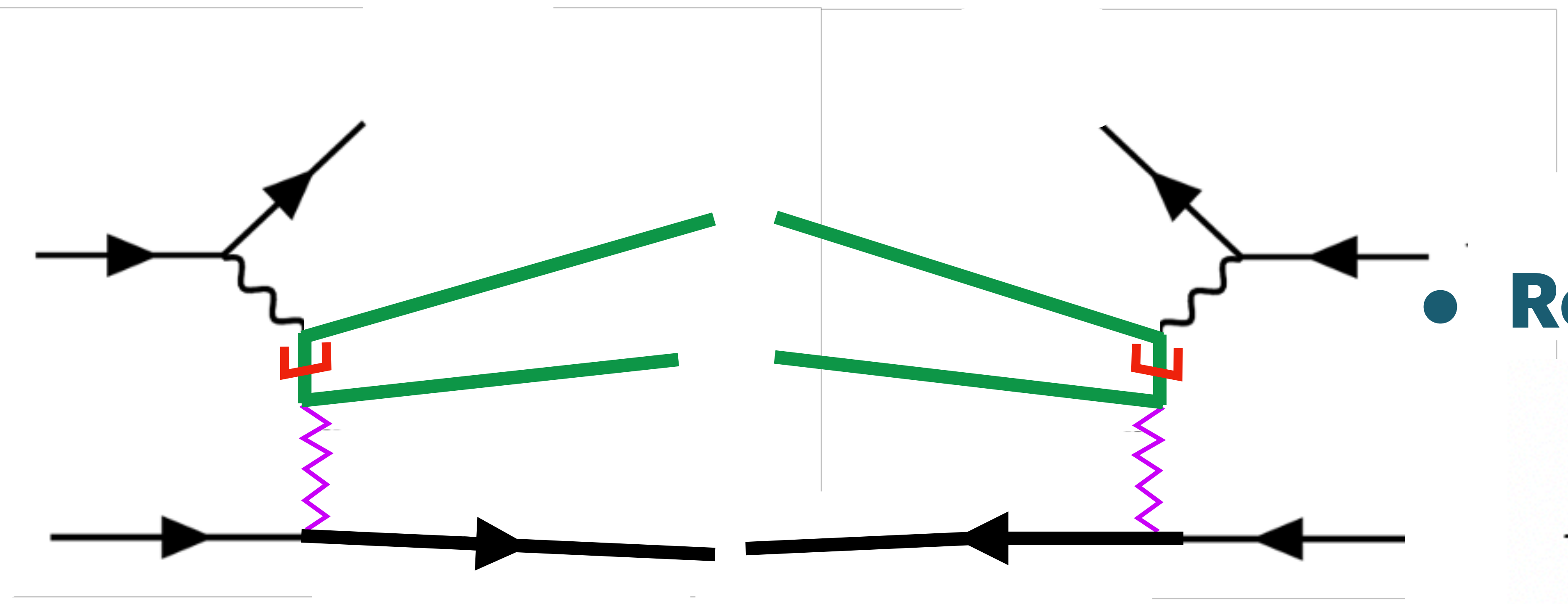
- **Regge / forward scattering factorization** (For singlet)

$$F_i^{D\,\rm diff} = \sum_{\substack{N,N'=1 \\ N+N'=\rm even}}^{\infty} \sum_{R^{NN'}=1} \iint_{(N,N')}^{\perp} B^{R^{NN'}}_{(N,N')}(Qz, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, m_Y^2, \nu) \times S^{R^{NN'}}_{i(N,N')}(Q/\beta, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \nu). \longleftarrow \text{small } \lambda$$

GENERAL POWER COUNTING

- **Diffractive process have multiple ratio of mass scales that enrich the analyses**

$$\lambda = \frac{Q}{\sqrt{s}}\,, \qquad \lambda_t = \frac{\sqrt{-t}}{Q}\,, \qquad \rho = \frac{m_J}{\sqrt{-t}}\,, \qquad \lambda_\Lambda = \frac{\Lambda_{\rm QCD}}{Q}$$



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- **Simultaneous limits**

$$F_i^{D\,\rm diff} = \sum_{j,\delta} \int_\beta^1 \frac{d\zeta}{\zeta} \mathcal{H}_i^{j,\delta}\left(\frac{\beta}{\zeta}, Q, \mu\right) \sum_{\substack{N,N'=1\\ N+N'={\rm even}}}^{\infty} \sum_{R^{NN'}=1} \iint_{(N,N')}^{\perp} B^{R^{NN'}}_{(N,N')}\left(Qz, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, m_Y^2, \nu\right) \times S^{j,\delta;R^{NN'}}_{{\rm cs}(N,N')}\left(\zeta, Q/\beta, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, \nu, \mu\right) \longleftarrow \text{small } \lambda, \lambda_t$$

REFACTORIZATION OF DPDF

$$f^D_{\kappa/p}\left(\zeta,\xi,t,m_J^2,\mu\right) = \sum_{\substack{N,N'=1\\ N+N'=\text{even}}}^{\infty} \sum_{R^{NN'}=1} \iint^{\perp}_{(N,N')} B^{R^{NN'}}_{(N,N')}(Qz,\{\tau_{i\perp},\tau'_{j\perp}\},t,m_Y^2,\nu)\, S^{\kappa;R^{NN'}}_{\text{cs}(N,N')}\left(\zeta,Q/\beta,\left\{\tau_{i\perp},\tau'_{j\perp}\right\},t,\nu,\mu\right)$$

- **Simultaneous expansion in λ and λ_t give explicit refactorization of the diffractive pdf studied in the literature**

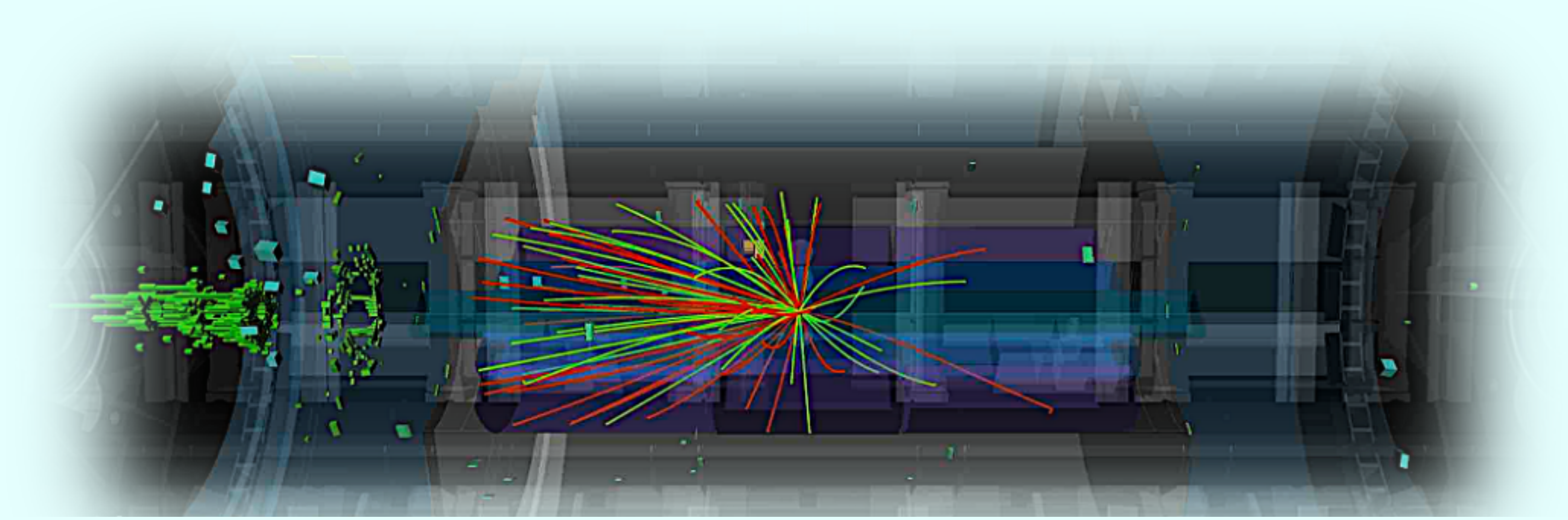
$$f^D_{\kappa/p} \propto S^{\kappa}_{\text{cs}}(\zeta,Q/\beta,\{\tau_{i,\perp}\},t) \otimes_\perp B(Qz,\{\tau_{i,\perp}\},t) \qquad \text{(Effective Field Theory Method)}$$

$$f^D_{\kappa/p} \propto \frac{1}{8\pi^2}\left|\beta_p(t)\right|^2 \xi^{-2\alpha(t)} f_{a/\mathbb{P}}\left(\zeta/\xi,t,\mu\right) \qquad \text{(Ingelman-Schlein Model)}$$

"**Unfortunately, Regge theory in the form used by Ingelman and Schlein has not been derived from QCD, and indeed is probably false**"

Collins `97, `01

outline



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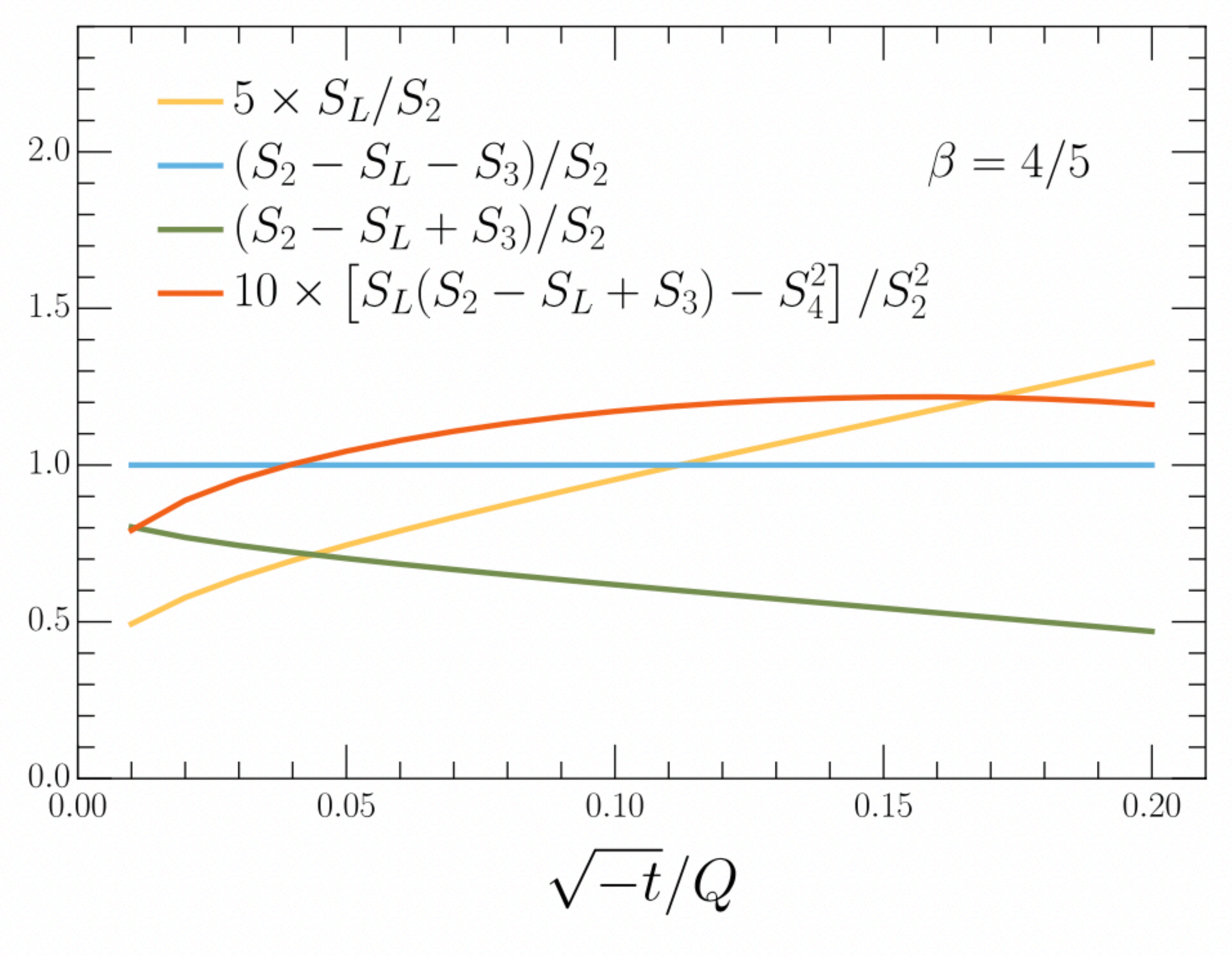
RATIO OF STRUCTURE FUNCTIONS

$$\frac{F_i(x,Q^2,\beta,t)}{F_2(x,Q^2,\beta,t)}\Big|_{\rm LO} = \frac{S_i(x,Q^2,\beta,t)}{S_2(x,Q^2,\beta,t)}\Big|_{\rm LO} \equiv \hat{S}_i\left(\beta,\frac{\sqrt{-t}}{Q}\right)$$



- **Convolution turns into a product form for the single glauber case (say singlet photon)**
- **$\hat{S}_4$ is suppressed in λ_t relative to $\hat{S}_2, \hat{S}_3, \hat{S}_L$**
- **Each of these combinations must be positive**

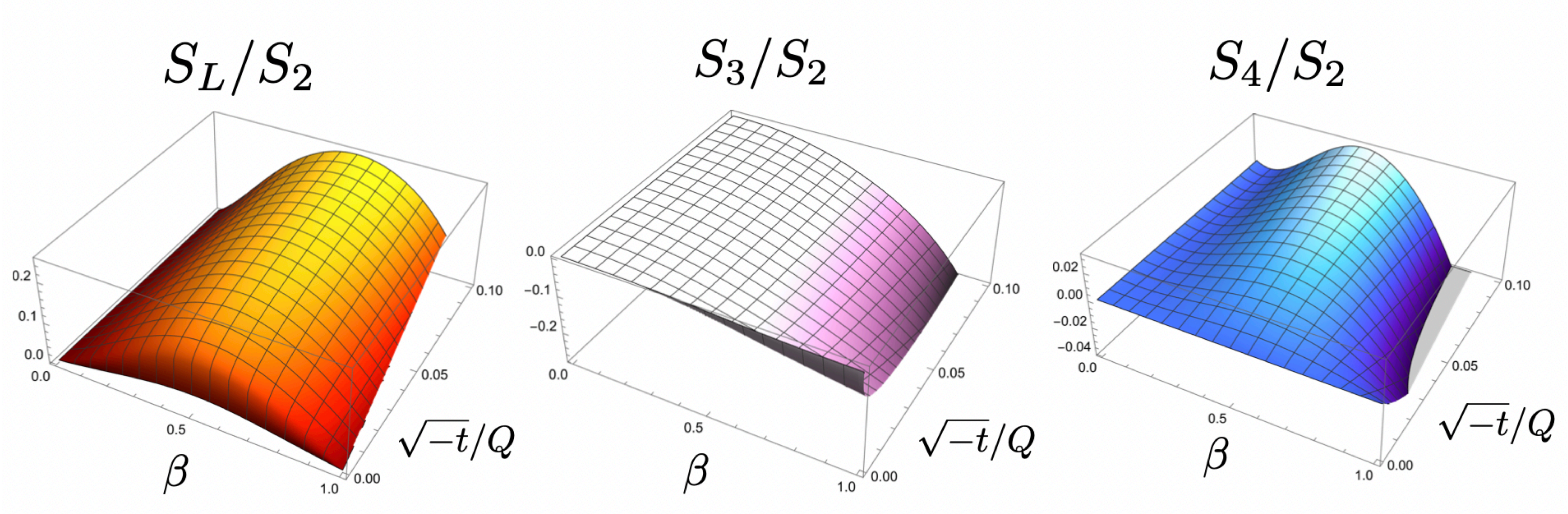
Comes from the fact that the cross-section matrix of various helicity states of virtual photon and proton must be positive-definite.

RATIO OF STRUCTURE FUNCTIONS

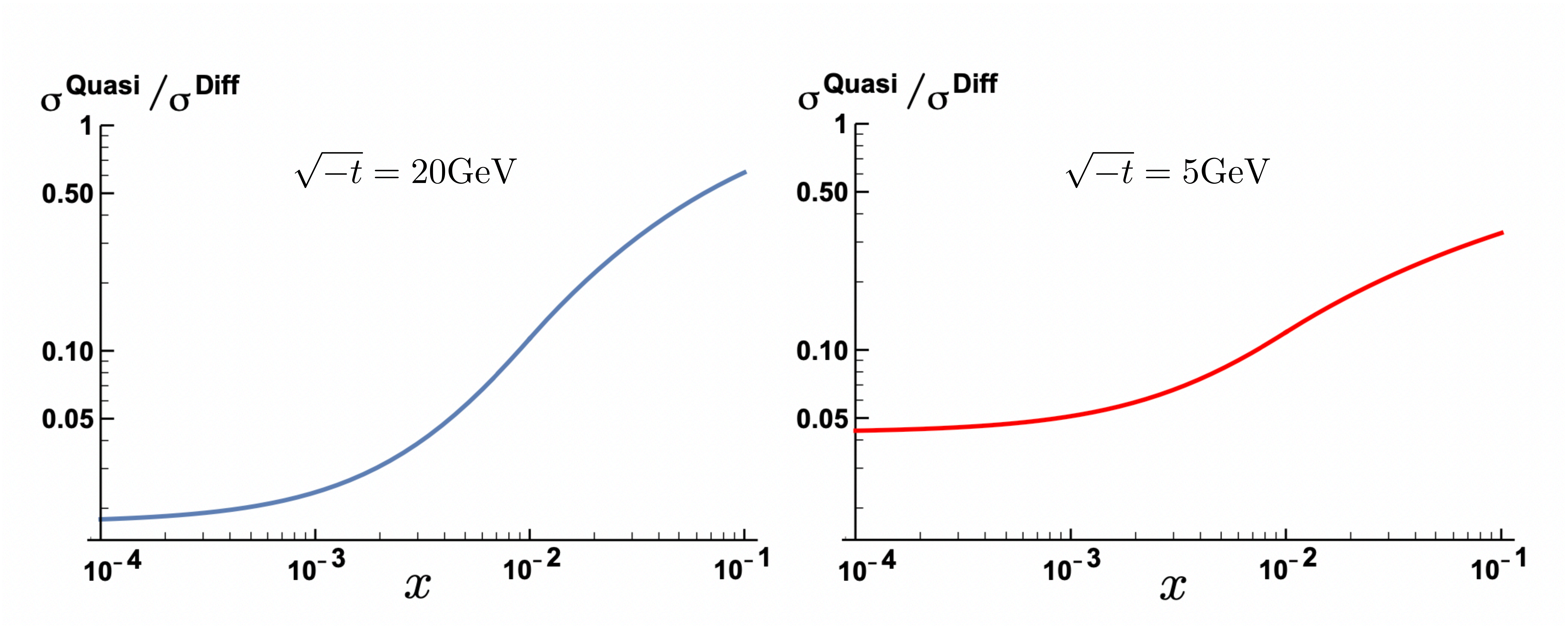
$$\frac{F_i(x,Q^2,\beta,t)}{F_2(x,Q^2,\beta,t)}|_{\rm LO} = \frac{S_i(x,Q^2,\beta,t)}{S_2(x,Q^2,\beta,t)}|_{\rm LO} \equiv \hat{S}_i\left(\beta, \frac{\sqrt{-t}}{Q}\right)$$

- **Concrete perturbative predictions for the diffraction!**

- **With the larger coefficients for F_3 relative to F_L, we have a great opportunity to measure new structure function!**

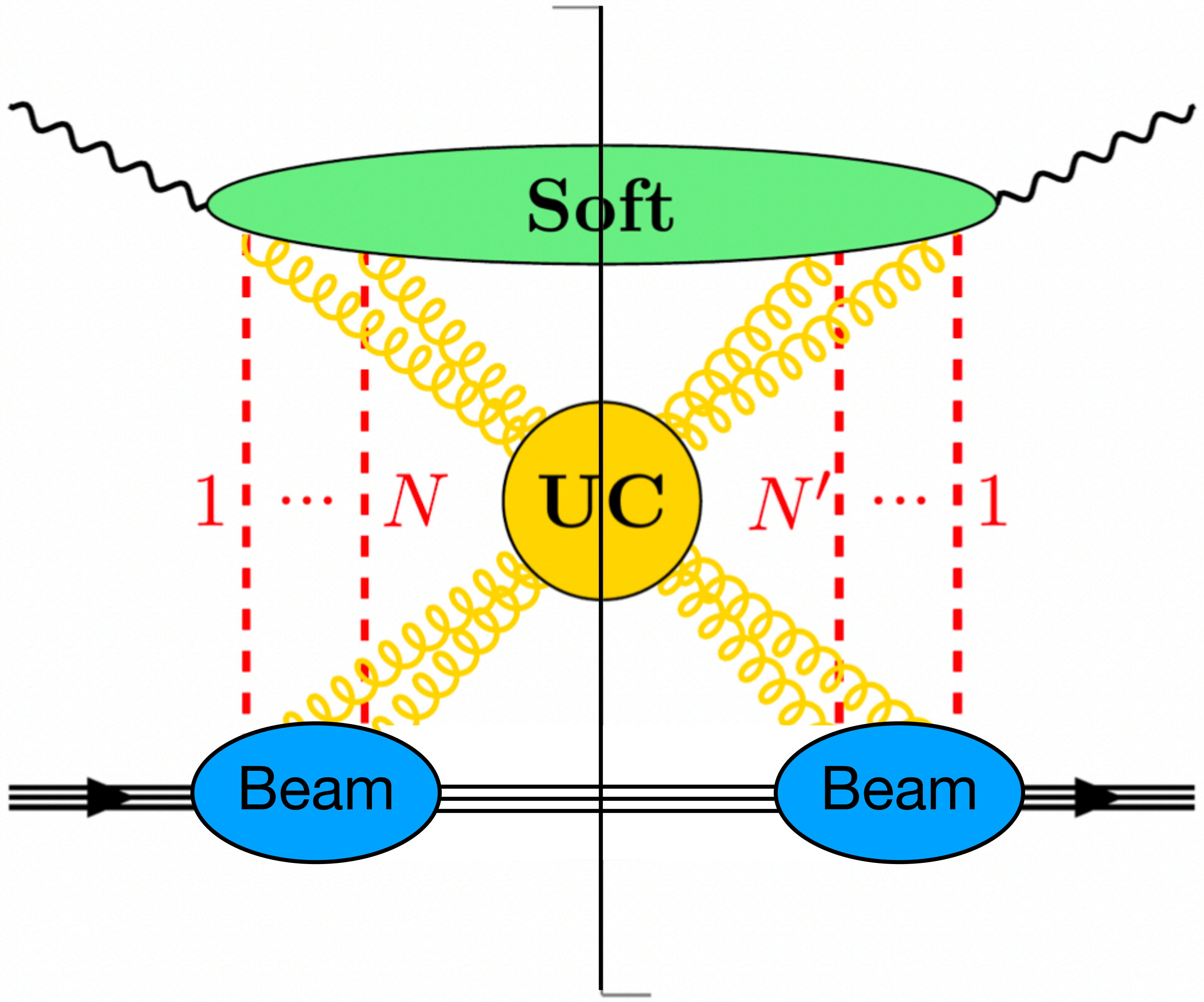


NON-SINGLET BACKGROUND

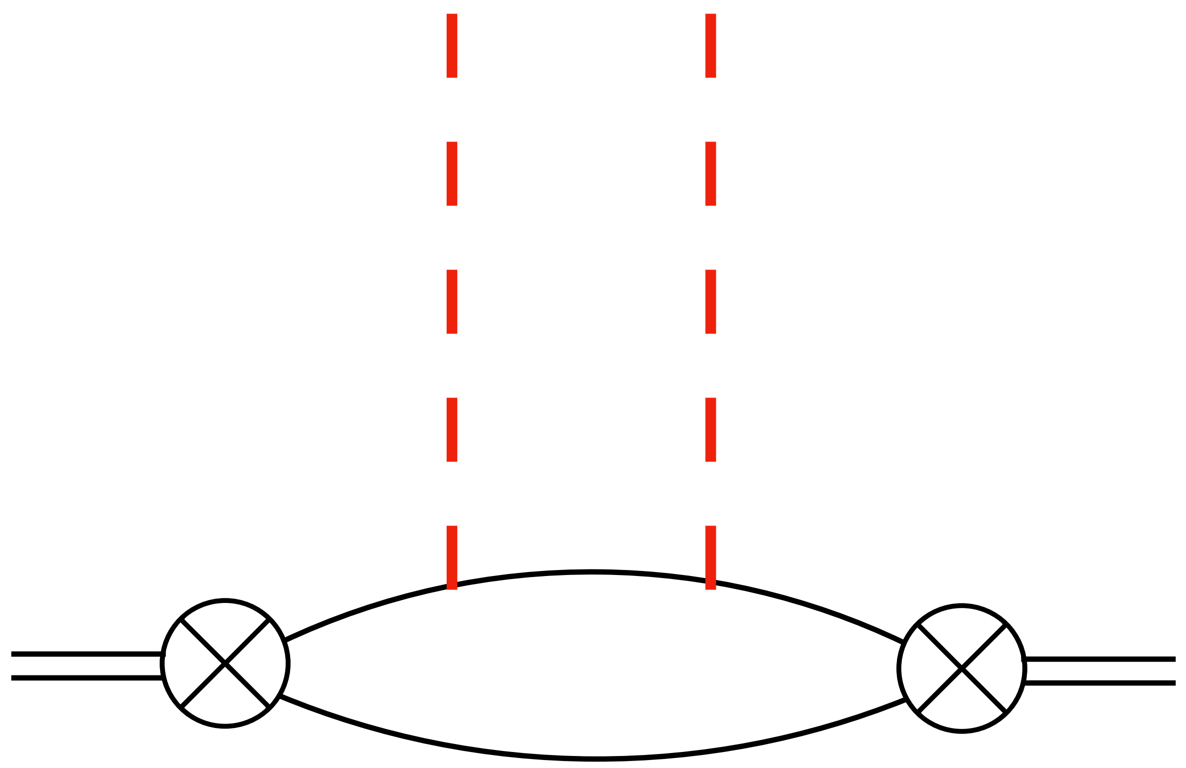


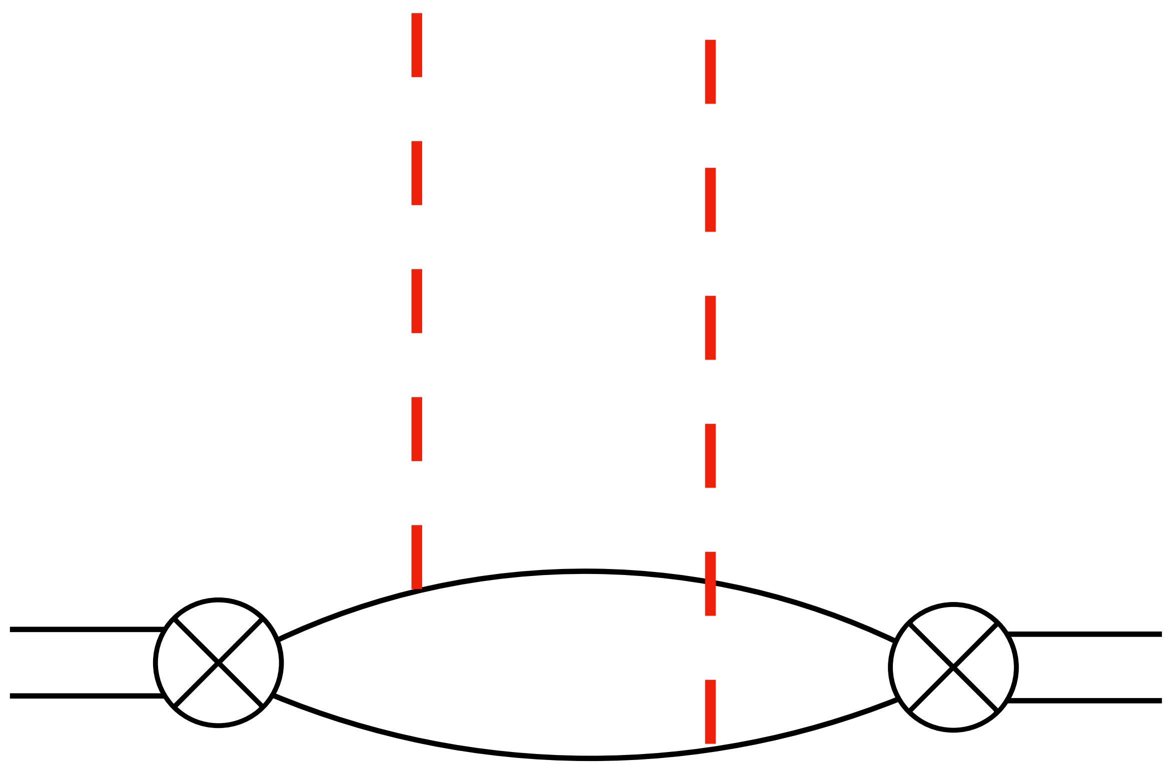
- **Sudakov suppression for the quasi-diffractive process**

NEW HADRON STRUCTURE ?



- Look at the beam function at the amplitude level





- Glauber interactions are instantaneous in time and longitudinal coordinate.
- The collapse gives the same matrix element as GPD when glaubers attach to the same fermion line

CONCLUSION

- **Carried out power-counting analyses for different hierarchy of scales present for diffraction**
- **Achieved factorization using Glauber SCET for diffractive processes for both singlet diffraction and non-singlet background**
- **Carried out simultaneous expansion in λ and λ_t in order to factorize the diffractive PDF and identify the usual hard matching coefficients from the soft-functions**
- **Explicit predictions of the single glauber level soft functions and of the Sudakov suppression from the nonsinglet background**

OUTLOOK

- **Higher order and resummation**
- **Connection to saturation**
- **Analysis of the beam-functions**