Taming Diffractive Scattering with Effective Field Theory

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<u>YITP International School on EIC Physics</u>
Kyoto University
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- arXiv:2508.10231 (JHEP), with Kyle Lee and Stella Schindler
- work in progress with Kyle Lee, Stella Schindler, and Philipp Aretz

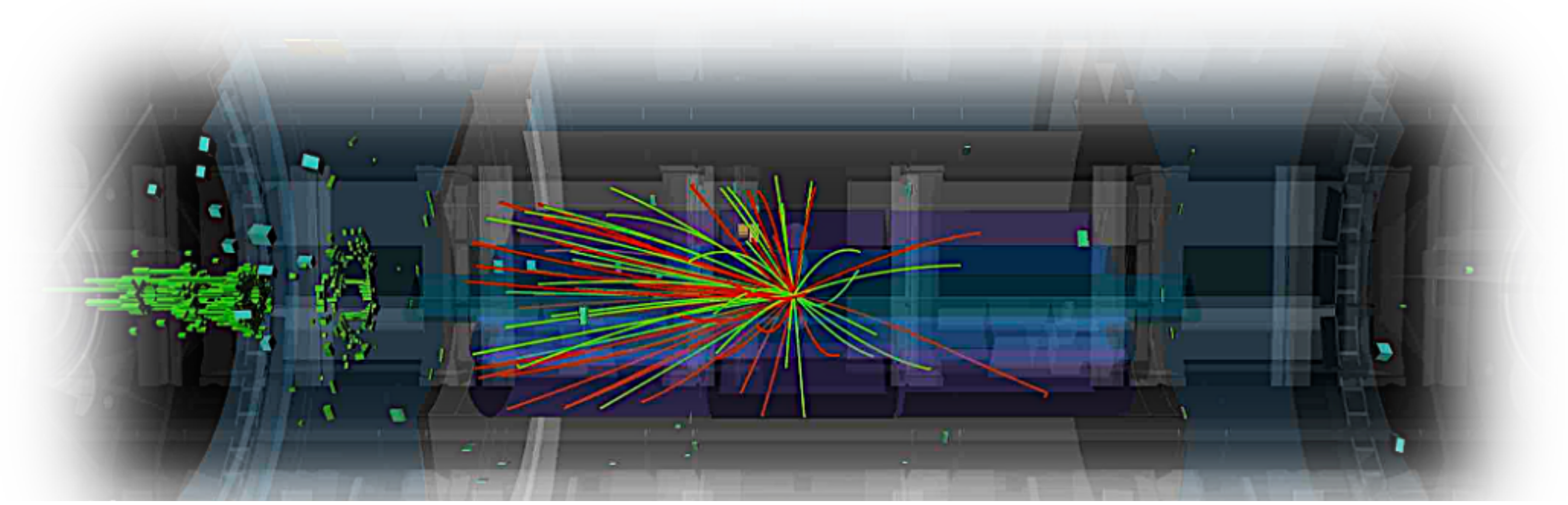

(ANL)


(LANL/Harvard)


(MIT)

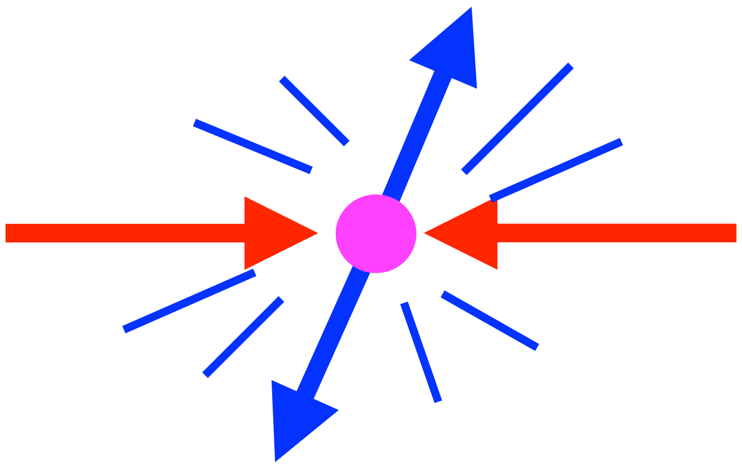
Outline

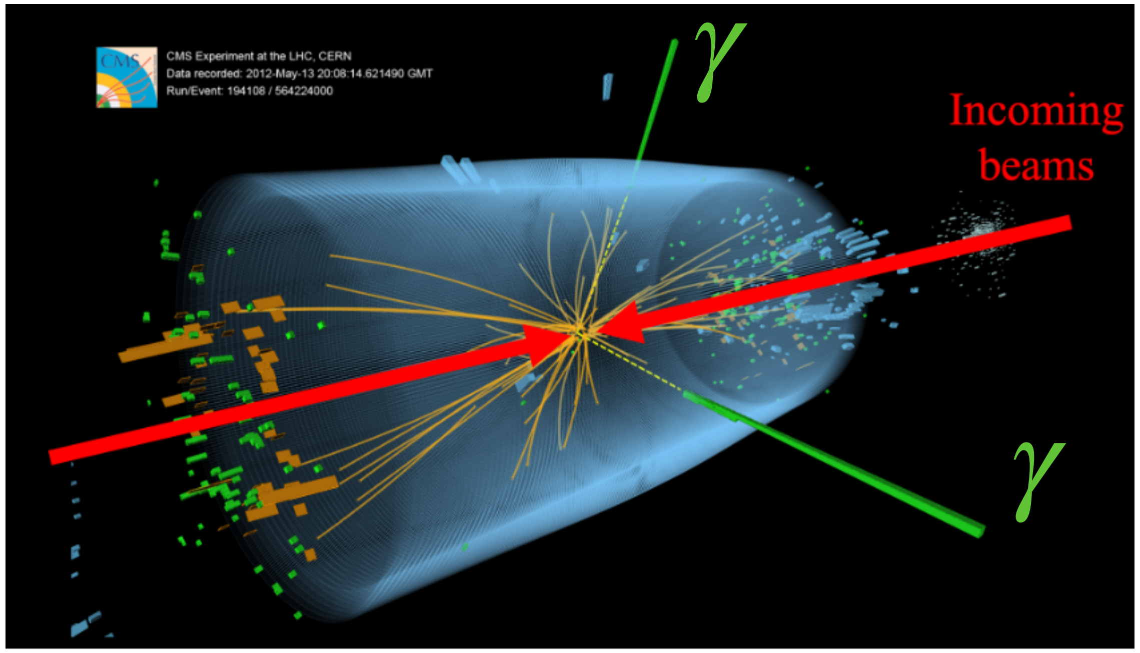
- Introduction: Diffraction
- Introduction: Soft Collinear Effective Theory (SCET)
- Kinematics and Structure Functions
- Power Counting and Regge Factorization
- Applications and Phenomenology



Hard Scattering versus Diffractive Scattering

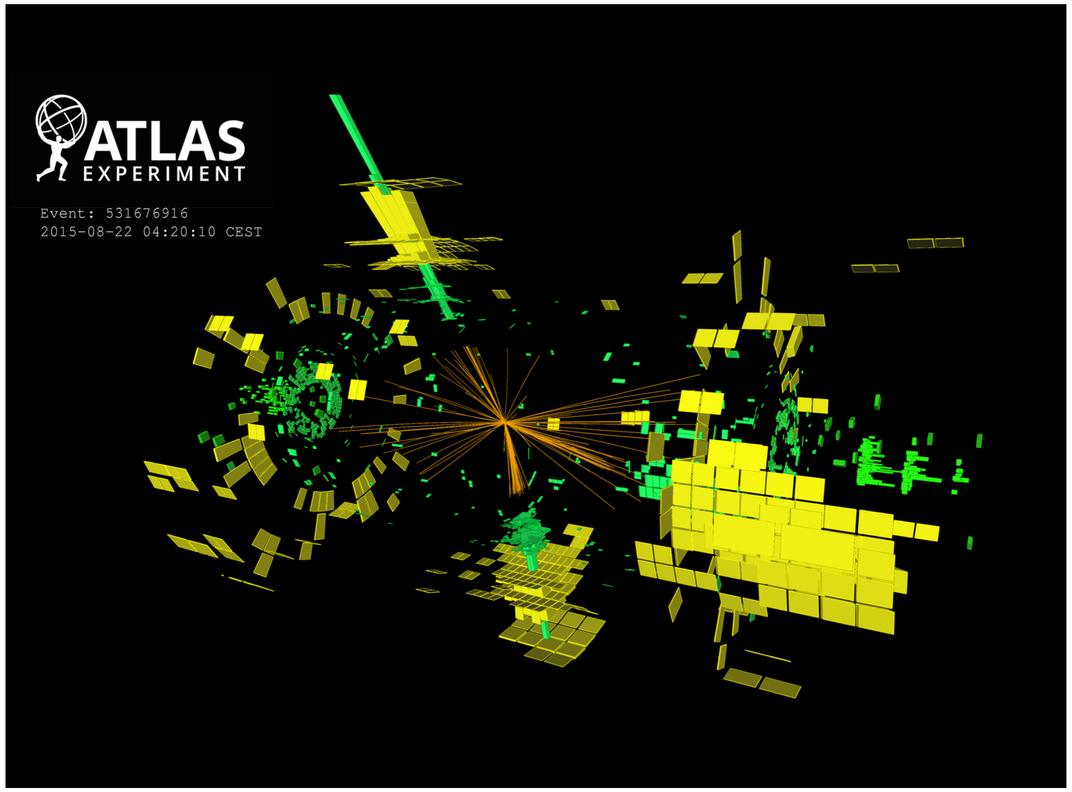
Hard Scattering Collisions





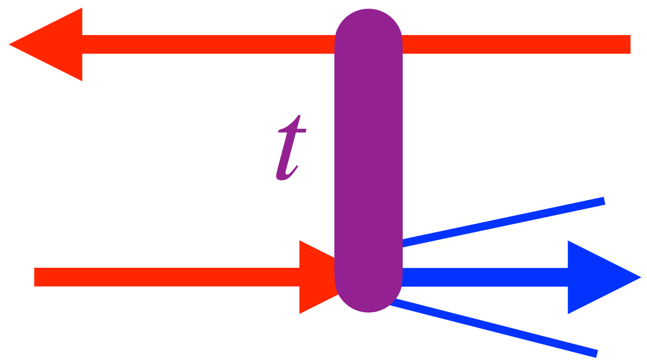
- energetic particles transverse to the beam
- probe physics at large energy Q^2
- measure particles (H, W, top, …)

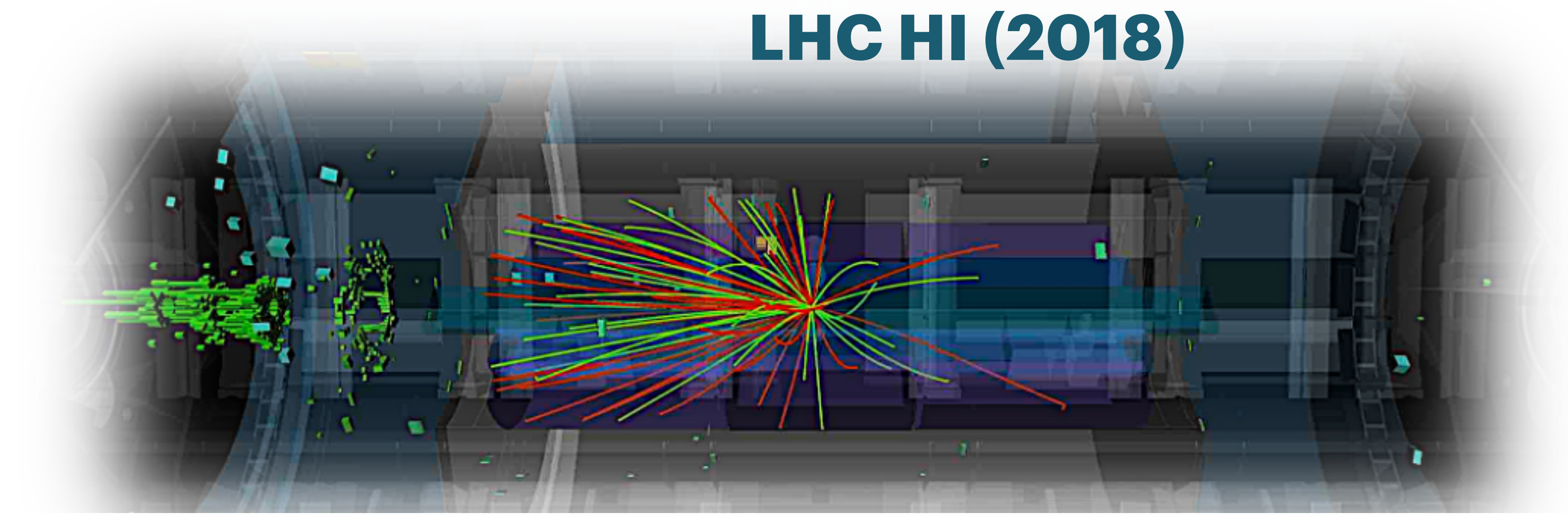
  & interactions in standard model



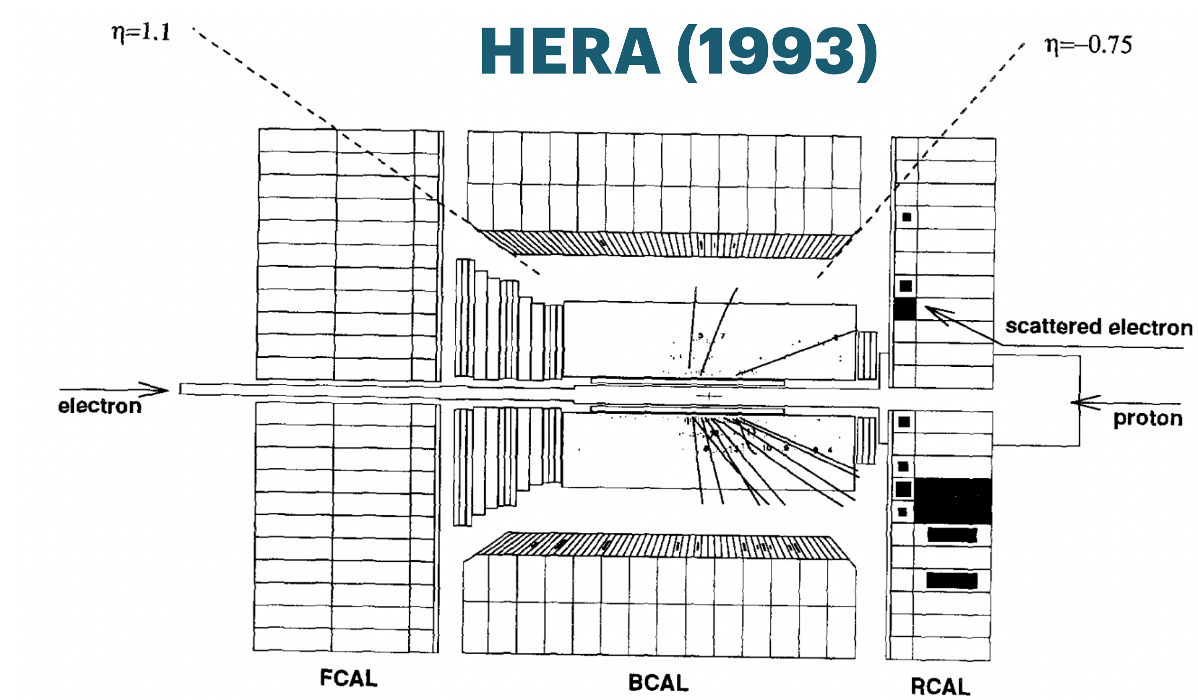
- search for new physics
- study dynamics of the proton

Diffractive Scattering



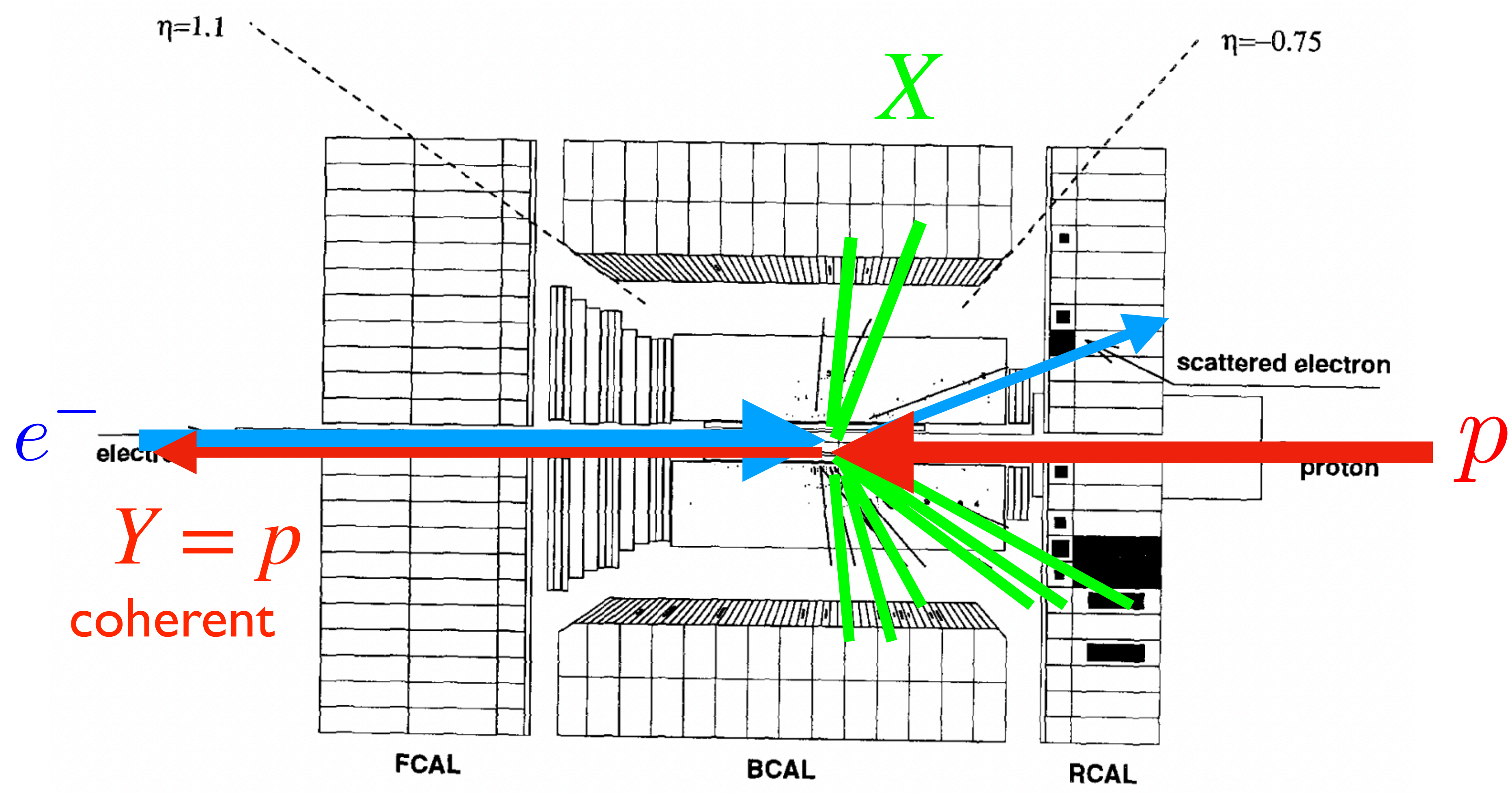


- forward scattering process
- (small momentum transfer)^2 = t
- scattered particles may remain intact (coherent) or not (incoherent)
- empty angular region ("rapidity gap")



Diffractive Deep Inelastic Scattering (DIS)

- **HERA (1993)**

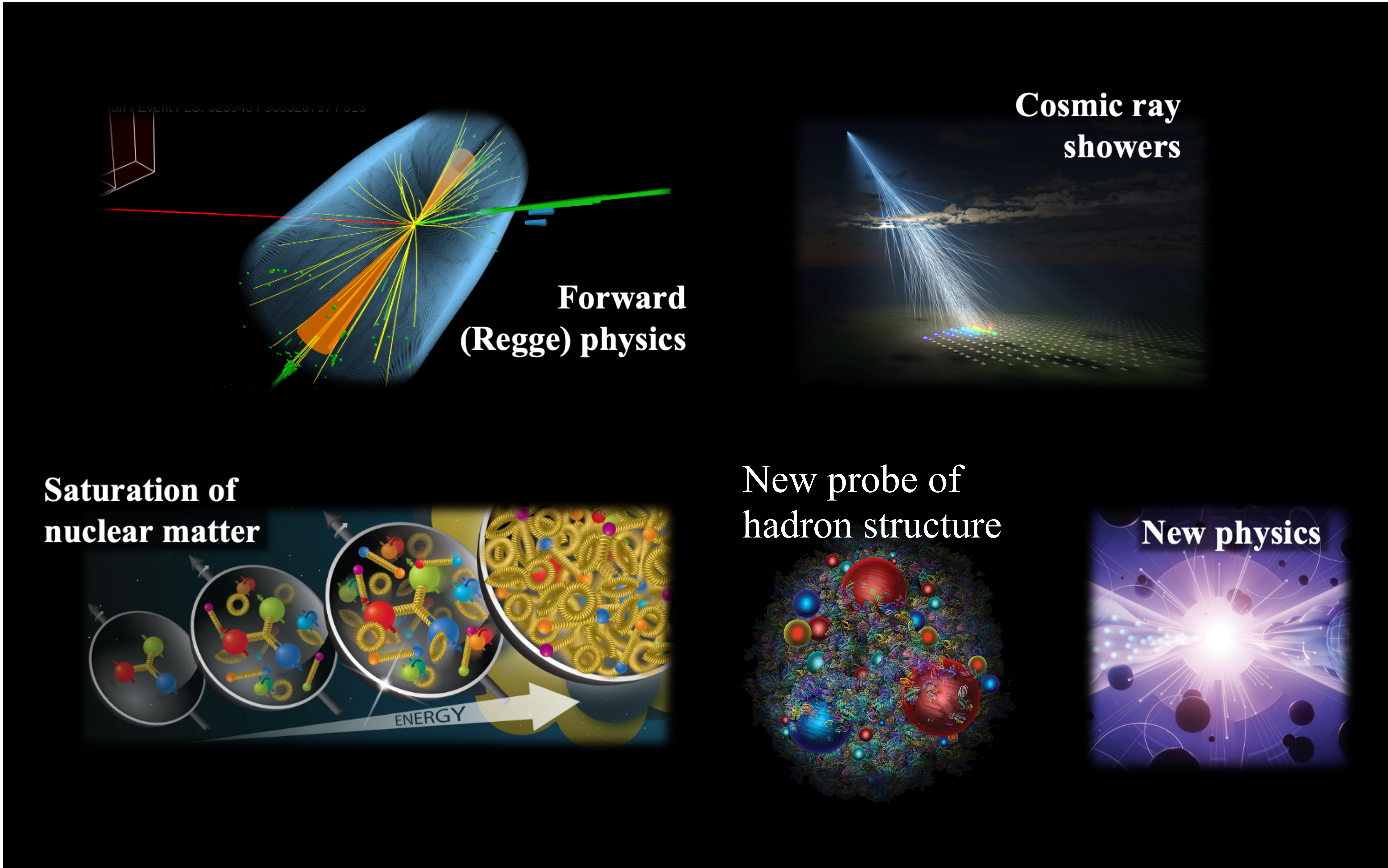


Focus today: single gapped Diffractive DIS

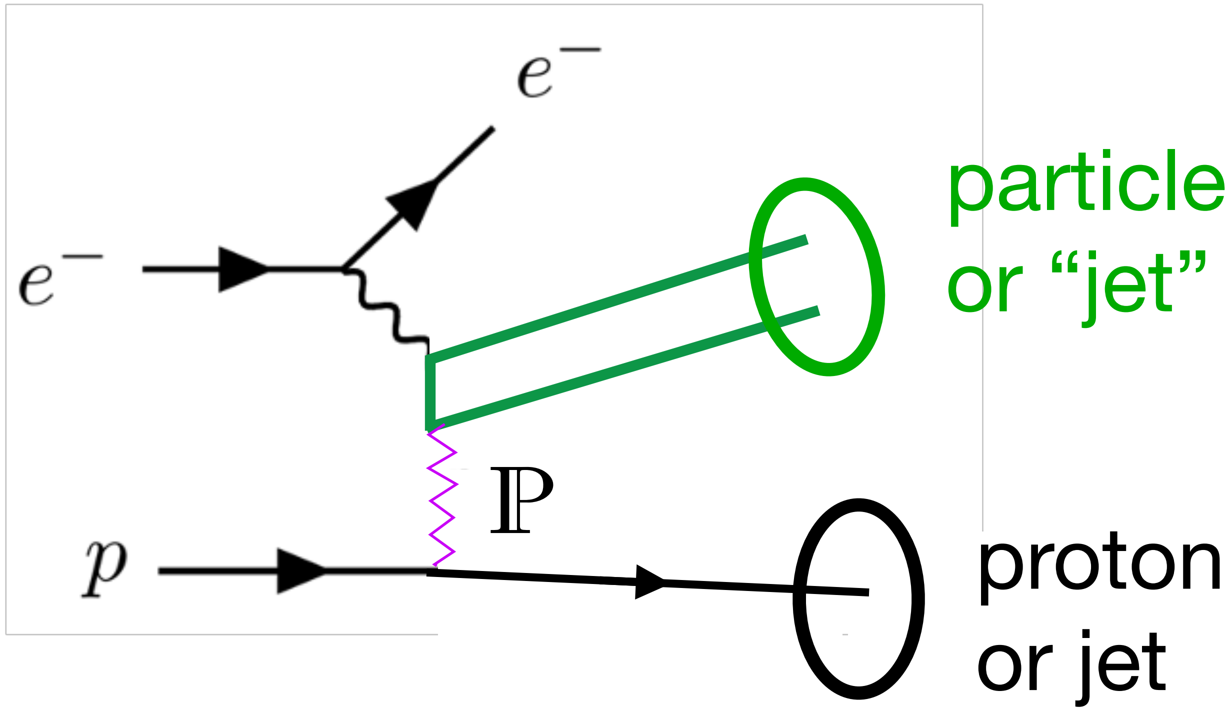
$e^- p \to e^- X Y$, X & Y systems separated by angular gap

I will also briefly discuss the extension to pp scattering.

Why study diffraction?



Why study Diffraction?



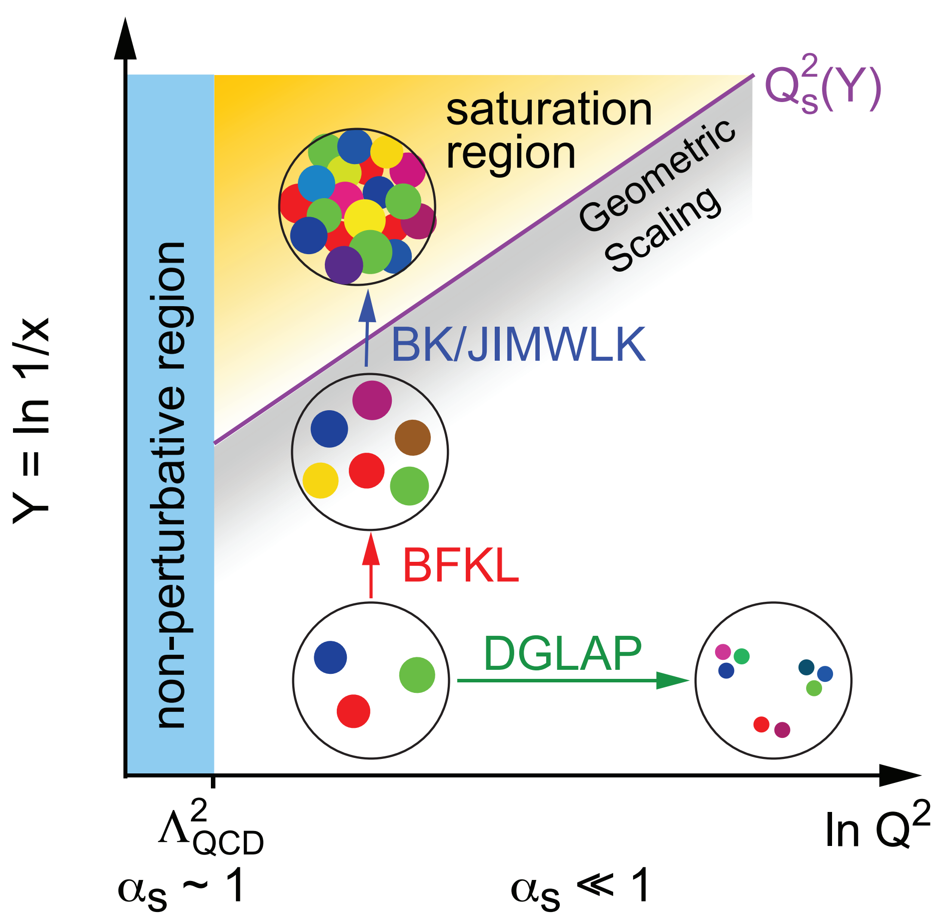


Figure from [Accardi et al, 1212.1701]

- **Diffractive cross-sections give direct and leading access to Regge physics!**

➡ ***Nature of pomeron***

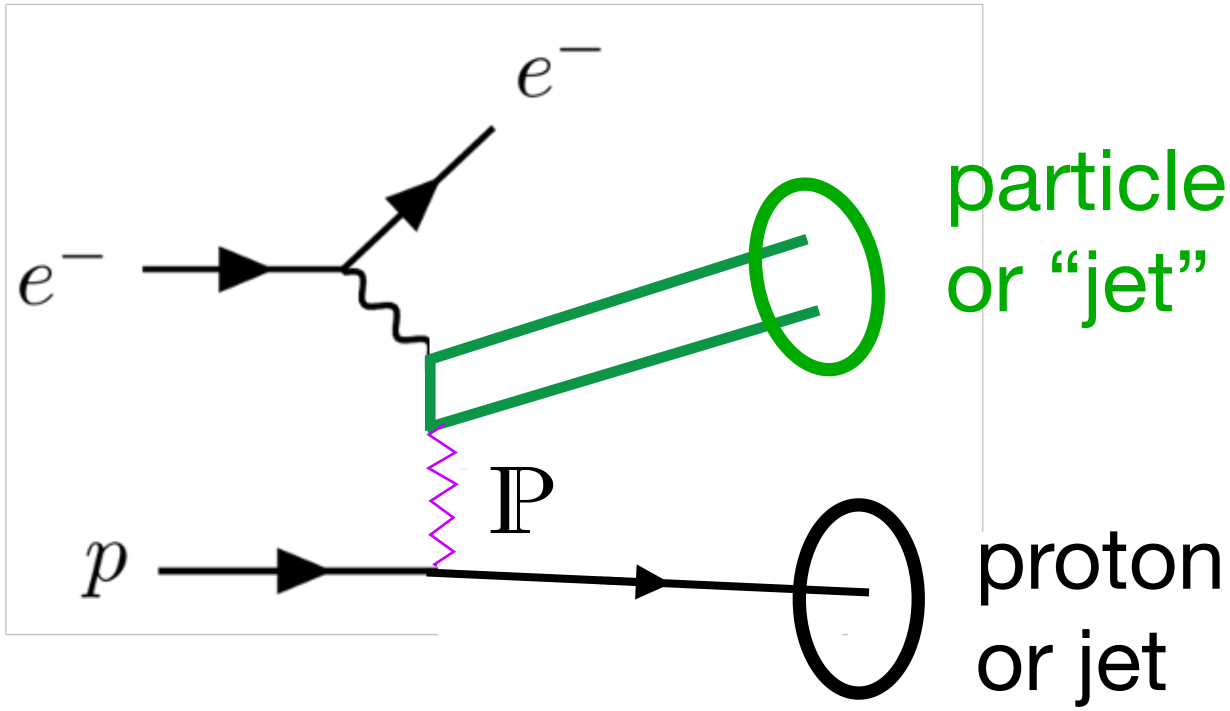
➡ ***New hadron structure (GPD-like structure + more?)***

➡ ***Small-x and saturation physics (BFKL and heavy-ion)***

$$x \sim \frac{-t}{s} \ll 1$$

See your YITP lectures by: A.Stasto, Y.Hatta, Z.Kang, and A.Deshpand

Why Diffraction?



- **Diffractive cross-sections give direct and leading access to Regge physics!**
  - ➡ ***Nature of pomeron***
  - ➡ ***New hadron structure (GPD-like structure + more?)***
  - ➡ ***Small-x and saturation physics (BFKL and heavy-ion)***

$$x \sim \frac{-t}{s} \ll 1$$

- **Ample existing data and bright experimental outlook!**
  - ***10% of HERA***
  - ***20% of EIC (flagship of program!)***
  - ***30% of inelastic LHC events***

Motivation: to understand the "Pomeron"

Example: Total pp cross section

$$\sigma_{\text{tot}} = \frac{1}{s}\,\text{Im}\,T_{\text{el}}(s, t=0)$$

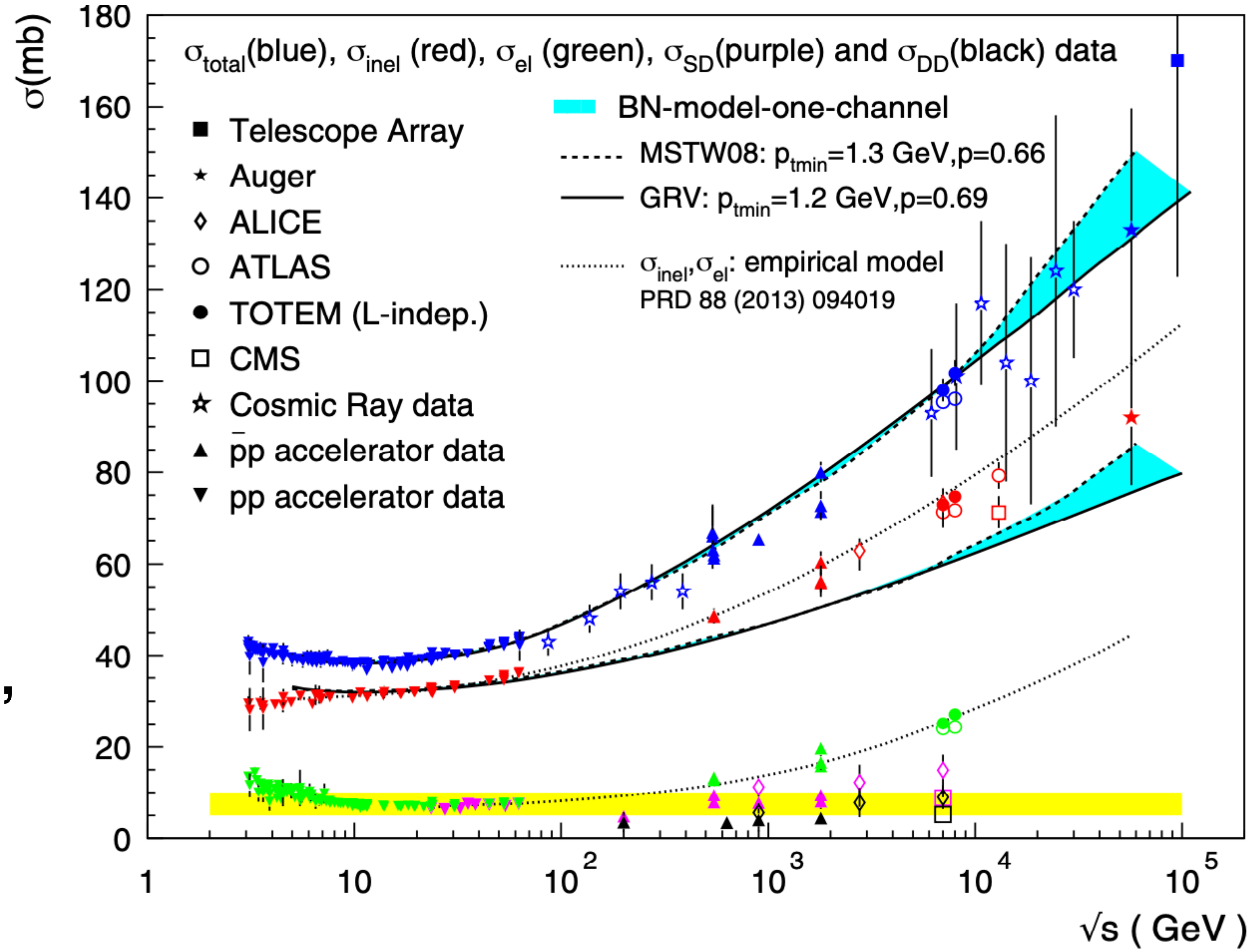
(optical theorem)

- **Regge theory**

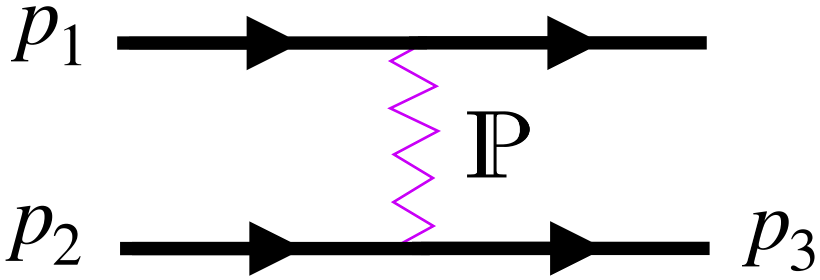
  $s \gg |t|$

  $\sigma_{\text{tot}} \propto s^{\alpha_{\mathbb{P}(0)}-1}$

"Pomeron Regge Exponent"



Regge models:
fit using sum of power law terms



$s = (p_1 + p_2)^2 \qquad t = (p_2 - p_3)^2$

from review by
Pancheri and Srivastavea
(fig by Fagundes, Grau, Shekhovtsova)

Tools for forward physics

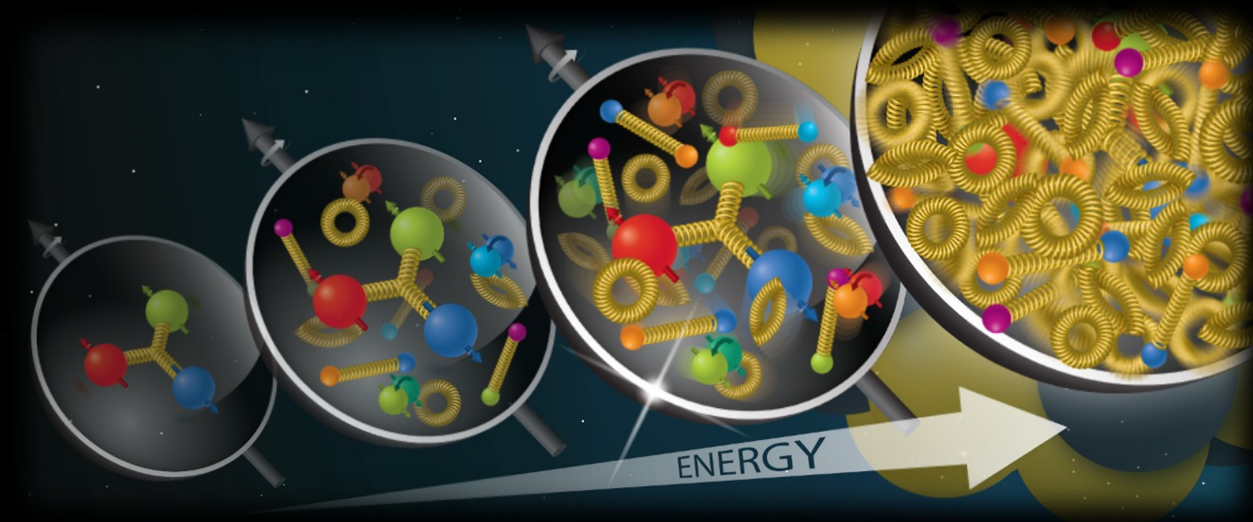
1950s Pomeron & Reggeon description of high-energy scattering
(Regge, Pomeranchuk, Chew, Frautschi…)

1973 Development of QCD
(Gross, Politzer, Wilczek)

1977 BFKL equation for small-*x* evolution
(Balitsky, Fadin, Kuraev, Lipatov)

1983 Discussion of saturation
(Gribov, Levin, Ryskin)

1986 Nonlinear corrections to DGLAP
(Mueller & Qiu)

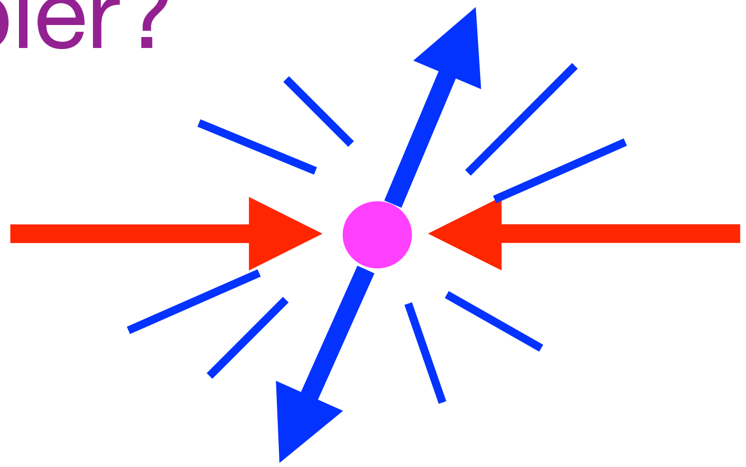


1994 Color Glass Condensate formalism
(McLerran & Venugopalan)

1999 BK/JIMWLK equations, smaller-*x* evolution
(Balitsky, Kochegov, Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner)

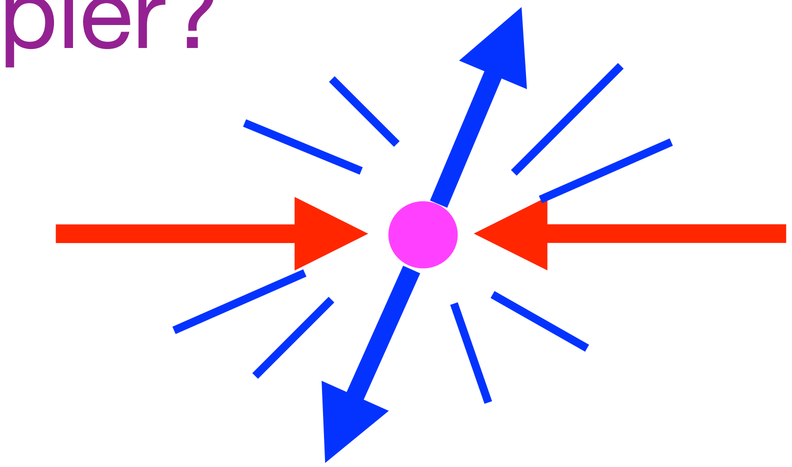
2016 **Effective field theory: Glauber SCET**
(Rothstein & IS)

What principles make hard scattering simpler?



- Scale separation → Factorization
- Single hard interaction
- Low momentum physics described by QCD operators

What principles make hard scattering simpler?



- Scale separation → Factorization
- Single hard interaction
- Low momentum physics described by QCD operators

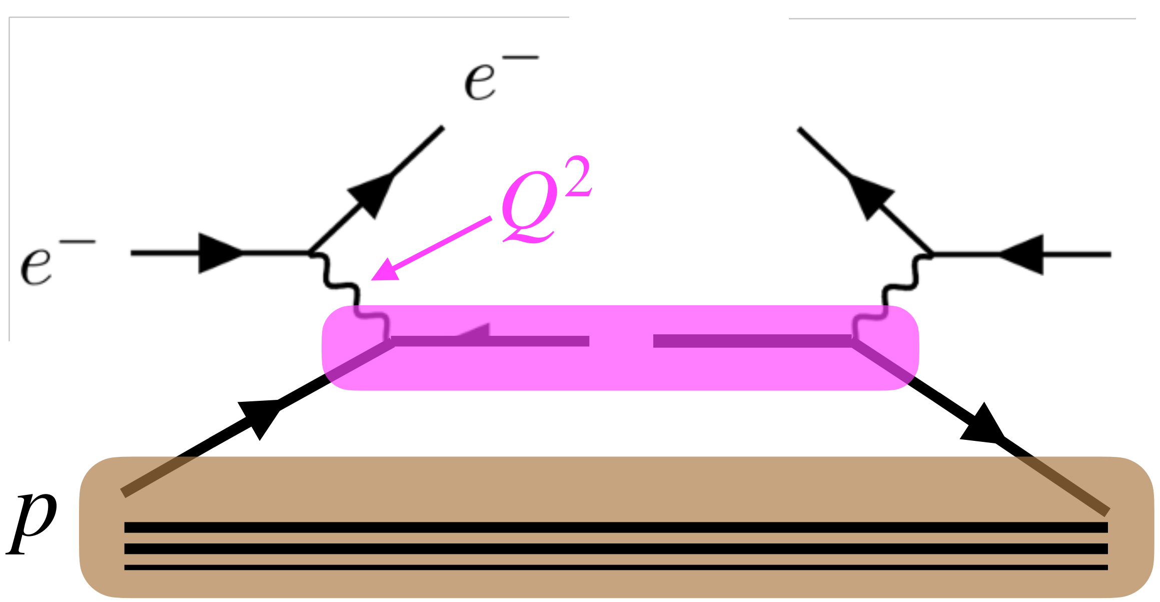
eg. Deep Inelastic Scattering (DIS): $e^- p \to e^- X$

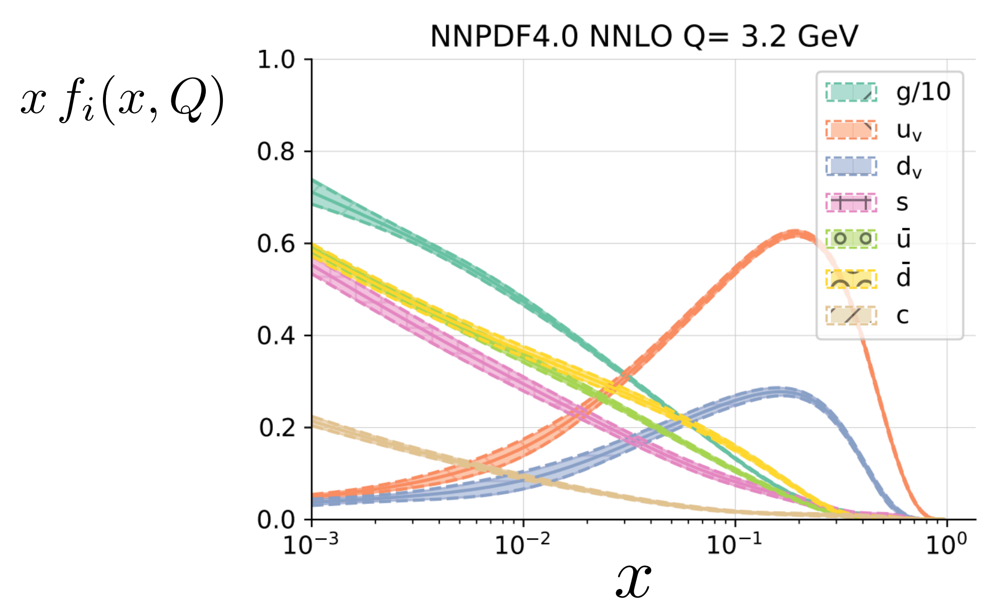
$$d\sigma = H_i(Q,\mu) \otimes f_i(x,\mu)$$

$$Q^2 \gg \Lambda^2_{\mathrm{QCD}}$$

$$f_i(x,\mu) = \langle p | O_i(x,\mu) | p \rangle$$

parton distribution function (probability to find parton i with momentum fraction x)





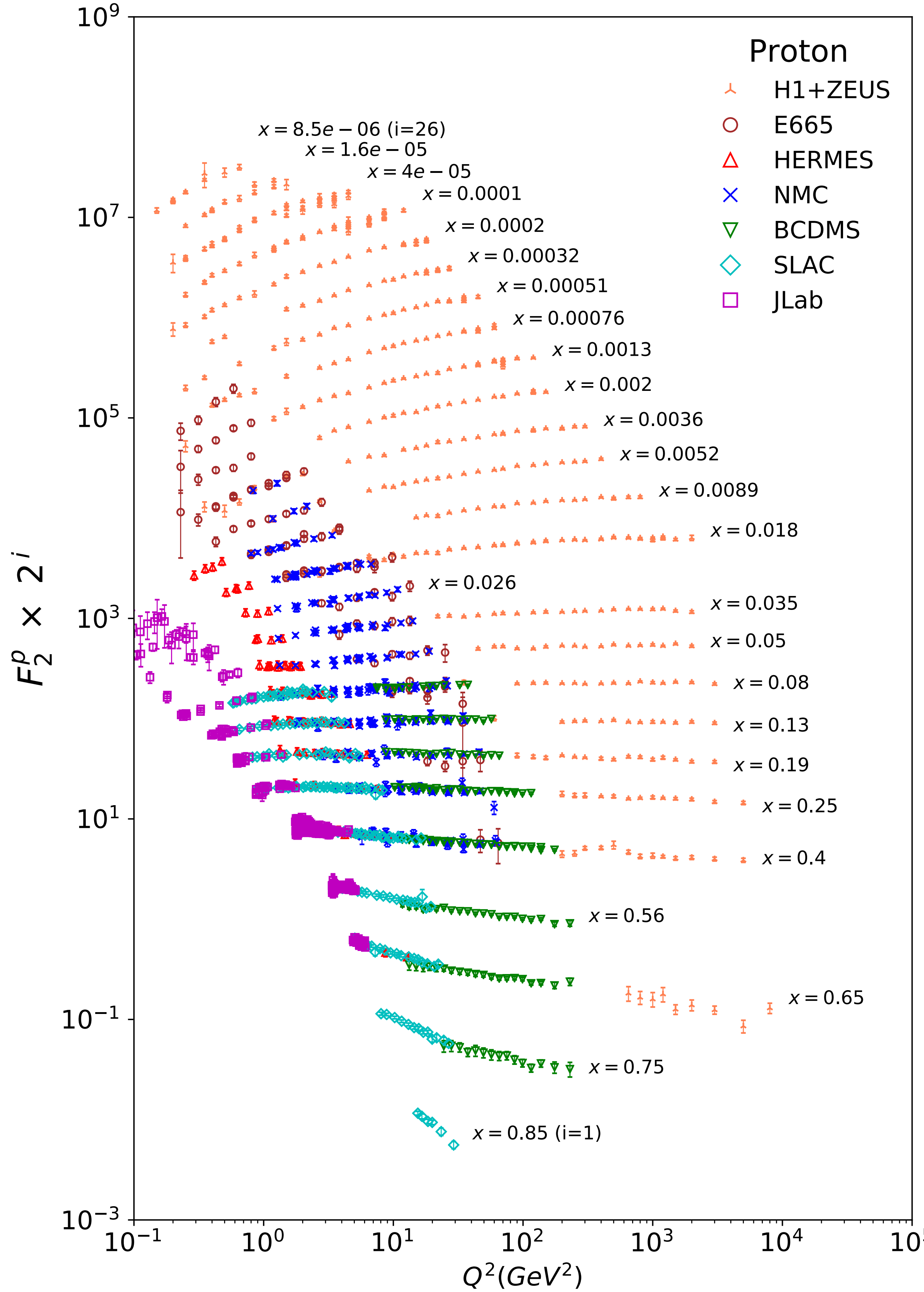
Deep Inelastic Scattering (DIS)

$$d\sigma = H_i(Q,\mu) \otimes f_i(x,\mu)$$

- excellent description of data
- Q dependence calculable (DGLAP), logarithmic “scaling violation”
- higher order QCD calculations improve agreement with data

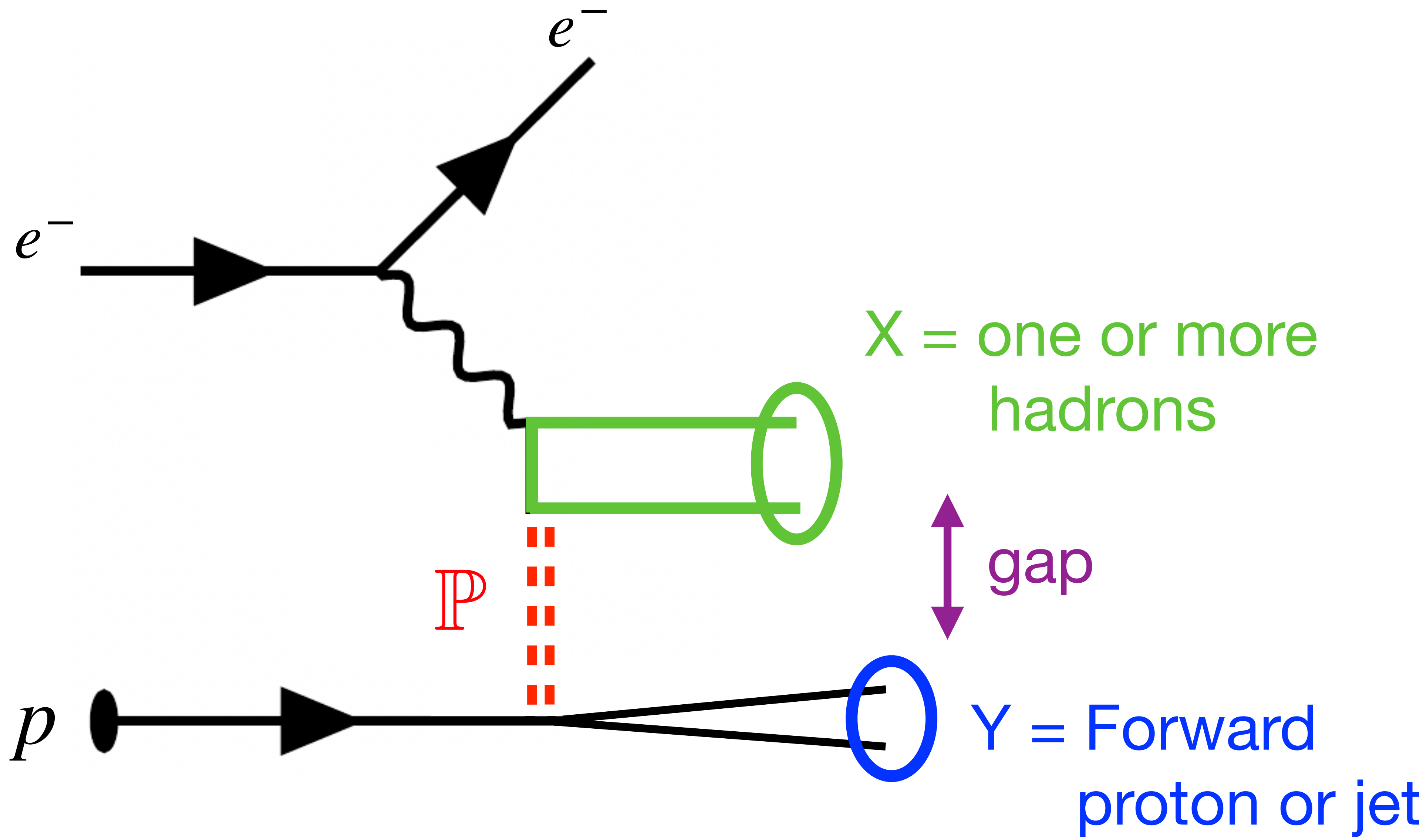
- universal f_i, useful for many observables

$$pp \to X\mu^+\mu^-$$
$$pp \to XH$$
$$pp \to H + 2\text{-jets}$$
$$\cdots$$ (+ many many more)



Diffractive *ep* Scattering

$e^- p \rightarrow e^- X\, Y$



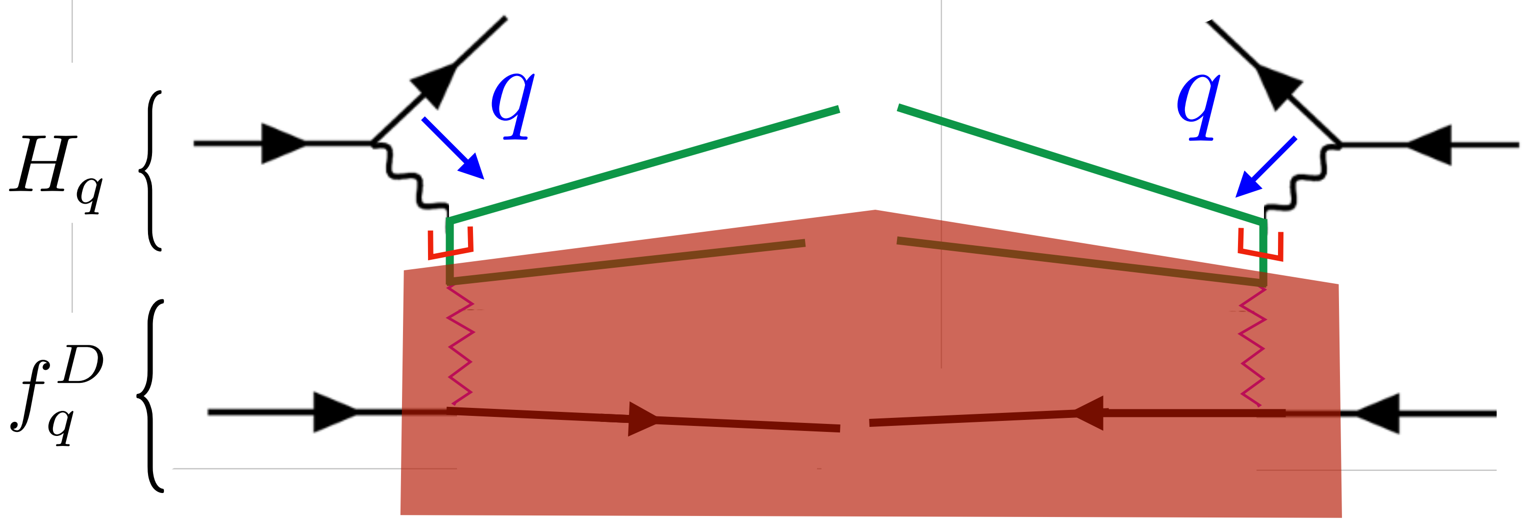
Diffractive *ep* Scattering

- Scale separation $\rightarrow$ Factorization ?
- Multiple forward interactions
- Description of $\mathbb{P}$ and rest of process with operators?

Hard-collinear Diffractive Factorization

- **DIS style hard-collinear factorization for large Q^2**

Collins `97, `01, Berera, Soper `95



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

same as DIS

DPDF

DPDF = *Diffractive* parton distribution functions

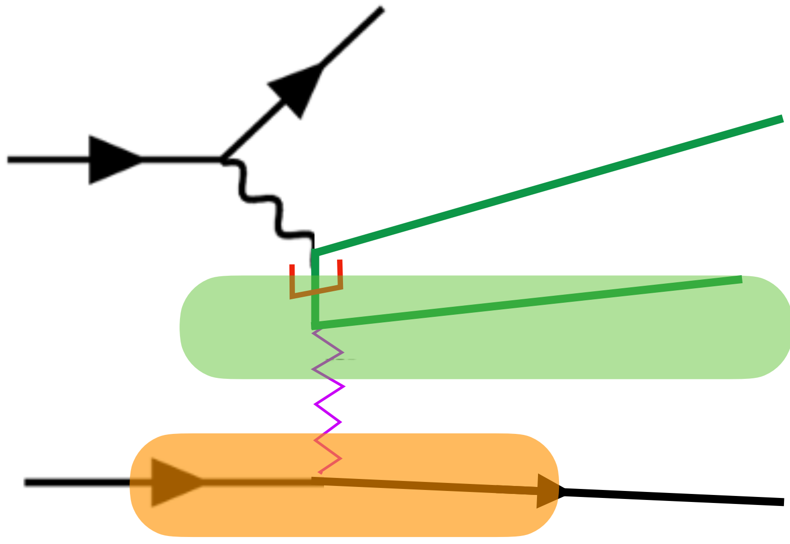
$$f_i^D\left(\zeta, \frac{x}{\beta}, t, m_Y^2, \mu\right)$$

Depends on more kinematic variables
Does not address Regge Factorization or nature of $\mathbb{P}$

Treatments of diffractive Regge physics usually rely on models

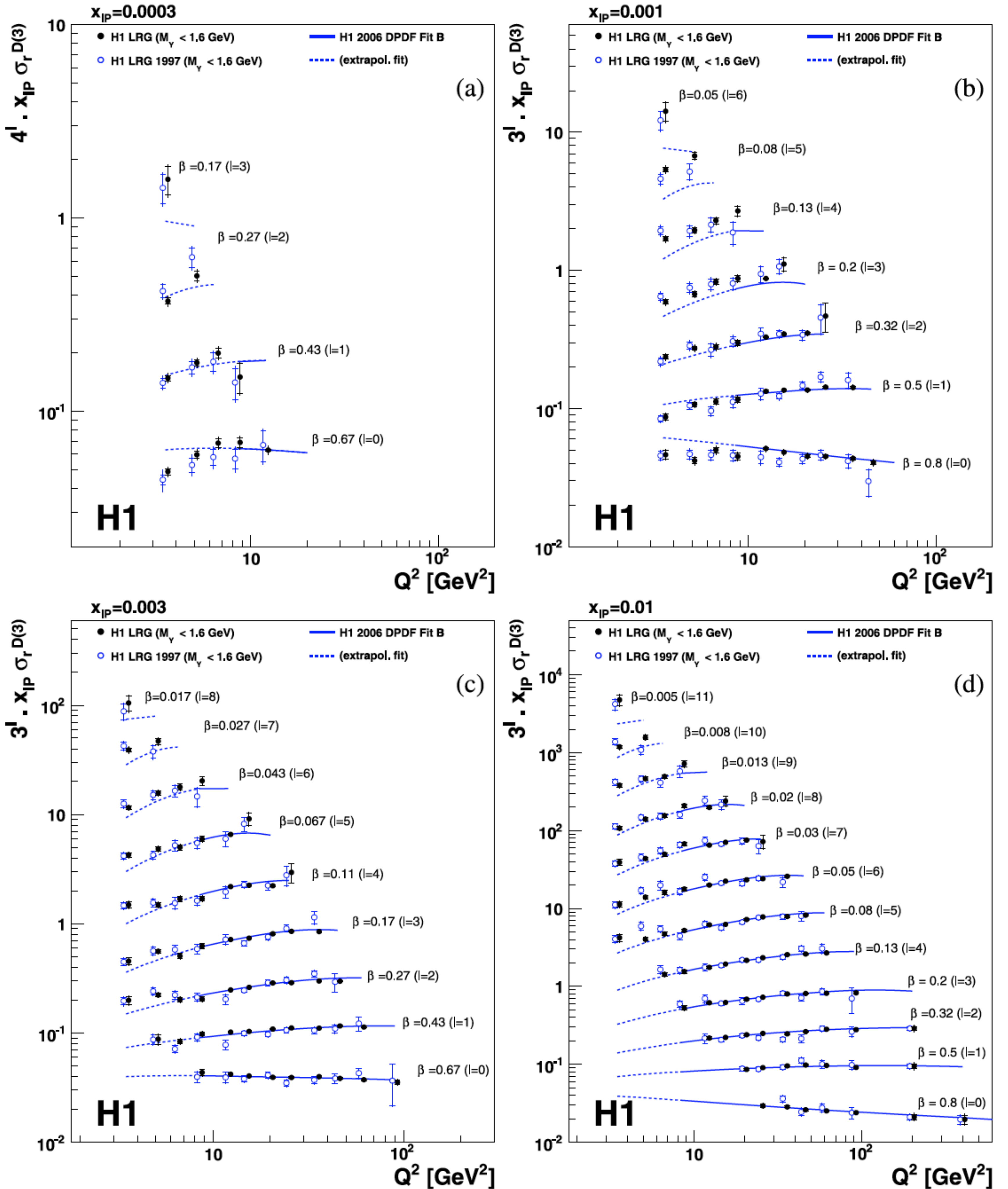
Ingelman-Schlein model is quite popular:

$$f^D_{i/p}(\zeta, \xi, t, m_Y^2, \mu) = f_{i/\mathbb{P}}(\zeta, \mu)\, f_{\mathbb{P}/p}(\xi, t, m_Y^2)$$



DGLAP evolution describes Q^2 dependence

Ingelman-Schlein as boundary condition for HERA fits



The dPDF description of Diffraction fails for pp collisions

Non-universal dPDF? Factorization Violation? …

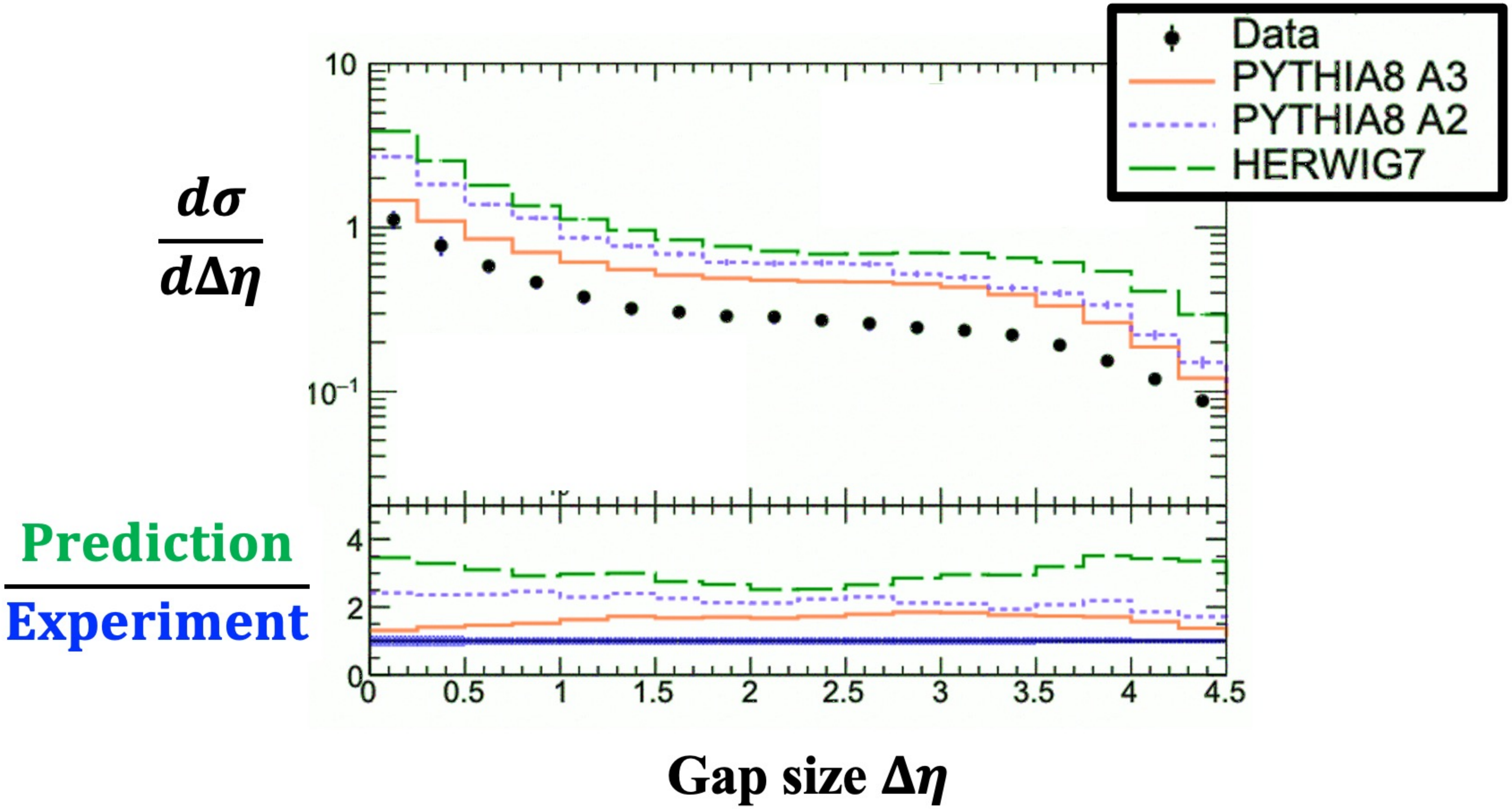


Figure: ATLAS, 1911.00453. $\sqrt{s} = 8\,TeV$, $0.016 < |t| < 0.43$ GeV^2, $-4.0 < \log_{10}\xi < -1.6$

Diffractive ep Scattering

- Scale separation → Factorization ?
- Multiple forward interactions
- Description of $\mathbb{P}$ and rest of process with operators?

Yes

Regge Factorization Theorem for ep

Lee, Schindler, IS arXiv:2508.10231 (JHEP)

Tool: Soft Collinear Effective Field Theory

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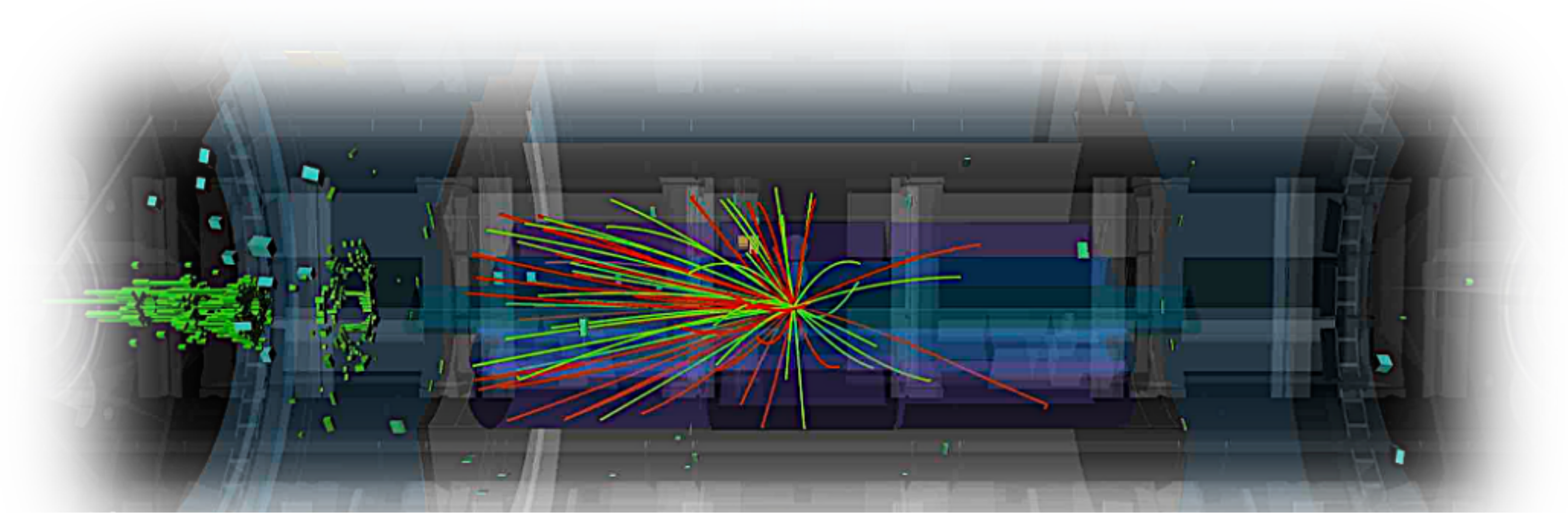


Soft Collinear Effective Theory

“EFT for Collider Physics”

EFT for hard interactions which produce energetic (collinear) and soft particles.

Bauer, Fleming, Luke, Pirjol, IS `00, `01

Higgs, W, Z, top, ... production

Jet Physics

Jet Substructure

B-Decays and CP violation

Quarkonia Production

TMDs / Nuclear Physics

(Heavy Ion collisions)

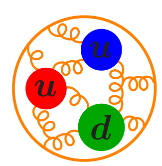
Higher order Resummation

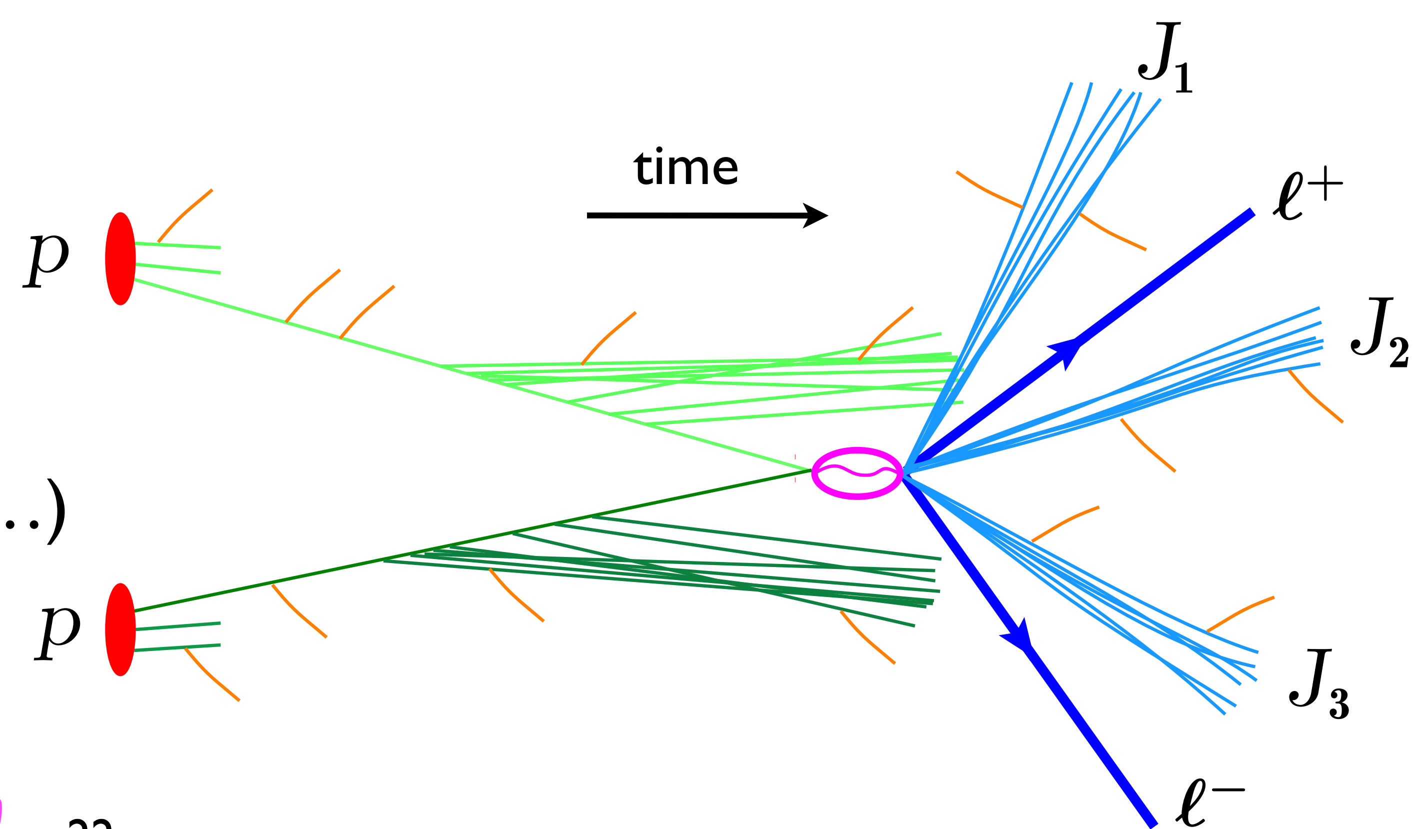
Infrared Structure of Gauge Theory

Subtractions for Fixed Order QCD

Gauge theory at Subleading Power

Forward Scattering and Regge Limit





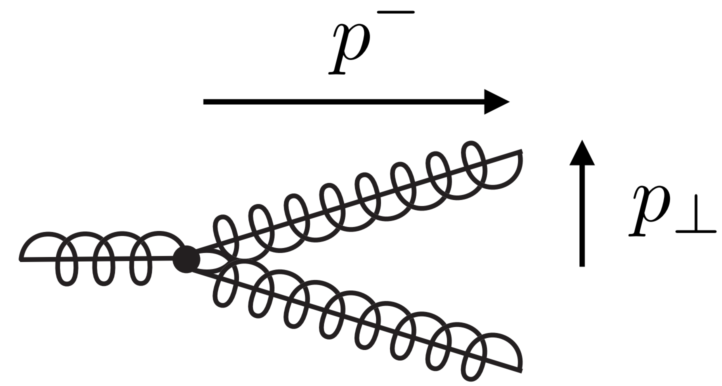
builds on extensive past literature
(CSS factorization, exclusive fact, pQCD…)

For guide to SCET literature see my review in 50 yrs of QCD, 2212.11107

Detailed description in my YITP lectures next week!

Relevant Momentum Regions:

- Collinear Splittings

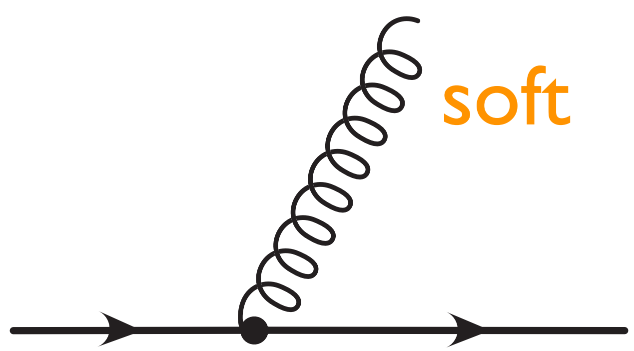


"n-collinear"

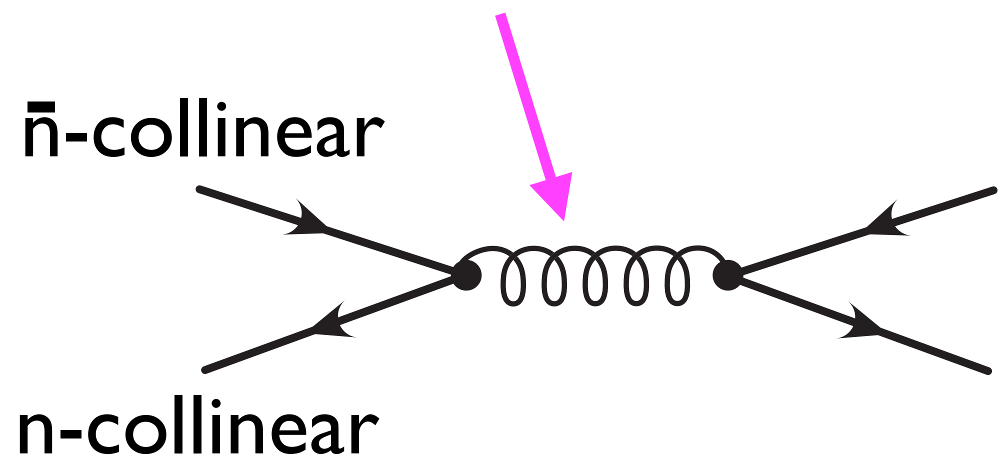
$$p^- \gg p_\perp \gg p^+$$

$$\text{onshell: } p^+ p^- = \vec{p}_\perp^{\,2}$$

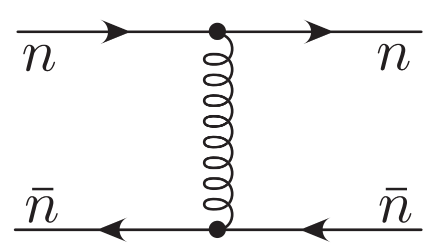
- Soft Emission



- Hard Propagators (short dist.)



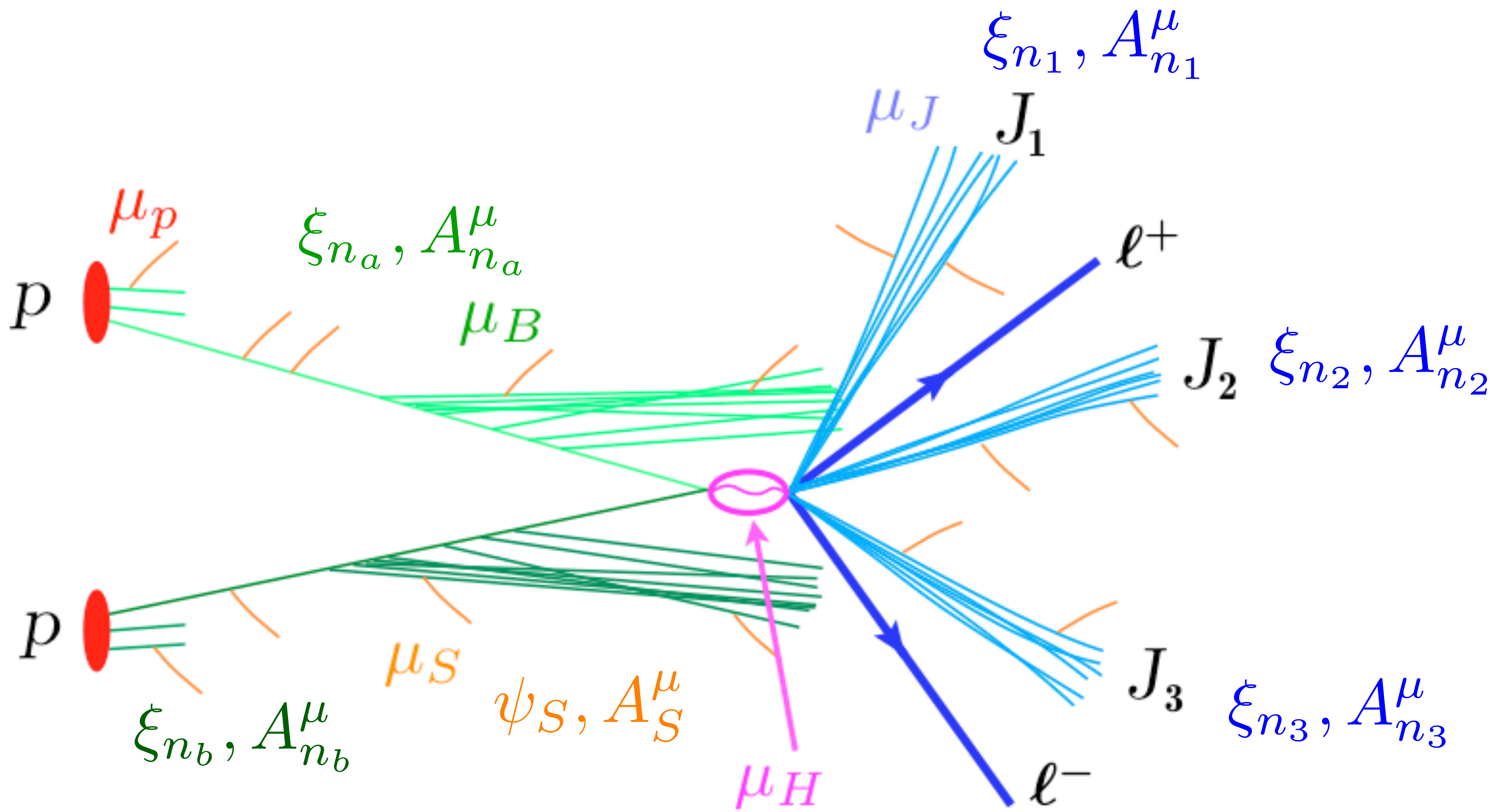
- Glauber Exchange

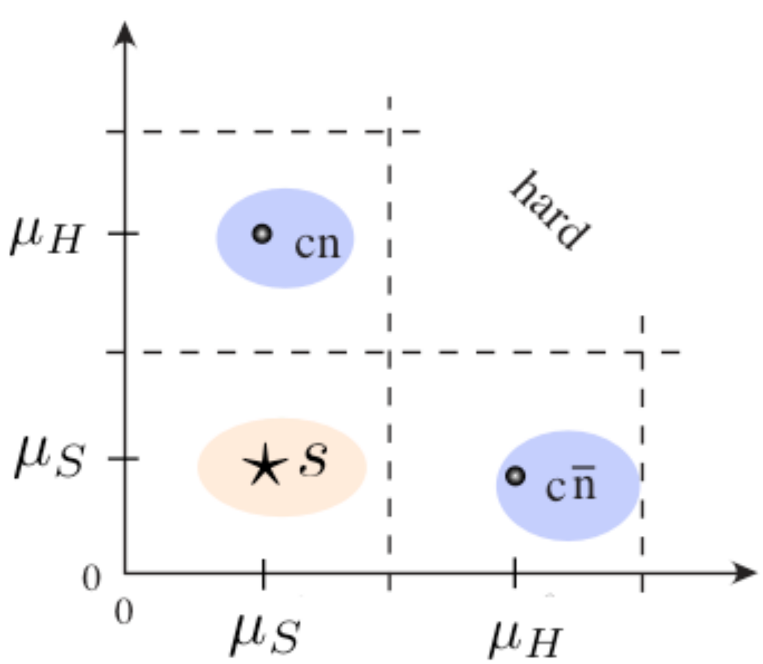


forward scattering

Soft Collinear EFT (SCET)

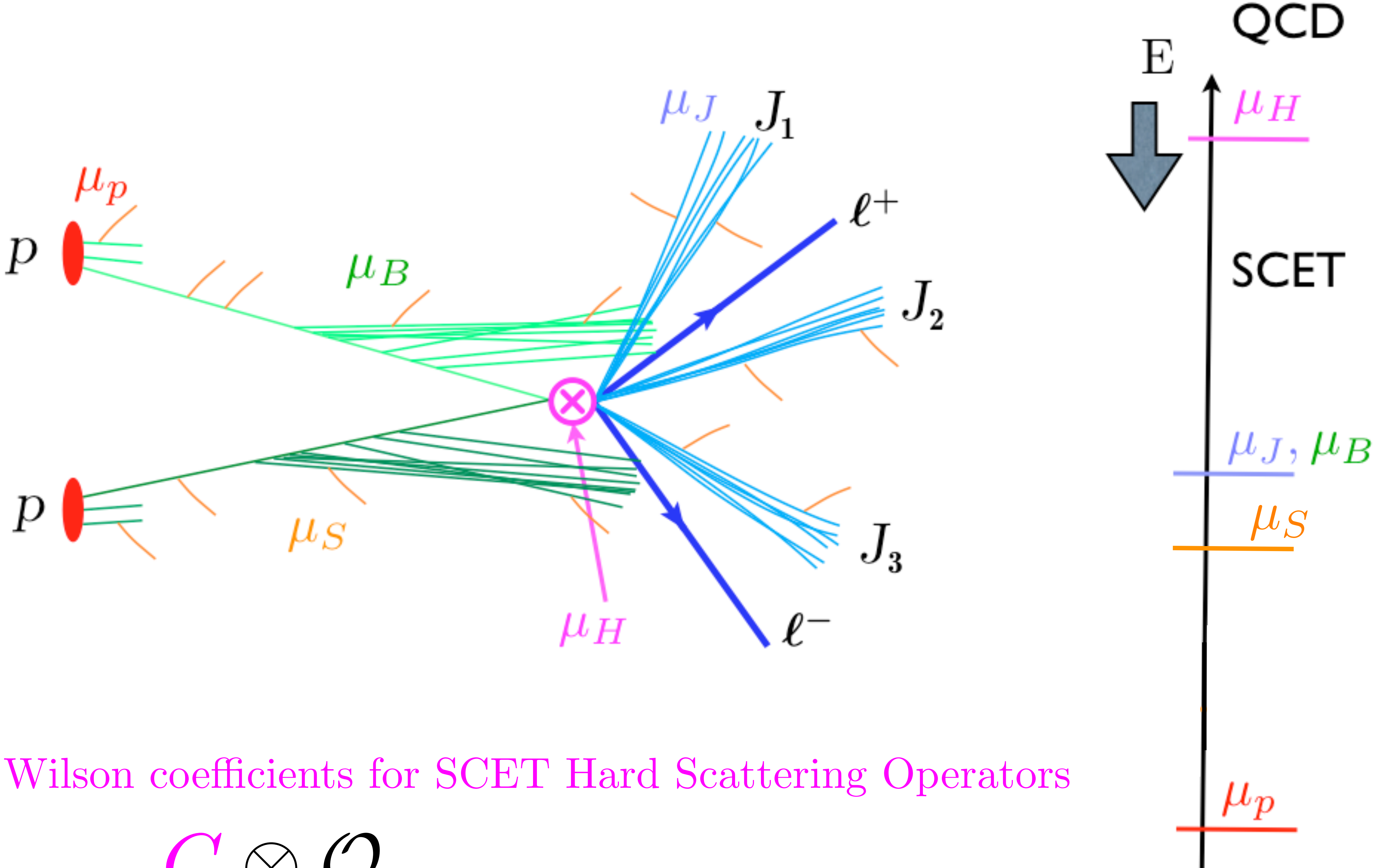
SCET Fields for various Modes





- dominant contributions from specific regions of momentum space

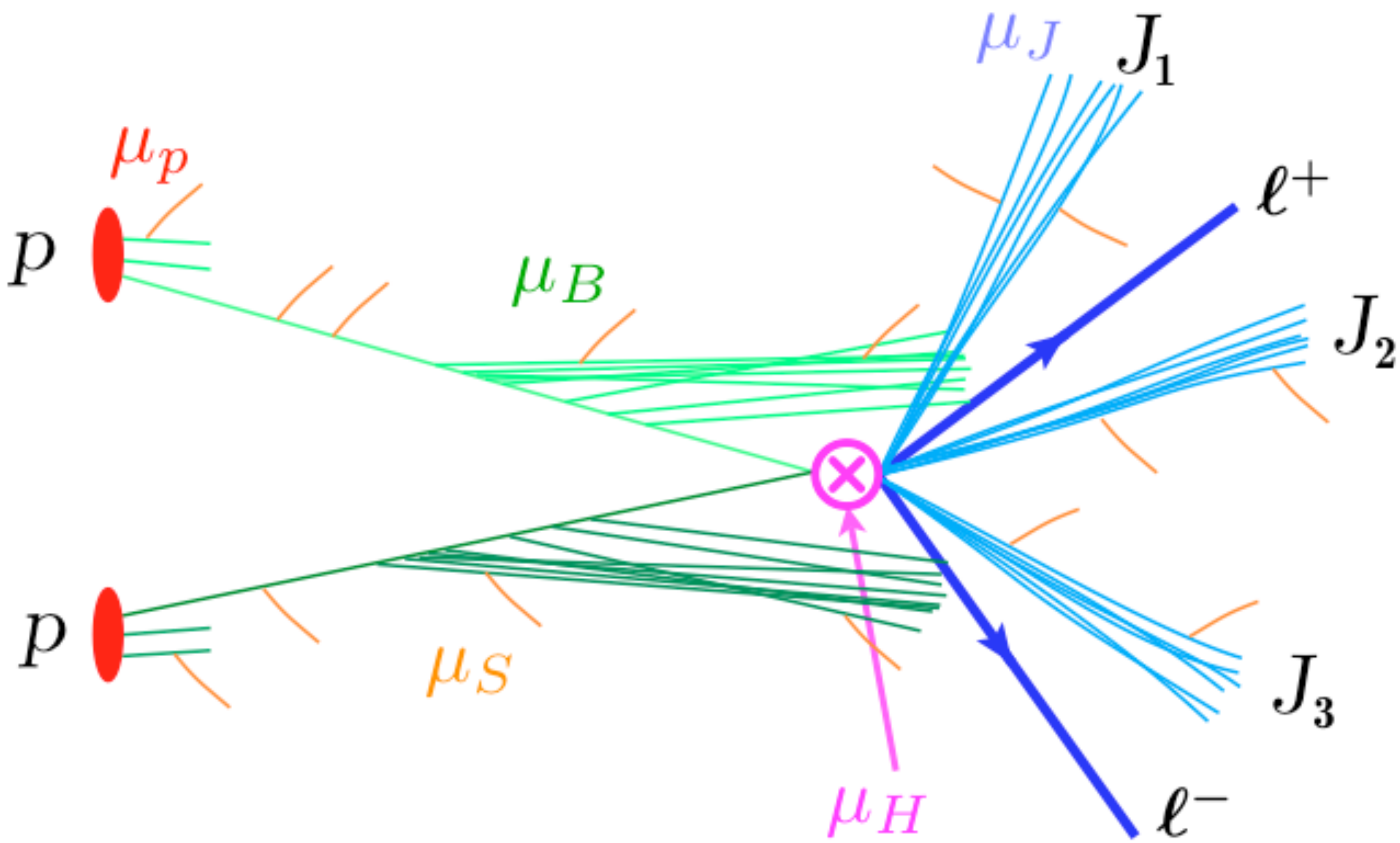
Hard-collinear factorization

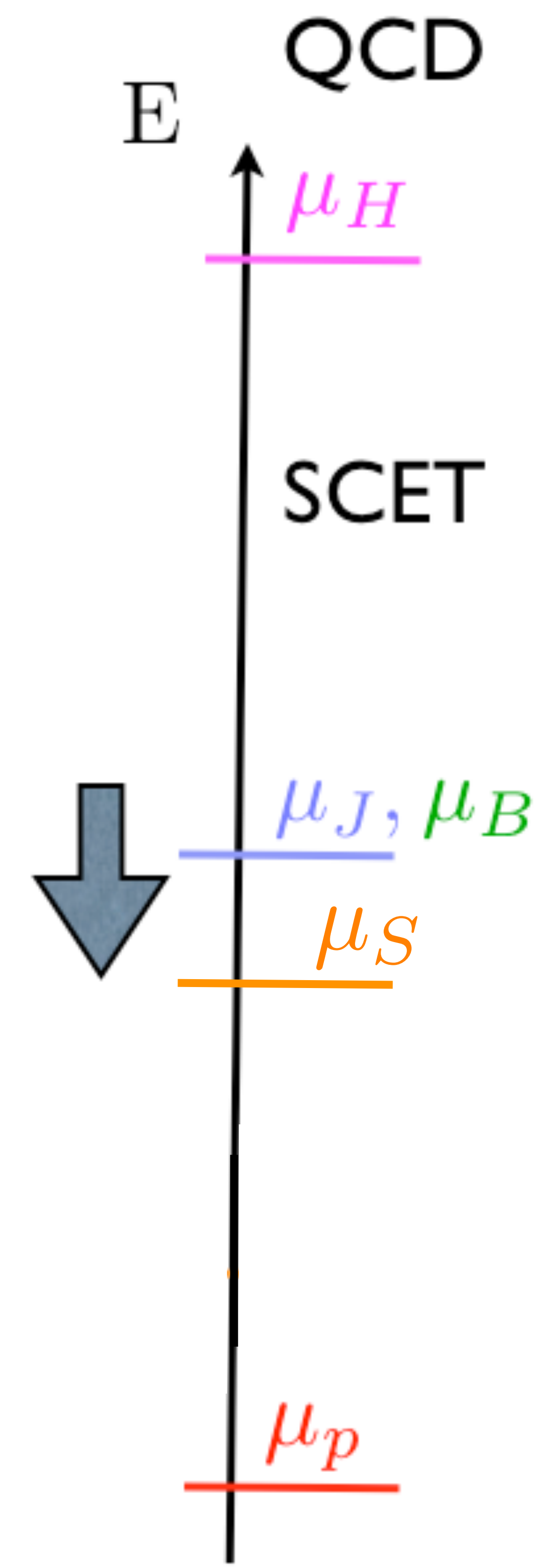


μ_H: Wilson coefficients for SCET Hard Scattering Operators

$$C \otimes \mathcal{O}$$

Hard-collinear factorization





Operators are built of building block fields:

$$\mathcal{O} = (\mathcal{B}_{n_a\perp})(\mathcal{B}_{n_b\perp})(\mathcal{B}_{n_1\perp})(\bar{\chi}_{n_2})(\chi_{n_3})$$

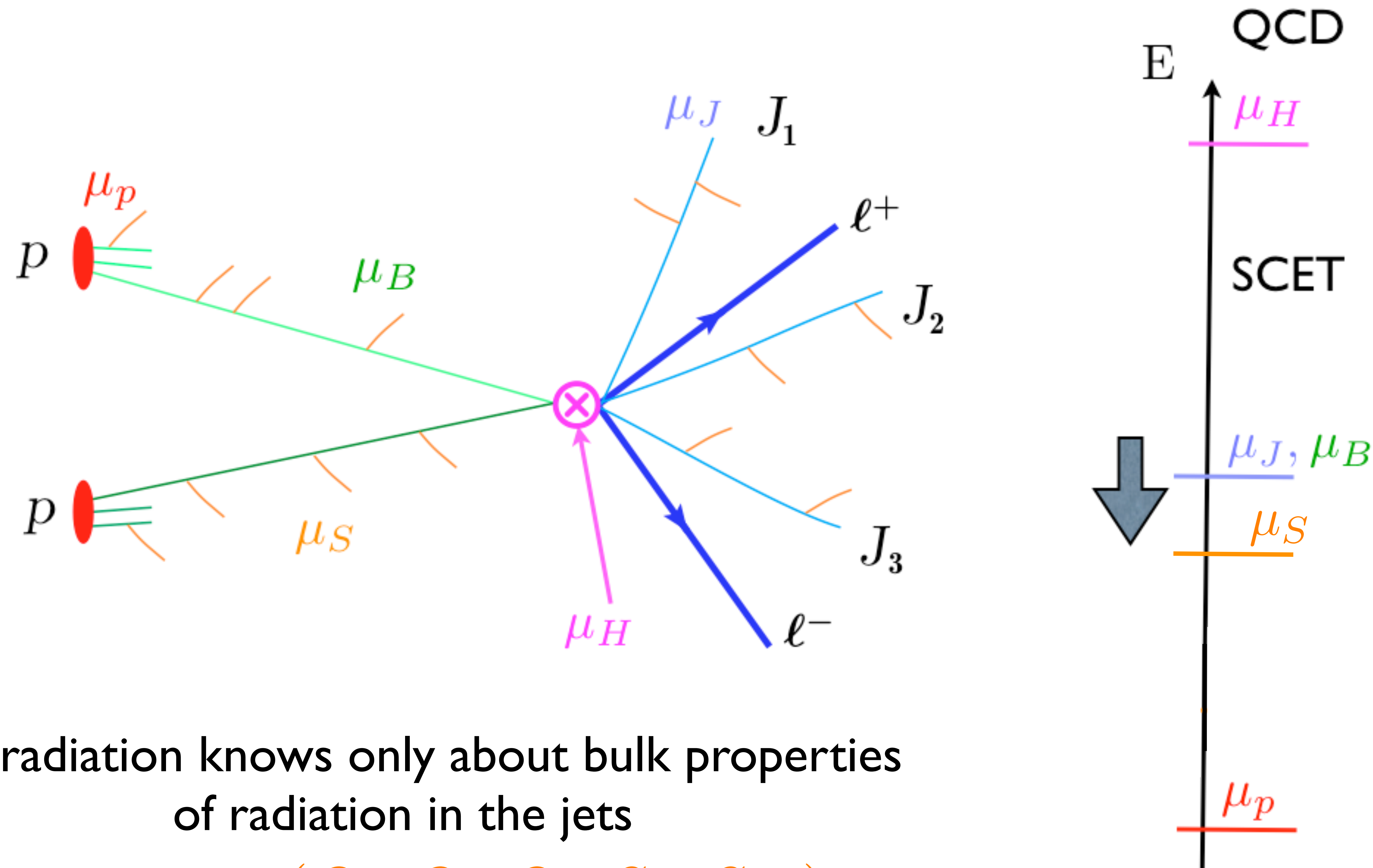
$$\chi_n = (W_n^\dagger \xi_n)$$ "quark jet"

$$\mathcal{B}_{n\perp}^\mu = \frac{1}{g}[W_n^\dagger iD_\perp^\mu W_n]$$ "gluon jet"

Wilson lines

$$W_n = P\exp\left(ig\int_{-\infty}^{0} ds\, \bar{n}\cdot A_n(x+\bar{n}s)\right)$$

Soft-collinear factorization



Soft radiation knows only about bulk properties of radiation in the jets

$$\left(S_{n_a} S_{n_b} S_{n_1} S_{n_2} S_{n_3}\right)$$

Soft Wilson Lines

SCET Lagrangian at leading power

$$\mathcal{L} = \mathcal{L}^{(0)}_{\rm dyn} + \mathcal{L}^{(0)}_{\rm hard} + \mathcal{L}^{(0)}_{\rm G}$$

Dynamics of infrared modes

Hard Scattering operators (typically once)

Glauber gluon exchange (only factorization violating term)

- $\mathcal{L}^{(0)}_{\rm hard} = \sum_i C_i^{(0)} \mathcal{O}_i^{(0)}$ Leading operators for a hard process

  $C \otimes (\mathcal{B}_{n_a\perp})(\mathcal{B}_{n_b\perp})(\mathcal{B}_{n_1\perp})(\bar{\chi}_{n_2})(\chi_{n_3})(\mathcal{S}_{n_a}\mathcal{S}_{n_b}\mathcal{S}_{n_1}\mathcal{S}_{n_2}\mathcal{S}_{n_3})$

- $\mathcal{L}^{(0)}_{\rm dyn} = \sum_n \mathcal{L}^{(0)}_n + \mathcal{L}^{(0)}_{\rm soft}$ Collinear and Soft dynamics decoupled

- ~~$\mathcal{L}^{(0)}_{\rm G}$~~ ➡ Factorization for hard process!

SCET Lagrangian at leading power

$$\mathcal{L} = \mathcal{L}^{(0)}_{\mathrm{dyn}} + \mathcal{L}^{(0)}_{\mathrm{hard}} + \mathcal{L}^{(0)}_{\mathrm{G}}$$

Dynamics of infrared modes

Hard Scattering operators (typically once)

Glauber gluon exchange (only factorization violating term)

- $\mathcal{L}^{(0)}_{\mathrm{hard}} = \sum_i C_i^{(0)} \mathcal{O}_i^{(0)}$ Leading operators for a given process
- $\mathcal{L}^{(0)}_{\mathrm{dyn}} = \sum_n \mathcal{L}_n^{(0)} + \mathcal{L}^{(0)}_{\mathrm{soft}}$ Collinear and Soft dynamics (Factorizes after soft-collinear decoupling)

Factorization →

$$d\sigma = f_a f_b \otimes \hat{\sigma} \otimes F$$

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

Glauber Lagrangian:

part we need for ep diffraction

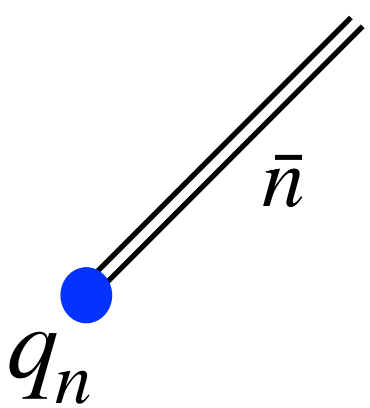
$$\mathcal{L}_{\textbf{Glauber}} = \sum_n \sum_{i,j=q,g} \mathcal{O}_n^{iB} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s^{j_n B} \quad + \text{(3 sector terms)}$$

acts as $\frac{1}{k_\perp^2} = \frac{1}{k_x^2 + k_y^2}$ potential

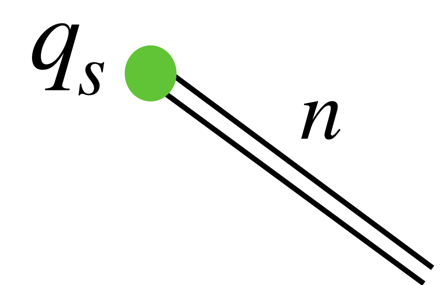
- Operators involve quark & gluon fields, and gluon Wilson lines

$$\mathcal{O}_n^{qB} = \bar{\chi}_n T^B \frac{\bar{n}\!\!\!/}{2} \chi_n \qquad \mathcal{O}_n^{gB} = \frac{i}{2} f^{BCD} \mathcal{B}_{n\perp\mu}^C \frac{\bar{n}}{2} \cdot (\mathcal{P} + \mathcal{P}^\dagger) \mathcal{B}_{n\perp}^{D\mu}$$

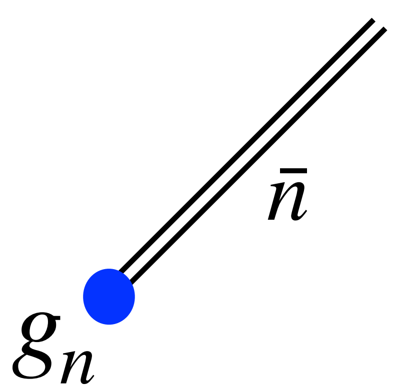
$$\chi_n = (W_n^\dagger \xi_n)$$



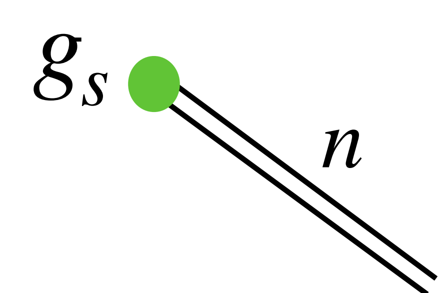
$$\psi_s^n = S_n^\dagger \psi_s$$



$$\mathcal{B}_{n\perp}^\mu = \frac{1}{g} [W_n^\dagger i D_\perp^\mu W_n]$$



$$\mathcal{B}_{S\perp}^{n\mu} = \frac{1}{g} \left[S_n^\dagger i D_{S\perp}^\mu S_n \right]$$



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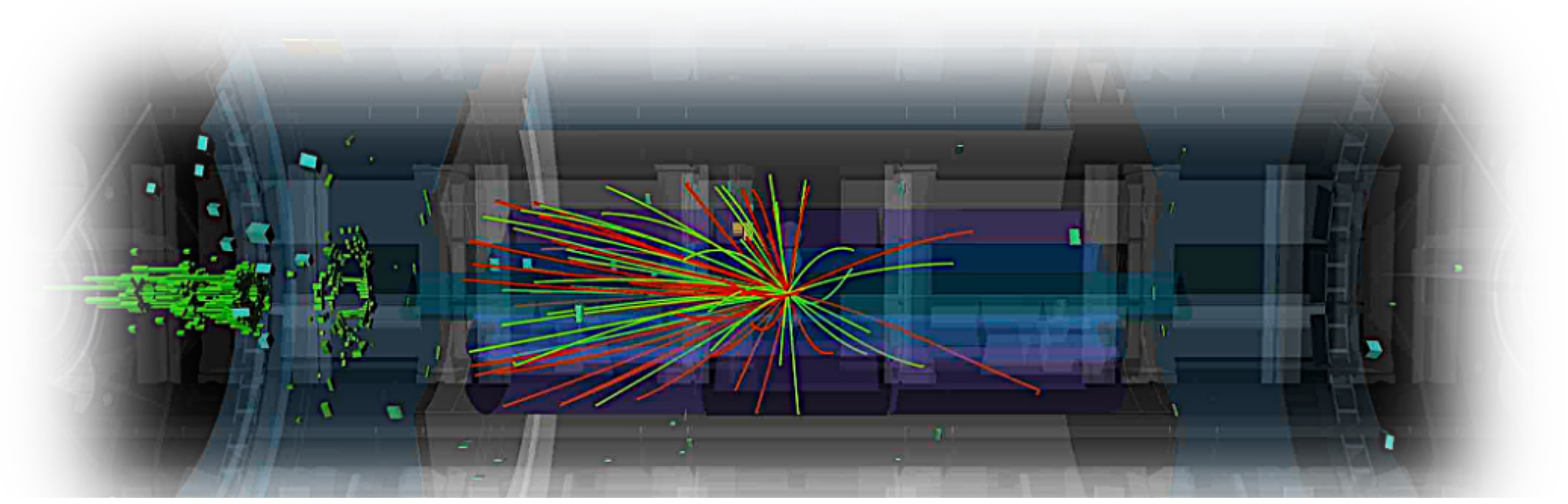
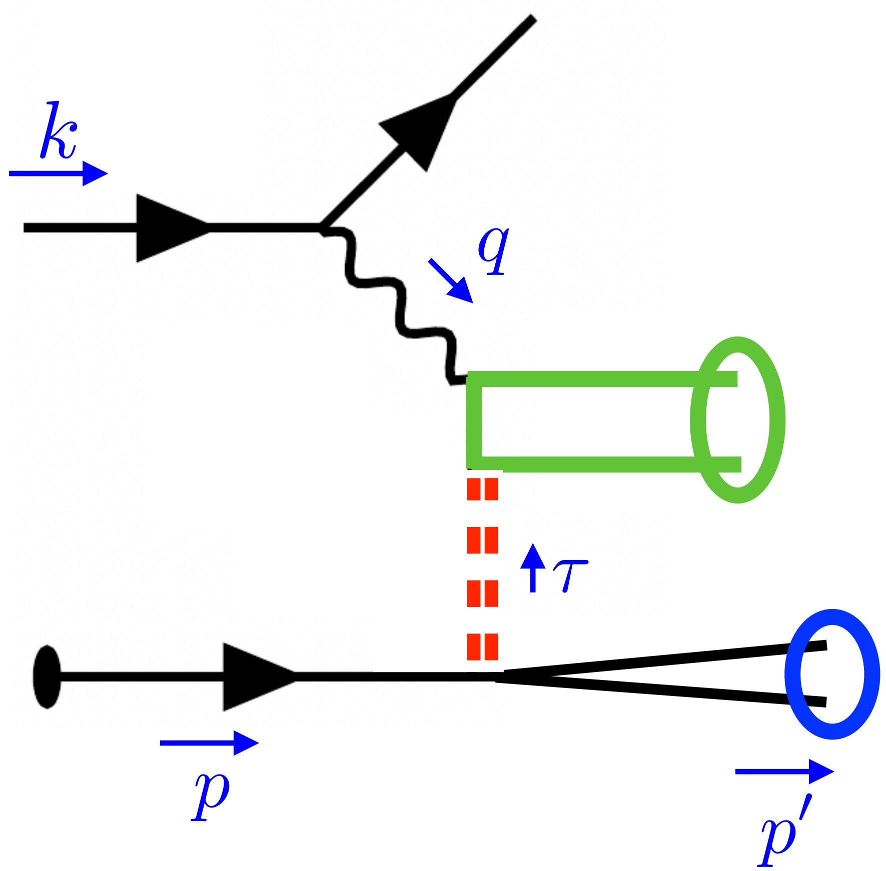
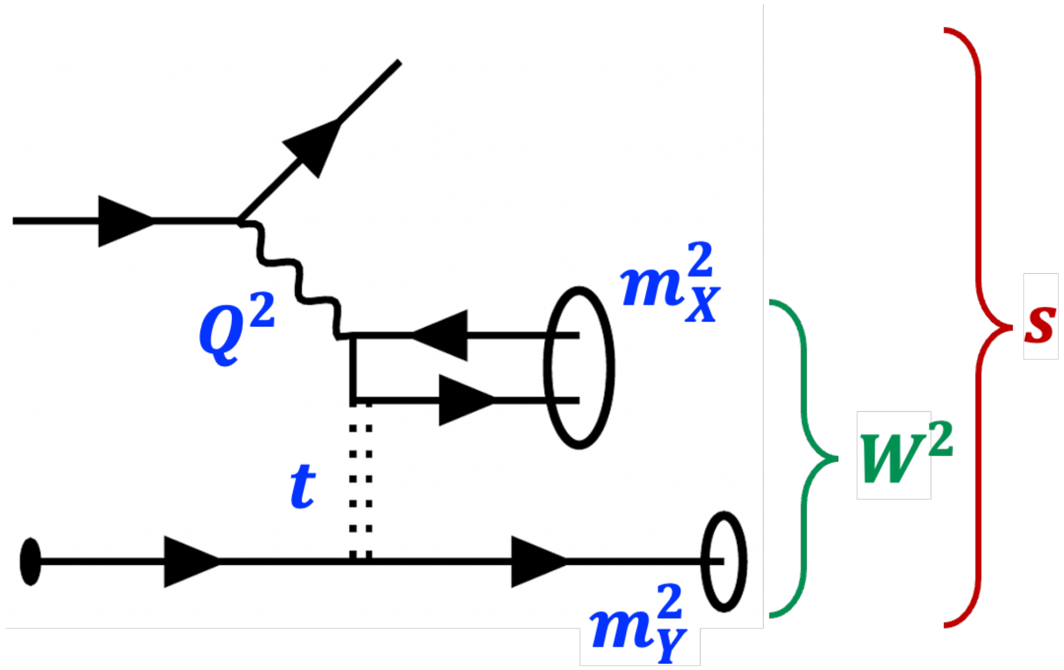


Kinematics

4-vectors: $\{k, q, p, \tau\}$





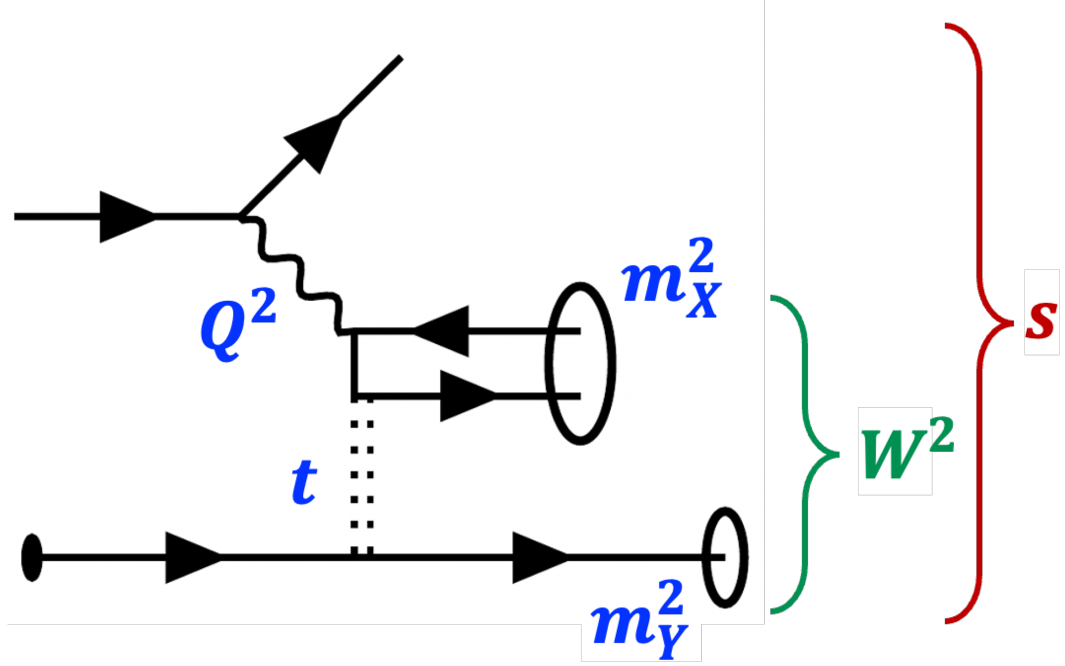
	Energy scales	Momentum fractions
Familiar from DIS	$Q^2 = -q^2$ $W^2 = (p+q)^2$ $s = (p+k)^2$	$x = \frac{Q^2}{2p\cdot q}$ $y = \frac{p\cdot q}{p\cdot k}$
Diffraction	$t = \tau^2 < 0$ $m_Y^2 = p'^2 > 0$ $m_X^2 = p_X^2 > 0$	$\beta = \frac{Q^2}{2q\cdot\tau}$ $\bar{x} = \frac{k\cdot\tau}{k\cdot p}$ $z = \frac{p\cdot p'}{p\cdot q}$

Not all variables independent:

3 for DIS, 7 for diffraction (2 leptonic)

Kinematics

Energy scales:



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

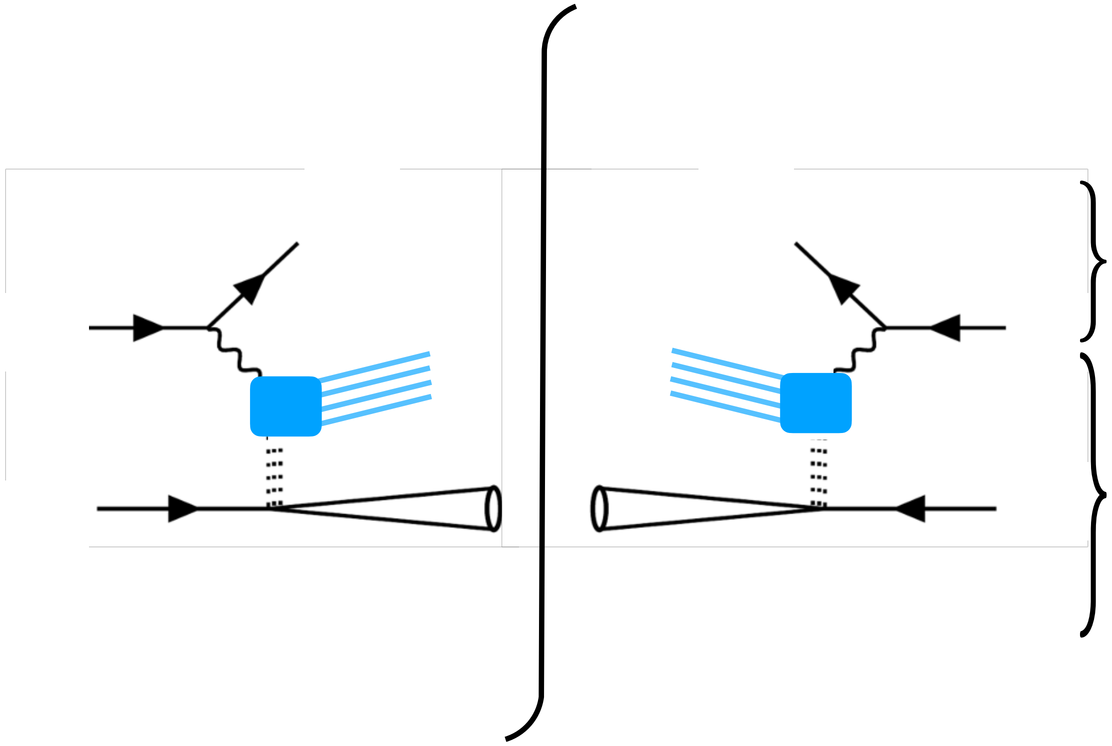
Not all variables independent:

3 for DIS, 7 for diffraction (2 leptonic)

$$Q^2 = sxy \quad , \quad W^2 = Q^2\frac{1-x}{x} + m_p^2$$

$$m_X^2 = Q^2\frac{1-\beta}{\beta} + t \quad , \quad z = \frac{x}{Q^2}(m_Y^2 - t)$$

Structure Functions



$L_{\mu\nu}$

$W_D^{\mu\nu}$

4 structure functions for unpolarized:

$$\frac{d^6\sigma}{d\{x,y,\bar{x},t,\beta,m_Y^2\}} \sim L_{\mu\nu} W_D^{\mu\nu}$$

trivial:

$$L^{\mu\nu}(k,k') = 2\left[k^\mu k'^\nu + k^\nu k'^\mu - k\cdot k'\, g^{\mu\nu} + \mathrm{i}\lambda_e \epsilon^{\mu\nu\rho\sigma} k_\rho k_\sigma\right]$$

e.m. current

non-trivial QCD:

$$W_D^{\mu\nu}(q,p,p') = \sum\!\!\!\!\!\!\int_X \sum\!\!\!\!\!\!\int_Y \delta^4(q+p-p'-p_X)\, \langle p|J^{\dagger\,\mu}(0)|YX\rangle\langle YX|J^\nu(0)|p\rangle \delta(m_Y^2 - p'^{\,2})$$

$$= \sum_i w_i^{\mu\nu}(q,U,X,S)\, F_i^D(x,Q^2,\beta,t,m_Y^2)$$

unpolarized:

$$w_L^{\mu\nu} = \frac{1}{2x}\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)$$

$$w_2^{\mu\nu} = \frac{1}{2x}\left(U^\mu U^\nu - g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right)$$

$$w_3^{\mu\nu} = \frac{1}{2x}\left(2X^\mu X^\nu - U^\mu U^\nu + g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)$$

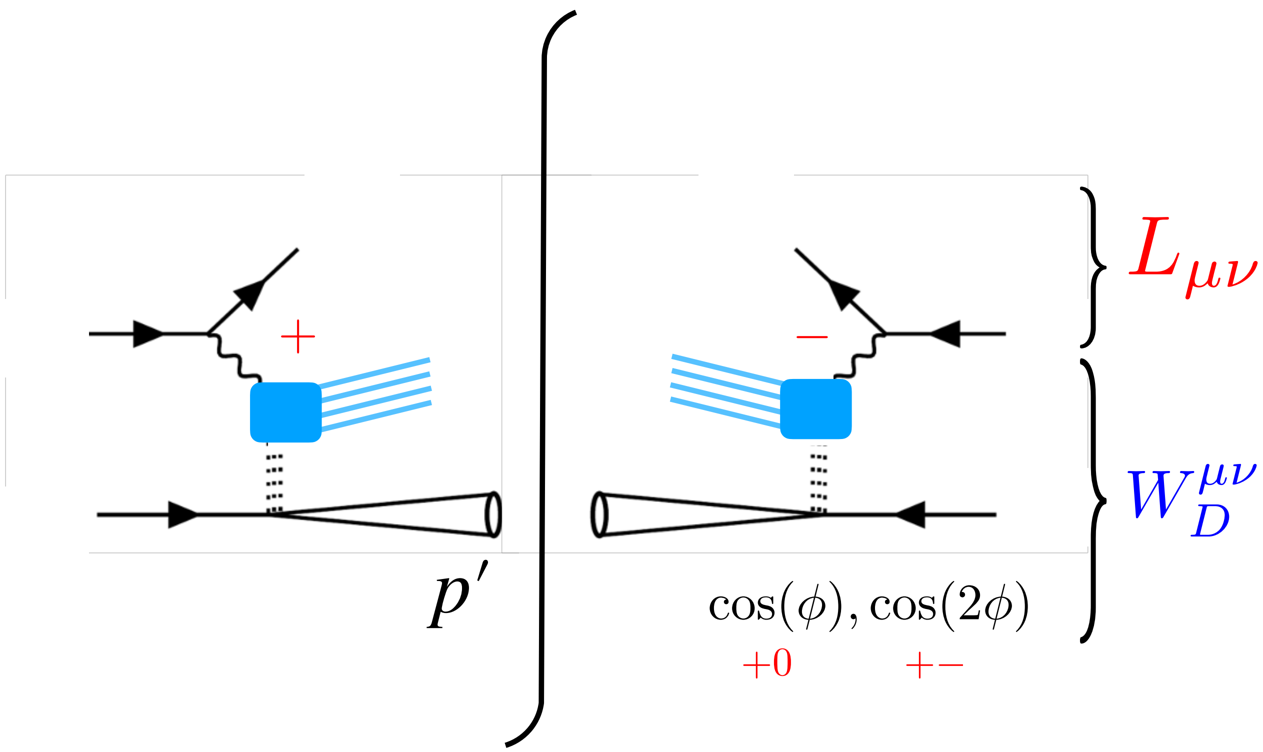
$$w_4^{\mu\nu} = \frac{1}{2x}(U^\mu X^\nu + X^\mu U^\nu)$$

$$U^\mu = \frac{2x}{Q}\left(p^\mu - \frac{p\cdot q}{q^2} q^\mu\right)$$

$$X^\mu = \frac{1}{N_X}\left(V^\mu - \frac{U\cdot V}{U^2} U^\mu\right)$$

$$V^\mu = p'^\mu - q^\mu\,(p'\cdot q)/q^2$$

Structure Functions



4 structure functions for unpolarized:

$$\frac{d^6\sigma}{d\{x,y,\bar{x},t,\beta,m_J^2\}} \sim L_{\mu\nu}W_D^{\mu\nu}$$

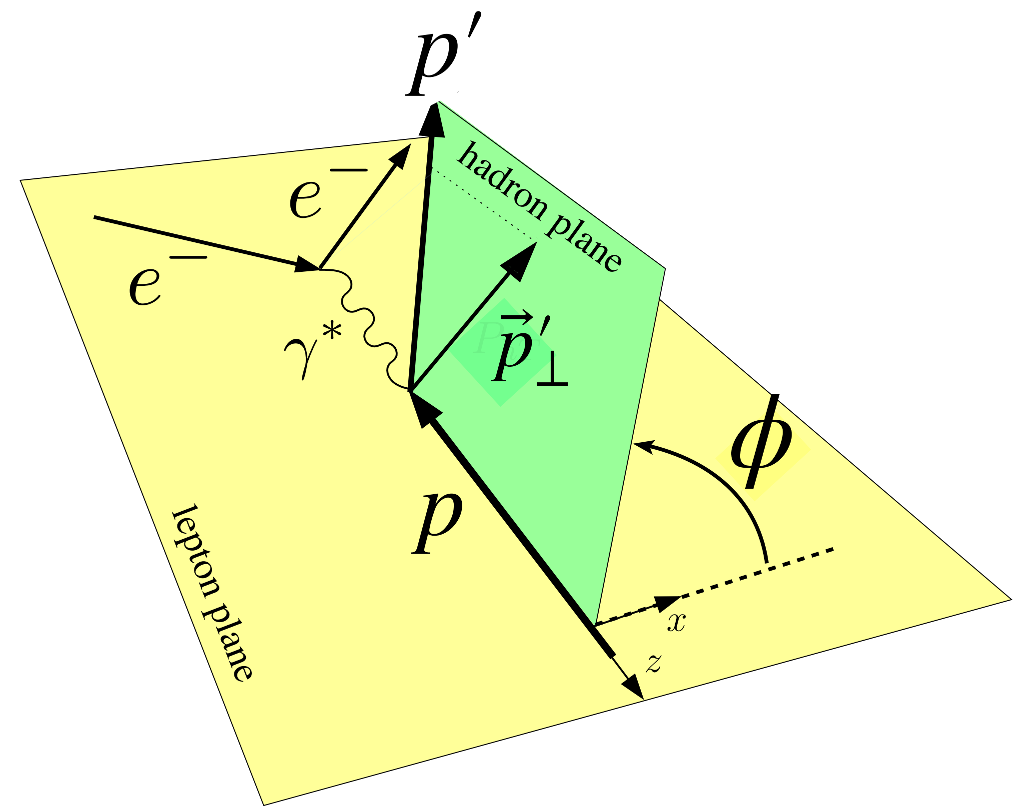
$$\sim \sum_i c_i F_i^D(x,Q^2,\beta,t,m_Y^2)$$

$$\sim \Big\{\left(1-y+\frac{y^2}{2}\right)F_2^D - \frac{y^2}{2}F_L^D$$

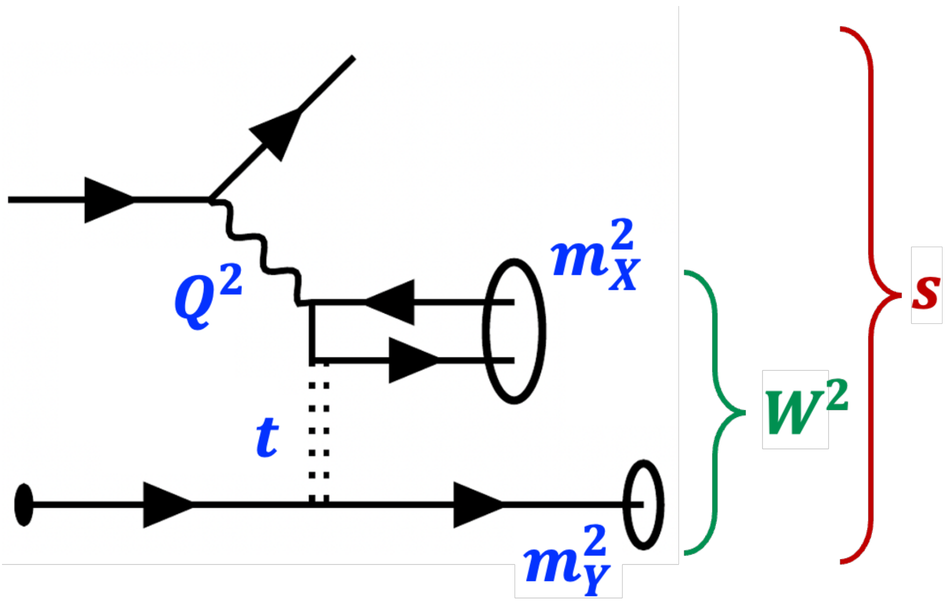
$$+(1-y)\cos 2\phi\, F_3^D + (2-y)\sqrt{1-y}\cos\phi\, F_4^D\Big\}$$

$$\cos\phi = \frac{\bar{x} - x/\beta + (2-y)xz}{2x\sqrt{(1-y)\,(z^2 - z/\beta - t/Q^2)}}$$

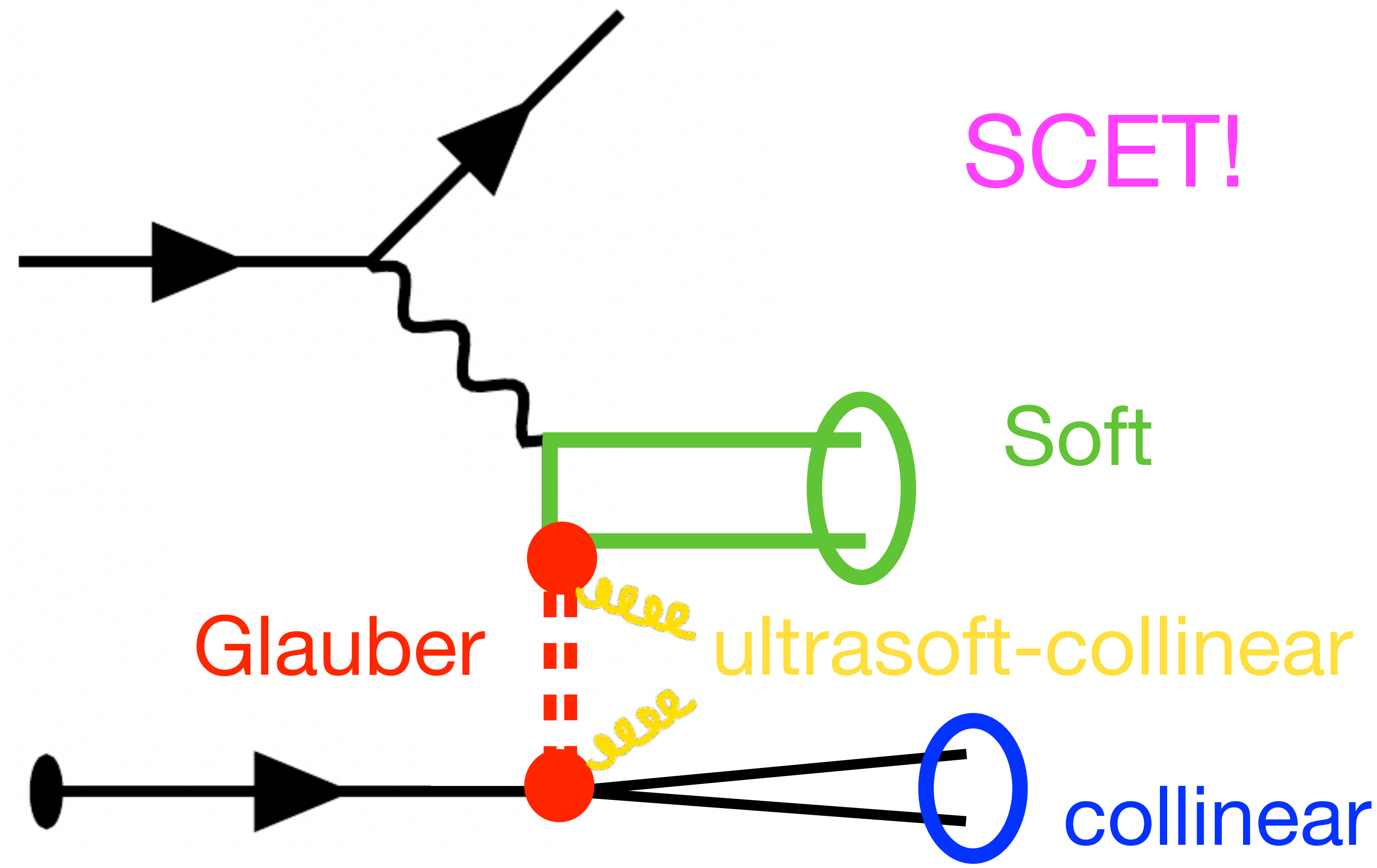
$$-1 \leq \cos\phi \leq 1$$



Scales



Diffractive Limit



Forward Scattering: $x \ll 1, -t \ll W^2$

X & Y distinguishable: $m_X^2 \ll W^2, m_Y^2 \ll W^2$

Rapidity gap: ✓

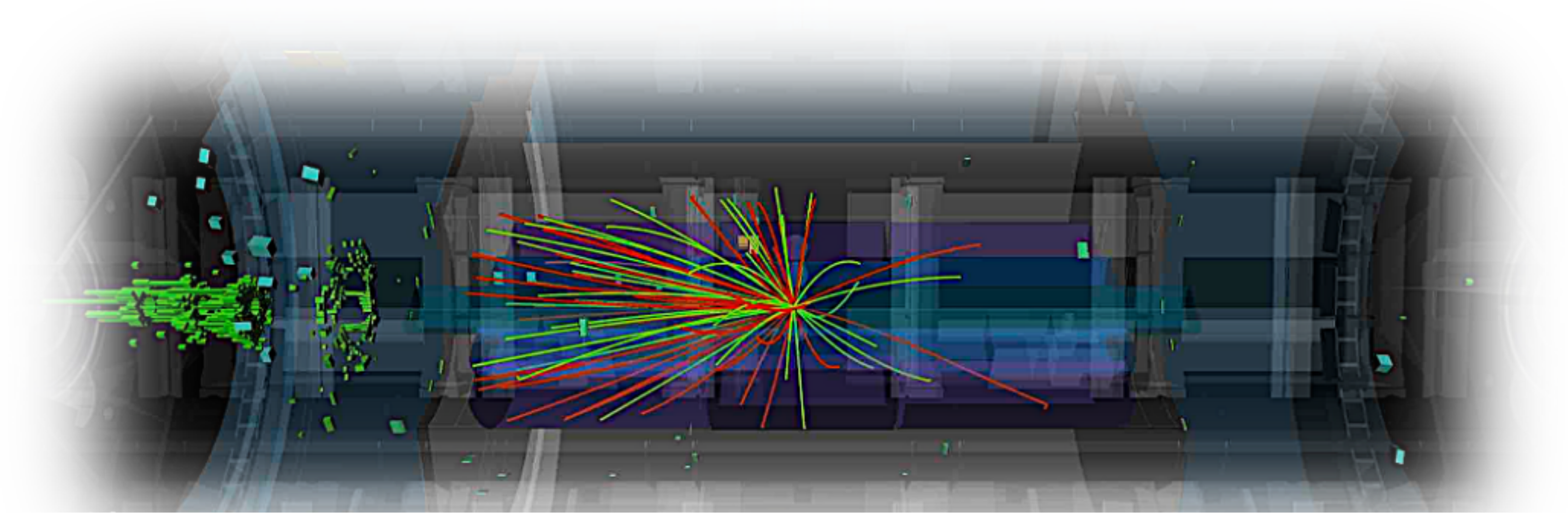
Key expansion:

$$x \sim \frac{Q^2}{s} = \lambda \ll 1$$

(Regge limit)

Outline

- Introduction: Diffraction
- Introduction: Soft Collinear Effective Theory (SCET)
- Kinematics and Structure Functions
- Power Counting and Regge Factorization
- Applications and Phenomenology



Power Counting

Power counting parameters

$$\lambda = \frac{Q}{\sqrt{s}}\,, \qquad \lambda_t = \frac{\sqrt{-t}}{Q}\,, \qquad \rho = \frac{m_Y}{\sqrt{-t}}\,, \qquad \lambda_g = \frac{\gamma}{e^{\eta_{\rm cut}^{\rm lab}}}\,, \qquad \lambda_\Lambda = \frac{\Lambda_{\rm QCD}}{\sqrt{-t}}$$

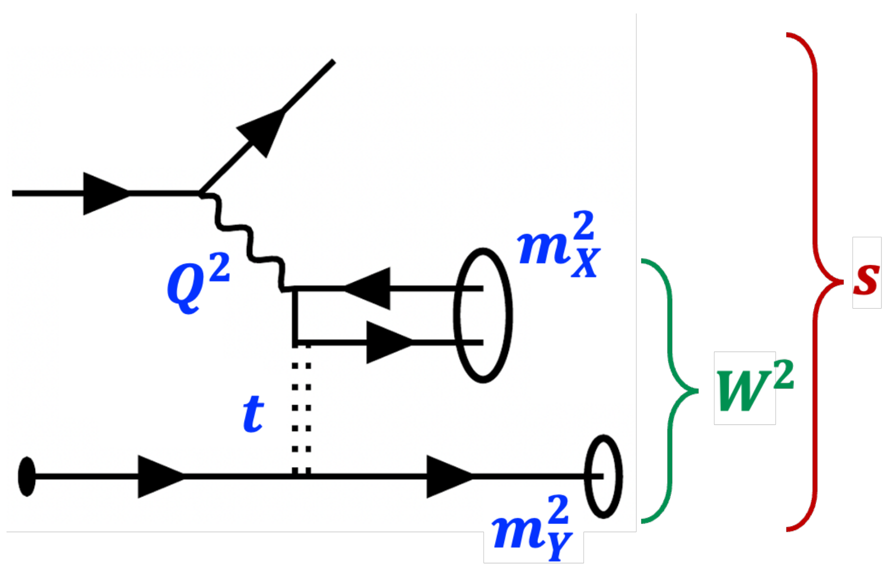
cut on radiation in gap $\gamma = \sqrt{E_p/E_e}$

I. collimated "jet" conditions $W^2 \gg p'^2 = m_Y^2, m_X^2$

$$W^2 = Q^2 \frac{1-x}{x}$$

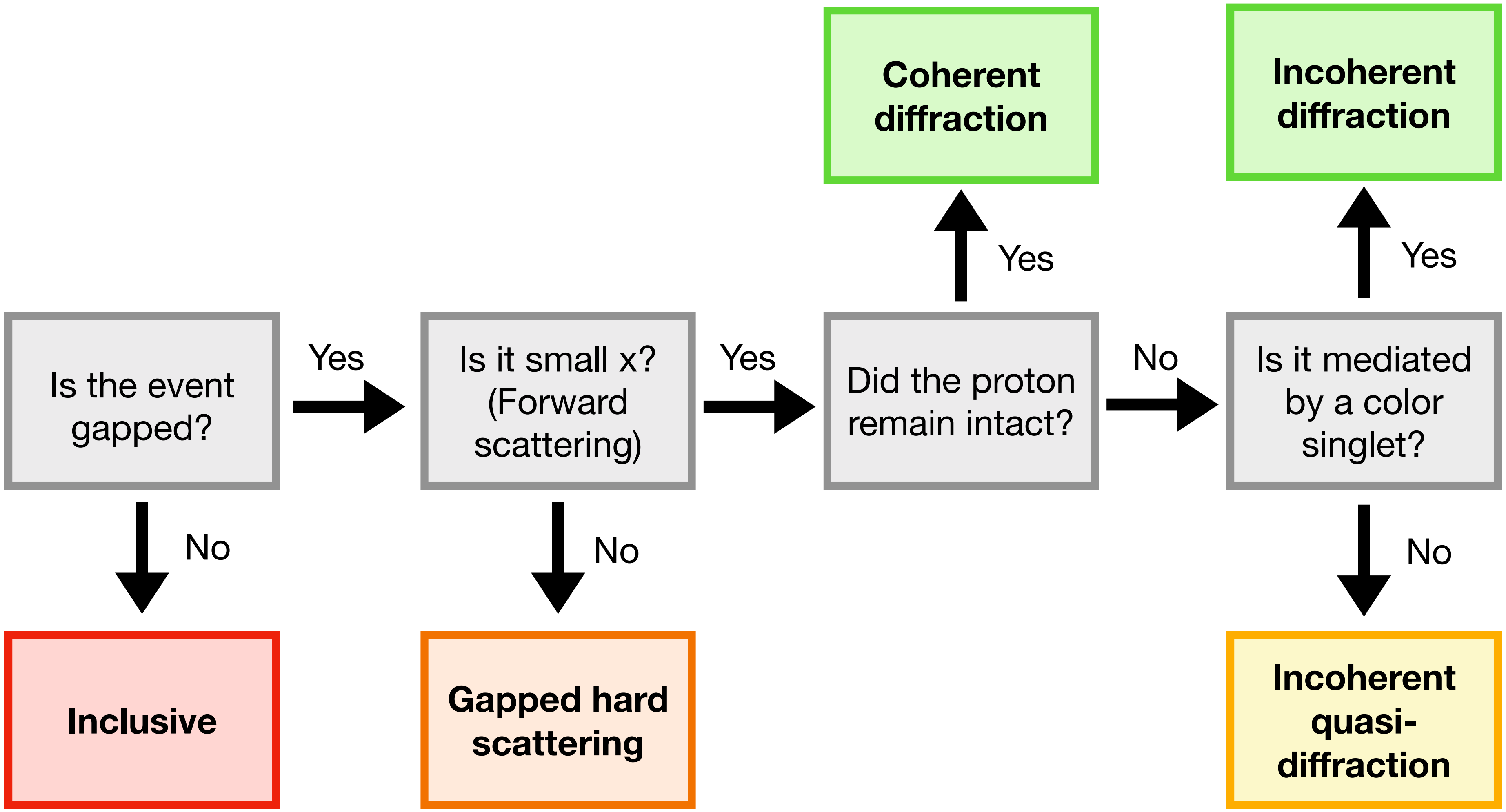
$$m_X^2 = Q^2 \frac{1-\beta}{\beta} + t$$

II. rapidity gap for X & Y $\quad \dfrac{p'^-}{p'^+} \gg \dfrac{p_X^-}{p_X^+}$

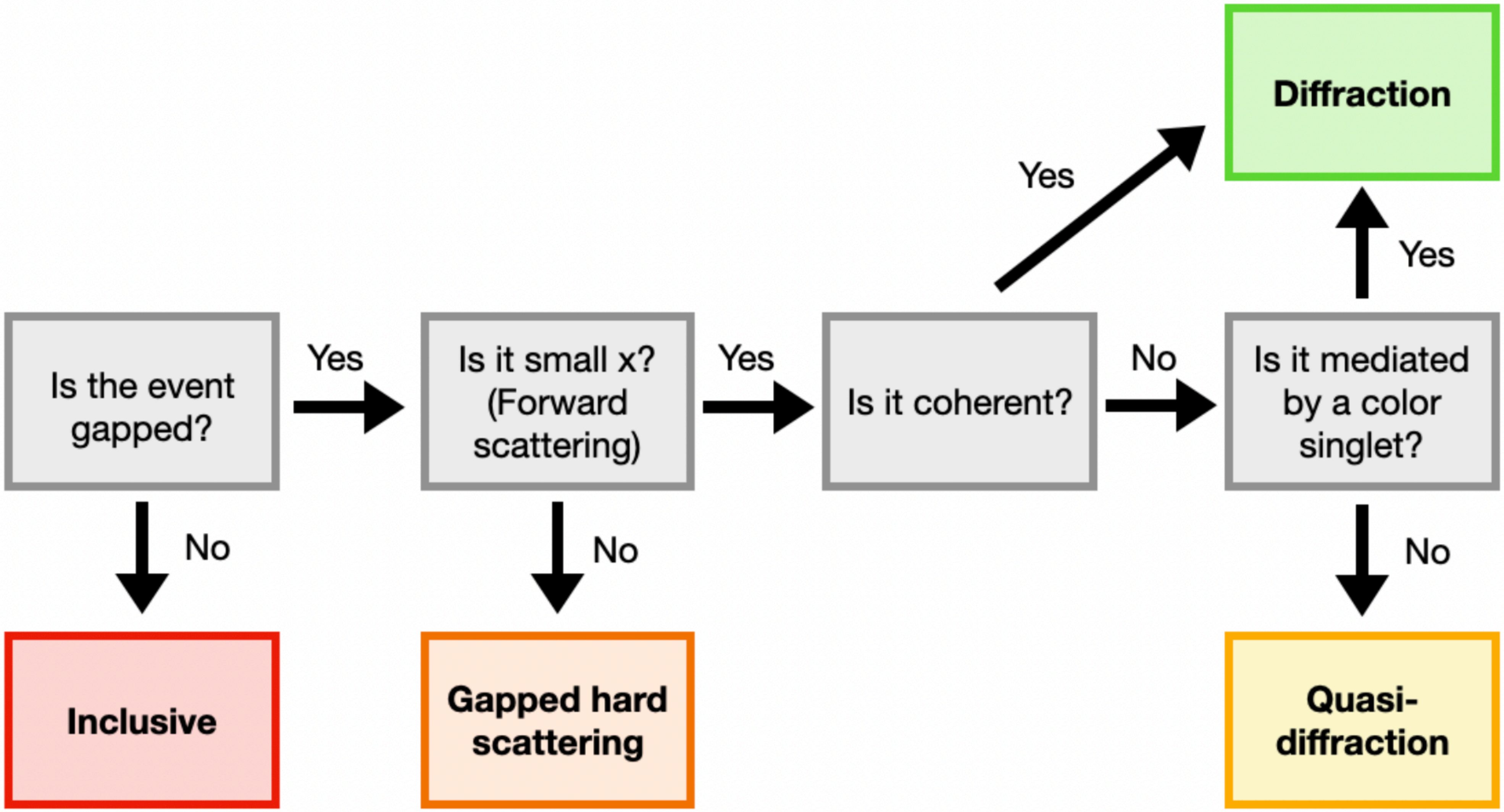


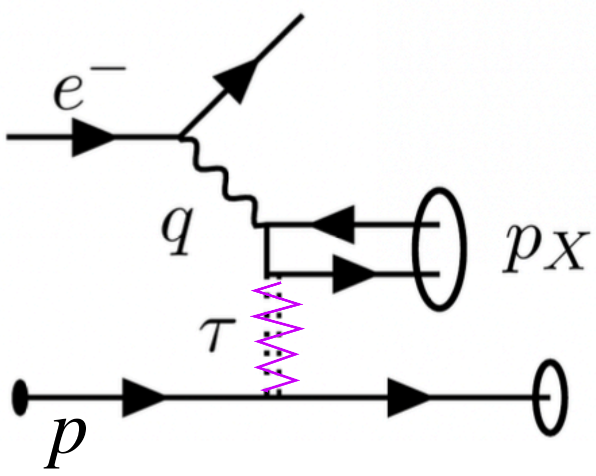
Is this enough to make event "diffractive" ?

Signal vs. Backgrounds?



Backgrounds?

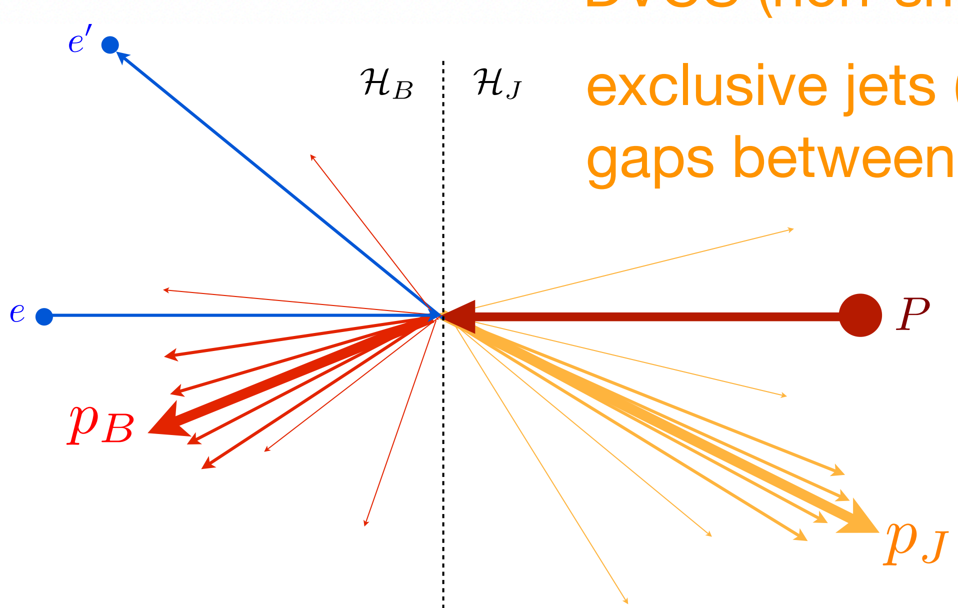


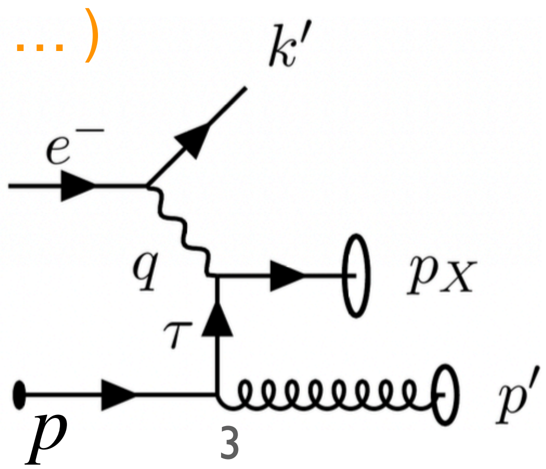


irreducible background

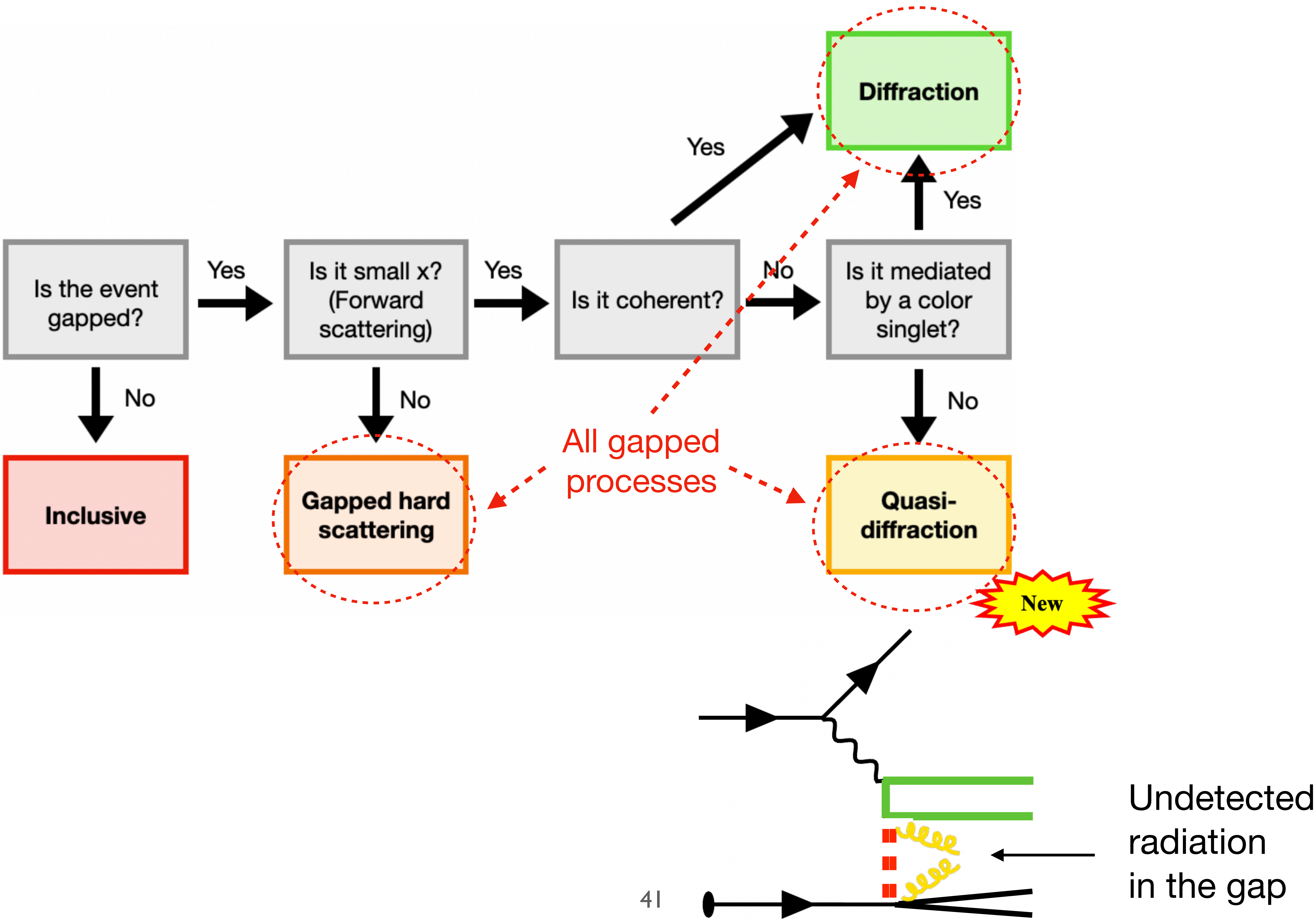
DVCS (non-small-x)

exclusive jets (eg. 1-jettiness, gaps between jets, …)





Backgrounds?



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$$m_X^2 = Q^2\frac{1-\beta}{\beta} + t$$

II. rapidity gap for X & Y $\quad \frac{p'^-}{p'^+} \gg \frac{p_X^-}{p_X^+}$

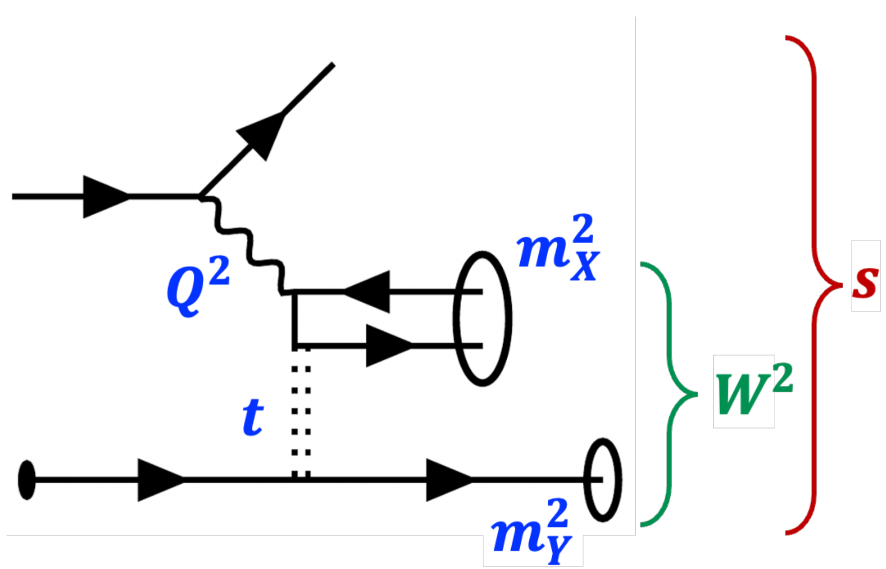
III. forward conditions $\quad -t \ll W^2, x \ll 1$

$\Rightarrow$ $\boxed{\lambda \ll 1}$

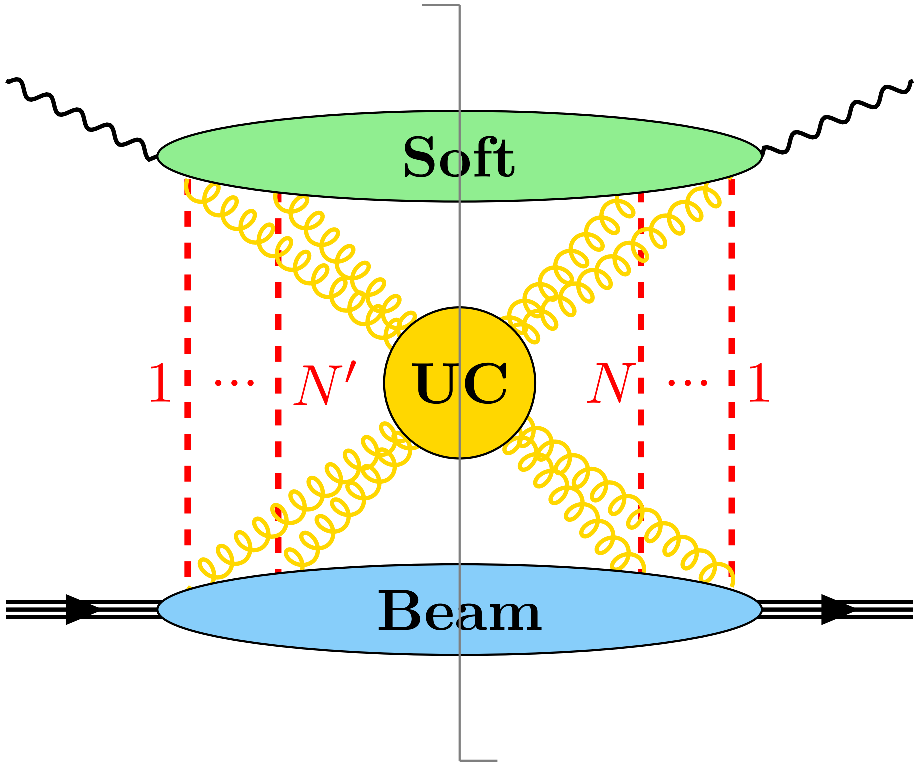
$$\lambda\lambda_t \ll 1$$

$$\frac{Q^2}{s} = xy$$

$$x \sim \lambda^2$$



Regge Factorization for ep



kinematics

$$d\sigma = \sum_{i=2,L,3,4} c_i\, F_i^D$$

structure functions (observables)

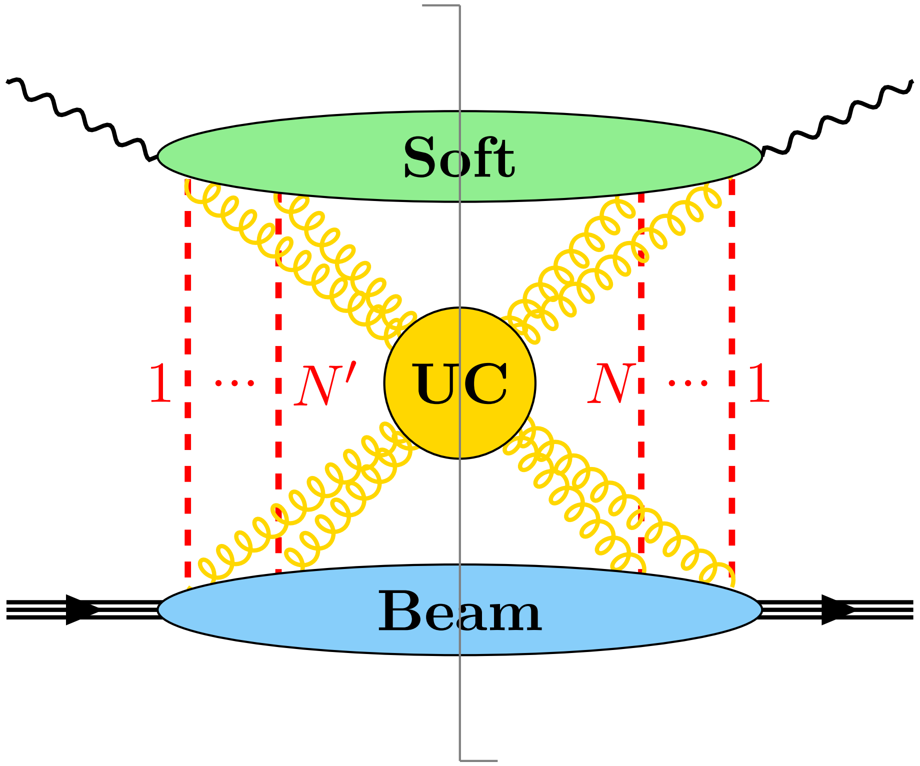
color irreps.

$$\boldsymbol{F_i^D} = \mathcal{P}_i^{\mu\nu} \times \sum_{N,N'} \sum_{\{R_X\}} \langle \textbf{Soft} \rangle_{\mu\nu} \otimes_{\perp} \langle \textbf{Beam} \rangle \otimes_{\pm} \langle \boldsymbol{UC} \rangle$$

Projectors

multiple scattering

Regge Factorization for ep



$$d\sigma = \sum_{i=2,L,3,4} c_i \, F_i^D$$

kinematics → c_i

structure functions (observables) → F_i^D

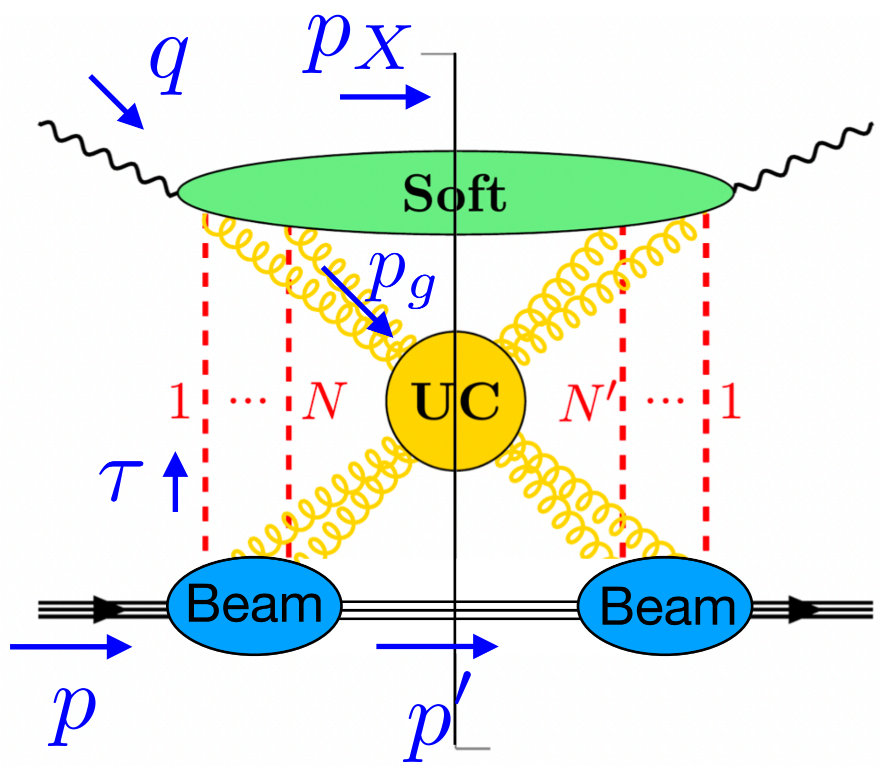
Diffraction $R_X = 1$ (singlet):

$$F_i^D = \mathcal{P}_i^{\mu\nu} \times \sum_{N,N'} \sum_{\{R_X=1\}} \langle \mathbf{Soft} \rangle_{\mu\nu} \otimes_\perp \langle \mathbf{Beam} \rangle$$

Quasi-diffraction $R_X \neq 1$:

$$F_i^D = \mathcal{P}_i^{\mu\nu} \times \sum_{N,N'} \sum_{\{R_X\neq 1\}} \langle \mathbf{Soft} \rangle_{\mu\nu} \otimes_\perp \langle \mathbf{Beam} \rangle \otimes_\pm \langle \boldsymbol{UC} \rangle$$

Regge Factorization



SCET (Breit frame) $\lambda \sim \frac{Q}{\sqrt{s}} \sim \sqrt{x}$

$+ \quad - \quad \perp$

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

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

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

Usoft-collinear mode (radiation in gap): $p_g \sim \sqrt{s}(\lambda^3, \lambda, \lambda^2)$

Regge factorization to all orders in α_s:

Includes both diffraction (signal) & quasi-diffraction (bkgnd)

Glaubers — color reps. — hadronic matrix elt.

$$F_i^D = \sum_{\substack{N,N'=1\\ N+N'=\text{even}}}^{\infty} \sum_{\{R_X\}} \iint_{(N,N')}^{\perp} \int dp_g^+ dp_g^- \, B_{A\,(N,N')}^{R^{NN'}}\Big(m_Y^2 - t - p^- p_g^+, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, \mu, \frac{\nu}{Q/x}\Big) \frac{Q^2}{x}$$

$$\times\, U_{(N,N')}^{R_A^{NN'} R_B^{NN'}}\Big(\frac{1}{h\sqrt{x}} p_g^+, h\sqrt{x}\, p_g^-, \mu\Big)\, S_{i(N,N')}^{R_B^{NN'}}\Big(\frac{Q^2}{\beta} - q^+ p_g^-, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \mu, \frac{\nu}{Q/\beta}\Big)$$

vacuum matrix elt. of Wilson lines (generalized "hemisphere" usoft fn.)

vacuum matrix elt. with photon currents

only S_i depends on i

rest universal for all i

Operators

(as promised)

$$F_i^D = \mathcal{P}_i^{\mu\nu} \times \sum_{N,N'} \sum_{\{R_X\}} \langle \text{Soft} \rangle_{\mu\nu} \otimes_\perp \langle \text{Beam} \rangle \otimes_\pm \langle UC \rangle$$

$$B^{R_A^{NN'}}_{(N,N')}(p^- k_n^+, \{\tau_{i\perp}, \tau'_{j\perp}\}, t) = \frac{1}{(\bar{n}\cdot p)^2} \int \frac{dv^-}{2p^-}\, e^{\frac{i}{2}v^- k_n^+} \sum_{Y_n}$$

$$\times \langle p| \Big\{ \prod_{i=1}^{N-1} \mathcal{O}_n^{A_i}(v^- \tfrac{n}{2}, \tau_{i\perp}) \bar{\mathcal{O}}_n^{A_N}(v^- \tfrac{n}{2}) \Big\} P_{NR_A} |Y_n\rangle\langle Y_n| P_{N'R_A} \Big\{ \prod_{j=1}^{N'-1} \mathcal{O}_n^{A'_j}(0, \tau'_{j\perp}) \bar{\mathcal{O}}_n^{A'_{N'}}(0) \Big\} |p\rangle$$

$$S^{R_B^{NN'}}_{i(N,N')}(q^+ k_s^-, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t) = \Big(\frac{Q}{n\cdot q}\Big)^2 \mathcal{P}'_{i\,\mu\nu} \int [d\tilde{y}]\,[d\tilde{y}']\, \text{đ}^d z\; e^{\frac{i}{2}(y^+ - y'^+)k_s^-}\, e^{iz\cdot q}$$

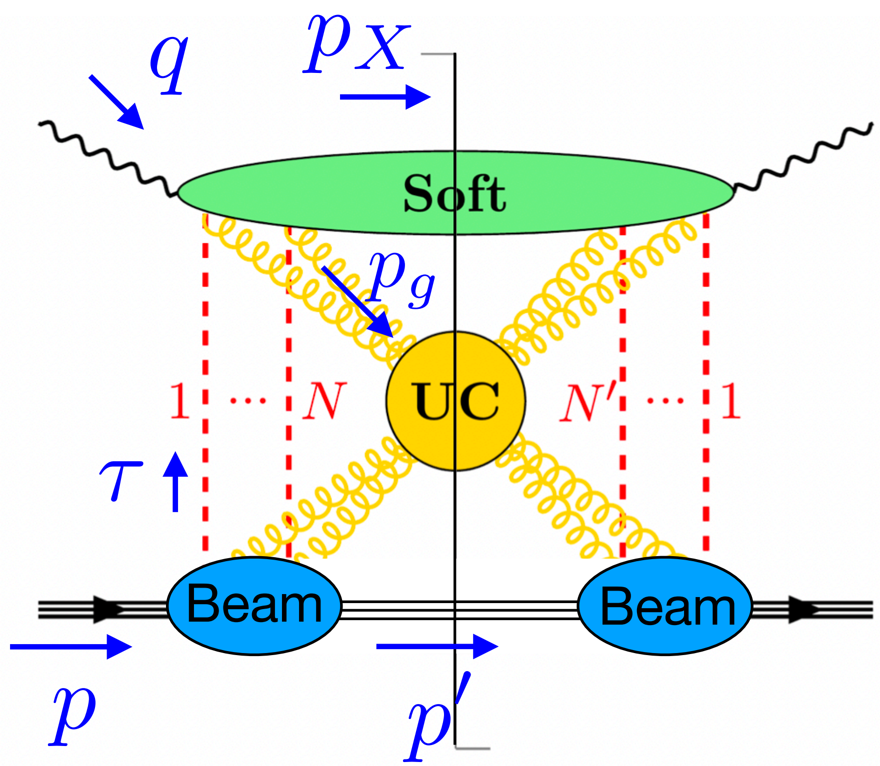
$$\times \sum_{X_s} \langle 0| \bar{T}\, J_s^\mu(z) \Big\{ \prod_{i=1}^{N} \mathcal{O}_s^{B_i}(\tilde{y}, -\tau_{i\perp}) \Big\} P_{NR_B} |X_s\rangle\langle X_s| P_{N'R_{B'}} T\, J_s^\nu(0) \Big\{ \prod_{j=1}^{N'} \mathcal{O}_s^{B'_j}(\tilde{y}', -\tau'_{j\perp}) \Big\} |0\rangle$$

$$U^{R_A^{NN'} R_B^{NN'}}_{(N,N')}(p_H^+, p_H^-) = \sum_{Z_{uc}} \delta\Big(p_H^+ - p_{uc}^{\mathcal{H}_Y +}\Big)\, \delta\Big(p_H^- - p_{uc}^{\mathcal{H}_X -}\Big)$$

$$\times \langle 0| P_{NR_A} \bar{T} \prod_{i=1}^{N} \mathbb{U}_{n\bar{n}}^{A_i B_i}(0)\, P_{NR_B} |Z_{uc}\rangle\langle Z_{uc}| P_{N'R_{A'}} T \prod_{j=1}^{N'} \mathbb{U}_{n\bar{n}}^{A'_j B'_j}(0) P_{N'R_{B'}} |0\rangle$$

- A further factorization of S_i gives H_i and fact. for dPDF

Regge Factorization



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Convolutions between momentum components that are of the same size

$$F_i^D = \sum_{\substack{N,N'=1 \\ N+N'=\text{even}}}^{\infty} \sum_{\{R_X\}} \iint^{\perp}_{(N,N')} \int dp_g^+ dp_g^- \; B^{R_A^{NN'}}_{(N,N')}\Big(m_Y^2 - t - p^- p_g^+, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, \mu, \frac{\nu}{Q/x}\Big) \; \frac{Q^2}{x}$$

$$\times\, U^{R_A^{NN'} R_B^{NN'}}_{(N,N')}\Big(\frac{1}{h\sqrt{x}} p_g^+, h\sqrt{x}\, p_g^-, \mu\Big) \; S^{R_B^{NN'}}_{i(N,N')}\Big(\frac{Q^2}{\beta} - q^+ p_g^-, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \mu, \frac{\nu}{Q/\beta}\Big)$$

$$h = \sqrt{\frac{E_p}{yE_e}}\, e^{-\eta_{\rm cut}^{\rm lab}}$$

$$\iint^{\perp}_{(N,N')} \equiv \frac{(-\mathrm{i})^N (\mathrm{i})^{N'}}{N!\,N'!} \int \prod_{i=1}^{N} \frac{d^{d'}\tau_{i\perp}}{\vec{\tau}_{i\perp}^{\,2}}\, \delta^{d'}\Big(\sum_i \tau_{i\perp} + \tau_\perp\Big) \int \prod_{j=1}^{N'} \frac{d^{d'}\tau'_{j\perp}}{\vec{\tau}_{j\perp}^{\,\prime 2}}\, \delta^{d'}\Big(\sum_j \tau'_{j\perp} - \tau_\perp\Big)$$

Regge Factorization

Diffraction (signal): $R_X = 1$ can prove U = δ-functions (to all orders)

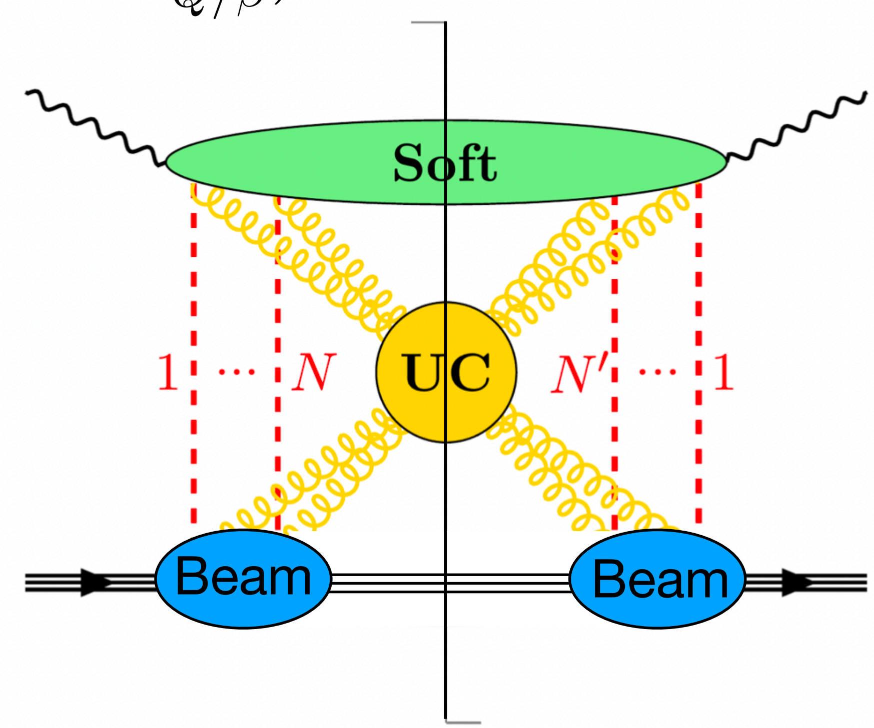
for singlet follows from $\mathscr{U}^\dagger \mathscr{U} = 1$ **no uc radiation in gap!**

$$F_i^{D\,\text{diff}} = \sum_{\substack{N,N'=1\\N+N'=\text{even}}}^{\infty} \sum_{R^{NN'}=1} \iint_{(N,N')}^{\perp} B_{(N,N')}^{R^{NN'}}\Big(m_Y^2 - t, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, \frac{\nu}{Q/x}\Big) \quad S_{i(N,N')}^{R^{NN'}}\Big(\frac{Q^2}{\beta}, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \frac{\nu}{Q/\beta}\Big) \frac{Q^2}{x}$$

Quasi-diffraction (bkgnd): $R_X \neq 1$

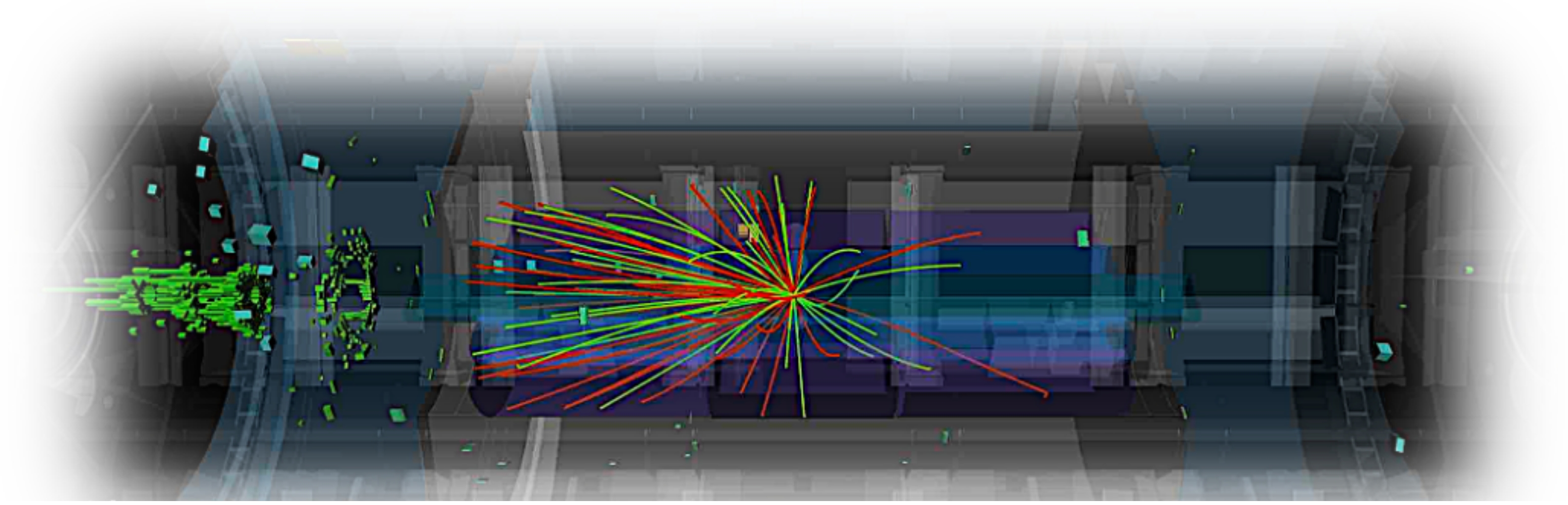
$$F_i^{D\,\text{quasi}} = \sum_{\substack{N,N'=1\\N+N'=\text{even}}}^{\infty} \sum_{\{R_X \neq 1\}} \iint_{(N,N')}^{\perp} \int dp_g^+ dp_g^- \, B_{(N,N')}^{R_A^{NN'}}\Big(m_Y^2 - t - p^- p_g^+, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, \mu, \frac{\nu}{Q/x}\Big) \quad \frac{Q^2}{x}$$
$$\times\, U_{(N,N')}^{R_A^{NN'} R_B^{NN'}}\Big(\frac{1}{h\sqrt{x}} p_g^+, h\sqrt{x}\, p_g^-, \mu\Big) \, S_{i(N,N')}^{R_B^{NN'}}\Big(\frac{Q^2}{\beta} - q^+ p_g^-, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \mu, \frac{\nu}{Q/\beta}\Big)$$

allows radiation in gap



Outline

- Introduction: Diffraction
- Introduction: Soft Collinear Effective Theory (SCET)
- Kinematics and Structure Functions
- Power Counting and Regge Factorization
- Applications and Phenomenology



What is $\mathbb{P}$ here?

- Has contributions from an ∞ number of Glauber exchanges

- Color singlet projection: $(8\otimes)^N = 1 \oplus \cdots \oplus 1 \oplus$ (others)

many singlets

- Can distinguish nonperturbative $\tau_\perp \sim \Lambda_{\rm QCD}$ and perturbative $\tau_\perp \gg \Lambda_{\rm QCD}$ contributions to the "Pomeron"

- Differs from Ingelman-Schlein model

$$F_i^{D\,\rm diff} = \frac{Q^2\varsigma^2}{x} \sum_{N,N'=1}^{\infty} \sum_{R^{NN'}=1} \iint_{(N,N')}^{\perp} B_{(N,N')}^{R^{NN'}}\Big(m_Y^2 - t, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, \frac{\nu}{Q/x}\Big)\; S_{i(N,N')}^{R^{NN'}}\Big(\frac{Q^2}{\beta}, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \frac{\nu}{Q/\beta}\Big)$$

$$\iint_{(N,\,N')}^{\perp} \equiv \frac{(-{\rm i})^N({\rm i})^{N'}}{N!\,N'!} \int \prod_{i=1}^{N} \frac{{d\!\!\!^-}^{d'}\tau_{i\perp}}{\vec\tau_{i\perp}^{\,2}}\, \bar\delta^{d'}\Big(\sum_i \tau_{i\perp} + \tau_\perp\Big) \int \prod_{j=1}^{N'} \frac{{d\!\!\!^-}^{d'}\tau'_{j\perp}}{\vec\tau_{j\perp}^{\prime 2}}\, \bar\delta^{d'}\Big(\sum_j \tau'_{j\perp} - \tau_\perp\Big)$$

Applications

Lots of things still to explore, so I only provide some examples of what we've done so far:

1) Identify observables F_i^D that are leading order in $\lambda \ll 1$:
 4 for spin independent scattering,
 6 more for spin dependent (not discussed here)

 [8 more at subleading orders in λ]

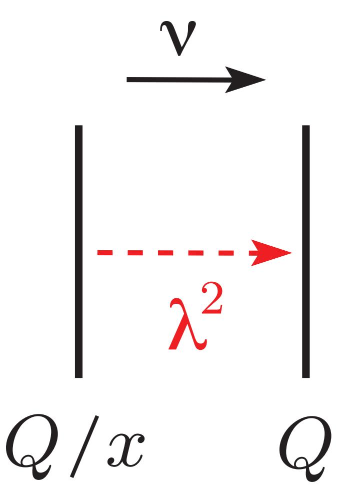
$$F_2^D \sim F_L^D \sim F_3^D \sim F_4^D \sim \lambda^{-6} \qquad \text{(incoherent)}$$

2) More general kinematic regions of diffractive phase space (larger t), provide additional experimental targets

Applications

virtuality rapidity

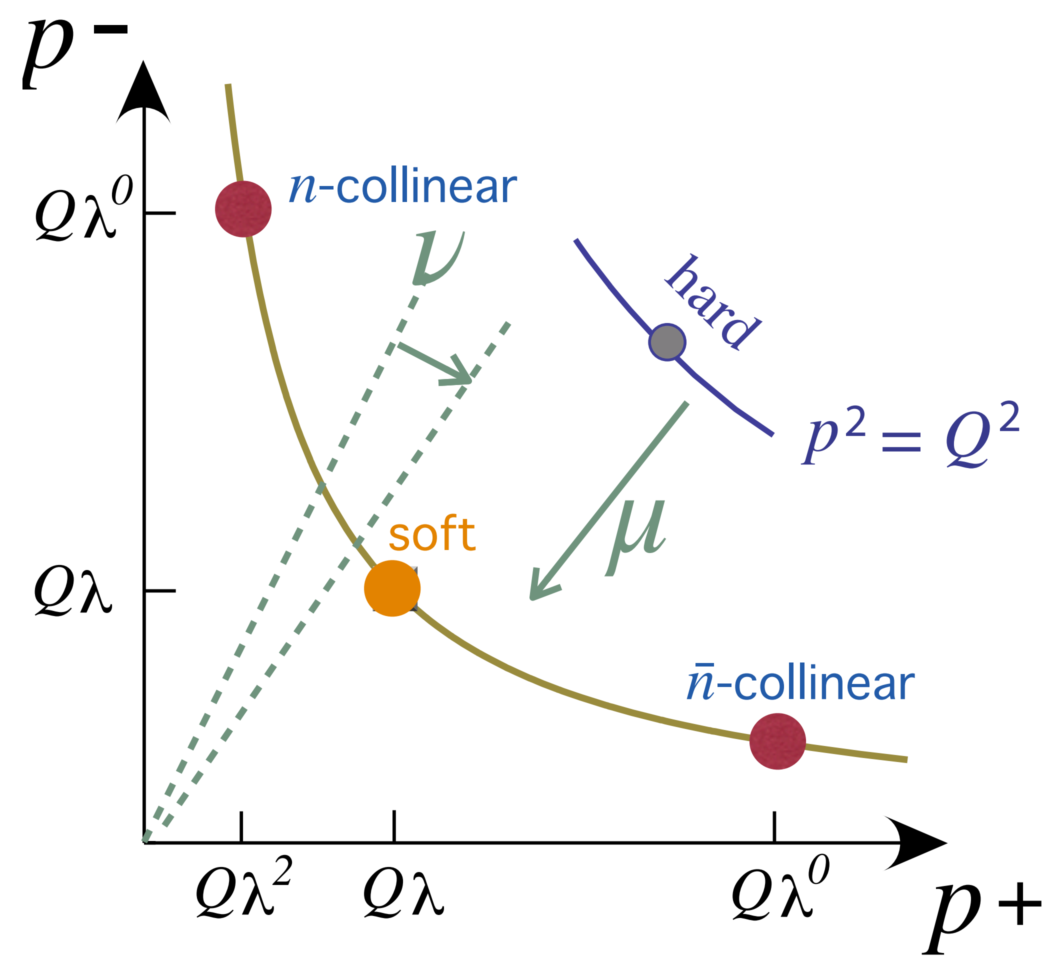
Two types of RGE (μ, ν)



BFKL-type logs

both signal and bkgnd have "rapidity logs"

$$\sum_k (\alpha_s \ln x)^k$$



only the quasi-diffractive background has large virtuality (invariant mass) logs

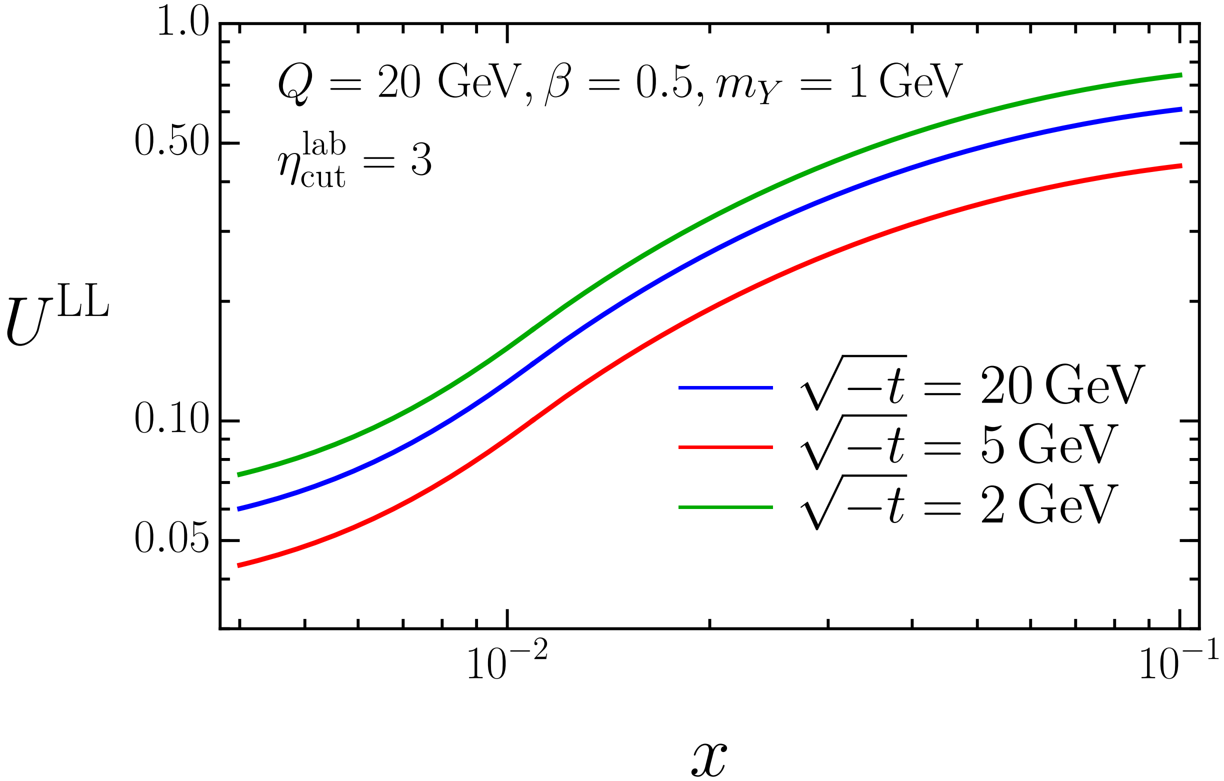
3) Can compute size of quasi-diffractive background with EFT
its suppressed by $U \sim \exp\Big(- \text{Sudakov}\Big)$

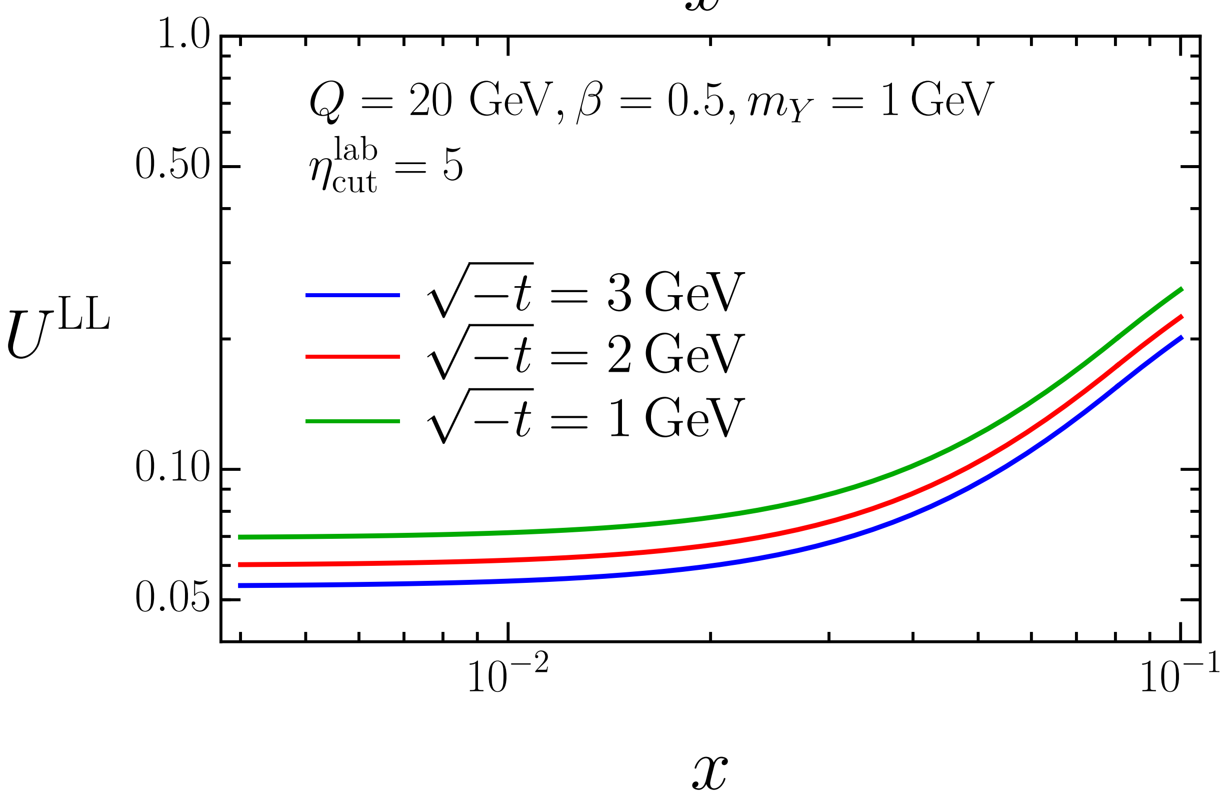
~ probability for no emission into the gap from U

$\sim \exp(-\alpha_s \ln^2 x)$

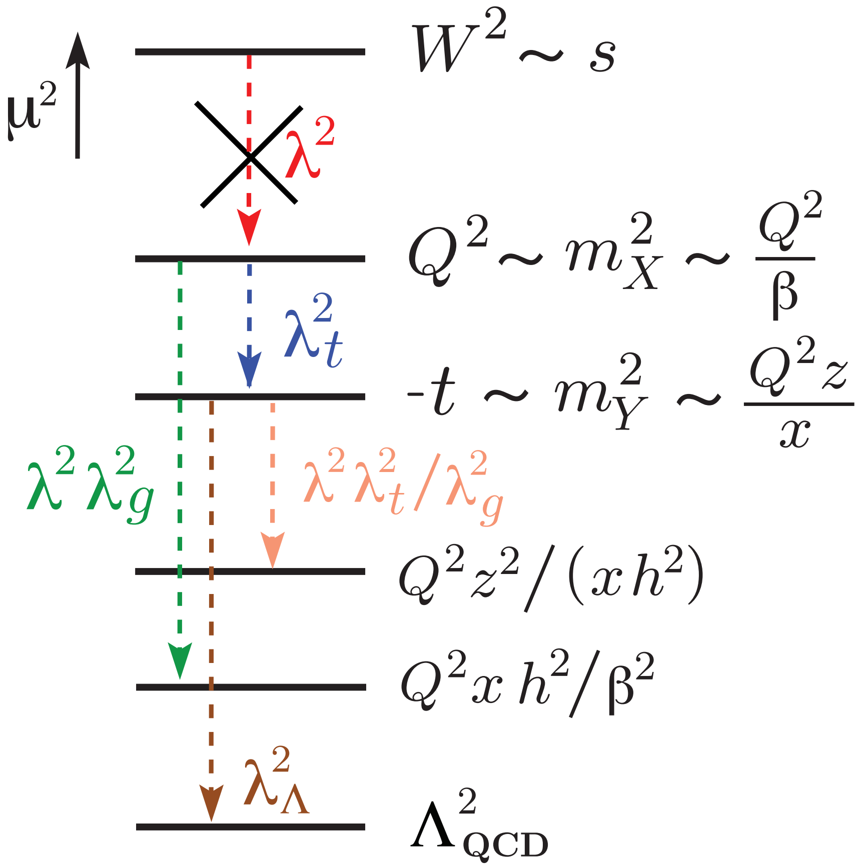
Applications

3) Can compute size of quasi-diffractive background
its suppressed by $U \sim \exp\big(-\text{Sudakov}\big)$



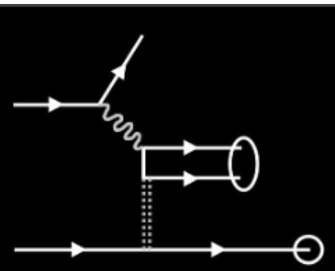


- **Quasi-Diffraction background is not always negligible**



Applications

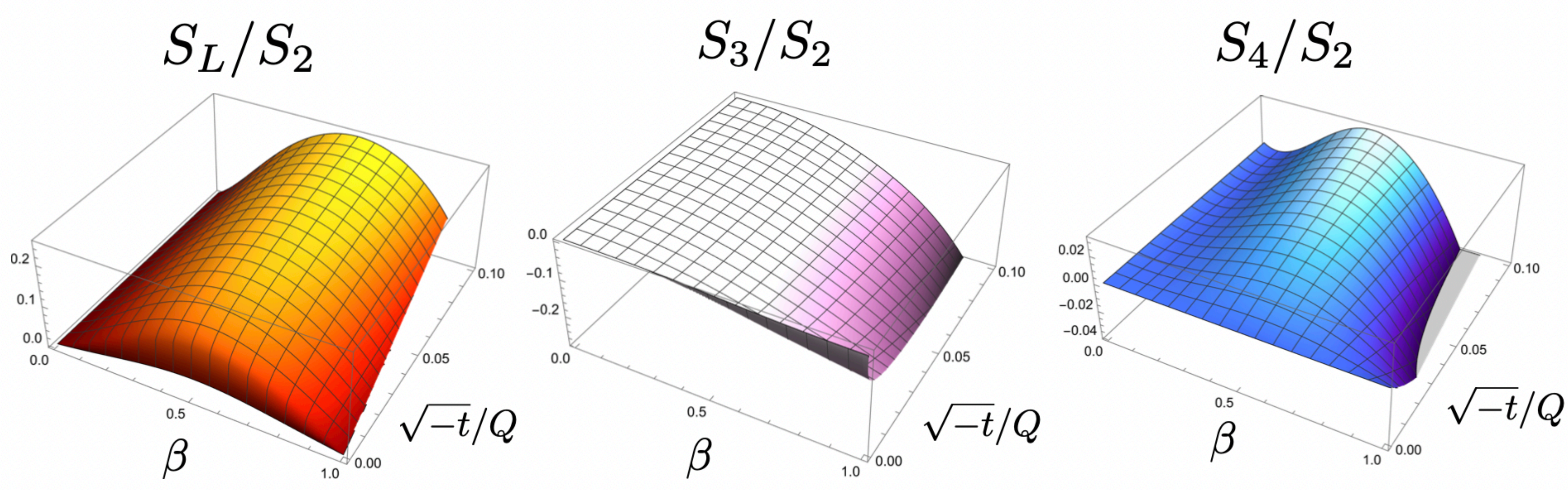
3) Can compute size of quasi-diffractive background
its suppressed by $U \sim \exp\big(-\text{Sudakov}\big)$

	$\frac{F_i^{\text{quasi}}}{F_i^{\text{diff}}} = \frac{\text{background}}{\text{signal}}$	
Coherent diffraction (intact proton)	0	Pure singlet
Incoherent $-t \sim \Lambda^2_{\text{QCD}}$	$\sim U_{LL}$	Dominated by singlet
Incoherent $-t \gg \Lambda^2_{\text{QCD}}$	$\sim \frac{U_{LL}}{\alpha_s(-t)}$	Can be similar size

Applications

4) For $|t| \gg \Lambda^2_{\rm QCD}$ can compute ratios of quasi-F_i^D

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



- Exploit to reduce quasi-background with linear combinations

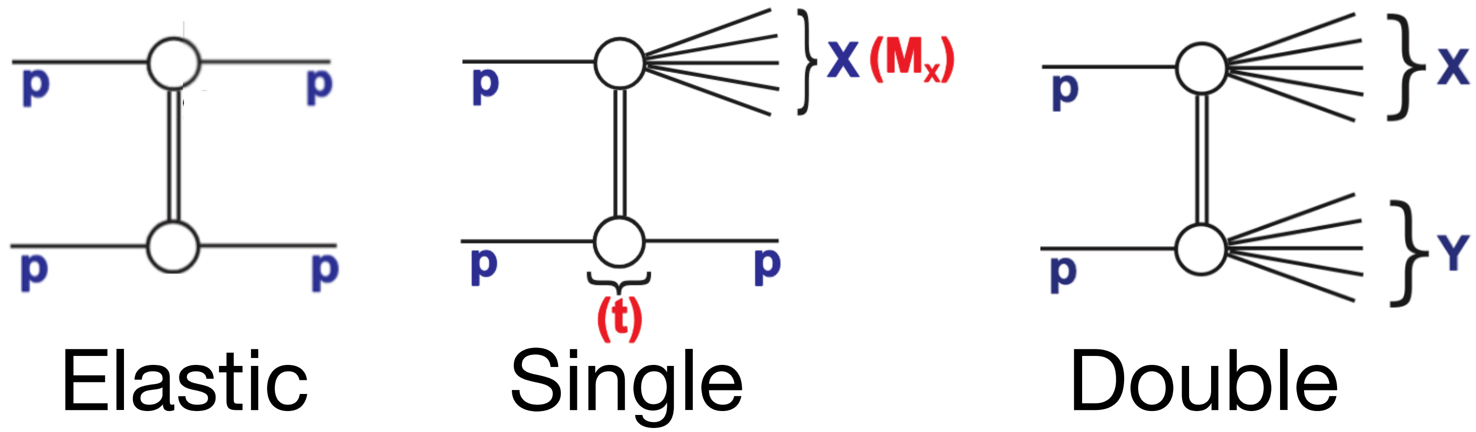
(nontrivial: requires demonstrating cancellation of infinite number of nonperturbative Glauber exchanges in the ratios)

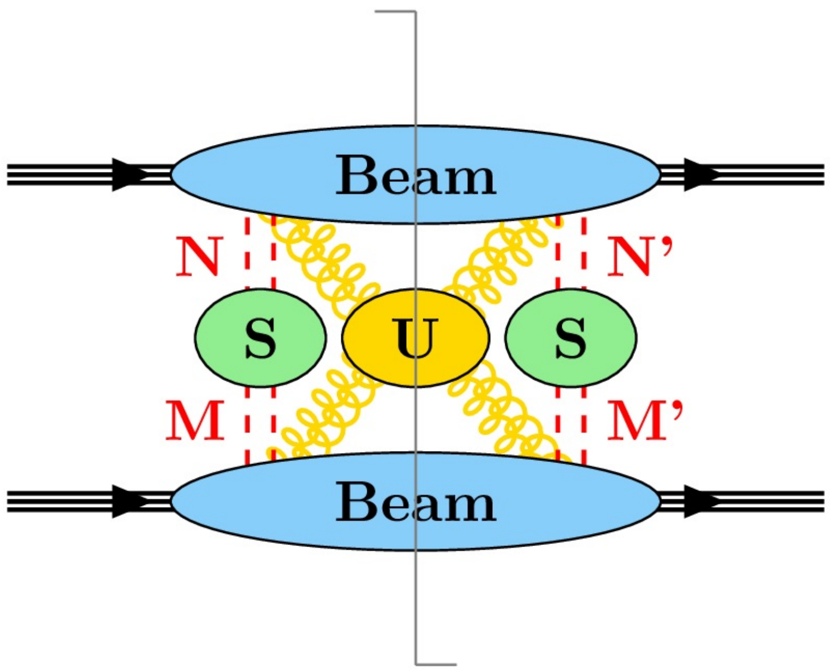
Applications

Philipp Aretz

5) universality between *ep* and *pp* diffraction?
(paper to appear soon)

Double: $pp \to XY$





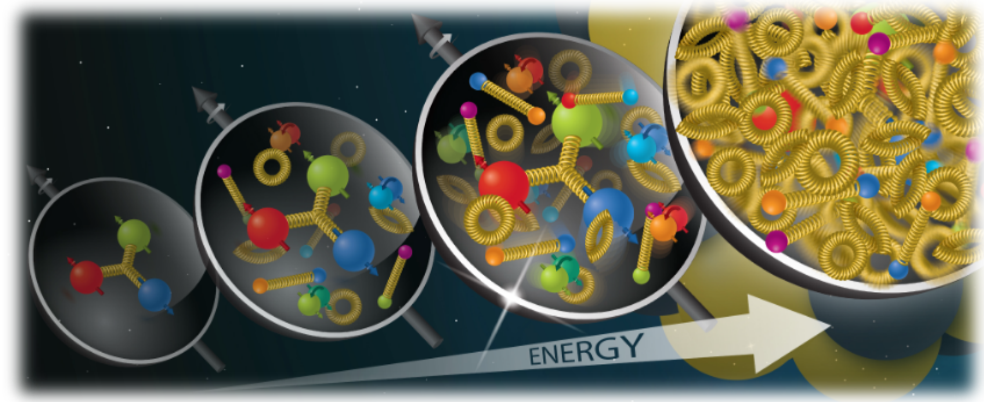
$$\frac{d^3\sigma}{dM_1^2 dM_2^2 dt} = \sum_{\{R_X\}} \sum_{\substack{N,N' \\ M,M'}} S_{NM}^{\hat{R}_A} \otimes_\perp B_{NN'}^{R_A} \otimes_\perp S_{N'M'}^{\hat{R}_A} \otimes_\perp B_{MM'}^{R_B} \otimes_\pm U_{NN'MM'}^{R_A R_B \hat{R}_A}$$

- Beam functions are universal (*ep* & *pp*)
- Soft & Usoft functions are not universal
  (explains failure of using dPDFs)

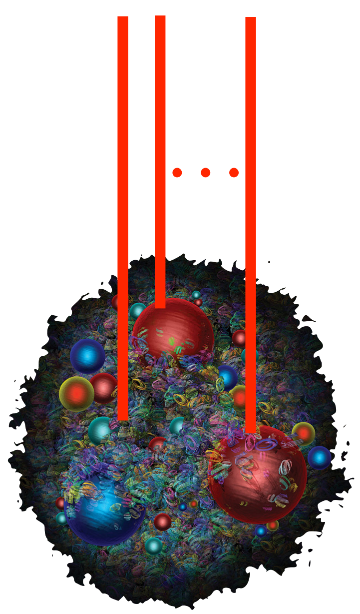
- Rapidity anom.dimensions are universal (small-x resummation)

Future Directions

a) ratio predictions F_i^D/F_2^D for signal?
(calculations in progress)



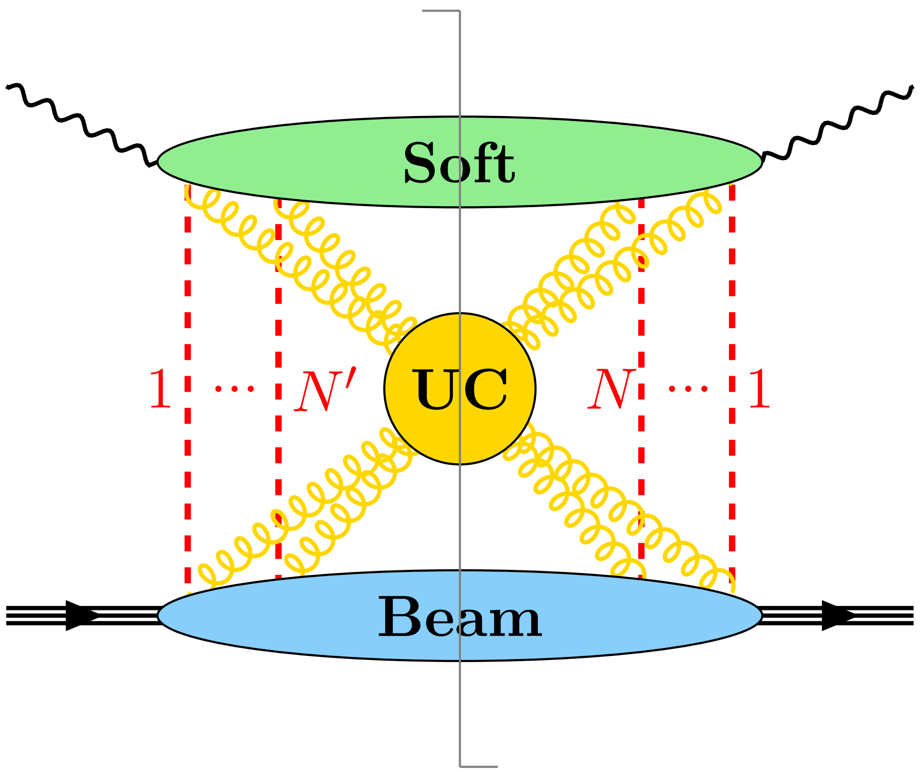
b) EFT description of saturation (1st steps)

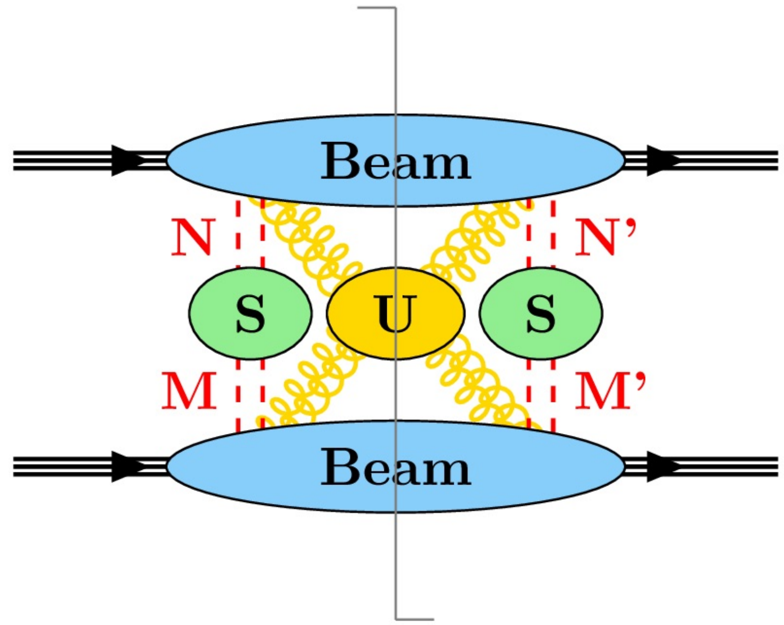


c) hadron structure

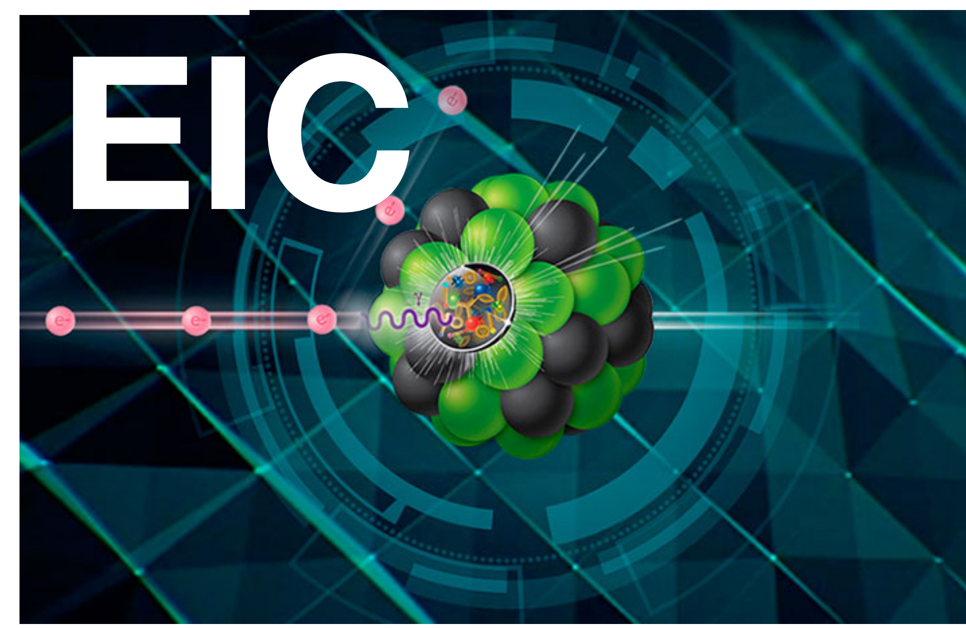
d) generalization to multi-gap, exclusive, heavy meson, … processes

Conclusion: new tools & a bright future for Diffraction in QCD





FAIR



HiLumi
HL-LHC PROJECT

Backup

Backgrounds

Monte Carlo predictions:

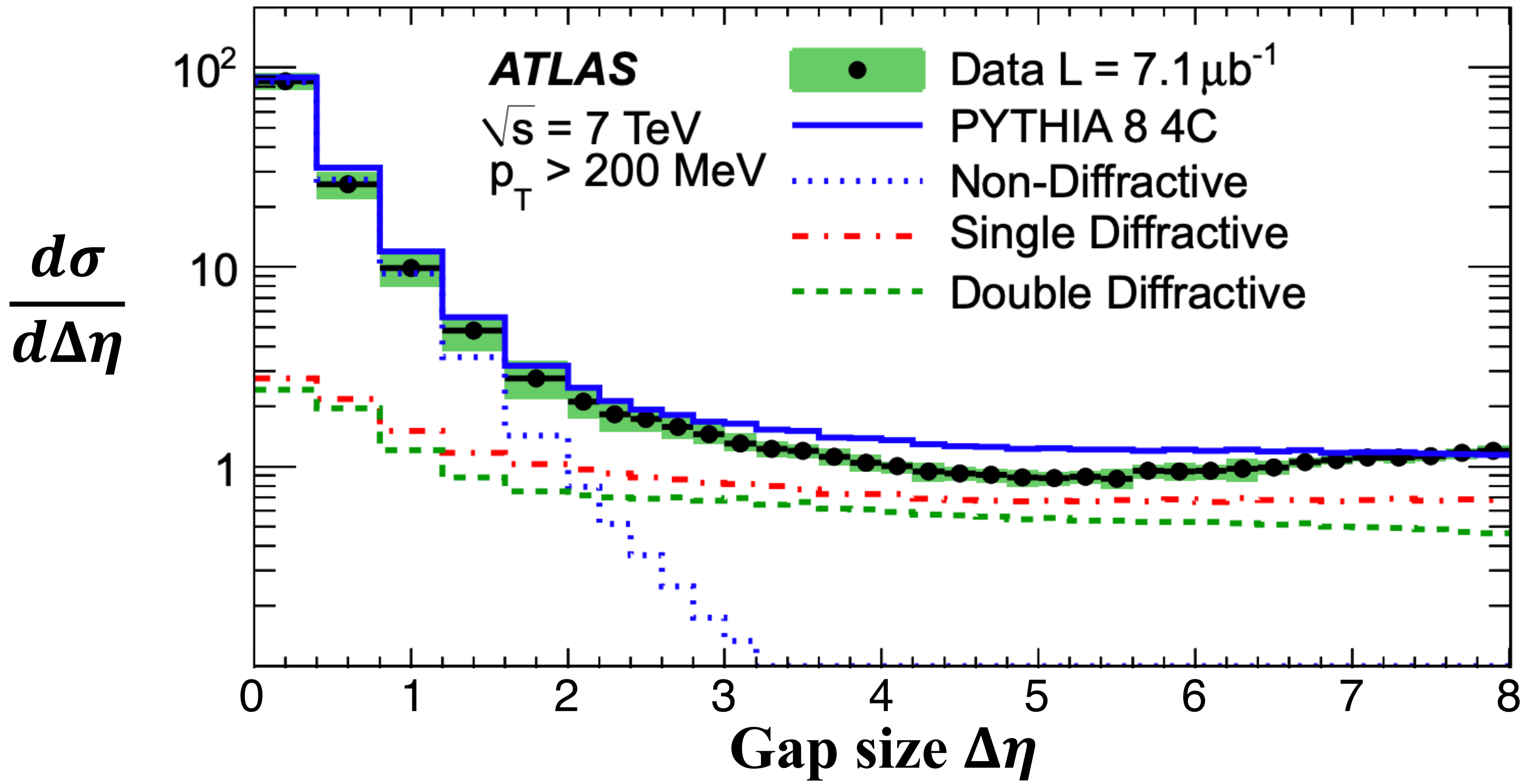
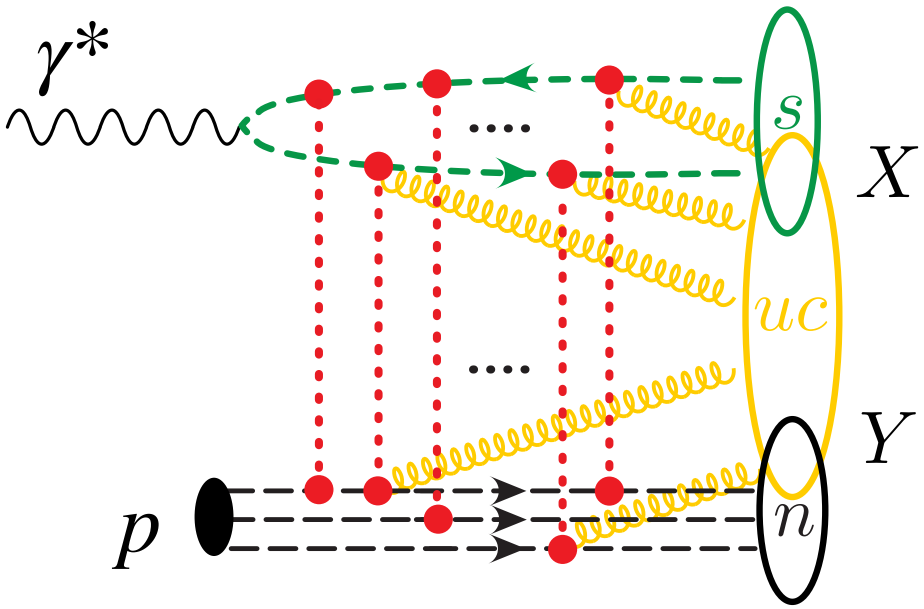


Figure: ATLAS, 1201.2808.

Regge Factorization



SCET (Breit frame) $\lambda \sim \frac{Q}{\sqrt{s}} \sim \sqrt{x}$

$+ \quad - \quad \perp$

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

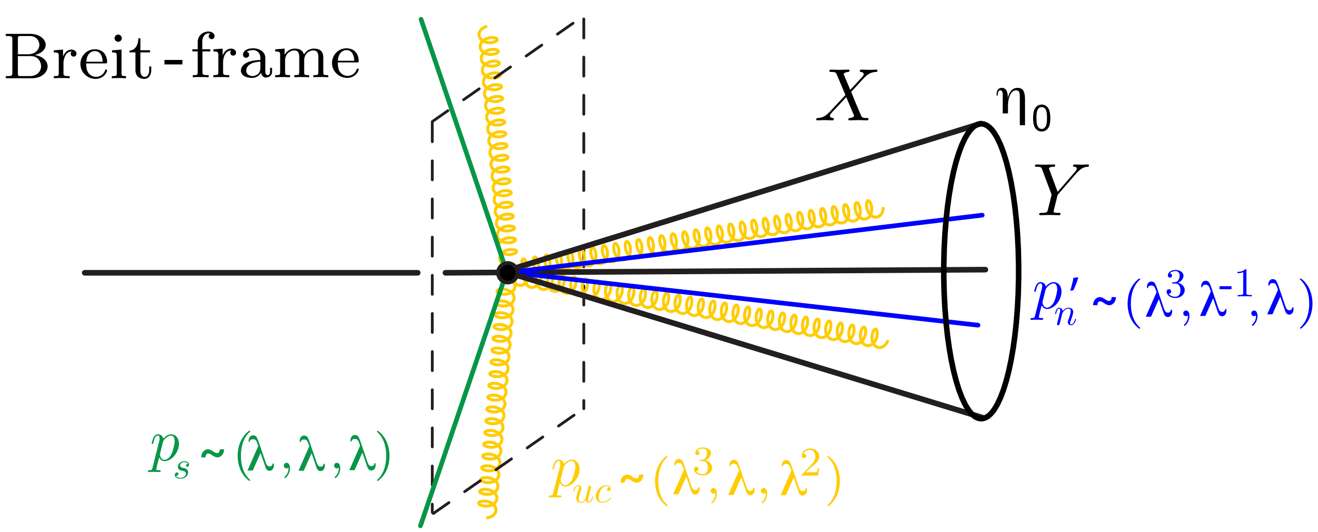
Glauber: $\tau \sim \sqrt{s}(\lambda^3, \lambda, \lambda)$

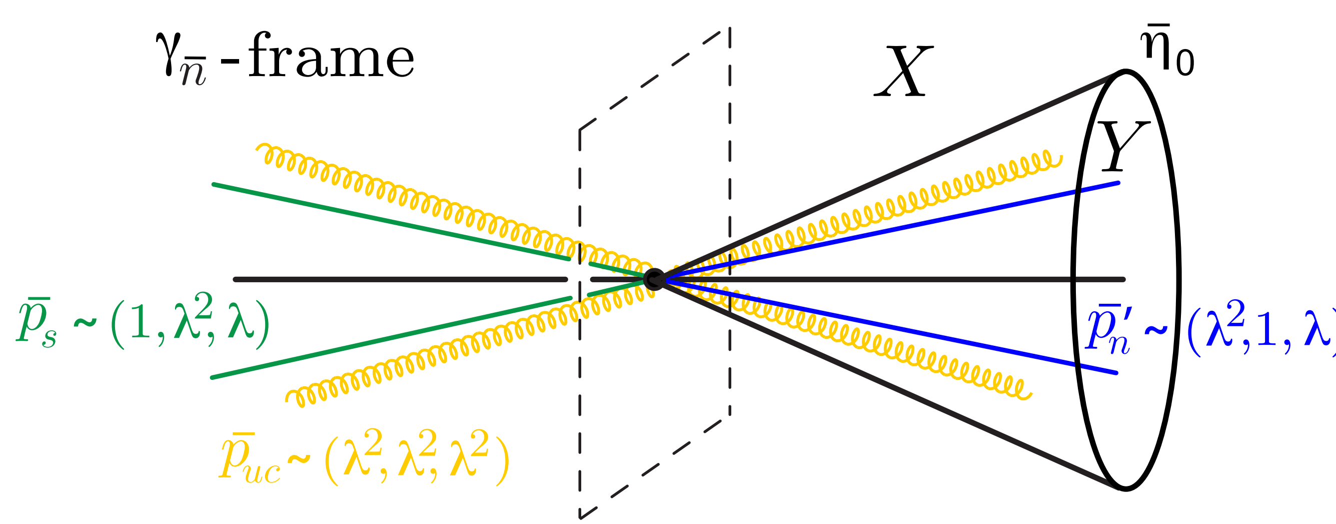
Collinear mode (p,Y): $p' \sim \sqrt{s}(\lambda^3, \lambda^{-1}, \lambda)$

Usoft-collinear mode (radiation in gap): $p_g \sim \sqrt{s}(\lambda^3, \lambda, \lambda^2)$

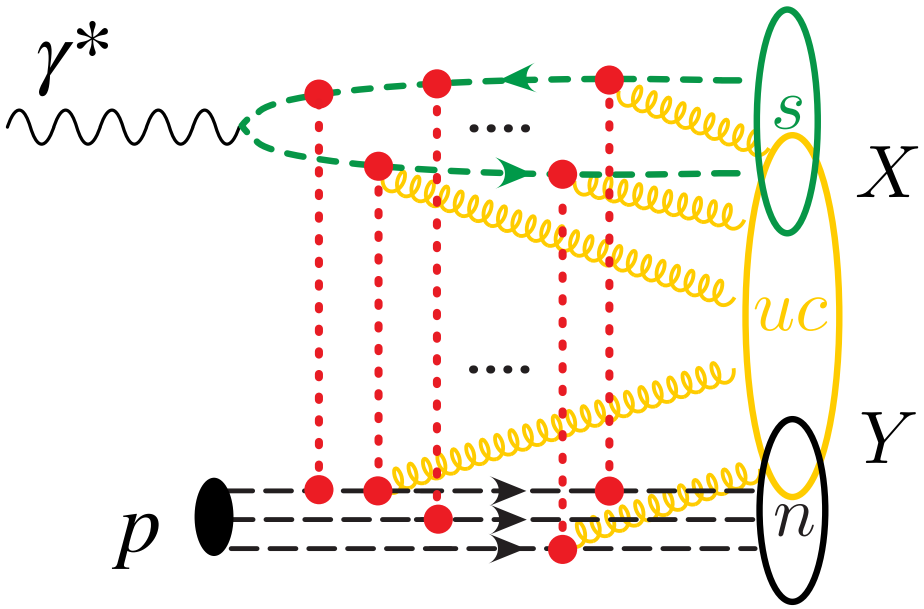
$$q^\mu = Q\frac{\bar{n}^\mu}{2} - Q\frac{n^\mu}{2} = (0,0,0,Q)$$

$$q^\mu = \sqrt{ys}\,\frac{\bar{n}^\mu}{2} - \frac{Q^2}{\sqrt{ys}}\,\frac{n^\mu}{2}$$





Regge Factorization



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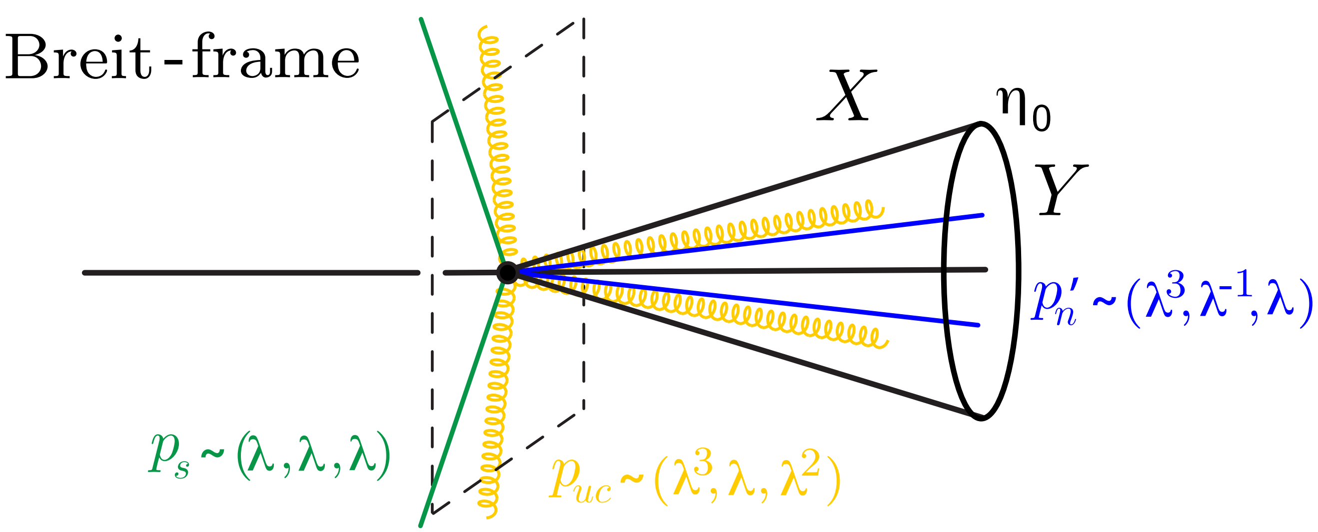
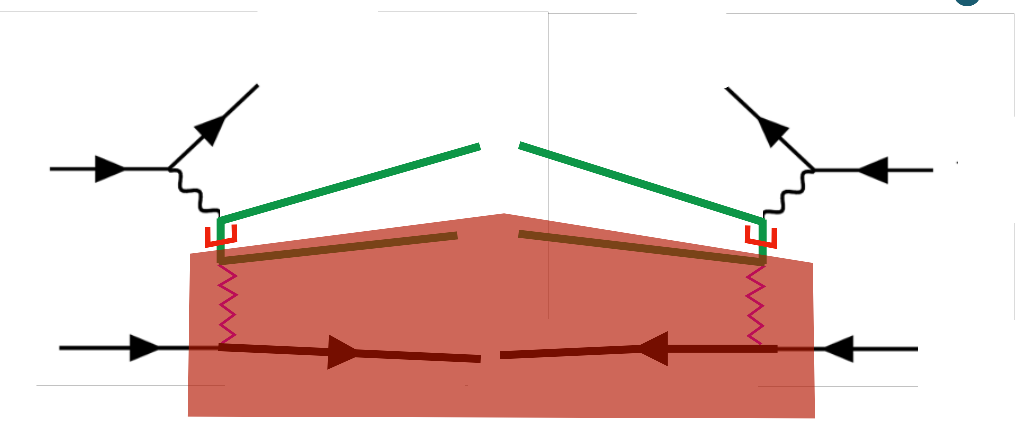


Equivalent to lab frame rapidity cut

$$e^{-\eta_0} = h\sqrt{x}$$

$$h = \sqrt{\frac{E_p}{yE_e}}\, e^{-\eta_{\rm cut}^{\rm lab}}$$

Regge & Hard-collinear Factorization



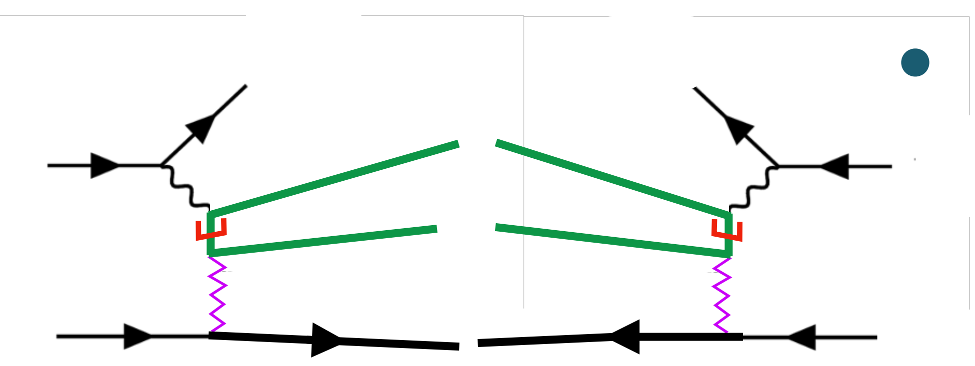
- **hard-collinear factorization**

Diffractive PDF

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

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

Collins `97, Berera, Soper `95



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

$$F_i^{D\,\text{diff}} = \sum_{\substack{N,N'=1 \\ N+N'=\text{even}}}^{\infty} \sum_{R^{NN'}=1} \iint_{(N,N')}^{\perp} B_{(N,N')}^{R^{NN'}}\left(m_Y^2 - t, \{\tau_{i\perp}, \tau'_{j\perp}\}, t, \frac{\nu}{Q/x}\right)$$

$$\times\, S_{i(N,N')}^{R^{NN'}}\left(\frac{Q^2}{\beta}, \{\tau_{i\perp}, \tau'_{j\perp}\}, Q, t, \frac{\nu}{Q/\beta}\right) \frac{Q^2}{x} \qquad \longleftarrow \text{small } \lambda$$

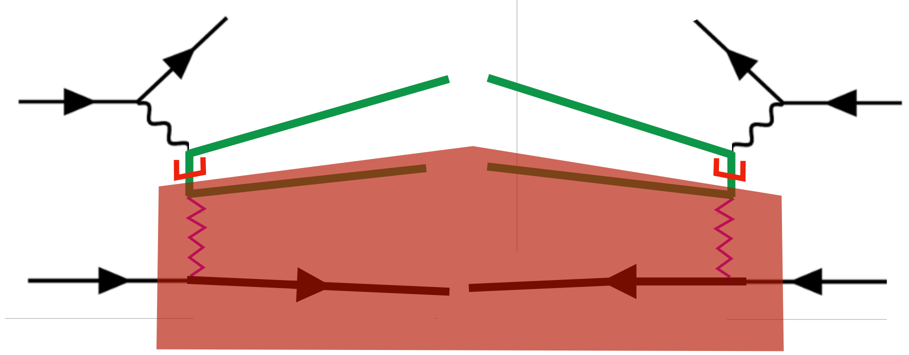
- **Simultaneous limits** $S_i = H_i^\kappa \otimes S_{\text{cs}}^\kappa$

$$f_\kappa^{D\,\text{diff}}\left(\zeta, \frac{x}{\beta}, t, m_Y^2, \mu\right) = \sum_{\substack{N,N'=1 \\ N+N'=\text{even}}}^{\infty} \sum_{R^{NN'}=1} \iint_{(N,N')}^{\perp} S_{\text{cs(N,N')}}^{\kappa;R^{NN'}}\left(\zeta, \{\tau_{k\perp}, \tau'_{\ell\perp}\}, t, \frac{\nu}{Q/\beta}, \mu\right) \qquad \longleftarrow \text{small } \lambda, \lambda_t$$

$$\times\, B_{(N,N')}^{R^{NN'}}\left(m_Y^2 - t, \{\tau_{k\perp}, \tau'_{\ell\perp}\}, t, \frac{\nu}{Q/x}\right) \frac{\beta^2}{x^2}$$

Regge Factorization for Diffractive PDF

Regge & Hard-collinear Factorization



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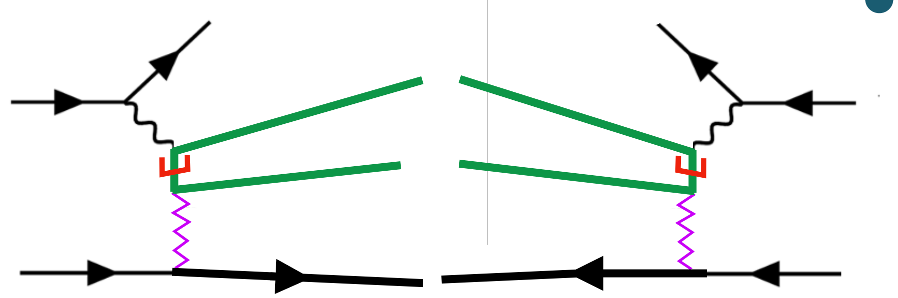

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- **Simultaneous limits** small λ, λ_t

Compare:

$$f_{\kappa/p}^{D} \propto S_{\mathrm{cs}}^{\kappa}(\zeta, \{\tau_{i,\perp}\}, t, \nu, \mu) \otimes_{\perp} B(m_Y^2 - t, \{\tau_{i,\perp}\}, t, \nu) \qquad \text{(Effective Field Theory Factorization)}$$

$$f_{\kappa/p}^{D} = f_{\kappa/\mathbb{P}}\left(\zeta, \mu\right) f_{\mathbb{P}/p}\left(\xi, t, m_Y^2\right) \qquad \text{(Ingelman-Schlein Model)}$$

differ: transverse vs longitudinal momenta, t dependence, ξ dependence,…