Diffraction and small-x dynamics at the EIC

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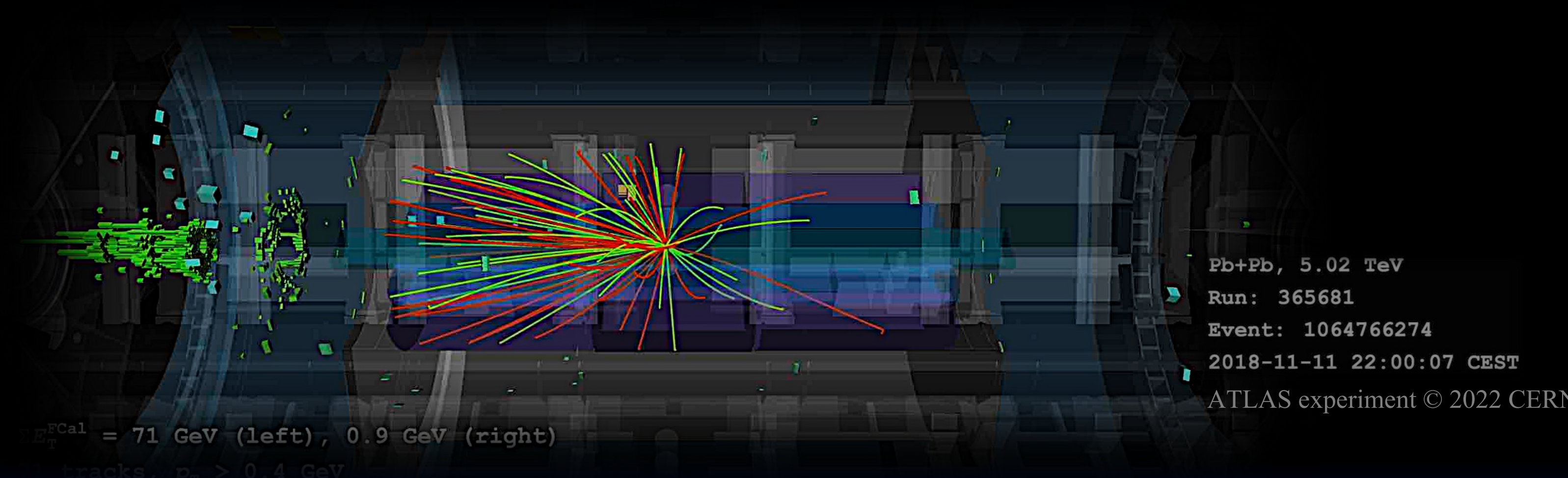


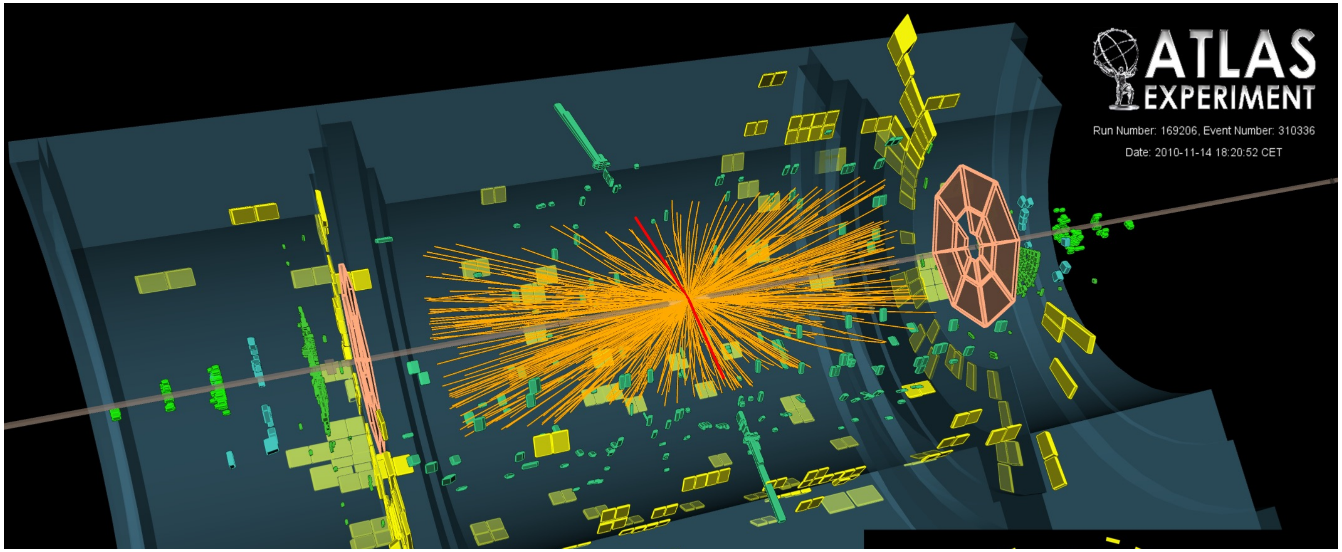
Uncovering New Laws of Nature at the EIC
Brookhaven National Laboratory
Thursday, November 21, 2024

LA-UR-24-32331

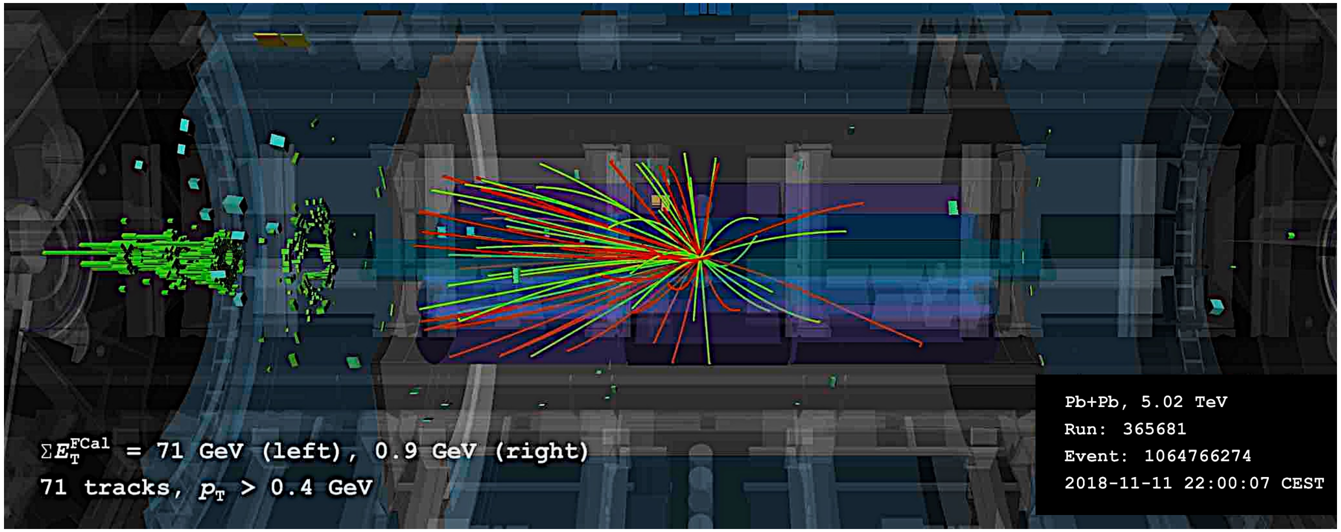
Collaborators
Iain Stewart (MIT)
Kyle Lee (MIT)

What is happening in these collisions?

Normal

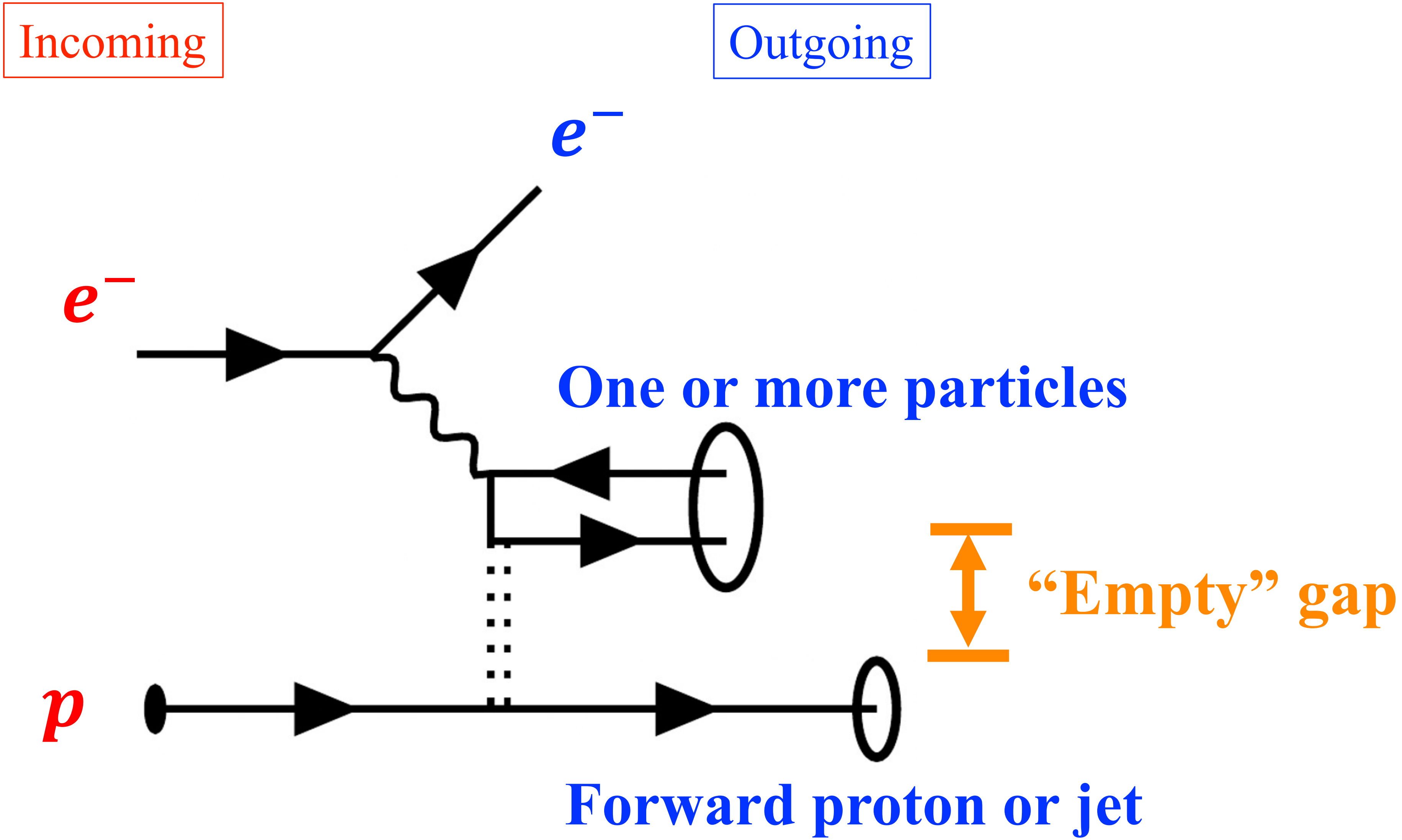


Gapped
(Diffraction)



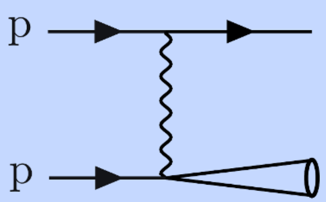
Figs: CERN.

Diffractive *ep* collision

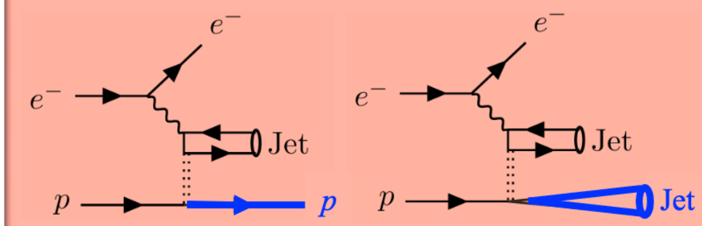


Many other types of diffractive collisions

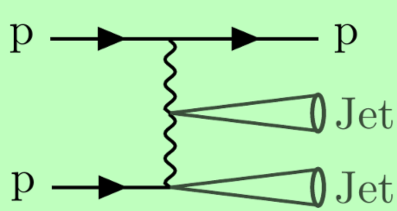
eA, *AA*, *ep*, *pp* collisions



Coherent or incoherent



Single or multi jet/gap



Tagged final states

Heavy mesons

Dijet photoproduction

Etc.

- **10%** of HERA events
- **20%** of EIC events
- **30%** of inelastic LHC events

Current state of diffractive understanding

Collins' factorization of the hard physics in diffraction:

$$\boldsymbol{F_{2/L}^{D}} = H_{2/L}^{(i)} \otimes \boldsymbol{f_i^D} \qquad \text{(Diffractive PDF)}$$

Berera/Soper, hep-ph/9509239. Collins, hep-ph/9709499.

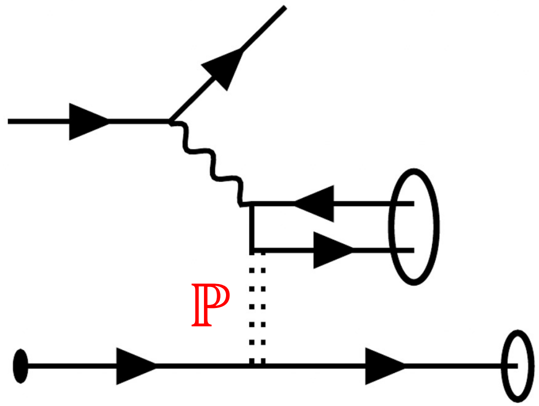
Large Q^2

These papers note that they do not rigorously factorize the forward scattering dynamics ("**Regge factorization**")

Ingelman-Schlein model for Regge physics:

$$\boldsymbol{f_i^D} = \boldsymbol{f_{i/\mathbb{P}}} \times \boldsymbol{f_{\mathbb{P}/p}} \qquad \text{(Pomeron PDFs)}$$

Ingelman/Schlein (1984). Frankfurt et al., 2203.12289.



How well can we do without a full factorization?

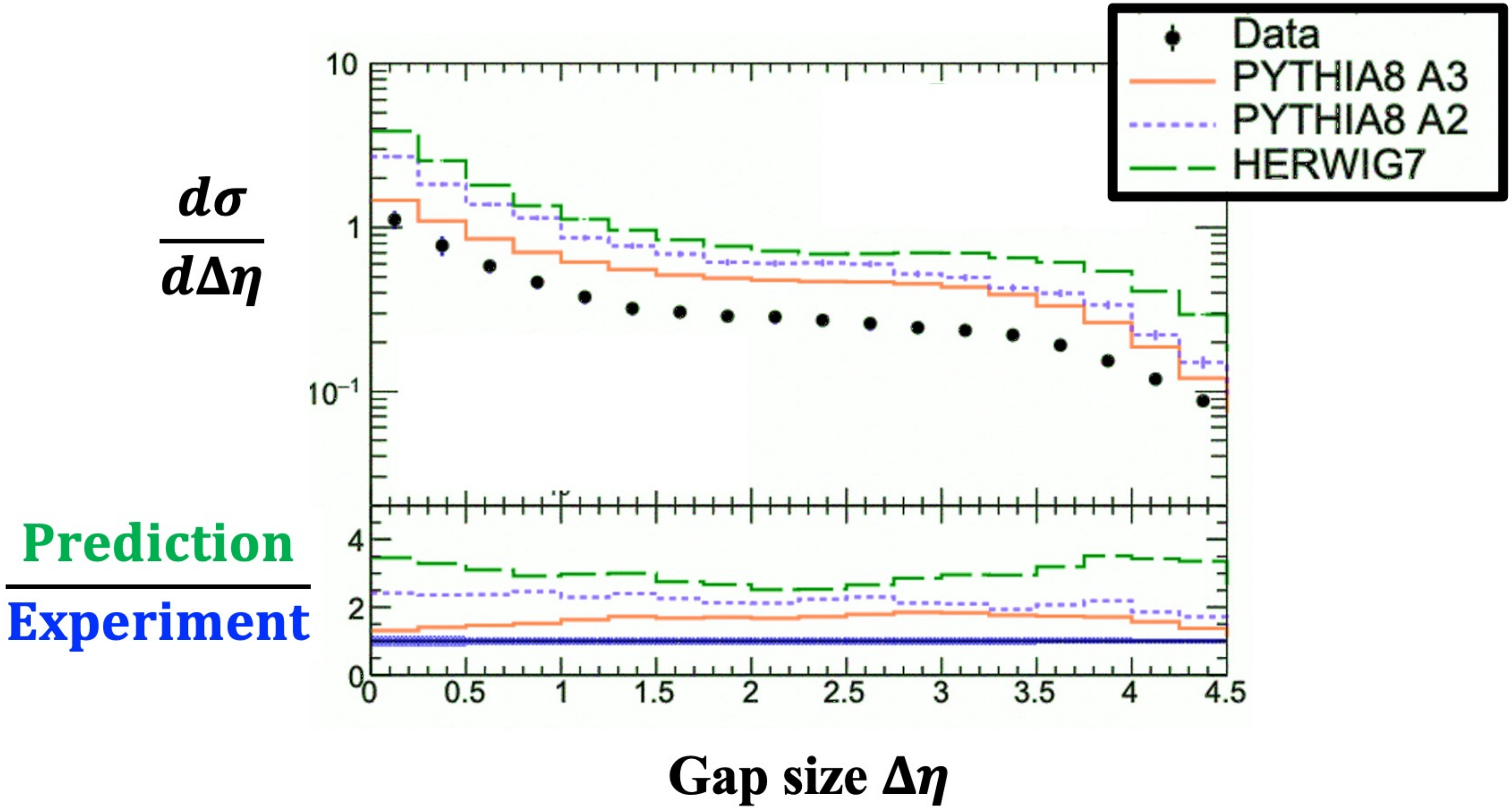
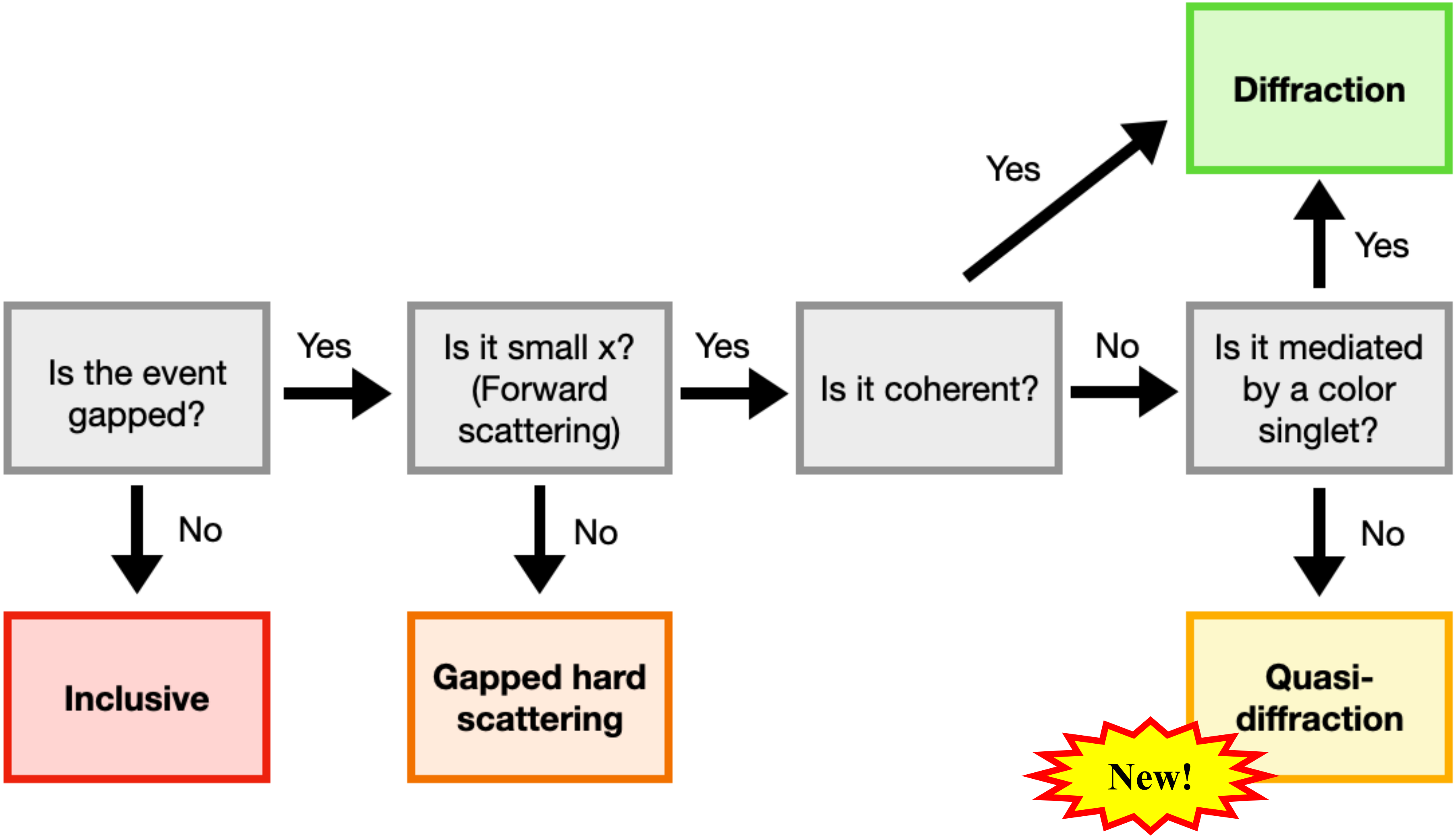


Figure: ATLAS, 1911.00453. $\sqrt{s} = 8\,TeV$, 0.016 < |t| < 0.43 GeV^2, -4.0 < $\log_{10}\xi$ < -1.6

Distinguishing diffraction from backgrounds



Tool building for small x physics

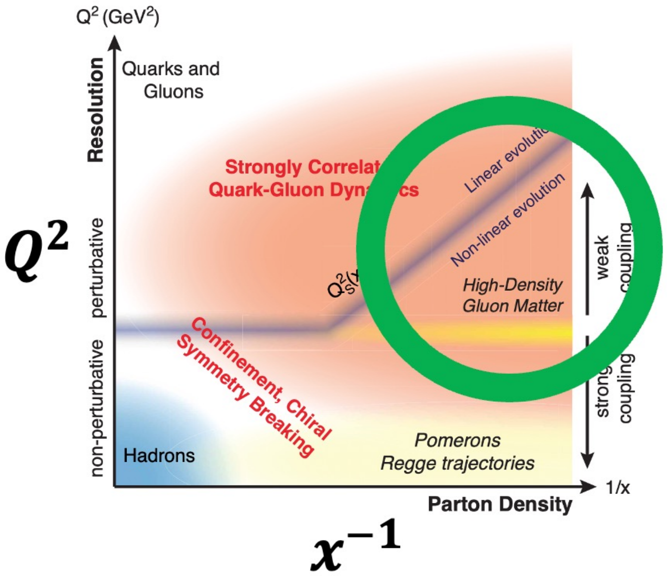
1950s Pomeron & Reggeon description of high-energy scattering
(Regge, Pomeranchuk, Chew, Frautschi…)

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)



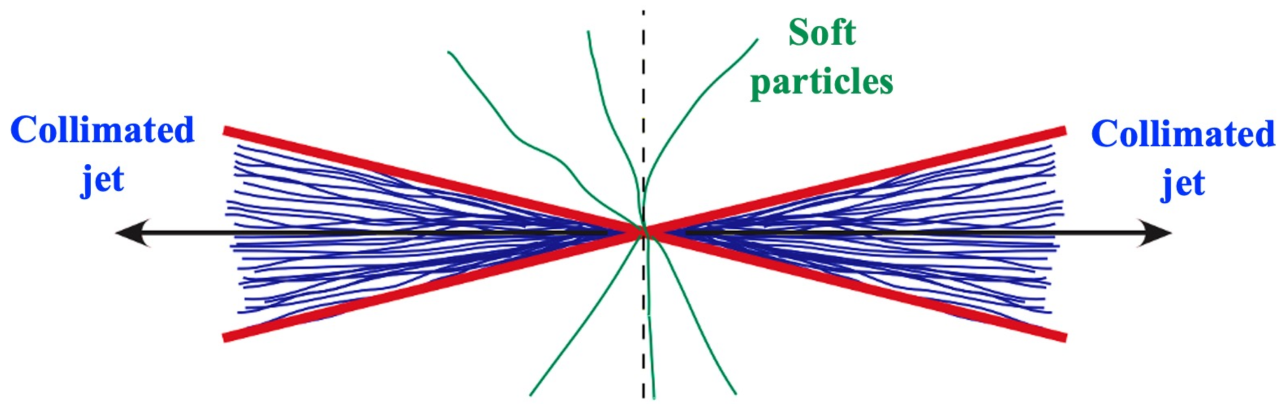
1994 Color Glass Condensate formalism for saturation regime
(McLerran, Venugopalan)

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

2016 A new tool for forward physics: Glauber SCET
(Rothstein, Stewart)

Effective field theory (EFT), schematically

- Collisions generally involve many distinct energy scales
- We can separately calculate the physics at each scale

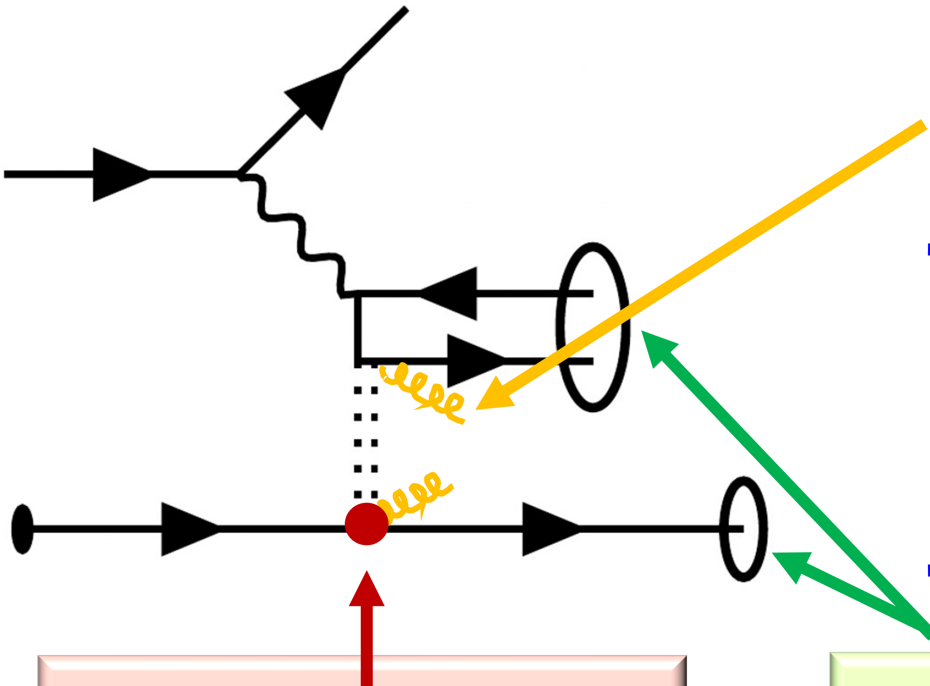


$$\mathcal{L}_{\text{QCD}} \xrightarrow[\text{irrelevant modes}]{\text{Integrate out}} \mathcal{L}_{\mathbf{EFT}} = \mathcal{L}_{\mathbf{jet}} + \mathcal{L}_{\mathbf{soft}}$$

$$\langle \mathcal{O} \rangle = \langle \mathcal{O}_{\mathbf{jet}} \rangle \times \langle \mathcal{O}_{\mathbf{soft}} \rangle \times \langle \mathcal{O}_{\mathbf{jet}} \rangle$$

Figure: I. Stewart. See e.g. 2303.02579.

Constraints on (quasi-)diffraction



Radiation into the gap that's below what our detector can see

Rapidity gap:

$$\ln \frac{p_X^-}{p_X^+} \ll \ln \frac{p'^-}{p'^+}$$

Forward scattering:

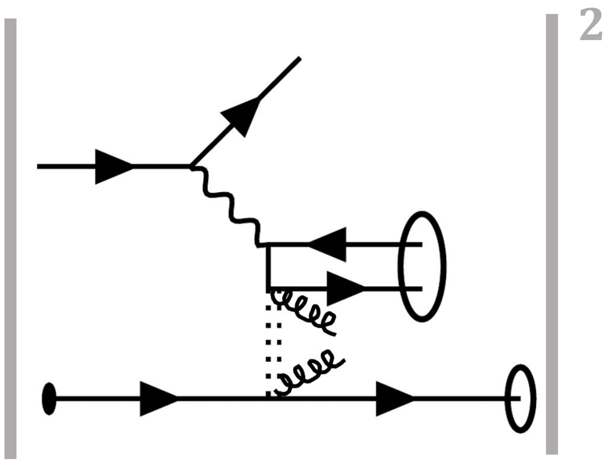
$$-t \ll W^2$$

Distinct sets of particles

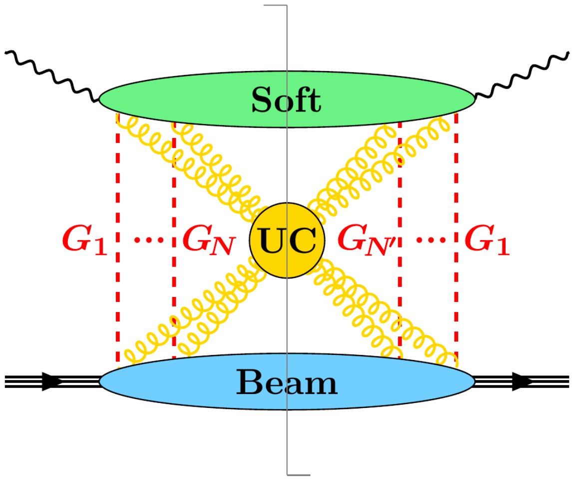
$$\Lambda_{\mathrm{QCD}}^2 \ll m_X^2, m_Y^2 \ll W^2$$

SCET is a useful EFT for diffraction

Factorizing (quasi-)diffraction using SCET



$\Longrightarrow$



$$F_i^D = B \otimes_\perp S_i \otimes_\pm U$$

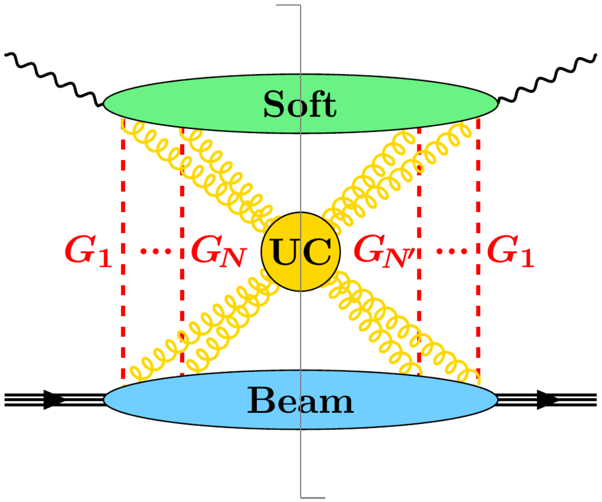
Beam function	Ultrasoft-collinear function	Soft function
Hadronic physics	Radiation into gap	Central region
Hadronic matrix element of SCET operators	Vacuum matrix element of Wilson line operators	Vacuum matrix element of SCET operators

Factorizing (quasi-)diffraction using SCET

$$\boldsymbol{F_i^D} = \sum_{N,N'=1}^{\infty} \sum_{\{R_X\}} \iint_{(N,N')}^{\perp} \int d\!\!{}^-p_n^+ \, d\!\!{}^-p_s^- \, d\!\!{}^-p_g^+ \, d\!\!{}^-p_g^- \, (2\pi)^2 \, \delta(Qz - p_n^+ - p_g^+) \, \delta(Q/\beta - p_s^- - p_g^-) \; \boldsymbol{B} \; \boldsymbol{U} \; \boldsymbol{S}$$

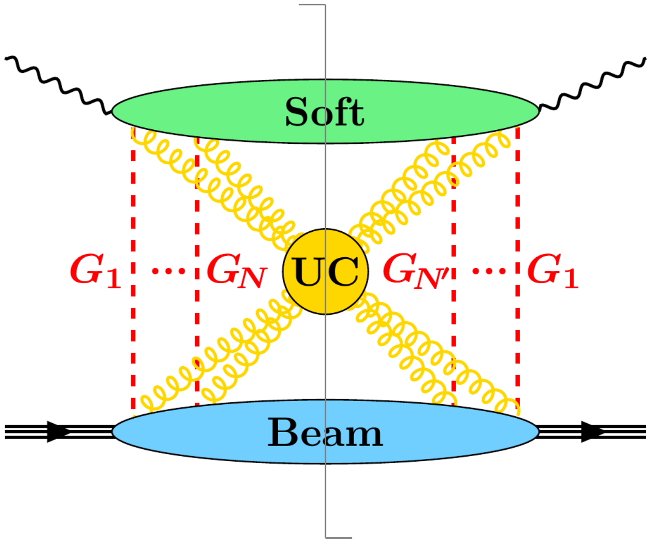
$$\boldsymbol{B} = \int [d\tilde{v}] \, e^{\frac{i}{2} v^- p_n^+} \sum\!\!\!\!\!\!\int_{Y_n} \langle p | \Big\{ \prod_{i=1}^{N-1} \mathcal{O}_n^{A_i}(\tilde{v}, \tau_{i\perp}) \bar{\mathcal{O}}_n^{A_N}(\tilde{v}) \Big\} P_{NR_A} | Y_n \rangle \langle Y_n | P_{N'R_A} \Big\{ \prod_{j=1}^{N'-1} \mathcal{O}_n^{A'_j}(0, \tau'_{j\perp}) \bar{\mathcal{O}}_n^{A'_{N'}}(0) \Big\} | p \rangle$$

$$\boldsymbol{U} = \frac{N_{\vec{R}}}{4} \int dy^+ dy^- e^{\frac{i}{2} y^+ \bar{p}_g^- + \frac{i}{2} y^- \bar{p}_g^+} \sum\!\!\!\!\!\!\int_{X'_{uc}} \langle 0 | P_{NR_A} \bar{T} \prod_{i=1}^{N} \mathbb{U}_{n\bar{n}}^{A_i B_i}(y^+, y^-) \, P_{NR_B} | X'_{uc} \rangle \langle X'_{uc} | P_{N'R_{A'}} T \prod_{j=1}^{N'} \mathbb{U}_{n\bar{n}}^{A'_j B'_j}(0) P_{N'R_{B'}} | 0 \rangle$$



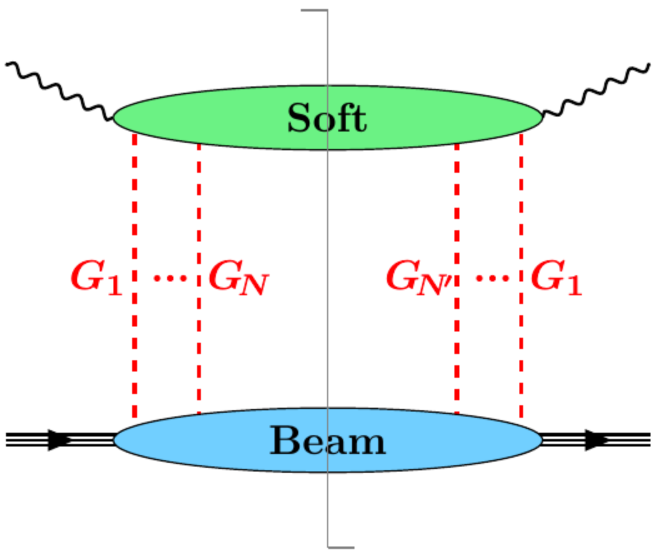
$$\boldsymbol{S} = \int [d\tilde{y}_1] \, [d\tilde{y}'_1] \, d^d z \; e^{\frac{i}{2}(y_1^+ - y_1'^+) p_s^-} \; e^{+iz\cdot q} \, \mathcal{P}_{i\,\mu\nu}$$
$$\times \sum\!\!\!\!\!\!\int_{X_s} \langle 0 | \bar{T} \, J_s^{\mu}(z) \Big\{ \prod_{i=1}^{N} \mathcal{O}_s^{B_i}(\tilde{y}_1, -\tau_{i\perp}) \Big\} P_{NR_B} | X_s \rangle$$
$$\times \; \langle X_s | P_{N'R_{B'}} T \, J_s^{\nu}(0) \Big\{ \prod_{j=1}^{N'} \mathcal{O}_s^{B'_j}(\tilde{y}'_1, -\tau'_{j\perp}) \Big\} | 0 \rangle$$

Diffraction vs quasi-diffraction



$$F_i^{\mathbf{quasi}} = B \otimes U \otimes S$$

- **Color non-singlet:** U nontrivial
- Can radiate into the gap



$$F_i^D = B \otimes S$$

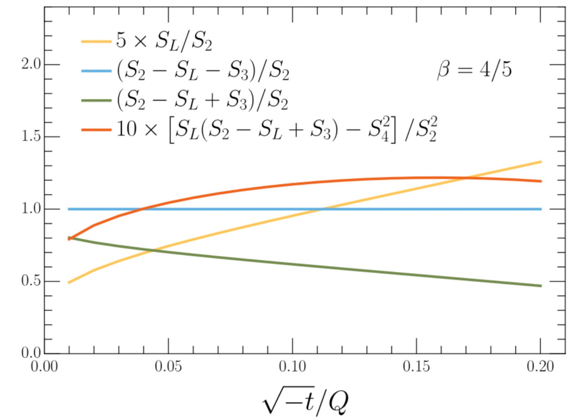
- **Color singlet:** U is a δ-function
- Nontrivial result: can't radiate into the gap!

Many predictions we can make

E.g., leading $F_i^{\textbf{quasi}}$ ratio predictions for $t \ll Q^2 \ll s$

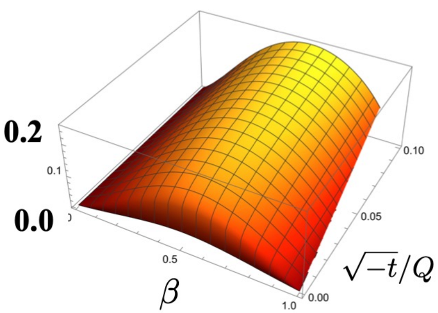
One Glauber: no convolution!

$$\frac{F_i^{\text{quasi}}}{F_2^{\text{quasi}}} = \frac{B \times U \times S_i}{B \times U \times S_2} = \frac{S_i}{S_2}$$

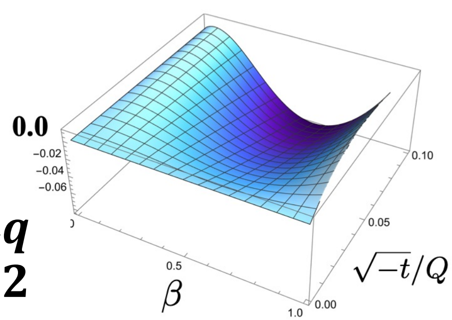


Cross-check: **Positivity bounds** from Arens et al. hep-ph/9605376

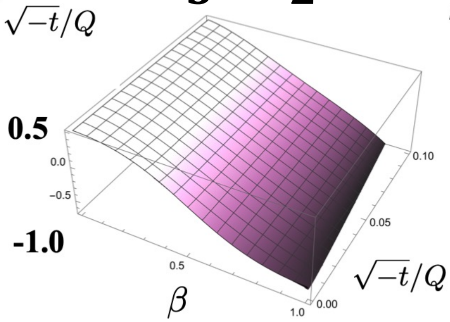
F_L^q/F_2^q



F_4^q/F_2^q



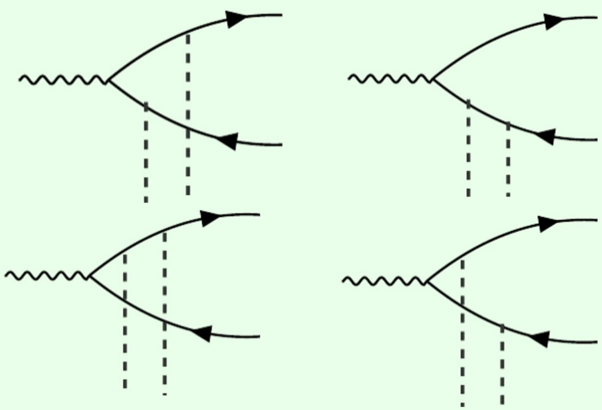
F_3^q/F_2^q



- 4 unpolarized & 4 polarized F_i^D at leading power, **large!**
- $F_{3,4}^D$ are largely ignored in literature

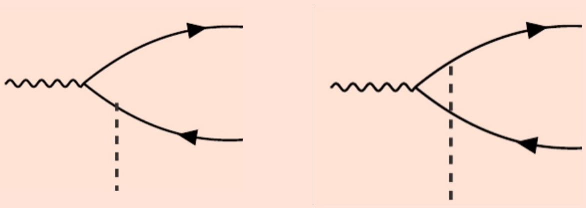
Color singlet & nonsinglet exchange have similar size

Diffraction
(color singlet)



- α_s^2 from two Glaubers
- No suppression from *U* (we can show it's trivial!)

Quasi-diffraction
(color non-singlet)

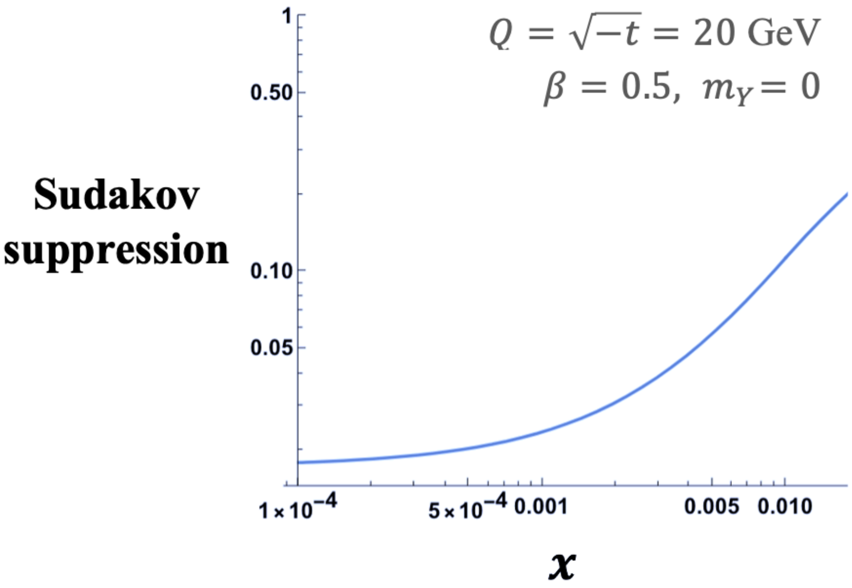


- α_s^1 from one Glauber
- Sudakov suppression from nontrivial *U*

Radiation into the gap

Ultrasoft-collinear function:

- Result obtained from e^+e^- hemisphere soft function
- $U \propto \exp\left[-C_A \alpha_s \log^2 \frac{W^2}{Q^2}\right]$
  $\propto \exp\left[-C_A \alpha_s \log^2 \frac{1}{x}\right]$

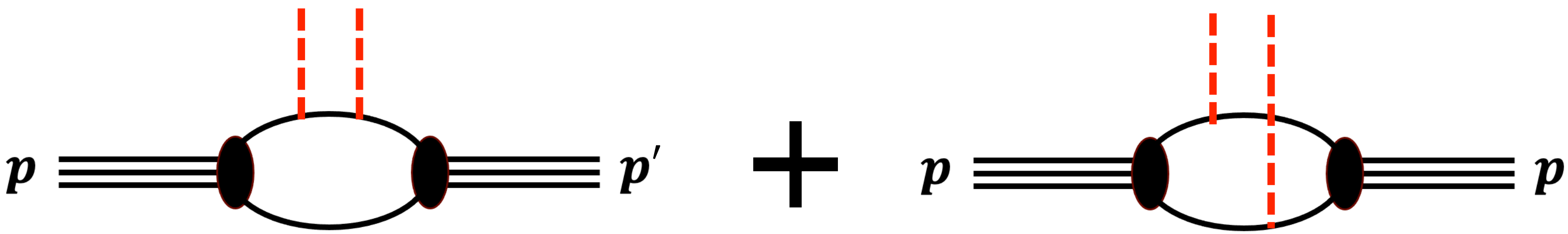


- Can’t measure color of incoherent exchange
- Irreducible color-nonsinglet (quasi-diffractive) background!

What type of PDF does diffraction access?

$$\boldsymbol{B} = \int [d\tilde{v}]\, e^{\frac{i}{2} v^- p_n^+} \sum_{Y_n} \langle p | \Big\{ \prod_{i=1}^{N-1} \mathcal{O}_n^{A_i}(\tilde{v}, \tau_{i\perp}) \bar{\mathcal{O}}_n^{A_N}(\tilde{v}) \Big\} P_{NR_A} | Y_n \rangle \langle Y_n | P_{N'R_A} \Big\{ \prod_{j=1}^{N'-1} \mathcal{O}_n^{A'_j}(0, \tau'_{j\perp}) \bar{\mathcal{O}}_n^{A'_{N'}}(0) \Big\} | p \rangle$$

Many beam function topologies, e.g.



Like a 3D GPD

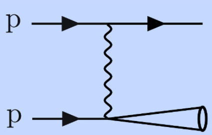
Definitely ***not*** a GPD

Ongoing work:

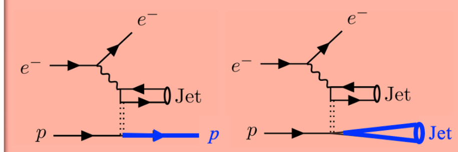
- What is the nature of the diffractive beam function?
- Does it match onto any traditional PDFs, etc., in any limits?

Much more we can do now…

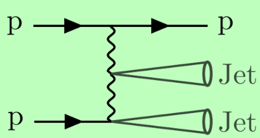
eA, AA, ep, pp collisions



Coherent or incoherent



Single or multi jet/gap

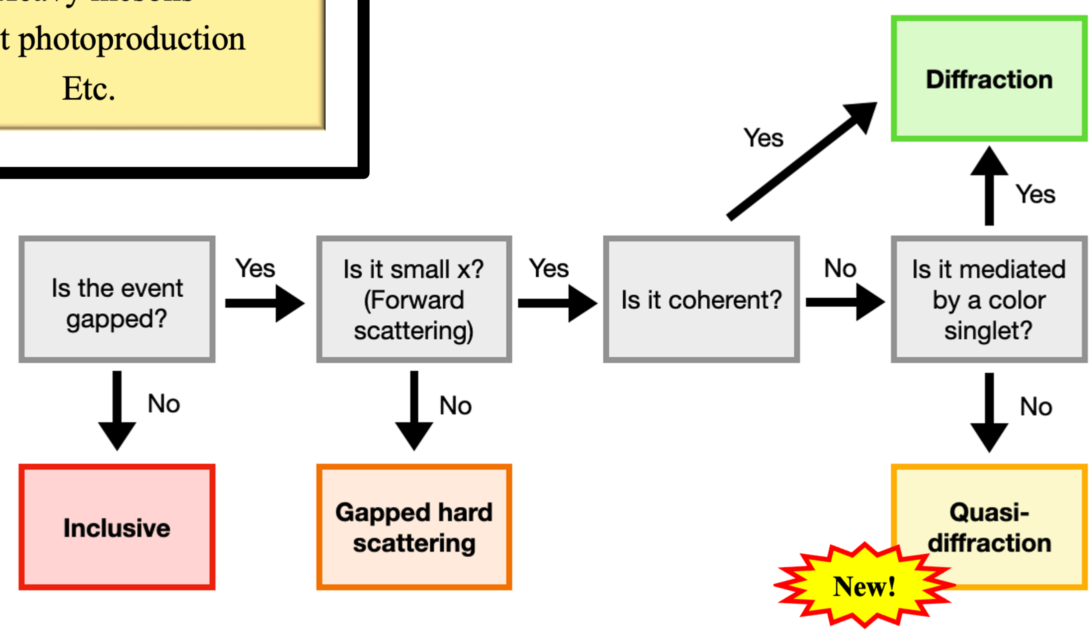


Tagged final states

Heavy mesons

Dijet photoproduction

Etc.



EFT vs. Collins' hard scattering approach

SCET: $F_j^D(x, Q^2, \beta, t, m_Y^2) = \mathcal{P}_j^{\mu\nu} \boldsymbol{S_{\mu\nu}(Q^2, \beta, t, \tau_{i\perp})} \otimes \boldsymbol{B(t, m_Y^2, \tau_{i\perp})}$

Collins: $F_{2/L}^D(x, Q^2, \beta, t) = H_{2/L}^{(i)}\left(\frac{\beta}{\zeta}, Q^2\right) \otimes \boldsymbol{f_i^D\left(\zeta, Q^2, \frac{x}{\beta}, t\right)}$

"Diffractive PDF"

Differences:

- SCET $\boldsymbol{\lambda = Q/\sqrt{s} \ll 1}$ vs. Collins $\boldsymbol{\lambda_t = \sqrt{-t}/Q \ll 1}$
- As explained by Collins, his formula does **not** include the Regge factorization for forward physics at bottom vertex
- However, these results should match for $\boldsymbol{\lambda}$ & $\boldsymbol{\lambda_t \ll 1}$

Regge factorization of dPDF

SCET: $F_j^D(x, Q^2, \beta, t, m_Y^2) = \mathcal{P}_j^{\mu\nu} \boldsymbol{S_{\mu\nu}(Q^2, \beta, t, \tau_{i\perp})} \otimes \boldsymbol{B(t, m_Y^2, \tau_{i\perp})}$

Collins: $F_{2/L}^D(x, Q^2, \beta, t) = H_{2/L}^{(i)}\left(\frac{\beta}{\zeta}, Q^2\right) \otimes \boldsymbol{f_i^D\left(\zeta, Q^2, \frac{x}{\beta}, t\right)}$

Refactorize dPDF for $\boldsymbol{\lambda}$ & $\boldsymbol{\lambda_t} \ll \mathbf{1}$, giving $F = H \otimes S_c \otimes B'$:

$$\boldsymbol{f_i^D\left(\zeta, Q^2, \frac{x}{\beta}, t, m_Y^2\right) = S_c(\zeta, Q, t) \otimes B'(Qz, t, m_Y^2)}$$

Comparison to Ingelman-Schlein ($\lambda, \lambda_t \ll 1$)

SCET: $$f_i^D\left(\zeta, Q^2, \frac{x}{\beta}, t, m_Y^2\right) = S_c(\zeta, Q, t) \otimes B'\left(Qz, t, m_Y^2\right)$$

IS model: $$f_i^D\left(\zeta, Q^2, \frac{x}{\beta}, t\right) = f_{i/\mathbb{P}}\left(\zeta, Q^2\right) \times f_{\mathbb{P}/p}\left(\frac{x}{\beta}, t\right)$$

Differences:

- Convolution vs. multiplication
- Number and nature of arguments
- Transverse momentum dependence vs. longitudinal-type PDFs

Summary

1. Four interesting structure functions
2. First all-orders Regge (forward) factorization
3. Study of backgrounds (e.g. color nonsinglet)
4. Experimental implications

Next steps:

- **Precision physics:** Higher order, resummation, …
- **Underlying physics:** Behavior in saturation regime? Connection to PDFs/GPDs/etc. in any limit?
- **Other cases:** Hadron colliders, semi-inclusive processes, more jets/gaps, etc.

New horizons for HEP theorists?

- **Theory:** New tools for EIC physics can naturally extend to HEP-focused colliders like the LHC

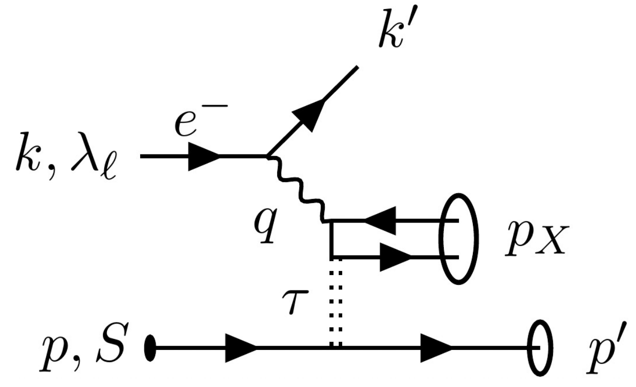
- **Phenomenology:** Improves understanding of Standard Model physics, which enables studies of new physics in the far-forward region

- **Experiment:** Better understanding of diffraction can improve tracking of luminosity, understanding pile-up, building MC generators

Backup slides

Lorentz invariants

	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	$t = \tau^2 < 0$ $m_Y^2 = p'^2 > 0$ $m_X^2 = p_X^2 > 0$	$\beta = \frac{Q^2}{2q\cdot \tau}$ $\bar{x} = \frac{k\cdot\tau}{k\cdot p}$ $z = \frac{p\cdot p'}{p\cdot q}$



Largely unexplored variable $\bar{x}$

Note that only 7 of these are linearly independent

New kinematic bounds

$$0 < x < 1, \quad 0 < y < 1, \quad 0 < Q^2 < s$$

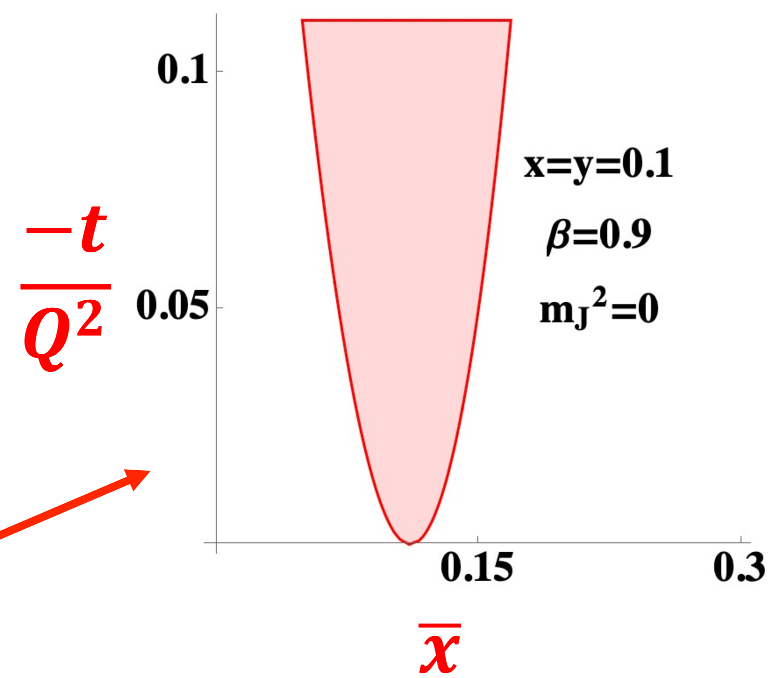
$$\frac{1}{1 + \frac{-t}{Q^2} + \left(\frac{\bar{x}}{x} - y\right)(1 - z)} < \beta < \frac{1}{1 + \frac{-t}{Q^2}}$$

$$\Lambda_{QCD}^2 \lesssim m_Y^2 < \frac{1 - \bar{x}}{\bar{x}}(-t)$$

$$\frac{\bar{x}}{1 - \bar{x}} \frac{m_Y^2}{Q^2} < \frac{-t}{Q^2} < \frac{1 - \beta}{\beta}$$

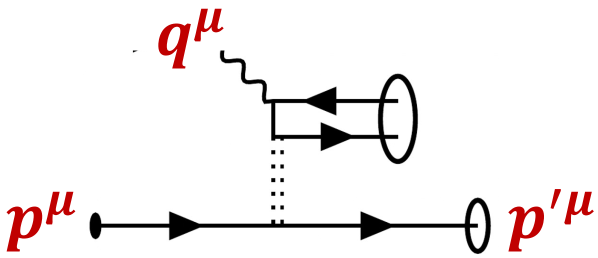
$$-1 < \frac{\beta xyz - 2\beta xz + x - \beta \bar{x}}{2\sqrt{\beta xz(1 - y)(\beta xz - x + \beta)}} < 1$$

Etc.



Lee, **Schindler**, & Stewart, in preparation.

Constructing structure functions



Constraints: $q_\mu W_D^{\mu\nu} = 0$ and $W_D^{\mu\nu} = W_D^{\nu\mu}$

- Convenient to build orthonormal basis $q^\mu \perp U^\mu \perp X^\mu$

$$W_D^{\mu\nu} = \frac{1}{2x}\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) F_L^D + \frac{1}{2x}\left(U^\mu U^\nu - g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) F_2^D$$

$$+ \frac{1}{2x}\left(2X^\mu X^\nu - U^\mu U^\nu + g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) F_3^D + \frac{U^\mu X^\nu + X^\mu U^\nu}{2x} F_4^D$$

Literature often neglects F_3^D & F_4^D !

Lee, **Schindler**, Stewart, in prep. Arens et al, hep-ph/9605376. Blumlein/Robaschik, hep-ph/0106037,0202077.

Coefficients

$$L_{\mu\nu}W_D^{\mu\nu} = \frac{2s}{y}\left[-\frac{y^2}{2}F_L^D + \left(1 - y + \frac{y^2}{2}\right)F_2^D + \left(\frac{2(k\cdot X)^2 y^2}{Q^2} - 1 + y\right)F_3^D + \frac{2y^2(k\cdot X)(k\cdot U)}{Q^2}F_4^D\right]$$

$\bar{x}$ & y only appear in coefficients, not

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

How to miss $F_{3,4}^D$:

- Integrate over $\bar{x}$
- Assume $p' \parallel p$

Coefficients:

- $k \cdot X = Q^2 \frac{x - \bar{x}\beta - (2-y)xz\beta}{2N_X xy\beta}$
- $k \cdot U = \frac{Q(2-y)}{2y}$

Auxiliary:

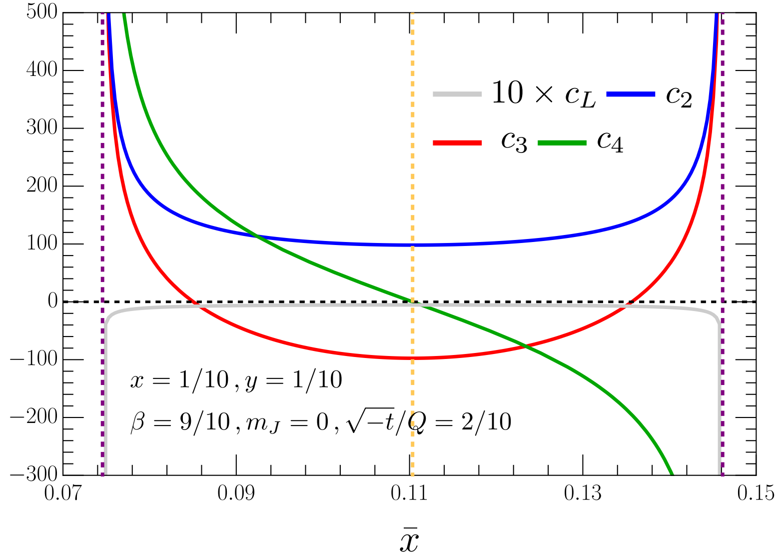
- $N_X^2 = -t + z^2Q^2 - \frac{zQ^2}{\beta}$
- $z = \frac{x}{Q^2}(m_Y^2 - t)$

Lee, **Schindler**, & Stewart, in preparation.

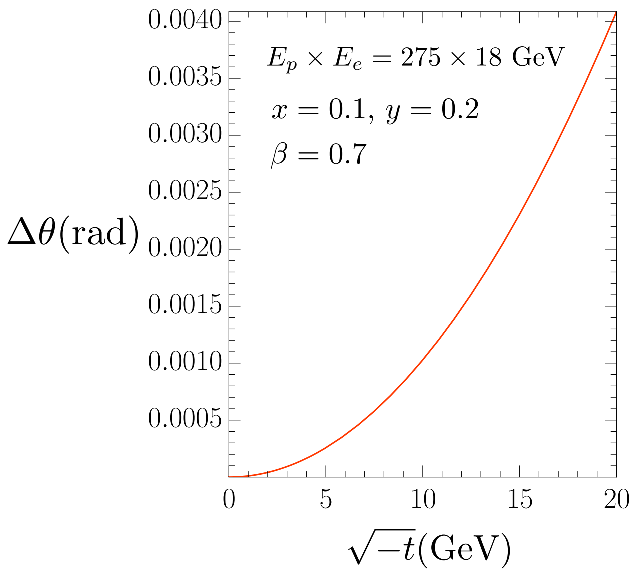
Seeing $F_{3,4}^D$ in experiments

Why did ZEUS not see $F_{3,4}^D$ in hep-ex/0408009 ?

Coefficients c_i of F_i^D



Resolution to resolve four bins of $\bar{x}$



Coefficients are large, **but** need good angular resolution at small t

Lee, **Schindler**, & Stewart, in preparation.

Summary of kinematics

	Our work	**Most of the literature**
Independent invariants	7 (DIS + $\bar{\boldsymbol{x}}, t, \beta, m_Y^2$)	6 **(No $\bar{\boldsymbol{x}}$)**
Unpolarized structure functions	4	2
Polarized structure functions	14 (4 nonzero at leading power)	2

+ Classification of backgrounds

+ New kinematic bounds

Lee, **Schindler**, & Stewart, in preparation. Diffractive literature: see e.g. EIC Yellow Report, 2103.05419.
Exceptions: Arens et al., hep-ph/9605376. Blumlein & Robaschik, hep-ph/0202077.

Advantages of EFT

$$\mathcal{L}_{\mathrm{QCD}} \to \lambda^0 \mathcal{L}_{\mathrm{EFT}}^{(0)} + \lambda^1 \mathcal{L}_{\mathrm{EFT}}^{(1)} + \lambda^2 \mathcal{L}_{\mathrm{EFT}}^{(2)} + \cdots$$

- Power expansion, efficient for multi-scale problems
- Calculations are systematically improvable, to arbitrary precision

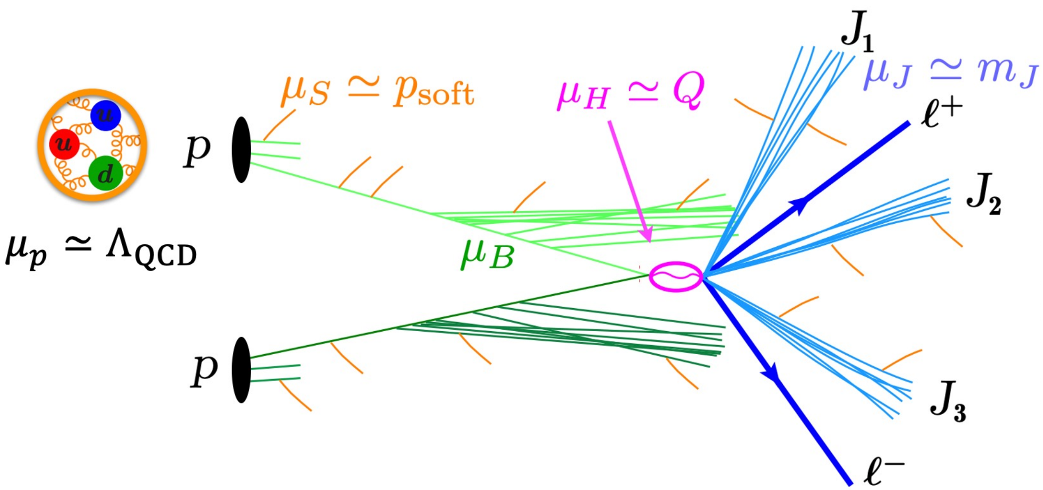


Figure: I. Stewart.

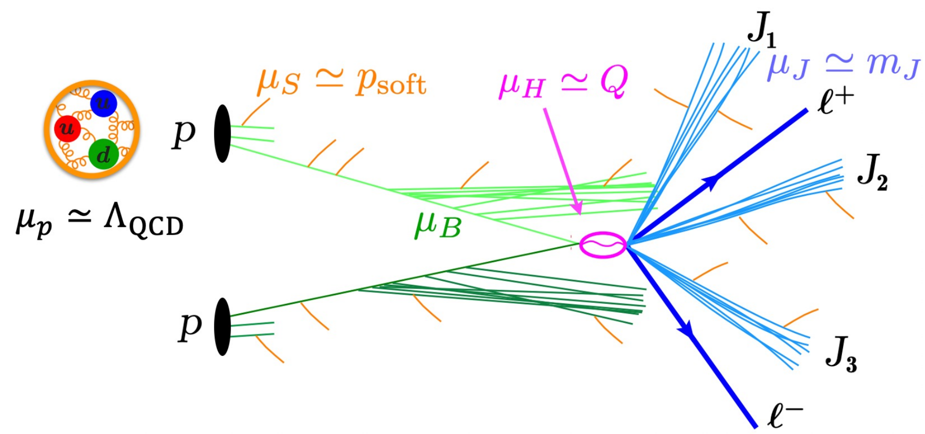
Simplifies study of:

- Factorization
- Perturbative calculations
- Resummation
- Power corrections

SCET Lagrangian

Mode	Momentum in $(+,-,\perp)$
Hard	$(1,0,0)$
Collinear	$(1,\lambda^2,\lambda)$ or $(\lambda^2,1,\lambda)$
Soft	$(\lambda,\lambda,\lambda)$
Ultrasoft	$(\lambda^2,\lambda^2,\lambda^2)$
Glauber	$(\lambda^a,\lambda^b,\lambda)$ for $a+b>2$

$p^\pm = p^t \mp p^z$



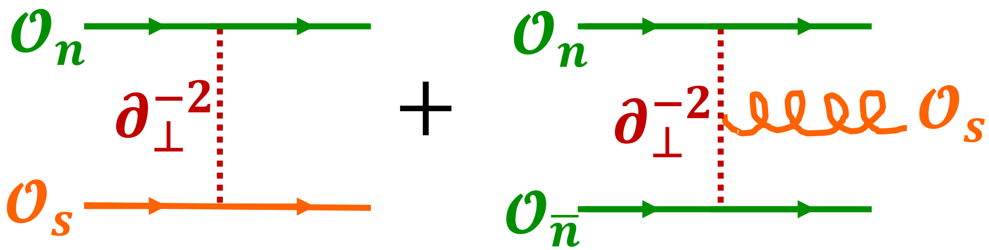
$$\mathcal{L}_{\rm SCET}^{(0)} = \mathcal{L}_{\rm hard} + \mathcal{L}_{\rm collinear} + \mathcal{L}_{\rm soft} + \mathcal{L}_{\rm ultrasoft} + \mathcal{L}_{\rm Glauber}$$

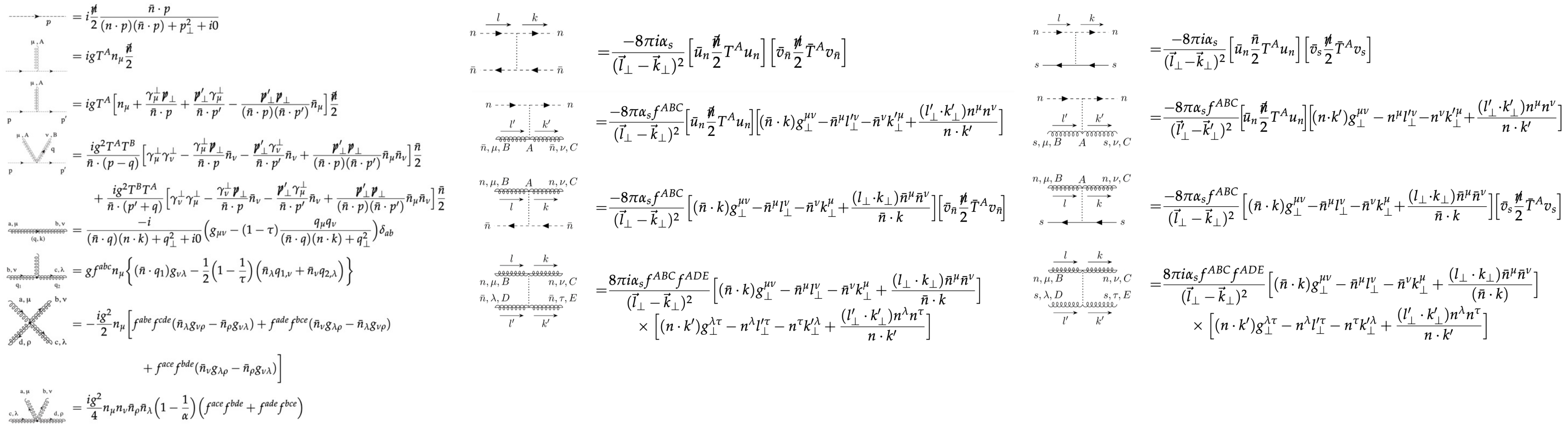
- **Glauber:** talks between different sectors
- **Hard interaction:** also connects sectors, but only occurs ***once***

SCET operators

Example:

$$\mathcal{L}^{(0)}_{\text{Glauber}} =$$





The upshot of EFT: Helpful for organizing calculations for multi-scale problems

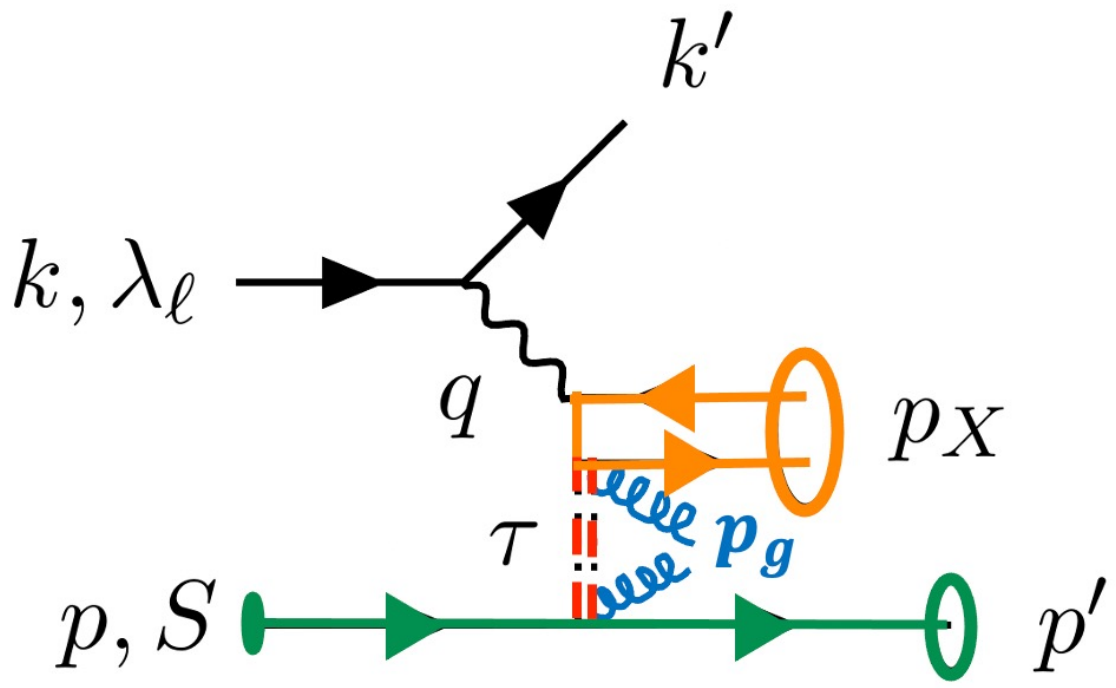
Rothstein & Stewart, 1601.04695.

SCET modes in diffraction

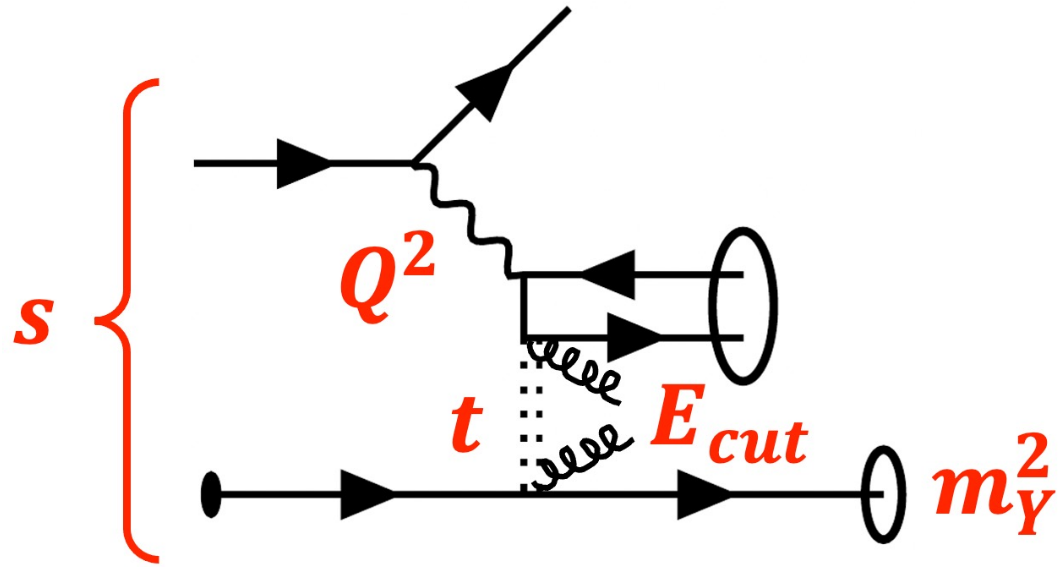
Mode	$(+,-,\perp)$
Collinear	$\sqrt{s}(\lambda^3, \lambda^{-1}, \lambda)$
Soft	$\sqrt{s}(\lambda, \lambda, \lambda)$
Glauber	$\sqrt{s}(\lambda^3, \lambda, \lambda)$
Ultrasoft-collinear	$\sqrt{s}(\lambda^3, \lambda, \lambda^2)$

$$\lambda = \frac{Q}{\sqrt{s}} \ll 1$$

Ultrasoft in CM frame
(Here: Breit frame) → Ultrasoft-collinear



Further expansions & refactorizations



Required:

$$\lambda = \frac{Q}{\sqrt{s}} \ll 1$$

Optional: $\lambda_t = \frac{\sqrt{-t}}{Q}, \ \lambda_g = \frac{E_{\text{cut}}}{Q}, \ \rho = \frac{m_Y}{\sqrt{-t}}, \ \lambda_\Lambda = \frac{\Lambda_{\text{QCD}}}{Q}$

Subject to bounds, can have $\boldsymbol{\lambda_i \ll 1}$ **,** $\boldsymbol{\lambda_i \sim 1}$**, or** $\boldsymbol{\lambda_i \gg 1}$