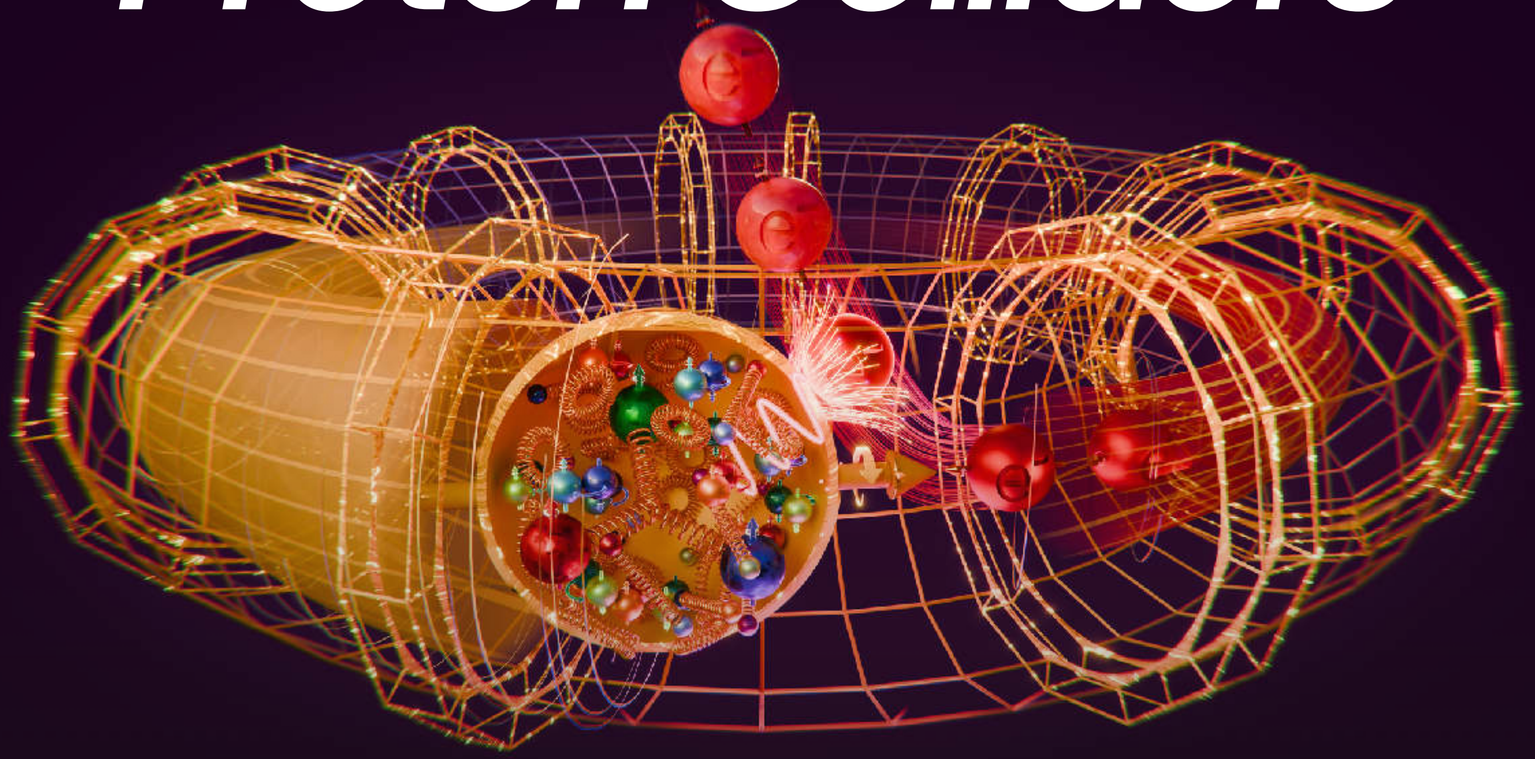
Forward Neutrons in Electron–Proton Colliders



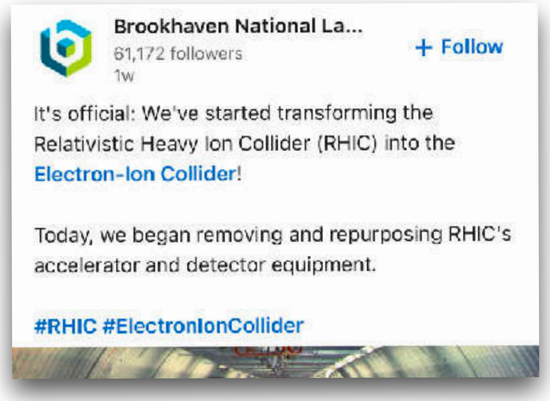
Daria Trotsenko
Harvard University

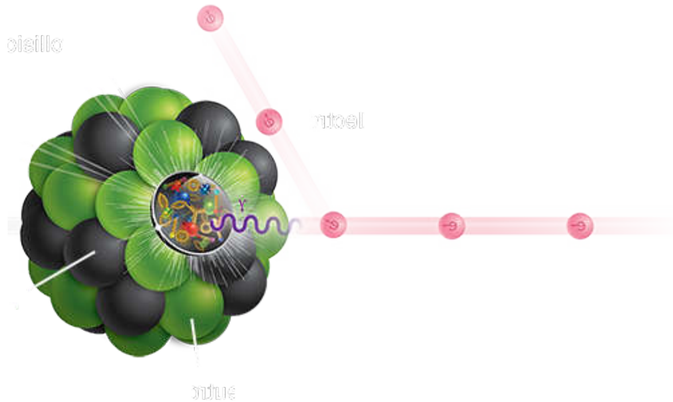
MAY 1st 2026

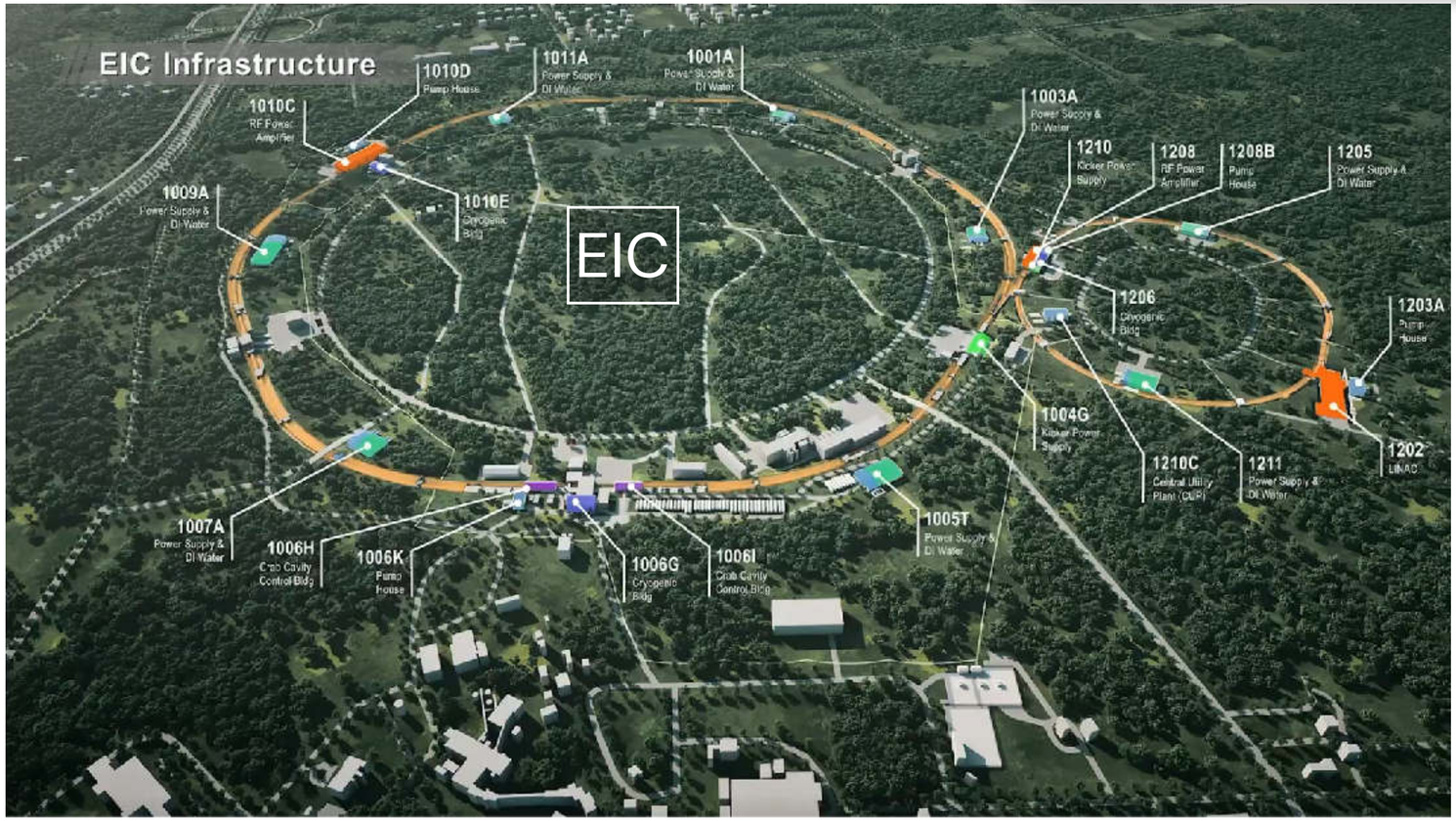
EFT Group Meeting MIT

Electron-Ion Collider at Brookhaven

EIC is in CD-3B stage of approval (long lead procurement and site preparation)!



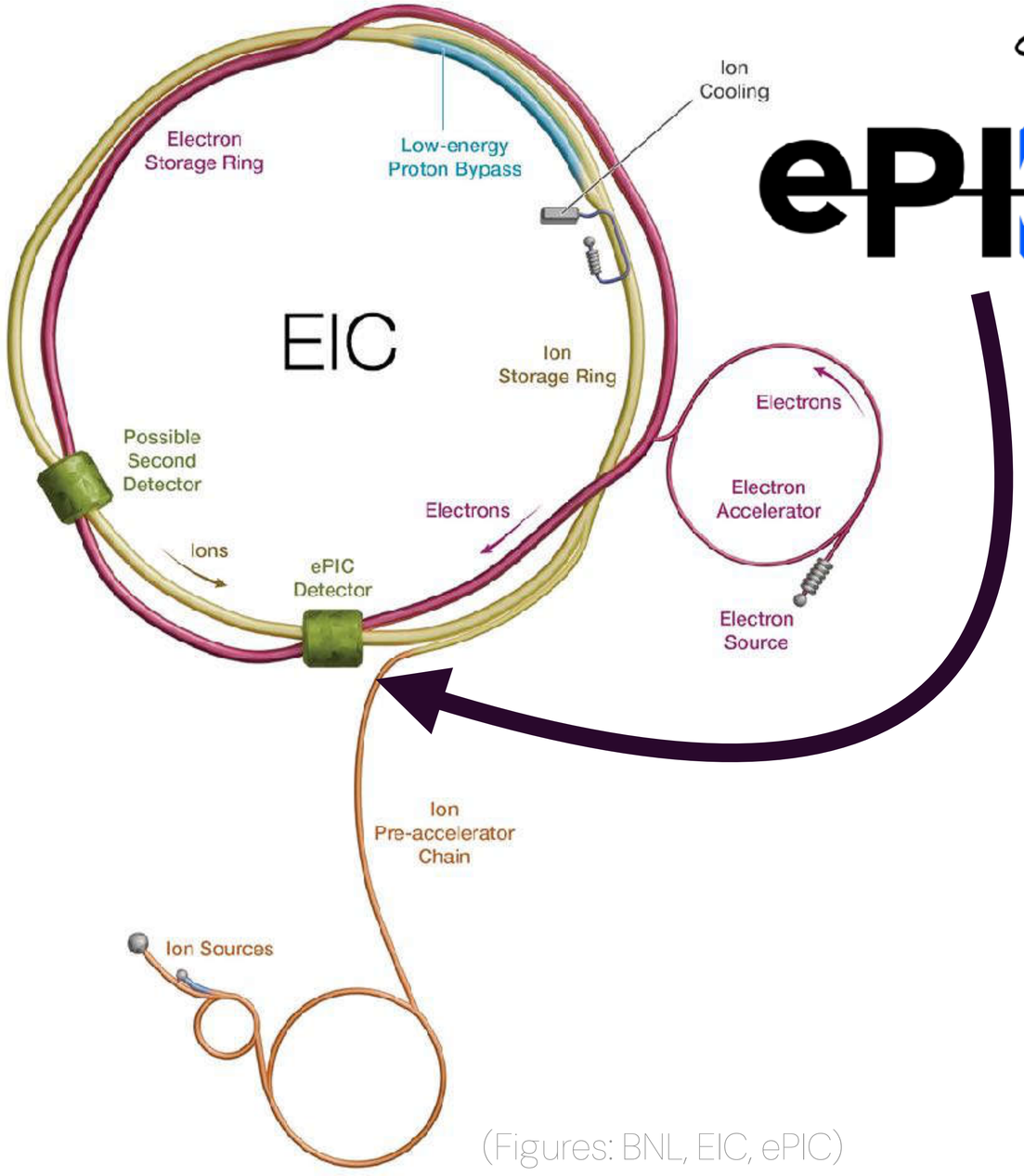




- $3 billion dollar instrument
- Polarized $e + p$, $e + A$
- COM energy 20-140 GeV
- First light: early 2030s
- Access to 3D partonic structure and small-x gluon dynamics

(Figures: BNL, EIC)

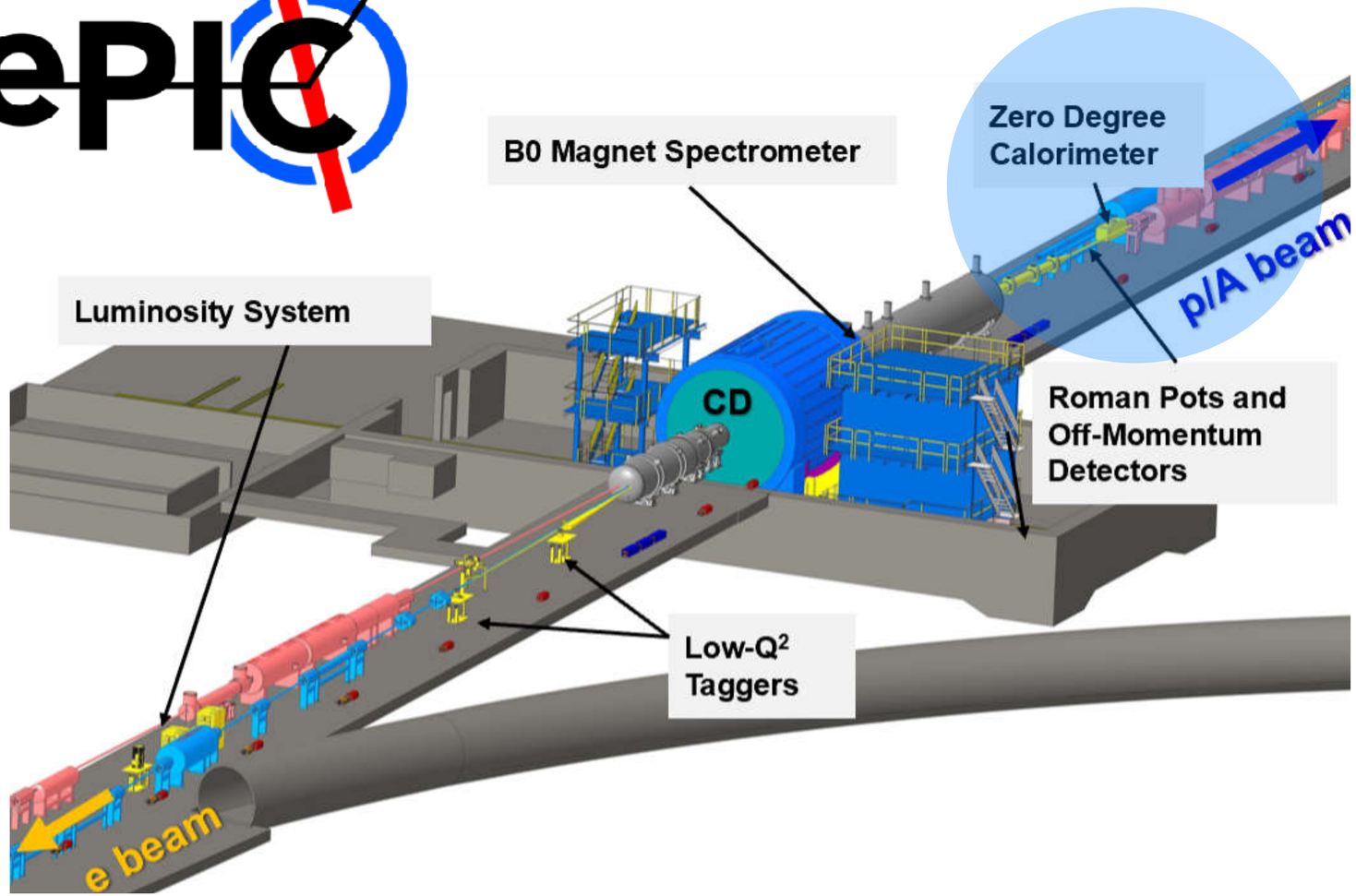
Electron–Proton/Ion Collider



- First EIC experiment
- Large acceptance detector (3°–177°)
- Hermetic recoil tagging and exclusive final-state reconstruction
- Compact (~10 m)
- Both polarized e and p

(Figures: BNL, EIC, ePIC)

Electron–Proton/Ion Collider



(Figure: ePIC)

Zero Degree Calorimeter:

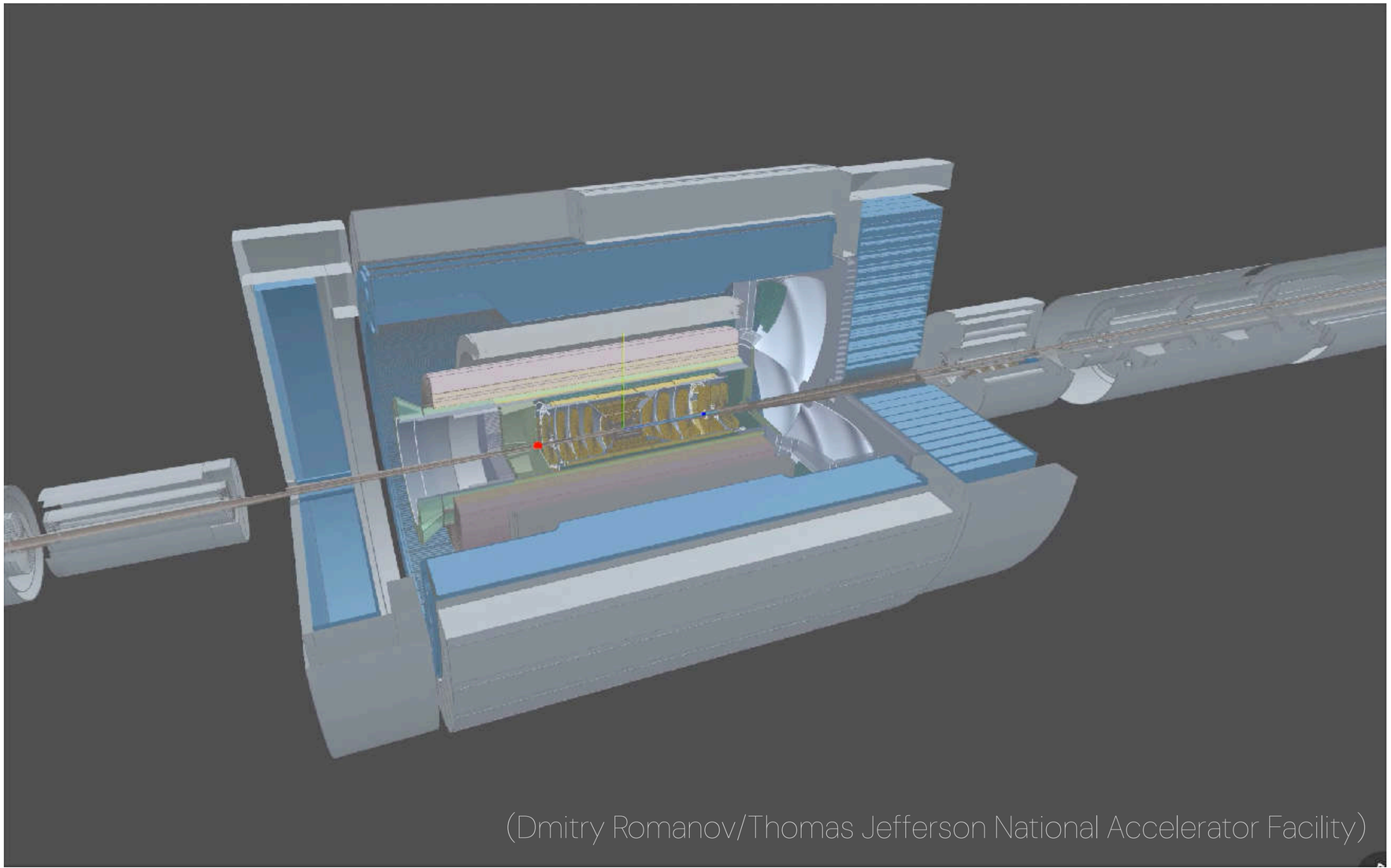
- 35.8 m from the int. point
- high rapidities $\eta > 6$
- measure forward particles with energies up to 275 GeV
- transverse-momentum resolution of ~8.4 MeV

time is right to start developing the theory to match the future data

Forward neutrons at the EIC

$$ep \to eXn$$

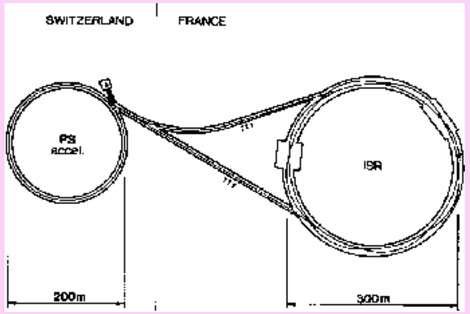
- Very unusual topology: quark change, big gap with very forward isolated neutrons



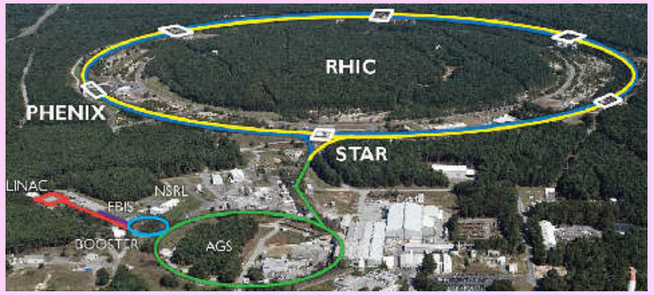
(Dmitry Romanov/Thomas Jefferson National Accelerator Facility)

Forward neutrons at other experiments

$$pp \to XYn$$



ISR
first inclusive zero-angle
forward-neutron spectra in p+p
1976



RHIC (PHENIX)
2006



LHC (LHCf at 13 TeV)
2015

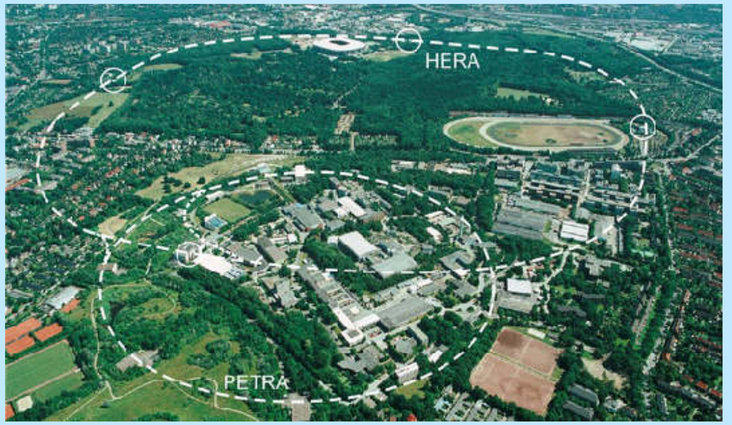
LHC (LHCf at 7 TeV)
2010

RHIC (PHENIX)
2015

RHIC (RHICf)
2017

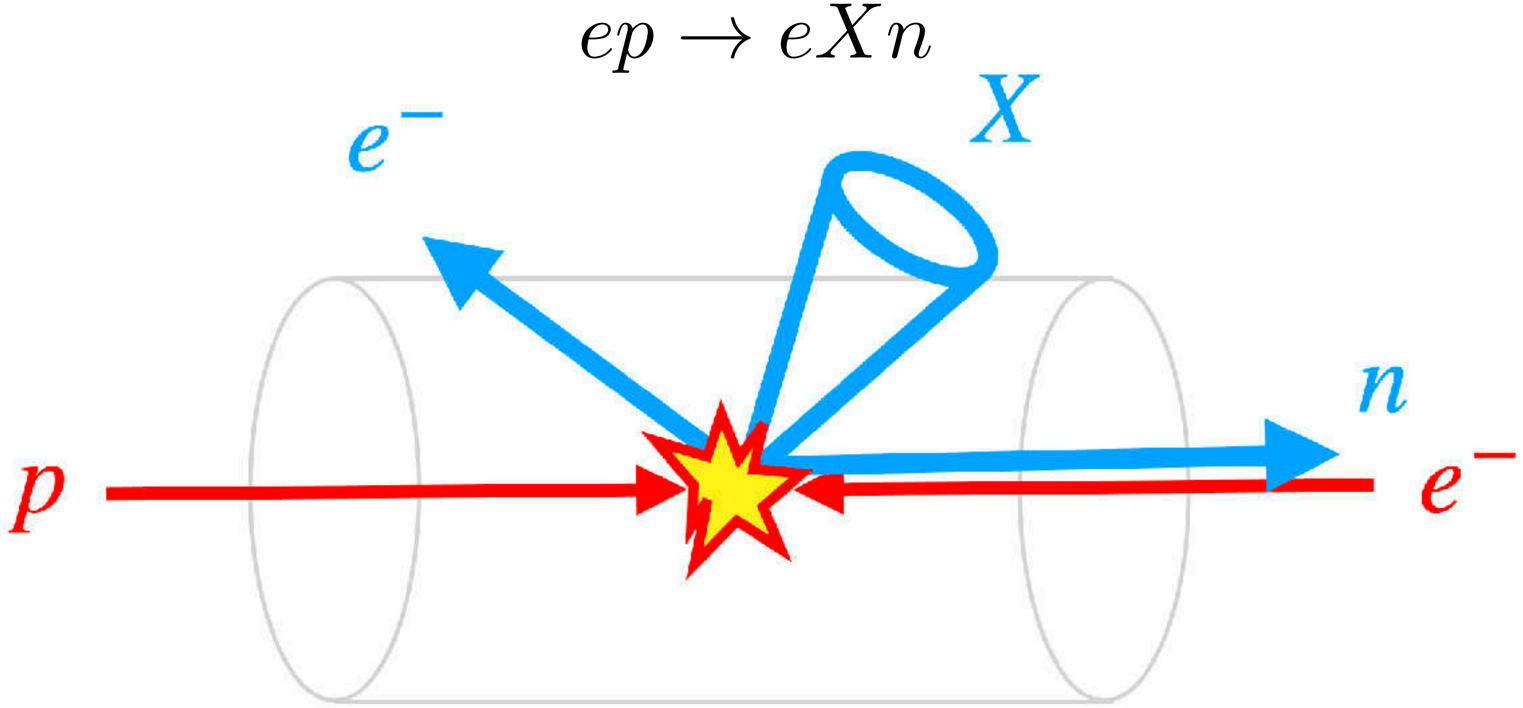
1992–1997
HERA (H1 & ZEUS)

2006–2007
HERA-II



$$ep \to eXn$$

Forward neutrons at the EIC



- ~2–8% of the ep events at HERA had forward neutrons
- ~20%* of the ep events estimated to reach ZDC in EIC

*this number is based on extrapolating the HERA data, we don't know if we believe it

(H1 Collaboration, 1001.0532) (Y. Yamazaki, "Neutron angular distribution and dose in ZDC")

Why study forward neutrons at the EIC?

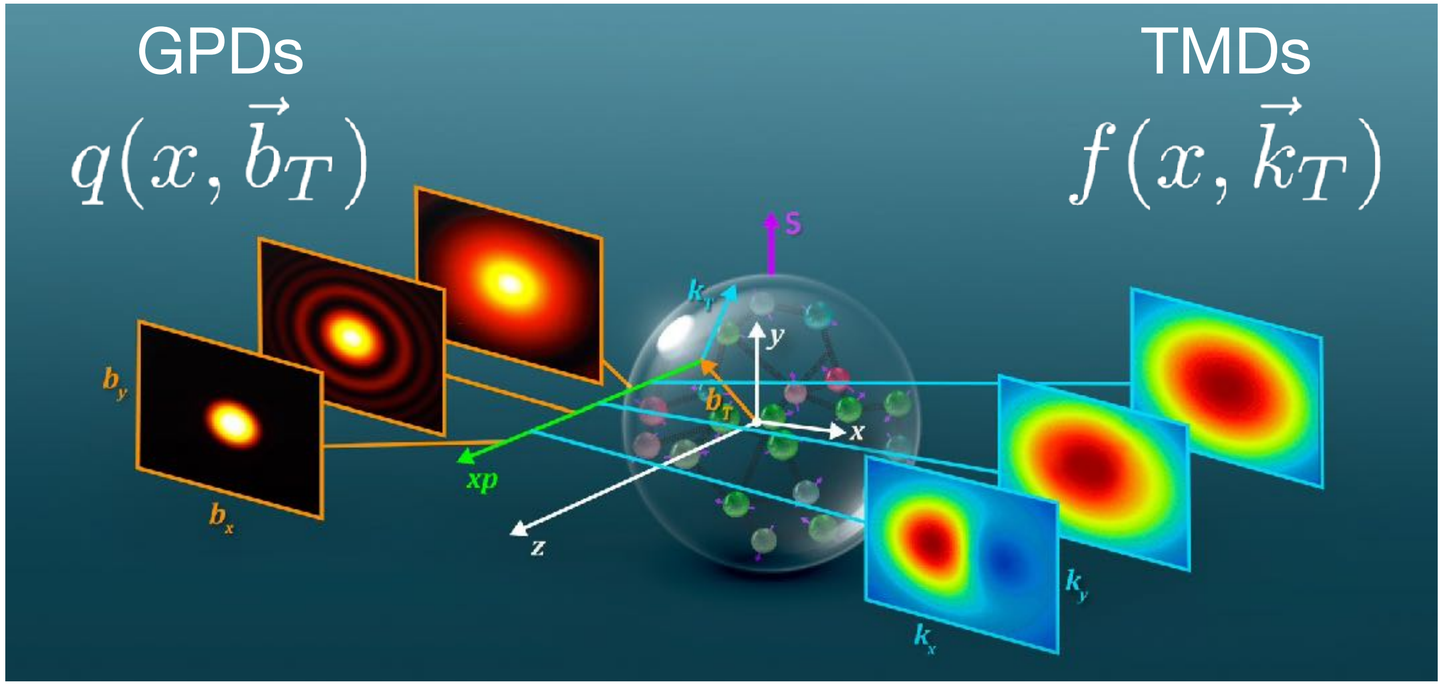
Sullivan process: $ep \to eXn$ *is thought to be mediated by a* ***pion***

- Can access pion's **Generalized Parton Distributions**?
- Learn about **pion's emergent mass**:

  Higgs vs QCD contributions?

  (lattice picture)

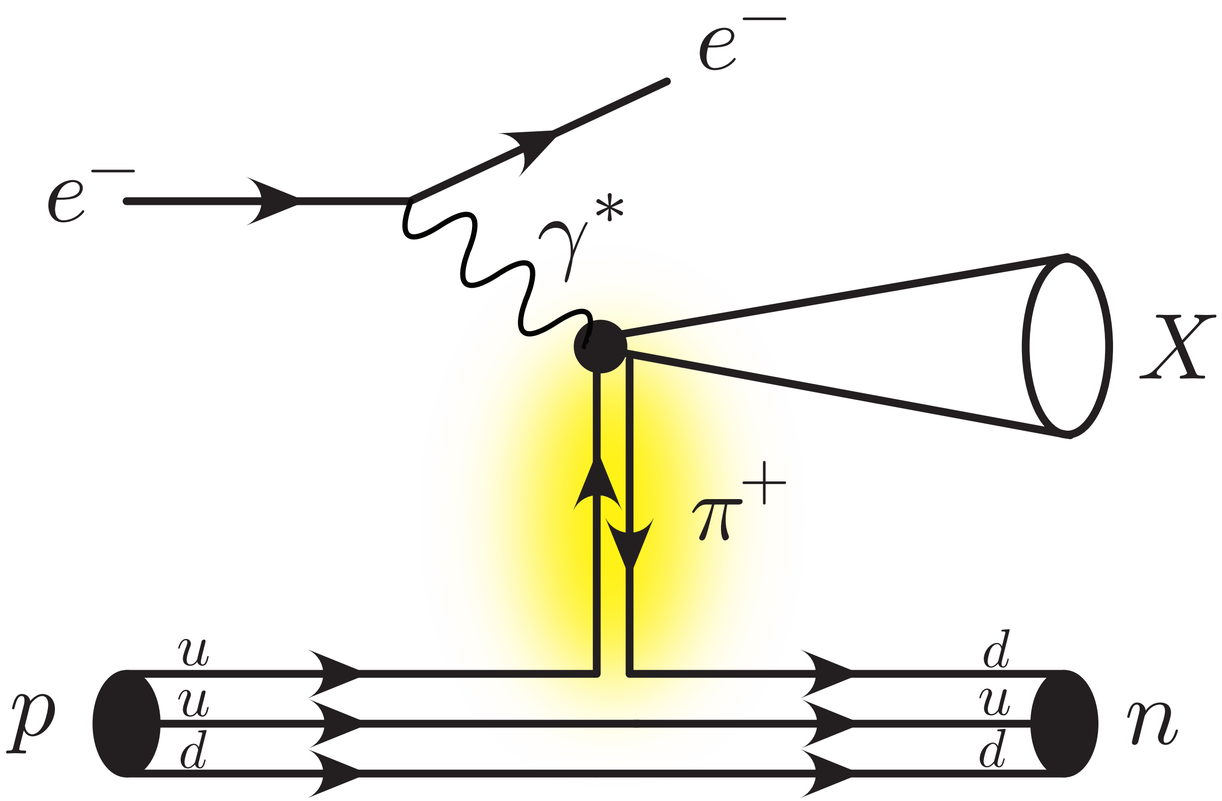
Naïve picture: it was proposed before QCD, yet people still use it!



PDFs: *longitudinal momentum only,*
GPDs: *longitudinal momentum + transverse position*
TMDs: *longitudinal momentum + transverse momentum*

(Figure: Argonne and Jefferson Lab)

Theory is incomplete



Sullivan process: Belief

But! It…

- *is forward*
- *has a rapidity gap*

Forward gapped processes = **diffractive**

not known how to do until last year (2025)

(Lee, Schindler, Stewart)

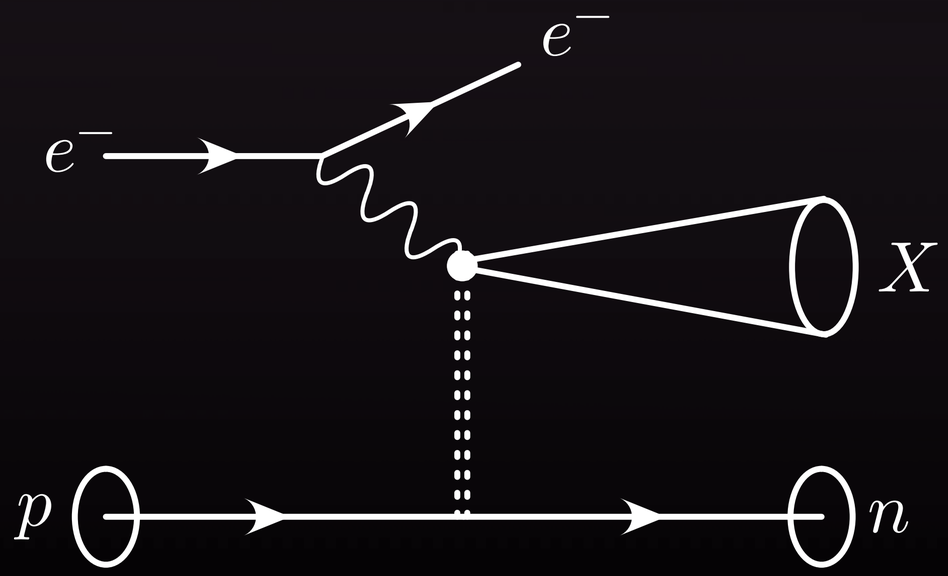
PART I.

What Sullivan process is(n't)

PART II. *EFT for diffraction*

PART III. *Towards predictions*

PART IV. *What's next?*



The Sullivan process: history

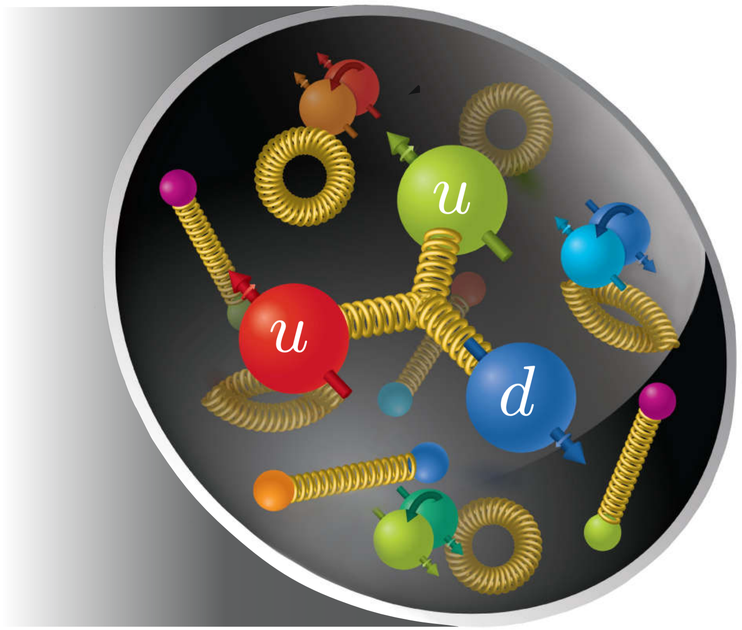
$ep \to eXn$

Proposed in 1971 right after SLAC-MIT DIS experiment revealing inner structure of the proton

(Sullivan, Phys. Rev. D 5 (1972) 1732–1737)

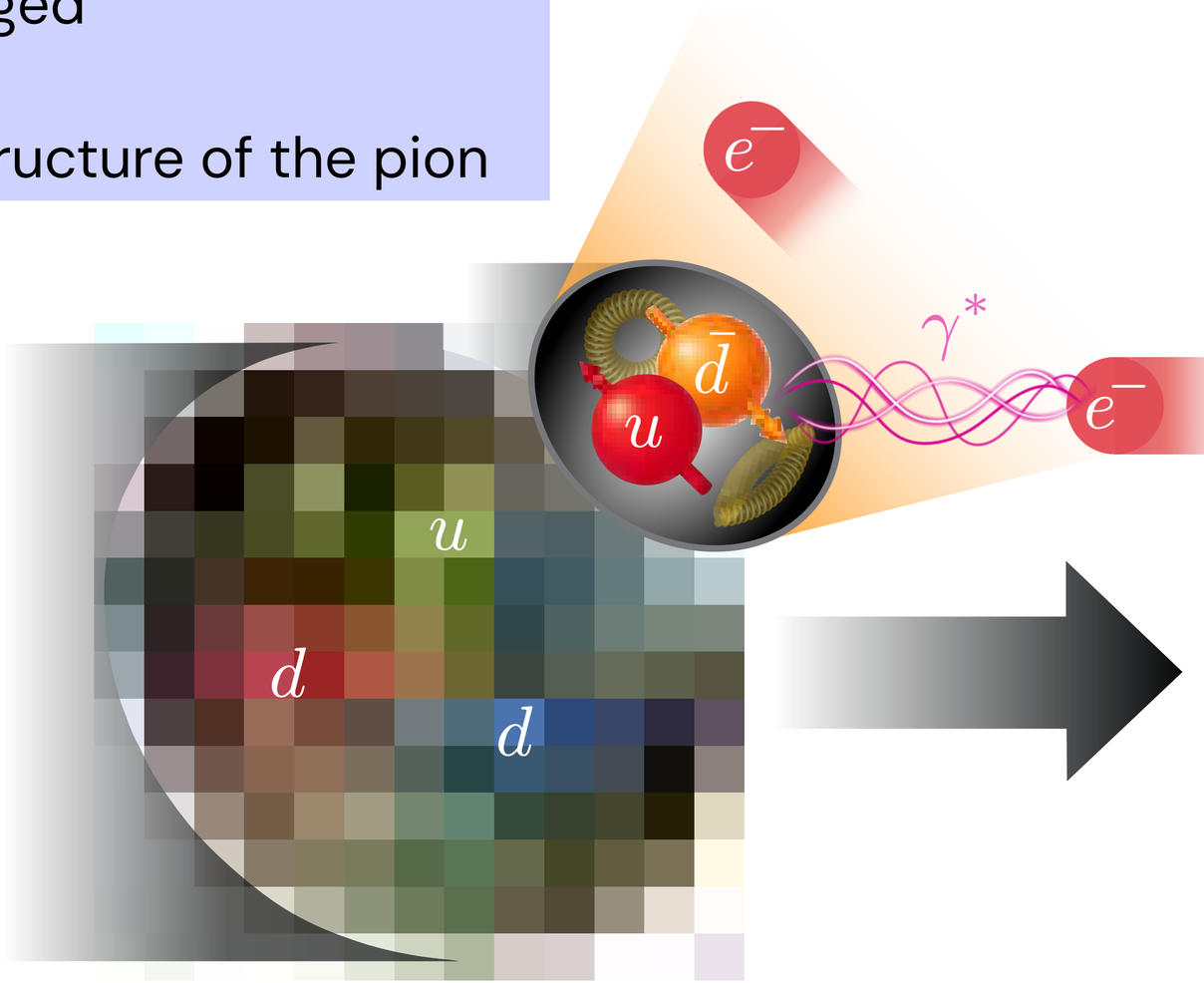
Idea: only one pion exchanged

Claim: able to access the internal gluon structure of the pion



(Figure: Brookhaven National Laboratory)

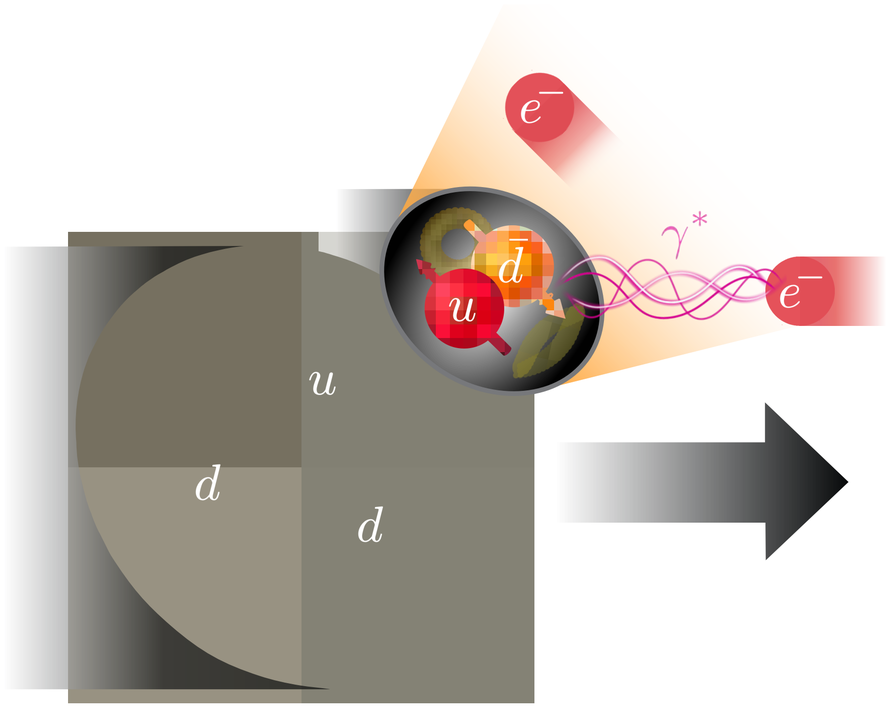




'Meson cloud' or

'five-quark component of the nucleon wave function'

The Sullivan process: history



James D. Sullivan (Boston U.)

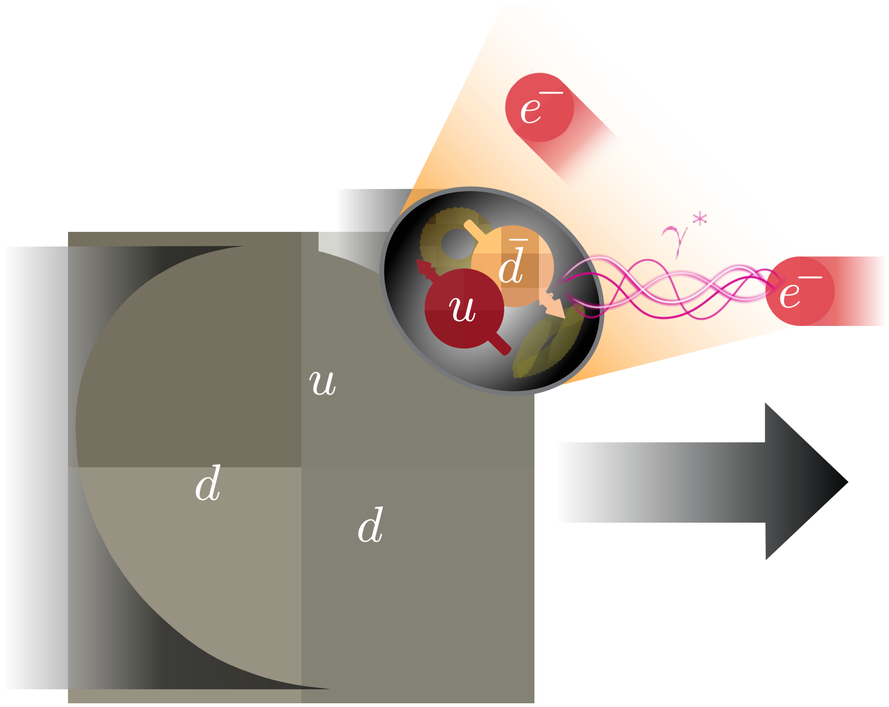
astro-ph | hep-ex | nucl-ex

The Sullivan process: history



James Sullivan (governor)

Article Talk



James D. Sullivan (Boston U.)

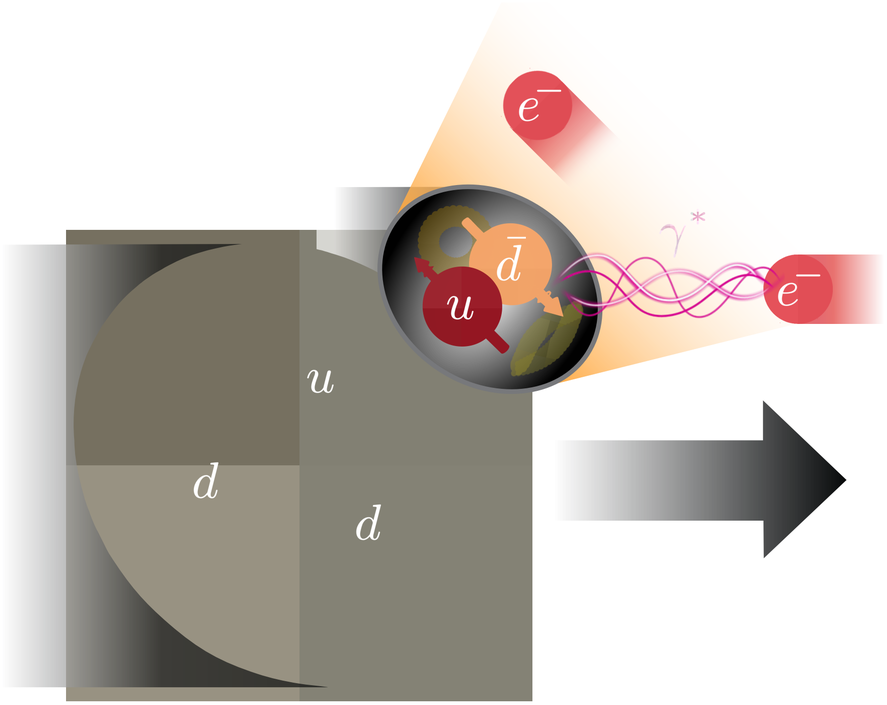
astro-ph hep-ex nucl-ex

The Sullivan process: history



James Sullivan (governor)

Article Talk



James D. Sullivan (Boston U.)

astro-ph hep-ex nucl-ex



James P. Sullivan

"Hey, may the best monster win!"

—Sulley to Randall Boggs

The Sullivan process: history

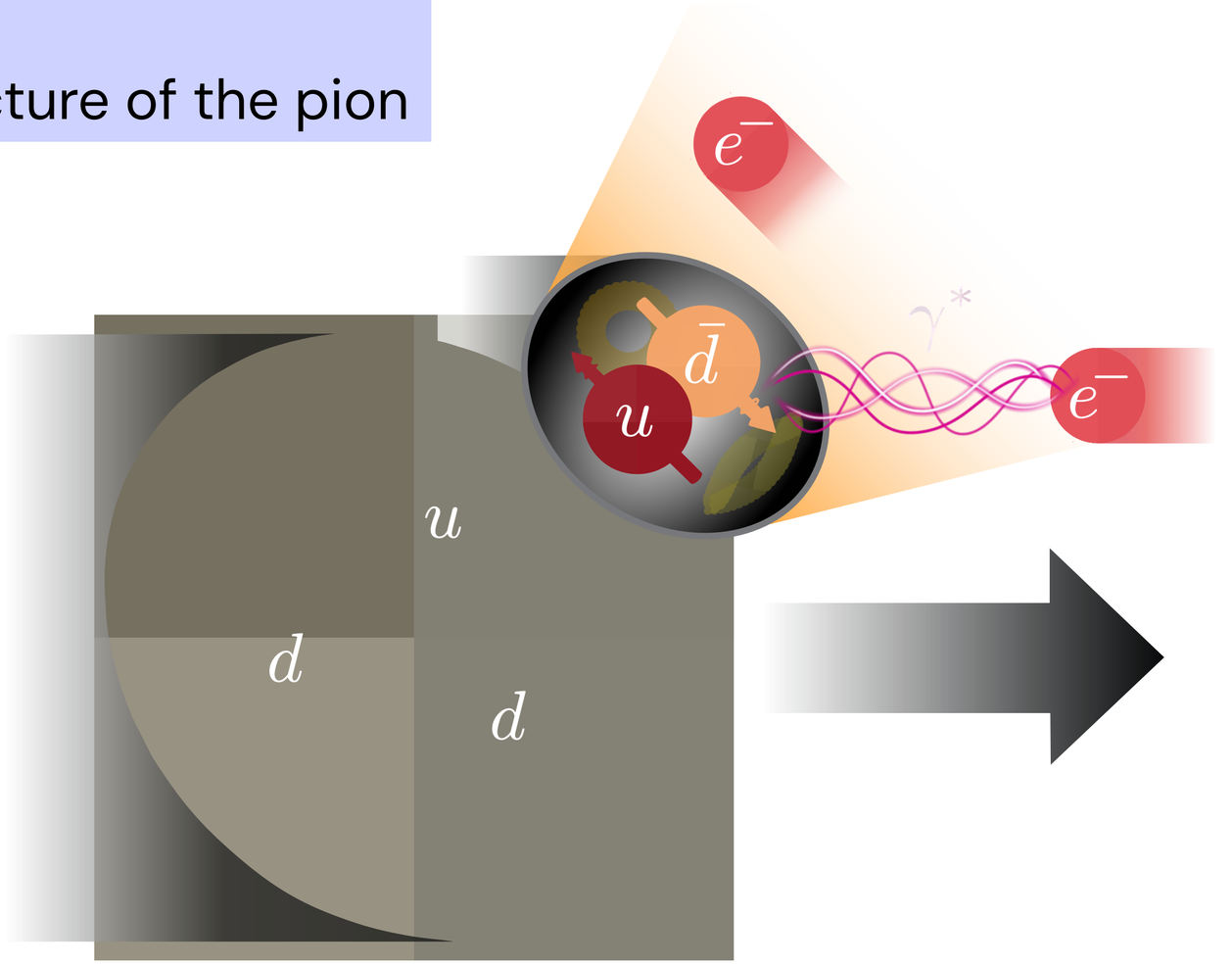
$ep \to eXn$

Idea: only one pion exchanged

Claim: able to access the internal gluon structure of the pion

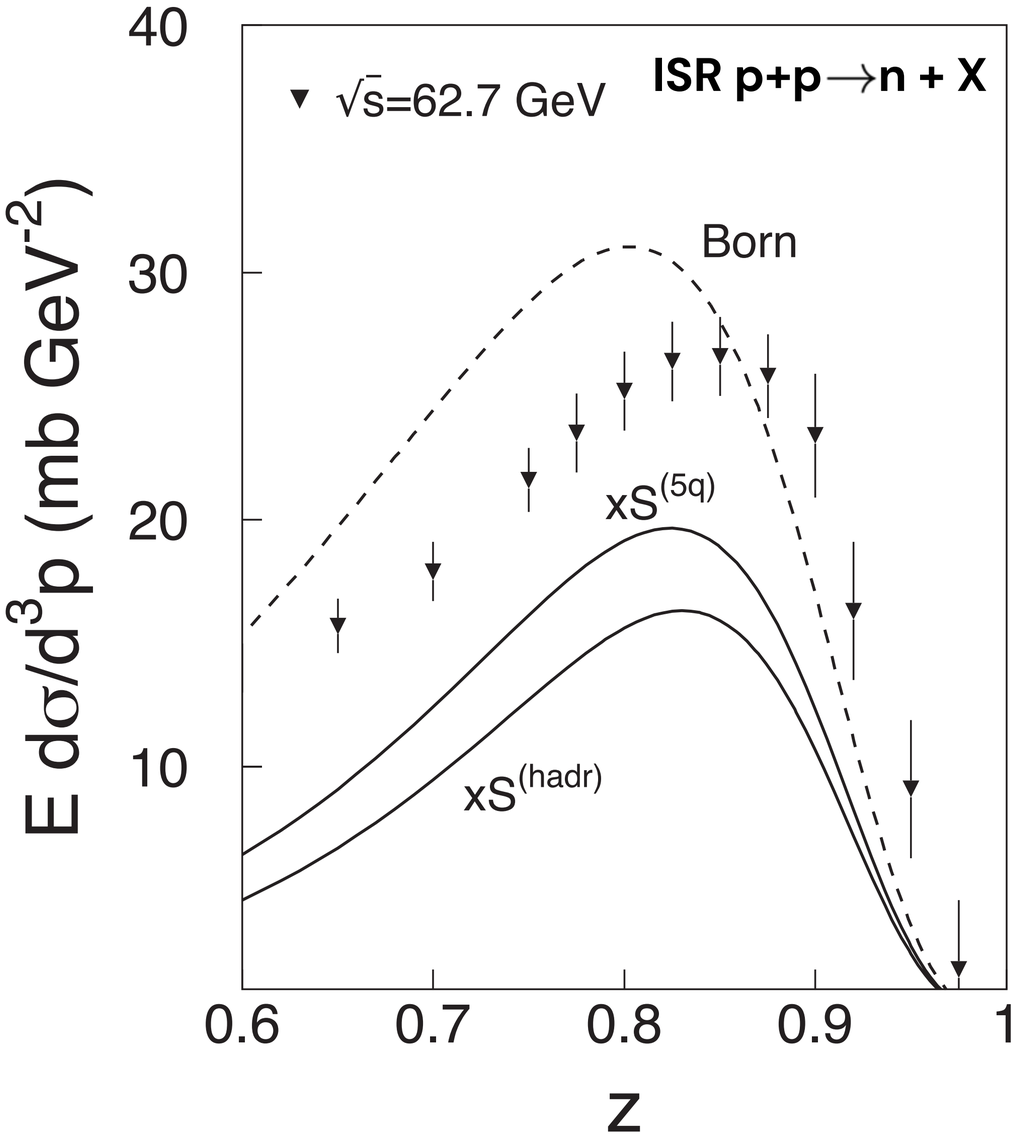
Why not:

- intermediate particle is highly off shell
- can't be a bound state hadron



The Sullivan process: history

$ep \to eXn$



Pion **overpredicts** forward neutrons measurements for cross section

Born: pion exchange

xS: cross section with different types of absorptive corrections

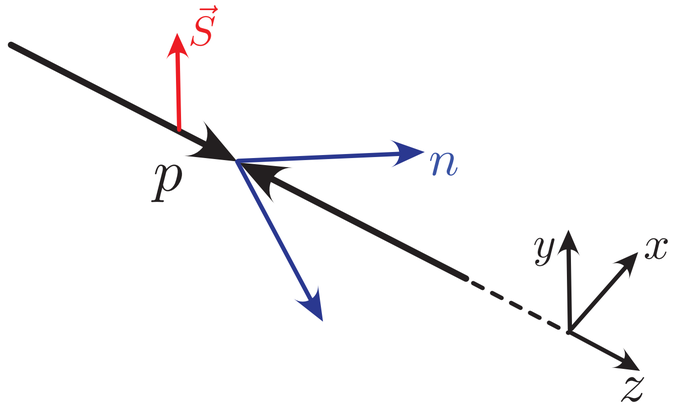
(Kopeliovich, Potashnikova, Schmidt, Soffer 0805.4534, 1109.2500)

The Sullivan process: history

$ep \to eXn$

Pion does not **create enough spin asymmetry.**

People try to model difference with absorptive corrections or extra resonances.



$$A_N \propto \frac{N_L - N_R}{N_L + N_R}$$

$$A^B_{p\to n}(\vec{q}, z) = \bar{\xi}_n \left[\sigma_3 \, q_L + \frac{1}{\sqrt{z}} \vec{\sigma}\cdot\vec{q}_T \right] \xi_p \, \phi^B(q_T, z)$$

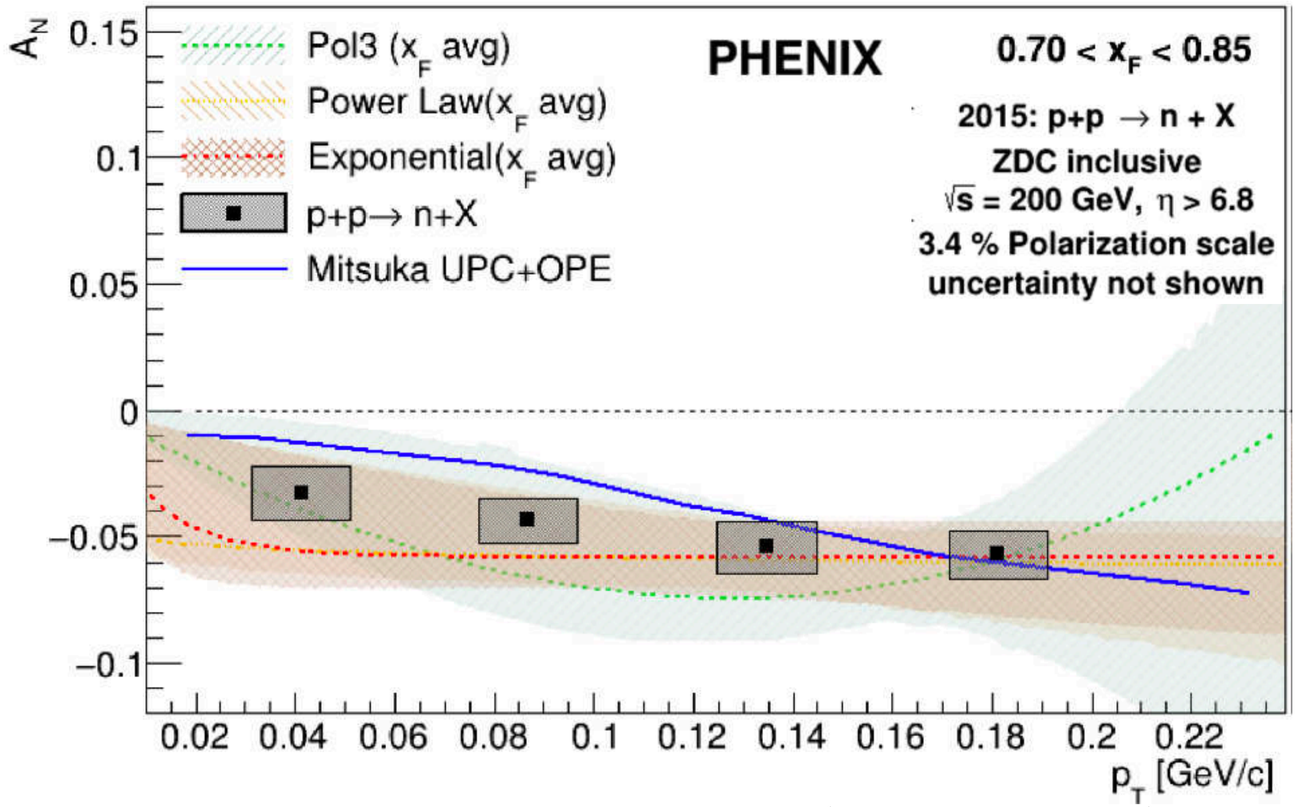
spin non-flip spin-flip

$$A_N \sim \sin(\delta_{\text{flip}} - \delta_{\text{non-flip}})$$

phase difference of the flip/non-flip

$$\delta_{\text{flip}} = \delta_{\text{non-flip}} \Rightarrow A_N = 0$$

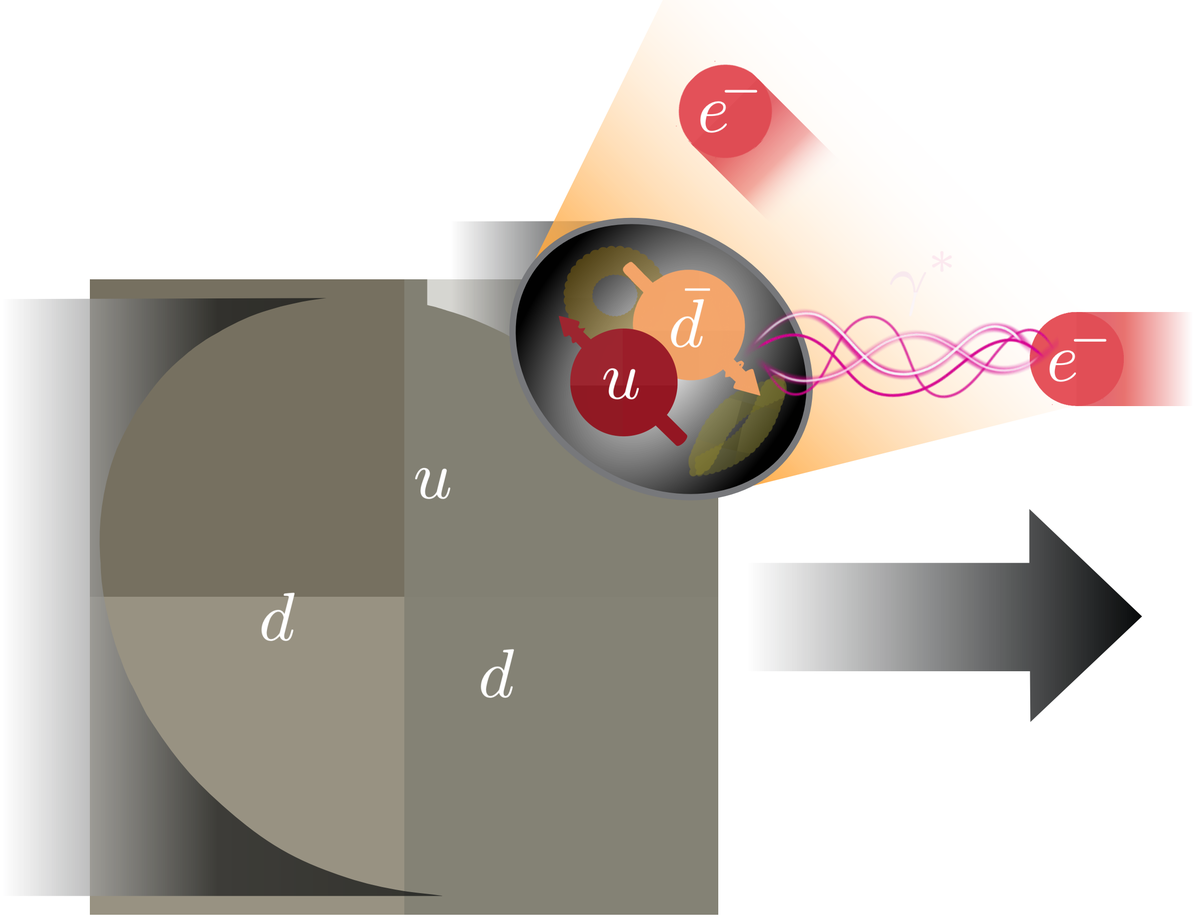
Prediction: no single-transverse spin asymmetry



(Kopeliovich, Potashnikova, Schmidt, Soffer 0805.4534, 1109.2500)

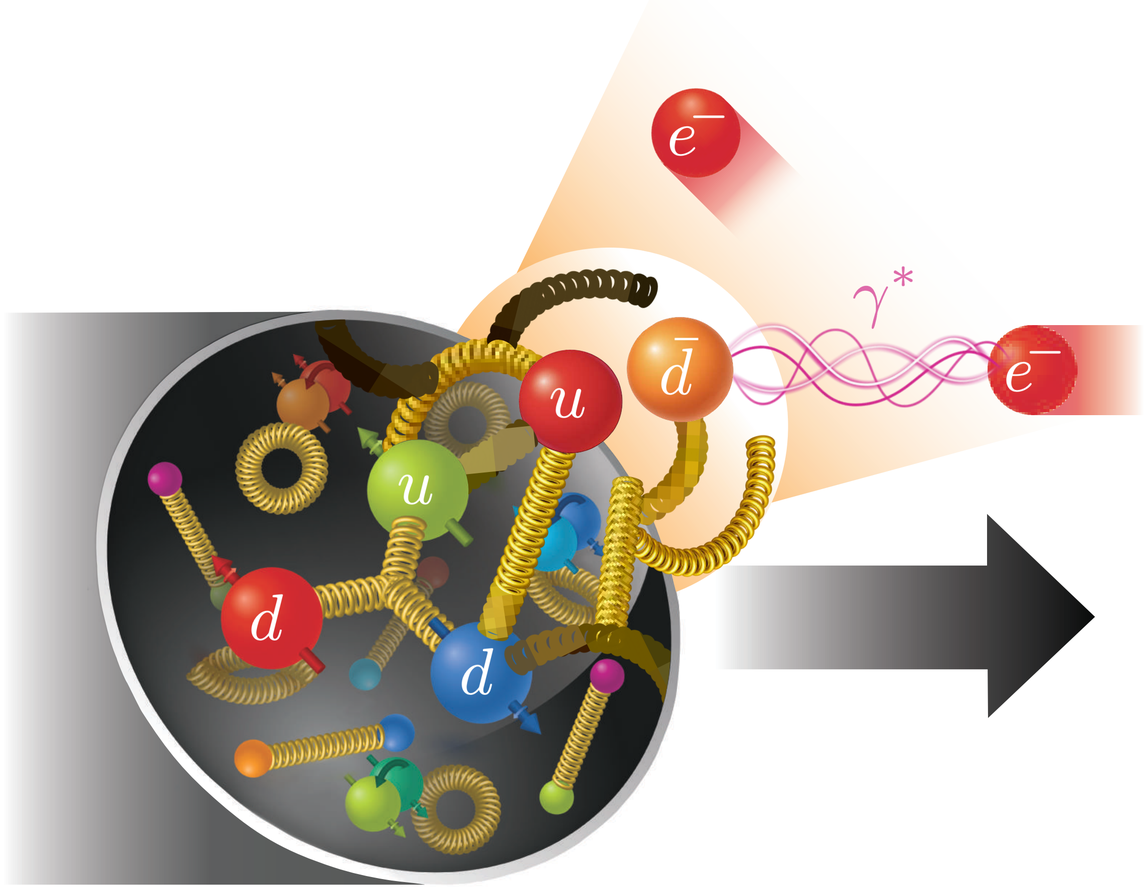
(PHENIX 2110.07504)

The Sullivan process: reality



Experimentalists' dream

- Mediated by a pion
- Can access pion's GPDs
- But models don't fit data

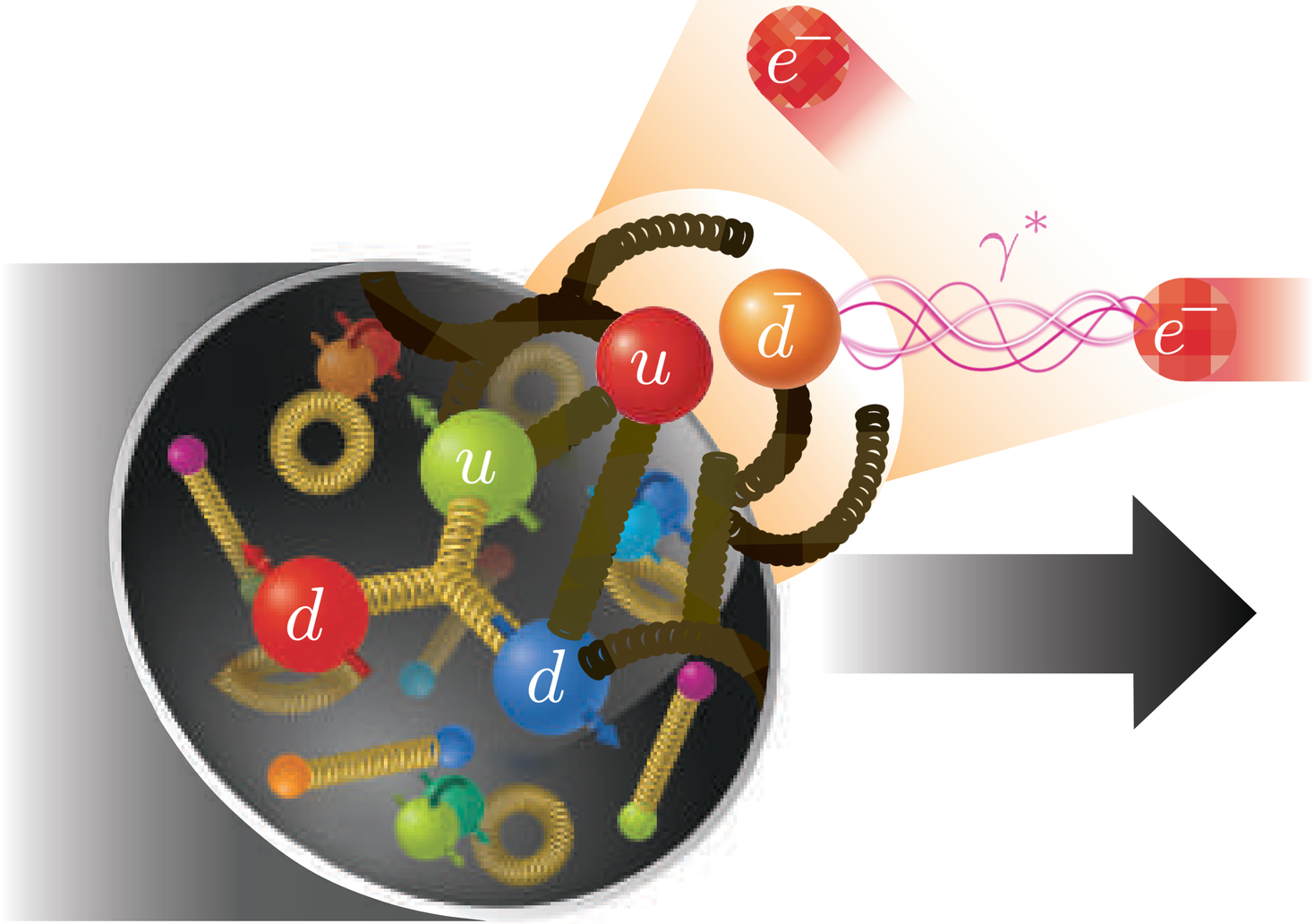


Theorists' reality

- Mediated by a sea of (Glauber) gluons and two quarks
- Not even close to GPDs

The Sullivan process: reality

A complicated mess of gluons and quarks,
which is highly off-shell and ***diffractive***

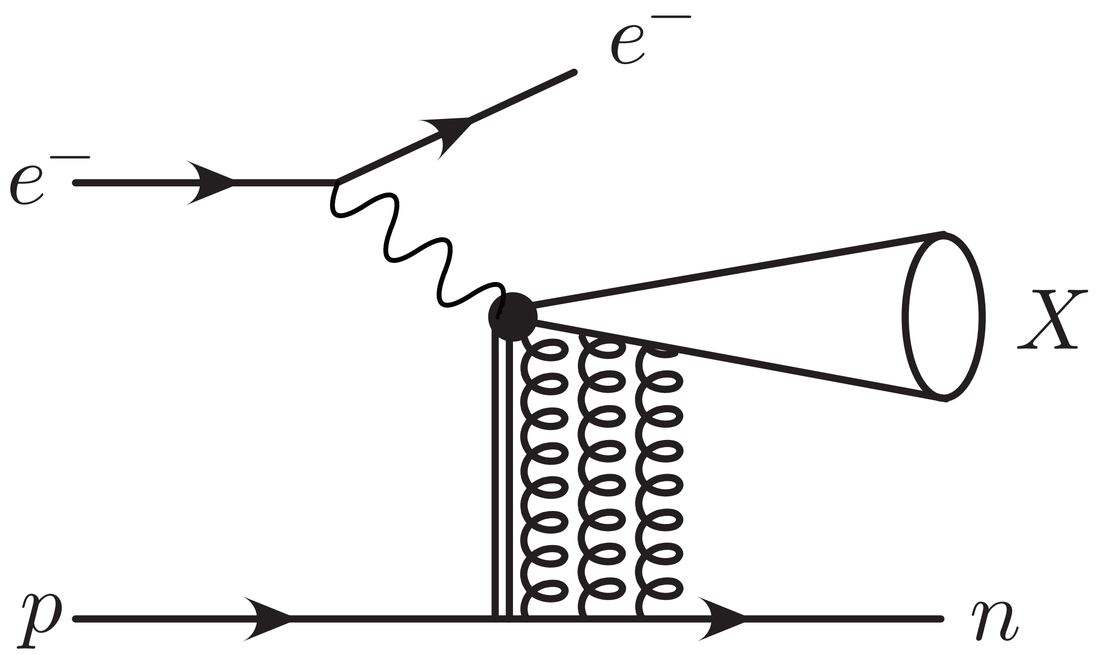


All roads lead to…
SCET for diffraction

(Lee, Schindler, Stewart)

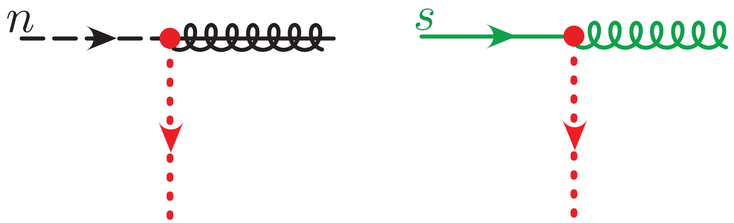
The Sullivan process: reality

A complicated mess of gluons and quarks,
which is highly off-shell and ***diffractive***

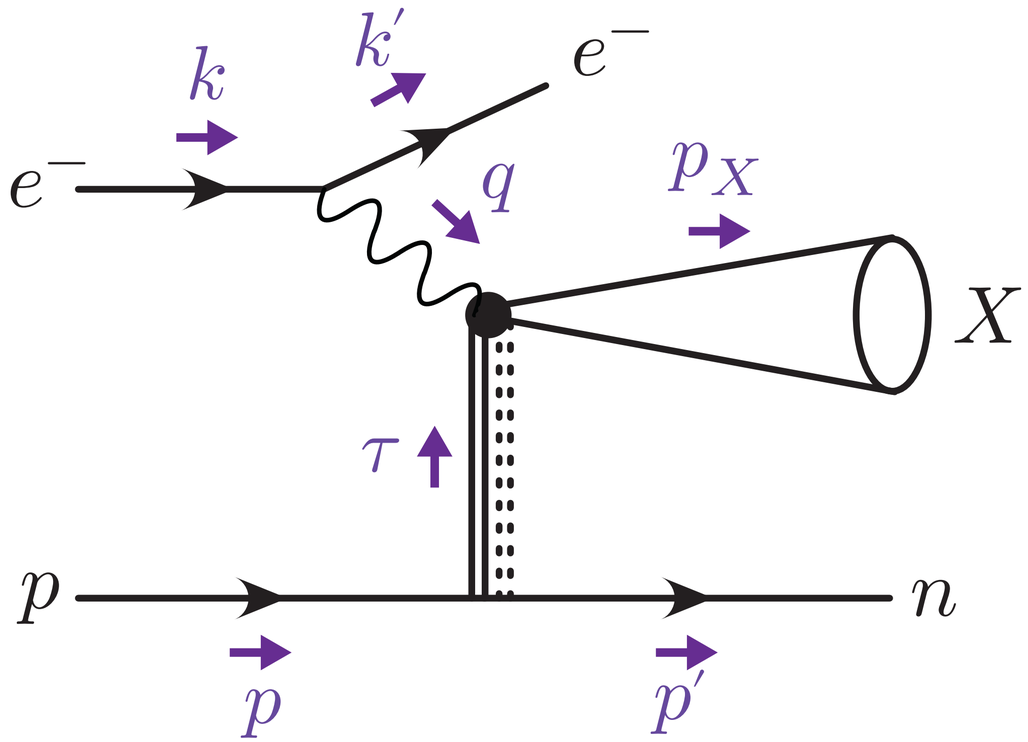


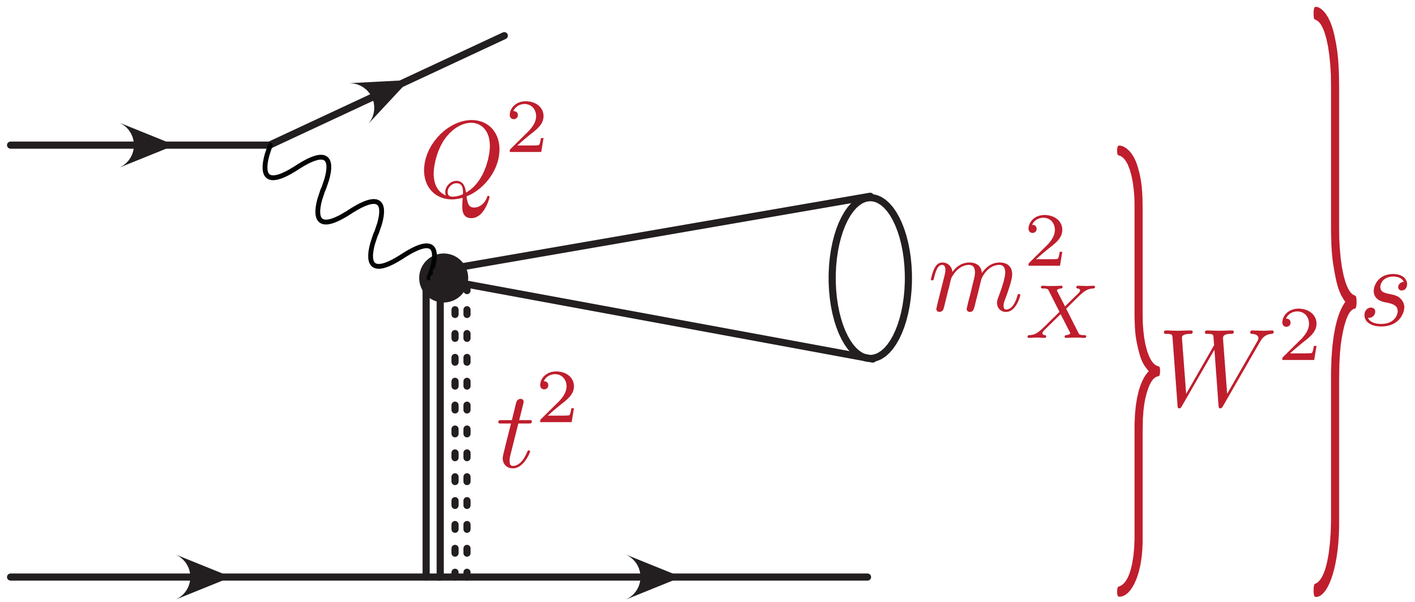
All roads lead to…
SCET for diffraction

with Glauber fermions!



Kinematic variables for Sullivan





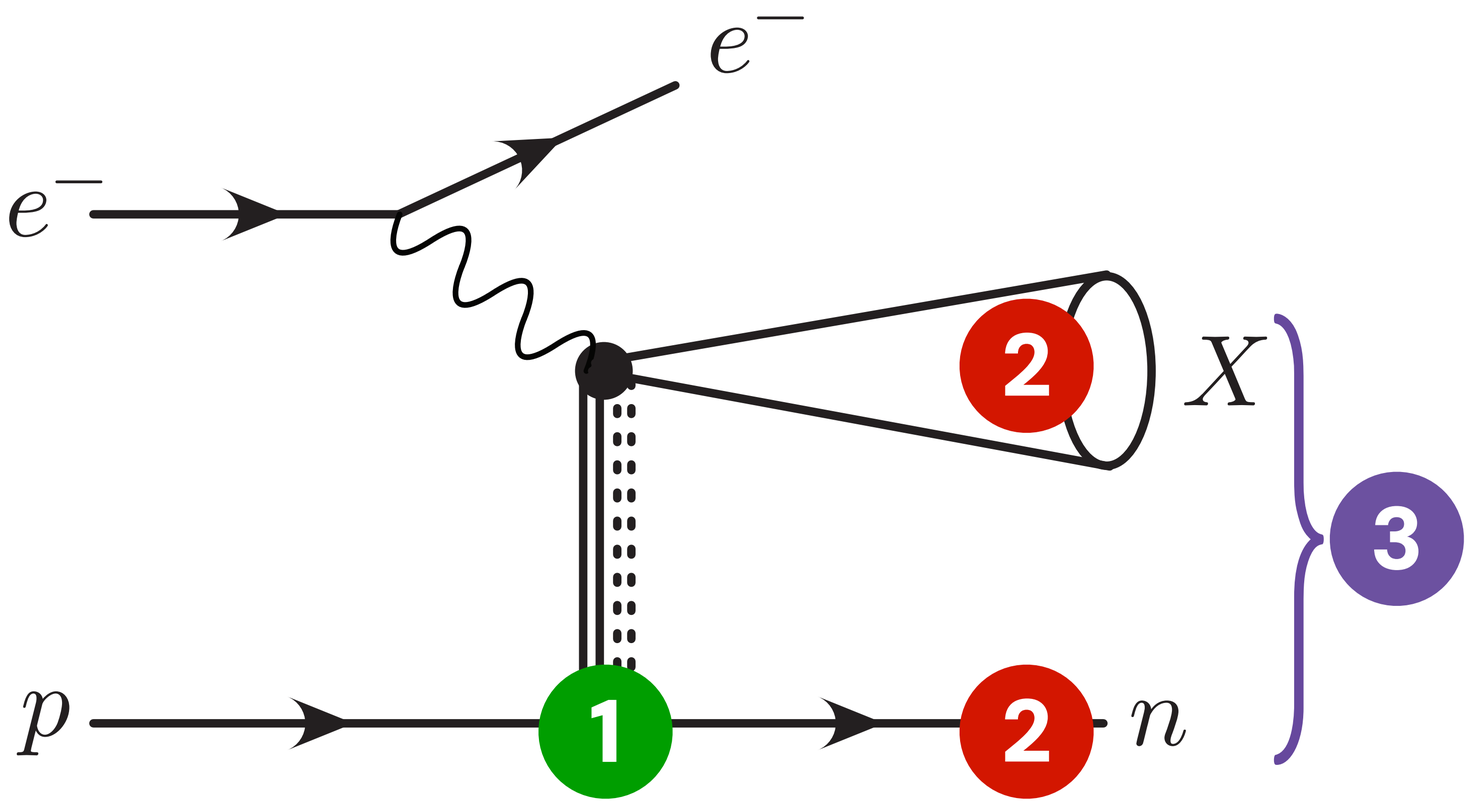
Momentum fractions			
$x = \dfrac{Q^2}{2p \cdot q}$	$\beta = \dfrac{Q^2}{2q \cdot \tau}$	$y = \dfrac{p \cdot q}{p \cdot k}$	$\bar{x} = \dfrac{k \cdot \tau}{k \cdot p}$

$$W^2 \equiv (p+q)^2$$

$$s = (p+k)^2$$

Diffractive process: kinematic reqs.

*Not dealing with the leptonic part



1. High energy, forward scattering:

high energy $x \ll 1$,

small mom. transfer $-t \ll W^2$

2. Clear separation: *small invariant mass of the final states*

$$\Lambda^2_{\mathrm{QCD}} \lesssim m_X^2 \ll W^2,$$

$$\Lambda^2_{\mathrm{QCD}} \sim m_n^2 \ll W^2$$

*coherent

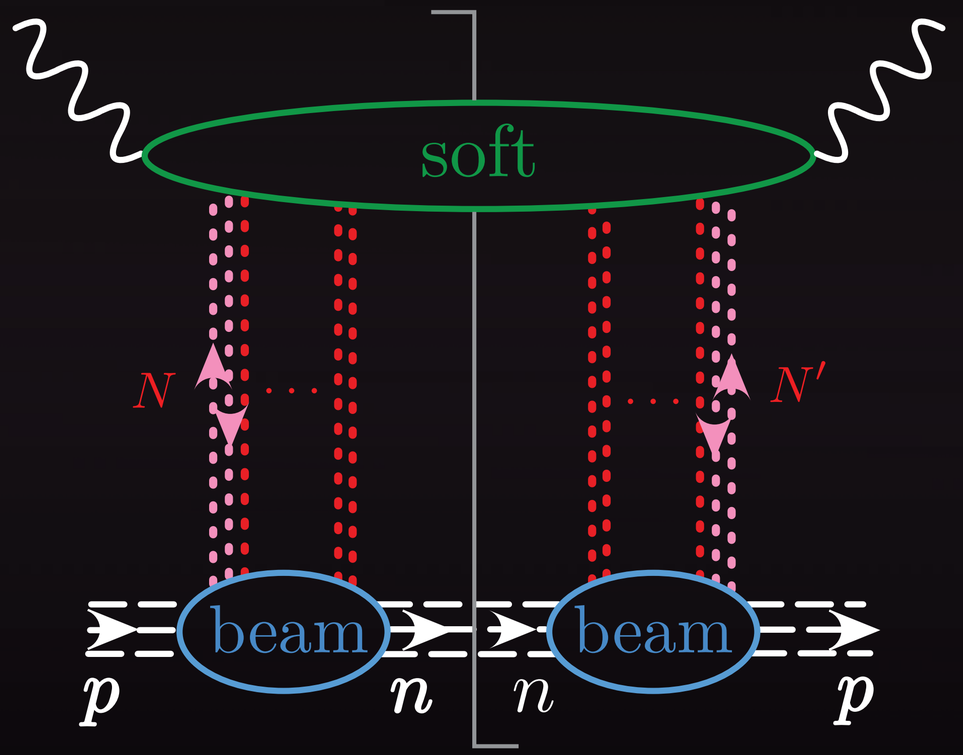
3. Rapidity gap:

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

Small-x Sullivan process is always diffractive

PART I. *What Sullivan process is(n't)*

PART II. *EFT for diffraction*

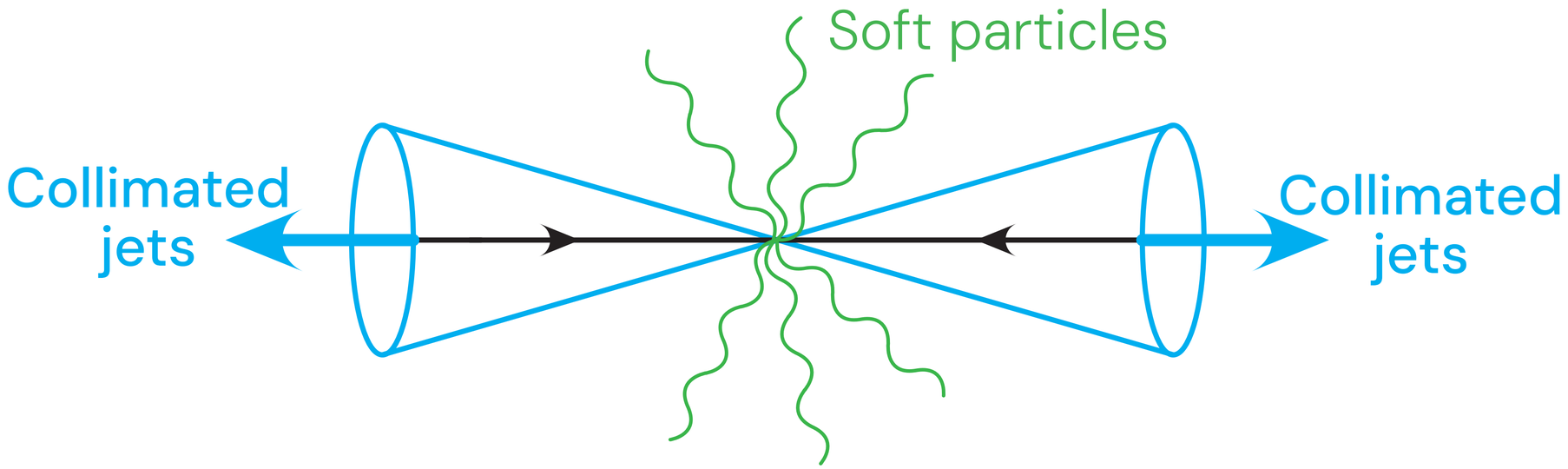


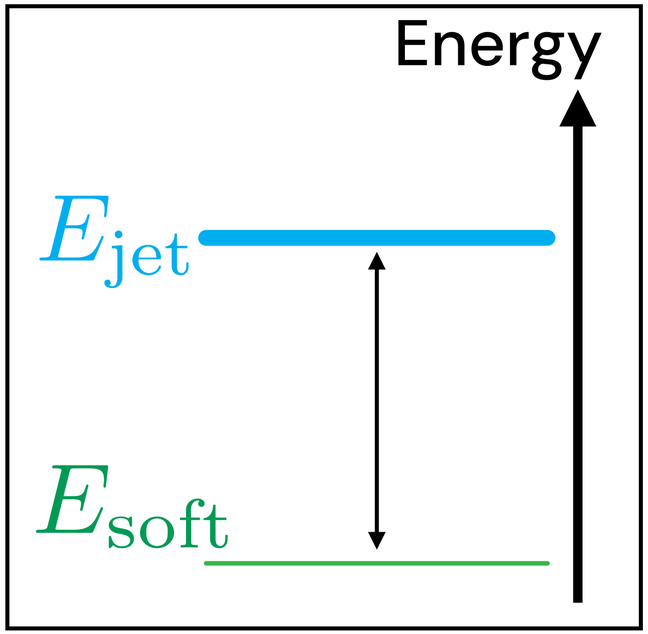
PART III. *Towards predictions*

PART IV. *What's next?*

Effective field theory in a nutshell

- Collisions include multiple energy scales
- Can simplify calculations by looking only at the relevant scales and integrating out the irrelevant ones





Lagrangian: $\mathcal{L}_{\rm QCD} \xrightarrow[\text{irrelevant modes}]{\text{integrate out}} \mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm jet} + \mathcal{L}_{\rm soft}$

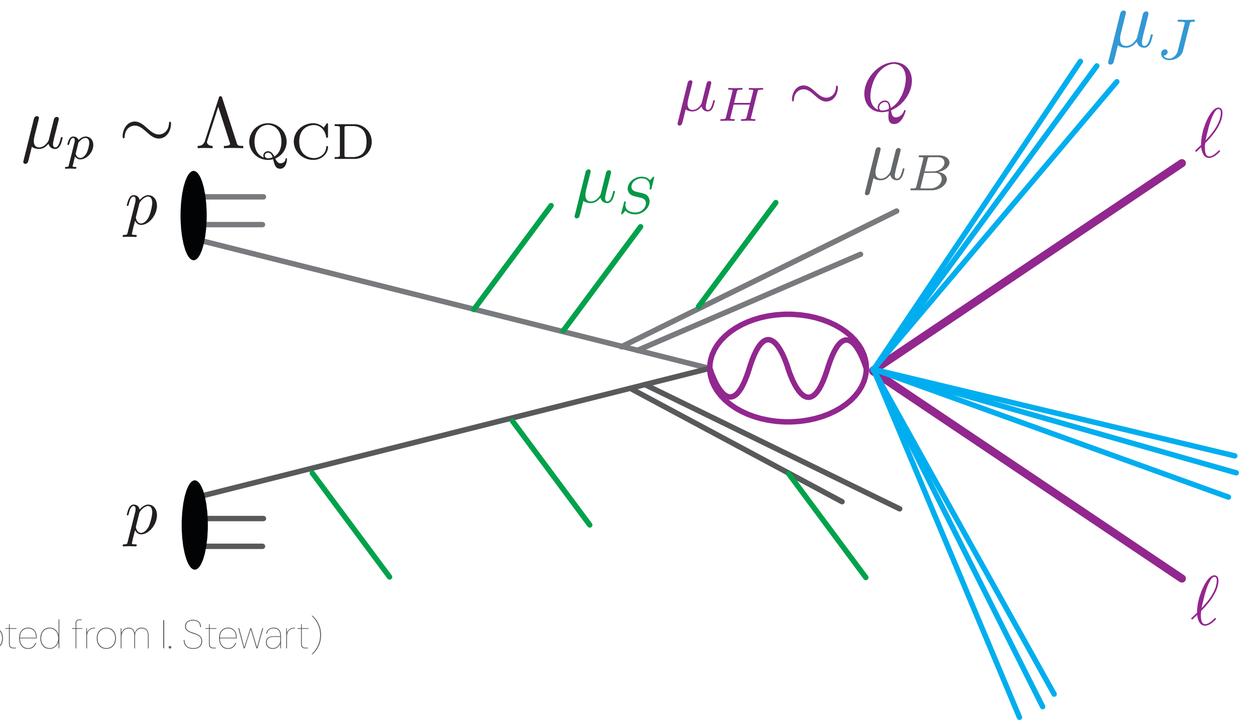
Observables: $\langle \mathcal{O} \rangle \to \langle \mathcal{O}_{\rm jet} \rangle \times \langle \mathcal{O}_{\rm soft} \rangle \times \langle \mathcal{O}_{\rm jet} \rangle$

(Figure adapted from I. Stewart. See e.g. 2303.02579)

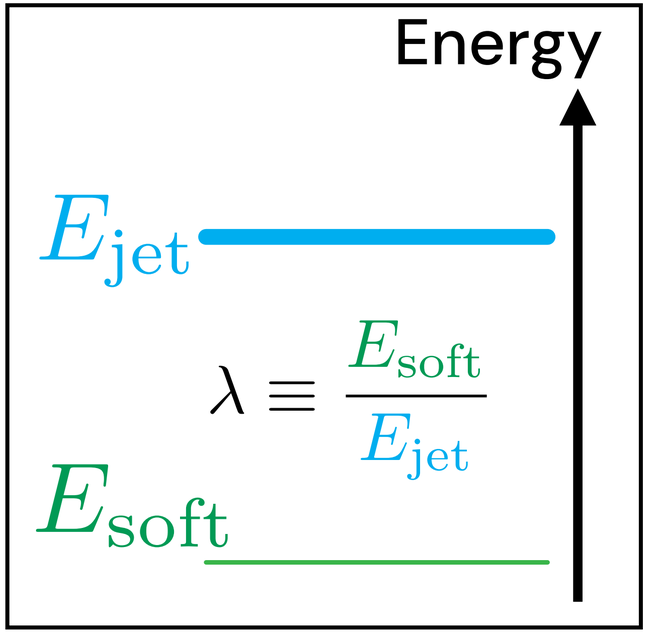
Effective field theory in a nutshell

- Systematically improvable
- Simplifies study of: factorization, perturbative corrections…

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



(Figure adapted from I. Stewart)



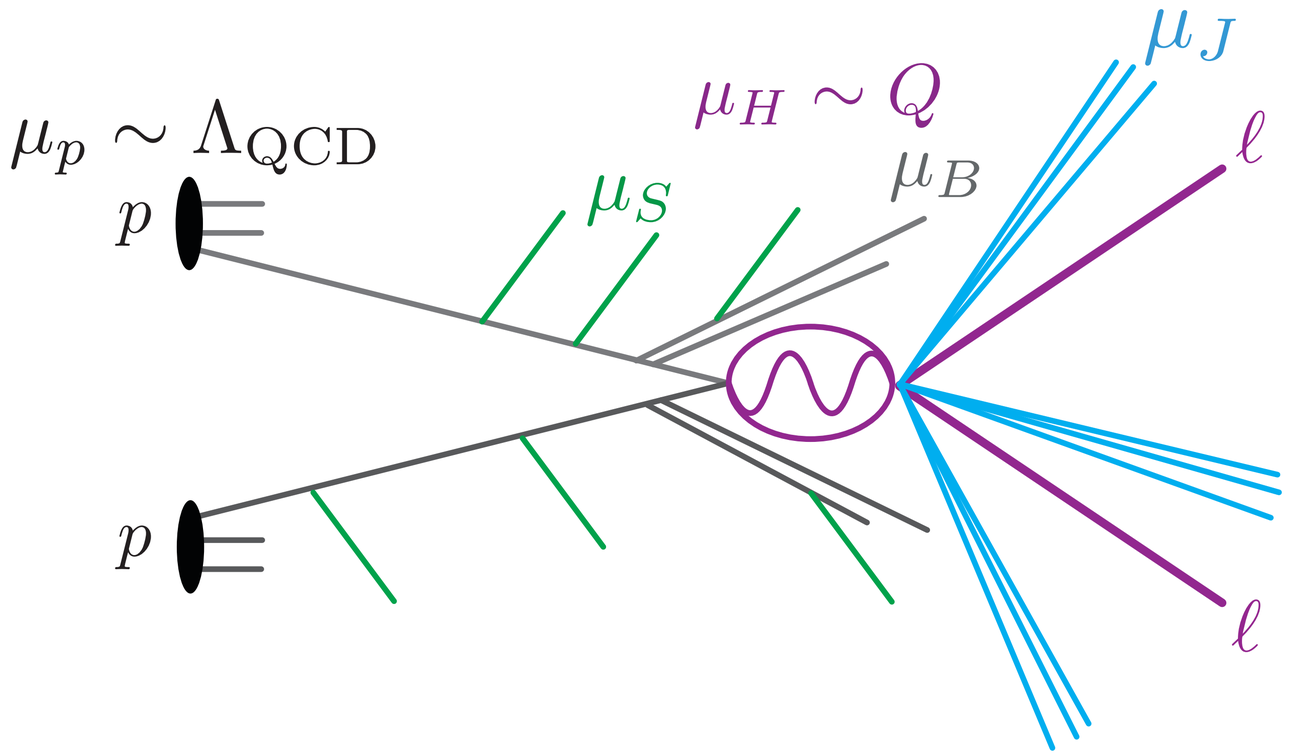
- In general: multiple scales!

SCET Lagrangian

Relevant modes

$p^\mu = (p^+, p^-, |\vec{p}_\perp|)$

Hard	$\sqrt{s}(1, 0, 0)$
Collinear	$\sqrt{s}(1, \lambda^2, \lambda)$ or $\sqrt{s}(\lambda^2, 1, \lambda)$
Soft	$\sqrt{s}(\lambda, \lambda, \lambda)$



*Picture for Drell-Yan

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

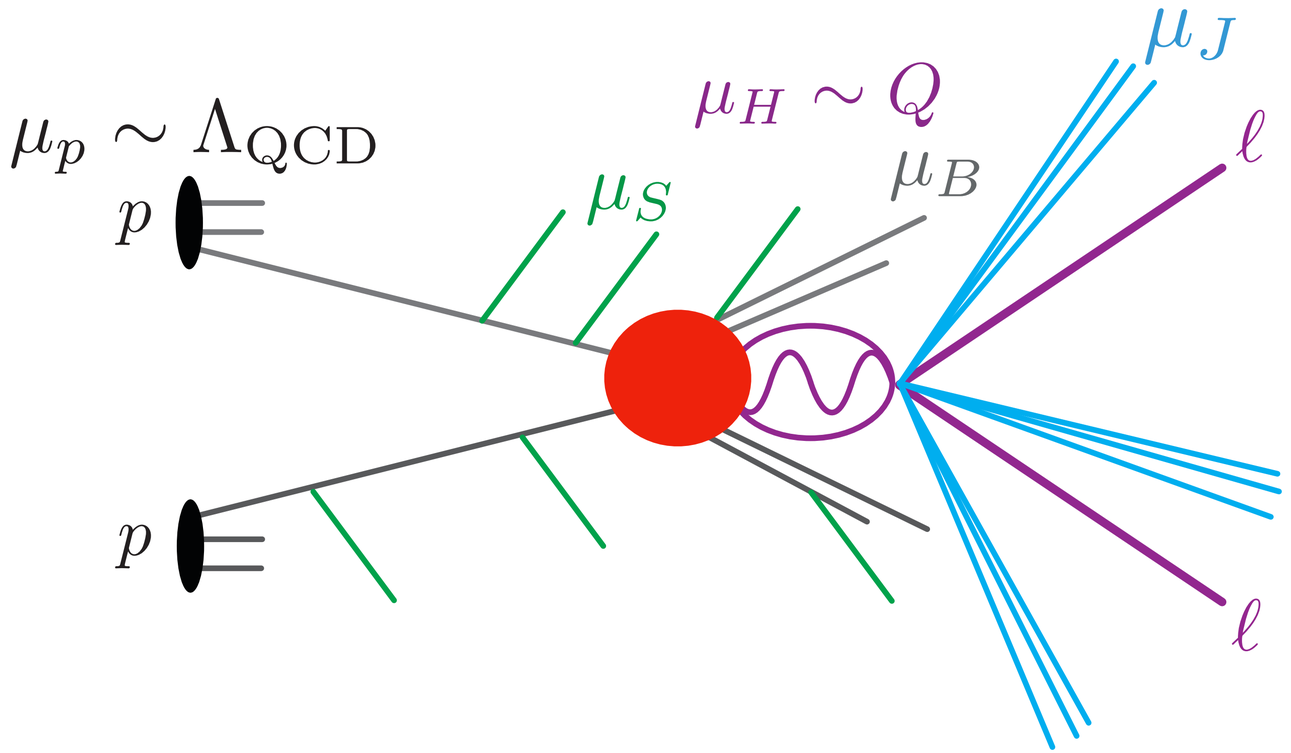
(Bauer, Fleming, and Luke, hep-ph/0005275), (Bauer, Fleming, Pirjol, and Stewart, hep-ph/0011336), (Bauer and Stewart, hep-ph/0107001), (Bauer, Pirjol, and Stewart, hep-ph/0205289)

SCET Lagrangian for (Sullivan) Diffraction

Relevant modes

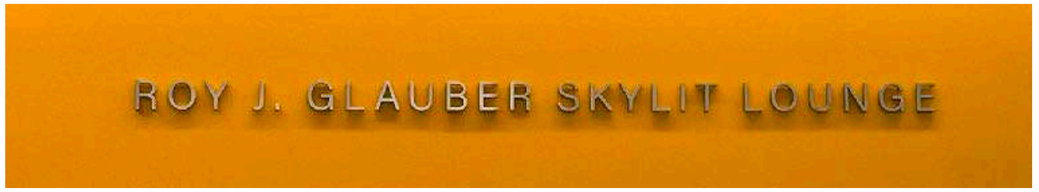
$p^\mu = (p^+, p^-, |\vec{p}_\perp|)$

Hard	$\sqrt{s}(1, 0, 0)$
Collinear	$\sqrt{s}(1, \lambda^2, \lambda)$ or $\sqrt{s}(\lambda^2, 1, \lambda)$
Soft	$\sqrt{s}(\lambda, \lambda, \lambda)$
Glauber	$\sqrt{s}(\lambda^a, \lambda^b, \lambda)$ for $a + b > 2$



*Picture for Drell–Yan

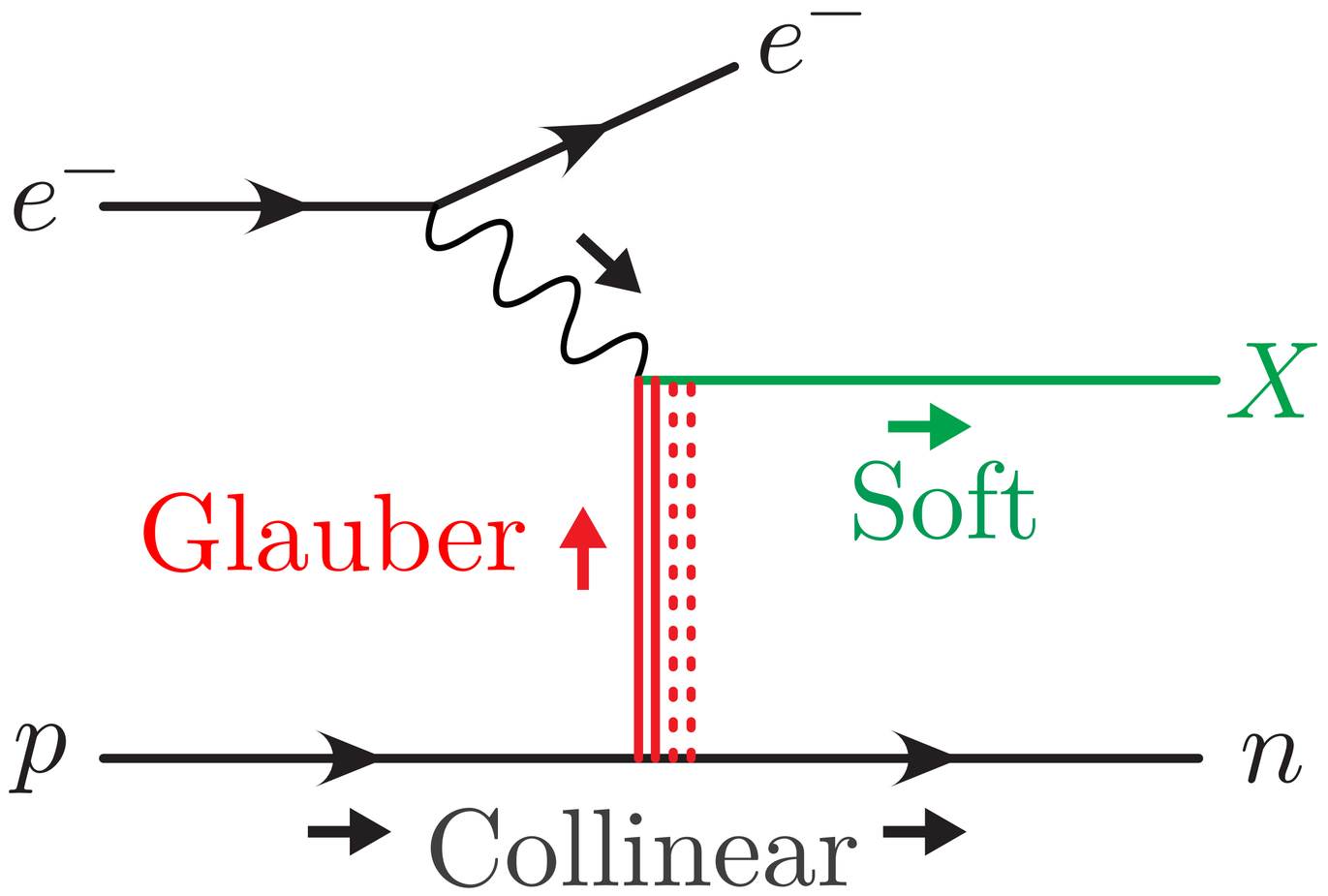
$$\mathcal{L}^{(0)}_{\rm SCET} \supset \mathcal{L}_{\rm hard} + \mathcal{L}_{\rm collinear} + \mathcal{L}_{\rm soft} + \mathcal{L}_{\rm Glauber}$$

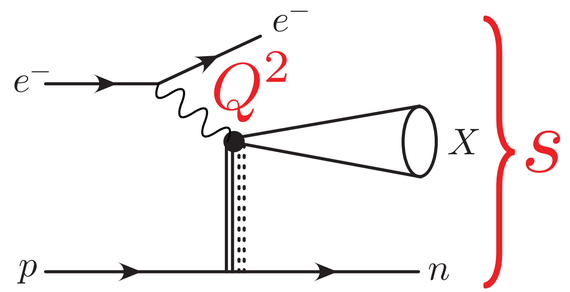


@ Quantum Computing building at Harvard

(Rothstein and Stewart, 1601.04695)

SCET modes in Sullivan





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

Both Glauber quarks and gluons!

*No ultrasoft contribution since the exchanged particle is a color singlet

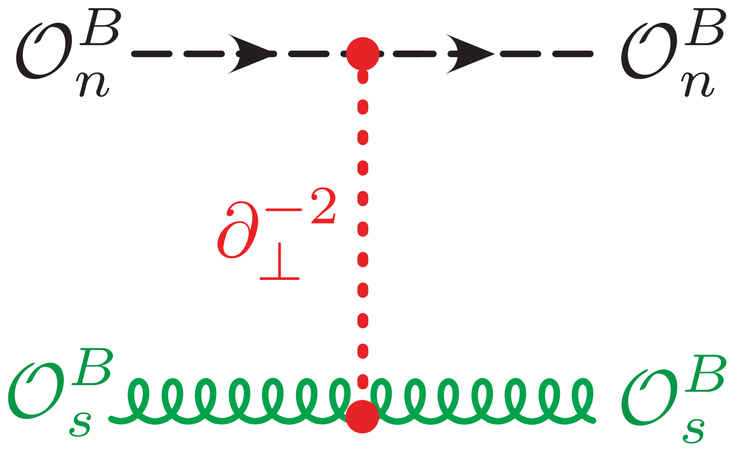
Glauber gluons

Leading power ‘connections’ between sectors

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

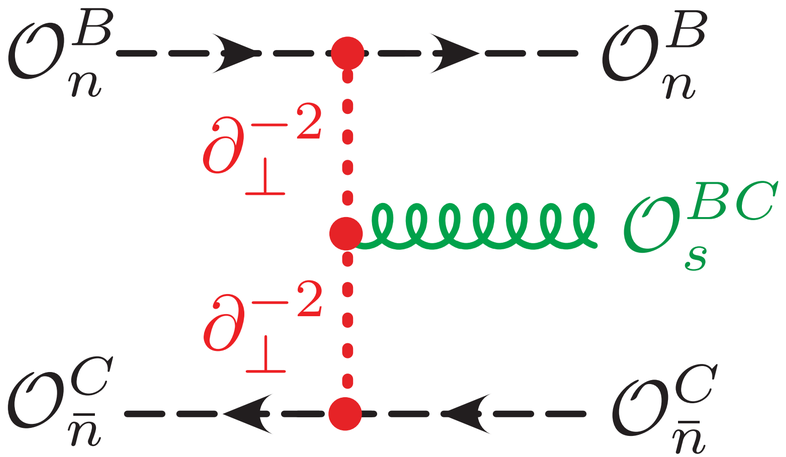
$\mathcal{O}(\lambda^0)$

$=$



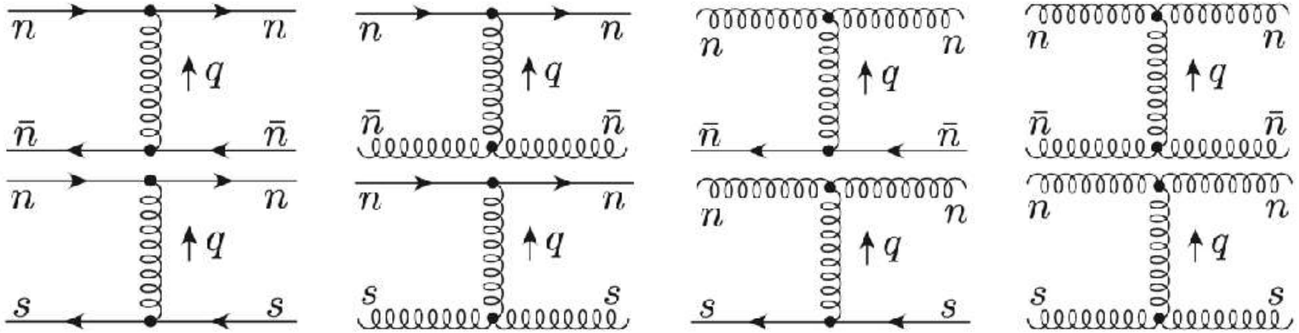
$\mathcal{O}_n^B \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s^B$

$+$



$\mathcal{O}_n^B \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s^{BC} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_n^C$

derived from tree-level matching to QCD diagrams:



$\cdots$

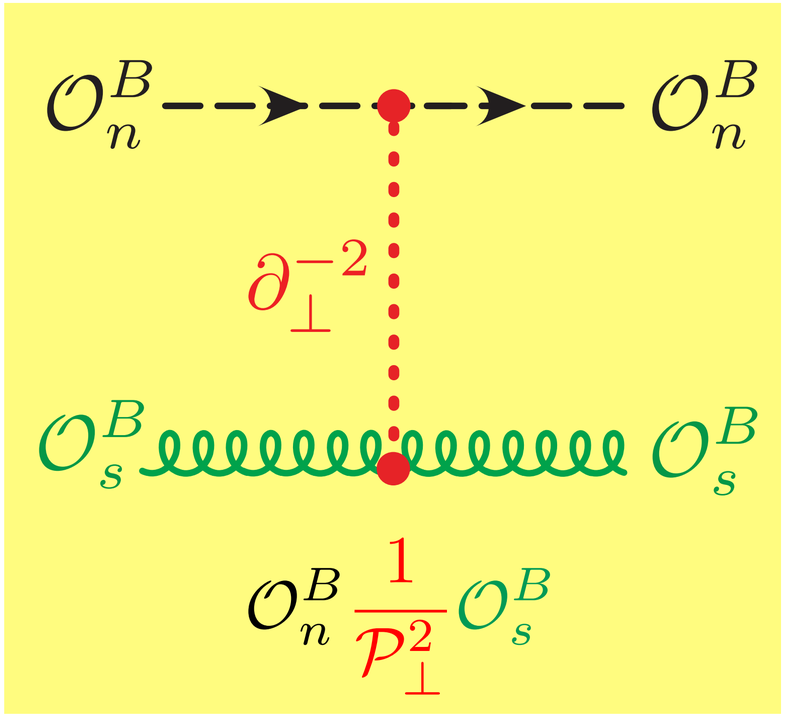
(Rothstein, Stewart, 1601.04695v3)

Glauber gluons

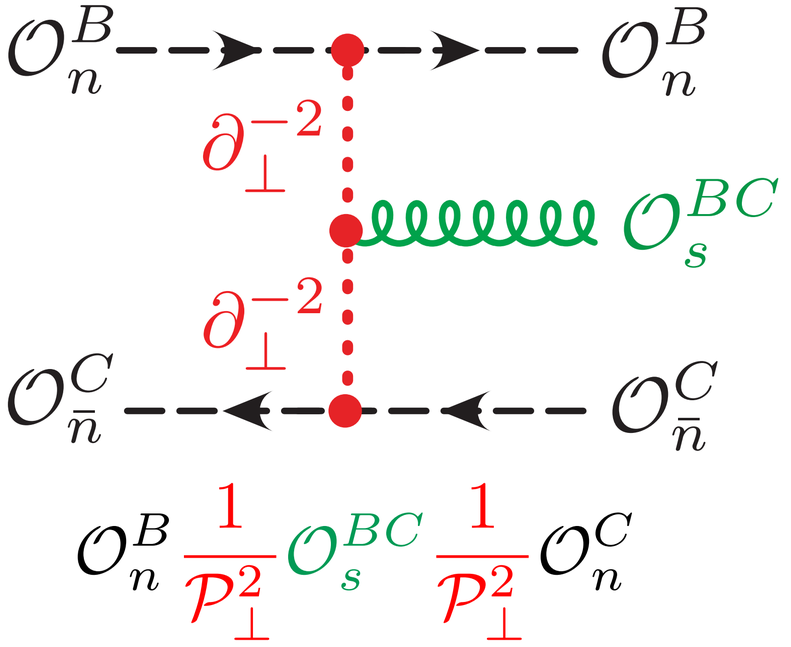
Leading power ‘connections’ between sectors

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

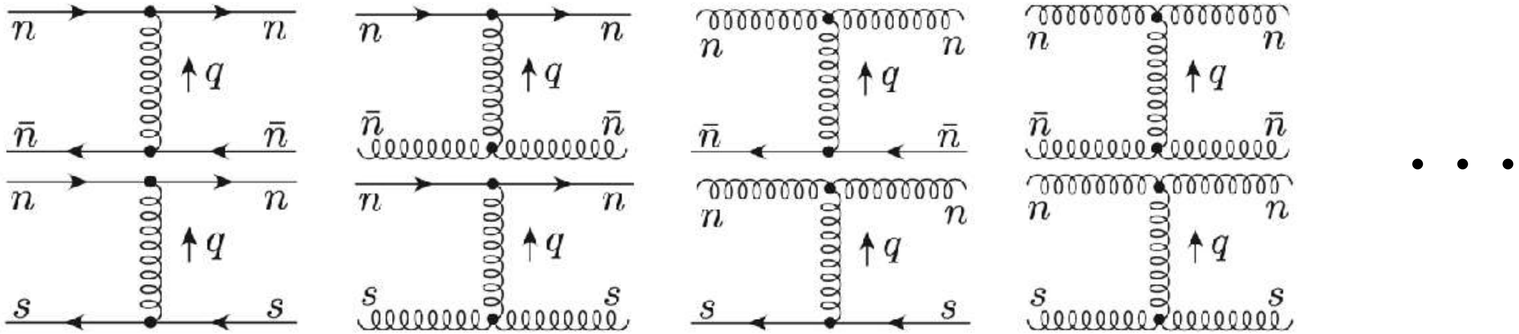
$=$



$+$



derived from tree-level matching to QCD diagrams:

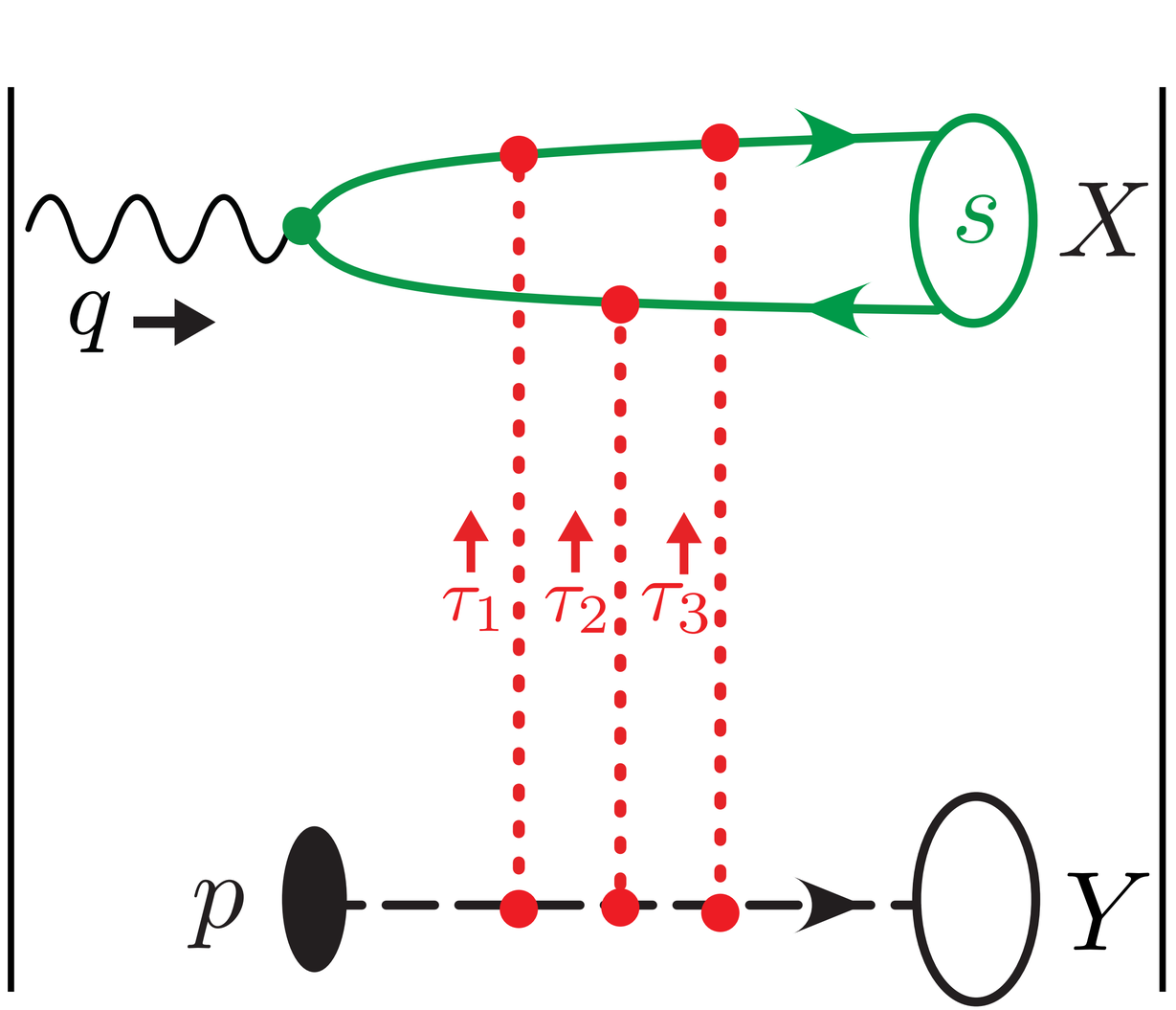


$\cdots$

(Rothstein, Stewart, 1601.04695v3)

Glauber gluons

Rough factorization with only Glauber gluons



$=$

Soft

$$\left|\langle 0|J^\mu \mathcal{O}_s^{B_1}\mathcal{O}_s^{B_2}\mathcal{O}_s^{B_3}|X\rangle\right|^2$$

$\otimes_\perp$

$$\left(\tau_{1\perp}^{-2}\tau_{2\perp}^{-2}\tau_{3\perp}^{-2}\right)^2$$

$\otimes_\perp$

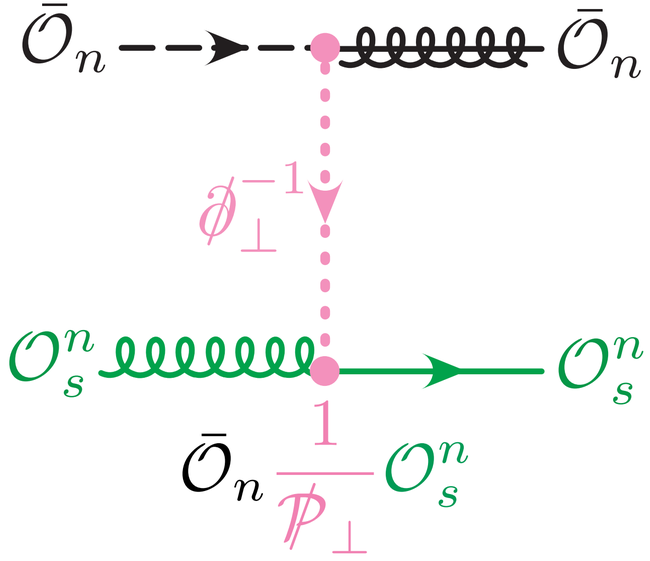
Beam

$$\left|\langle p|\mathcal{O}_n^{A_1}\mathcal{O}_n^{A_2}\mathcal{O}_n^{A_3}|Y\rangle\right|^2$$

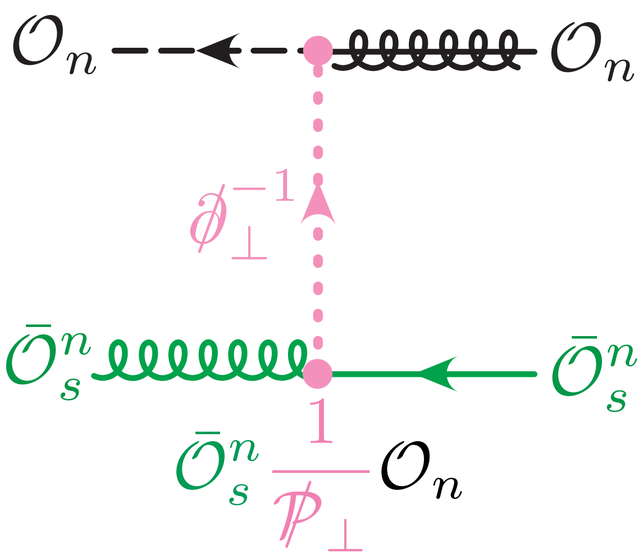
Glauber quarks

Sub-leading power ‘connections’ between sectors

$\mathcal{L}^{(1/2)}_{\text{Glauber}} \supset$



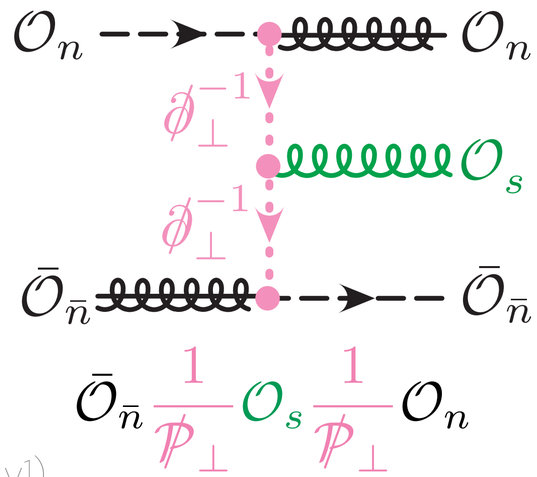
$+$



$+ \quad \bar{n}$ terms

$\mathcal{O}(\lambda^{1/2})$

$\mathcal{L}^{(1)}_{\text{Glauber}} \supset$



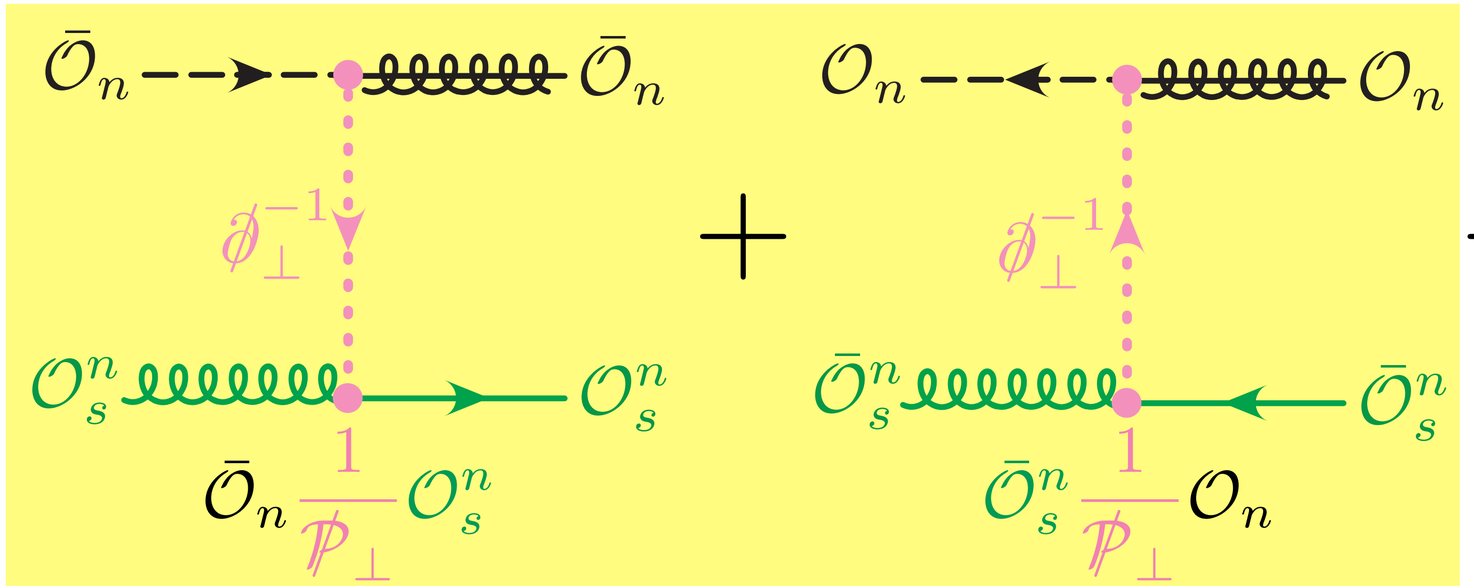
$\mathcal{O}(\lambda^1)$

(Moult, Solon,, Stewart, Vita,, 1709.09174v1)

Glauber quarks

Sub-leading power ‘connections’ between sectors

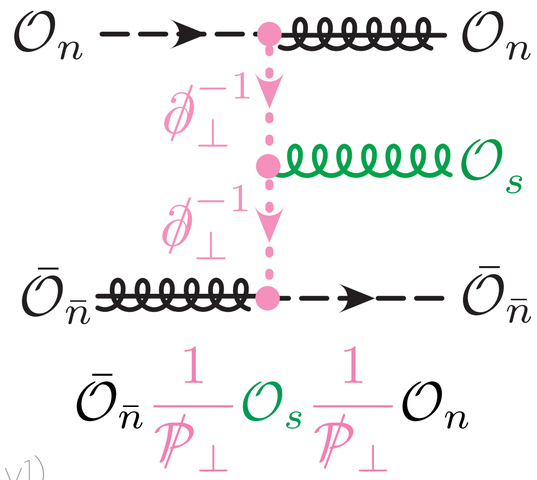
$\mathcal{L}^{(1/2)}_{\text{Glauber}} \supset$



+ $\bar{n}$ terms

$\mathcal{O}(\lambda^{1/2})$

$\mathcal{L}^{(1)}_{\text{Glauber}} \supset$

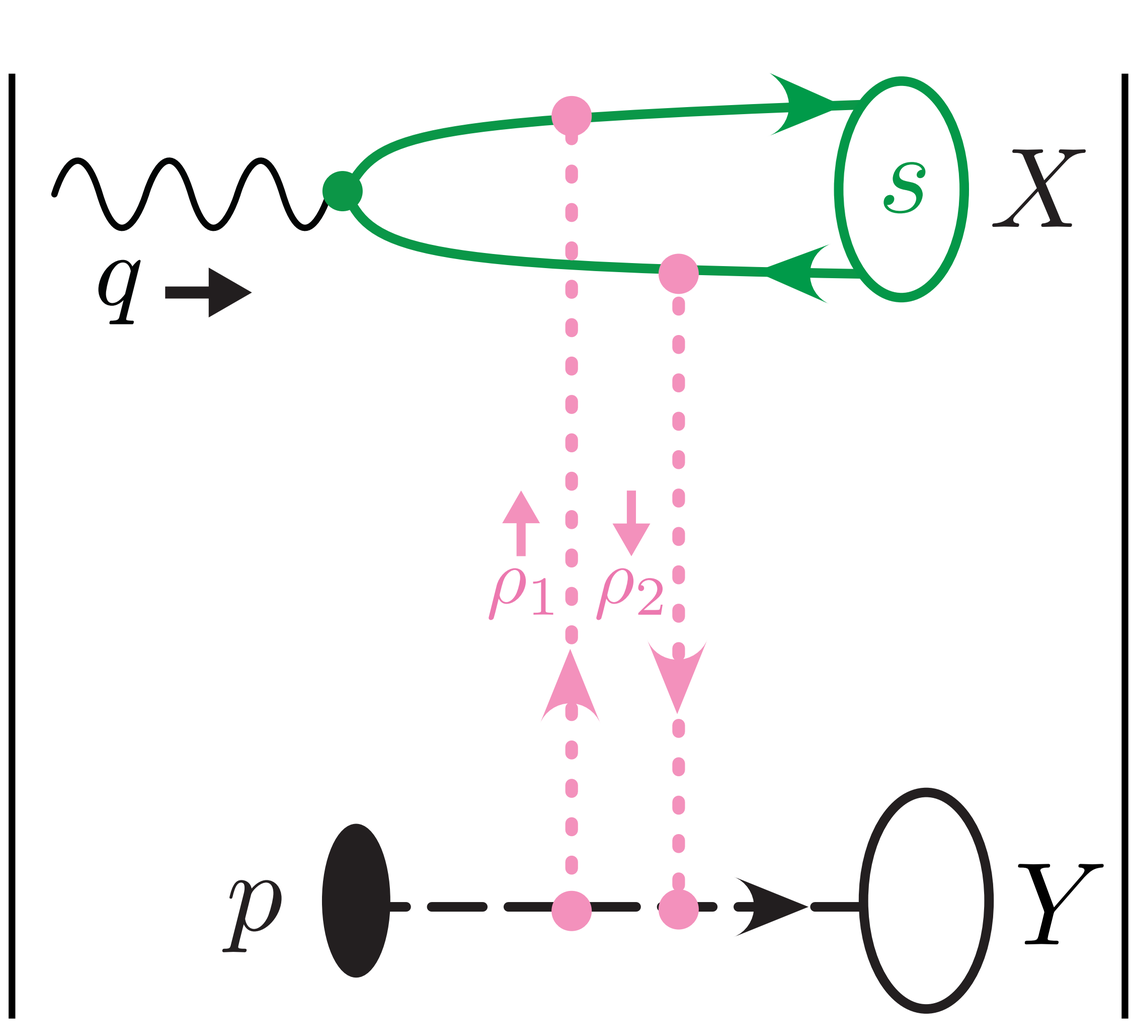


$\mathcal{O}(\lambda^1)$

(Moult, Solon,, Stewart, Vita,, 1709.09174v1)

Glauber quarks

Rough factorization with only Glauber quarks



$=$

Soft

$$\left|\langle 0|J^\mu \mathcal{O}_s^\beta \bar{\mathcal{O}}_s^{\beta'}|X\rangle\right|^2$$

$$\otimes_\perp$$

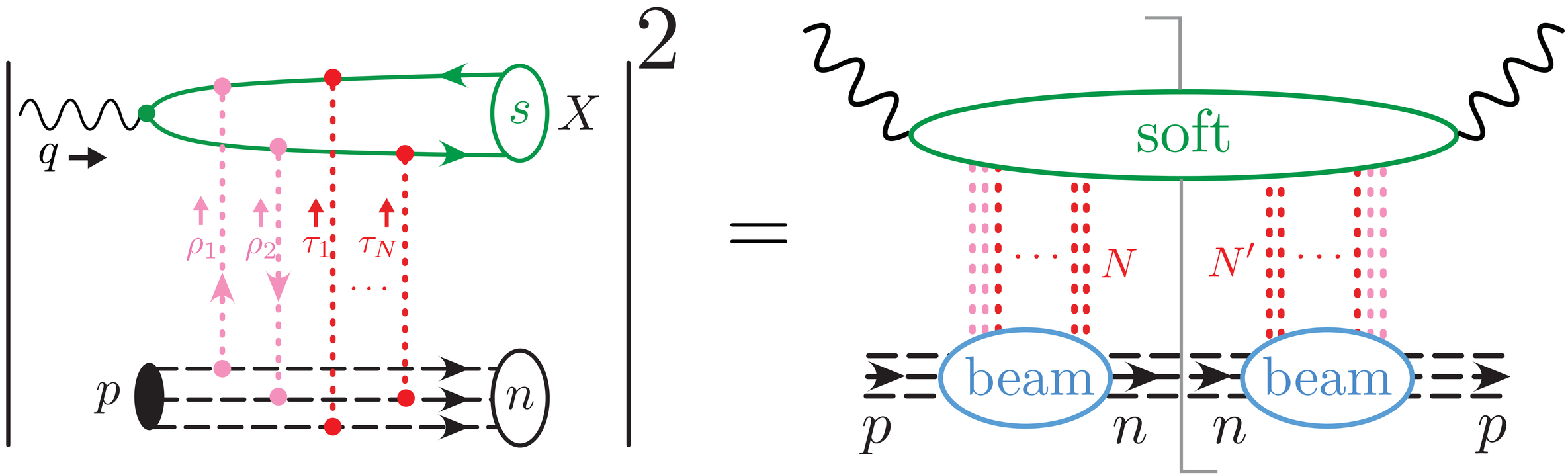
$$\left((\not{p}_{1\perp}^{-1})_{\alpha\beta}(\not{p}_{2\perp}^{-1})_{\alpha'\beta'}\right)^2$$

$$\otimes_\perp$$

Beam

$$\left|\langle p|\bar{\mathcal{O}}_n^\alpha \mathcal{O}_n^{\alpha'}|Y\rangle\right|^2$$

Factorization of the Sullivan process



$$F_i^D = \sum_{N,N'=1}^{\infty} \sum_{R=1} \iint_{(N,N')}^{\perp} \iint^{\perp} B^R_{N,(\alpha\gamma)} B^R_{N',(\alpha'\gamma')} \Big(\dots\Big) S^R_{i,(NN'),(\beta\sigma\beta'\sigma')} \Big(\dots\Big)$$

$$\times \, (\not{p}_{1\perp})_{\alpha\beta} \, (\not{p}_{2\perp})_{\gamma\sigma} \, (\not{p}'_{1\perp})_{\alpha'\beta'} \, (\not{p}'_{2\perp})_{\gamma'\sigma'}$$

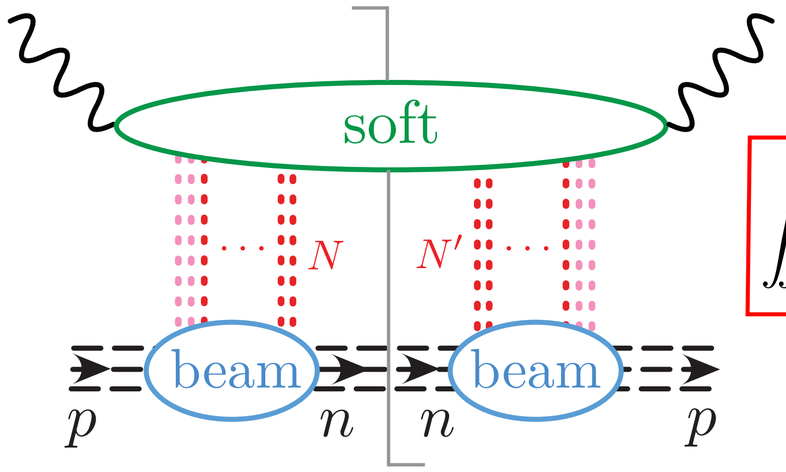
*The neutron is an exclusive particle, so the beam function factorizes at the amplitude level

Factorization of the Sullivan process

$$F_i^D = \left[B_{(\alpha\gamma)} B_{(\alpha'\gamma')} \otimes_\perp S_{(\beta\sigma\beta'\sigma')}\right] \times (\phi_{1\perp})_{\alpha\beta} (\phi_{2\perp})_{\gamma\sigma} (\phi'_{1\perp})_{\alpha'\beta'} (\phi'_{2\perp})_{\gamma'\sigma'}$$

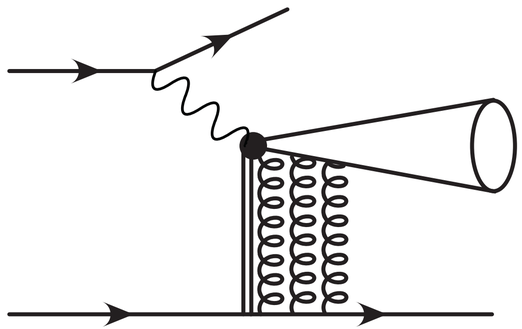
$$B^{R_A^N}_{N,(\alpha,\gamma)} \sim \mathrm{FT}\langle p | \Big\{ \bar{\mathcal{O}}_n^\alpha(v^-\frac{n}{2}, \rho_{1\perp})\, \mathcal{O}_n^\gamma(v^-\frac{n}{2}, \rho_{2\perp}) \prod_{i=1}^{N-1} \mathcal{O}_n^{A_i}(v^-\frac{n}{2}, \tau_{i\perp}) \bar{\mathcal{O}}_n^{A_N}(v^-\frac{n}{2}) \Big\} P_{NR_A} | n \rangle$$

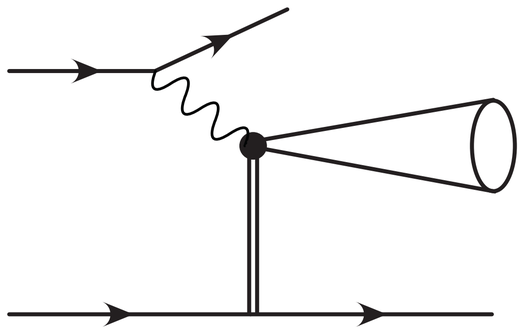
$$S^{R_B^{NN'}}_{i(N,N'),(\beta,\sigma,\beta',\sigma')} = \left(\frac{Q}{n\cdot q}\right)^2 \mathcal{P}'_{i\,\mu\nu} \int [d\tilde{y}]\,[d\tilde{y}']\, đ^d z\; e^{\frac{i}{2}(y^+ - y'^+)k_s^-}\, e^{iz\cdot q}$$
$$\times \sum\!\!\!\!\!\!\int_{X_s} \langle 0 | \bar{T}\, J_s^\mu(z) \Big\{ \mathcal{O}_s^\beta(\tilde{y}, -\rho_{1\perp})\, \bar{\mathcal{O}}_s^\sigma(\tilde{y}, -\rho_{2\perp}) \prod_{i=1}^{N} \mathcal{O}_s^{B_i}(\tilde{y}, -\tau_{i\perp}) \Big\} P_{NR_B} | X_s \rangle$$
$$\times \langle X_s | P_{N'R_{B'}} T\, J_s^\nu(0) \Big\{ \mathcal{O}_s^{\beta'}(\tilde{y}', -\rho'_{1\perp})\, \bar{\mathcal{O}}_s^{\sigma'}(\tilde{y}', -\rho'_{2\perp}) \prod_{j=1}^{N'} \mathcal{O}_s^{B'_j}(\tilde{y}', -\tau'_{j\perp}) \Big\} | 0 \rangle \delta^{D_1}_{D_2} \delta^{D'_1}_{D'_2}.$$

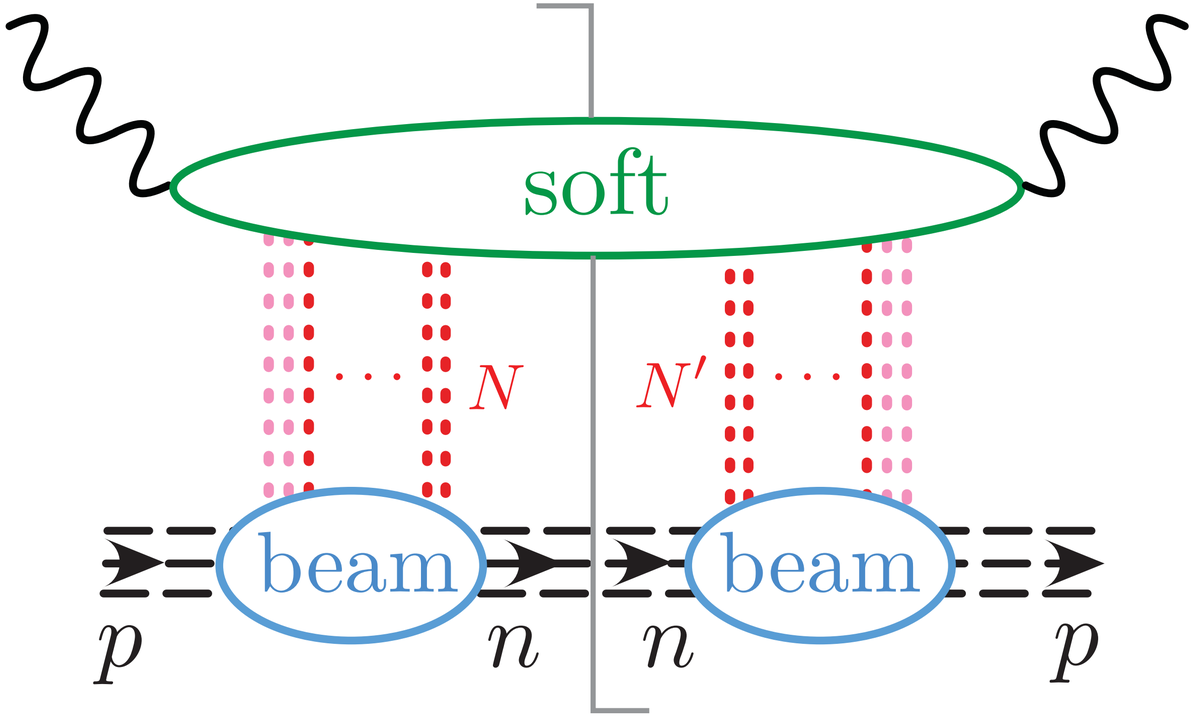


$$\iint^\perp_{(N,\,N')} \equiv \frac{(-\mathrm{i})^N (+\mathrm{i})^{N'}}{N!N'!} \int \frac{đ^{d'}\rho_{1\perp}}{\rho_{1\perp}^2} \frac{đ^{d'}\rho_{2\perp}}{\rho_{2\perp}^2} \prod_{i=1}^{N} \frac{đ^{d'}\tau_{i\perp}}{\tau_{i\perp}^2}\, \bar{\delta}^{d'}\left(\rho_{1\perp} + \rho_{2\perp} + \sum_i \tau_{i\perp} + \tau_\perp\right)$$
$$\times \int \frac{đ^{d'}\rho'_{1\perp}}{\rho'^2_{1\perp}} \frac{đ^{d'}\rho'_{2\perp}}{\rho'^2_{2\perp}} \prod_{j=1}^{N'} \frac{đ^{d'}\tau'_{j\perp}}{\tau'^2_{j\perp}}\, \bar{\delta}^{d'}\left(\rho_{1\perp} + \rho_{2\perp} + \sum_i \tau_{i\perp} - \tau_\perp\right)$$

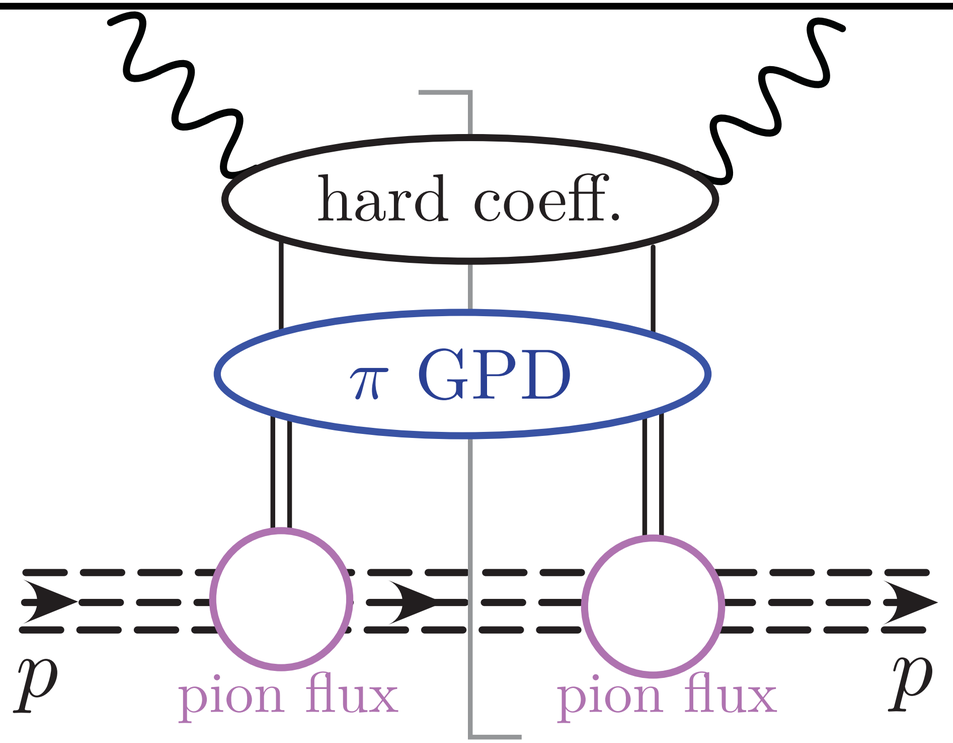
Glauber vs. pion exchange







$$F_i^D \sim [B^2 \otimes_\perp S] \ldots$$

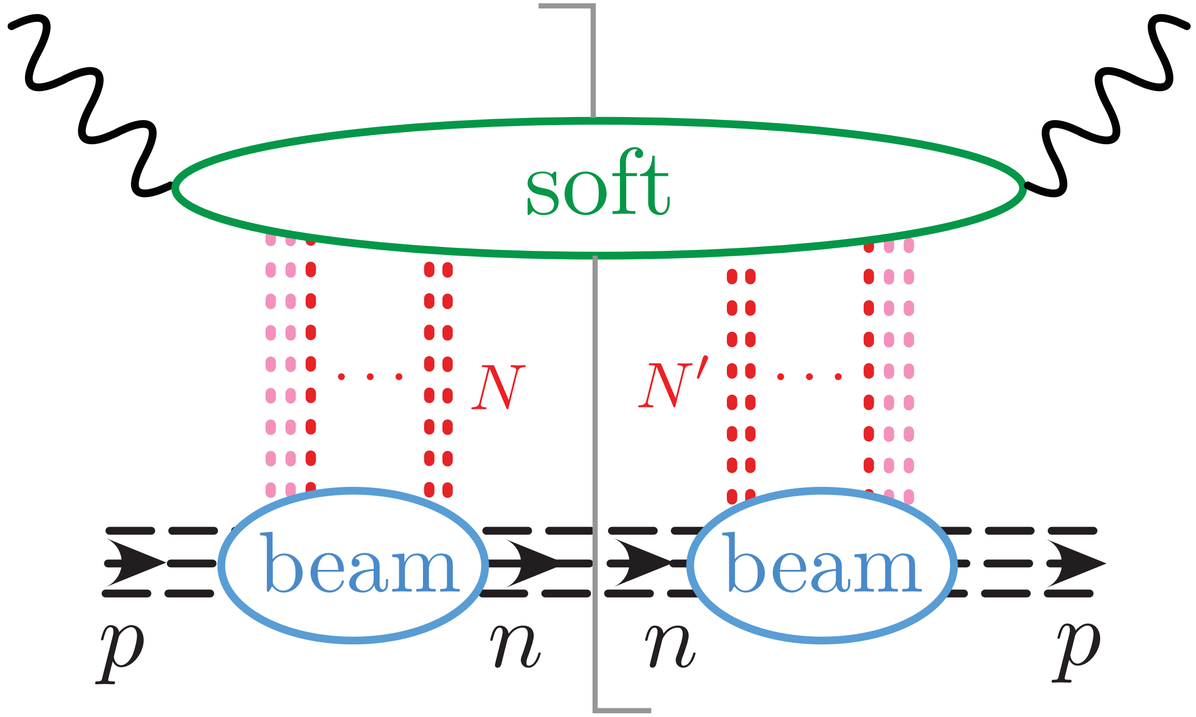


$$F_i \sim (f^2_{\pi/p}) \otimes [H \otimes f_{i/\pi}]$$

(H1 Collaboration, 1001.0532v1)

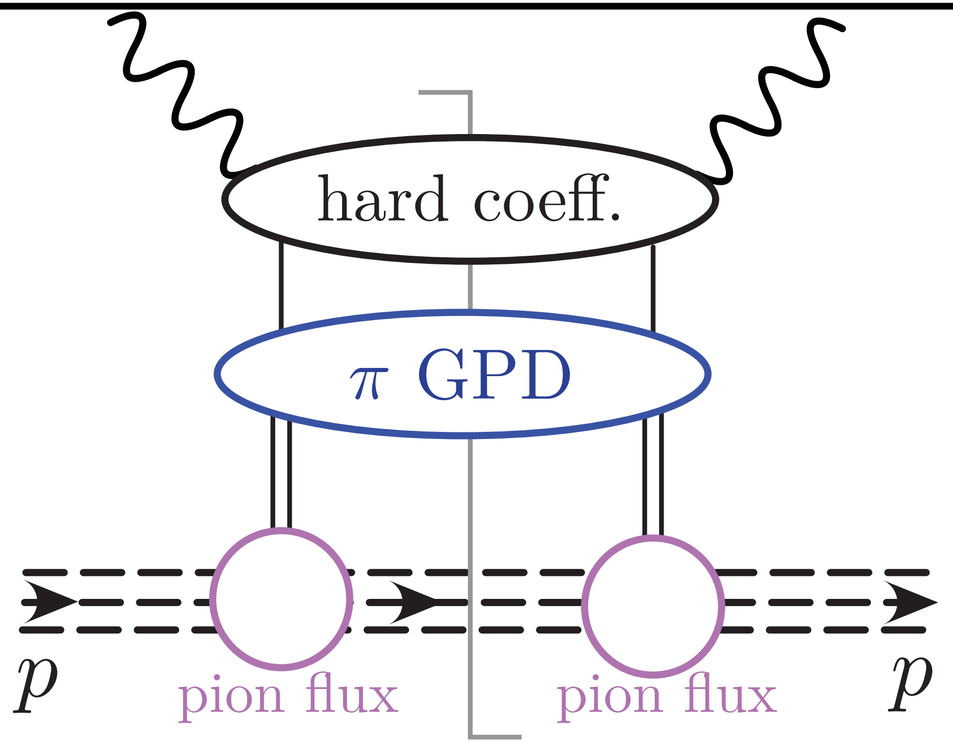
Glauber vs. pion exchange

- Offshell intermediate particle
- Subleading power in λ
- Beam: not a PDF, GPD, or form factor



$$F_i^D \sim [B^2 \otimes_\perp S] \ldots$$

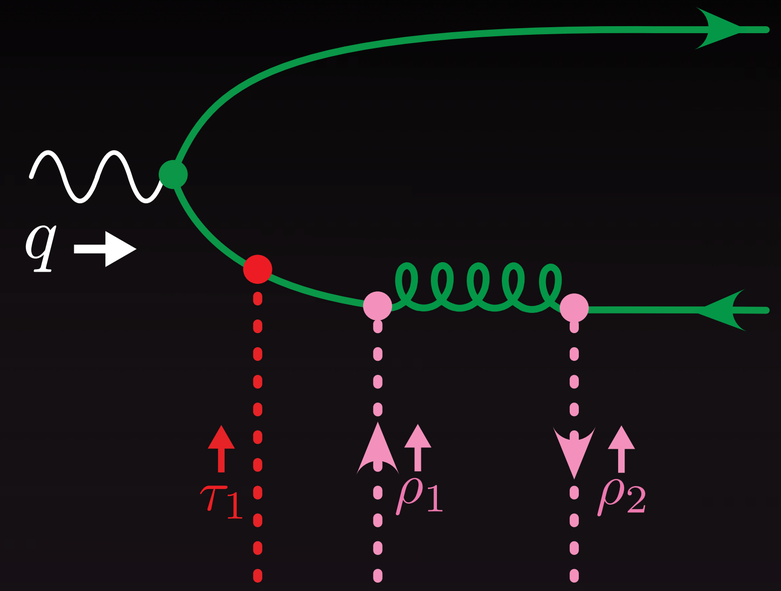
- Assumed pion propagator
- Pion contribution to structure function = hard + GPD



$$F_i \sim (f^2_{\pi/p}) \otimes [H \otimes f_{i/\pi}]$$

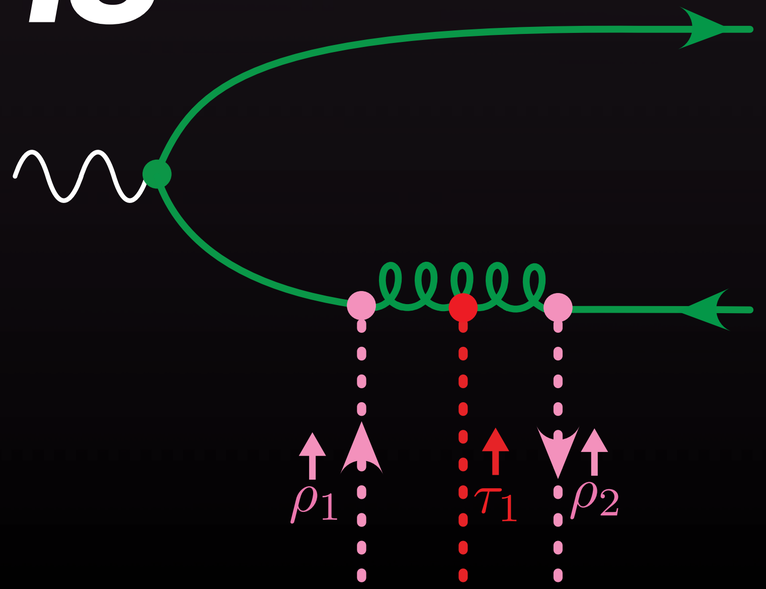
PART I. *What Sullivan process is(n't)*

PART II. *EFT for diffraction*



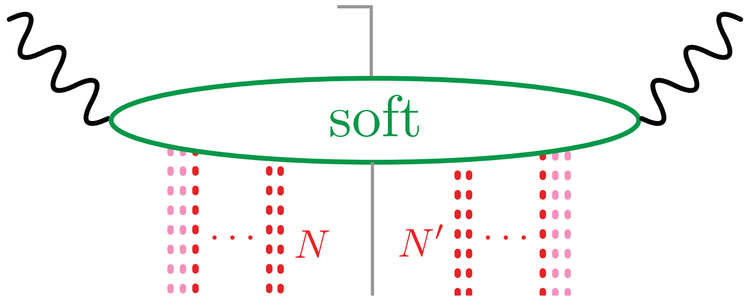
PART III. *Towards predictions*

PART IV. *What's next?*

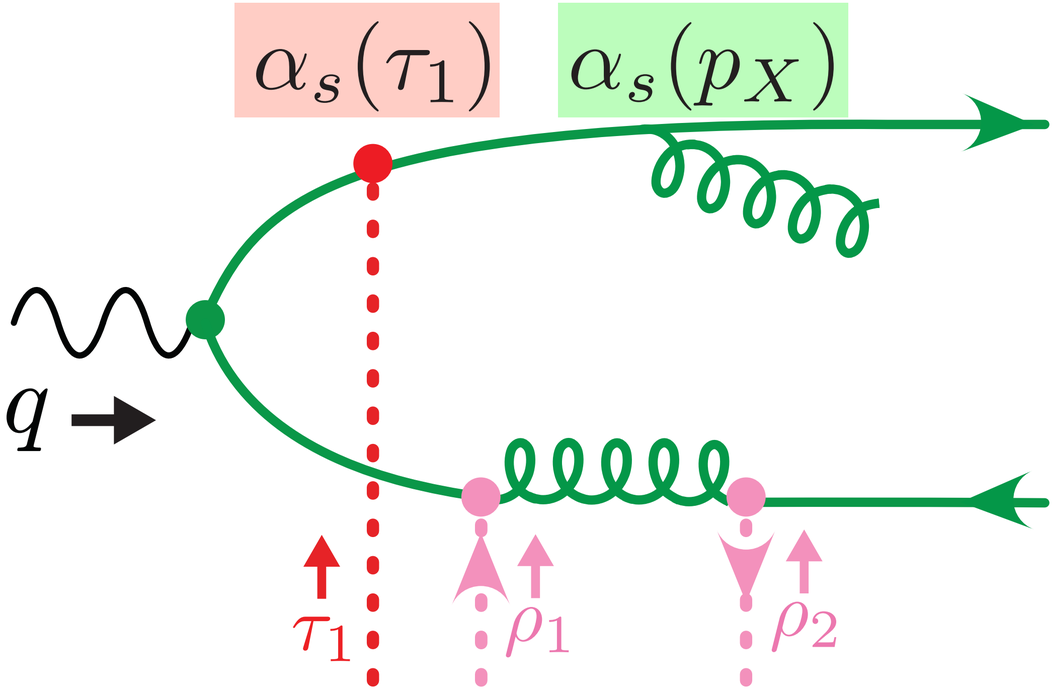


Calculating LO Soft

$$-\sum_i \tau_i^2 = -t \gg \Lambda_{\rm QCD}$$



$S_{(\beta\sigma\beta'\sigma')}$ can be perturbatively calculated



Types of strong couplings

soft:	perturbative:	$\alpha_s(p_X) \ll 1$
Glauber:	perturbative:	$\alpha_s(\tau_1 \gg \Lambda_{\rm QCD}) \ll 1$
	non-perturbative:	$\alpha_s(\tau_1 \sim \Lambda_{\rm QCD}) \sim 1$

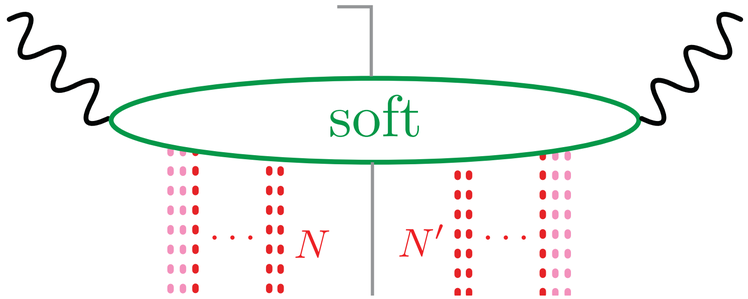
$\Rightarrow$ *LO: no soft couplings*

Calculating LO Soft

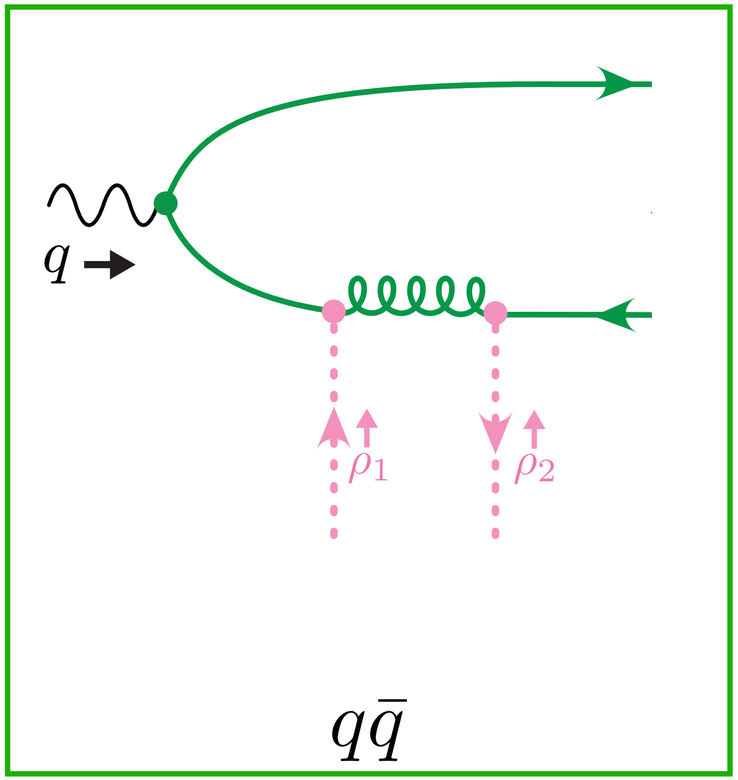
$$-\sum_i \tau_i^2 = -t \gg \Lambda_{\rm QCD}$$

perturbative: $\tau_i \gg \Lambda_{\rm QCD}$

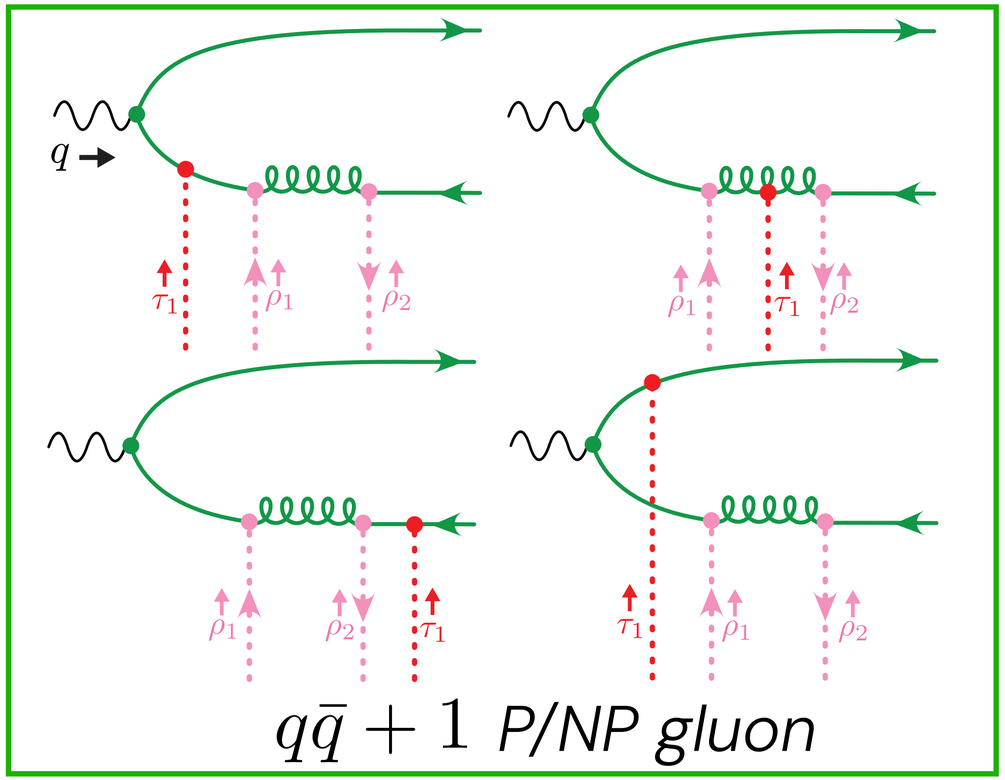
non-perturbative: $\tau_i \sim \Lambda_{\rm QCD}$



$S_{(\beta\sigma\beta'\sigma')}$ can be perturbatively calculated:



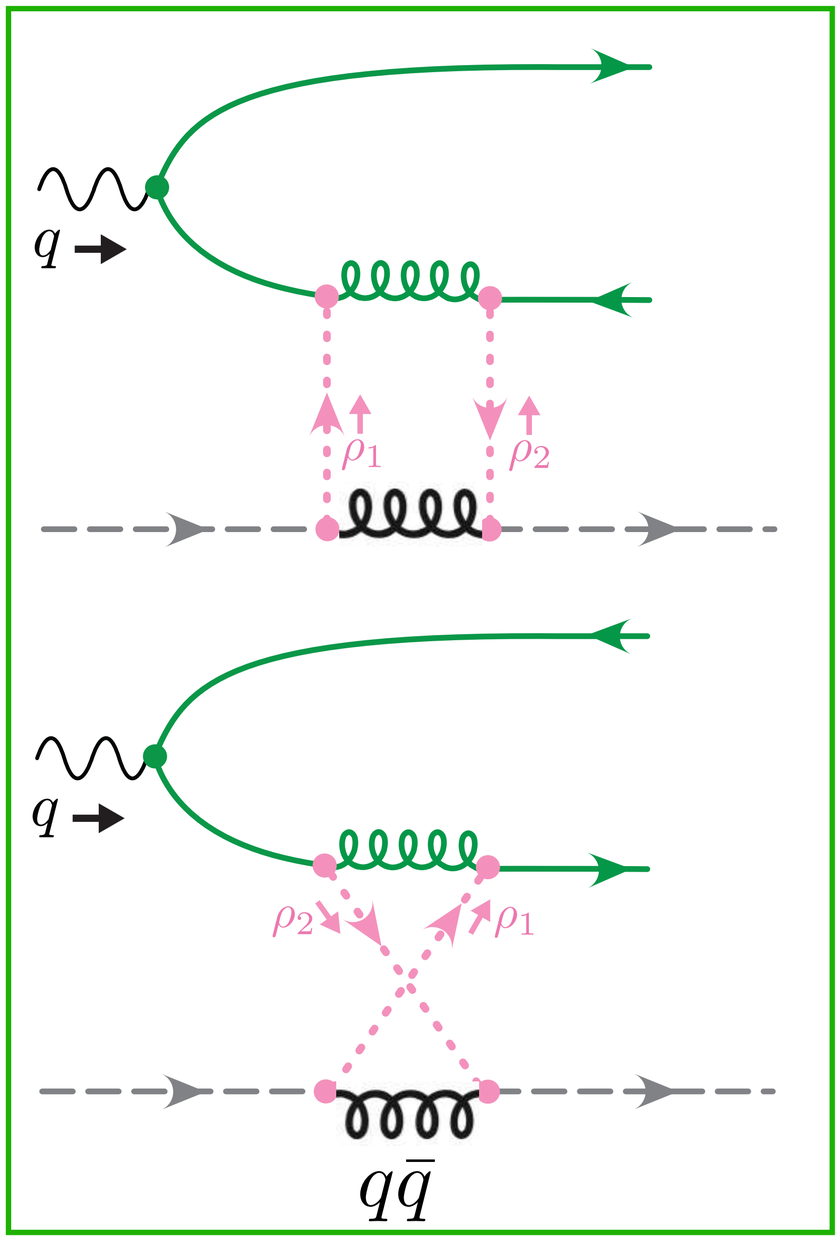
$q\bar{q}$



$q\bar{q} + 1$ *P/NP gluon*

. . .

Calculating LO Soft

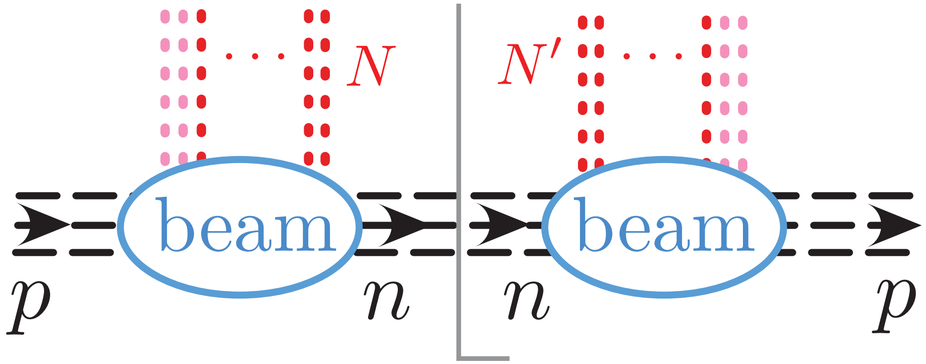


$$A^{(q\bar{q})}_{(0,0)} \sim \left[\frac{1}{4k_2^+ p^-} (T^C)\gamma_{\perp\alpha}\, v(-k_2)\bar{u}(k_1)\, \gamma^\mu \frac{1}{\not{k}_2 - \not{\tau}} (T^C)\gamma_\perp^\alpha \right]_{uv}$$
$$\times \int d^{d-2}\rho'_{1\perp} \left(\frac{1}{\not{\tau}_\perp + \not{\rho}'_{1\perp}} \right)_{vt} \left[\gamma_\perp^\nu T^A u_n(p) \right]_t \left[\bar{u}_n(p-\tau)\gamma_{\perp\nu} T^A \right]_s \left(\frac{1}{\not{\rho}'_{1\perp}} \right)_{su}$$

More to discuss:

- 1 P, 1 NP quarks and 1 NP gluon?
- 2 NP quarks and 1 P gluon?
- recursive relations for $q\bar{q} + \infty$ non-perturbative gluons?

Calculating Beam?



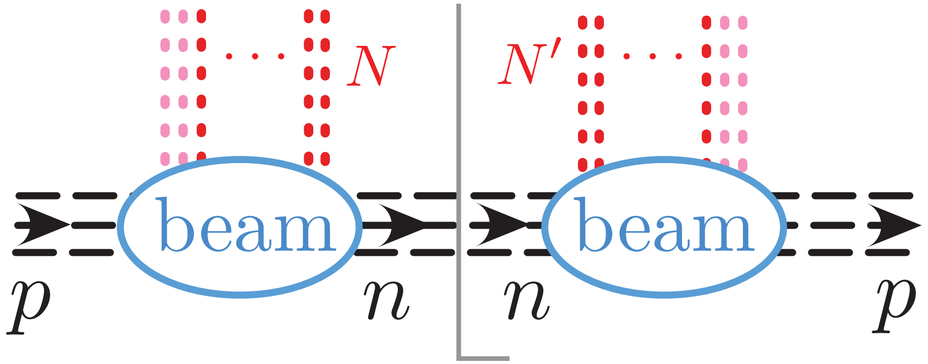
- cannot perturbatively calculate $\longrightarrow$ *NP effects in protons*
- cannot use lattice calculations
- cannot extract from experiment

$\longrightarrow$ *difficult to deal with Glaubers connecting the soft and collinear modes*

- cannot take ratios

$\longrightarrow$ *have non-trivial convolution (at least two quarks present = at least one integral over the momenta)*

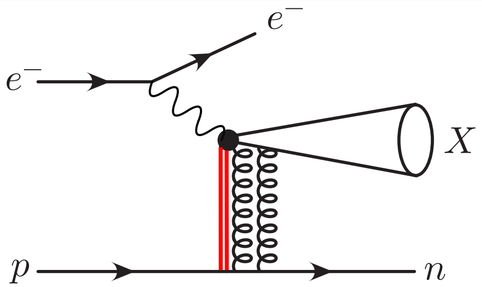
What can we predict?



- can estimate structure function sizes (their scaling with λ):

$F_i^D(ep \to eXn) \sim \lambda^{-5}$

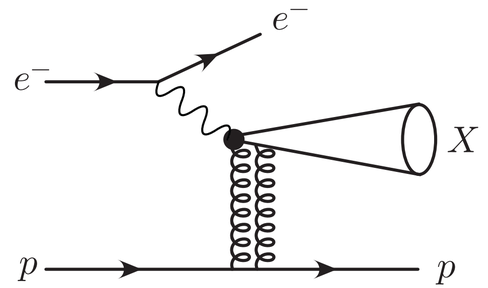
$\mathcal{L}_{\text{Glauber } q} \sim \lambda^{1/2}$



more suppressed!

$F_i^D(ep \to eXp) \sim \lambda^{-6}$

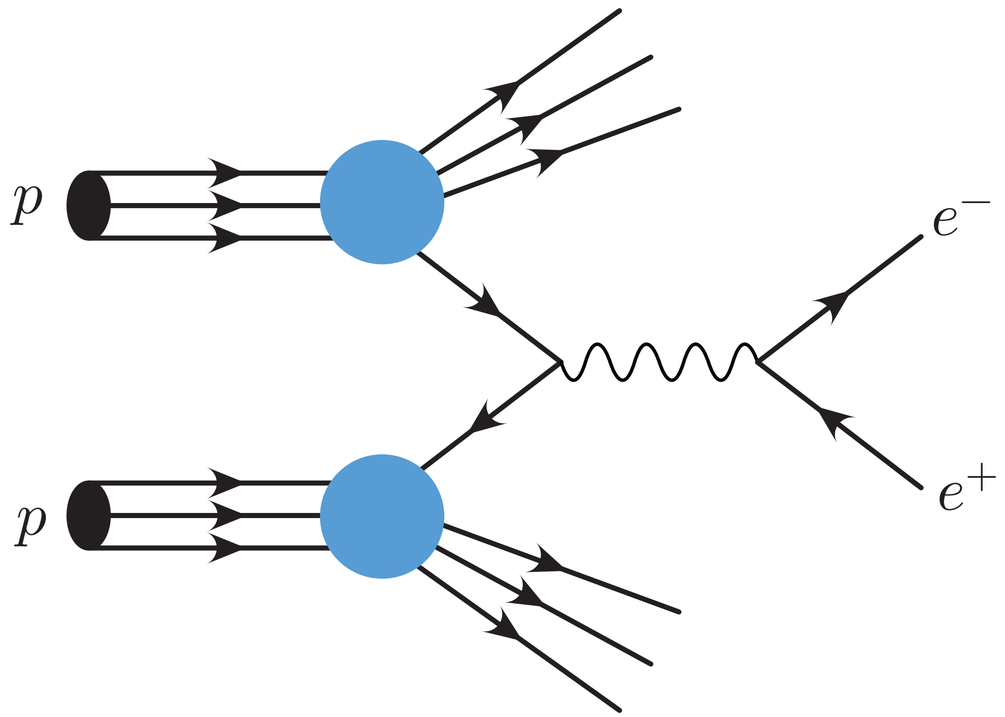
$\mathcal{L}_{\text{Glauber } g} \sim \lambda^{0}$



- can do positivity/consistency checks for structure-functions
- can model beam function to approximate the cross sections

↳ *what model to use? Not PDF, GPD...*

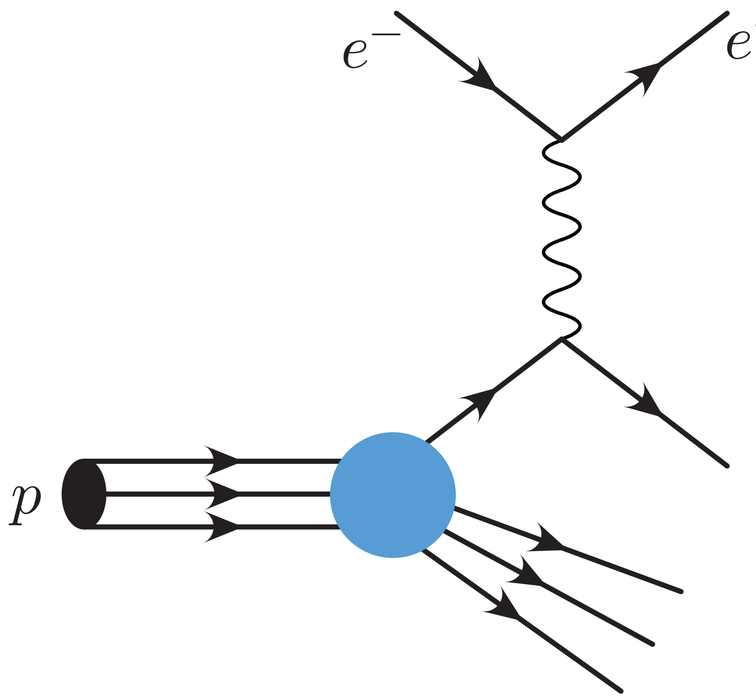
Universality



$$d\sigma_{\rm DY} \sim H \otimes B_n \otimes B_{\bar{n}} \otimes S$$

$$d\sigma_{\rm DY} \sim H \otimes f^{\rm TMD}_{q/p_1} \otimes f^{\rm TMD}_{\bar{q}/p_2}$$

Drell-Yan



$$d\sigma_{\rm SIDIS} \sim H \otimes B_n \otimes J^{\rm frag}_{\bar{n}} \otimes S$$

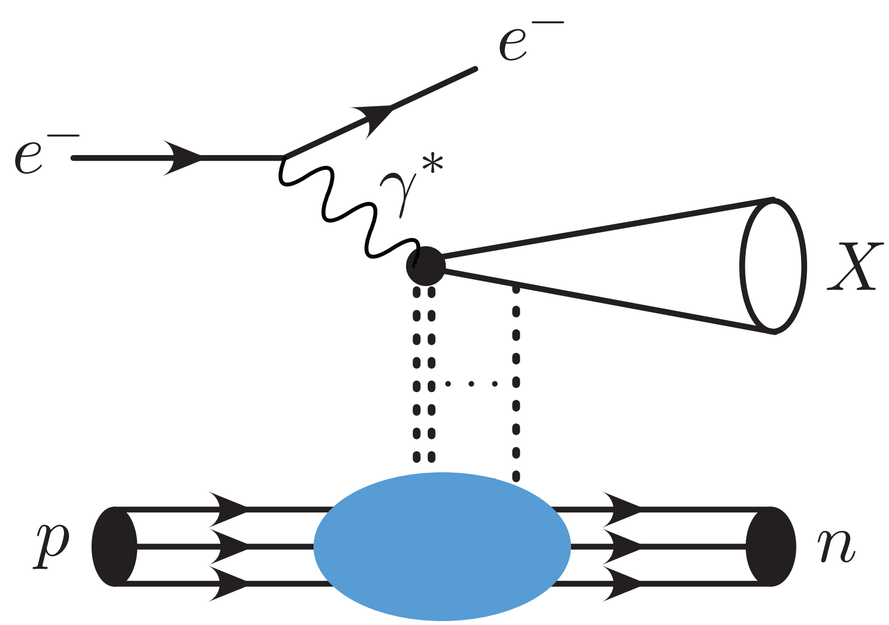
$$d\sigma_{\rm SIDIS} \sim H \otimes f^{\rm TMD}_{q/p_1} \otimes d^{\rm TMDFF}$$

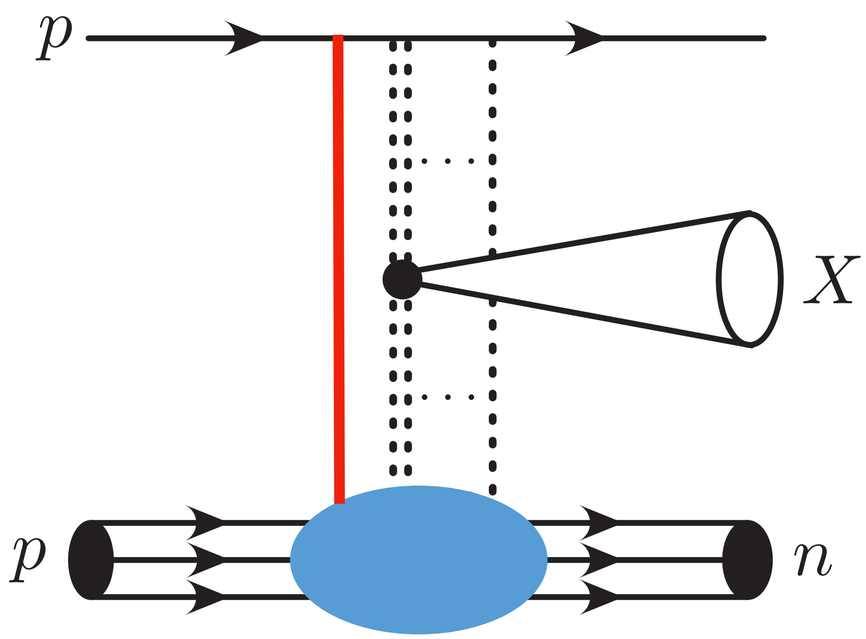
Semi-Inclusive Deep Inelastic Scattering

…have universal TMD/PDF

Universality

Is Sullivan universal to anything?



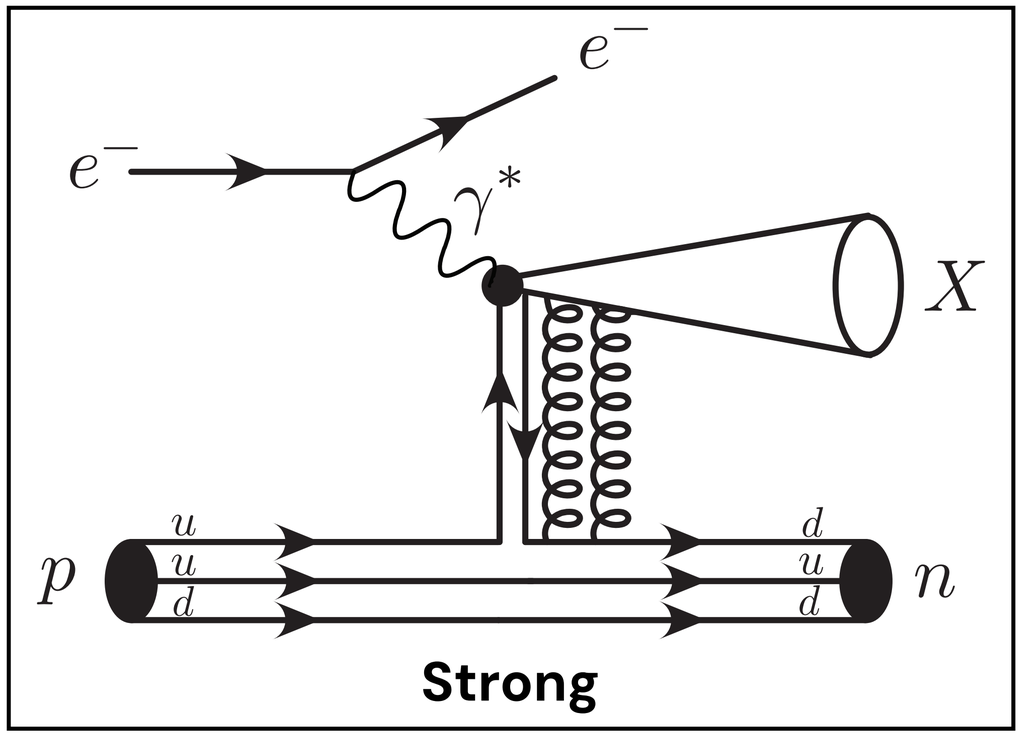


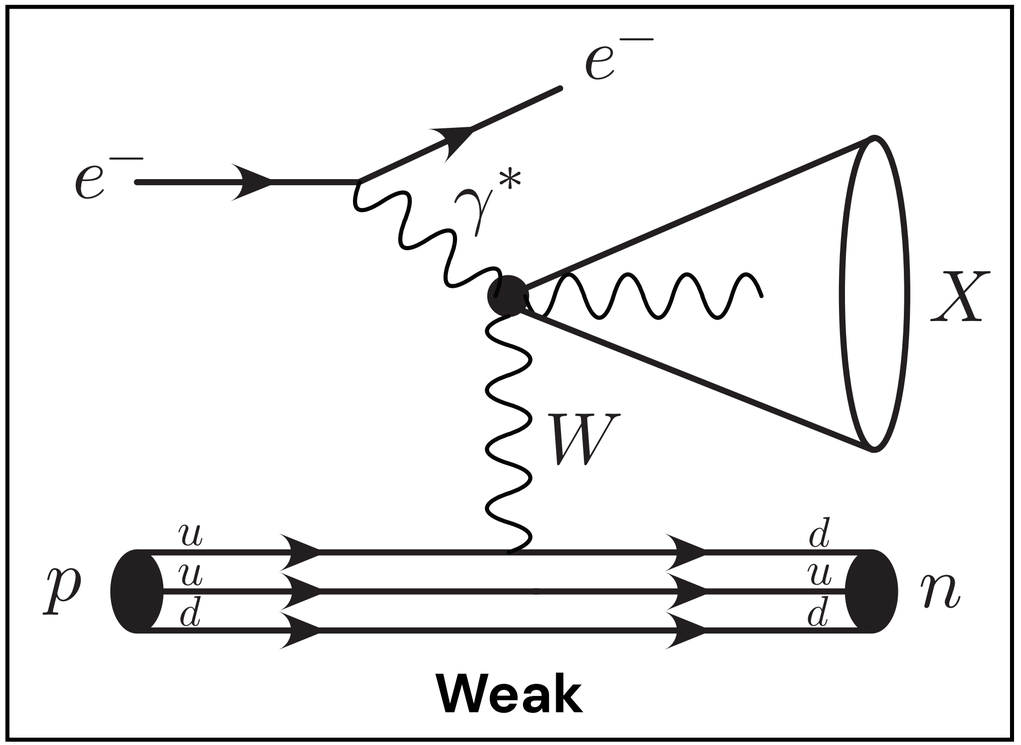
$$d\sigma(ep \to eXn) \sim L \otimes (B_{p\to n} \otimes S)$$

$$d\sigma(pp \to pXn) \sim B_{p\to p} \otimes (B_{p\to n} \otimes S)$$

Very suggestive that beam and/or its evolution is **universal between EIC/RHIC**.
However there may be technical complications (from color factors).

Electroweak background





Glauber quark is suppressed by $\sqrt{\frac{-t}{s}}$

$$\sqrt{\frac{-t}{s}} \sim 10^{-3} - 10^{-2}$$

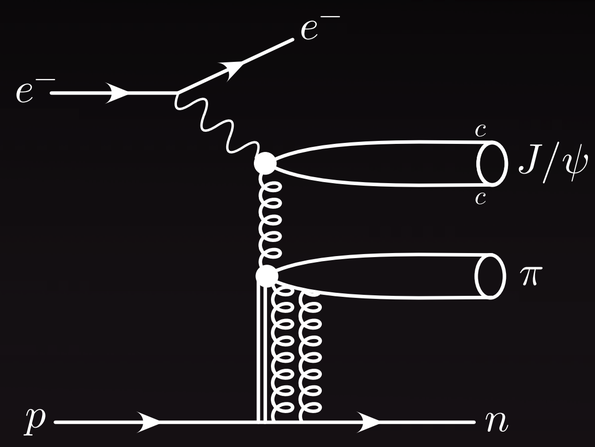
$p \to Wn$ transition is suppressed by G_F

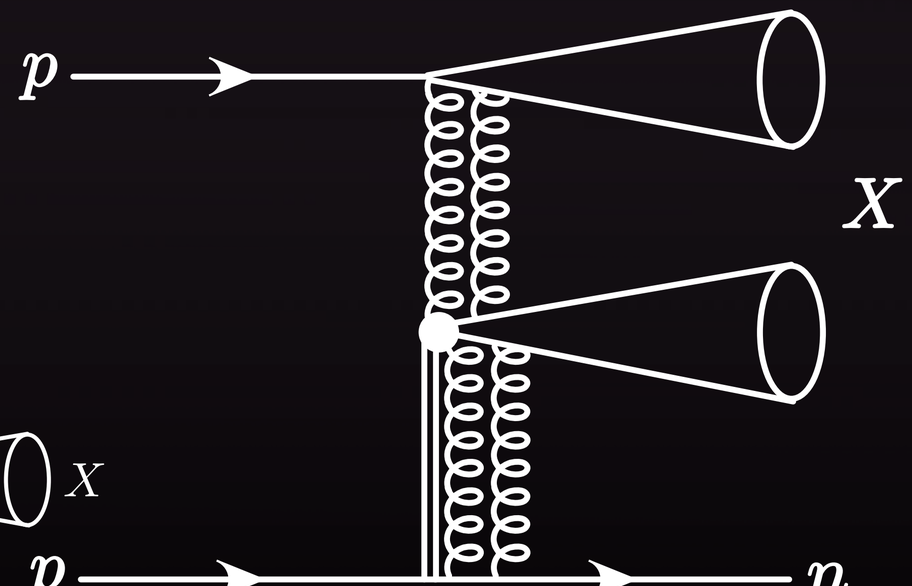
$$G_F|t| \sim 10^{-5} - 10^{-4}$$

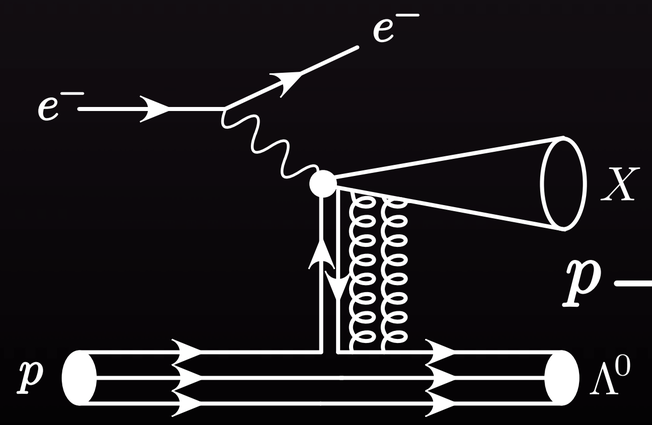
At EIC energies (28-140 GeV) strong dominates

PART I. *What Sullivan process is(n't)*
PART II. *EFT for diffraction*
PART III. *Towards predictions*

PART IV.
What's next?

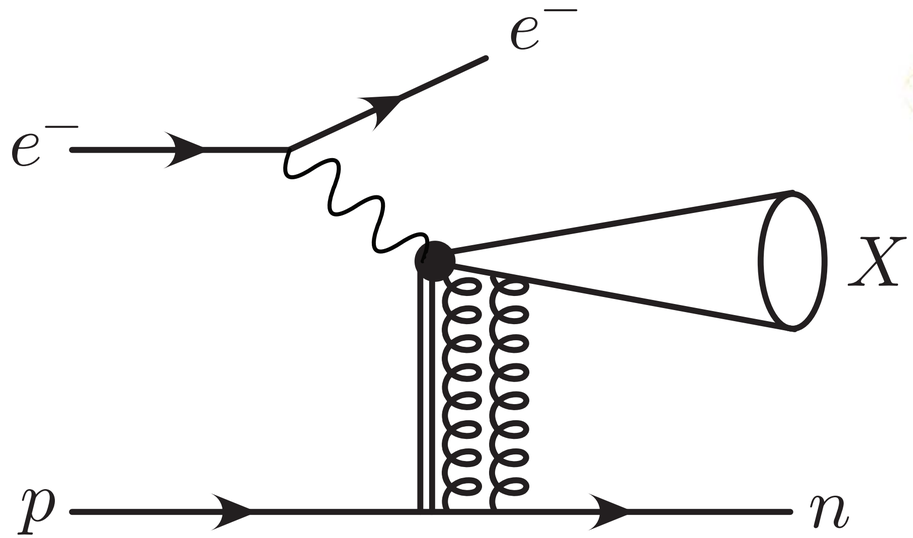


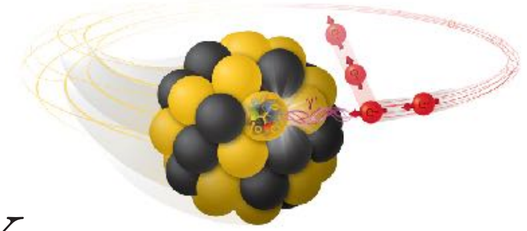




Natural extensions

- Now: $ep \to eXn$

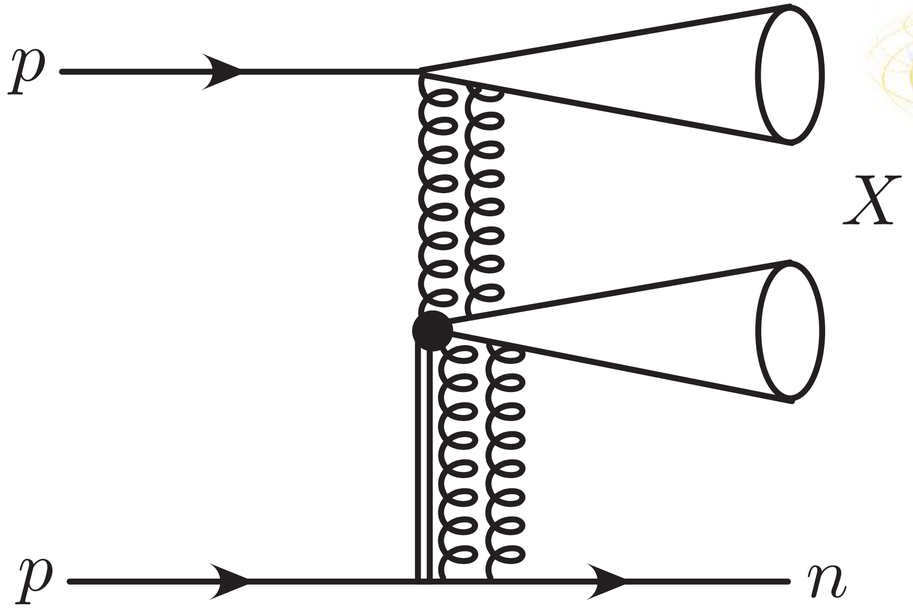


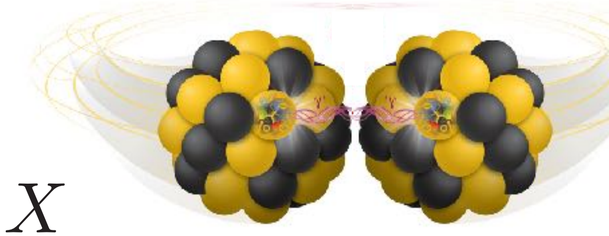


- Future: $pp \to pXn$

(RHIC already has relevant data)

with Chris Lee, Ming Xiong Liu @ LANL



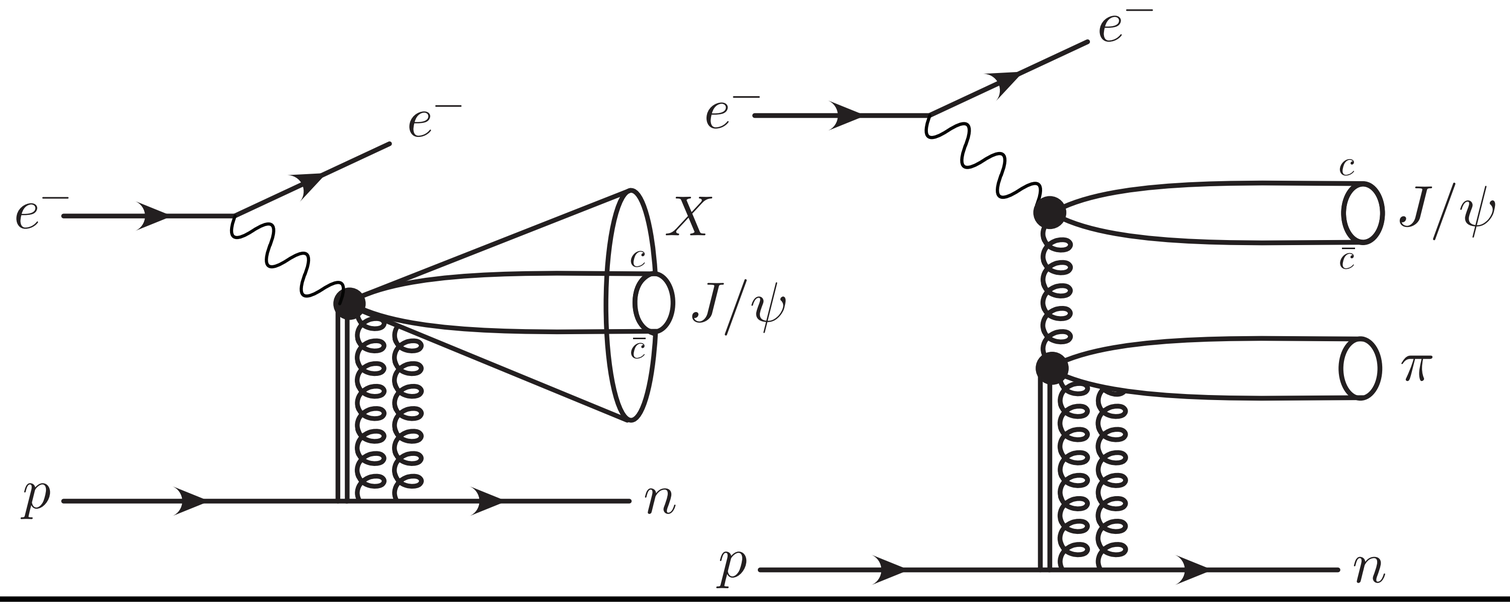


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Possible extensions

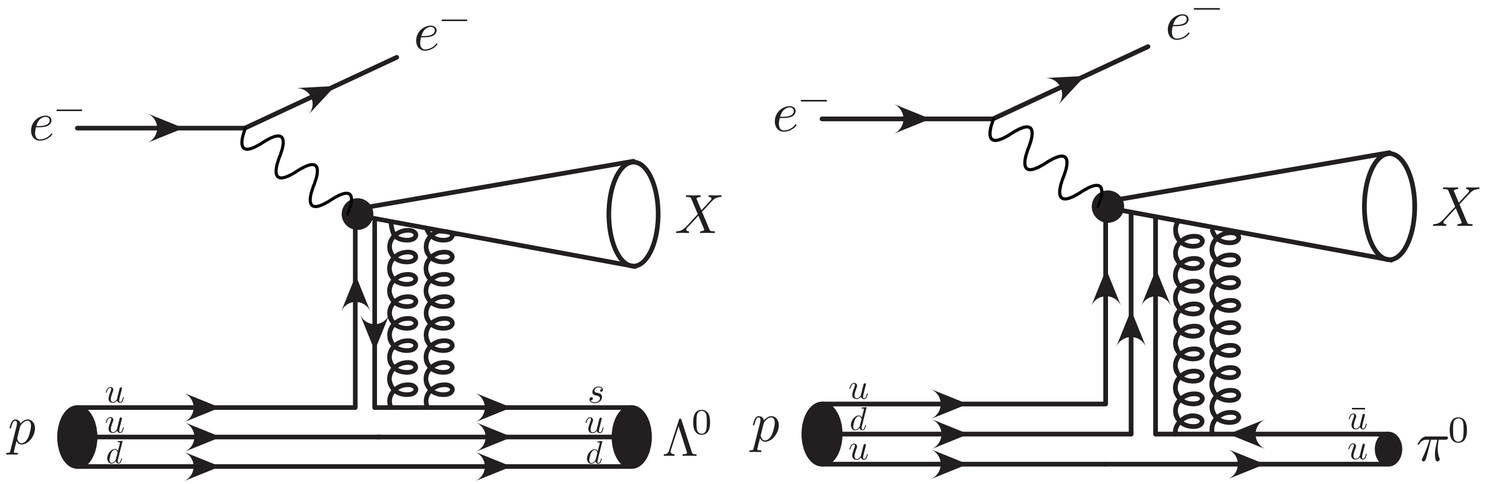
- Tagged J/ψ:
both pp and ep,
semi-inclusive/fully exclusive

people plan to measure it



- $ep \to eX\Lambda^0$:
other forward particles?
- $ep \to eX\pi$:
more suppressed?

with Chris Lee, Ming Xiong Liu @ LANL



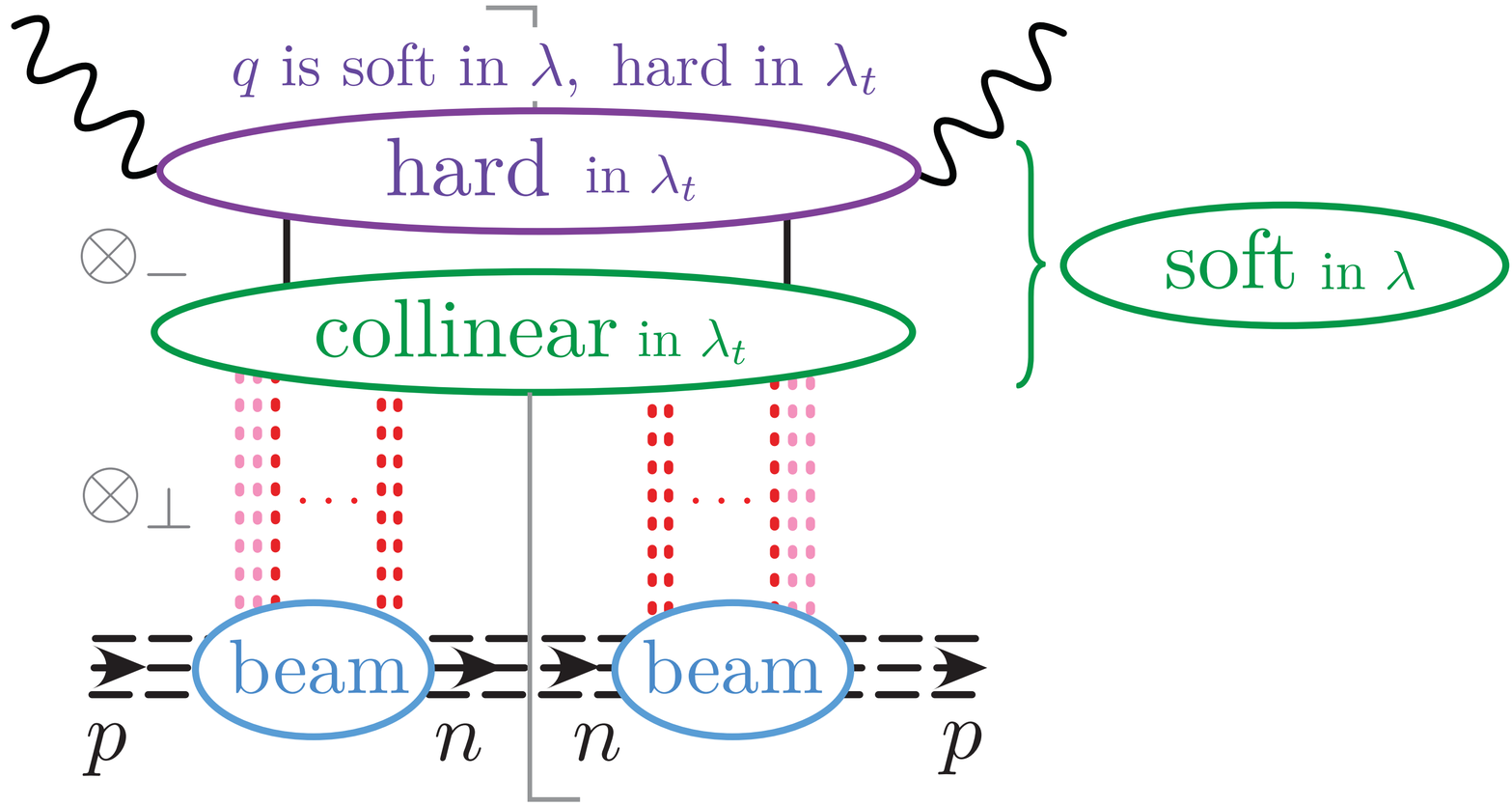
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Nearest future

- Soft function analysis
- $\lambda_t \equiv \dfrac{\sqrt{-t}}{Q} \ll 1$ refactorization
- Spin dependence
- Flavor-crossed channels and excited forward baryons

$$S \to H \otimes_- S_c$$

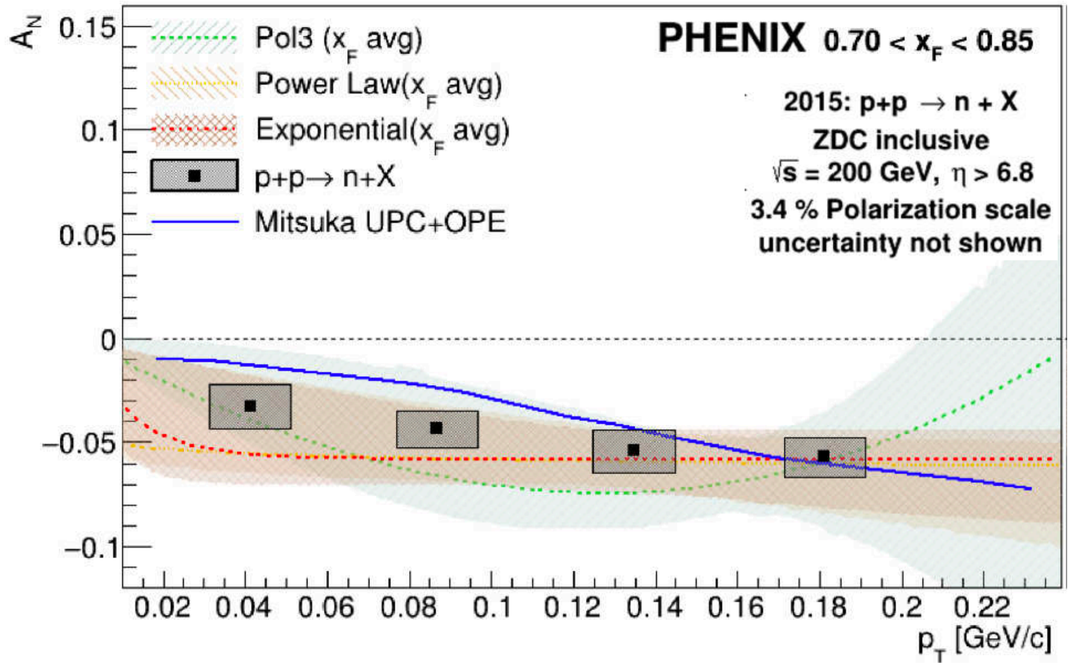
soft-collinear: soft in λ
collinear in λ_t



Nearest future

- Soft function analysis
- $\lambda_t \equiv \dfrac{\sqrt{-t}}{Q} \ll 1$ refactorization
- Spin dependence
- Flavor-crossed channels and excited forward baryons

Can explain the observed spin asymmetry:



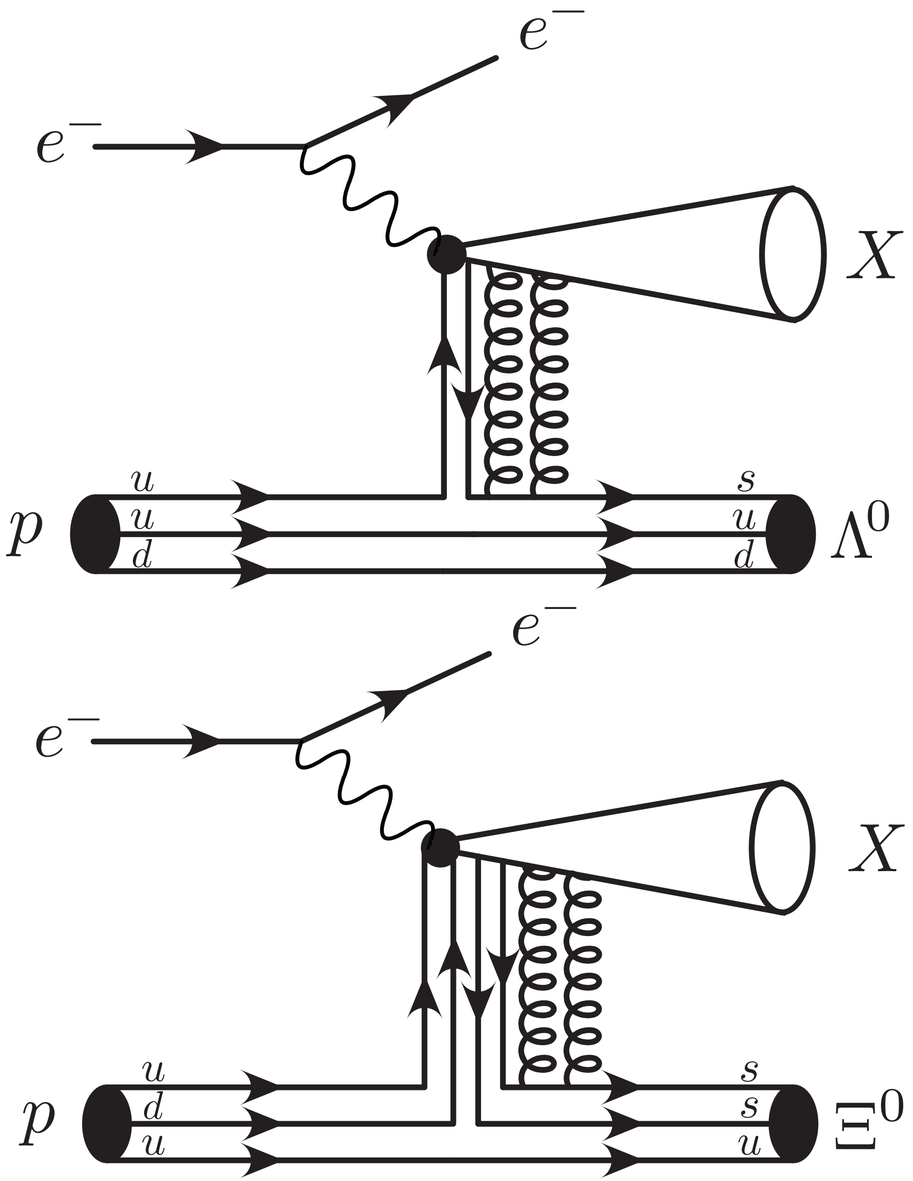
(PHENIX 2110.07504)

Glauber fermions carry spin: *larger possible set of leading power structure functions*

Both polarized e and p/A: *probing this larger set for the first time*

Nearest future

- Soft function analysis
- $\lambda_t \equiv \dfrac{\sqrt{-t}}{Q} \ll 1$ refactorization
- Spin dependence
- Flavor-crossed channels and excited forward baryons



Strong experimental motivation at the EIC

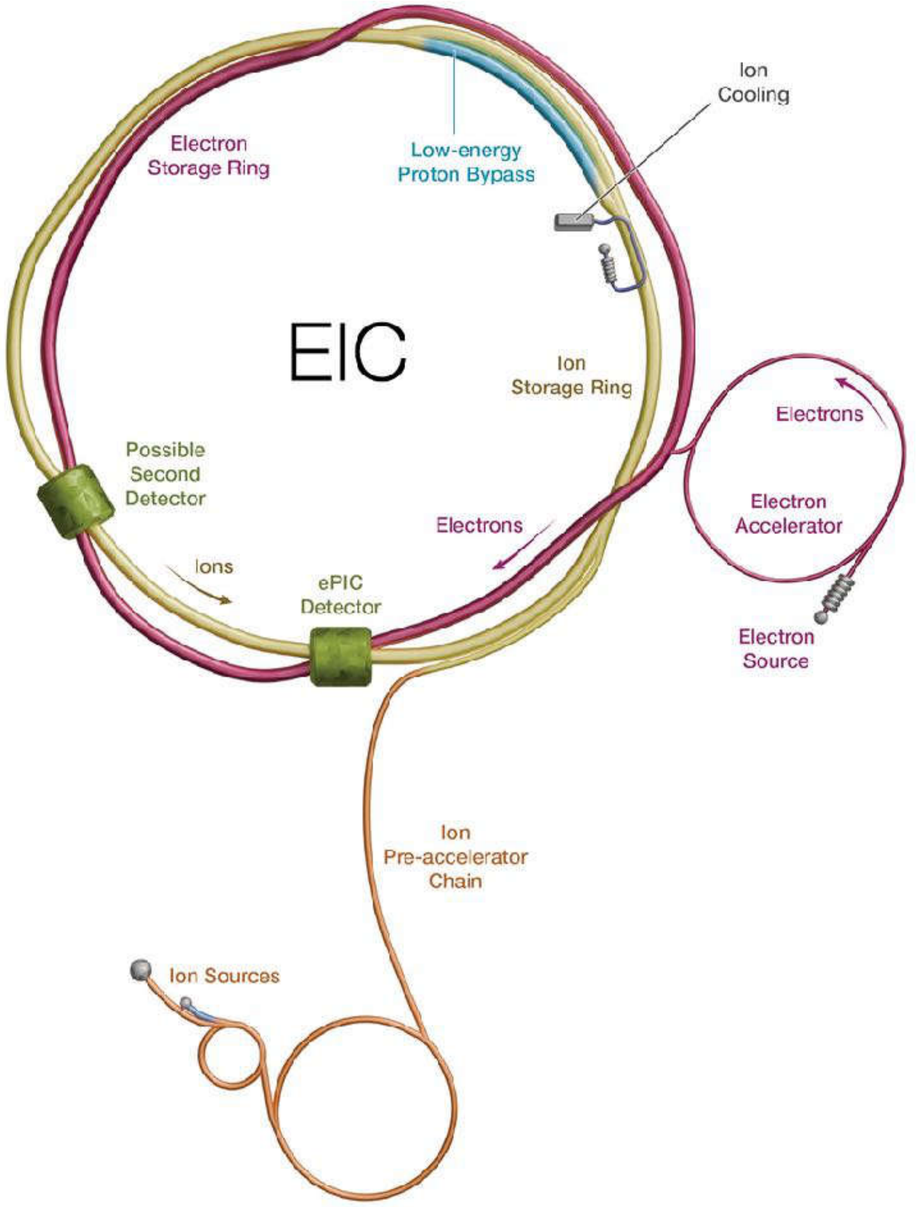
Capitalize on the ZDC

1. Overall forward-neutron measurements at the EIC look feasible

2. Can estimate overall forward flux

3. Feasibility studies can help define realistic EIC observables

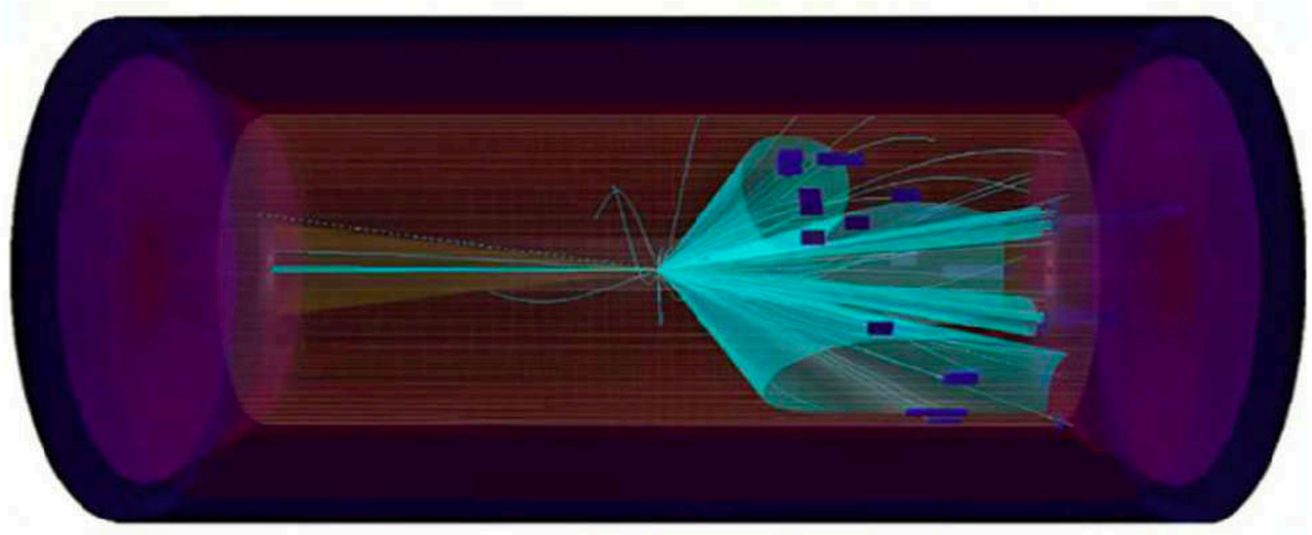
4. Can inform EIC detector design and science priorities



Big picture

1st Glauber fermion calculation…

forward physics: *gives a concrete theory target for leading-neutron measurements at the EIC ZDC*

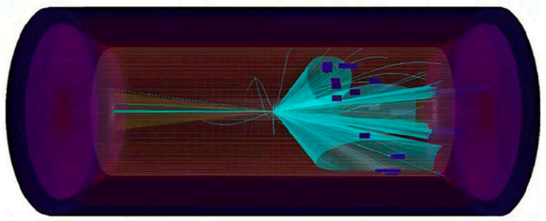


(Figure: Rodríguez, Corral, Quijada, Eur.Phys.J.C 86 (2026) 3, 228)

Big picture

1st Glauber fermion calculation…

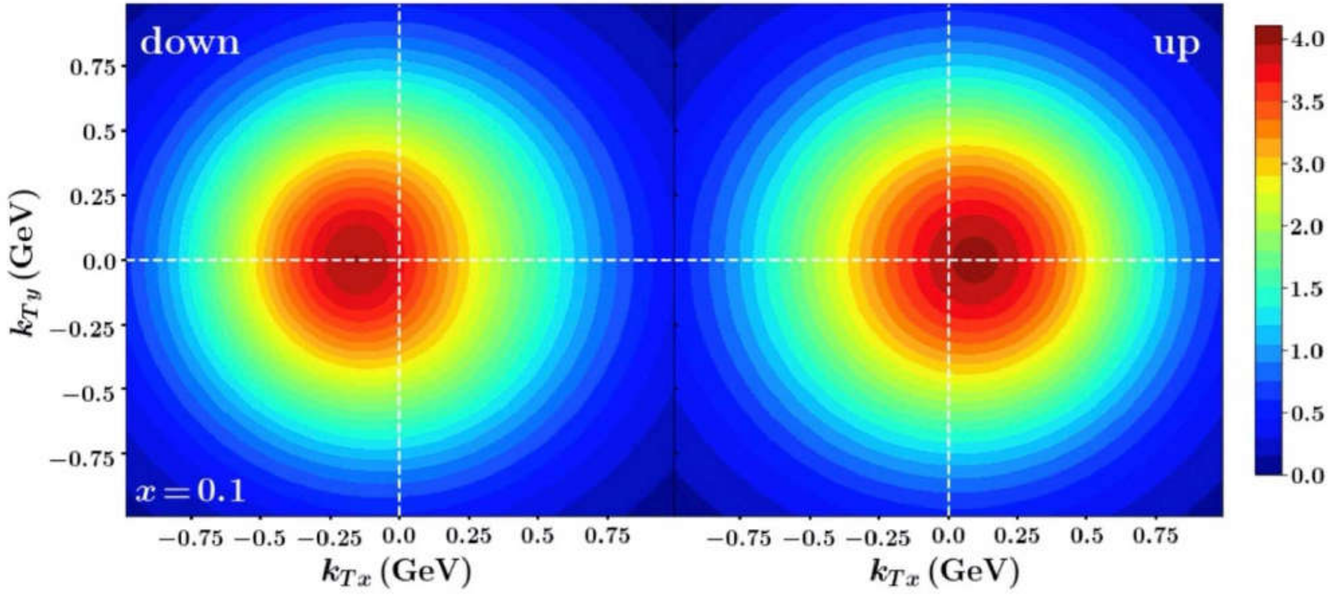
forward physics



hadron structure:

can be used to probe the proton-to-neutron transition

"How much of the proton-to-neutron transition really looks pion-like, vs. quarks-plus-gluon exchange?"

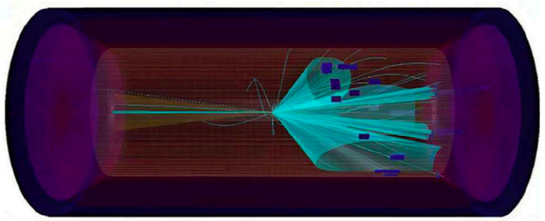


(Figure: Pitonyak Open Access Government April 2023, pp.258-259)

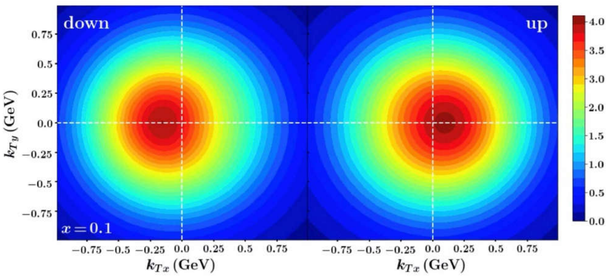
Big picture

1st Glauber fermion calculation…

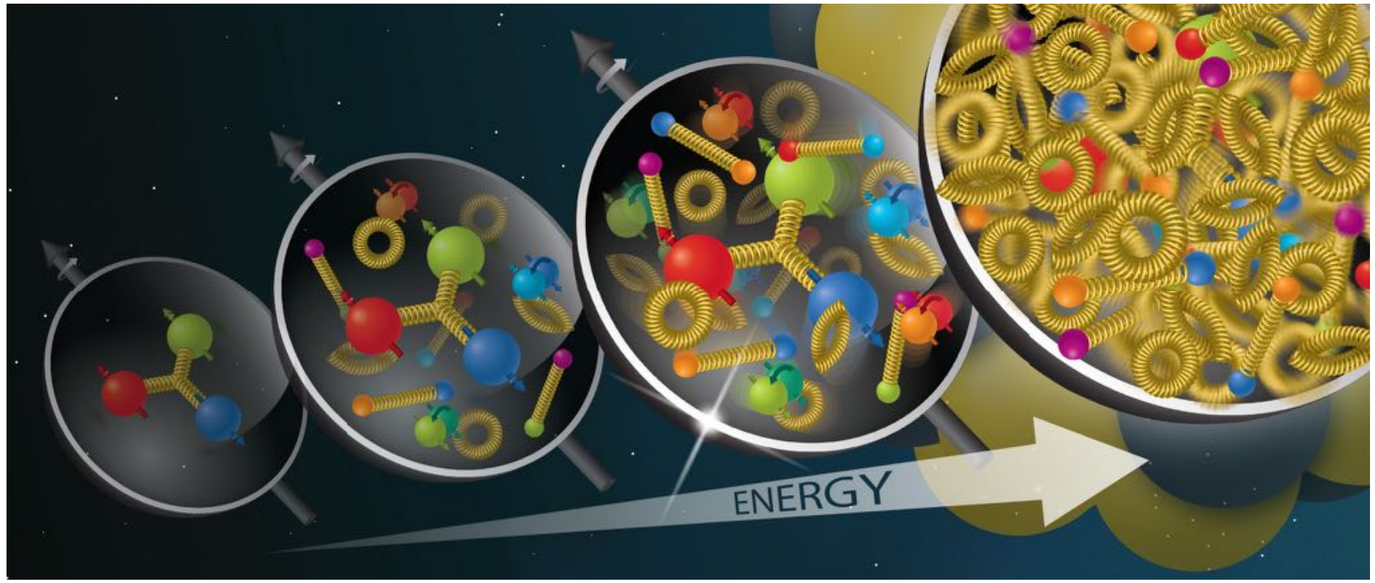
forward physics



hadron structure



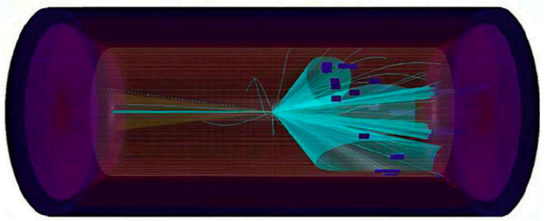
saturation: *provides a framework to test whether forward-neutron observables develop nonlinear small-x saturation effects*
Especially in future eA measurements!



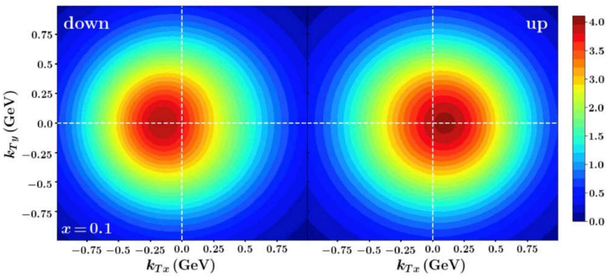
(Figure: BNL, EIC)

Big picture

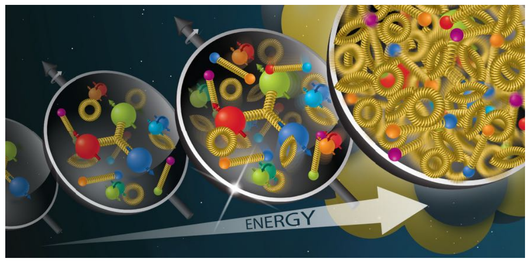
forward physics



hadron structure

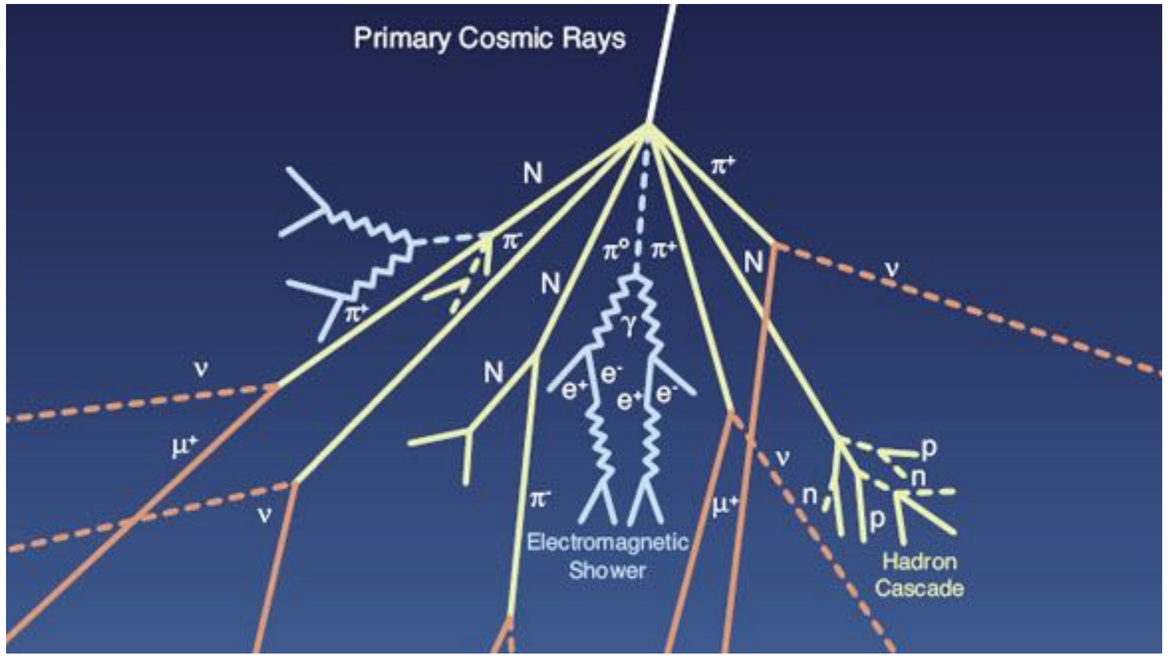


saturation



1st Glauber fermion calculation…

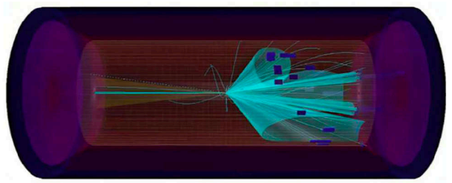
cosmic-rays: *helps constrain MC modeling that decides if energy stays in the hadronic cascade or gets dumped earlier into the EM part of the shower*



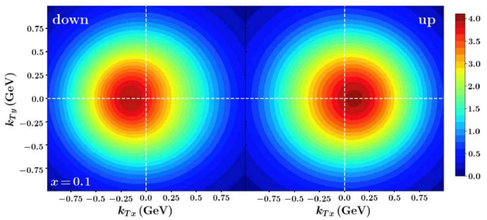
(Figure: CERN)

Big picture

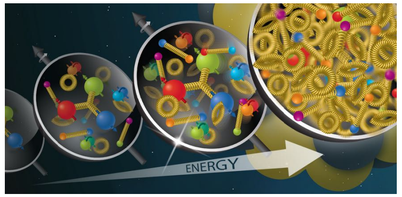
forward physics



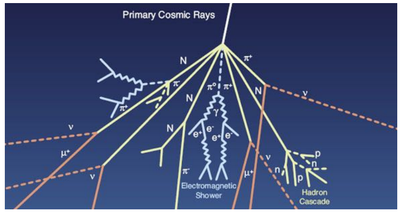
hadron structure



saturation

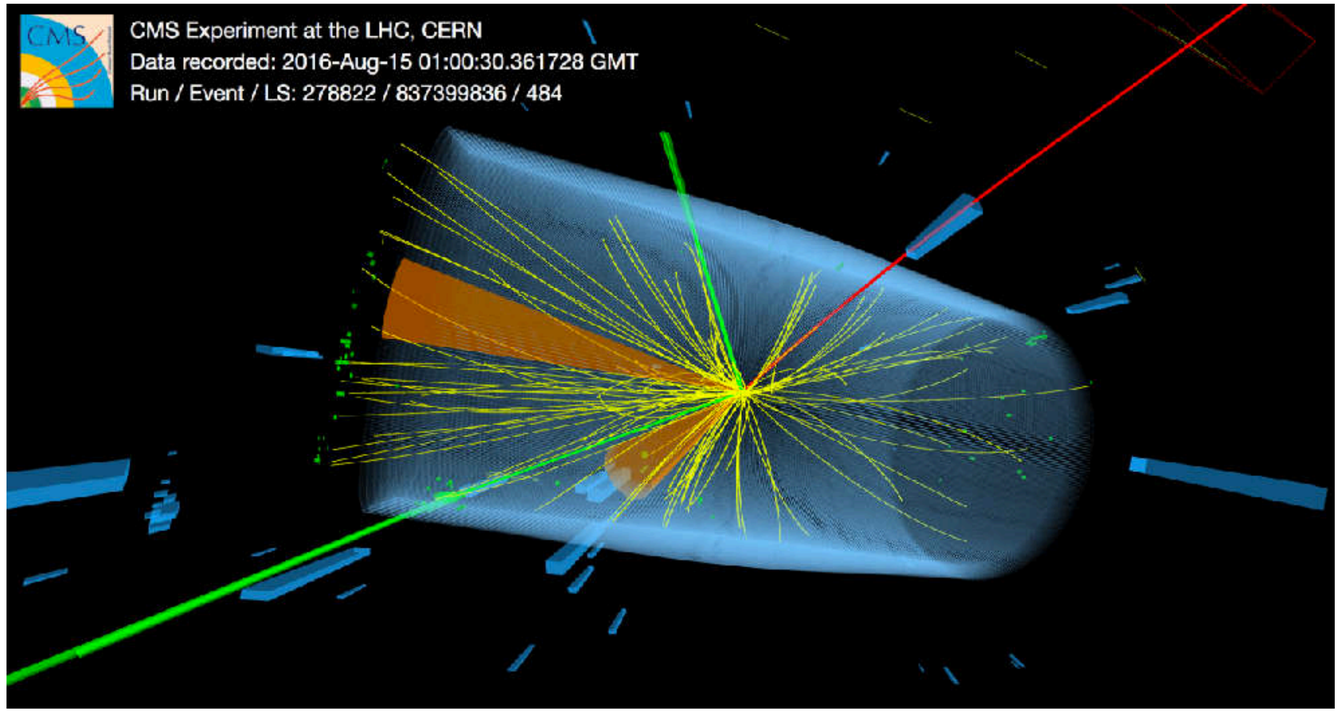


cosmic-rays:



1st Glauber fermion calculation…

new physics: *better background modeling for any search that uses forward detectors, rapidity gaps, or missing activity in parts of the event*



(Figure: CERN; CMS)

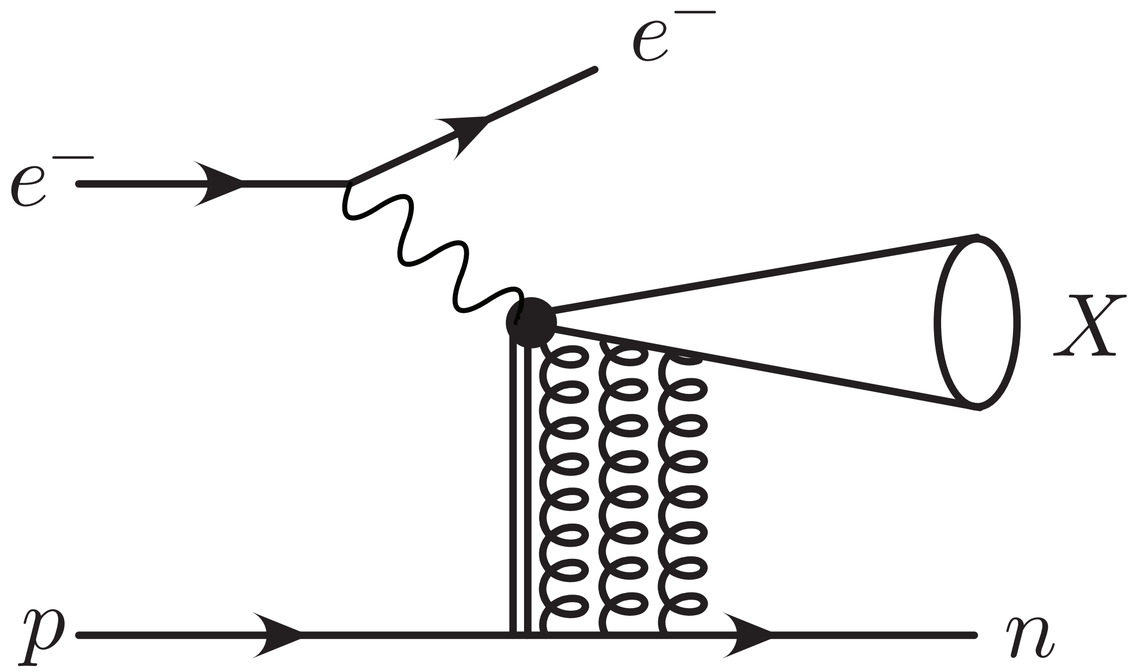
Conclusion

Sullivan process: not just pion exchange, but a diffractive mixed-Glauber process

So far have...

- Factorization for $ep \to eXn$
- Soft function predictions

More to come!



Thank you!

Backup

Lorentz invariants

2.1.1 Lorentz invariants

From four independent momentum measurements $\{k, k', p, p'\}$, we can form ten linearly independent Lorentz invariants. Of these, we let four vanish:

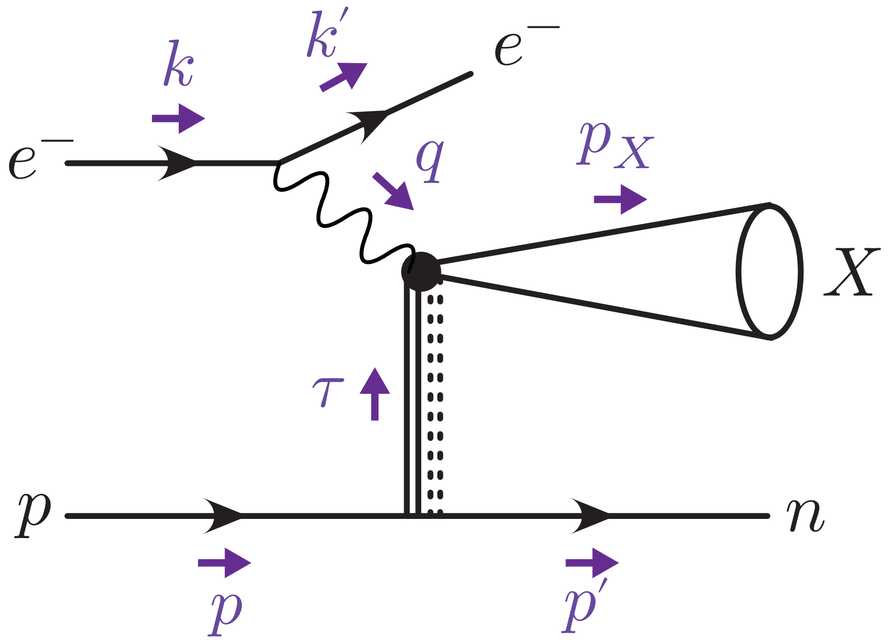
$$p^2 = m_p^2 \approx 0\,, \qquad (p')^2 = m_n^2 \approx 0\,, \qquad k^2 = (k')^2 = m_e^2 \approx 0\,, \tag{2.1}$$

dropping hadronic and leptonic mass corrections. A common choice for the six remaining independent invariants is

$$\begin{aligned} Q^2 &= -q^2\,, & t &= \tau^2\,, & \bar{x} &= \frac{k\cdot\tau}{k\cdot p}\,, \\ x &= \frac{Q^2}{2p\cdot q}\,, & y &= \frac{p\cdot q}{p\cdot k}\,, & \beta &= \frac{Q^2}{2q\cdot\tau}\,. \end{aligned} \tag{2.2}$$

It is conventional to define several auxiliary invariants:

$$\begin{aligned} W^2 &\equiv (p+q)^2 = \frac{1-x}{x}Q^2\,, & m_X^2 &\equiv p_X^2 = Q^2\frac{1-\beta}{\beta} + t\,, \\ z &\equiv \frac{p\cdot p'}{p\cdot q} = \frac{x}{Q^2}\,(m_Y^2 - t) \simeq \frac{x}{Q^2}\,(m_n^2 - t)\,, & s &= (p+k)^2 = \frac{Q^2}{xy} \\ \xi &\equiv x_{\mathbb{P}} = 1 - x_{\mathbb{L}} \equiv \frac{q\cdot\tau}{p\cdot q} = \frac{x}{\beta}\,. \end{aligned} \tag{2.3}$$



Structure functions

$$\frac{d^5\sigma}{dx\,dQ^2\,d\beta\,dt\,d\bar{x}} = \frac{\pi\alpha^2 x y^2}{4Q^6\beta^2 N_\sigma} L_{\mu\nu}(k,k')W^{\mu\nu}(p,q,p')\,,$$

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

$$\begin{aligned} L^{\mu\nu}(k,k') &= \langle k|J_e^{\dagger\mu}(0)|k'\rangle\langle k'|J_e^{\nu}(0)|k\rangle \\ &= 2\left[k^\mu k'^\nu + k^\nu k'^\mu - k\cdot k'\,g^{\mu\nu} + \mathrm{i}\lambda_e\epsilon^{\mu\nu\rho\sigma}k_\rho k_\sigma\right]. \end{aligned}$$

$$W_D^{\mu\nu} = \sum_{n\in\{L,1,2,3,4,4A\ldots\}} F_n^D w_n^{\mu\nu}$$

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

$$w_3^{\mu\nu} = \frac{1}{2x}\left(2X^\mu X^\nu - U^\mu U^\nu + g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right), \qquad w_4^{\mu\nu} = \frac{1}{2x}\left(U^\mu X^\nu + X^\mu U^\nu\right),$$

$$w_{4A}^{\mu\nu} = \frac{i}{2x}\left(U^\mu X^\nu - X^\mu U^\nu\right), \qquad w_{LP}^{\mu\nu} = \tilde{S}_T\, w_L^{\mu\nu},$$

$$w_{2P}^{\mu\nu} = \tilde{S}_T\, w_2^{\mu\nu}, \qquad w_{3P}^{\mu\nu} = \tilde{S}_T\, w_3^{\mu\nu},$$

$$w_{4P}^{\mu\nu} = \tilde{S}_T\, w_4^{\mu\nu}, \qquad w_{4AP}^{\mu\nu} = \tilde{S}_T\, w_{4A}^{\mu\nu},$$

$$w_5^{\mu\nu} = \frac{1}{2x}\left(U^\mu \bar{U}^\nu + \bar{U}^\mu U^\nu\right), \qquad w_6^{\mu\nu} = \frac{1}{2x}\left(U^\mu \bar{X}^\nu + \bar{X}^\mu U^\nu\right),$$

$$w_7^{\mu\nu} = \frac{1}{2x}\left(X^\mu \bar{U}^\nu + \bar{U}^\mu X^\nu\right), \qquad w_8^{\mu\nu} = \frac{1}{2x}\left(X^\mu \bar{X}^\nu + \bar{X}^\mu X^\nu\right),$$

$$w_{5A}^{\mu\nu} = \frac{i}{2x}\left(U^\mu \bar{U}^\nu - \bar{U}^\mu U^\nu\right), \qquad w_{6A}^{\mu\nu} = \frac{i}{2x}\left(U^\mu \bar{X}^\nu - \bar{X}^\mu U^\nu\right),$$

$$w_{7A}^{\mu\nu} = \frac{i}{2x}\left(X^\mu \bar{U}^\nu - \bar{U}^\mu X^\nu\right), \qquad w_{8A}^{\mu\nu} = \frac{i}{2x}\left(X^\mu \bar{X}^\nu - \bar{X}^\mu X^\nu\right). \qquad (2.3)$$

Channel	Beam config.	# SFs	Characteristic modulations	Structure functions	Asymmetry type
UU	e unpol., p unpol.	4	$1, \cos\phi, \cos 2\phi$	F_L^D, F_2^D, F_3^D, F_4^D	No spin asymmetry
UL	e unpol., p_L pol.	2	$\sin\phi, \sin 2\phi$	$F_{UL}^{\sin\phi}$, $F_{UL}^{\sin 2\phi}$	Target SSA
LU	e_L pol., p unpol.	1	$\sin\phi$	F_{4A}^D	Beam SSA
LL	e_L pol., p_L pol.	2	$1, \cos\phi$	F_{LL}, $F_{LL}^{\cos\phi}$	Double-spin asymmetry (DSA)
UT	e unpol., p_T pol.	6	$\sin(\phi-\phi_S)$, $\sin(\phi+\phi_S)$, $\sin(3\phi-\phi_S)$, $\sin\phi_S$, $\sin(2\phi-\phi_S)$	$F_{UT,T}^{\sin(\phi-\phi_S)}$, $F_{UT,L}^{\sin(\phi-\phi_S)}$, $F_{UT}^{\sin(\phi+\phi_S)}$, $F_{UT}^{\sin(3\phi-\phi_S)}$, $F_{UT}^{\sin\phi_S}$, $F_{UT}^{\sin(2\phi-\phi_S)}$	Target SSA
LT	e_L pol., p_T pol.	3	$\cos(\phi-\phi_S)$, $\cos\phi_S$, $\cos(2\phi-\phi_S)$	$F_{LT}^{\cos(\phi-\phi_S)}$, $F_{LT}^{\cos\phi_S}$, $F_{LT}^{\cos(2\phi-\phi_S)}$	Double-spin asymmetry

$UU \leftrightarrow \{L,2,3,4\}$,
$LU \leftrightarrow 4A$,
$UT \leftrightarrow \{LP,2P,3P,4P\}$, i.e. transverse-spin copies of $\{L,2,3,4\}$,
$LT \leftrightarrow 4AP$,

while the remaining full-basis polarized structures live in

$$\{5,6,7,8,5A,6A,7A,8A\} \in UL, LL, UT, TT,$$

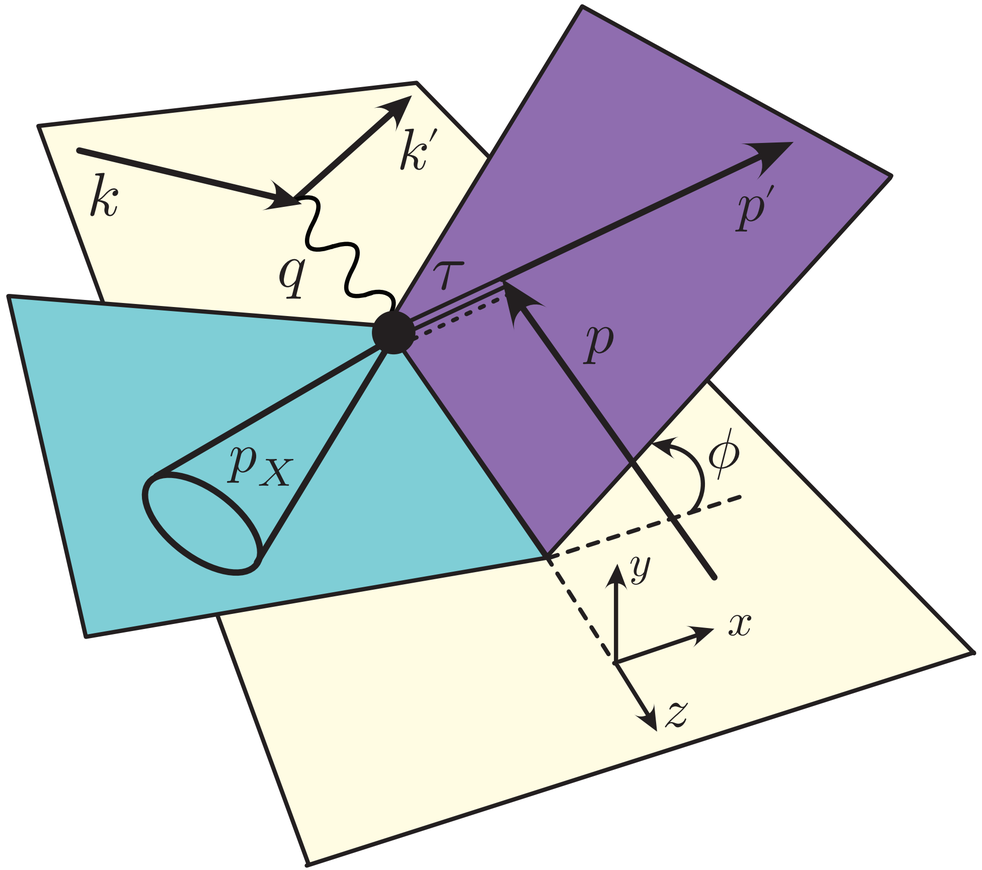
and are power suppressed in the leading diffraction factorization.

SCET modes in diffraction

In Breit frame

$$q^\mu = (0, 0, 0, -Q) = Q(1, -1, 0_\perp)$$

$$p^\mu = \frac{m_p^2}{p^-}\frac{\bar{n}^\mu}{2} + p^- \frac{n^\mu}{2} \approx Q\Big(0, \frac{1}{x}, 0_\perp\Big)$$



$$\tau = Q\Big(-z, \frac{1}{\beta} - z, \sqrt{-t/Q^2 - z(1/\beta - z)}\Big)\,,$$

$$p' = Q\Big(z, \frac{1}{x} - \frac{1}{\beta} + z, \sqrt{-t/Q^2 - z(1/\beta - z)}\Big)\,,$$

$$p_X = Q\Big(1 - z, \frac{1-\beta}{\beta} - z, \sqrt{-t/Q^2 - z(1/\beta - z)}\Big)$$

In Breit frame

$\sqrt{s}\lambda^{-1}(\lambda^2, \lambda^2, 0)$

$\sqrt{s}\lambda^{-1}(0, 1, 0)$ or $\sqrt{s}\lambda^{-1}(\lambda^4, 1, \lambda^2)$

$\sqrt{s}\lambda^{-1}(\lambda^2, \lambda^2, \lambda^2)$

$\sqrt{s}\lambda^{-1}(\lambda^4, \lambda^2, \lambda^3)$

$\sqrt{s}\lambda^{-1}(\lambda^4, \lambda^2, \lambda^2)$

$$p \sim \sqrt{s}(0, \lambda^{-1}, 0)\,,$$

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

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

$$p' \sim \sqrt{s}(\lambda^3\lambda_t^2, \lambda^{-1}, \lambda\lambda_l)$$

$$\tau \sim \sqrt{s}(\lambda^3\lambda_t^2, \lambda/\beta, \lambda\lambda_t)$$

Glauber quarks

$$\mathcal{L}_G^{(1/2)} \supset e^{-ix\cdot\mathcal{P}} \sum_n \bar{\mathcal{O}}_n \frac{1}{\not{\mathcal{P}}_\perp} \mathcal{O}_s^n + \bar{\mathcal{O}}_s^n \frac{1}{\not{\mathcal{P}}_\perp} \mathcal{O}_n \,. \tag{2.35}$$

The superscript $\frac{1}{2}$ indicates that this Lagrangian is at power $\lambda^{1/2}$ relative to leading power. Here we have the operators

$$\mathcal{O}_n = \not{\mathcal{B}}_{\perp n} \chi_n \,, \qquad \mathcal{O}_s^n = -4\pi\alpha_s \not{\mathcal{B}}_{\perp s}^n \psi_s^n \,, \qquad \bar{\mathcal{O}}_s^n = -4\pi\alpha_s \bar{\psi}_s^n \not{\mathcal{B}}_{\perp s}^n \,. \tag{2.36}$$

	Fundamental	Definition	Adjoint	Definition
Collinear fermion	χ_n	$W_n^\dagger \xi_n$	–	–
Soft fermion	ψ_s^n	$S_n^\dagger \psi_s$	–	–
Collinear gluon	$\mathcal{B}_{n\perp}^{\mu A}$	$\frac{1}{g} W_n^\dagger i D_{n\perp}^\mu W_n$	$\mathcal{B}_{n\perp}^{\mu}$	$\mathcal{B}_{n\perp}^{\mu A} T^A$
Soft gluon	$\mathcal{B}_{s\perp}^{n\mu A}$	$\frac{1}{g} S_n^\dagger i D_{s\perp}^\mu S_n$	$\mathcal{B}_{s\perp}^{n\mu}$	$\mathcal{B}_{s\perp}^{n\mu A} T^A$

Glauber gluons

Glauber gluons. At leading power, the Glauber Lagrangian [75] is

$$\mathcal{L}_G^{(0)} = e^{-ix\cdot\mathcal{P}} \sum_{n,\bar{n}} \sum_{i,j=q,g} \mathcal{O}_{ns\bar{n}}^{ij} + e^{-ix\cdot\mathcal{P}} \sum_{n} \sum_{i,j=q,g} \mathcal{O}_{ns}^{ij}\,, \tag{2.31}$$

where the two- and three-rapidity-sector Glauber operators are

$$\mathcal{O}_{ns}^{ij} = \mathcal{O}_n^{iB} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s^{j_n B} \qquad \mathcal{O}_{ns\bar{n}}^{ij} = \mathcal{O}_n^{iB} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_s^{BC} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}_{\bar{n}}^{jC}\,. \tag{2.32}$$

The building block definitions of these operators are:

$$\begin{aligned}
\mathcal{O}_n^{qB} &= \frac{1}{2}\bar{\chi}_n T^B \bar{n}\!\!\!/ \chi_n & \mathcal{O}_{\bar{n}}^{qB} &= \frac{1}{2}\bar{\chi}_{\bar{n}} T^B n\!\!\!/ \chi_{\bar{n}} \\
\mathcal{O}_n^{gB} &= \frac{i}{4} f^{BCD} \mathcal{B}_{n\perp\mu}^C \Big[\bar{n}\cdot(\mathcal{P}+\mathcal{P}^\dagger)\Big] \mathcal{B}_{n\perp}^{D\mu} & \mathcal{O}_{\bar{n}}^{gB} &= \frac{i}{4} f^{BCD} \mathcal{B}_{\bar{n}\perp\mu}^C \Big[n\cdot(\mathcal{P}+\mathcal{P}^\dagger)\Big] \mathcal{B}_{\bar{n}\perp}^{D\mu} \\
\mathcal{O}_s^{q_n B} &= 4\pi\alpha_s(\bar{\psi}_s^n T^B \bar{n}\!\!\!/ \psi_s^n) & \mathcal{O}_s^{q_{\bar{n}} B} &= 4\pi\alpha_s(\bar{\psi}_s^{\bar{n}} T^B n\!\!\!/ \psi_s^{\bar{n}}) \\
\mathcal{O}_s^{g_n B} &= 2\pi i\alpha_s f^{BCD} \mathcal{B}_{s\perp\mu}^{nC} \Big[n\cdot(\mathcal{P}+\mathcal{P}^\dagger)\Big] \mathcal{B}_{s\perp}^{nD\mu} & \mathcal{O}_s^{g_{\bar{n}} B} &= 2\pi i\alpha_s f^{BCD} \mathcal{B}_{s\perp\mu}^{\bar{n}C} \Big[\bar{n}\cdot(\mathcal{P}+\mathcal{P}^\dagger)\Big] \mathcal{B}_{s\perp}^{\bar{n}D\mu}
\end{aligned} \tag{2.33}$$

as well as

$$\mathcal{O}_s^{BC} = 8\pi\alpha_s \Big[\mathcal{P}_\perp^\mu S_n^T S_{\bar{n}} \mathcal{P}_{\perp\mu} - g\mathcal{P}_\perp^\mu \tilde{B}_{S\perp}^{n\mu} S_n^T S_{\bar{n}} - g S_n^T S_{\bar{n}} \tilde{B}_{s\perp}^{\bar{n}\mu} - g^2 \tilde{B}_{s\perp}^{n\mu} S_n^T S_{\bar{n}} \tilde{B}_{s\perp\mu}^{\bar{n}} - \frac{ig}{2} n_\mu \bar{n}_\nu S_n^T \tilde{G}_s^{\mu\nu} S_{\bar{n}}\Big]^{BC}$$

A useful shorthand for eq. (2.31), which makes the sum over i, j implicit, is

$$\mathcal{O}_n^B = \mathcal{O}_n^{qB} + \mathcal{O}_n^{gB}\,, \qquad \mathcal{O}_s^B = \mathcal{O}_s^{q_n B} + \mathcal{O}_s^{g_n B}\,. \tag{2.34}$$

Note that Glauber gluons carry no power suppression in λ; i.e., each is of order $\sim \mathcal{O}(\lambda^0)$.