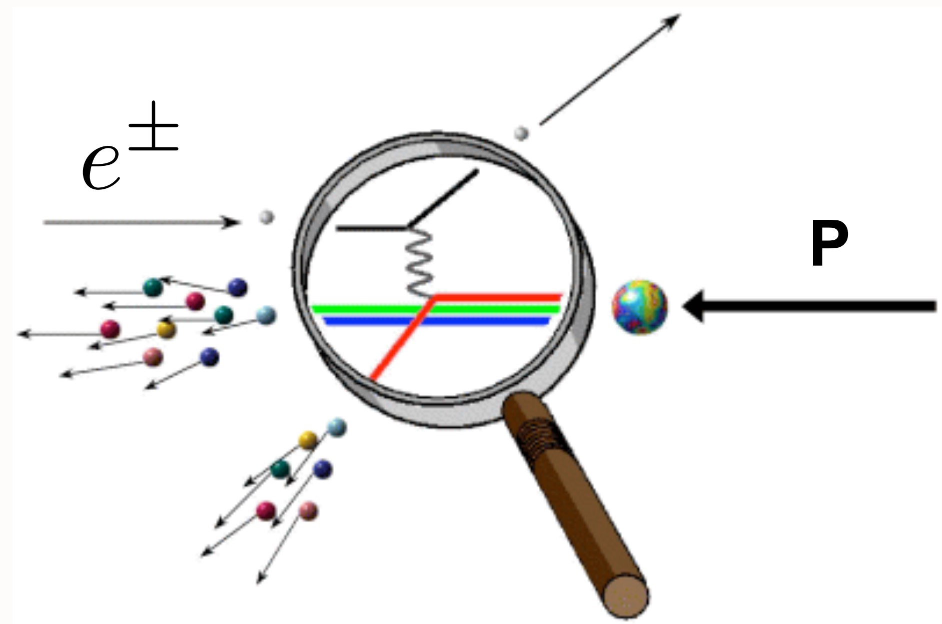
LHeC Physics Highlights

Stan Brodsky, SLAC

$e^{\pm}p \quad e^{\pm}A$



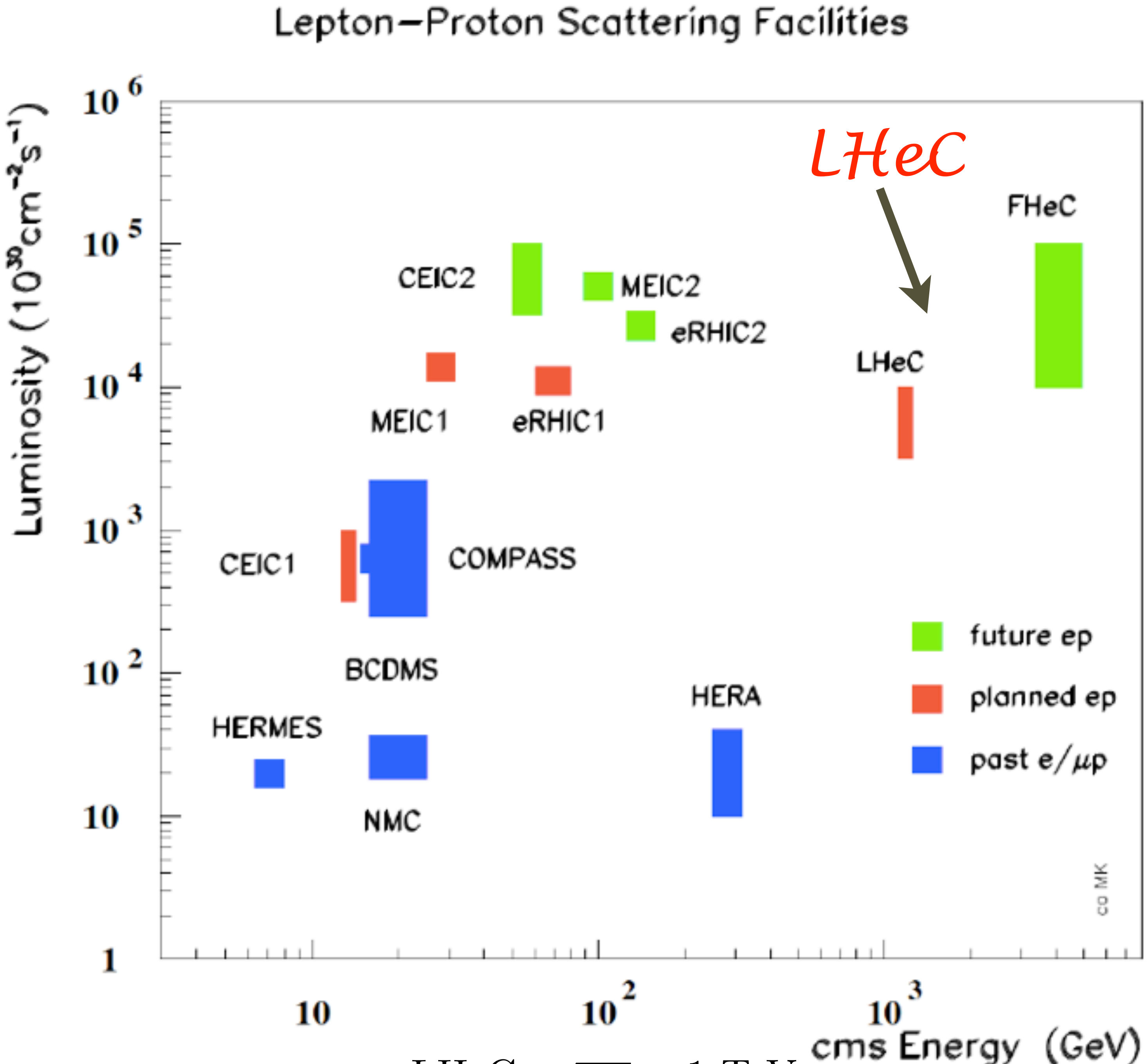
e^-/e^+ polarization

$$\mathcal{L} = 10^{33} - 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$$

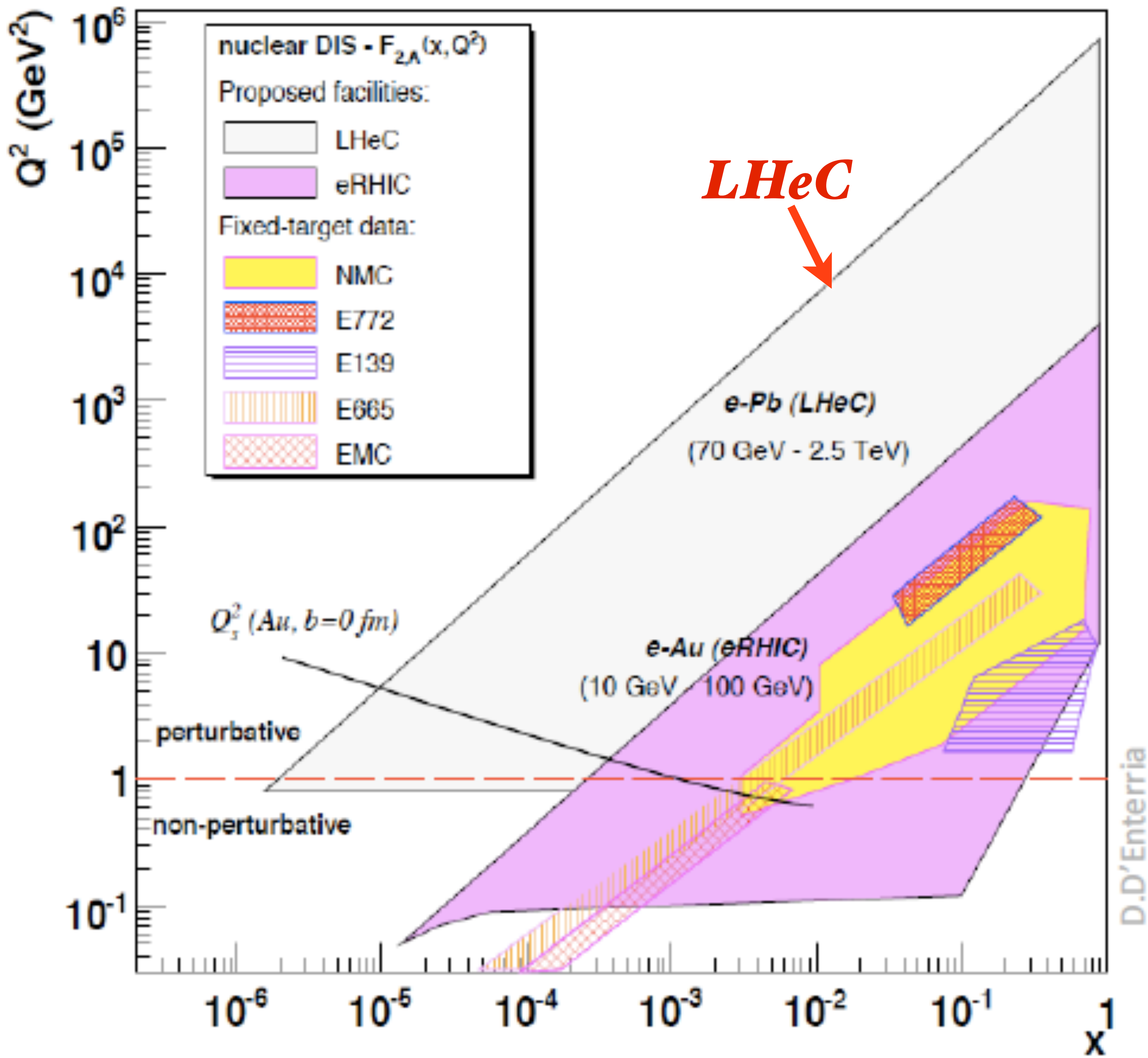
$$E_e = 60 \text{ GeV}, E_p = 7 \text{ TeV}, \sqrt{s}_{ep} > 1 \text{ TeV}$$

Chavannes-de-Bogis

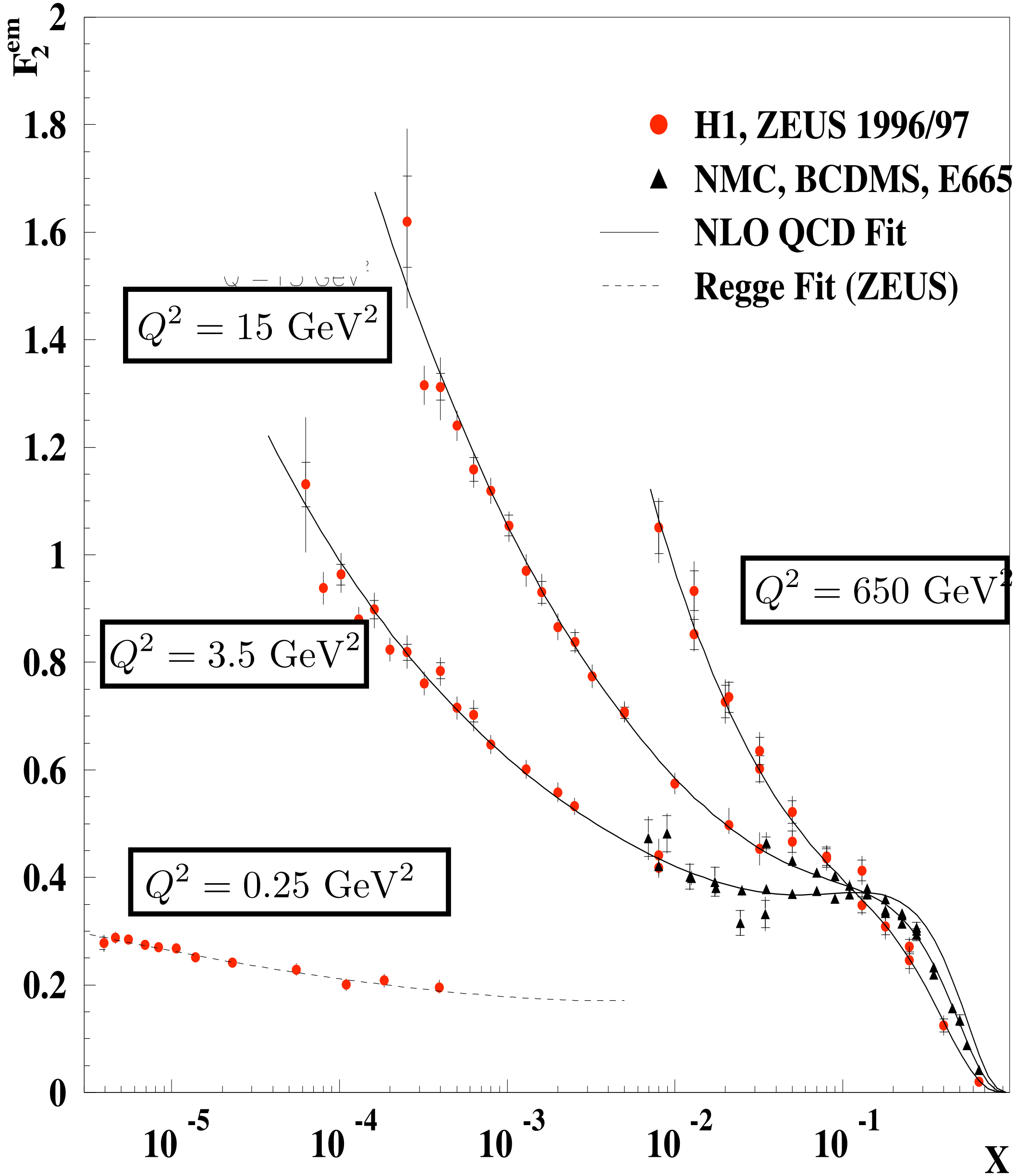
LHeC: Beyond $t\bar{t}$ plus Higgs threshold



LHeC: $\sqrt{s_{ep}} > 1$ TeV


nuclear DIS - $F_{2,A}(x,Q^2)$
Proposed facilities:
LHeC
eRHIC
Fixed-target data:
NMC
E772
E139
E665
EMC
LHeC
e-Pb (LHeC)
(70 GeV - 2.5 TeV)
e-Au (eRHIC)
(10 GeV - 100 GeV)
Q_s^2 (Au, b=0 fm)
perturbative
non-perturbative
Q^2 (GeV^2)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
D.D'Enterria

$F_2(x, Q^2)$

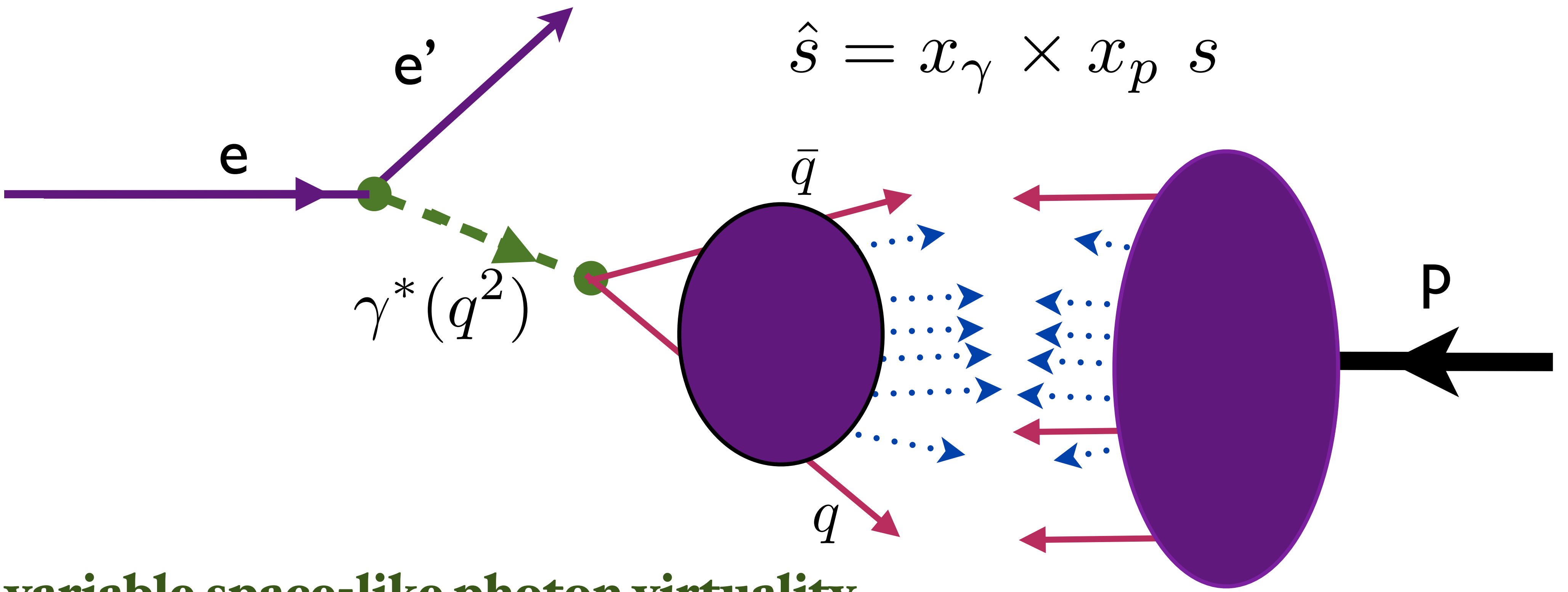


LHeC:
Measure
Structure Function
at very small x

Unitarity
Bound?
Saturation?

LHeC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame

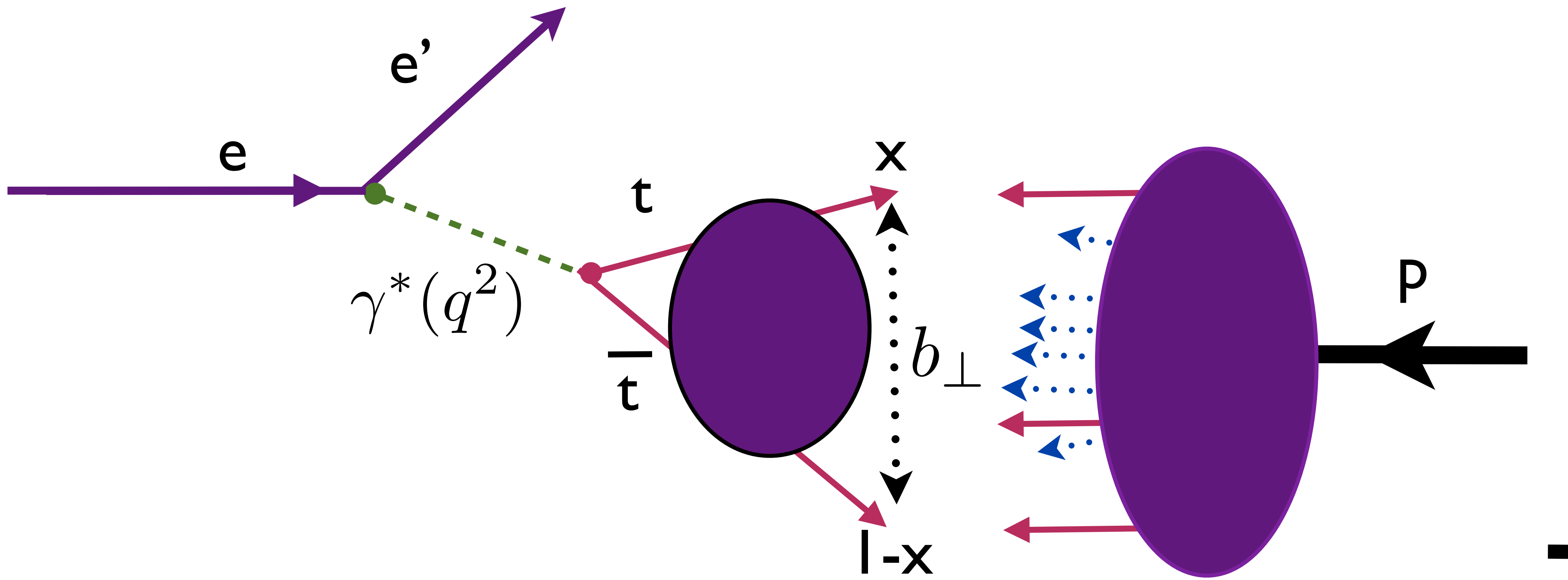


variable space-like photon virtuality, various primary flavors

$q\,\bar{q}$ plane aligned with lepton scattering plane ~ $\cos^2\phi$

$\bar{t}\,t$ acts as a 'drill'

$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$

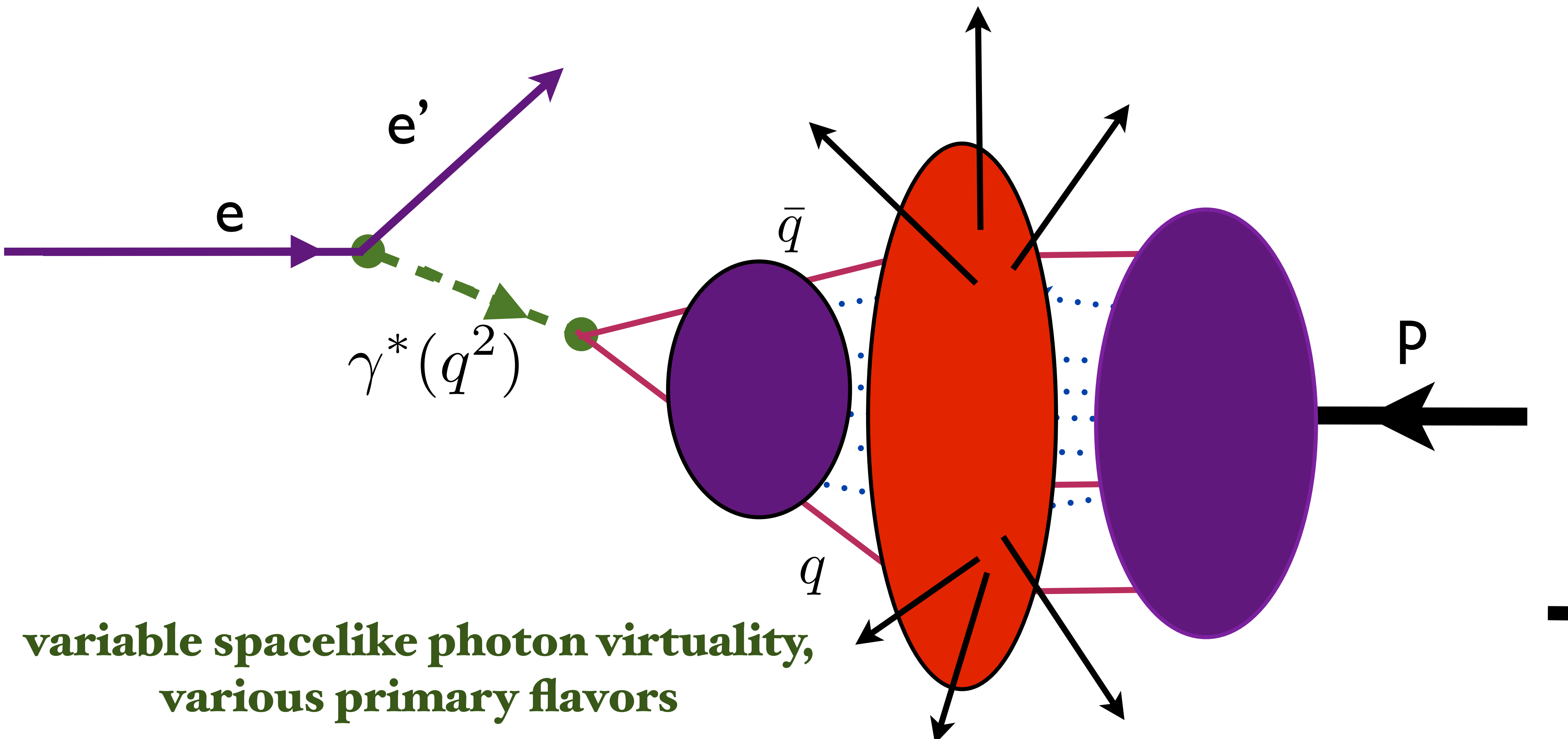


Cross section enhanced by BFKL:

$$\sigma(\gamma^* p) \simeq \frac{\pi \alpha}{Q^2 x(1-x) + M_t^2} s^{\alpha_{\mathrm{BFKL}} - 1}$$

LHeC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame

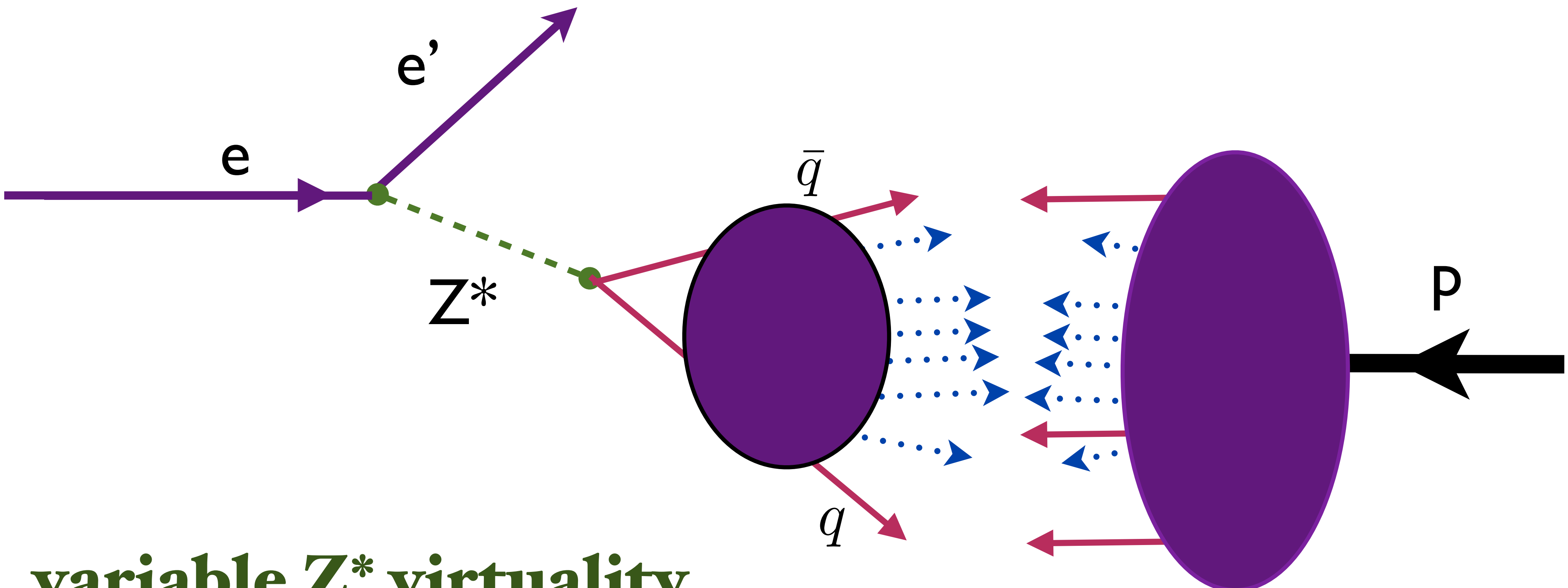


photon and proton fragmentation vs. central regions

Saturation, nuclear shadowing, antishadowing

LHeC: Virtual Z-Proton Collider

Interferes with virtual photon amplitude
e^+ e^- and $q\,\bar{q}$ asymmetries, parity violation

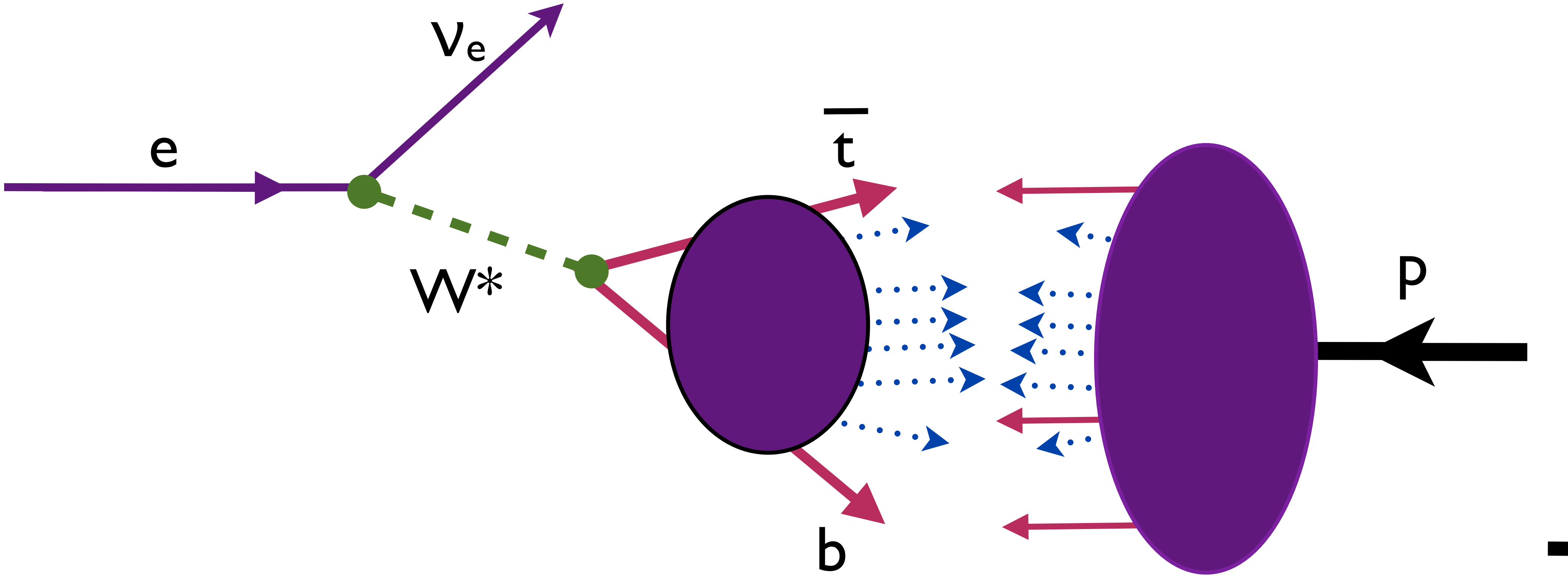


variable Z* virtuality, various flavors

proton or ions

$q\,\bar{q}$ plane aligned with lepton scattering plane ~ $\cos^2\phi$

LHeC: Virtual Weak Boson-Proton Collider



variable W* virtuality, variable flavors

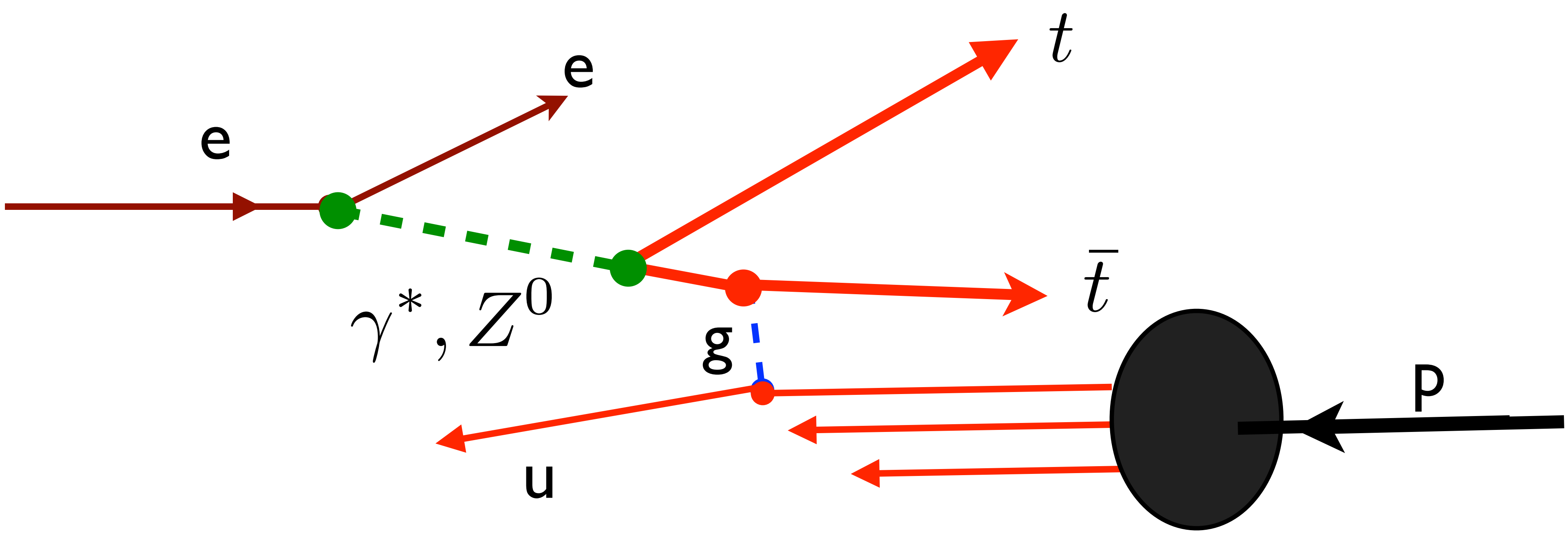
proton or ions

LHeC: Virtual Photon-Proton Collider

Inclusive Top Electroproduction at the LHeC

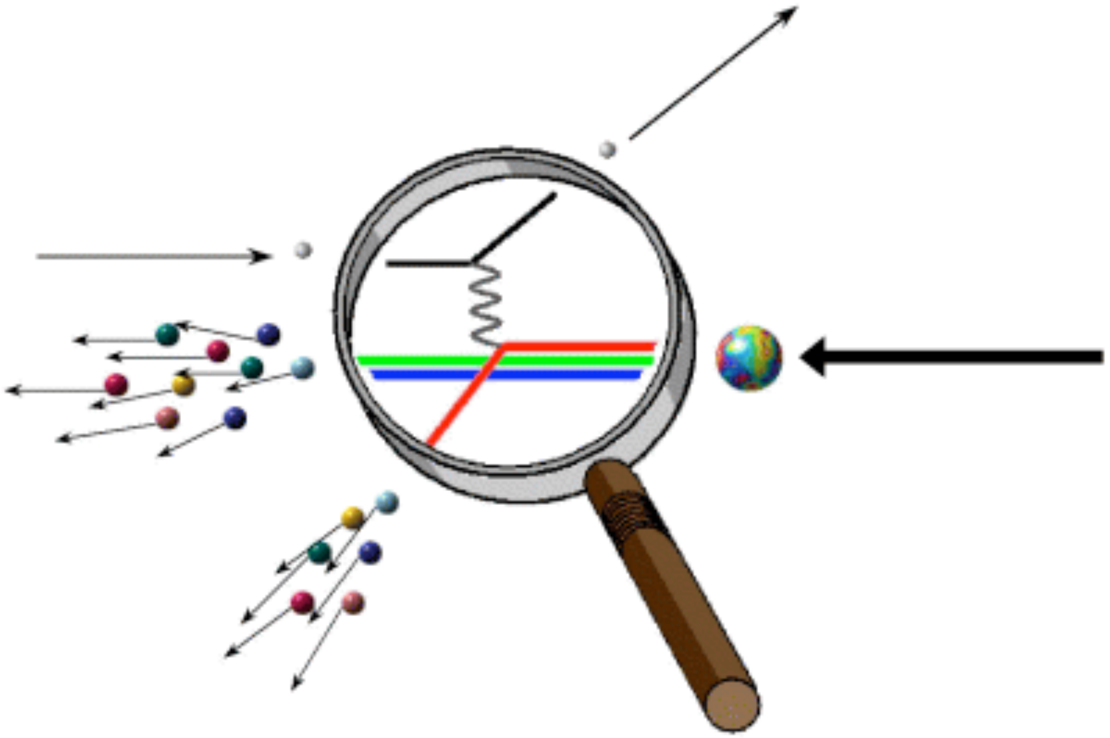
$t - \bar{t}$ asymmetry from γ^* and Z^* or $\gamma^*\gamma^*$ interference

Ambiguous: Top quark in photon vs. heavy sea quark in proton?



$t\,\bar{t}$ Plane correlated with Electron Scattering Plane

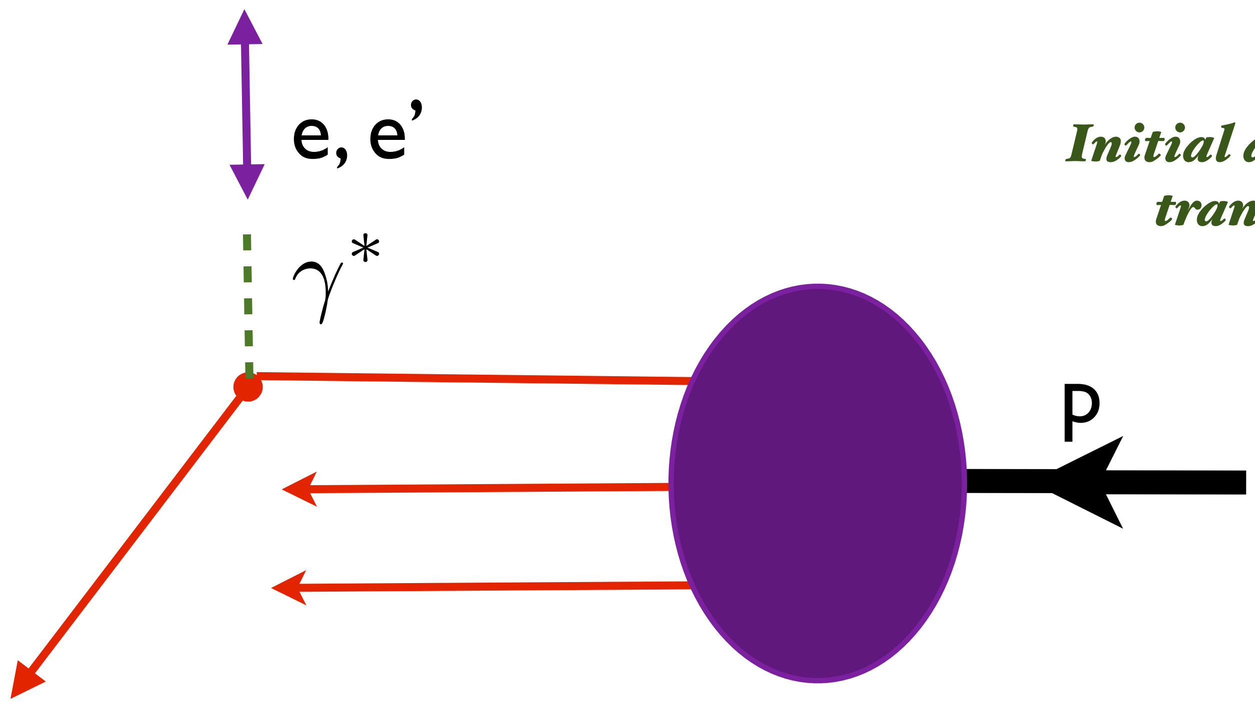
LHeC in the "Infinite Momentum Frame"



$$q^+ = q^0 + q^3 = 0,$$
$$q^0 = -q^3, Q^2 = -q^2 = q_\perp^2$$

All hadronic physics assumed to come from the structure function of the proton or nucleus

LHeC in the "Infinite Momentum Frame"

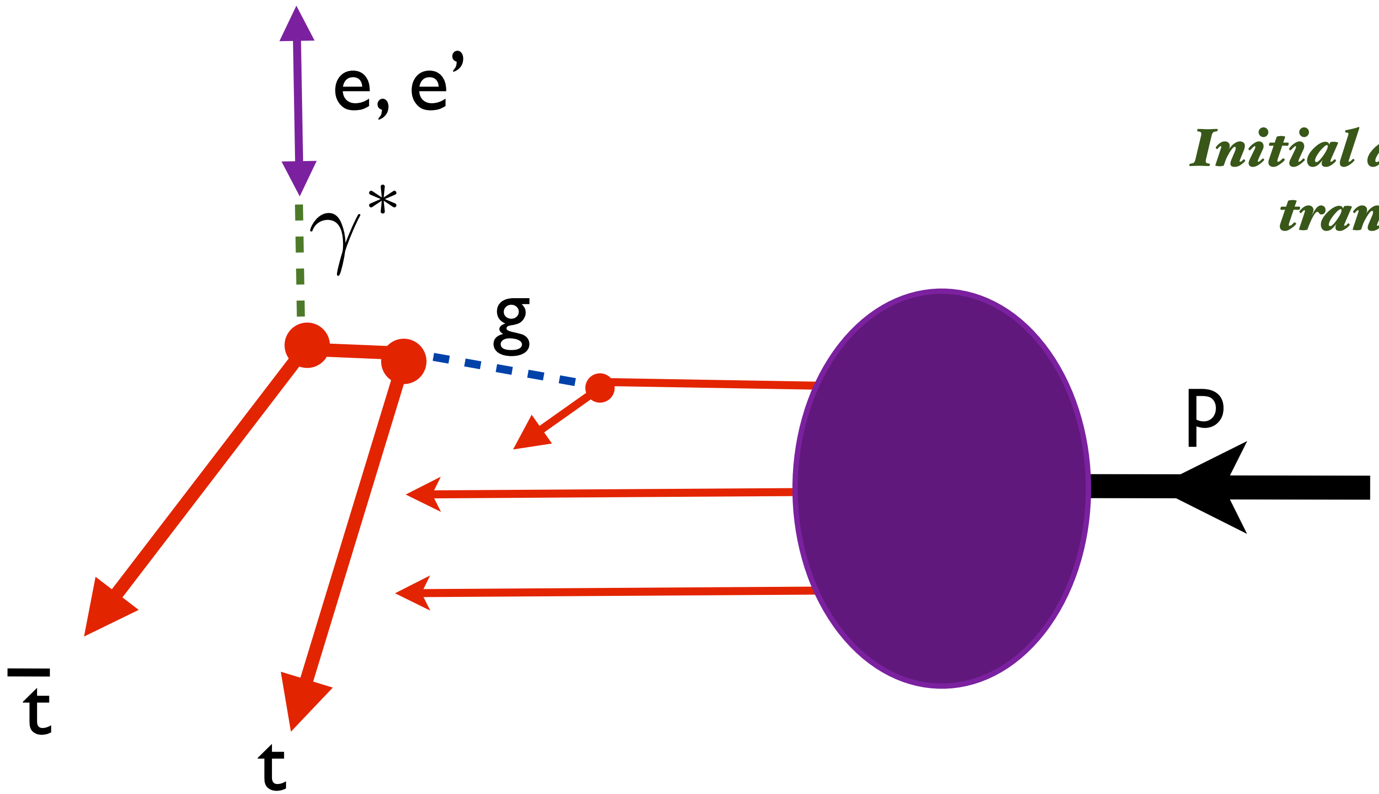


Initial and final electron in transverse direction

$$q^+ = q^0 + q^3 = 0,$$
$$q^0 = -q^3, Q^2 = -q^2 = q_\perp^2$$

All hadronic physics assumed to come from the structure function of the proton or nucleus

LHeC in the "Infinite Momentum Frame"



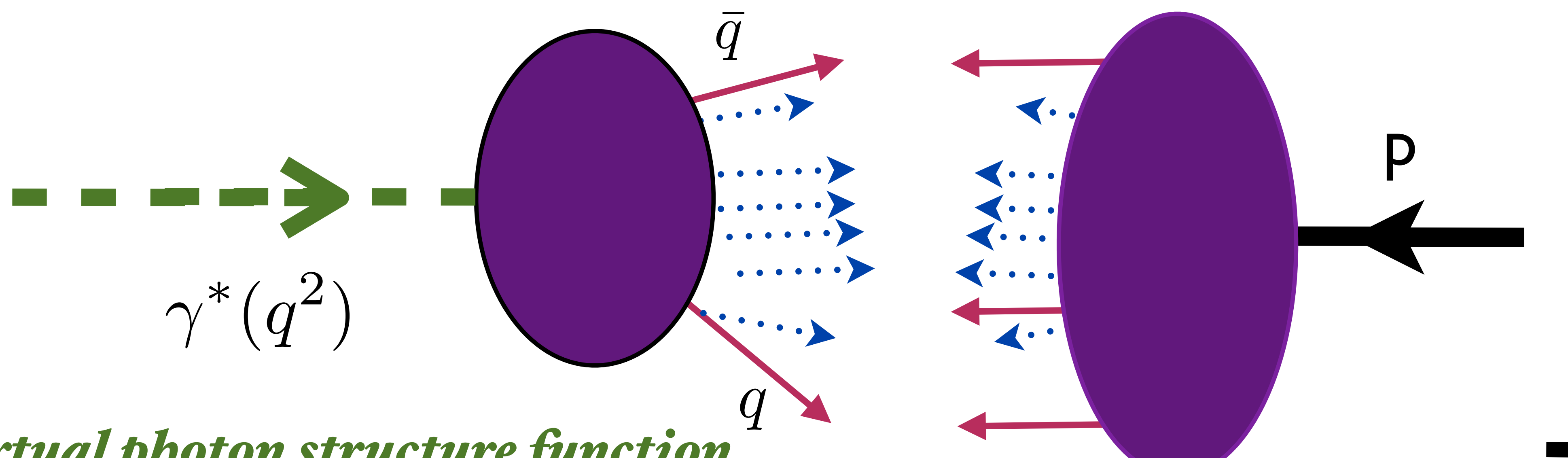
$$q^+ = q^0 + q^3 = 0,$$
$$q^0 = -q^3, Q^2 = -q^2 = q_\perp^2$$

All hadronic physics assumed to come from the structure function of the proton or nucleus

LHeC: Virtual Photon-Proton Collider

Perspective from the photon-proton collider frame

QCD Factorization: Interactions of Light-Front Wavefunctions of photon and proton

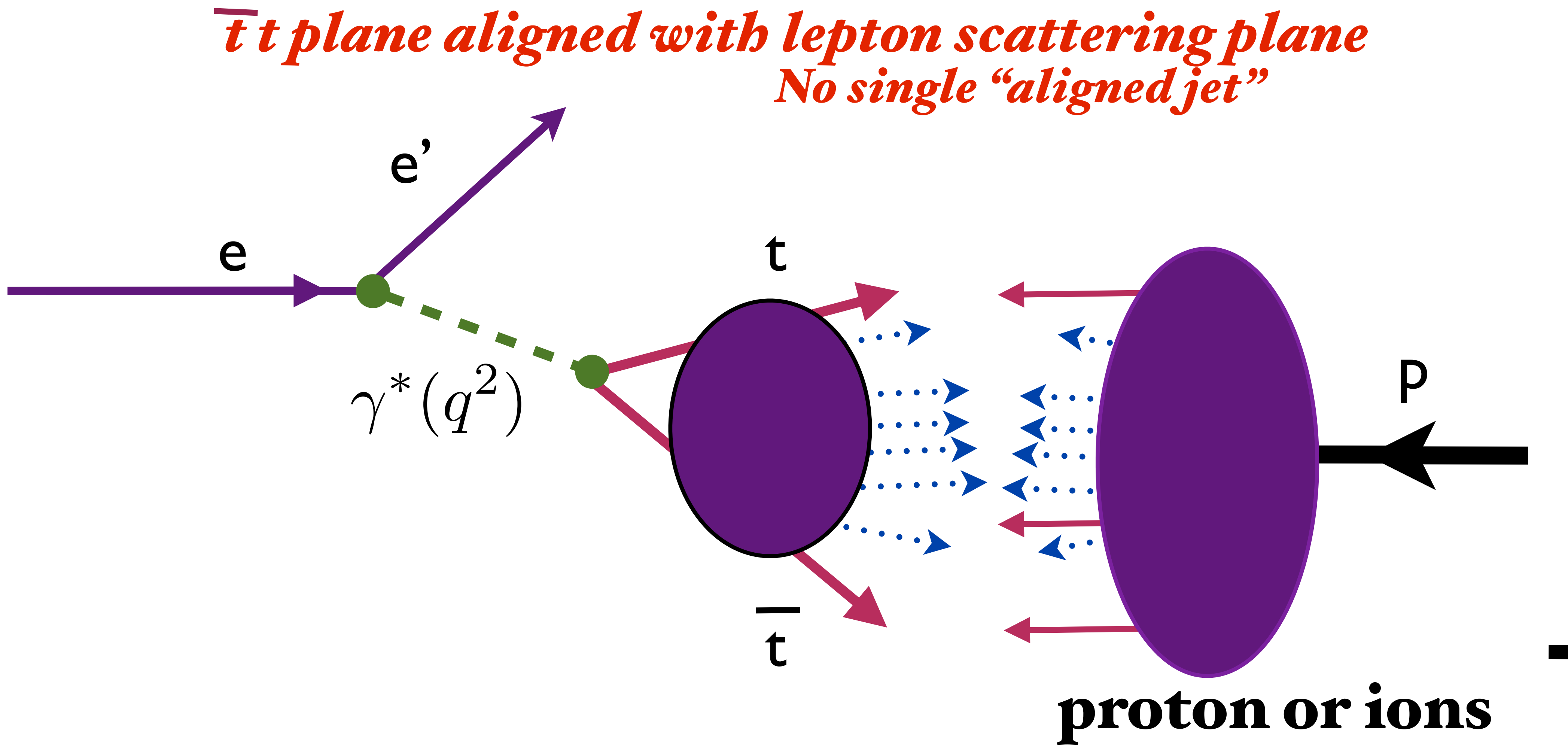


Virtual photon structure function

variable spacelike photon virtuality
various primary flavors

$q\,\bar{q}$ plane aligned with lepton scattering plane ~ $\cos^2\phi$

LHeC: "Top Quark-Proton Collider"

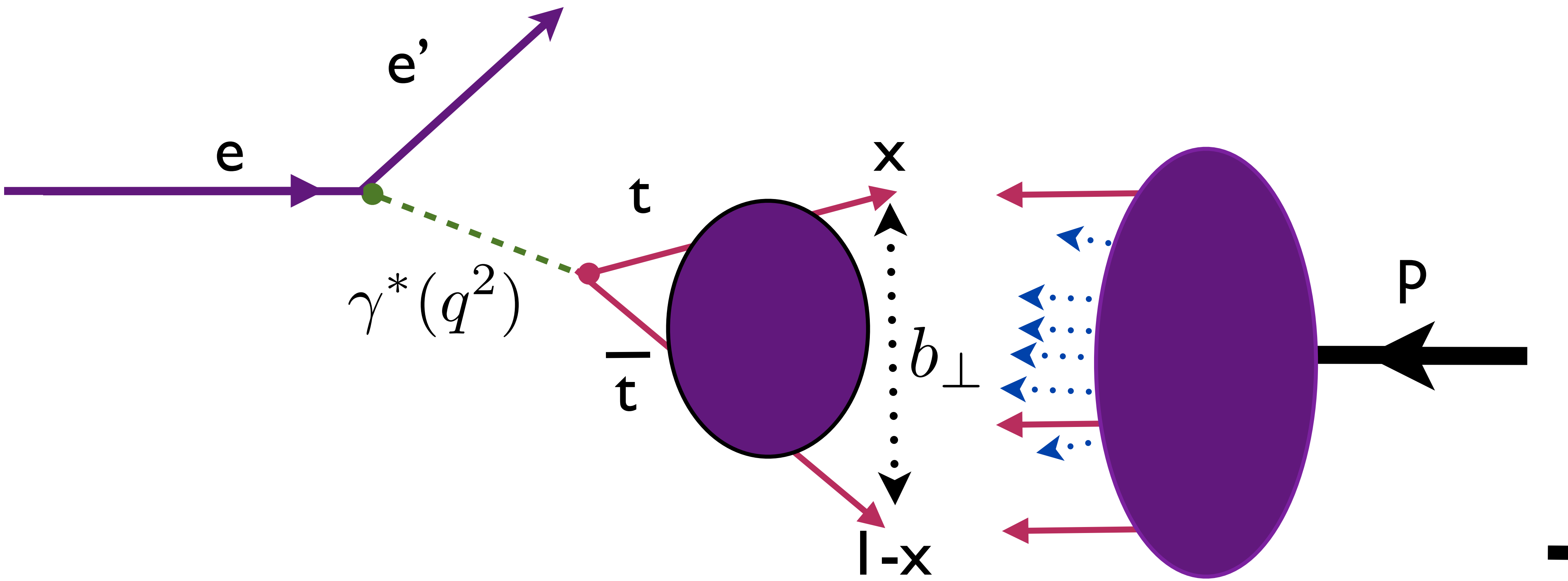


Only partially included by DGLAP in proton pdf

Strong enhancement at top threshold

$\bar{t}\,t$ acts as a 'drill'

$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$

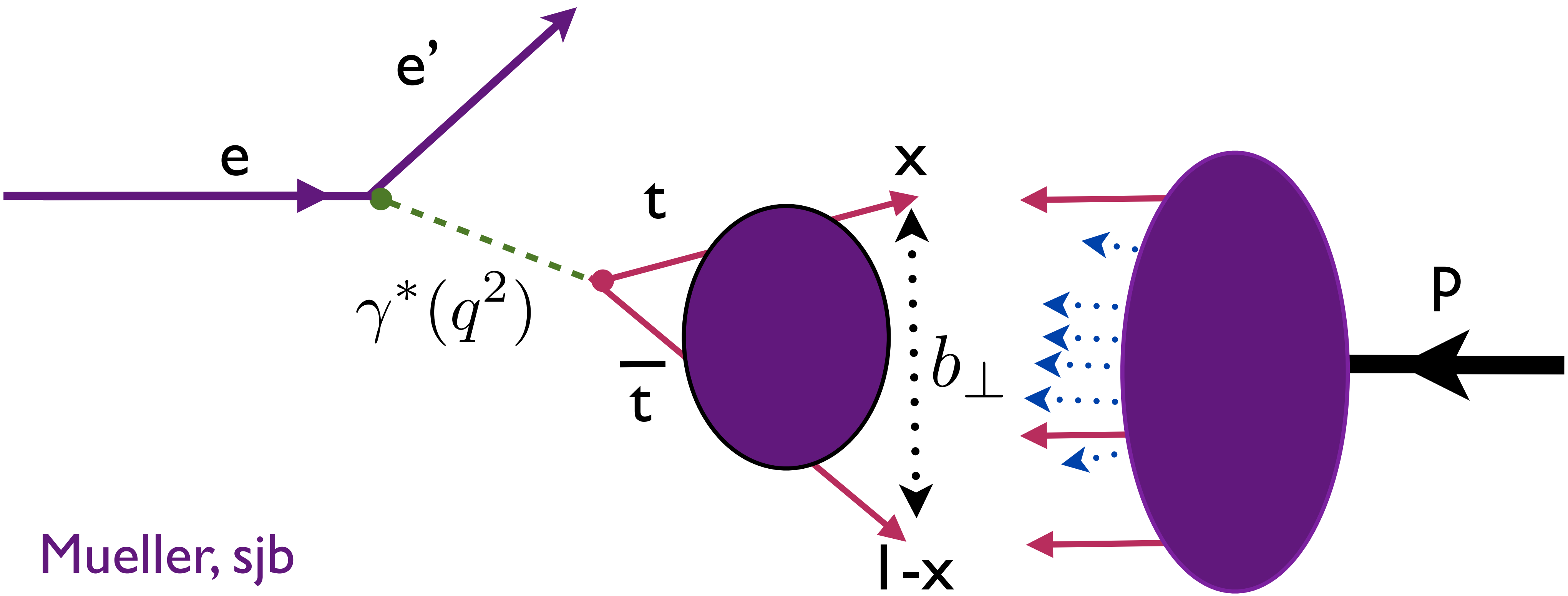


High Q^2, high M^2_Q virtual photon at LHeC acts as a precision, small bore, linearly oriented, flavor-dependent probe acting on a proton or nuclear target.

Study final-state hadron multiplicity distributions, ridges, nuclear dependence, etc.

$\bar{t}\, t$ *acts as a 'drill'*

$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$

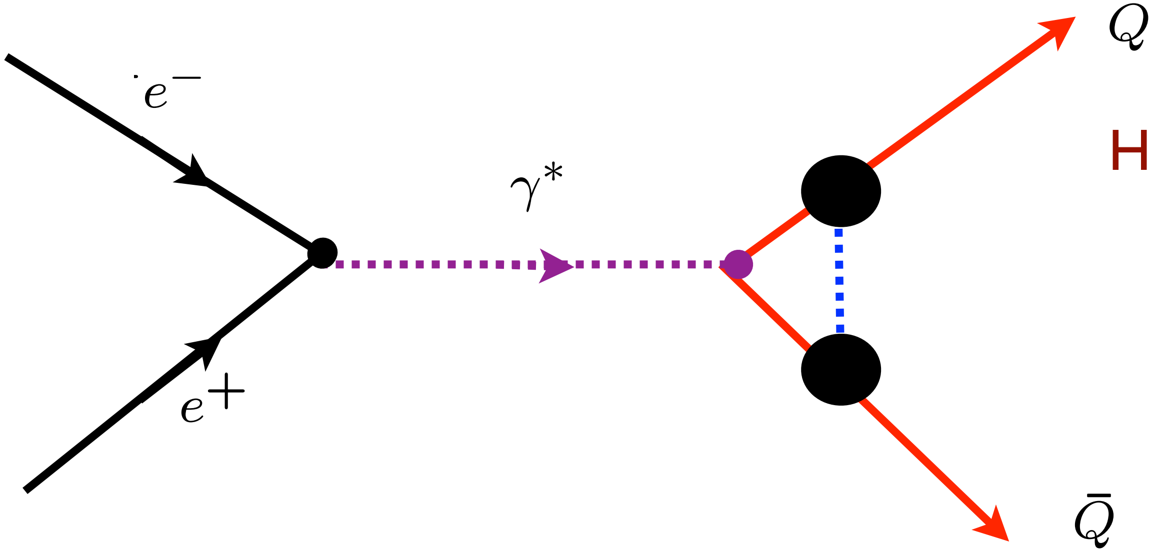


Mueller, sjb

$$\text{Color transparency: } \sigma(\gamma^* p) \propto \pi\alpha\langle b_\perp^2 \rangle$$

Cross section independent of photon virtuality for $Q^2 < M_t^2$

No nuclear shadowing at high Q^2 or M^2_Q



Hoang, Kühn, Teubner, sjb

Sommerfeld Threshold Enhancement

$$F_1 + F_2 = 1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta} - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi}$$

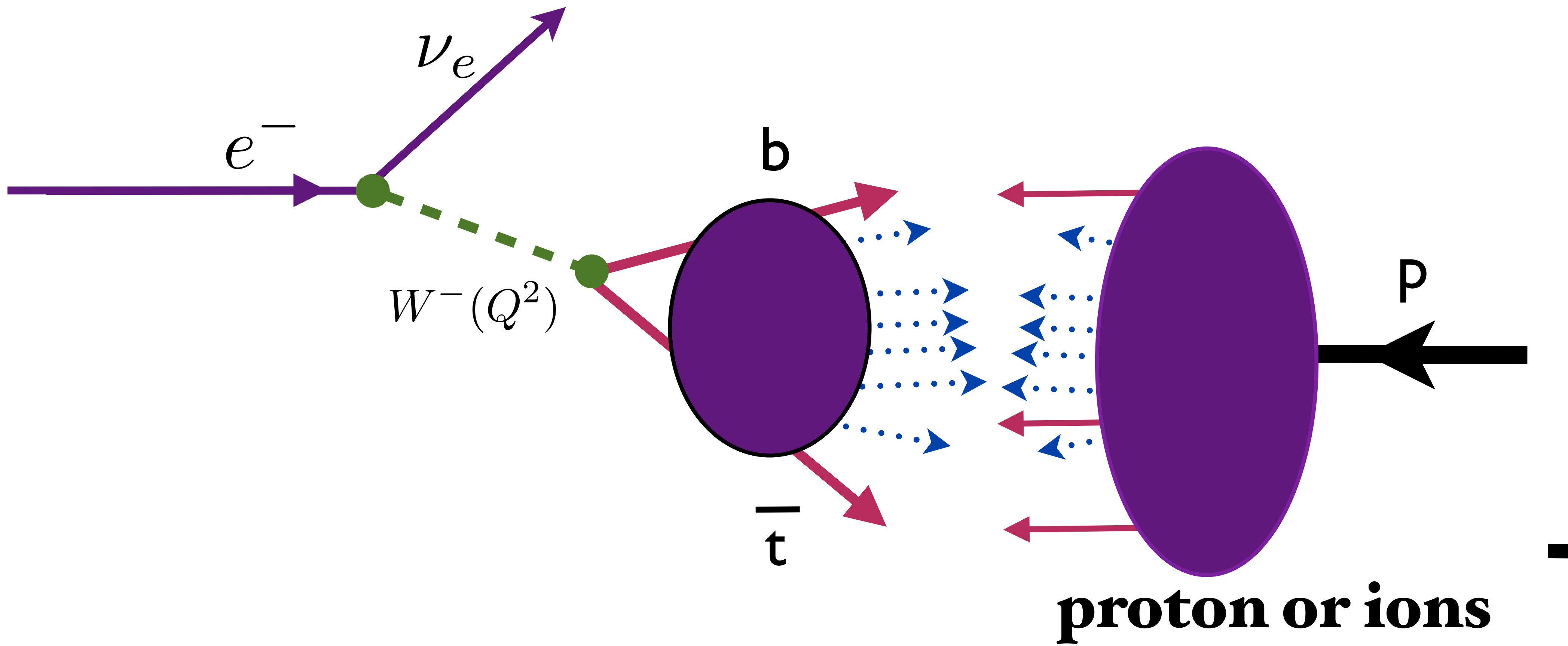
$$\cong \left(1 - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi}\right)\left(1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta}\right)$$

Sommerfeld Enhancement of massive quark and lepton production close to threshold.

Multiple Renormalization Scales

Principle of Maximum Conformality

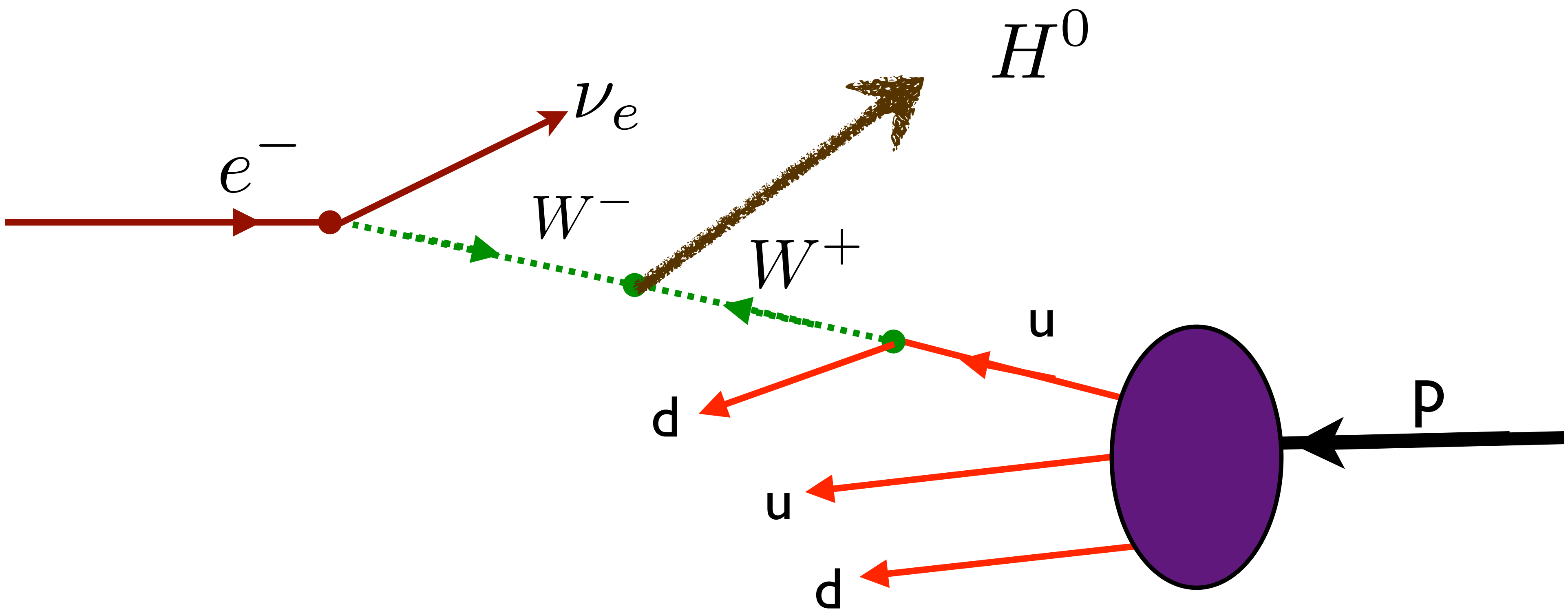
LHeC: “W-Proton Collider”



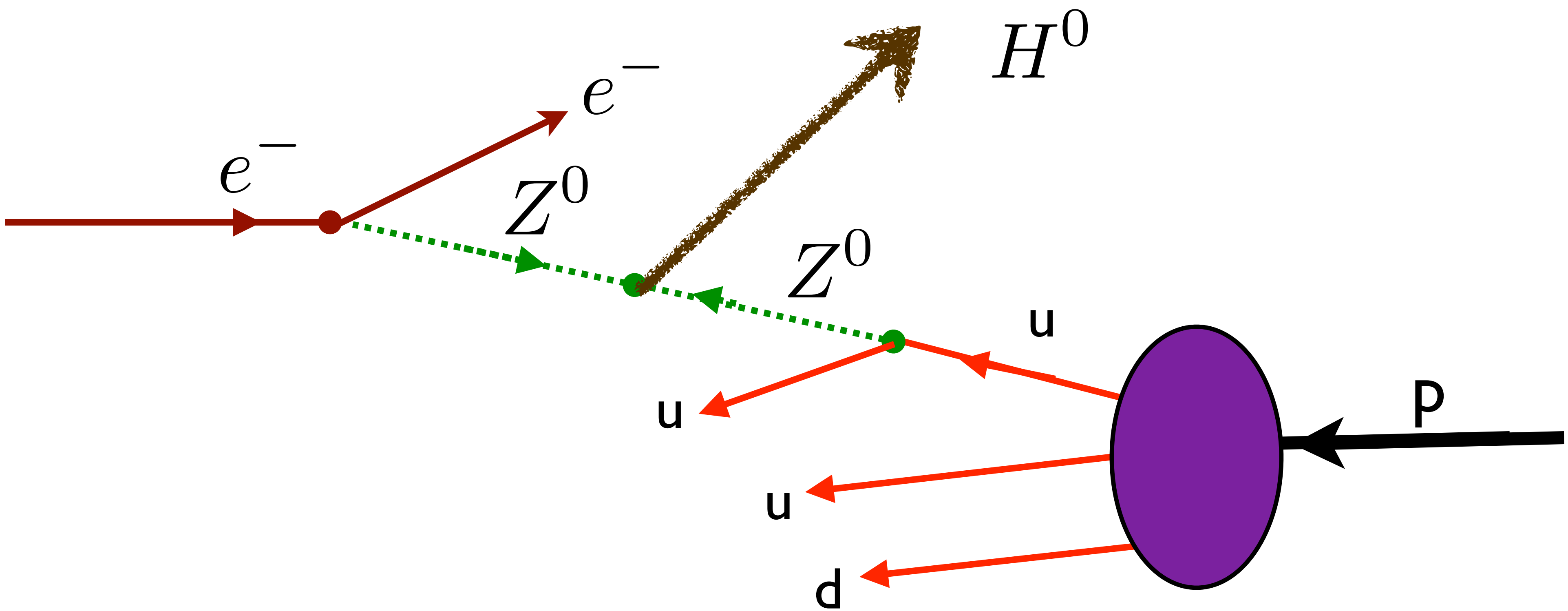
Only partially included by DGLAP in proton pdf

Strong enhancement at threshold

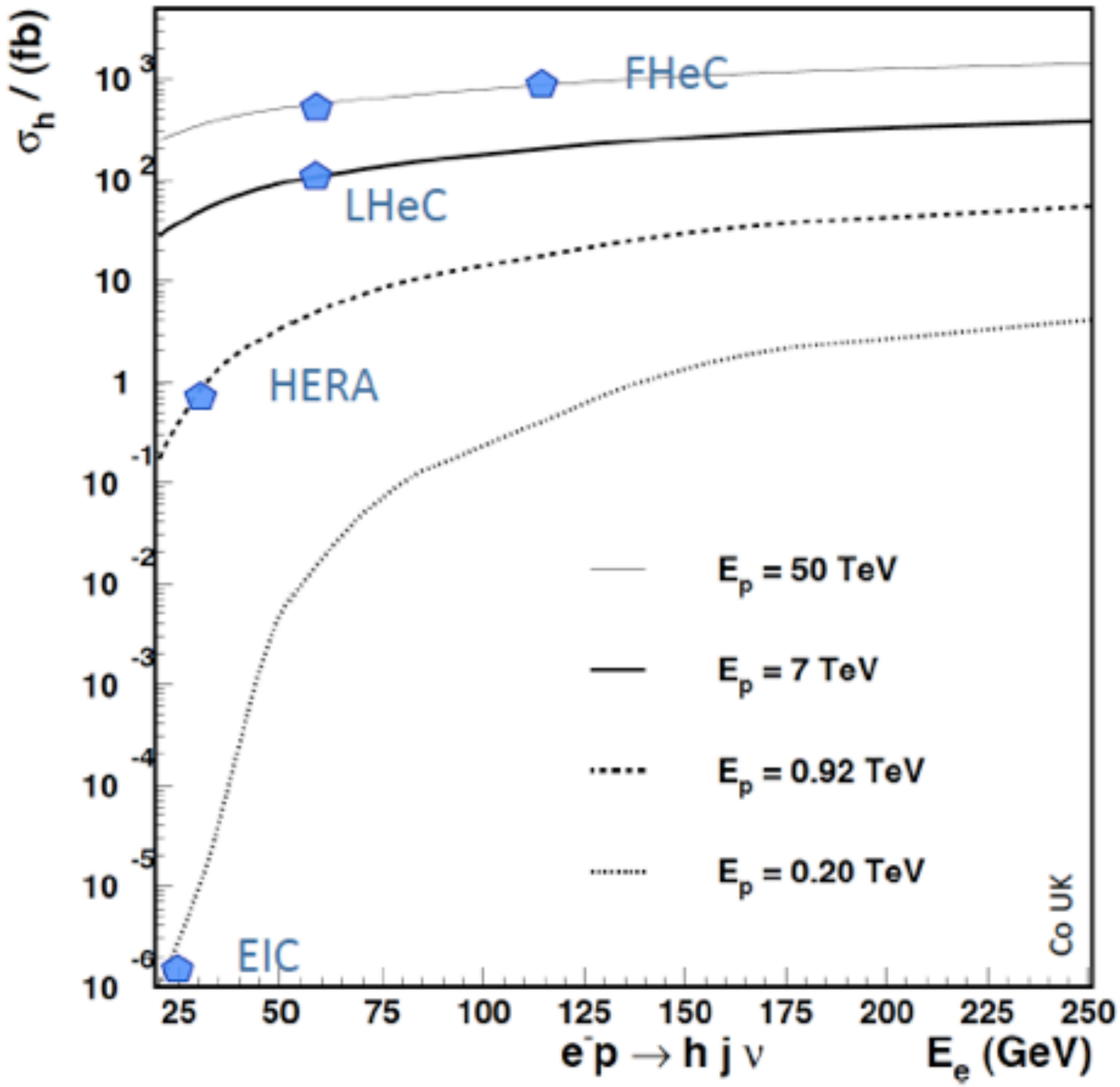
Inclusive Higgs Electroproduction at the LHeC from the Charged Current



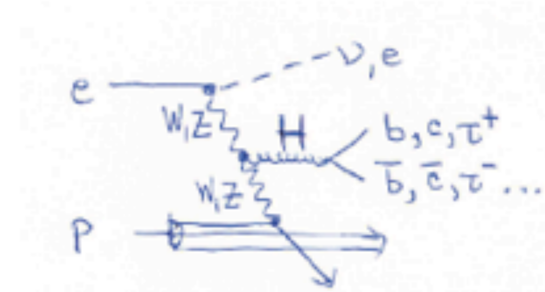
Inclusive Higgs Electroproduction at the LHeC from the Neutral Current



Higgs in Deep Inelastic Scattering



Charged current ep: Cross section as large as at TLEP/ILC



R. Godbole PRD 18 (78) 95

LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

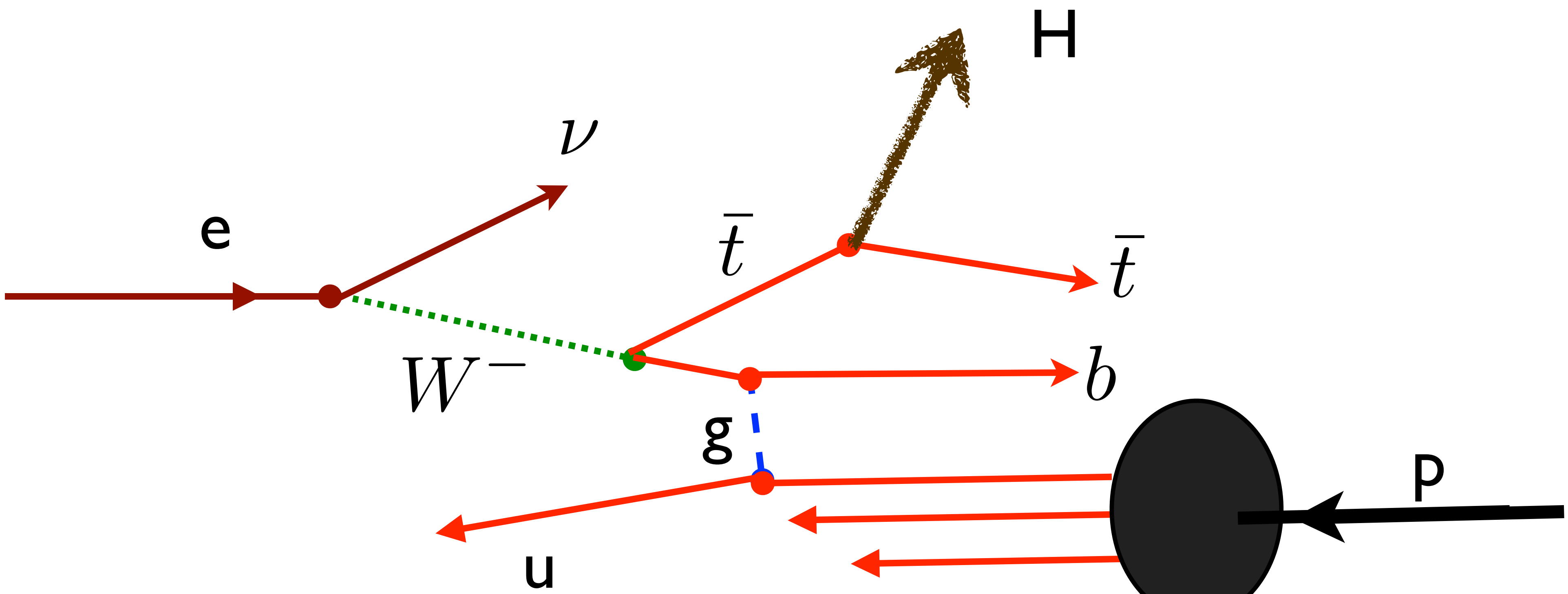
LHeC O(10^5) H from VBF

bb: S/N = 1: coupling to 1%

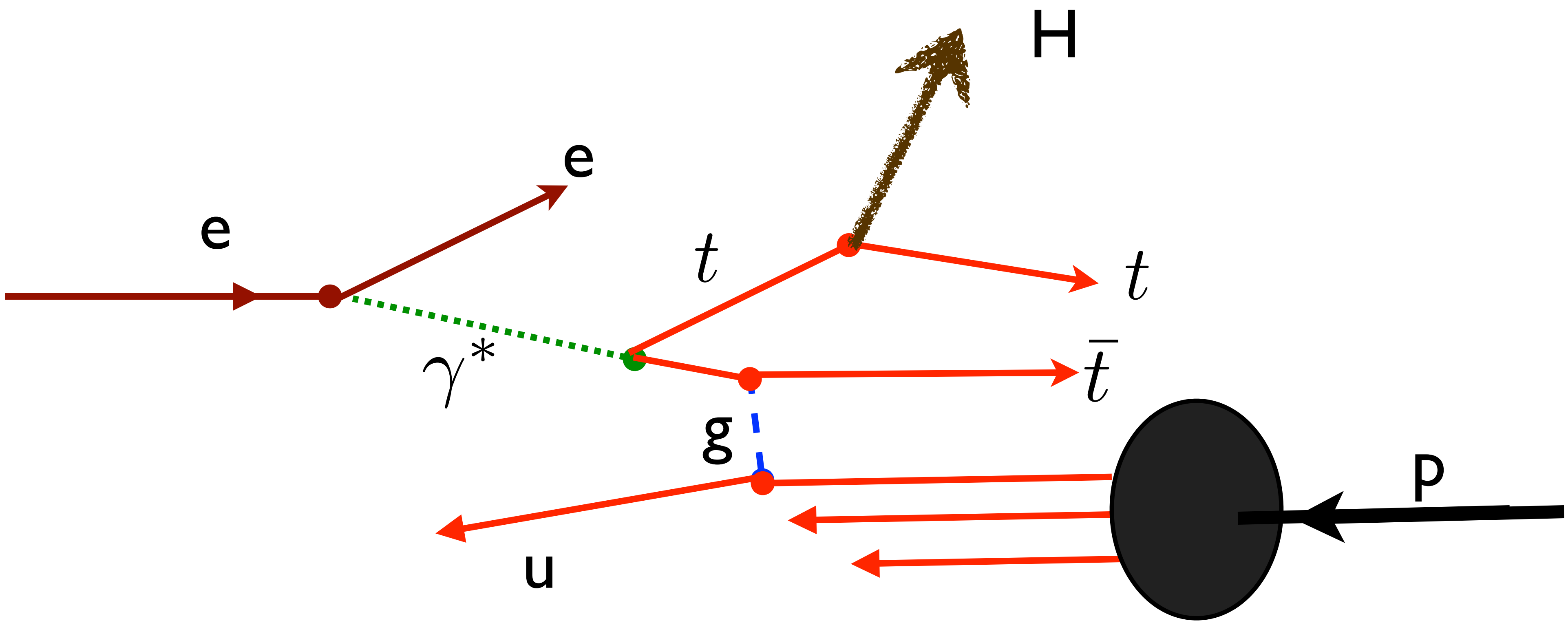
Under study cc, ττ, ... CP with LHeC detector takes much effort+time

Inclusive Higgs Electroproduction at the LHeC

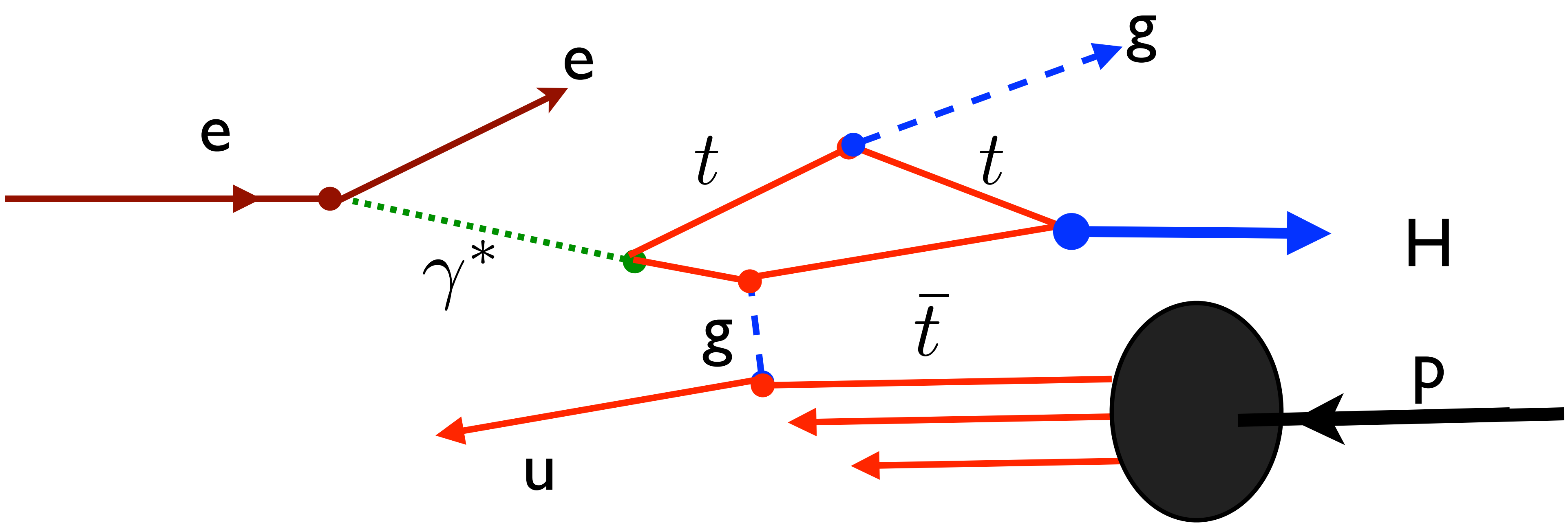
Higgs production from top



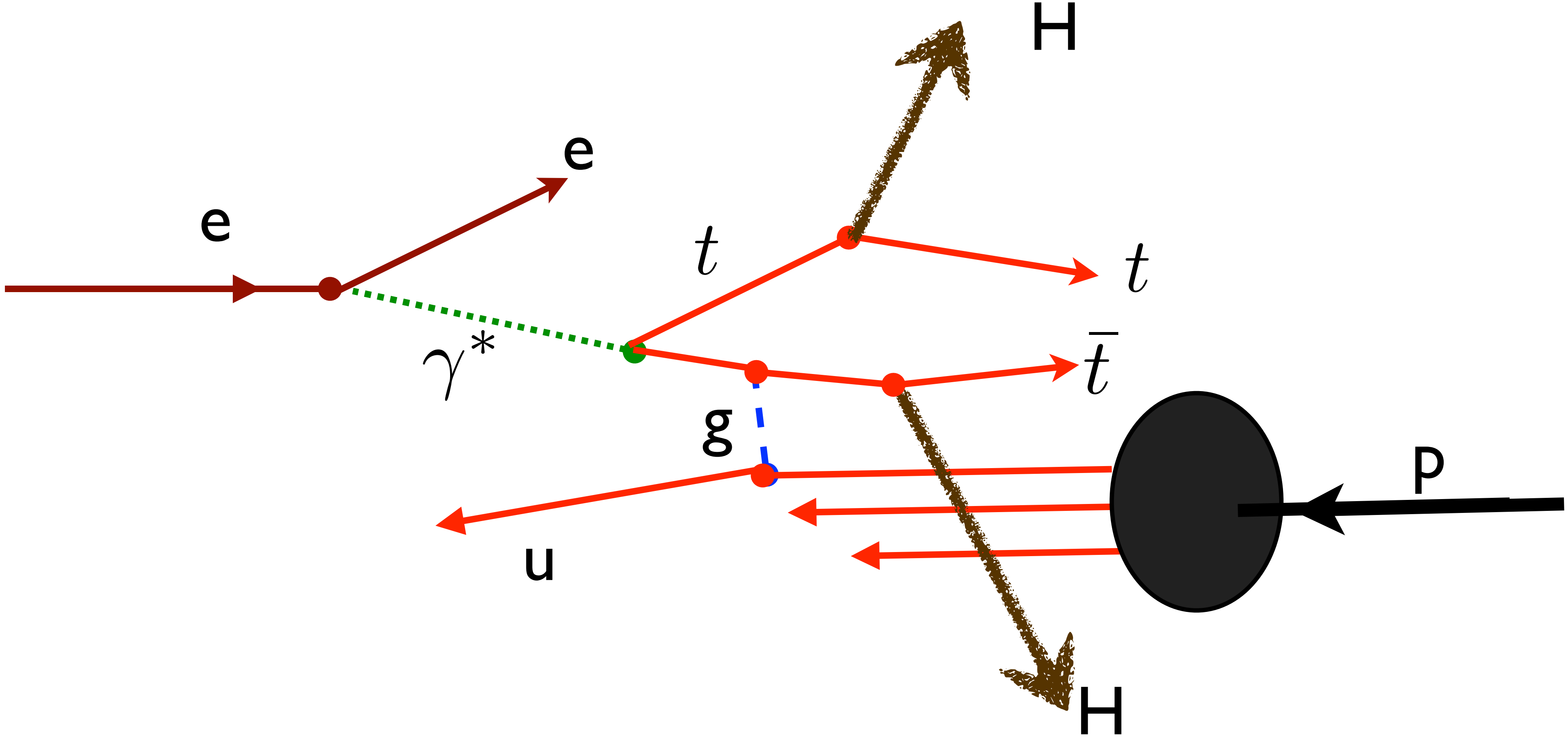
Inclusive Higgs Electroproduction at the LHeC



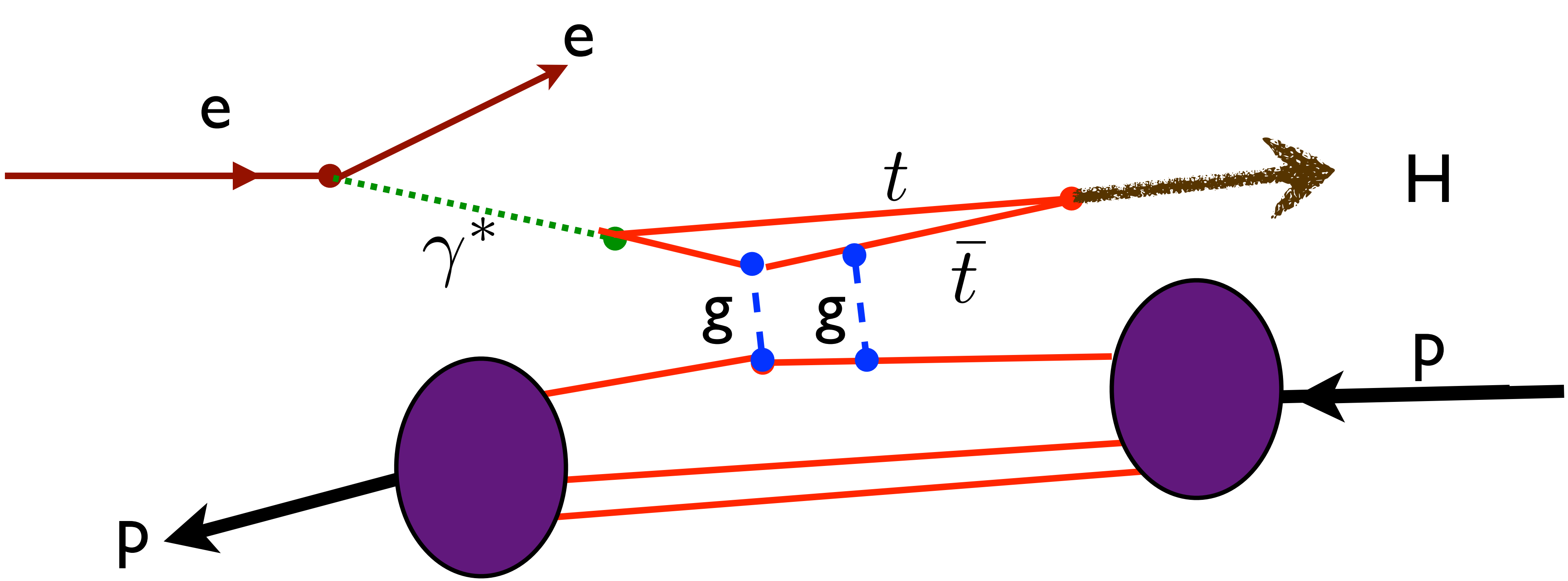
Inclusive Higgs Electroproduction at the LHeC



Inclusive Two-Higgs Electroproduction or photoproduction at the LHeC!

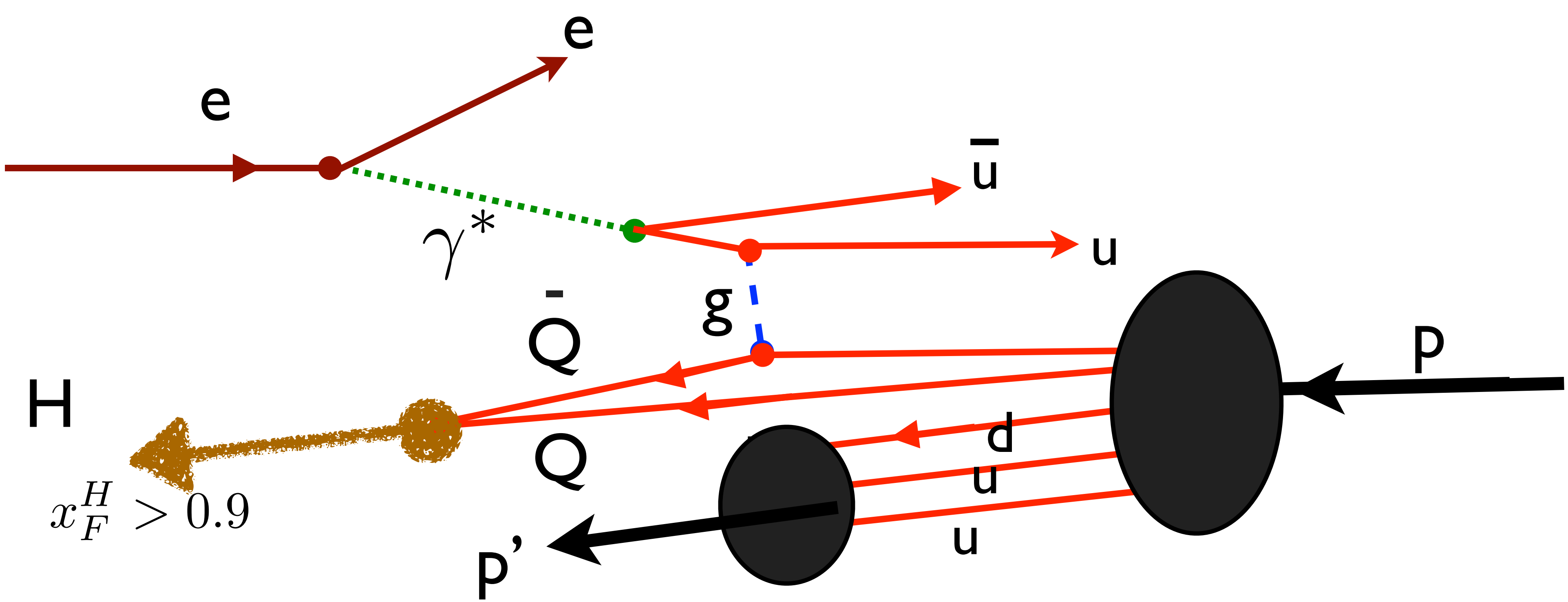


Diffractive Higgs Electroproduction at the LHeC

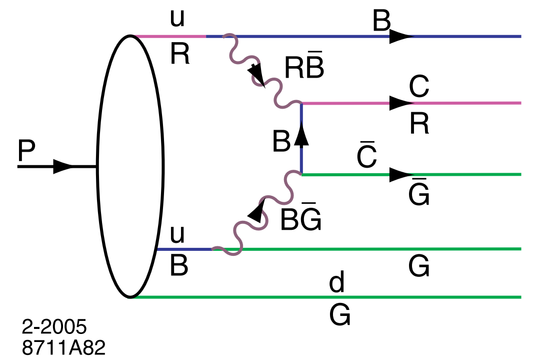


Kopeliovich, Schmidt, sjb

Diffractive Higgs Electroproduction at the LHeC from Intrinsic Heavy Quarks at very high x_F



Intrinsic Heavy-Quark Fock States



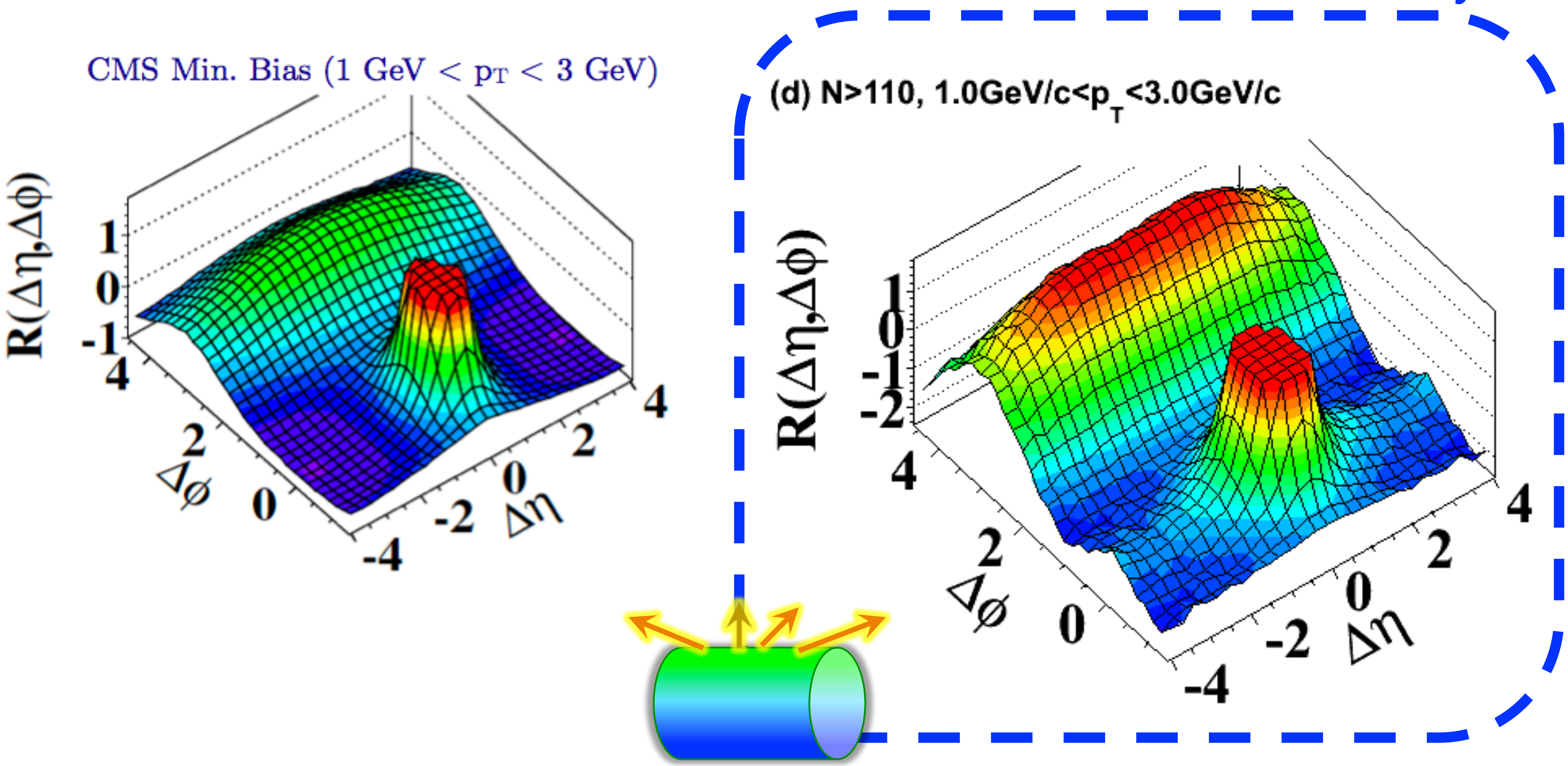
- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State!**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)**
- **Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)**

Ridge in p p collisions

Raju Venugopalan

Two particle correlations: CMS results

"Discovery"

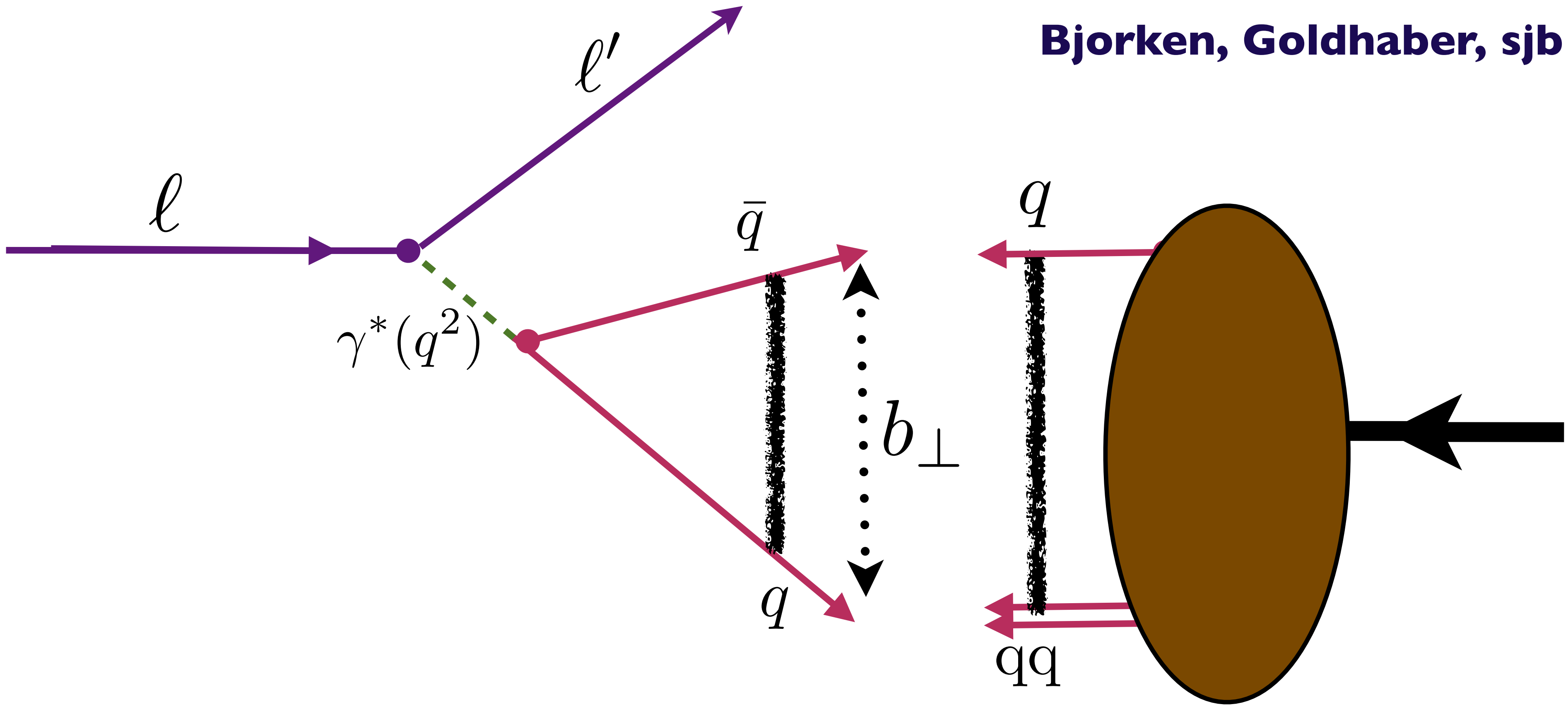


- Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate $1 < p_T, q_T < 3$ GeV

Scattered lepton produces flux-tube in lepton's scattering plane

Colliding flux-tubes produce opposite-side ridge of hadrons over full range of rapidity

Bjorken, Goldhaber, sjb



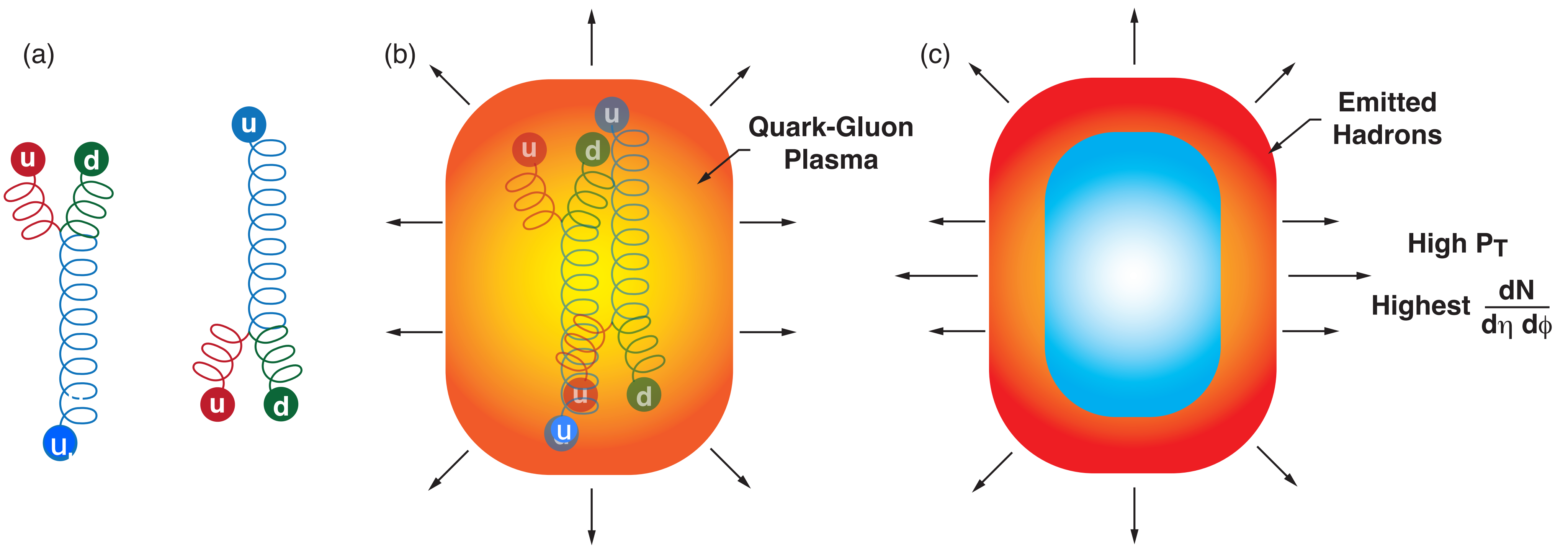
Ridge axes correlated with leptonic scattering plane

$$\langle b_\perp^2 \rangle \sim \frac{1}{Q^2 x(1-x) + M_t^2}$$

Small size domain activated

Possible origin of same-side CMS ridge in p p Collisions

Bjorken, Goldhaber, sjb



$$\vec{V} = \sum_{i=1}^{N} [\cos 2\phi_i \hat{x} + \sin 2\phi_i \hat{y}]$$

Bjorken, Goldhaber, sjb

Multiparticle ridge-like correlations in very high multiplicity proton-proton collisions

We suggest that this "ridge"-like correlations are a reflection of the rare events generated by the collision of aligned flux tubes connecting the valence quarks in the wave functions of the colliding protons.

The "spray" of particles resulting from the approximate line source produced in such inelastic collisions then gives rise to events with a strong correlation between particles produced over a large range of both positive and negative rapidity.

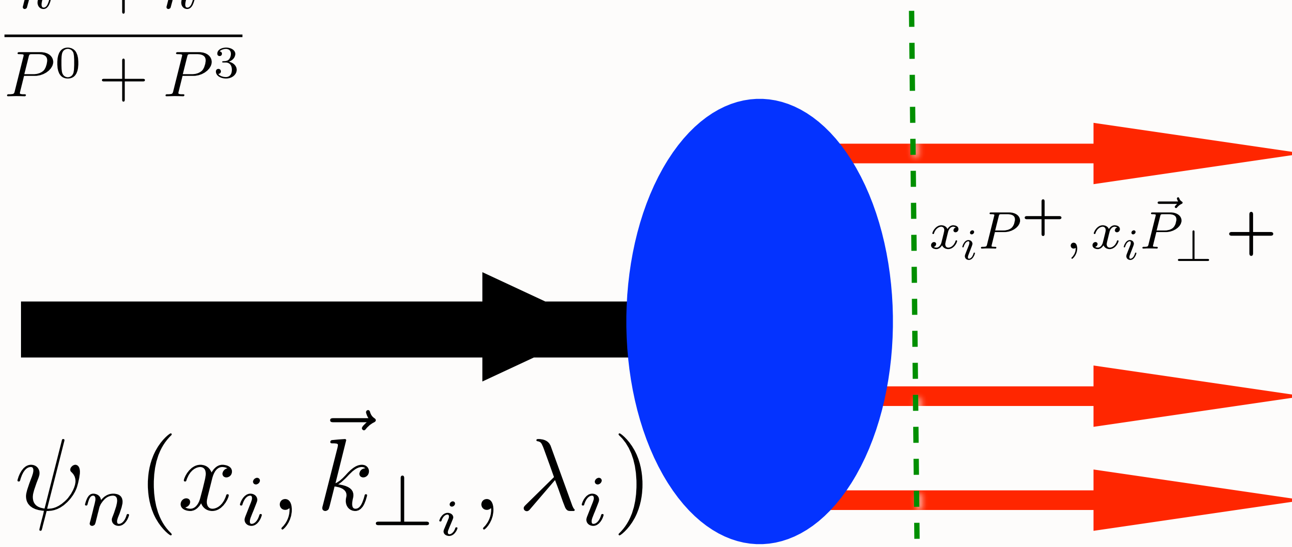
LHeC: Variable plane and photon size: enhanced sensitivity to ridge mechanism

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of LF Hamiltonian

Fixed $\tau = t + z/c$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

$P^+, \vec{P}_\perp$

$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

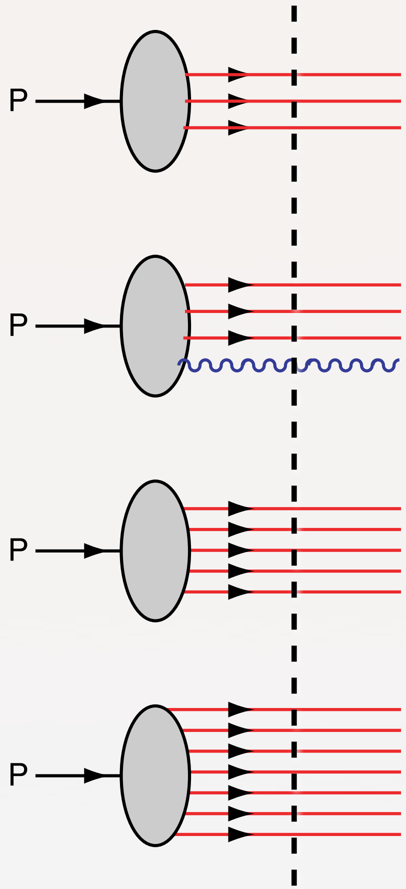
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Fixed LF time

Intrinsic heavy quarks

s(x), c(x), b(x) at high x !

$\bar{s}(x) \neq s(x)$

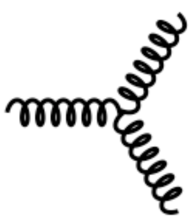
$\bar{u}(x) \neq \bar{d}(x)$

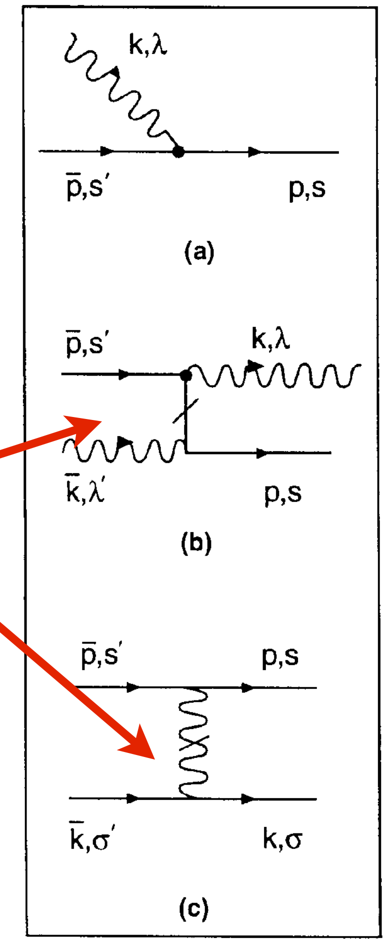
Mueller: gluon Fock states **BFKL Pomeron**

Hidden Color

$$\mathcal{L}_{QCD} = -\frac{1}{4} Tr(G^{\mu\nu} G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$\begin{aligned}
H^{LF}_{QCD} &= \frac{1}{2}\int d^3x \overline{\tilde{\psi}} \gamma^+ \frac{(\mathrm{i}\partial^\perp)^2 + m^2}{\mathrm{i}\partial^+} \tilde{\psi} - A^i_a (\mathrm{i}\partial^\perp)^2 A_{ia} \\
&- \frac{1}{2} g^2 \int d^3x \mathbf{Tr}\left[\tilde{A}^\mu, \tilde{A}^\nu\right]\left[\tilde{A}_\mu, \tilde{A}_\nu\right] \\
&+ \frac{1}{2} g^2 \int d^3x \overline{\tilde{\psi}} \gamma^+ T^a \tilde{\psi} \frac{1}{(\mathrm{i}\partial^+)^2} \overline{\tilde{\psi}} \gamma^+ T^a \tilde{\psi} \\
&- g^2 \int d^3x \overline{\tilde{\psi}} \gamma^+ \left(\frac{1}{(\mathrm{i}\partial^+)^2}\left[\mathrm{i}\partial^+ \tilde{A}^\kappa, \tilde{A}_\kappa\right]\right) \tilde{\psi} \\
&+ g^2 \int d^3x \mathbf{Tr}\left(\left[\mathrm{i}\partial^+ \tilde{A}^\kappa, \tilde{A}_\kappa\right] \frac{1}{(\mathrm{i}\partial^+)^2}\left[\mathrm{i}\partial^+ \tilde{A}^\kappa, \tilde{A}_\kappa\right]\right) \\
&+ \frac{1}{2} g^2 \int d^3x \overline{\tilde{\psi}} \tilde{\not{A}} \frac{\gamma^+}{\mathrm{i}\partial^+} \tilde{\not{A}} \tilde{\psi} \\
&+ g \int d^3x \overline{\tilde{\psi}} \tilde{\not{A}} \tilde{\psi} \\
&+ 2g \int d^3x \mathbf{Tr}\left(\mathrm{i}\partial^\mu \tilde{A}^\nu \left[\tilde{A}_\mu, \tilde{A}_\nu\right]\right)
\end{aligned}$$





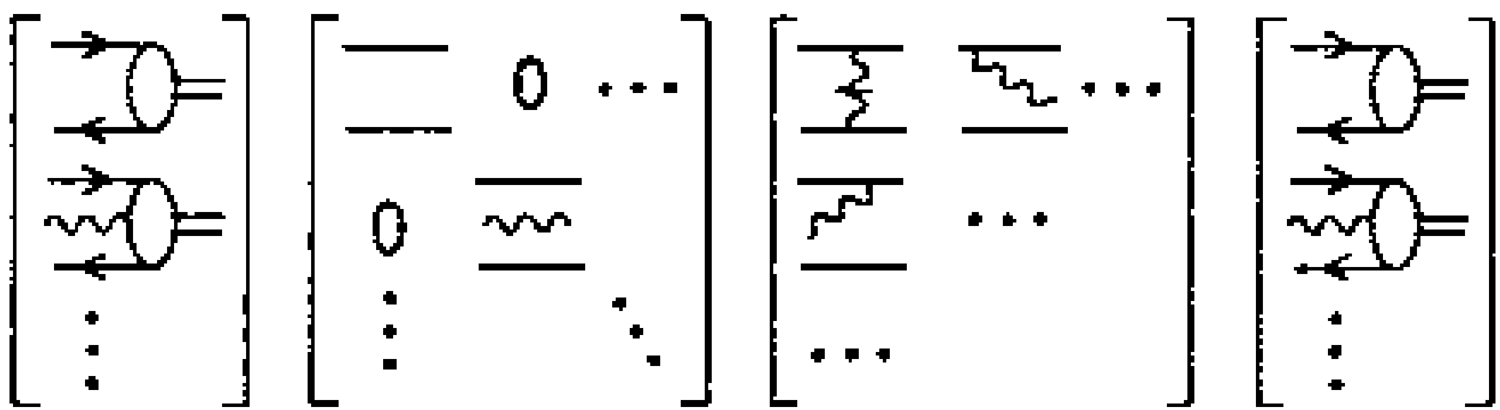
Rigorous First-Principle Formulation of Non-Perturbative QCD

LIGHT-FRONT MATRIX EQUATION

Rigorous Method for Solving Non-Perturbative QCD!

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^{\,2} + m_i^2}{x_i}\right) \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\, V\, |q\bar{q}\rangle & \langle q\bar{q}|\, V\, |q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\, V\, |q\bar{q}\rangle & \langle q\bar{q}g|\, V\, |q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix}$$

$A^+ = 0$



Minkowski space; frame-independent; no fermion doubling; no ghosts

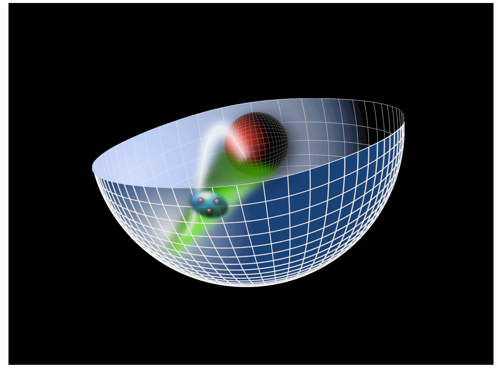
- Light-Front Vacuum = vacuum of free Hamiltonian!

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent
fundamental mass scale

κ



$$\zeta^2 = x(1-x)\mathbf{b}^2_\perp .$$

Light-Front Holography

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique
Confinement Potential!

Conformal Symmetry
of the action

Confinement scale:

(m_q=0)

$$\kappa \simeq 0.6 \ GeV$$

$$1/\kappa \simeq 1/3 \ fm$$

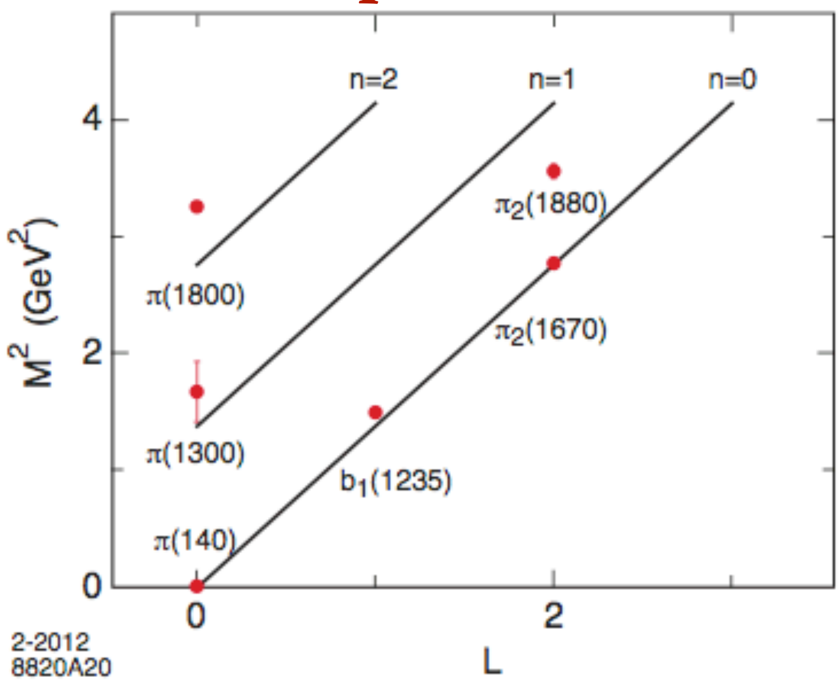
- **de Alfaro, Fubini, Furlan:** Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

- $J = L + S, I = 1$ meson families $\mathcal{M}^2_{n,L,S} = 4\kappa^2 \left(n + L + S/2\right)$

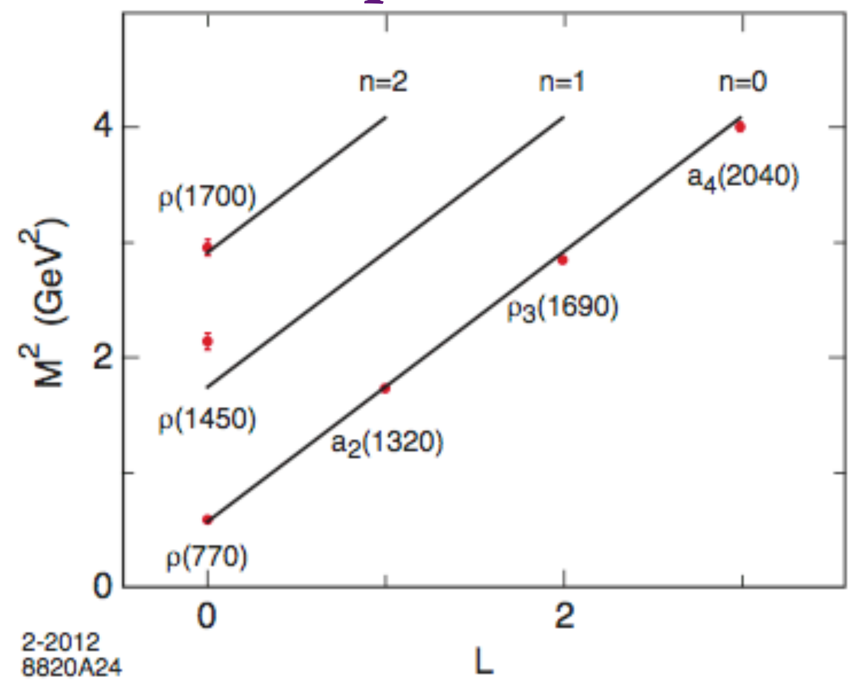
$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

$$m_q = 0$$

Massless pion in Chiral Limit!



Same slope in n and L!



I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

- Triplet splitting for the $I = 1$, $L = 1$, $J = 0, 1, 2$, vector meson a-states

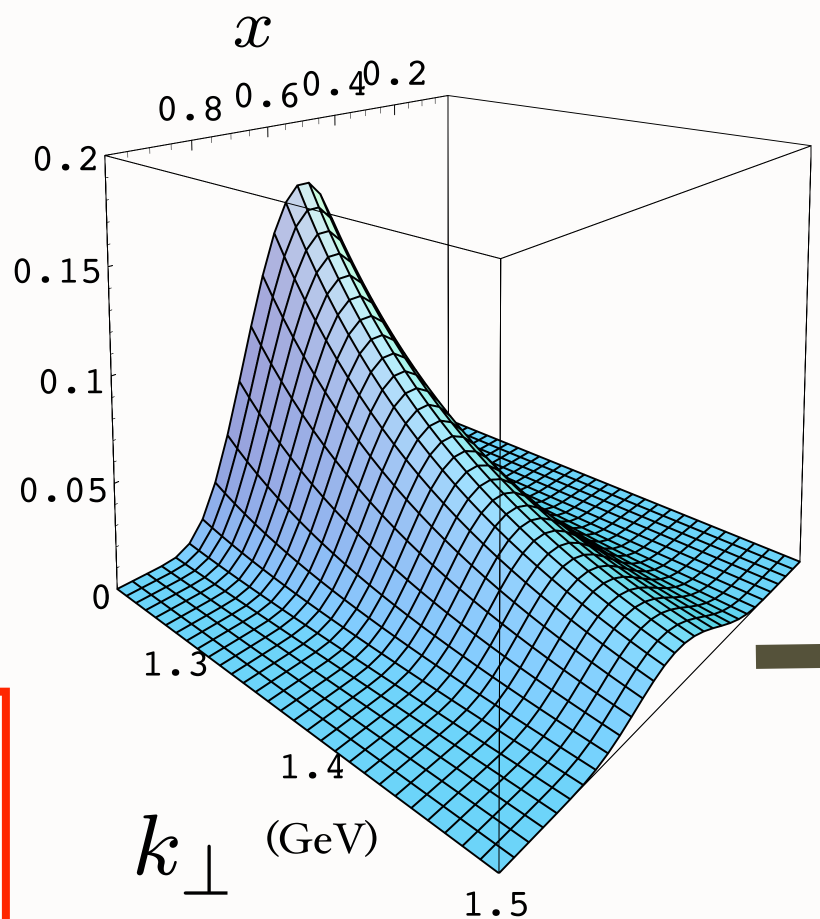
$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

Mass ratio of the ρ and the a_1 mesons: coincides with Weinberg sum rules

G. de Teramond, H. G. Dosch, sjb

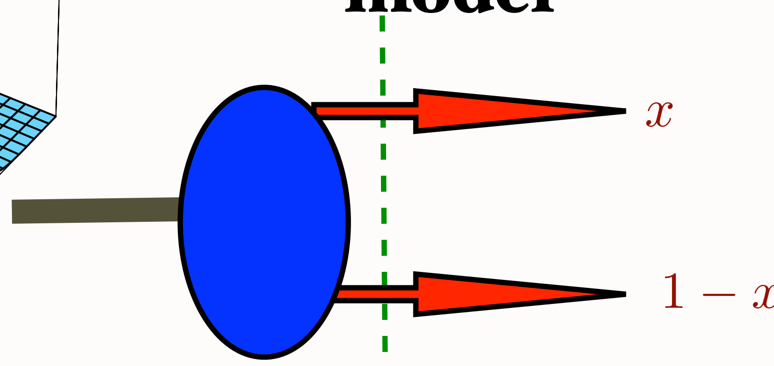
Prediction from AdS/QCD: Meson LFWF

$\psi_M(x, k_\perp^2)$



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling $k_\perp^2, x$

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

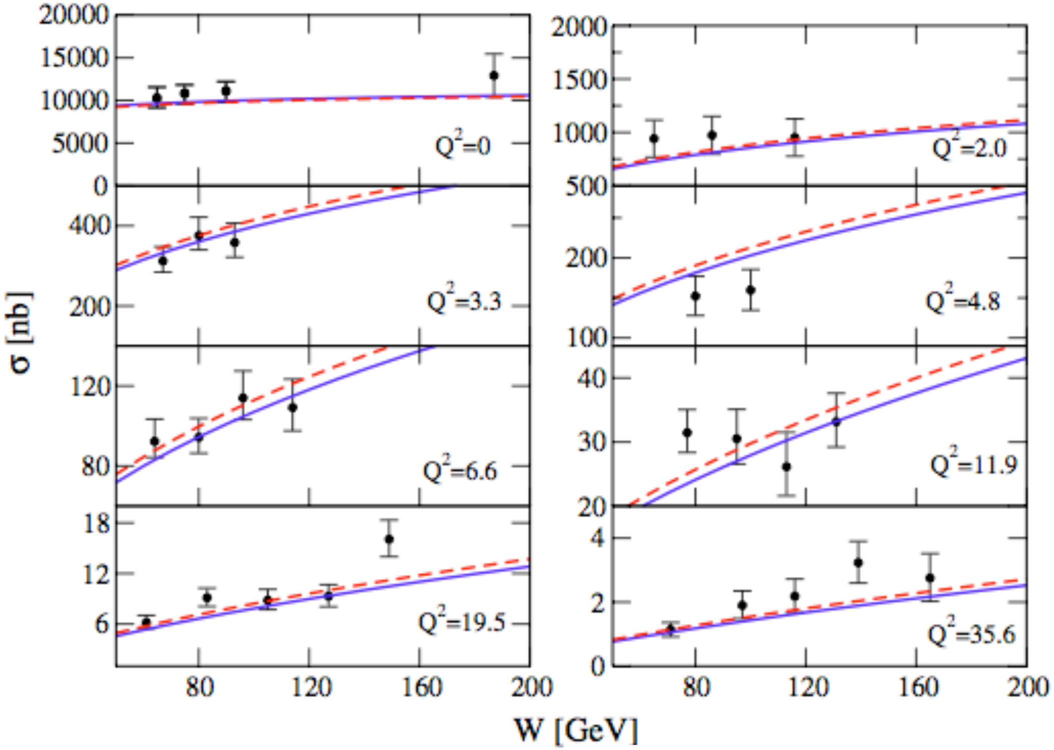
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

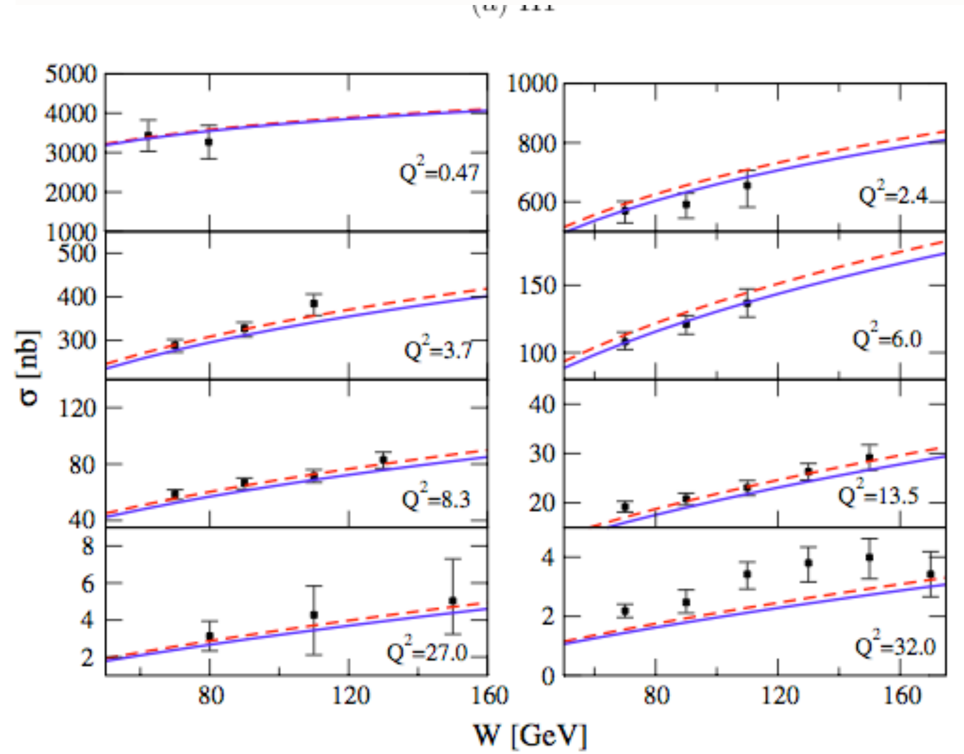
Provides Connection of Confinement to Hadron Structure

PRL 109, 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction



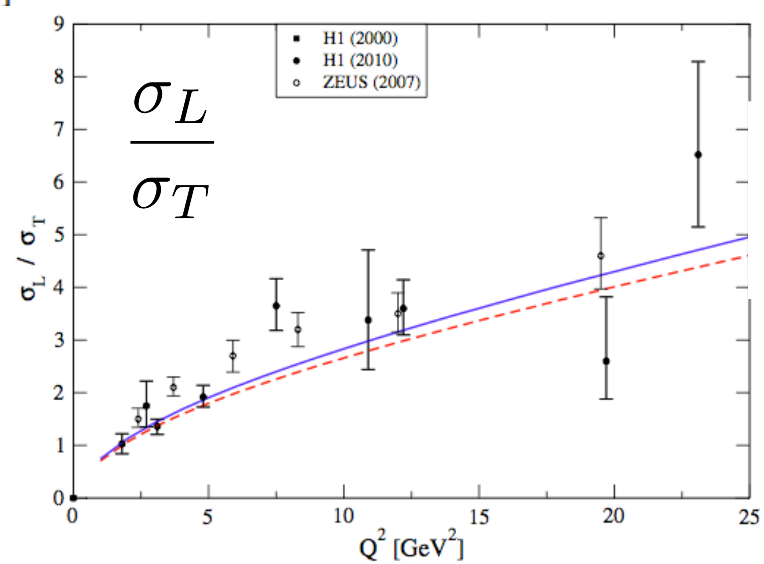
(a) H



(b) ZEUS

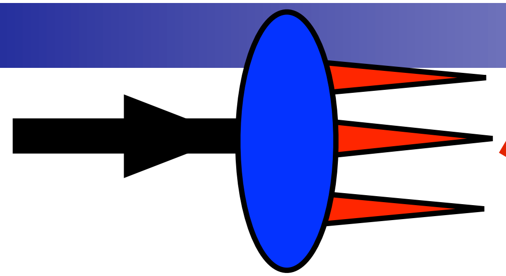
J. R. Forshaw,
R. Sandapen

$$\gamma^* p \to \rho^0 p'$$

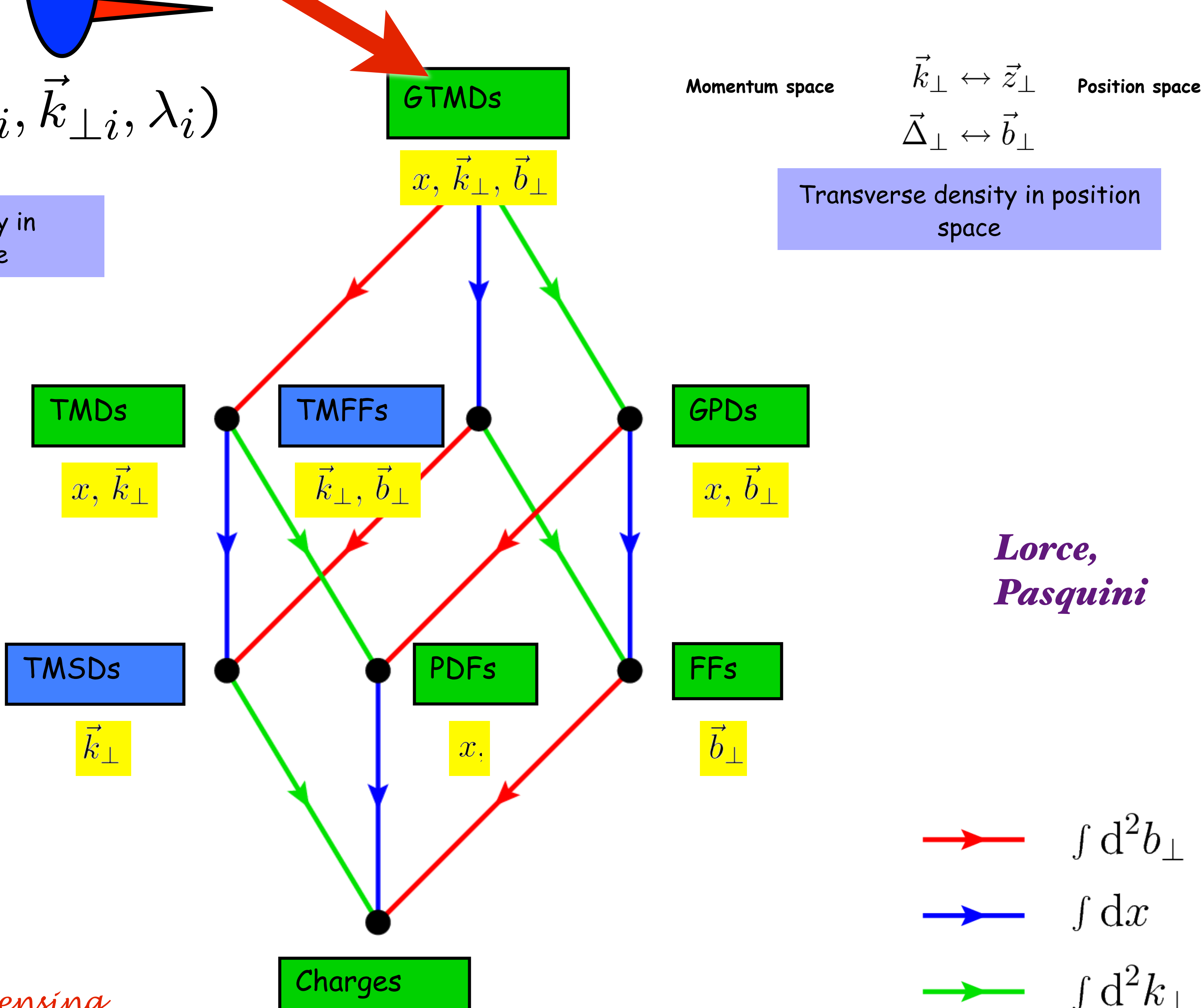


$$\tilde{\phi}(x, k) \propto \frac{1}{\sqrt{x(1-x)}} \exp\left(-\frac{M_{q\bar{q}}^2}{2\kappa^2}\right),$$

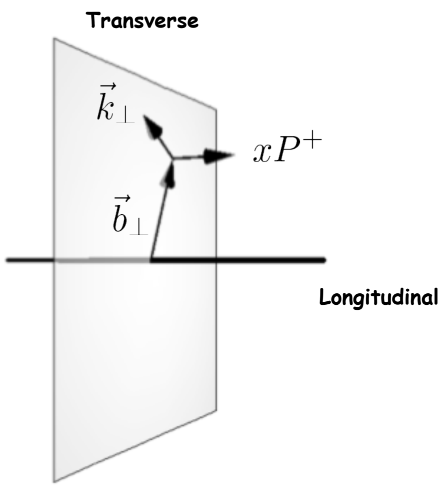
- *Light Front Wavefunctions:*



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Lorce, Pasquini

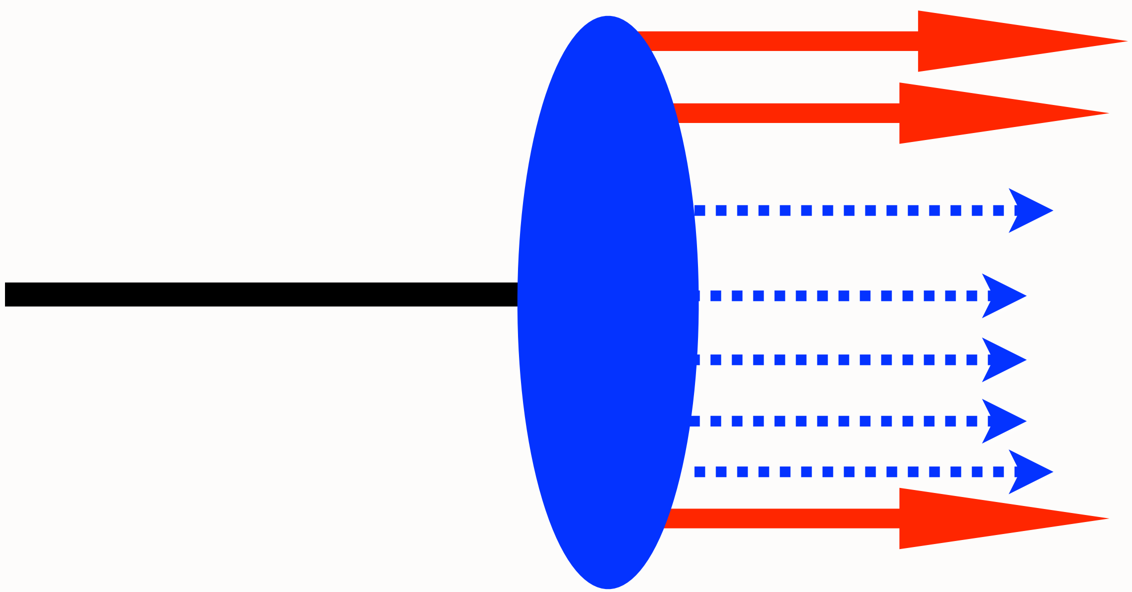


Sivers, T-odd from lensing

Soft gluons in the infinite momentum wave function and the BFKL pomeron.
Alfred H. Mueller (SLAC & Columbia U.) . SLAC-PUB-10047, CU-TP-609, Aug 1993. 12pp.
Published in **Nucl.Phys.B415:373-385,1994**.

Light cone wave functions at small x.
F. Antonuccio (Heidelberg, Max Planck Inst. & Heidelberg U.) , S.J. Brodsky (SLAC) , S. Dalley (CERN) .
Phys.Lett.B412:104-110,1997.
e-Print: **hep-ph/9705413**

Mueller: BFKL derived from multi-gluon Fock State



Antonuccio, Dalley, sjb: Ladder Relations

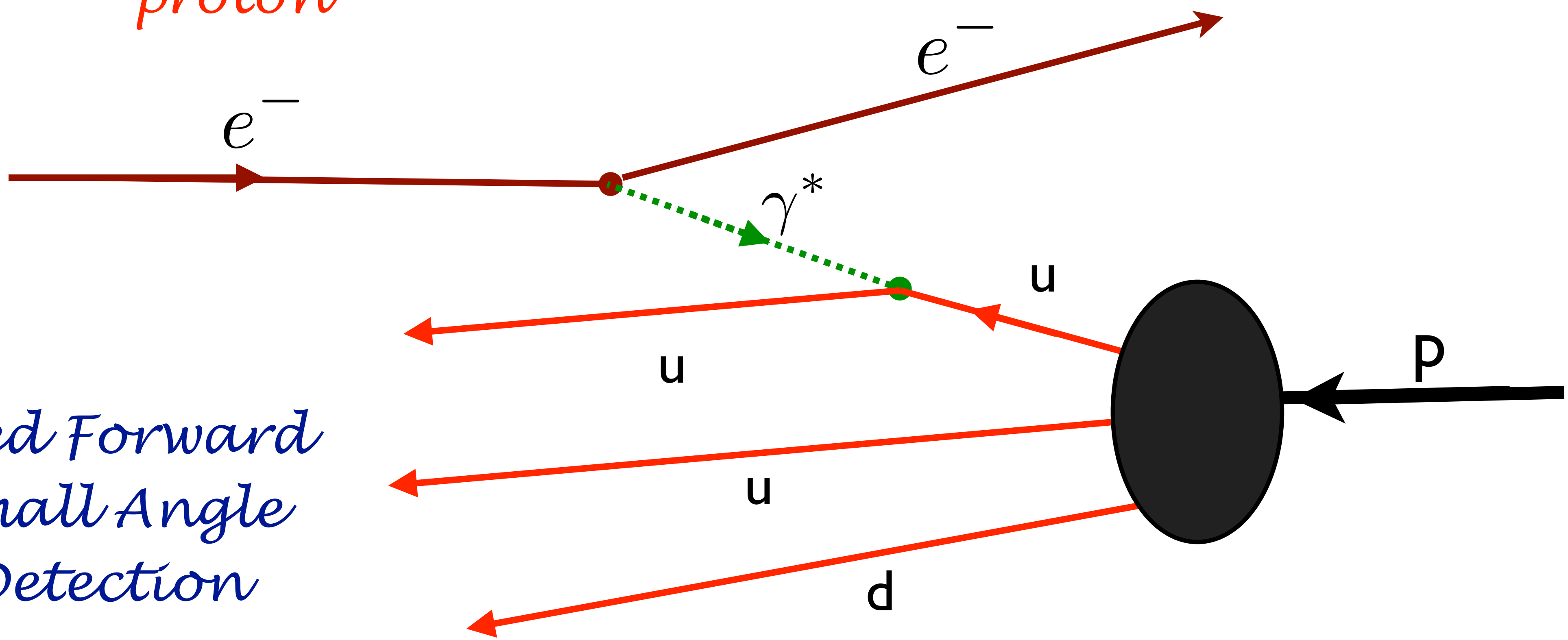
Coulomb Exchange analogous to diffractive excitation *Ashery, et al*

Electromagnetic Tri-Jet Excitation of Proton

$$ep \to e \text{ jet jet jet}$$

Measure light-front wavefunction of proton

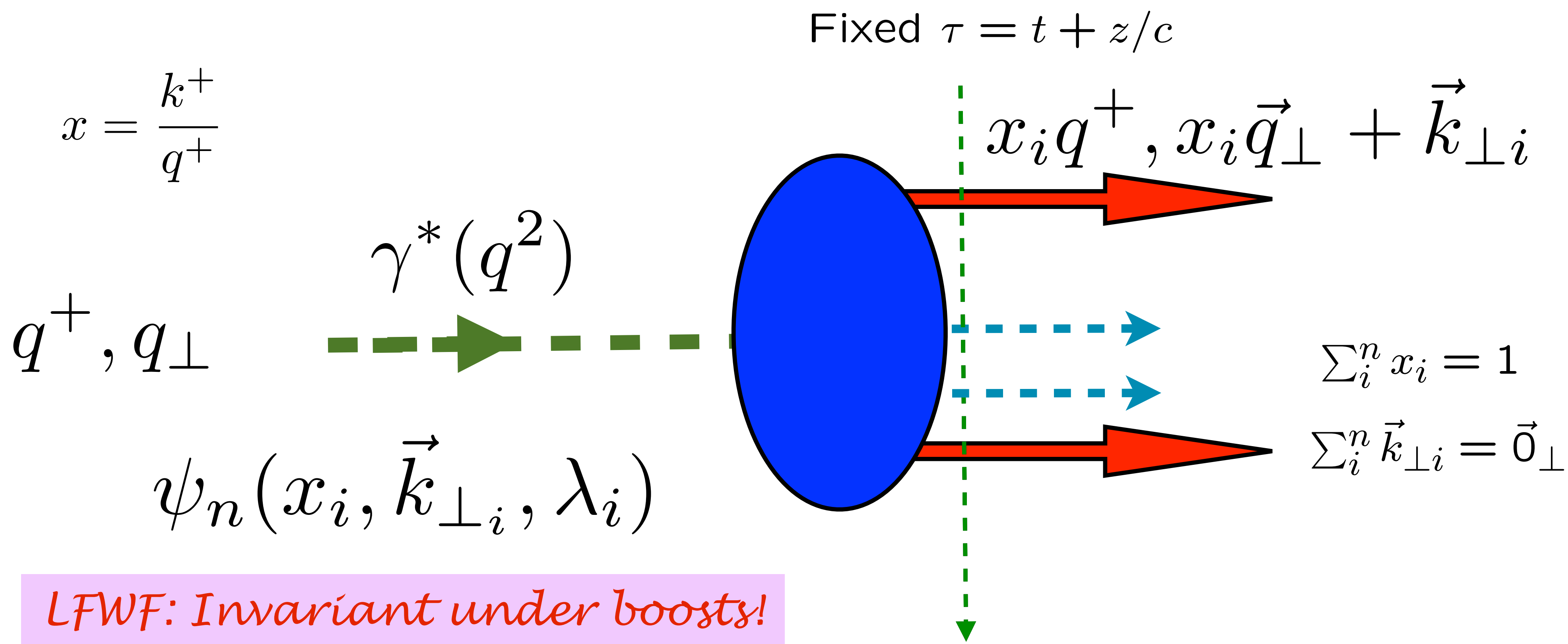
$$\frac{\partial}{\partial k_\perp} \Psi^p_{n=3}(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Need Forward Small Angle Detection

Light-Front Wavefunctions of Virtual Photon

Virtual photon has space-like mass $q^2 = -Q^2 < 0$

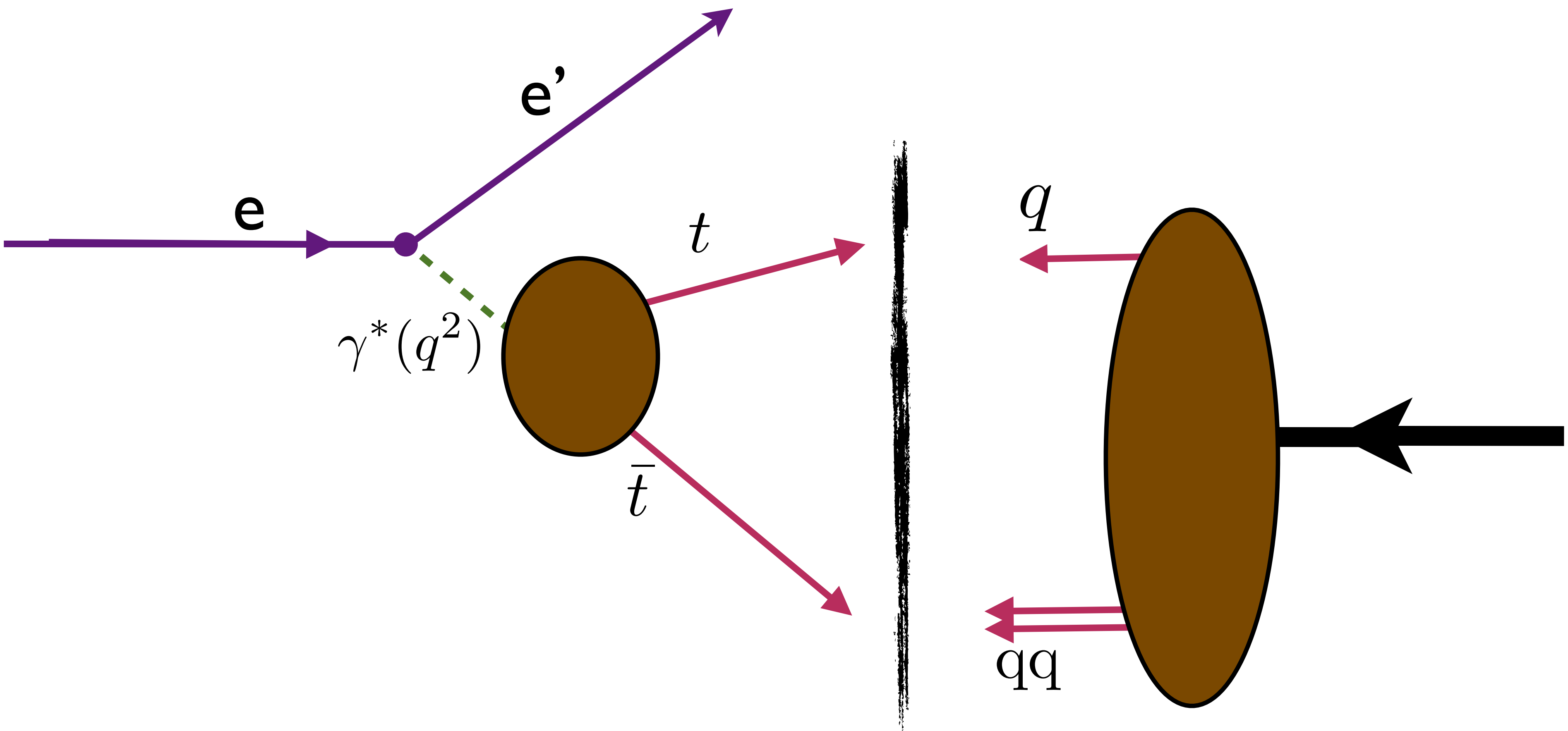


Feynman virtuality from sum over all electron LF time-orderings

$$q^2 = q^+ q^- - \vec{q}_\perp^{\,2}$$

Scattered lepton produces a virtual top-quark pair in lepton's scattering plane

Factorization: Product of LFWFs

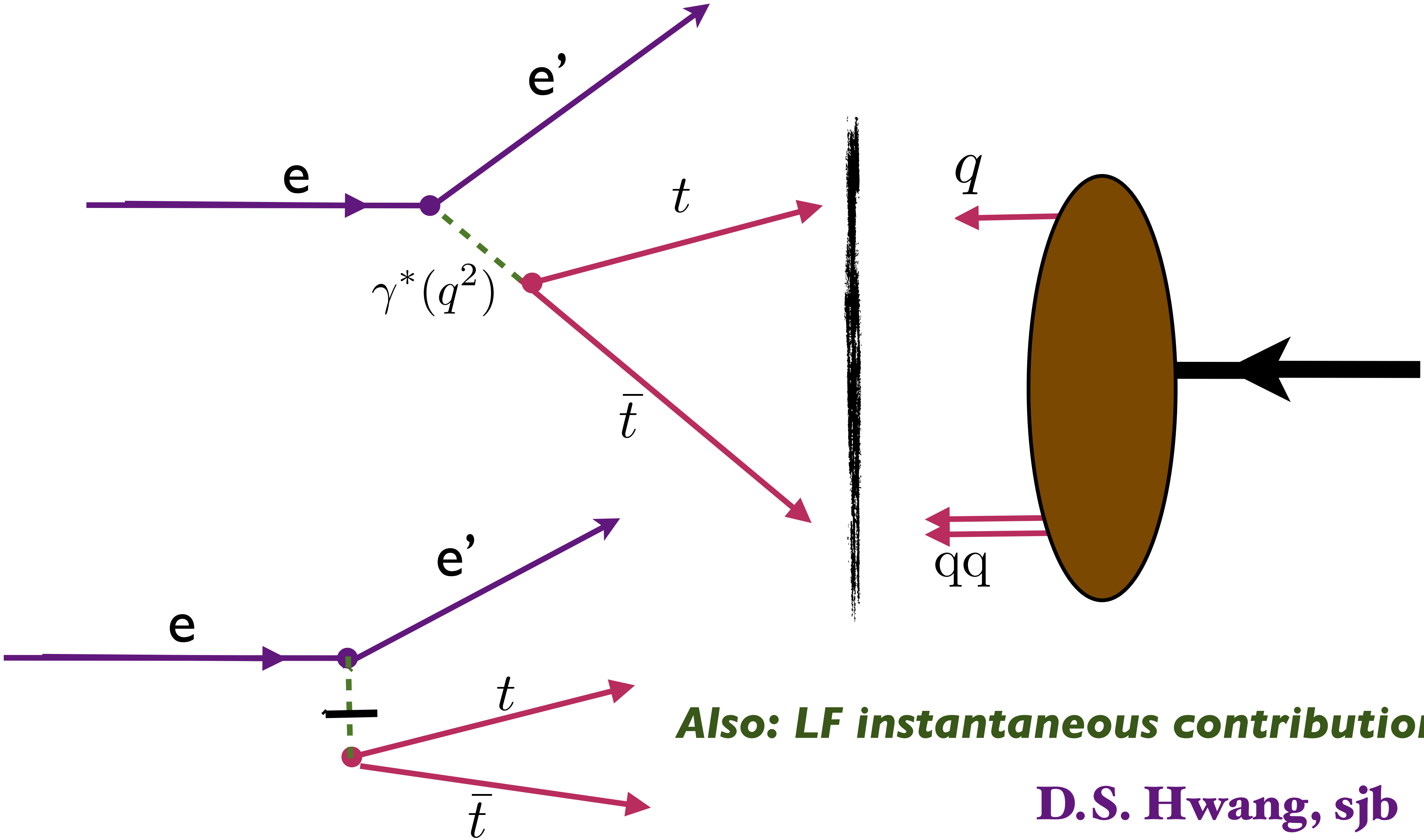


Forward rapidity in final state: Intrinsic to Virtual Photon

Backward in final state: Intrinsic to Proton

Scattered lepton produces a virtual top-quark pair in lepton's scattering plane

Factorization: Product of LFWFs

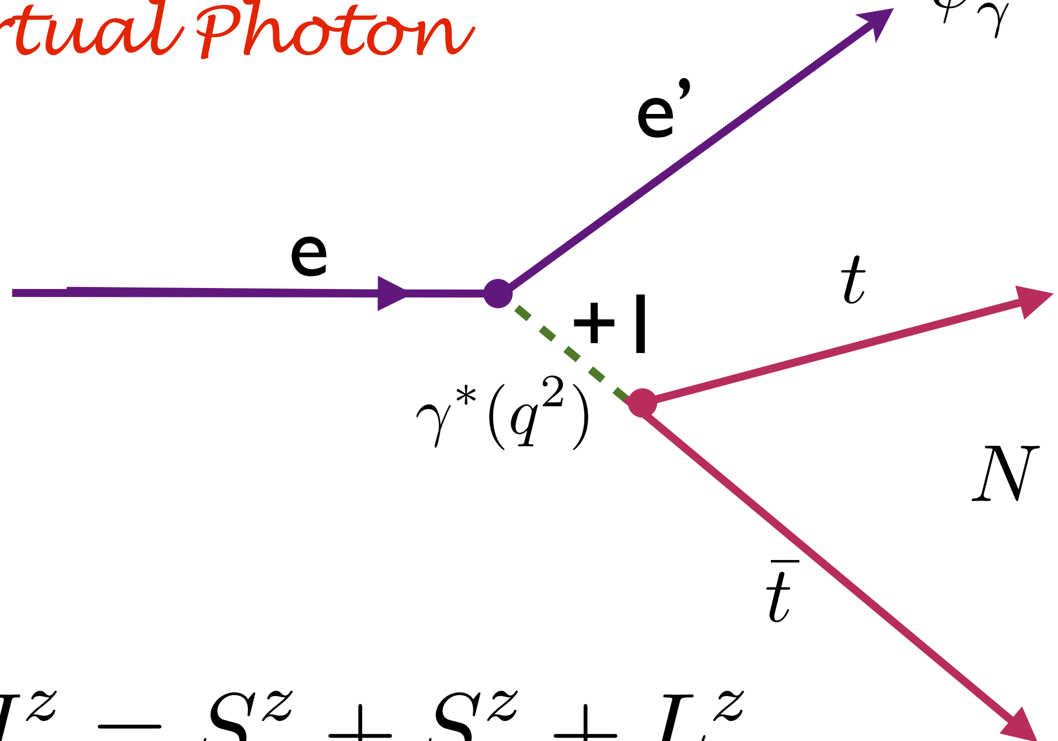


Also: LF instantaneous contribution

D.S. Hwang, sjb

Scattered lepton produces a virtual top-quark pair in lepton's scattering plane

Born LFWFs of Virtual Photon



$$\psi^*_\gamma = \frac{N}{Q^2(1-x)+k_\perp^2+m_t^2}$$

$$N = \sqrt{2}e_q(1-x)(k_x - ik_y)$$

L^z=+1

$$J^z = S^z_q + S^z_{\bar{q}} + L^z$$

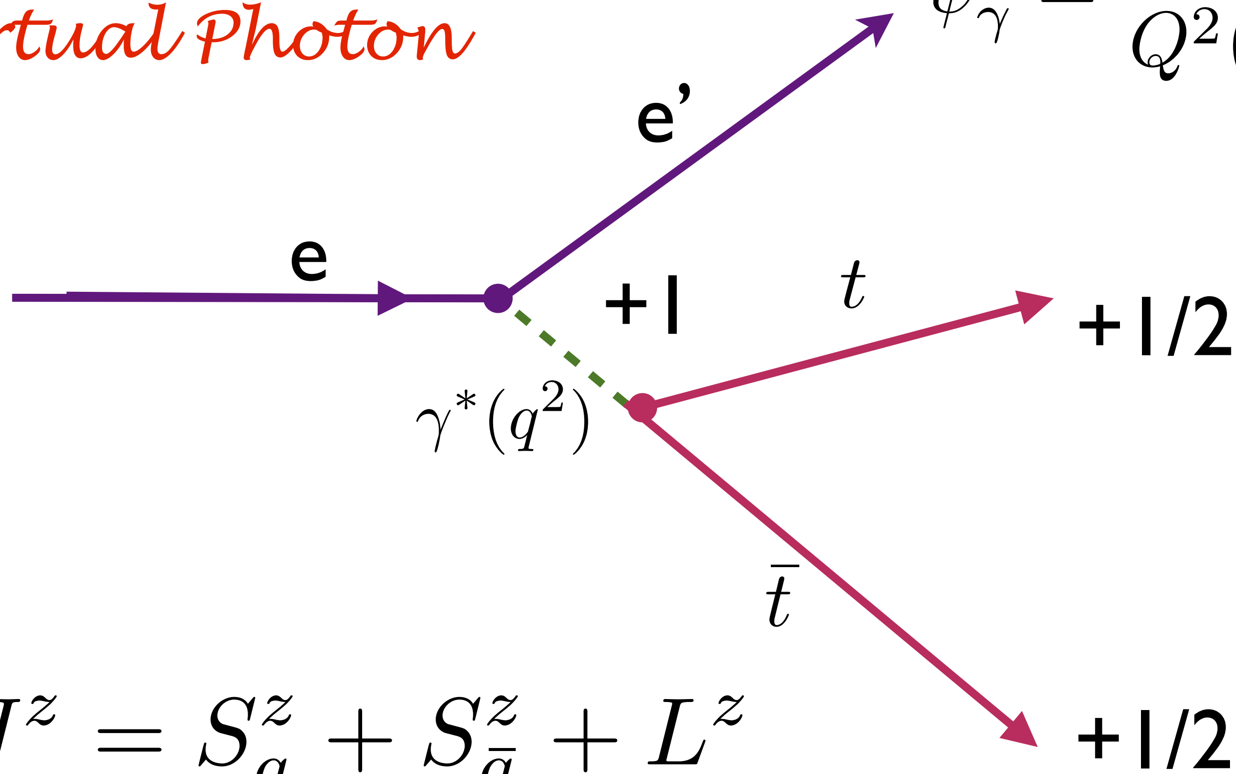
$$+1 \rightarrow (1/2) + (-1/2) + 1$$

D.S. Hwang, sjb

Witten evolution of Photon Structure Function!

Scattered lepton produces a virtual top-quark pair in lepton's scattering plane

Born LFWFs of Virtual Photon



$$\psi^*_\gamma = \frac{N}{Q^2(1-x) + k_\perp^2 + m_t^2}$$

$$N = \sqrt{2} e_q m_t$$

L^z=0

$$J^z = S^z_q + S^z_{\bar{q}} + L^z$$

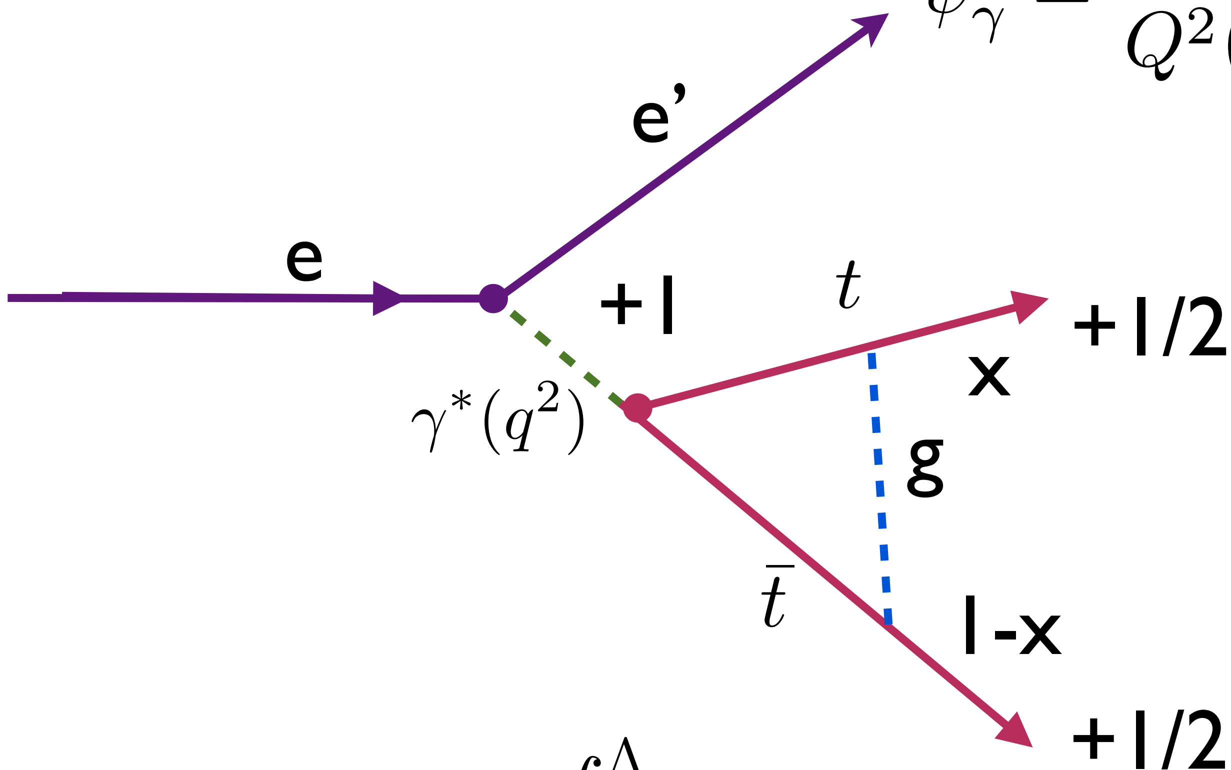
$$+1 \to (1/2) + (1/2) + 0$$

DGLAP evolution of Photon Structure Function!

Kinoshita, Terazawa, sjb

Scattered lepton produces a virtual top-quark pair in lepton's scattering plane

$$\psi^*_\gamma = \frac{N}{Q^2(1-x)+k_\perp^2+m_t^2}$$



$$N = \sqrt{2} e_q m_t$$

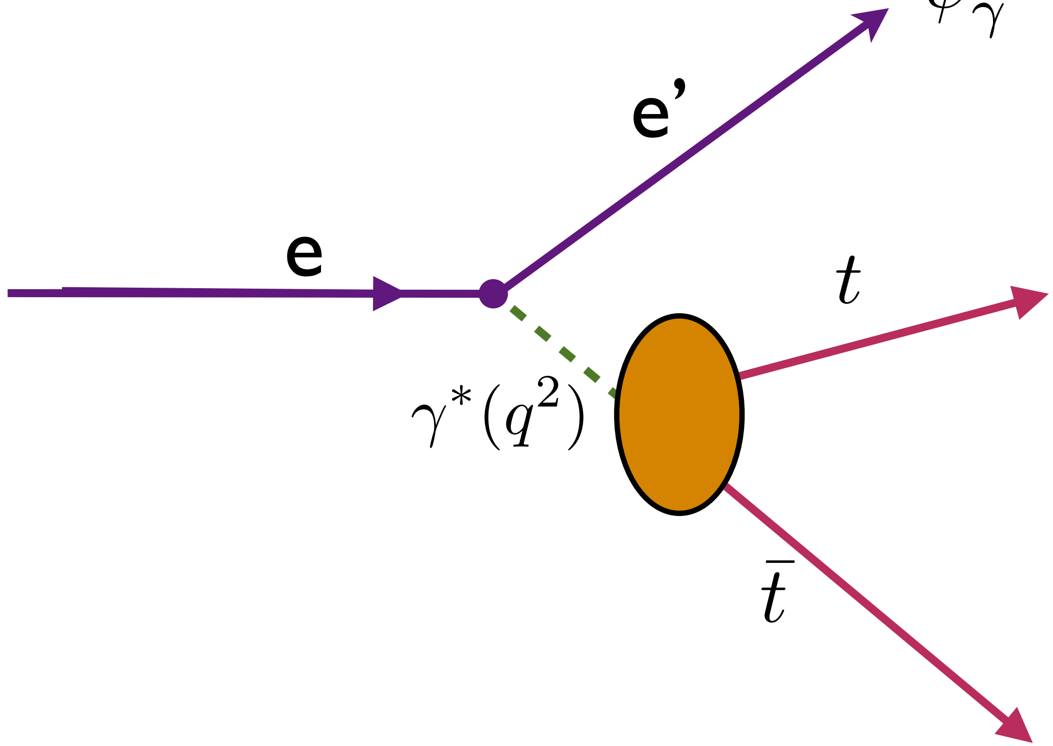
$L^z=0$

$$\phi^*_\gamma(x,Q^2,\Lambda^2) = \int^\Lambda d^2k_\perp \psi_{\gamma^*}(x,k_\perp,Q^2)$$

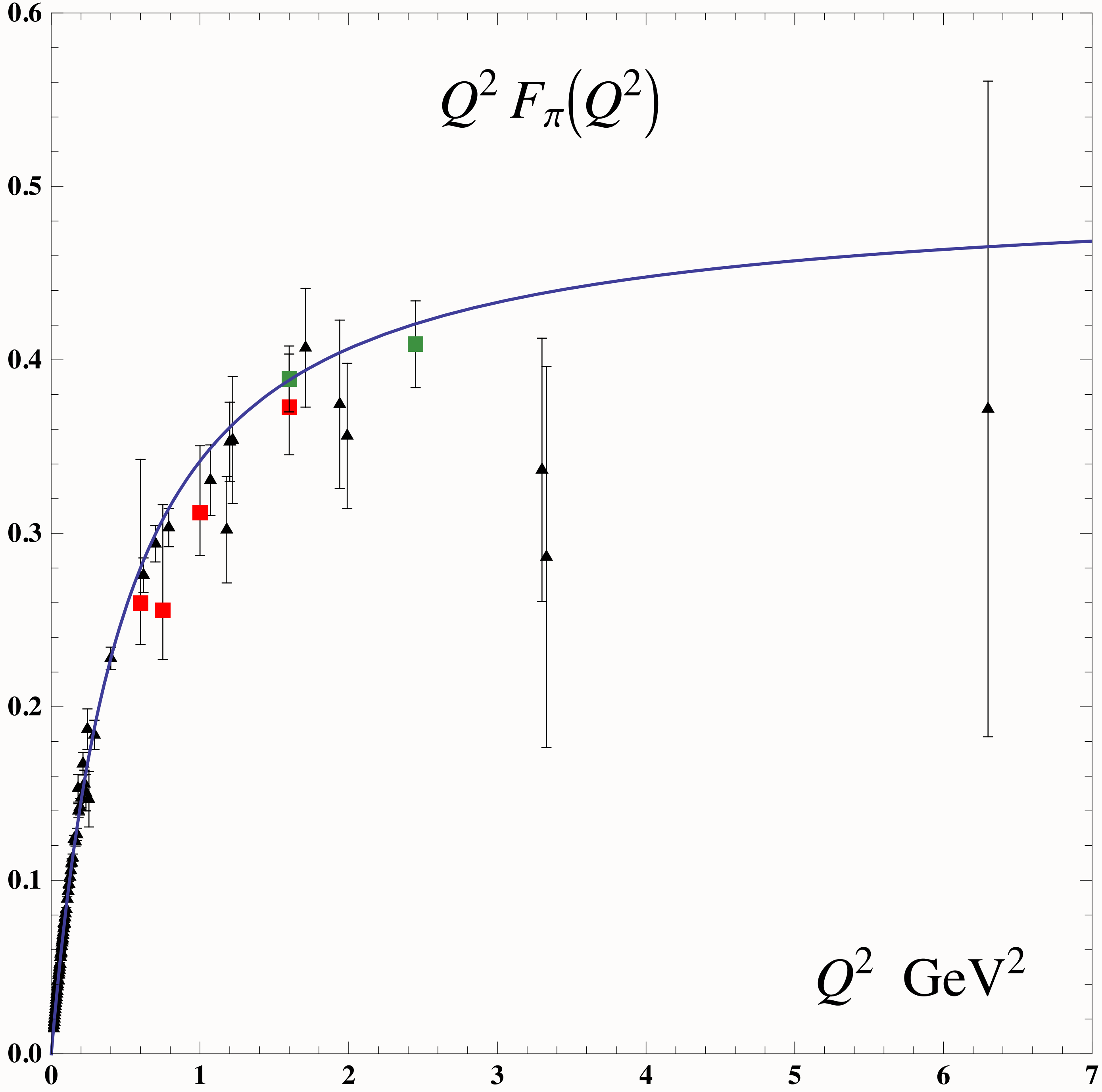
Hard-Gluon exchange: ERBL evolution of shape of Photon Distribution Amplitude!

Scattered lepton produces a virtual top-quark pair in lepton's scattering plane

$$\psi^*_\gamma = \frac{N}{Q^2(1-x)+k_\perp^2+m_t^2}$$

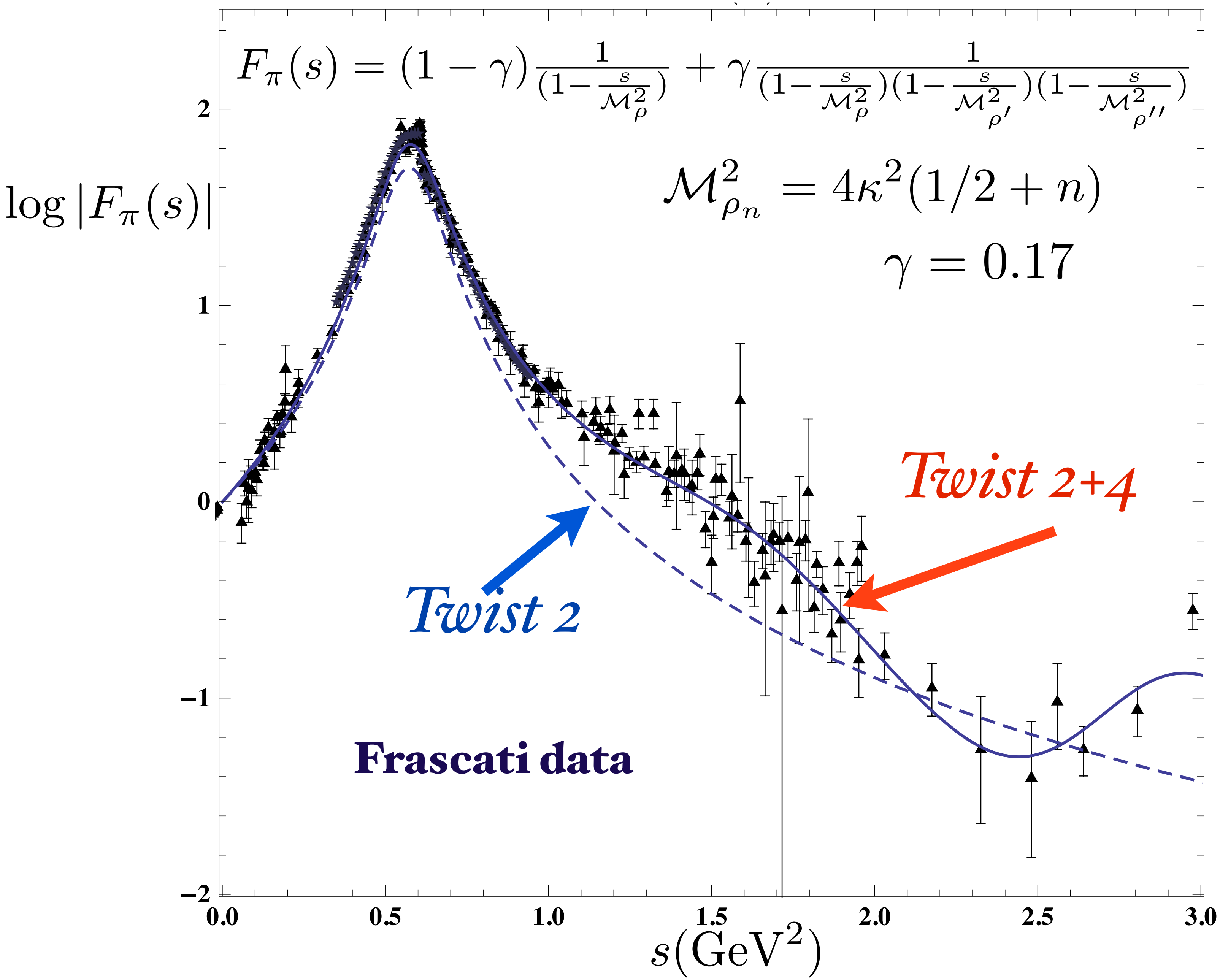


Dressed Heisenberg current predicted by AdS/QCD and LF Holography: VM Poles in s-channel



$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
5
6
7

Timelike Pion Form Factor from AdS/QCD and Light-Front Holography



Prescription for Timelike poles :

$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb

Excitation of Intrinsic Heavy Quarks in Proton

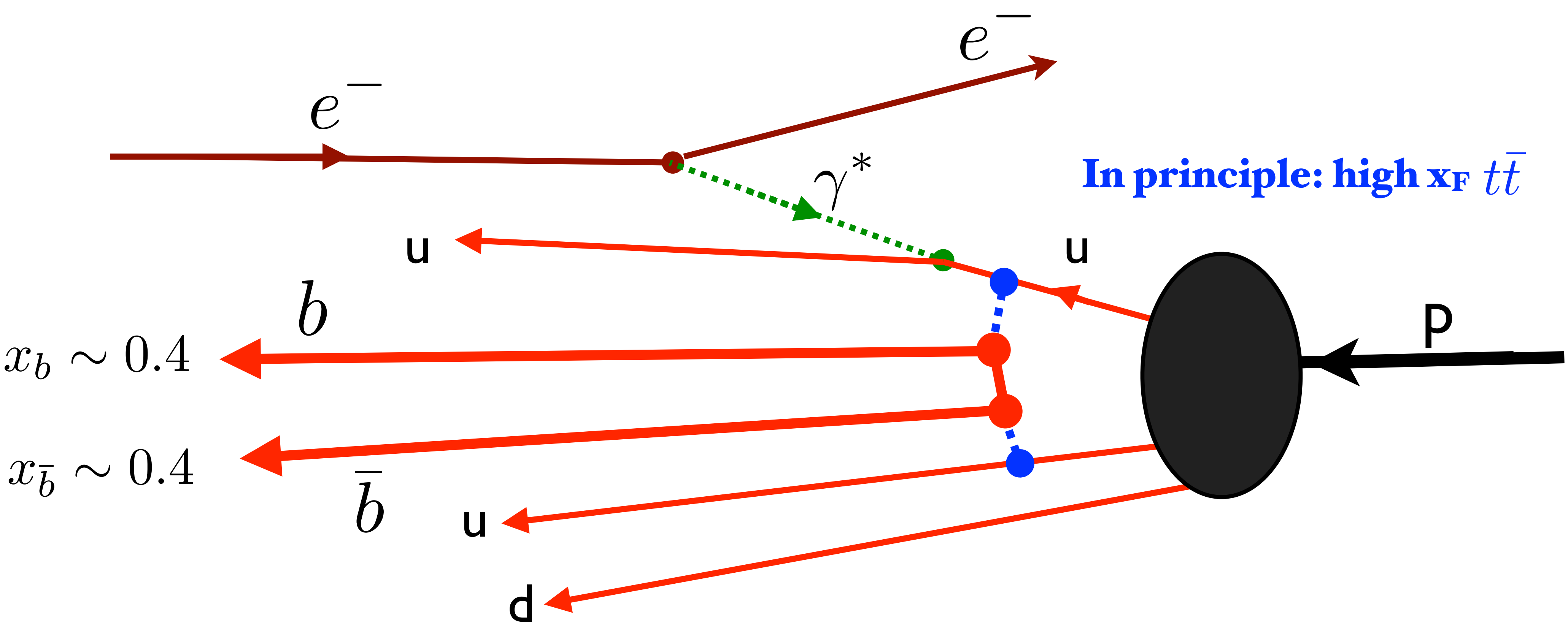
Amplitude maximal at small invariant mass, equal rapidity

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

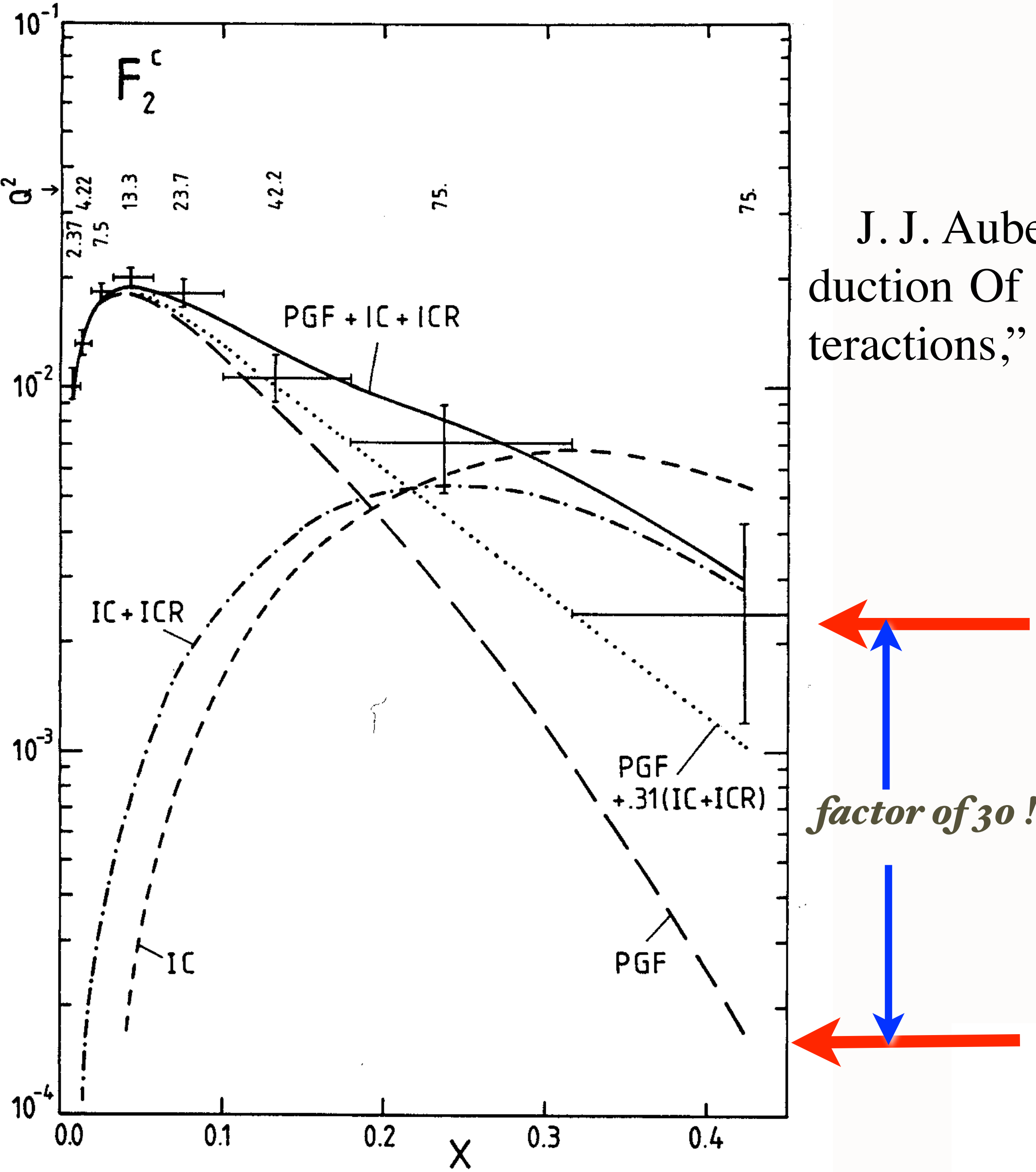
Produce forward, high x_F

$\Upsilon(b\bar{b}), \Lambda_b(bud), B^+(\bar{b}u), B^0(\bar{b}d)$

Need Forward Small Angle Detection

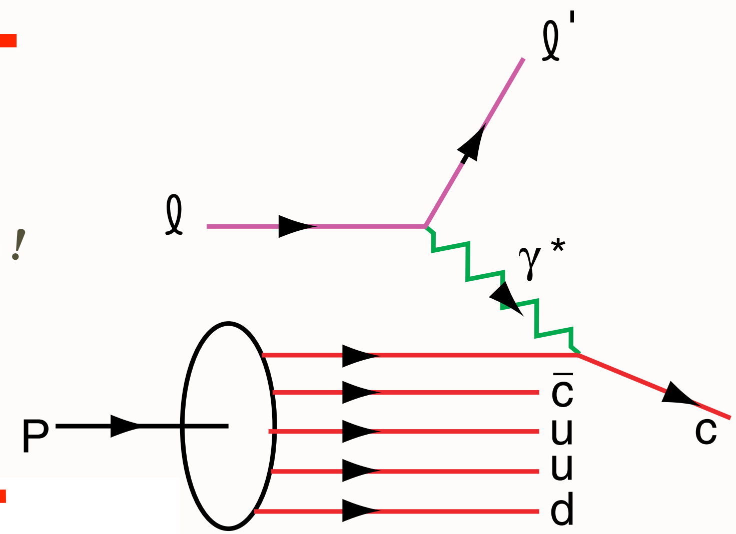


Measurement of Charm Structure Function

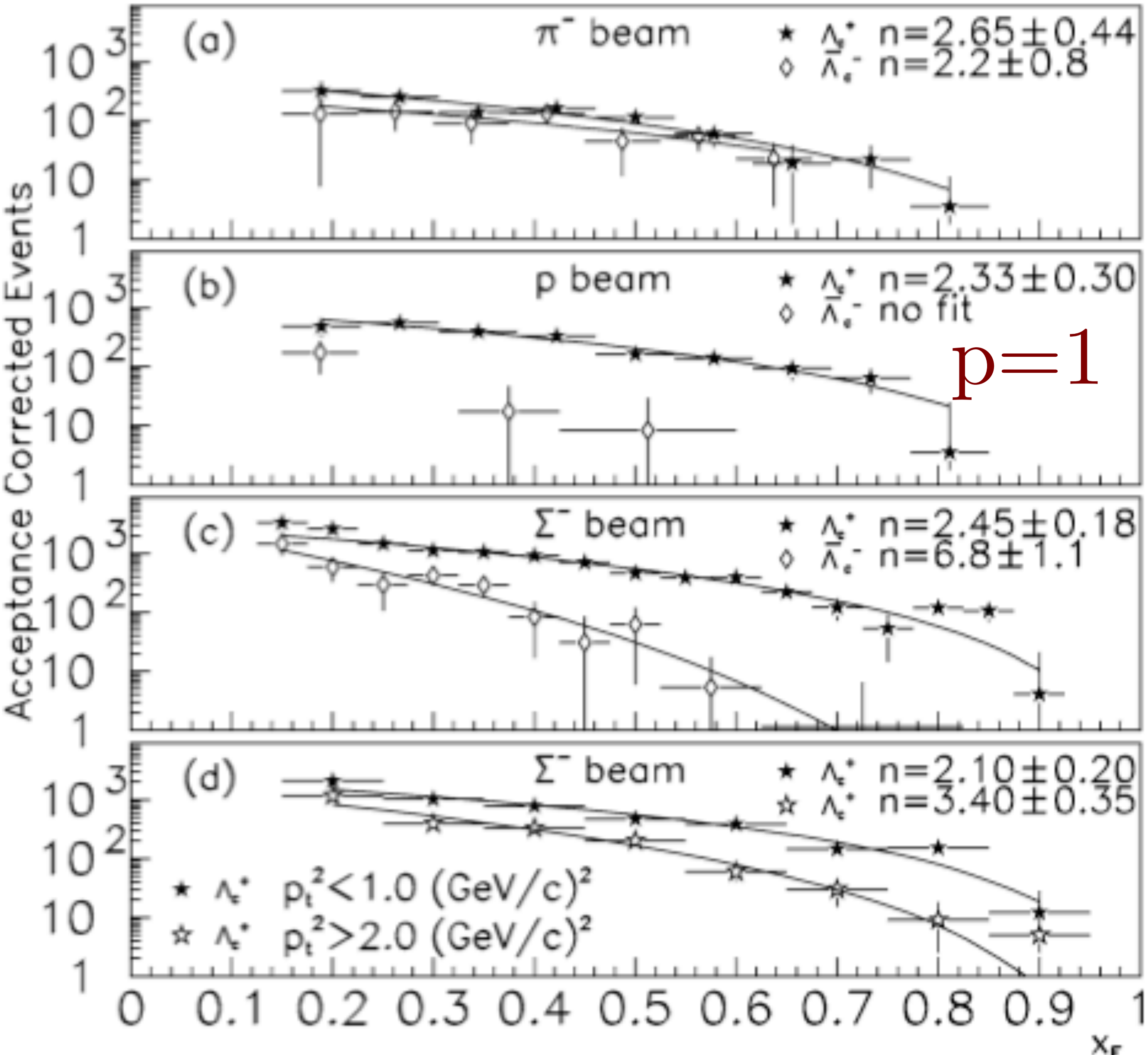


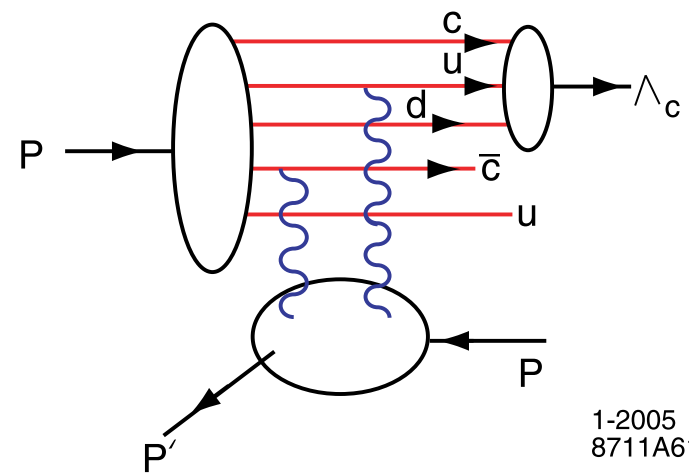
J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm



DGLAP / Photon-Gluon Fusion: factor of 30 too small





$$p(uudc\bar{c})$$

$$\rightarrow \Lambda_c(cud)$$

$$n_s = 2$$

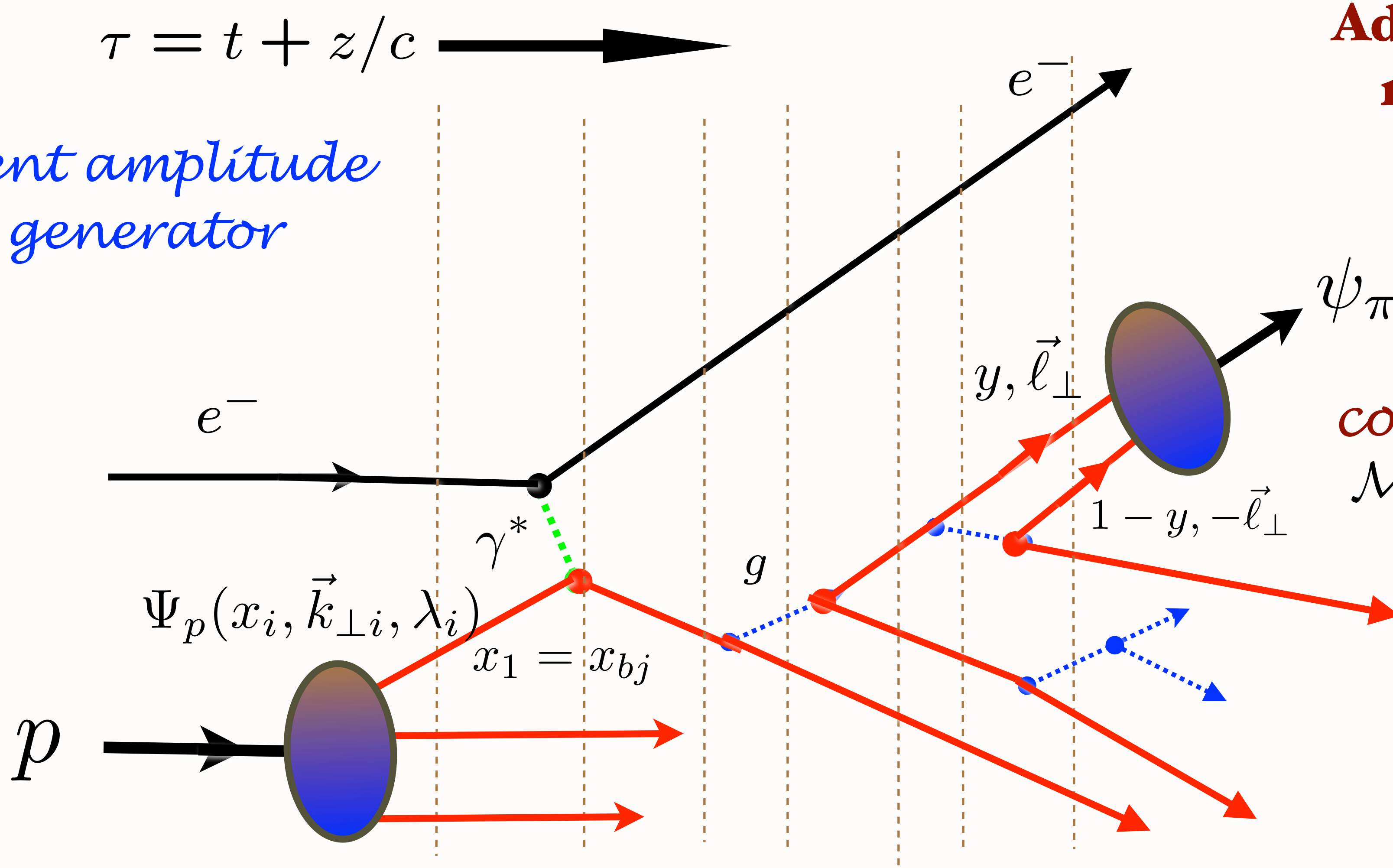
Phase space gives minimum power p

$$(1 - x_F)^p, p = n_s - 1$$

Jet Hadronization at the Amplitude Level

AdS/QCD model

Event amplitude generator



coalesce if
$\mathcal{M}^2 < \Lambda^2_{QCD}$

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via Light-Front Wavefunctions

- EMC data: $c(x,Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

C.H. Chang, J.P. Ma, C.F. Qiao and X.G.Wu

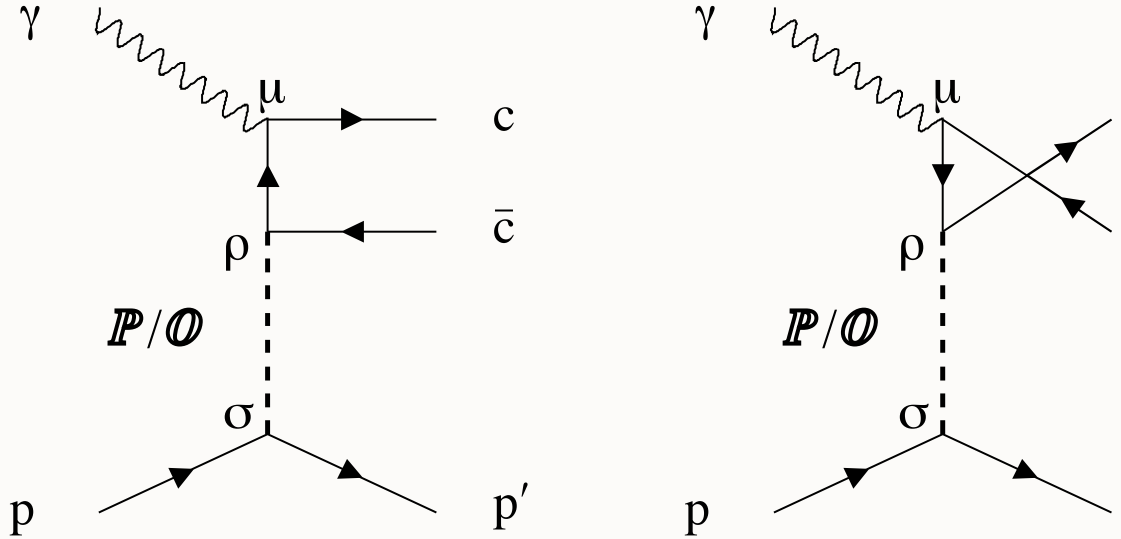
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

Critical Measurements at threshold

Interesting spin, charge asymmetry, threshold, spectator effects

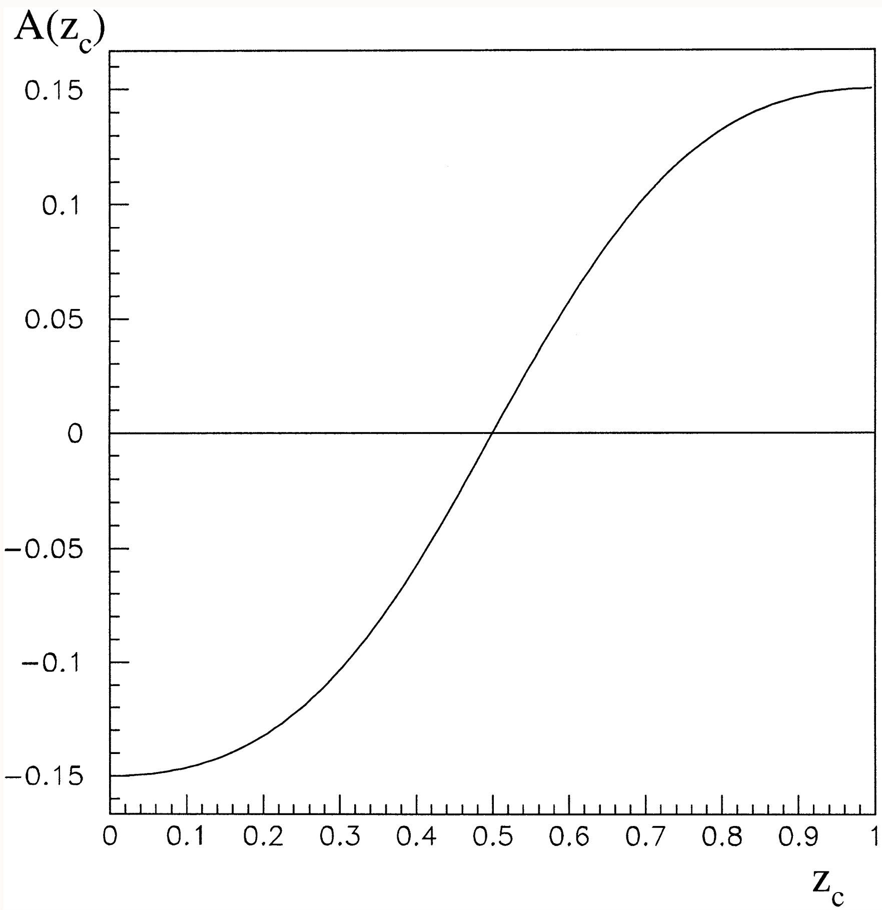
Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb



$$\gamma^* p \to c\bar{c}p$$

Odderon-Pomeron Interference!

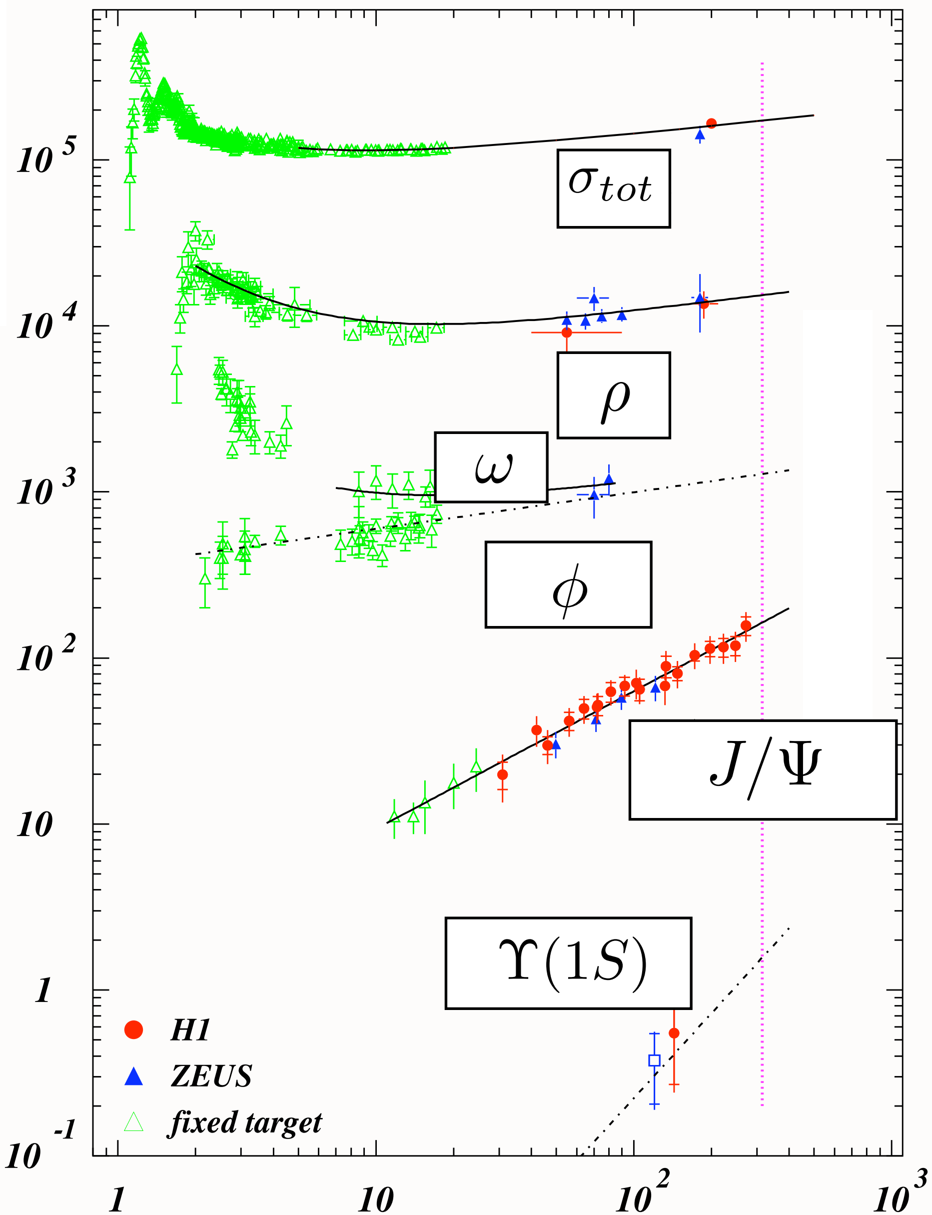


$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2z_c - 1}{z_c^2 + (1 - z_c)^2}$$

Measure charm asymmetry in photon fragmentation region

Merino, Rathsman, sjb

$\sigma(\gamma p \to Vp)[nb]$



$\sqrt{s_{\gamma p}}(GeV)$

Diffractive Processes

Unitarity Bound?
Saturation?

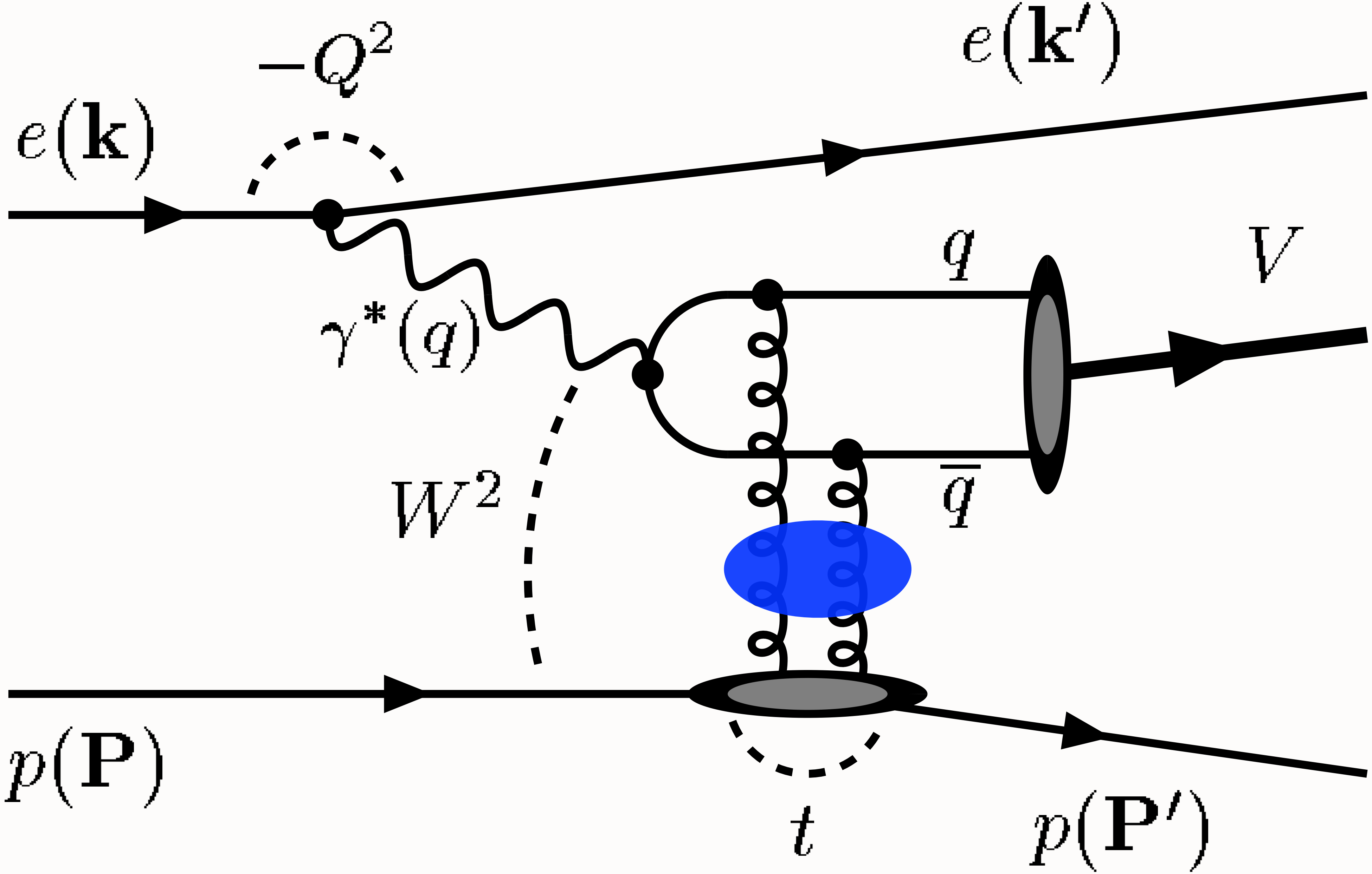
Hard Diffraction

$$\gamma p \to \Upsilon p$$

$$\gamma^* p \to \rho p$$

Odderon

$$\gamma^* p \to \pi^0 p$$

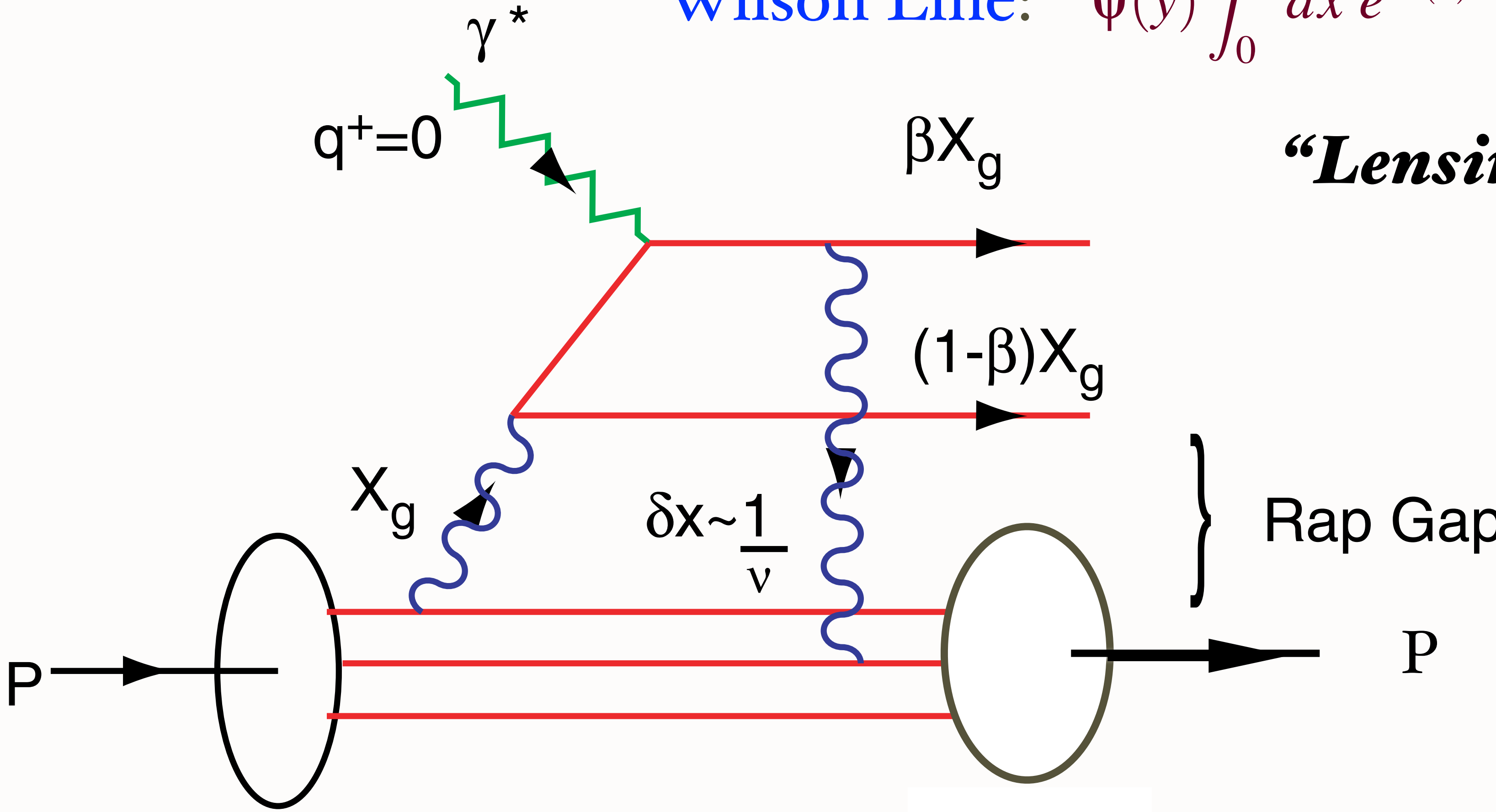


BFKL hard pomeron exchange
+ BLM NLO scale fixing

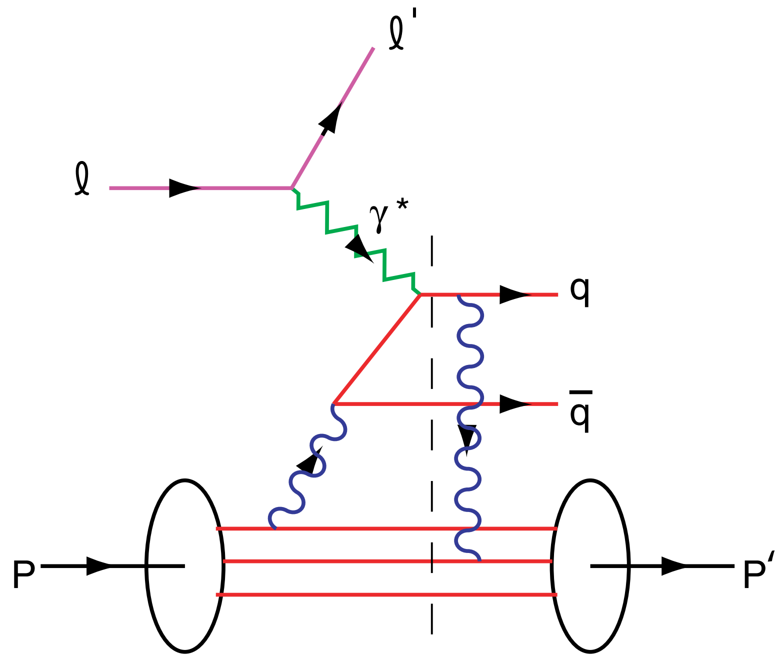
Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Reproduces lab-frame color dipole approach



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

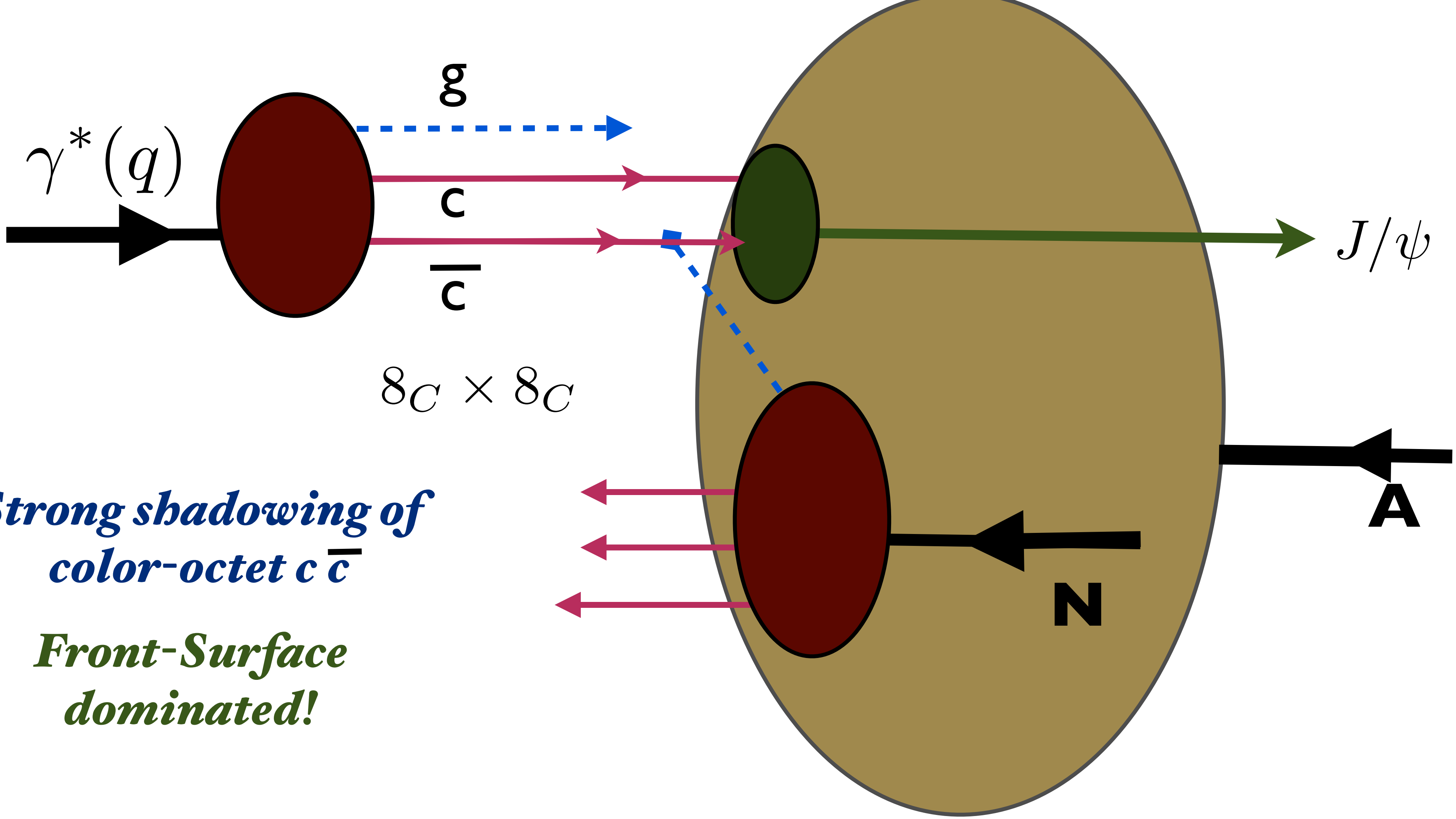
Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Zhu, sjb

$pA \to J/\psi X$

$$(gg)_{8_C} + g_{8_C} \to J/\psi$$



Strong shadowing of color-octet $c\,\bar{c}$

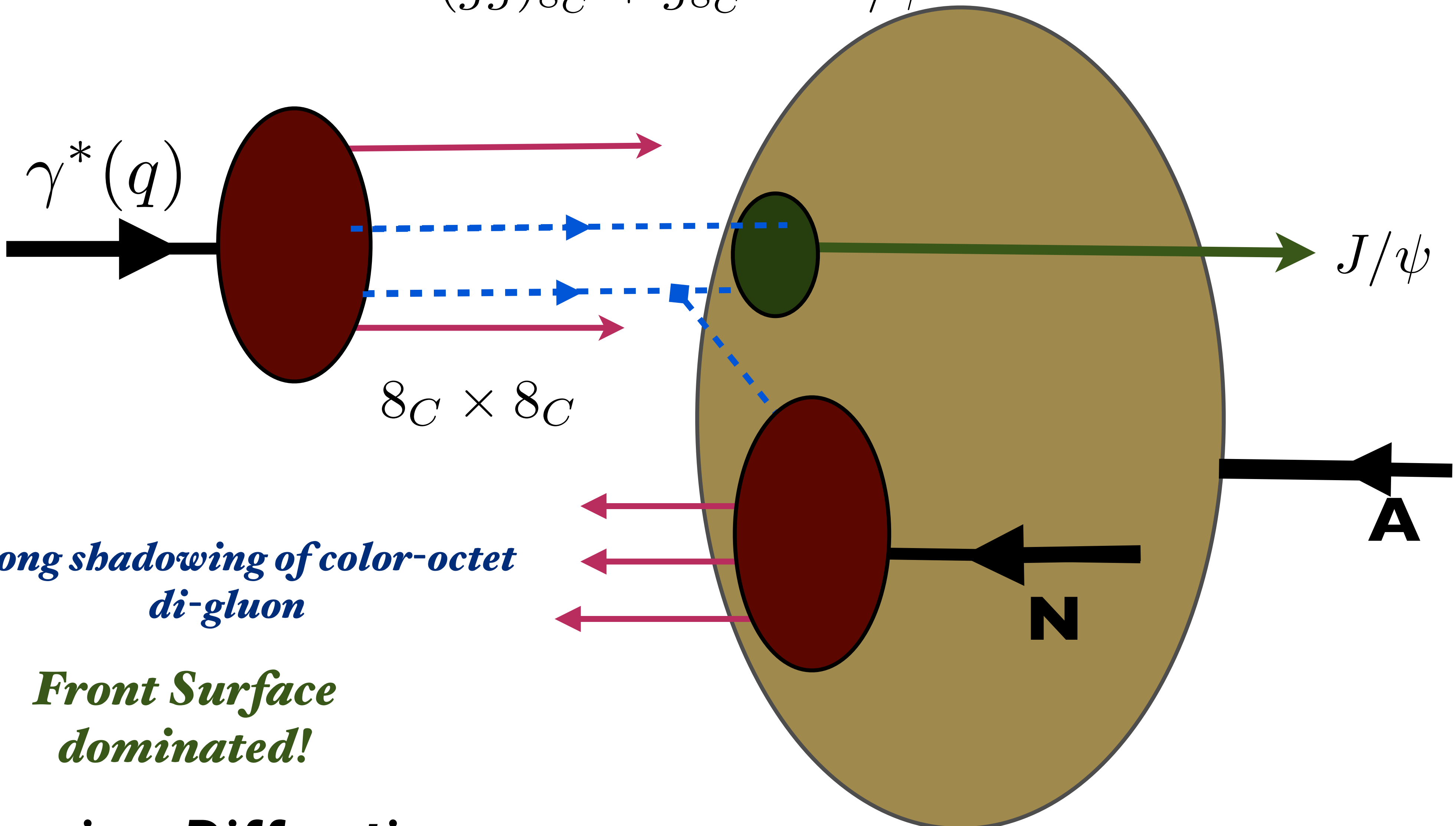
Front-Surface dominated!

Novel nuclear effect at the LHeC

Zhu, sjb

$pA \to J/\psi X$

$$(gg)_{8_C} + g_{8_C} \to J/\psi$$

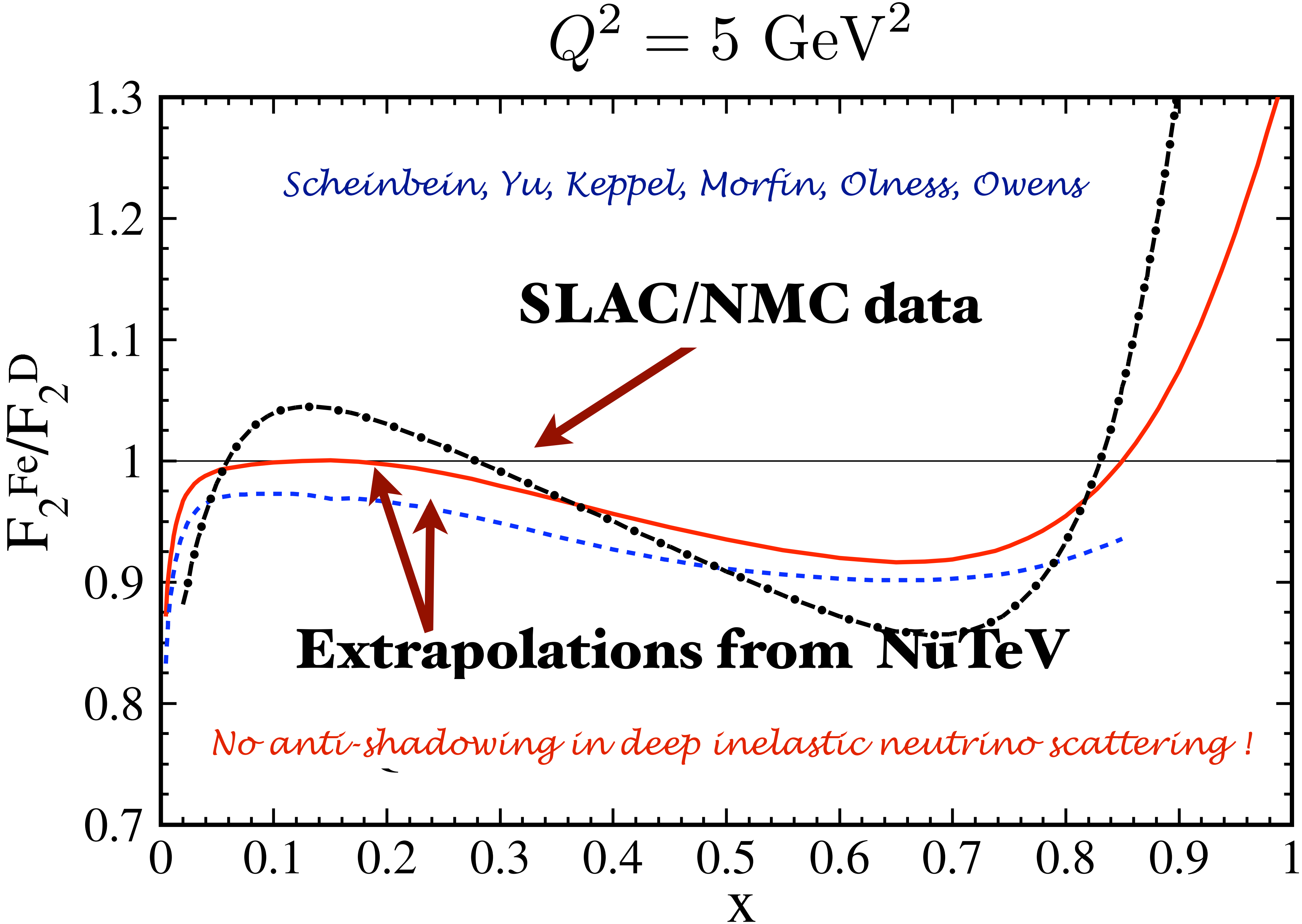


Strong shadowing of color-octet di-gluon

Front Surface dominated!

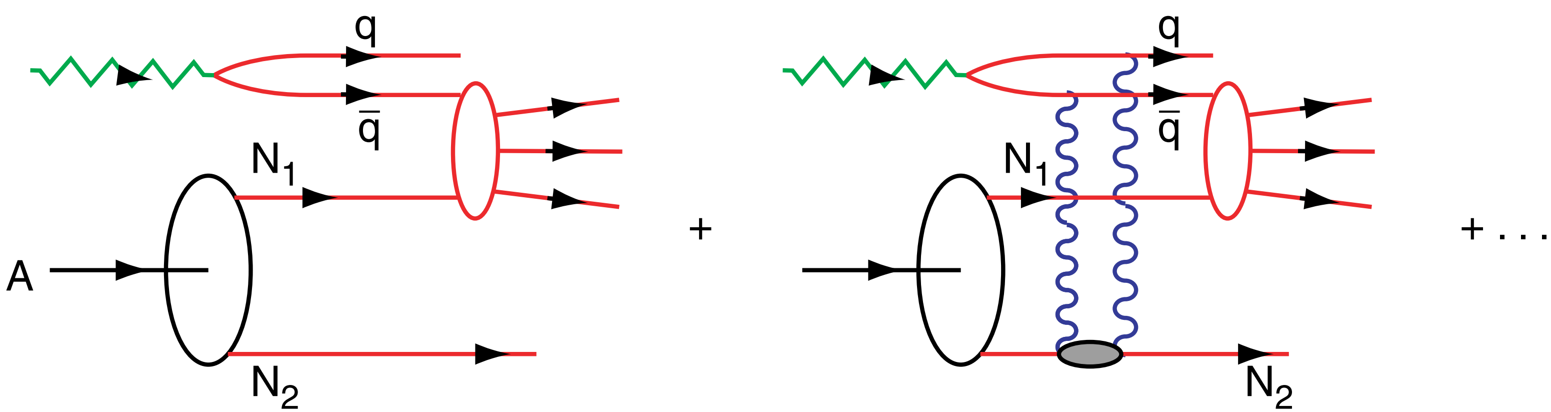
Crossing: Diffractive & pomeron exchange

Double-gluon subprocess


$Q^2 = 5\ \mathrm{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
F_2^{Fe}/F_2^{D}
x
1.3
1.2
1.1
1
0.9
0.8
0.7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Stodolsky
Pumplin, sjb
Gribov

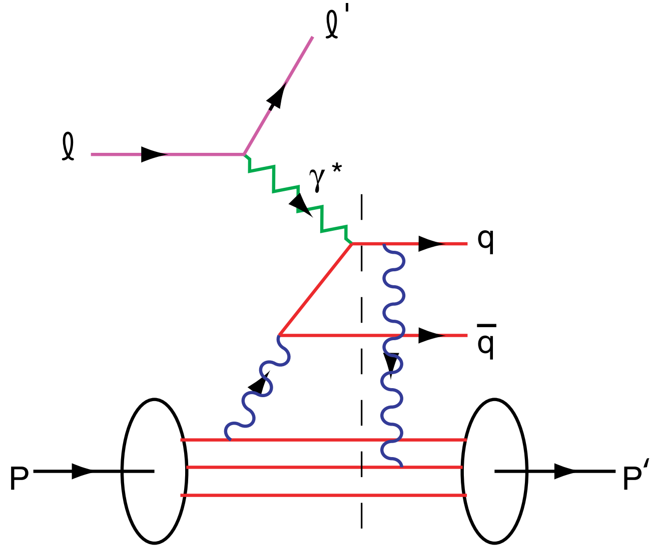
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



Shadowing depends on understanding leading-twist-diffraction in DIS

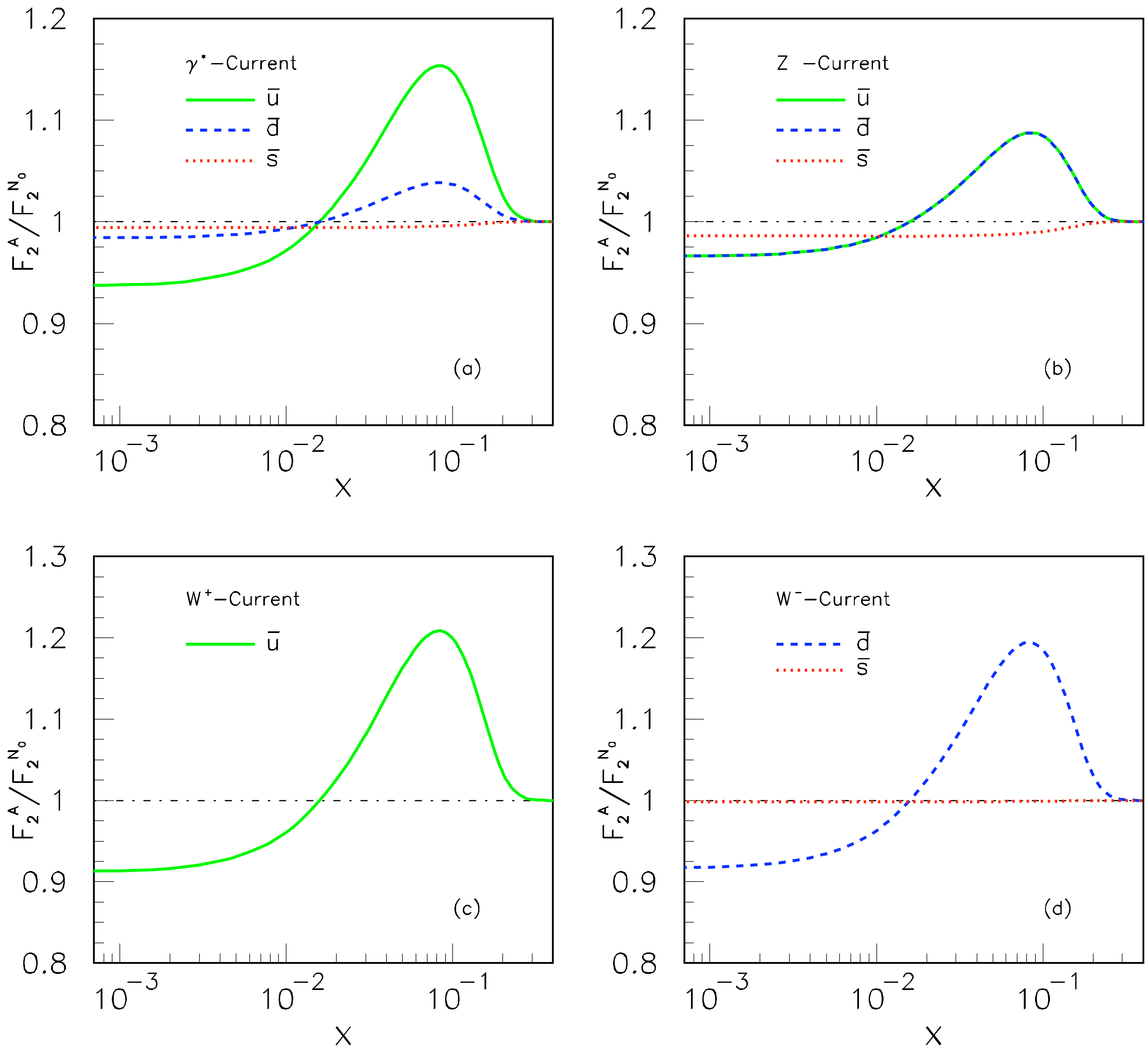
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry

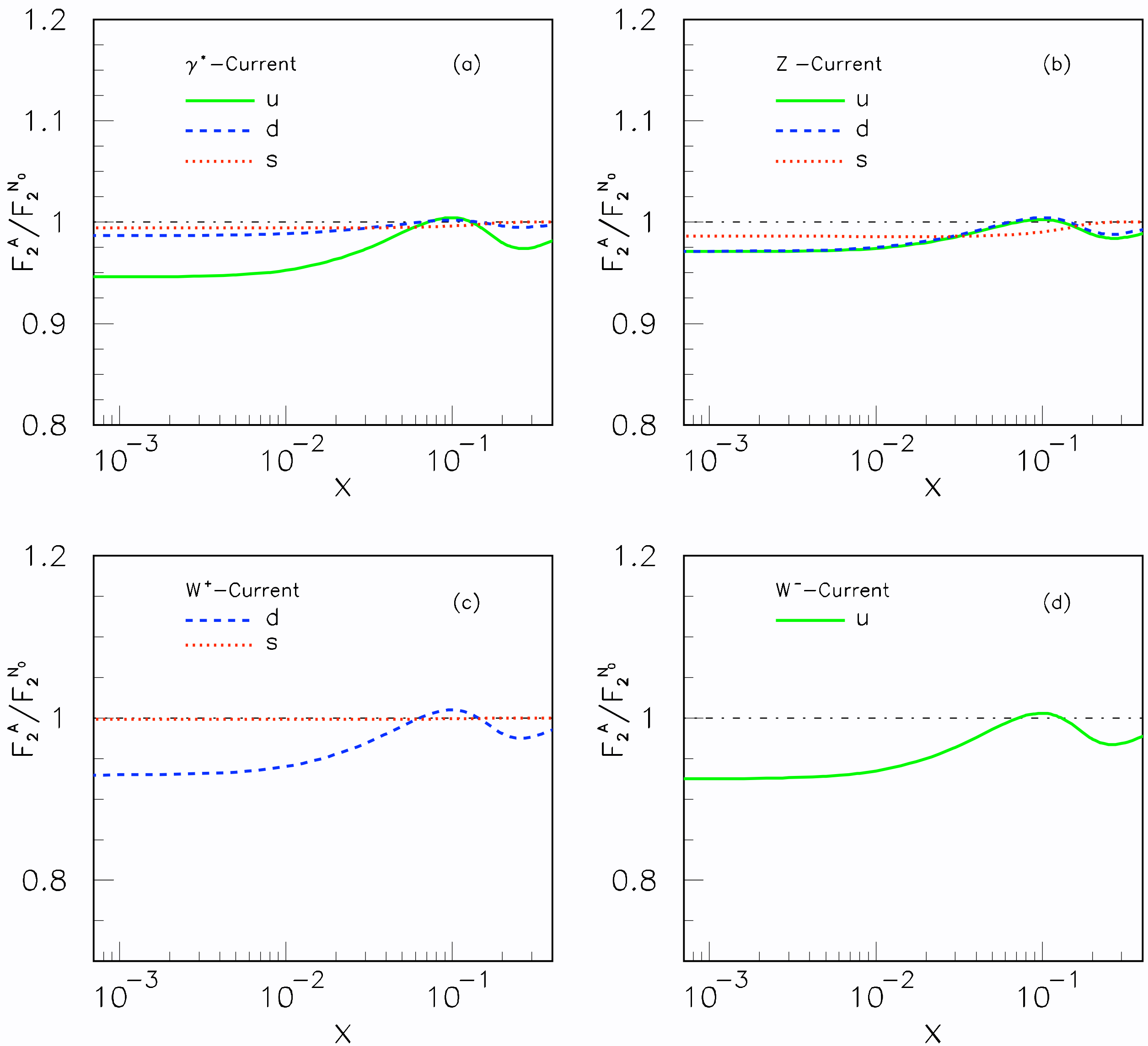
Physics of FSI not in Wavefunction of Target

Antishadowing (from Reggeon exchange) is not universal!



Nuclear Effect not Universal !

Shadowing and Antishadowing of DIS Structure Functions



S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Crucial Test of Leading -Twist QCD: Scaling at fixed x_T

$$x_T = \frac{2p_T}{\sqrt{s}}$$

$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}}$$

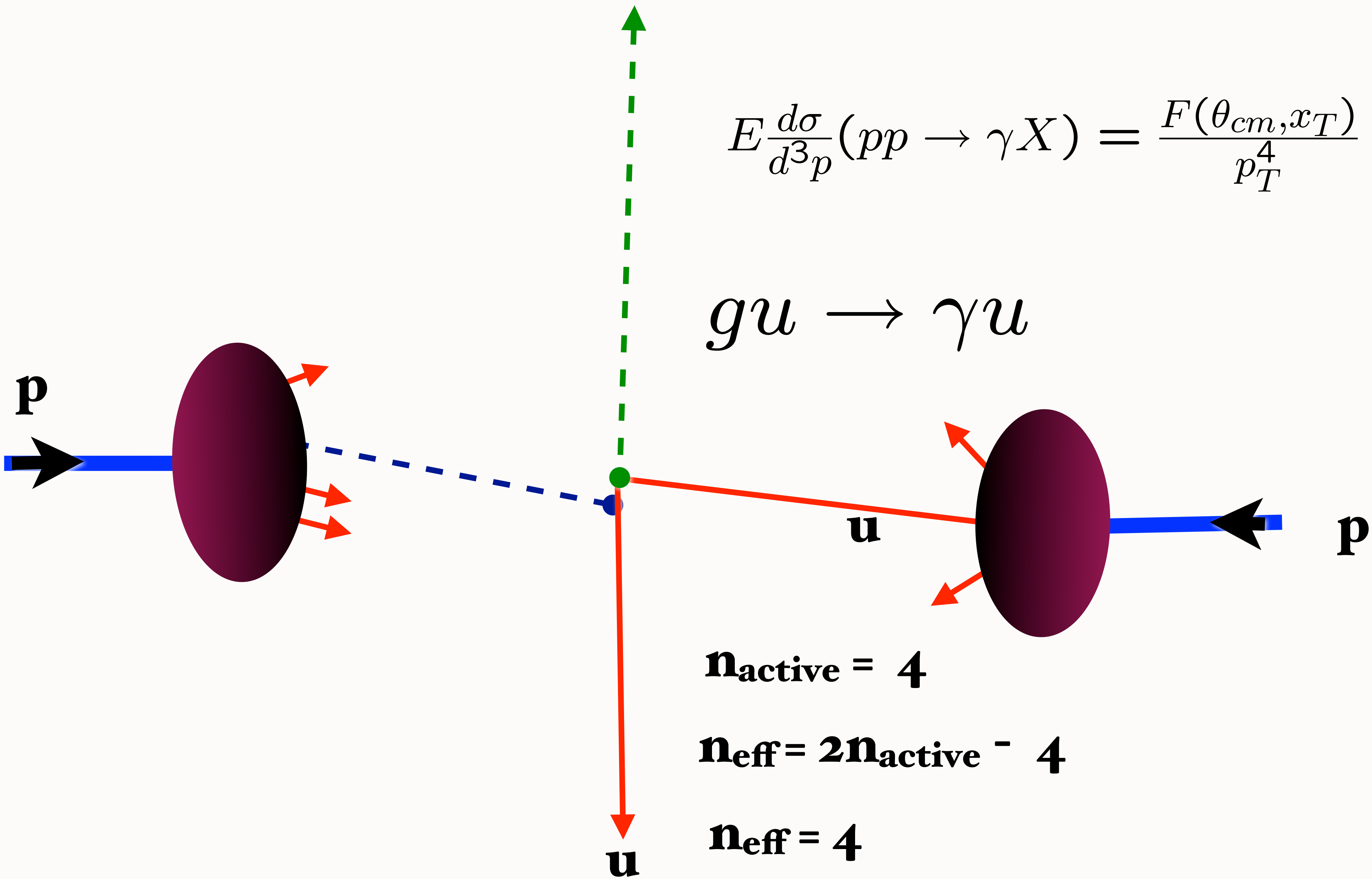
Parton model: $n_{eff} = 4$

As fundamental as Bjorken scaling in DIS

Conformal scaling: $n_{eff} = 2\, n_{active} - 4$

$$pp \to \gamma X$$

$$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$$



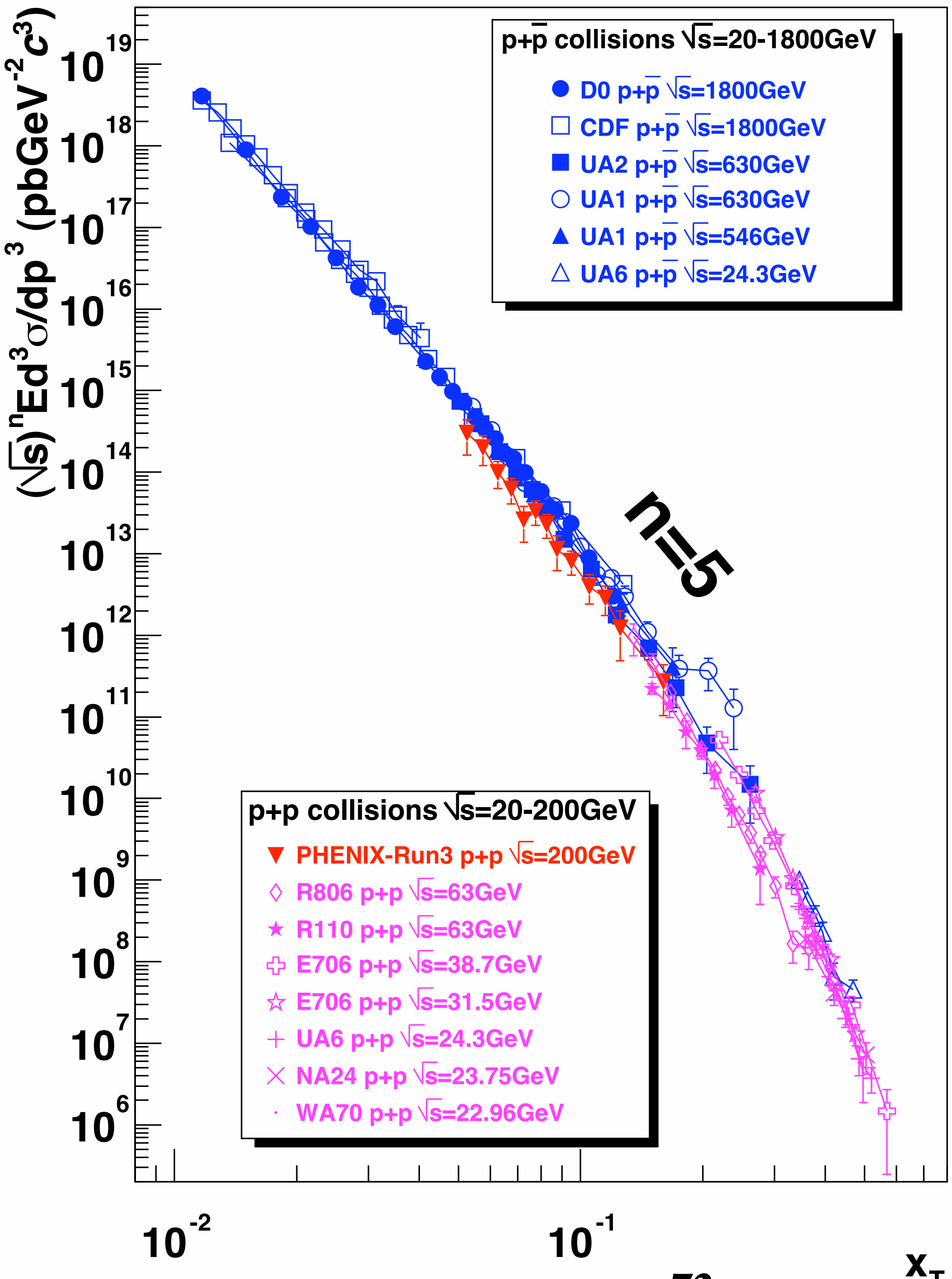
$n_{active} = 4$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 4$

$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum

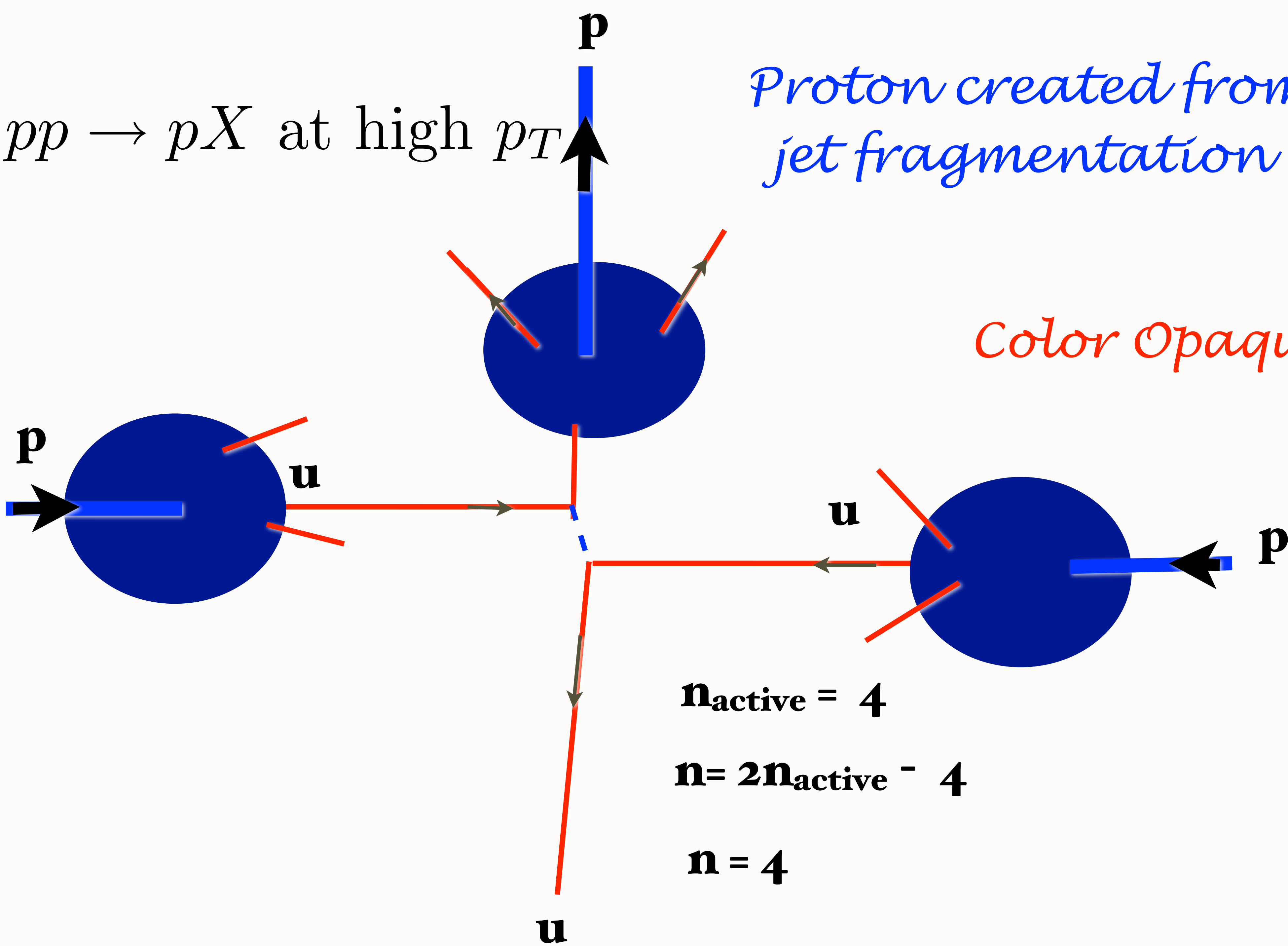


Scaling of direct photon production consistent with PQCD

$pp \to pX$ at high p_T

Proton created from jet fragmentation

Color Opaque

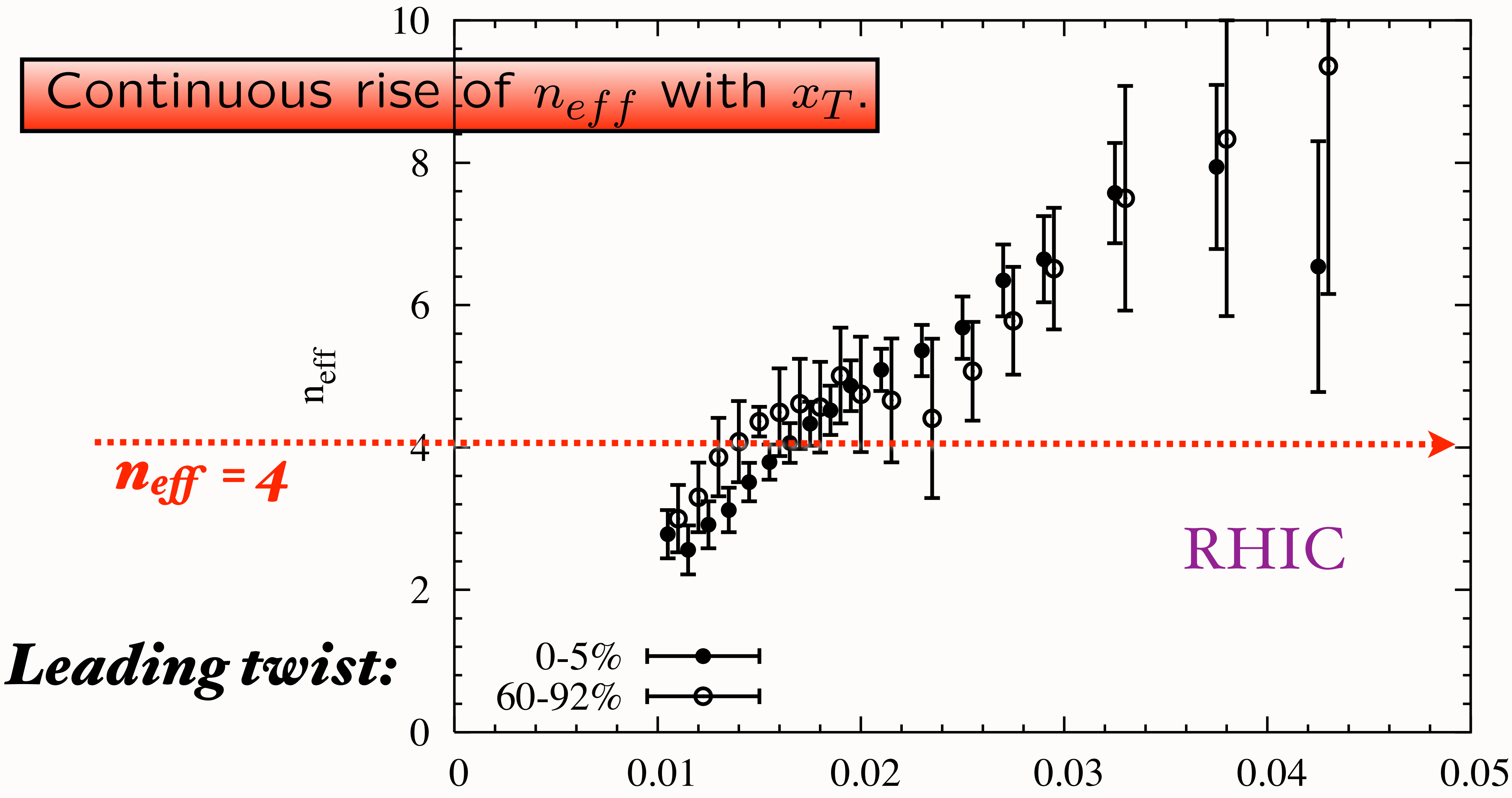


$n_{active} = 4$

$n = 2n_{active} - 4$

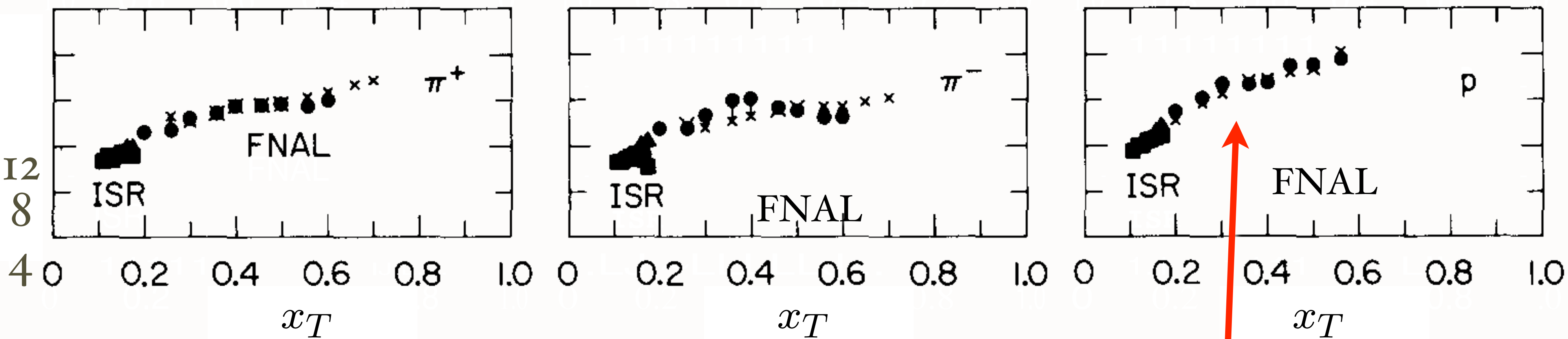
$n = 4$

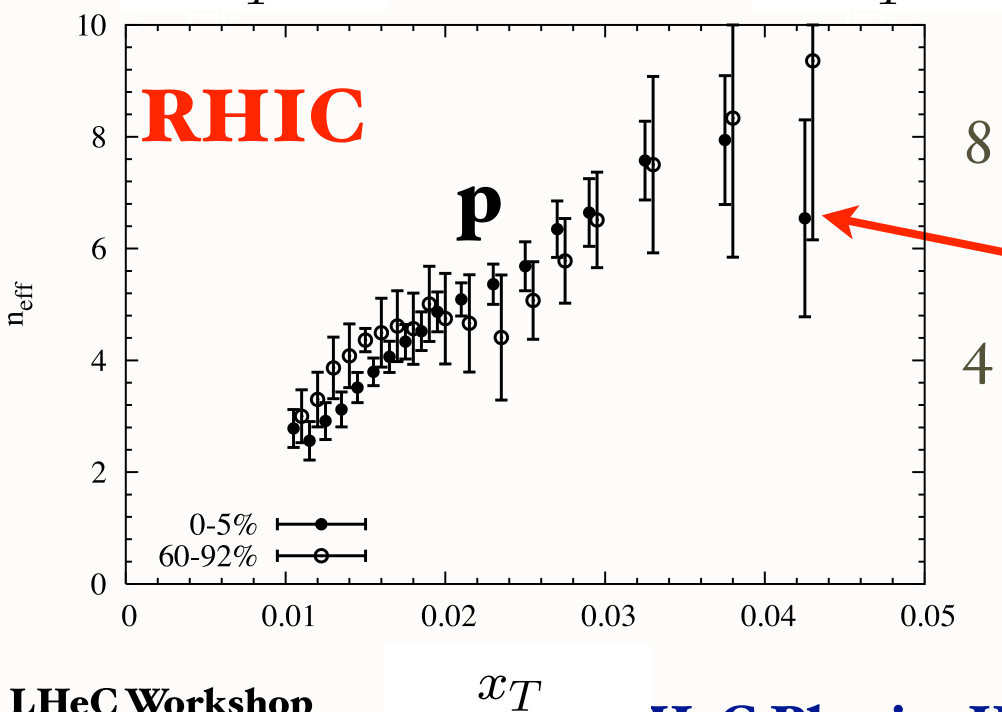
Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available p_T range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.



$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$





$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

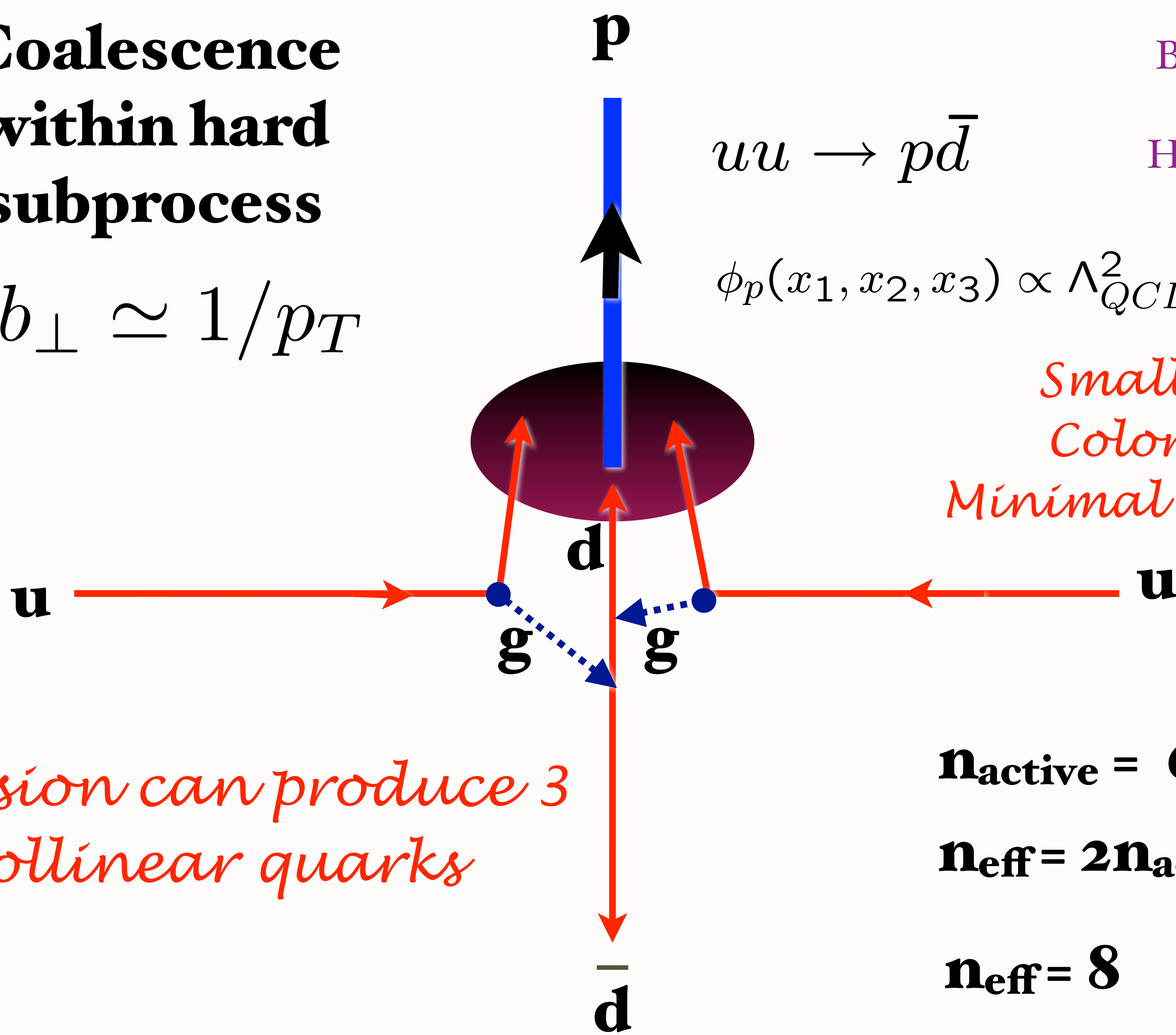
$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{8}}$$

Trend consistent with RHIC at small x_T

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

$$b_\perp \simeq 1/p_T$$



$$uu \to p\bar{d}$$

$$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$$

Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Hoyer, et al: Semi-Exclusive

Small color-singlet
Color Transparent
Minimal same-side energy

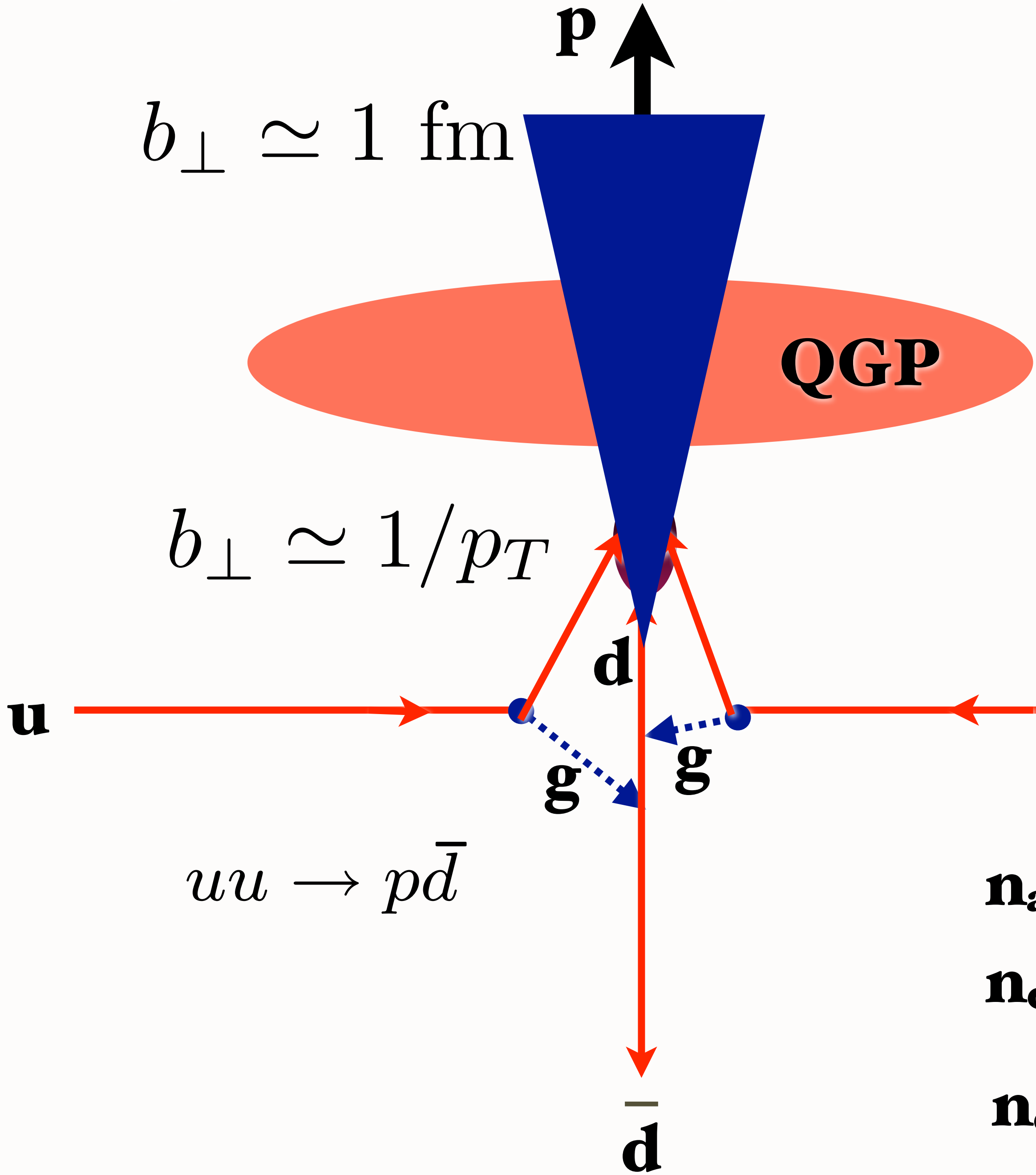
Collision can produce 3 collinear quarks

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

Baryon made directly within hard subprocess



Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

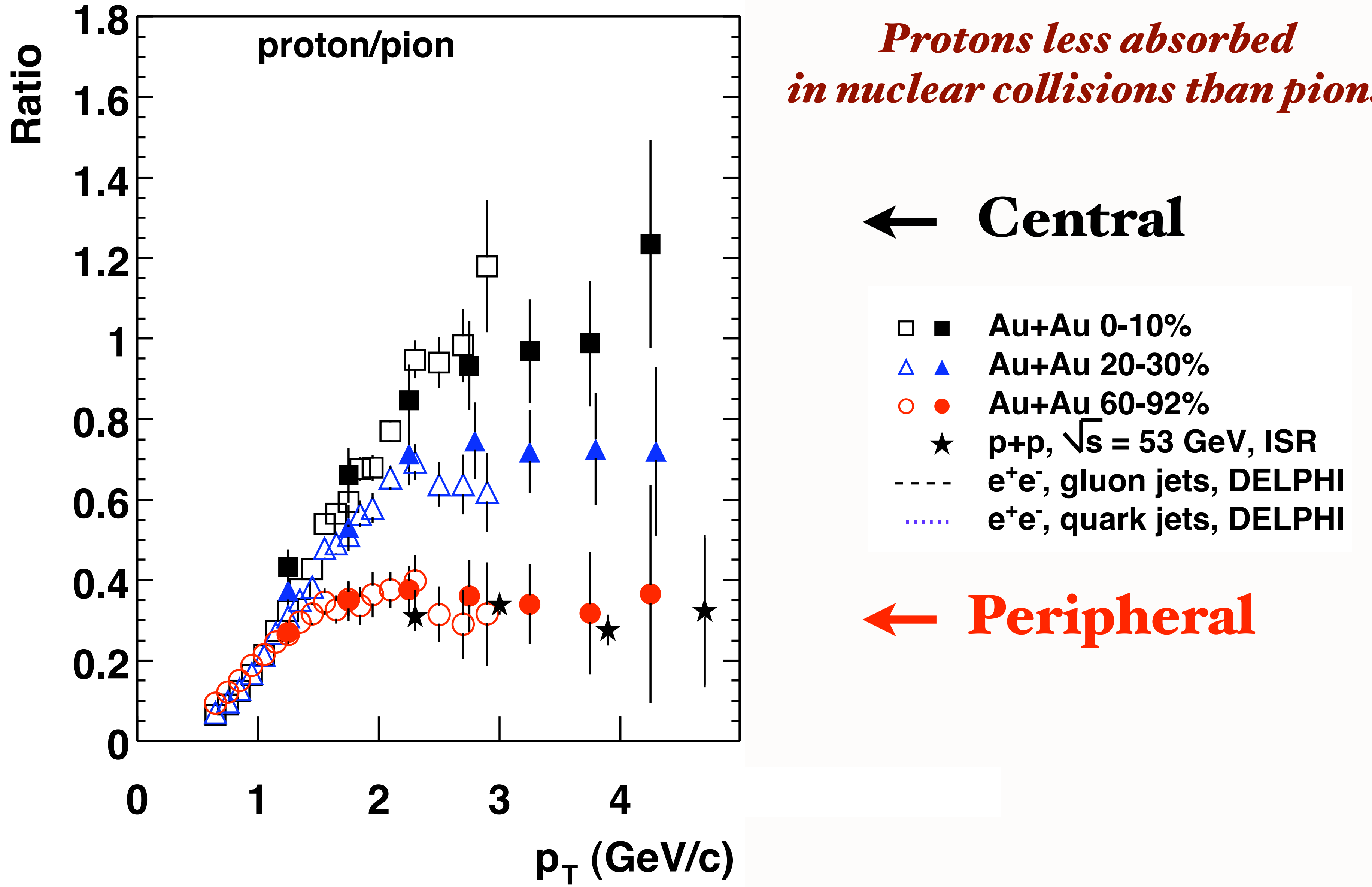
$n_{eff} = 8$

Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- **Explains anomalous power behavior at fixed x_T**
- **Protons more likely to come from direct higher-twist subprocess than pions**
- **Protons less absorbed than pions in central nuclear collisions because of color transparency**
- **Predicts increasing proton to pion ratio in central collisions**
- **Proton power n_{eff} increases with centrality since leading twist contribution absorbed**
- **Fewer same-side hadrons for proton trigger at high centrality**
- **Exclusive-inclusive connection at $x_T = 1$**

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett.* **91**, 172301 (2003).

Particle ratio changes with centrality!

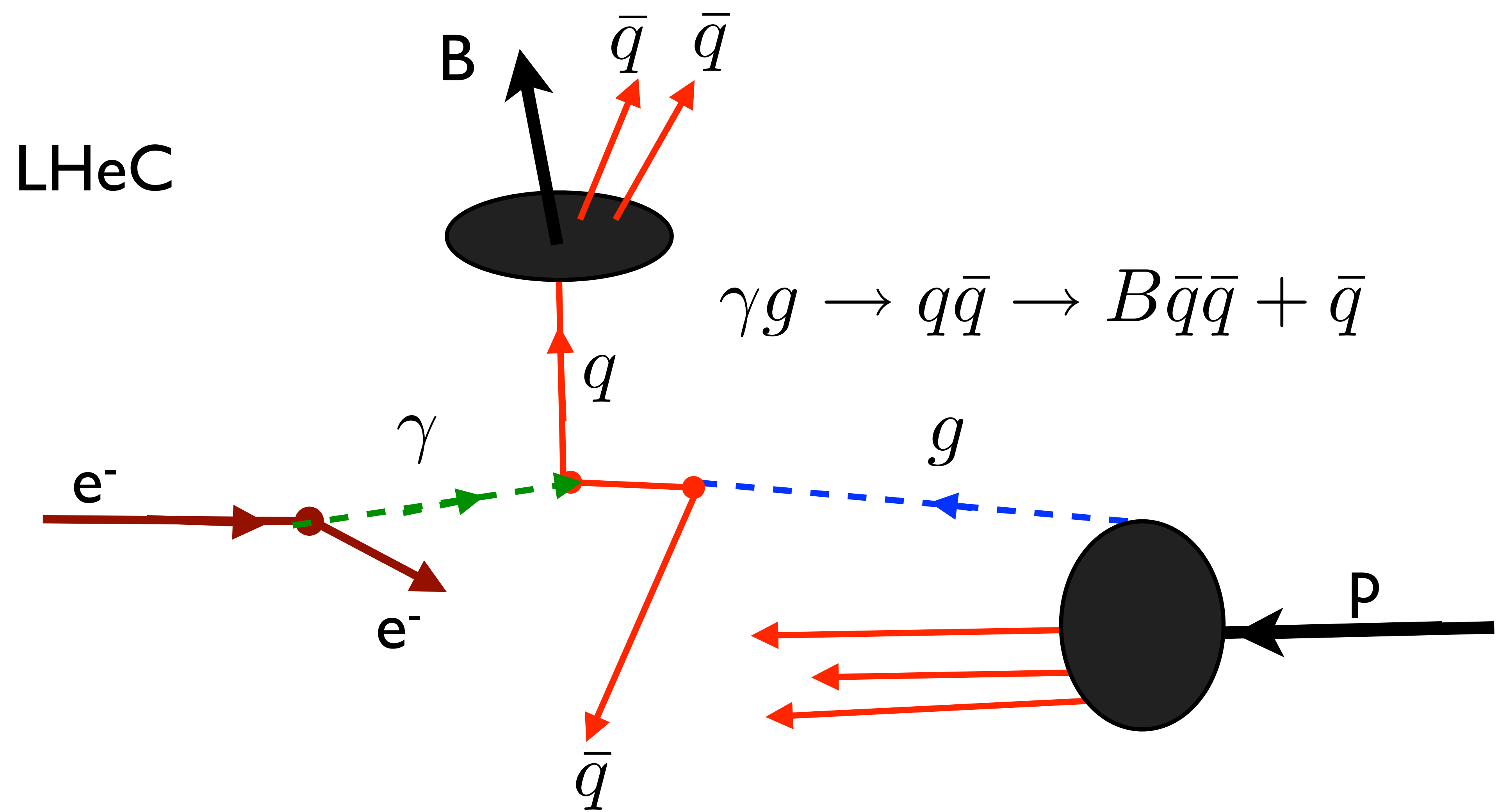


Protons less absorbed in nuclear collisions than pions

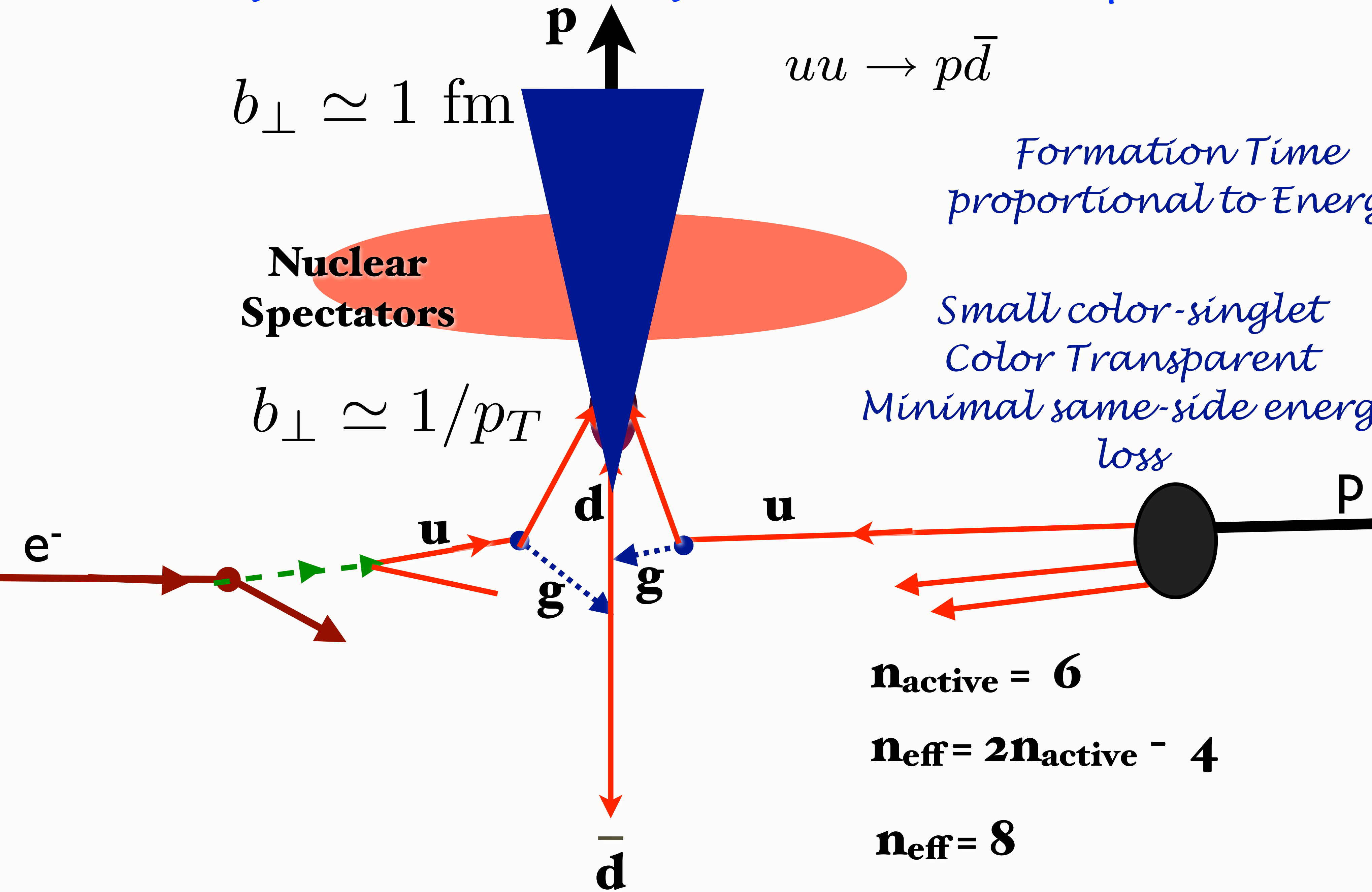
← **Central**

← **Peripheral**

Standard PQCD Factorization Ansatz for Hadron via Fragmentation



Baryon made directly within hard subprocess



Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy loss

$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

LHeC QCD Physics Highlights

- **Diffractive Deep Inelastic Scattering**
- **Non-Universal Anti-Shadowing**
- **The Odderon**
- **Deeply Virtual Meson Production and Color Transparency**
- **Heavy Quark Interactions at Threshold**
- **Heavy Quark Distributions**
- **Higgs Production at high x_F**

Theory Advances

- **PMC/BLM: Eliminate Renormalization Scale Ambiguity**
- **AdS/QCD: Unique form of confinement potential; light-front Schrödinger Equation; spectroscopy, dynamics, running coupling; hadronization at amplitude level**
- **Multi-parton and direct processes**
- **Hidden Color**
- **Non-Universal Antishadowing**

Novel Aspects of QCD in ep scattering

- **Clash of DGLAP and BFKL with unitarity: saturation phenomena; off-shell effects at high x**
- **Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction:**
  Intrinsic c(x,Q), b(x,Q), t(x,Q):
- **Hidden-Color of Nuclear Wavefunction**
- **Antishadowing is quark specific!**
- **Polarized u(x) and d(x) at large x; duality**
- **Virtual Compton scattering : DVCS, DVMS, GPDs; J=0 fixed pole reflects elementary source of electromagnetic current**
- **Initial-and Final-State Interactions: leading twist SSA, DDIS**
- **Direct Higher-Twist Processes; Color Transparency**

Challenging PQCD Conventional Wisdom

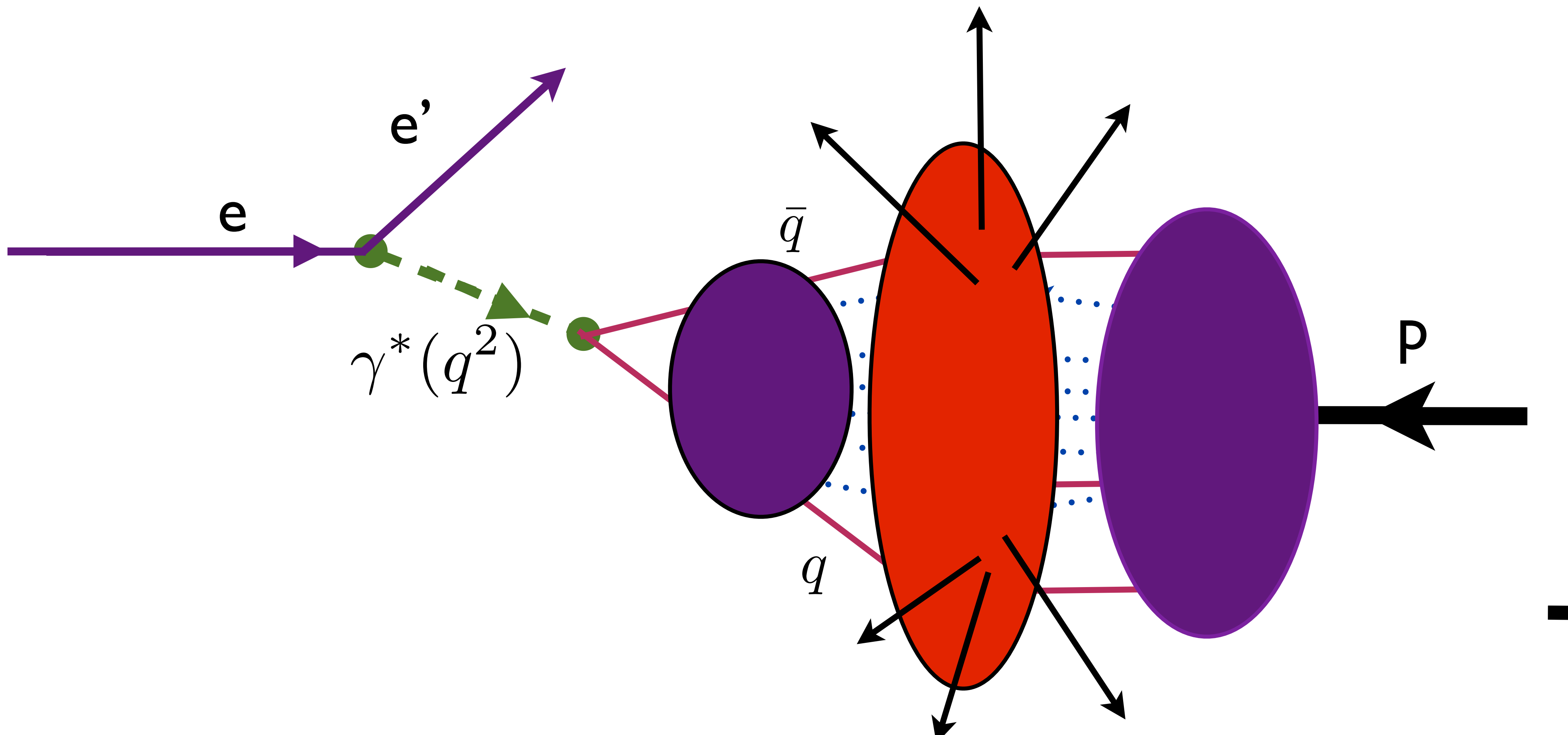
- **Renormalization scale is not arbitrary; multiple scales, unambiguous at given order**
- **Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction**
- **Initial and final-state interactions are not always power suppressed in a hard QCD reaction**
- **LFWFS are universal, but measured nuclear parton distributions are not universal -- antishadowing is flavor dependent**
- **Hadroproduction at large transverse momentum does not derive exclusively from 2 to 2 scattering subprocesses**

New Physics at the LHeC

- Leptoquark, squark Production and Decay
- ZZ, WZ, WW elastic and inelastic collisions
- Technicolor
- Novel Higgs Production Mechanisms
- Composite electrons
- Lepton-Flavor Violation
- QCD at High Density in ep and eA collisions
- Odderon

LHeC: Virtual Photon-Proton Collider

variable spacelike photon virtuality,
various primary flavors



$$E_e = 60 \text{ GeV}, E_p = 7 \text{ TeV}, \sqrt{s_{ep}} > 1 \text{ TeV}$$

Saturation, nuclear shadowing, antishadowing