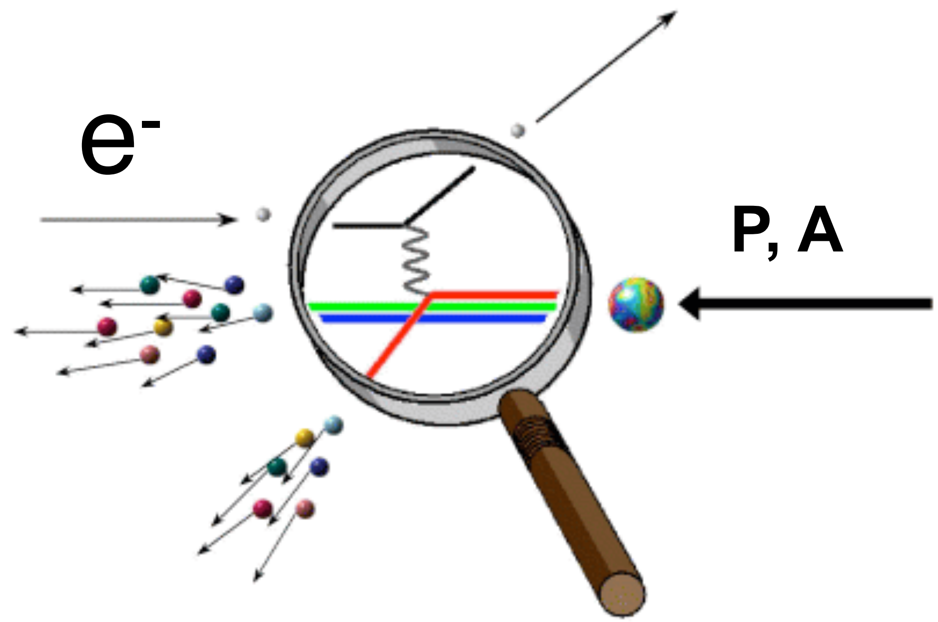
Novel LHeC Physics

Electron-proton and electron-nucleus collisions at unprecedented energy

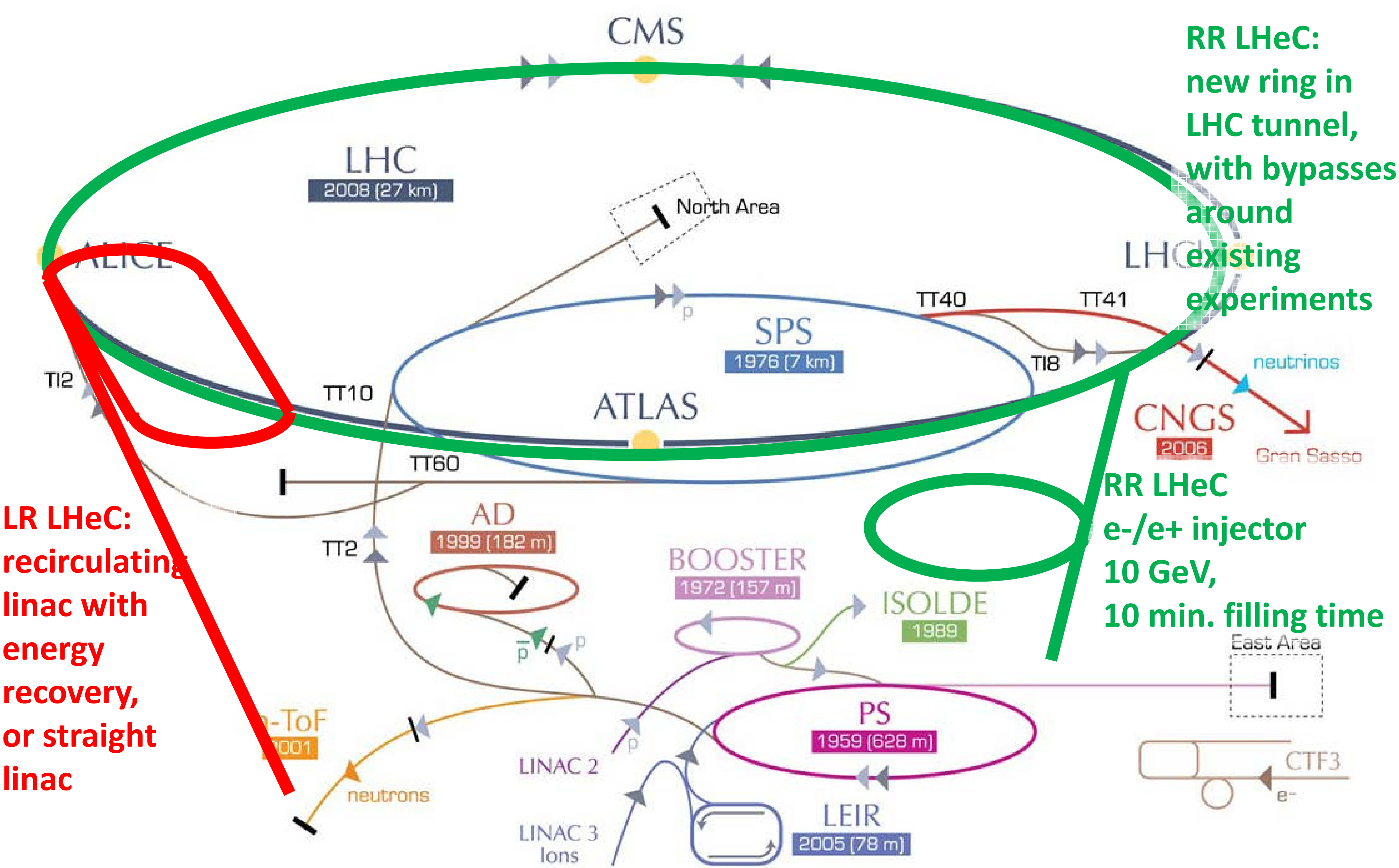
Options: positrons, polarization

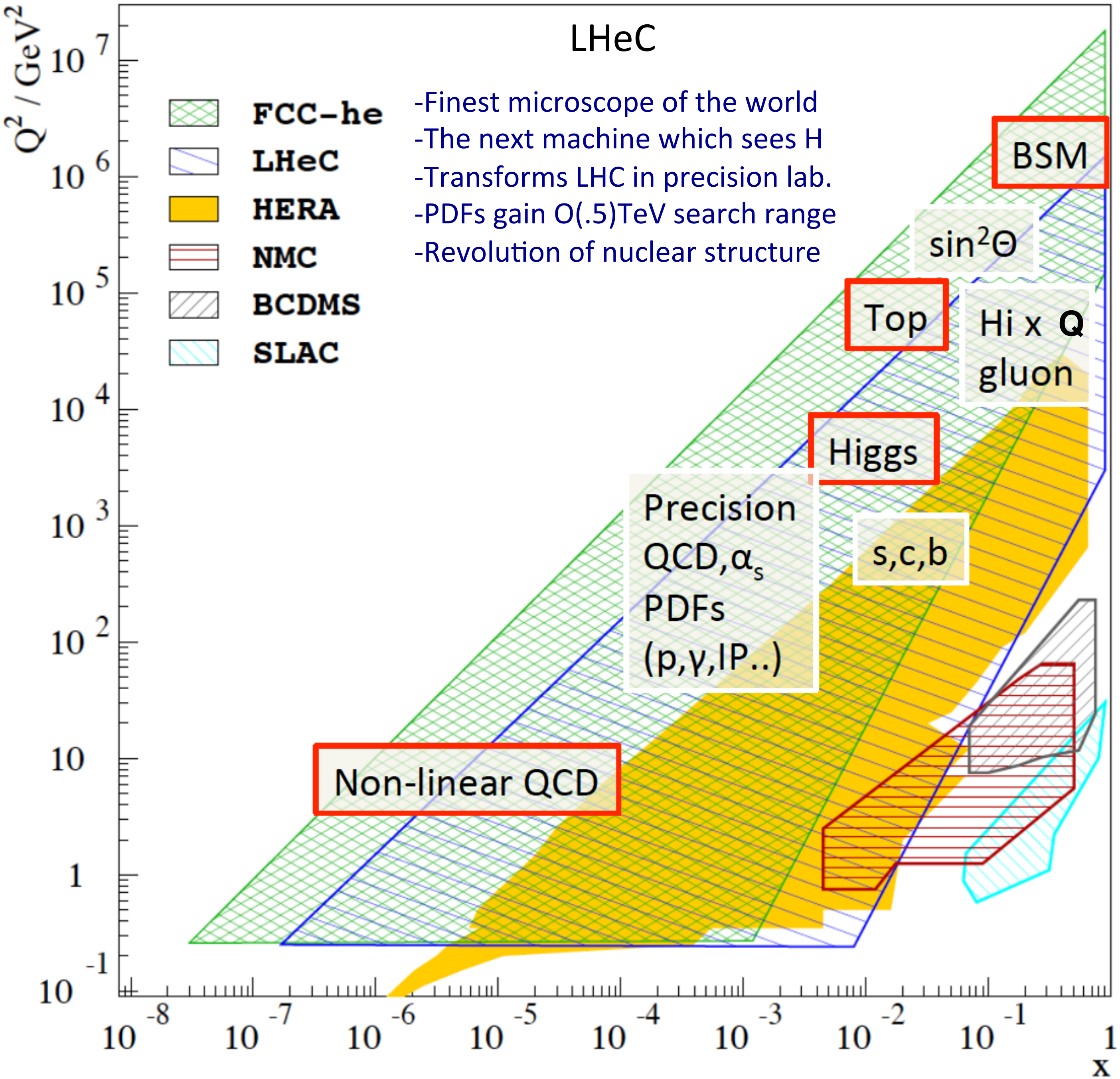


$$\mathcal{L} = 10^{33} - 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

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

LHeC options: RR and LR

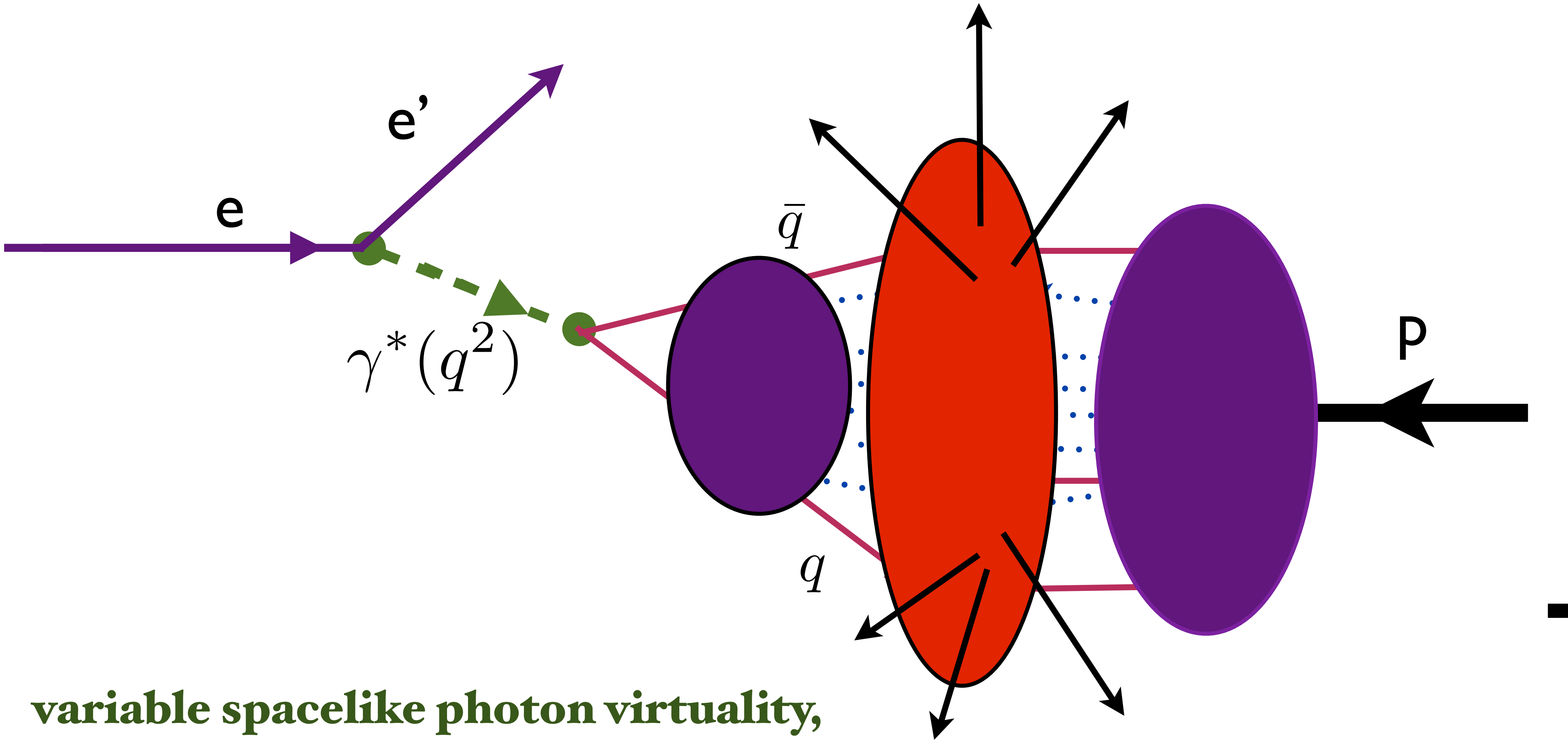




Luminosity of order 10^{34}cm^{-2} s^{-1}
in concurrent ep-pp operation

LHeC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame



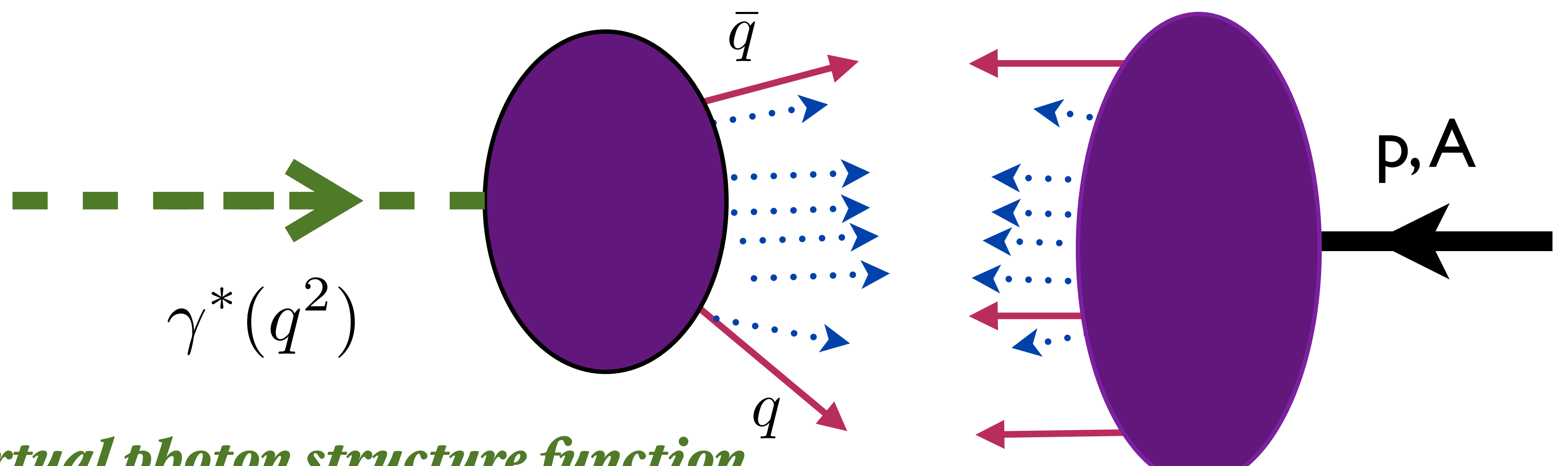
variable spacelike photon virtuality,
various primary flavors

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

LHeC: Virtual Photon-Proton Collider

Perspective from the photon-proton collider frame

QCD Factorization: Interactions of Frame-Independent Light-Front Wavefunctions of photon and proton or nucleus



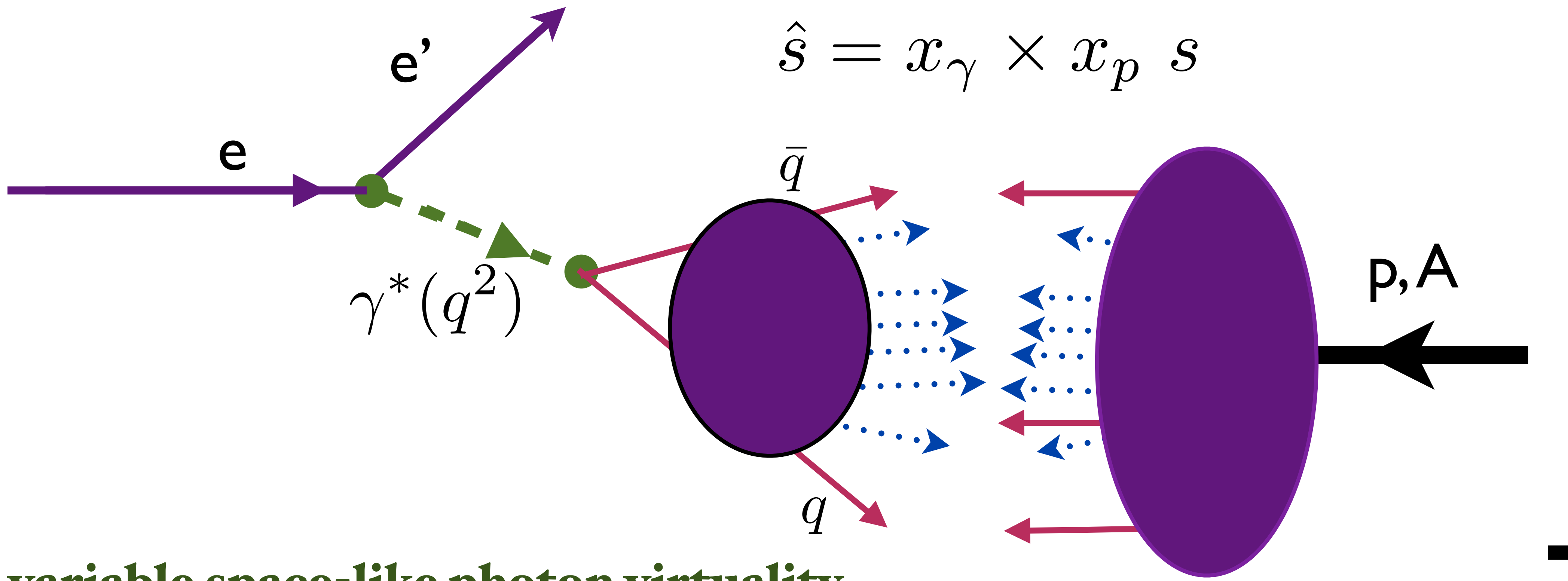
Virtual photon structure function

variable spacelike photon virtuality
various primary flavors

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

LHeC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame



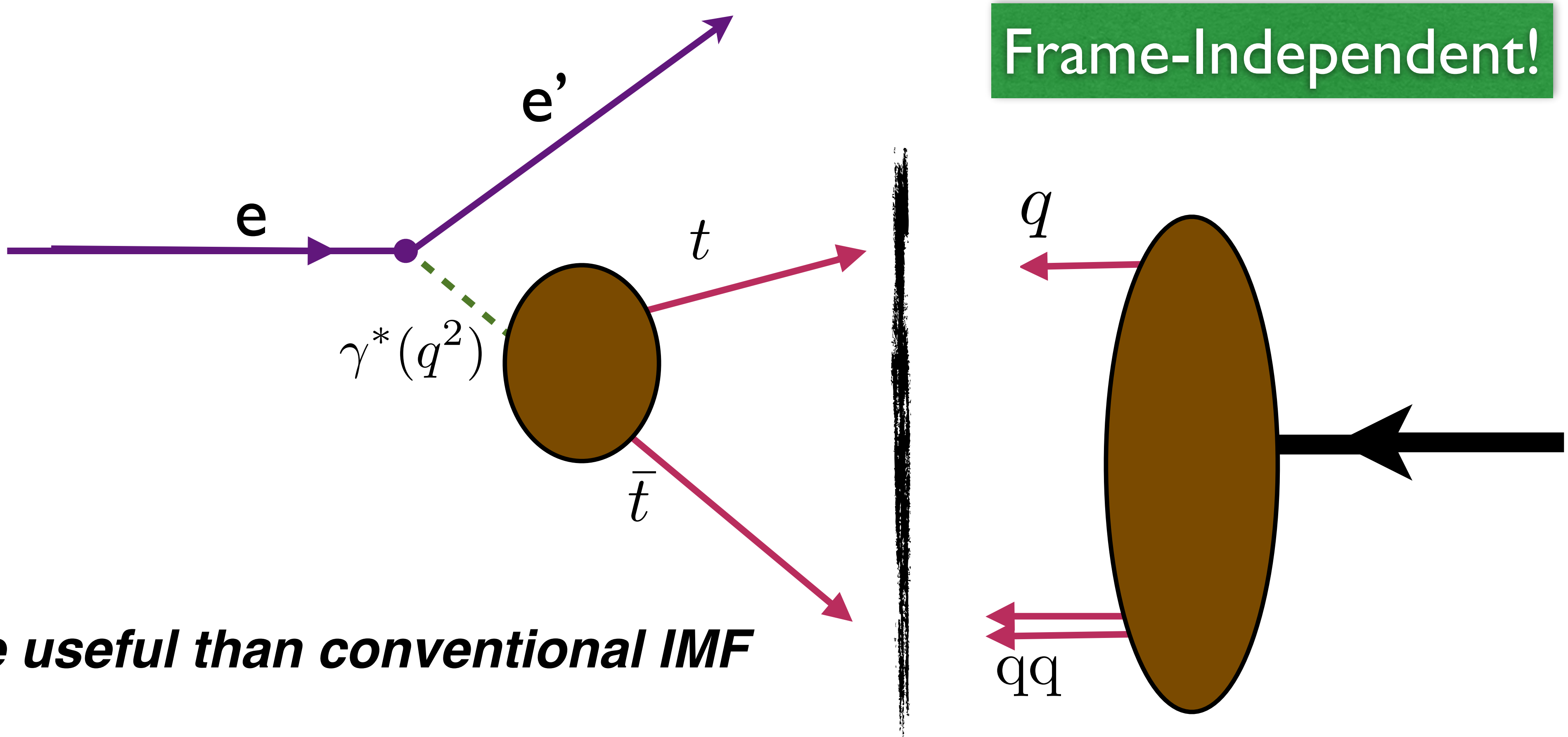
variable space-like photon virtuality, various primary flavors

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

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

Factorization: Product of LFWFs

Frame-Independent!



More useful than conventional IMF

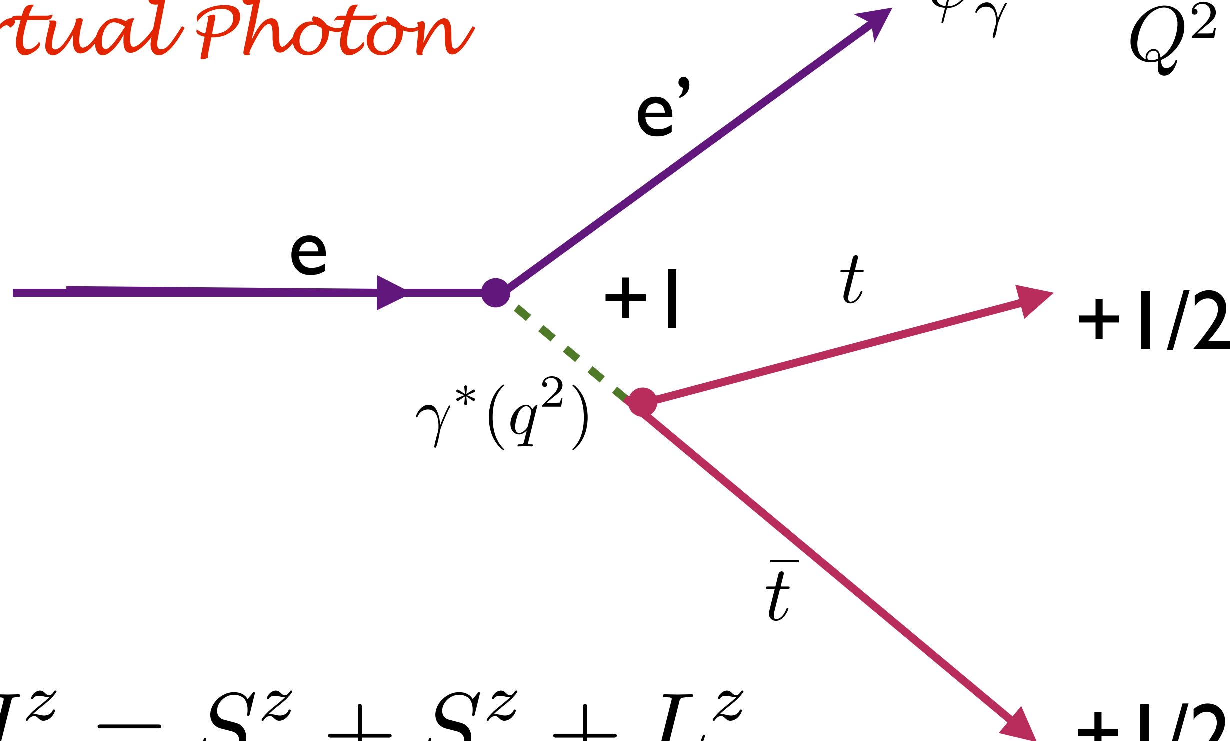
Forward rapidity in final state: Intrinsic to Virtual Photon

Backward in final state: Intrinsic to Proton

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

Born LFWFs of Virtual Photon

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



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

L^z=0

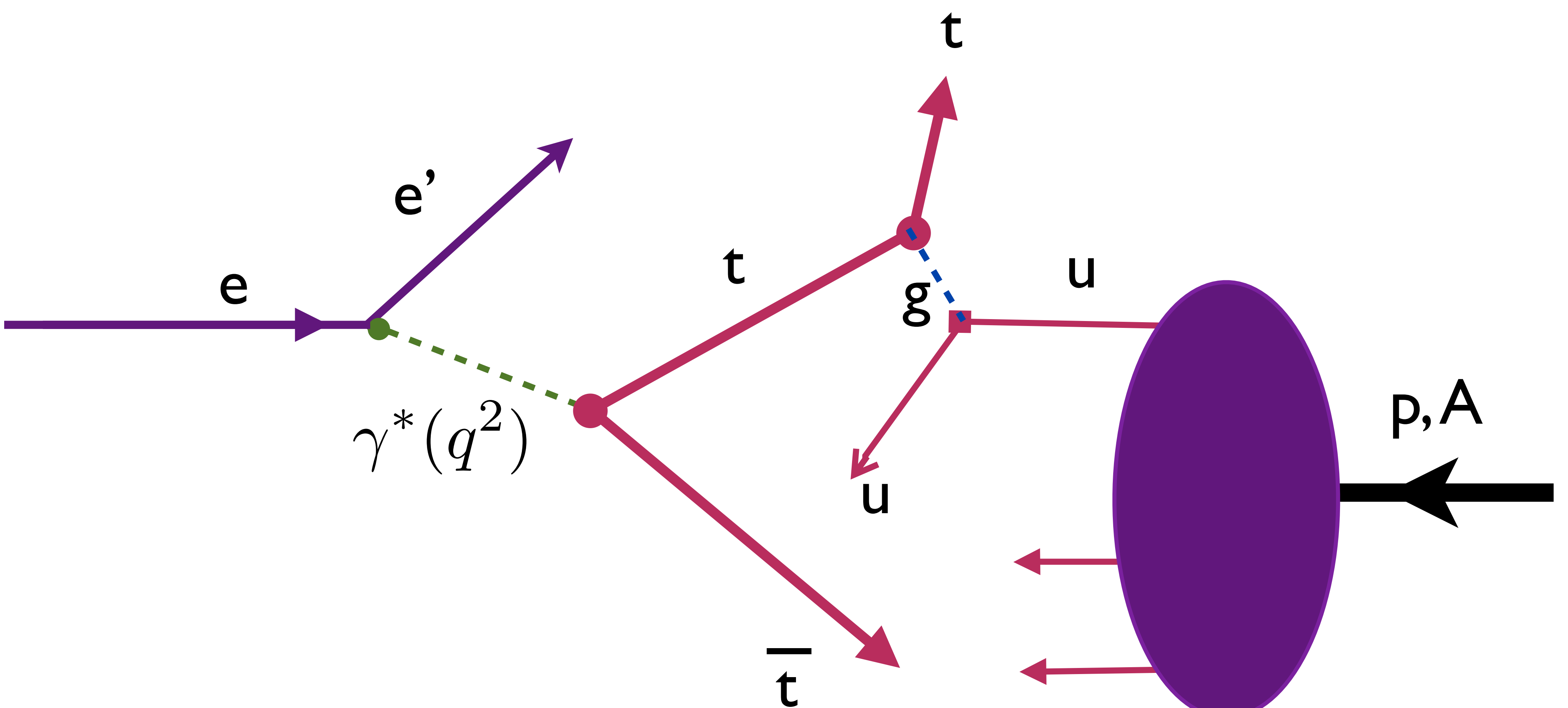
$$J^z = S^z_q + S^z_{\bar{q}} + L^z$$

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

DGLAP-Witten evolution of Photon Structure Function!

Kinoshita, Terazawa, sjb

LHeC: Top Quark-Proton Collider



$tq \to tq$

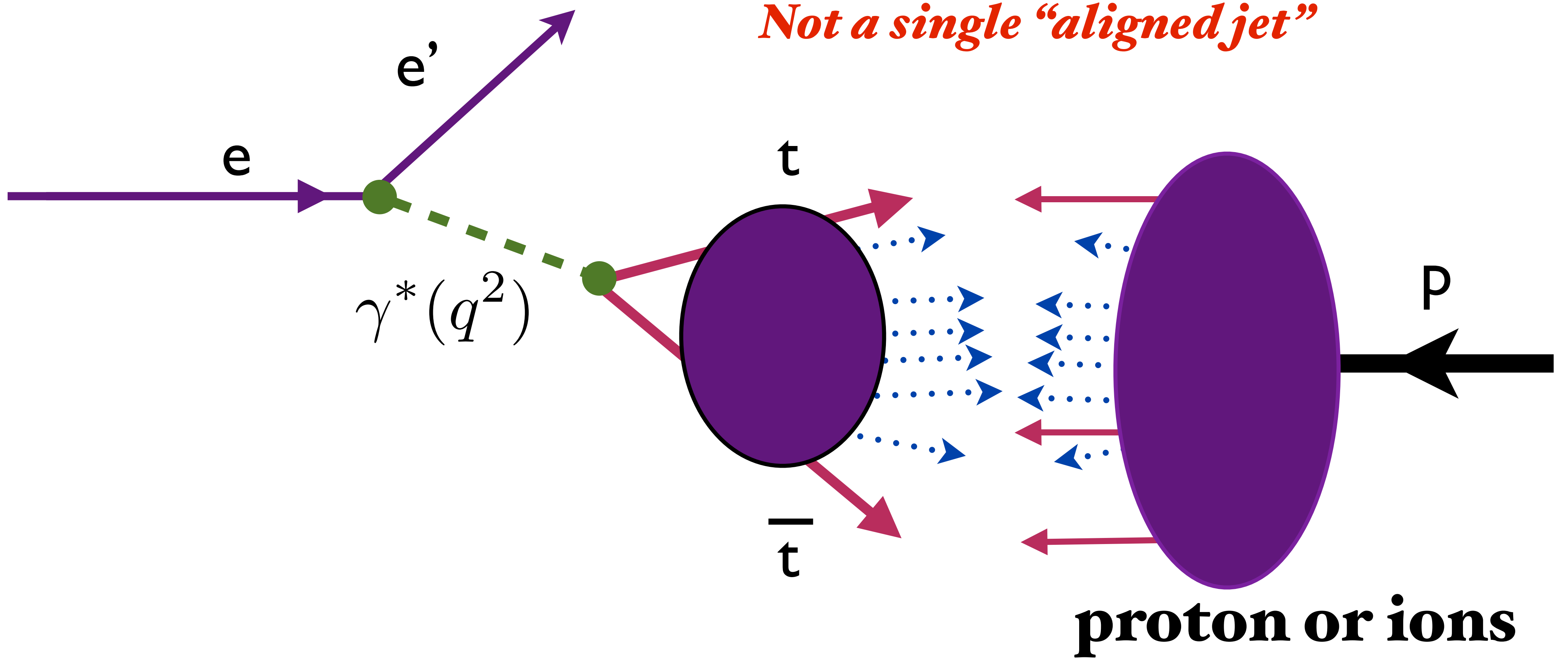
hard scattering event

Analogous to Bethe-Heitler Pair Production $\gamma^* Z \to \tau^+\tau^- Z$

LHeC: “Top Quark-Proton Collider”

$\bar{t}\,t$ plane aligned with lepton scattering plane

Not a single “aligned jet”



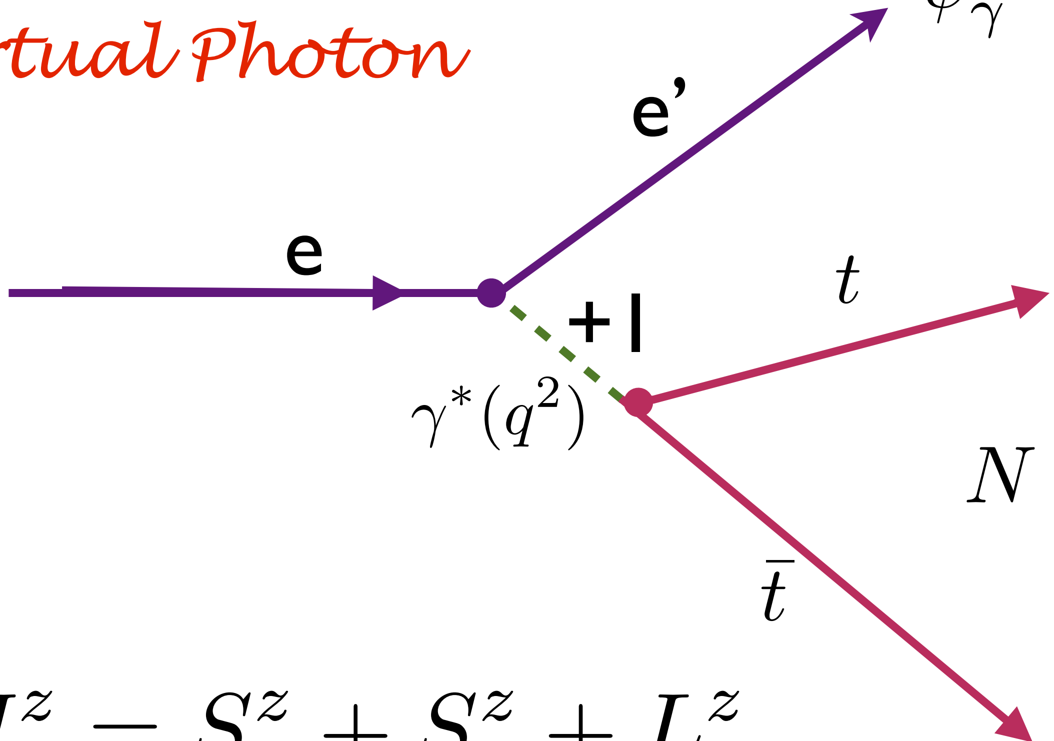
Only partially included by DGLAP in proton pdf

Enhancement at top threshold

Electron produces a virtual top-quark pair correlated with electron's scattering plane

Born LFWFs of Virtual Photon

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



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

L^z=+1

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

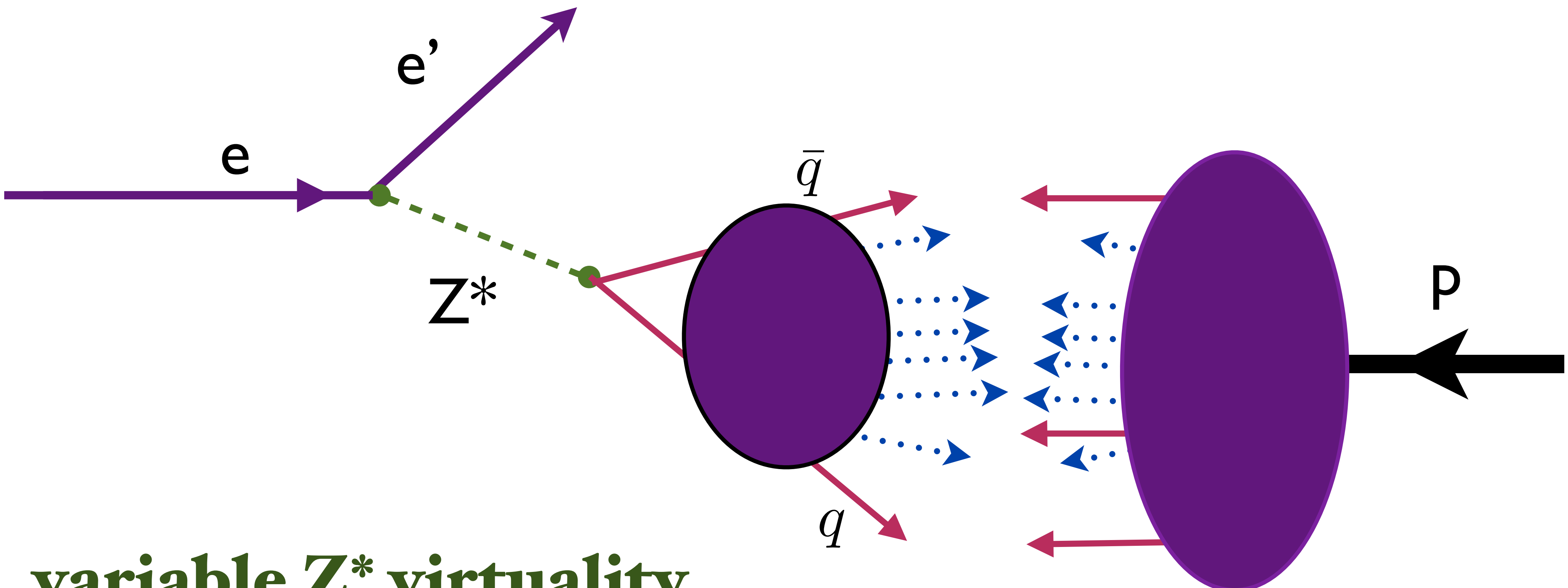
$$+1 \rightarrow (1/2) + (-1/2) + 1$$

Scattering on p, A puts process on-shell

Witten evolution of Photon Structure Function!

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

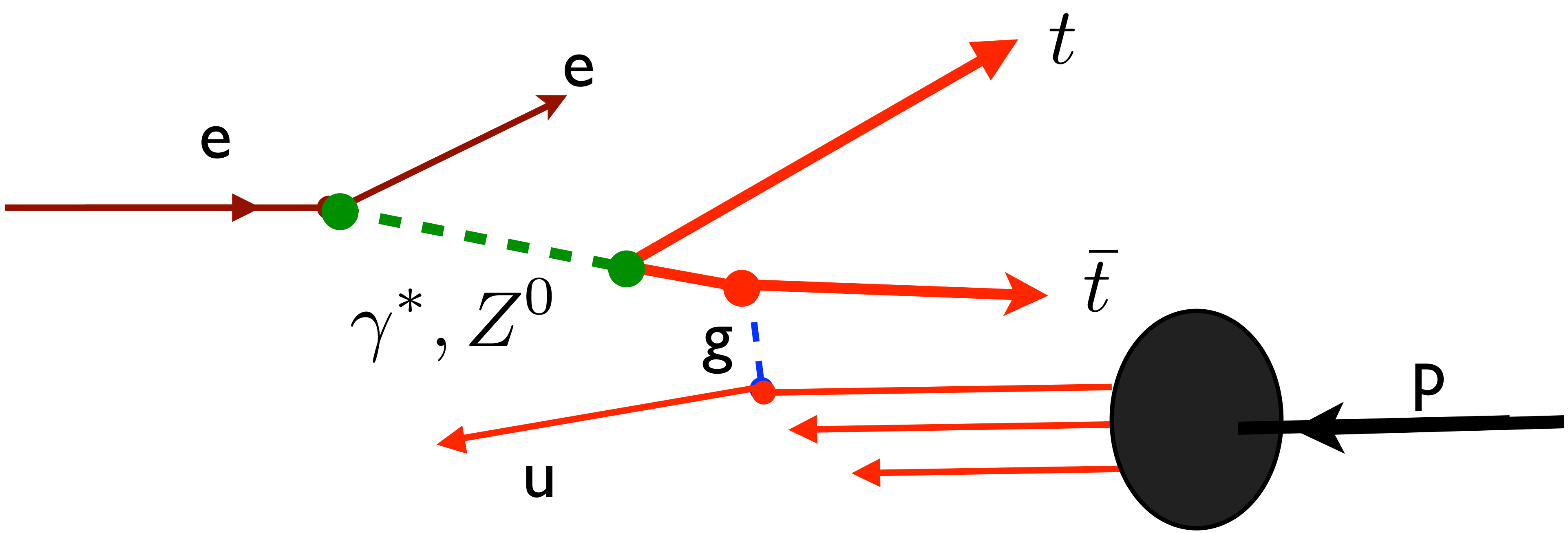
q $\bar{q}$ plane aligned with lepton scattering plane ~ $\cos^2\phi$

LHeC: Virtual Photon-Proton Collider

Inclusive Top Electroproduction at the LHeC

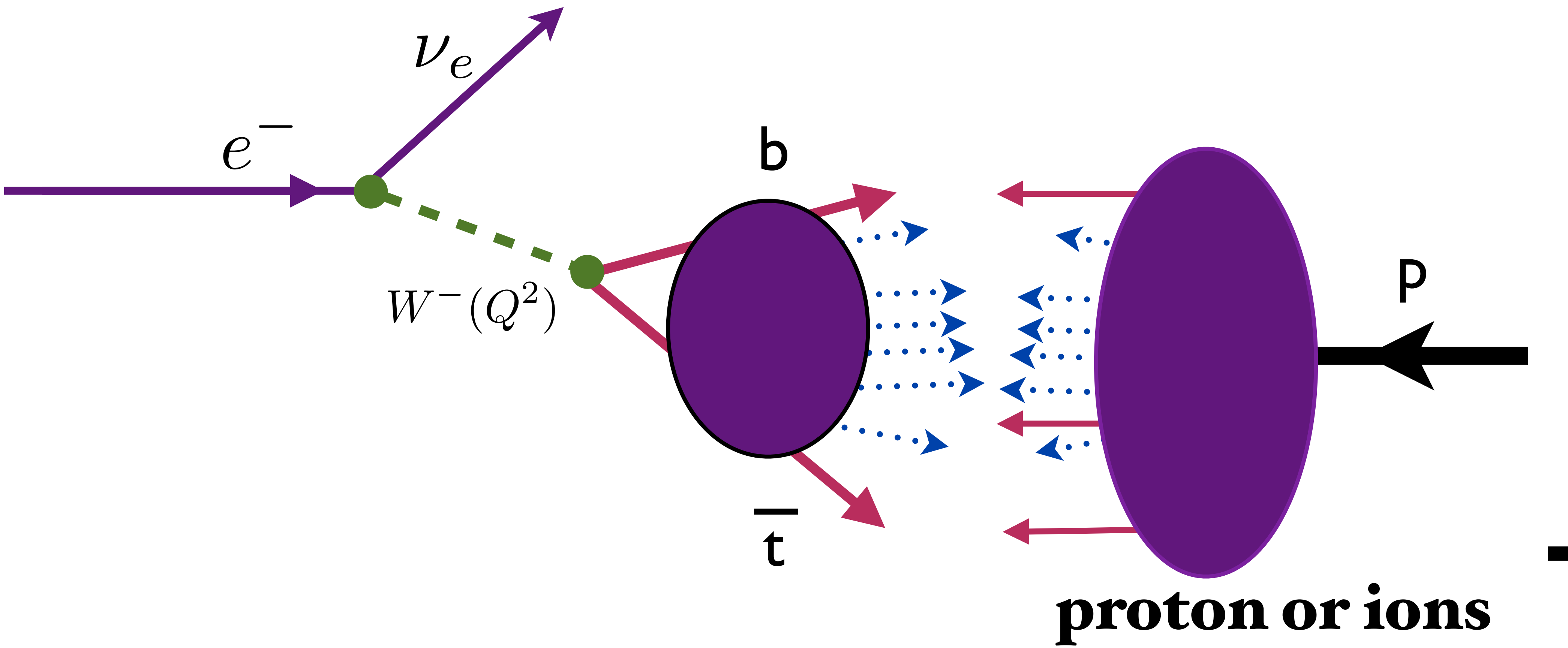
$t-\bar{t}$ asymmetry from γ^* and Z^* or $\gamma^*\gamma^*$ interference

Dual Interpretation: Top quark in photon vs. heavy sea quark in proton



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

LHeC: "W-Proton Collider"



Only partially included by DGLAP in proton pdf

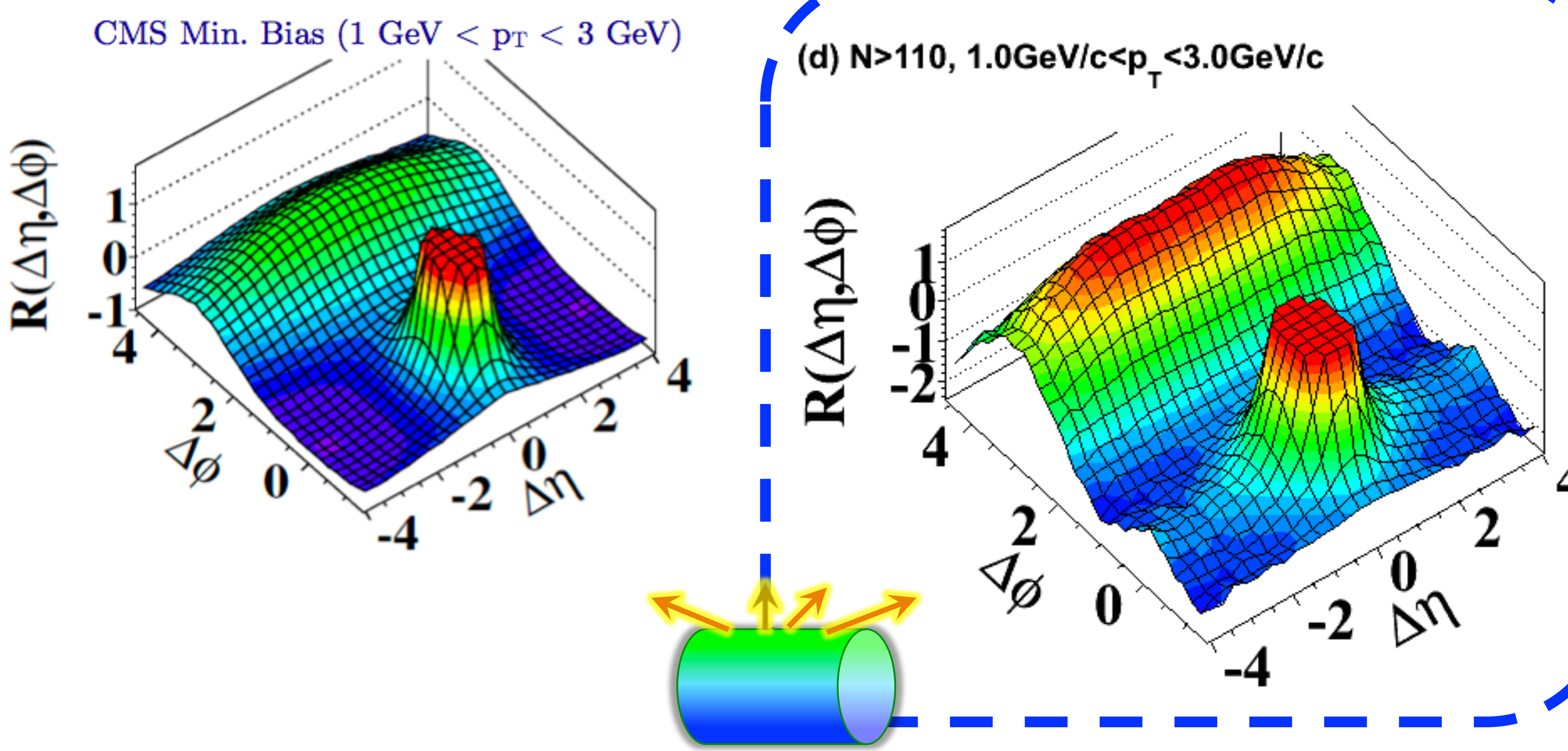
Enhancement at threshold

Ridge in p p collisions!

Raju Venugopalan

Two particle correlations: CMS results

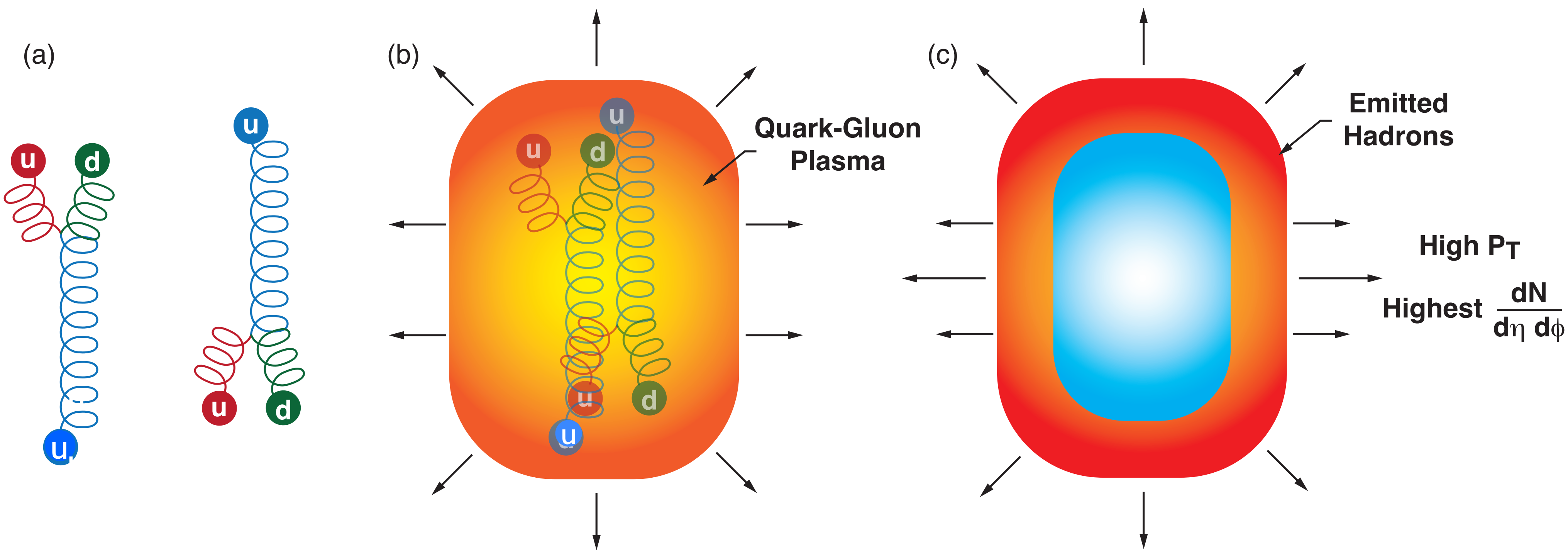
"Discovery"



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

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.

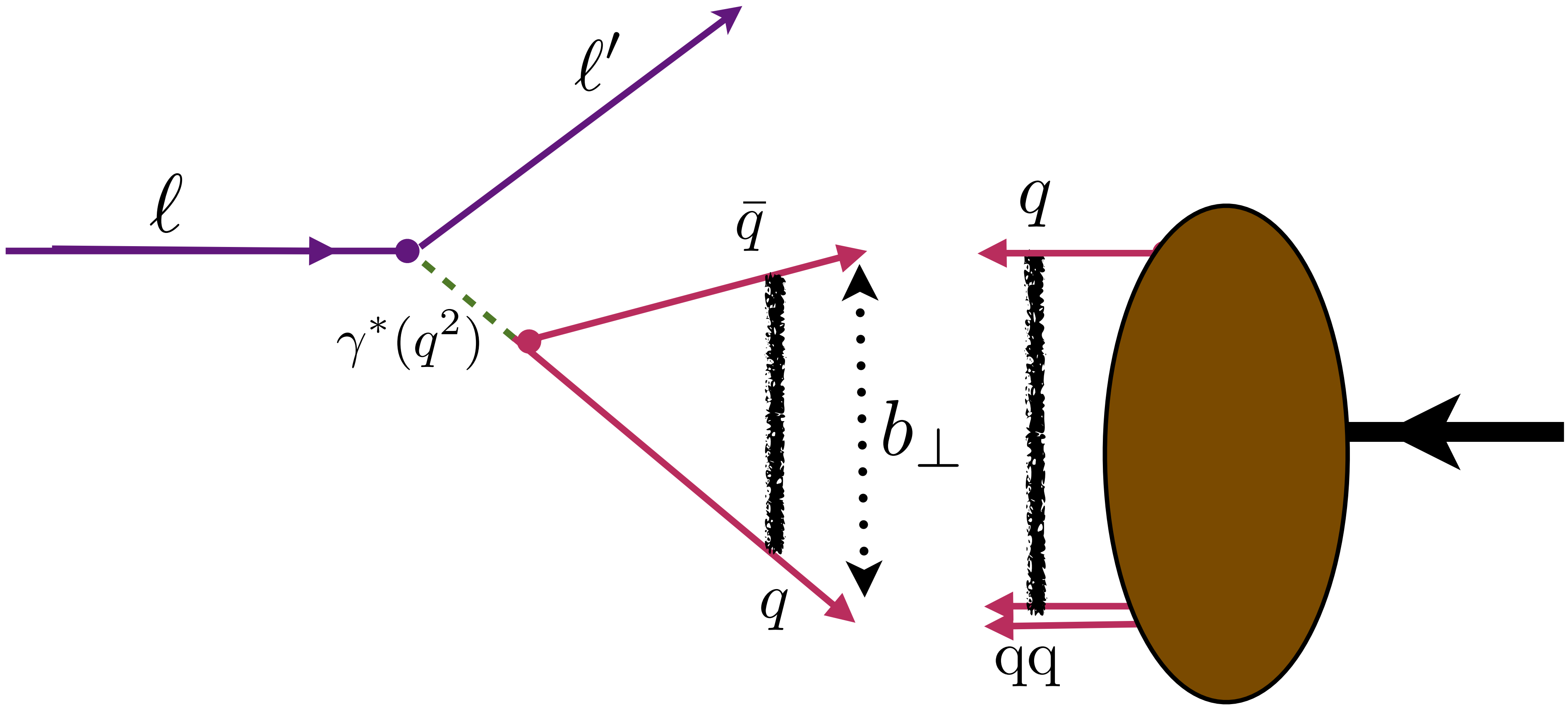
The "spray" of particles resulting from the approximate line source produced in such inelastic collisions then gives rise to events with a strong correlation between particles produced over a large range of both positive and negative rapidity.

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

Bjorken, Goldhaber, sjb

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

LHeC: Colliding flux-tubes produce opposite-side ridges of hadrons over full range of rapidity



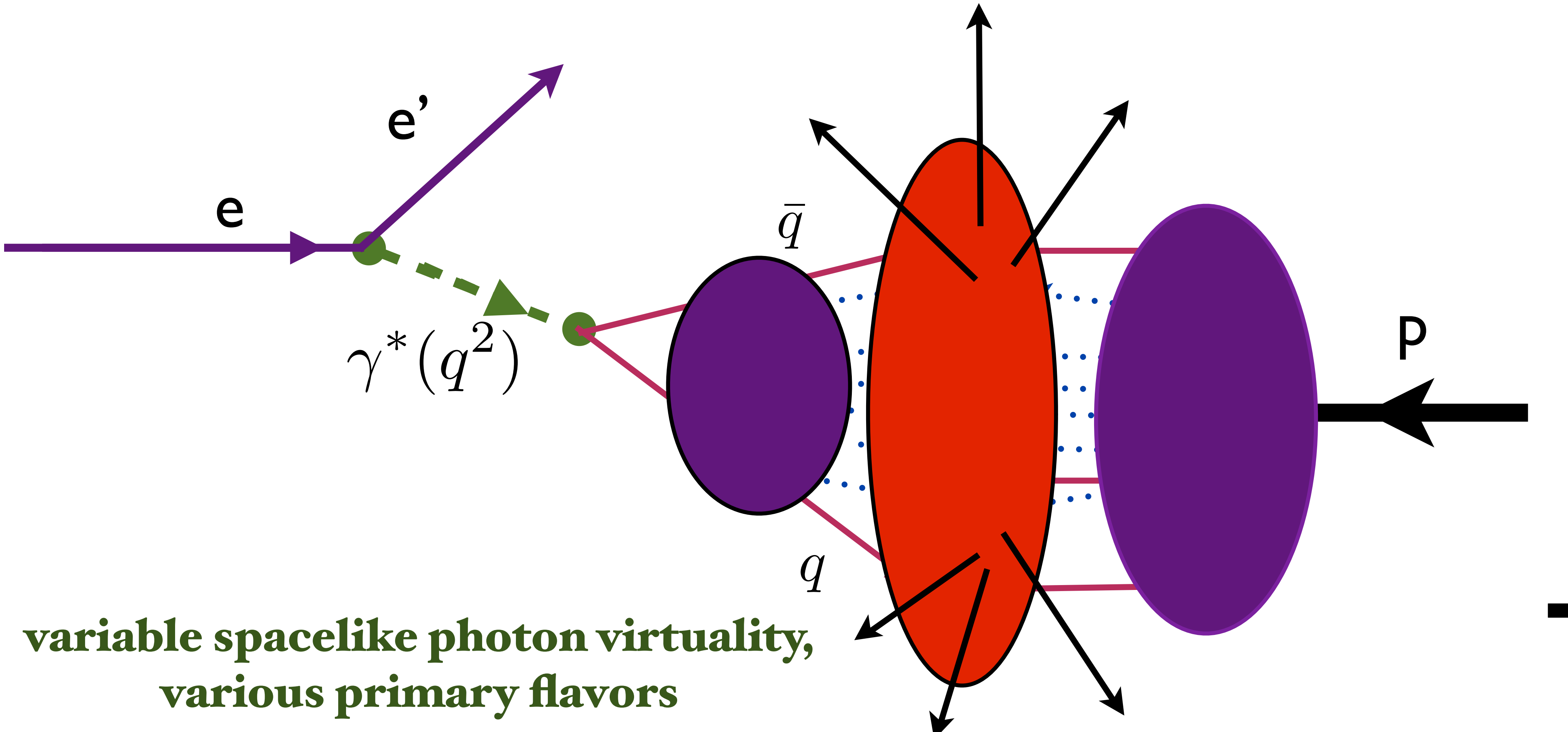
Ridge axes correlated with leptonic scattering plane

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

Small size domain activated

LHeC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame



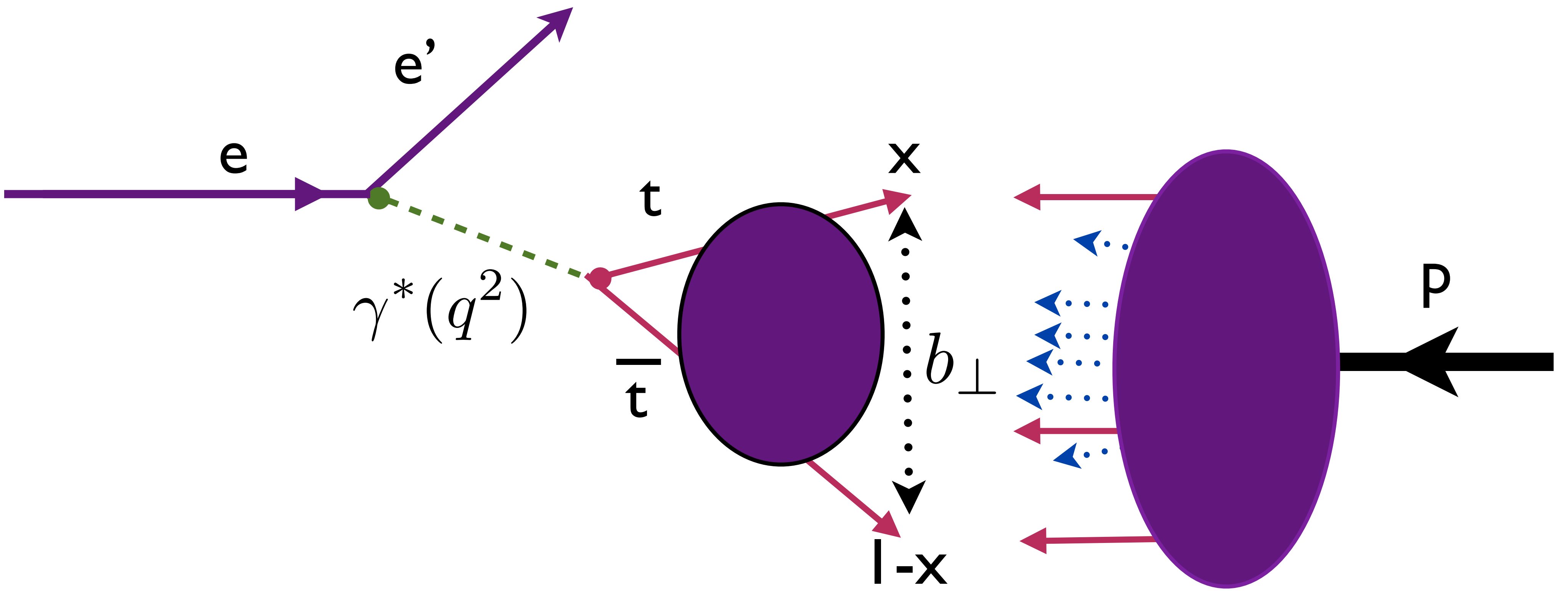
variable spacelike photon virtuality, various primary flavors

photon and proton fragmentation vs. central regions

Collisions of Photon and Proton Flux Tubes

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

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

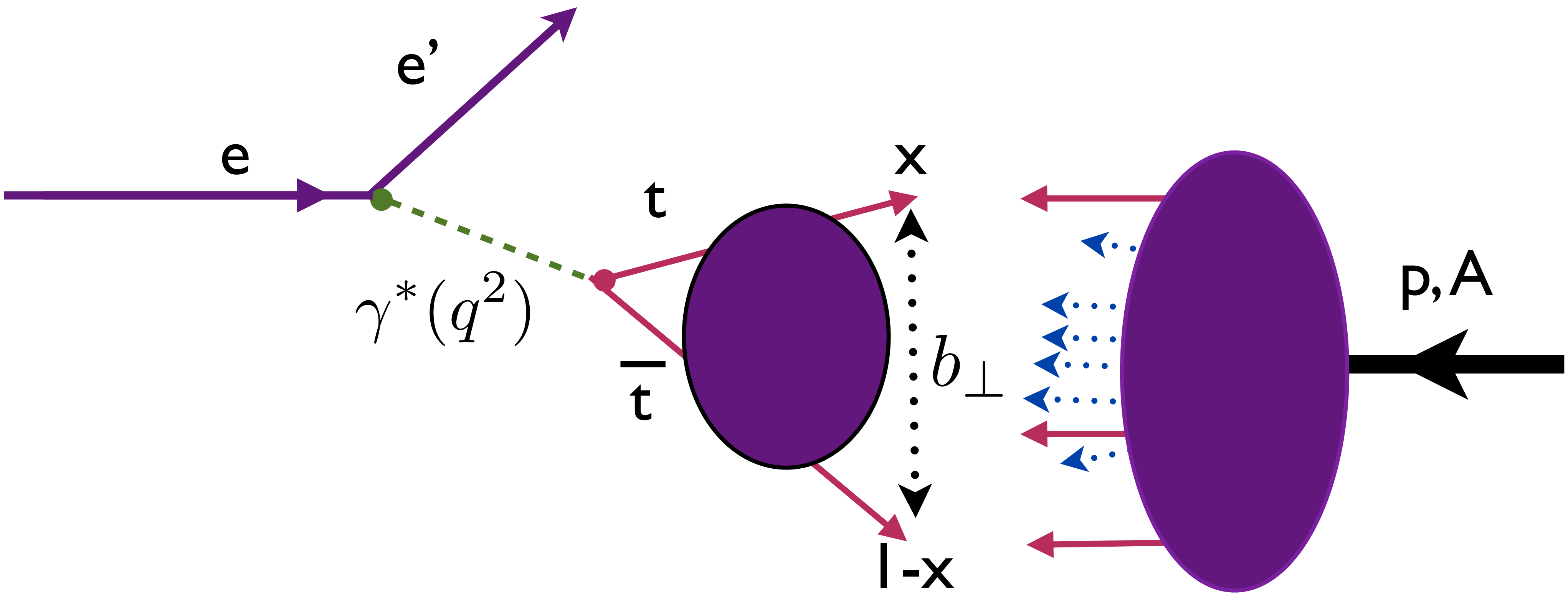


Cross section enhanced by BFKL:

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

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

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

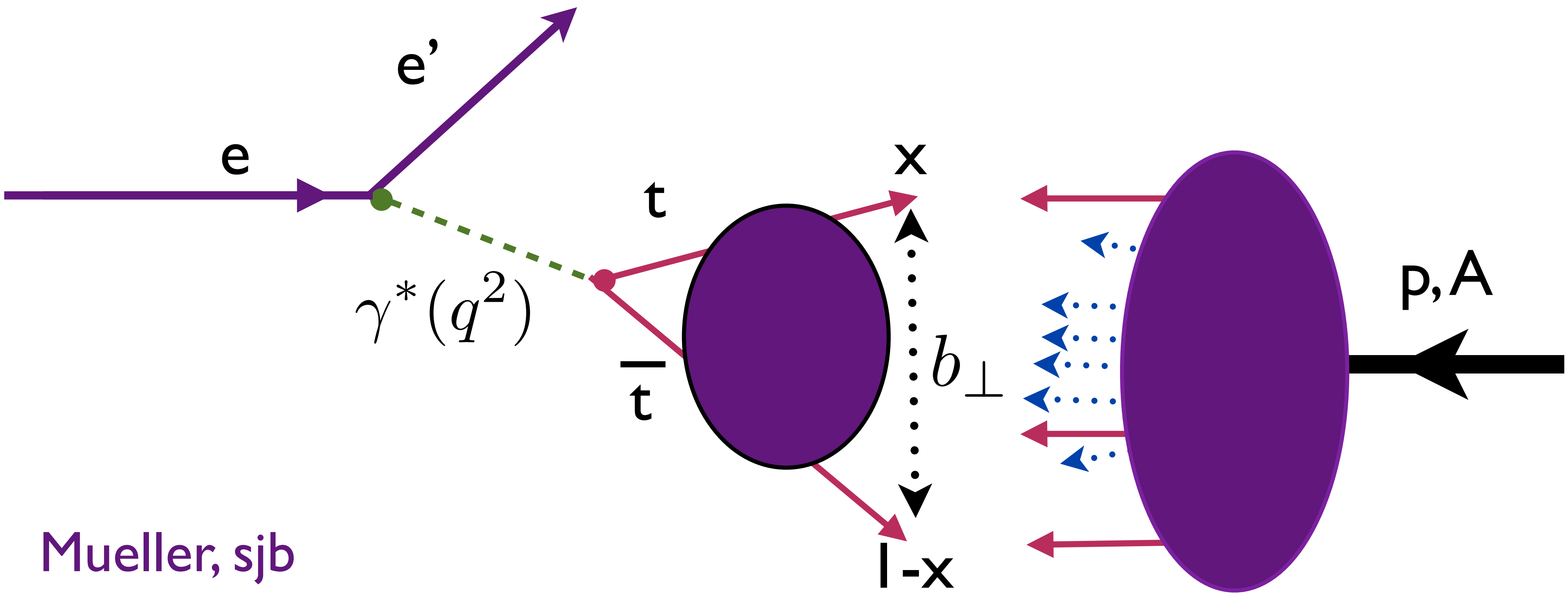


High Q^2, high M^2_Q virtual photon at LHeC acts as a precision, small bore, linearly oriented, flavor-dependent probe acting on a proton or nuclear target.

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

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

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



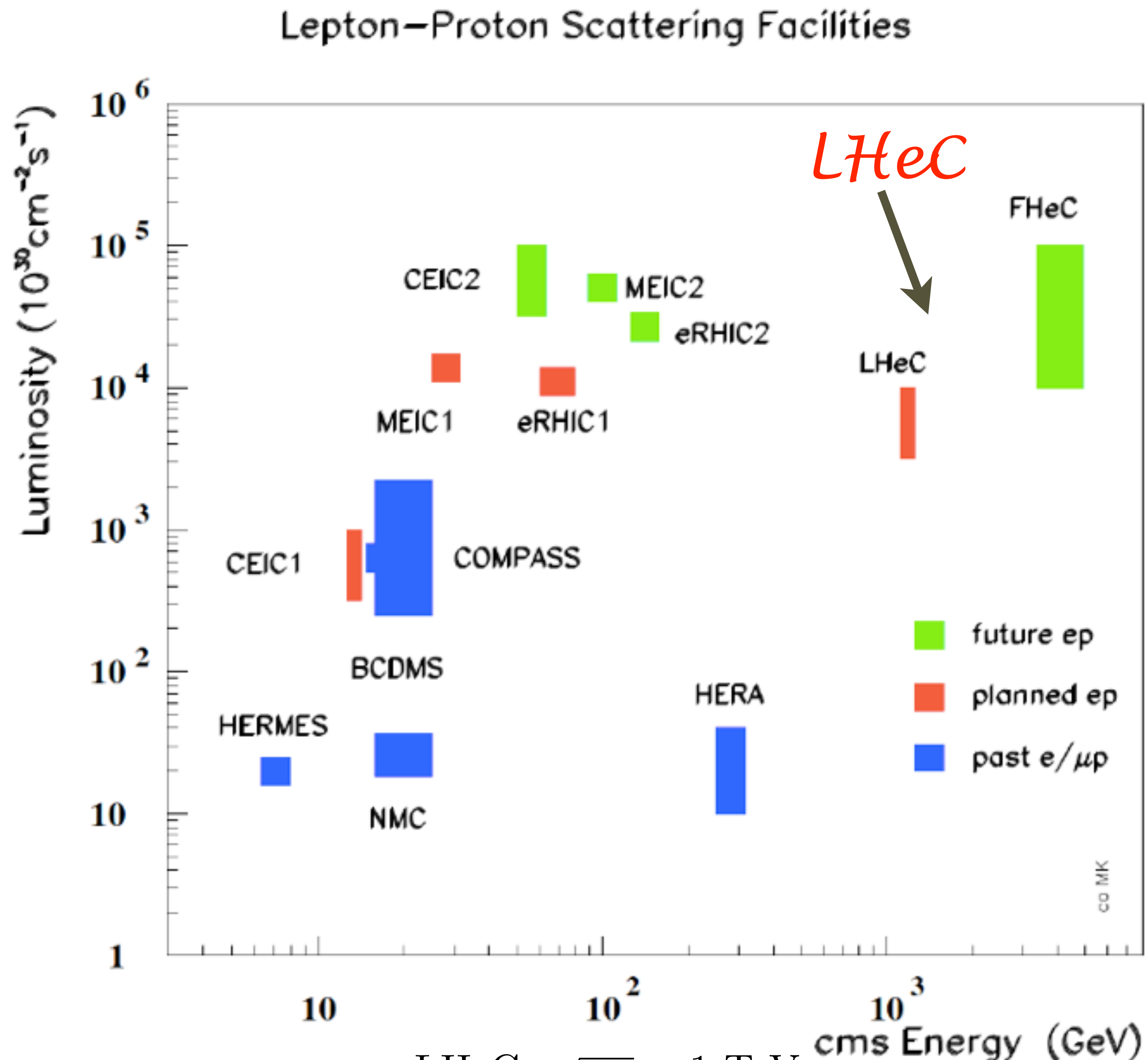
Mueller, sjb

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

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

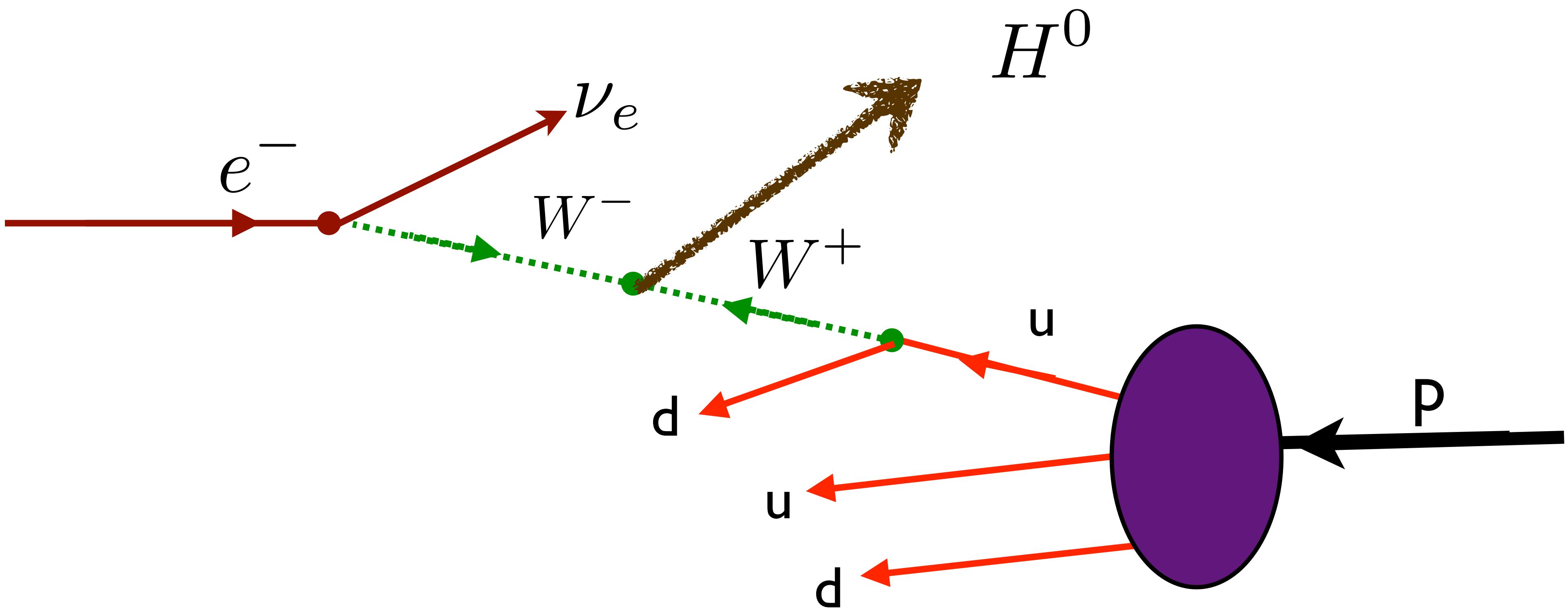
No nuclear shadowing at high Q^2 or M^2_Q

LHeC: Above the $\bar{t}\,t$ +Higgs threshold

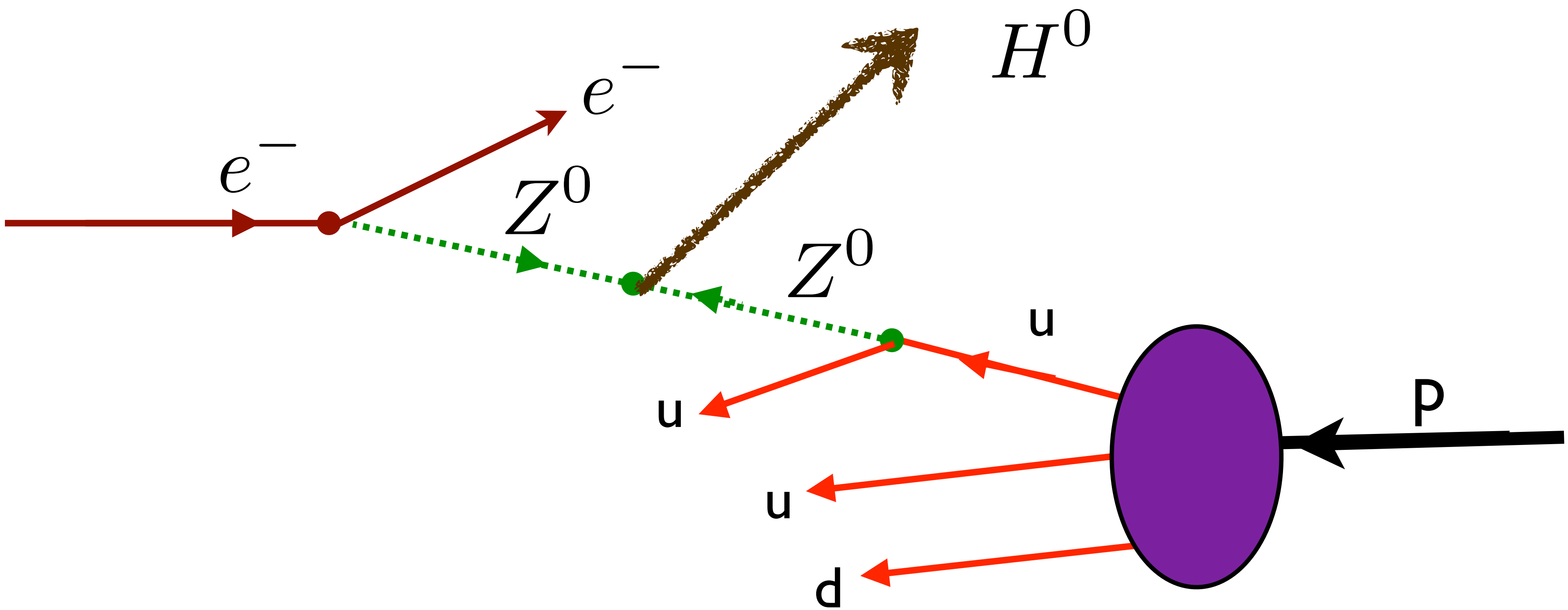


LHeC: $\sqrt{s_{ep}} > 1$ TeV

Inclusive Higgs Electroproduction at the LHeC from the Charged Current

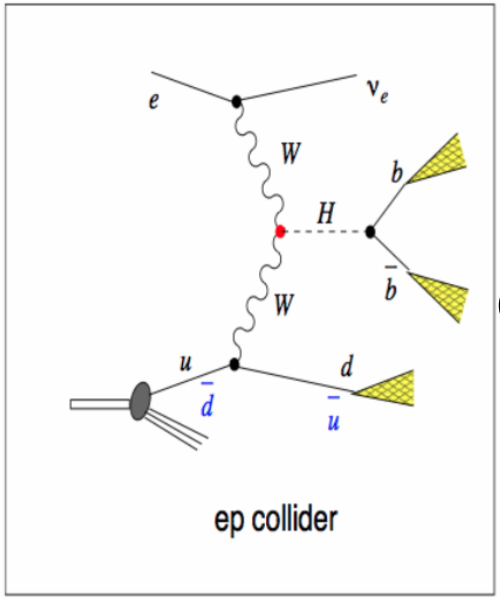


Inclusive Higgs Electroproduction at the LHeC from the Neutral Current

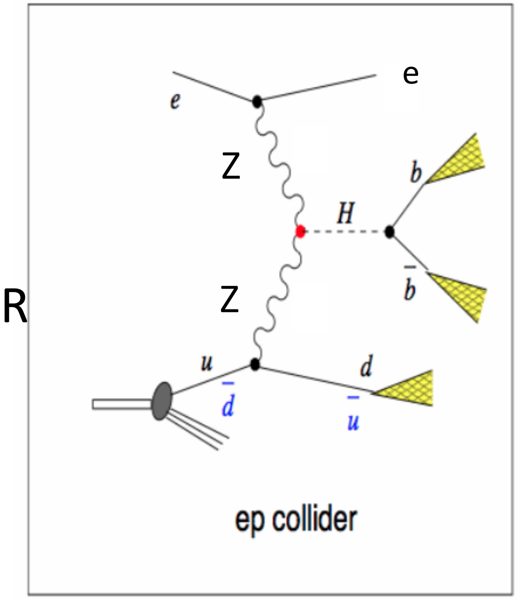


VBF Higgs production: e-p vs p-p

ep



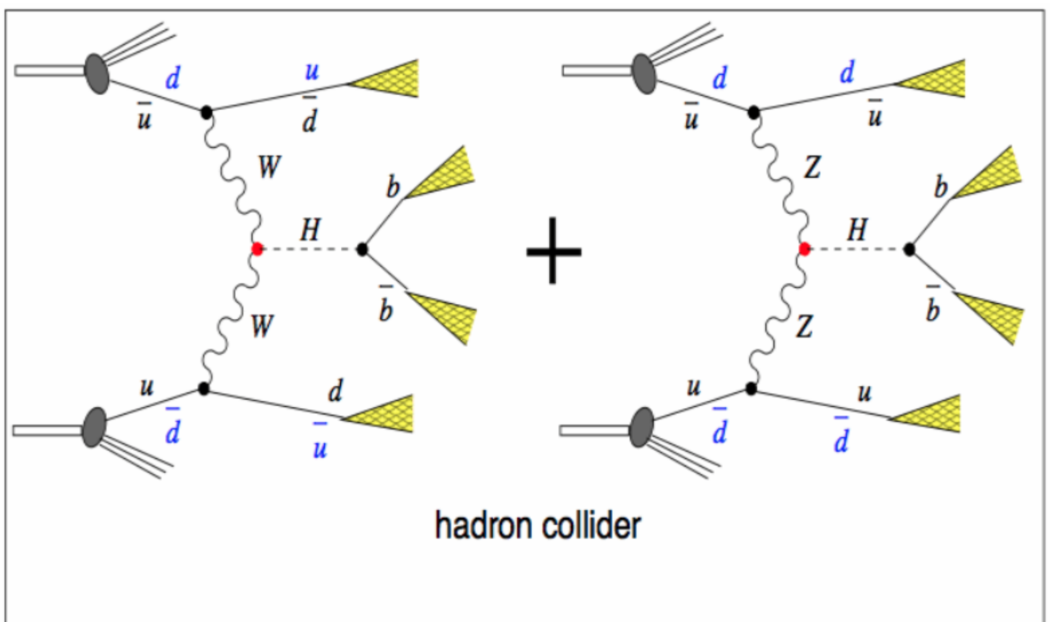
OR



- Higgs production in ep comes uniquely from either CC or NC
  - Pile-up in e-p at 10^{34} = 0.1
  - Clean(er) bb final state, S/B ~ 1

→ Clean, precise reconstruction and easy distinction of ZZH and WWH

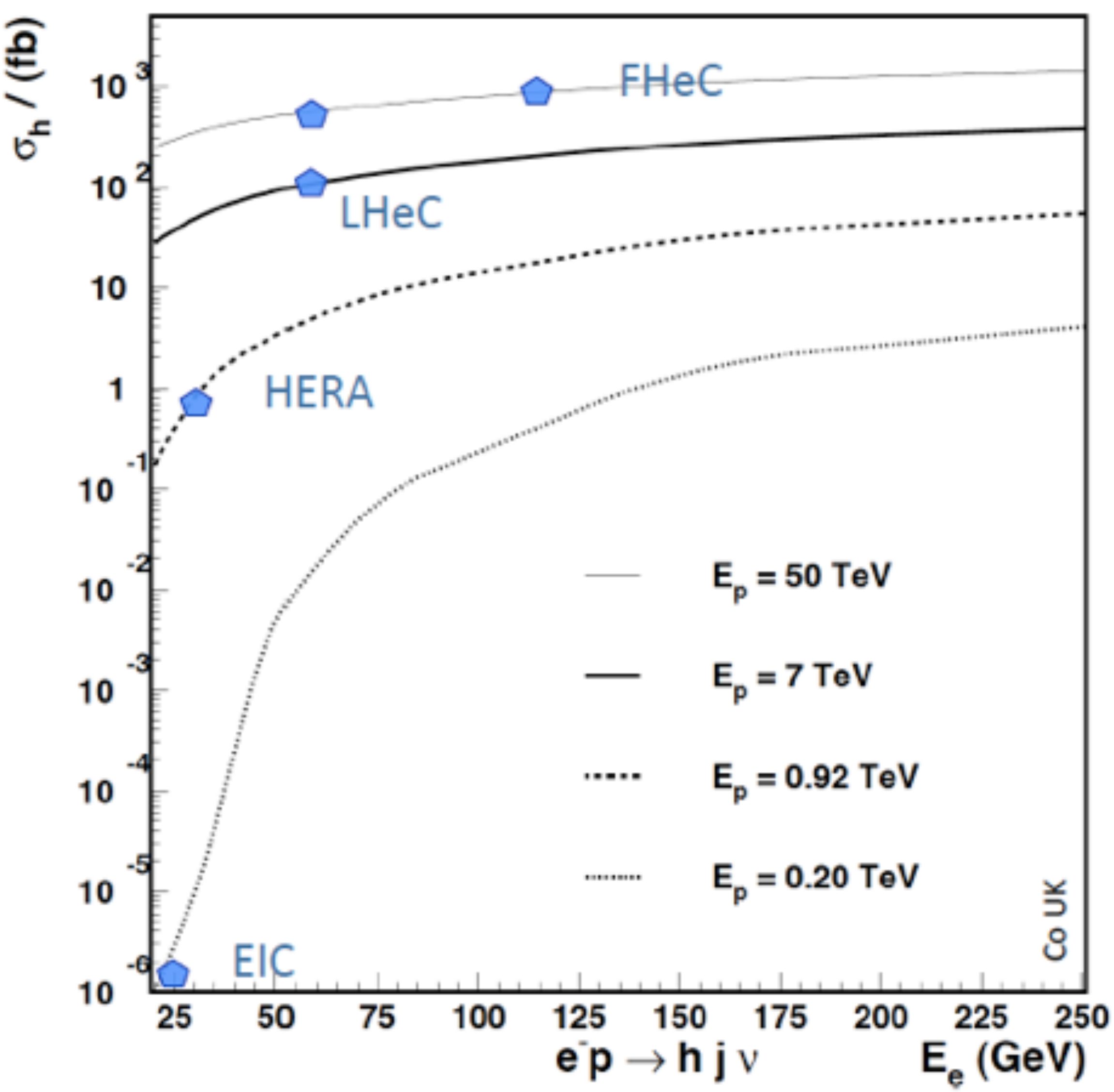
pp



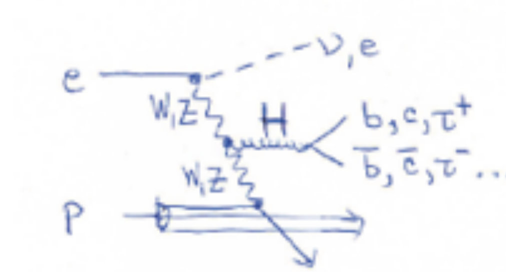
- Higgs production in pp comes predominantly from gg→H
  - VBF cross section about 200 fb (about as large as at the ILC).
  - Pile-up in pp at 5 x 10^{34} is 150, S/B very small for bb
  - Precision needs accurate PDFs

Higgs Production via Vector-Boson Fusion

R. Godpole



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

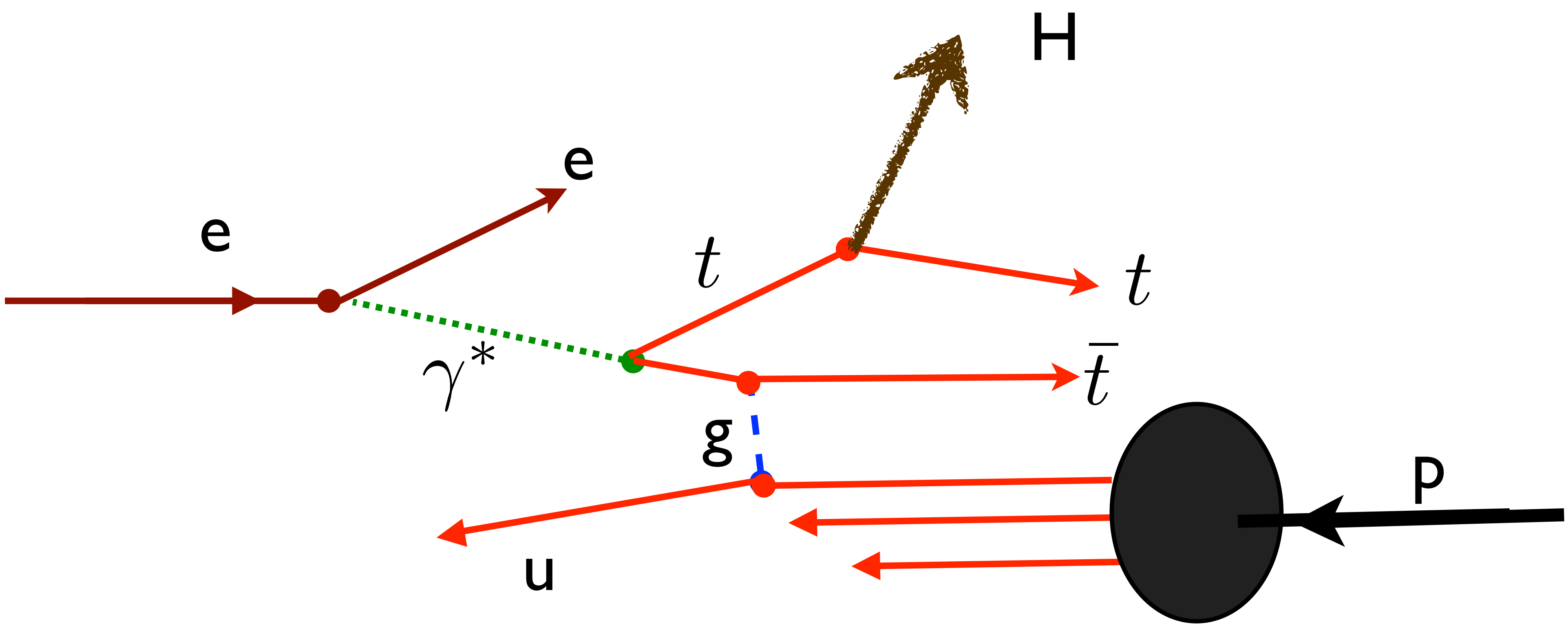
LHeC O(10^5) H from VBF

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

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

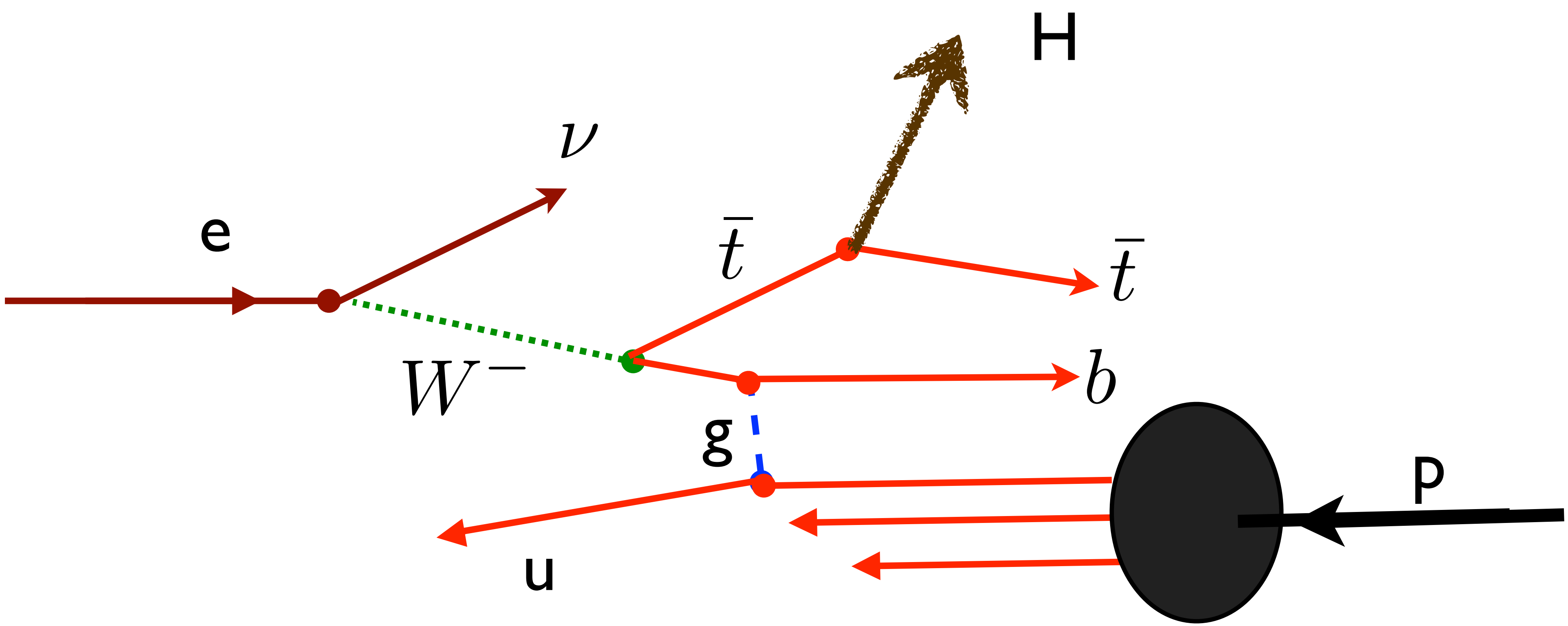
Inclusive Higgs Electroproduction at the LHeC

Higgs production from top

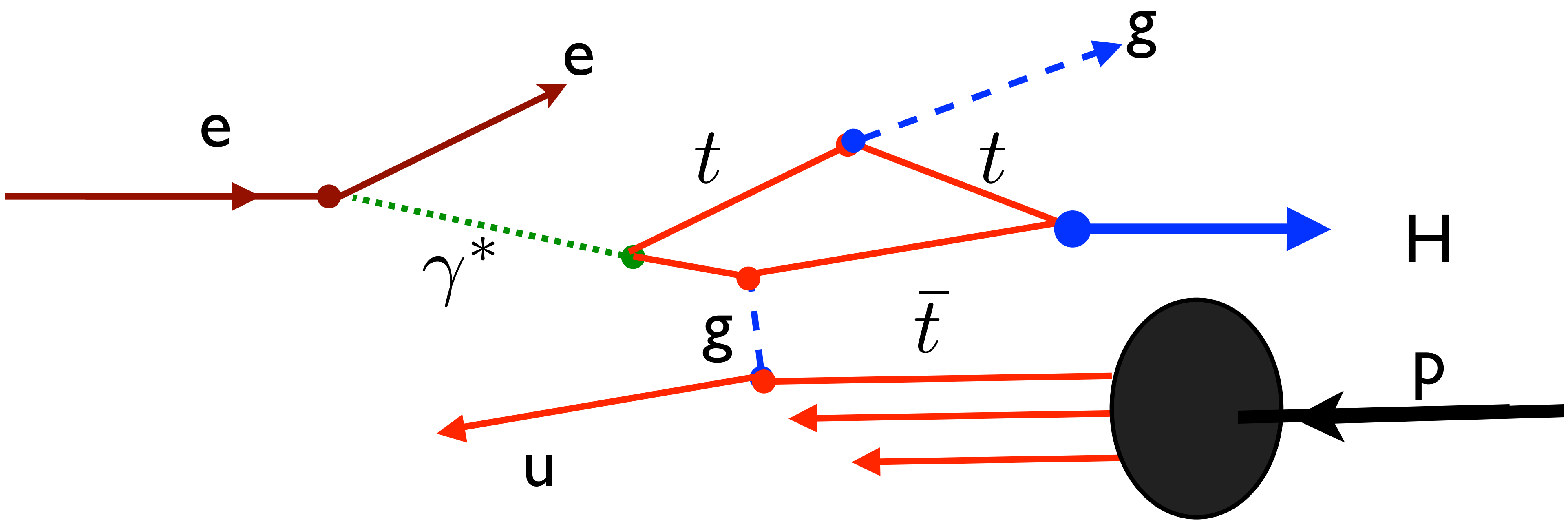


Inclusive Higgs Electroproduction at the LHeC

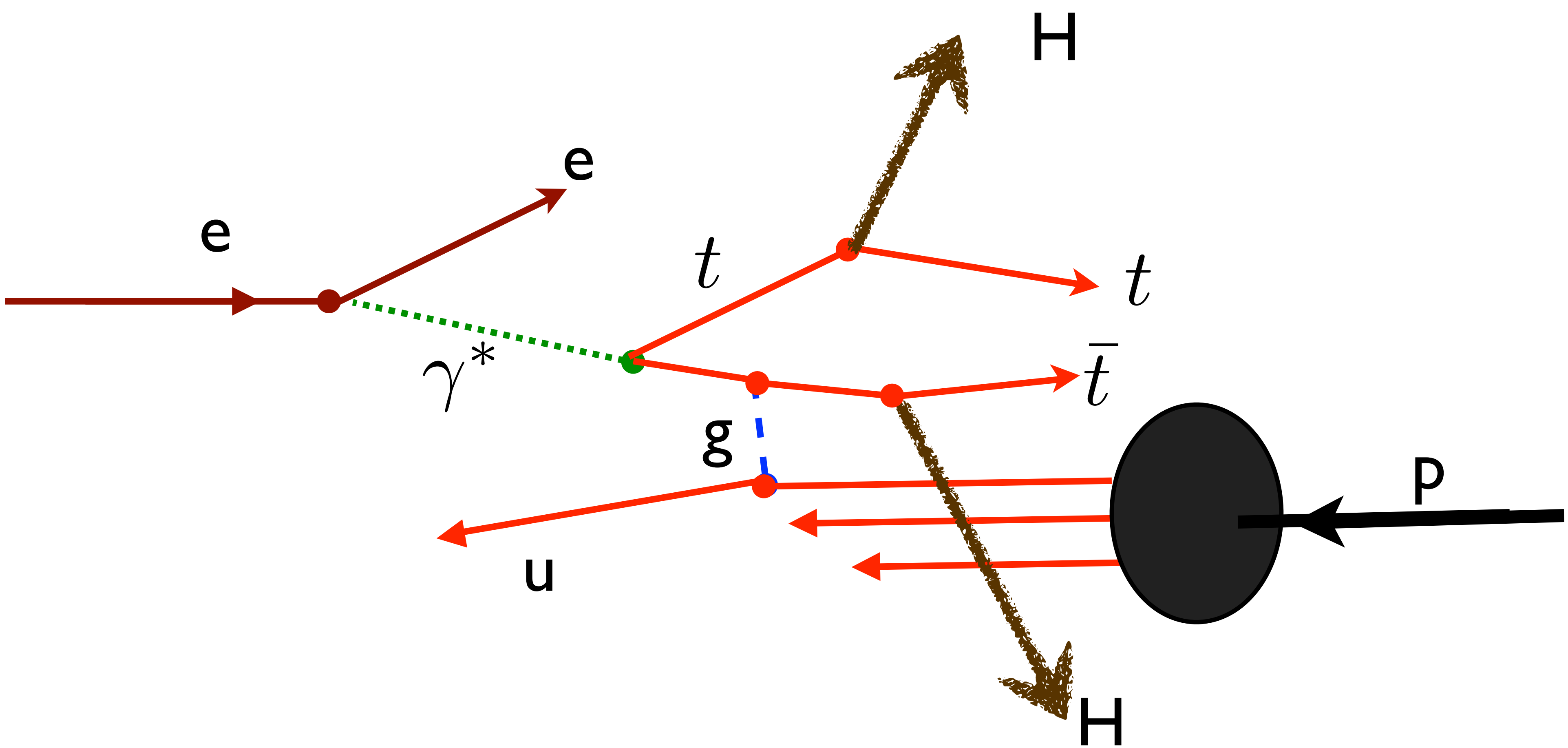
Higgs production from single top



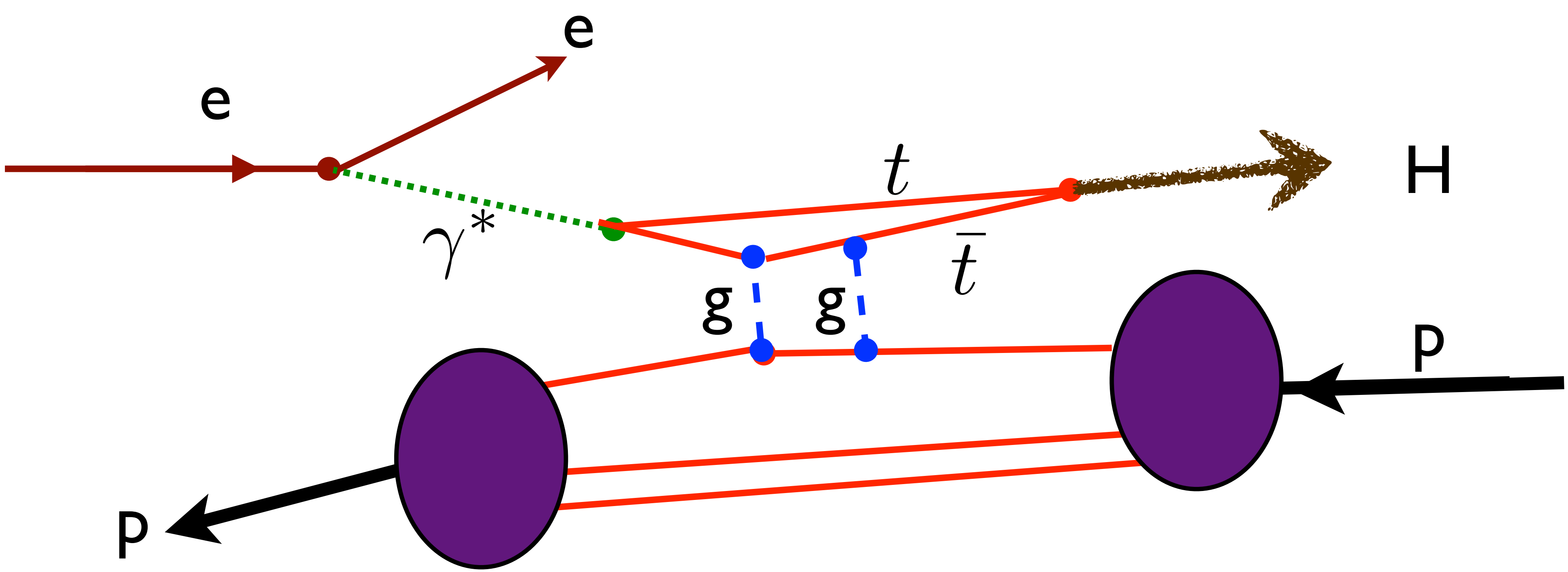
Higgs Electroproduction at the LHeC



Two-Higgs Electroproduction or photoproduction at the LHeC!

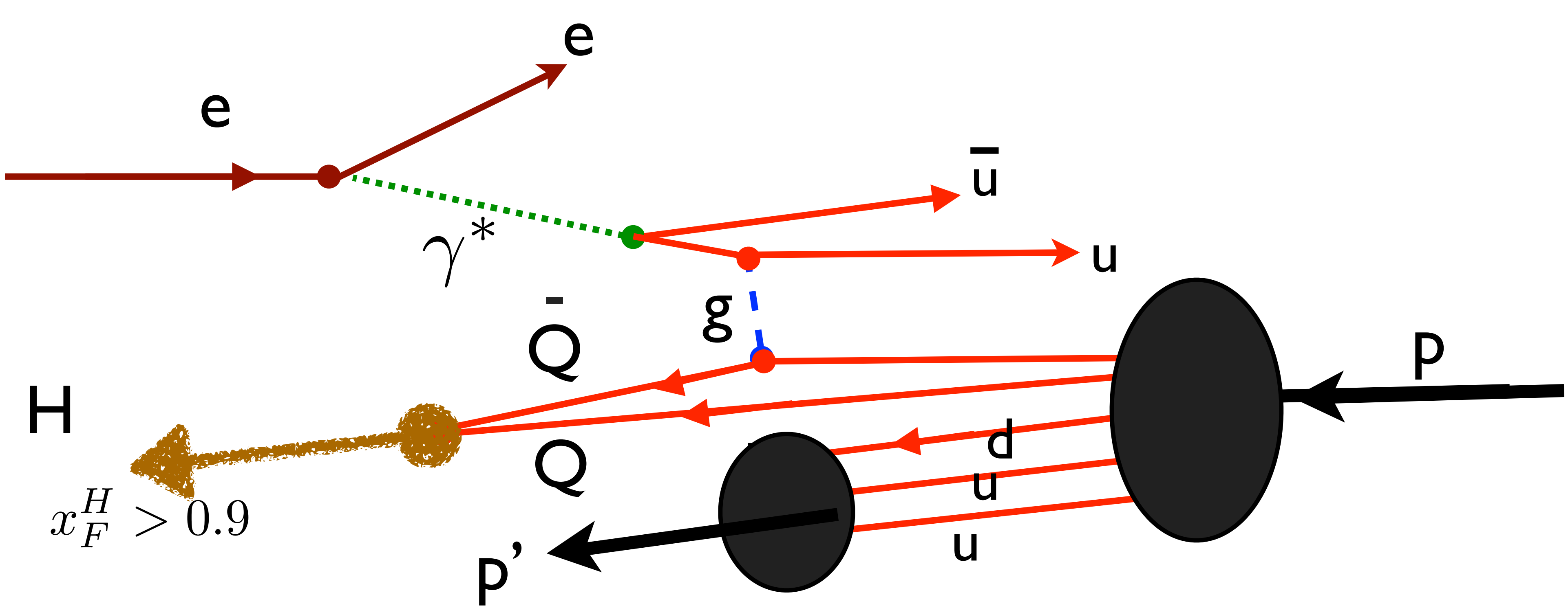


Diffractive Higgs Electroproduction at the LHeC



Kopeliovich, Schmidt, sjb

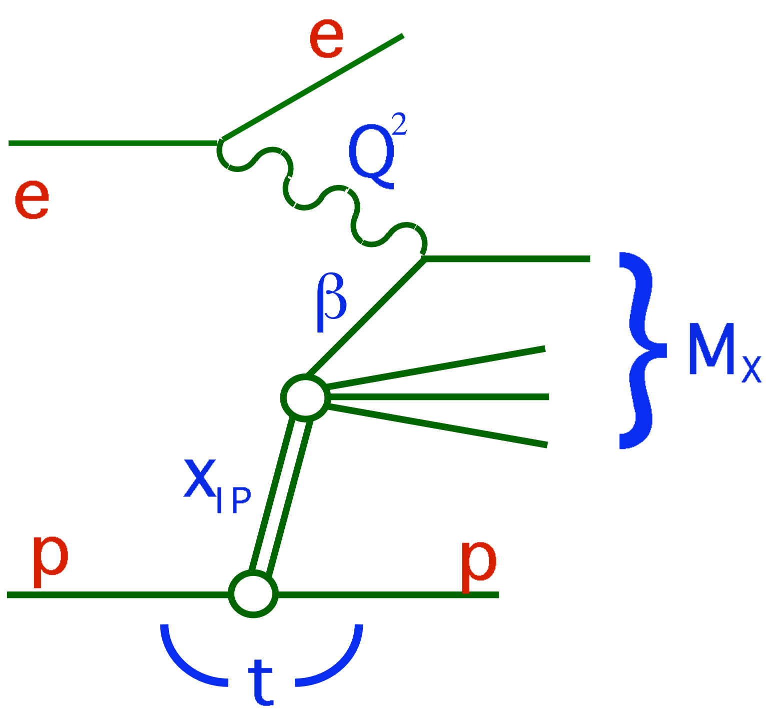
Diffractive Higgs Electroproduction at the LHeC from Intrinsic Heavy Quarks at very high x_F

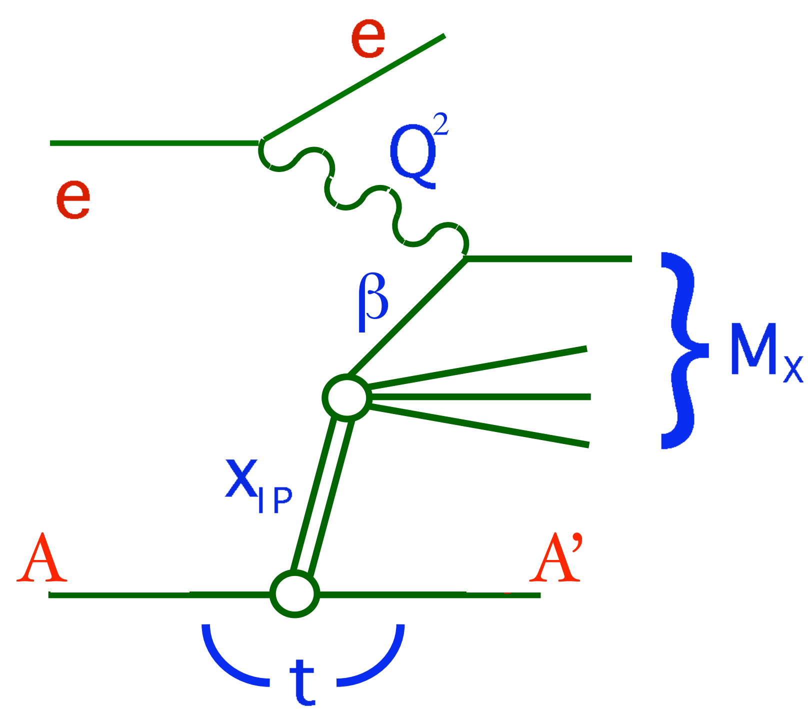


Diffractive Deep Inelastic Scattering

Diffractive DIS $ep \to epX$ where there is a large rapidity gap and the target nucleon remains intact probes the final state interaction of the scattered quark with the spectator system via gluon exchange.

Diffractive DIS on nuclei $eA \to e'AX$ and hard diffractive reactions such as $\gamma^* A \to VA$ can occur coherently leaving the nucleus intact.

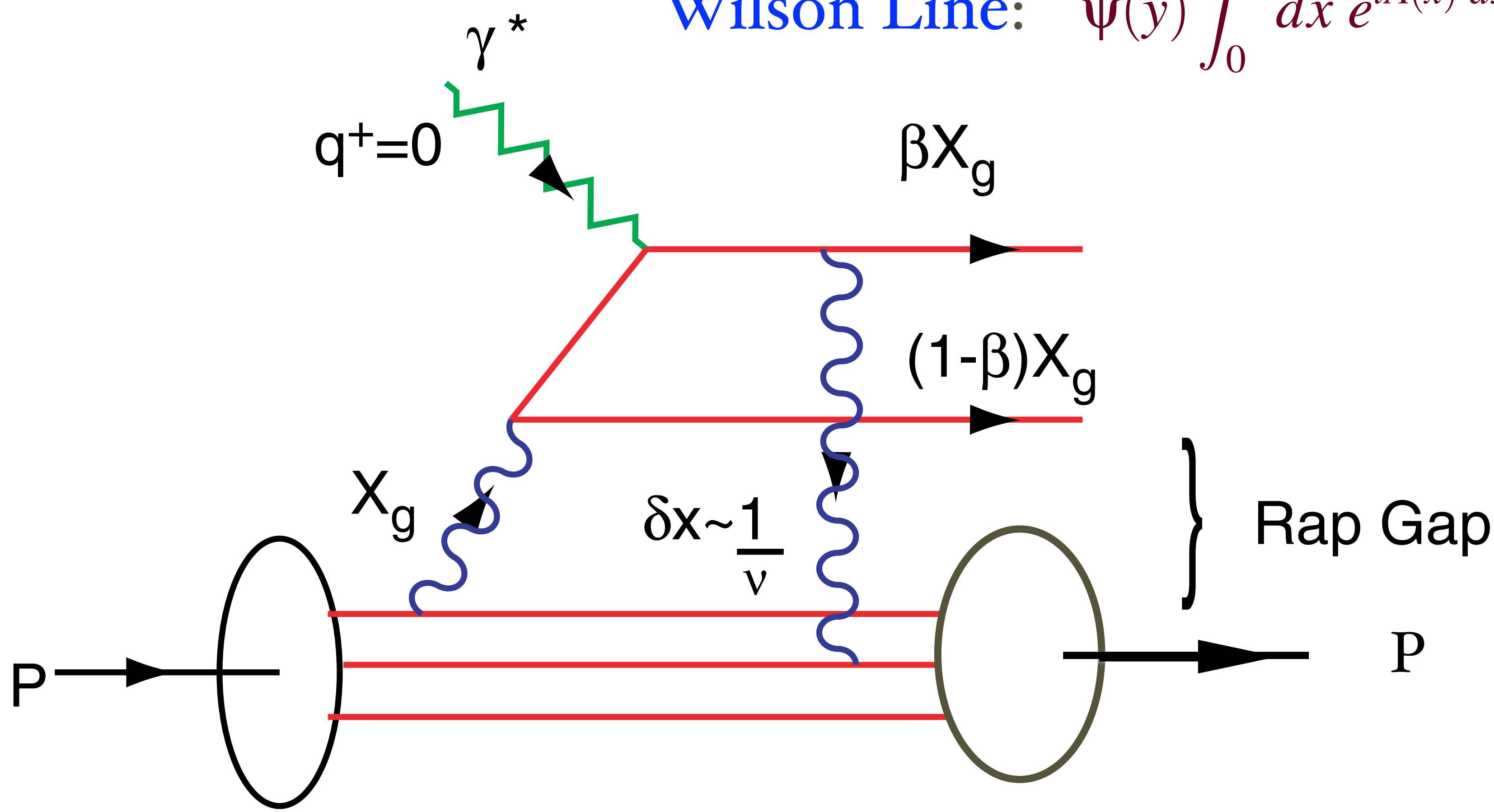




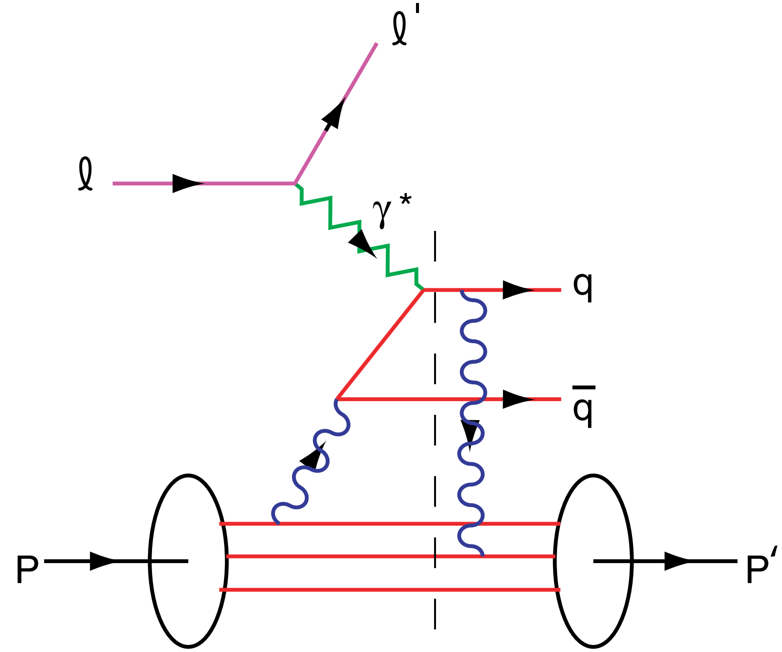
Hoyer, Marchal, Peigne, Sannino, sjb

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

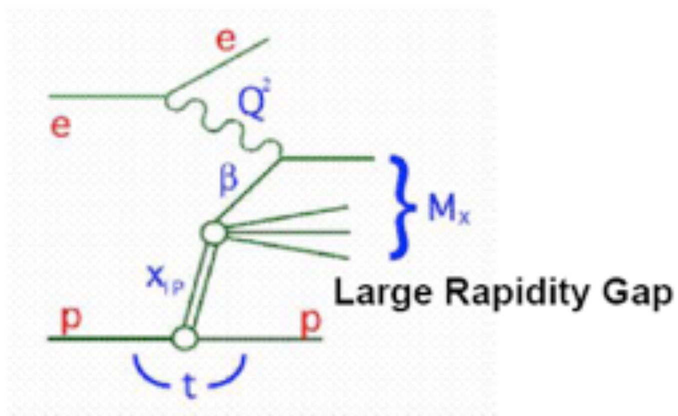
Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target

de Roeck

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

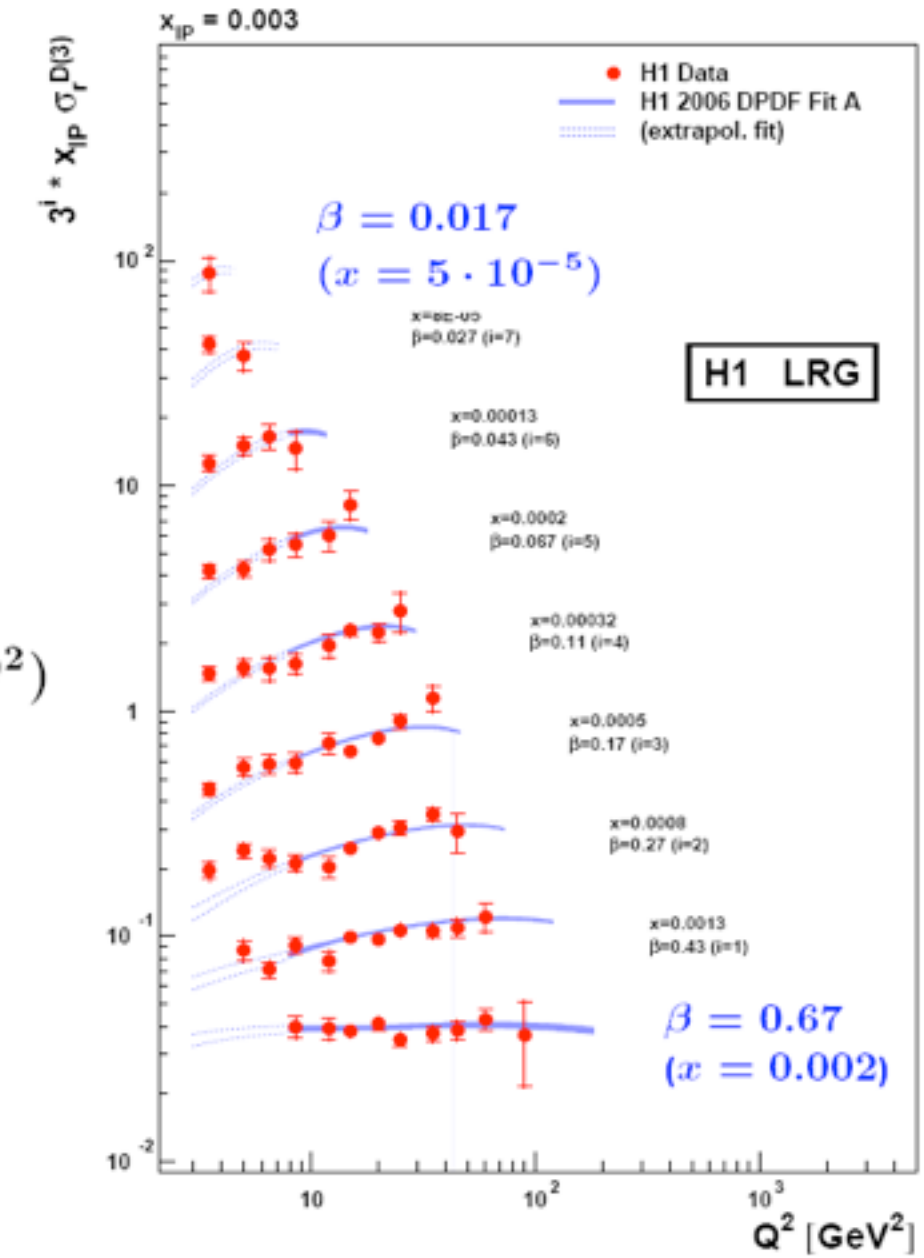
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

extract DPDF and $xg(x)$ from scaling violation

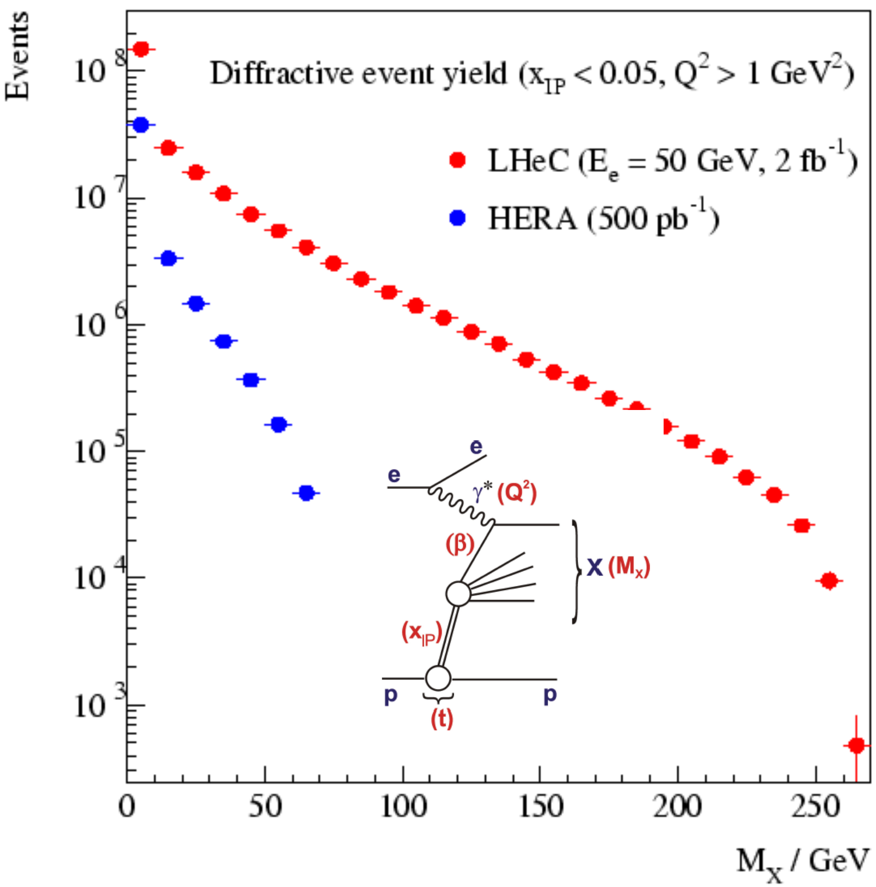
Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

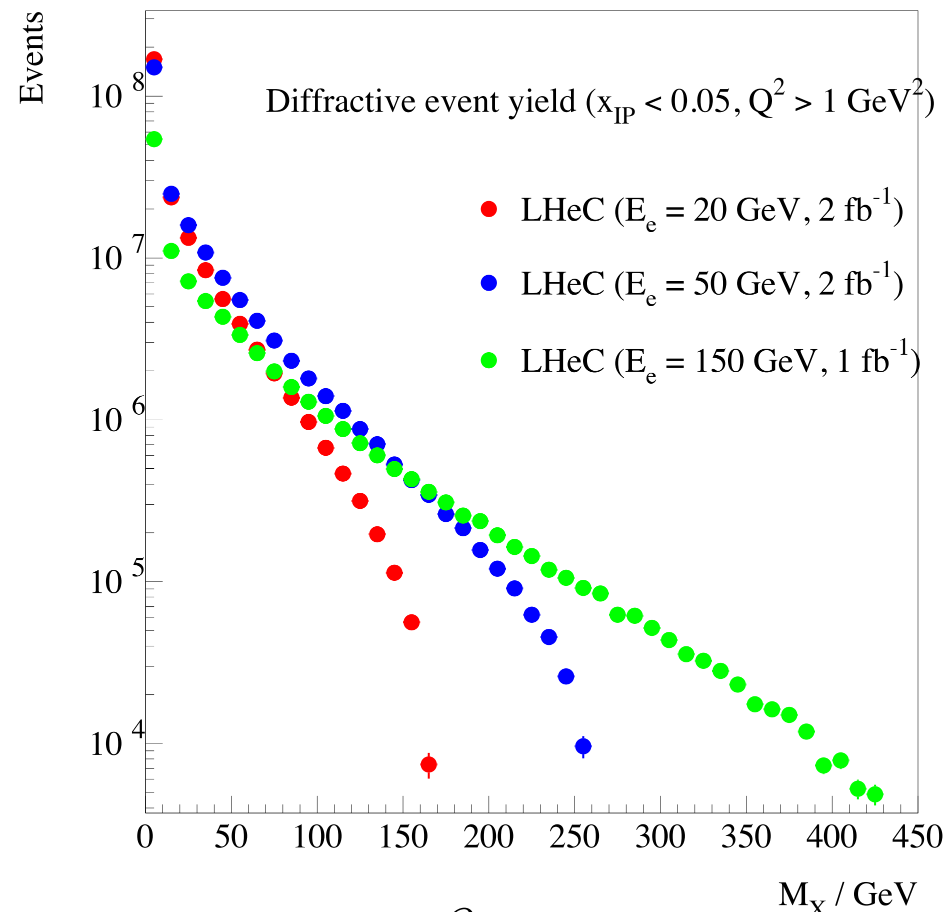
Precise measurements *sys 5%, stat 5–20%*



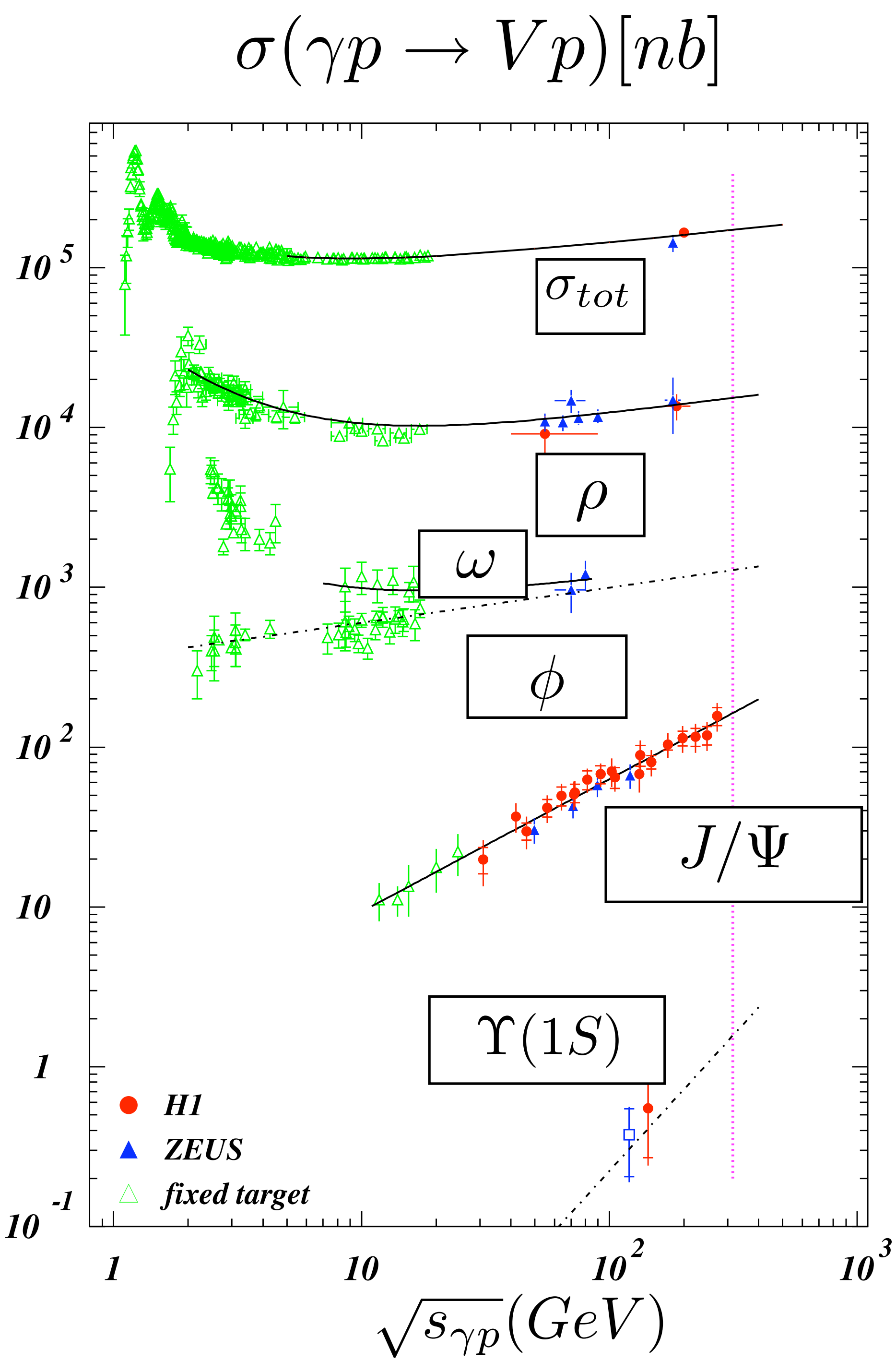
Diffractive Deep Inelastic Scattering at the LHeC

- Unique program for diffractive PDF and generalized parton distributions. DIS diffraction brought to a completely new regime with the extended kinematic range and higher luminosity





LHeC can explore very low values of β
New domain of diffractive masses.
M_X can include W/Z/beauty or any state with 1^-



Exclusive Diffractive Processes

Unitarity Bound?
Saturation?

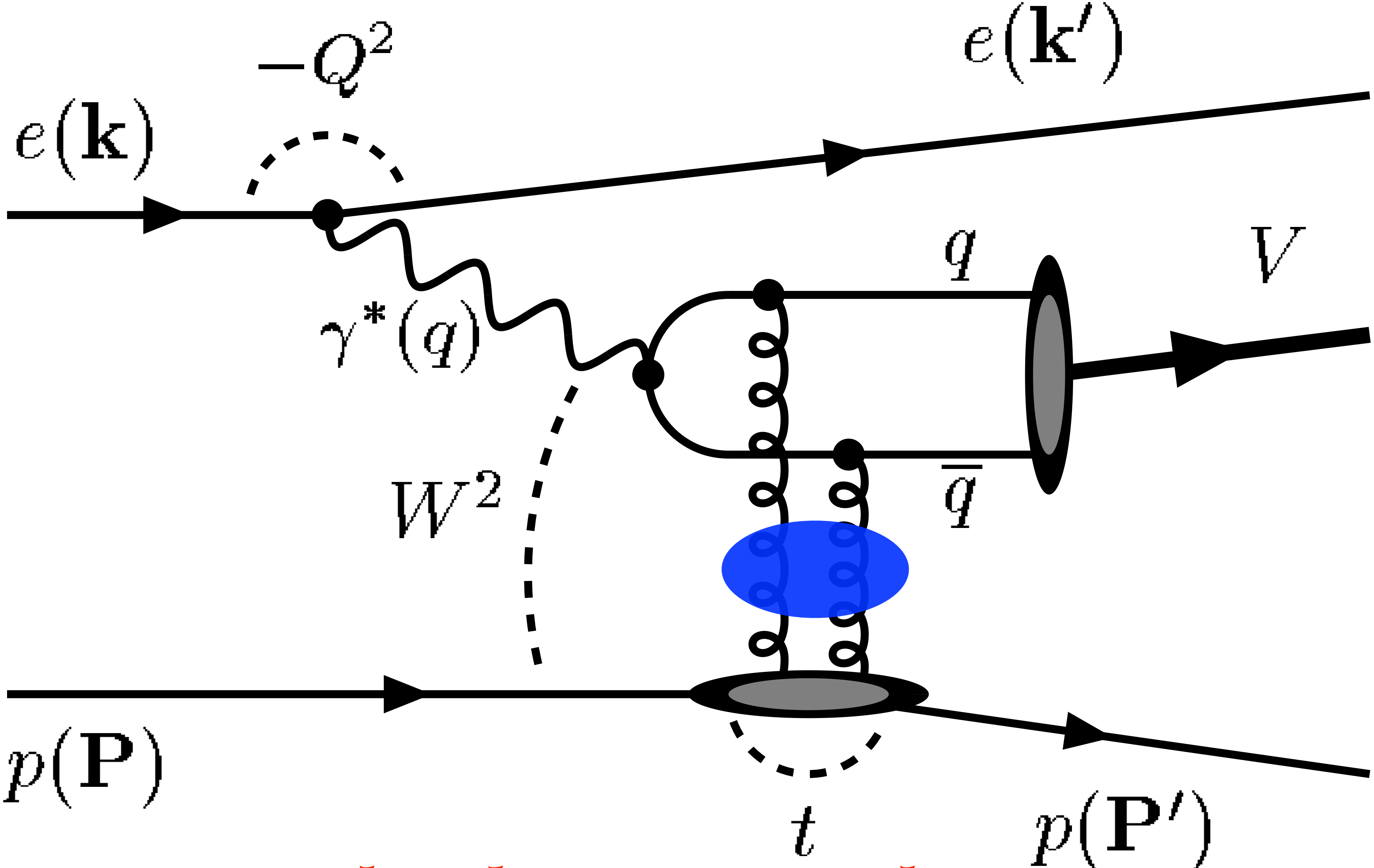
Hard Diffraction

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

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

Odderon

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



BFKL hard pomeron exchange

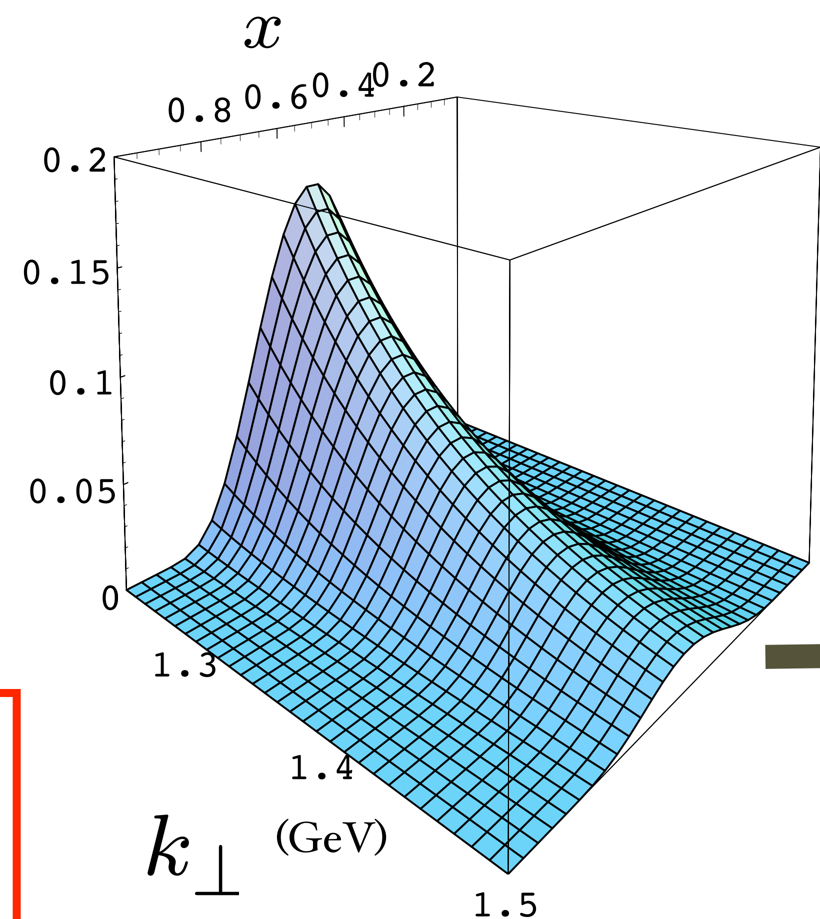
Color Transparency at high Q^2

LHeC: Electroproduction of huge range of excited vector mesons

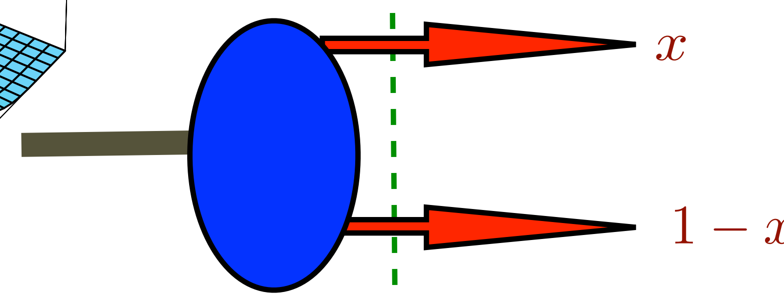
Prediction from AdS/QCD: Meson LFWF

de Teramond, Cao, sjb

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



"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

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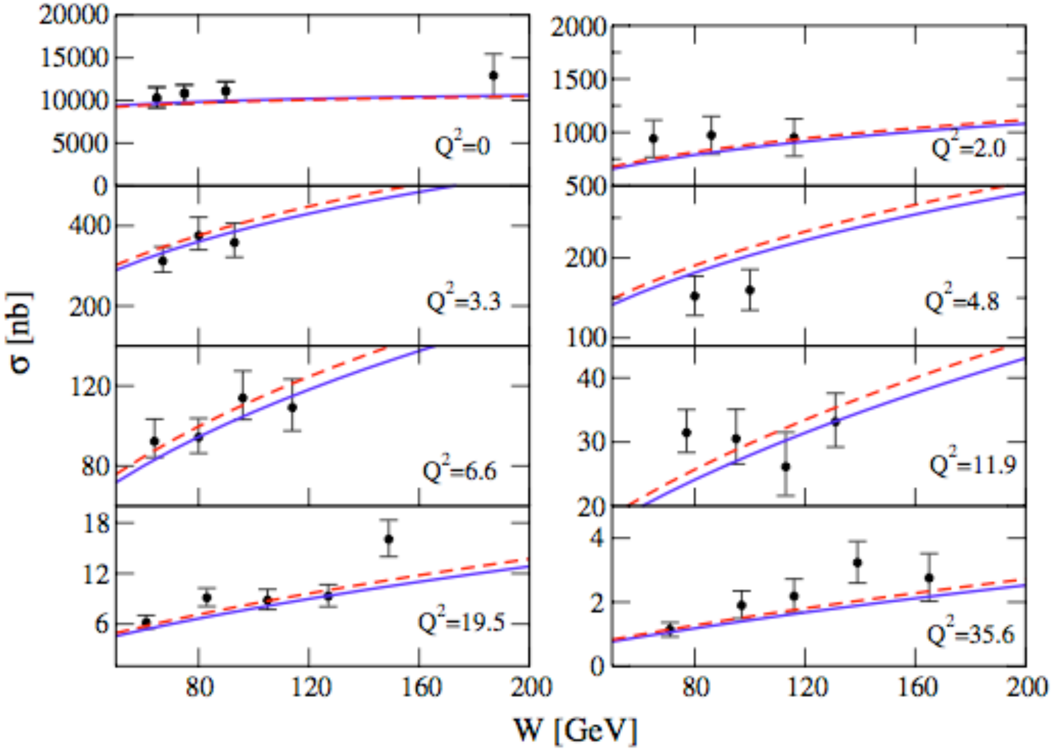
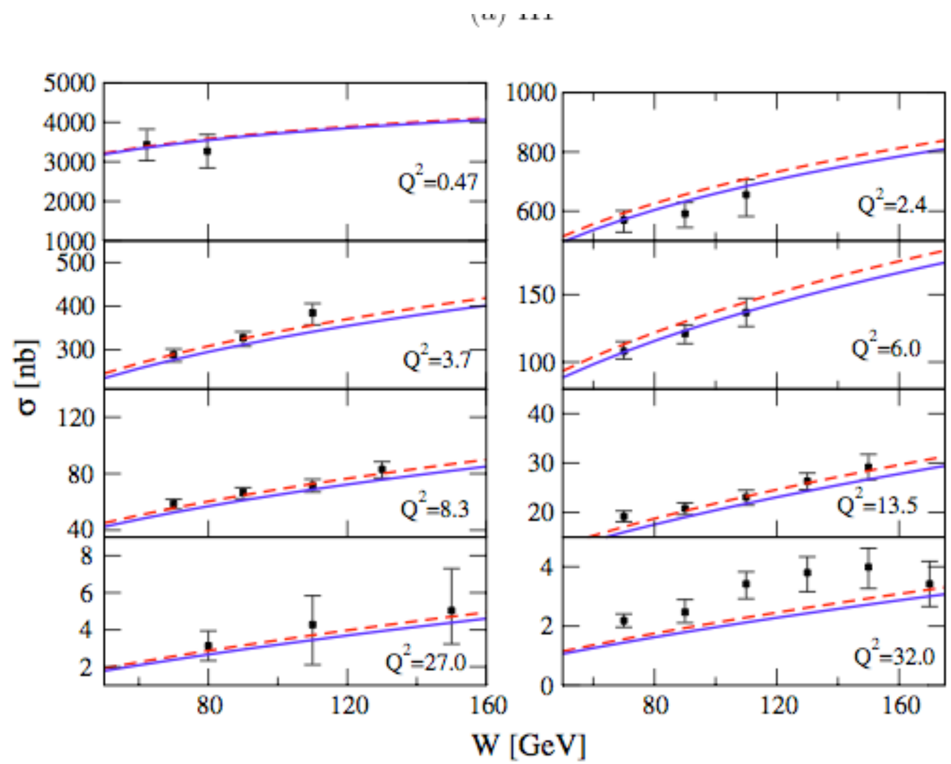
(Received 5 April 2012; published 20 August 2012)

We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive *ρ*-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

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

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

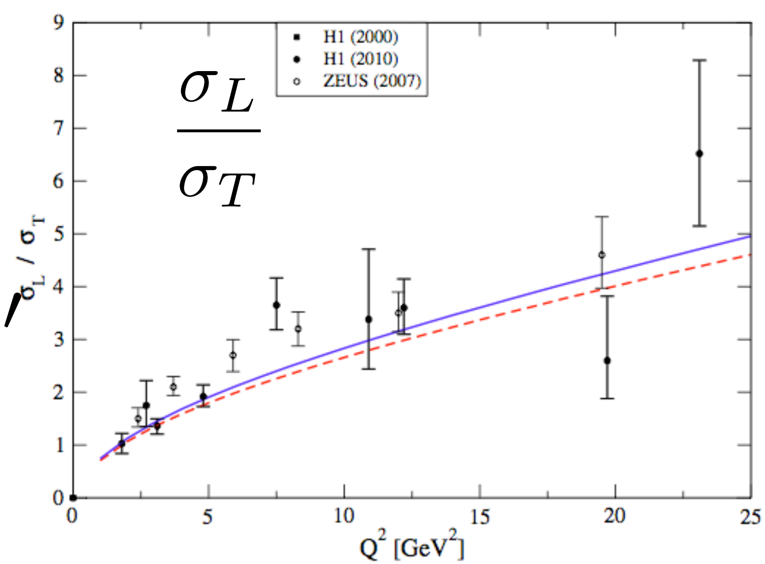




(b) ZEUS

J. R. Forshaw, R. Sandapen

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

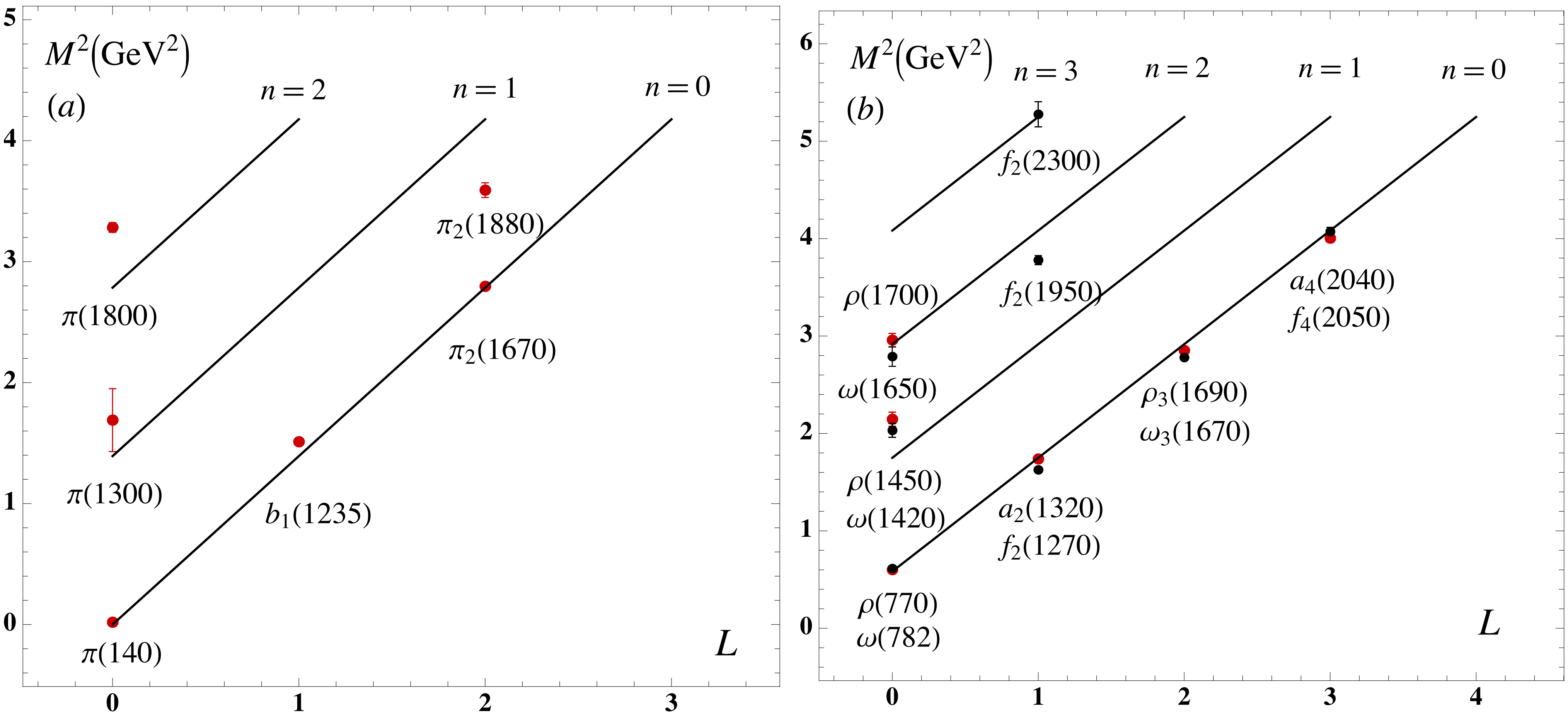


Prediction from Light-Front Holography

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

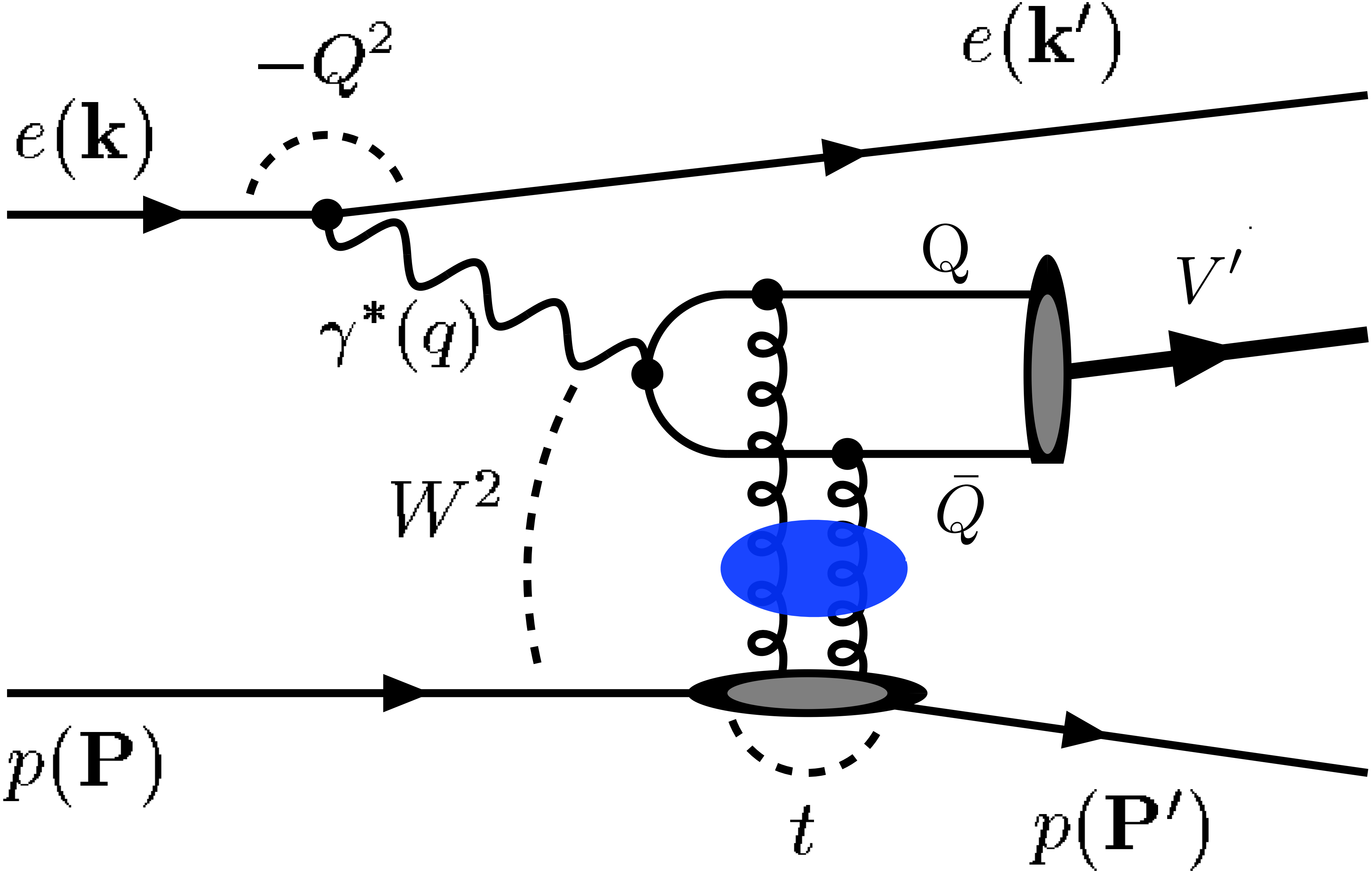
Prediction from AdS/QCD

De Teramond, Dosch, sjb



$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

$$m_u = m_d = 0$$



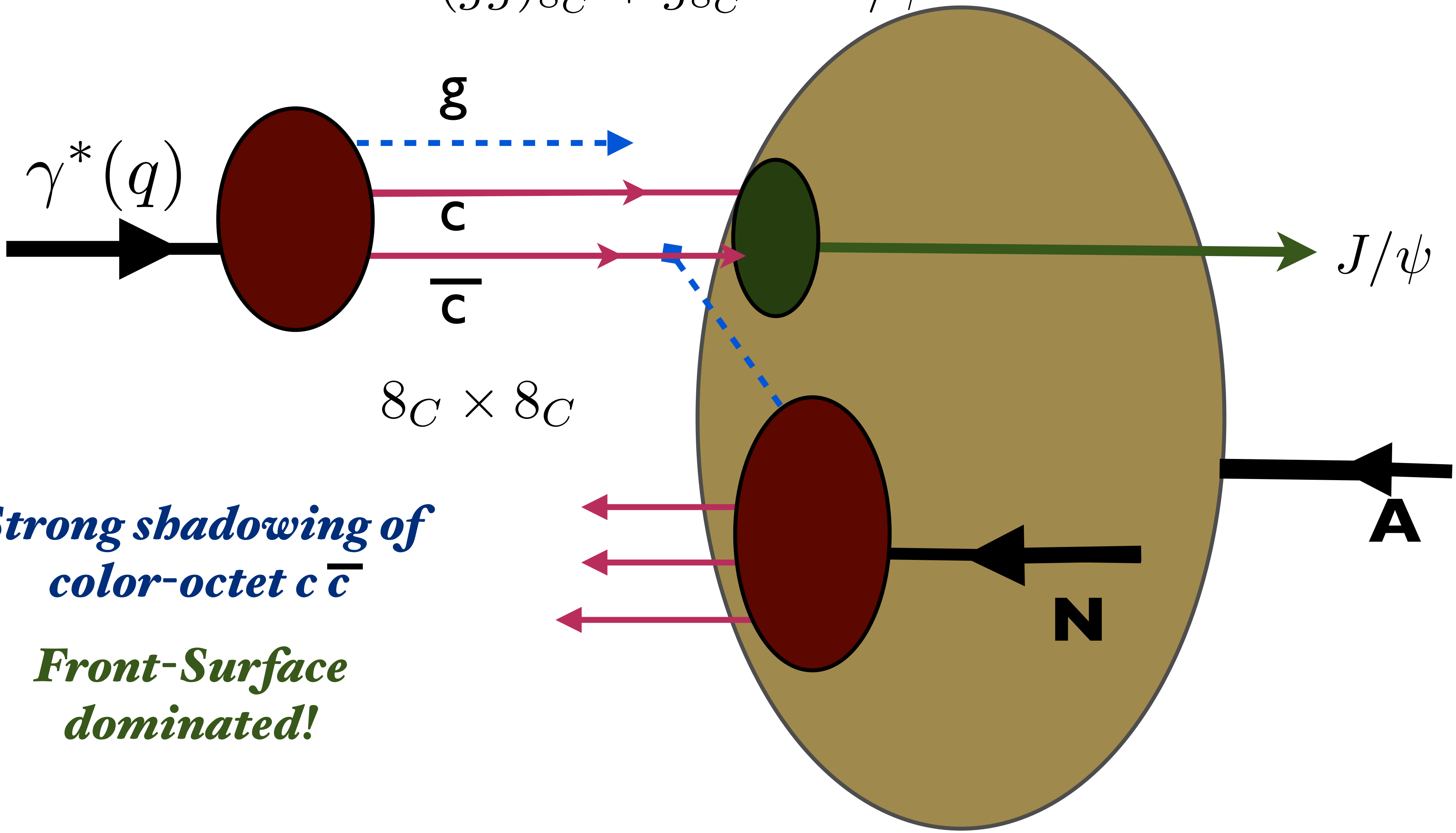
LHeC: Electroproduce huge range of excited vector mesons V'

Test Regge Spectroscopy, AdS/QCD

Zhu, sjb

$$pA \to J/\psi X$$

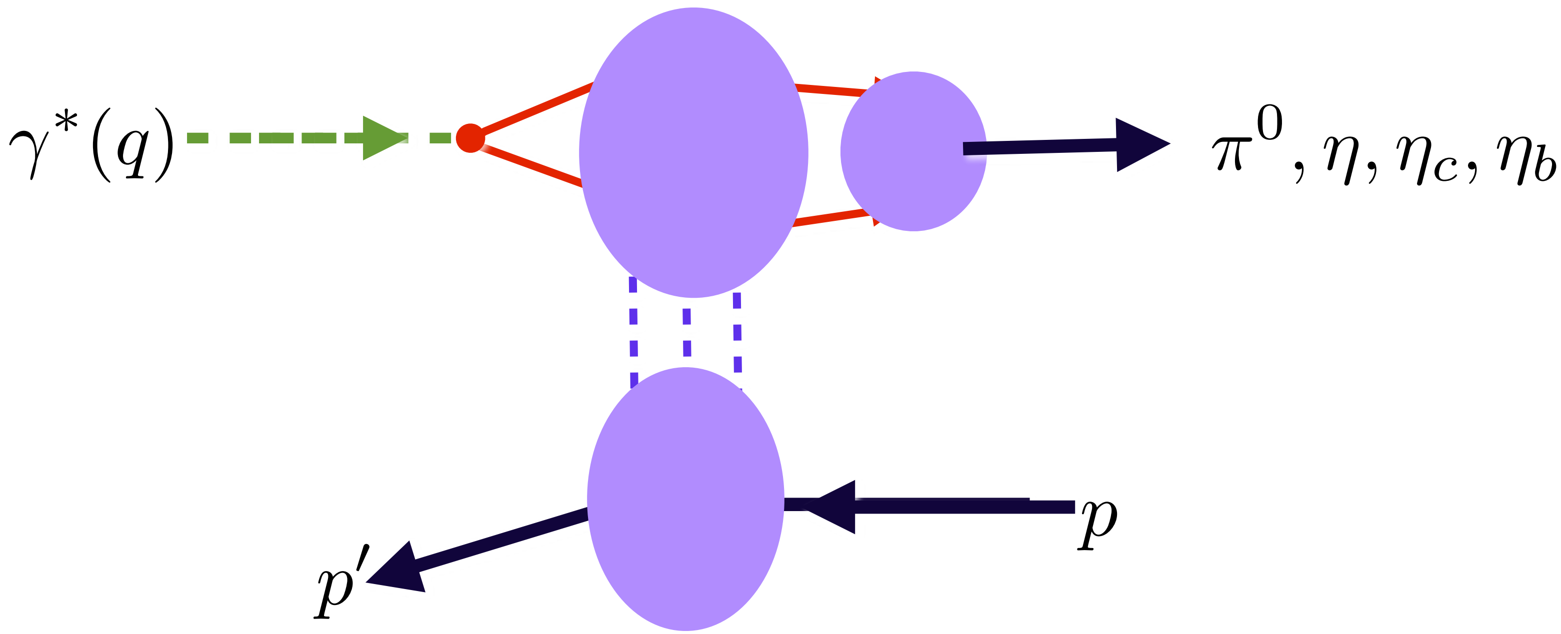
$$(gg)_{8_C} + g_{8_C} \to J/\psi$$



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

Front-Surface dominated!

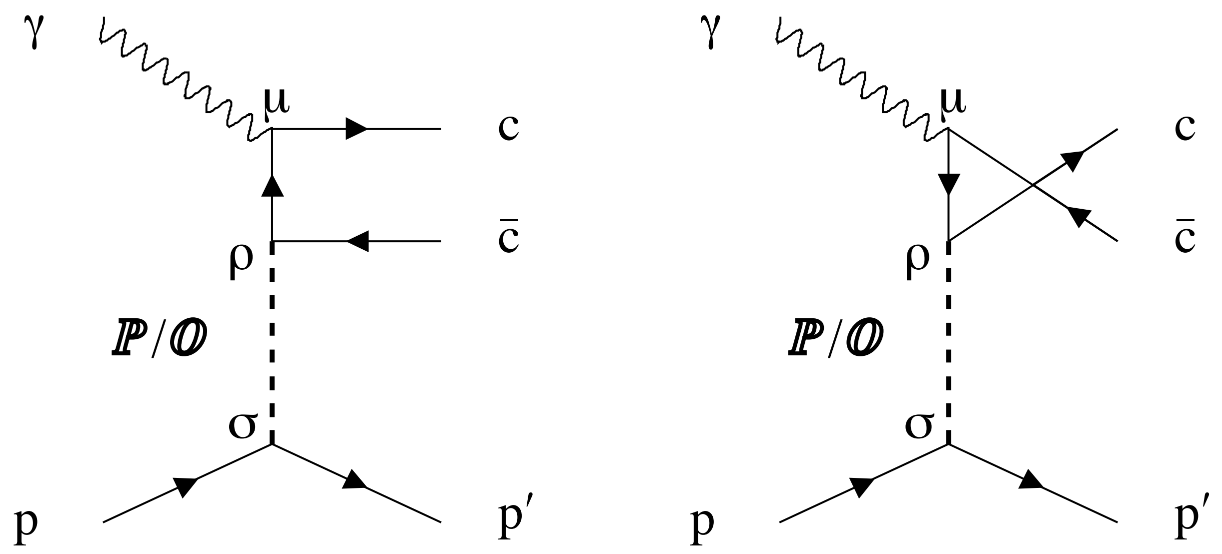
Novel nuclear effect at the LHeC



Odderon has never been observed!

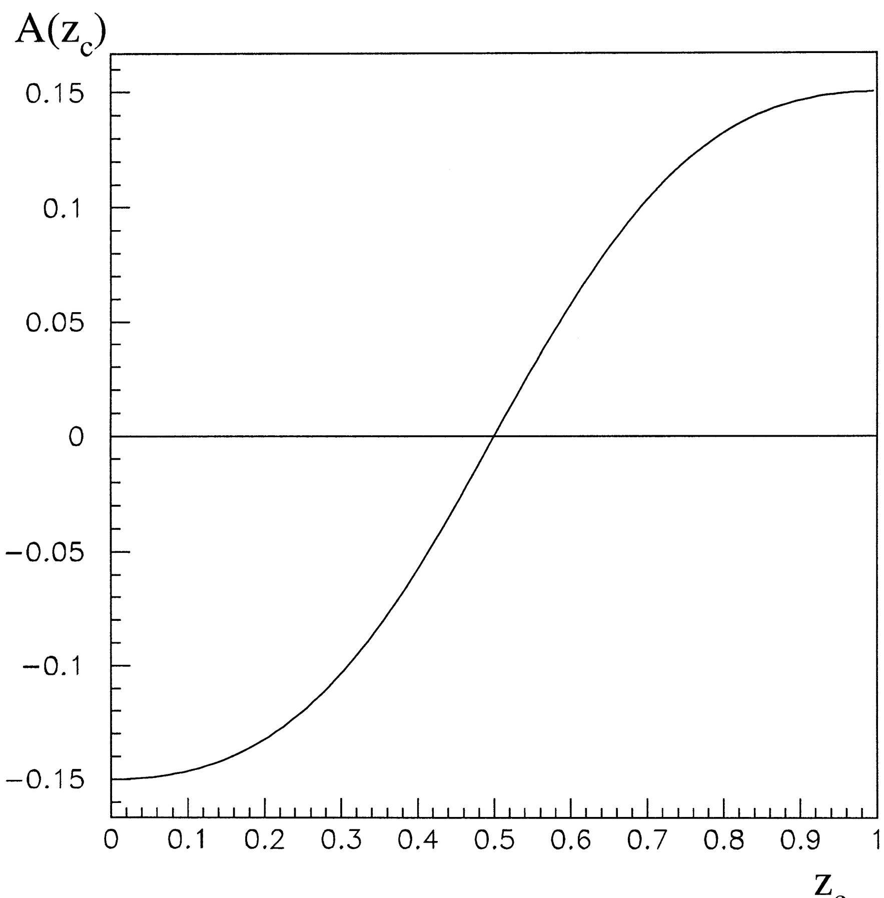
Look for Charge Asymmetries from Odderon-Pomeron Interference

Merino, Rathsman, sjb



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

Odderon-Pomeron Interference!

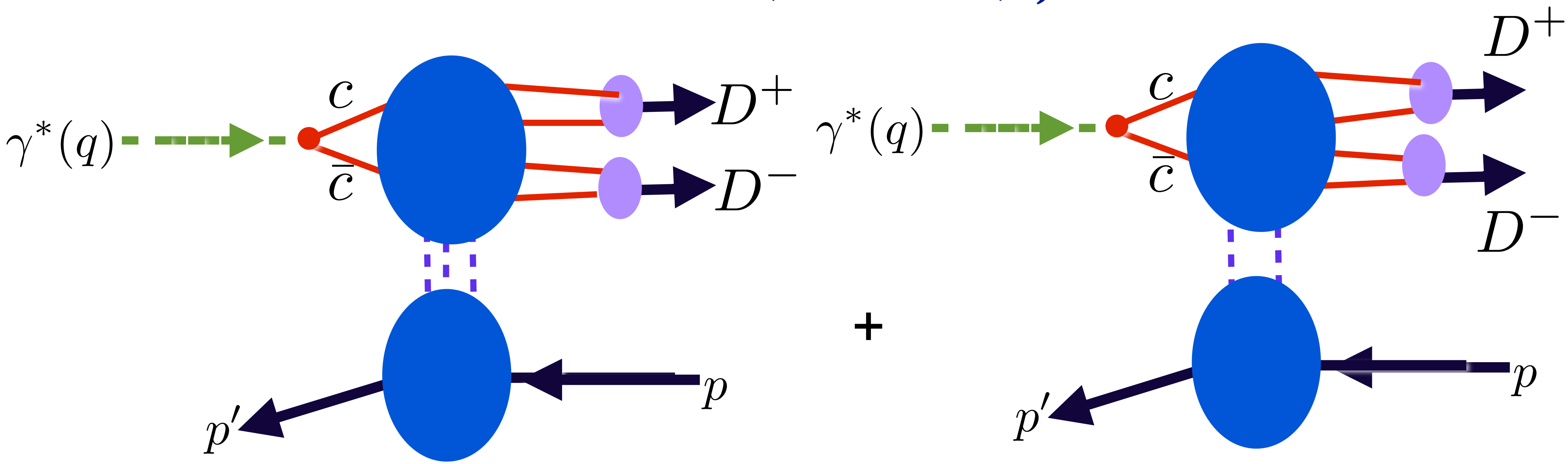


$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2 z_c - 1}{z_c^2 + (1 - z_c)^2}$$

Measure charm asymmetry in photon fragmentation region

Merino, Rathsman, sjb

Merino, Rathsman, sjb



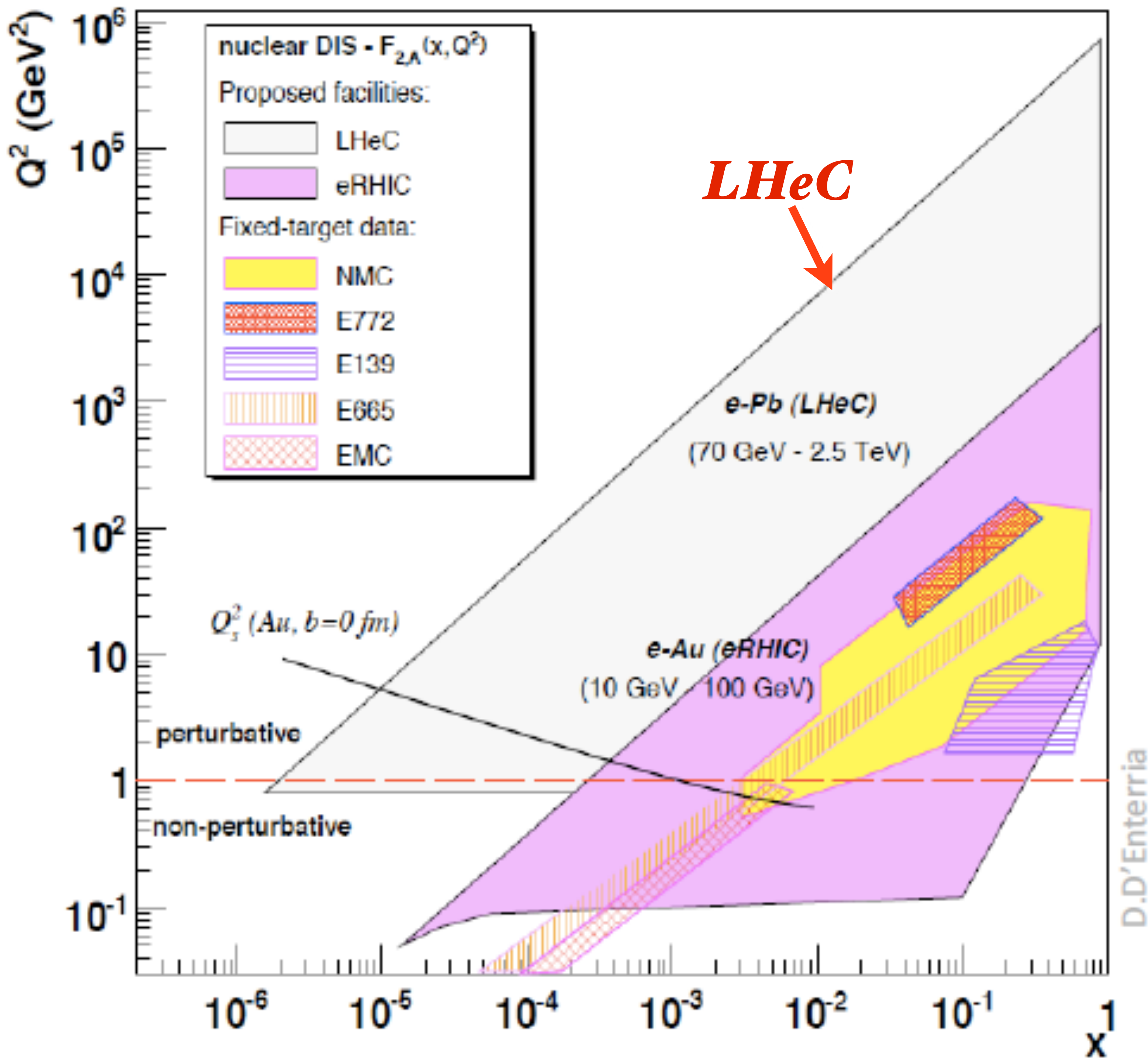
Odderon-Pomeron Interference leads to $K^+ K^-$, $D^+ D^-$ and $B^+ B^-$ charge and angular asymmetries

Odderon at amplitude level

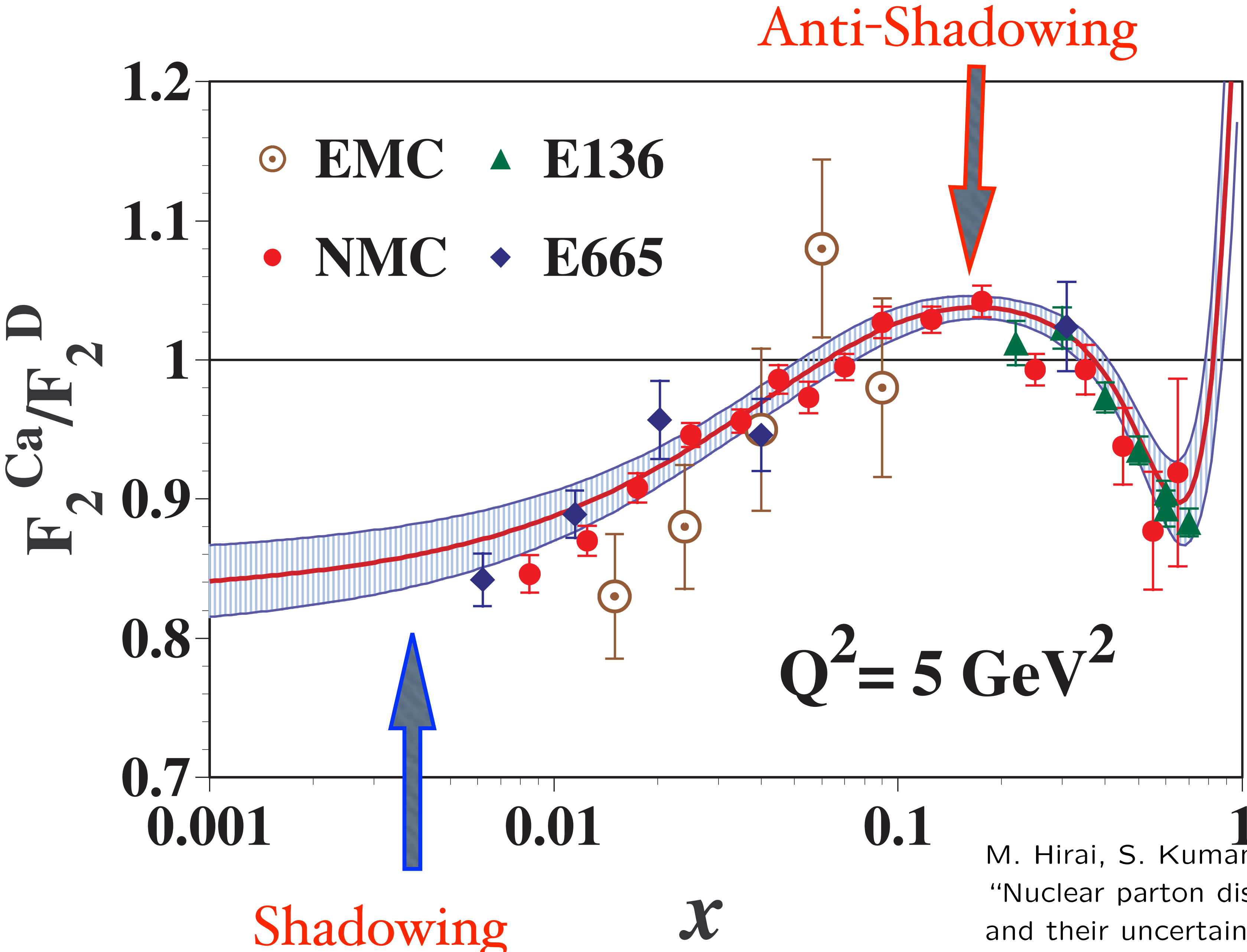
Strong enhancement at heavy-quark pair threshold from QCD Sakharov-Schwinger-Sommerfeld effect

$$\frac{\pi \alpha_s(\beta^2 s)}{\beta}$$

Hoang, Kuhn, sjb



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)
x
D.D'Enterria

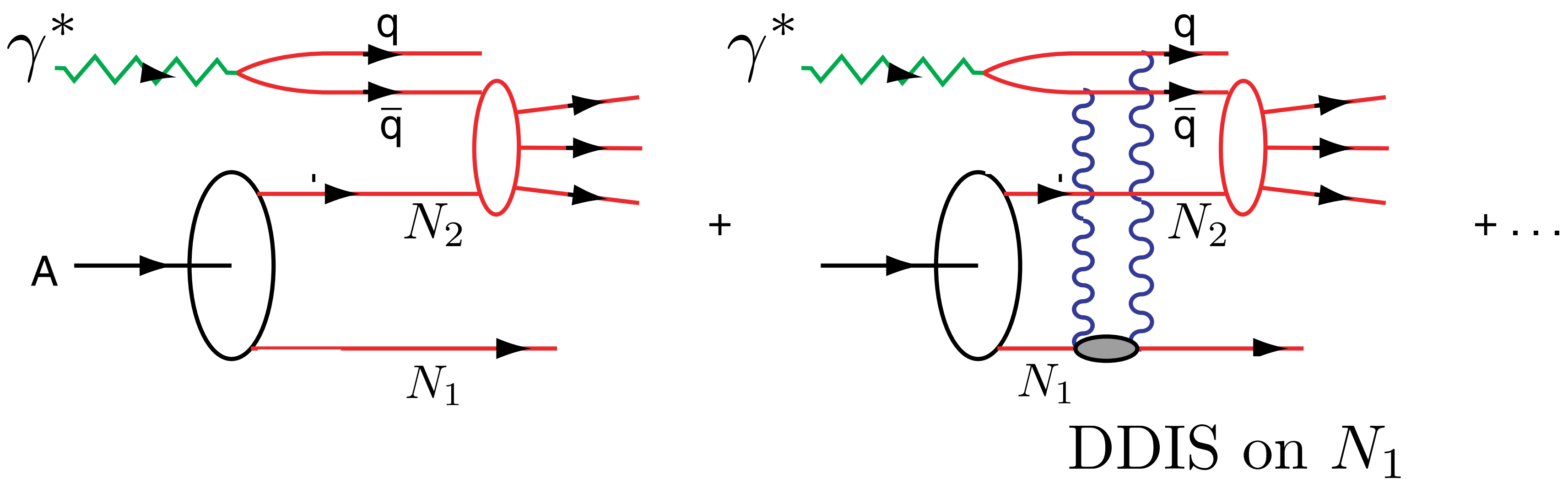


M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

Stodolsky
Pumplin, sjb
Gribov

Nuclear Shadowing in QCD

Two-Beams hit N_2: Destructive Interference

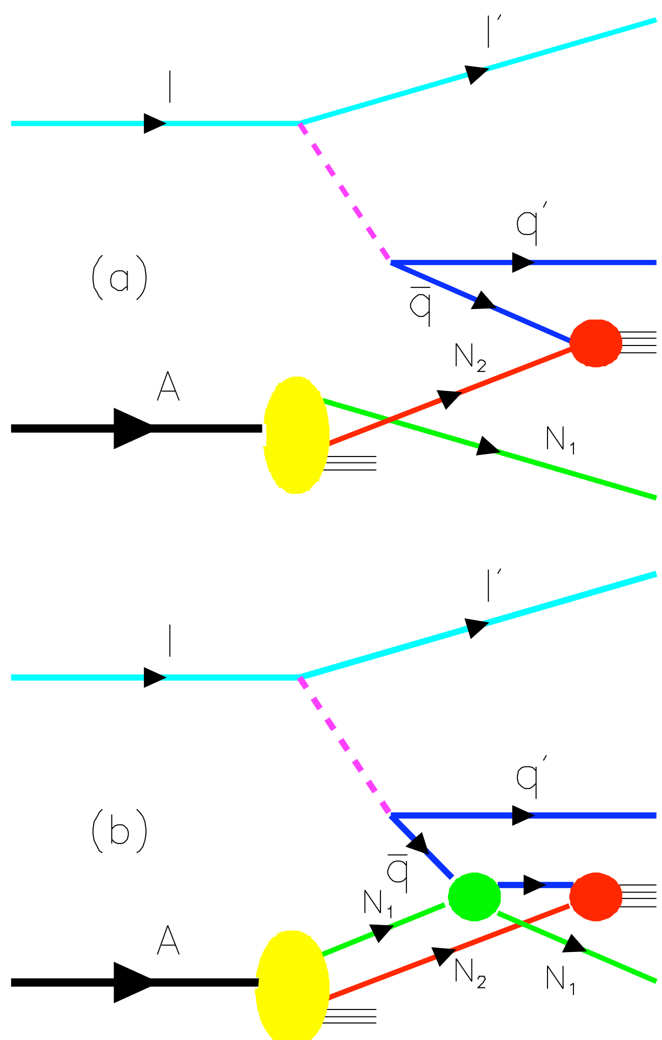


Shadowing requires leading-twist diffractive DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

Interior nucleons N_2 shadowed



DDIS on N_1

The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.

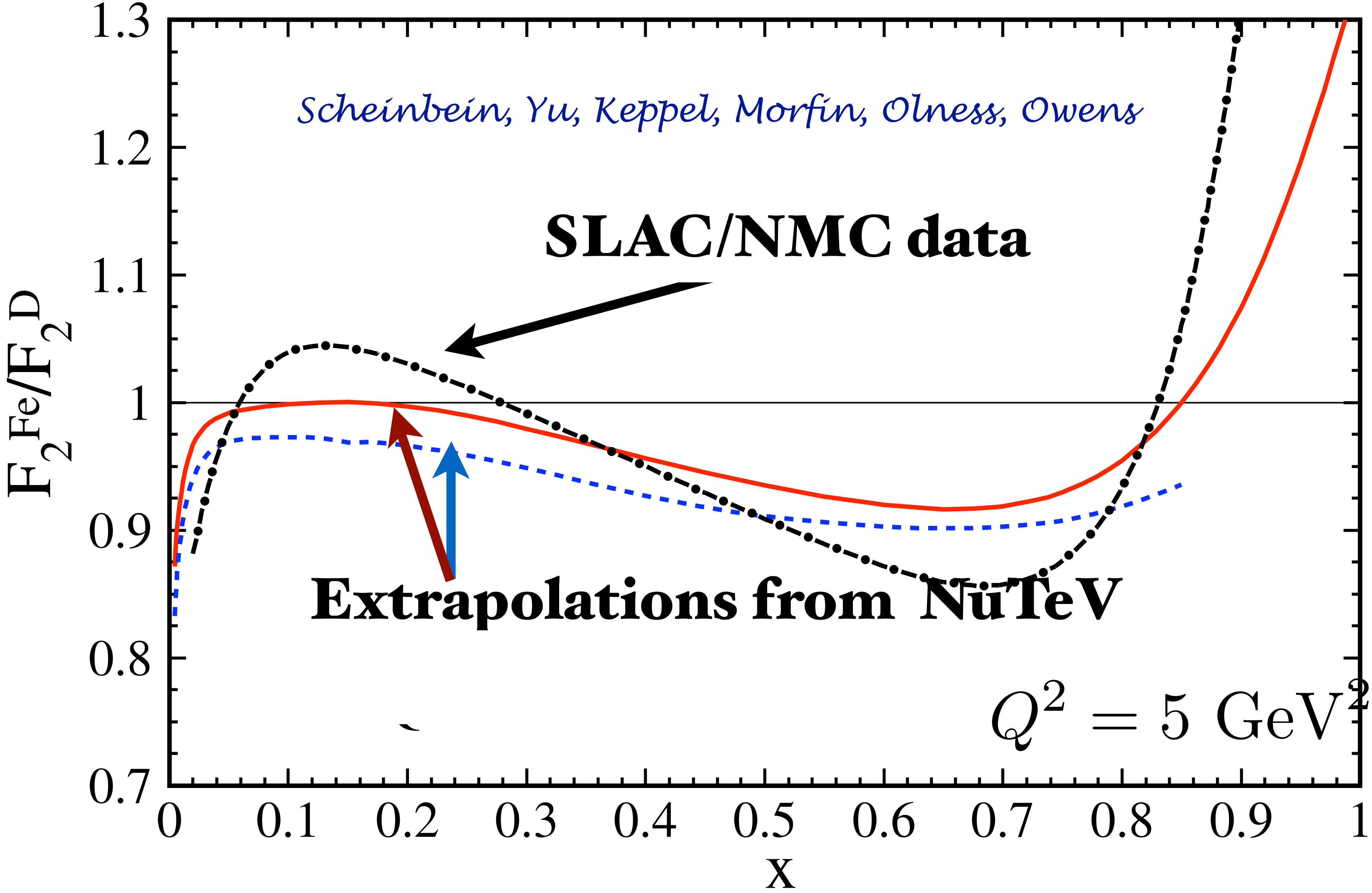
If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.

Two-Beams hit N_2: Destructive Interference

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

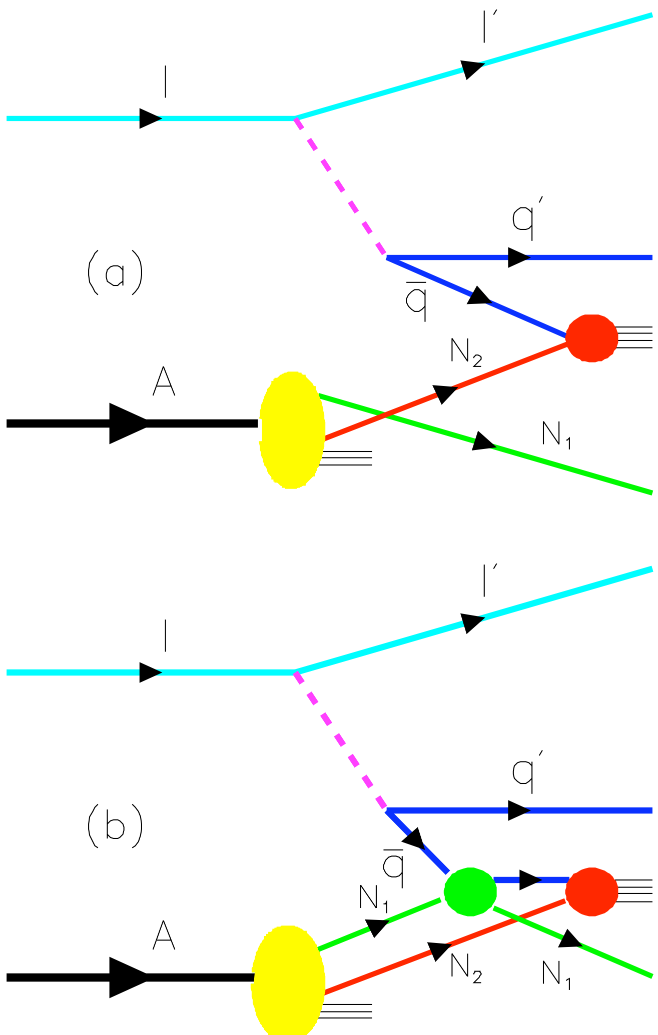
Observed HERA DDIS produces nuclear shadowing

Are Nuclear Distributions Universal?



No anti-shadowing in deep inelastic neutrino scattering!

Schmidt, Lu, Yang, sjb



DDIS on N_1

The one-step and two-step processes in DIS on a nucleus.

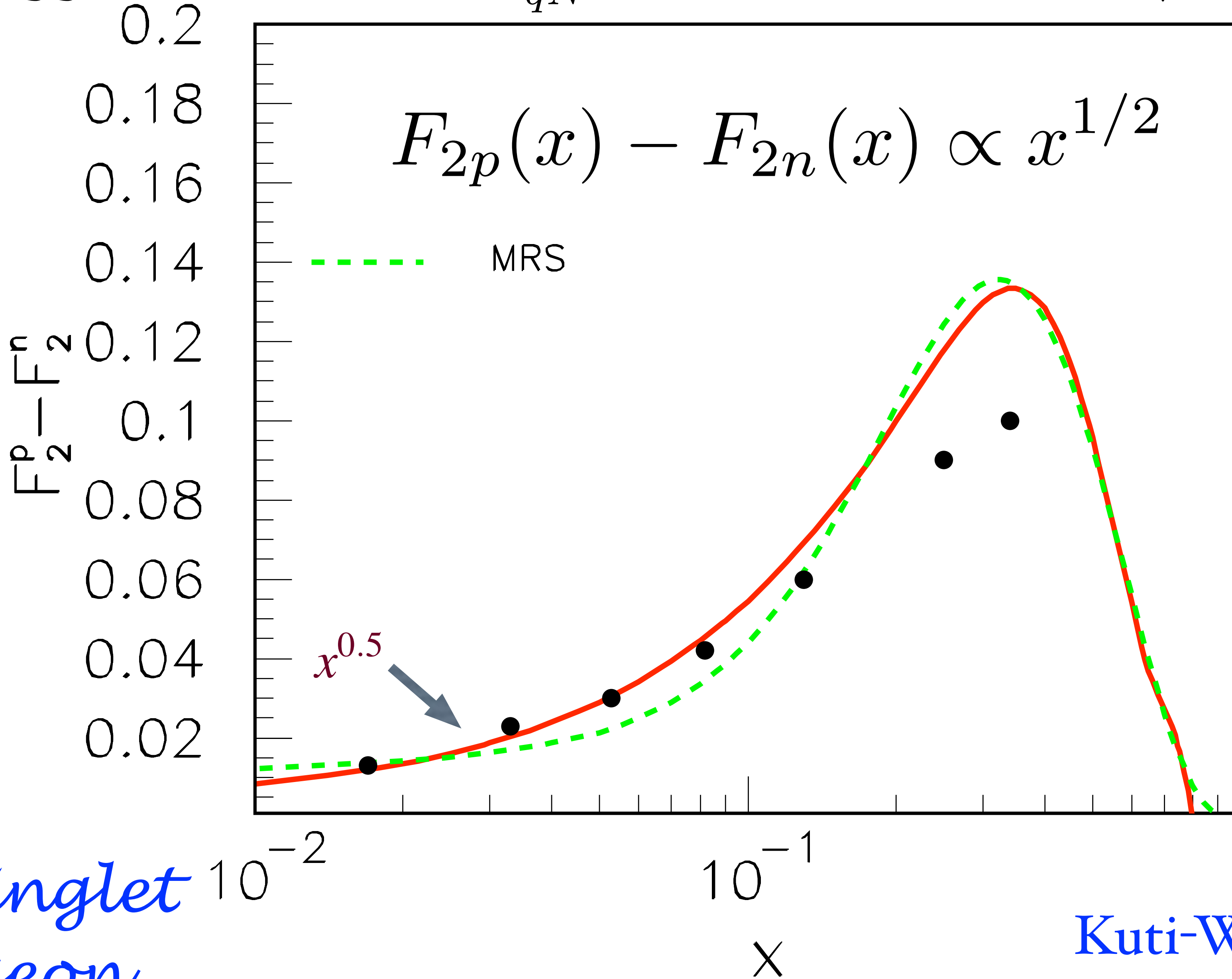
Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon N_1 is via ~~pomeron~~ Regge exchange, the one-step and two-step amplitudes are ~~opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.~~ constructive in phase thus ***increasing*** the flux reaching N_2

Interior nucleons anti-shadowed

Regge Exchange in DDIS produces nuclear anti-shadowing

Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\alpha_R \simeq 1/2$



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\alpha_R \simeq 1/2$

Phase of two-step amplitude relative to one step:

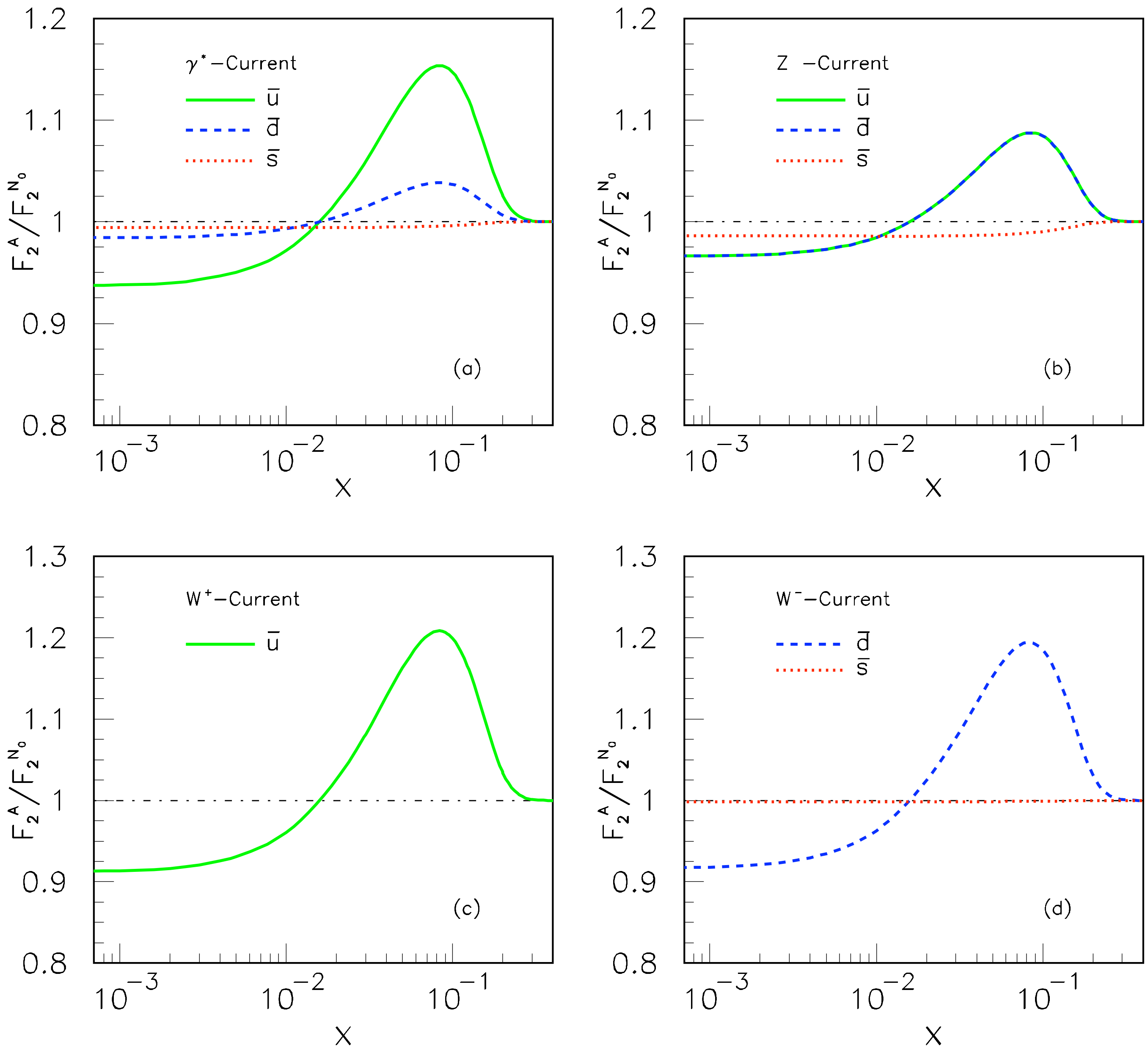
$$\frac{1}{\sqrt{2}}(1 - i) \times i = \frac{1}{\sqrt{2}}(i + 1)$$

Constructive Interference

Depends on quark flavor!

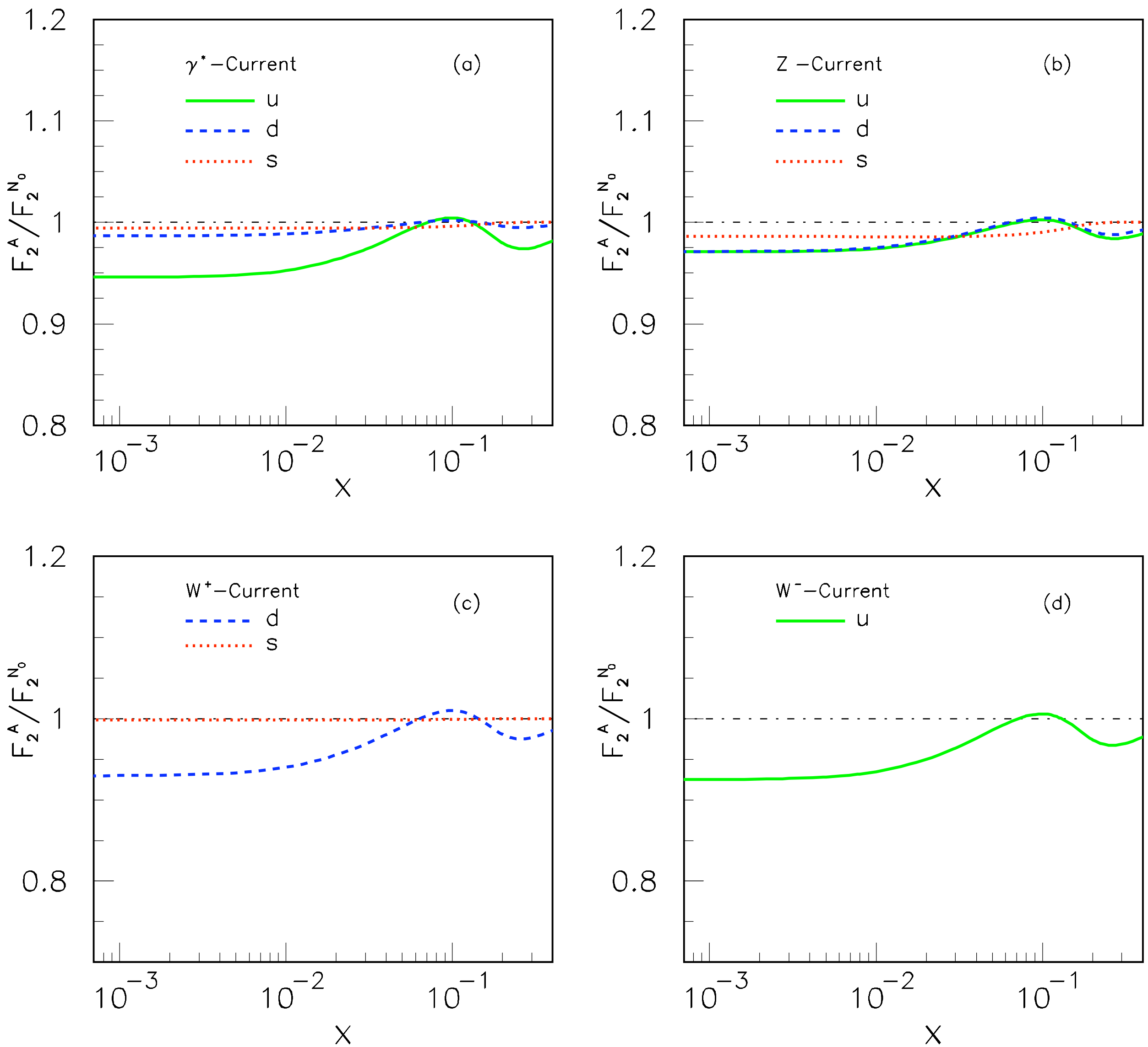
Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$



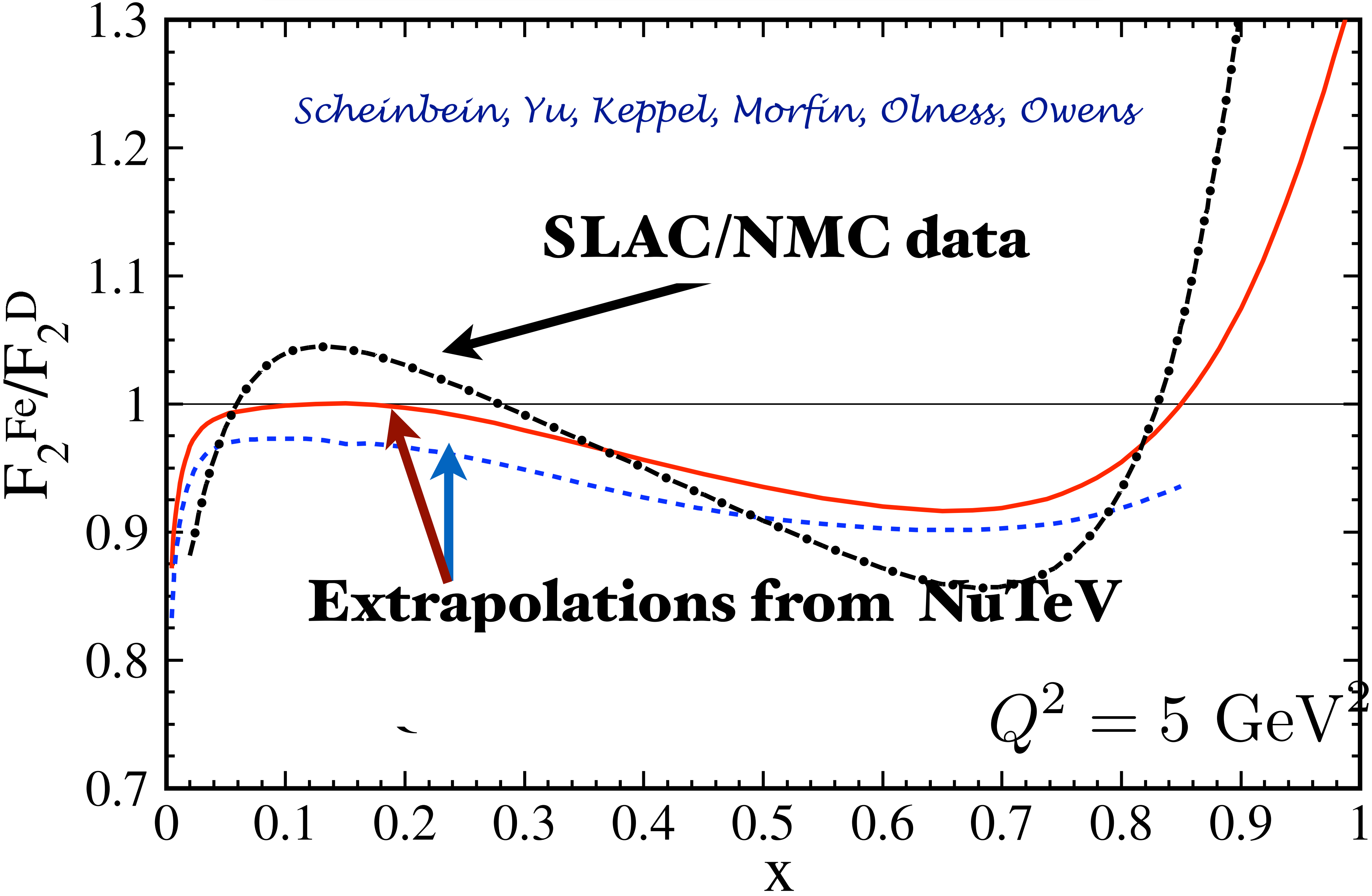
Nuclear Distributions are not Universal !

Shadowing and Antishadowing of Nuclear Structure Functions

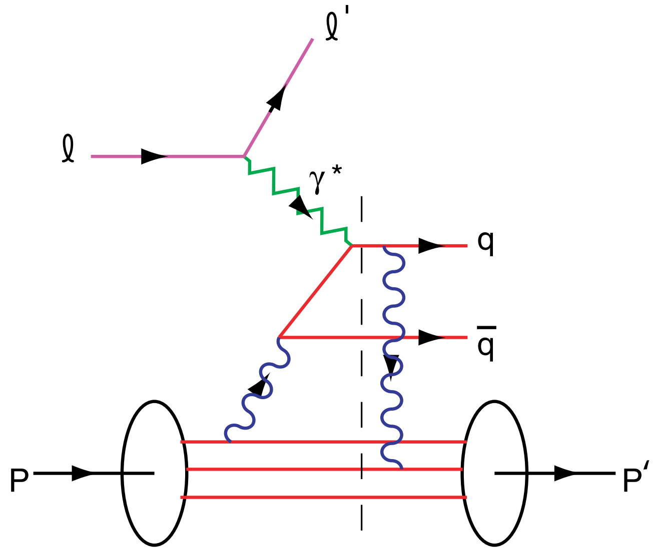


S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Are Nuclear Distributions Universal?



No anti-shadowing in deep inelastic neutrino scattering!



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!

[Structure functions are not parton probabilities.](#)
By Stanley J. Brodsky, Paul Hoyer,
Nils Marchal, Stephane Peigne, Francesco Sannino.
Phys.Rev. D65 (2002) 114025.

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

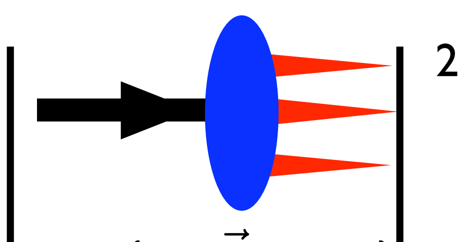
Hwang, Schmidt, sjb,

Mulders, Boer

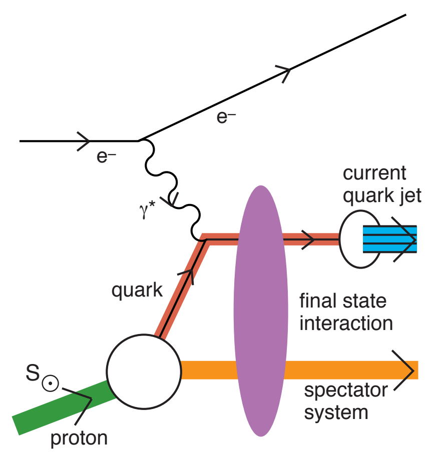
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



$$\left|\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\right|^2$$

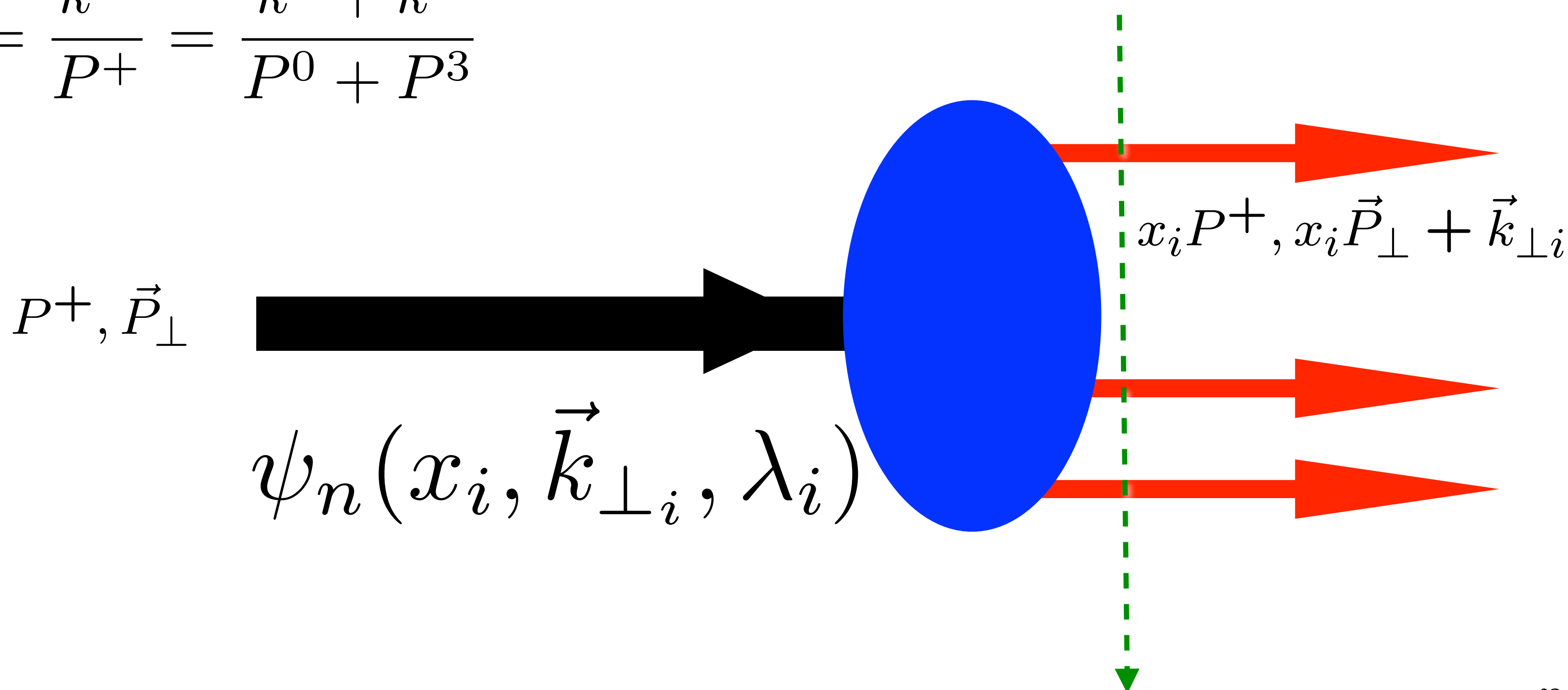


Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of LF Hamiltonian

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

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

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

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

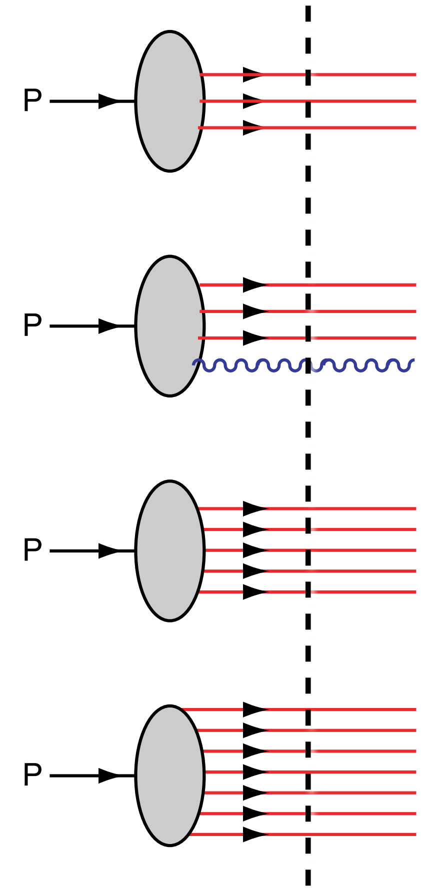
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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 !

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

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

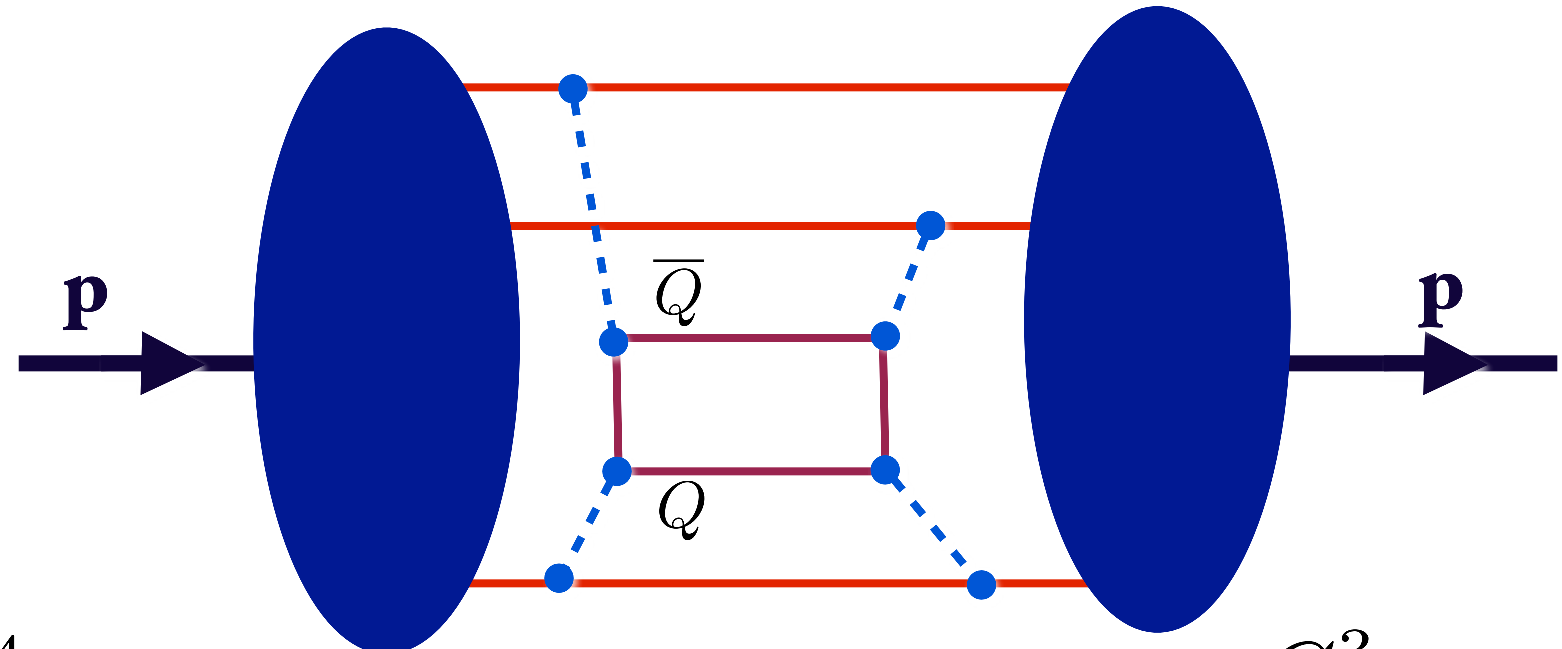
Mueller: gluon Fock states BFKL Pomeron

Hidden Color

Proton Self Energy from g g to gg scattering

QCD predicts Intrinsic Heavy Quarks!

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



$$\frac{F_{\mu\nu}^4}{M_\ell^2}$$

$$\frac{G_{\mu\nu}^3}{M_Q^2}$$

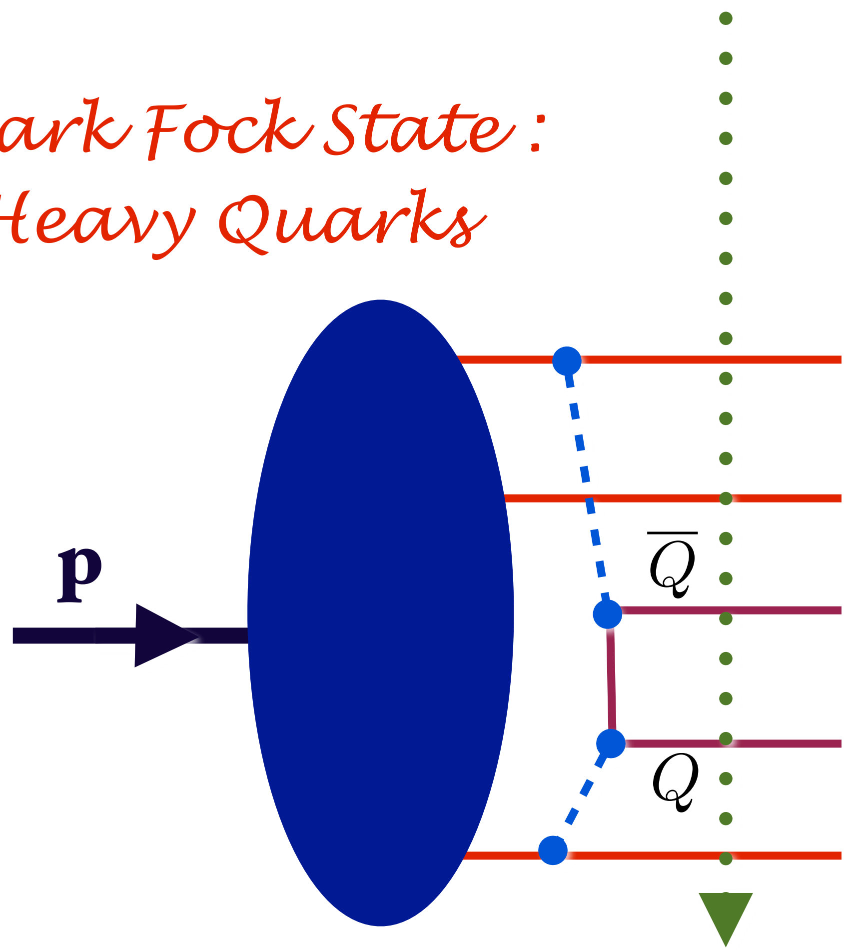
Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

Fixed LF time

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts
Intrinsic Heavy
Quarks at high x

Minimal off-shellness

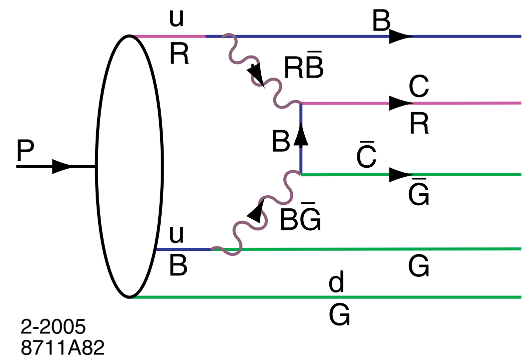
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov

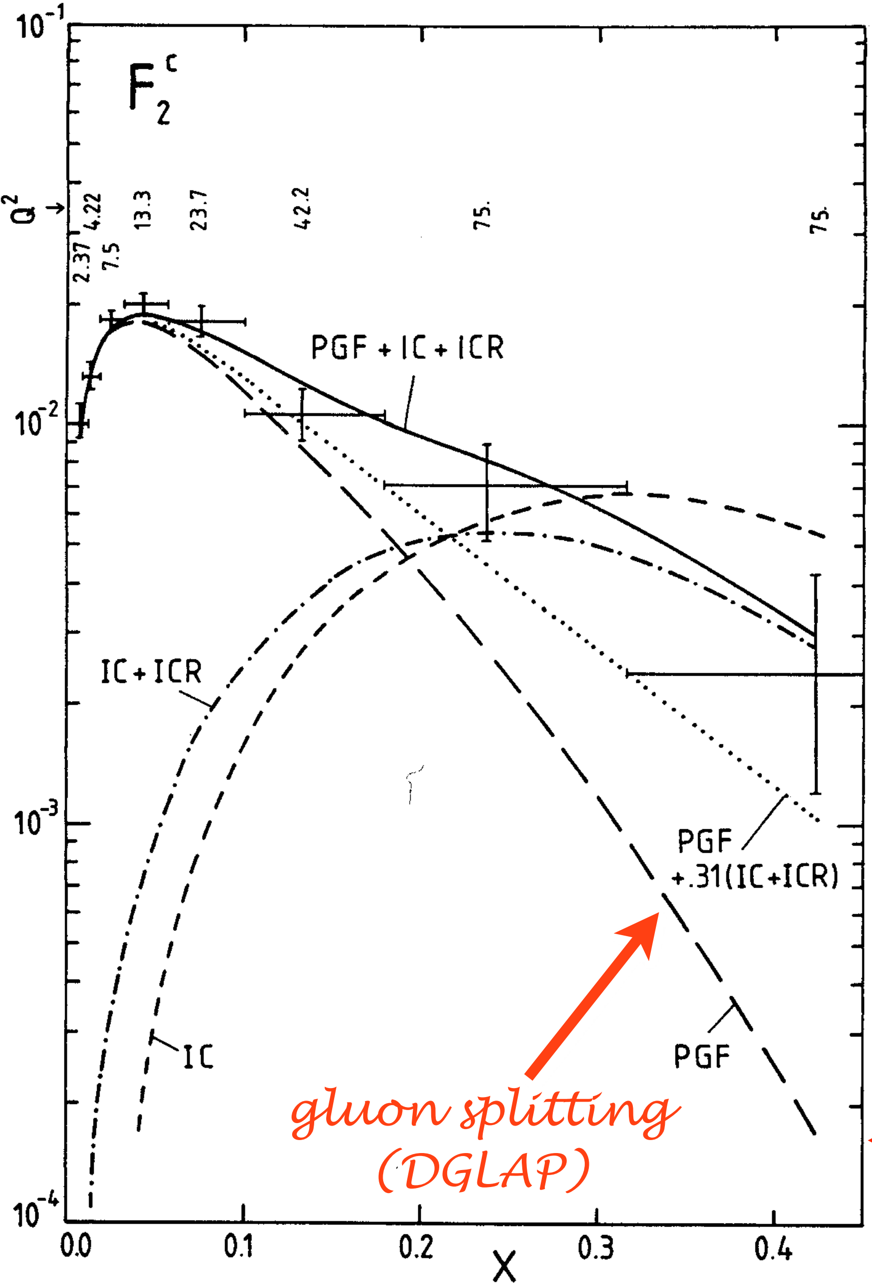
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State!**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $\quad P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $\quad P_{c\bar{c}/p} \simeq 1\%$
- **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)**

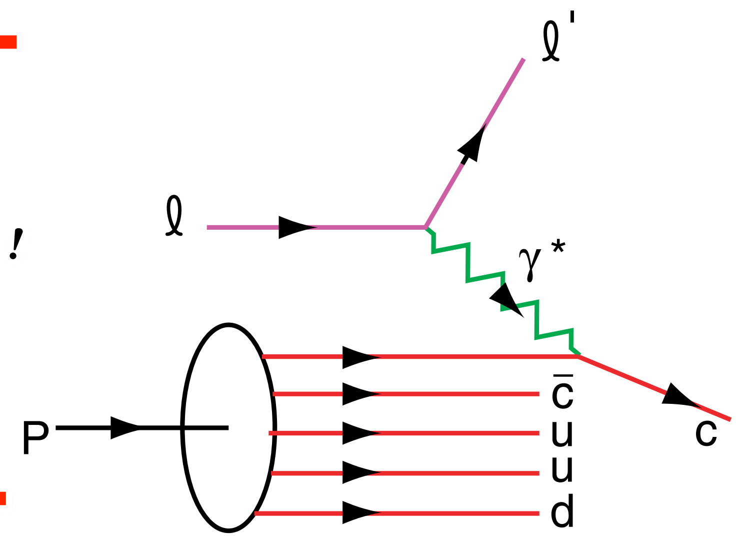
Measurement of Charm Structure Function



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

factor of 30 !



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

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

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

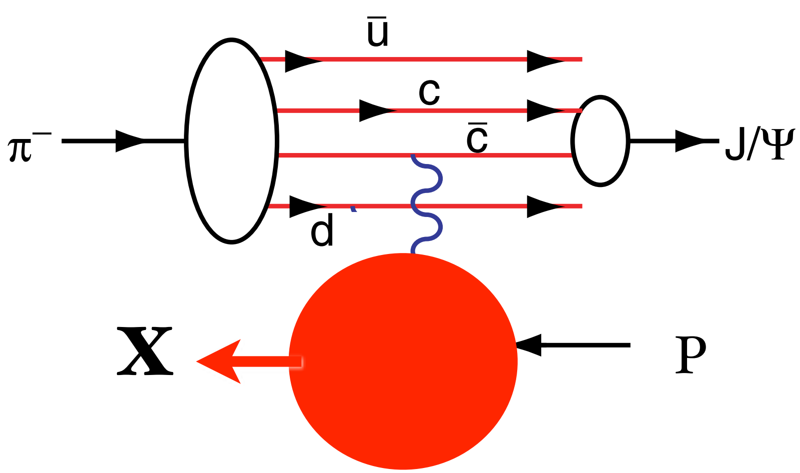
Critical Measurements at threshold for JLab, PANDA

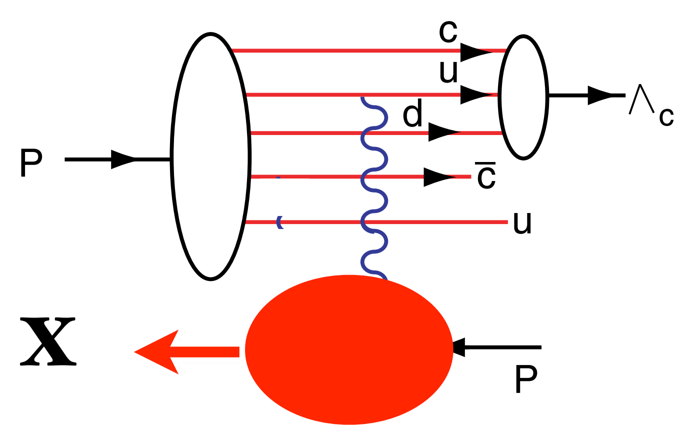
Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

Leading Hadron Production from Intrinsic Charm

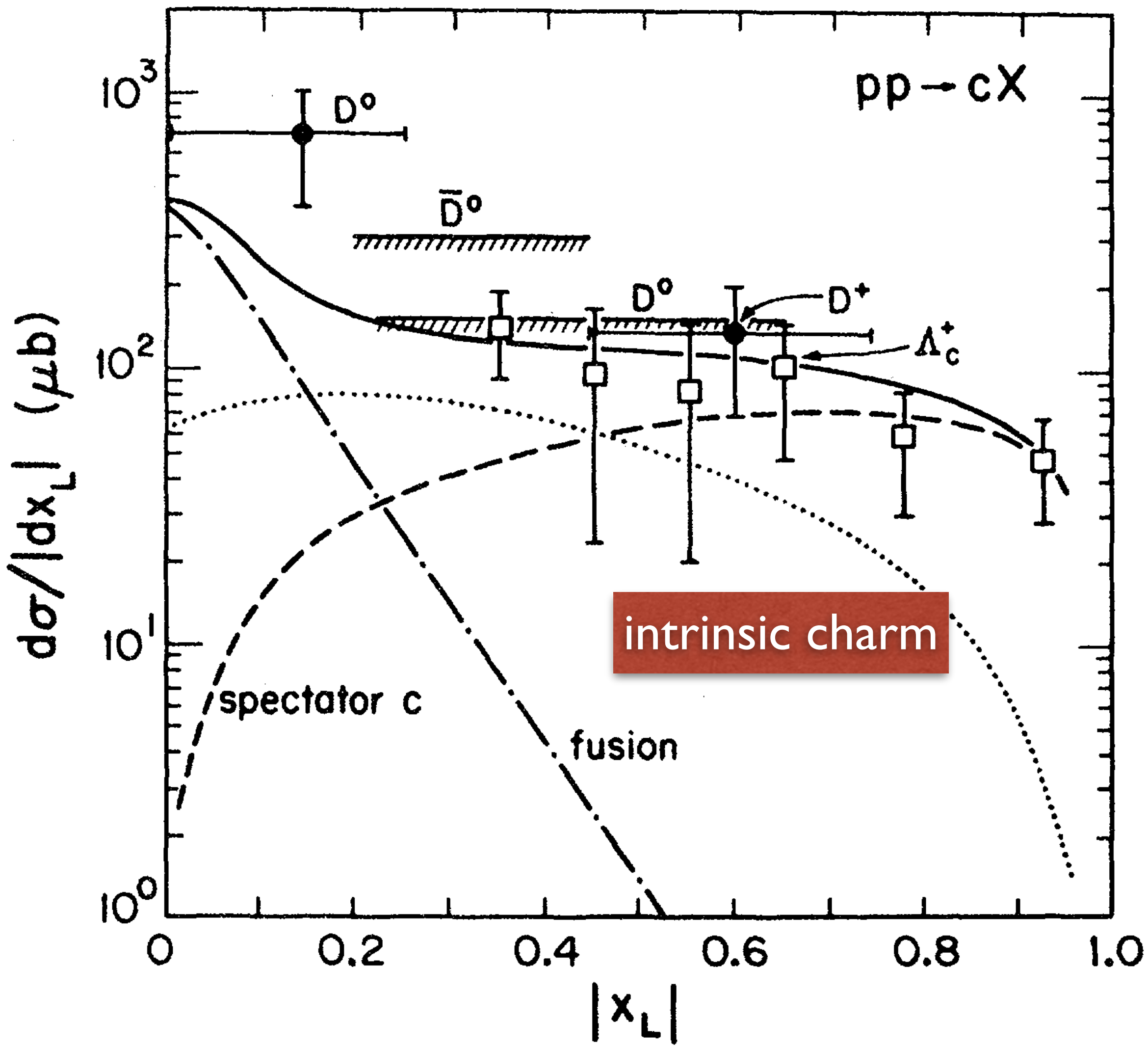




Spectator counting rules

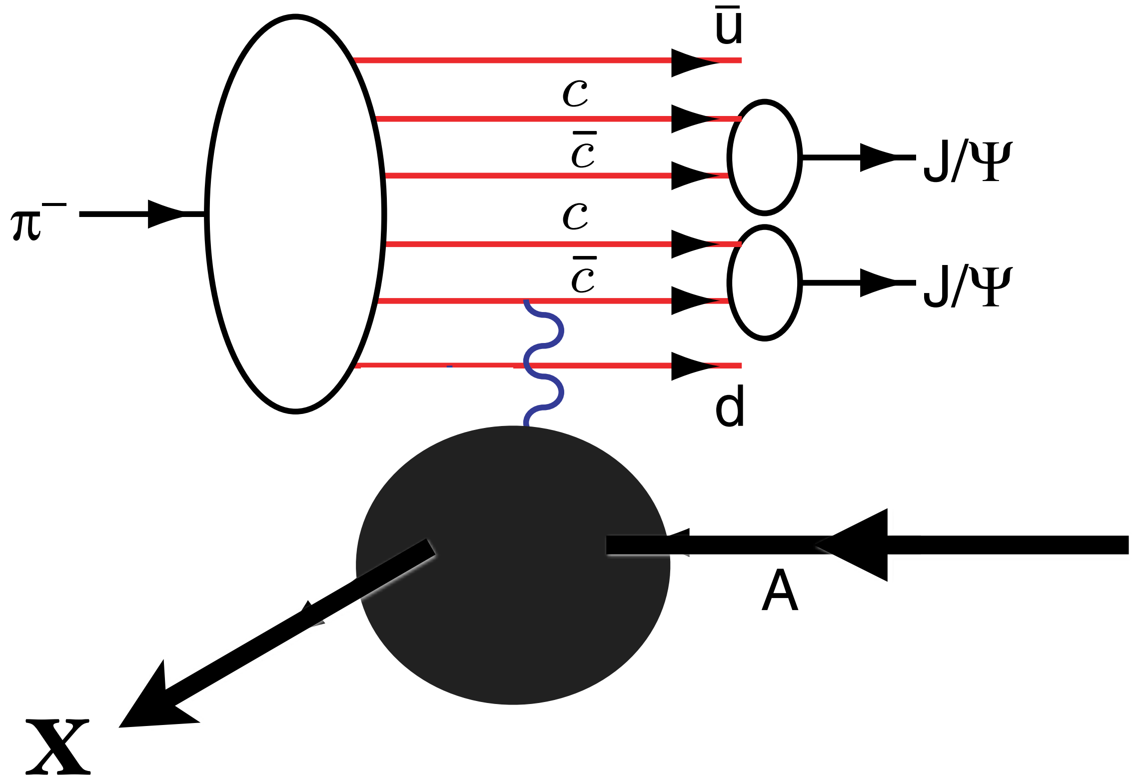
$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F



Barger, Halzen, Keung

Evidence for charm at large x



NA3: All events at high $x_F = x_\psi + x_\psi$!

Excludes PYTHIA 'color drag' model

All events have $x^F_{\psi\psi} > 0.4$!

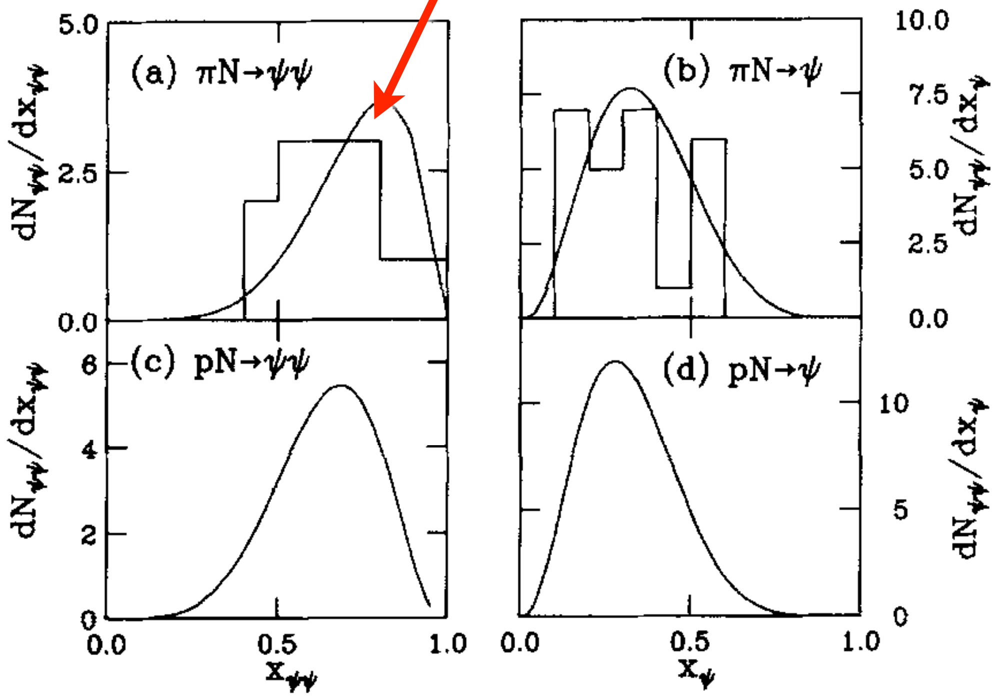


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

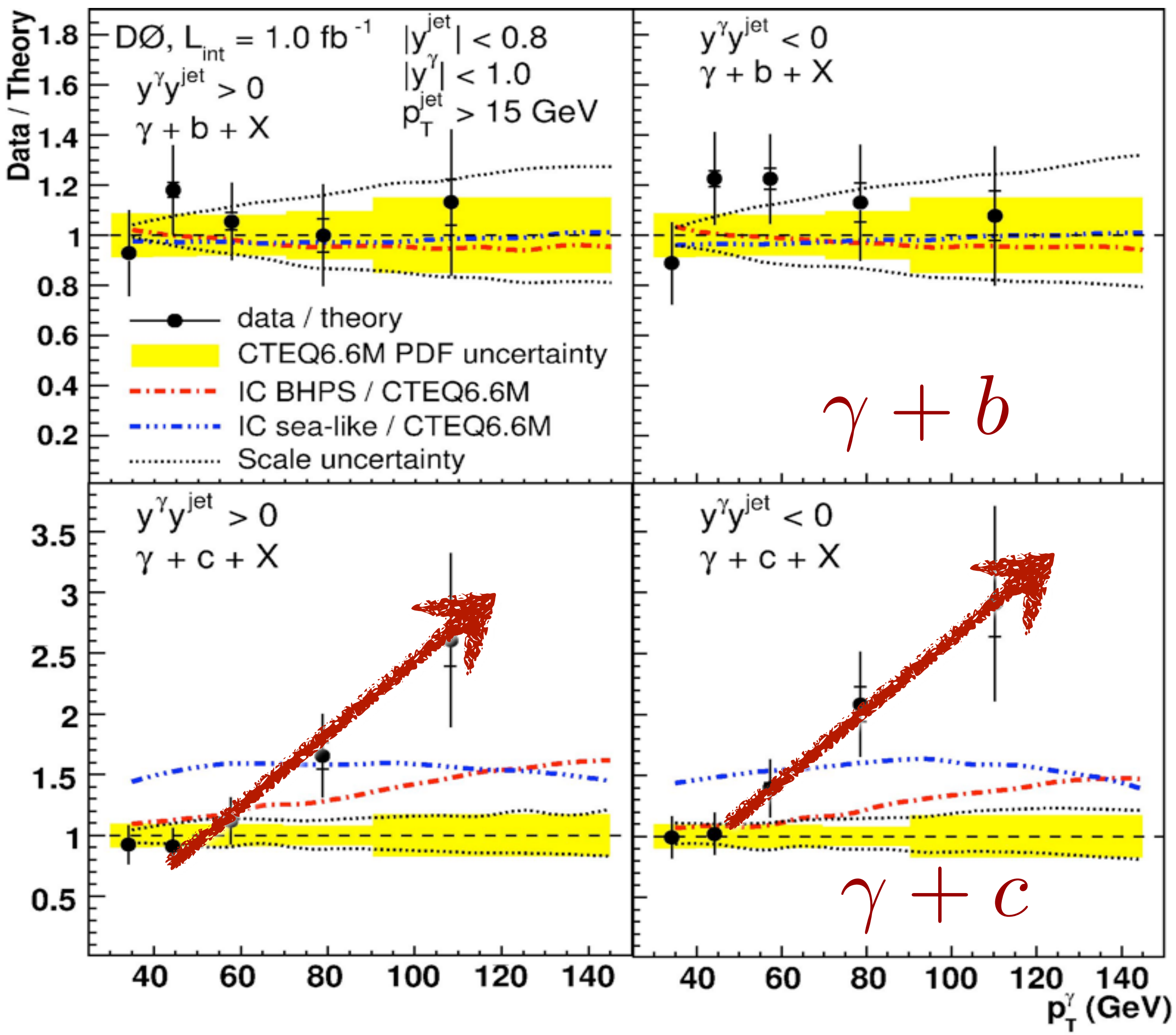
$$\pi A \to J/\psi J/\psi X$$

R, Vogt, sjb

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV



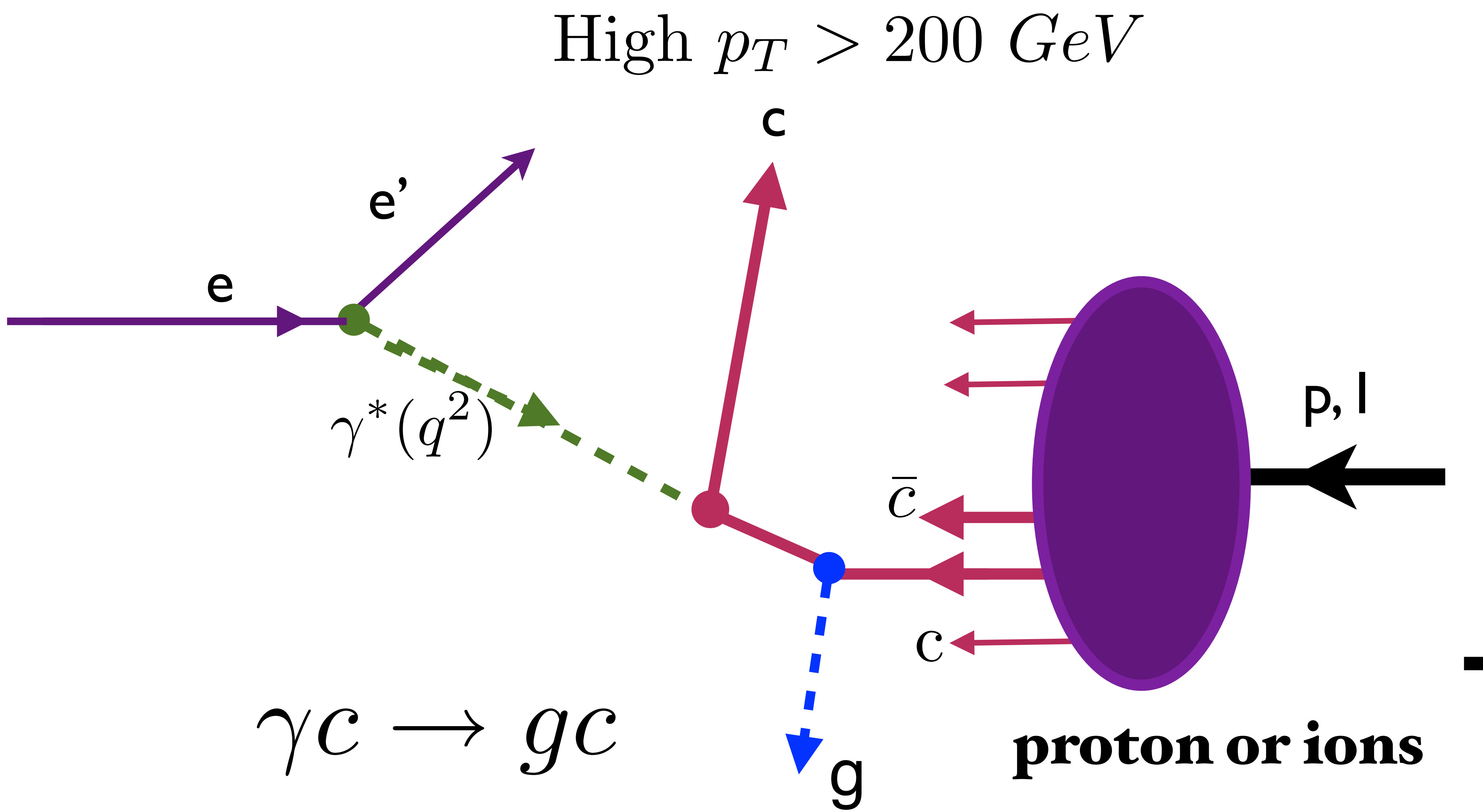
$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1

Need COMPASS Measurement of c(x,Q^2)!

LHeC: Crucial Test of Intrinsic Charm



Look for anomalous rate matching Tevatron anomaly

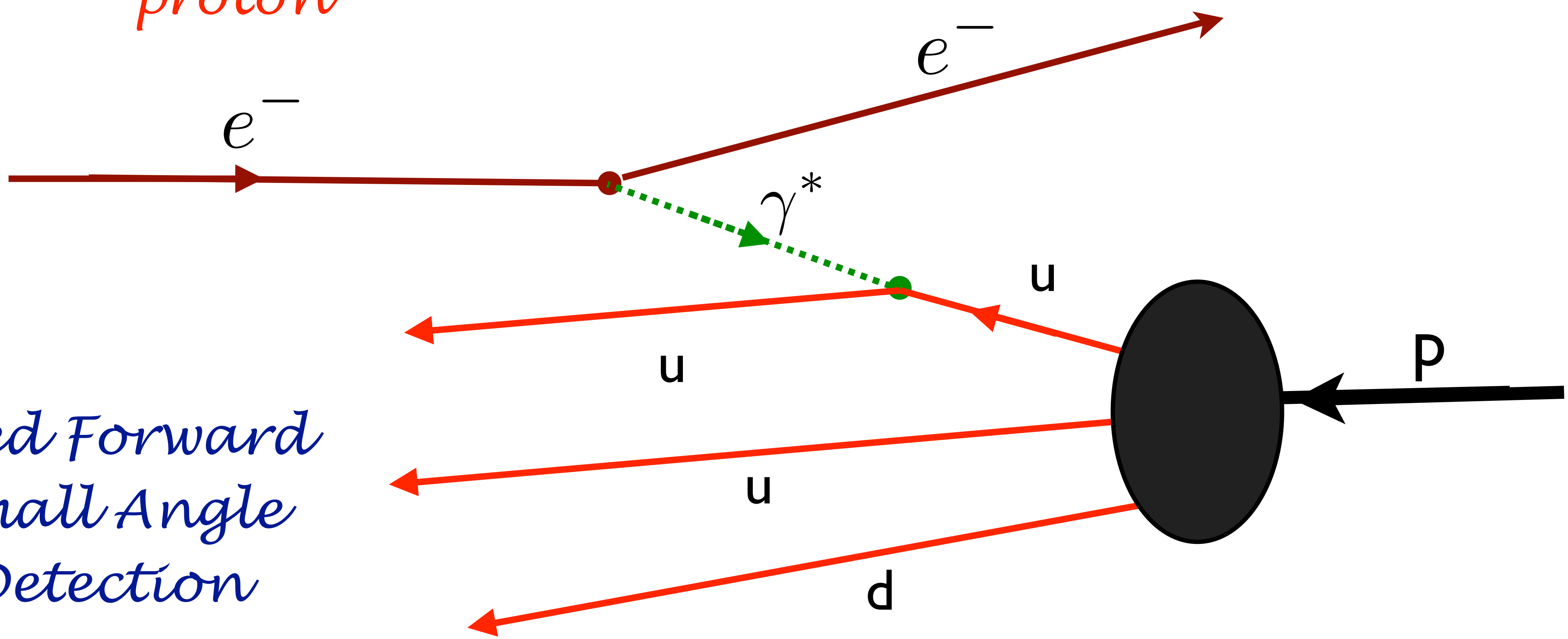
Coulomb Exchange analogous to diffractive excitation *Ashery, et al*

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

Excitation of Intrinsic Heavy Quarks in Proton

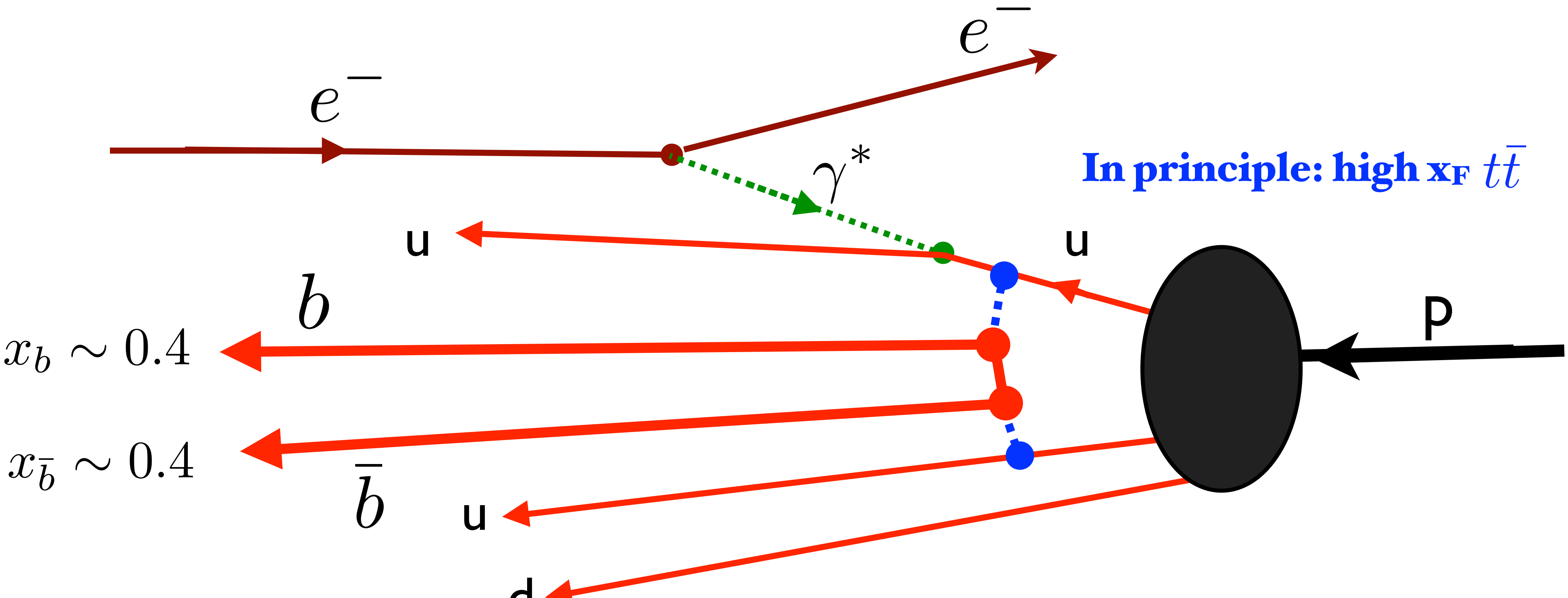
Amplitude maximal at small invariant mass, equal rapidity

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

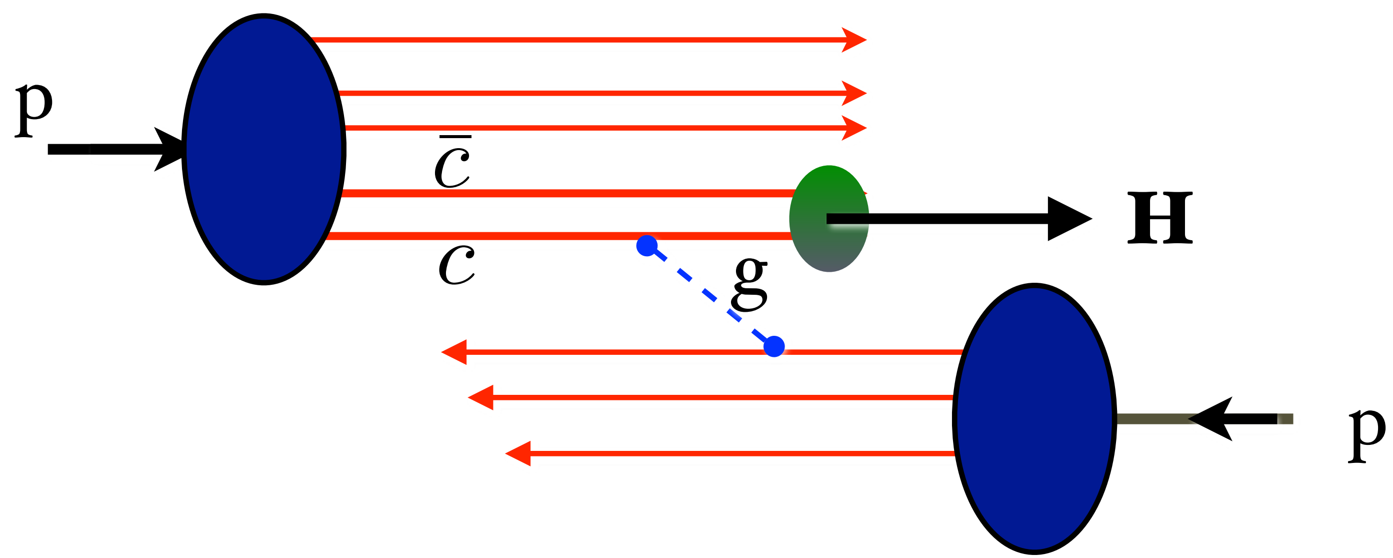
Produce forward, high x_F

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

Need Forward Small Angle Detection



Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to HX$$

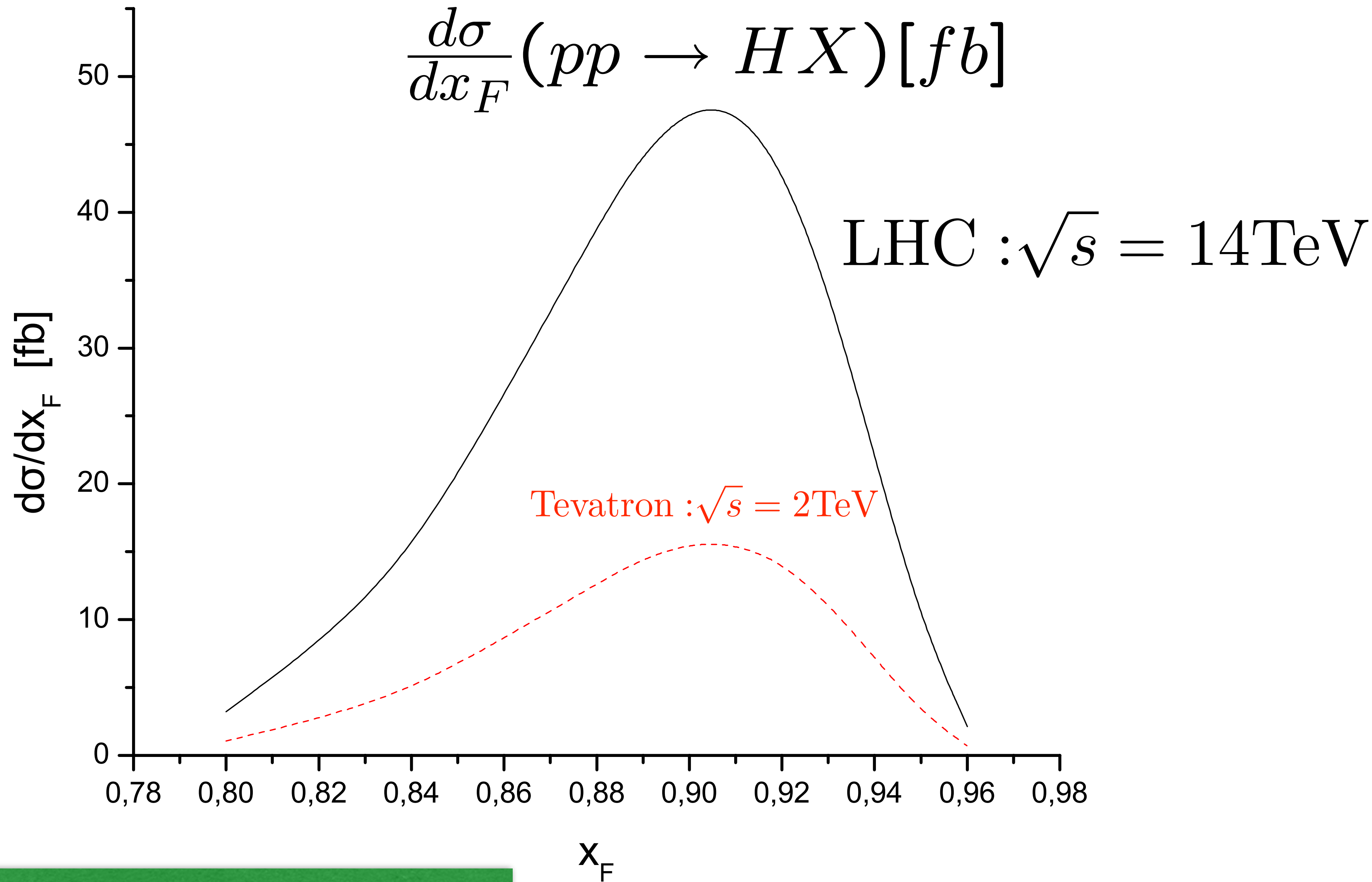
Also: intrinsic bottom, top

Goldhaber, Soffer, Kopeliovich, Schmidt, sjb

Higgs can have 80% of Proton Momentum at LHC!

New search strategy for Higgs

AFTER: Higgs production at threshold!



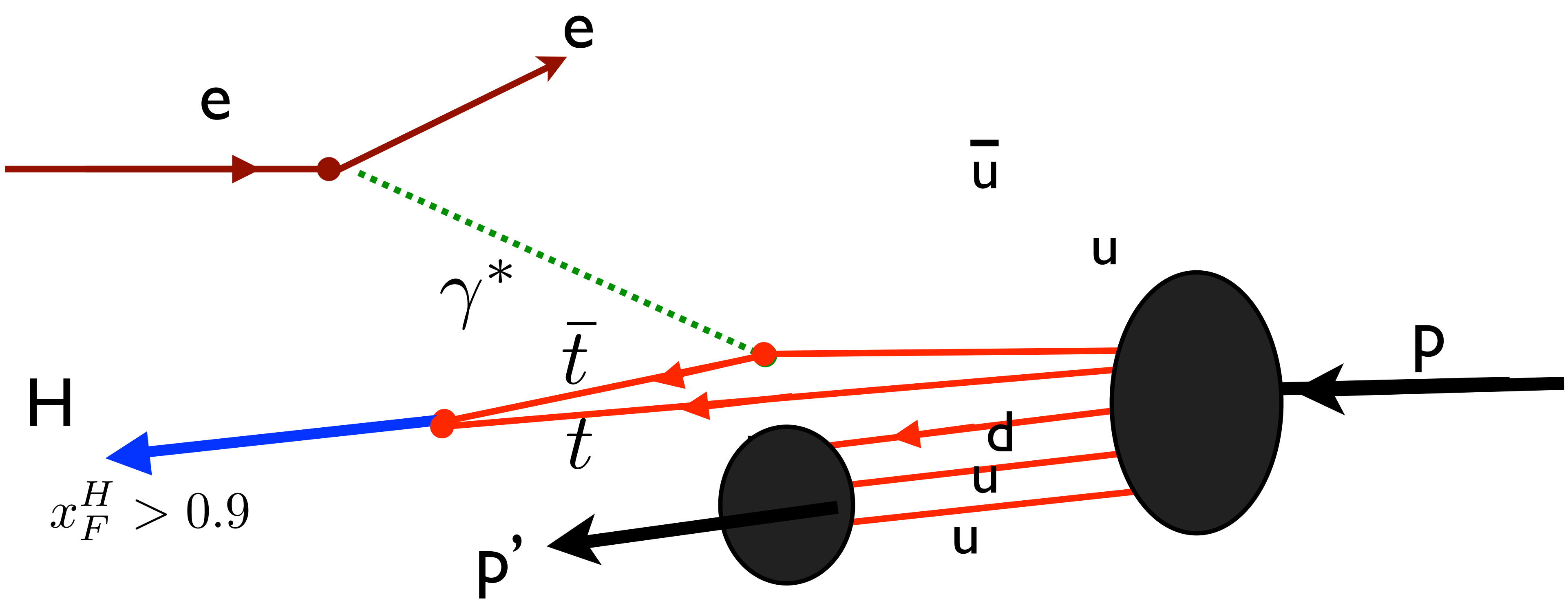
Need High x_F Acceptance

Most practical: Higgs to 2 or 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

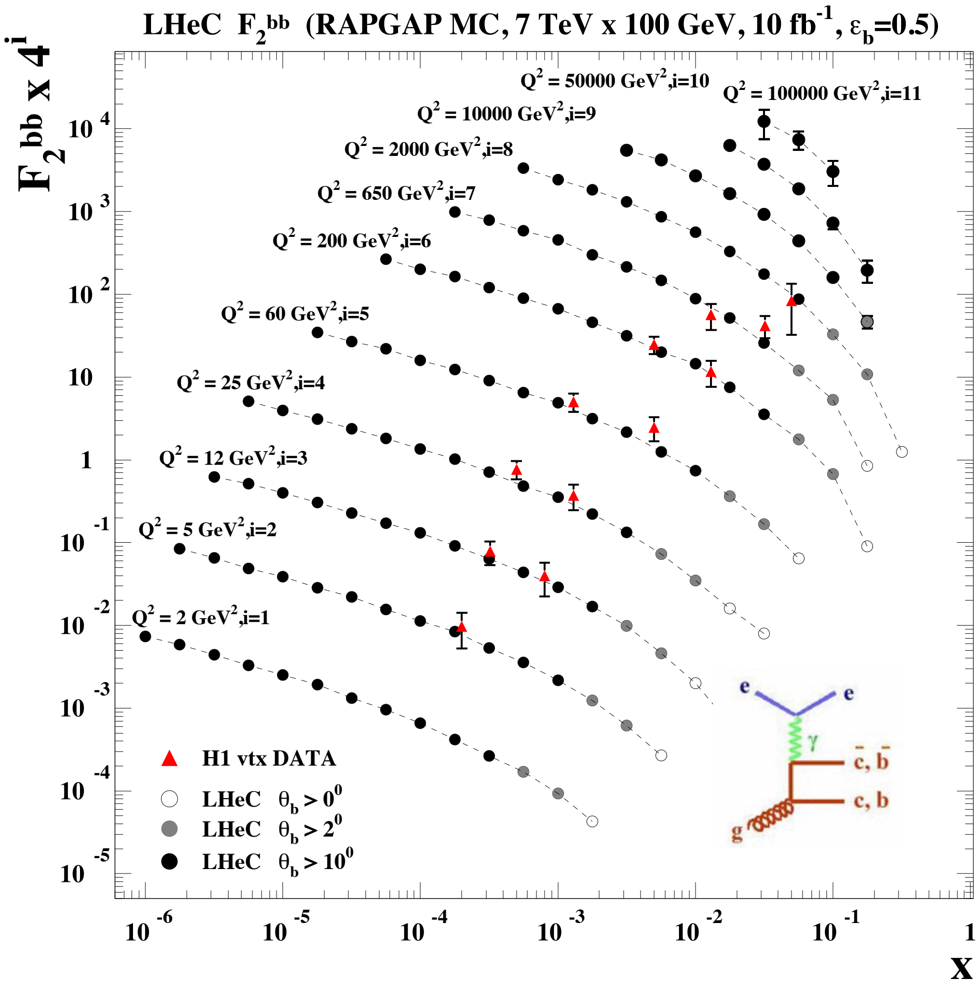
Diffractive Higgs Electroproduction at the LHeC from Intrinsic Heavy Quarks at very high x_F

- Kopeliovich, Schmidt, Soffer, sjb



PDF, α_S uncertainties and the Higgs

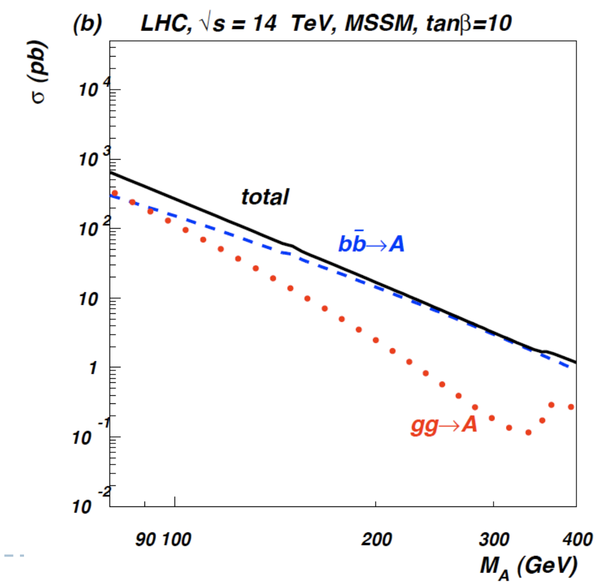
- With LHeC: huge improvements in PDFs and precision in α_S → full exploitation of LHC data for Higgs physics
  - PDF and α_S uncertainties as limiting factor for several channels at the HL-LHC
  - **HQ treatment is crucial subject in QCD and matters at high scales!**



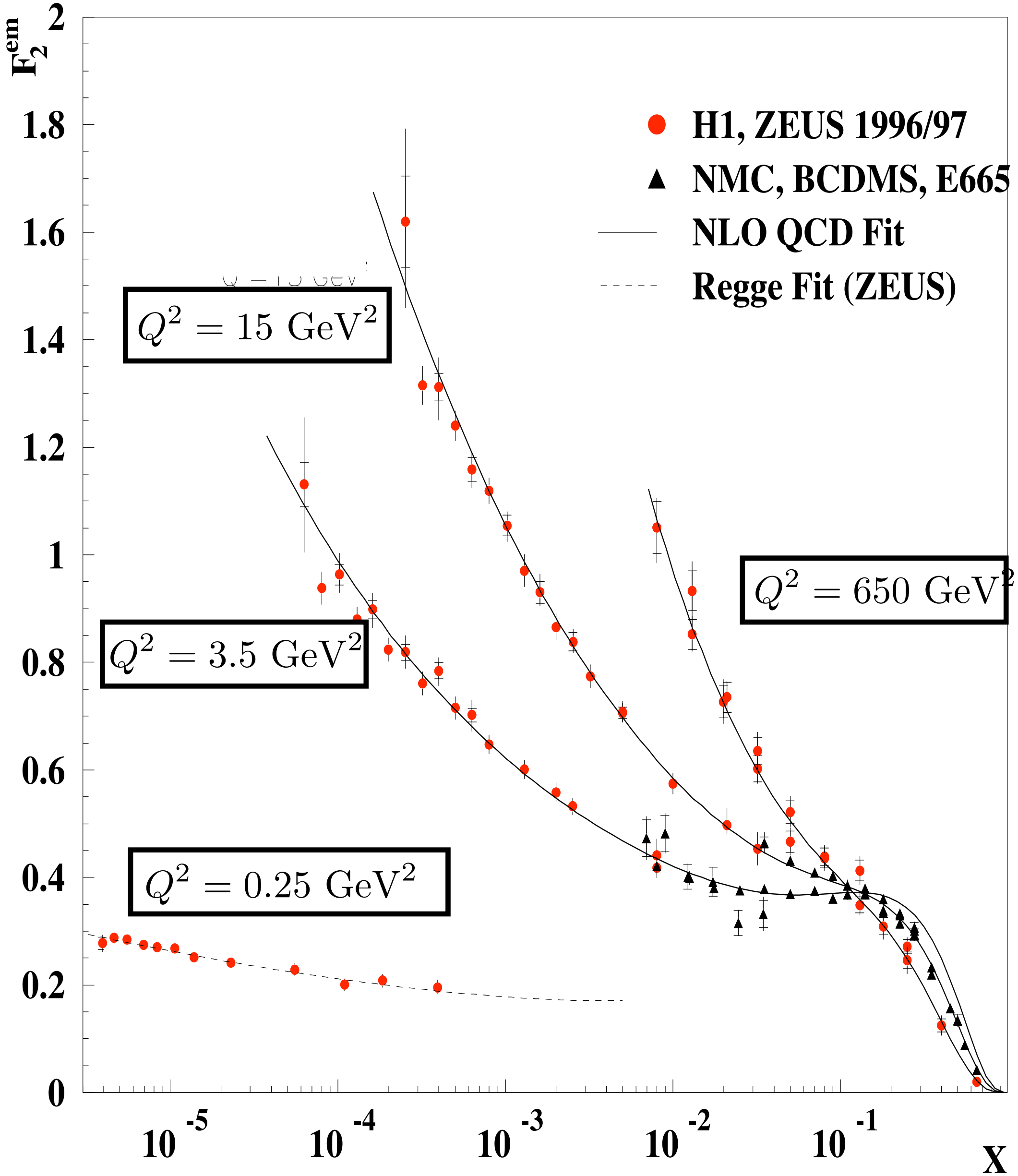
At LHeC: flavor decomposition (charm/beauty) → 20 times better precision for charm and bottom mass

E.g. relevant for **MSSM Higgs** production with A produced predominantly via bbbar

CTEQ Belyayev et al. JHEP 0601:069,2006



$F_2(x, Q^2)$



LHeC:
Measure
Structure Function
at very small x

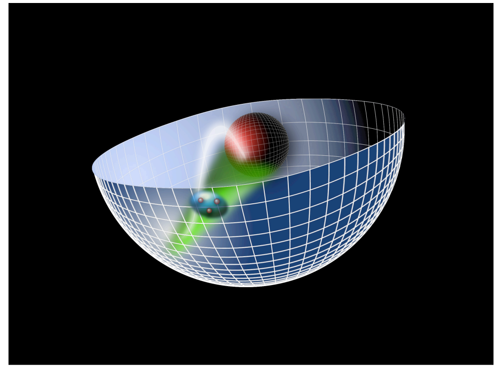
Unitarity
Bound?
Saturation?

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent fundamental mass scale

κ



Light-Front Holography

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

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

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)

$$\kappa \simeq 0.6 \ GeV$$

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

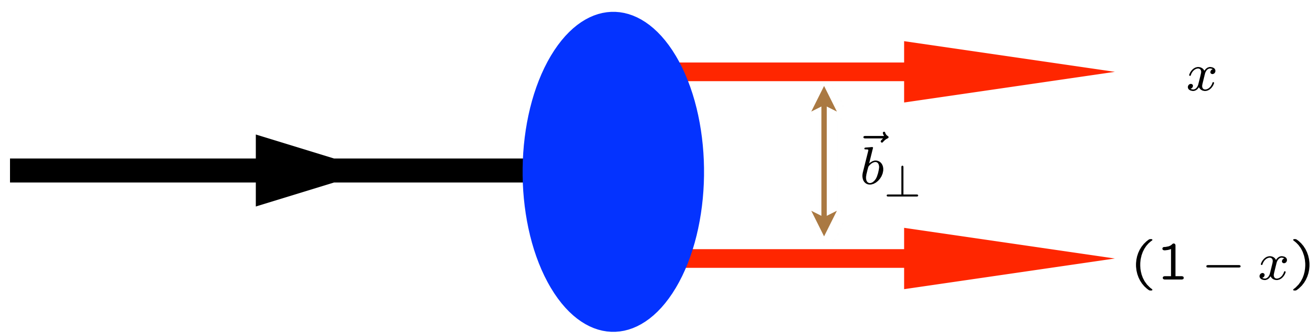
- **de Alfaro, Fubini, Furlan:** ***Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!***

de Teramond, sjb

LF(3+1) ⟷ AdS_5

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

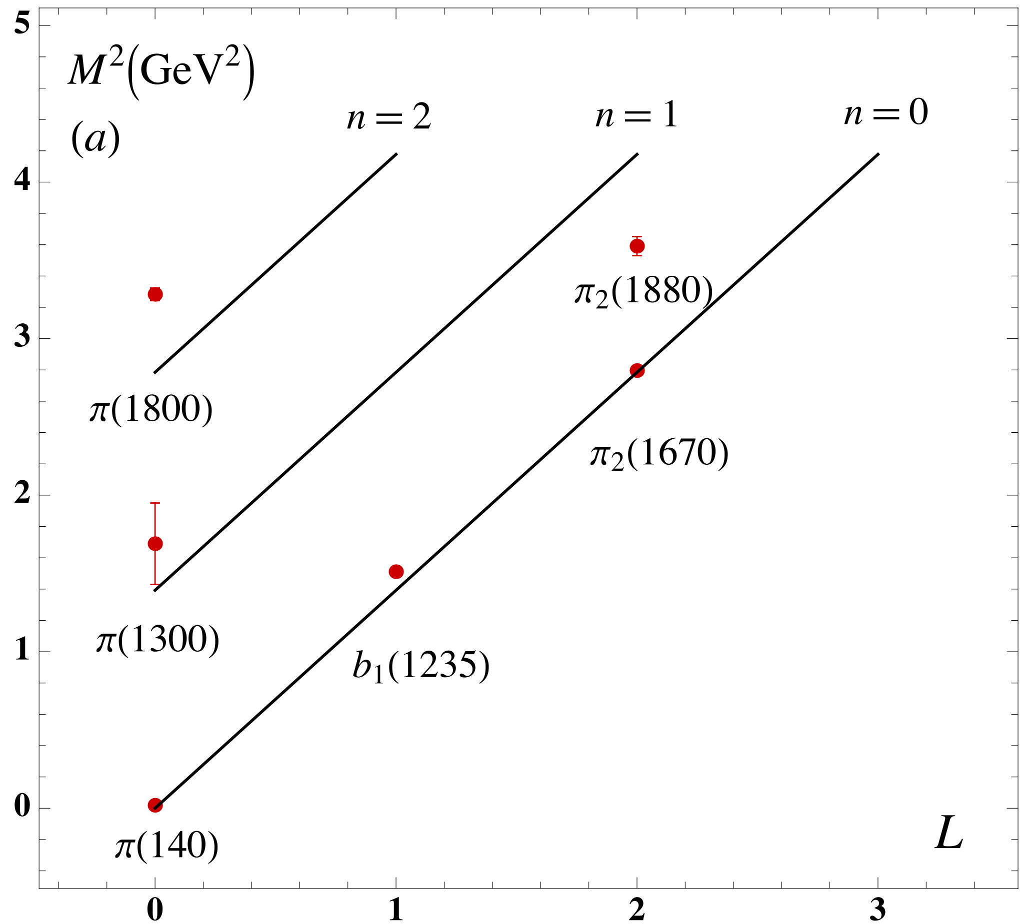
$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2} \longleftrightarrow z$$

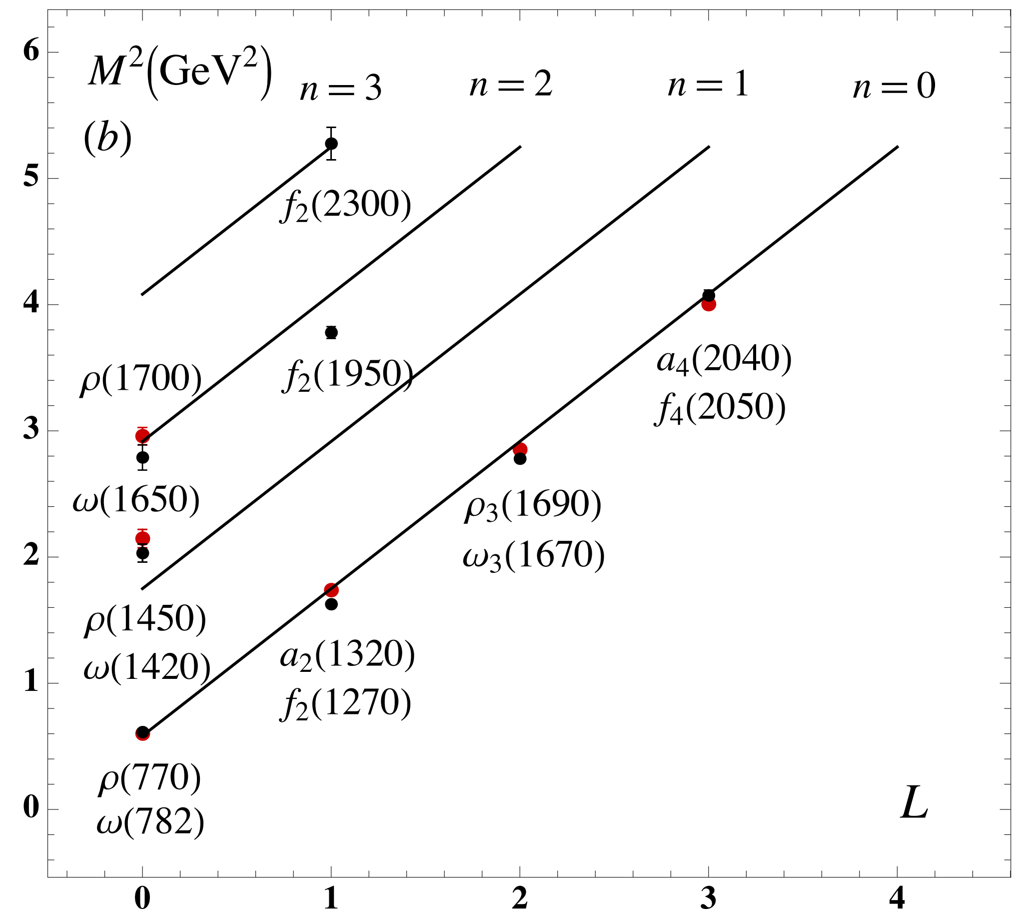


$$\psi(x, \zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

Light Front Holography: Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements

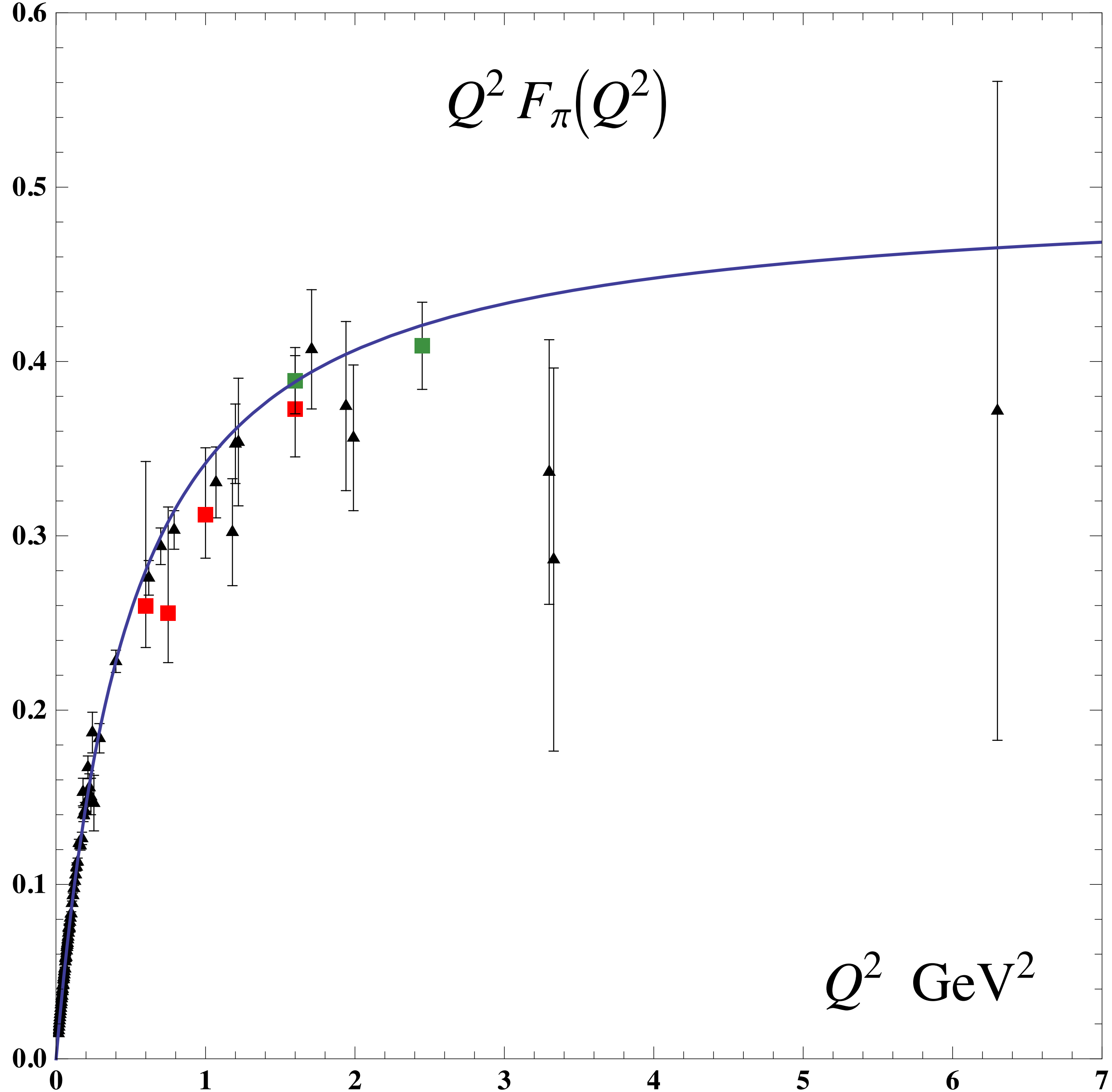
Prediction from AdS/QCD





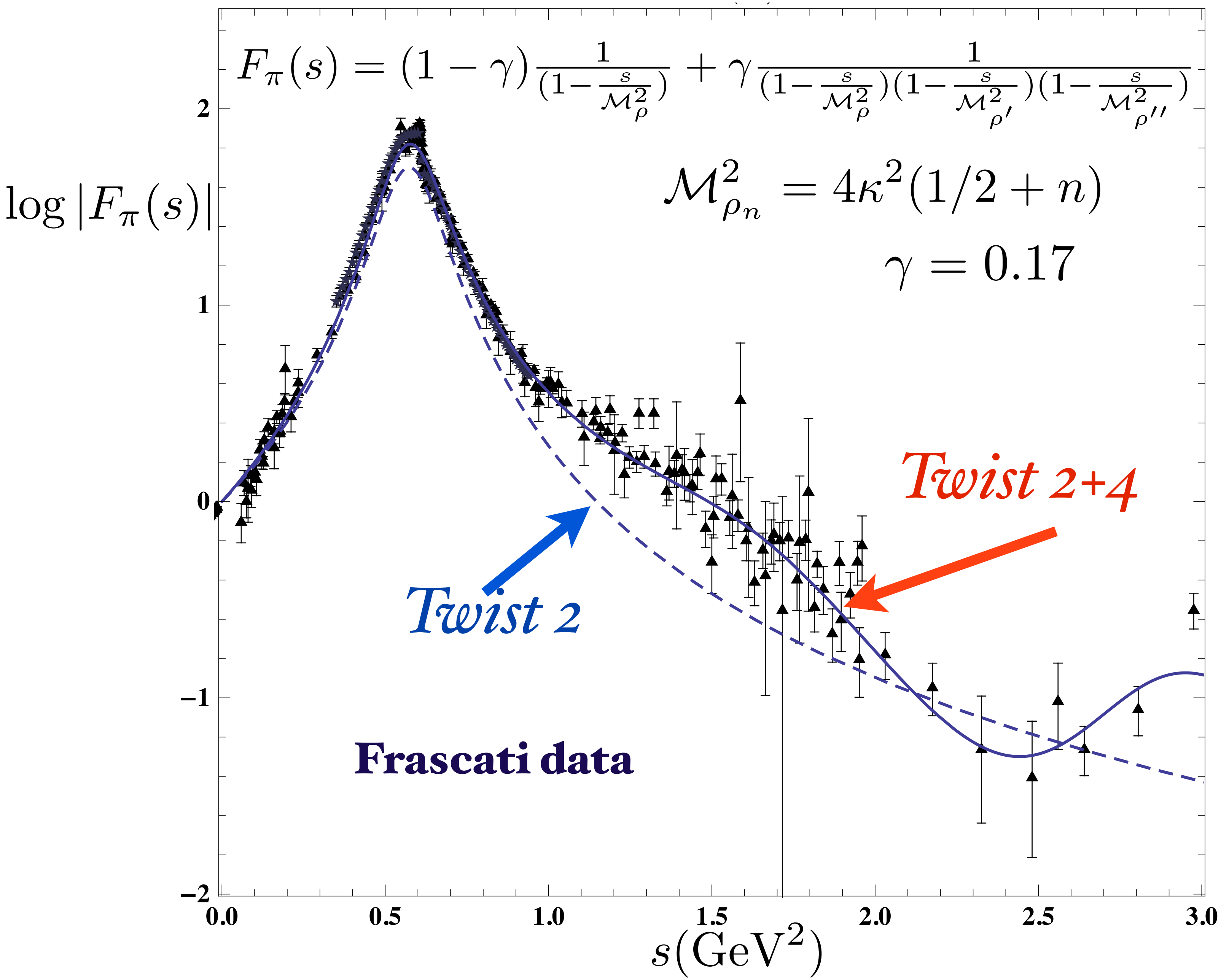
$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

$$m_u = m_d = 0$$



$Q^2 F_\pi(Q^2)$
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

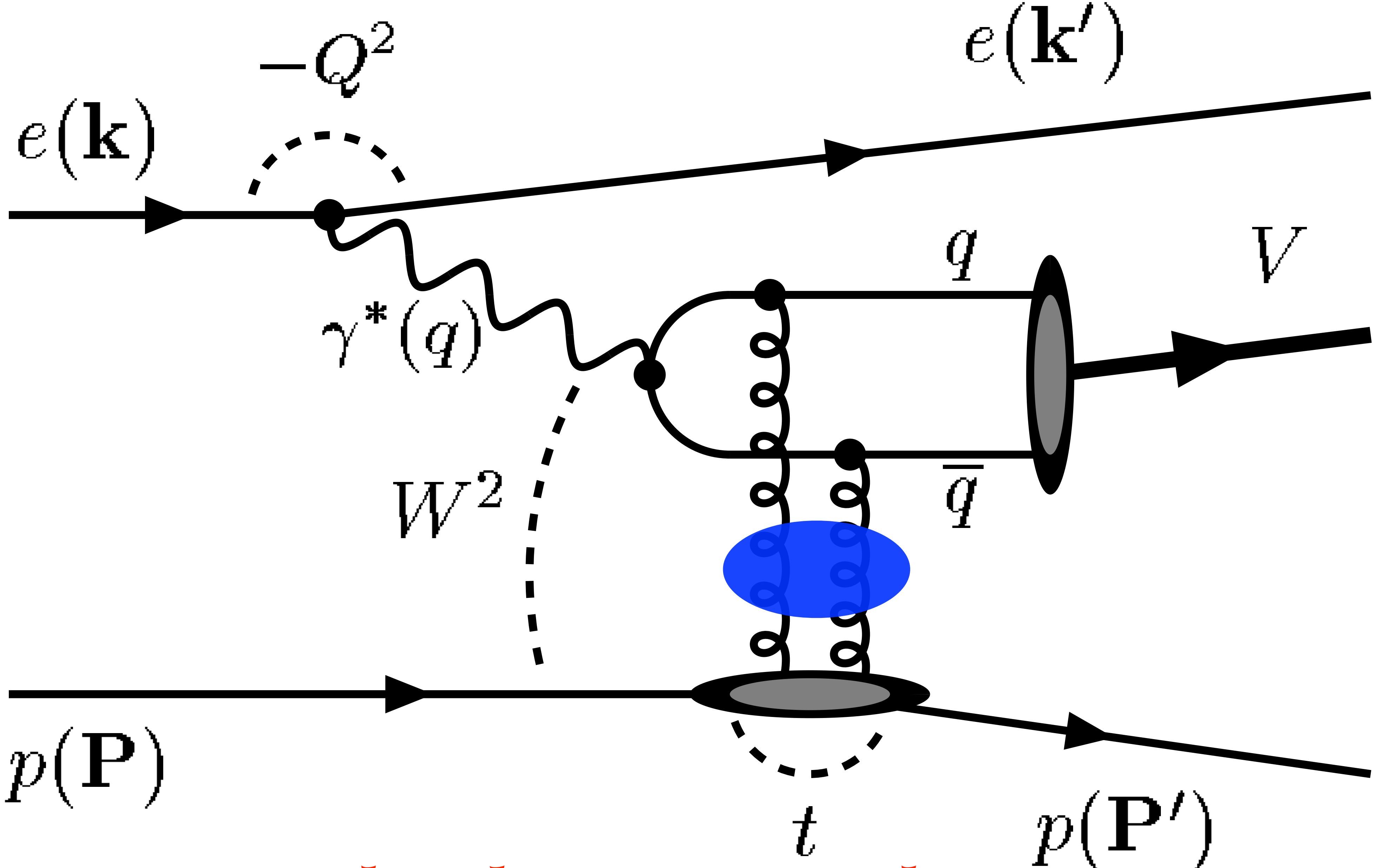


Prescription for Timelike poles :

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

14% four-quark probability

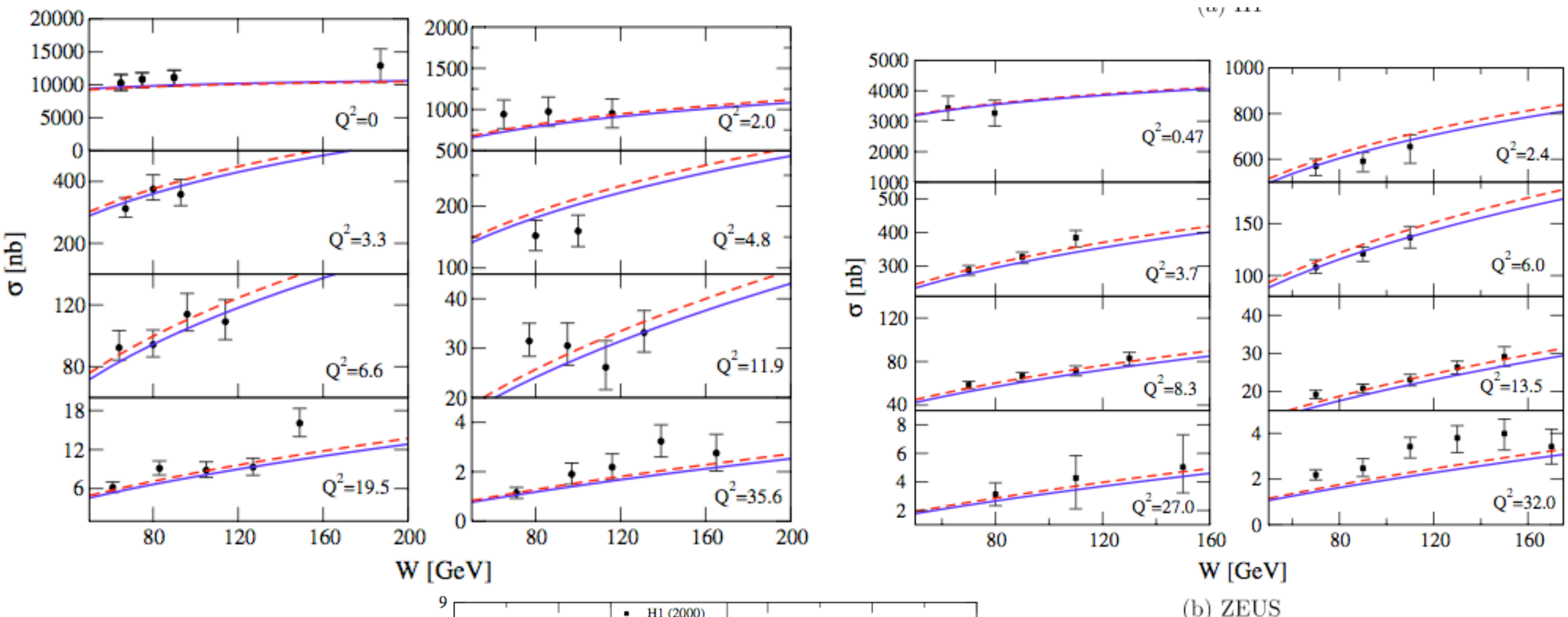
G. de Teramond & sjb



BFKL hard pomeron exchange
Color Transparency at high Q^2

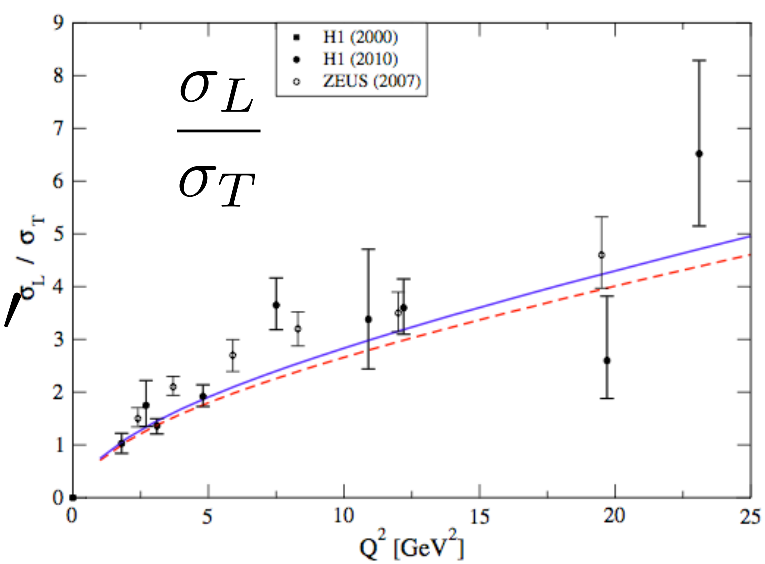
LHeC: Electroproduction of huge range of excited vector mesons

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



J. R. Forshaw, R. Sandapen

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



Prediction from Light-Front Holography

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

LF Holography

Baryon Equation

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2}\right)\psi_J^+ = M^2\psi_J^+$$ G_{22}

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2}\right)\psi_J^- = M^2\psi_J^-$$ G_{11}

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

S=1/2, P=+

both chiralities

Meson Equation

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(J-1) + \frac{4L_M^2-1}{4\zeta^2}\right)\phi_J = M^2\phi_J$$ G_{11}

$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Same κ !

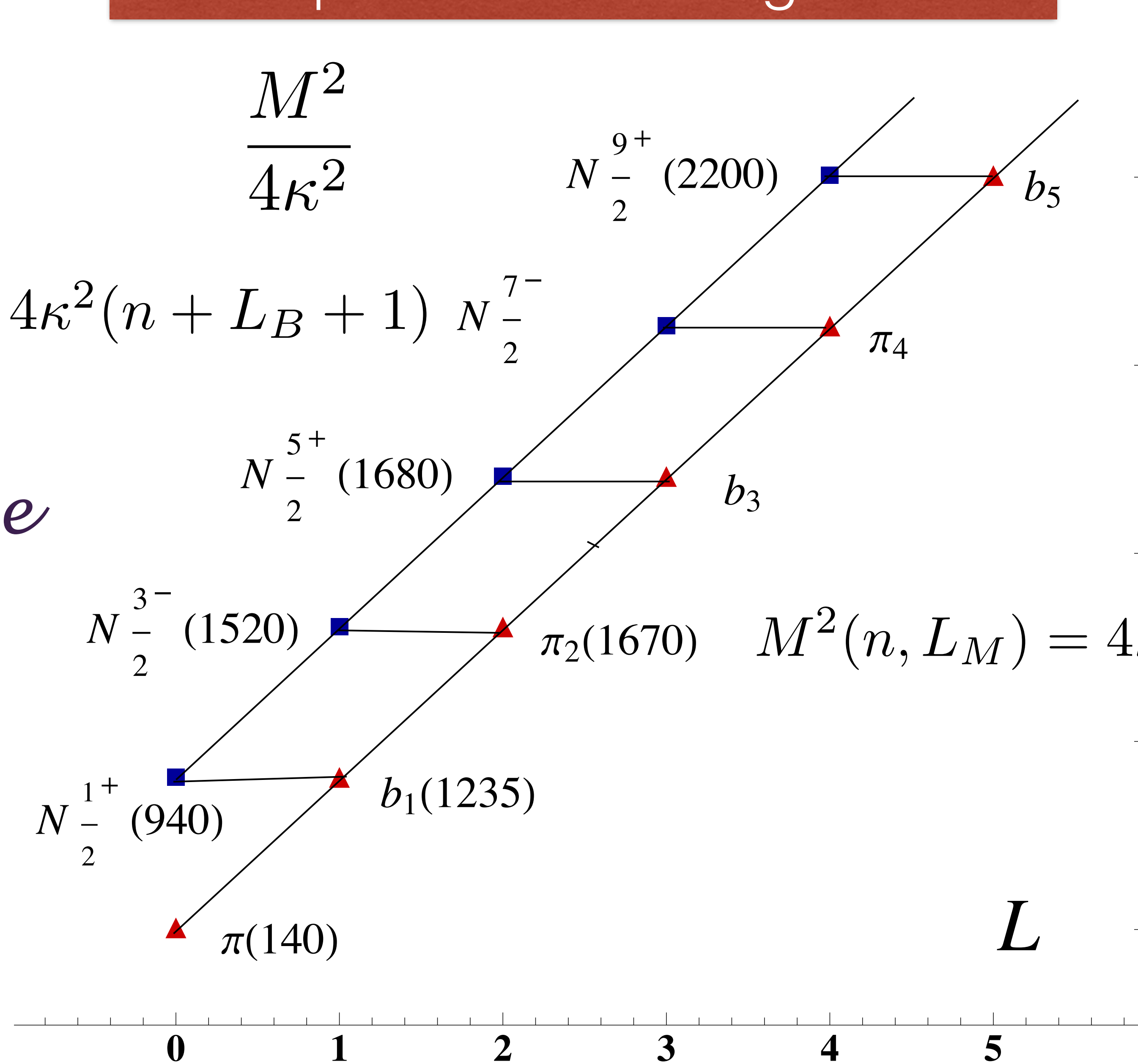
S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

Meson-Baryon Degeneracy for $L_M=L_B+1$

Superconformal Algebra

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

Same slope

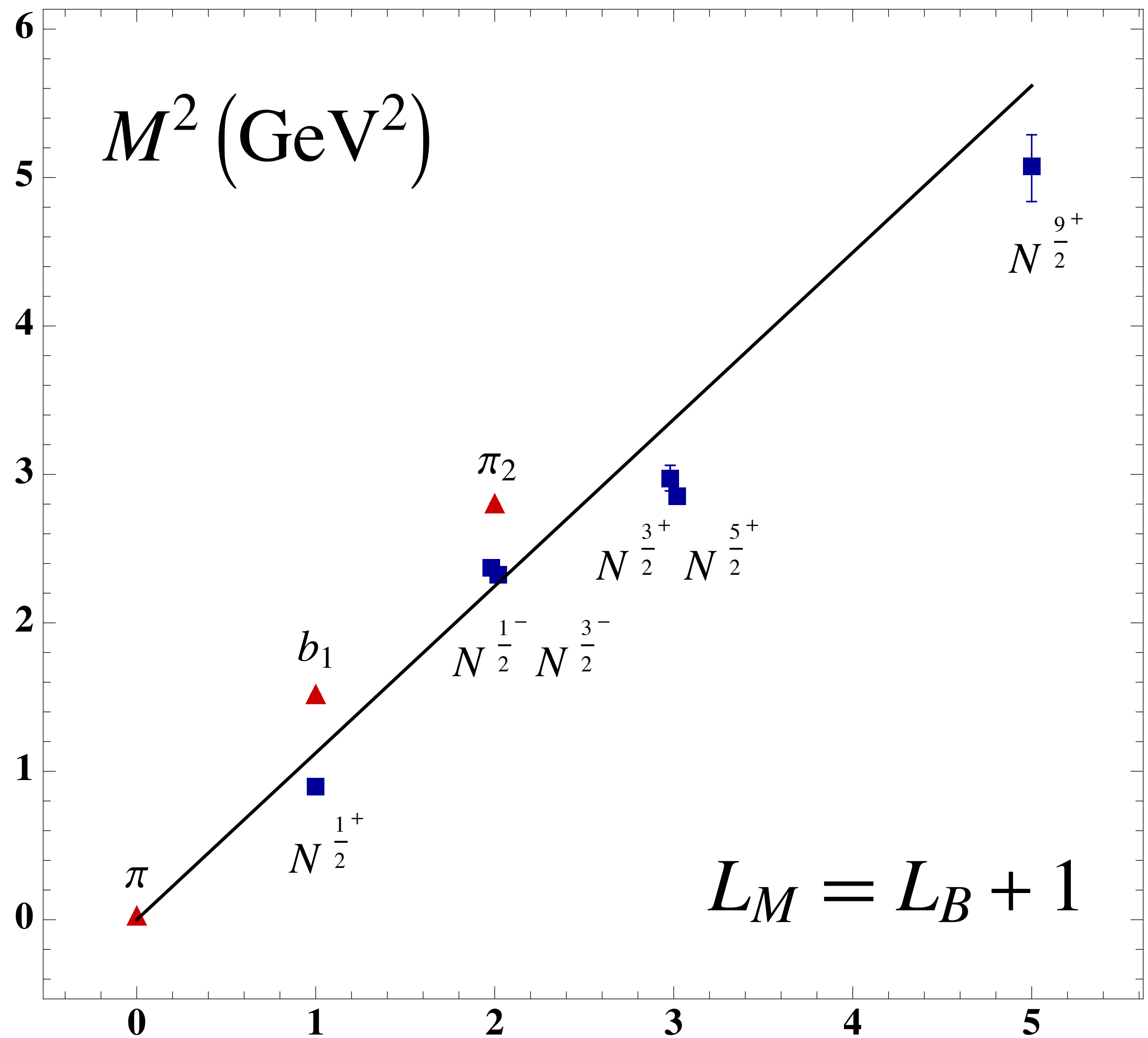


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

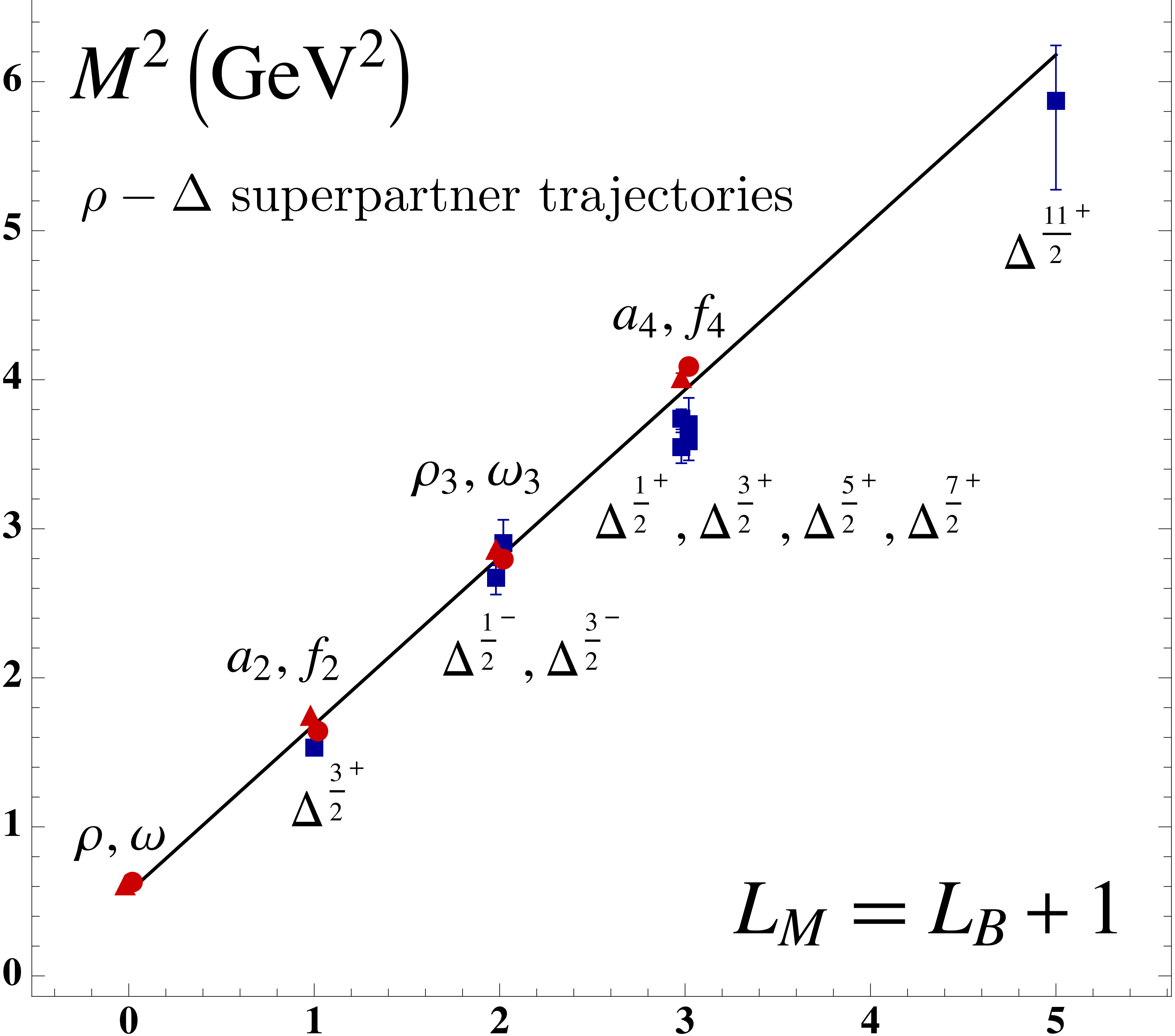
Dosch, de Teramond, sjb

Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



Meson-Baryon Mass Degeneracy for L_M=L_B+1

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon



Dosch, de Teramond, sjb

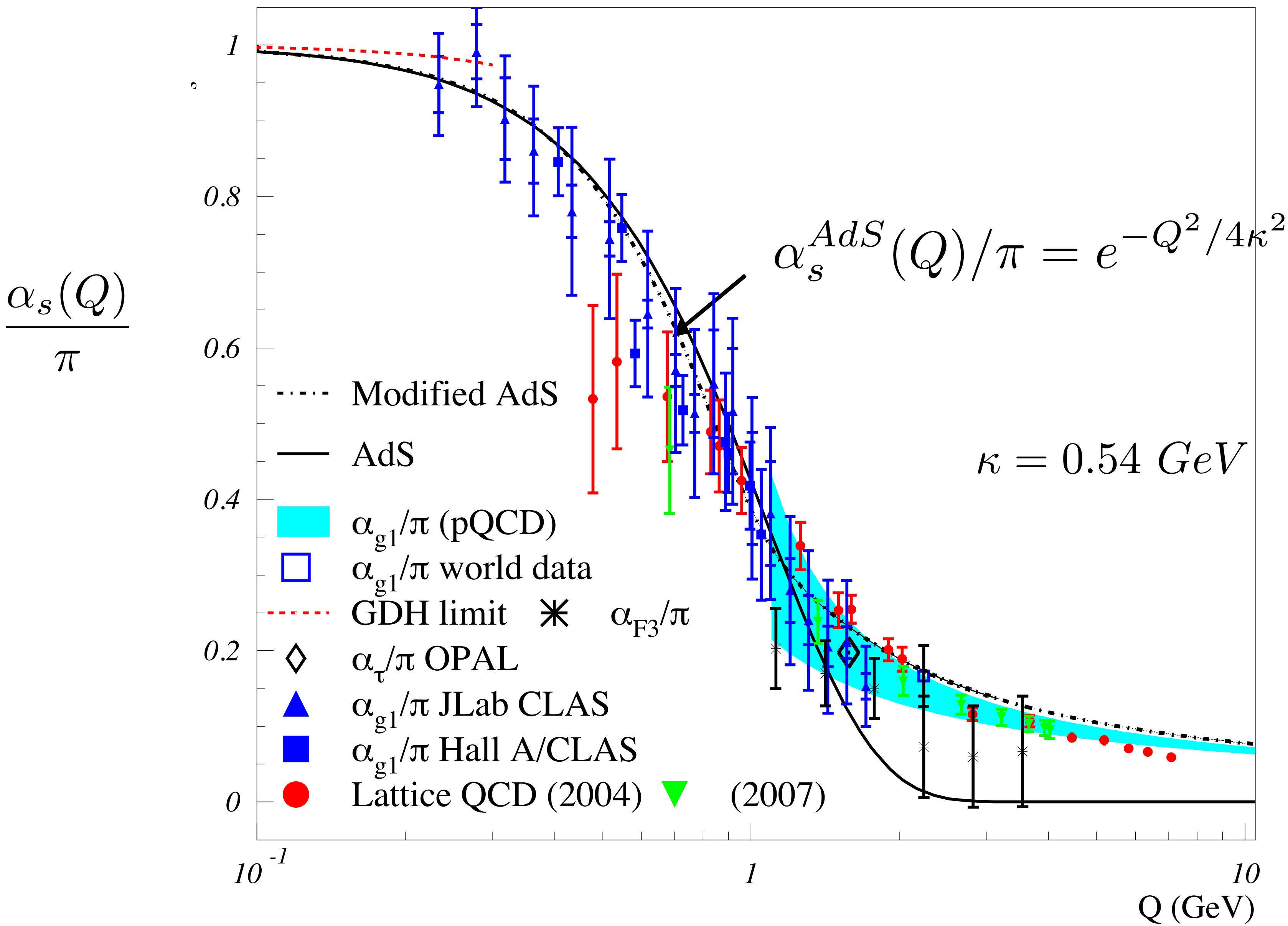
Predictions from AdS Holographic QCD

Dosch, Deur, de Teramond, sjb

- Zero-Mass pion for zero quark mass
- Regge Spectroscopy $$M_\pi^2(n, L) = 4\kappa^2(n + L)$$
- Same slope in n, L
- LFWFs, Distribution Amplitudes $$\phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$$
- Form Factors, Structure Functions, GPDs
- Non-perturbative running coupling $$\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$$
- Meson-Baryon Supersymmetry for $L_M = L_{B+1}$

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

$$e^{\varphi} = e^{+\kappa^2 z^2}$$

Deur, de Teramond, sjb

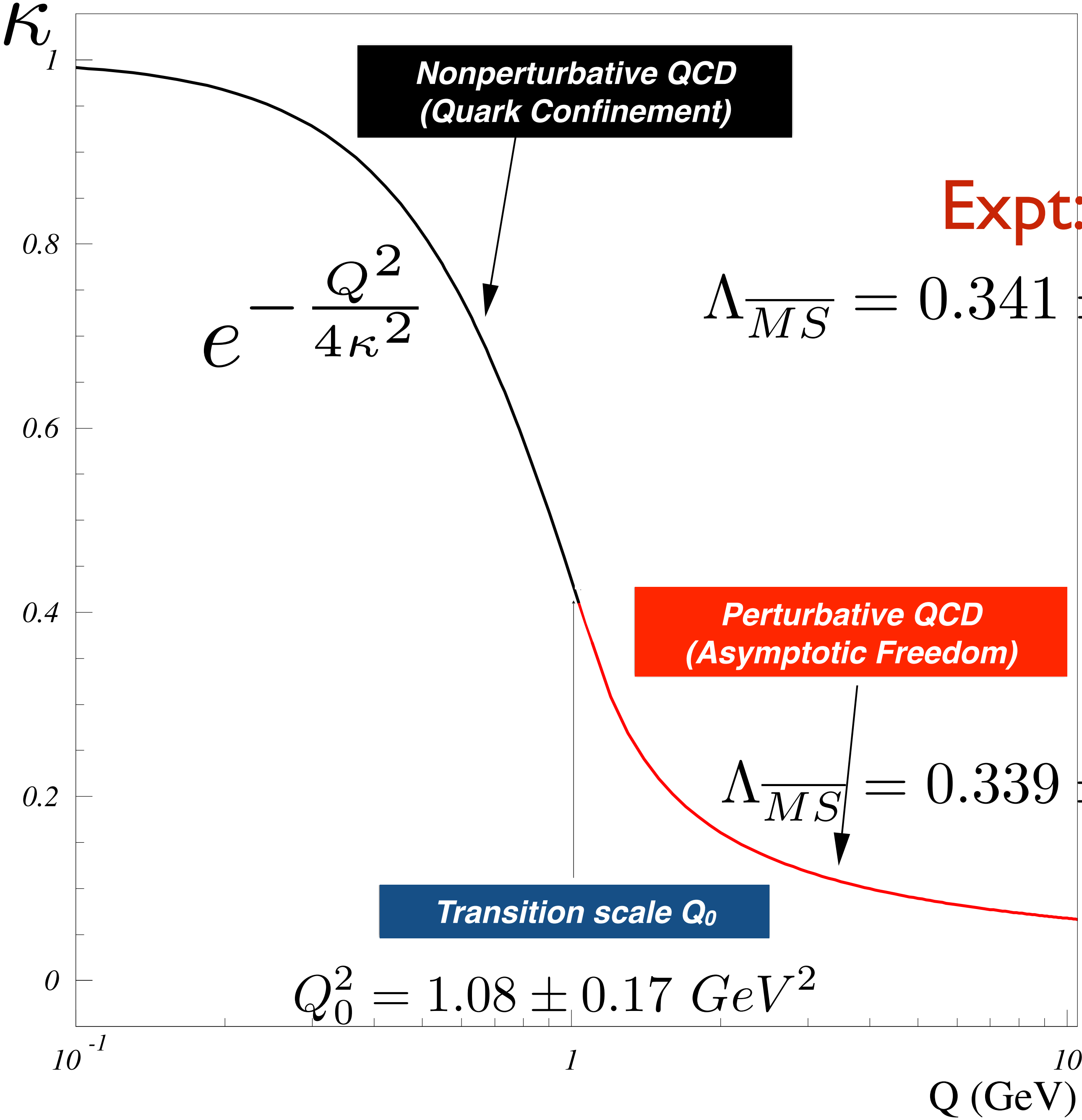
All-Scale QCD Coupling

Deur, de Tèramond, sjb

$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

$$\frac{\alpha^s_{g_1}(Q^2)}{\pi}$$



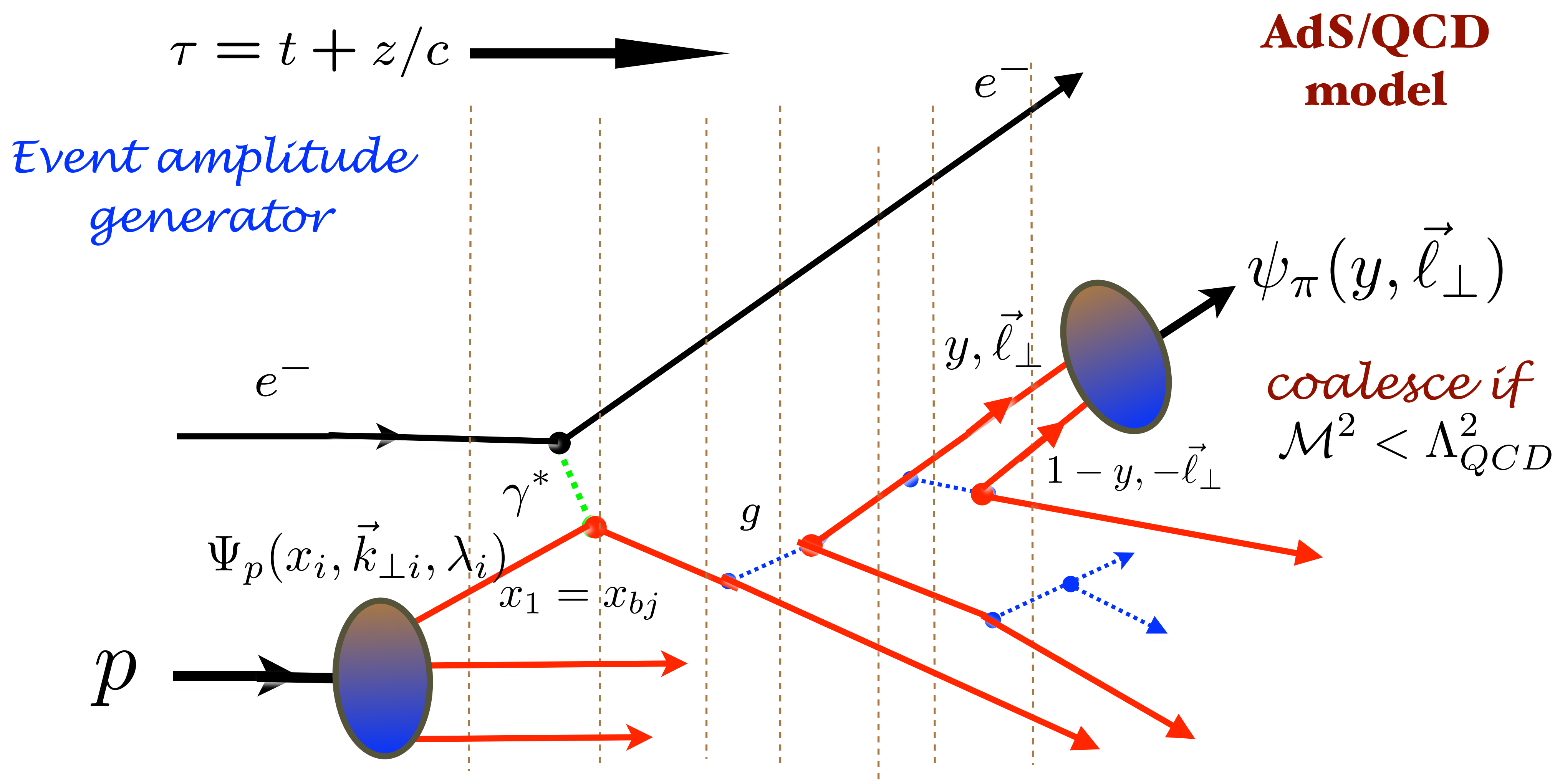
Expt:

$$\Lambda_{\overline{MS}} = 0.341 \pm 0.024\ GeV$$

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.016\ GeV$$

$$\lambda \equiv \kappa^2$$

Jet Hadronization at the Amplitude Level



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

LHeC QCD Physics Highlights

- **Diffractive Deep Inelastic Scattering**
- **Electroproduction of vector mesons - test confinement**
- **Non-Universal Anti-Shadowing**
- **The Odderon**
- **Deeply Virtual Meson Production and Color Transparency**
- **Heavy Quark Interactions at Threshold**
- **Heavy Quark Distributions at High x**
- **Higgs Production at high x_F**

Remarkable Features of Hadron Structure

- Valence quark helicity represents less than half of the proton's spin and momentum
- Non-zero quark orbital angular momentum!
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$relation to meson cloud
- Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$
  $\Delta s(x) \neq \Delta \bar{s}(x)$
- Intrinsic charm and bottom at high x
- Hidden-Color Fock states of the Deuteron

New Physics at the LHeC

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

Theory Advances

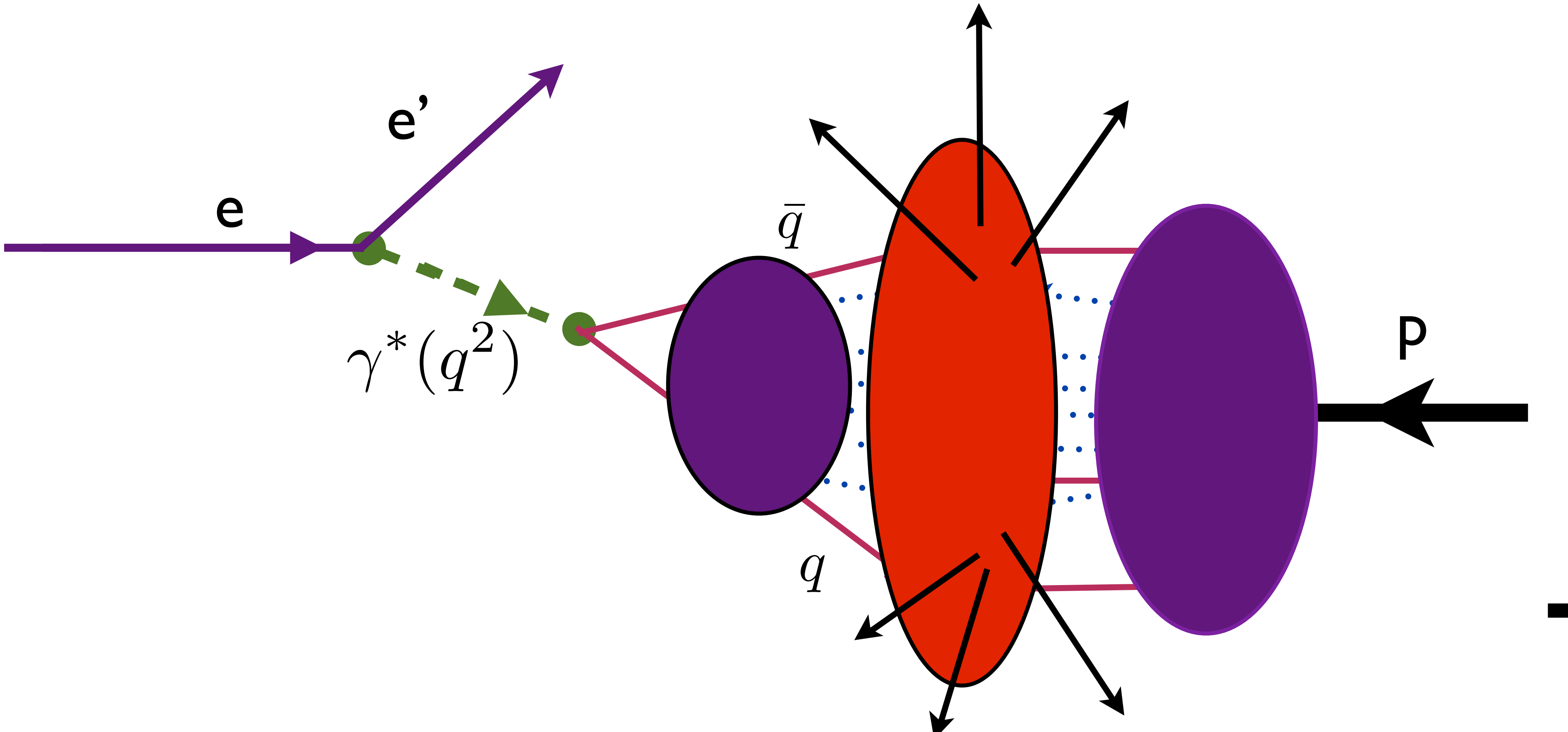
- **PMC/BLM: Eliminate Renormalization Scale Ambiguity**
- **AdS/QCD: Unique form of confinement potential; light-front Schrödinger Equation; spectroscopy, dynamics, running coupling; hadronization at amplitude level**
- **Superconformal algebra relates mesons, baryons**
- **Multi-parton and direct processes**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

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; factorization breaking — Sivers, Boer-Mulders
- 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

LHeC: Virtual Photon-Proton Collider

variable spacelike photon virtuality,
various primary flavors



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

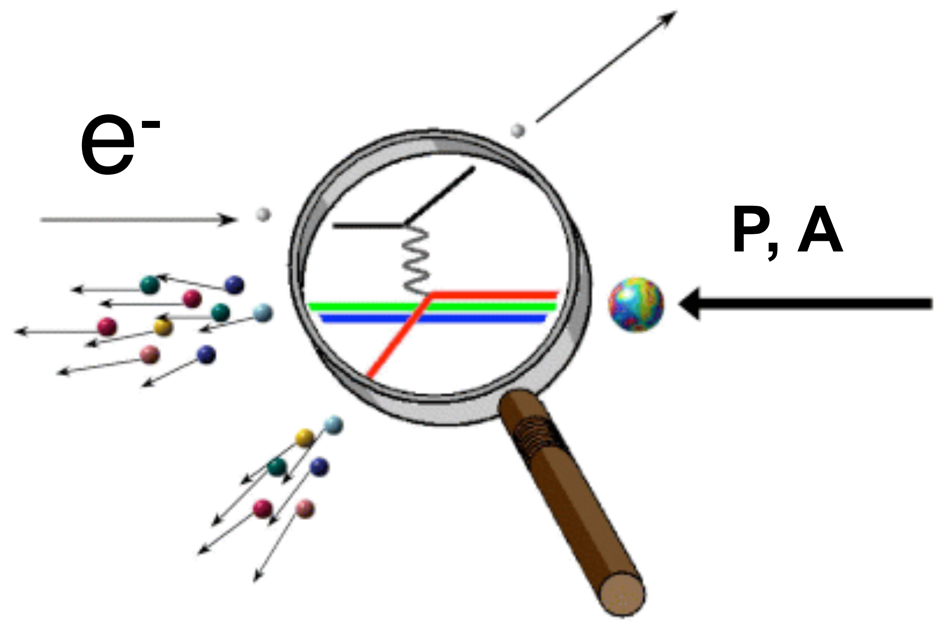
Saturation, nuclear shadowing, antishadowing

Novel LHeC Physics

LHeC

Electron-proton and electron-nucleus collisions at unprecedented energy

Options: positrons, polarization



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

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