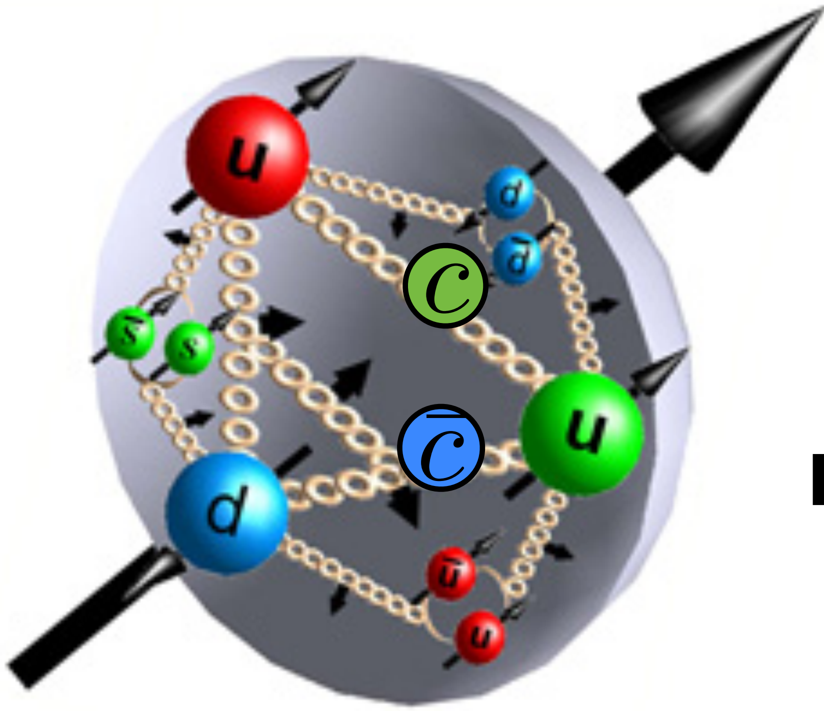
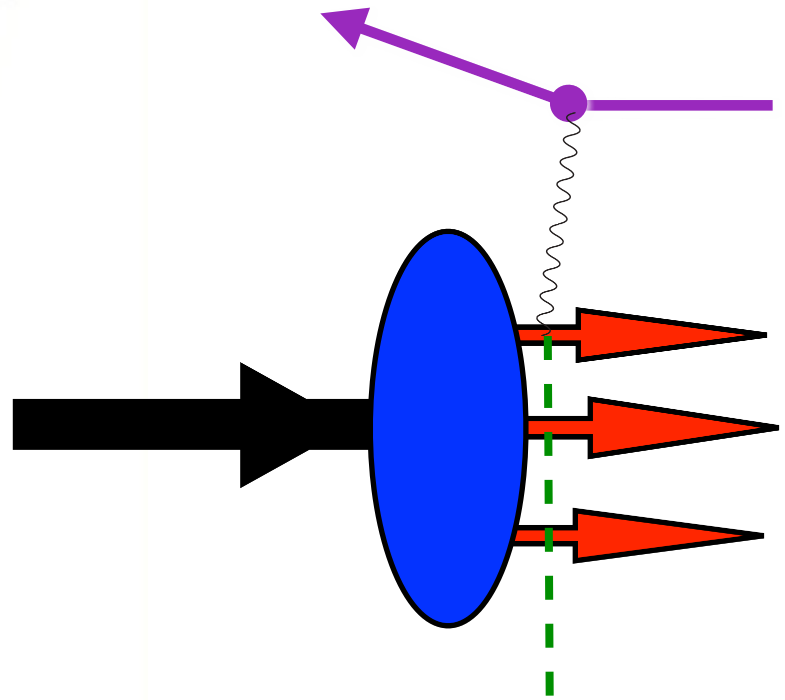
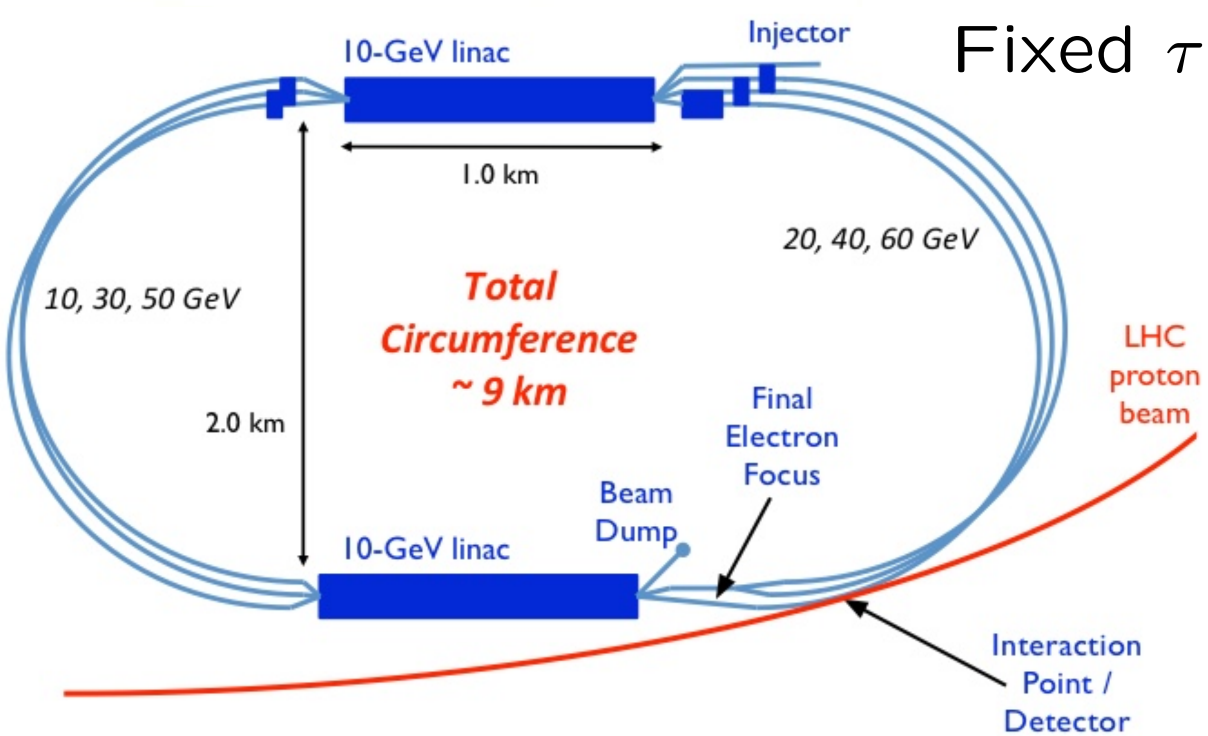
Novel Physics Opportunities at the LHeC





Fixed $\tau = t + z/c$



LHeC PERLE FCC hh ee he

Stan Brodsky

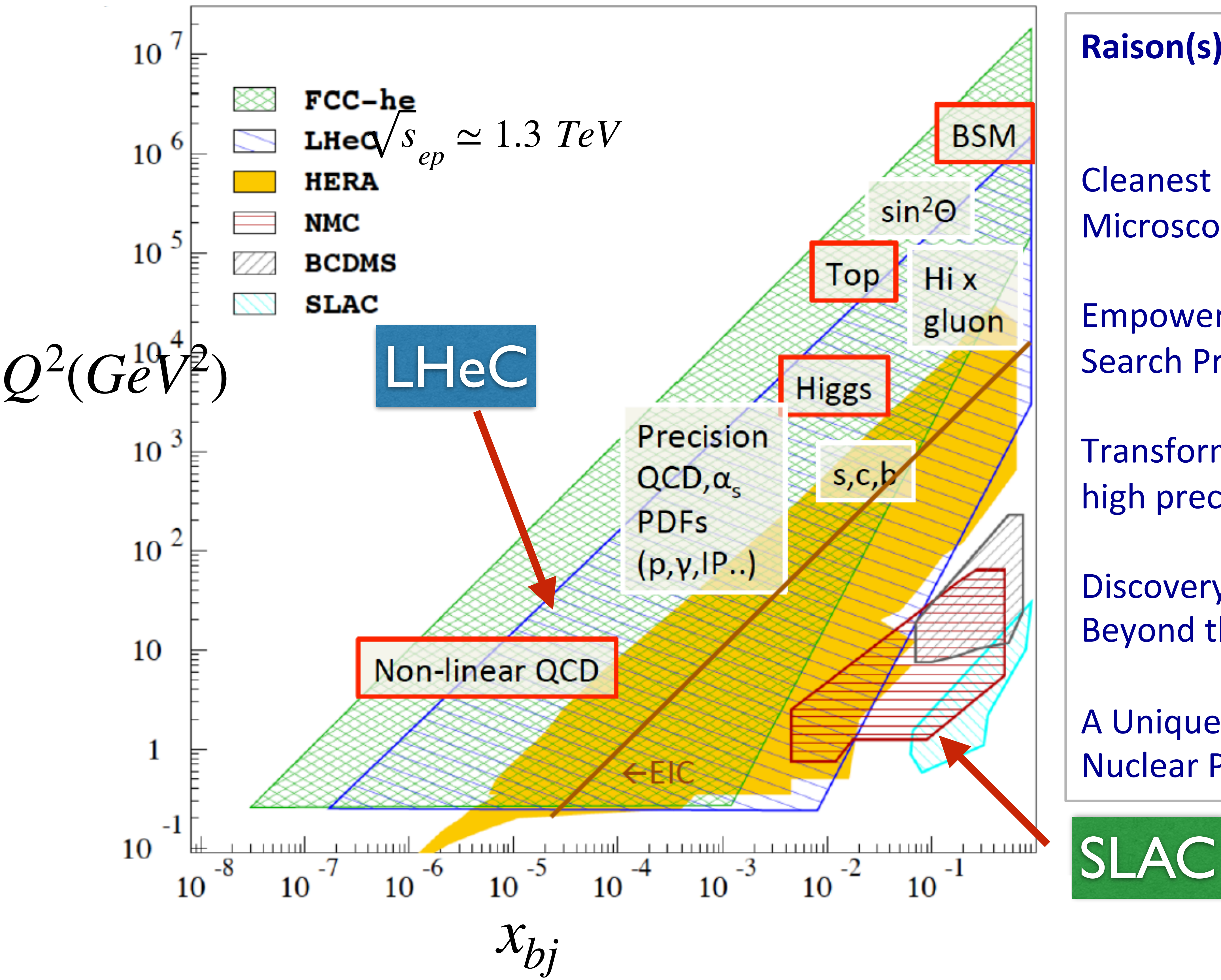
SLAC NATIONAL ACCELERATOR LABORATORY

ELECTRONS FOR THE LHC: Workshop on the LHeC, FCC-eh and PERLE

October 24, 2019

Physics at the DIS Frontier

M. Klein



Raison(s) d'etre of the LHeC

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

Discovery (top, H, heavy ν's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

The LHeC

$$s_{ep} = (p_e + p_p)^2 = 4E_eE_p = 4 \times 60\ GeV \times 7\ TeV \simeq 1.7\ TeV^2$$

Equivalent to an e-p collider in the CM:

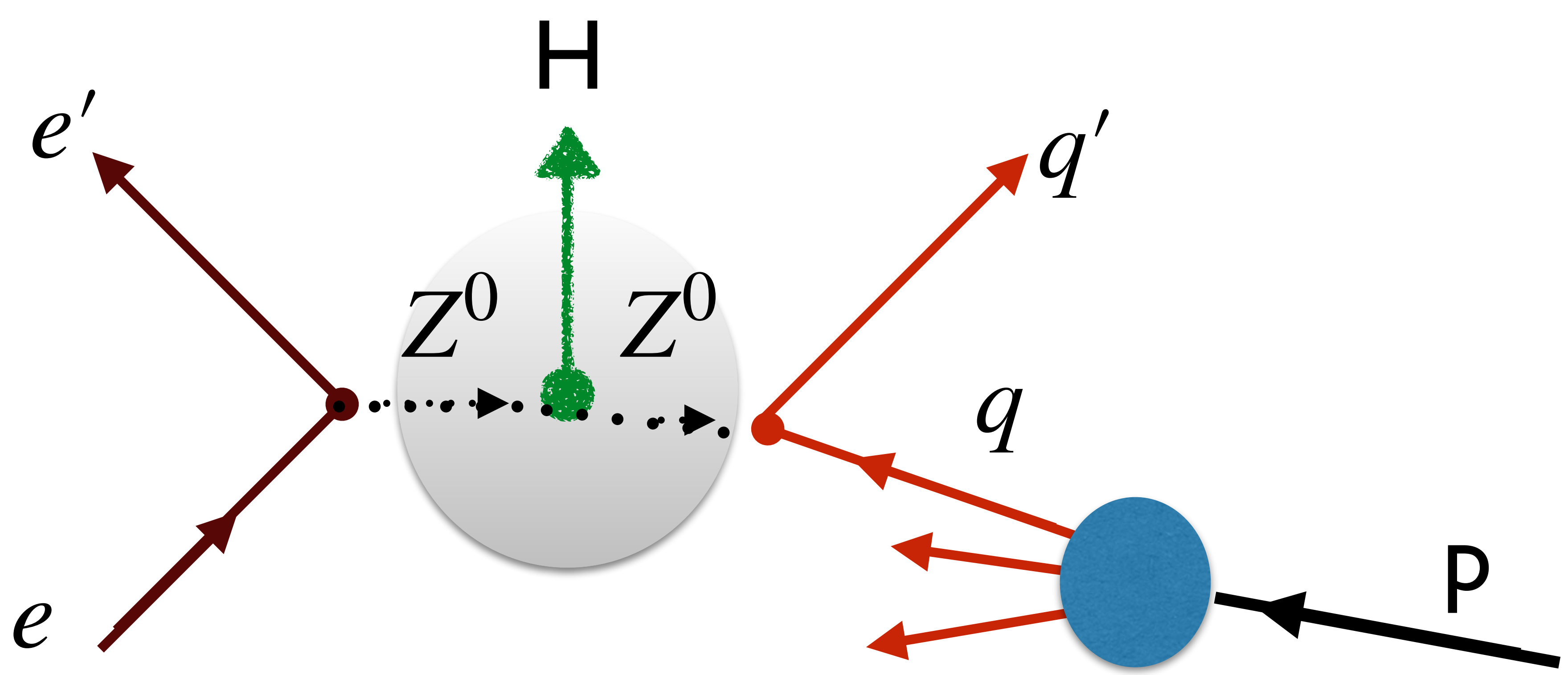
$$E_e^{CM} = E_p^{CM} \simeq 650\ GeV \qquad \sqrt{s}_{ep} \simeq 1.3\ TeV$$

Equivalent to SLAC Fixed-Target DIS with $E_e^{FT} \simeq 900\ TeV$

(A SLAC Linear Accelerator: 60,000 Miles Long!)

$$x_{bj} = \frac{Q^2}{2q \cdot p} > 10^{-7}\ for\ Q^2 > 1GeV^2$$

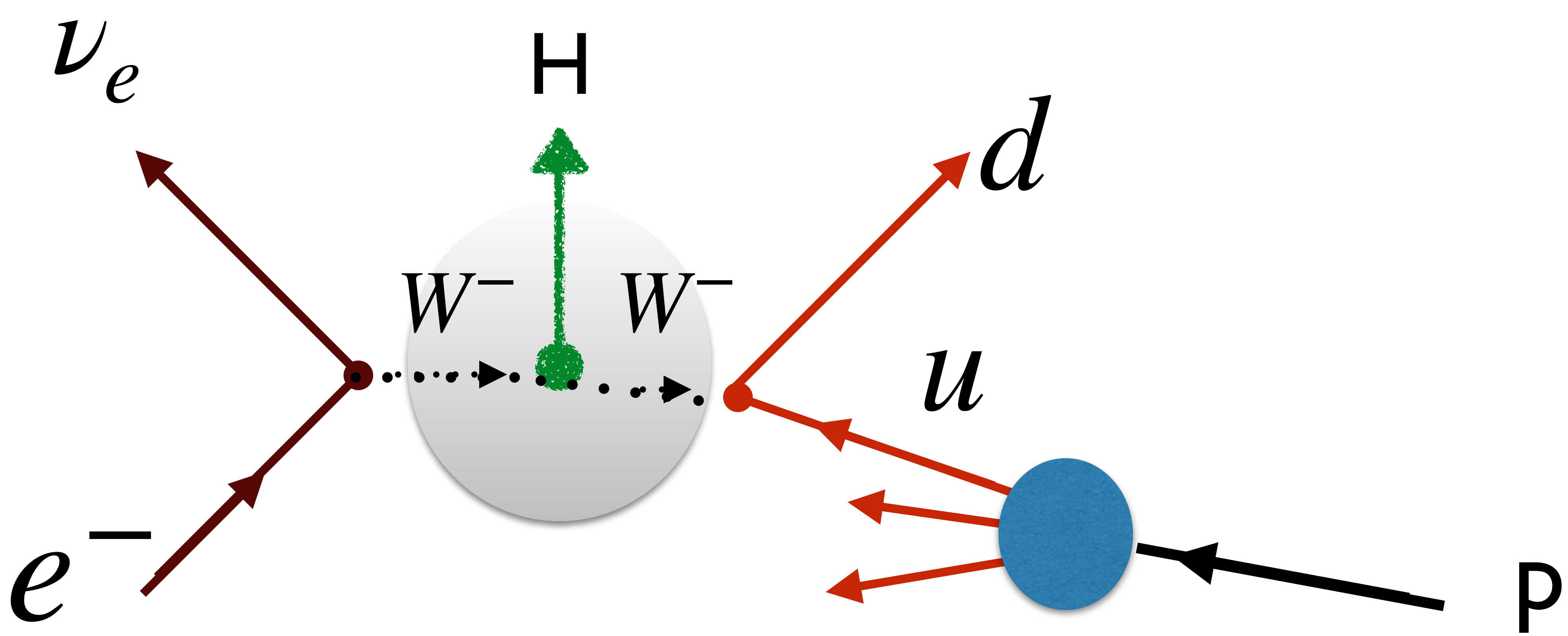
Test Higgs Emission from the Z^0 at the LHeC



$$Z^0 q \to H q'$$

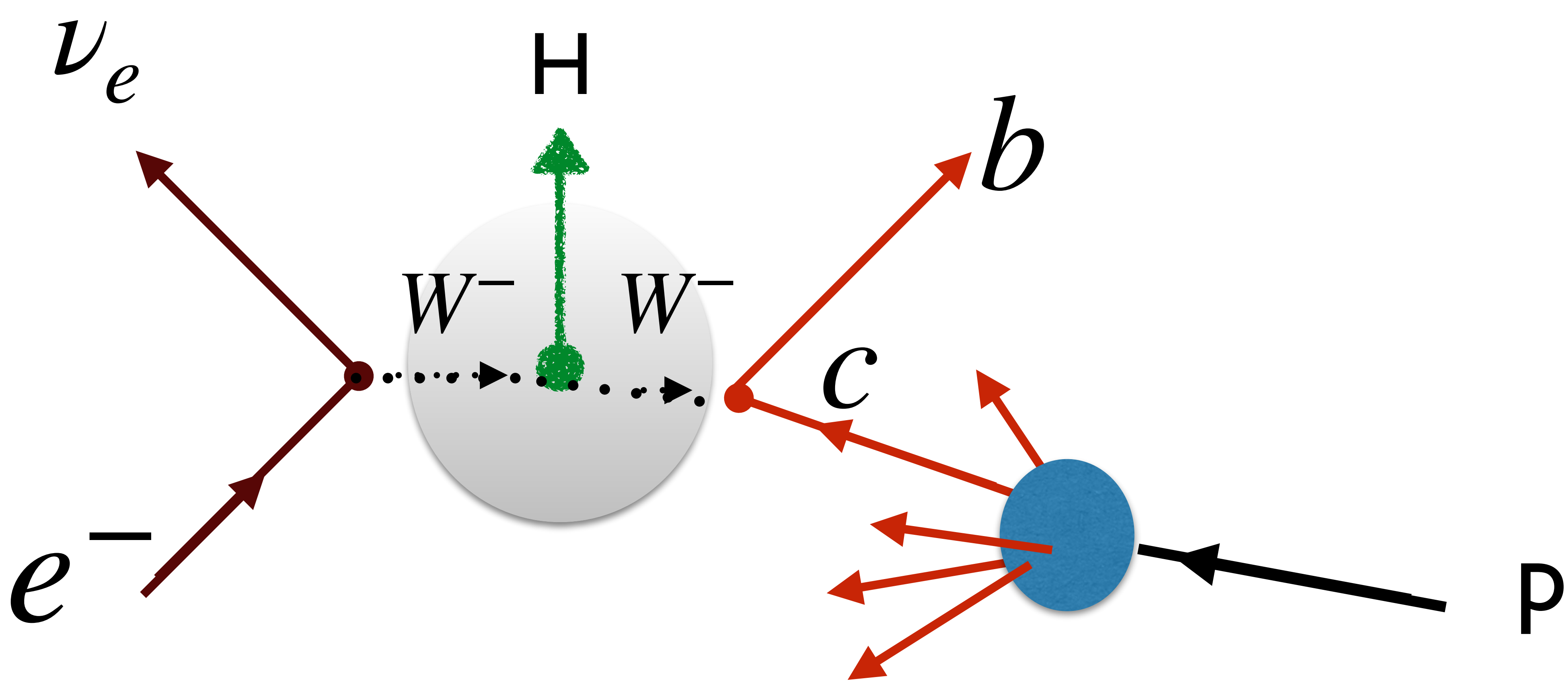
Precise Higgs Factory

Test Higgs Emission from the W- at the LHeC



$$W^- u \rightarrow Hd$$

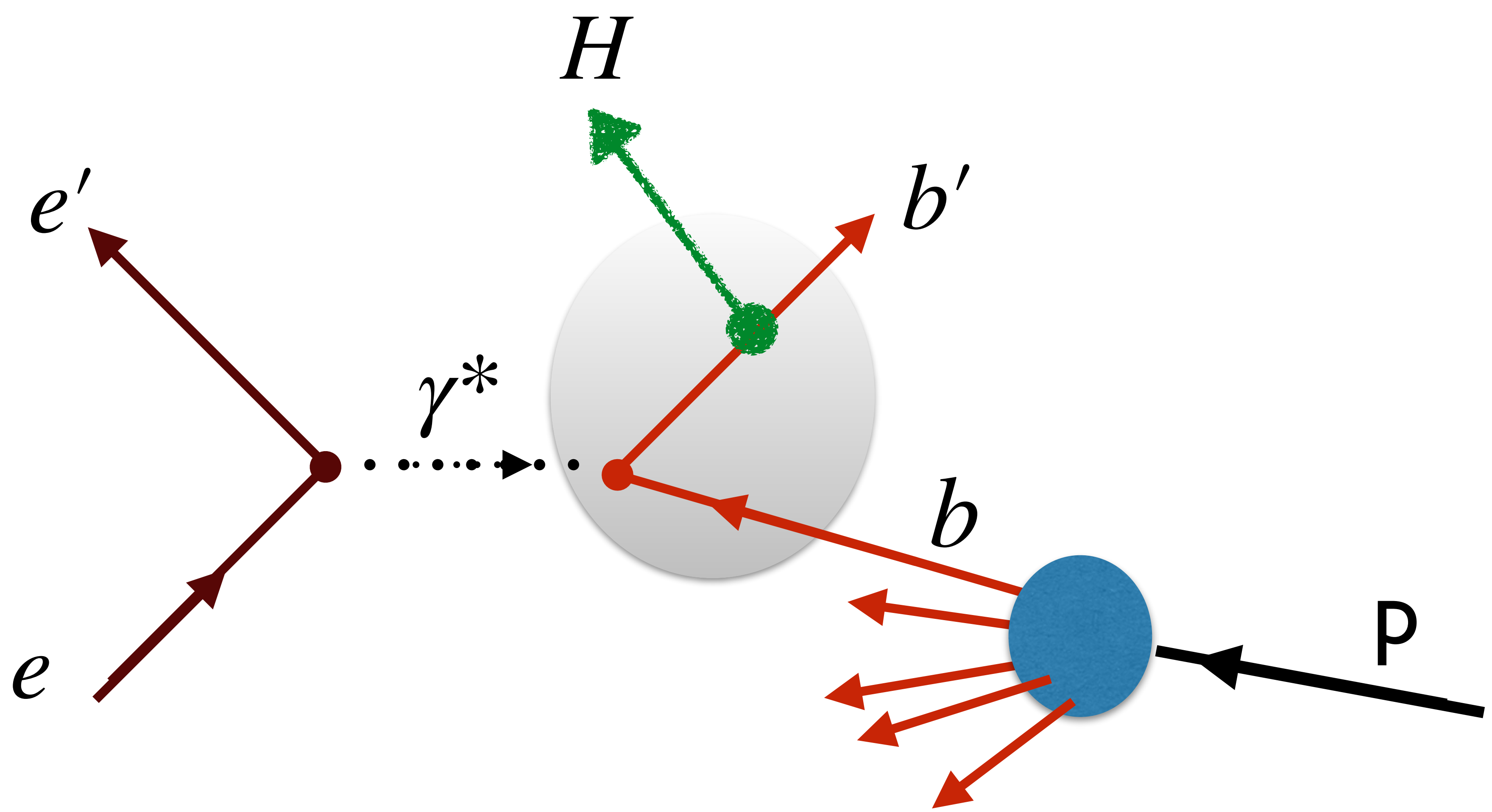
Test Higgs Emission from the W- at the LHeC



$$W^- c \to H\ b$$

Intrinsic Charm at high x

Test Higgs-strahlung from Heavy Quarks at the LHeC

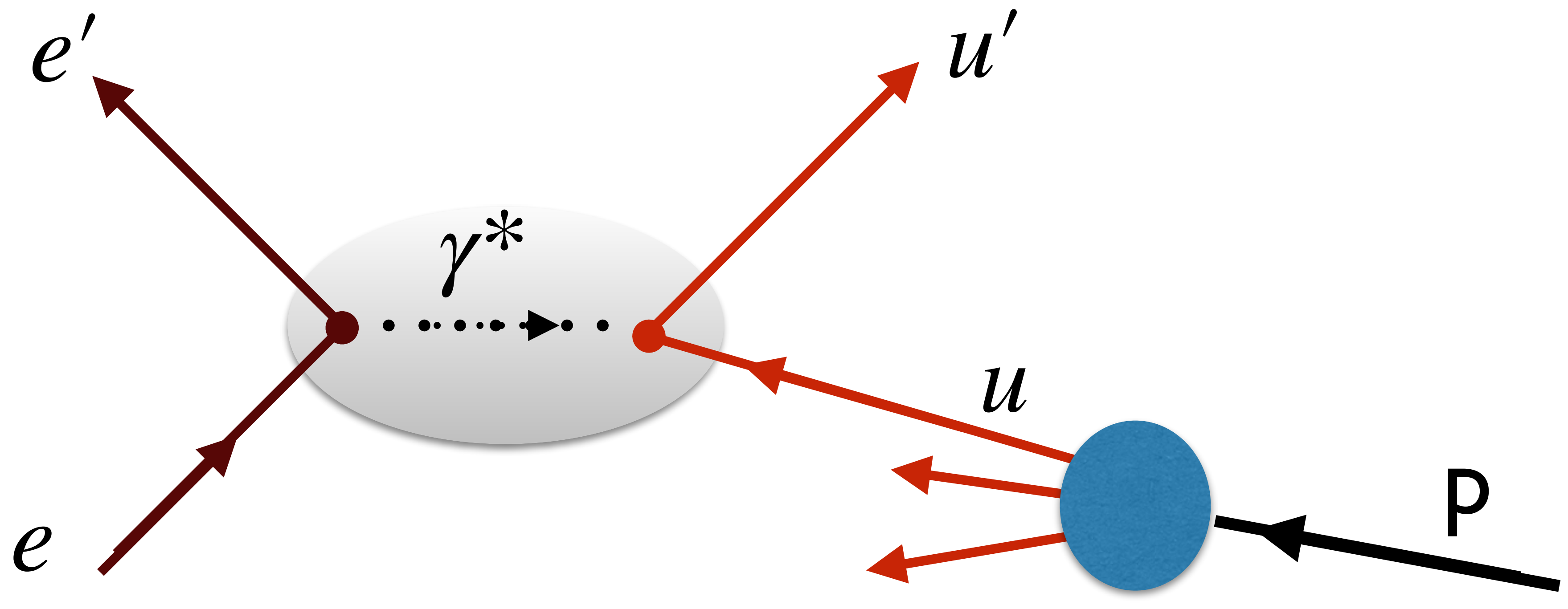


Test $\gamma b \to H b'$

$b(x, Q)$ at high x (Intrinsic Bottom)

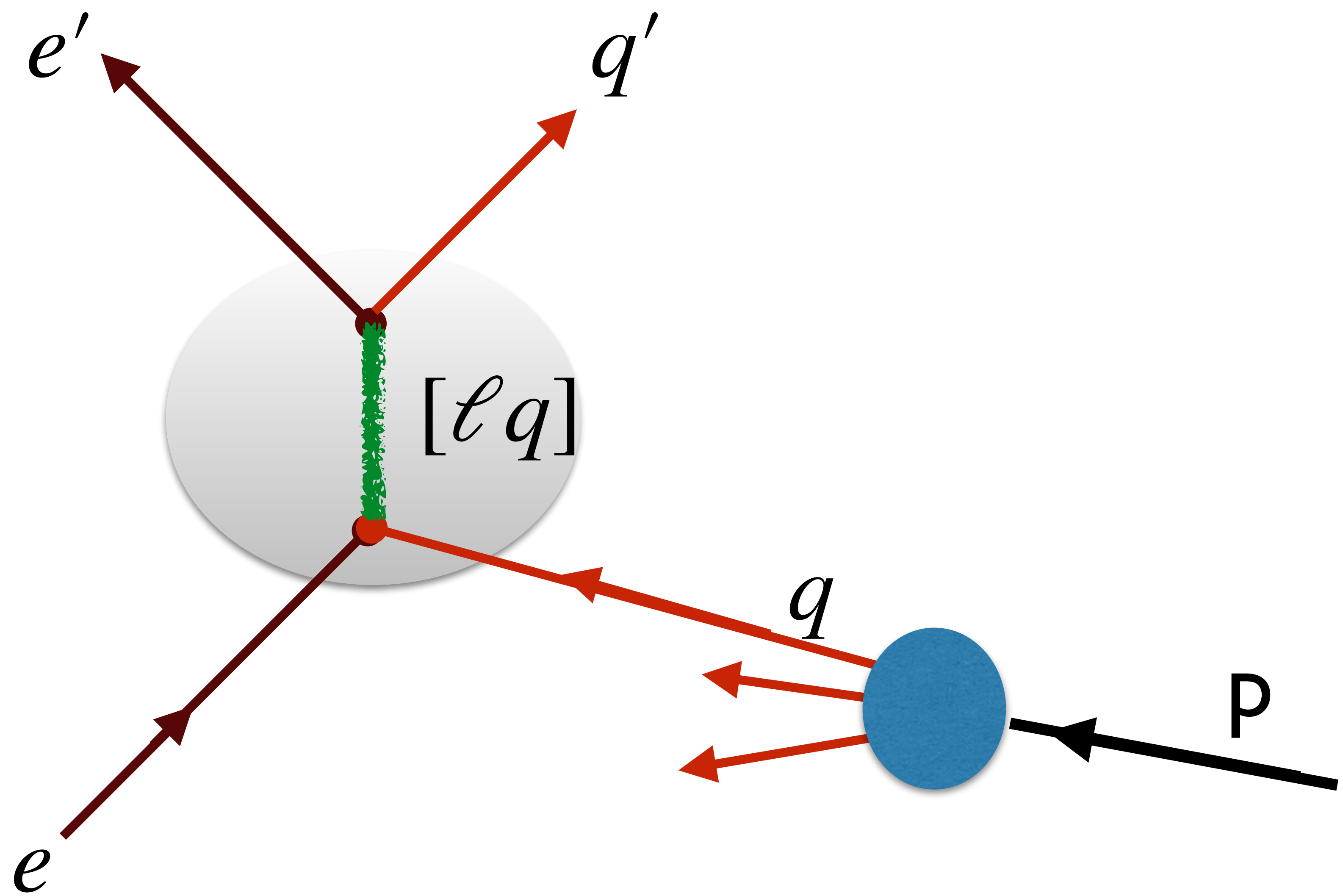
Crucial Physics for the LHeC

Test for Lepton/Quark Compositeness at the LHeC



Measure $\frac{d\sigma}{dt}(eq \to e'q')$ at very high Q^2

Test for Lepto-Quarks at the LHeC

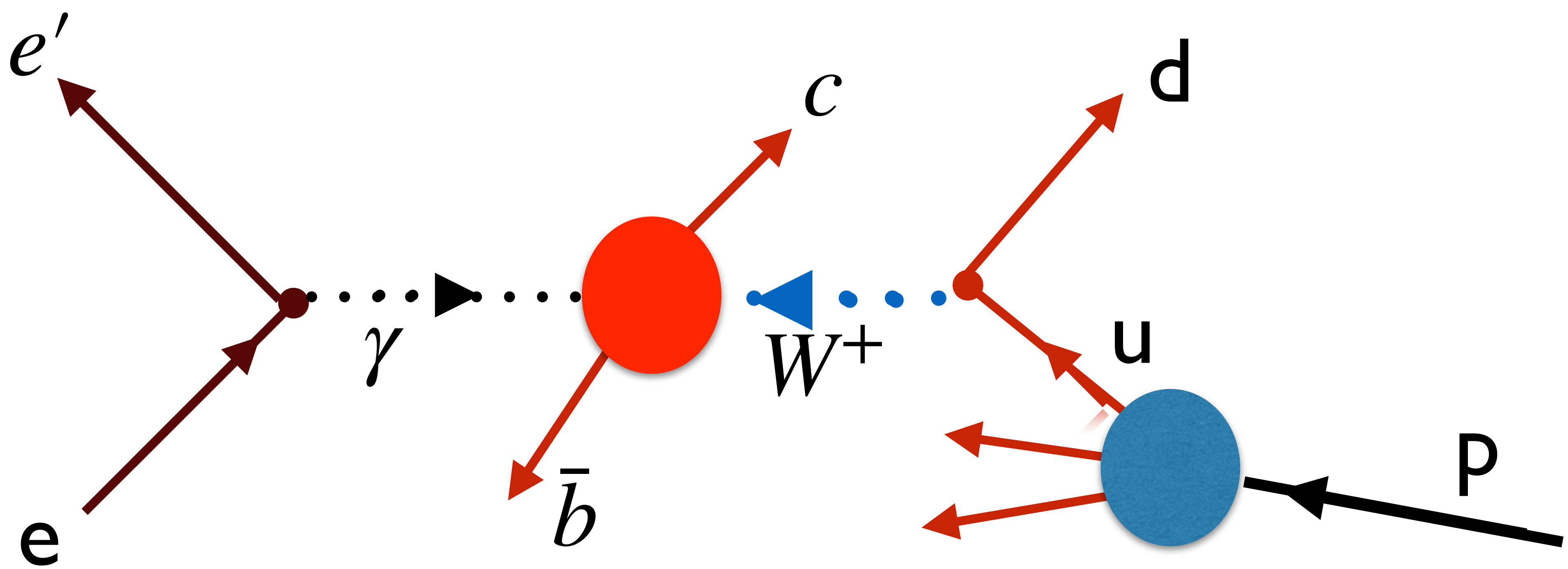


$$\text{s} - \text{channel resonance}: \quad eq \to [\ell q] \to e'q' \text{ at } \hat{s} = m_{\ell q}^2$$

Brown, Samuel, Sahdev, Mikaelian, Kowalski, sjb

Radiation-Amplitude Zero at the LHeC

$$\gamma W^+ \to c\bar{b}$$



$$\frac{d\sigma}{dt}(W^+\gamma \to c\bar{b}) = 0$$

$$\text{at} \quad \cos\theta = \frac{e_{\bar{b}}}{e_{W^+}} = \frac{1}{3}$$

$$\text{Tests } g_W = g_q = 2$$

Fundamental Standard Model Physics Tests at the LHeC

Elimination of Scale Ambiguities!

Stan Brodsky
SLAC
NATIONAL ACCELERATOR LABORATORY

An Important Theoretical Physics Advance for the LHeC

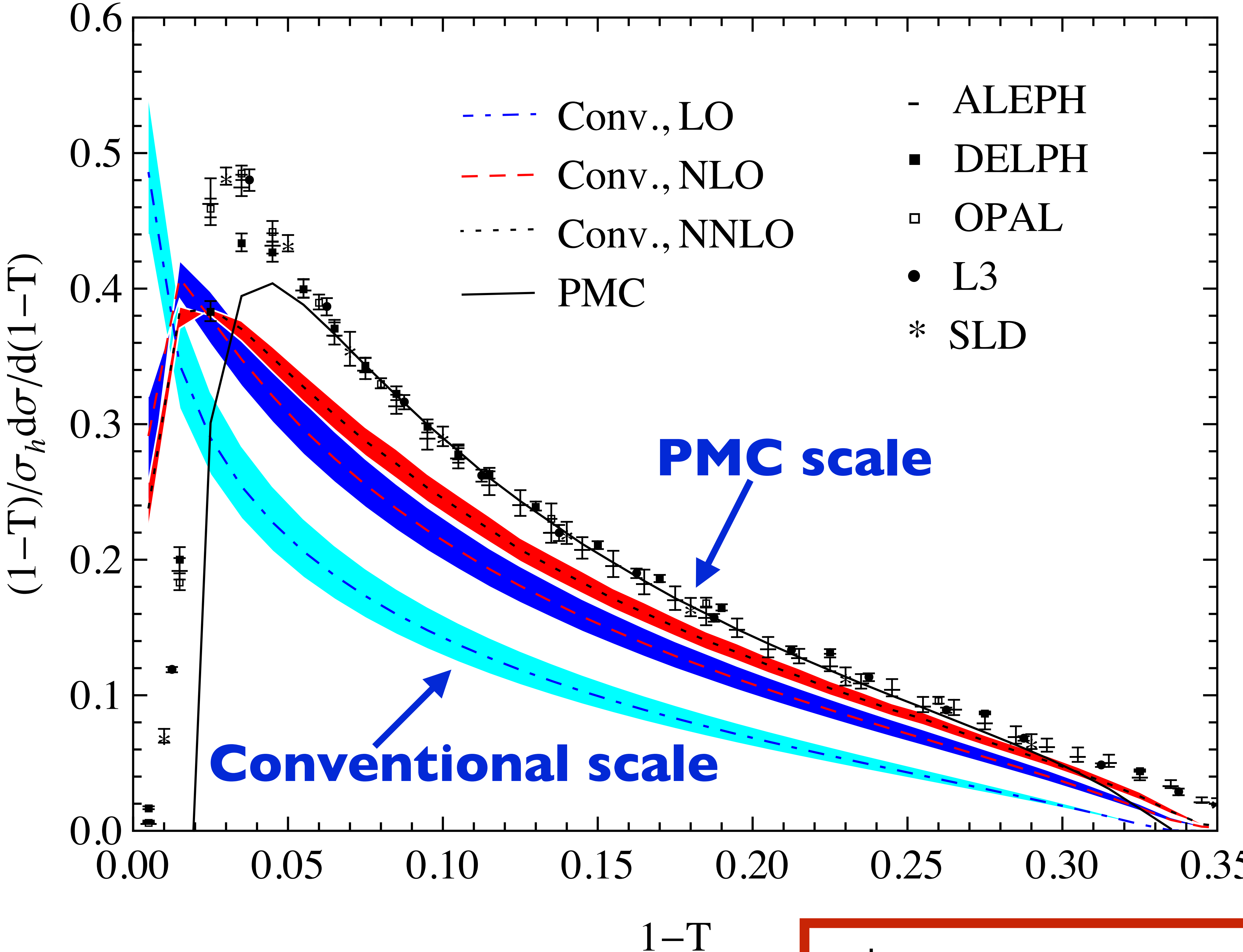
BLM/PMC ***Principle of Maximum Conformality***

$$\alpha_s(q^2) \text{ sums all } \beta \text{ terms}$$

- Eliminates renormalization scale ambiguities for pQCD and SM predictions
- Predictions are independent of scheme and initial scale choice
- Convergent conformal series: No "renormalons" $C_n \sim \alpha_s^n \beta_o^n n!$
- Consistent with Gell-Mann Low for QED $\alpha(t) = \dfrac{\alpha(t_o)}{1 - \Pi(t, t_0)}$
- Eliminates many outstanding conflicts of pQCD with experiment
- Maximizes sensitivity of LHeC measurements to new physics

T. Gehrmann, N. H˙afliger, P. F. Monni

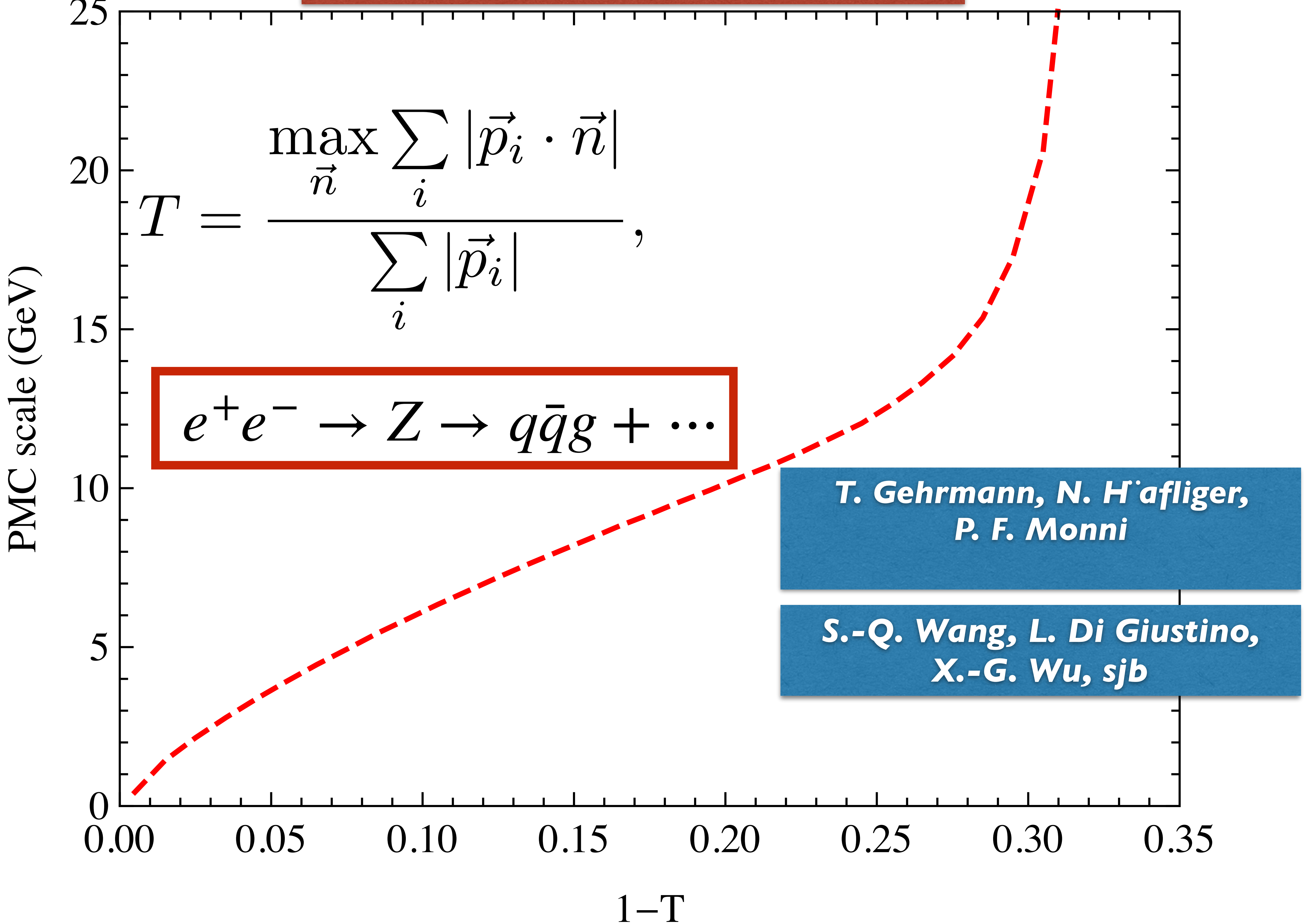
S.-Q. Wang, L. Di Giustino, X.-G. Wu, sjb



$$e^+e^- \to Z \to q\bar{q}g + \cdots$$

Renormalization scale depends on the thrust

Not constant ! Not M_Z



T. Gehrmann, N. H˙afliger, P. F. Monni

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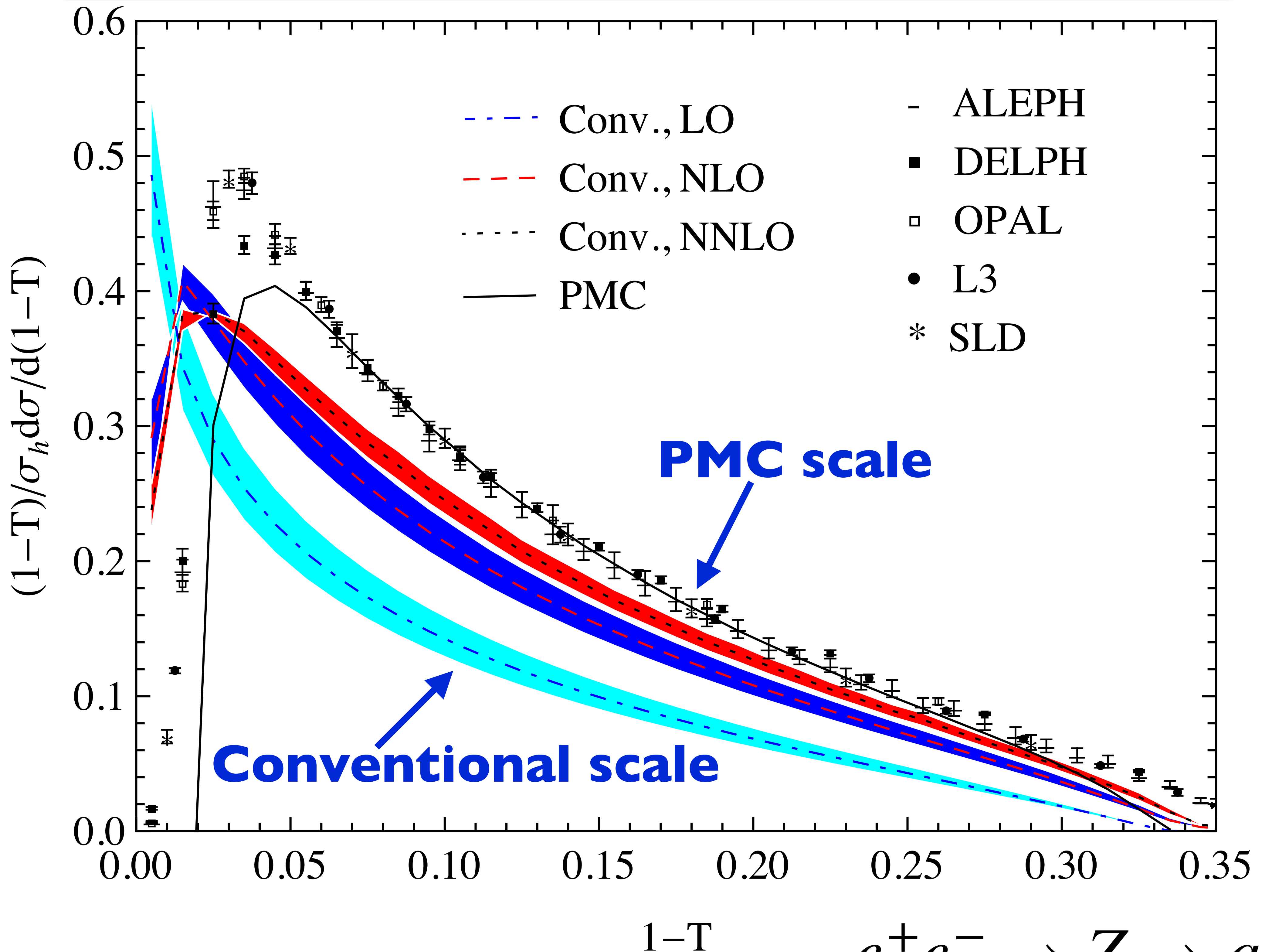
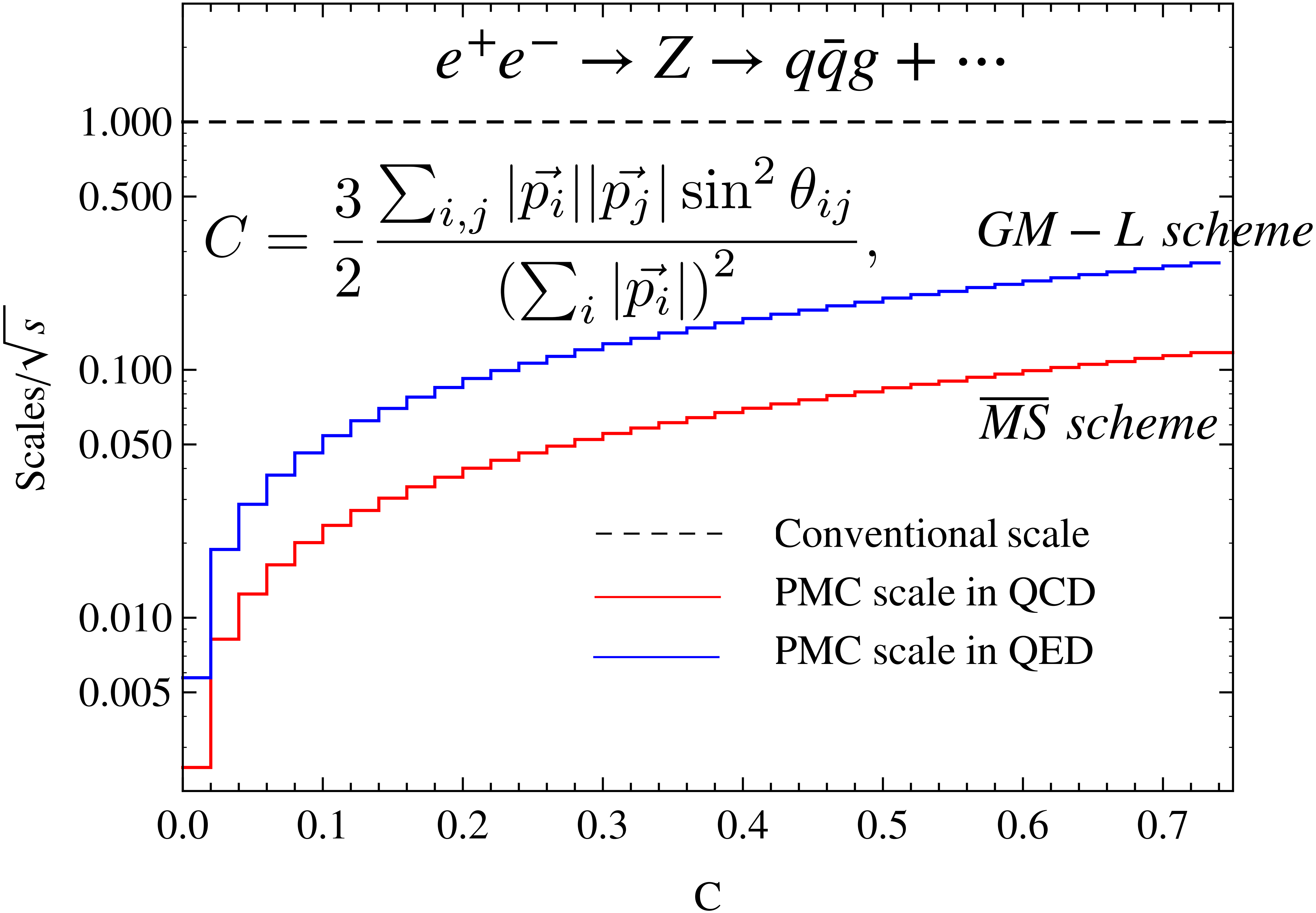


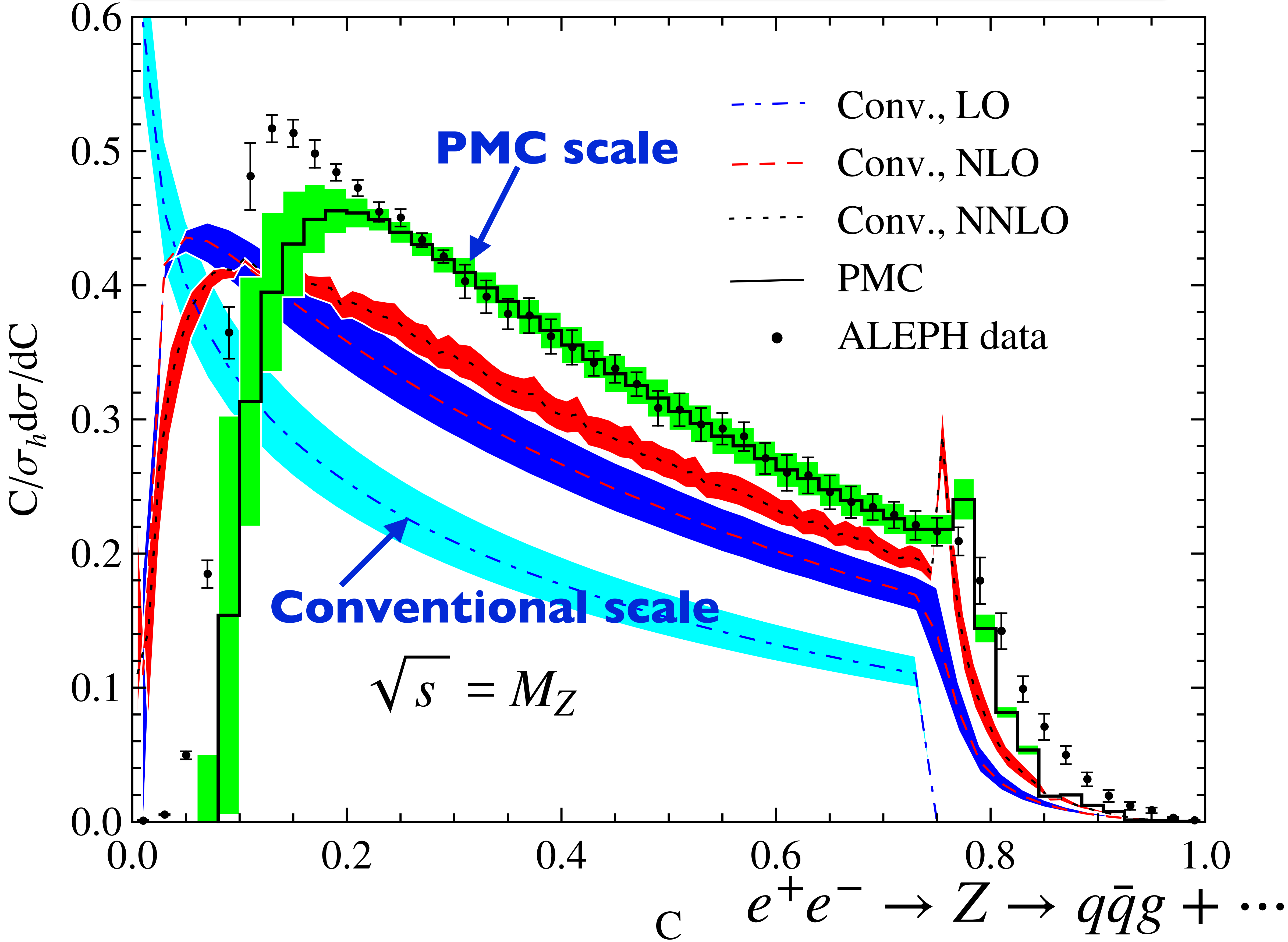
$$e^+e^- \to Z \to q\bar{q}g + \cdots$$

Renormalization scale depends on the C-parameter



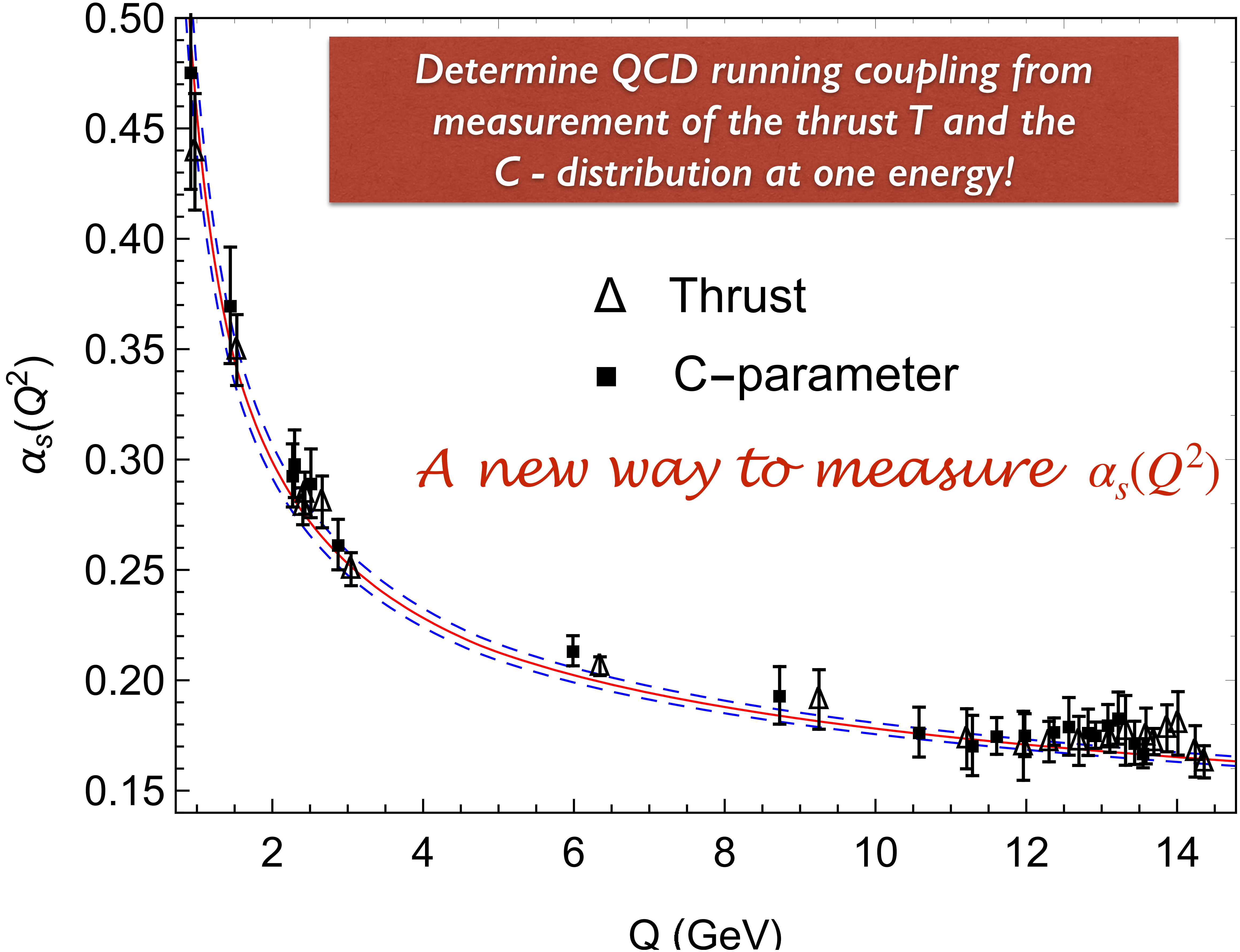
S.-Q. Wang, L. Di Giustino, X.-G. Wu, sjb

S.-Q. Wang, L. Di Giustino, X.-G. Wu, sjb



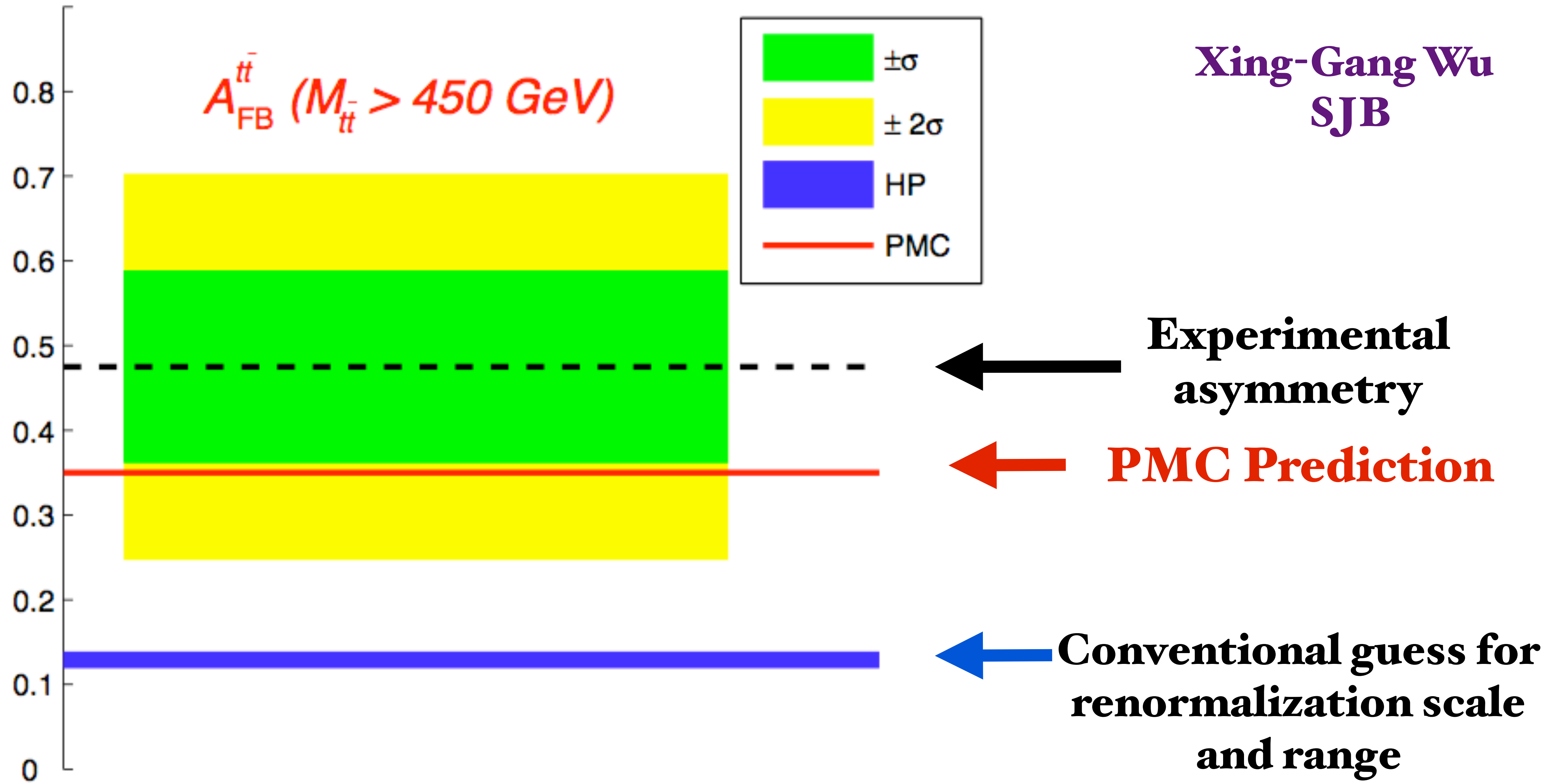
Principle of Maximum Conformality (PMC)

$e^+e^- \to Z^0 \to q\bar{q}g + \cdots \quad \alpha_s(Q^2)$ *in* $\overline{MS}$ *scheme*



S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB

The Renormalization Scale Ambiguity for Top-Pair Production Eliminated Using the 'Principle of Maximum Conformality' (PMC)



Xing-Gang Wu
SJB

Top quark forward-backward asymmetry predicted by pQCD NNLO within 1 σ of CDF/D0 measurements using PMC/BLM scale setting

BLM-PMC

- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$ at all scales
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Relate renormalization schemes without ambiguity
- Maximize sensitivity to new physics

Crucial for LHeC

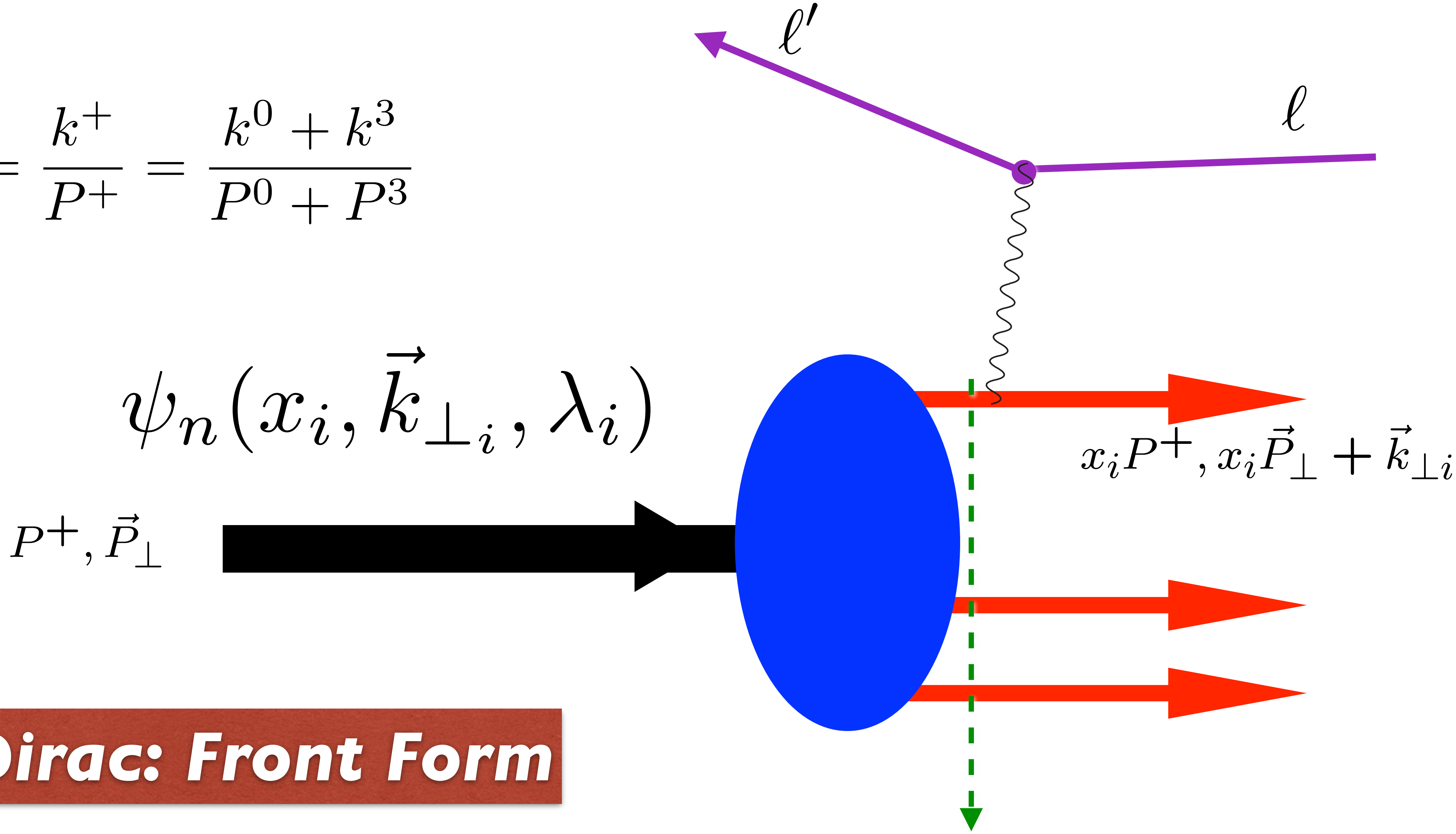
The QCD pomeron with optimal renormalization

Stanley J. Brodsky (SLAC), Victor S. Fadin (Novosibirsk, IYF), Victor T. Kim (St. Petersburg, INP & Iowa State U., IITAP), Lev N. Lipatov (St. Petersburg, INP), Grigorii B. Pivovarov (Moscow, INR & Iowa State U., IITAP). Dec 1998. 11 pp.
Published in **JETP Lett. 70 (1999) 155-160**
SLAC-PUB-8037, IITAP-98-010
DOI: 10.1134/1.568145
e-Print: **hep-ph/9901229** | **PDF**

BFKLP

Based on BLM/PMC

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



Dirac: Front Form

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

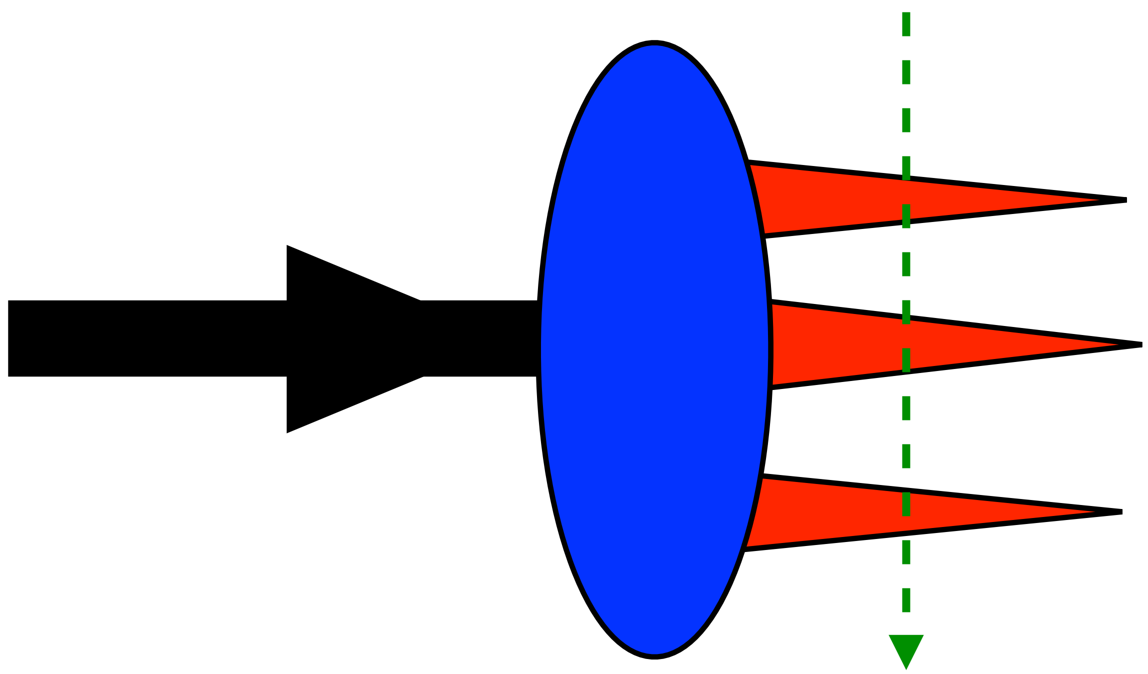
Like a flash photograph

$$x_{bj} = x = \frac{k^+}{P^+}$$

Invariant under boosts! Independent of P^μ

The LHeC:
Key Measurements of Hadron Dynamics and Structure

Fixed $\tau = t + z/c$



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

Light Front Wavefunctions: Boost Invariant, Causal

Novel High-Energy Electron-Proton Collider Physics at the LHeC

Stan Brodsky
SLAC
NATIONAL ACCELERATOR LABORATORY

Advantages of the Dirac's Front Form for Hadron Physics
Poincare' Invariant

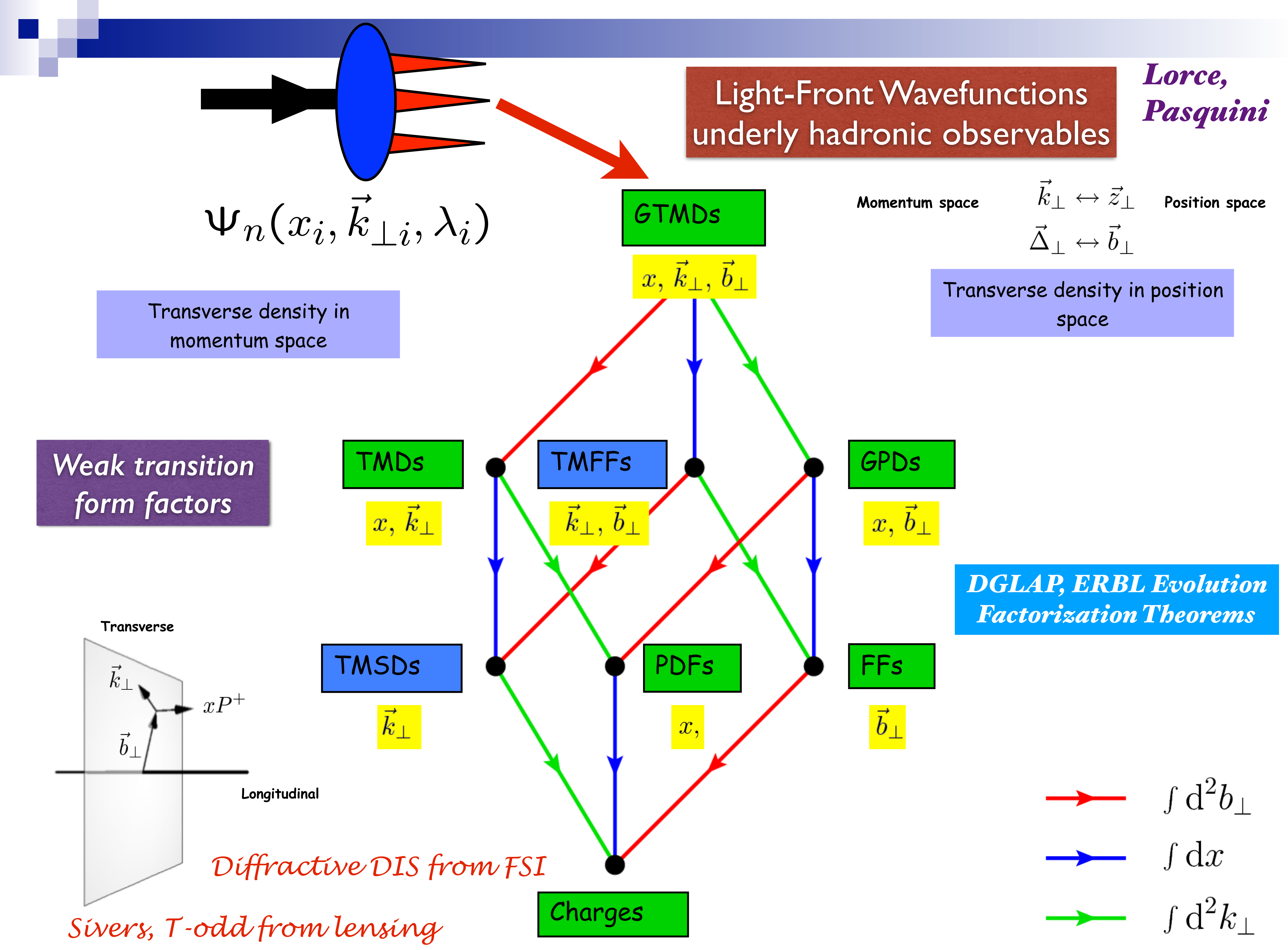
Physics Independent of Observer's Motion

- LHeC Measurements are made at fixed τ
- Causality is automatic
- Structure Functions are squares of LFWFs
- Form Factors are overlap of LFWFs
- LFWFs are frame-independent: no boosts, no pancakes!

Penrose, Terrell, Weisskopf

- Same structure function measured at an e p collider and in the proton rest frame
- No dependence of hadron structure on observer's frame
- LF Holography: Dual to AdS space
- LF Vacuum trivial -- no vacuum condensates!
- Profound implications for Cosmological Constant

Roberts, Shrock, Tandy, sjb



Light-Front Wavefunctions underly hadronic observables
Lorce, Pasquini
$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$
GTMDs
$x, \vec{k}_\perp, \vec{b}_\perp$
Momentum space
$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$
Position space
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$
Transverse density in momentum space
Transverse density in position space
Weak transition form factors
TMDs
$x, \vec{k}_\perp$
TMFFs
$\vec{k}_\perp, \vec{b}_\perp$
GPDs
$x, \vec{b}_\perp$
DGLAP, ERBL Evolution Factorization Theorems
Transverse
TMSDs
$\vec{k}_\perp$
PDFs
$x,$
FFs
$\vec{b}_\perp$
$\vec{k}_\perp$
xP^+
$\vec{b}_\perp$
Longitudinal
$\int d^2 b_\perp$
$\int dx$
$\int d^2 k_\perp$
Diffractive DIS from FSI
Charges
Sivers, T-odd from lensing

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

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

The Light Front Fock State Wavefunctions

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

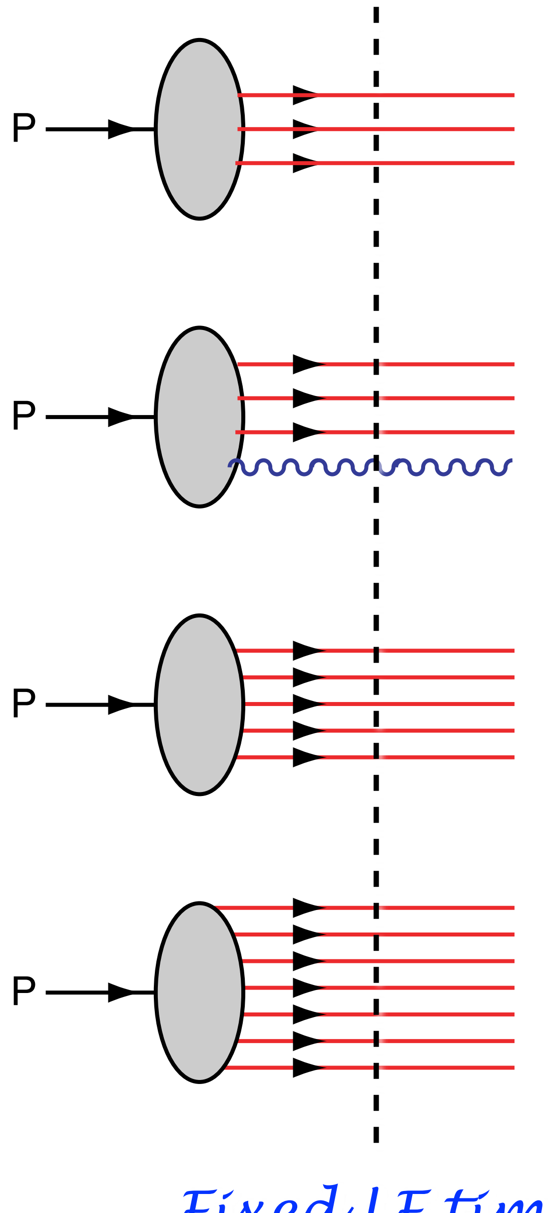
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



$$\tau = t + z/c$$

Intrinsic heavy quarks

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

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

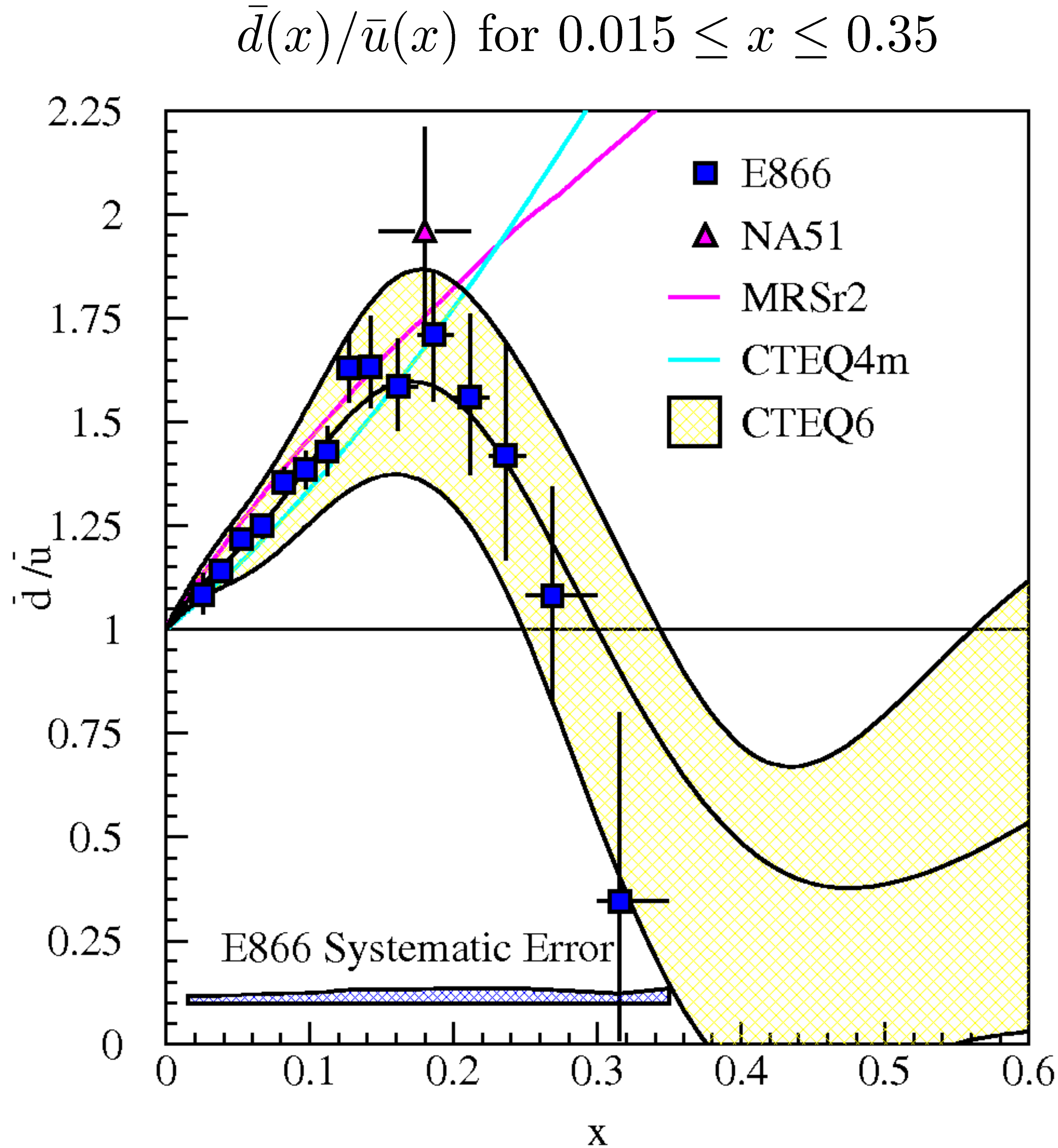
Deuteron: Hidden Color

- E866/NuSea (Drell-Yan)

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

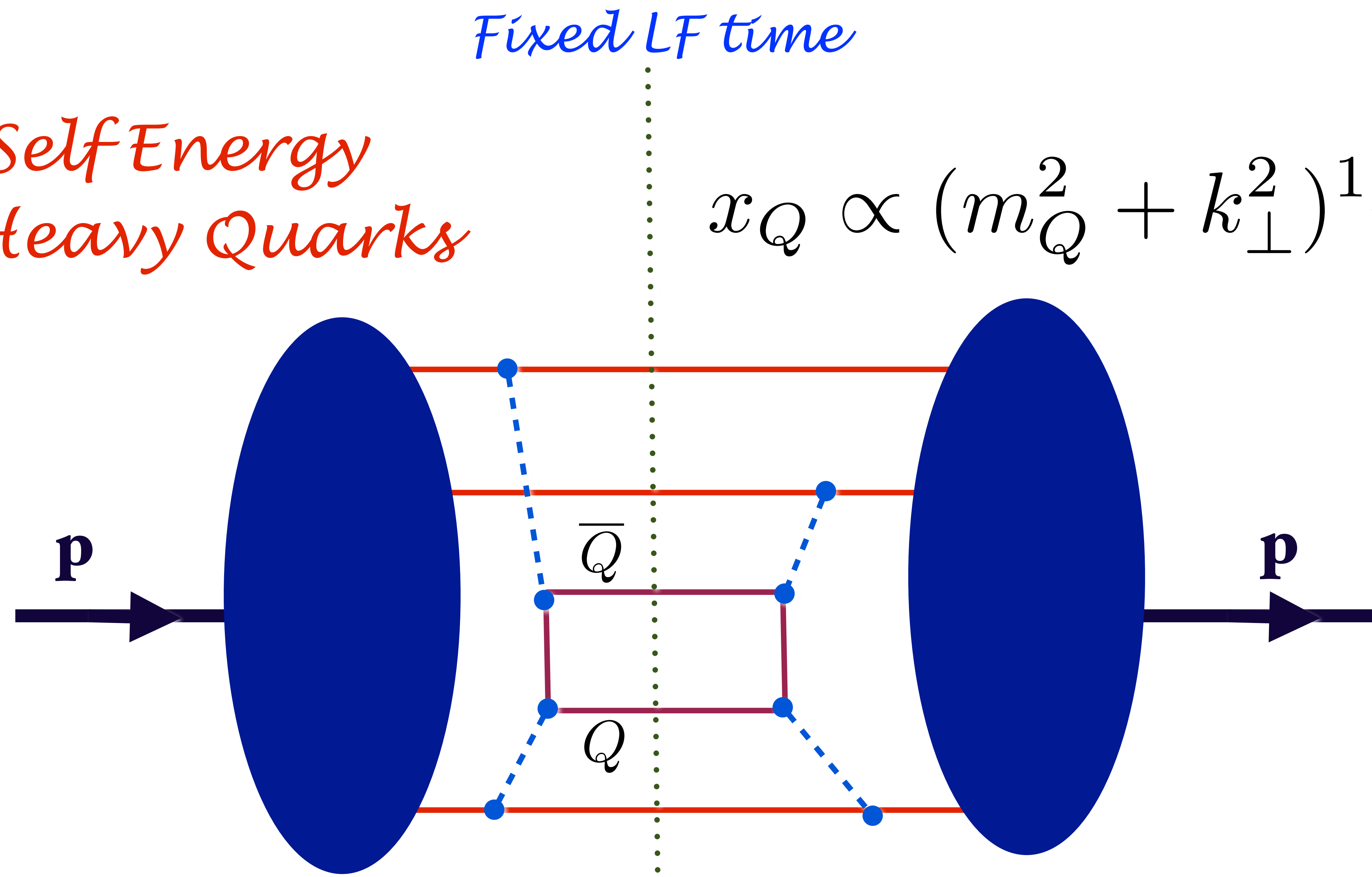
Interactions of quarks at same rapidity in 5-quark Fock state

Intrinsic sea quarks



Proton Self Energy
Intrinsic Heavy Quarks

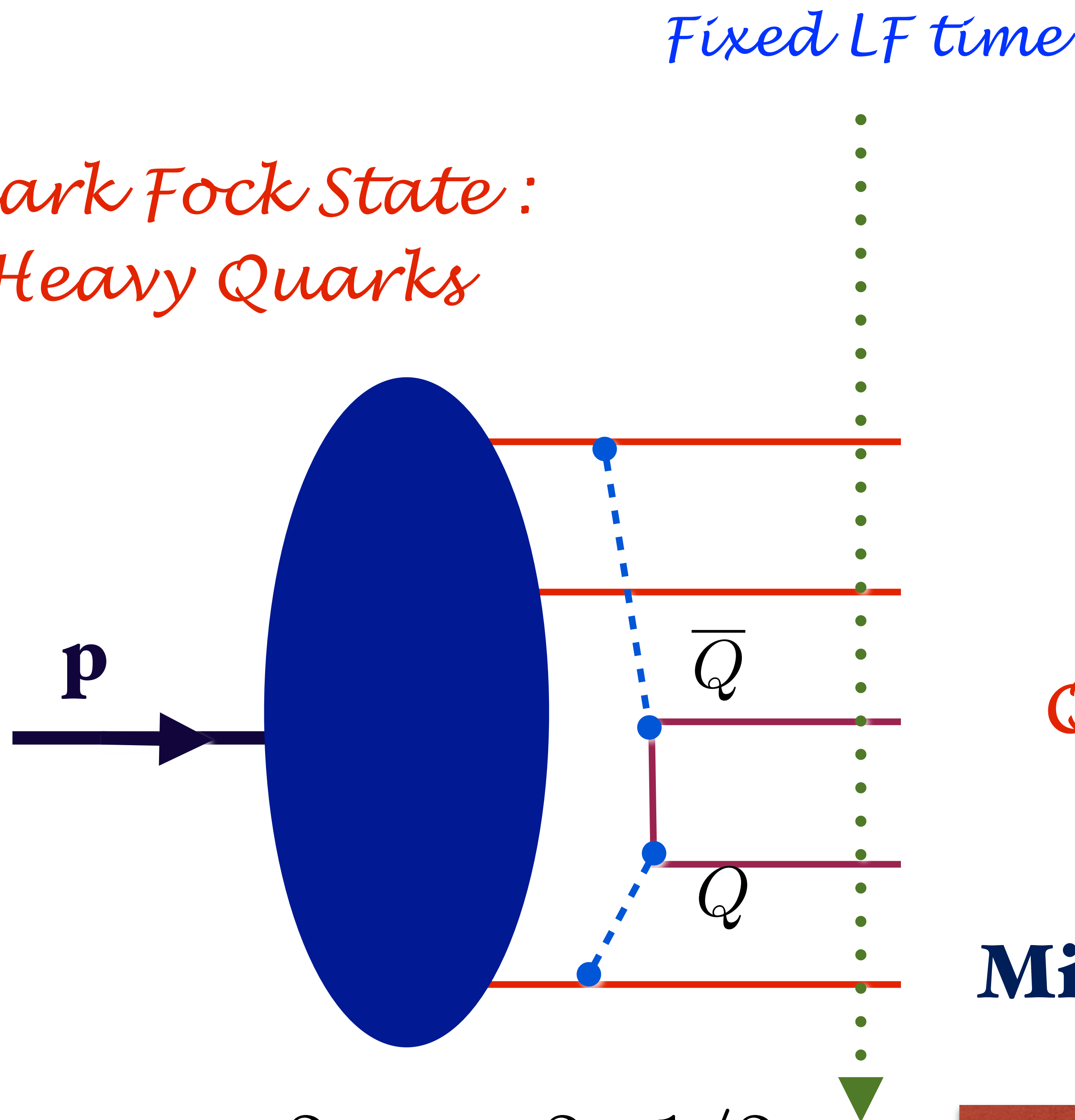
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



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

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

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness

Maximum at Equal rapidity!

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

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

Rigorous OPE Analysis

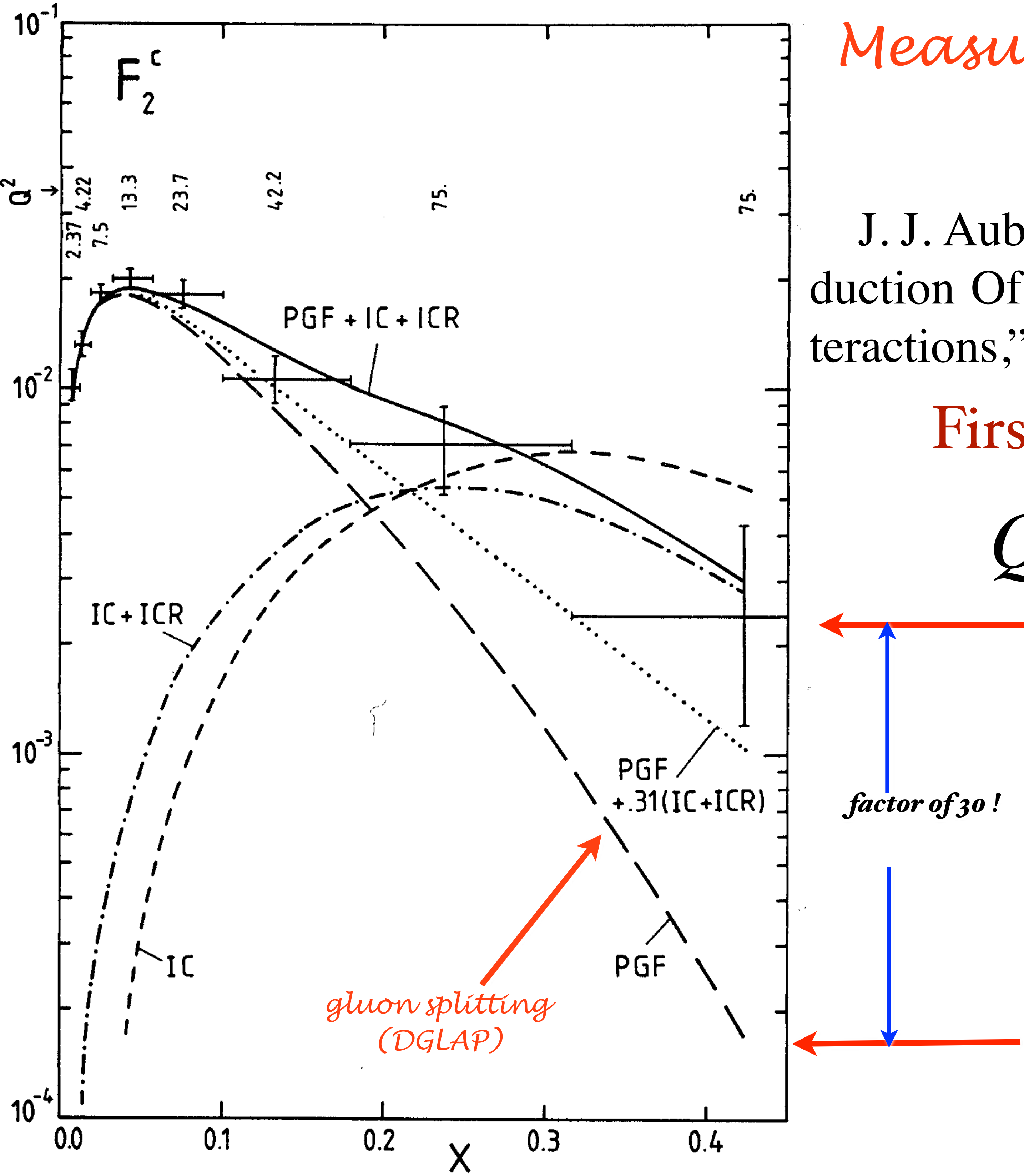
Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

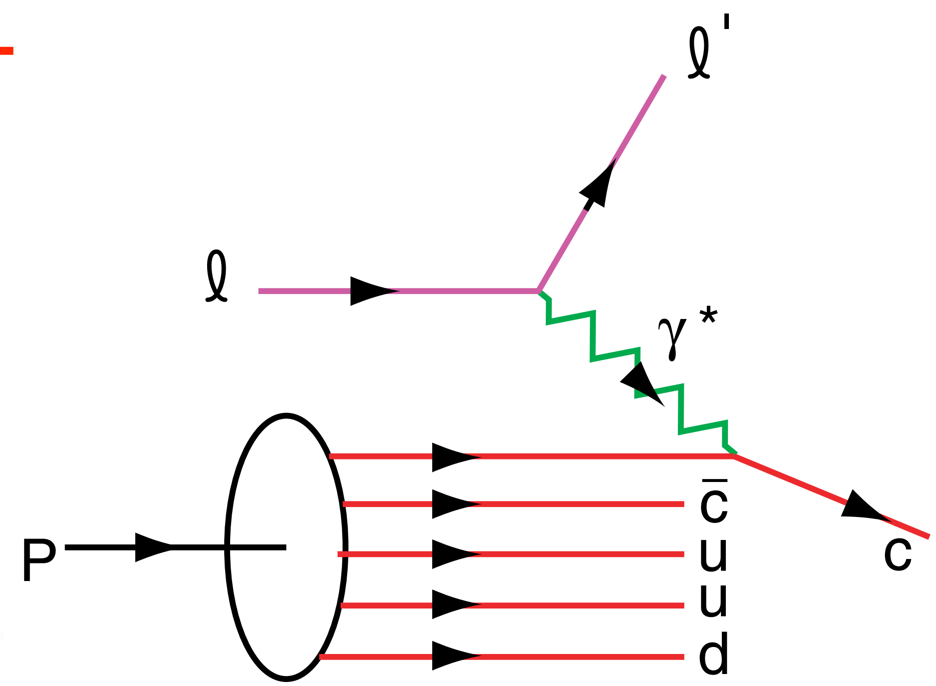
Measurement of Charm Structure Function!

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

$$Q^2 = 75\ GeV^2, x = 0.42$$





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

Two Components (separate evolution):

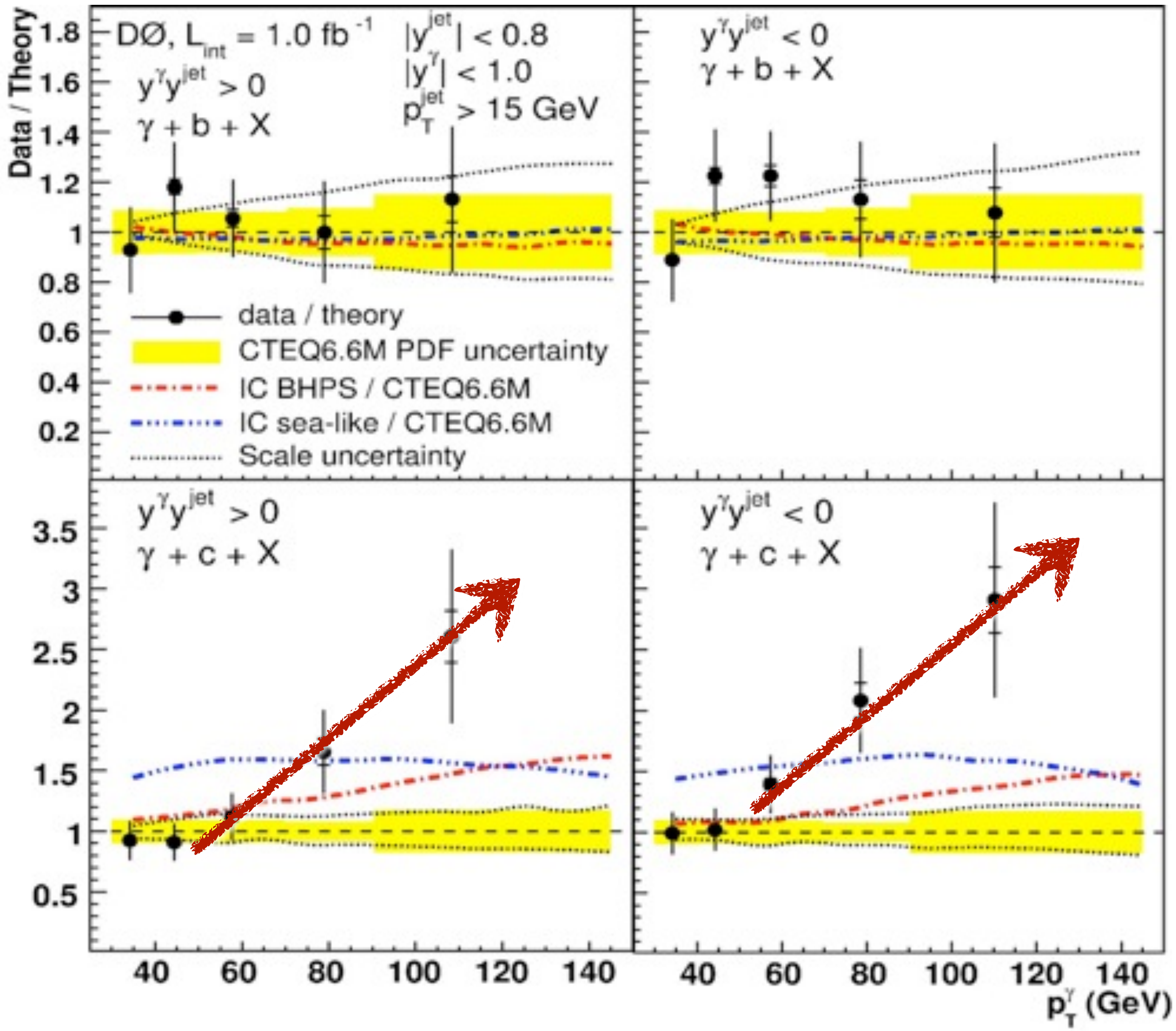
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

DO

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

$$p\bar{p} \to \gamma + Q + X$$



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

Ratio is insensitive to gluon PDF, scales

$$gc \to \gamma c$$

Signal for significant intrinsic charm

Mesropian, Bandurin

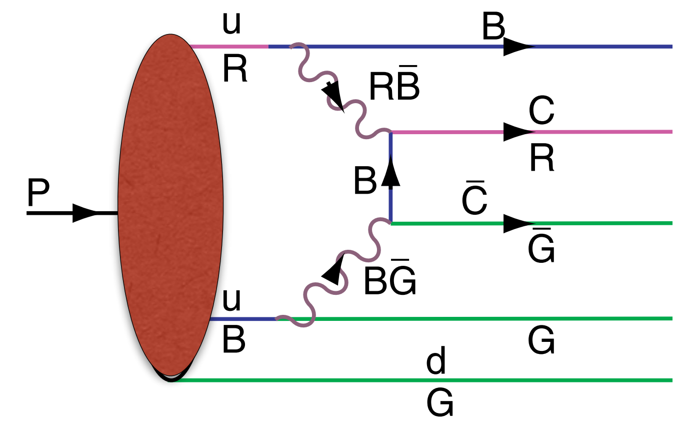
LHC: $pp \to Z^0 c X$

Boettcher, Ilten, Williams

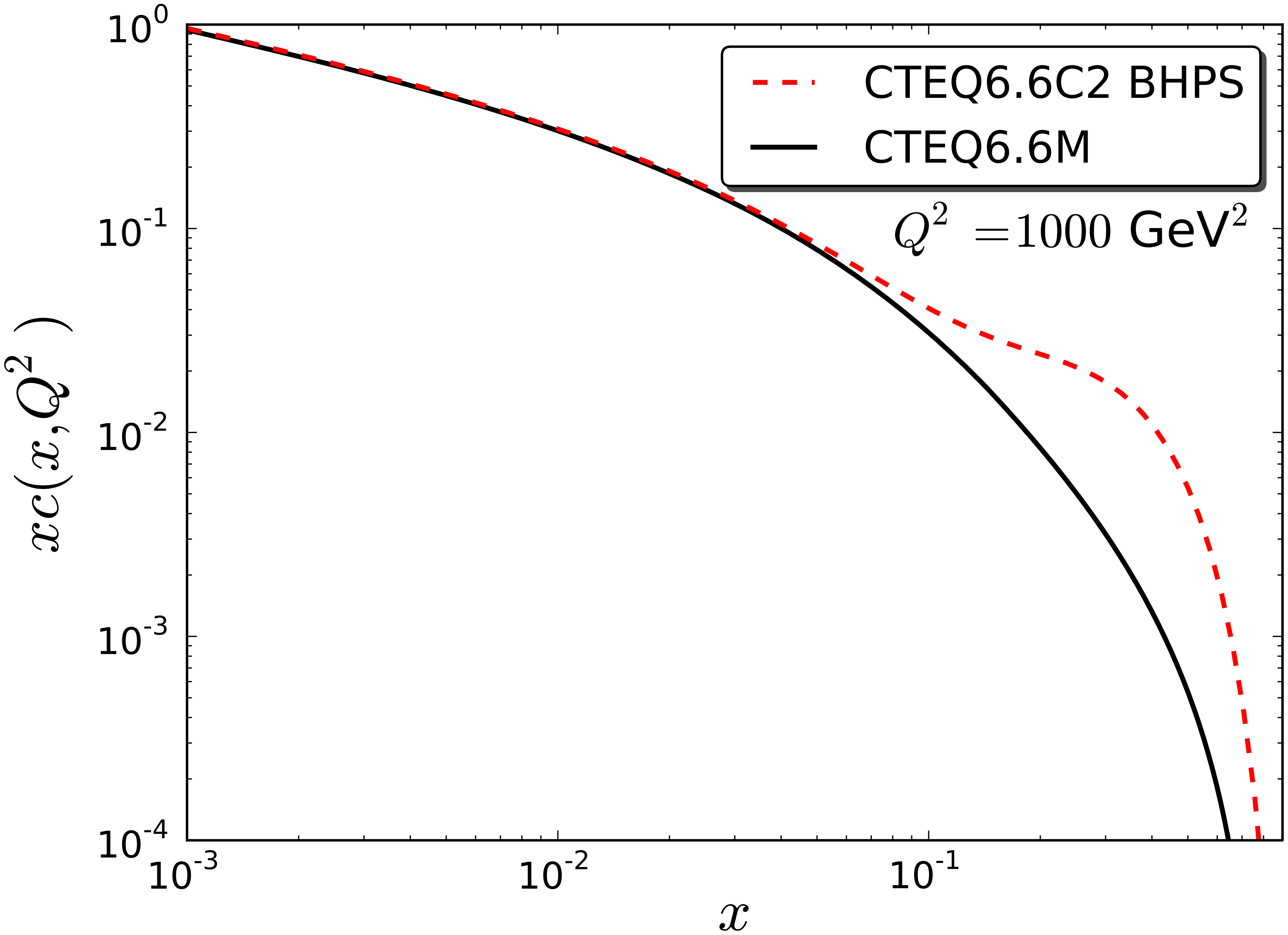
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock



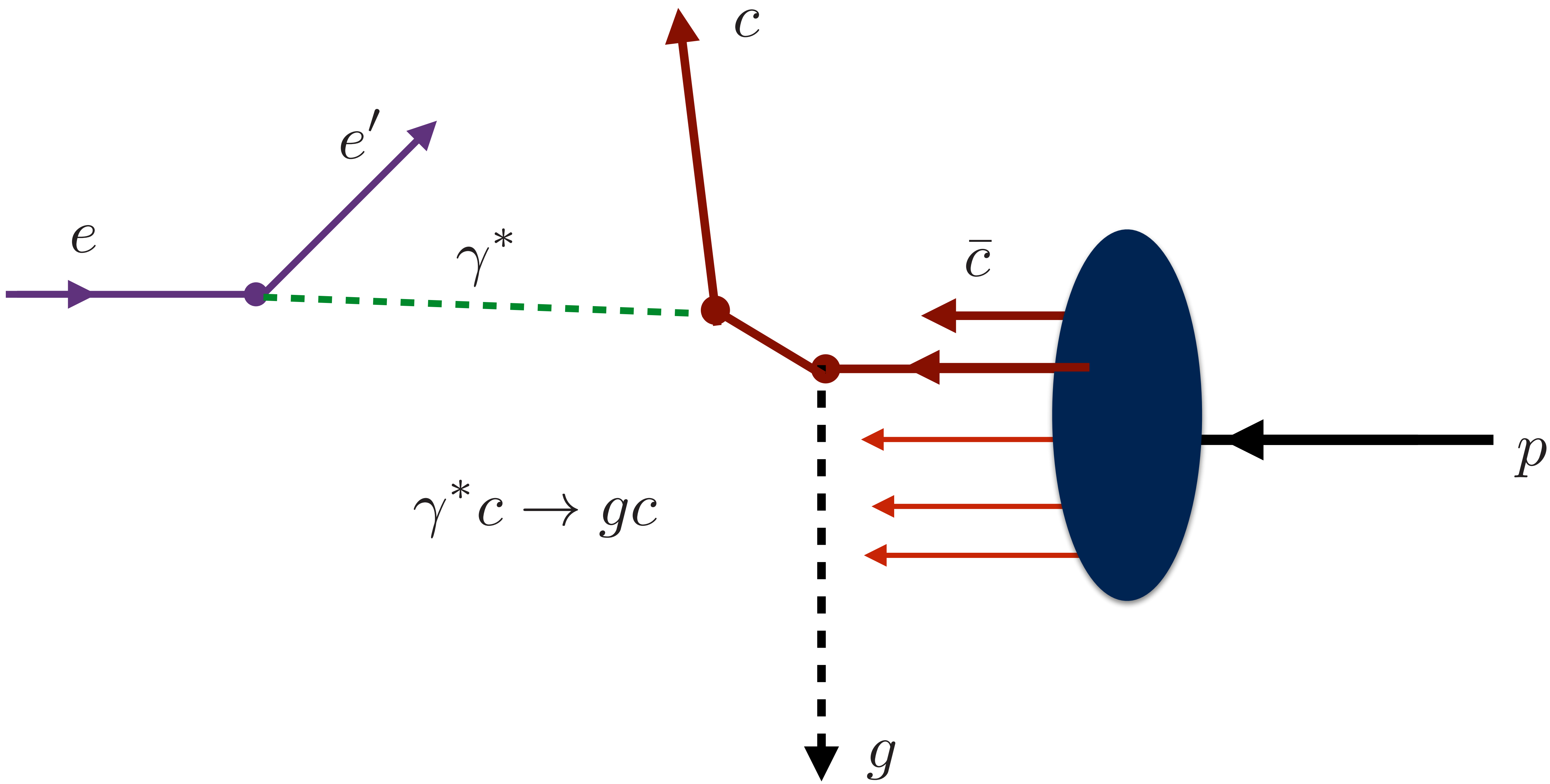
- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs production !!**
- **Underestimated in conventional parameterizations of heavy quark distributions**
- **Many EIC, LHeC tests**



Produce charm hadrons at high x

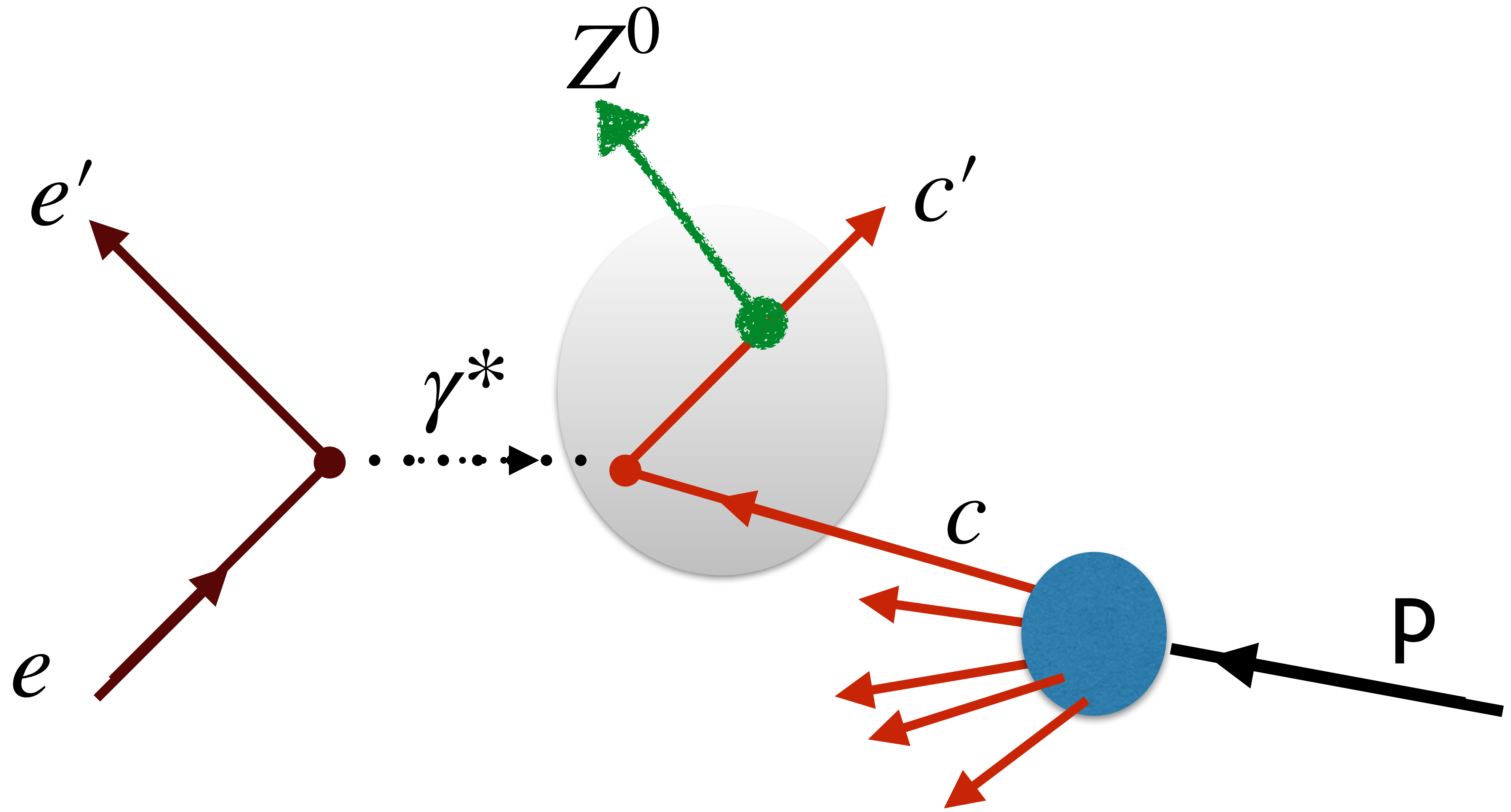
Charm not a reliable signal for the high - gluon distribution

$$ep \to e'cgX, ep \to e'bgX,$$



LHeC: Measure c(x,Q), b(x,Q) at large x

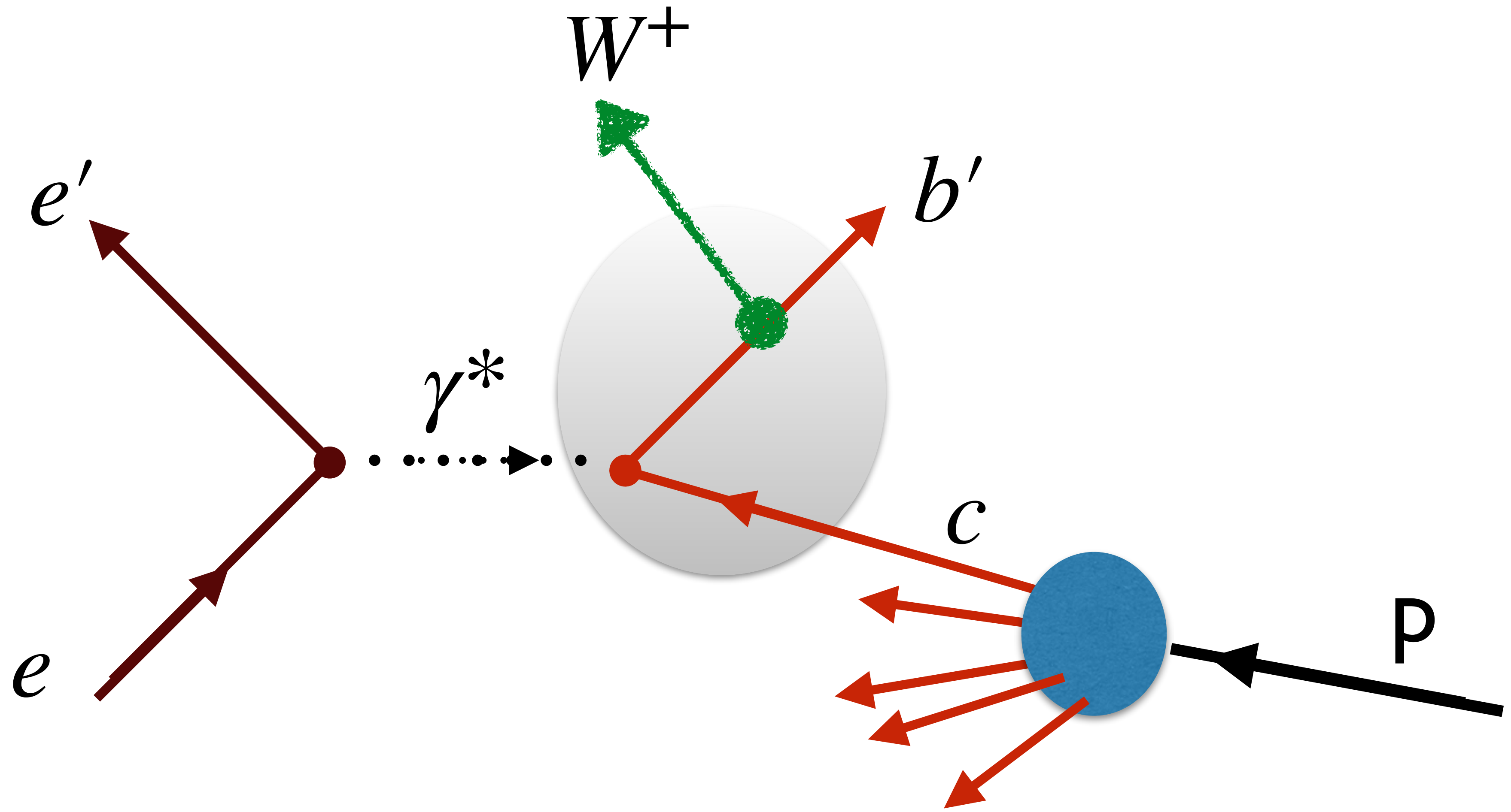
Test Standard Model Hard Processes at the LHeC



Test $\gamma c \to Z^0 c'$

$c(x, Q)$ at high x (Intrinsic Charm)

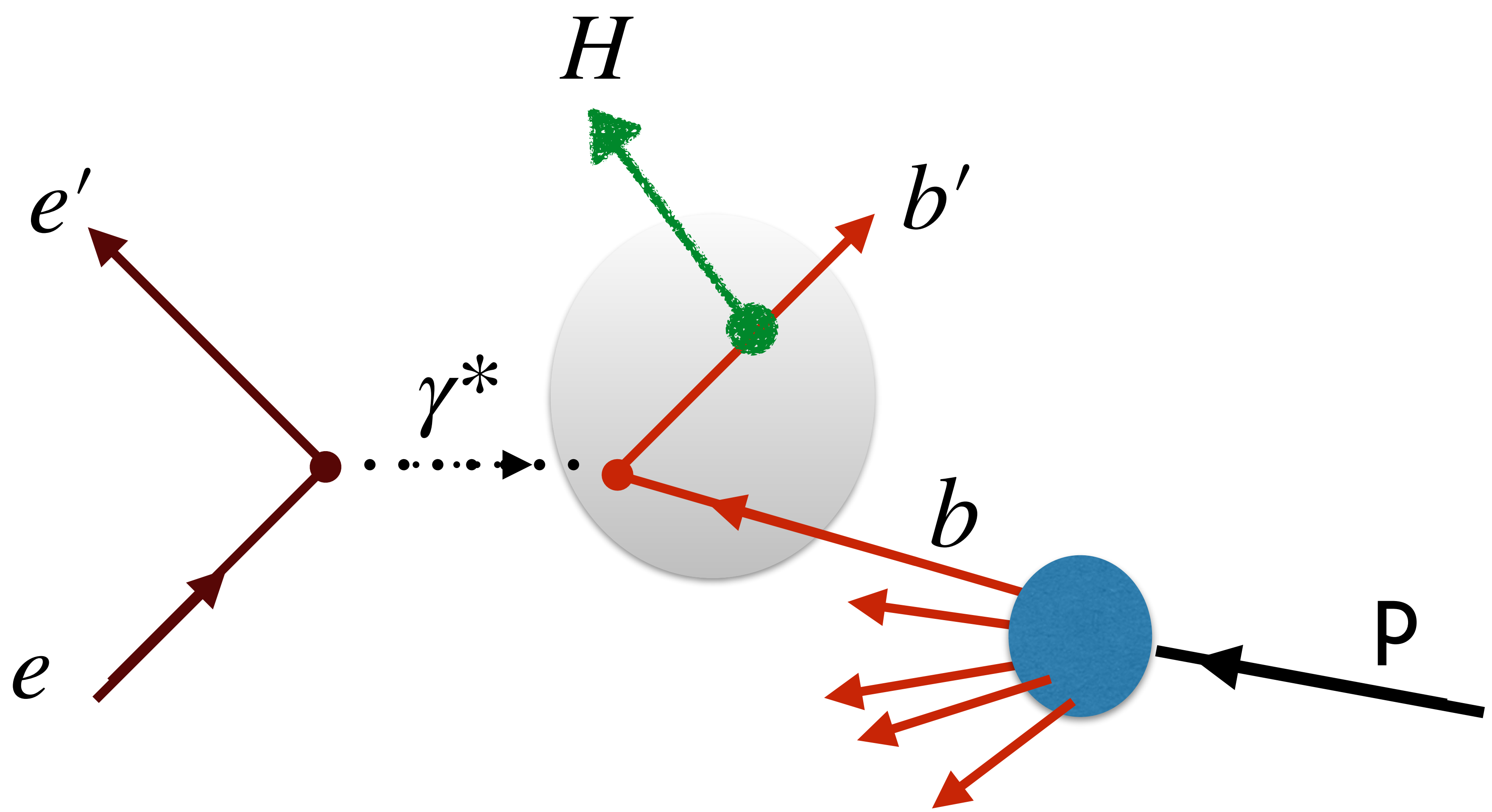
Test Standard Model Hard Processes at the LHeC



Test $\gamma c \to W^+ b'$

$c(x, Q)$ at high x (Intrinsic Charm)

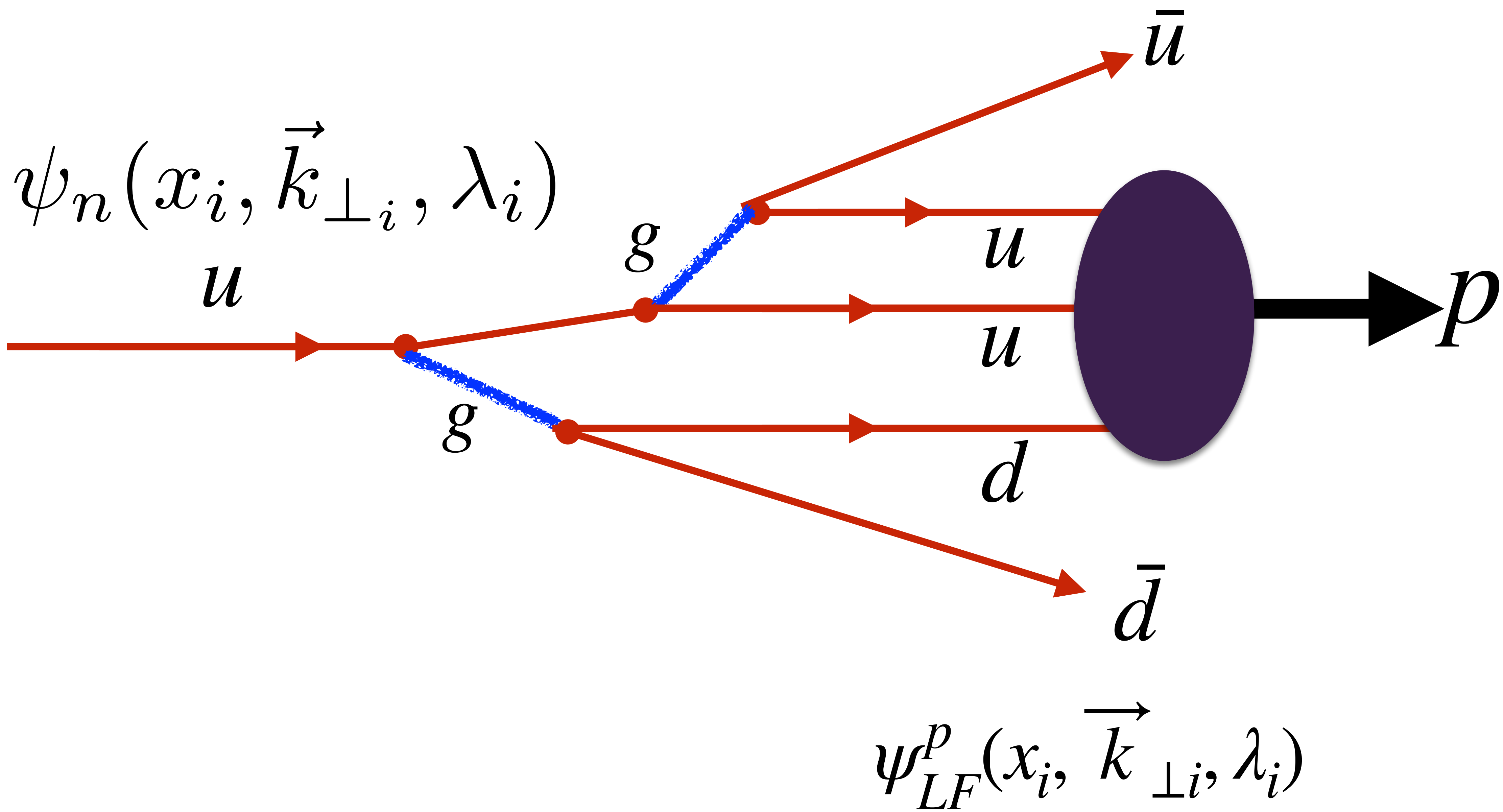
Test Higgs-strahlung from Heavy Quarks at the LHeC



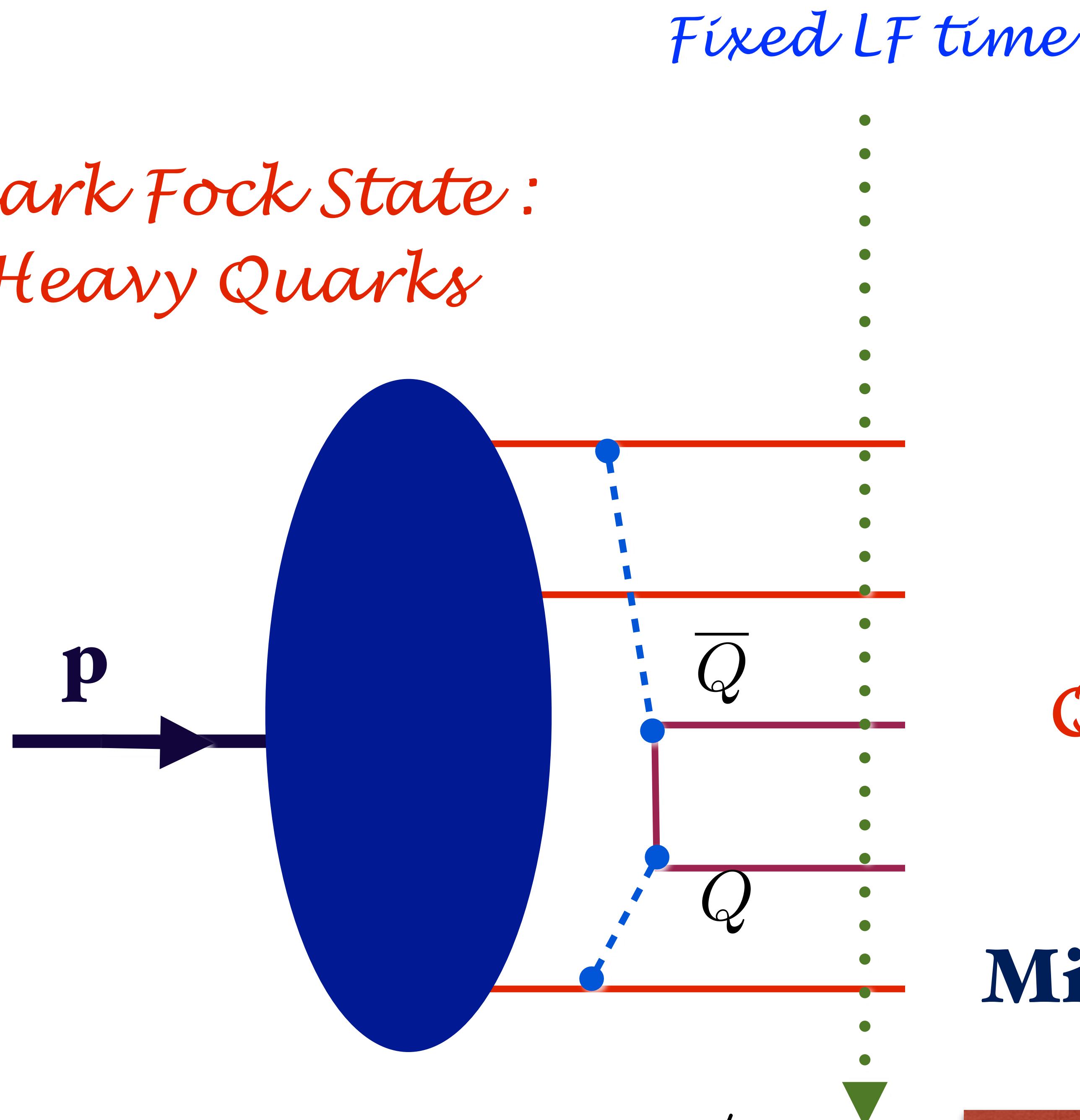
Test $\gamma b \to H b'$

$b(x, Q)$ at high x (Intrinsic Bottom)

“Hadronization at the Amplitude Level”



Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness

Maximum at Equal rapidity!

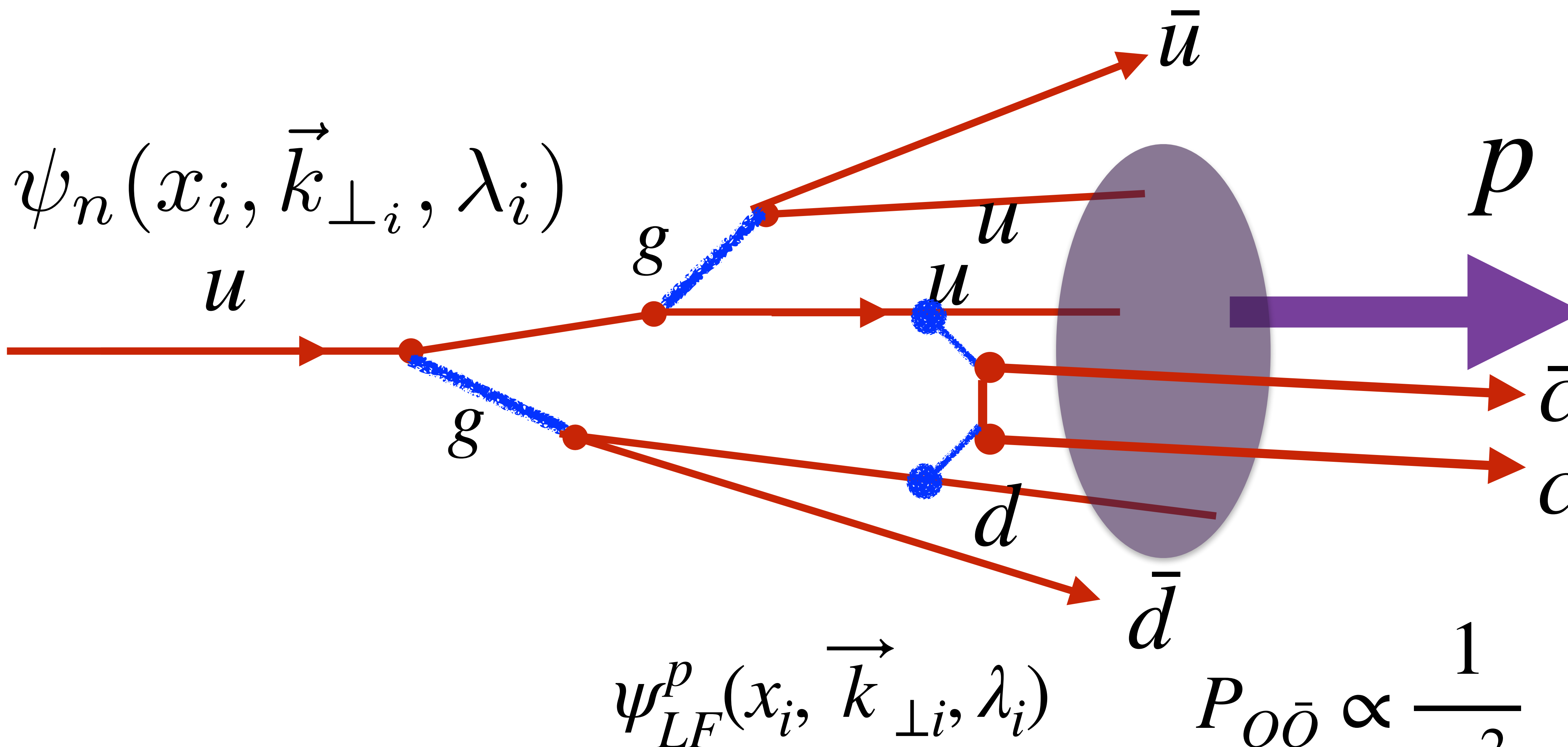
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

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

Rigorous OPE Analysis

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

"Hadronization at the Amplitude Level"

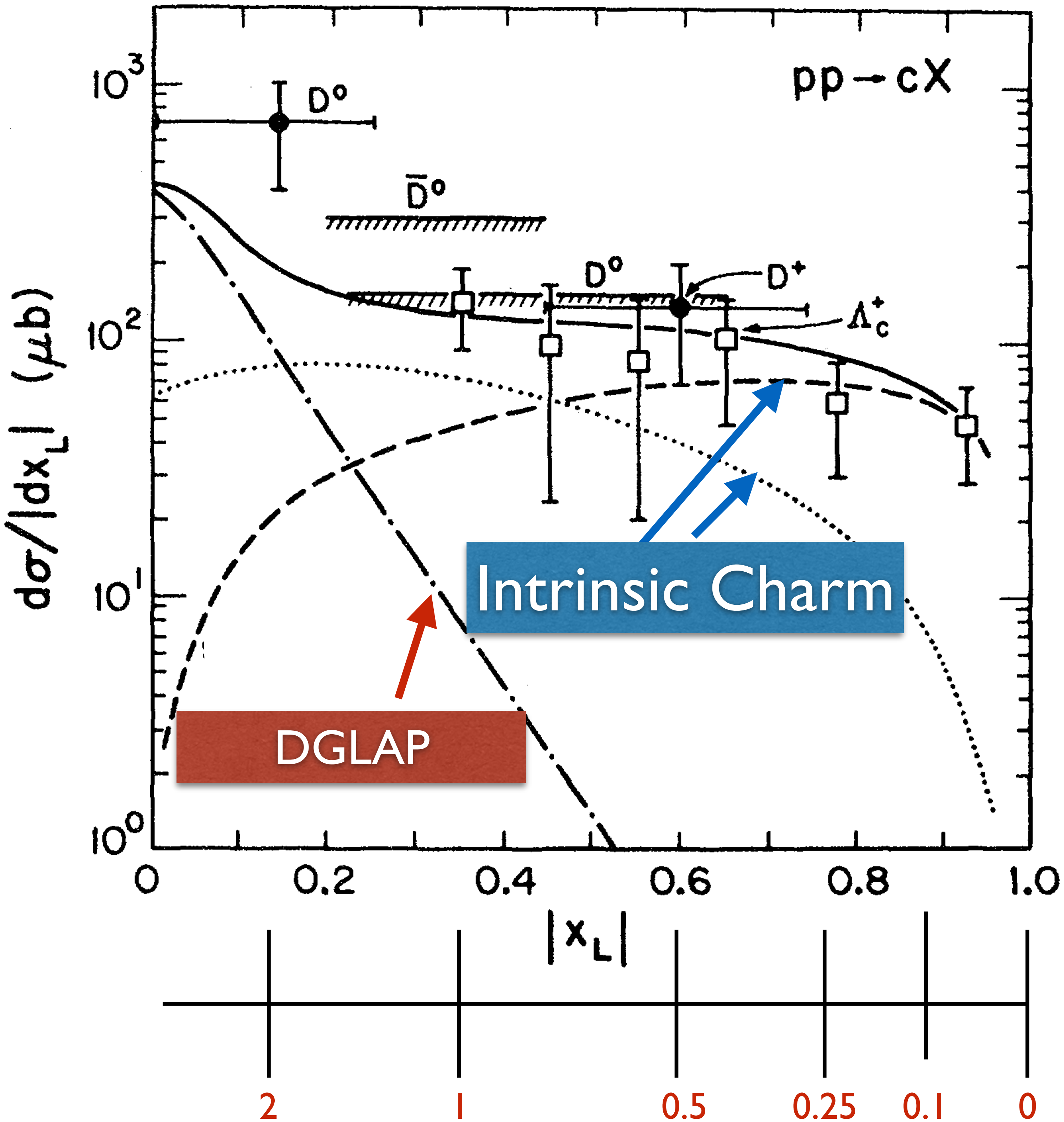


$$P_{Q\bar{Q}} \propto \frac{1}{m_Q^2}$$

Effect of Intrinsic Charm Fock States

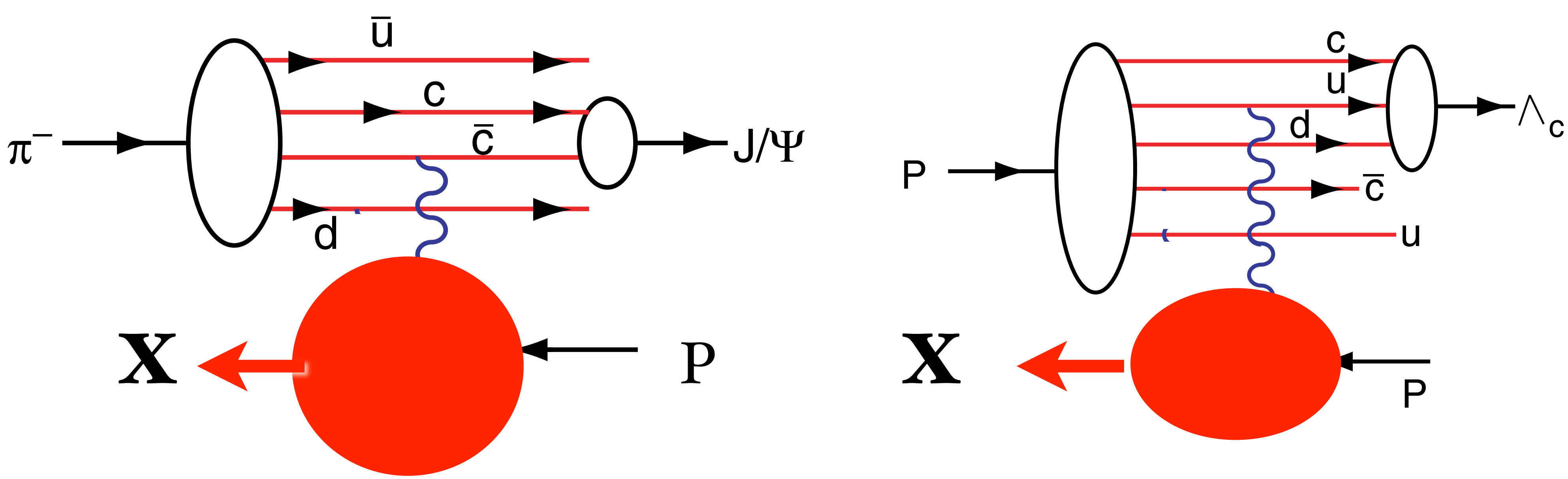
Collinear heavy quarks and heavy hadrons at ***same rapidity*** as proton

Barger, Halzen, Keung
PRD 25 (1981)



$\Delta y = \log x$

Coalesece of comovers produces high-x_F heavy hadrons



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

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

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

Rules out color drag model (Pythia)

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

- High x_F $pp \to \Lambda_c X$

Evidence for IQ

- High x_F $pp \to \Lambda_b X$

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

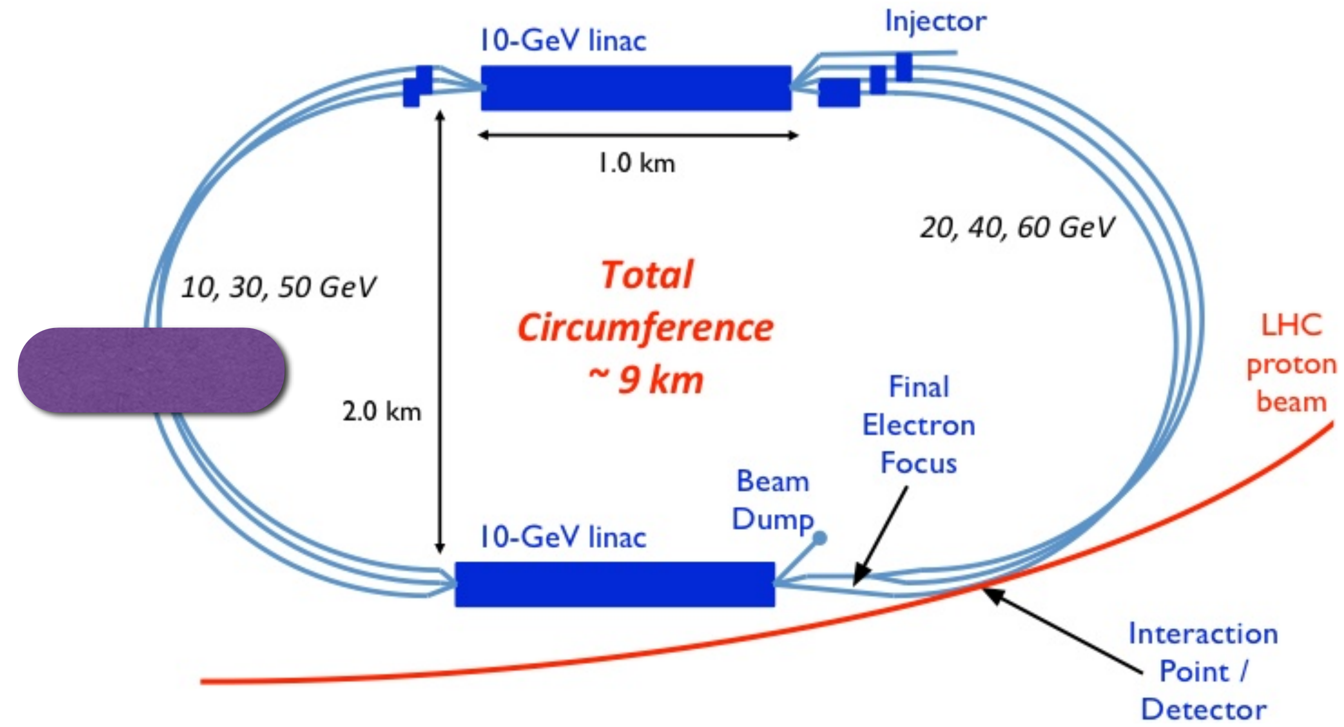
Explain Tevatron anomalies: $p\bar{p} \to \gamma c X, Z c X$

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

Fixed Target

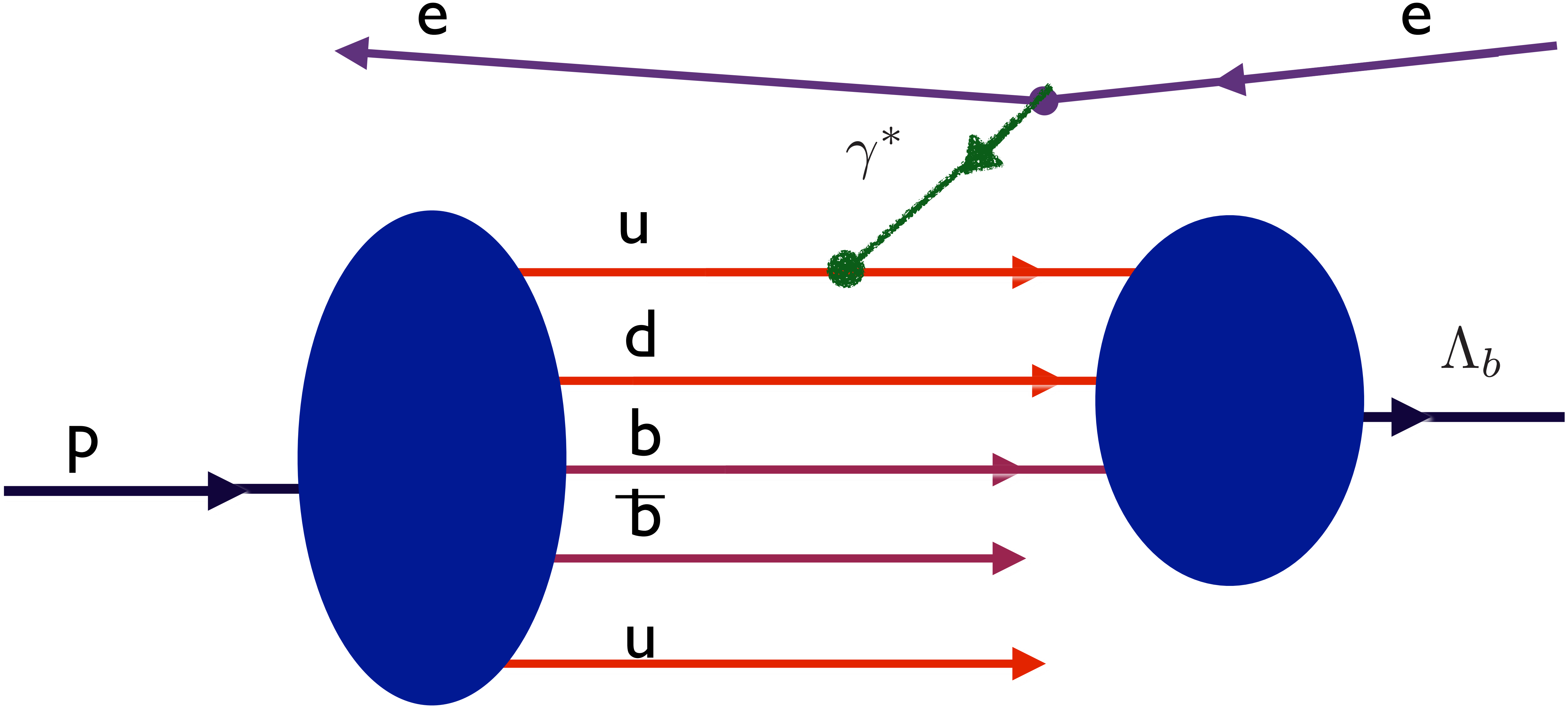


Use LHeC 60 GeV Electron Ring in Fixed-Target Mode

HERMES (HERA), SMOG(LHCb)

Complimentary to LHeC Program
Nuclear and Polarized Proton Targets
Large-x Domain of DIS

$\gamma^* p \to \Lambda_b X$



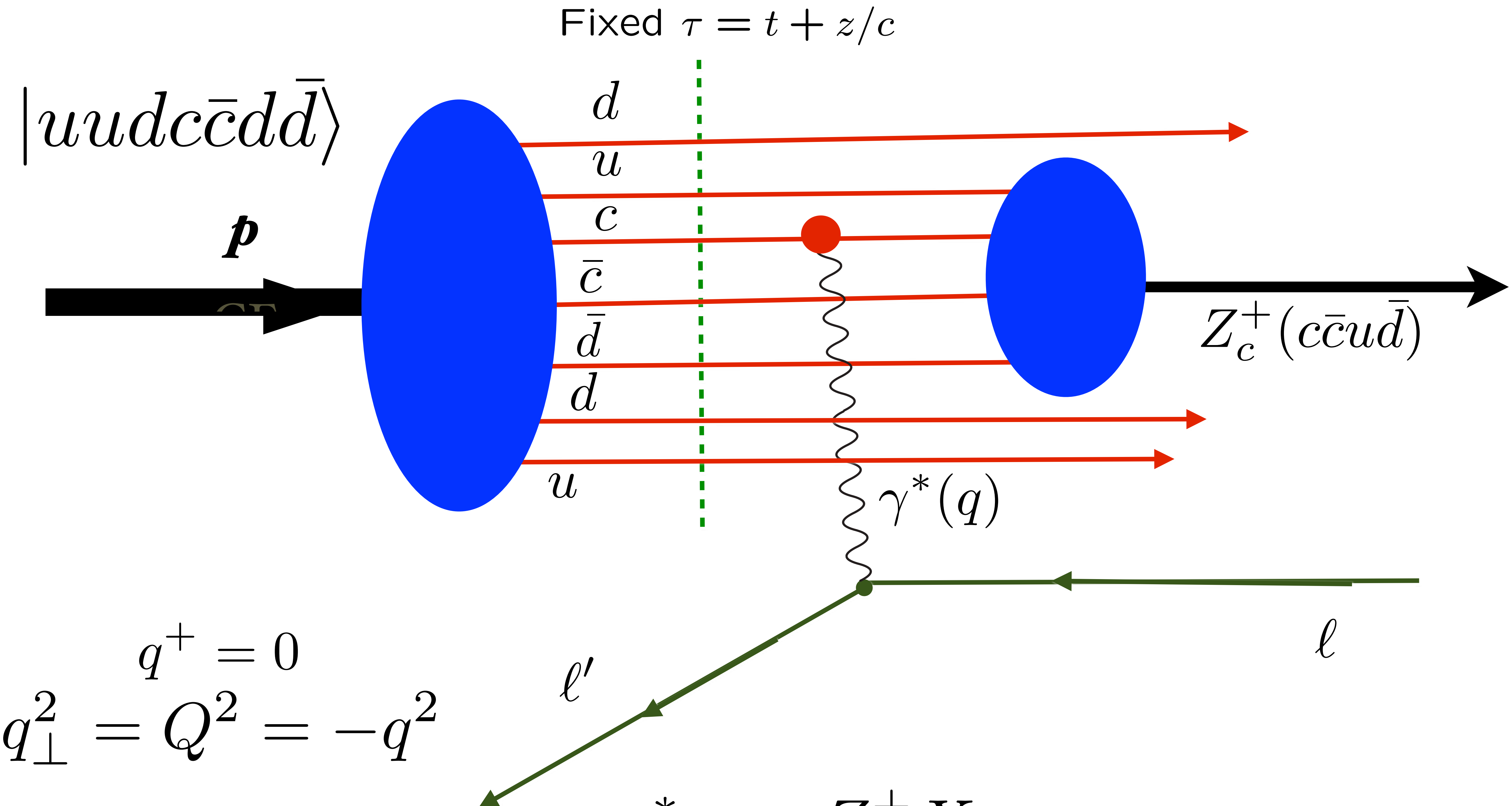
$$x_{\Lambda_b} = x_u + x_d + x_b$$

Coalescence maximal at matching rapidities

High $x^F_{\Lambda_b}$

LHeC: Measure heavy hadrons produced at high x_F

Light-Front Wavefunctions and Heavy-Quark Electroproduction



$$\gamma^* p \to Z_c^+ X$$

Coalescence of comovers produces Z_c^+ tetraquark

Why is Intrinsic Heavy Quark Phenomenon Important?

- ***Test Fundamental QCD predictions OPE, Non-Abelian QCD***

  Non-Abelian: $P_{Q\bar{Q}} \propto \frac{1}{M^2_{Q\bar{Q}}}$ Abelian: $P_{Q\bar{Q}} \propto \frac{1}{M^4_{Q\bar{Q}}}$

- ***Test non-perturbative effects***

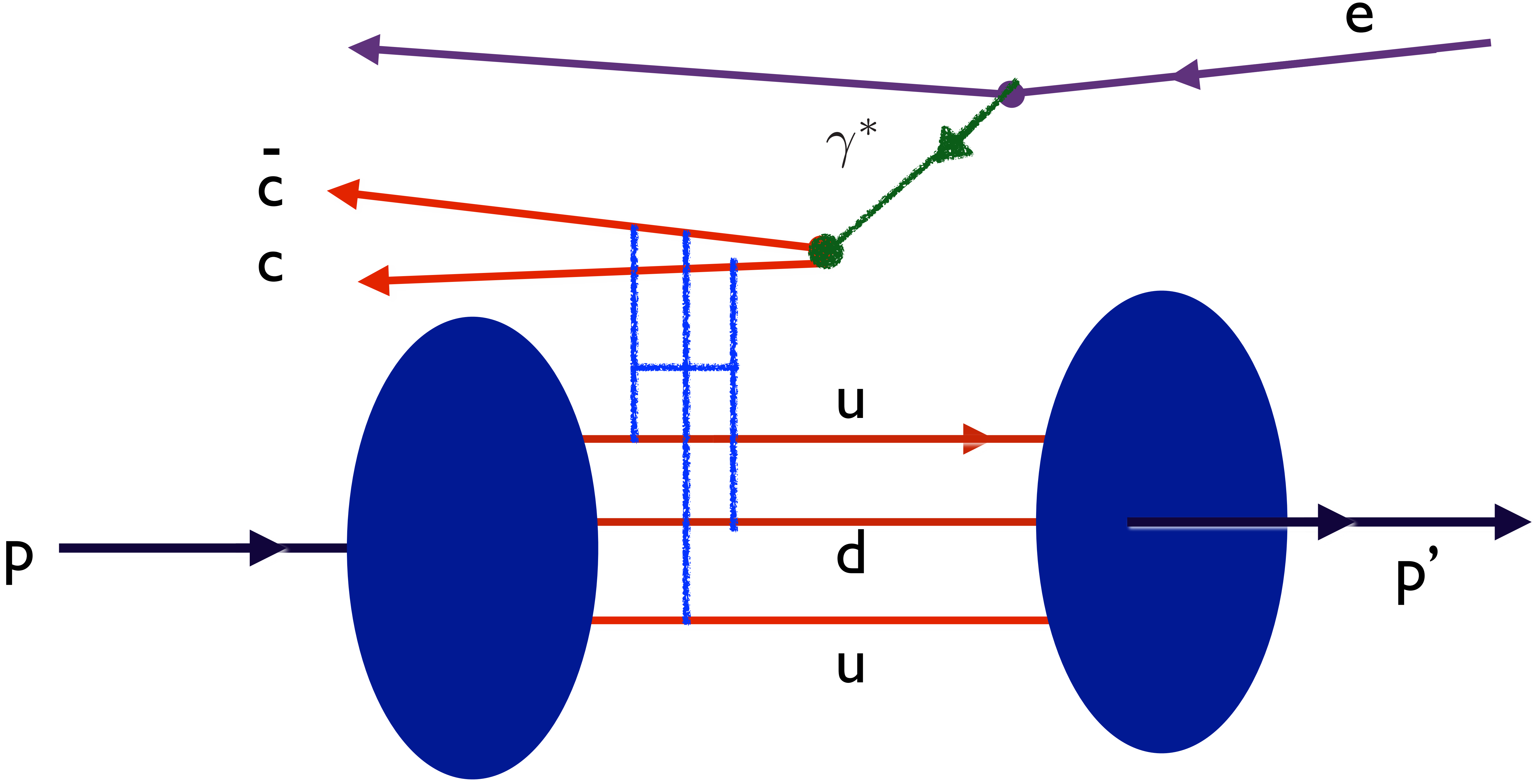
- ***Important for correctly identifying the gluon distribution***

- ***High-x_F open and hidden charm and bottom; discover exotic states***

- ***Explain anomalous high pT charm jet + γ data at Tevatron***

- ***Important source of high energy ν at IceCube***

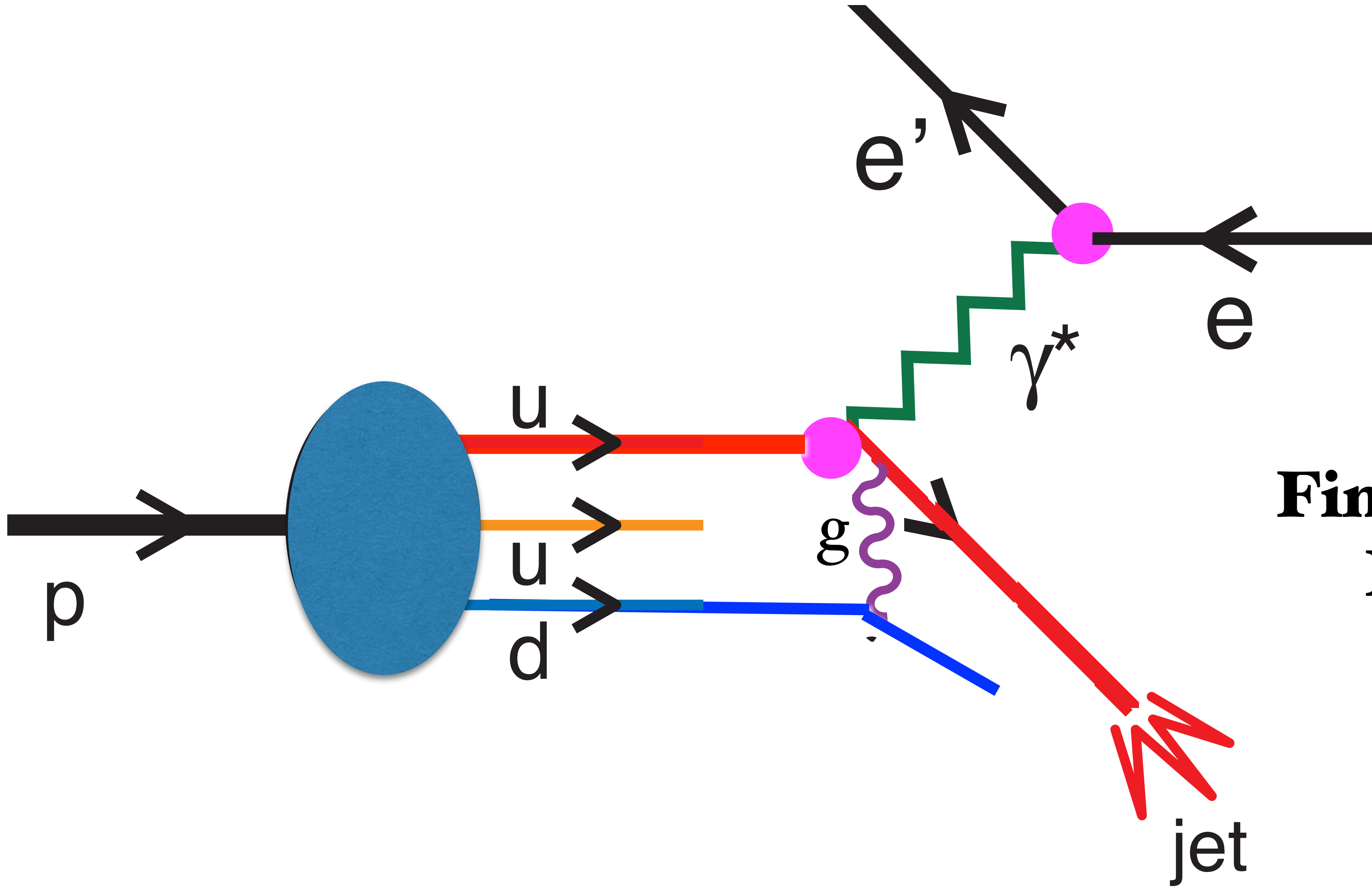
$$\gamma * p \to c\bar{c} + p'$$



Odderon-Pomeron Interference gives c vs. $\bar{c}$ asymmetry

Rathsman, Merino, sjb

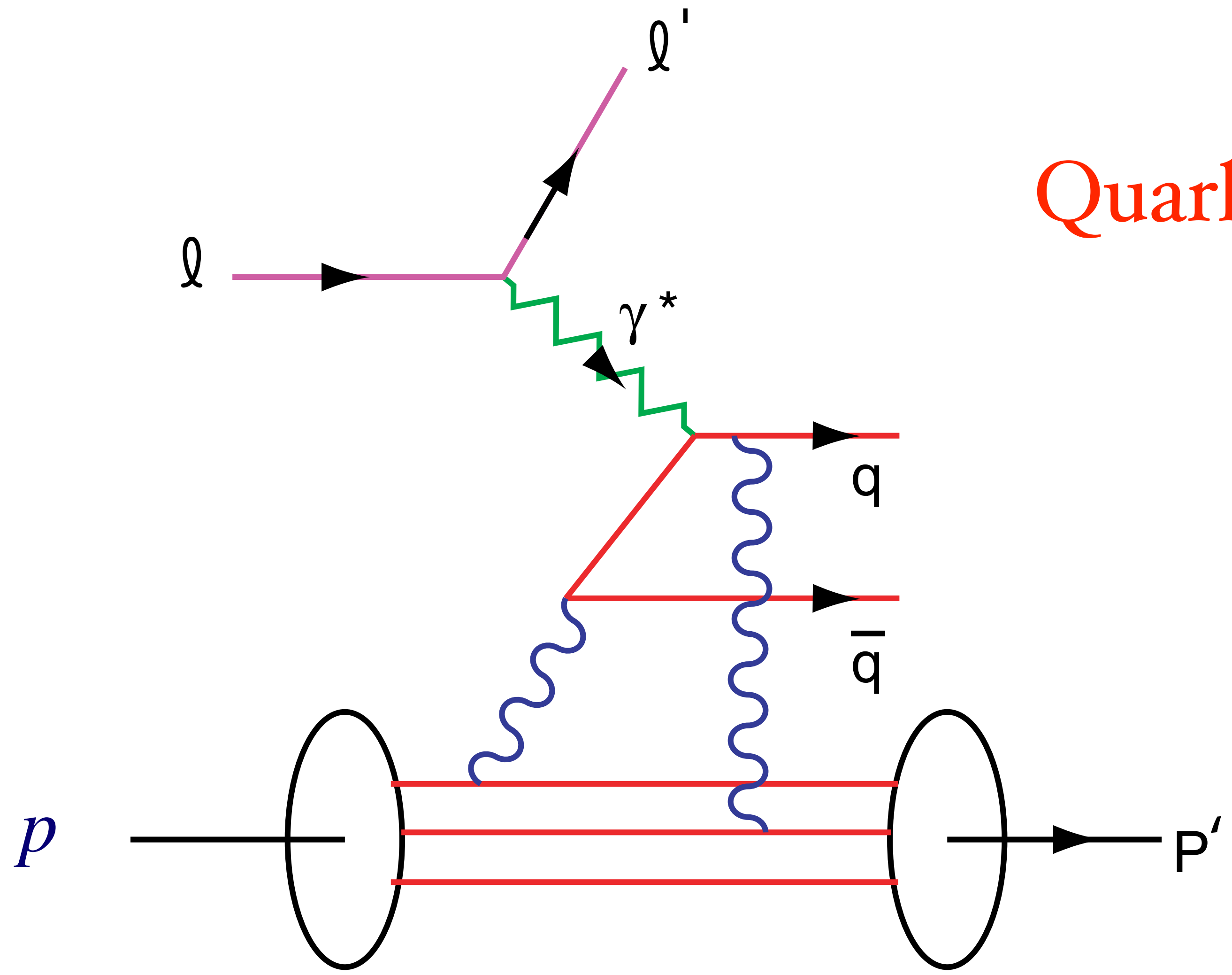
Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:
Final-state interactions of struck quark can be neglected

Final-State Gluonic Interactions Produce Diffractive Deep Inelastic Scattering (DDIS)



Quark Rescattering in Final State

Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

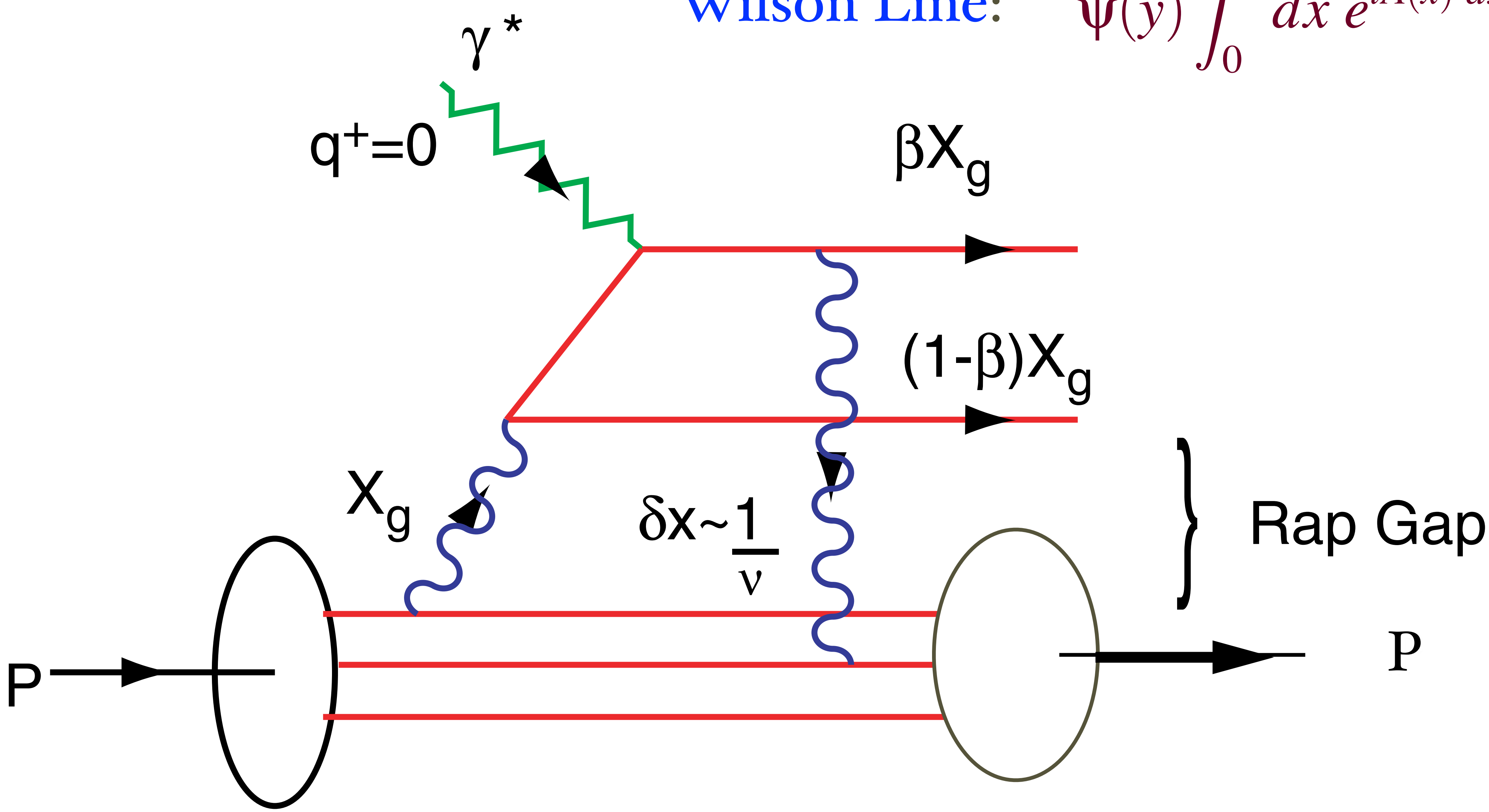
Leading Twist: Bj Scaling

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

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

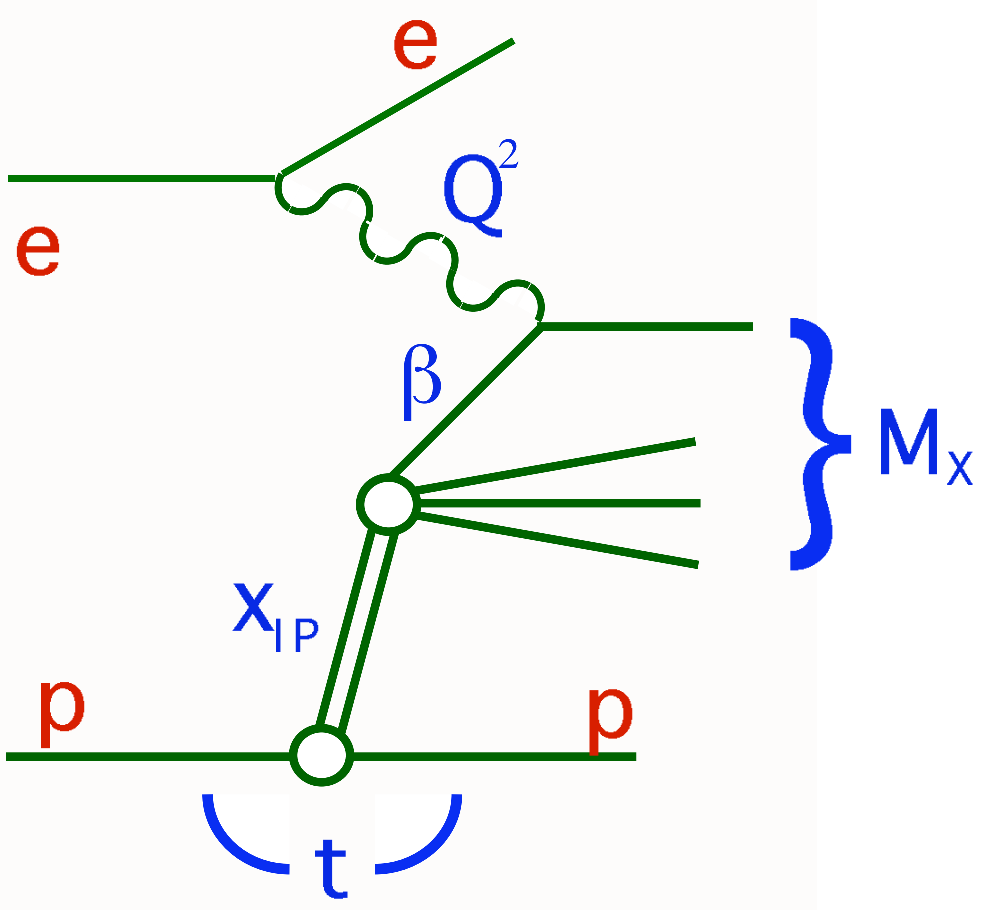


Reproduces lab-frame color dipole approach

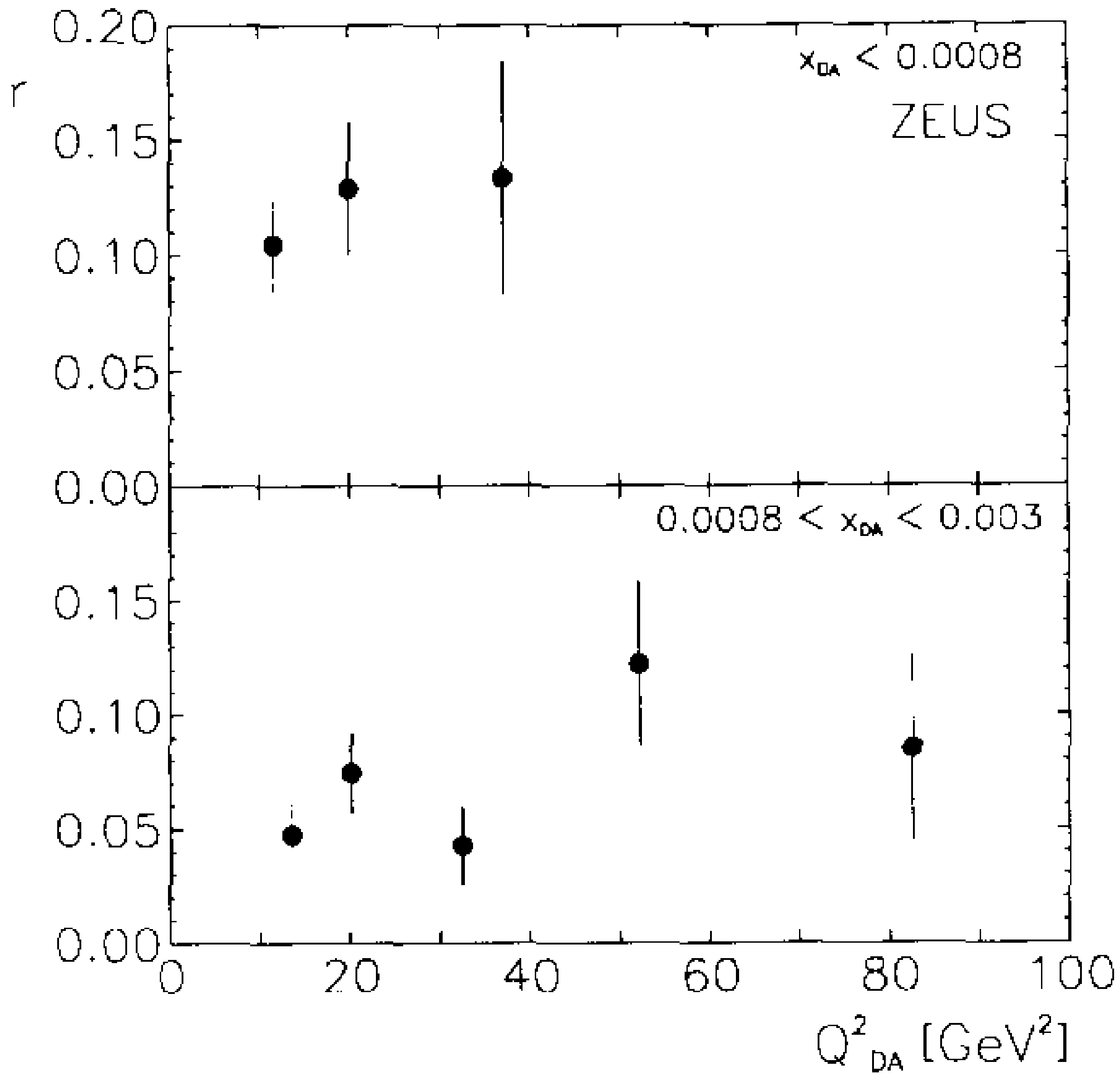
DDIS: Crucial Input for leading-twist nuclear shadowing

DDIS: Diffractive Deep Inelastic Scattering

Remarkable observation at HERA



10% to 15%
of DIS events
are
diffractive !

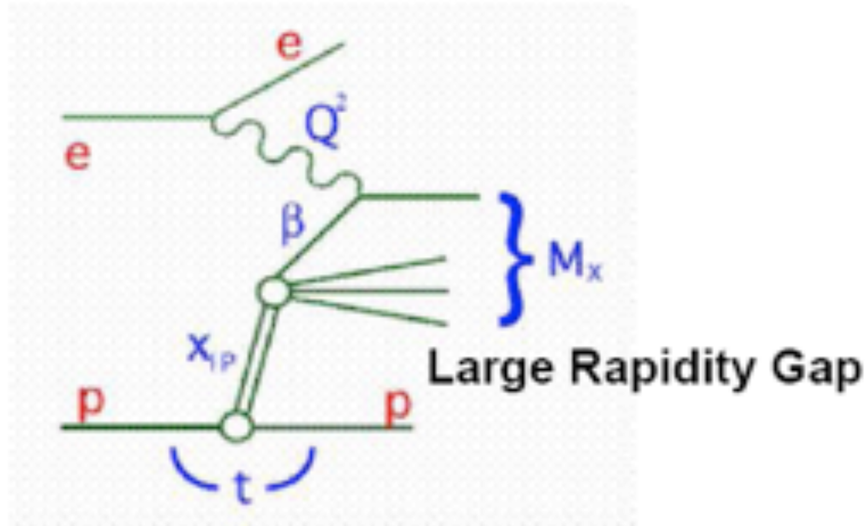


Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993)

H1: de Roeck, et al.

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

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

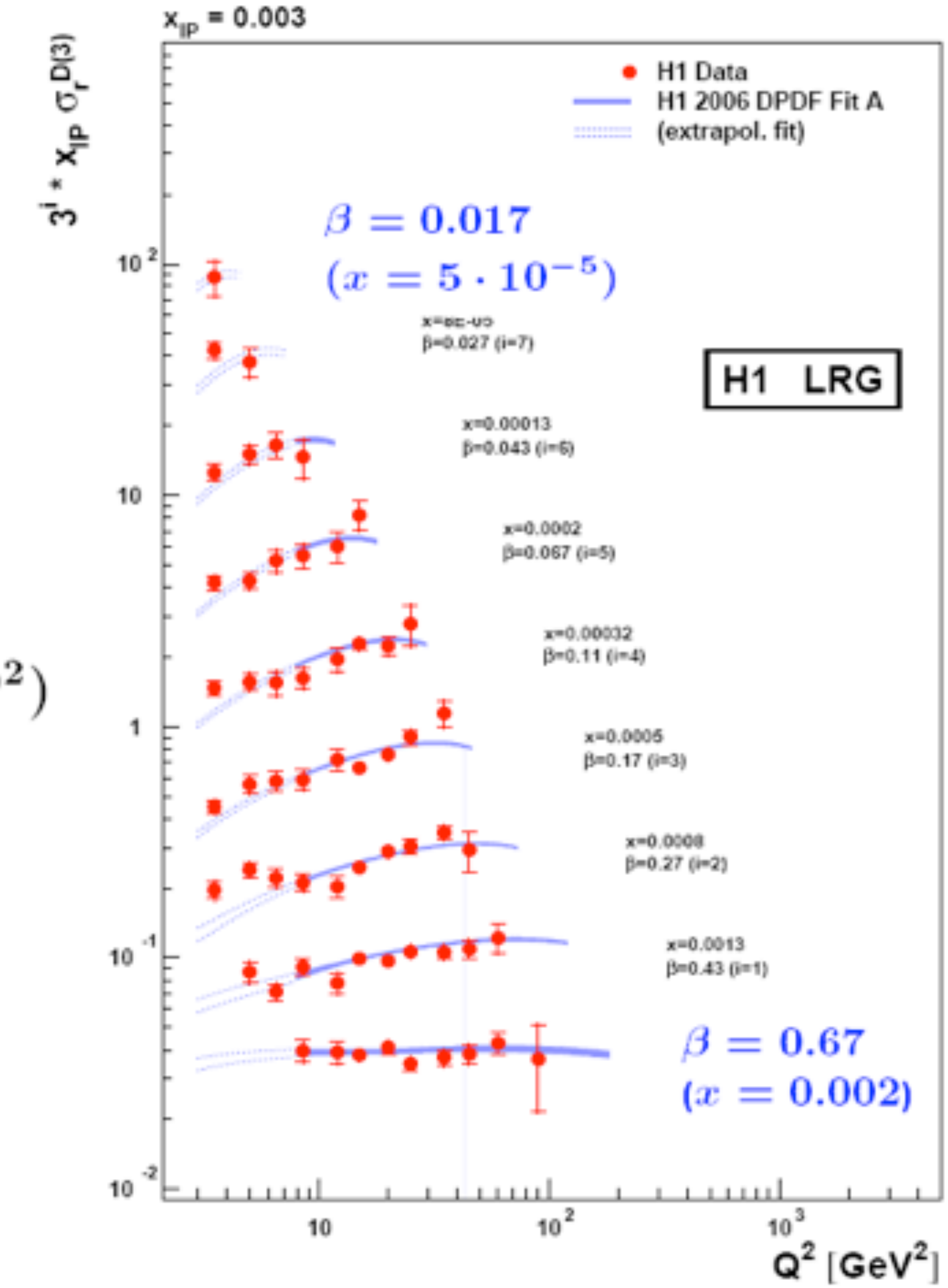
$$F_2^D(x_{I\!P},\beta,Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta,Q^2)$$

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

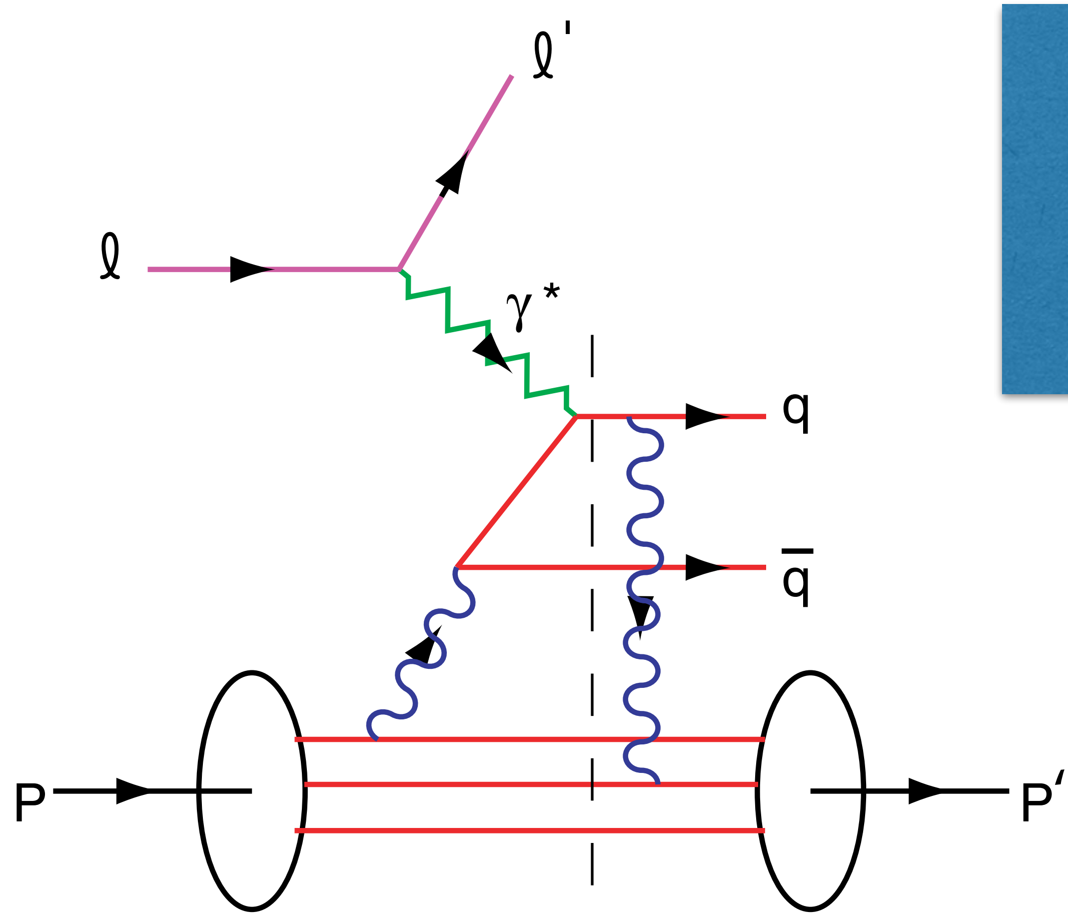
Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

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

About 15% of DIS events are diffractive !



DDIS: Diffractive Deep Inelastic Scattering



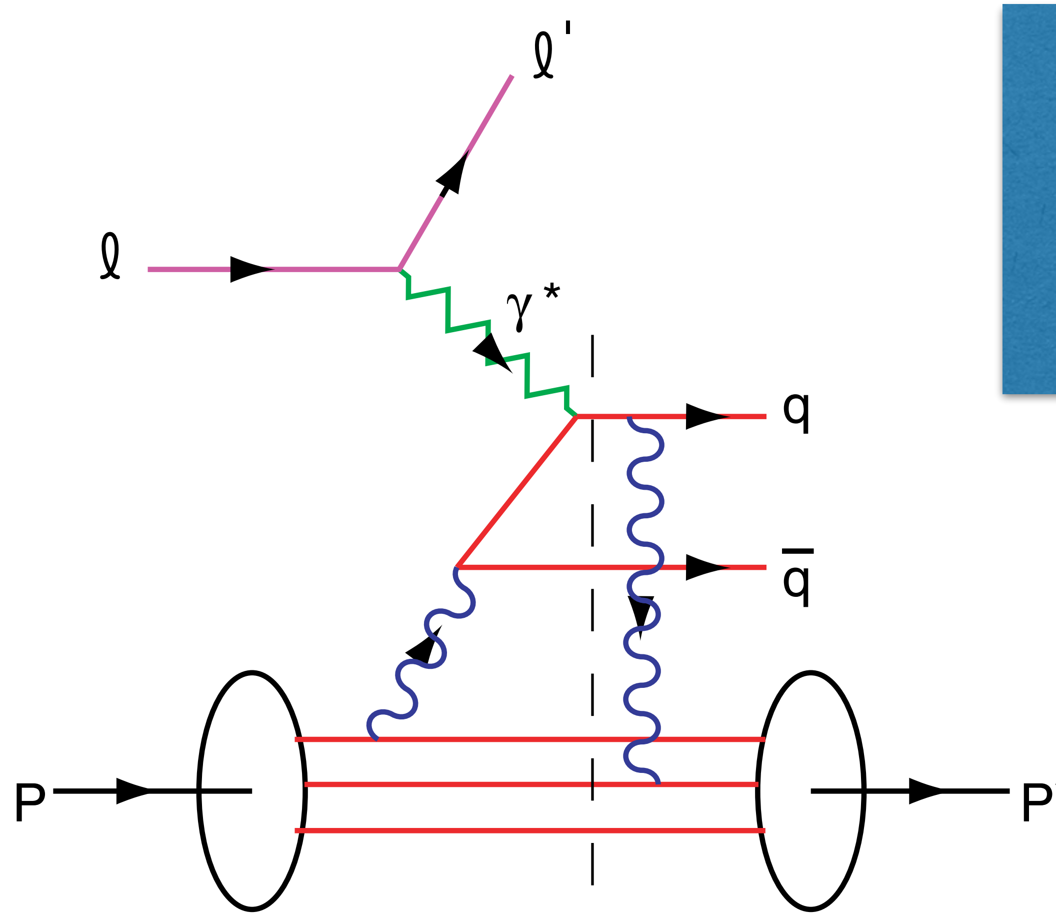
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

Also: Need Imaginary Phase to Generate "Sivers Effect"
T-Odd Single-Spin Asymmetry

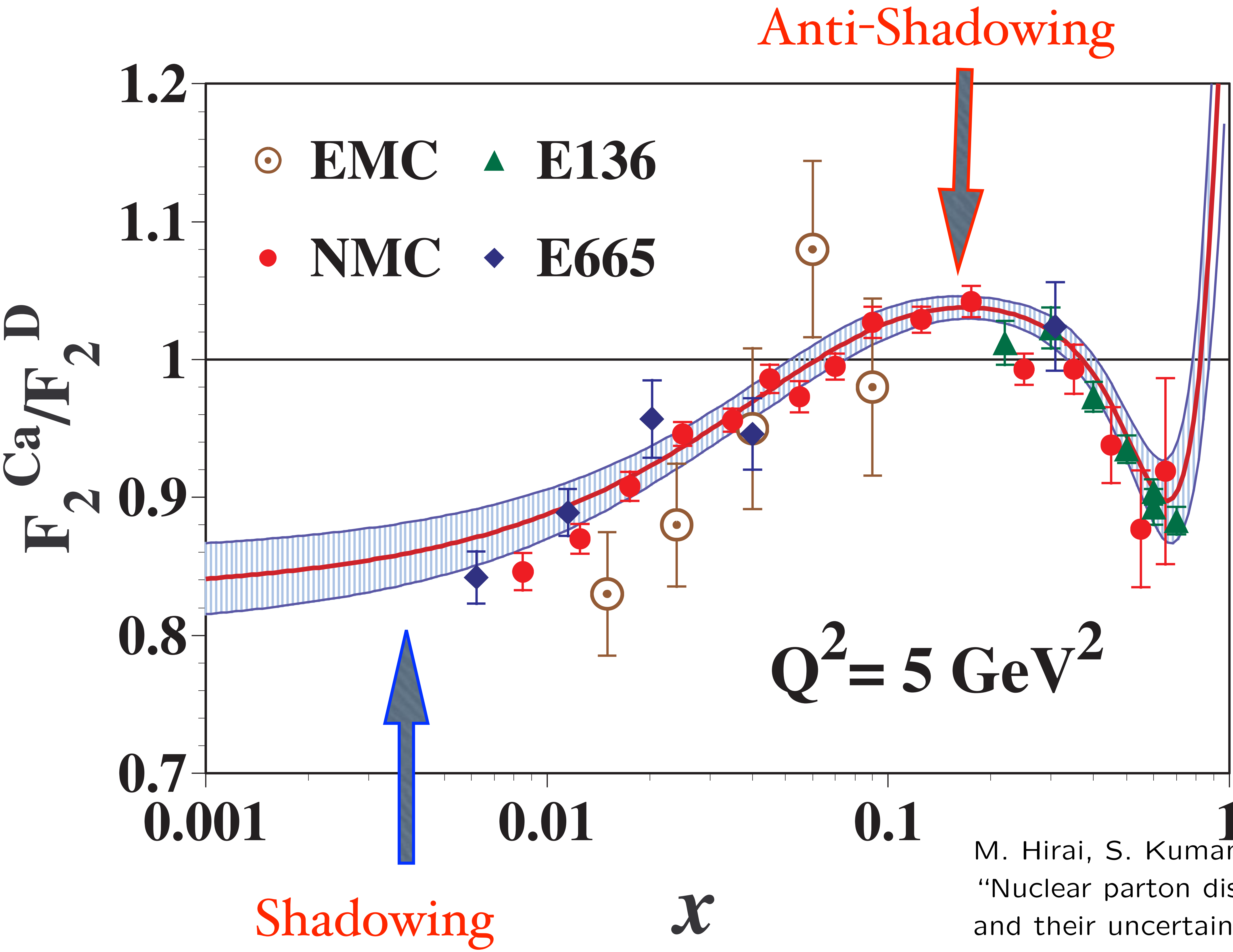
Physics of FSI not in LF Wavefunction of Target

DDIS: Diffractive Deep Inelastic Scattering



90% of proton momentum carried off by final state p' in 15% of events!

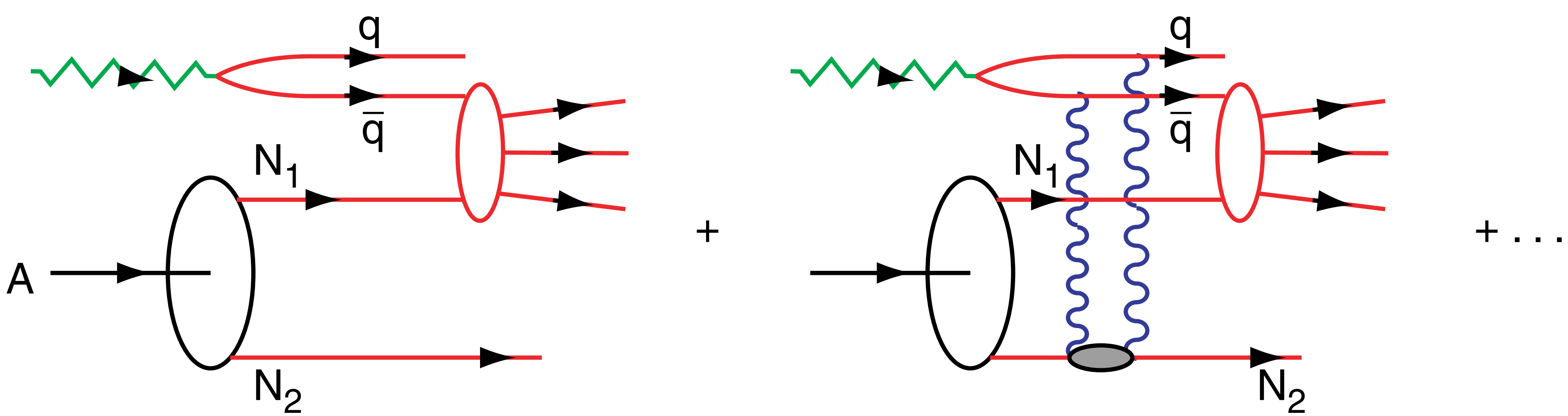
Gluon momentum fraction misidentified!



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



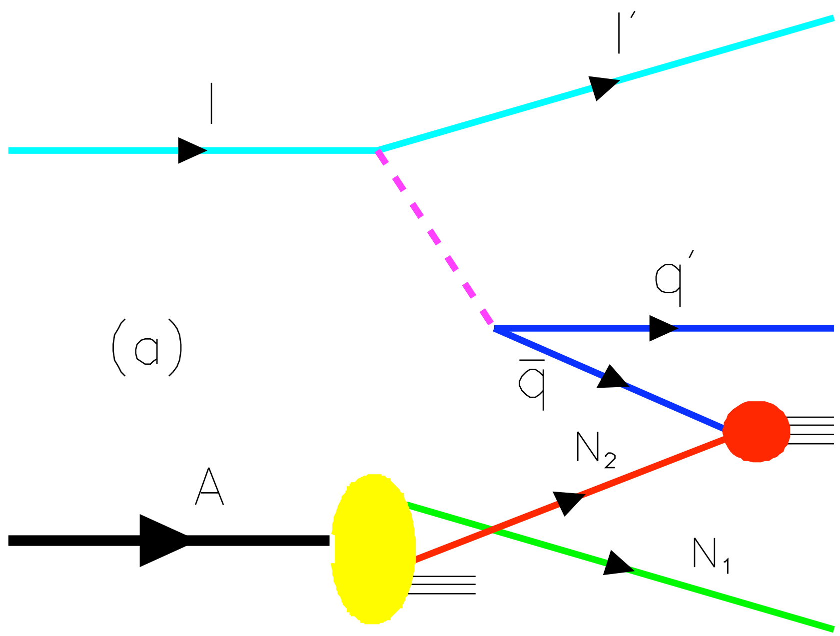
Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

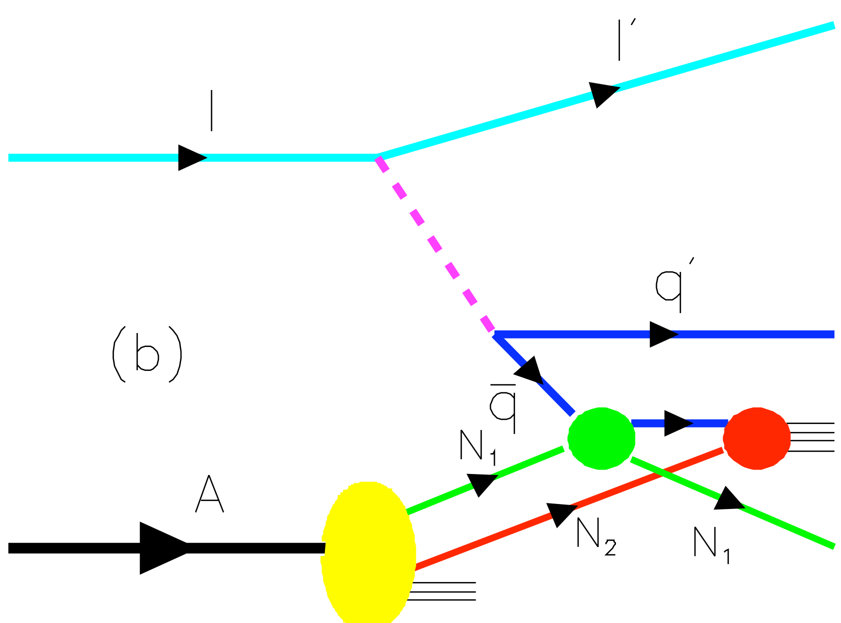
Diffraction via Reggeon gives constructive interference!

Anti-shadowing not universal



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.

→ Shadowing of the DIS nuclear structure functions.

Diffraction via Pomeron gives destructive interference!

Shadowing

Observed HERA DDIS produces nuclear shadowing

Reggeon Exchange

Phase of two-step amplitude relative to one step:

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

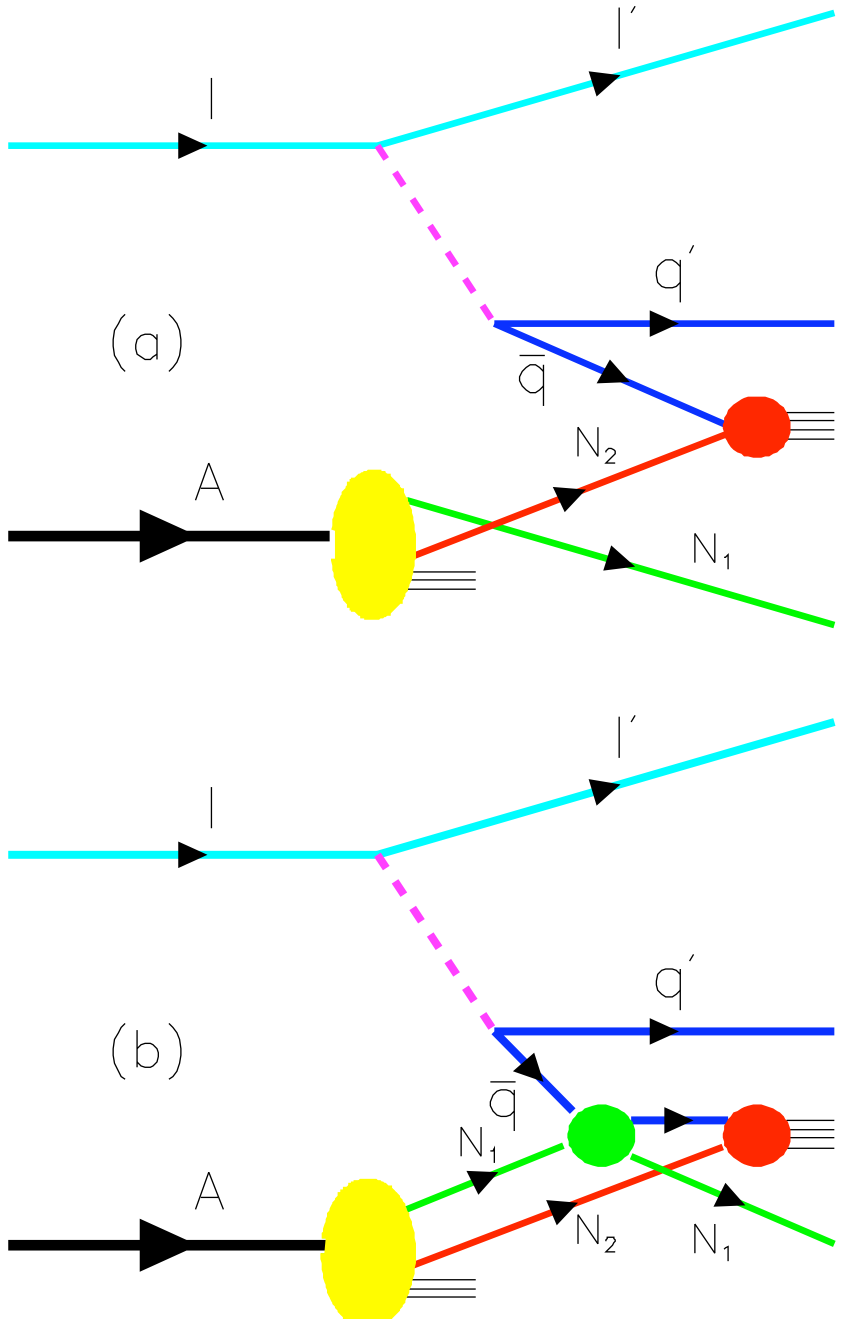
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

Critical tests: Tagged SIDIS, Drell-Yan



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

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

Regge

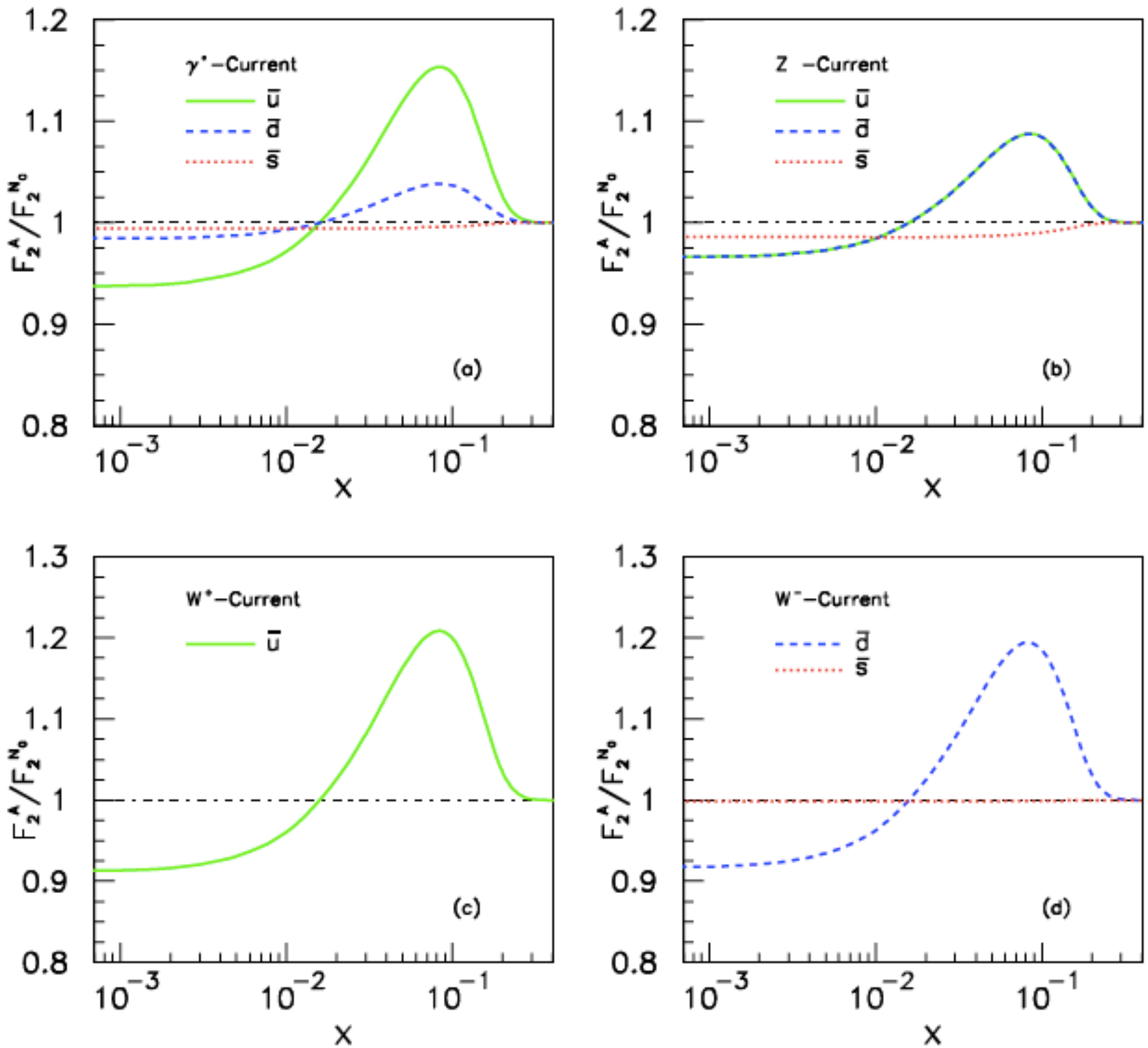
If the scattering on nucleon N_1 is via ~~pomeron~~ exchange, the one-step and two-step amplitudes are ~~opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.~~

constructive in phase

thus increasing the flux reaching N_2

Reggeon DDIS produces nuclear flavor-dependent anti-shadowing

Anti-shadowing



Schmidt, Yang; sjb

Reggeon Contribution to DDIS

Constructive Interference!

Phase from signature factor

Nuclear Antishadowing not universal !

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference
of Two-Step and One-Step Processes
Pomeron Exchange

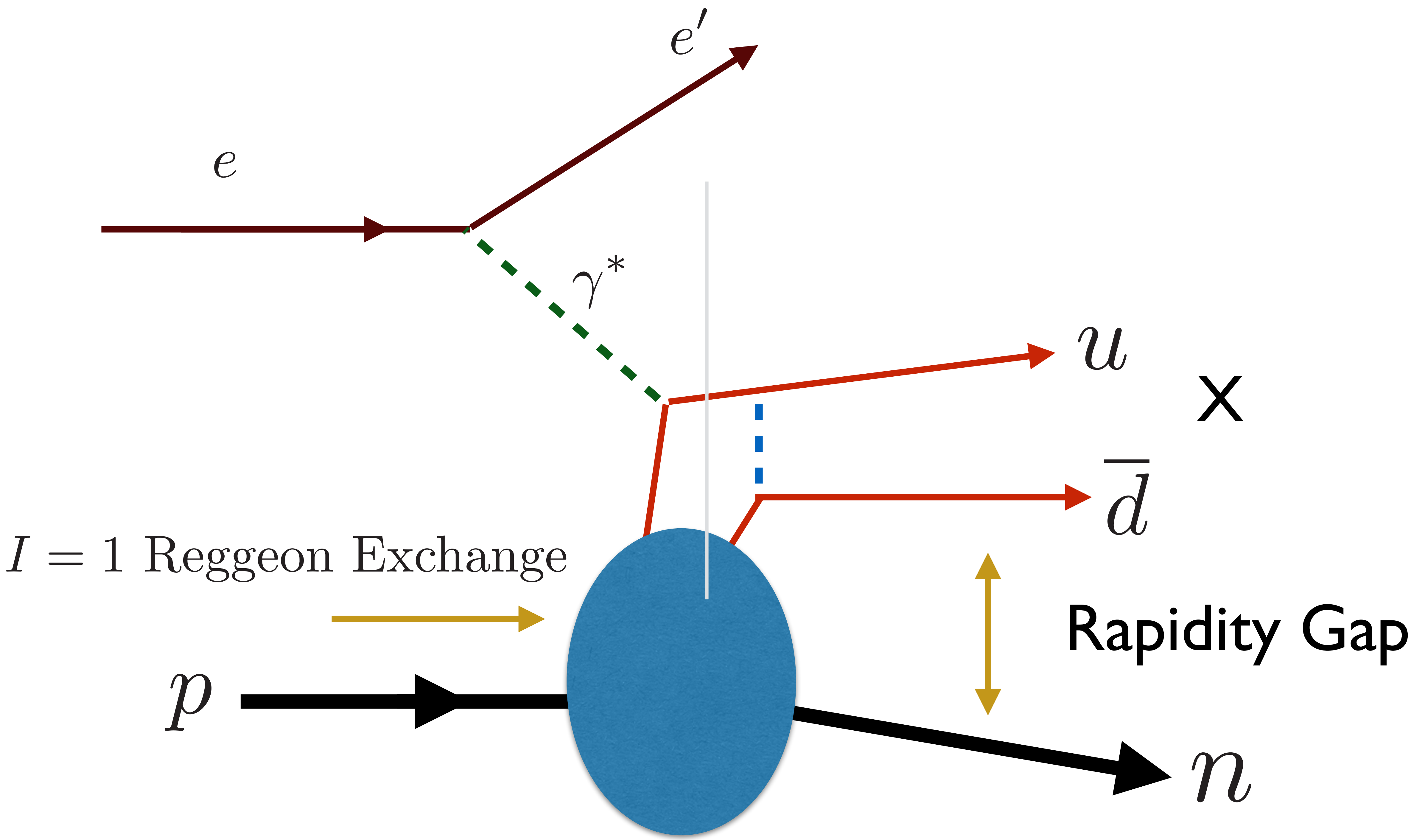
- Antishadowing: Constructive Interference
of Two-Step and One-Step Processes!
Reggeon and Odderon Exchange

- Antishadowing is Not Universal!
Electromagnetic and weak currents:
different nuclear effects !
Potentially significant for NuTeV Anomaly}

Jian-Jun Yang
Ivan Schmidt
Hung Jung Lu
sjb

Crucial LHeC Tests

$$\gamma^* p \to nX$$



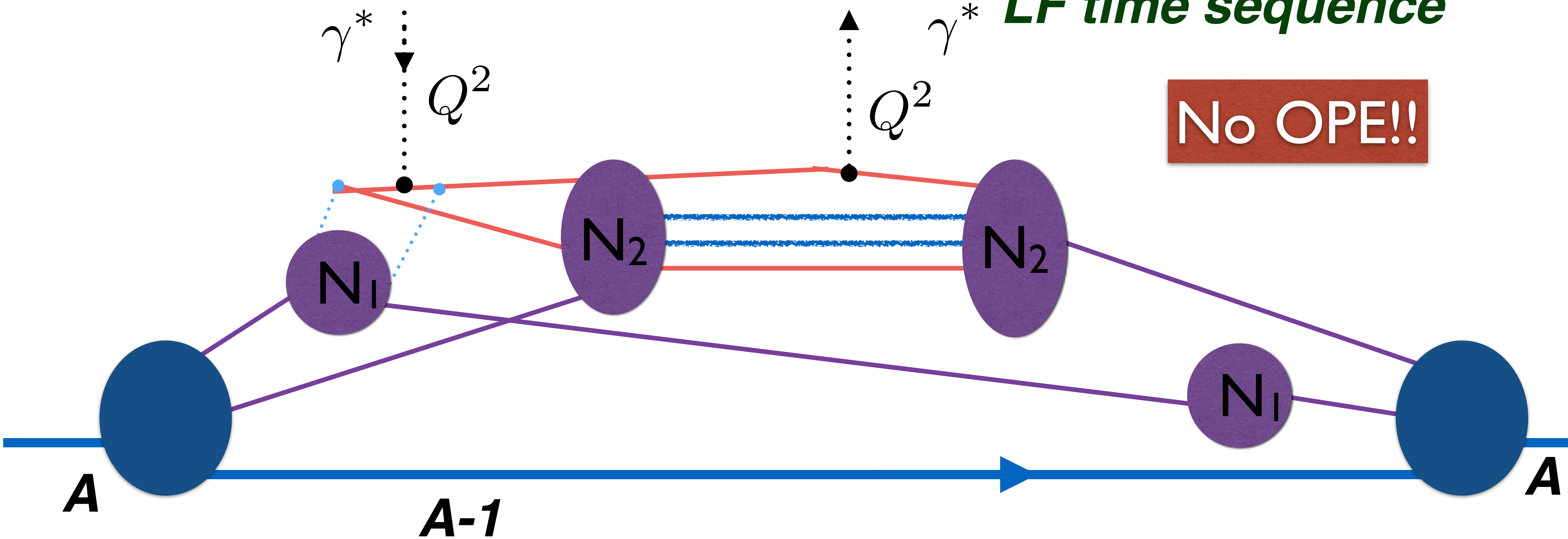
Charge-Exchange Diffractive Deep Inelastic Scattering

CEDDIS

$\gamma^* A \to \gamma^* A$ **Nuclear Forward DVCS**

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

Illustrates the LF time sequence



Front-Face Nucleon N_1 struck

Front-Face Nucleon N_1 not struck

One-Step / Two-Step Interference

Study Double Virtual Compton Scattering $\gamma^* A \to \gamma^* A$

Cannot reduce to real phase matrix element of local operator! No Sum Rules!

I. Schmidt, S. Liuti, sjb

Nuclear PDFs

- Shadowing from destructive interference of 2-step and 1-step processes

  Gribov-Glauber, Stodolsky

- Anti-Shadowing from constructive interference of 2-step and 1-step processes

  H. Lu, sjb

- Diffractive DIS and Charge-Exchange DDIS crucial inputs

- Handbag amplitude for nuclear DVCS not applicable

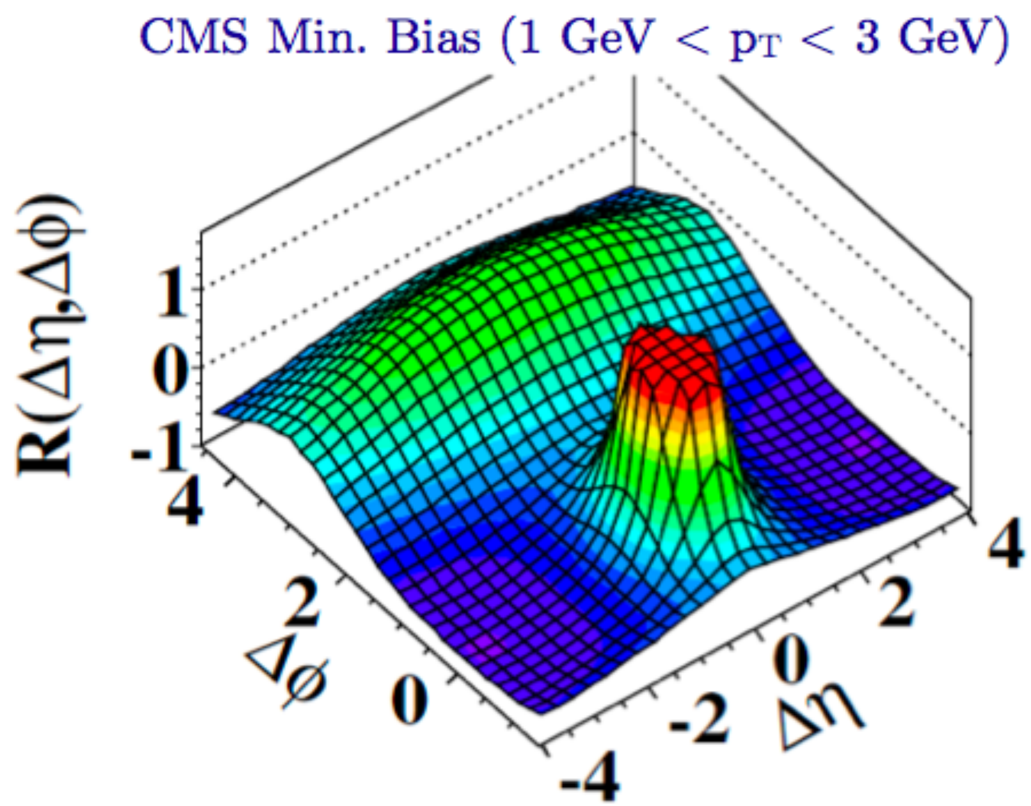
- **OPE and Sum Rules inapplicable to nuclear pdfs!**

  I. Schmidt, S. Liuti, sjb

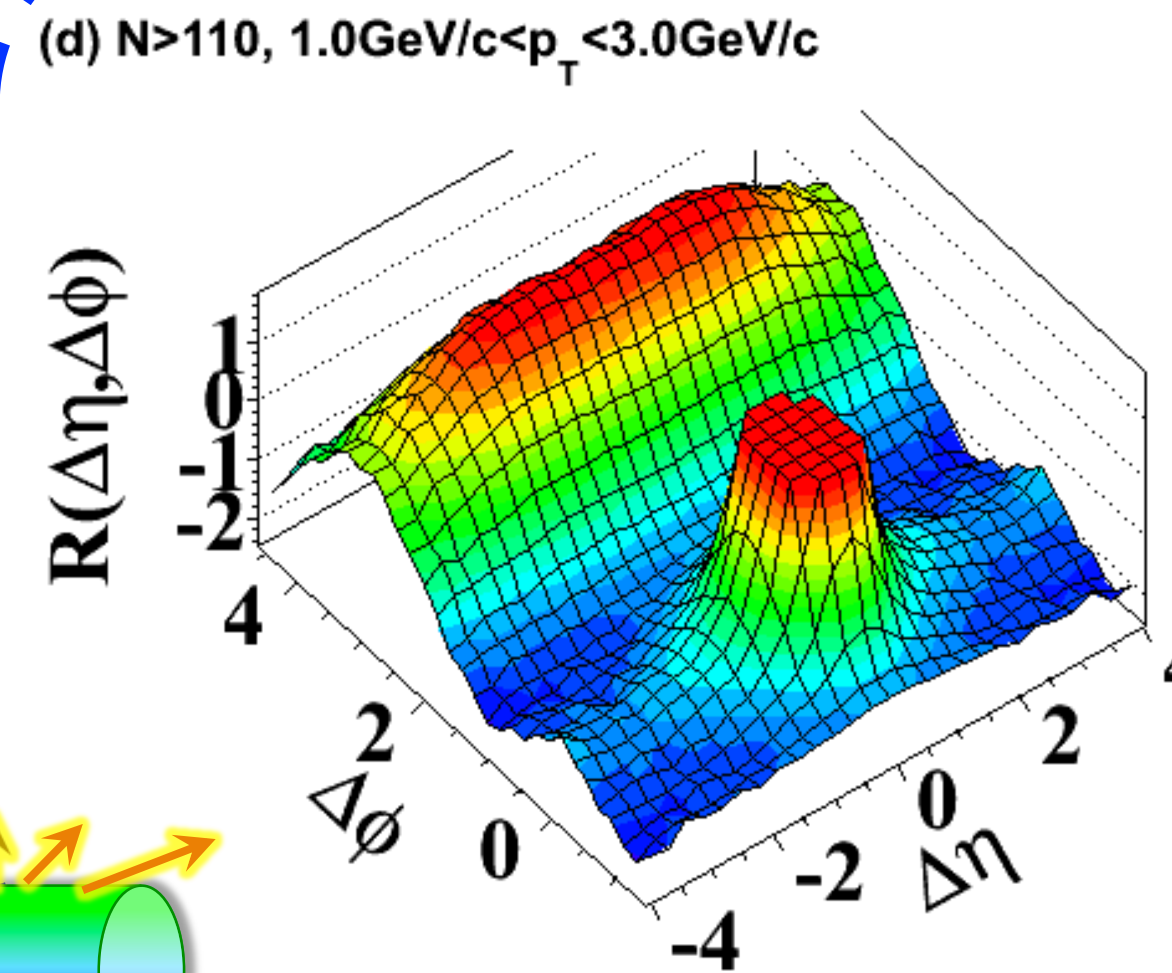
- Multiple scattering effects in high density proton pdf at low x. Nonlinear QCD.

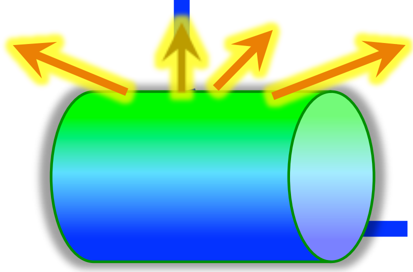
Ridge Formation

Two particle correlations: CMS results



"Discovery"



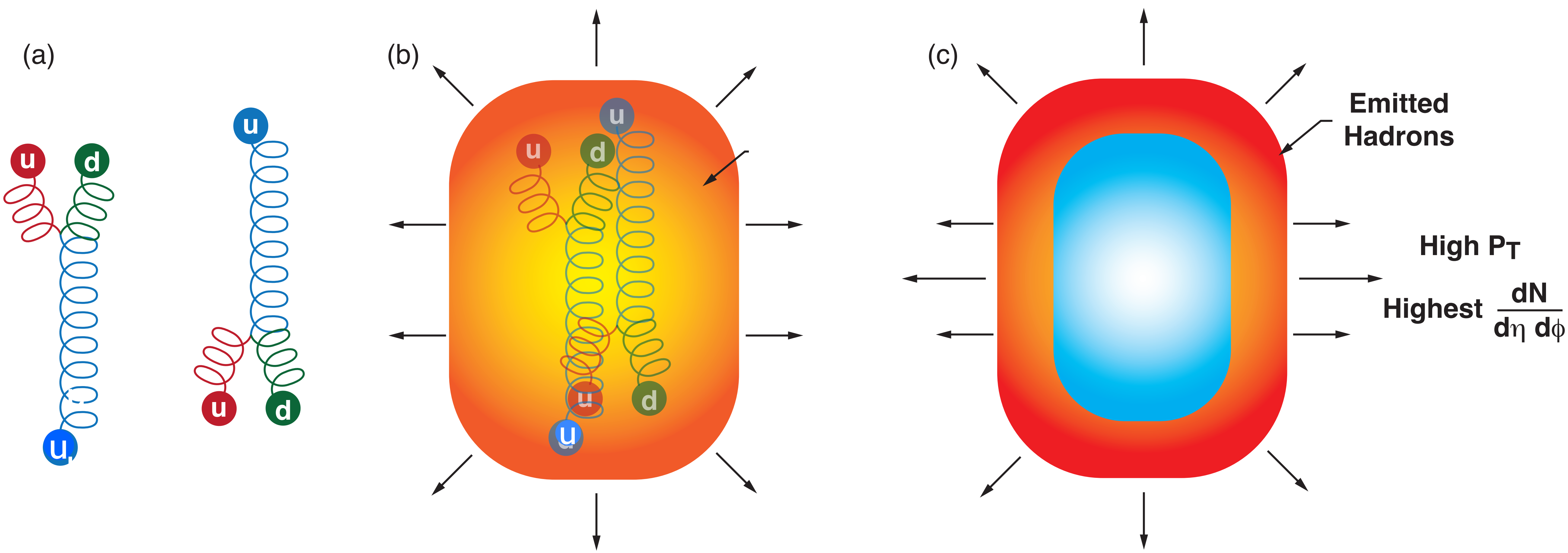


- Ridge: Distinct long range correlation in η collimated around $\Delta\Phi \approx 0$ for two hadrons in the intermediate $1 < p_T, q_T < 3$ GeV

High Multiplicity Events

Origin of same-side CMS ridge in p p Collisions

Collision of Flux Tubes **Bjorken, Goldhaber, sjb**



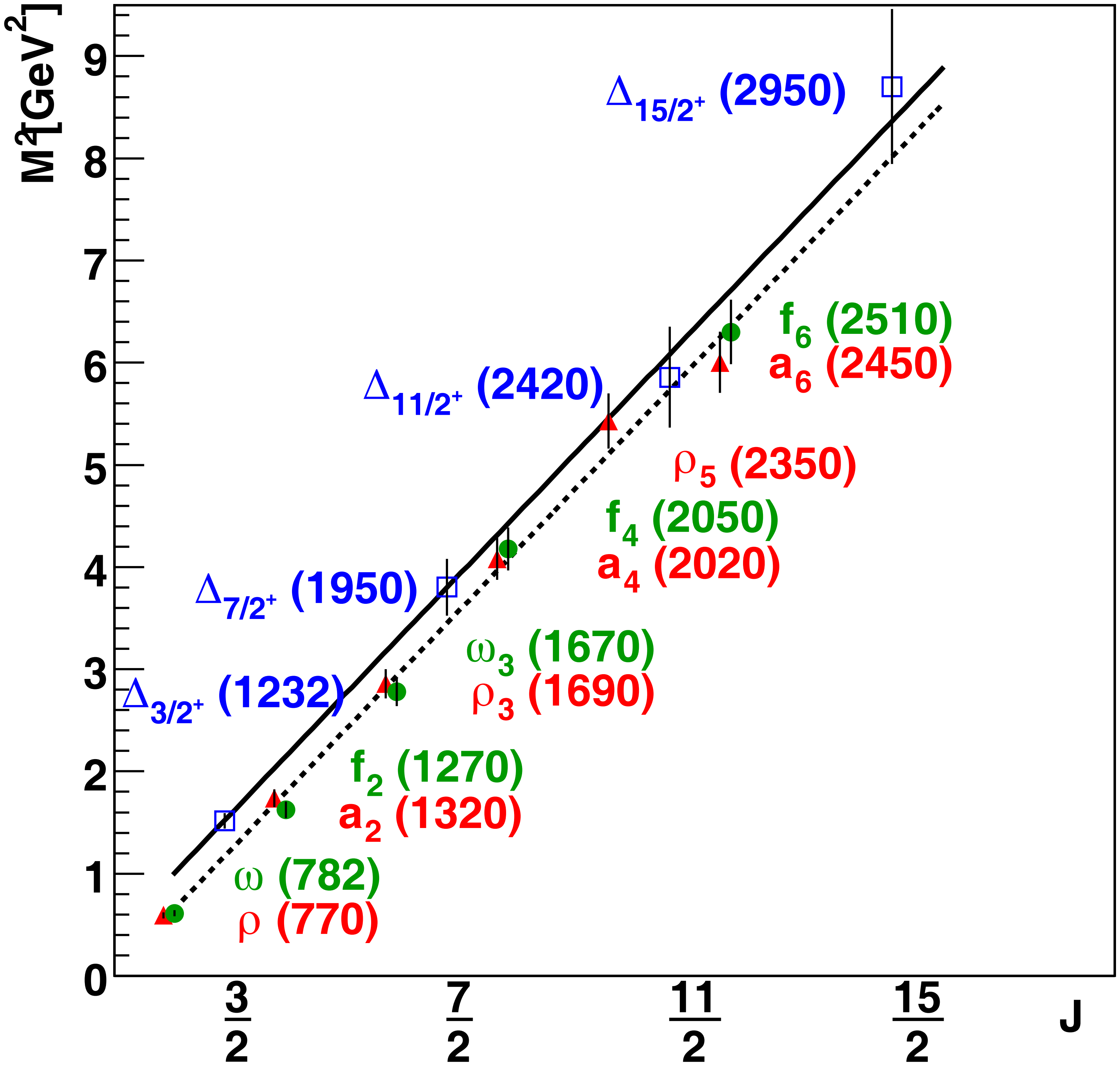
$$\vec{V} = \sum_{i=1}^{N} [\cos 2\phi_i \hat{x} + \sin 2\phi_i \hat{y}]$$

LFHQD *Light-Front Holographic QCD*

- Predicts Hadron Spectra and Dynamics (LFWFs)
- Color Confinement; Universal Mass Scale
- Illuminates Supersymmetric Features of Hadron Physics: Equal-Mass Mesons, Baryons and Tetraquarks for Light and Heavy Quarks
- Universal Regge Trajectories: in n and L
- Massless composite pion for m_q=0
- Predicts Running QCD coupling at all scales: $\alpha_s(Q^2)$

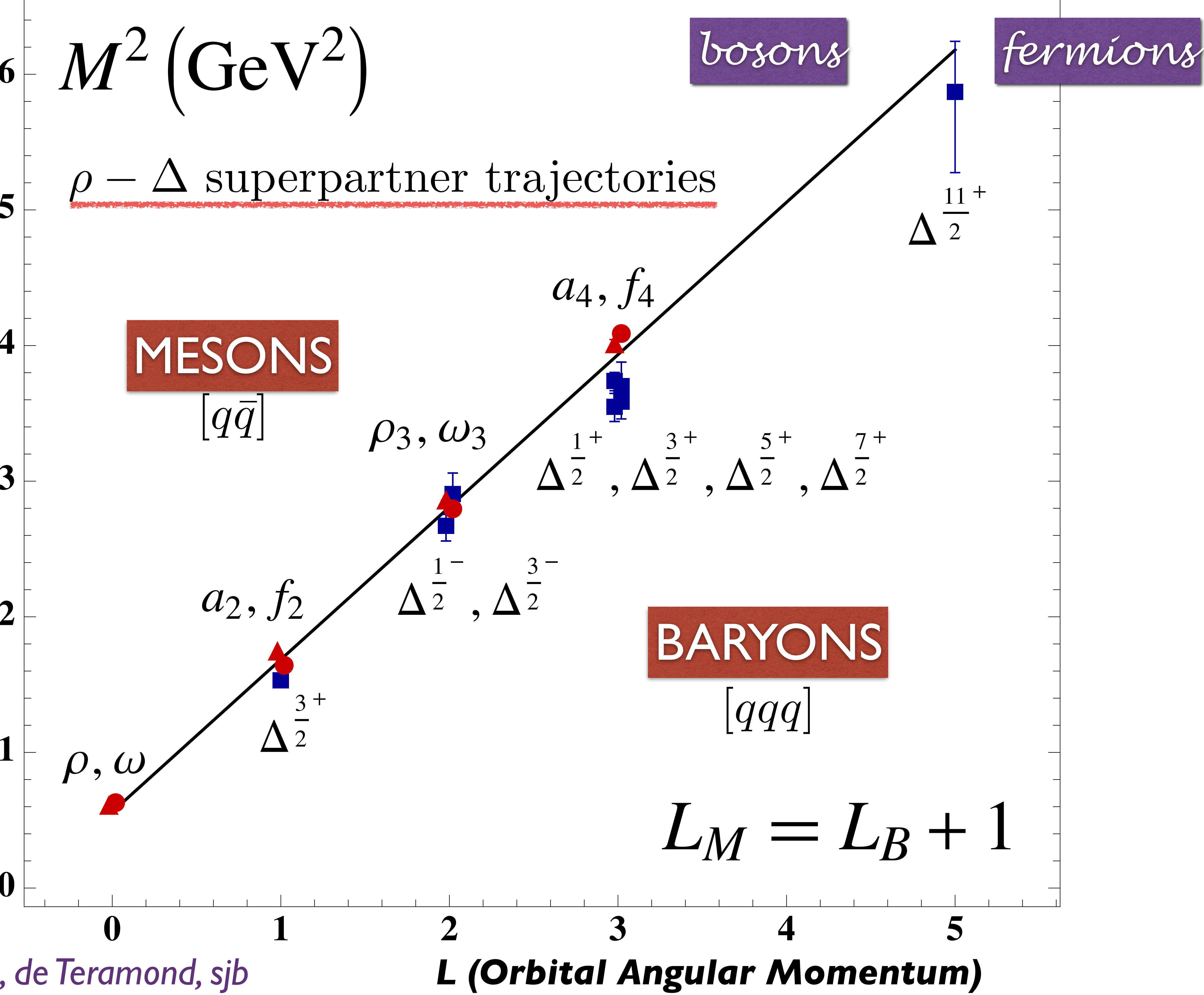
Mesons and Baryons: Same Regge Slope $M^2 \propto J$!

M²[GeV²]



The leading Regge trajectory: Δ resonances with maximal J in a given mass range. Also shown is the Regge trajectory for mesons with J = L+S.

E. Klempt and B. Ch. Metsch

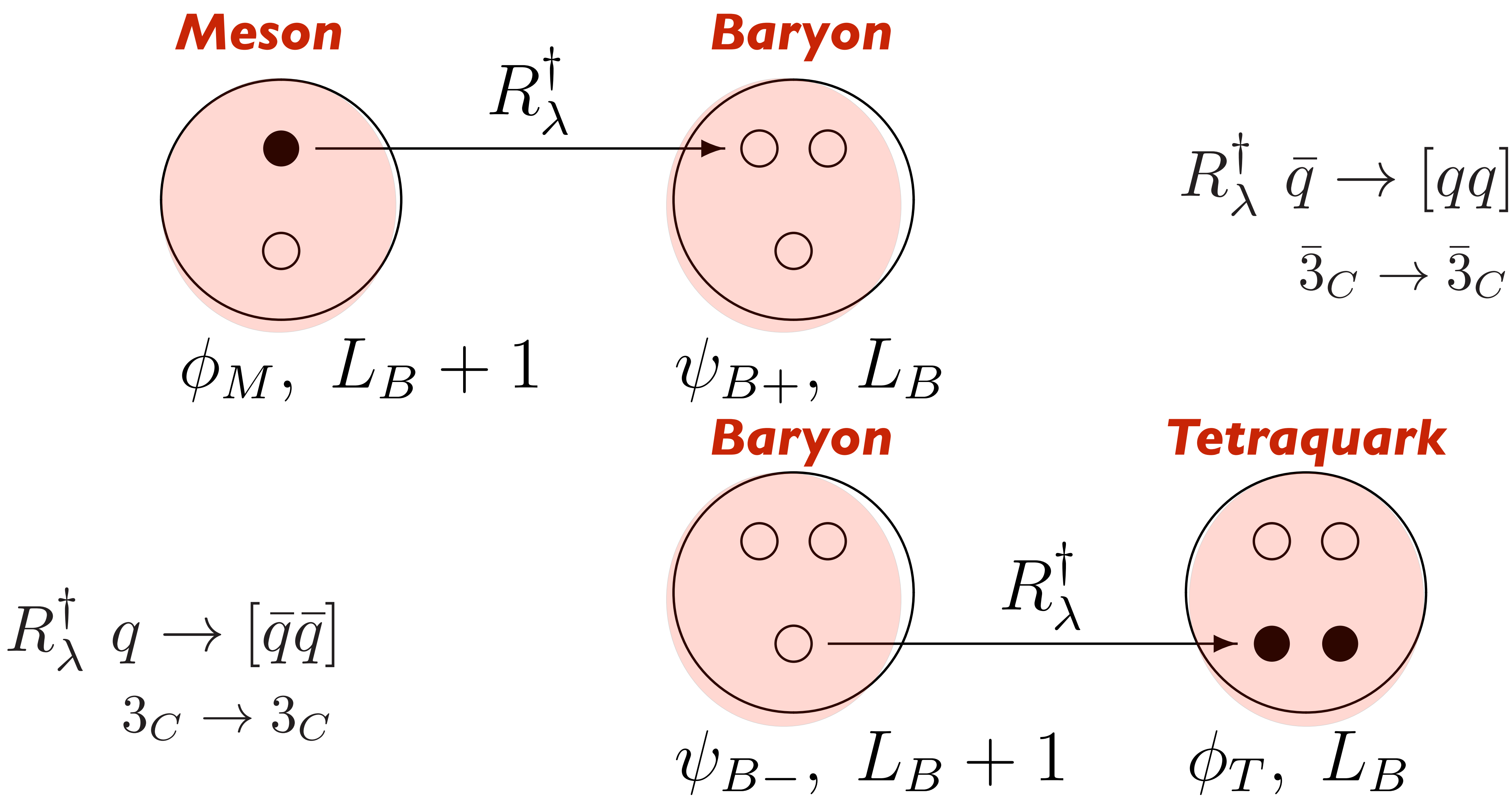


Dosch, de Teramond, sjb

Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



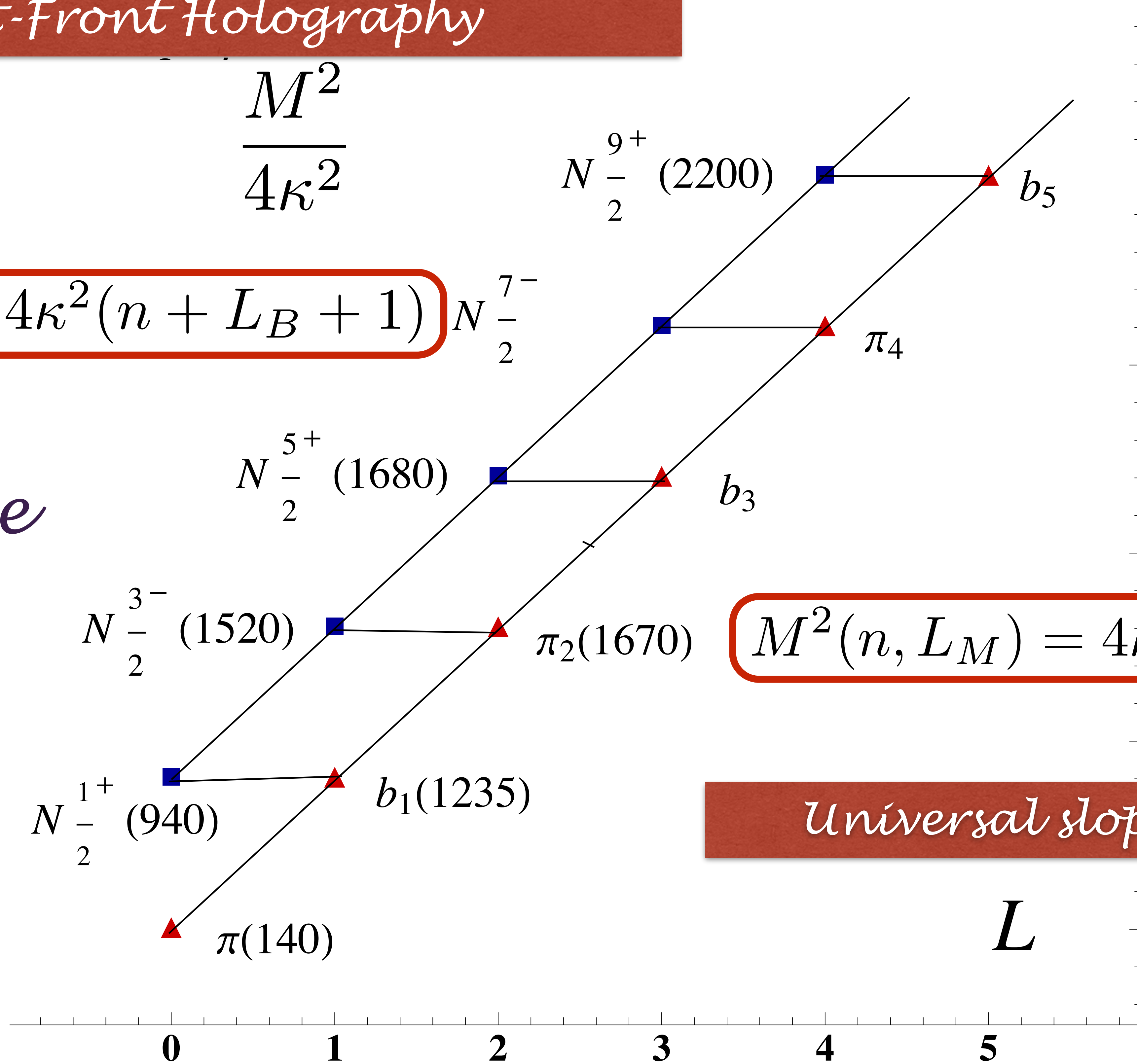
Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

Superconformal Quantum Mechanics
Light-Front Holography

de Tèramond, Dosch, Lorcè, sjb

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

Same slope



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

Universal slopes in n, L

$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

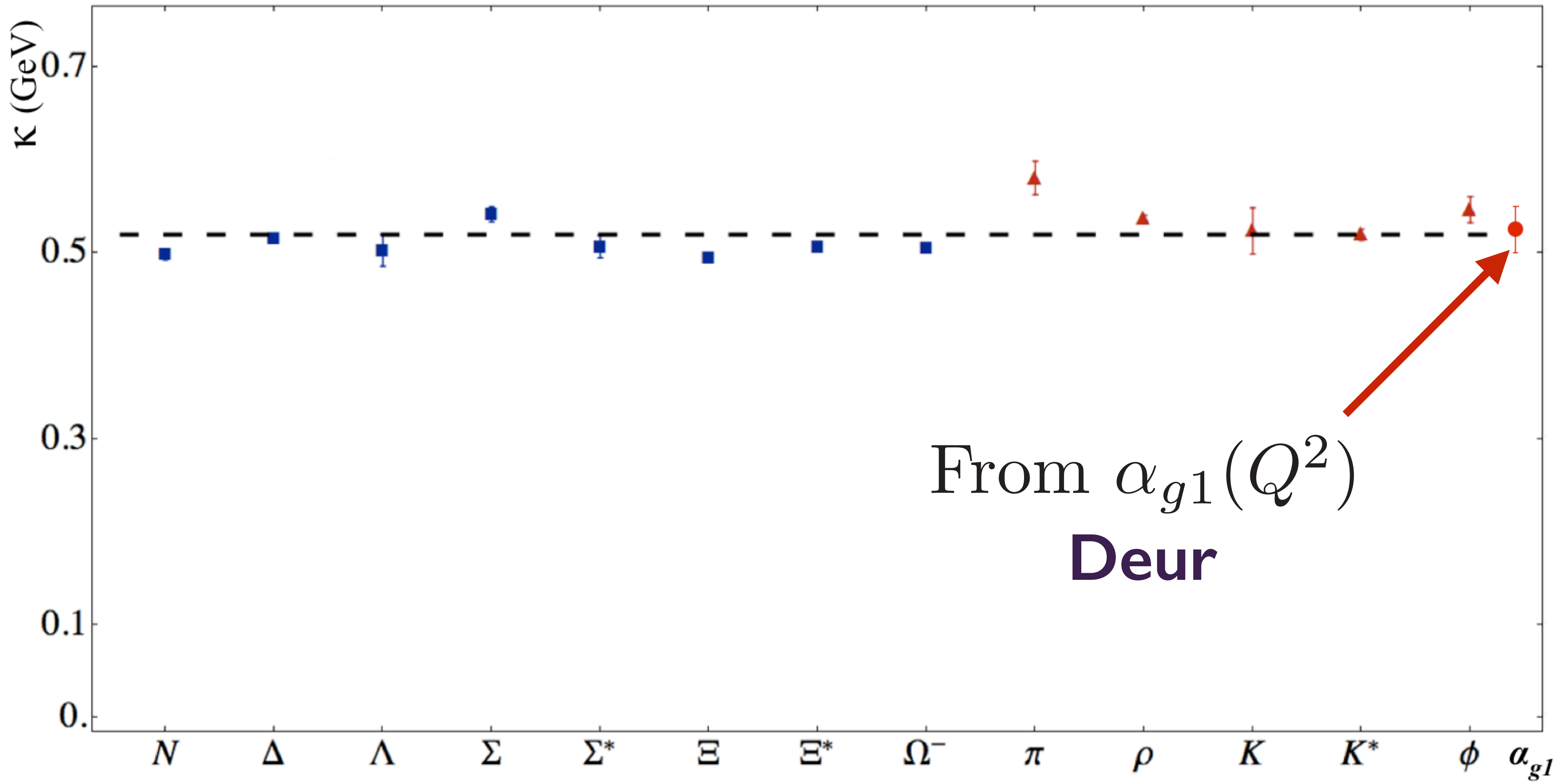
Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

$\lambda = \kappa^2$

de Tèramond, Dosch, Lorce', sjb

$$m_u = m_d = 46 \text{ MeV}, \; m_s = 357 \text{ MeV}$$

κ

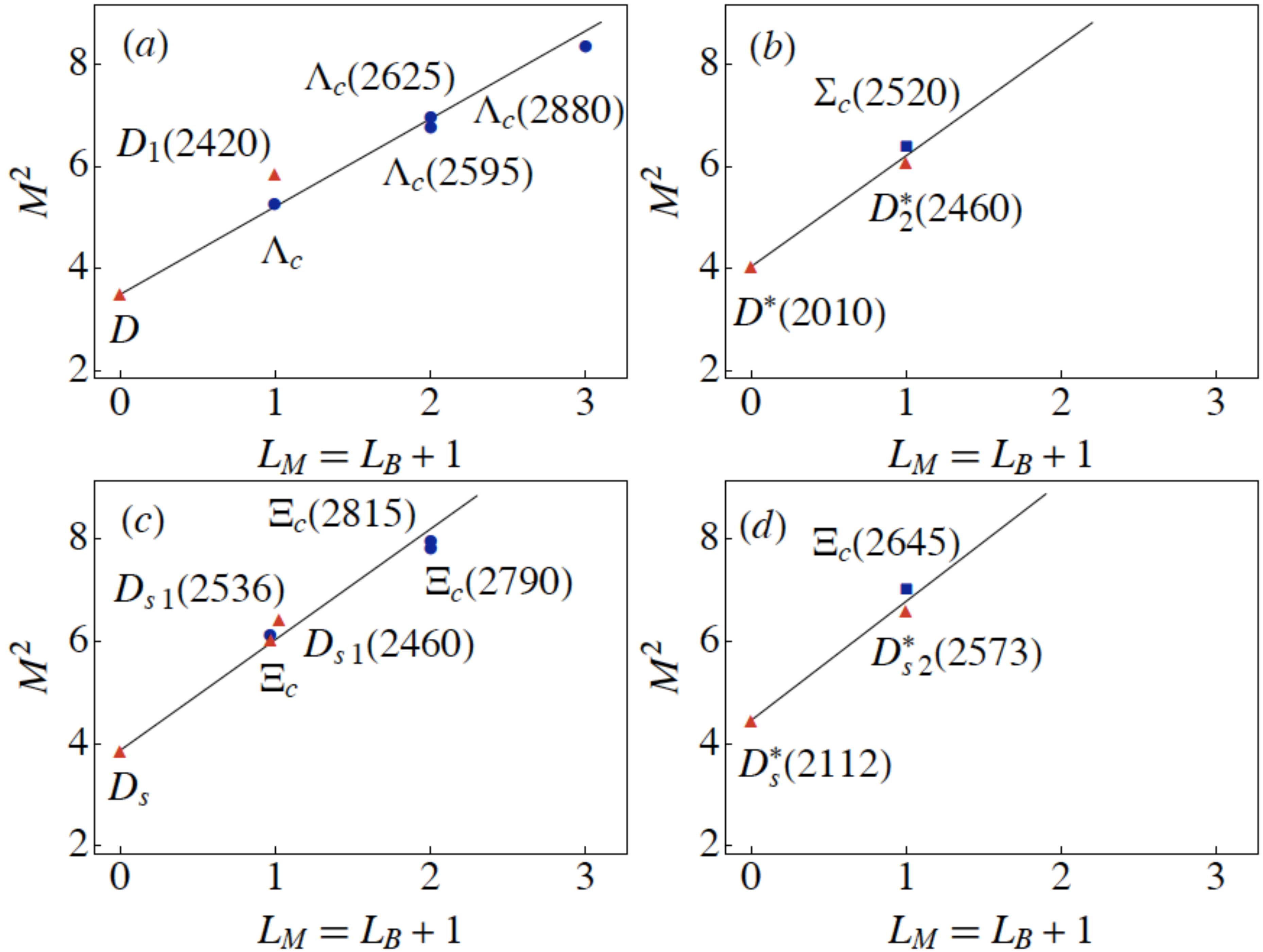


Fit to the slope of Regge trajectories, including radial excitations

Same Regge Slope for Meson, Baryons: Supersymmetric feature of hadron physics

de Téramond, Dosch, Nielsen, sjb

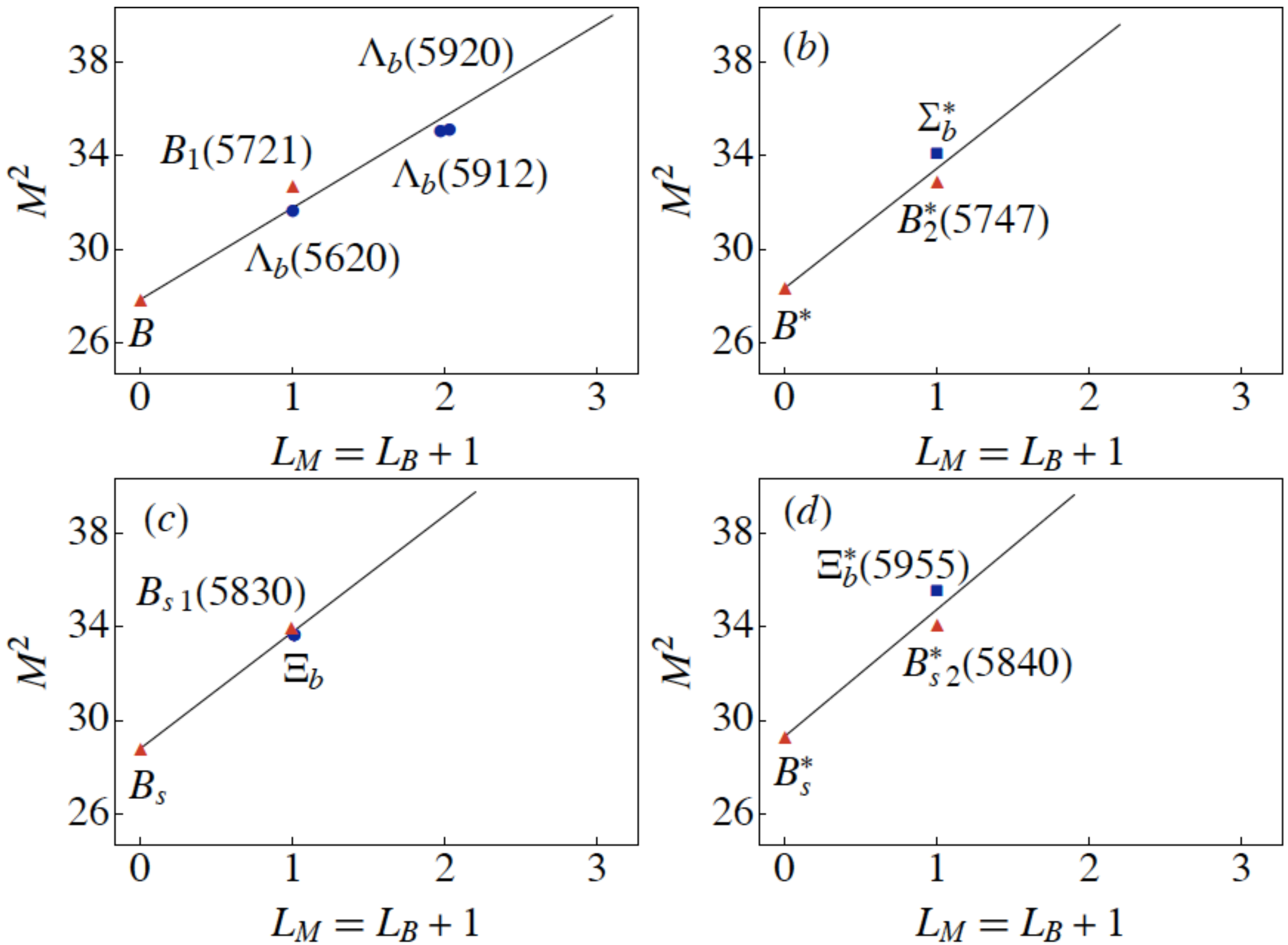
Supersymmetry across the light and heavy-light spectrum



Heavy charm quark mass does not break supersymmetry

de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum

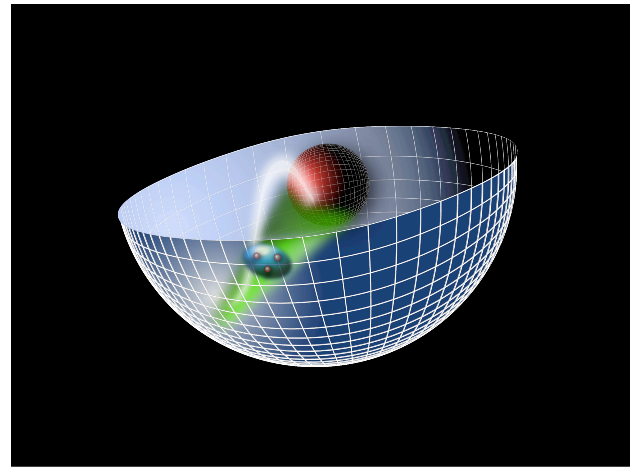


Heavy bottom quark mass does not break supersymmetry

Supersymmetry in QCD

- A hidden symmetry of Color SU(3) in hadron physics
- QCD: No squarks or gluinos!
- Emerges from Light-Front Holography and Super-Conformal Algebra
- Color Confinement
- Massless Pion in Chiral Limit
- QCD coupling $\alpha_s(Q^2)$ in non-perturbative domain

de Tèramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

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

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

Light-Front Holography

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

Light-Front Schrödinger Equation

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

Single variable ζ

Unique Confinement Potential!

Conformal Symmetry of the action

Confinement scale: $\kappa \simeq 0.5\ GeV$

- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

GeV units external to QCD: Only Ratios of Masses Determined

Massless pion!

Meson Spectrum in Soft Wall Model

$$m_\pi = 0 \text{ if } m_q = 0$$

Pion: Negative term for J=0 cancels positive terms from LFKE and potential

- Effective potential: $U(\zeta^2) = \kappa^4\zeta^2 + 2\kappa^2(J-1)$
- LF WE

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2\phi_J(\zeta)$$

- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta\, \phi^2(z)^2 = 1$

$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L}e^{-\kappa^2\zeta^2/2}L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

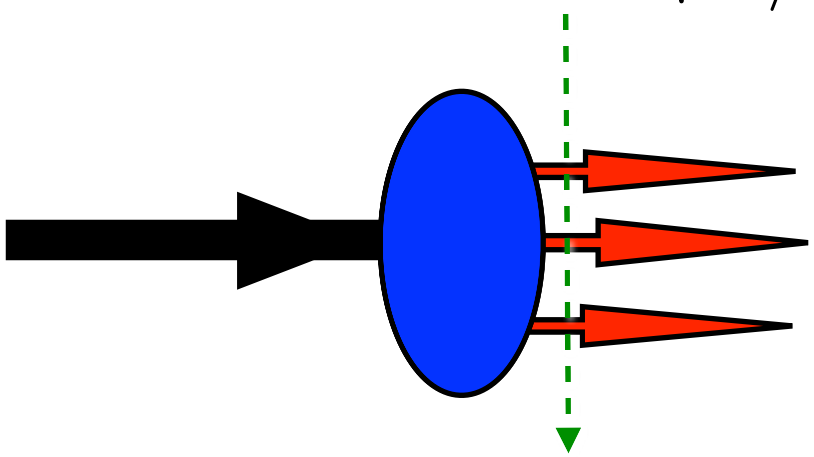
$$\vec{\zeta}^2 = \vec{b}^2_\perp x(1-x)$$

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

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

Dirac's Front Form: Fixed $\tau = t + z/c$



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

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

Invariant under boosts. Independent of P^μ

$$\mathrm{H}_{LF}^{QCD} |\psi> = M^2 |\psi>$$

Direct connection to QCD Lagrangian

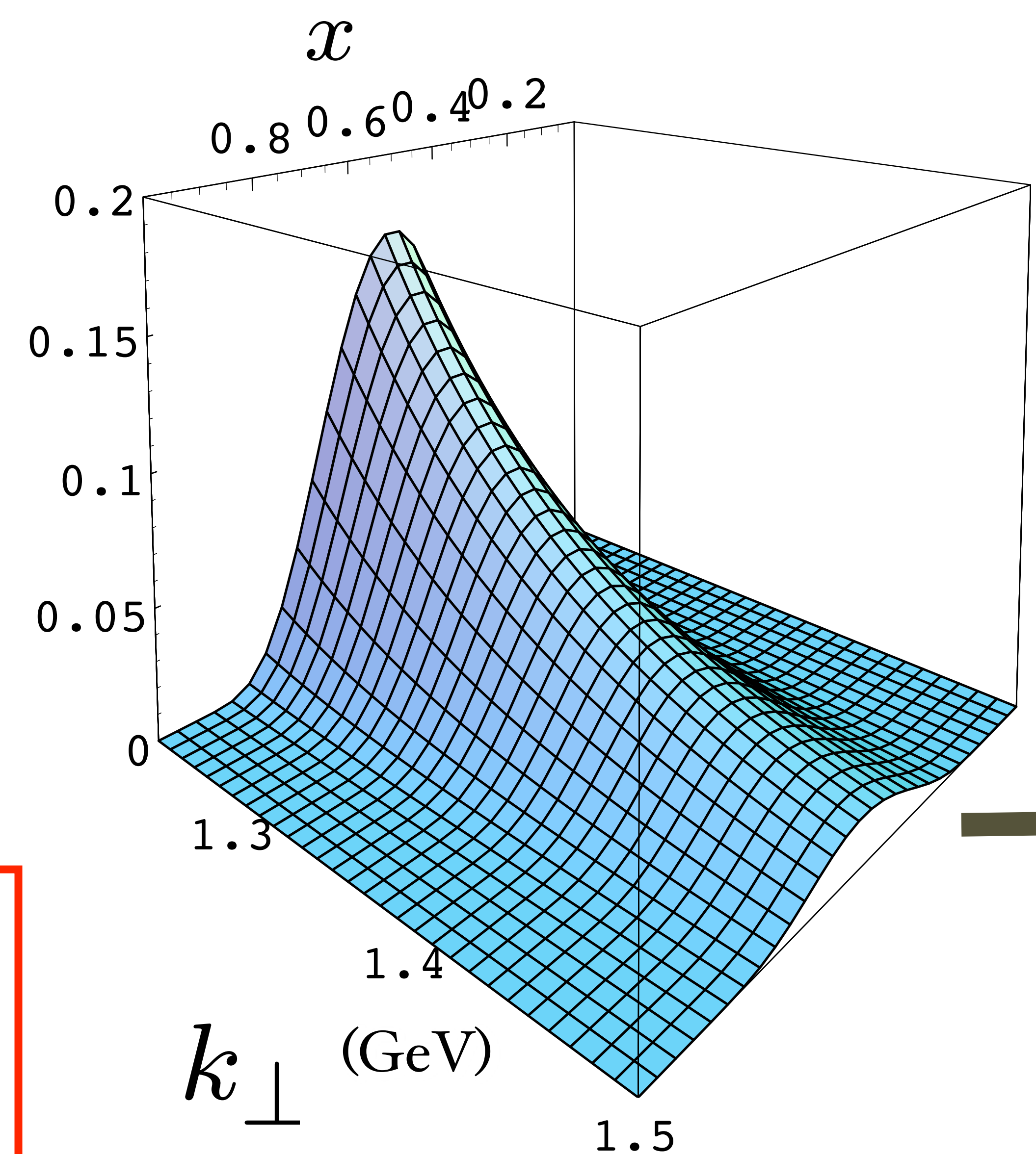
Off-shell in invariant mass

Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Prediction from AdS/QCD: Meson LFWF

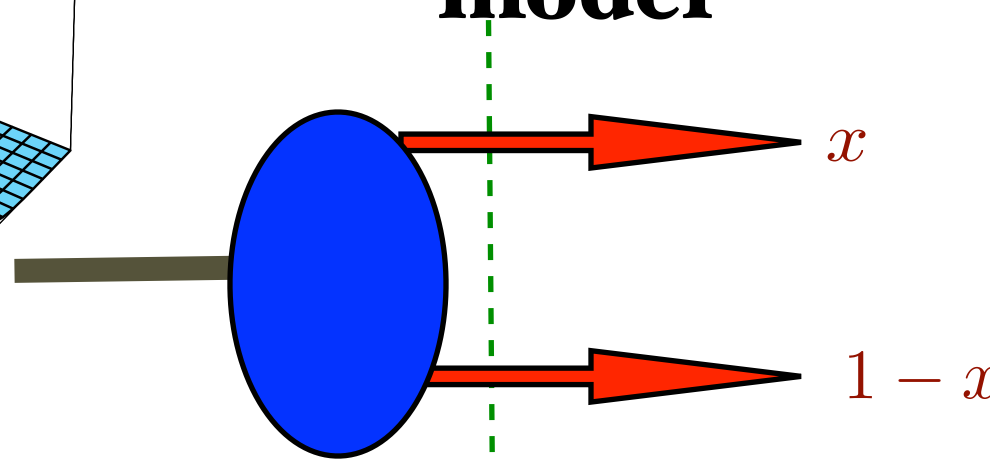
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

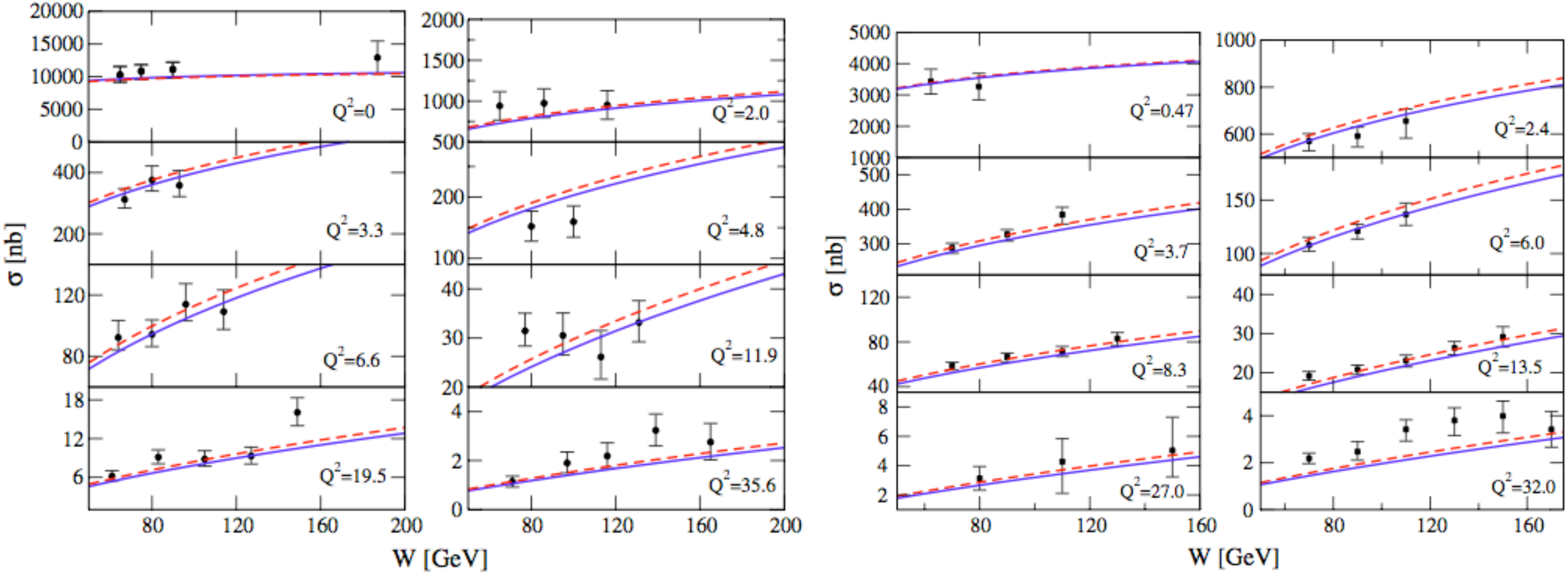
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

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

Same as DSE! **C. D. Roberts et al.**

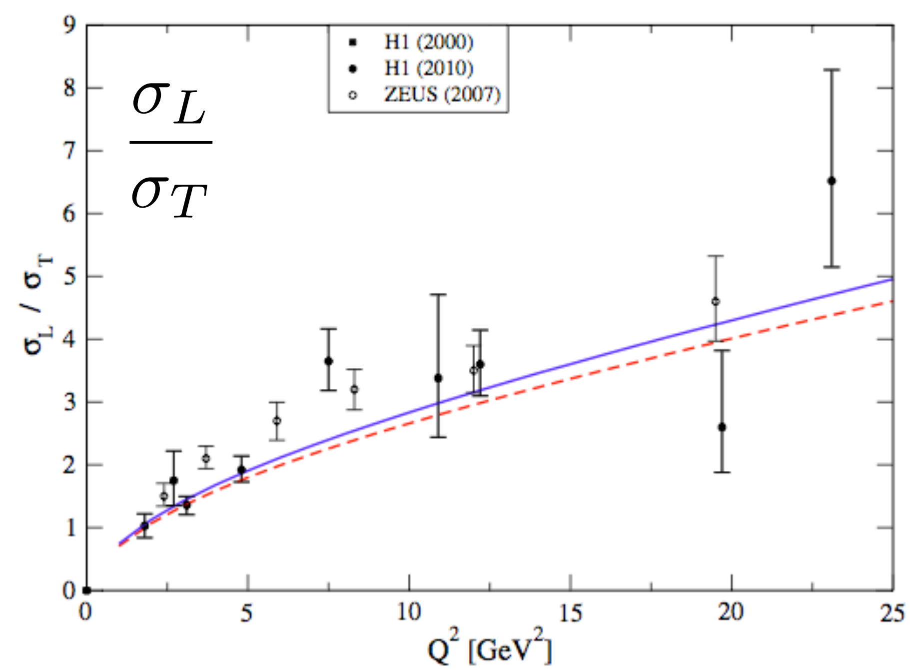
Provides Connection of Confinement to Hadron Structure

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



(a) H1

(b) ZEUS



J. R. Forshaw, R. Sandapen

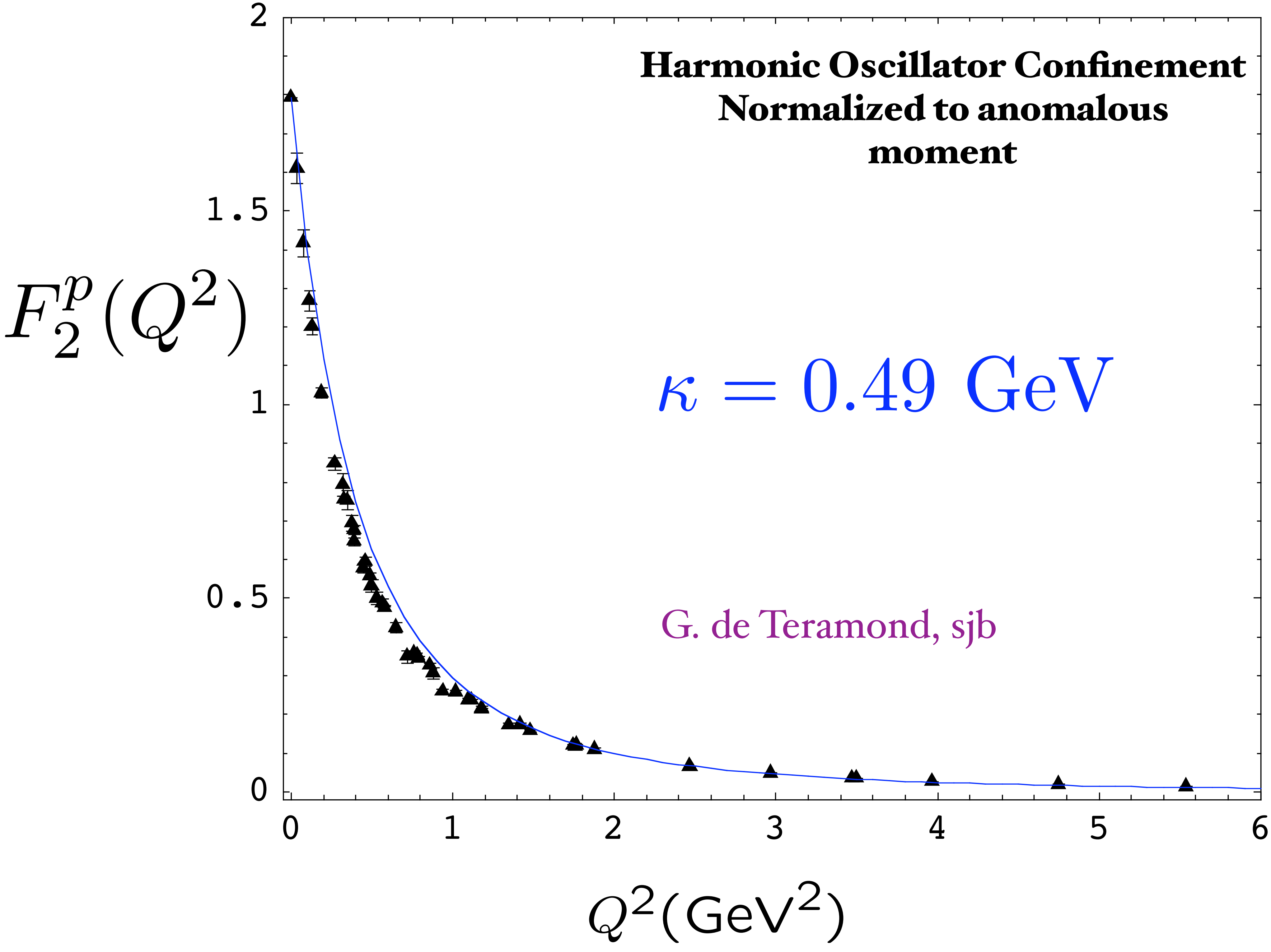
$$\frac{\sigma_L}{\sigma_T}$$

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

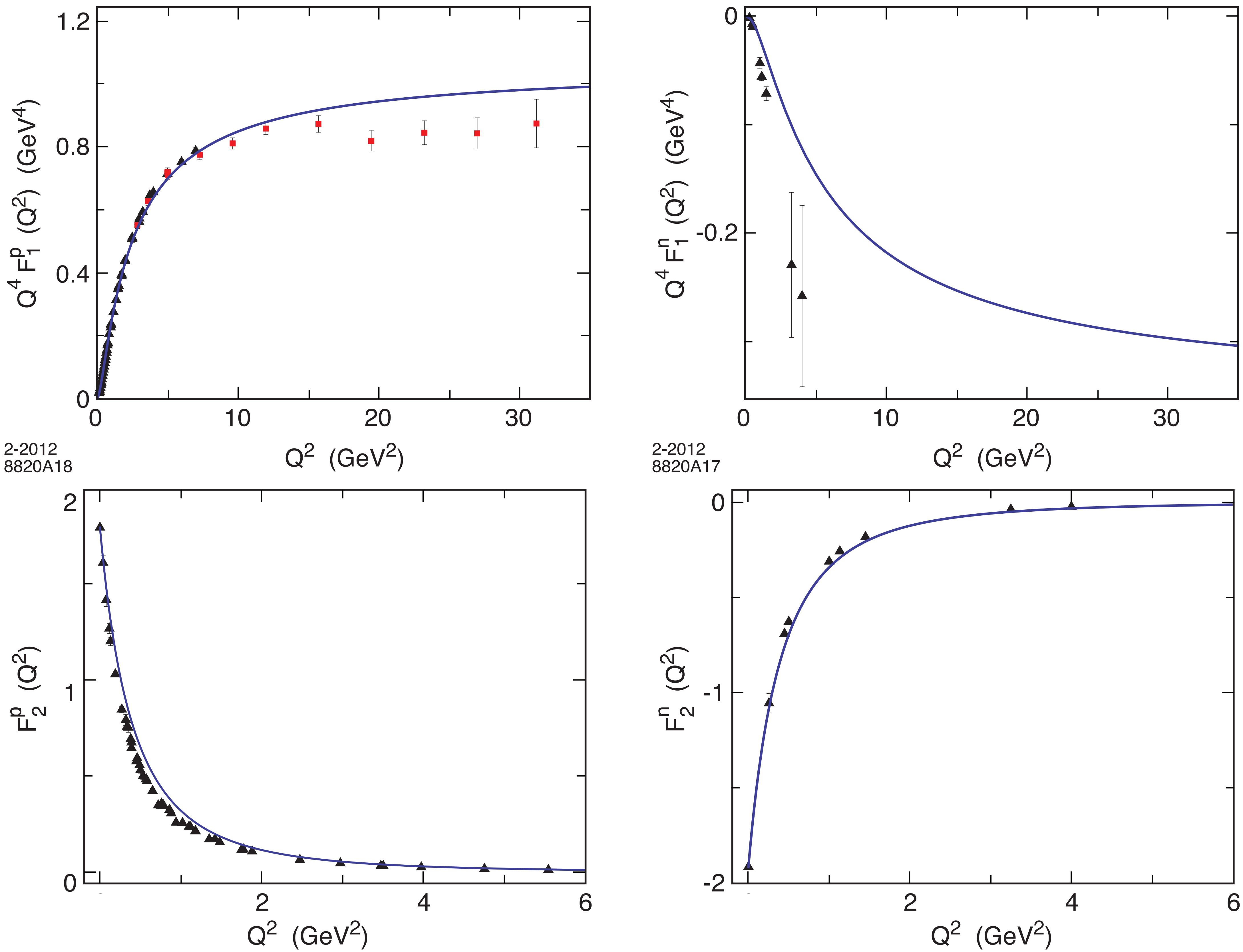
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

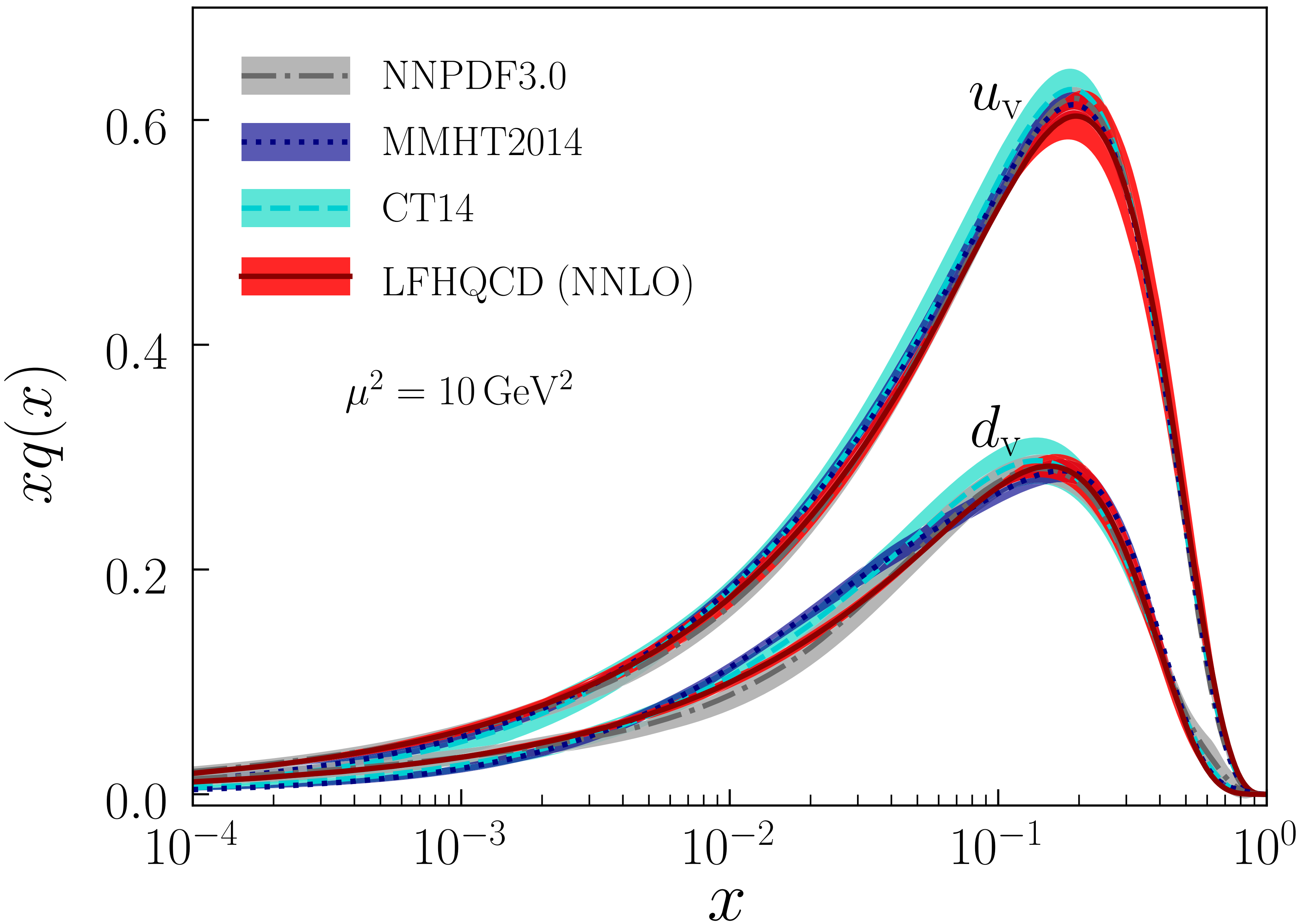
Spacelike Pauli Form Factor

From overlap of $L = 1$ and $L = 0$ LFWFs



Using $SU(6)$ flavor symmetry and normalization to static quantities



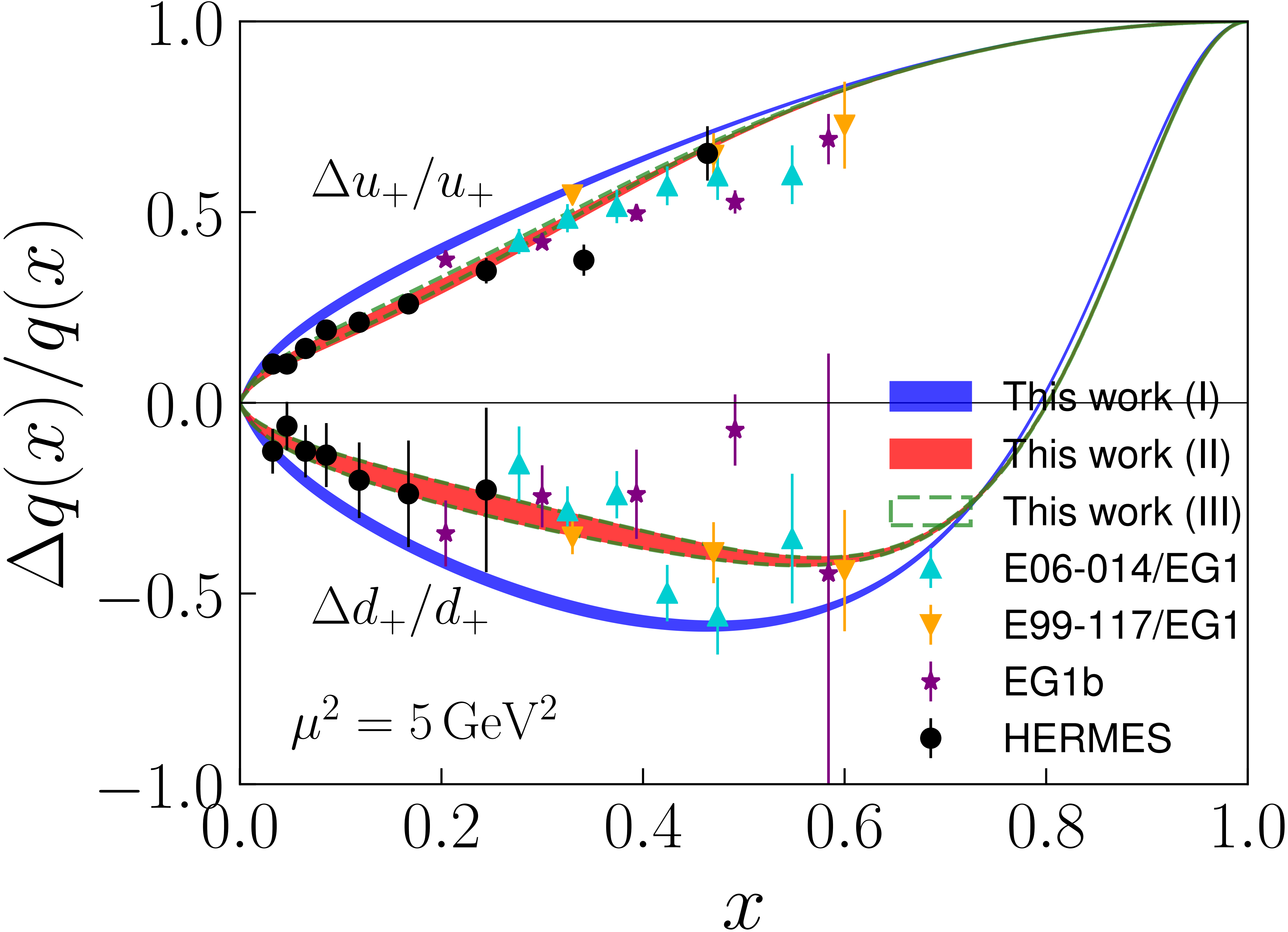


Comparison for $xq(x)$ in the proton from LFHQCD (red bands) and global fits: MMHT2014 (blue bands) [5], CT14 [6] (cyan bands), and NNPDF3.0 (gray bands) [77]. LFHQCD results are evolved from the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV.

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur

PHYSICAL REVIEW LETTERS 120, 182001 (2018)



Helicity asymmetries of $u(x) + \bar{u}(x)$ and $d(x) + \bar{d}(x)$ compared with measurements.

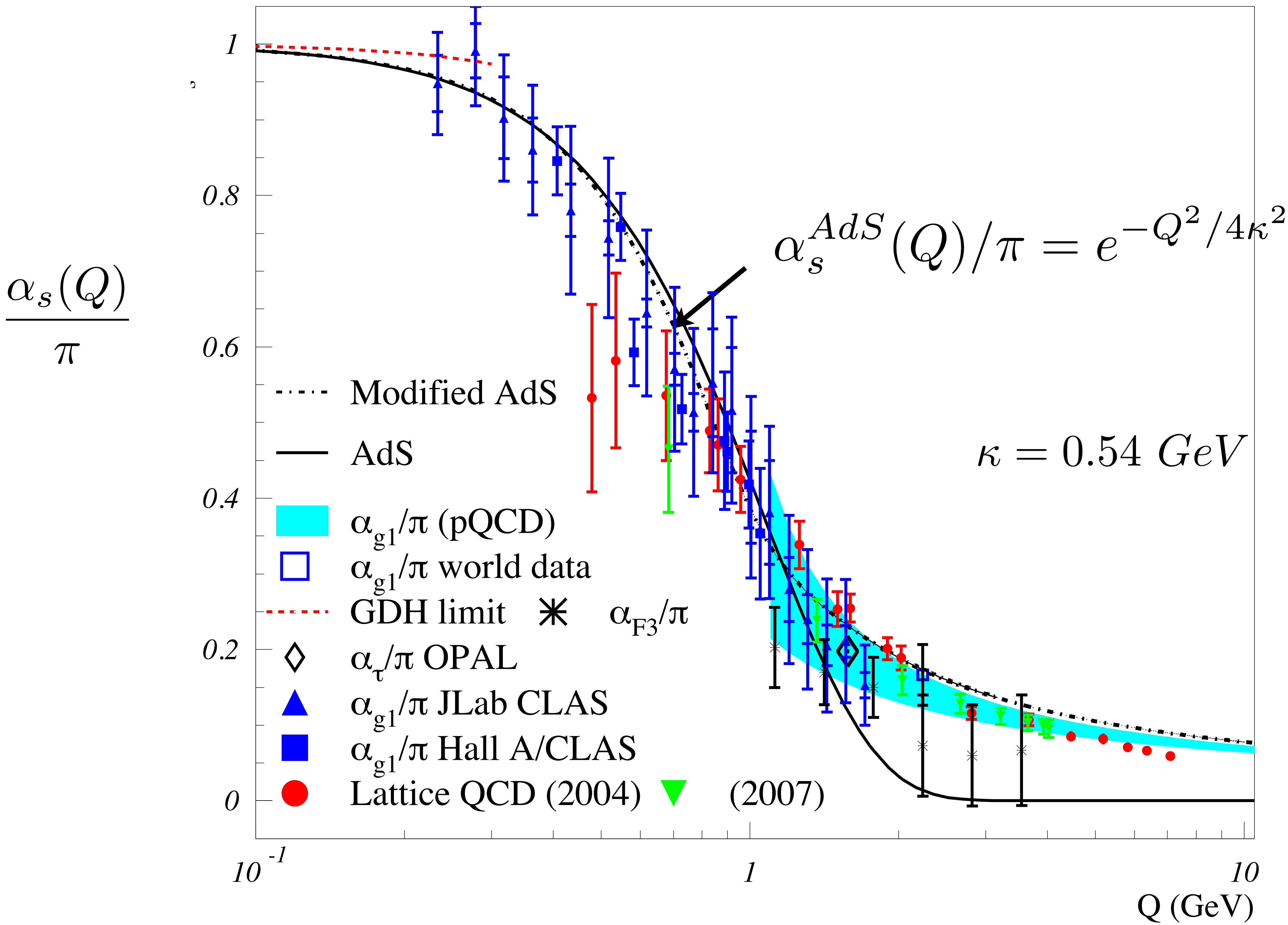
Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur

Bjorken sum rule defines effective charge $\alpha_{g1}(Q^2)$

$$\int_0^1 dx[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{g_a}{6}[1 - \frac{\alpha_{g1}(Q^2)}{\pi}]$$

- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal β_0, β_1***

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

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

$$m_p = 2\kappa$$

All-Scale QCD Coupling

Deur, de Tèramond, sjb

Fit to Bj + DHG Sum Rules:

$$\kappa = 0.513 \pm 0.007 \ GeV$$

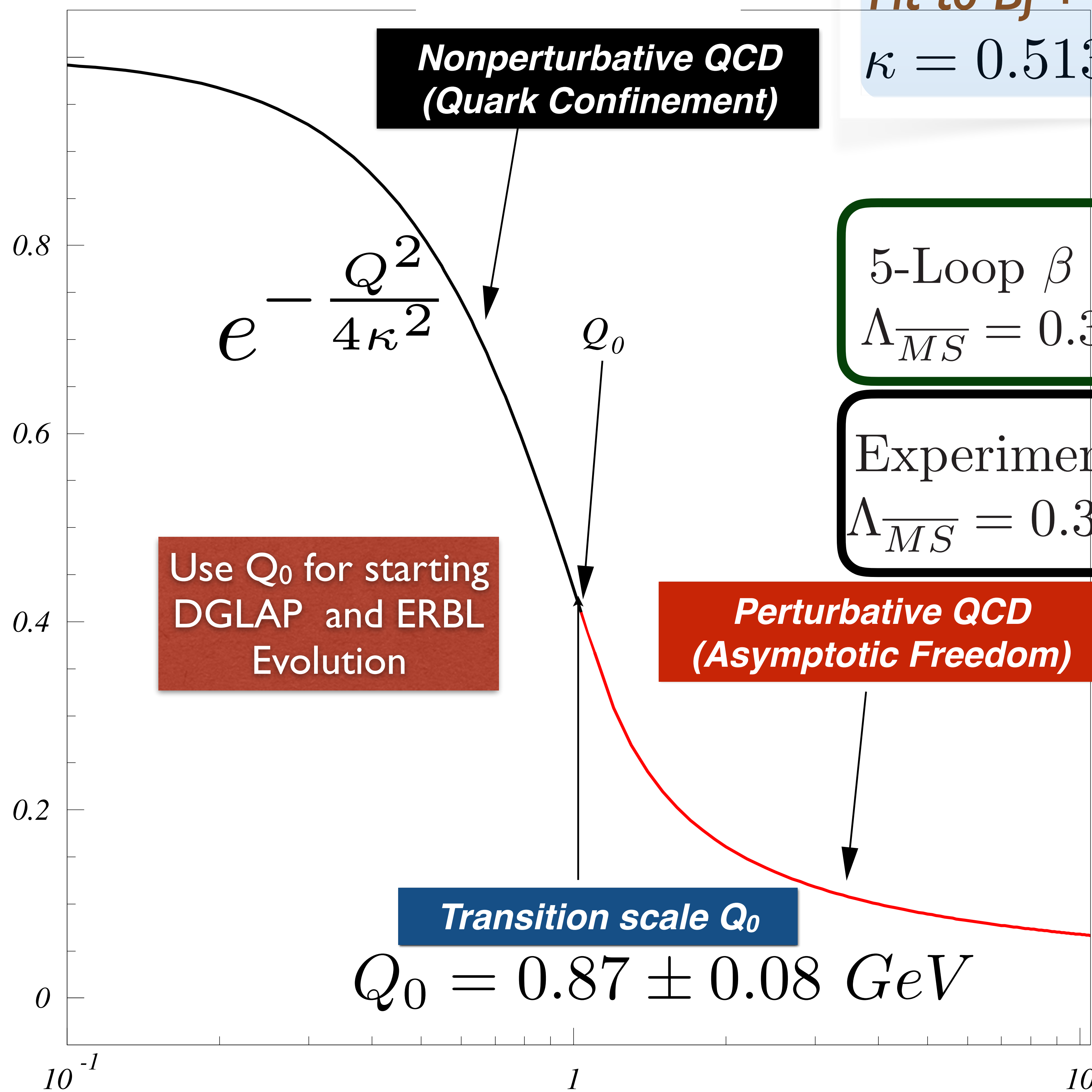
5-Loop β Prediction:

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.019 \ GeV$$

Experiment:

$$\Lambda_{\overline{MS}} = 0.332 \pm 0.017 \ GeV$$

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



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

$\overline{MS}$ scheme

Reverse Dimensional Transmutation!

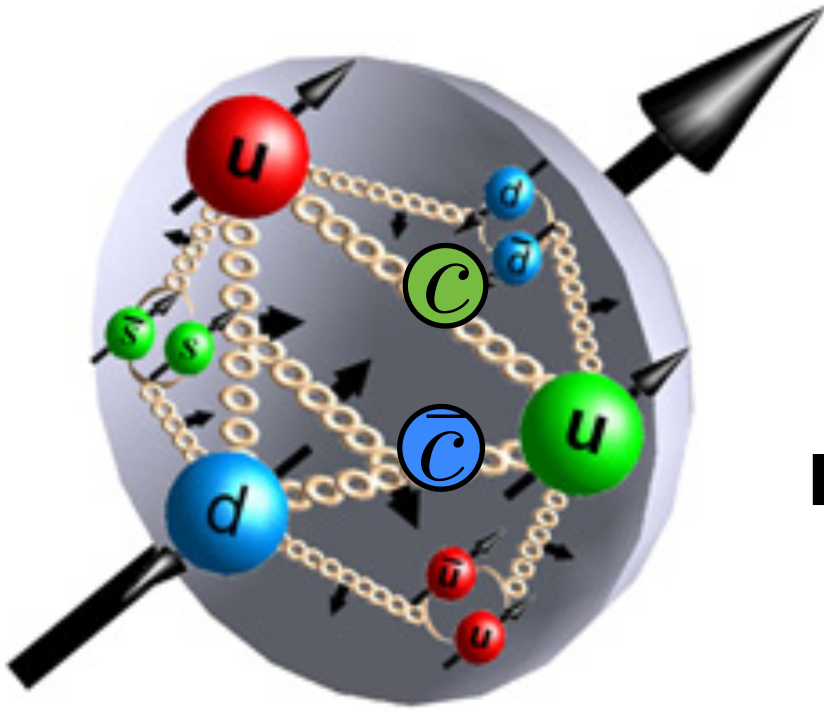
Light-Front Holography: First Approximation to QCD

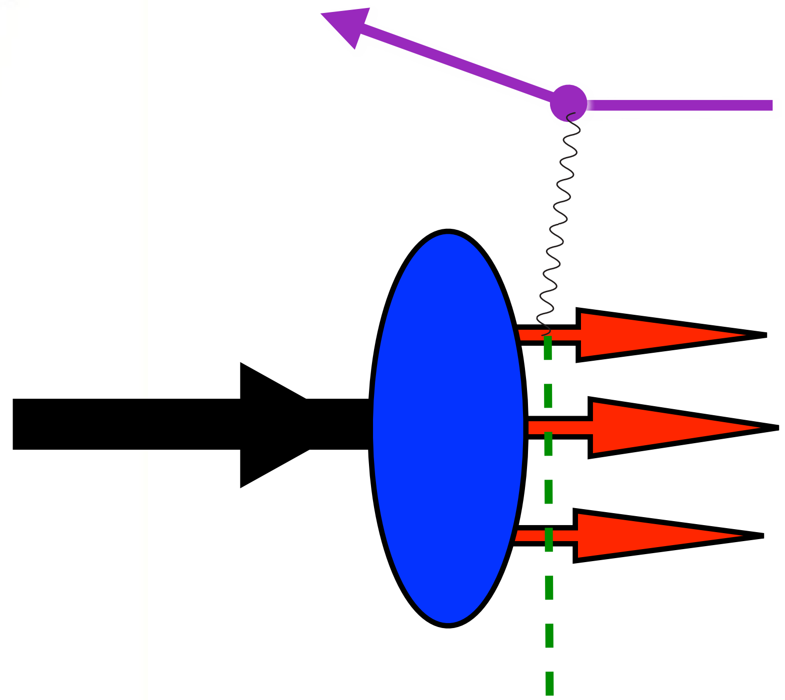
- Color Confinement, Analytic form of confinement potential
- Retains underlying conformal properties of QCD despite mass scale (DeAlfaro-Fubini-Furlan Principle)
- Massless quark-antiquark pion bound state in chiral limit, GMOR
- QCD coupling at all scales
- Connection of perturbative and nonperturbative mass scales
- Poincarè Invariant
- Hadron Spectroscopy-Regge Trajectories with universal slopes in n, L
- Supersymmetric 4-Plet: Meson-Baryon -Tetraquark Symmetry
- Light-Front Wavefunctions
- Form Factors, Structure Functions, Hadronic Observables
- OPE: Constituent Counting Rules
- Hadronization at the Amplitude Level: Many Phenomenological Tests
- Systematically improvable: Basis LF Quantization (BLFQ)

The Impact of the LHeC on Advancing QCD

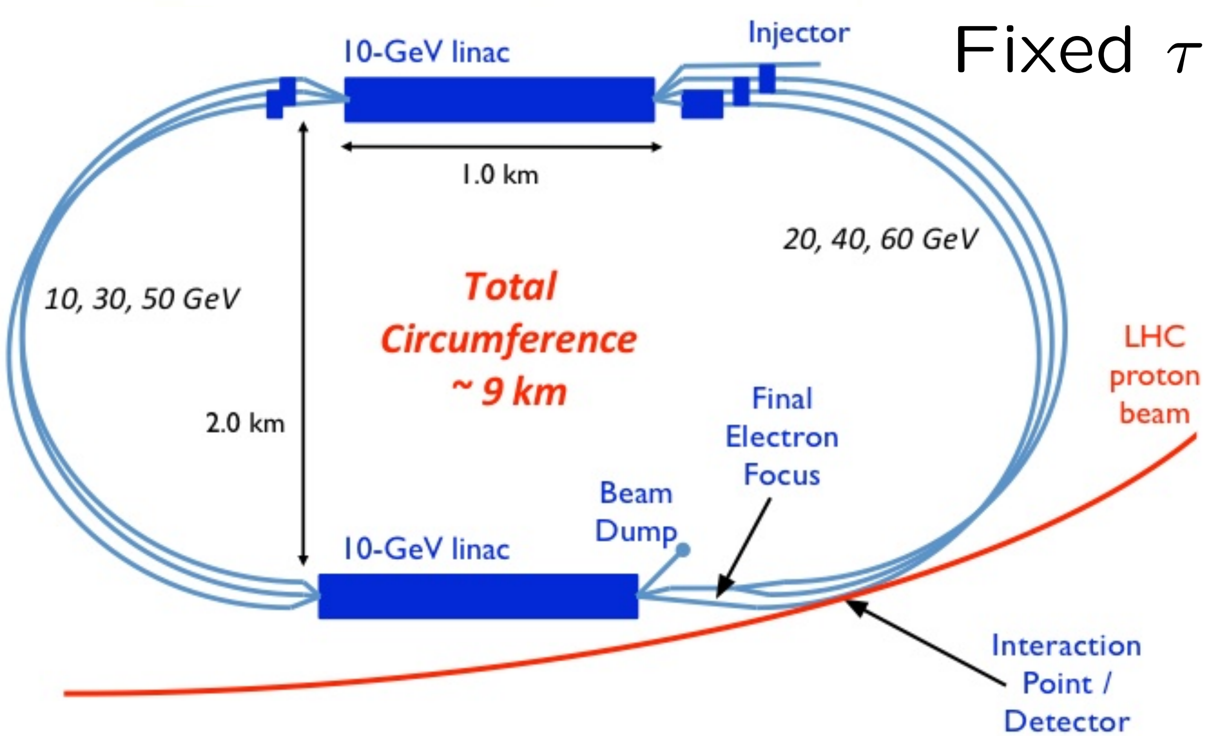
- Testing a New Approach to Color Confinement, Hadron Spectroscopy, Light-Front Dynamics: *Light-Front Holographic QCD*
- Exotic Hadron Production
- Ridge Production from Flux Tube Collisions: *Novel Azimuthal Correlations*
- Hadronization at the Amplitude Level
- Heavy Quark and Flavor Dynamics: Intrinsic Distributions
- Novel Nuclear Structure Phenomena: *Breakdown of Sum Rules for Nuclear PDFs, Flavor-Dependent Antishadowing, Hidden Color, Color Transparency,*
- Violation of Factorization Theorems: *Initial &Final-State Interactions, Novel Spin Phenomena*
- Elimination of Scale Ambiguities:*Principle of Maximum Conformality*

Novel Physics Opportunities at the LHeC





Fixed $\tau = t + z/c$

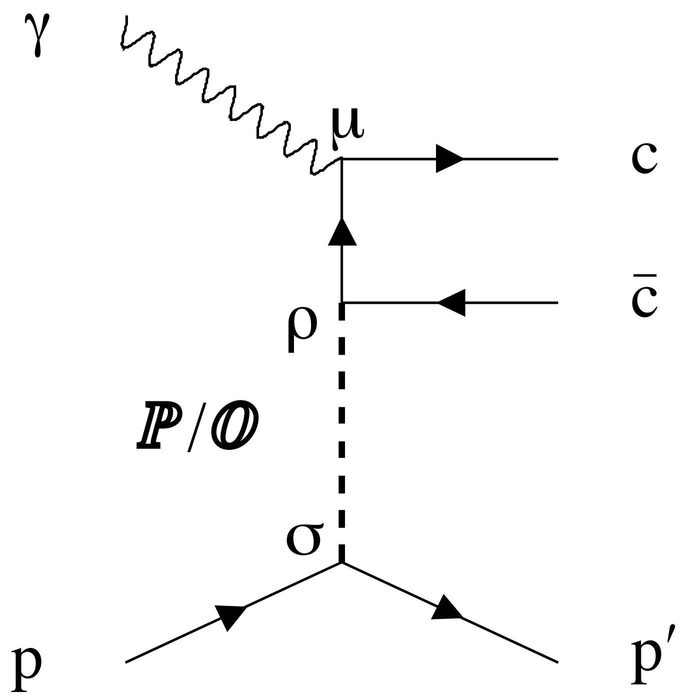


Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

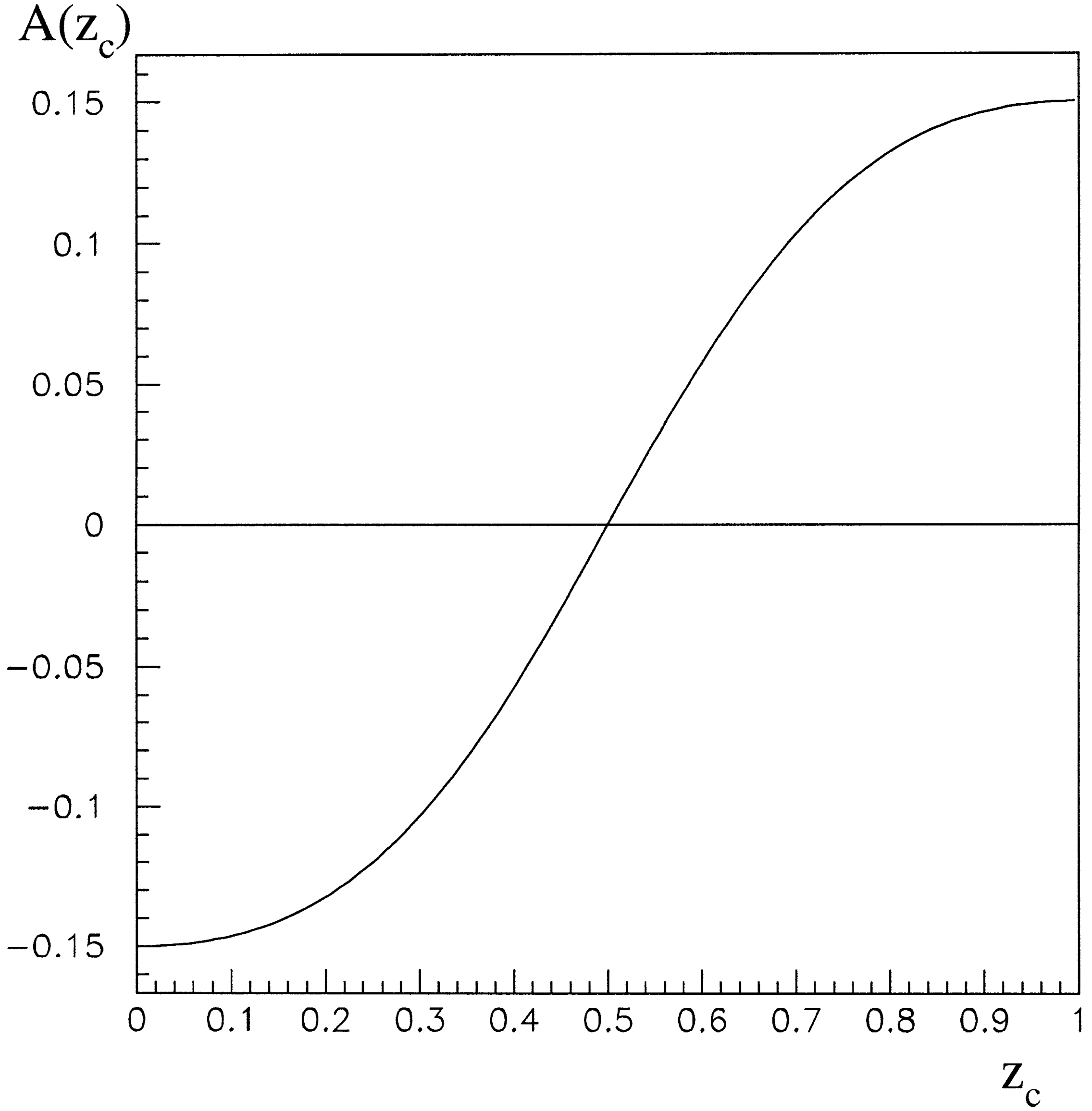
ELECTRONS FOR THE LHC: Workshop on the LHeC, FCC-eh and PERLE

October 24, 2019



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

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