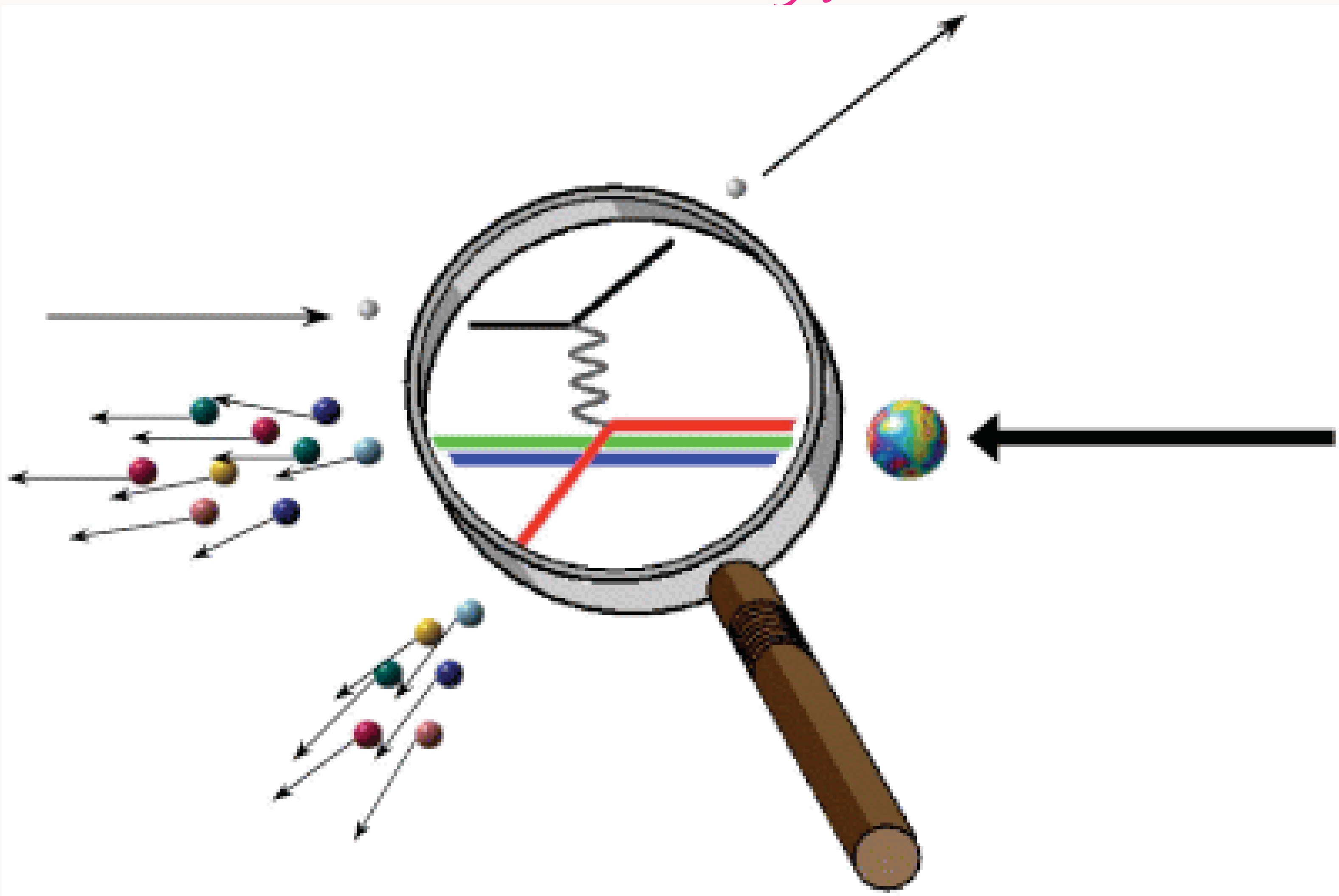
Wish List for HERA

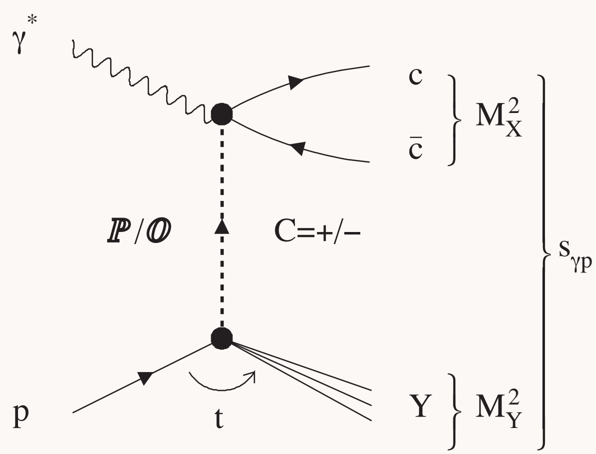
Stan Brodsky, SLAC

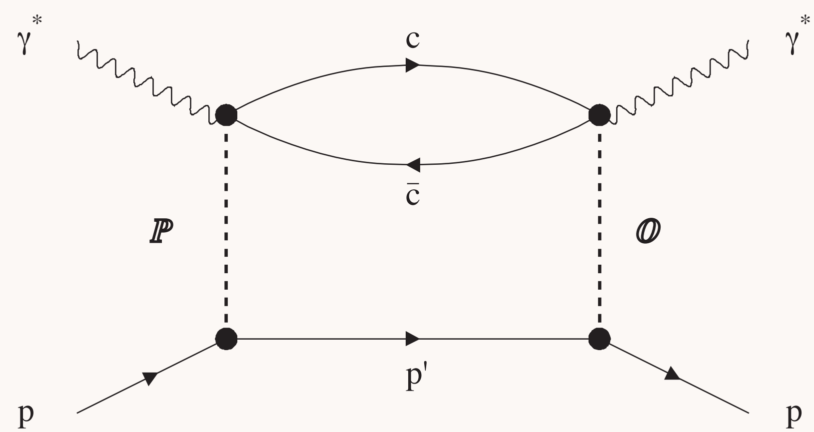


The Odderon

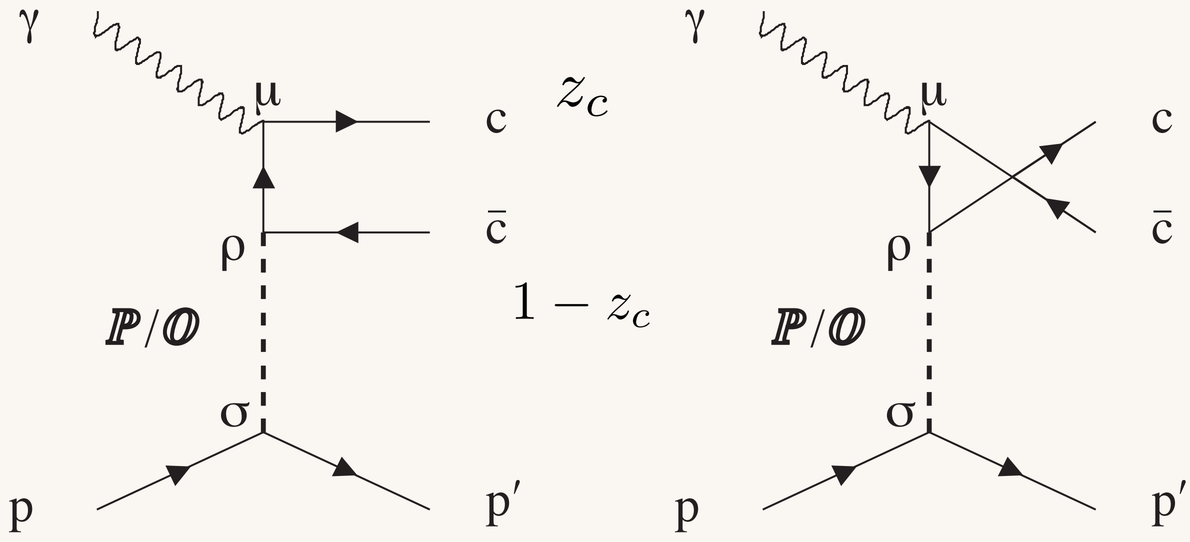
Merino, Rathsman, sjb

A fundamental prediction of QCD is the existence of the Odderon exchange with odd charge conjugation in the t-channel reflecting three-gluon exchange. The measurement of the asymmetry in the fractional energy distribution of charm versus anti-charm jets produced in high energy diffractive photoproduction $\gamma p \to c\bar{c} + p$ at eRHIC would provide a sensitive test of the interference of the Odderon and Pomeron exchange amplitudes in QCD. Another possible test is to measure the energy dependence of exclusive process such as $\gamma p \to \pi^0 p$.

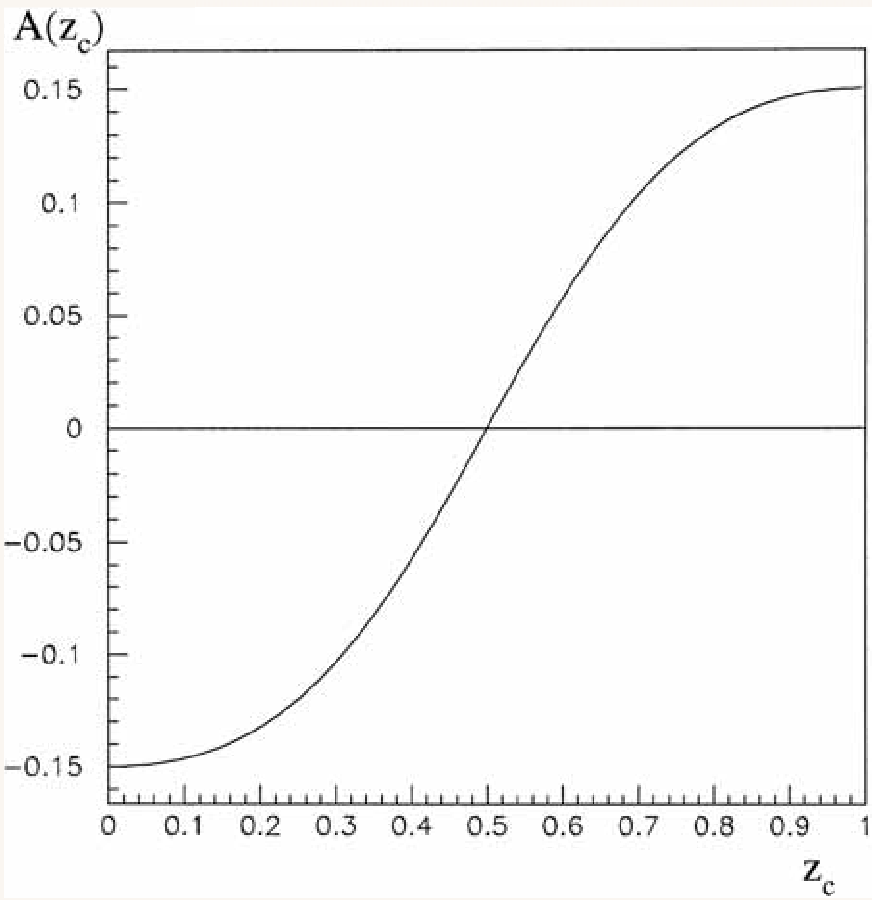




hep-ph/9904280



Odderon-Pomeron Interference!

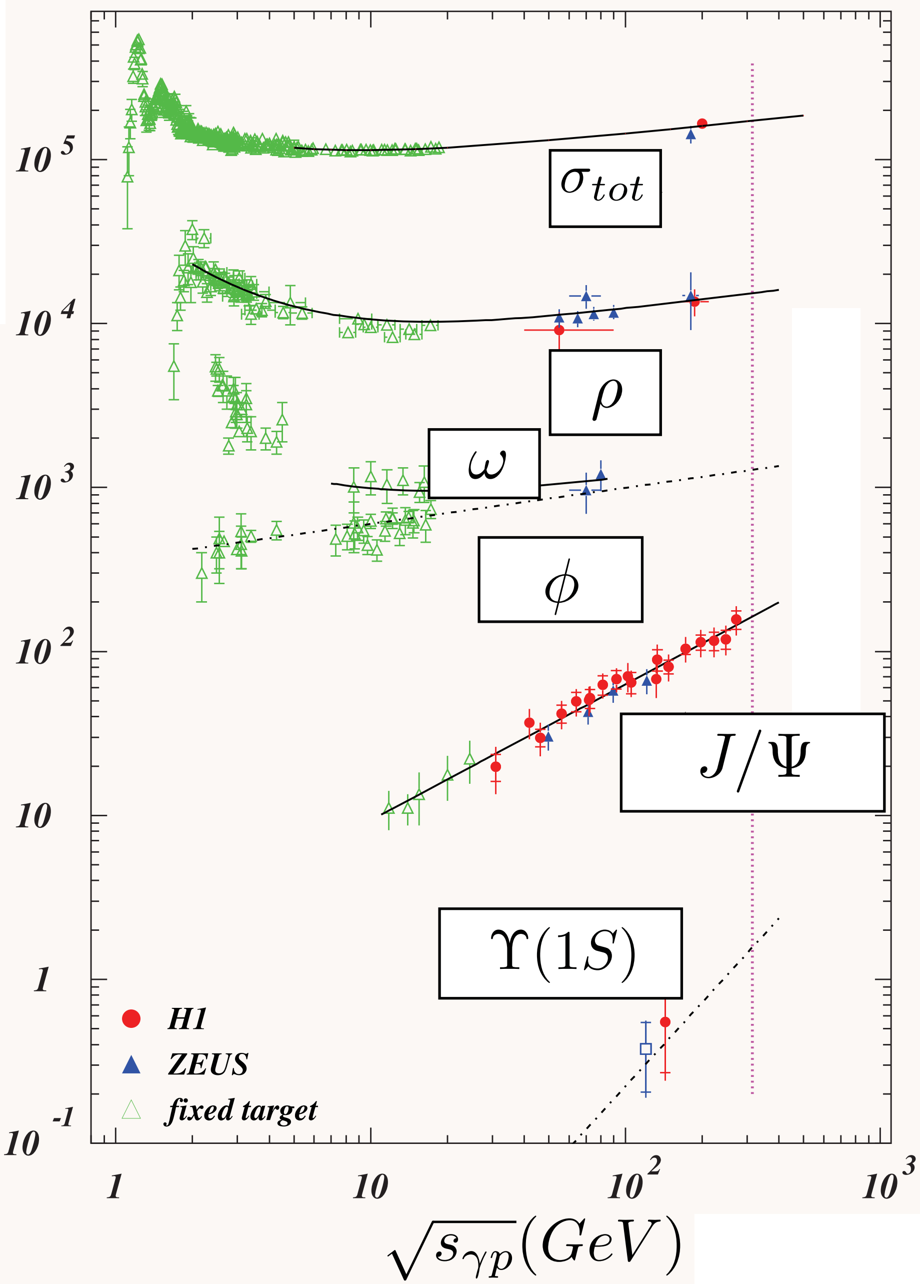


$$\mathscr{A}(t \simeq 0, M_X^2, z_c) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2z_c - 1}{z_c^2 + (1 - z_c)^2}$$

Measure charm asymmetry in photon fragmentation region

Merino, Rathsman, sjb

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



Diffractive Processes

Unitarity Bound?
Saturation?

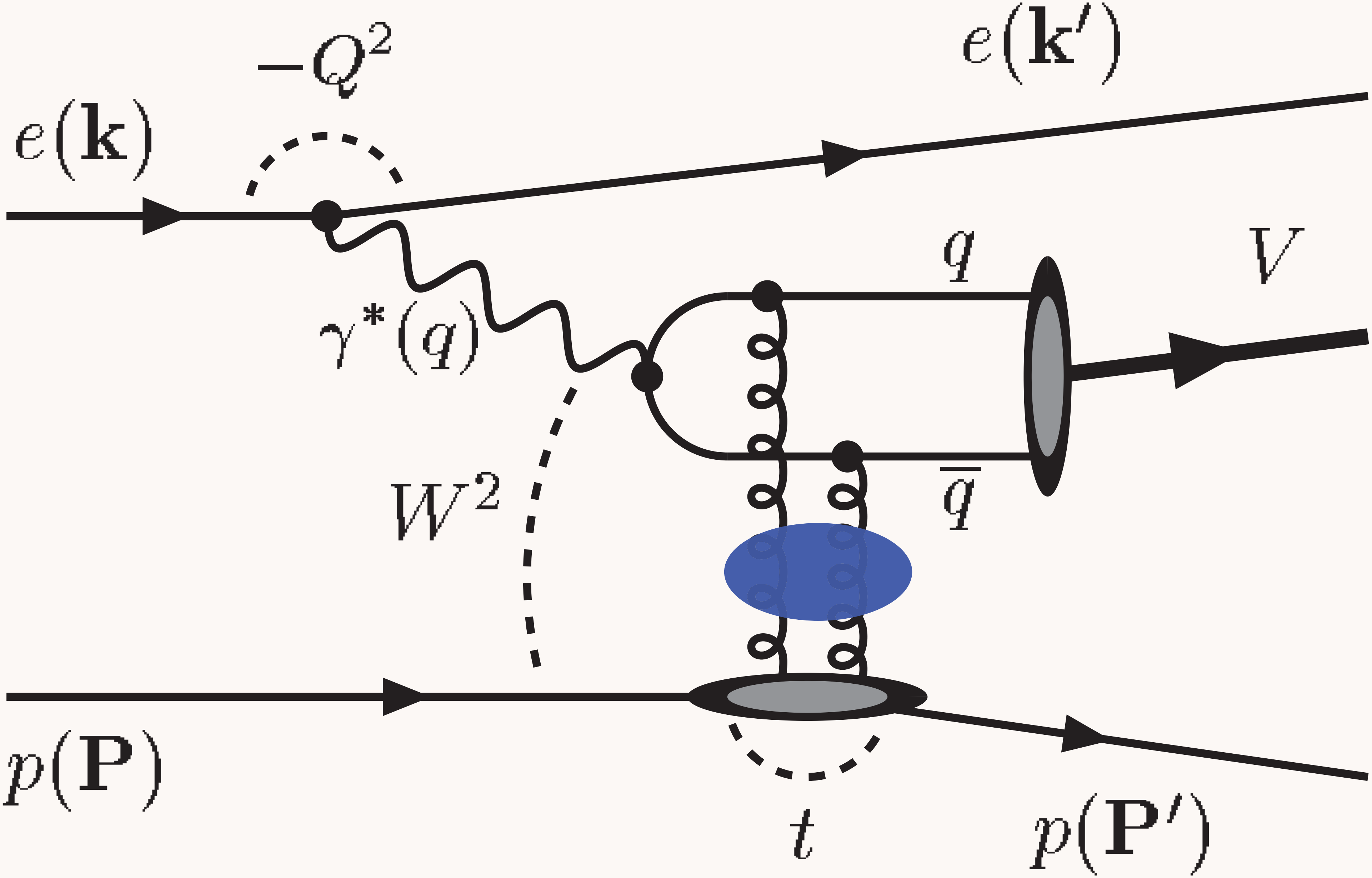
Hard Diffraction

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

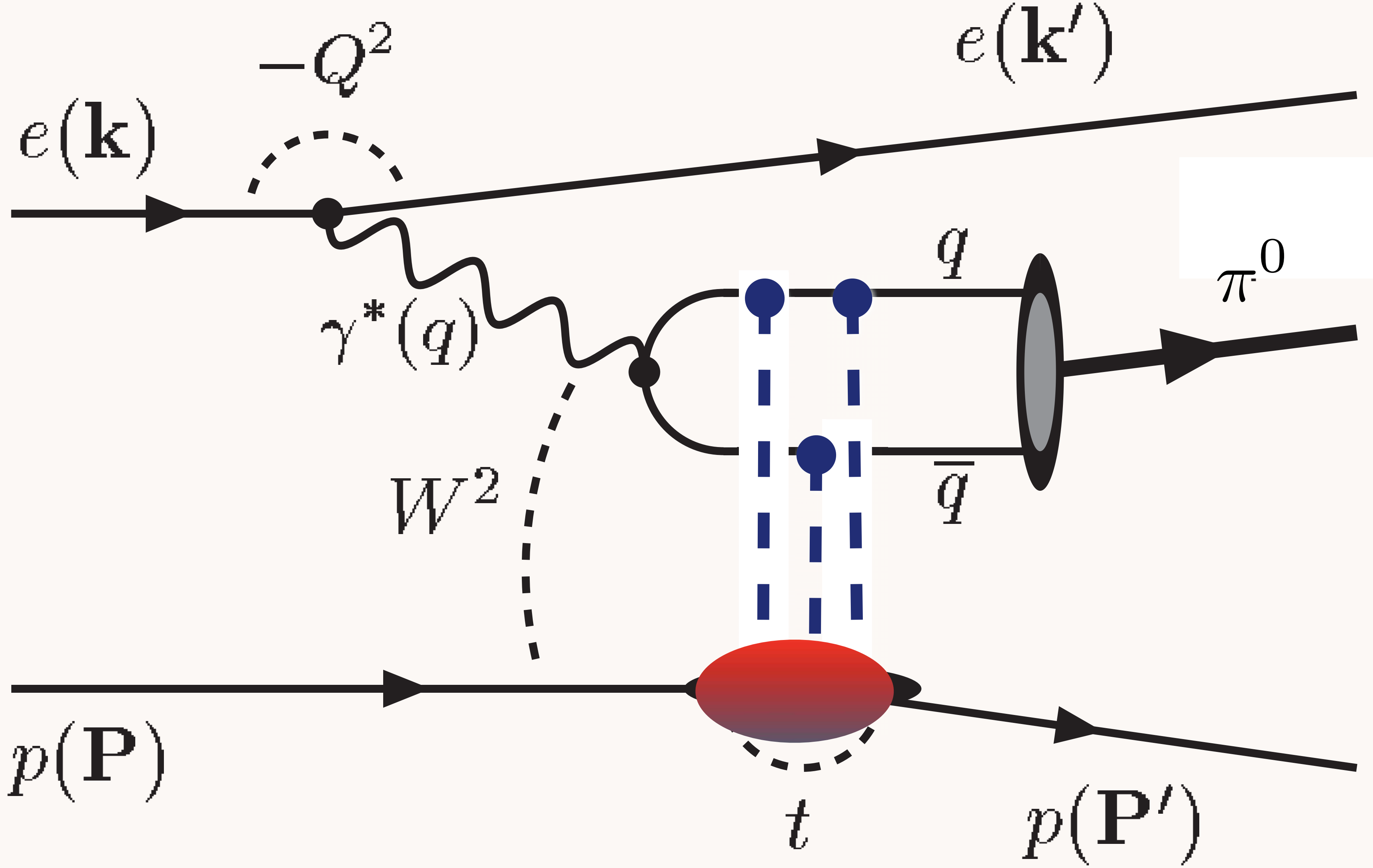
$$\gamma^* p \to \rho p$$

Odderon

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



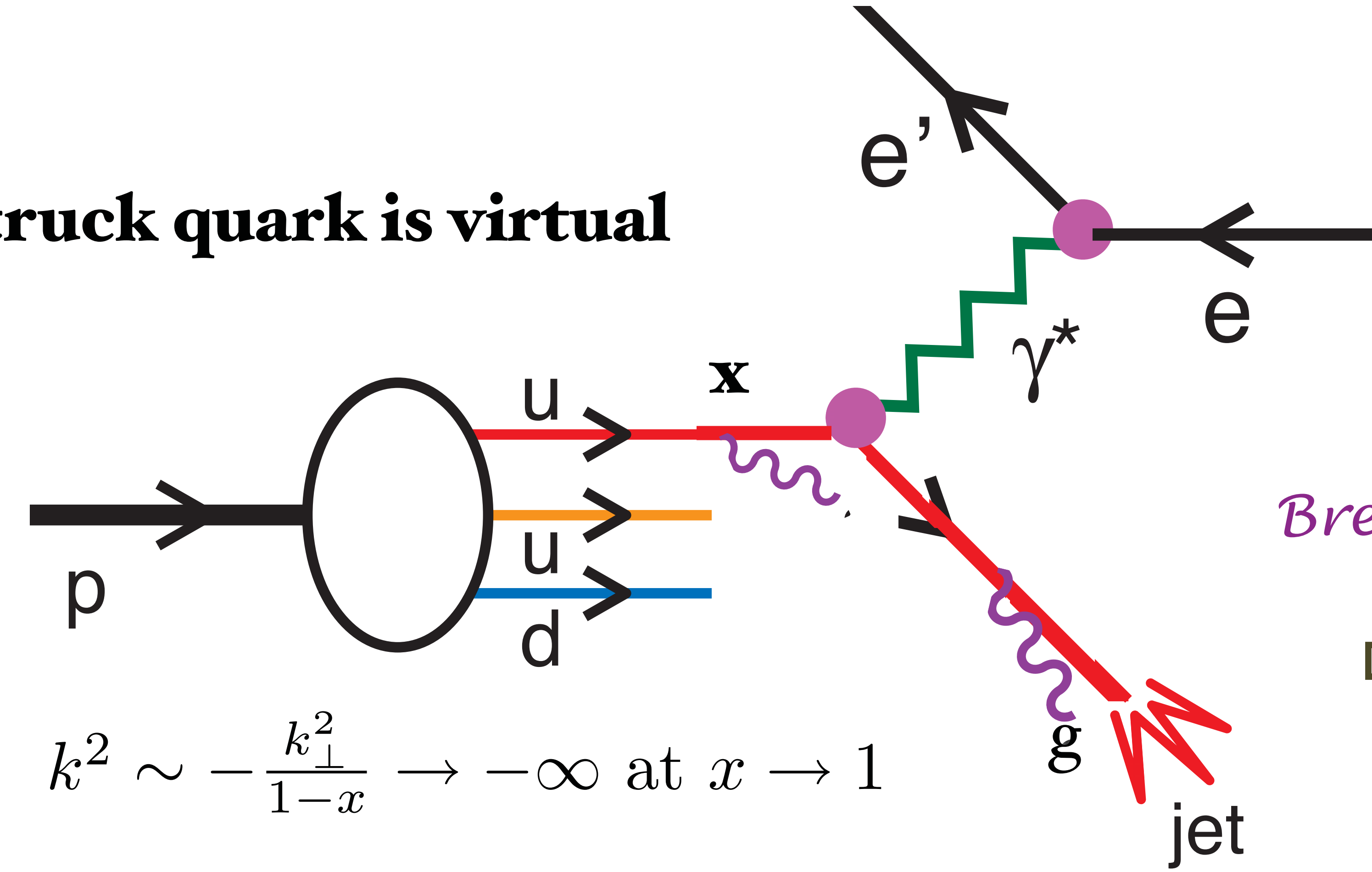
BFKL hard pomeron exchange
+ BLM NLO scale fixing



BFKL hard Odderon exchange

Deep Inelastic Electron-Proton Scattering

Struck quark is virtual



$$k^2 \sim -\frac{k_\perp^2}{1-x} \rightarrow -\infty \text{ at } x \rightarrow 1$$

Gluonic Bremmstrahlung

DGLAP Evolution

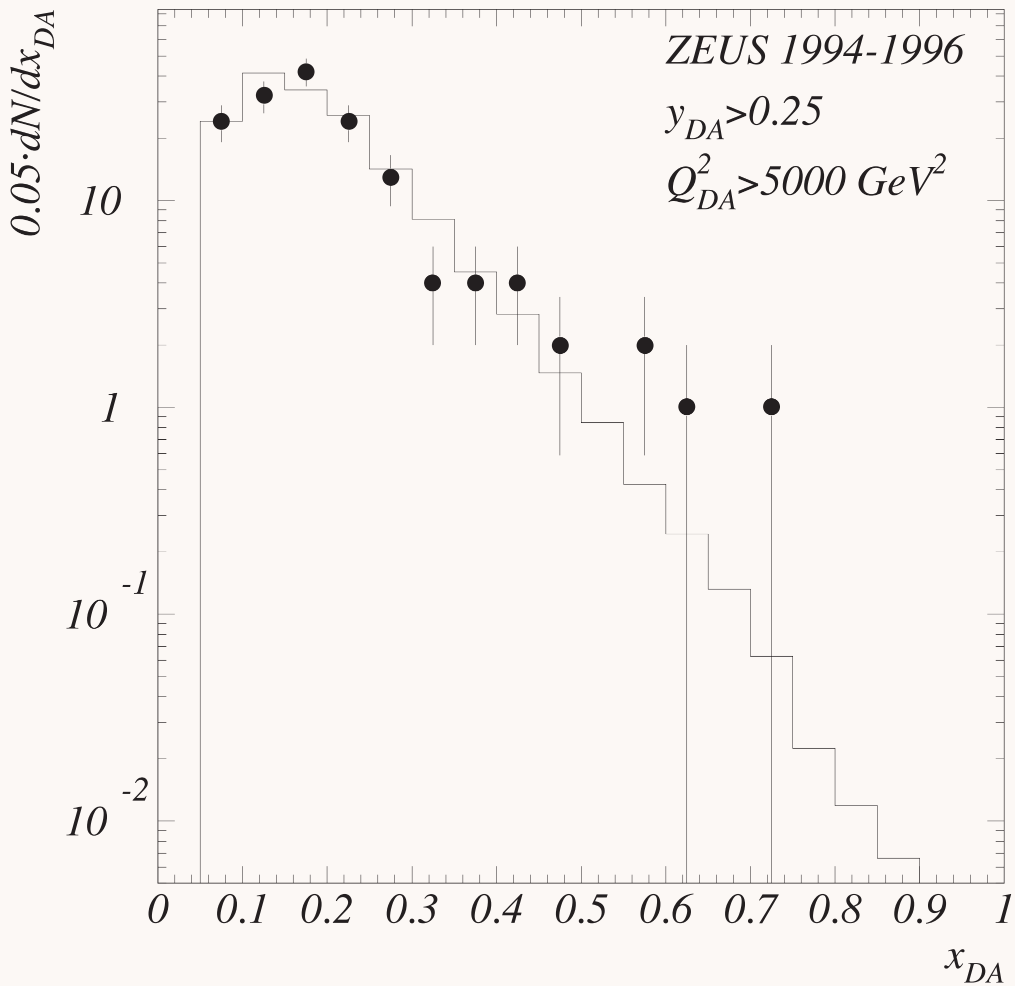
Off-shell Effect: Breakdown of DGLAP at x~1 !

Test DIS at HERA at large x   Test PQCD counting rules at large x

Comparison of ZEUS data with standard model predictions for $e^+p \to e^+X$ scattering at high x and Q^2

Z. Phys. C 74, 207–220 (1997)

ZEUS Collaboration



The x_{DA} distribution of the observed events with the cuts shown (*full dots*), compared to the Standard Model e^+p NC expectation (*histogram*). The error bars on the data points are obtained from the square root of the number of events in the bin

Test DIS at HERA at large x

Double-angle method

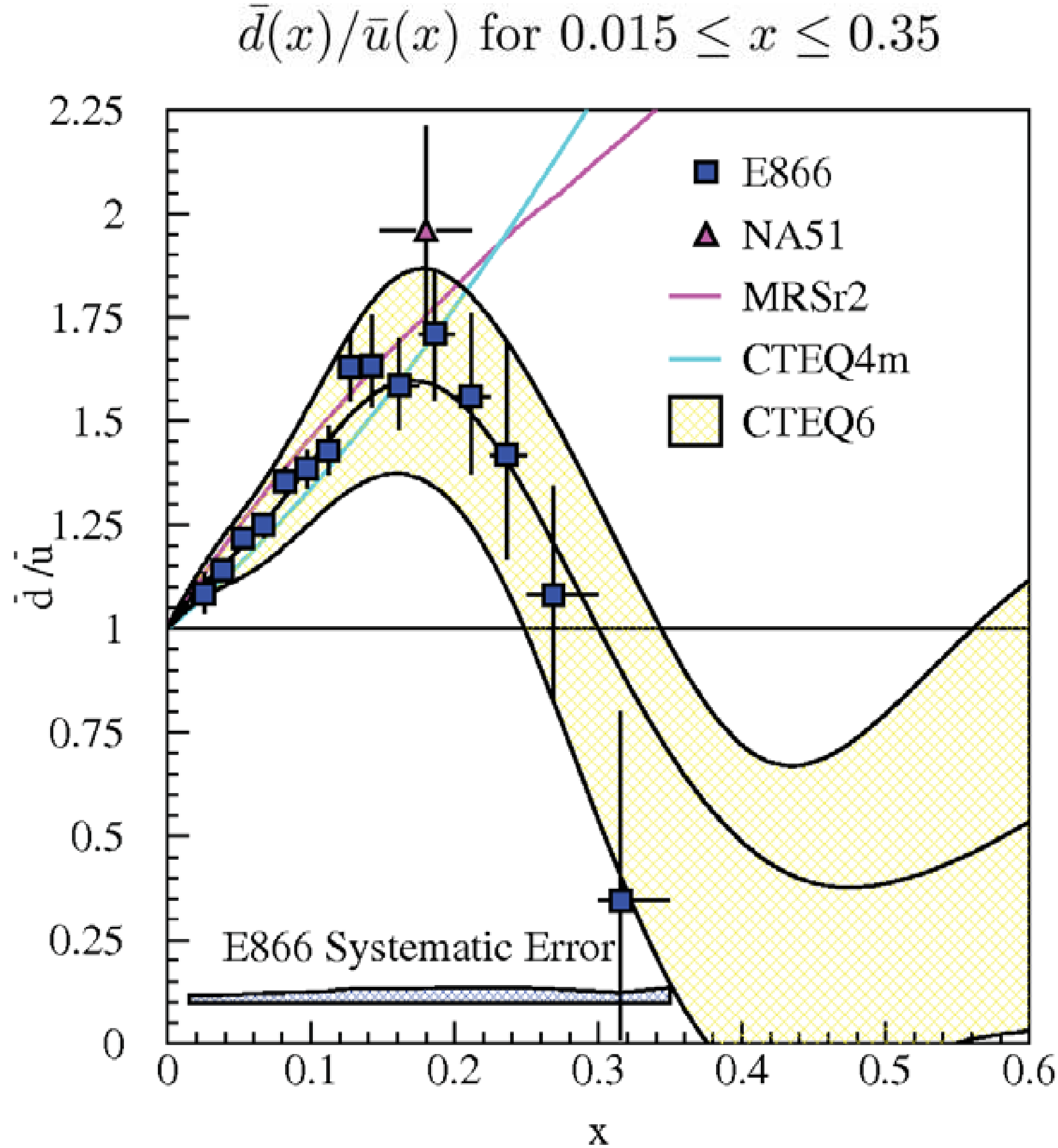
Light Antiquark Flavor Asymmetry

- Naïve Assumption from gluon splitting:

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

- E866/NuSea (Drell-Yan)

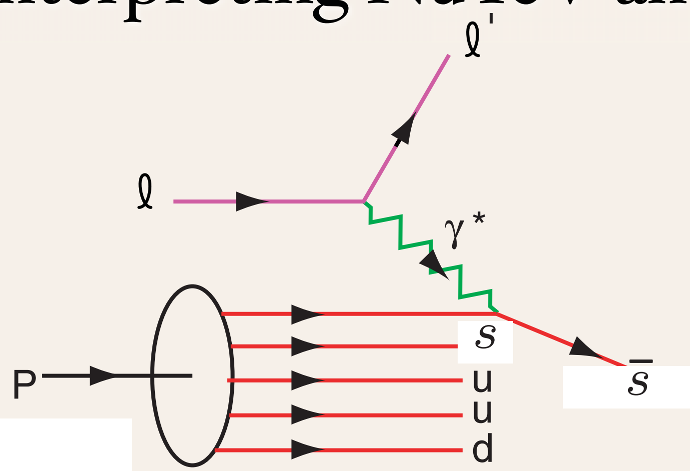
Measure strangeness distribution from DIS at HERA



Measure strangeness distribution from DIS at HERA

$$\bar{s}(x) \neq s(x) \qquad ep \to e'KX$$

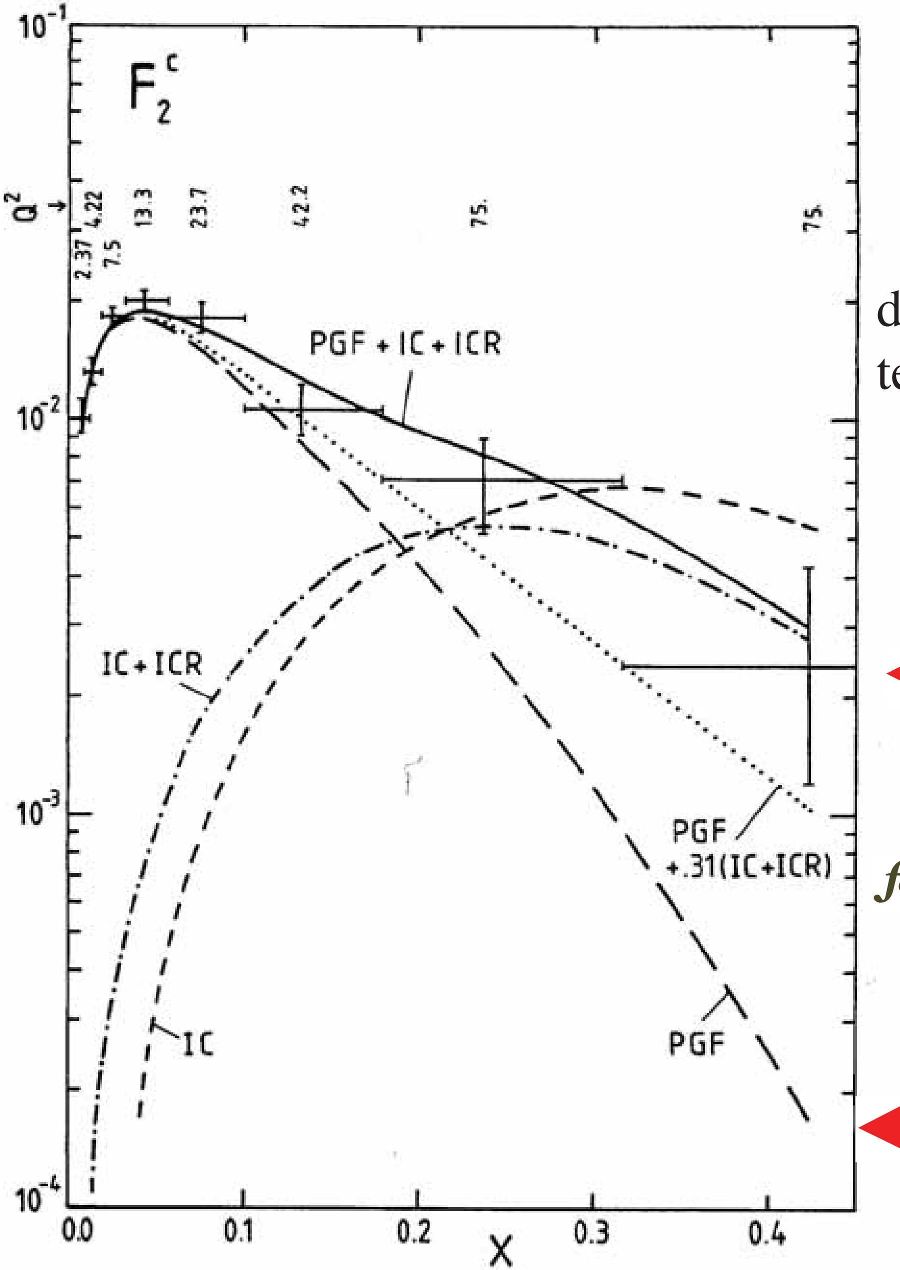
- Non-symmetric strange and antistrange sea
- Non-perturbative input; e.g $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- Crucial for interpreting NuTeV anomaly



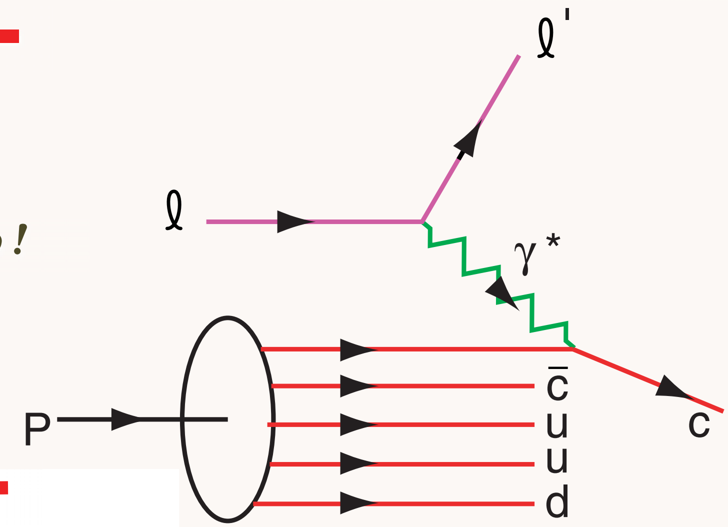
Measurement of Charm Structure Function

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

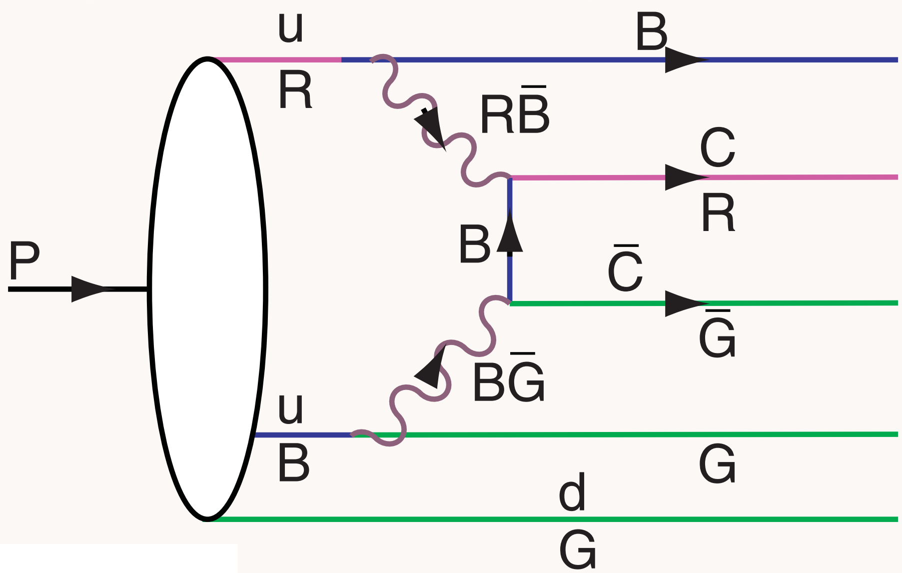


factor of 30 !



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

Hoyer, Peterson, Sakai, sjb



$|uudc\bar{c}>$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^- >$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$ $c\bar{c}$ in Color Octet

Distribution peaks at equal rapidity (velocity)

Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm! *Charm at Threshold*

- 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 $pp \to \Lambda_c X$

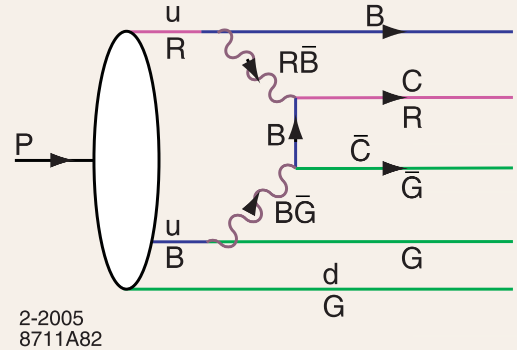
- High x_F $pp \to \Lambda_b X$

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

IC Structure Function: Critical Measurement for EIC

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)
- Many empirical tests

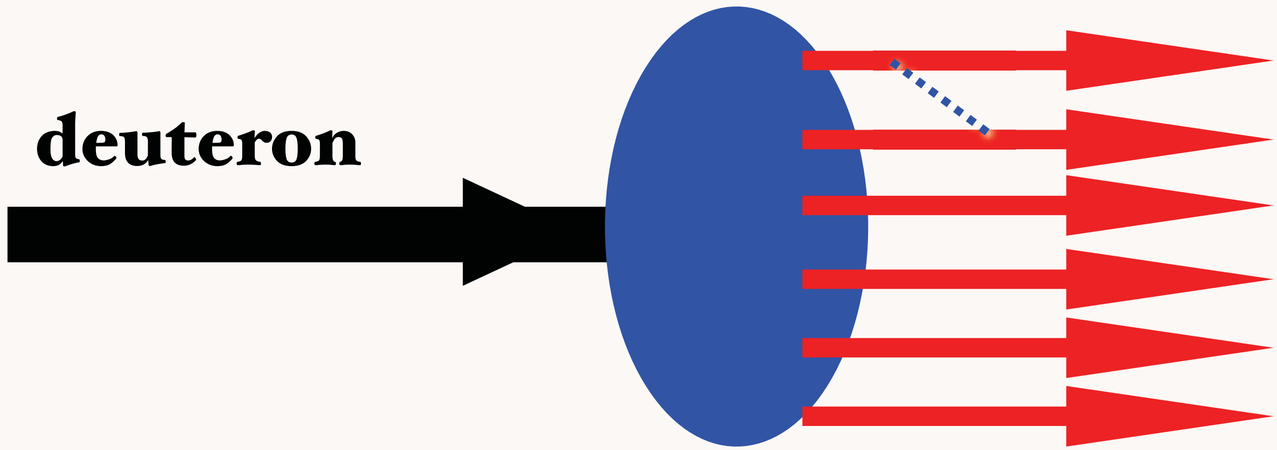
Measure charm distribution at HERA in DIS at large x and Q

Use extreme caution when using
$\gamma g \to c\bar{c}$ or $gg \to \bar{c}c$
to tag gluon dynamics

Hidden Color of Deuteron

Evolution of 5 color-singlet Fock states

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



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

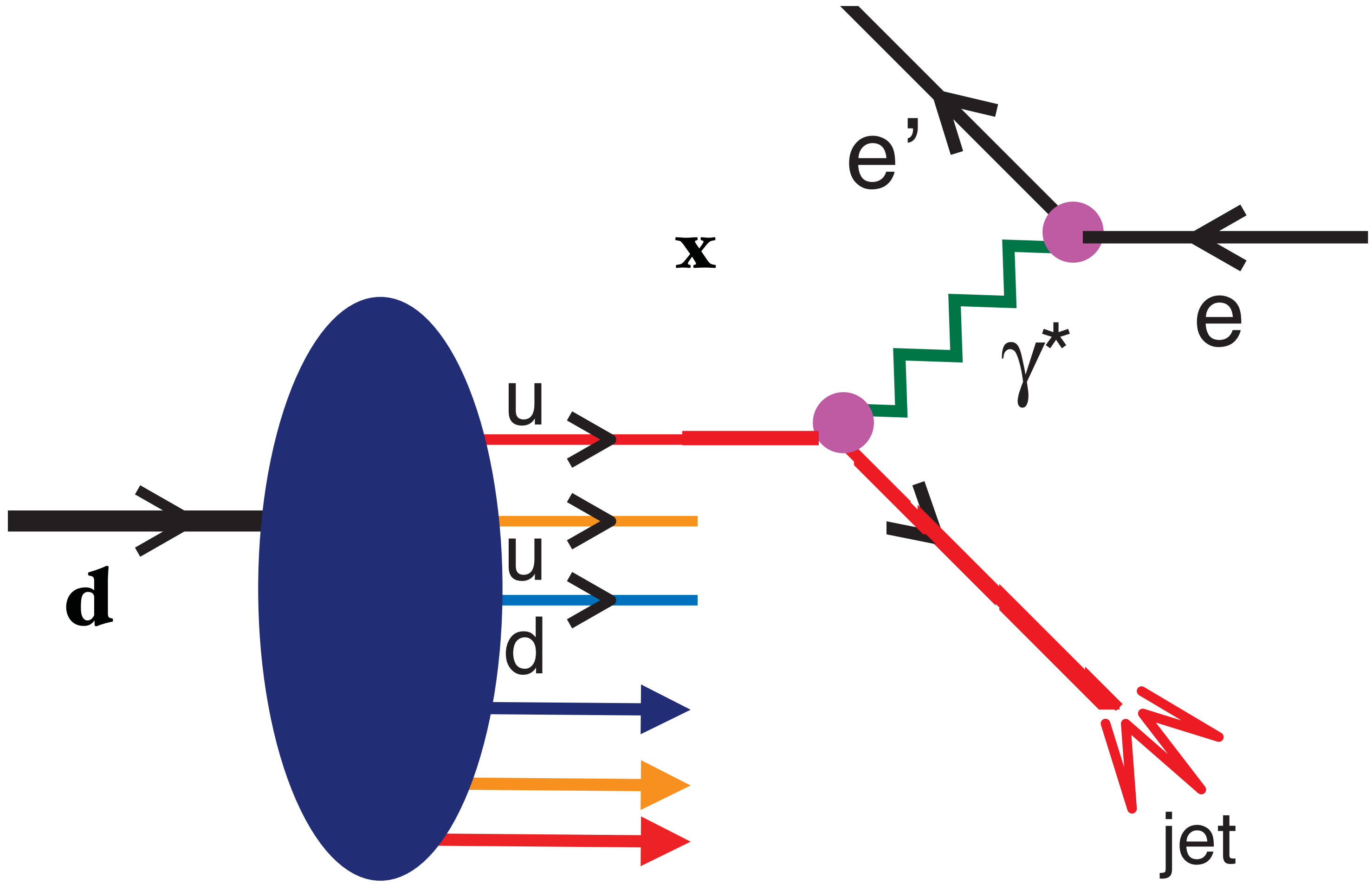
$\sum_i^n x_i = 1$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

Ji, Lepage, sjb

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Deep Inelastic Electron-Deuteron Scattering



Hidden color: excited target spectator system

No nucleon spectator

Conventional wisdom in QCD concerning scale setting

- Renormalization scale "unphysical": No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess $\mu_R = Q$
- with an arbitrary range $Q/2 < \mu_R < 2Q$
- Factorization scale should be taken equal to renormalization scale $\mu_F = \mu_R$

These assumptions are untrue in QED and thus they cannot be true for QCD!

Electron-Electron Scattering in QED

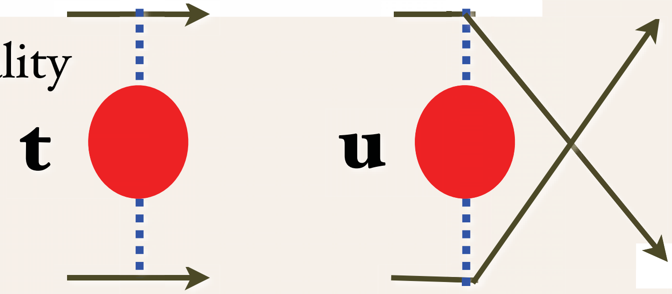
$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell Mann-Low Effective Charge

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$



- Two separate physical scales: t, u = photon virtuality
- Gauge Invariant. Dressed photon propagator
- Sums all vacuum polarization, non-zero beta terms into running coupling.
- If one chooses a different scale, one can sum an infinite number of graphs -- but always recover same result!
- Number of active leptons correctly set
- Analytic: reproduces correct behavior at lepton mass thresholds
- No renormalization scale ambiguity!

Electron-Electron Scattering in QED

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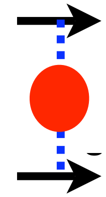
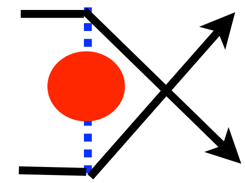

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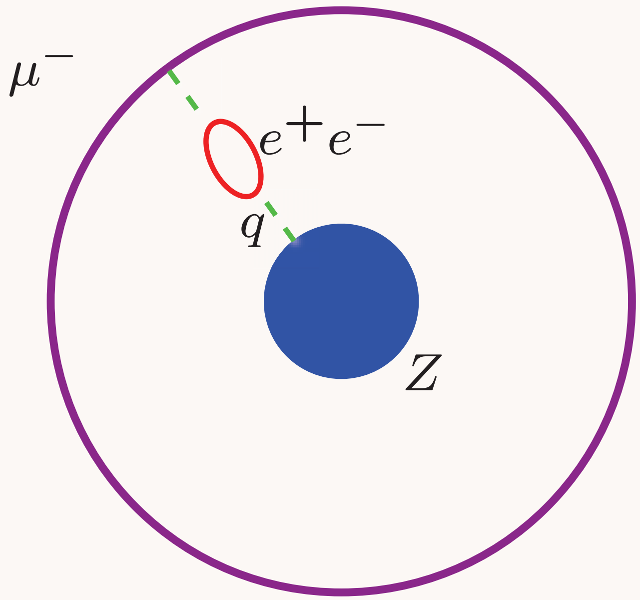
- If one chooses a different scale, one must sum an infinite number of graphs -- but then recover same result!
- Number of active leptons correctly set
- Analytic: reproduces correct behavior at lepton mass thresholds

Another Example in QED: Muonic Atoms



$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

$$\mu_R^2 \equiv q^2$$

$$\alpha_{QED}(q^2) = \frac{\alpha_{QED}(0)}{1-\Pi(q^2)}$$

Scale is unique: Tested to ppm

Gyulassy: Higher Order VP verified to 0.1% precision in μ Pb

Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb

Phys.Rev.D28:228,1983

- All terms associated with non-zero beta function summed into running coupling
- Identical procedure in QED:
- Correct $N_C = 0$ limit
- Resulting series identical to conformal series
- Renormalon n! growth of PQCD coefficients from beta function eliminated!
- In general, scale depends on all invariants

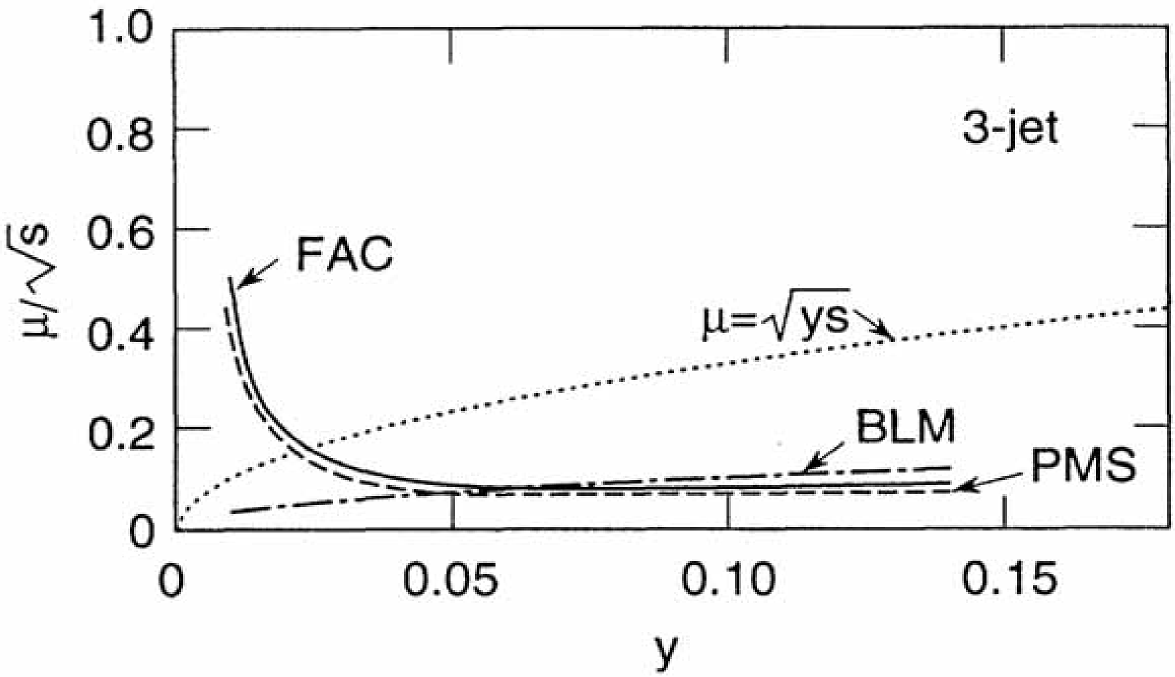
Huet, sjb

$$\lim N_C \to 0 \text{ at fixed } \alpha = C_F \alpha_s, n_\ell = n_F / C_F$$

$$\text{QCD} \to \text{Abelian Gauge Theory}$$

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED



Kramer & Lampe

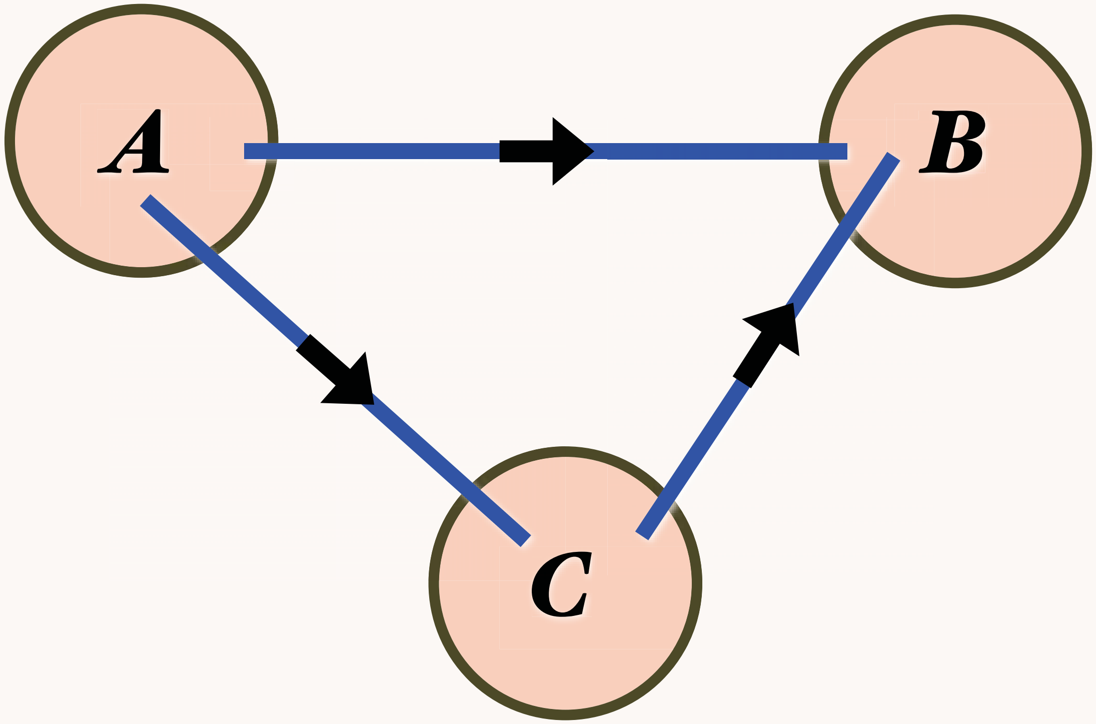
Three-Jet Rate

The scale $\mu/\sqrt{s}$ according to the BLM (dashed-dotted), PMS (dashed), FAC (full), and $\sqrt{y}$ (dotted) procedures for the three-jet rate in e^+e^- annihilation, as computed by Kramer and Lampe [10]. Notice the strikingly different behavior of the BLM scale from the PMS and FAC scales at low y. In particular, the latter two methods predict increasing values of μ as the jet invariant mass $\mathcal{M} < \sqrt{(ys)}$ decreases.

Rathsman

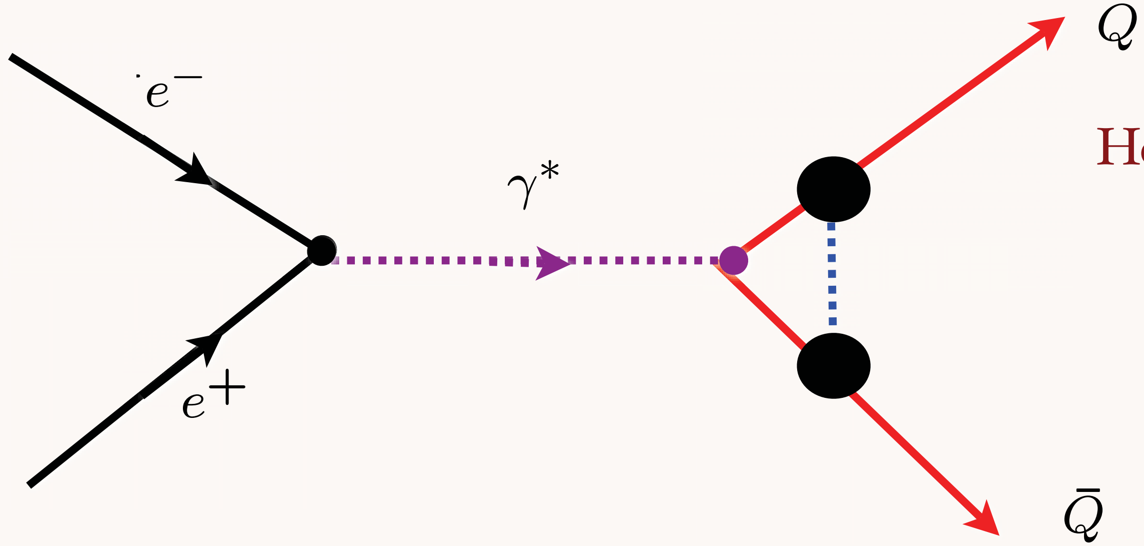
Other Jet Observables:

Transitivity Property of Renormalization Group



A→C   ***C→B***   ***identical to A→B***

Relation of observables independent of intermediate scheme C



Hoang, Kuhn, Teubner, sjb

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

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

Example of Multiple BLM Scales

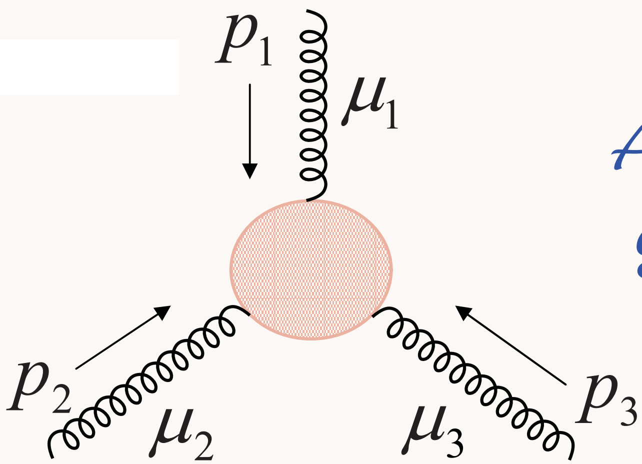
Angular distributions of massive quarks and leptons close to threshold.

General Structure of the Three-Gluon Vertex

"THE FORM-FACTORS OF THE GAUGE-INVARIANT THREE-GLUON VERTEX"

M. Binger, sjb

$\hat{\Gamma}_{\mu_1 \mu_2 \mu_3} =$

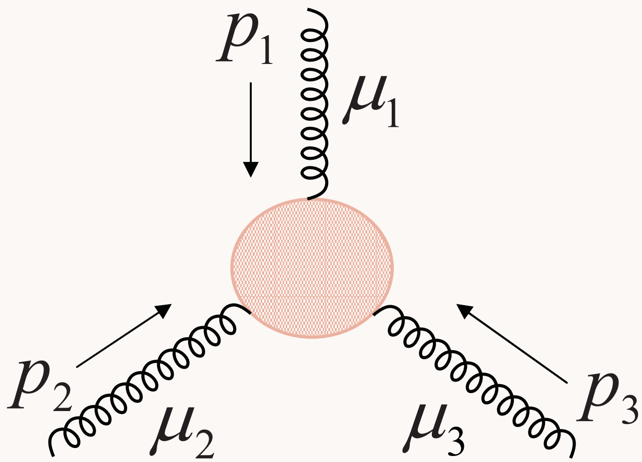


Analytic calculation: general masses, spin

3 index tensor $\hat{\Gamma}_{\mu_1 \mu_2 \mu_3}$ built out of $g_{\mu\nu}$ and p_1, p_2, p_3
with $p_1 + p_2 + p_3 = 0$

⇒ 14 basis tensors and form factors

$$\hat{\Gamma}_{\mu_1\mu_2\mu_3} =$$



H. J. Lu

$$\mu_R^2 \simeq \frac{p_{min}^2 p_{med}^2}{p_{max}^2}$$

Properties of the Effective Scale

$$Q^2_{eff}(a,b,c) = Q^2_{eff}(-a,-b,-c)$$

$$Q^2_{eff}(\lambda a, \lambda b, \lambda c) = |\lambda| Q^2_{eff}(a,b,c)$$

$$Q^2_{eff}(a,a,a) = |a|$$

$$Q^2_{eff}(a,-a,-a) \approx 5.54 |a|$$

$$Q^2_{eff}(a,a,c) \approx 3.08 |c| \quad \text{for} \quad |a| >> |c|$$

$$Q^2_{eff}(a,-a,c) \approx 22.8 |c| \quad \text{for} \quad |a| >> |c|$$

$$Q^2_{eff}(a,b,c) \approx 22.8 \frac{|bc|}{|a|} \quad \text{for} \quad |a| >> |b|,|c|$$

Surprising dependence on Invariants

Elimination of Renormalization Scale Ambiguity

- ***Multi-scale analytic*** renormalization based on ***physical, gauge-invariant*** Green's functions

- ***Optimal*** improvement of perturbation theory with ***no scale-ambiguity*** since physical kinematic invariants are the arguments of the (multi-scale) couplings

BLM Method

- Satisfies Transitivity, all aspects of Renormalization Group; scheme independent
- Analytic at Flavor Thresholds
- Preserves Underlying Conformal Template
- Physical Interpretation of Scales; Multiple Scales
- Correct Abelian Limit ($N_C = 0$)
- Eliminates unnecessary source of imprecision of PQCD predictions
- Commensurate Scale Relations: Fundamental Tests of QCD free of renormalization scale and scheme ambiguities
- BLM used in many applications, QED, LGTH, BFKL, ...

Eliminate renormalization scale ambiguity in HERA analysis!