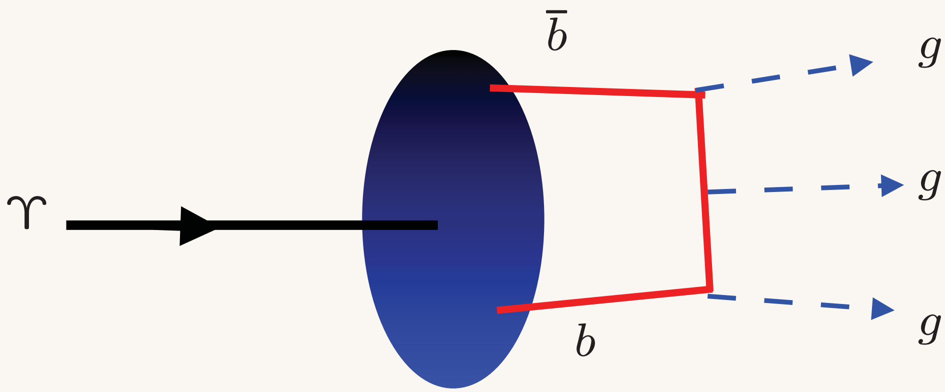
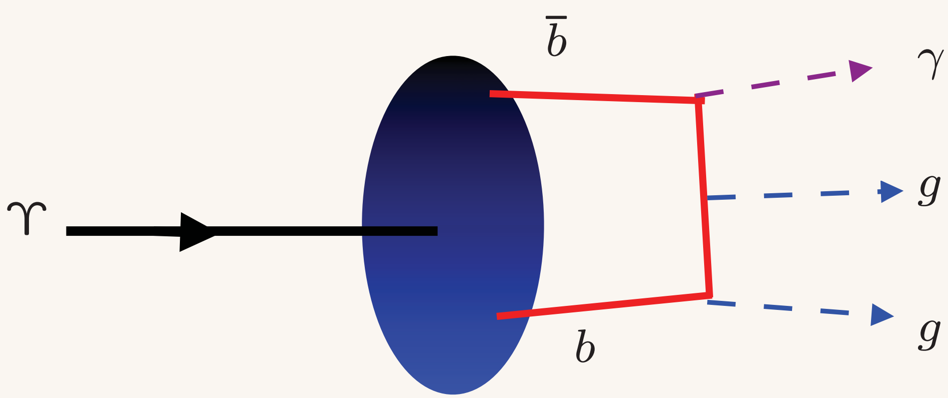


$$\Upsilon \rightarrow ggg$$

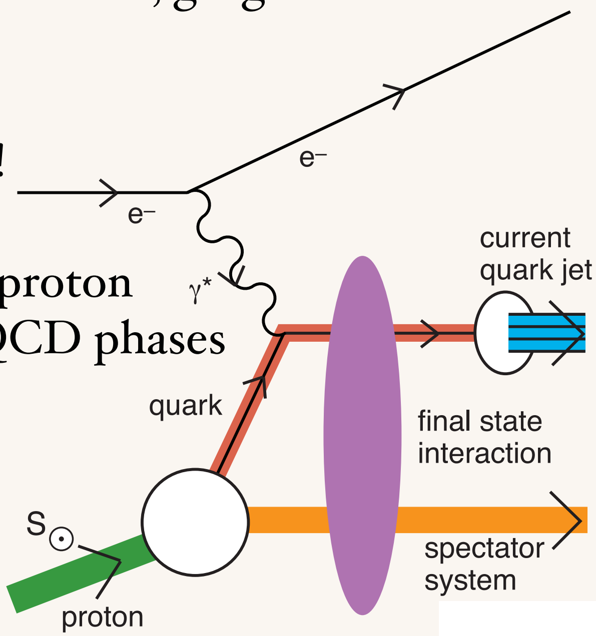


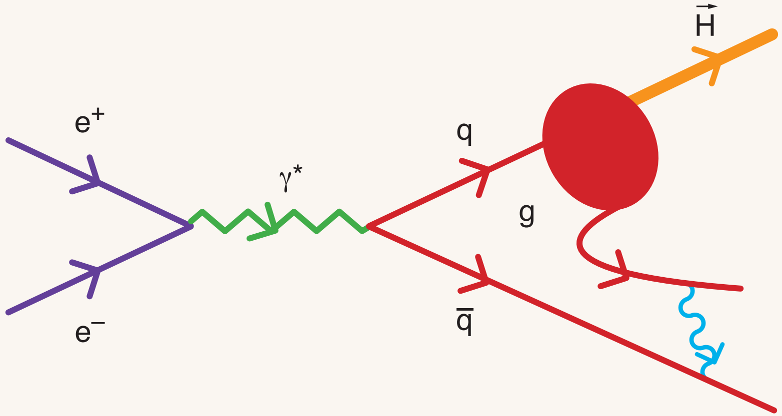
$$\Upsilon \rightarrow \gamma gg$$

C=+ Glueball factory

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark! $\mathbf{i}\, \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Unexpected QCD Effect -- thought to be zero!
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD Coulomb phase at soft scale
- Measure in jet trigger or leading hadron
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment: B(0)= 0)

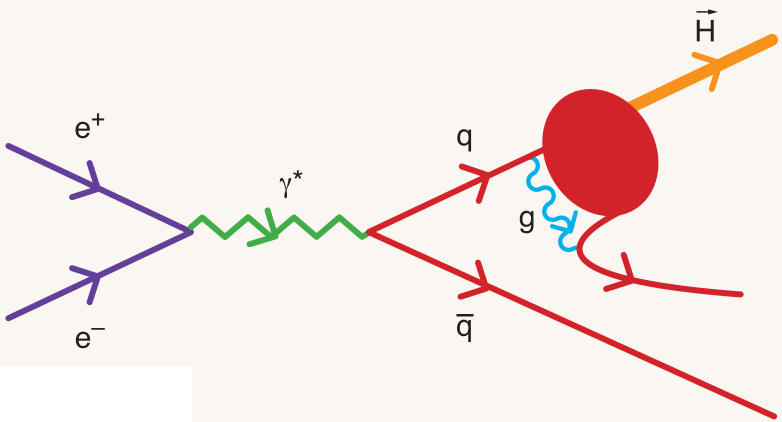




$$e^+e^- \to \gamma^* \to \pi \Lambda X.$$

Λ reveals its polarization via decay

$$\Lambda \to p\pi^-$$



$$\epsilon_{\mu\nu\rho\sigma} S^\mu_\Lambda p^\nu_\Lambda q^\rho_{\gamma^*} p^\sigma_\pi .$$

$$i\vec{S}_\Lambda \cdot \vec{q}_{\gamma^*} \times \vec{p}_\pi$$

in Λ rest frame

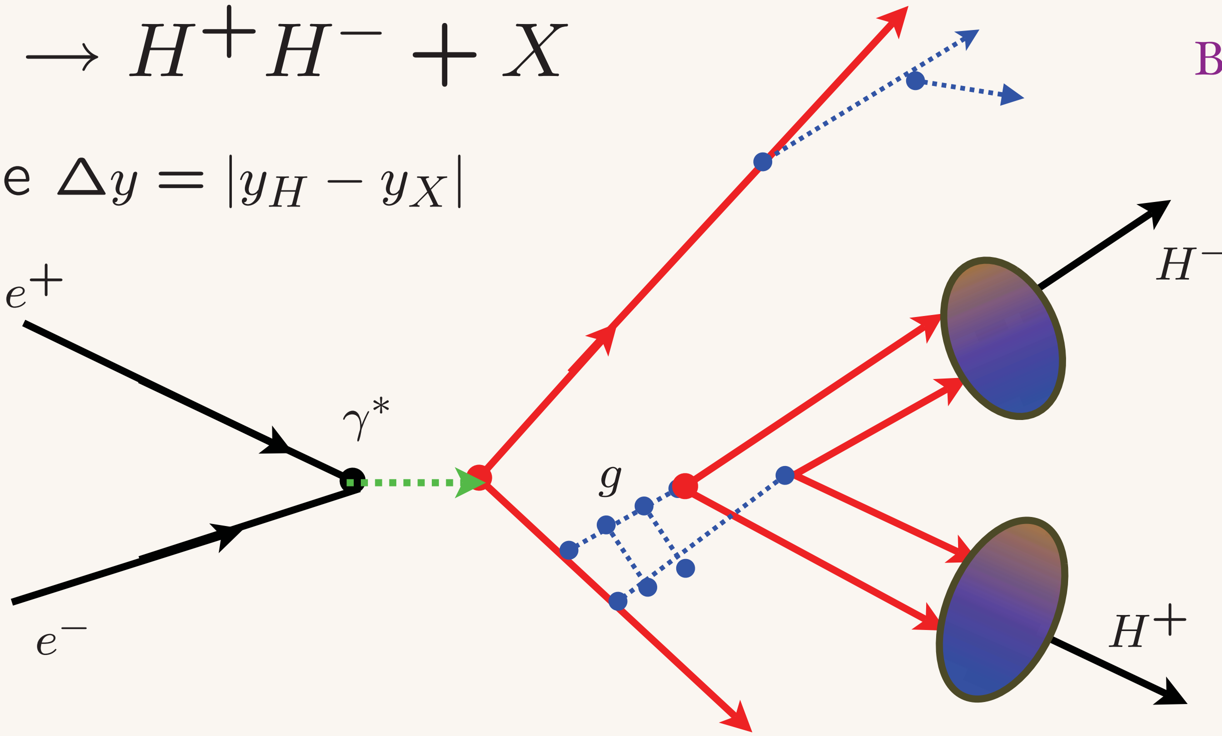
Final-state gluon exchange produces leading-twist T-odd single-spin asymmetries in inclusive electron-positron collisions.

Hadronization at the Amplitude Level

$$e^+e^- \to H^+H^- + X$$

Large $\Delta y = |y_H - y_X|$

Bjorken, Lu, sjb
Kopeliovich, Schmidt, sjb

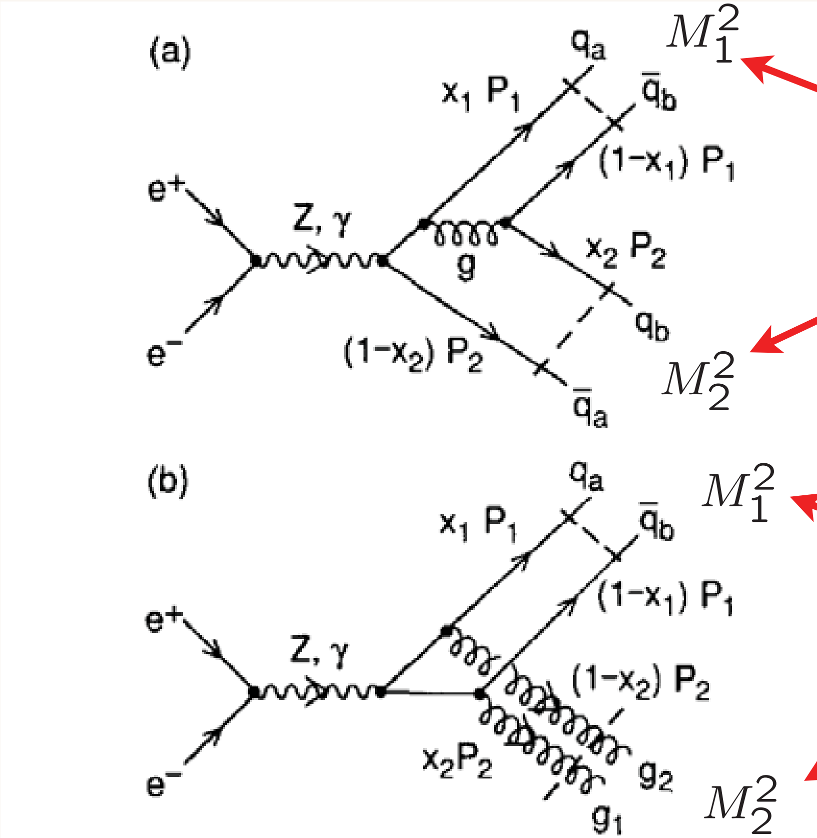


Timelike Pomeron

C= + Gluonium Trajectory

Large Rapidity Gap Events

Crossing analog of Diffractive DIS $eH \to eH + X$



J. Bjorken, H. Lu, sjb

Physics Letters B 286 (1992) 153–159

color-singlet states

color-singlet states

Dimensional Counting:

$$R_{\text{gap}} = \sigma_{\text{gap}}/\sigma_{\text{tot}} \sim \alpha_s^2 \frac{M_1^2}{s} \frac{M_2^2}{s}$$

Kopeliovich, Schmidt, sjb

Reggeon Exchange at small pair mass

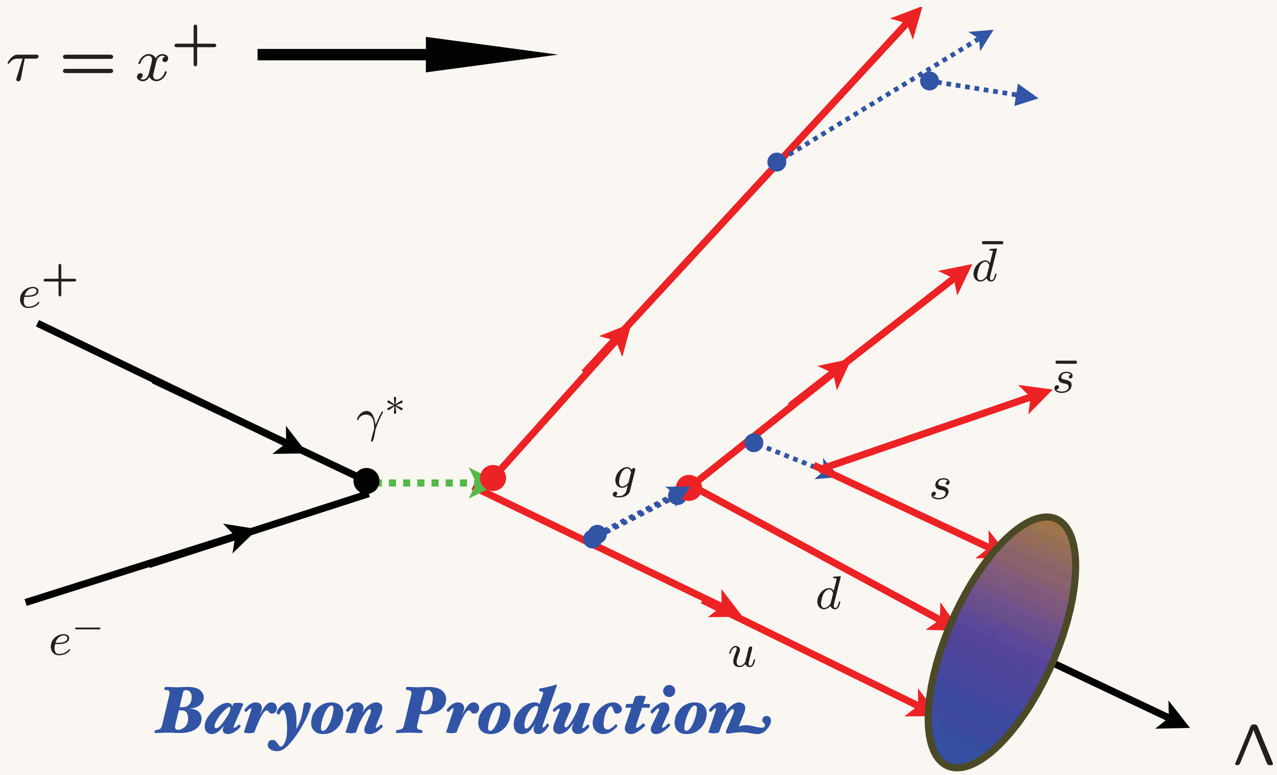
Timelike Pomeron

Large Rapidity Gap Events

$$D_{q\to qgg}(z) \propto (1-z)^{\alpha_R(0)-1} = \exp -\tfrac{1}{2}\Delta y$$

$$s = \frac{\mathcal{M}_{gg}^2 + k_\perp^2}{1-z} + \frac{\mathcal{M}_{q\bar{q}}^2 + k_\perp^2}{z} = \frac{\mathcal{M}_{\perp gg}^2}{1-z} + \frac{\mathcal{M}_{\perp q\bar{q}}^2}{z}$$

Hadronization at the Amplitude Level



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

Counting rules at large z

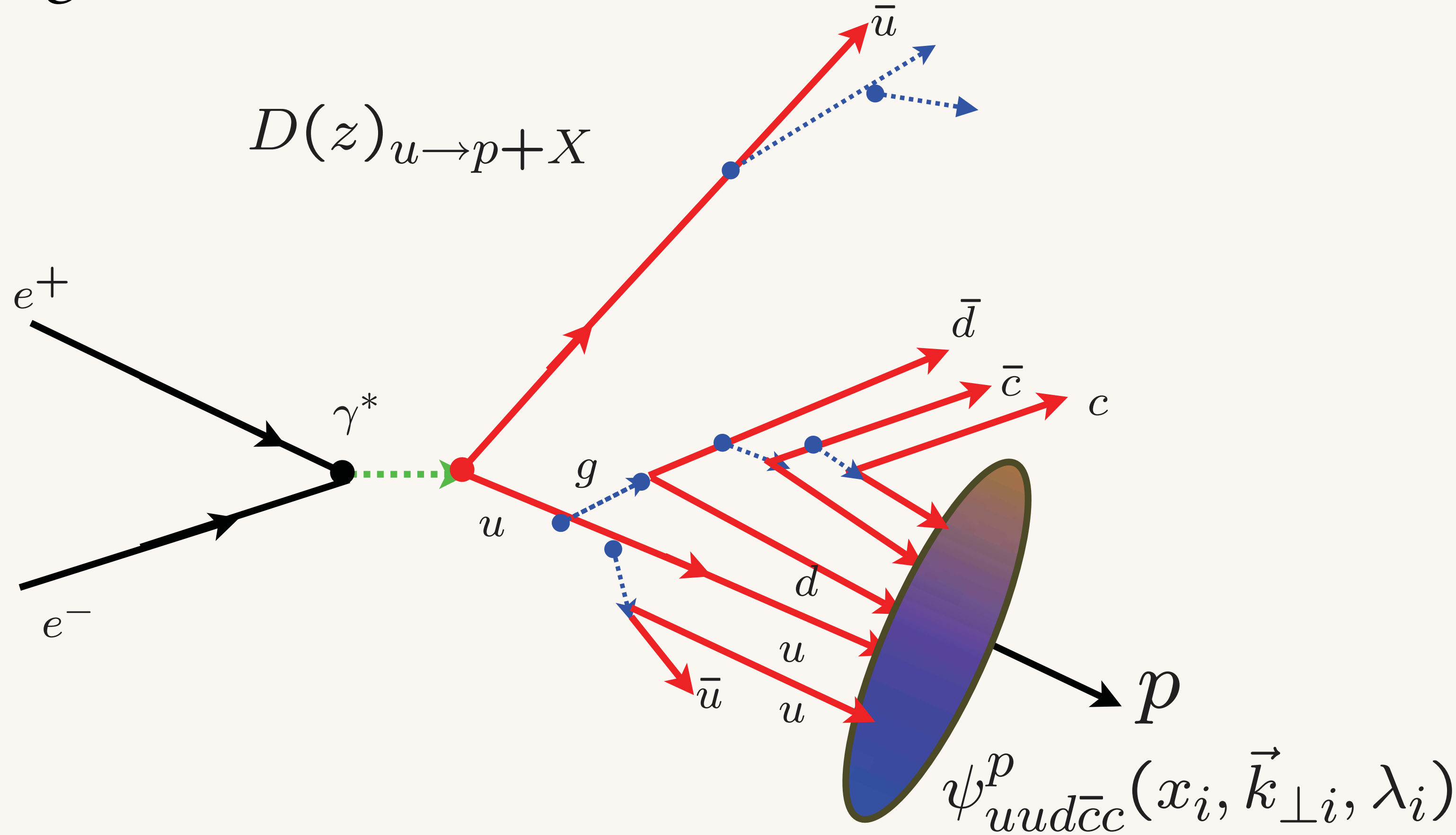
$$D(z) \sim (1 - z)^{2N_{spect}-1}$$

Gribov-Lipatov crossing at large z

$$zD(z) = \pm F(x = 1/z)$$

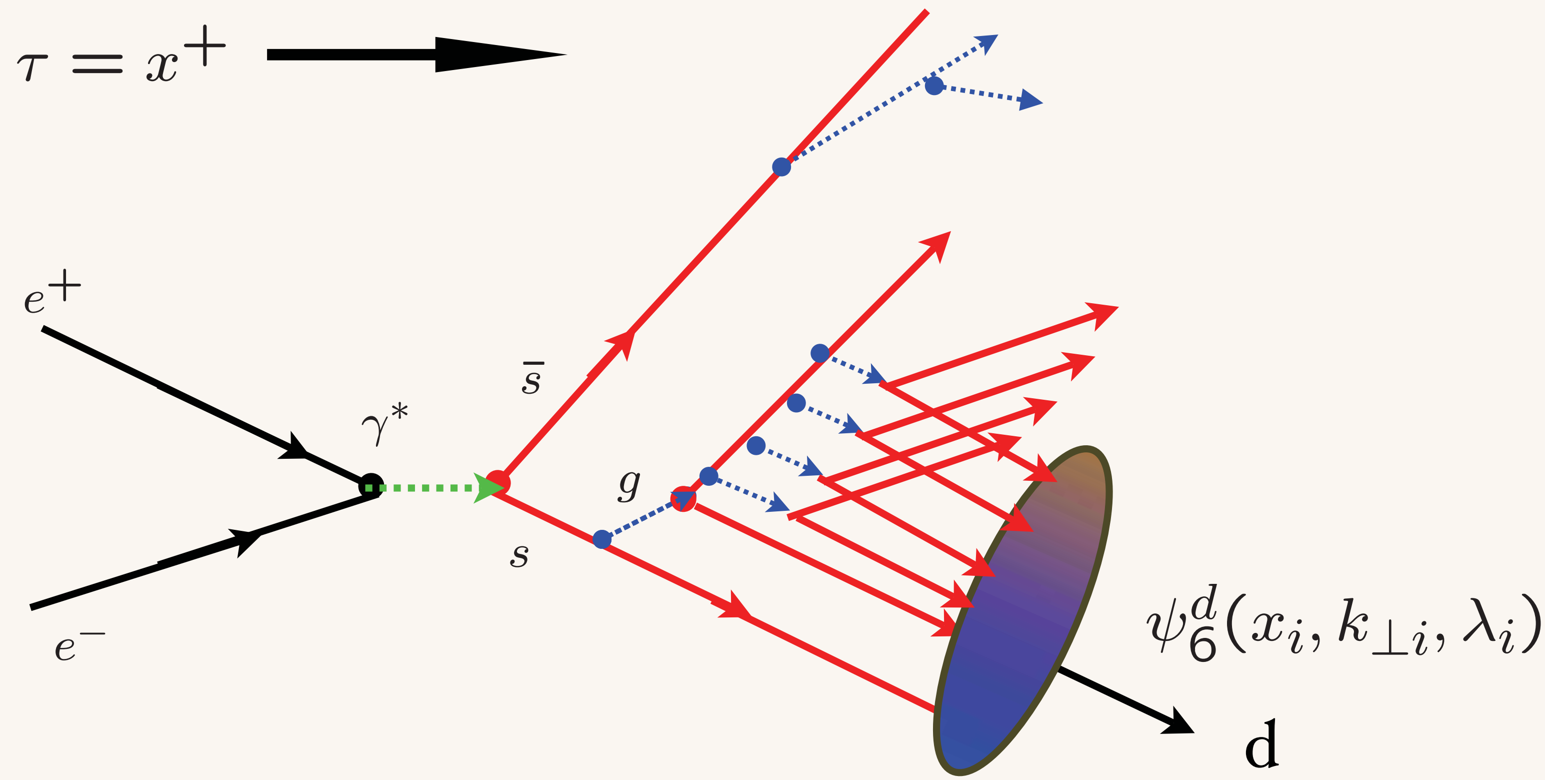
Hadronization at the Amplitude Level

Higher Fock State: Proton Production



Dual momentum distribution of spectators
$c\bar{c}\bar{u}\bar{d}$ reflects proton bound-state structure

Hadronization at the Amplitude Level



"Hidden-Color" Components $|(uud)_{8C}(ddu)_{8C}>$

New Hadronization Mechanism

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

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

The Light Front Fock State Wavefunctions

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

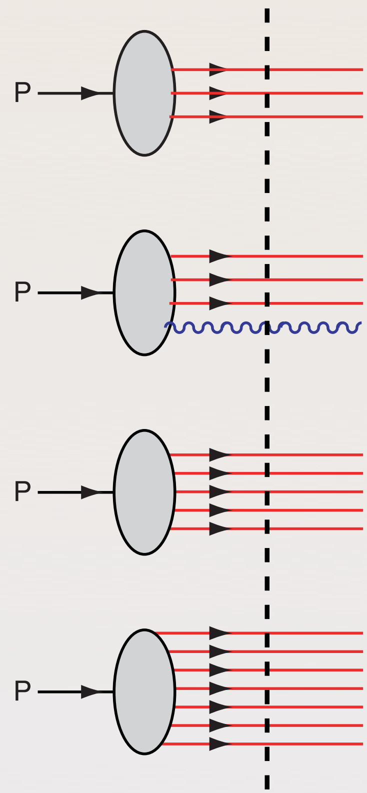
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

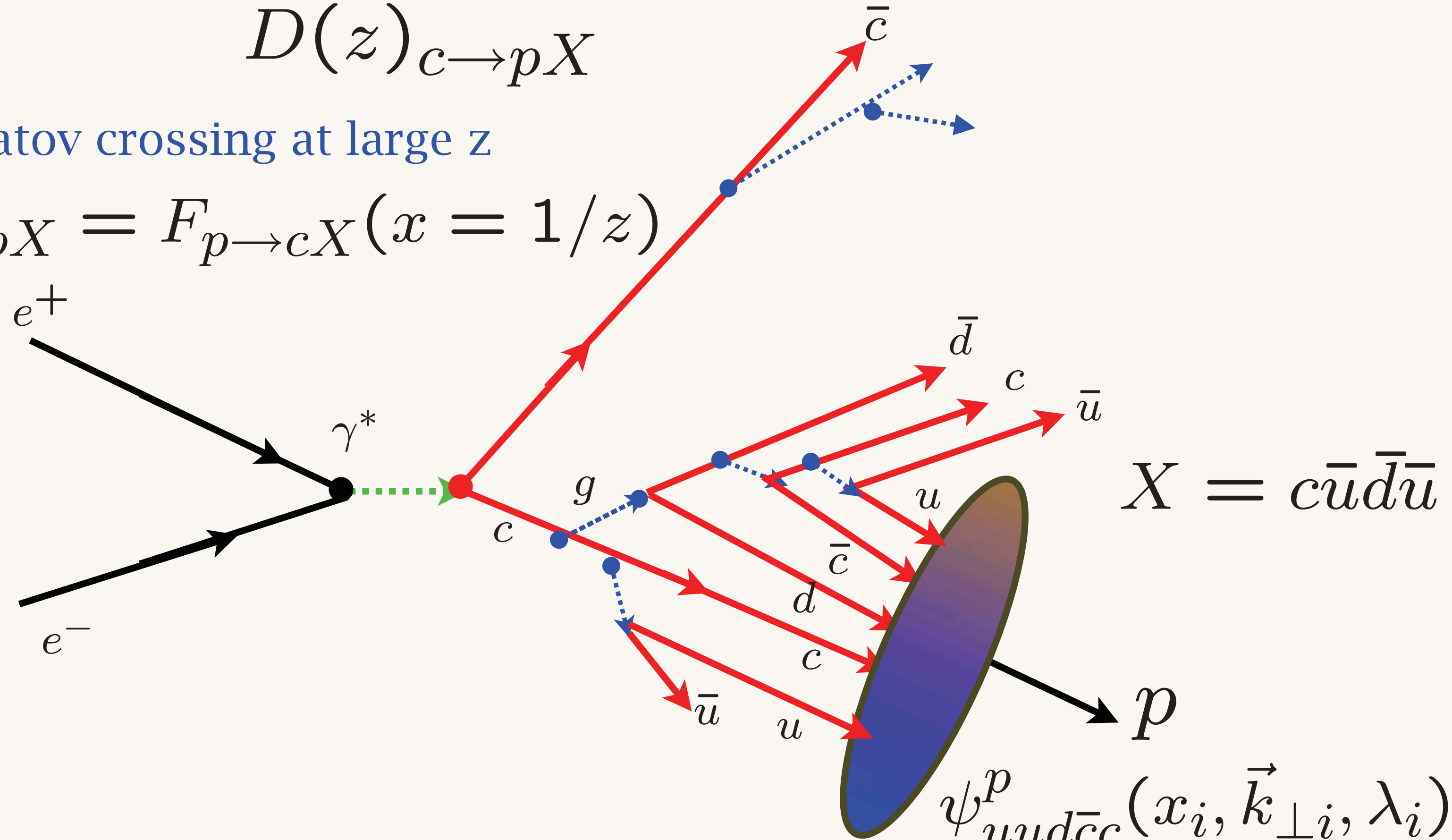
Intrinsic heavy quarks, $\bar{s}(x) \neq s(x)$ $\bar{u}(x) \neq \bar{d}(x)$

Timelike Test of Charm Distribution in Proton

$$D(z)_{c \to pX}$$

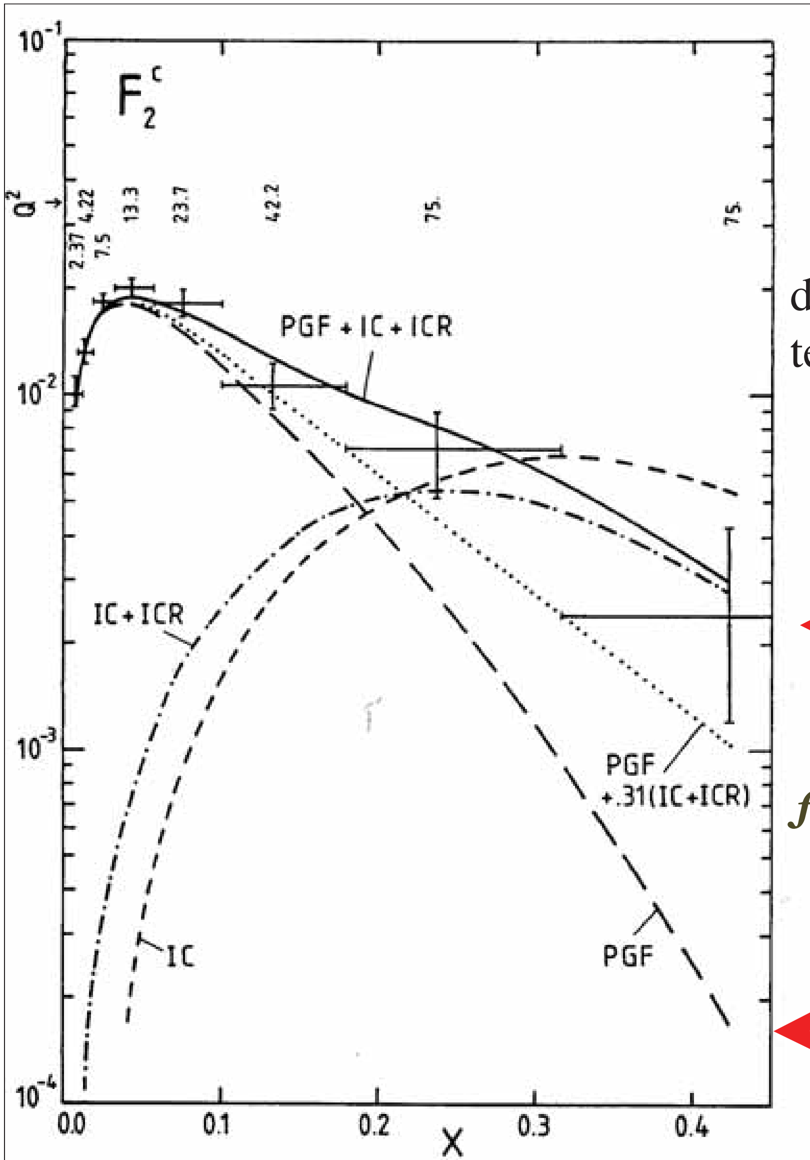
Gribov-Lipatov crossing at large z

$$zD(z)_{c \to pX} = F_{p \to cX}(x = 1/z)$$



Intrinsic charm model:
predict proton at same rapidity as charm quark: high z

$$z_i \propto m_{\perp i} = \sqrt{m_i^2 + k_\perp^2}$$

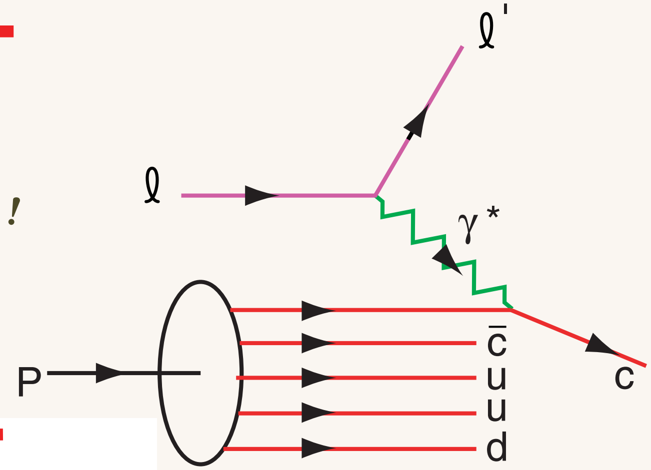


Measurement of Charm Structure Function

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

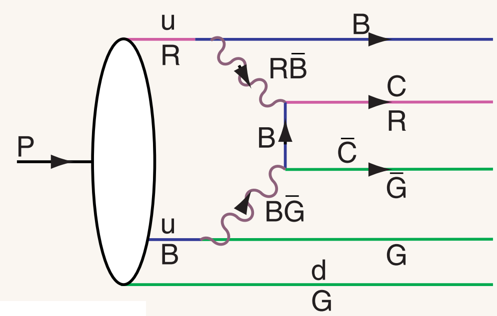
factor of 30 !



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

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



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

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

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

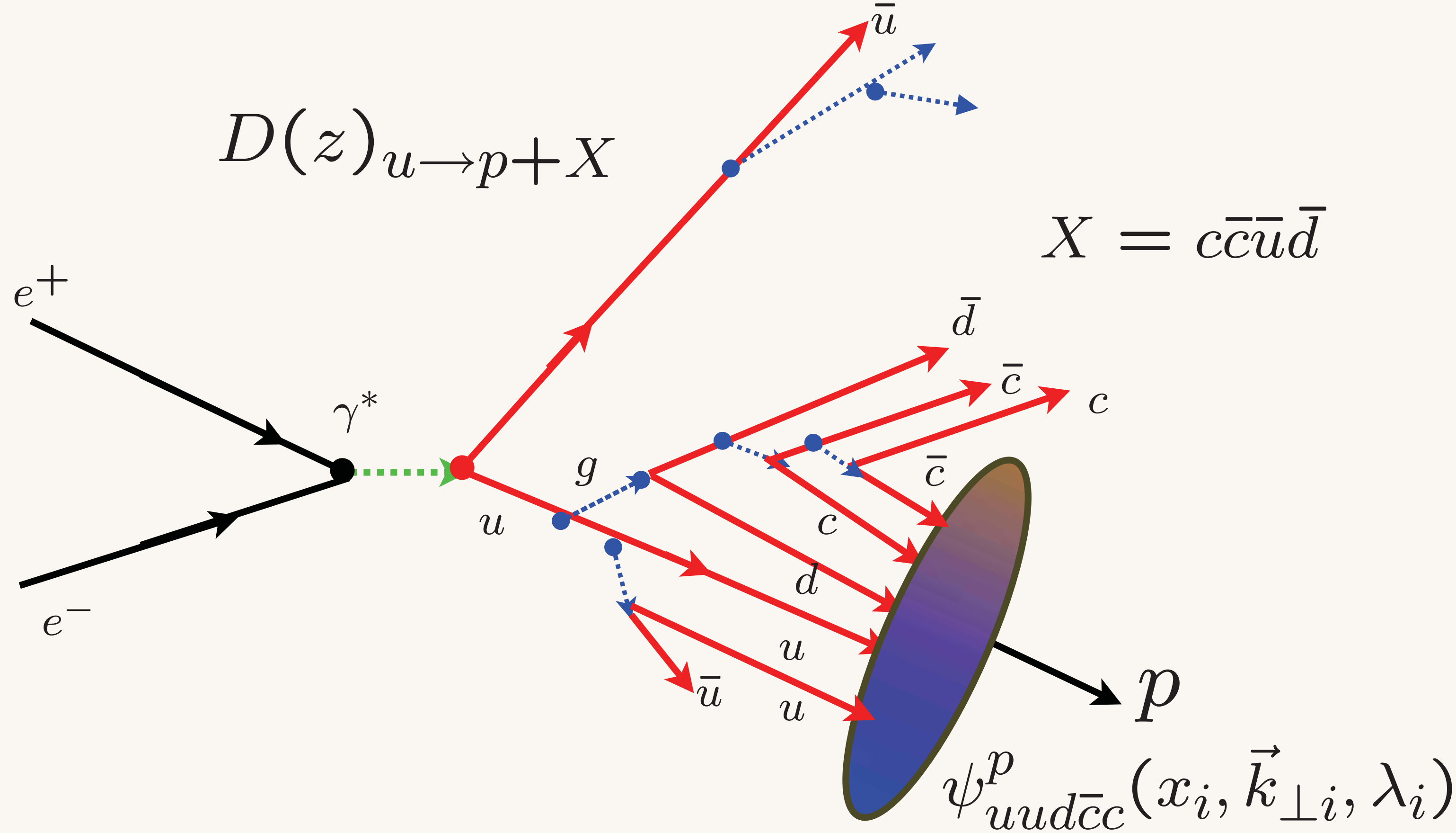
- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

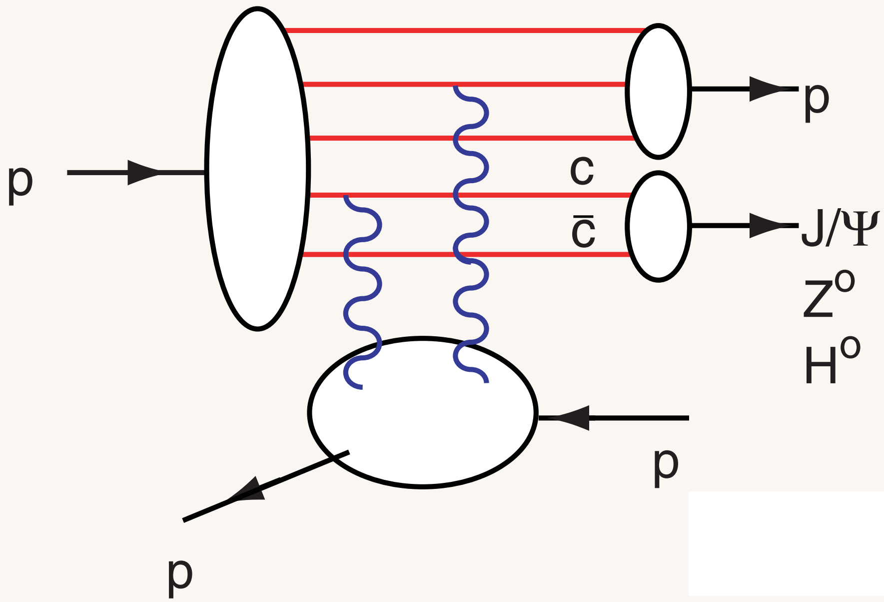
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

Distribution of spectators in X reflects proton bound-state structure



Intrinsic charm model: predict dual spectator charm hadrons at same rapidity as proton: high z

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$p\,p \rightarrow J/\psi\, p\, p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

Exclusive Diffractive High-X_F Higgs Production

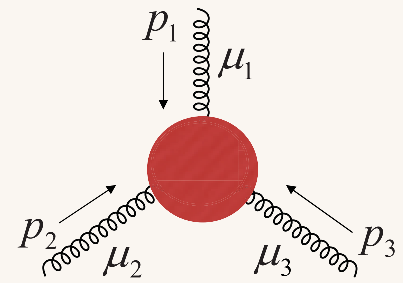
Kopeliovitch, Schmidt, Soffer, sjb

Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

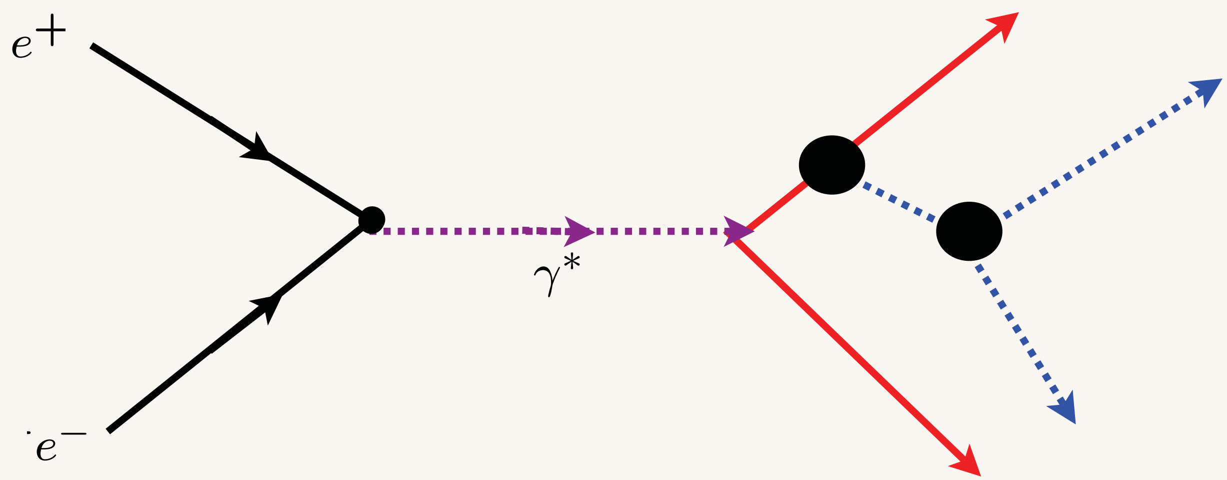
Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

Jet Physics at BaBar



$$e^+e^- \to \gamma^* \to \text{4jets}$$



Measurement of the strong coupling α_S from the four-jet rate in e^+e^- annihilation using JADE data

J. Schieck[1,a], S. Bethke[1], O. Biebel[2], S. Kluth[1], P.A.M. Fernández[3], C. Pahl[1], The JADE Collaboration[b]

Eur. Phys. J. C 48, 3–13 (2006)

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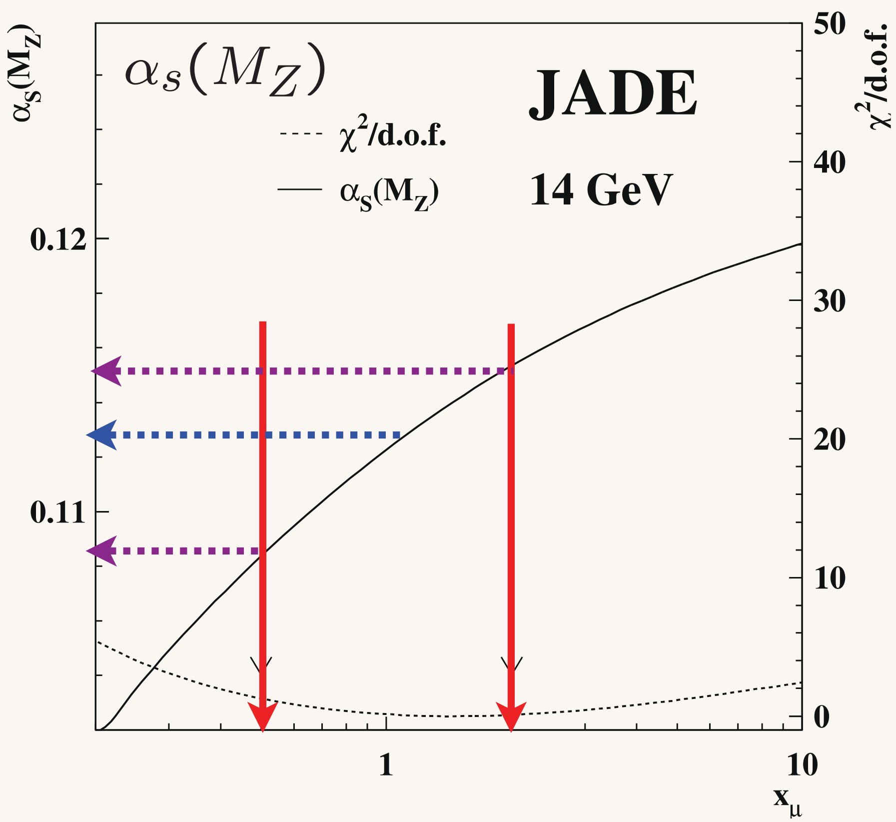


$\alpha_S(M_{Z^0})$ and the χ^2/d.o.f. of the fit to the four-jet rate as a function of the renormalization scale x_μ for $\sqrt{s} = 14$ GeV to 43.8 GeV. The arrows indicate the variation of the renormalization scale factor used for the determination of the systematic uncertainties

The theoretical uncertainty, associated with missing higher order terms in the theoretical prediction, is assessed by varying the renormalization scale factor x_μ. The predictions of a complete QCD calculation would be independent of x_μ, but a finite-order calculation such as that used here retains some dependence on x_μ. The renormalization scale factor x_μ is set to 0.5 and two. The larger deviation from the default value of α_S is taken as systematic uncertainty.

$$x_\mu = \frac{\mu_R}{\sqrt{s}}$$

No PMS

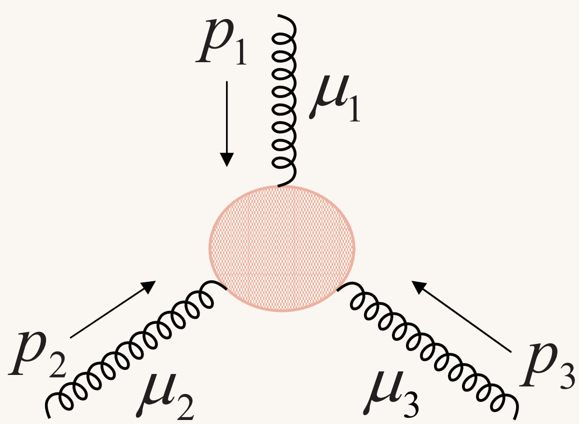
The Renormalization Scale Problem

$$\rho(Q^2) = C_0 + C_1\alpha_s(\mu_R) + C_2\alpha_s^2(\mu_R) + \cdots$$

$$\mu_R^2 = CQ^2$$

Is there a way to set the renormalization scale μ_R ?

What happens if there are multiple physical scales ?



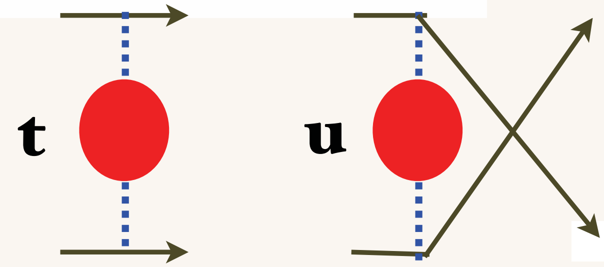
Conventional wisdom concerning scale setting

- Renormalization scale can be set to any value; e.g. $\mu_R = Q$
- Sensitivity to renormalization scale disappears at high order
- No optimal scale *(only true if mass thresholds are incorporated)*
- Ignore problem of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking a range $Q/2 < \mu_R < 2Q$
- Factorization scale should be taken equal to renormalization scale $\mu_F = \mu_R$

All of these assumptions are fallacious

Electron-Electron Scattering in QED

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

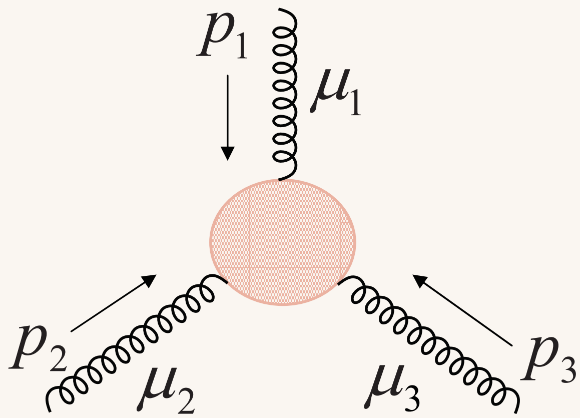


- Two separate physical scales.
- Gauge Invariant. Dressed photon propagator
- Sums all vacuum polarization, non-zero beta terms into running coupling.
- If one chooses a different scale, one must sum an infinite number of graphs -- but then recover same result!
- Number of active leptons correctly set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

Lessons from QED : Summary

- Effective couplings are complex analytic functions with the correct threshold structure expected from unitarity
- Multiple “renormalization” scales appear
- The scales are unambiguous since they are physical kinematic invariants
- Optimal improvement of perturbation theory

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



H. J. Lu

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

Binger, sjb

3 Scale Effective Charge

$$\tilde{\alpha}(a,b,c) \equiv \frac{\tilde{g}^2(a,b,c)}{4\pi}$$

(First suggested by H.J. Lu)

$$\frac{1}{\tilde{\alpha}(a,b,c)} = \frac{1}{\alpha_{bare}} + \frac{1}{4\pi}\beta_0\left(L(a,b,c) - \frac{1}{\varepsilon} + \cdots\right)$$

$$\frac{1}{\tilde{\alpha}(a,b,c)} = \frac{1}{\tilde{\alpha}(a_0,b_0,c_0)} + \frac{1}{4\pi}\beta_0\left[L(a,b,c) - L(a_0,b_0,c_0)\right]$$

L(a,b,c) = 3-scale “log-like” function

L(a,a,a) = log(a)

Binger, sjb

Properties of the Effective Scale

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

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

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

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

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

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

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

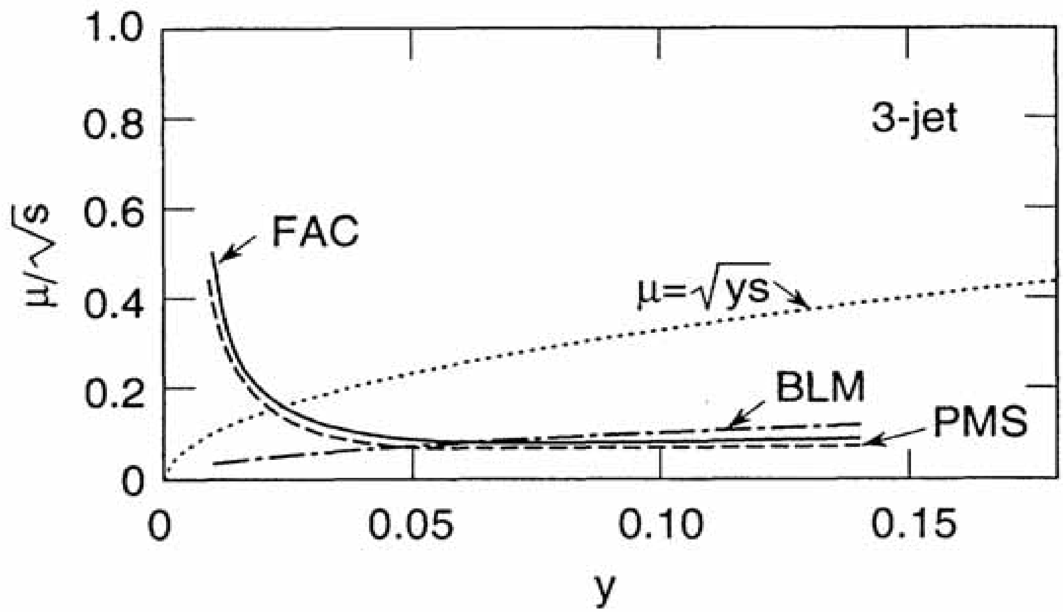
Surprising dependence on Invariants

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 nonzero beta function summed into running coupling
- Identical procedure in QED
- Resulting series identical to conformal series
- Renormalon n! growth of PQCD coefficients from beta function eliminated!
- In general, BLM scale depends on all invariants



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

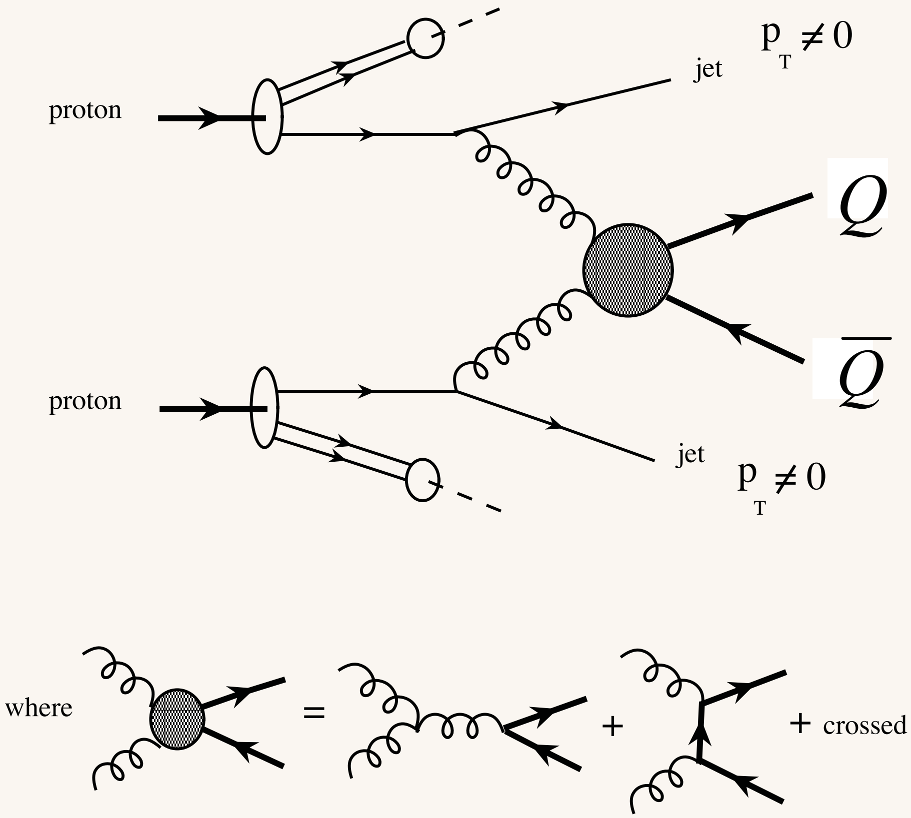
Other Jet Observables:

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

Heavy Quark Hadro-production



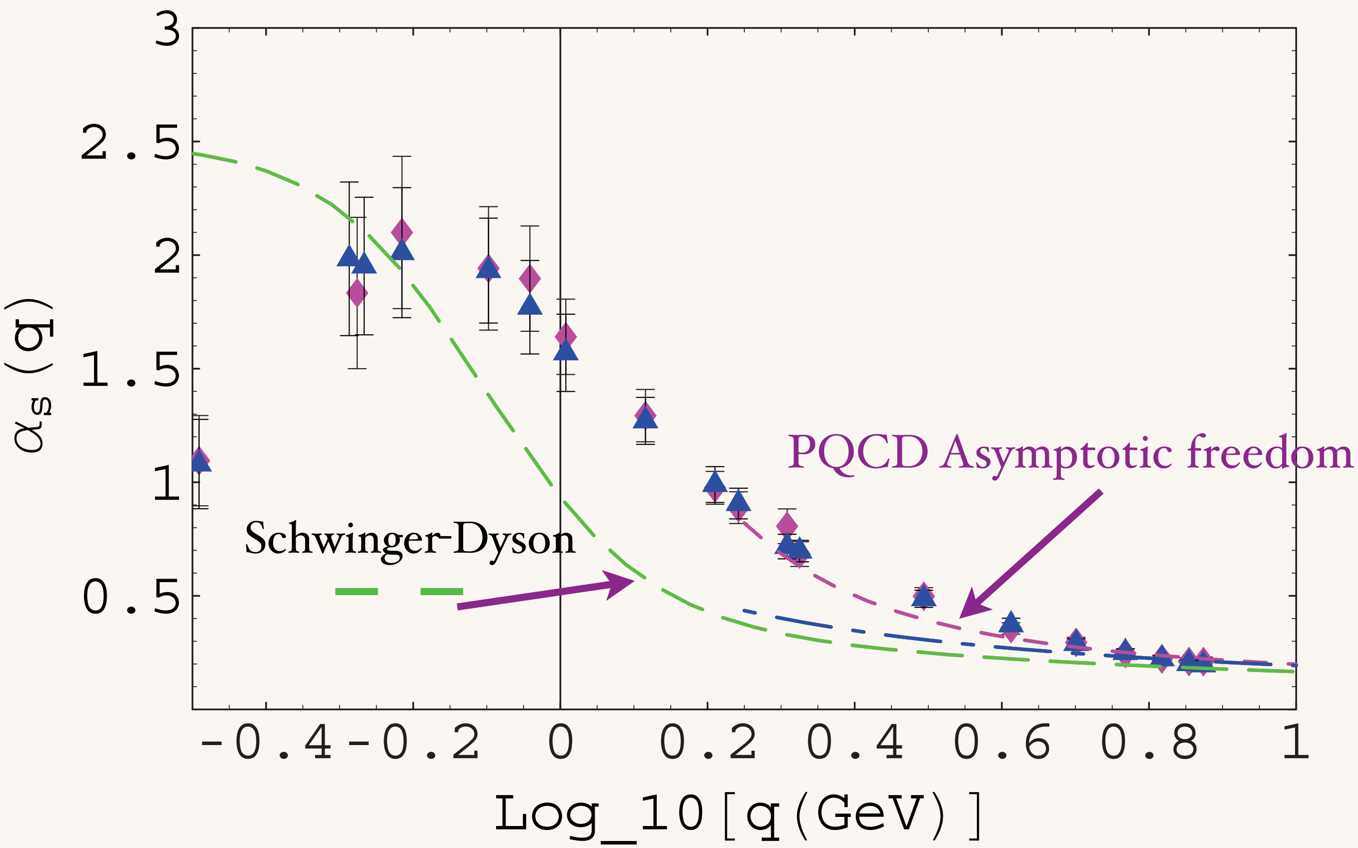
- Preliminary calculation using (massless) results for tree level form factor
- Very low effective scale

→ much larger cross section than $\overline{MS}$ with scale $\mu_R = M_{Q\overline{Q}}$ or M_Q

- Future : repeat analysis using the full mass-dependent results and include all form factors

Expect that this approach accounts for most of the one-loop corrections

Infrared-Finite QCD Coupling?

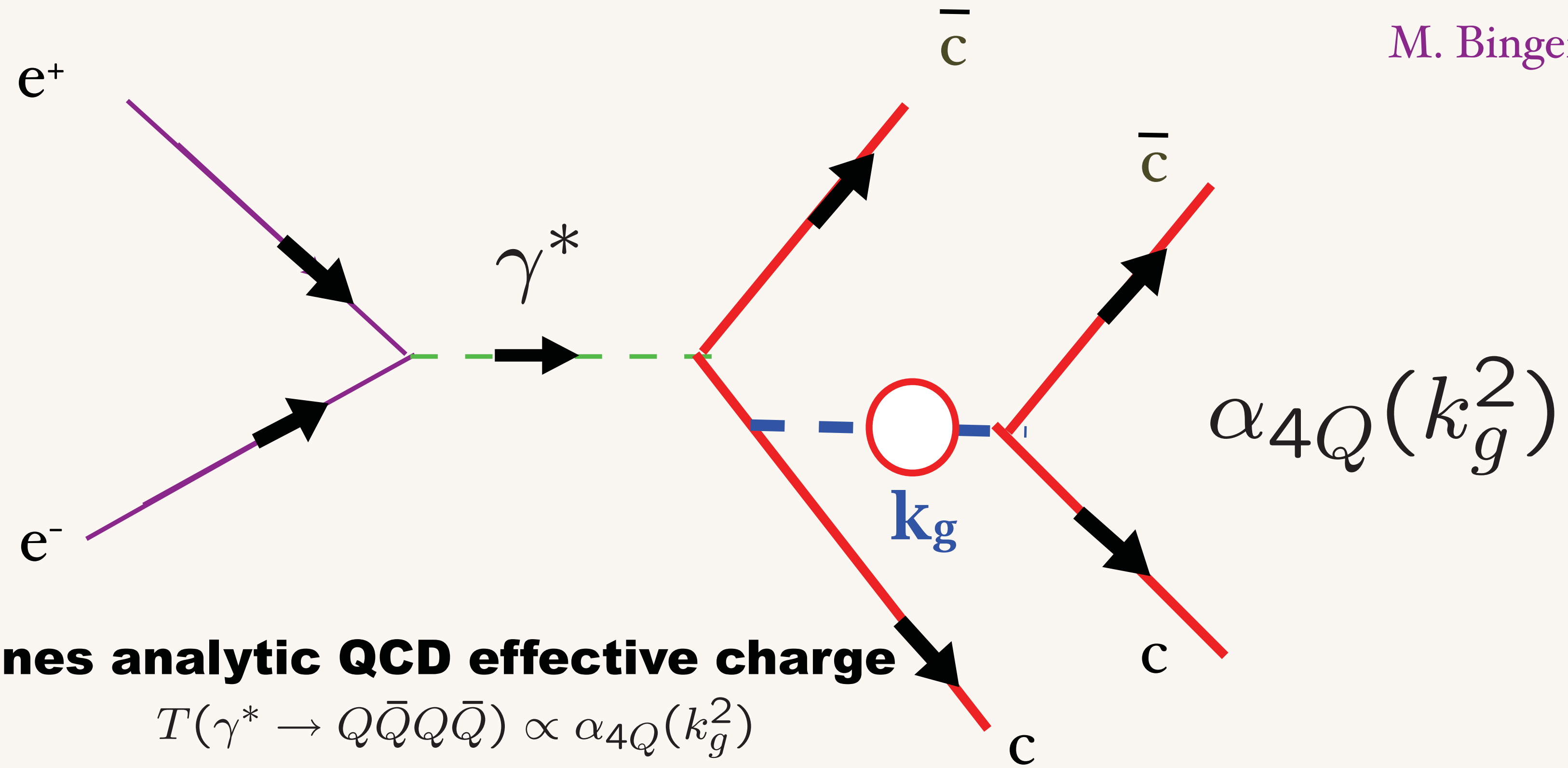


Lattice simulation
(MILC)

Furui, Nakajima

DSE: Alkofer, Fischer, von Smekal et al.

Production of four heavy-quark jets



Defines analytic QCD effective charge

$$T(\gamma^* \to Q\bar{Q}Q\bar{Q}) \propto \alpha_{4Q}(k_g^2)$$

time-like values not same as space-like

coupling similar to "pinch" scheme

complex for time-like argument

Define QCD Coupling from Observable

Grunberg

$$R_{e^+e^-\to X}(s) \equiv 3\Sigma_q e_q^2\ [1+\frac{\alpha_R(s)}{\pi}]$$

$$\Gamma(\tau \to X e\nu)(m_\tau^2) \equiv \Gamma_0(\tau \to u\bar{d}e\nu)\times[1+\frac{\alpha_\tau(m_\tau^2)}{\pi}]$$

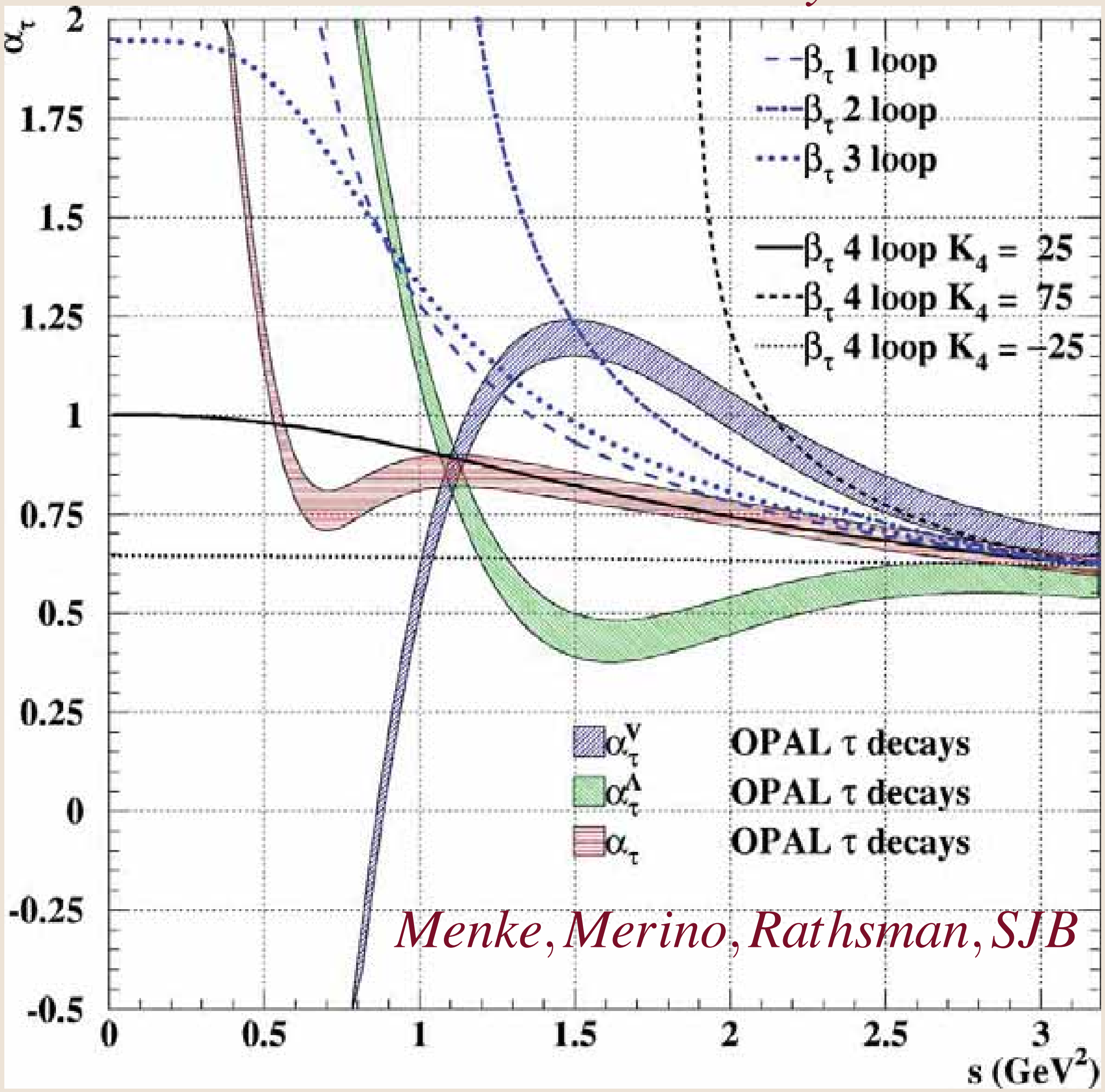
Commensurate scale relations:
Relate observable to observable at commensurate scales

Effective Charges: analytic at quark mass thresholds, finite at small momenta

H.Lu, Rathsman, sjb

Pinch scheme: Cornwall, et al

QCD Effective Coupling from *hadronic τ decay*



$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.$$

Eliminate MSbar, Find Amazing Simplification

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

$$\sqrt{s^*} \simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)
Analytic matching at quark thresholds
No renormalization scale ambiguity!

QCD Opportunities at BaBar

- Fundamental tests of hadron structure, dynamics, and wavefunctions
- Tests of novel nonperturbative and perturbative QCD phenomena
- Hadronization at the amplitude level
- Scale-fixed predictions, commensurate scale relations
- Tests of AdS/CFT holography
- Production of new gluonium, heavy quark, and C=+ states
- Novel diffraction, spin, and fractional charge tests

QCD Opportunities at BaBar

- Photon-Photon Collisions -- real and virtual
- Photon structure functions
- Upsilon decay: ggg, gg factory
- Heavy quark phenomena
- Spin correlations
- Need high luminosity continuum data as well as radiative return
- Fully exploit BaBar capabilities