QCD Phenomenology and Nucleon Structure

Stan Brodsky, SLAC

Lecture V

National Nuclear Physics Summer School
QCD: $N_C = 3$  
Quarks: $3_C$  
Gluons: $8_C$.

$\alpha_s = \frac{g^2}{4\pi}$ is dimensionless

Classical Lagrangian is scale invariant for massless quarks

If $\beta = \frac{d\alpha_s(Q^2)}{d\log Q^2} = 0$ then QCD is invariant under conformal transformations:

Parisi
Conformal symmetry: Template for QCD

- Initial approximation to PQCD; then correct for non-zero beta function and quark masses

- Commensurate scale relations: relate observables at corresponding scales: Generalized Crewther Relation

- Arguments for Infrared fixed-point for $\alpha_s$ (Alhofer, et al.)

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

- Eigensolutions of Evolution Equation of distribution amplitudes
The Renormalization Scale Problem

\[ \rho = C_1 \alpha_s(\mu_R) + C_2 \alpha_s^2(\mu_R) + C_3 \alpha_s^3(\mu_R) + \cdots \]

How does one set the renormalization scale \( \mu_R \)?
Electron-Electron Scattering in QED

\[ M_{ee\rightarrow ee}(++;++) = \frac{8\pi s}{t} \alpha(t) + \frac{8\pi s}{u} \alpha(u) \]

- No renormalization scale ambiguity!
- 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

\[ \text{Analytic: reproduces correct behavior at lepton mass thresholds} \]
$e^+e^- \rightarrow \mu^+\mu^-$

Scale of $\alpha(\mu_r)$ unique!

$\mu^2_R = s$

$M \propto \alpha(s)$

The QED Effective Charge

• Complex
• Analytic through mass thresholds
• Distinguishes between timelike and spacelike momenta

Analyticity essential!
The Renormalization Scale Problem

- No renormalization scale ambiguity in QED

- Gell Mann-Low-Dyson QED Coupling defined from physical observable;

- Sums all Vacuum Polarization Contributions

- Recover conformal series

- Renormalization Scale in QED scheme: Identical to Photon Virtuality

- Analytic: Reproduces lepton-pair thresholds

- Examples: muonic atoms, g-2, Lamb Shift

- Time-like and Space-like QED Coupling related by analyticity

- Uses Dressed Skeleton Expansion
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
BLM Scale Setting

\[ \rho = C_0 \alpha_{\overline{\text{MS}}}(Q) \left[ 1 + \frac{\alpha_{\overline{\text{MS}}}(Q)}{\pi} \left( -\frac{3}{2} \beta_0 A_{VP} + \frac{33}{2} A_{VP} + B \right) + \cdots \right] \]

by

\[ \rho = C_0 \alpha_{\overline{\text{MS}}}(Q^*) \left[ 1 + \frac{\alpha_{\overline{\text{MS}}}(Q^*)}{\pi} C_1^* + \cdots \right], \]

where

\[ Q^* = Q \exp(3A_{VP}) , \]

\[ C_1^* = \frac{33}{2} A_{VP} + B . \]

The term \( 33A_{VP}/2 \) in \( C_1^* \) serves to remove that part of the constant \( B \) which renormalizes the leading-order coupling. The ratio of these gluonic corrections to the light-quark corrections is fixed by \( \beta_0 = 11 - \frac{2}{3} n_f \).

Use \( n_f \) dependence at NLO to identify \( A_{VP} \)

Use skeleton expansion: Gardi, Rathsman, sjb

Conformal Coefficient

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\[ R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q^2 \left[ 1 + \frac{\alpha_R(Q)}{\pi} \right]. \]

\[ R_{e^+e^-}(Q^2) = 3 \sum_q e_q^2 \left[ 1 + \frac{\alpha_{\overline{\text{MS}}}(Q)}{\pi} + \frac{\alpha_{\overline{\text{MS}}}^2}{\pi^2} (1.98 - 0.115n_f) \right] + \cdots \]

\[ \rightarrow 3 \sum_q e_q^2 \left[ 1 + \frac{\alpha_{\overline{\text{MS}}}(Q^*)}{\pi} + \frac{\alpha_{\overline{\text{MS}}}^2(Q^*)}{\pi^2} 0.08 \right] + \cdots , \]

\[ Q^* = 0.710Q. \]

Notice that \( \alpha_R(Q) \) differs from \( \alpha_{\overline{\text{MS}}}(Q^*) \) by only \( 0.08\alpha_{\overline{\text{MS}}}/\pi \), so that \( \alpha_R(Q) \) and \( \alpha_{\overline{\text{MS}}}(0.71Q) \) are effectively interchangeable (for any value of \( n_f \)).
\[ V(Q^2) = -\frac{C_F 4\pi \alpha_{\overline{MS}}(Q)}{Q^2} \left[ 1 + \frac{\alpha_{\overline{MS}}}{\pi} \left( \frac{5}{12} \beta_0 - 2 \right) + \cdots \right] \]

\[ \rightarrow -\frac{C_F 4\pi \alpha_{\overline{MS}}(Q^*)}{Q^2} \left[ 1 - \frac{\alpha_{\overline{MS}}(Q^*)}{\pi} 2 + \cdots \right], \]

where \( Q^* = e^{-5/6}, Q \approx 0.43 Q \). This result shows that the effective scale of the \( \overline{MS} \) scheme should generally be about half of the true momentum transfer occurring in the interaction. In parallel to QED, the effective potential \( V(Q^2) \) gives a particularly intuitive scheme for defining the QCD coupling constant

\[ V(Q^2) \equiv -\frac{4\pi C_F \alpha_v(Q)}{Q^2} \]
Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb


- All terms associated with nonzero beta function summed into running coupling
- BLM Scale $Q^*$ sets the number of active flavors
- Only $n_f$ dependence required to determine renormalization scale at NLO
- Result is scheme independent: $Q^*$ has exactly the correct dependence to compensate for change of scheme
- Correct Abelian limit

- **Resulting series identical to conformal series!**
- Renormalon $n!$ growth of PQCD coefficients from beta function eliminated!
- In general, BLM scale depends on all invariants
Deep-inelastic scattering. The moments of the nonsinglet structure function $F_2(x,Q^2)$ obey the evolution equation

$$Q^2 \frac{d}{dQ^2} \ln M_n(Q^2)$$

$$= - \frac{\gamma_n^{(0)}}{8\pi} \alpha_{\text{MS}}(Q) \left[ 1 + \frac{\alpha_{\text{MS}}}{4\pi} \frac{2\beta_0 \beta_n + \gamma_n^{(1)}}{\gamma_n^{(0)}} + \cdots \right]$$

$$\rightarrow - \frac{\gamma_n^{(0)}}{8\pi} \alpha_{\text{MS}}(Q_n^*) \left[ 1 - \frac{\alpha_{\text{MS}}(Q_n^*)}{\pi} C_n + \cdots \right],$$

where, for example,

$$Q_2^* = 0.48Q, \quad C_2 = 0.27,$$

$$Q_{10}^* = 0.21Q, \quad C_{10} = 1.1.$$

For $n$ very large, the effective scale here becomes $Q_n^* \sim Q/\sqrt{n}$

BLM scales for DIS moments
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 $\mu$ as the jet invariant mass $M < \sqrt{(ys)}$ decreases.

Other Jet Observables:

Kramer & Lampe

Rathsman

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\[ V(Q^2) = - \frac{C_F 4\pi \alpha_{\overline{\text{MS}}}(Q)}{Q^2} \left[ 1 + \frac{\alpha_{\overline{\text{MS}}}}{\pi} \left( \frac{5}{12} \beta_0 - 2 \right) + \cdots \right] \]

\[ \rightarrow - \frac{C_F 4\pi \alpha_{\overline{\text{MS}}}(Q^*)}{Q^2} \left[ 1 - \frac{\alpha_{\overline{\text{MS}}}(Q^*)}{\pi} 2 + \cdots \right], \]

where \( Q^* = e^{-5/6} Q \approx 0.43 Q \). This result shows that the effective scale of the \( \overline{\text{MS}} \) scheme should generally be about half of the true momentum transfer occurring in the interaction. In parallel to QED, the effective potential \( V(Q^2) \) gives a particularly intuitive scheme for defining the QCD coupling constant

\[ V(Q^2) \equiv - \frac{4\pi C_F \alpha_v(Q)}{Q^2} \]
The unperturbed effective weak hamiltonian is
\[ H = \sum_{i} J_{i} J_{i}^* \]  
(1)

of \( o_{q} (Q^2) \). The disconnected diagram vanishes after integration with collinear meson distribution amplitudes.

\[ \rho = C_1 \alpha_s(\mu_R) + C_2 \alpha^2_s(\mu_R) + C_3 \alpha^3_s(\mu_R) + \cdots \]

\[ \alpha_{MS}(e^{-5/3Q^2}) \]

Multiple BLM scales

\[ \begin{align*}
B &\rightarrow \pi \ell \bar{\nu} \\
B &\rightarrow \pi \pi
\end{align*} \]
Features of BLM Scale Setting

- All terms associated with nonzero beta function summed into running coupling
- Conformal series preserved
- BLM Scale $Q^*$ sets the number of active flavors
- Correct analytic dependence in the quark mass
- Only $n_f$ dependence required to determine renormalization scale at NLO
- Result is scheme independent: $Q^*$ has exactly the correct dependence to compensate for change of scheme
- Correct Abelian limit!
\[ \lim_{N_C \to 0} \text{ at fixed } \alpha = C_F \alpha_s, \quad n_\ell = n_F / C_F \]

QCD \rightarrow \text{ Abelian Gauge Theory}

Analytic Feature of \( SU(N_c) \) Gauge Theory 

Huet, sjb
Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Example: Generalized Crewther Relation
\[ \frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\text{MS}}(Q)}{\pi} + \left( \frac{\alpha_{\text{MS}}(Q)}{\pi} \right)^2 \left[ \left( \frac{41}{8} - \frac{11}{3} \zeta_3 \right) C_A - \frac{1}{8} C_F + \left( -\frac{11}{12} + \frac{2}{3} \zeta_3 \right) f \right] \\
+ \left( \frac{\alpha_{\text{MS}}(Q)}{\pi} \right)^3 \left\{ \left( \frac{90445}{2592} - \frac{2737}{108} \zeta_3 - \frac{55}{18} \zeta_5 - \frac{121}{432} \pi^2 \right) C_A^2 + \left( -\frac{127}{48} - \frac{143}{12} \zeta_3 + \frac{55}{3} \zeta_5 \right) C_A C_F - \frac{23}{32} C_F^2 \right. \\
+ \left[ \left( -\frac{970}{81} + \frac{224}{27} \zeta_3 + \frac{5}{9} \zeta_5 + \frac{11}{108} \pi^2 \right) C_A + \left( -\frac{29}{96} + \frac{19}{6} \zeta_3 - \frac{10}{3} \zeta_5 \right) C_F \right] f \\
+ \left( \frac{151}{162} - \frac{19}{27} \zeta_3 - \frac{1}{108} \pi^2 \right) f^2 + \left( \frac{11}{144} - \frac{1}{6} \zeta_3 \right) d_{abc} d_{abc} \left( \frac{\sum_f Q_f}{C_F d(R)} \right)^2 \left( \frac{\sum_f Q_f^2}{\sum_f Q_f^2} \right) \right\}. \]

\[ \frac{\alpha_{g1}(Q)}{\pi} = \frac{\alpha_{\text{MS}}(Q)}{\pi} + \left( \frac{\alpha_{\text{MS}}(Q)}{\pi} \right)^2 \left[ \frac{23}{12} C_A - \frac{7}{8} C_F - \frac{1}{3} f \right] \\
+ \left( \frac{\alpha_{\text{MS}}(Q)}{\pi} \right)^3 \left\{ \left( \frac{5437}{648} - \frac{55}{18} \zeta_5 \right) C_A^2 + \left( -\frac{1241}{432} + \frac{11}{9} \zeta_3 \right) C_A C_F + \frac{1}{32} C_F^2 \right. \\
+ \left[ \left( -\frac{3535}{1296} - \frac{1}{2} \zeta_3 + \frac{5}{9} \zeta_5 \right) C_A + \left( \frac{133}{864} + \frac{5}{18} \zeta_3 \right) C_F \right] f + \frac{115}{648} f^2 \left\} \right. \]
\[
\int_0^1 dx \left[ g_{1}^{ep}(x, Q^2) - g_{1}^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[ 1 - \frac{\alpha g_1(Q)}{\pi} \right]
\]

\[
\frac{\alpha g_1(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left( \frac{\alpha_R(Q^{**})}{\pi} \right)^2 + \left( \frac{\alpha_R(Q^{***})}{\pi} \right)^3
\]

**Geometric Series in Conformal QCD**

**Generalized Crewther Relation**

add Light-by-Light

Lu, Kataev, Gabadadze, Sjb

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Generalized Crewther Relation

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

\[ \sqrt{s^*} \approx 0.52Q \]

Conformal relation true to all orders in perturbation theory
Transitivity property - Renormalization Group

A → C → B
same as A → B

indep of C

Relation between observables A ↔ B
independent of choice of C and scheme or
theoretical convention.

PMS violates transitivity
Commensurate Scale Relation:

\[ \alpha_s(Q_B) = \alpha_s(Q_A) \left[ 1 + C_{A/B} \frac{\alpha_s}{\pi} + \ldots \right] \]

\[ \frac{Q_B}{Q_A} = \lambda B/A \]

Peterson\hspace{1cm}\begin{align*}
\frac{\lambda B/A}{\lambda B/C} &= \frac{\lambda A/C}{\lambda A/B} \\
\frac{\lambda B/A}{\lambda A/B} &= 1
\end{align*}\hspace{1cm} \text{transverse symmetry}

Süßclenberg

Renormalization "Group"

\[ \frac{\lambda A/B}{\lambda A/B} = 1 \hspace{1cm} \text{identity} \]
Leading Order Commensurate Scales

\[
\begin{align*}
\alpha_{\tau}(1.36Q) & \quad \alpha_{\tau}(2.77Q) \\
\alpha_{\eta_b}(1.67Q) & \quad \alpha_{p}(Q) \\
\alpha_{GLS}(1.18Q) & \quad \alpha_{M_2}(0.904Q) \\
\alpha_{MS}(0.435Q) & \quad \alpha_{R}(0.614Q) \\
\alpha_{g_1}(1.18Q) &
\end{align*}
\]

Translate between schemes at LO

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Production of four heavy-quark jets

\[ e^+ \rightarrow \gamma^* \rightarrow Q\bar{Q}Q\bar{Q} \]

Defines analytic QCD effective charge

\[ T(\gamma^* \rightarrow Q\bar{Q}Q\bar{Q}) \propto \alpha_{4Q}(k_g^2) \]

time-like values not same as space-like

coupling similar to “pinch” scheme

complex for time-like argument
Conventional renormalization scale-setting method:

- Guess arbitrary renormalization scale and take arbitrary range. Wrong for QED and Precision Electroweak.
- Prediction depends on choice of renormalization scheme
- Variation of result with respect to renormalization scale only sensitive to nonconformal terms; no information on genuine (conformal) higher order terms
- Conventional procedure has no scientific basis.
- FAC and PMS give unphysical results; have no validity.
- Renormalization scale not arbitrary! Sets # active flavors
The Pinch Technique

(Cornwall, Papavassiliou)

\[
q \cdot V(p, k) = S^{-1}(p) - S^{-1}(k)
\]

Gauge-dependent

\[
\text{PT} = \begin{align*}
\text{self-energy-like projection} \\
\begin{array}{c}
\phantom{\text{self-energy-like projection}} \\
\end{array}
\end{align*}
\]

Gauge-invariant gluon self-energy!

natural generalization of QED charge
Use Physical Scheme to Characterize QCD Coupling

• Use Observable to define QCD coupling or Pinch Scheme

• Analytic: Smooth behavior as one crosses new quark threshold

• New perspective on grand unification
Asymptotic Unification

\[ \alpha_i^{-1}(Q) \]

\[ Q(\text{GeV}) \]

Binger, sjb

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Analyticity and Mass Thresholds

\( \overline{MS} \) does not have automatic decoupling of heavy particles

Must define a set of schemes in each desert region and match

\[
\alpha_s^{(f)}(M_Q) = \alpha_s^{(f+1)}(M_Q)
\]

- The coupling has **discontinuous derivative** at the matching point
- At higher orders the coupling itself becomes **discontinuous**!
- Does not distinguish between spacelike and timelike momenta

“AN ANALYTIC EXTENSION OF THE MS-BAR RENORMALIZATION SCHEME”
Unification in Physical Schemes

- Smooth analytic threshold behavior with automatic decoupling
- More directly reflects the unification of the forces
- Higher “unification” scale than usual
General Structure of the Three-Gluon Vertex

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

Full calculation, general masses, spin
The Gauge Invariant
Three Gluon Vertex

Cornwall and Papavassiliou performed the PT construction:

The “pinched” parts are added to the “regular” 3 gluon vertex

Later shown to = BFMFG

Integrals were not evaluated…

gauge
dependent

gauge
invariant
# Summary of Supersymmetric Relations

<table>
<thead>
<tr>
<th>Massless</th>
<th>Massive</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ F_G + 4F_Q + (10 - d)F_S = 0 ]</td>
<td>[ F_{MG} + 4F_{MQ} + (9 - d)F_{MS} = 0 ]</td>
</tr>
<tr>
<td>[ \Sigma_{QG}(F) \equiv \frac{d - 2}{2} F_Q + F_G ]</td>
<td>[ \Sigma_{MQG}(F) \equiv \frac{d - 1}{2} F_{MQ} + F_{MG} ]</td>
</tr>
<tr>
<td>= simple</td>
<td>= simple</td>
</tr>
</tbody>
</table>
Multi-scale Renormalization of the Three-Gluon Vertex

\[ \tilde{g}(p_1^2, p_2^2, p_3^2) \]

\[ g(p_1^2) \]

\[ g(p_2^2) \]

\[ g(p_3^2) \]

Gauge-invariant subset of radiative correction.

Coupling at each vertex absorbs the radiative correction.
3 Scale Effective Charge

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

(First suggested by H.J. Lu)

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

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

\[L(a,b,c) = 3\text{-scale "log-like" function}\]

\[L(a,a,a) = \log(a)\]
3 Scale Effective Scale

\[ L(a,b,c) \equiv \log\left(Q_{\text{eff}}^2(a,b,c)\right) + i \text{Im} L(a,b,c) \]

Governs strength of the three-gluon vertex

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

\[
\hat{\Gamma}_{\mu_1 \mu_2 \mu_3} \propto \sqrt{\tilde{\alpha}(a,b,c)}
\]

Generalization of BLM Scale to 3-Gluon Vertex
Properties of the Effective Scale

\[
Q_{\text{eff}}^2 (a, b, c) = Q_{\text{eff}}^2 (-a, -b, -c)
\]

\[
Q_{\text{eff}}^2 (\lambda a, \lambda b, \lambda c) = |\lambda| Q_{\text{eff}}^2 (a, b, c)
\]

\[
Q_{\text{eff}}^2 (a, a, a) = |a|
\]

\[
Q_{\text{eff}}^2 (a, -a, -a) \approx 5.54 |a|
\]

\[
Q_{\text{eff}}^2 (a, a, c) \approx 3.08 |c| \quad \text{for} \quad |a| >> |c|
\]

\[
Q_{\text{eff}}^2 (a, -a, c) \approx 22.8 |c| \quad \text{for} \quad |a| >> |c|
\]

\[
Q_{\text{eff}}^2 (a, b, c) \approx 22.8 \frac{|bc|}{|a|} \quad \text{for} \quad |a| >> |b|, |c|
\]

Surprising dependence on Invariants
The Effective Scale

$Q_{\text{eff}}^2 (10 \text{ GeV}^2, 10 \text{ GeV}^2, p^2)$

$Q_{\text{eff}}^2 (-10 \text{ GeV}^2, -10 \text{ GeV}^2, p^2)$

$Q_{\text{eff}}^2 (10 \text{ GeV}^2, p^2, p^2)$

$Q_{\text{eff}}^2 (-10 \text{ GeV}^2, p^2, p^2)$
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

$\propto \propto$ $\propto$ $\propto$ $\propto$

where

$p_T \neq 0$

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Future Directions

Gauge-invariant four gluon vertex

\[ L_4(p_1, p_2, p_3, p_4) \]
\[ Q_{4\text{eff}}^2(p_1, p_2, p_3, p_4) \]

Hundreds of form factors!
Summary and Future

- **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
Conventional renormalization scale-setting method:

- Guess arbitrary renormalization scale and take arbitrary range. Wrong for QED and Precision Electroweak.
- Prediction depends on choice of renormalization scheme
- Variation of result with respect to renormalization scale only sensitive to nonconformal terms; no information on genuine (conformal) higher order terms
- Conventional procedure has no scientific basis.
- FAC and PMS give unphysical results.
- Renormalization scale not arbitrary: Analytic constraint from flavor thresholds
Use BLM!

- 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, ...
Factorization scale

\[ \mu_{\text{factorization}} \neq \mu_{\text{renormalization}} \]

- Arbitrary separation of soft and hard physics

- Dependence on factorization scale not associated with beta function - present even in conformal theory

- Keep factorization scale separate from renormalization scale

\[ \frac{d\mathcal{O}}{d\mu_{\text{factorization}}} = 0 \]

- Residual dependence when one works in fixed order in perturbation theory.
Light-Front QCD Phenomenology

- Hidden color, Intrinsic glue, sea, Color Transparency
- Near Conformal Behavior of LFWFs at Short Distances; PQCD constraints
- Vanishing anomalous gravitomagnetic moment
- Relation between edm and anomalous magnetic moment
- Cluster Decomposition Theorem for relativistic systems
- OPE: DGLAP, ERBL evolution; invariant mass scheme
New Perspectives for QCD from AdS/CFT

- LFWFs: Fundamental description of hadrons at amplitude level
- Holographic Model from AdS/CFT: Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra: many applications!
- New basis for diagonalizing Light-Front Hamiltonian
- Physics similar to MIT bag model, but covariant. No problem with support $0 < x < 1$.
- Quark Interchange dominant force at short distances
Essential to test QCD

- J-PARC
- GSI antiprotons
- 12 GeV Jlab
- BaBar/Belle: ISR, two-gamma, timelike DVCS
- RHIC/LHC Nuclear Collisions; LHCb
- electron-proton, electron-nucleus collisions
Novel Tests of QCD at GSI

Polarized antiproton Beam  Secondary Beams

- Characteristic momentum scale of QCD: 300 MeV
- Many Tests of AdS/CFT predictions possible
- Exclusive channels: Conformal scaling laws, quark-interchange
- \( \bar{p}p \) scattering: fundamental aspects of nuclear force
- Color transparency: Coherent color effects
- Nuclear Effects, Hidden Color, Anti-Shadowing
- Anomalous heavy quark phenomena
- Spin Effects: \( A_N, A_{NN} \)
QCD Phenomenology and Nucleon Structure

Thanks to Adam and Steve!

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