Setting the Renormalization Scale in QCD: The Principle of Maximum Conformality PMC

SLAC Exp Seminar, 21th July 2011

Based on the work done in collaboration with:
Stanley J. Brodsky

SLAC-PUB-14425, Apr 2011;

Stanley J. Brodsky, L.D.G.: **arXiv:1107.0338** [hep-ph];

Outlook

- The Renormalization Scale Setting
- The QED scenario
- The BLM approach
- The PMC scale setting procedure in details : Analytic&Num
- Examples: 3-jet, Exclusive decays,…
- Properties of the PMC (CSR, Conformal Template,…)

The QCD Scale Setting: a Key Issue

- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Maximize sensitivity to new physics at the LHC

No scale ambiguity in QED

- The Gell Mann-Low scheme

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

e-e scattering

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

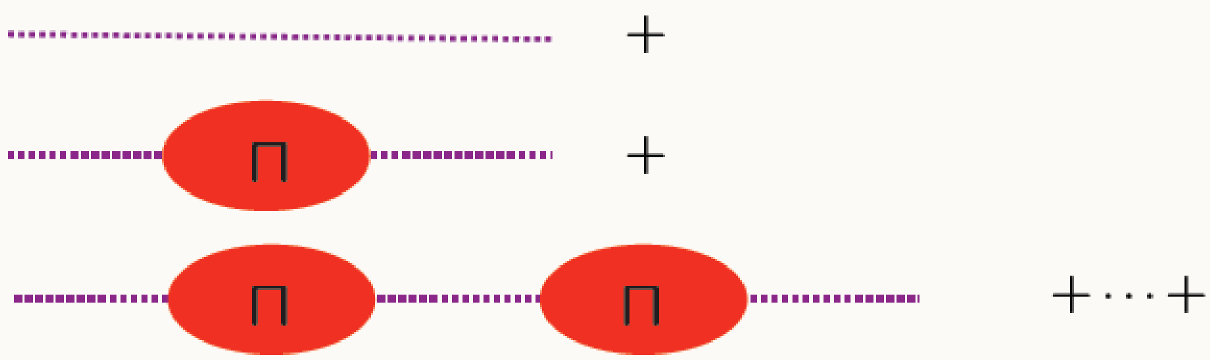
The Vacuum Polarization

Gell-Mann--Low Effective Charge

The Renormalization scale in QED is not arbitrary

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

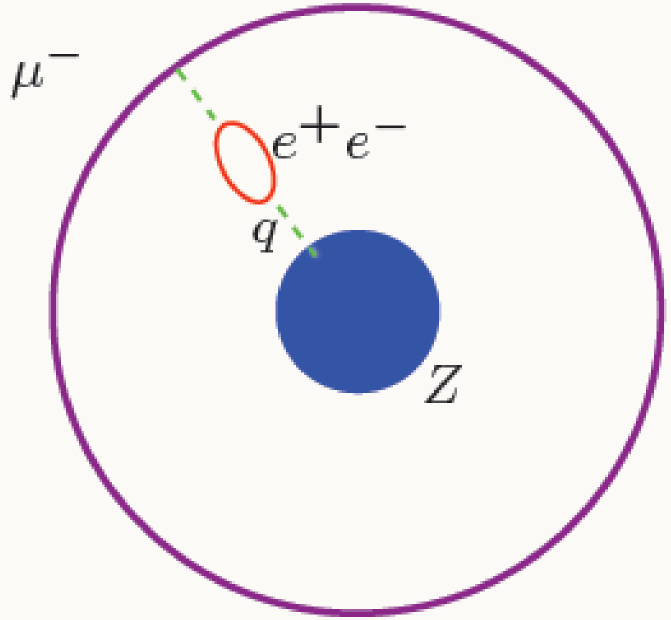
All-orders lepton loop corrections to dressed photon propagator



$$\alpha(t) = \frac{\alpha(t_0)}{1 - \Pi(t, t_0)} \qquad \Pi(t, t_0) = \frac{\Pi(t) - \Pi(t_0)}{1 - \Pi(t_0)}$$

Initial scale t_o is arbitrary -- Variation gives RGE Equations
Physical renormalization scale t not arbitrary!

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

Relation between scales of the Gell-Mann--Low and $\overline{\text{MS}}$ schemes

$$\log \frac{\mu_0^2}{m_\ell^2} = 6 \int_0^1 x(1-x) \log \frac{m_\ell^2 + Q_0^2 x(1-x)}{m_\ell^2}$$

$$\log \frac{\mu_0^2}{m_\ell^2} = \log \frac{Q_0^2}{m_\ell^2} - 5/3$$

$$\mu_0^2 = Q_0^2 \; e^{-5/3}$$

$$\text{when } Q_0^2 >> m_\ell^2$$

Space-Like q^2

Dimensional Reg.

D.S. Hwang, S.J. Brodsky
M. Binger

Can use MS scheme in QED; answers are scheme independent
Analytic extension: coupling is complex for timelike argument

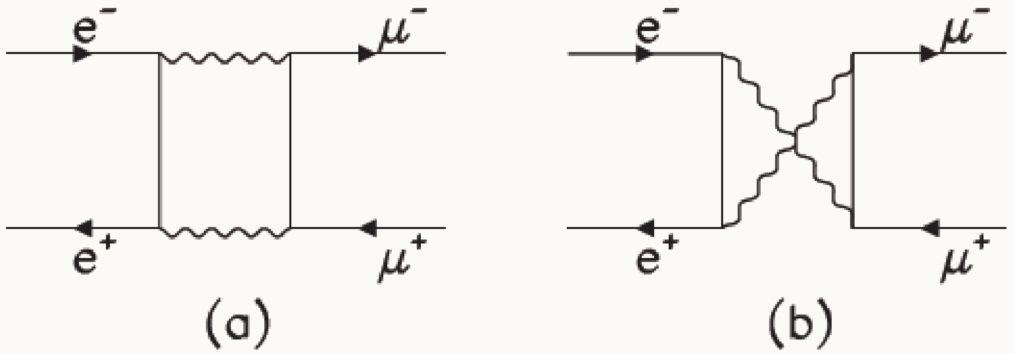
PHYSICAL REVIEW D 74, 013003 (2006)

Target normal spin asymmetry and charge asymmetry for $e\mu$ elastic scattering and the crossed processes

E. A. Kuraev, V. V. Bytev, and Yu. M. Bystritskiy
JINR-BLTP, 141980 Dubna, Moscow region, Russian Federation

E. Tomasi-Gustafsson
DAPNIA/SPhN, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France

Physics of conformal series; not associated with renormalization

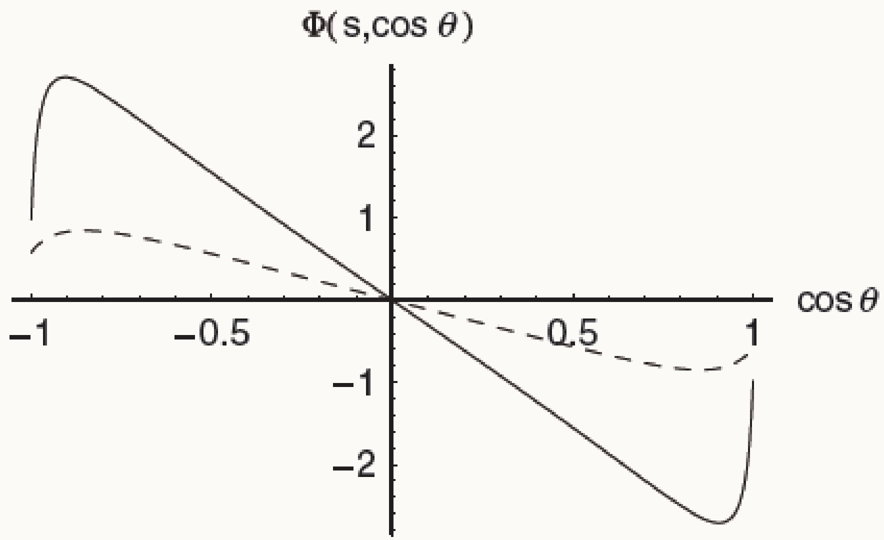


$$A(\theta, \Delta E) = \frac{d\sigma(\theta) - d\sigma(\pi - \theta)}{d\sigma_B(\theta)} = \frac{4\alpha}{\pi} \Upsilon$$

$$\frac{d\sigma_{\rm ann}}{d\Omega} = \frac{\alpha^3 \beta}{2\pi s}(2 - \beta^2 + \beta^2 c^2)\Upsilon,$$

$$\Upsilon = 2 \ln\frac{1+\beta c}{1-\beta c} \ln\left(\frac{2\Delta E}{m}\right) + \Phi(s, \cos\theta)$$

$$\Phi(s, \cos\theta) = \mathcal{D}_S^{\rm ann} - \frac{\mathcal{D}_V^{\rm ann}}{2 - \beta^2 + \beta^2 c^2}.$$



The Renormalization Scale Problem in QED

- No renormalization scale ambiguity in QED
- Gell Mann-Low 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 -- number of active leptons set
- Examples: muonic atoms, g-2, Lamb Shift
- Time-like and Space-like QED Coupling related by analyticity
- Uses Dressed Skeleton Expansion
- Results are scheme independent!

QCD: The Abelian Limit

Huet, S.J.Brodsky

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

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

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED

Legends on the scale setting in QCD

- 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 $\mu_F = \mu_R$

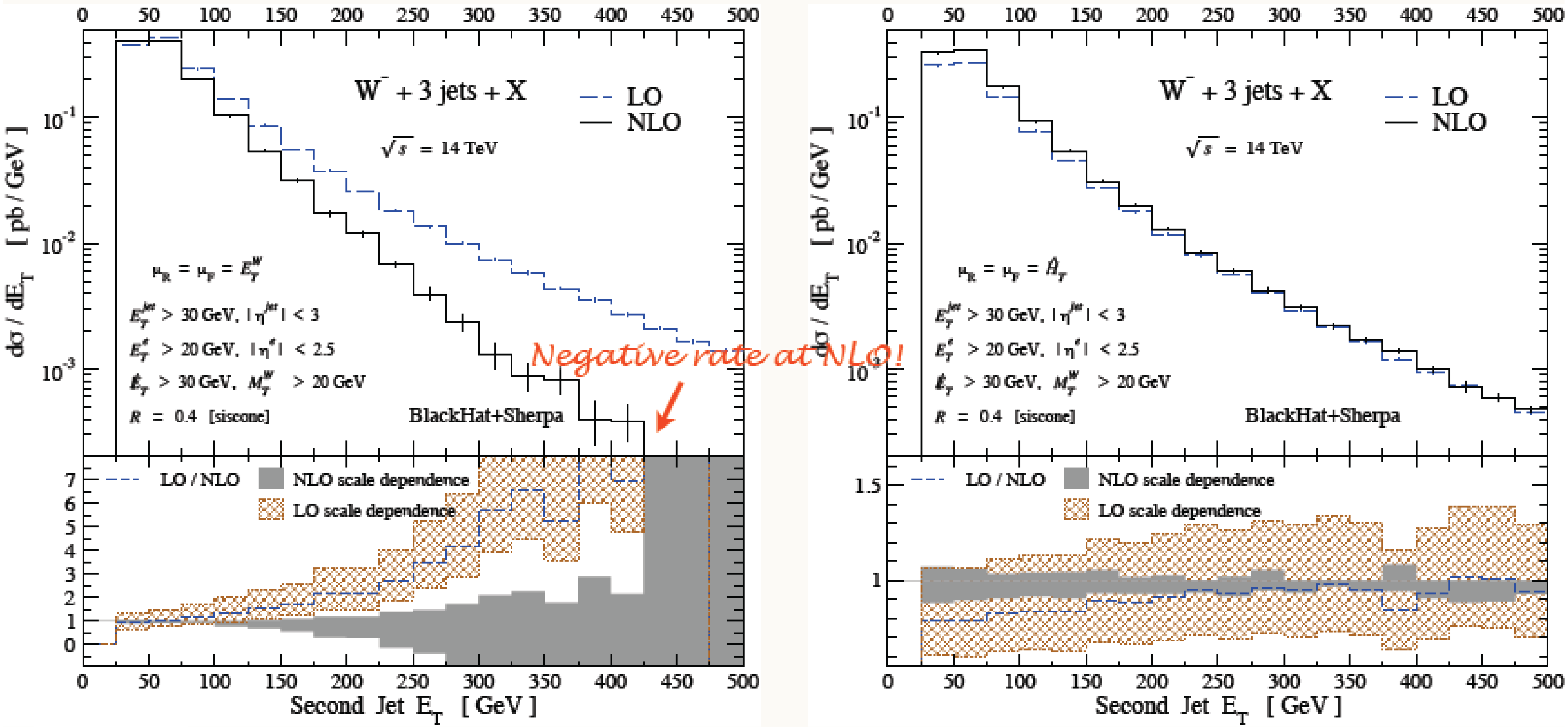
These assumptions are untrue in QED and thus they cannot be true for QCD

Wrong in QED, Scheme dependent!

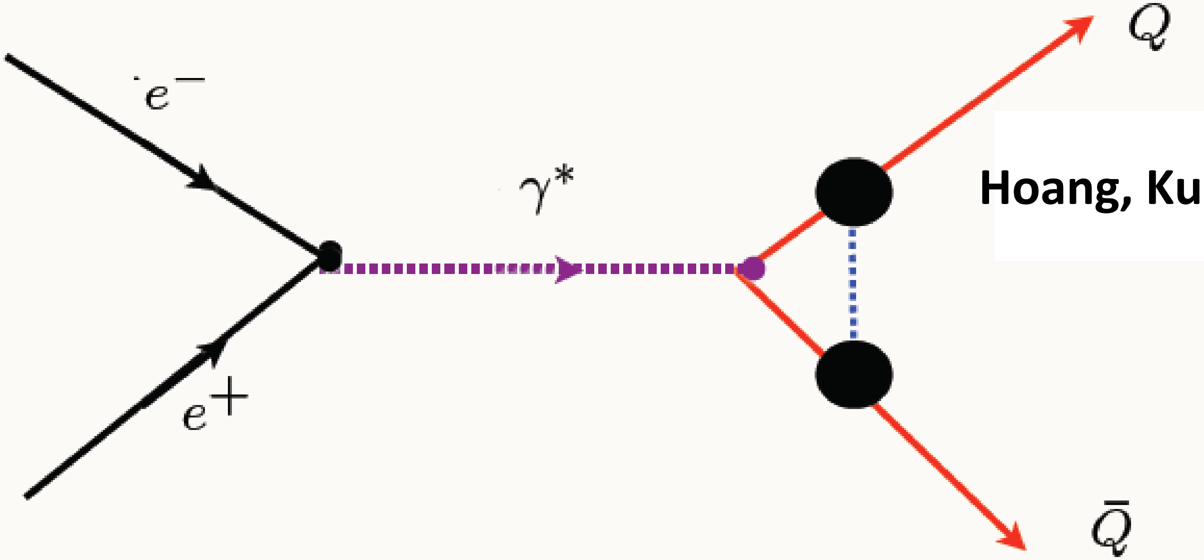
NLO QCD predictions for W-> 3Jet distributions at LHC

Black Hat

$\mu_R = \mu_F = E_T^W$ $\mu_R = \mu_F = \hat{H}_T$



. F. Berger, Z. Bern, L. J. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, H. Ita, D. A. Kosower, and D. Maitre



Hoang, Kuhn, Teubner, S.J. Brodsky

$$F_1 + F_2 = [1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}] \times [1 + \frac{\pi\alpha_s(sv^2)}{4v}]$$

Angular distributions of massive quarks close to threshold.

Example of Multiple BLM Scales

Need QCD coupling at small scales at low relative velocity v

Features of the BLM/PMC scale

- All terms associated with the beta-function are included into the running coupling;
- BLM/PMC scale sets the number of active flavors;
- Only the nf-terms are required to fix the BLM/PMC scale at NLO;
- Results are scheme independent +Transitivity Property is valid
- Correct Abelian limit;
- No renormalon growth n! in PQCD associated with the beta function;
- In general the BLM/PMC scale depends on all the invariants;
- Resulting series is identical to conformal series! (CSR - Crewther Relation ;)

The BLM scale fixing

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

n_f dependent coefficient identifies quark loop VP contribution

by

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

where

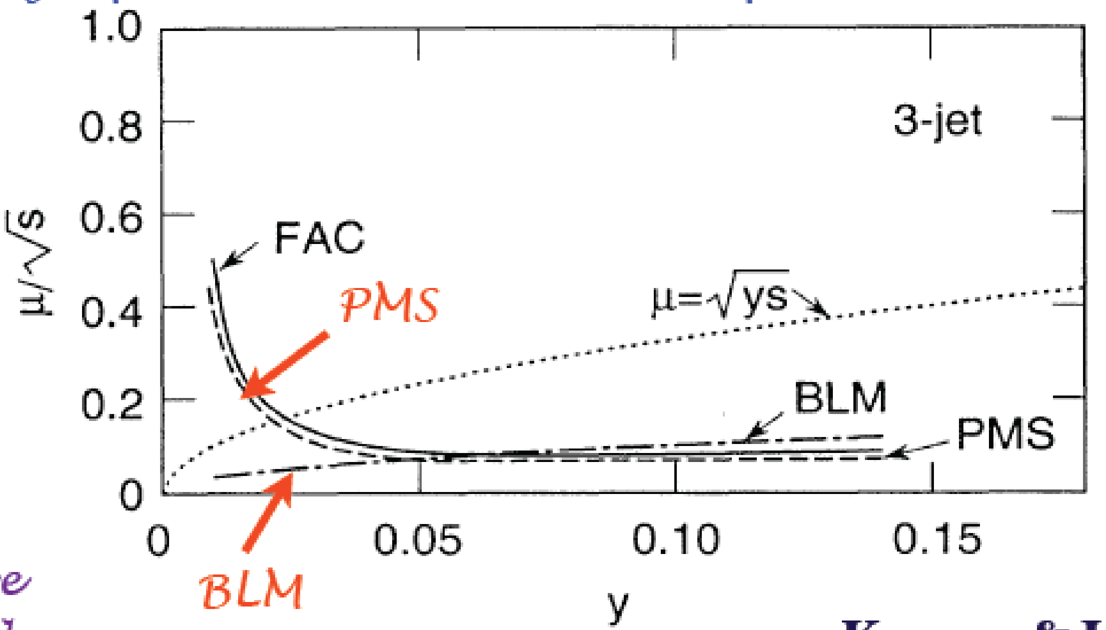
Conformal coefficient - independent of β

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

$$C_1^* = \tfrac{33}{2} A_{VP} + B .$$

The term $33 A_{VP}/2$ in C_1^* serves to remove that part of the constant B which renormalizes the leading-order coupling.

Three-jet production in electron-positron annihilation



Jet Invariant mass squared:

$$\mathcal{M}^2 = ys$$

PMS & FAC have wrong physical dependence!

Kramer & Lampe

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 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.

Other Jet Observables using BLM: Rathsman

The Principle of Maximum Conformality

Stanley J. Brodsky, L.D.G.:
arXiv:1107.0338 [hep-ph];

- BLM: Set scale in each skeleton graph to absorb all nonzero beta terms.
- In practice easier to set a single global scale
- Consider general hard subprocess: $a + b \to c + d + e + \cdots$

$$p_{ij}^2 = p_i \cdot p_j$$

e.g., $pp \to W + 3 \text{ jets} + X$

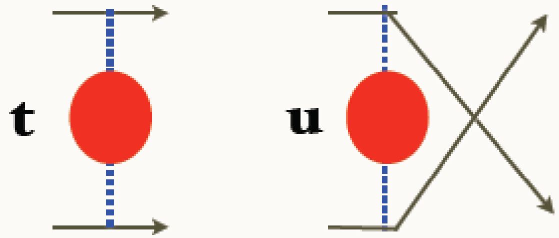
$$\hat{\mu}^2 = C \times \Pi_{ij} \; [p_{ij}^2]^{w_{ij}} \qquad \log \hat{\mu}^2 = \sum_{i \neq j} w_{ij} \log p_{ij}^2 + \log C$$

$$w_{ij} = \frac{f_{ij}}{\sum_{i \neq j} f_{ij}}.$$

C is the scheme displacement

$C = e^{-5/3}$ for $\overline{MS}$

Example: spinless electron-electron scattering



$$M = \frac{s-t}{t}\alpha(t) + \frac{s-u}{u}\alpha(u)$$

Scales sum VP to all orders

$$M \simeq [\tfrac{s-t}{t} + \tfrac{s-u}{u}]\alpha(\mu_0^2)$$
$$+[\tfrac{s-t}{t}]\frac{\alpha^2(\mu_0^2)}{3\pi} n_\ell \log(\tfrac{t}{\mu_0^2}) + [\tfrac{s-u}{u}]\frac{\alpha^2(\mu_0^2)}{3\pi} n_\ell \log(\tfrac{u}{\mu_0^2})$$

$$M = [\frac{s-t}{t} + \frac{s-u}{u}]\alpha(\hat{\mu}^2)$$

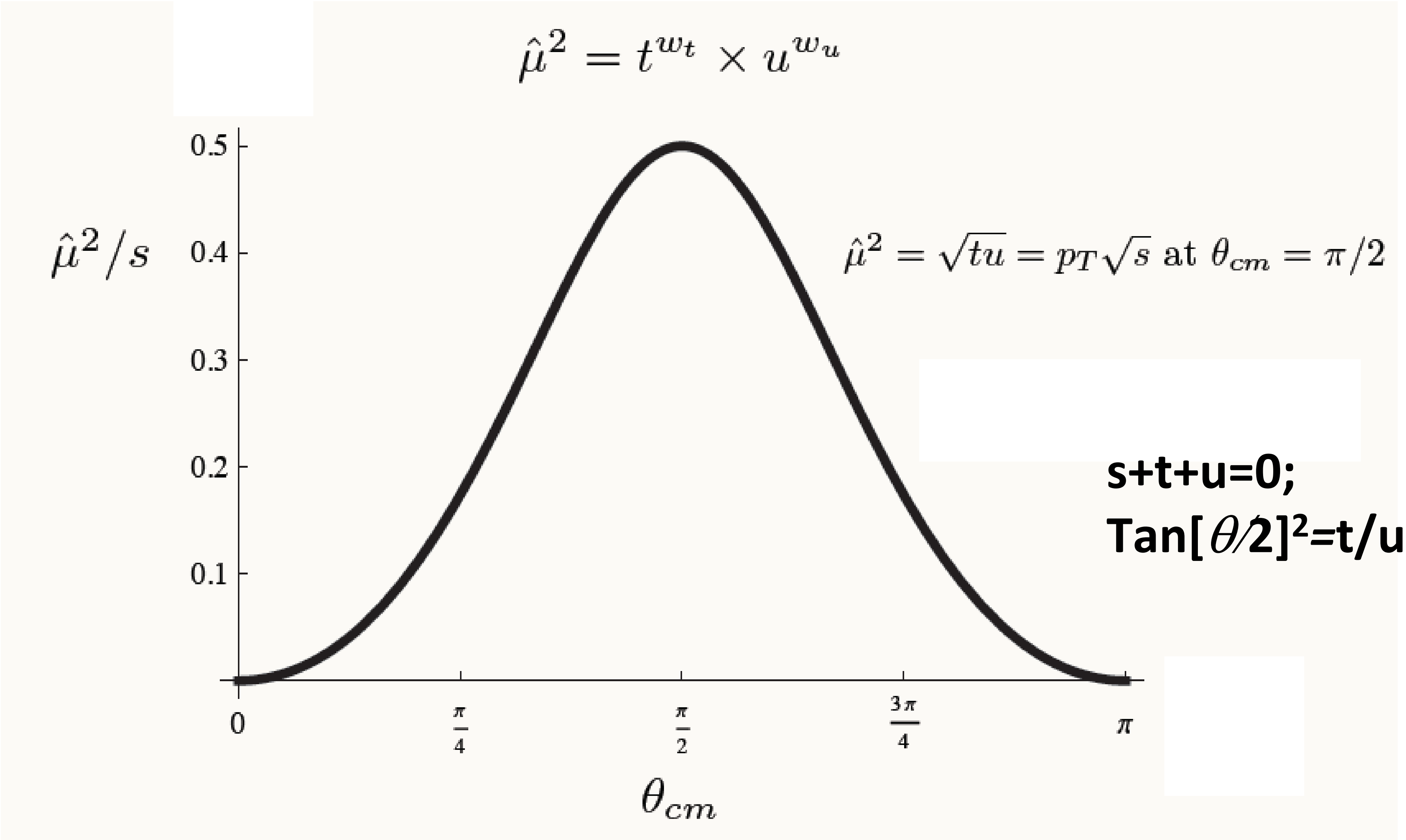
$$\hat{\mu}^2 = t^{w_t} \times u^{w_u}$$

$$w_t = \frac{\frac{s-t}{t}}{\frac{s-t}{t} + \frac{s-u}{u}} \qquad w_u = \frac{\frac{s-u}{u}}{\frac{s-t}{t} + \frac{s-u}{u}}$$

Identify w_t from $\frac{dM}{d\log t}$

Remaining $\mathcal{O}(\alpha^2)$ correction is conformal

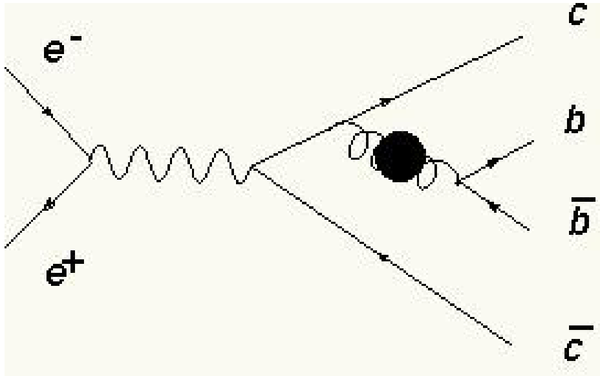
Spinless electron-electron scattering



s+t+u=0;

$\mathrm{Tan}[\theta/2]^2 = t/u$.

PMC – Exclusive Case



All flavors and momenta in the final state are identified

- The nf terms at NLO come from the quark loop in the gluon propagator.
- The PMC scale for the differential cross section in the $\overline{MS}$ scheme is given by the scheme displacement of the gluon virtuality:

$$\mu^2_{PMC} = e^{-5/3}(p_b + p_{\bar{b}})^2$$

3-Jet case: Integrated results

* R. K. Ellis *et Al,* Nucl. Phys. B178, 421-456 (1981)

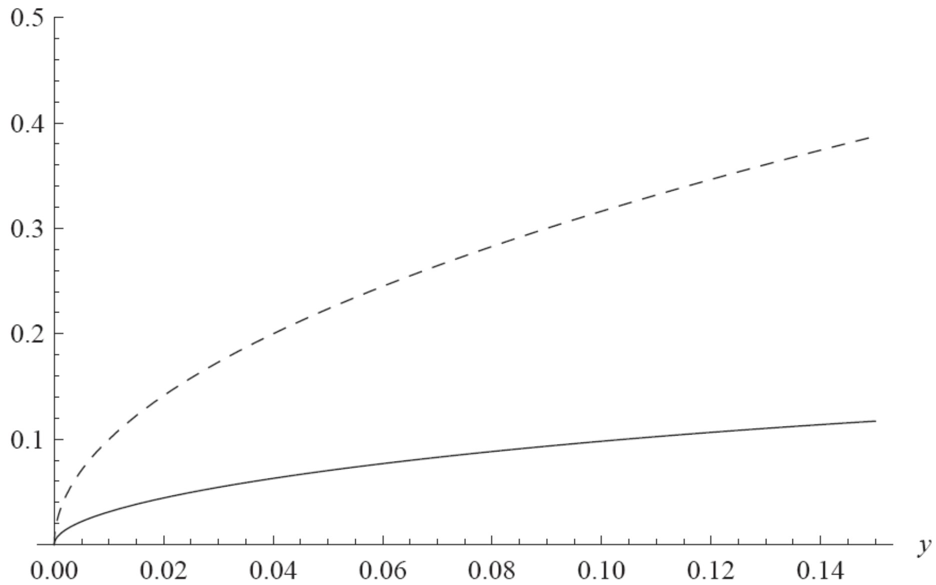
$$\frac{1}{\sigma_0}\frac{d\sigma^{(s)}+d\sigma^{3}}{dy}^{*} = \int_y^{1-2y} dz \int_y^{1-y-z} dx\ T[1-x-z,x,z]\alpha_s(Q^2)(1-\beta_0\,\alpha_s(Q^2)(\log[x]+\log[z]-\frac{5}{3}......))$$

y: the maximum virtuality of the jet

$$= \alpha_s(Q^2)\,(T(y) - \beta_0\,\alpha_s(Q^2)\,(C(y)+....))$$

$$\equiv T(y)\alpha_s(Q^2)\,(1-\beta_0\,\alpha_s(Q^2)\,2\log[\frac{\mu_{BLM}}{\sqrt{s}}]) = T(y)\alpha_s(\mu^2_{BLM});$$

$$\mu^2_{PMC/BLM} = s \times e^{-\frac{5}{3}+\frac{C(y)}{T(y)}}$$



For comparison the dashed line is $\sqrt{\boldsymbol{y}}$

We recover the Kramer and Lampe results

3-jet case: differential X-section

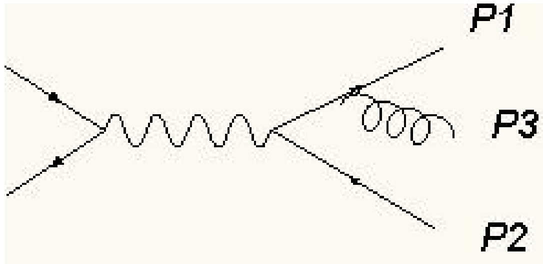
$$\frac{1}{\alpha_s(Q^2)}\frac{d}{d\beta_0}\left.\frac{d\sigma^3(Q^2)}{dz\,dy\,dx}\right|_{Born}^{-1}\left(\frac{d\sigma^{(s)}+d\sigma^3}{dz\,dy\,dx}\right)=\left[\log[x\,y]-\frac{5}{3}\right]+O(\alpha_s).$$

$$\omega_i=\frac{d}{d\log(x_i)}\frac{1}{\alpha_s(Q^2)}\frac{d}{d\beta_0}\left.\left(\frac{d\sigma^3(Q^2)}{dz\,dy\,dx}\right)\right|_{Born}^{-1}\left(\frac{d\sigma^{(s)}+d\sigma^3}{dz\,dy\,dx}\right)$$

The **Analytic Form** of the PMC scale can be determined by isolating the nf term and then varying the subprocess amplitude with respect to each invariant and thus determinig the **weights Wi** for each invariant.

$$\mu^2_{PMC}\simeq Q^2\times C\times\prod_i x_i^{\omega_i}=Q^2\;x\;y\;e^{-\frac{5}{3}}.$$

3-Jet case: Numerical PMC scale fixing



* K. Fabricius *et Al* ,Z. Phys. C 11, 315 (1981)

$$\frac{d^2\sigma^{(3)}(\epsilon,\delta)}{dx_1 dx_2}^{*} = \sigma_0 \frac{\alpha_s(q^2)}{2\pi} C_F \times$$

$$\left\{ B^V(x_1,x_2)\left[1-\alpha_s(q^2)\ \beta_0\ \left(\log(\frac{1-\ \cos\delta}{2}) +\ \log\hat{x}_3^2 -\ \frac{13}{3}\right)\right] - B^S(x_1,x_2)\,\alpha_s(q^2)\,\frac{\beta_0}{2}\right\} + \mathcal{O}(\delta^2)) + \cdots$$

$$y_{ij} = s_{ij}/q^2 = (p_i+p_j)^2/q^2 \qquad x_1 = 1 - y_{23} \quad x_2 = 1 - y_{13},$$

$$x_1 + x_2 + x_3 = 2.$$

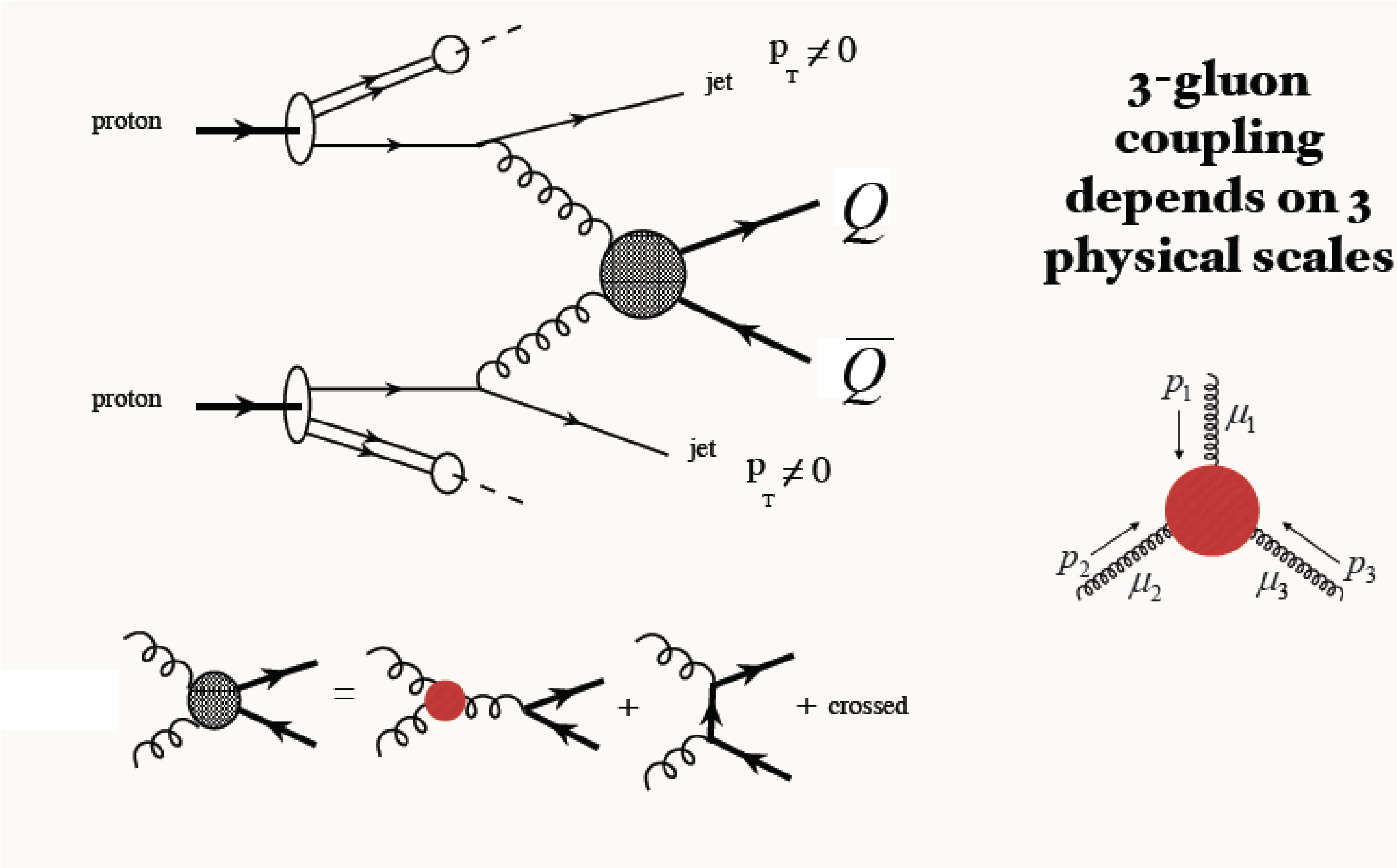
$$\left[\frac{d\sigma^{(3)}(\mu^2)}{dx_1 dx_2}\bigg|_{\rm Born}^{-1} \cdot \left(\frac{d}{dn_f} \frac{d^2\sigma^{(3)}(\epsilon,\delta;\ \mu^2)}{dx_1 dx_2} \right)\bigg|_{n_f=0} \right] \Bigg|_{\mu^2=\mu^2_{PMC}} = 0$$

$$\frac{df}{d\beta_0} = \frac{df}{dn_f} \times \frac{d\beta_0}{dn_f}^{-1}$$

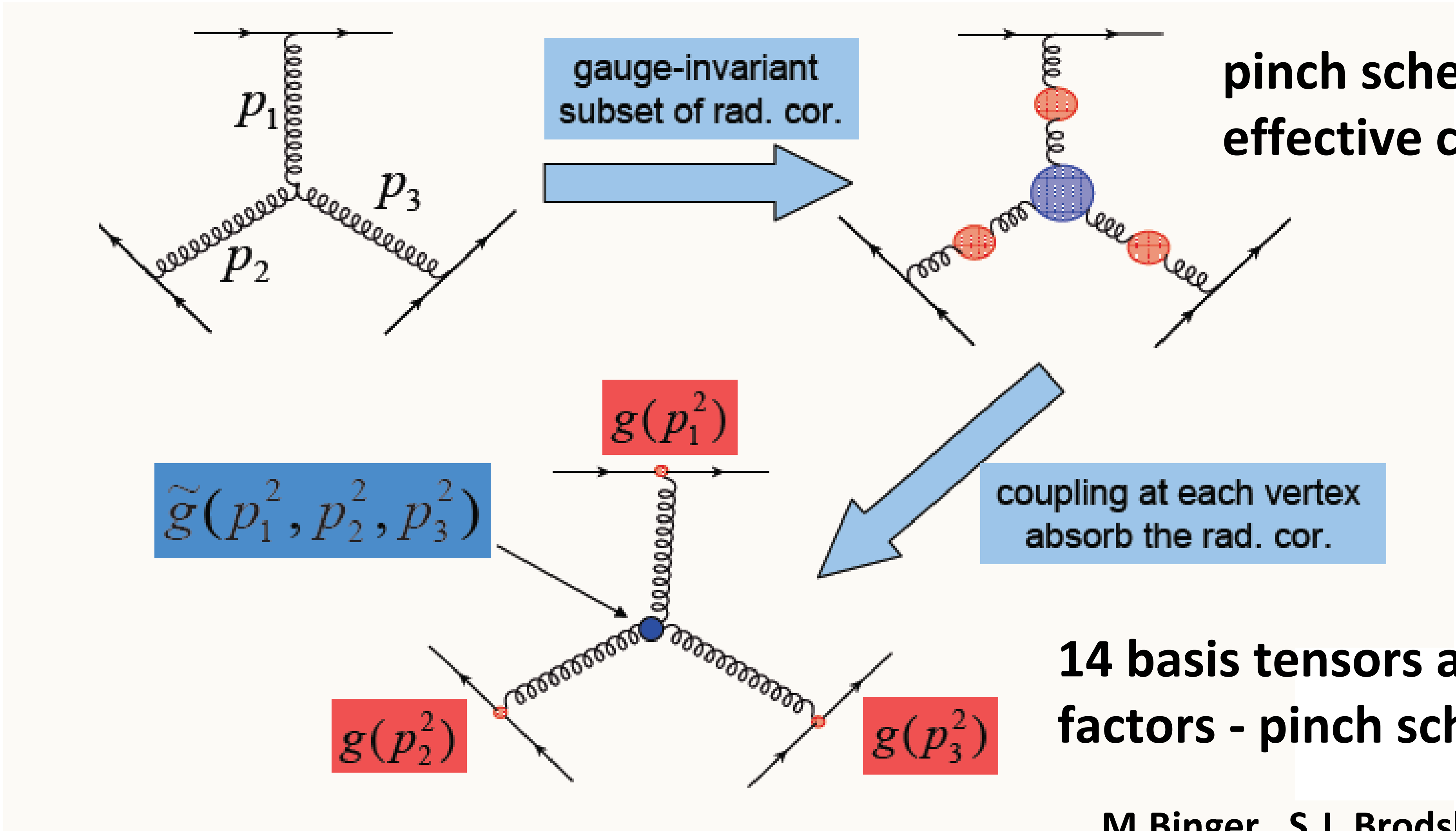
$$\mu^2_{PMC} \simeq q^2\ (2-x_1-x_2)^2\ \frac{\delta^2}{4}\, e^{-\frac{13}{3}+\frac{B_S(x_1,x_2)}{2\,B_V(x_1,x_2)}}$$

3-jet PMC scale : Analytic form

Heavy Quark Hadroproduction



Multi-scale renormalization



pinch scheme effective charge

14 basis tensors and form factors - pinch scheme

M.Binger , S.J. Brodsky
Phys.Rev D 74, 054016 (2006)

3 Scale Effective Charge

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

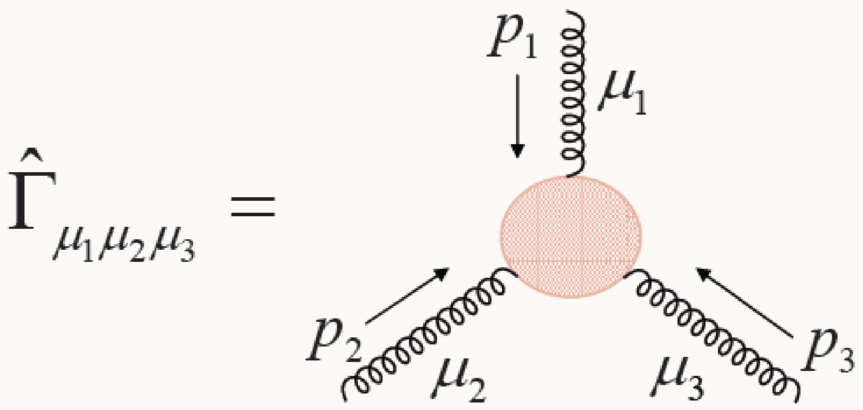
$$\frac{1}{\tilde{\alpha}(a,b,c)} = \frac{1}{\alpha_{bare}} + \frac{1}{4\pi}\beta_0\left(L(a,b,c) - \frac{1}{\varepsilon} + \cdots\right)$$

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

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

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

Effective Scale properties



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

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

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

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

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

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

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

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

H. J. Lu

Scale determines effective number of flavors

QCD observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Scale-Free Conformal Series

Running Coupling Effects

Higher Twist from Hadron Dynamics

Intrinsic Heavy Quarks

Light by Light Loops

BLM: Absorb β terms into running coupling

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

BLM/PMC: Scheme independent

Define QCD coupling from observables

Grunberg

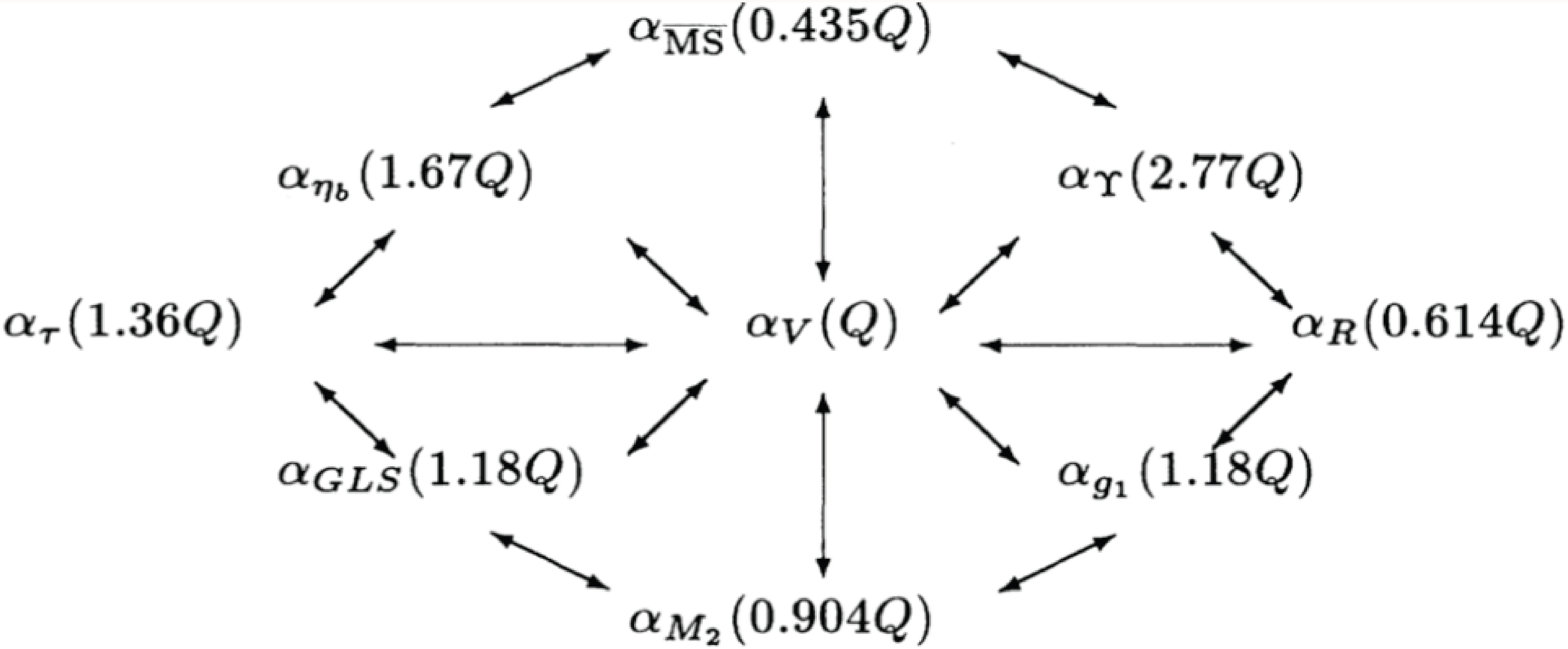
Effective Charges: analytic at quark mass thresholds, finite at small momenta

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

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

Commensurate scale relations:
Relate observable to observable at commensurate scales

H. Lu, Rathsman, S.J. Brodsky

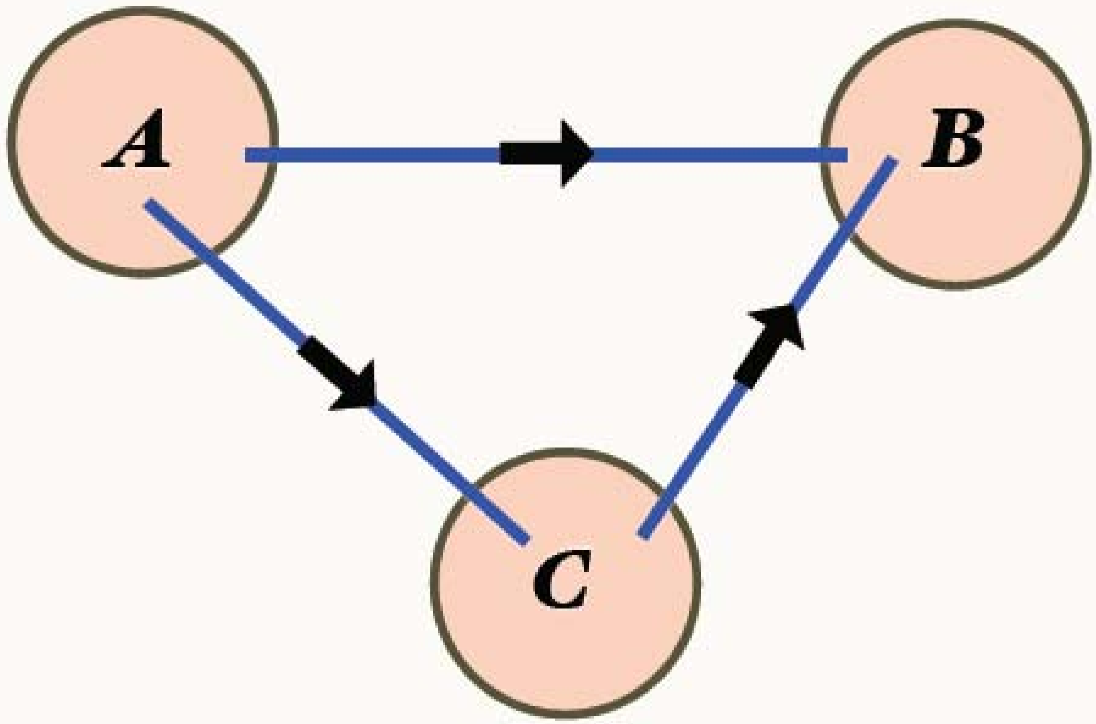


$$\frac{\alpha_\tau(M_\tau)}{\pi} = \frac{\alpha_R(Q^*)}{\pi},$$

$$Q^* = M_\tau \exp\left[-\frac{19}{24} - \frac{169}{128}\frac{\alpha_R(M_\tau)}{\pi}\right]$$

Transitivity Property of Renormalization Group

Relation of observables must be independent of intermediate scheme



A → C   C → B   identical to   A → B

Violated by PMS!

BLM/PMC: Relate Observables to each other

- Eliminate Intermediate schemes
- No Scale Ambiguity
- Transitivity
- Commensurate Scale Relations
- Conformal Template
- Generalized Crewther Relation

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

$$\int_0^1 dx \left[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

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

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

Eliminate MS

Find Amazing Simplification

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

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi} \right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi} \right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze ,S.J. Brodsky

Lu, Kataev, Gabadadze ,S.J. Brodsky

PMC: 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

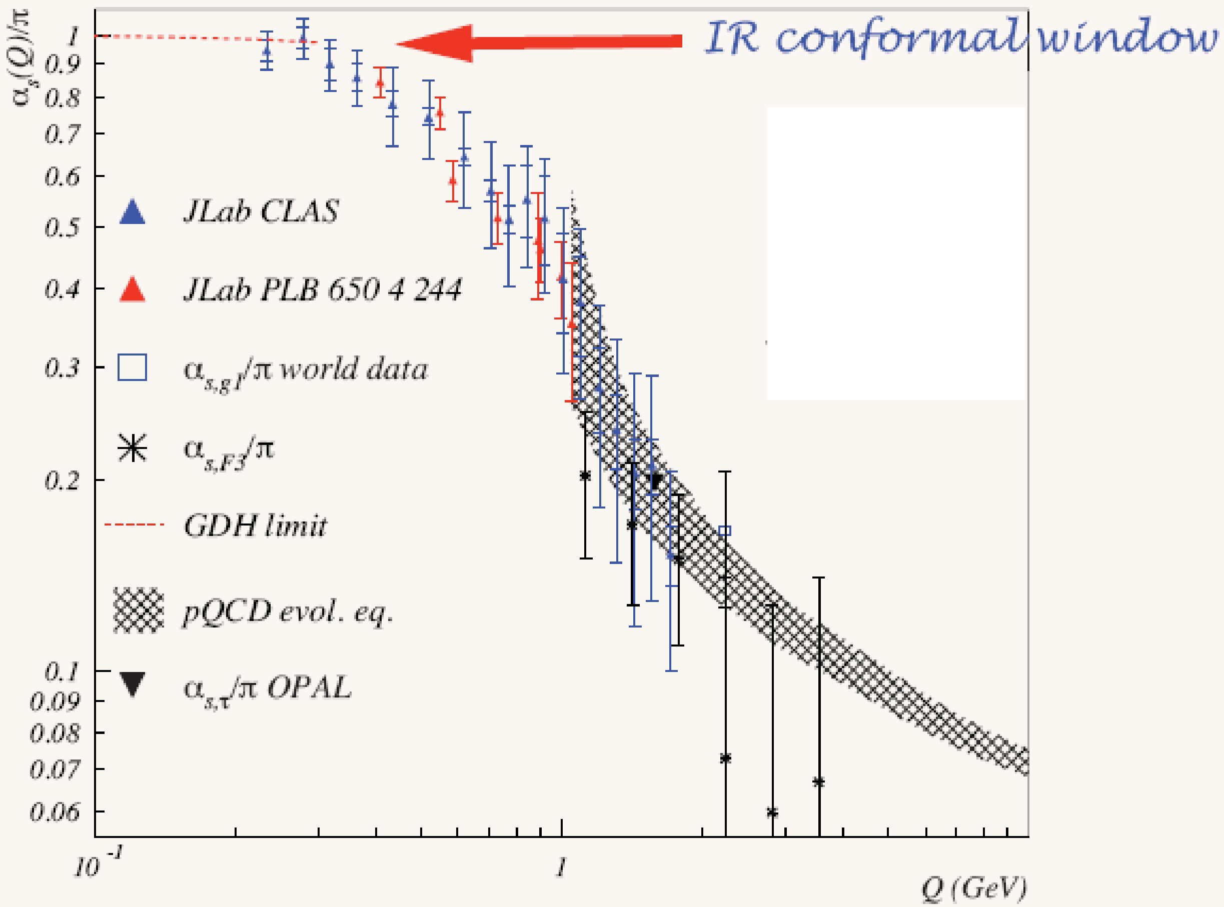
Nonconformal terms set relative scales (BLM)

No renormalization scale ambiguity!

Both observables go through new quark thresholds at commensurate scales!

Effective Charge from Bjorken Sum Rule

$$\Gamma^{p-n}_{bj}(Q^2) \equiv \frac{g_A}{6}[1 - \frac{\alpha_s^{g_1}(Q^2)}{\pi}]$$



Conformal window: $\alpha_s(Q^2) \simeq$ const at small Q^2

Deur, Korsch, et al

Hints for IR Fixed Point for QCD

- Effective gluon mass – maximal wavelength
- Dyson-Schwinger Analysis: QCD coupling (mom scheme) has IR Fixed point
- Lattice Gauge Theory
- Define coupling from observable, indications of IR fixed point for QCD effective charges
- Confined gluons and quarks: Decoupling of QCD vacuum polarization at small Q^2
- Justifies application of AdS/CFT in strong-coupling conformal window

QCD is not conformal; however, it has manifestations of a scale invariant theory

Conformal Symmetry: Template for QCD

- Take conformal symmetry as initial approximation; then correct for nonzero beta function and quark masses
- Eigensolutions of ERBL evolution equation for distribution amplitudes
- Commensurate scale relations: relate observables at corresponding scales: Generalized Crewther Relation
- Fix Renormalization Scale PMC/BLM
- IR Fixed Point -- A Conformal Domain
- Use AdS/CFT

Conclusions: PMC points

- PMS/FAC - incorrectly sums conformal terms -- even minimizes physical asymmetries!
- PMC/BLM: exposes conformal series - no renormalons
- Conformal series has new physics -- not associated with renormalization
- PMC: No need to analyze diagrams or codes -- simply identify non-conformal logarithms -- then shift scale
- PMC: Applies to subprocesses with multiple final particles- recursive procedure
- PMC/BLM: Agrees with QED in Abelian limit
- PMC/BLM: Result is independent of scheme and initial scale choice