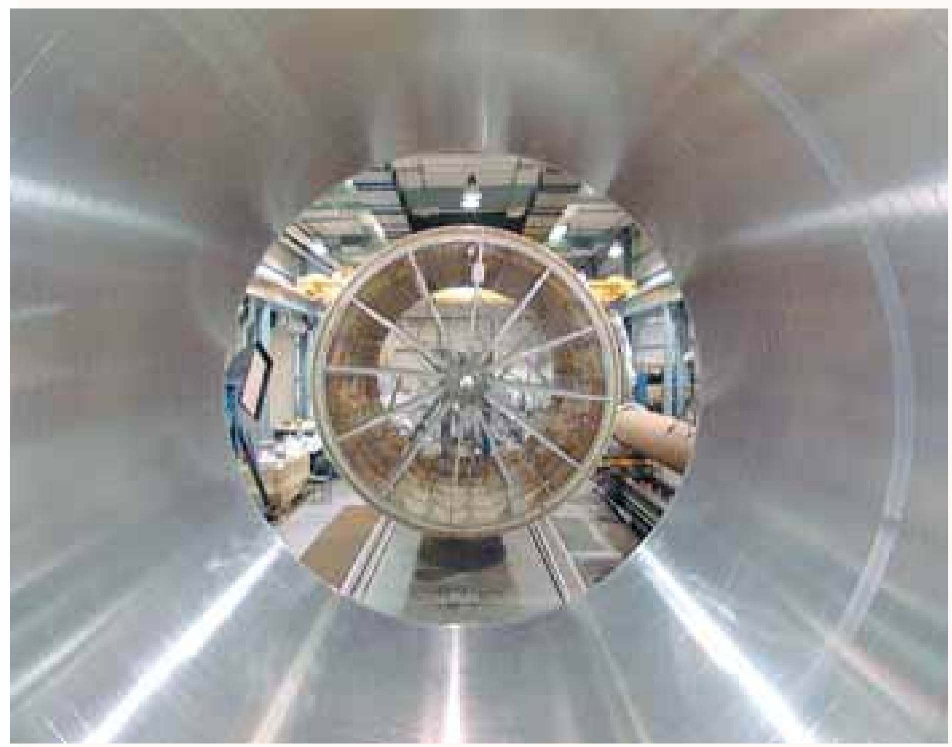
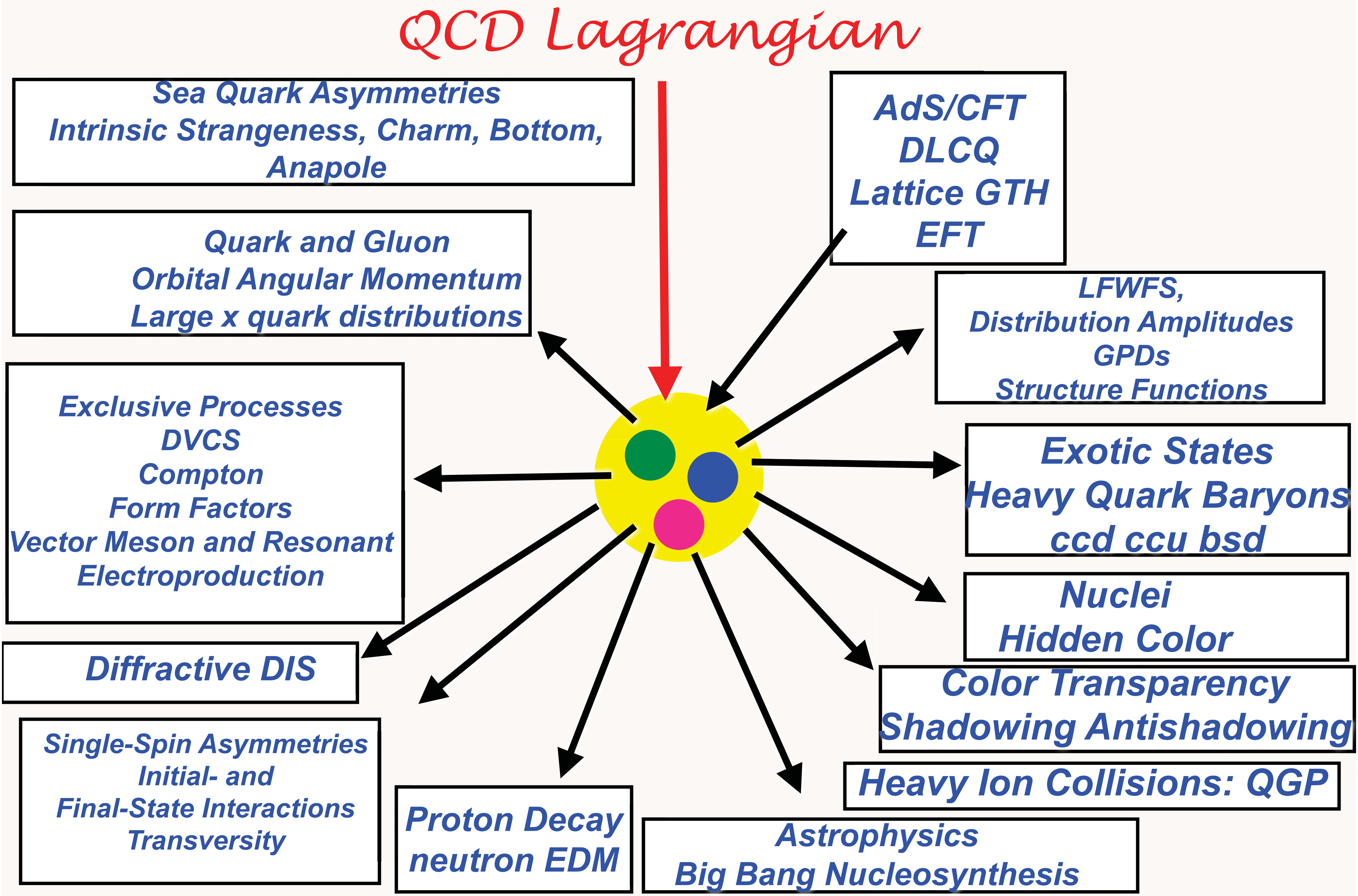
Novel QCD Phenomena

Stan Brodsky, SLAC

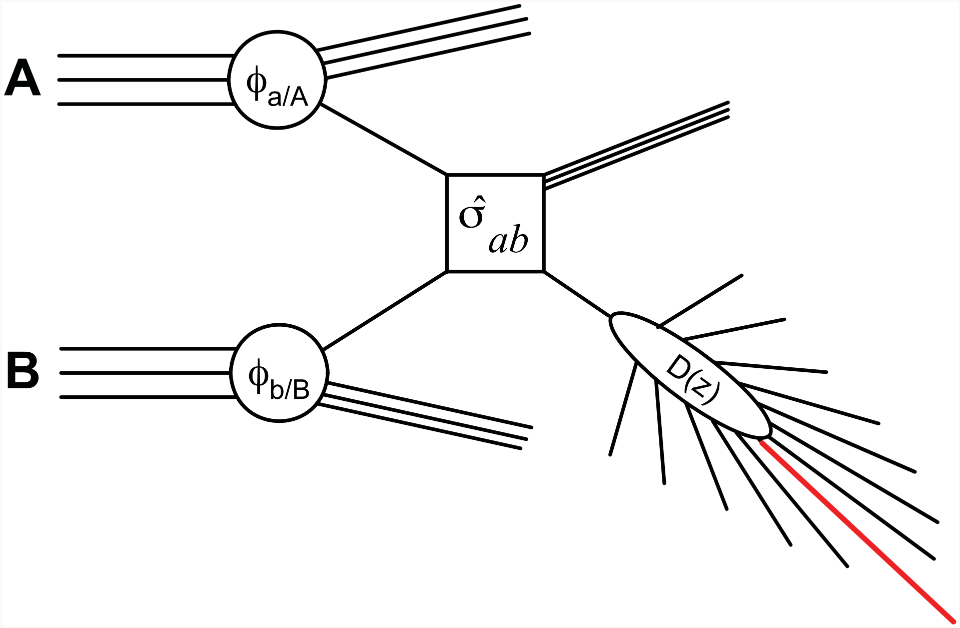
January 8, 2008 **BNL**

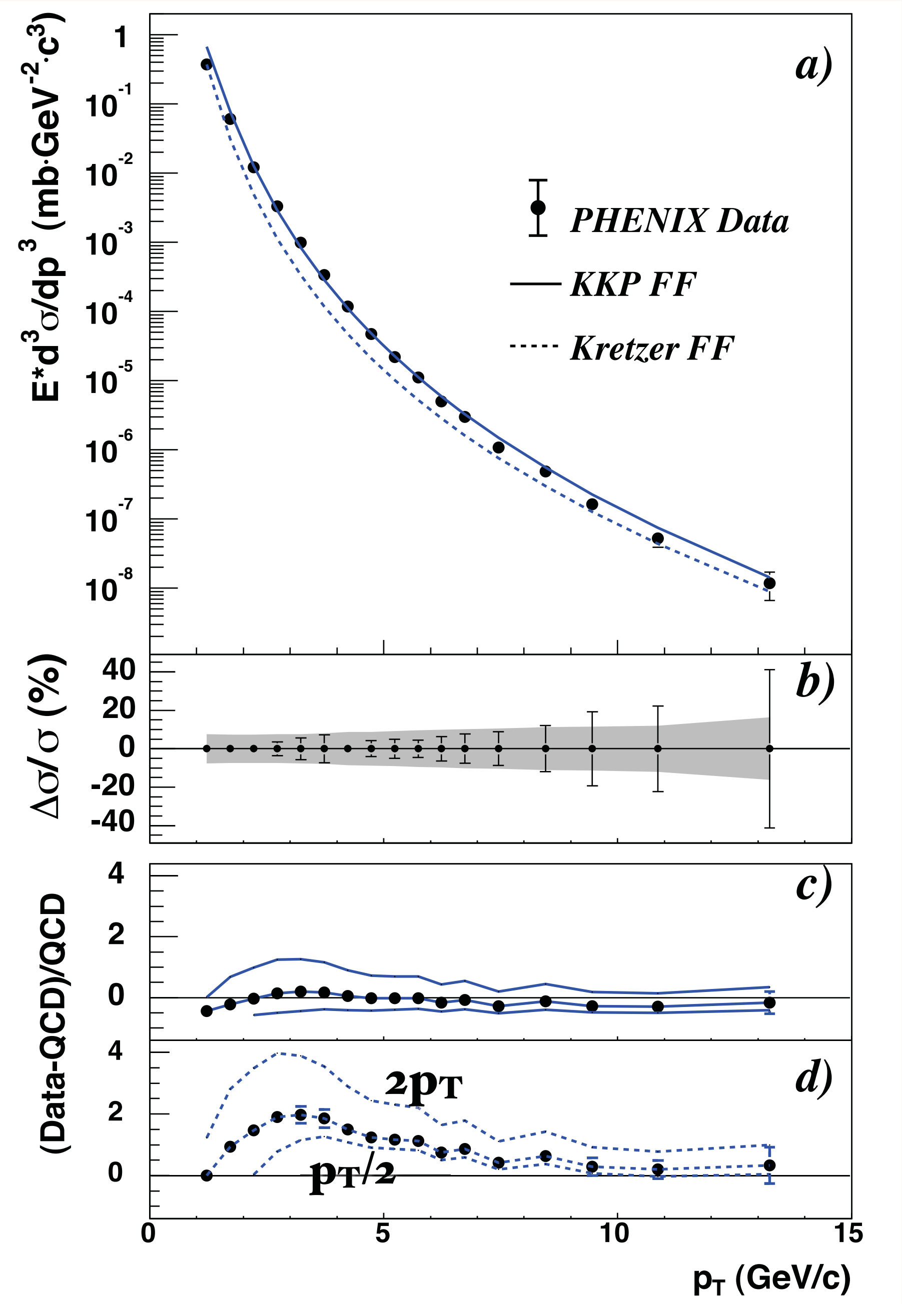



QCD Lagrangian
Sea Quark Asymmetries
Intrinsic Strangeness, Charm, Bottom,
Anapole
AdS/CFT
DLCQ
Lattice GTH
EFT
Quark and Gluon
Orbital Angular Momentum
Large x quark distributions
LFWFS,
Distribution Amplitudes
GPDs
Structure Functions
Exclusive Processes
DVCS
Compton
Form Factors
Vector Meson and Resonant
Electroproduction
Exotic States
Heavy Quark Baryons
ccd ccu bsd
Nuclei
Hidden Color
Diffractive DIS
Color Transparency
Shadowing Antishadowing
Single-Spin Asymmetries
Initial- and
Final-State Interactions
Transversity
Heavy Ion Collisions: QGP
Proton Decay
neutron EDM
Astrophysics
Big Bang Nucleosynthesis

$$E\frac{d\sigma}{d^3p}(pp \to \pi^0 X)$$

$\sqrt{s} = 200$ GeV





NLO pQCD predictions
Vogelsang

Assumes equal factorization and renormalization scales:
$p_T/2$, p_T, $2p_T$

Challenging Conventional Wisdom

- **Renormalization scale is arbitrary**
- **Initial and final-state interactions are power suppressed in a hard QCD reaction**
- **Heavy quark distributions derive exclusively from gluon splitting**
- **Nuclear parton distributions are universal**
- **Hadroproduction at large transverse momentum derives exclusively from 2 to 2 scattering subprocesses**

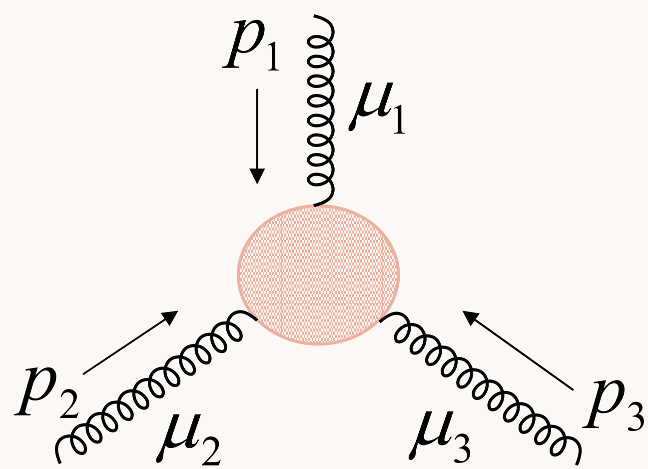
The Renormalization Scale Problem

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

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

Is there a way to set the renormalization scale μ_R ?

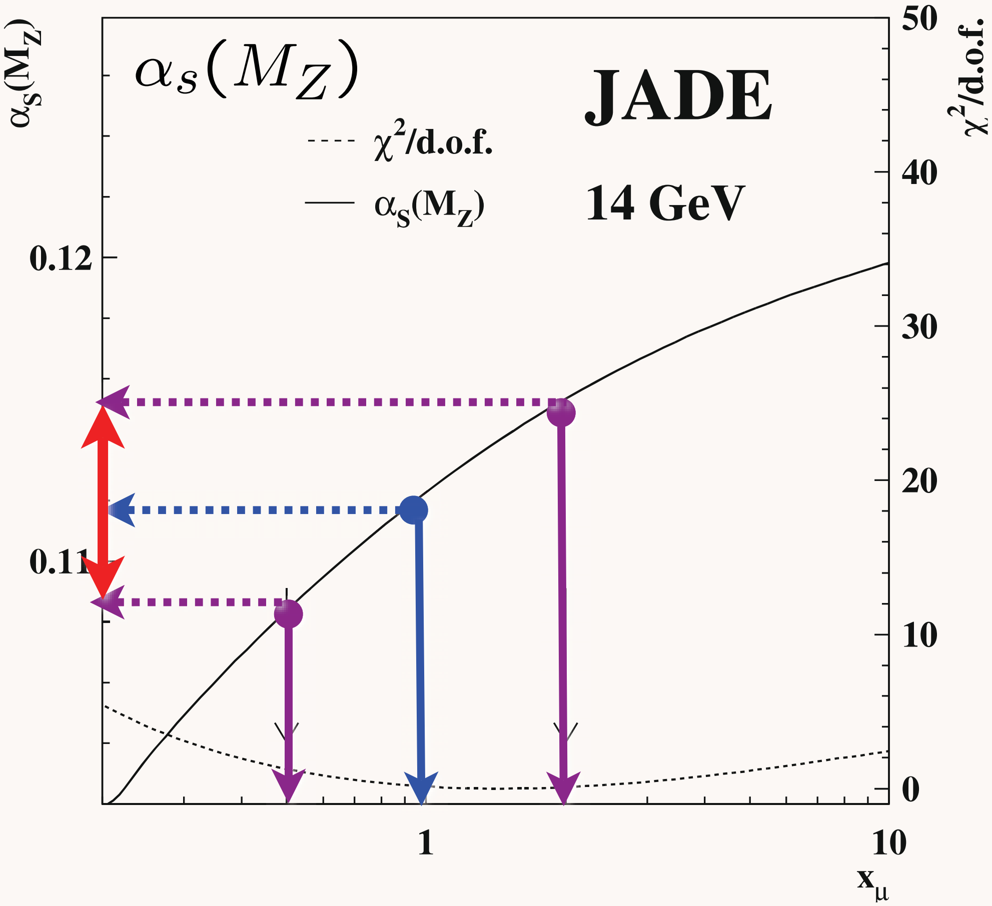
What happens if there are multiple physical scales ?



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)



$\alpha_S\,(M_{Z^0})$ 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

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

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.

No PMS

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

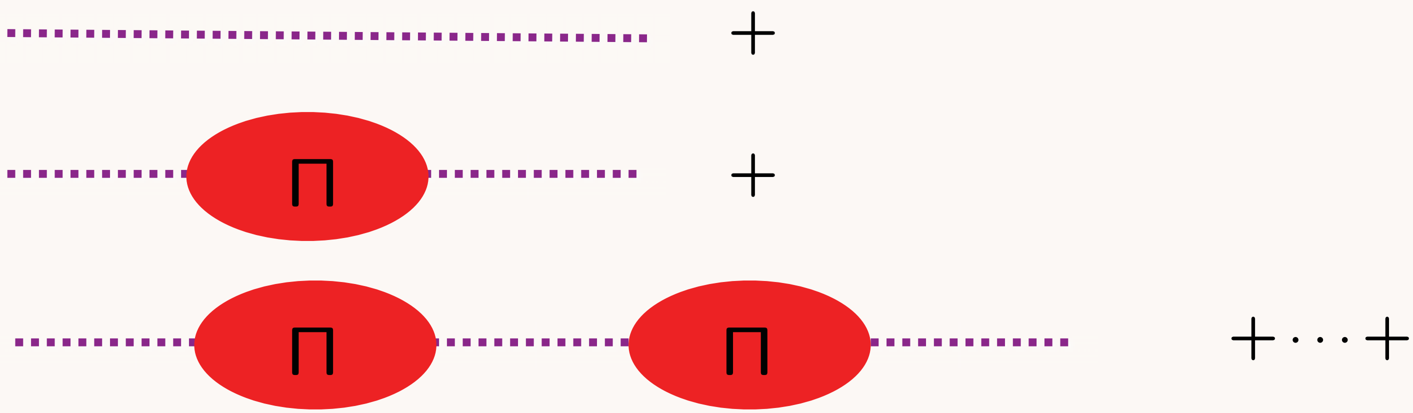
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell Mann-Low Effective Charge

QED Effective Charge

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

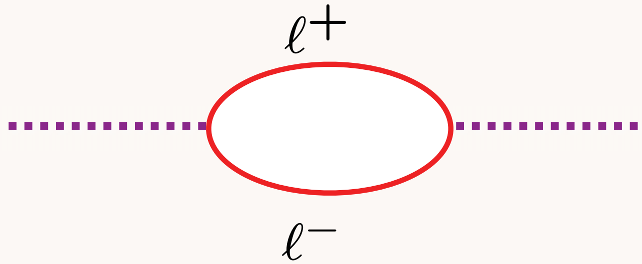
All-orders lepton loop corrections to dressed photon propagator



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

Initial scale t_0 is arbitrary -- Variation gives RGE Equations
Physical renormalization scale t not arbitrary

QED One-Loop Vacuum Polarization



$t = -Q^2 < 0$

(t spacelike)

$$\Pi(Q^2) = \frac{\alpha(0)}{3\pi}\left[\frac{5}{3} - \frac{4m^2}{Q^2} - \left(1 - \frac{2m^2}{Q^2}\right)\sqrt{1 + \frac{4m^2}{Q^2}}\,\log\frac{1+\sqrt{1+\frac{4m^2}{Q^2}}}{\left|1-\sqrt{1+\frac{4m^2}{Q^2}}\right|}\right]$$

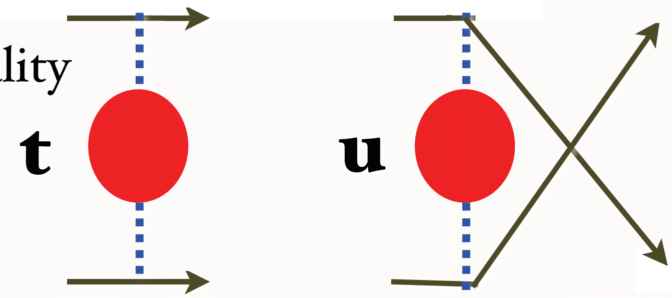
Analytically continue to timelike t: Complex

$$\Pi(Q^2) = \frac{\alpha(0)}{15\pi}\frac{Q^2}{m^2}$$ $Q^2 << 4M^2$ **Serber-Uehling**

$$\Pi(Q^2) = \frac{\alpha(0)}{3\pi}\frac{\log Q^2}{m^2}$$ $Q^2 >> 4M^2$ **Landau Pole**

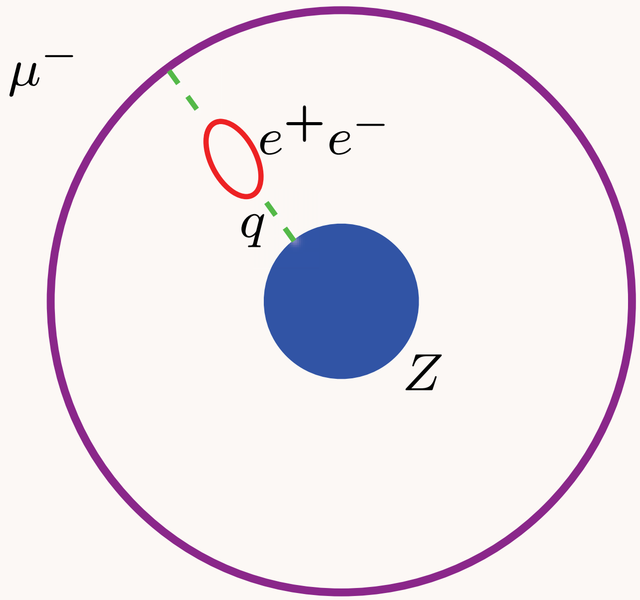
$$\beta = \frac{d(\frac{\alpha}{4\pi})}{d\log Q^2} = \frac{4}{3}\left(\frac{\alpha}{4\pi}\right)^2 n_\ell > 0$$

Electron-Electron Scattering in QED



- 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!

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

Huet, sjb

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

QCD $\to$ Abelian Gauge Theory

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED

Lessons from QED : Summary

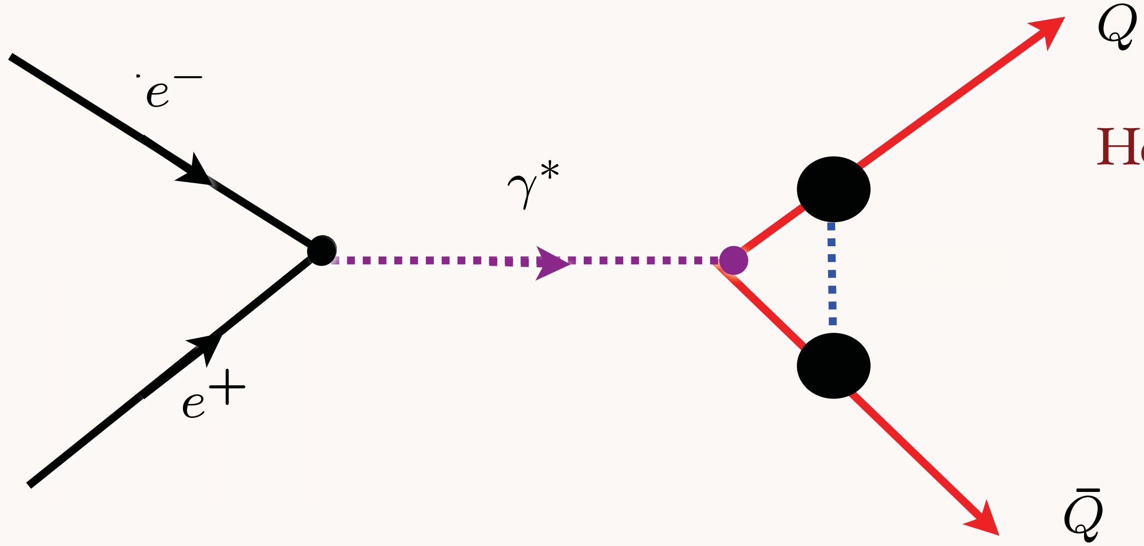
- Effective couplings are complex analytic functions with the correct threshold structure expected from unitarity
- Multiple “renormalization” scales appear
- The scales are unambiguous since they are physical kinematic invariants
- Optimal improvement of perturbation theory

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



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.

Three-Jet Rate

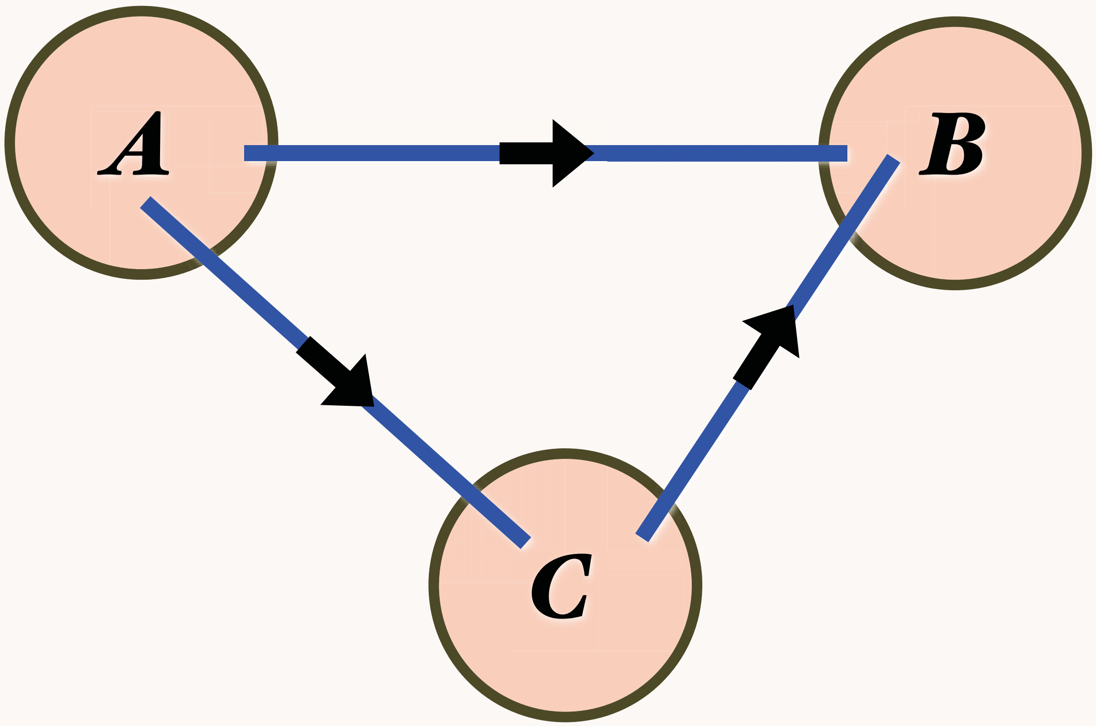
Th

Kramer & Lampe

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

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
- FAC and PMS give unphysical results.
- PMS violates transitivity property of renormalization group
- Renormalization scale not arbitrary! Analytic constraint from flavor thresholds

BLM Method

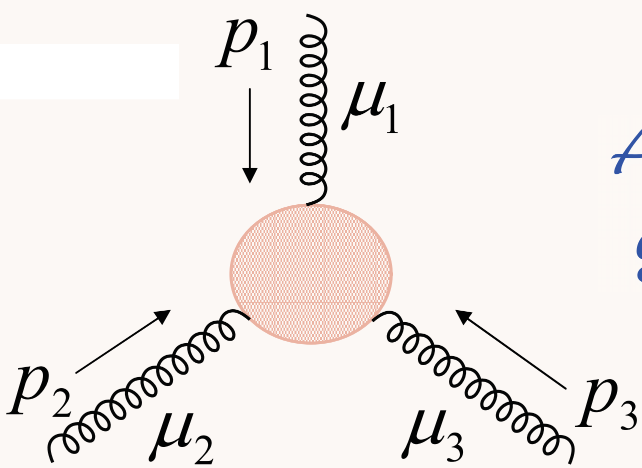
- Satisfies Transitivity, all aspects of Renormalization Group; scheme independent
- Analytic at Flavor Thresholds
- Preserves Underlying Conformal Template
- Physical Interpretation of Scales; Multiple Scales
- Correct Abelian Limit ($N_C = 0$)
- Eliminates unnecessary source of imprecision of PQCD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

General Structure of the Three-Gluon Vertex

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

M. Binger, sjb

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



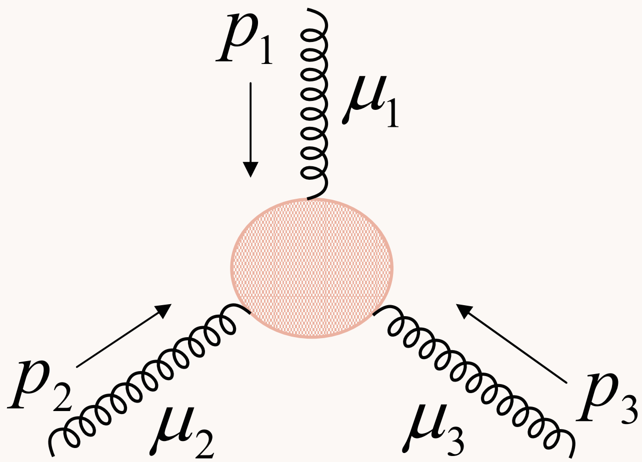
Analytic calculation: general masses, spin

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

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

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)

Mass Effects

Binger, sjb

Calculated for all form factors

SUSY relations $F_{MG} + 4F_{MQ} + (9-d)F_{MS} = 0$

FF of tree level tensor structure ⟺ Effective Charge

Massive “log-like” function : $L_{MQ}\left(\frac{a}{M^2}, \frac{b}{M^2}, \frac{c}{M^2}\right)$

$$L_{MQ}\left(\frac{a}{M^2}, \frac{b}{M^2}, \frac{c}{M^2}\right) \approx 5.125 \ \text{ for } \ M^2 >> |a|,|b|,|c|$$

$$L_{MQ}\left(\frac{a}{M^2}, \frac{b}{M^2}, \frac{c}{M^2}\right) \approx L(a,b,c) - \log M^2 \ \text{ for } \ M^2 << |a|,|b|,|c|$$

Properties of the Effective Scale

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

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

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

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

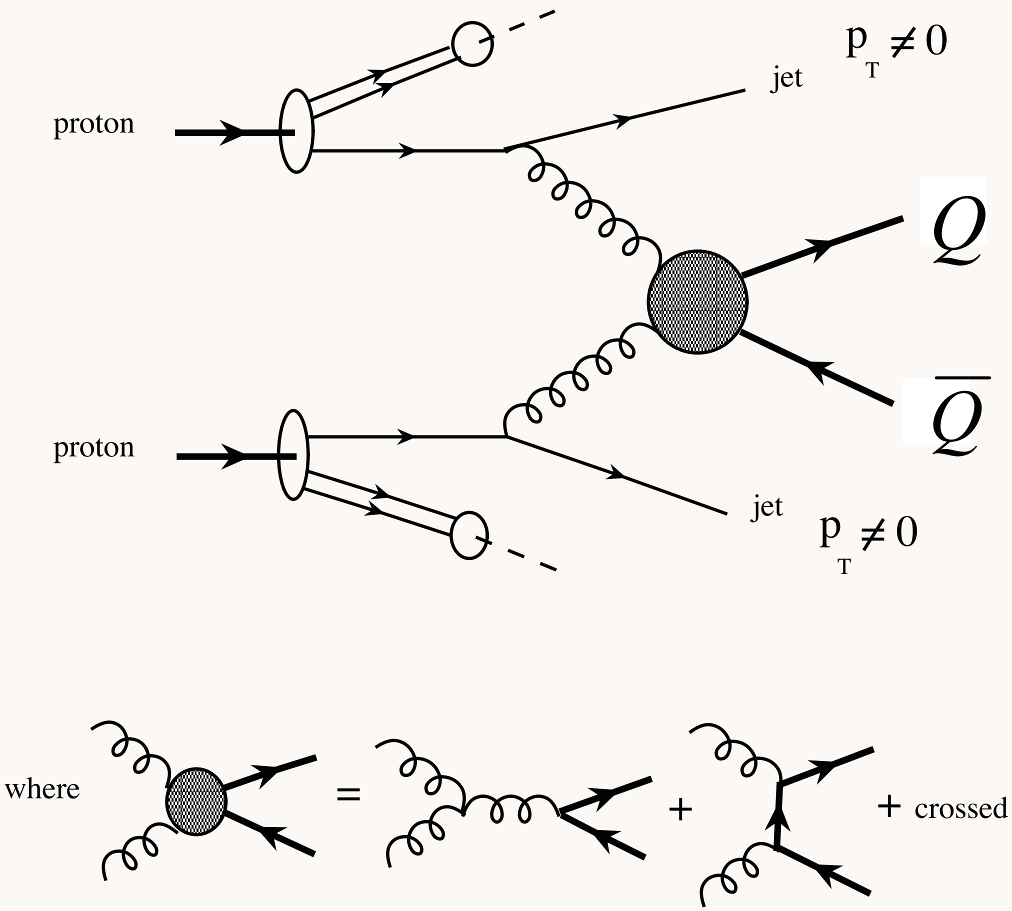
$$Q^2_{eff}(a,a,c) \approx 3.08|c| \quad \text{for} \quad |a| >> |c|$$

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

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

Surprising dependence on Invariants

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

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

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Example: Generalized Crewther Relation

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze, Sjb

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!

Leading Order Commensurate Scales

p(Q

Translation between schemes at LO

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"
S. Brodsky, M. Gill, M. Melles, J. Rathsman. **Phys.Rev.D58:116006,1998**

Conformal symmetry: Template for QCD

- Initial approximation to PQCD; then correct for non-zero beta function and quark masses: BLM
- Commensurate scale relations: relate observables at corresponding scales: Generalized Crewther Relation
- Arguments for Infrared fixed-point for α_s
- Effective Charges: analytic at quark mass thresholds, finite at small momenta
- Eigensolutions of Evolution Equation of distribution amplitudes

V. Braun et al;
Frishman, Lepage, Sachrajda, sjb

- AdS/QCD

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

Binger, Sjb

Unification in Physical Schemes

"PHYSICAL RENORMALIZATION SCHEMES AND GRAND UNIFICATION"
M.B. and Stanley J. Brodsky. **Phys.Rev.D69:095007,2004**

$$\alpha_i(Q) = \frac{\alpha_i(Q_0)}{1 + \hat{\Pi}_i(Q) - \hat{\Pi}_i(Q_0)}$$

i=1,2,3

$$\hat{\Pi}_i(Q) = \frac{\alpha_i}{4\pi} \sum_p \beta_i^{(p)} \left(L_{s(p)}(Q^2 / m_p^2) + \cdots \right)$$

"log-like" function:

$$L_{s(p)} \approx \log(e^{\eta_p} + Q^2 / m_p^2)$$

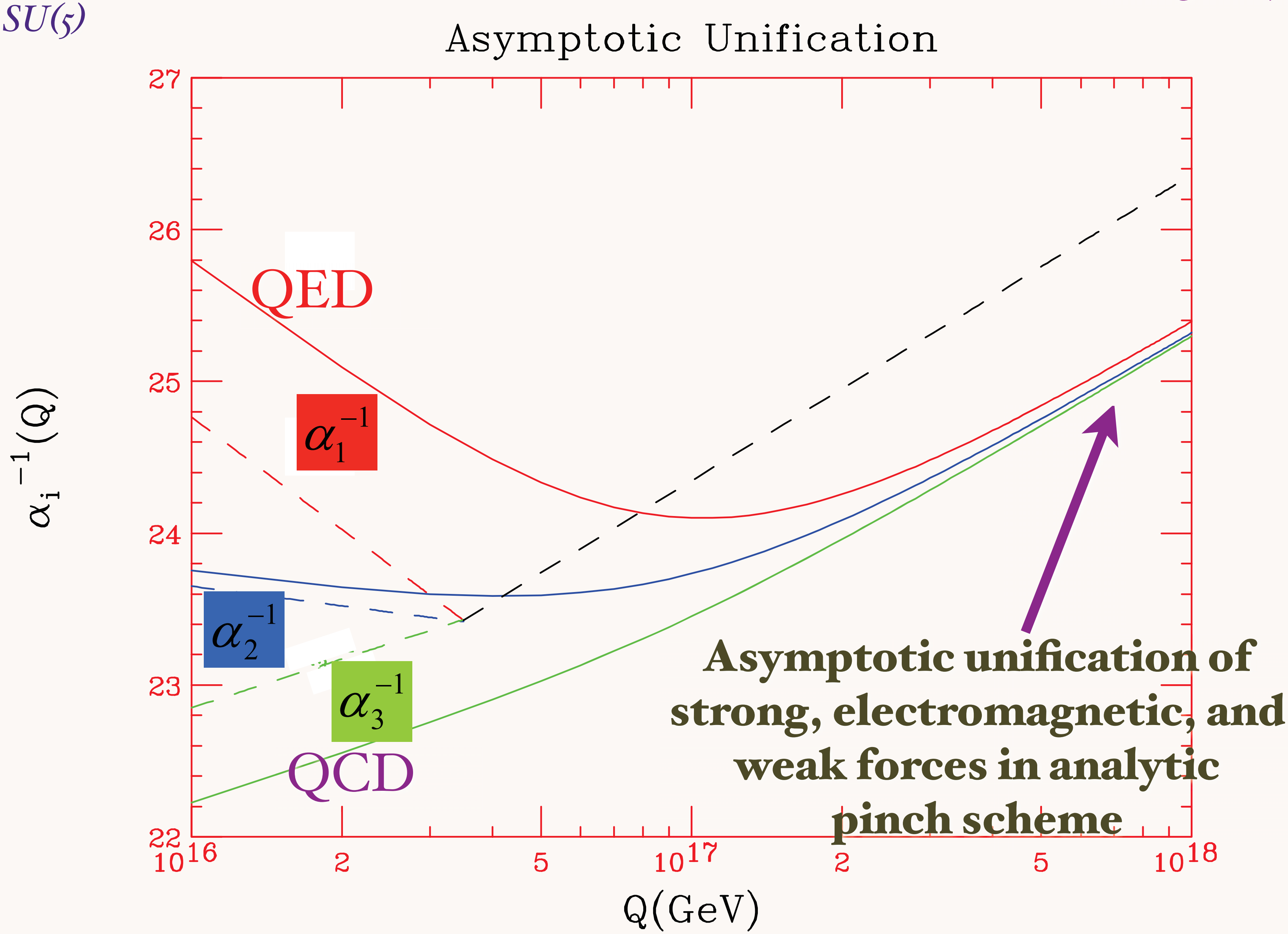
$$\eta_p = 8/3,\, 5/3,\, 40/21$$

For spin s(p) = 0, ½, and 1

→ Elegant and natural formalism for all threshold effects

Supersymmetric SU(5)

Binger, sjb



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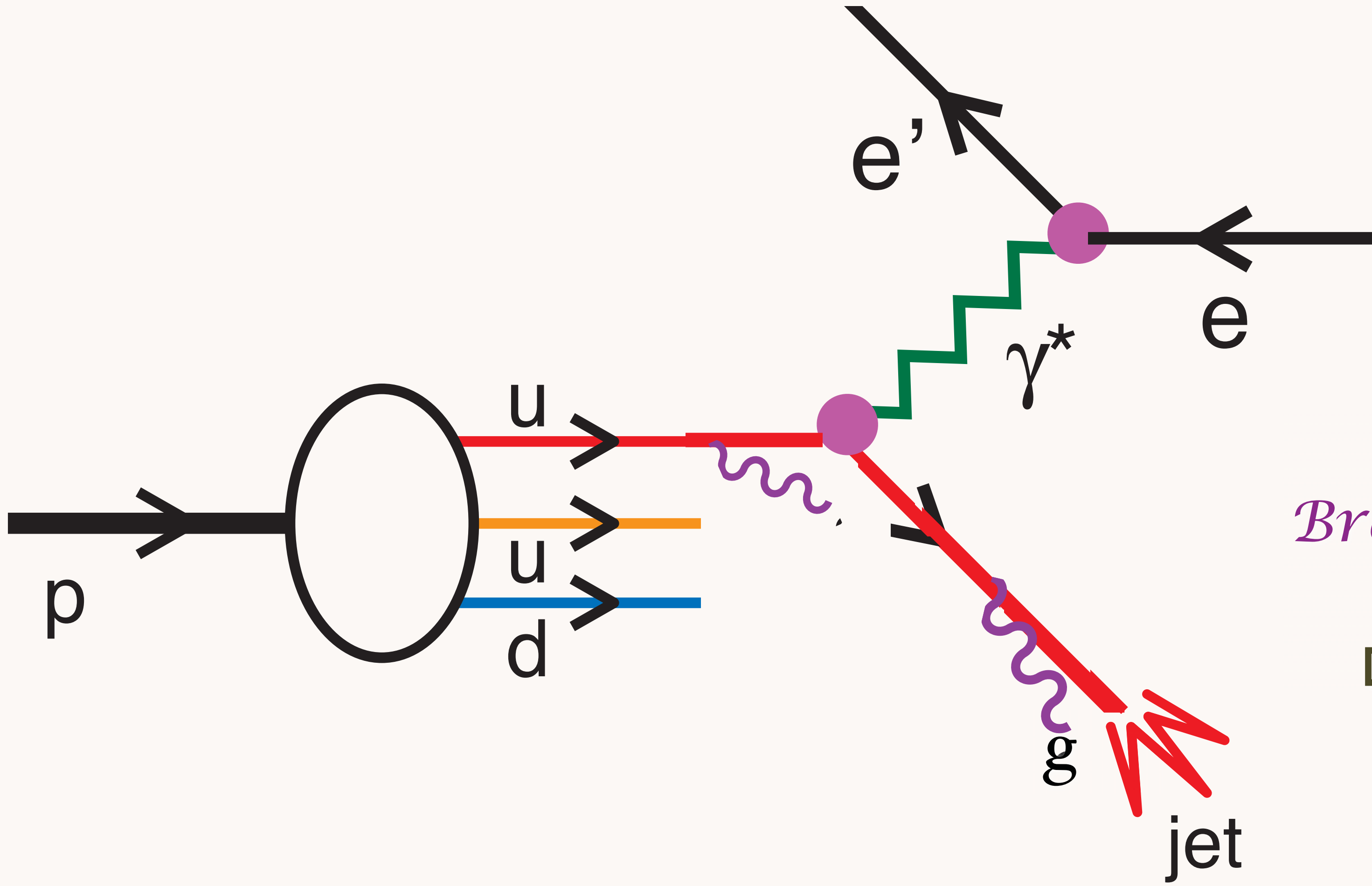
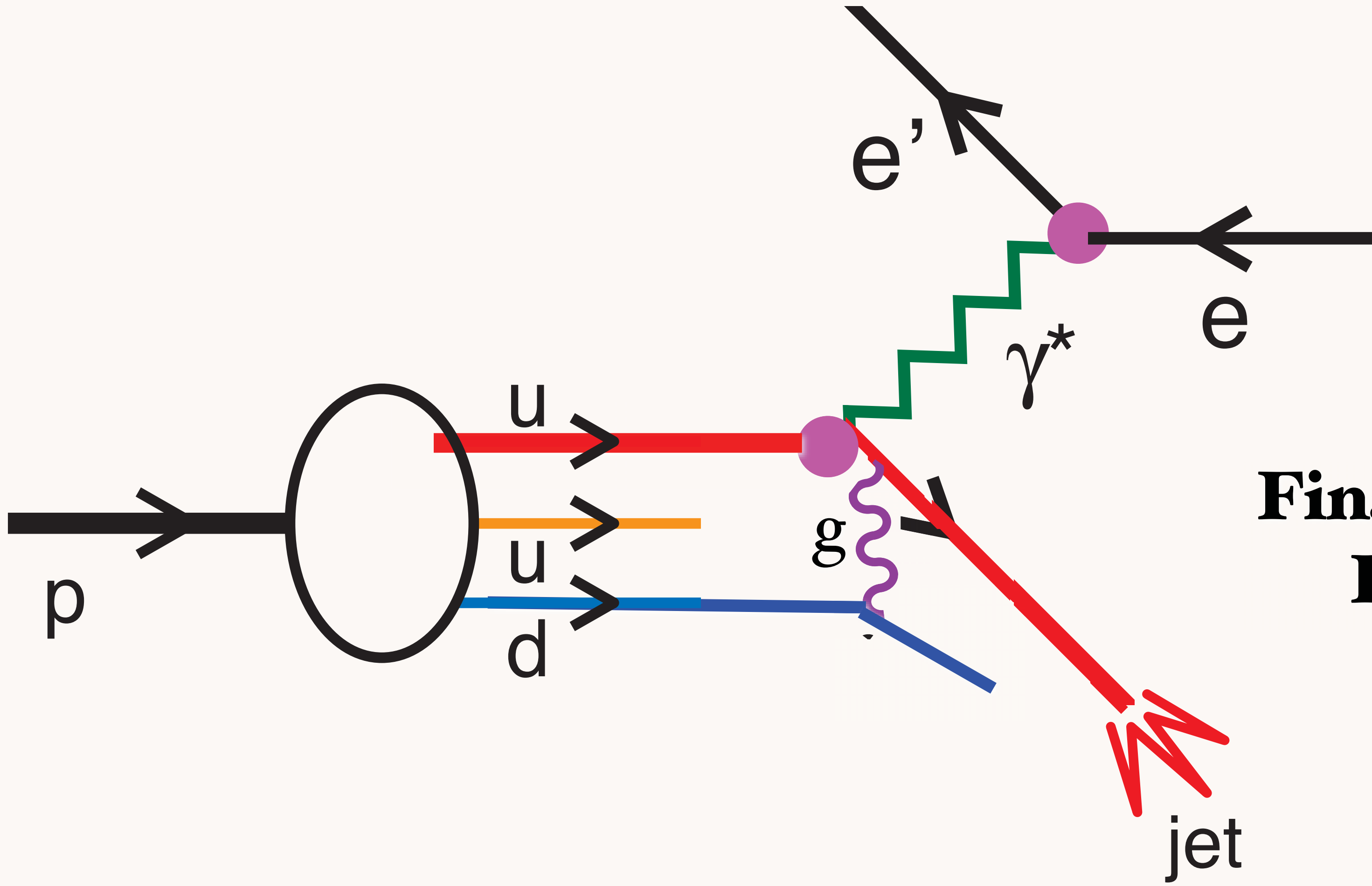
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:

Final-state interactions of struck quark can be neglected

Physics of Rescattering

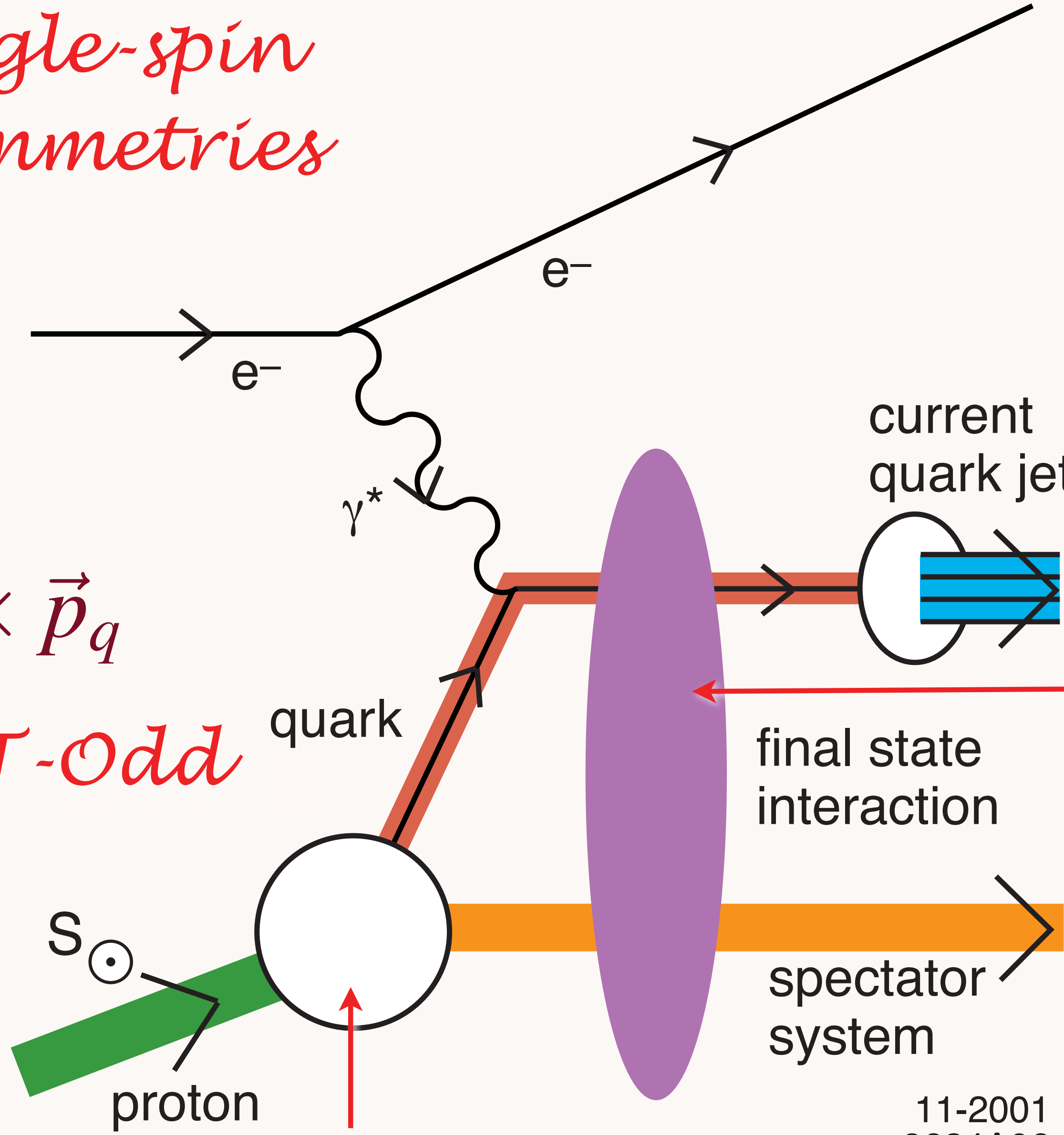
- Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

Single-spin asymmetries

Leading Twist Sivers Effect

$$i\,\vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo-T-Odd



QCD S- and P- Coulomb Phases

Light-Front Wavefunction S and P- Waves

D. S. Hwang, I. A. Schmidt, sjb

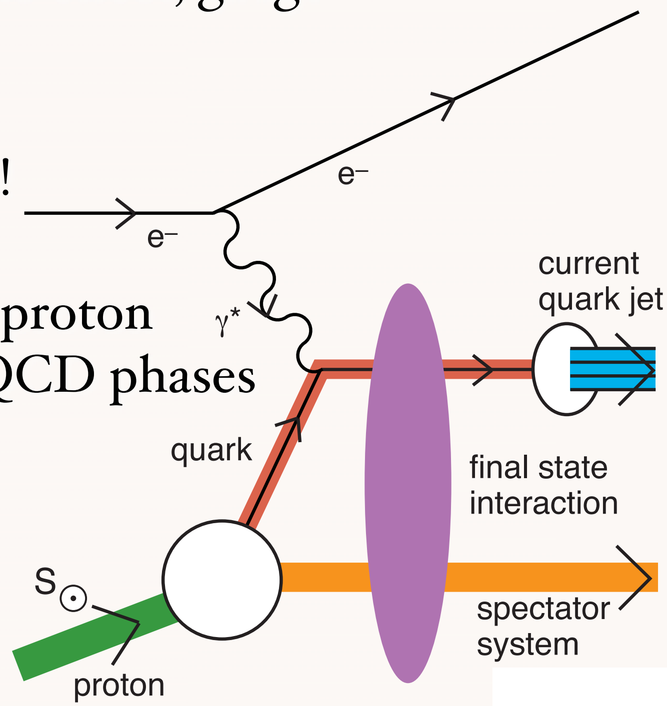
Final-State Interactions Produce T-Odd (Sivers Effect) $\mathbf{i}\,\vec{S}\cdot\vec{p}_{jet}\times\vec{q}$

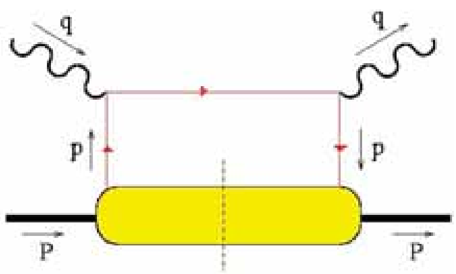
- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment

Hwang, Schmidt. sjb;
Burkardt

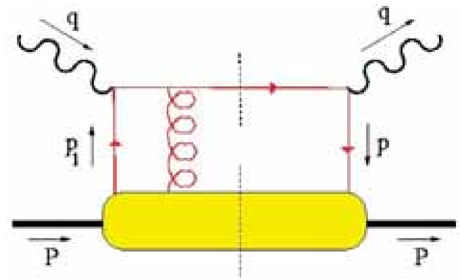
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

- 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)

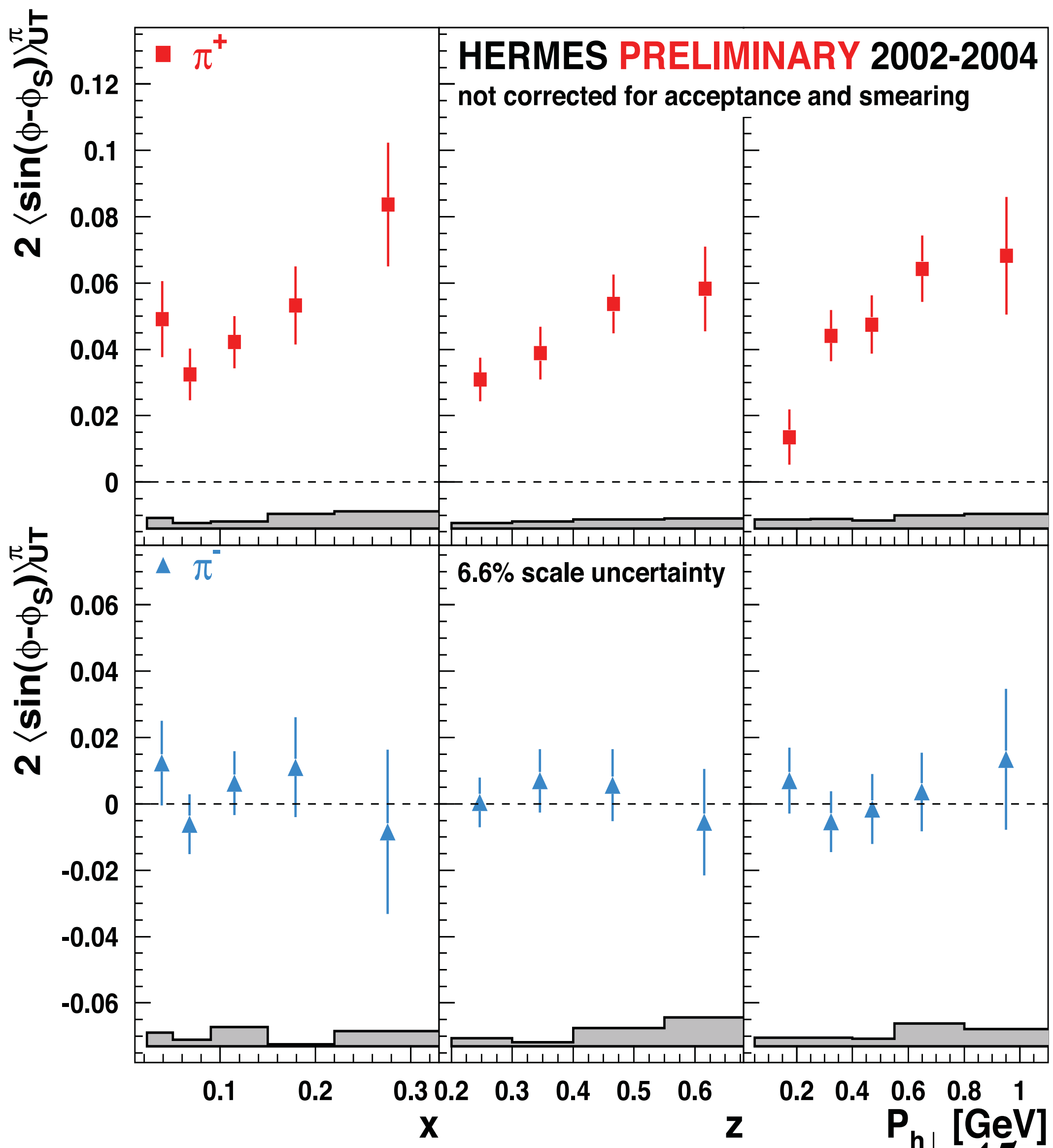




can interfere with



and produce
a T-odd effect!
(also need $L_z \neq 0$)

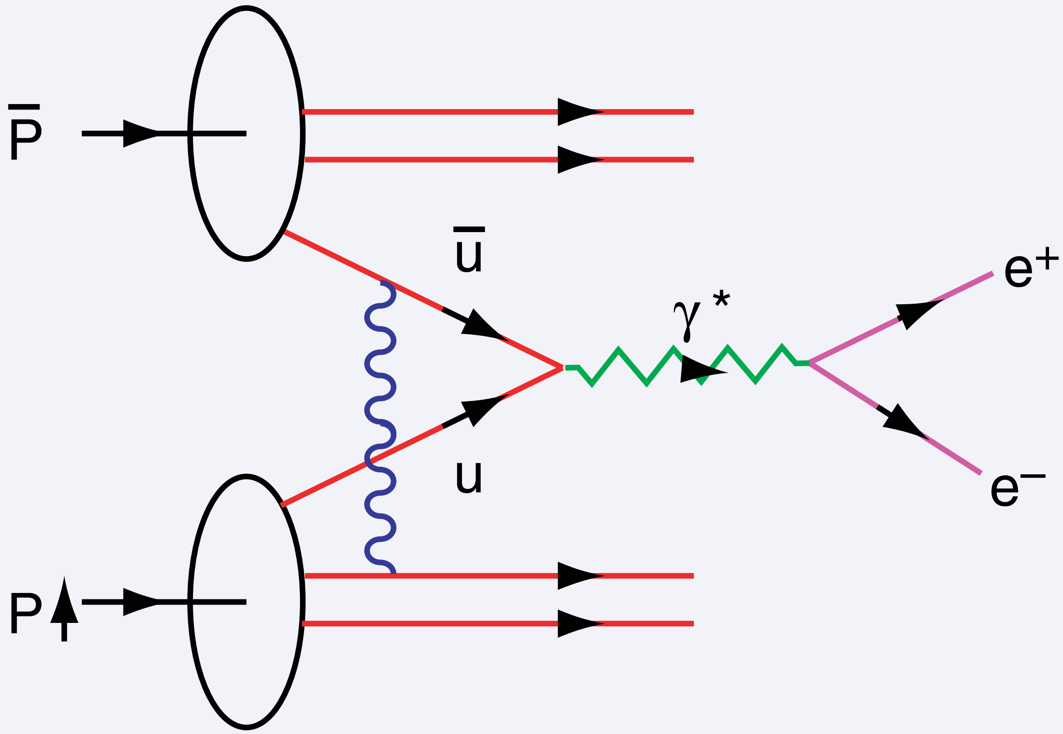


- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**...
  Consistent with zero for **π⁻**...

Gamberg: Hermes data compatible with BHS model

Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

Predict Opposite Sign SSA in DY !



Collins;
Hwang, Schmidt.
sjb

Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{\bar{p}} \times \vec{q}_{\gamma^*}$

Quarks Interact in the Initial State

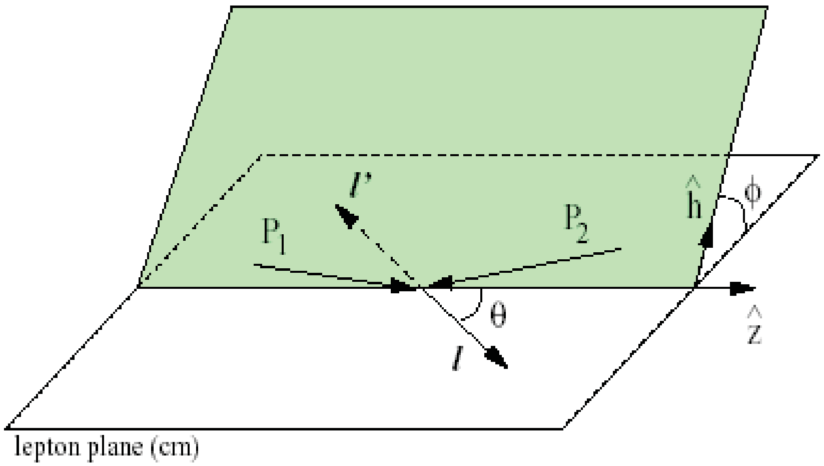
Interference of Coulomb Phases for *S* and *P* states

Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.

Opposite Sign to DIS! No Factorization

Drell-Yan angular distribution

Unpolarized DY



- Experimentally, a violation of the Lam-Tung sum rule is observed by sizeable cos2Φ moments
- Several model explanations
  - higher twist
  - spin correlation due to non-triva QCD vacuum
  - Non-zero Boer Mulders function

$\text{Lam} - \text{Tung SR}: \; 1 - \lambda = 2\nu$

$\text{NLO pQCD}: \lambda \approx 1 \; \mu \approx 0 \; \nu \approx 0$

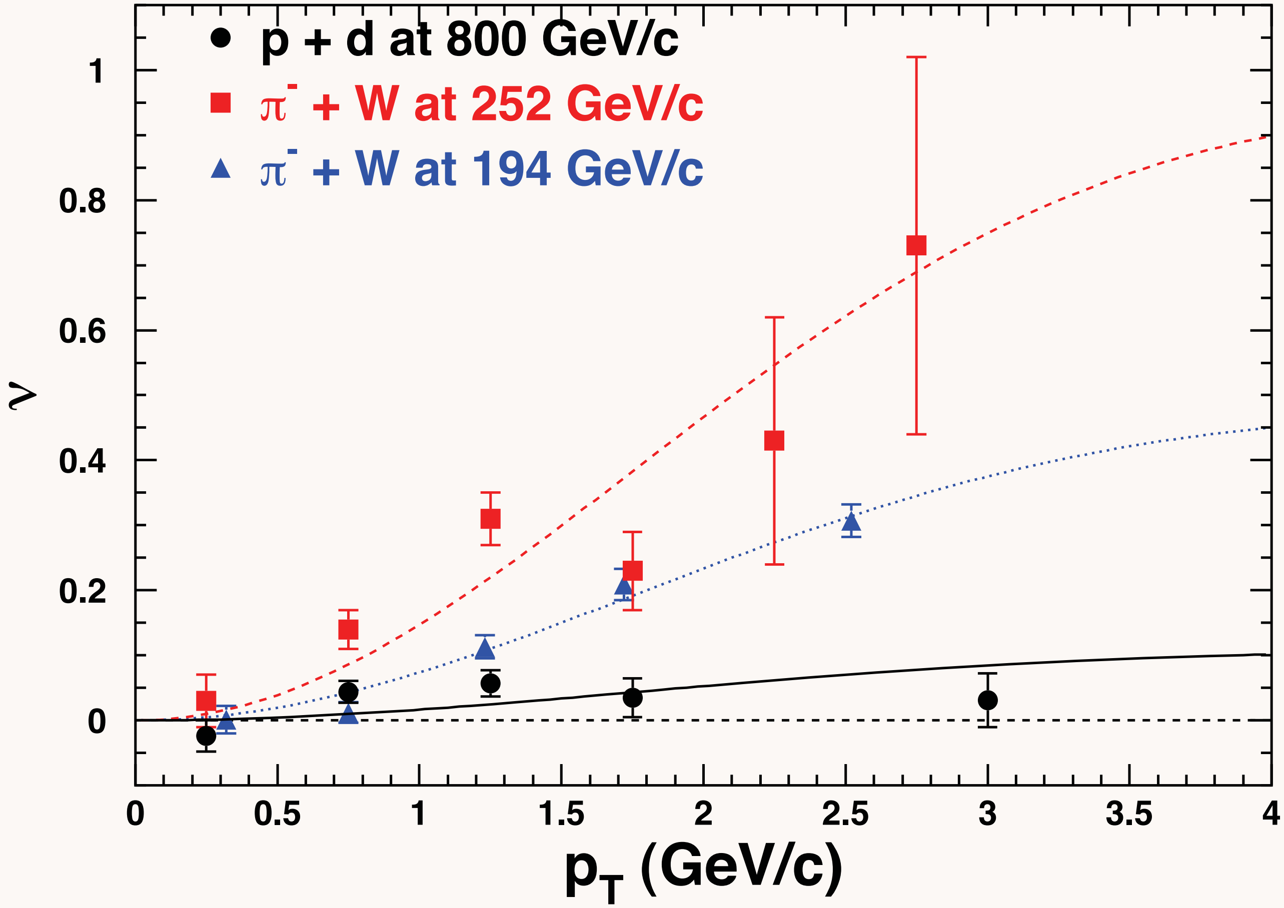
$\text{experiment}: \; \nu \approx 0.3$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

B. Seitz

Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)

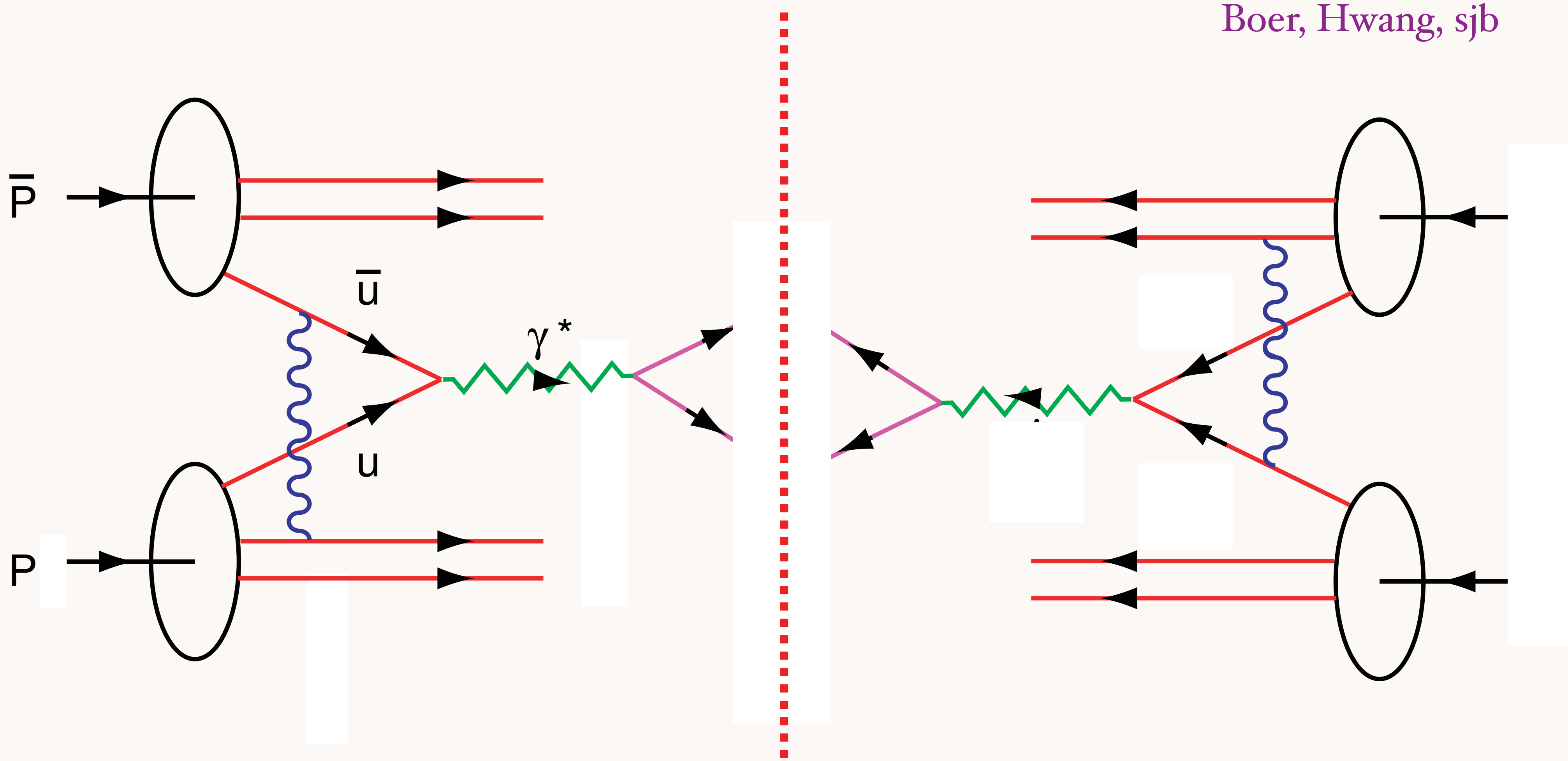


Huge Effect in $\pi W \to \mu^+ \mu^- X$

Negligible Effect $pd \to \mu^+ \mu^- X$

Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

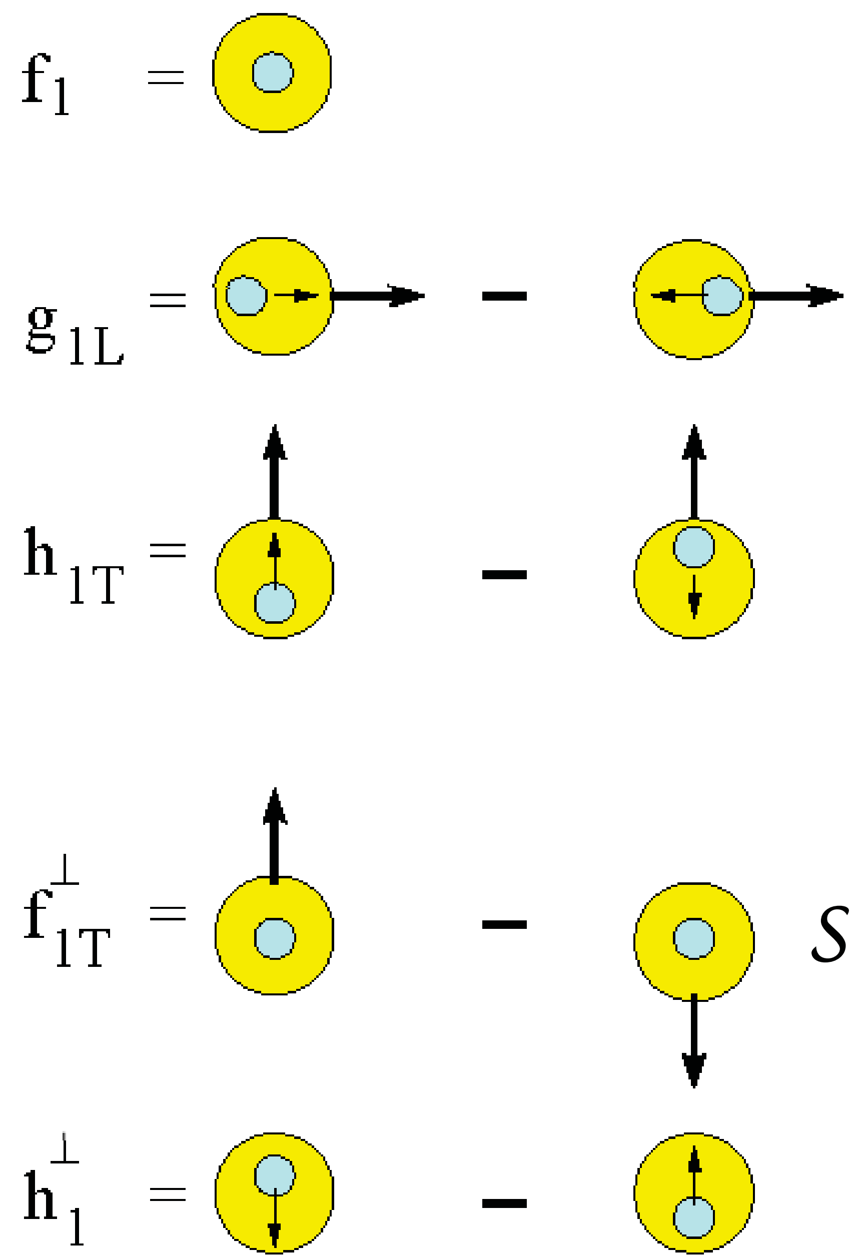
Boer, Hwang, sjb



DY $\cos 2\phi$ **correlation at leading twist from double ISI**

Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_{\perp}^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_{\perp}^2)$$



Unpolarized Distribution

Bj Sum Rule

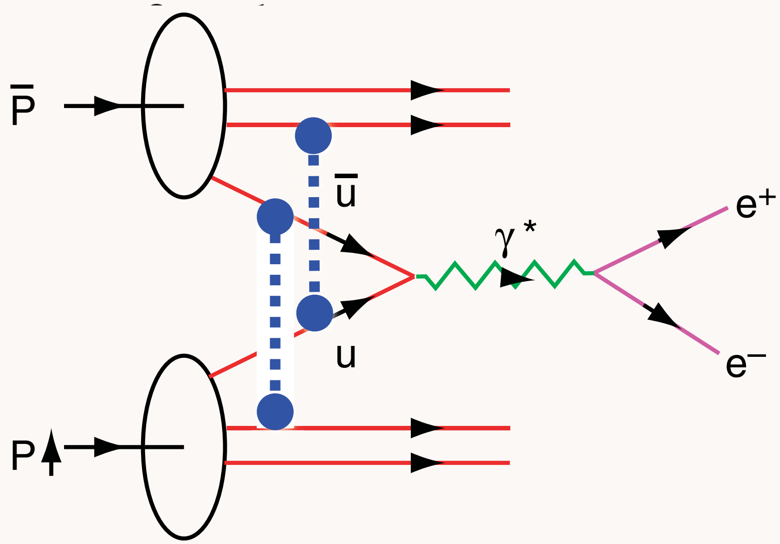
Transversity

Sivers Function

Boer-Mulders Function

T-Odd: Require ISI or FSI

DY $\cos 2\phi$ correlation at leading twist from double ISI



Product of Boer - Mulders Functions

$$h_1^\perp(x_1, \boldsymbol{p}_\perp^2) \times \bar{h}_1^\perp(x_2, \boldsymbol{k}_\perp^2)$$

$$\nu = \frac{2}{M_1 M_2} \frac{\sum_{a,\bar{a}} e_a^2 F_a}{\sum_{a,\bar{a}} e_a^2 G_a}.$$

$$F \equiv \mathcal{F}[(2\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp\ \hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp - \boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp) h_1^\perp \bar{h}_1^\perp]$$

$$= \int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp\, \delta^2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{q}_\perp)(2\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_\perp \hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp - \boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp)$$

$$\times h_1^\perp(\Delta, \boldsymbol{p}_\perp^2)\bar{h}_1^\perp(\bar{\Delta}, \boldsymbol{k}_\perp^2),$$

(40

$$G \equiv \mathcal{F}[f_1 \bar{f}_1]$$

$$= \int d^2\boldsymbol{p}_\perp\ d^2\boldsymbol{k}_\perp\, \delta^2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{q}_\perp) f_1(\Delta, \boldsymbol{p}_\perp^2)\bar{f}_1(\bar{\Delta}, \boldsymbol{k}_\perp^2),$$

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Double Initial-State Interactions generate anomalous $\cos 2\phi$

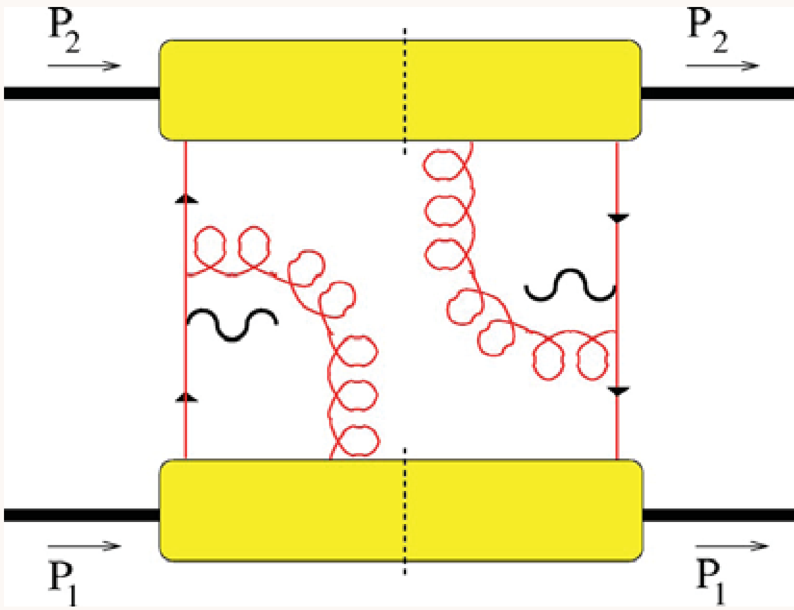
Boer, Hwang, sjb

Drell-Yan planar correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

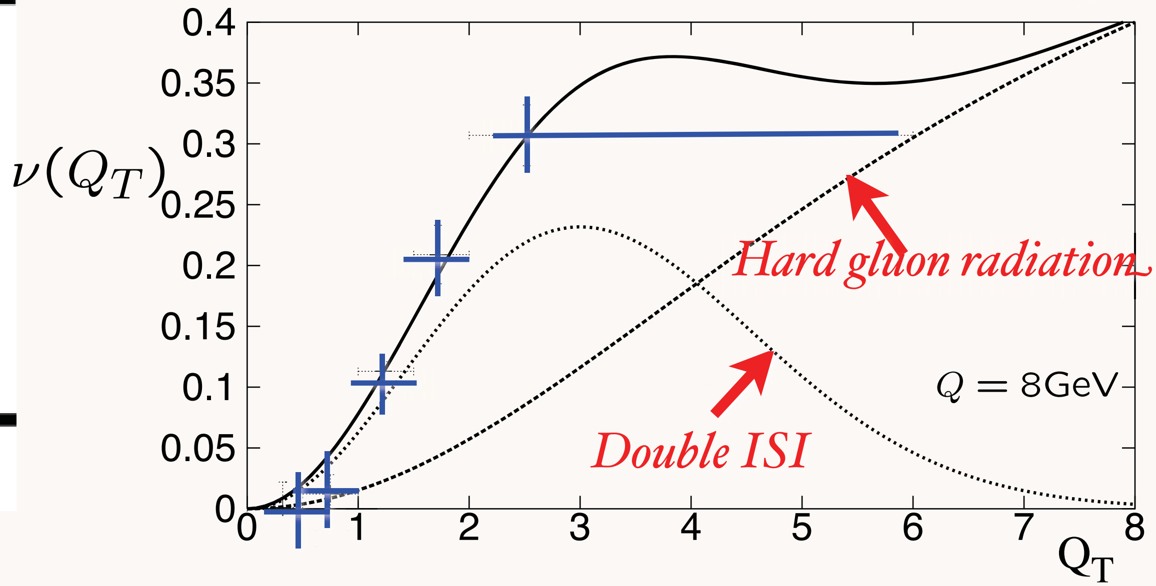
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$



Violates Lam-Tung relation!

$\pi N \rightarrow \mu^+\mu^- X$ NA10



Model: Boer,

Anomalous effect from Double ISI in Massive Lepton Production

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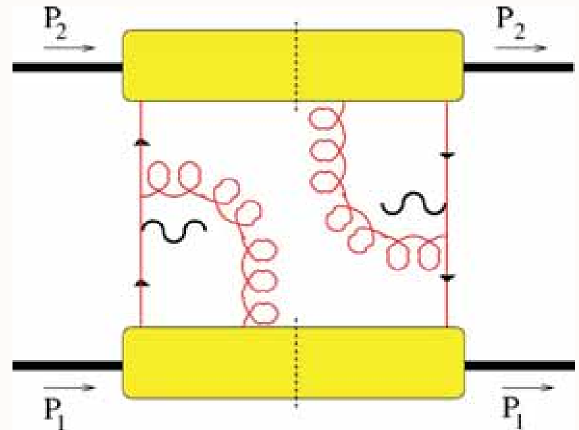
$\cos 2\phi$ correlation



- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization