E791 Fermilab

E.M. Aitala, et al   hep-ex/0010044
Oct 2000

Observation of Color-Transparency in Diffractive Dissociation of Pions

$$\sigma_A \propto A^{\alpha}$$

$k_\perp$ range (GeV/c)	α	$\alpha(CT)^*$	α(Incoh)
$1.5 < k_\perp < 2.0$	1.52 ± 0.12	1.45	~0.7
$2.0 < k_\perp < 2.5$	1.55 ± 0.16	1.60	~0.7

* Frankfurt, Miller, Strikman

* $\sigma(Pt)/\sigma(C) \sim 87$ compared to 7 for $A^{2/3}$

* Nucleus transparent to Fock state of pion

Shape of $\varphi_\pi(x_i, Q)$

$F_{\gamma^*\gamma \to \pi^0}(Q^2)$

E791 Diffractive Di-Jet

$\pi A \to J_1 J_2 A$

* both suggest $\varphi_\pi(x, Q) \cong \varphi_{Asym}(x)$

$= \sqrt{3} f_\pi \, x(1-x)$

why?

Highly relativistic quarks in pion?

Maybe: $\varphi_\Delta(x_i) = C_1 \, x_1 x_2 x_3$

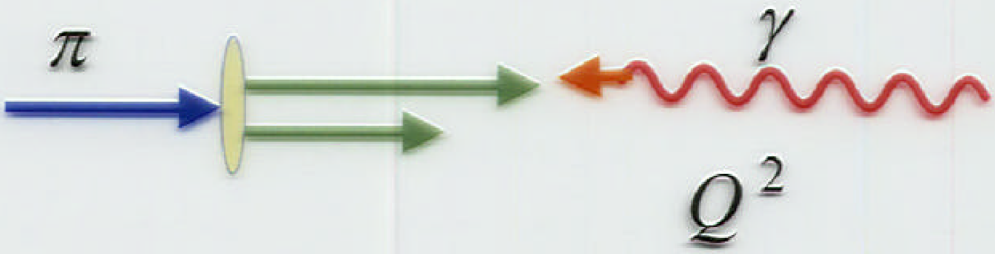
$\varphi_p(x_i)$: asymmetric

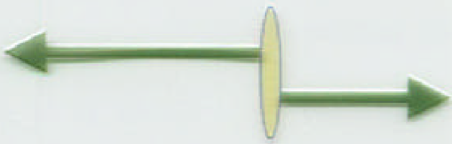
due to SU(6) Flavor-spin

$\Rightarrow$ * $F_{1p}(Q^2) \sim \frac{1}{Q^4}$; $F_{p \to \Delta}(Q^2) \sim \frac{1}{Q^6}$

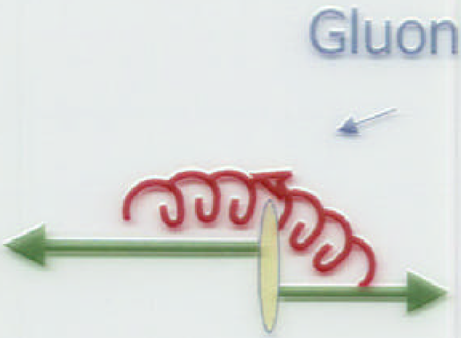
Stoler, Carlson

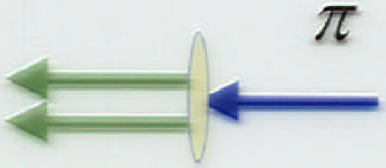
PQCD approach to pion form factor

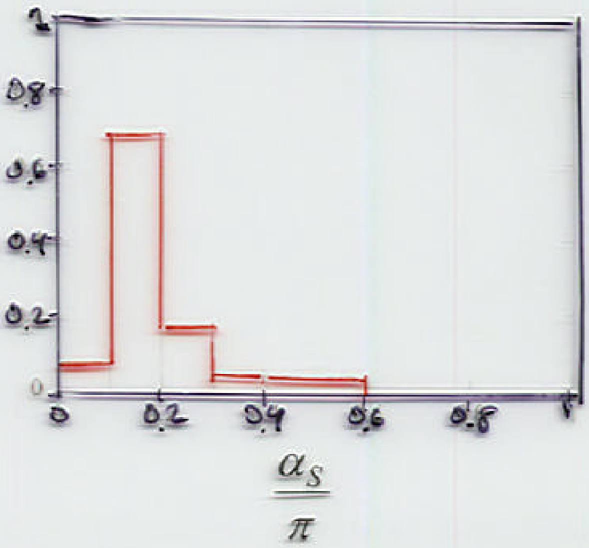




$$\pi + "\gamma" \rightarrow X$$







General Features of Exclusive Reactions at Large Momentum Transfer

- Power Law Scaling–Quark Counting Rules

F: ($\lambda = \lambda' = \pm 1/2$)
B: ($\lambda = \lambda' = 0$)

$$F_H(Q^2) \sim \left\{\frac{1}{Q^2}\right\}^{n_H - 1}$$

SJB+ Farrar
Muradyan, et al

$$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{1}{s^{N-2}} f(\theta_{cm})$$

$$(N = n_A + n_B + n_C + n_D)$$

Sudakov Suppression of Landshoff pinch contributions

- Hadron Helicity Conservation

Mueller
Botts + Sterman

$$\sum_{initial} \lambda_{had} = \sum_{final} \lambda_{had}$$

- Factorization Theorem

$$\mathcal{M}_{AB \to CD} = \int \phi_A \phi_B T_H \phi_C \phi_D \prod dx_i$$

Lepage
SJB

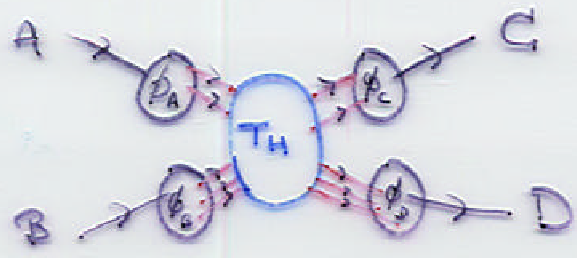
T_H : Hard q-g Scattering Amplitude

$\phi_A(x_i, Q)$: Hadron Distribution Amplitude

Efremov
Radyushkin

Chernyak
Zhitnitsky

2



Farrar
Jackson

Mueller
Duncan

Factorization of Exclusive Amplitudes at Large Momentum Transfer

Lepage SJB
Efremov Radyushkin
Chernyak etc

* $$\mathcal{M} = \int [dx] \prod_i \phi_i(x, Q) \, T_H$$

- Accurate to leading twist $+ O\left(\frac{\Lambda}{Q}\right)^n$
- ϕ_i: universal distribution amplitude
- T_H: hard scattering amplitude
  - perturbative calculable in α_s
- Hadron helicity conservation $\sum_{init} \lambda_H = \sum_{final} \lambda_H$
- Quark Counting Rules
- Color Transparency
- End-point suppression by Sudakov effect

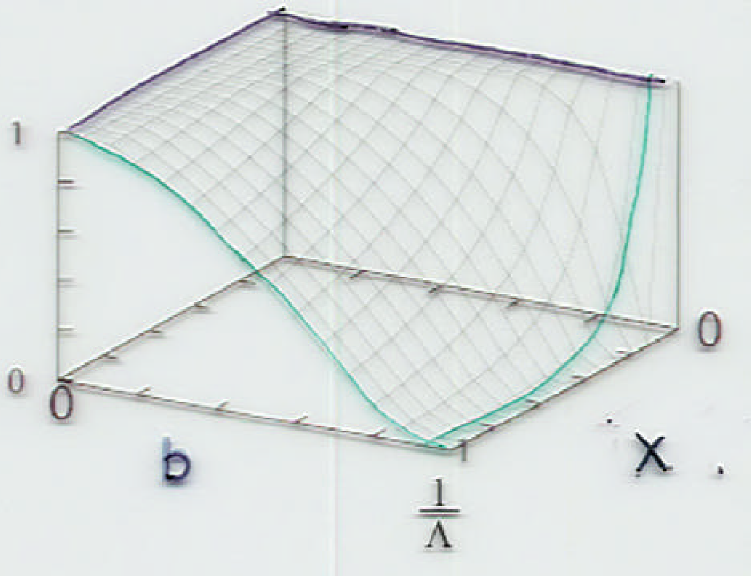
Berger + SJB

Many applications: form factors, higher twist DY, fixed θ_{cm} scattering, heavy hadron decay

Pion form factor

Color Singlet
state does not
radiate

Sudakov factor



Sanda
et al

high $Q^2 = -q^2$

$Q^2 >> \langle k_\perp^2 \rangle$

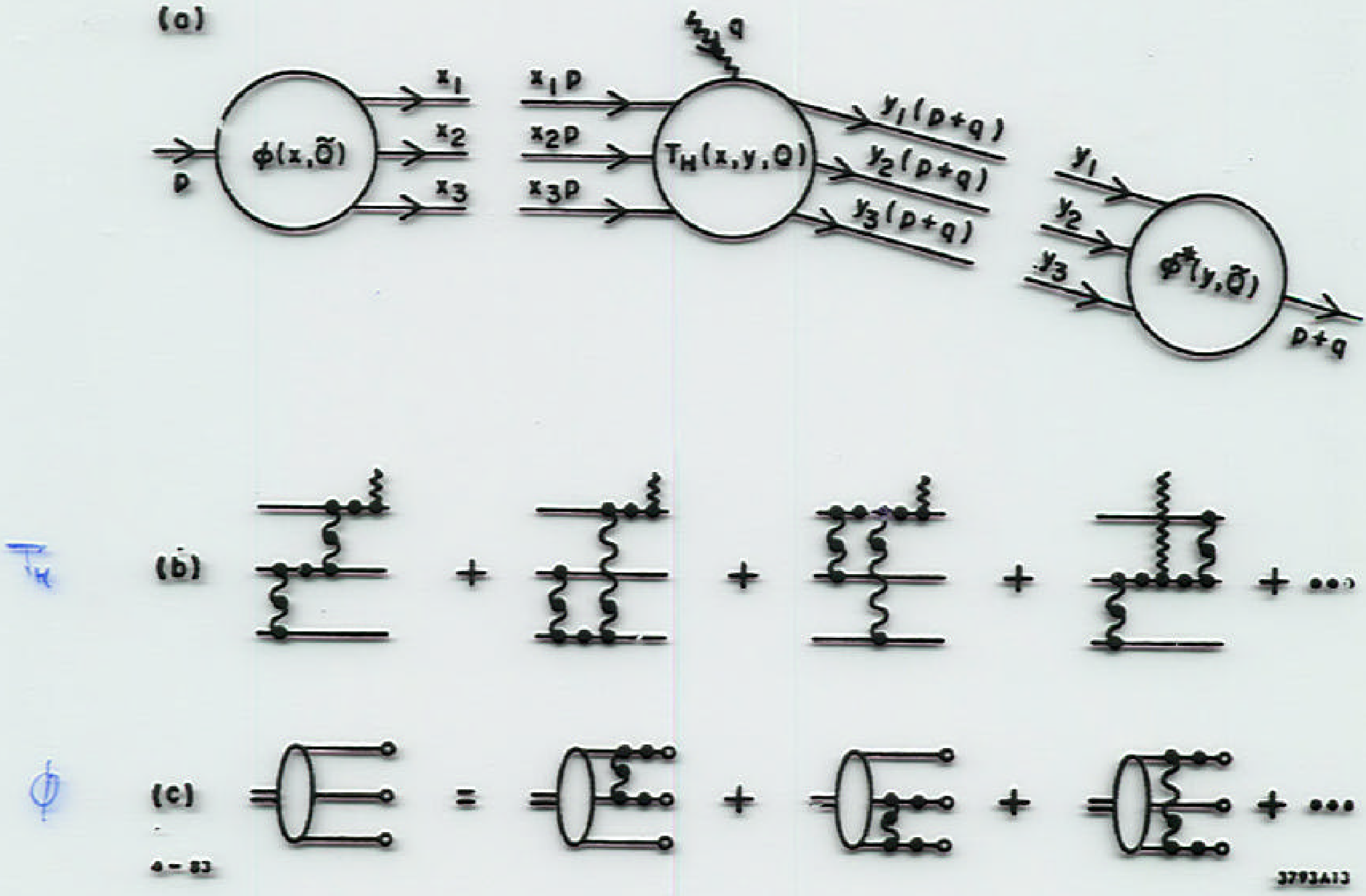


Figure 19. (a) Factorization of the nucleon form factor at large Q^2 in QCD. (b) The leading order diagrams for the hard scattering amplitude T_H. The dots indicate insertions which enter the renormalization of the coupling constant. (c) The leading order diagrams which determine the Q^2 dependence of the distribution amplitude $\phi(x,Q)$.

Calculation of proton form factor in PQCD

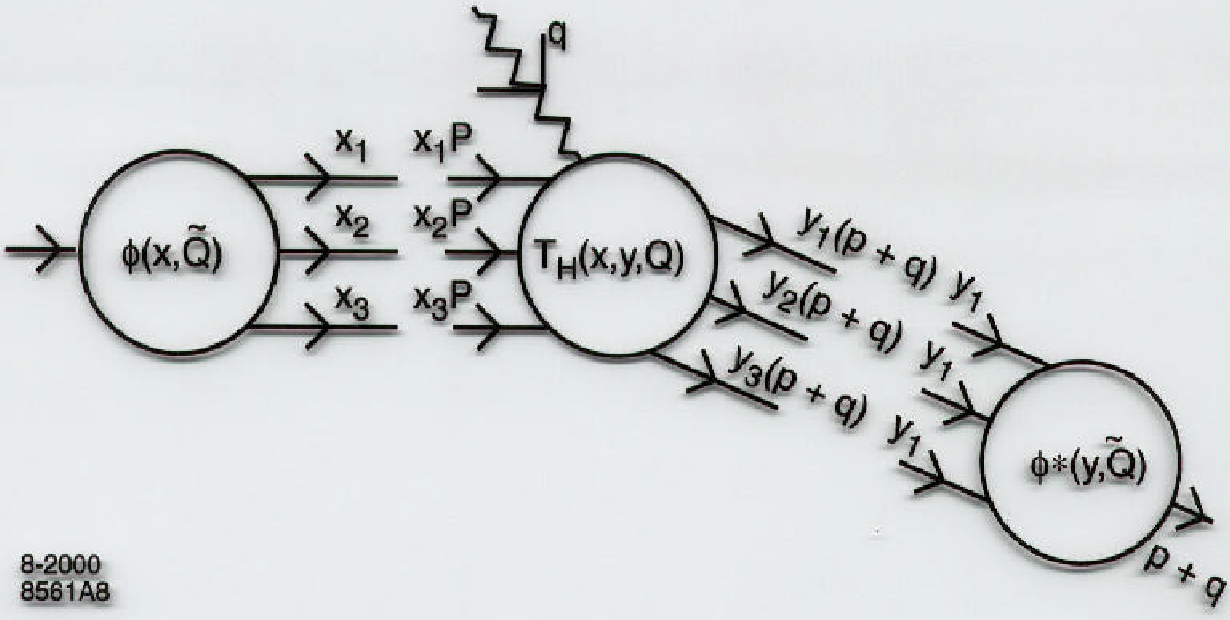
Lepage + SJB

Chernyak + Zhit

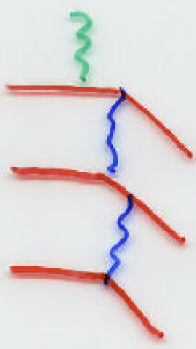
Radyushkin

Mueller + Duncan

Feynman endpoint: Kroll et al

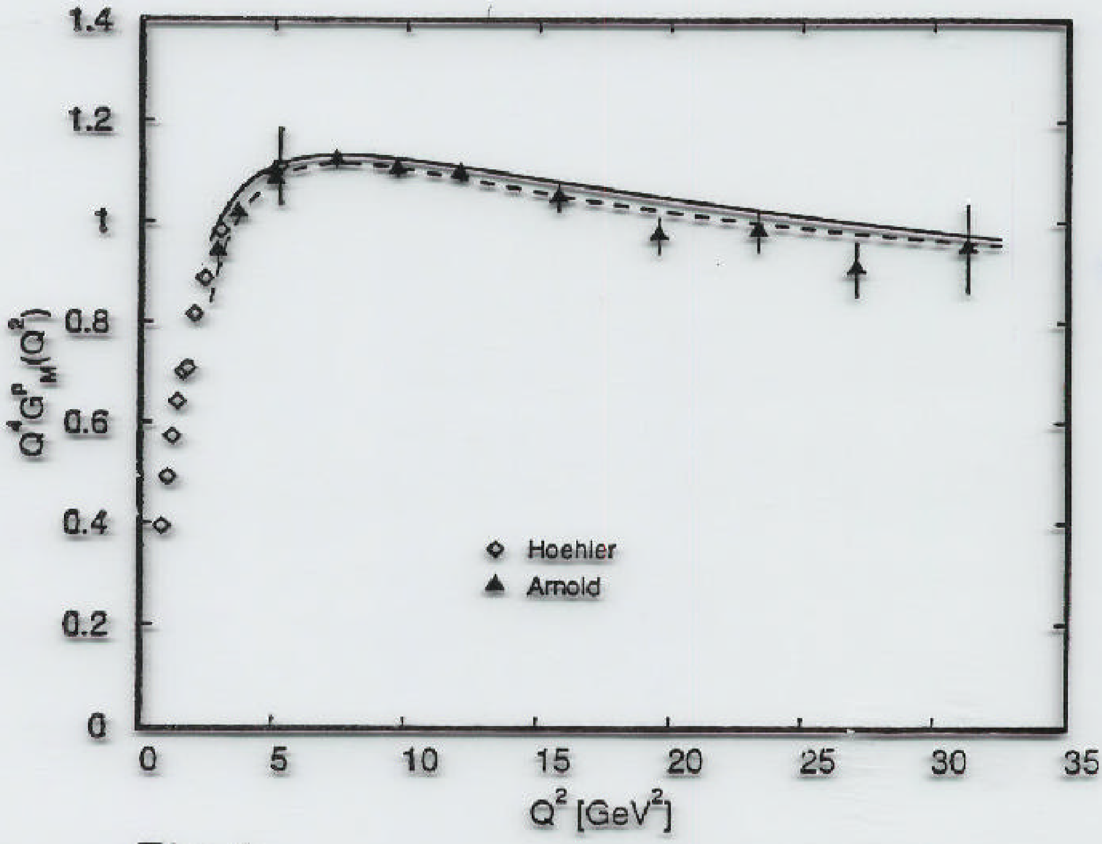


8-2000
8561A8



$$\frac{\alpha_s^2(Q^*)}{Q^4}$$

Fig from Kroll et al



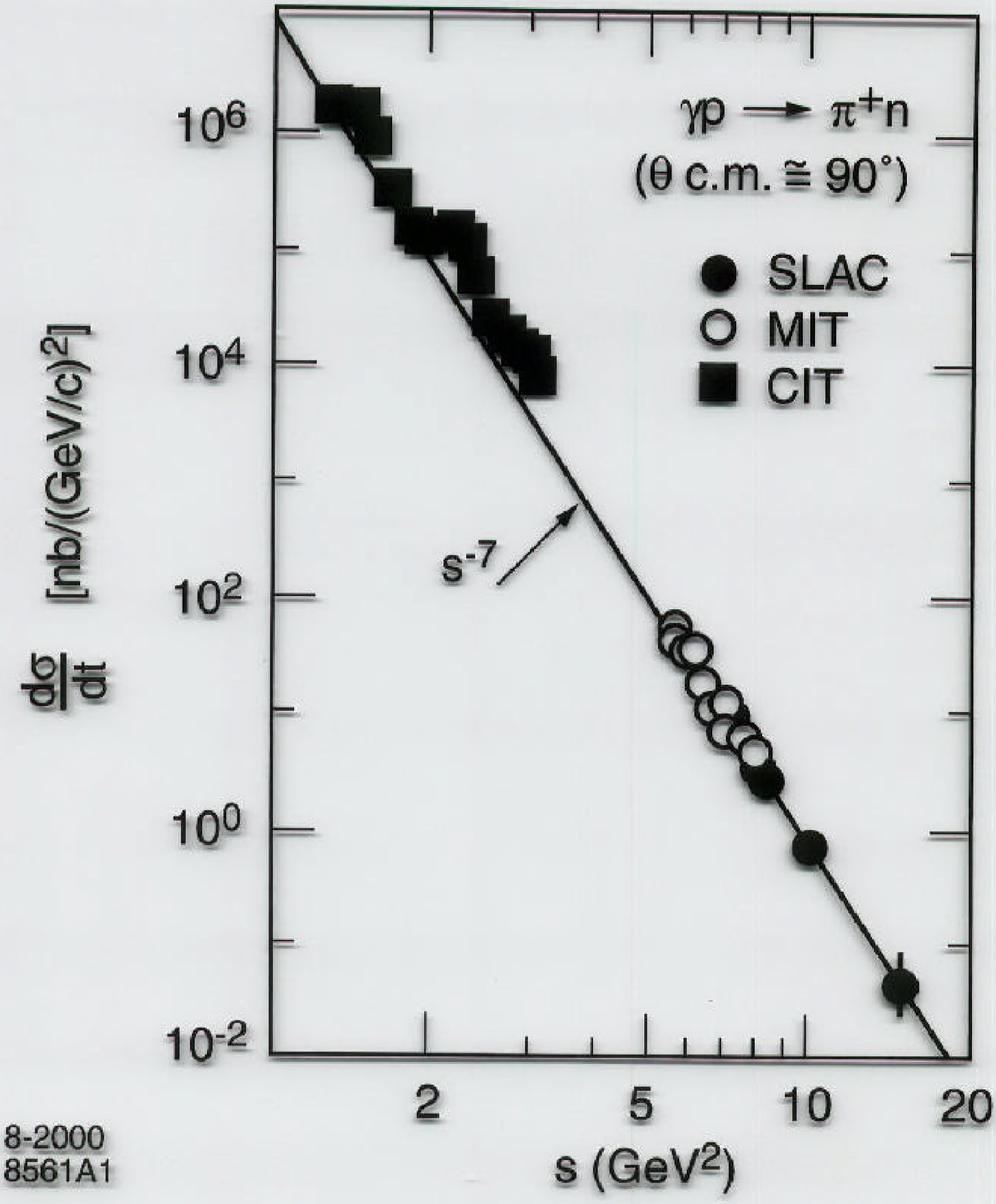
$\sim \alpha_s^2(Q^2)$

Fig. 4

PQCD predicts $\frac{1}{Q^4}$!

consistent with

$F_1(Q^2) \sim \frac{\alpha_s^2(Q^2)}{Q^4}$



$\gamma p \longrightarrow \pi^+ n$
(θ c.m. ≅ 90°)
SLAC
MIT
CIT
s^{-7}
10^6
10^4
10^2
10^0
10^{-2}
$\frac{d\sigma}{dt}$ [nb/(GeV/c)^2]
2
5
10
20
s (GeV^2)
8-2000
8561A1

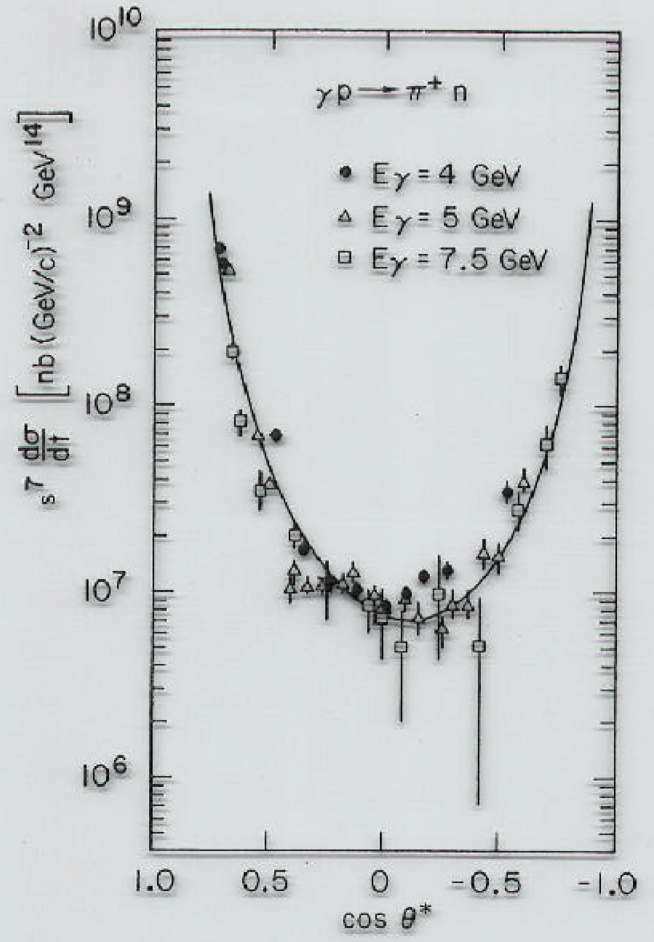


FIG. 6. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \to \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where $(z = \cos\theta^*)$, which is an empirical fit to the angular distribution.

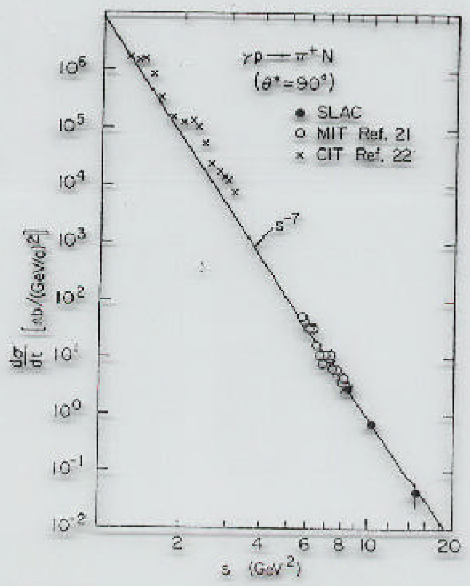
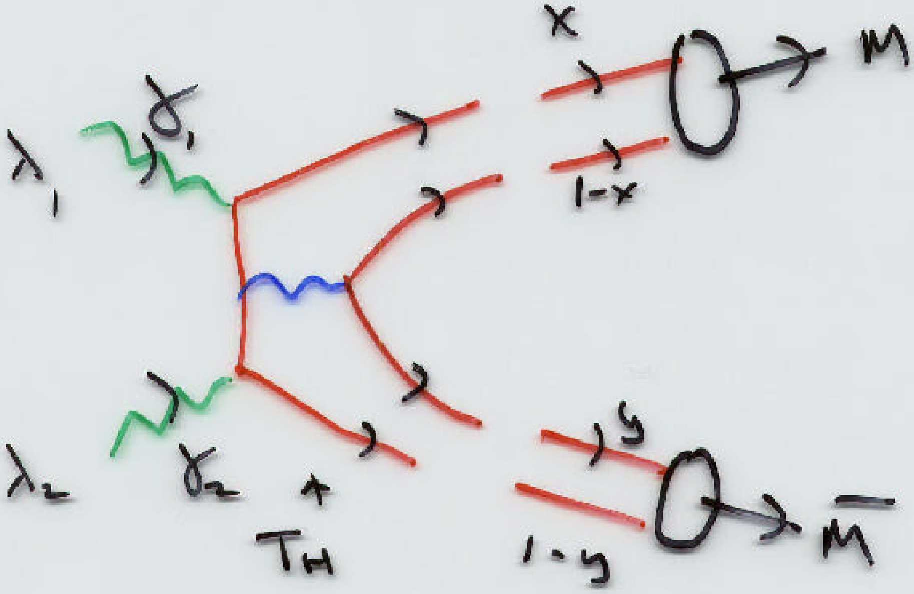


FIG. 20. 90° c.m. values of $d\sigma/dt$ versus s for the process $\gamma p \to \pi^+ n$ from several experiments from E_γ = 700 MeV to E_γ = 7.5 GeV. The solid line shows the function s^{-7} for reference.

PQCD Factorization
at large s, t

G.P. Lepage
+ SJB
Vast and
Cheng [illegible]

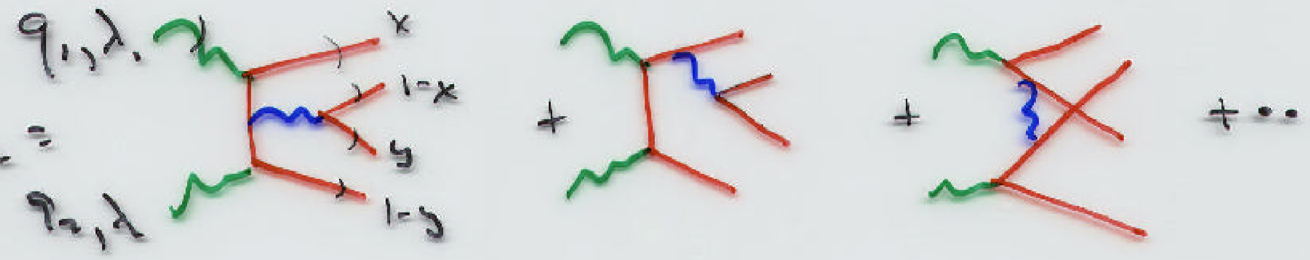


no FSI!

$$\boxed{\mathcal{M}(\gamma_1, \gamma_2 \to M \bar{M}) = \int_0^1 dx \int_0^1 dy \, T_H(x, y; s, \theta_{cm}) \, \phi_M(x, \tilde{Q}) \, \phi_{\bar{M}}(y, \tilde{Q})}$$

$$\phi_M(x, \tilde{Q}) = \int^{\tilde{Q}} d^2k_\perp \, \psi_{q\bar{q}/M}(x, \vec{k_\perp})$$

$T_{\lambda_1\lambda_2} =$

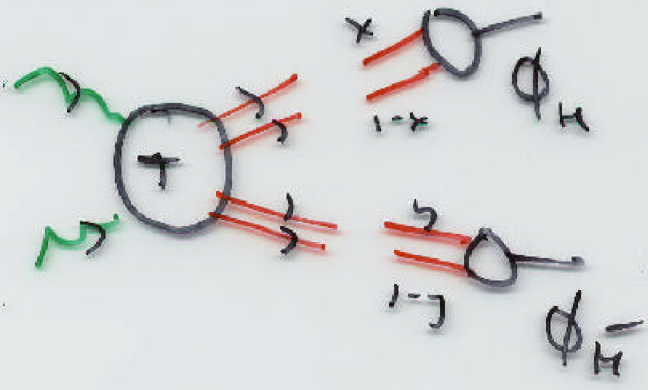


$$\mathcal{M}_{\lambda_1\lambda_2}(s,\theta_{cm}) = \int_0^1 dx \int_0^1 dy$$

$$\phi_H^*(x,Q)\, \phi_{\bar{H}}^*(y,Q)\, T_{\lambda_1\lambda_2}(x,y;s,\theta_{cm})$$

Factorization theorem

* Separate perturbative $T_{\lambda_1\lambda_2}$
  from non-perturbative $\phi_H(x,Q)$



* ϕ_H universal; no FSI!

B+L

$$\boxed{T_{\lambda_1\lambda_2} \text{ for } \gamma_1\gamma_2 \to M\bar{M}}$$

helicity zero mesons

leading twist

$$T_{++} = T_{--} = \frac{16\pi\alpha_s}{3s}\,\frac{32\pi\alpha}{x(1-x)\,y(1-y)}\,\frac{e_M^2\,a}{1-\cos^2\theta_{cm}}$$

$$T_{+-} = T_{-+} = \qquad \text{''} \qquad \left[\frac{e_M^2(1-a)}{1-\cos^2\theta_{cm}} + \frac{e_1e_2\,c}{a^2-b^2\cos^2\theta_{cm}}\right]$$

$$a = (1-x)(1-y) + xy$$

$$b = (1-x)(1-y) - xy$$

$$c = (1-a)\left[y(1-y) + x(1-x)\right]$$

$$e_M = e_1 - e_2$$

Compare

$$T_{\gamma^* \to q\bar{q}} = \frac{16\pi\alpha_s}{3s}\,\frac{1}{x(1-x)}\,\frac{1}{y(1-y)}$$

$$\therefore \quad \mathcal{M}_{++} = \mathcal{M}_{--} = 16\pi\alpha\, F_M(s)\,\frac{e_M^2}{1-\cos^2\theta_{cm}}$$

$$\mathcal{M}_{+-} = \mathcal{M}_{-+} = 16\pi\alpha\, F_M(s)\left[\frac{e_M^2}{1-\cos^2\theta_{cm}} + 2e_1e_2\, g(\theta_{cm})\right]$$

if $\phi(x) = \phi(1-x)$

Ingredients

* $\phi_\pi(x,Q) = \int^{Q} d^2k_\perp \, \psi^{\pi}_{q\bar{q}}(x,\vec{k}_\perp)$

G.P.L
SJB

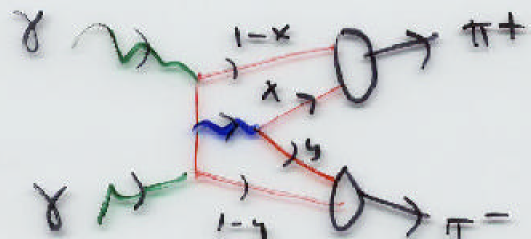
$\psi^{\pi}_{q\bar{q}}(x,\vec{k}_\perp)$ $\qquad (\tau = t - z/c = 0)$

$$x = \frac{k^+}{p^+_\pi} = \frac{k^0+k^3}{p^0_\pi+p^3_\pi}$$

* $\alpha_s(Q^2)$ at low scales

e.g.: $Q^2 = \hat{s} = xys \sim \frac{s}{4}$

*

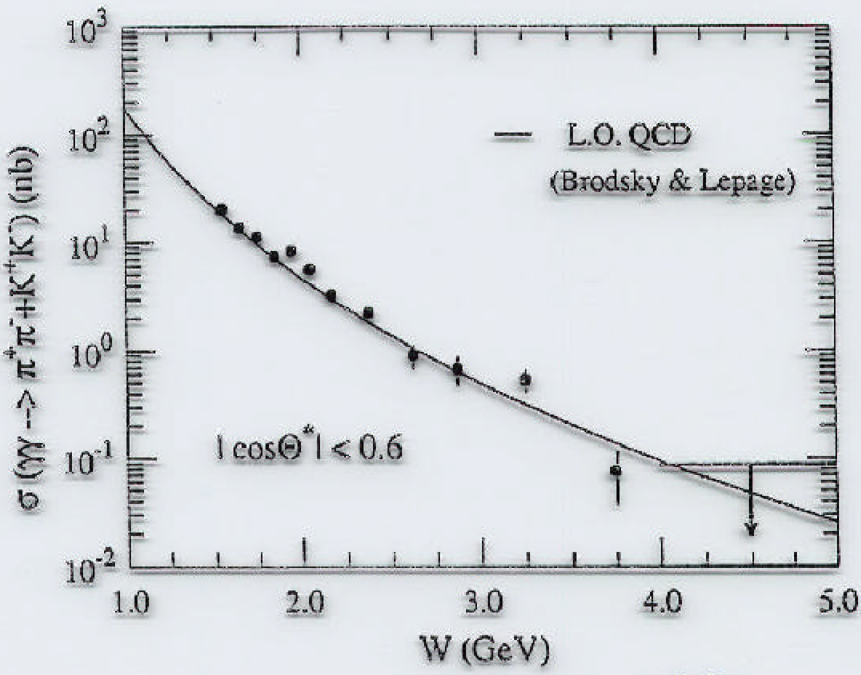


* Color Transparency
(suppressed F.S.I)

A.H. Mueller
SJB

$\gamma\gamma \rightarrow \pi^+\pi^-, K^+K^-$

CLEO

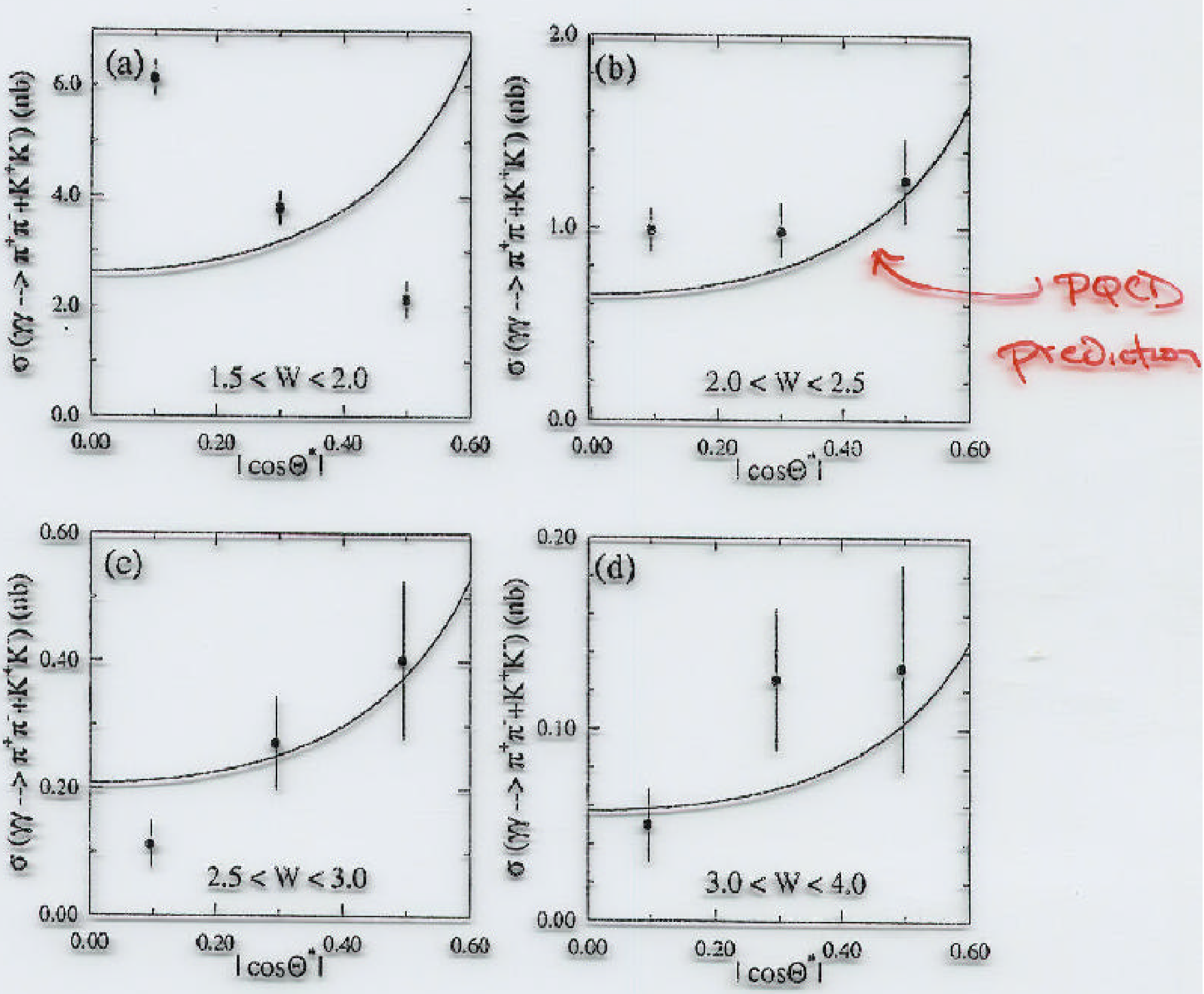


$W_{\gamma\gamma}$

HPP
HPQCD

$\gamma\gamma \to \pi^+\pi^-, K^+K^-$
(Θ^* dep)

CLEO

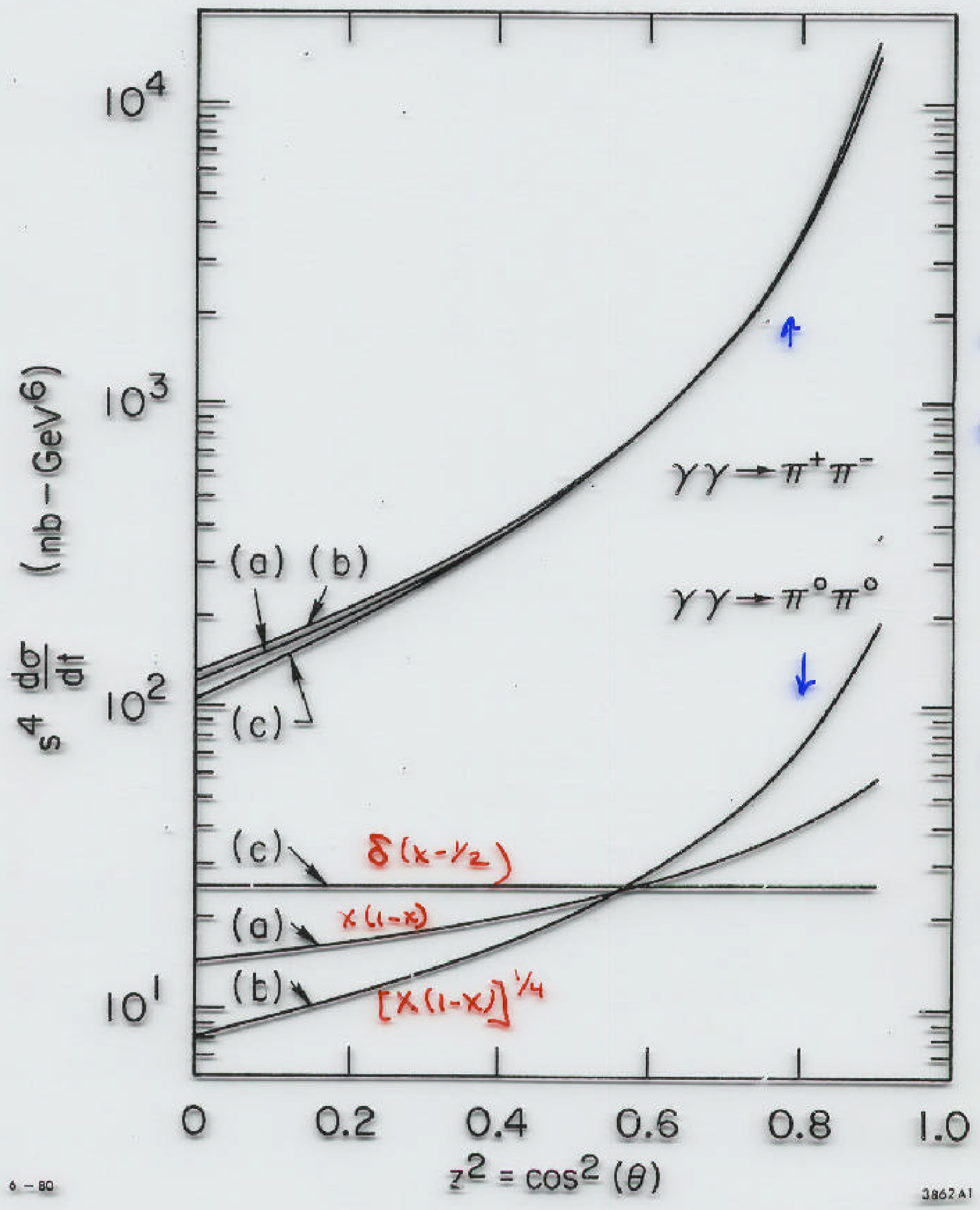


$|\cos\Theta^*|$

Evidence for PQCD at $W_{\gamma\gamma} \gtrsim 2.5$ GeV

HPP

BHL

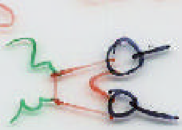


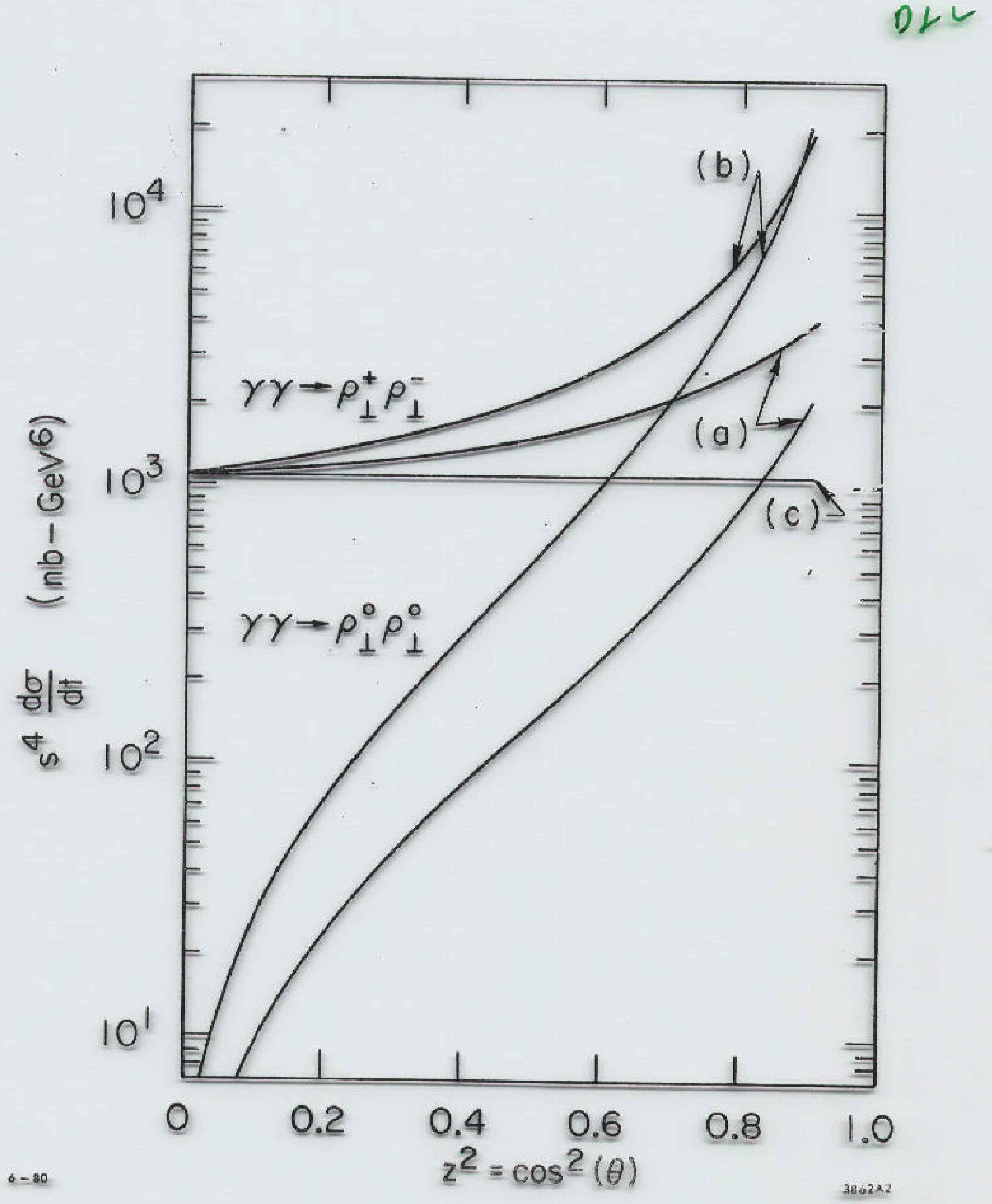
insensitive to $\phi_{\pi^\pm}(x)$!

strong sensitivity to $\phi_{\pi^0}(x)$!

Fig. 3

Strong suppression of $\gamma\gamma \to \pi^0\pi^0$

not true if  only



OLC
10^4
10^3
10^2
10^1
$s^4 \frac{d\sigma}{dt}$ (nb-GeV6)
(b)
(a)
(c)
$\gamma\gamma \to \rho_\perp^+ \rho_\perp^-$
$\gamma\gamma \to \rho_\perp^\circ \rho_\perp^\circ$
0
0.2
0.4
0.6
0.8
1.0
$z^2 = \cos^2(\theta)$
6-80
3862A2

Fig. 5

For $\gamma\gamma \to \pi^+\pi^-$:

DIV

$$\boxed{\frac{\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma \to \mu^+\mu^-)} = \frac{4 F_\pi^2(s)}{1-\cos^2\theta_{cm}}}$$

nearly independent of shape of $\phi_\pi(x,Q)$

$$\int_0^1 dx\, \phi_M(x,Q) = \frac{F_M}{2\sqrt{3}}$$

$$\frac{d\sigma}{dt}(\gamma\gamma \to K^+K^-) \cong 2\,\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)$$

$$K_L K_S \cong 0.3 \qquad \pi^0\pi^0$$

$$\underset{\lambda=0}{\rho^+}\;\underset{\lambda=0}{\rho^-} \cong 7.5 \qquad \pi^+\pi^-$$

Many such predictions of similar ϕ_M

Measurements of

$$\phi_H(x_i, Q)$$

Central problem of QCD

$$\frac{d\sigma}{dt}\left[\underset{\lambda_1\lambda_2}{\gamma\gamma} \to \underset{\lambda_3\ \lambda_4}{H\,\bar{H}}\right]$$

scaling, helicity, angular structure

Ratios critical [α_s ~ cancels]

$$\frac{\gamma\gamma \to \pi^0\pi^0}{\gamma\gamma \to \pi^+\pi^-} \Rightarrow \phi_{\pi^0}(x, Q)$$

$$\frac{\gamma\gamma \to n\bar{n}}{\gamma\gamma \to p\bar{p}} \Rightarrow \phi_N(x, Q)$$

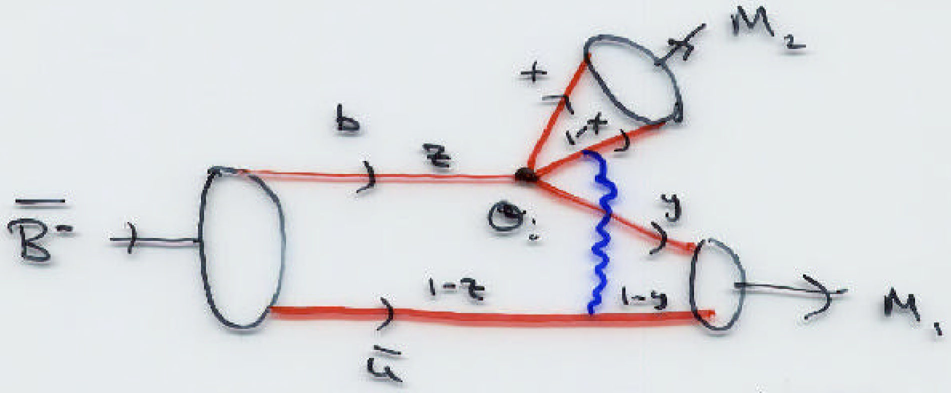
CLEO, Babar, Belle, LEP, ..

opportunity for fundamental physics

New Analyses of $B \to MM$ in PQCD

BBNS : Beneke, Buchalla, Neubert, Sachrajda

KLS : Keum, Li, Sanda



"octet" non-factorizable

$\alpha_s(k^2)$: BLM scale

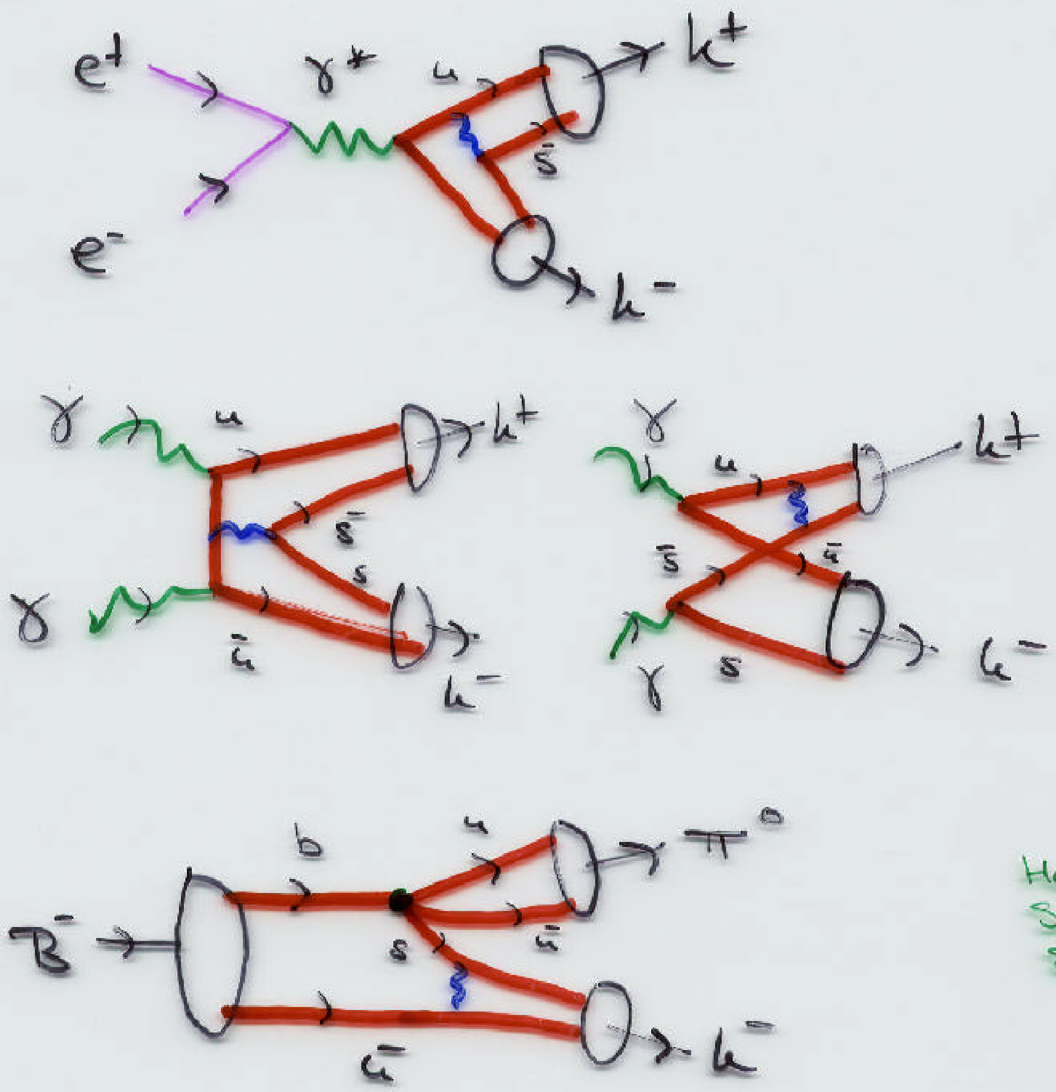
* $$\mathcal{M}_{B \to M_1 M_2} = \int_0^1 dz \int_0^1 dx \int_0^1 dy$$

$$\phi_B(z, Q)\, T_H(z, x, y; Q)\, \phi_{M_2}(x, Q)\, \phi_{M_1}(y, Q)$$

$b\bar{u} \to q\bar{q}\, q\bar{q}$

* No end-point singularities
* Color Transparency
* $Q^2 = O(M_B^2)$: Factorization scale

Universal Light-Front Wavefunctions



G. P. Lepage
SJB

Henley
Szepaniak
SJB

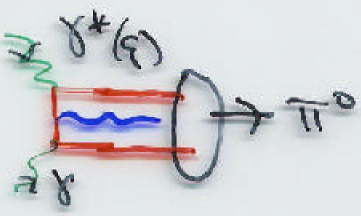
Common Ingredients:

* $\phi_\pi(x, Q)$, $\phi_K(x, Q)$ — Distribution Amplitudes
* $\alpha_s(Q)$ at low scales

Proof of PQCD Factorization

Lepage + SJB
H.N. Li
Mueller, Duncan
⋮

- 1. Decoupling of soft gluons to hard lines (simplest in l.c.g.)



- 2. Decoupling of soft gluons to states with small color dipole moment

   ⇒ color transparency

   ⇒ suppression of FSI (no violation of Watson's Theorem)

Mueller
SJB

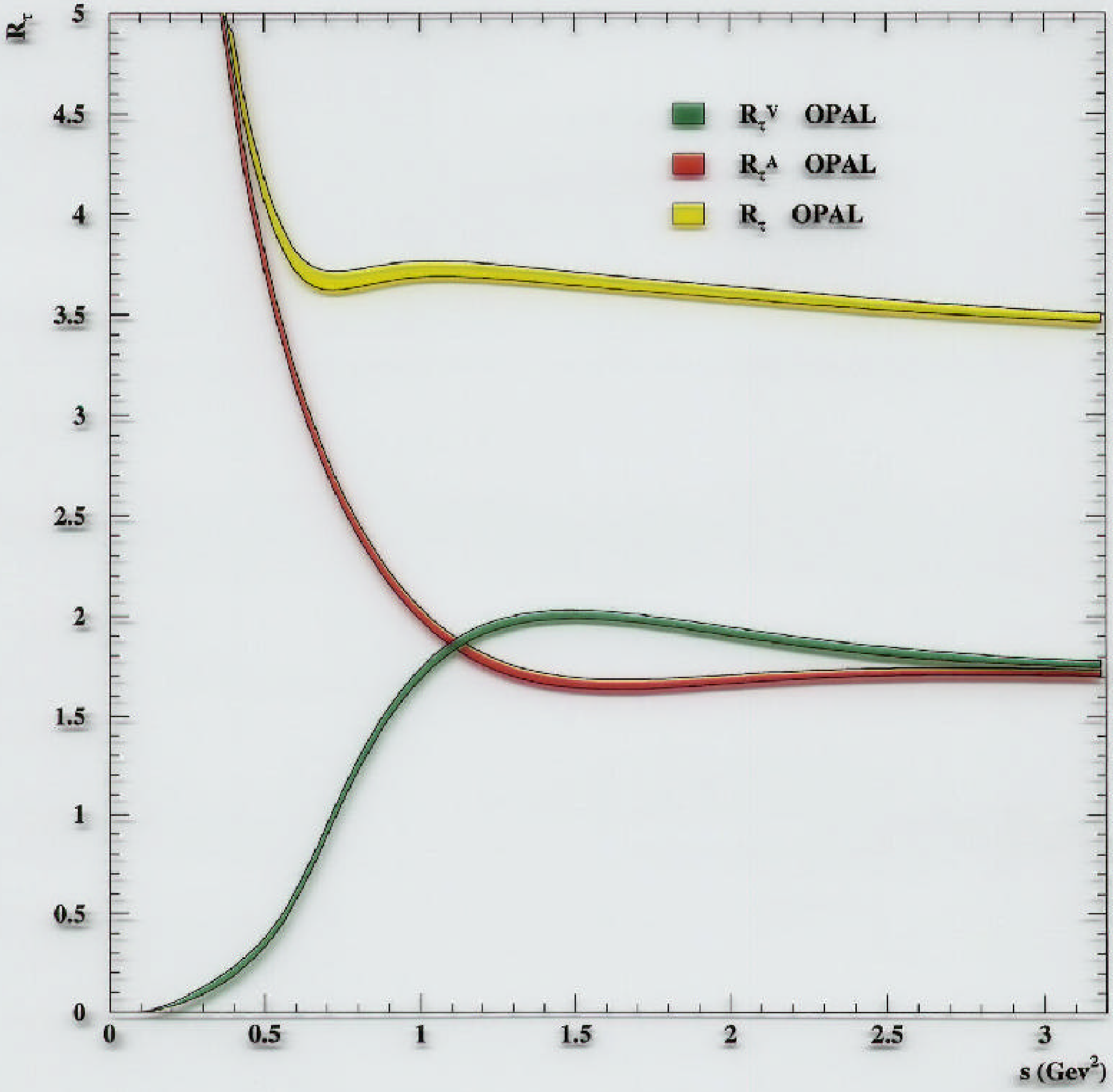
Wolfenstein

- 3. End-point suppression $x \to 1$, $k_\perp$ fixed

   (Feynman region)

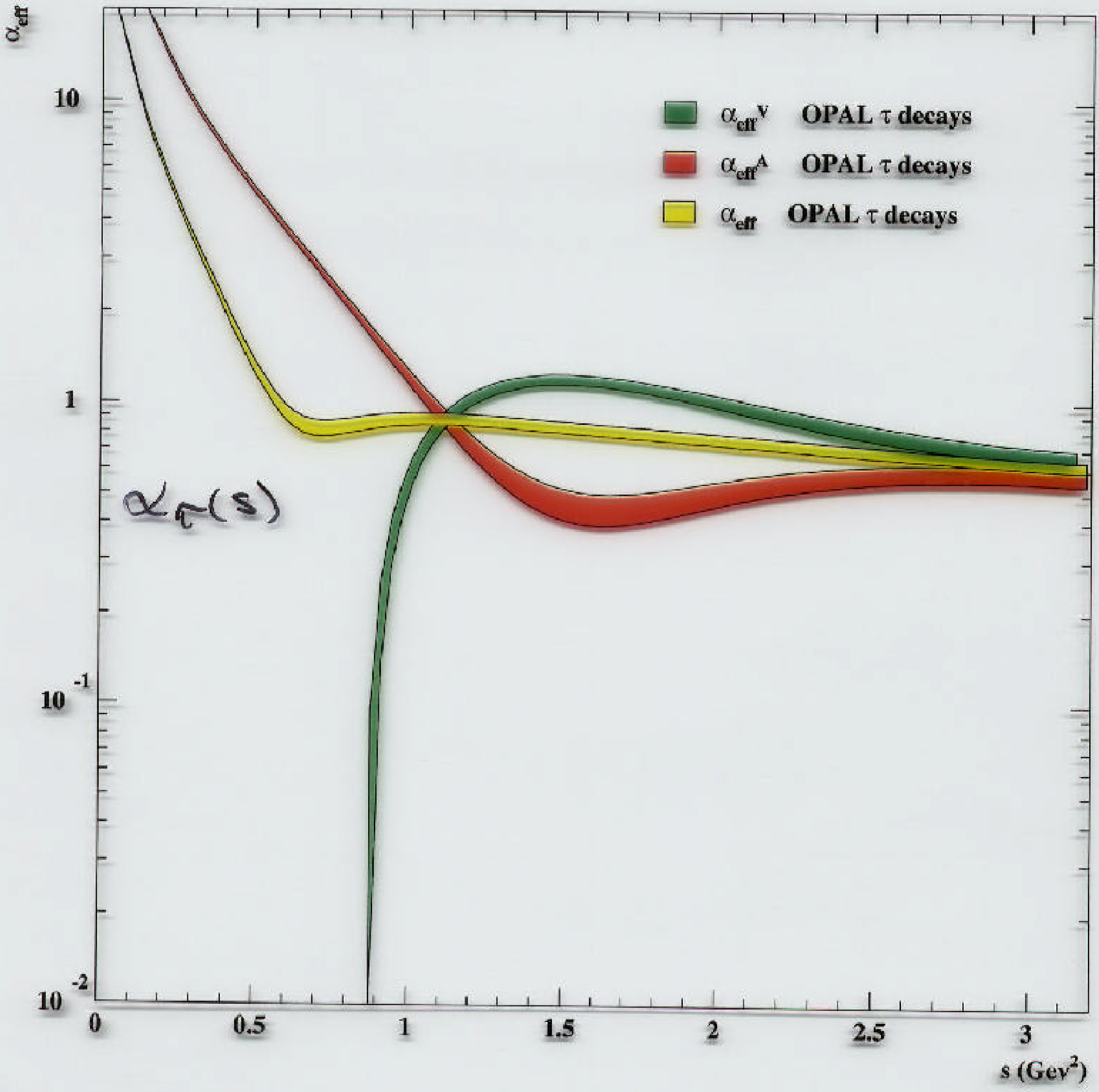
   from dynamical suppression of w.f.

   and Sudakov suppression



R_τ
R_τ^V OPAL
R_τ^A OPAL
R_τ OPAL
s (Gev^2)

S. Menke
(prelim)



$\alpha_\tau \sim$ flat
~ 1
not .3 to .4

Effective Charges:

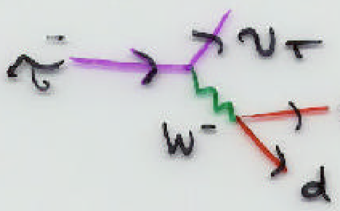
Define $\alpha_s(Q^2)$ from single observable

Elim $\overline{MS}$: relate observables

e.g.:

$$R_{e^+e^-}(s) \equiv R_0(s)\left[1 + \frac{\alpha_R(s)}{\pi}\right]$$

* $BR(\tau \to \text{hadrons} + \nu_\tau) \equiv (BR)_0\left[1 + \frac{\alpha_\tau(m_\tau^2)}{\pi}\right]$

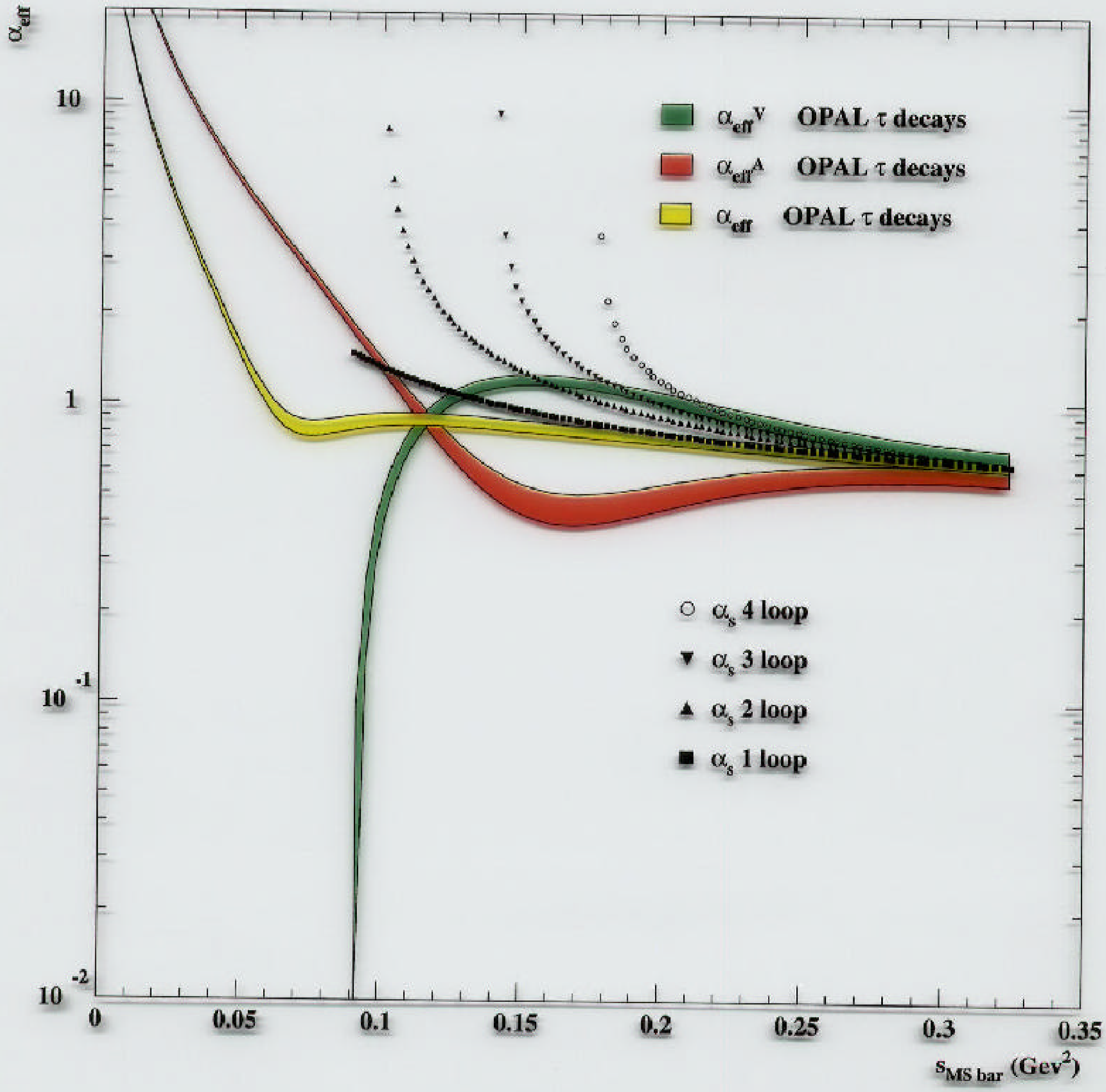


→ hadrons (V, A)

S. Menke: Isolate all channels
(OPAL) Separate V, A, $s\bar{u}$

* $\alpha_\tau(s)$ Obeys standard RGE
β_τ: known to 3-loops

Menke, Merino, SJB



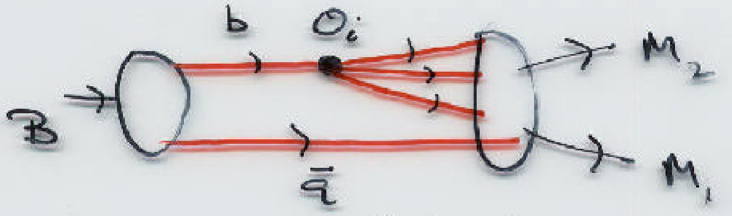
α_{eff}
10
1
10^{-1}
10^{-2}
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
α_{eff}^V OPAL τ decays
α_{eff}^A OPAL τ decays
α_{eff} OPAL τ decays
α_s 4 loop
α_s 3 loop
α_s 2 loop
α_s 1 loop
$s_{MS\ bar}$ (Gev^2)

QCD Factorization for Exclusive B-decays

Beneke
Buchalla
Neubert
Sachrajda

$B \to M_1 M_2$

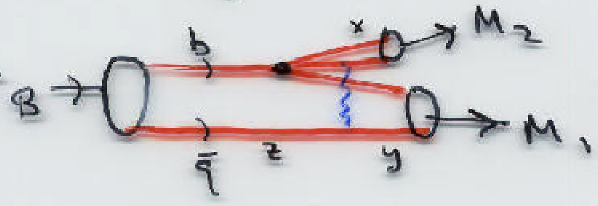
$\langle M_1(p_1)\, M_2(p_2) \,|\, O_i \,|\, B(p) \rangle$



$=$

I

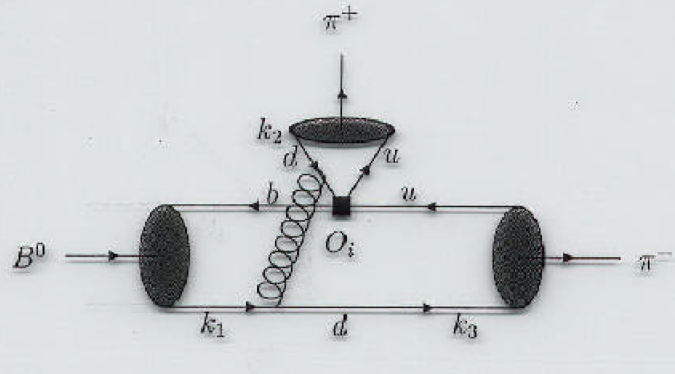
$+$



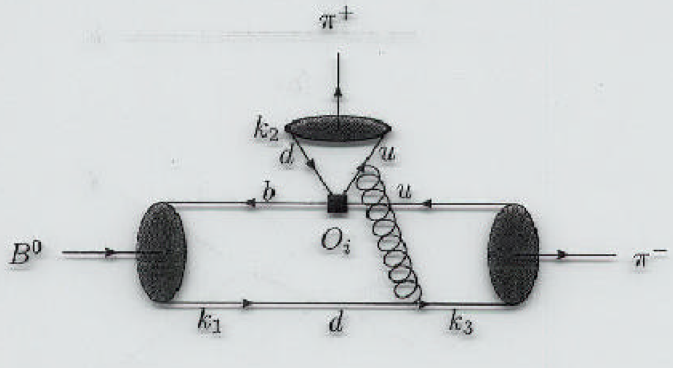
II

$$= F^{B\to M_1}(M_2^2) \int_0^1 dx\; T_i^{I}(x)\, \phi_{M_2}(x)$$

$$+ \int_0^1 dx \int_0^1 dy \int_0^1 dz\; T_i^{II}(x,y,z)\, \phi_{M_1}(x)\, \phi_{M_2}(y)\, \phi_B(z)$$



(a)

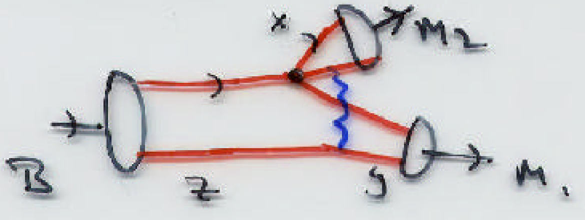


(b)

Essential Ingredients of BBNS

* $F^{B\to M_1}(M_2^2)$ measurable in semileptonic decays

Distribution amplitudes $\phi_{M_1}(x,Q)\ \phi_{M_2}(y,Q)\ \phi_B(z,Q)$



$T_i^{II} \sim \dfrac{1}{xyz}$

* Distribution amplitudes $\phi(x) \sim x^1$ at $x \to 0$.
$\therefore$ No endpoint singularities

* T_i^{I}, T_i^{II} Calculable in P.T.

Similar to $F_\pi(Q^2)$.

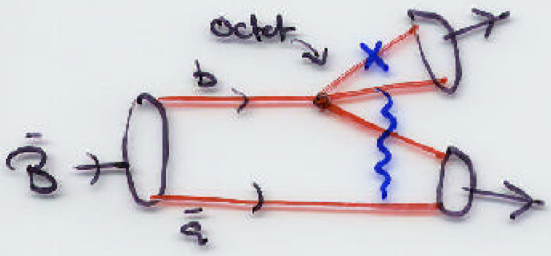
* $\phi_M(x)$ measurable in $MA \to$ Jet Jet X
and $\gamma\gamma \to M\bar{M}$, $\gamma^*\gamma \to M^0$, F_π, etc.

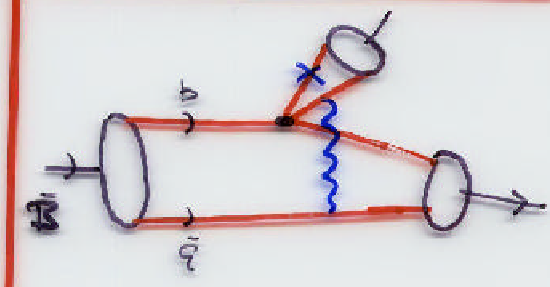
* $\phi_M(x,Q)$: log evolution known

* $\phi_M(x,Q)$: calculable in l.g.t., DLCQ

$$\boxed{B \to M_1 M_2}$$

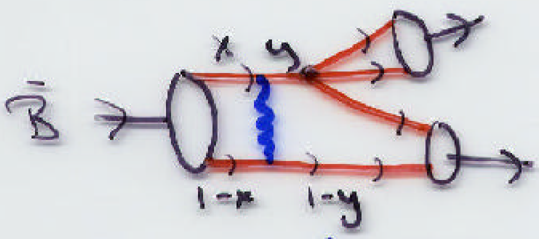
KLS'	BBNS'
non-factorizable PQCD calculable	non-factorizable PQCD calculable
Analyze in PQCD	factorizable non-perturbative relate to $B \to \ell\nu M$
PQCD calculable; possible large Im M from higher twist w.f.	Not computed.





non-factorizable
PQCD calculable

non-factorizable
PQCD calculable



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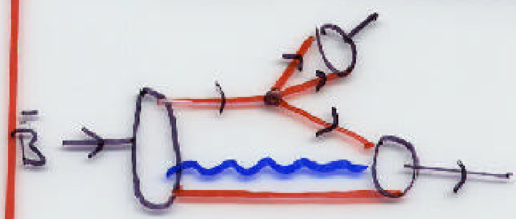


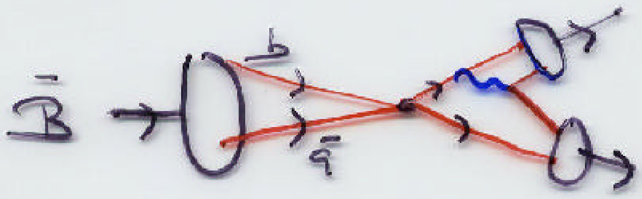
factorizable
non-perturbative
relate to $B \to \ell \nu M$

Henley
Szczepaniak
SJB

Analyze in PQCD

$$\int \frac{dy\, \phi(y)}{(1-y)^2}$$

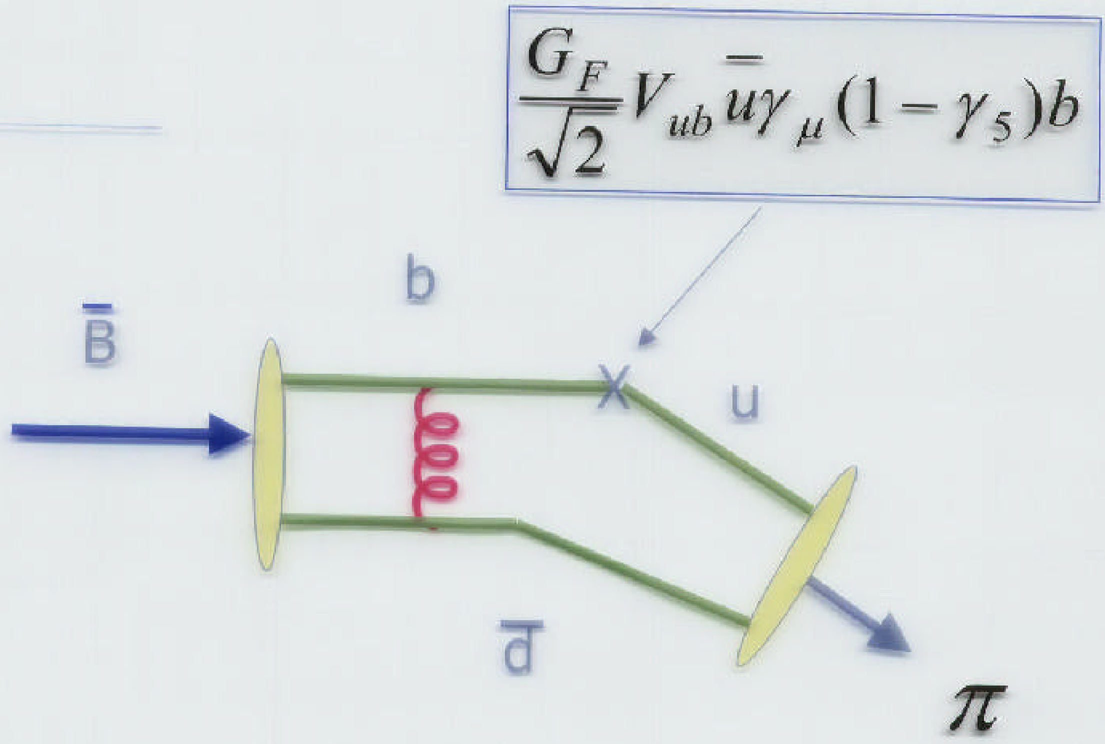
Li:
controlled
by Sudakov F.F. !



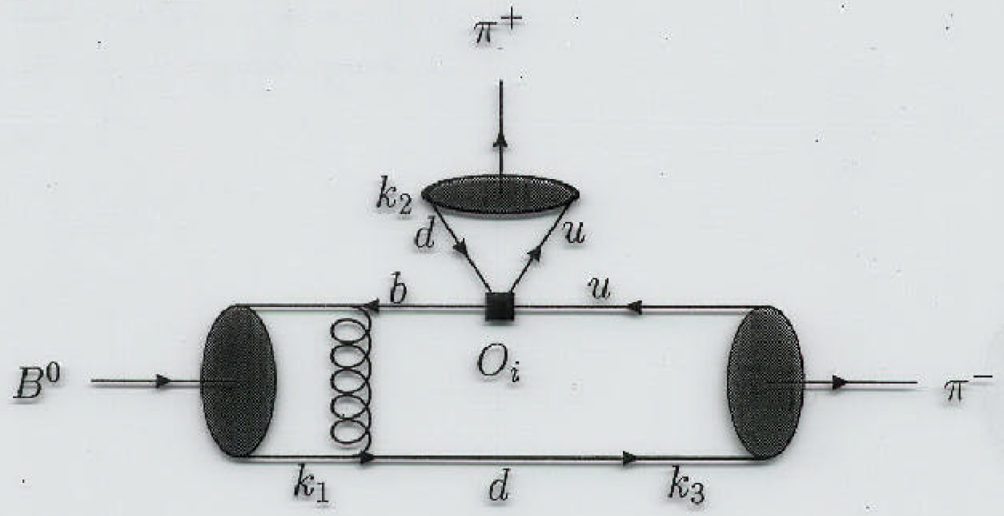
Not computed.

PQCD calculable
possible large Im M from higher twist w.f.

$B \to \pi$ transition form factor



$$\langle \pi(p_2) | \bar{u}\gamma_\mu (1-\gamma_5) b | B(p_1) \rangle$$
$$= \left[(p_1 + p_2)_\mu - \frac{M_B{}^2 - m_\pi{}^2}{q^2} q_\mu \right] F_1(q^2)$$
$$+ \frac{M_B{}^2 - m_\pi{}^2}{q^2} q_\mu F_2(q^2)$$

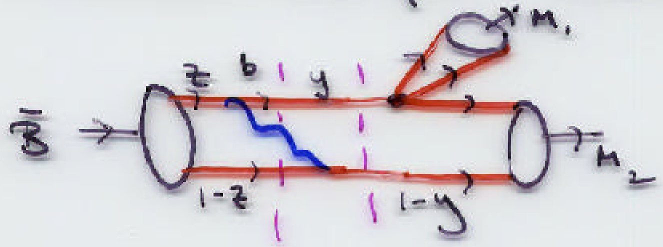


π^+
k_2
d
u
b
u
B^0
O_i
π^-
k_1
d
k_3

Li, Keum, Sanda

Comments on Applications of PQCD to $B \to M_1 M_2$

* Anomalous end-point behavior from



$\phi_{M_2}(y) \sim (1-y)$

$$\frac{1}{M_B^2 - \frac{m_b^2 + k_\perp^2}{y} + \dots} = \frac{-y}{M_B^2 (1-y) + k_\perp^2 + \dots}$$

Comes in twice!

* Integrable singularity

$$\int_0^1 dy \, \frac{\phi_{M_2}(y) \, S^1(k_\perp^2, y)}{\left[M_B^2 (1-y) + k_\perp^2 + \dots\right]^2}$$

Li

* Effective cutoff at $k_\perp^2 = M_B \Lambda_{QCD} \sim 1.5\,\text{GeV}^2$

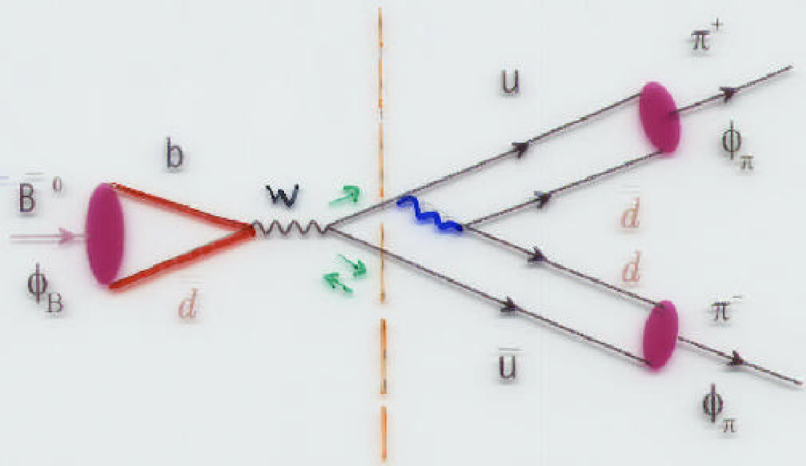
* PQCD at $1.5\ \text{GeV}^2$!

* $\alpha_s(1.5\ \text{GeV}^2) \sim 0.5$ to 1.0

* Enhanced Wilson coeff.

$\Rightarrow$ $\left.\begin{array}{l} F_{B \to M_2}(M_1^2) \\ \Gamma(B \to M_1 M_2) \end{array}\right\}$ in experimental range

KLS



The diagram which produces strong interaction phase -> CP violation

Li et al

Enhancement of Im part
from parallel helicity operator

Crucial input to Exclusive B-decays

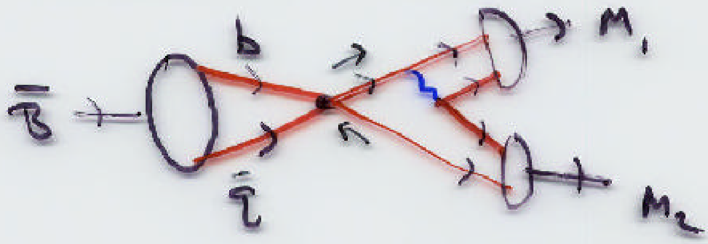
$$\phi_B(z),\ \phi_{M_1}(x),\ \phi_{M_2}(y)$$

at $\bar{k}_\perp^2 \sim \Lambda_{QCD} M_B \sim 1.5\ \mathrm{GeV}^2$

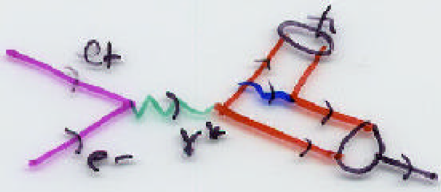
Universal distribution amplitudes:

* measure in $\gamma^* \to M\bar{M}$, $\gamma\gamma \to M\bar{M}$, ...

Annihilation Contribution



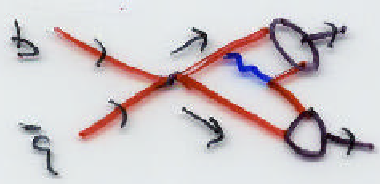
Similar to



at $Q^2 = (5\ \mathrm{GeV})^2$

Anomalous contributions from B-decay

Li et al



Sudakov controlled

anomalous Imaginary part

higher twist ϕ

Methods to obtain light-cone wavefunctions

* Diffractive Dissociation

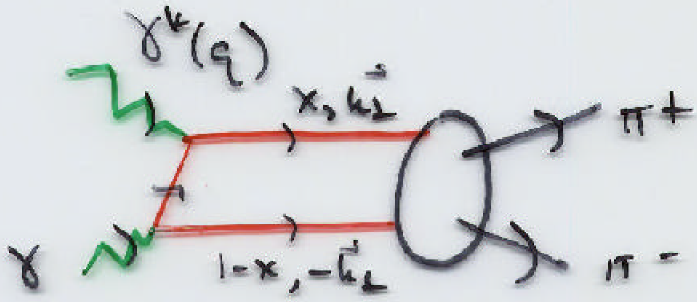
$$K^{+} A \to \text{Jet Jet } A$$

$$\frac{\partial^2}{\partial k_\perp^2} \psi_{q\bar{q}}(x, k_\perp)$$

* Discretized Light-Cone Quantization
* Bethe-Salpeter / Schwinger-Dyson
* Equal Time plus boosts
* QCD Sum Rules plus Conformal Expansion
* Lattice Gauge Theory Moments
* Evolution from low scales
* Evolution from reduced QCD (1+1)
* Spin construction from Jz conservation

Use $\gamma^* \gamma \to M \bar{M}$

to predict B-decays

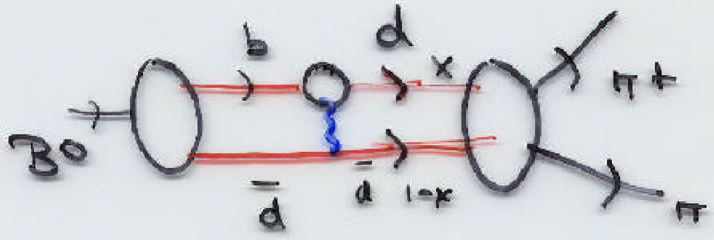


$k_\perp^2 < (1-x)\, Q^2$

Measures

$$\frac{1}{Q^2} \int_0^1 \frac{dx}{1-x}\ \phi_{\pi^+\pi^-}(x, k^2_{\perp max}; M^2_{\pi\pi}$$

M. Diehl et al



Measures $\phi_{\pi^+\pi^-}(x, k^2_{\perp max} = M^2_B, M^2_B)$

weighted by $\phi^B_{d\bar{d}}(x)$

Discretized Light-Cone Quantization

- program for solving quantum field theory

★ $\boxed{\text{Diagonalize } H_{LC}!}$

SJB + H.-C. Pauli
Eller, Hornbostel
Burkardt, Thorn
Hiller, McCartor

$$H_{LC}|\Psi\rangle = M^2|\Psi\rangle$$

$$\langle n|H_{LC}|m\rangle\langle m|\Psi\rangle = M^2\langle n|\Psi\rangle$$

$|n\rangle$: e.states of H^0_{LC}

★ Periodic, anti-periodic boundary conditions

$$k_i^+ = \frac{2\pi}{L} n_i \quad , \quad P^+ = \frac{2\pi}{L} K$$

$$\sum_i n_i = K \quad , \quad n_i > 0$$

Finite matrix repn of QFT

LFTD: Wilson, Perry, Glazek
Review: SJB, Pauli, Pinsky
Connection to M-theory: Susskind, Klebanov, Antonuccio et al