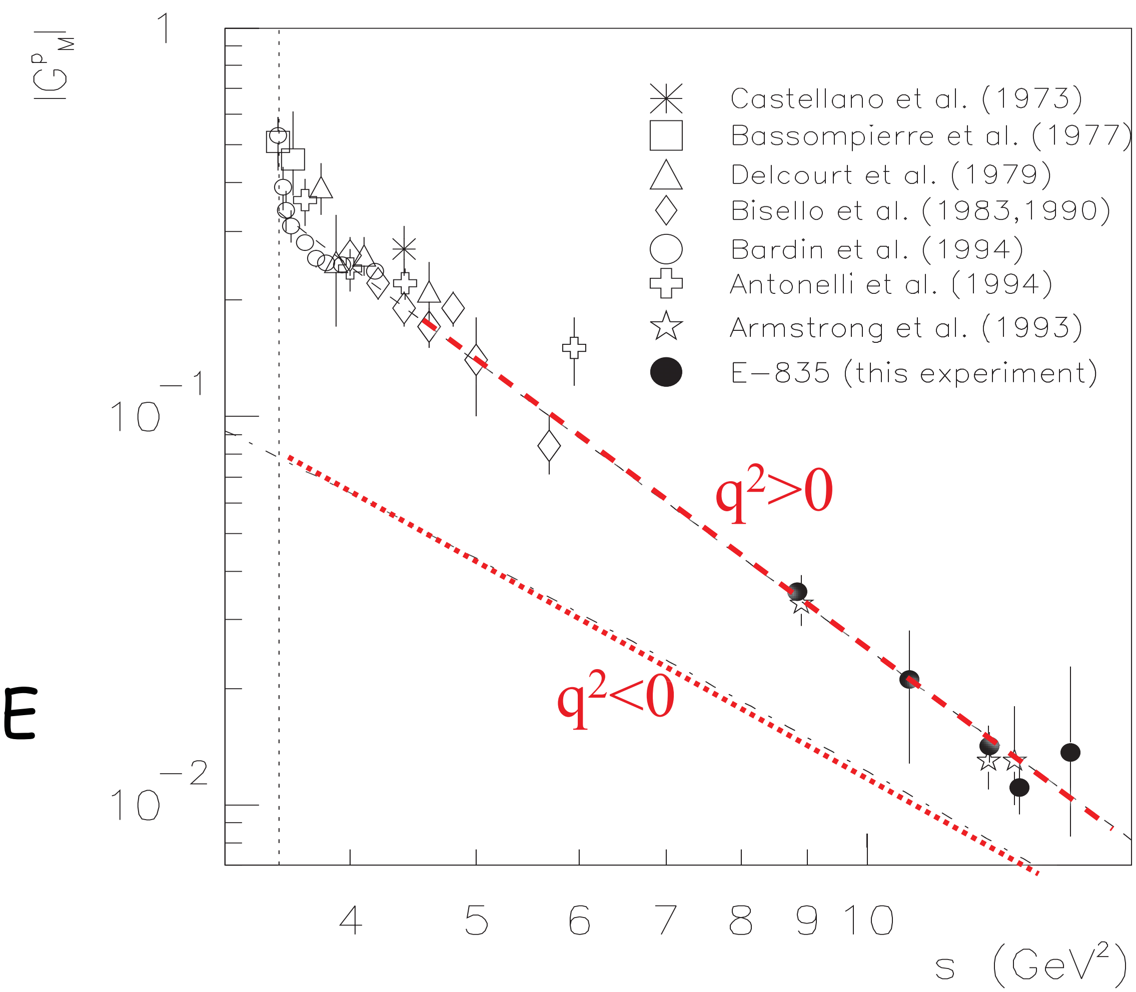
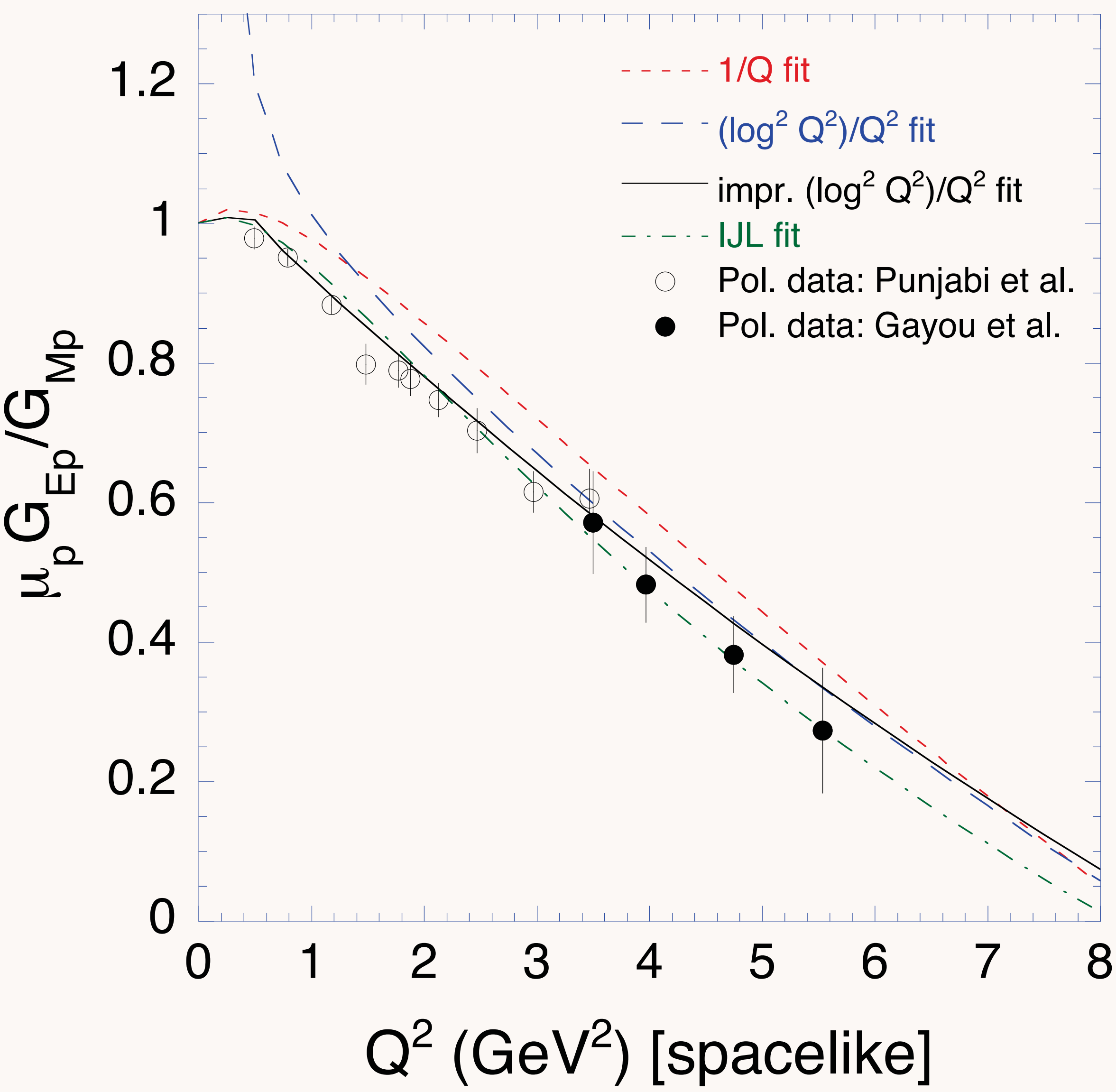
Time-like proton Formfactors at large q^2



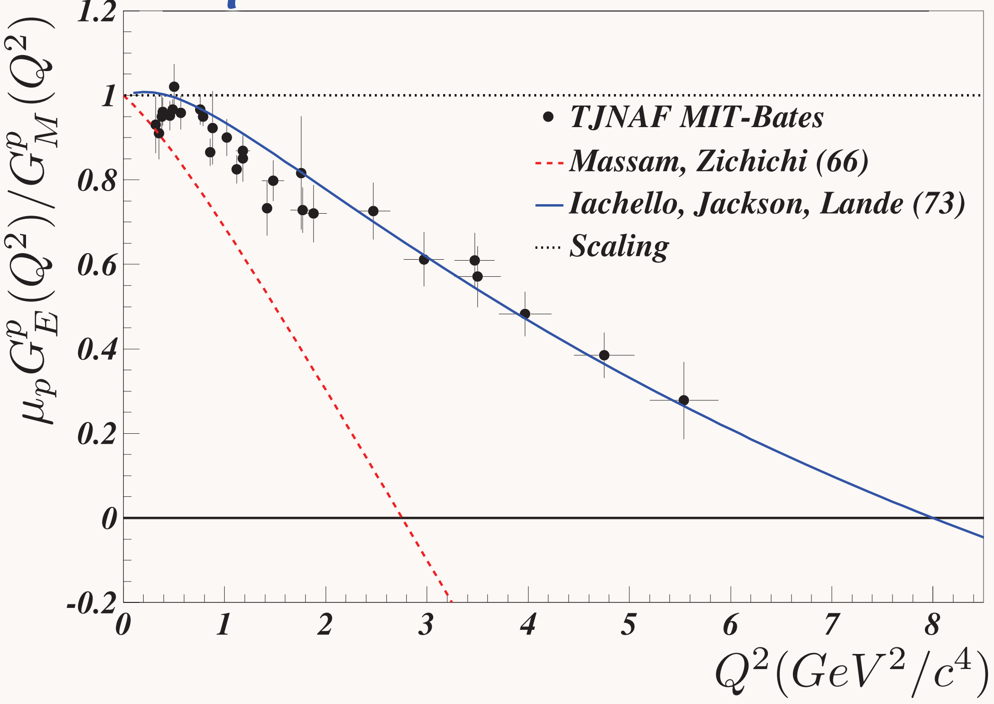
- separate GM and GE

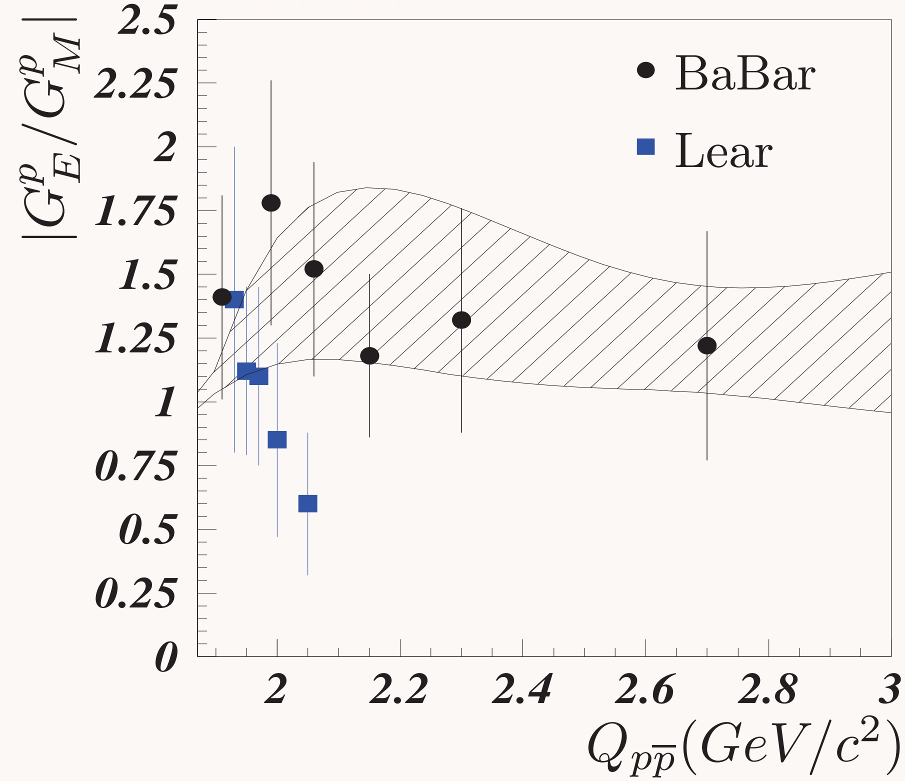
Michael Düren

Model Description of spacelike ratio



Space-like Ratio G_E^p/G_M^p Time-like Ratio

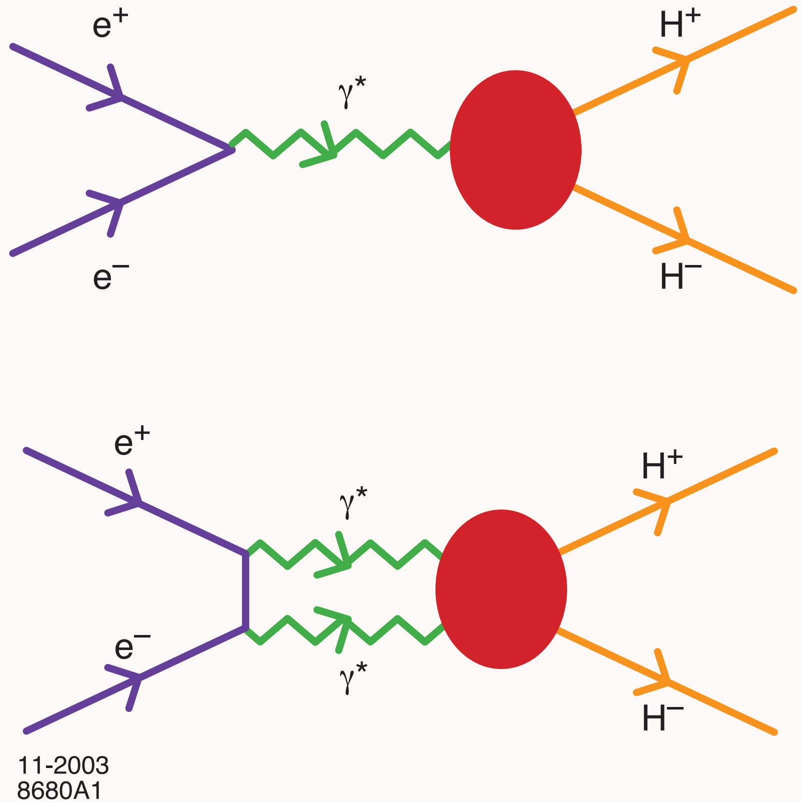




$$\frac{d\sigma(e^+e^-\to p\overline{p})}{d\cos\theta}=\frac{\pi\alpha^2\beta C}{2Q^2_{p\overline{p}}}\left[(1+\cos^2\theta)|G_M^p(Q^2_{p\overline{p}})|^2+\frac{4M_N^2}{Q^2}\sin^2\theta|G_E^p(Q^2_{p\overline{p}})|^2\right].$$

Expect same power law scaling in timelike and spacelike domain

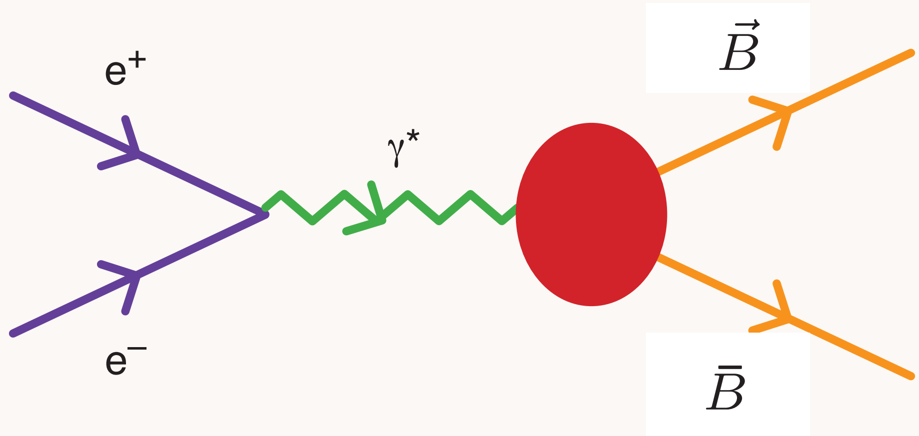
Study interference of one and two-photon contributions to exclusive processes



Believed to account for breakdown of Rosenbluth separation in spacelike scattering

Measure $p\bar{p}$ asymmetry in $e^+e^- CM$ Few %

T-odd single-spin asymmetry in Exclusive Hadron Pair Production



$T-$ odd single-spin asymmetry normal to the scattering plane in baryon pair production

Dubnickova, Dubnicka, Rekalo, Rock

$$e^- e^+ \to \vec{B}^{\updownarrow} \bar{B}$$

Carlson, Hiller, Hwang, sjb

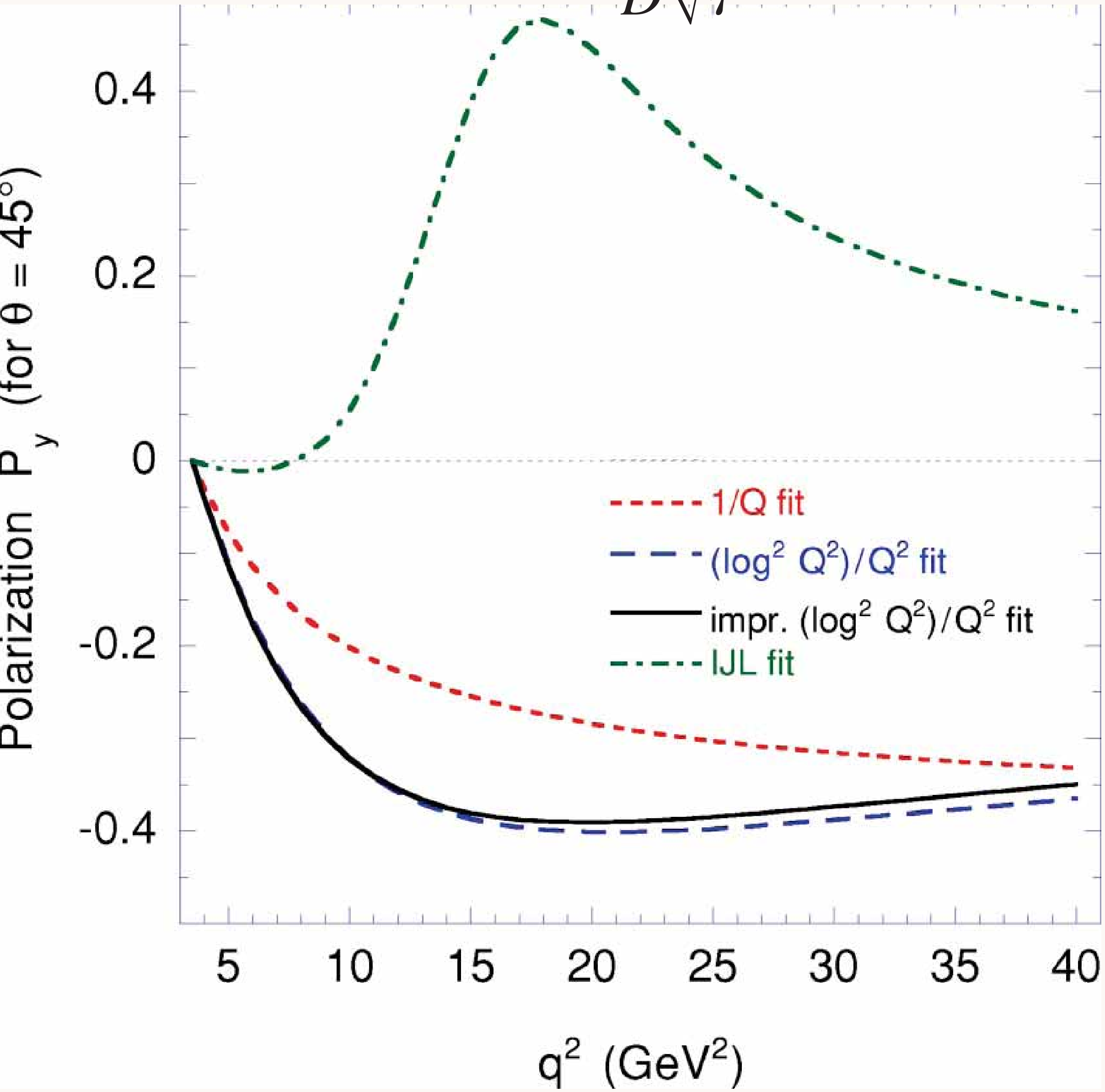
Requires a nonzero phase difference between the G_E and G_M form factors.

Complex phases of the form factors in the timelike region make it possible for a single outgoing baryon to be polarized

Single-spin polarization effects and the determination of timelike proton form factors

$$\mathcal{P}_y = \frac{\sin 2\theta \,\mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta \,\mathrm{Im}\, F_2^* F_1}{D\sqrt{\tau}}$$

Carlson, Hiller, Hwang, sjb



$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

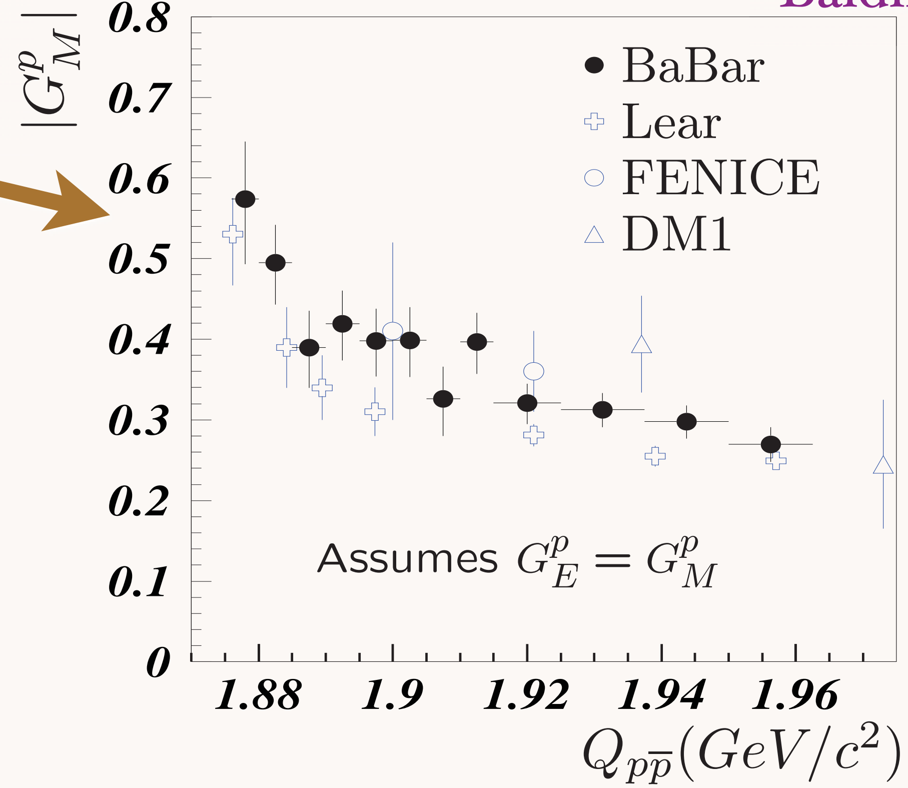
$$\tau \equiv q^2/4m_B^2$$

Measure relative phase of form factors

Baldini

Threshold enhancement at small velocity

$$e^+e^- \to p\bar{p}$$



Signal for dibaryon 4-quark resonance or hidden-color state?

Look for similar threshold enhancements in

$$e^+e^- \to B\bar{B}$$

$$e^+e^- \to \Lambda_b\overline{\Lambda_b}$$

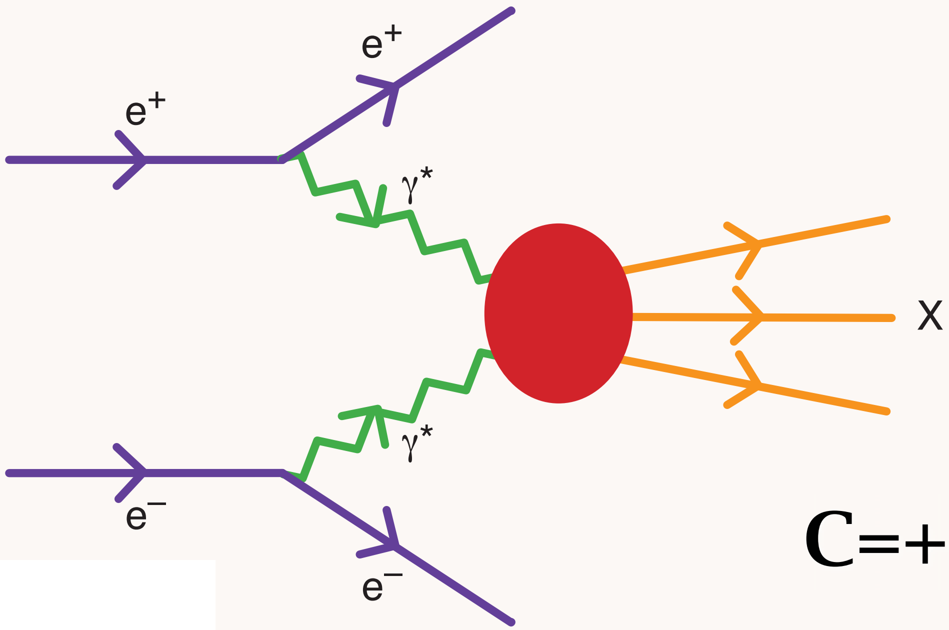
$$\gamma\gamma \to B\bar{B}$$

General principle:

Resonance formation at small relative velocity

Two-Photon Physics at BaBar

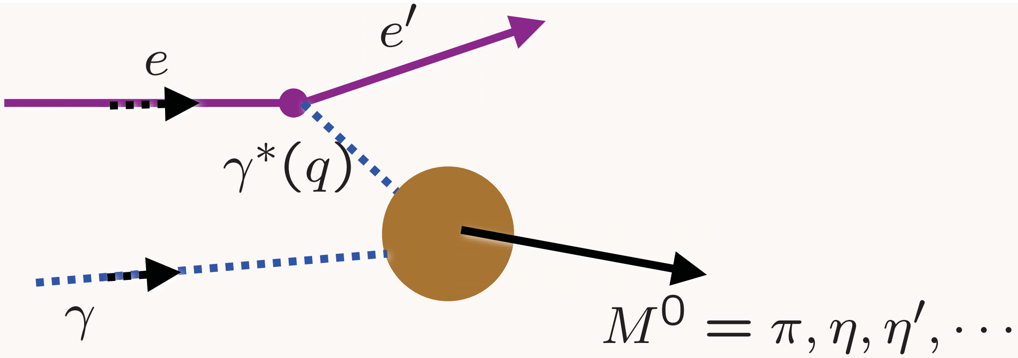
$$e^+e^- \to e^+e^- X$$



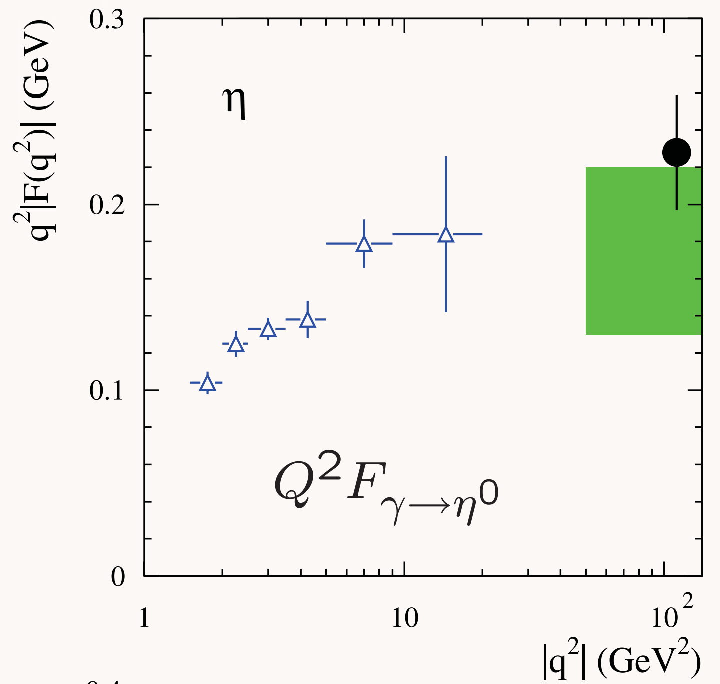
C=+ Hadron Final States

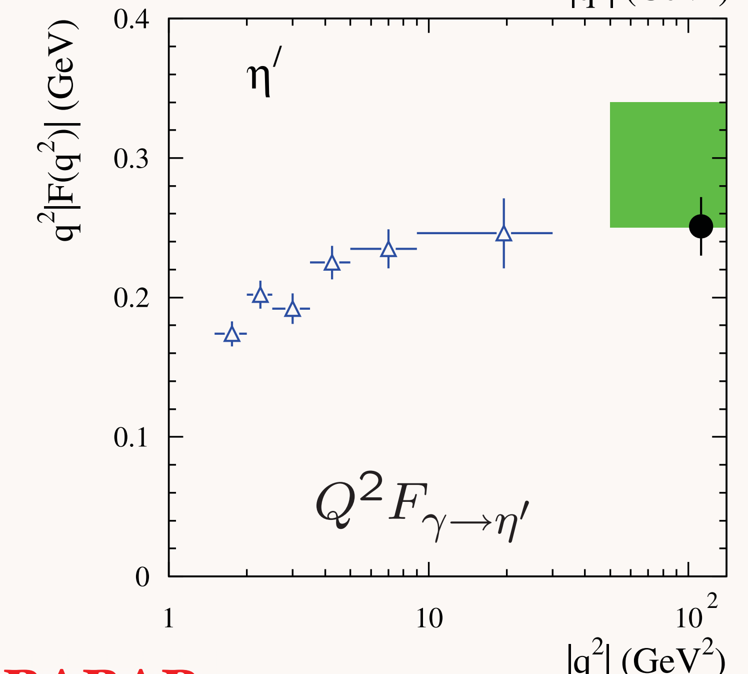
Tag one or both scattered leptons

$$\gamma^*\gamma^* \to X$$



BaBar PHYSICAL REVIEW D **74,** 012002 (2006)





$$\Gamma^\mu = -ie^2 F_{\pi\gamma}(Q^2)\epsilon^{\mu\nu\rho\sigma} p^\pi_\nu \epsilon_\rho q_\sigma$$

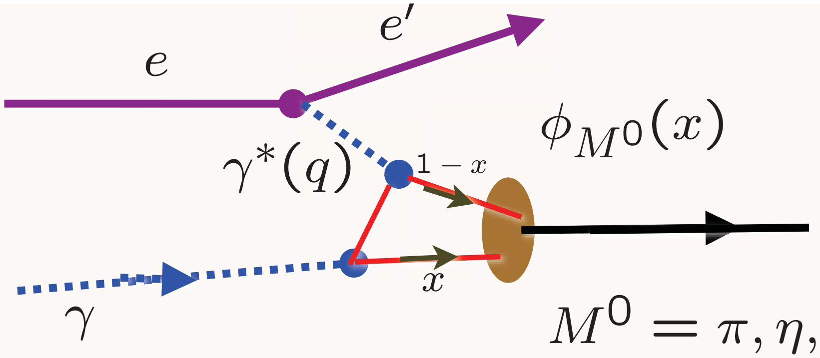
Simplest Exclusive QCD Test

PQCD Prediction

$$Q^2 F_{\gamma\pi}(Q^2) = 2 f_\pi \left(1 - \frac{5}{3}\frac{\alpha_V(Q^*)}{\pi}\right)$$

$$Q^* = e^{-3/2} Q$$

$$Q^2 F_{\gamma \to M^0} \to \text{const}$$



$$M^0 = \pi, \eta, \eta', \cdots$$

$$\Gamma^\mu = -ie^2 F_{\pi\gamma}(Q^2)\epsilon^{\mu\nu\rho\sigma} p^\pi_\nu \epsilon_\rho q_\sigma$$

PQCD Factorization

$$F_{\gamma M}(Q^2) = \frac{4}{\sqrt{3}} \int_0^1 dx \phi_M(x, \widetilde{Q}) T^H_{\gamma \to M}(x, Q^2)$$

$$T^H_{\gamma M}(x, Q^2) = [(1-x)Q^2]^{-1}(1 + \mathcal{O}(\alpha_s))$$

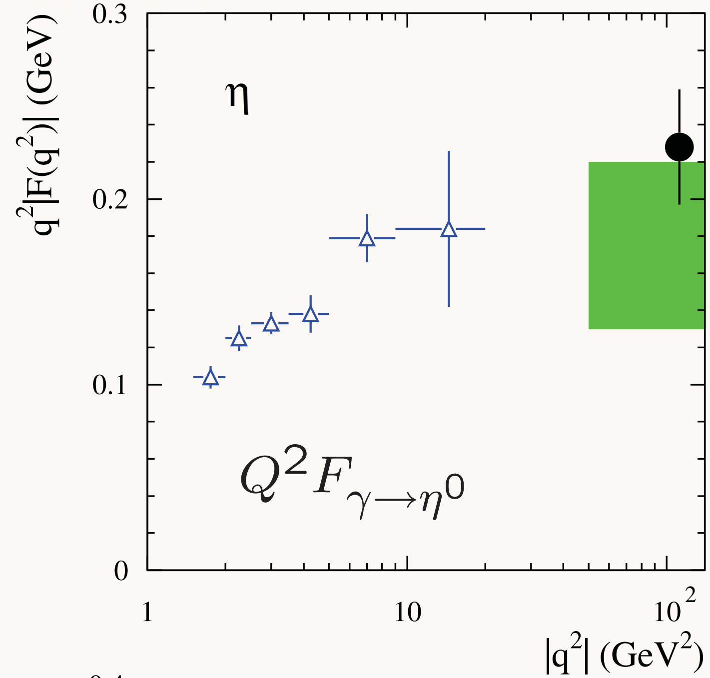
$$\phi_\pi^{\text{asympt}}(x) = \sqrt{3} f_\pi x(1-x)$$

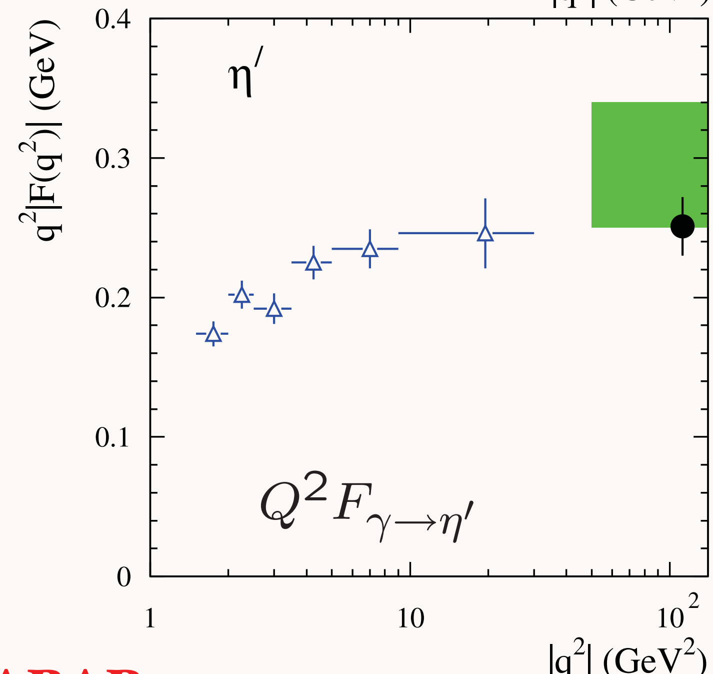
$$Q^2 F_{\gamma\pi}(Q^2) = 2f_\pi \left(1 - \frac{5}{3}\frac{\alpha_V(Q^*)}{\pi}\right)$$

$$Q^* = e^{-3/2} Q$$

Lepage, sjb

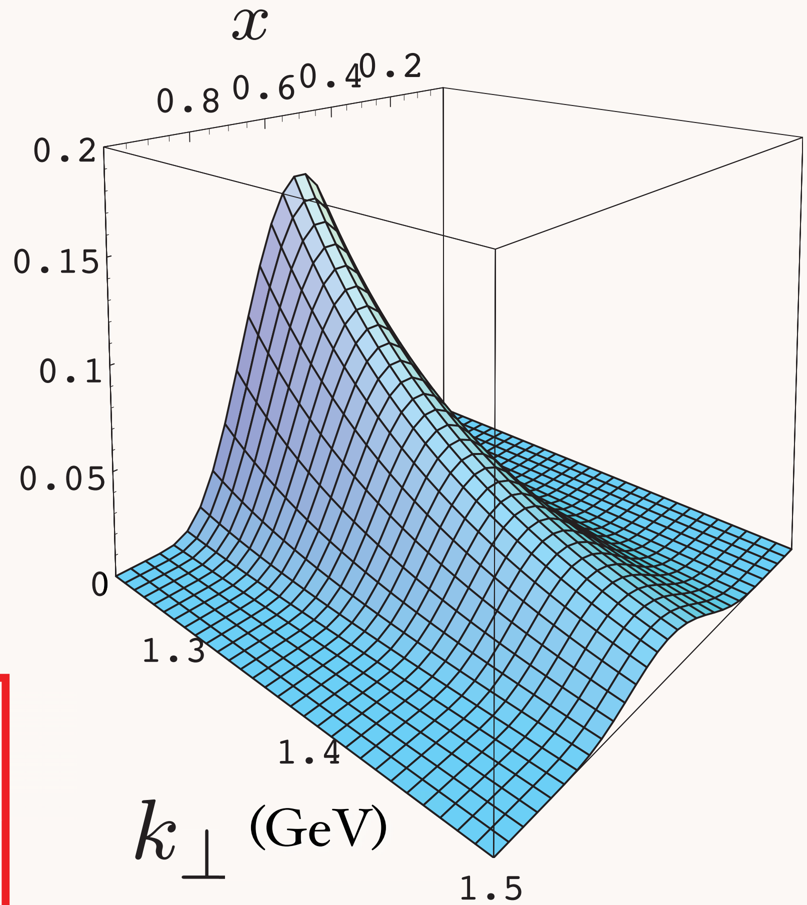
BaBar PHYSICAL REVIEW D **74**, 012002 (2006)





Prediction from AdS/CFT: Meson LFWF

de Teramond, sjb



$\psi_M(x, k^2_\perp)$

"Soft Wall" model

$\kappa = 0.375$ GeV

massless quarks

Note coupling
$k^2_\perp, x$

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k^2_\perp}{2\kappa^2 x(1-x)}}$$

$$\phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

Connection of Confinement to TMDs

Second Moment of Pion Distribution Amplitude

$$< \xi^2 >= \int_{-1}^{1} d\xi \ \xi^2 \phi(\xi)$$

$$\xi = 1 - 2x$$

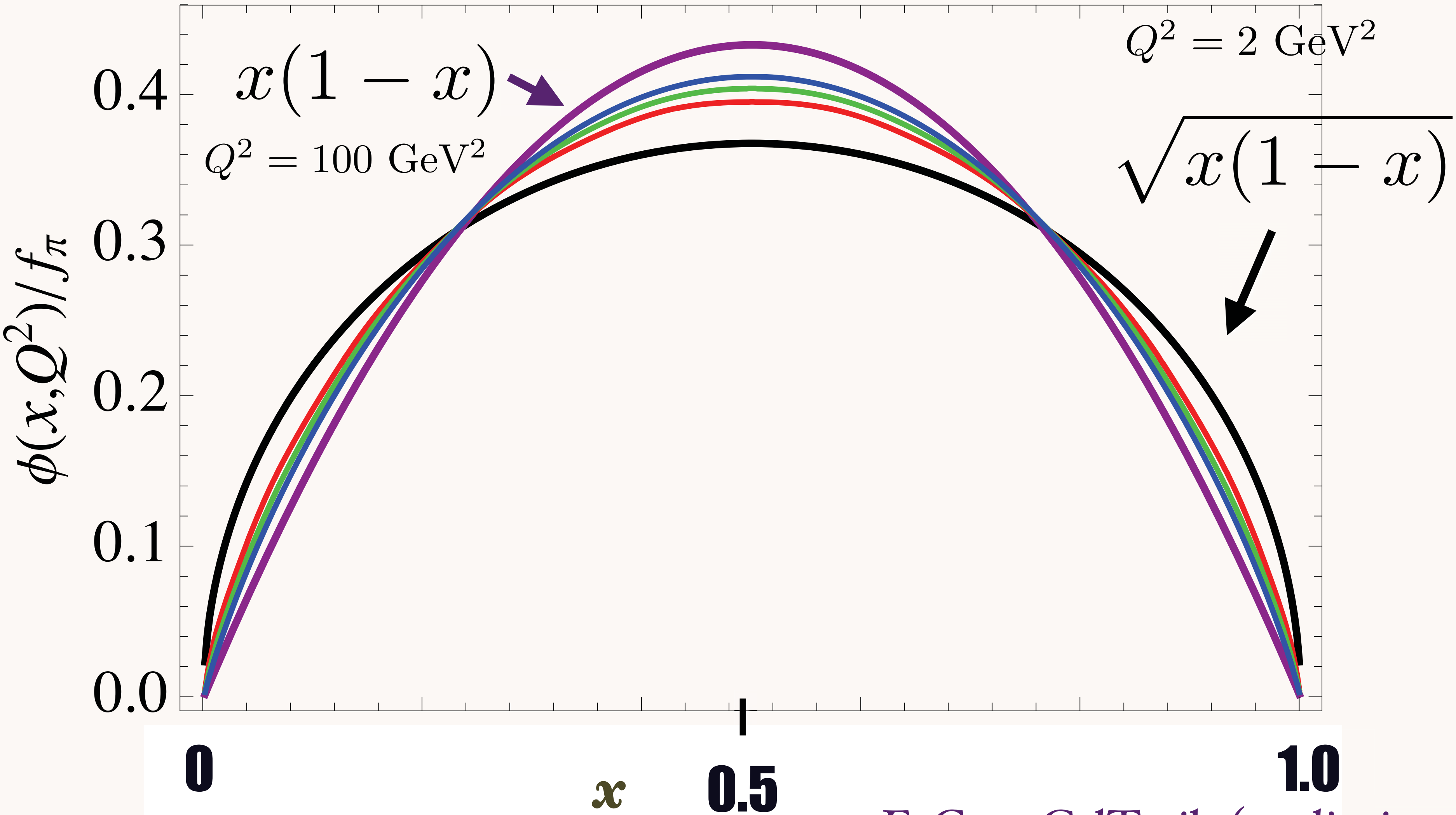
$$< \xi^2 >_\pi = 1/5 = 0.20 \qquad \phi_{asympt} \propto x(1-x)$$

$$< \xi^2 >_\pi = 1/4 = 0.25 \qquad \phi_{AdS/QCD} \propto \sqrt{x(1-x)}$$

Lattice (I) $< \xi^2 >_\pi = 0.28 \pm 0.03$ Donnellan et al.

Lattice (II) $< \xi^2 >_\pi = 0.269 \pm 0.039$ Braun et al.

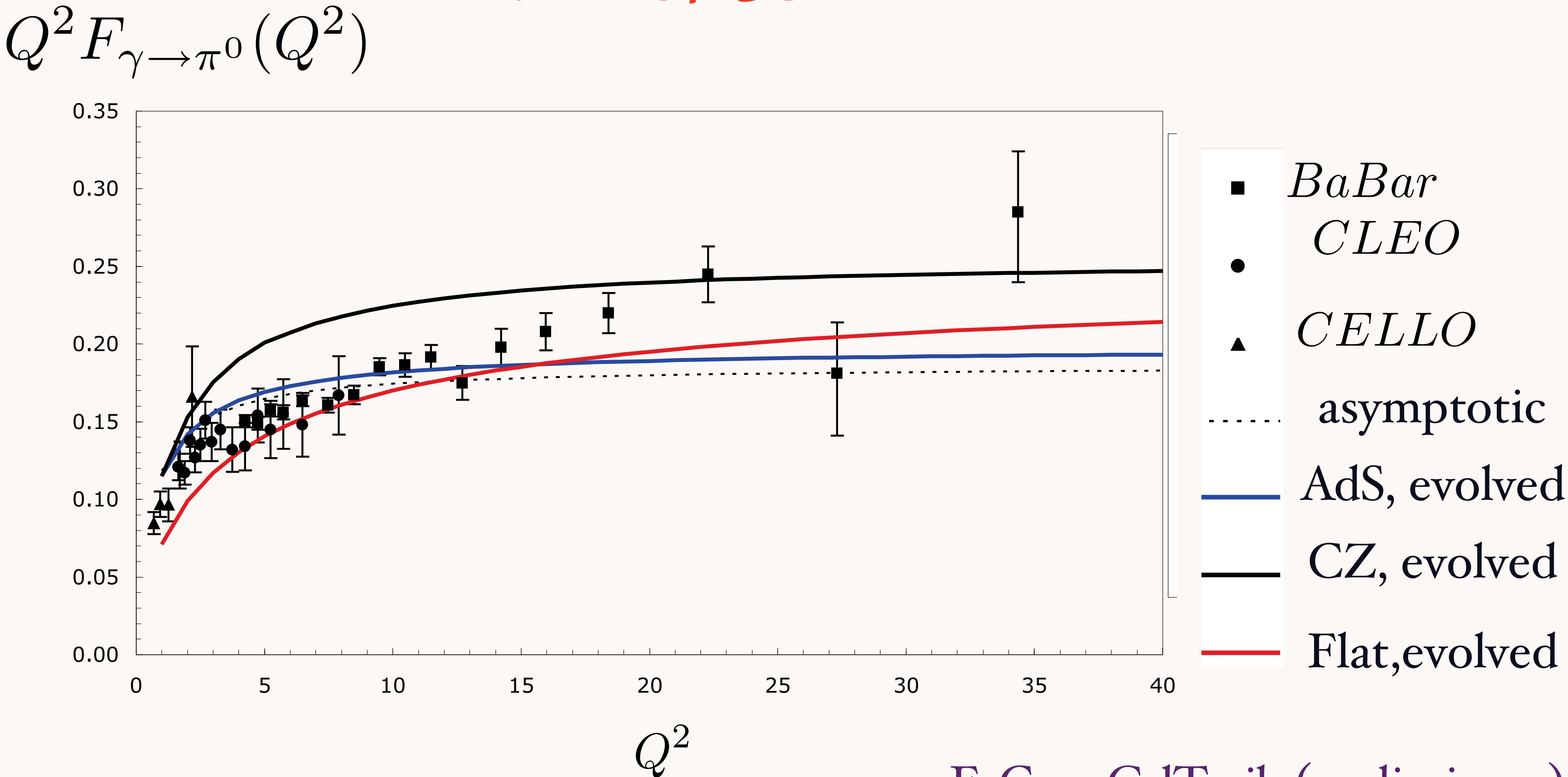
ERBL Evolution of Pion Distribution Amplitude



F. Cao, GdT, sjb (preliminary)

NLO: Diehl, Kroll

Photon-to-pion transition form factor with ERBL evolution

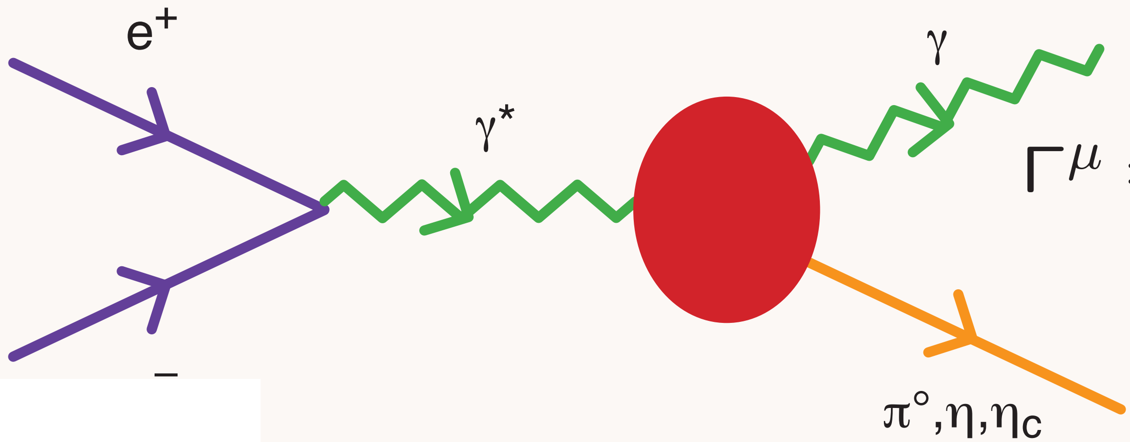


F. Cao, GdT, sjb (preliminary)

Double-virtual: important test!

Timelike Transition Form Factor

Simplest QCD Timelike Exclusive Channel

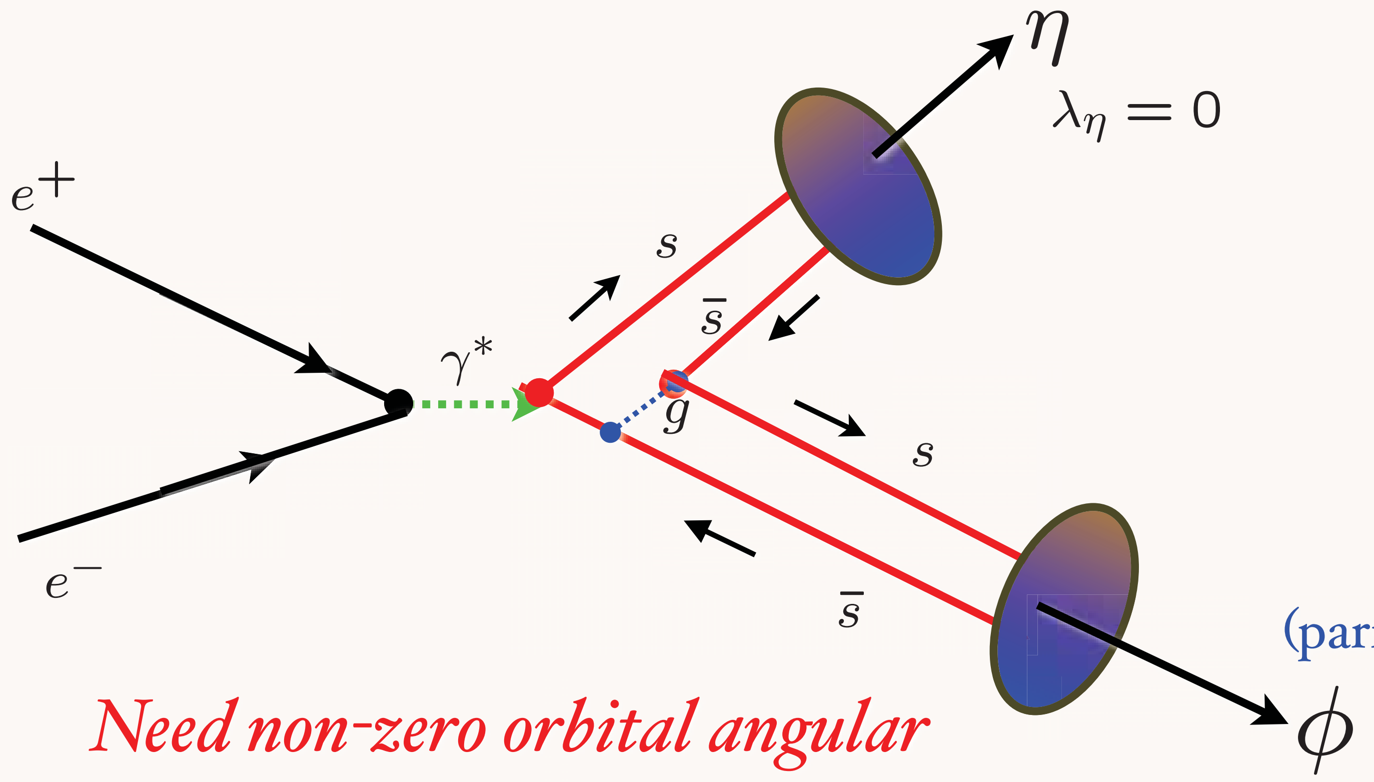


$$\Gamma^\mu = -ie^2 F_{\pi\gamma}(Q^2)\epsilon^{\mu\nu\rho\sigma} p_\nu^\pi \epsilon_\rho q_\sigma$$

Test scaling, normalization for light and heavy neutral mesons

Sensitive to shape of meson distribution amplitude

PQCD Analysis: Violation of Hadron Helicity Conservation in vector-pseudo scalar meson pair production



Related to

$J/\psi \rightarrow \rho\pi$

problem

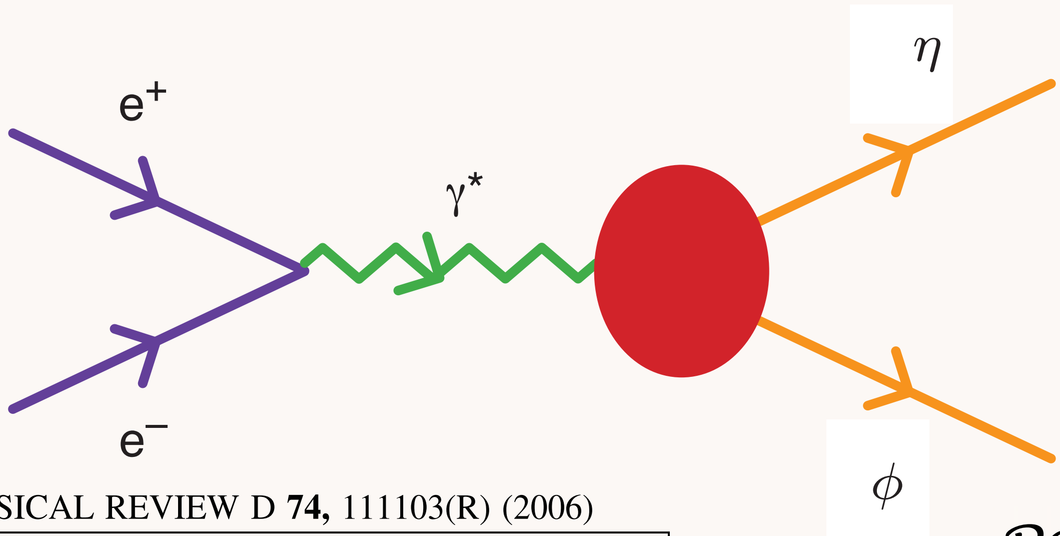
(parity conservation)

Need non-zero orbital angular momentum in meson LFWF

Predict extra power-law suppression (modulo logs)

$$\Delta\sigma_{e^+e^-\rightarrow\eta\phi}(s) \propto \frac{F^2_{\eta\phi}(s)}{s} \simeq \frac{1}{s^4}$$

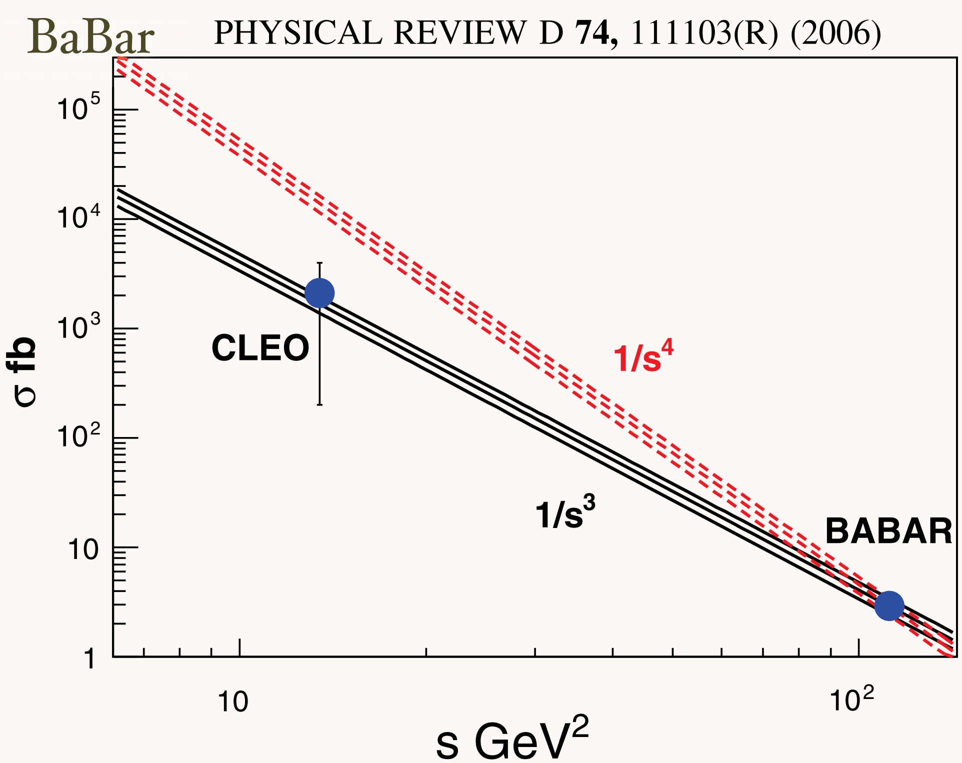
Exclusive Vector-Pseudoscalar Final States



Related to

$J/\psi \to \rho\pi$

problem



PQCD predicts

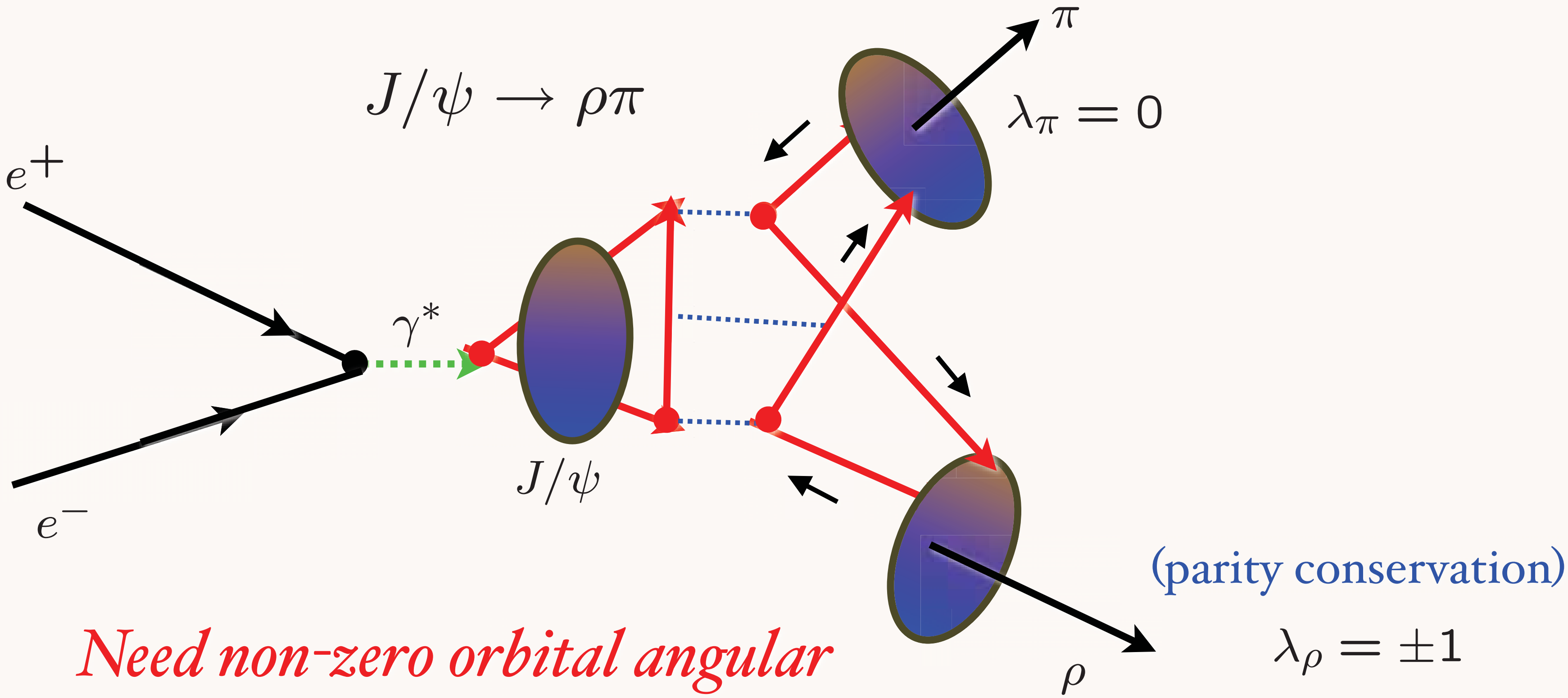
$$\Delta\sigma_{e^+e^-\to\eta\phi}(s) \propto \frac{F^2_{\eta\phi}(s)}{s} \simeq \frac{1}{s^4}$$

possible log enhancement ?

$$\frac{F_2(Q^2)}{F_1(Q^2)} \sim \frac{\log^2 Q^2}{Q^2}$$

$$\Delta\sigma_{e^+e^-\to\eta\phi}(s) \simeq \frac{(\log s)^N}{s^4}$$

PQCD Analysis: Violation of Hadron Helicity Conservation in vector-pseudo scalar meson pair production



Need non-zero orbital angular momentum in meson LFWF

Predict extra power-law suppression (modulo logs)

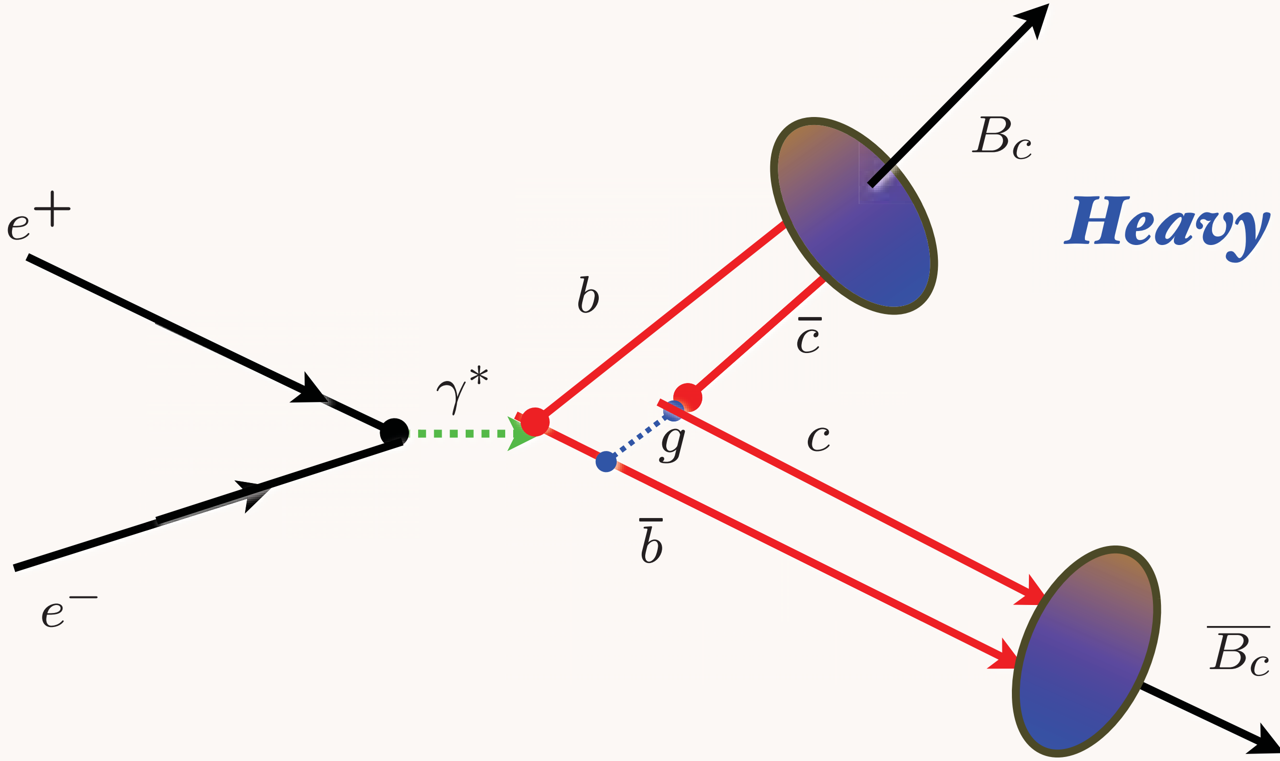
However $J/\psi \to \rho\pi$ is largest two-body hadron decay

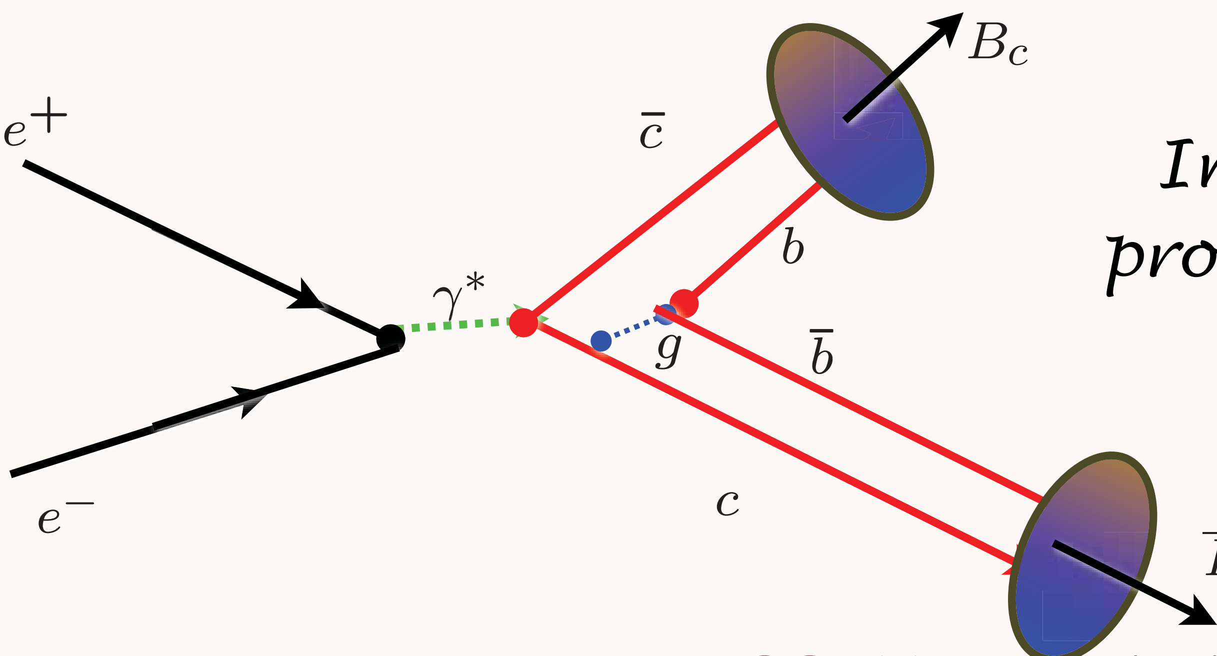
(1.69±0.15) %

Small value for $\psi' \to \rho\pi$

$(3.2 \pm 1.2) \times 10^{-5}$

Heavy Meson Pair Production

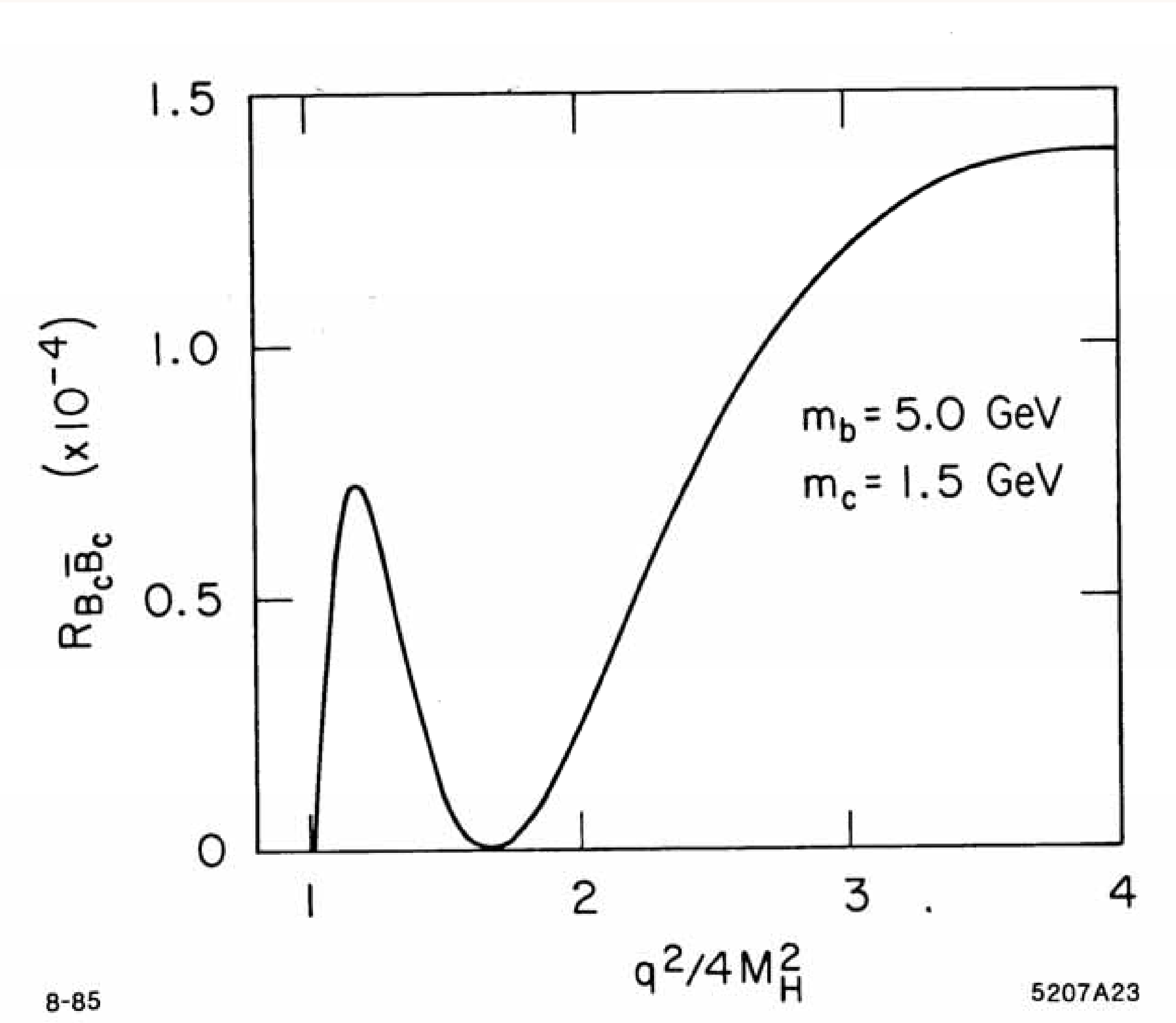




Interfering amplitudes produce form factor zero !

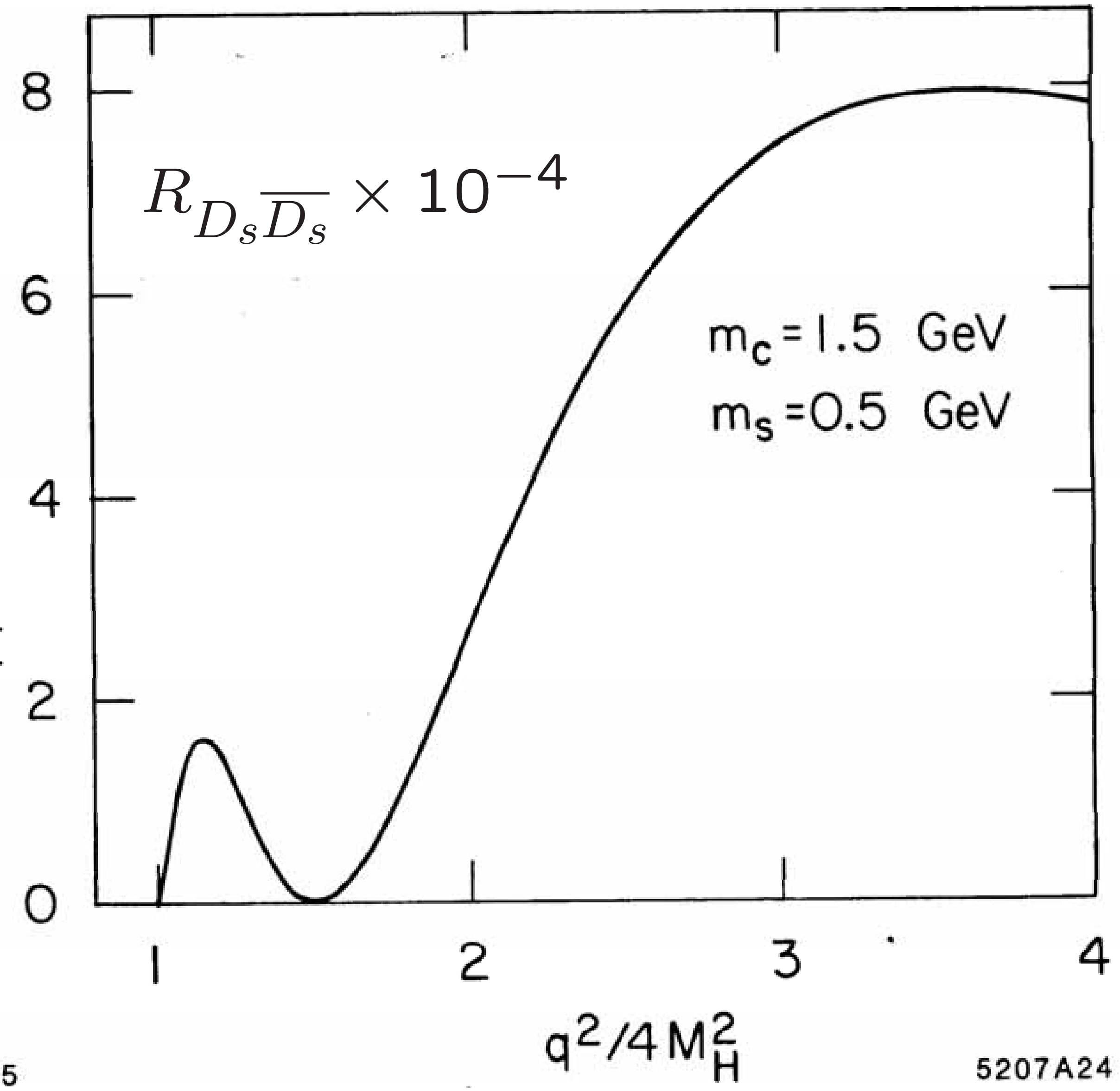
C-R Ji, sjb

C-R Ji, sjb



$$R_{B_c\overline{B_c}} = \frac{\sigma(e^+e^- \to B_c\overline{B_c})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

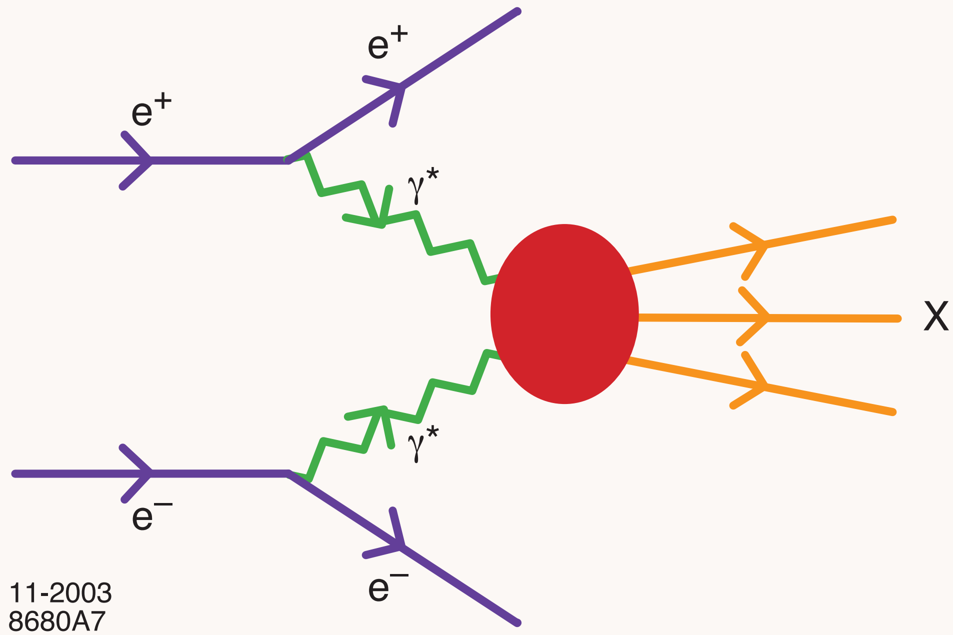
Interfering amplitudes produce form factor zero

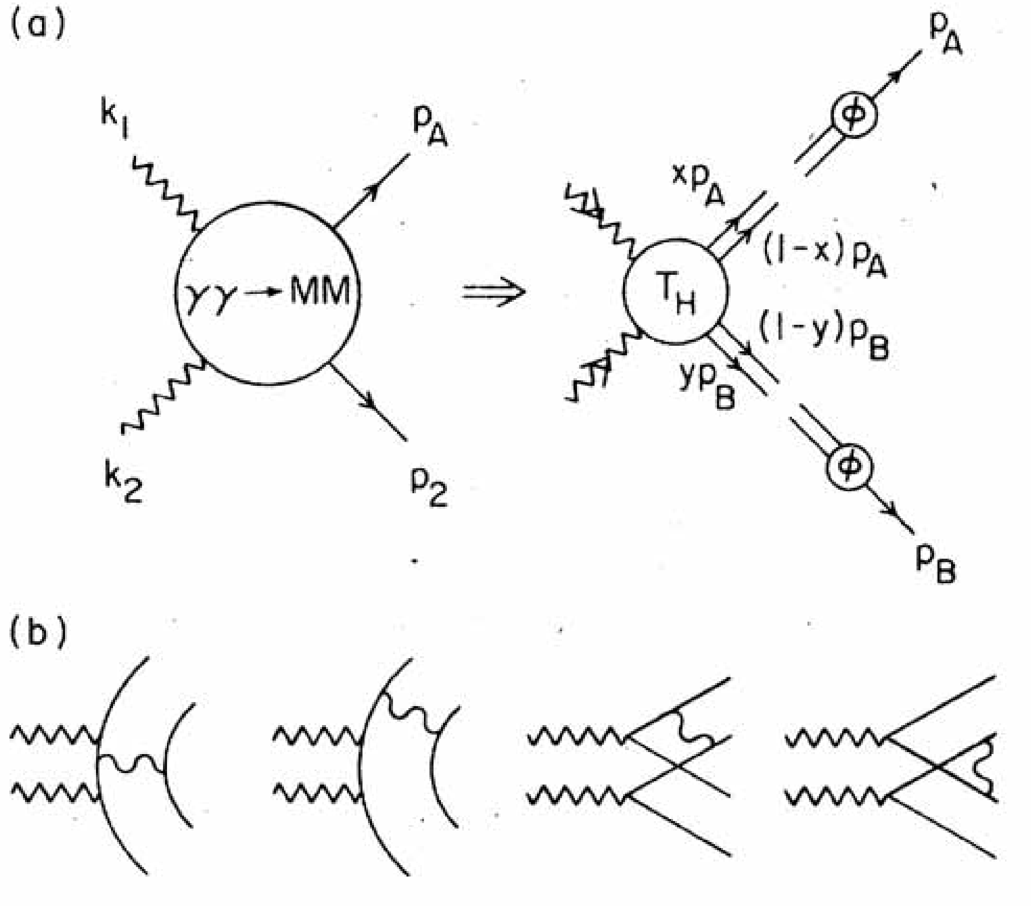


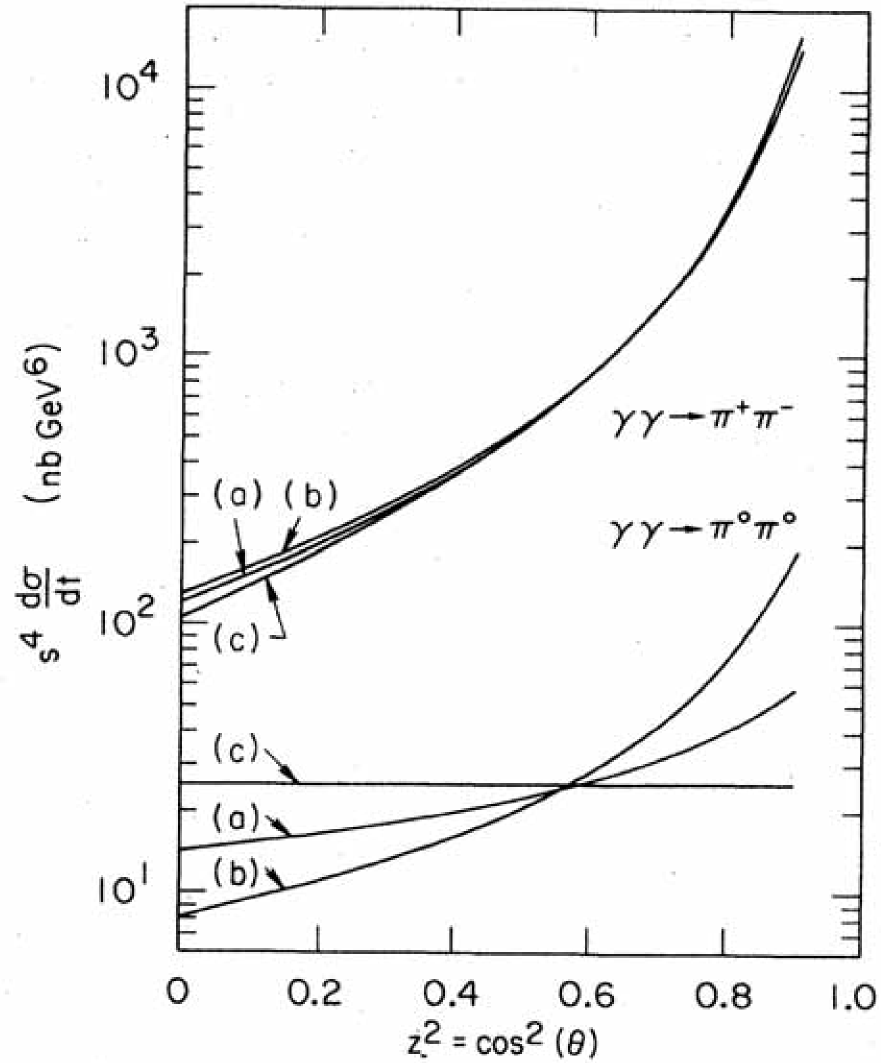
C-R Ji, sjb

$$R_{D_s\overline{D_s}} = \frac{\sigma(e^+e^-\to D_s\overline{D_s})}{\sigma(e^+e^-\to\mu^+\mu^-)}$$

Two-Photon Exclusive Channels

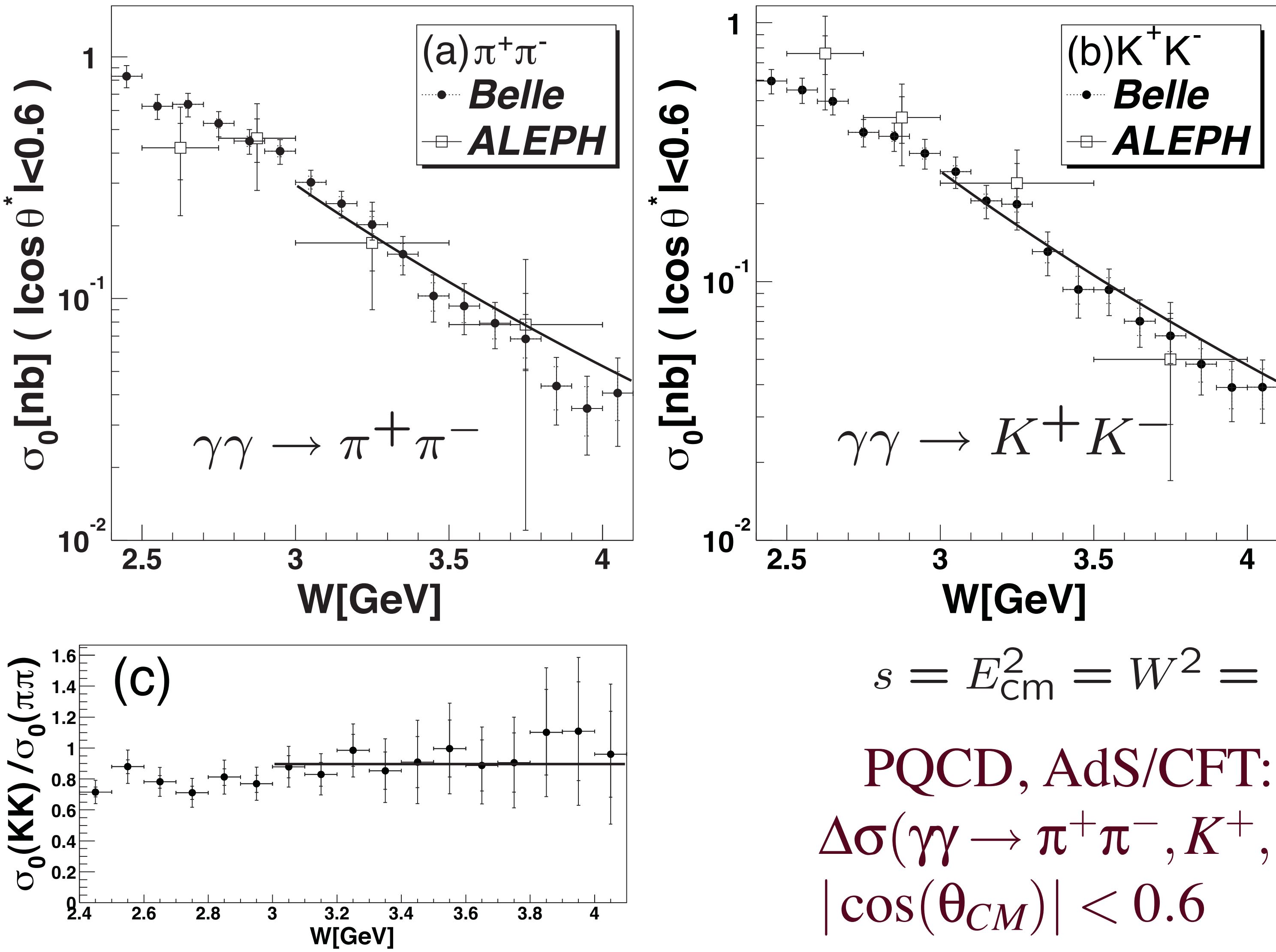






$$\frac{\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma \to \mu^+\mu^-)} \sim \frac{4|F_\pi(s)|^2}{1-\cos^4\theta_{c.m.}}$$

Crucial test: $\gamma\gamma \to \pi^0\pi^0$



Possible extension to very high invariant mass using LHC UPC

$$s = E^2_{\rm cm} = W^2 = Q^2$$

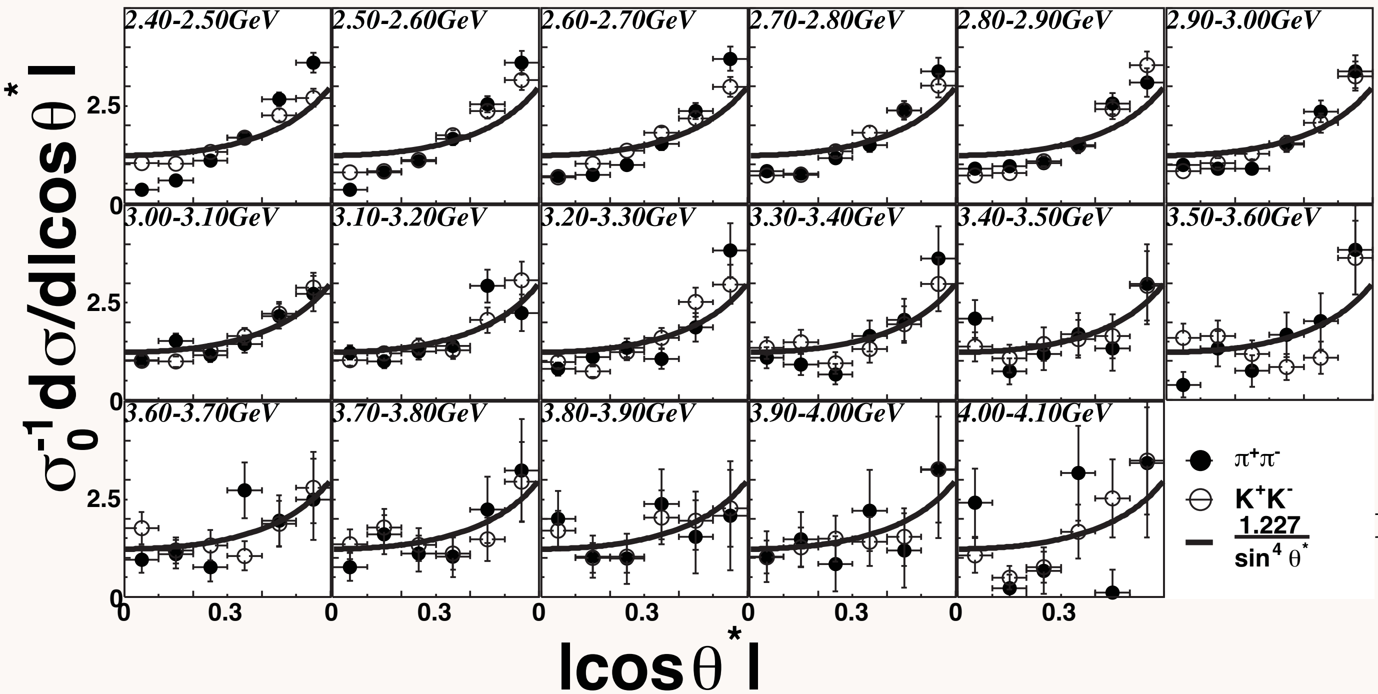
PQCD, AdS/CFT:

$$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$$

$$|\cos(\theta_{CM})| < 0.6$$

Fig. 5. Cross section for (a) $\gamma\gamma\to\pi^+\pi^-$, (b) $\gamma\gamma\to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above 3 GeV. The errors indicated by short ticks are statistical only.

$$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \approx \frac{16\pi\alpha^2}{s}\frac{|F_M(s)|^2}{\sin^4\theta^*},$$

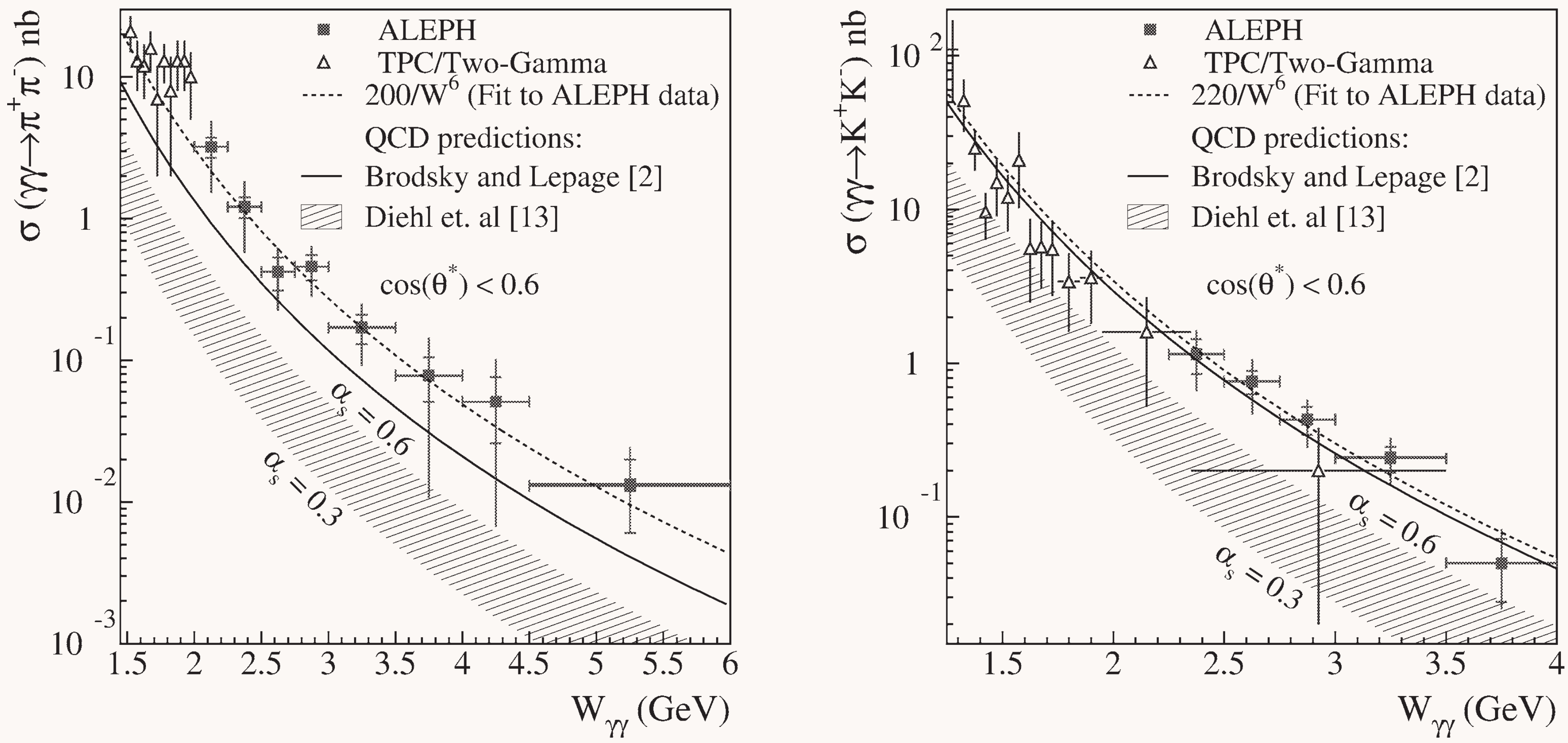


Measurement of the $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ processes at energies of 2.4–4.1 GeV

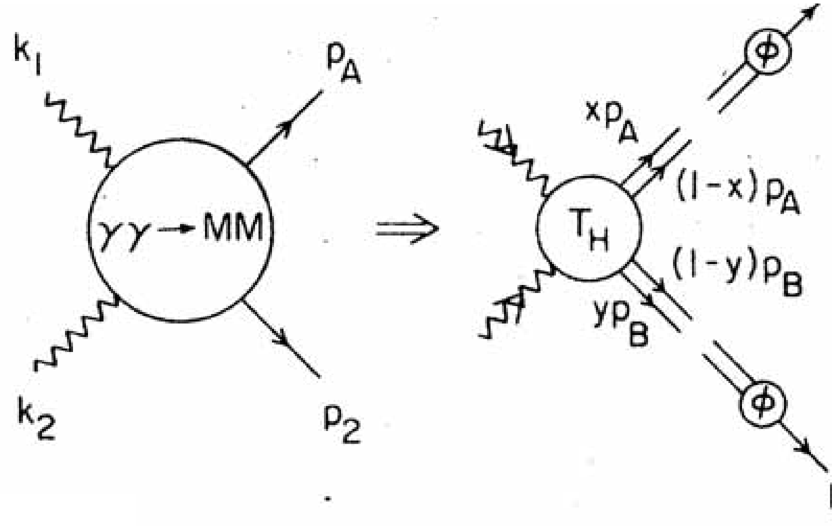
Belle Collaboration

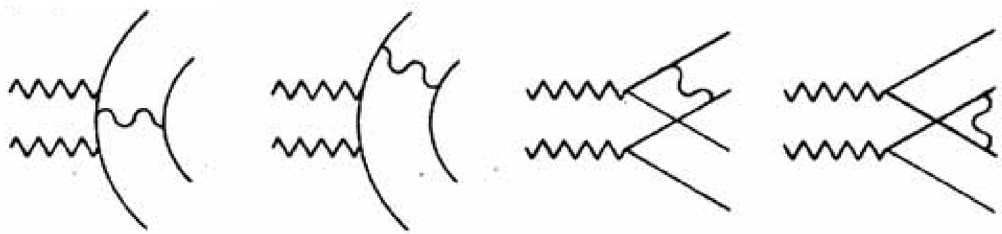
Angular dependence of the cross section, $\sigma_0^{-1}d\sigma/d|\cos\,\theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.

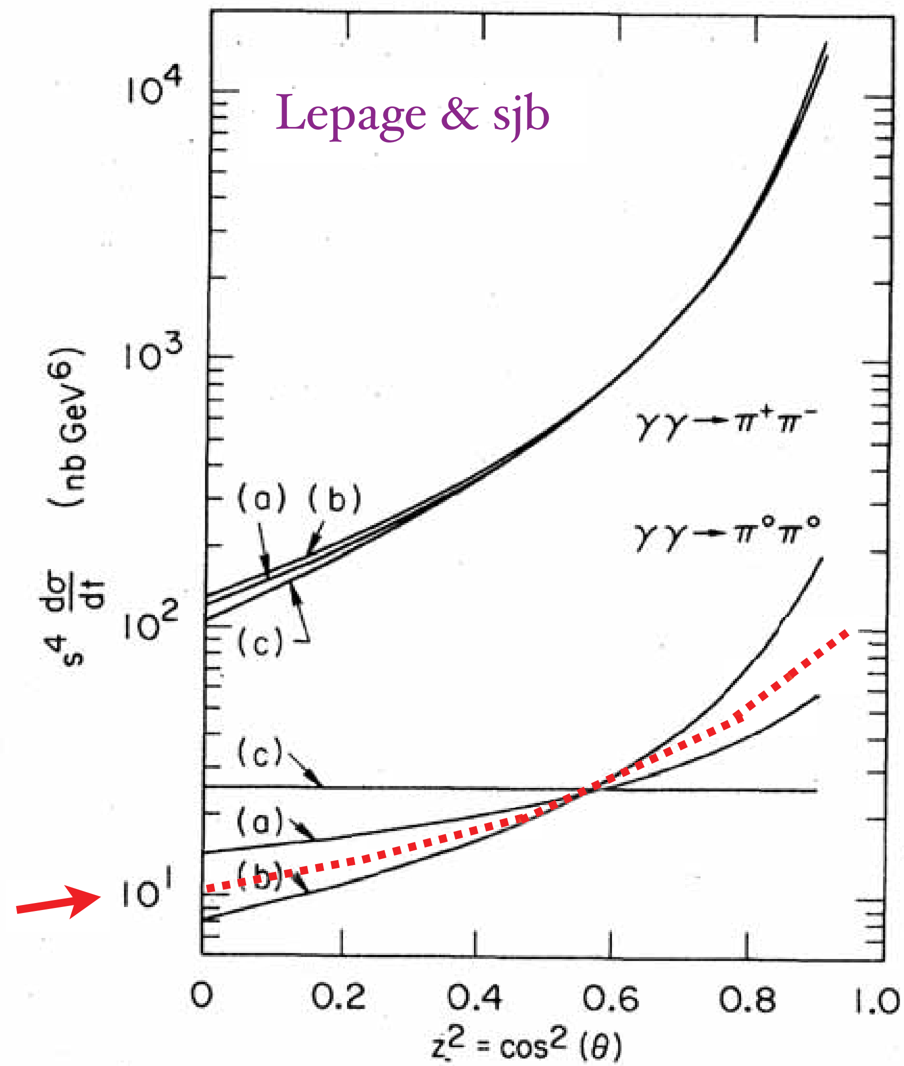
ALEPH Collaboration / Physics Letters B 569 (2003) 140–150



Measured distribution for $\gamma\gamma \to \pi^+\pi^-$ (left) and $\gamma\gamma \to K^+K^-$ (right) as a function of $W_{\gamma\gamma}$. Also shown are results from TPC/Two-Gamma], the result of a fit to the ALEPH data and a leading twist QCD calculation with two alternative normalizations as described in the text.







Neutral pair angular distribution sensitive to AdS/CFT distribution!

$$\phi_\pi^{AdS/QCD}(x) \propto [x(1-x)]^{1/2}$$

de Teramond & sjb

(a): $\phi_\pi(x) \propto x(1-x)$

(b): $\phi_\pi(x) \propto [x(1-x)]^{1/4}$

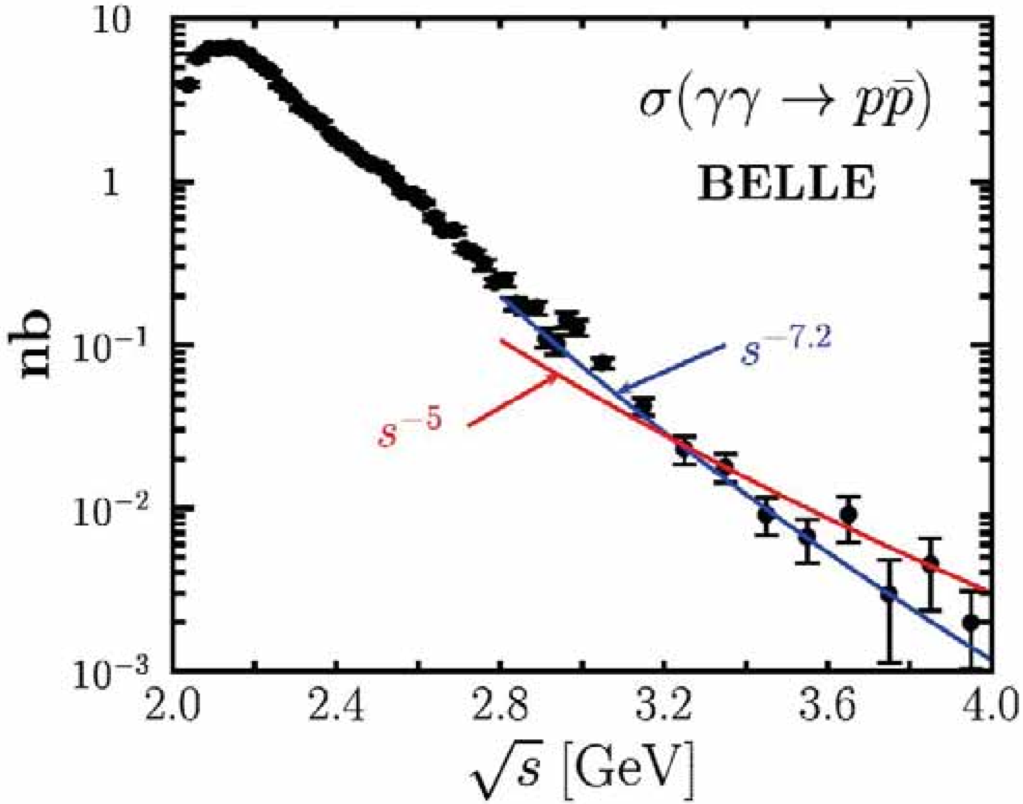
(c): $\phi_\pi(x) \propto \delta(x-1/2)$

Recent results from Belle

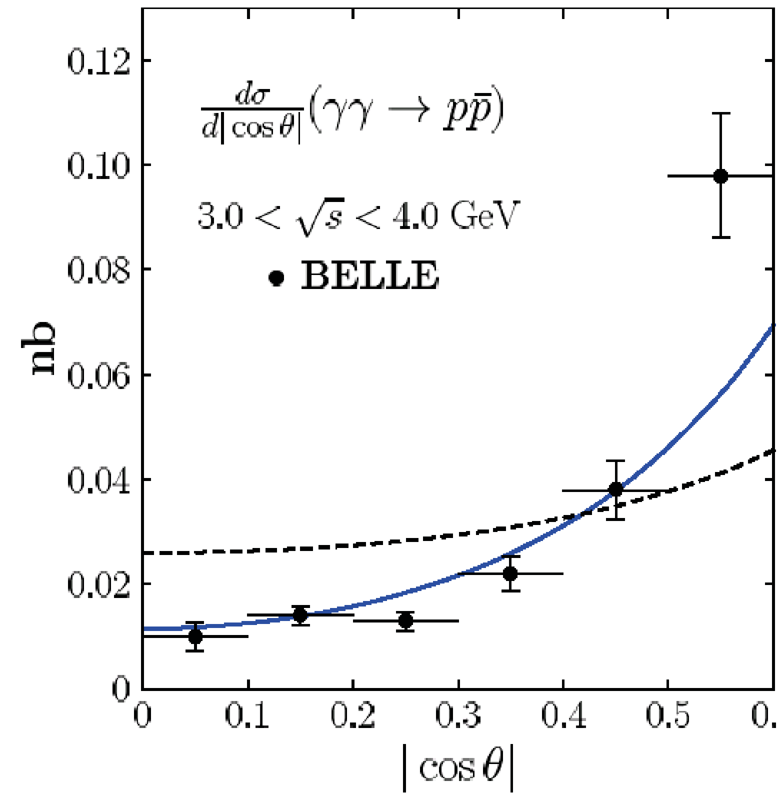
$\gamma\gamma \to p\bar{p}$

PQCD Conformal Scaling for range of θ_{CM}

$s^5 \Delta\sigma(\gamma\gamma \to \bar{p}p) \simeq \text{const}$



Energy dependence



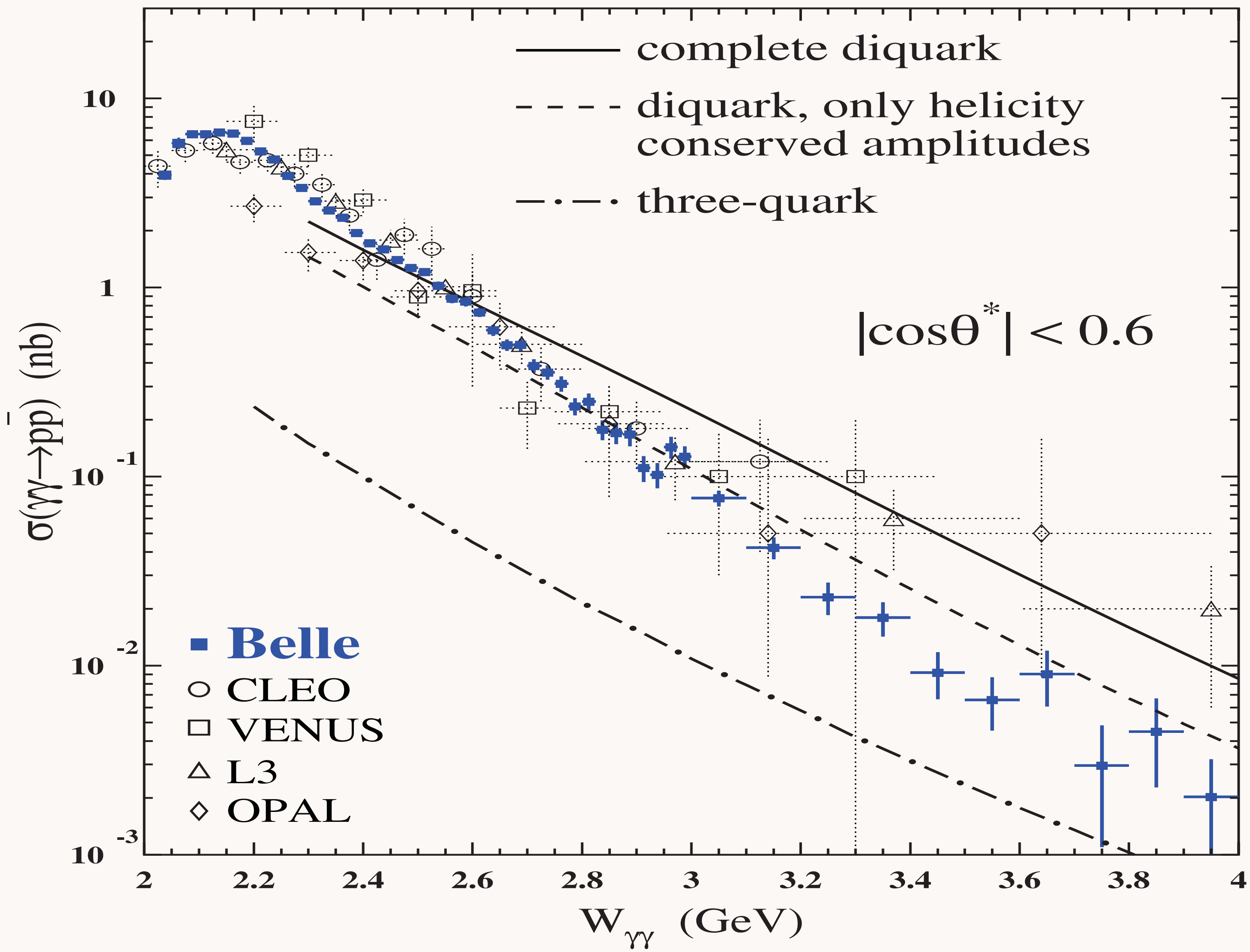
Angular dependence
(GPD curve from Kroll/Schäfer)

Michael Düren

TWO PHOTON PHYSICS AT BELLE

A.E. Chen

International Journal of Modern Physics A
Vol. 21, No. 27 (2006) 5543–5551

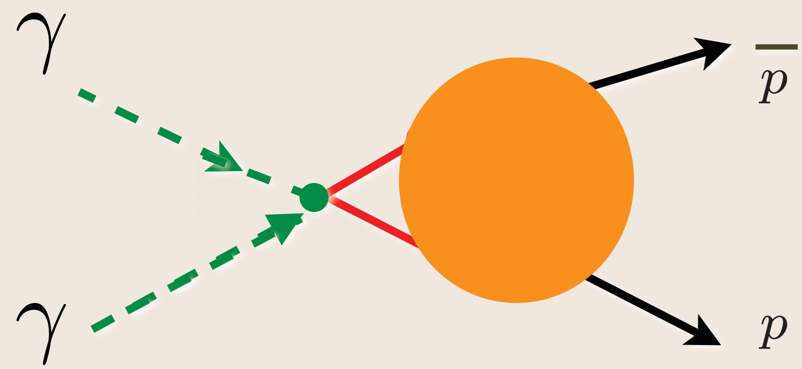


Measured cross sections for $\gamma\gamma \to p\bar{p}$ as a function of $W_{\gamma\gamma}$

PQCD: Brooks, Dixon

Key QCD Experiment

$$\frac{d\sigma}{dt}(\gamma\gamma \to \bar{p}p) = \frac{F(t/s)}{s^6}$$



$\frac{d\sigma}{dt}(\gamma\gamma \to \bar{p}p)$ at fixed angle, large p_T

Tests PQCD and AdS/CFT Conformal Scaling

Close, Gunion, sjb
Szczepaniak,
Llanes Estrada, sjb

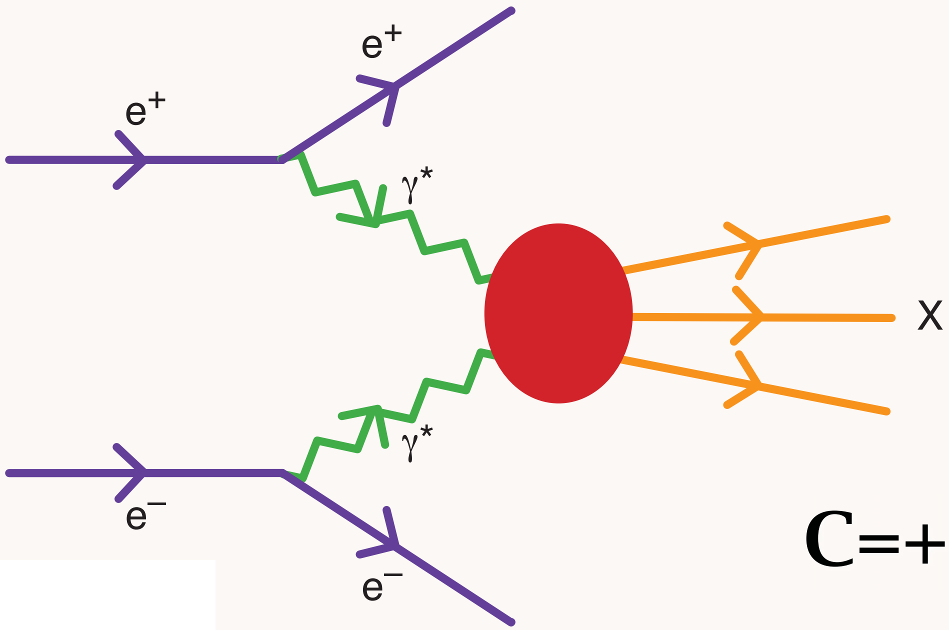
$$M(\gamma\gamma \to \bar{p}p) = F(s) \propto \frac{1}{s^2}$$

Local Two-Photon (Seagull) Contribution

J=0 Fixed pole

More Two-Photon Physics at BaBar

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



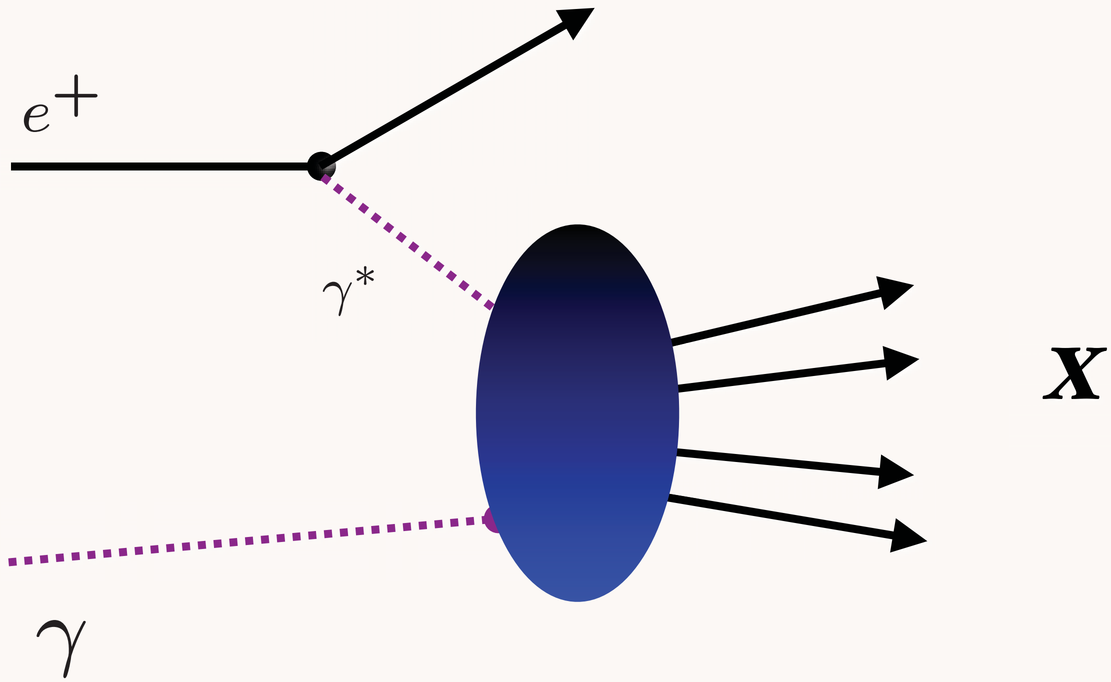
C=+ Hadron Final States

Tag one or both scattered leptons

$$\gamma^*\gamma^* \to X$$

Photon Structure Function

Kinoshita, Terazawa, sjb
Walsh, Zerwas



$$\gamma^*\gamma \to X$$

Anomalous logarithmic evolution from pointlike photon coupling

$$F_2^\gamma(x, Q^2) \sim \frac{\alpha}{\alpha_s(Q^2)} f(x)$$

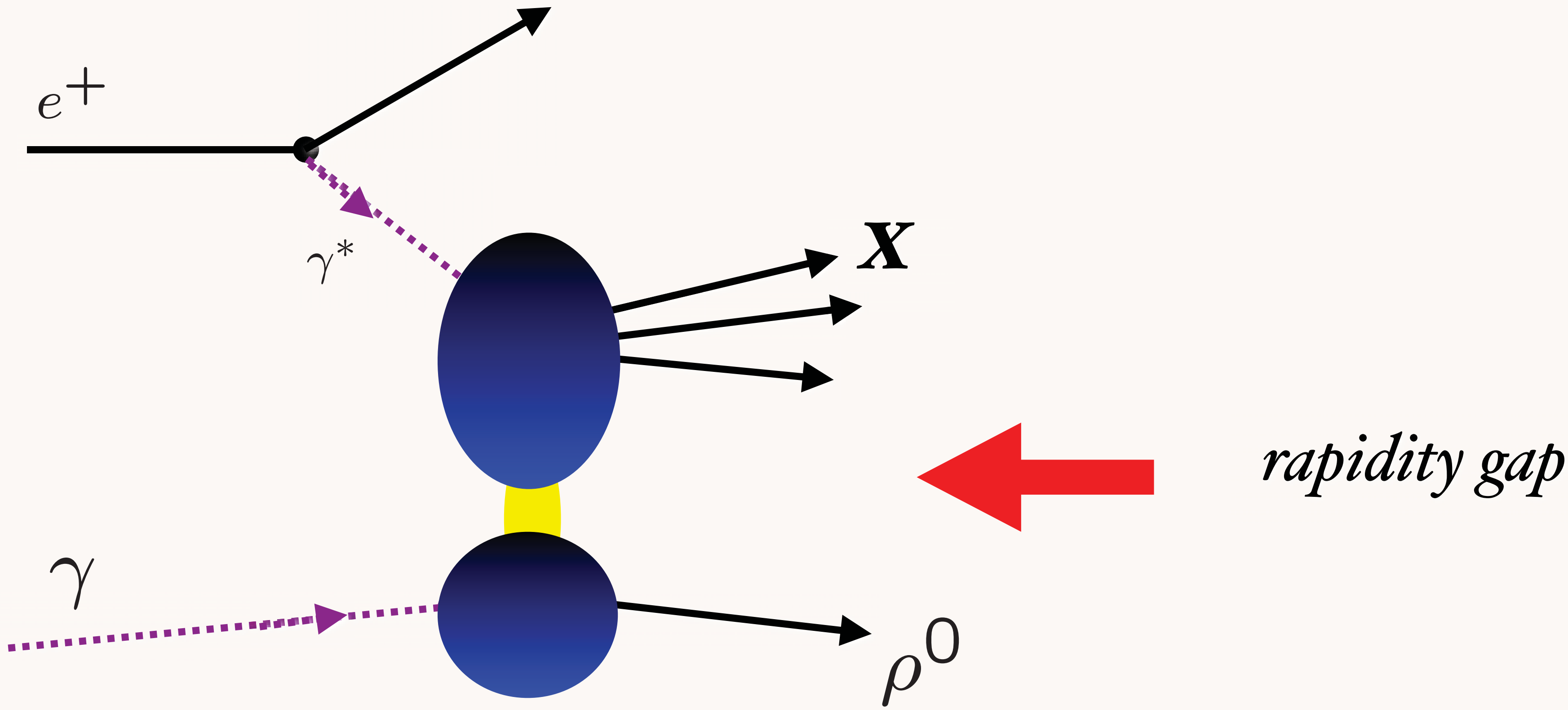
Witten

Tag one lepton

Use Equivalent photon approximation

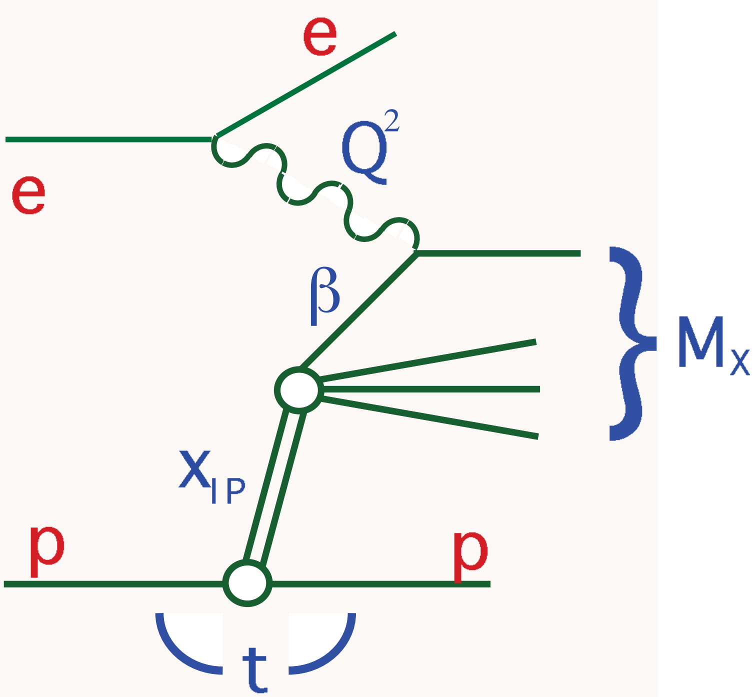
Diffractive Deep Inelastic Scattering on a Photon Target

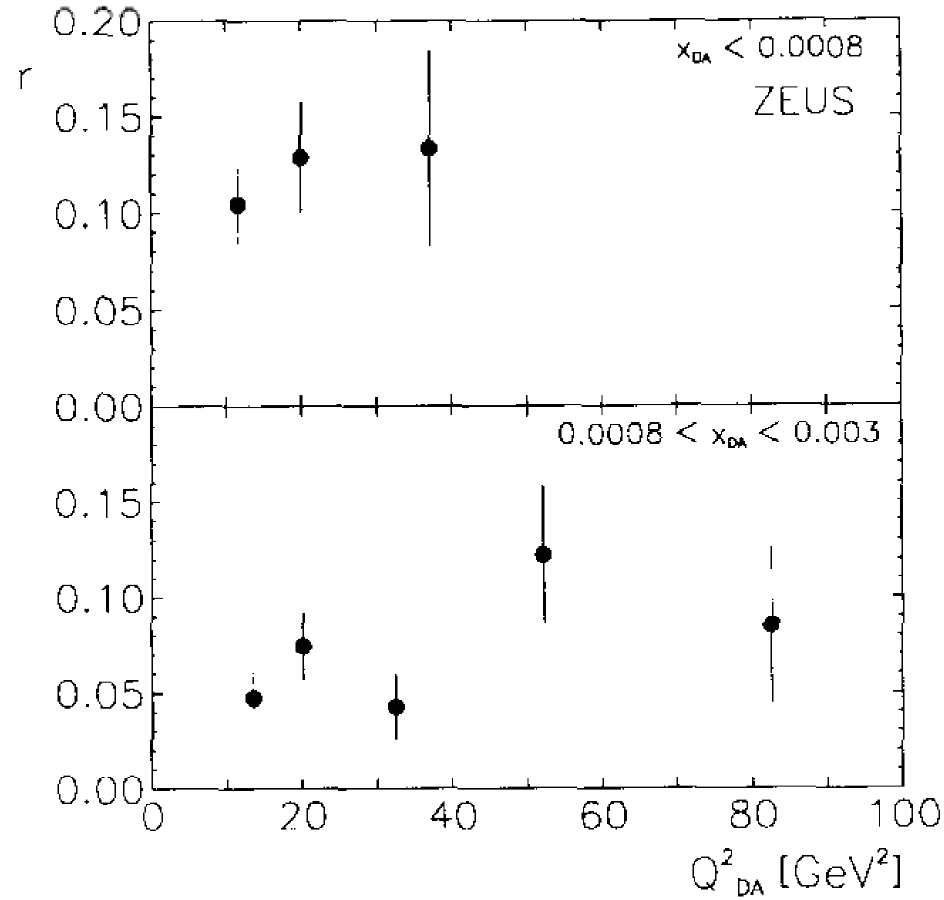
$$\gamma^* \gamma \to X + V^0$$



Leading twist: DDIS

Remarkable observation at HERA





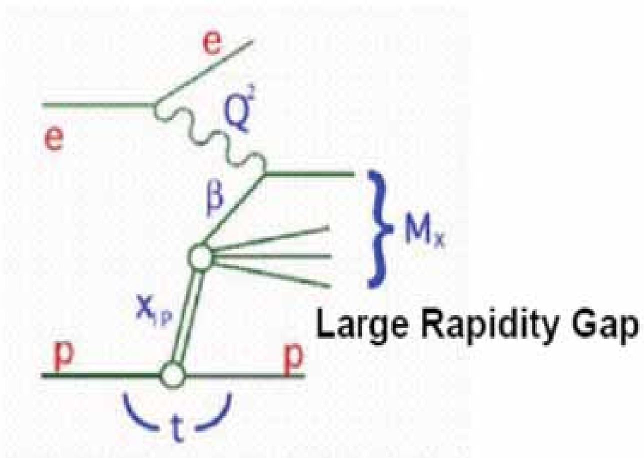
Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of $Q^2_{\rm DA}$ for two ranges of $x_{\rm DA}$. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993)

Diffractive Structure Function F_2^D

de Roeck



Diffractive inclusive cross section

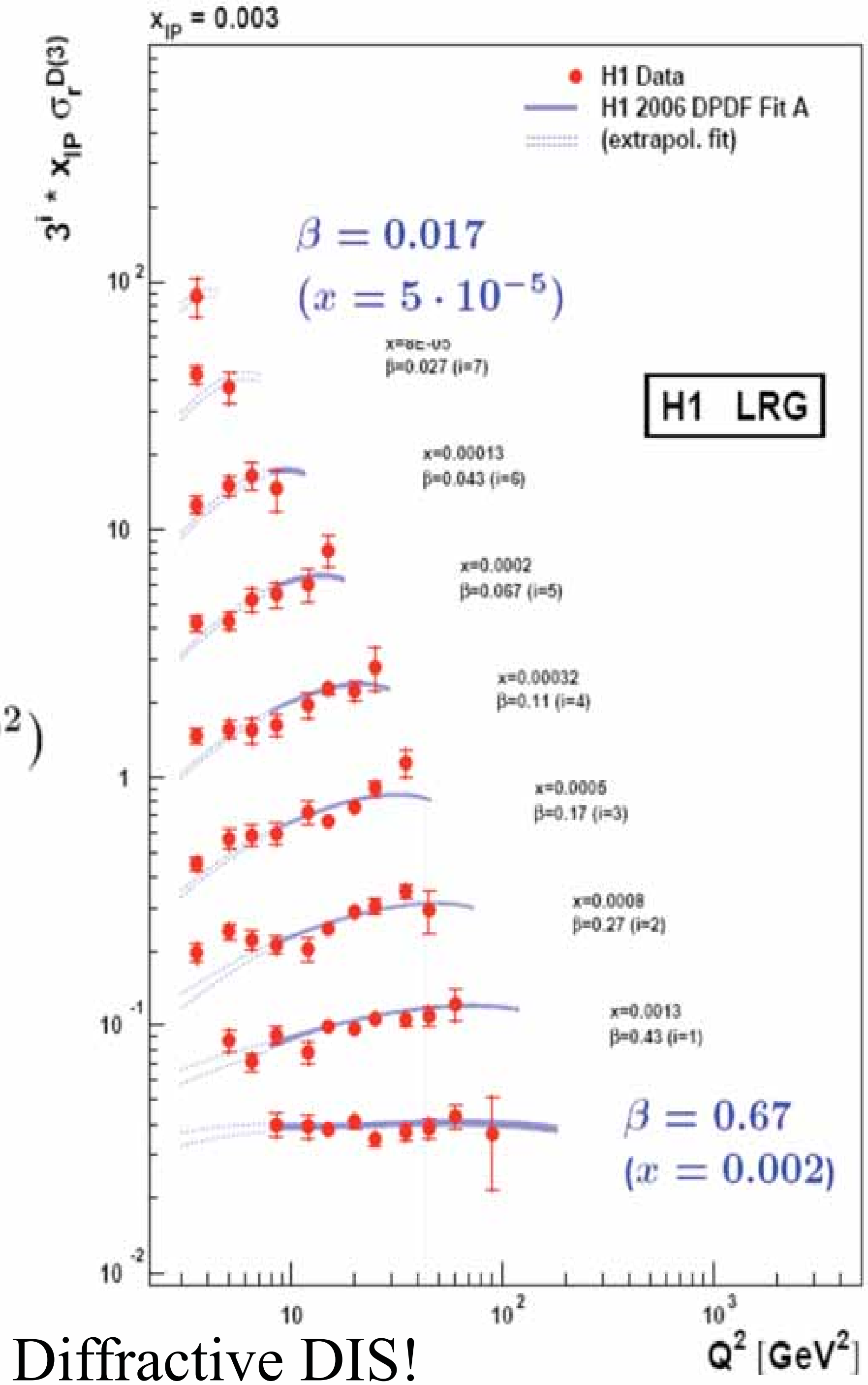
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

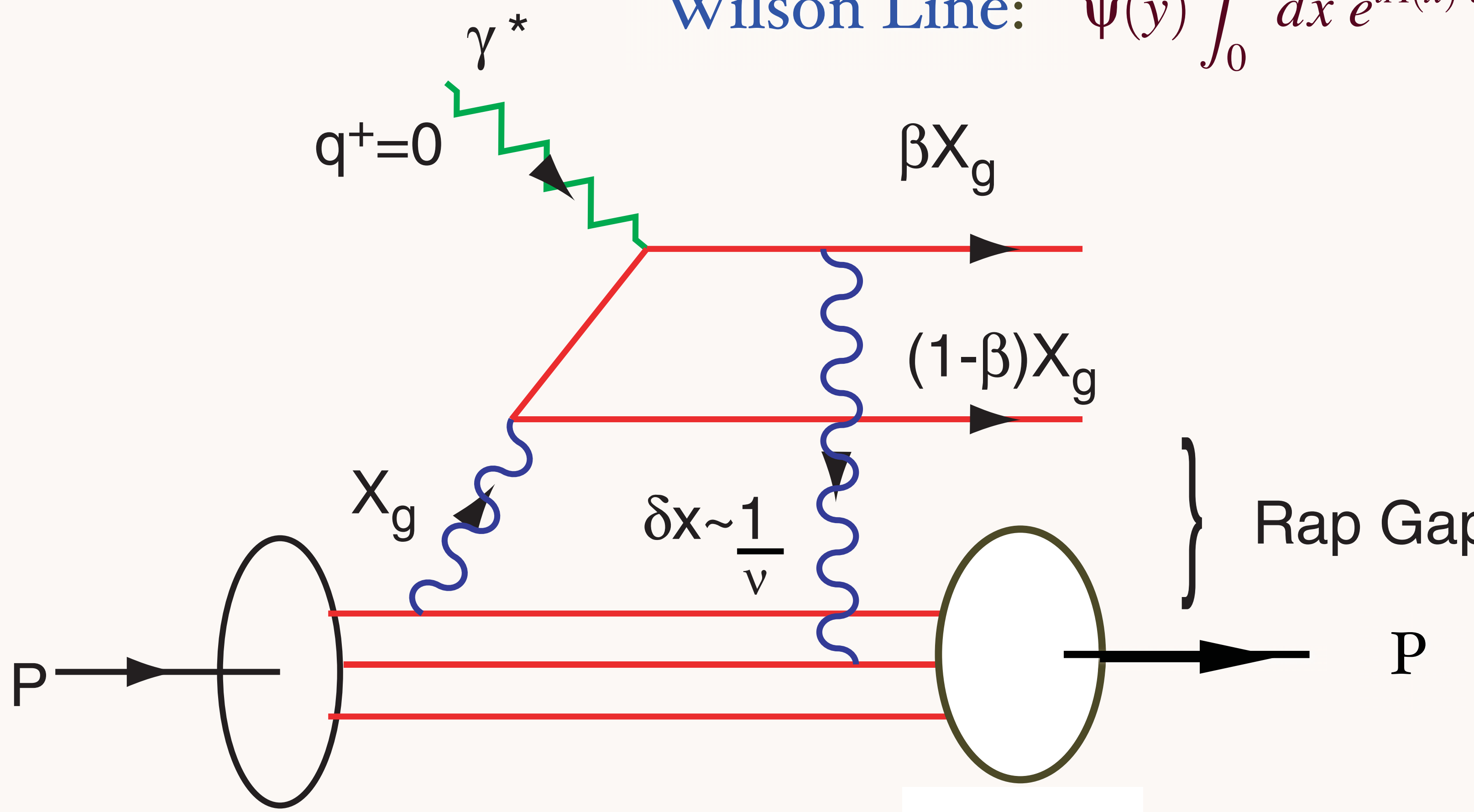
Precise measurements *sys 5%, stat 5–20%*



10 to 15 % of HERA DIS is Diffractive DIS!

QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

QCD Mechanism for Rapidity Gaps

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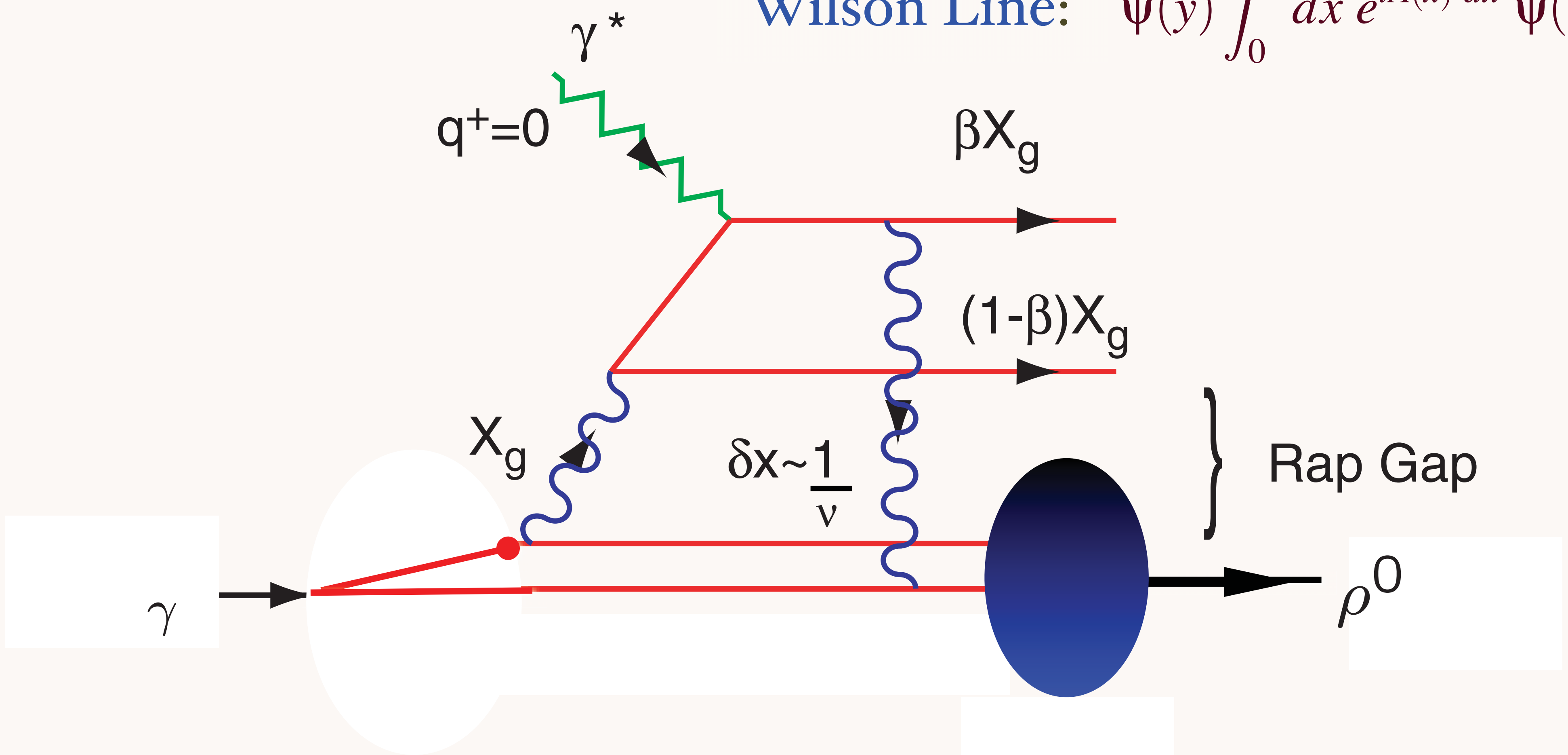
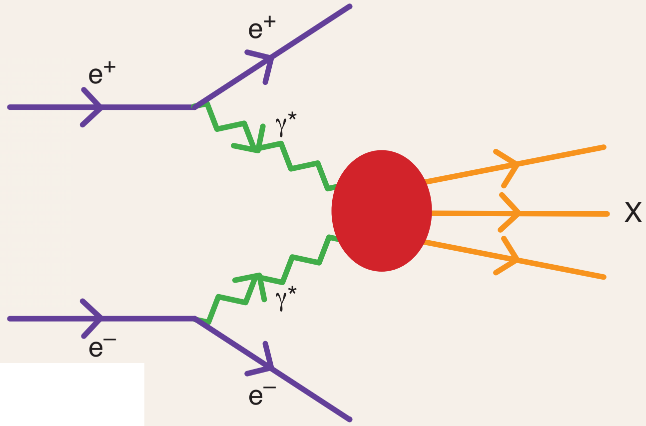


Measure in $e\gamma \rightarrow eX + \rho$

Physics Opportunities in Two-Photon Collisions

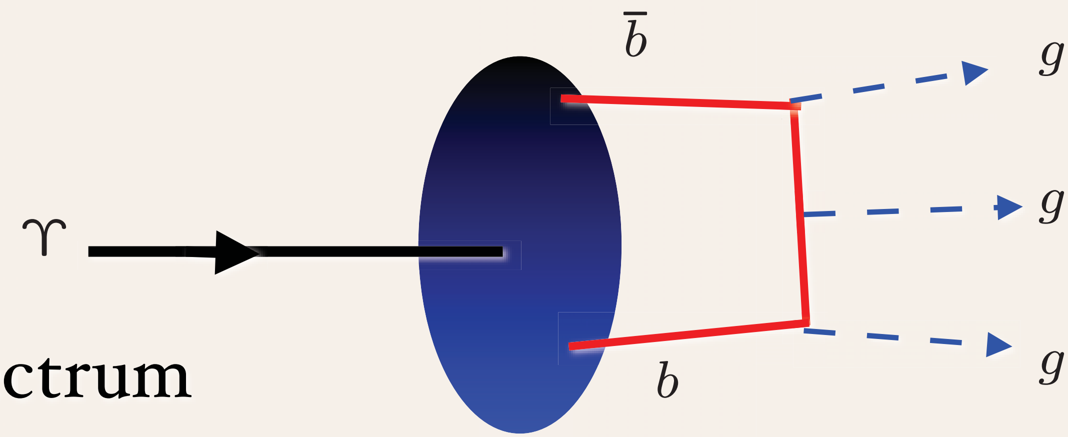


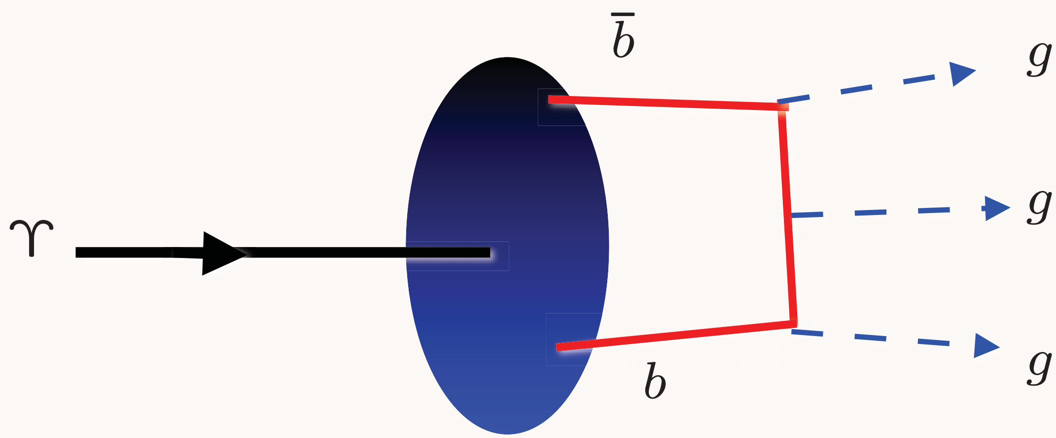
- Photon Structure Function - Charm Contributions
- Diffractive DIS on a Photon Target
- Hard Two-Photon Exclusive Channels
- Charge asymmetries from C=+ & C=- amplitudes
- Timelike Deeply virtual Compton Scattering
- C = + Hadron Formation

Physics Opportunities in Upsilon Decay

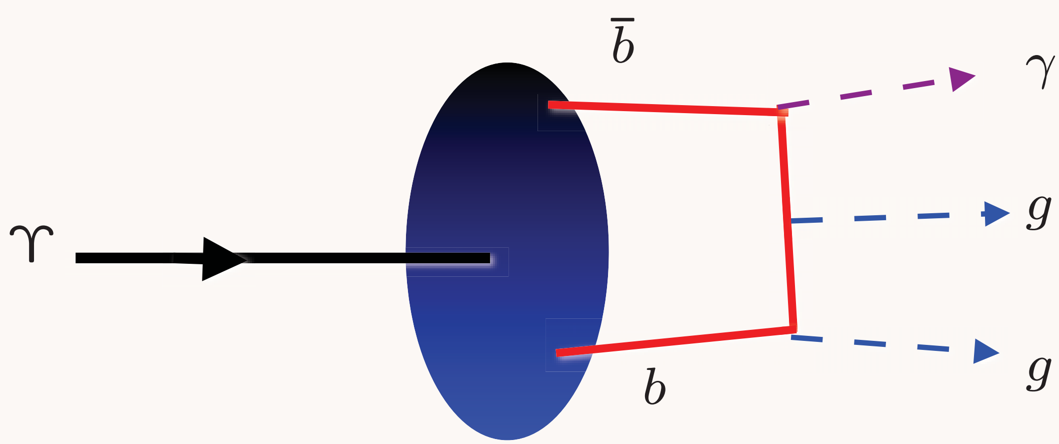
$$\Upsilon \to ggg$$

- Hadronization of three-gluon final states
- Exclusive Decays
- Glueball factory
- High z Photon Spectrum
- Rho-Pi Puzzle
- Double Quarkonium Production





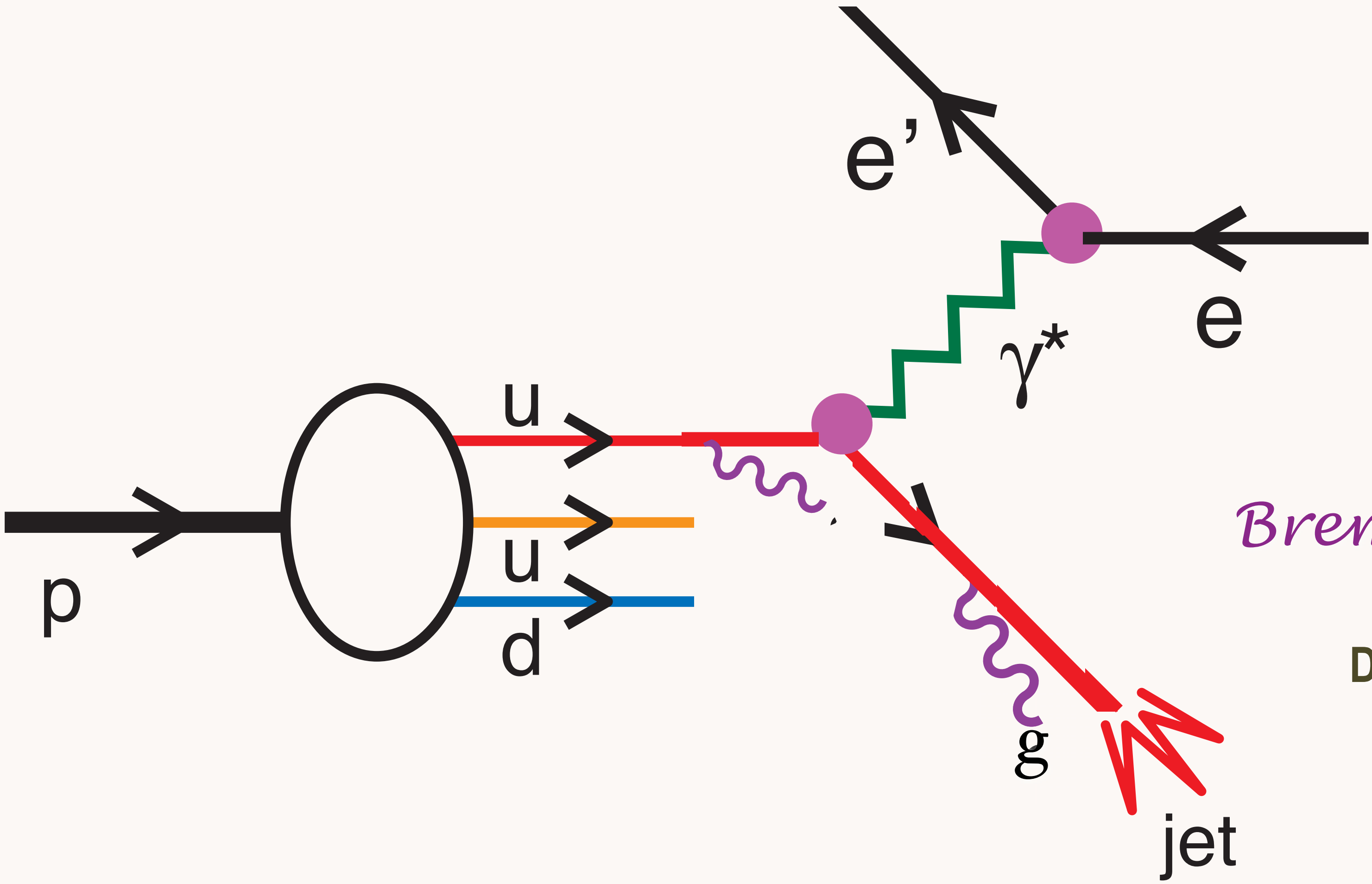
$$\Upsilon \to ggg$$



$$\Upsilon \to \gamma gg$$

C=+ Glueball factory

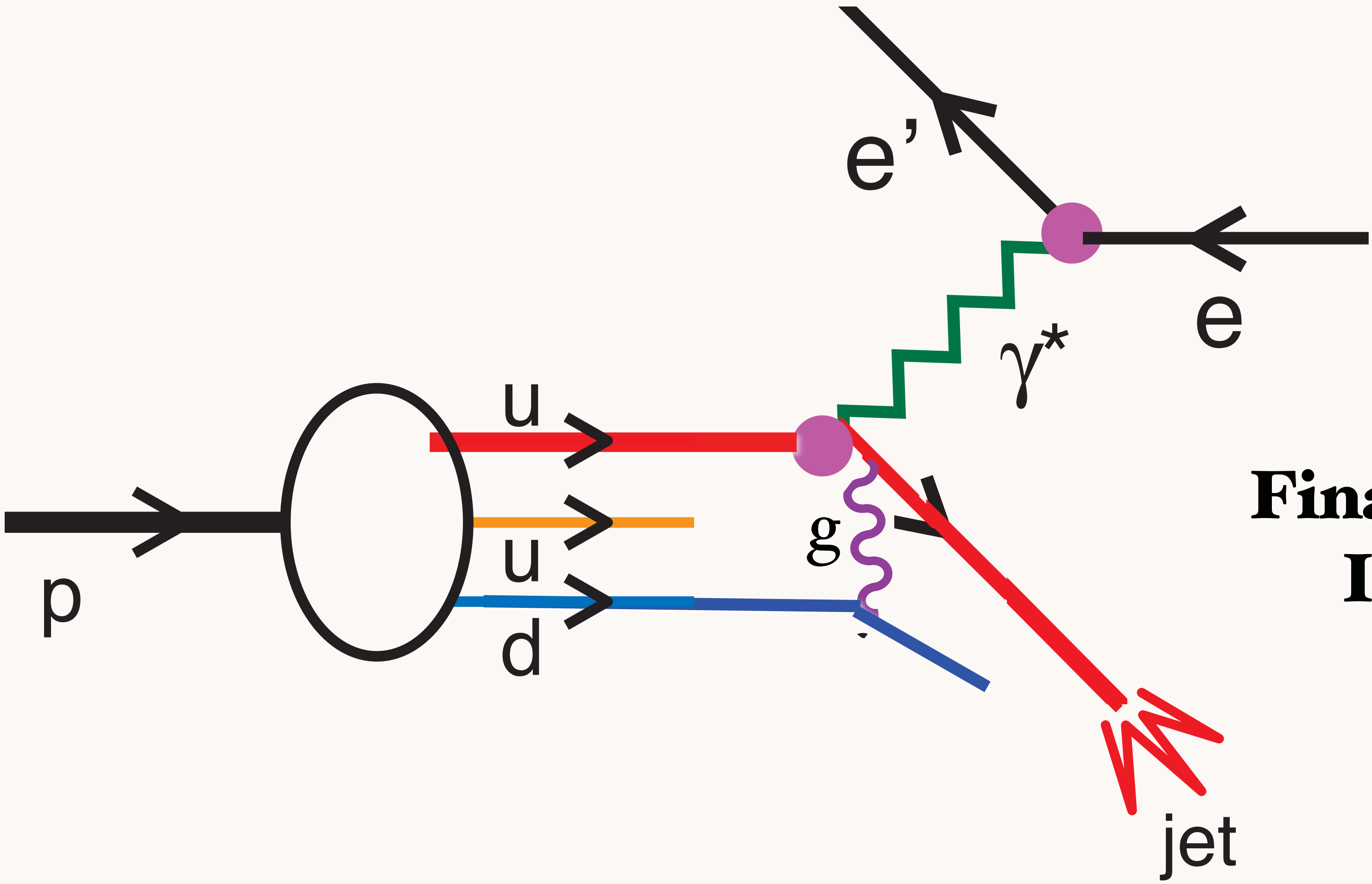
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

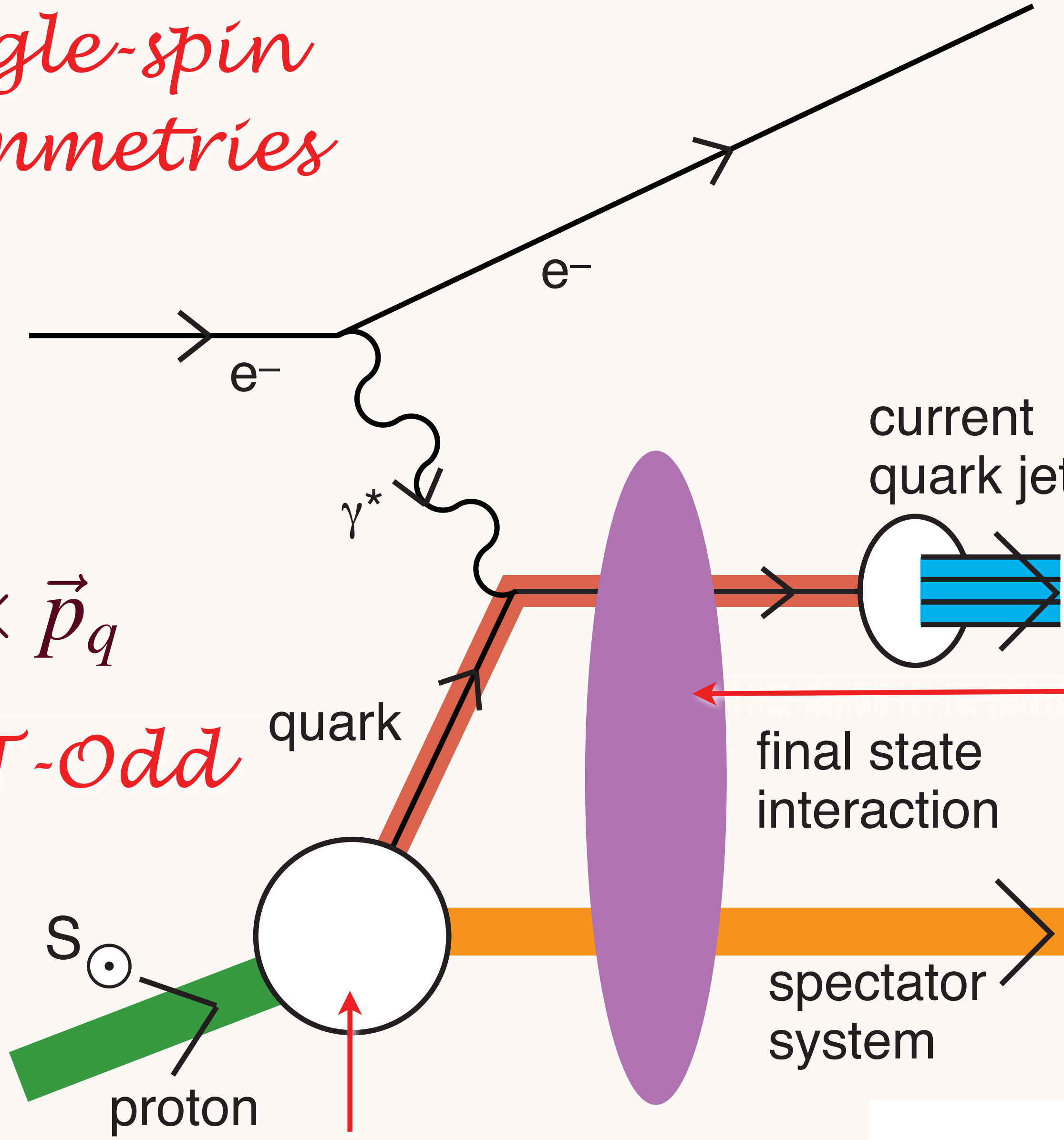
Conventional wisdom:
Final-state interactions of struck quark can be neglected

Leading Twist Sivers Effect

Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, **Burkardt**, Ji, Yuan



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

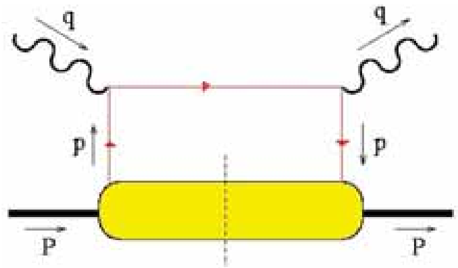
Pseudo-T-Odd

QCD S- and P-Coulomb Phases --Wilson Line

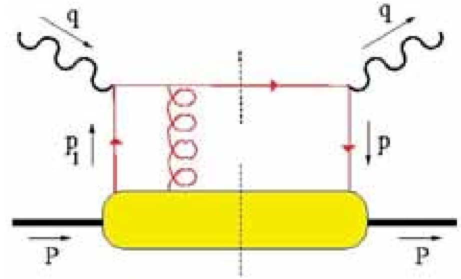
Light-Front Wavefunction S and P- Waves

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!



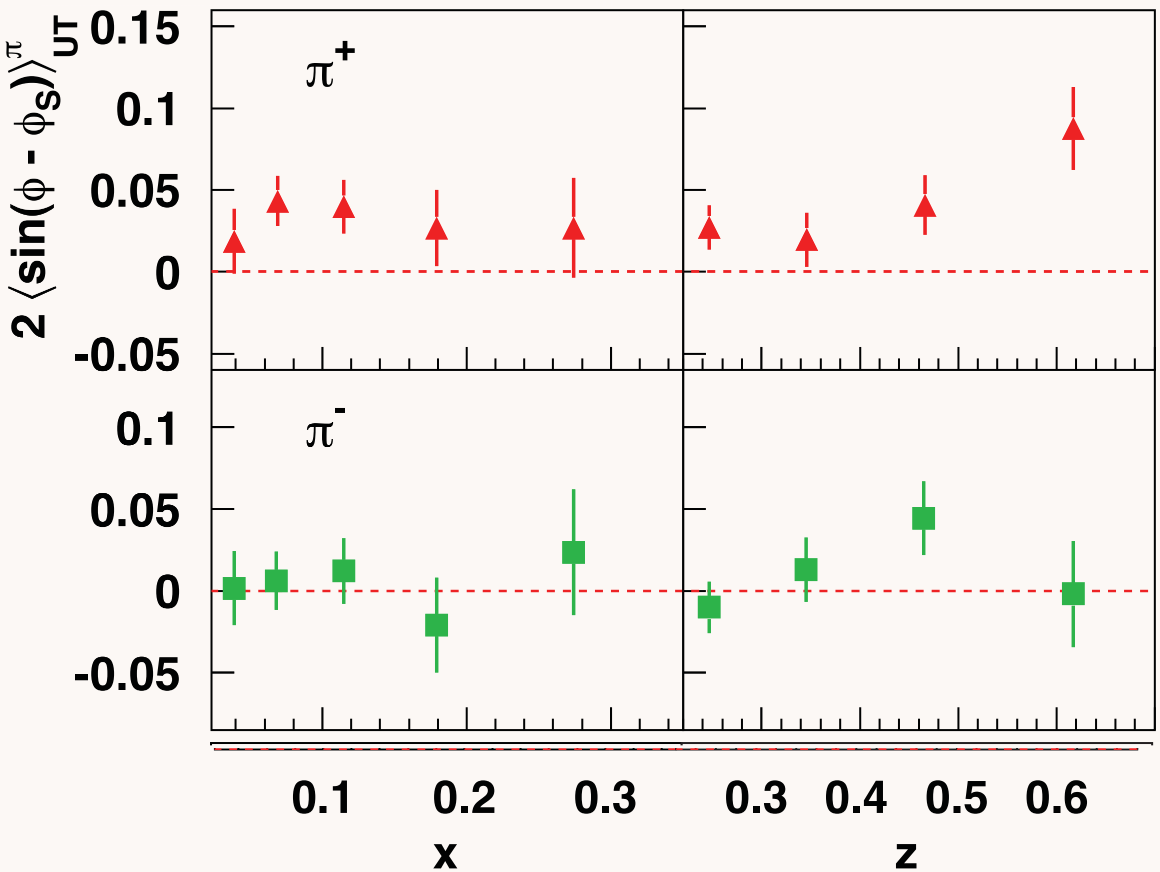
can interfere with



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

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES



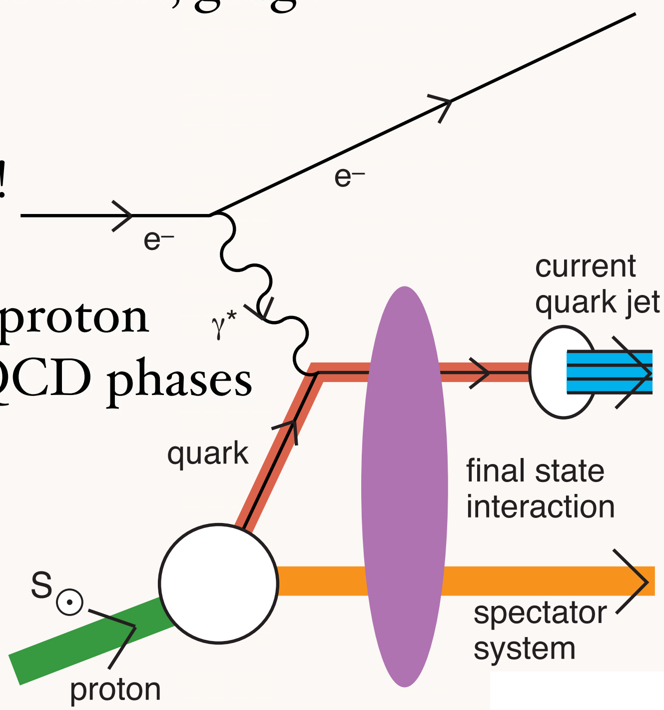
- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π^+**... Consistent with zero for **π^-**...

Gamberg: Hermes data compatible with BHS model

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

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)



Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

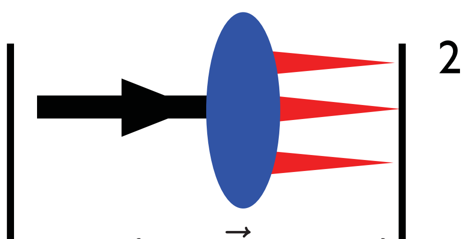
Hwang, Schmidt, sjb,

Mulders, Boer

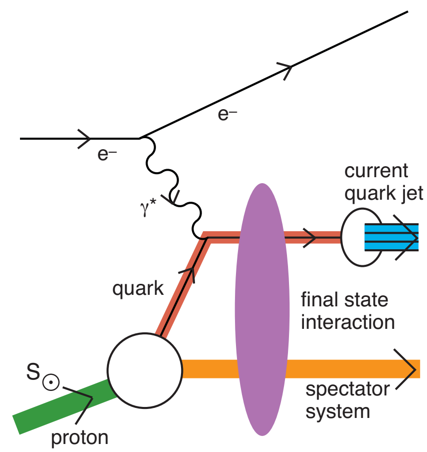
Qiu, Sterman

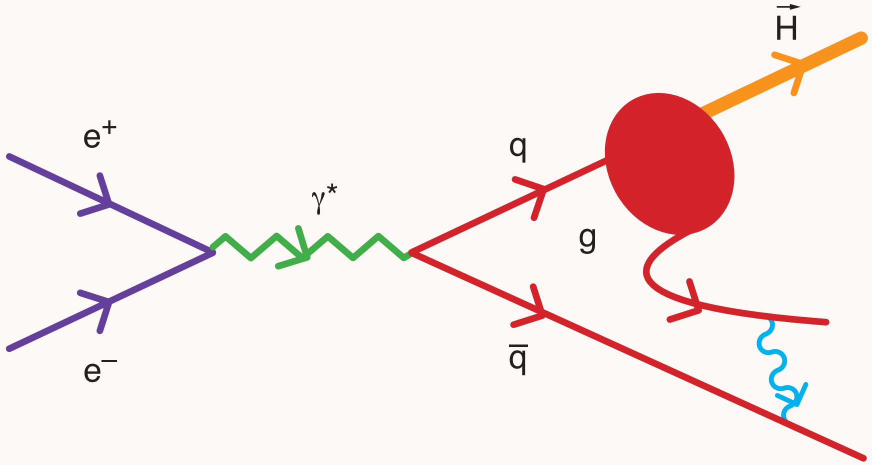
Collins, Qiu

Pasquini, Xiao, Yuan, sjb



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

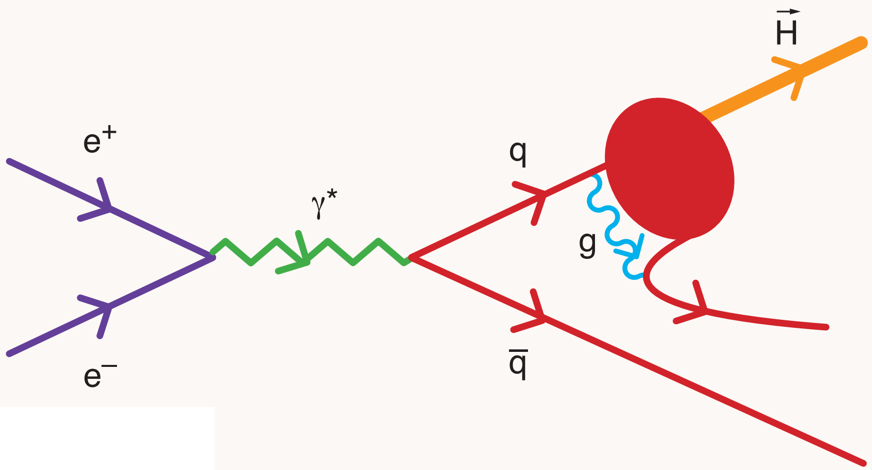




$$e^+e^- \to \gamma^* \to \pi\Lambda X.$$

Λ reveals its polarization via decay

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



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

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

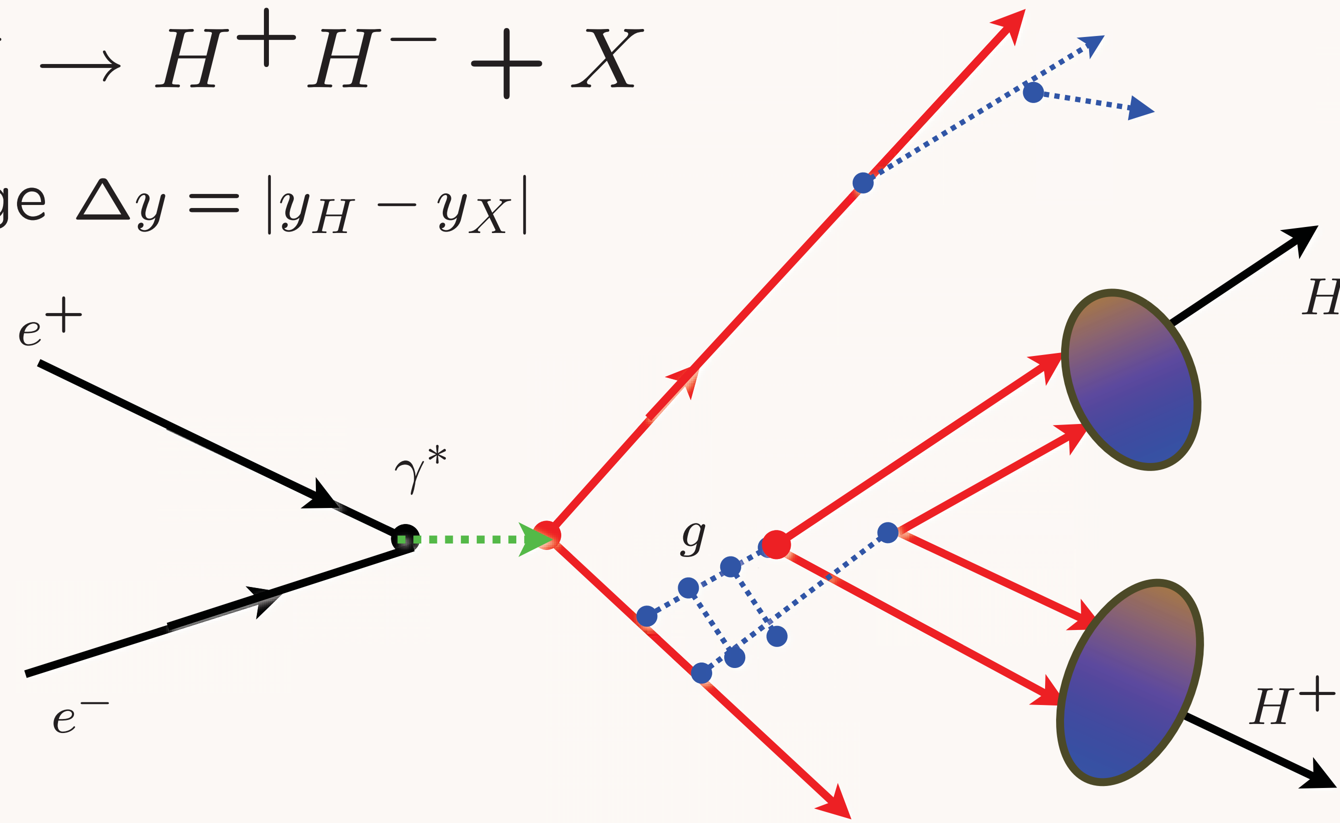
in Λ rest frame

Final-state gluon exchange produces leading-twist T-odd single-spin asymmetries in 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

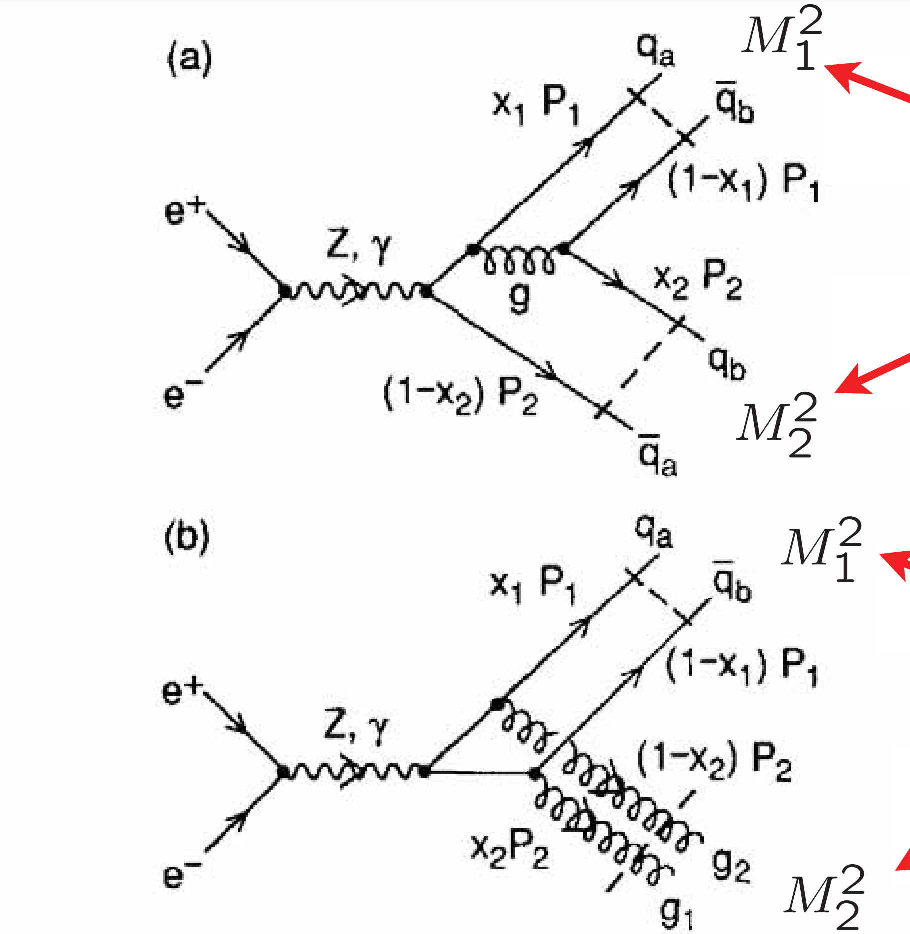
C= + Gluonium Trajectory

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

Dimensional Counting:

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

color-singlet states

Kopeliovich, Schmidt, sjb

Reggeon Exchange at small pair mass

Timelike Pomeron

Large Rapidity Gap Events

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

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

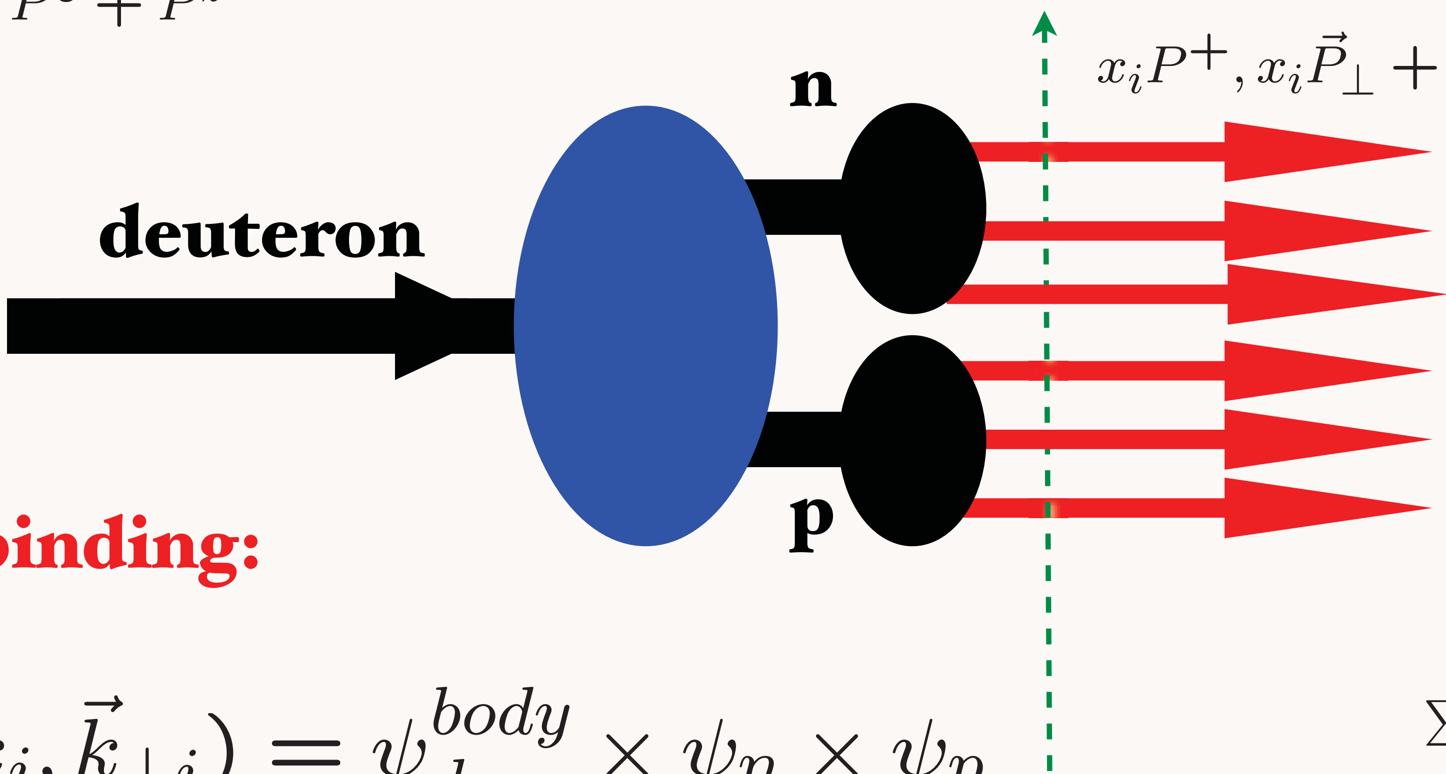
Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

$P^+ = P^0 + P^z$

$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

$P^+, \vec{P}_\perp$



Weak binding:

$$\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$$

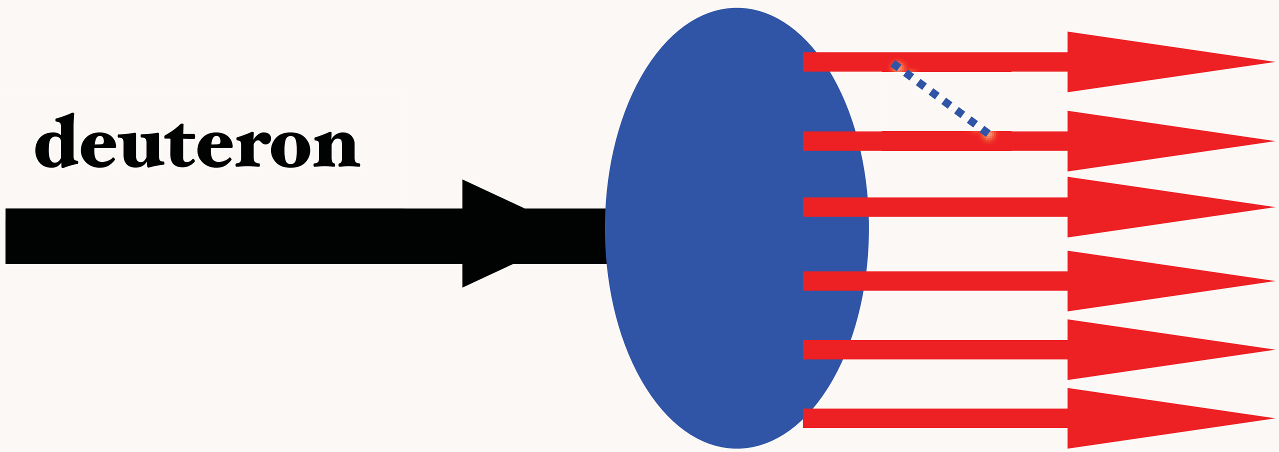
$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Two color-singlet combinations of three 3_C

Evolution of 5 color-singlet Fock states

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



$$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$$

$$\sum_i^n x_i = 1$$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color in QCD

Lepage, Ji, sjb

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Ratio = 2/5 for asymptotic wf

QCD Prediction for Deuteron Form Factor

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn}\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d-\gamma_m^d}\left[1+O\left(\alpha_s(Q^2),\frac{m}{Q}\right)\right]$$

Define "Reduced" Form Factor

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N{}^2(Q^2/4)}\,.$$

Same large momentum transfer behavior as pion form factor

$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2}\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-(2/5)\,C_F/\beta}$$

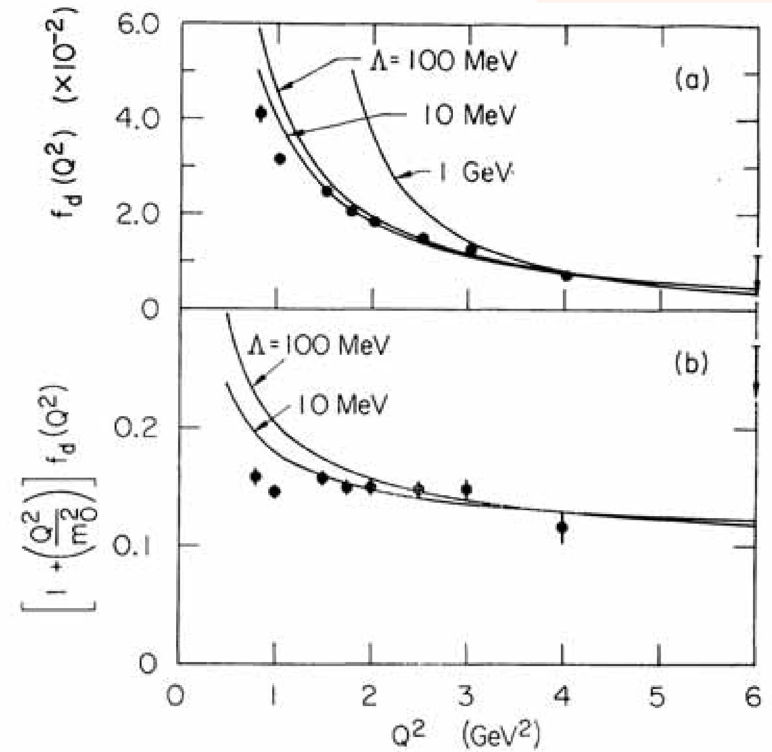
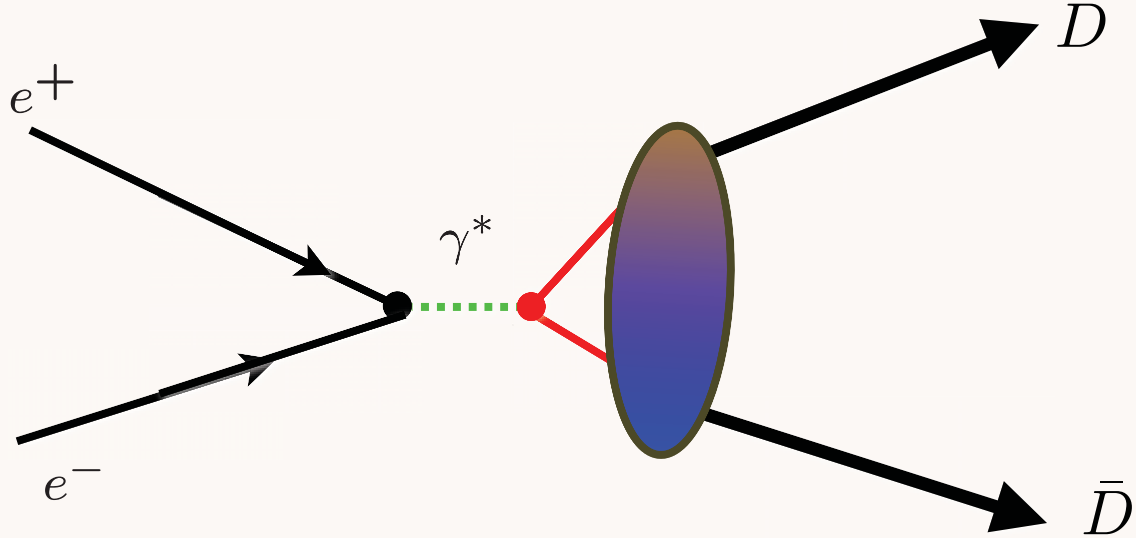


FIG. 2. (a) Comparison of the asymptotic QCD pre diction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with fin data of Ref. 10 for the reduced deuteron form factor where $F_N(Q^2) = [1+Q^2/(0.71\ \text{GeV}^2)]^{-2}$. The normaliz tion is fixed at the $Q^2 = 4$ GeV^2 data point. (b) Compa son of the prediction $[1+(Q^2/m_0^2)] f_d(Q^2) \propto [\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with the above data. The value $m_0^2 = 0.28$ GeV^2 is used (Ref. 8).

Measure timelike deuteron form factors

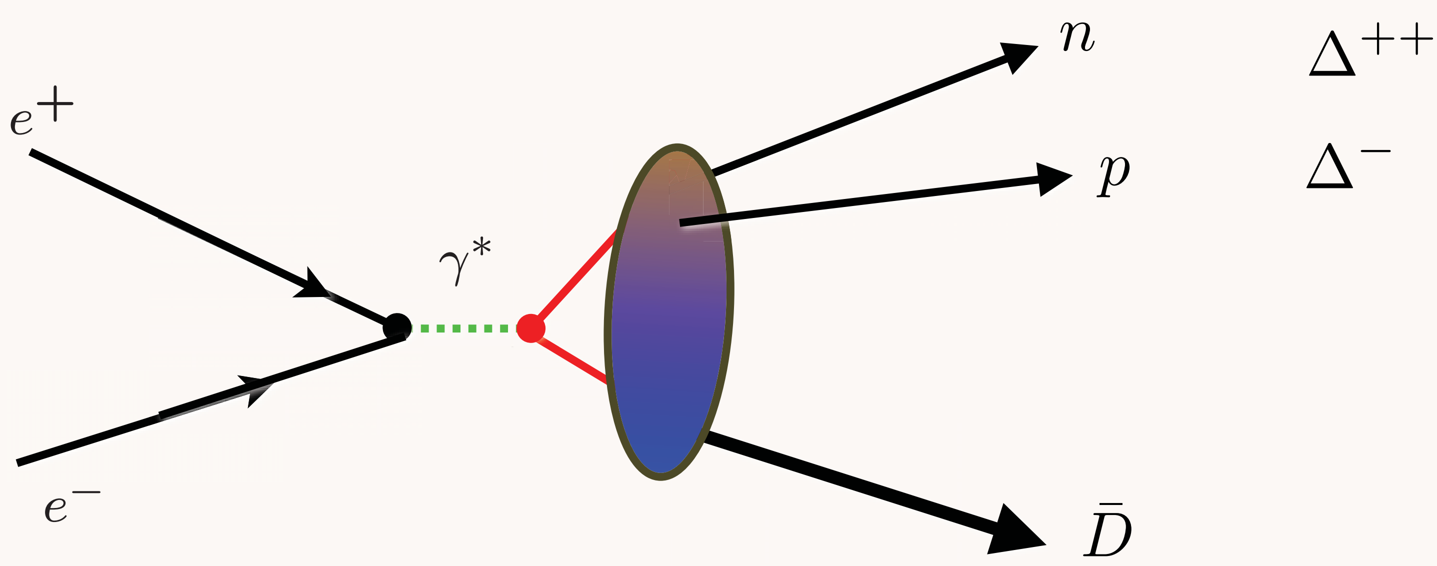
$$F(s) \sim \frac{1}{s^5}$$



Sensitive to "Hidden-Color" Components of Deuteron WF

$$|(uud)_{8C}(ddu)_{8C} >$$

Measure timelike deuteron associated production

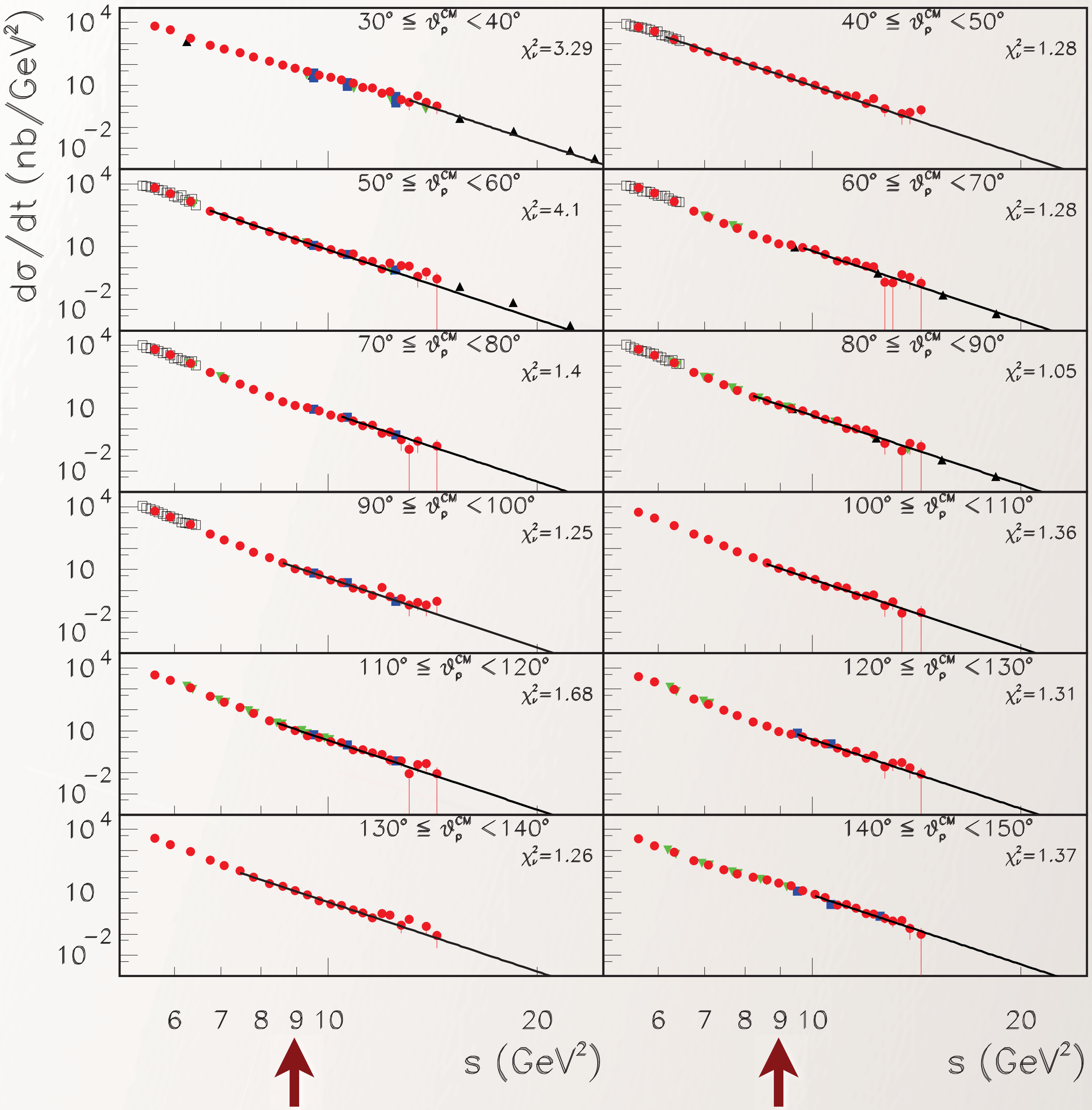


Ratio Sensitive to "Hidden-Color" Components of Deuteron WF

$$|(uud)_{8C}(ddu)_{8C} >$$

Deuteron Photodisintegration and Dimensional Counting

P.Rossi et al, P.R.L. 94, 012301 (2005)



PQCD and AdS/CFT:

$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B\to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np) = F(\theta_{CM})$$

$n_{tot} - 2 =$
$(1 + 6 + 3 + 3) - 2 = 11$

$\gamma d \to (uuddddus\bar{s}) \to np$

at $s \simeq 9$ GeV^2

$\gamma d \to (uuddduc\bar{c}) \to np$

at $s \simeq 25$ GeV^2

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

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

The Light Front Fock State Wavefunctions

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

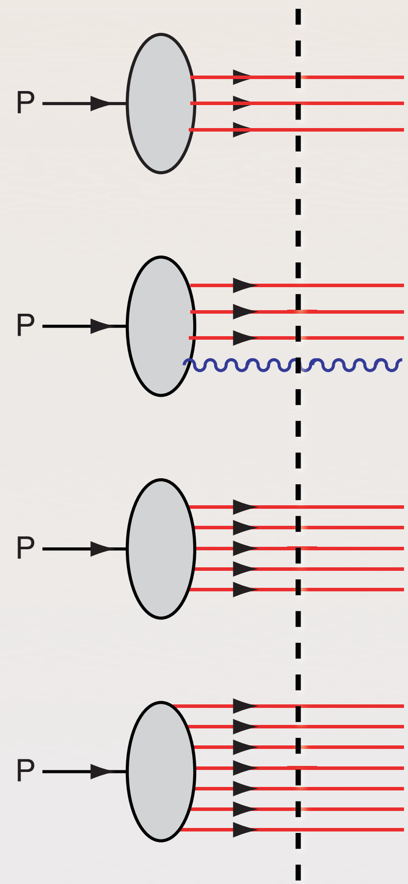
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

c(x), b(x) at high x !

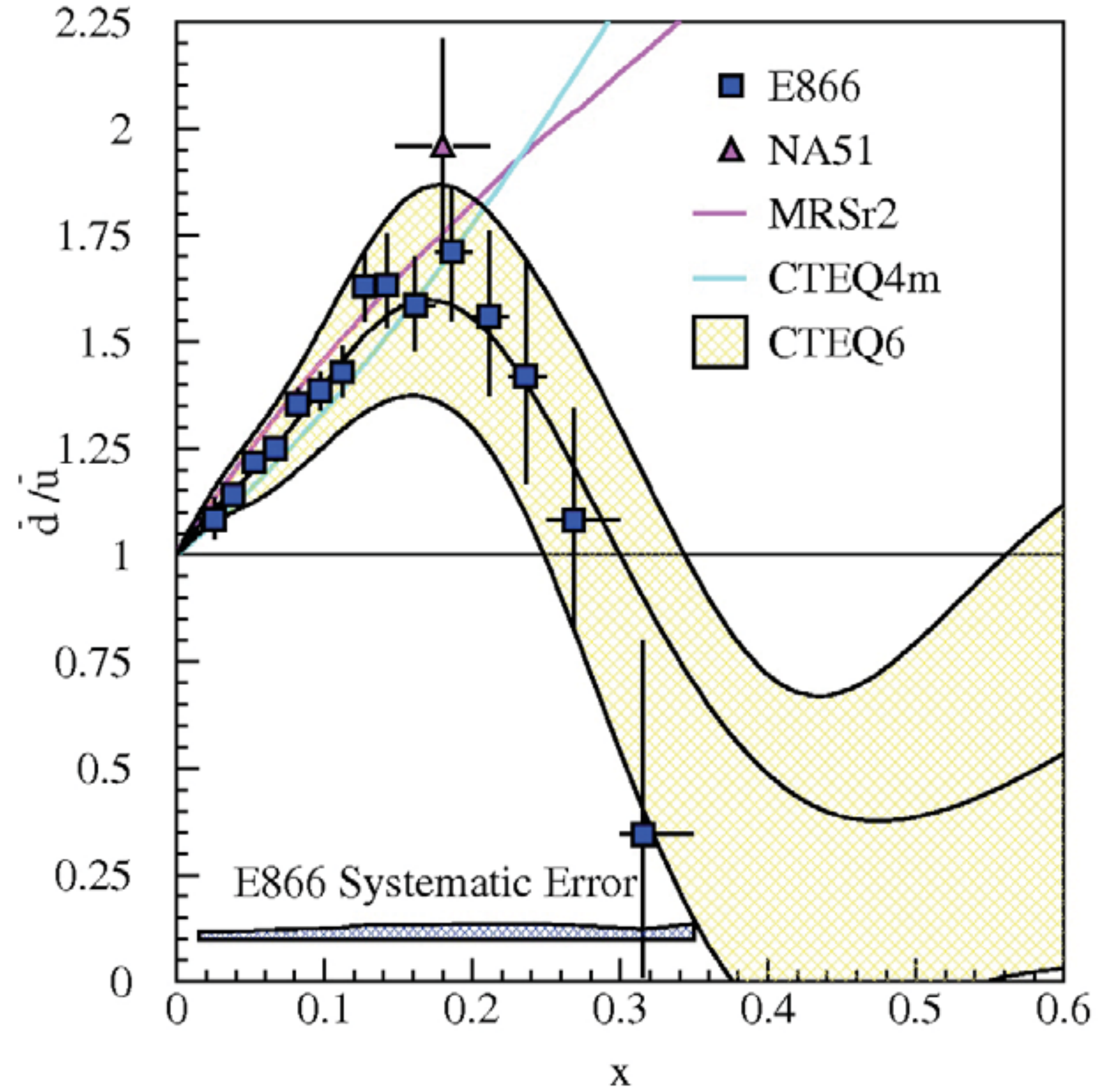
$\bar{s}(x) \neq s(x)$

$\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states → BFKL

Hidden Color

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$

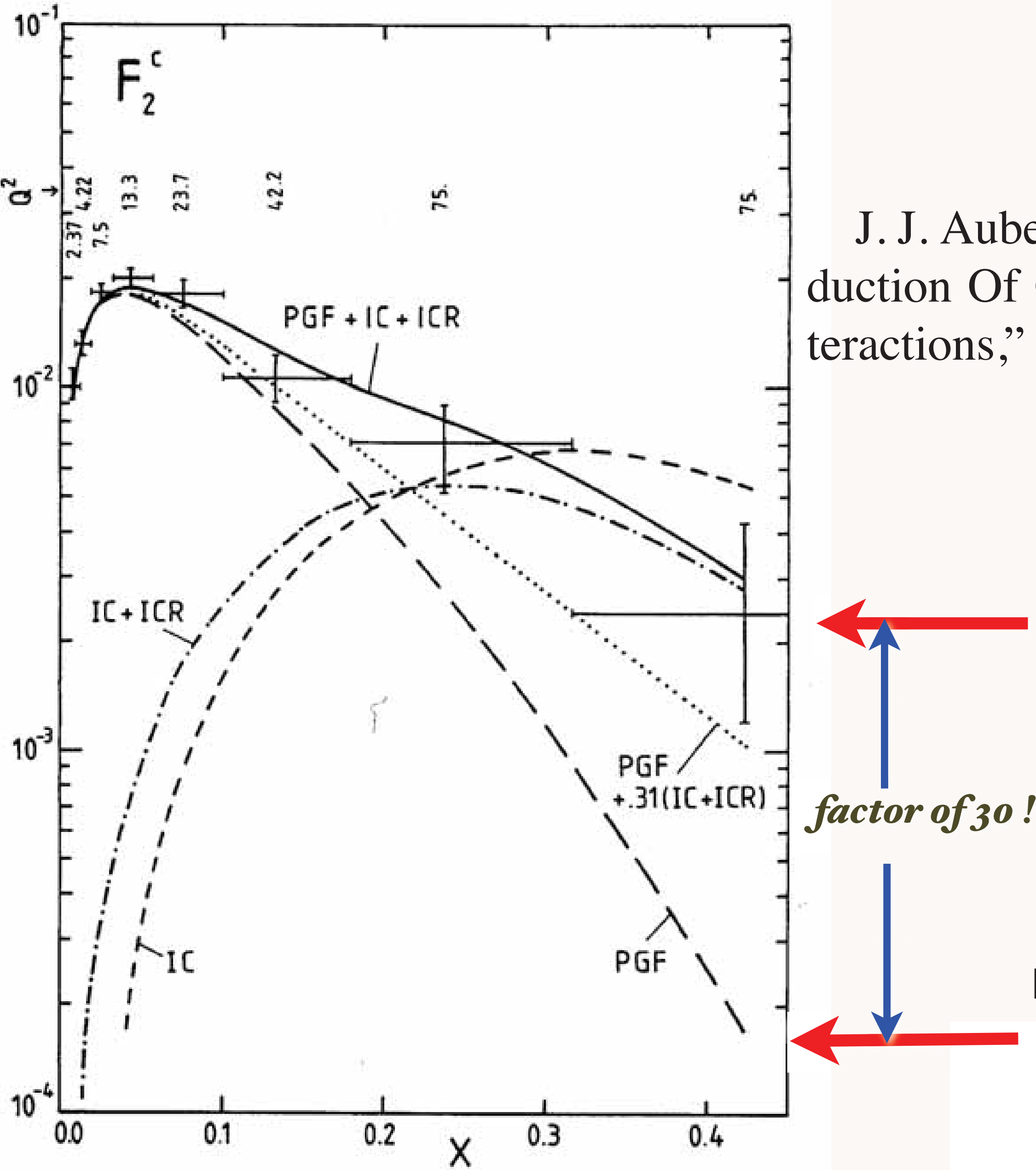


- E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$

$$s(x) \neq \bar{s}(x)$$

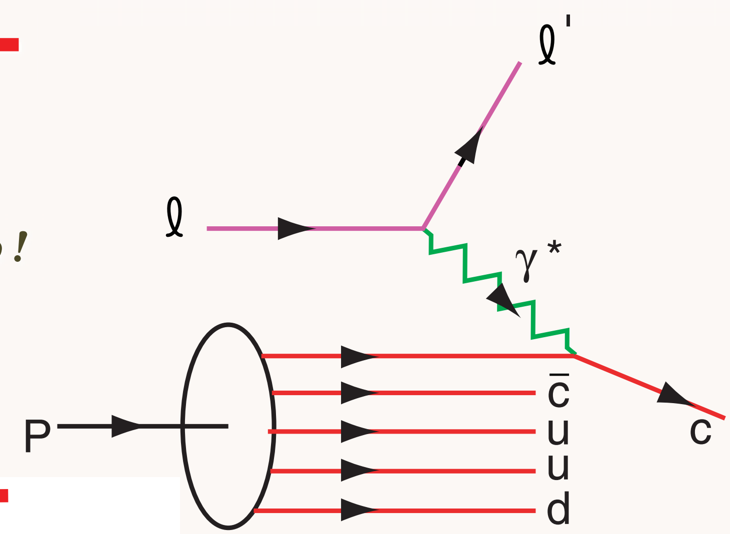
Intrinsic glue, sea, heavy quarks



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).

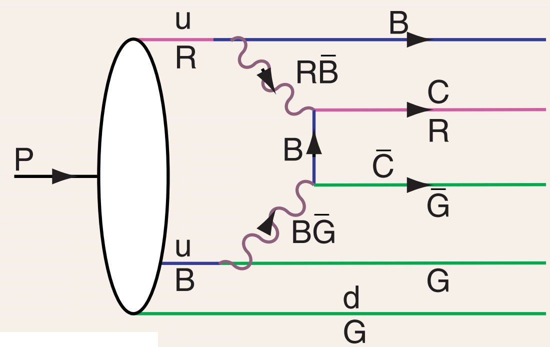
First Evidence for Intrinsic Charm



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

Hoyer, Peterson, Sakai, sjb;
M. Polyakov et al

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 $pp \to J/\psi X$

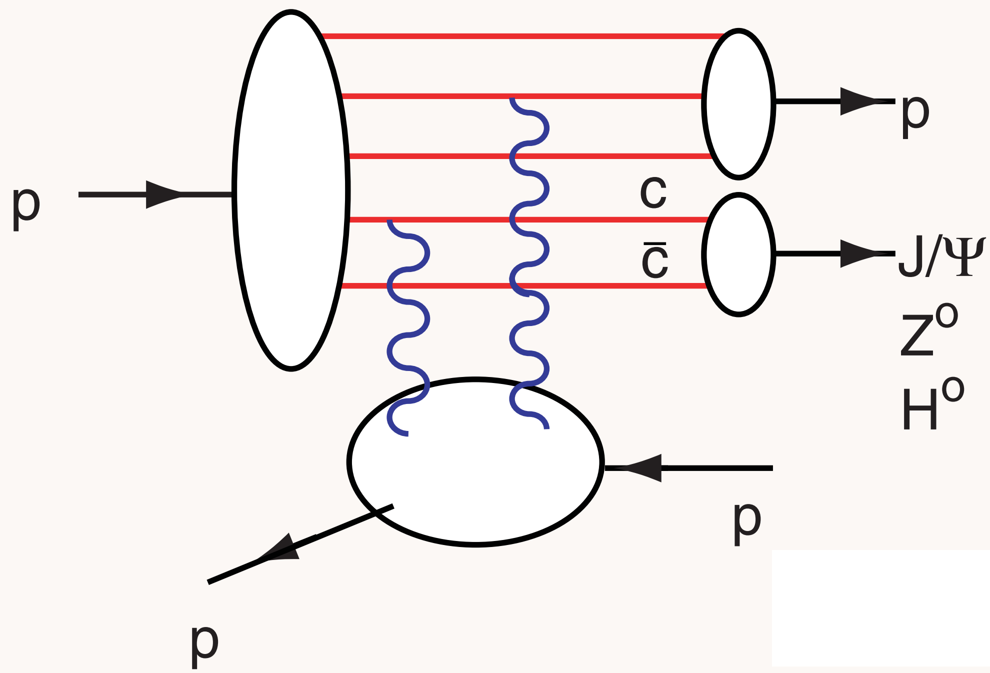
- High x_F $pp \to J/\psi J/\psi X$

- 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)

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

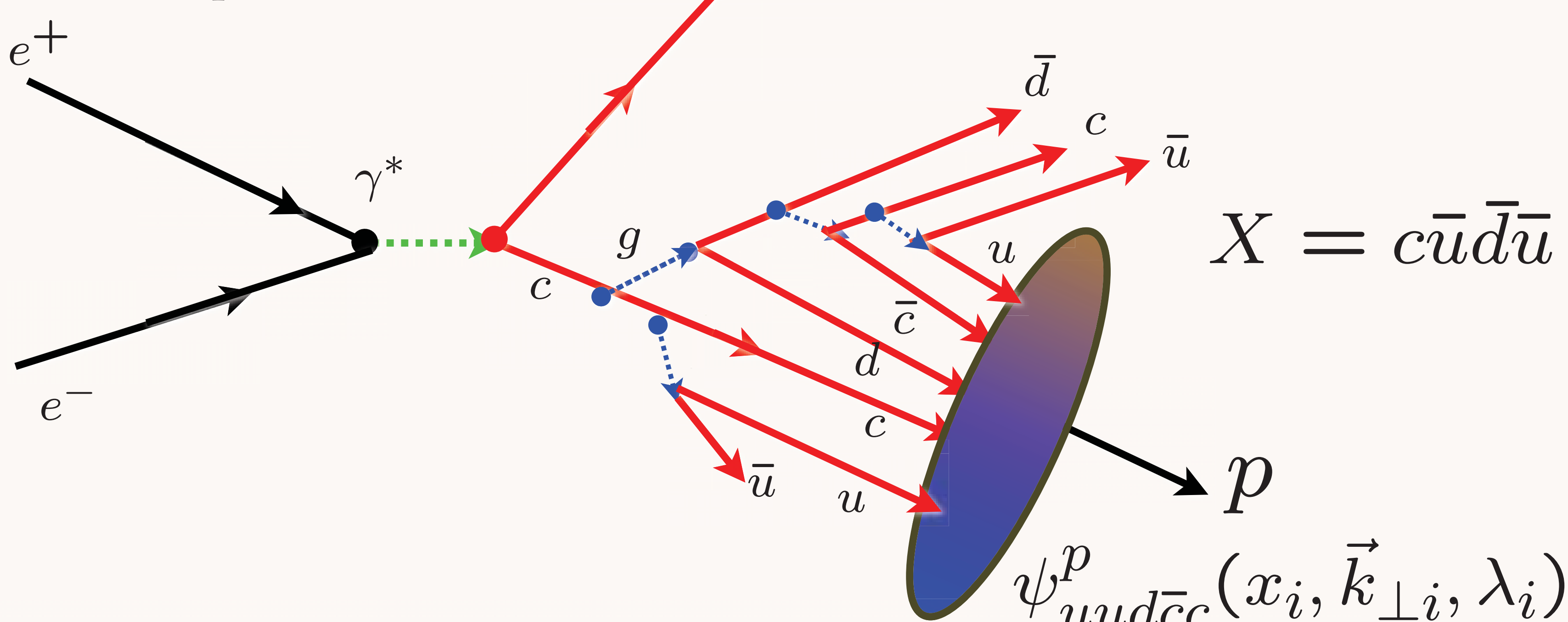
RHIC Experiment

Timelike Test of Charm Distribution in Proton

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

Gribov-Lipatov crossing at large z

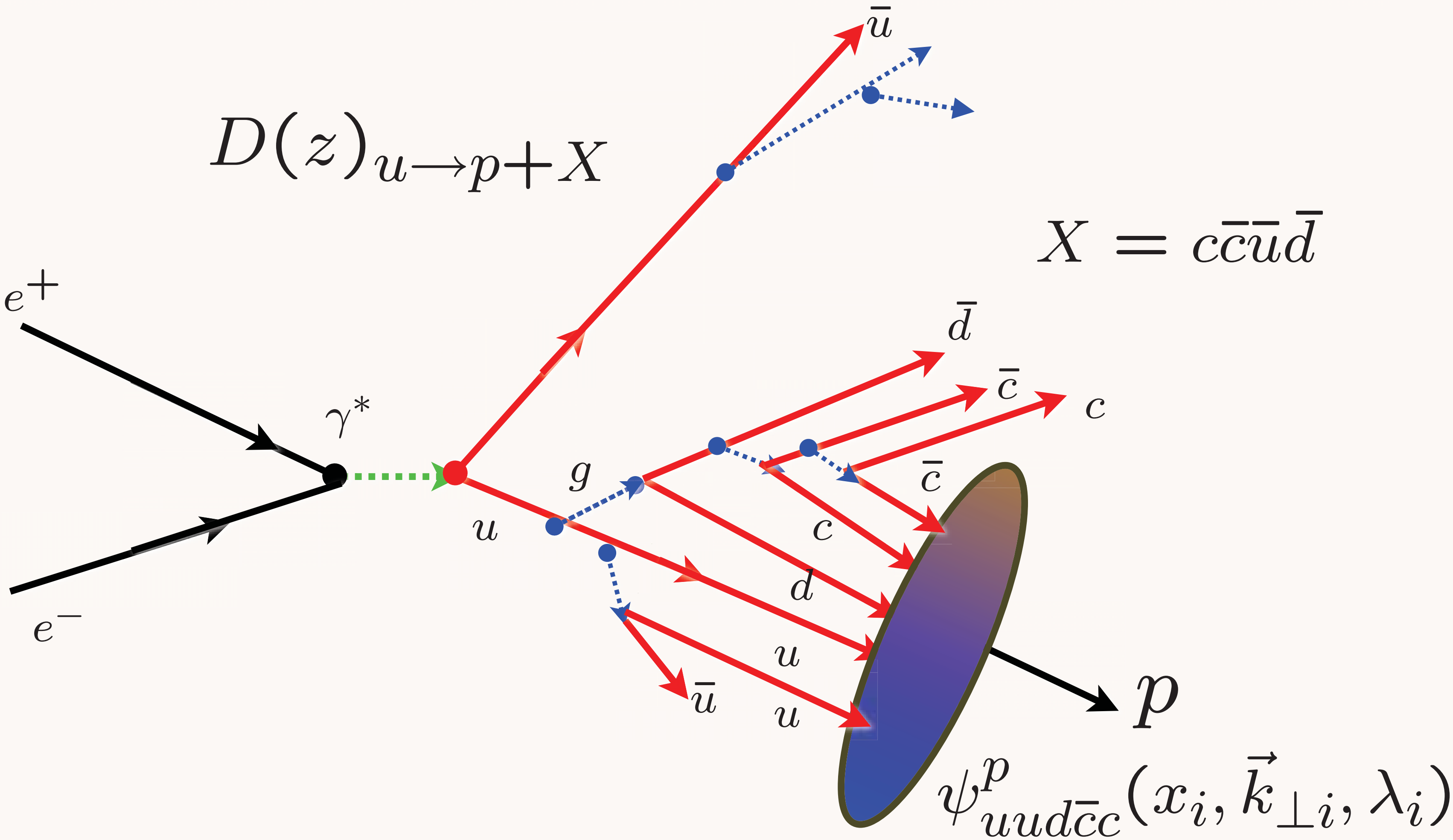
$$zD(z)_{c\to pX} = F_{p\to cX}(x = 1/z)$$



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

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

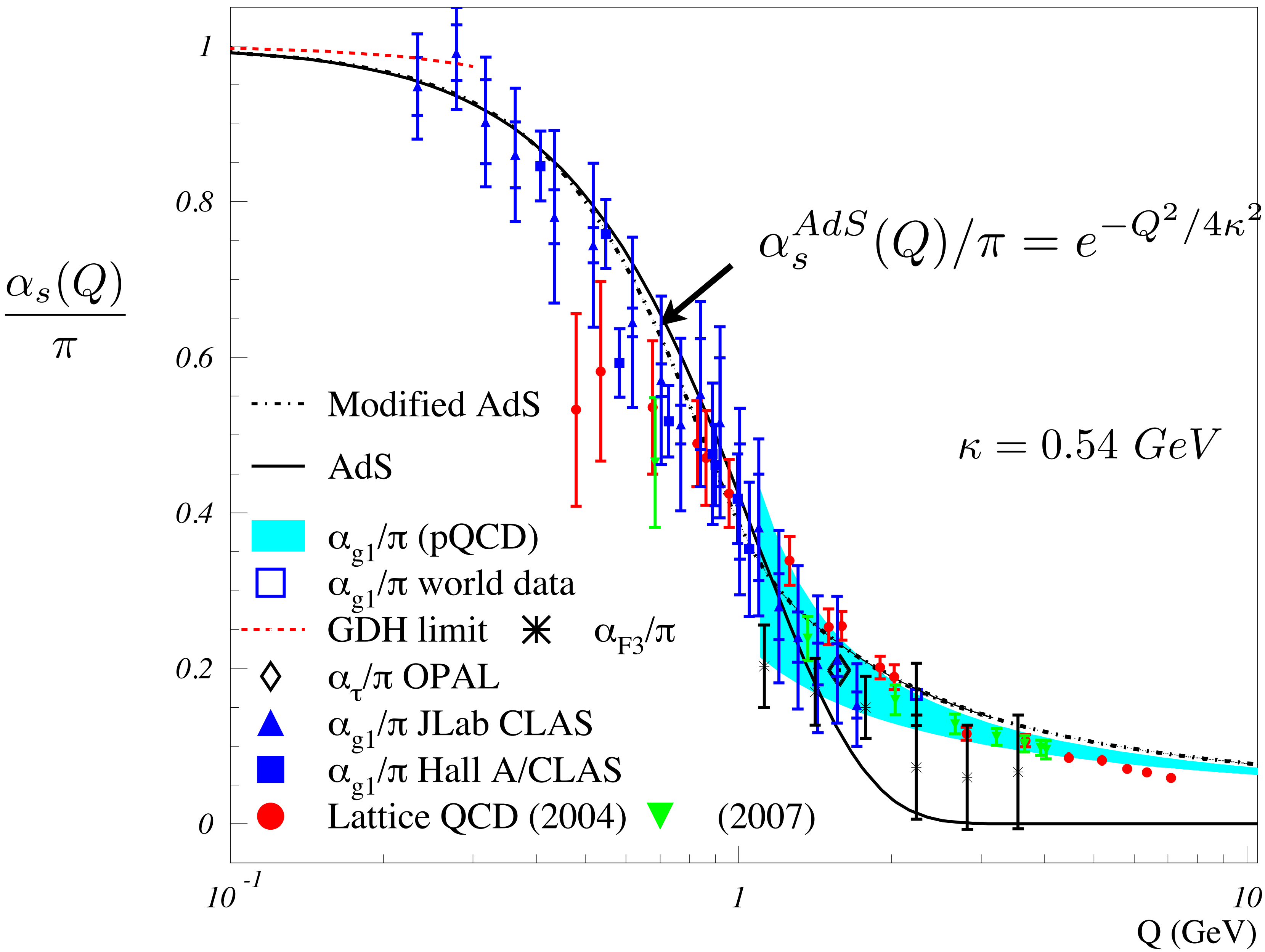
Distribution of spectators in X reflects proton bound-state structure



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

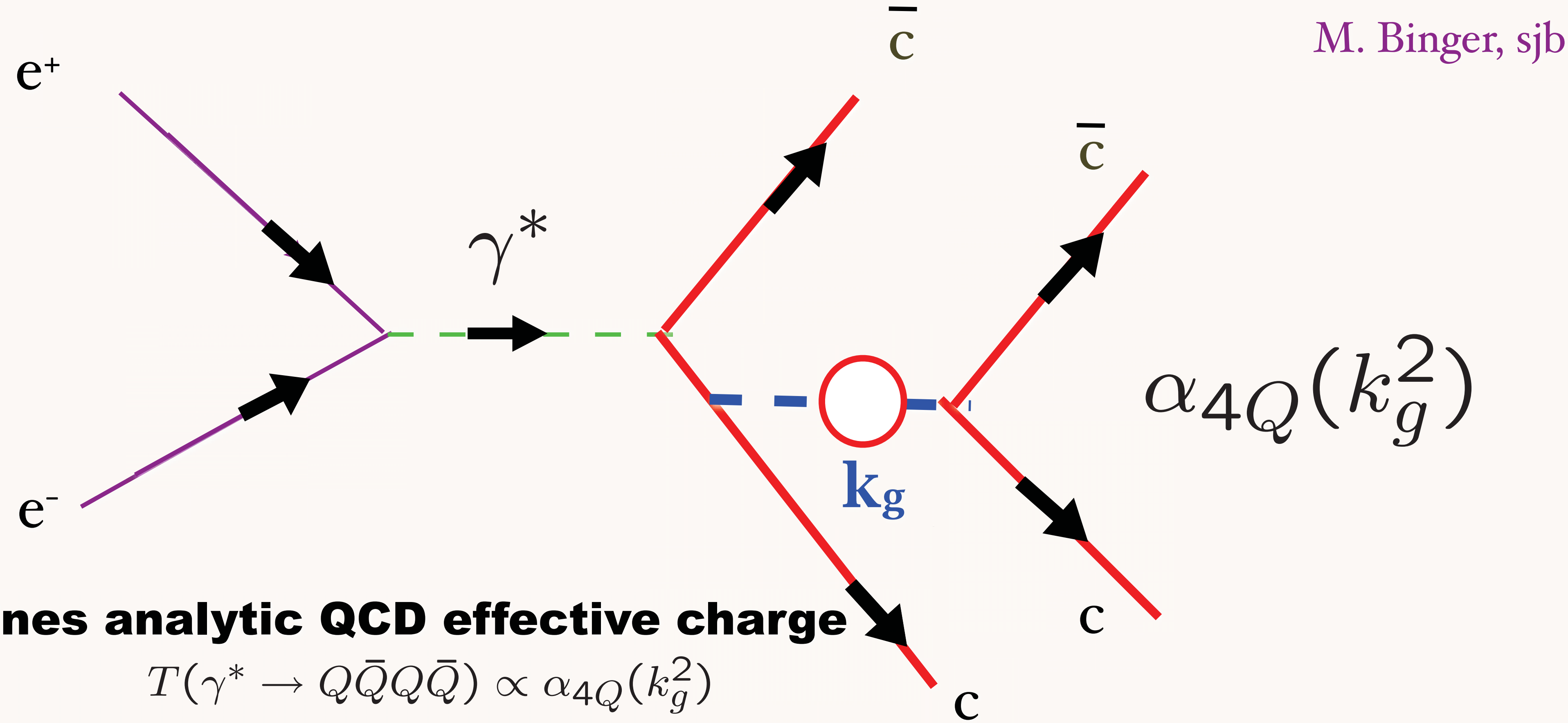
Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



Deur, de Teramond, sjb

Production of four heavy-quark jets



Defines analytic QCD effective charge

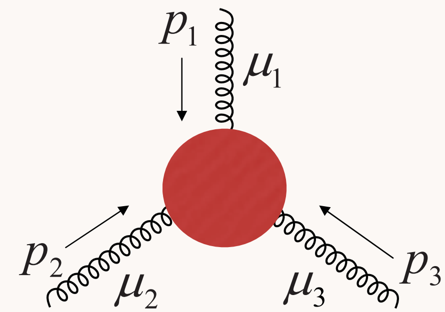
$$T(\gamma^* \to Q\bar{Q}Q\bar{Q}) \propto \alpha_{4Q}(k_g^2)$$

time-like values not same as space-like

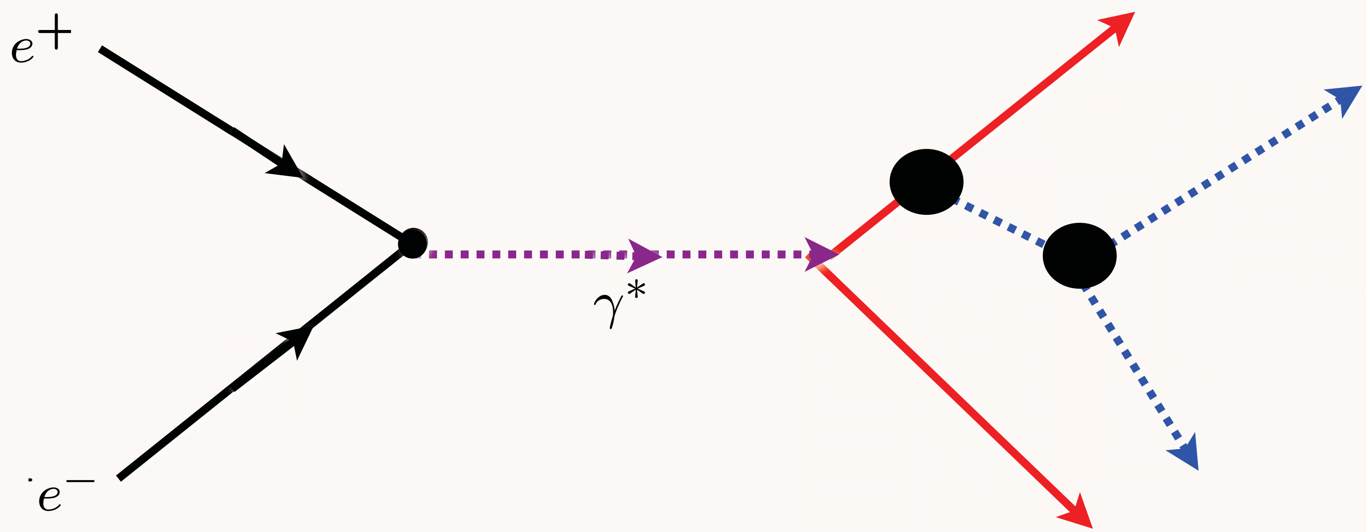
coupling similar to "pinch" scheme

complex for time-like argument

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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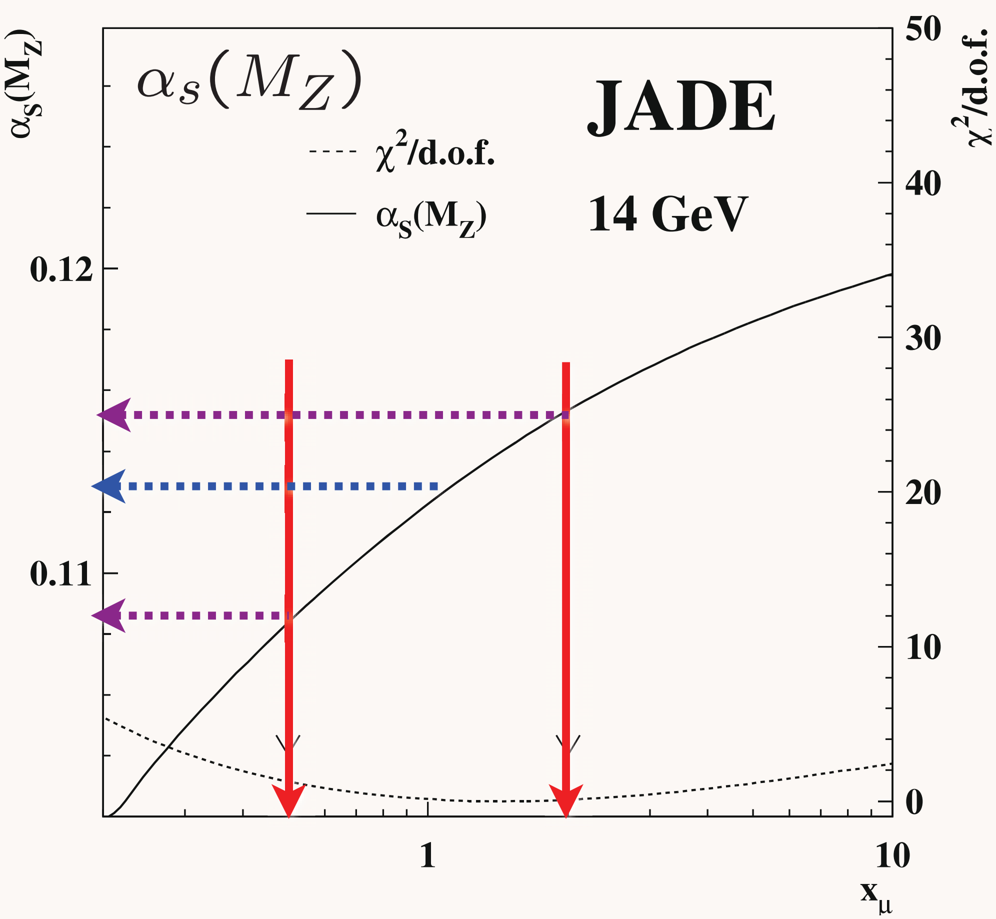
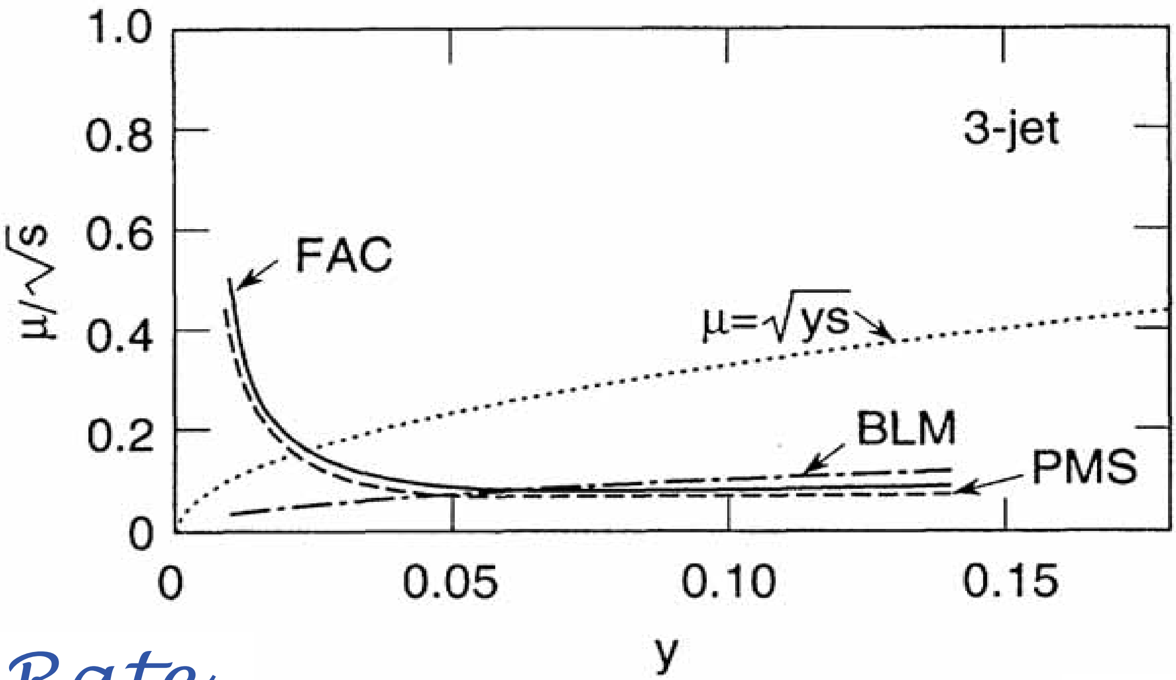


$$x_\mu = \frac{\mu_R}{\sqrt{s}}$$

No PMS

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



Three-Jet Rate

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 [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.

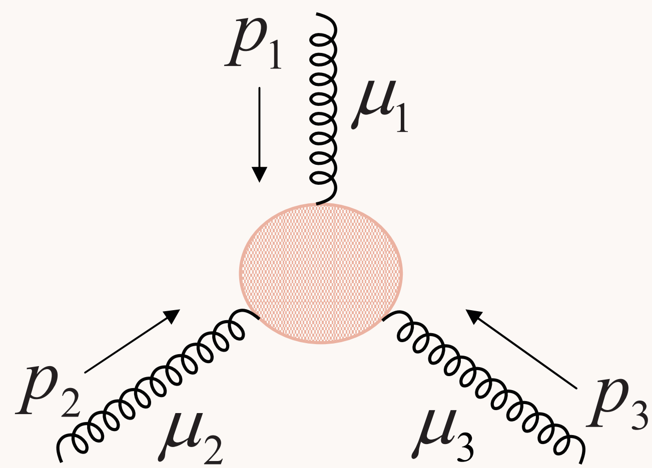
The Renormalization Scale Problem

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

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

Is there a way to set the renormalization scale μ_R ?

What happens if there are multiple physical scales ?



Electron-Electron Scattering in QED

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

- Gauge Invariant. Dressed photon propagator
- Sums all vacuum polarization, non-zero beta terms into running coupling.
- Crucial for precision muonic atom spectroscopy
- 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!
- Two separate physical scales. Sums all vacuum polarization, non-zero beta terms.

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

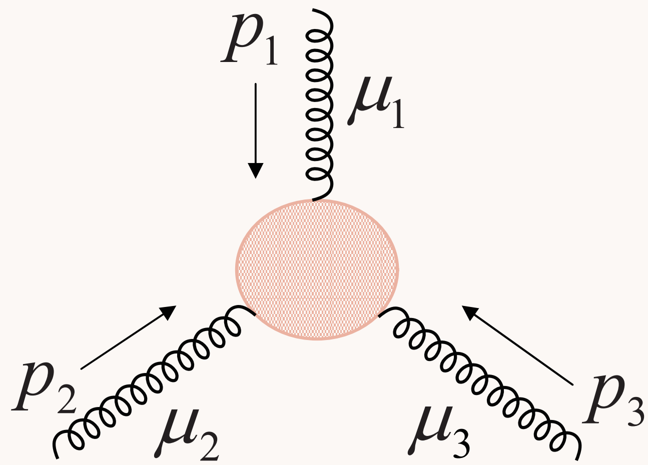
Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb **Phys.Rev.D28:228,1983**

- All terms associated with 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

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



H. J. Lu
Binger, sjb

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

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

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

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

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

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!

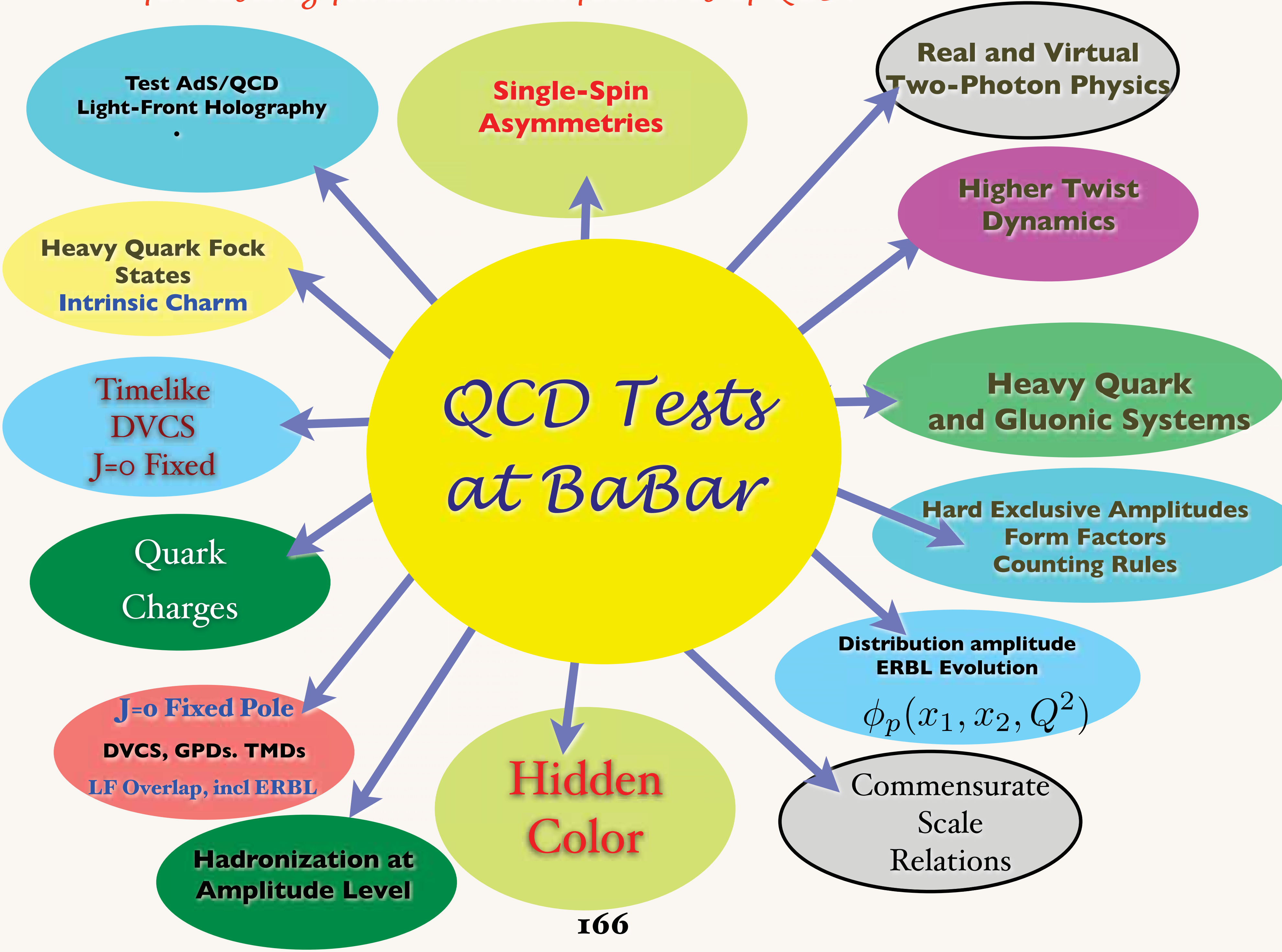
QCD Opportunities at BaBar

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

QCD Opportunities at BaBar

- Timelike DVCS, Form Factors
- 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
- Several energies
- Fully exploit BaBar data
- Complimentary to GSI-FAIR, JLab Studies

The BABAR energy range is an ideal domain for testing fundamental features of QCD.



- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, rescattering, shadowing, non-universal antishadowing ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities.

—Mark Twain

Top-Ten BaBar QCD Measurements

		Slide
Timelike Transition Form Factors	$\gamma^* \to \pi^0 \gamma$	5
Direct Production of Hadrons	$\gamma^* \to \pi X$	26
Timelike Pion DVCS	$\gamma^* \to \pi^+ \pi^- \gamma$	17
Two-Photon Production of Neutral Pions	$\gamma\gamma \to \pi^0 \pi^0$	111
Timelike Test of Intrinsic Charm via Fragmentation	$\gamma^* \to c + p + \bar{c}$	147
Strangeness Asymmetry of Fragmentation Functions	$\gamma^* \to s + p + \bar{s}$	74
Timelike Single-Spin Asymmetries	$\gamma^* \to \Lambda + \pi + X$	131
Diffractive Photon Structure Functions	$\gamma^* \gamma \to X + \rho$ (with rapidity gap)	117
Fractional Charges of Quarks	$\gamma^* \to q + \bar{q} + \gamma$	5
Deuteron Production as a test of Hidden Color	$\gamma^* \to \bar{D} + \Delta + \Delta$	139