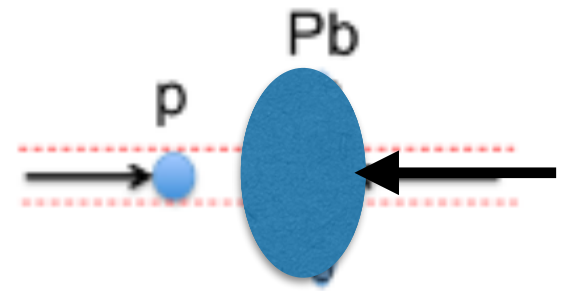
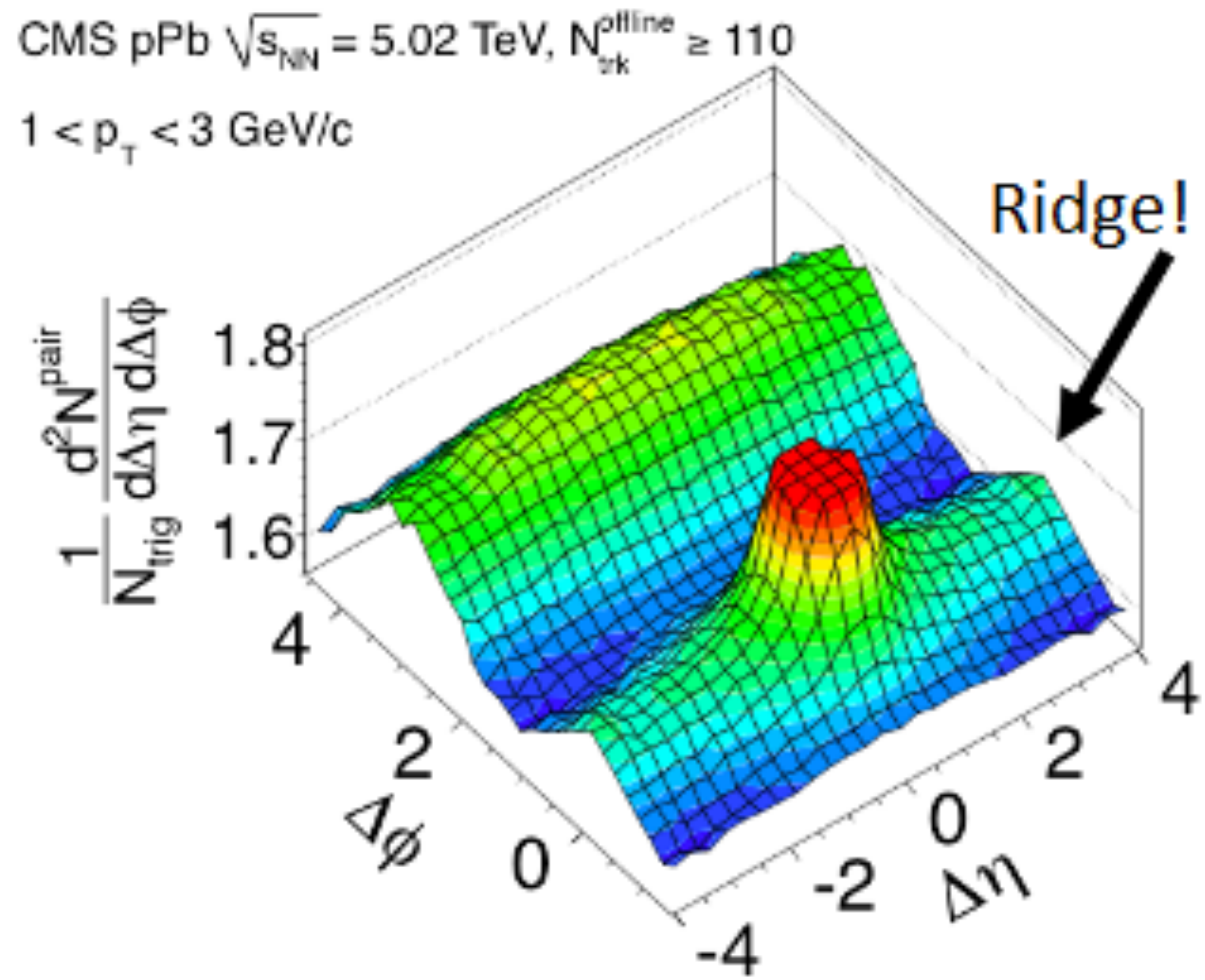
Ridge phenomena in photon-photon collisions





Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

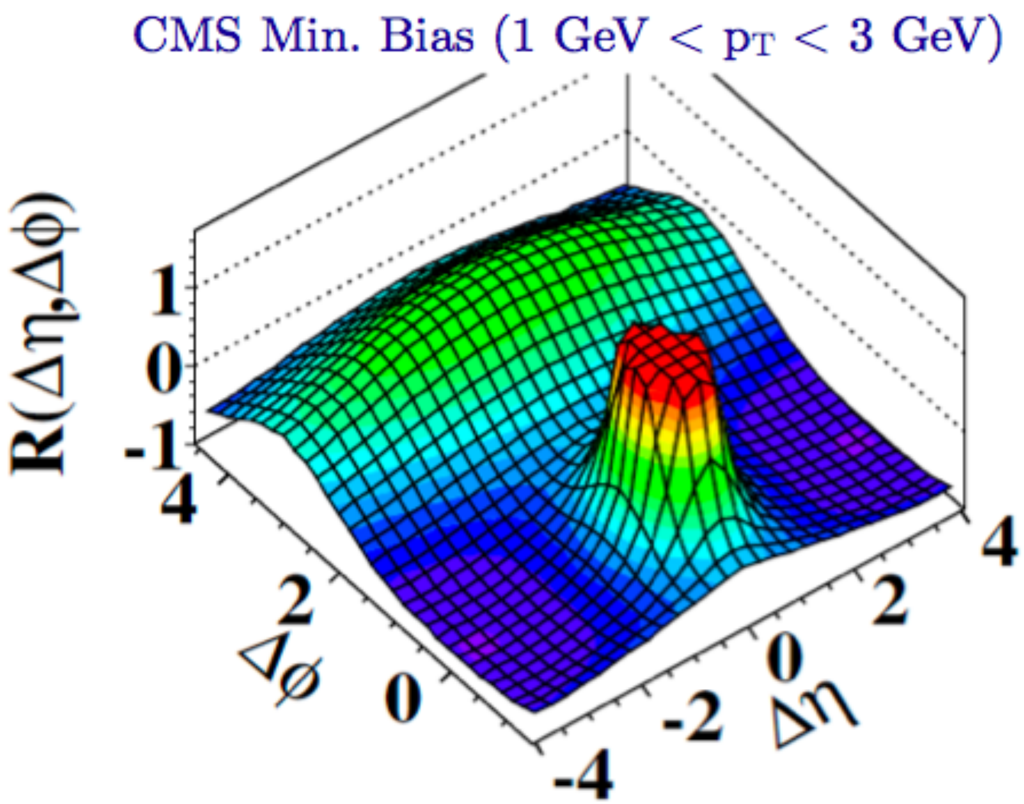
with Fred Goldhaber, Stan Glazek, Patryk Kubiczek, and Robert Brown

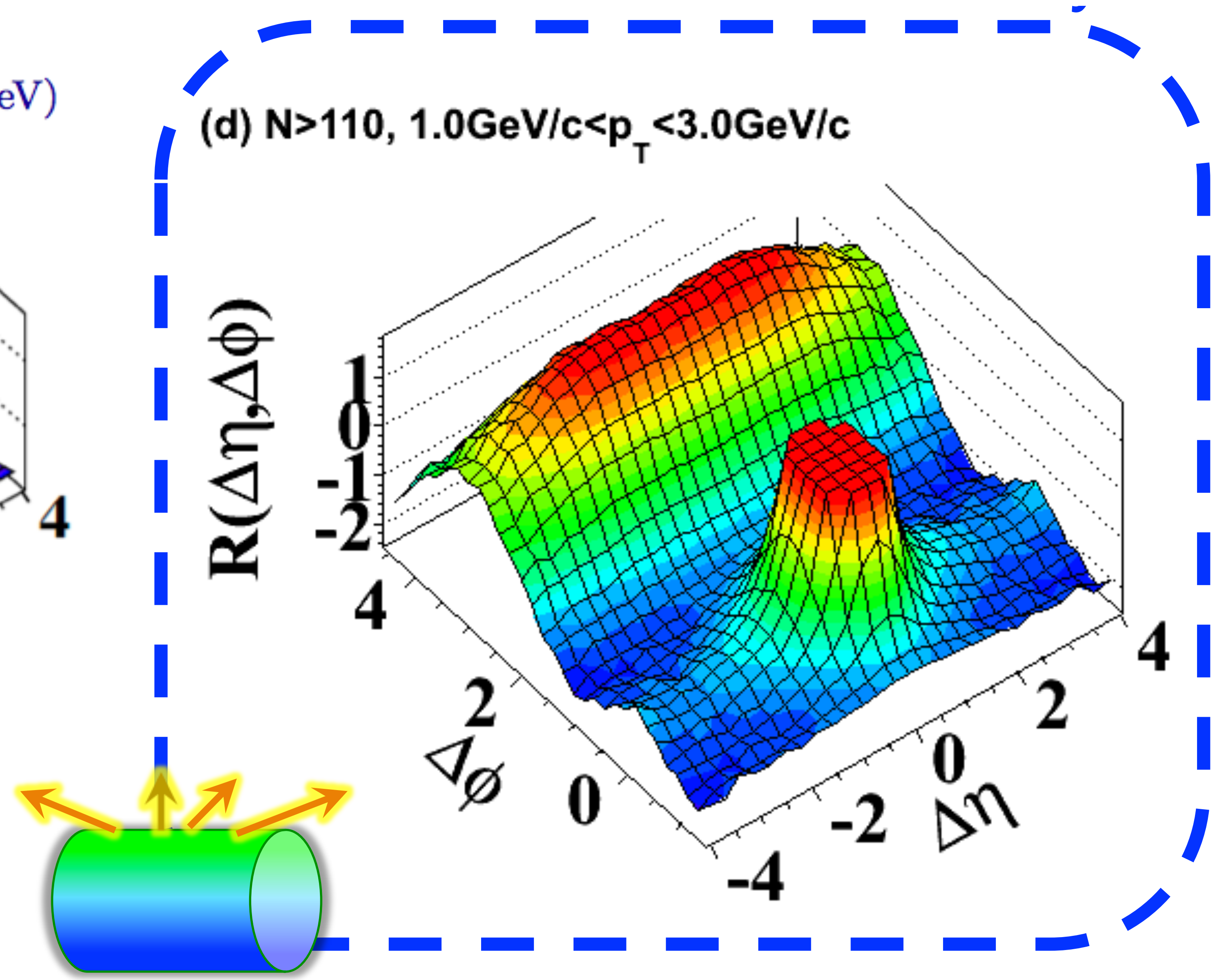
2017 International Conference on the Structure and Interactions of the Photon
22th International Workshop on Photon-Photon Collisions
International Workshop on High Energy Photon Colliders

Ridge in high-multiplicity p p collisions

Two-particle correlations: CMS results

$pp \to X$

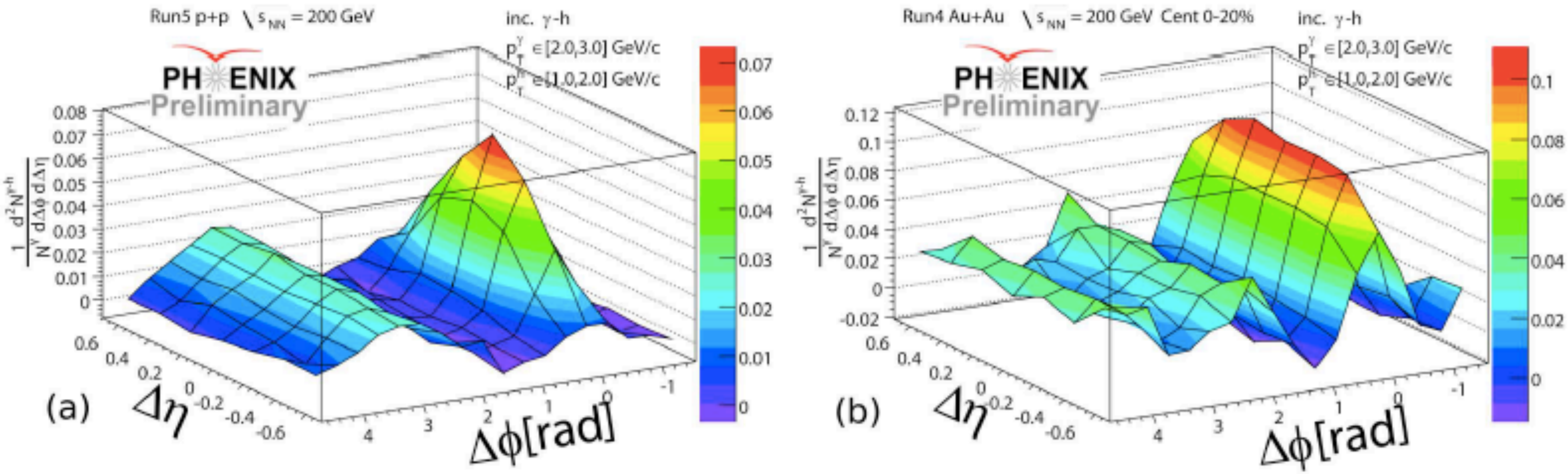




- Ridge: Distinct long range correlation in η collimated around $\Delta\Phi \approx 0$ for two hadrons in the intermediate $1 < p_T, q_T < 3$ GeV

Same-side long-range correlation in rapidity

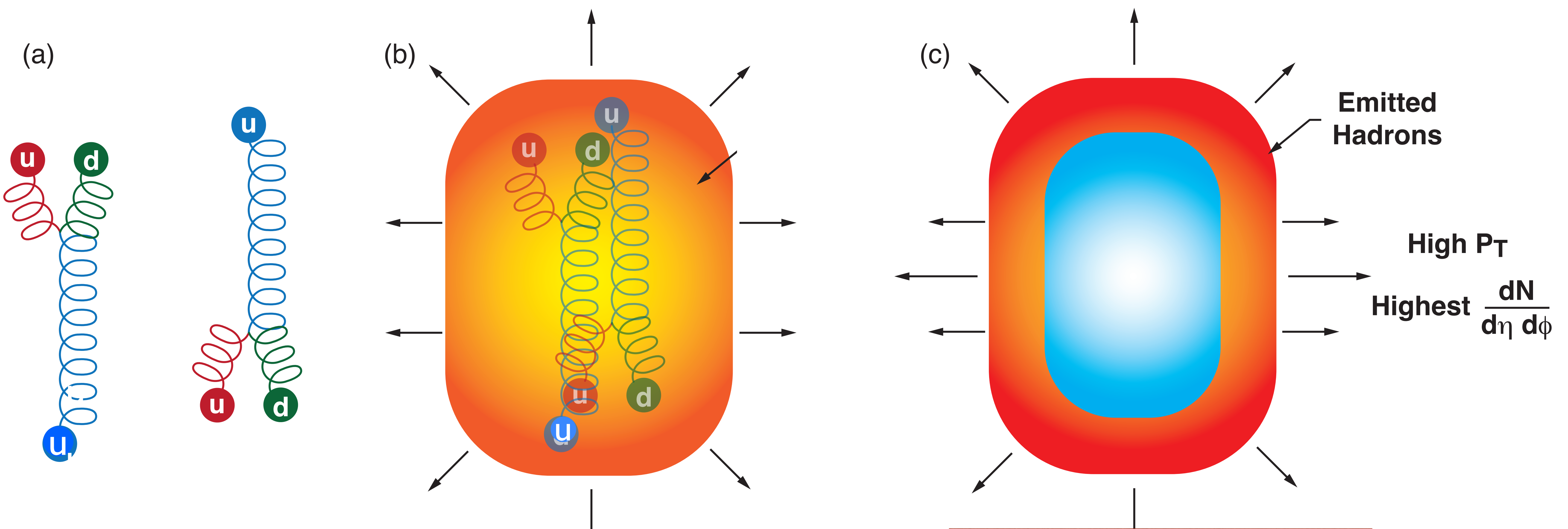
$$p + p \to X, \; \sqrt{s} = 200 \text{ GeV} \qquad Au + Au \to X, \; \sqrt{s} = 200 \text{ GeV}$$



Ridge phenomena observed in both p-p and Au-Au collisions

Collisions of Flux Tubes Can Produce Ridge Phenomena in photon-photon (EIC) and in ultra-peripheral collisions (UPC)

Ridge may reflect collision of aligned flux tubes

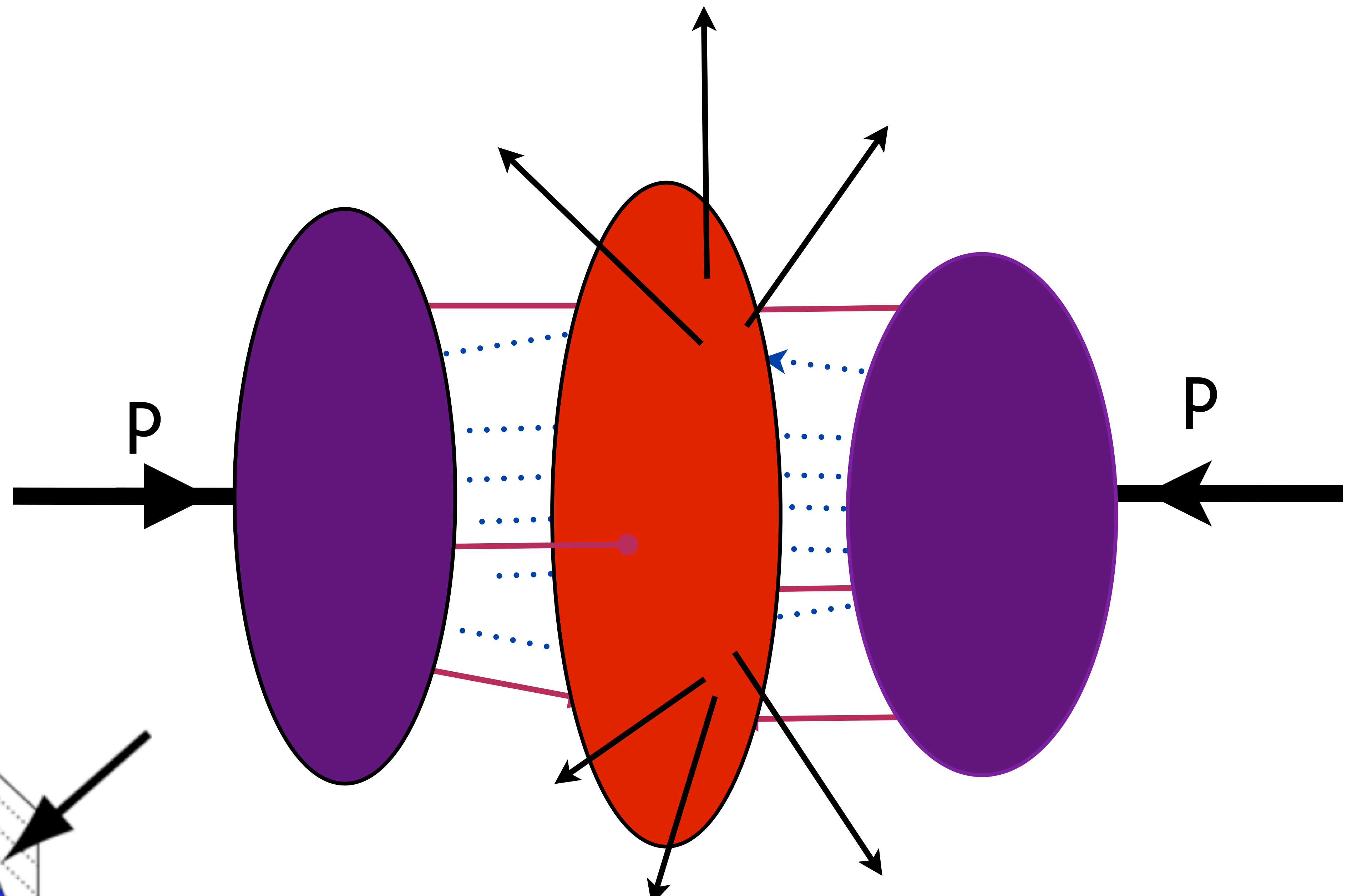


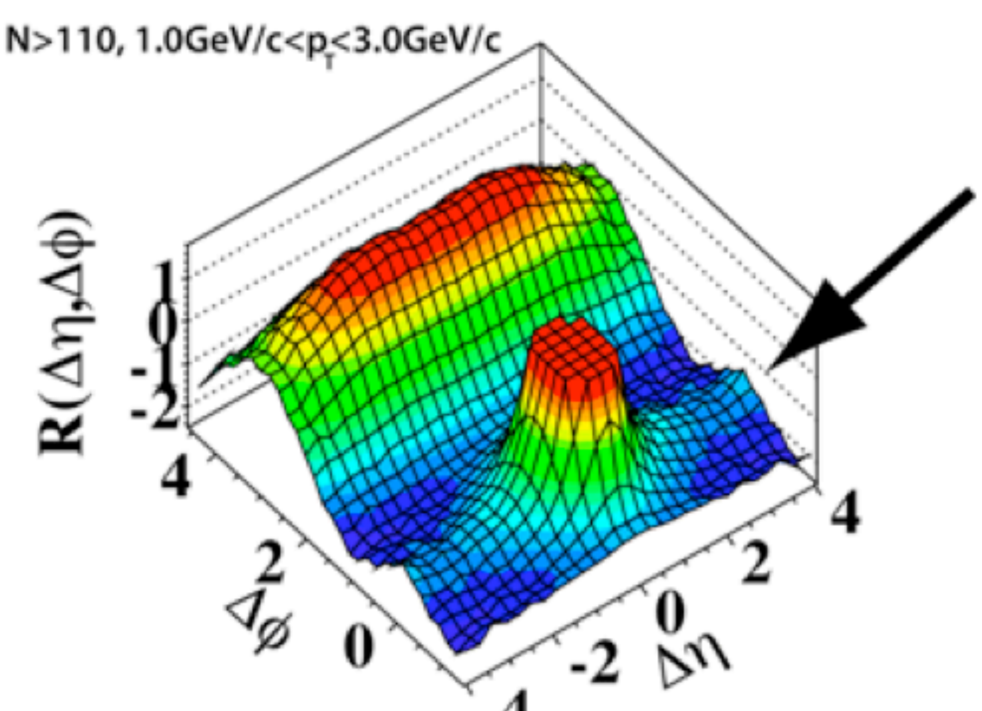
High density QCD regime

Hadrons produced at all rapidities alignment in Φ

Bjorken, Goldhaber, sjb

Collisions of Aligned Flux Tubes Can Produce Ridge Phenomena





Multiparticle ridge-like correlations in very high multiplicity proton-proton collisions

Bjorken, Goldhaber, sjb

We suggest that the "ridge" correlations may be a reflection of the rare events generated by the collision of aligned flux tubes connecting the valence quarks in the wave functions of the colliding protons.

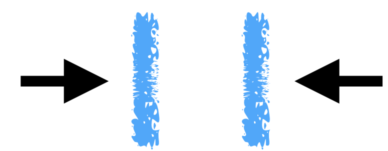
The "spray" of particles resulting from the approximate line source produced in such inelastic collisions then gives rise to events with a strong correlation between particles produced over a large range of both positive and negative rapidity.

Collisions of flux tubes of protons

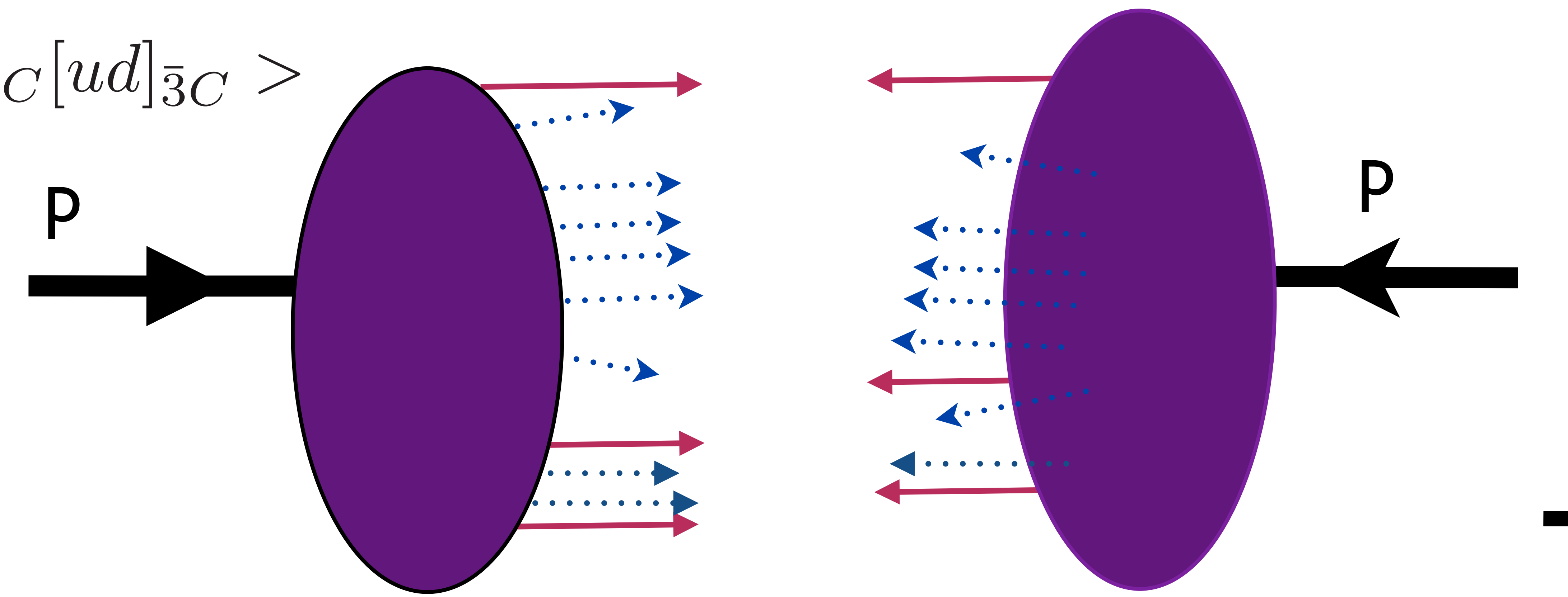
Color confinement potential —> high density gluon field: flux tube

Highest hadron multiplicity produced when the two flux tubes are aligned and overlap completely along their length.

Hadrons produced from the collisions of flux tubes



$$|p >= |u_{3C} [ud]_{\bar{3}C} >$$



Gluonic distribution reflects quark+diquark color structure of the protons

v_2 (dominant) + v_3 (from `Y' quark + diquark configurations)

Bjorken, Goldhaber, sjb

AdS/QCD + Light Front Holography: Proton is bound state of a quark + scalar diquark

de Teramond, Dosch, Lorce, sjb

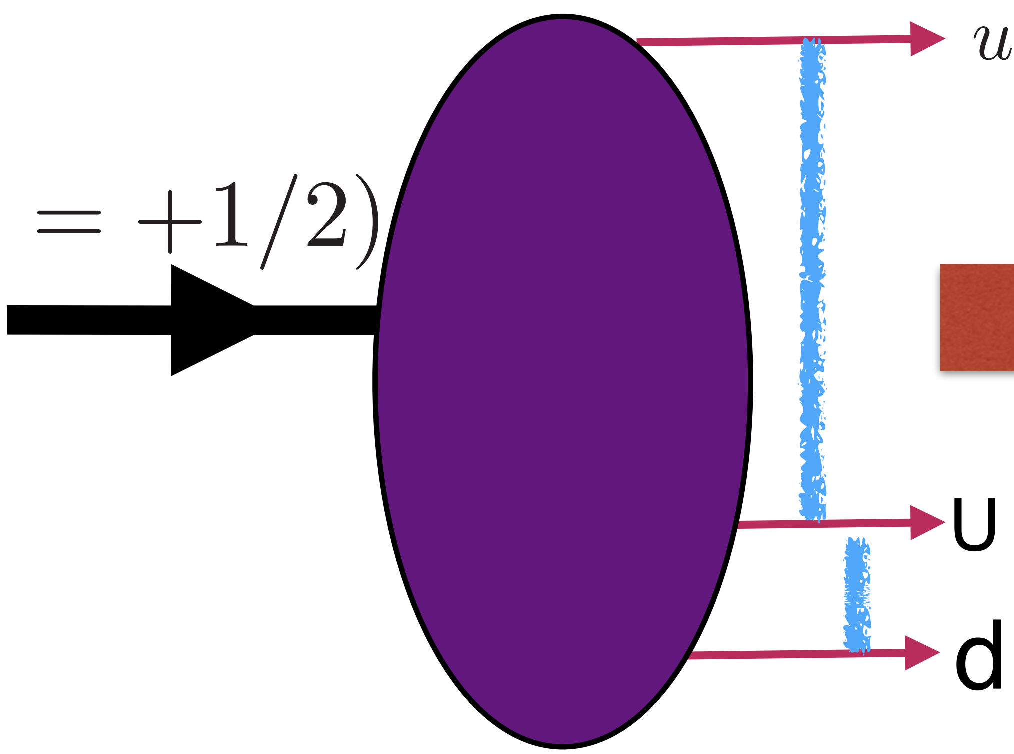
Skyrme model: Ellis, Karliner, sjb

LF J^z conservation: K. Chiu, sjb

$$3_C \times 3_C = \bar{3}_C + \cancel{6_C}$$

$$|p> = |u_{3C}[ud]_{\bar{3}C}>$$

$p(J^z = +1/2)$



$u(S^z = +1/2)$

$L^z = 0$

or

$u(S^z = -1/2)$

$L^z = +1$

Equal probability L=0, L=1

J=0

Quark chiral symmetry
Anomalous moment nonzero
Leading Twist Sivers Effect

Gluonic distribution reflects quark+diquark color structure of the proton

Color confinement potential —> high density gluon field: flux tube

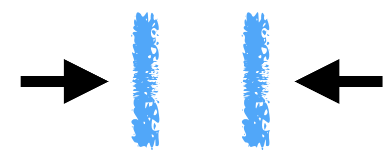
Collisions of flux tubes of protons

Color confinement potential —> high density gluon field: flux tube

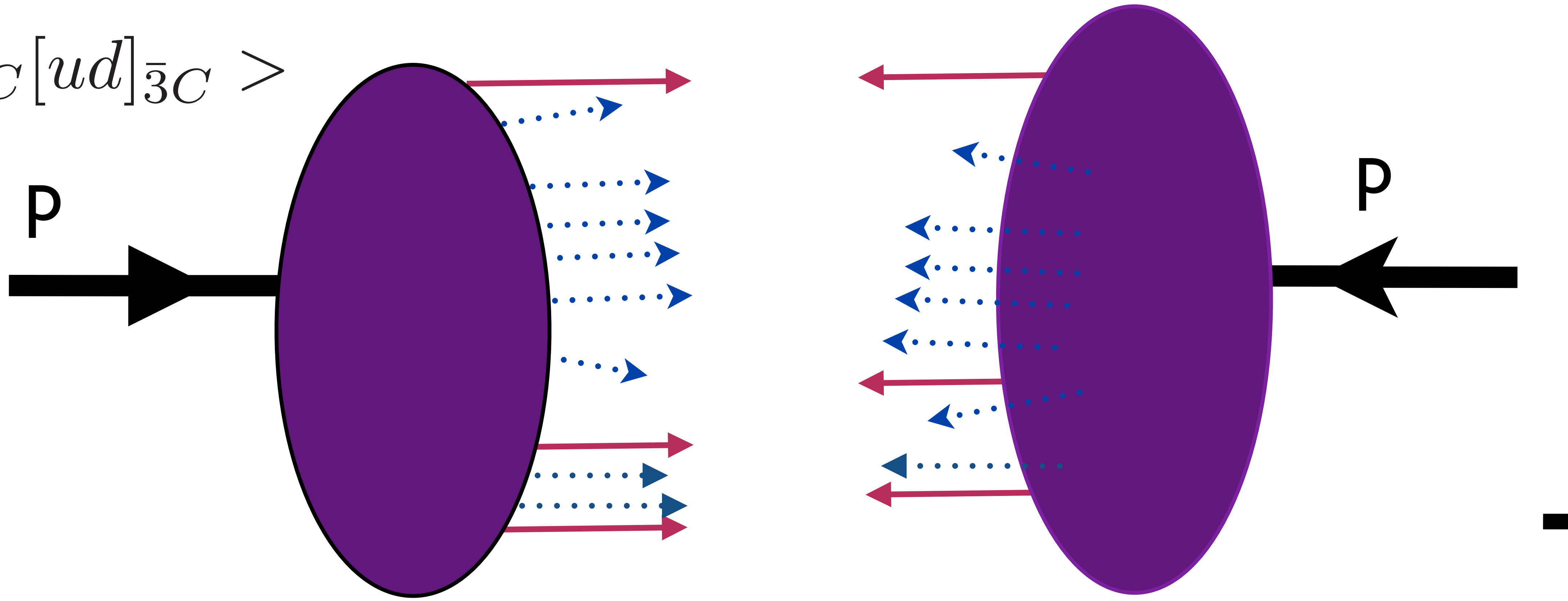
Highest hadron multiplicity produced when the two flux tubes are aligned and overlap completely along their length.

Bjorken, Goldhaber, sjb

Hadrons produced from the collisions of flux tubes



$$|p> = |u_{3C}[ud]_{\bar{3}C}>$$



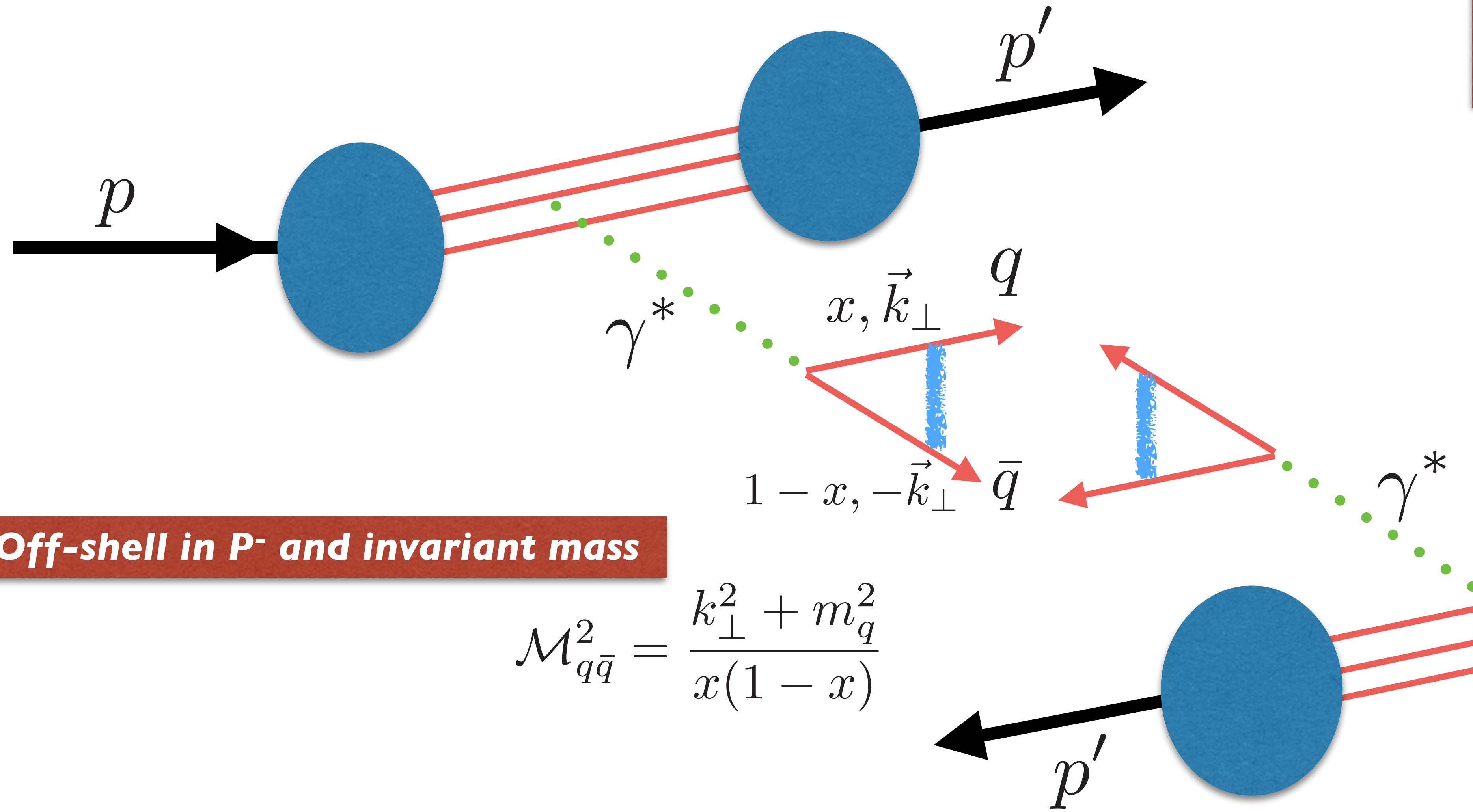
Gluonic distribution reflects quark+diquark color structure of the protons

v_2 (dominant) + v_3 (from \`Y' quark + diquark configurations)

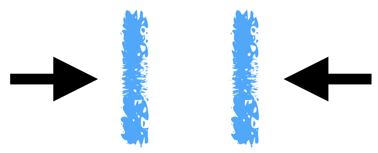
- ***Strangeness and charm enhancements***

Ridge creation in Ultra-Peripheral pp scattering

$$pp \to \gamma^* \gamma^* p' p' \to X p' p'$$



Hadrons produced from the collisions of flux tubes



Off-shell in P⁻ and invariant mass

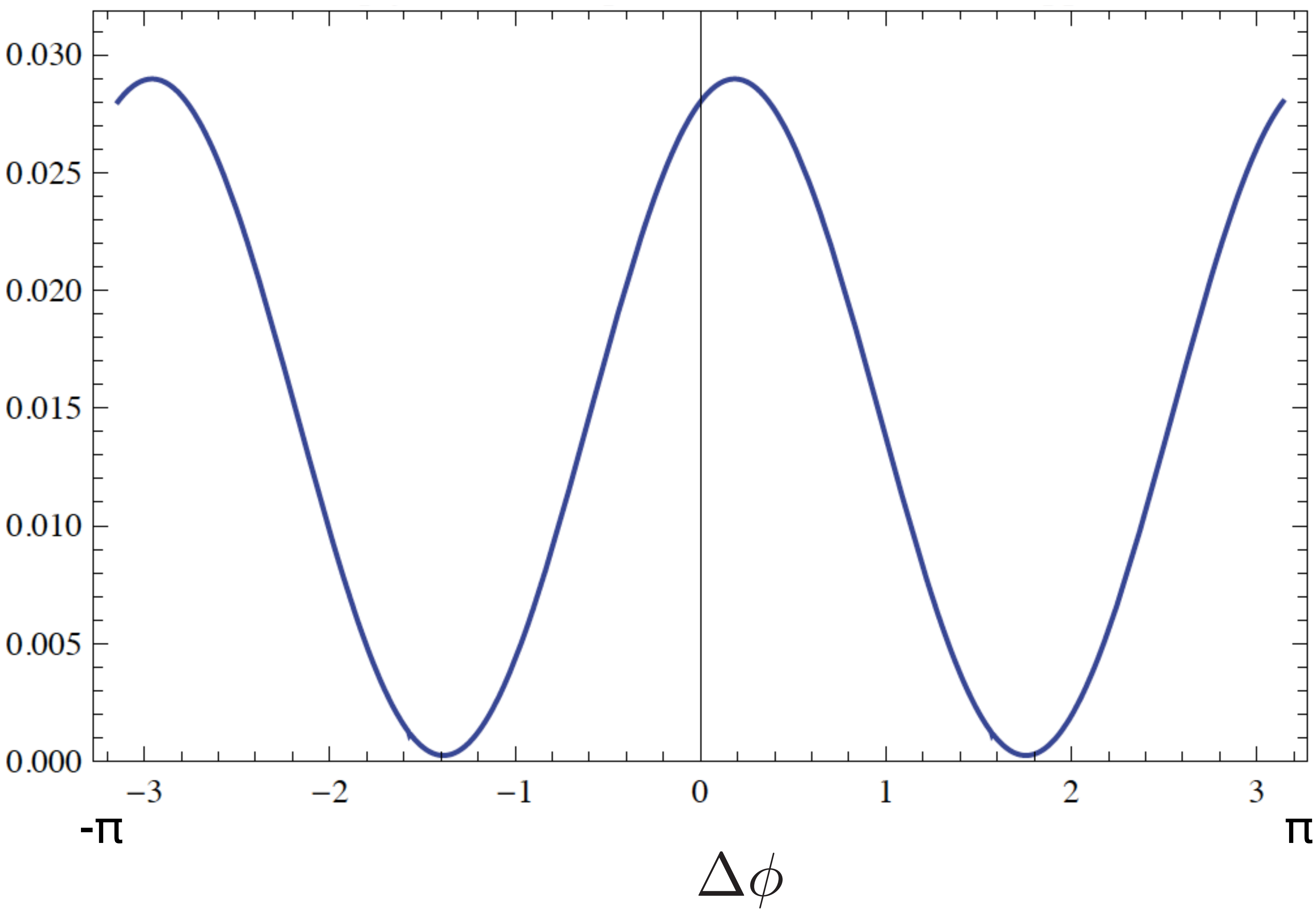
$$\mathcal{M}^2_{q\bar{q}} = \frac{k_\perp^2 + m_q^2}{x(1-x)}$$

Planes of quark anti-quark and produced ridges aligned with planes of proton scattering!

Correlation of $q\bar{q}$ and proton scattering planes: $\sim \cos^2 \Delta\phi$

Angular correlation ΔΦ between the proton scattering plane and quark-antiquark production plane

$$\frac{dN}{d\Delta\phi}(\Delta\phi, x, Q^2, \mathcal{M}^2_{q\bar{q}})$$



$$x = \frac{k^+_{P'}}{k^+_P} = 0.5$$

$$\mathcal{M}_{q\bar{q}} = 8 \text{ GeV}$$

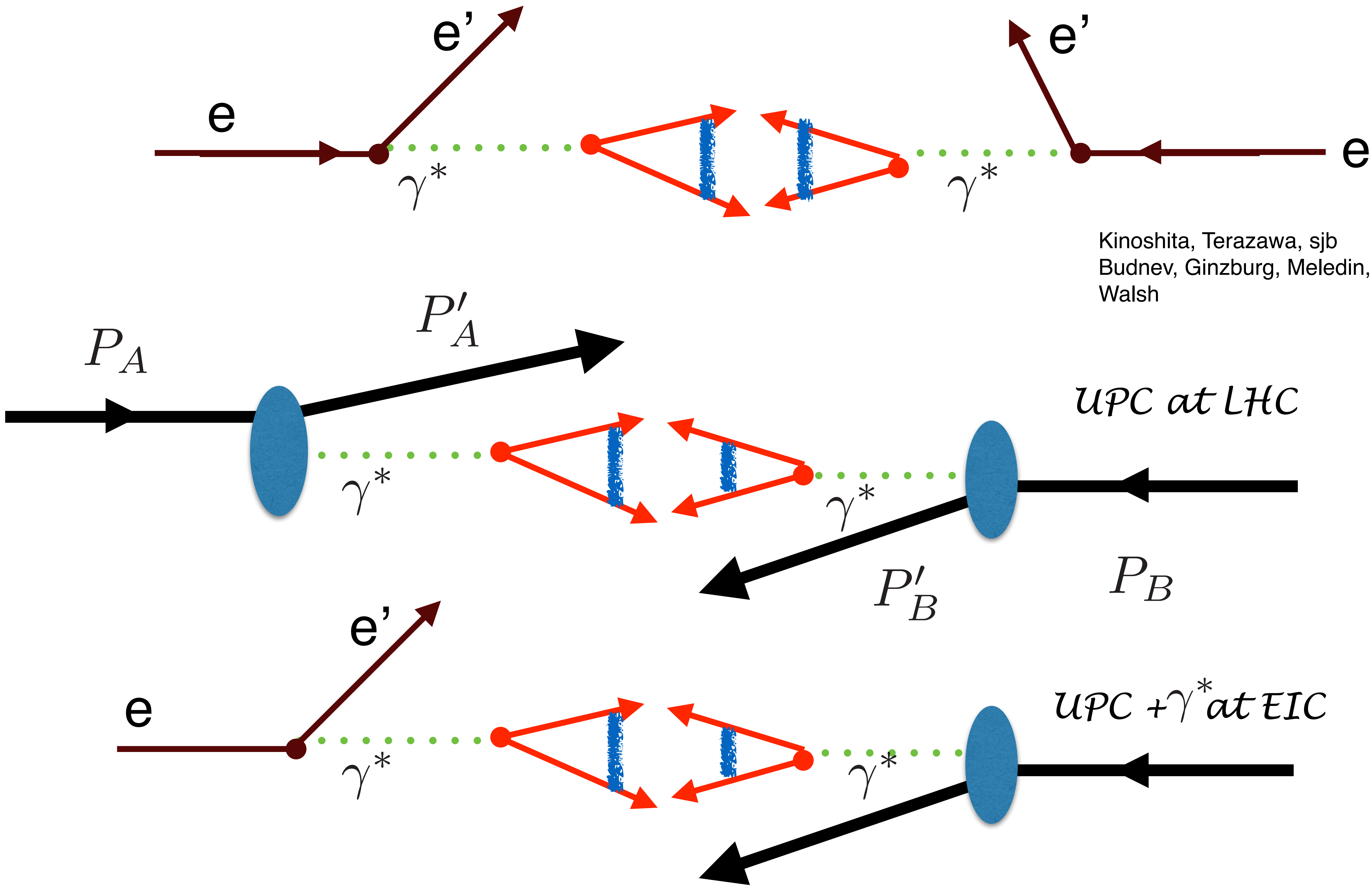
$$Q^2 = 0.94 \text{ GeV}^2$$

(preliminary)

Collisions of Gluonic Strings in Ultra-Peripheral Collisions

- ***Virtual photon polarization correlates quark-antiquark plane with the proton scattering planes***
- ***quark-antiquark plane aligned with proton scattering plane*** $\sim \cos^2 \Delta\phi$
- ***maximum hadron multiplicity from flux tubes of colliding strings between two aligned quark-antiquark pairs***
- ***maximum hadron multiplicity produced when both protons scatter in same plane!***
- ***mininum hadron multiplicity when protons scatter at orthogonal angles*** $\Delta\phi = \pi/2$
- ***quark-antiquark pair distributions determined from each virtual photon LFWF***
- ***Strangeness and charm enhancements***

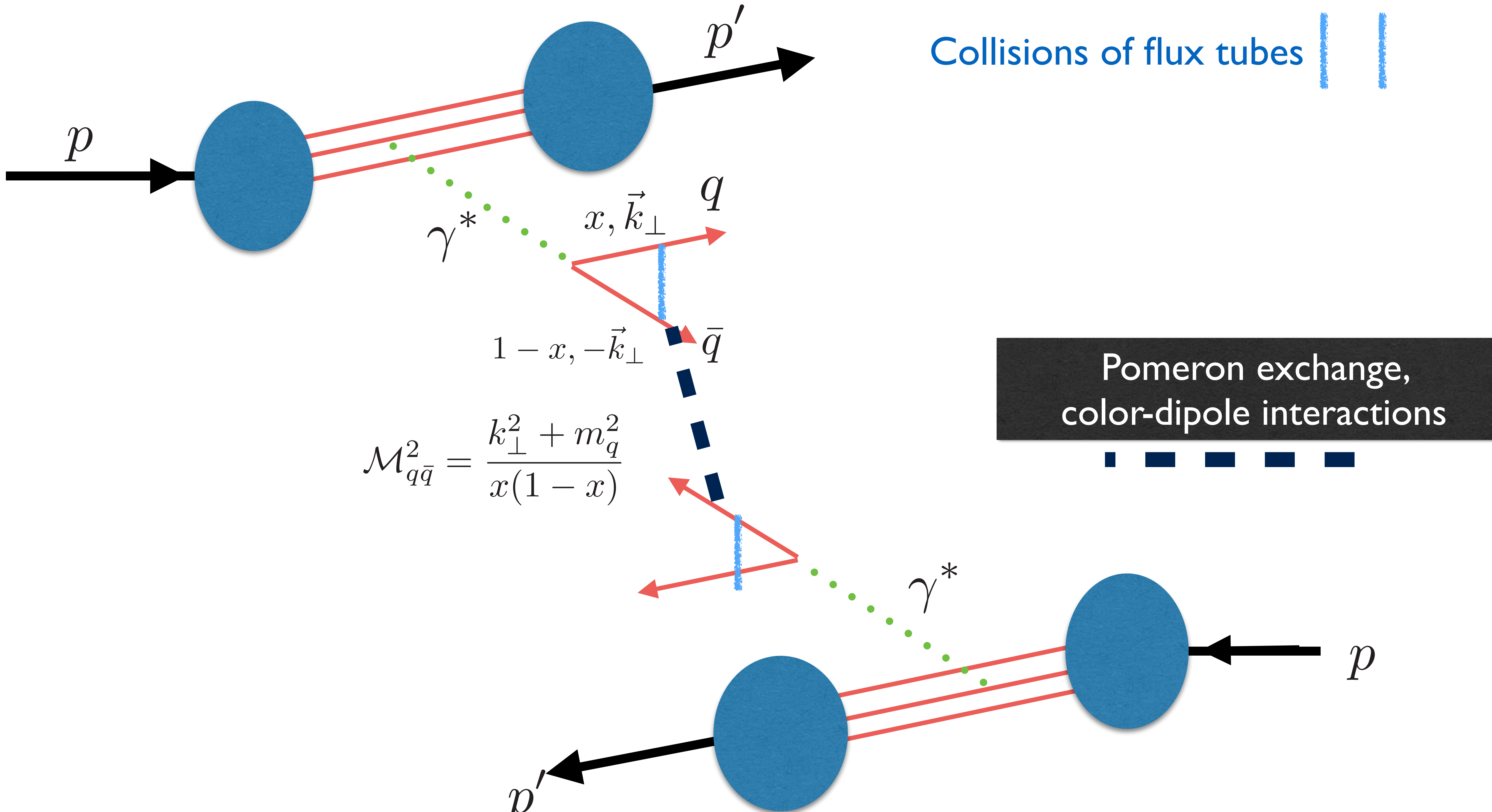
Collisions of Aligned Flux Tubes in Photon-Photon and UPC Interactions



Kinoshita, Terazawa, sjb
Budnev, Ginzburg, Meledin, Serbo
Walsh

Ridge creation in Ultra-Peripheral pp scattering

$$pp \to \gamma^* \gamma^* p' p' \to X p' p'$$



Estimate of total cross section: $\sigma_{\rm UPC}(pp \to p'p'\gamma^*\gamma^* \to p'p'X) \sim 5$ pb

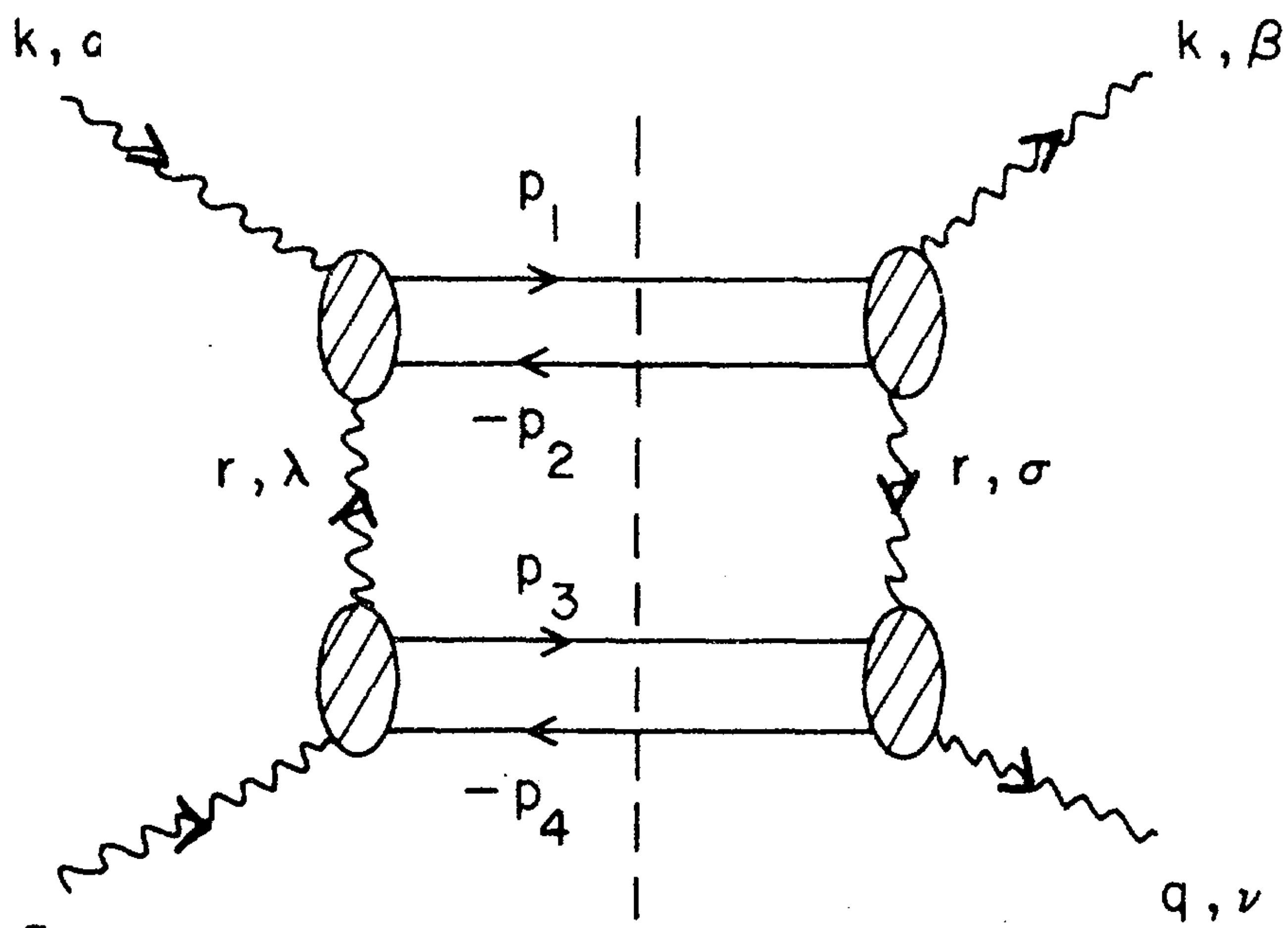
QED Analog

$$e^- e^+ \to e^- \gamma^* e^+ \gamma^* \to e^- (\mu^+ \mu^-) e^+ (\mu^+ \mu^-)$$

Role of γ+γ→e⁺+e⁻+e⁺+e⁻ in Photoproduction, Colliding Beams, and Cosmic Photon Absorption

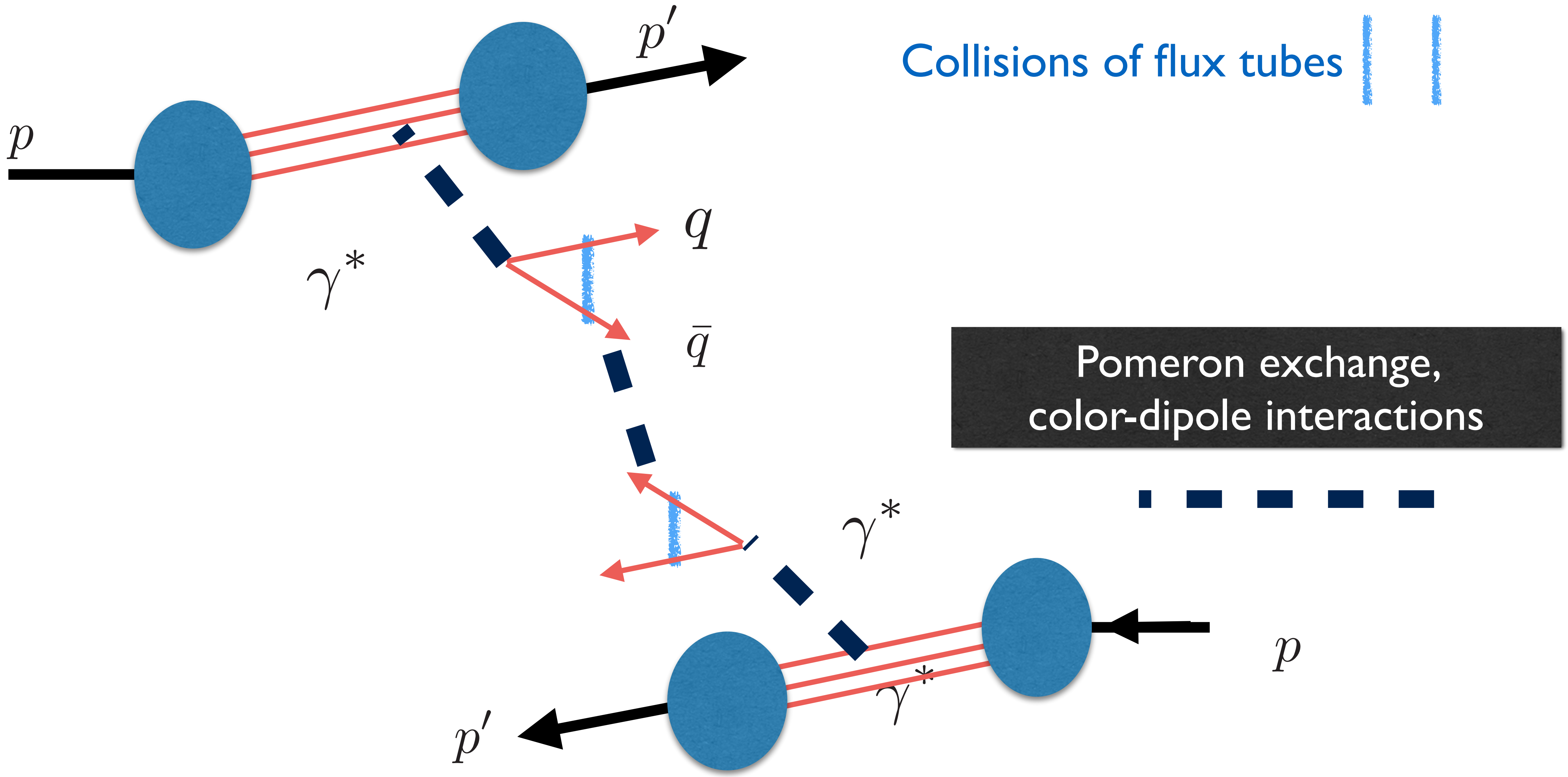
R. W. Brown, W. F. Hunt, K. O. Mikaelian, and I. J. Muzinich

Phys. Rev. D 8, 3083 (1973)



Ridge creation in Doubly Diffractive pp scattering

$$\sigma_{\rm DD}(pp \to p'p'X)$$

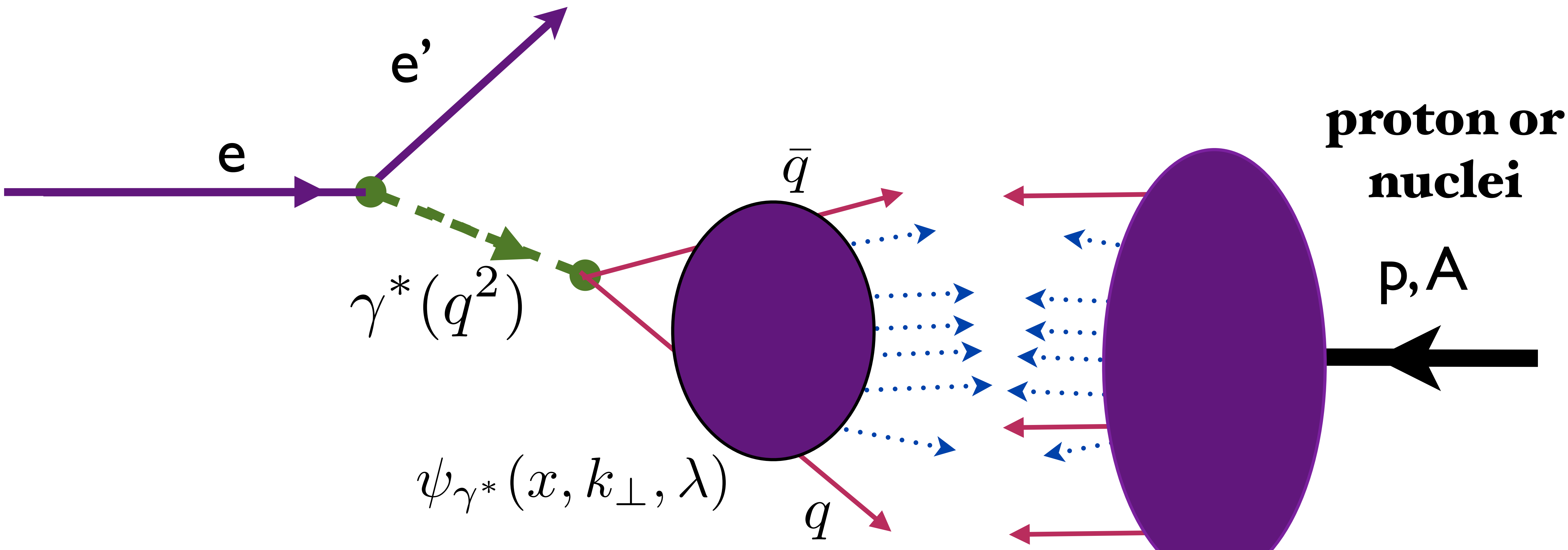


Estimate double diffractive cross section:

$$\sigma_{\rm DD}(pp \to p'p'X) \sim \frac{1}{\alpha^4}\sigma_{\rm UPC}(pp \to p'p'\gamma^*\gamma^* \to p'p'X) \sim 50\mu b$$

Electron-Ion Colliders: Virtual Photon-Ion Collider

Perspective from the e-p collider frame



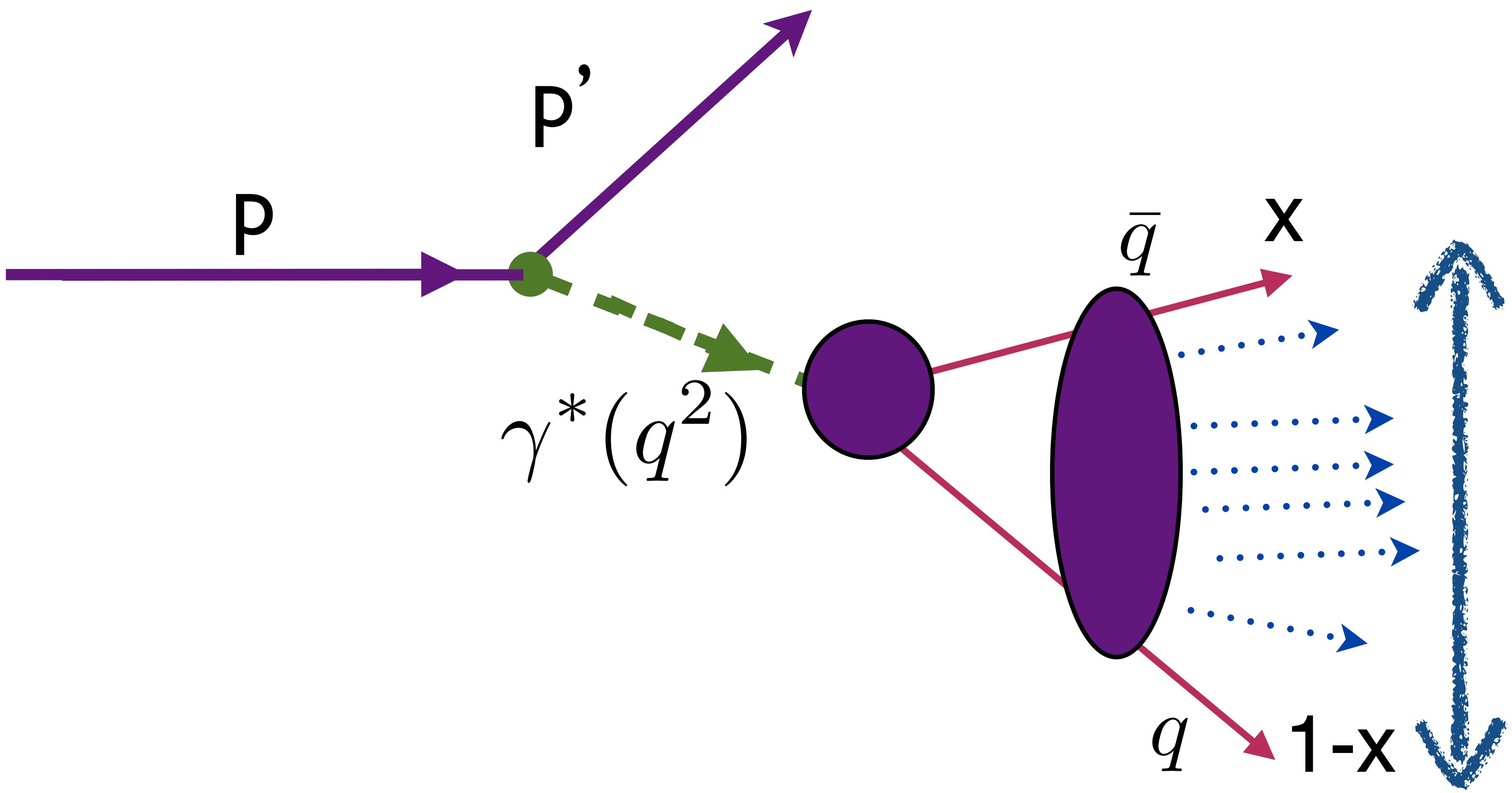
variable space-like photon virtuality, various primary flavors

$\bar{q}\, q$ plane aligned with lepton scattering plane ~ $\cos^2\phi$

Front-surface nuclear dynamics: shadowing/antishadowing

Characteristics of the quark-antiquark flux tube

Planar structure reflects color-confinement



Evolution in Light-Front Time

$$\tau = x^+ = t + z/c$$

Off-shell in $P^- = P^0 + P^z$ and invariant mass

$$\mathcal{M}^2_{q\bar{q}} = \frac{k^2_\perp + m^2_q}{x(1-x)}$$

Connection of Gluon Density to Color Confinement

Related to Trace (Conformal) Anomaly $< H|G^2|H >$

Characteristics of the quark-antiquark flux tube

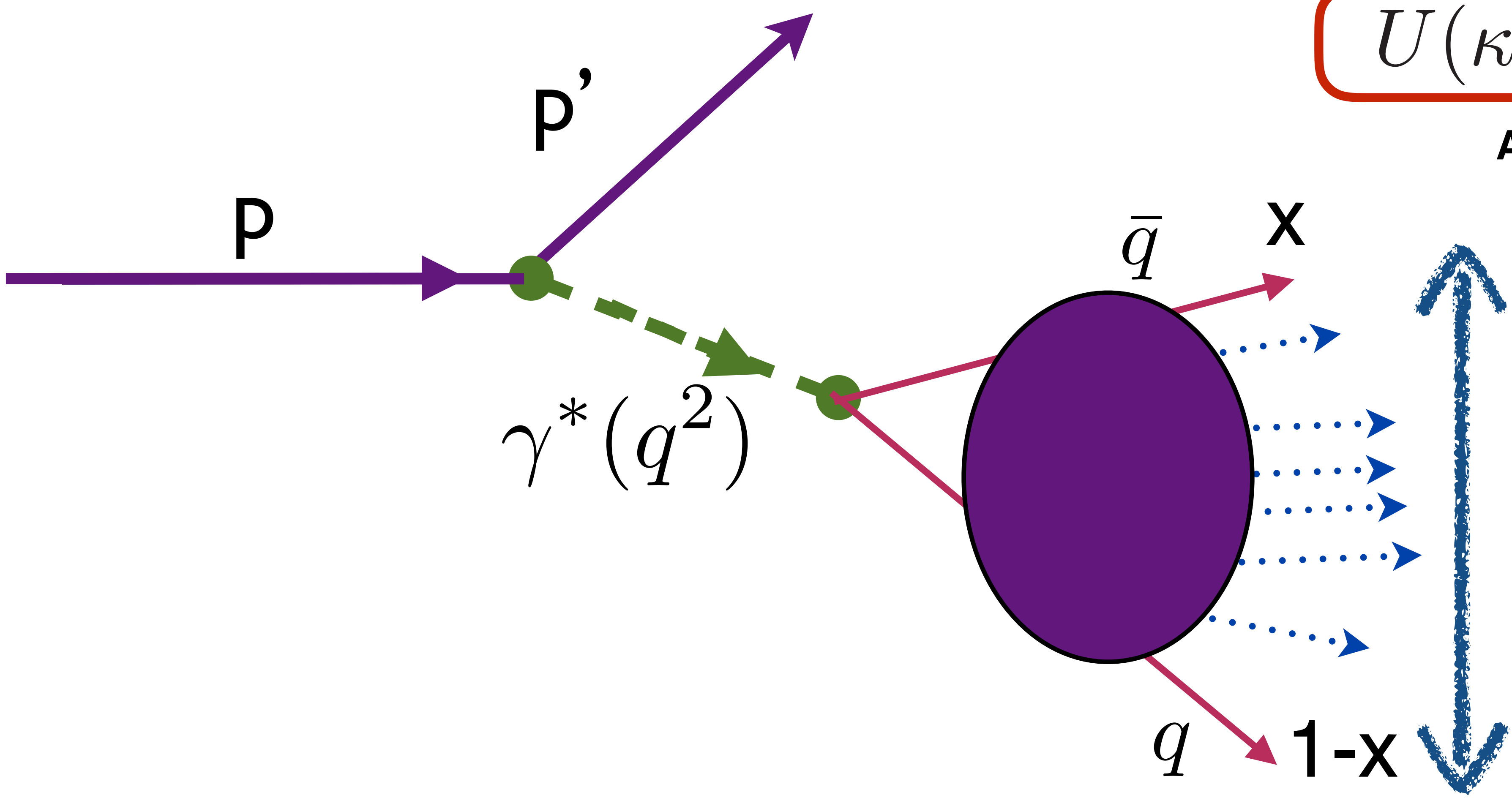
$$\psi(x, b_\perp^2, Q^2) \propto \exp -[b_\perp^2 x(1-x)(\kappa^2 + Q^2)]$$

Planar structure reflects color-confinement potential

$$U(\kappa^2) = \kappa^4 b_\perp^2 x(1-x)$$

AdS/QCD + Light-Front Holography

de Teramond, Dosch, Lorce, sjb



$$< b_\perp^2 > \propto \frac{1}{x(1-x)(\kappa^2+Q^2)}$$

massless quarks

$$< b_\perp^2 > \to \infty \text{ if } x \to 0, 1$$

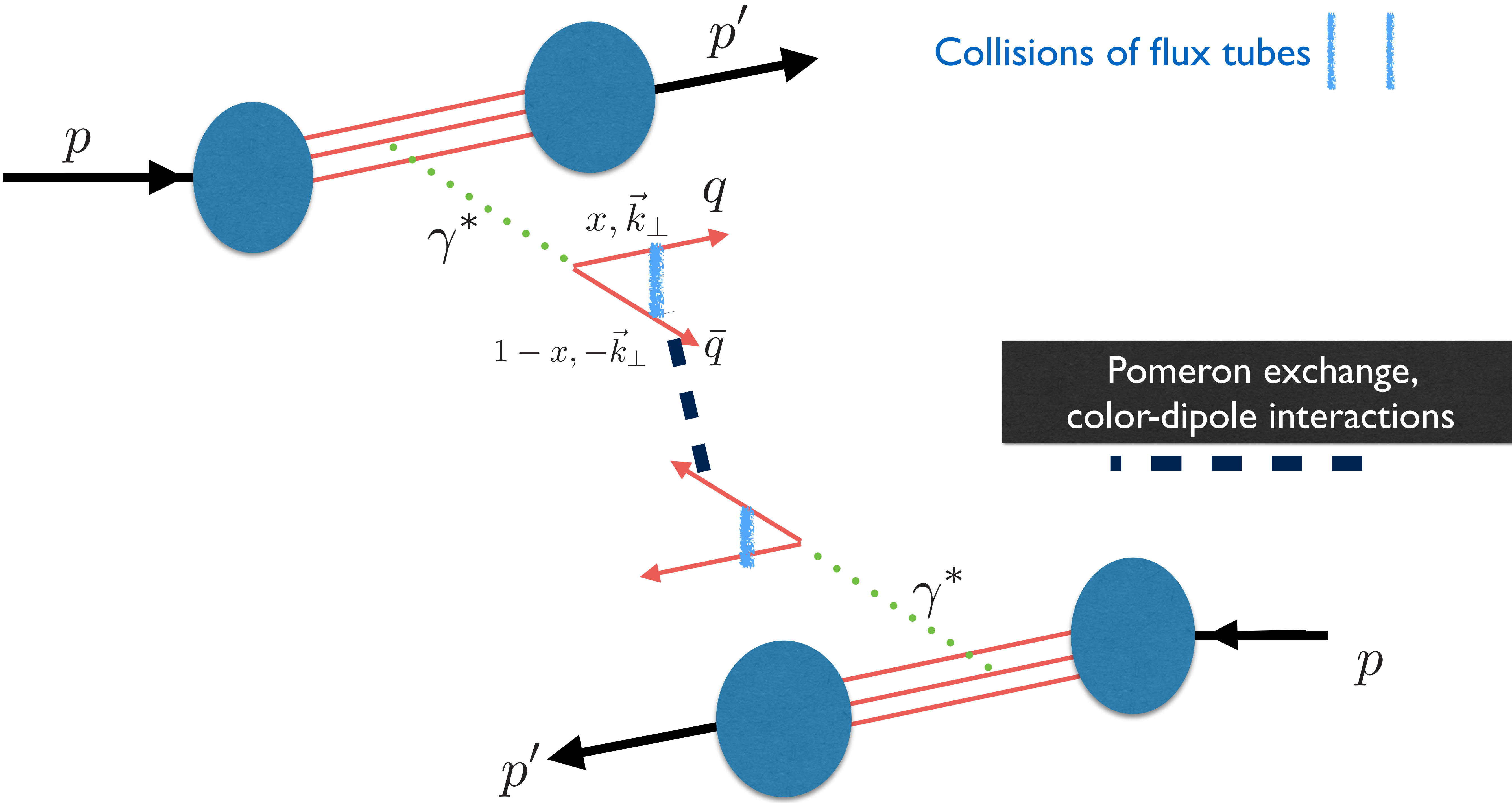
$$\mathcal{M}^2 = \frac{k_\perp^2}{x(1-x)} \propto \frac{1}{b_\perp^2 x(1-x)}$$

$$< b_\perp^2 > \propto \frac{1}{x(1-x)(\kappa^2+Q^2)+m_q^2}$$

massive quarks

Ridge creation in Ultra-Peripheral pp scattering

$$pp \to \gamma^* \gamma^* p' p' \to X p' p'$$



Important Issue: Do interactions modify the planar orientations?

Color Confinement and Gluonic Flux Tubes

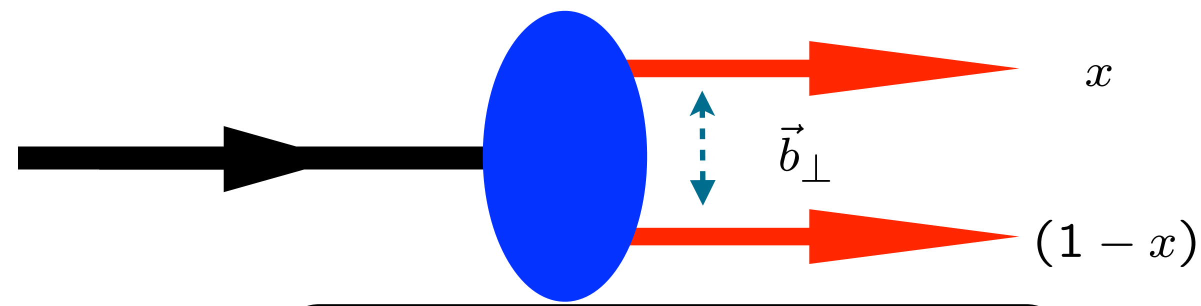
Unique
Confinement Potential!

Connection of Gluon Density to Color Confinement
Related to Trace (Conformal) Anomaly $< H|G^2|H >$

Light-Front QCD

$\mathcal{L}_{QCD} \rightarrow H^{LF}_{QCD}$

Fixed $\tau = t + z/c$



$$\zeta^2 = x(1-x)b^2_\perp$$

$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2|\Psi>$$

Coupled Fock states

Eliminate higher Fock states
and retarded interactions

$$[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\rm eff}]\ \psi_{LF}(x,\vec{k}_\perp) = M^2\ \psi_{LF}(x,\vec{k}_\perp)$$

Effective two-particle equation

$$\left[-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = M^2\psi(\zeta)$$

Azimuthal Basis ζ, ϕ

$m_q = 0$

Single variable ζ

AdS/QCD:

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Confining AdS/QCD
potential!

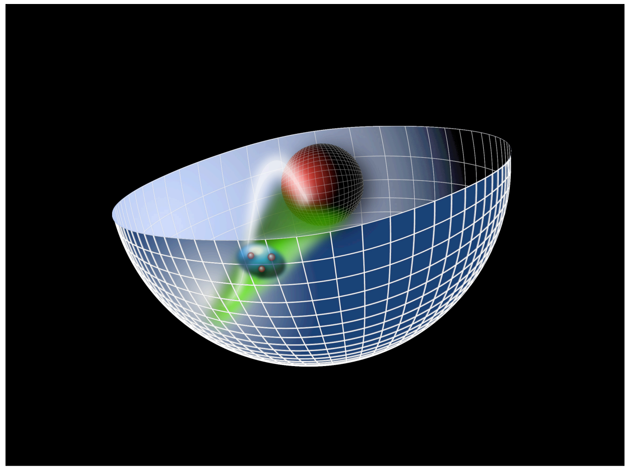
Semiclassical first approximation to QCD

Sums an infinite # diagrams

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$



$$\zeta^2 = x(1-x)\mathbf{b}^2_\perp.$$

Light-Front Holography

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Preserves Conformal Symmetry of the action

$$\kappa \simeq 0.5\ GeV$$

Confinement scale:

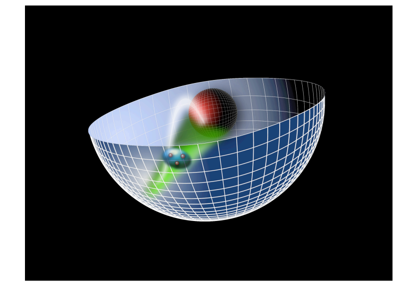
$$1/\kappa \simeq 1/3\ fm$$

- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

Dilaton-Modified AdS/QCD

$$ds^2 = e^{\varphi(z)} \frac{R^2}{z^2}(\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$



- Soft-wall dilaton profile breaks conformal invariance $e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- Color Confinement in z
- Introduces confinement scale κ
- Uses AdS_5 as template for conformal theory

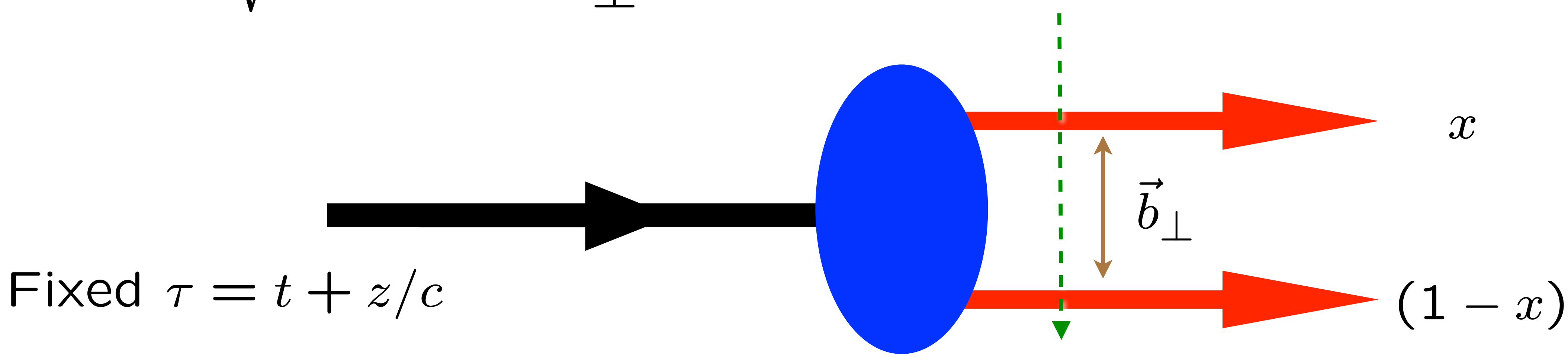
de Teramond, sjb

LF(3+1) ⟷ AdS_5

Light-Front Holographic Dictionary

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2} \longleftrightarrow z$$



$$\psi(x, \zeta) = \sqrt{x(1-x)}\zeta^{-1/2}\phi(\zeta)$$

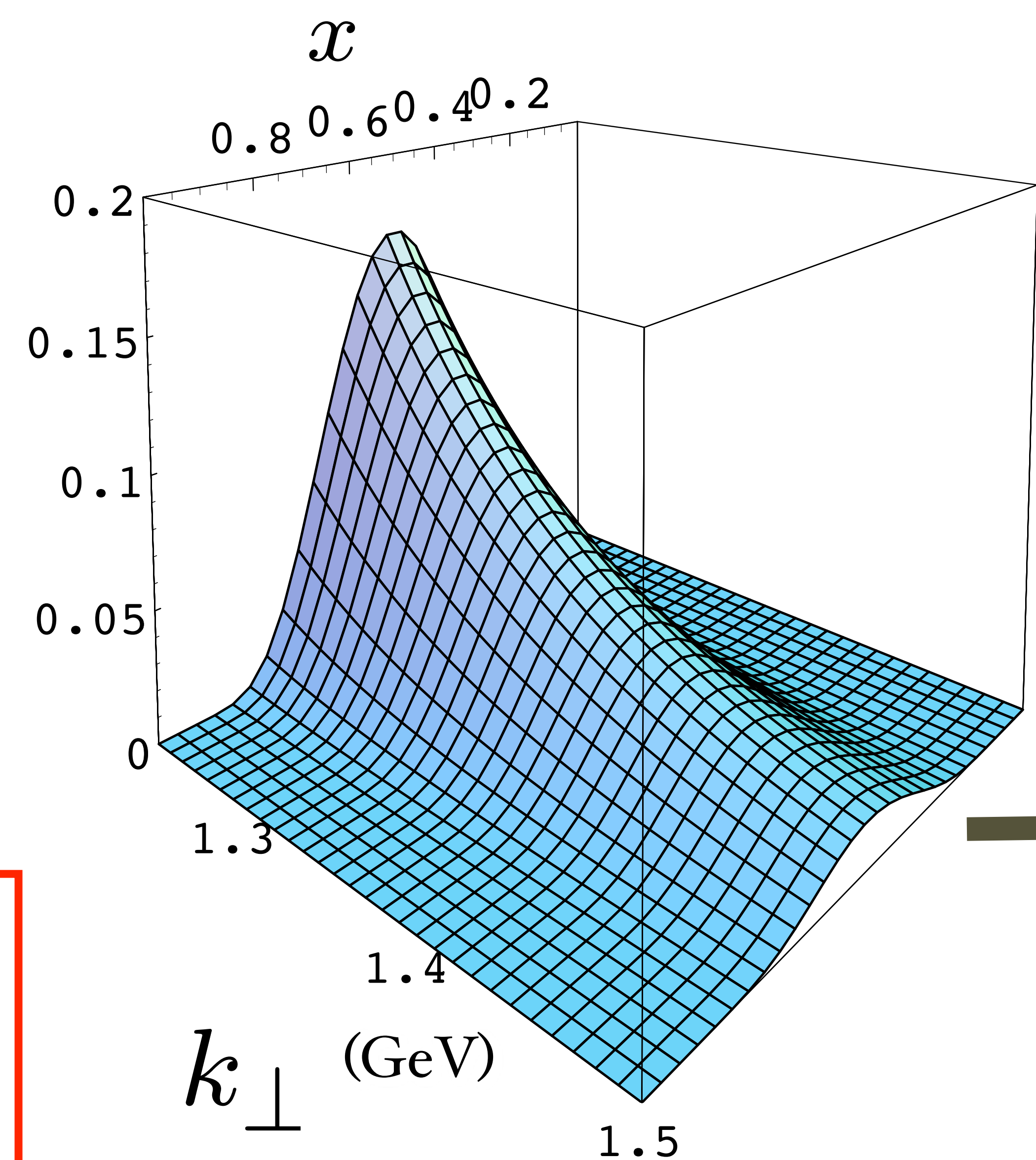
$$(\mu R)^2 = L^2 - (J-2)^2$$

Light-Front Holography: *Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion*

Prediction from AdS/QCD: Meson LFWF

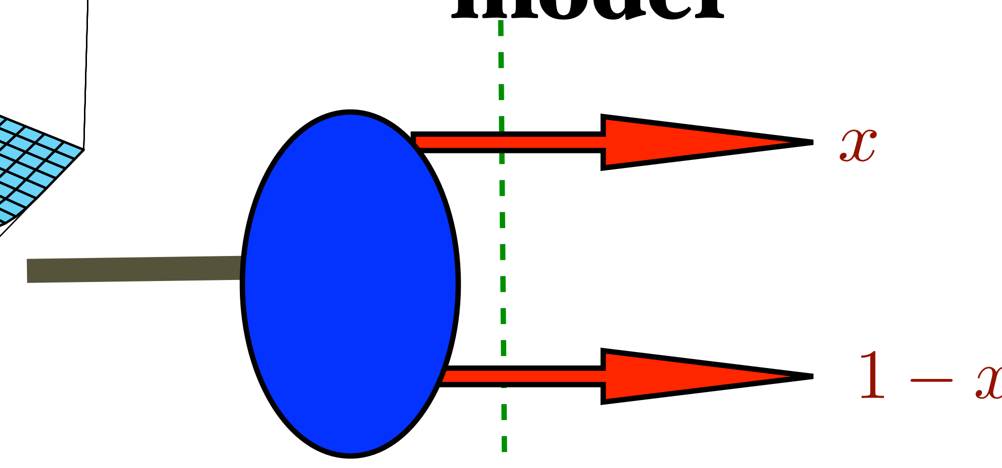
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

$$\psi_M(x, k_\perp^2)$$



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

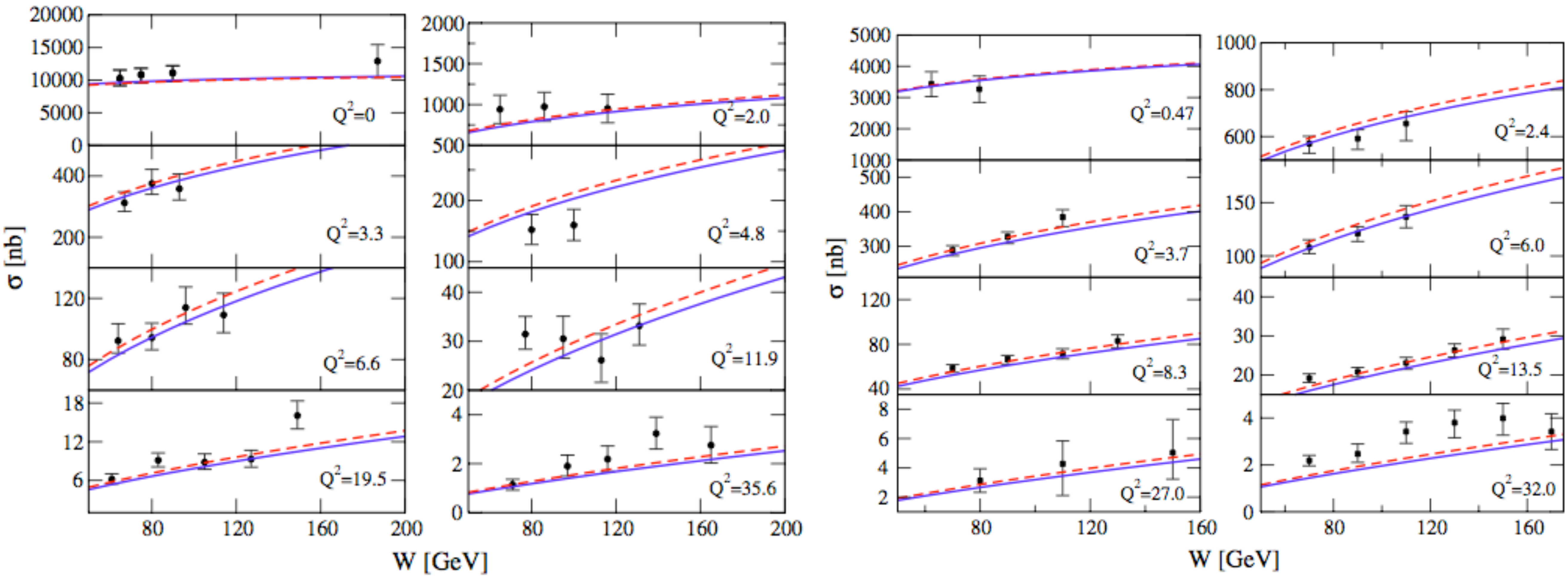
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

Same as DSE! **C. D. Roberts et al.**

Provides Connection of Confinement to Hadron Structure

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

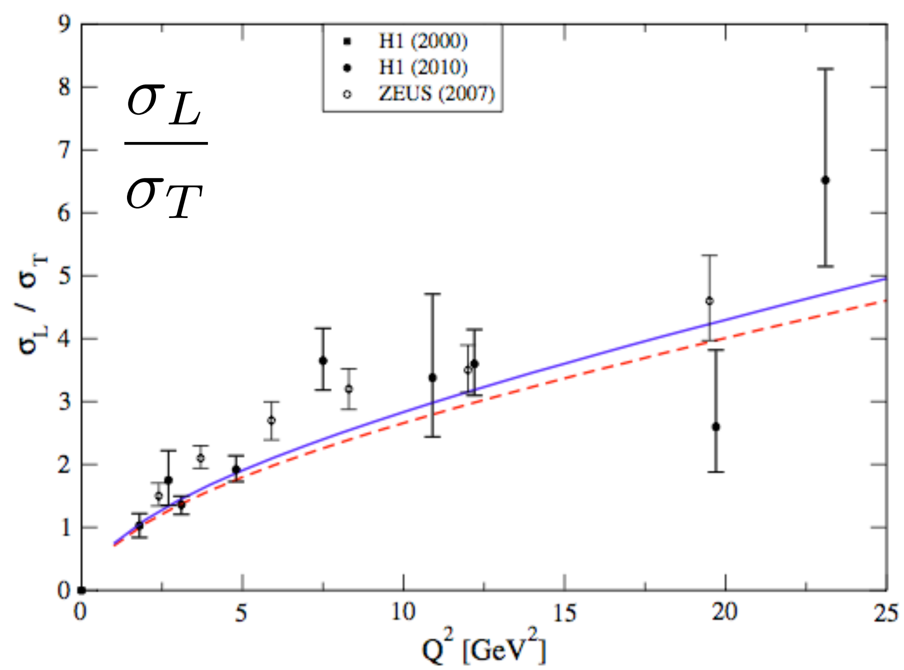


(a) H1

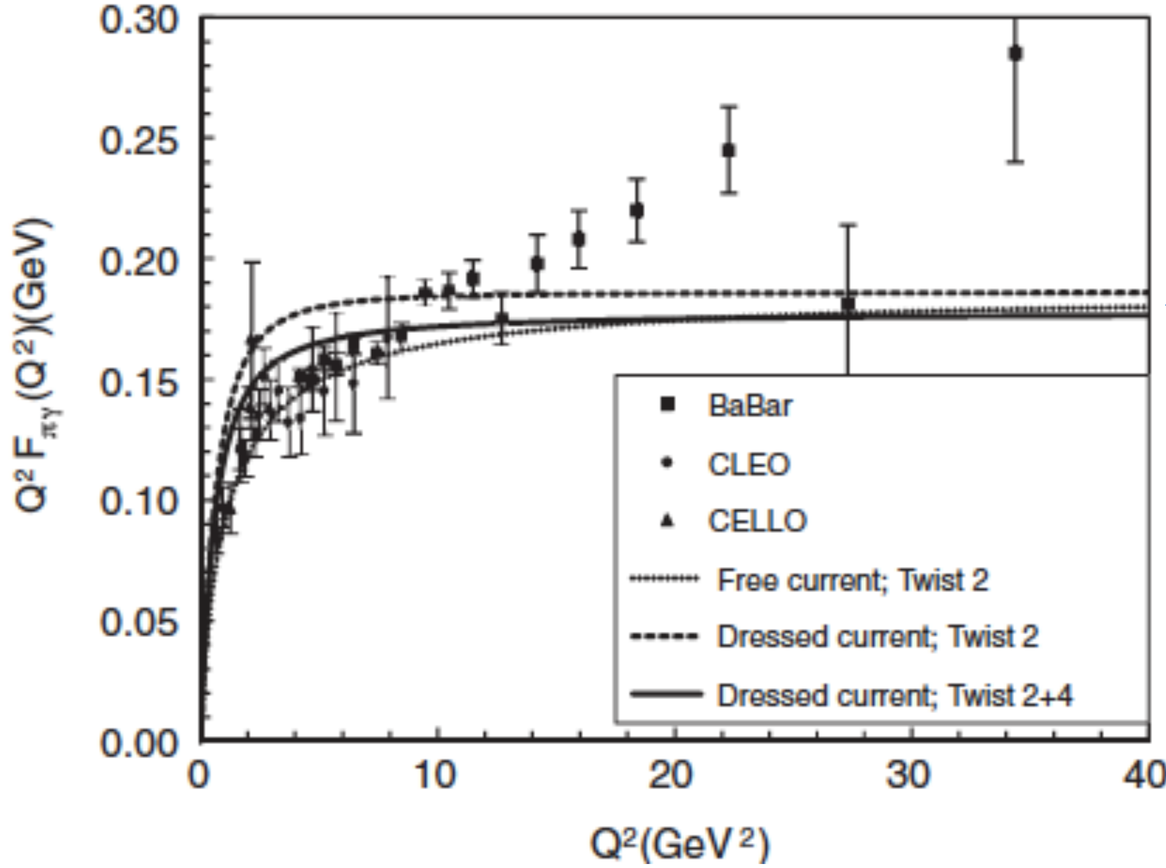
(b) ZEUS

J. R. Forshaw,
R. Sandapen

$$\gamma^* p \to \rho^0 p'$$



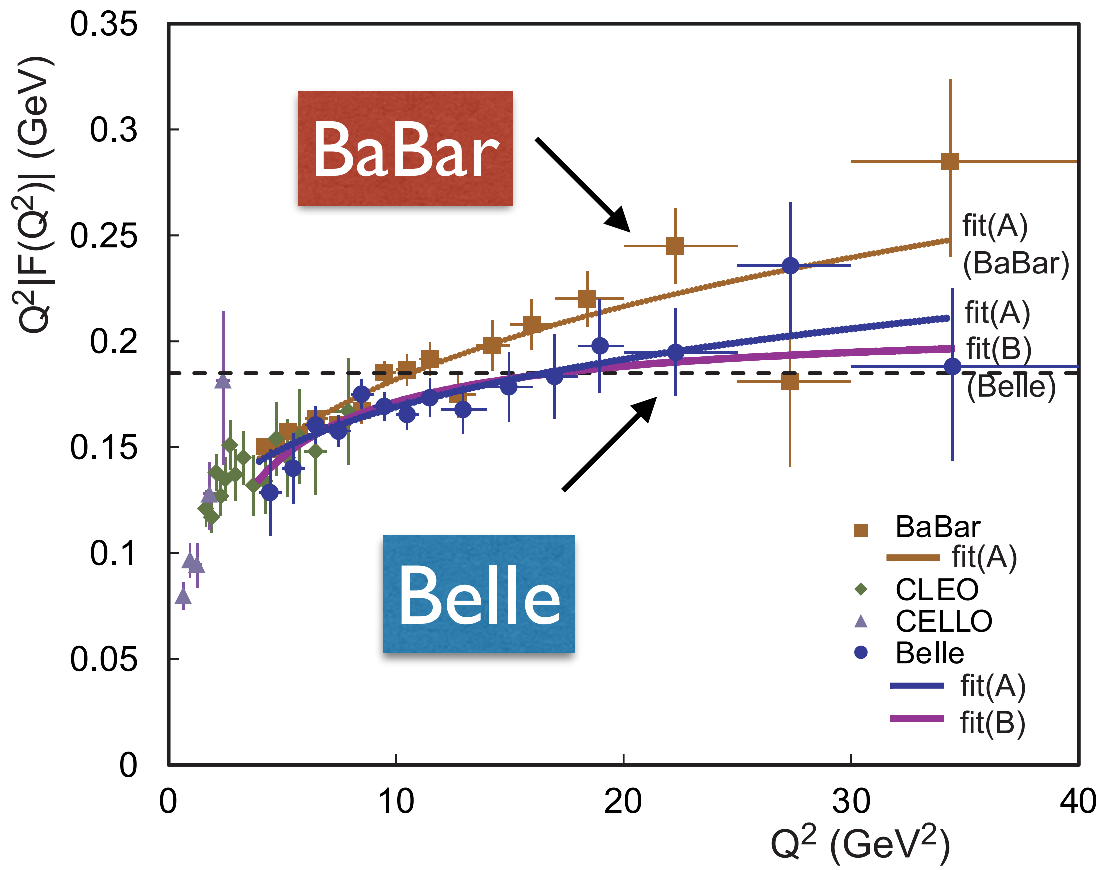
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$



Prediction from AdS/QCD:

$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

Cao, de Teramond, sjb

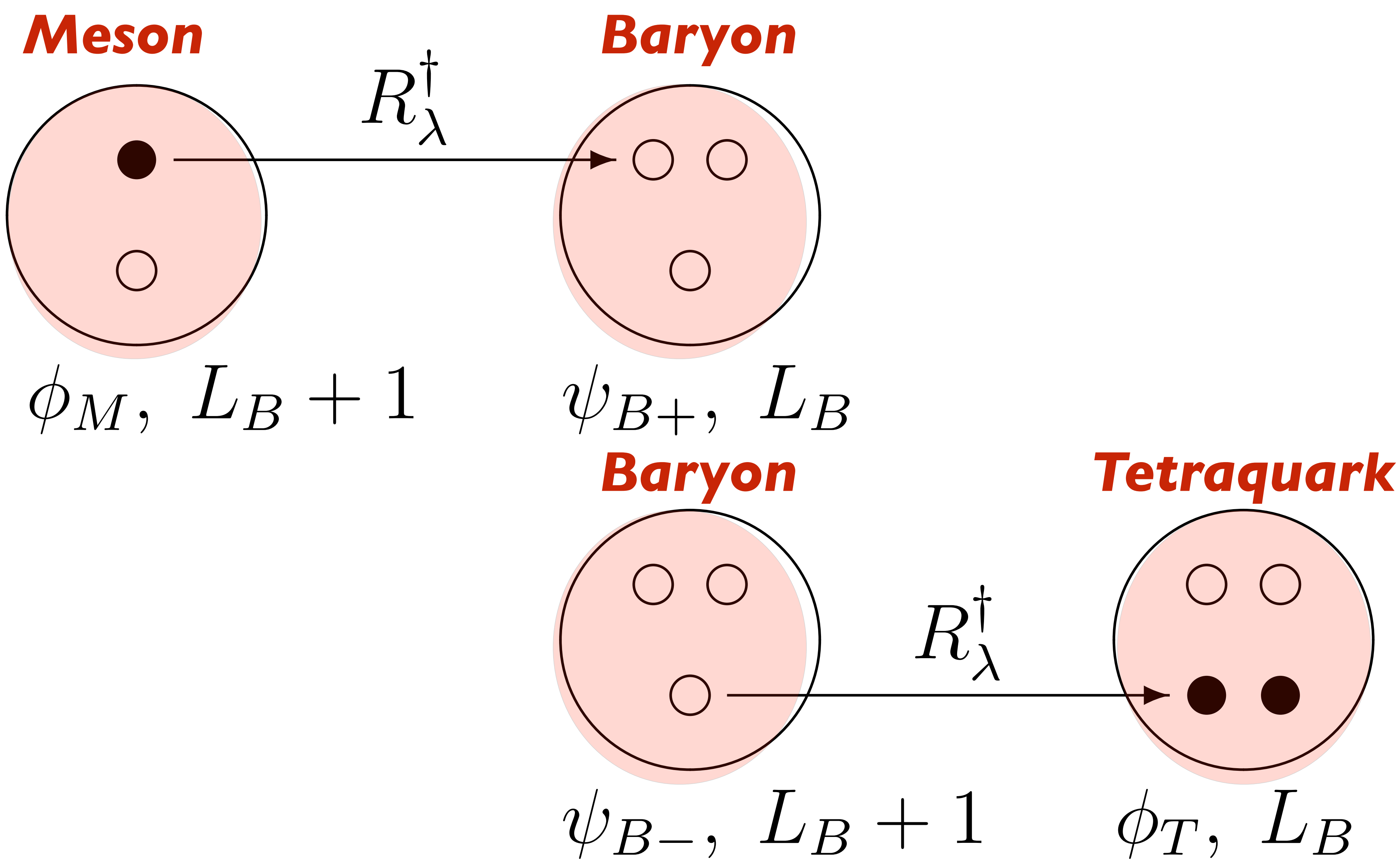


Belle:
Agreement with AdS/QCD and pQCD evolution

Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



Proton: quark + scalar diquark $|q(qq)>$
(Equal weight: $L = 0, L = 1$)

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2}\right)\psi_J^+ = M^2\psi_J^+$$

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2}\right)\psi_J^- = M^2\psi_J^-$$

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

S=1/2, P=+

both chiralities

Meson Equation

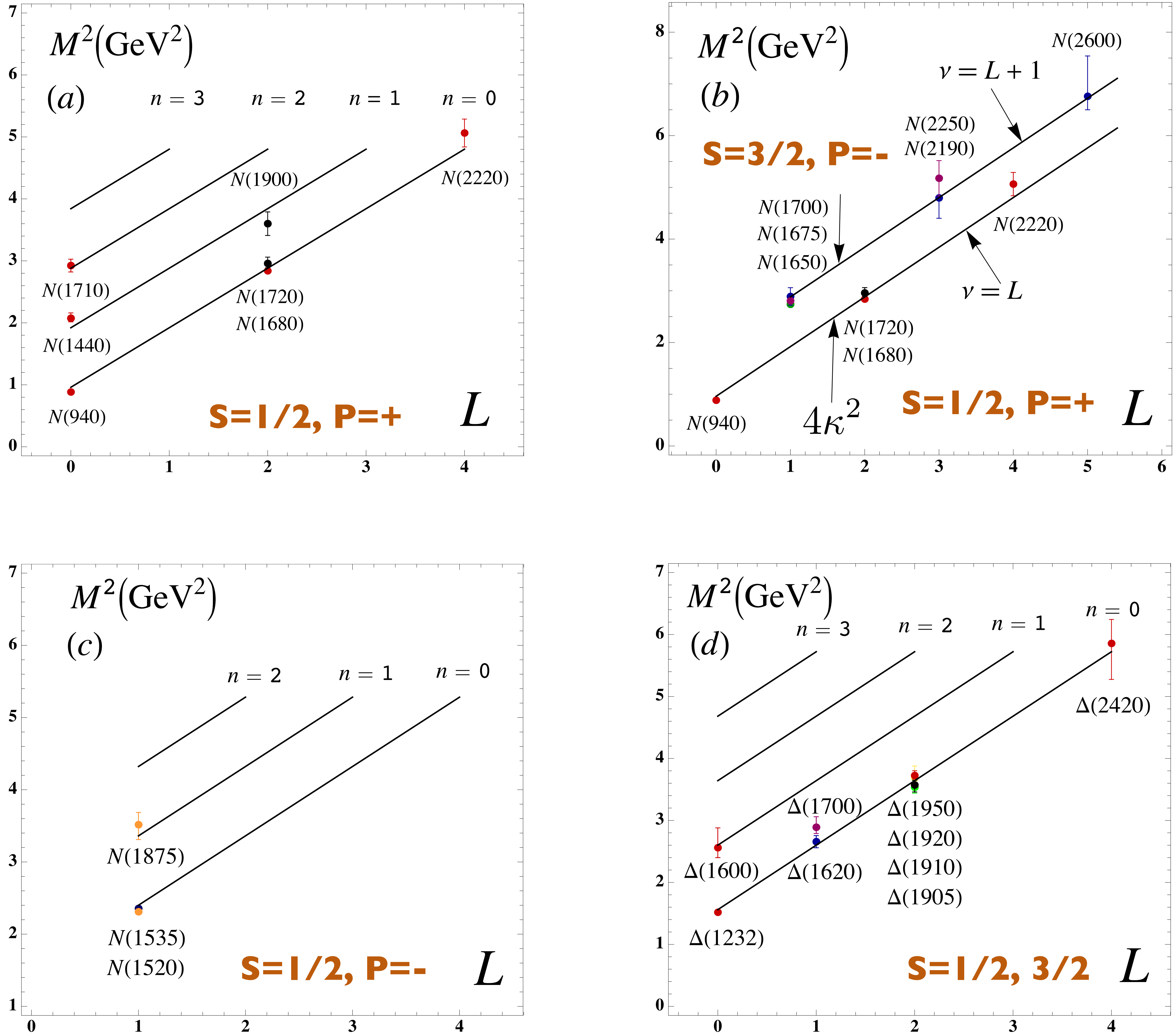
$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(J-1) + \frac{4L_M^2-1}{4\zeta^2}\right)\phi_J = M^2\phi_J$$

$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Same κ!

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

Meson-Baryon Degeneracy for $L_M=L_B+1$



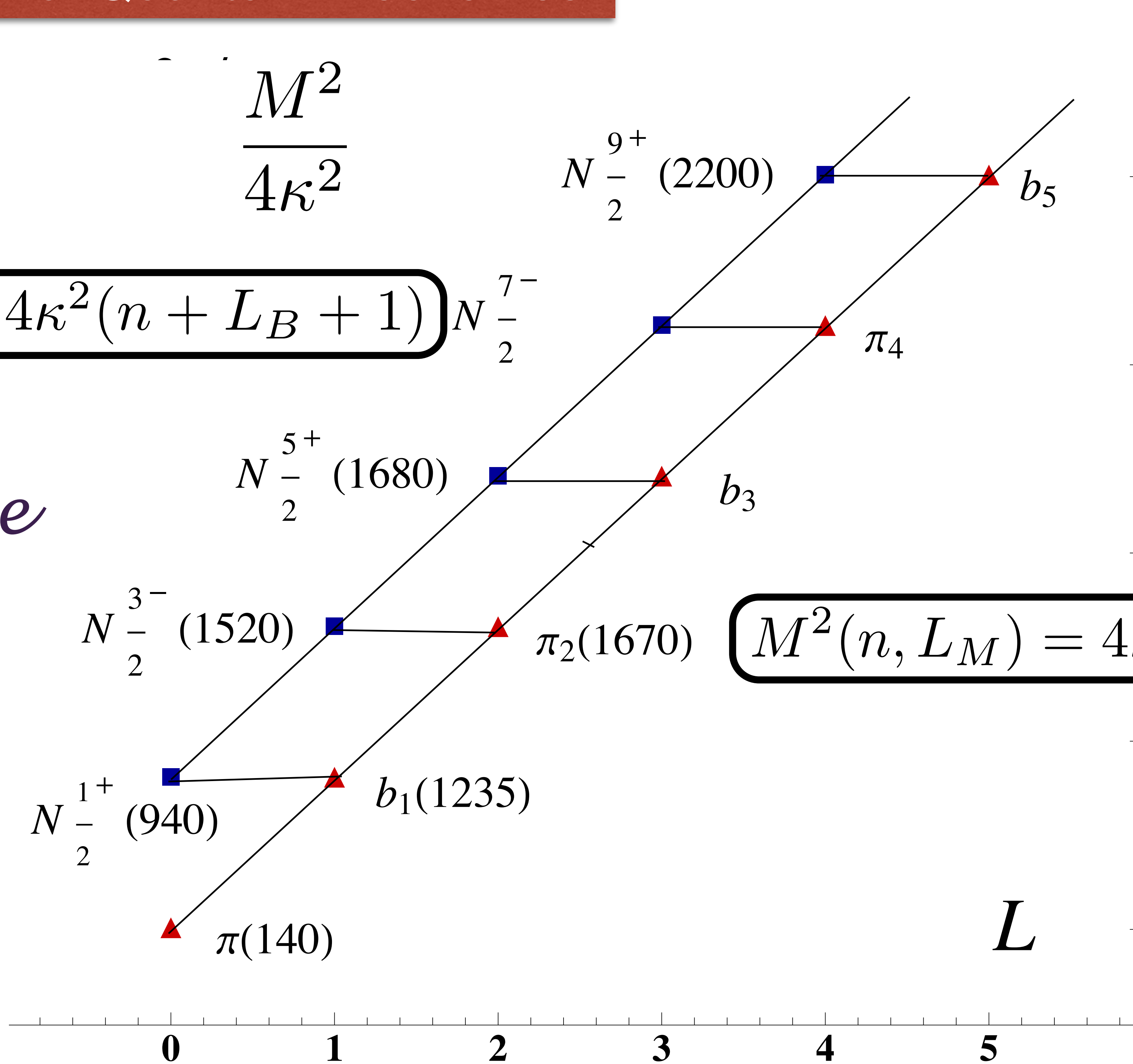
$M^2(\mathrm{GeV}^2)$
(a)
n = 3
n = 2
n = 1
n = 0
N(1900)
N(2220)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(b)
N(2600)
ν = L + 1
N(2250)
N(2190)
S=3/2, P=-
N(1700)
N(1675)
N(1650)
N(2220)
ν = L
N(1720)
N(1680)
N(940)
$4\kappa^2$
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
S=1/2, P=-
L
$M^2(\mathrm{GeV}^2)$
(d)
n = 3
n = 2
n = 1
n = 0
Δ(2420)
Δ(1700)
Δ(1950)
Δ(1920)
Δ(1910)
Δ(1905)
Δ(1600)
Δ(1620)
Δ(1232)
S=1/2, 3/2
L

Superconformal Quantum Mechanics

de Tèramond, Dosch, sjb

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

Same slope

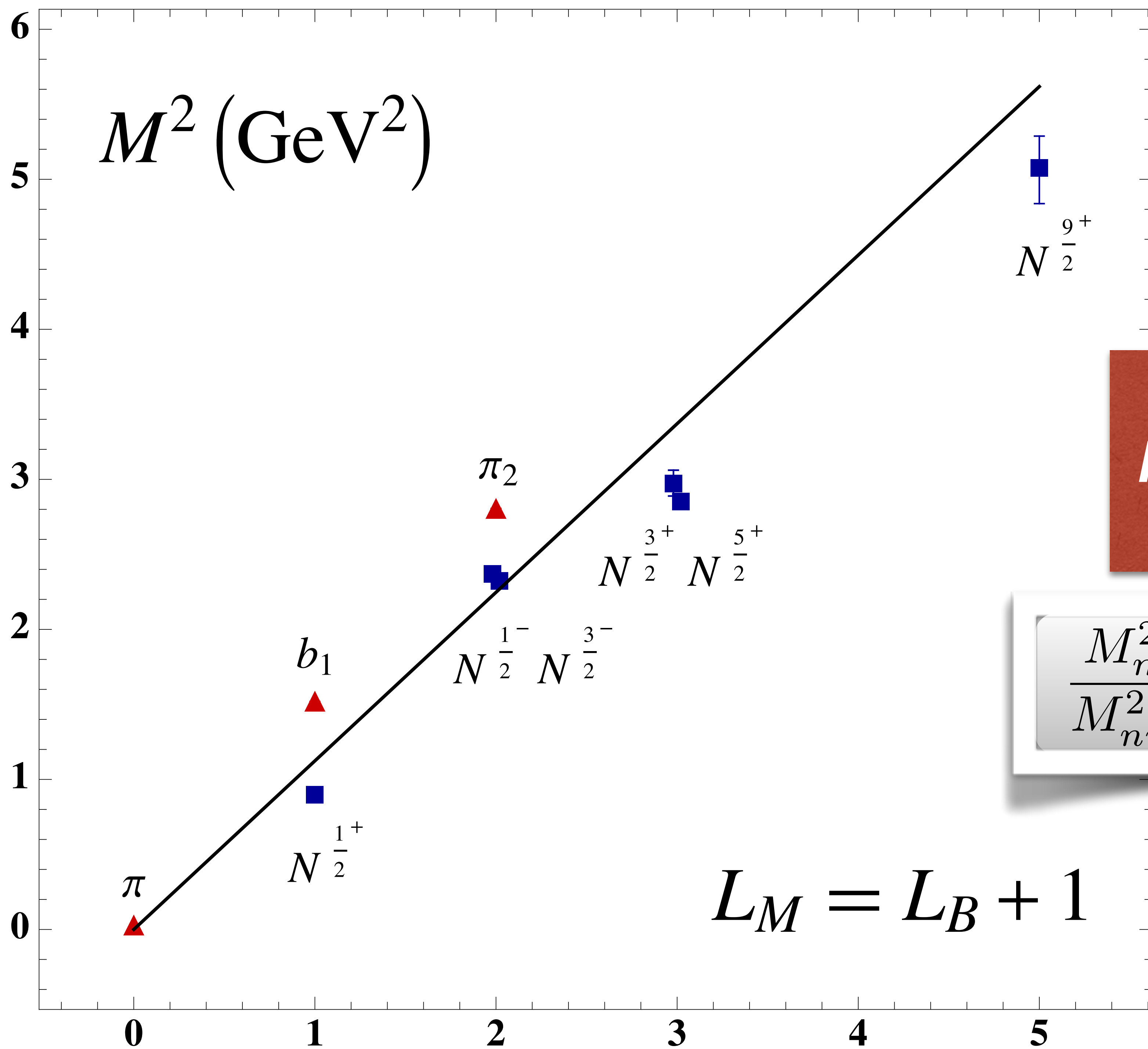


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

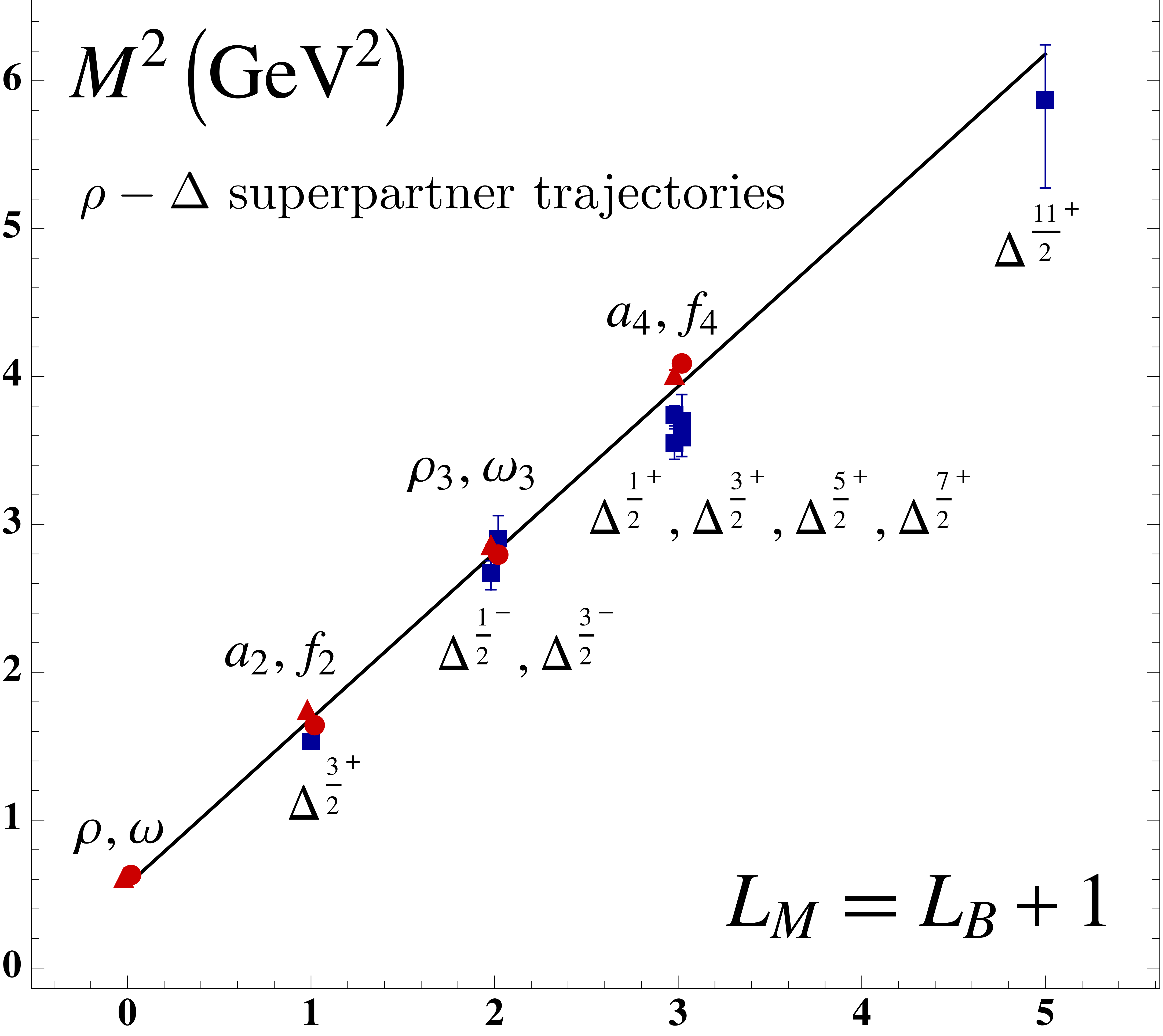
Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

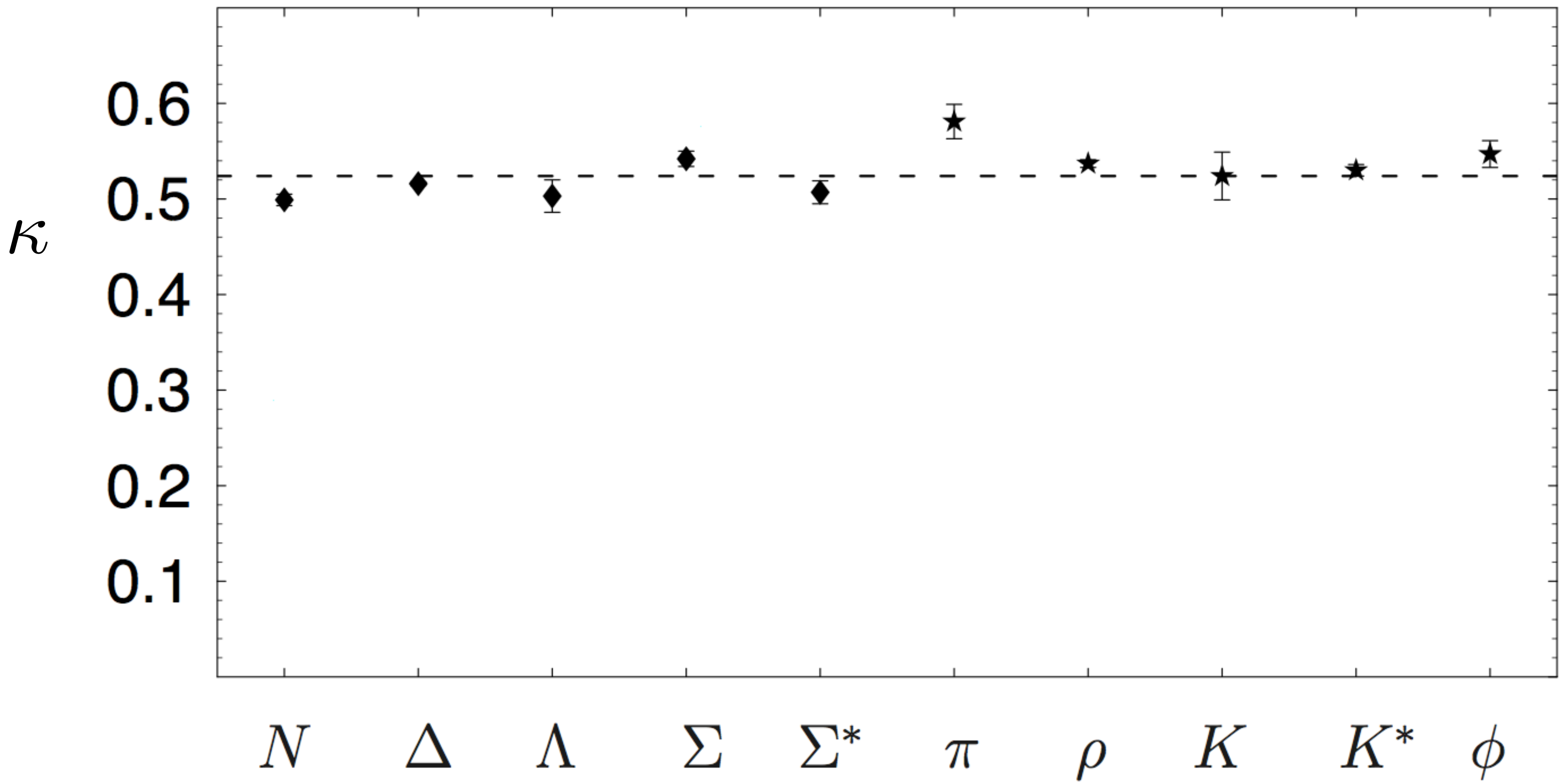
S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon



Dosch, de Teramond, sjb

Dosch, de Teramond, Lorce, sjb

$$m_u = m_d = 46 \text{ MeV}, \; m_s = 357 \text{ MeV}$$



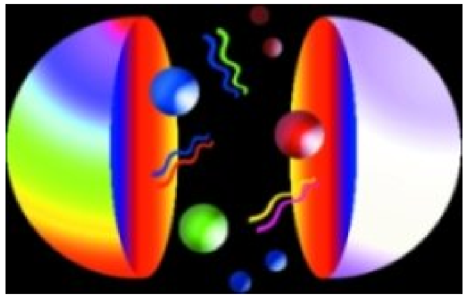
Fit to the slope of Regge trajectories, including radial excitations

Same Regge Slope for Meson, Baryons: Supersymmetric feature of hadron physics

Fermionic Modes and Baryon Spectrum

[Hard wall model: GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Soft wall model: GdT and S. J. Brodsky, (2005), arXiv:1001.5193]



From Nick Evans

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\, \psi_+^2(\zeta) = \int d\zeta\, \psi_-^2(\zeta) = 1$$

Quark Chiral Symmetry of Eigenstate!

- Eigenvalues

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

Nucleon: Equal Probability for L=0,1

Features of Supersymmetric Equations

- J =L+S baryon simultaneously satisfies both equations of G with L , L+1 with same mass eigenvalue

- $J^z = L^z + 1/2 = (L^z + 1) - 1/2$ $\quad S^z = \pm 1/2$

- Proton spin carried by quark L^z

$$< J^z >= \frac{1}{2}(S_q^z = \frac{1}{2}, L^z = 0) + \frac{1}{2}(S_q^z = -\frac{1}{2}, L^z = 1) =< L^z >= \frac{1}{2}$$

- Mass-degenerate meson "superpartner" with $L_M = L_B + 1$. *"Shifted meson-baryon Duality"*

Mesons and baryons have same κ !

AdS/QCD + Light Front Holography: Proton is bound state of a quark + scalar diquark

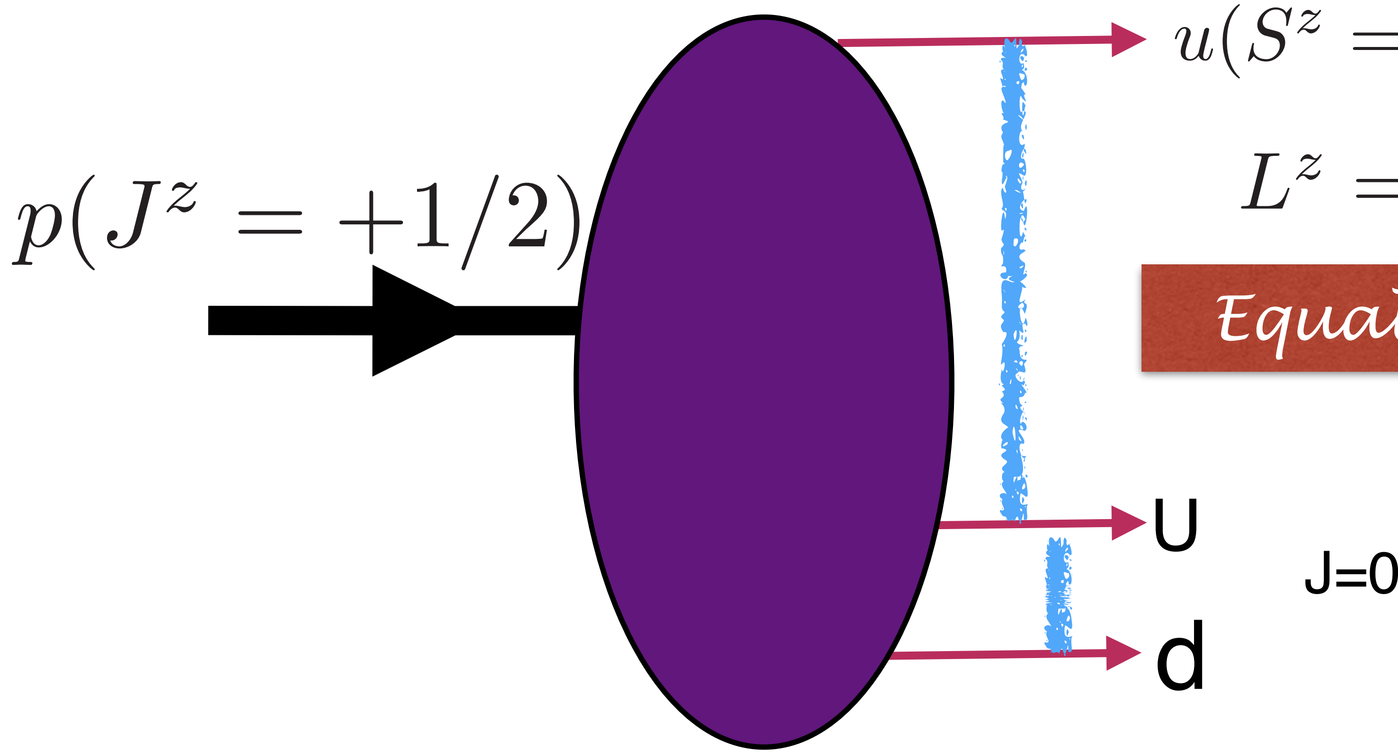
de Teramond, Dosch, Lorce, sjb

Skyrme model: Ellis, Karliner, sjb

LF J^z conservation: K. Chiu, sjb

$$3_C \times 3_C = \bar{3}_C + \cancel{6}_C$$

$$|p> = |u_{3C}[ud]_{\bar{3}C}>$$



$u(S^z = +1/2)$ $\quad$ $u(S^z = -1/2)$

$L^z = 0$ $\quad$ $L^z = -1$

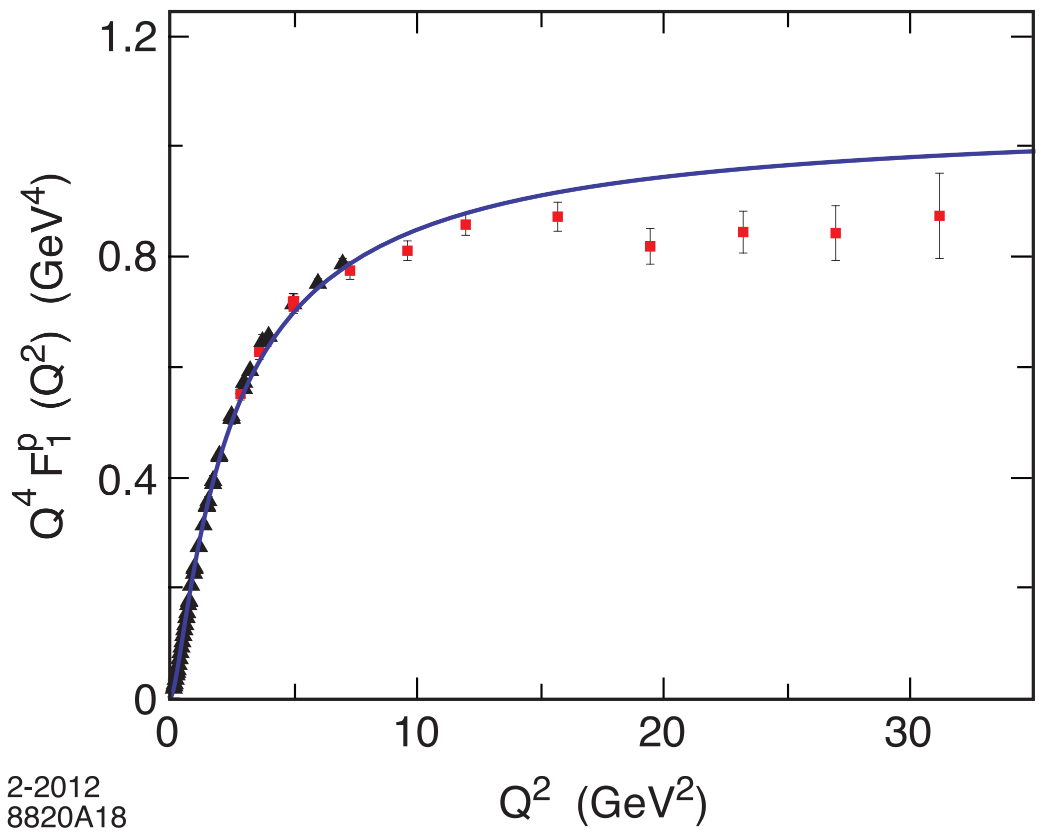
Equal probability L=0, L=1

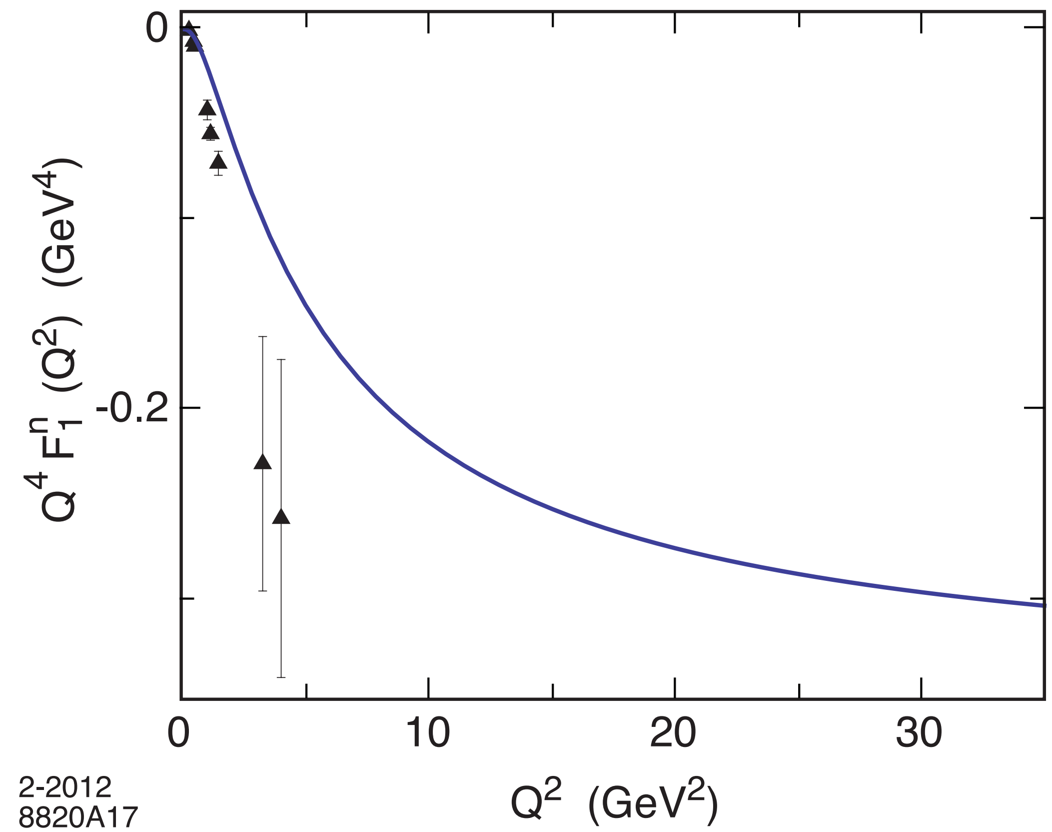
Quark chiral symmetry
Anomalous moment nonzero
Leading Twist Sivers Effect

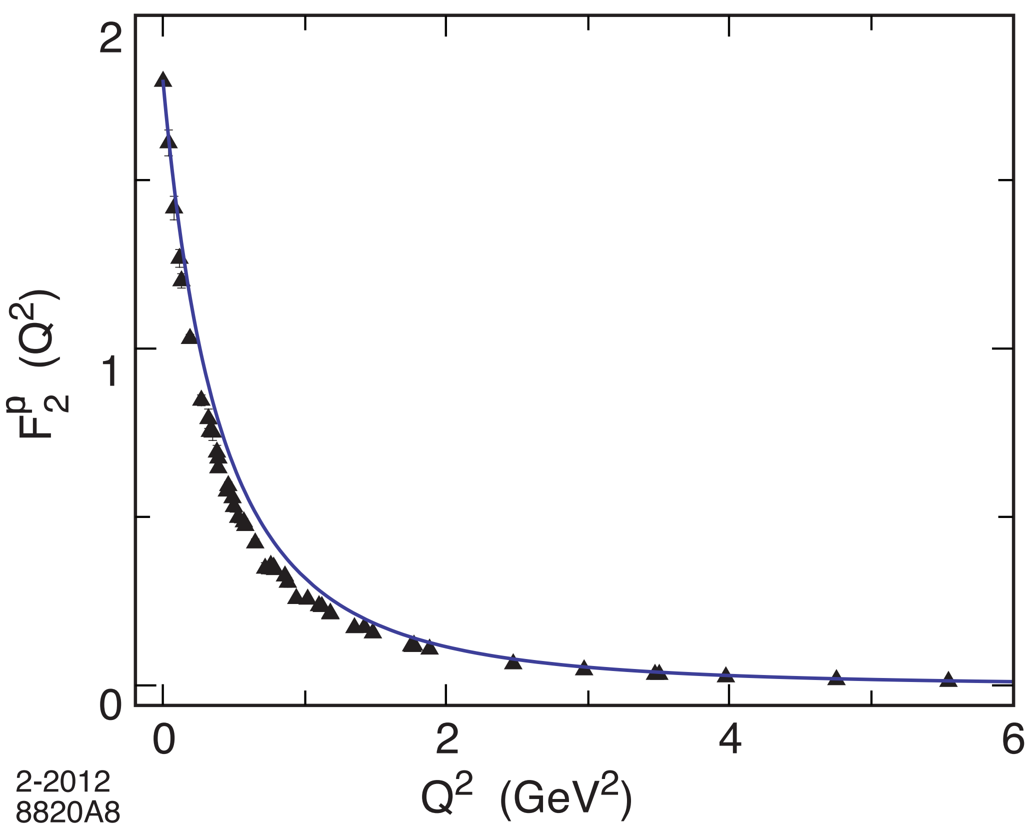
Gluonic distribution reflects quark+diquark color structure of the proton

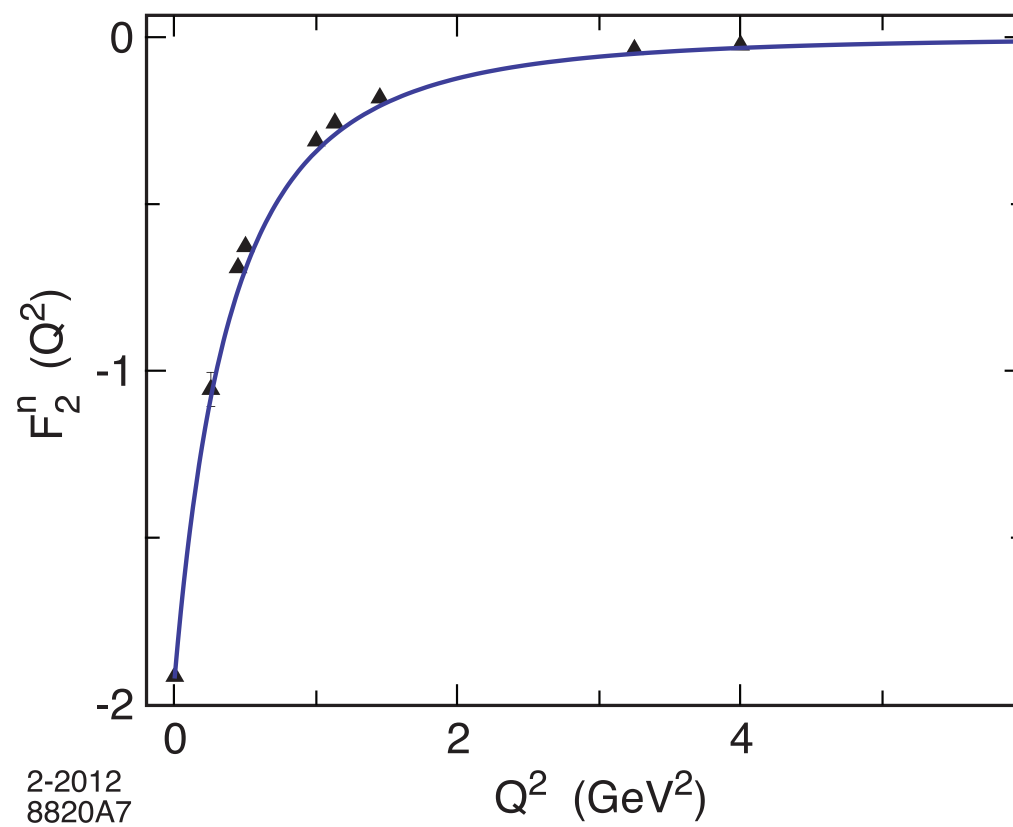
Color confinement potential —> high density gluon field: flux tube

Using $SU(6)$ flavor symmetry and normalization to static quantities



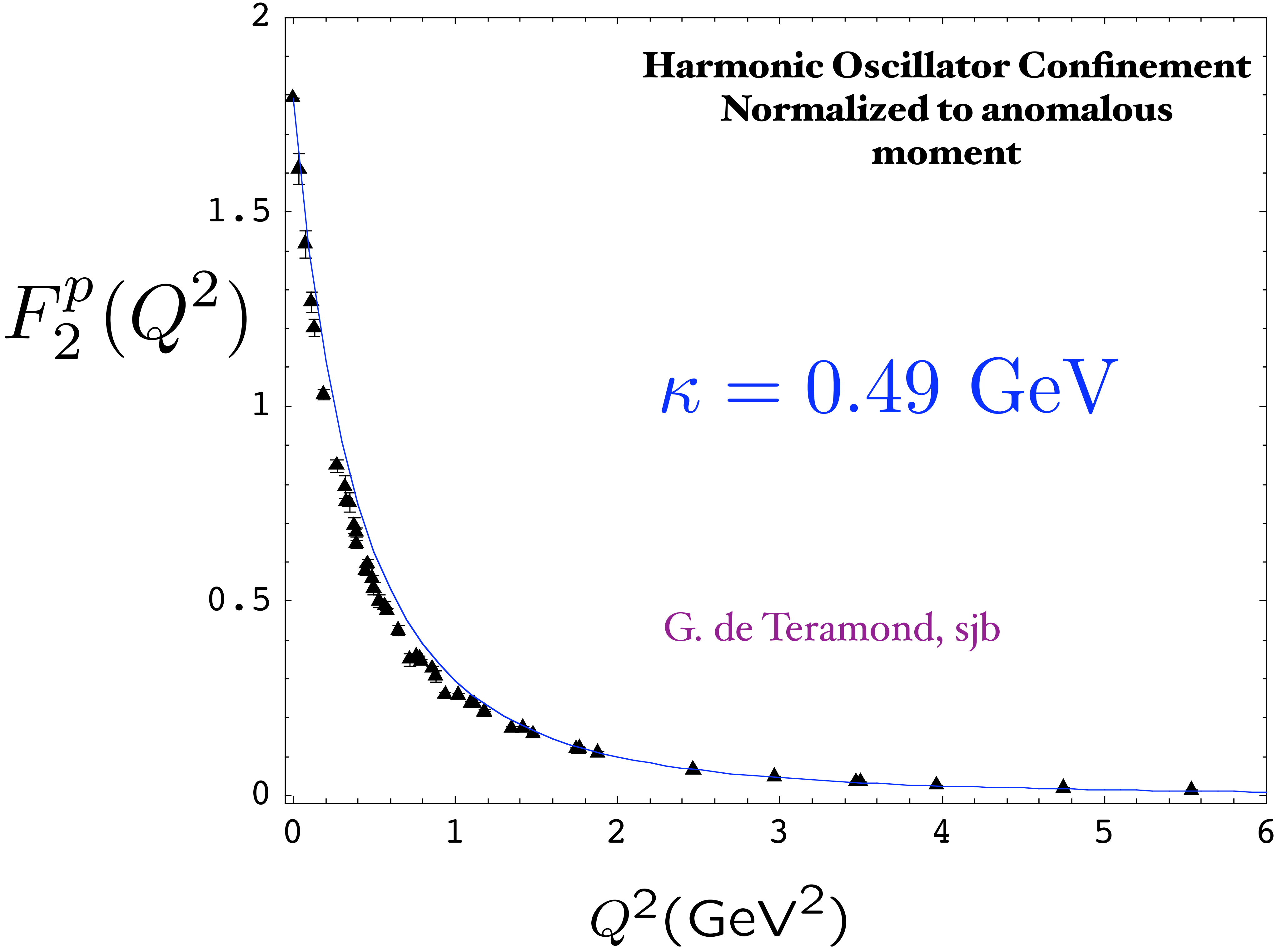






Spacelike Pauli Form Factor

From overlap of $L = 1$ and $L = 0$ LFWFs



- Compute Dirac proton form factor using SU(6) flavor symmetry

$$F_1^p(Q^2) = R^4 \int \frac{dz}{z^4} \, V(Q,z) \Psi_+^2(z)$$

- Nucleon AdS wave function

$$\Psi_+(z) = \frac{\kappa^{2+L}}{R^2} \sqrt{\frac{2n!}{(n+L)!}} z^{7/2+L} L_n^{L+1}\left(\kappa^2 z^2\right) e^{-\kappa^2 z^2/2}$$

- Normalization $\quad (F_1{}^p(0) = 1, \quad V(Q=0,z) = 1)$

$$R^4 \int \frac{dz}{z^4} \, \Psi_+^2(z) = 1$$

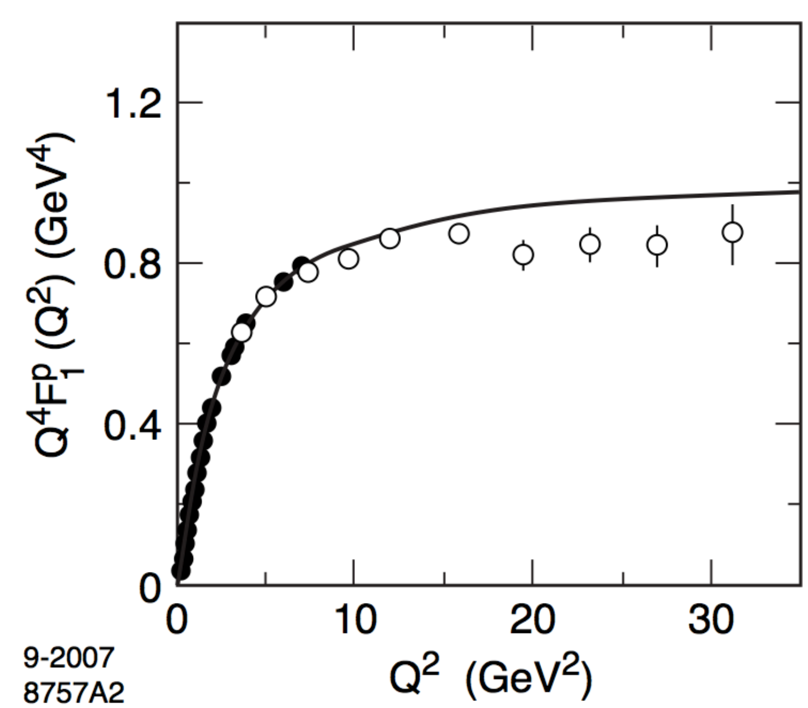
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

$$V(Q,z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \, x^{\frac{Q^2}{4\kappa^2}} \, e^{-\kappa^2 z^2 x/(1-x)}$$

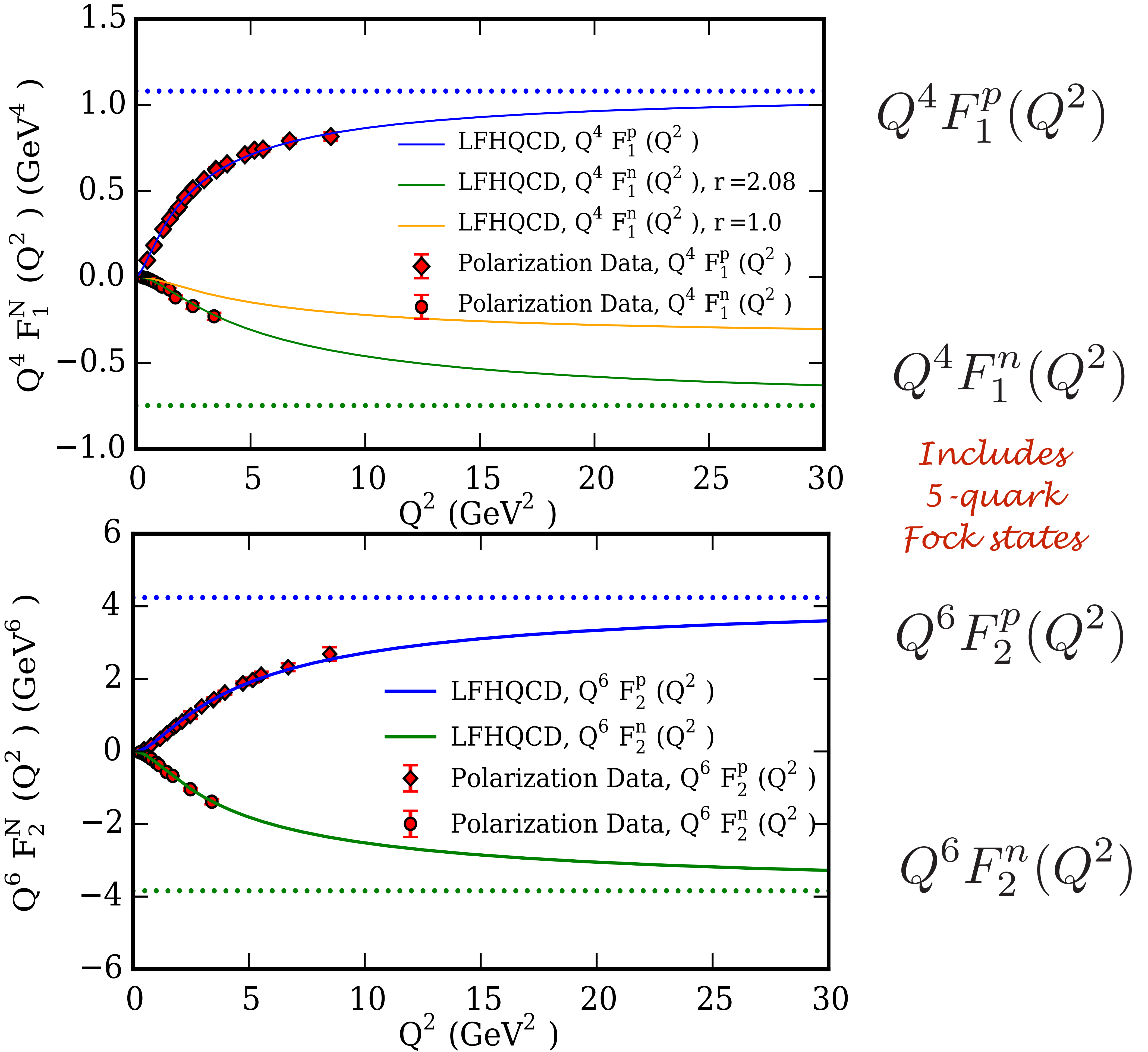
- Find

$$F_1^p(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}$$

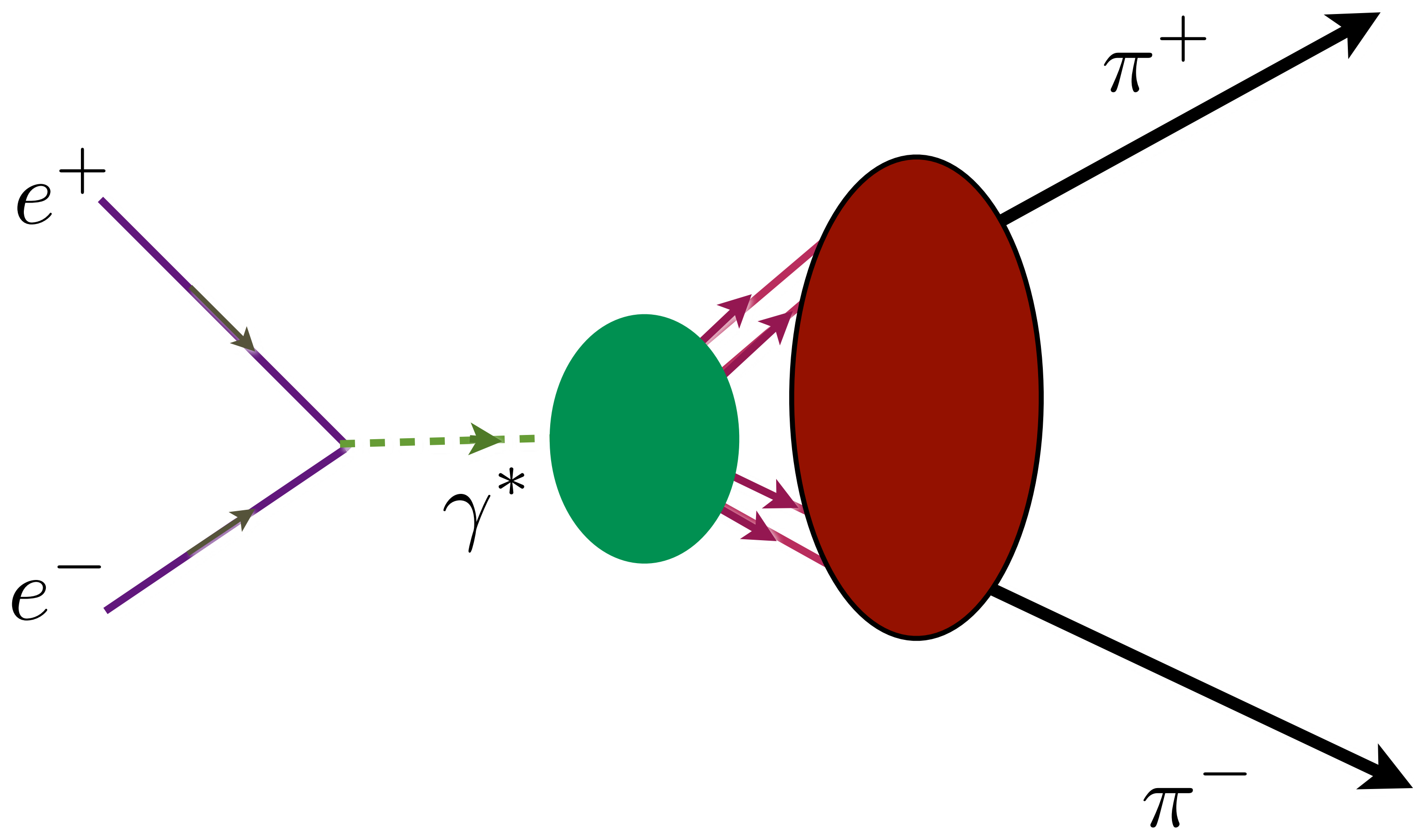
with $\mathcal{M}_{\rho_n}{}^2 \to 4\kappa^2(n + 1/2)$



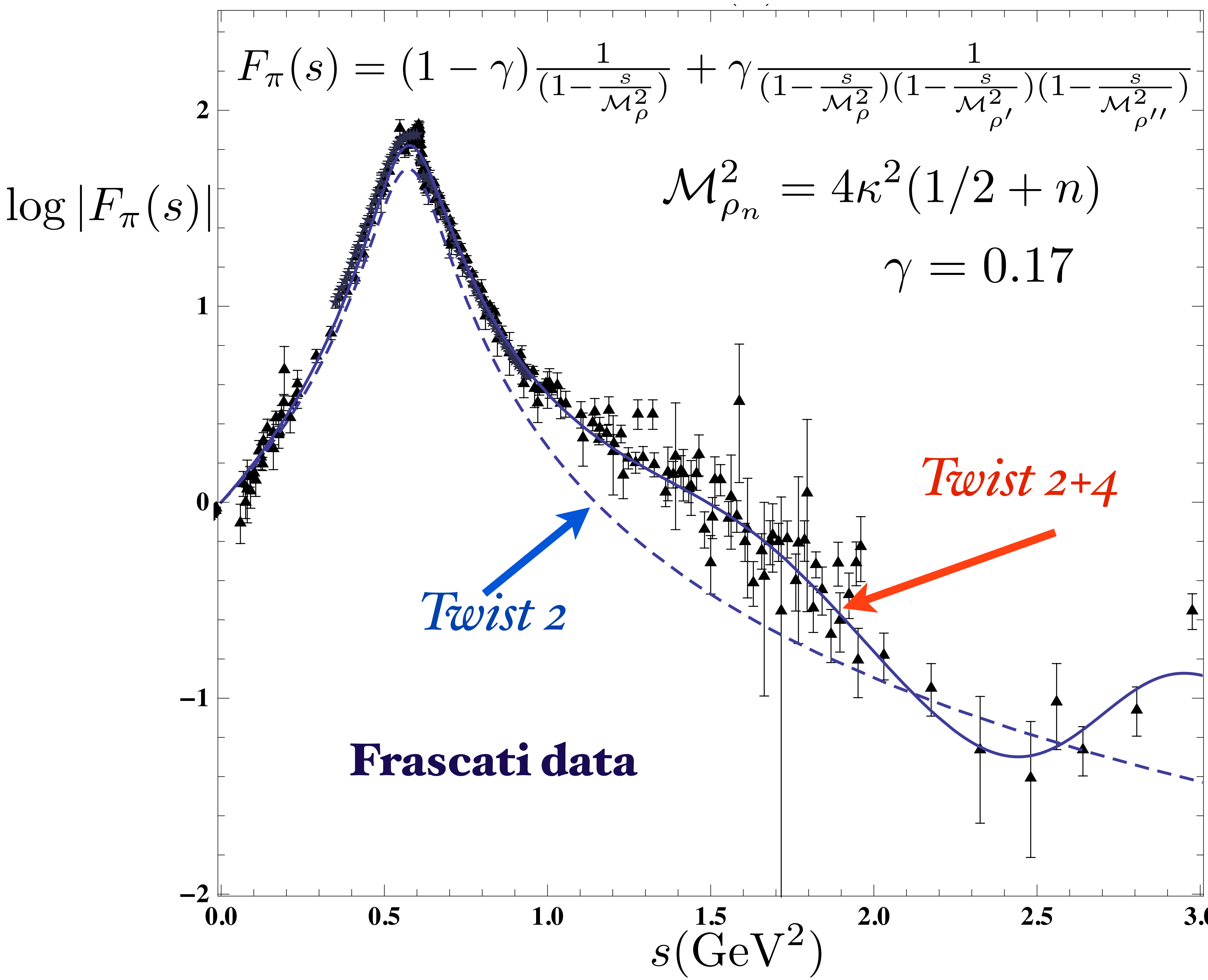
Sufian, de Teramond, Deur, Dosch, sjb



Dressed soft-wall current brings in higher Fock states and more vector meson poles



Timelike Pion Form Factor from AdS/QCD and Light-Front Holography



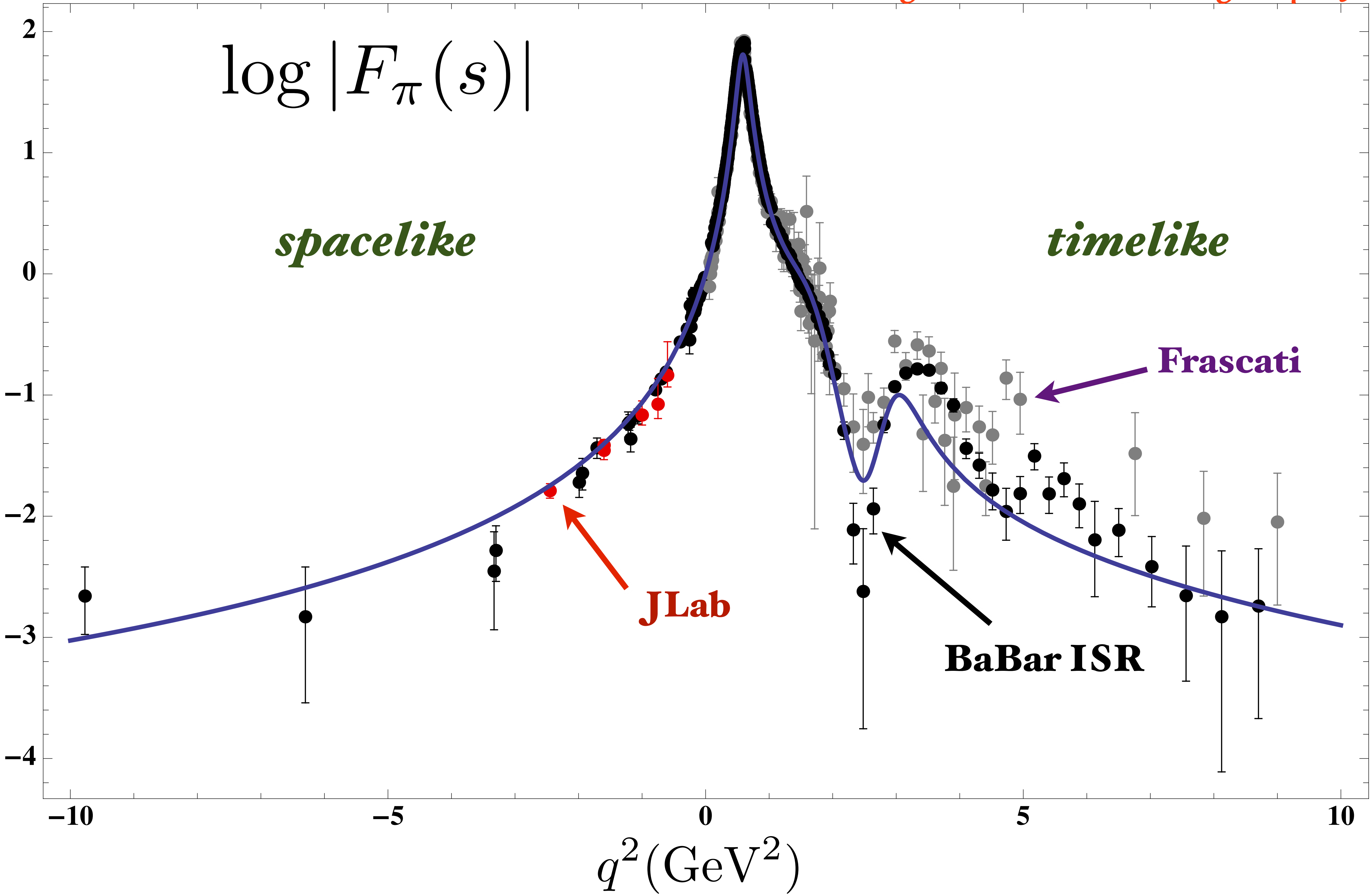
Prescription for Timelike poles :

$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb

Pion Form Factor from AdS/QCD and Light-Front Holography



Bjorken sum rule defines effective charge $\alpha_{g1}(Q^2)$

$$\int_0^1 dx[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{g_a}{6}[1 - \frac{\alpha_{g1}(Q^2)}{\pi}]$$

- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal*** β_0, β_1

Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS$_5$ space in dilaton background $\varphi(z) = \kappa^2 z^2$

$$S = -\frac{1}{4} \int d^4x \, dz \, \sqrt{g} \, e^{\varphi(z)} \, \frac{1}{g_5^2} \, G^2$$

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$

- Coupling measured at momentum scale Q

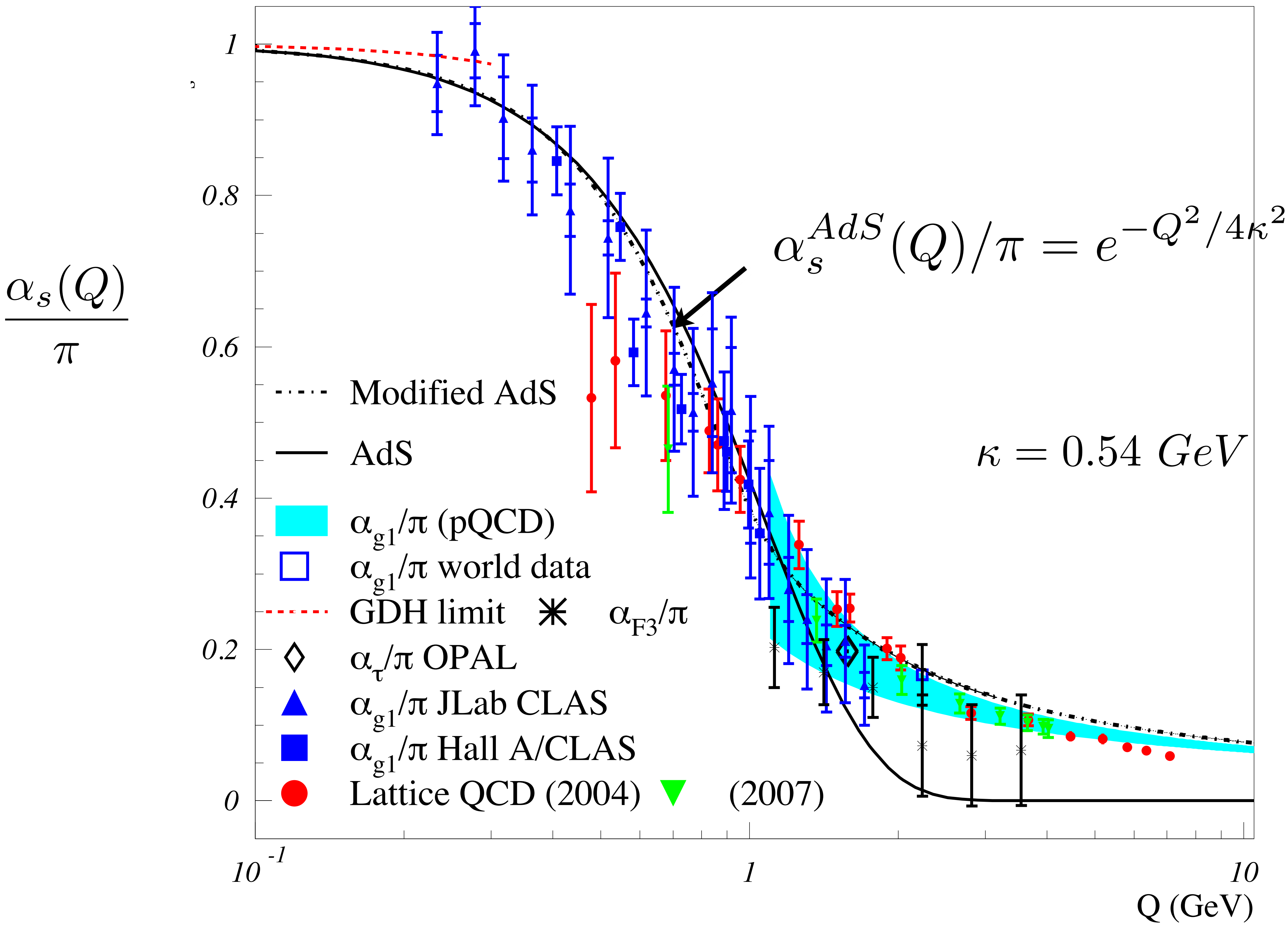
$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta \, J_0(\zeta Q) \, \alpha_s^{AdS}(\zeta)$$

- Solution

$$\boxed{\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0) \, e^{-Q^2/4\kappa^2}.}$$

where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

$$e^{\varphi} = e^{+\kappa^2 z^2}$$

Deur, de Teramond, sjb

Deur, de Tèramond, sjb

All-Scale QCD Coupling

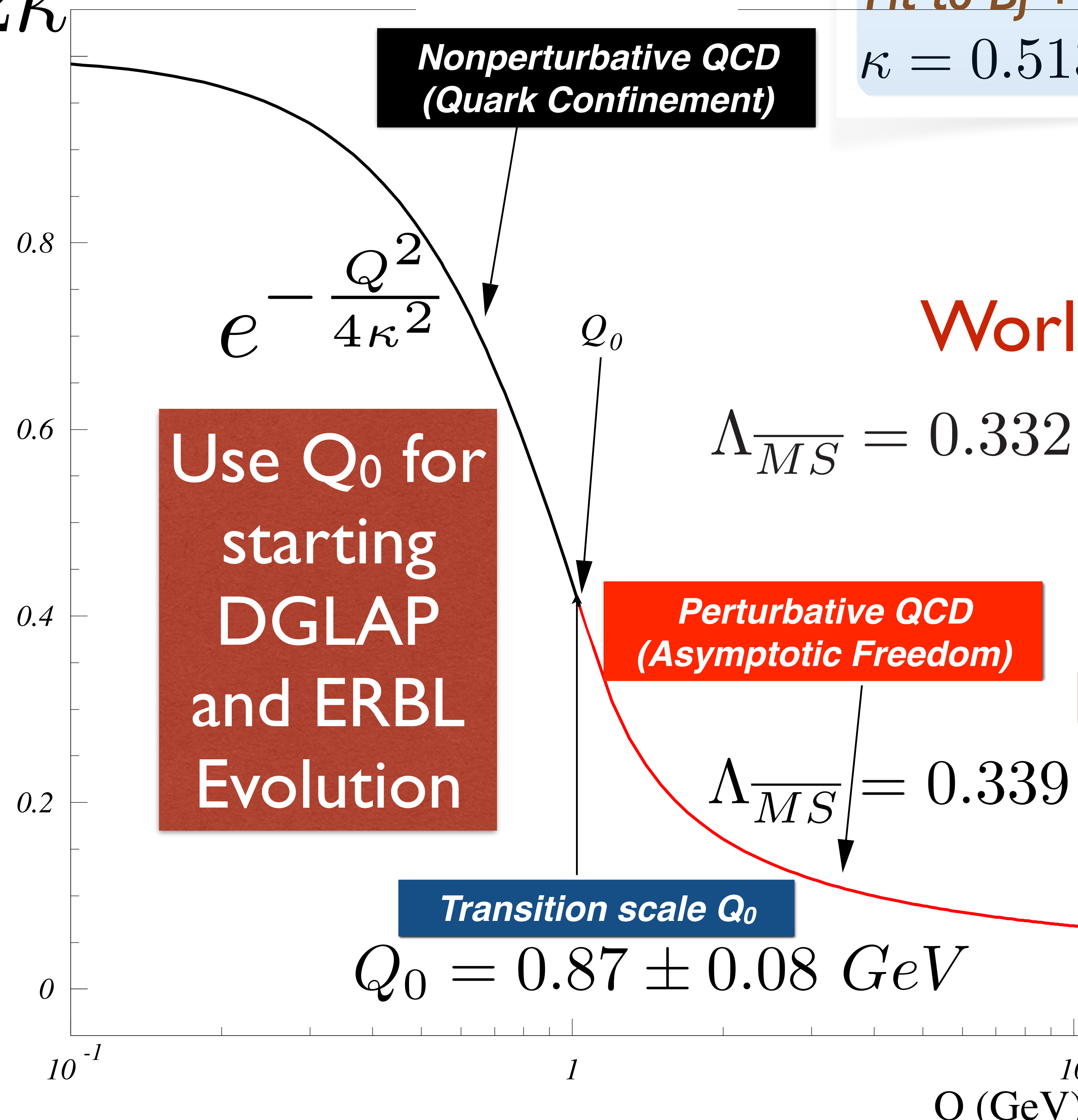
$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

Fit to Bj + DHG Sum Rules:

$$\kappa = 0.513 \pm 0.007\ GeV$$

$$\frac{\alpha^s_{g_1}(Q^2)}{\pi}$$



World Data:

$$\Lambda_{\overline{MS}} = 0.332 \pm 0.017\ \mathrm{GeV}$$

Prediction

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.019\ GeV$$

$\overline{MS}$ *scheme*

$$\lambda \equiv \kappa^2$$

de Tèramond, Dosch, Lorce, sjb

Future Directions for AdS/QCD

- **Hadronization at the Amplitude Level**
- **Diffractive dissociation of pion and proton to jets**
- **Factorization Scale for ERBL, DGLAP evolution: Q_0**
- **Calculate Sivers Effect including FSI and ISI**
- **Compute Tetraquark Spectroscopy: Sequential Clusters**
- **Update SU(6) spin-flavor symmetry**
- **Heavy Quark States: Supersymmetry, not conformal**
- **Compute higher Fock states; e.g. Intrinsic Heavy Quarks**
- **Nuclear States — Hidden Color**
- **Basis LF Quantization** *Vary, sjb*

Hard Two-Photon Exclusive Processes, Photon Structure Functions, TMDs, C=+ Spectroscopy

Characteristics of the quark-antiquark flux tube

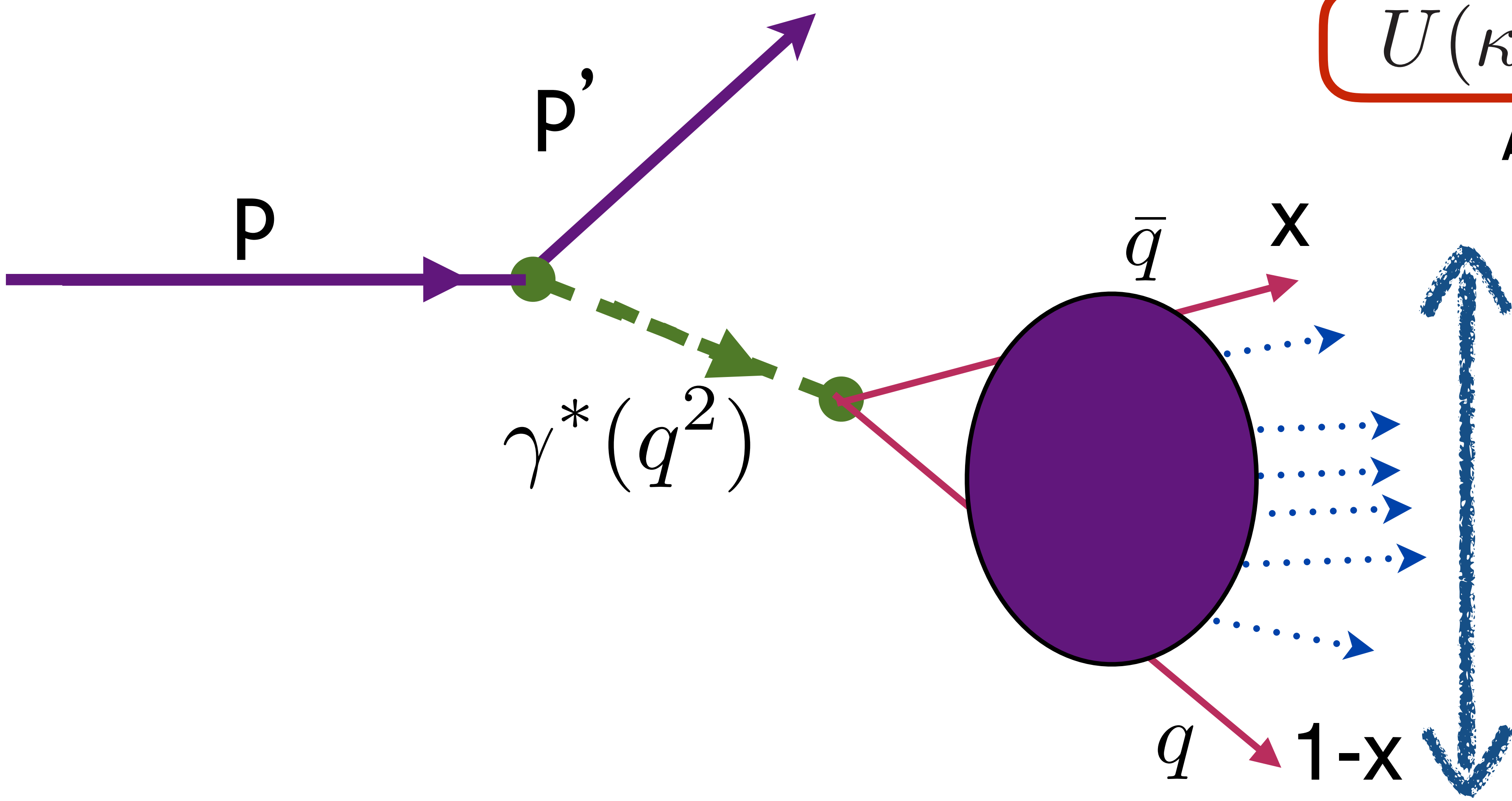
$$\psi(x, b_\perp^2, Q^2) \propto \exp -[b_\perp^2 x(1-x)(\kappa^2 + Q^2)]$$

Planar structure reflects color-confinement potential

$$U(\kappa^2) = \kappa^4 b_\perp^2 x(1-x)$$

AdS/QCD + Light-Front Holography

de Teramond, Dosch, Lorce, sjb



$$< b_\perp^2 > \propto \frac{1}{x(1-x)(\kappa^2+Q^2)}$$

massless quarks

$$< b_\perp^2 > \to \infty \text{ if } x \to 0, 1$$

$$\mathcal{M}^2 = \frac{k_\perp^2}{x(1-x)} \propto \frac{1}{b_\perp^2 x(1-x)}$$

$$< b_\perp^2 > \propto \frac{1}{x(1-x)(\kappa^2+Q^2)+m_q^2}$$

massive quarks

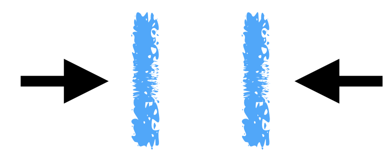
Collisions of flux tubes of protons

Color confinement potential —> high density gluon field: flux tube

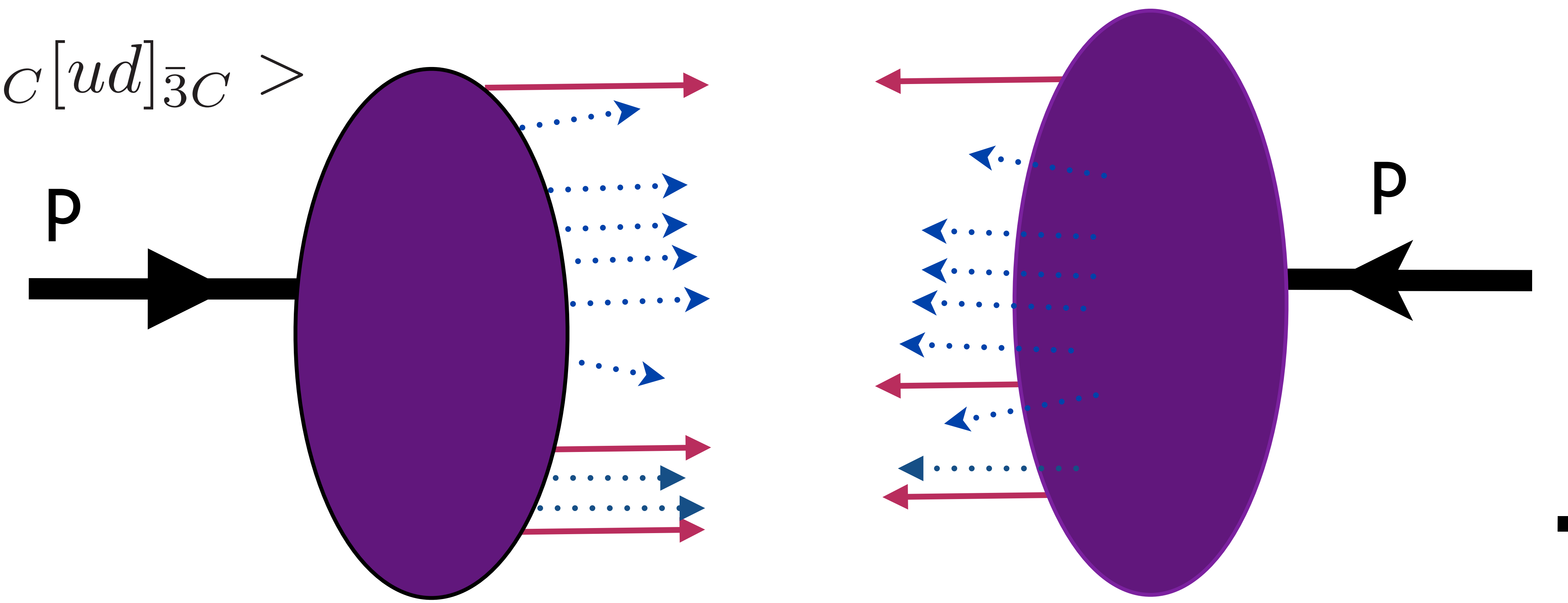
Highest hadron multiplicity produced when the two flux tubes are aligned and overlap completely along their length.

Bjorken, Goldhaber, sjb

Hadrons produced from the collisions of flux tubes



$$|p> = |u_{3C}[ud]_{\bar{3}C}>$$



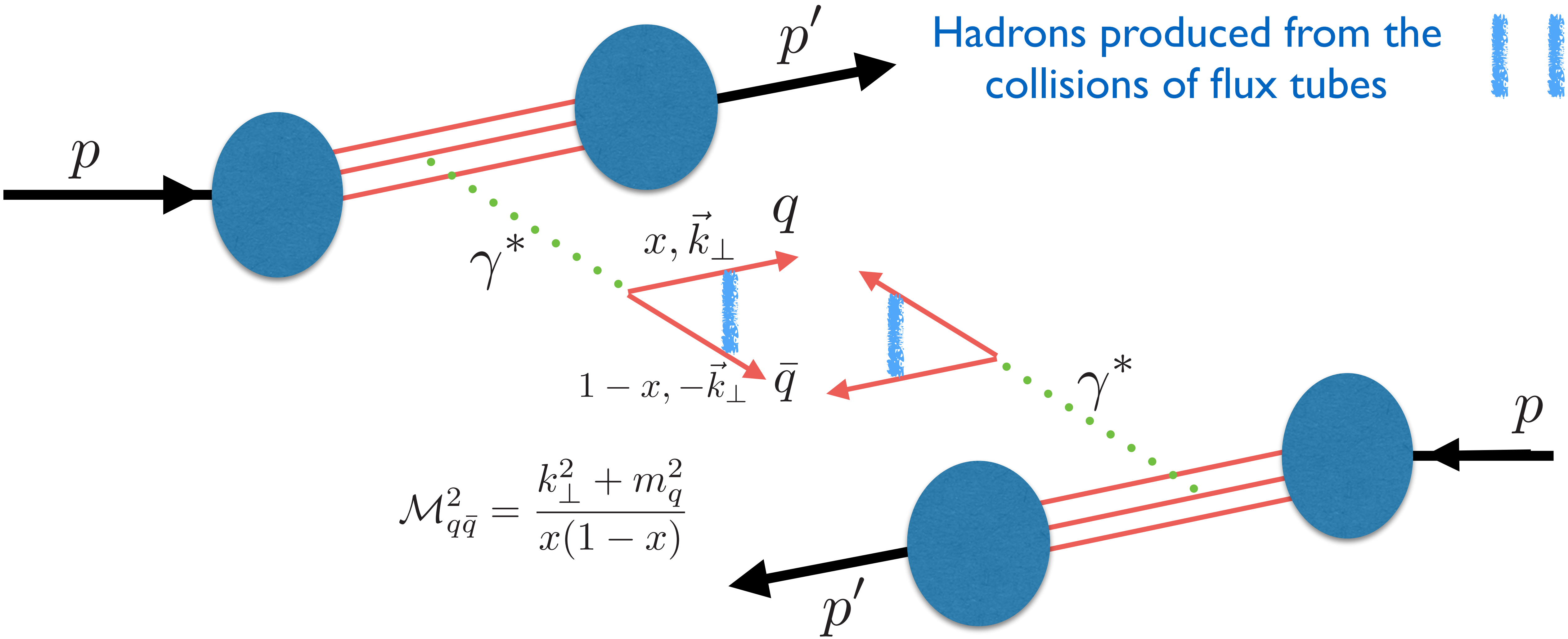
Gluonic distribution reflects quark+diquark color structure of the protons

v_2 (dominant) + v_3 (from `Y' quark + diquark configurations)

- ***Strangeness and charm enhancements***

Ridge creation in Ultra-Peripheral pp scattering

$$pp \to \gamma^* \gamma^* p' p' \to X p' p'$$



Plane of quark anti-quark and produced ridges aligned with plane of electron scattering

Correlation of $q\bar{q}$ and proton scattering planes: $\sim \cos^2 \Delta\phi$

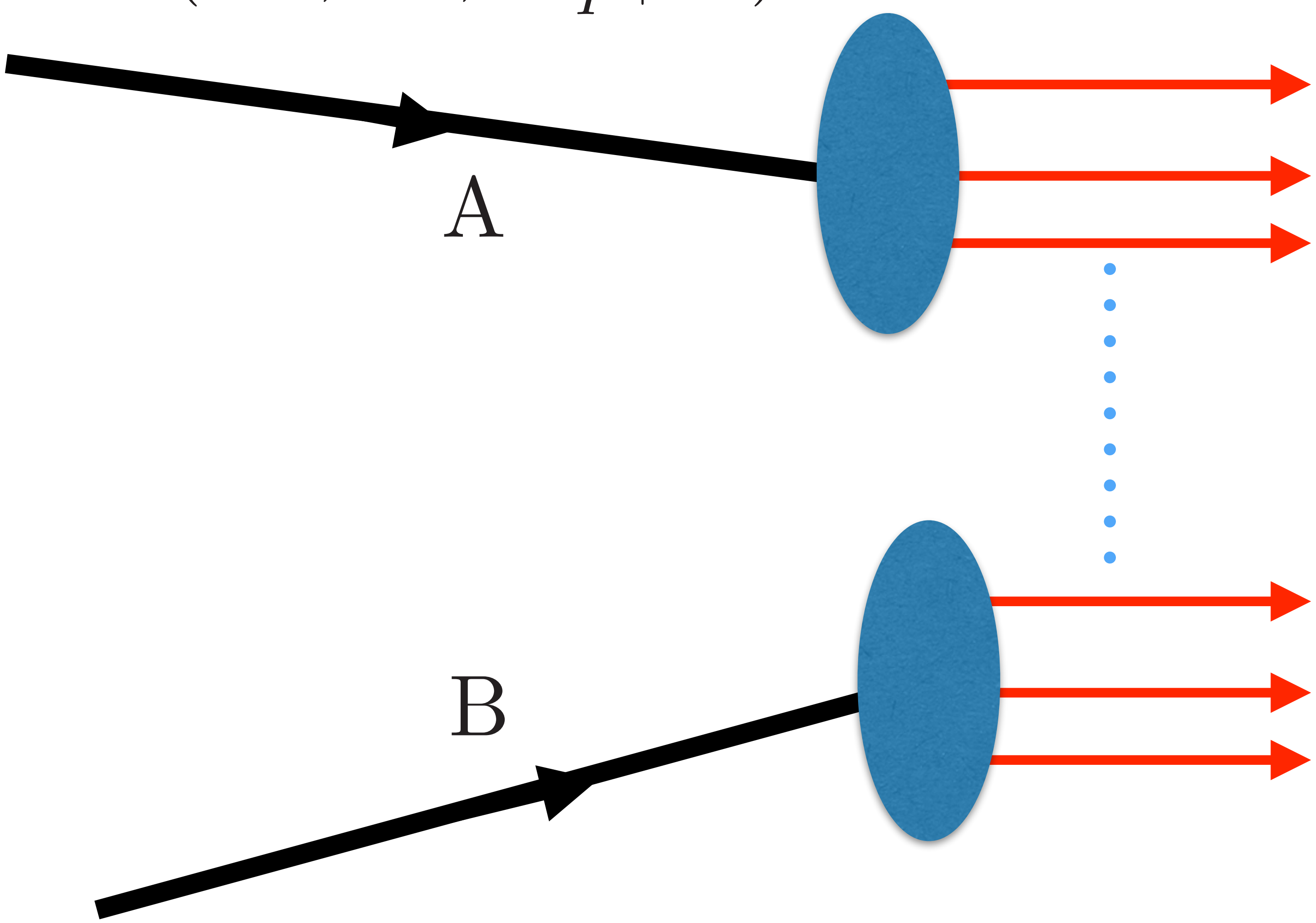
Collisions of Gluonic Strings in Ultra-Peripheral Collisions

- *quark-antiquark plane aligned with proton scattering plane*
- *maximum hadron multiplicity from flux tubes of colliding strings between two aligned quark-antiquark pairs — flux tubes aligned along their length* $\sim \cos^2 \Delta\phi$
- *maximum multiplicity produced when both protons scatter in same plane!*
- *minimum multiplicity when protons scatter at orthogonal angles*
- *Control ridge phenomena and multiplicity from orientations of UPC proton scattering planes*
- *Issue: Do the collisions modify the planar correlations?*
- *quark-antiquark pair distributions determined from each virtual photon LFWF*
- *Virtual photon polarization correlates quark-antiquark plane with the proton scattering planes*
- *Dependence on quark flavor, invariant mass of quark-antiquark pair*
- *New Domain for Hadron Dynamics*
- *Connection of Flux Tube to Color Confinement*
- *Similar results for photon-photon collisions* $\sigma(ee \to e'e'\gamma^*\gamma^* \to e'e'X)$

Useful Theory Tool: "Fool's ISR Frame"

Bjorken

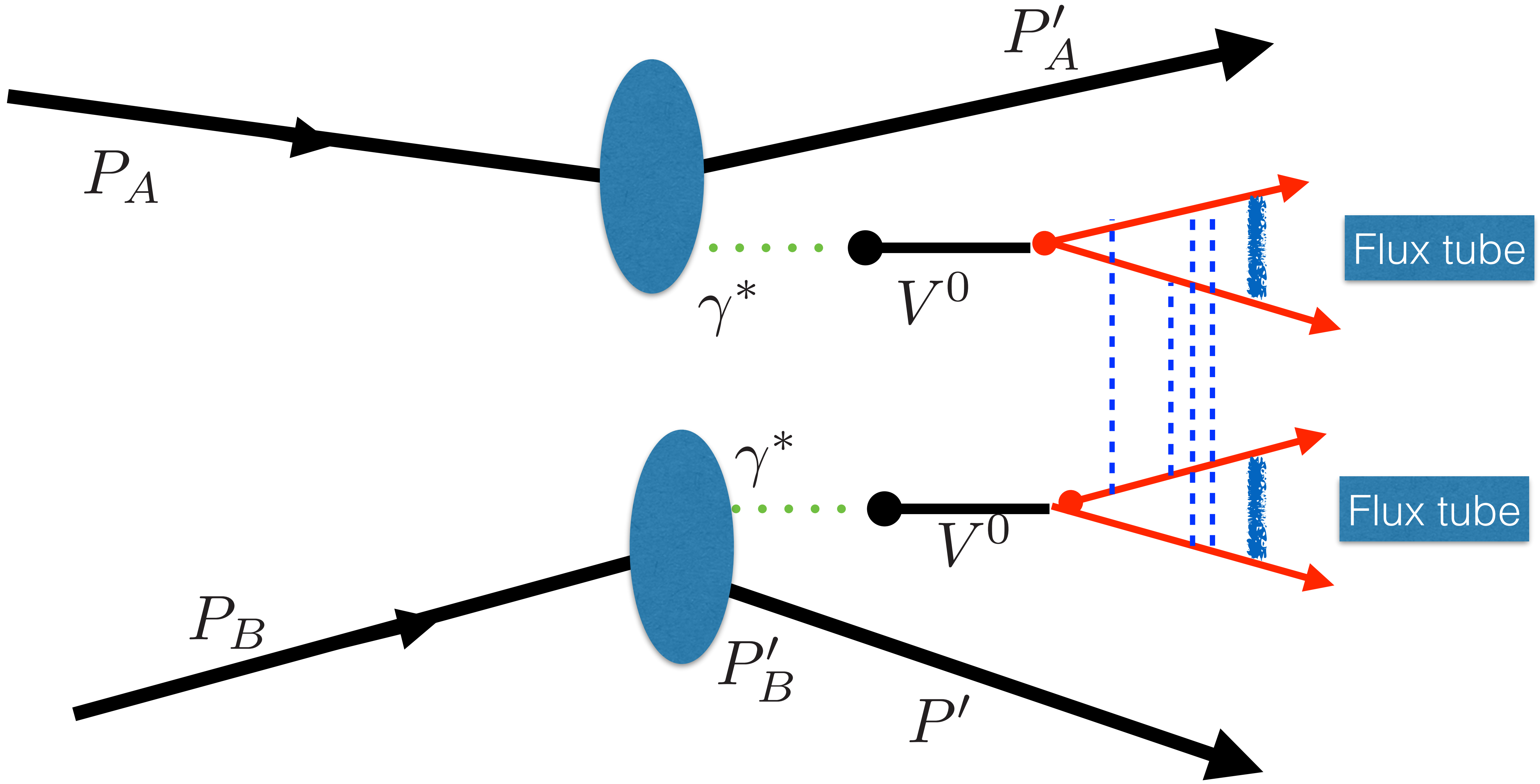
$$p_A = (P^+, \vec{P}_\perp, \frac{M_A^2 + P_\perp^2}{P^+})$$



Use $A^+ = 0$ gauge consistently

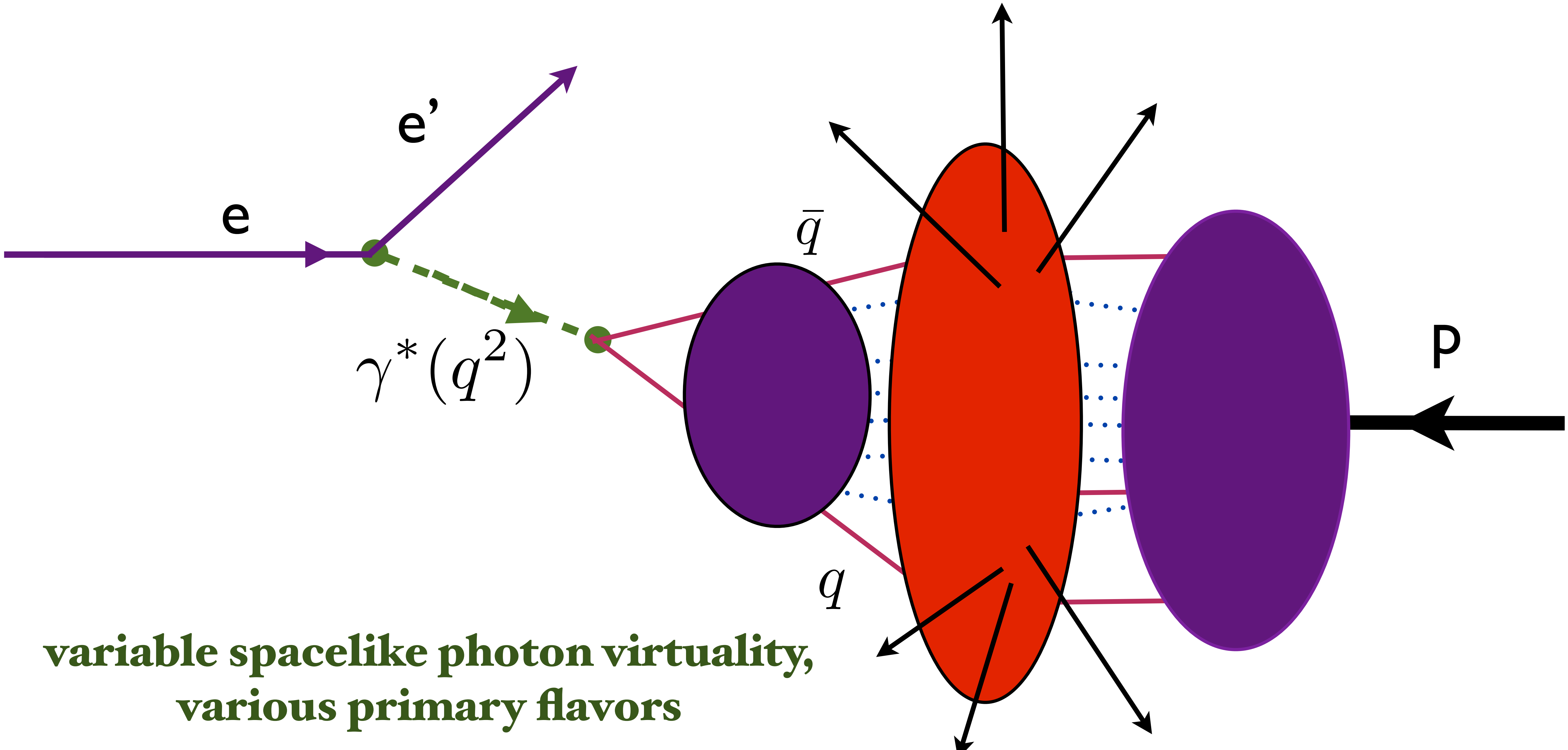
$$p_B = (P^+, -\vec{P}_\perp, \frac{M_B^2 + P_\perp^2}{P^+})$$

$$s = (p_A + p_B)^2 = M_A^2 + M_B^2 + 2(p_A^+ + p_B^+)(p_A^- + p_B^-) = 2M_A^2 + 2M_B^2 + 4P_\perp^2$$


P'_A
P_A
Flux tube
γ^*
V^0
γ^*
Flux tube
V^0
P_B
P'_B
P'

LHeC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame



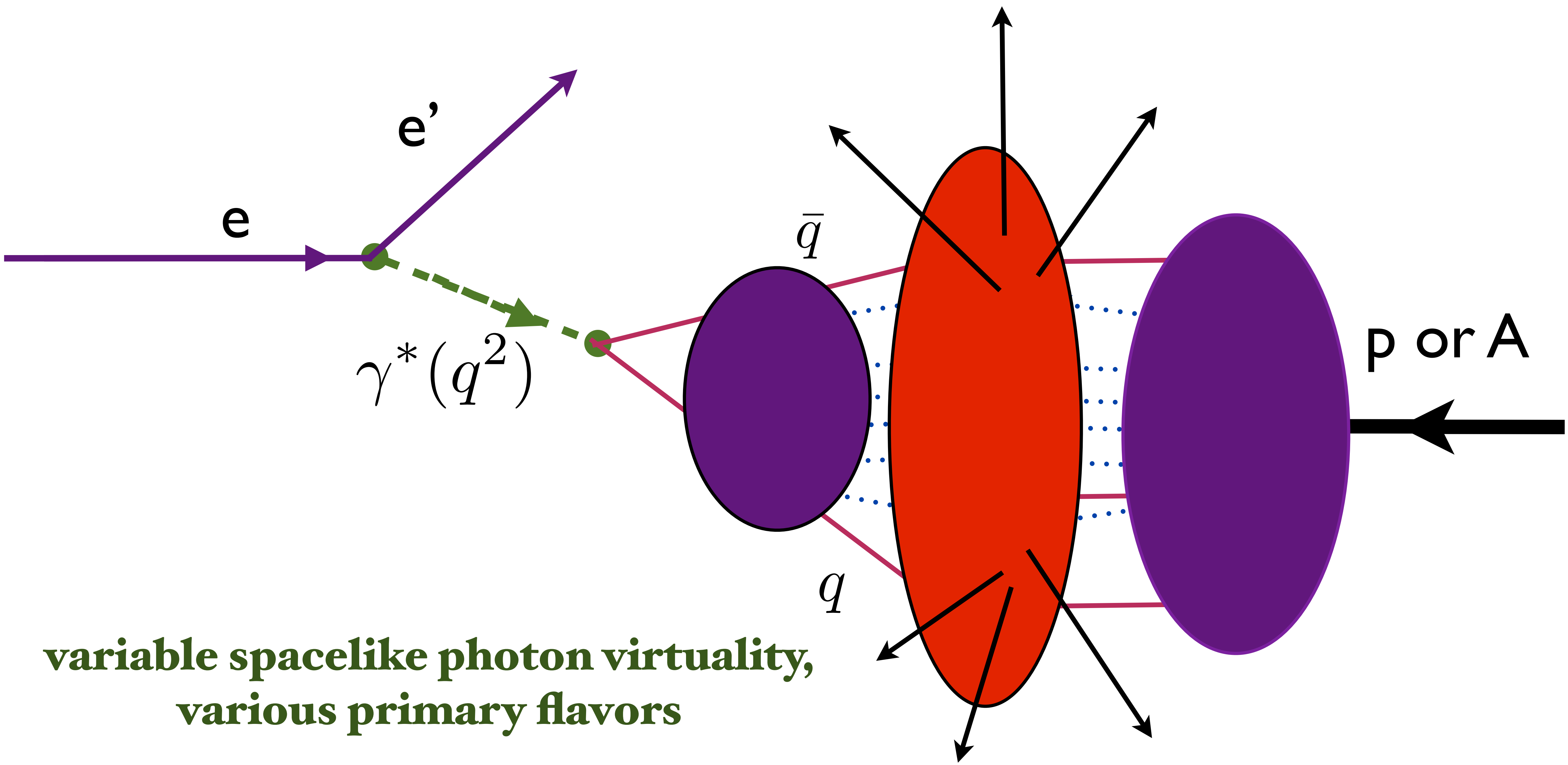
variable spacelike photon virtuality, various primary flavors

Plane of quark anti-quark and ridges aligned with plane of electron scattering

$$\sim \cos^2 \Delta\phi$$

EIC: Virtual Photon-Proton Collider

Perspective from the e-p collider frame

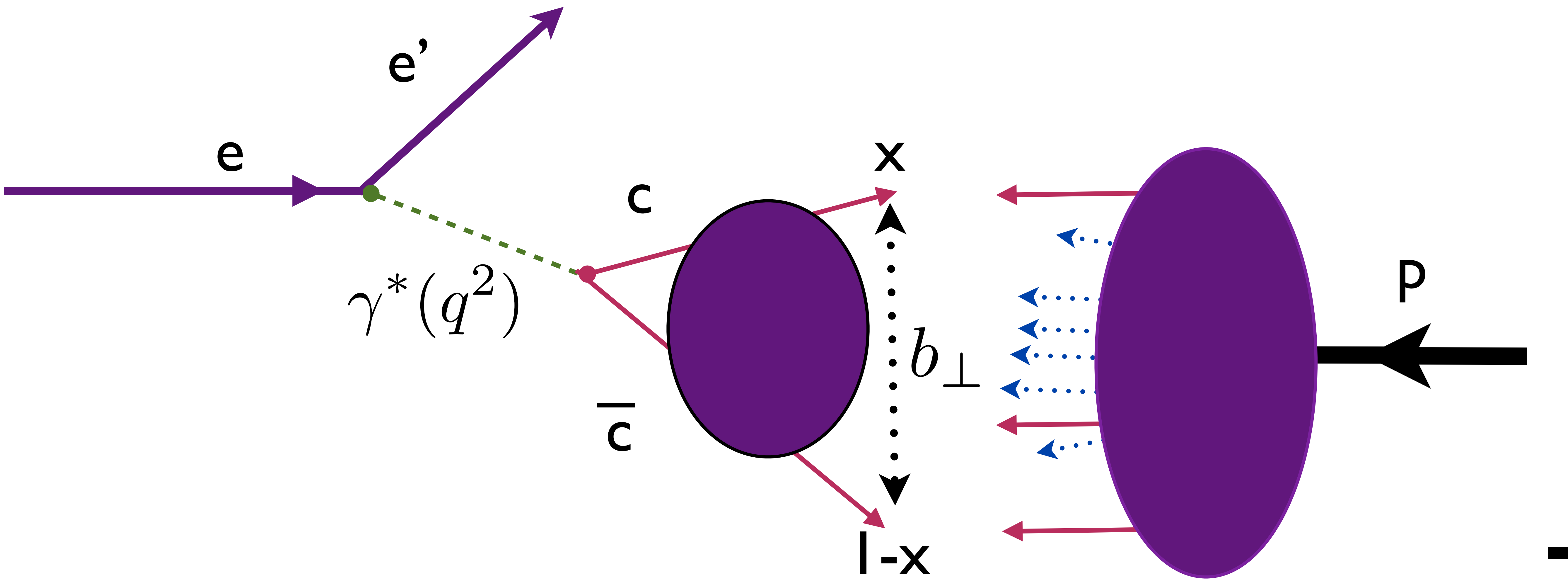


variable spacelike photon virtuality, various primary flavors

Saturation, nuclear shadowing, antishadowing

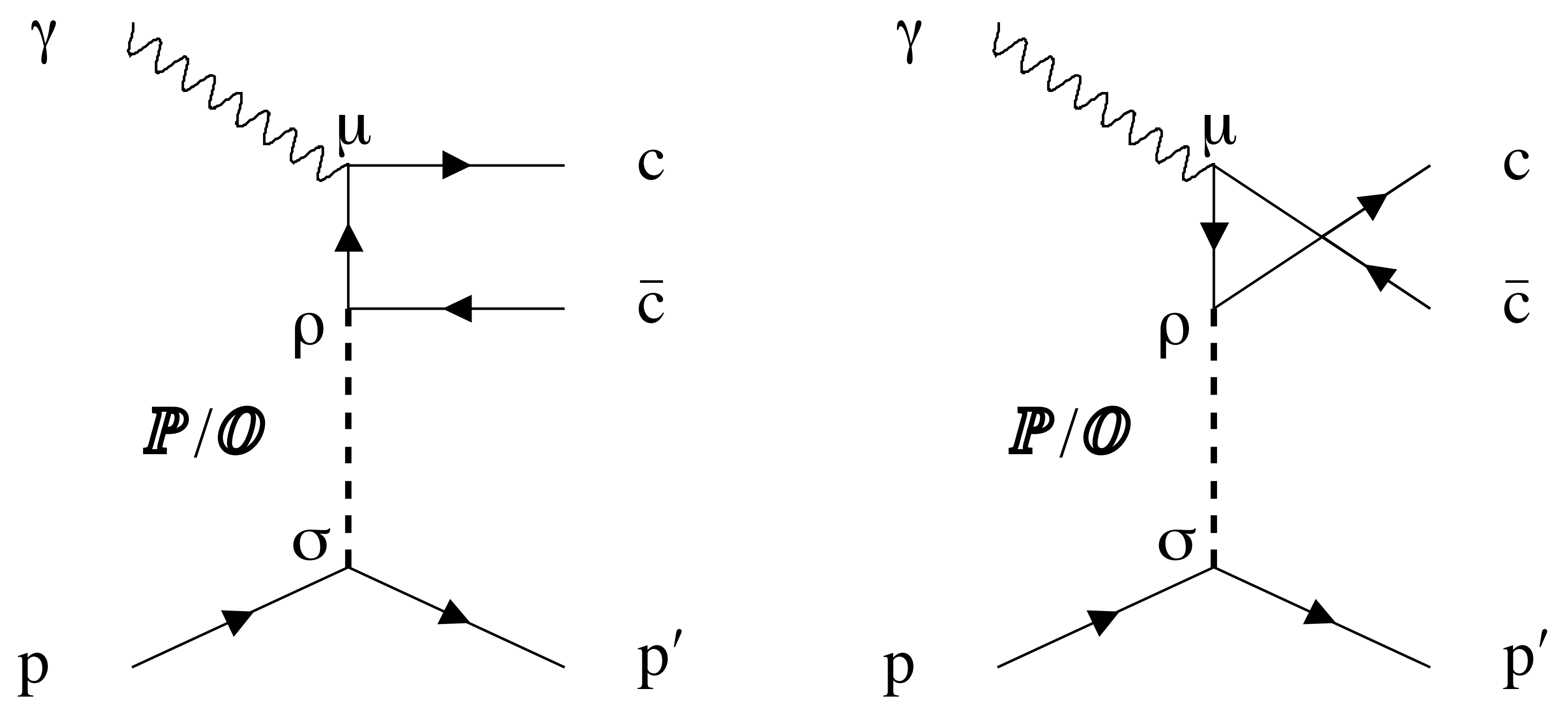
$\bar{c}\,c$ acts as a 'drill'

$$b_\perp^2 \sim \frac{1}{Q^2 x(1-x)+m_c^2}$$



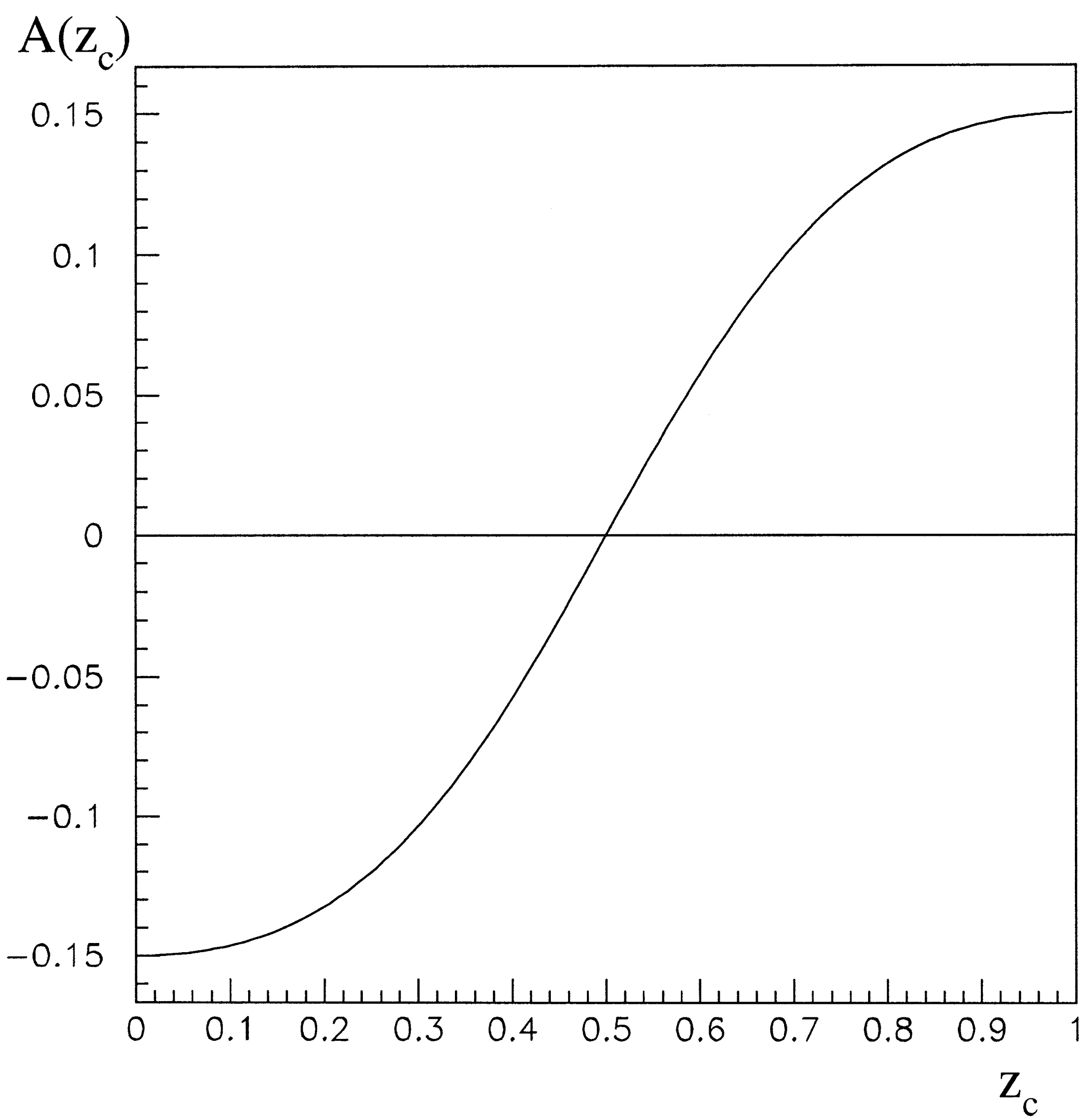
High Q^2, high M^2_Q virtual photon acts as a precision, small bore, linearly oriented, flavor-dependent probe acting on a proton or nuclear target.

Study final-state hadron multiplicity distributions, ridges, nuclear dependence



$$\gamma^* p \to c\bar{c}p$$

Odderon-Pomeron Interference!

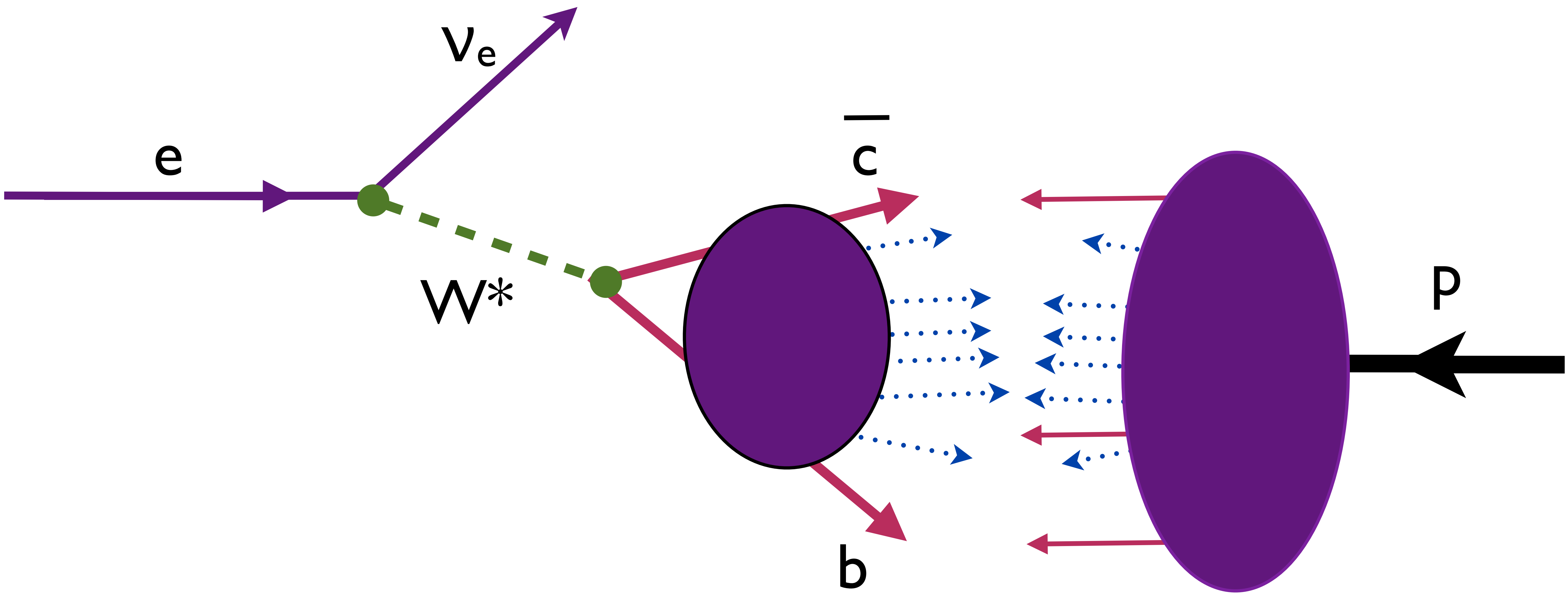


$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2z_c - 1}{z_c^2 + (1 - z_c)^2}$$

Measure charm asymmetry in photon fragmentation region

Merino, Rathsman, sjb

EIC: Virtual Weak Boson-Proton Collider



variable W* virtuality, variable flavors

proton or ions

Novel QCD Physics at the EIC

- Control Collisions of Flux Tubes and Ridge Phenomena
- Study Flavor-Dependence of Anti-Shadowing
- Heavy Quarks at Large x; Exotic States
- Direct, color-transparent hard subprocesses and the baryon anomaly
- Tri-Jet Production and the proton's LFWF
- Odderon-Pomeron Interference
- Digluon-initiated subprocesses and anomalous nuclear dependence of quarkonium production
- Factorization-Breaking Lensing Corrections

Principle of Maximum Conformality (PMC)

PRL **110,** 192001 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities in Perturbative QCD

Matin Mojaza*
CP3-Origins, Danish Institute for Advanced Studies, University of Southern Denmark, DK-5230 Odense, Denmark and SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Stanley J. Brodsky†
SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Xing-Gang Wu‡
Department of Physics, Chongqing University, Chongqing 401331, People's Republic of China
(Received 13 January 2013; published 10 May 2013)

We introduce a generalization of the conventional renormalization schemes used in dimensional regularization, which illuminates the renormalization scheme and scale ambiguities of perturbative QCD predictions, exposes the general pattern of nonconformal $\{\beta_i\}$ terms, and reveals a special degeneracy of the terms in the perturbative coefficients. It allows us to systematically determine the argument of the running coupling order by order in perturbative QCD in a form which can be readily automatized. The new method satisfies all of the principles of the renormalization group and eliminates an unnecessary source of systematic error.

Electron-Electron Scattering in QED

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

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

Gell-Mann--Low Effective Charge

- **Dressed Photon Propagator sums all β (vacuum polarization) contributions, proper and improper**

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

- **Initial Scale Choice t_o is Arbitrary!**

- **Any renormalization scheme can be used** $\alpha(t) \to \alpha_{\overline{MS}}(e^{-\frac{5}{3}}t)$

Set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

Choose renormalization scheme; e.g. $\alpha_s^R(\mu_R^{\rm init})$

↓

Choose μ_R^{init}; *arbitrary initial renormalization scale*

↓

Identify $\{\beta_i^R\}$ *– terms using* δ- *terms*

through the PMC – BLM correspondence principle

↓ *order by order*

Shift scale of α_s *to* $\mu_R^{\rm PMC}$ *to eliminate* $\{\beta_i^R\}$ *– terms*

↓

Conformal Series

Result is independent of $\mu_R^{\rm init}$ *and scheme at fixed order*

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at N_C=0

Eliminates unnecessary systematic uncertainty

Scale fixed at each order

δ-Scheme automatically identifies β-terms!

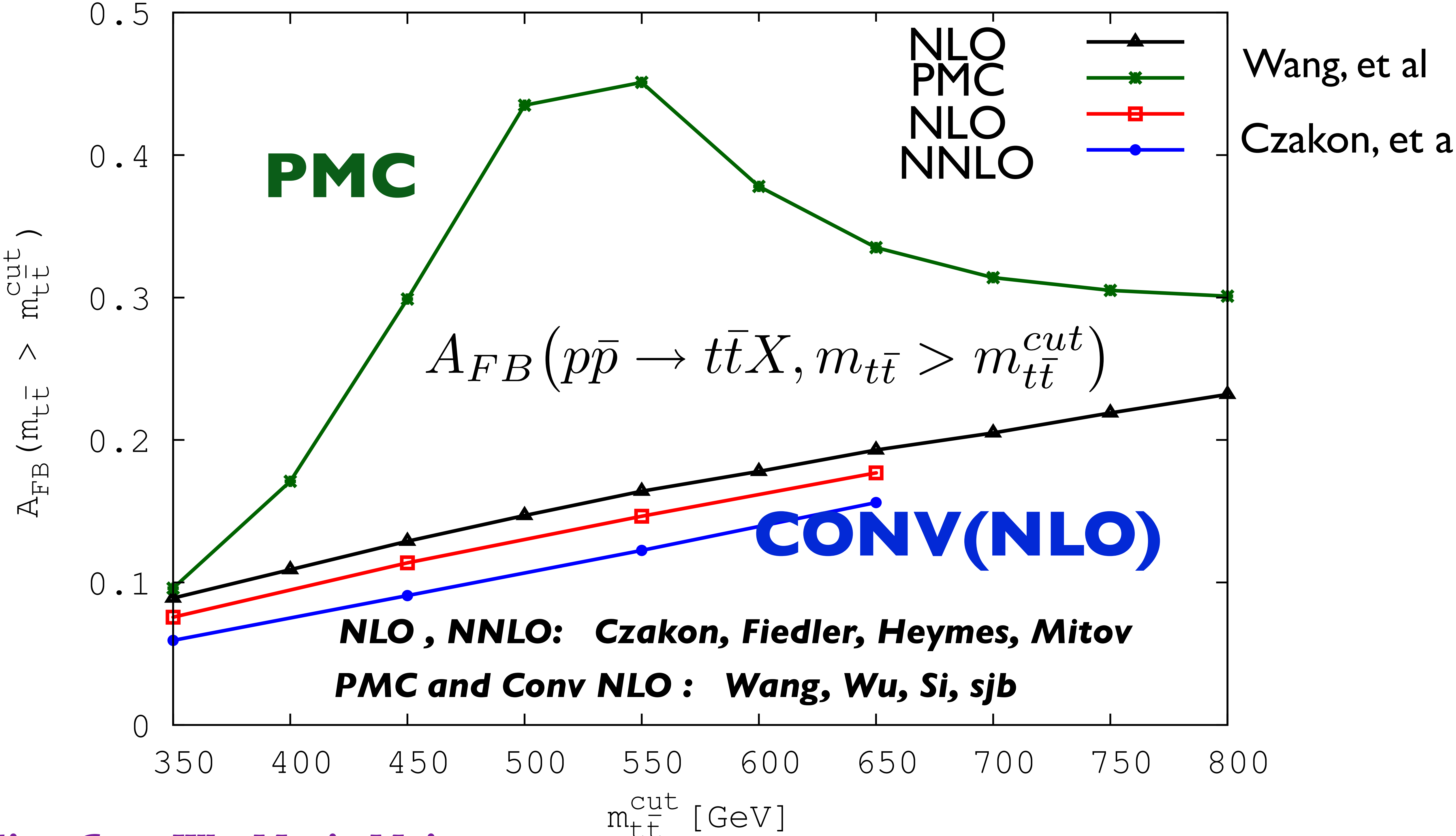
Principle of Maximum Conformality

Xing-Gang Wu, Matin Mojaza Leonardo di Giustino, SJB

A robot can compute the PMC scales

NNLO QCD predictions for fully-differential top-quark pair production at the Tevatron arXiv:1601.05375

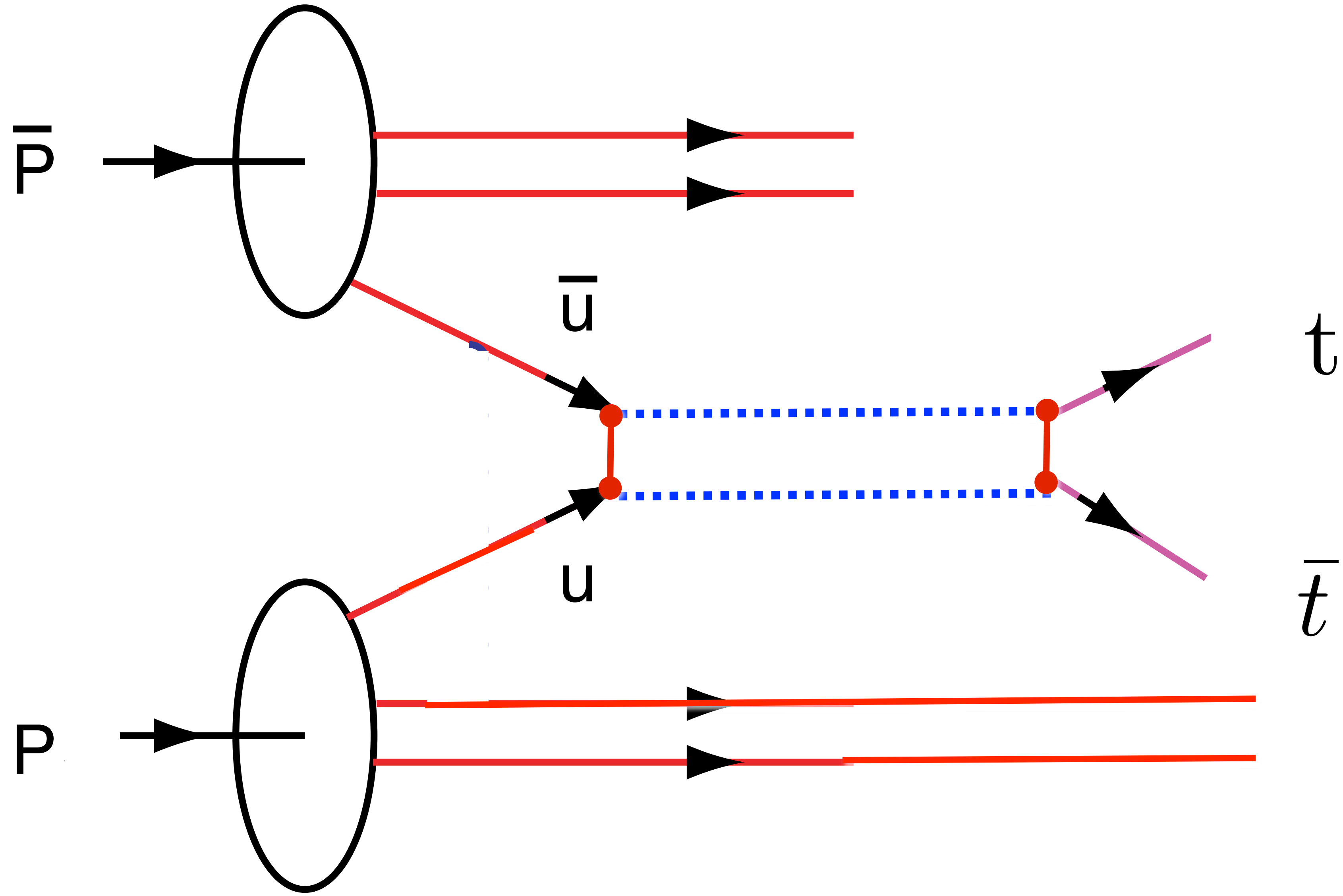
Michał Czakon,[a] Paul Fiedler,[a] David Heymes[b] and Alexander Mitov[b]



Xing-Gang Wu, Matin Mojaza
Leonardo di Giustino, SJB

Predictions for the cumulative front-back asymmetry.

Implications for the $\bar{p}p \to t\bar{t}X$ asymmetry at the Tevatron



Interferes with Born term.

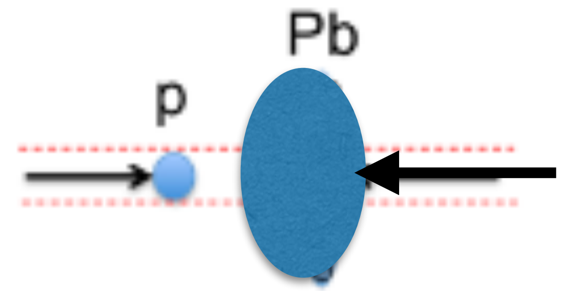
Small value of renormalization scale increases asymmetry, just as in QED

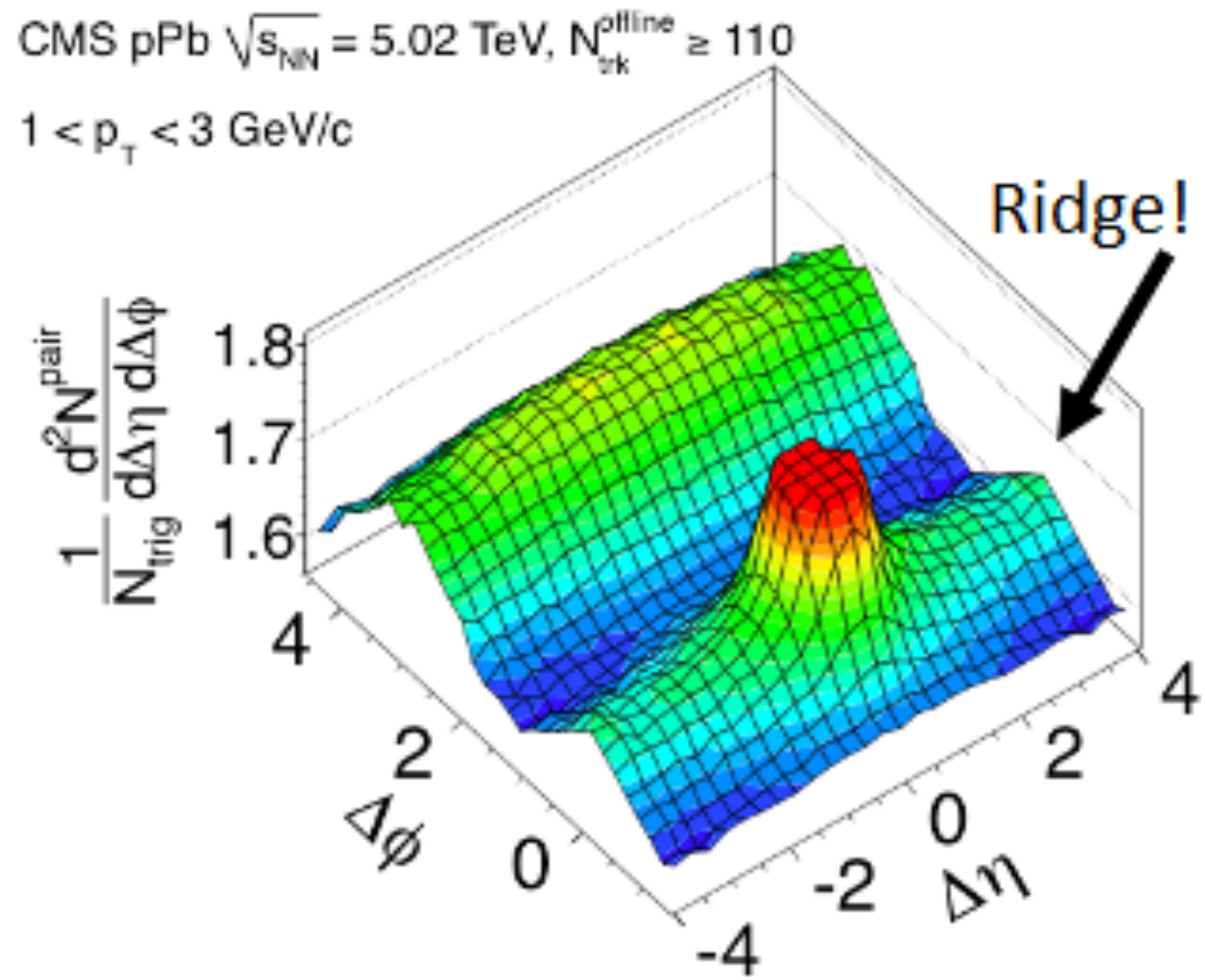
Xing-Gang Wu, sjb

Features of BLM/PMC

- ***Predictions are scheme-independent at every order***
- ***Matches conformal series***
- ***Commensurate Scale Relations between observables: Generalized Crewther Relation (Kataev, Lu, Rathsman, sjb)***
- ***No n! Renormalon growth***
- ***New scale appears at each order; n_F determined at each order - matches virtuality of quark loops***
- ***Multiple Physical Scales Incorporated (Hoang, Kuhn, Tuebner, sjb)***
- ***Rigorous: Satisfies all Renormalization Group Principles***
- ***Realistic Estimate of Higher-Order Terms***
- ***Same as Gell-Mann Low for QED*** $N_C \to 0$
- ***GUT: Must use the same scale setting procedure for QED, QCD***
- ***Eliminates unnecessary theory error***
- ***Maximal sensitivity to new physics***
- ***Example: BFKL intercept*** **(Fadin, Kim, Lipatov, Pivovarov, sjb)**

Ridge phenomena in photon-photon collisions





Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

with Fred Goldhaber, Stan Glazek, Patryk Kubiczek, and Robert Brown

2017 International Conference on the Structure and Interactions of the Photon
22th International Workshop on Photon-Photon Collisions
International Workshop on High Energy Photon Colliders