# New Perspectives for Hadron Physics

Fixed $\tau = t + z/c$

September 21 2013

LC2014 Registration opens October 1, 2013.

May 21 2013

LC2014-Raleigh was formally approved at the ILCAC Meeting in

Duke 昆山杜克大学
KUNSHAN UNIVERSITY

*Kunshan, China*
*August 3, 2015*

*Stan Brodsky*

SLAC
NATIONAL ACCELERATOR LABORATORY

7th Workshop on Hadron Physics in China and Opportunities Worldwide

# Goal: An analytic first approximation to QCD

- As Simple as Schrödinger Theory in Atomic Physics

- Relativistic, Frame-Independent, Color-Confining

- Confinement in QCD -- What is the analytic form of the confining interaction?

- What sets the QCD mass scale?

- QCD Running Coupling at all scales

- Hadron Spectroscopy-Regge Trajectories

- Light-Front Wavefunctions

- Form Factors, Structure Functions, Hadronic Observables

- Constituent Counting Rules

- Hadronization at the Amplitude Level

- Insights into QCD Condensates

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- Chiral Symmetry

- Systematically improvable

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*New Perspectives for Hadron Physics*
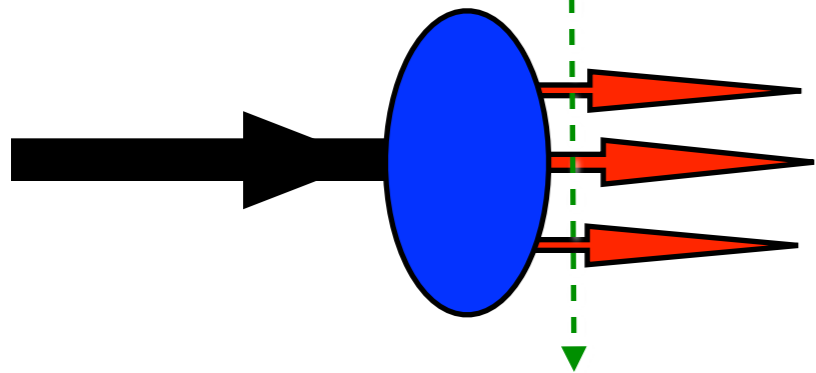
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# Bound States in Relativistic Quantum Field Theory:

## *Light-Front Wavefunctions*

### Dirac's Front Form: Fixed $\tau = t + z/c$

Fixed $\tau = t + z/c$

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

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

***Invariant under boosts. Independent of $P^\mu$***

$$H_{LF}^{QCD} |\psi> = M^2 |\psi>$$

**Direct connection to QCD Lagrangian**

## *Off-shell in invariant mass*

*Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space*

Each element of
flash photograph
illuminated
at same LF time

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

**Causal, frame-independent**
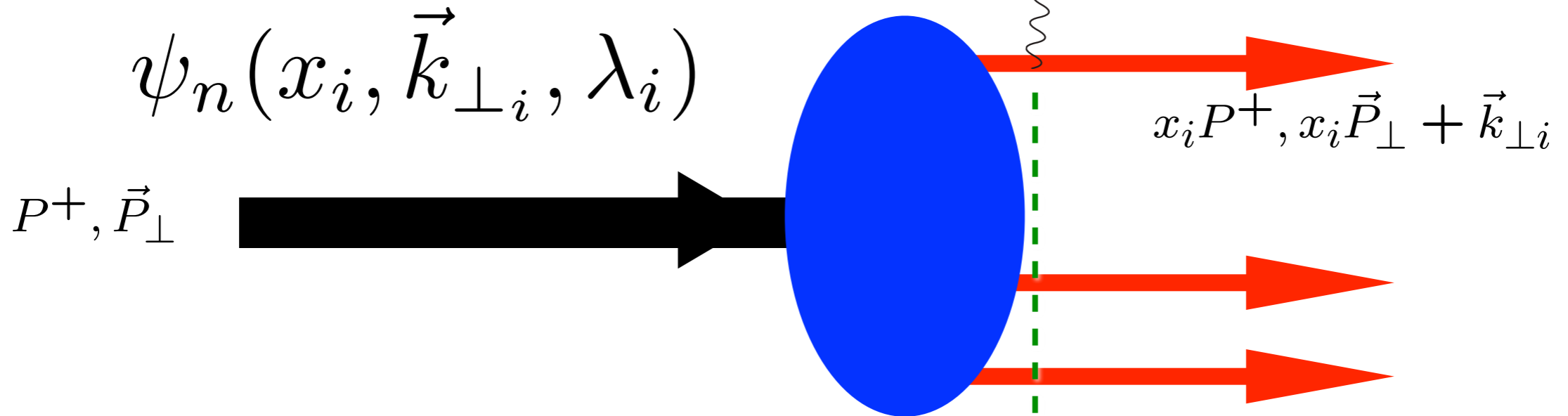
*Evolve in LF time*

$$P^- = i\frac{d}{d\tau}$$

Eigenstate -- independent of $\tau$

$$H_{LF} = P^+P^- - \vec{P}_\perp^2$$

$$H_{LF}^{QCD}|\Psi_h> = \mathcal{M}_h^2|\Psi_h>$$



HELEN BRADLEY - PHOTOGRAPHY

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

$\ell'$

$\ell$

$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$

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

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

*Measurements of hadron LF wavefunction are at fixed LF time*

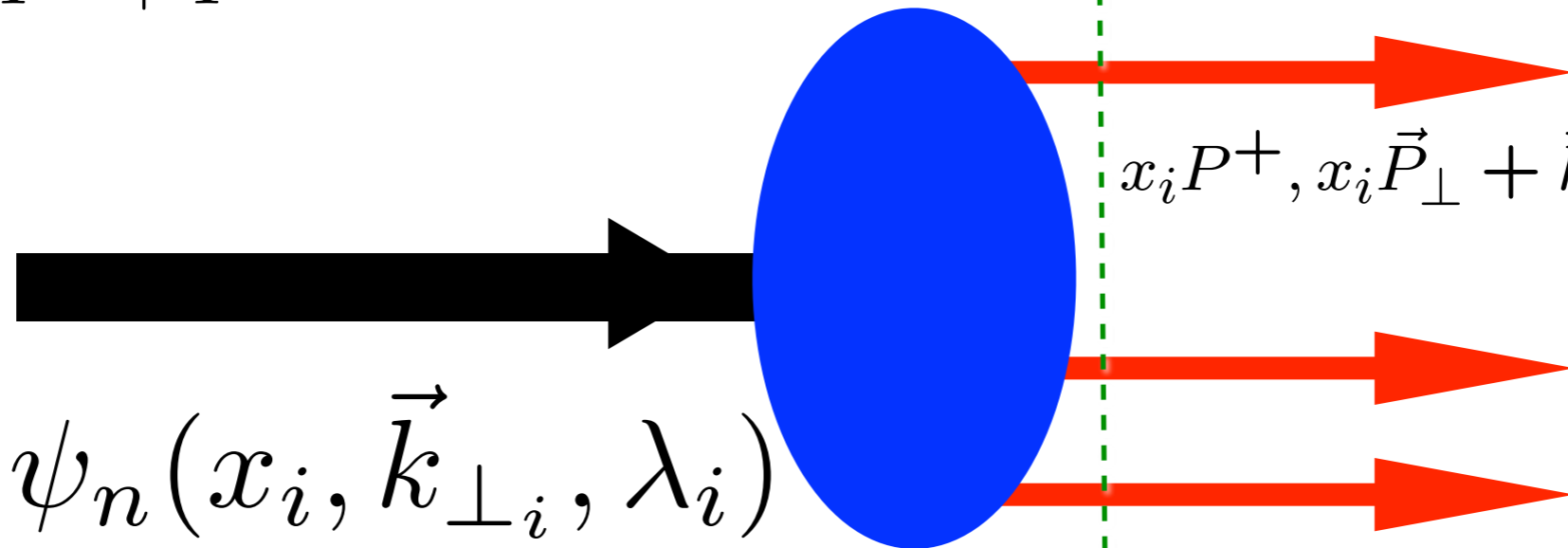Fixed $\tau = t + z/c$

*Like a flash photograph*

$$x_{bj} = x = \frac{k^+}{P^+}$$

# Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

*Eigenstate of LF Hamiltonian*

Fixed $\tau = t + z/c$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

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

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

$\sum_i^n x_i = 1$

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

$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$

$$\int \psi_{BS}(p,k) dk^- \to \psi_{LF}$$

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

*Invariant under boosts! Independent of $P^\mu$*

*Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS*
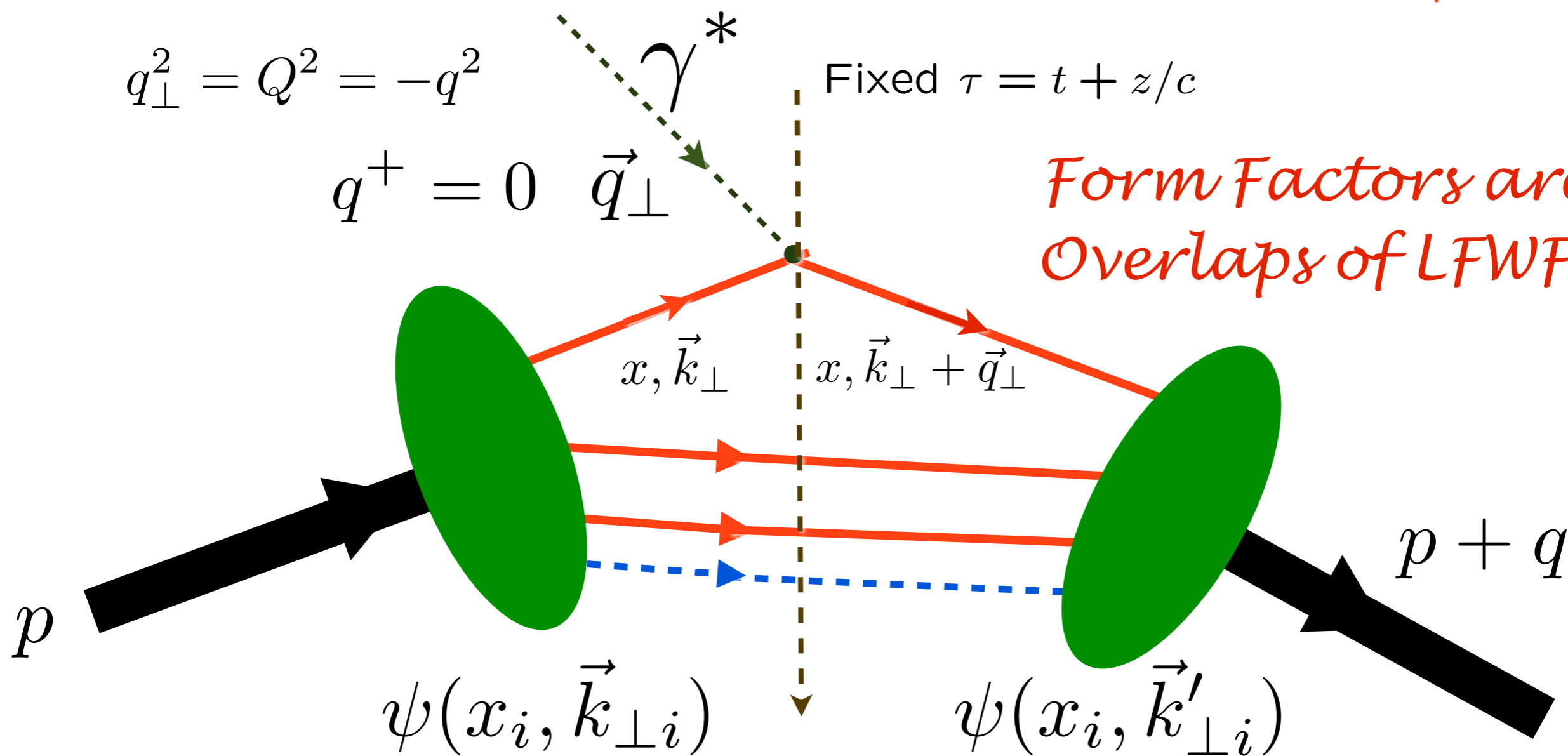
$$< p + q|j^+(0)|p >= 2p^+ F(q^2)$$

$$q_\perp^2 = Q^2 = -q^2$$

$$q^+ = 0 \quad \vec{q}_\perp$$

$\gamma^*$

Fixed $\tau = t + z/c$

*Form Factors are Overlaps of LFWFs*

$x, \vec{k}_\perp \quad x, \vec{k}_\perp + \vec{q}_\perp$

$p$

$p + q$

$\psi(x_i, \vec{k}_{\perp i}) \qquad \psi(x_i, \vec{k}'_{\perp i})$

**Drell &Yan, West Exact LF formula!**

*struck* $\quad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

*spectators* $\quad \vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\vec{q}_\perp$

***No comparable formula in instant form***

$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \frac{1}{2} \times$$

Drell, sjb

$$\left[ -\frac{1}{q^L} \psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R} \psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad\qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$
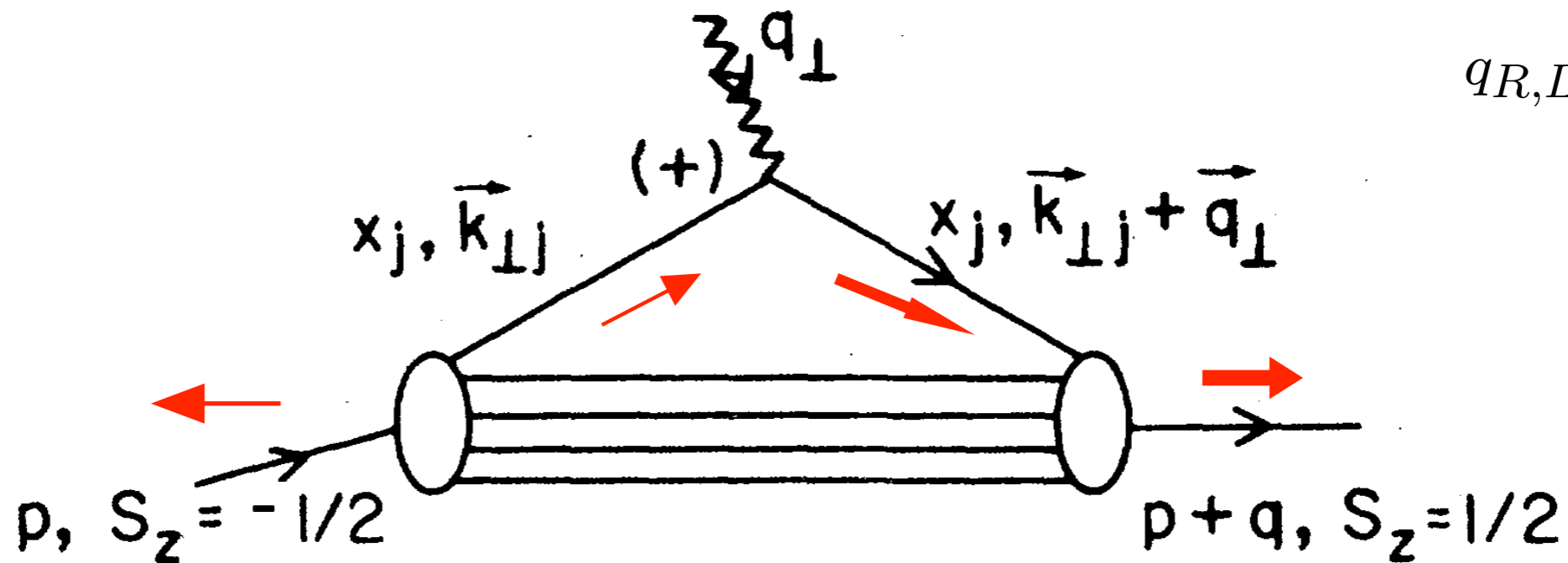
$$q_{R,L} = q^x \pm i q^y$$



Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

*Nonzero Proton Anomalous Moment -->*
*Nonzero orbital quark angular momentum*

# *Advantages of the Dirac's Front Form for Hadron Physics*

- **Measurements are made at fixed $\tau$**

- **Causality is automatic**

- **Structure Functions are squares of LFWFs**

- **Form Factors are overlap of LFWFs**

- **LFWFs are frame-independent -- no boosts!**

- **No dependence on observer's frame**

- **LF Holography: Dual to AdS space**

- **LF Vacuum trivial -- no condensates!**

- **Profound implications for Cosmological Constant**

- *Light Front Wavefunctions:*
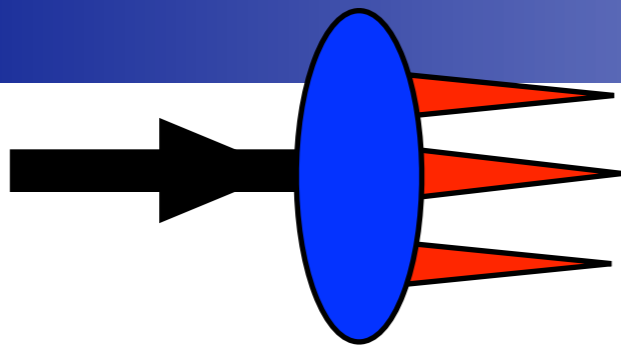
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

GTMDs

$x, \vec{k}_\perp, \vec{b}_\perp$

Momentum space $\qquad \vec{k}_\perp \leftrightarrow \vec{z}_\perp \qquad$ Position space
$$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$$

Transverse density in momentum space

Transverse density in position space

TMDs

$x, \vec{k}_\perp$

TMFFs

$\vec{k}_\perp, \vec{b}_\perp$

GPDs

$x, \vec{b}_\perp$

*Lorce, Pasquini*

**Transverse**

$\vec{k}_\perp$

$xP^+$

$\vec{b}_\perp$

**Longitudinal**

TMSDs

$\vec{k}_\perp$

PDFs

$x,$

FFs

$\vec{b}_\perp$

Charges
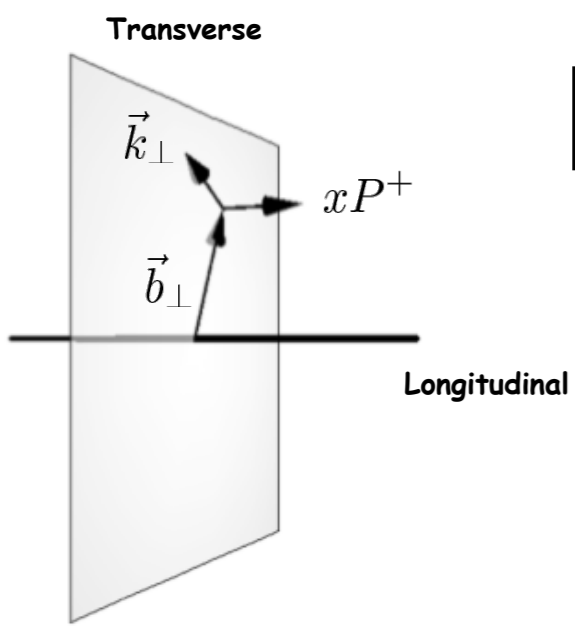
*Sivers, T-odd from lensing*

$\longrightarrow \int \mathrm{d}^2 b_\perp$

$\longrightarrow \int \mathrm{d}x$

$\longrightarrow \int \mathrm{d}^2 k_\perp$
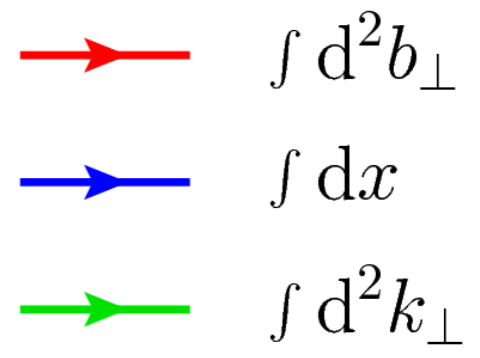
Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt, Ji, Yuan. Pasquini, …

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

Pseudo- T-Odd

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

"Lensing" involves soft scales

"Lensing Effect"

e⁻

e⁻

γ*

current quark jet

quark

final state interaction

spectator system

S ⊙

proton

Light-Front Wavefunction S and P - Waves!

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!

11

| 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 |
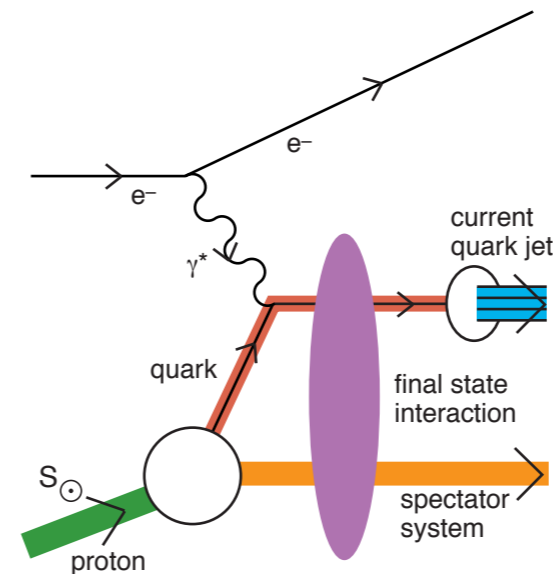
Hwang, Schmidt, sjb,

Mulders, Boer

Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb

$$\left| \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2$$



current quark jet

$e^-$

$e^-$

$\gamma^*$

quark

final state interaction

$S_\odot$

proton

spectator system

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**August 3, 2015**

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12

Anti-Shadowing

Shadowing

$\frac{F_2^{Ca}}{F_2^D}$

EMC    E136

NMC    E665

$Q^2 = 5\ \text{GeV}^2$

$x$

0.001    0.01    0.1    1

0.7    0.8    0.9    1    1.1    1.2
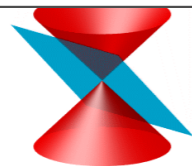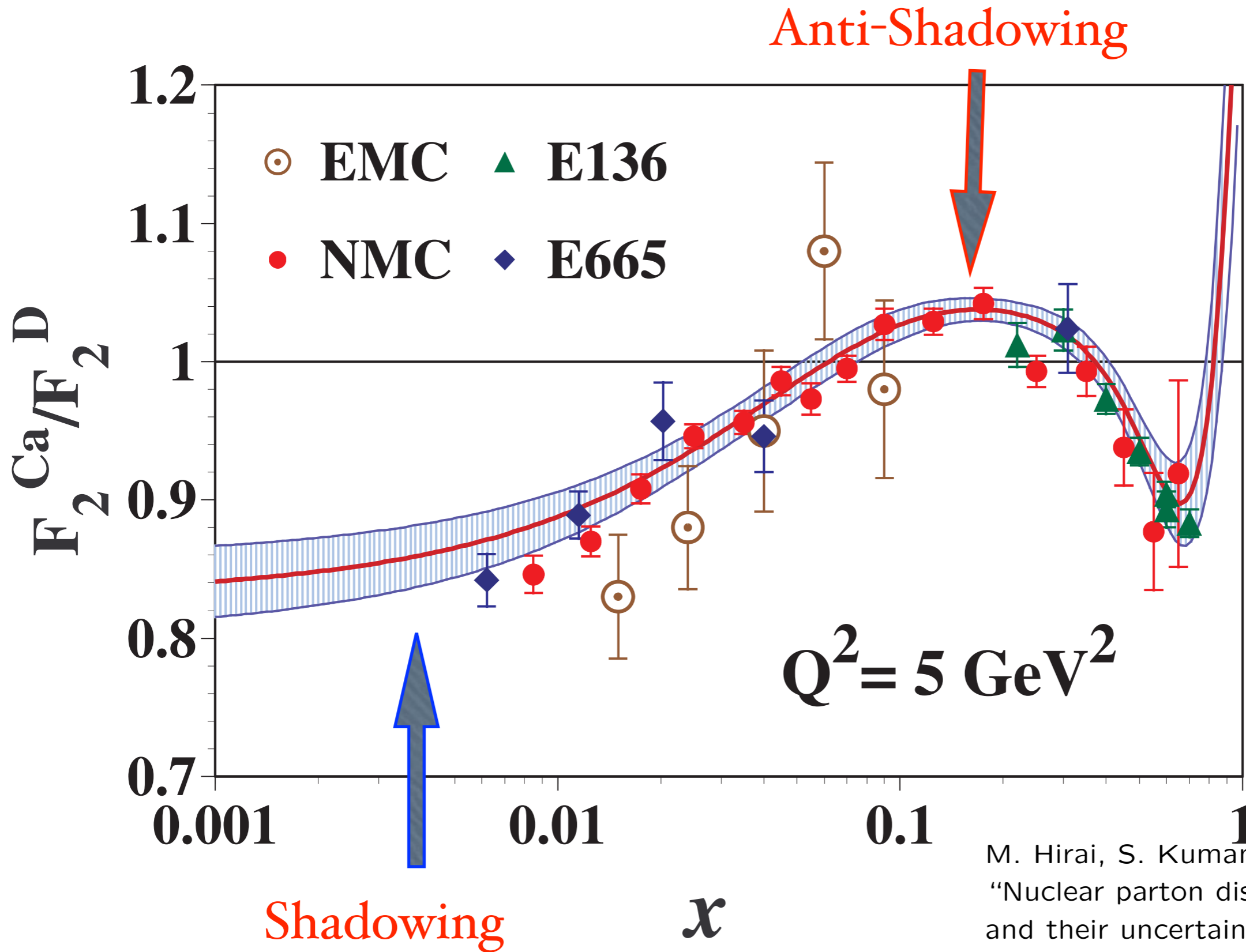
M. Hirai, S. Kumano and T. H. Nagai,
"Nuclear parton distribution functions
and their uncertainties,"
Phys. Rev. C **70**, 044905 (2004)
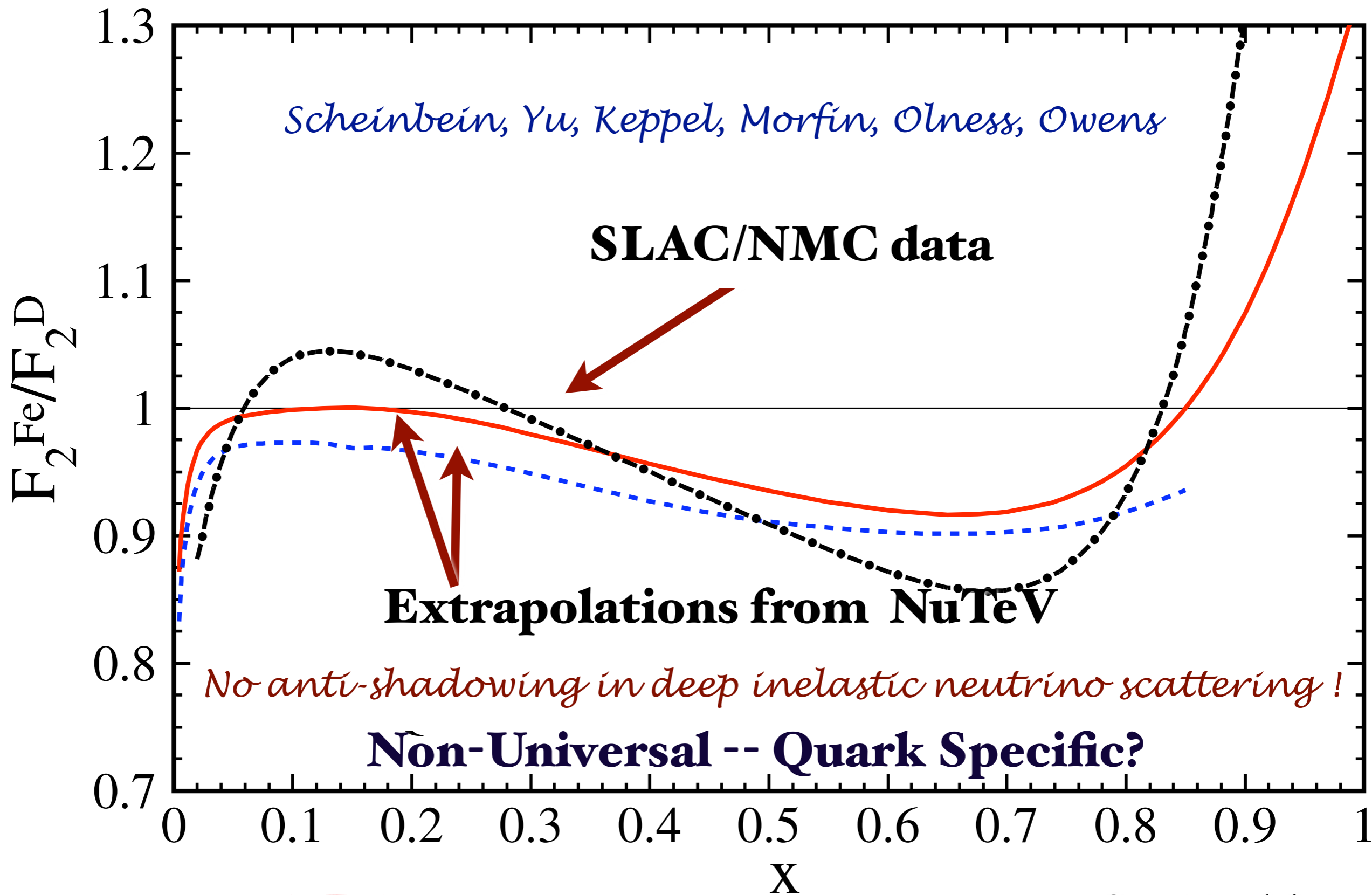[arXiv:hep-ph/0404093].

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E772

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$$Q^2 = 5 \text{ GeV}^2$$

*Scheinbein, Yu, Keppel, Morfin, Olness, Owens*

**SLAC/NMC data**

$F_2^{Fe}/F_2^D$

X

**Extrapolations from NuTeV**

*No anti-shadowing in deep inelastic neutrino scattering !*

**Non-Universal -- Quark Specific?**

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14

# Nuclear Shadowing in QCD
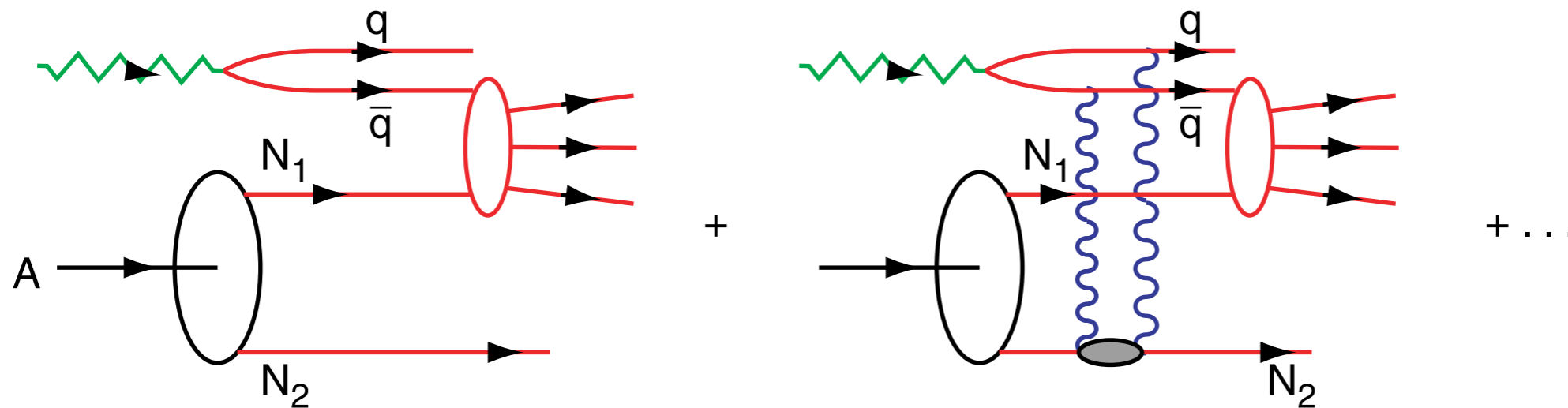


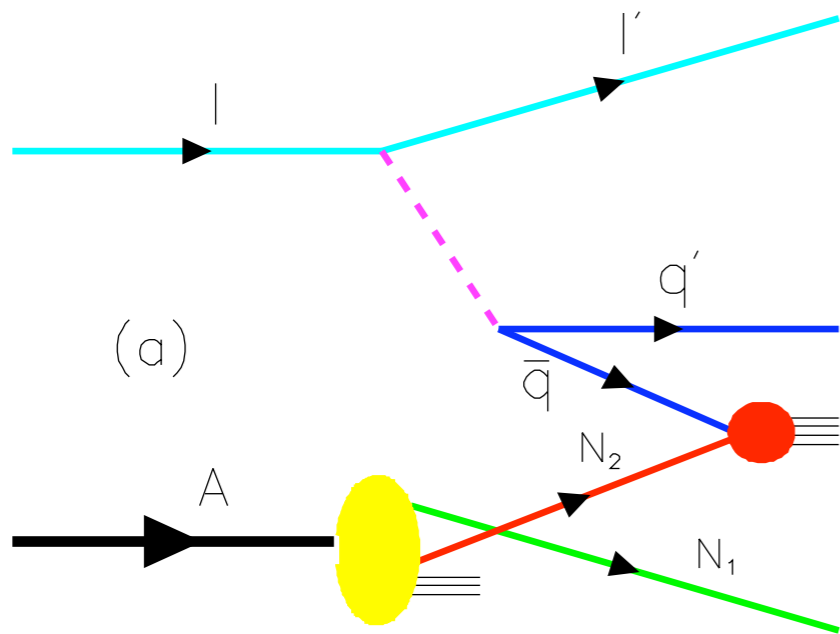*Shadowing depends on understanding leading twist-diffraction in DIS*

**Nuclear Shadowing not included in nuclear LFWF !**

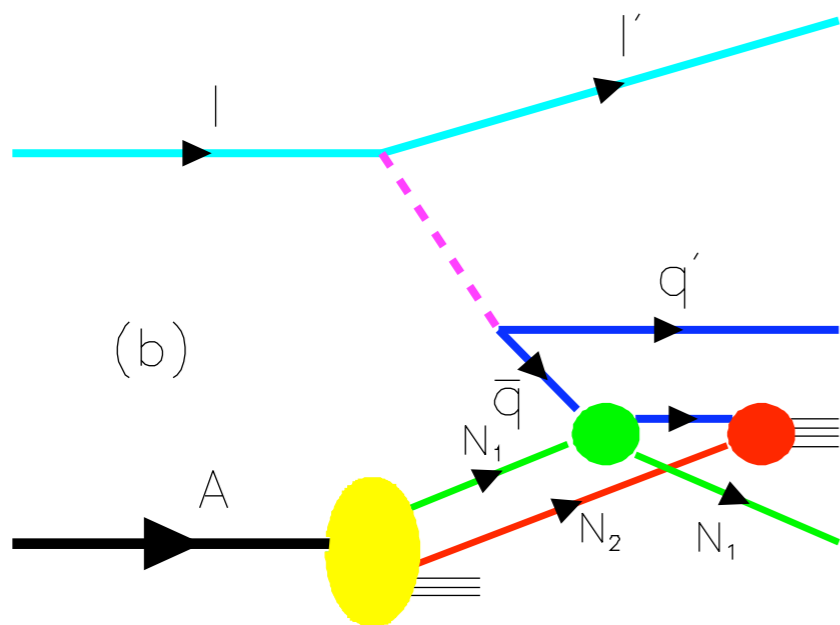**Dynamical effect due to virtual photon interacting in nucleus**

**Diffraction via Reggeon gives constructive interference!**

*Anti-shadowing not universal*

The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken $x_B$ :
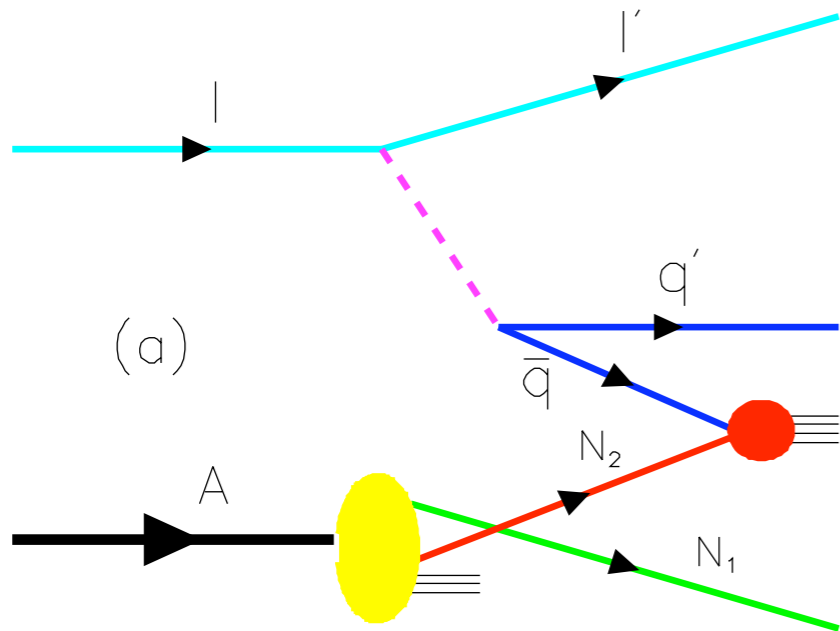$$1/M x_B = 2\nu/Q^2 \geq L_A.$$

If the scattering on nucleon $N_1$ is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching $N_2$.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

**Diffraction via Pomeron gives destructive interference!**

*Shadowing*

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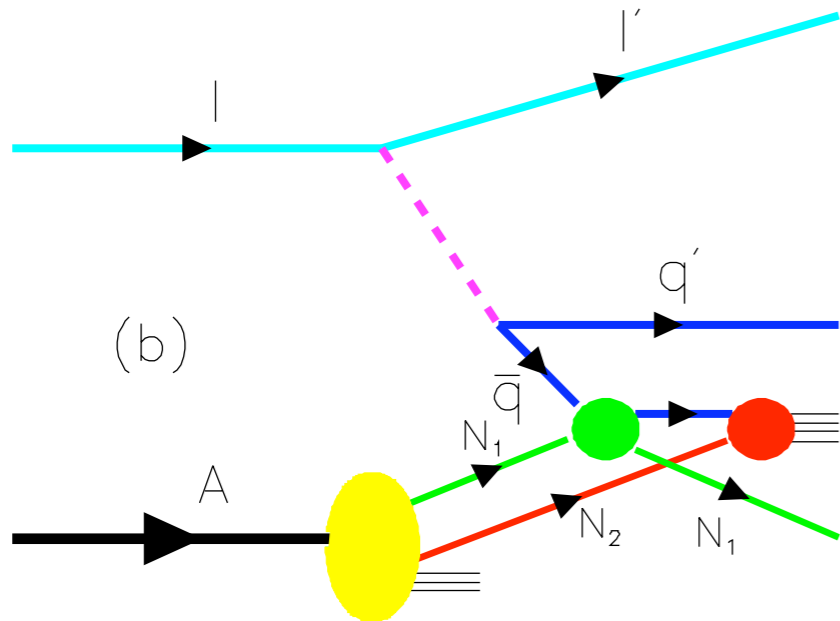
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16

The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken $x_B$ :
$$1/Mx_B = 2\nu/Q^2 \geq L_A.$$

Regge

If the scattering on nucleon $N_1$ is via ~~pomeron~~ exchange, the one-step and two-step amplitudes are ~~opposite in phase, thus diminishing the $\bar{q}$ flux reaching $N_2$.~~

constructive in phase
thus increasing the flux reaching $N_2$

(a)

(b)

Reggeon DDIS produces nuclear flavor-dependent anti-shadowing

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17

# Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

Depends on quark flavor!

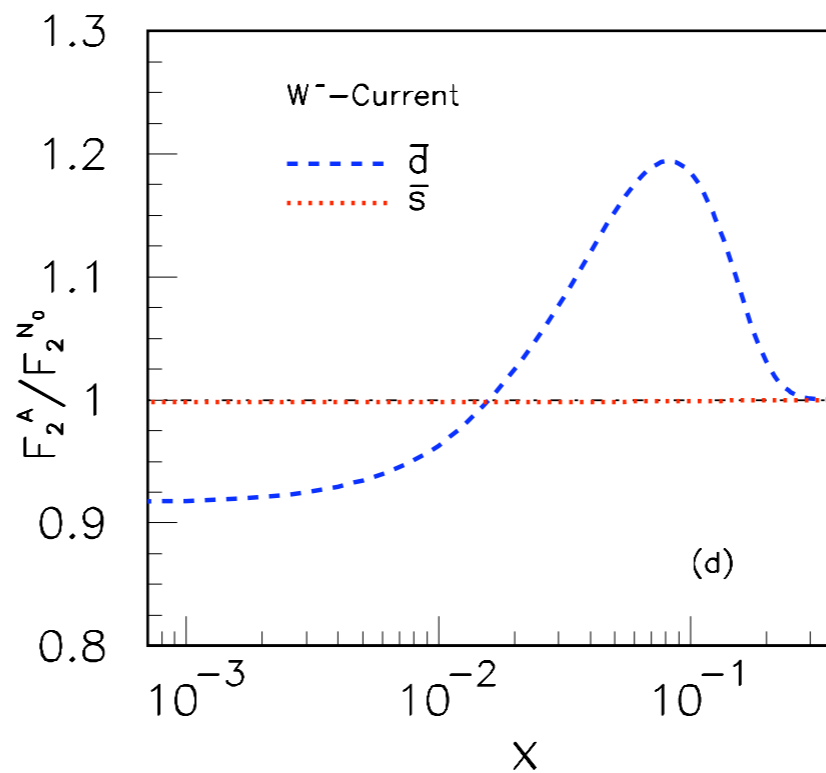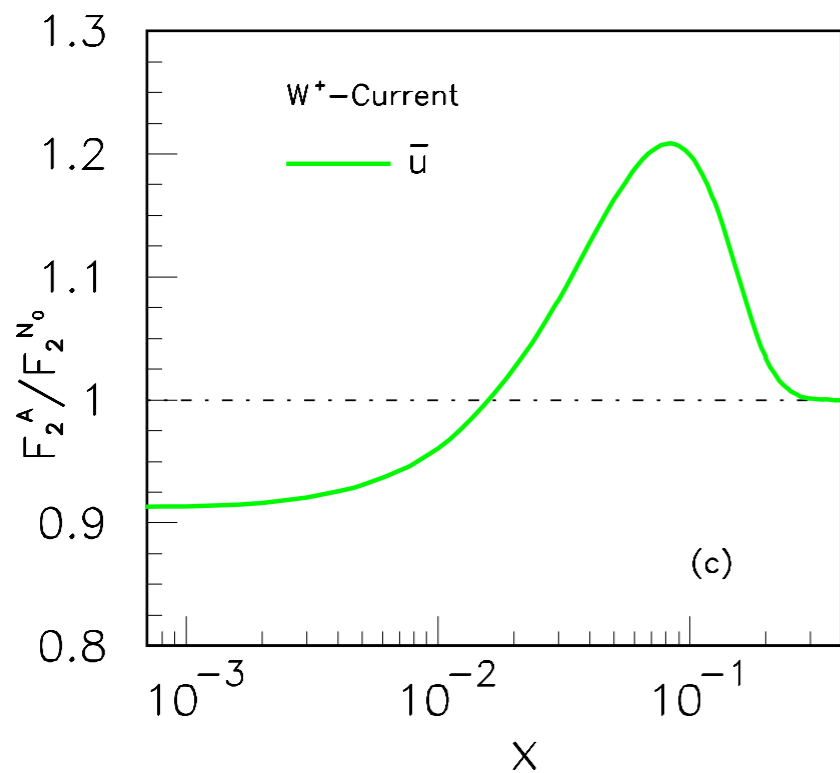Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

*Critical test: Tagged Drell-Yan*

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Schmidt, Yang; sjb
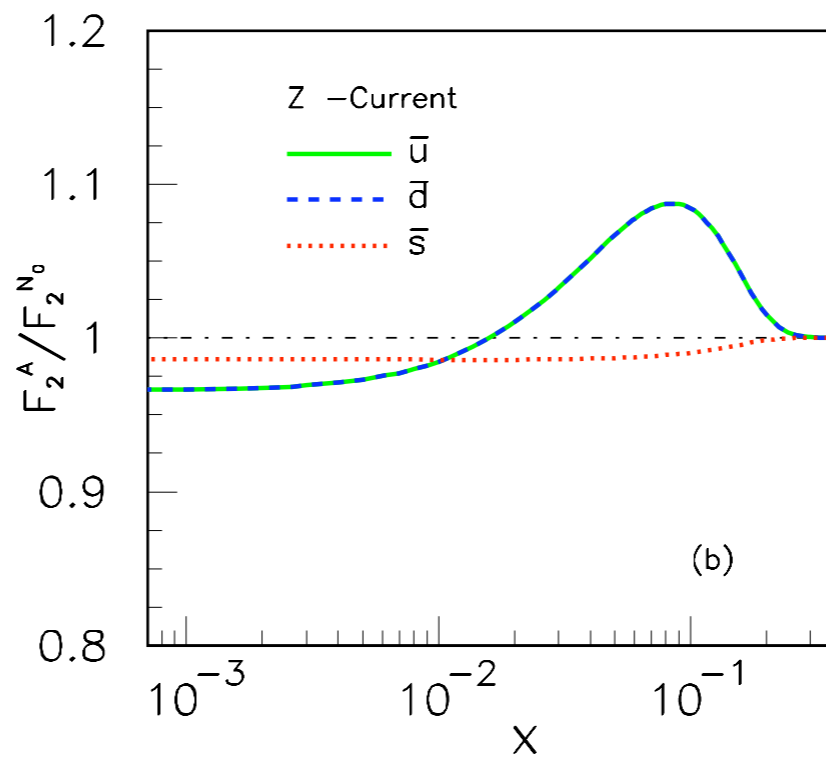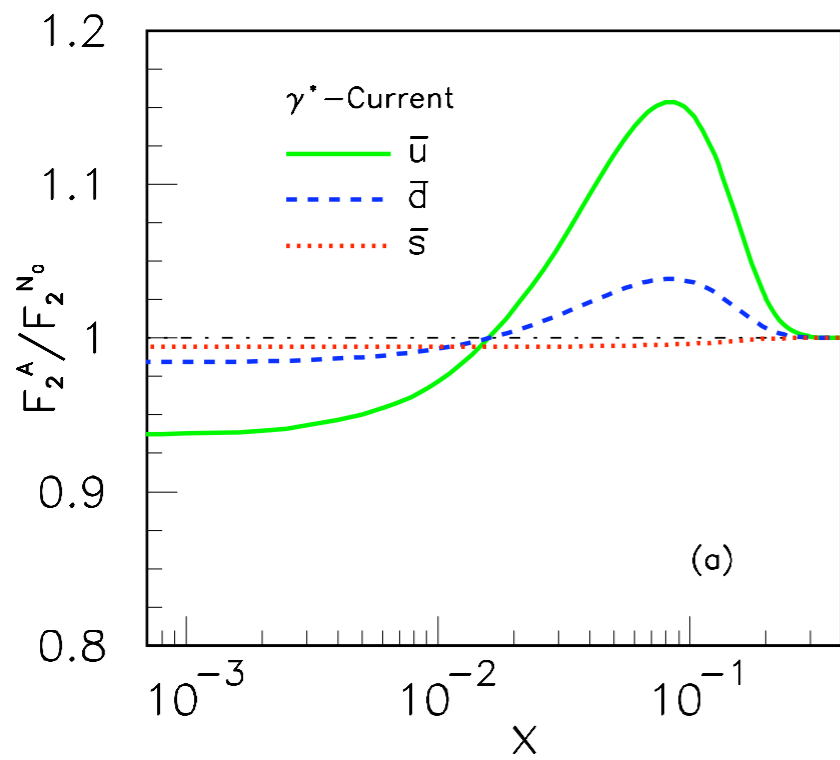
Modifies
NuTeV extraction of
$$\sin^2 \theta_W$$

Test in flavor-tagged
DIS at the EIC

## Nuclear Antishadowing not universal !

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19

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# Shadowing and Antishadowing of DIS Structure Functions
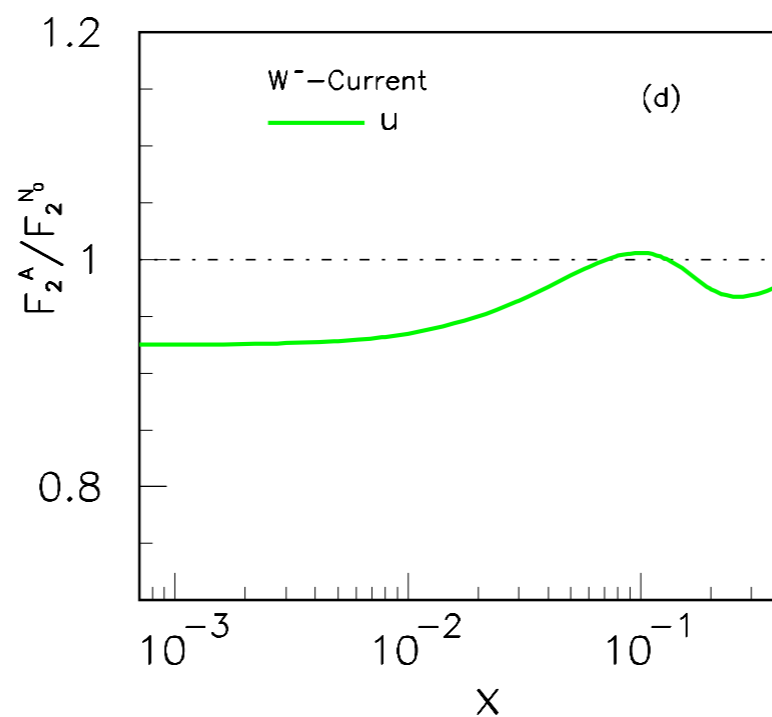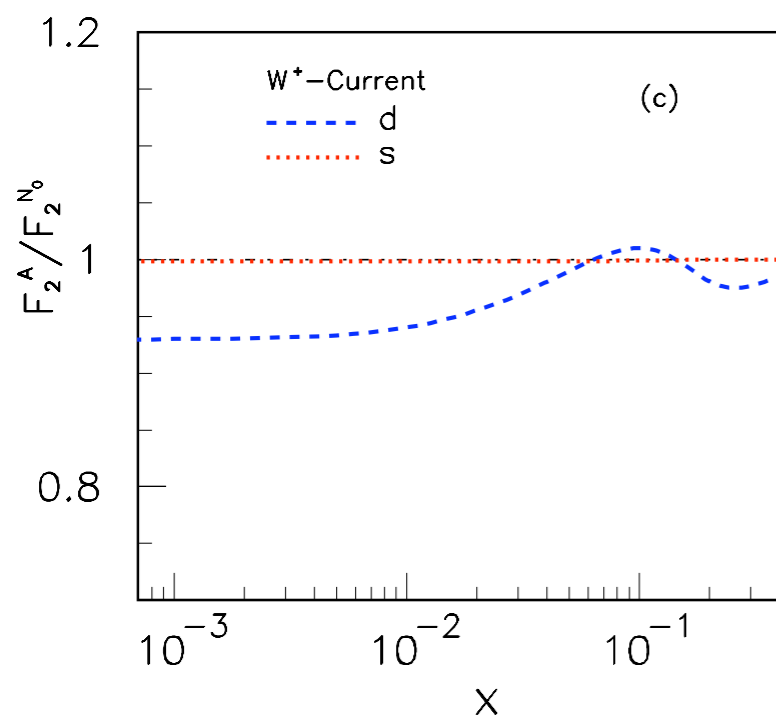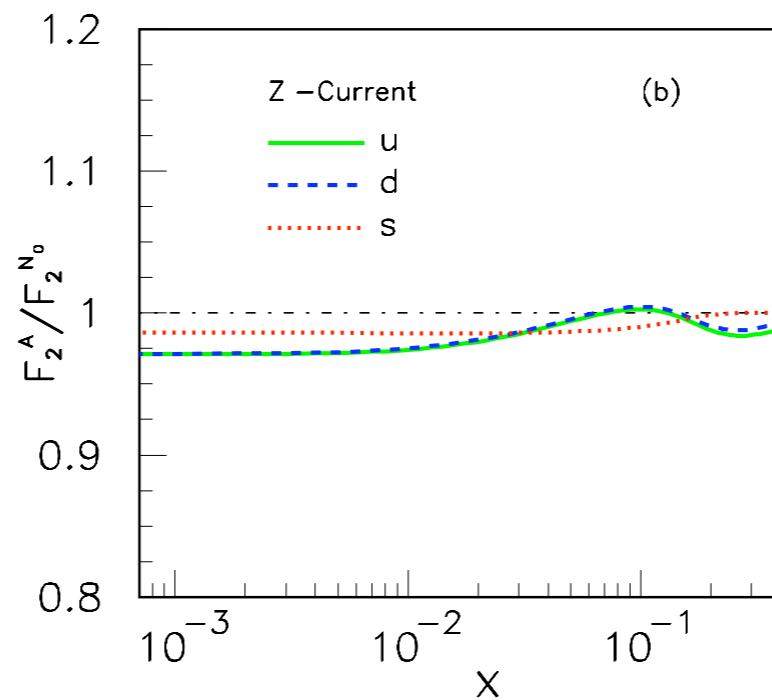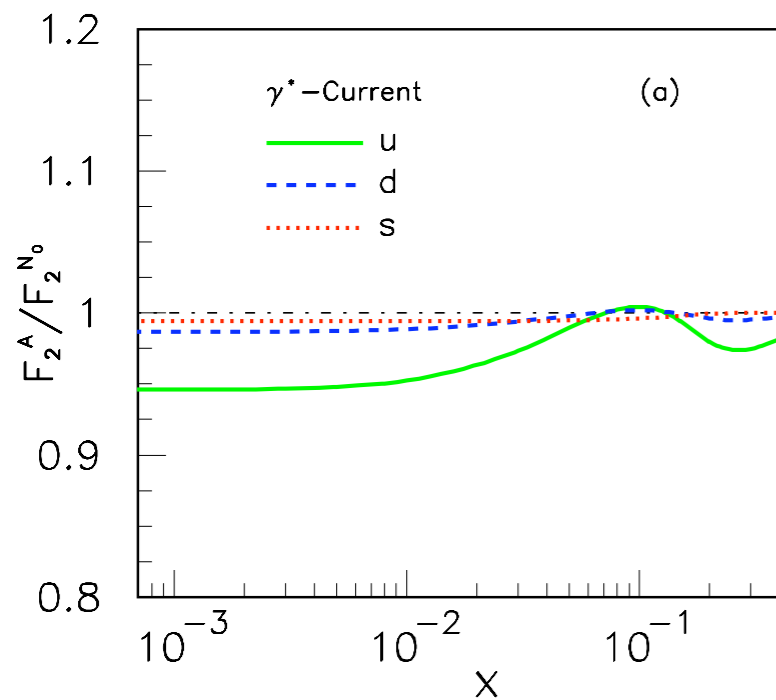


S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

## Modifies NuTeV extraction of $\sin^2 \theta_W$

**Test in flavor-tagged lepton-nucleus collisions**

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# LHeC: Virtual Photon-Proton Collider

## Perspective from the e-p collider frame
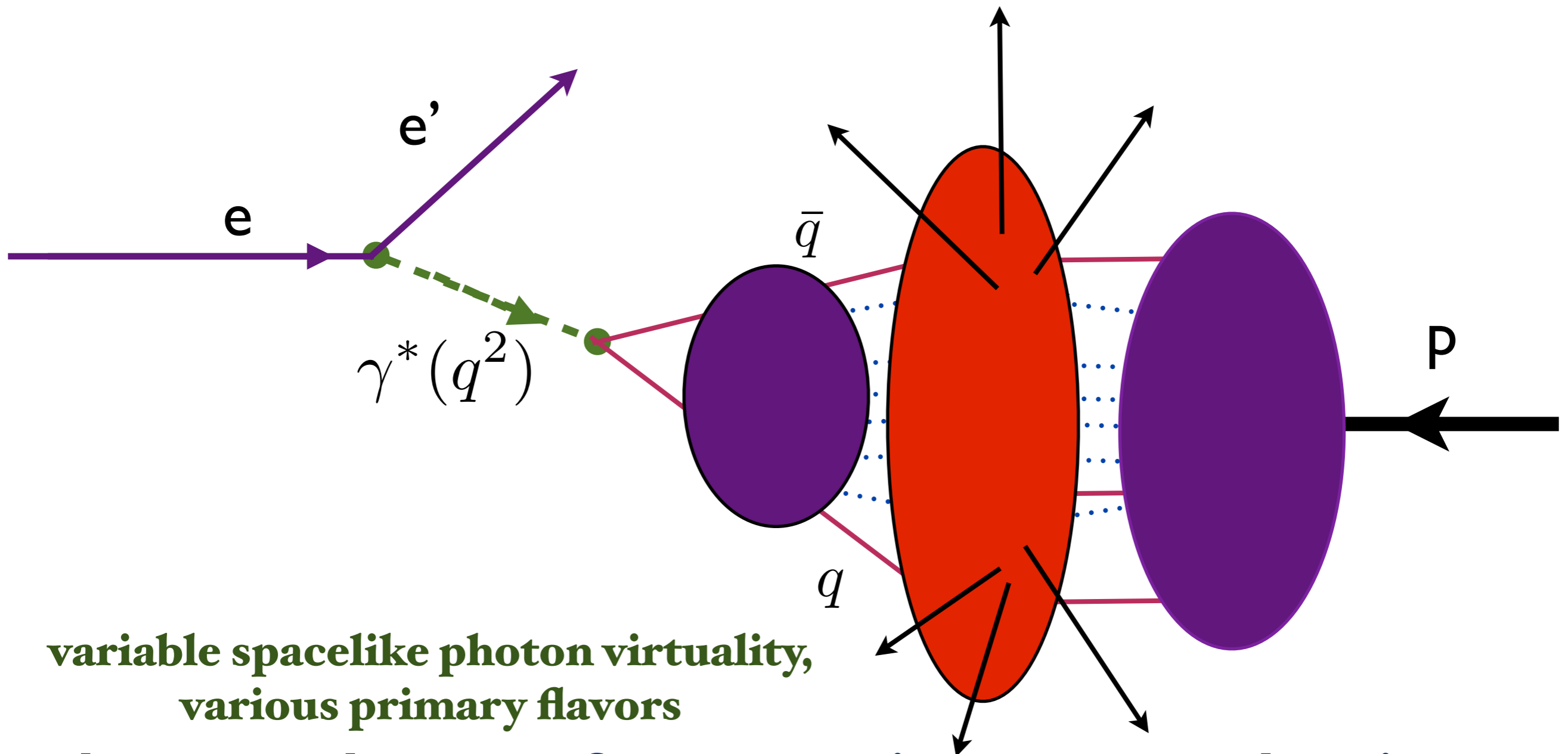


variable spacelike photon virtuality,
various primary flavors

photon and proton fragmentation vs. central regions

Saturation, nuclear shadowing, antishadowing

## *Perspective from the e-p collider frame*



$$\hat{s} = x_\gamma \times x_p\, s$$

e'

e

proton or ions

$\gamma^*(q^2)$

$\bar{q}$

P

$\psi_{\gamma^*}(x, k_\perp, \lambda)$

$q$

**variable space-like photon virtuality, various primary flavors**

$\psi_{p,A}(x, k_\perp, \lambda)$
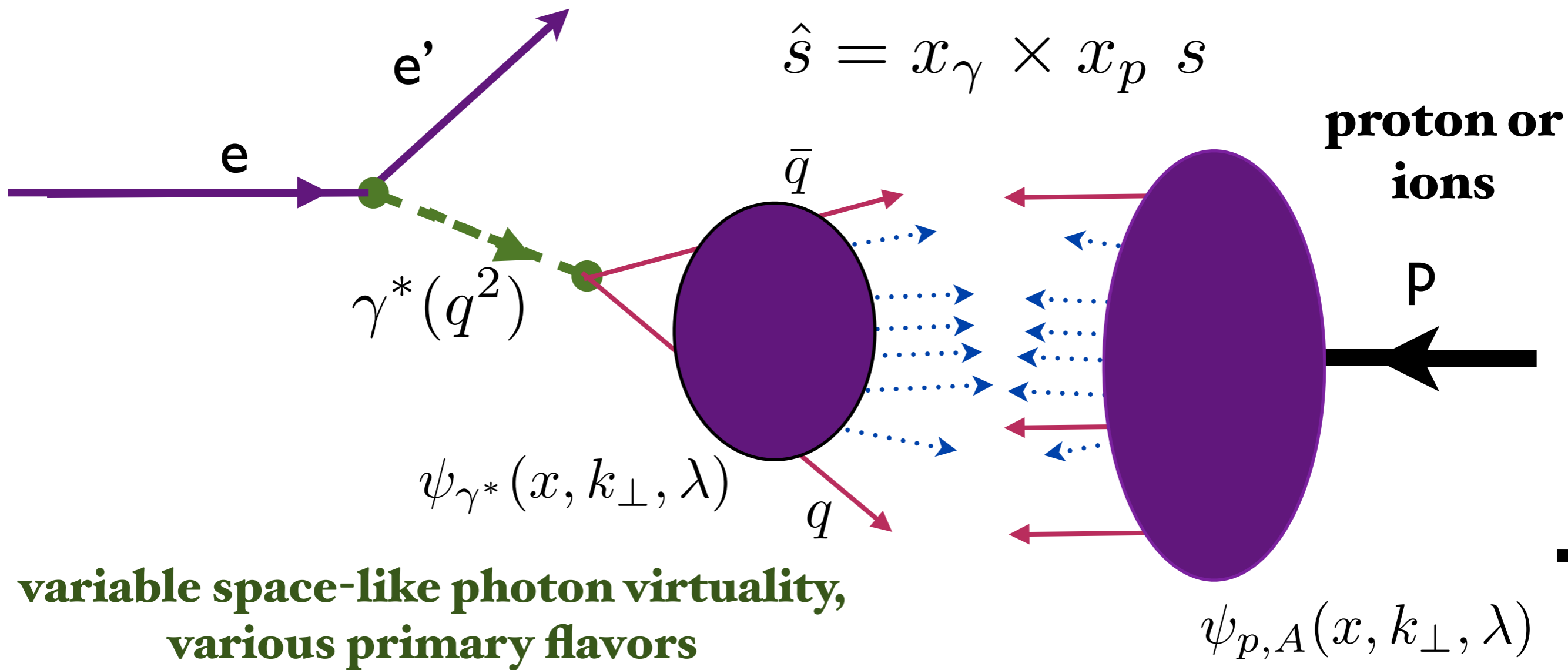
$\bar{q}\, q$ *plane aligned with lepton scattering plane ~ cos²$\phi$*

*Front-surface dynamics: shadowing/antishadowing*

# Novel QCD Physics at an Electron-Ion Collider

- **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**

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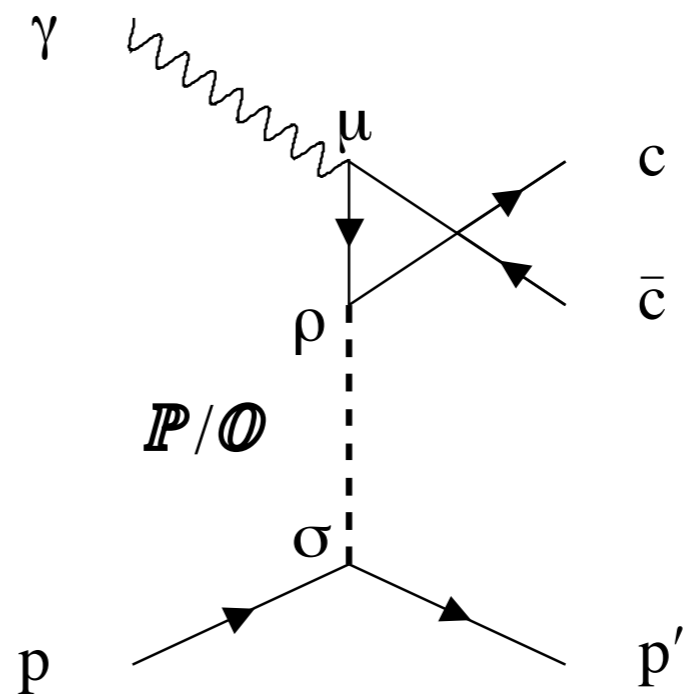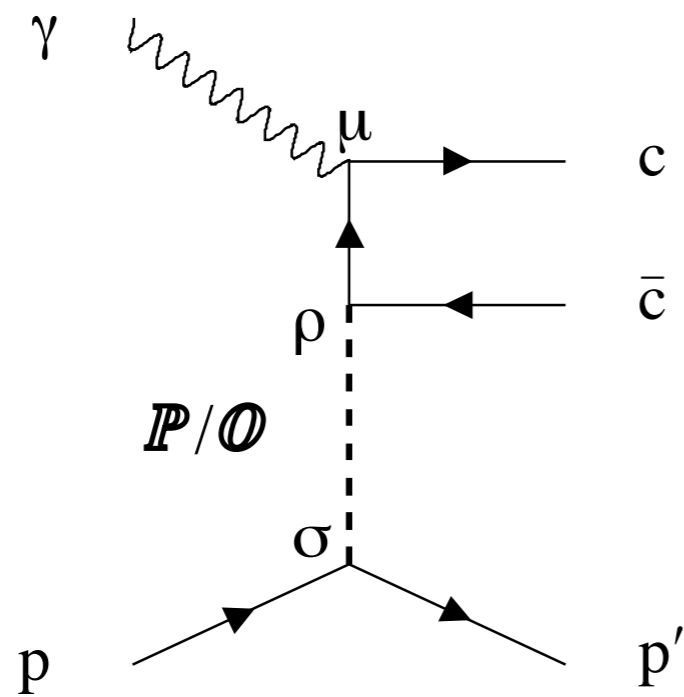
$$\gamma^* p \rightarrow c \bar{c} p$$

*Odderon-Pomeron Interference!*
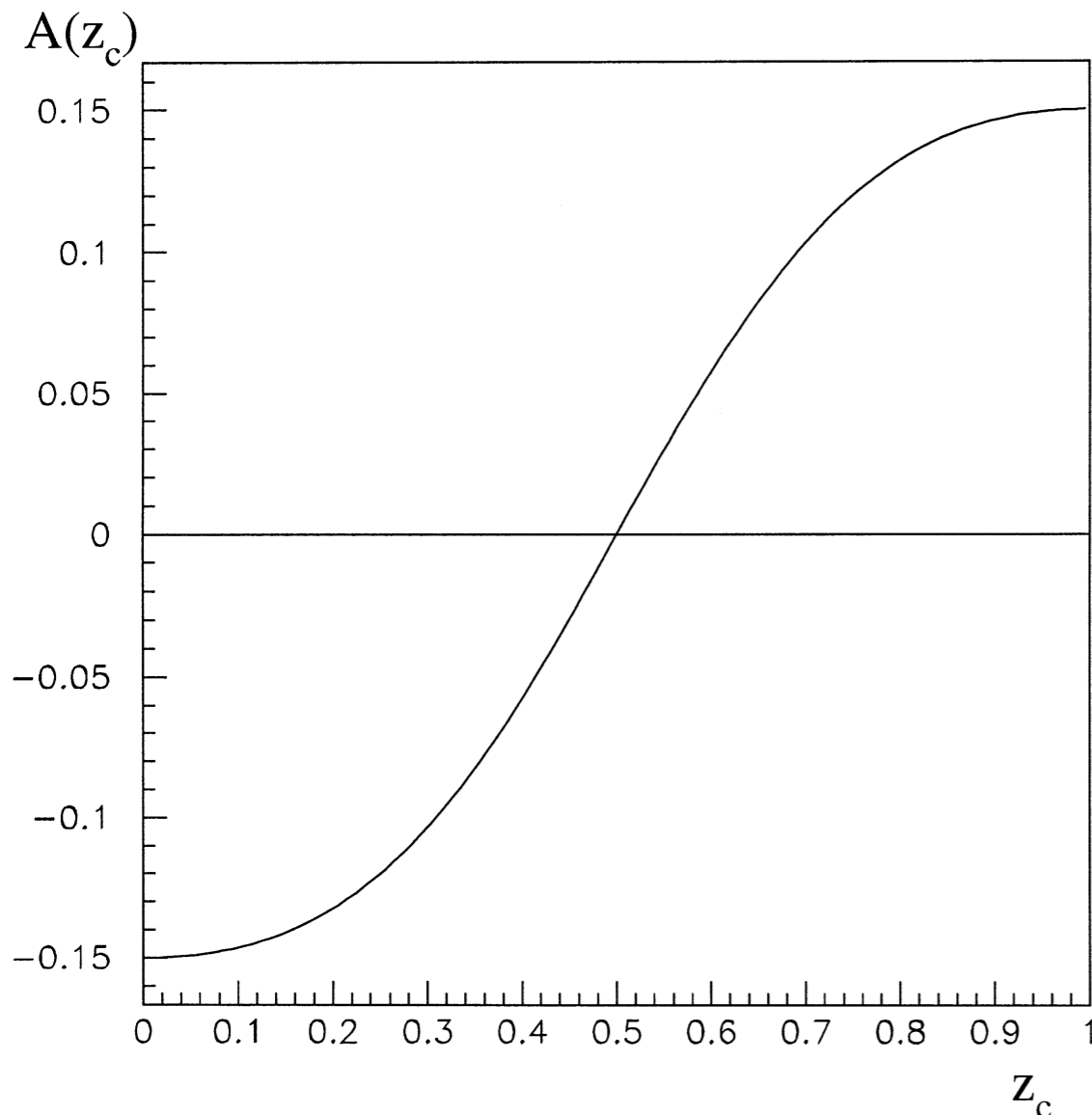


$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2 z_c - 1}{z_c^2 + (1 - z_c)^2}$$

*Measure charm asymmetry in photon fragmentation region*

**Merino, Rathsman, sjb**

24

# $pA \rightarrow J/\psi X$

$$(gg)_{8_C} + g_{8_C} \rightarrow J/\psi$$



$8_C \times 8_C$
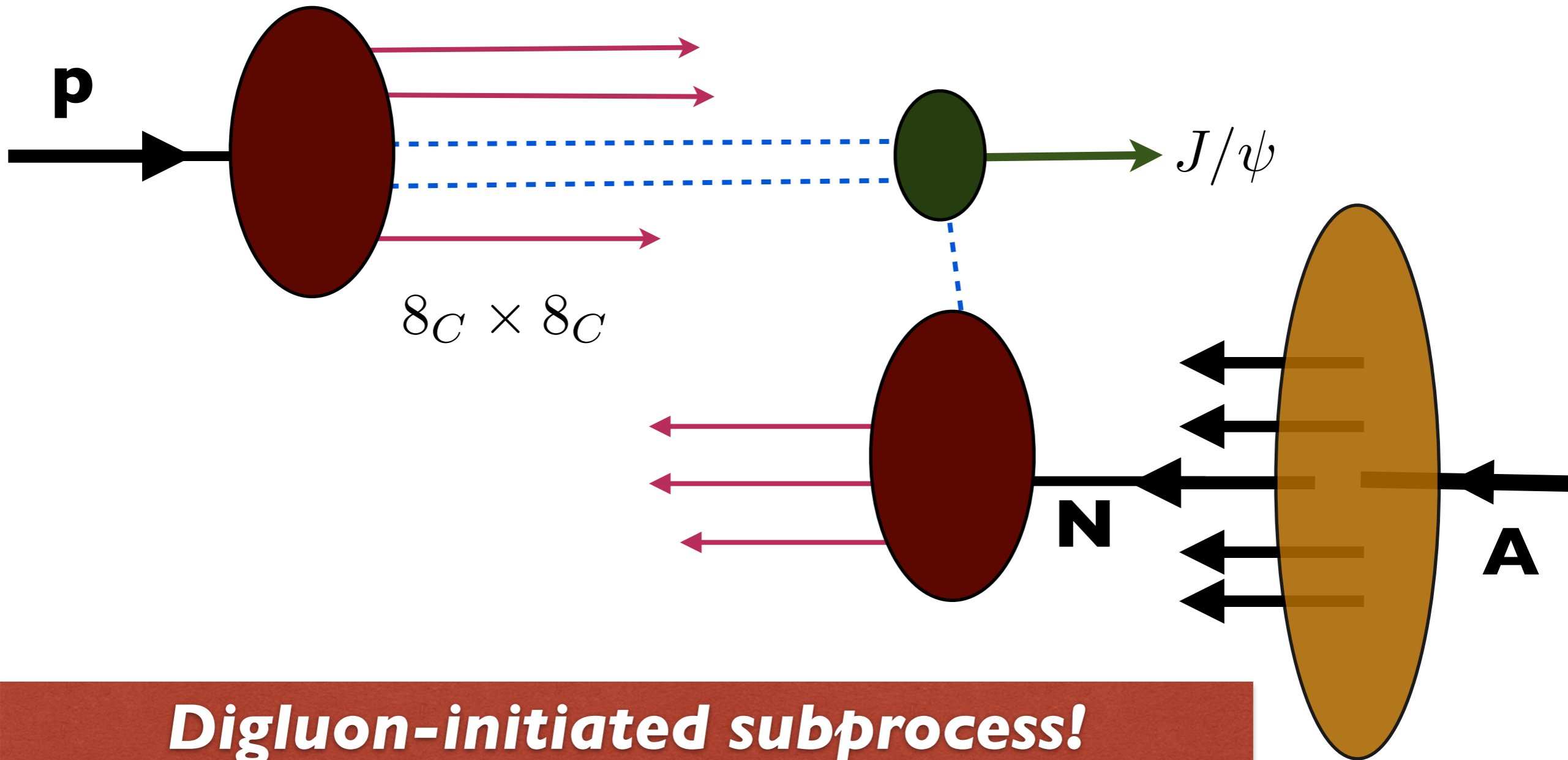
**Digluon-initiated subprocess!**

*Higher-Twist but can dominate at forward rapidity, small $p_T$*

Two gluons at $g(0.005) \sim \frac{13}{0.005} = 2600$ vs. one gluon at $g(0.01) \sim \frac{8}{0.01} = 800$
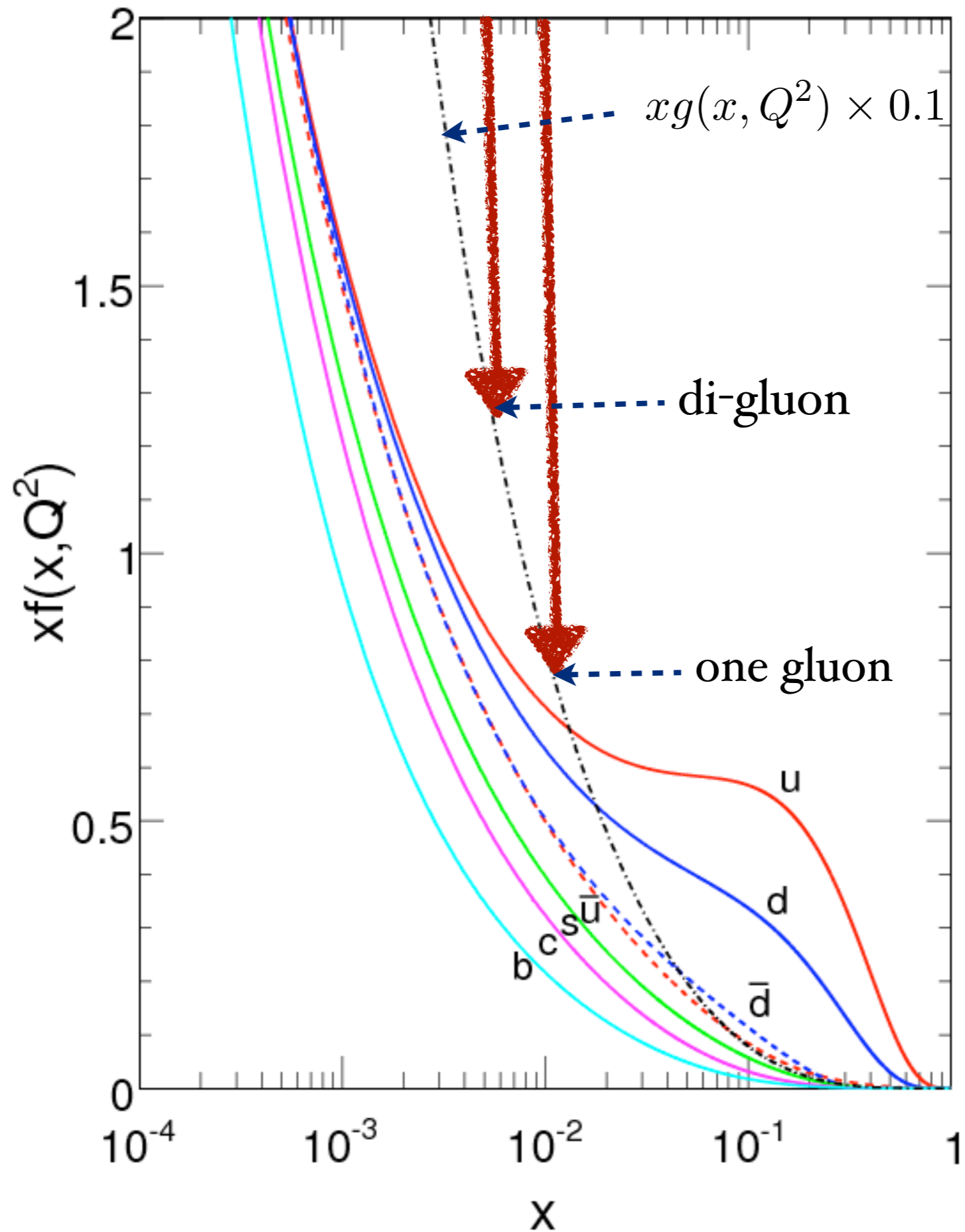
**Forward rapidity y ~ 4**

$$pA \rightarrow J/\psi X$$

$$(gg)_{8_C} + g_{8_C} \rightarrow J/\psi$$



**p**

$$8_C \times 8_C$$

$$J/\psi$$

**A**

**N**
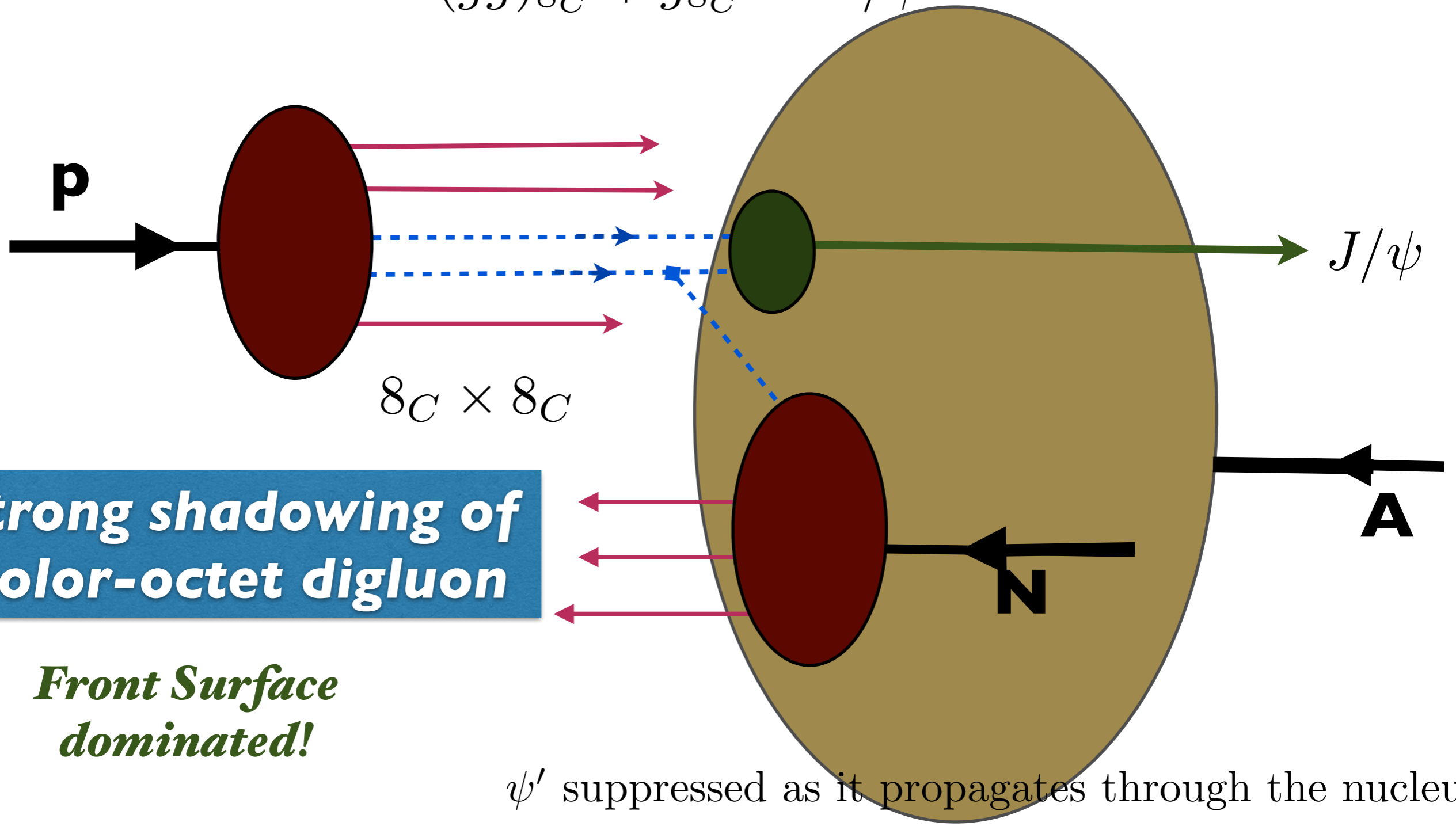
**Strong shadowing of color-octet digluon**

*Front Surface dominated!*

$\psi'$ suppressed as it propagates through the nucleus

**Crossing: Diffractive & pomeron exchange**

**Digluon-initiated subprocess!**

27

# *Light-Front QCD*

*Exact frame-independent formulation of nonperturbative QCD!*

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

$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k_\perp^2}{x}]_i + H^{int}_{LF}$$

$H^{int}_{LF}$: Matrix in Fock Space

$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}_h^2 |\Psi_h>$$

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; x_i, \vec{k}_{\perp i}, \lambda_i>$$
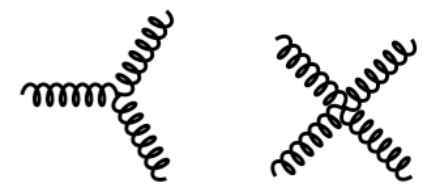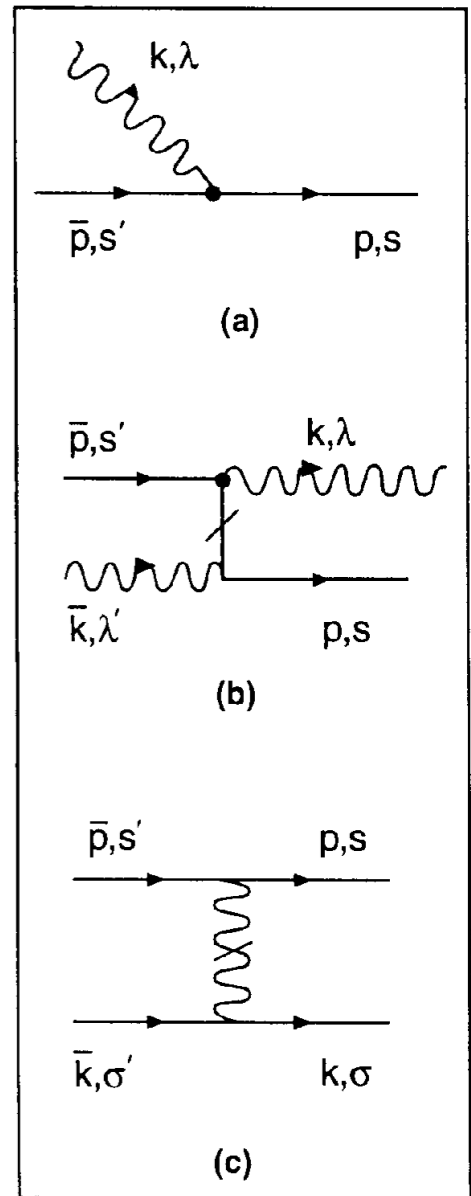
*Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions*

**LFWFs: Off-shell in P- and invariant mass**



$H^{int}_{LF}$

*Light-Front QCD*
*Heisenberg Equation*

$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle$$

*DLCQ: Solve QCD(1+1) for*
*any quark mass and flavors*

**Hornbostel, Pauli, sjb**
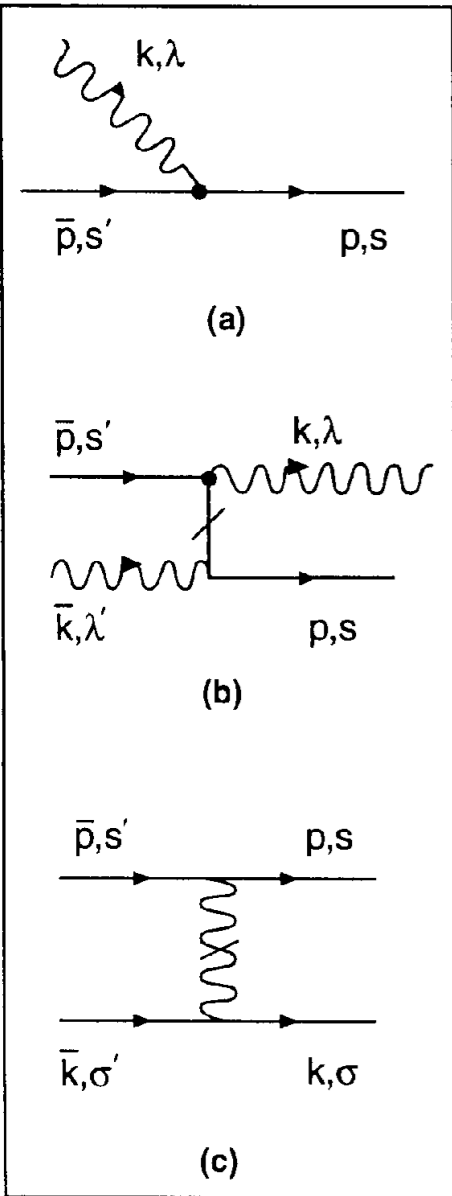


| n | Sector | 1 $q\bar{q}$ | 2 $gg$ | 3 $q\bar{q}\,g$ | 4 $q\bar{q}\,q\bar{q}$ | 5 $gg\,g$ | 6 $q\bar{q}\,gg$ | 7 $q\bar{q}\,q\bar{q}\,g$ | 8 $q\bar{q}\,q\bar{q}\,q\bar{q}$ | 9 $gg\,gg$ | 10 $q\bar{q}\,gg\,g$ | 11 $q\bar{q}\,q\bar{q}\,gg$ | 12 $q\bar{q}\,q\bar{q}\,q\bar{q}\,g$ | 13 $q\bar{q}\,q\bar{q}\,q\bar{q}\,q\bar{q}$ |
|---|--------|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $q\bar{q}$ | ▨ | ◹ | ◿ | ◿ | · | ◿ | · | · | · | · | · | · | · |
| 2 | $gg$ | ◹ | ▨ | ◿ | · | ◹ | ◹ | · | · | ◹ | · | · | · | · |
| 3 | $q\bar{q}\,g$ | ◿ | ◿ | ▨ | ◿ | ◹ | ◹ | ◿ | · | · | ◿ | · | · | · |
| 4 | $q\bar{q}\,q\bar{q}$ | ◿ | · | ◿ | ▨ | · | ◹ | ◿ | ◹ | · | · | ◿ | · | · |
| 5 | $gg\,g$ | · | ◹ | ◹ | · | ▨ | ◿ | · | · | ◹ | ◹ | · | · | · |
| 6 | $q\bar{q}\,gg$ | ◿ | ◹ | ◿ | ◹ | ◿ | ▨ | ◿ | · | ◹ | ◹ | ◿ | · | · |
| 7 | $q\bar{q}\,q\bar{q}\,g$ | · | · | ◿ | ◿ | · | ◿ | ▨ | ◿ | · | ◹ | ◿ | ◹ | · |
| 8 | $q\bar{q}\,q\bar{q}\,q\bar{q}$ | · | · | · | ◿ | · | · | ◹ | ▨ | · | · | ◹ | ◿ | ◹ |
| 9 | $gg\,gg$ | · | ◹ | · | · | ◹ | ◹ | · | · | ▨ | ◿ | · | · | · |
| 10 | $q\bar{q}\,gg\,g$ | · | · | ◿ | · | ◿ | ◿ | ◹ | · | ◿ | ▨ | ◿ | · | · |
| 11 | $q\bar{q}\,q\bar{q}\,gg$ | · | · | ◿ | · | ◹ | ◿ | ◹ | ◿ | · | ◿ | ▨ | ◿ | · |
| 12 | $q\bar{q}\,q\bar{q}\,q\bar{q}\,g$ | · | · | · | · | · | ◿ | ◹ | · | · | ◿ | ◿ | ▨ | ◿ |
| 13 | $q\bar{q}\,q\bar{q}\,q\bar{q}\,q\bar{q}$ | · | · | · | · | · | · | ◹ | · | · | · | · | ◿ | ▨ |

*Minkowski space; frame-independent; no fermion doubling; no ghosts*
*trivial vacuum*

**29**

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

*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 $P^\mu$.

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.

$$\sum_i^n k_i^+ = P^+, \quad \sum_i^n x_i = 1, \quad \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$

*Fixed LF time*

**Intrinsic heavy quarks**
**s(x), c(x), b(x) at high x !**

$$\bar{s}(x) \neq s(x)$$
$$\bar{u}(x) \neq \bar{d}(x)$$
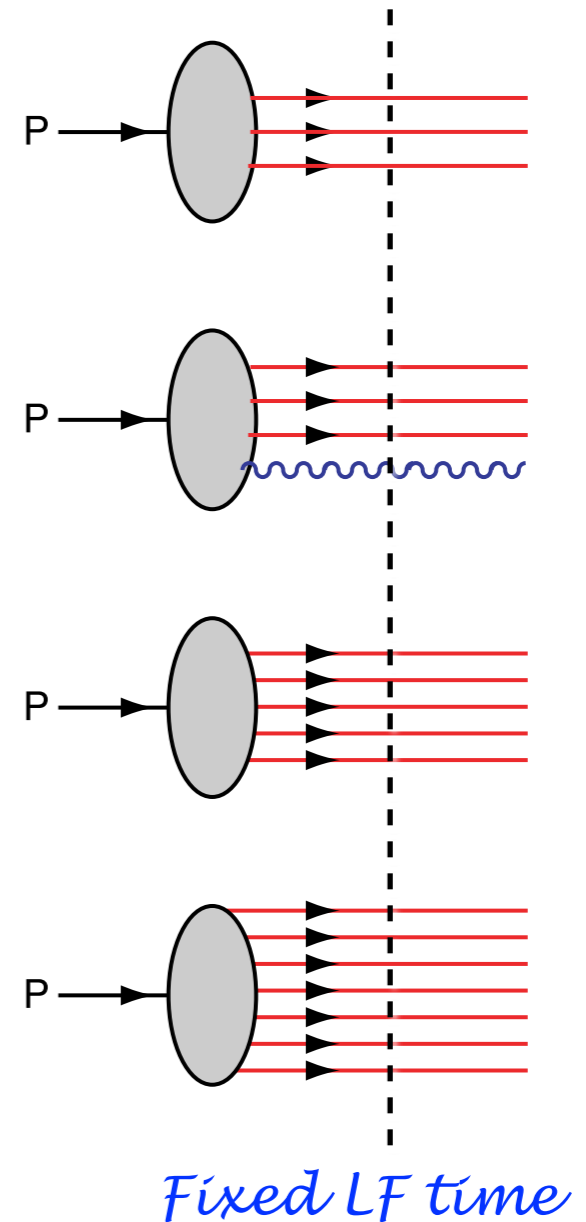
*Hidden Color*

Proton Self Energy
Intrinsic Heavy Quarks

Fixed LF time

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$
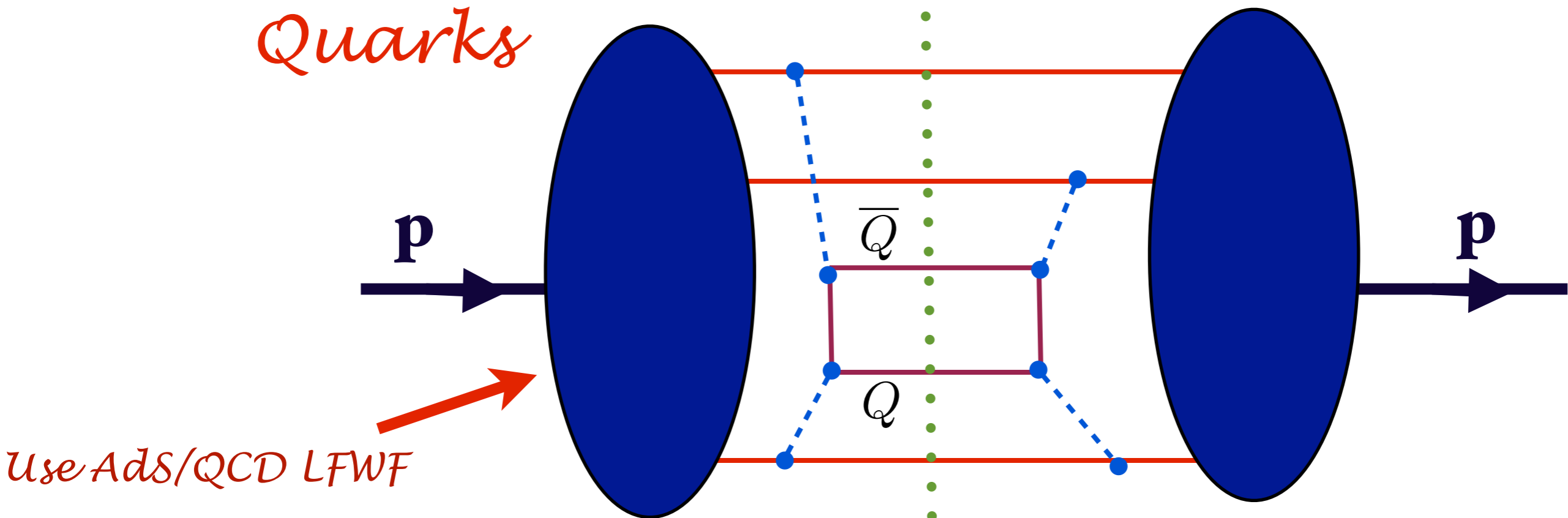
**p**

Use AdS/QCD LFWF

$\overline{Q}$

$Q$

**p**

Probability (QED) $\propto \dfrac{1}{M_\ell^4}$

Probability (QCD) $\propto \dfrac{1}{M_Q^2}$

**Collins, Ellis, Gunion, Mueller, sjb**
**Polyakov, et al.**

*Fixed LF time*

*Proton 5-quark Fock State :*
*Intrinsic Heavy Quarks*

**p**

*Use AdS/QCD LFWF*

$\overline{Q}$

$Q$
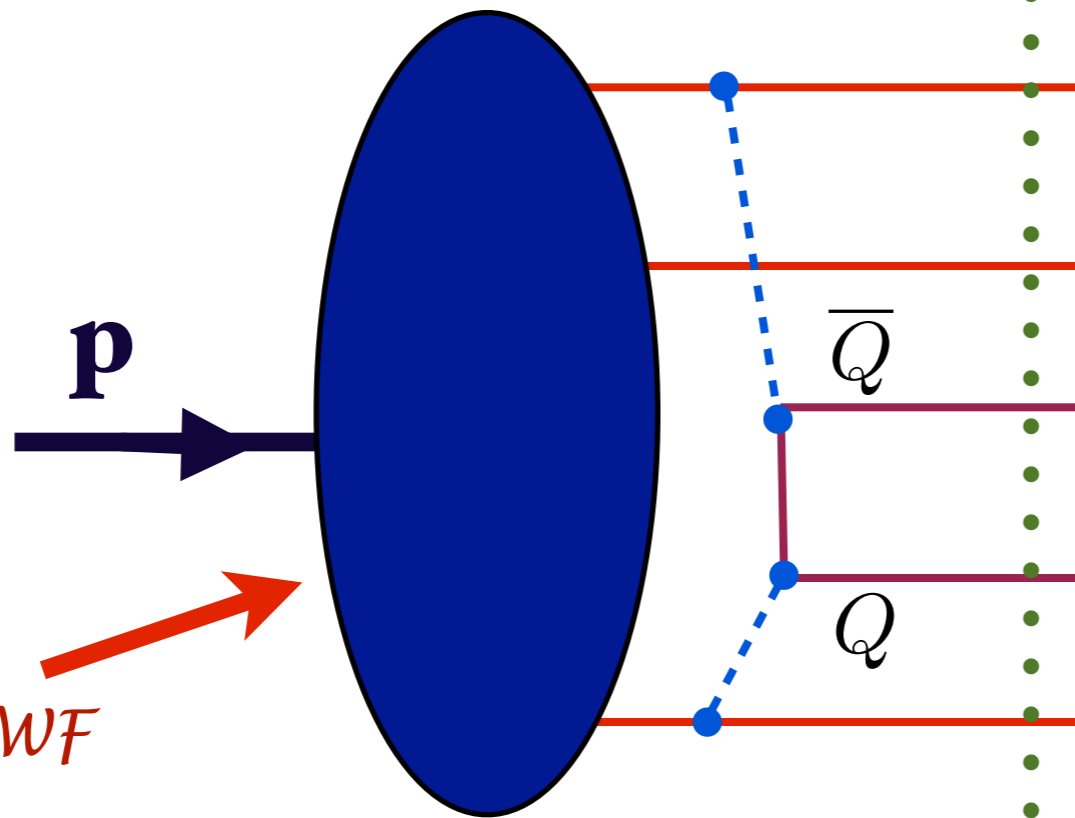
*QCD predicts Intrinsic Heavy Quarks at high x*

**Minimal off-shellness**

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

**Collins, Ellis, Gunion, Mueller, sjb**
**Polyakov, et al.**

32

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

**Hoyer, Peterson, Sakai, sjb**



*factor of 30 !*

*gluon splitting (DGLAP)*
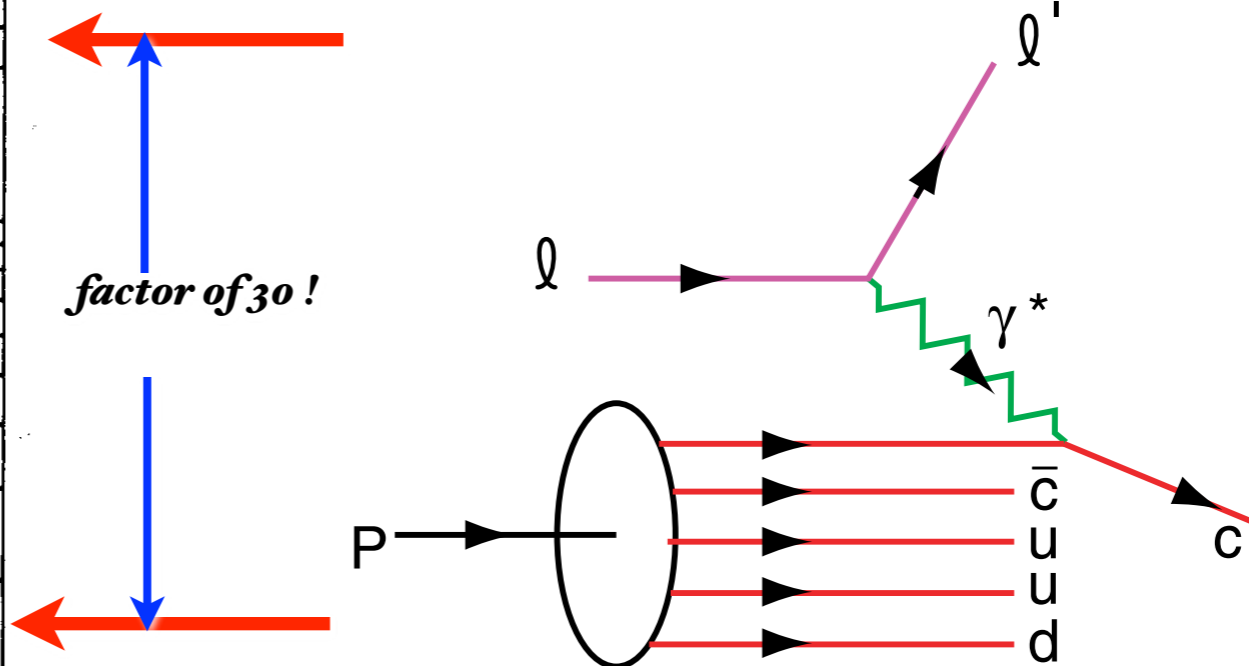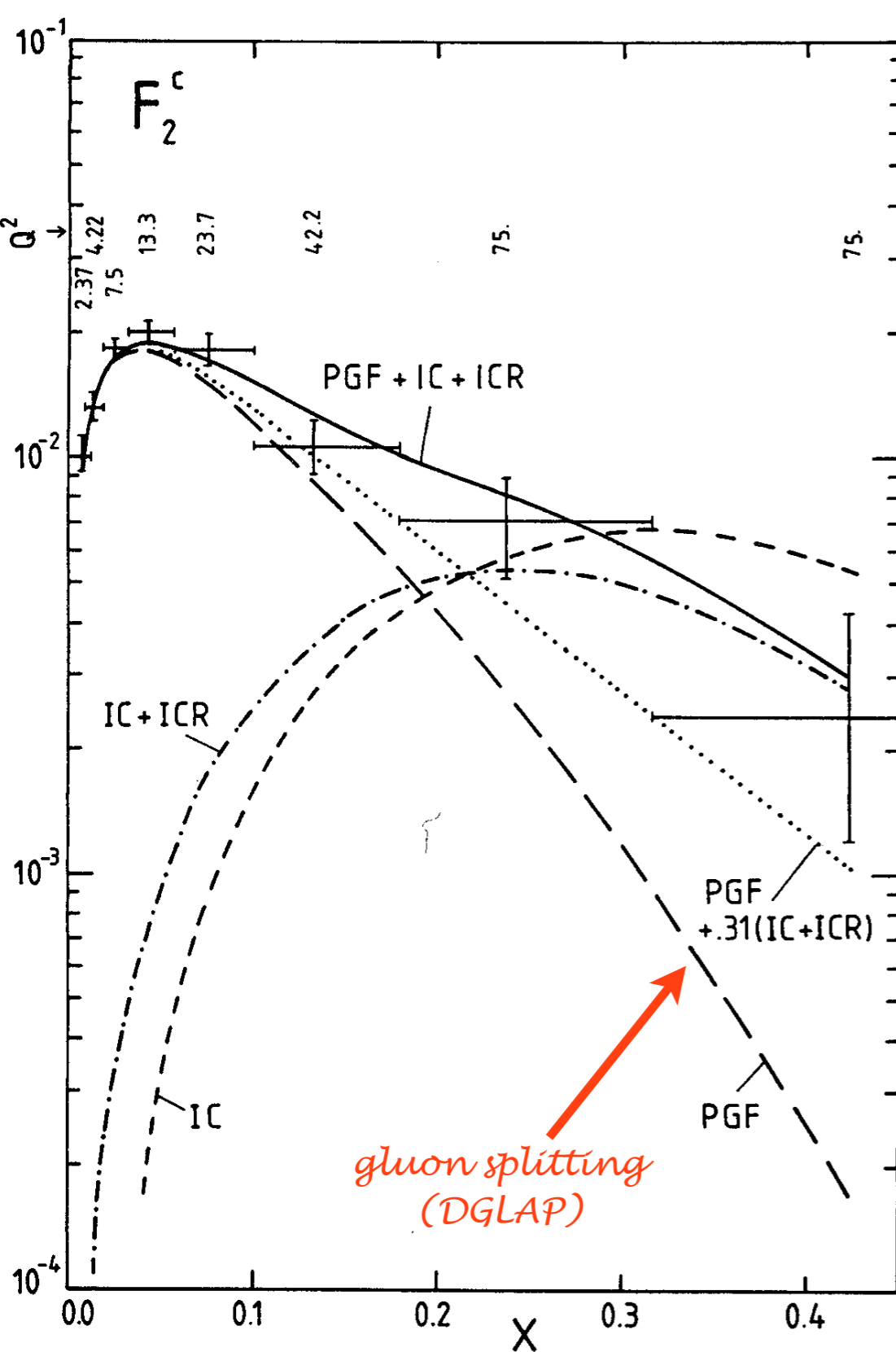
# DGLAP / Photon-Gluon Fusion: factor of 30 too small

*Two Components (separate evolution):*

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections
in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

## Data/Theory
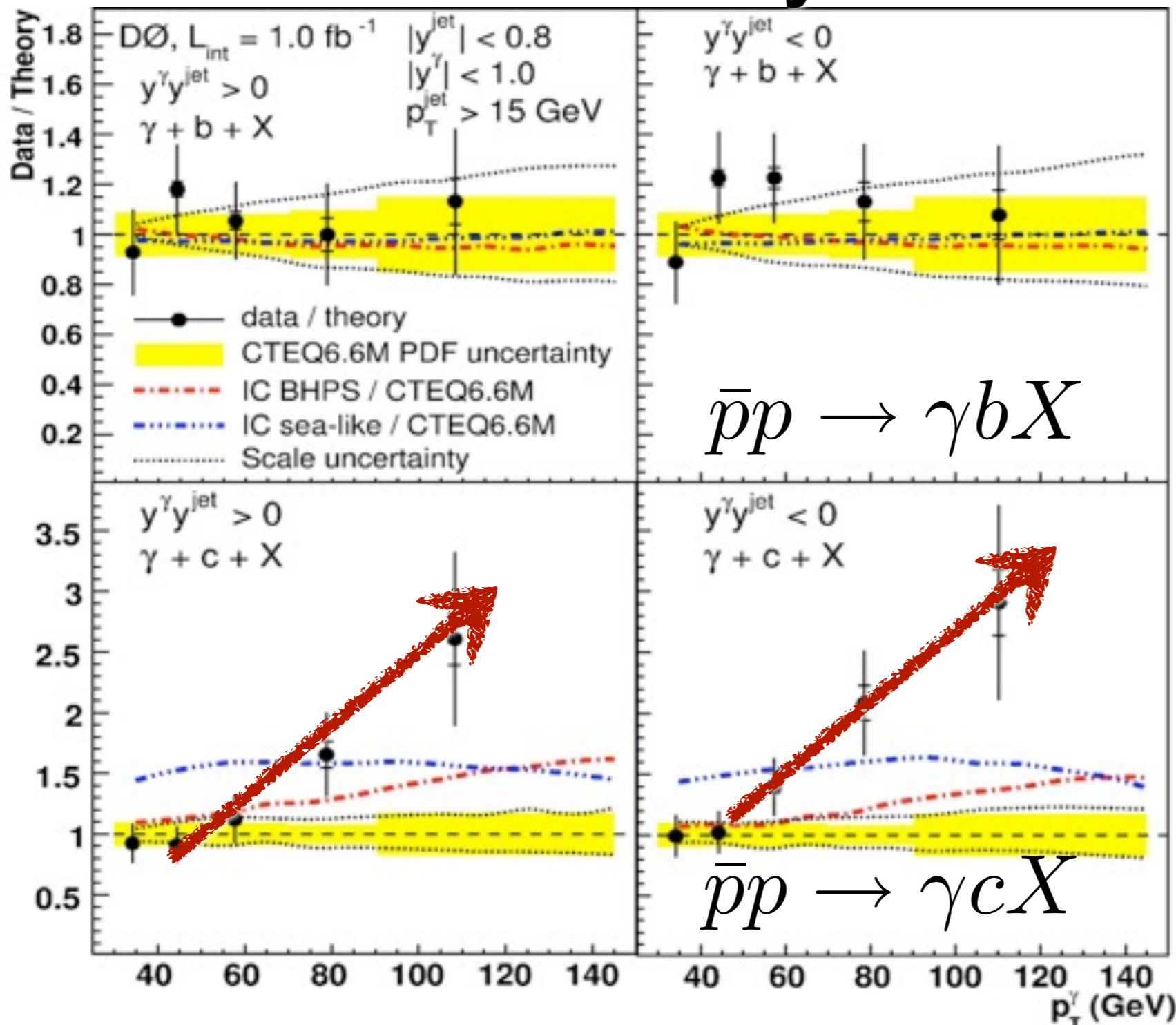


$$\frac{\Delta\sigma(\bar{p}p \rightarrow \gamma cX)}{\Delta\sigma(\bar{p}p \rightarrow \gamma bX)}$$

**Ratio insensitive
to gluon PDF,
scales**

**Signal for significant
IC**

**at x > 0.1**

*Consistent with EMC measurement of charm
structure function at high x*

# Intrinsic Charm Mechanism for Inclusive High-$X_F$ Higgs Production

$$pp \rightarrow H X$$
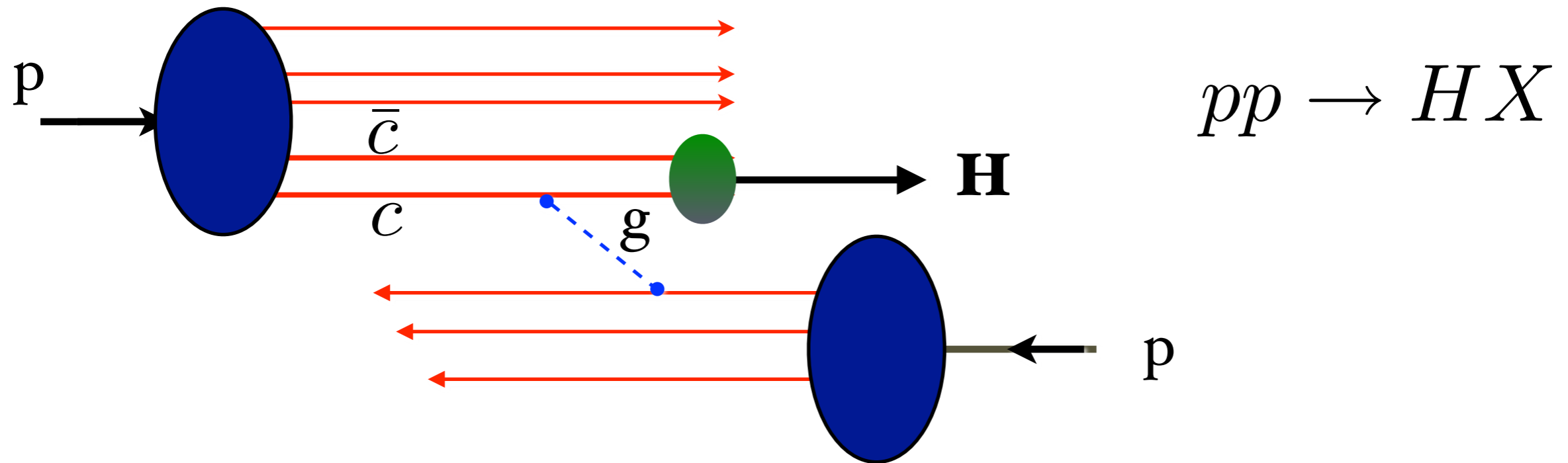
**Also: intrinsic strangeness, bottom, top**

**Higgs can have > 80% of Proton Momentum!**

*New production mechanism for Higgs*

*AFTER: Higgs production at threshold!*

*JLab: Charm production near threshold!*

- **LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics**

- **LFWFs=Hadron Eigensolutions: Direct Connection to QCD Lagrangian**

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

- **Relativistic, frame-independent: no boosts, no disc contraction, Melosh built into LF spinors**

- **Hadronic observables computed from LFWFs: Form factors, Structure Functions, Distribution Amplitudes, GPDs, TMDs, Weak Decays, .... modulo `lensing' from ISIs, FSIs**

- **Cannot compute current matrix elements using instant form from eigensolutions alone -- need to include vacuum currents!**

- <span style="color:red">**Hadron Physics without LFWFs is like Biology without DNA!**</span>

*Kunshan*
*August 3, 2015*

*New Perspectives for Hadron Physics*

**Stan Brodsky**

**36**

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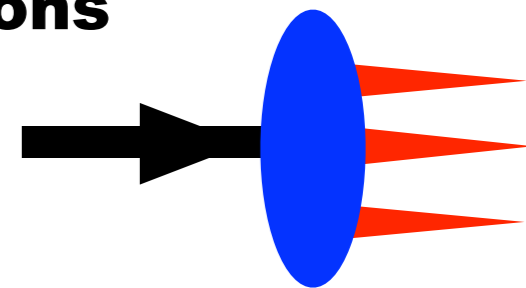
# *Need a First Approximation to QCD*

## *Comparable in simplicity to Schrödinger Theory in Atomic Physics*

**Relativistic, Frame-Independent, Color-Confining**

$$H_{QED}$$

*QED atoms: positronium and muonium*

$$(H_0 + H_{int}) \, |\Psi> = E \, |\Psi>$$

*Coupled Fock states*

$$\left[-\frac{\Delta^2}{2m_{\text{red}}} + V_{\text{eff}}(\vec{S}, \vec{r})\right] \psi(\vec{r}) = E \, \psi(\vec{r})$$

*Effective two-particle equation*

**Includes Lamb Shift, quantum corrections**

$$\left[-\frac{1}{2m_{\text{red}}}\frac{d^2}{dr^2} + \frac{1}{2m_{\text{red}}}\frac{\ell(\ell+1)}{r^2} + V_{\text{eff}}(r, S, \ell)\right] \psi(r) = E \, \psi(r)$$

*Spherical Basis* $\quad r, \theta, \phi$

$$V_{eff} \to V_C(r) = -\frac{\alpha}{r}$$

*Coulomb potential*

**Bohr Spectrum**

*Semiclassical first approximation to QED*

*Schrödinger Eq.*

# Light-Front QCD

Fixed $\tau = t + z/c$

$$\mathcal{L}_{QCD} \longrightarrow \boxed{H^{LF}_{QCD}}$$

$$\zeta^2 = x(1-x)b_\perp^2$$
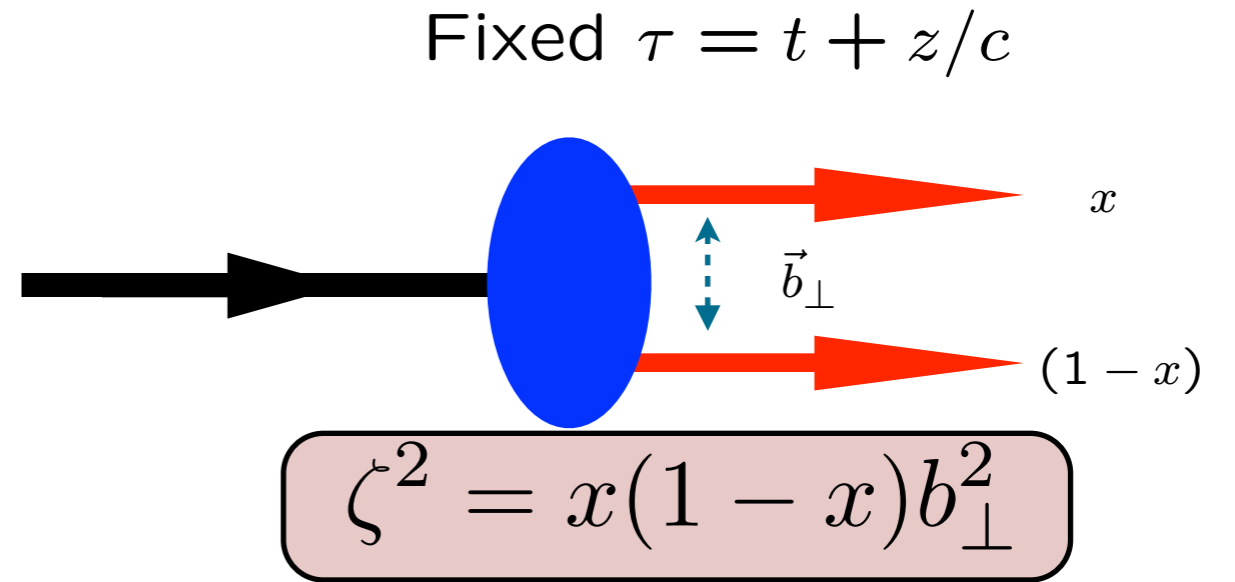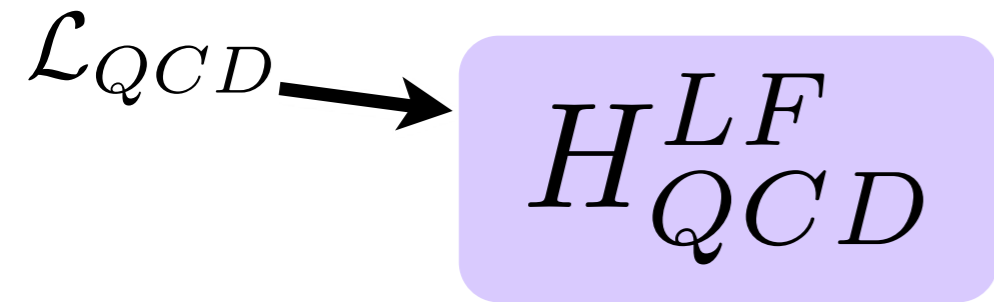
$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2|\Psi>$$

*Coupled Fock states*

*Eliminate higher Fock states and retarded interactions*

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

*Effective two-particle equation*

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

*Azimuthal Basis*

$$\zeta, \phi$$
$$m_q = 0$$

**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***

39

# Fixed $\tau = t + z/c$



$$x \qquad \vec{k}_\perp$$

$$\vec{b}_\perp$$

$$(1 - x) \qquad -\vec{k}_\perp$$
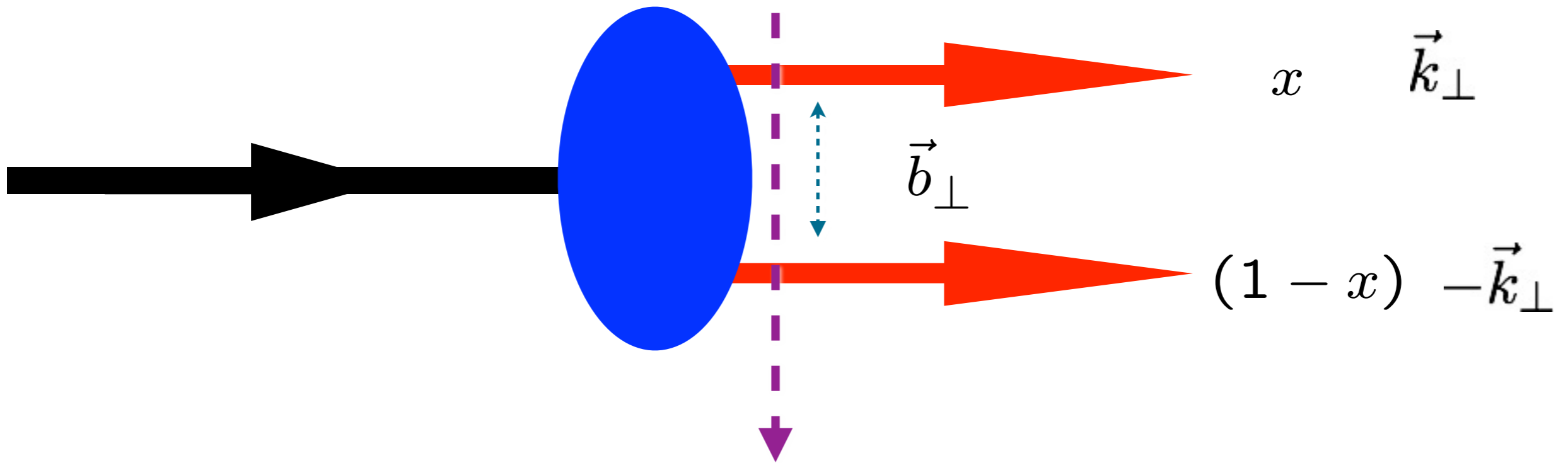
$$\zeta^2 \equiv b_\perp^2 x(1 - x)$$

Invariant transverse separation

$$\zeta^2 \text{ conjugate to } \frac{k_\perp^2}{x(1-x)} = (p_q + p_{\bar{q}})^2 = \mathcal{M}_{q+\bar{q}}^2$$

$$\int dk^- \Psi_{BS}(P, k) \rightarrow \psi_{LF}(x, \vec{k}_\perp)$$

*de Tèramond, Dosch, sjb*

**AdS/QCD Soft-Wall Model**

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

**Light-Front Holography**

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

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

**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*

$$\kappa \simeq 0.6 \ GeV$$

**Confinement scale:**

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

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

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

41

$$m_u = m_d = 0$$

(a) $M^2(\text{GeV}^2)$ vs $L$

$n = 2$, $n = 1$, $n = 0$

$\pi(1800)$

$\pi_2(1880)$

$\pi(1300)$

$\pi_2(1670)$

$b_1(1235)$

$\pi(140)$

(b) $M^2(\text{GeV}^2)$ vs $L$

$n = 3$, $n = 2$, $n = 1$, $n = 0$

$f_2(2300)$

$\rho(1700)$

$f_2(1950)$

$a_4(2040)$
$f_4(2050)$

$\omega(1650)$

$\rho_3(1690)$
$\omega_3(1670)$

$\rho(1450)$
$\omega(1420)$

$a_2(1320)$
$f_2(1270)$

$\rho(770)$
$\omega(782)$

$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

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*August 3, 2015*

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42

$Q^2 \, F_\pi(Q^2)$

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

**(a)** $M^2(\text{GeV}^2)$

$n = 3$  $n = 2$  $n = 1$  $n = 0$

$N(1900)$

$N(2220)$

$N(1710)$

$N(1440)$

$N(1720)$
$N(1680)$

$N(940)$

**S=1/2, P=+**  $L$

**(b)** $M^2(\text{GeV}^2)$

$N(2600)$

$\nu = L + 1$

**S=3/2, P=-**

$N(2250)$
$N(2190)$

$N(1700)$
$N(1675)$
$N(1650)$

$\nu = L$

$N(2220)$

$N(1720)$
$N(1680)$

$4\kappa^2$

**S=1/2, P=+**  $L$

$N(940)$

**(c)** $M^2(\text{GeV}^2)$

$n = 2$  $n = 1$  $n = 0$

$N(1875)$

$N(1535)$
$N(1520)$

**S=1/2, P=-**  $L$

**(d)** $M^2(\text{GeV}^2)$

$n = 3$  $n = 2$  $n = 1$  $n = 0$

$\Delta(2420)$

$\Delta(1700)$

$\Delta(1950)$
$\Delta(1920)$
$\Delta(1910)$
$\Delta(1905)$

$\Delta(1600)$

$\Delta(1620)$

$\Delta(1232)$

**S=1/2, 3/2**  $L$

44

Superconformal Algebra

$$\frac{M^2}{4\kappa^2}$$

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

*Same slope*

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

$N\frac{9^+}{2}$ (2200)

$N\frac{7^-}{2}$

$b_5$

$\pi_4$

$N\frac{5^+}{2}$ (1680)

$b_3$

$N\frac{3^-}{2}$ (1520)

$\pi_2(1670)$

$N\frac{1^+}{2}$ (940)

$b_1(1235)$

$\pi(140)$

$L$

0  1  2  3  4  5

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

45

$M^2 \, (\mathrm{GeV}^2)$

$\rho - \Delta$ superpartner trajectories

$a_4, f_4$

$\rho_3, \omega_3$

$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$

$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$

$a_2, f_2$

$\Delta^{\frac{11}{2}^+}$

$\Delta^{\frac{3}{2}^+}$

$\rho, \omega$

$L_M = L_B + 1$

*Dosch, de Teramond, sjb*

46
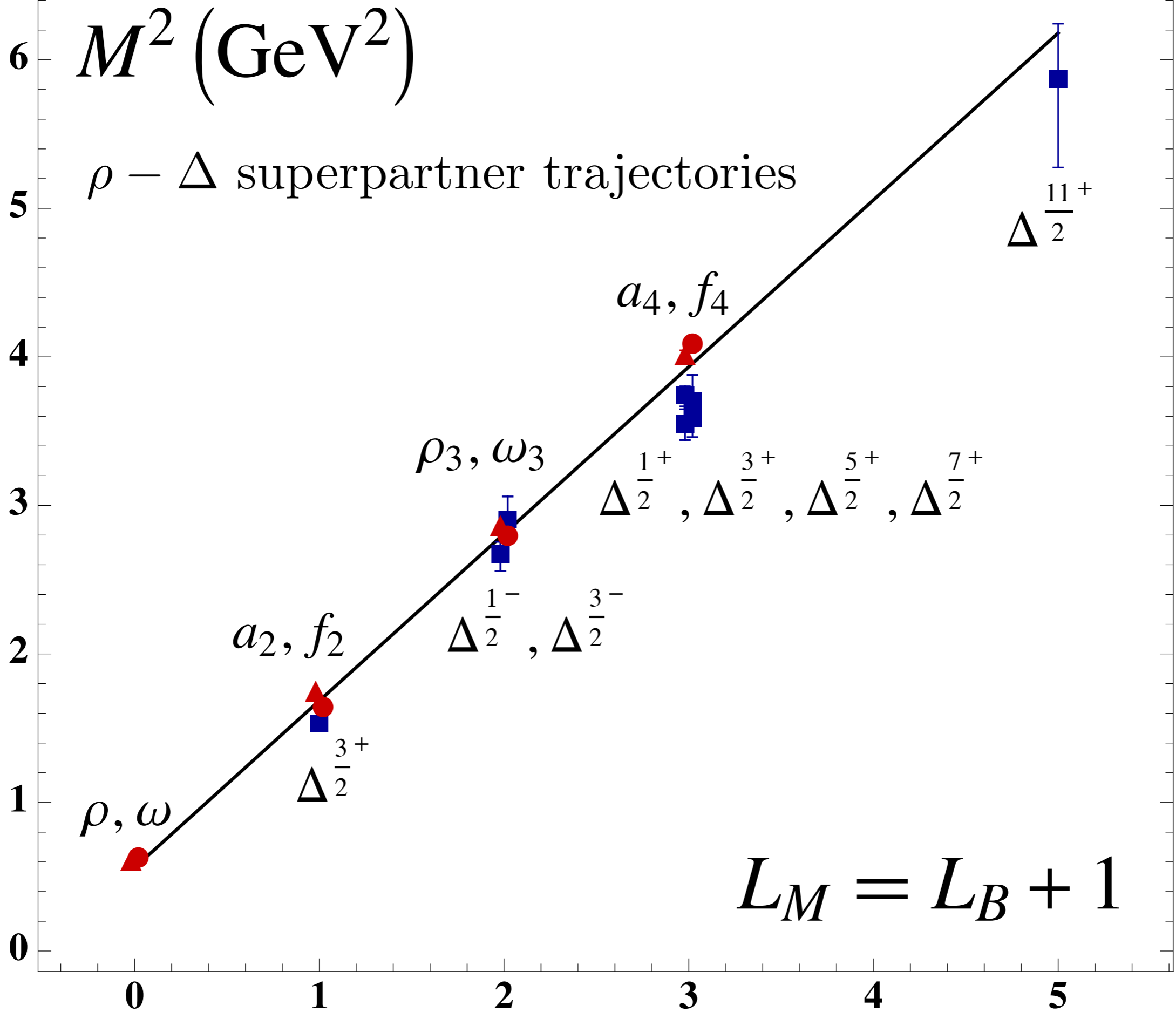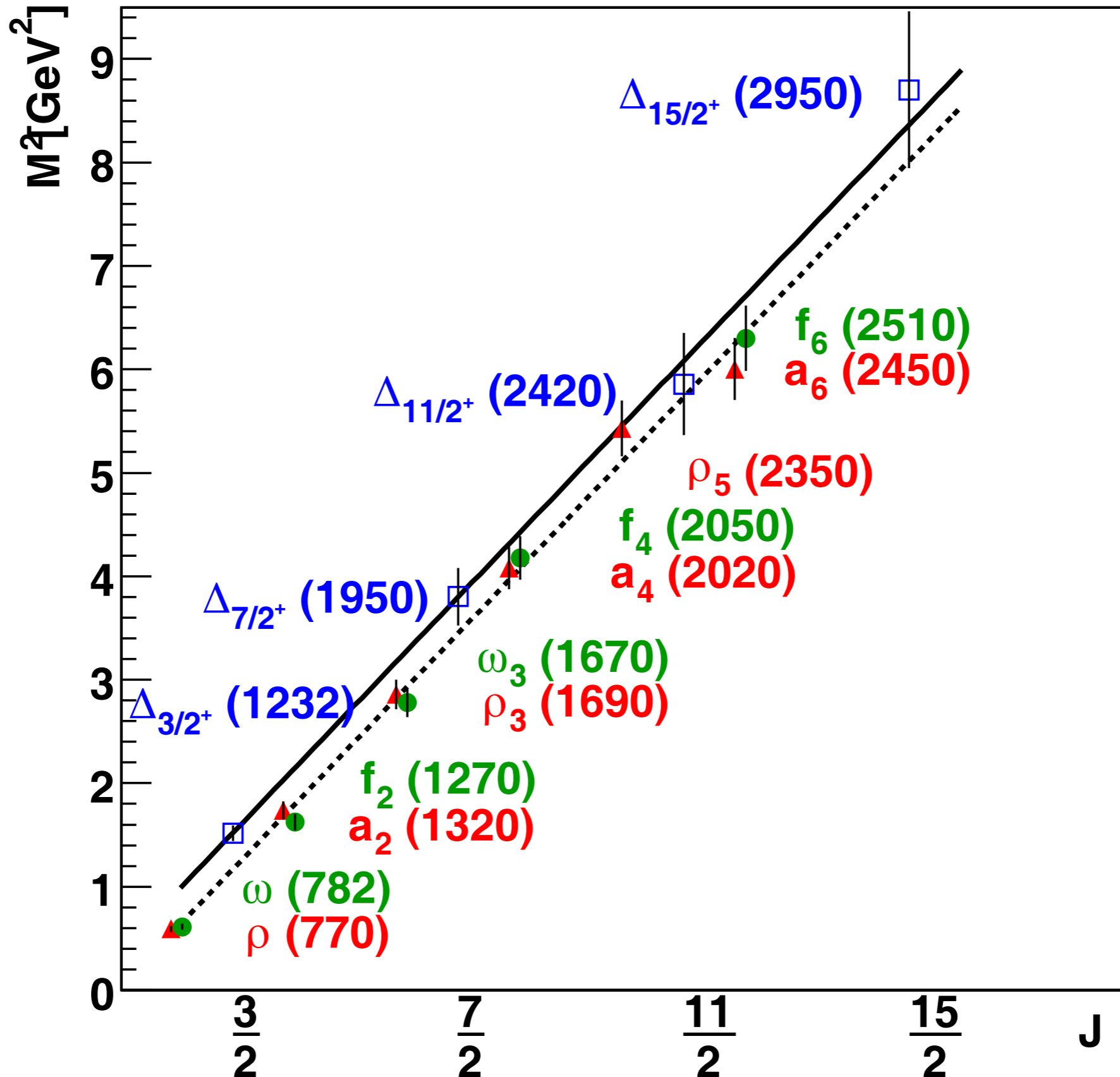
The leading Regge trajectory: $\Delta$ resonances with maximal J in a given mass range.
Also shown is the Regge trajectory for mesons with J = L+S.

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

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

$$L_M = L_B + 1$$
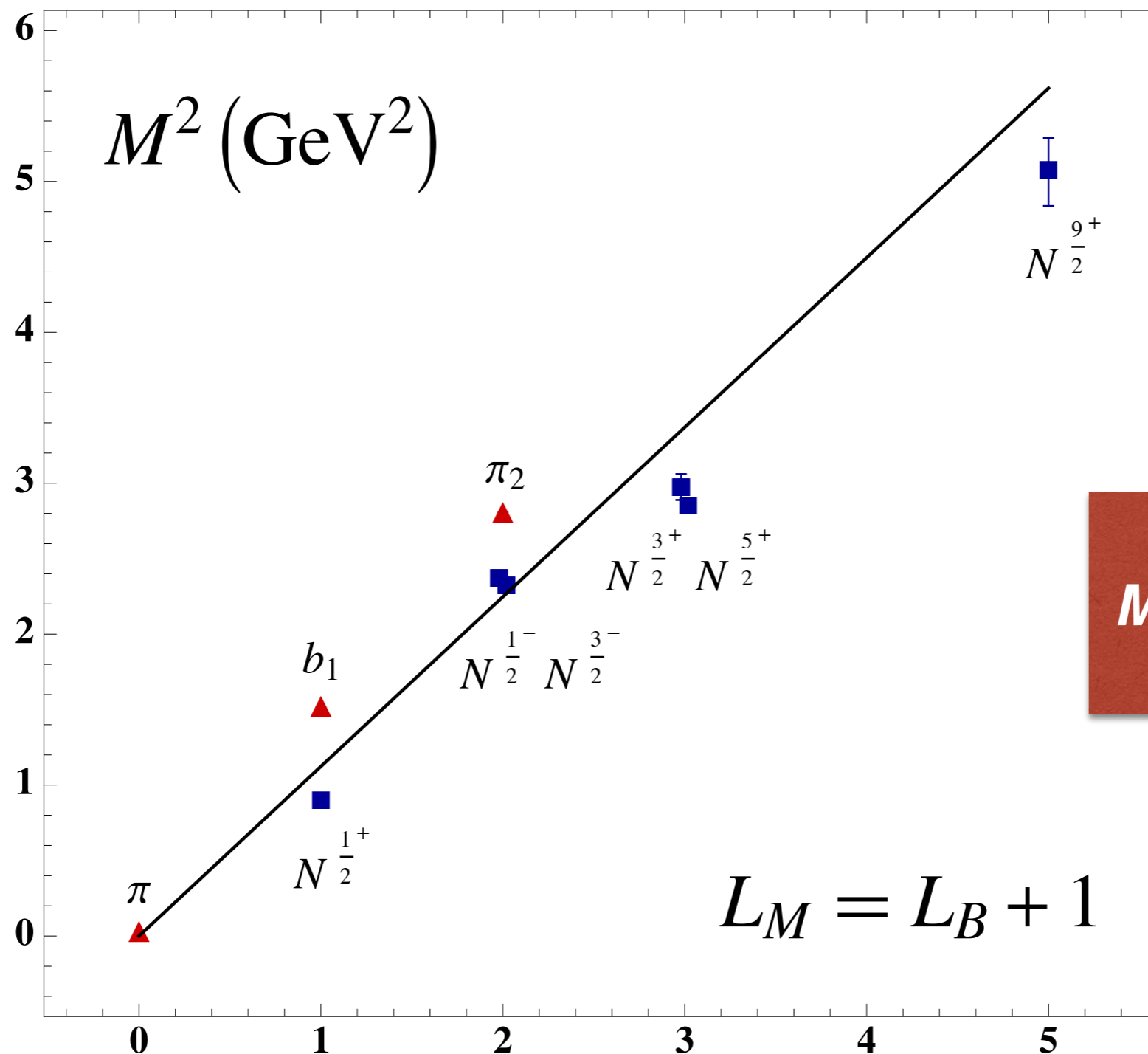
$S=0$, $I=1$ Meson is superpartner of $S=1/2$, $I=1$ Baryon

**LF Holography**

$$\left( -\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2} \right)\psi_J^+ = M^2\psi_J^+ \qquad \mathsf{G_{22}}$$

$$\left( -\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2} \right)\psi_J^- = M^2\psi_J^- \qquad \mathsf{G_{11}}$$

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1) \qquad \text{S=1/2, P=+}$$

*both chiralities*

**Meson Equation**

$$\left( -\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(J-1) + \frac{4L_M^2-1}{4\zeta^2} \right)\phi_J = M^2\phi_J \qquad \mathsf{G_{11}}$$

$$M^2(n, L_M) = 4\kappa^2(n + L_M) \qquad \textit{Same } \kappa \text{ !}$$

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

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

# Some Features of AdS/QCD

- **Regge spectroscopy—same slope in n,L for mesons,**

- **Chiral features for $m_q=0$: $m_\pi=0$, chiral-invariant proton**

- **Hadronic LFWFs**

- **Counting Rules**

- **Connection between hadron masses and** $\Lambda_{\overline{MS}}$

**Superconformal AdS Light-Front Holographic QCD (LFHQCD)**

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

ILCAC Meeting in

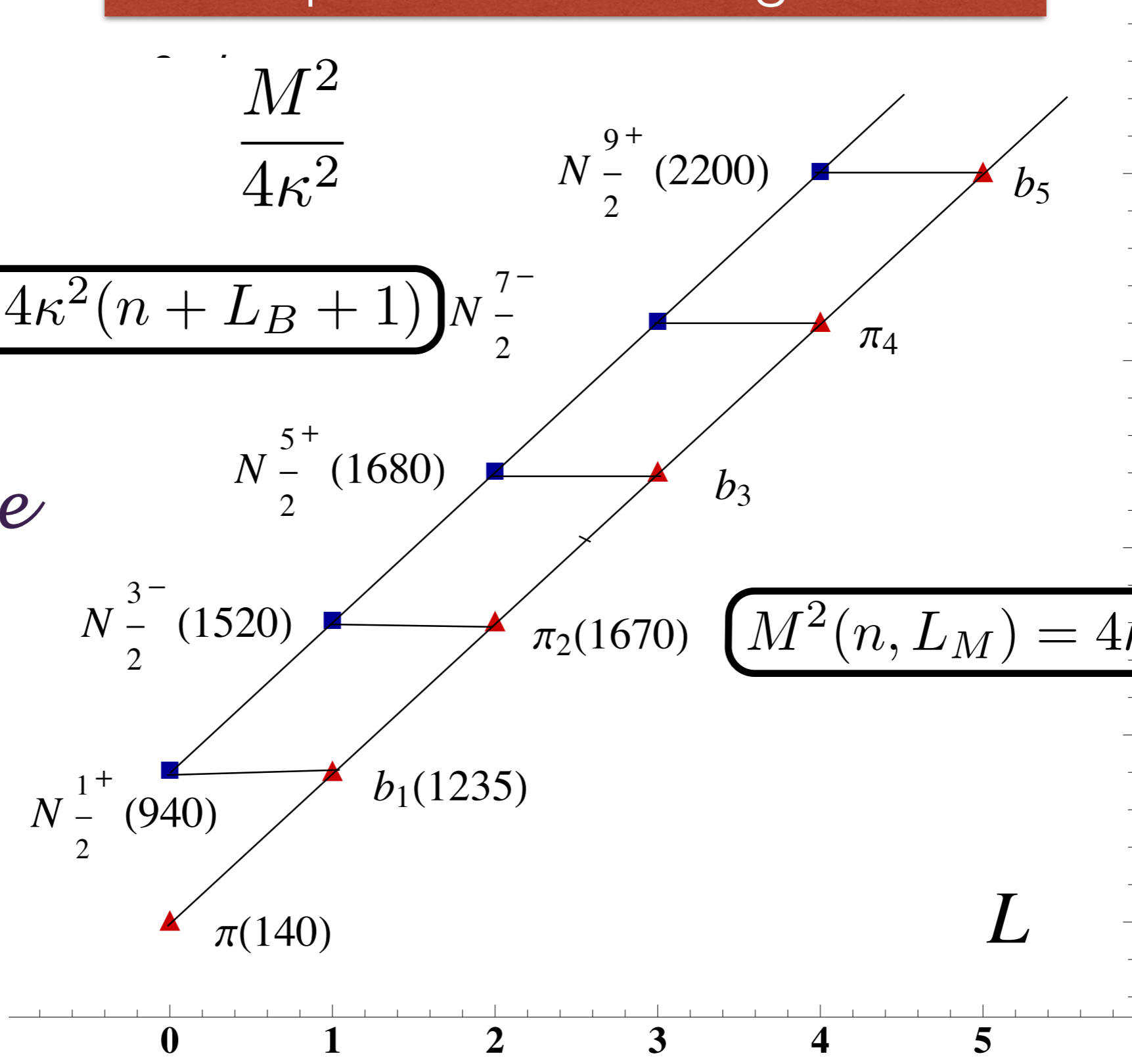**Kunshan**
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50

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

$$m_p = 2\kappa$$

**Deur, de Tèramond, sjb**

**All-Scale QCD Coupling**

*Nonperturbative QCD (Quark Confinement)*

Expt:

$$\frac{\alpha_{g_1}^s(Q^2)}{\pi}$$

$$e^{-\frac{Q^2}{4\kappa^2}}$$

$$\Lambda_{\overline{MS}} = 0.341 \pm 0.024 \ GeV$$

*Perturbative QCD (Asymptotic Freedom)*

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.016 \ GeV$$

*Transition scale $Q_0$*

$$Q_0^2 = 1.08 \pm 0.17 \ GeV^2$$

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

Q (GeV)

**Analytic, defined at all scales, IR Fixed Point**

$$\frac{\alpha_s(Q)}{\pi}$$

$$\alpha_s^{AdS}(Q)/\pi = e^{-Q^2/4\kappa^2}$$

$$\kappa = 0.54\ GeV$$

- ∙∙∙ Modified AdS
- —— AdS
- ▮ $\alpha_{g1}/\pi$ (pQCD)
- ▢ $\alpha_{g1}/\pi$ world data
- ∙∙∙ GDH limit  ✳ $\alpha_{F3}/\pi$
- ◇ $\alpha_{\tau}/\pi$ OPAL
- ▲ $\alpha_{g1}/\pi$ JLab CLAS
- ▮ $\alpha_{g1}/\pi$ Hall A/CLAS
- ● Lattice QCD (2004)  ▼ (2007)

$10^{-1}$   1   10

Q (GeV)

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

**Deur, de Tèramond, sjb**
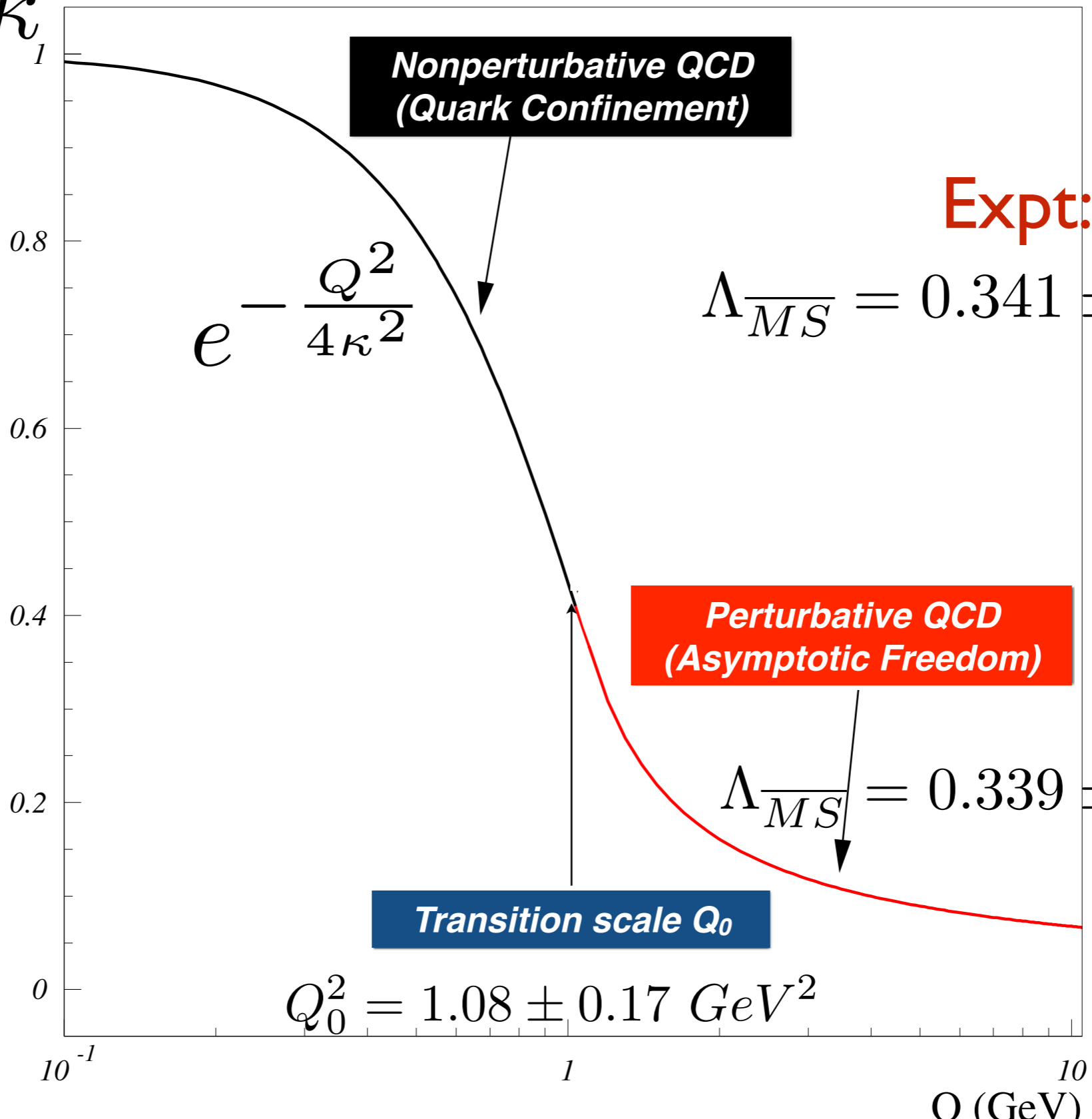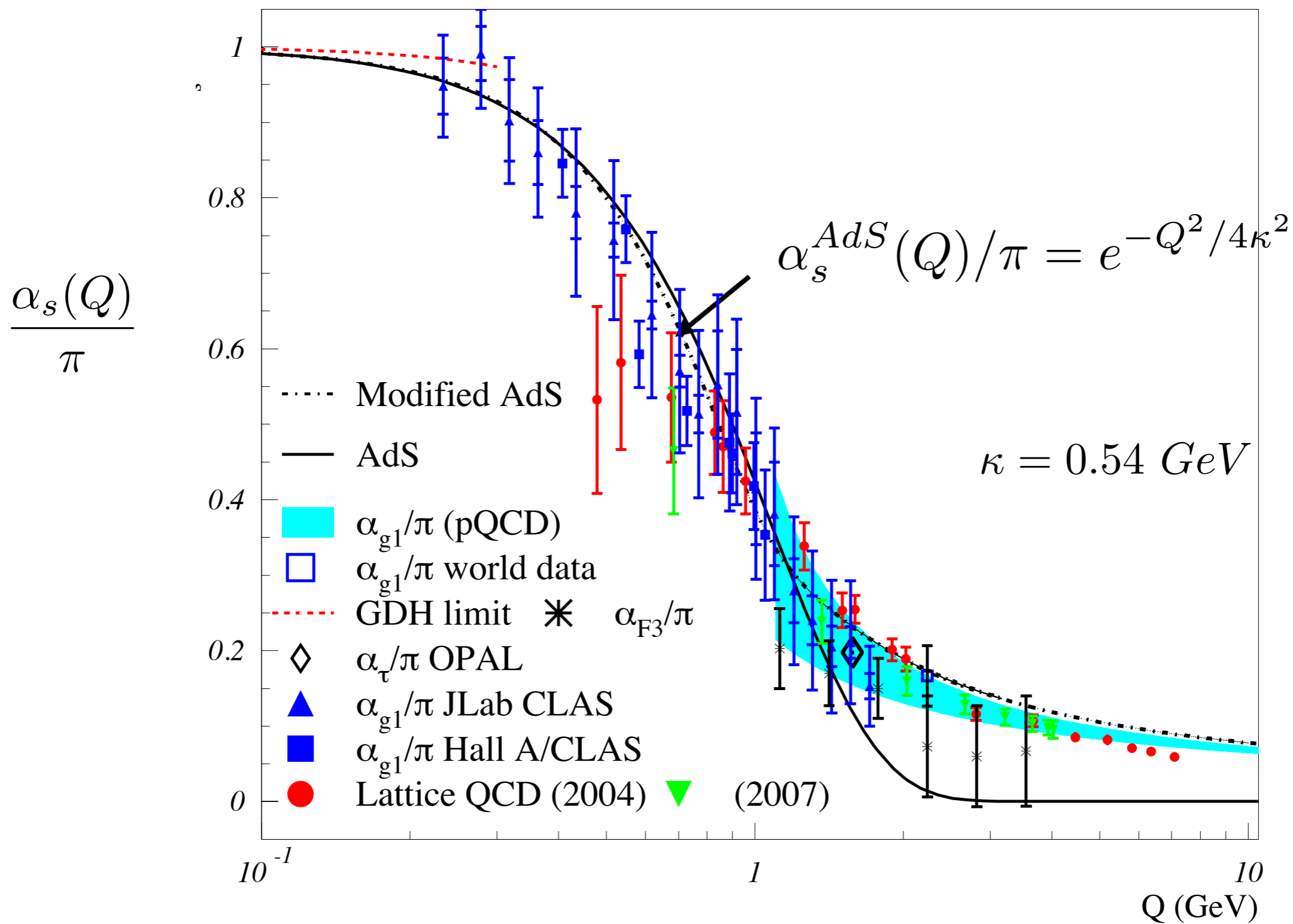
52

# Dirac's Front Form: Fixed $\tau = t + z/c$
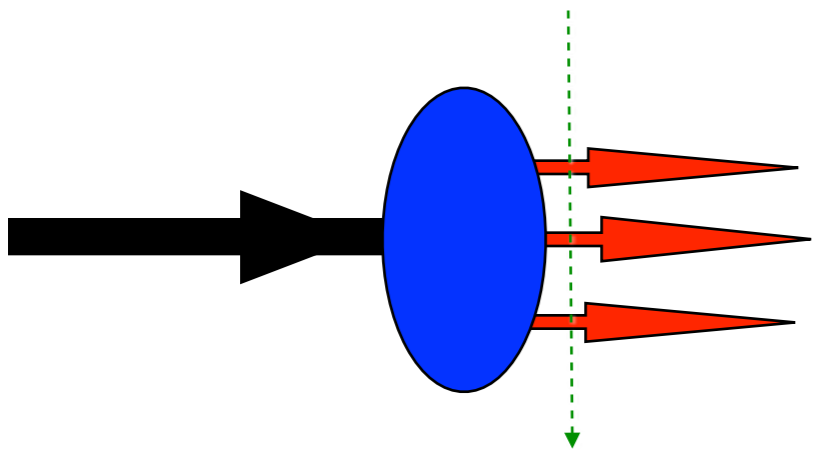
$$\psi(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$$x_i = \frac{k_i^+}{P^+}$$

**Invariant under boosts. Independent of $P^\mu$**

$$H_{LF}^{QCD}|\psi> = M^2|\psi>$$

**Direct connection to QCD Lagrangian**

*Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space*

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**53**

# Light-Front Holography and Non-Perturbative QCD

**Goal:**
**Use AdS/QCD duality to construct a first approximation to QCD**

*Hadron Spectrum*
*Light-Front Wavefunctions,*
*Form Factors, DVCS, etc*
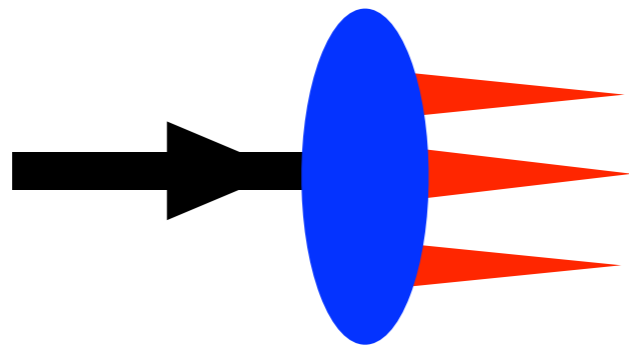


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$
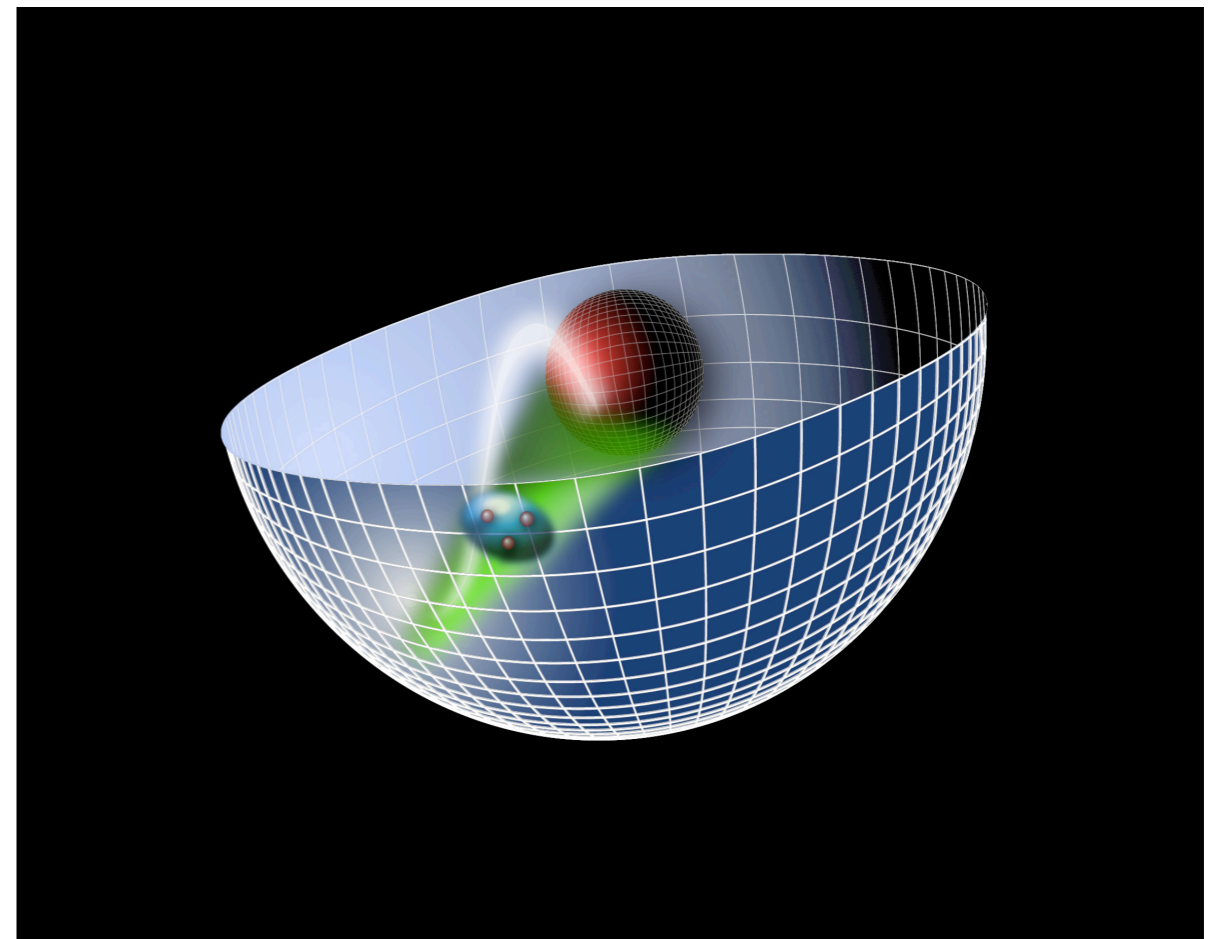
**in collaboration with Guy de Teramond and H. Guenter Dosch**

5-Dimensional
Anti-de Sitter
Spacetime

Confinement
Radius

$\Psi(x, z)$

AdS
Boundary
$(z=0)$

$z_0 = 1/\Lambda_{QCD}$

$\Psi \sim z^\Delta$

4-Dimensional
Flat Spacetime
(hologram)
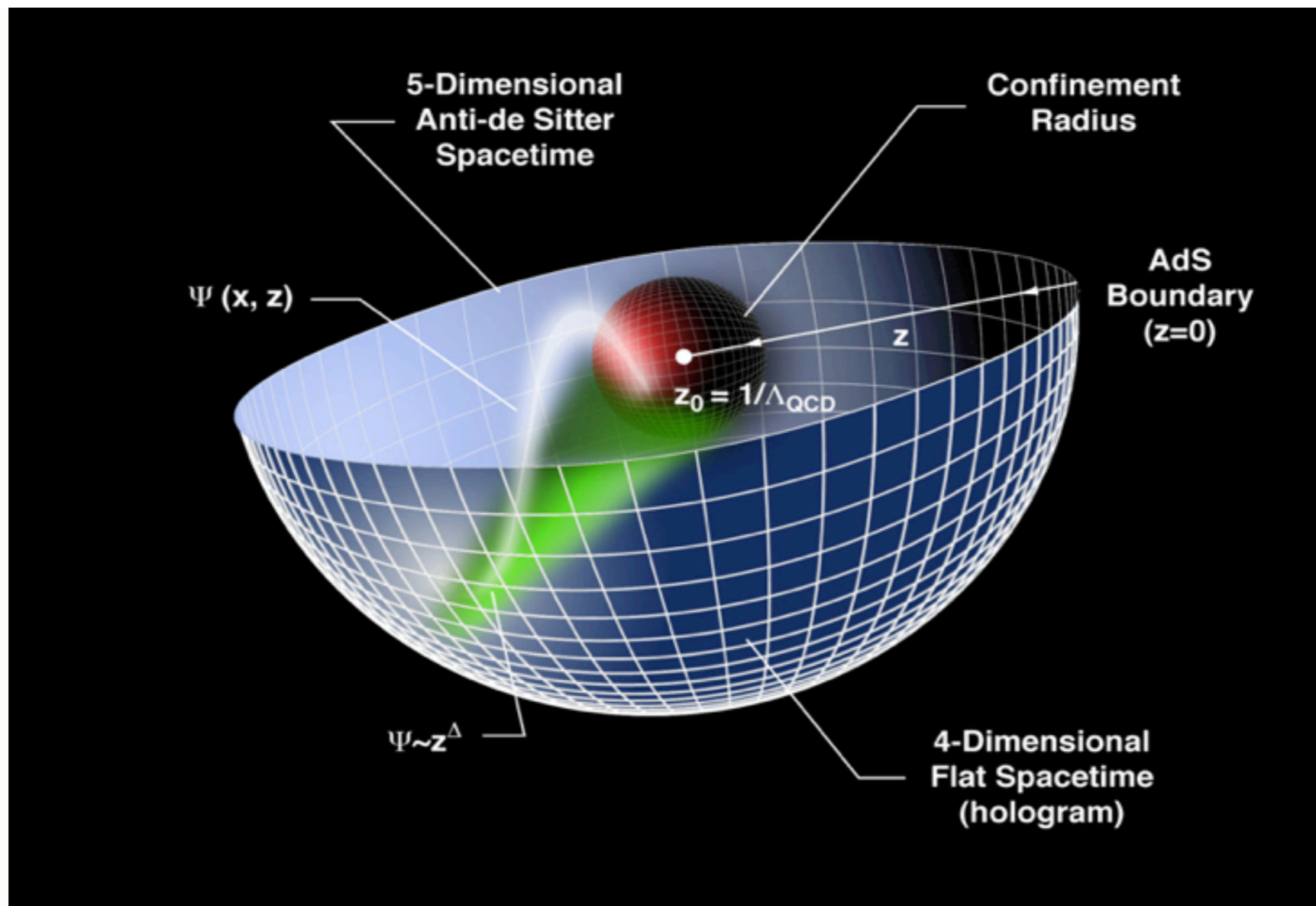
8-2007
8685A14

*Changes in physical length scale mapped to evolution in the 5th dimension z*

- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\mathrm{QCD}}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model)   Polchinski and Strassler (2001).

- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model)   Karch, Katz, Son and Stephanov (2006).

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*August 3, 2015*

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# AdS/CFT

- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

*invariant measure*

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2),$$

$x^\mu \to \lambda x^\mu, \ z \to \lambda z$, maps scale transformations into the holographic coordinate $z$.

- AdS mode in $z$ is the extension of the hadron wf into the fifth dimension.

- Different values of $z$ correspond to different scales at which the hadron is examined.

$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$

$x^2 = x_\mu x^\mu$: invariant separation between quarks

- The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.

# 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**

- **Introduces confinement scale** $\kappa$

- **Uses AdS$_5$ as template for conformal theory**

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

*AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:*

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

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

*Derived from variation of Action for Dilaton-Modified AdS₅*

**Identical to Light-Front Bound State Equation!**

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

$$LF(3+1) \longleftrightarrow AdS_5$$

## *Light-Front Holographic Dictionary*

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

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

Fixed $\tau = t + z/c$

$x$

$\vec{b}_\perp$

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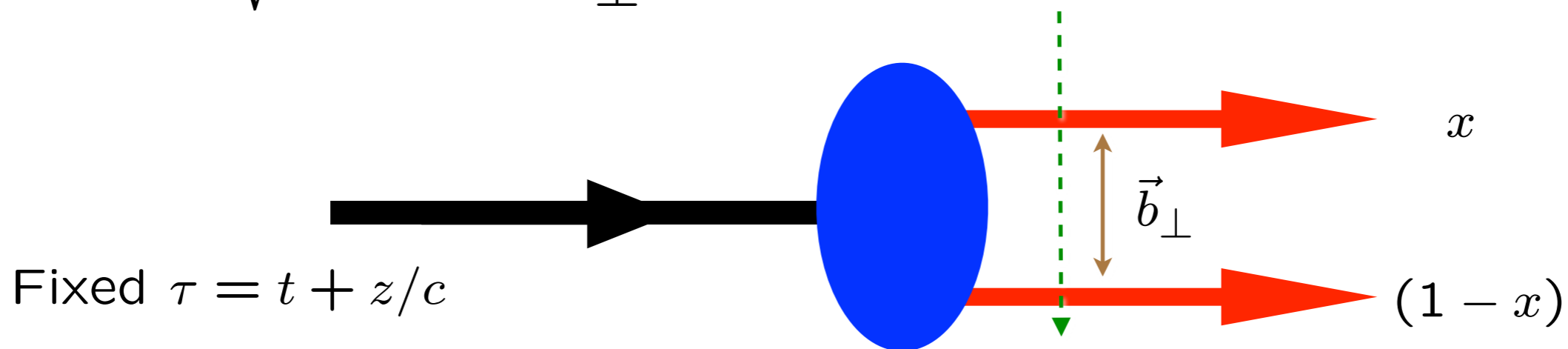
$$\psi(x, \zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

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

*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*
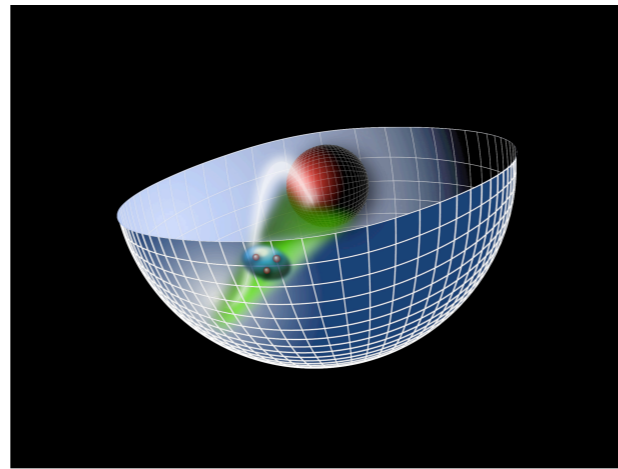
59

de Tèramond, Dosch, sjb

**AdS/QCD Soft-Wall Model**

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

**Light-Front Holography**

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

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

**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*

$$\kappa \simeq 0.6 \ GeV$$

**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!*

## Meson Spectrum in Soft Wall Model

*Pion: Negative term for J=0 cancels positive terms from LFKE and potential*

- Effective potential: $U(\zeta^2) = \kappa^4 \zeta^2 + 2\kappa^2(J-1)$

- LF WE

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

- Normalized eigenfunctions $\langle \phi | \phi \rangle = \int d\zeta \, \phi^2(z)^2 = 1$

$$\phi_{n,L}(\zeta) = \kappa^{1+L} \sqrt{\frac{2n!}{(n+L)!}} \zeta^{1/2+L} e^{-\kappa^2\zeta^2/2} L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

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

**G. de Teramond, H. G. Dosch, sjb**

*Quark separation increases with L*
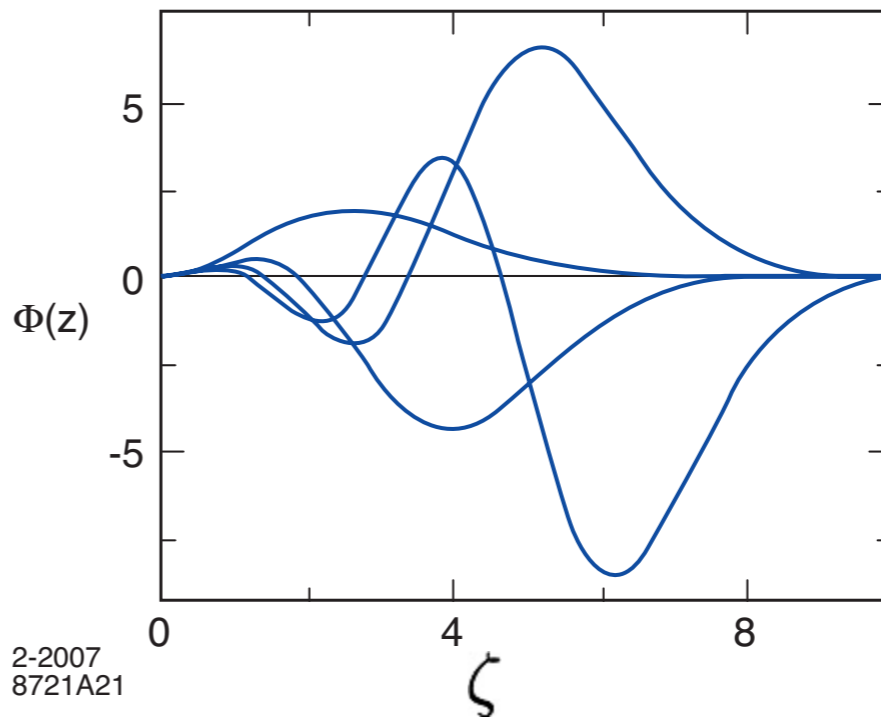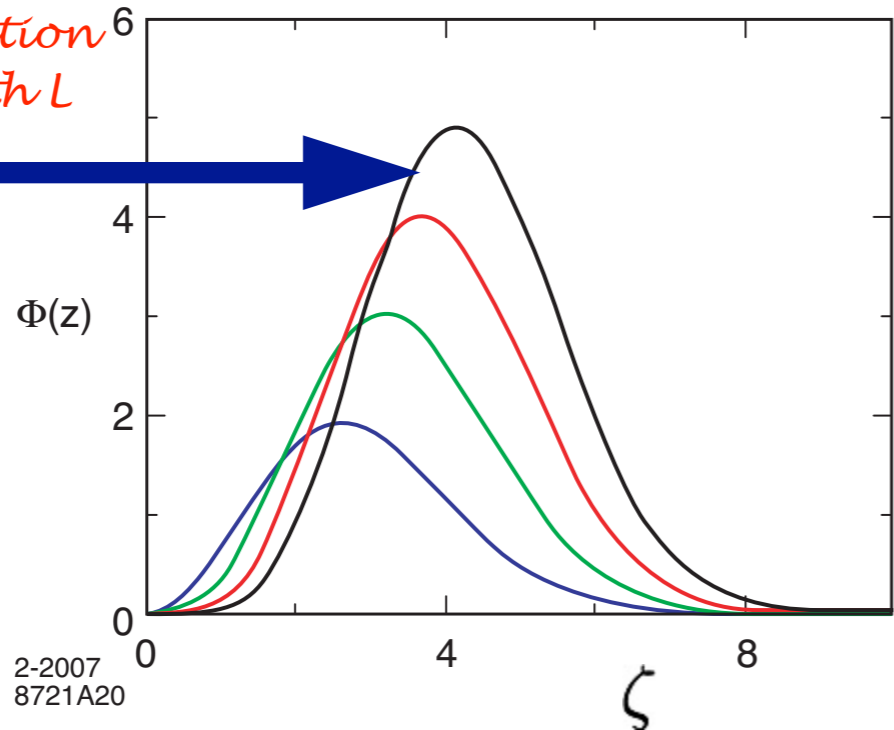
Fig: Orbital and radial AdS modes in the soft wall model for $\kappa = 0.6$ GeV .

*Same slope in n and L!*

*Soft Wall Model*

2-2007
8721A20

2-2007
8721A21



$S = 0$

(a)

$\pi_2$ (1670)

$b_1$ (1235)

$\pi$ (140)

$S = 0$

(b)

$\pi$ (1800)

$\pi$ (1300)

$\pi$ (140)
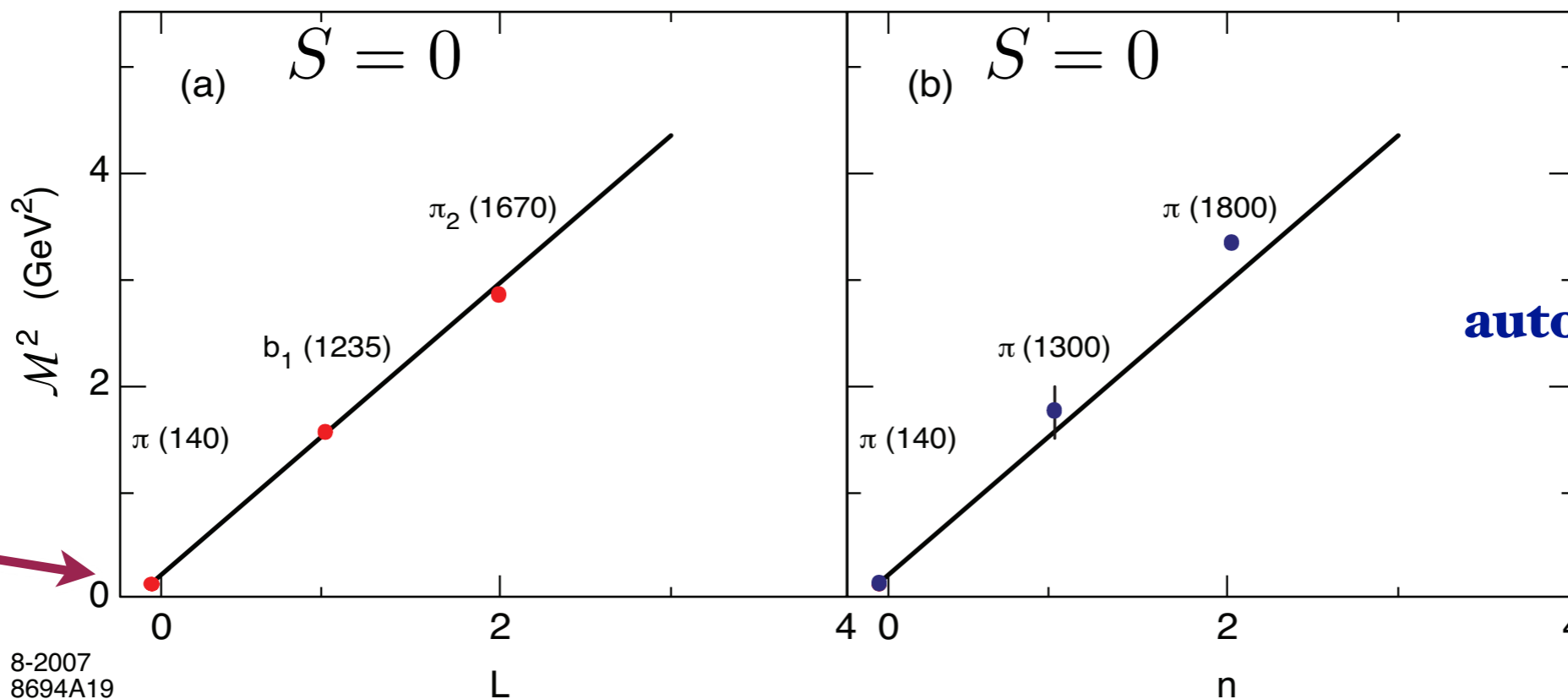
*Pion has zero mass!*

**Pion mass automatically zero!**

$$m_q = 0$$

8-2007
8694A19

Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

**62**

- $J = L + S,\ I = 1$ meson families $\boxed{\mathcal{M}^2_{n,L,S} = 4\kappa^2\,(n + L + S/2)}$

$m_q = 0$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

*Massless pion in Chiral Limit!*    *Same slope in n and L!*
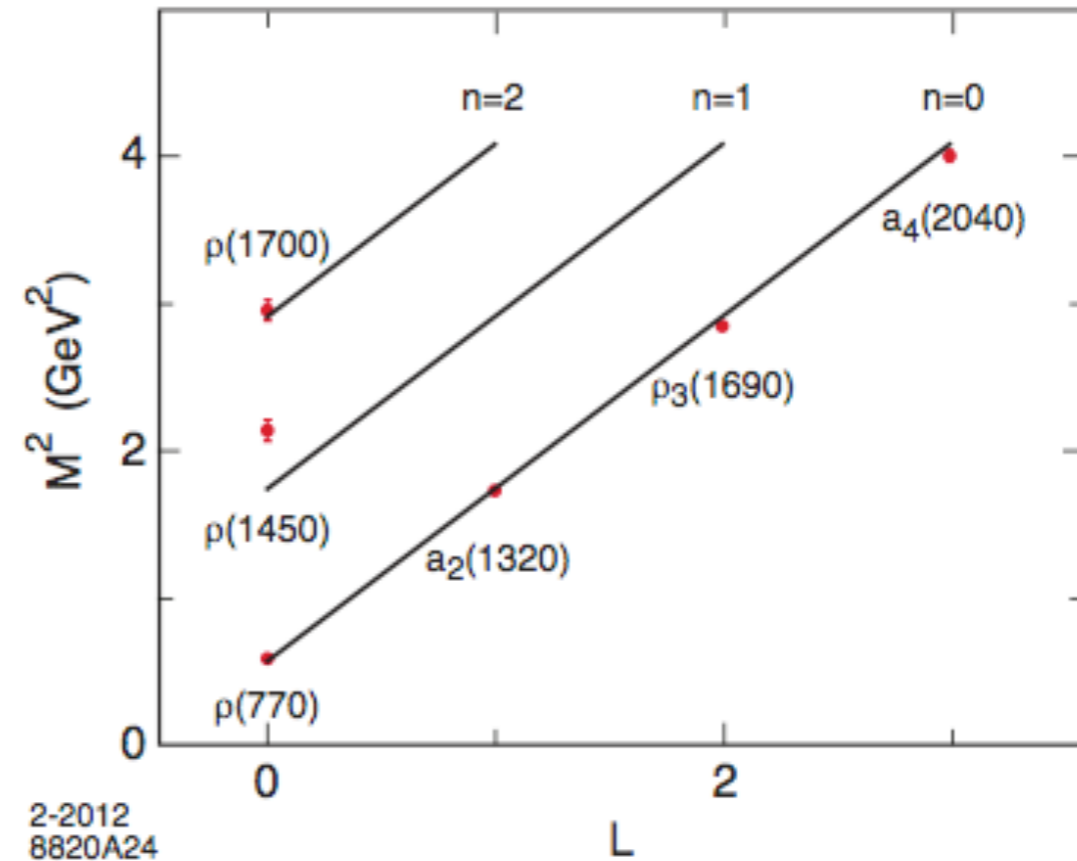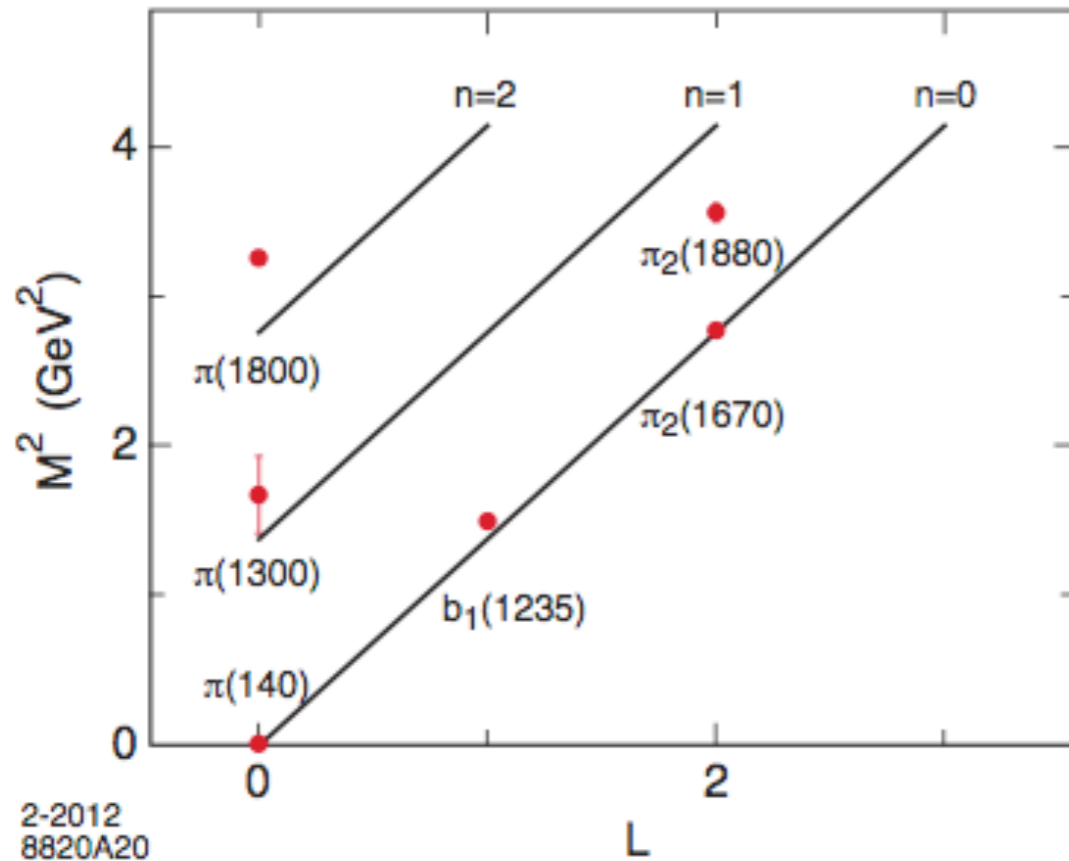


I=1 orbital and radial excitations for the $\pi$ ($\kappa = 0.59$ GeV) and the $\rho$-meson families ($\kappa = 0.54$ GeV)

- Triplet splitting for the $I = 1,\ L = 1,\ J = 0, 1, 2$, vector meson $a$-states

$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

Mass ratio of the ρ and the a₁ mesons: coincides with Weinberg sum rules

**G. de Teramond, H. G. Dosch, sjb**

63

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

$$M^2 = M_0^2 + \left\langle X \left| \frac{m_q^2}{x} \right| X \right\rangle + \left\langle X \left| \frac{m_{\bar{q}}^2}{1-x} \right| X \right\rangle$$



**(a)** $M^2(\text{GeV}^2)$ — $n=2$, $n=1$, $n=0$; $\pi(1800)$, $\pi_2(1880)$, $\pi(1300)$, $\pi_2(1670)$, $b_1(1235)$, $\pi(140)$, $L$

**(b)** $M^2(\text{GeV}^2)$ — $n=2$, $n=1$, $n=0$; $K_2(1820)$, $K_2(1770)$, $K_1(1400)$, $K_1(1270)$, $K(494)$, $L$

**(a)** $M^2(\text{GeV}^2)$ — $n=3$, $n=2$, $n=1$, $n=0$; $f_2(2300)$, $\rho(1700)$, $f_2(1950)$, $a_4(2040)$, $f_4(2050)$, $\omega(1650)$, $\rho_3(1690)$, $\omega_3(1670)$, $\rho(1450)$, $\omega(1420)$, $a_2(1320)$, $f_2(1270)$, $\rho(770)$, $\omega(782)$, $L$

**(b)** $M^2(\text{GeV}^2)$ — $n=2$, $n=1$, $n=0$; $K_4^*(2045)$, $K^*(1680)$, $K_3^*(1780)$, $K^*(1410)$, $K_2^*(1430)$, $K^*(892)$, $L$

**64**
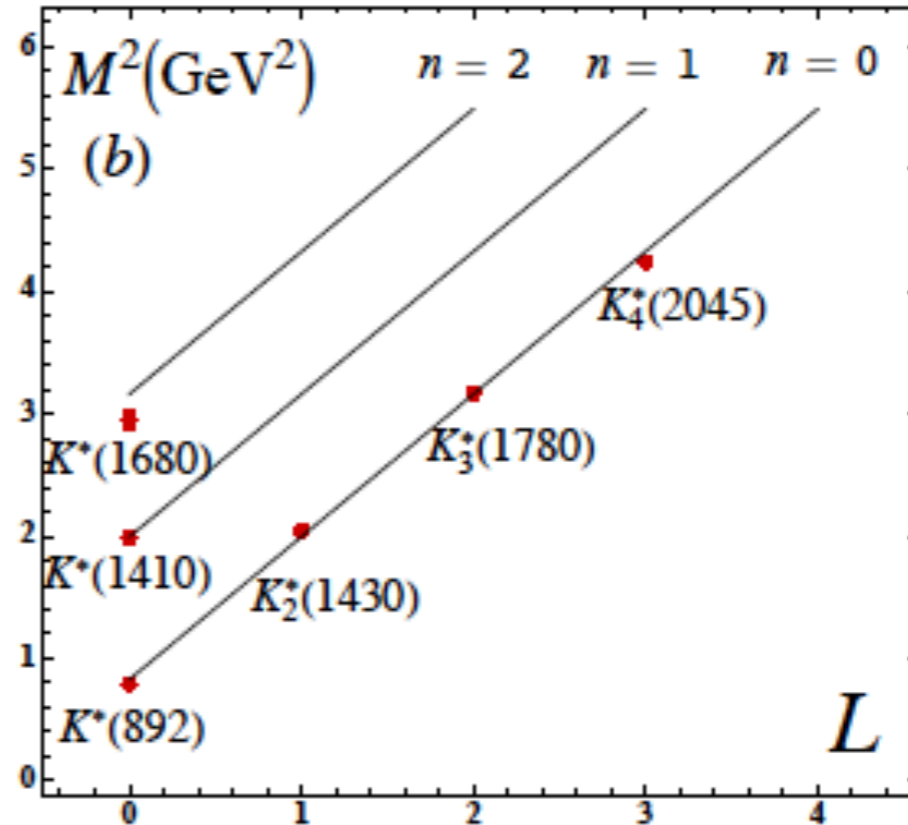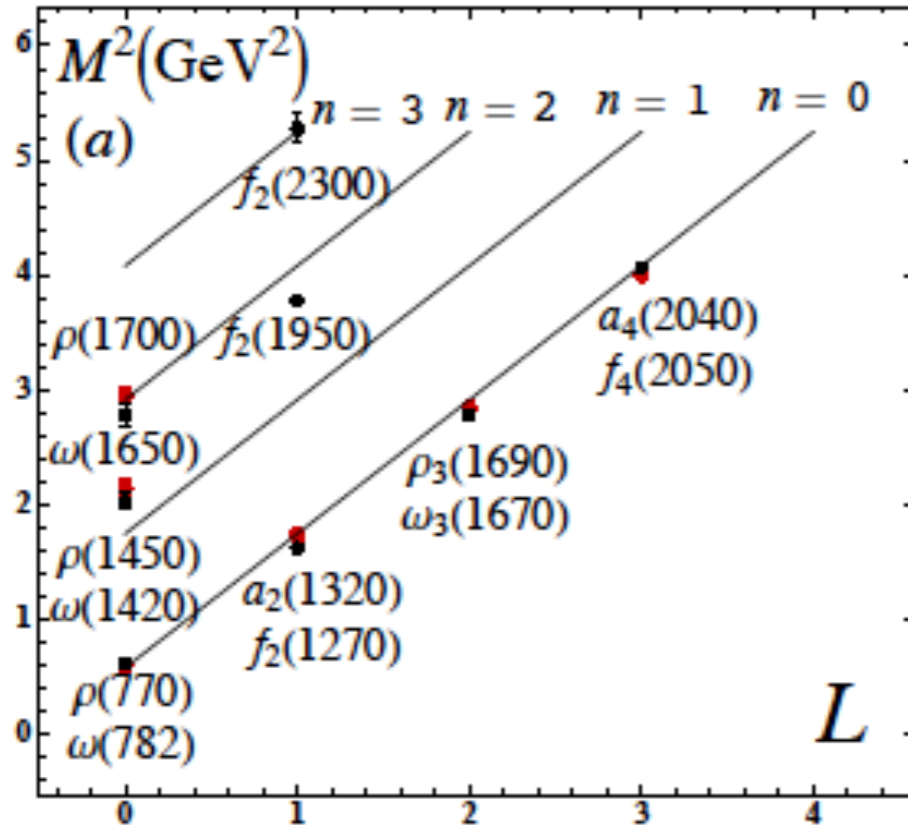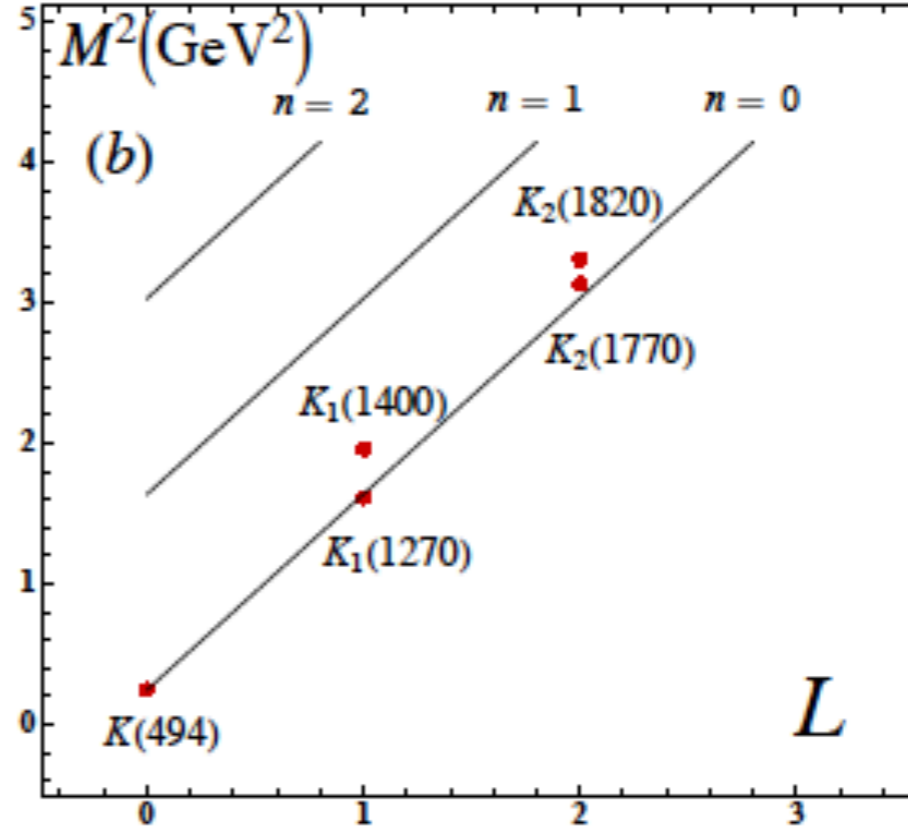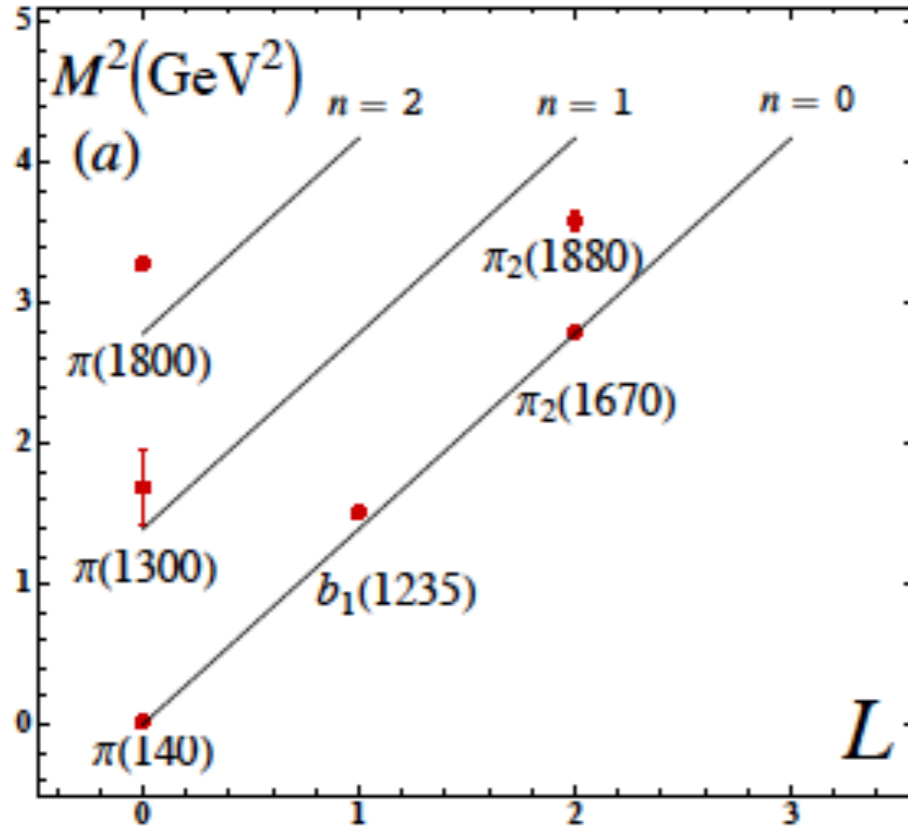
# Prediction from AdS/QCD: Meson LFWF

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

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



$x$

0.8   0.6   0.4   0.2

0.2

0.15

0.1

0.05

0

1.3

1.4

$k_\perp$ (GeV)

1.5

**de Teramond, Cao, sjb**

**"Soft Wall" model**

$x$

$1-x$

massless quarks
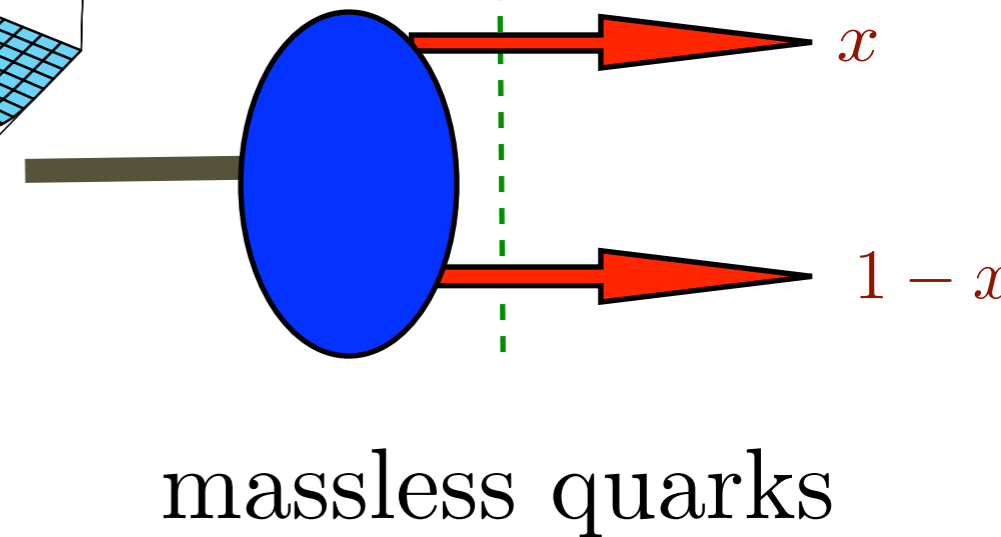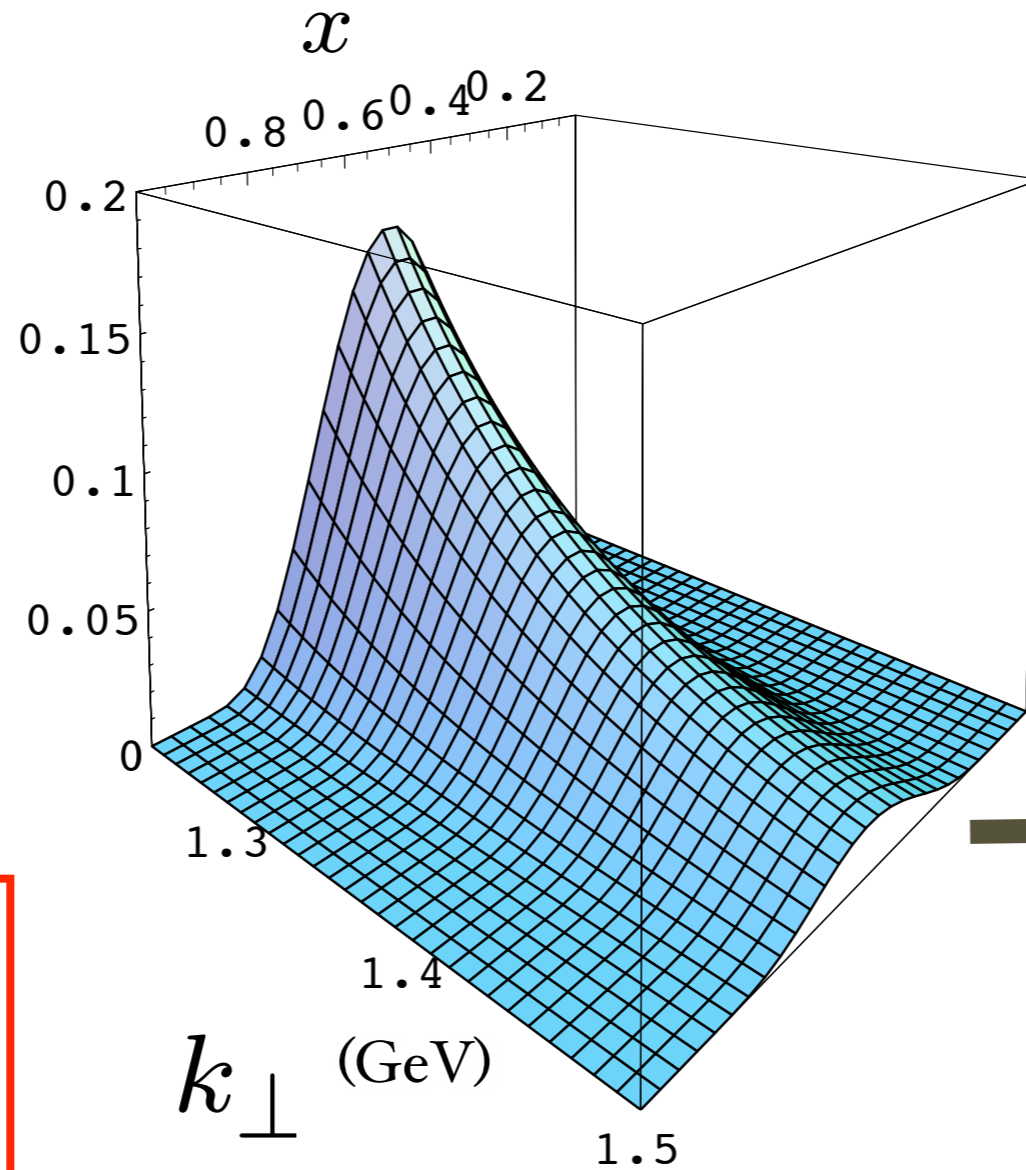
**Note coupling**

$$k_\perp^2, x$$

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

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

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

***Same as DSE!***

*Provides Connection of Confinement to Hadron Structure*

# AdS/QCD Holographic Wave Function for the $\rho$ Meson and Diffractive $\rho$ Meson Electroproduction

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(Received 5 April 2012; published 20 August 2012)

We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive $\rho$-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

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

**See also Ferreira and Dosch**

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

**66**

## AdS/QCD Holographic Wave Function for the $\rho$ Meson and Diffractive $\rho$ Meson Electroproduction
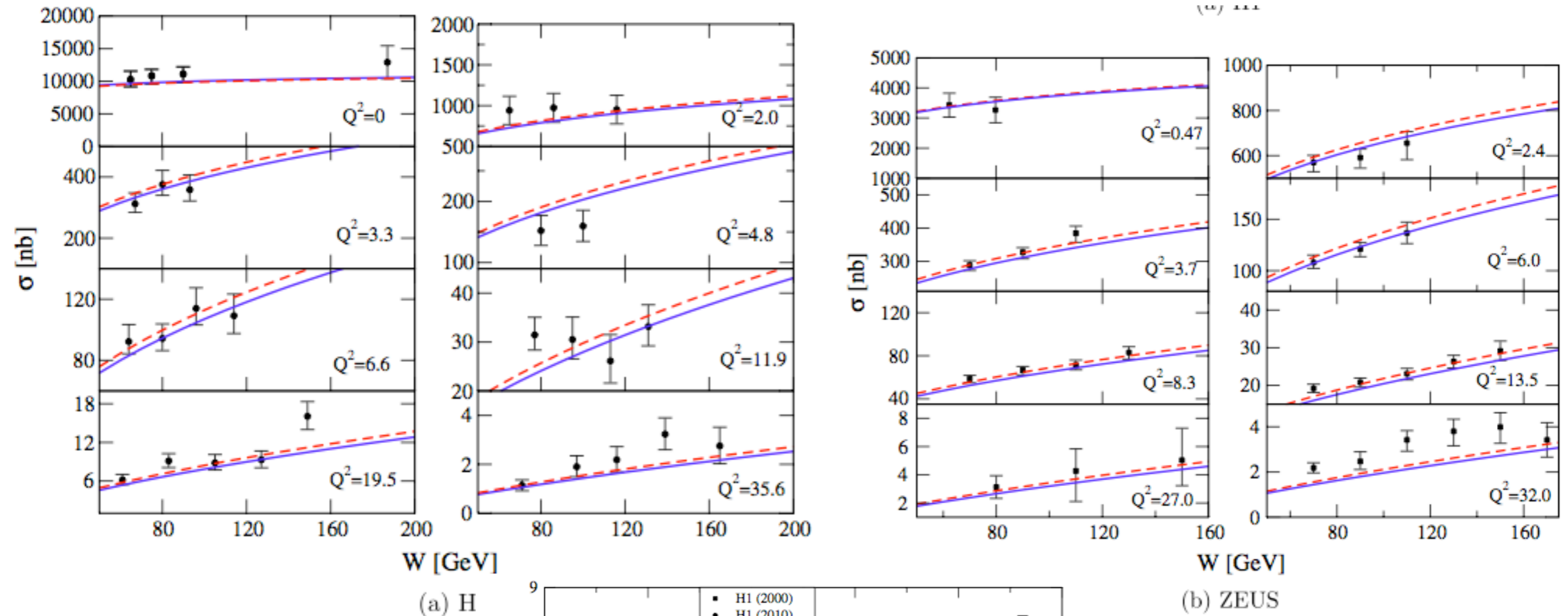


**J. R. Forshaw,
R. Sandapen**

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

$$\frac{\sigma_L}{\sigma_T}$$
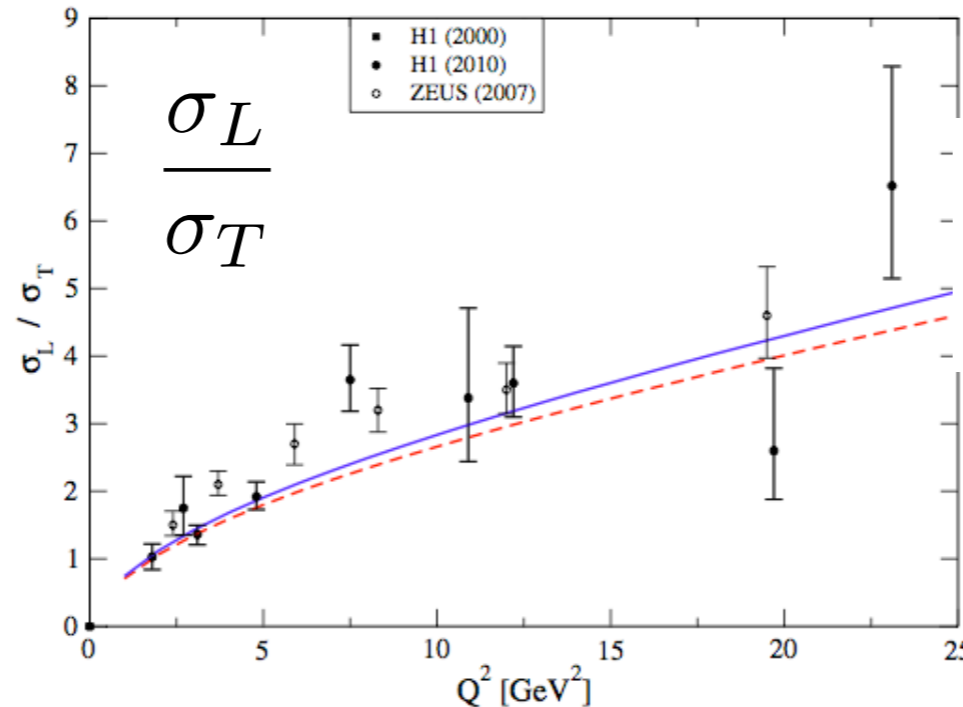
$$\tilde{\phi}(x, k) \propto \frac{1}{\sqrt{x(1-x)}} \exp\left(-\frac{M_{q\bar{q}}^2}{2\kappa^2}\right),$$

*See also Ferreira
and Dosch*

# *Uniqueness*

de Tèramond, Dosch, sjb

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L + S - 1) \qquad e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

- $\zeta^2$ confinement potential and dilaton profile unique!

- Linear Regge trajectories in n and L: same slope!

- Massless pion in chiral limit!  No vacuum condensate!

- Conformally invariant action for massless quarks retained despite mass scale

- Same principle, equation of motion as de Alfaro, Furlan, Fubini, <u>Conformal Invariance in Quantum Mechanics</u> Nuovo Cim. A34 (1976) 569

# Hadron Form Factors from AdS/QCD

Propagation of external perturbation suppressed inside AdS.

$$J(Q, z) = zQK_1(zQ)$$

$$F(Q^2)_{I \to F} = \int \frac{dz}{z^3} \Phi_F(z) J(Q, z) \Phi_I(z)$$

High Q$^2$
from
small z ~ 1/Q

$J(Q, z)$  $\Phi(z)$

high $Q^2$
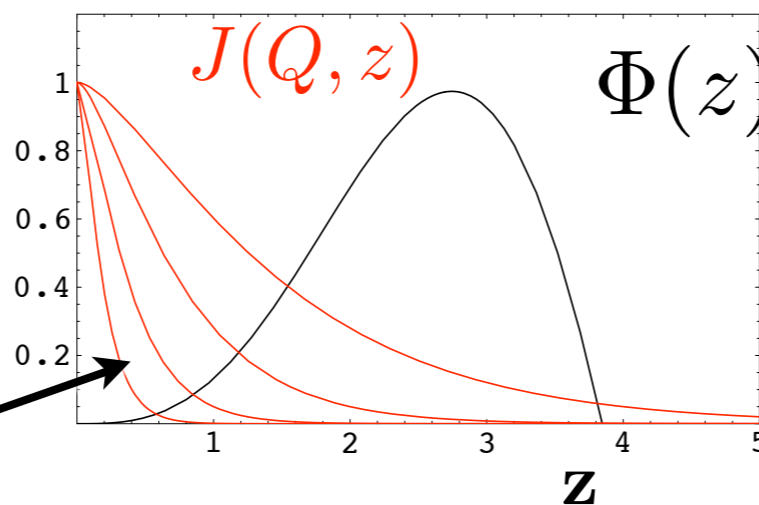
**Polchinski, Strassler**
**de Teramond, sjb**

Consider a specific AdS mode $\Phi^{(n)}$ dual to an $n$ partonic Fock state $|n\rangle$. At small $z$, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^{n} \sigma_i$.

**Dimensional Quark Counting Rules:**
**General result from**
**AdS/CFT and Conformal Invariance**

$$\text{Twist } \tau = n + L$$

$Q^2 F_\pi(Q^2)$

$Q^2 \ \text{GeV}^2$
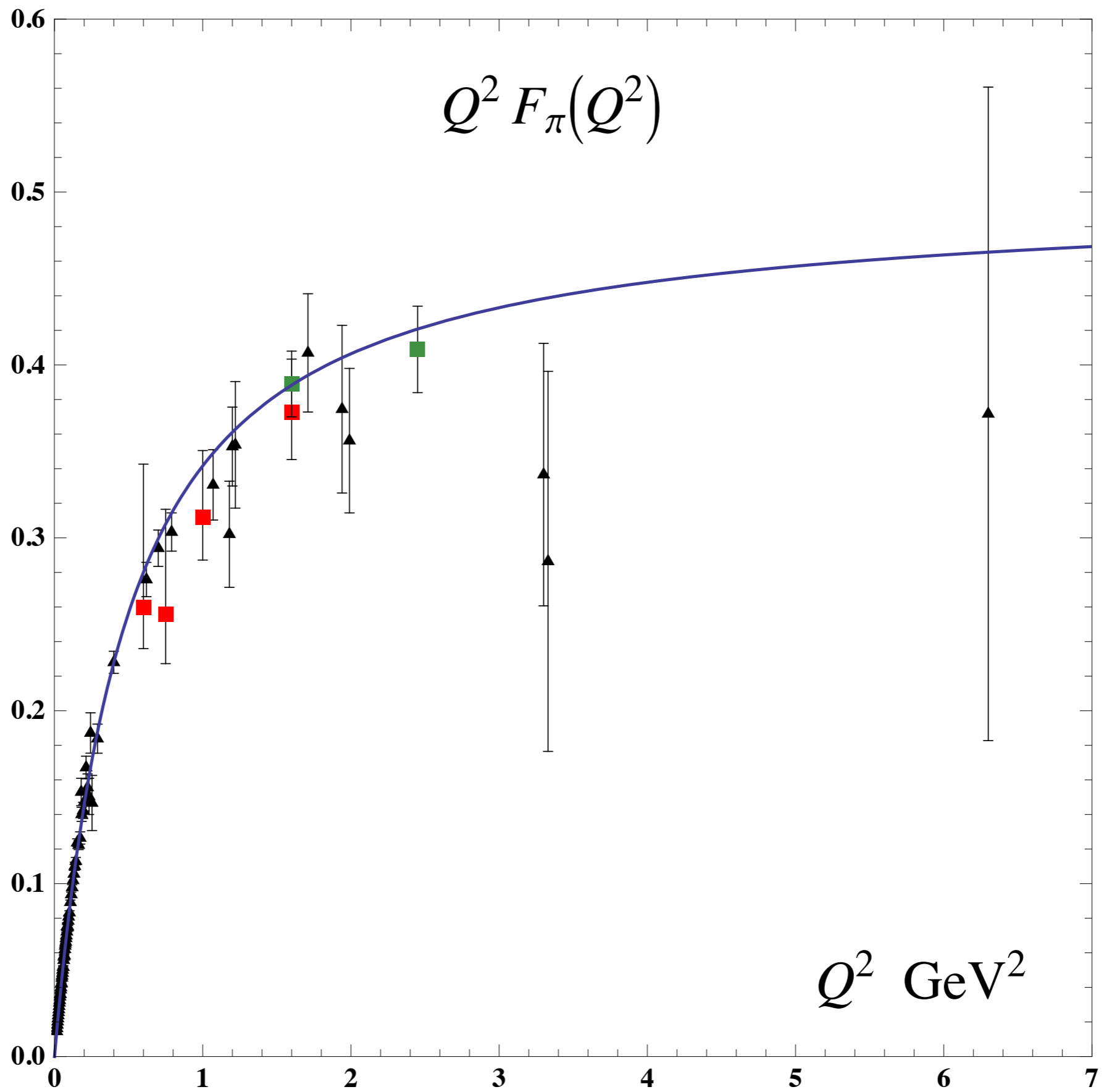
# Dressed soft-wall current brings in higher Fock states and more vector meson poles
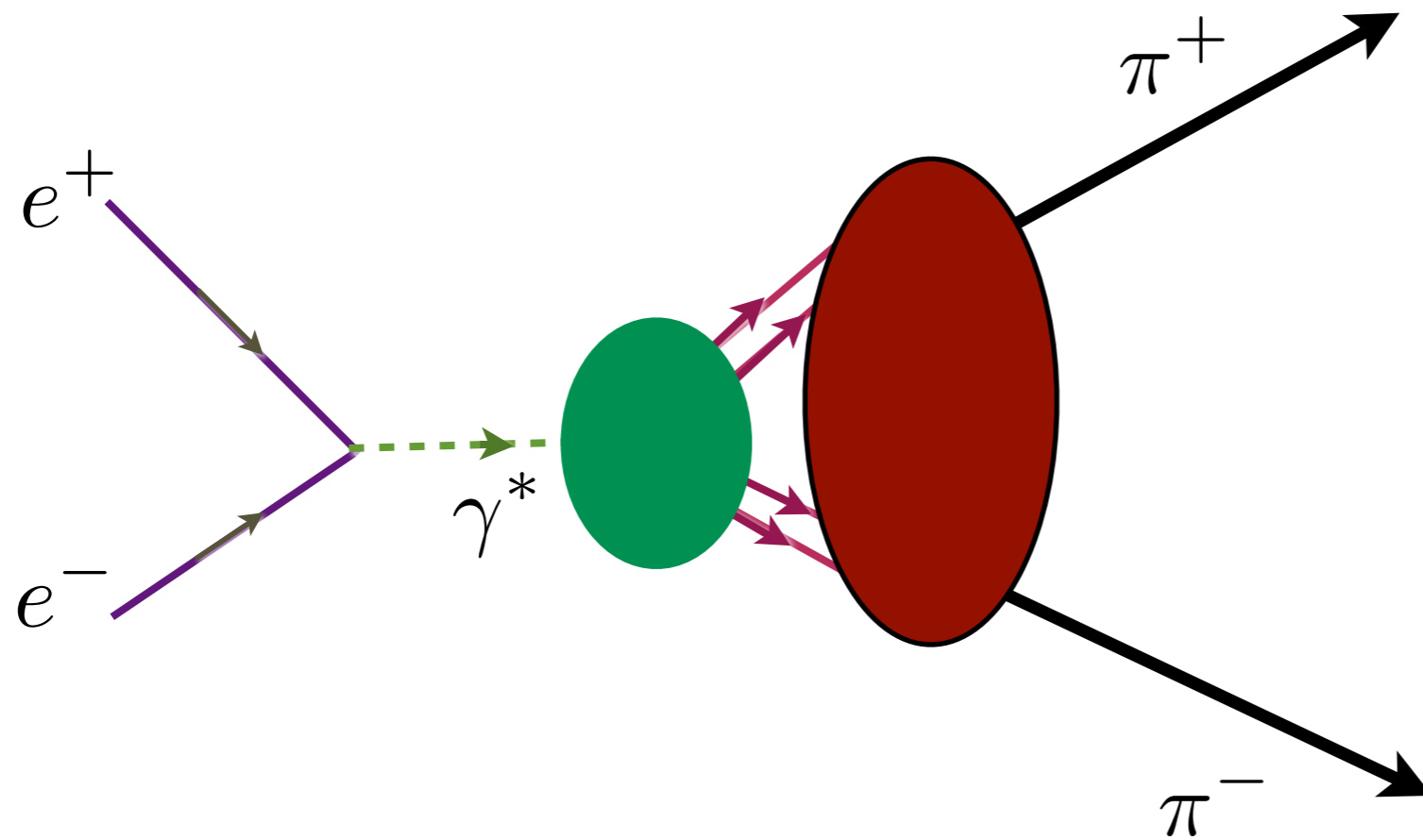
# Timelike Pion Form Factor from AdS/QCD and Light-Front Holography

$$F_\pi(s) = (1-\gamma)\frac{1}{(1-\frac{s}{\mathcal{M}_\rho^2})} + \gamma\frac{1}{(1-\frac{s}{\mathcal{M}_\rho^2})(1-\frac{s}{\mathcal{M}_{\rho'}^2})(1-\frac{s}{\mathcal{M}_{\rho''}^2})}$$

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

$$\gamma = 0.17$$

$\log|F_\pi(s)|$

*Twist 2+4*

*Twist 2*

**Frascati data**
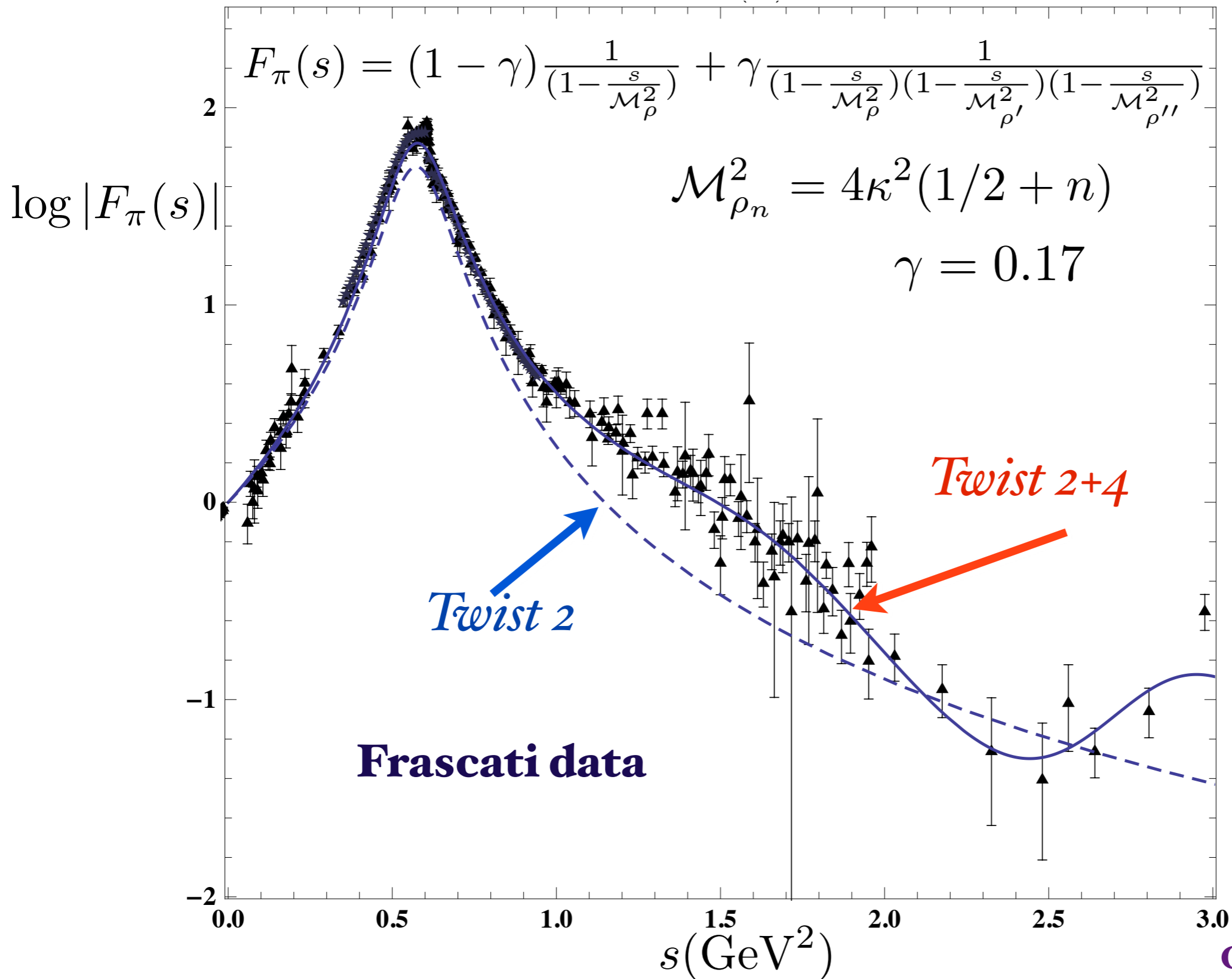
*Prescription for Timelike poles :*

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

**14% four-quark probability**

$s(\mathrm{GeV}^2)$

**G. de Teramond & sjb**

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

$\log |F_\pi(s)|$

*spacelike*

*timelike*

Frascati

JLab

BaBar ISR

$q^2 (\text{GeV}^2)$
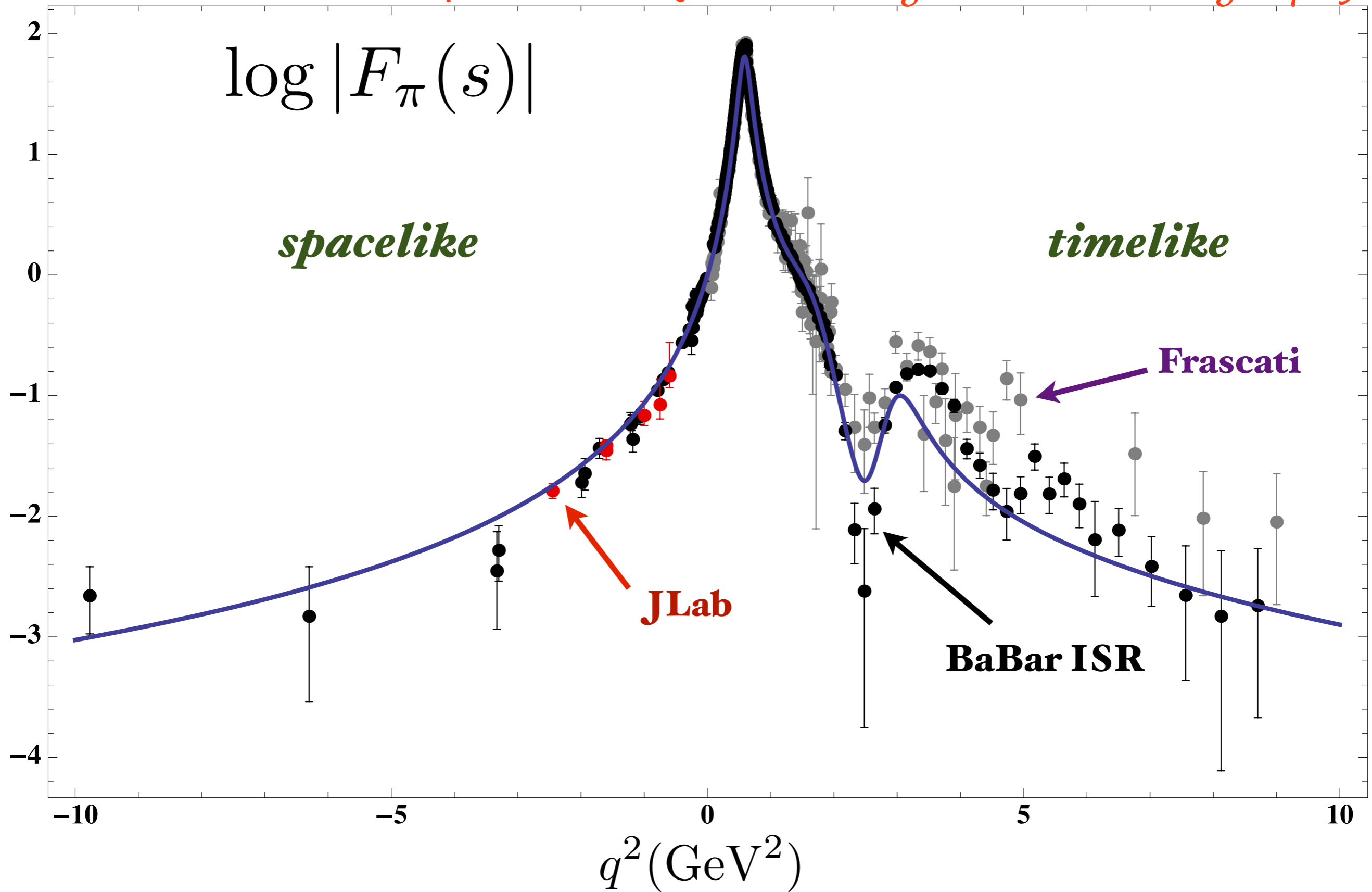
# Remarkable Features of Light-Front Schrödinger Equation

- **Relativistic, frame-independent**

- **QCD scale appears - unique LF potential**

- **Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter**

- **Zero-mass pion for zero mass quarks!**

- **Regge slope same for n and L  -- not usual HO**

- **Splitting in L persists to high mass   -- contradicts conventional wisdom based on breakdown of chiral symmetry**

- **Phenomenology: LFWFs, Form factors, electroproduction**

- **Extension to heavy quarks**

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

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$$\phi(z)$$

# AdS5: Conformal Template for QCD

- *Light-Front Holography*
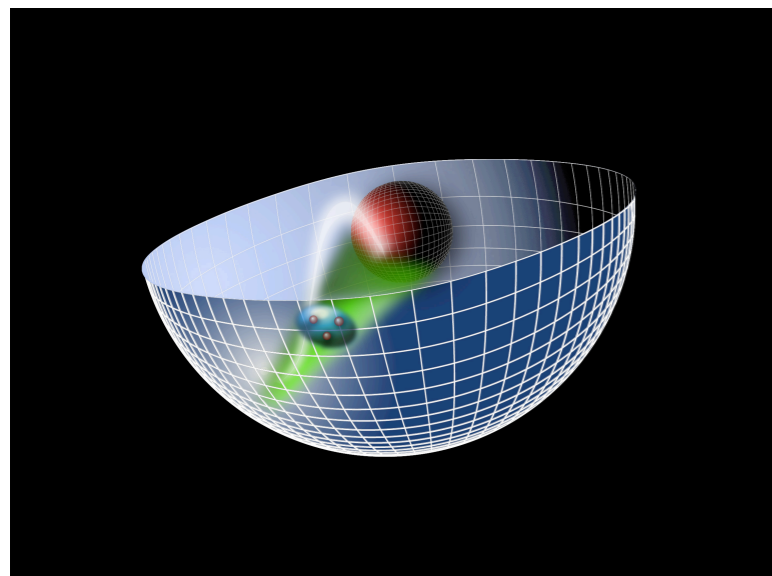
Fixed $\tau = t + z/c$
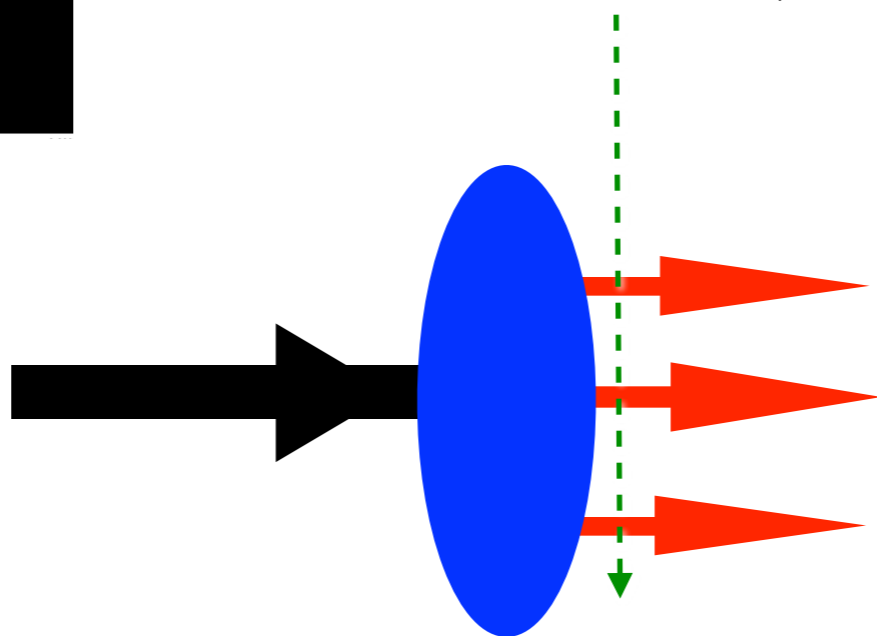
**Duality of AdS₅ with LF Hamiltonian Theory**

$x$

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

$k_\perp (\text{GeV})$
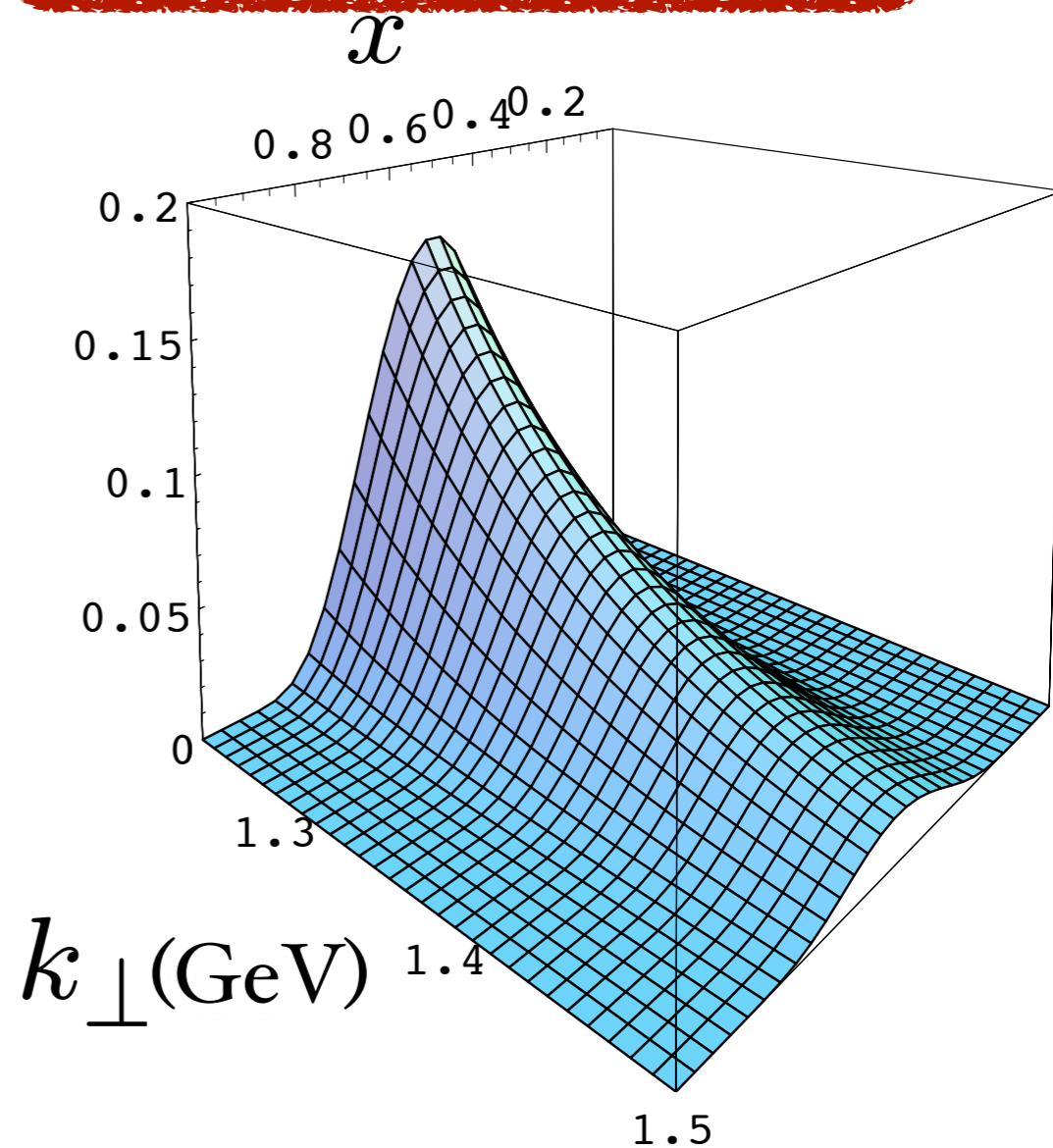
- *Light Front Wavefunctions:*

*Light-Front Schrödinger Equation Spectroscopy and Dynamics*

# QCD Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} \underline{\hspace{0.5cm}}_{m_f}\bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \qquad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

**Classical Chiral Lagrangian is Conformally Invariant**

**Where does the QCD Mass Scale $\Lambda_{QCD}$ come from?**

*How does color confinement arise?*

● **de Alfaro, Fubini, Furlan:**   *Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!*

*Unique confinement potential!*

$$G|\psi(\tau) >= i\frac{\partial}{\partial\tau}|\psi(\tau) >$$

$$G = uH + vD + wK$$

*New term*

$$G = H_\tau = \frac{1}{2}\Big(-\frac{d^2}{dx^2} + \frac{g}{x^2} + \frac{4uw - v^2}{4}x^2\Big)$$

*Retains conformal invariance of action despite mass scale!*

$$4uw - v^2 = \kappa^4 = [M]^4$$

*Identical to LF Hamiltonian with unique potential and dilaton!*

● **Dosch, de Teramond, sjb**

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

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

# *What determines the QCD mass scale* $\Lambda_{QCD}$?

- Mass scale does not appear in the QCD Lagrangian (massless quarks)

- Dimensional Transmutation? Requires external constraint such as $\alpha_s(M_Z)$

- dAFF: Confinement Scale κ appears spontaneously via the Hamiltonian: $G = uH + vD + wK$ $\qquad 4uw - v^2 = \kappa^4 = [M]^4$

- The confinement scale regulates infrared divergences, connects $\Lambda_{QCD}$ to the confinement scale κ

- Only dimensionless mass ratios (and M times R ) predicted

- Mass and time units [GeV] and [sec] from physics external to QCD

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- New feature: bounded frame-independent relative time between constituents

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# *dAFF: New Time Variable*

$$\tau = \frac{2}{\sqrt{4uw - v^2}} \arctan\left(\frac{2tw + v}{\sqrt{4uw - v^2}}\right),$$

- **Identify with difference of LF time Δx⁺/P⁺ between constituents**

- **Finite range**

- **Measure in Double-Parton Processes**
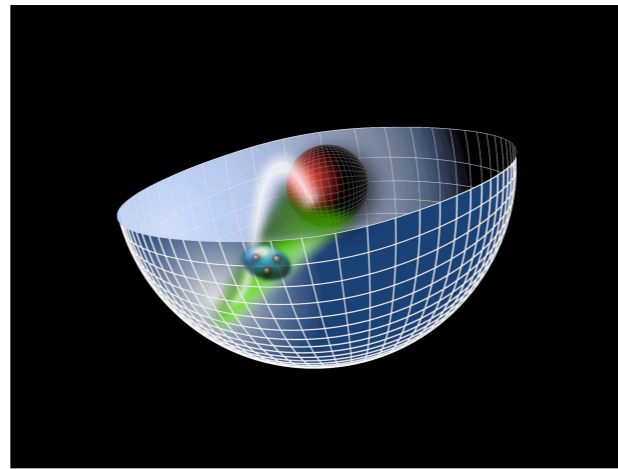
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79

*de Tèramond, Dosch, sjb*

**AdS/QCD Soft-Wall Model**

**Light-Front Holography**

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

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

**Light-Front Schrödinger Equation**

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

*Unique Confinement Potential!*

*Conformal Symmetry of the action*

$$\kappa \simeq 0.6 \; GeV$$

**Confinement scale:**

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

● **de Alfaro, Fubini, Furlan:**

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

de Teramond, Dosch, sjb
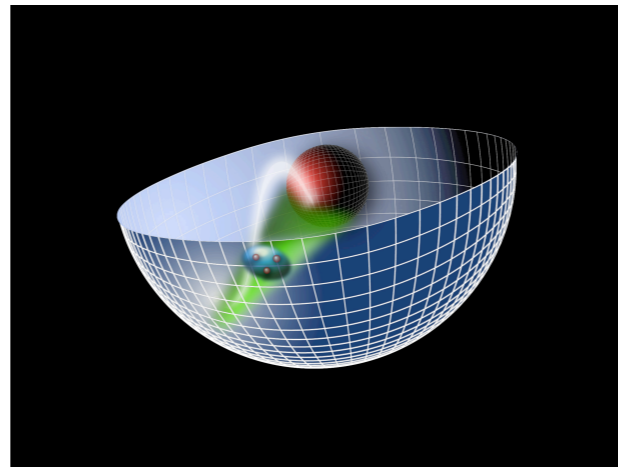
AdS/QCD
Soft-Wall Model



Light-Front Holography

*Semi-Classical Approximation to QCD*

**Relativistic, frame-independent**
**Unique color-confining potential**
**Zero mass pion for massless quarks**
**Regge trajectories with equal slopes in n and L**
**Light-Front Wavefunctions**

*Conformal Symmetry*
*of the action*

*Light-Front Schrödinger Equation*

## Superconformal Algebra

*1+1*

$$\{\psi, \psi^+\} = 1$$

*two anti-commuting fermionic operators*

$$\psi = \frac{1}{2}(\sigma_1 - i\sigma_2), \quad \psi^+ = \frac{1}{2}(\sigma_1 + i\sigma_2)$$

*Realization as Pauli Matrices*

$$Q = \psi^+[-\partial_x + W(x)], \quad Q^+ = \psi[\partial_x + W(x)], \qquad W(x) = \frac{f}{x}$$

**(Conformal)**

$$S = \psi^+ x, \quad S^+ = \psi x$$

*Introduce new spinor operators*

$$\{Q, Q^+\} = 2H, \quad \{S, S^+\} = 2K$$

$$\boxed{Q \simeq \sqrt{H}, \quad S \simeq \sqrt{K}}$$

$$\{Q, Q\} = \{Q^+, Q^+\} = 0, \quad [Q, H] = [Q^+, H] = 0$$

**Baryon Equation**

Consider $R_w = Q + wS;$     $w$: dimensions of mass squared

$$G = \{R_w, R_w^+\} = 2H + 2w^2K + 2wfI - 2wB \qquad 2B = \sigma_3$$

Retains Conformal Invariance of Action     **Fubini and Rabinovici**

*New Extended Hamiltonian $G$ is diagonal:*

$$G_{11} = \left( -\partial_x^2 + w^2x^2 + 2wf - w + \frac{4(f + \frac{1}{2})^2 - 1}{4x^2} \right)$$

$$G_{22} = \left( -\partial_x^2 + w^2x^2 + 2wf + w + \frac{4(f - \frac{1}{2})^2 - 1}{4x^2} \right)$$

Identify $f - \frac{1}{2} = L_B$ ,   $w = \kappa^2$

Eigenvalue of $G$: $M^2(n, L) = 4\kappa^2(n + L_B + 1)$

*LF Holography*  **Baryon Equation**  $x \to \zeta$

$$\left( -\frac{d^2}{d\zeta^2} + \lambda_B^2\,\zeta^2 + 2\lambda_B(L_B+1) + \frac{4L_B^2-1}{4\zeta^2} \right)\psi_J^+ \;=\; M^2\,\psi_J^+, \quad \text{G}_{22}$$

$$\left( -\frac{d^2}{d\zeta^2} + \lambda_B^2\,\zeta^2 + 2\lambda_B\,L_B + \frac{4(L_B+1)^2-1}{4\zeta^2} \right)\psi_J^- \;=\; M^2\,\psi_J^-. \quad \text{G}_{11}$$

$$\boxed{M_B^2(N, L_B) = 4\lambda_B(n + L_B + 1)}$$

**S=1/2, P=+**

*both chiralities*

**Meson Equation**

$$\left( -\frac{d^2}{d\zeta^2} + \lambda_M^2\zeta^2 + 2\lambda_M(J-1) + \frac{4L_M^2-1}{4\zeta^2} \right)\phi_J = M^2\phi_j \quad \text{G}_{11}$$

$$\boxed{M_M^2(N, L_M, S=0) = 4\lambda_M(n + L_M)}$$

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

**Meson-Baryon Degeneracy for L_M=L_B+1**  $\quad {}_{84}\,\lambda_M^2 = \lambda_B^2 = \kappa^4$

$$\frac{M^2}{4\kappa^2}$$

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

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

*Same slope*

$N\frac{9^+}{2}$ (2200)

$N\frac{7^-}{2}$

$N\frac{5^+}{2}$ (1680)

$N\frac{3^-}{2}$ (1520)

$N\frac{1^+}{2}$ (940)

$b_5$

$\pi_4$

$b_3$

$\pi_2(1670)$

$b_1(1235)$

$\pi(140)$

$L$

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

86
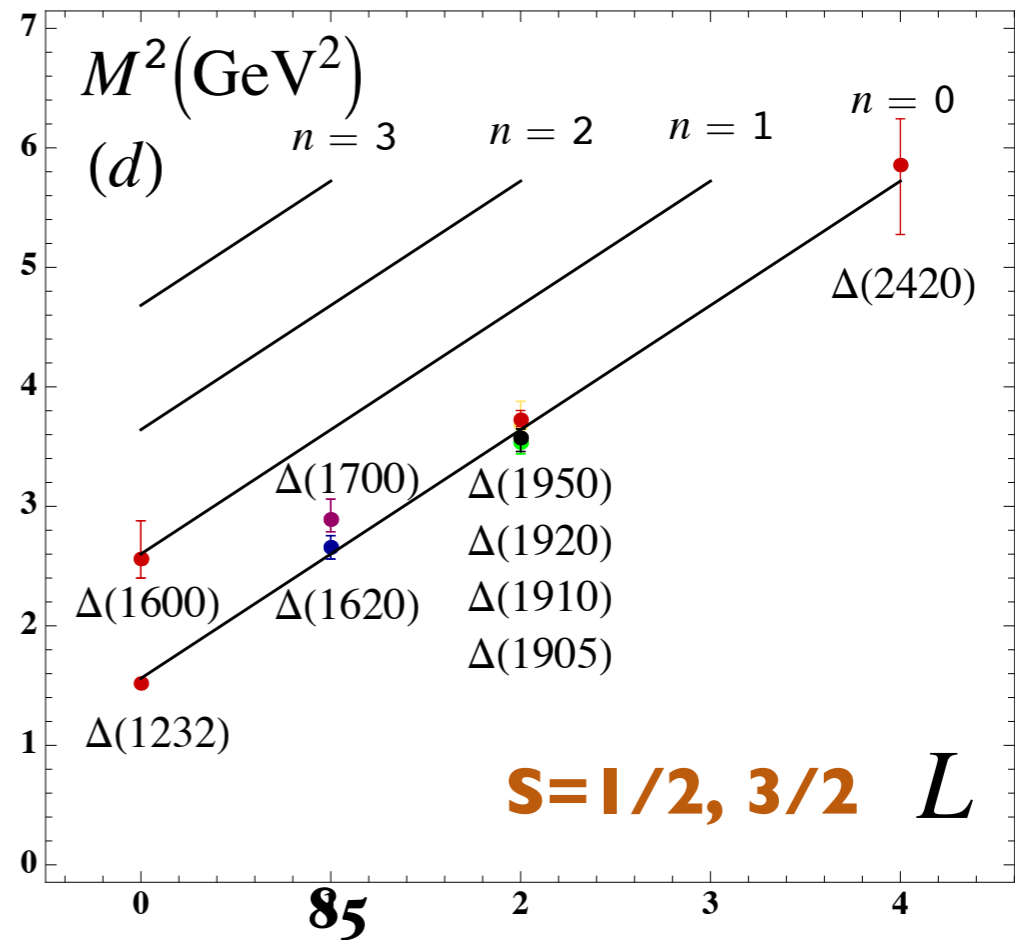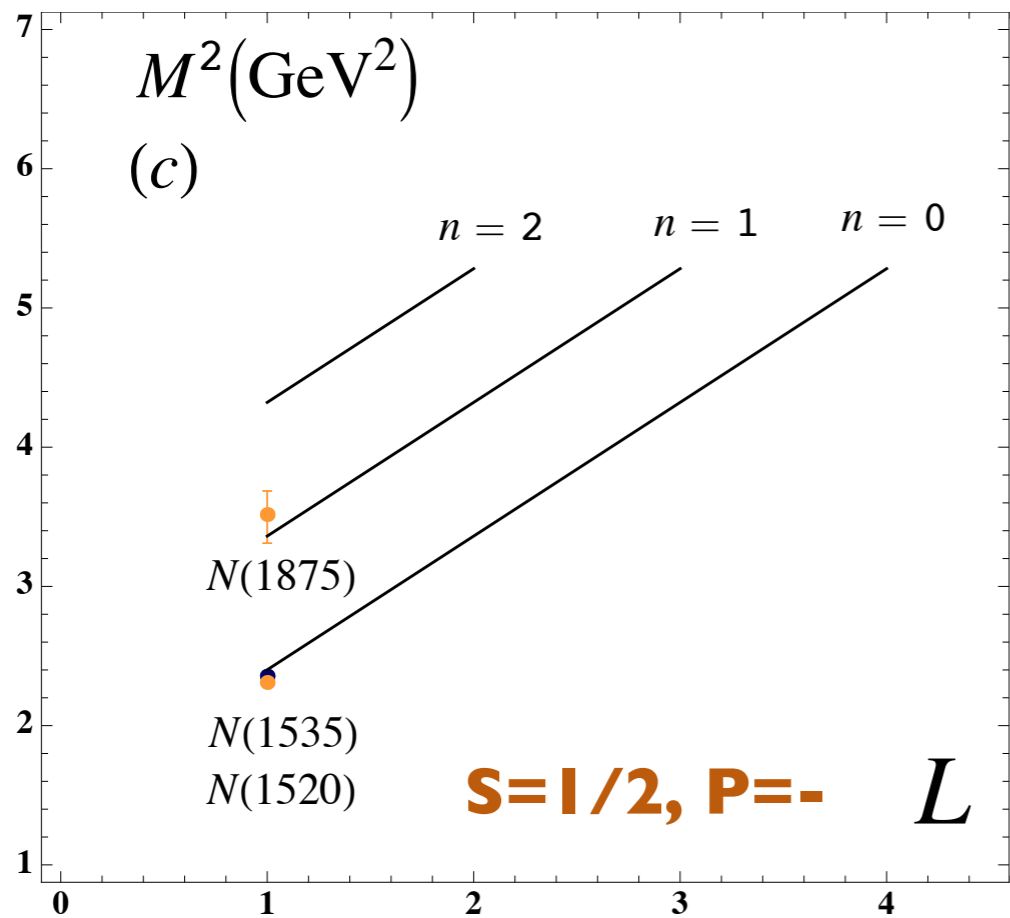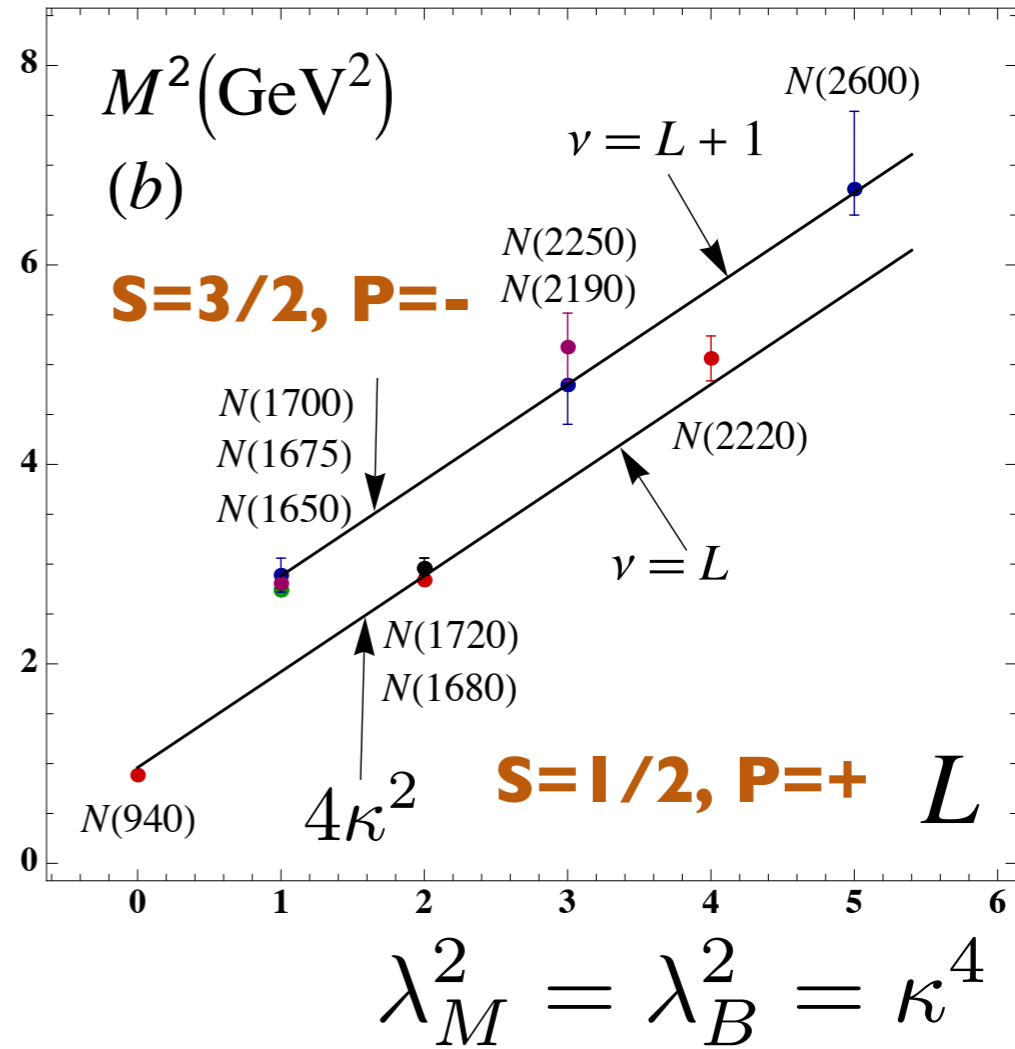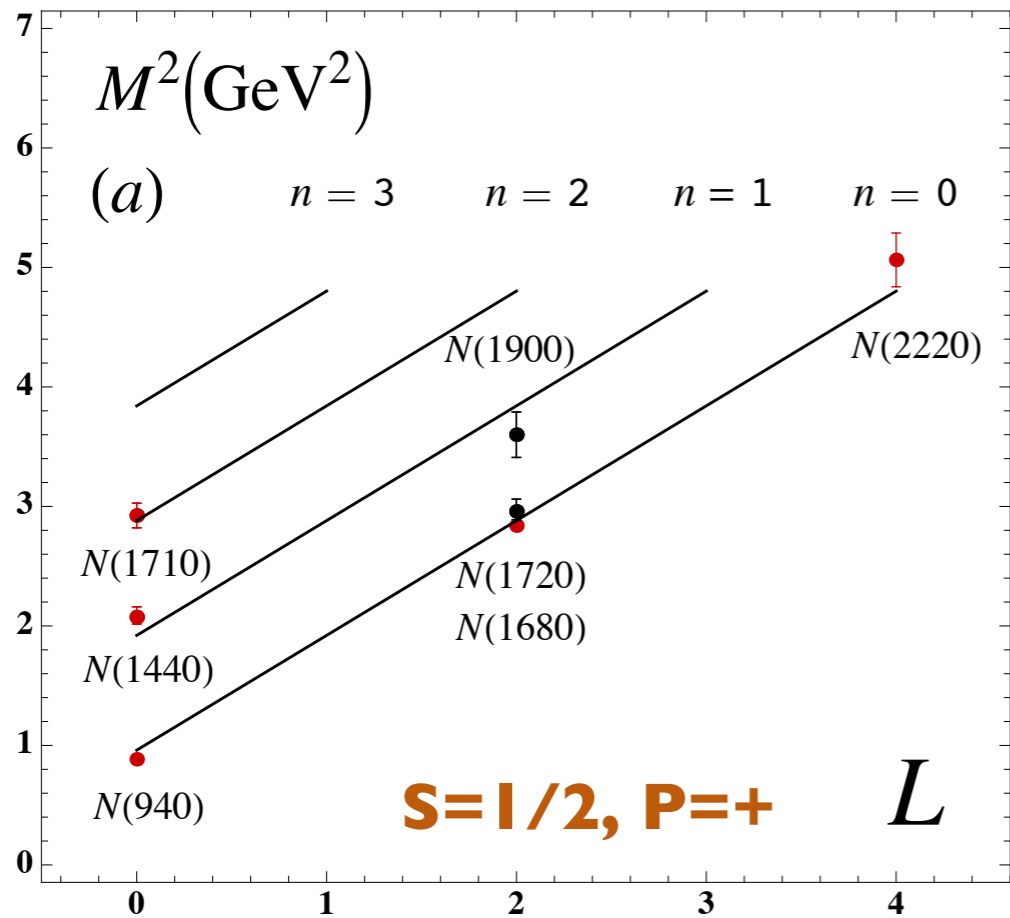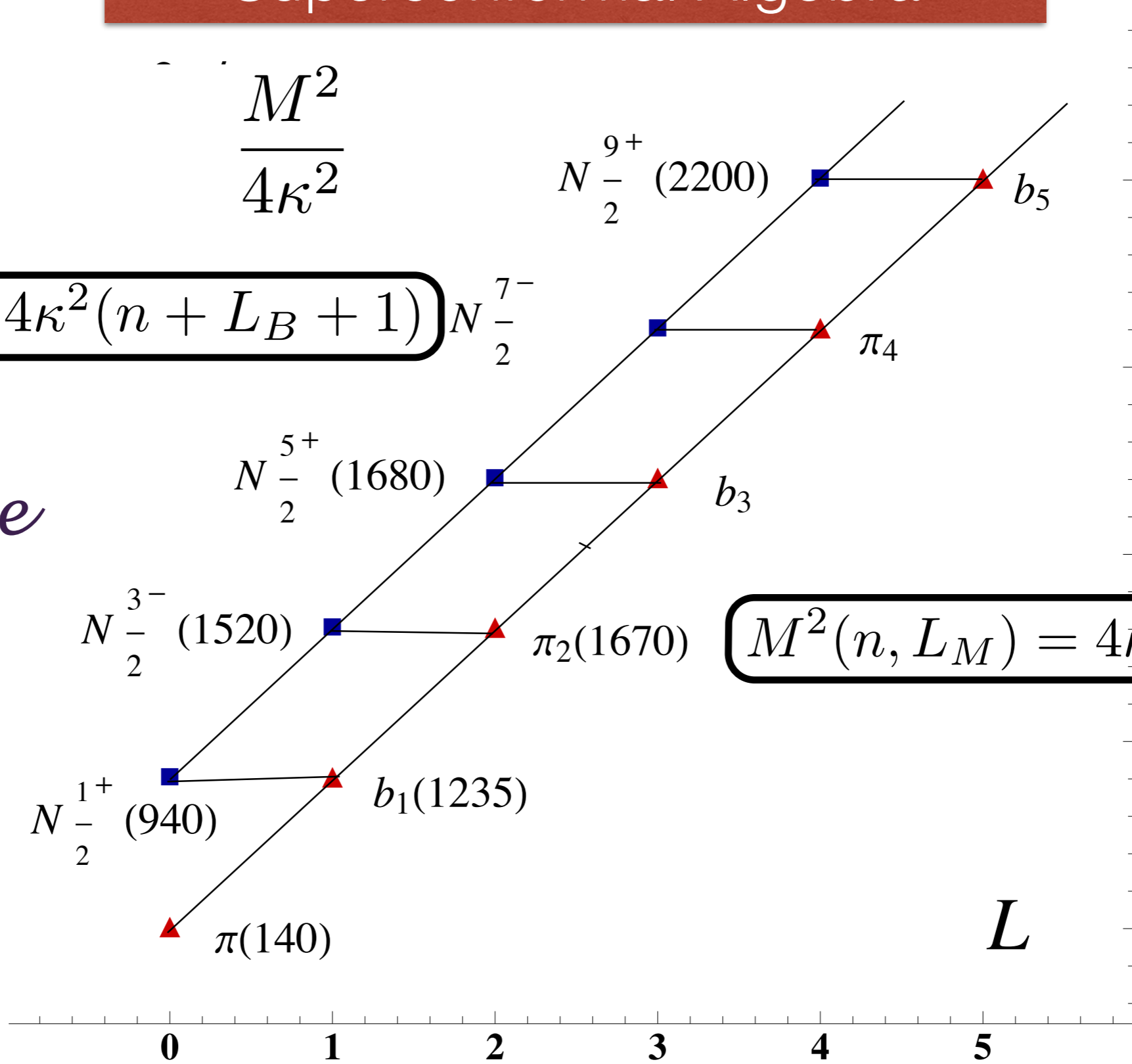
$$\lambda_M^2 = \lambda_B^2 = \kappa^4$$

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

$\lambda = \kappa^2$

$M^2\,(\mathrm{GeV}^2)$

$\lambda_M = \lambda_B$

$\pi_2$

$b_1$

$N\,\frac{1}{2}^-$ $\quad N\,\frac{3}{2}^-$

$N\,\frac{3}{2}^+$ $\quad N\,\frac{5}{2}^+$

$N\,\frac{9}{2}^+$

$N\,\frac{1}{2}^+$

$\pi$

$L_M = L_B + 1$

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

$M^2\,(\mathrm{GeV}^2)$

$\rho - \Delta$ superpartner trajectories

$a_4, f_4$

$\rho_3, \omega_3$

$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$

$\Delta^{\frac{11}{2}^+}$

$a_2, f_2$

$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$

$\Delta^{\frac{3}{2}^+}$

$\rho, \omega$

$L_M = L_B + 1$
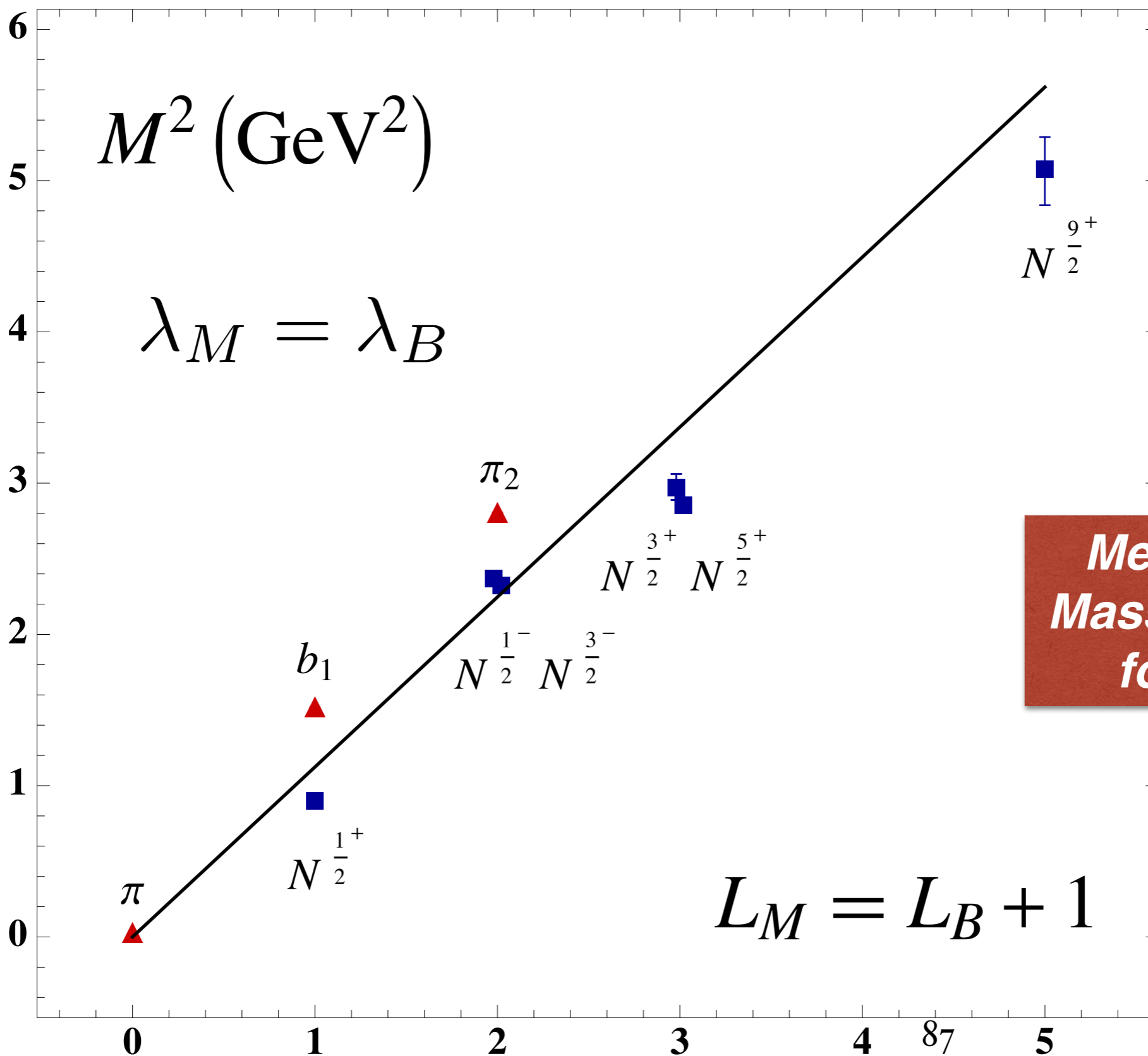
# *Chiral Features of Soft-Wall AdS/QCD Model*

- **Boost Invariant**

- **Trivial LF vacuum! No condensate, but consistent with GMOR**

- **Massless Pion**

- **Hadron Eigenstates (even the pion) have LF Fock components of different $L^z$**

- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S^z_q >= 0$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**

- **Label State by minimum L as in Atomic Physics**

- **Minimum L dominates at short distances**

- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

*No mass -degenerate parity partners!*

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

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

- Baryon spin carried by quark orbital angular momentum:  $\langle J^z \rangle$ =$L^z$+1/2

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

Meson and baryon have the same  $\kappa$ !

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Regge
November 2013.
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**90**

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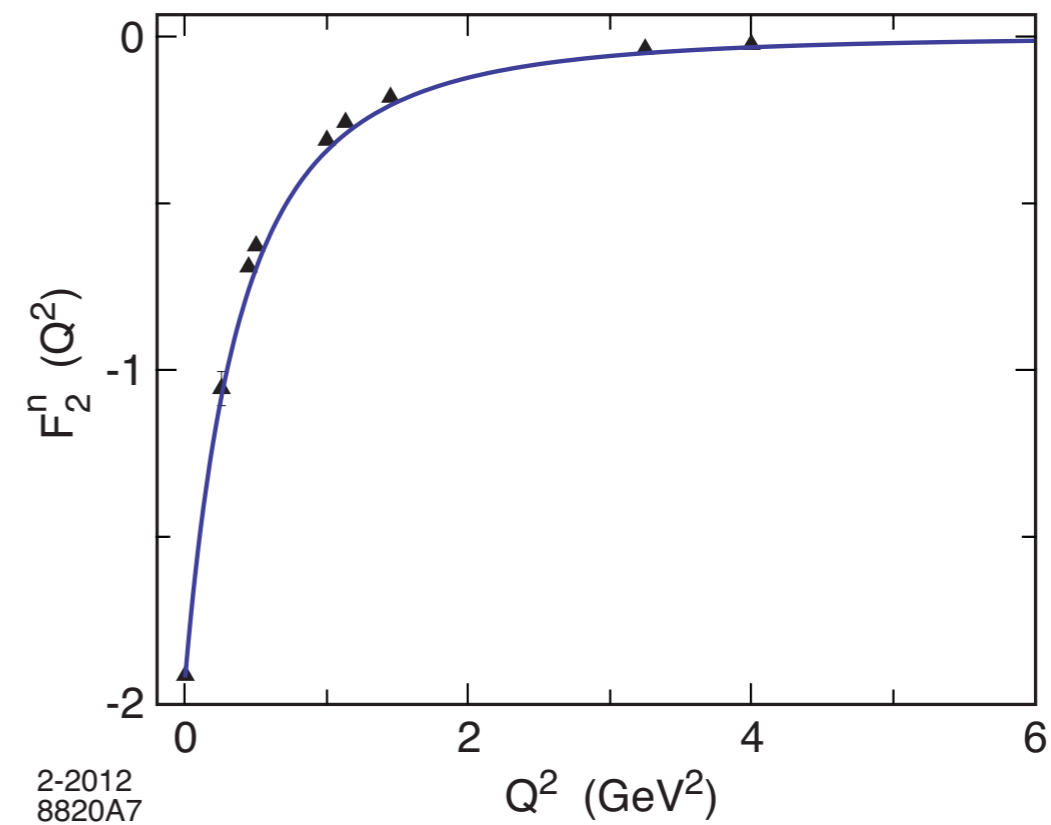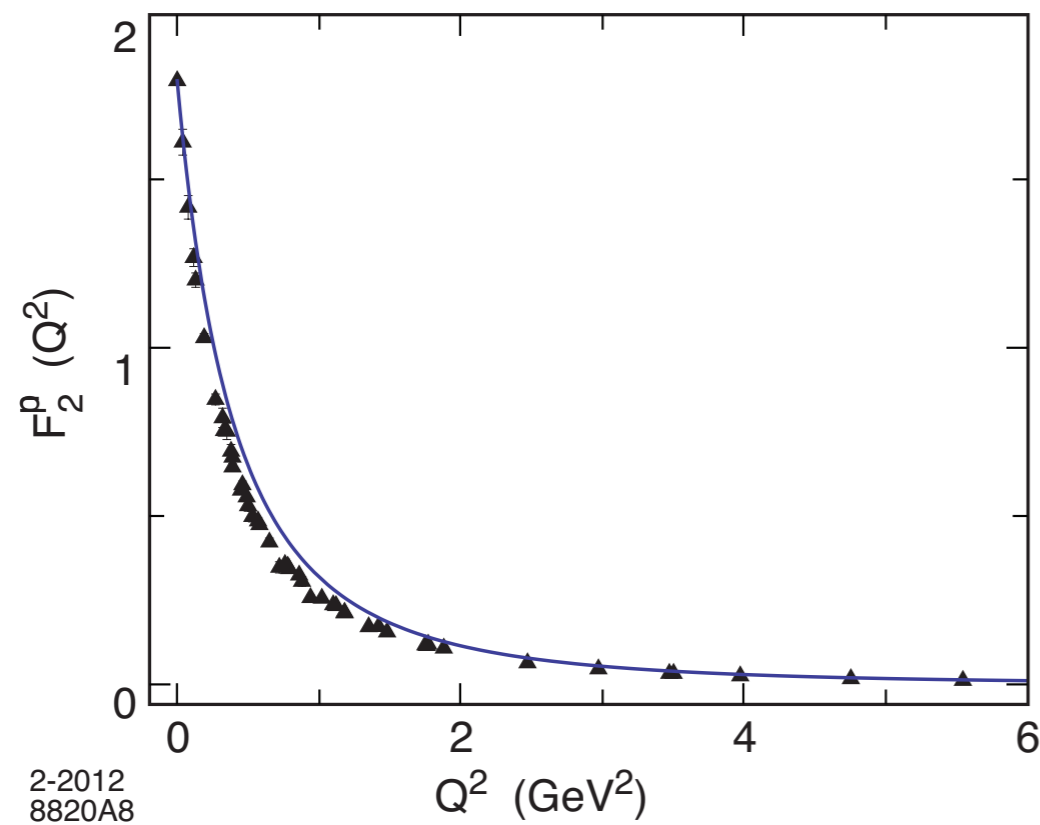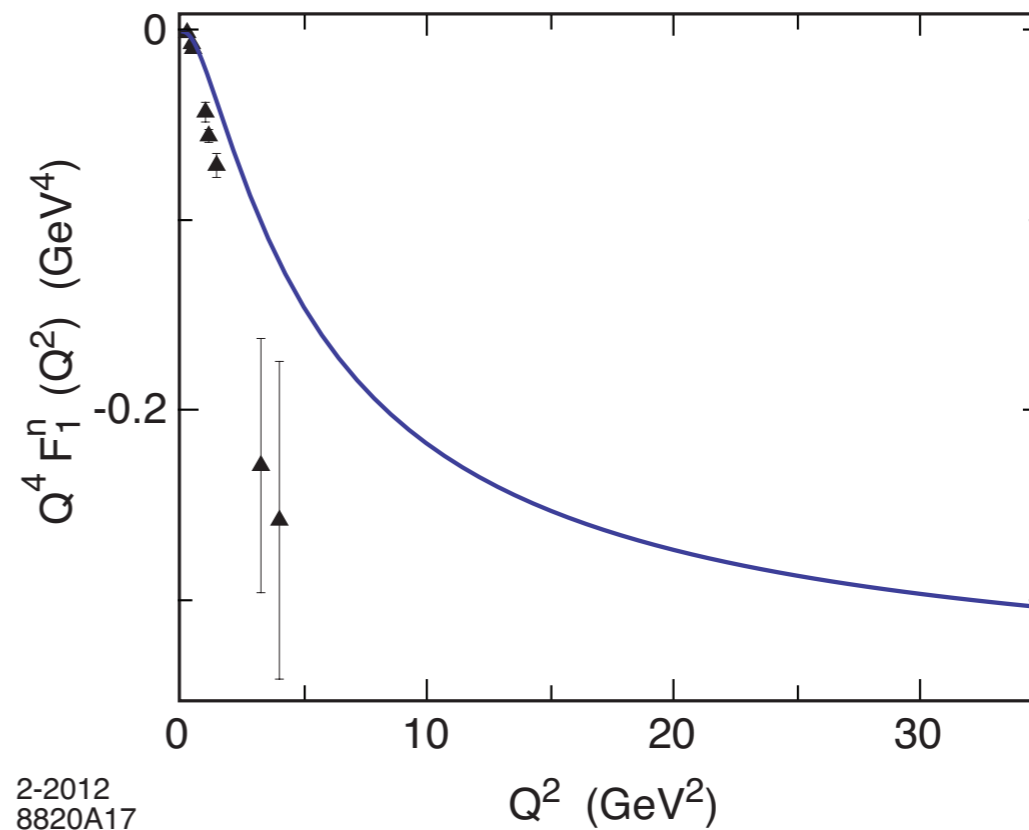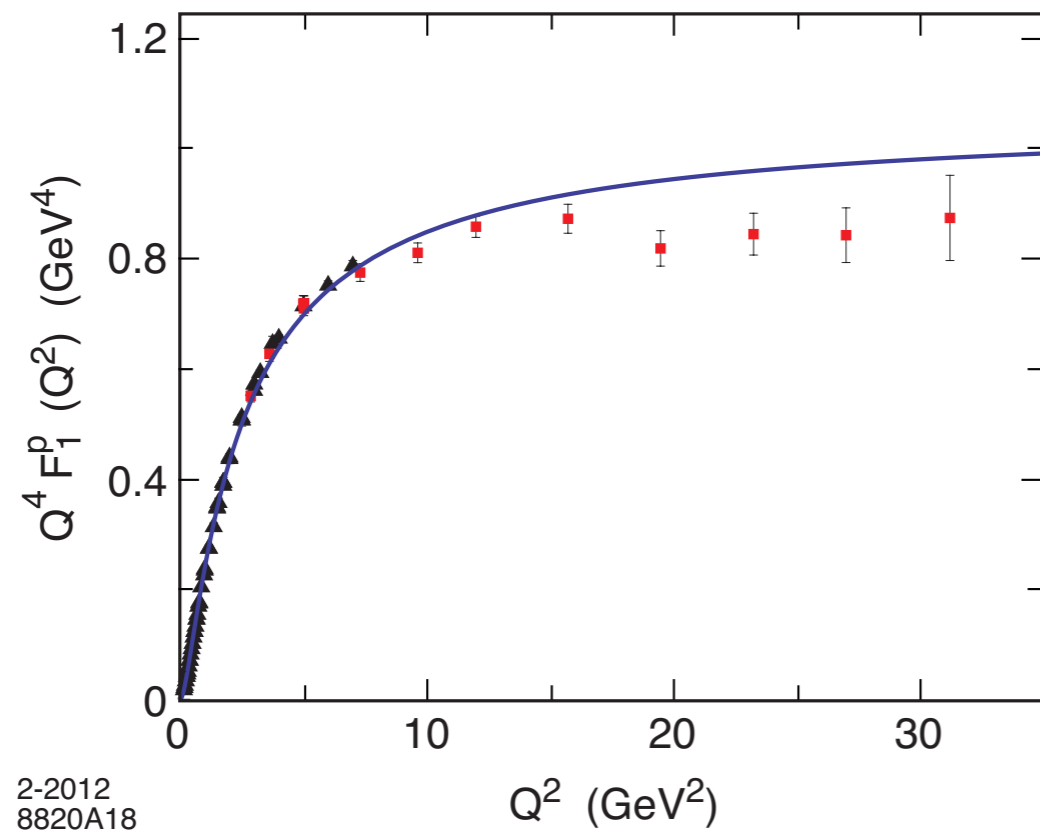
# *Spacelike Pauli Form Factor*

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



**Harmonic Oscillator Confinement Normalized to anomalous moment**

$\kappa = 0.49$ GeV

G. de Teramond, sjb

$F_2^p(Q^2)$

$Q^2(\text{GeV}^2)$
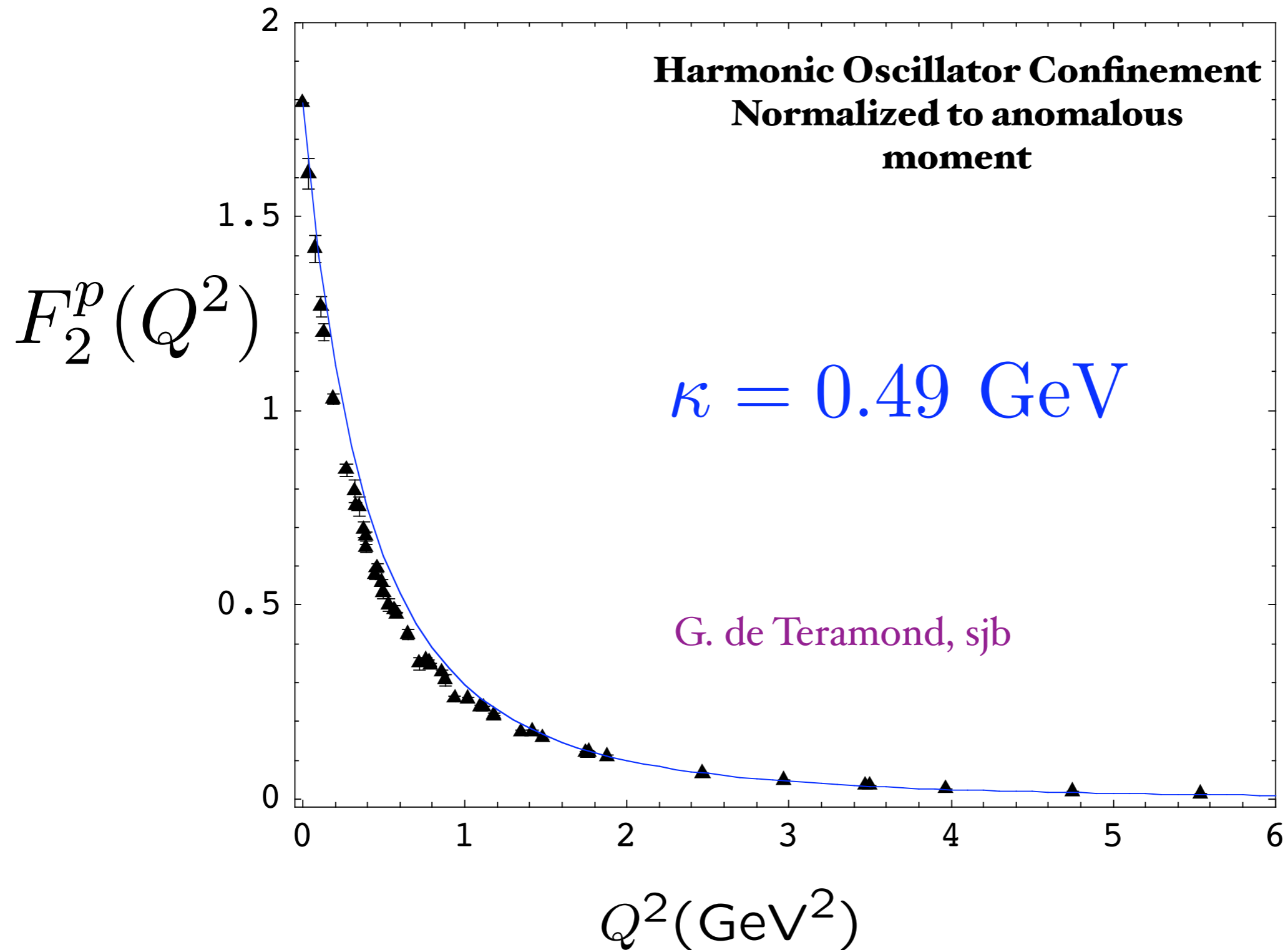
## Excited Baryons in Holographic QCD

**G. de Teramond & sjb**



Top left plot: $Q^4 F_1^p(Q^2)$ versus $Q^2\,\mathrm{GeV}^2$

Top right plot: $F_{1\,N\to N^*}^p(Q^2)$ versus $Q^2\,\mathrm{GeV}^2$

Bottom plot (a): $M^2$ versus $L$, with lines labeled $n=3$, $n=2$, $n=1$, $n=0$; data points N(940), N(1440), N(1710), N(1680), N(1720), N(2200)

Bottom plot (b): $M^2$ versus $L$, with lines labeled $n=3$, $n=2$, $n=1$, $n=0$; data points Δ(1232), Δ(1600), Δ(1950), Δ(1905), Δ(1920), Δ(1910), Δ(2420)

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**93**
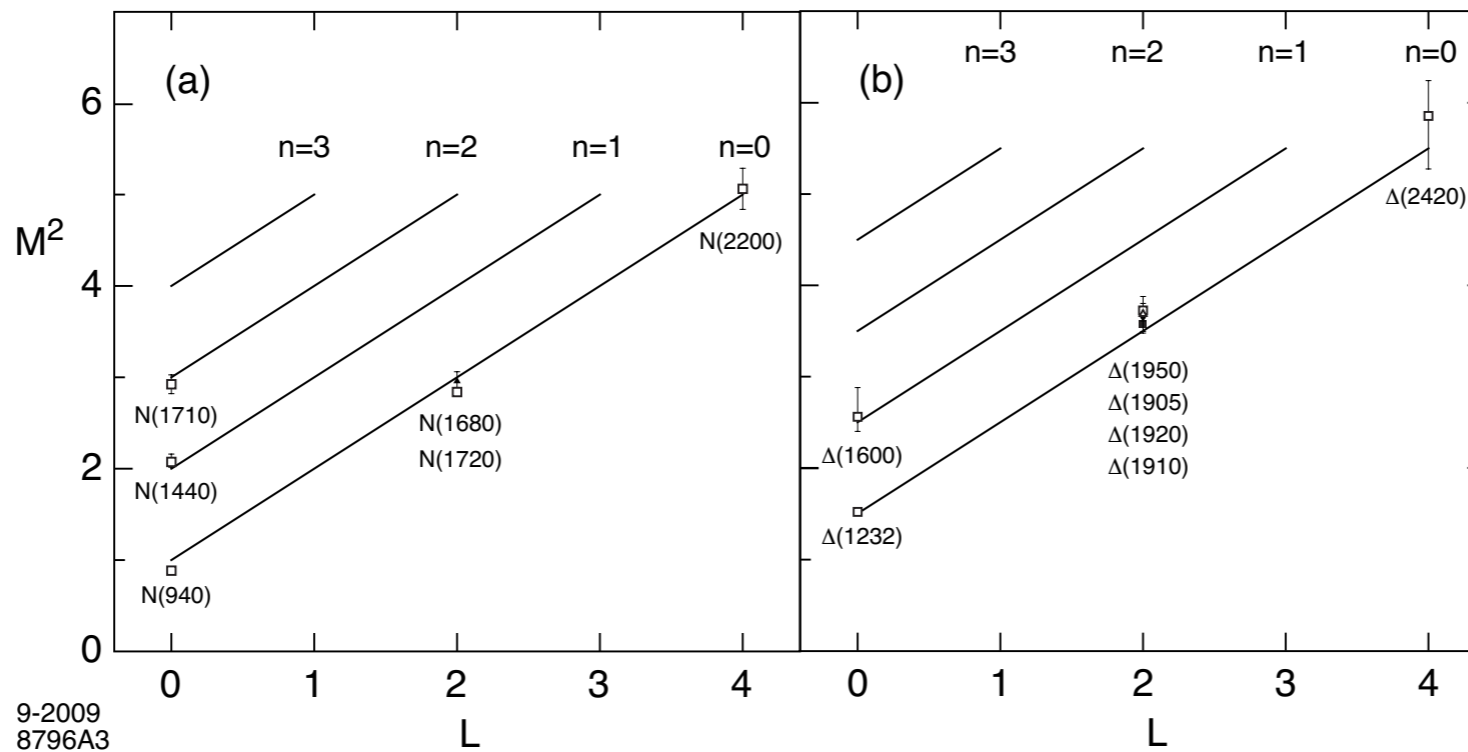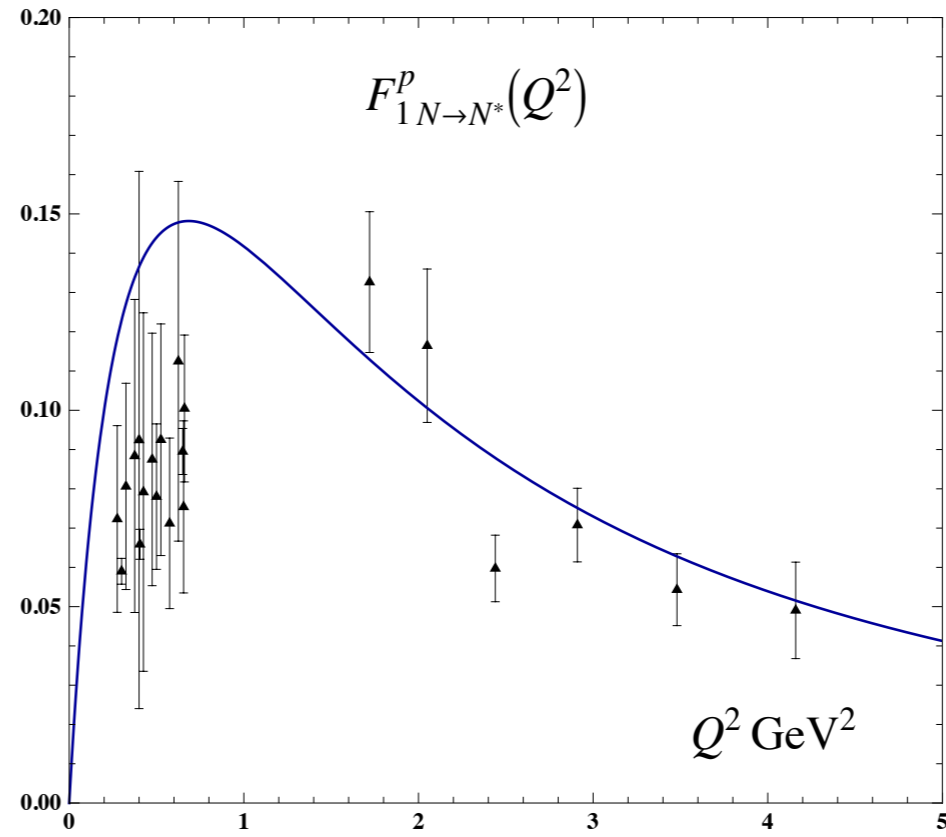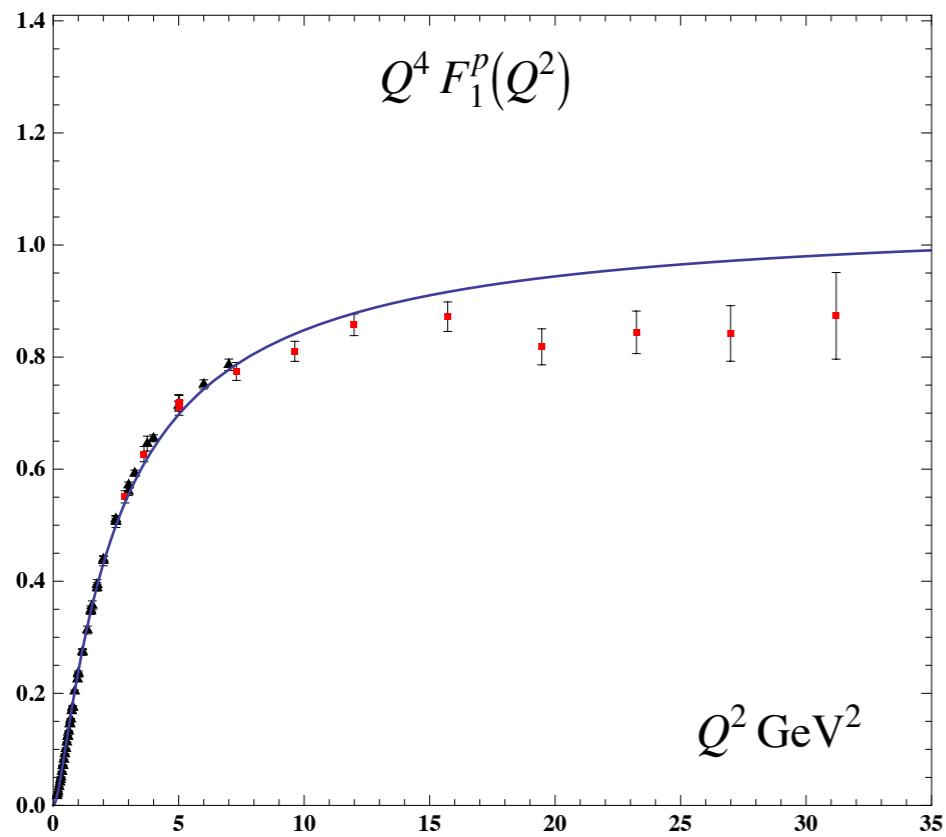
## Nucleon Transition Form Factors

- Compute spin non-flip EM transition $N(940) \to N^*(1440)$:   $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$

- Transition form factor

$$F1_{N \to N^*}^p(Q^2) = R^4 \int \frac{dz}{z^4}\, \Psi_+^{n=1,L=0}(z) V(Q,z) \Psi_+^{n=0,L=0}(z)$$

- Orthonormality of Laguerre functions   $\left( F1_{N \to N^*}^p(0) = 0, \quad V(Q=0,z) = 1 \right)$

$$R^4 \int \frac{dz}{z^4}\, \Psi_+^{n',L}(z) \Psi_+^{n,L}(z) = \delta_{n,n'}$$

- Find

$$F1_{N \to N^*}^p(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

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

de Teramond, sjb

*Consistent with counting rule, twist 3*

## Nucleon Transition Form Factors

$$F^p_{1\,N\to N^*}(Q^2) = \frac{\sqrt{2}}{3} \frac{\frac{Q^2}{\mathcal{M}^2_\rho}}{\left(1 + \frac{Q^2}{\mathcal{M}^2_\rho}\right)\left(1 + \frac{Q^2}{\mathcal{M}^2_{\rho'}}\right)\left(1 + \frac{Q^2}{\mathcal{M}^2_{\rho''}}\right)}.$$



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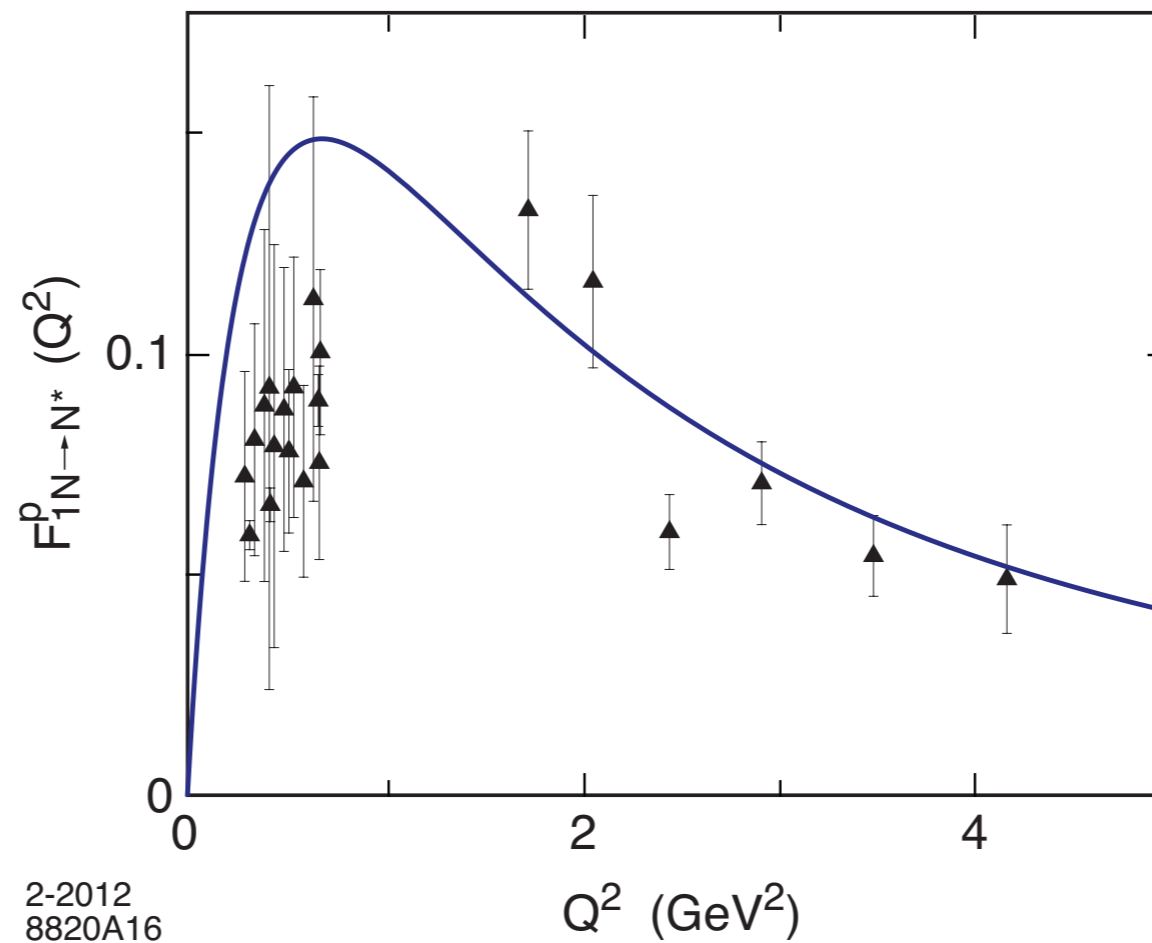
Proton transition form factor to the first radial excited state. Data from JLab

$H^*$

$\bar{H}$

*Dosch, de Teramond, sjb*

$q$

$\bar{q}$

$\gamma^*$

$F_{\gamma^* \to H^* \bar{H}}(s)$

$e^-$

$e^+$
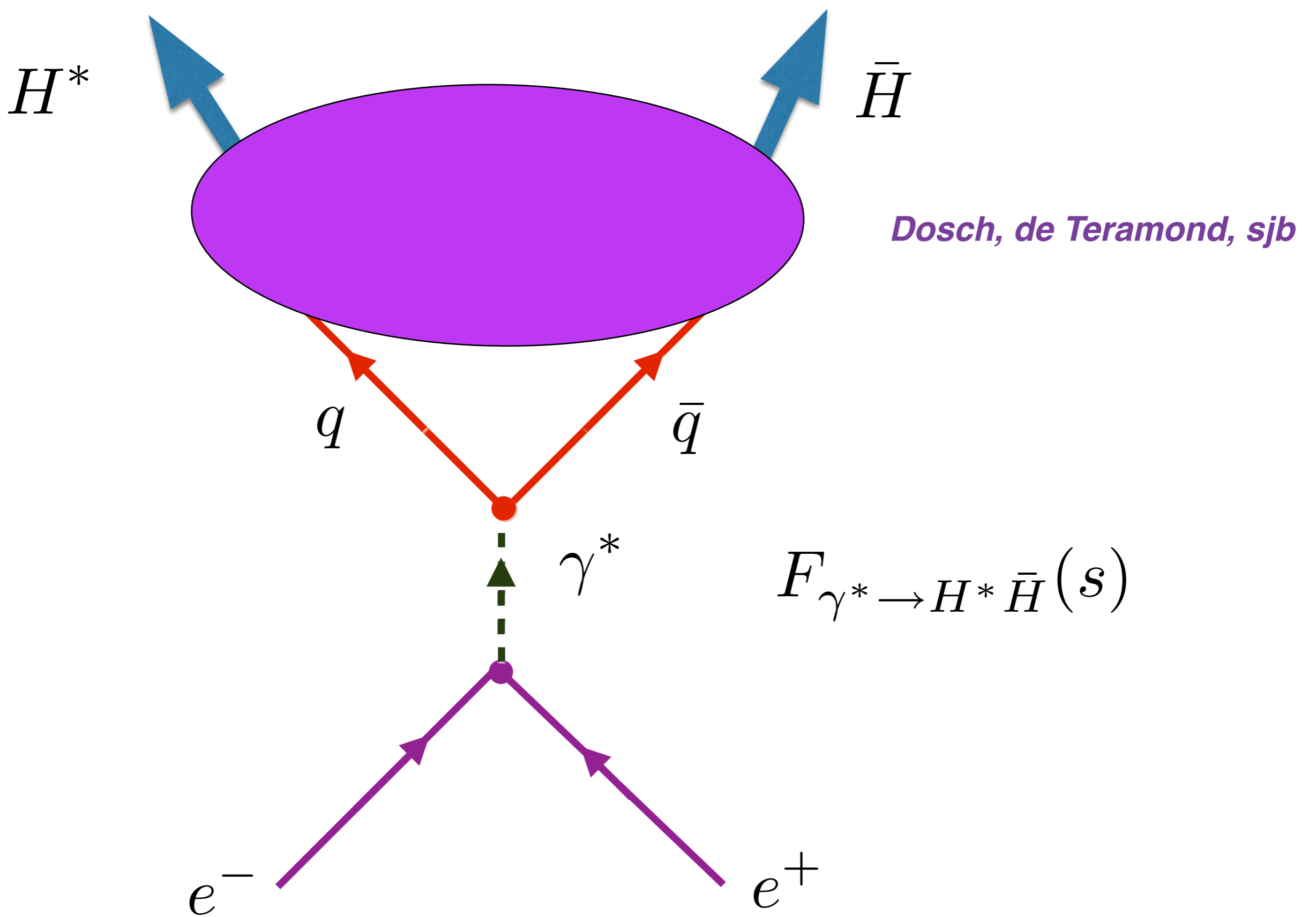
Prediction from Super Conformal AdS/QCD:
Same Form Factors for H= M and H=B if $L_M = L_B + 1$

## 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$_1$**

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# *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 $\alpha_s^{AdS}$ incorporates the non-conformal dynamics of confinement

# Analytic, defined at all scales, IR Fixed Point



$$\alpha_s^{AdS}(Q)/\pi = e^{-Q^2/4\kappa^2}$$

$$\kappa = 0.54 \; GeV$$

Legend:
- ·-··- Modified AdS
- —— AdS
- $\alpha_{g1}/\pi$ (pQCD)
- □ $\alpha_{g1}/\pi$ world data
- ·-·-· GDH limit  ✳ $\alpha_{F3}/\pi$
- ◇ $\alpha_{\tau}/\pi$ OPAL
- ▲ $\alpha_{g1}/\pi$ JLab CLAS
- ■ $\alpha_{g1}/\pi$ Hall A/CLAS
- ● Lattice QCD (2004) ▼ (2007)

$\dfrac{\alpha_s(Q)}{\pi}$

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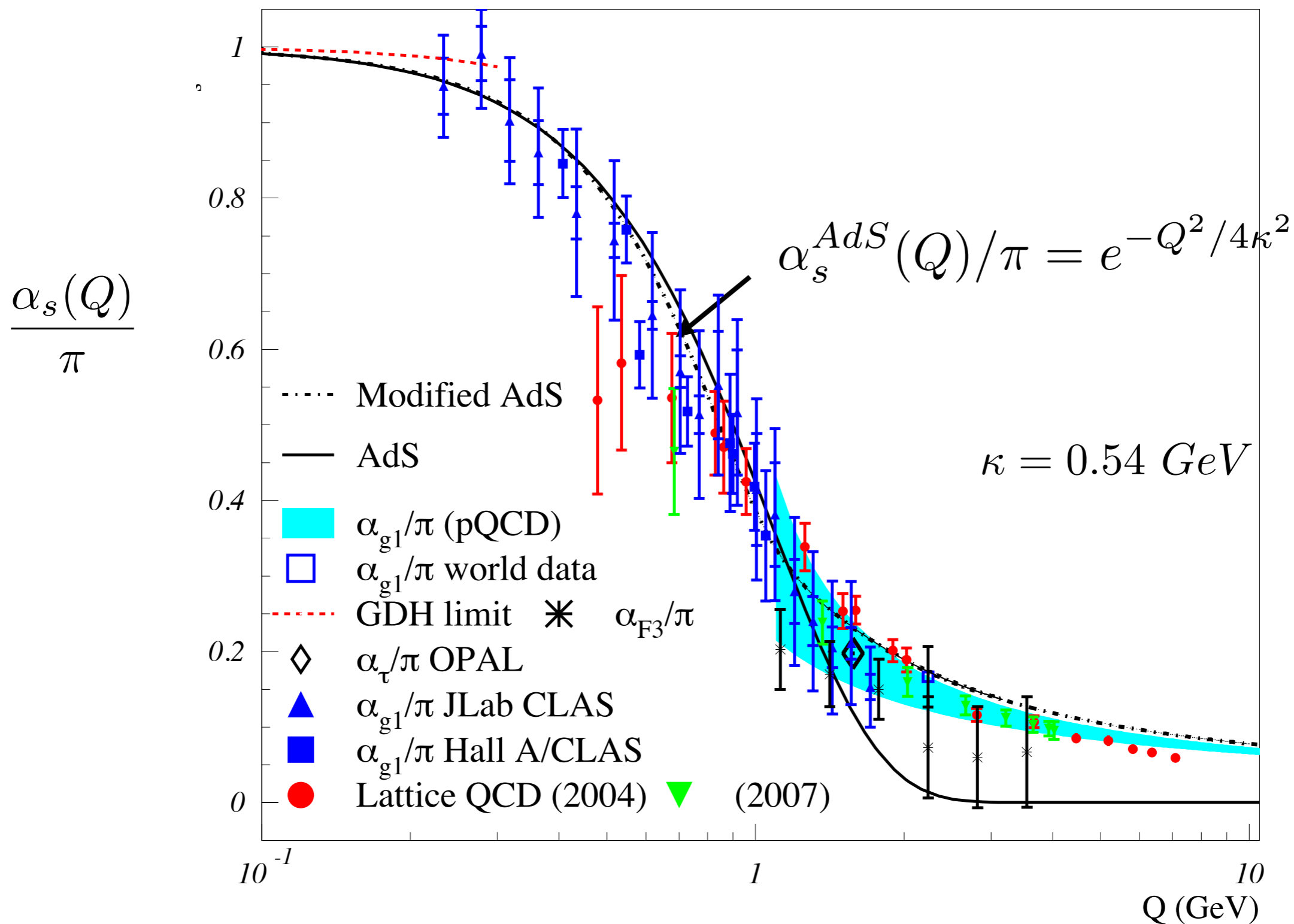
**AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV**

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

**Deur, de Teramond, sjb**

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

$$m_p = 2\kappa$$

**Deur, de Teramond, sjb**

**All-Scale QCD Coupling**

*Nonperturbative QCD
(Quark Confinement)*

Expt:

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

$$e^{-\frac{Q^2}{4\kappa^2}}$$

$$\Lambda_{\overline{MS}} = 0.341 \pm 0.024 \; GeV$$

*Perturbative QCD
(Asymptotic Freedom)*

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.016 \; GeV$$

*Transition scale $Q_0$*

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

$$Q_0^2 = 1.08 \pm 0.17 \; GeV^2$$

Q (GeV)
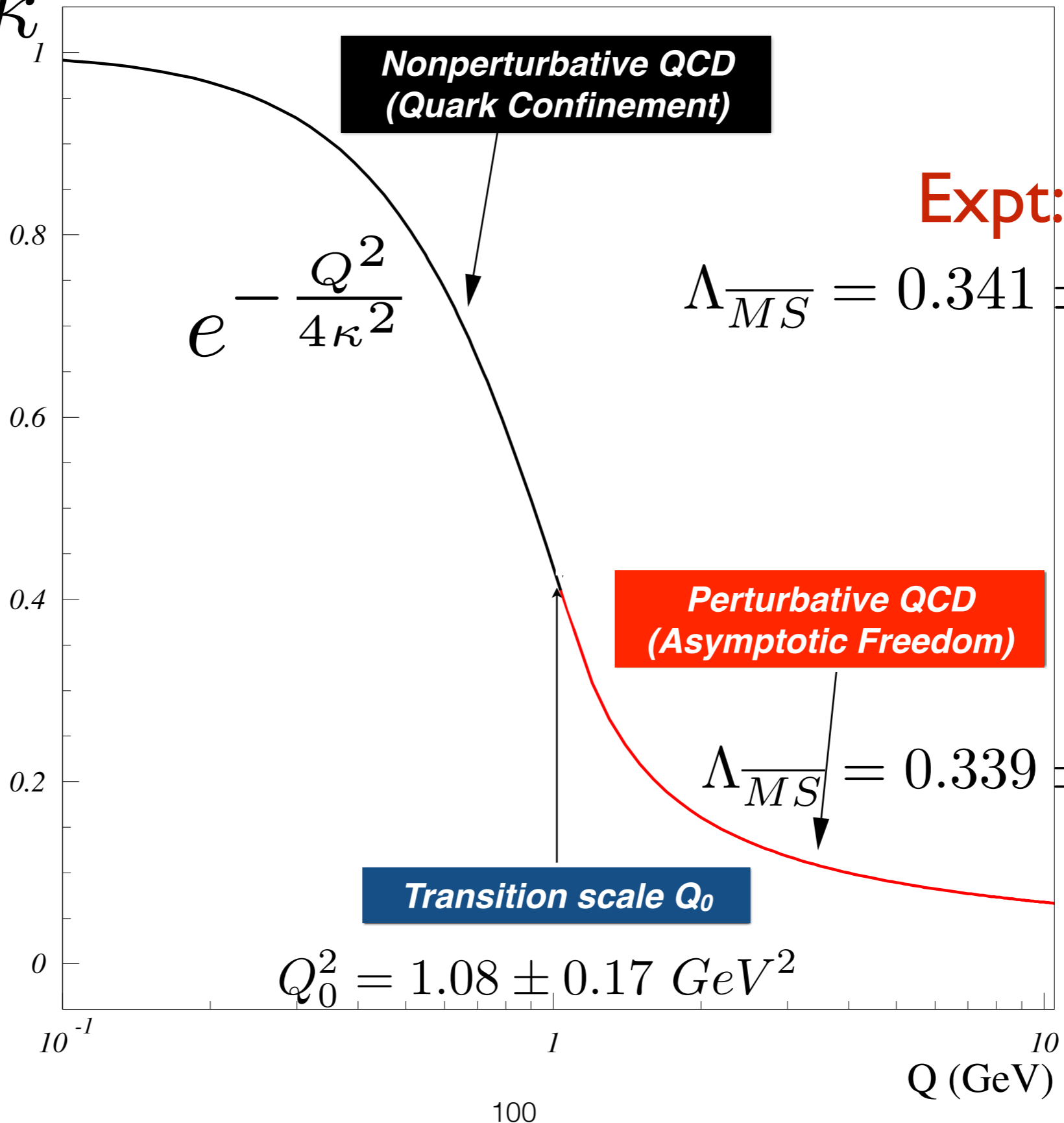
# *Interpretation of Mass Scale $\kappa$*

- Does not affect conformal symmetry of QCD action

- Self-consistent regularization of IR divergences

- Determines all mass and length scales for zero quark mass

- Compute scheme-dependent $\Lambda_{\overline{MS}}$ determined in terms of $\kappa$

- Value of $\kappa$ itself not determined -- place holder

- Need external constraint such as $f_\pi$

# AdS/QCD and Light-Front Holography

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

- **Zero mass pion for $m_q = 0$ (n=J=L=0)**

- **Regge trajectories: equal slope in n and L**

- **Form Factors at high $Q^2$: Dimensional counting** $[Q^2]^{n-1} F(Q^2) \to \text{const}$

- **Space-like and Time-like Meson and Baryon Form Factors**

- **Running Coupling for NPQCD** $\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$

- **Meson Distribution Amplitude** $\phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$

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# *Features of AdS/QCD*

*de Tèramond, Dosch, Deur, sjb*

- **Color confining potential $\kappa^4 \zeta^2$ and universal mass scale from dilaton**
$$e^{\phi(z)} = e^{\kappa^2 z^2} \qquad \alpha_s(Q^2) \propto \exp{-Q^2/4\kappa^2}$$

- **Dimensional transmutation** $\quad \Lambda_{\overline{MS}} \leftrightarrow \kappa \leftrightarrow m_H$

- **Chiral Action remains conformally invariant despite mass scale** *DAFF*

- **Light-Front Holography: Duality of AdS and frame-independent LF QCD**

- **Reproduces observed Regge spectroscopy — same slope in n, L, and J for mesons and baryons**

- **Massless pion for massless quark**

- **Supersymmetric meson-baryon dynamics and spectroscopy: L$_M$=L$_B$+1**

*Superconformal Algebra*
*Fubini and Rabinovici*

- **Dynamics: LFWFs, Form Factors, GPDs**

# An analytic first approximation to QCD

## *AdS/QCD + Light-Front Holography*

- **As Simple as Schrödinger Theory in Atomic Physics**

- **LF radial variable $\zeta$ conjugate to invariant mass squared**

- **Relativistic, Frame-Independent, Color-Confining**

- **Unique confining potential!**

- **QCD Coupling at all scales: Essential for Gauge Link phenomena**

- **Hadron Spectroscopy and Dynamics from one parameter**

- **Wave Functions, Form Factors, Hadronic Observables, Constituent Counting Rules**

- **Insight into QCD Condensates: Zero cosmological constant!**

- **Systematically improvable with DLCQ-BLFQ Methods**

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*de Tèramond, Dosch, Lorce, sjb*

# *Future Directions for AdS/QCD*

- **Hadronization at the Amplitude Level**

- **Diffractive dissociation of pion and proton to jets**

- **Identify the factorization Scale for ERBL, DGLAP evolution: $Q_0$**

- **Compute Tetraquark Spectroscopy Sequentially**

- **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**

We view the universe
as light reaches us
along the light-front
at fixed

$$\tau = t + z/c$$
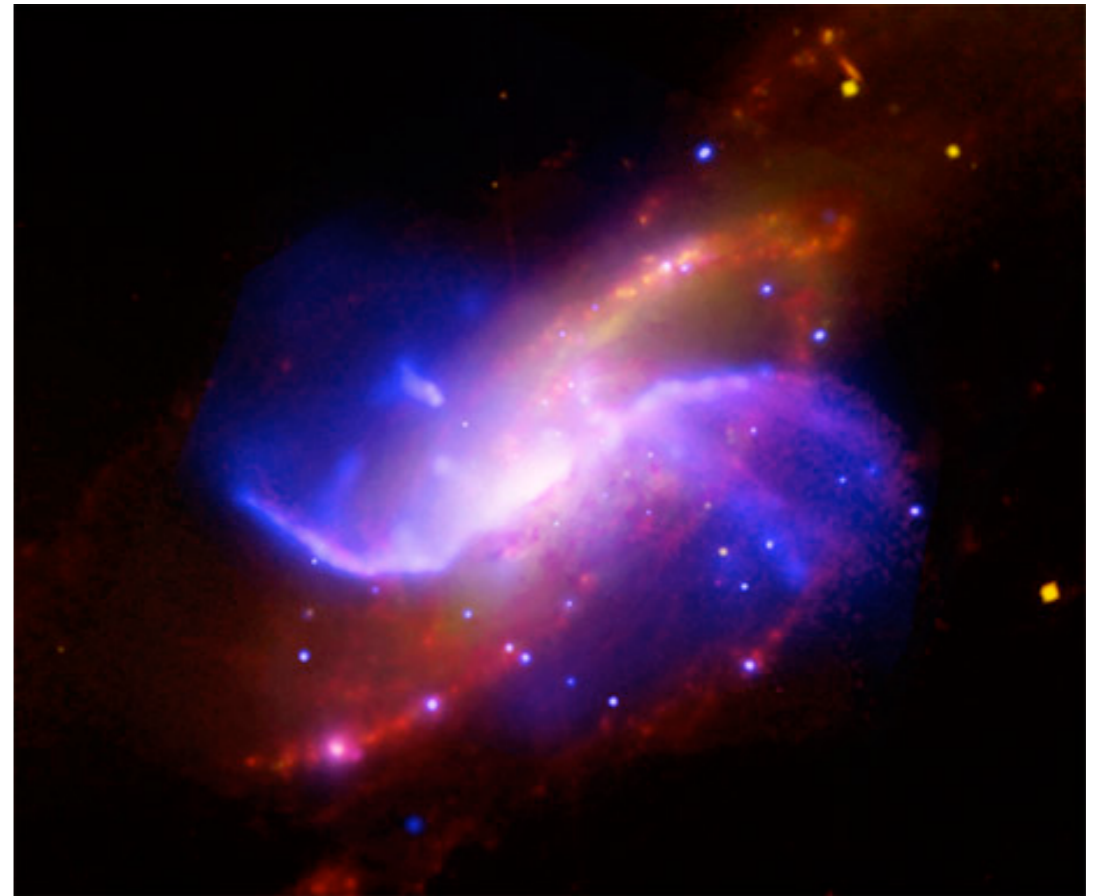
*Front Form Vacuum Describes the Empty, Causal Universe*

# *"One of the gravest puzzles of theoretical physics"*

## DARK ENERGY AND
## THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE

*Department of Physics, University of California, Santa Barbara, CA 93106, USA*
*Kavli Institute for Theoretical Physics, University of California,*
*Santa Barbara, CA 93106, USA*
*zee@kitp.ucsb.edu*

$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$\Omega_\Lambda = 0.76 (expt)$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

*Extraordinary conflict between the conventional definition of the vacuum in quantum field theory and cosmology*

*Elements of the solution:*
*(A) Light-Front Quantization: causal, frame-independent vacuum*
*(B) New understanding of QCD "Condensates"*
*(C) Higgs Light-Front Zero Mode*

# *Two Definitions of Vacuum State*

**Instant Form: Lowest Energy Eigenstate of Instant-Form Hamiltonian**

$$H|\psi_0 > = E_0|\psi_0 >, E_0 = min\{E_i\}$$

*Eigenstate defined at one time t over all space; Acausal! Frame-Dependent*

**Front Form: Lowest Invariant Mass Eigenstate of Light-Front Hamiltonian**

$$H_{LF}|\psi_0 >_{LF} = M_0^2|\psi_0 >_{LF}, M_0^2 = 0.$$

*Frame-independent eigenstate at fixed LF time τ = t+z/c within causal horizon*

*Frame-independent description of the causal physical universe!*

# *Light-Front vacuum can simulate empty universe*

**Shrock, Tandy, Roberts, sjb**

- **Independent of observer frame**

- **Causal**

- **Lowest invariant mass state M= 0.**

- **Trivial up to $k^+=0$ zero modes-- already normal-ordering**

- **Higgs theory consistent with trivial LF vacuum (Srivastava, sjb)**

- **QCD and AdS/QCD: "In-hadron"condensates (Maris, Tandy Roberts) -- GMOR satisfied.**

- **QED vacuum; no loops**

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- **Zero cosmological constant from QED, QCD**

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# *Standard Model on the Light-Front*

- **Same phenomenological predictions**

- **Higgs field has three components**

- **Real part creates Higgs particle**

- **Imaginary part (Goldstone) become longitudinal components of W, Z**

- *Higgs VEV of instant form becomes $k^+=0$ LF zero mode!*

- **Analogous to a background static classical Zeeman or Stark Fields**

- **Zero contribution to $T_{\mu\nu}$; zero coupling to gravity**

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# *Goals*

- **Test QCD to maximum precision at the LHC**

- **Maximize sensitivity to new physics**

- **High precision determination of fundamental parameters**

- **Determine renormalizations scales without ambiguity**

- **Eliminate scheme dependence**

**Predictions for physical observables cannot depend on theoretical conventions such as the renormalization scheme**

# *Electron-Electron Scattering in QED*

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

- **Two separate physical scales: t, u = photon virtuality**

- **Gauge Invariant.  Dressed photon propagator**

- **Sums all vacuum polarization, non-zero beta terms into running coupling.  This is the purpose of the running coupling!**

- **If one chooses a different initial scale, one must sum an infinite number of graphs -- but always recover same result!**

- **Number of active leptons correctly set**

- **Analytic: reproduces correct behavior at lepton mass thresholds**

- **No renormalization scale ambiguity!**
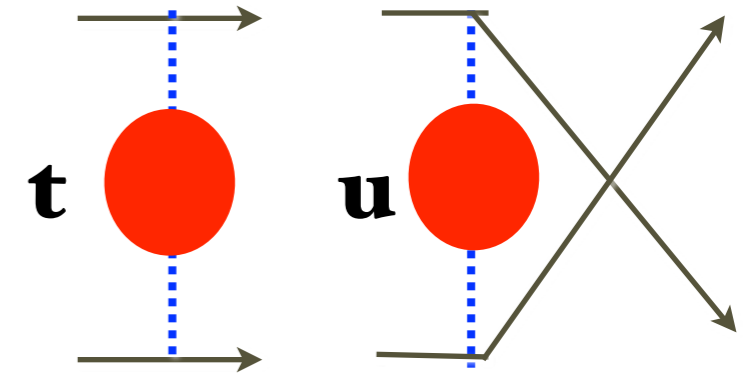
# $\delta$-$\mathcal{R}$enormalization Scheme ( $\mathcal{R}_\delta$ scheme)

In dim. reg. $1/\epsilon$ poles come in powers of [Bollini & Gambiagi, 't Hooft & Veltman, '72]

$$\ln \frac{\mu^2}{\Lambda^2} + \frac{1}{\epsilon} + c$$

In the modified minimal subtraction scheme (MS-bar) one subtracts together with the pole a constant [Bardeen, Buras, Duke, Muta (1978) on DIS results]:

$$\ln(4\pi) - \gamma_E$$

This corresponds to a shift in the scale:

$$\mu_{\overline{\mathrm{MS}}}^2 = \mu^2 \exp(\ln 4\pi - \gamma_E)$$

A finite subtraction from infinity is arbitrary. *Let's make use of this!*

Subtract an arbitrary constant and keep it in your calculation: $\mathcal{R}_\delta$-scheme

**M. Mojaza, Xing-Gang Wu, sjb**
$$\ln(4\pi) - \gamma_E - \delta;$$

$$\mu_\delta^2 = \mu_{\overline{\mathrm{MS}}}^2 \exp(-\delta) = \mu^2 \exp(\ln 4\pi - \gamma_E - \delta)$$

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113

# Exposing the Renormalization Scheme Dependence

Observable in the $\mathcal{R}_\delta$-scheme:

$$\rho_\delta(Q^2) = r_0 + r_1 a(\mu) + [r_2 + \beta_0 r_1 \delta]a(\mu)^2 + [r_3 + \beta_1 r_1 \delta + 2\beta_0 r_2 \delta + \beta_0^2 r_1 \delta^2]a(\mu)^3 + \cdots$$

$$\mathcal{R}_0 = \overline{\mathrm{MS}} , \quad \mathcal{R}_{\ln 4\pi - \gamma_E} = \mathrm{MS} \qquad \mu^2 = \mu_{\overline{\mathrm{MS}}}^2 \, \exp(\ln 4\pi - \gamma_E) , \quad \mu_{\delta_2}^2 = \mu_{\delta_1}^2 \, \exp(\delta_2 - \delta_1)$$

Note the divergent 'renormalon series'   $n! \beta^n \alpha_s^n$

Renormalization Scheme Equation

$$\frac{d\rho}{d\delta} = -\beta(a)\frac{d\rho}{da} \overset{!}{=} 0 \quad \longrightarrow \mathrm{PMC}$$

$$\rho_\delta(Q^2) = r_0 + r_1 a_1(\mu_1) + (r_2 + \beta_0 r_1 \delta_1)a_2(\mu_2)^2 + [r_3 + \beta_1 r_1 \delta_1 + 2\beta_0 r_2 \delta_2 + \beta_0^2 r_1 \delta_1^2]a_3(\mu_3)^3$$

The $\delta_k^p a^n$-term indicates the term associated to a diagram with $1/\epsilon^{n-k}$ divergence for any $p$. Grouping the different $\delta_k$-terms, one recovers in the $N_c \to 0$ Abelian limit the dressed skeleton expansion.

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# Special Degeneracy in PQCD

There is nothing special about a particular value for $\delta$, thus for any $\delta$

$$\rho(Q^2) = r_{0,0} + r_{1,0}a(Q) + [r_{2,0} + \beta_0 r_{2,1}]a(Q)^2 + [r_{3,0} + \beta_1 r_{2,1} + 2\beta_0 r_{3,1} + \beta_0^2 r_{3,2}]a(Q)^3$$
$$+ [r_{4,0} + \beta_2 r_{2,1} + 2\beta_1 r_{3,1} + \frac{5}{2}\beta_1\beta_0 r_{3,2} + 3\beta_0 r_{4,1} + 3\beta_0^2 r_{4,2} + \beta_0^3 r_{4,3}]a(Q)^4$$

According to the principal of maximum conformality we must set the scales such to absorb all 'renormalon-terms', i.e. non-conformal terms
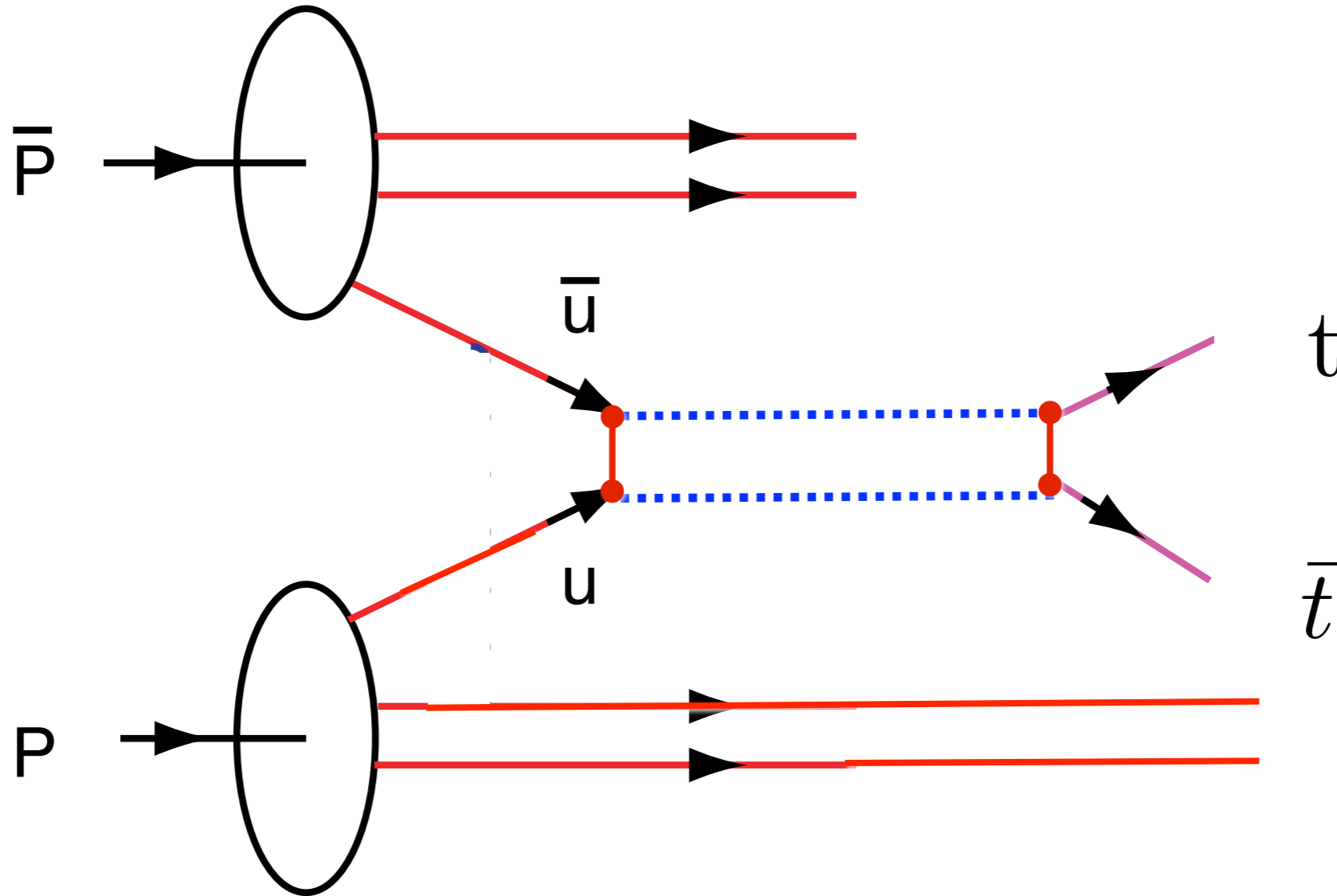
$$\rho(Q^2) = r_{0,0} + r_{1,0}a(Q) + (\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \beta_2 a(Q)^4 + \cdots)r_{2,1}$$
$$+ (\beta_0^2 a(Q)^3 + \frac{5}{2}\beta_1\beta_0 a(Q)^4 + \cdots)r_{3,2} + (\beta_0^3 + \cdots)r_{4,3}$$
$$+ r_{2,0}a(Q)^2 + 2a(Q)(\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \cdots)r_{3,1}$$
$$+ \cdots$$

$$r_{1,0}a(Q_1) = r_{1,0}a(Q) - \beta(a)r_{2,1} + \frac{1}{2}\beta(a)\frac{\partial\beta}{\partial a}r_{3,2} + \cdots + \frac{(-1)^n}{n!}\frac{d^{n-1}\beta}{(d\ln\mu^2)^{n-1}}r_{n+1,n}$$

$$r_{2,0}a(Q_2)^2 = r_{2,0}a(Q)^2 - 2a(Q)\beta(a)r_{3,1} + \cdots$$

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# 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*
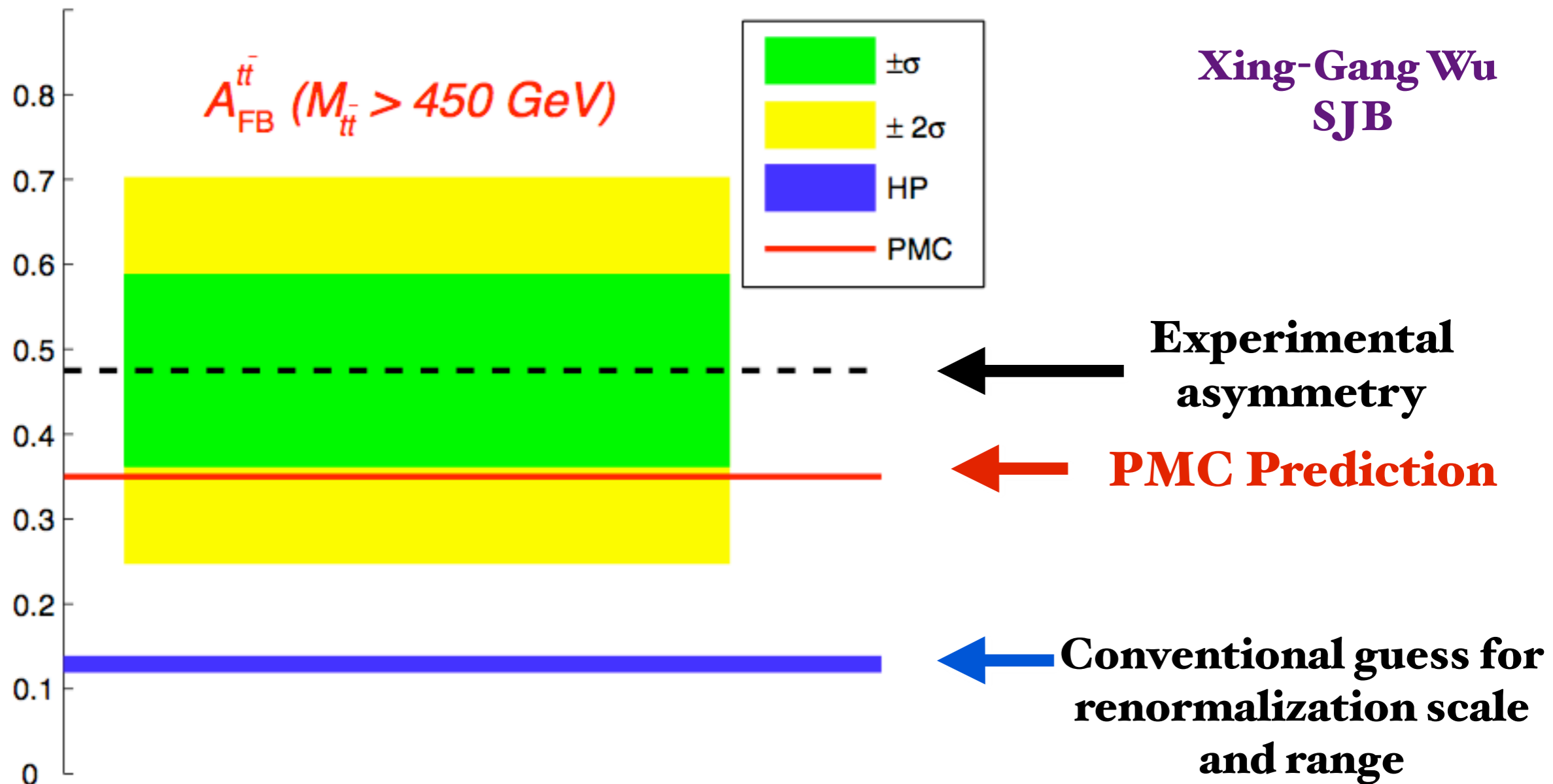
Xing-Gang Wu, sjb

Stan Brodsky

# The Renormalization Scale Ambiguity for Top-Pair Production Eliminated Using the 'Principle of Maximum Conformality' (PMC)



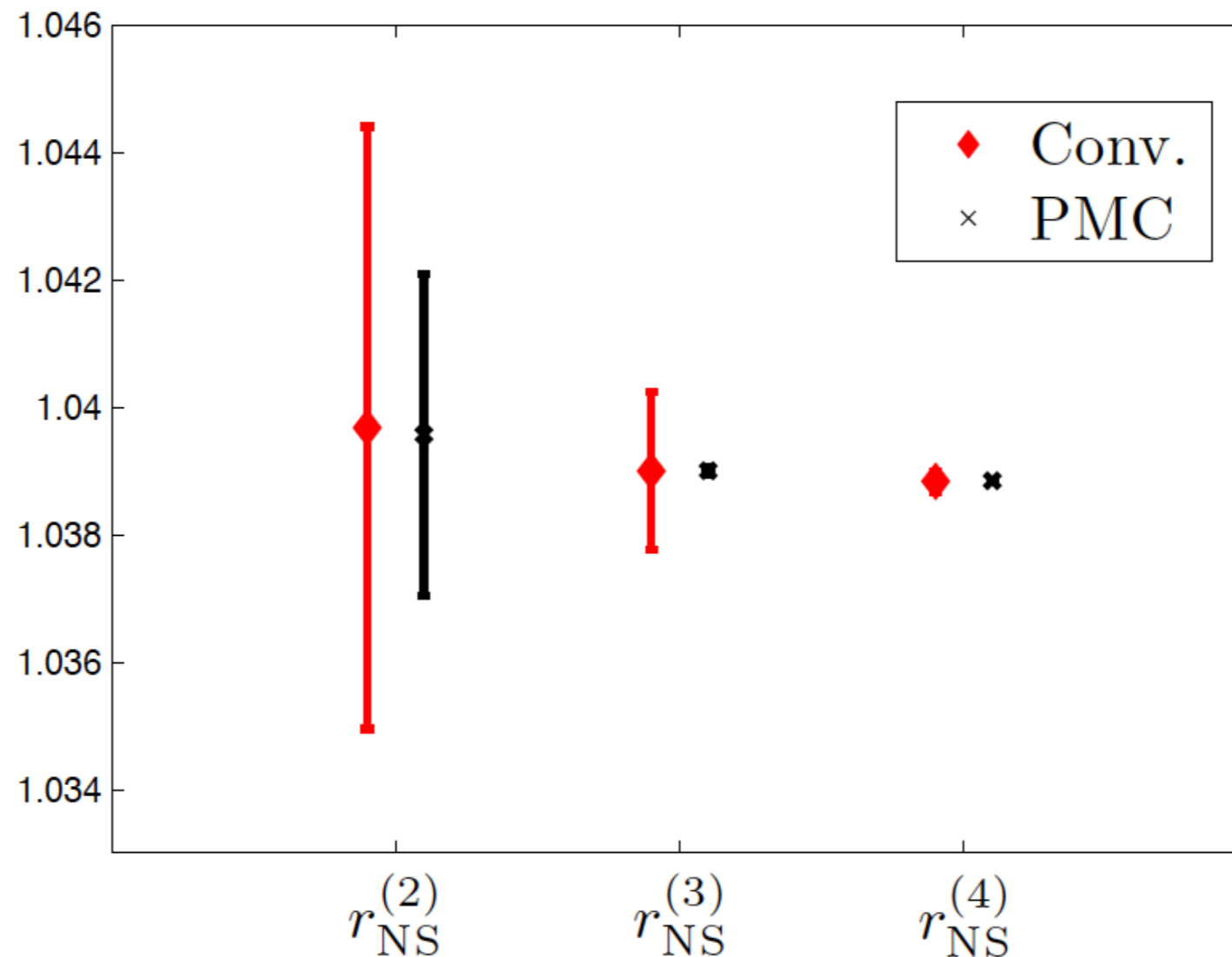$A^{t\bar{t}}_{FB}\ (M_{t\bar{t}} > 450\ GeV)$

**Xing-Gang Wu**
**SJB**

Legend:
- $\pm\sigma$
- $\pm 2\sigma$
- HP
- PMC

Experimental asymmetry

**PMC Prediction**

**Conventional guess for renormalization scale and range**

*Top quark forward-backward asymmetry predicted by pQCD NNLO within 1 σ of CDF/D0 measurements using PMC/BLM scale setting*

S-Q Wang, X-G Wu, sjb

The values of $r_{\mathrm{NS}}^{(n)} = 1 + \sum_{i=1}^{n} C_i^{\mathrm{NS}} a_s^i$ and their errors $\pm |C_n^{\mathrm{NS}} a_s^n|_{\mathrm{MAX}}$. The diamonds and the crosses are for conventional (Conv.) and PMC scale settings, respectively. The central values assume the initial scale choice $\mu_r^{\mathrm{init}} = M_Z$.

# What is PMC ?

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

*Choose* $\mu_R^{\text{init}}$; *arbitrary initial renormalization scale*

*Identify* $\{\beta_i^R\}$ *– terms using* $n_f$ *– terms through the* $PMC - BLM$ *correspondence principle*

order-by-order

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

*Conformal Series*

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

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

PMC–BLM – one

Phys. Rev. Lett. **109**, 042002 (2012)

$R_\delta$–scheme – two

Phys. Rev. Lett. **110**, 192001 (2013)

Eliminate β–terms

***$n_f$ dependence of pQCD series does not uniquely identify the β terms***

119

## Features of BLM/PMC

- **Predictions are scheme-independent**

- **Matches conformal series**

- **Commensurate Scale Relations between observables: Generalized Crewther Relation (Kataev, Lu, Rathsman, sjb)**

- **No n! Renormalon growth**

- **New scale at each order; $n_F$ determined at each order**

- **Multiple Physical Scales Incorporated**

- **Rigorous: Satisfies all Renormalization Group Principles**

- **Realistic Estimate of Higher-Order Terms**

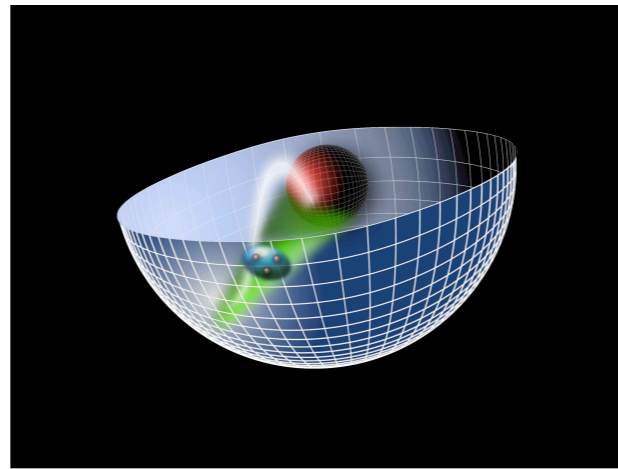- **Eliminates unnecessary theory error**

- **Anti-Shadowing is Universal**

- **ISI and FSI are higher twist effects and universal**

- **High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!**

- **Heavy quarks only from gluon splitting**

- **Renormalization scale cannot be fixed**

- **QCD condensates are vacuum effects**

- **QCD gives $10^{42}$ to the cosmological constant**

September 21 2013

LC2014 Registration opens October 1, 2013

LC2014-Raleigh was formally approved at the ILCAC Meeting in

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*de Tèramond, Dosch, sjb*



**AdS/QCD Soft-Wall Model**

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

**Light-Front Holography**

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

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

**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*

$$\kappa \simeq 0.6 \ GeV$$

**Confinement scale:**

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

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

● **de Alfaro, Fubini, Furlan:**

● **Fubini, Rabinovici:**

# New Perspectives for Hadron Physics

Fixed $\tau = t + z/c$

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7th Workshop on Hadron Physics in China and Opportunities Worldwide