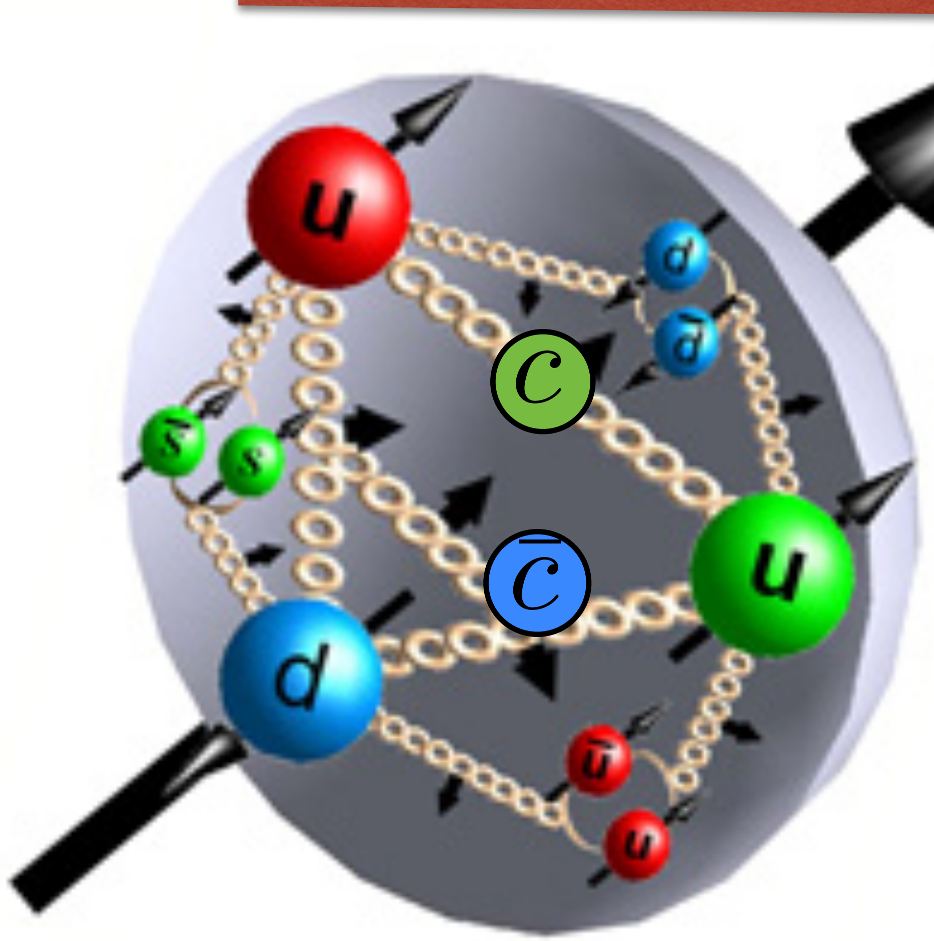
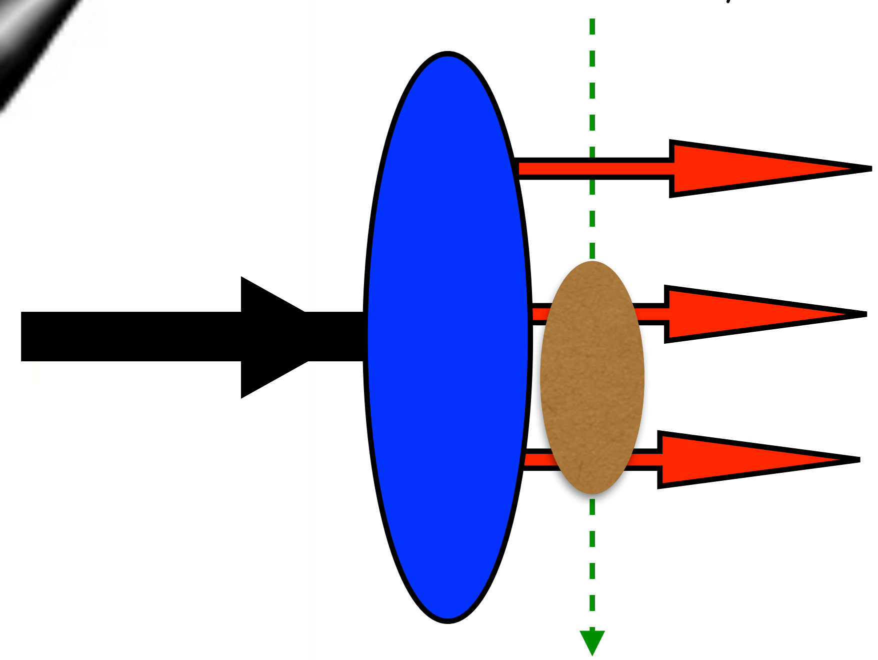
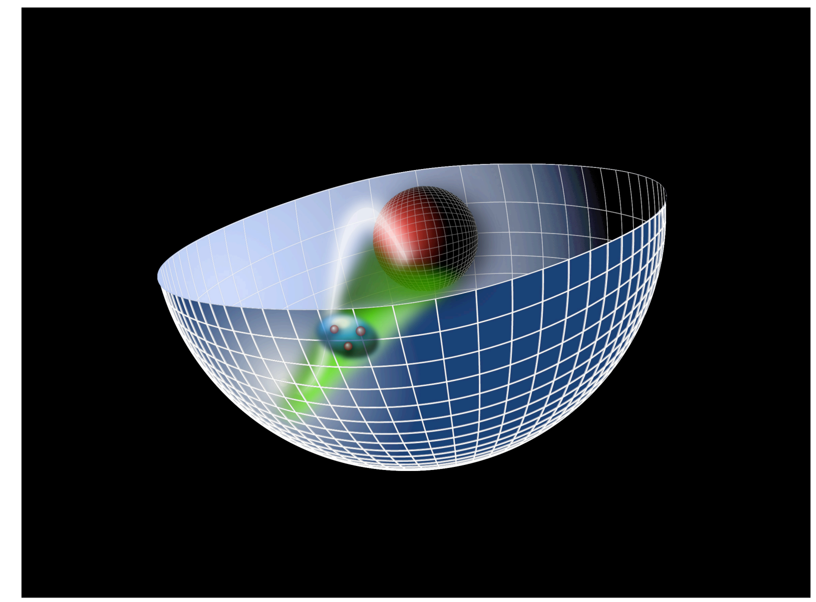
Supersymmetric Properties of Hadron Physics, Color Transparency, Intrinsic Heavy Quarks, and other Novel Features of QCD



Fixed $\tau = t + z/c$





|p>=|u[ud]> quark-diquark cluster

with Guy de Tèramond, Hans Günter Dosch, Marina Nielsen, Ivan Schmidt, F. Navarra, Jennifer Rittenhouse West, G. Miller, Keh-Fei Liu, Tianbo LIu, Liping Zou, S. Groote, S. Koshkarev, Xing-Gang Wu, Sheng-Quan Wang, Cedric Lorcè, R. S. Sufian, A. Deur, R. Vogt, G. Lykasov, S. Gardner, S. Liuti

INSTITUTE for NUCLEAR THEORY

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY · DIE LUFT DER FREIHEIT WEHT · 1891

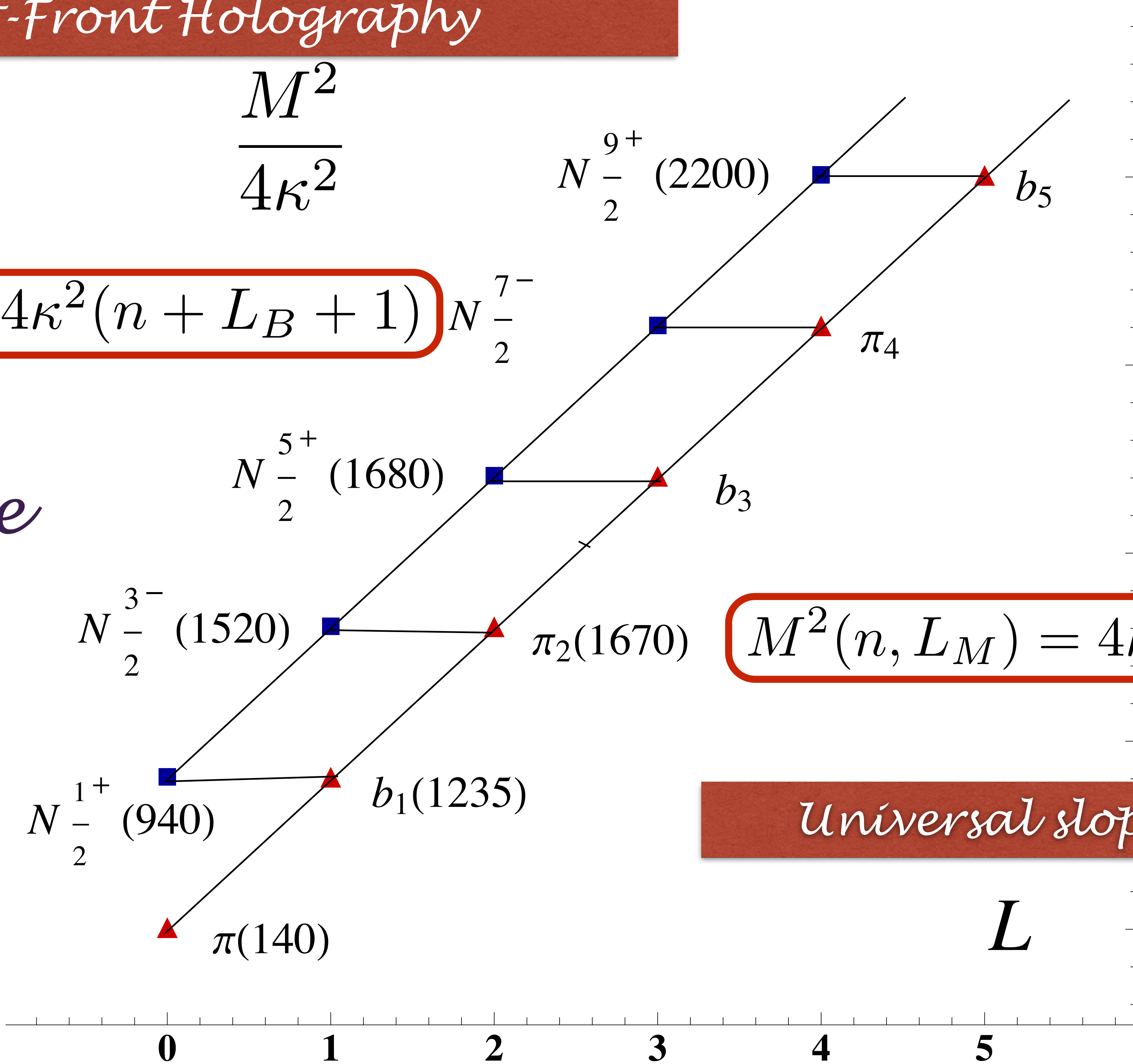
INT October 10, 2022

Superconformal Quantum Mechanics
Light-Front Holography

de Téramond, Dosch, Lorcé, sjb

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

Same slope

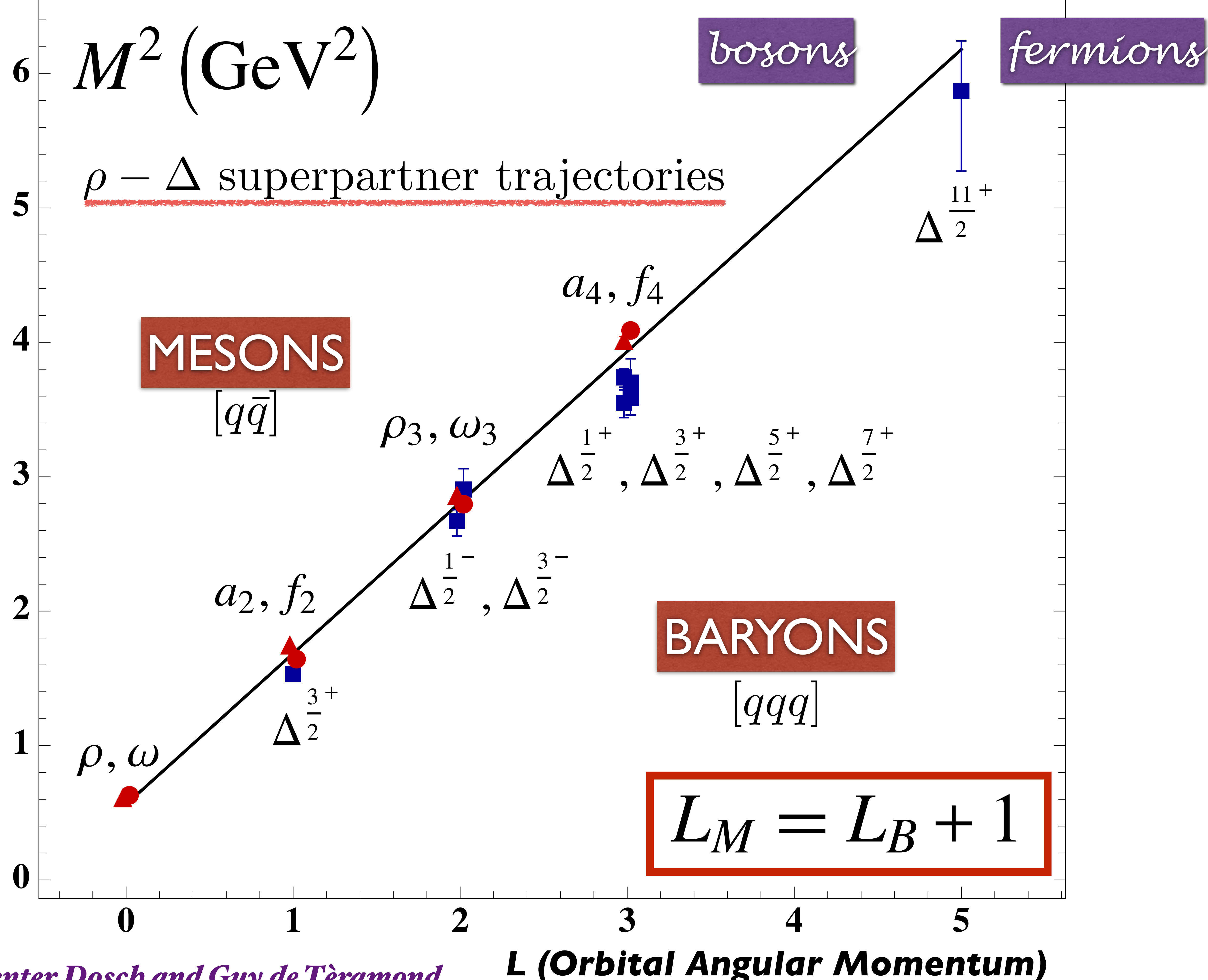


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Universal slopes in n, L

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

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

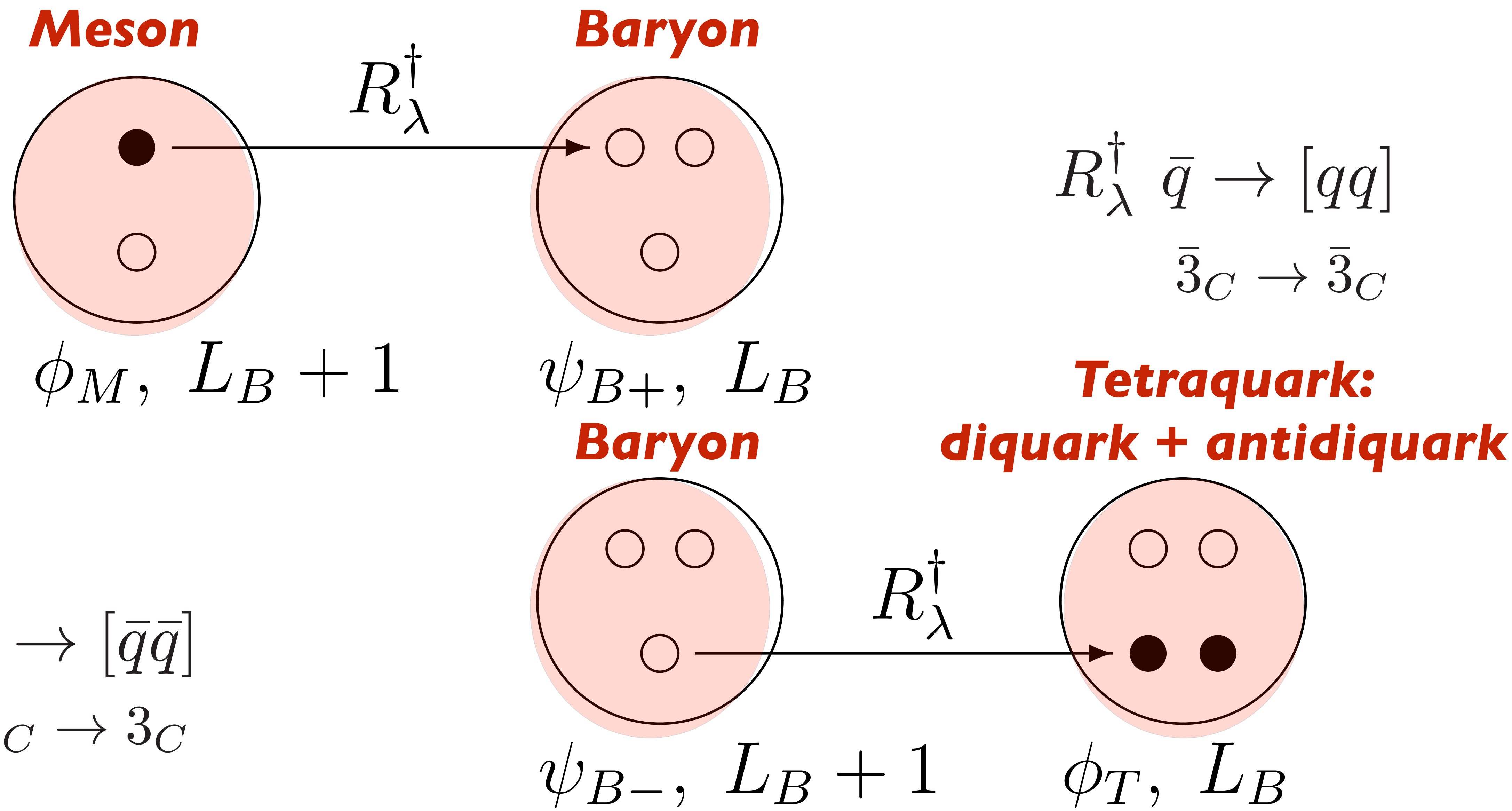


with Guenter Dosch and Guy de Tèramond

Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



$R^\dagger_\lambda \; \bar{q} \to [qq]$

$\bar{3}_C \to \bar{3}_C$

$R^\dagger_\lambda \; q \to [\bar{q}\bar{q}]$

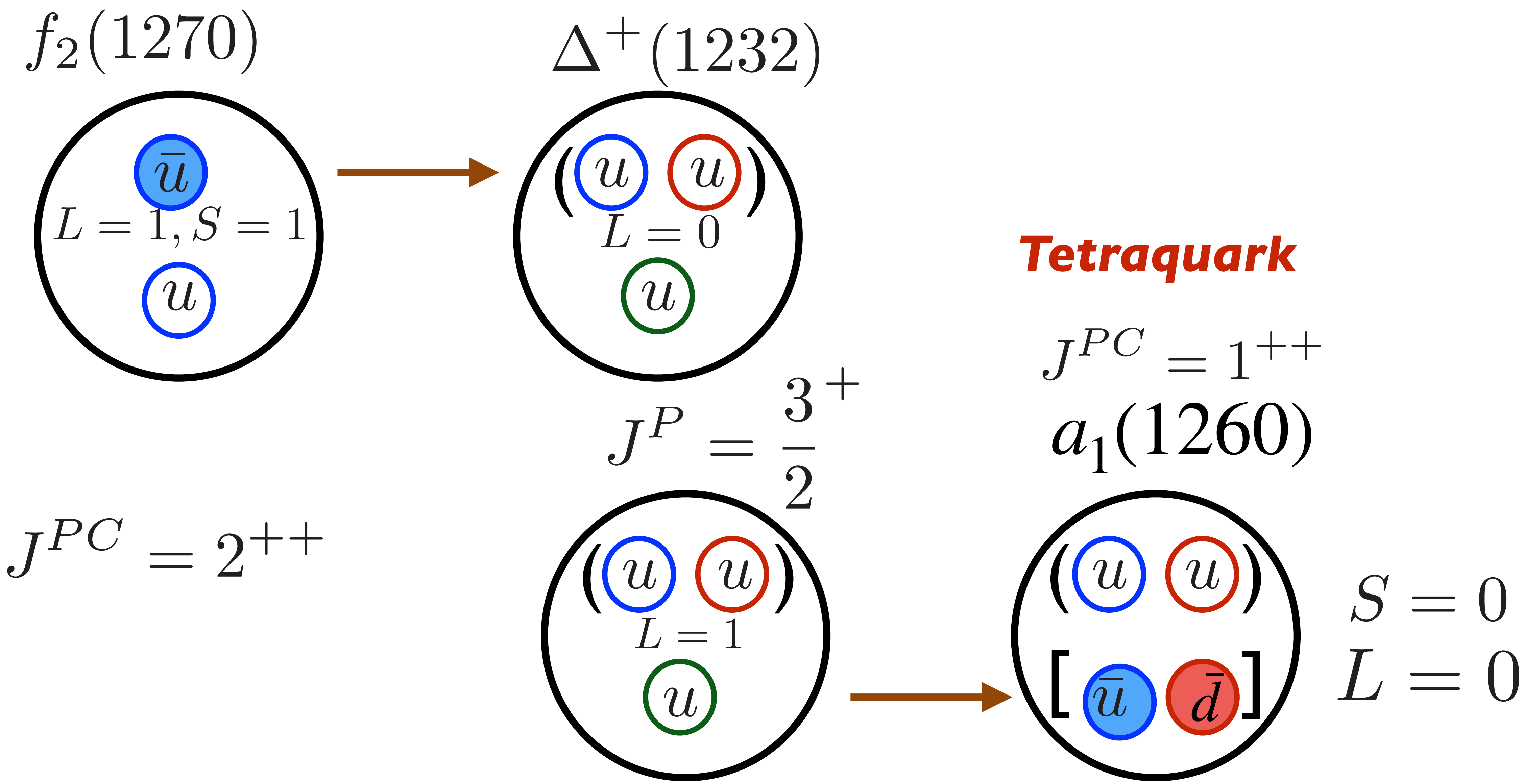
$3_C \to 3_C$

Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

Superconformal Algebra 4-Plet

$$R^\dagger_\lambda \quad \bar q \to (qq) \quad S = 1$$
$$\bar 3_C \to \bar 3_C$$

Vector ()+ Scalar [] Diquarks



Meson **Baryon**

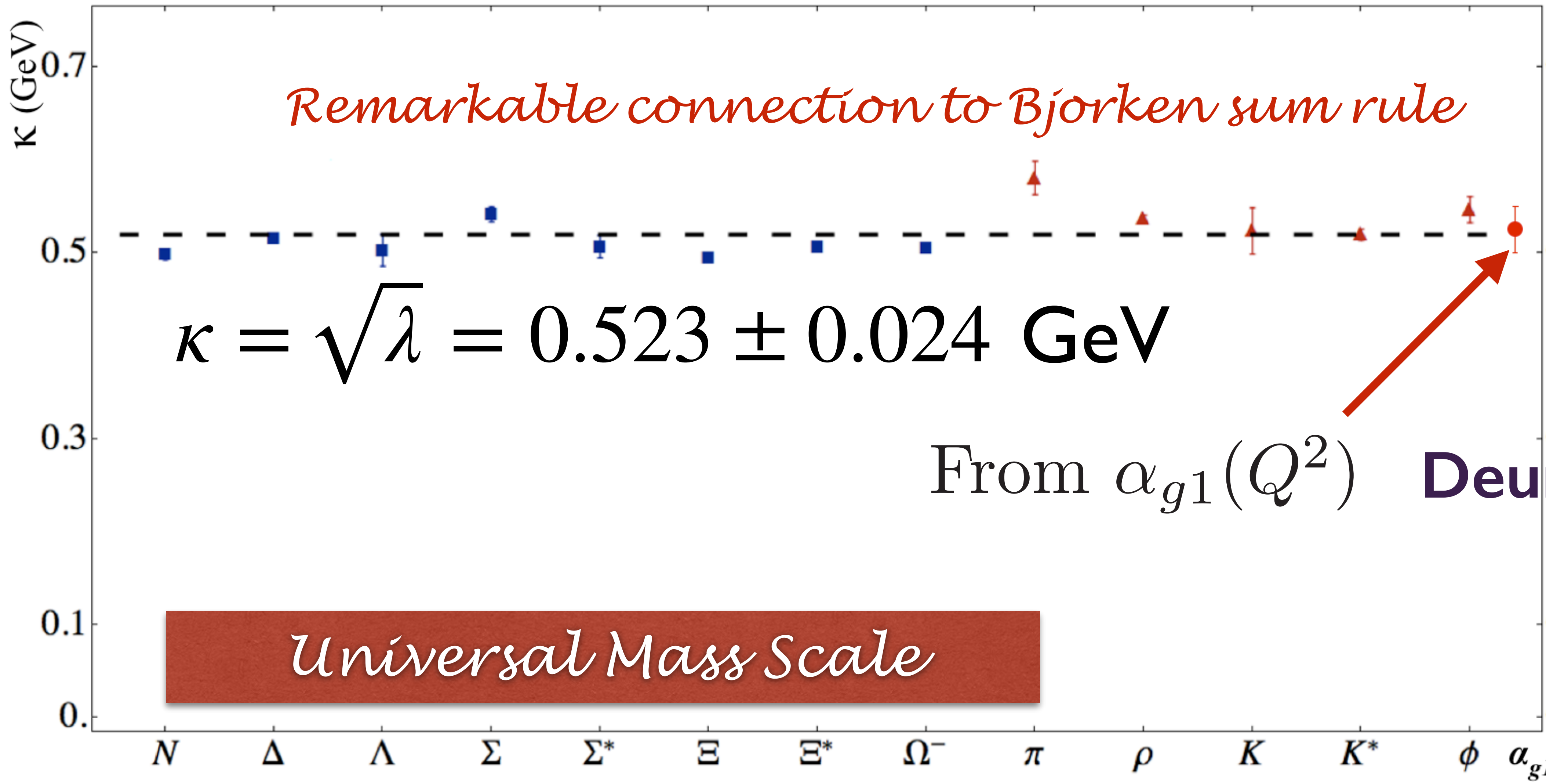
$$R^\dagger_\lambda \quad q \to [\bar q \bar q]$$
$$3_C \to 3_C$$

$\lambda = \kappa^2$

de Tèramond, Dosch, Lorce', sjb

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

κ



Remarkable connection to Bjorken sum rule

$$\kappa = \sqrt{\lambda} = 0.523 \pm 0.024 \text{ GeV}$$

From $\alpha_{g1}(Q^2)$ **Deur, et al.**

Universal Mass Scale

Fit to the slope of Regge trajectories, including radial excitations

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

Challenge: Compute Hadron Structure, Spectroscopy, and Dynamics from QCD!

- *Color Confinement*
- *Origin of the QCD Mass Scale*
- *Meson and Baryon Spectroscopy*
- *Exotic States: Tetraquarks, Pentaquarks, Gluonium,*
- *Universal Regge Slopes: n, L, Mesons and Baryons*
- *Almost Massless Pion: GMOR Chiral Symmetry Breaking*
  $M_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u+m_d)\langle\bar{u}u+\bar{d}d\rangle+\mathcal{O}\big((m_u+m_d)^2\big)$
- *QCD Coupling at all Scales* $\alpha_s(Q^2)$
- *Eliminate Scale Uncertainties and Scheme Dependence*

$$\mathscr{L}_{QCD} \to \psi_n^H(x_i, \overrightarrow{k}_{\perp i}, \lambda_i)$$ *Valence and Higher Fock States*

Supersymmetry in QCD

- A hidden symmetry of Color $SU(3)_C$ in hadron physics:
- Relates meson and baryon spectroscopy
- QCD: No squarks or gluinos!
- Emerges from Light-Front Holography and Super-Conformal Algebra
- Color Confinement

de Téramond, Dosch, Lorcé, sjb

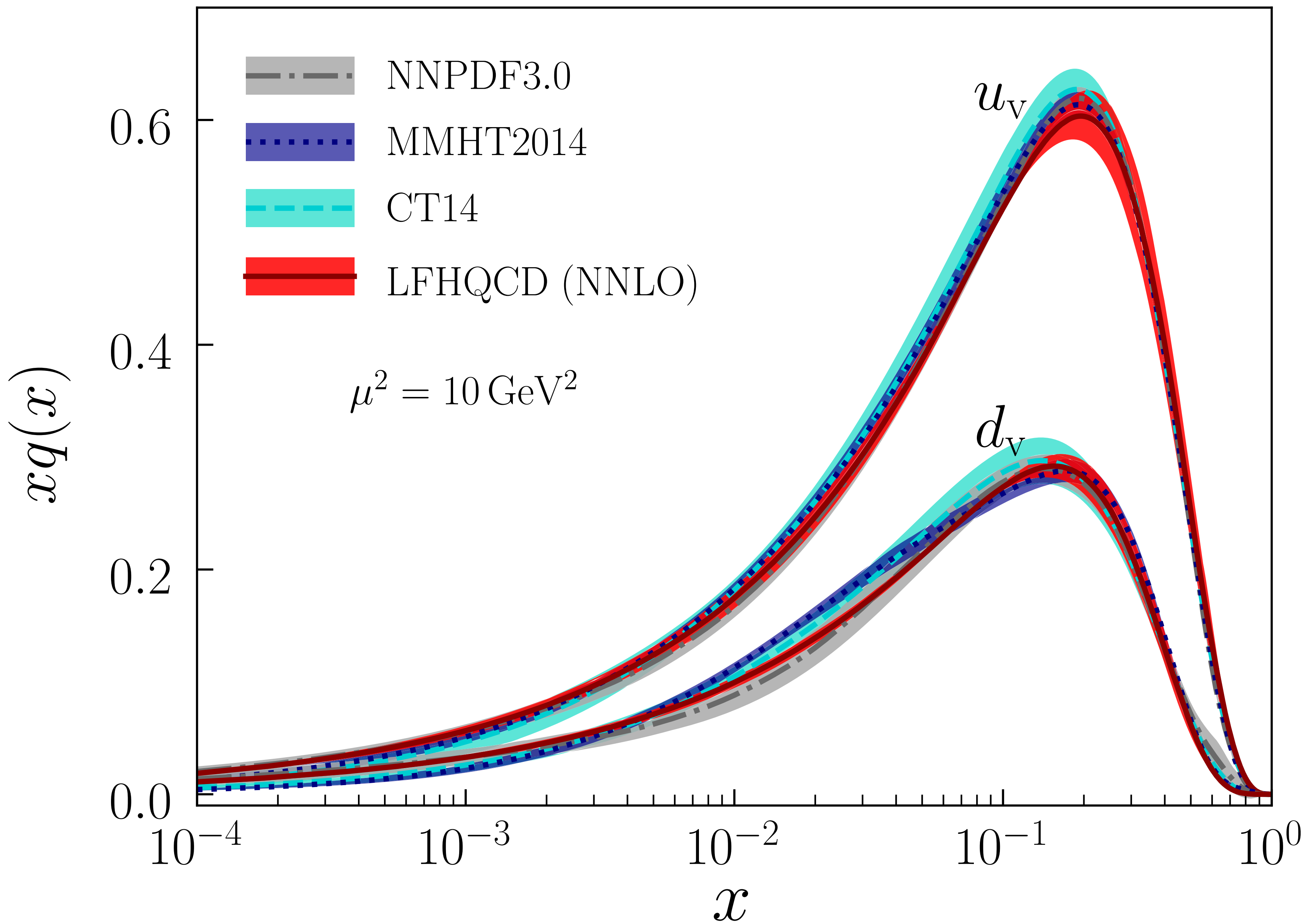
Input: one fundamental mass scale

$$\kappa = \sqrt{\lambda} = 0.523 \pm 0.024 \text{ GeV}$$

Light-Front Holography: First Approximation to QCD

- Color Confinement, Analytic form of confinement potential
- Retains underlying conformal properties of QCD despite mass scale (DeAlfaro-Fubini-Furlan Principle)
- Massless quark-antiquark pion bound state in chiral limit, GMOR
- QCD coupling at all scales
- Connection of perturbative and nonperturbative mass scales
- Poincarè Invariant
- Hadron Spectroscopy-Regge Trajectories with universal slopes in n, L
- Supersymmetric 4-Plet: Meson-Baryon -Tetraquark Symmetry
- Light-Front Wavefunctions
- Form Factors, Structure Functions, Hadronic Observables
- OPE: Constituent Counting Rules
- Hadronization at the Amplitude Level: Many Phenomenological Tests
- Systematically improvable: Basis LF Quantization (BLFQ)

Supersymmetric Features of Hadron Physics from Superconformal Algebra and Light-Front Holography



Comparison for $xq(x)$ in the proton from LFHQCD (red bands) and global fits: MMHT2014 (blue bands) [5], CT14 [6] (cyan bands), and NNPDF3.0 (gray bands) [77]. LFHQCD results are evolved from the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV.

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur

PHYSICAL REVIEW LETTERS 120, 182001 (2018)

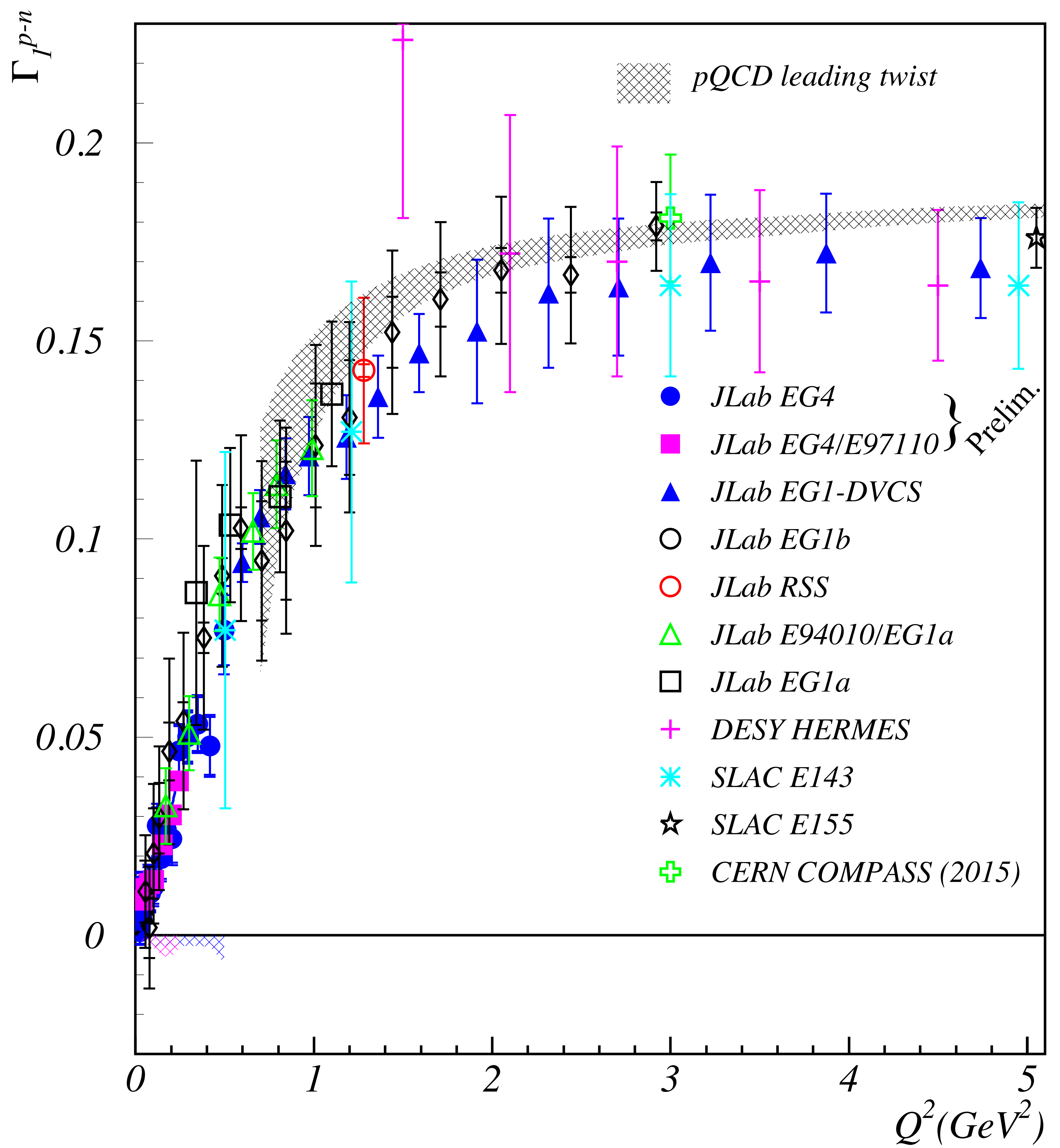
Bjorken sum rule defines effective charge

$\alpha_{g1}(Q^2)$

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

- ***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***

Bjorken sum Γ_1^{p-n} measurements



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

$$m_p = 2\kappa$$

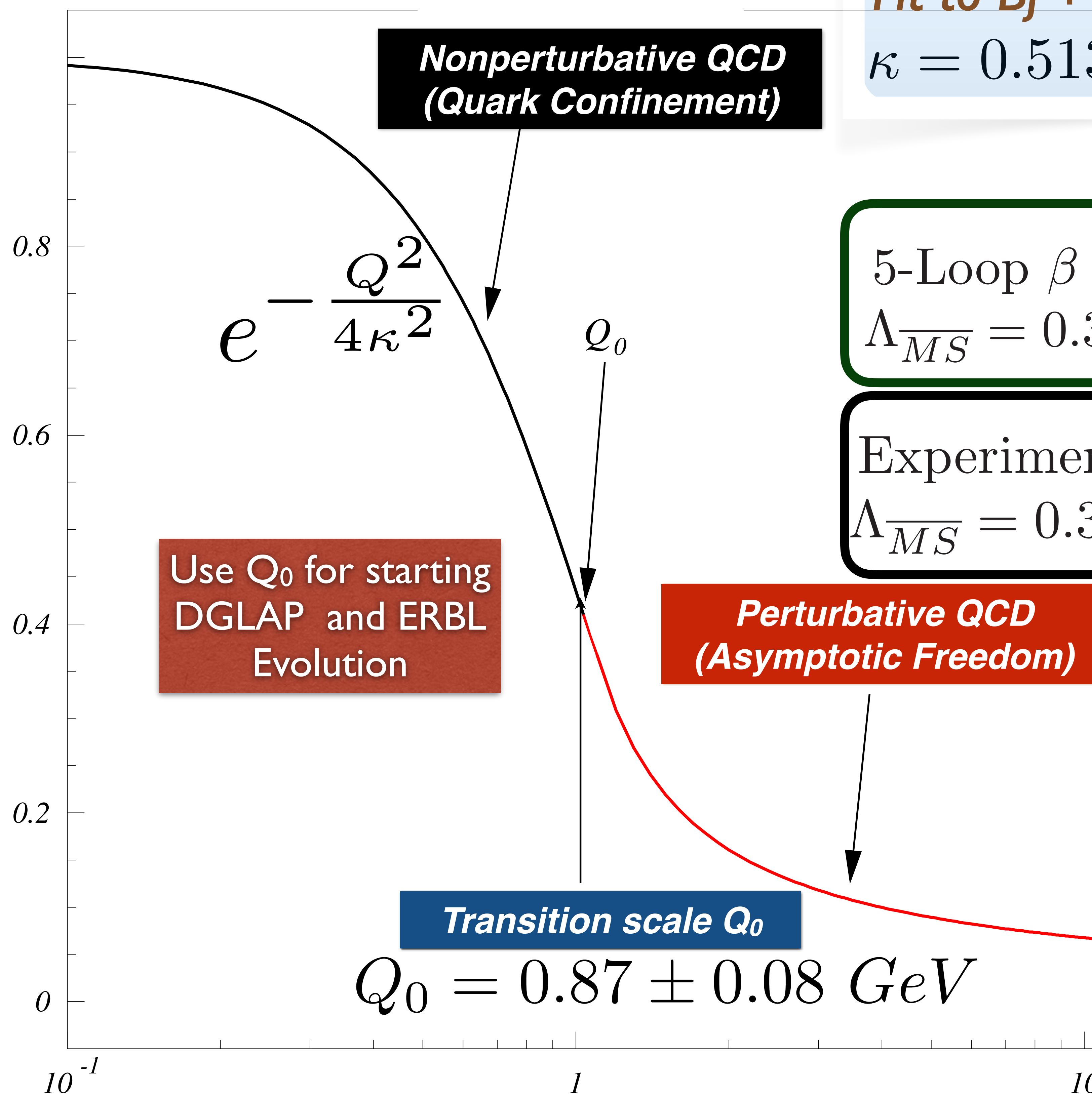
All-Scale QCD Coupling

Deur, de Tèramond, sjb

Fit to Bj + DHG Sum Rules:

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

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



5-Loop β Prediction:

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

Experiment:

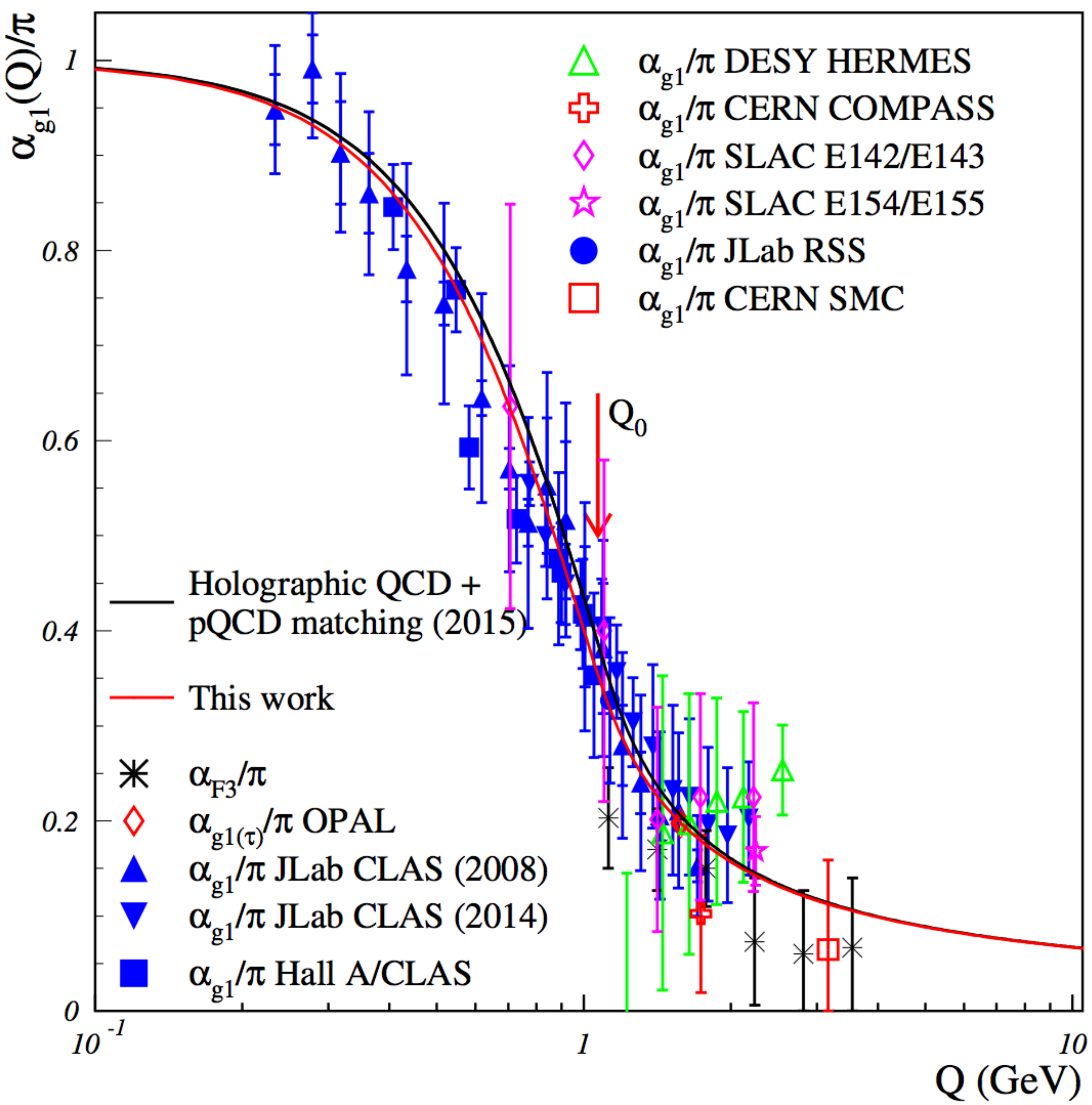
$\Lambda_{\overline{MS}} = 0.332 \pm 0.017 \; GeV$

$\lambda \equiv \kappa^2$

$\overline{MS}$ *scheme*

Reverse Dimensional Transmutation!

Running Coupling from AdS/QCD



Bjorken sum rule:

$$\frac{\alpha_{g_1}(Q^2)}{\pi} = 1 - \frac{6}{g_A}\int_0^1 dx\, g_1^{p-n}(x, Q^2)$$

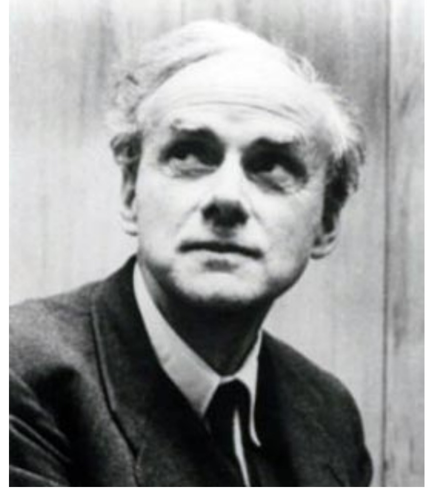
Effective coupling in LFHQCD (valid at low-Q^2)

$$\alpha_{g_1}^{AdS}(Q^2) = \pi \exp\left(-Q^2/4\kappa^2\right)$$

Imposing continuity for α and its first derivative

A. Deur, S.J. Brodsky, G.F. de Téramond, Phys. Lett. B 750, 528 (2015); J. Phys. G 44, 105005 (2017).

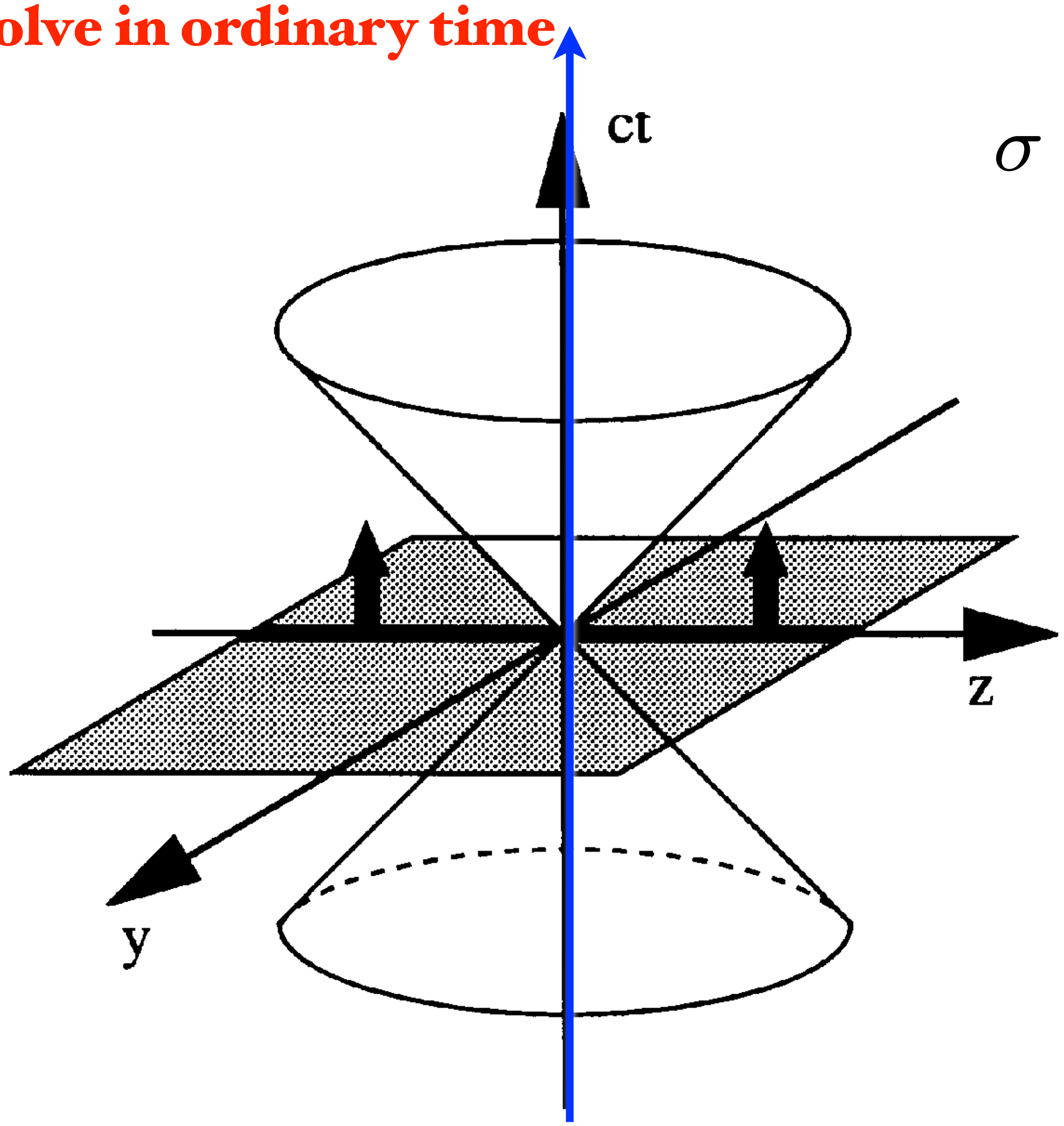
Analytic, defined at all scales, IR Fixed Point



P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

Dirac's Amazing Idea:
The "Front Form"

Evolve in ordinary time

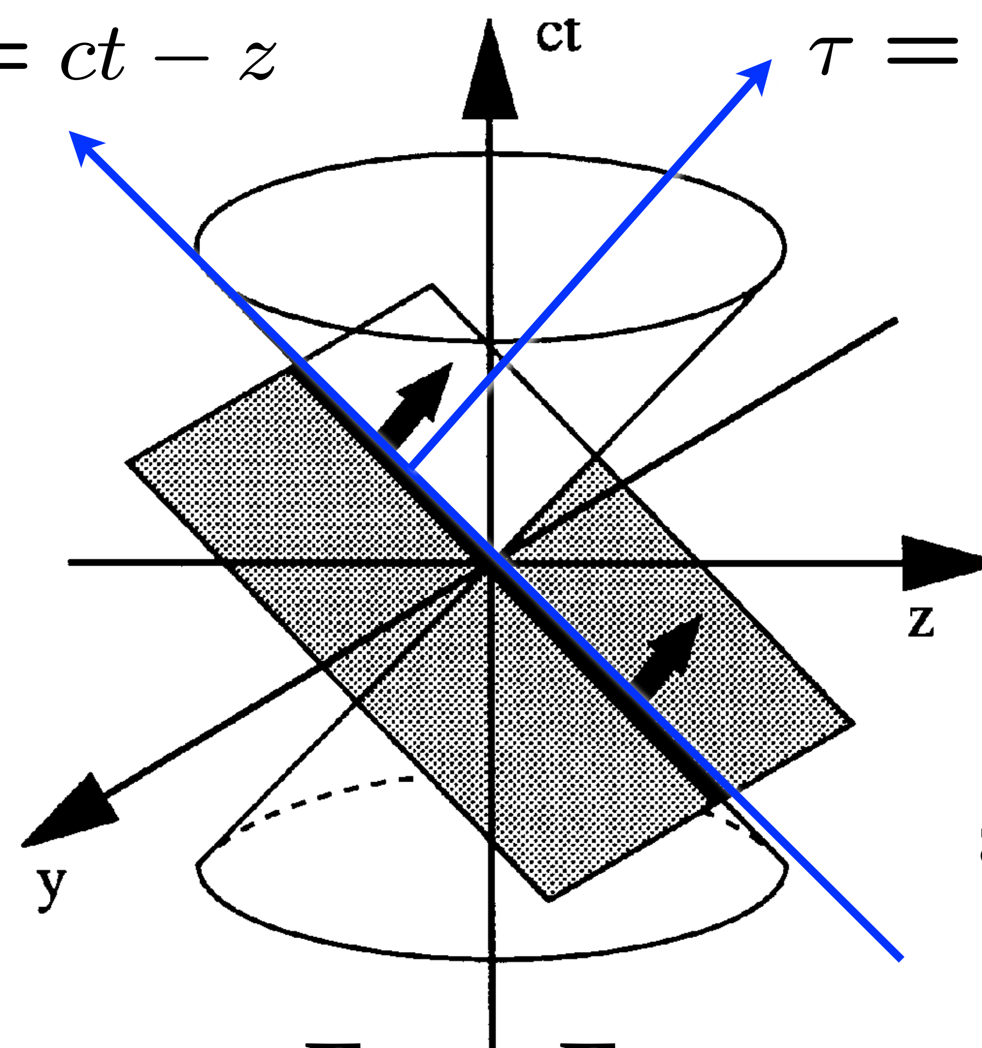


Instant Form

Evolve in light-front time!

$$\sigma = ct - z$$

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



Front Form

analogous to a flash photo

Casual, Boost Invariant!

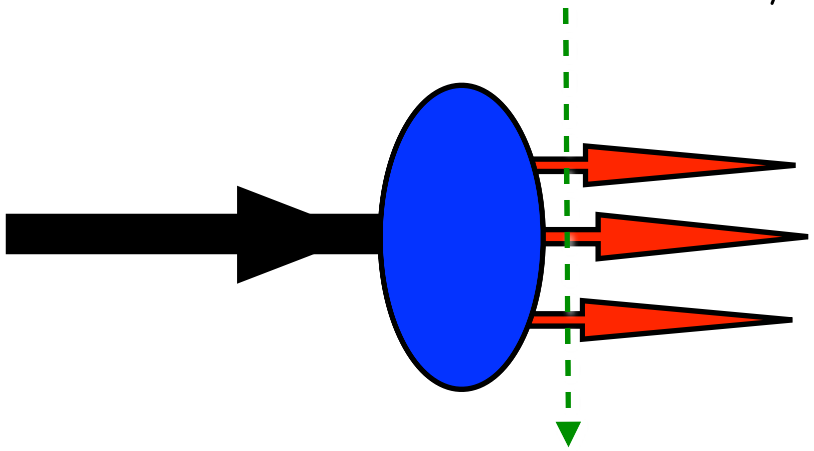
Comparing light-front quantization with instant-time quantization
Philip D. Mannheim(Connecticut U.),
Peter Lowdon(Ecole Polytechnique, CPHT),
Stanley J. Brodsky(SLAC)

- e-Print: 2005.00109 [hep-ph]

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

Dirac's Front Form: 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^μ

$$\boxed{H^{QCD}_{LF}|\psi> = M^2|\psi>}$$

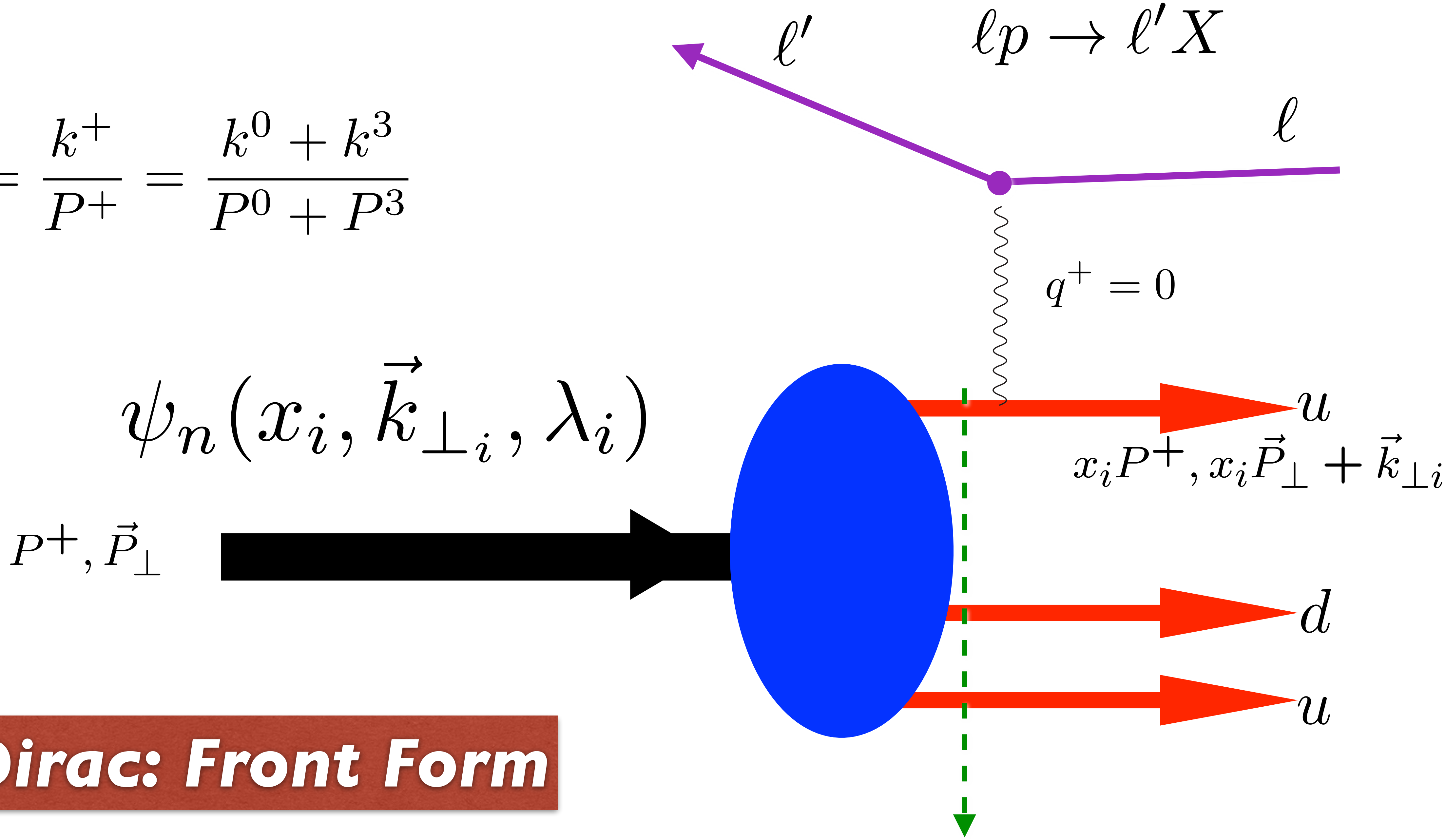
Direct connection to QCD Lagrangian

LF Wavefunction: off-shell in invariant mass

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

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

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



Dirac: Front Form

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

Like a flash photograph

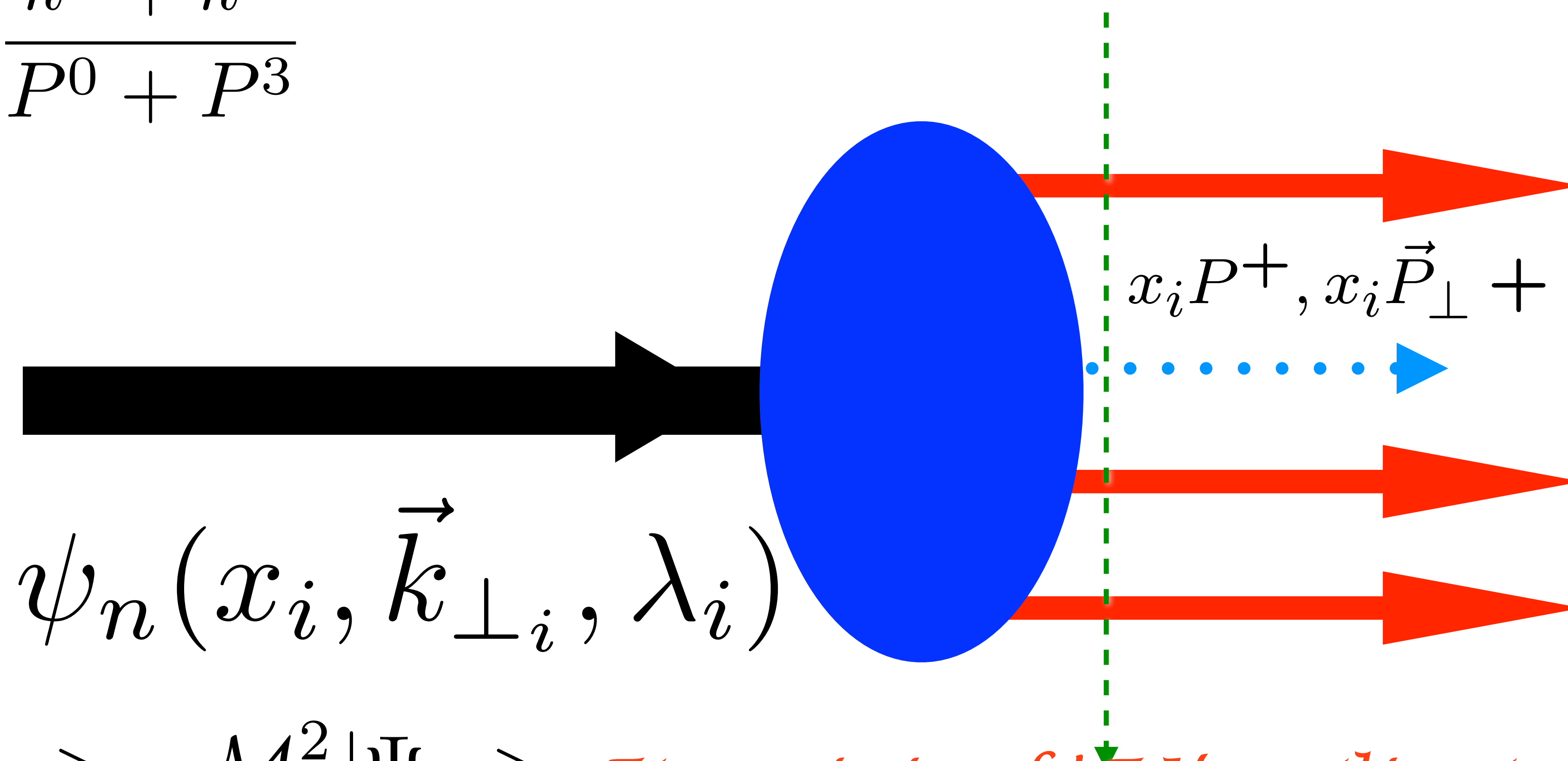
$$x_{bj} = x = \frac{k^+}{P^+}$$

Invariant under boosts! Independent of P^μ

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

Fixed $\tau = t + z/c$

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



$\sum_i^n x_i = 1$

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

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

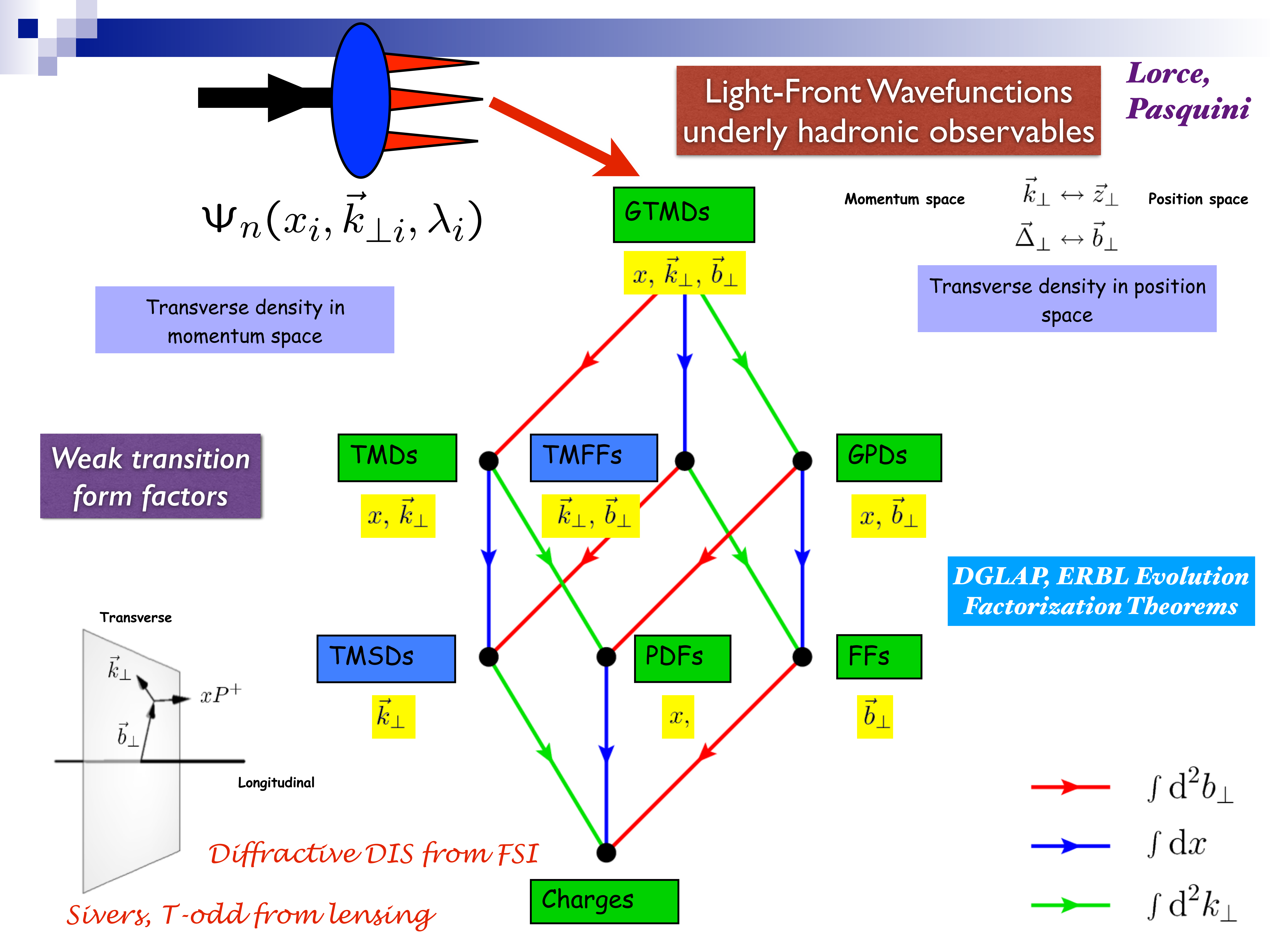
$$H^{QCD}_{LF} |\Psi_h >= \mathcal{M}^2_h |\Psi_h >$$ *Eigenstate of LF Hamiltonian*

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

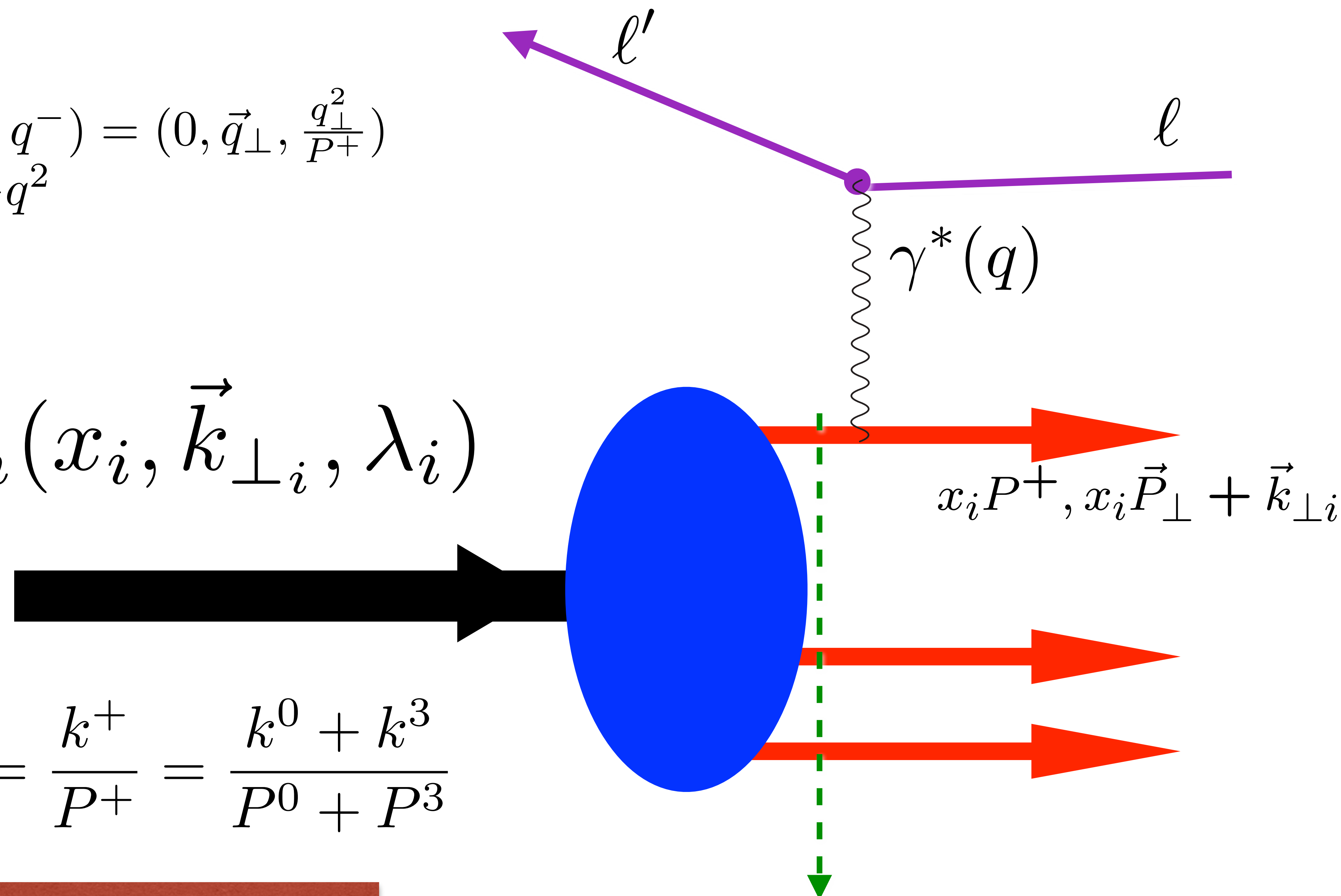
LFWF: Projection on free Fock state: $\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) =< p|n >$

Invariant under boosts! Independent of P^μ

Structure Function is square of LFWFs, summed over all Fock states. Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS


Light-Front Wavefunctions underly hadronic observables
Lorce, Pasquini
$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$
Momentum space
$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$
Position space
GTMDs
$x, \vec{k}_\perp, \vec{b}_\perp$
Transverse density in momentum space
Transverse density in position space
Weak transition form factors
TMDs
$x, \vec{k}_\perp$
TMFFs
$\vec{k}_\perp, \vec{b}_\perp$
GPDs
$x, \vec{b}_\perp$
DGLAP, ERBL Evolution
Factorization Theorems
Transverse
$\vec{k}_\perp$
xP^+
$\vec{b}_\perp$
Longitudinal
TMSDs
$\vec{k}_\perp$
PDFs
$x,$
FFs
$\vec{b}_\perp$
$\int d^2 b_\perp$
$\int dx$
$\int d^2 k_\perp$
Diffractive DIS from FSI
Sivers, T-odd from lensing
Charges

$$q^\mu = (q^+, \vec{q}_\perp, q^-) = (0, \vec{q}_\perp, \frac{q_\perp^2}{P^+})$$
$$q_\perp^2 = Q^2 = -q^2$$



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

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

Dirac: Front Form

Fixed $\tau = t + z/c$

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

1912.08911 [hep-ph]

G. A. Miller, sjb:

Ioffe Time: $\tilde{z}$ Third spatial LF coordinate.
Fourier Transform of x in LFWFs

$$< p+q|j^+(0)|p >= 2p^+F(q^2)$$

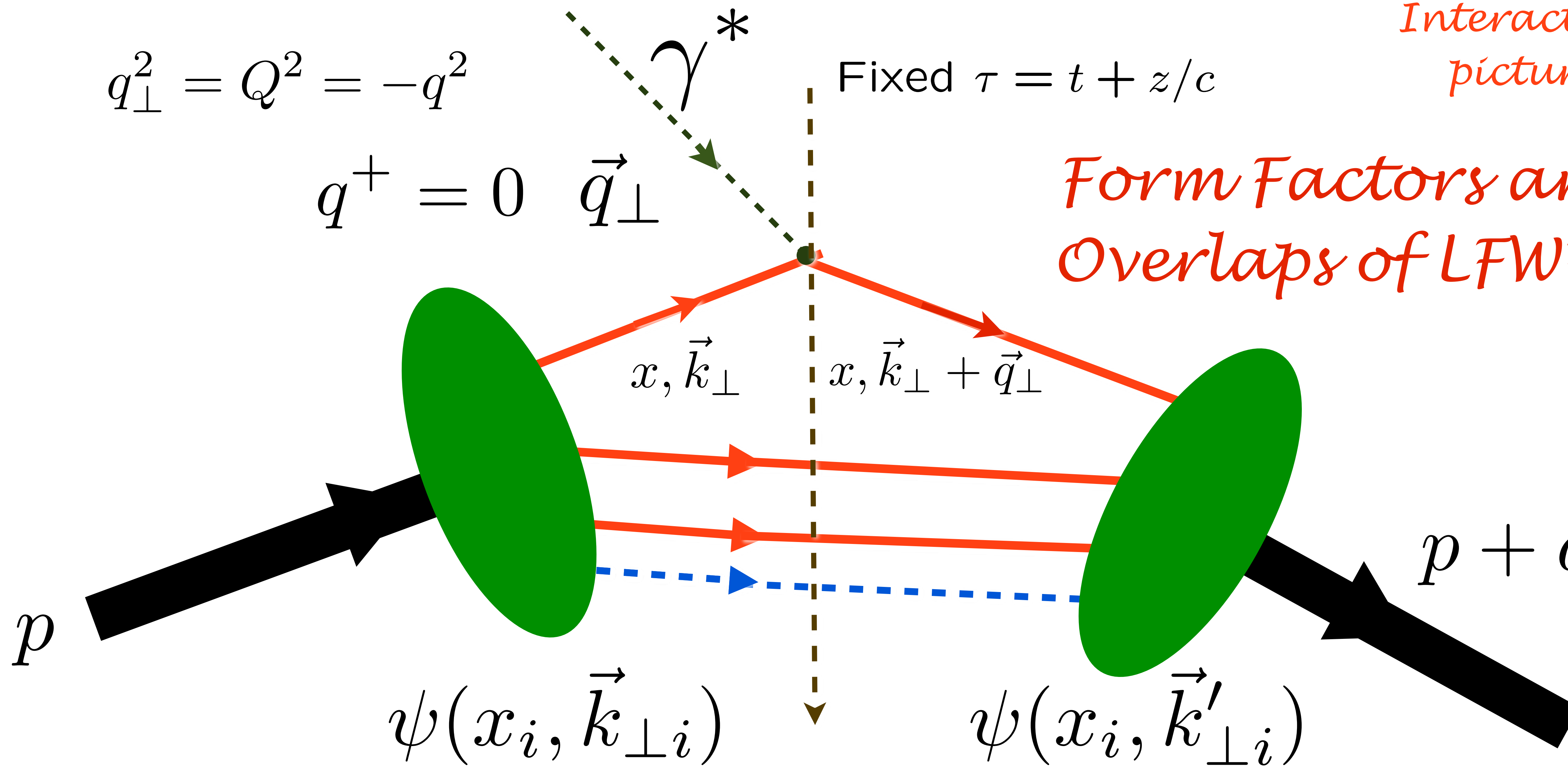
Front Form

Interaction picture

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

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

Form Factors are Overlaps of LFWFs



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

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

Drell & Yan, West
Exact LF formula!

Drell, sjb

Transverse size $\propto \frac{1}{Q}$

Exact LF Formula for Pauli Form Factor

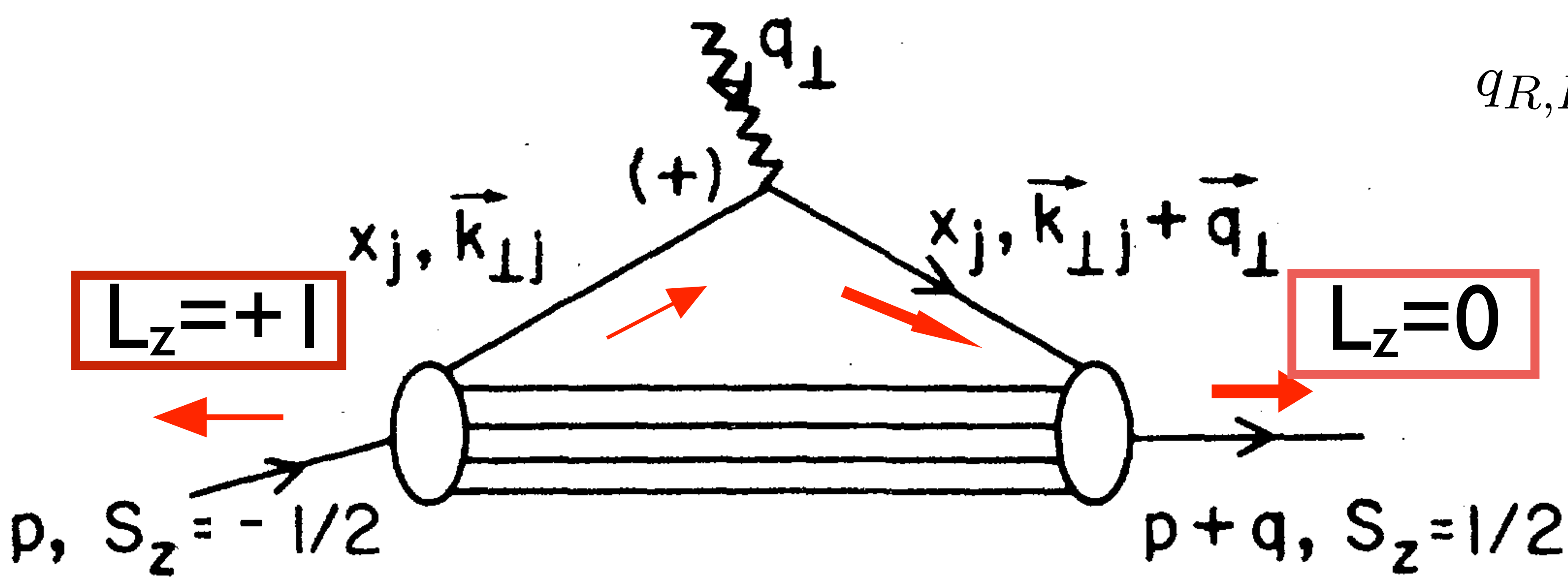
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

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

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

$$q_{R,L} = q^x \pm i q^y$$



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

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

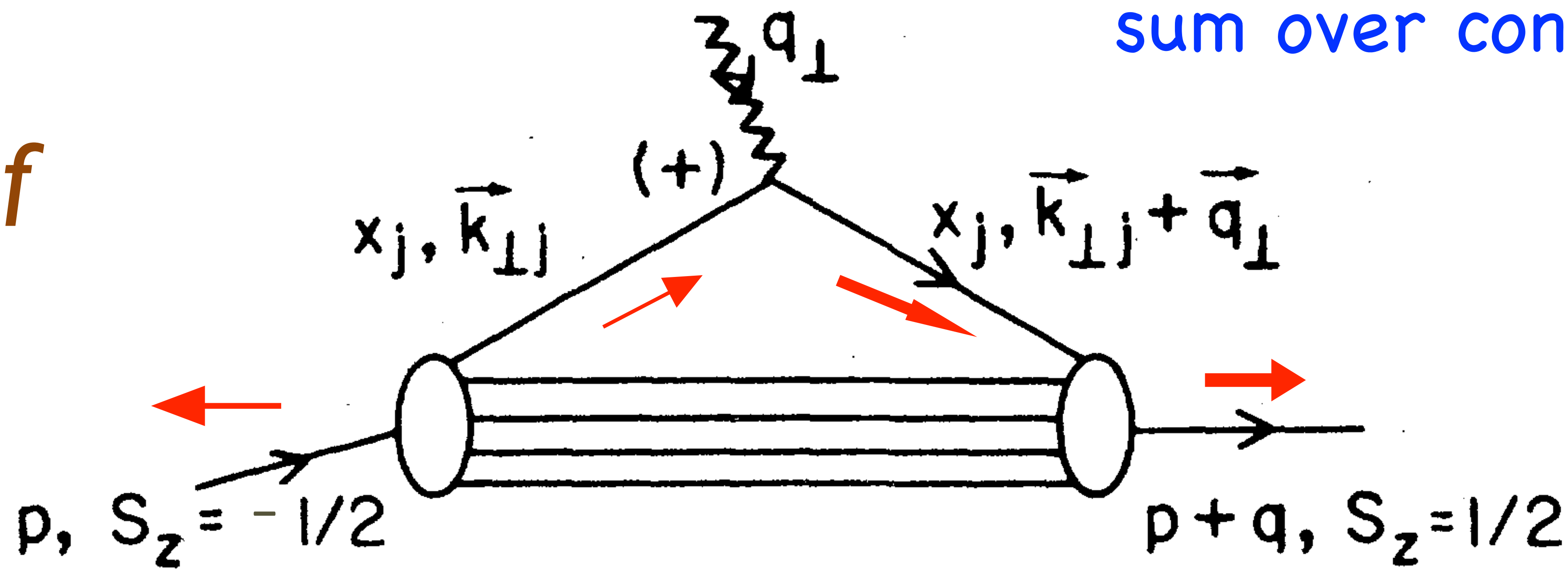
Dae Sung Hwang, Bo-Qiang Ma, Ivan Schmidt, sjb

Terayev, Okun: *B(0) Must vanish because of Equivalence Theorem*

graviton

sum over constituents

LF Proof

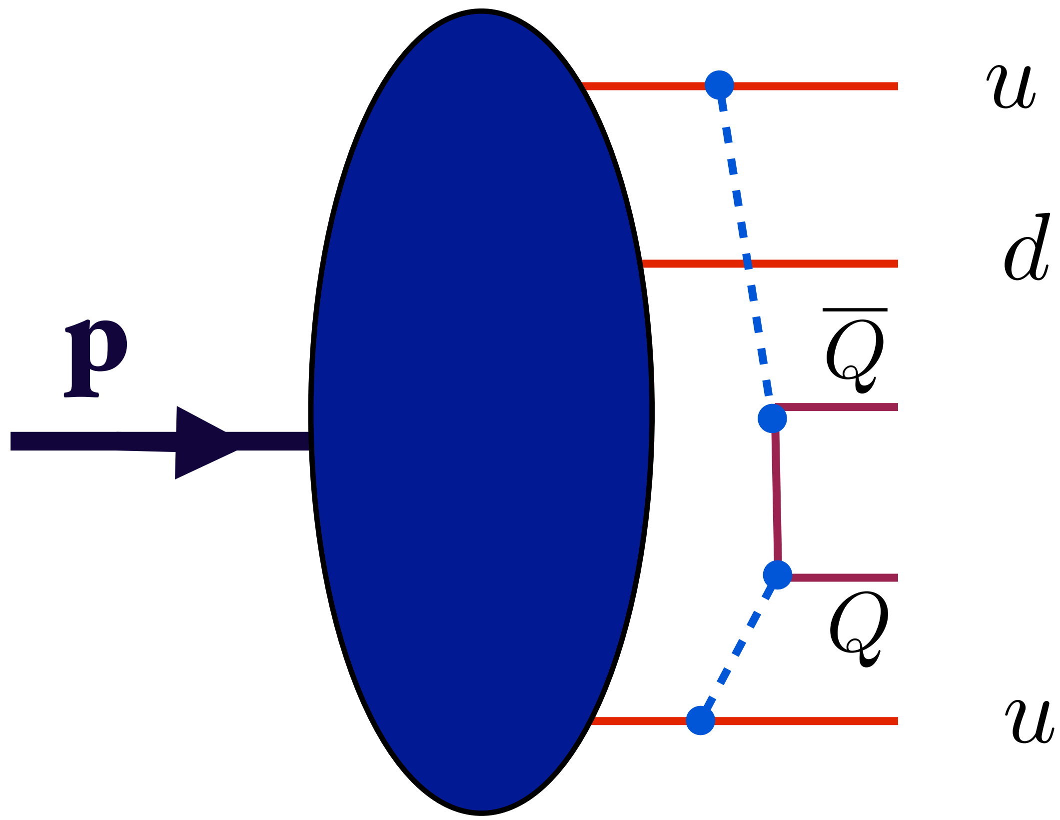


$\boxed{B(0) = 0}$

Each Fock State

Vanishing Anomalous gravitomagnetic moment B(0)

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts
Intrinsic
Heavy Quarks
at high x!

Perturbative contribution

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

Minimal off-shellness

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

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

Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

Intrinsic Chevrolets at the SSC

Stanley J. Brodsky (SLAC), John C. Collins (IIT, Chicago and Argonne), Stephen D. Ellis (Washington U., Seattle), John F. Gunion (UC, Davis), Alfred H. Mueller (Columbia U.) (Aug, 1984)

Published in: , Snowmass Summer Study 1984:0227 • Contribution to: 1984 DPF Summer Study on the Design and Utilization of the Superconducting Super Collider (SSC) (Snowmass 84), 227

Quantum Mechanics Uncertainty Principle on the Light Front:
Arbitrarily off-shell in invariant mass squared
$\mathcal{M}^2 = \sum_i \frac{m_i^2 + \vec{k}_{\perp i}^2}{x_i}$ at fixed LF time $\tau = t + z/c$

Intrinsic Heavy Quark States

Stanley J. Brodsky (SLAC), C. Peterson (SLAC), N. Sakai (Fermilab) (Jan, 1981)

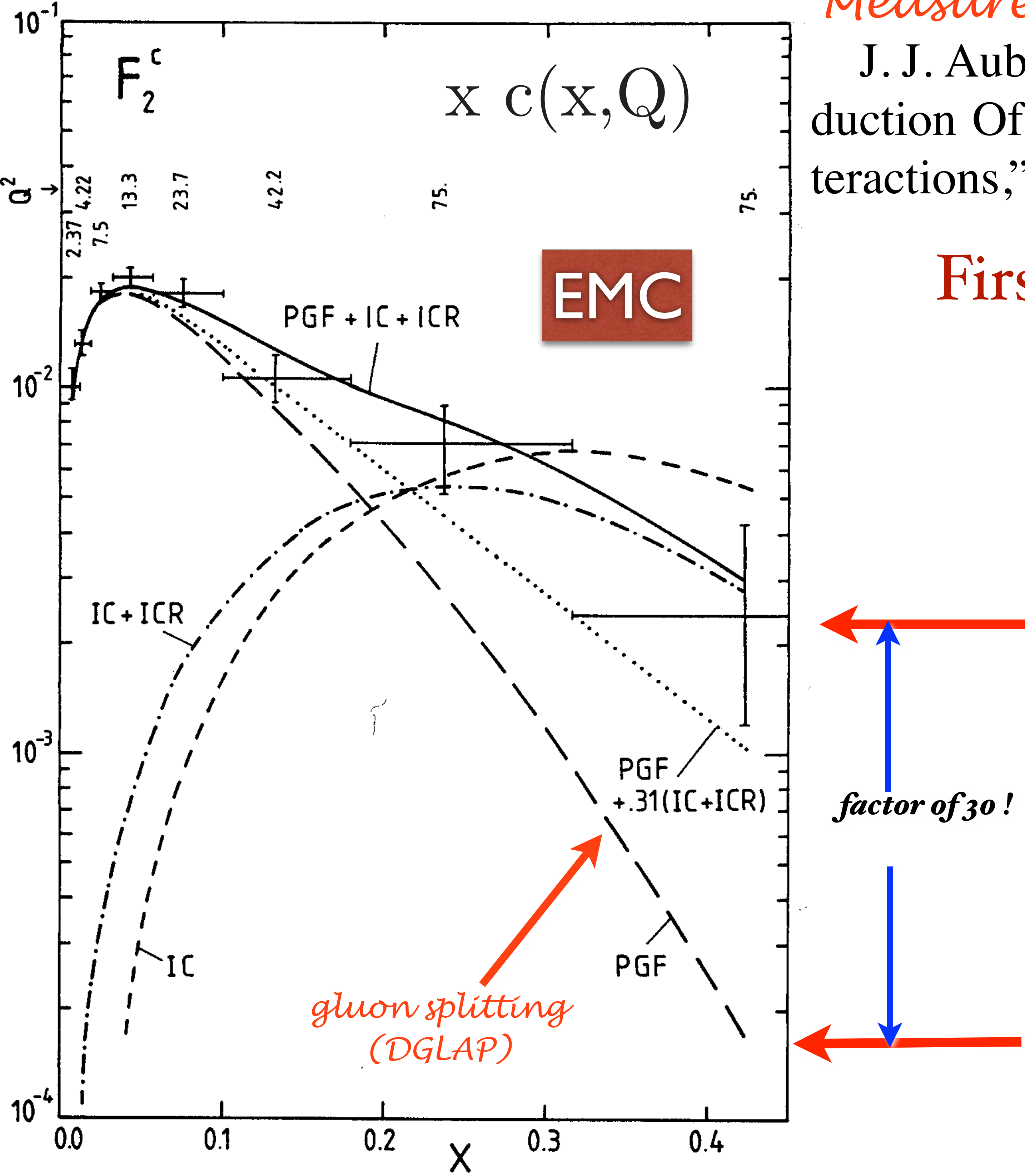
Published in: *Phys.Rev.D* 23 (1981) 2745

The Intrinsic Charm of the Proton

S.J. Brodsky (SLAC), P. Hoyer (Nordita), C. Peterson (Nordita), N. Sakai (Nordita) (Apr, 1980)

Published in: *Phys.Lett.B* 93 (1980) 451-455

42 years ago!



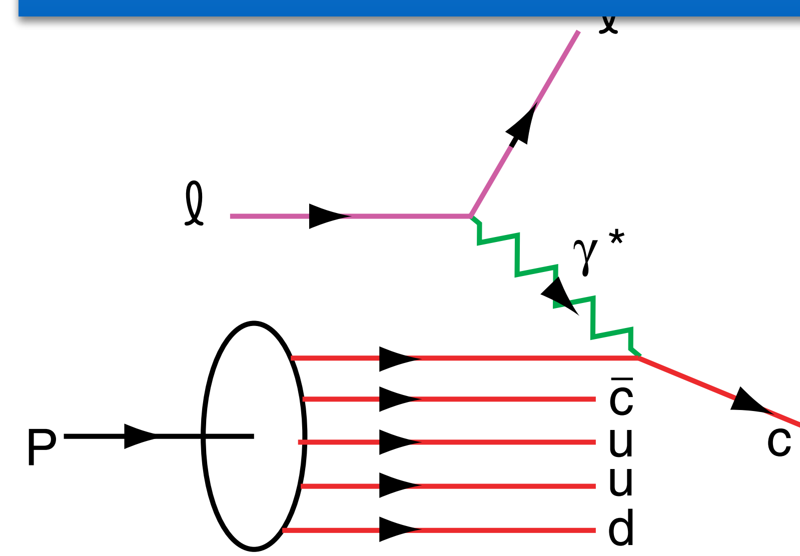
Measurement of Charm Structure Function!

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm

$$< x_{c\bar{c}} >_p \simeq 1\%$$

New Analysis:
R.D. Ball, et al. [NNPDF Collaboration],
"A Determination of the Charm Content of the Proton,"
arXiv:1605.06515 [hep-ph].



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

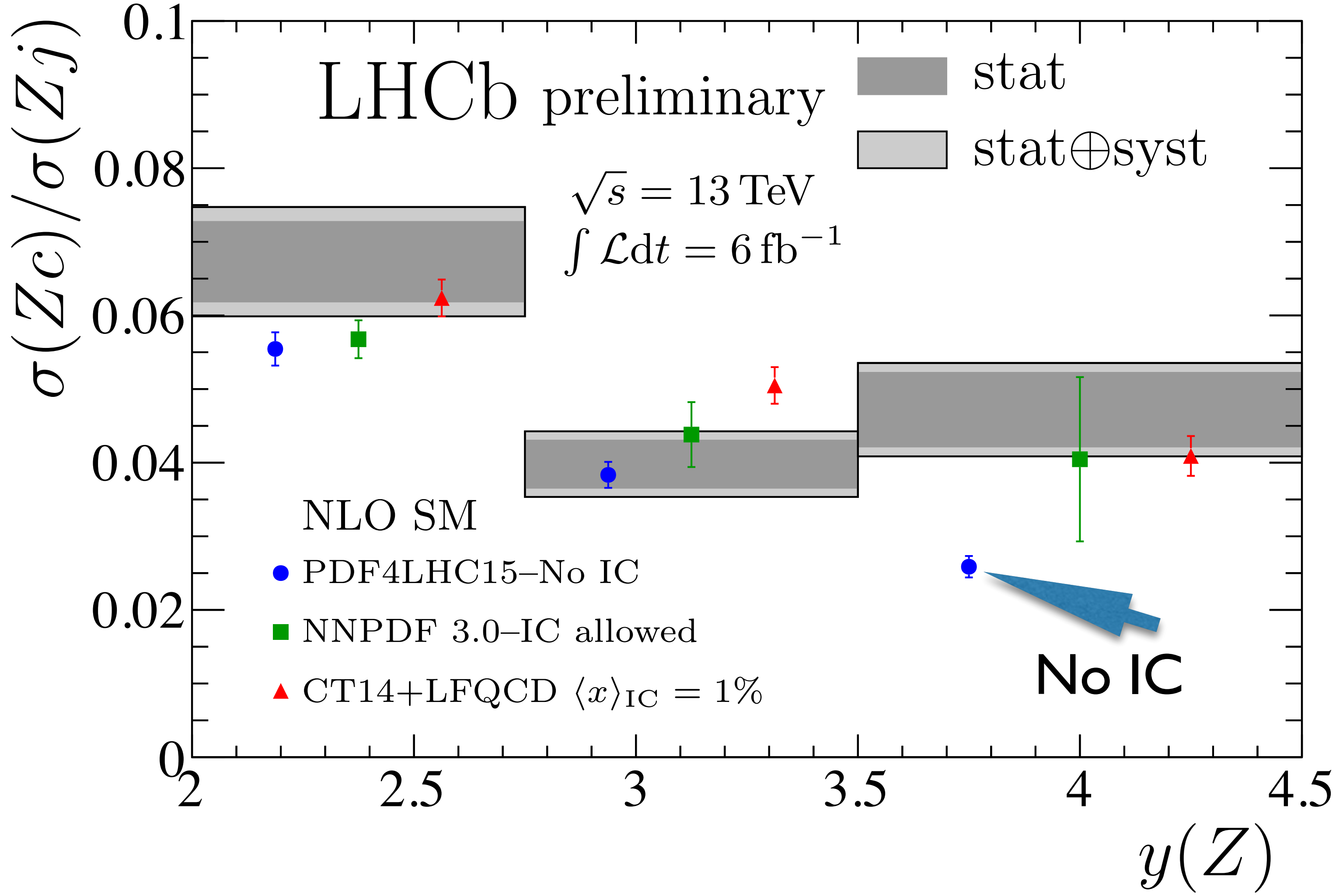
Two Components (separate evolution):

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

$$pp \to Z + c + X \qquad g + c \to Z + c$$

$Z + c$: results

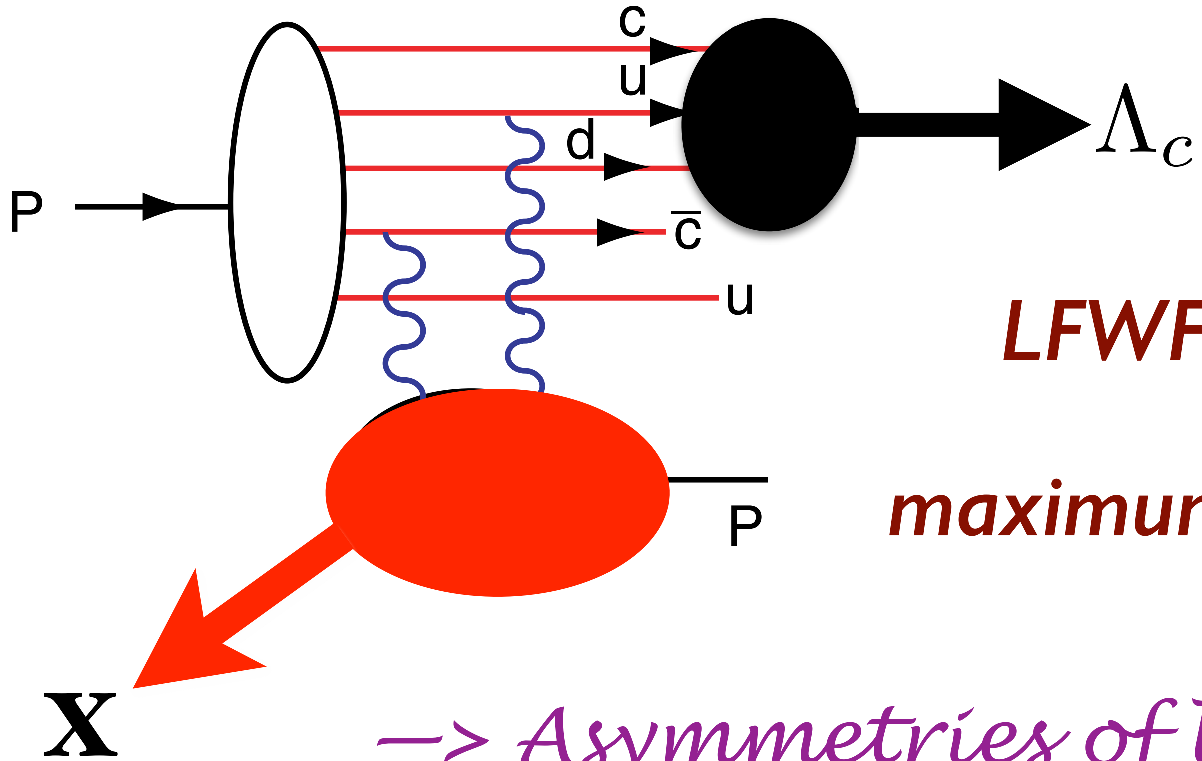
LHCb-PAPER-2021-029



- Clear enhancement in highest-y bin
- Consistent with expected effect from $|uudc\bar{c}\rangle$ component predicted by LFQCD
- Inconsistent with No-IC theory at ~ 3 standard deviations
- Global PDF analysis required to determine true significance

Coalesece of comovers produces high x_F heavy hadrons

High x_F hadrons combine most of the comovers, fewest spectators



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

LFWF maximum at equal rapidity

maximum at minimal invariant mass

—> Asymmetries of leading hadrons

Spectator counting rules

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect} - 1}$$

Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

Vogt, sjb

Stan Brodsky

University of Kentucky

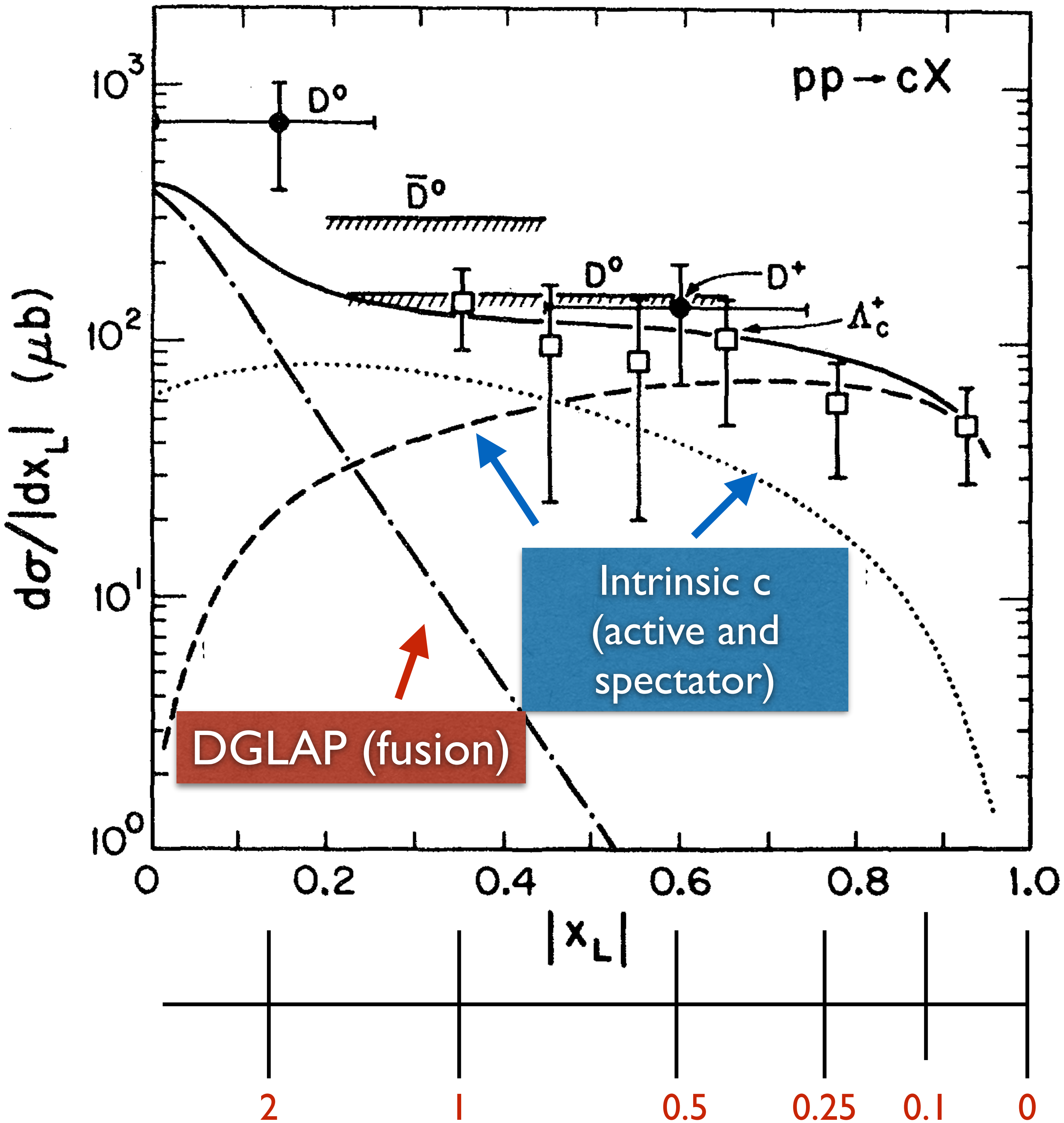
Supersymmetric Features of Hadron Physics from Superconformal Algebra and Light-Front Holography

SLAC NATIONAL ACCELERATOR LABORATORY

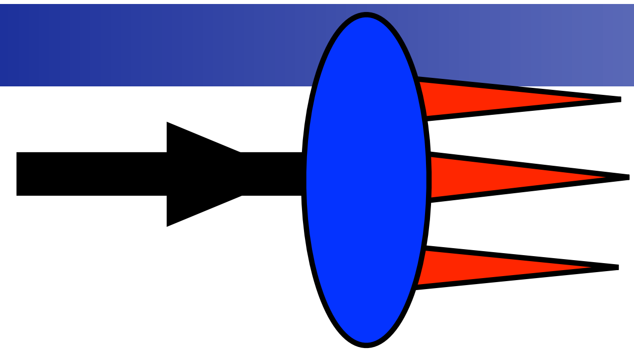
19 April 2021

Barger, Halzen, Keung

PRD 25 (1981)



$\Delta y = \log x$



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

Light-Front Wavefunctions underly hadronic observables

Lorce, Pasquini

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

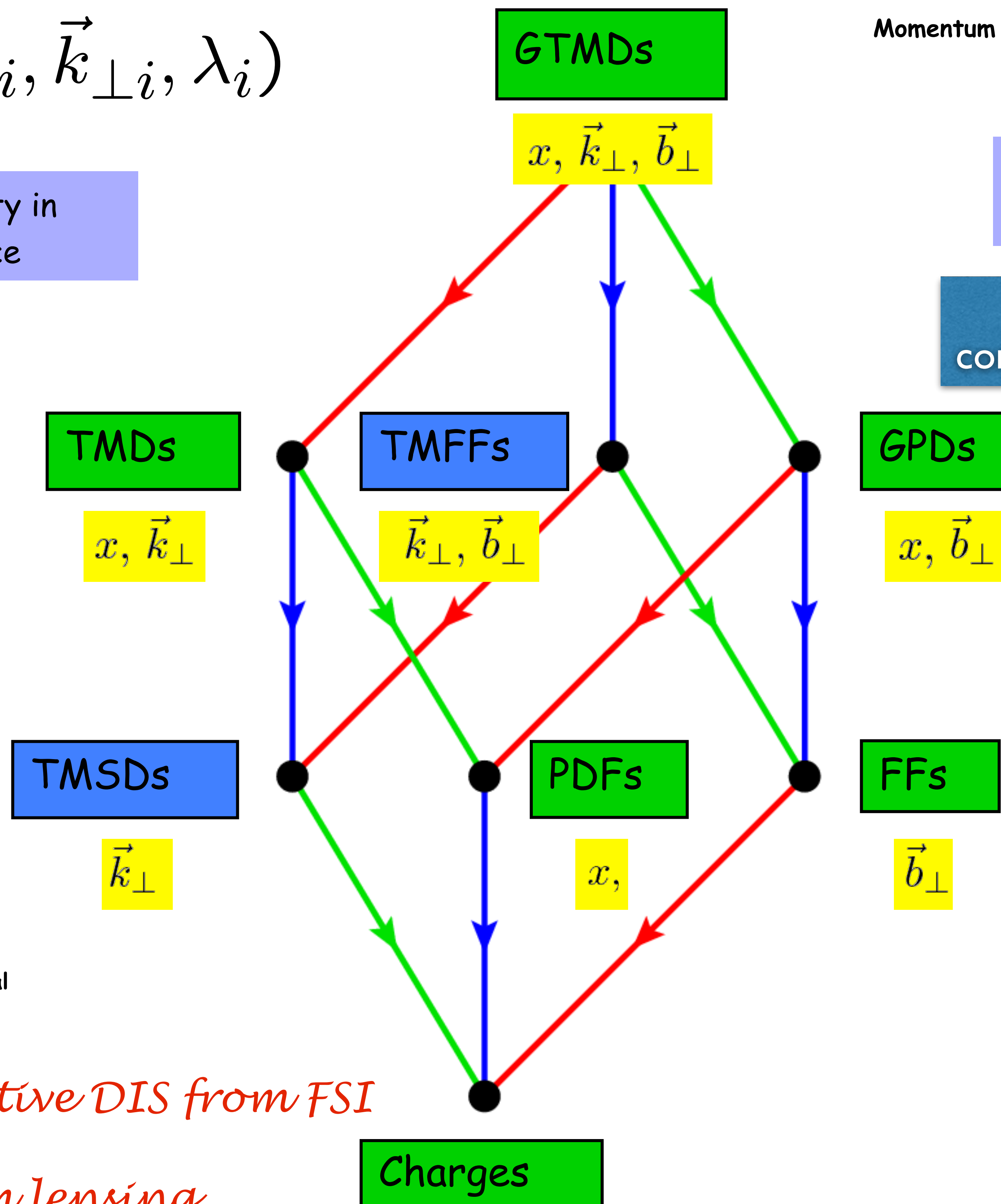
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in momentum space

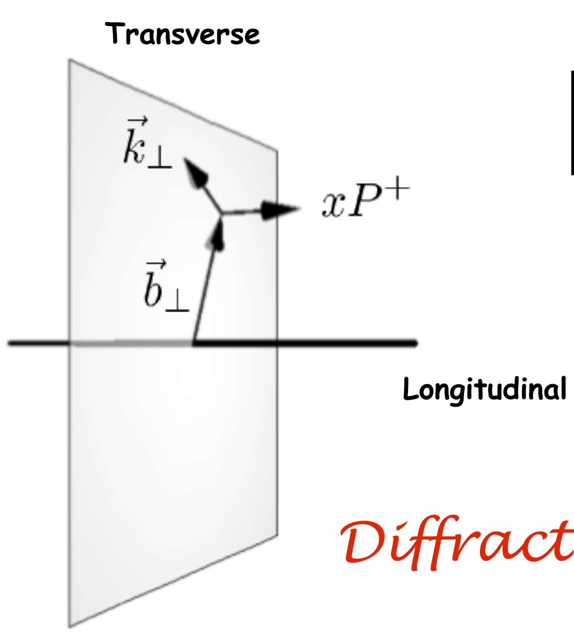
Transverse density in position space

Structure Functions computed from squares of LFWFs

Weak transition form factors

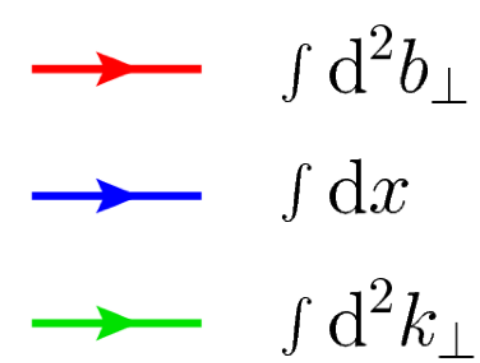


DGLAP, ERBL Evolution Factorization Theorems



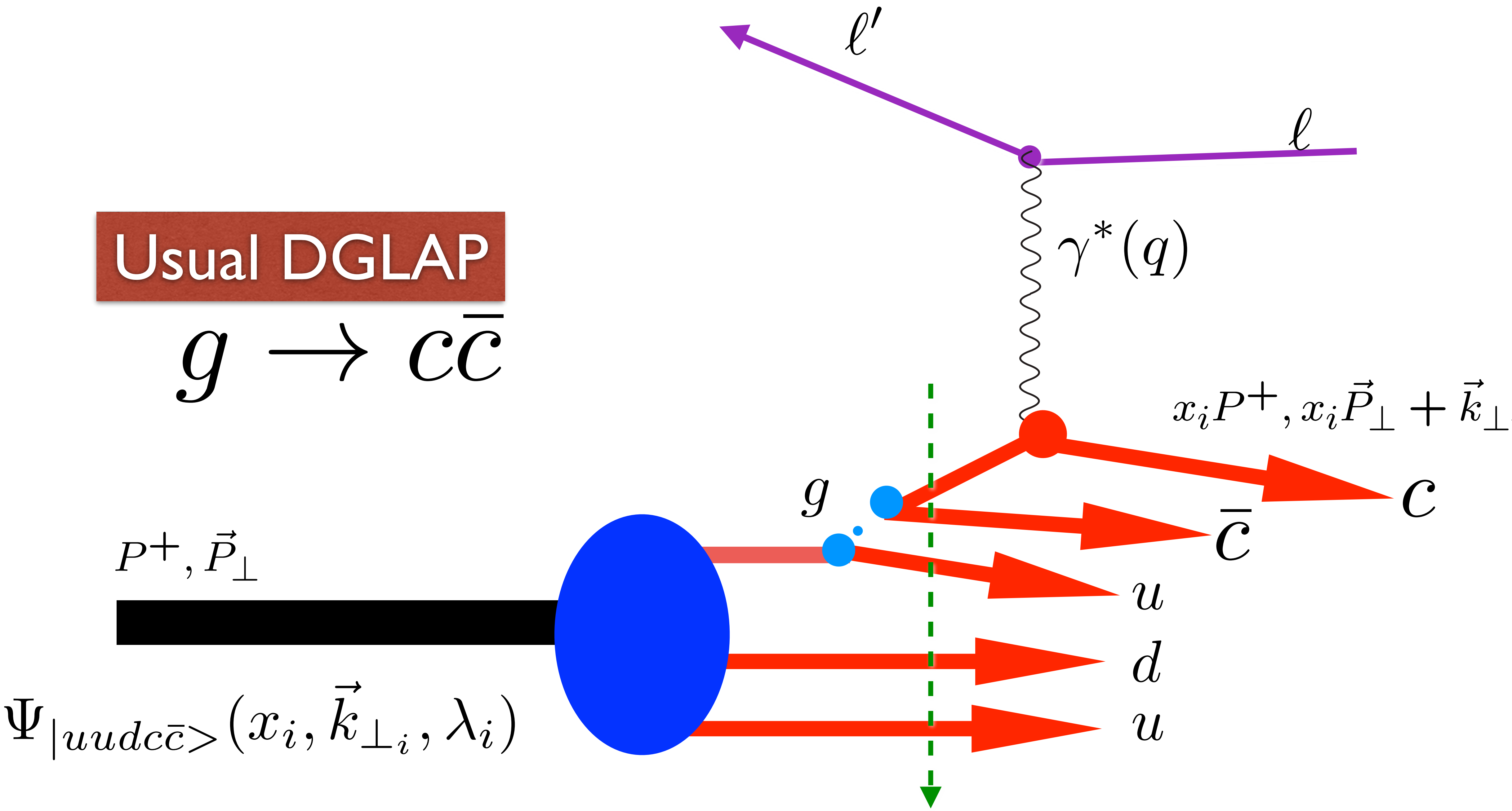
Diffractive DIS from FSI

Sivers, T-odd from lensing



Usual DGLAP

$$g \rightarrow c\bar{c}$$



Fixed $\tau = t + z/c$

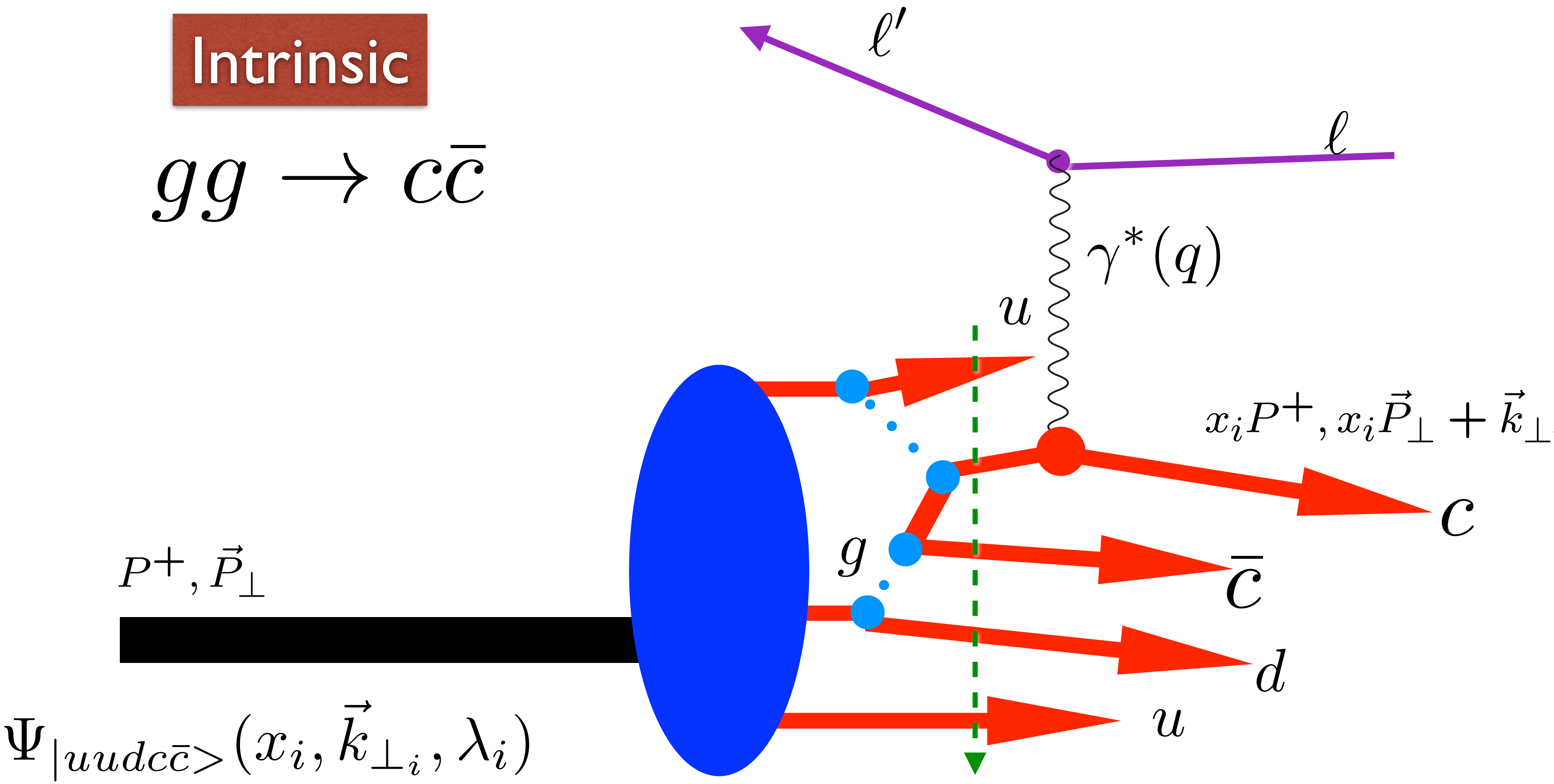
$$\text{Probability } P_{uudc\bar{c}} \sim \log \frac{Q^2+M_c^2}{\Lambda^2_{QCD}}$$

$$\text{low } x\text{: } c(x) \sim (1-x)g(x) \sim (1-x)^4, (1-x)^6$$

Low x extrinsic charm!

Intrinsic

$$gg \to c\bar{c}$$

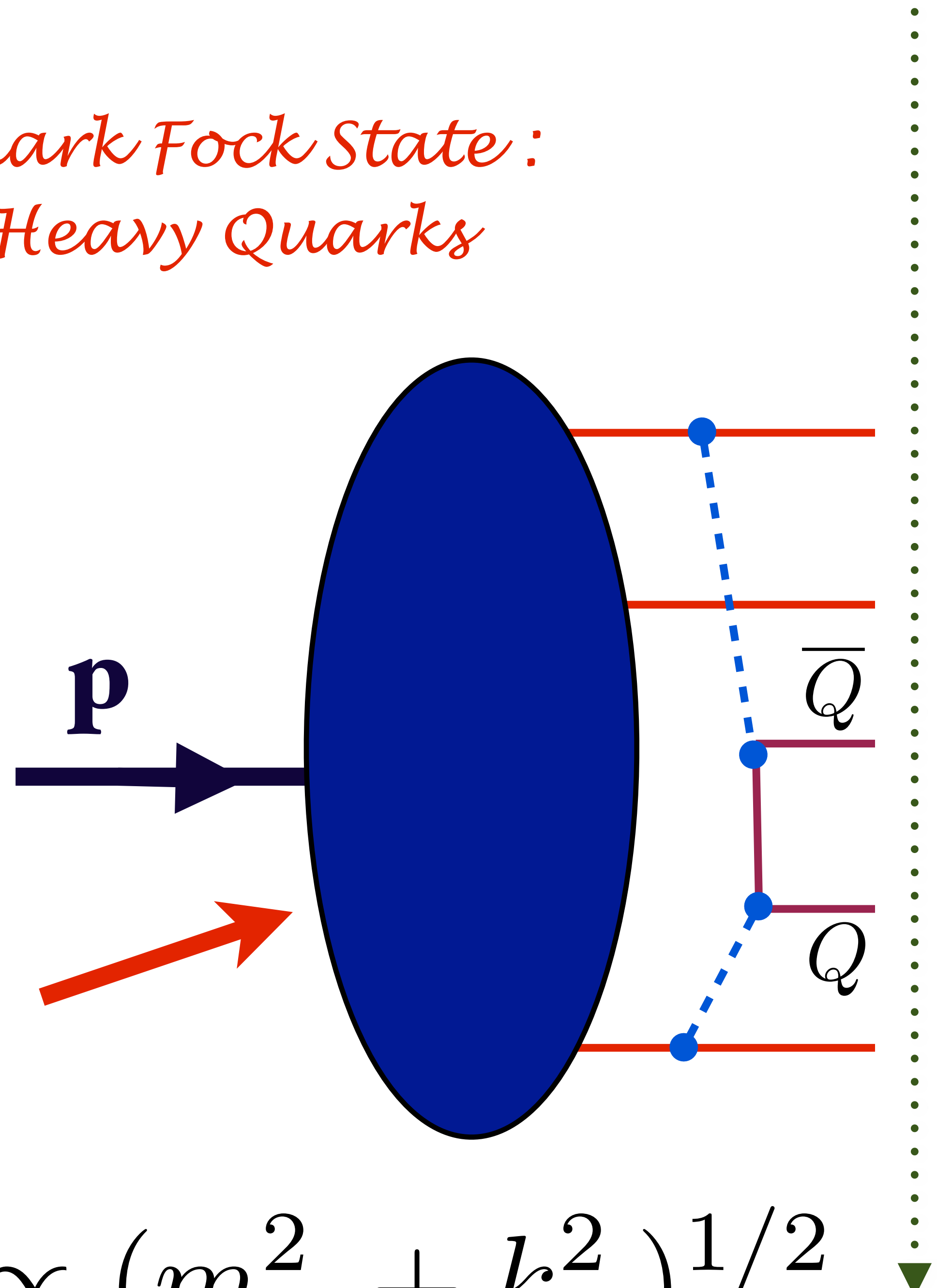


Probability $P_{uudc\bar{c}} \propto \frac{1}{M_c^2}$

$$\hat{x}_c \sim \frac{m_{\perp c}}{\sum_{i=1}^{5} m_{\perp i}} \qquad m_{\perp i}^2 = m_i^2 + \vec{k}_{\perp i}^2$$

High x intrinsic charm!

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



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

QCD predicts Intrinsic Heavy Quarks at high x!

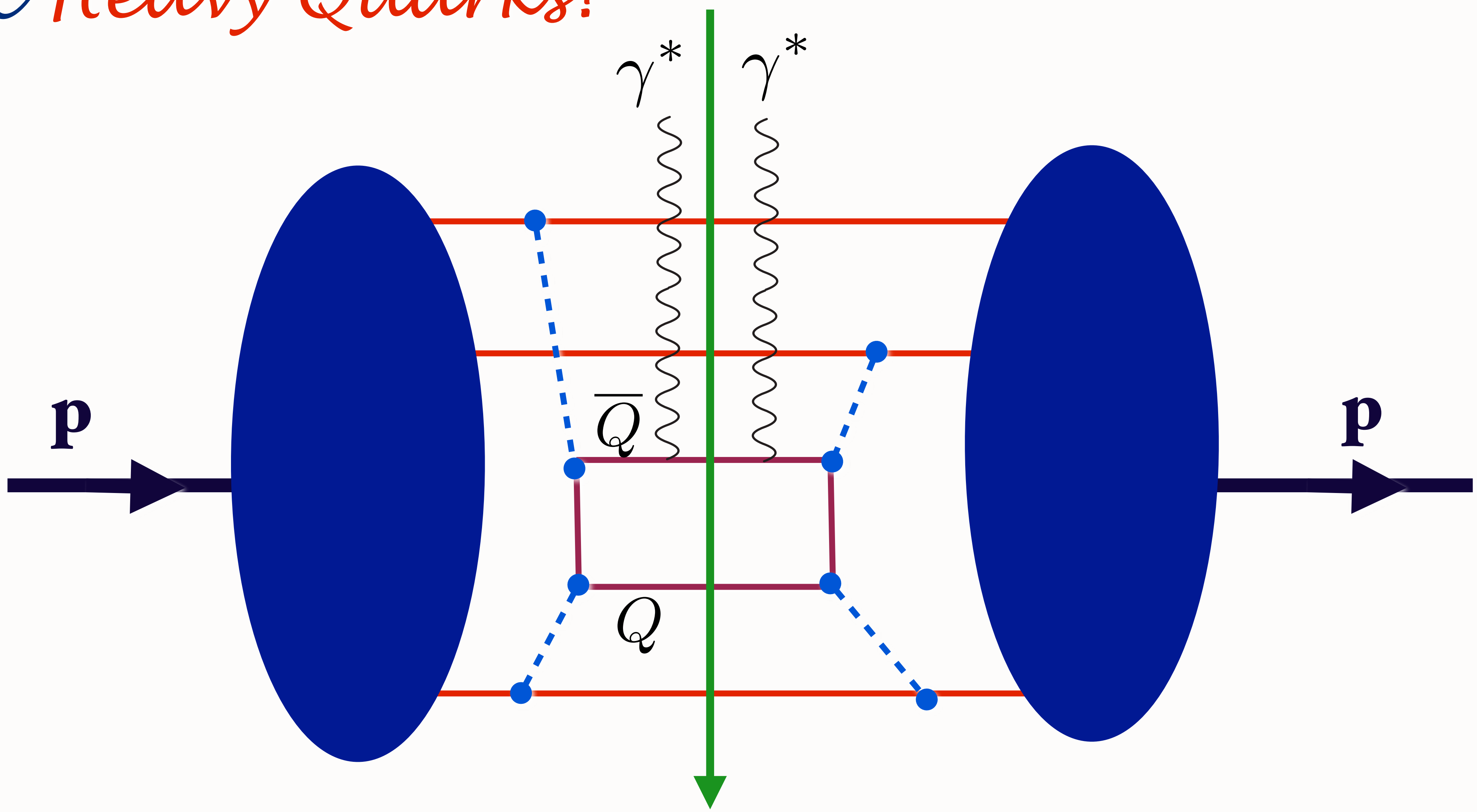
Minimal off-shellness!

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

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

Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

Cut of Proton Self Energy: QCD predicts Intrinsic Heavy Quarks!

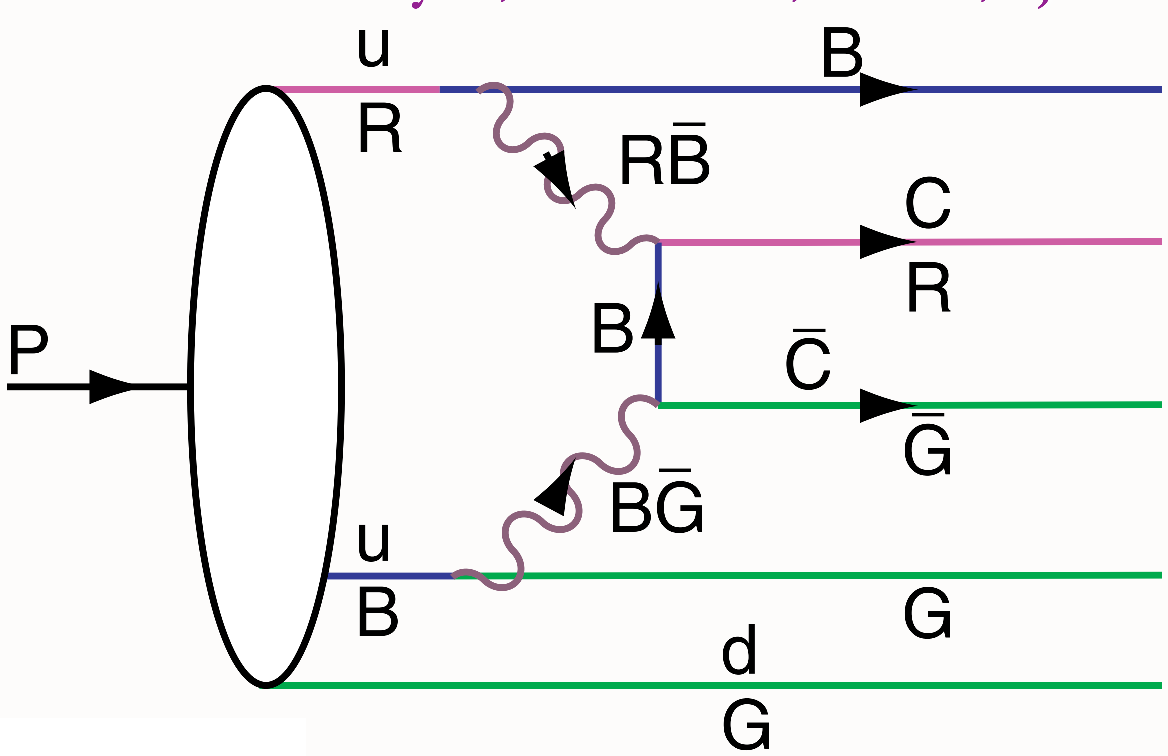


$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

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

Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

BHPS: Hoyer, Peterson, Sakai, sjb



$|uudc\bar{c} >$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^- >$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

$c\bar{c}$ in Color Octet

Distribution peaks at equal rapidity (velocity) Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

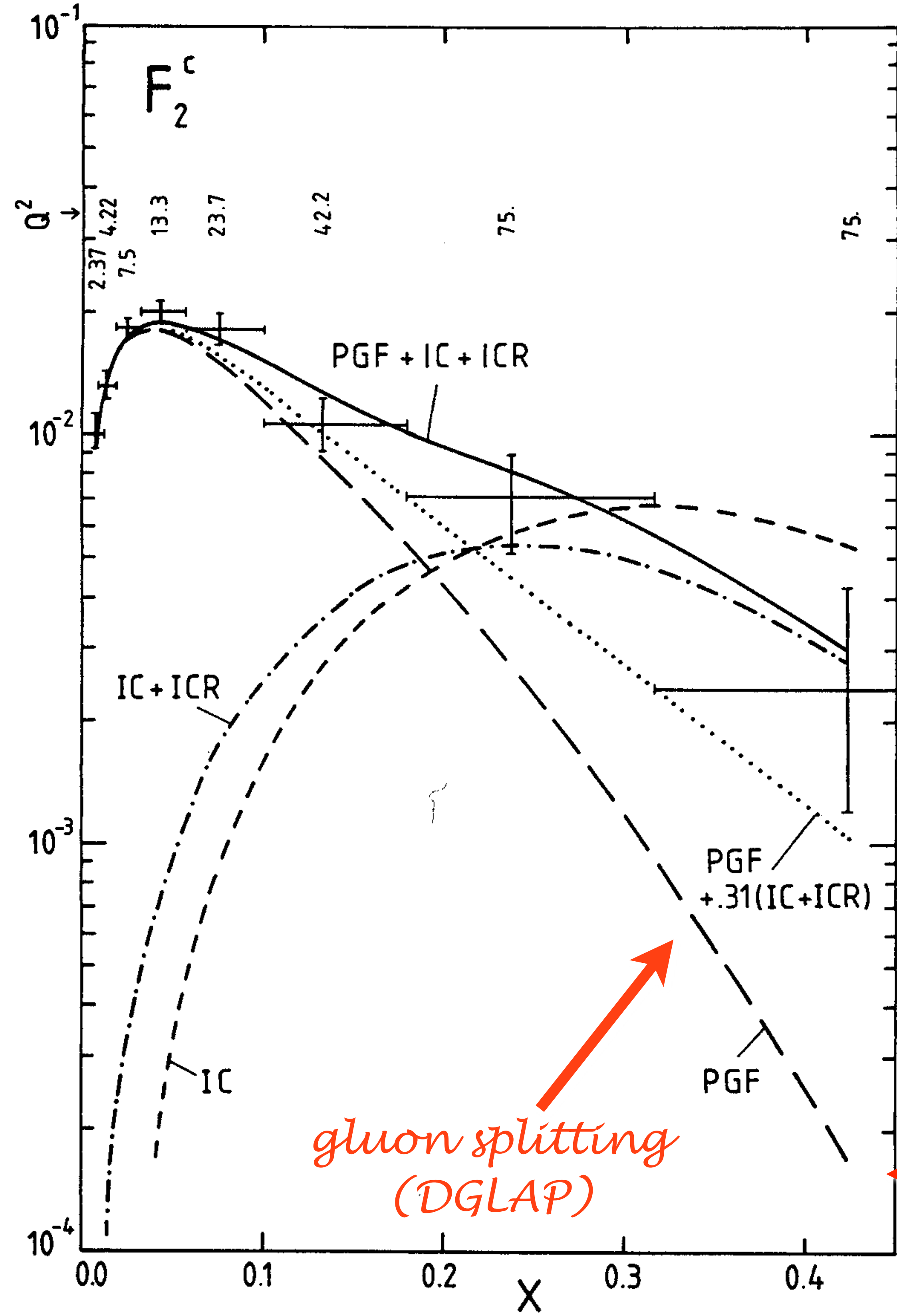
High x charm! *Charm at Threshold*

Action Principle: Minimum KE, maximal potential

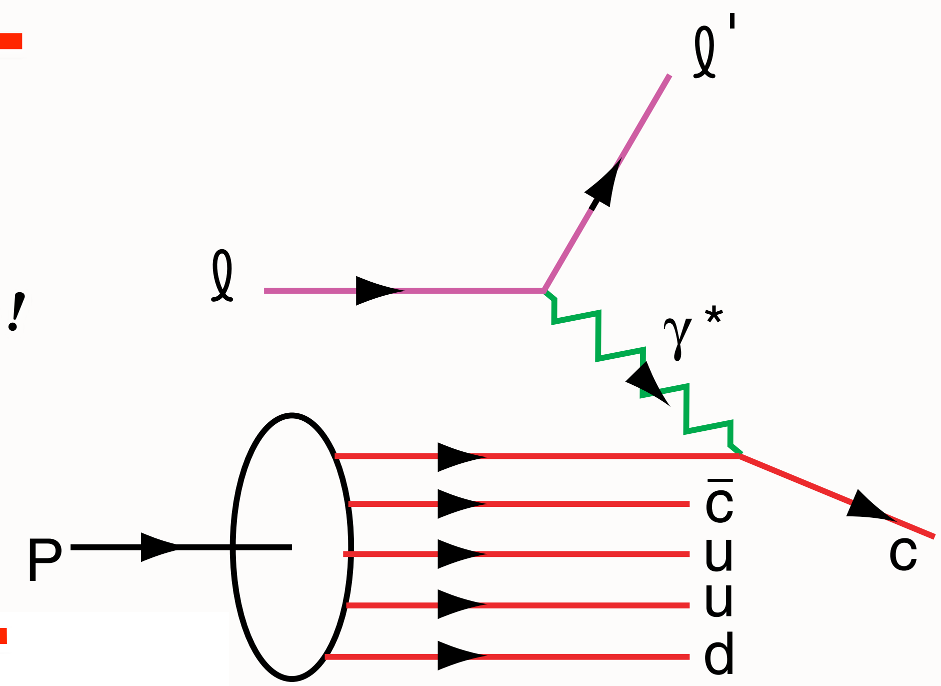
Measurement of Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm



factor of 30 !



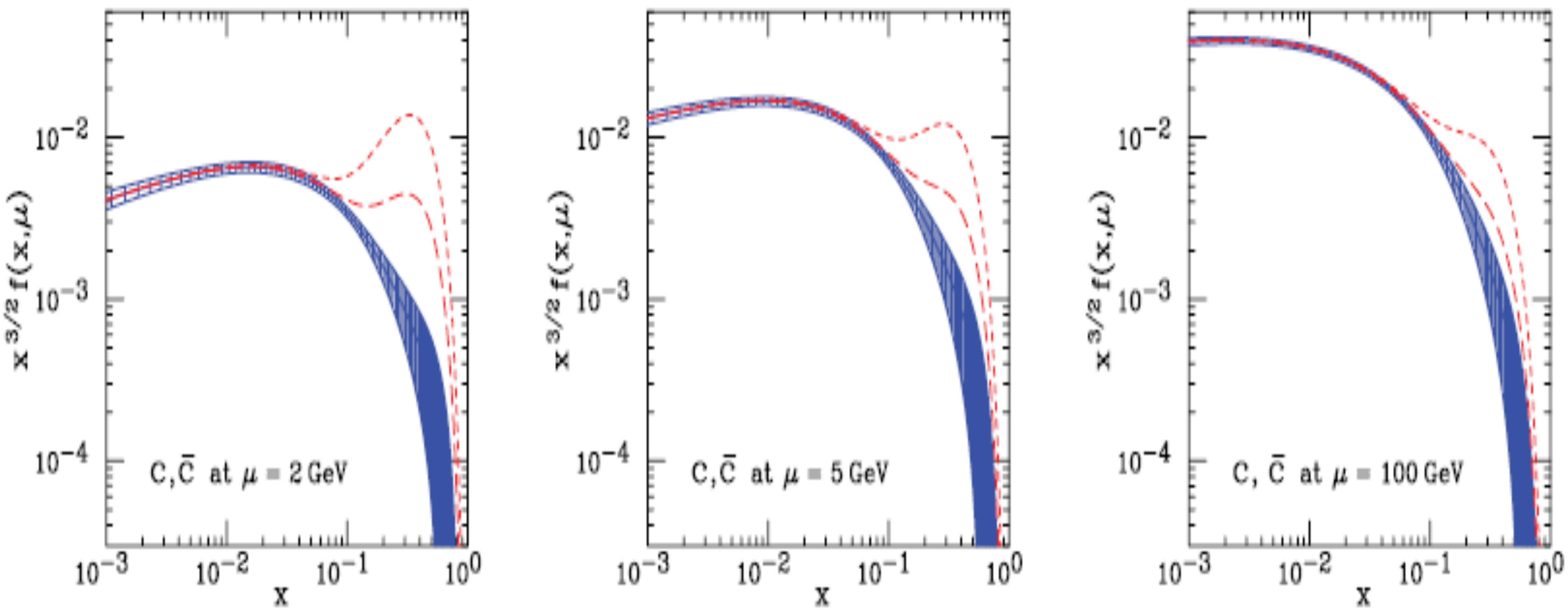
DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

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

G. Lykasov, et al.

CHARM QUARK DISTRIBUTIONS IN PROTON

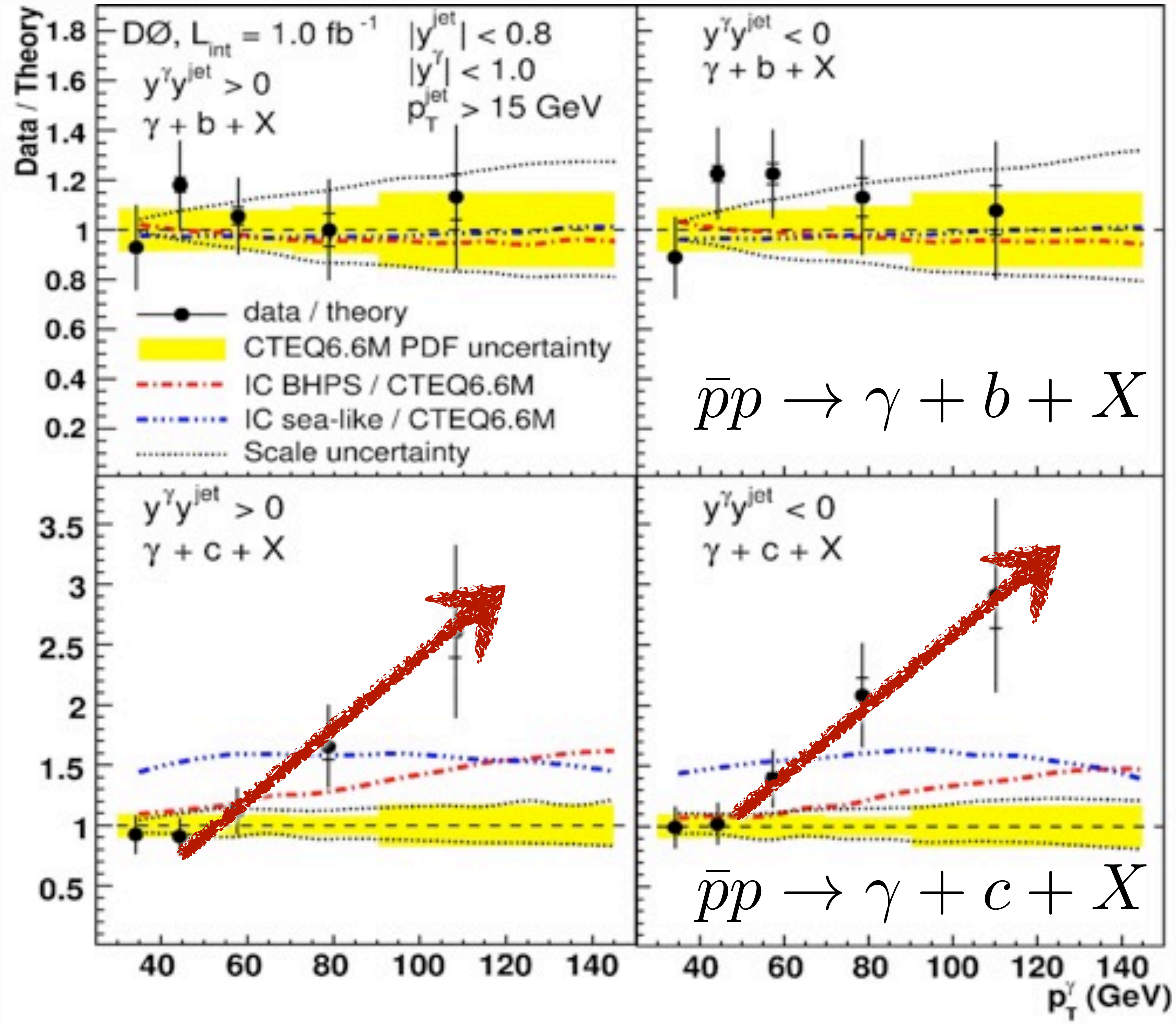


Charm quark distributions within the BHPS model.

DØ

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

$$p\bar{p} \longrightarrow \gamma + Q + X$$



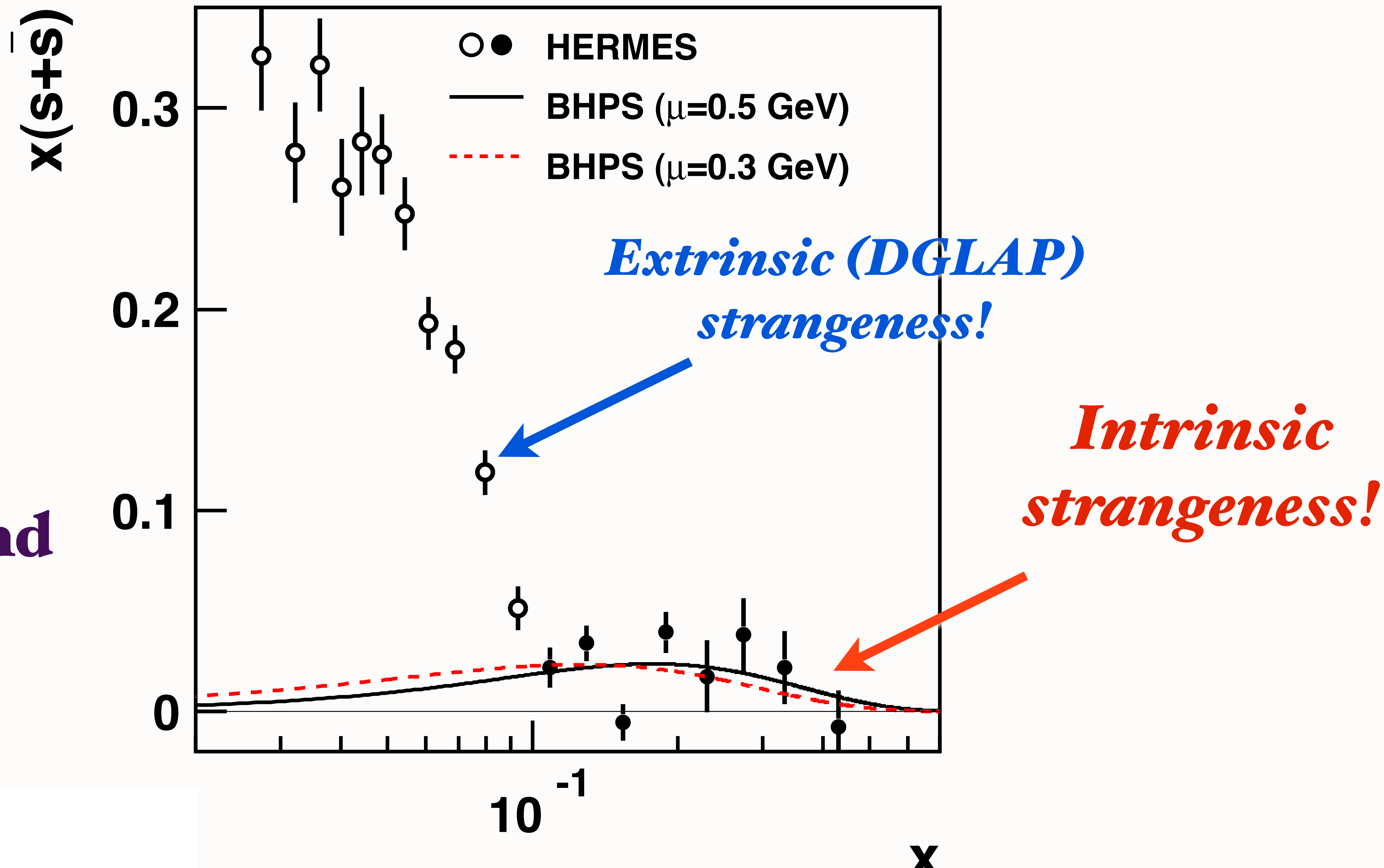
$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio is insensitive to gluon PDF, scales

Consistent with $\frac{m_c^2}{m_b^2}$ relative suppression of intrinsic bottom

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

HERMES: Two components to s(x,Q²)!



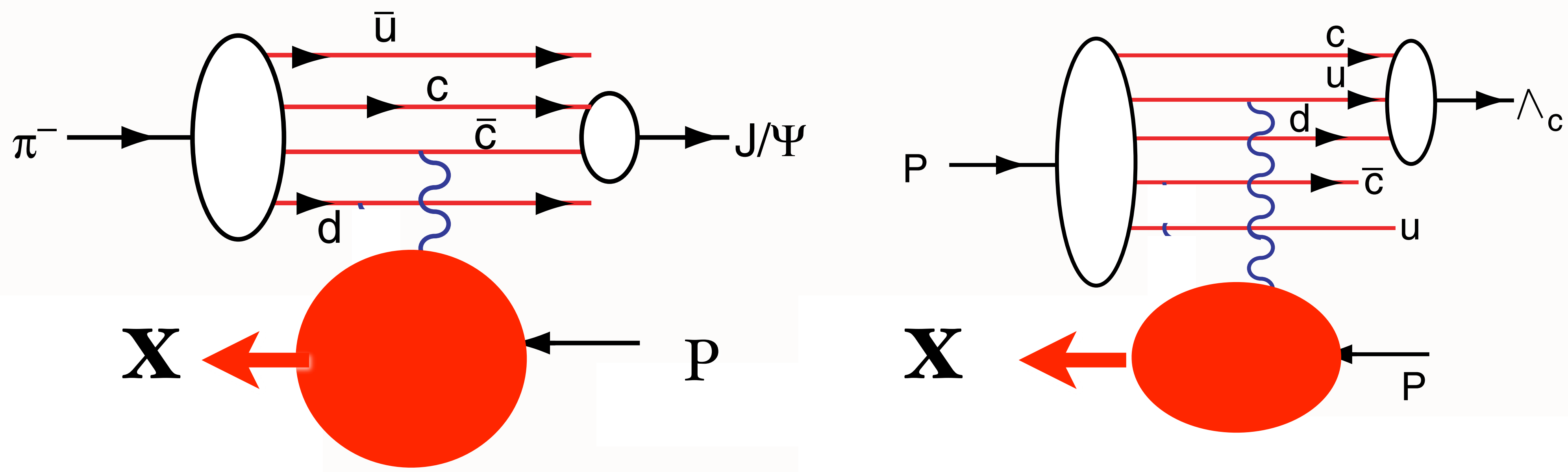
W. C. Chang and J.-C. Peng

arXiv:1105.2381

Comparison of the HERMES $x(s(x) + \bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

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

Leading Hadron Production from Intrinsic Charm



Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

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

CERN NA3

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

- High x_F $pp \to \Lambda_c X$

ISR

- High x_F $pp \to \Lambda_b X$

Intrinsic Bottom!
Zichichi, Cifarelli, et al.

- High x_F $pp \to \Xi(ccd) X$ (SELEX)

FermiLab

IC Structure Function: Critical Measurement for EIC

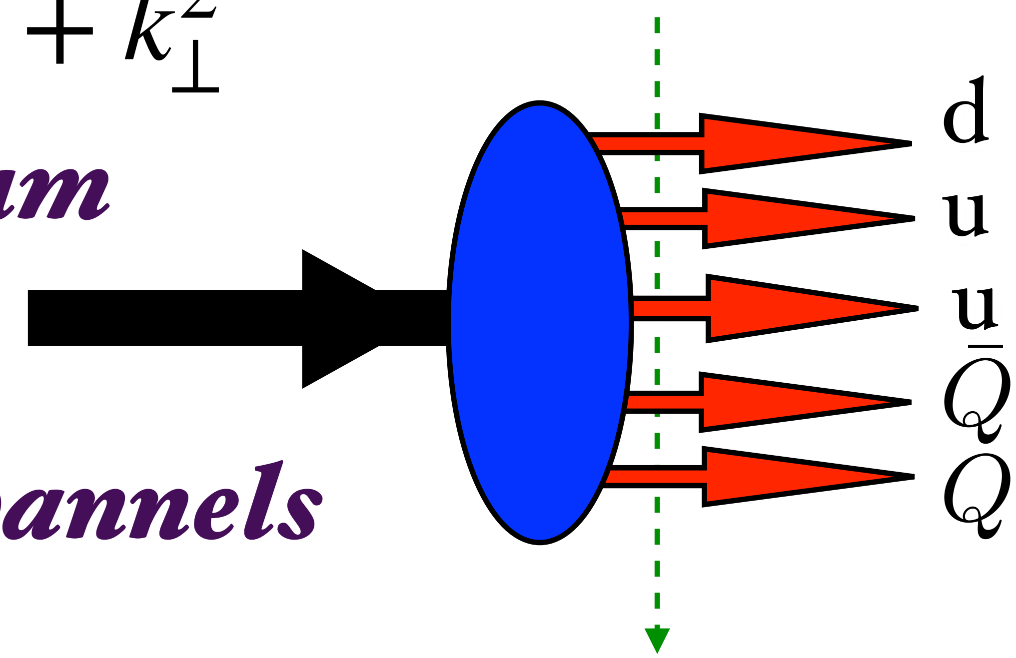
Many interesting spin, charge asymmetry, spectator effects

Properties of Non-Perturbative Five-Quark Fock-State

- ***Dominant configuration: mininum off-shell, same rapidity***
- ***Heavy quarks have most of the LF momentum***

$$< x_Q > \propto \sqrt{m_Q^2 + k_\perp^2}$$

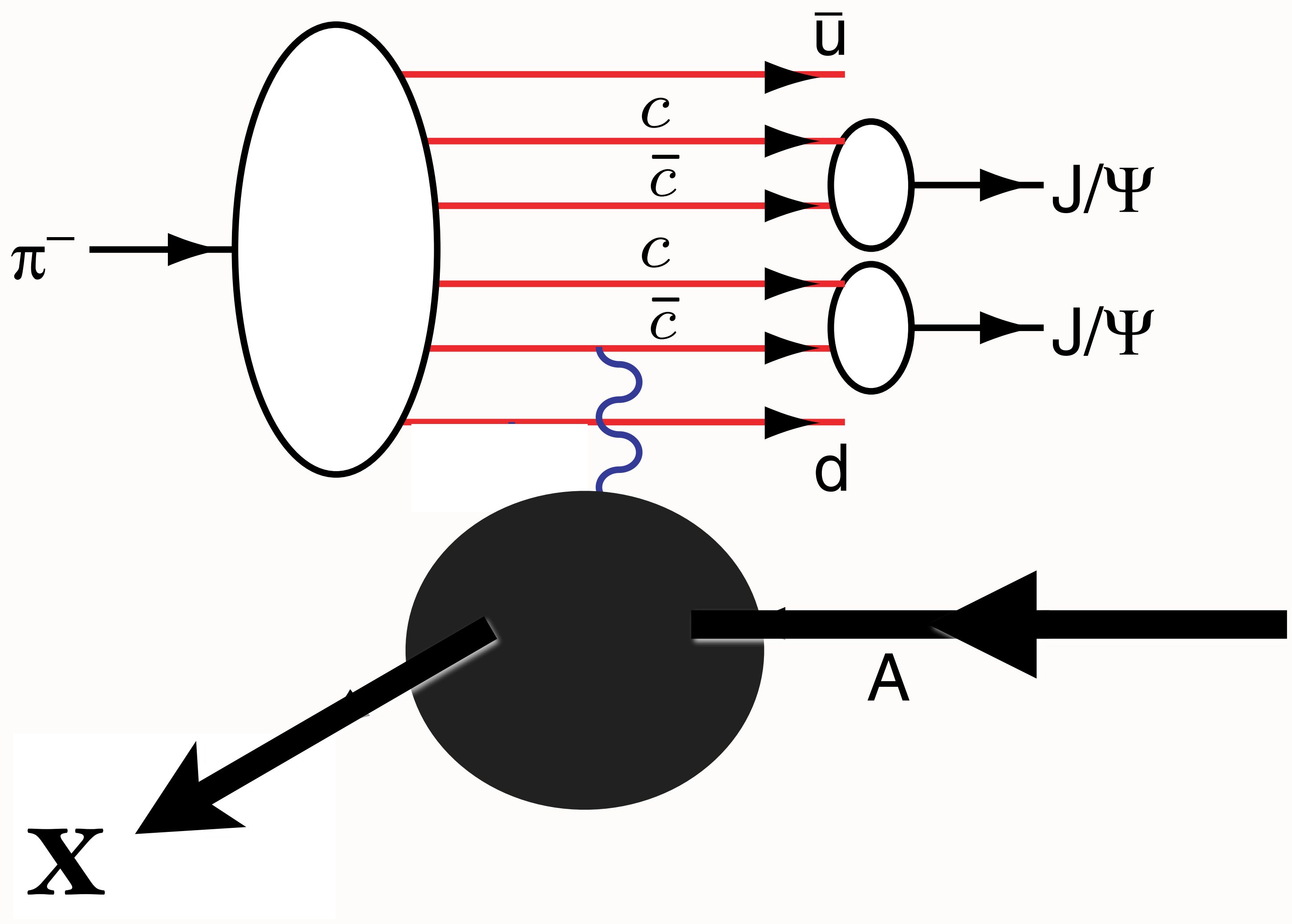
Fixed $\tau = t + z/c$



- ***Correlated with proton quantum numbers***
- ***Duality with meson-baryon channels***
- ***Strangeness, charm asymmetry at x > 0.1***

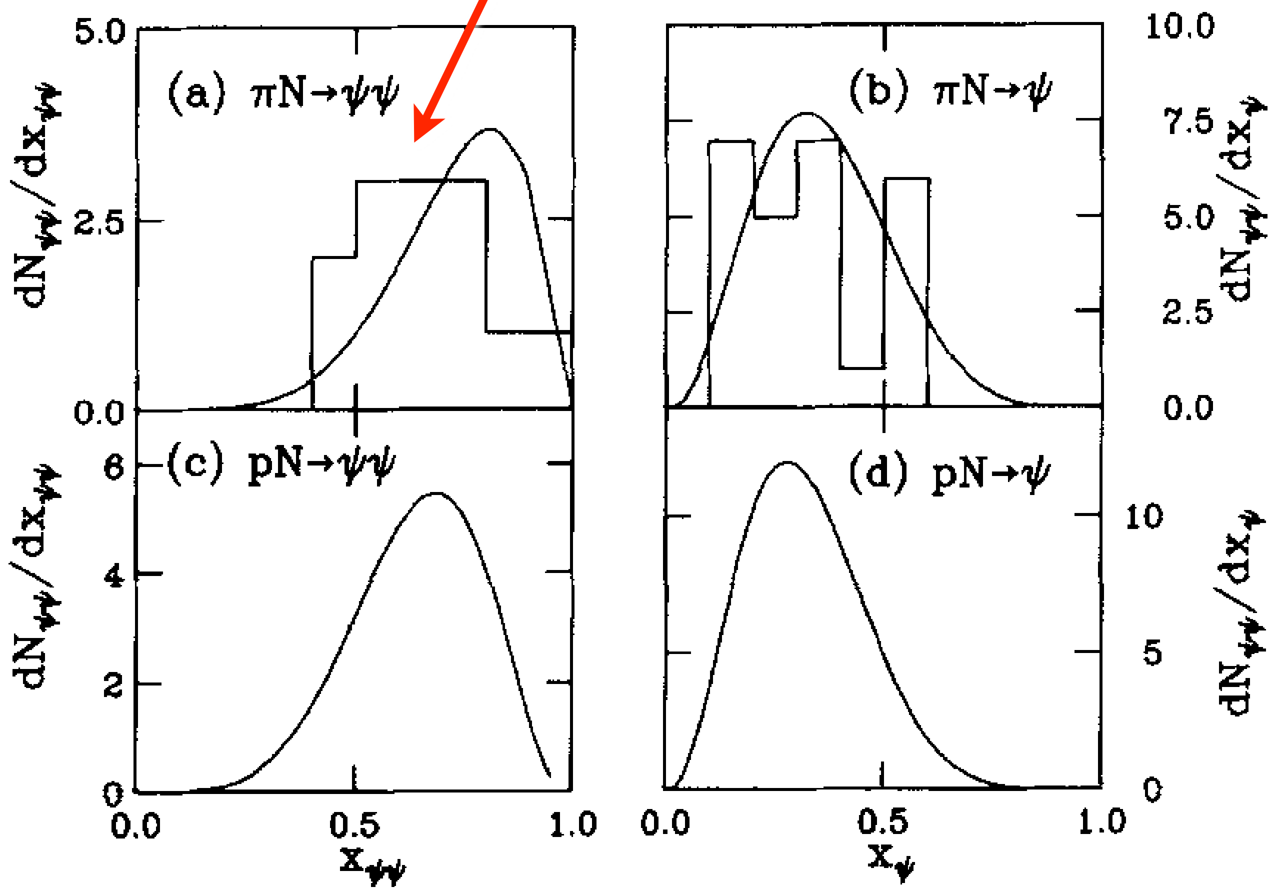
$$s_p(x) \neq \bar{s}_p(x) \quad c_p(x) \neq \bar{c}_p(x)$$

Production of Two Charmonia at High x_F



R. Vogt, sjb

All events have $x^F_{\psi\psi} > 0.4$!



. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

Double J/ψ Production

$\pi A \to J/\psi J/\psi X$

R. Vogt, sjb

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

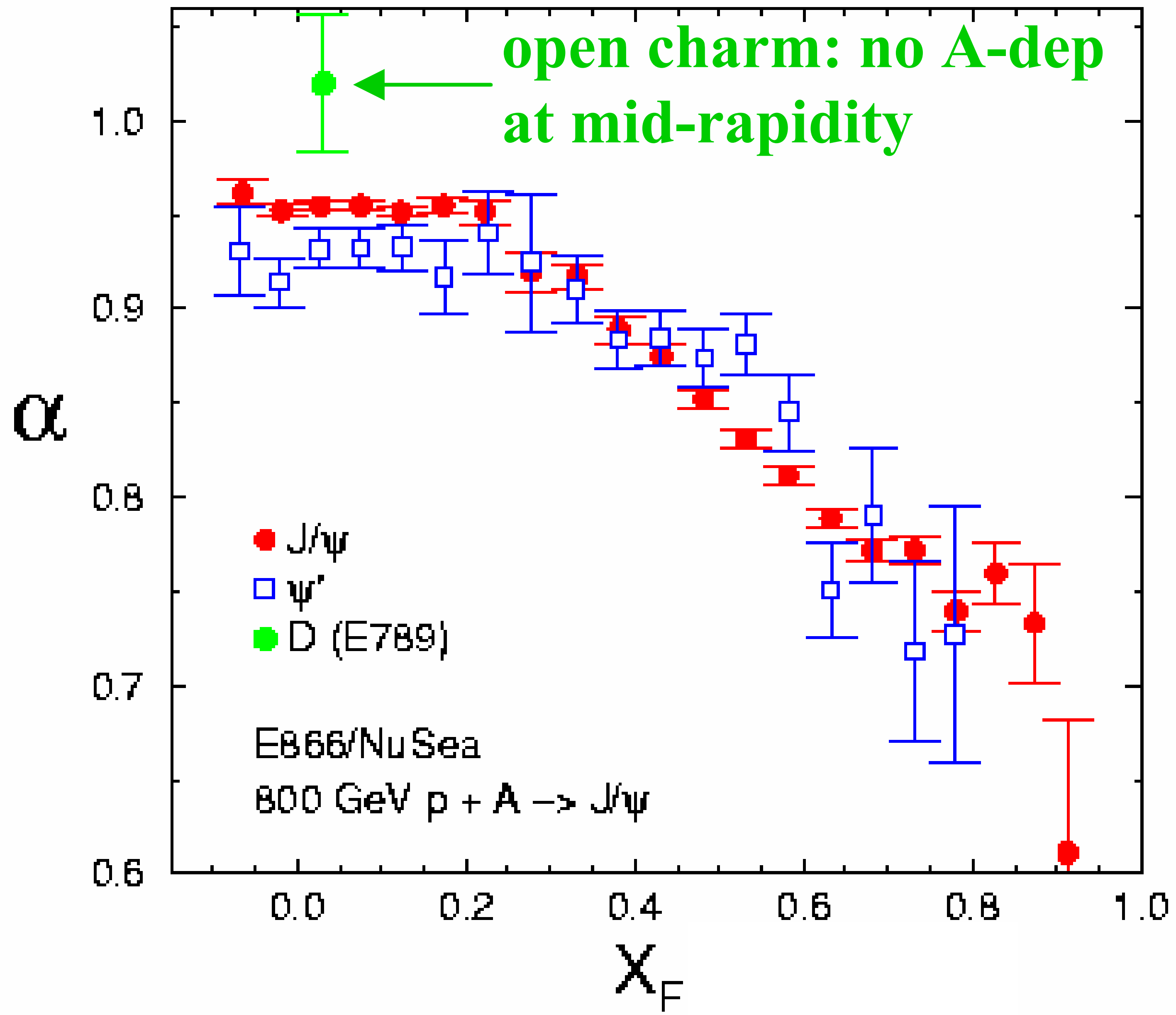
$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\,\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2} \,,$$

Excludes PYTHIA 'color drag' model

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

M. Leitch



Remarkably Strong Nuclear Dependence for Fast Charmonium

$$\frac{\frac{d\sigma}{dx_F}(pA \to J/\psi X)}{\frac{d\sigma}{dx_F}(pp \to J/\psi X)} = A^{\alpha(x_F)}$$

Violation of PQCD Factorization!

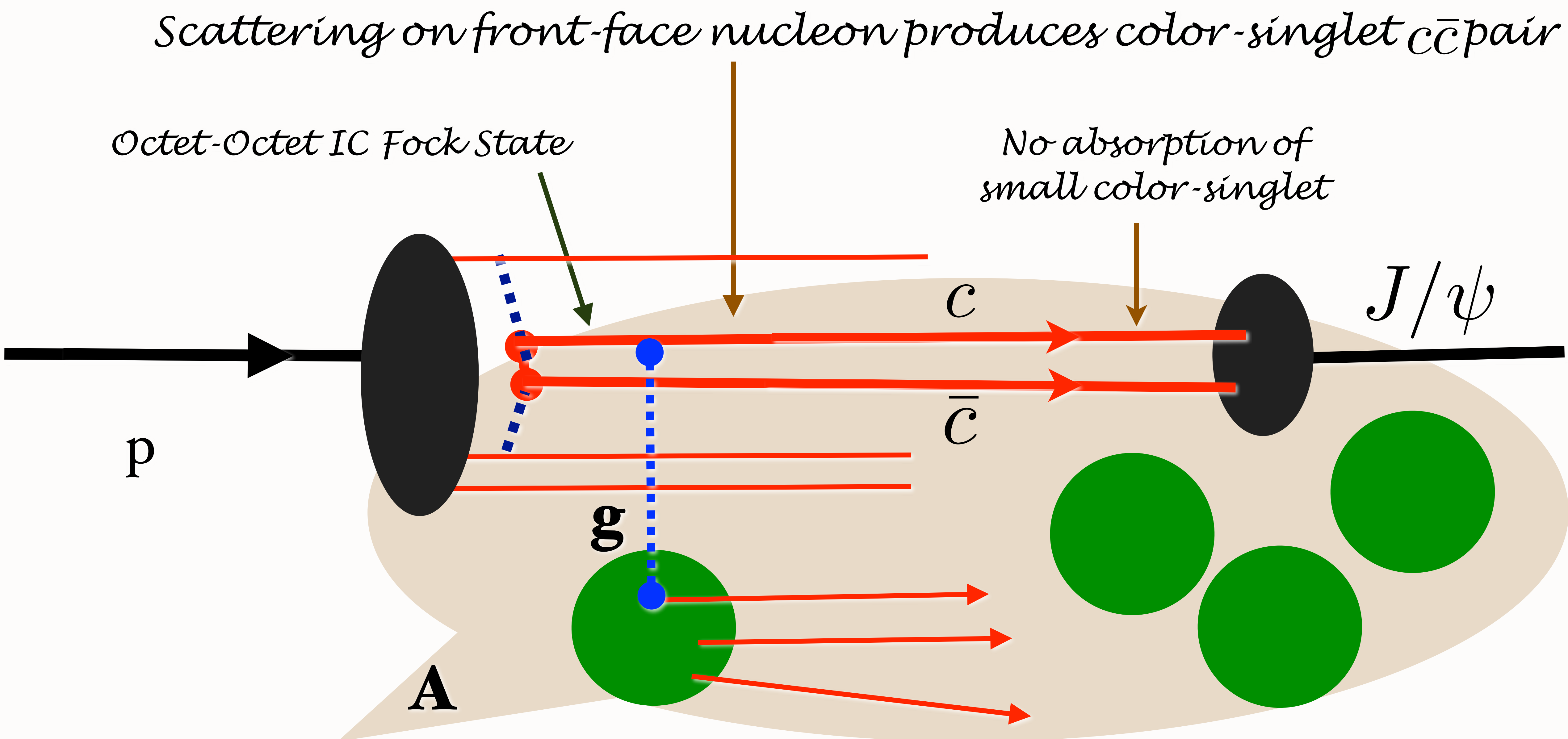
Violation of factorization in charm hadroproduction.
P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) . **HU-TFT-90-14, May 1990. 7pp.**

IC Explains large excess of quarkonia at large x_F, A-dependence

E866/NuSea data for the nuclear A dependence of J/ψ and ψ' hadroproduction.

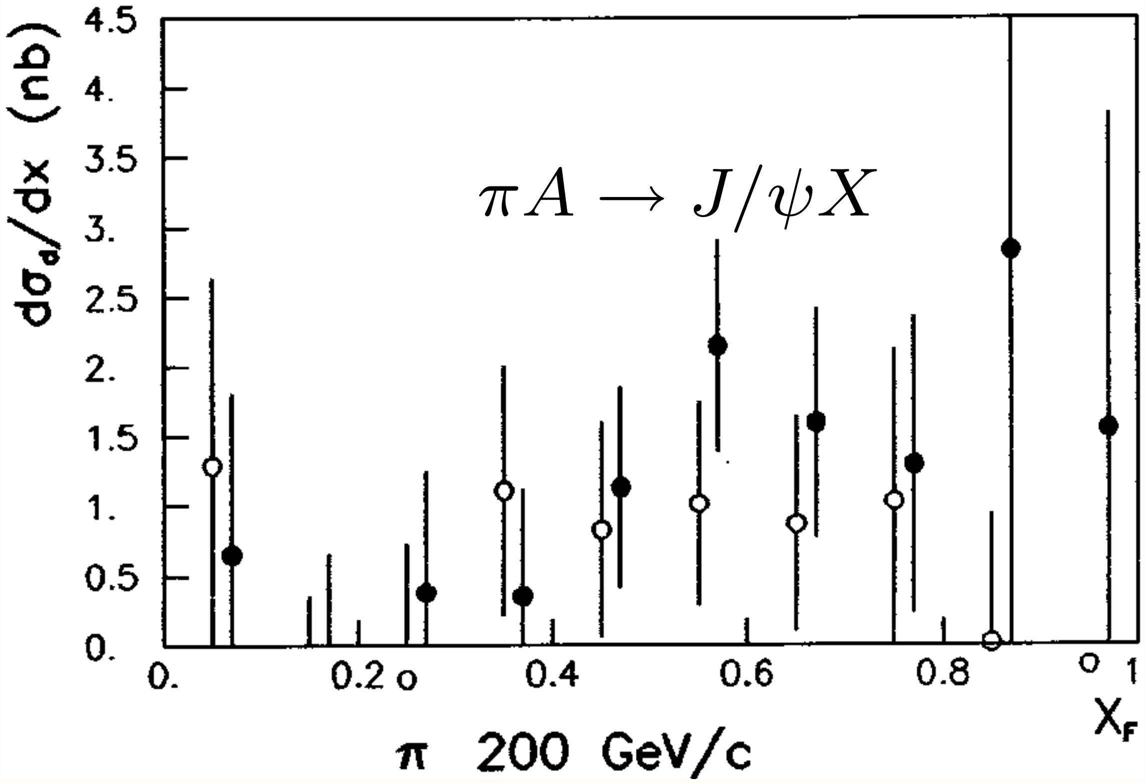
Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb



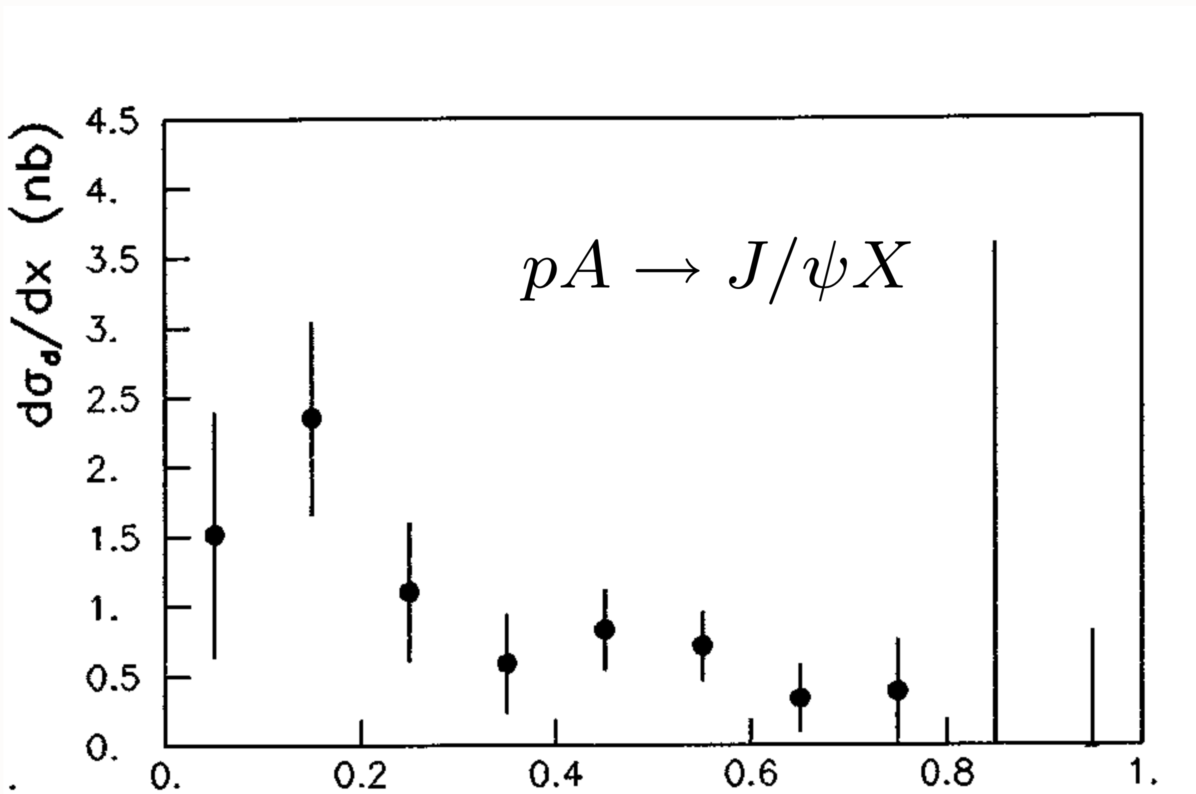
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

J. Badier et al, NA3



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_2}{dx_F}$$

$A^{2/3}$ component



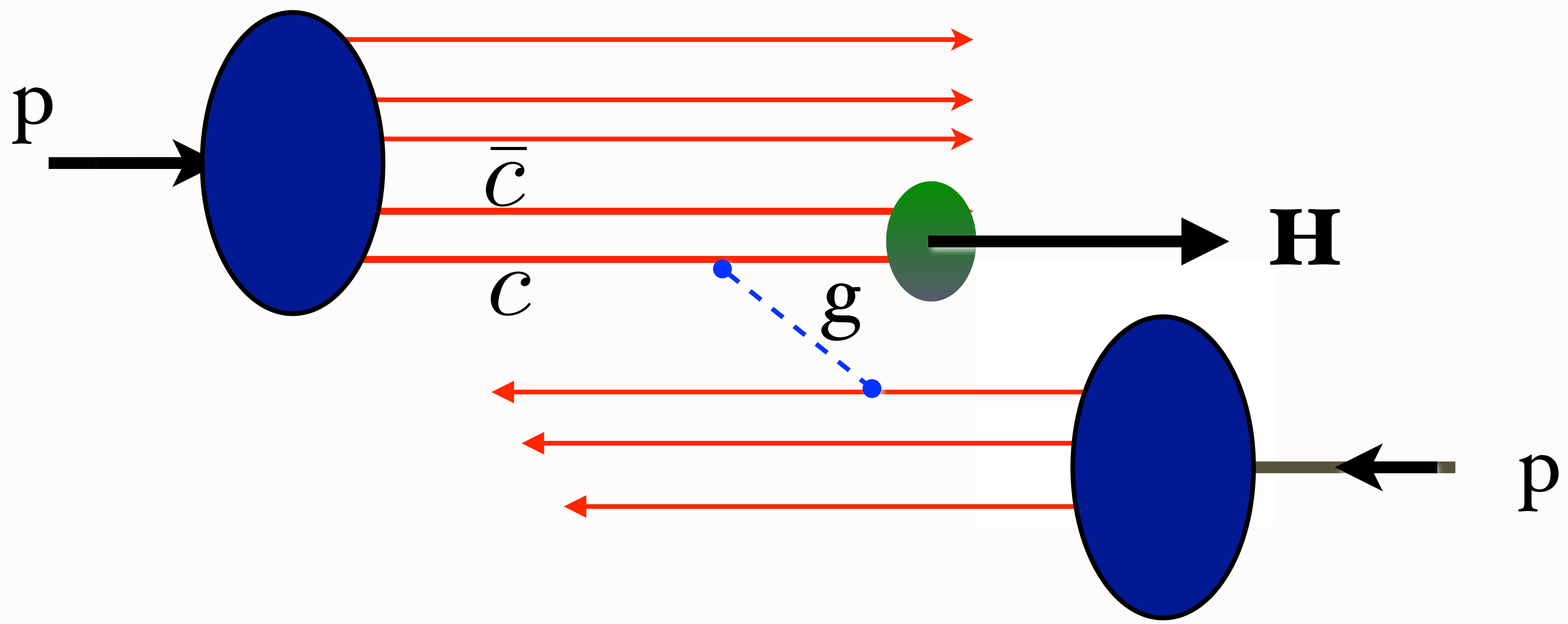
p 200 GeV/c

High x_F:

Consistent with color -octet intrinsic charm

Excess beyond conventional gluon-splitting PQCD subprocesses

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to HX$$

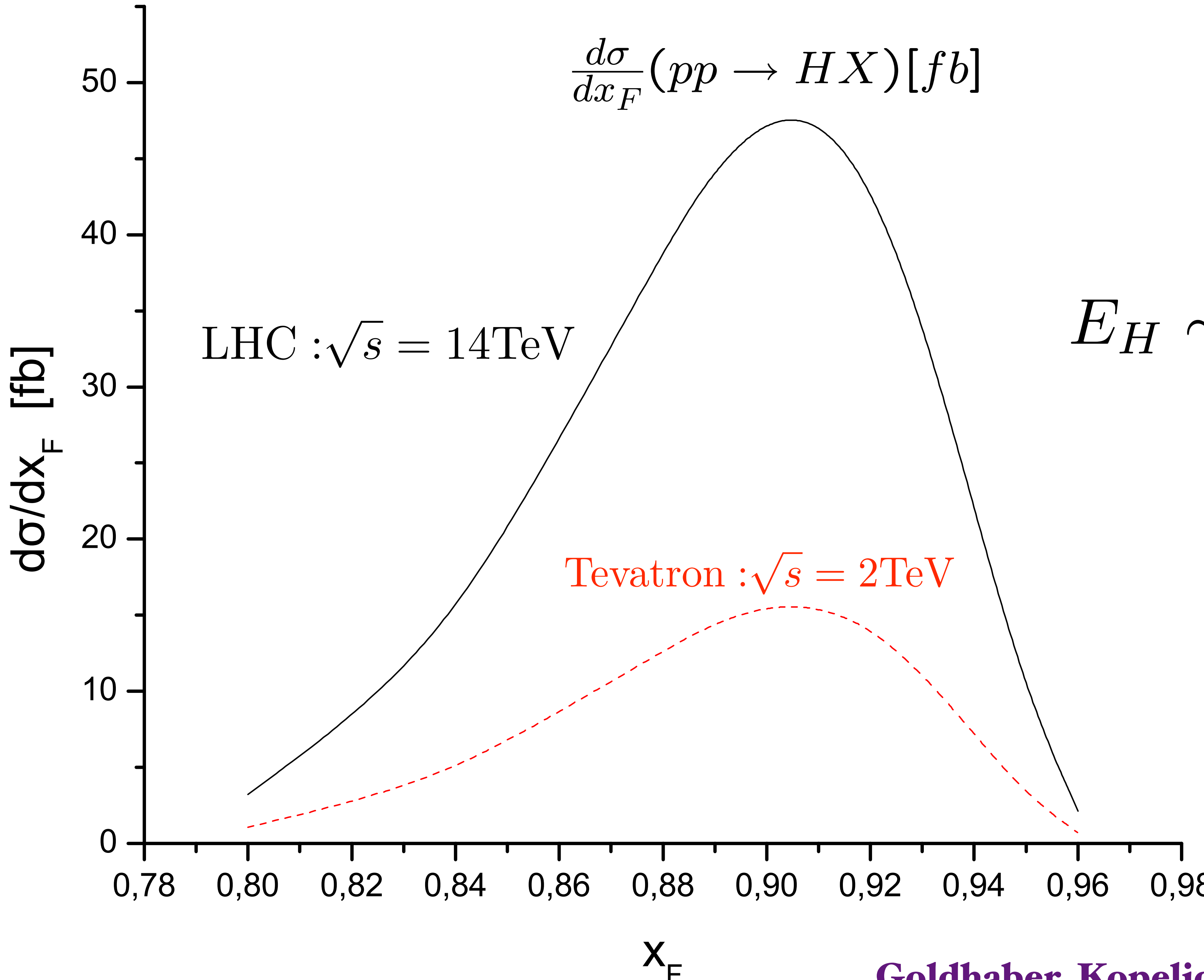
Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$$E_H \sim 0.9 E_p$$

Goldhaber, Kopeliovich, Schmidt, sjb

$$\text{Measure } H \to ZZ^* \to \mu^+\mu^-\mu^+\mu^-.$$

Constraints on charm-anticharm asymmetry in the nucleon from lattice QCD

Raza Sabbir Sufian[a], Tianbo Liu[a], Andrei Alexandru[b,c], Stanley J. Brodsky[d], Guy F. de Téramond[e], Hans Günter Dosch[f], Terrence Draper[g], Keh-Fei Liu[g], Yi-Bo Yang[h]

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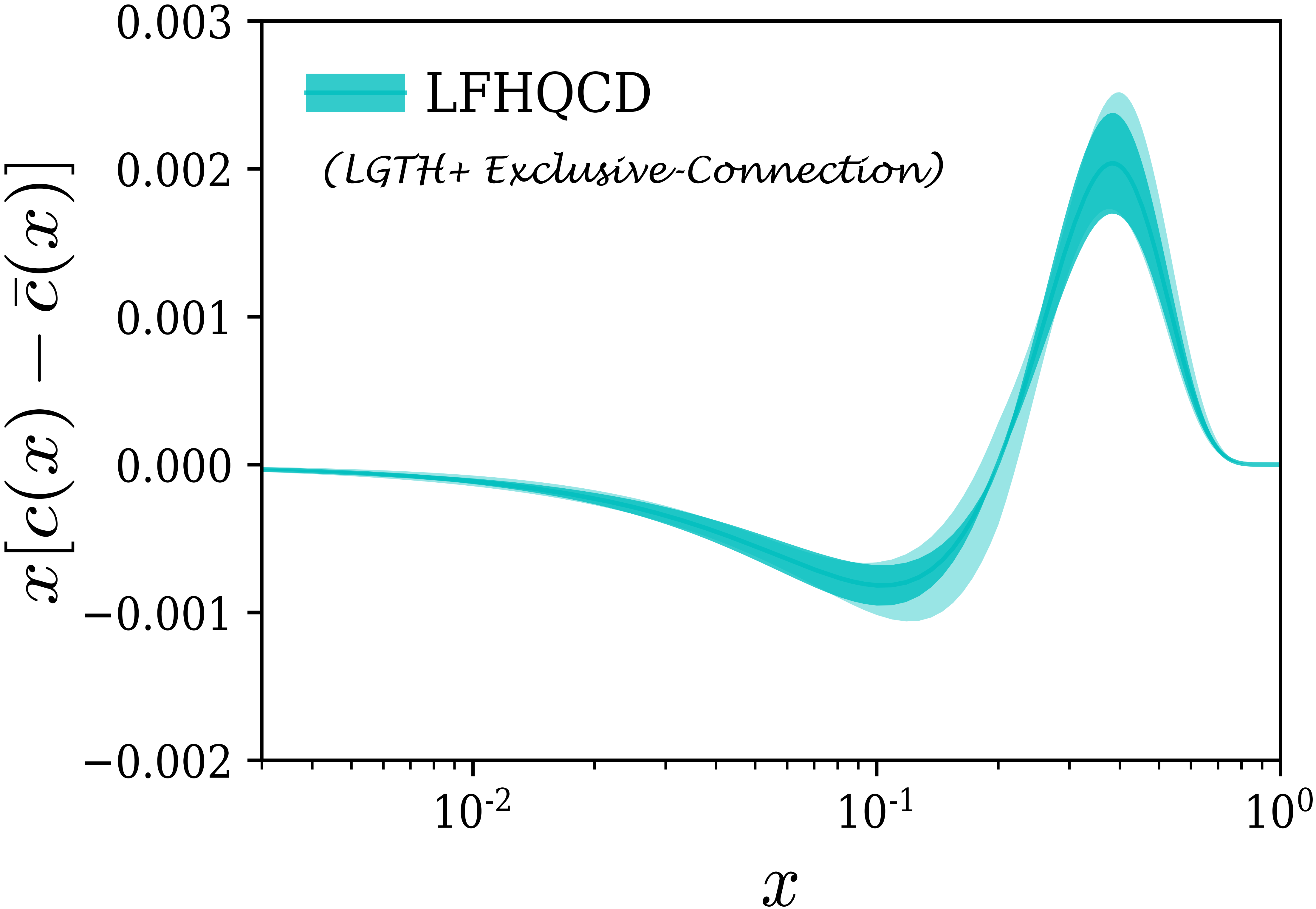
[g] *Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506, USA*
[h] *CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

Abstract

We present the first lattice QCD calculation of the charm quark contribution to the nucleon electromagnetic form factors $G^c_{E,M}(Q^2)$ in the momentum transfer range $0 \leq Q^2 \leq 1.4\ \mathrm{GeV}^2$. The quark mass dependence, finite lattice spacing and volume corrections are taken into account simultaneously based on the calculation on three gauge ensembles including one at the physical pion mass. The nonzero value of the charm magnetic moment $\mu^c_M = -0.00127(38)_{\mathrm{stat}}(5)_{\mathrm{sys}}$, as well as the Pauli form factor, reflects a nontrivial role of the charm sea in the nucleon spin structure. The nonzero $G^c_E(Q^2)$ indicates the existence of a nonvanishing asymmetric charm-anticharm sea in the nucleon. Performing a nonperturbative analysis based on holographic QCD and the generalized Veneziano model, we study the constraints on the $[c(x) - \bar{c}(x)]$ distribution from the lattice QCD results presented here. Our results provide complementary information and motivation for more detailed studies of physical observables that are sensitive to intrinsic charm and for future global analyses of parton distributions including asymmetric charm-anticharm distribution.

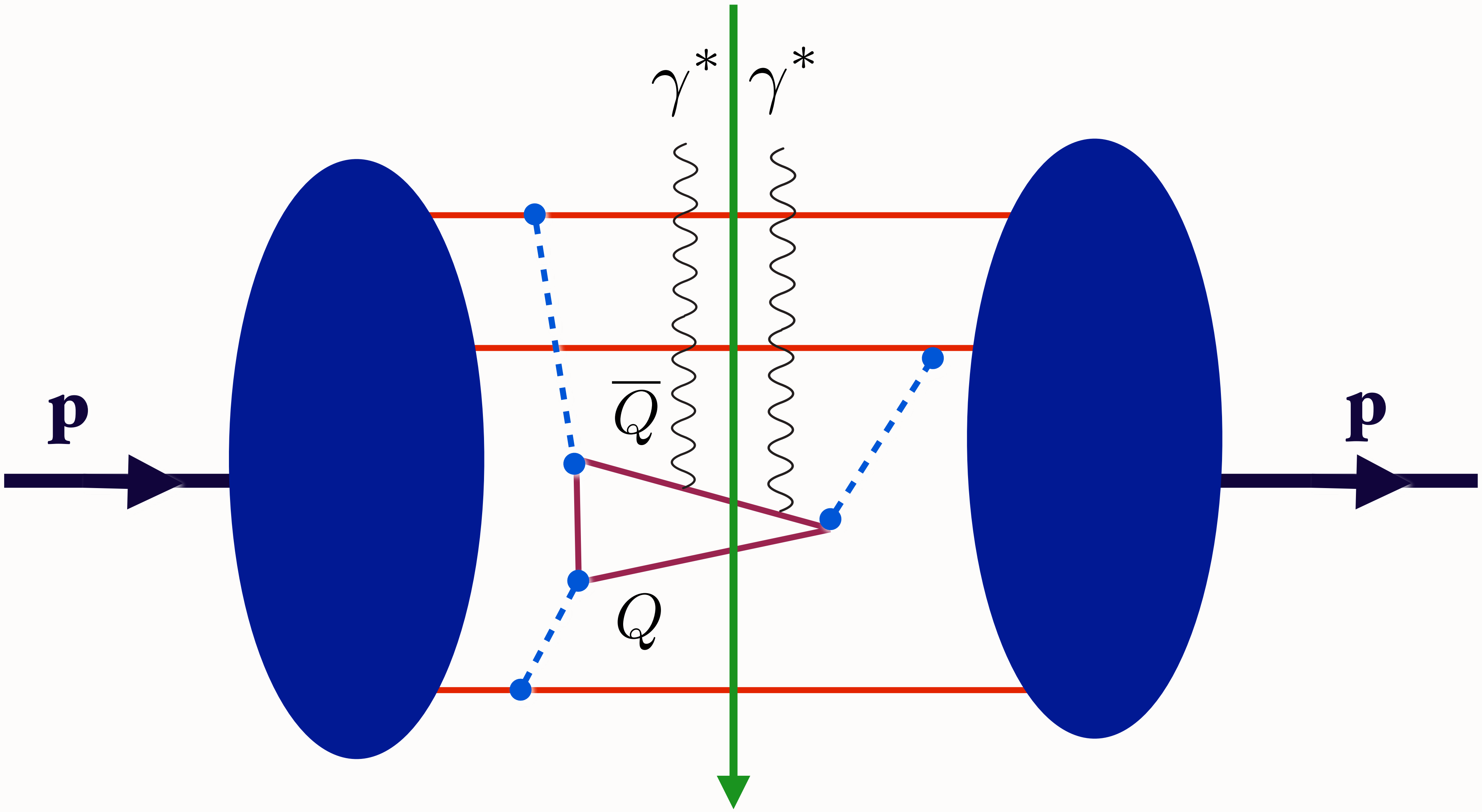
Keywords: Intrinsic charm, Form factor, Parton distributions, Lattice QCD, Light-front holographic QCD, JLAB-THY-20-3155, SLAC-PUB-17515



The distribution function $x[c(x) - \bar{c}(x)]$ obtained from the LFHQCD formalism using the lattice QCD input of charm electromagnetic form factors $G^c_{E,M}(Q^2)$. The outer cyan band indicates an estimate of systematic uncertainty in the $x[c(x) - \bar{c}(x)]$ distribution obtained from a variation of the hadron scale κ_c by 5%.

I.A. Schmidt, V. Lyubovitskij, sjb

Interference of Intrinsic and Extrinsic Heavy Quark Amplitudes



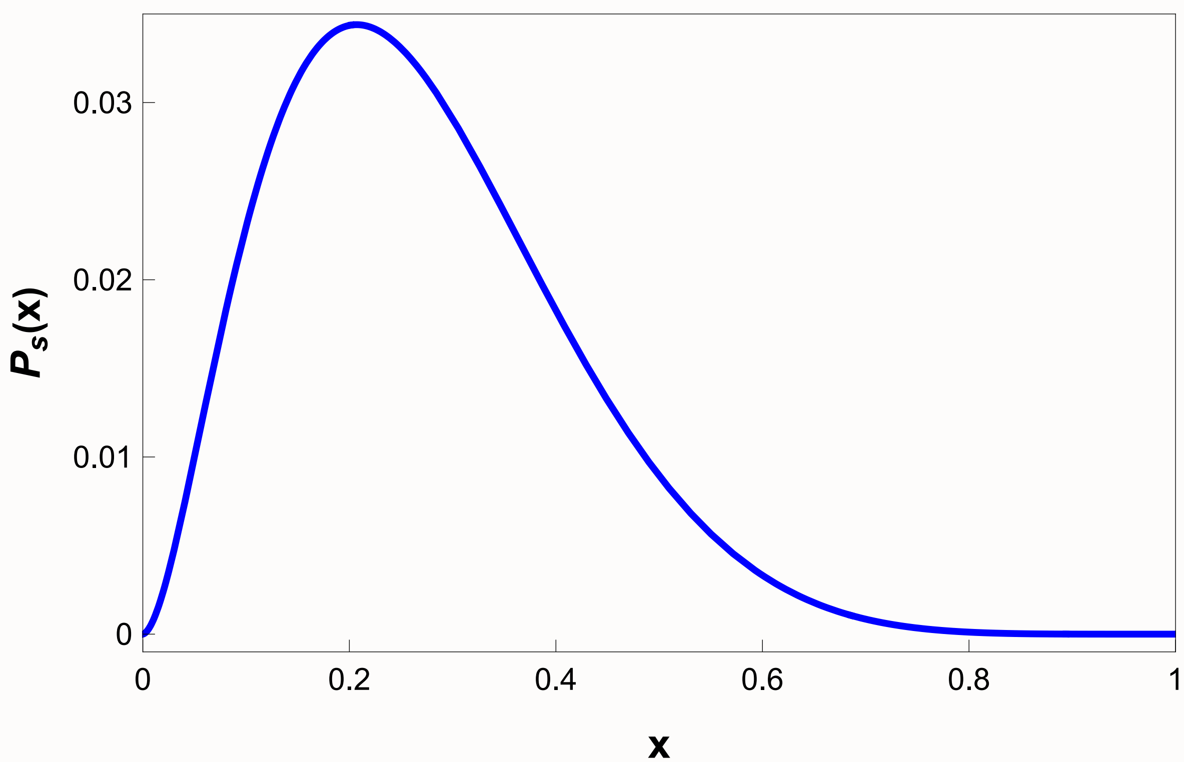
Interference predicts $Q(x) \neq \bar{Q}(x)$

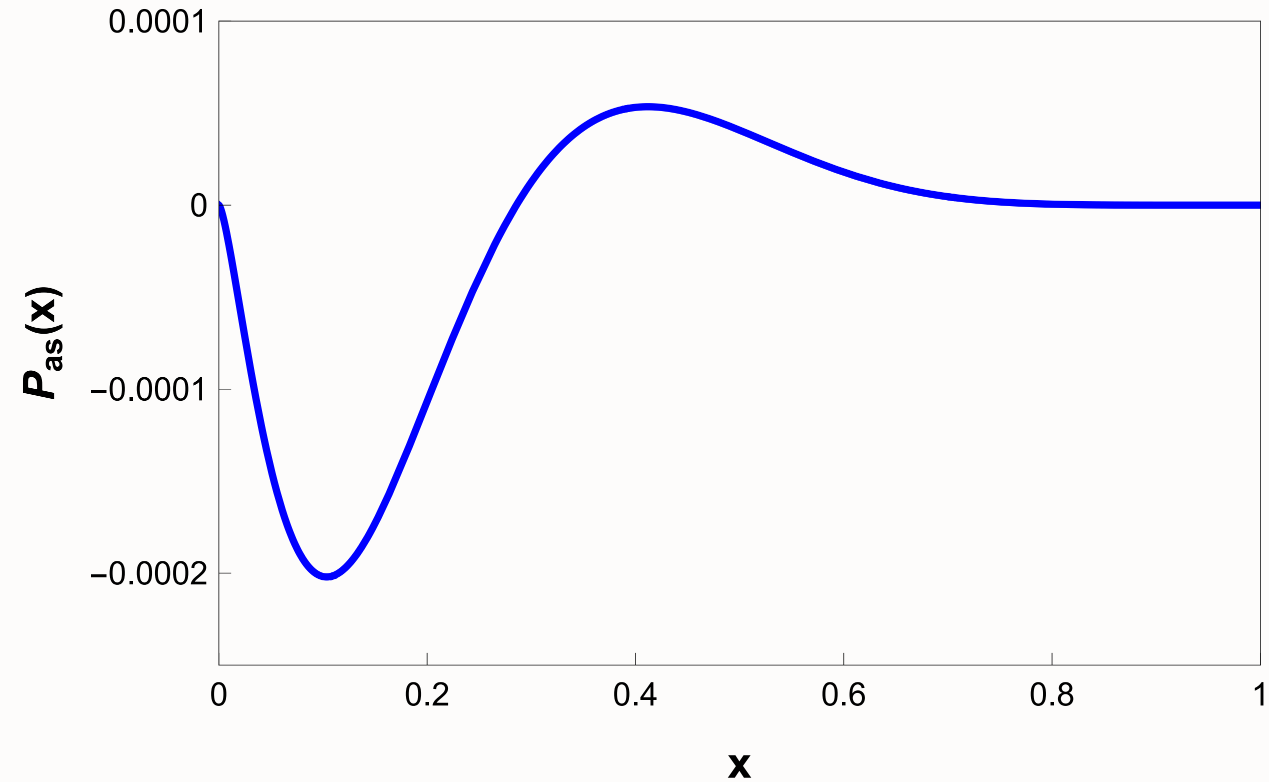
$$\frac{d\sigma}{dy dp_T^2}(pp \to D^+ c\bar{d}X) \neq \frac{d\sigma}{dy dp_T^2}(pp \to D^- \bar{c}dX)$$

QED Analog: J. Gillespie, sjb (1968)

I.A. Schmidt, V. Lyubovitskij, sjb

$$e^- + p \to e^- + Q + \bar{Q} + X.$$



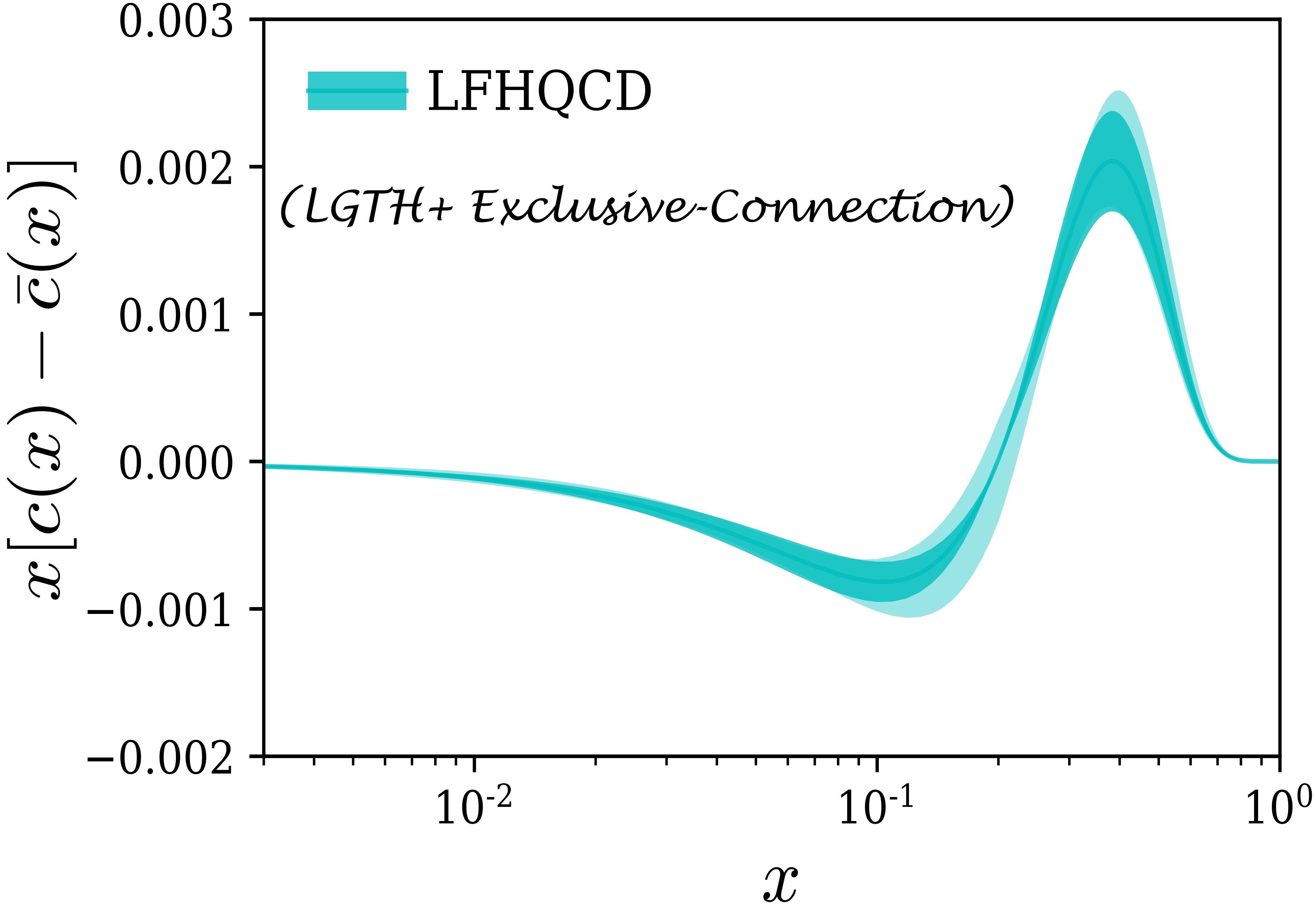


Interference of DGLAP and Intrinsic Heavy Quark Amplitudes

Also: Novel Asymmetry odd in transverse momentum

but CP invariant

$$\begin{aligned}
\psi^{\uparrow}_{Q/\bar{Q};+\frac{1}{2}}(x,\mathbf{k}_\perp) &= -\Big[\psi^{\downarrow}_{Q/\bar{Q};-\frac{1}{2}}(x,\mathbf{k}_\perp)\Big]^\dagger = \frac{\alpha_s C_F}{2\pi}\,\frac{k^1 - ik^2}{\kappa}\,x(1-x)\,\varphi^{(2)}(x,\mathbf{k}_\perp) \quad (L_z = -1)\,,\\
\psi^{\uparrow}_{Q/\bar{Q};+\frac{1}{2}}(x,\mathbf{k}_\perp) &= +\Big[\psi^{\downarrow}_{-1+\frac{1}{2}}(x,\mathbf{k}_\perp)\Big]^\dagger = \frac{\alpha_s C_F}{2\pi}\,x(1-x)\,\varphi^{(1)}(x,\mathbf{k}_\perp^2) \quad (L_z = 0)\,,\\
\psi^{\uparrow}_{Q/\bar{Q};-\frac{1}{2}}(x,\mathbf{k}_\perp) &= -\Big[\psi^{\downarrow}_{Q/\bar{Q};+\frac{1}{2}}(x,\mathbf{k}_\perp)\Big]^\dagger = -\frac{\alpha_s C_F}{2\pi}\,\frac{k^1 + ik^2}{\kappa}\,x(1-x)^2\,\varphi^{(2)}(x,\mathbf{k}_\perp^2) \quad (L_z = 1)\,,
\end{aligned}$$



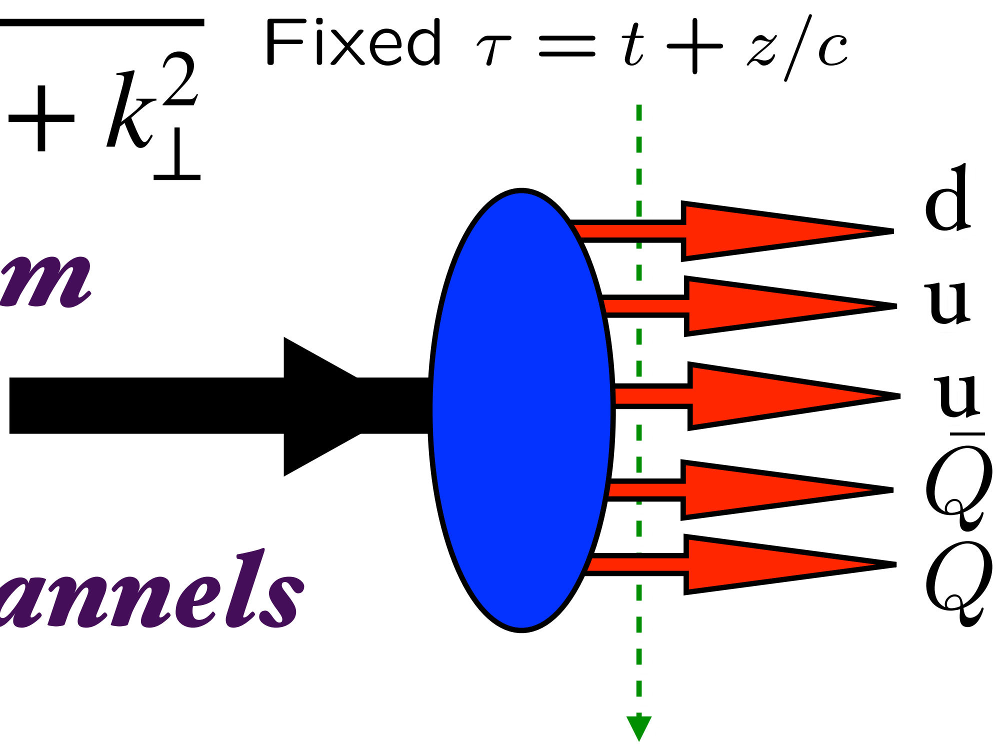
Predict charm hadron asymmetries
$\frac{d\sigma}{dx_F dp_T^2}(pp \to D^+(c\bar{d})X) >$
$\frac{d\sigma}{dx_F dp_T^2}(pp \to D^-(\bar{c}d)X)$
at high p_T and high x_F

Properties of Non-Perturbative Five-Quark Fock-State

- ***Dominant configuration: mininum off-shell, same rapidity***
- ***Heavy quarks have most of the LF momentum***

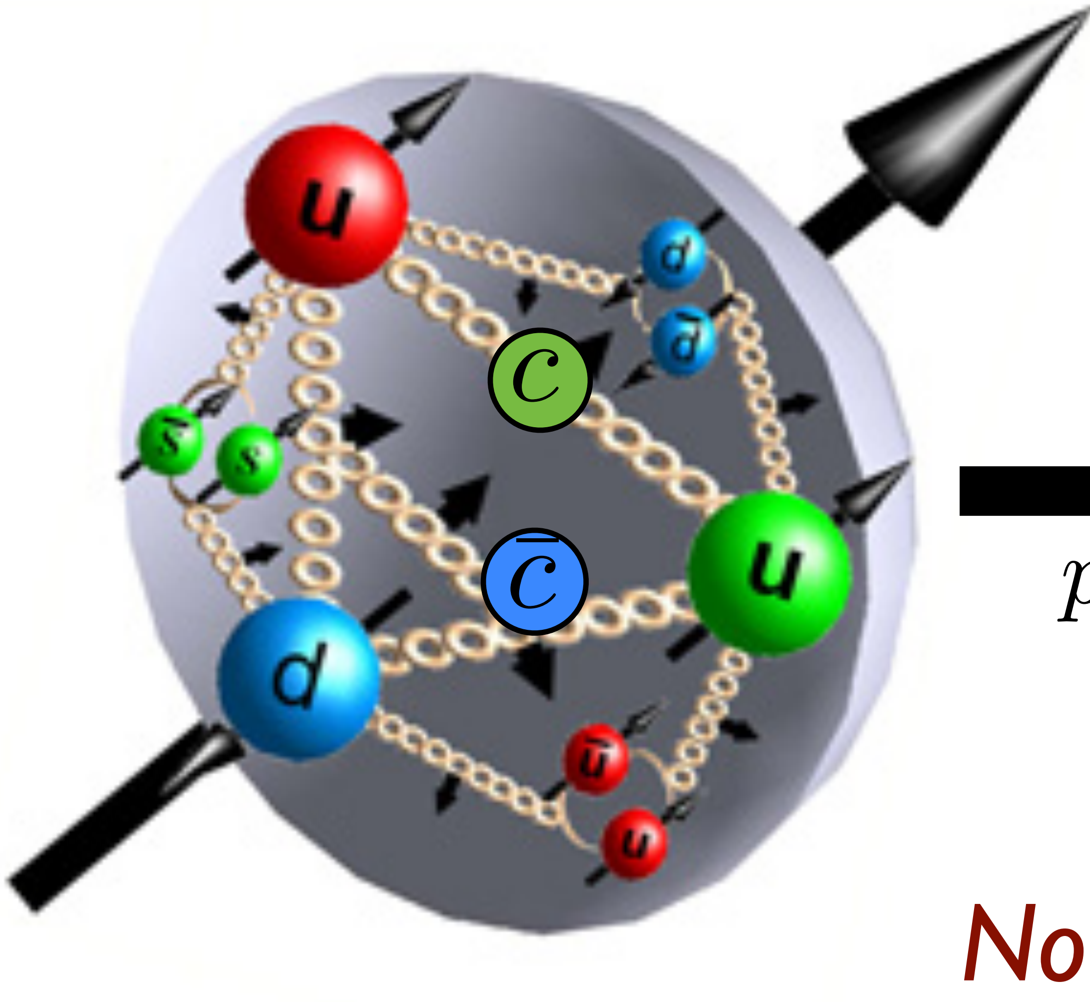
$$< x_Q > \propto \sqrt{m_Q^2 + k_\perp^2}$$

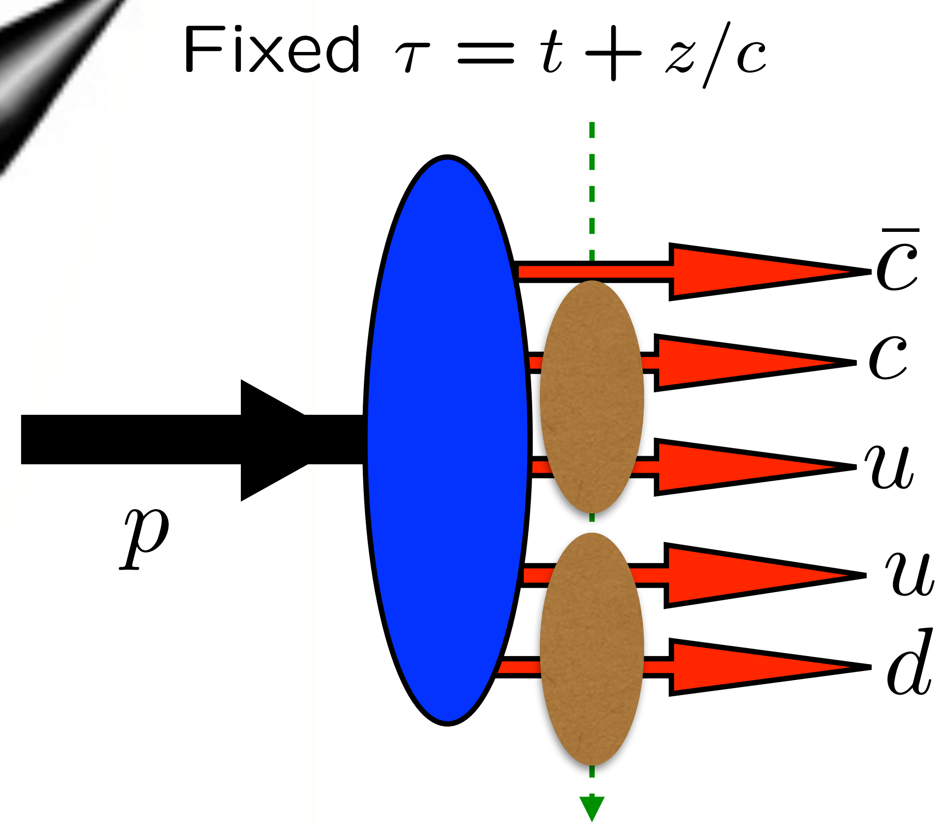
- ***Correlated with proton quantum numbers***
- ***Duality with meson-baryon channels***
- ***Strangeness, charm asymmetry at x > 0.1***

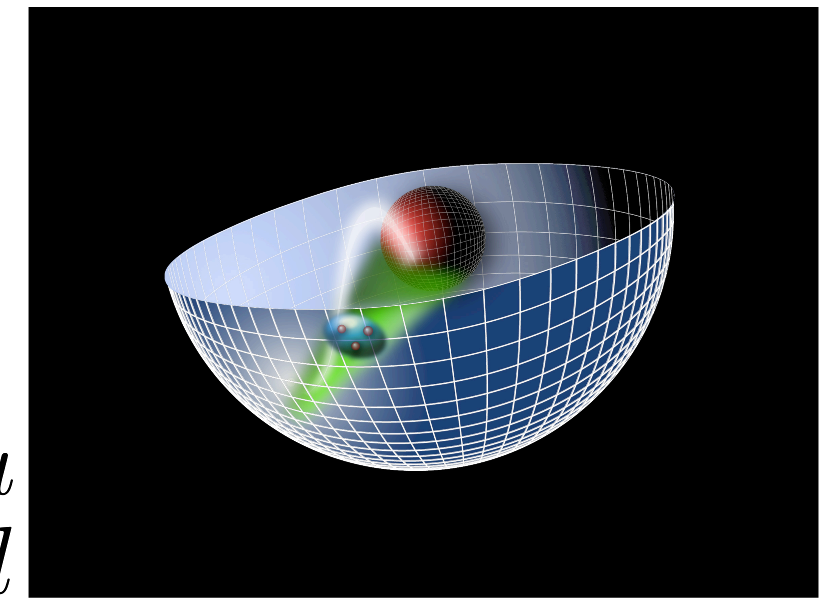


$$s_p(x) \neq \bar{s}_p(x) \quad c_p(x) \neq \bar{c}_p(x)$$

Intrinsic Heavy Quark Phenomena
A Novel Property of QCD







Non-perturbative QCD

$$|p> = C_{valence}|u[ud]> + C_{intrinsic}|\bar{c}[cu][ud]>$$

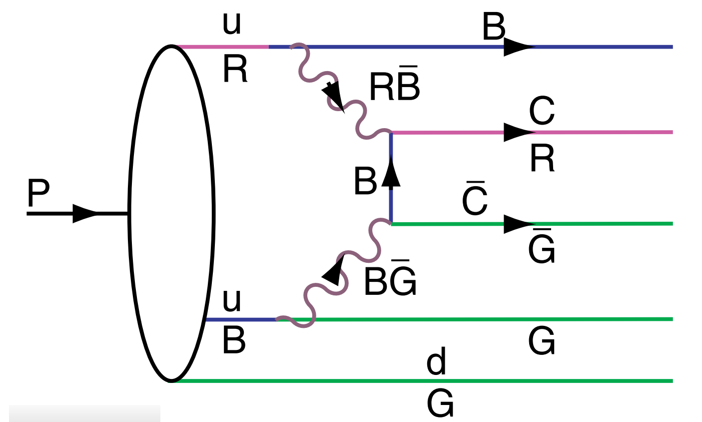
$$[du]_{\bar{3}_C} \text{ and } [cu]_{\bar{3}_C} \; J = 0 \text{ diquark dominance}$$

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

$\bar{c}(x)$ carries proton spin in the $|[ud][uc]\bar{c}>$ intrinsic charm Fock state.

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

Intrinsic Heavy-Quark Fock States



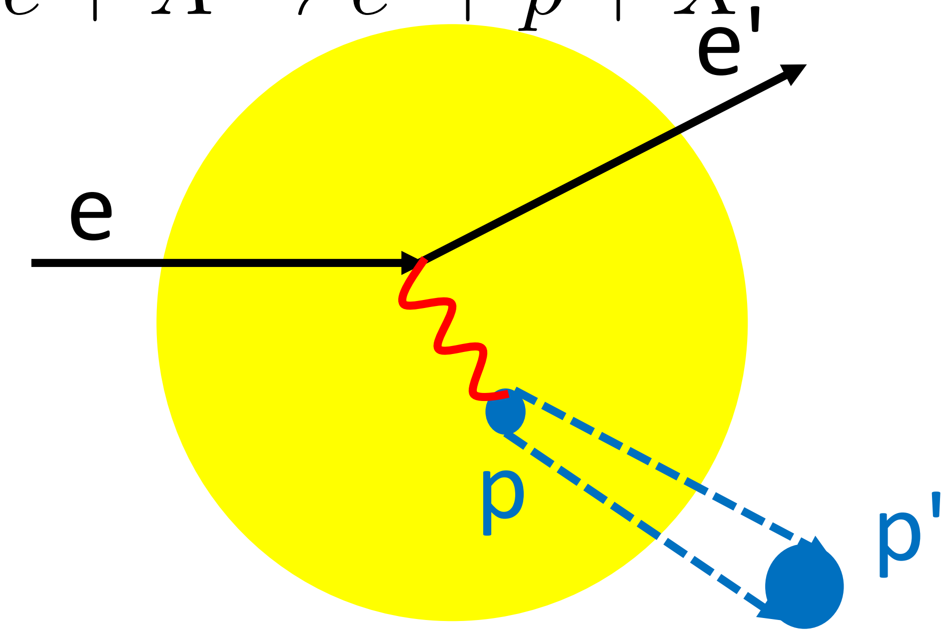
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production at high x_F (Kopeliovich, Schmidt, Soffer, Goldhaber, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests (Gardner, Karliner, ..)

Review: G. Lykasov, et al

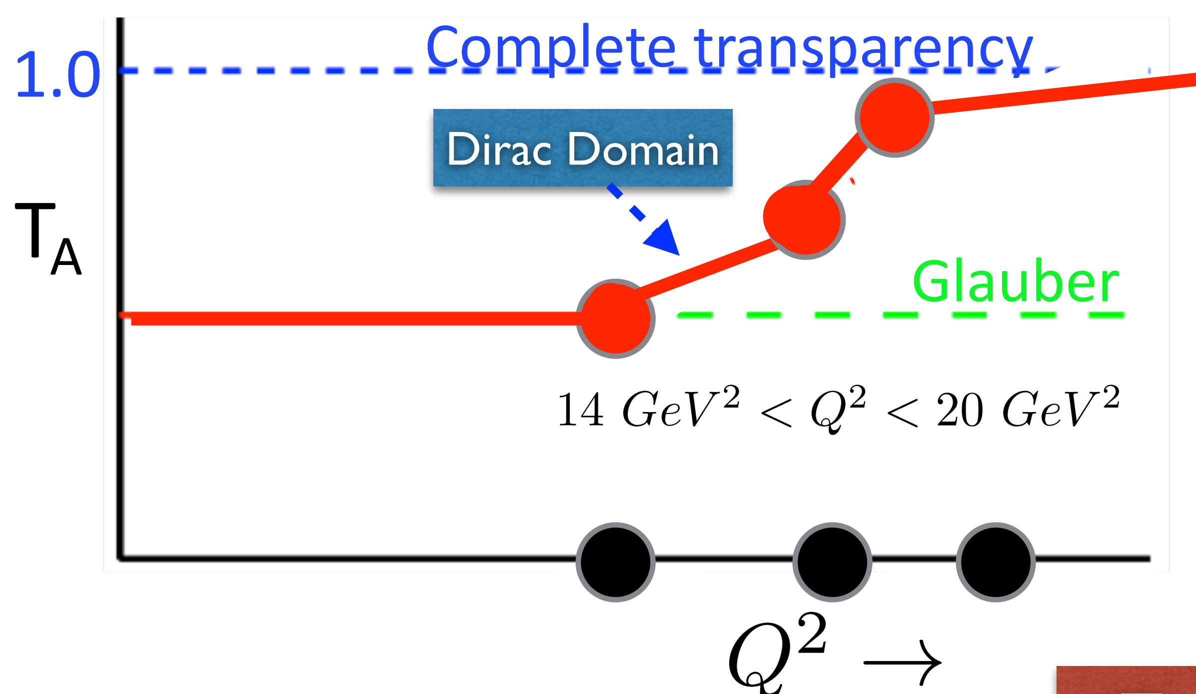
A.H. Mueller, sjb

Color transparency: fundamental prediction of QCD

$$e + A \to e' + p + X$$



- Not predicted by strongly interacting hadronic picture → arises in picture of quark-gluon interactions
- QCD: color field of singlet objects vanishes as size is reduced
- Signature is a rise in nuclear transparency, T_A, as a function of the momentum transfer, Q^2



$$T_A = \frac{\sigma_A}{A\ \sigma_N}$$ (nuclear cross section) (free nucleon cross section)

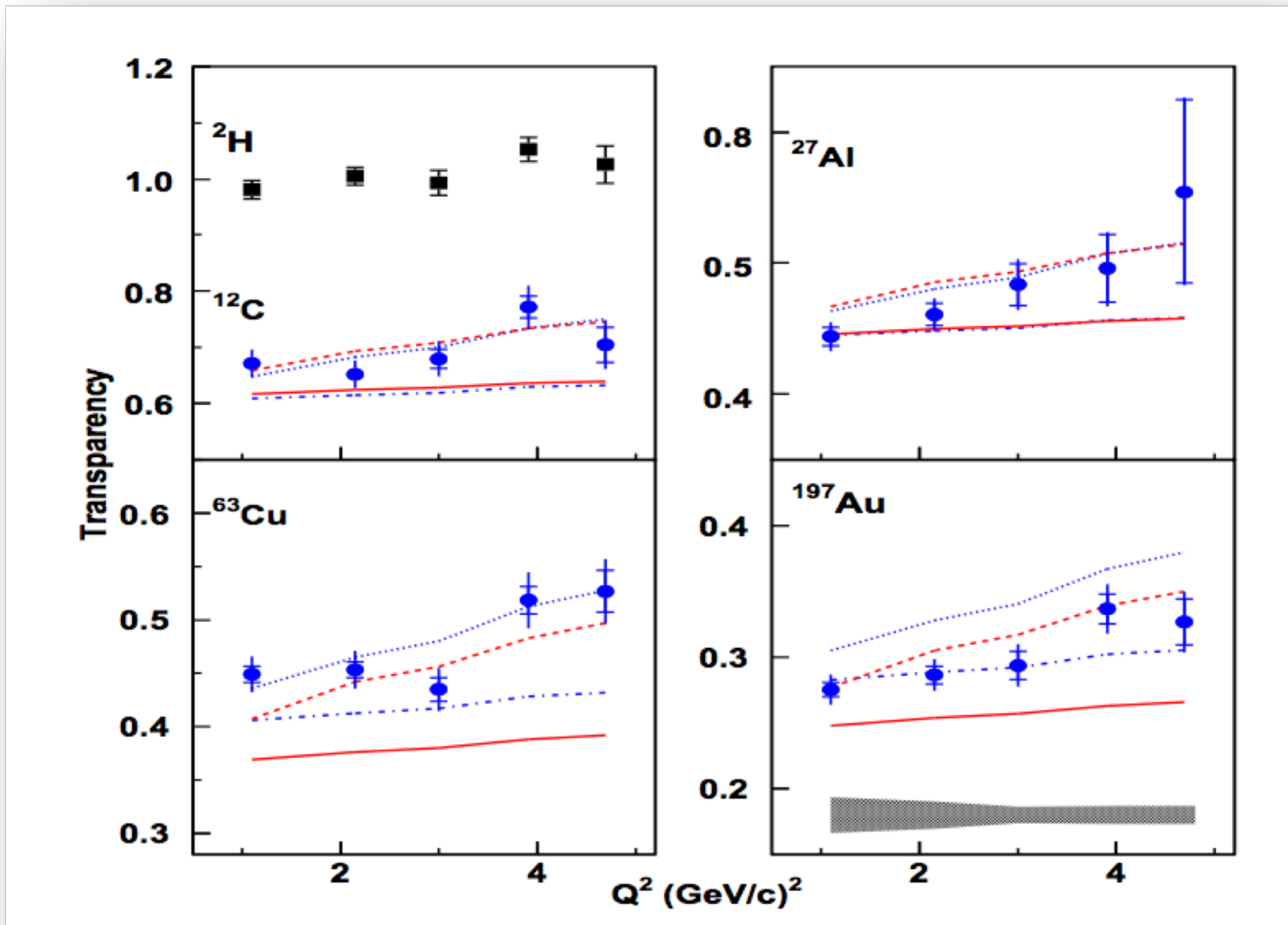
G. de Teramond, sjb

Two-Stage Color Transparency for Proton

Color Transparency verified for π^+ and ρ electroproduction

Hall C E01-107 pion electro-production

$A(e,e'\pi^+)$

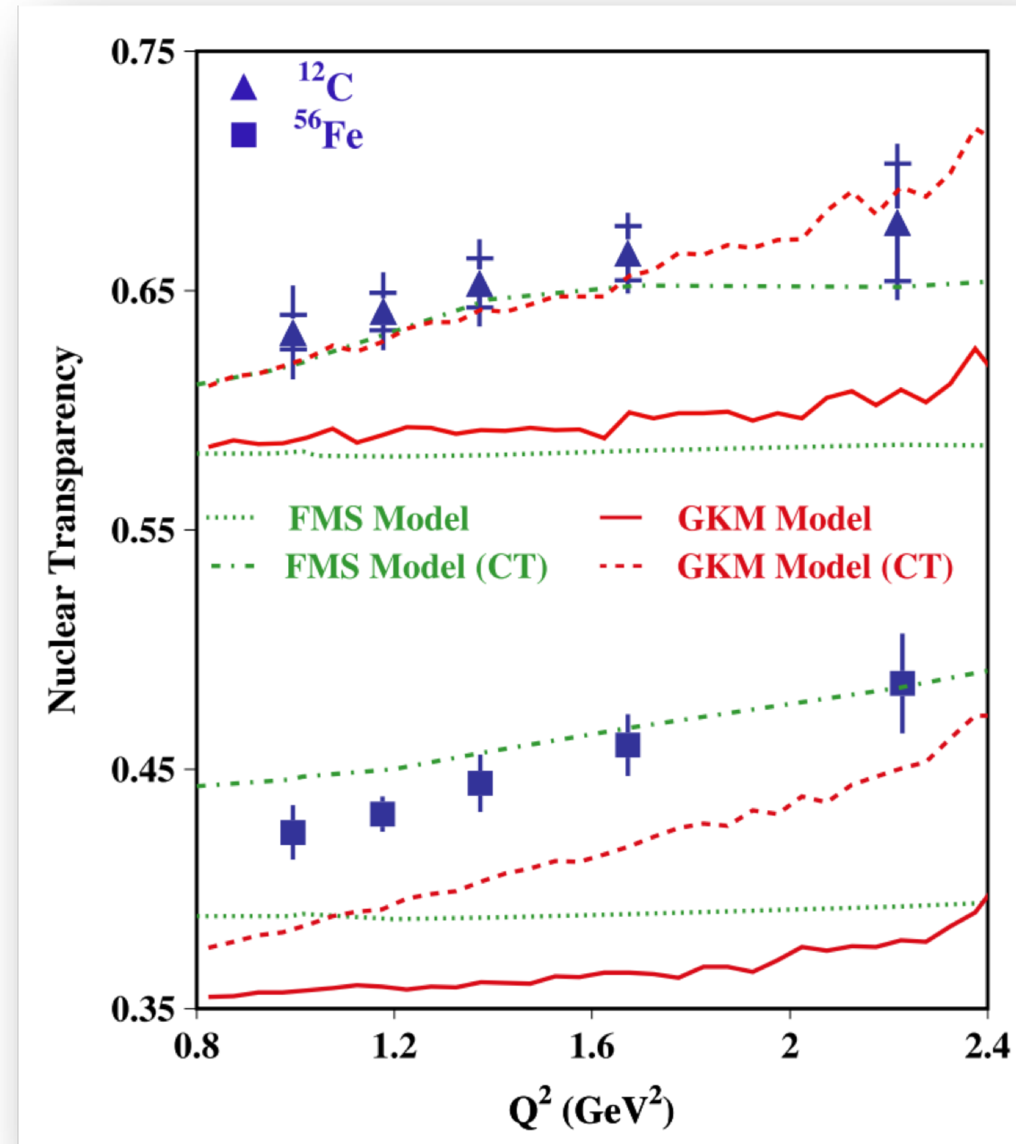


B.Clasie *et al.* PRL 99:242502 (2007)

X. Qian *et al.* PRC81:055209 (2010)

CLAS E02-110 rho electro-production

$A(e,e'\rho^0)$



L. El Fassi *et al.* PLB 712,326 (2012)

$$T_A = \frac{\frac{d\sigma}{dQ^2}(pA \to \pi^+ X)}{\frac{d\sigma}{dQ^2}(pp \to \pi^+ X)}$$

$$T_A = \frac{\frac{d\sigma}{dQ^2}(pA \to \rho^0 X)}{\frac{d\sigma}{dQ^2}(pp \to \rho^0 X)}$$

$F(q^2) =$

Drell-Yan-West Formula in Impact Space

$$\sum_n \prod_{i=1}^{n} \int dx_i \int \frac{d^2\mathbf{k}_{\perp i}}{2(2\pi)^3}\, 16\pi^3\, \delta\Big(1 - \sum_{j=1}^{n} x_j\Big)\, \delta^{(2)}\Big(\sum_{j=1}^{n} \mathbf{k}_{\perp j}\Big)$$

$$\sum_j e_j \psi_n^*(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\psi_n(x_i, \mathbf{k}_{\perp i}, \lambda_i),$$

$$= \sum_n \prod_{j=1}^{n-1} \int dx_j \int d^2\mathbf{b}_{\perp j} \exp\Big(i\mathbf{q}_\perp \cdot \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}\Big) \left|\psi_n(x_j, \mathbf{b}_{\perp j})\right|^2$$

$$\textstyle\sum_{i=1}^{n} x_i = 1 \text{ and } \sum_{i=1}^{n} \mathbf{b}_{\perp i} = 0.$$

$$F(q^2) = \int_0^1 dx \int d^2\mathbf{a}_\perp e^{i\mathbf{a}_\perp \cdot \mathbf{q}_\perp} q(x, \mathbf{a}_\perp),$$

where $\boxed{\mathbf{a}_\perp = \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}}$ is the x-weighted transverse position coordinate of the $n-1$ spectators.

$F(q^2) =$

G. de Teramond, sjb

$$\sum_n \prod_{j=1}^{n-1} \int dx_j \int d^2\mathbf{b}_{\perp j} \exp\left(i\mathbf{q}_\perp \cdot \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}\right) |\psi_n(x_j, \mathbf{b}_{\perp j})|^2$$

$$\sum_i x_i = 1$$

$$\boxed{\vec{a}_\perp \equiv \sum_{j=1}^{n-1} x_j \vec{b}_{\perp j}}$$

$$\vec{a}_\perp^2(Q^2) = -4 \frac{\frac{d}{dQ^2} F(Q^2)}{F(Q^2)}$$

Proton radius squared at $Q^2 = 0$

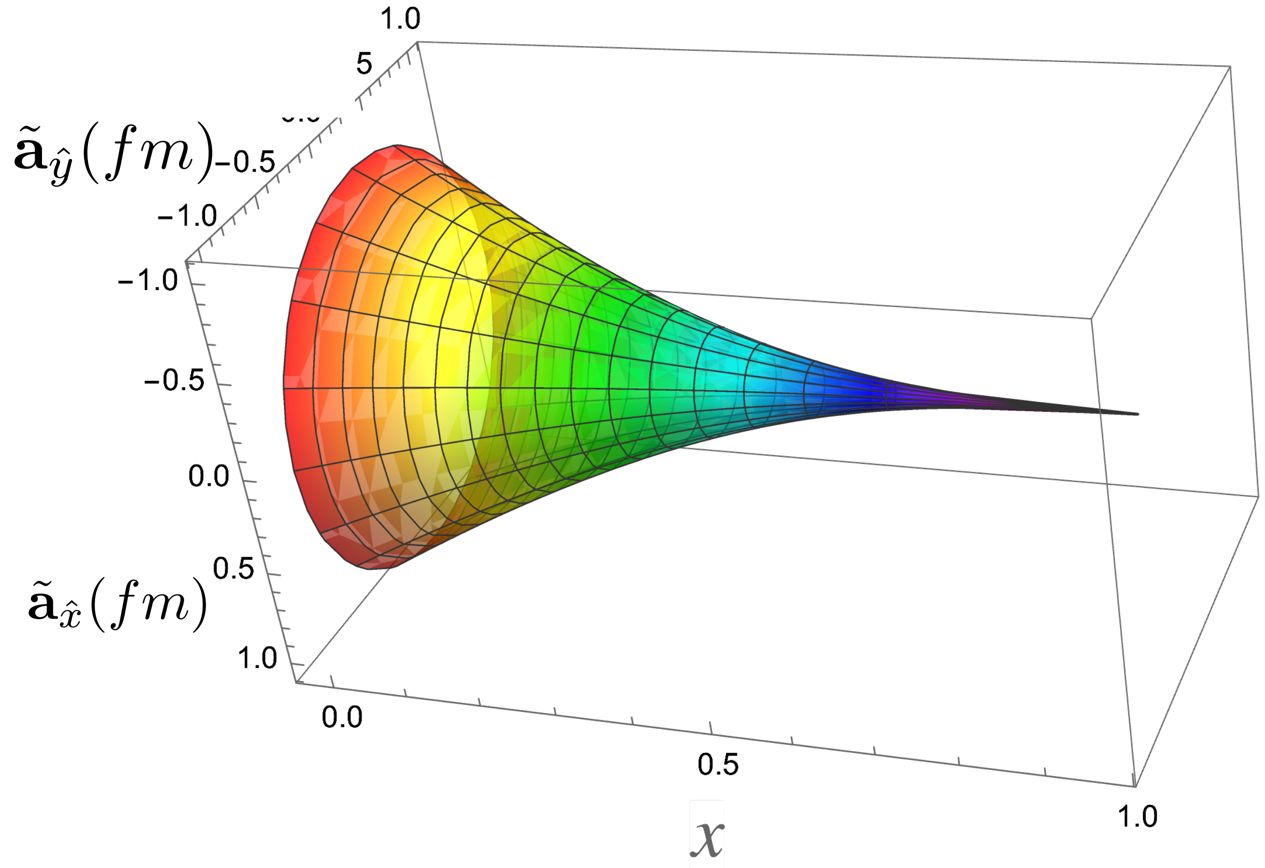
Color Transparency is controlled by the transverse-spatial size $\vec{a}_\perp^2$ and its dependence on the momentum transfer $Q^2 = -t$:
The scale Q^2_τ required for Color Transparency grows with twist τ

Light-Front Holography:

$$\boxed{\langle \mathbf{a}_\perp^2(t) \rangle_\tau = \frac{1}{\lambda} \sum_{j=1}^{\tau-1} \frac{1}{j - \alpha(t)},}$$

For large Q^2 :

$$\boxed{\langle \mathbf{a}_\perp^2(Q^2) \rangle_\tau \to \frac{4(\tau - 1)}{Q^2}.}$$



$$< \tilde{\mathbf{a}}_\perp^2(x) >= \frac{\int d^2\mathbf{a}_\perp \mathbf{a}_\perp^2 q(x,\mathbf{a}_\perp)}{\int d^2\mathbf{a}_\perp q(x,\mathbf{a}_\perp)}$$

At large light-front momentum fraction x, and equivalently at large values of Q^2, the transverse size of a hadron behaves as a point-like color-singlet object. This behavior is the origin of color transparency in nuclei.

Although the dependence of the transverse impact area as a function of x is universal, the behavior in Q^2 depends on properties of the hadron, such as its twist.

$$\langle \mathbf{a}_\perp^2(Q^2)\rangle_\tau \to \frac{4(\tau-1)}{Q^2}.$$

Mean transverse size as a function of Q and Twist

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Alexandre Deur, SJB

(HLFHS Collaboration)

$$F_\tau(t) = \frac{1}{N_\tau} B\left(\tau - 1, \frac{1}{2} - \frac{t}{4\lambda}\right),$$

$$N_\tau = B(\tau - 1, 1 - \alpha(0))$$

$$B(u, v) = \int_0^1 dy y^{u-1} (1-y)^{v-1} = [\Gamma(u)\Gamma(v)/\Gamma(u+v)]$$

$$\boxed{F_\tau(Q^2) = \frac{1}{\left(1+\frac{Q^2}{M_0^2}\right)\left(1+\frac{Q^2}{M_1^2}\right)\cdots\left(1+\frac{Q^2}{M_{\tau-2}^2}\right)}}$$

$$\boxed{F_\tau(Q^2) \sim \left(\frac{1}{Q^2}\right)^{\tau-1}}$$

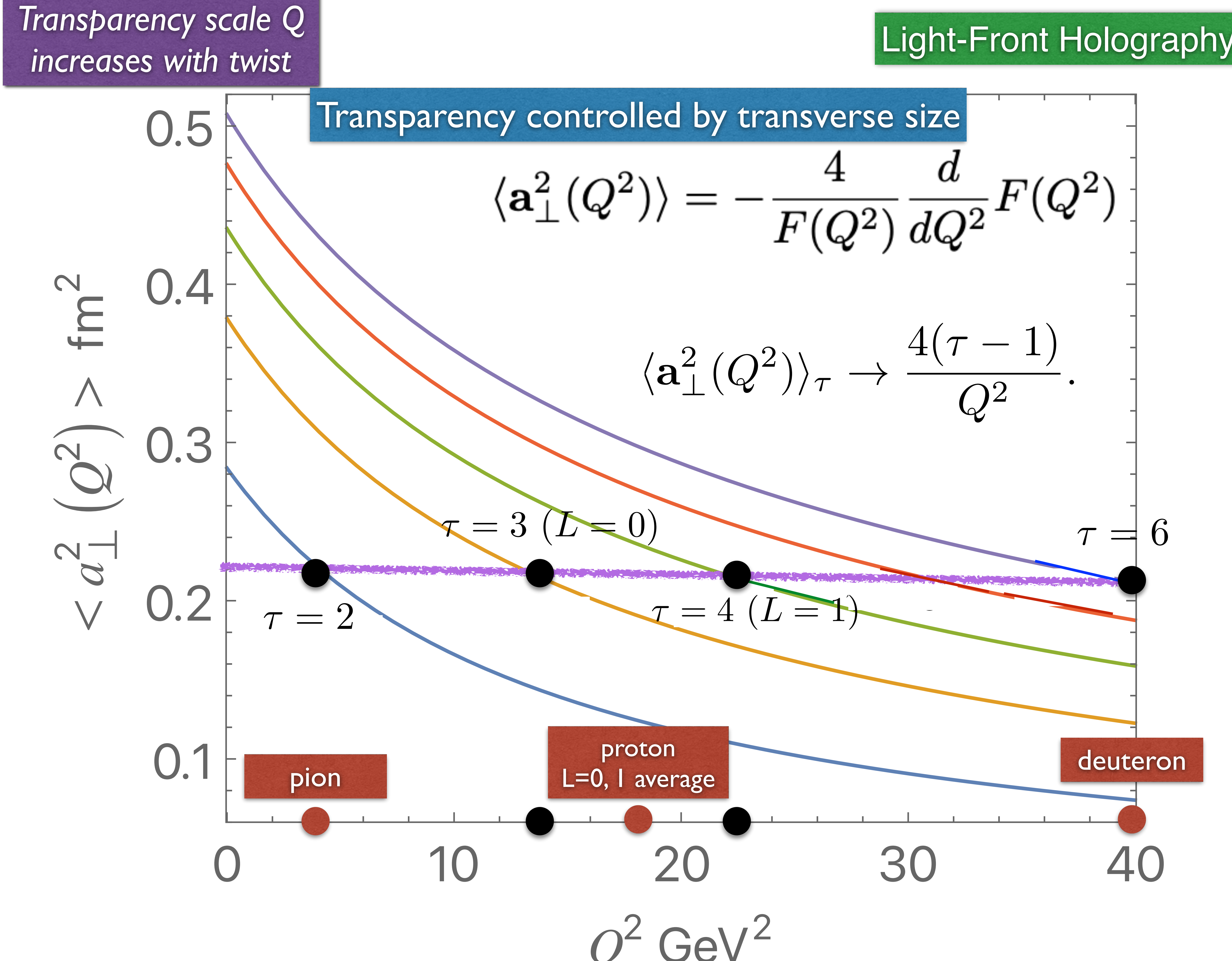
$$M_n^2 = 4\lambda(n + \tfrac{1}{2}), n = 0, 1, 2, \ldots, \tau - 2,$$

$$M_0 = m_\rho$$

$$\sqrt{\lambda} = \kappa = \frac{m_\rho}{\sqrt{2}} = 0.548\ GeV$$

$$\tfrac{1}{2} - \frac{t}{4\lambda} = 1 - \alpha_R(t)$$

$\alpha_R(t) = \rho$ Regge Trajectory



Proton has equal probability for $\tau = 3$ and $\tau = 4$

Color Transparency and Light-Front Holography

- Essential prediction of QCD
- LF Holography: Spectroscopy, dynamics, structure
- Transverse size predicted by LF Holography as a function of Q
- Q scale for CT increases with twist, number of constituents
- Two-Stage Proton Transparency: Equal probability L=0,1
- No contradiction with present experiments

$Q_0^2(p) \simeq 18 \ GeV^2$ vs. $Q_0^2(\pi) \simeq 4 \ GeV^2$ for onset of color transparency in ^{12}C

Two-Stage Color Transparency

$$\boxed{14\ GeV^2 < Q^2 < 20\ GeV^2}$$

If Q^2 is in the intermediate range, then the twist-3 state will propagate through the nuclear medium with minimal absorption, and the protons which survive nuclear absorption will only have L = 0 (twist-3).

The twist-4 L = 1 state which has a larger transverse size will be absorbed.

Thus 50% of the events in this range of Q^2 will have full color transparency and 50% of the events will have zero color transparency (T = 0).

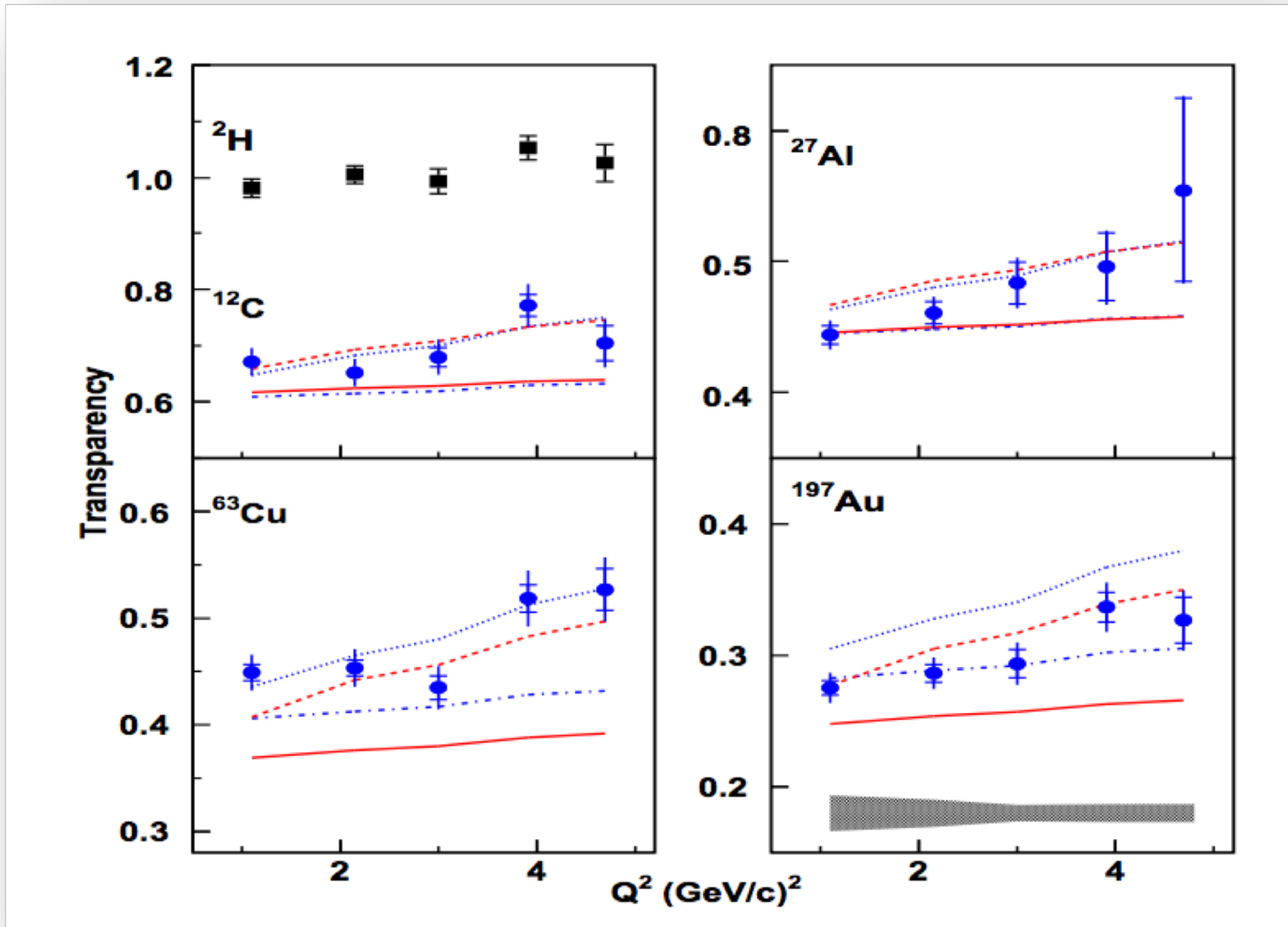
The $ep \to e'p'$ cross section will have the same angular and Q^2 dependence as scattering of the electron on an unphysical proton which has no Pauli form factor.

$$\boxed{Q^2 > 20\ GeV^2}$$

However, if the momentum transfer is increased to $Q^2 > 20\ GeV^2$, all events will have full color transparency, and the $ep \to e'p'$ cross section will have the same angular and Q^2 dependence as scattering of the electron on a physical proton eigenstate, with both Dirac and Pauli form factor components.

Hall C E01-107 pion electro-production

$A(e,e'\pi^+)$



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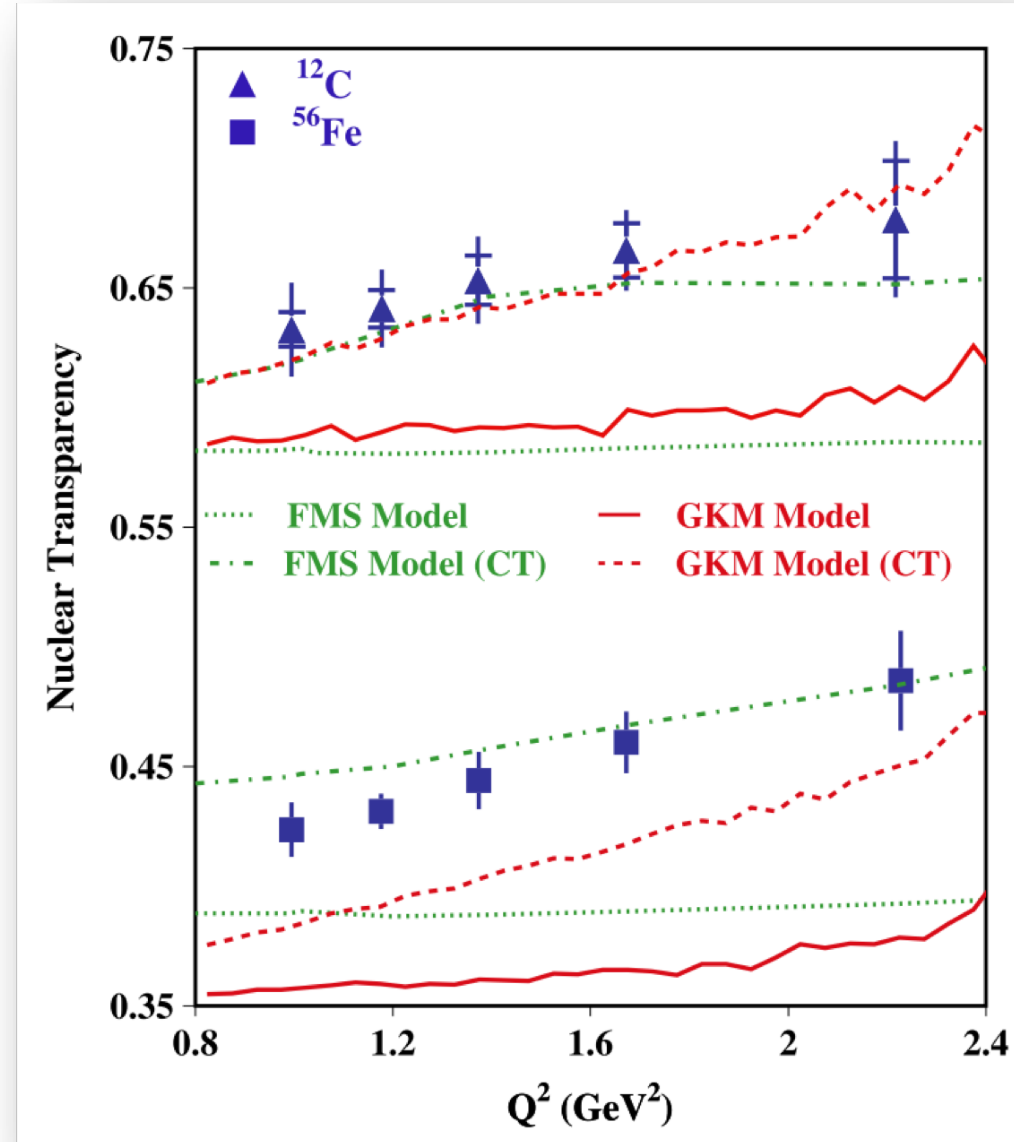


L. El Fassi *et al.* PLB 712,326 (2012)

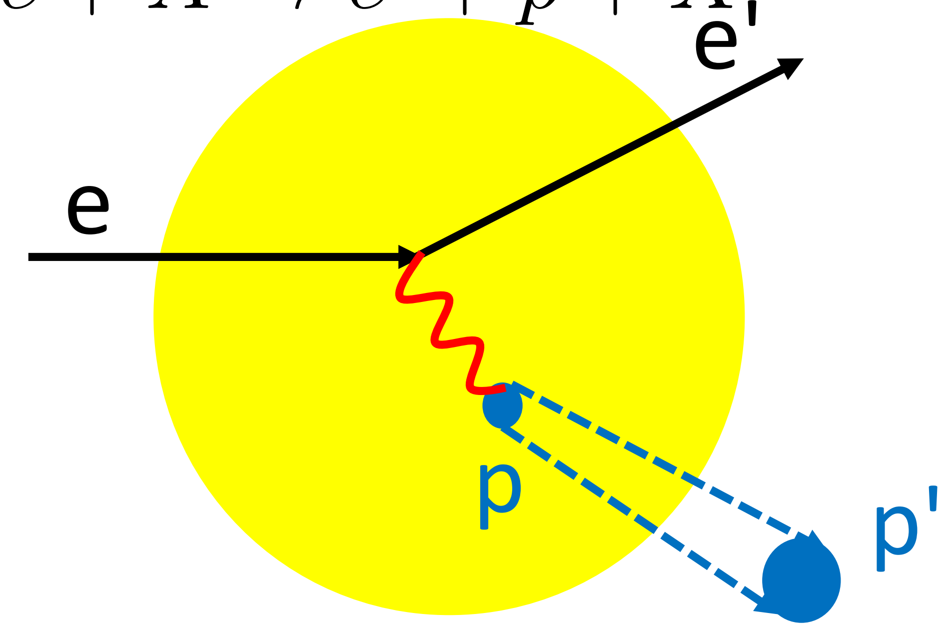
$$< a_\perp^2(Q^2=4\ GeV^2) >_{\tau=2} \simeq < a_\perp^2(Q^2=14\ GeV^2) >_{\tau=3} \simeq < a_\perp^2(Q^2=22\ GeV^2) >_{\tau=4} \simeq 0.24\ fm^2$$

5% increase for T_π in ^{12}C at $Q^2 = 4\ GeV^2$ implies 5% increase for T_p at $Q^2 = 18\ GeV^2$

A.H. Mueller, sjb

Color transparency fundamental prediction of QCD

$e + A \to e' + p + X$



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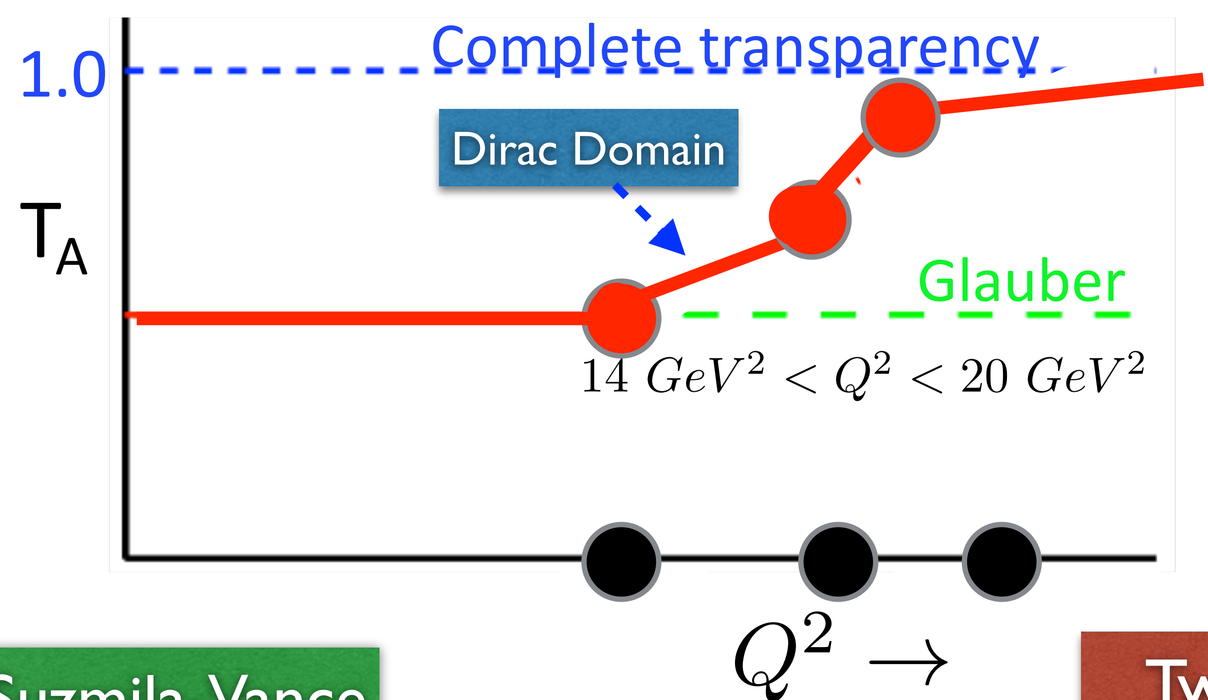

$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$

(nuclear cross section)

(free nucleon cross section)

Holly Suzmila-Vance

Two-Stage Color Transparency for Proton

Color Transparency and Light-Front Holography

- Essential prediction of QCD
- LF Holography: Spectroscopy, dynamics, structure
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$$Q_0^2(p) \simeq 18\ GeV^2 \text{ vs. } Q_0^2(\pi) \simeq 4\ GeV^2 \text{ for onset of color transparency in } {}^{12}C$$

Feynman domain also incorporated

Supersymmetry in QCD

- A hidden symmetry of Color SU(3)$_C$ in hadron physics
- QCD: No squarks or gluinos!
- Emerges from Light-Front Holography and Super-Conformal Algebra
- Color Confinement
- Massless Pion in Chiral Limit

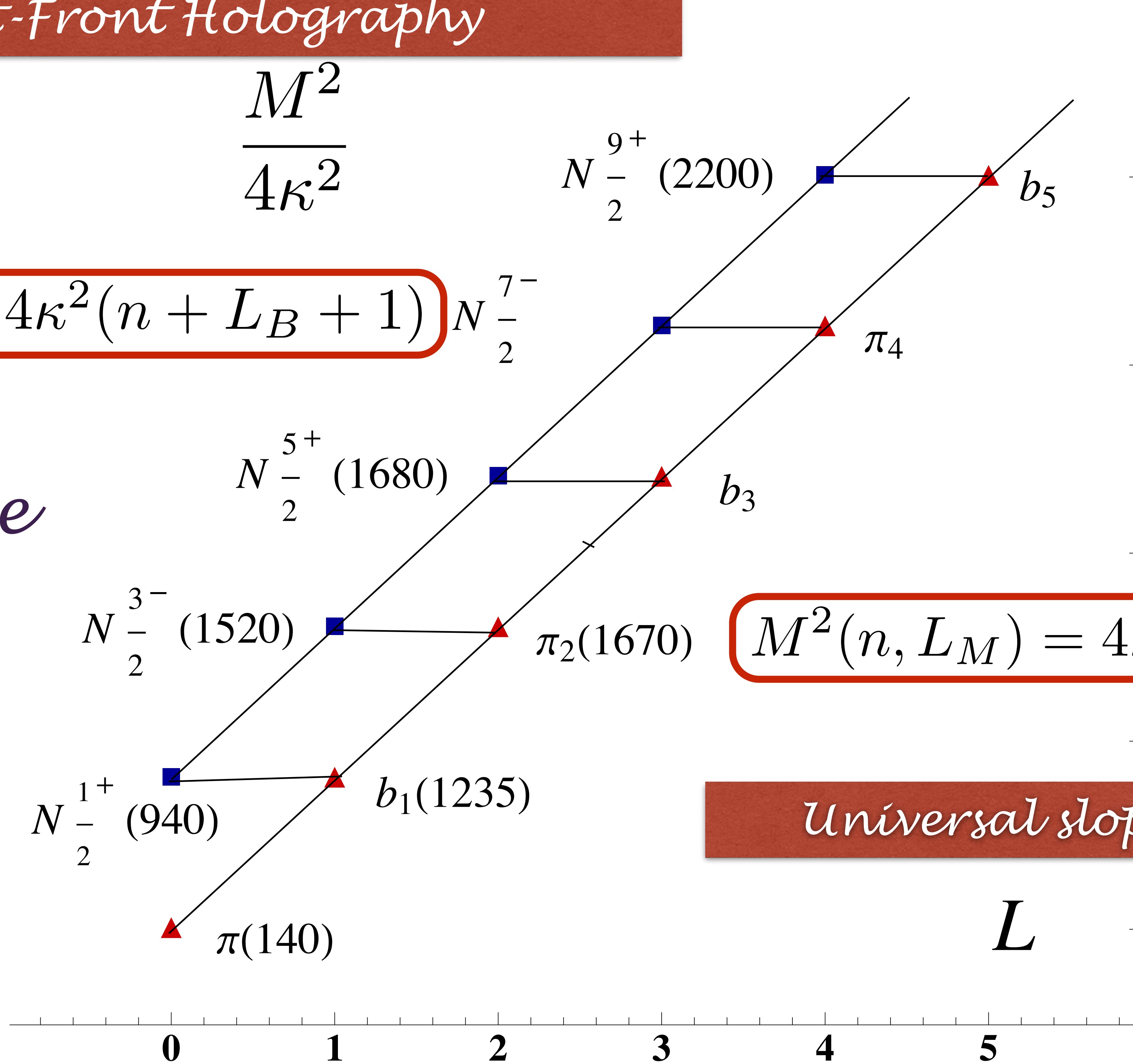
de Téramond, Dosch, Lorcé, sjb

Superconformal Quantum Mechanics
Light-Front Holography

de Téramond, Dosch, Lorcé, sjb

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

Same slope

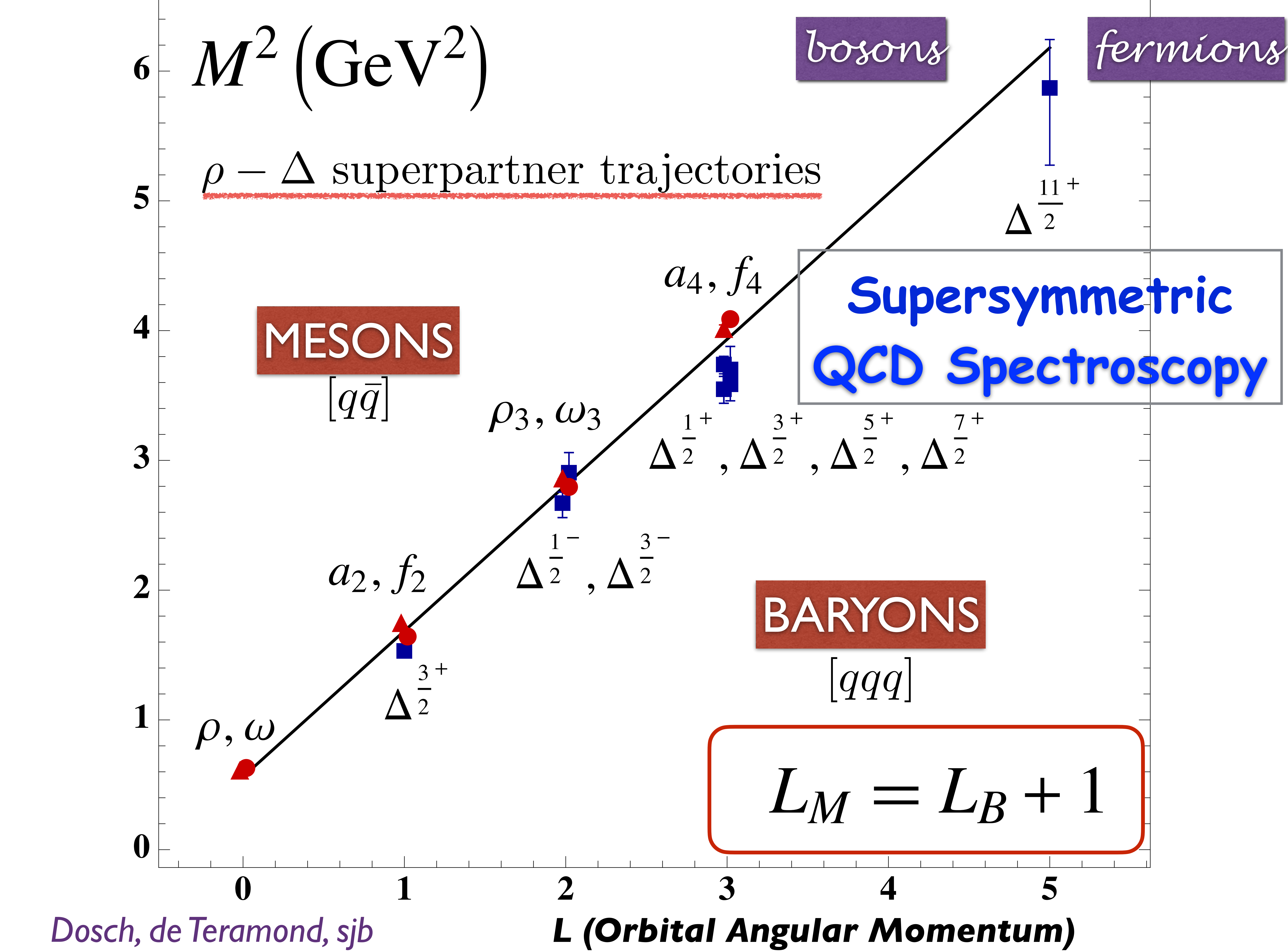


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Universal slopes in n, L

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

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



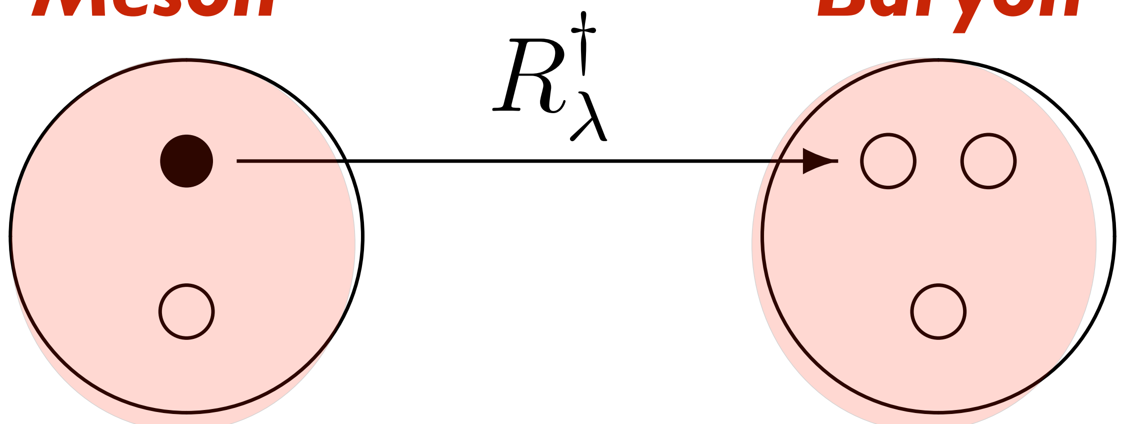
M^2 (GeV^2)
$\rho - \Delta$ superpartner trajectories
bosons
fermions
Supersymmetric QCD Spectroscopy
MESONS
$[q\bar{q}]$
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta^{\frac{3}{2}^+}$
$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$
$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$
$\Delta^{\frac{11}{2}^+}$
$L_M = L_B + 1$
0 1 2 3 4 5 6
0 1 2 3 4 5
L (Orbital Angular Momentum)
Dosch, de Teramond, sjb

Superconformal Algebra

Four-Plet Representations

Bosons, Fermions with Equal Mass!

Meson **Baryon**



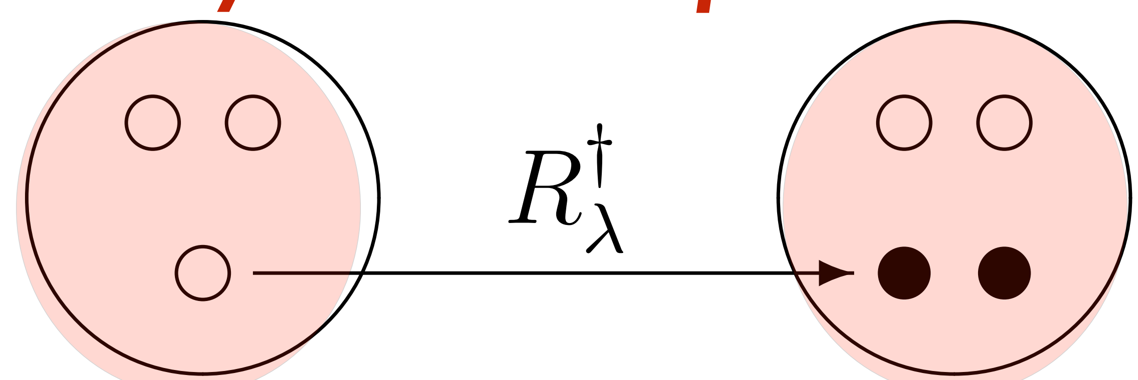
$\phi_M, \ L_B + 1$ $\psi_{B+}, \ L_B$

$R_\lambda^\dagger \ \bar{q} \to [qq]$

$\bar{3}_C \to \bar{3}_C$

Baryon

Tetraquark: diquark + antidiquark



$R_\lambda^\dagger \ q \to [\bar{q}\bar{q}]$

$3_C \to 3_C$

$\psi_{B-}, \ L_B + 1$ $\phi_T, \ L_B$

Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

Challenge: Compute Hadron Structure, Spectroscopy, and Dynamics from QCD!

- *Color Confinement*
- *Origin of the QCD Mass Scale*
- *Meson and Baryon Spectroscopy*
- *Exotic States: Tetraquarks, Pentaquarks, Gluonium,*
- *Universal Regge Slopes: n, L, Mesons and Baryons*
- *Almost Massless Pion: GMOR Chiral Symmetry Breaking*

  $M_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d \rangle + \mathcal{O}\big((m_u + m_d)^2\big)$

- *QCD Coupling at all Scales* $\alpha_s(Q^2)$
- *Eliminate Scale Uncertainties and Scheme Dependence*

$$\mathscr{L}_{QCD} \rightarrow \psi_n^H(x_i, \overrightarrow{k}_{\perp i}, \lambda_i)$$ *Valence and Higher Fock States*

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

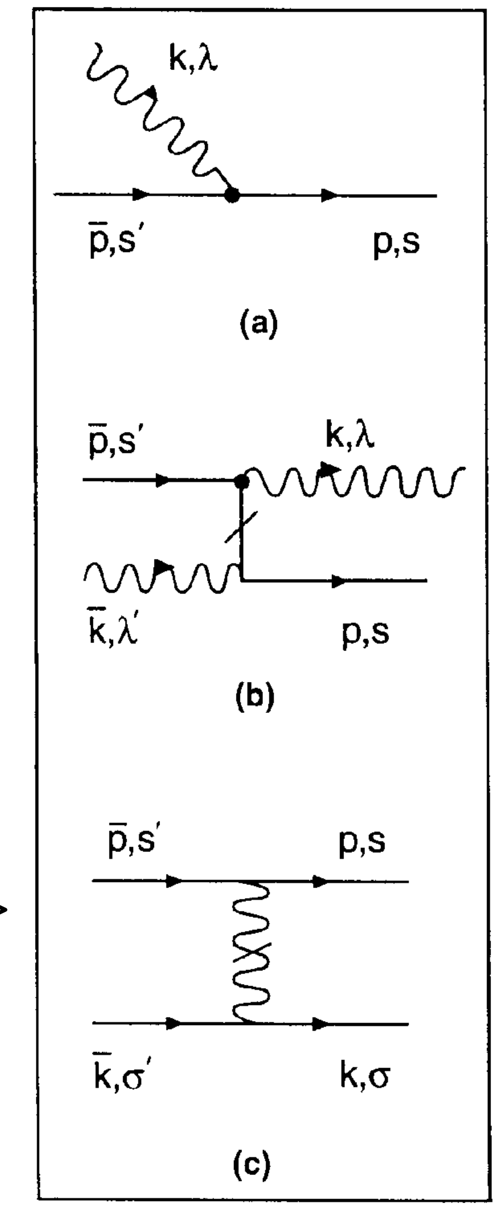
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

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

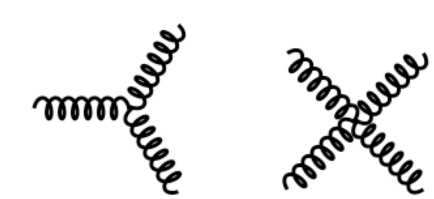
H^{int}_{LF}: Matrix in Fock Space

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

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



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



$$H^{int}_{LF}$$

LFWFs: Off-shell in P- and invariant mass

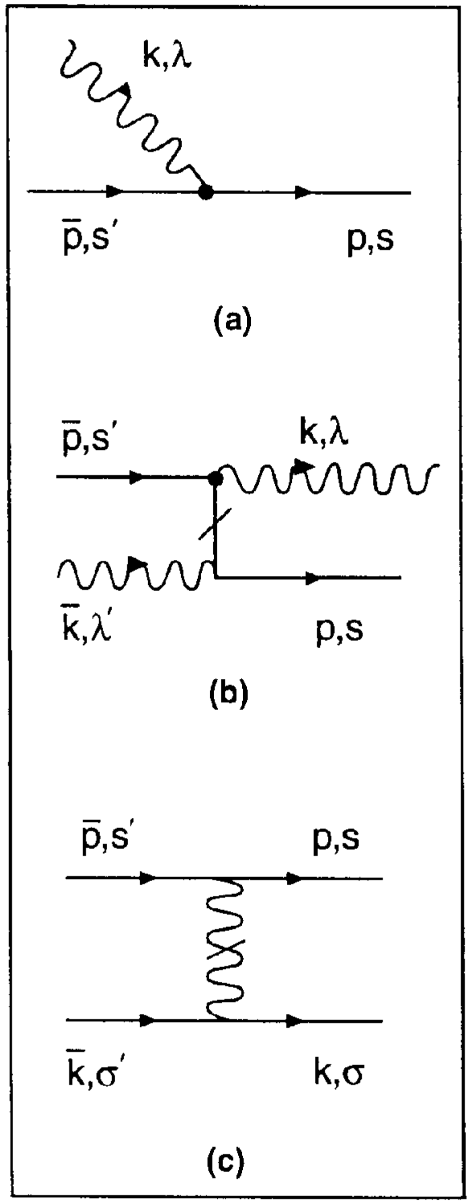
Light-Front QCD

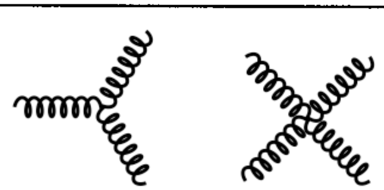
Heisenberg Equation

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

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

Hornbostel, Pauli, sjb



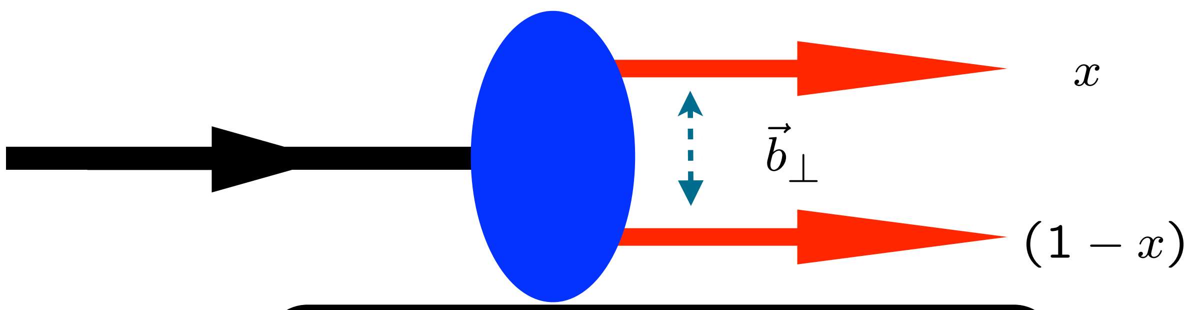


n	Sector	1 $q\bar{q}$	2 gg	3 $q\bar{q}$ g	4 $q\bar{q}$ $q\bar{q}$	5 gg g	6 $q\bar{q}$ gg	7 $q\bar{q}$ $q\bar{q}$ g	8 $q\bar{q}$ $q\bar{q}$ $q\bar{q}$	9 gg gg	10 $q\bar{q}$ gg g	11 $q\bar{q}$ $q\bar{q}$ gg	12 $q\bar{q}$ $q\bar{q}$ $q\bar{q}$ g	13 $q\bar{q}$ $q\bar{q}$ $q\bar{q}$ $q\bar{q}$
1	$q\bar{q}$					•		•	•	•	•	•	•	•
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

Light-Front QCD

Fixed $\tau = t + z/c$



$$\boxed{\zeta^2 = x(1-x)b_\perp^2}$$

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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

Effective two-particle equation

Azimuthal Basis ζ, ϕ

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

Single variable Equation

$$m_q = 0$$

AdS/QCD:

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

Confining AdS/QCD potential!

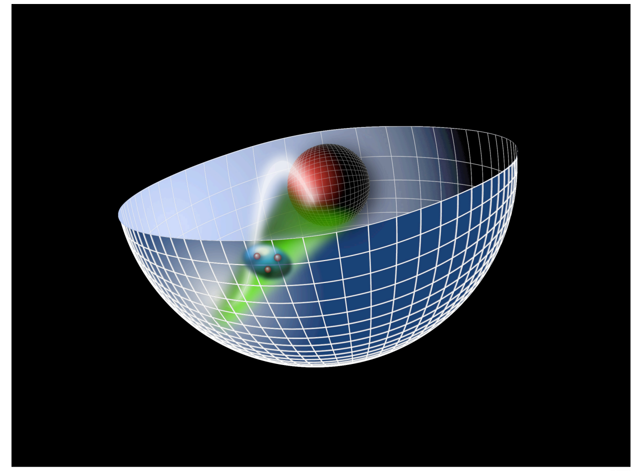
Semiclassical first approximation to QCD

Sums an infinite # diagrams

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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



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

Light-Front Holography

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

Light-Front Schrödinger Equation

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

Single variable ζ

Unique Confinement Potential!

Conformal Symmetry of the action

Confinement scale: $\kappa \simeq 0.5\ GeV$

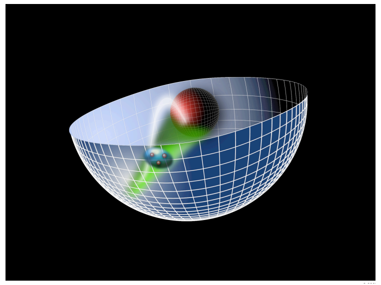
- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

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

GeV units external to QCD: Only Ratios of Masses Determined

Dilaton-Modified AdS

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



- **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**

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

Positive-sign dilaton

- de Teramond, sjb

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

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

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

Derived from variation of Action for Dilaton-Modified AdS_5

Identical to Single-Variable Light-Front Bound State Equation in ζ!

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

Light-Front Holography

de Teramond, sjb

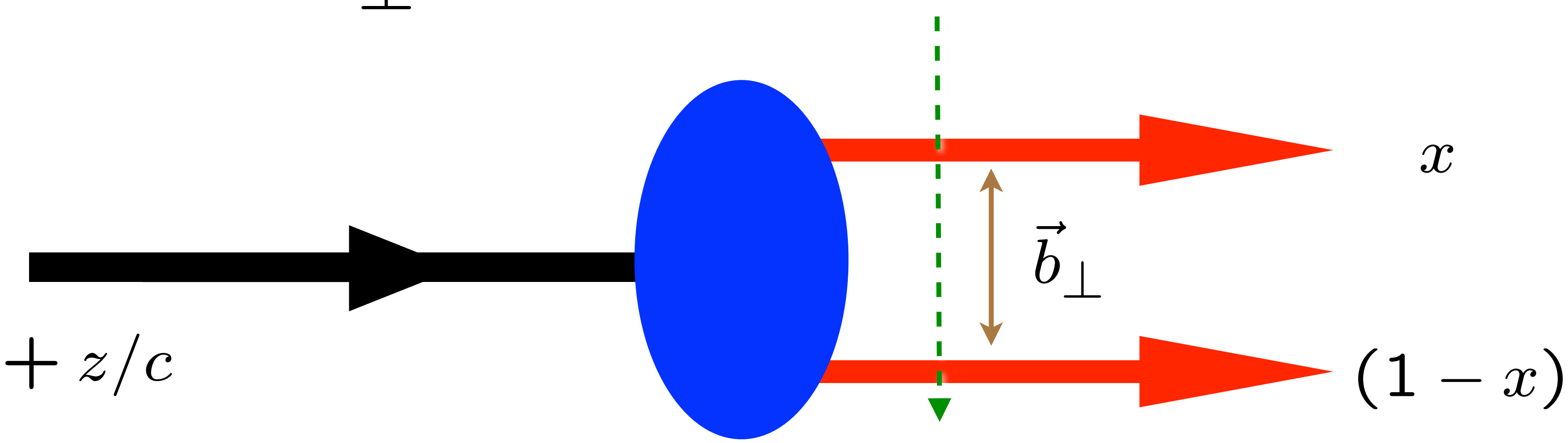
LF(3+1) $\longleftrightarrow$ AdS$_5$

Light-Front Holographic Dictionary

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

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

Fixed $\tau = t + z/c$



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

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

***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*

Holographic Mapping of AdS Modes to QCD LFWFs

Drell-Yan-West: Form Factors are Convolution of LFWFs

- Integrate Soper formula over angles:

$$F(q^2) = 2\pi \int_0^1 dx \, \frac{(1-x)}{x} \int \zeta d\zeta J_0\left(\zeta q \sqrt{\frac{1-x}{x}}\right) \tilde{\rho}(x,\zeta),$$

with $\widetilde{\rho}(x,\zeta)$ QCD effective transverse charge density.

- Transversality variable

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

- Compare AdS and QCD expressions of FFs for arbitrary Q using identity:

$$\int_0^1 dx J_0\left(\zeta Q \sqrt{\frac{1-x}{x}}\right) = \zeta Q K_1(\zeta Q),$$

the solution for $J(Q,\zeta) = \zeta Q K_1(\zeta Q)$!

de Teramond, sjb

Identical to Polchinski-Strassler Convolution of AdS Amplitudes de Téramond, Dosch, Lorcé, sjb

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

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

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

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

S=1/2, P=+

Meson Equation

$$\lambda=\kappa^2$$

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

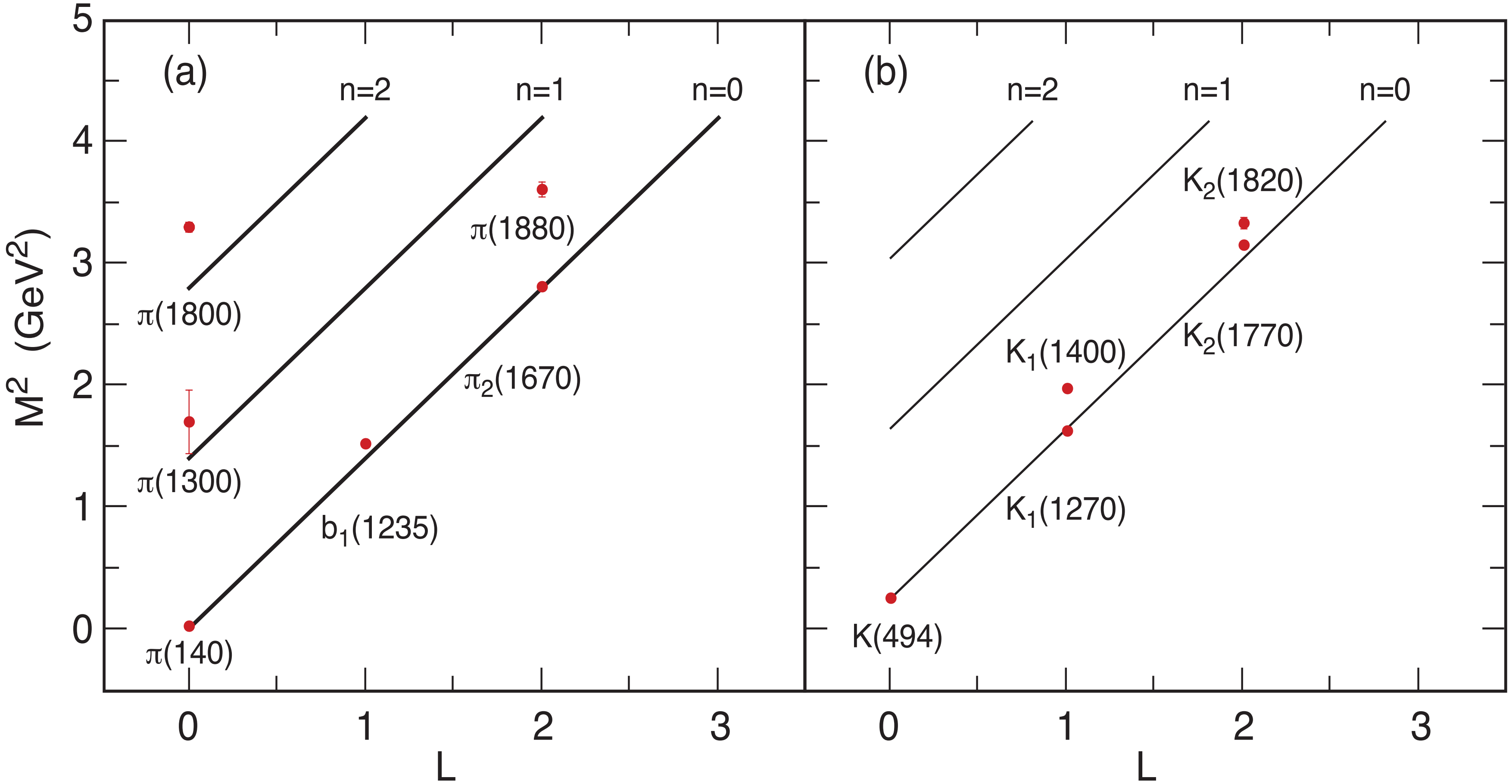
$$M^2(n,L_M)=4\kappa^2(n+L_M)$$

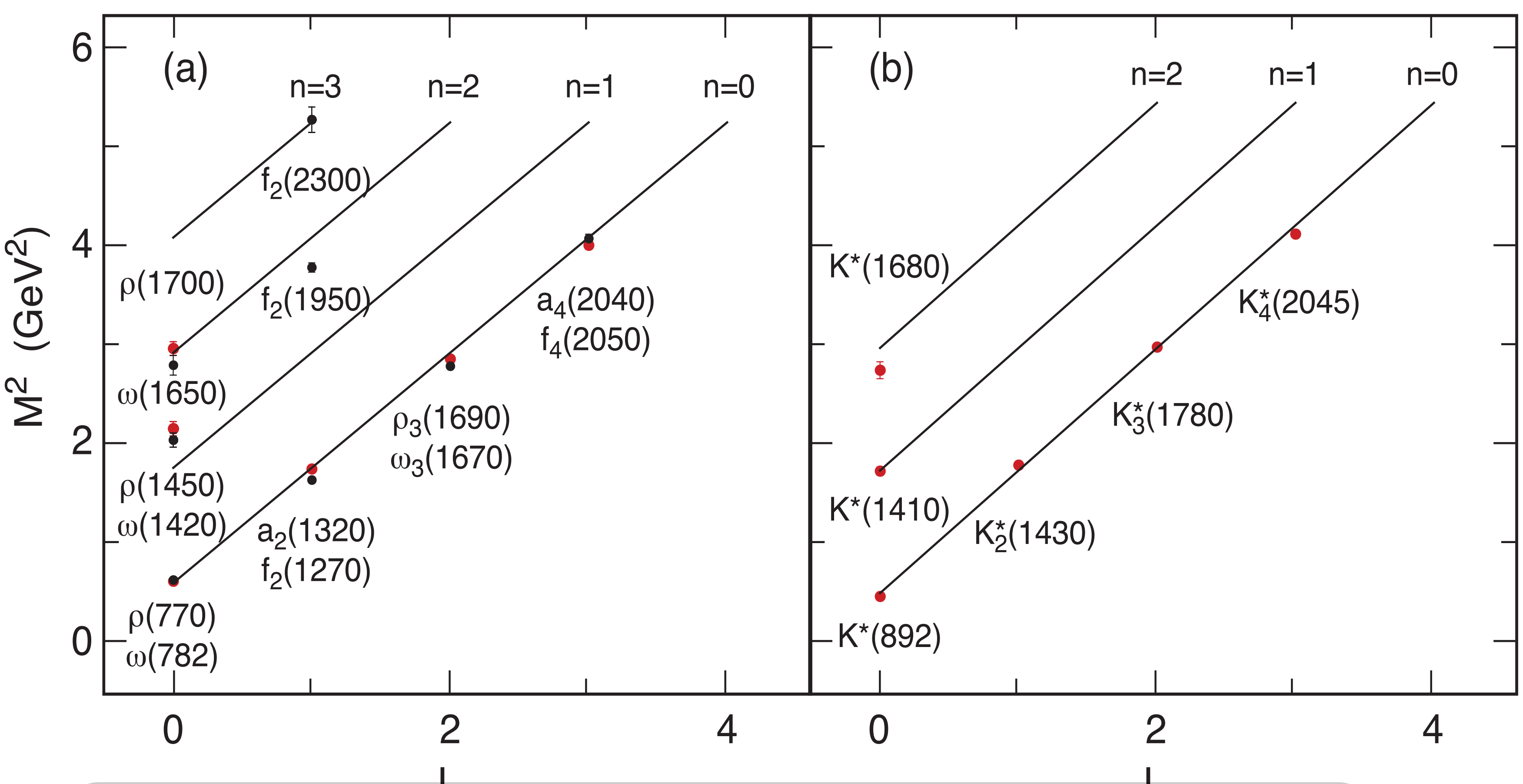
S=0, P=+

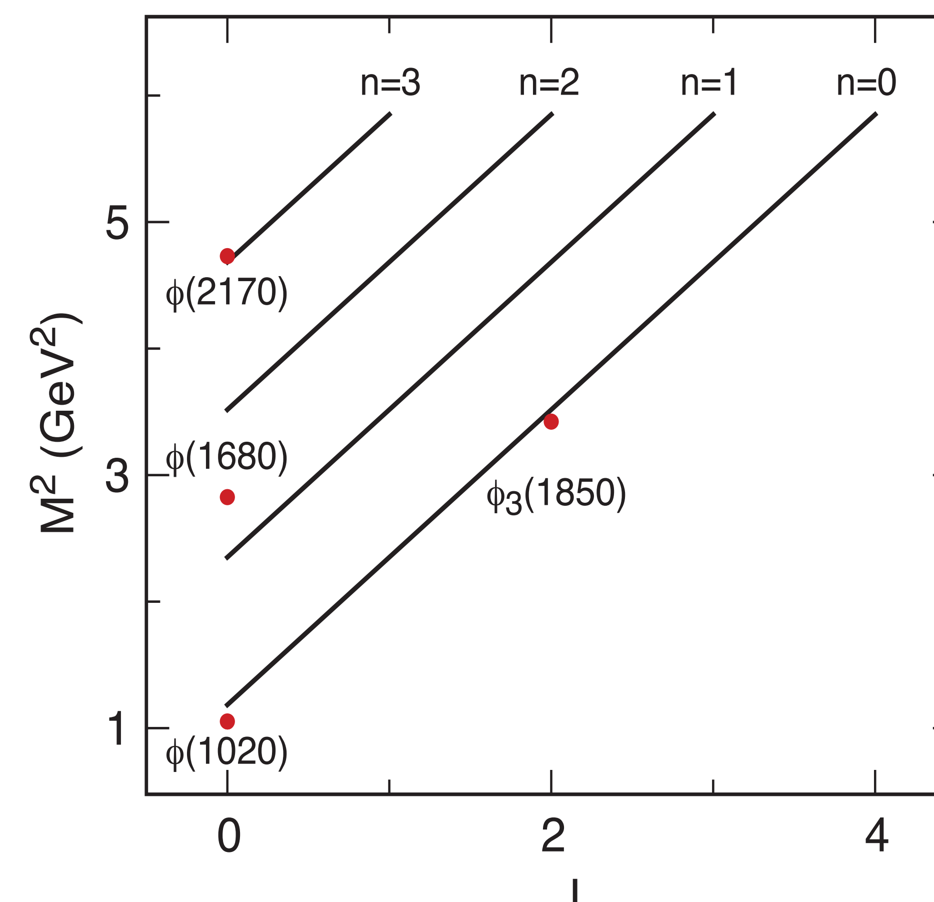
Same κ *!*

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

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





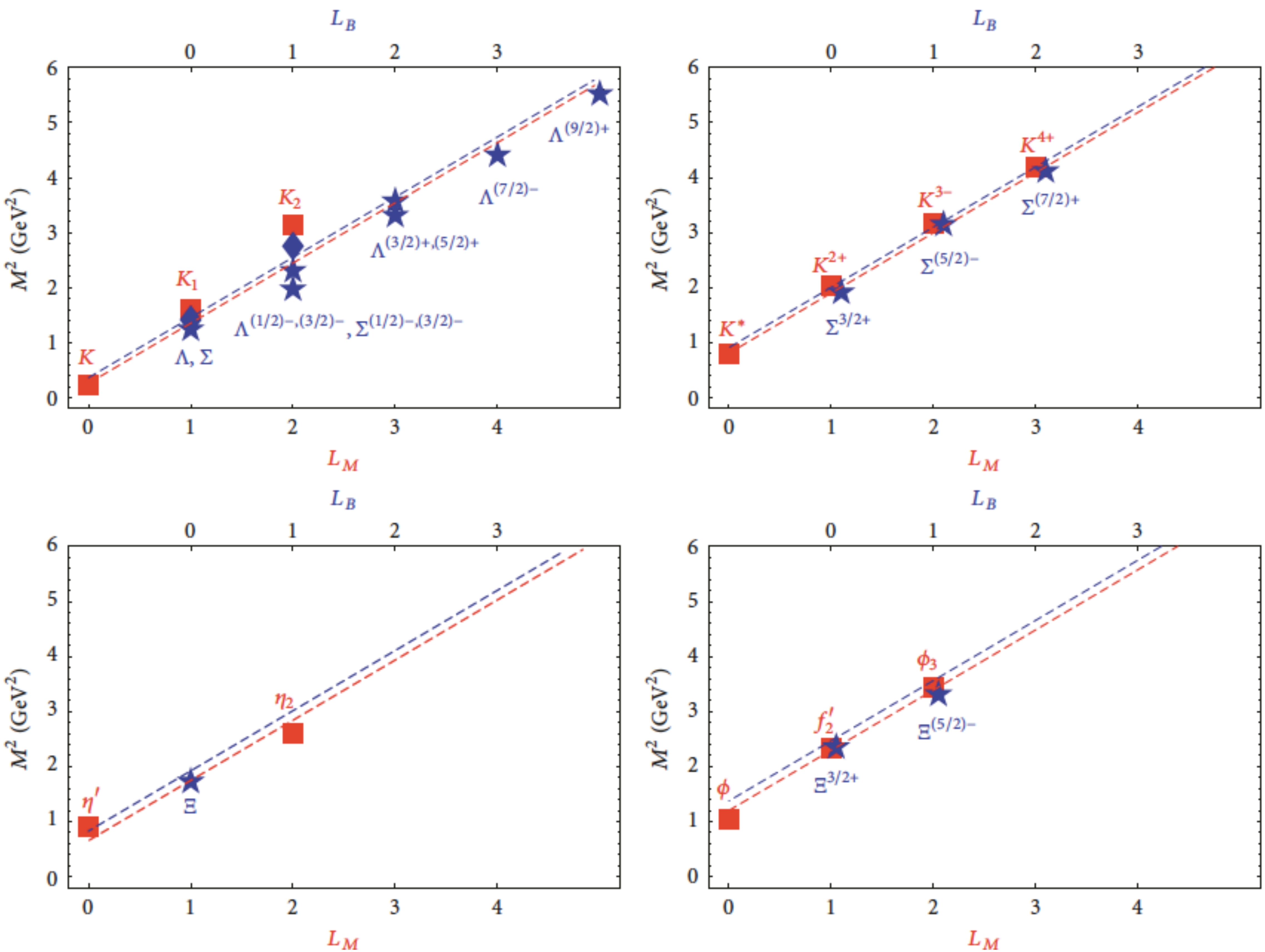


$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

Equal Slope in n and L

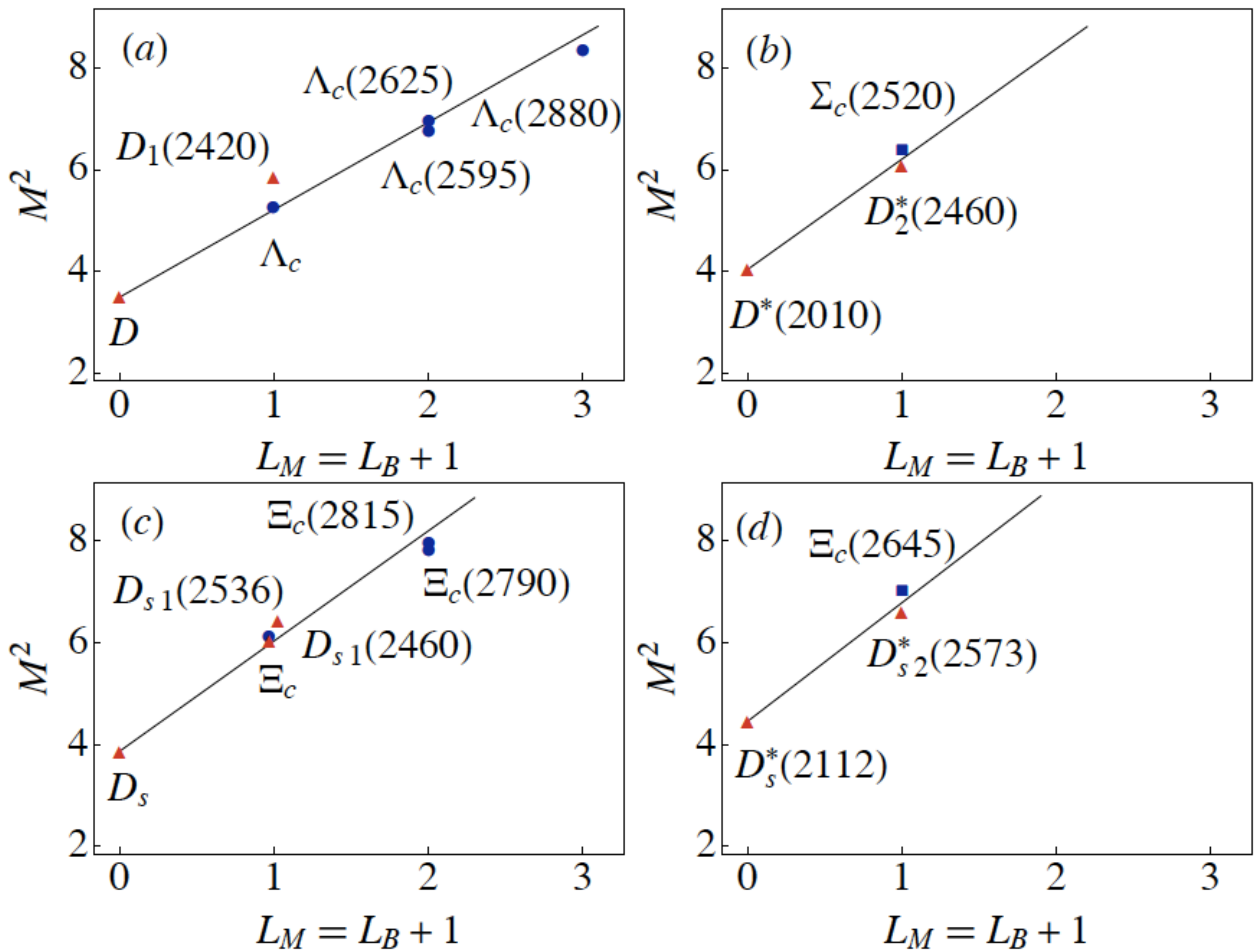
de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



Heavy charm quark mass does not break supersymmetry

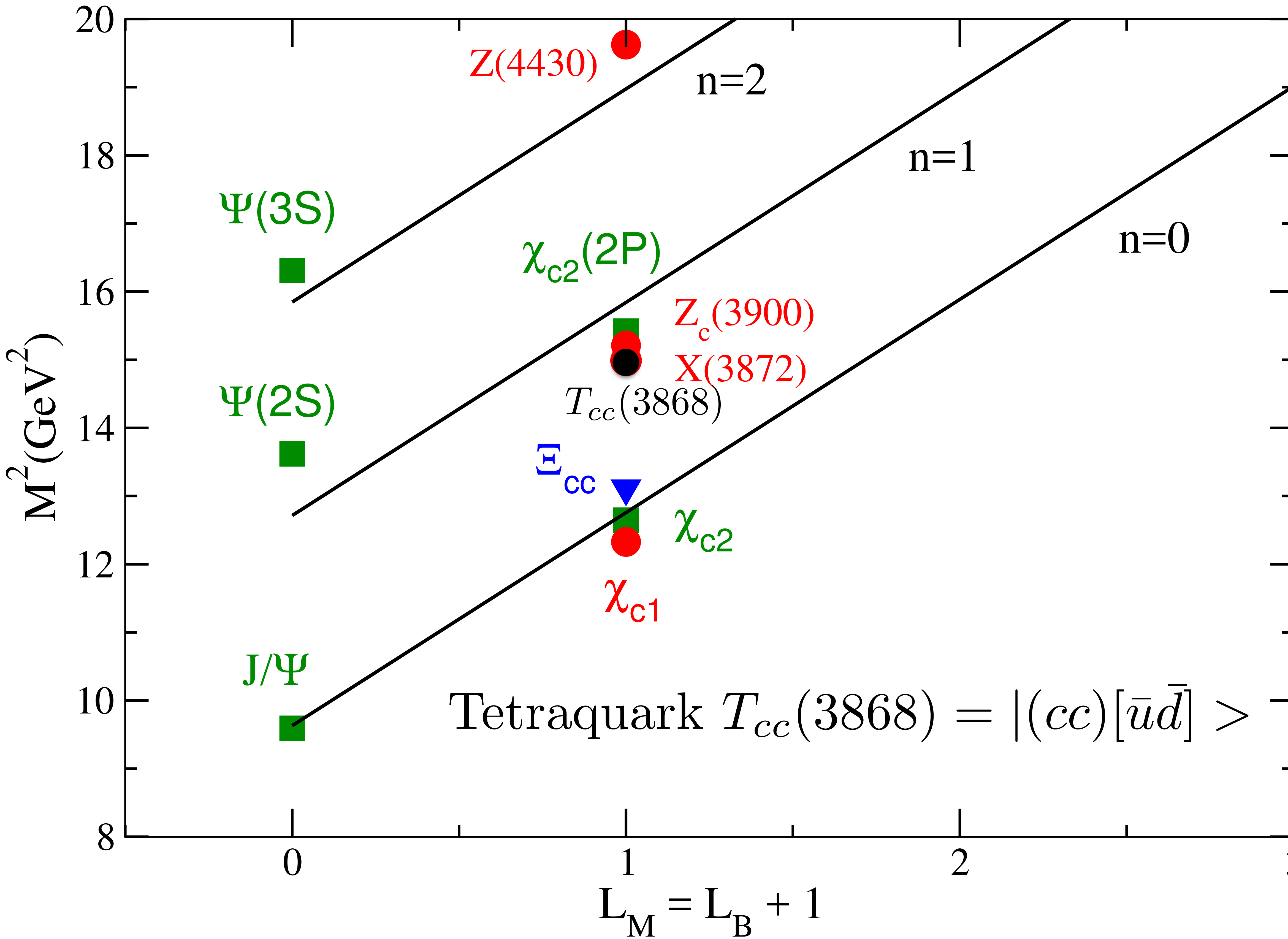
Connection to the Linear Instant-Form Potential

Linear instant nonrelativistic form $V(r) = Cr$ for heavy quarks

$\Updownarrow$

Harmonic Oscillator $U(\zeta) = \kappa^4 \zeta^2$ LF Potential for relativistic light quarks

A.P. Trawinski, S.D. Glazek, H. D. Dosch, G. de Teramond, sjb



$Mesons : GreenSquare, Baryons(BlueTriangle), Tetraquarks(RedCircle)$

Universal Hadronic Decomposition

$$\frac{\mathcal{M}_H^2}{\kappa^2} = (1 + 2n + L) + (1 + 2n + L) + (2L + 4S + 2B - 2)$$

- ***Universal quark light-front kinetic energy***

Equal: Virial Theorem

$$\Delta\mathcal{M}^2_{LFKE} = \kappa^2(1 + 2n + L)$$

- ***Universal quark light-front potential energy***

$$\Delta\mathcal{M}^2_{LFPE} = \kappa^2(1 + 2n + L)$$

- ***Universal Constant Contribution from AdS and Superconformal Quantum Mechanics***

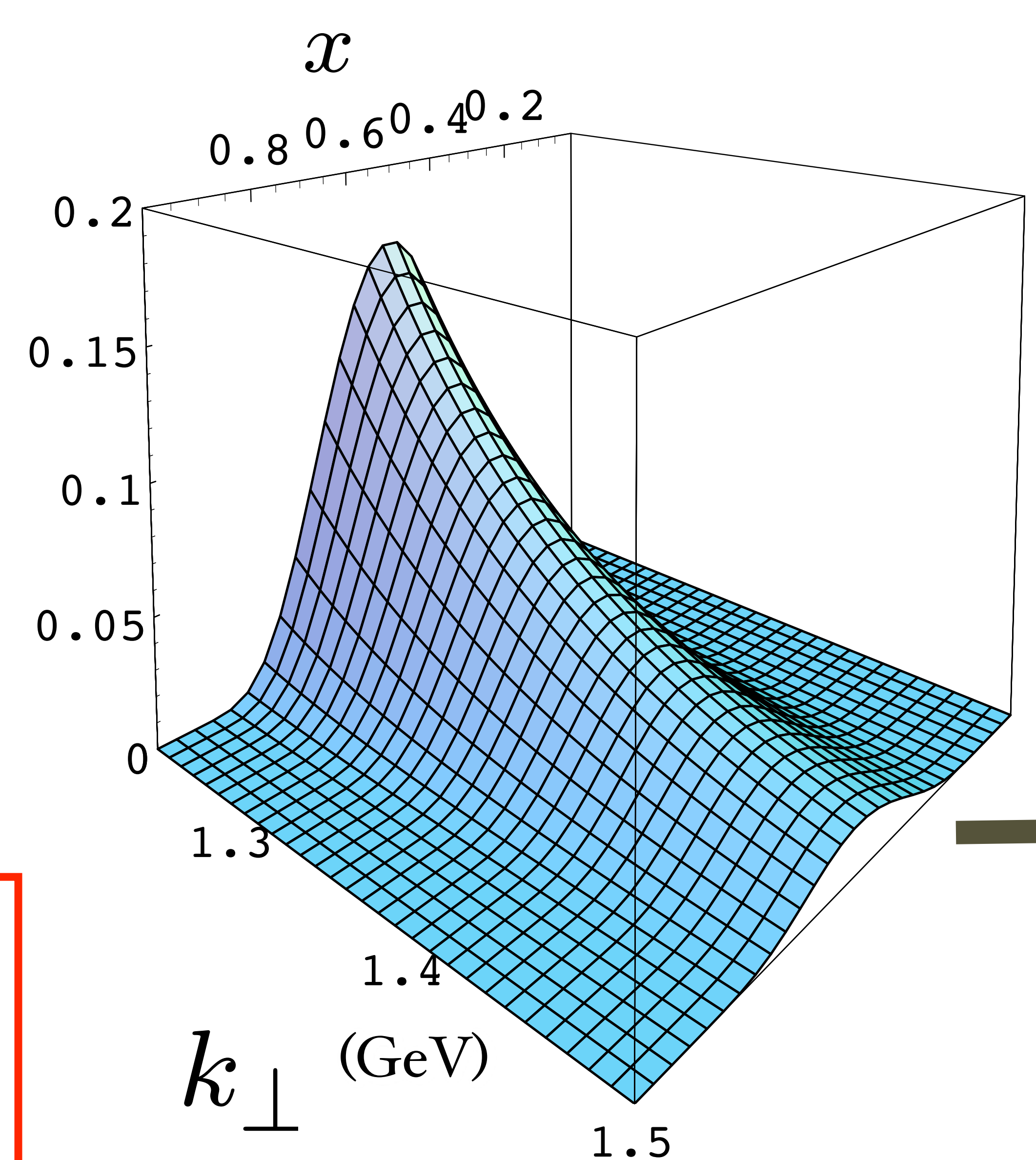
$$\Delta\mathcal{M}^2_{spin} = 2\kappa^2(L + 2S + B - 1)$$

hyperfine spin-spin

Prediction from AdS/QCD: Meson LFWF

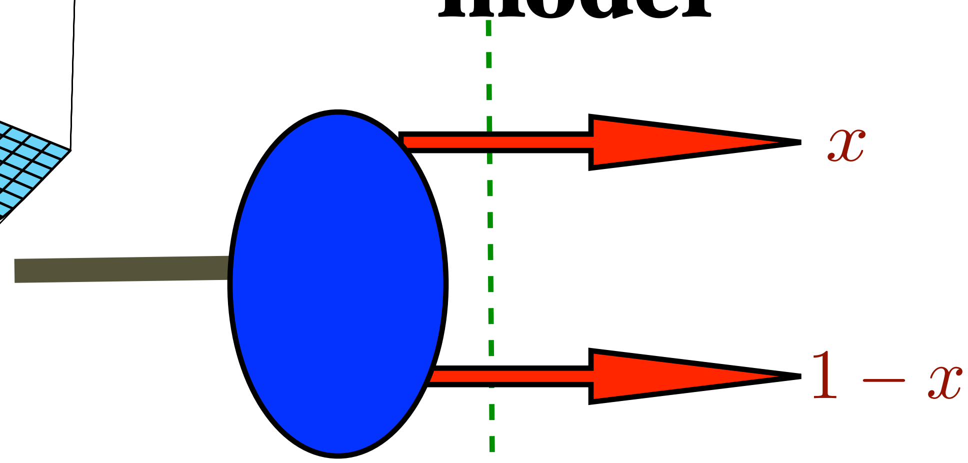
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

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

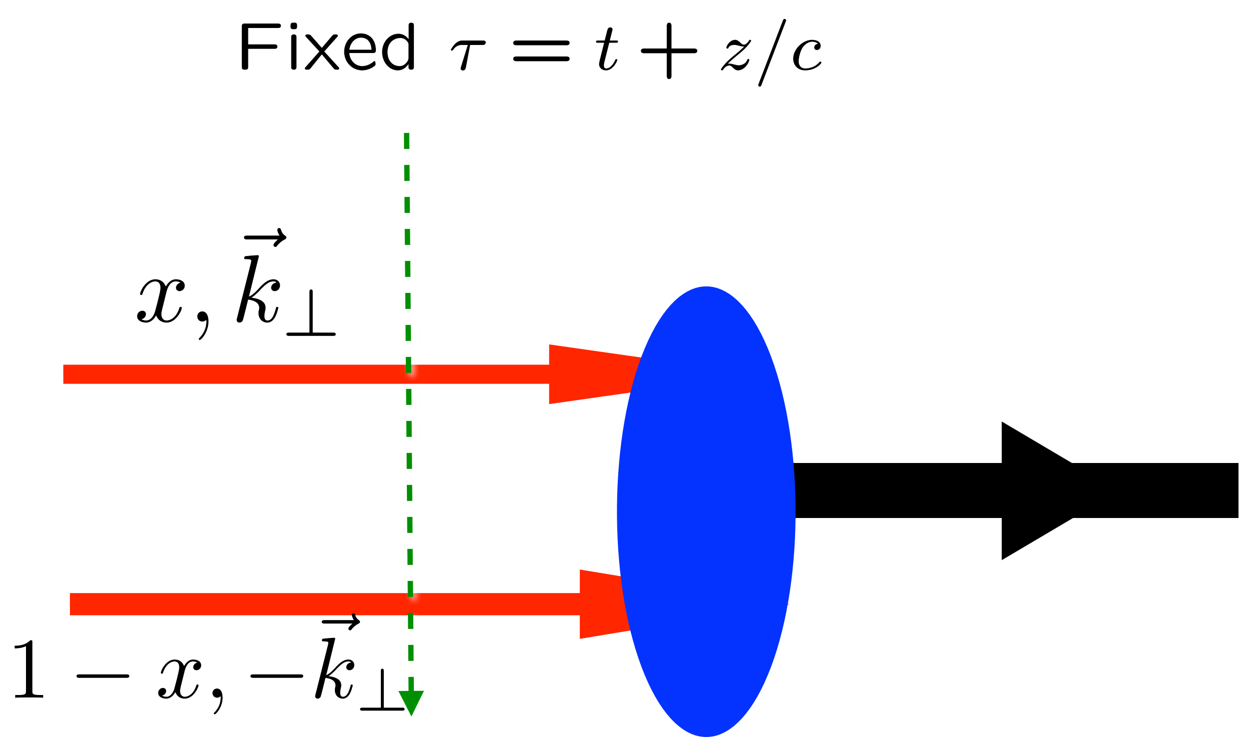
$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

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

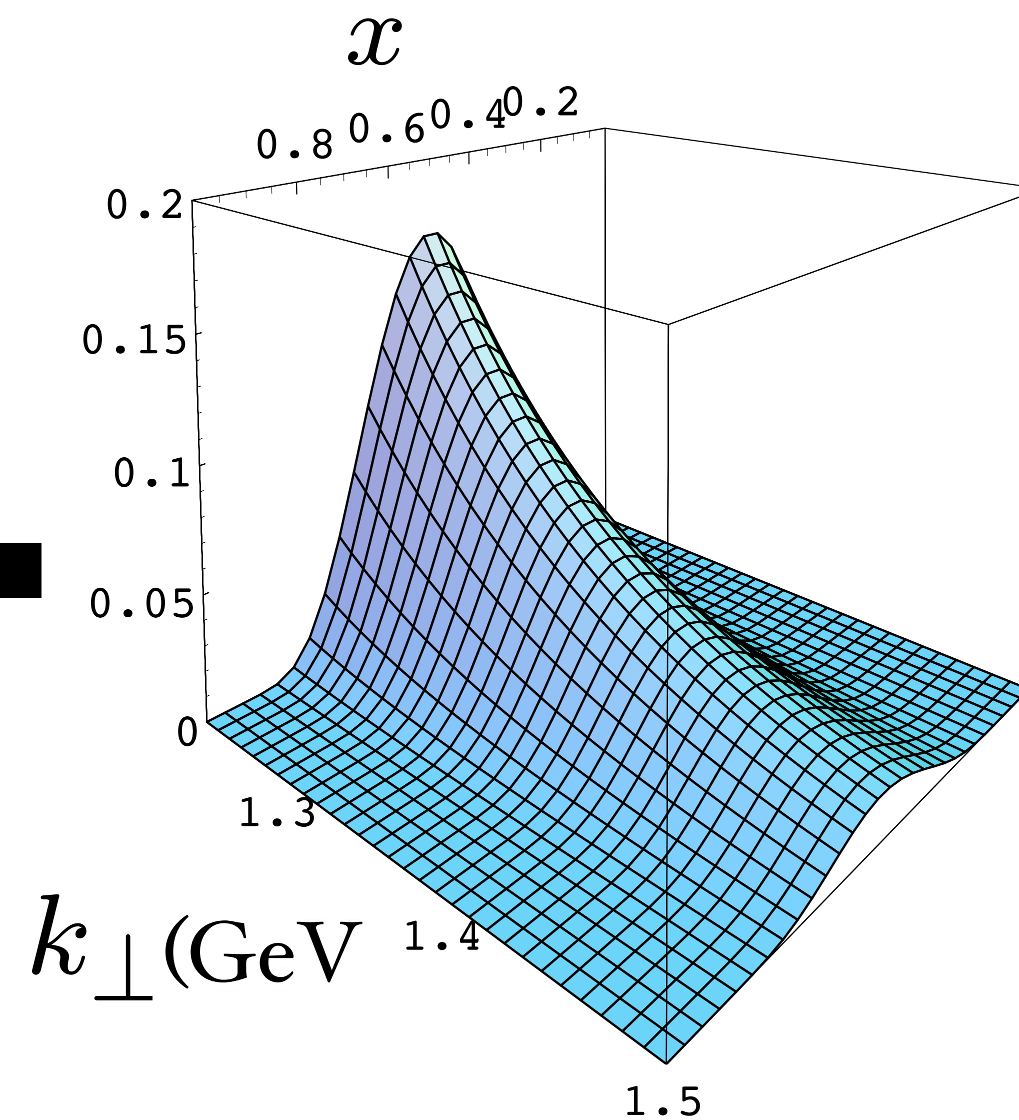
Provides Connection of Confinement to Hadron Structure

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

off-shell in P^- and invariant mass $\mathcal{M}^2_{q\bar{q}}$



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



"Hadronization at the Amplitude Level"

Boost-invariant LFWF connects confined quarks and gluons to hadrons

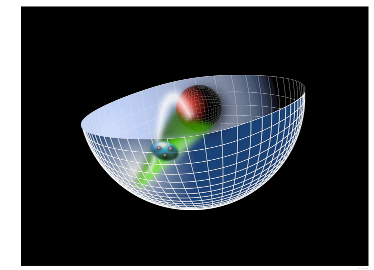
Proceeds in LF time τ within casual horizon
Instant time violates causality

LFHQCD: Underlying Principles

- *Poincarè Invariance: Independent of the observer's Lorentz frame: Quantization at Fixed Light-Front Time* τ

- *Causality: Information within causal horizon: Light-Front*

- *Light-Front Holography: AdS₅ = LF (3+1)*



$$z \leftrightarrow \zeta \text{ where } \zeta^2 = b_\perp^2 x(1-x)$$

- *Introduce Mass Scale* κ *while retaining the Conformal Invariance of the Action (dAFF)*

- *Unique Dilaton in AdS₅:* $e^{+\kappa^2 z^2}$

- *Unique color-confining LF Potential* $U(\zeta^2) = \kappa^4 \zeta^2$

- *Superconformal Algebra: Mass Degenerate 4-Plet:*

$$\boxed{\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]}$$

Remarkable Features of Light-Front Schrödinger Equation

Dynamics + Spectroscopy!

- ***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***

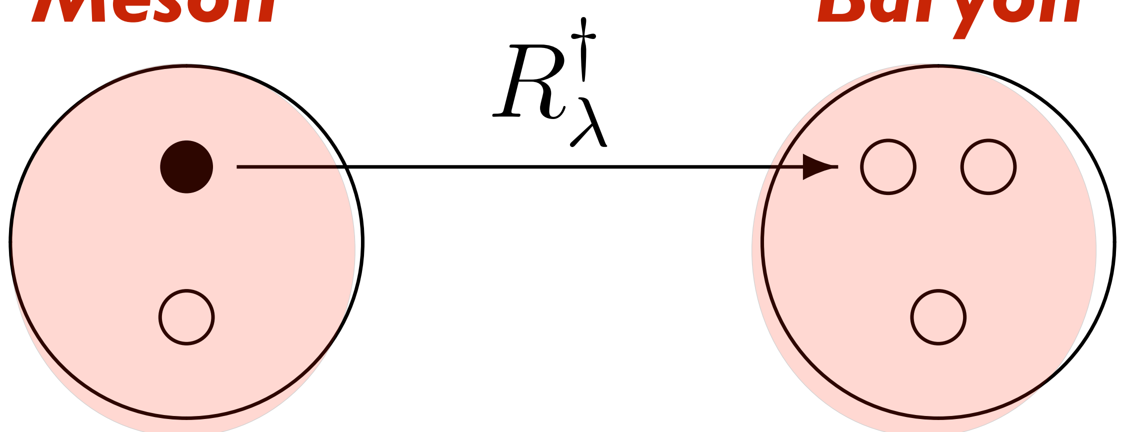
$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!

Meson **Baryon**



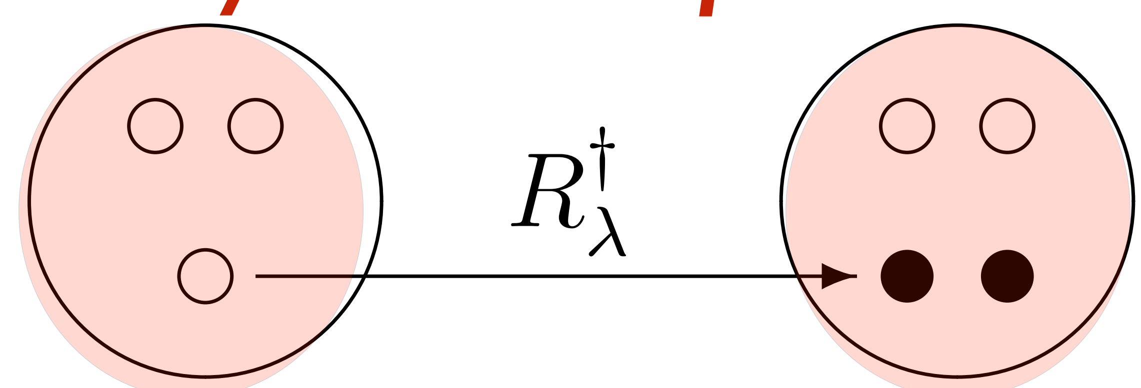
$\phi_M, \; L_B + 1$ $\psi_{B+}, \; L_B$

$R_\lambda^\dagger \; \bar{q} \to [qq]$

$\bar{3}_C \to \bar{3}_C$

Tetraquark: diquark + antidiquark

Baryon



$R_\lambda^\dagger \; q \to [\bar{q}\bar{q}]$

$3_C \to 3_C$

$\psi_{B-}, \; L_B + 1$ $\phi_T, \; L_B$

Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

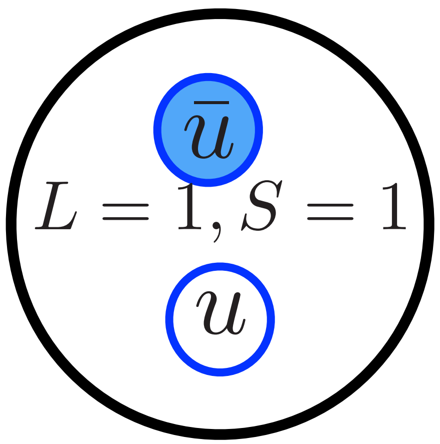
Superconformal Algebra 4-Plet

$R^\dagger_\lambda \quad \bar{q} \to (qq) \quad S = 1$

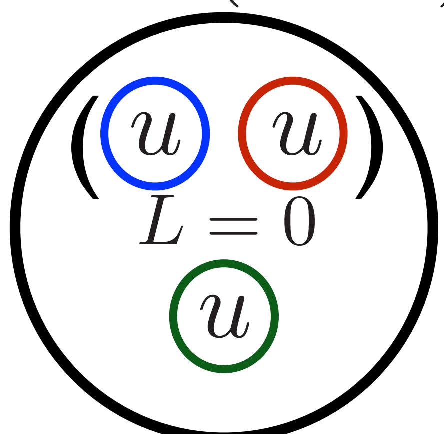
$\bar{3}_C \to \bar{3}_C$

Vector ()+ Scalar [] Diquarks

$f_2(1270)$

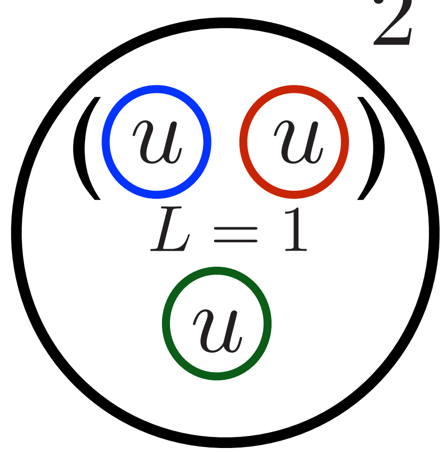


$\Delta^+(1232)$



$J^{PC} = 2^{++}$

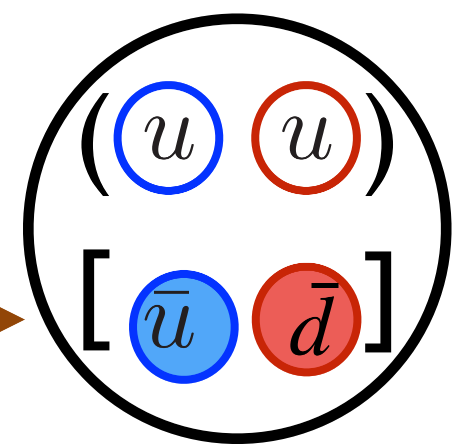
$J^P = \frac{3}{2}^+$



Tetraquark

$J^{PC} = 1^{++}$

$a_1(1260)$



$S = 0$

$L = 0$

$R^\dagger_\lambda \quad q \to [\bar{q}\bar{q}]$

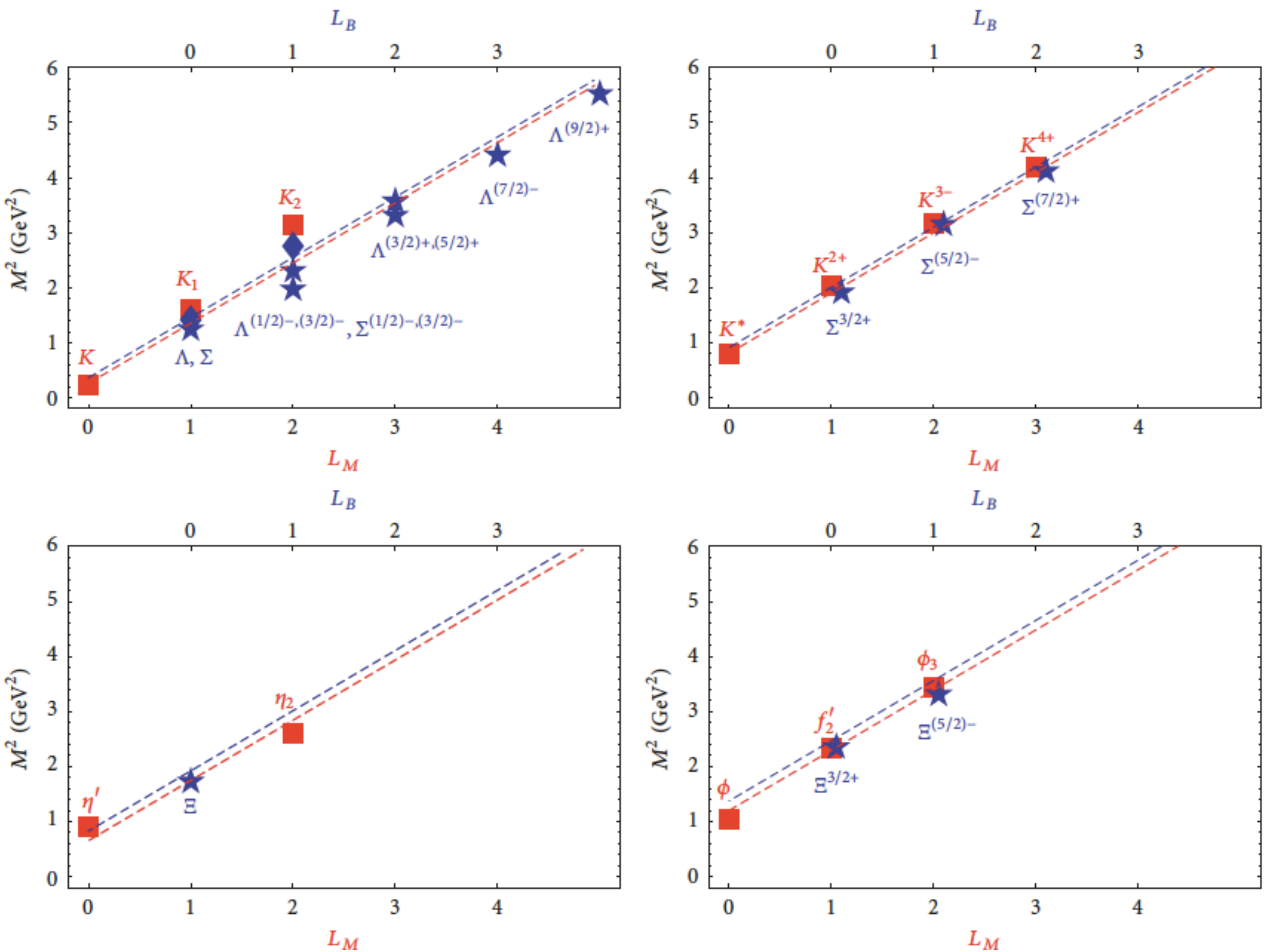
$3_C \to 3_C$

Meson

Baryon

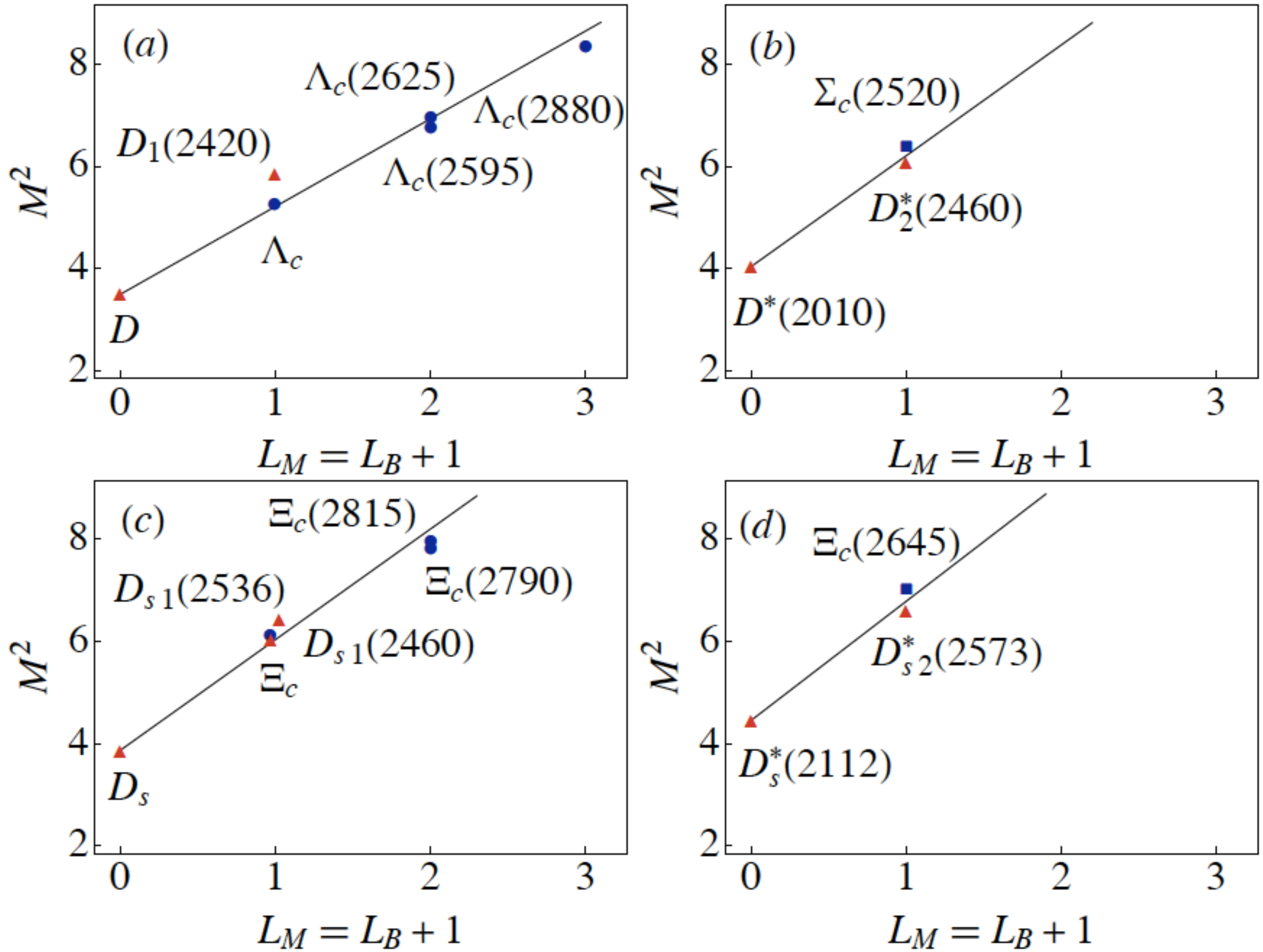
de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



Heavy charm quark mass does not break supersymmetry

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{q}q$	0^{-+}	$\pi(140)$	—	—	—	—	—	—
$\bar{q}q$	1^{+-}	$b_1(1235)$	$[ud]q$	$(1/2)^+$	$N(940)$	$[ud][\bar{u}\bar{d}]$	0^{++}	$f_0(980)$
$\bar{q}q$	2^{-+}	$\pi_2(1670)$	$[ud]q$	$(1/2)^-$	$N_{\frac{1}{2}^-}(1535)$	$[ud][\bar{u}\bar{d}]$	1^{-+}	$\pi_1(1400)$
				$(3/2)^-$	$N_{\frac{3}{2}^-}(1520)$			$\pi_1(1600)$
$\bar{q}q$	1^{--}	$\rho(770),\ \omega(780)$	—	—	—	—	—	—
$\bar{q}q$	2^{++}	$a_2(1320),\ f_2(1270)$	$[qq]q$	$(3/2)^+$	$\Delta(1232)$	$[qq][\bar{u}\bar{d}]$	1^{++}	$a_1(1260)$
$\bar{q}q$	3^{--}	$\rho_3(1690),\ \omega_3(1670)$	$[qq]q$	$(1/2)^-$	$\Delta_{\frac{1}{2}^-}(1620)$	$[qq][\bar{u}\bar{d}]$	2^{--}	$\rho_2(\sim 1700)?$
				$(3/2)^-$	$\Delta_{\frac{3}{2}^-}(1700)$			
$\bar{q}q$	4^{++}	$a_4(2040),\ f_4(2050)$	$[qq]q$	$(7/2)^+$	$\Delta_{\frac{7}{2}^+}(1950)$	$[qq][\bar{u}\bar{d}]$	3^{++}	$a_3(\sim 2070)?$
$\bar{q}s$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{q}s$	$1^{+(-)}$	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	$0^{+(+)}$	$K_0^*(1430)$
$\bar{q}s$	$2^{-(+)}$	$K_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar{s}\bar{q}]$	$1^{-(+)}$	$K_1^*(\sim 1700)?$
				$(3/2)^-$	$\Lambda(1520)$			
$\bar{s}q$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$a_0(980)$
								$f_0(980)$
$\bar{s}q$	$1^{-(-)}$	$K^*(890)$	—	—	—	—	—	—
$\bar{s}q$	$2^{+(+)}$	$K_2^*(1430)$	$[sq]q$	$(3/2)^+$	$\Sigma(1385)$	$[sq][\bar{q}\bar{q}]$	$1^{+(+)}$	$K_1(1400)$
$\bar{s}q$	$3^{-(-)}$	$K_3^*(1780)$	$[sq]q$	$(3/2)^-$	$\Sigma(1670)$	$[sq][\bar{q}\bar{q}]$	$2^{-(-)}$	$K_2(\sim 1700)?$
$\bar{s}q$	$4^{+(+)}$	$K_4^*(2045)$	$[sq]q$	$(7/2)^+$	$\Sigma(2030)$	$[sq][\bar{q}\bar{q}]$	$3^{+(+)}$	$K_3(\sim 2070)?$
$\bar{s}s$	0^{-+}	$\eta(550)$	—	—	—	—	—	—
$\bar{s}s$	1^{+-}	$h_1(1170)$	$[sq]s$	$(1/2)^+$	$\Xi(1320)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$f_0(1370)$
								$a_0(1450)$
$\bar{s}s$	2^{-+}	$\eta_2(1645)$	$[sq]s$	$(?)^?$	$\Xi(1690)$	$[sq][\bar{s}\bar{q}]$	1^{-+}	$\Phi'(1750)?$
$\bar{s}s$	1^{--}	$\Phi(1020)$	—	—	—	—	—	—
$\bar{s}s$	2^{++}	$f_2'(1525)$	$[sq]s$	$(3/2)^+$	$\Xi^*(1530)$	$[sq][\bar{s}\bar{q}]$	1^{++}	$f_1(1420)$
$\bar{s}s$	3^{--}	$\Phi_3(1850)$	$[sq]s$	$(3/2)^-$	$\Xi(1820)$	$[sq][\bar{s}\bar{q}]$	2^{--}	$\Phi_2(\sim 1800)?$
$\bar{s}s$	2^{++}	$f_2(1950)$	$[ss]s$	$(3/2)^+$	$\Omega(1672)$	$[ss][\bar{s}\bar{q}]$	$1^{+(+)}$	$K_1(\sim 1700)?$

Meson Baryon Tetraquark

New Organization of the Hadron Spectrum

M. Nielsen, sjb

Superpartners for states with one c quark

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{q}c$	0^-	$D(1870)$	—	—	—	—	—	—
$\bar{q}c$	1^+	$D_1(2420)$	$[ud]c$	$(1/2)^+$	$\Lambda_c(2290)$	$[ud][\bar{c}\bar{q}]$	0^+	$\bar{D}_0^*(2400)$
$\bar{q}c$	2^-	$D_J(2600)$	$[ud]c$	$(3/2)^-$	$\Lambda_c(2625)$	$[ud][\bar{c}\bar{q}]$	1^-	—
$\bar{c}q$	0^-	$\bar{D}(1870)$	—	—	—	—	—	—
$\bar{c}q$	1^+	$\bar{D}_1(2420)$	$[cq]q$	$(1/2)^+$	$\Sigma_c(2455)$	$[cq][\bar{u}\bar{d}]$	0^+	$D_0^*(2400)$
$\bar{q}c$	1^-	$D^*(2010)$	—	—	—	—	—	—
$\bar{q}c$	2^+	$D_2^*(2460)$	$(qq)c$	$(3/2)^+$	$\Sigma_c^*(2520)$	$(qq)[\bar{c}\bar{q}]$	1^+	$D(2550)$
$\bar{q}c$	3^-	$D_3^*(2750)$	$(qq)c$	$(3/2)^-$	$\Sigma_c(2800)$	$(qq)[\bar{c}\bar{q}]$	—	—
$\bar{s}c$	0^-	$D_s(1968)$	—	—	—	—	—	—
$\bar{s}c$	1^+	$D_{s1}(2460)$	$[qs]c$	$(1/2)^+$	$\Xi_c(2470)$	$[qs][\bar{c}\bar{q}]$	0^+	$\bar{D}_{s0}^*(2317)$
$\bar{s}c$	2^-	$D_{s2}(\sim 2860)?$	$[qs]c$	$(3/2)^-$	$\Xi_c(2815)$	$[sq][\bar{c}\bar{q}]$	1^-	—
$\bar{s}c$	1^-	$D_s^*(2110)$	—	—	—	—	—	—
$\bar{s}c$	2^+	$D_{s2}^*(2573)$	$(sq)c$	$(3/2)^+$	$\Xi_c^*(2645)$	$(sq)[\bar{c}\bar{q}]$	1^+	$D_{s1}(2536)$
$\bar{c}s$	1^+	$D_{s1}(\sim 2700)?$	$[cs]s$	$(1/2)^+$	$\Omega_c(2695)$	$[cs][\bar{s}\bar{q}]$	0^+	??
$\bar{s}c$	2^+	$D_{s2}^*(\sim 2750)?$	$(ss)c$	$(3/2)^+$	$\Omega_c(2770)$	$(ss)[\bar{c}\bar{s}]$	1^+	??

M. Nielsen, sjb

predictions

beautiful agreement!

Heavy-light and heavy-heavy hadronic sectors

- Extension to the heavy-light hadronic sector

  [H. G. Dosch, GdT, S. J. Brodsky, PRD **92**, 074010 (2015), PRD **95**, 034016 (2017)]

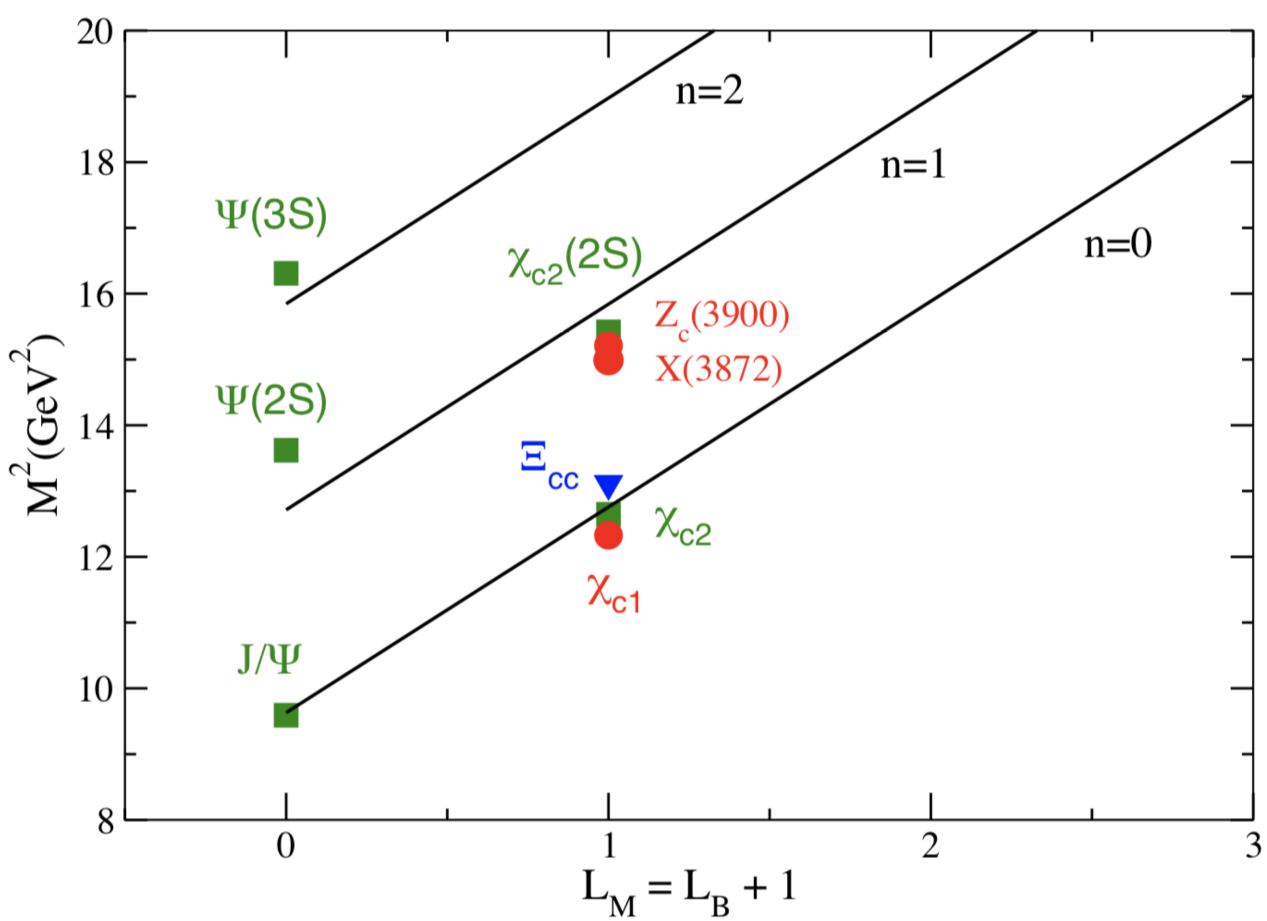
- Extension to the double-heavy hadronic sector

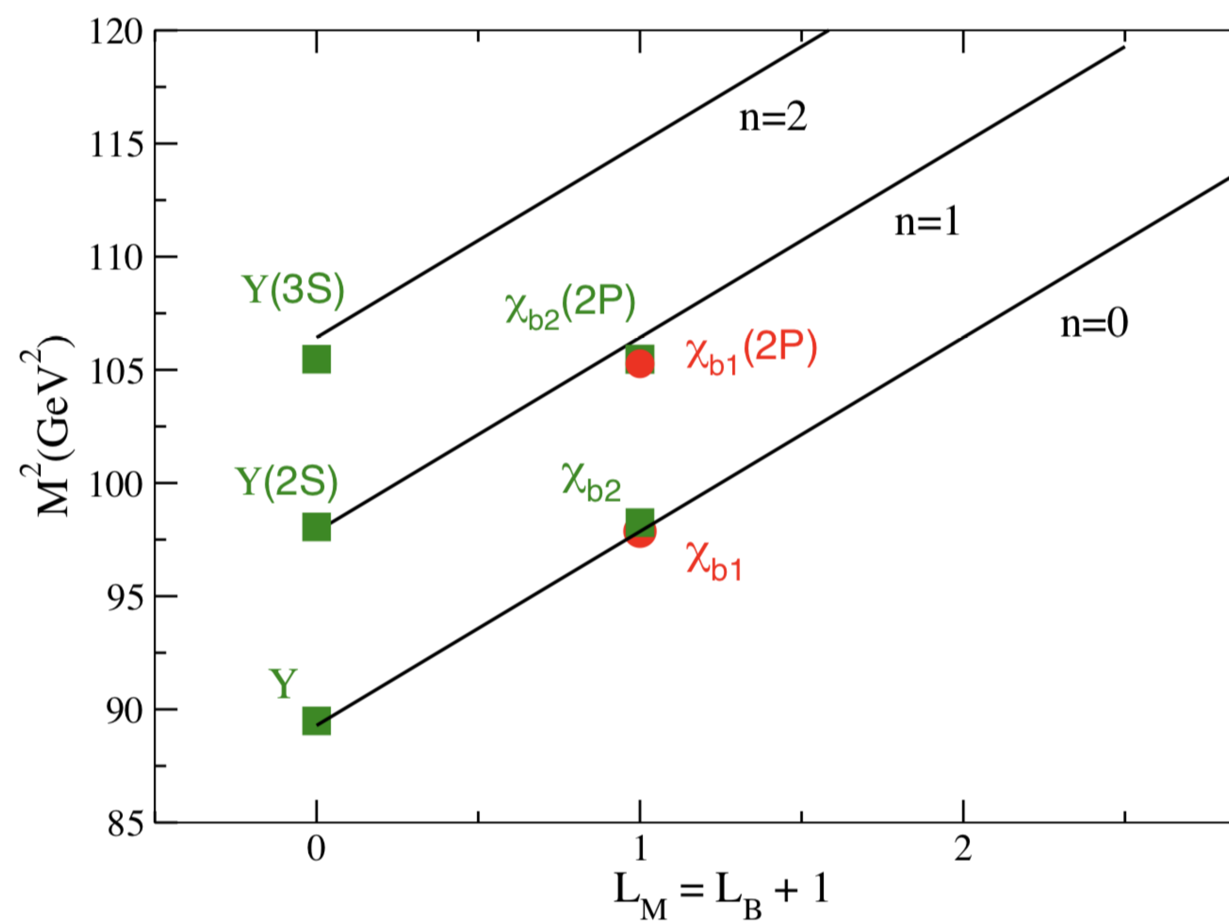
  [M. Nielsen and S. J. Brodsky, PRD, 114001 (2018)]

  [M. Nielsen, S. J. Brodsky, GdT, H. G. Dosch, F. S. Navarra, L. Zou, PRD **98**, 034002 (2018)]

- Extension to the isoscalar hadronic sector

  [L. Zou, H. G. Dosch, GdT,S. J. Brodsky, arXiv:1901.11205 [hep-ph]]





Massless pion!

Meson Spectrum in Soft Wall Model

$$\boxed{m_\pi = 0 \text{ if } m_q = 0}$$

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

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

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

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

Quark separation increases with L

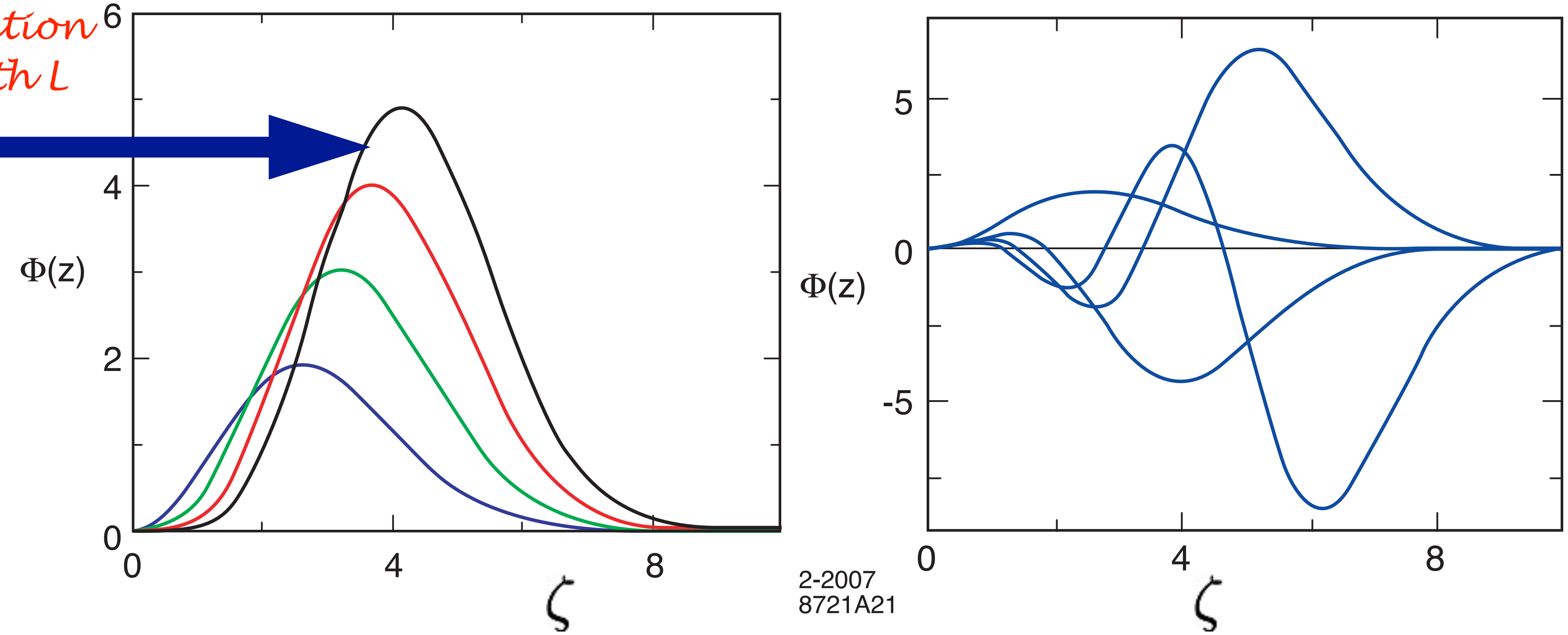
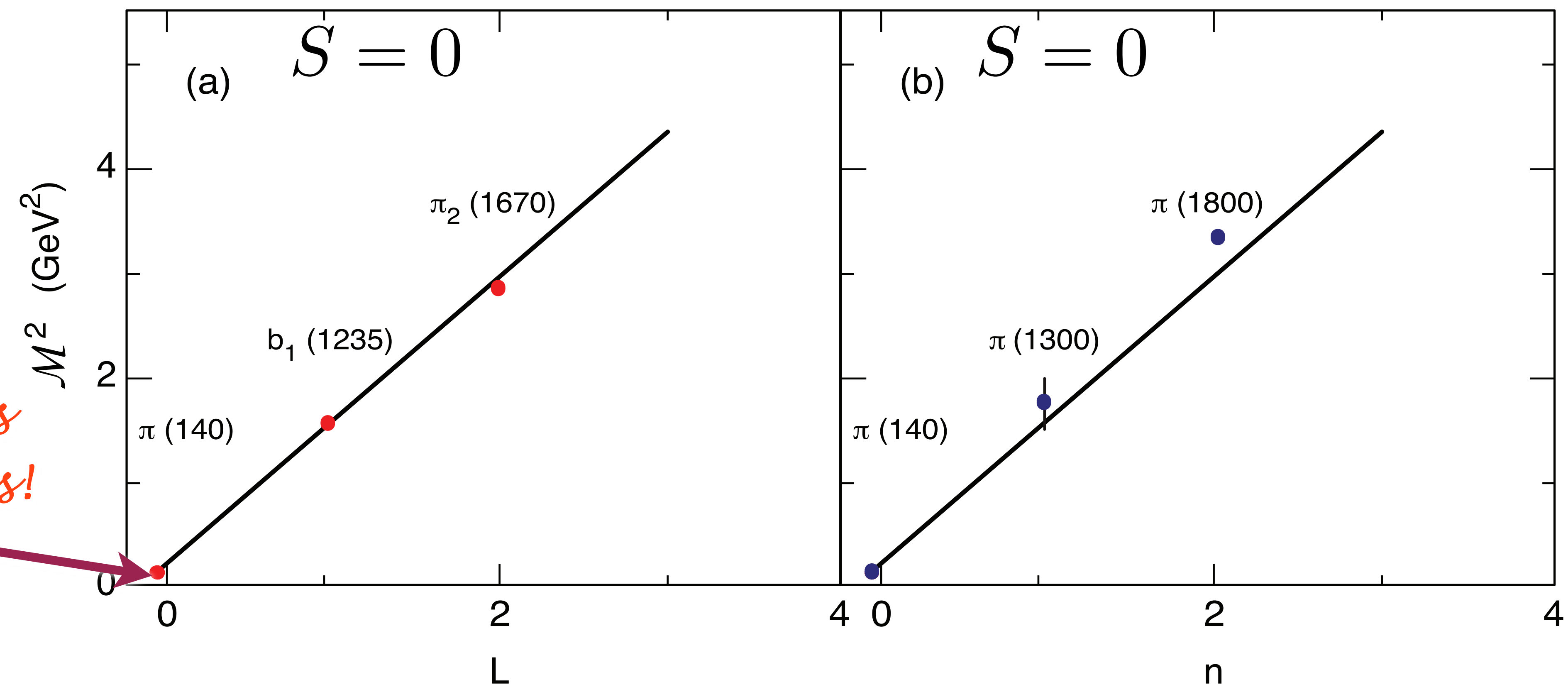


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Same slope in n and L!



Pion has zero mass!

$\boxed{m_q = 0}$

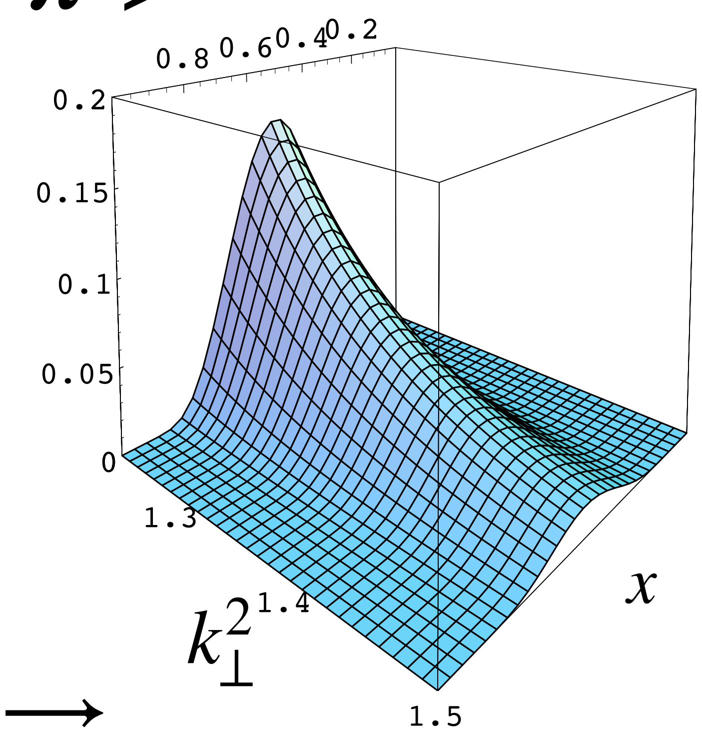
Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

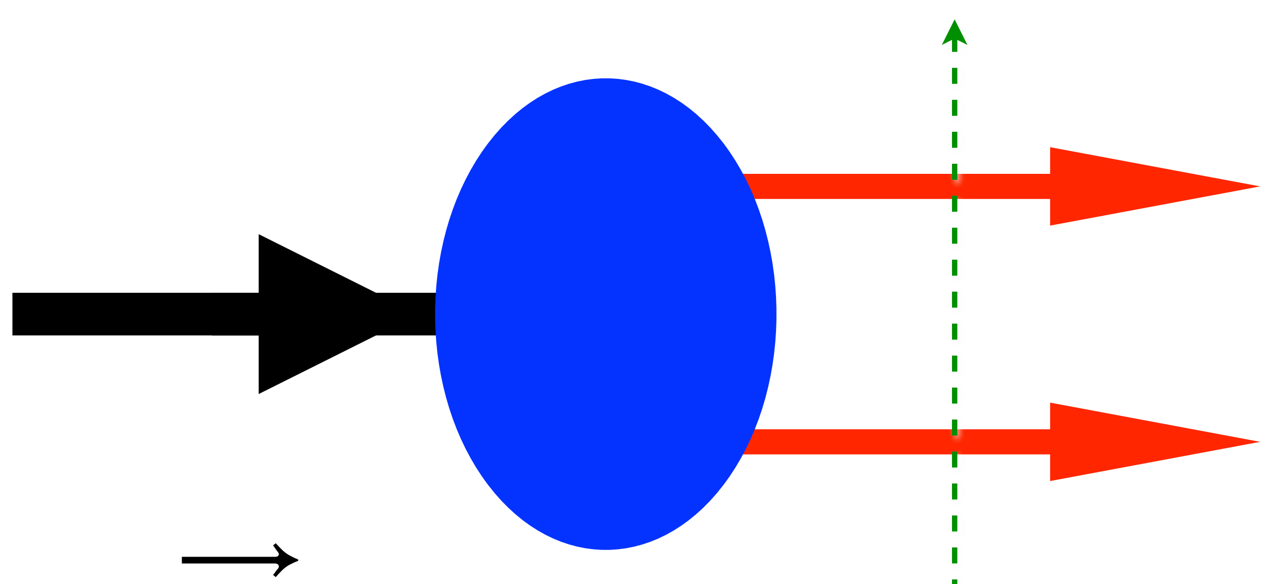
The Pion's Valence Light-Front Wavefunction

- Relativistic Quantum-Mechanical Wavefunction of the pion eigenstate $H_{LF}^{QCD}|\pi> = m_\pi^2|\pi>$

$$\Psi_\pi(x, \vec{k}_\perp) = < q(x, \vec{k}_\perp)\bar{q}(1-x, -\vec{k}_\perp)|\,\pi >$$

- Independent of the observer's or pion's motion
- No Lorentz contraction; causal
- ***Confined*** quark-antiquark bound state





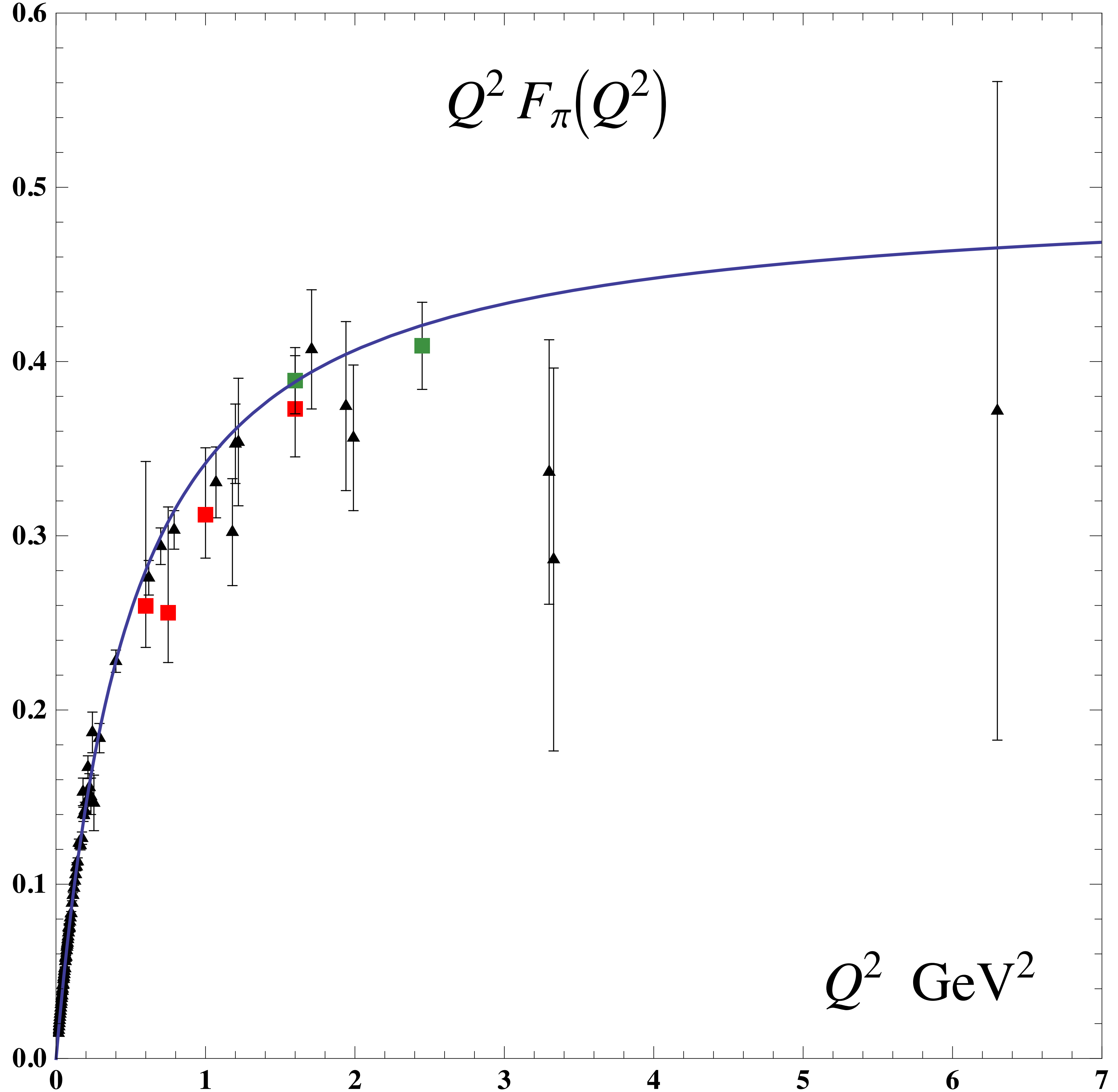
π

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

$1-x, -\vec{k}_\perp$

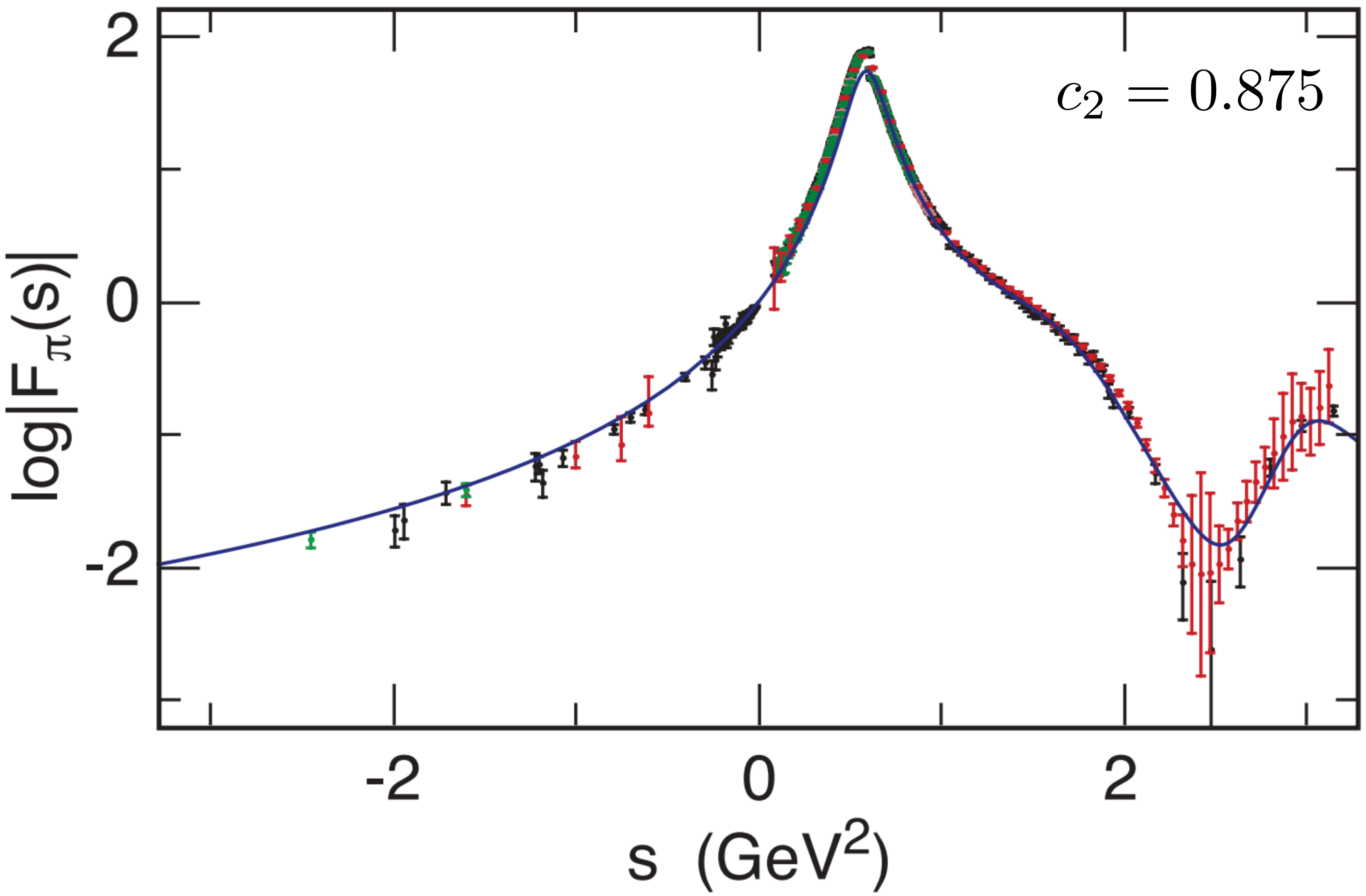
$\Psi_\pi(x, \vec{k}_\perp)$

Fixed $\tau = t + z/c$


$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
5
6
7

Pion EM Form Factor

Pion form factor compared with data



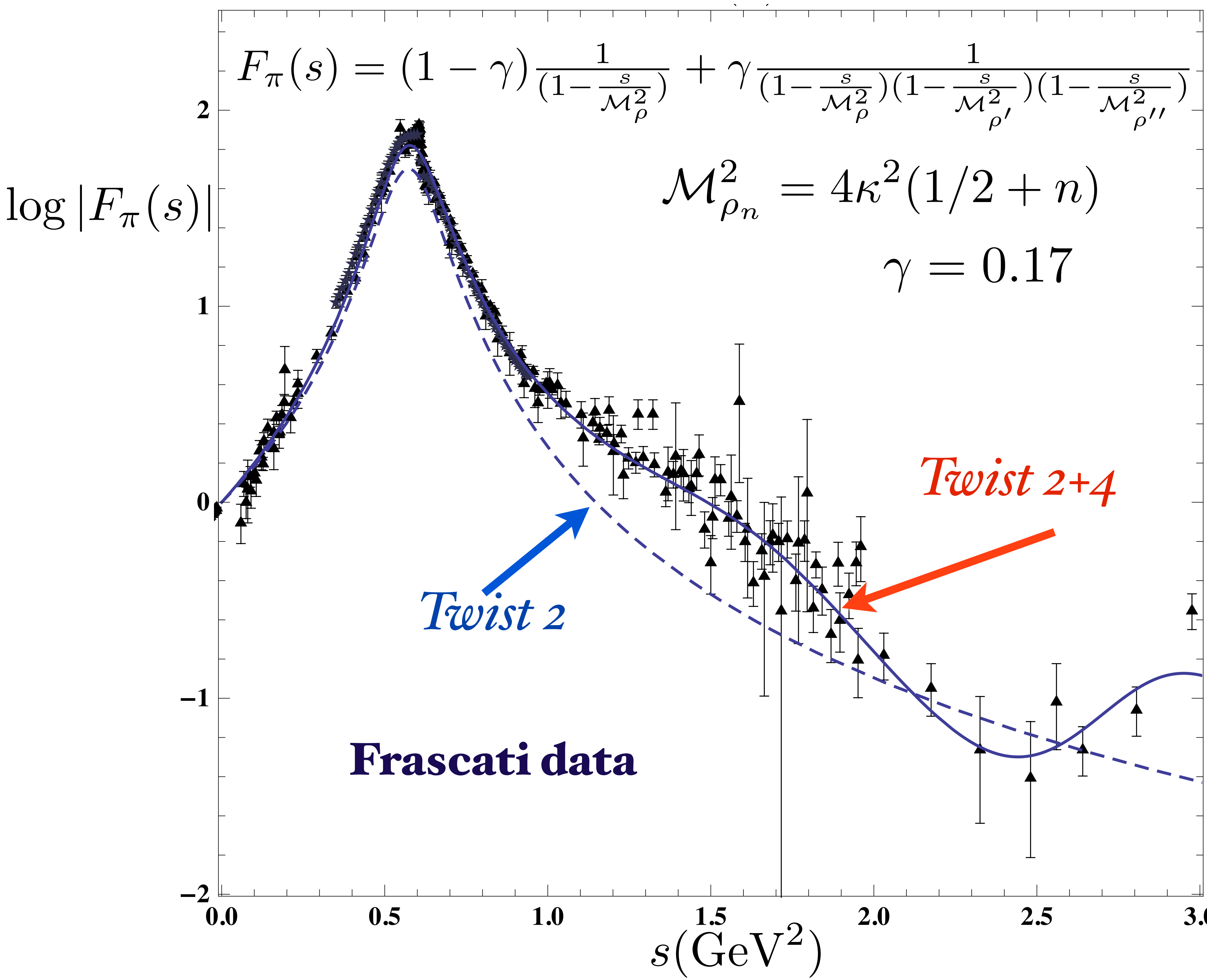
$$F_\pi(t) = \sum_\tau P_\tau F_\tau(t) \qquad \sum_\tau P_\tau = 1$$

Truncated at twist-τ = 4

$$F_\pi(t) = c_2 F_{\tau=2}(t) + (1 - c_2) F_{\tau=4}(t)$$

G.F. de Téramond and S.J. Brodsky, Proc. Sci. LC2010 (2010) 029.
S.J. Brodsky, G.F. de Téramond, H.G. Dosch, J. Erlich, Phys. Rep. 584, 1 (2015). [Sec. 6.1.5]

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



Prescription for Timelike poles :

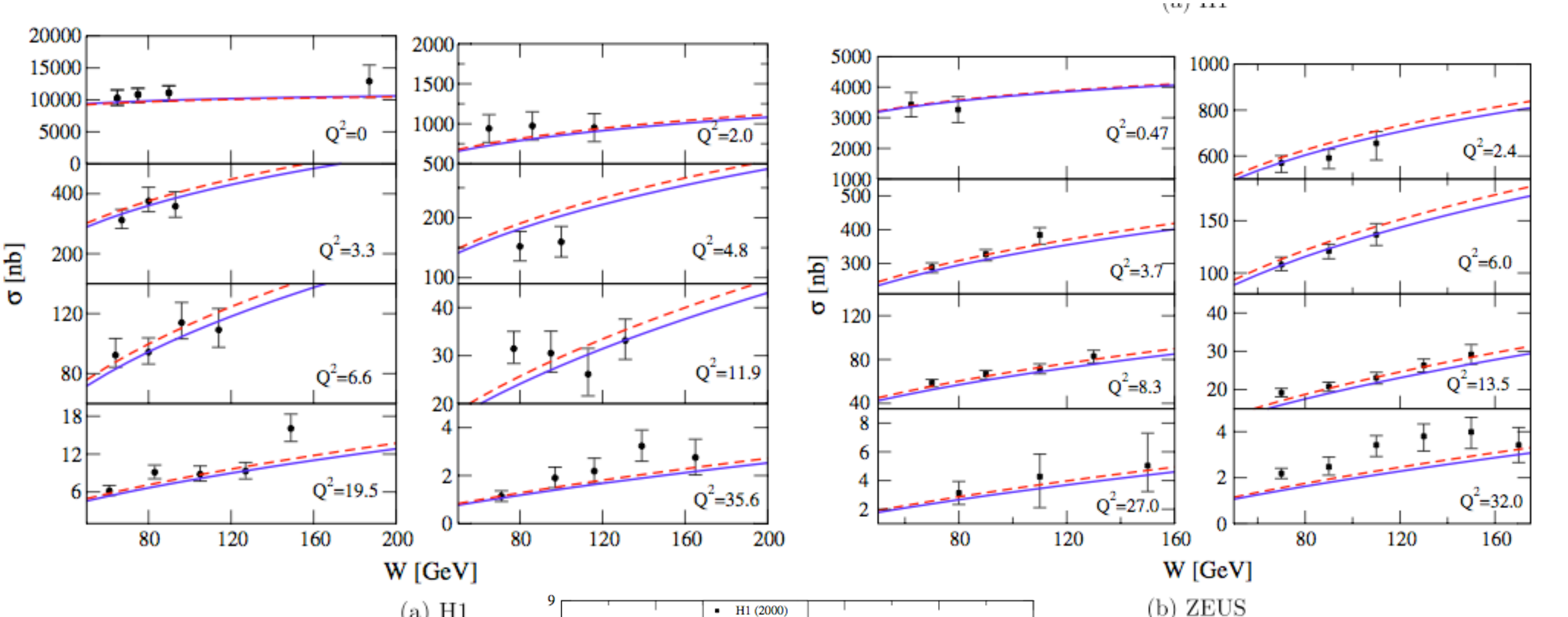
$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb

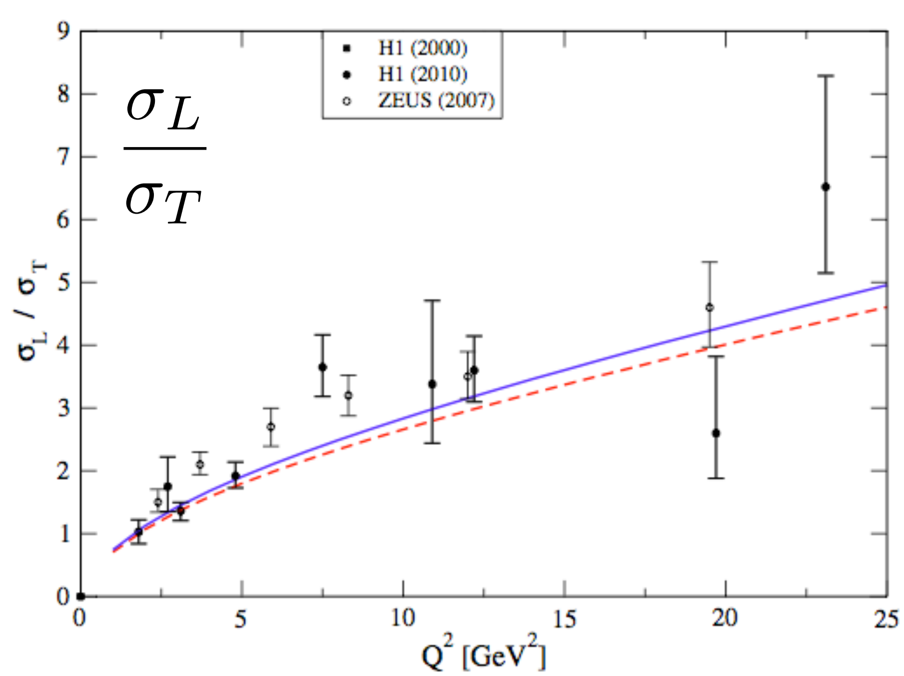
PRL **109,** 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

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

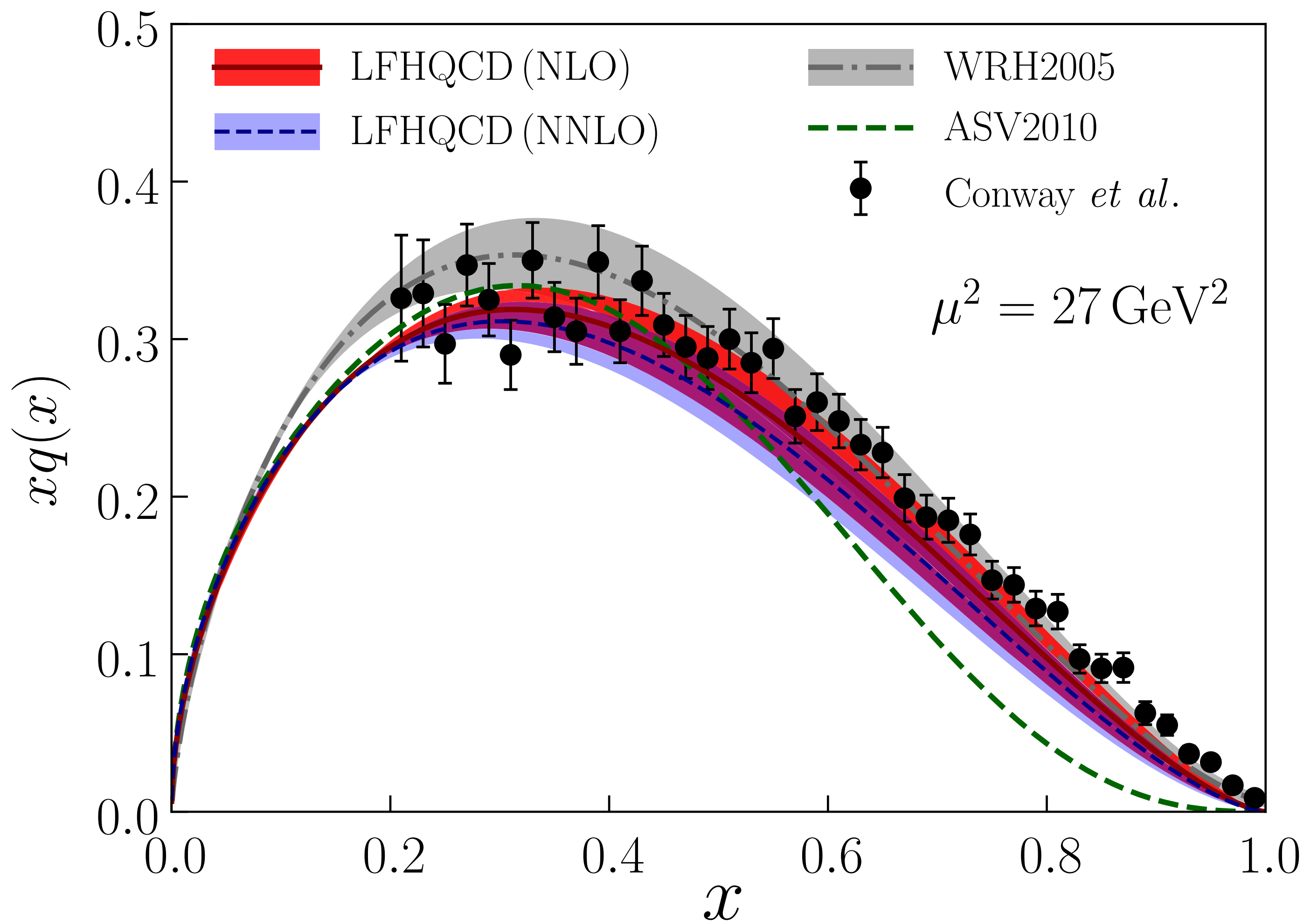


J. R. Forshaw, R. Sandapen

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



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

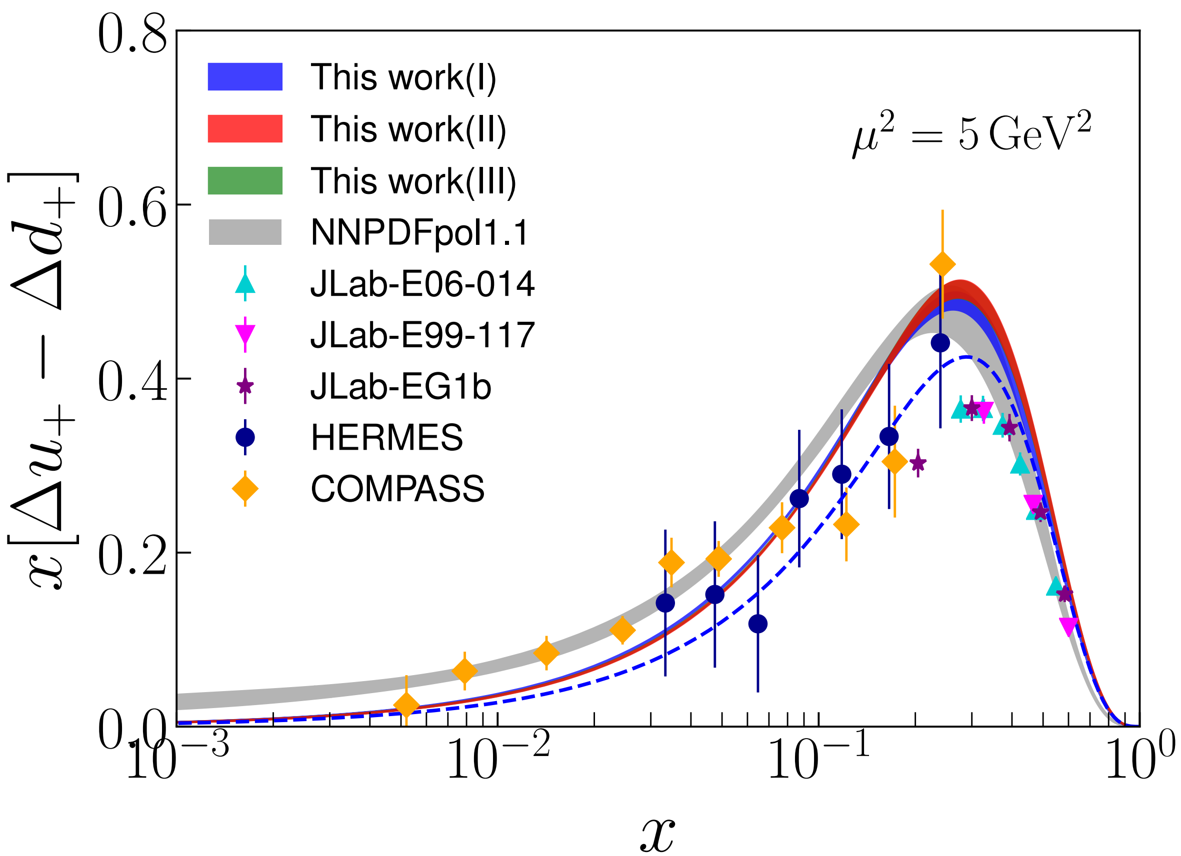


Comparison for $xq(x)$ in the pion from LFHQCD (red band) with the NLO fits [82,83] (gray band and green curve) and the LO extraction [84]. NNLO results are also included (light blue band). LFHQCD results are evolved from the initial scale $\mu_0 = 1.1 \pm 0.2$ GeV at NLO and the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV at NNLO.

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur *PHYSICAL REVIEW LETTERS 120, 182001 (2018)*

Tianbo Liu, Raza Sabbir Sufian, Guy F. de T´eramond, Hans Gunter Dösch, Alexandre Deur, sjb

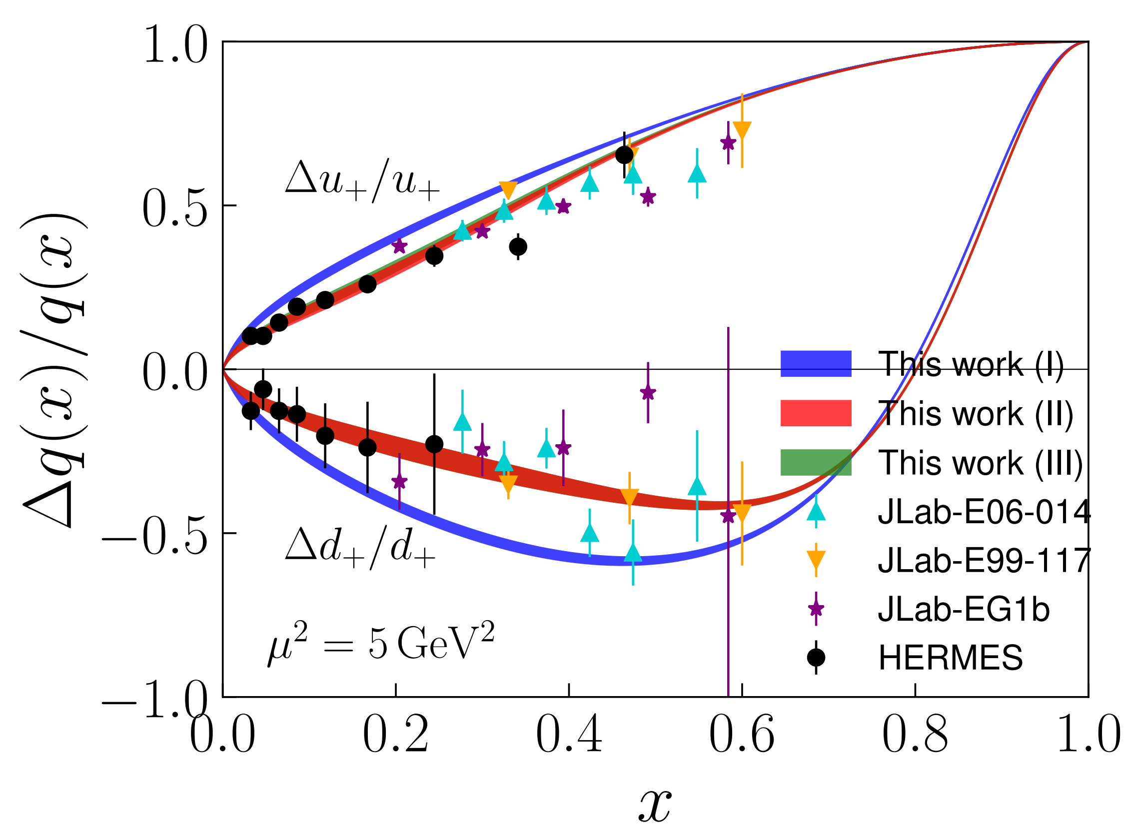


Polarized distributions for the

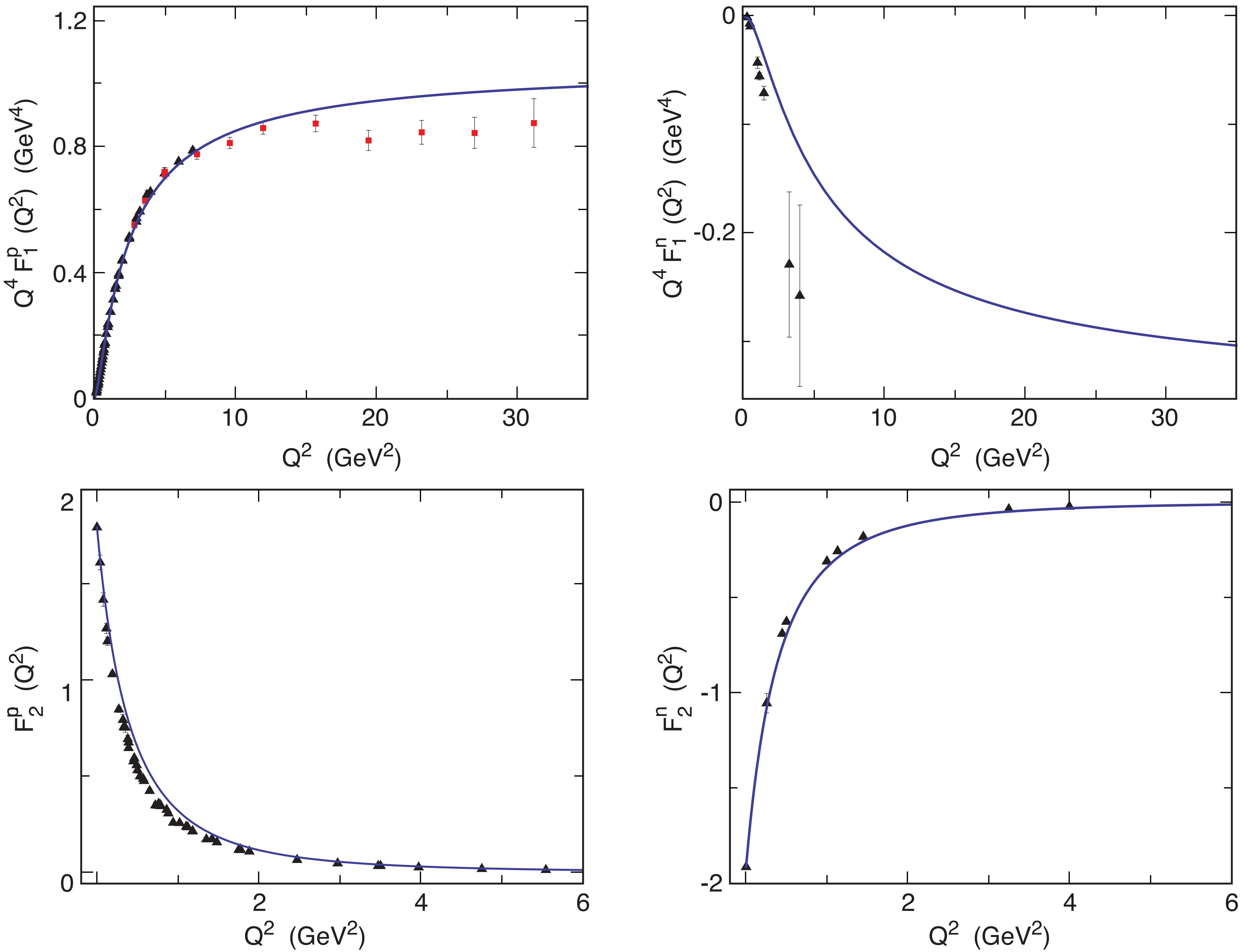
isovector combination $x[\Delta u_+(x) - \Delta d_+(x)]$

$$d_+(x) = d(x) + \bar{d}(x) \qquad u_+(x) = u(x) + \bar{u}(x)$$

$$\Delta q(x) = q_\uparrow(x) - q_\downarrow(x)$$

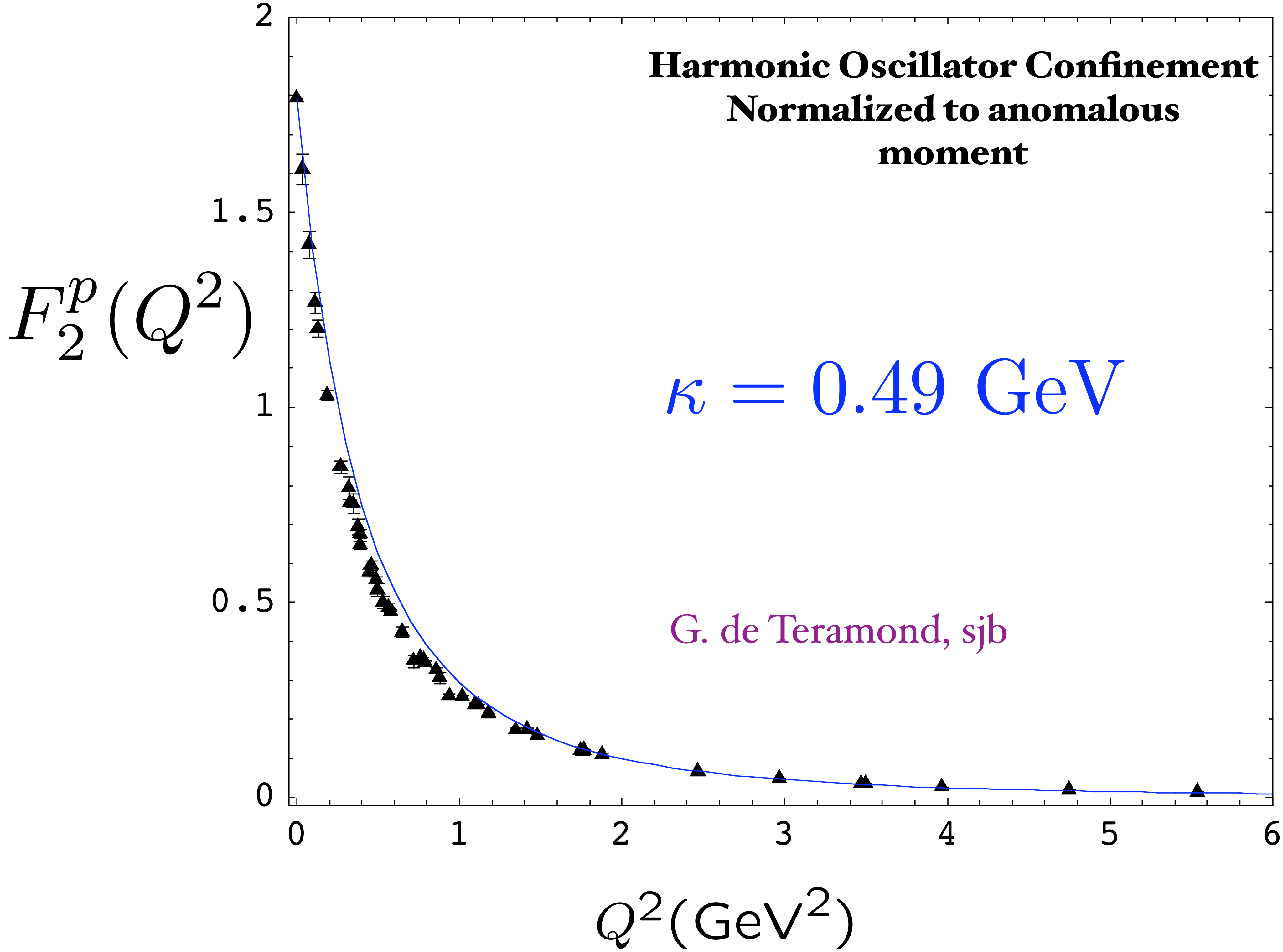


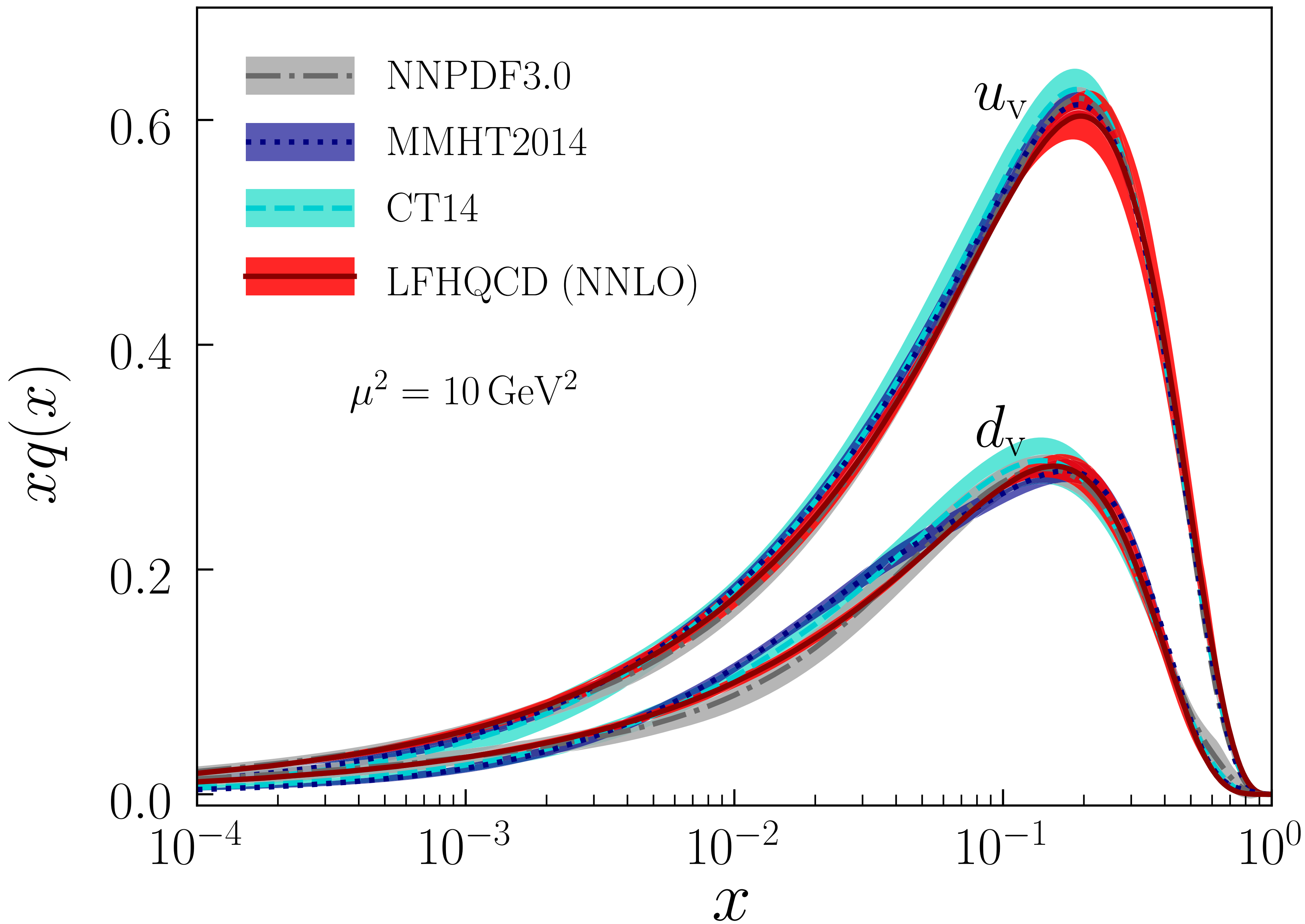
Using $SU(6)$ flavor symmetry and normalization to static quantities



Spacelike Pauli Form Factor

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





Comparison for $xq(x)$ in the proton from LFHQCD (red bands) and global fits: MMHT2014 (blue bands) [5], CT14 [6] (cyan bands), and NNPDF3.0 (gray bands) [77]. LFHQCD results are evolved from the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV.

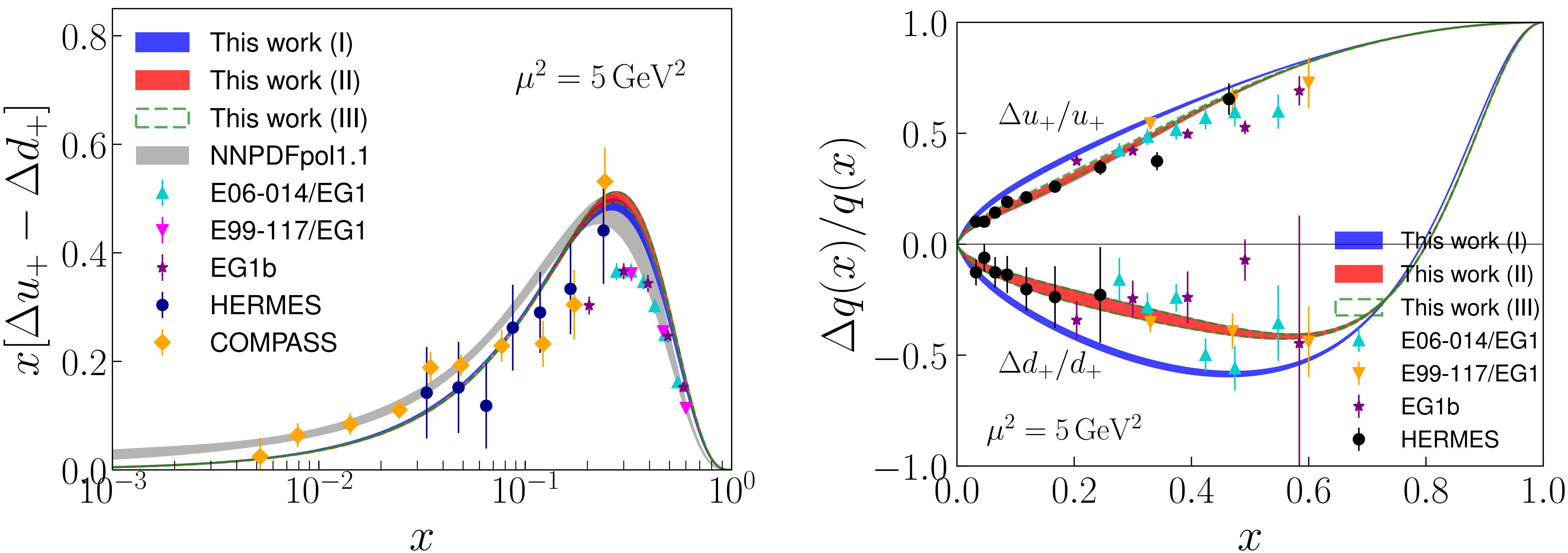
Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur

PHYSICAL REVIEW LETTERS 120, 182001 (2018)

Polarized GPDs and PDFs (HLFHS Collaboration, 2019)

- Separation of chiralities in the AdS action allows computation of the matrix elements of the axial current including the correct normalization, once the coefficients c_τ are fixed for the vector current
- Helicity retention between quark and parent hadron (pQCD prediction): $\lim_{x\to 1} \frac{\Delta q(x)}{q(x)} = 1$
- No spin correlation with parent hadron: $\lim_{x\to 0} \frac{\Delta q(x)}{q(x)} = 0$



Other Consequences of $[ud]_{\bar{3}_C, I=0, J=0}$ diquark cluster

QCD Hidden-Color Hexadiquark in the Core of Nuclei

J. Rittenhouse West, G. de Teramond, A. S. Goldhaber, I. Schmidt, sjb

$$|\Psi_{HDQ} >= |[ud][ud][ud][ud][ud][ud] >$$

mixes with

$${}^4He|npnp >$$

Increases alpha binding energy, EMC effects

Diquarks Can Dominate Five-Quark Fock State of Proton

$$|p >= \alpha|[ud]u > + \beta|[ud][ud]\bar{d} >$$

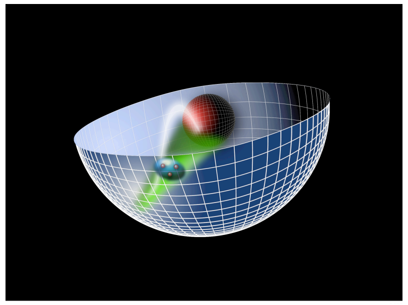
J. Rittenhouse West, sjb

Natural explanation why $\bar{d}(x) >> \bar{u}(x)$ in proton

Excitations and Decay of HdQ in Alpha-Nuclei
may explain ATOMKI X17 signal

Underlying Principles

- *Polncarè Invariance: Independent of the observer's Lorentz frame: Quantization at Fixed Light-Front Time τ*
- *Causality: Information within causal horizon: Light-Front*
- *Light-Front Holography: AdS_5 = LF (3+1)*



$$z \leftrightarrow \zeta \text{ where } \zeta^2 = b_\perp^2 x(1-x)$$

- *Introduce mass scale **κ** while retaining conformal invariance of the Action (dAFF)*

"Emergent Mass"

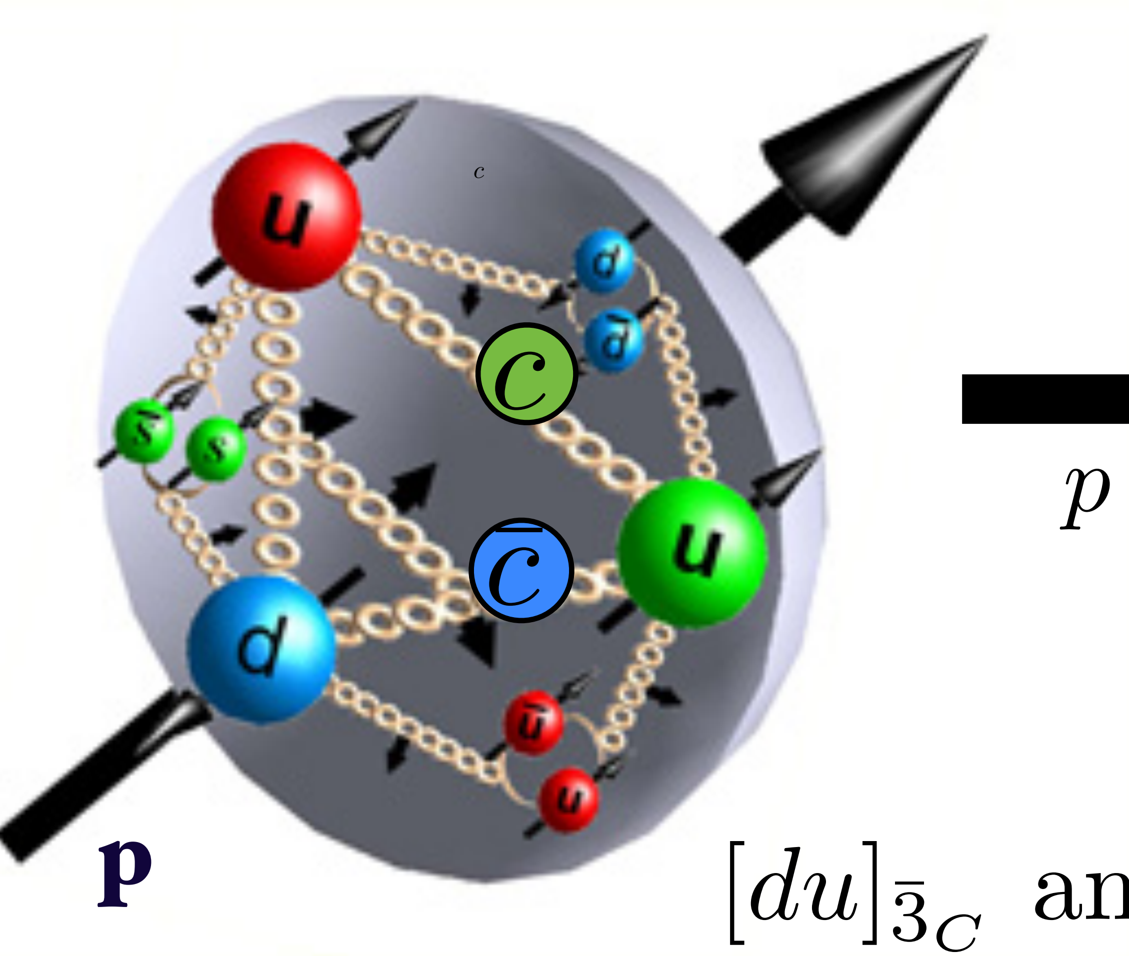
- *Unique Dilaton in AdS_5:* $e^{+\kappa^2 z^2}$
- *Unique color-confining LF Potential* $U(\zeta^2) = \kappa^4 \zeta^2$
- *Superconformal Algebra: Mass Degenerate 4-Plet:*

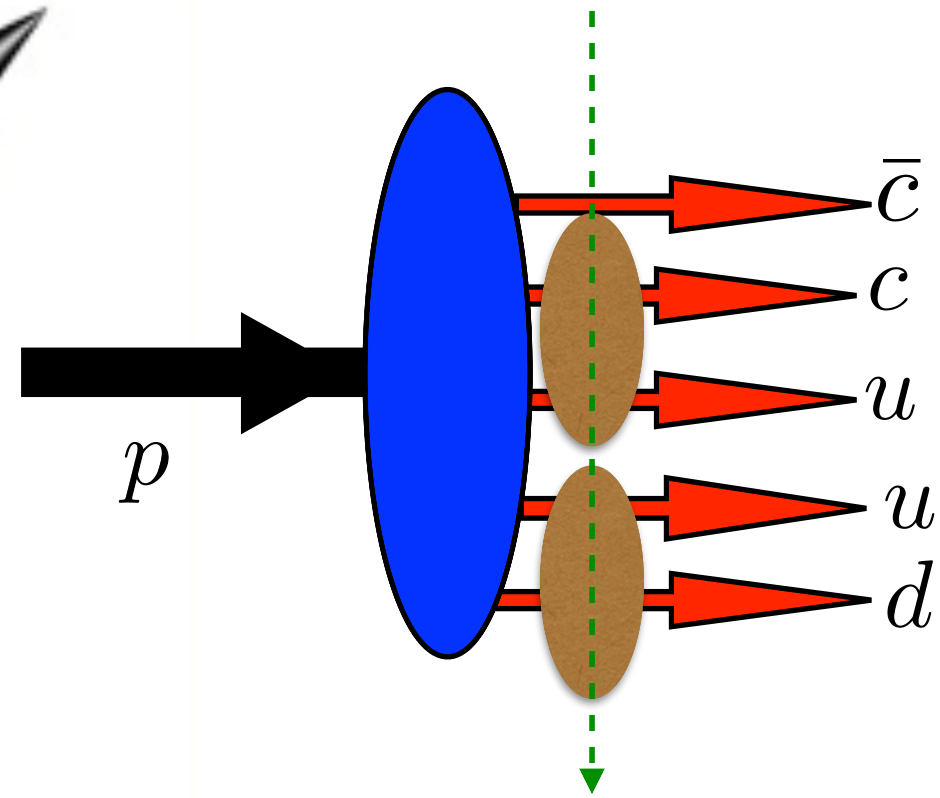
$$\boxed{\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]}$$

Color confinement potential from AdS/QCD

$$U(\zeta^2) = \kappa^4 \zeta^2, \zeta^2 = b^2_\perp x(1-x)$$

Fixed $\tau = t + z/c$





Intrinsic Charm

$$|\bar{c}[cu][ud] >$$

$[du]_{\bar{3}_C}$ and $[cu]_{\bar{3}_C}$ $J=0$ diquark dominance

$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}} \, e^{-\mathcal{M}^2_n/2\kappa^2} \, \Pi^n_{j=1} \frac{1}{\sqrt{x_j}}$$

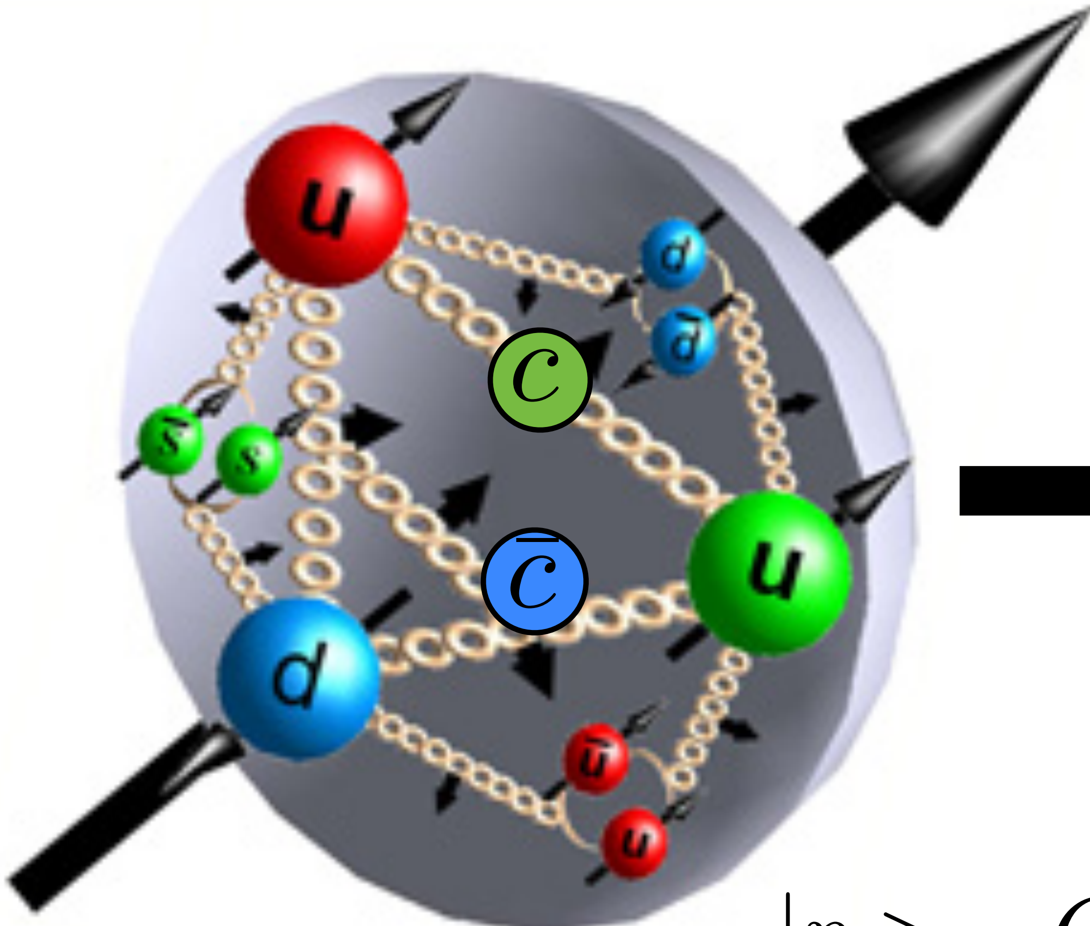
$$\mathcal{M}^2_n = \sum^n_{i=1} \left(\frac{k^2_\perp + m^2}{x}\right)_i$$

Light-Front Holography: First Approximation to QCD

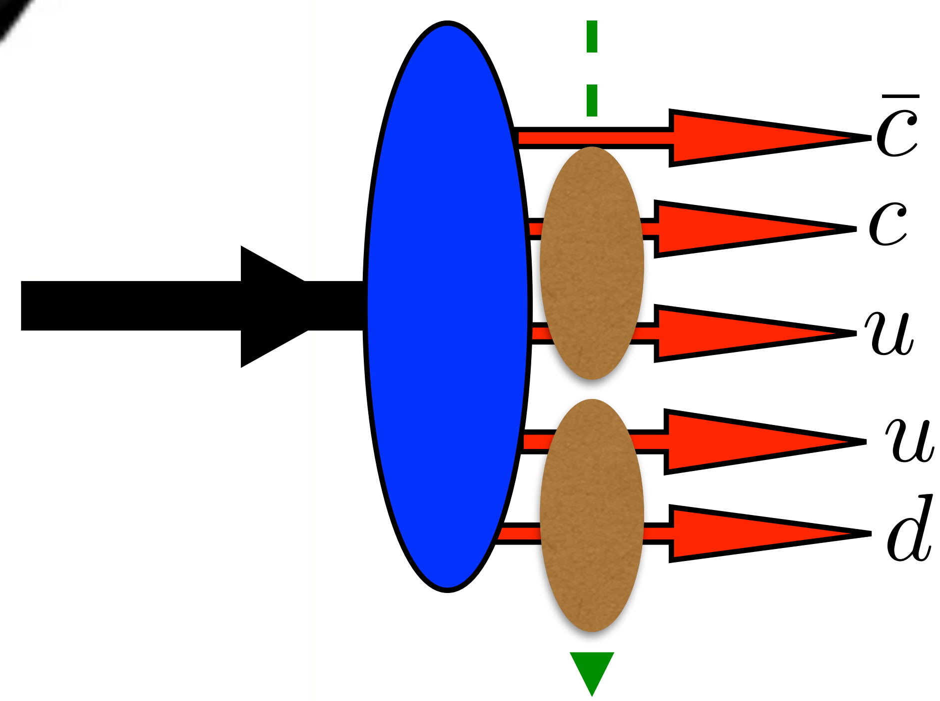
- **Color Confinement, Analytic form of confinement potential**
- **Retains underlying conformal properties of QCD despite mass scale (DeAlfaro-Fubini-Furlan Principle)**
- **Massless quark-antiquark pion bound state in chiral limit, GMOR**
- **QCD coupling at all scales**
- **Connection of perturbative and nonperturbative mass scales**
- **Poincarè Invariant**
- **Hadron Spectroscopy-Regge Trajectories with universal slopes in n, L**
- **Supersymmetric 4-Plet: Meson-Baryon -Tetraquark Symmetry**
- **Light-Front Wavefunctions**
- **Form Factors, Structure Functions, Hadronic Observables**
- **OPE: Constituent Counting Rules**
- **Hadronization at the Amplitude Level: Many Phenomenological Tests**
- **Systematically improvable: Basis LF Quantization (BLFQ)**

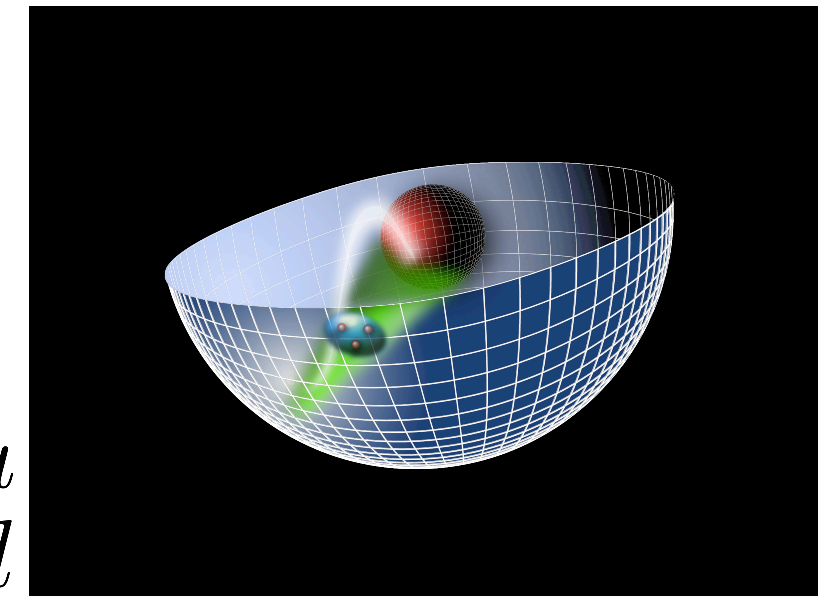
Supersymmetric Features of Hadron Physics from Superconformal Algebra and Light-Front Holography

Intrinsic Heavy Quark Phenomena
A Novel Property of QCD



Fixed $\tau = t + z/c$





$$|p> = C_{valence}|u[ud]> + C_{intrinsic}|\bar{c}[cu][ud]>$$

with P. Hoyer, N. Sakai, C. Peterson, A. Mueller, J. Collins, S. Ellis, J. Gunion, G. Lykasov

Implications of LHCb measurements and future prospects

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INT October 10, 2022