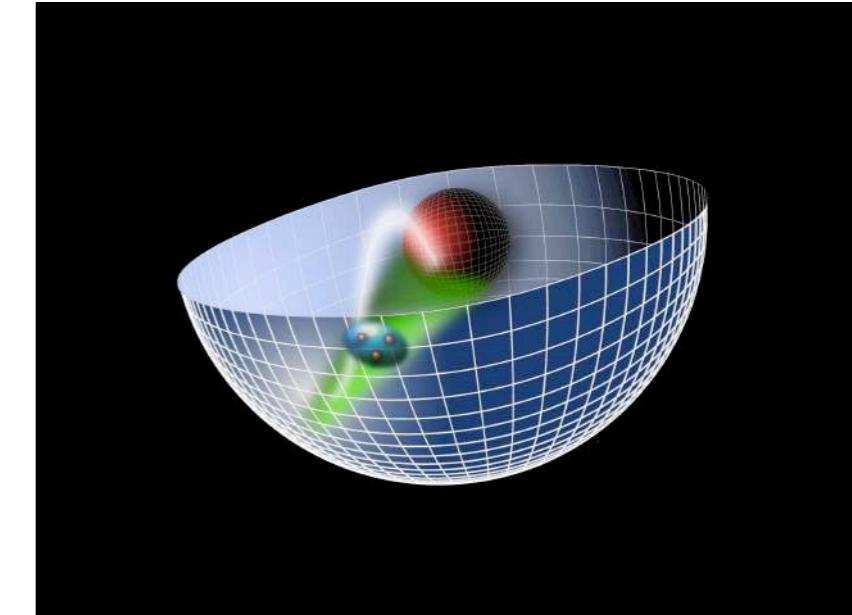
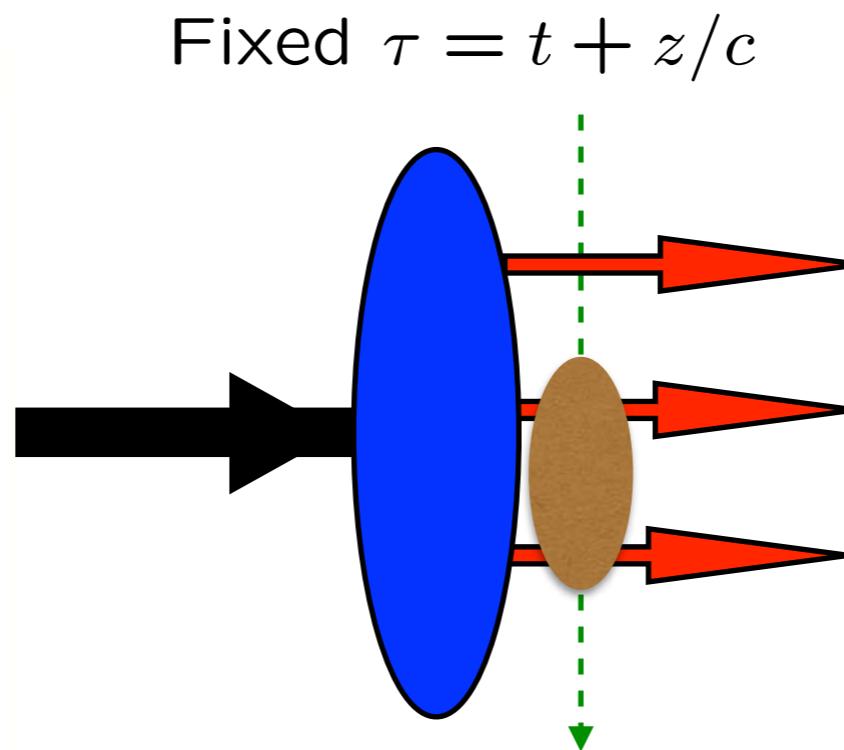
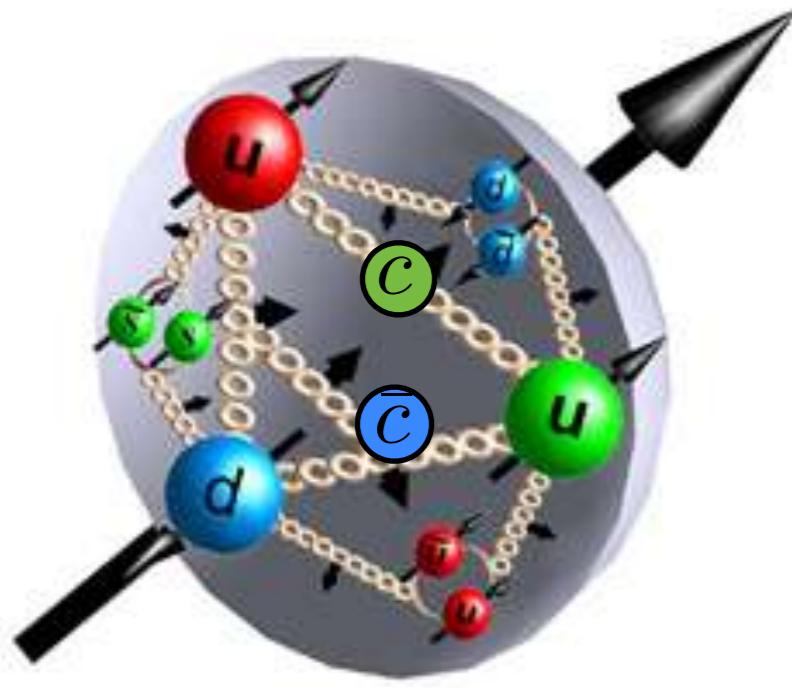
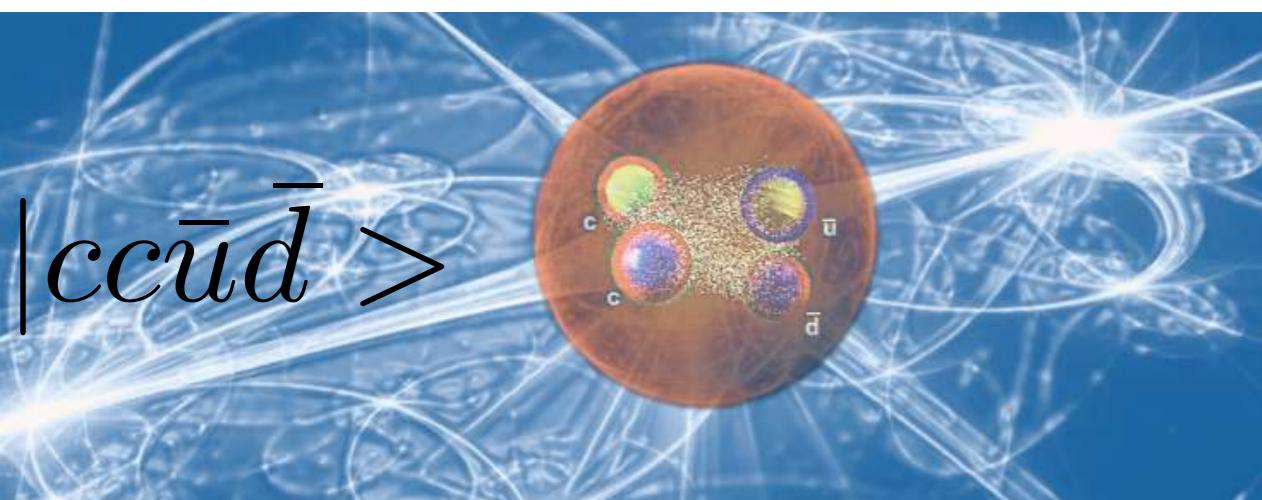


# Light Front Holography, Intrinsic Charm, and Tetraquarks



$|p\rangle = |u[ud]\rangle$  quark-diquark cluster

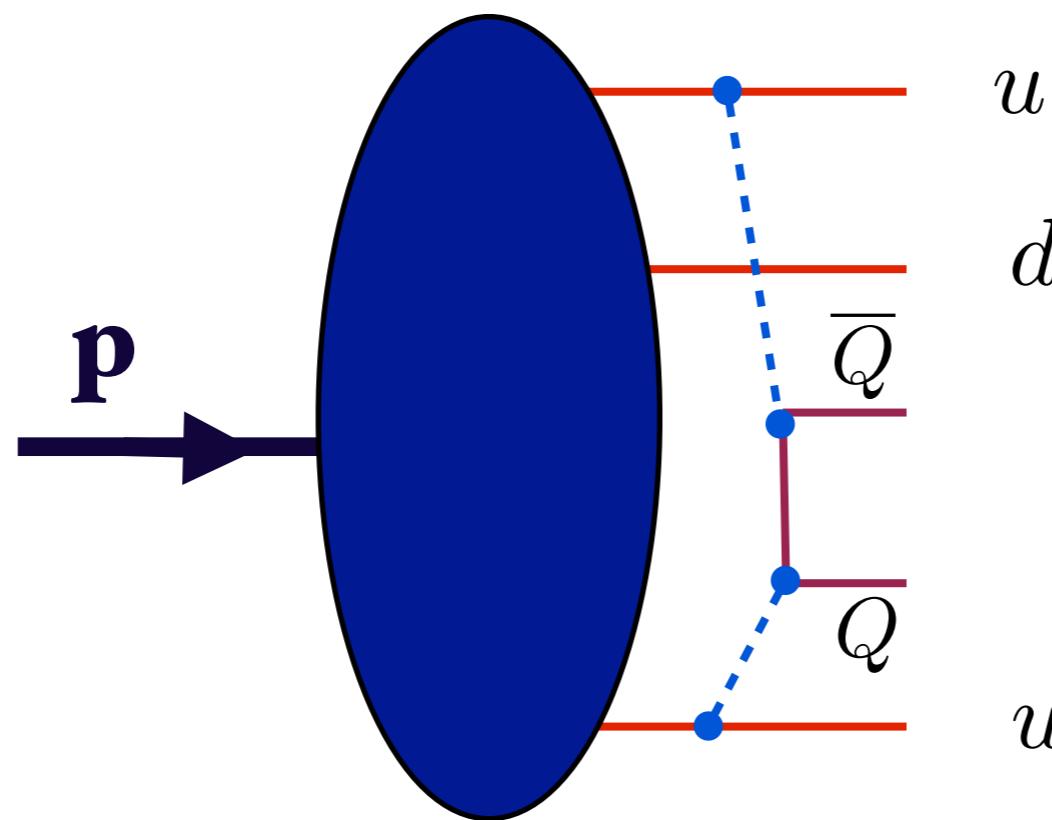


Double-charm tetraquarks  
and other exotics

Stan Brodsky  
**SLAC**  
NATIONAL  
ACCELERATOR  
LABORATORY



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



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

Perturbative contribution

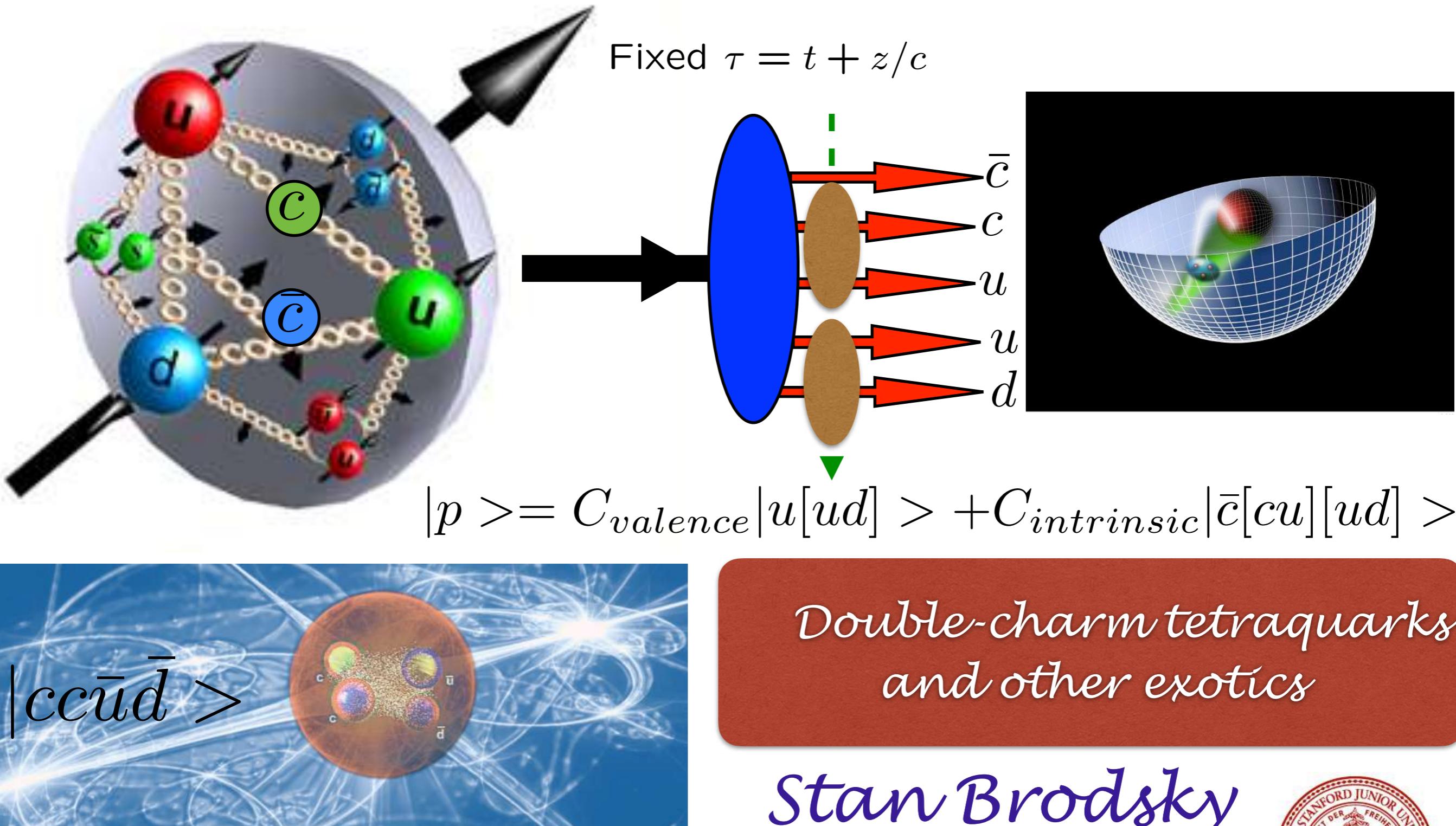
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

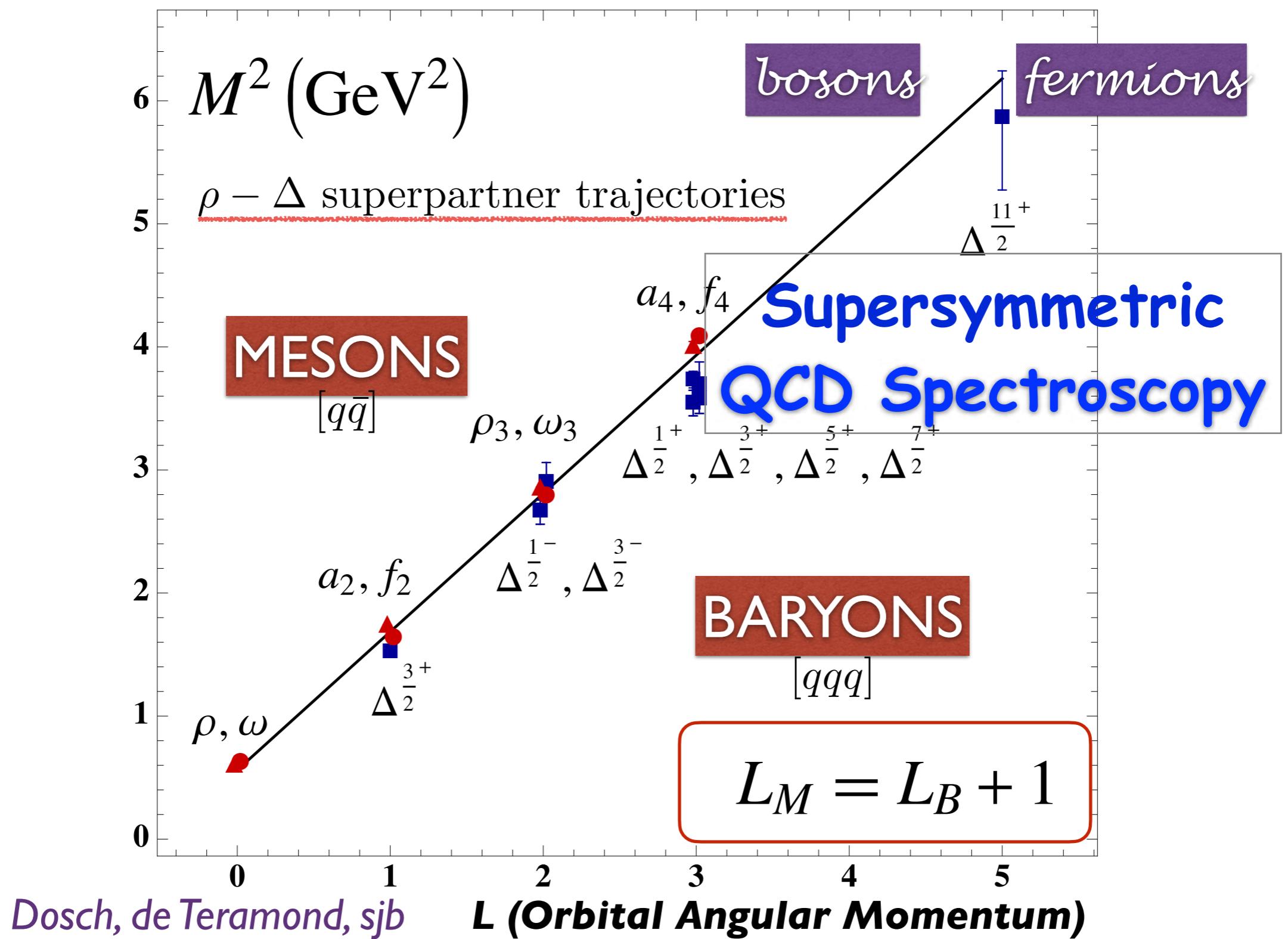
**Minimal off-shellness**

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

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

# Light Front Holography, Intrinsic Charm, and Tetraquarks



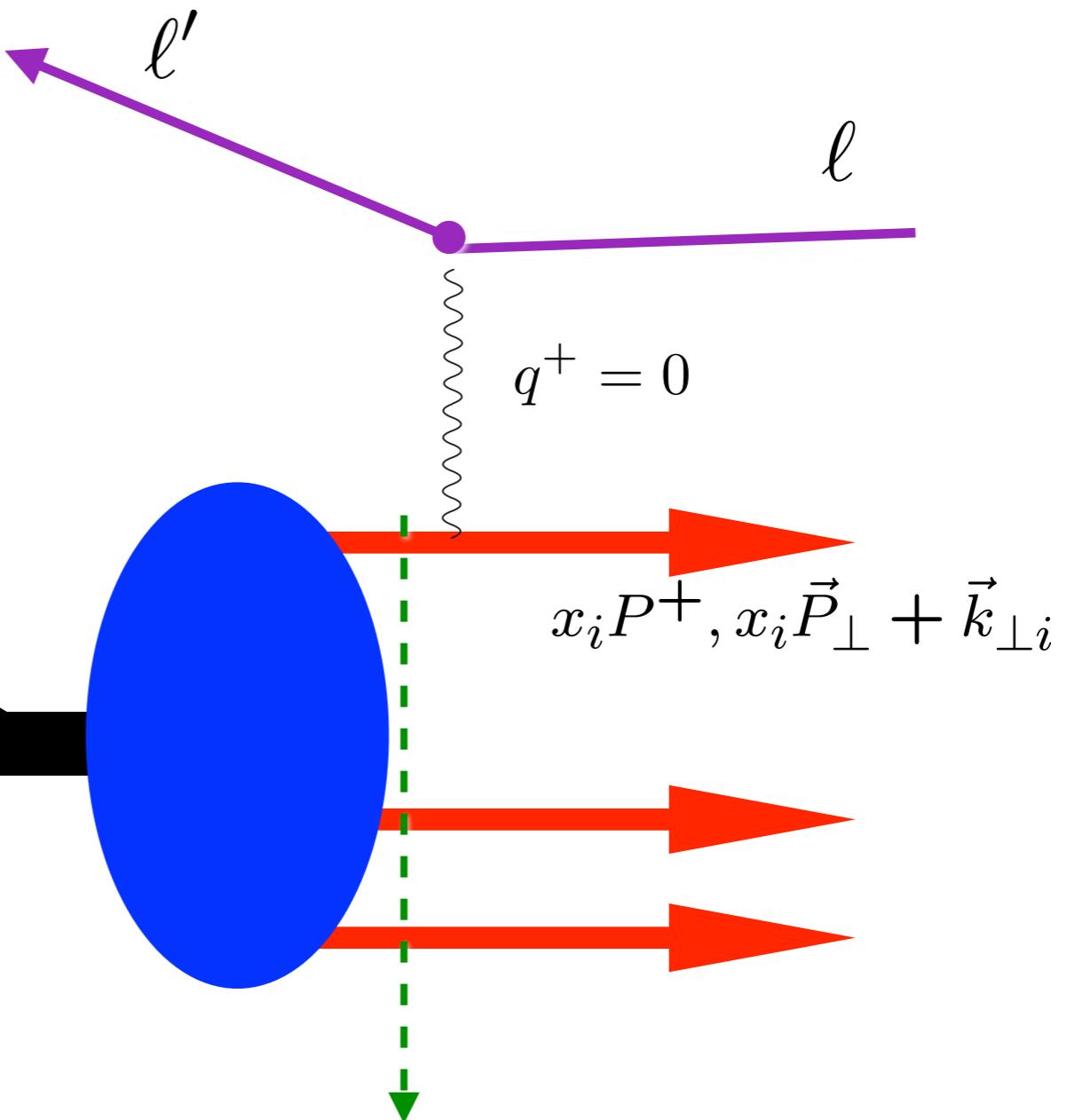


# *Challenge: Compute Hadron Structure, Spectroscopy, and Dynamics from QCD!*

- ***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***  
$$M_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u + m_d) \langle \bar{u}u + \bar{d}d \rangle + \mathcal{O}((m_u + m_d)^2)$$
- ***QCD Coupling at all Scales***  $\alpha_s(Q^2)$
- ***Eliminate Scale Uncertainties and Scheme Dependence***

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

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



**Dirac: Front Form**

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

**Like a flash photograph**

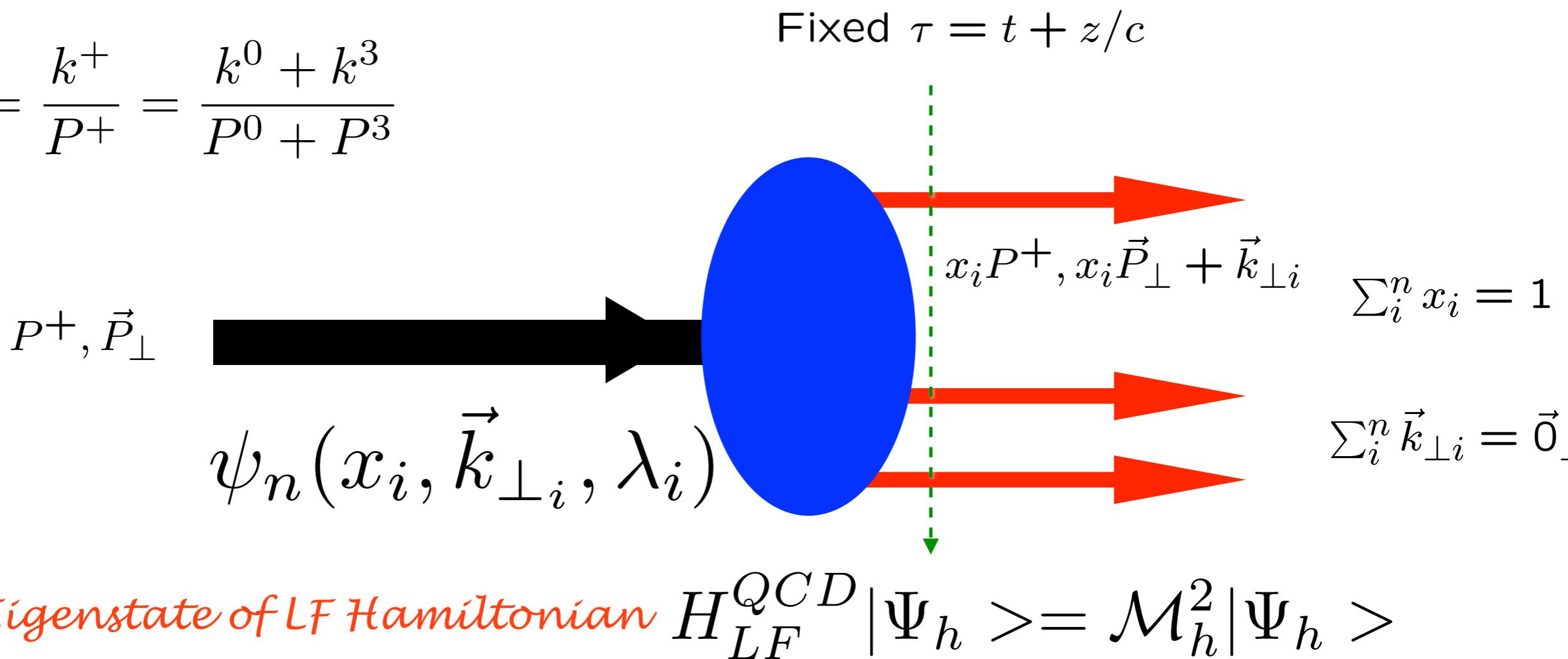
Fixed  $\tau = t + z/c$

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

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

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

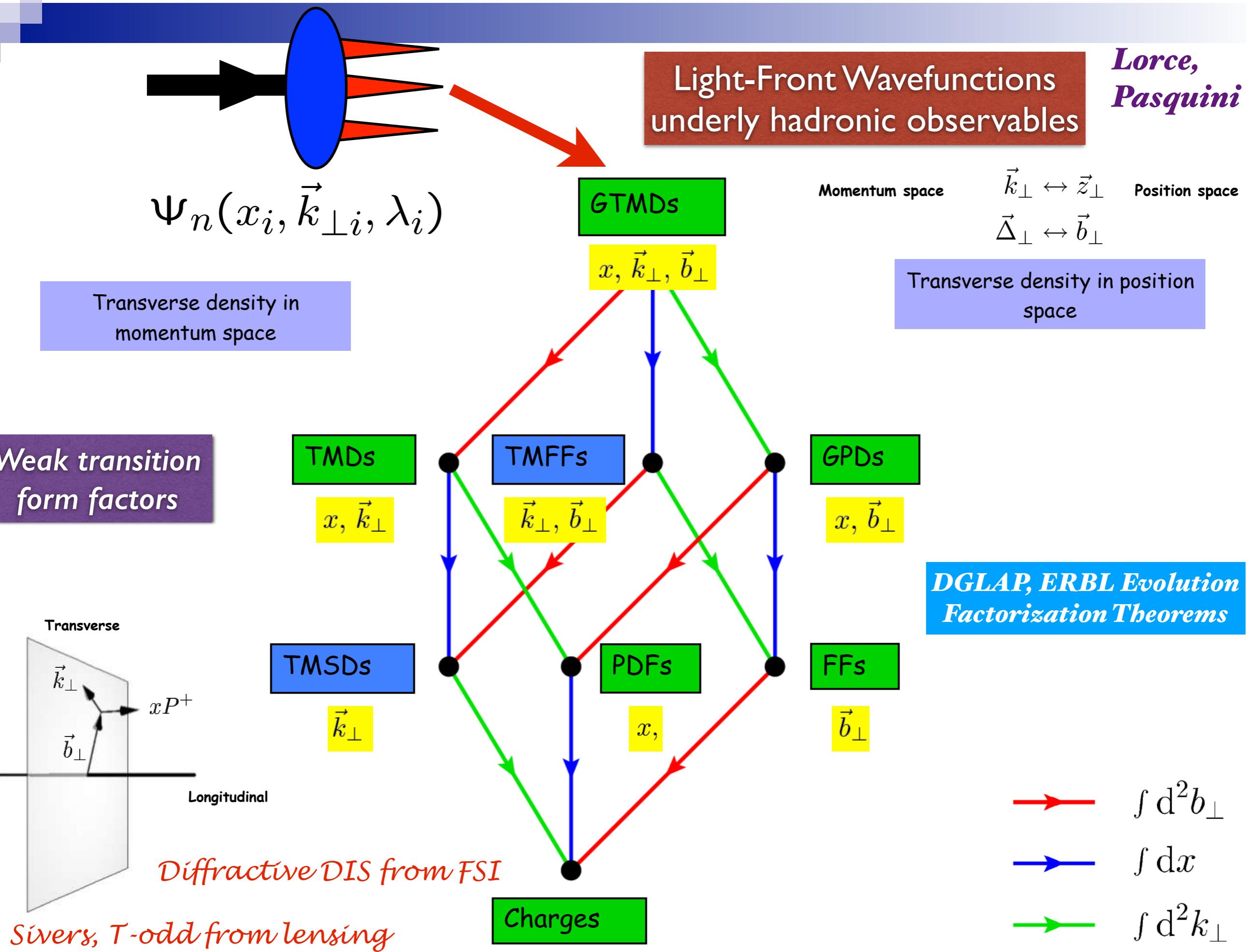
$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



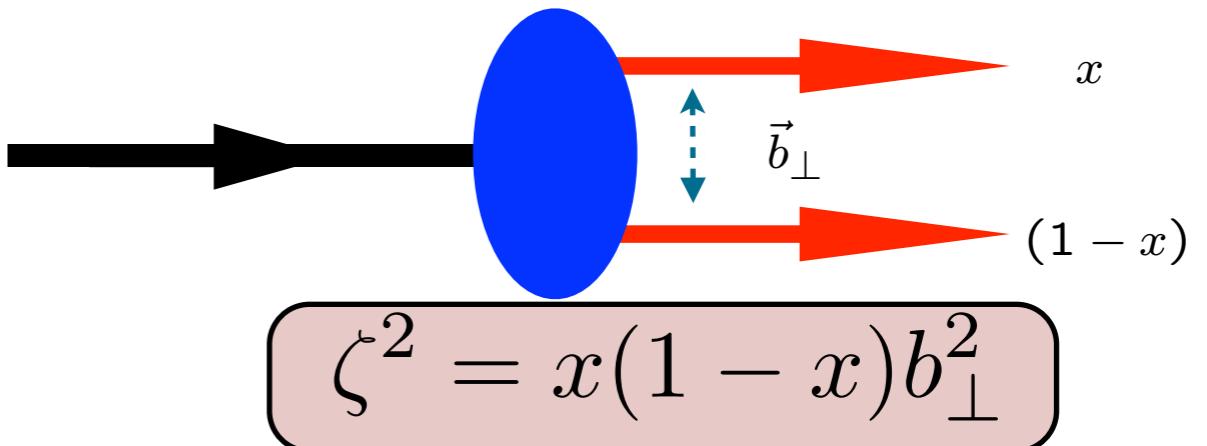
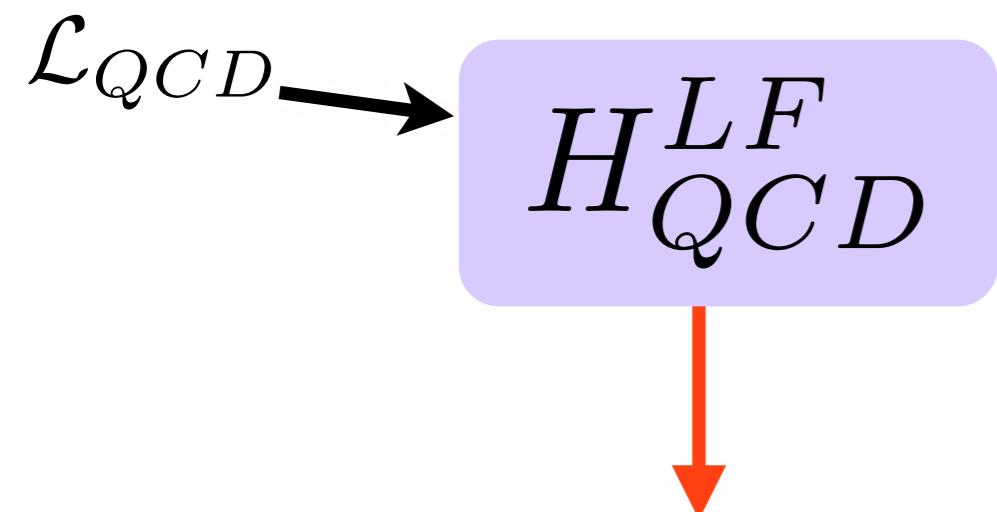
$$|p, J_z\rangle = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i\rangle$$

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

**Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS**



# Light-Front QCD



$$(H_{LF}^0 + H_{LF}^I)|\Psi\rangle = M^2|\Psi\rangle$$

Coupled Fock states

Eliminate higher Fock states  
and retarded interactions

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

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  $\zeta, \phi$

**Single variable Equation**

$$m_q = 0$$

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

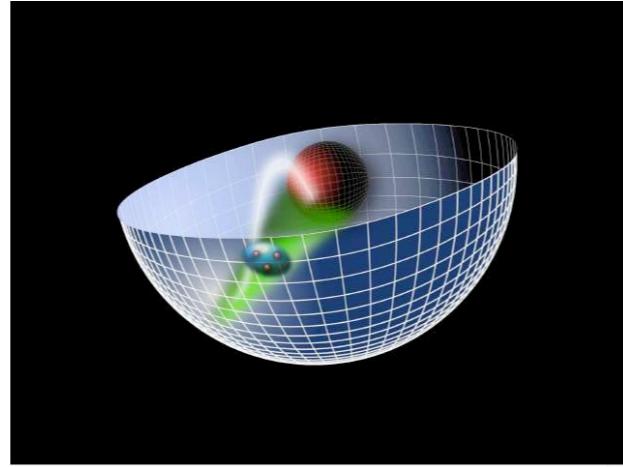
Confining AdS/QCD  
potential!

Semiclassical first approximation to QCD

Sums an infinite # diagrams

*AdS/QCD  
Soft-Wall Model*

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



*Light-Front Holography*

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

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



### ***Light-Front Schrödinger Equation***

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

*Single variable  $\zeta$*

***Confinement scale:***

$$\kappa \simeq 0.5 \text{ GeV}$$

*Unique  
Confinement Potential!  
Conformal Symmetry  
of the action*

- 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*

## ***Light-Front Holographic Dictionary***

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

$$\longleftrightarrow$$

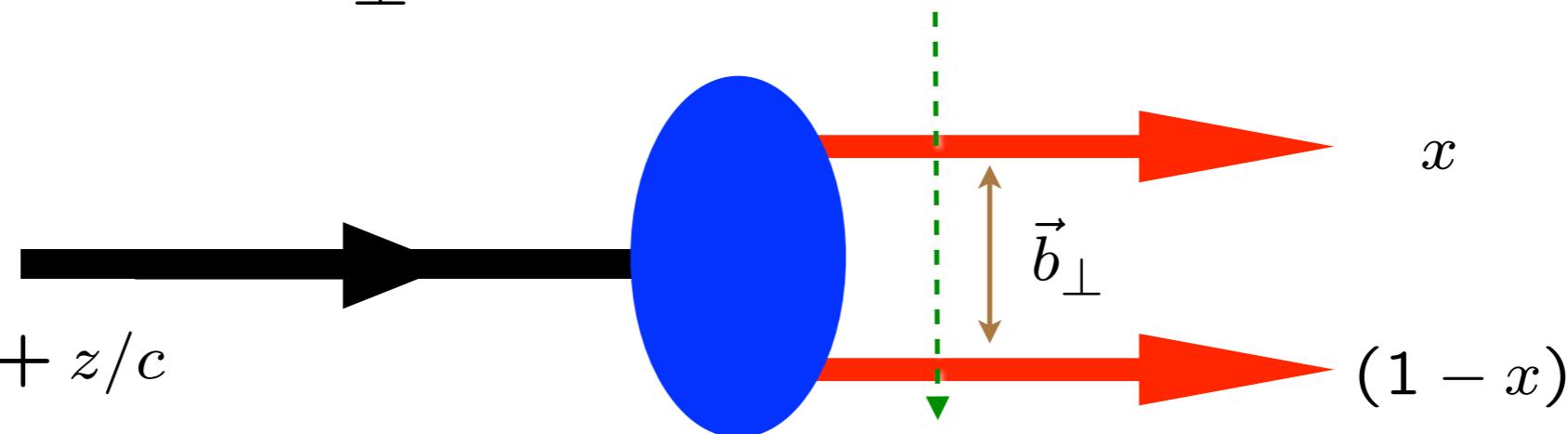
$$\phi(z)$$

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

$$\longleftrightarrow$$

$$z$$

Fixed  $\tau = t + z/c$



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

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

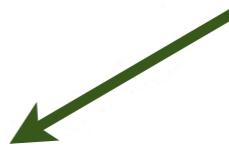
**Light-Front Holography:** Unique mapping derived from equality of LF and  $AdS$  formula for EM and gravitational current matrix elements and identical equations of motion

# Massless pion!

## Meson Spectrum in Soft Wall Model

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

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

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

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

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

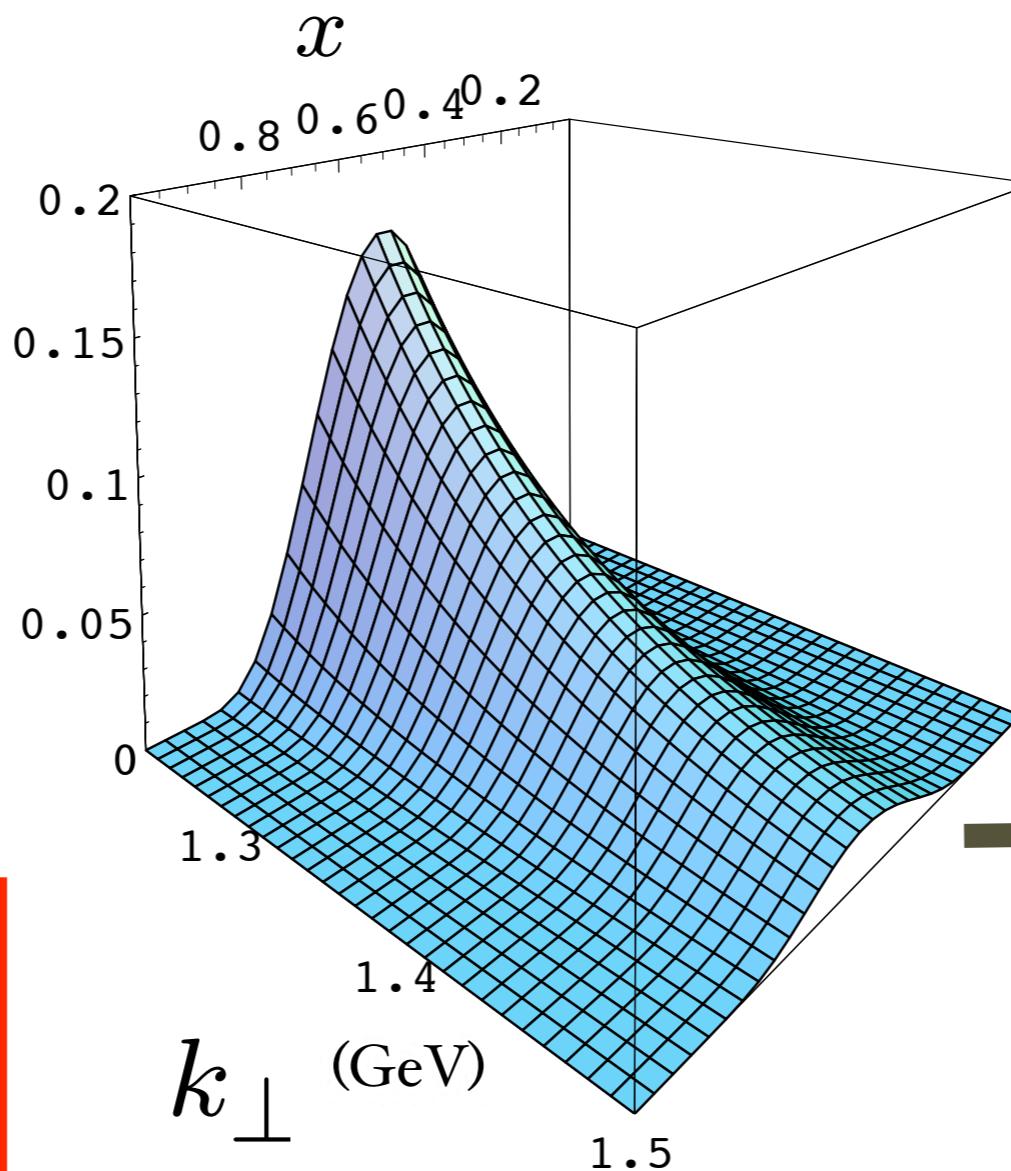
# Prediction from AdS/QCD: Meson LFWF

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

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

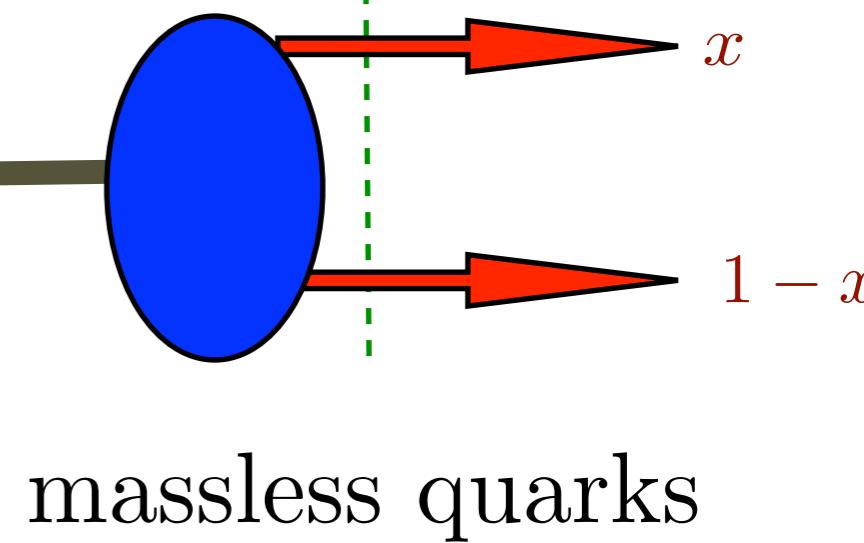
**Note coupling**

$$k_\perp^2, x$$



de Teramond,  
Cao, sjb

**“Soft Wall”  
model**



massless quarks

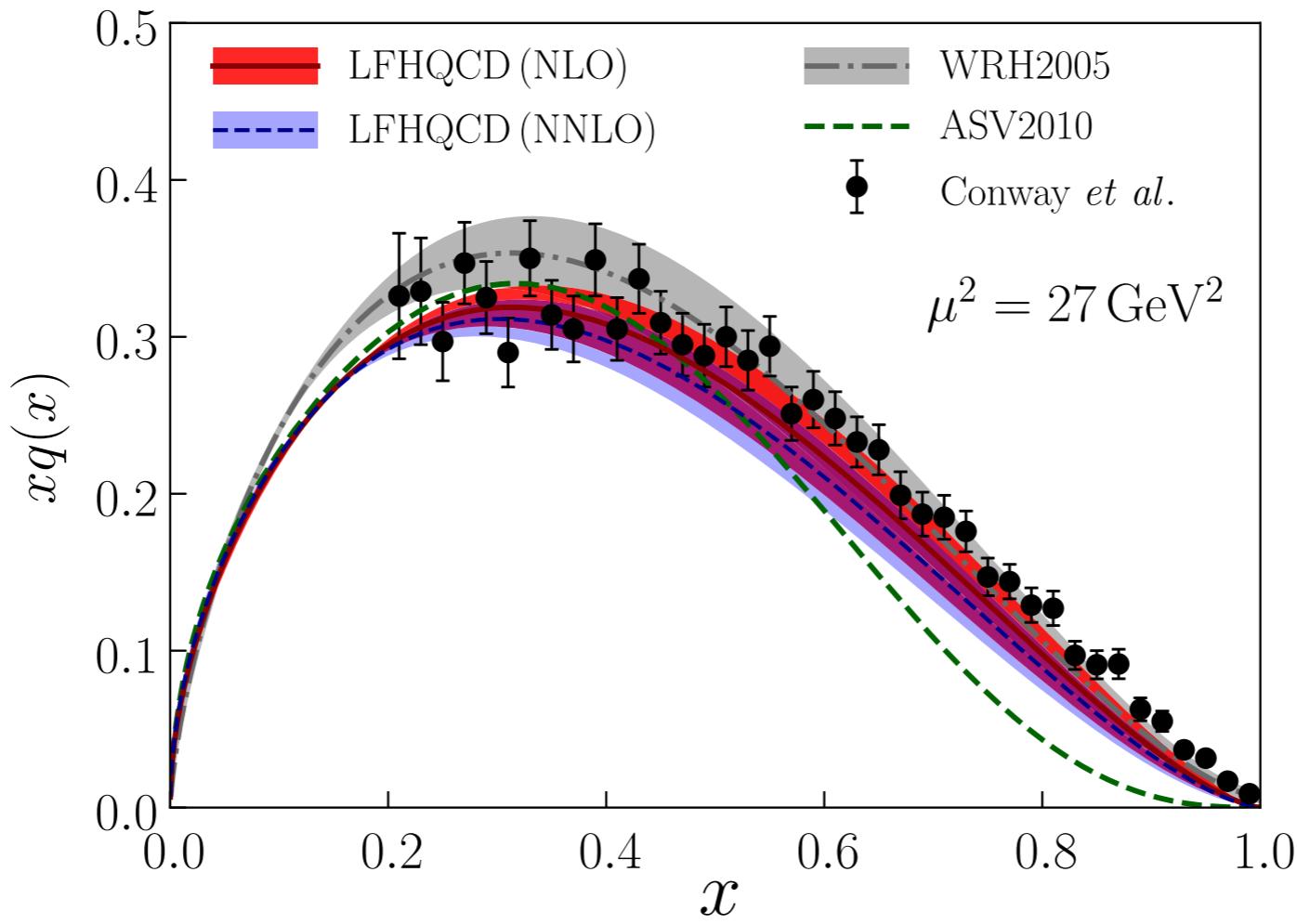
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa \sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

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

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

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

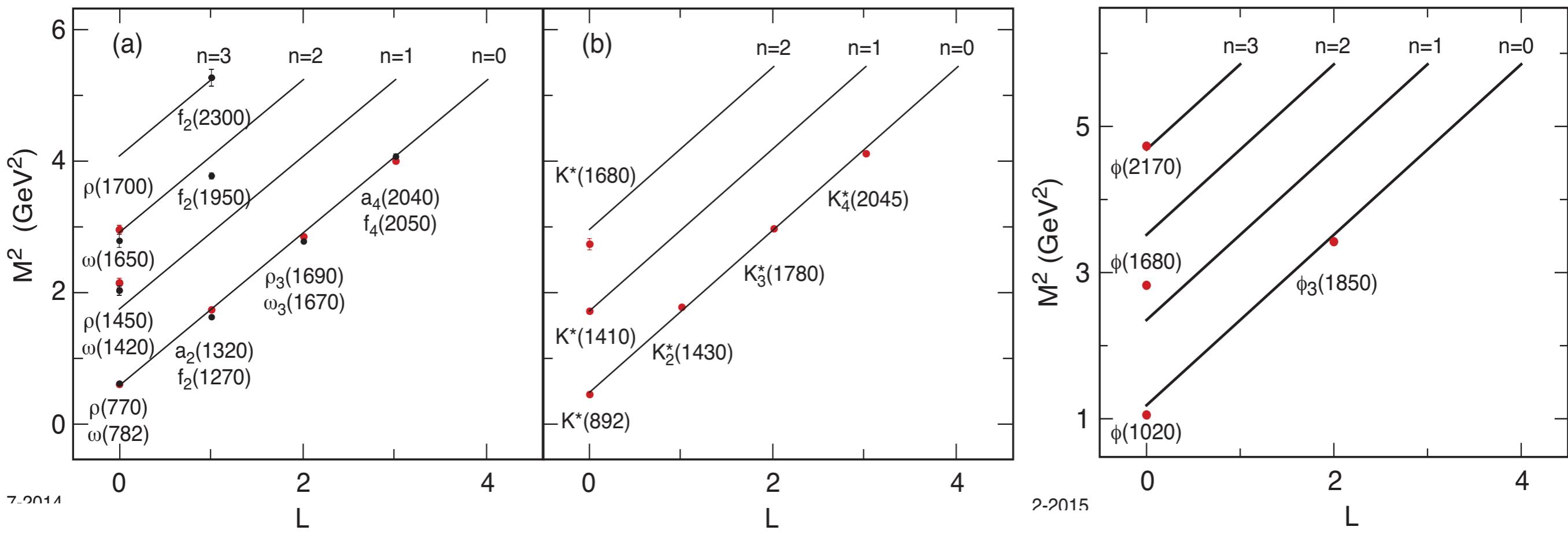
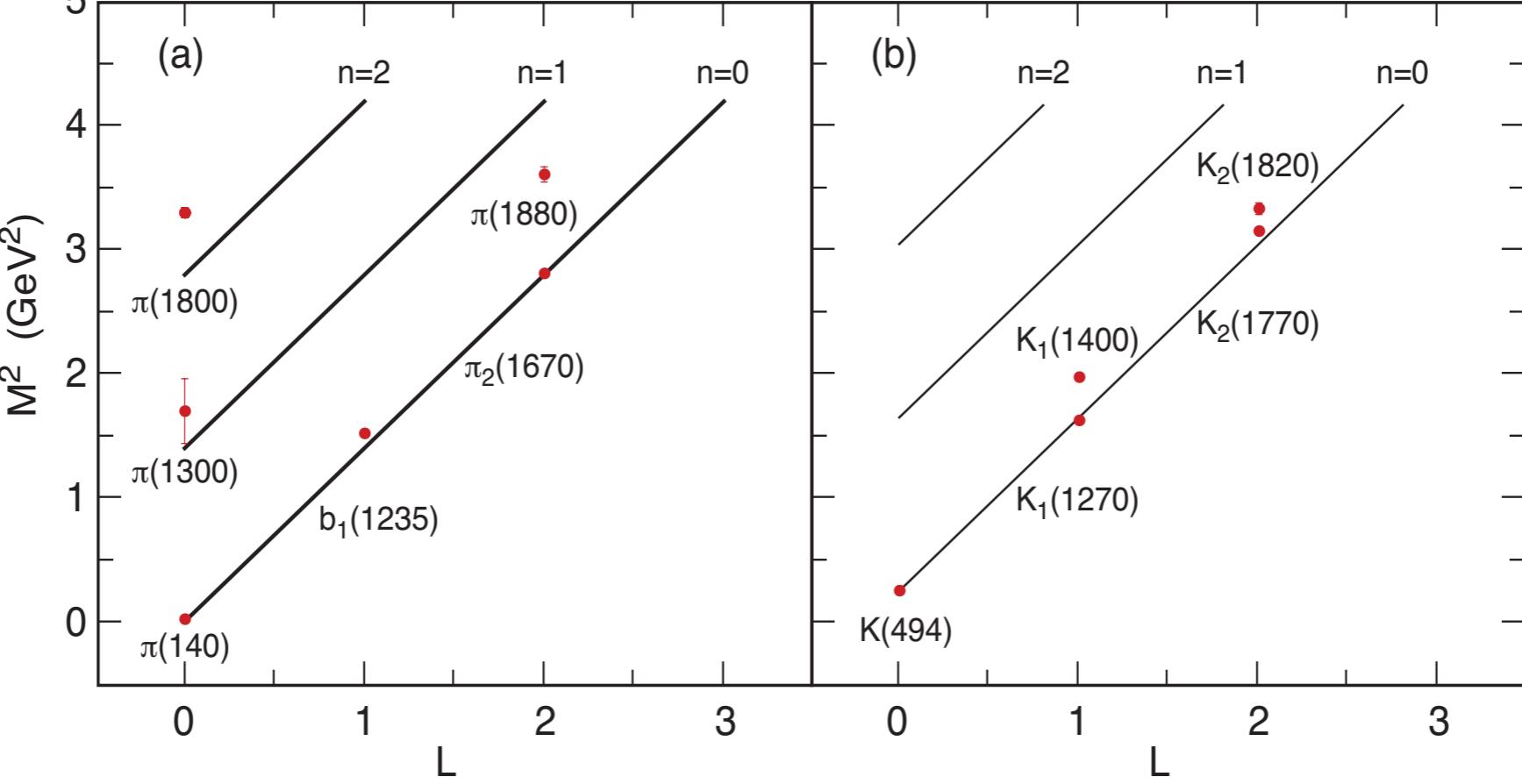
Provides Connection of Confinement to Hadron Structure



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  $\mu_0 = 1.1 \pm 0.2 \text{ GeV}$  at NLO and the initial scale  $\mu_0 = 1.06 \pm 0.15 \text{ GeV}$  at NNLO.

## *Universality of Generalized Parton Distributions in Light-Front Holographic QCD*

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

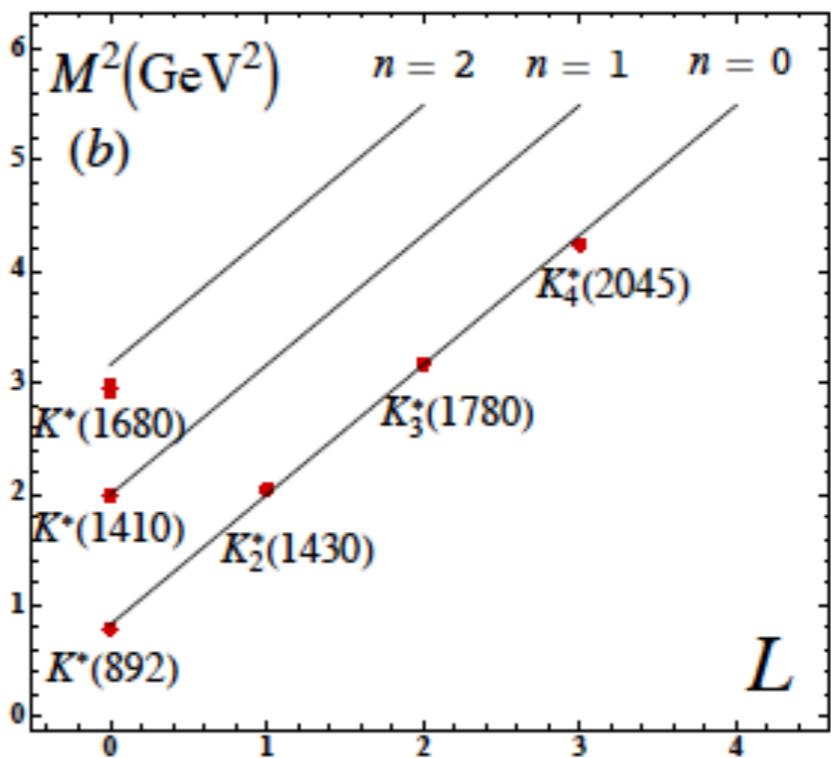
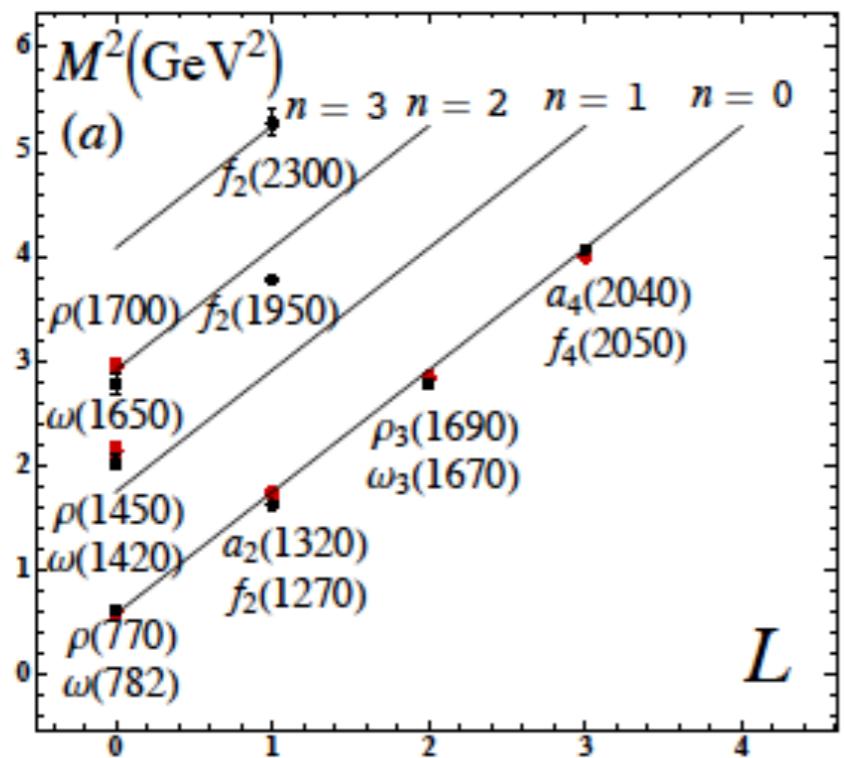
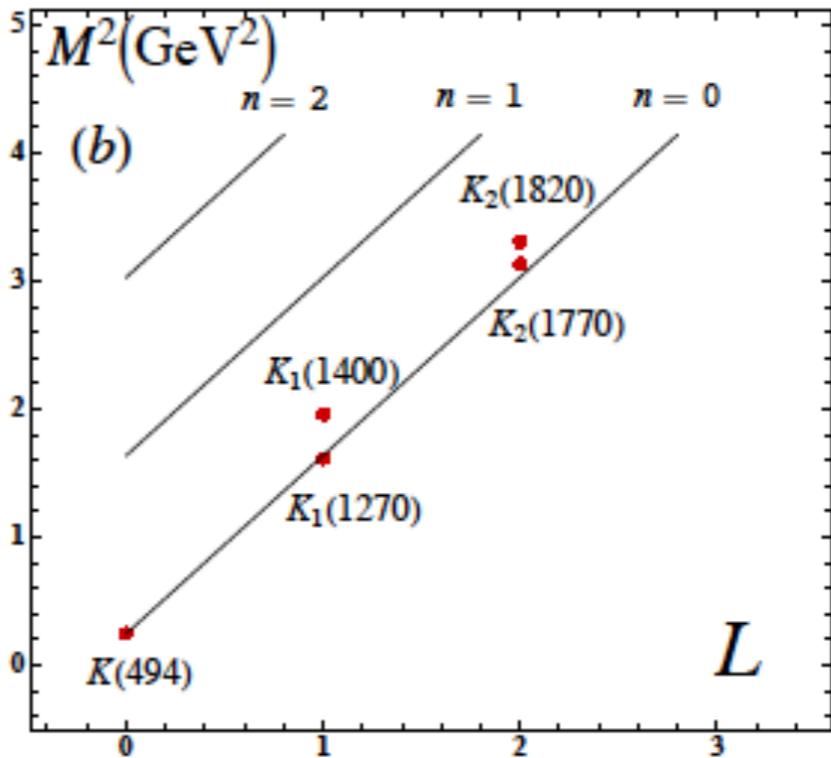
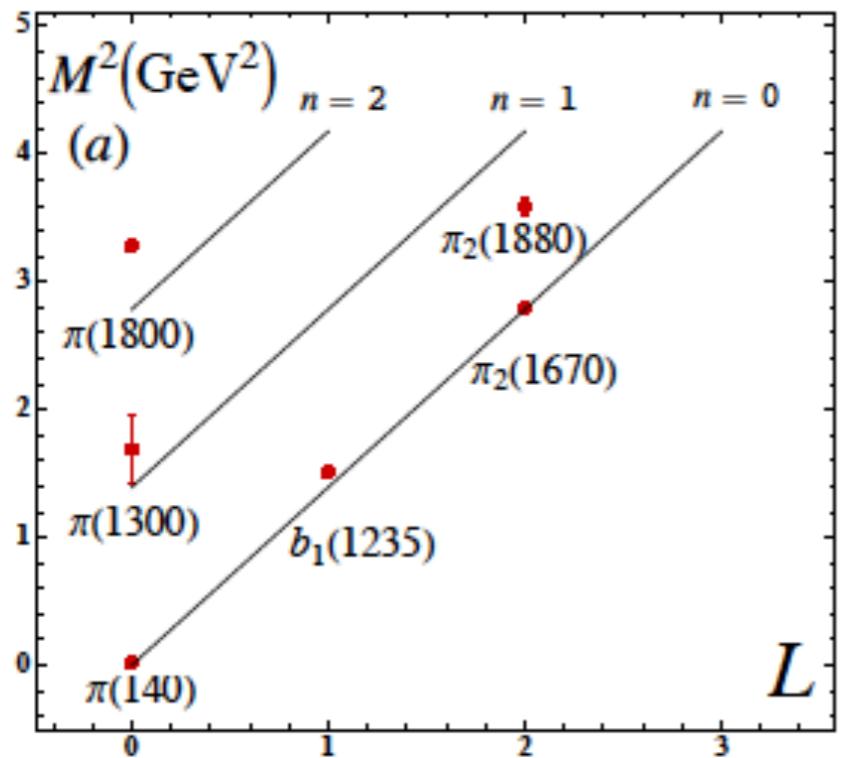


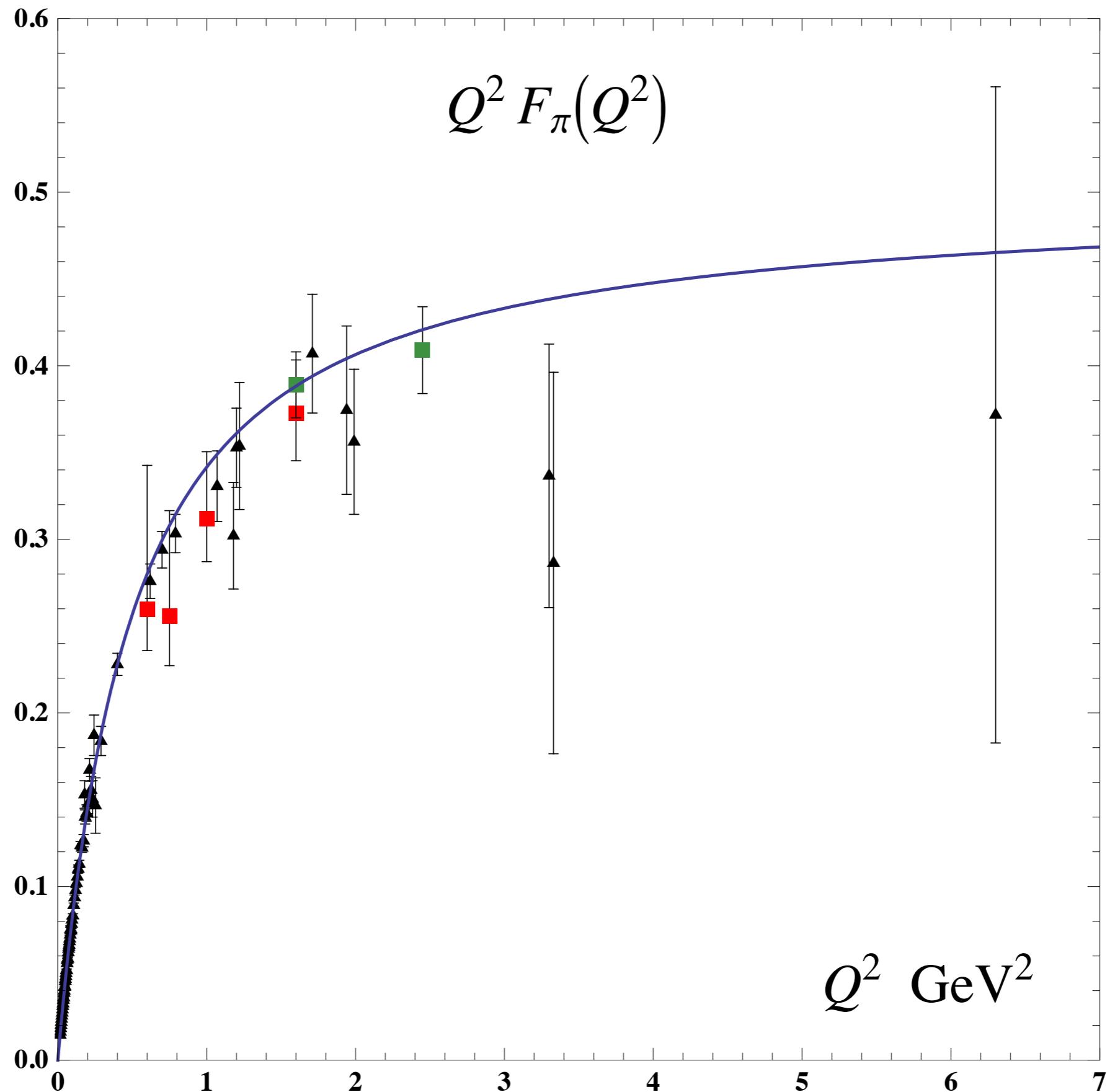
$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

Equal slope in  $n$  and  $L$

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

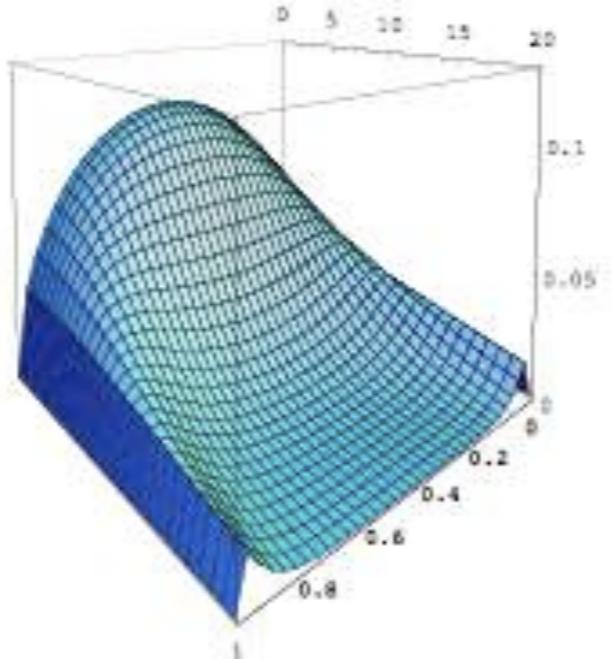
from LF Higgs mechanism





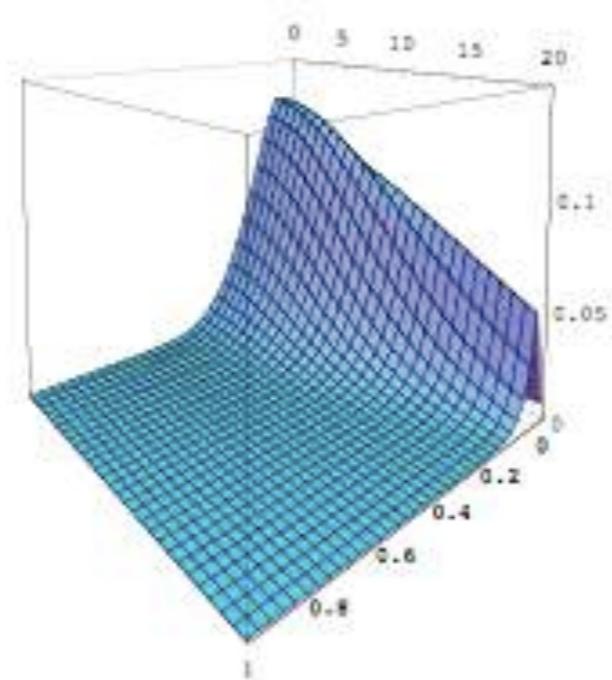
$|\pi^+> = |u\bar{d}>$

$m_u = 2 \text{ MeV}$   
 $m_d = 5 \text{ MeV}$



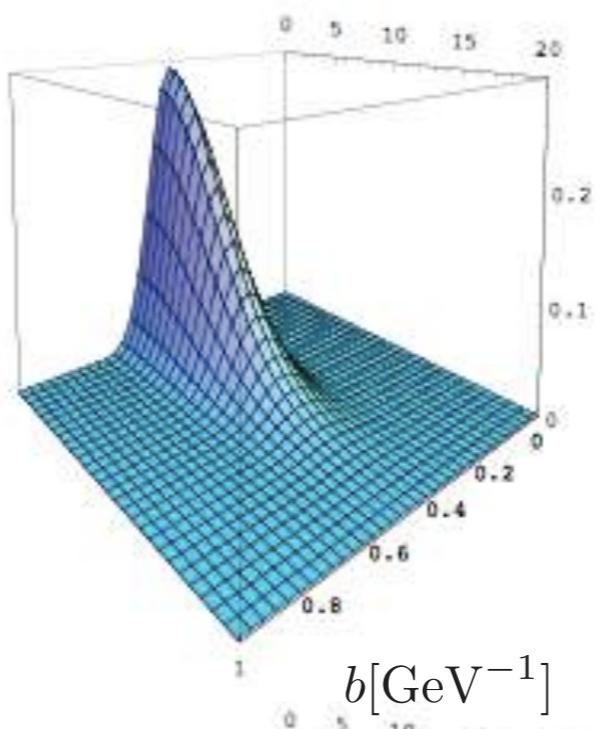
$|K^+> = |u\bar{s}>$

$m_s = 95 \text{ MeV}$



$|D^+> = |c\bar{d}>$

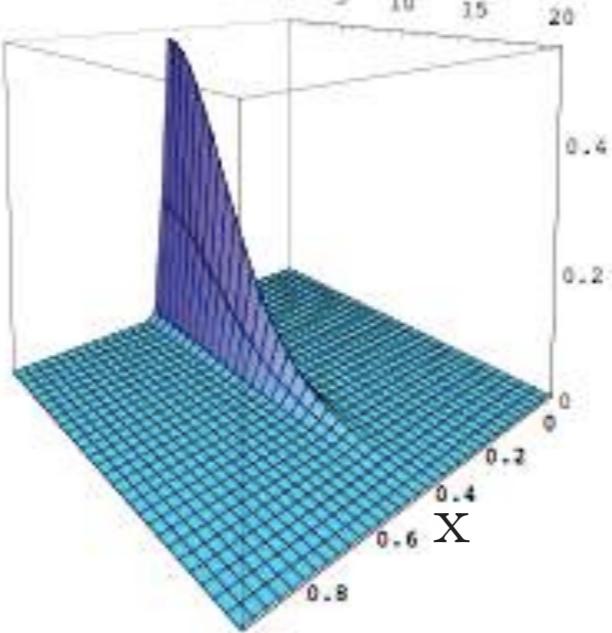
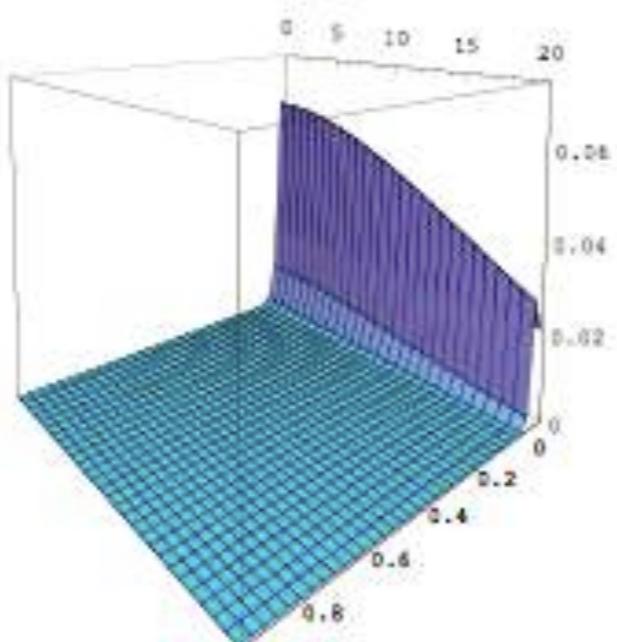
$m_c = 1.25 \text{ GeV}$



$|\eta_c> = |c\bar{c}>$

$|B^+> = |u\bar{b}>$

$m_b = 4.2 \text{ GeV}$



$|\eta_b> = |b\bar{b}>$

$\kappa = 375 \text{ MeV}$

# Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

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

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

- 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:  $g_5(z) \rightarrow g_{YM}(\zeta)$
- 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

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

where the coupling  $\alpha_s^{AdS}$  incorporates the non-conformal dynamics of confinement

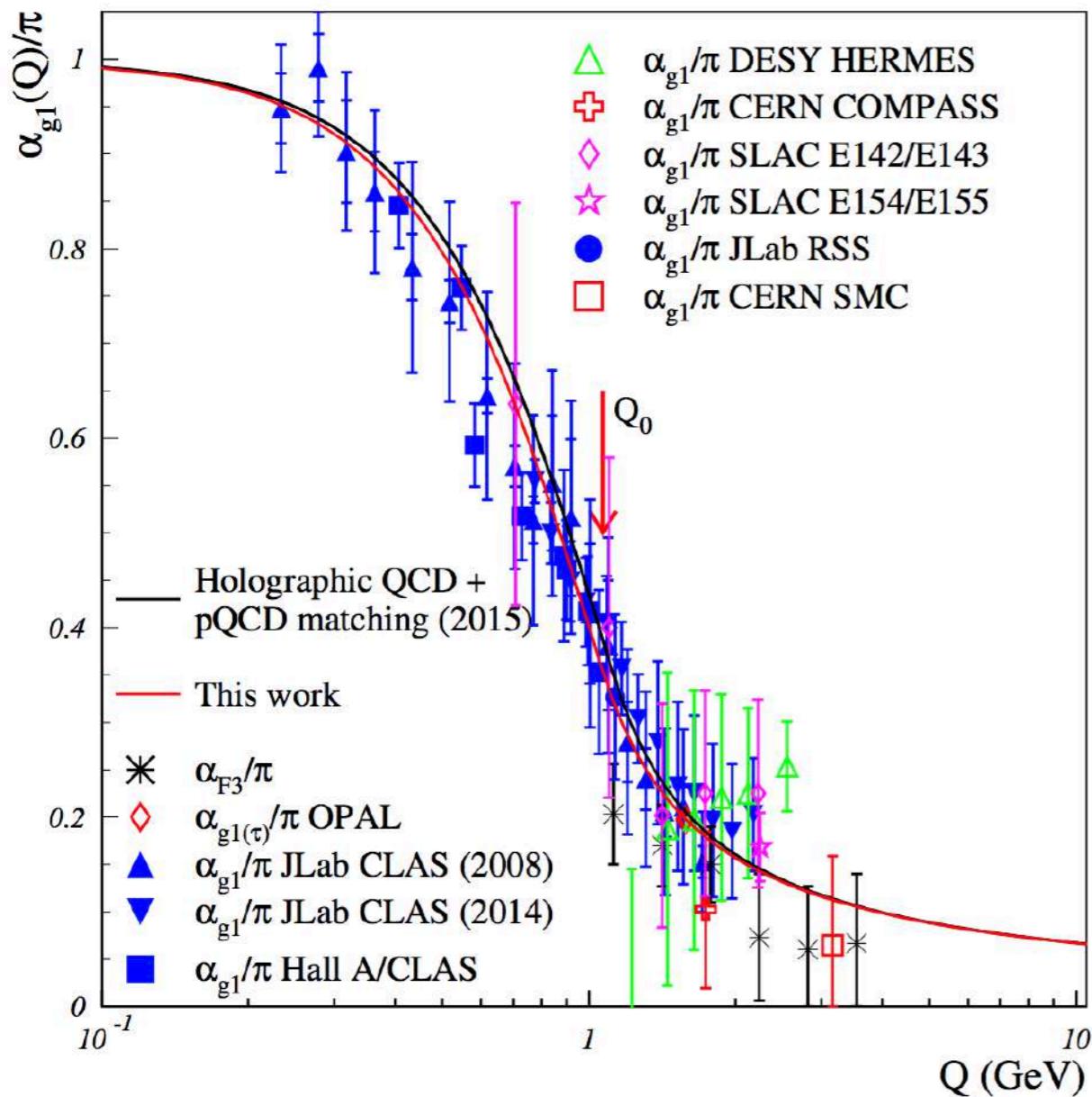
Bjorken sum rule defines effective charge

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

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

- ***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  $\beta_0, \beta_1$***

# Running Coupling from $AdS/QCD$



Bjorken sum rule:

$$\frac{\alpha_{g1}(Q^2)}{\pi} = 1 - \frac{6}{g_A} \int_0^1 dx g_1^{p-n}(x, Q^2)$$

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

$$\alpha_{g1}^{AdS}(Q^2) = \pi \exp(-Q^2/4\kappa^2)$$

Imposing continuity for  $\alpha$   
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**

## Superconformal Quantum Mechanics

$$\{\psi, \psi^+\} = 1 \quad B = \frac{1}{2}[\psi^+, \psi] = \frac{1}{2}\sigma_3$$

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

$$Q = \psi^+[-\partial_x + \frac{f}{x}], \quad Q^+ = \psi[\partial_x + \frac{f}{x}], \quad S = \psi^+x, \quad S^+ = \psi x$$

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

$$\{Q, S^+\} = f - B + 2iD, \quad \{Q^+, S\} = f - B - 2iD$$

generates conformal algebra

$$[H, D] = i H, \quad [H, K] = 2 i D, \quad [K, D] = -i K$$

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

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

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

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

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

## 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*  $\kappa$ !

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

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

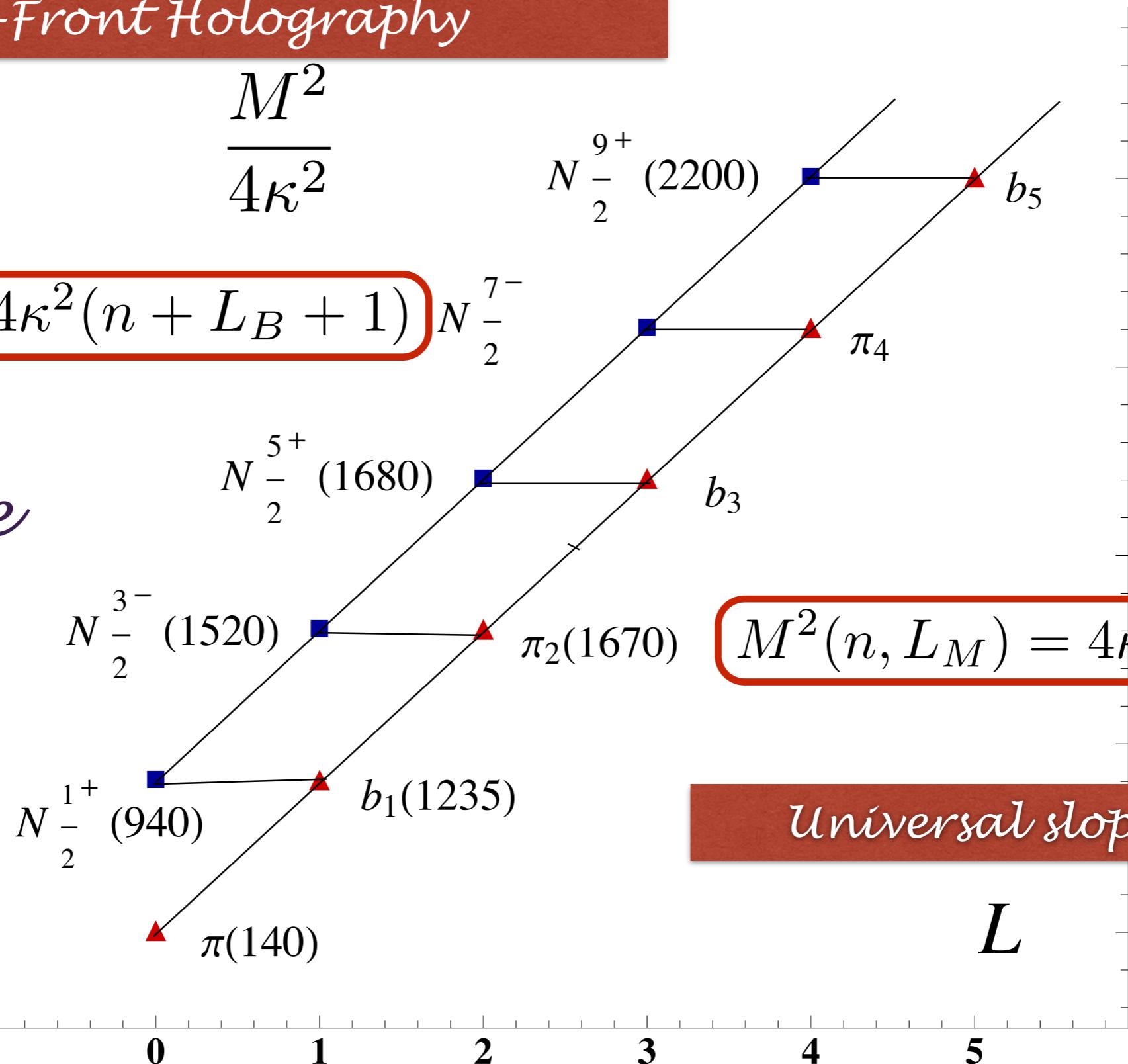
# Superconformal Quantum Mechanics Light-Front Holography

*de Téramond, Dosch, Lorcé, sjb*

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

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

Same slope



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

Universal slopes in  $n, L$

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

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

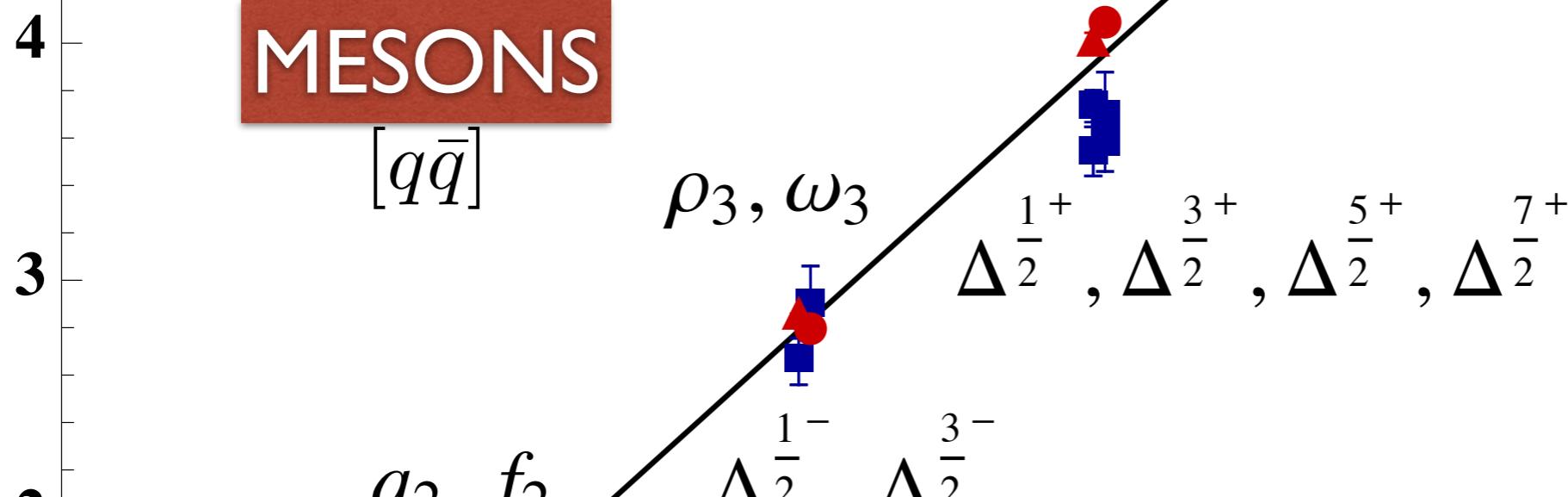
$M^2$  (GeV $^2$ )

$\rho - \Delta$  superpartner trajectories

MESONS  
[ $q\bar{q}$ ]

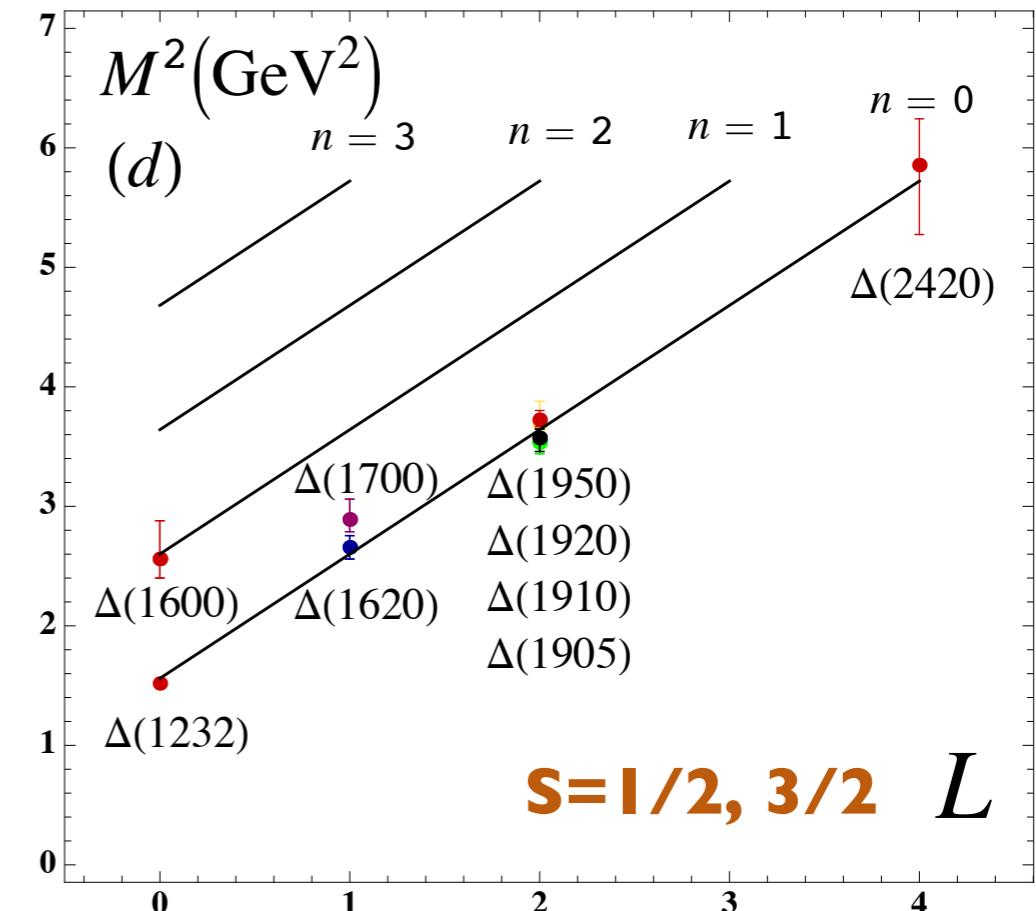
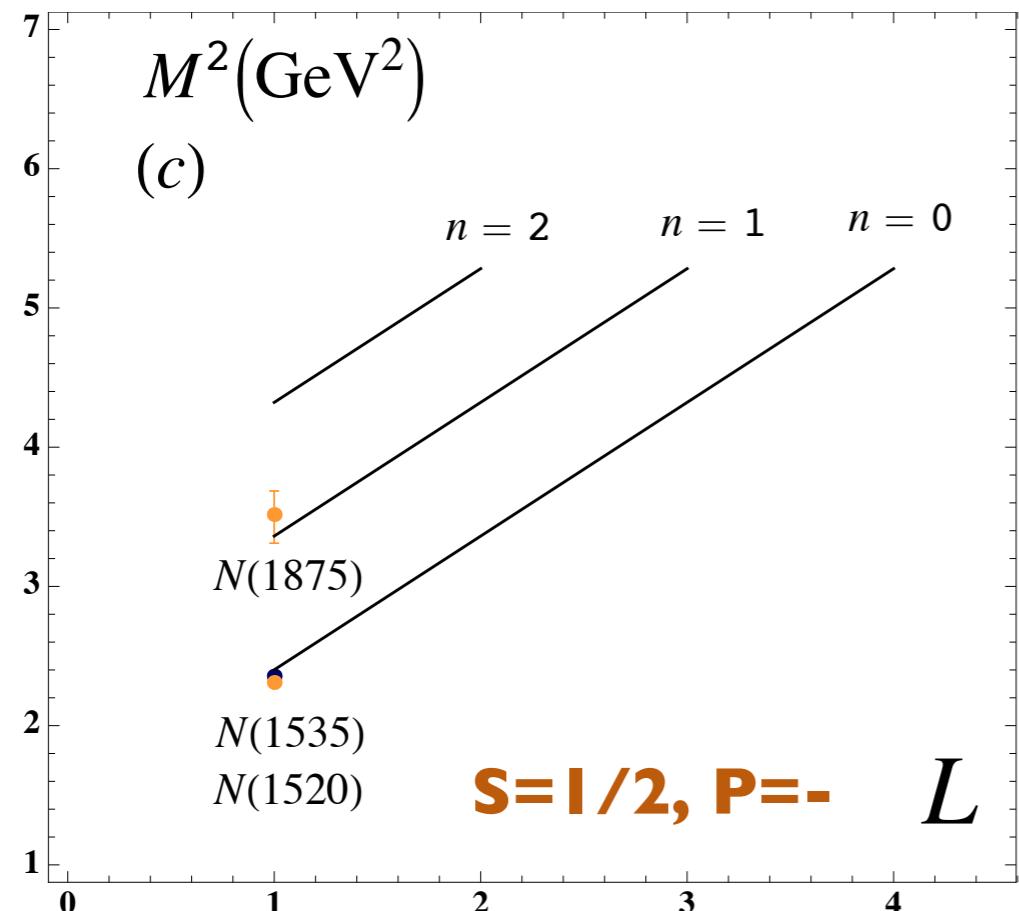
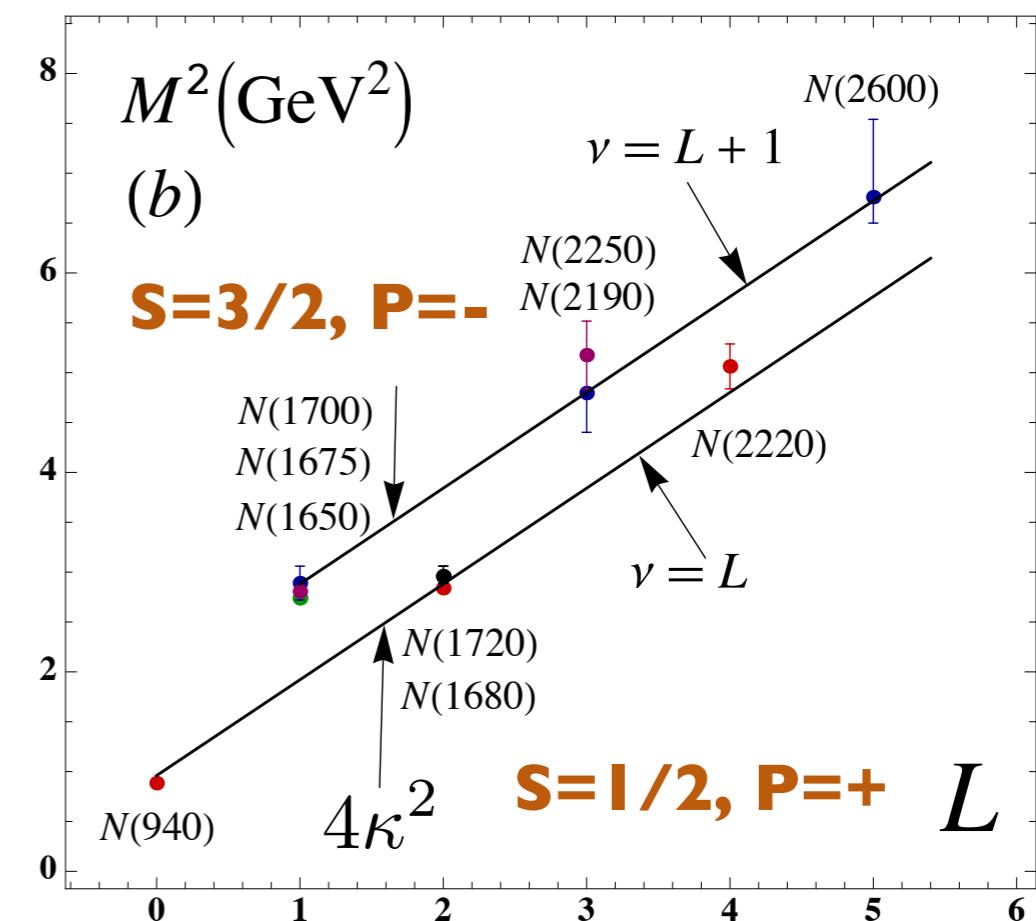
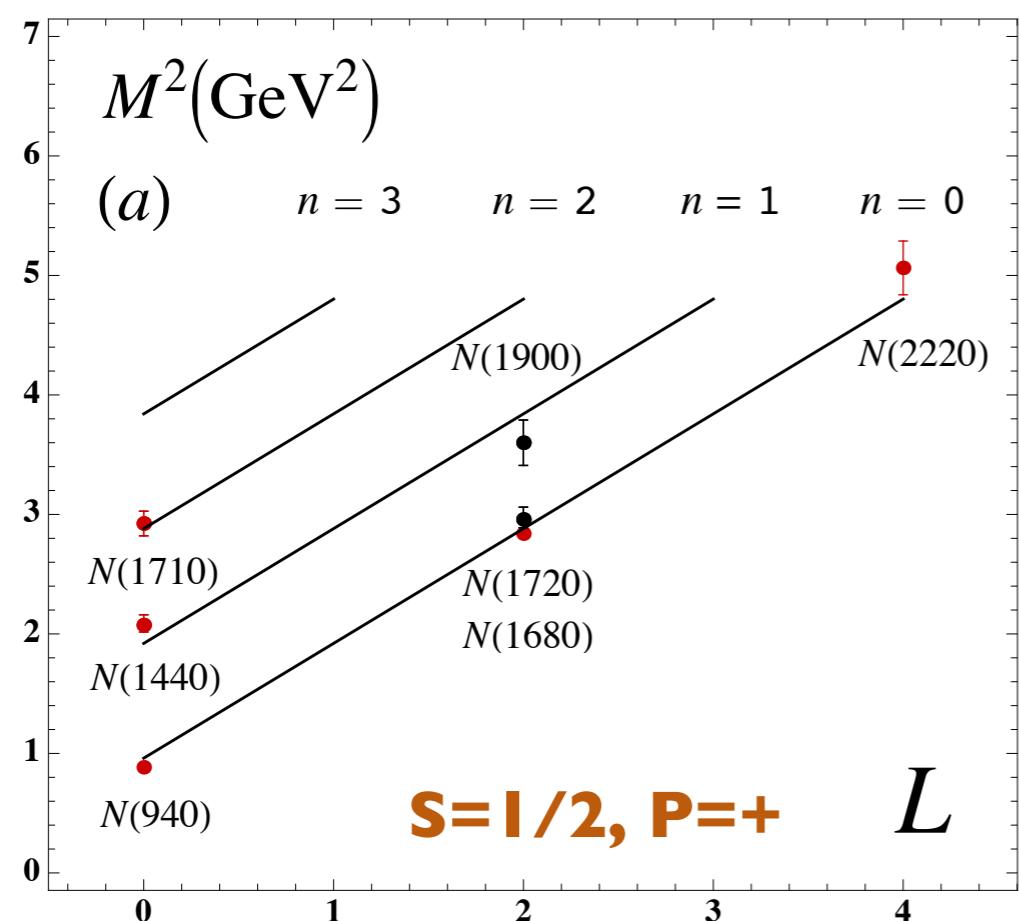
bosons

fermions



BARYONS  
[ $qqq$ ]

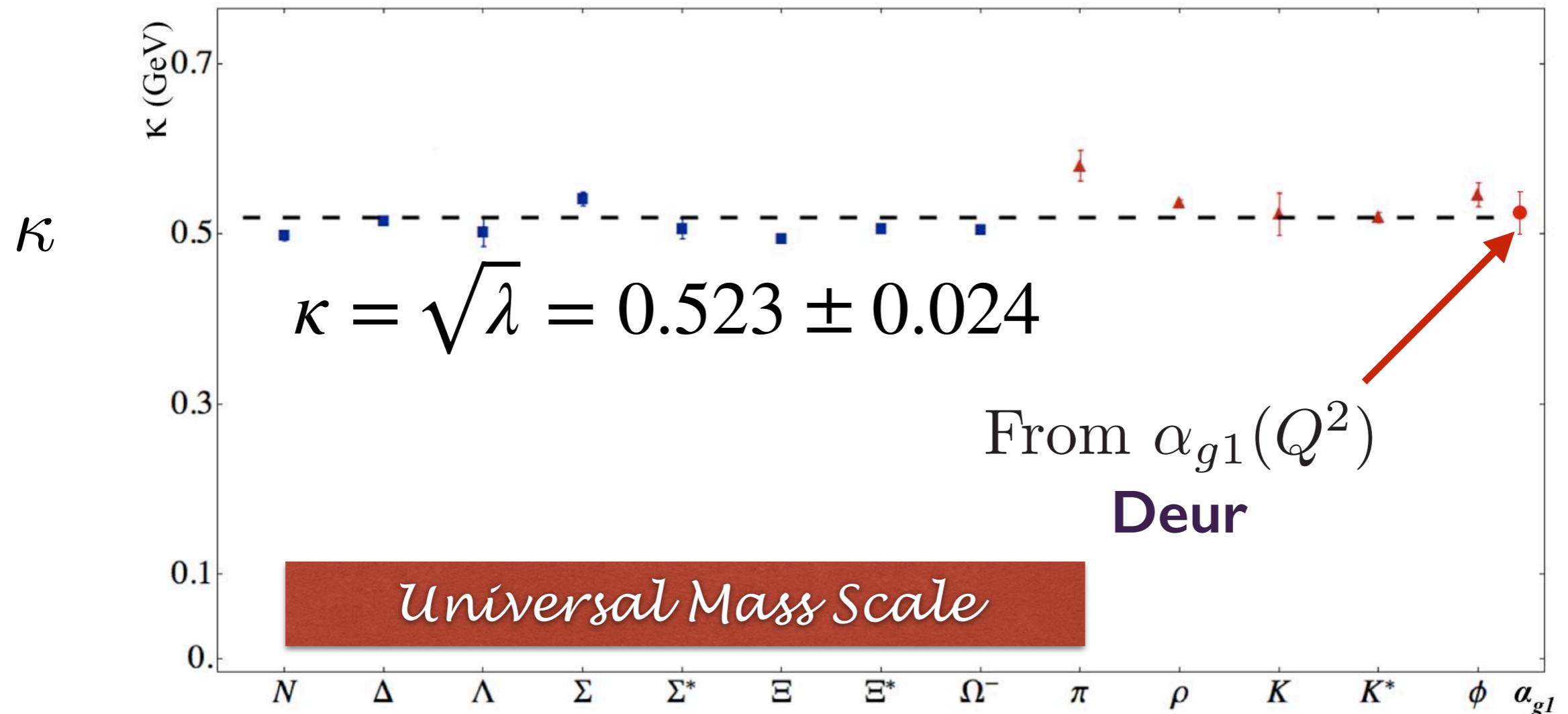
$$L_M = L_B + 1$$



$$\lambda = \kappa^2$$

*de Téramond, Dosch, Lorcé, sjb*

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



***Fit to the slope of Regge trajectories,  
including radial excitations***

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

- Nucleon LF modes

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

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

- Normalization

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

- Eigenvalues

$$\int_0^\infty d\zeta \int_0^1 dx \psi_+^2(\zeta^2, x) = \int_0^\infty d\zeta \int_0^1 dx \psi_-^2(\zeta^2, x) = \frac{1}{2}$$

*Quark Chiral  
Symmetry of  
Eigenstate!*

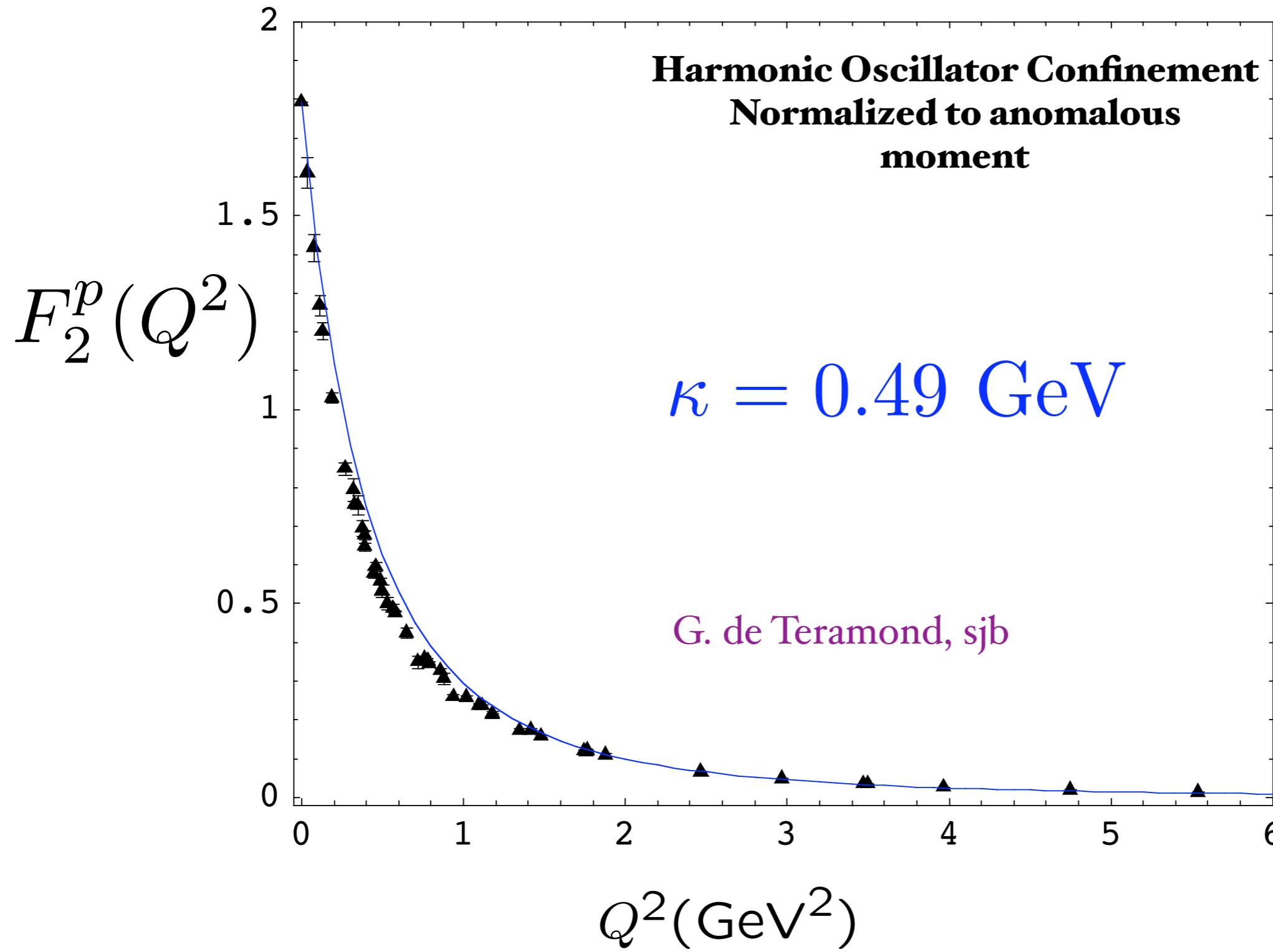
### Nucleon: Equal Probability for L=0, 1

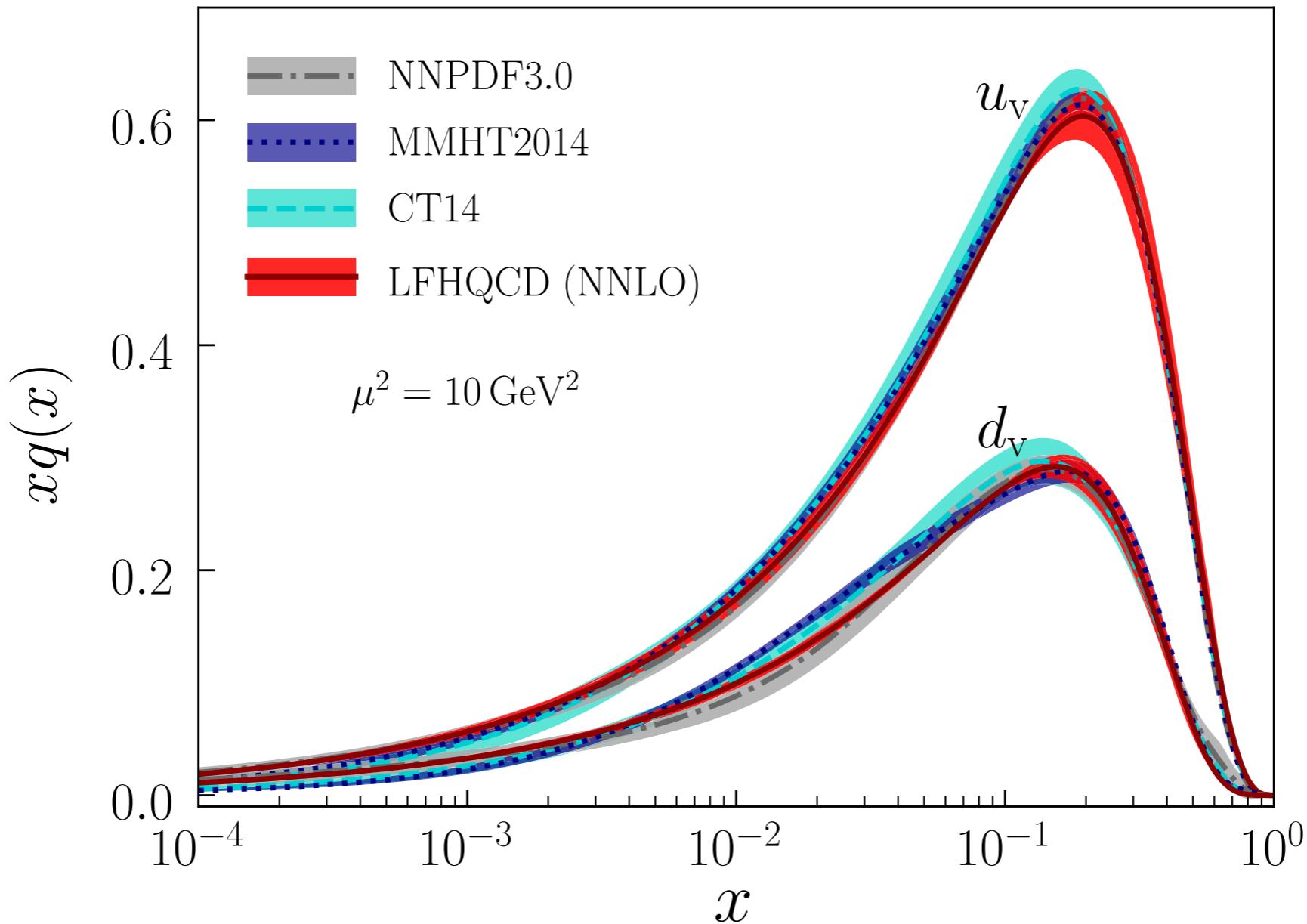
$$J^z = +1/2 : \frac{1}{\sqrt{2}} [ |S_q^z = +1/2, L^z = 0 \rangle + |S_q^z = -1/2, L^z = +1 \rangle ]$$

*Nucleon spin carried by quark orbital angular momentum*

# Spacelike Pauli Form Factor

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





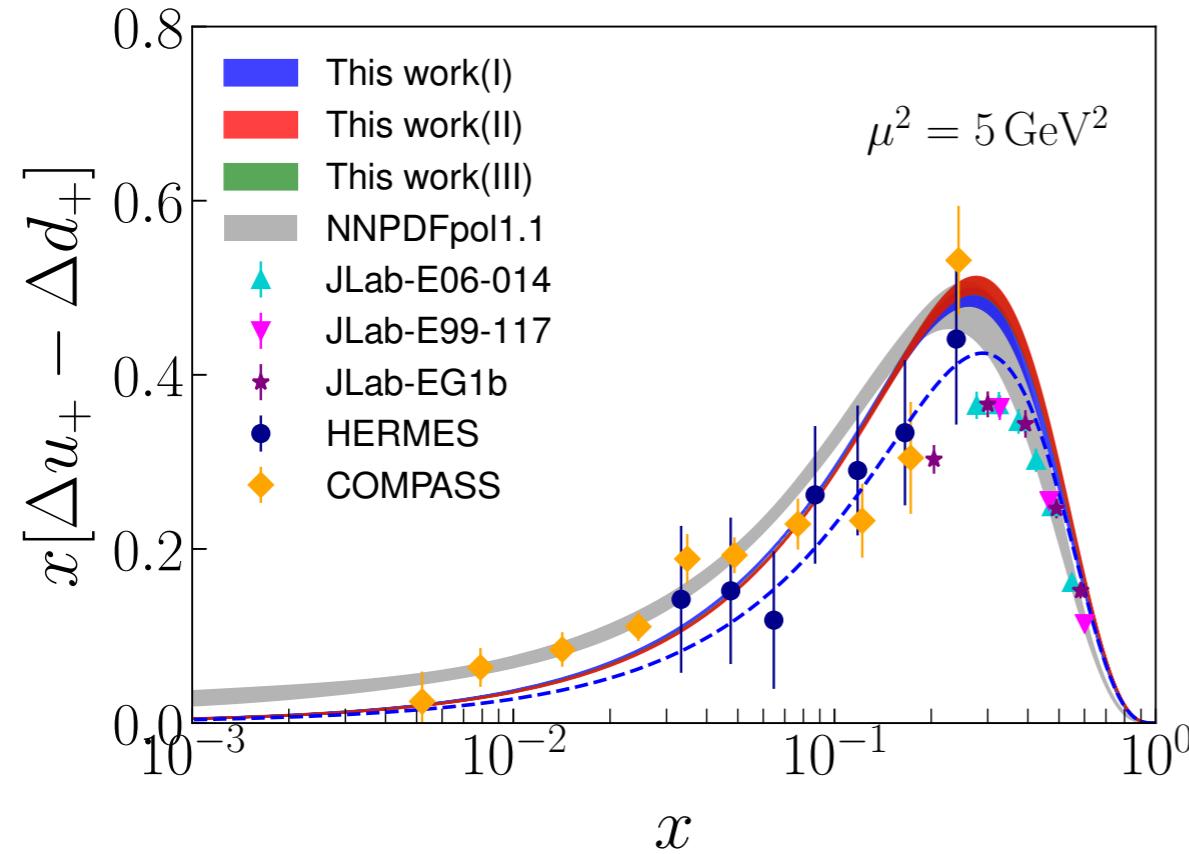
Comparison for  $xq(x)$  in the proton from LFHQCD (red bands) and global fits: MMHT2014 (blue bands) [5], CT14 [6] (cyan bands), and NNPDF3.0 (gray bands) [77]. LFHQCD results are evolved from the initial scale  $\mu_0 = 1.06 \pm 0.15$  GeV.

*Universality of Generalized Parton Distributions in Light-Front Holographic QCD*

*Guy F. de Téramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur*

*PHYSICAL REVIEW LETTERS 120, 182001 (2018)*

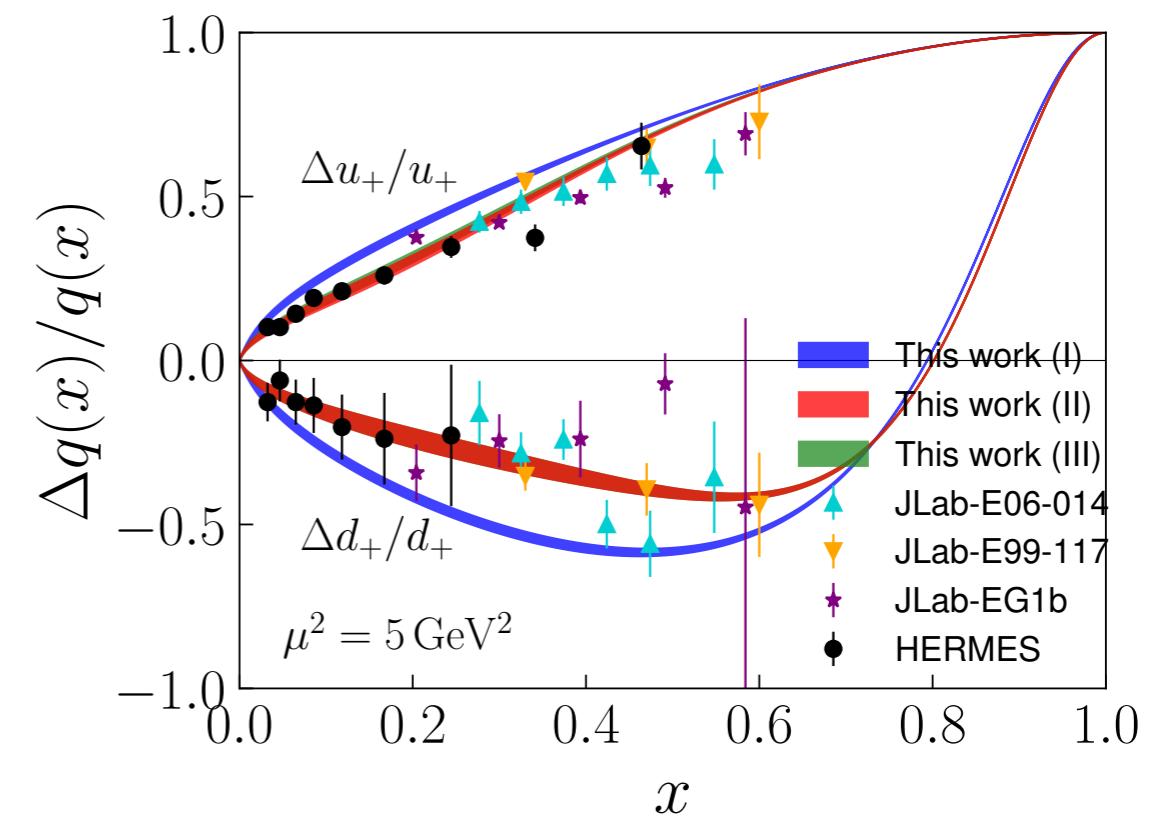
# Tianbo Liu, \* Raza Sabbir Sufian, Guy F. de T' eramond, Hans Gunter Dösch, Alexandre Deur, sjb



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

Polarized distributions for the isovector combination  $x[\Delta u_+(x) - \Delta d_+(x)]$

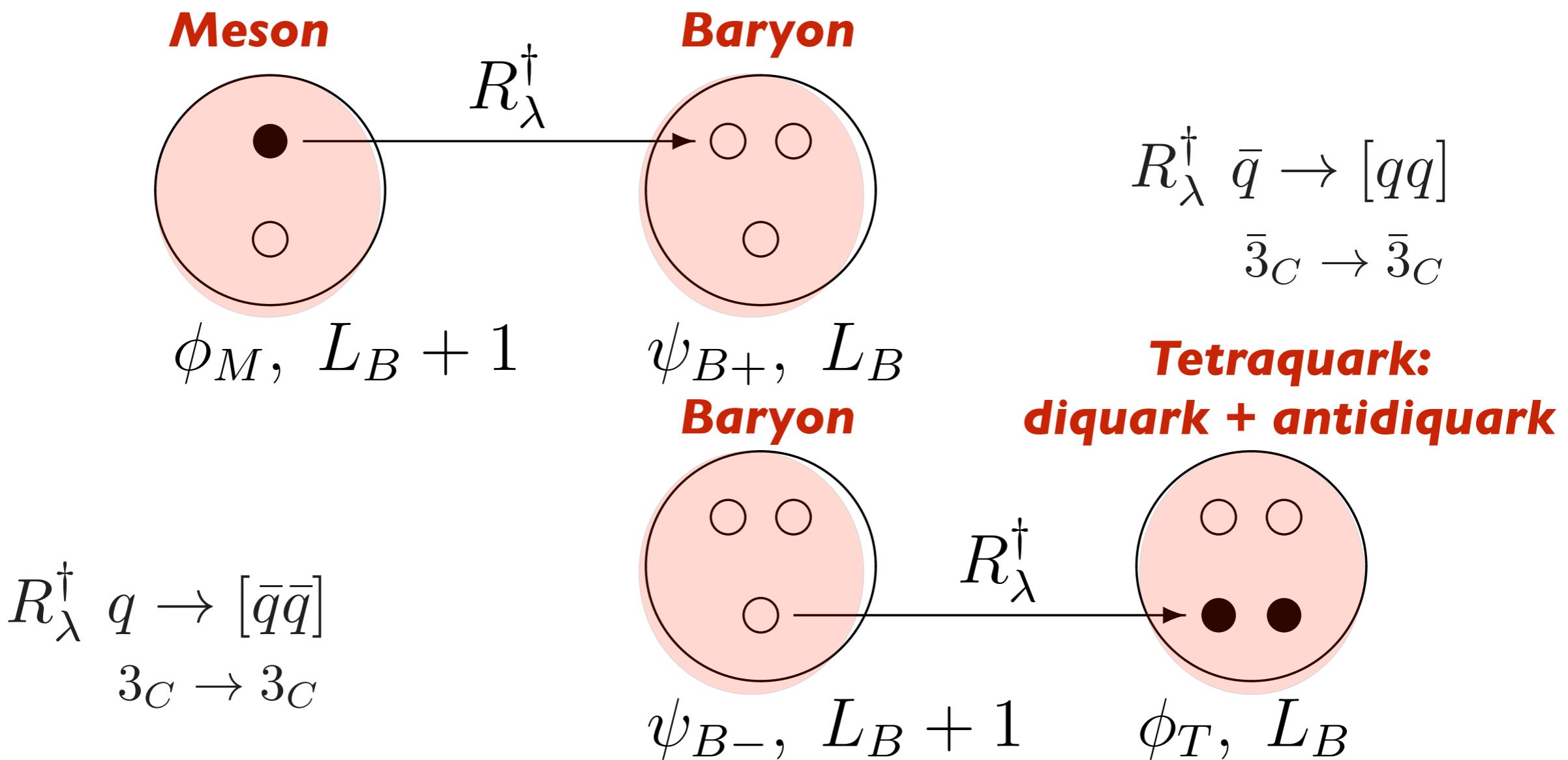
$$d_+(x) = d(x) + \bar{d}(x) \quad u_+(x) = u(x) + \bar{u}(x)$$



# Superconformal Algebra

## 2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



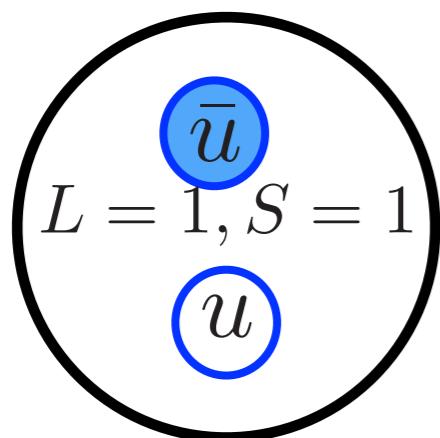
Proton: |u[ud]> Quark + Scalar Diquark  
Equal Weight: L=0, L=1

# Superconformal Algebra 4-Plet

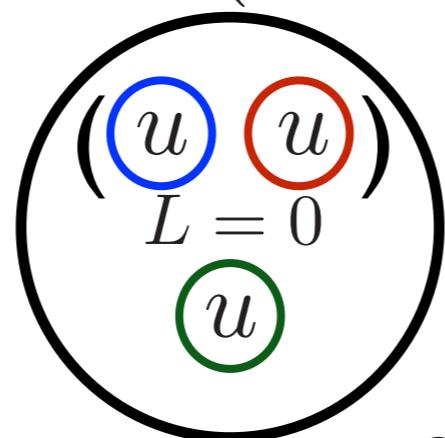
$$R_\lambda^\dagger \quad \bar{q} \rightarrow (qq) \quad S = 1 \\ \bar{3}_C \rightarrow \bar{3}_C$$

Vector ()+ Scalar [] Diquarks

$f_2(1270)$

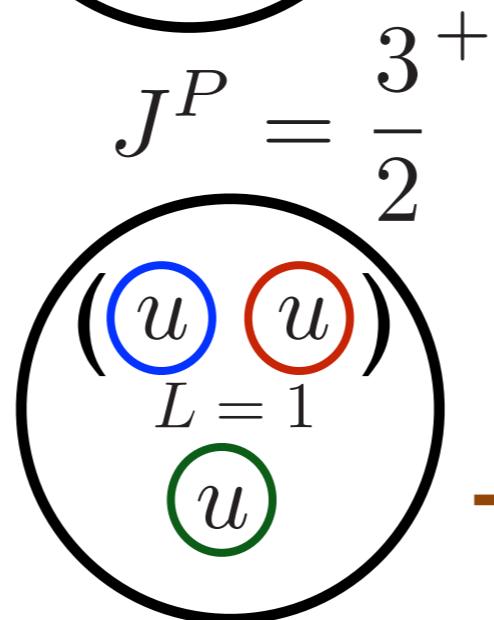


$\Delta^+(1232)$



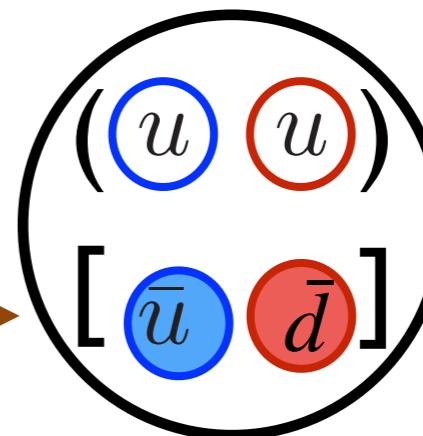
**Tetraquark**

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



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

$a_1(1260)$

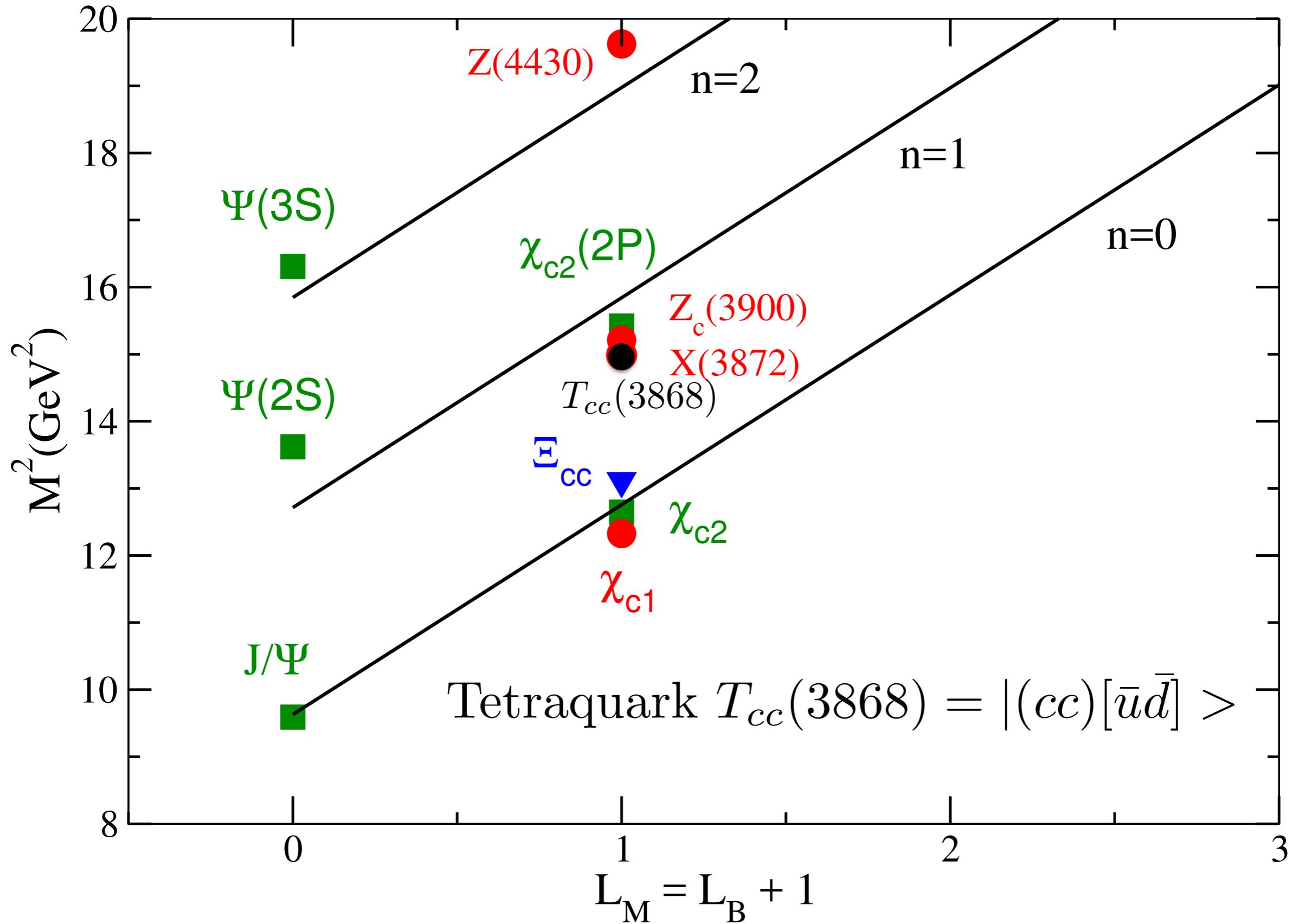


$L = 0$

**Meson**

**Baryon**

$$R_\lambda^\dagger \quad q \rightarrow [\bar{q}\bar{q}] \\ 3_C \rightarrow 3_C$$



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

Meson			Baryon			Tetraquark		
$q$ -cont	$J^{P(C)}$	Name	$q$ -cont	$J^P$	Name	$q$ -cont	$J^{P(C)}$	Name
$\bar{q}q$	$0^{-+}$	$\pi(140)$	—	—	—	—	—	—
$\bar{q}q$	$1^{+-}$	$b_1(1235)$	$[ud]q$	$(1/2)^+$	$N(940)$	$[ud][\bar{u}\bar{d}]$	$0^{++}$	$f_0(980)$
$\bar{q}q$	$2^{-+}$	$\pi_2(1670)$	$[ud]q$	$(1/2)^-$	$N_{\frac{1}{2}-}(1535)$	$[ud][\bar{u}\bar{d}]$	$1^{-+}$	$\pi_1(1400)$
				$(3/2)^-$	$N_{\frac{3}{2}-}(1520)$			$\pi_1(1600)$
$\bar{q}q$	$1^{--}$	$\rho(770), \omega(780)$	—	—	—	—	—	—
$\bar{q}q$	$2^{++}$	$a_2(1320), f_2(1270)$	$[qq]q$	$(3/2)^+$	$\Delta(1232)$	$[qq][\bar{u}\bar{d}]$	$1^{++}$	$a_1(1260)$
$\bar{q}q$	$3^{--}$	$\rho_3(1690), \omega_3(1670)$	$[qq]q$	$(1/2)^-$	$\Delta_{\frac{1}{2}-}(1620)$	$[qq][\bar{u}\bar{d}]$	$2^{--}$	$\rho_2(\sim 1700)?$
				$(3/2)^-$	$\Delta_{\frac{3}{2}-}(1700)$			
$\bar{q}q$	$4^{++}$	$a_4(2040), f_4(2050)$	$[qq]q$	$(7/2)^+$	$\Delta_{\frac{7}{2}+}(1950)$	$[qq][\bar{u}\bar{d}]$	$3^{++}$	$a_3(\sim 2070)?$
$\bar{q}s$	$0^{-(+)}\phantom{0}$	$K(495)$	—	—	—	—	—	—
$\bar{q}s$	$1^{+(-)}$	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	$0^{+(+)}\phantom{0}$	$K_0^*(1430)$
$\bar{q}s$	$2^{-(+)}\phantom{0}$	$K_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar{s}\bar{q}]$	$1^{-(+)}\phantom{0}$	$K_1^*(\sim 1700)?$
				$(3/2)^-$	$\Lambda(1520)$			
$\bar{s}q$	$0^{-(+)}\phantom{0}$	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	$0^{++}\phantom{0}$	$a_0(980)$
								$f_0(980)$
$\bar{s}q$	$1^{--}$	$K^*(890)$	—	—	—	—	—	—
$\bar{s}q$	$2^{++(+)}\phantom{0}$	$K_2^*(1430)$	$[sq]q$	$(3/2)^+$	$\Sigma(1385)$	$[sq][\bar{q}\bar{q}]$	$1^{++(+)}\phantom{0}$	$K_1(1400)$
$\bar{s}q$	$3^{--(-)}$	$K_3^*(1780)$	$[sq]q$	$(3/2)^-$	$\Sigma(1670)$	$[sq][\bar{q}\bar{q}]$	$2^{--(-)}\phantom{0}$	$K_2(\sim 1700)?$
$\bar{s}q$	$4^{+(+)}\phantom{0}$	$K_4^*(2045)$	$[sq]q$	$(7/2)^+$	$\Sigma(2030)$	$[sq][\bar{q}\bar{q}]$	$3^{++(+)}\phantom{0}$	$K_3(\sim 2070)?$
$\bar{s}s$	$0^{-+}\phantom{0}$	$\eta(550)$	—	—	—	—	—	—
$\bar{s}s$	$1^{+-}$	$h_1(1170)$	$[sq]s$	$(1/2)^+$	$\Xi(1320)$	$[sq][\bar{s}\bar{q}]$	$0^{++}\phantom{0}$	$f_0(1370)$
								$a_0(1450)$
$\bar{s}s$	$2^{-+}\phantom{0}$	$\eta_2(1645)$	$[sq]s$	$(?)^?$	$\Xi(1690)$	$[sq][\bar{s}\bar{q}]$	$1^{-+}\phantom{0}$	$\Phi'(1750)?$
$\bar{s}s$	$1^{--}$	$\Phi(1020)$	—	—	—	—	—	—
$\bar{s}s$	$2^{++}$	$f'_2(1525)$	$[sq]s$	$(3/2)^+$	$\Xi^*(1530)$	$[sq][\bar{s}\bar{q}]$	$1^{++}\phantom{0}$	$f_1(1420)$
$\bar{s}s$	$3^{--}$	$\Phi_3(1850)$	$[sq]s$	$(3/2)^-$	$\Xi(1820)$	$[sq][\bar{s}\bar{q}]$	$2^{--}\phantom{0}$	$\Phi_2(\sim 1800)?$
$\bar{s}s$	$2^{++}$	$f_2(1950)$	$[ss]s$	$(3/2)^+$	$\Omega(1672)$	$[ss][\bar{s}\bar{q}]$	$1^{++(+)}\phantom{0}$	$K_1(\sim 1700)?$

Meson

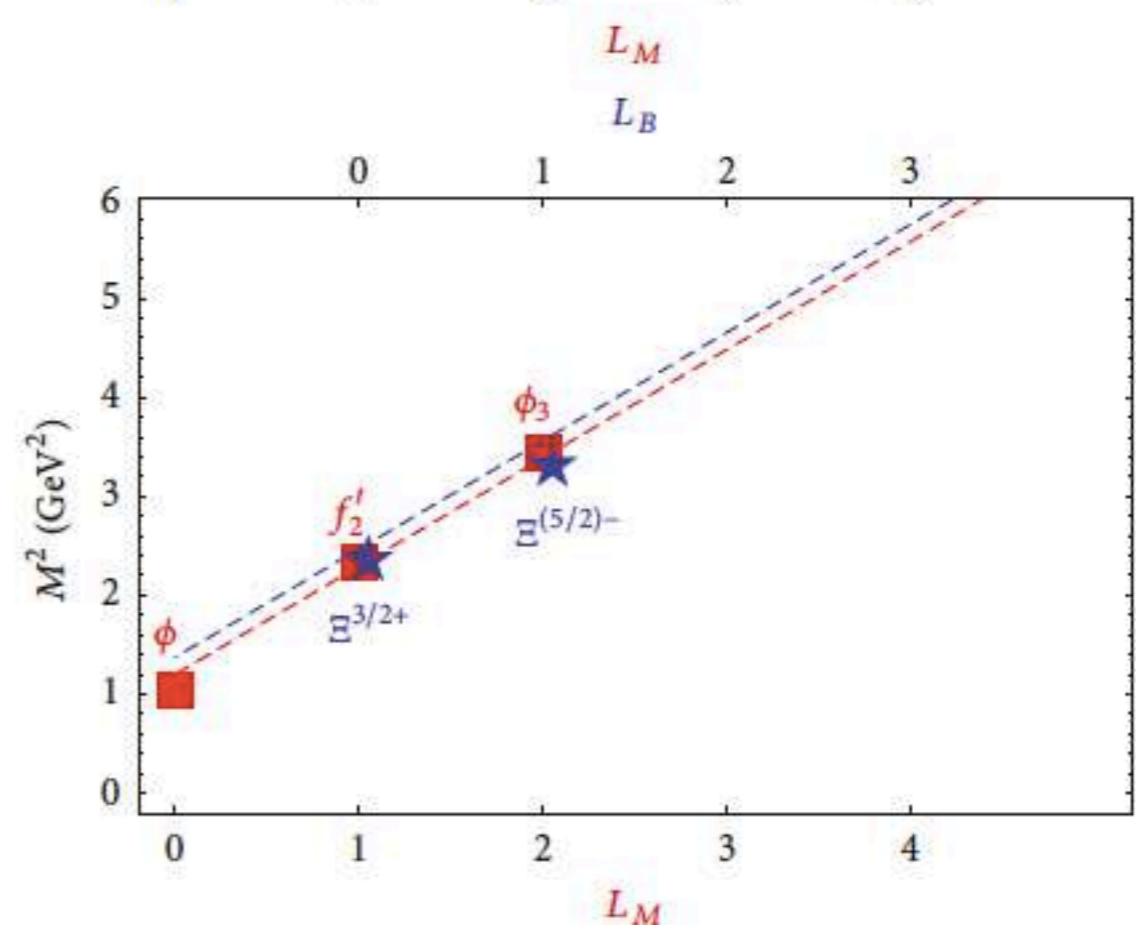
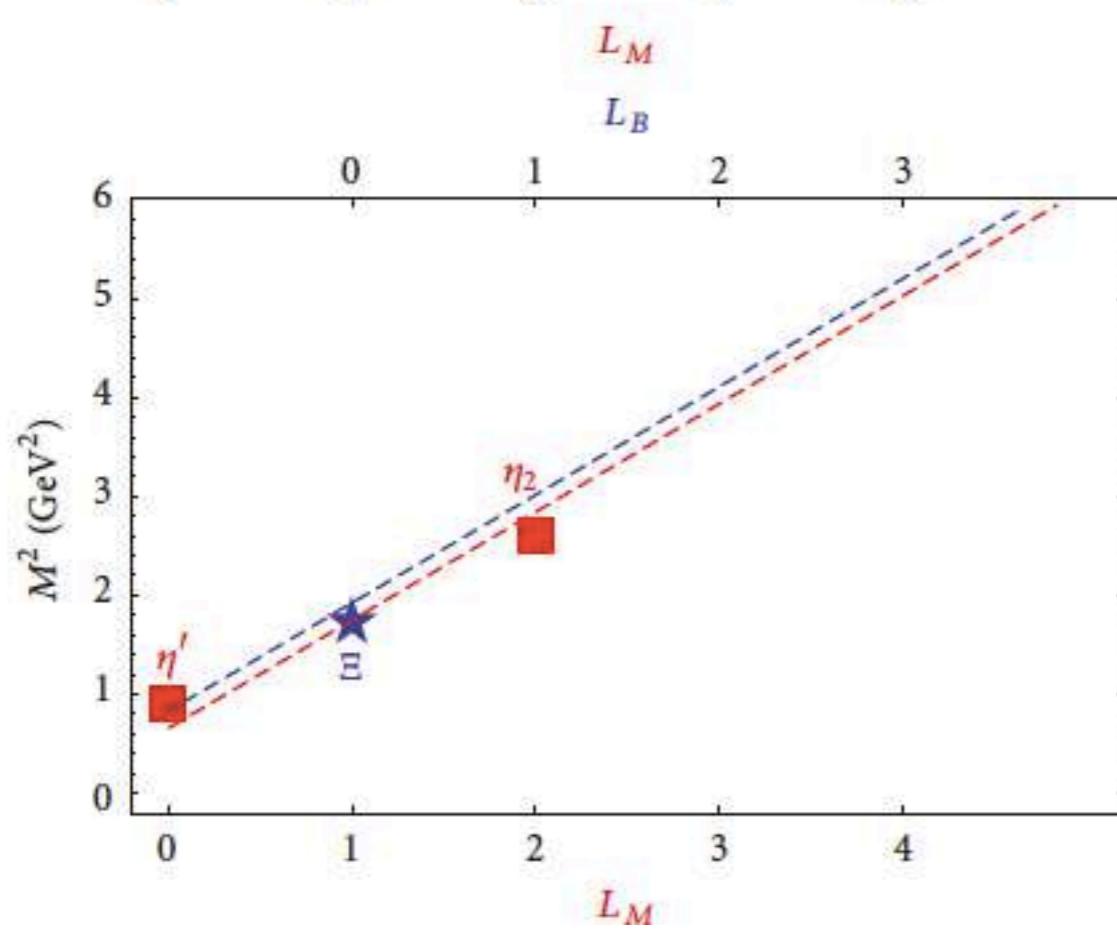
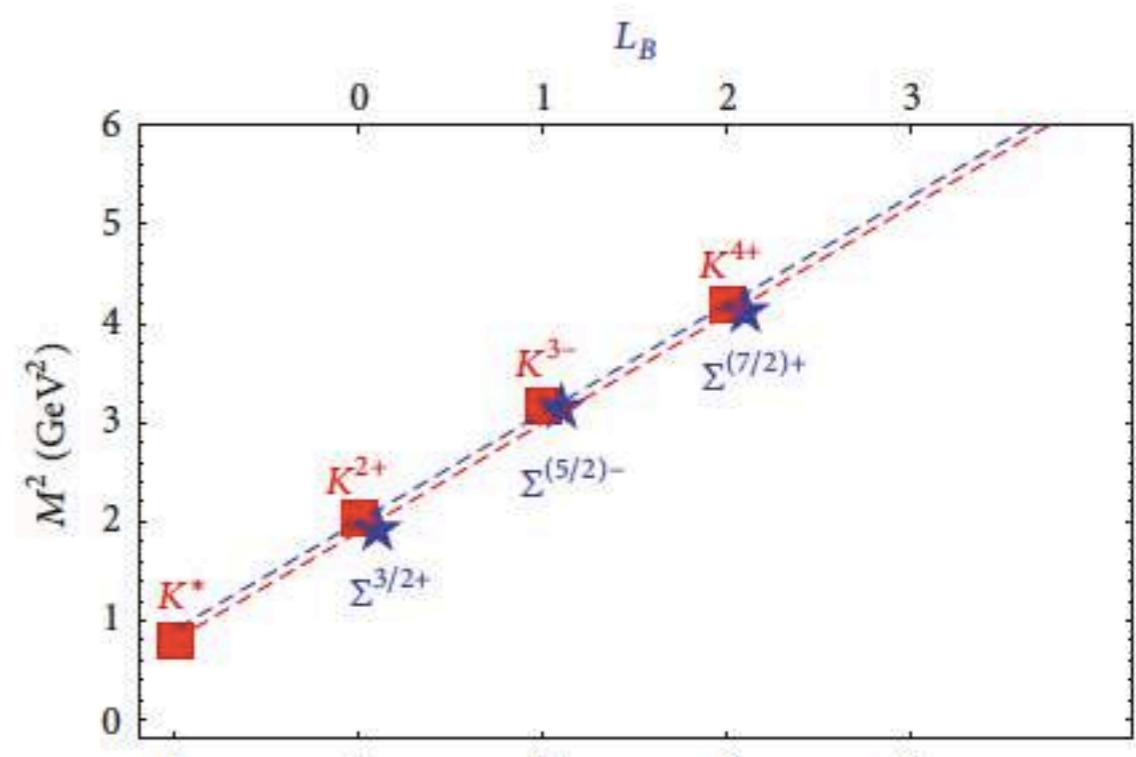
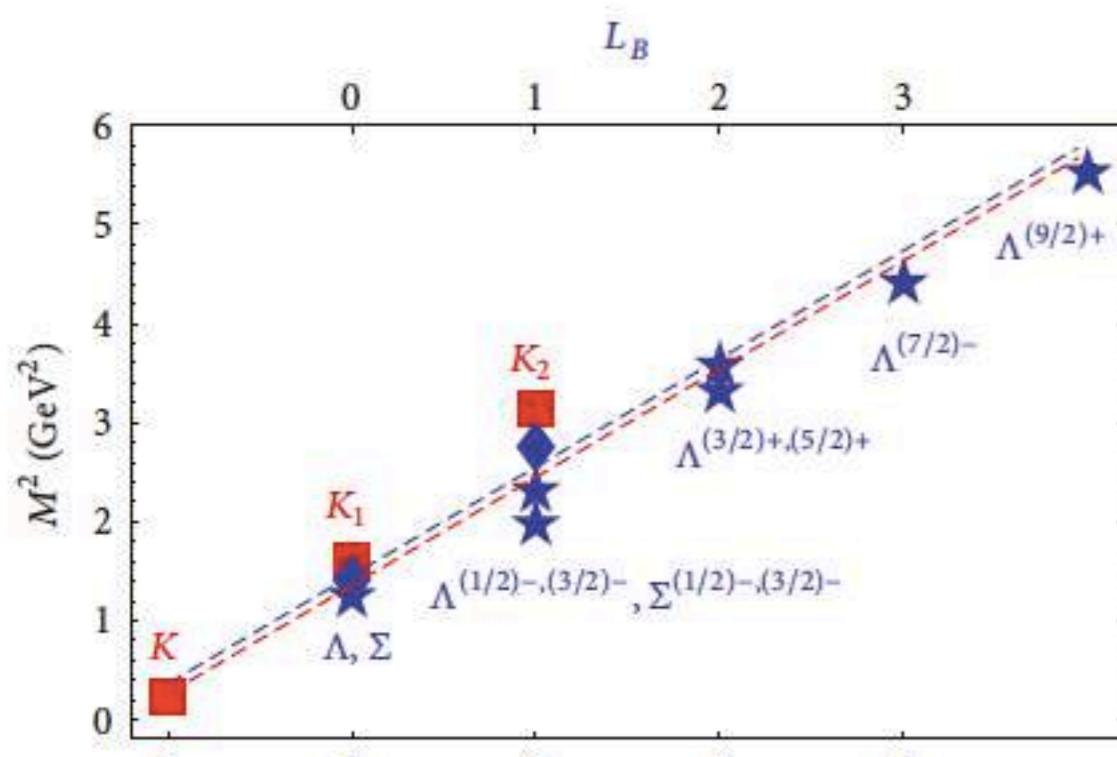
Baryon

Tetraquark

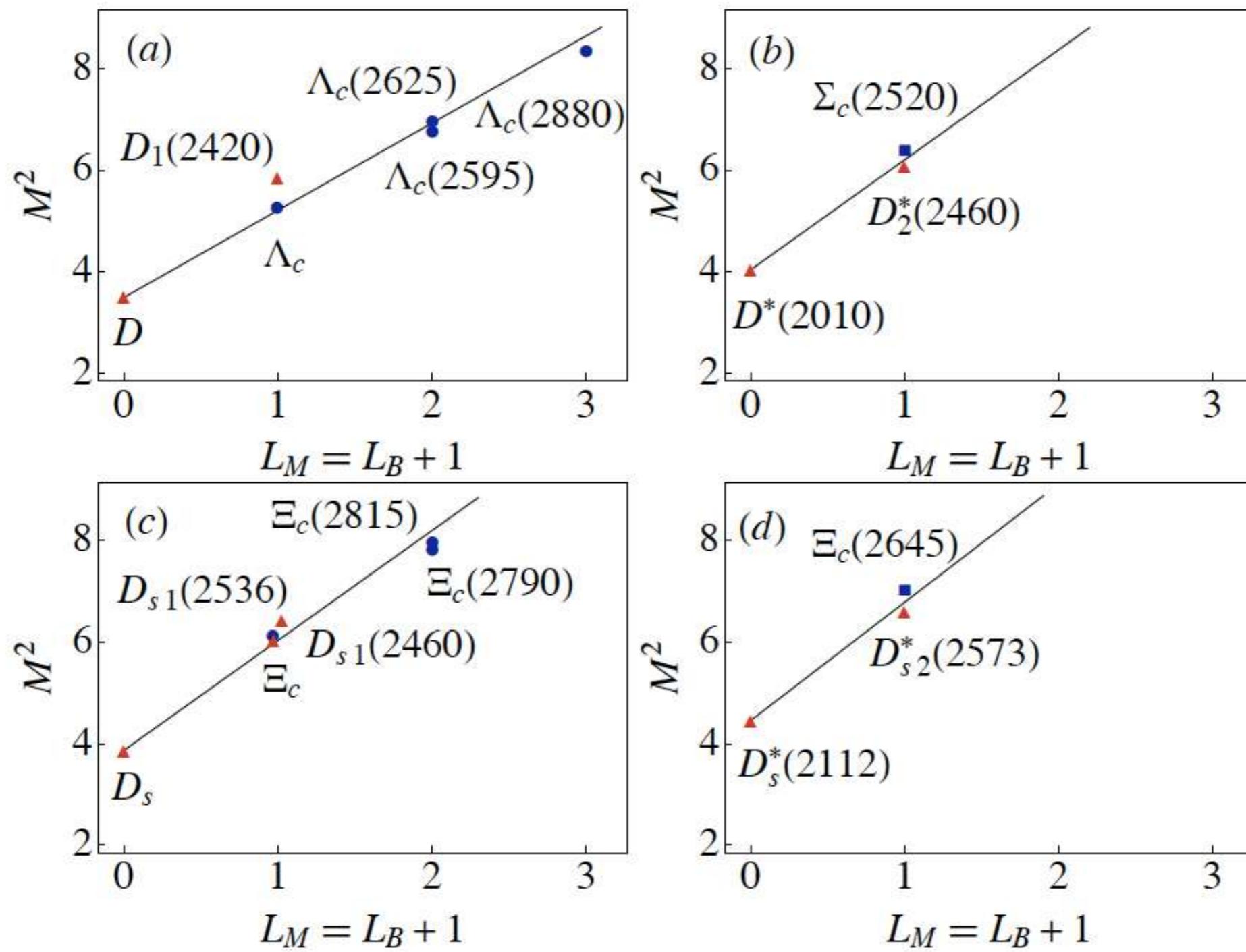
New Organization of the Hadron Spectrum

M. Nielsen,  
sjb

# Supersymmetry across the light and heavy-light spectrum

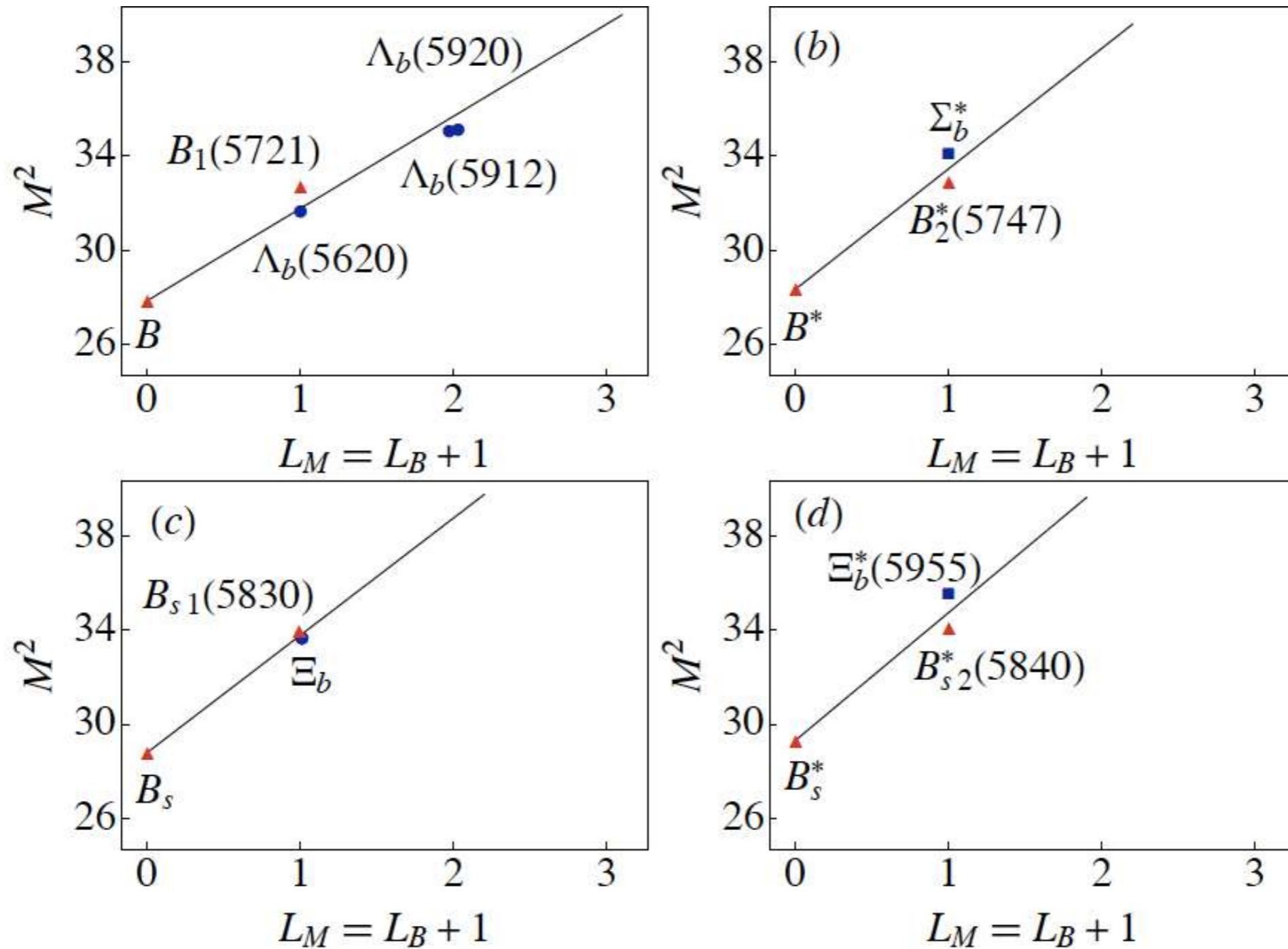


# *Supersymmetry across the light and heavy-light spectrum*



**Heavy charm quark mass does not break supersymmetry**

# *Supersymmetry across the light and heavy-light spectrum*



Heavy bottom quark mass does not break supersymmetry

# 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)]

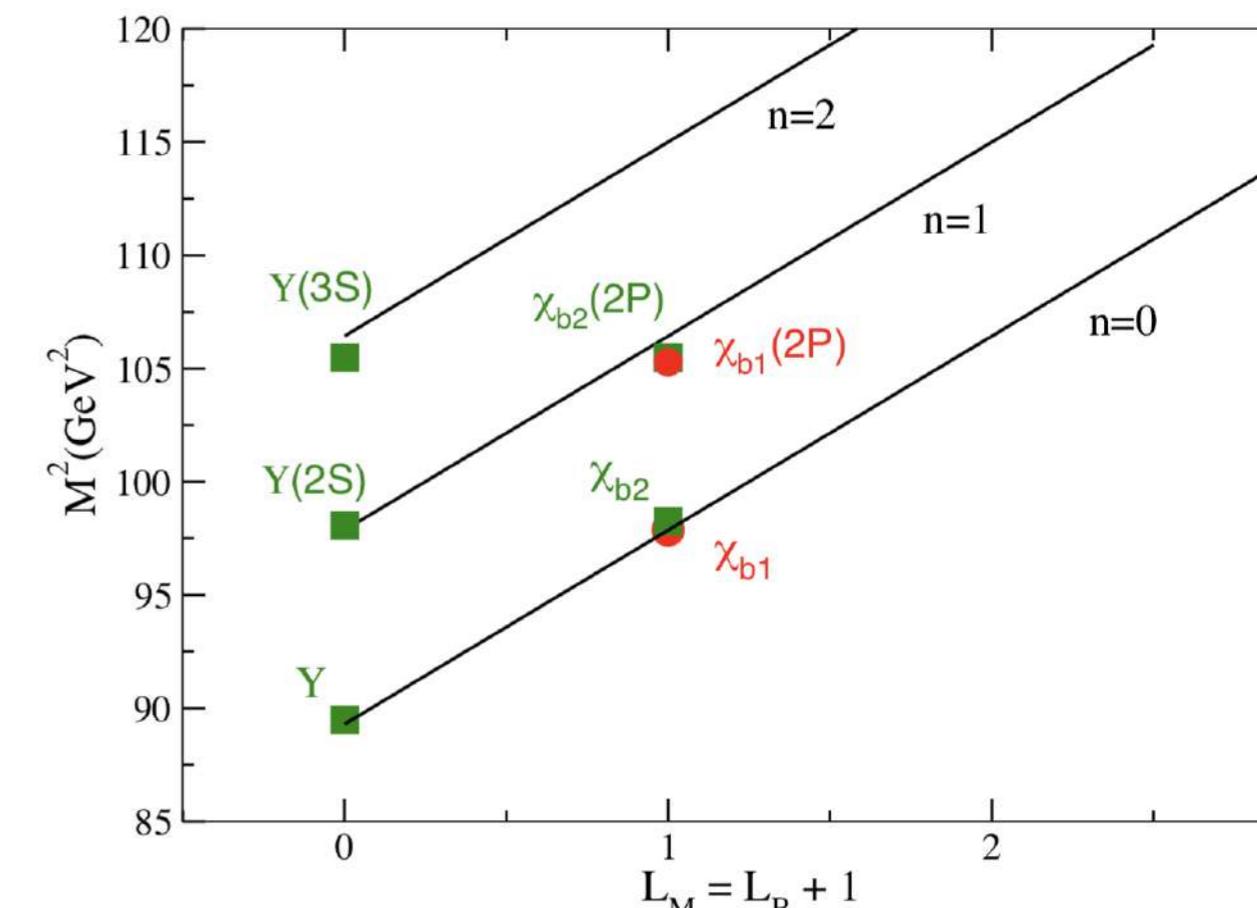
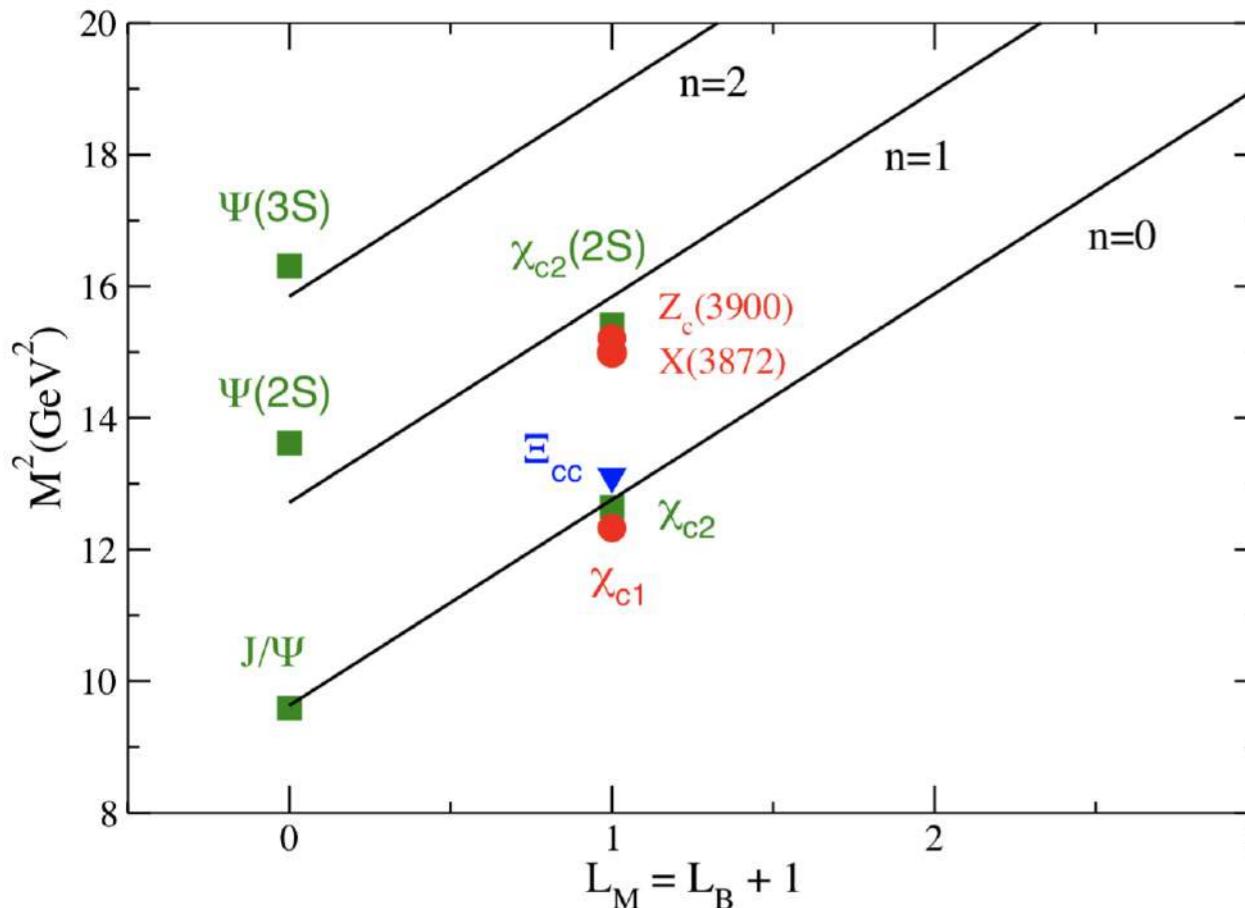
- Extension to the double-heavy hadronic sector

[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]]



# 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*

# 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

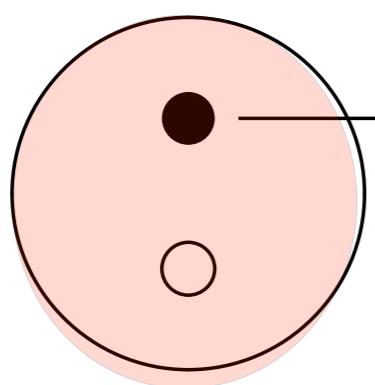
beautiful agreement!

# Superconformal Algebra

## Four-Plet Representations

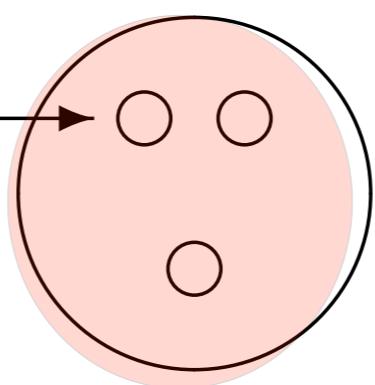
Bosons, Fermions with Equal Mass!

**Meson**



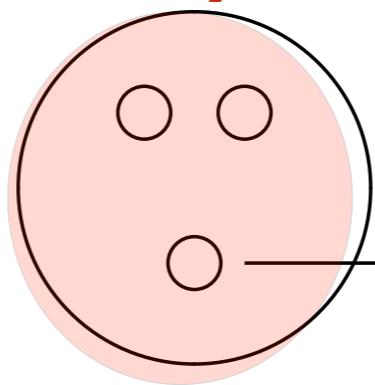
$\phi_M, L_B + 1$

**Baryon**



$\psi_{B+}, L_B$

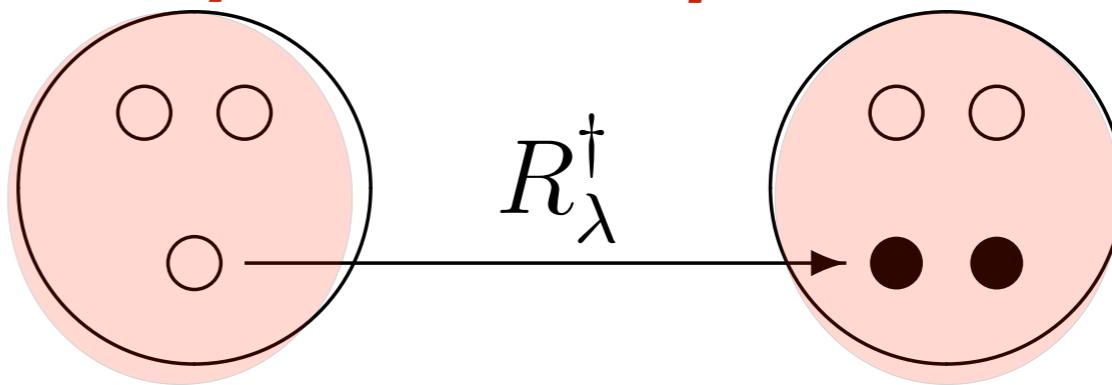
**Baryon**



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

$$R_\lambda^\dagger \bar{q} \rightarrow [qq]$$
$$\bar{3}_C \rightarrow \bar{3}_C$$

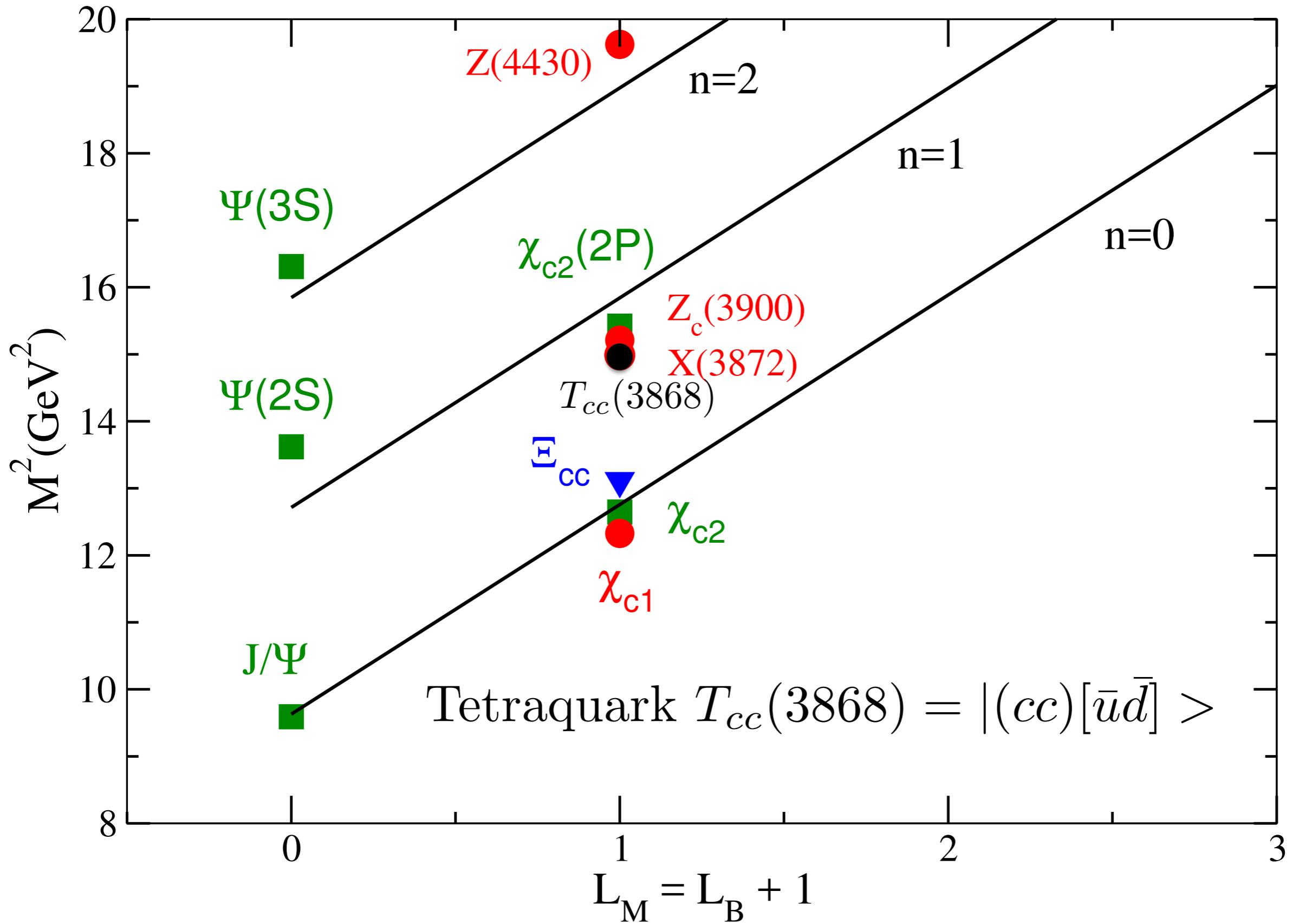
**Tetraquark:  
diquark + antiquark**



$\phi_T, L_B$

Proton: |u[ud]> Quark + Scalar Diquark

Equal Weight:  $L=0, L=1$

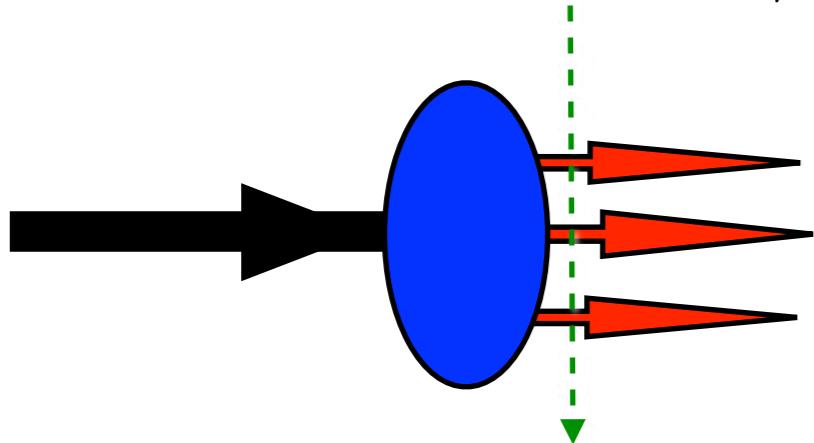


# Bound States in Relativistic Quantum Field Theory:

## 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  $P^\mu$*

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

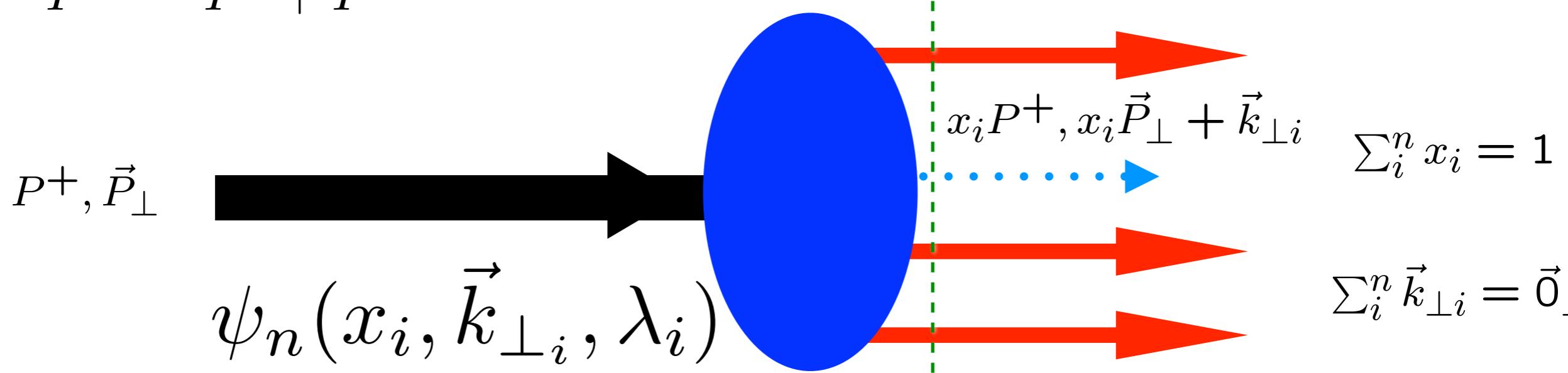
Direct connection to QCD Lagrangian

**LF Wavefunction: off-shell in invariant mass**

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

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

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



$H_{LF}^{QCD} |\Psi_h\rangle = \mathcal{M}_h^2 |\Psi_h\rangle$  Eigenstate of LF Hamiltonian

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

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

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

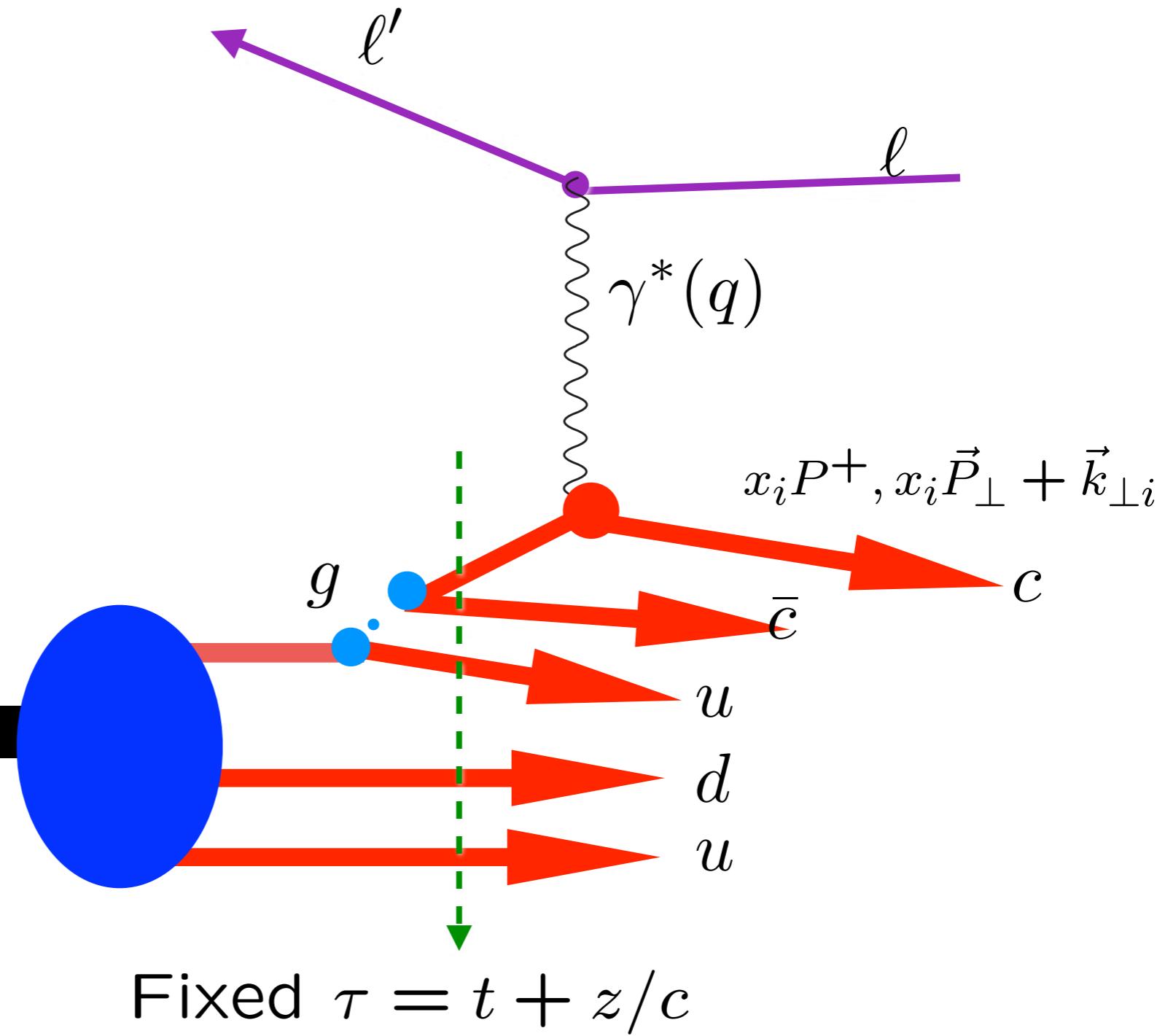
Structure Function is square of LFWFs, summed over all Fock states.  
 Causal, Frame-independent. Creation Operators on Simple Vacuum,  
 Current Matrix Elements are Overlaps of LFWFS

## Usual DGLAP

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

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

$\Psi_{|uudc\bar{c}>}(x_i, \vec{k}_{\perp i}, \lambda_i)$



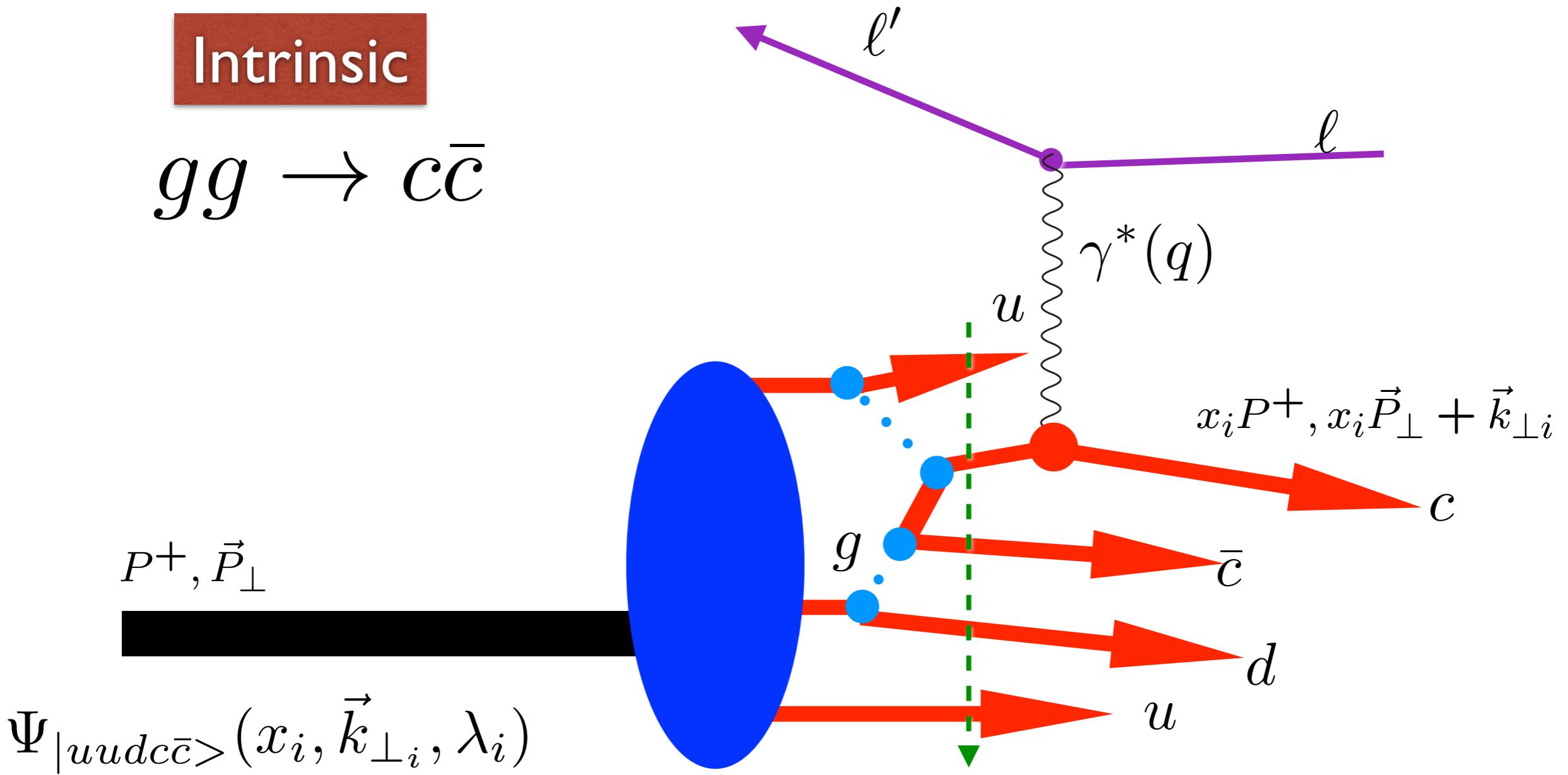
$$\text{Probability } P_{uudc\bar{c}} \sim \log \frac{Q^2 + M_c^2}{\Lambda_{QCD}^2}$$

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

*Low  $x$  extrinsic charm!*

Intrinsic

$$gg \rightarrow c\bar{c}$$



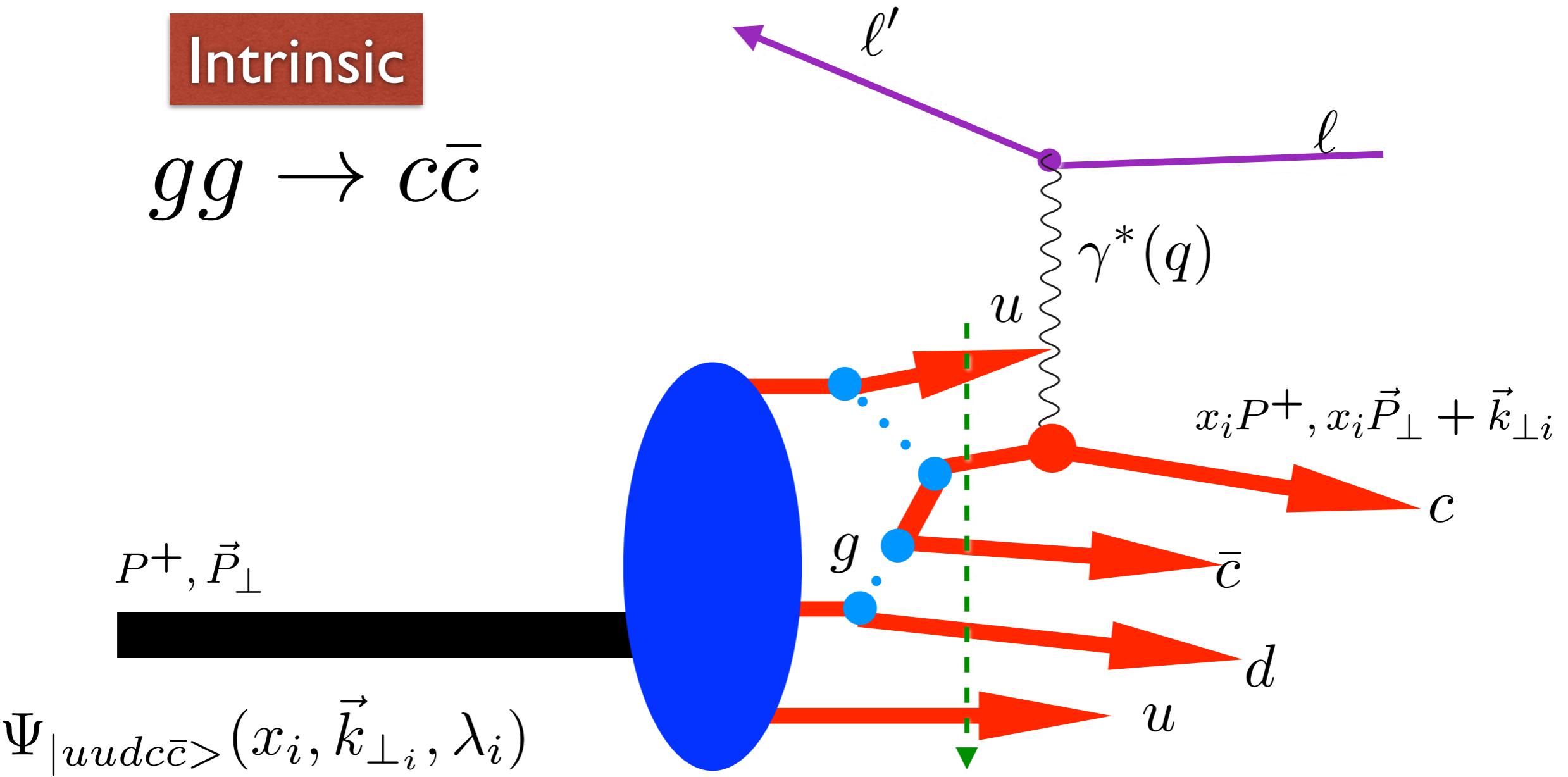
Probability  $P_{uudc\bar{c}} \propto \frac{1}{M_c^2}$

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

High  $x$  intrinsic charm!

# Intrinsic

$$gg \rightarrow c\bar{c}$$



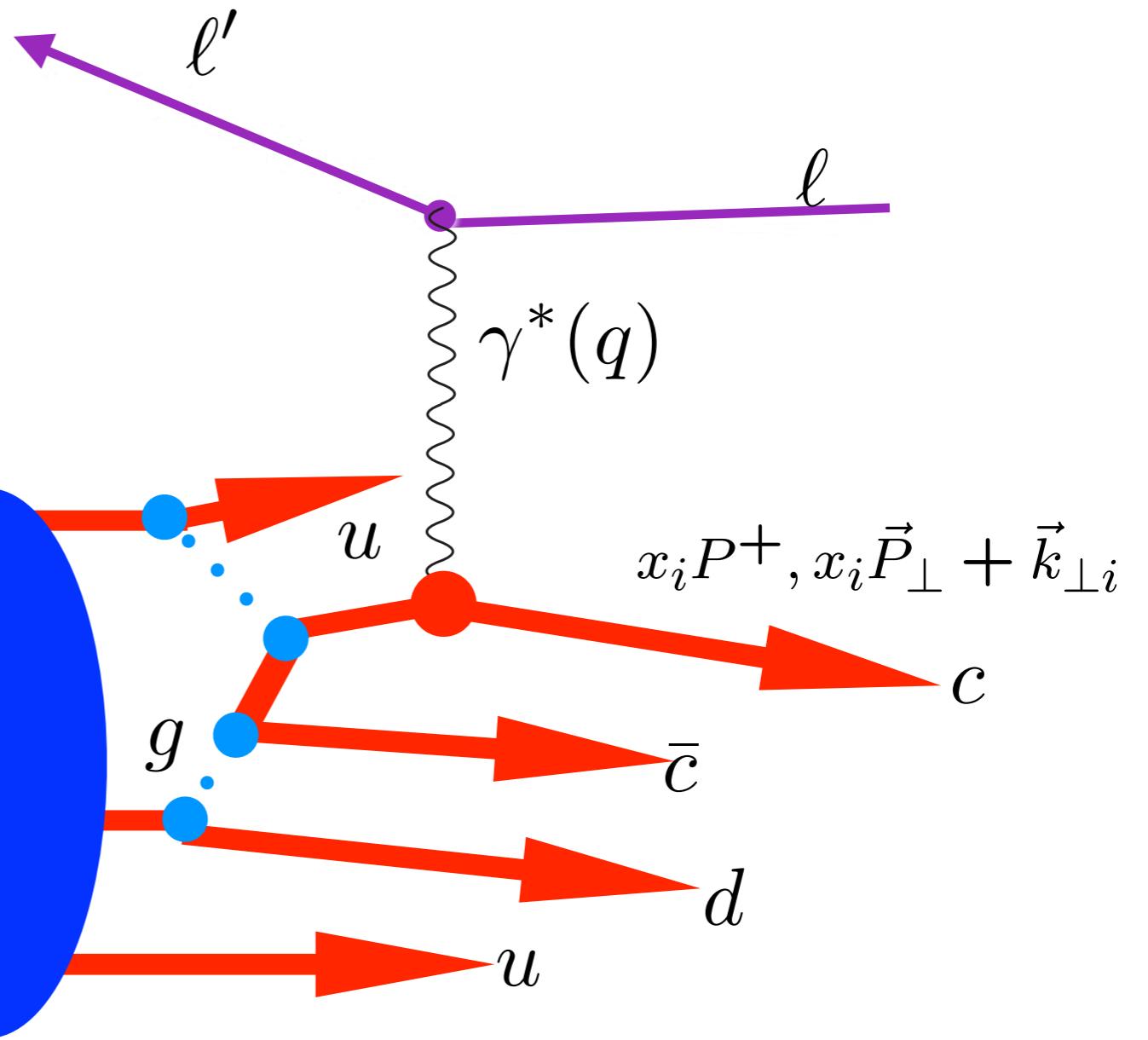
$$P(p \rightarrow uudc\bar{c}) \sim [m_p^2 - \sum_{i=1}^5 \frac{m_{\perp i}^2}{x_i}]^{-2} \quad m_{\perp i}^2 = m_i^2 + \vec{k}_{\perp i}^2$$

$$P(p \rightarrow c\bar{c} + X) \propto \frac{x_c^2 x_{\bar{c}}^2}{(x_c + x_{\bar{c}})^2} \times (1 - x_c - x_{\bar{c}})^2$$

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

Intrinsic

$$gg \rightarrow c\bar{c}$$



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

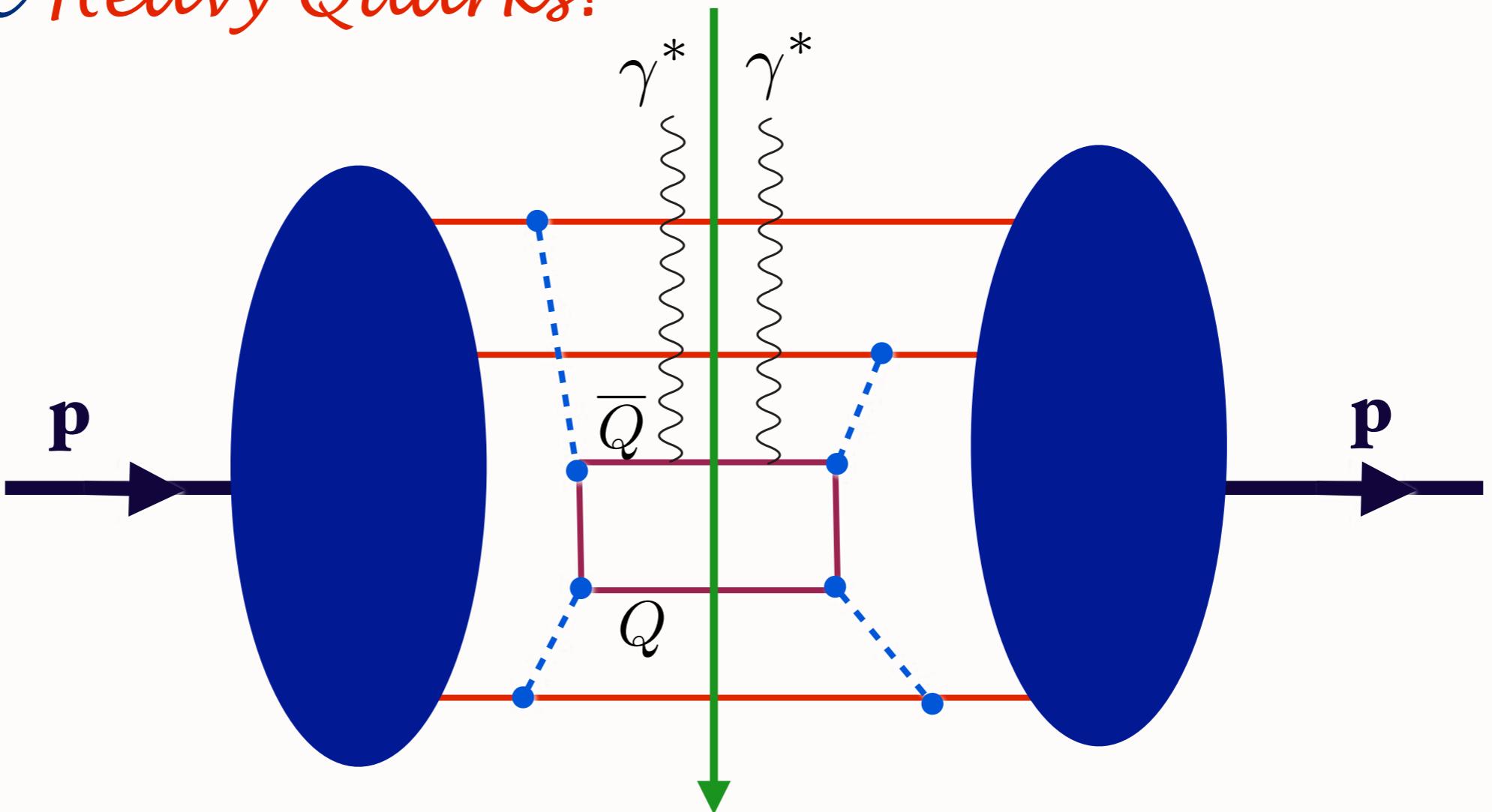
Property of Non-Abelian QCD

$$\begin{aligned} \mathcal{L}_{QCD}^{eff} = & -\frac{1}{4} G_{\mu\nu a} G^{\mu\nu a} - \frac{g^2 N_C}{120\pi^2 M_Q^2} D_a G_{\mu\nu a} D^a G^{\mu\nu a} \\ & + C \frac{g^3}{\pi^2 M_Q^2} G_\mu^{\nu a} G_\nu^{\tau b} G_\tau^{\mu c} f_{abc} + \mathcal{O}\left(\frac{1}{M_Q^4}\right) \end{aligned}$$

# Cut of Proton Self Energy:

*QCD predicts*

*Intrinsic Heavy Quarks!*



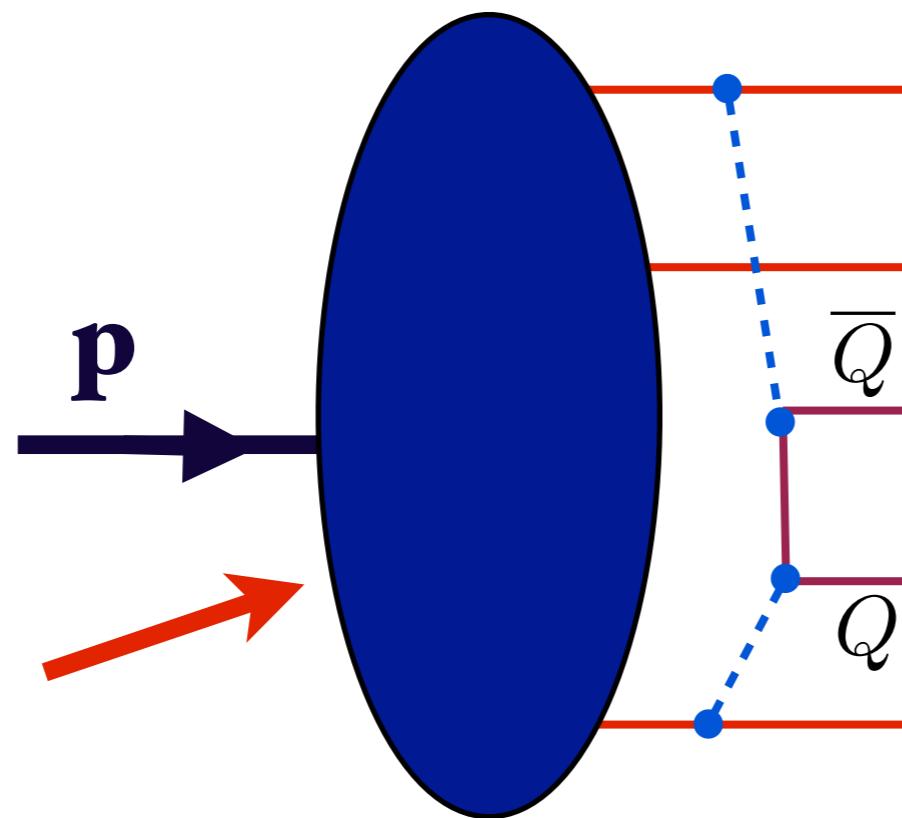
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

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

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

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

Proton 5-quark Fock State :  
Intrinsic Heavy Quarks



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

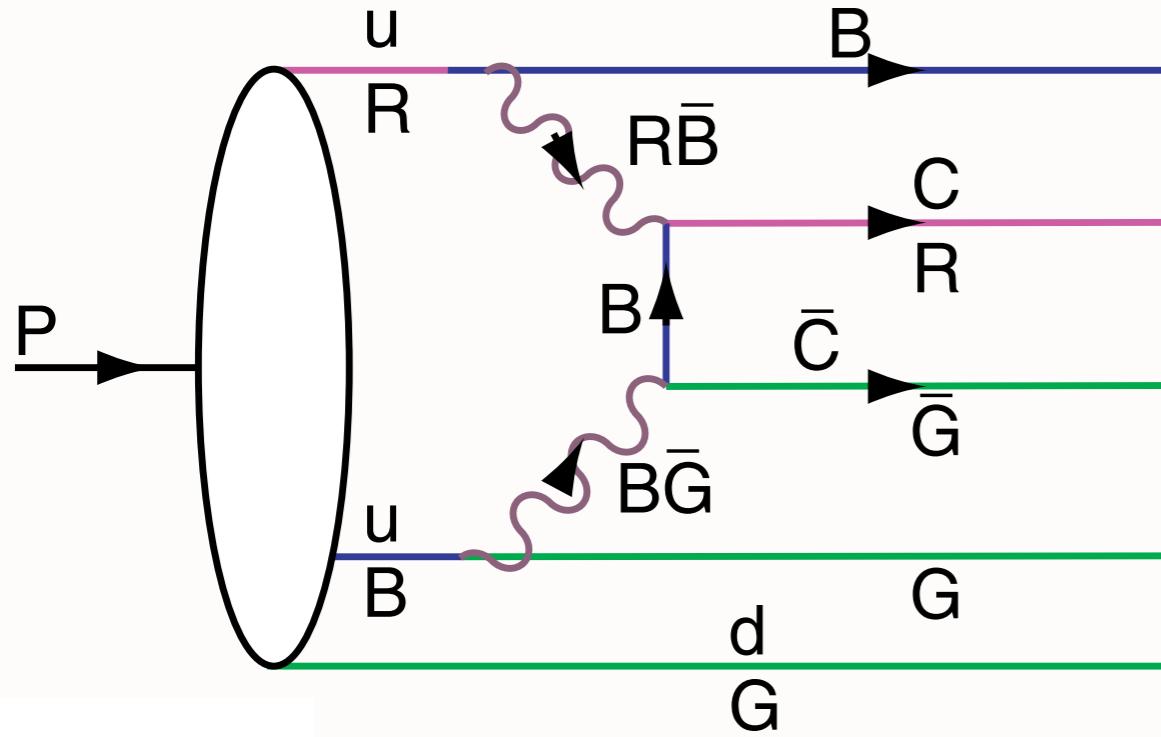
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

QCD predicts  
Intrinsic  
Heavy Quarks  
at high  $x$ !

**Minimal off-  
shellness!**

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

BHPS: Hoyer, Peterson, Sakai, sjb



$$\langle p | \frac{G_{\mu\nu}^3}{m_Q^2} | p \rangle \text{ vs. } \langle p | \frac{F_{\mu\nu}^4}{m_\ell^4} | p \rangle$$

$|uudcc\bar{c}\rangle$  Fluctuation in Proton

QCD: Probability  $\sim \frac{\Lambda_{QCD}^2}{M_Q^2}$

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

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

OPE derivation - M.Polyakov et al.

$c\bar{c}$  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!*

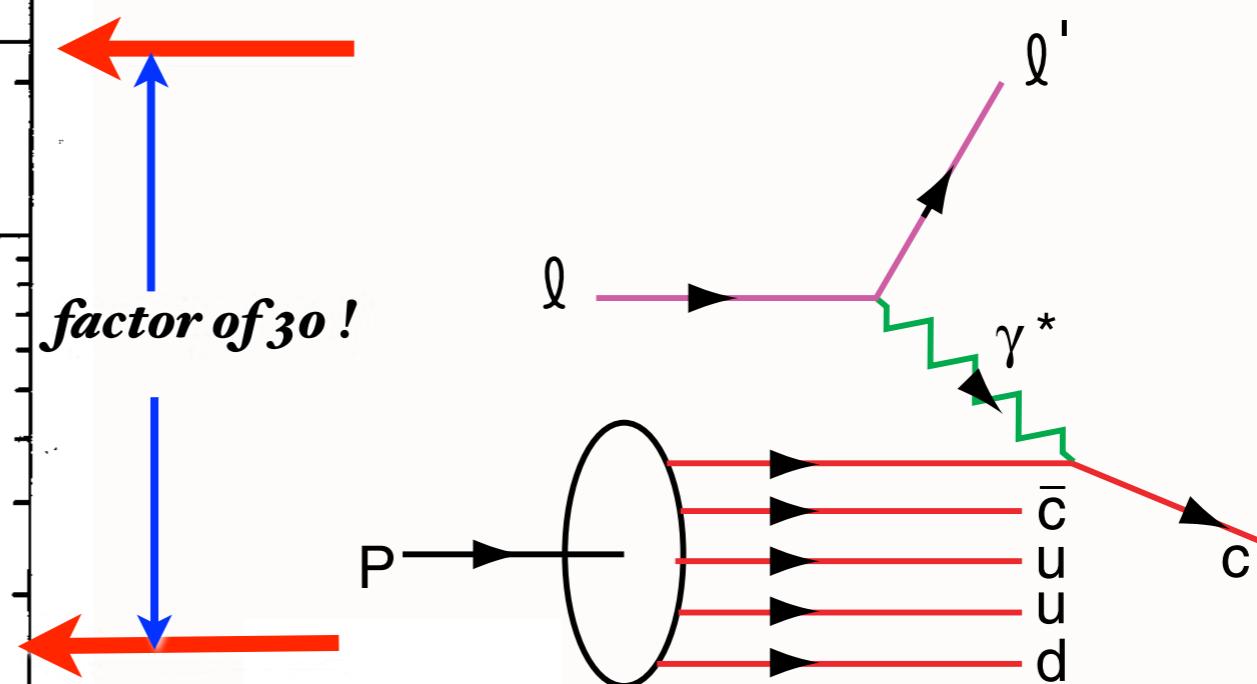
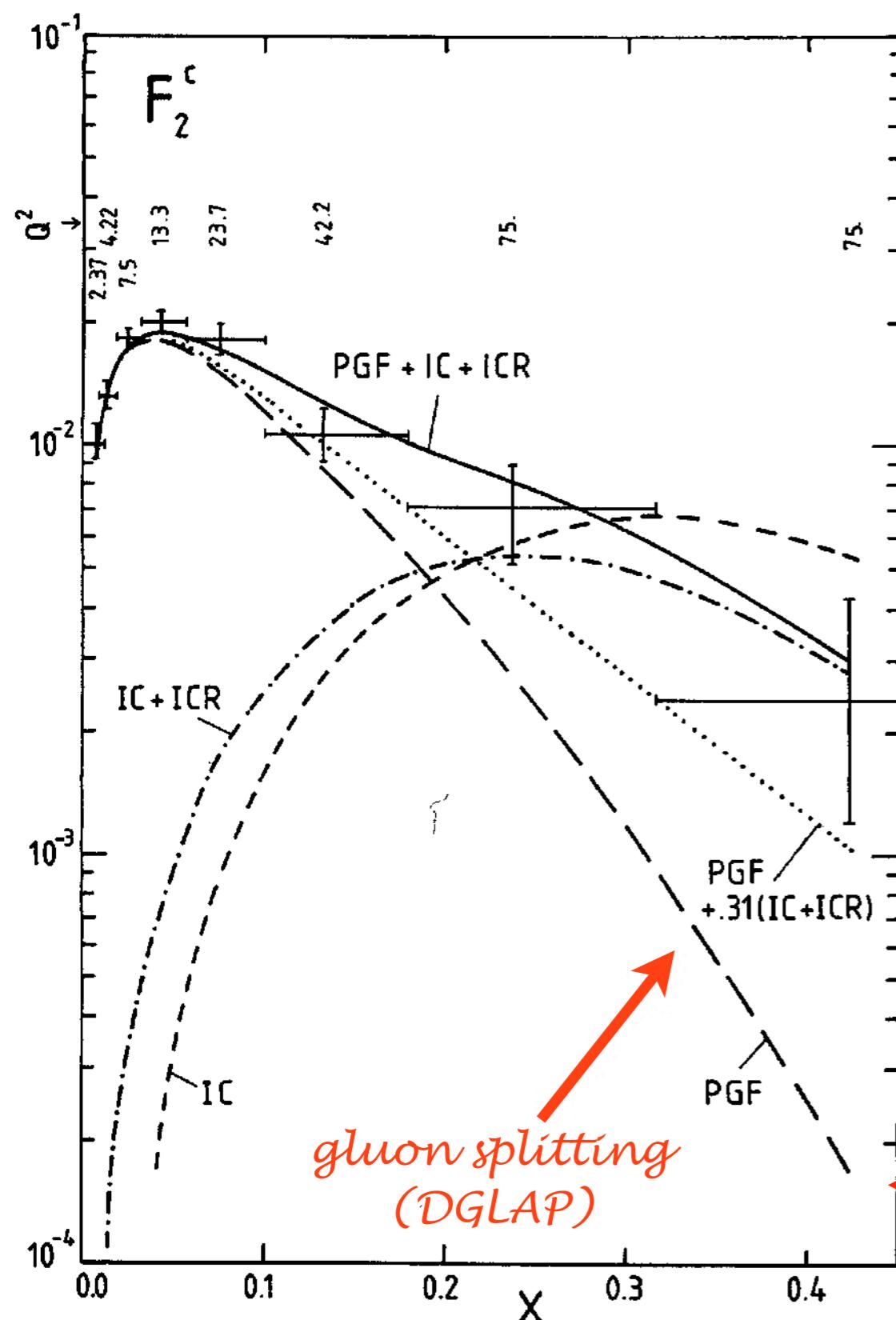
*Charm at Threshold*

**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



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

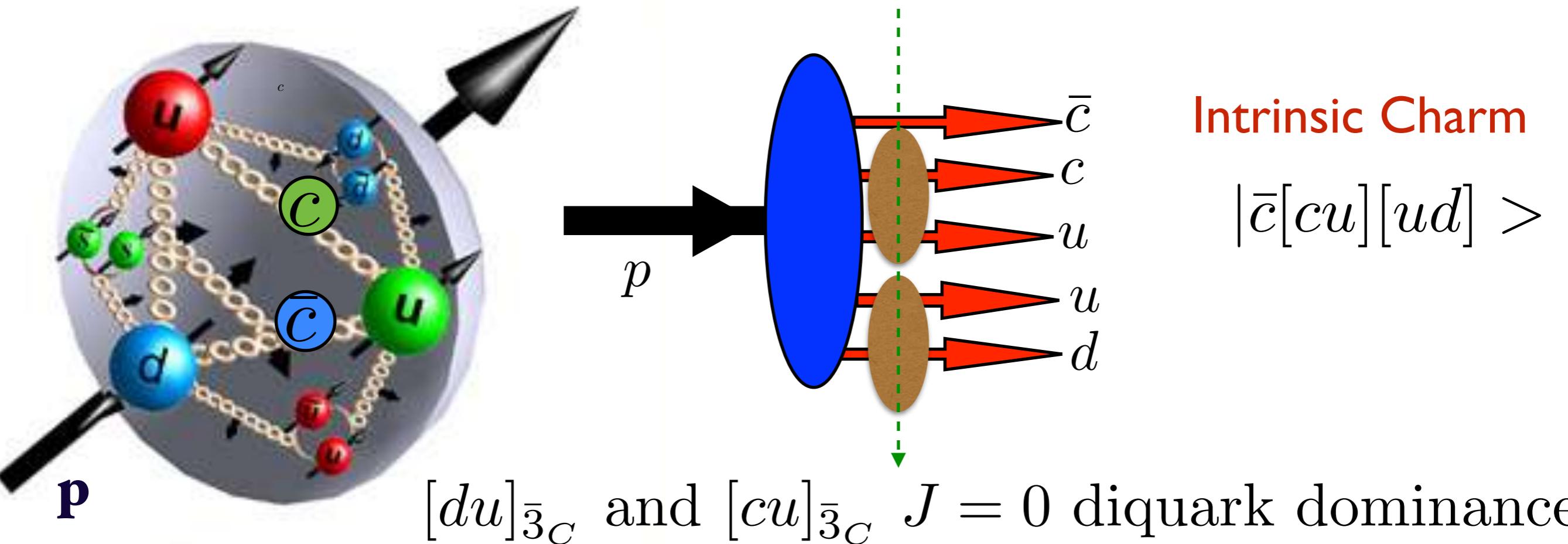
Two Components (separate evolution):

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

# Color confinement potential from AdS/QCD

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

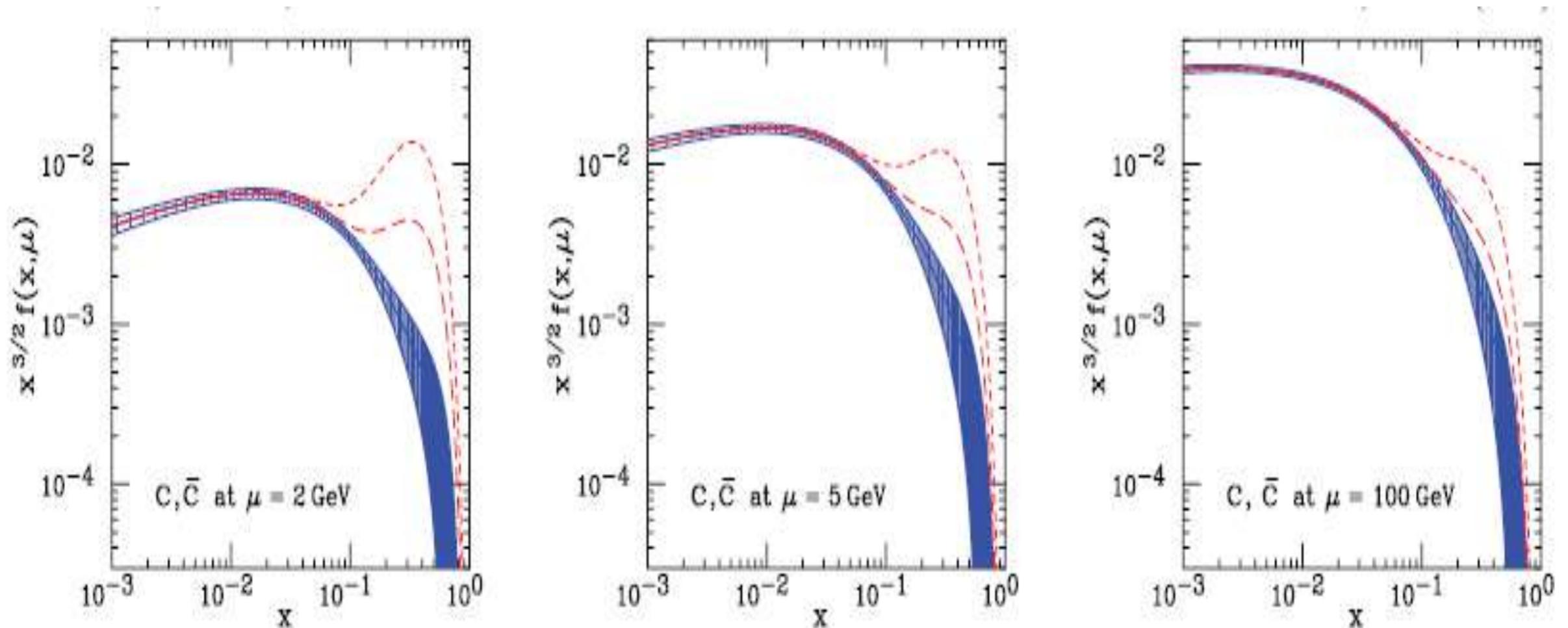
Fixed  $\tau = t + z/c$



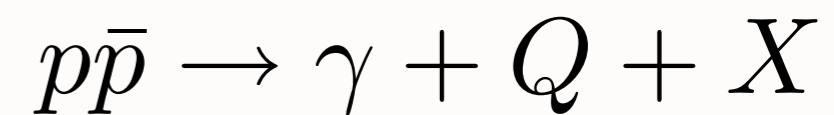
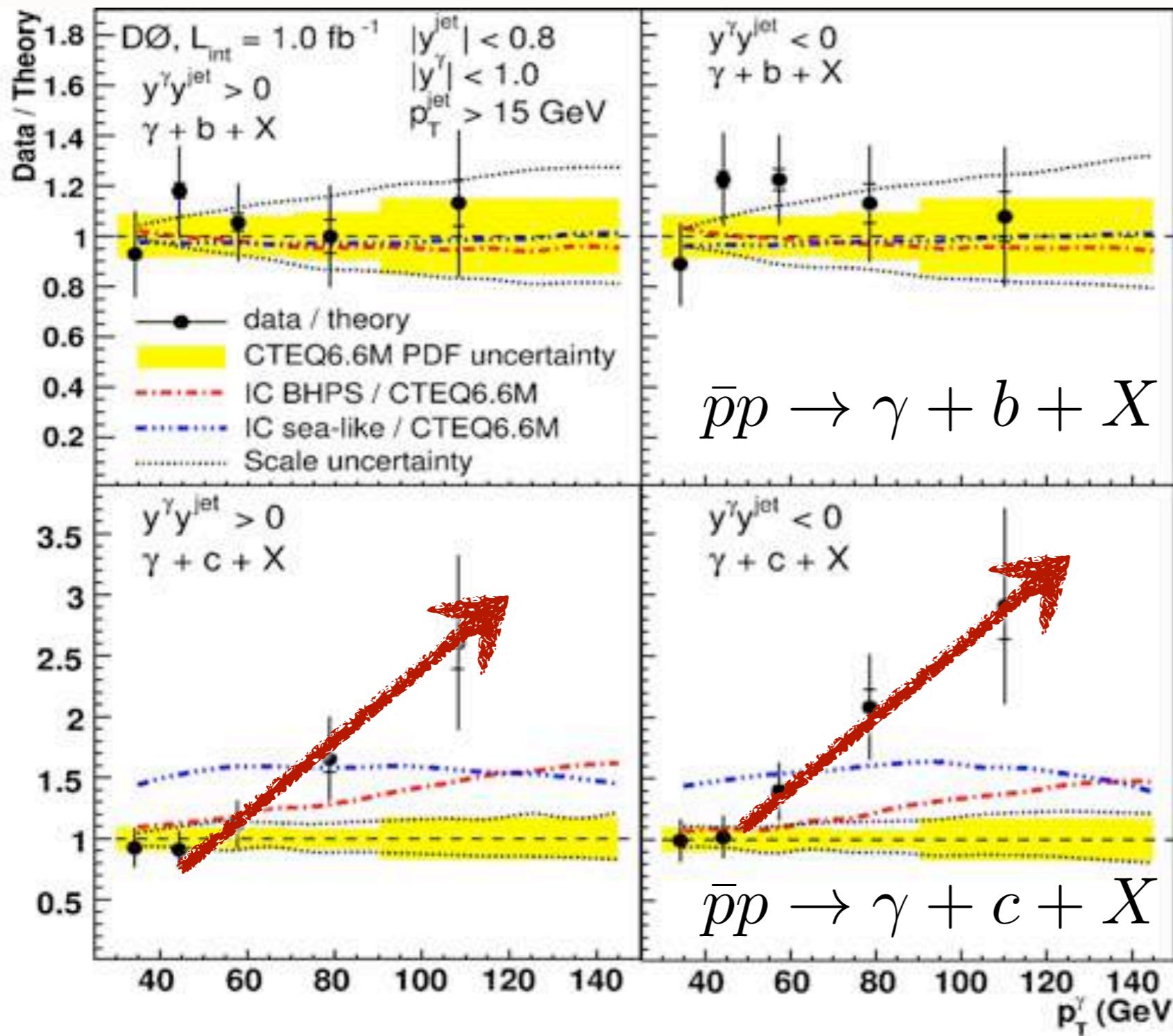
$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}} e^{-\mathcal{M}_n^2/2\kappa^2} \prod_{j=1}^n \frac{1}{\sqrt{x_j}}$$

$$\mathcal{M}_n^2 = \sum_{i=1}^n \left( \frac{k_{\perp}^2 + m^2}{x} \right)_i$$

## CHARM QUARK DISTRIBUTIONS IN PROTON



Charm quark distributions within the BHPS model.

**D0**
**Measurement of  $\gamma + b + X$  and  $\gamma + c + X$  Production Cross Sections  
in  $p\bar{p}$  Collisions at  $\sqrt{s} = 1.96$  TeV**


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

**Ratio is insensitive  
to gluon PDF,  
scales**

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

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

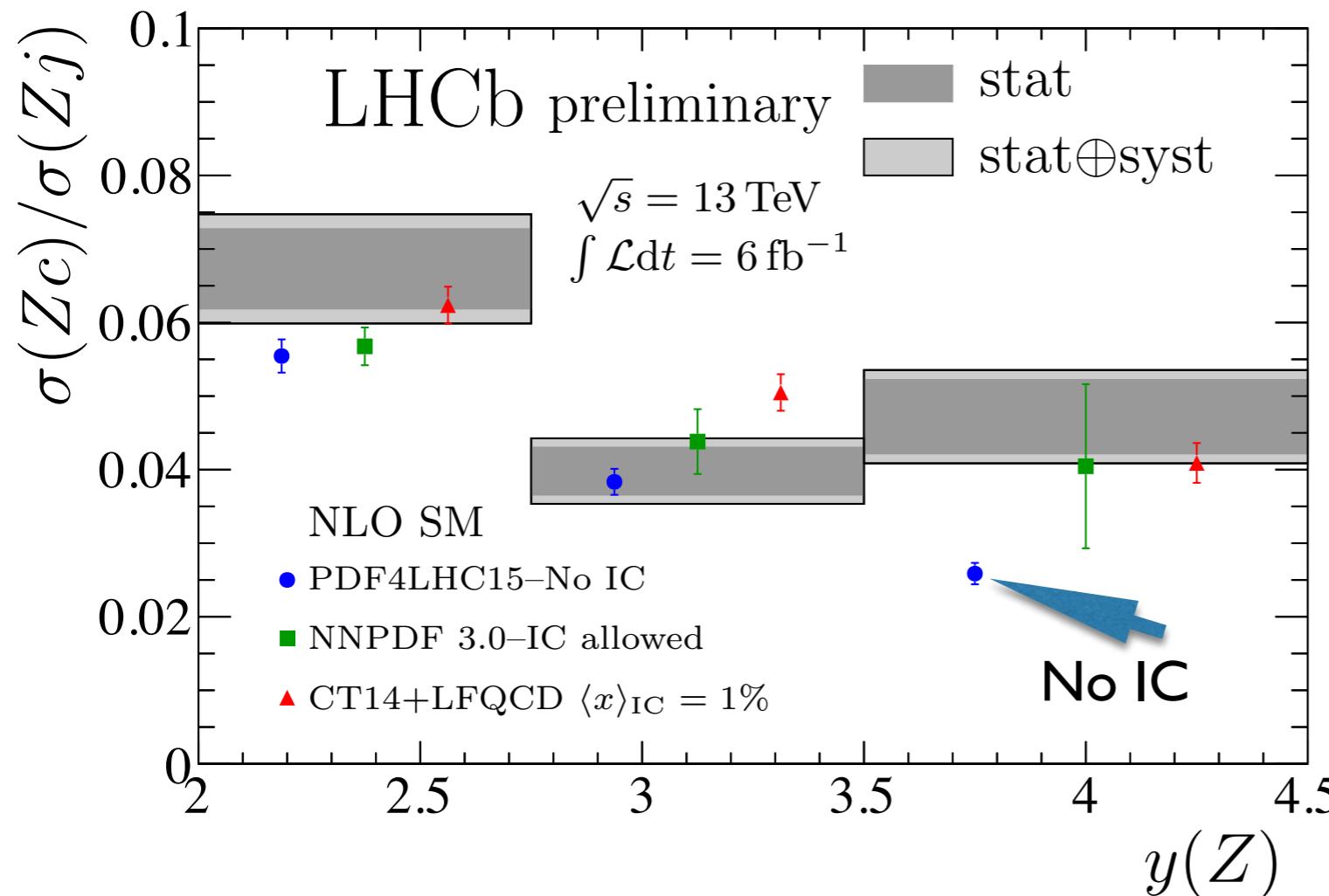
$$pp \rightarrow Z + c + X$$

$$g + c \rightarrow Z + c$$

## $Z + c$ : results

LHCb  
THCP

LHCb-PAPER-2021-029



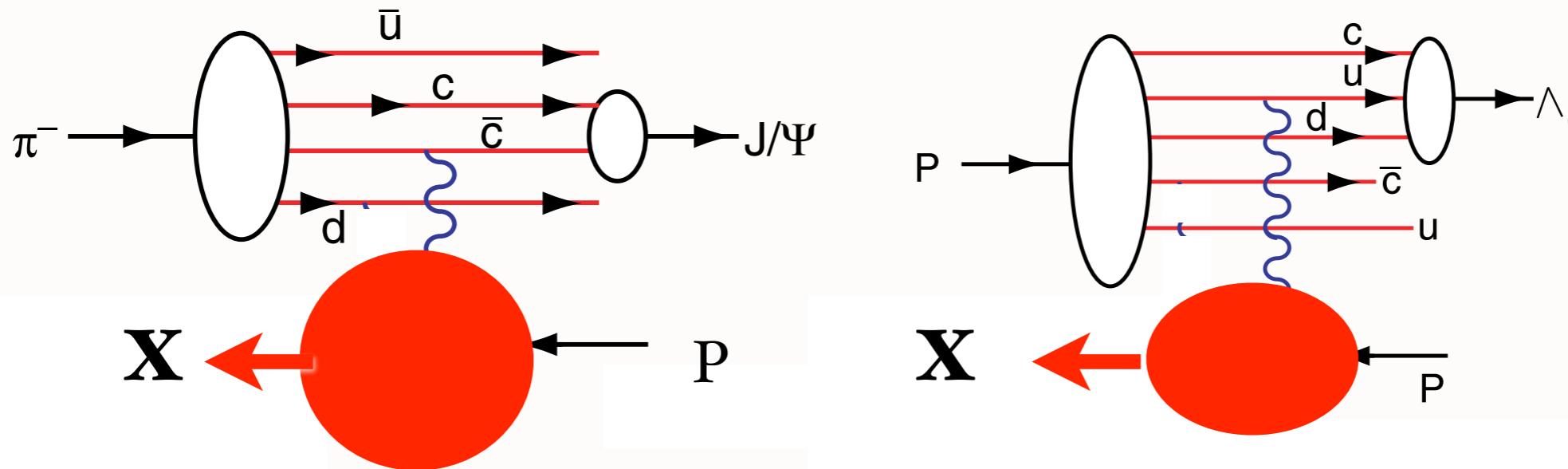
- ▶ Clear enhancement in highest- $y$  bin
- ▶ Consistent with expected effect from  $|uudcc\bar{c}\rangle$  component predicted by LFQCD
- ▶ Inconsistent with No-IC theory at  $\sim 3$  standard deviations
- ▶ Global PDF analysis required to determine true significance

QCD physics measurements at the LHCb experiment  
BOOST 2021

Daniel Craik  
on behalf of the LHCb collaboration

LHCb  
THCP

# Leading Hadron Production from Intrinsic Charm



Coalescence of Comoving Charm and Valence Quarks  
Produce  $J/\Psi$ ,  $\Lambda_c$  and other Charm Hadrons at High  $x_F$

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

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

**CERN NA<sub>3</sub>**

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

- High  $x_F$   $pp \rightarrow \Lambda_c X$

**ISR**

- High  $x_F$   $pp \rightarrow \Lambda_b X$

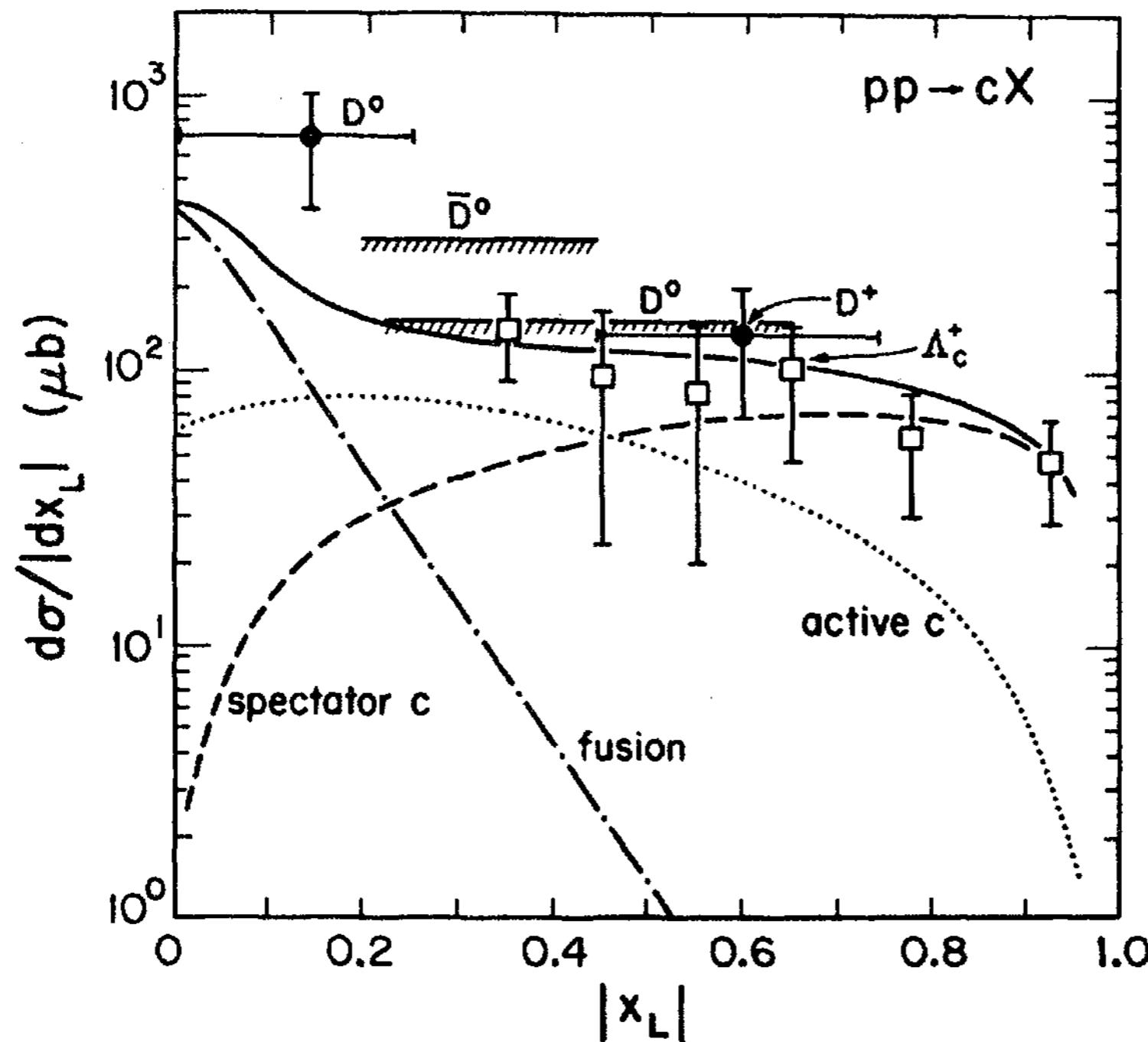
**Intrinsic Bottom!  
Zichichi, Cifarelli, et al.**

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

**FermiLab**

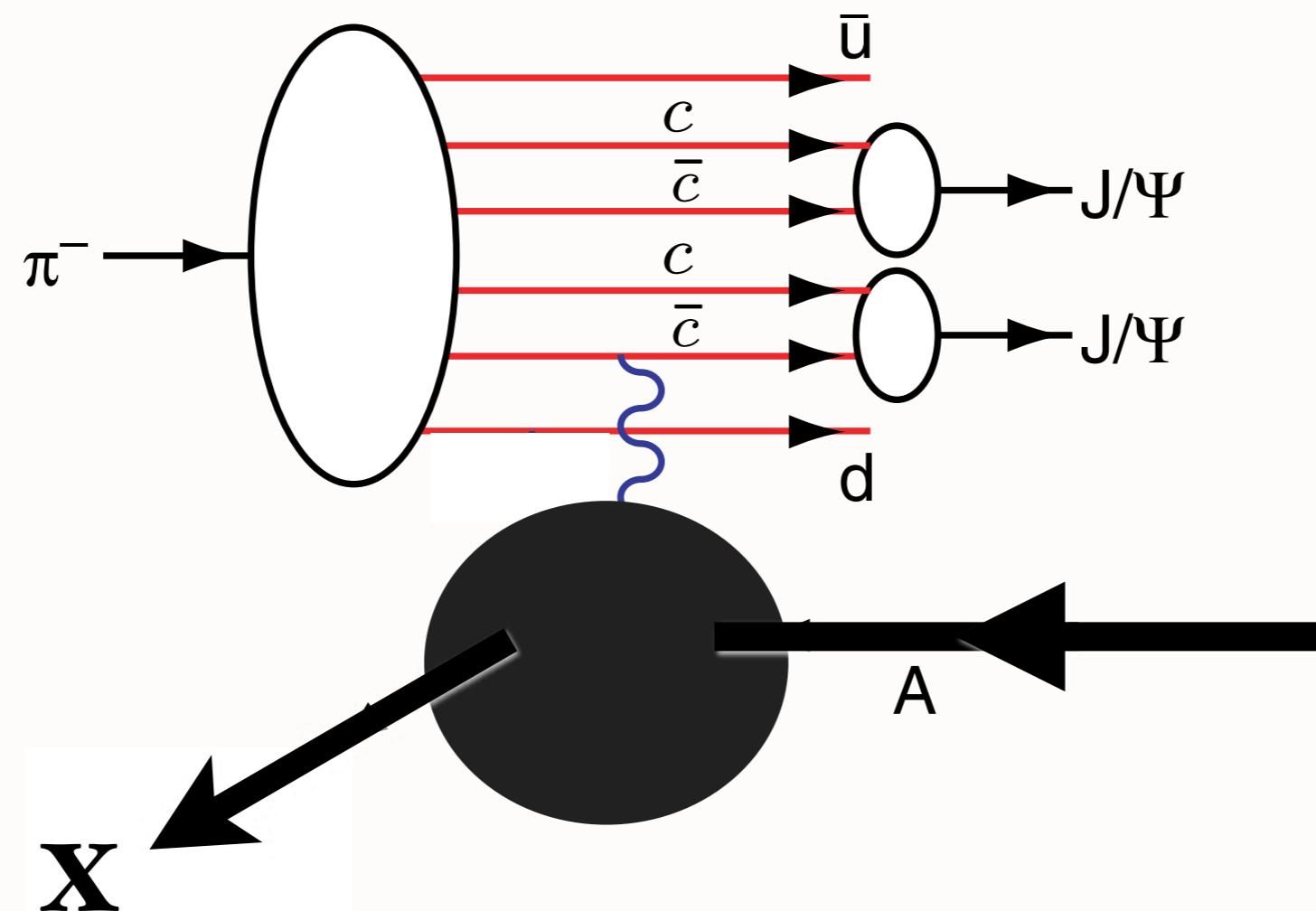
**IC Structure Function: Critical Measurement for EIC**

**Many interesting spin, charge asymmetry, spectator effects**

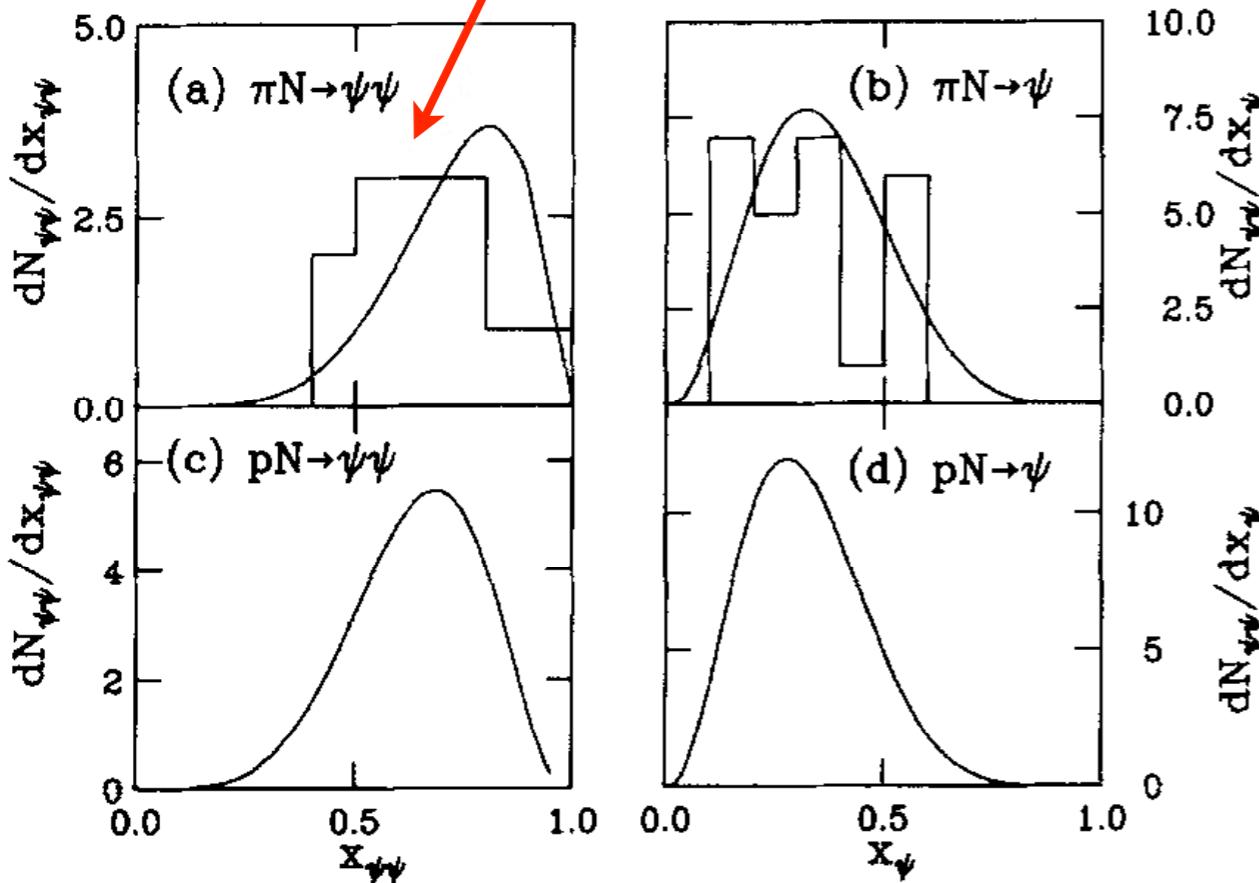


Barger, Halzen, Keung

# Production of Two Charmonia at High $x_F$



All events have  $x_{\psi\psi}^F > 0.4$  !



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

NA3 Data

# Double $J/\psi$ Production

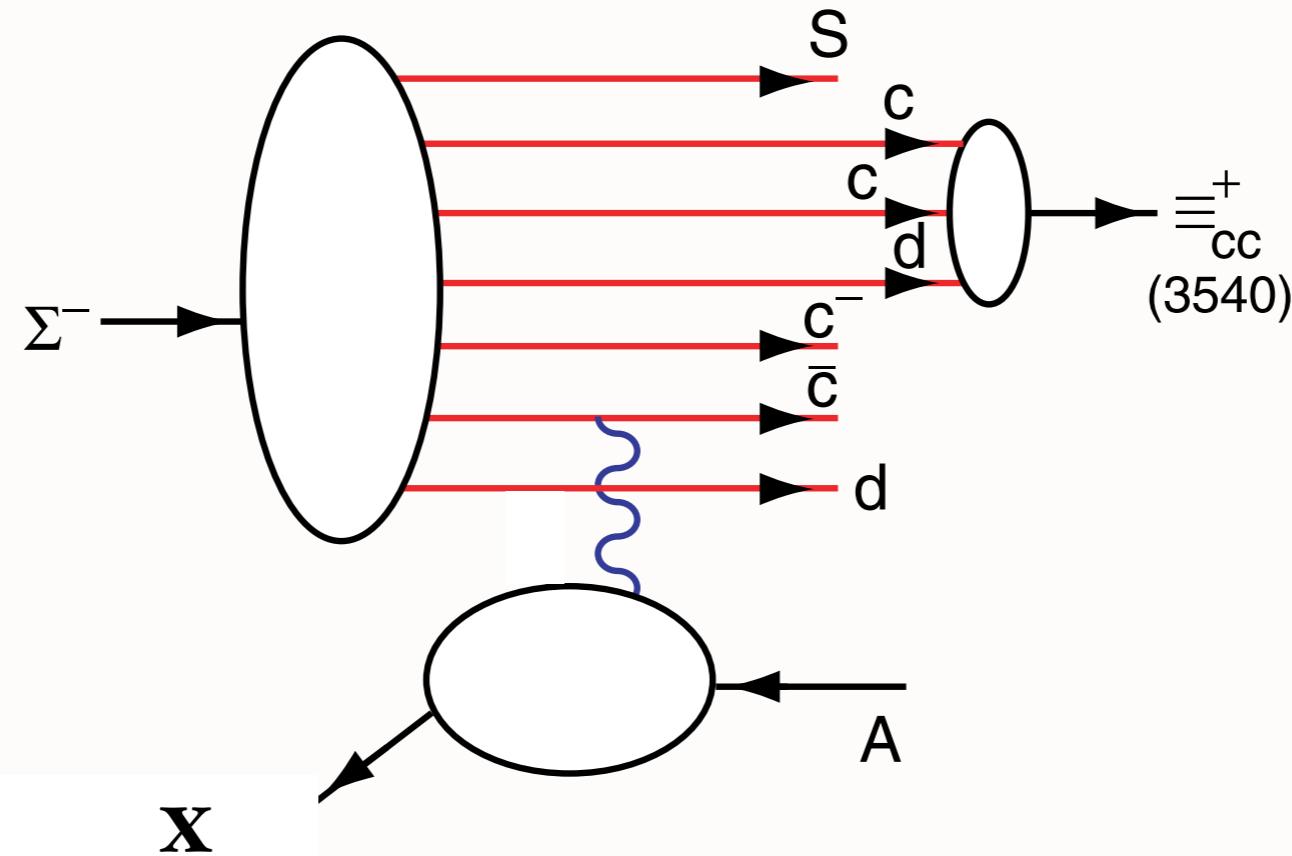


R. Vogt, sjb

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

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

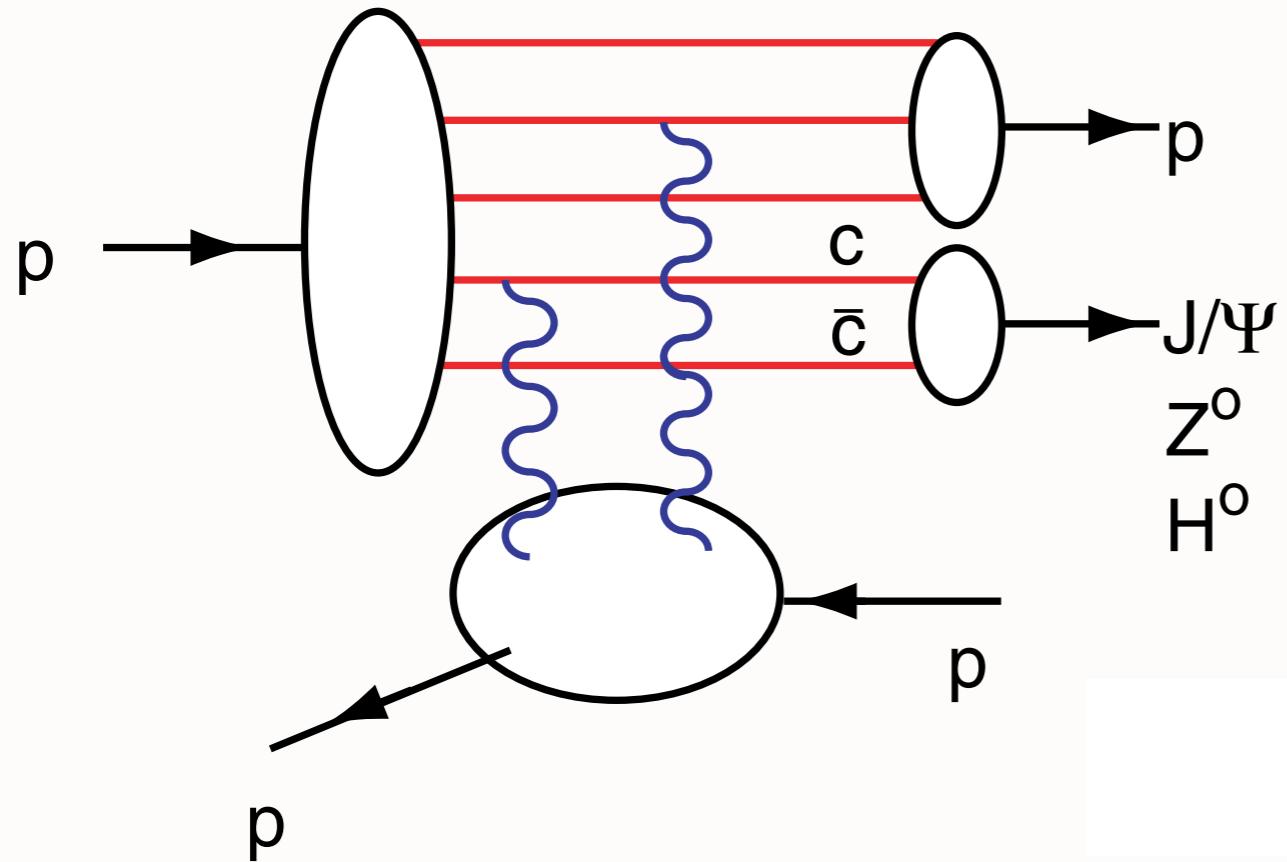
**Excludes PYTHIA  
'color drag' model**



*Production of a Double-Charm Baryon*

**SELEX high  $x_F$**        $\langle x_F \rangle = 0.33$

# Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$p \ p \rightarrow J/\Psi \ p \ p$$

$$x_{J/\Psi} = x_c + x_{\bar{c}}$$

**Exclusive Diffractive High- $X_F$  Higgs Production**

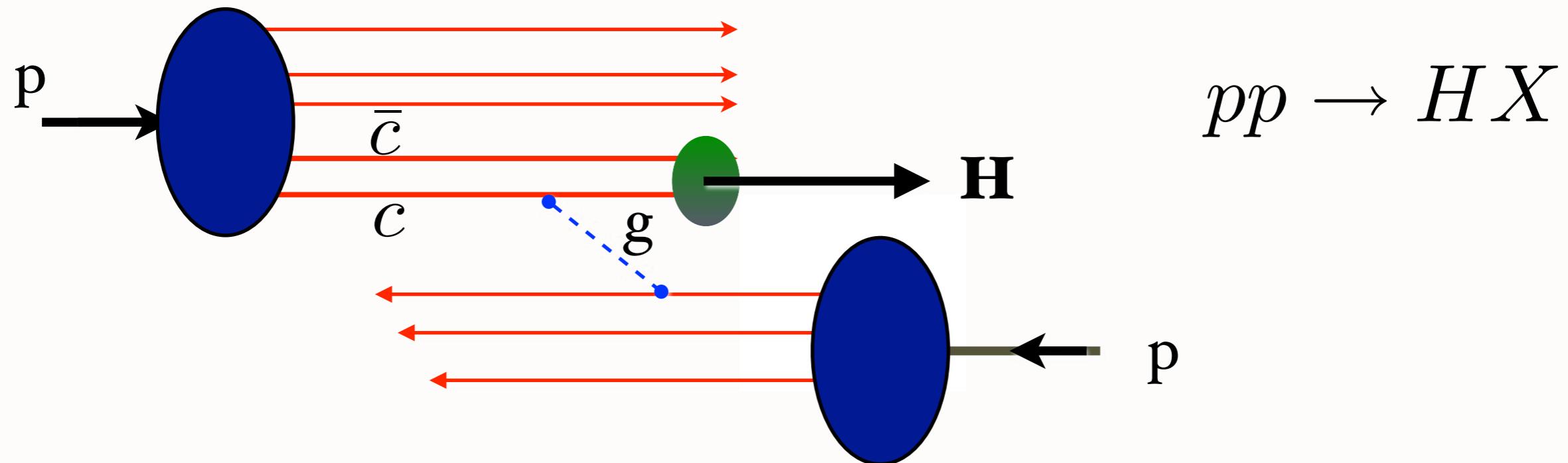
**Kopeliovitch,  
Schmidt, Soffer, sjb**

Intrinsic  $c\bar{c}$  pair formed in color octet  $8_C$  in proton wavefunction      Large Color Dipole

Collision produces color-singlet  $J/\Psi$  through color exchange

RHIC Experiment

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



Also: intrinsic bottom, top

Goldhaber, Kopeliovich,  
Schmidt, sjb

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

# Properties of Non-Perturbative Five-Quark Fock-State

- *Dominant configuration: minimum off-shell, same rapidity*

- *Heavy quarks have most of the LF momentum*

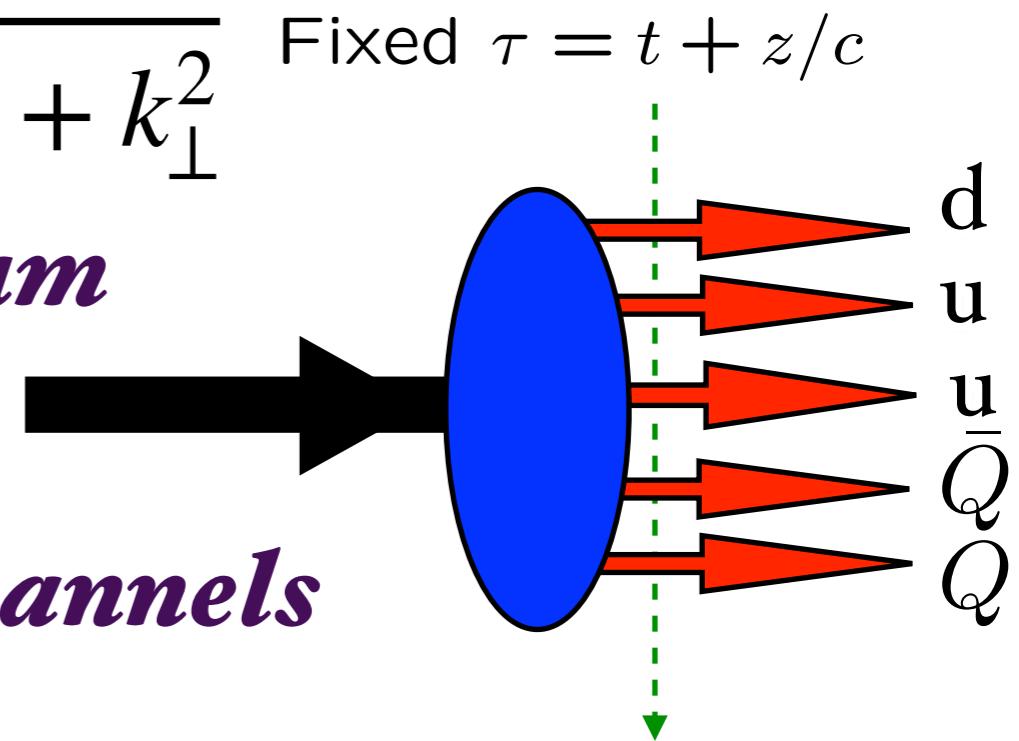
$$\langle x_Q \rangle \propto \sqrt{m_Q^2 + k_\perp^2} \quad \text{Fixed } \tau = t + z/c$$

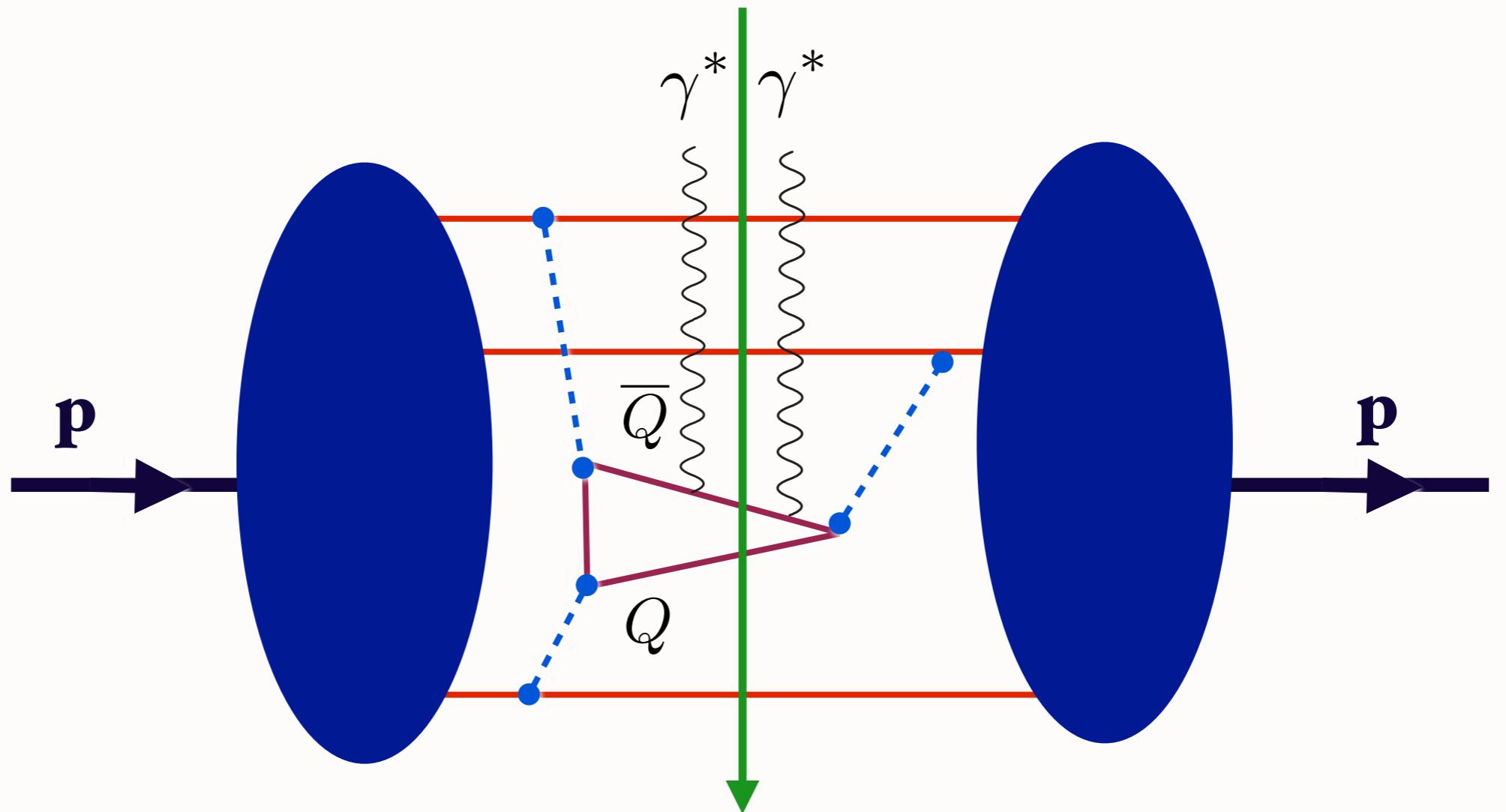
- *Correlated with proton quantum numbers*

- *Duality with meson-baryon channels*

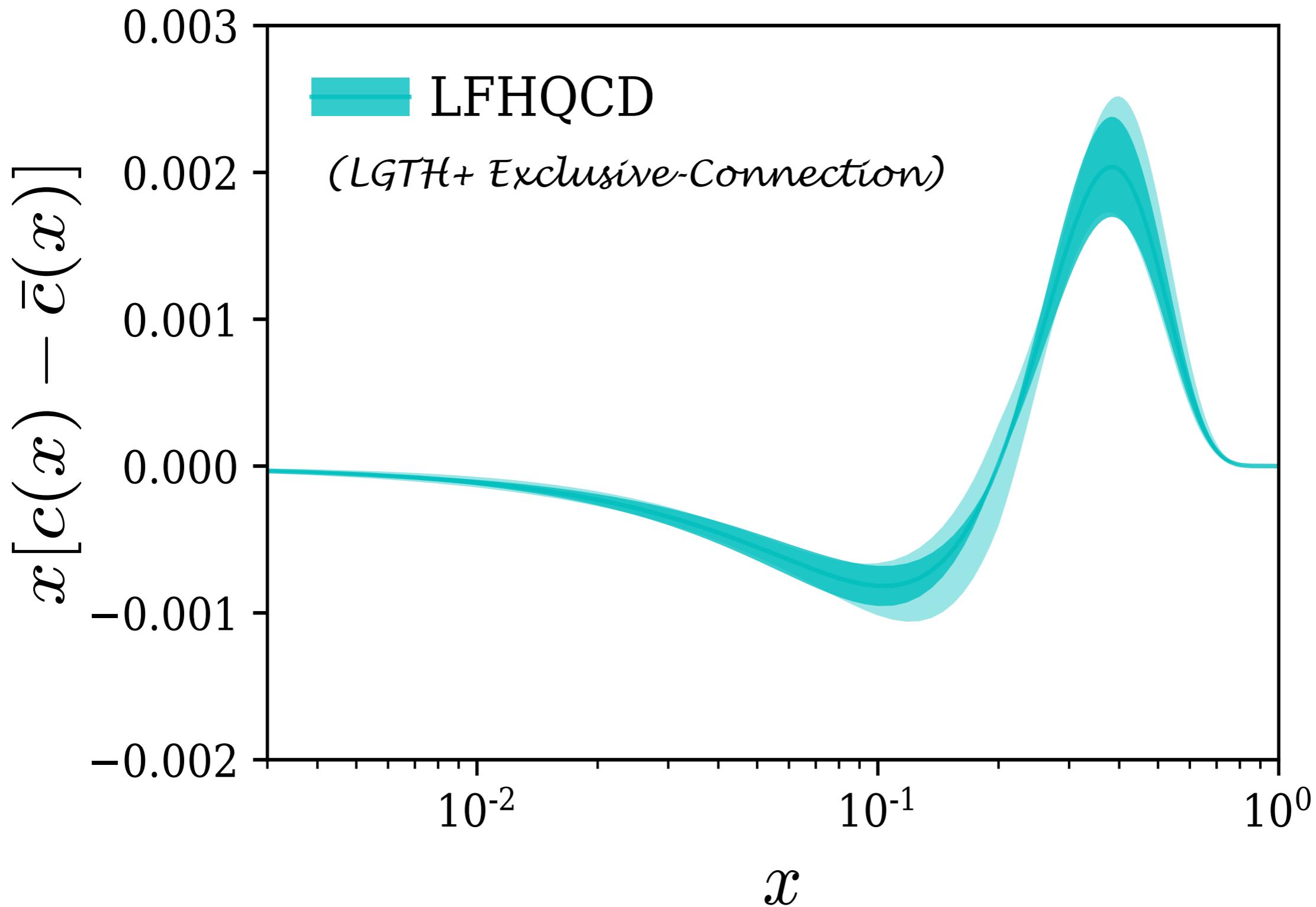
- *Strangeness, charm asymmetry at  $x > 0.1$*

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

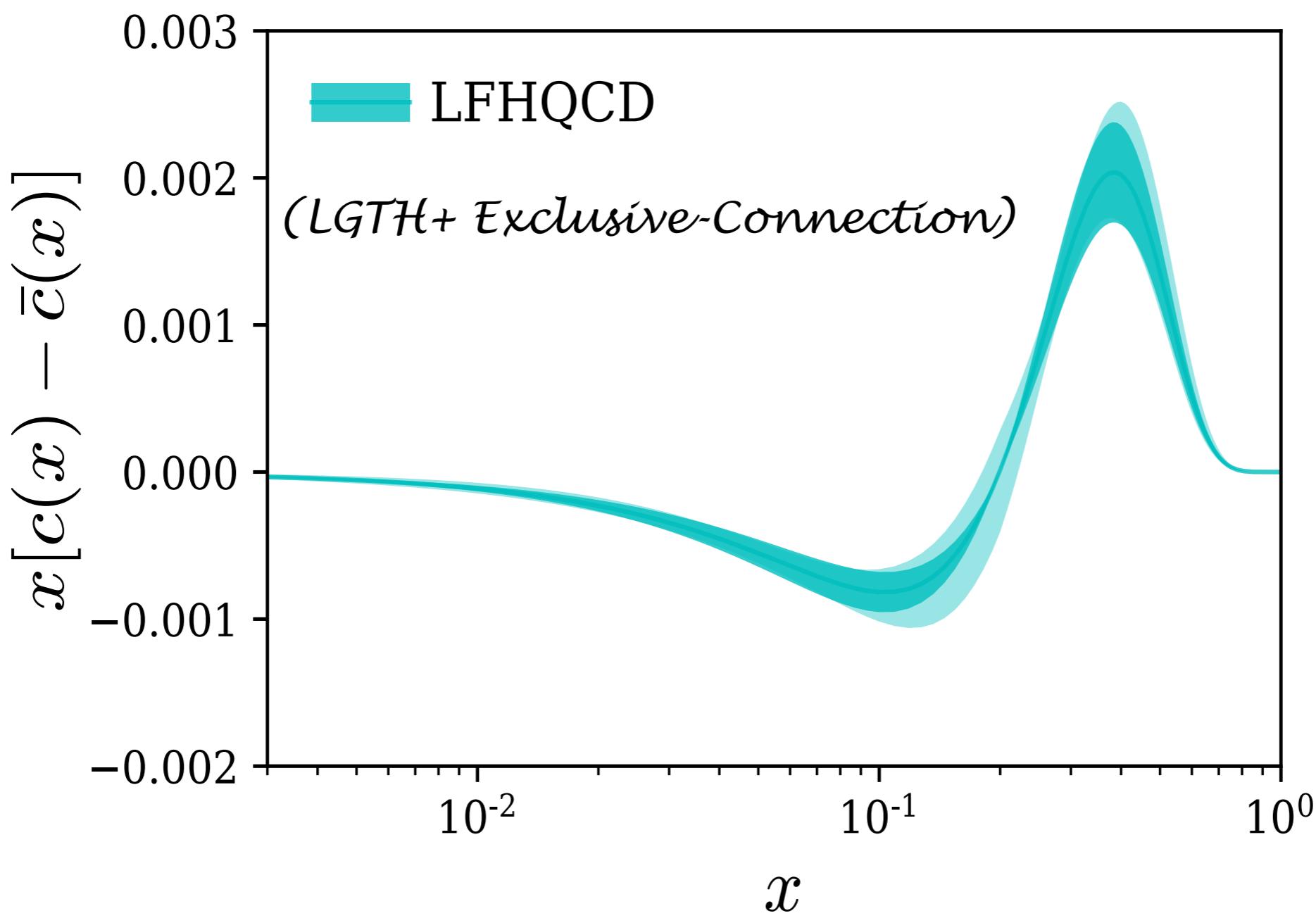




Interference predicts  $Q(x) \neq \bar{Q}(x)$   
 $\frac{d\sigma}{dy dp_T^2} (pp \rightarrow D^+ c\bar{d}X) \neq \frac{d\sigma}{dy dp_T^2} (pp \rightarrow D^- \bar{c}dX)$



The distribution function  $x[c(x) - \bar{c}(x)]$  obtained from the LFHQCD formalism using the lattice QCD input of charm electromagnetic form factors  $G_{E,M}^c(Q^2)$ . 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  $\kappa_c$  by 5%.



Predict charm hadron asymmetries

$$\frac{d\sigma}{dx_F dp_T^2} (pp \rightarrow D^+(c\bar{d})X) >$$

$$\frac{d\sigma}{dx_F dp_T^2} (pp \rightarrow D^-(\bar{c}d)X)$$

at high  $p_T$  and high  $x_F$

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

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

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<sup>d</sup>*SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA*

<sup>e</sup>*Laboratorio de Física Teórica y Computacional, Universidad de Costa Rica, 11501 San José, Costa Rica*

<sup>f</sup>*Institut für Theoretische Physik der Universität, D-69120 Heidelberg, Germany*

<sup>g</sup>*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506, USA*

<sup>h</sup>*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

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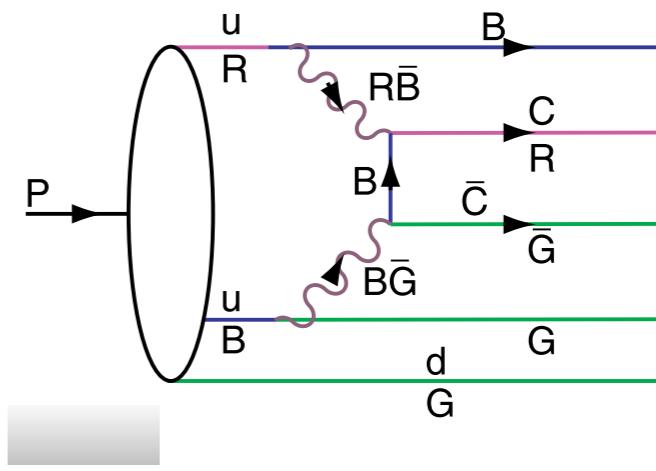
## Abstract

We present the first lattice QCD calculation of the charm quark contribution to the nucleon electromagnetic form factors  $G_{E,M}^c(Q^2)$  in the momentum transfer range  $0 \leq Q^2 \leq 1.4 \text{ GeV}^2$ . 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  $\mu_M^c = -0.00127(38)_{\text{stat}}(5)_{\text{sys}}$ , as well as the Pauli form factor, reflects a nontrivial role of the charm sea in the nucleon spin structure. The nonzero  $G_E^c(Q^2)$  indicates the existence of a nonvanishing asymmetric charm-anticharm sea in the nucleon. Performing a non-perturbative 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

# 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

# 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*

$M^2$  (GeV $^2$ )

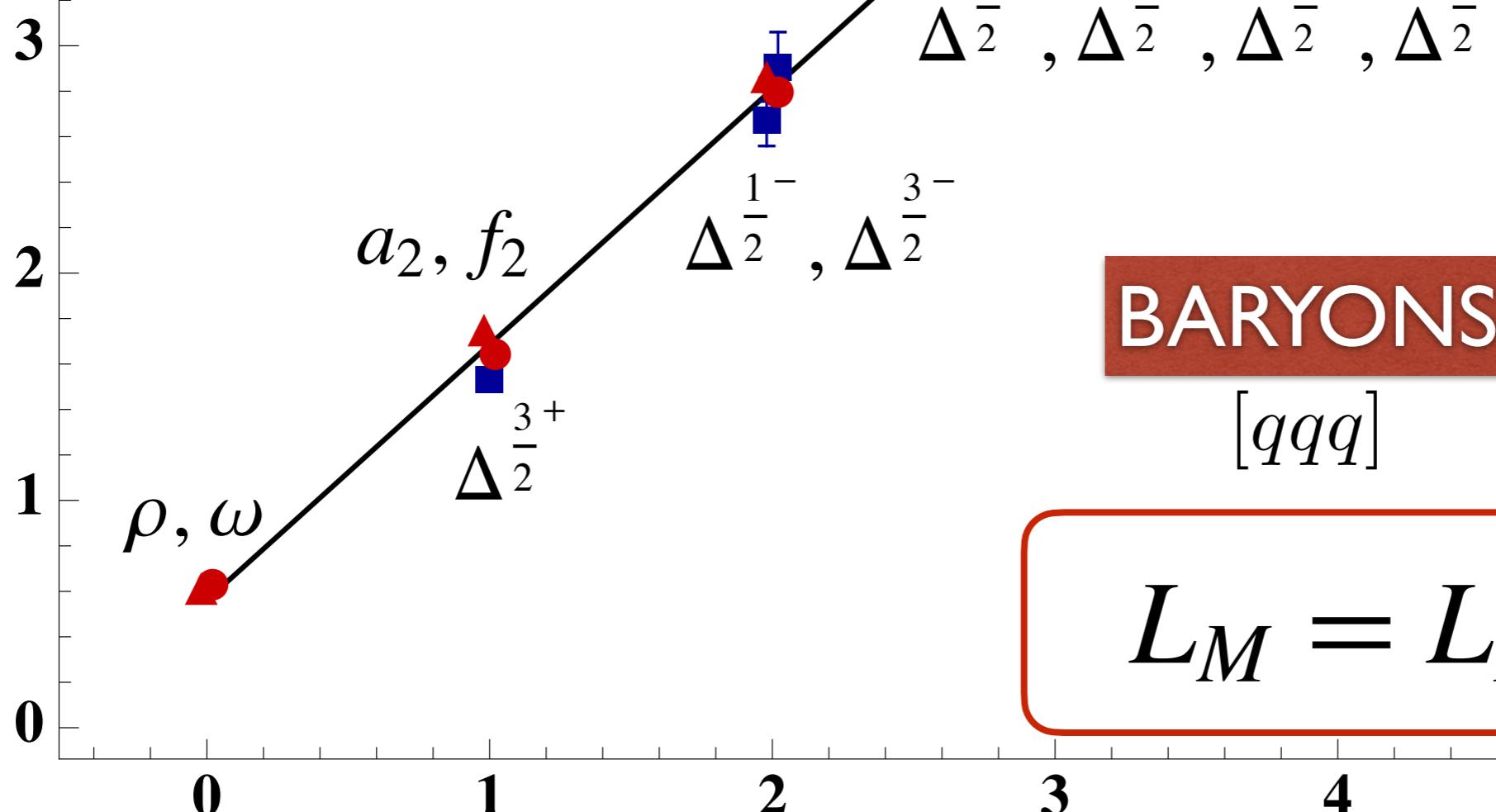
$\rho - \Delta$  superpartner trajectories

**MESONS**  
[ $q\bar{q}$ ]

bosons

fermions

**Supersymmetric  
QCD Spectroscopy**



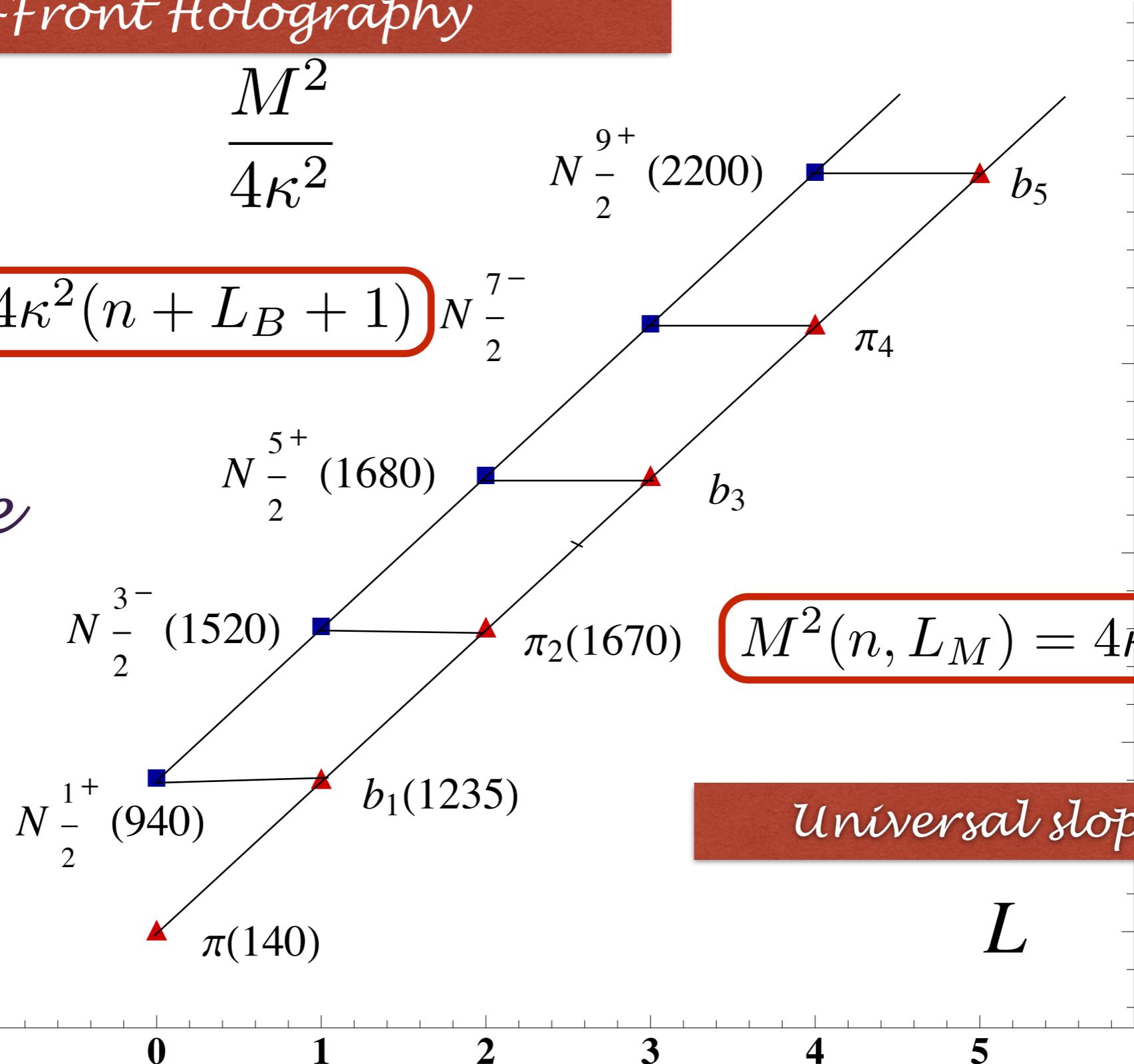
# Superconformal Quantum Mechanics Light-Front Holography

*de Téramond, Dosch, Lorcé, sjb*

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

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

Same slope



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

Universal slopes in  $n, L$

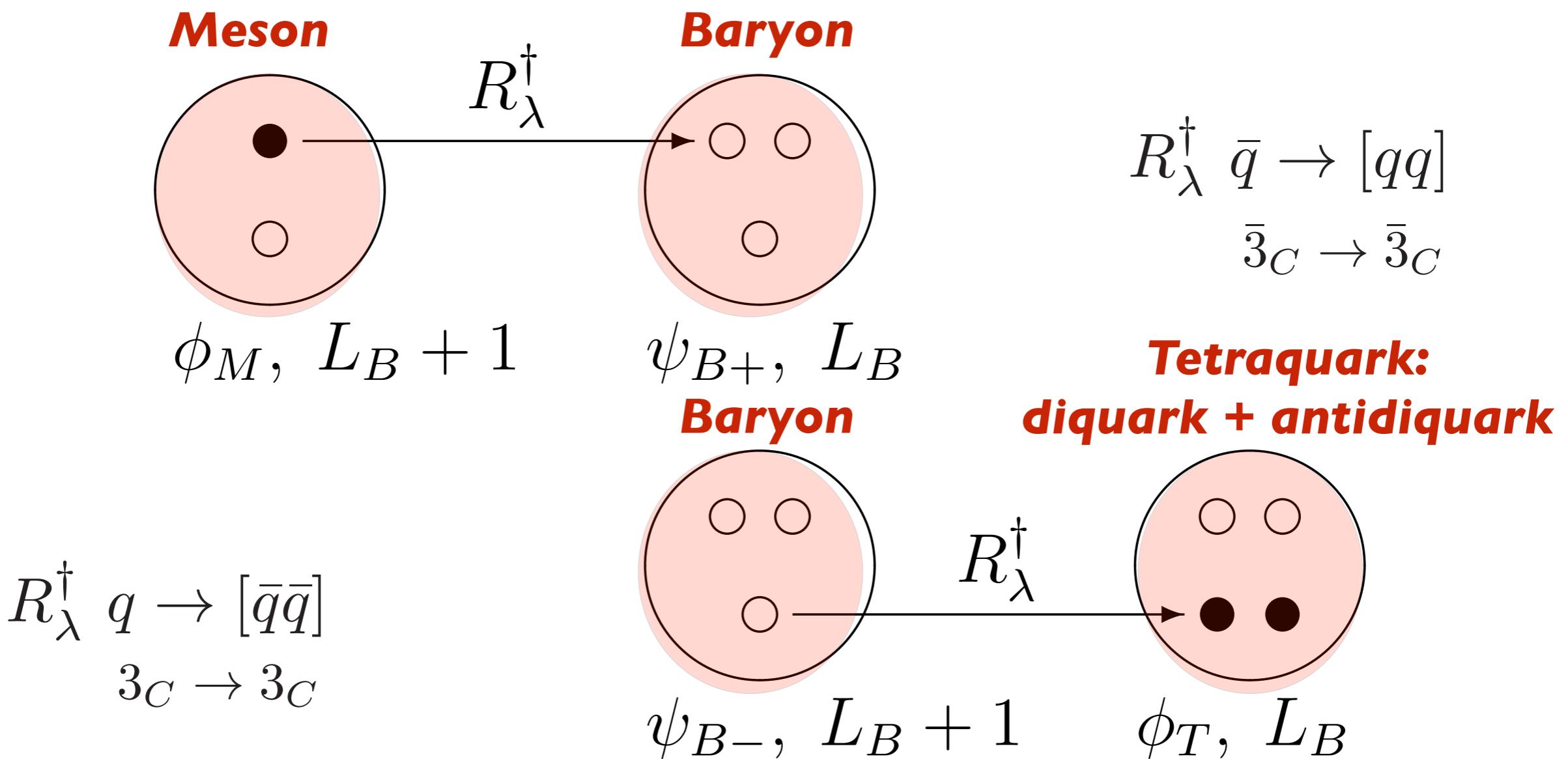
$$\frac{M_{meson}^2}{M_{nucleon}^2} = \frac{n + L_M}{n + L_B + 1}$$

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

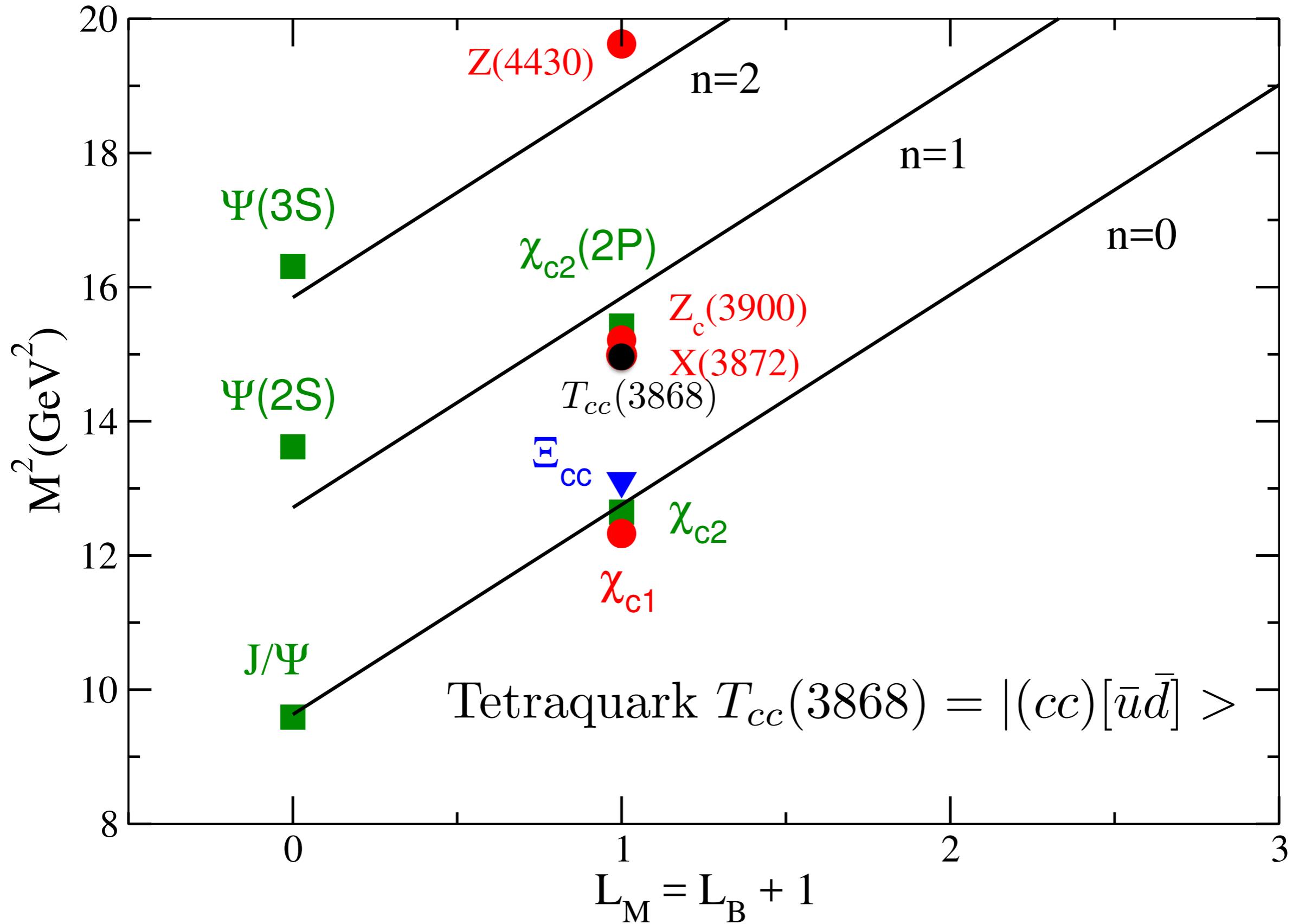
# Superconformal Algebra

## Four-Plet Representations

Bosons, Fermions with Equal Mass!

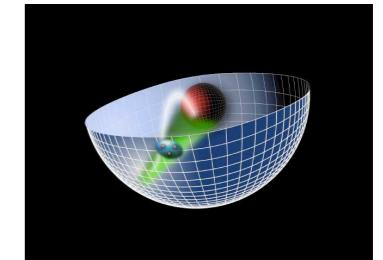


Proton: |u[ud]> Quark + Scalar Diquark  
Equal Weight:  $L=0, L=1$



- **Poincarè Invariance: Independent of the observer's Lorentz frame: Quantization at Fixed Light-Front Time  $T$**
- **Causality: Information within causal horizon: Light-Front**
- **Light-Front Holography:  $\text{AdS}_5 = \text{LF} (3+1)$**

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



- **Introduce Mass Scale  $\kappa$  while retaining the Conformal Invariance of the Action (dAFF)**
- **Unique Dilaton in  $\text{AdS}_5$ :  $e^{+\kappa^2 z^2}$**
- **Unique color-confining LF Potential  $U(\zeta^2) = \kappa^4 \zeta^2$**
- **Superconformal Algebra: Mass Degenerate 4-Plet:**

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

# Other Issues for Precision QCD

- Elimination of renormalization scale ambiguities  
PMC: Principle of Maximum Conformality
- Diffractive processes and violation of the OPE
- Validity of the Momentum Sum Rule
- Shadowing and Anti-Shadowing of Nuclear PDFs

## Transverse Confinement

$$\left( -\frac{d^2}{d\zeta^2} - \frac{1 - 4L^2}{4\zeta^2} + U_{\perp}(\zeta) \right) \phi(\zeta) = M_{\perp}^2 \phi(\zeta),$$

$$U_{\perp}(\zeta) = \lambda^2 \zeta^2 + 2\lambda(J-1). \quad \zeta^2 = b_{\perp}^2 x(1-x)$$

$$M_{\perp}^2(n, J, L) = 4\lambda \left( n + \frac{J+L}{2} \right),$$

and eigenfunctions

de Teramond, Dosch, sjb

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

$M_{\pi} = 0$  in chiral ( $m_q = 0$ ) limit

## Longitudinal Confinement

$$\left( \frac{m_q^2}{x} + \frac{m_{\bar{q}}^2}{1-x} + U_{||}(x) \right) \chi(x) = M_{||}^2 \chi(x)$$

$$U_{||}(x) = -\sigma^2 \partial_x (x(1-x) \partial_x)$$

Li, Maris, Zhao, Vary

$$U_{||} = \sigma^2 x(1-x) \tilde{z}^2$$

Ioffe length  $\tilde{z}$ : conjugate to LF  $x = \frac{k^+}{P^+}$

G.A. Miller, sjb

$\frac{\gamma^+ \gamma^+}{k^+{}^2}$  LF interaction in  $A^+ = 0$  gauge

de Teramond, sjb

Same potential: t' Hooft Equation QCD(1+1) $N_C \rightarrow \infty$

# Longitudinal dynamics and chiral symmetry breaking in holographic light-front QCD

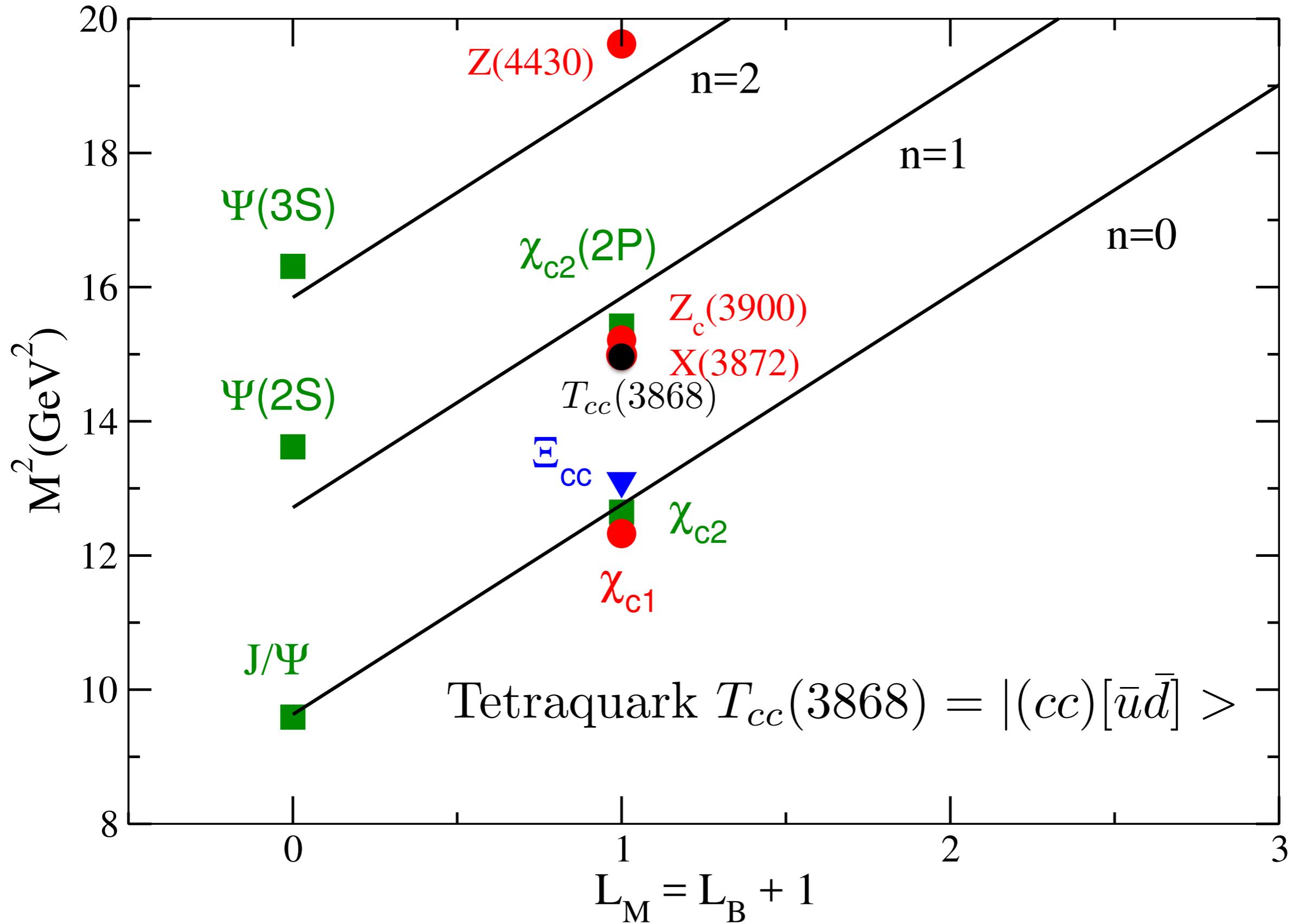
Guy F. de Téramond<sup>1,\*</sup> and Stanley J. Brodsky<sup>2,†</sup>

<sup>1</sup>*Laboratorio de Física Teórica y Computacional, Universidad de Costa Rica, 11501 San José, Costa Rica*

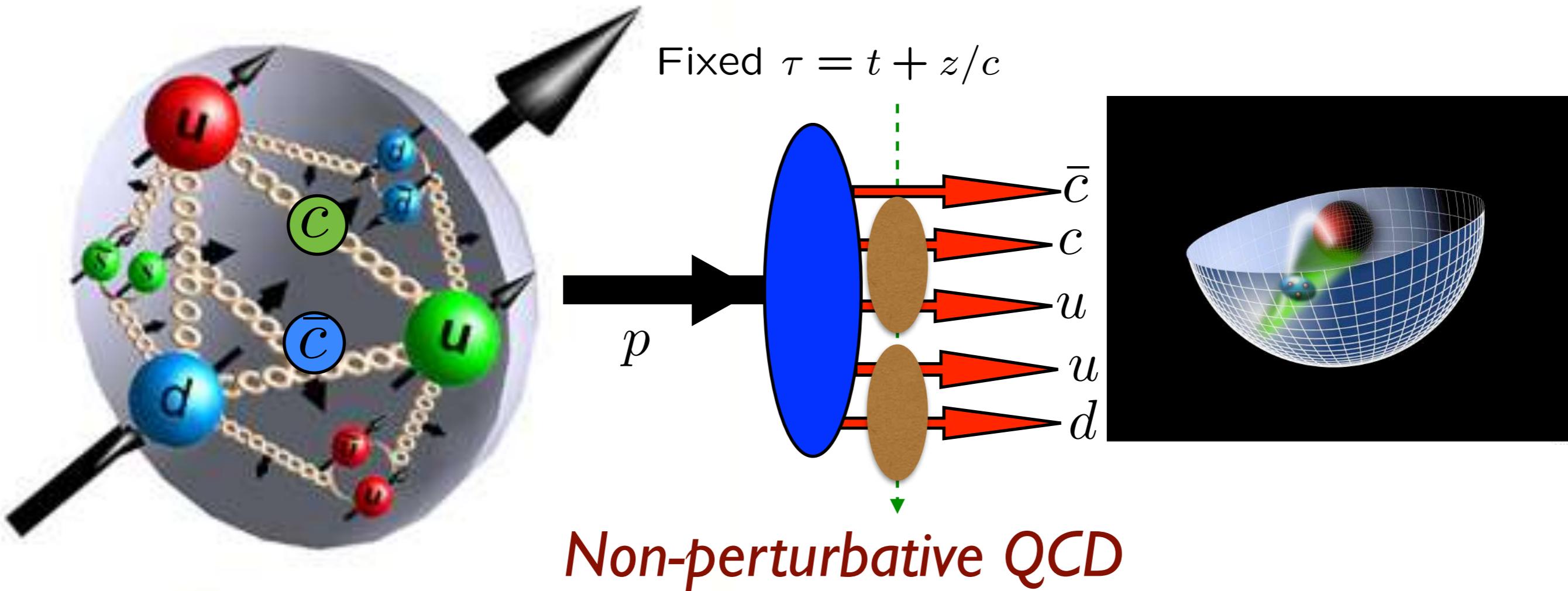
<sup>2</sup>*SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA*

(Dated: April 18, 2021)

The breaking of chiral symmetry in holographic light-front QCD is encoded in its longitudinal dynamics with its chiral limit protected by the superconformal algebraic structure which governs its transverse dynamics. The scale in the longitudinal light-front Hamiltonian determines the confinement strength in this direction: It is also responsible for most of the light meson ground state mass consistent with the Gell-Mann-Oakes-Renner constraint. Longitudinal confinement and the breaking of chiral symmetry are found to be different manifestations of the same underlying dynamics like in 't Hooft large  $N_C$  QCD(1 + 1) model.



# Light Front Holography, Intrinsic Charm, and Tetraquarks



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

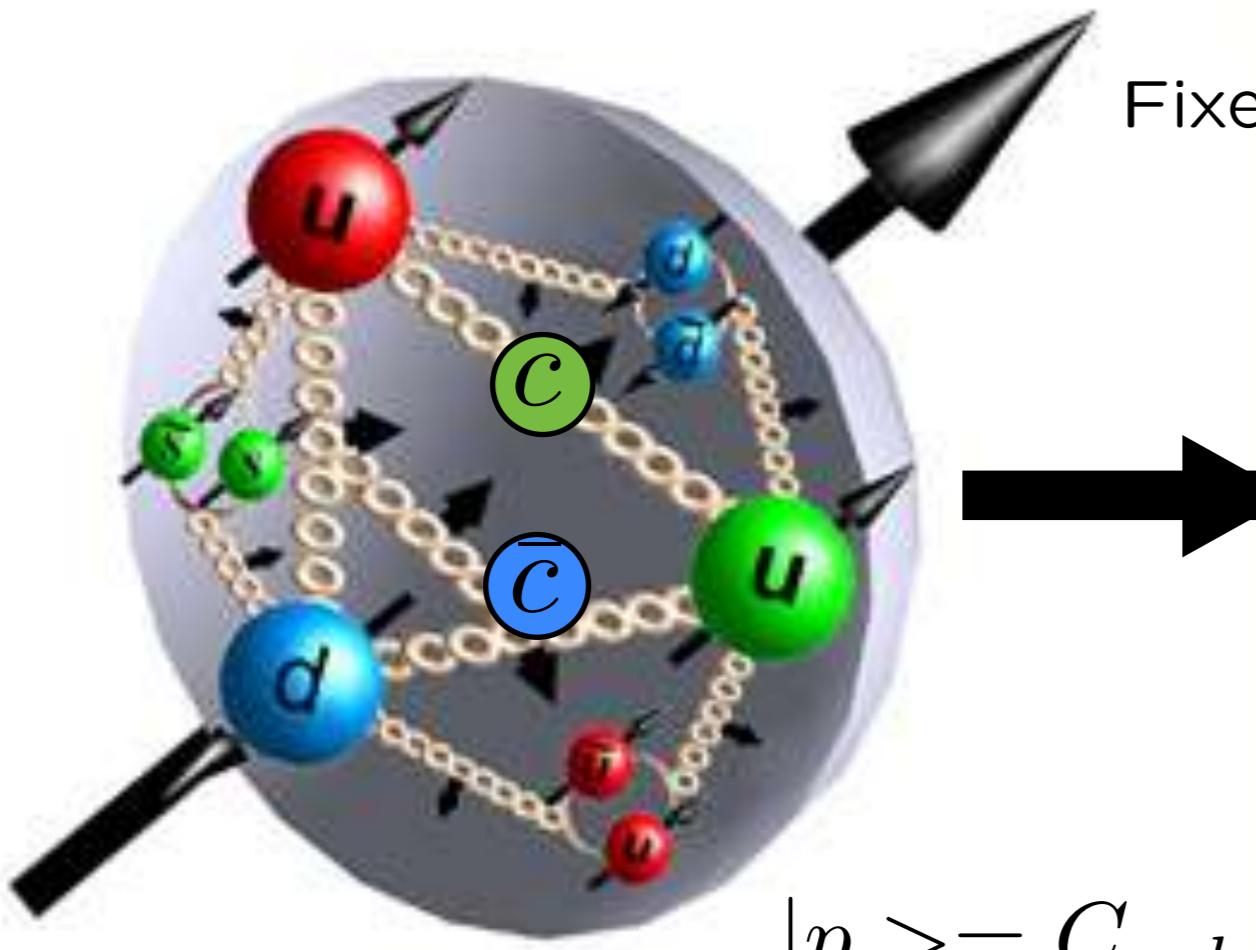
Implications of LHCb measurements and future prospects

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

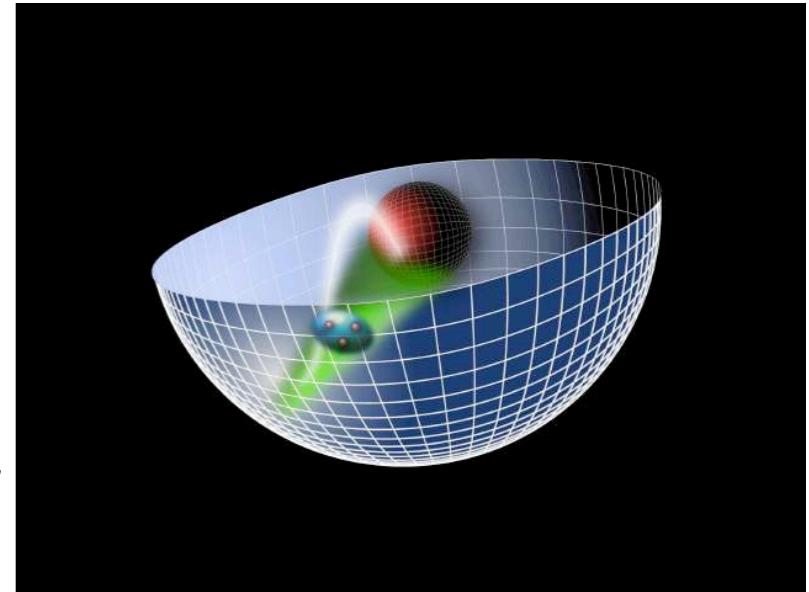
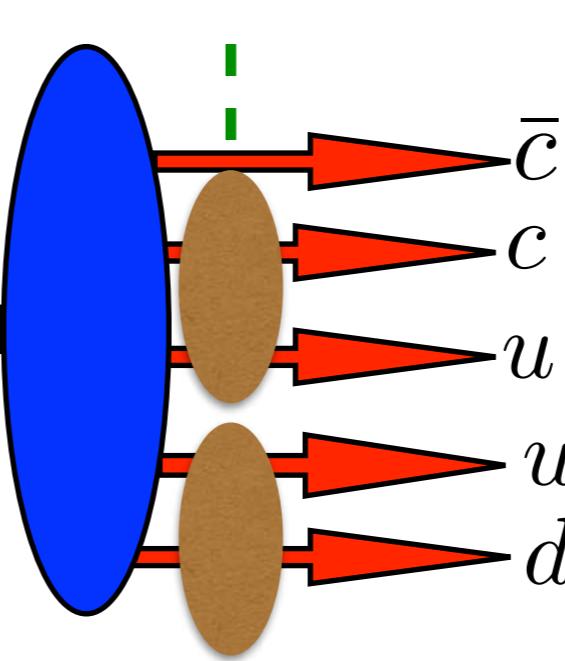
$$c(x) \neq \bar{c}(x)$$

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

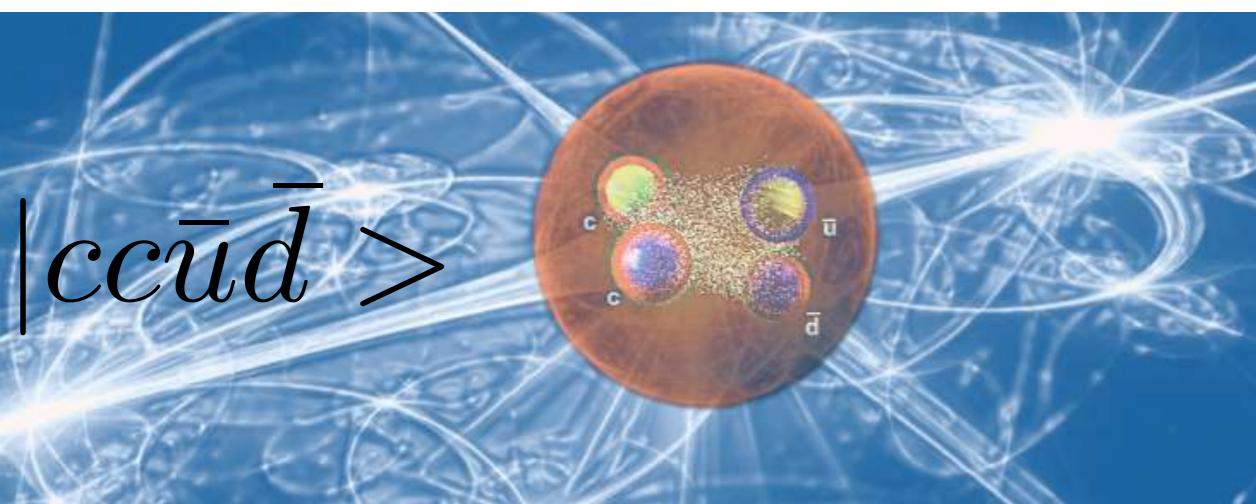
# Light Front Holography, Intrinsic Charm, and Tetraquarks



Fixed  $\tau = t + z/c$



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



Double-charm tetraquarks  
and other exotics

Stan Brodsky  
**SLAC** NATIONAL ACCELERATOR LABORATORY

