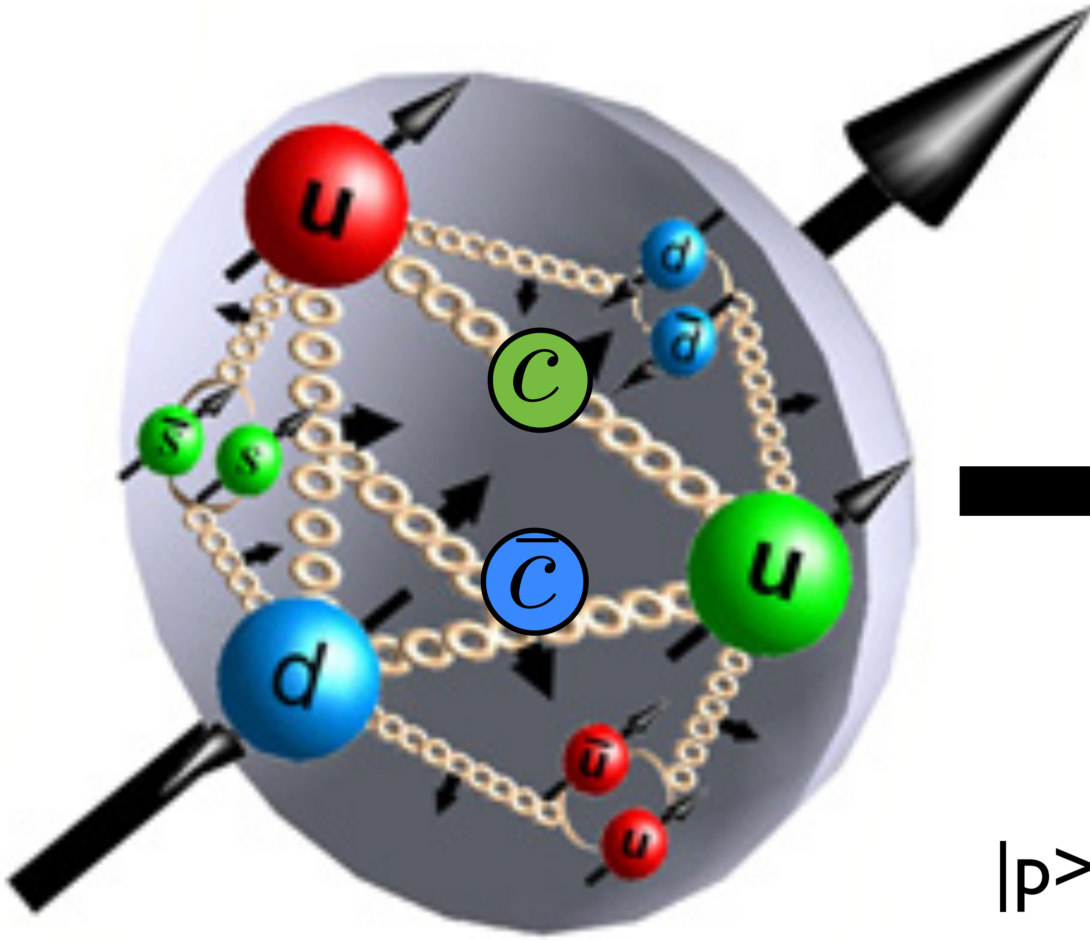
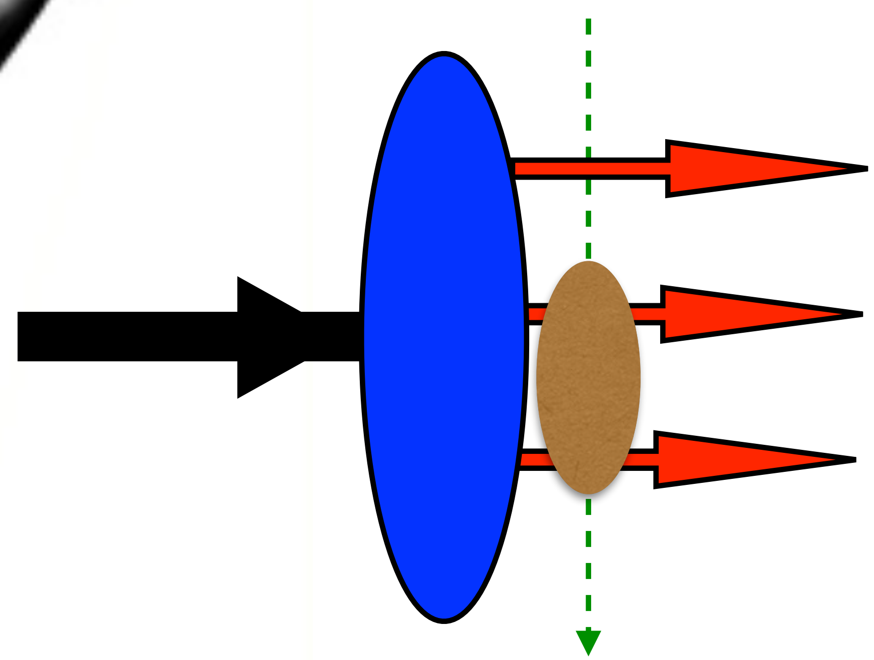
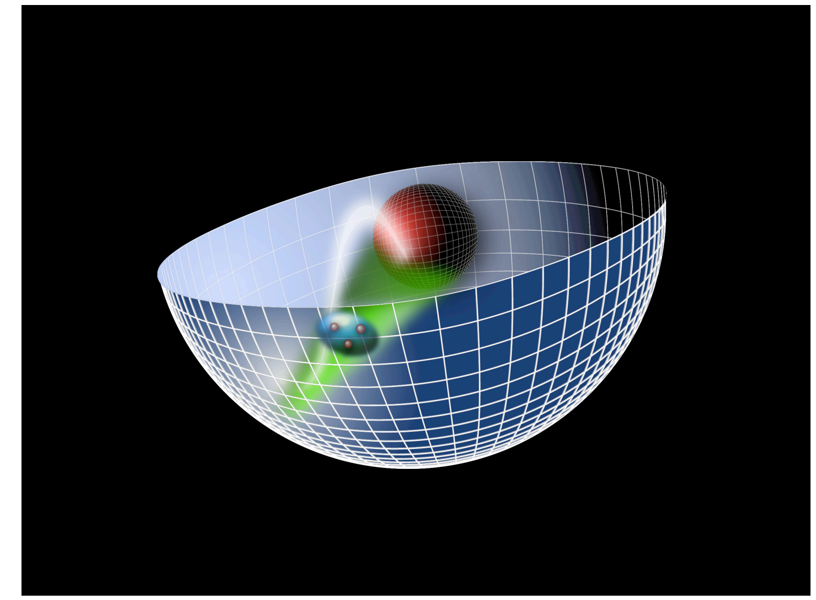
Intrinsic Heavy Quark Phenomena
A Novel Property of QCD



Fixed $\tau = t + z/c$





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

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

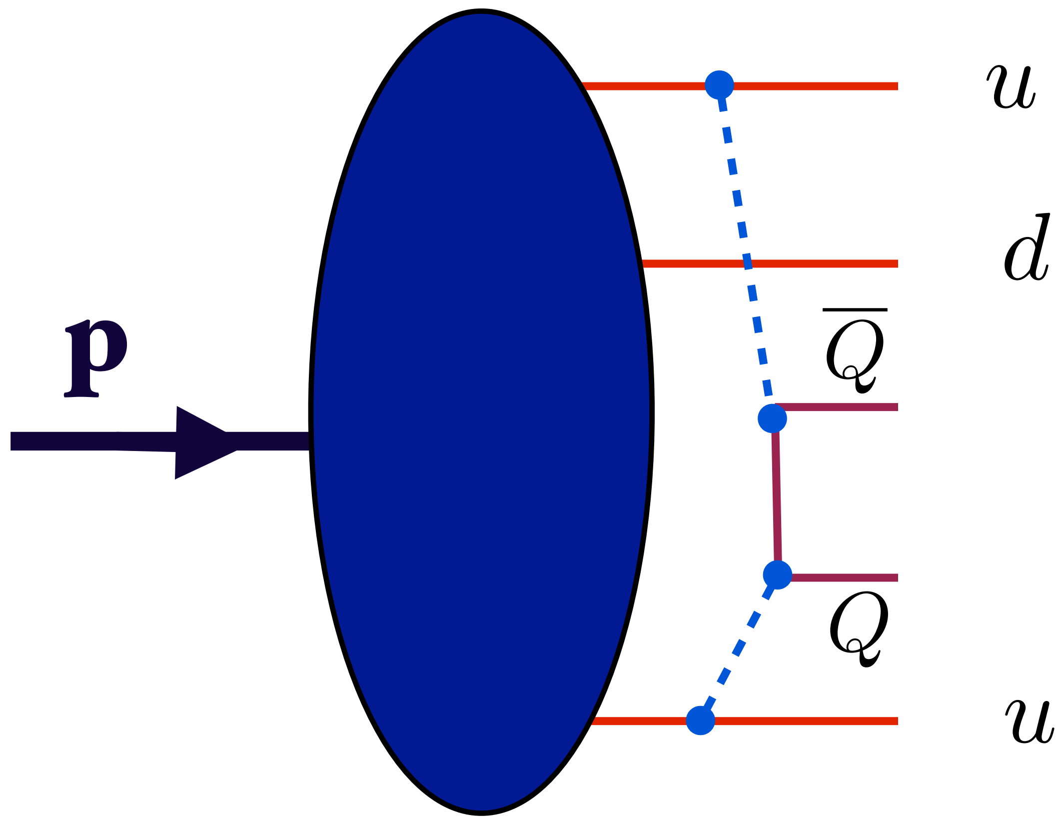
Implications of LHCb Measurements and Future Prospects

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

October 21, 2021

Proton 5-quark Fock State : Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Perturbative contribution

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

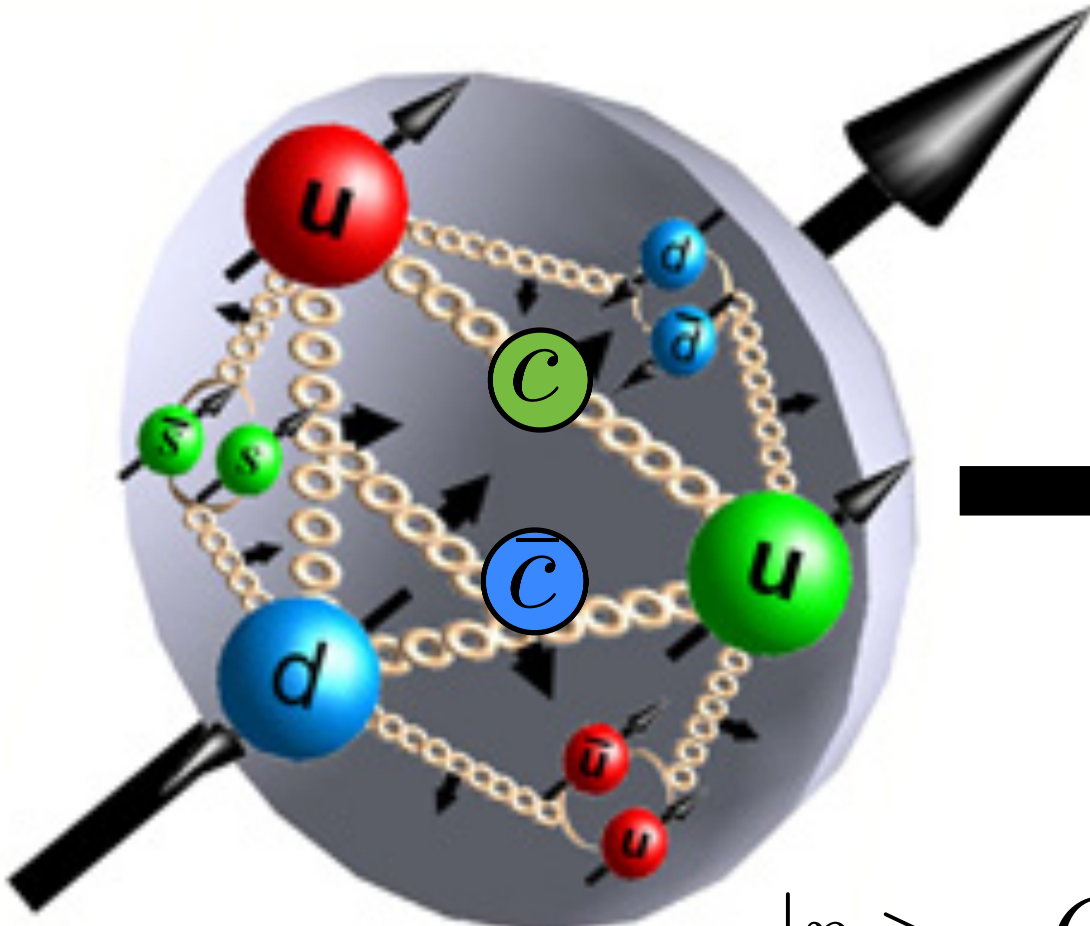
Minimal off-shellness

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

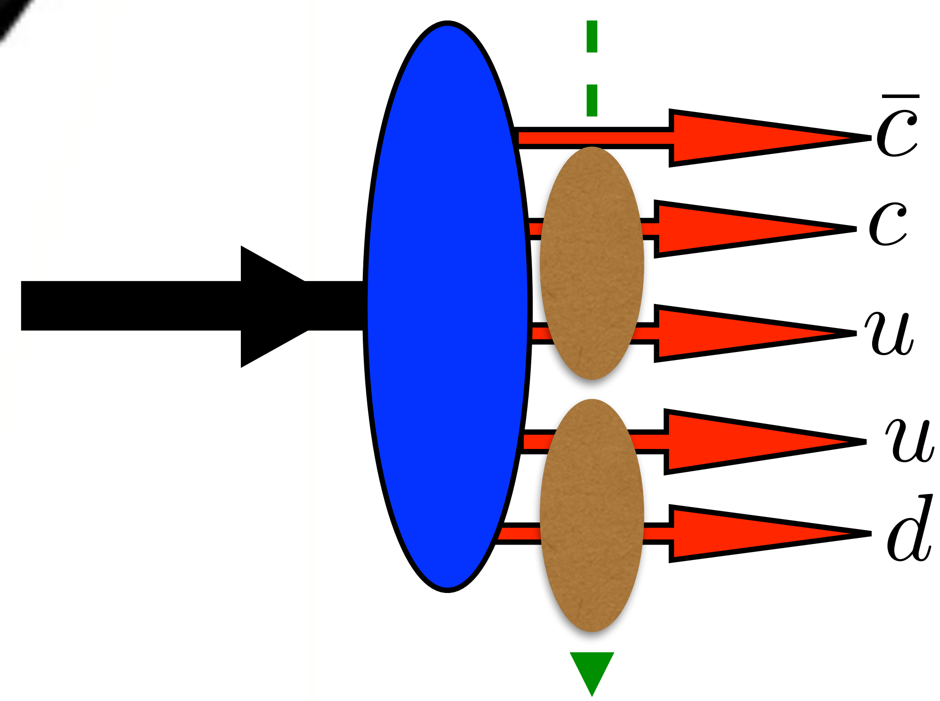
$$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

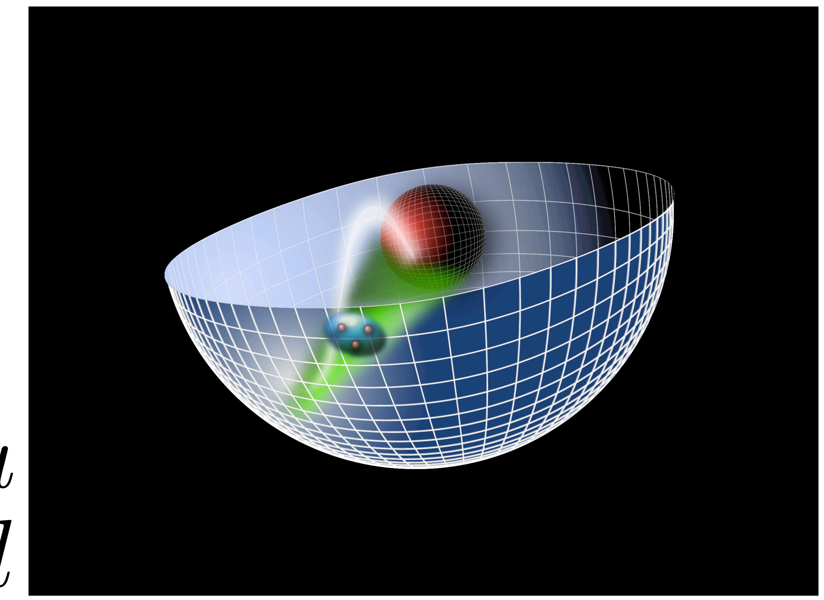
Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

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

Implications of LHCb measurements and future prospects

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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
$\mathcal{M}^2 = \sum_i \frac{m_i^2 + \vec{k}^2_{\perp i}}{x_i}$ 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)

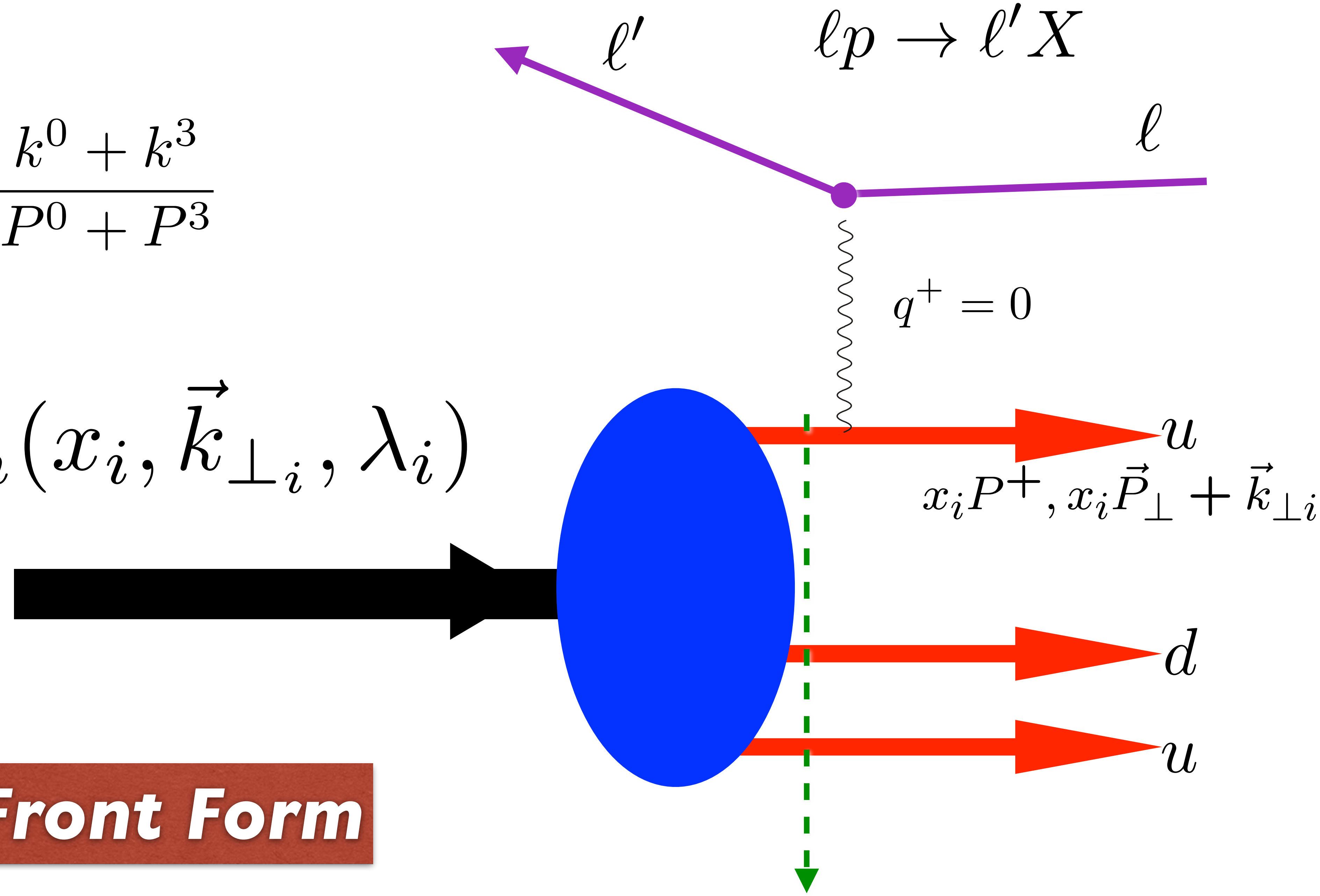
Published in: *Phys.Lett.B* 93 (1980) 451-455

41 years ago!

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

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

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



Dirac: Front Form

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

Like a flash photograph

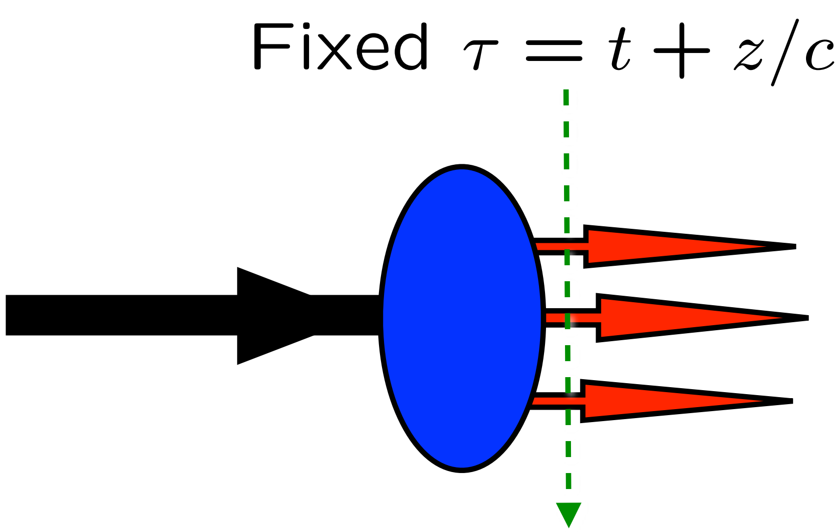
$$x_{bj} = x = \frac{k^+}{P^+}$$

Invariant under boosts! Independent of P^μ

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

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

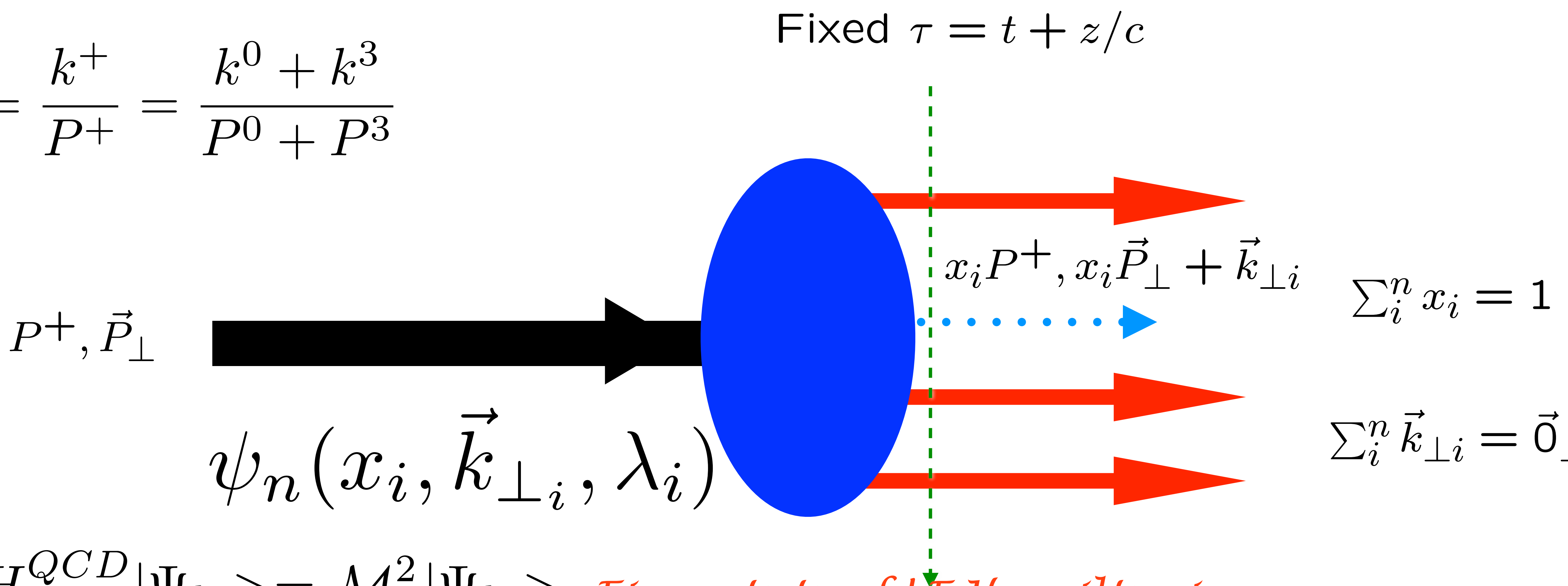
Direct connection to QCD Lagrangian

LF Wavefunction: off-shell in invariant mass

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

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

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



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

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

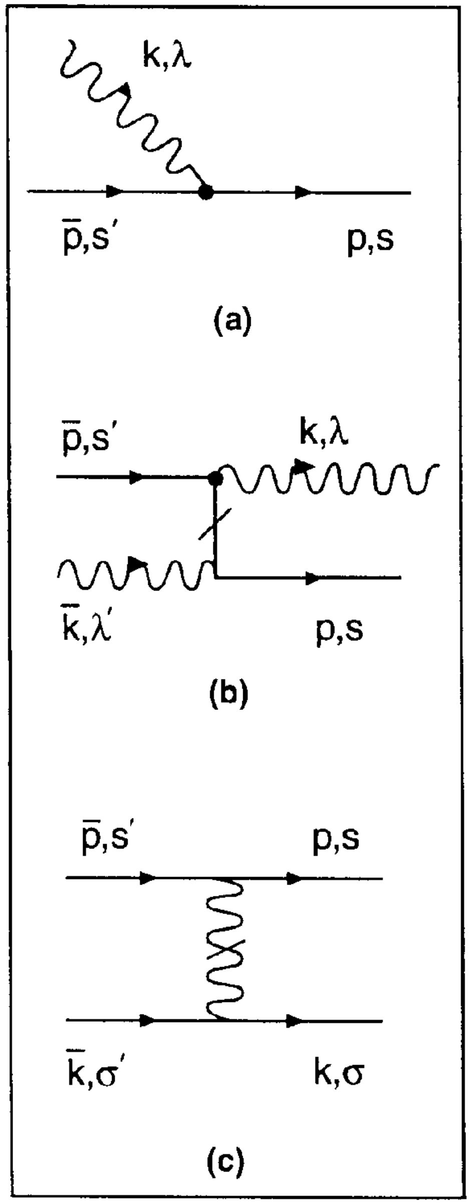
Light-Front QCD

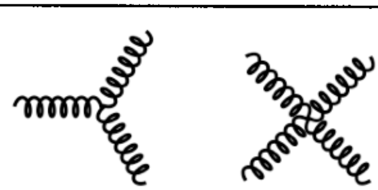
Heisenberg Equation

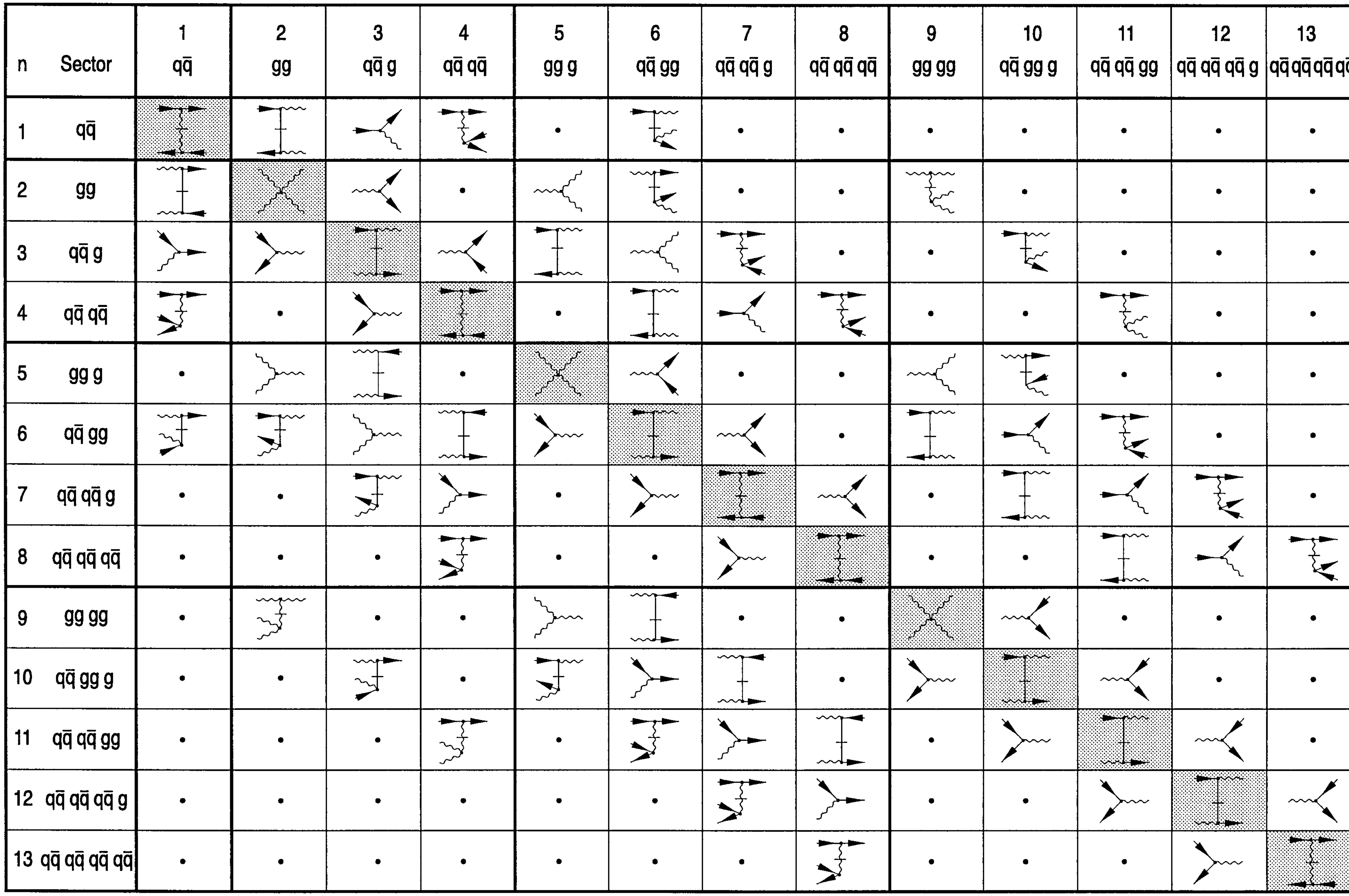
$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2 \; |\Psi_h\rangle$$

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

Hornbostel, Pauli, sjb

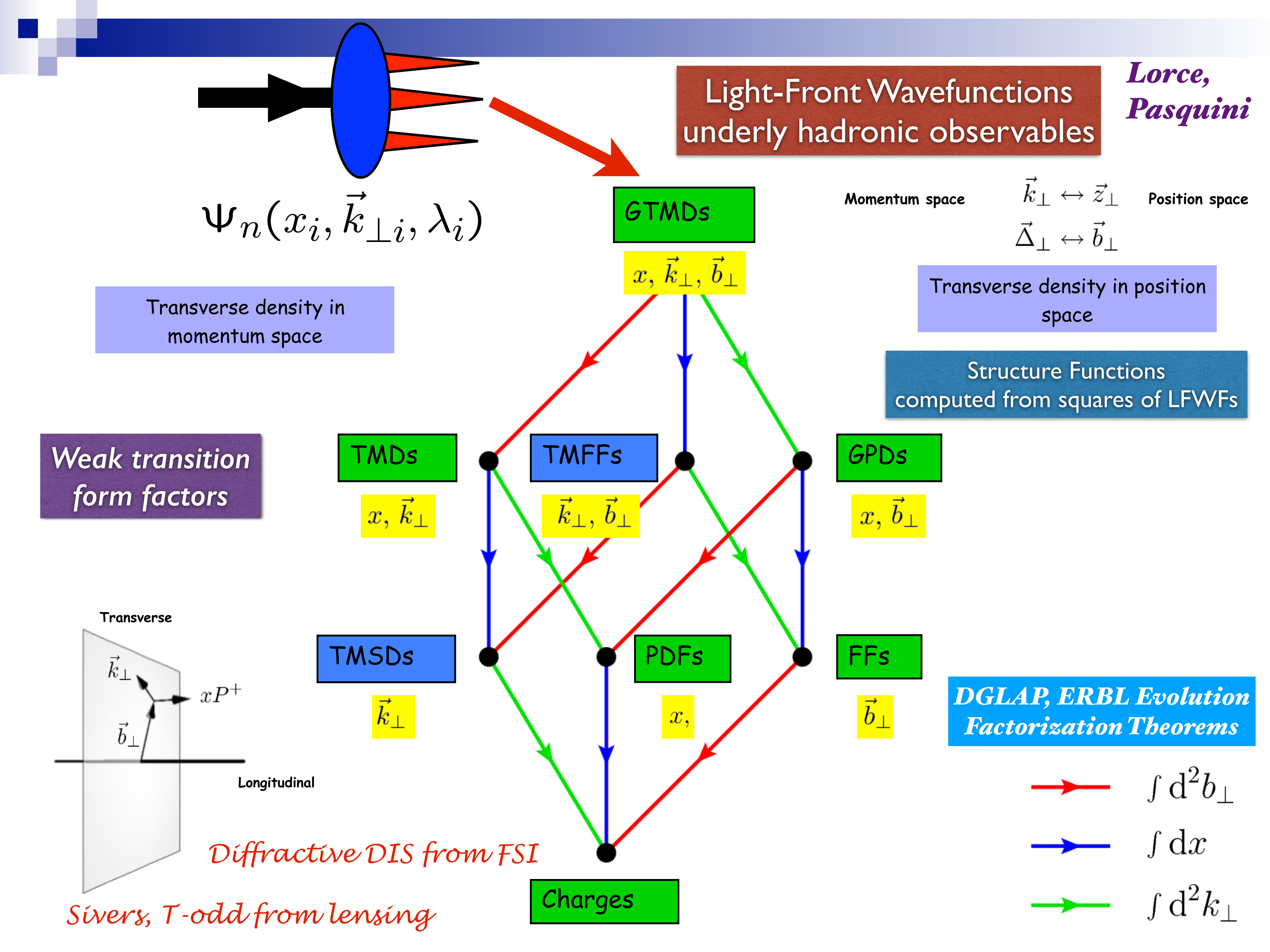






Minkowski space; frame-independent; no fermion doubling; no ghosts trivial vacuum

BLFQ (Vary et al)
Use LF Holographic Basis

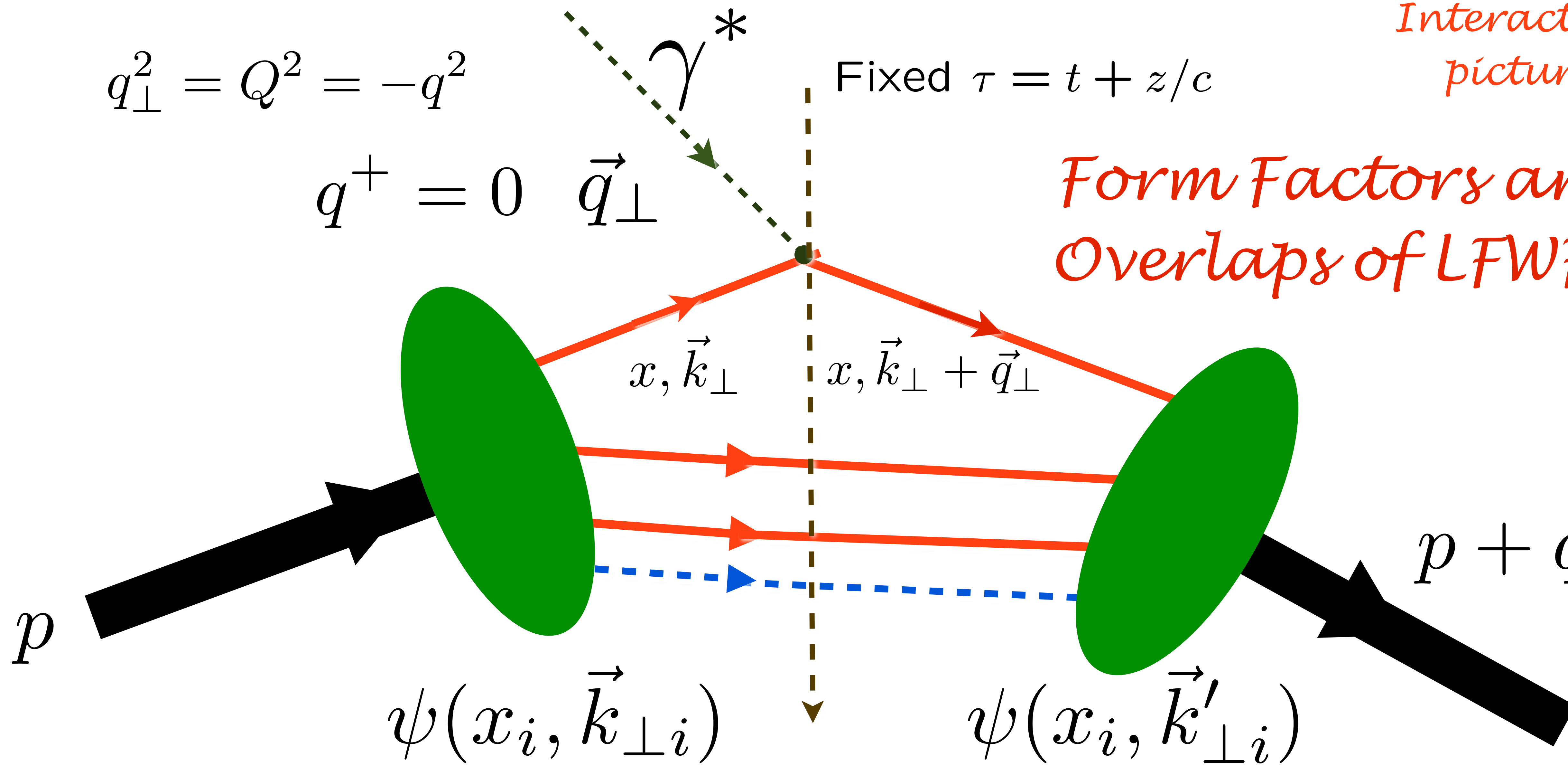


$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$
Light-Front Wavefunctions underly hadronic observables
Lorce, Pasquini
Momentum space
$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$
Position space
GTMDs
$x, \vec{k}_\perp, \vec{b}_\perp$
Transverse density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

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

Front Form

Interaction picture



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

Exact LF Formula for Pauli Form Factor

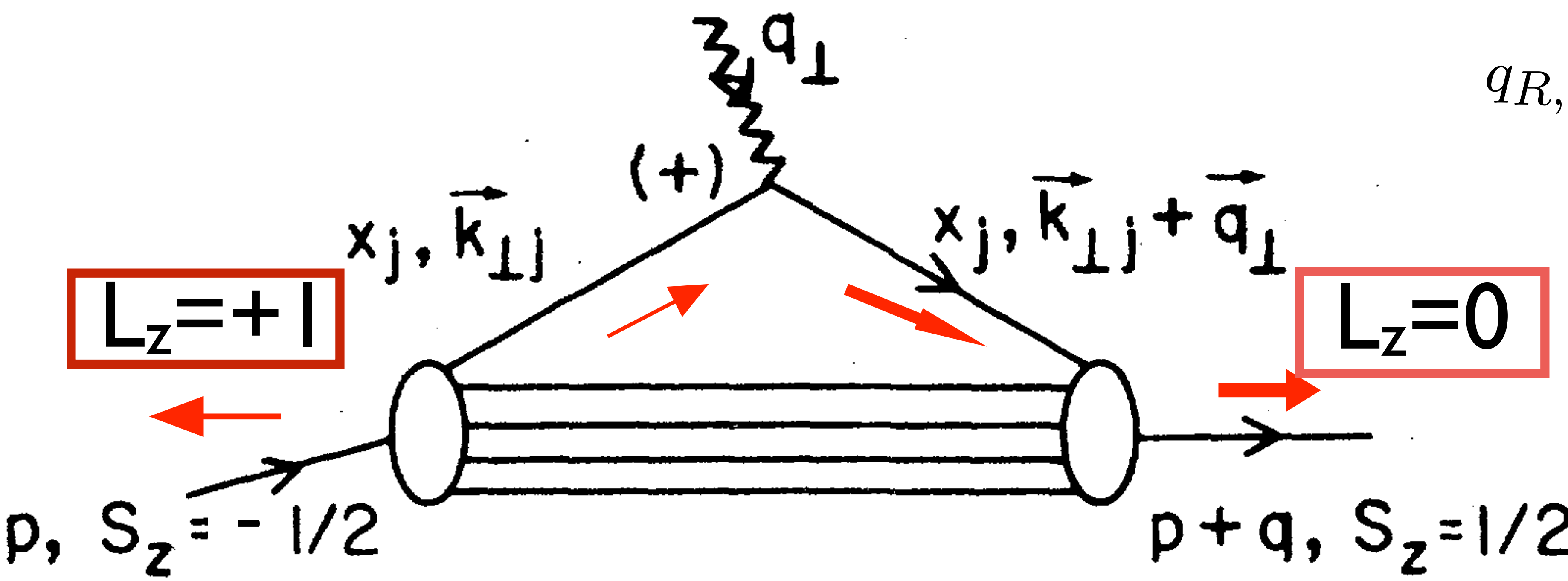
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

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

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

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

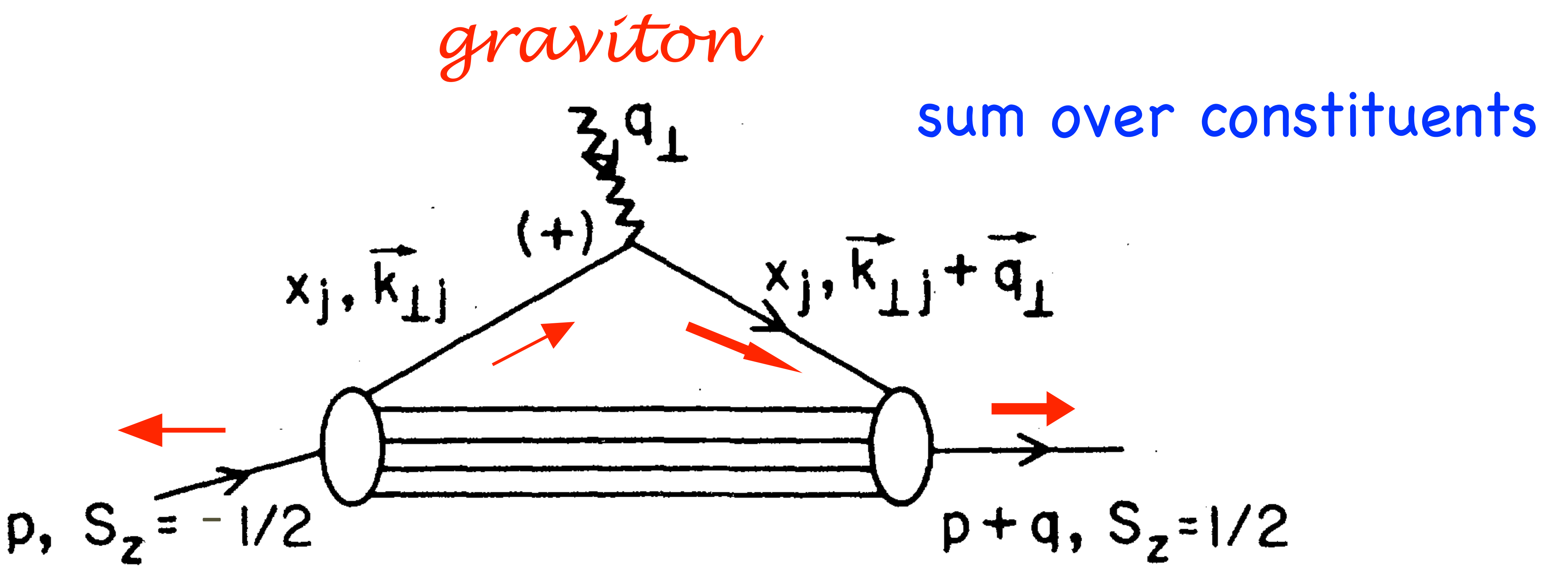


Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

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

LF Proof: Dae Sung Hwang, Bo-Qiang Ma, Ivan Schmidt, sjb

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

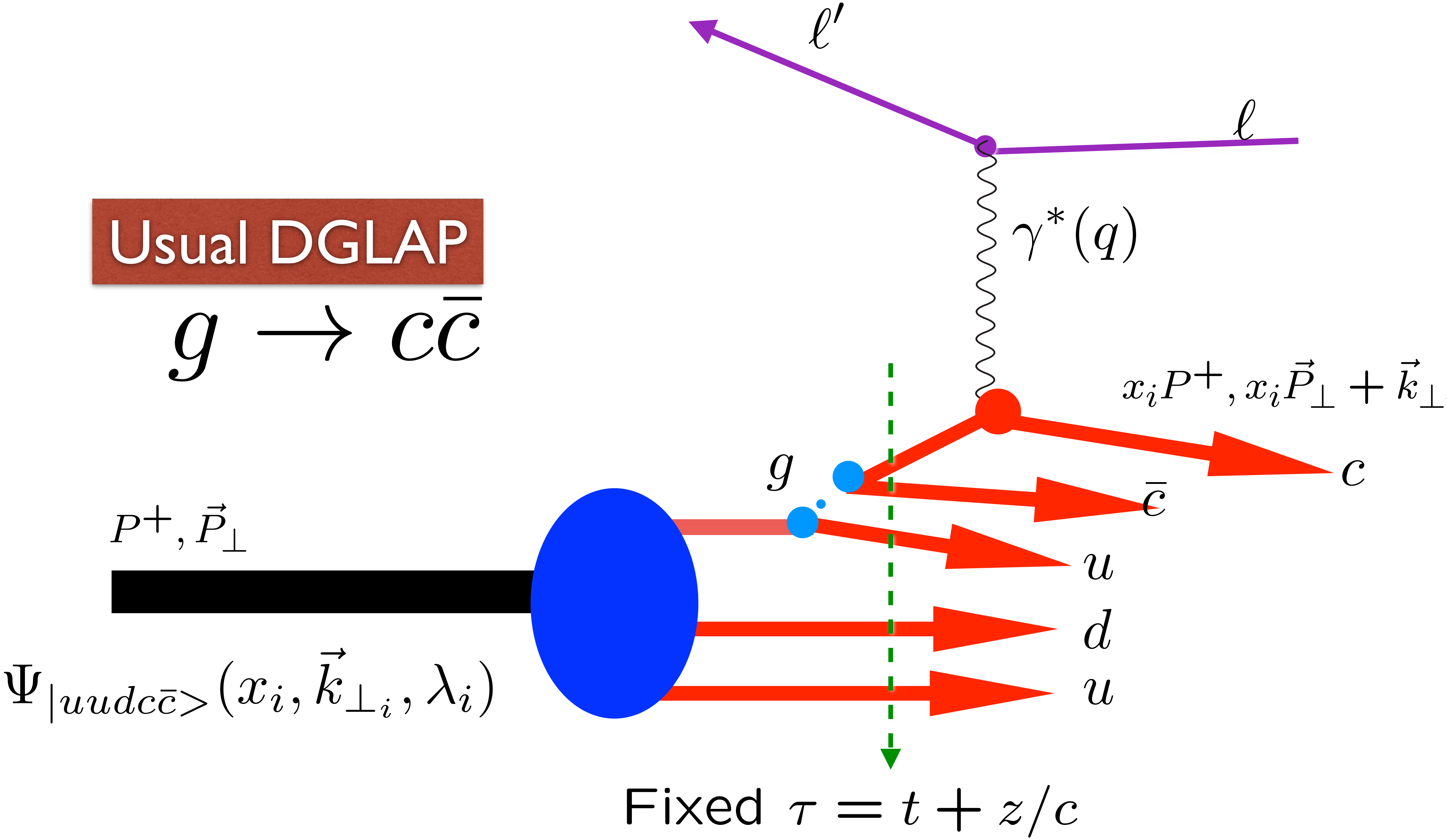


B(0) = 0

Each Fock State

Vanishing Anomalous gravitomagnetic moment B(0)

Important check of light-front theory



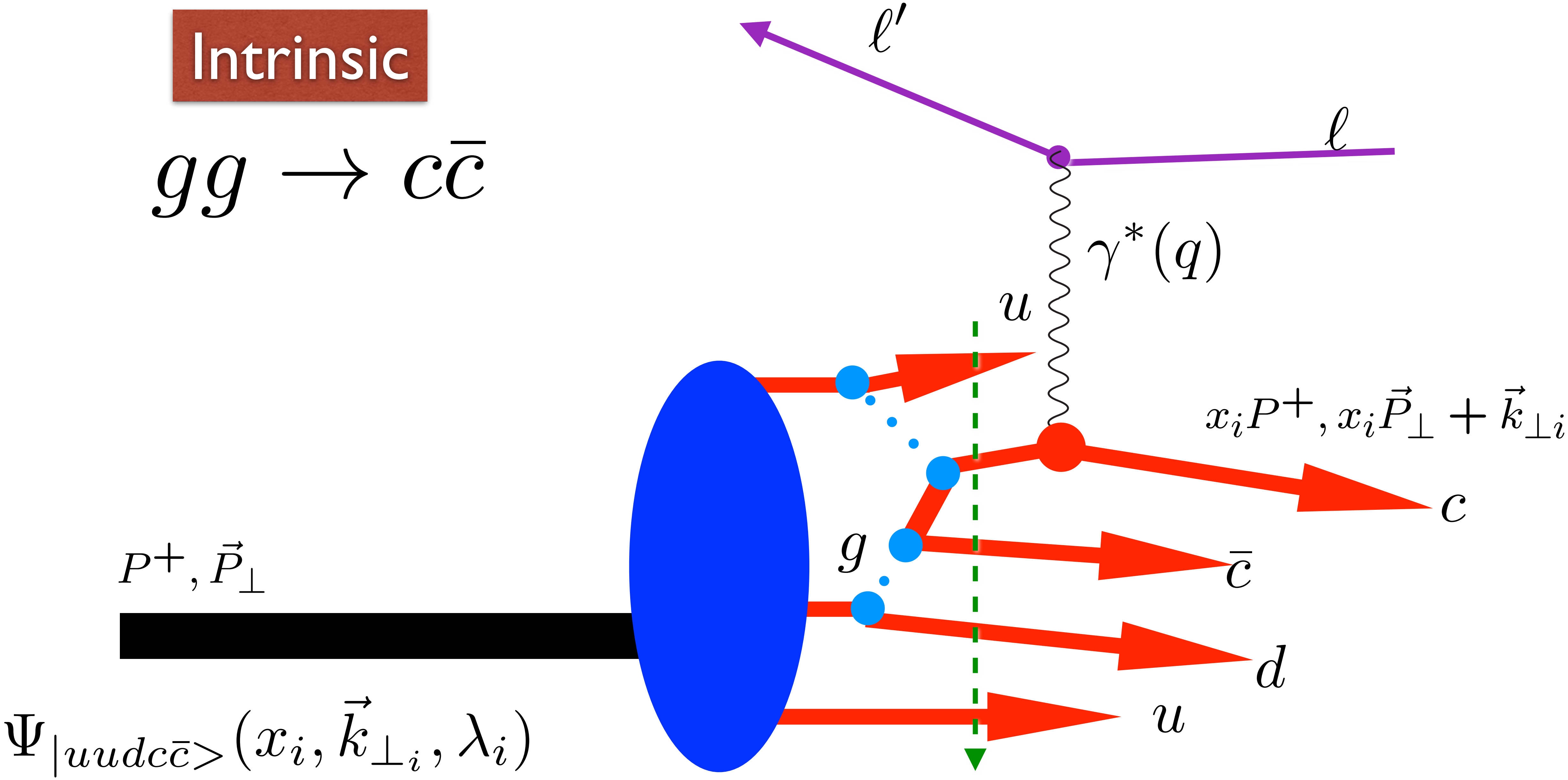
$$\text{Probability } P_{uudc\bar{c}} \sim \log \frac{Q^2+M_c^2}{\Lambda^2_{QCD}}$$

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

Low x extrinsic charm!

Intrinsic

$gg \to c\bar{c}$



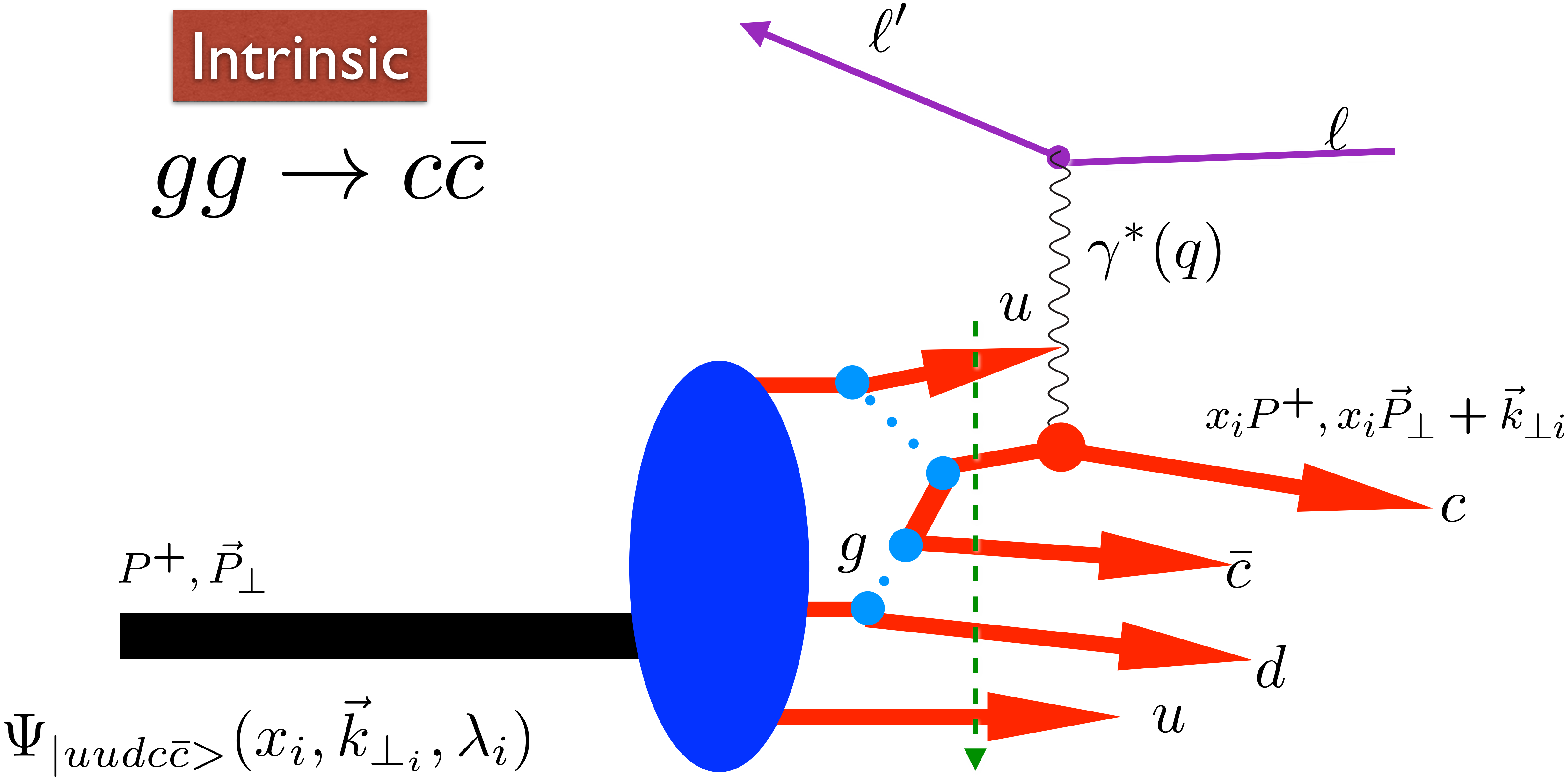
Probability $P_{uudc\bar{c}} \propto \frac{1}{M_c^2}$

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

High x intrinsic charm!

Intrinsic

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

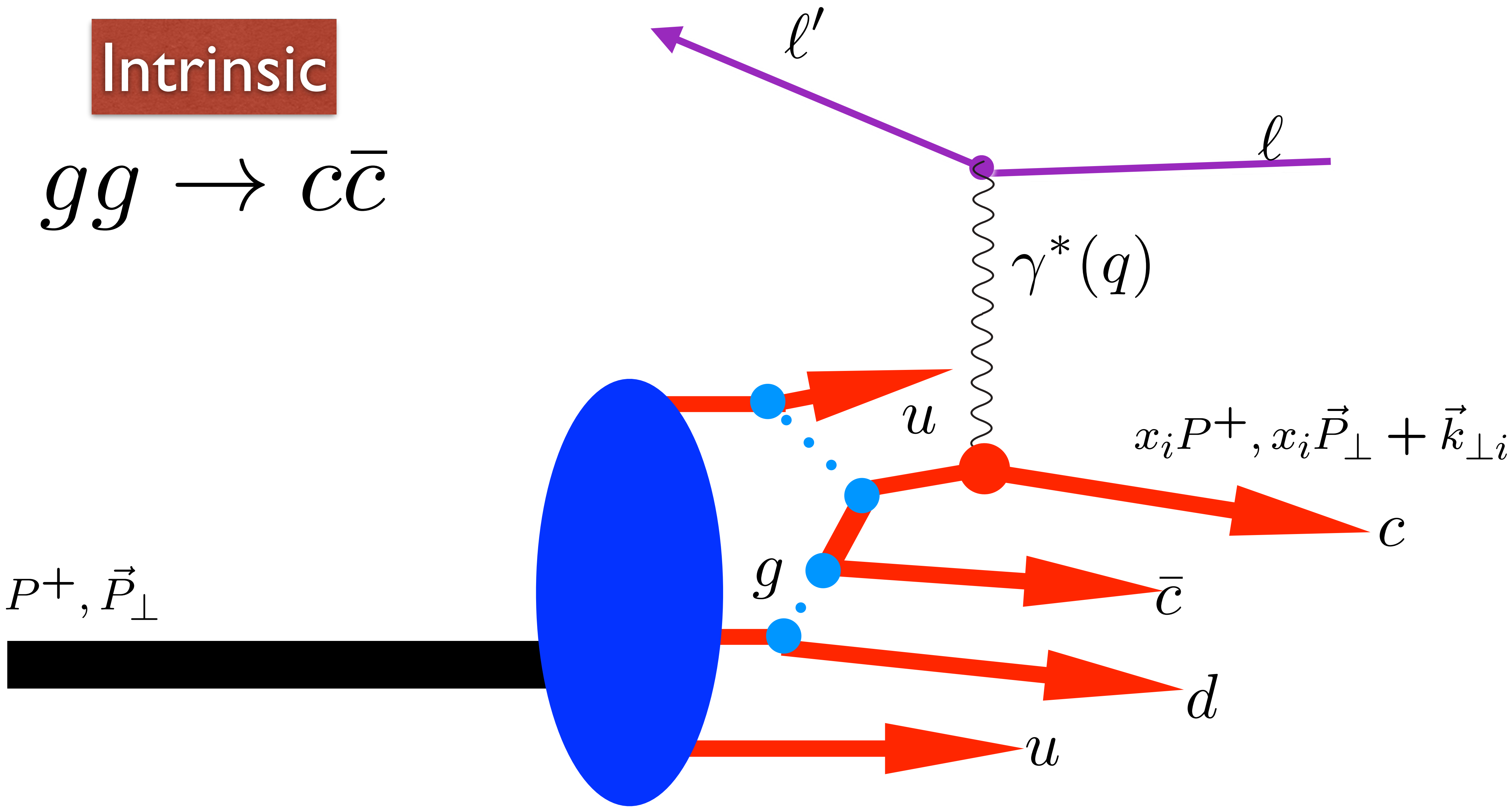


$$P(p \to uudc\bar{c}) \sim \left[m_p^2 - \sum_{i=1}^{5} \frac{m_{\perp i}^2}{x_i}\right]^{-2} \qquad m_{\perp i}^2 = m_i^2 + \vec{k}_{\perp i}^2$$

$$P(p \to c\bar{c} + X) \propto \frac{x_c^2 x_{\bar{c}}^2}{(x_c + x_{\bar{c}})^2} \times (1 - x_c - x_{\bar{c}})^2 \qquad \hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

Intrinsic

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

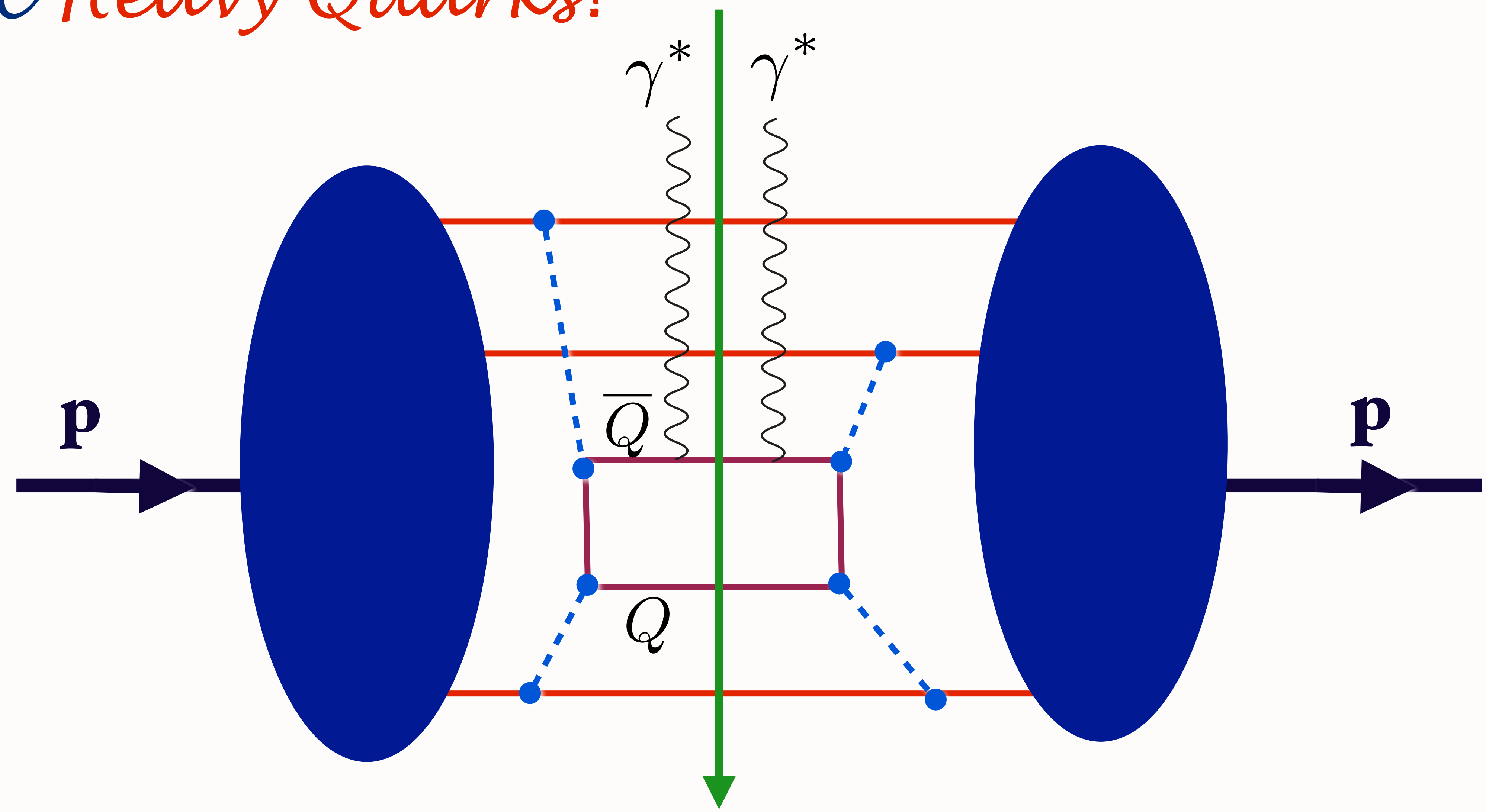


Probability $P_{uudc\bar{c}} \propto \frac{1}{M_c^2}$

Property of Non-Abelian QCD

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

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

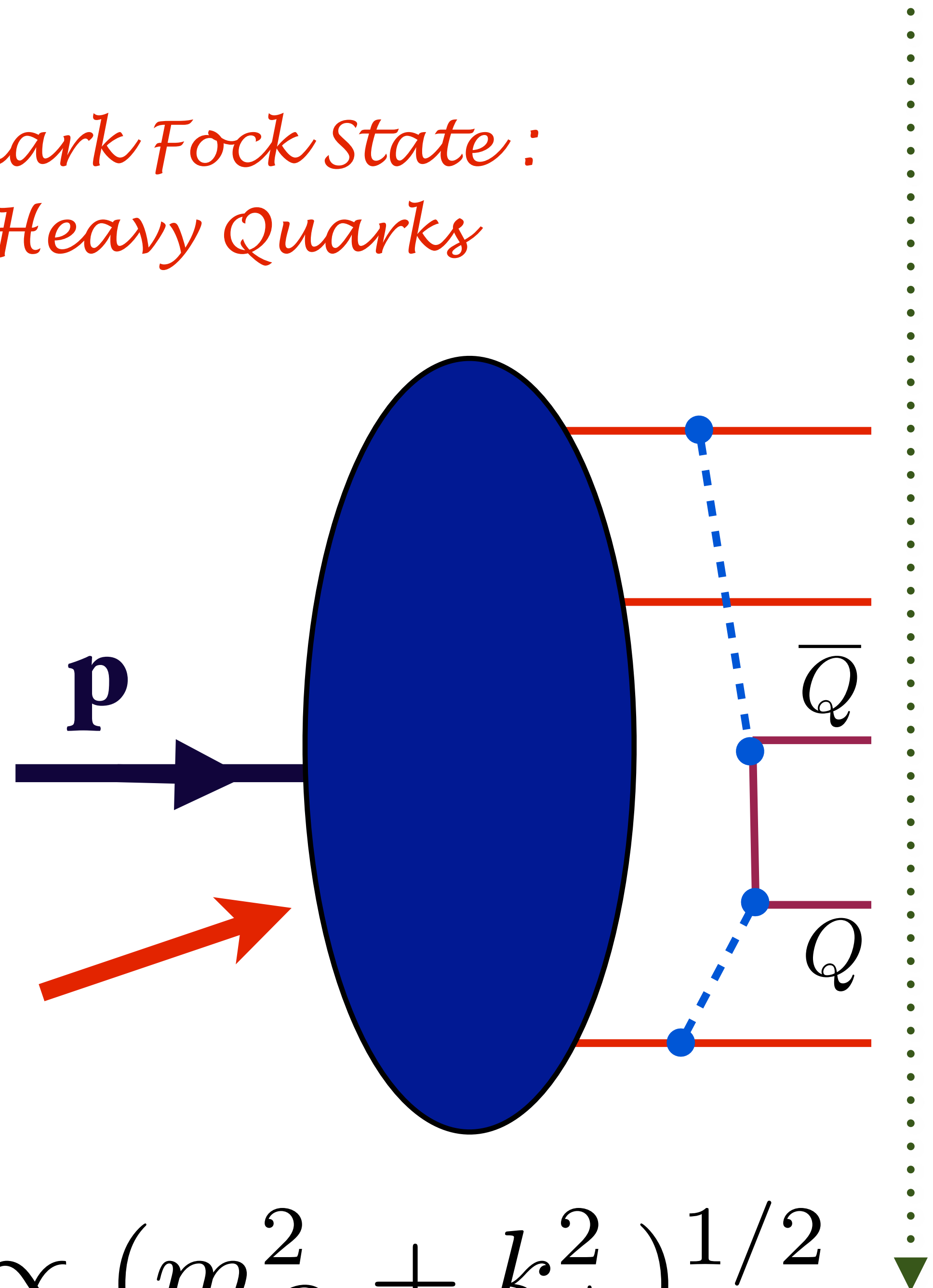


Probability (QED) $\propto \frac{1}{M_\ell^4}$ Probability (QCD) $\propto \frac{1}{M_Q^2}$

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

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

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness!

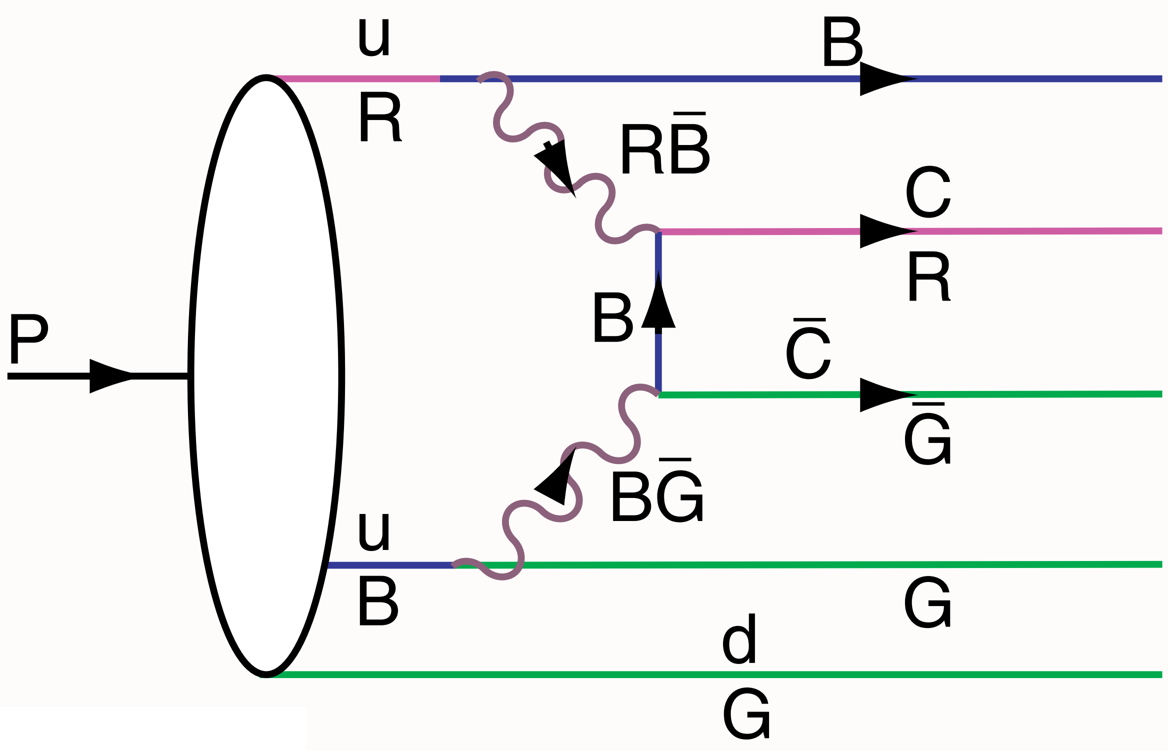
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

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

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

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

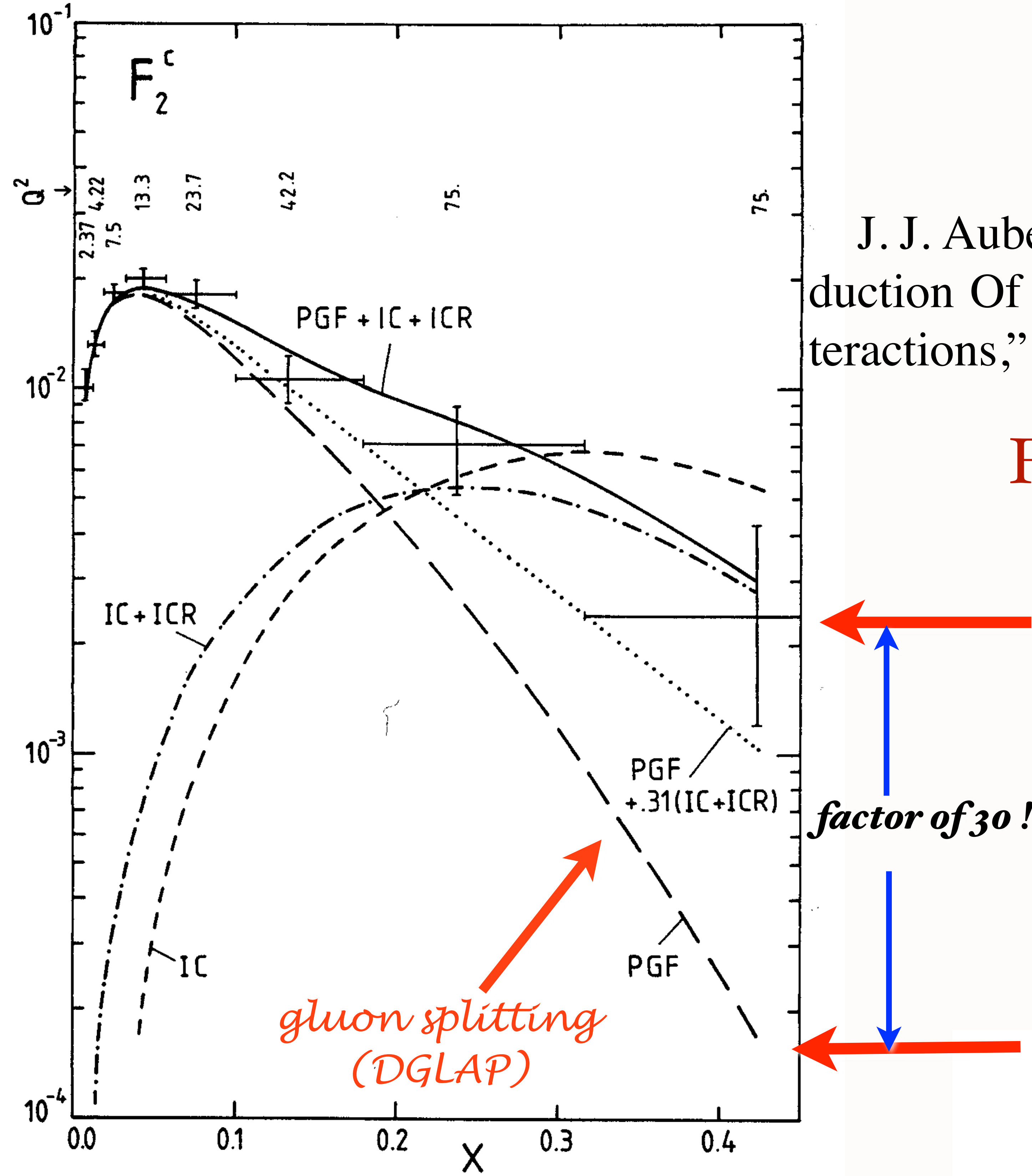
$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm! *Charm at Threshold*

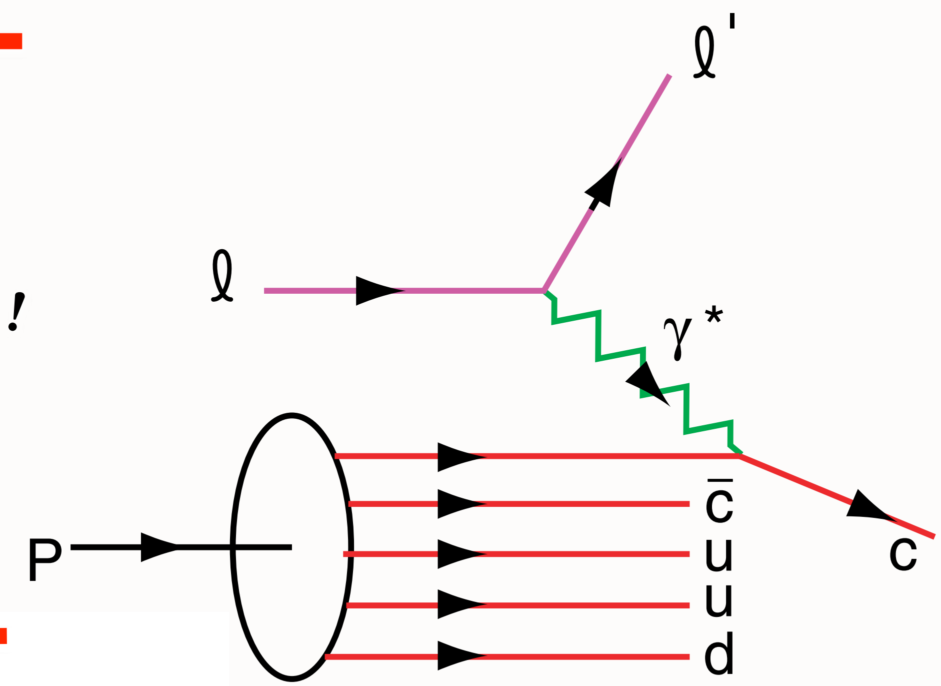
Action Principle: Minimum KE, maximal potential

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



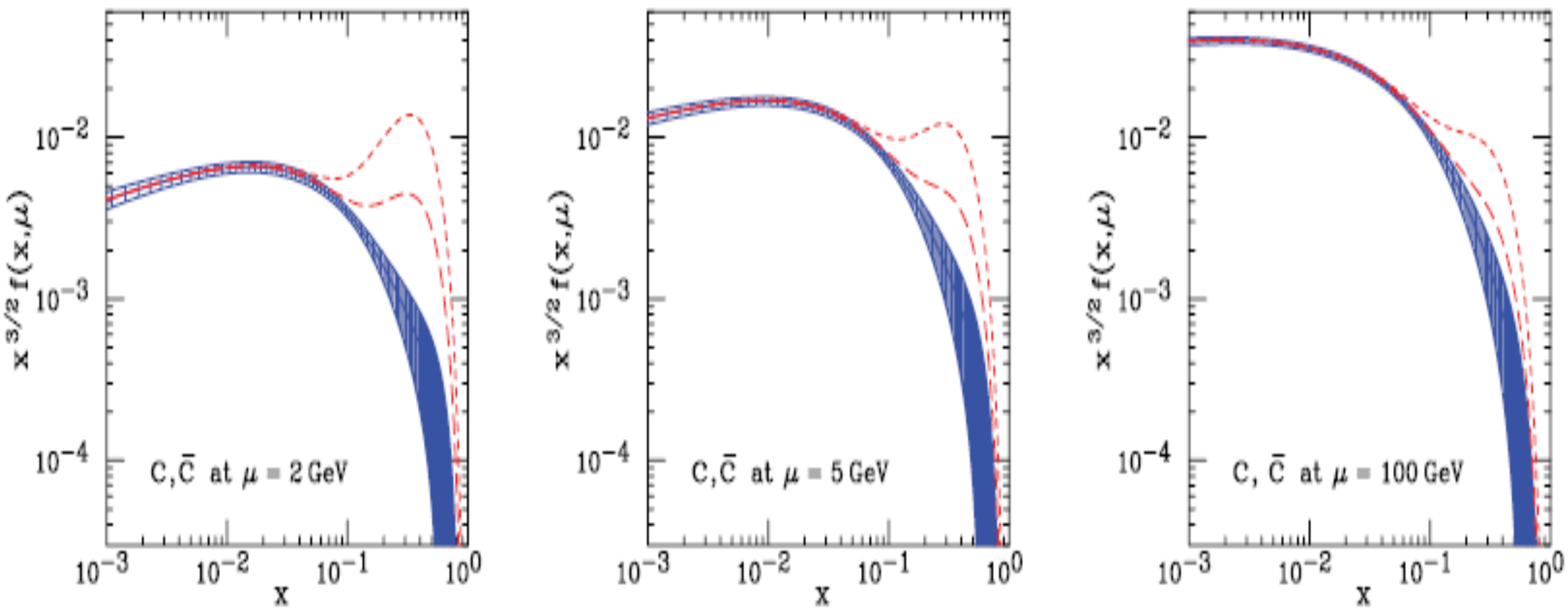
DGLAP / Photon-Gluon Fusion: factor of 30 too small

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

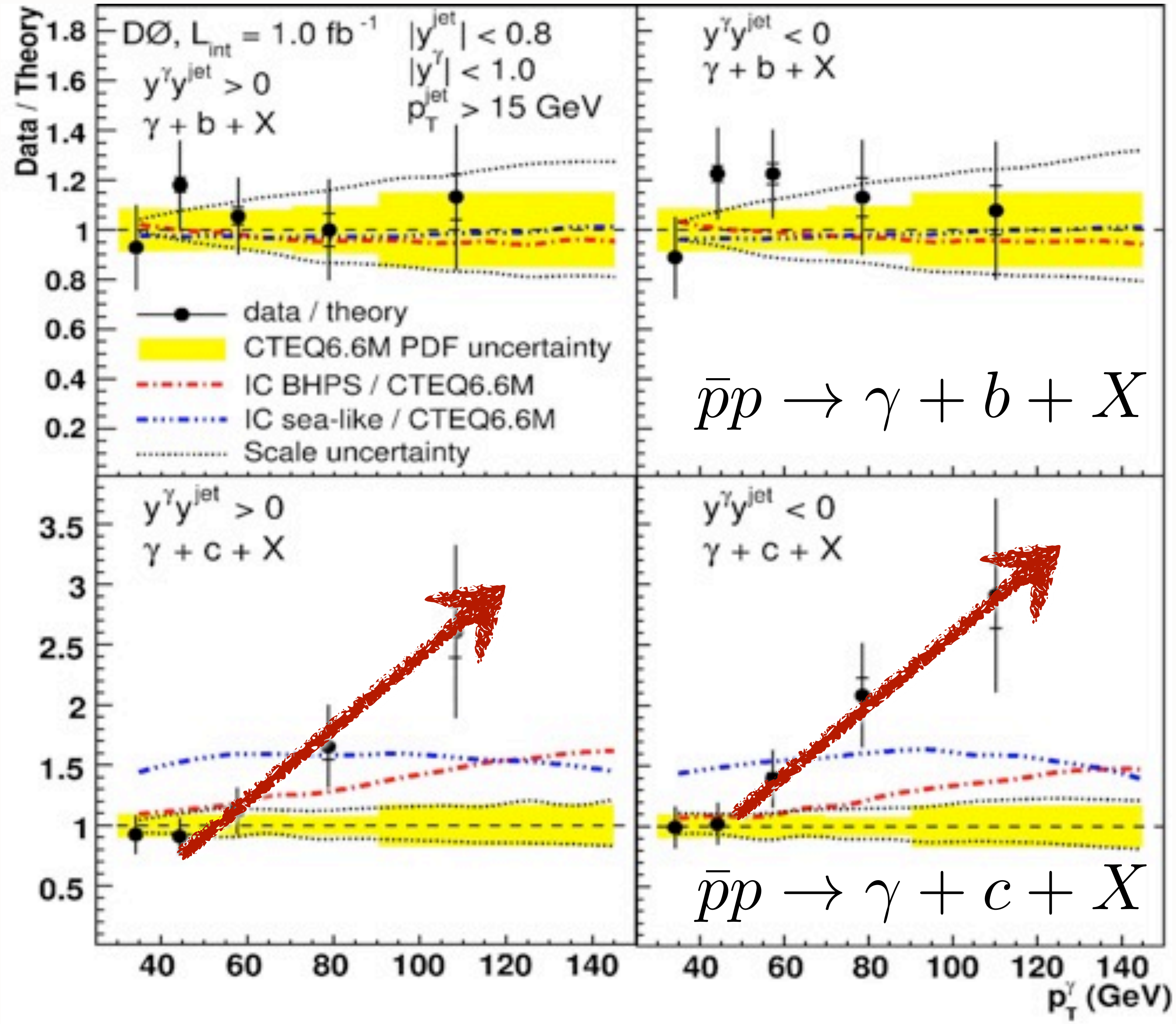


Charm quark distributions within the BHPS model.

PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

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

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



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

Ratio is insensitive to gluon PDF, scales

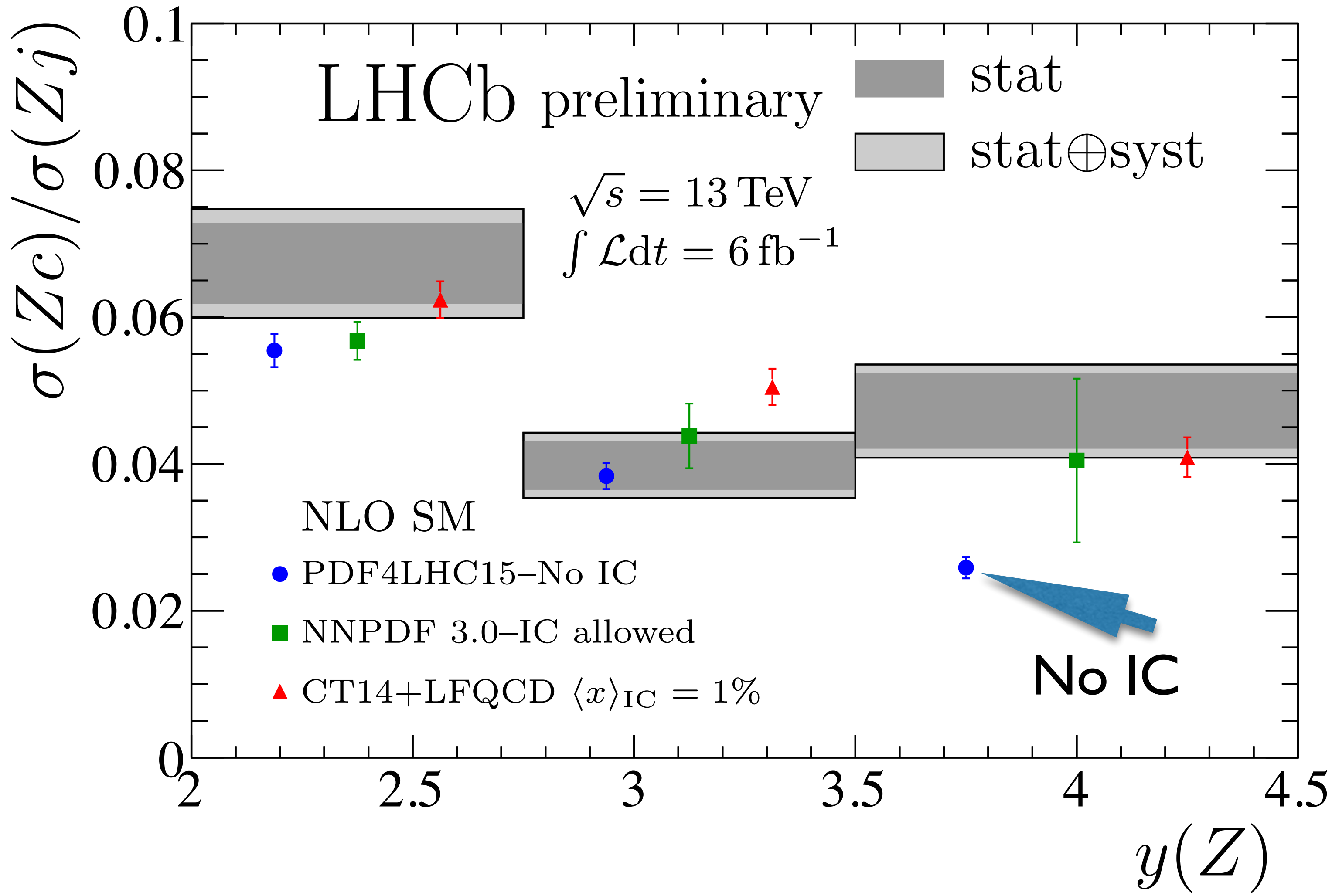
Consistent with $\frac{m_c^2}{m_b^2}$ relative suppression of intrinsic bottom

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

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

$Z + c$: results

LHCb-PAPER-2021-029

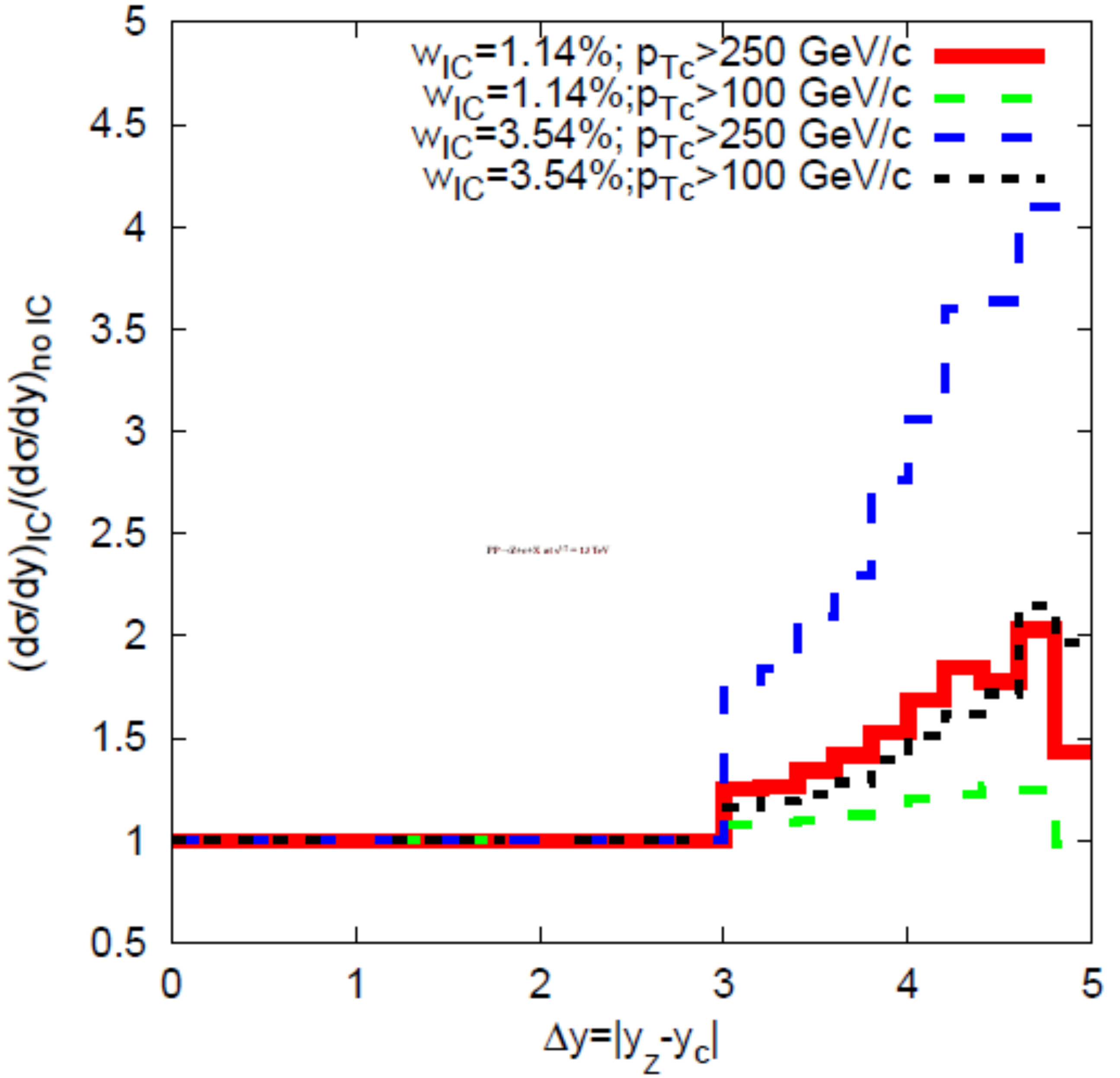


- Clear enhancement in highest-y bin
- Consistent with expected effect from $|uudc\bar{c}\rangle$ component predicted by LFQCD
- Inconsistent with No-IC theory at ~ 3 standard deviations
- Global PDF analysis required to determine true significance

Daniel Craik
on behalf of the LHCb collaboration

PP→Z+c+X at $s^{1/2}$ = 13 TeV

We suggest the following kinematics: 1.5 < y_c < 2.5 and -2.5 < y_Z < -1.5, i.e., c-jet is produced forward and Z-boson is emitted backward.

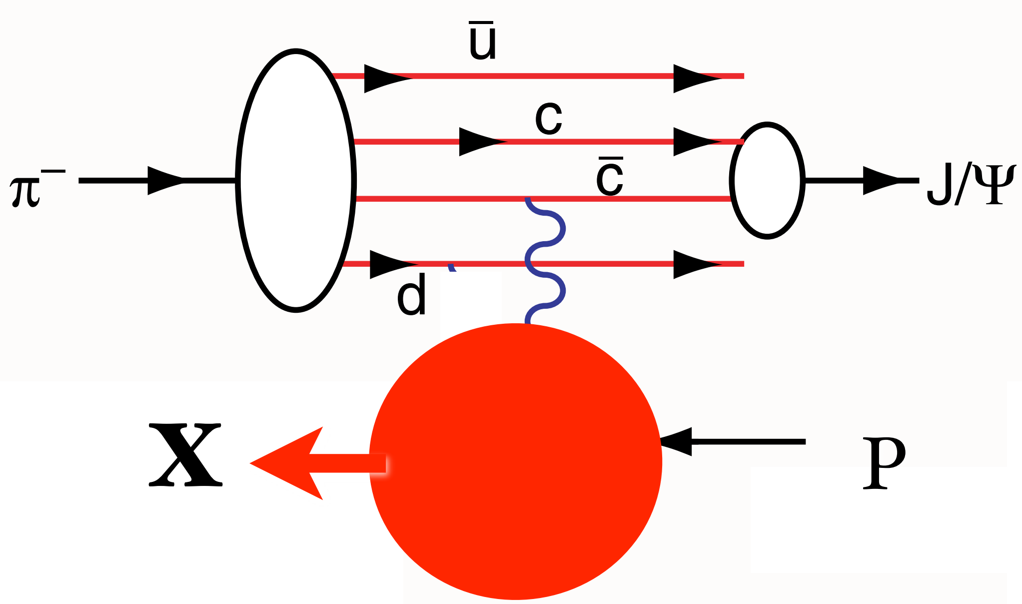


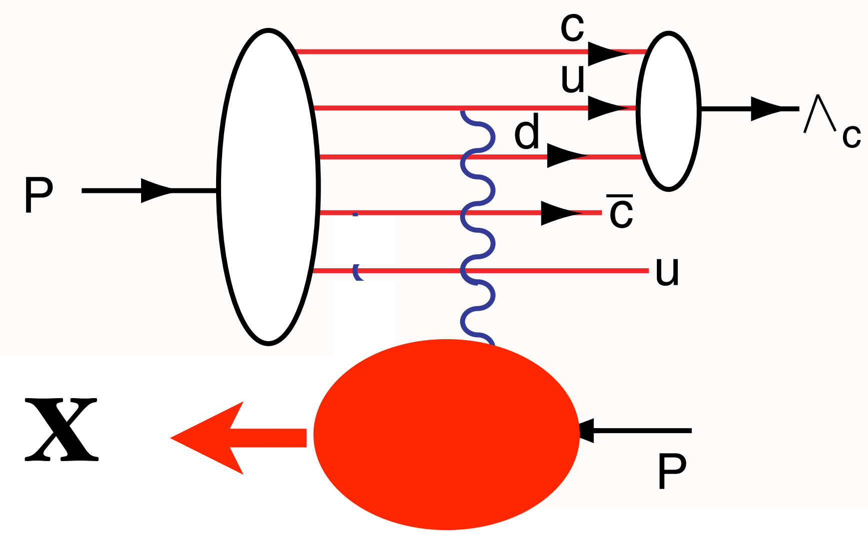
G. Lykasov, et al.

The flavour excitation graphs result in a sizable contribution to dσ/dy at large Δy.

The ratio of the rapidity distribution with IC contribution to PDF to the one without IC as a function of $\Delta y = |y_Z - yc|$ at different p_t cuts and IC probabilities w=1.14% (BHPS1) and w=3.54% (BHPS2).

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 $pp \to \Lambda_b X$

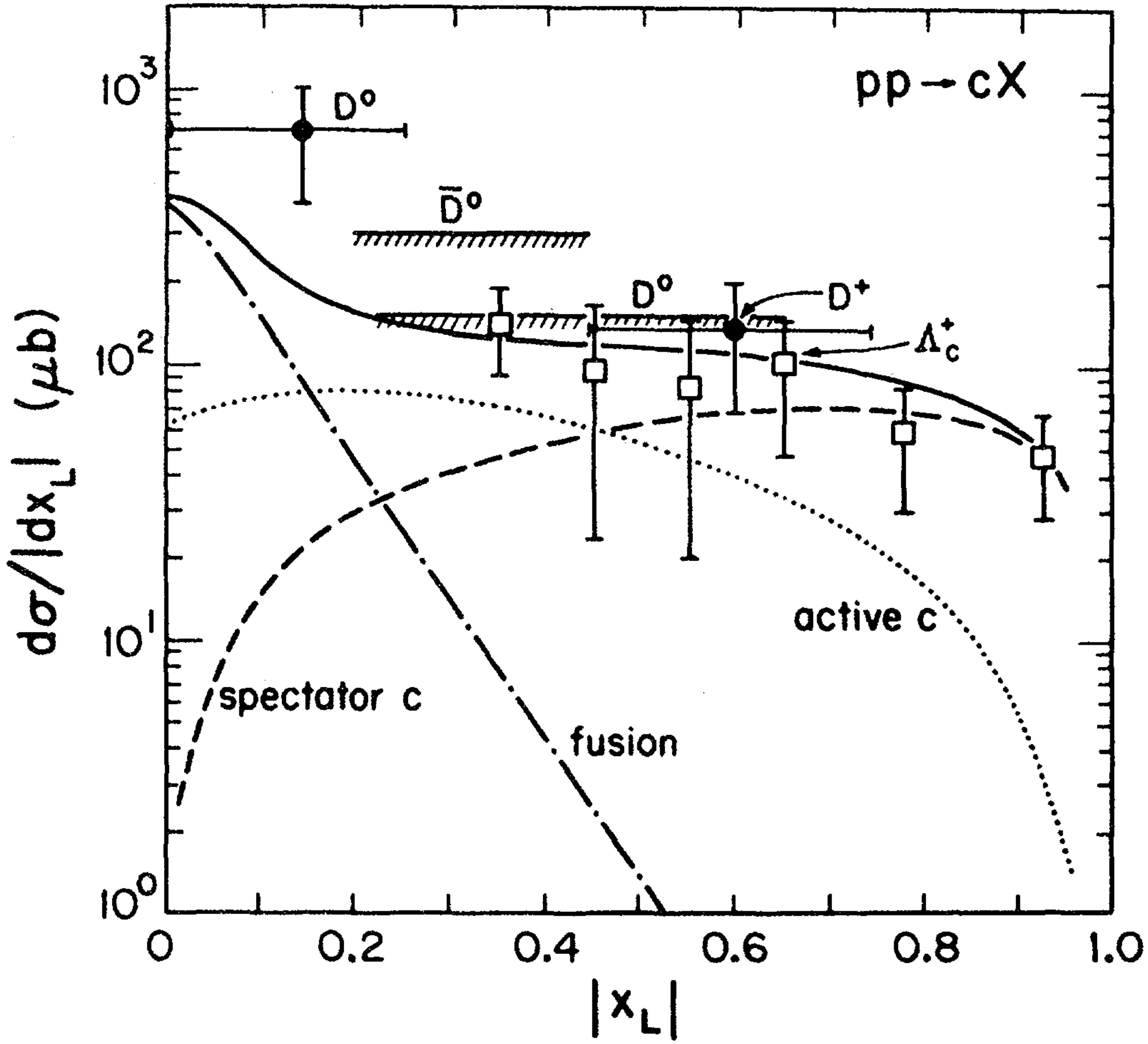
Intrinsic Bottom!
Zichichi, Cifarelli, et al.

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

FermiLab

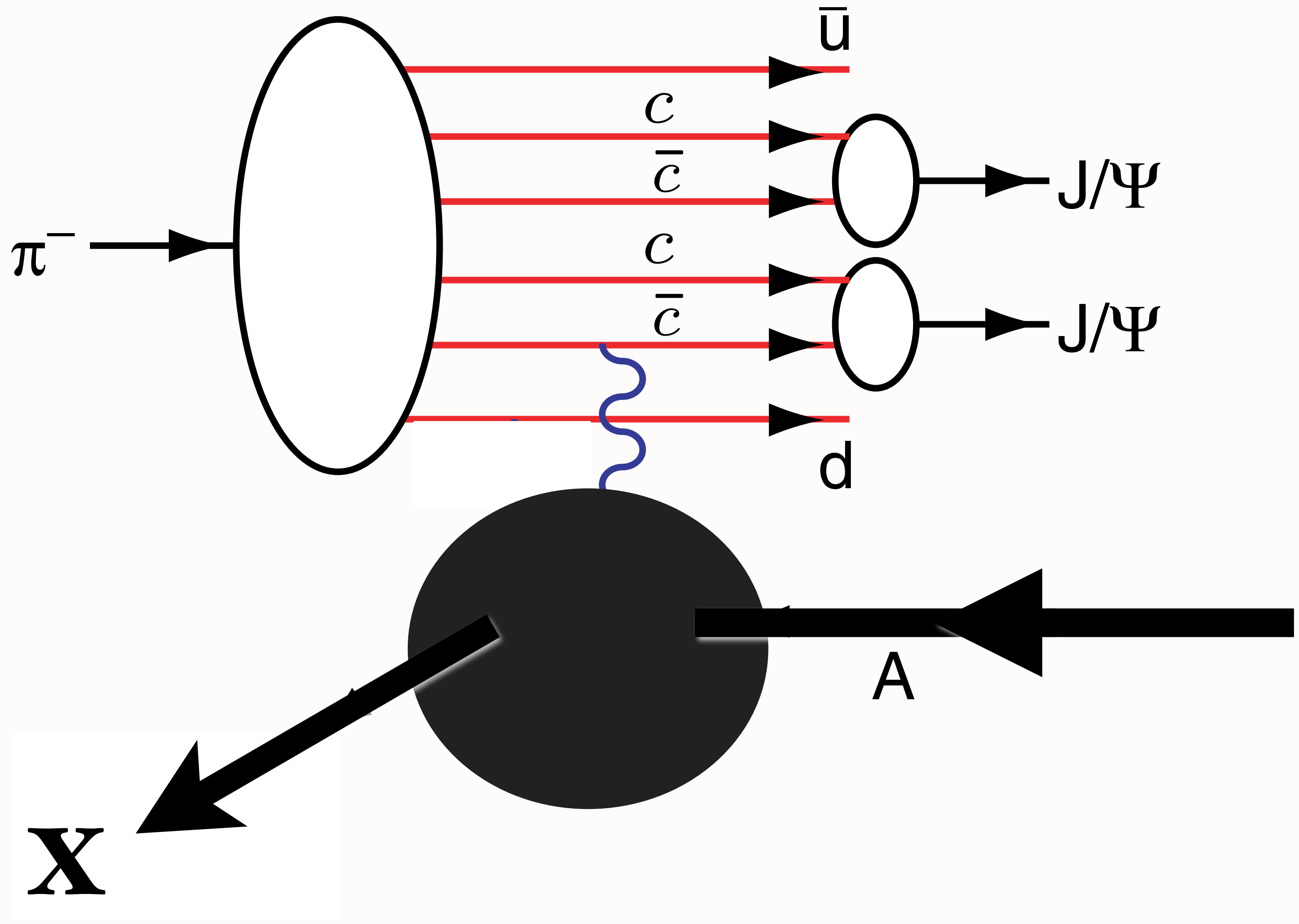
IC Structure Function: Critical Measurement for EIC

Many interesting spin, charge asymmetry, spectator effects

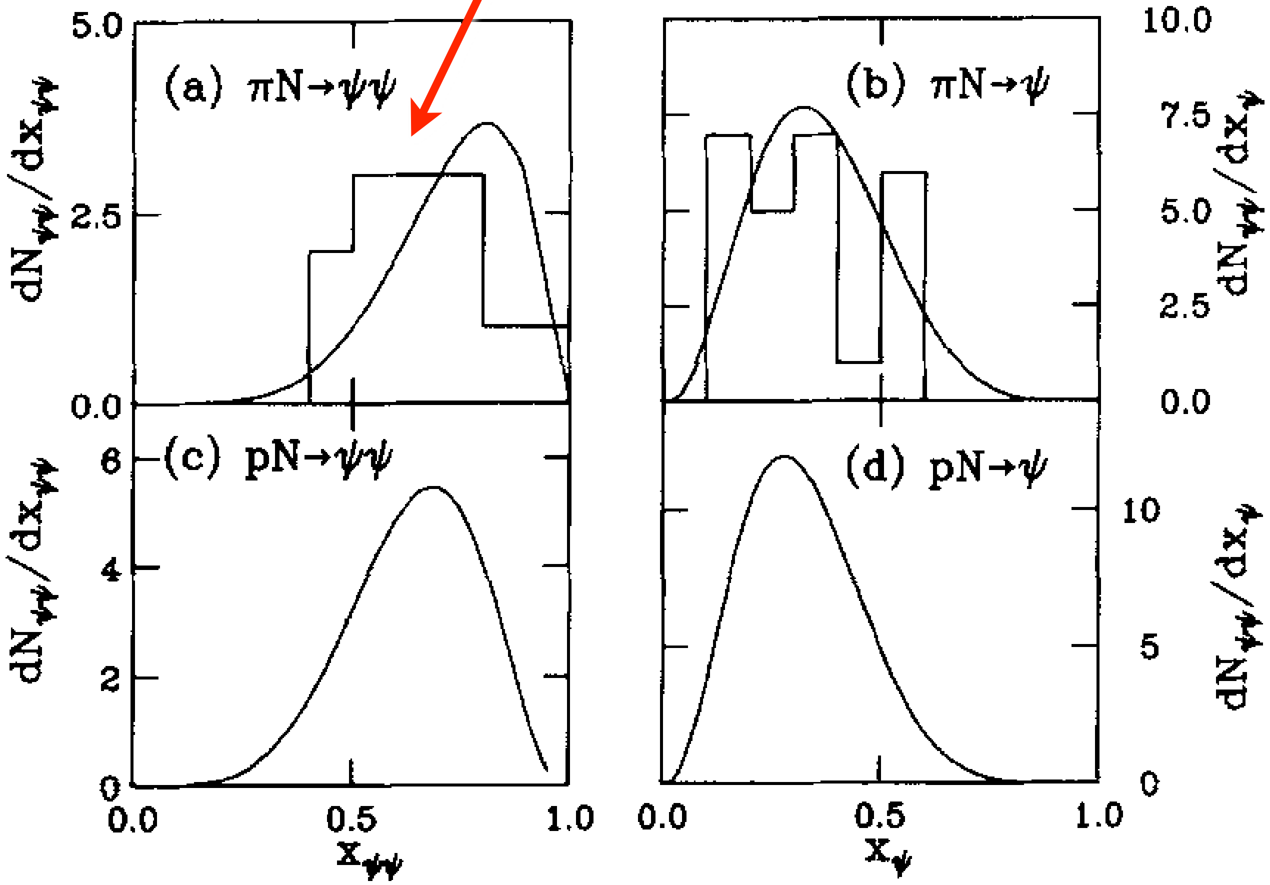


Barger, Halzen, Keung

Production of Two Charmonia at High x_F



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

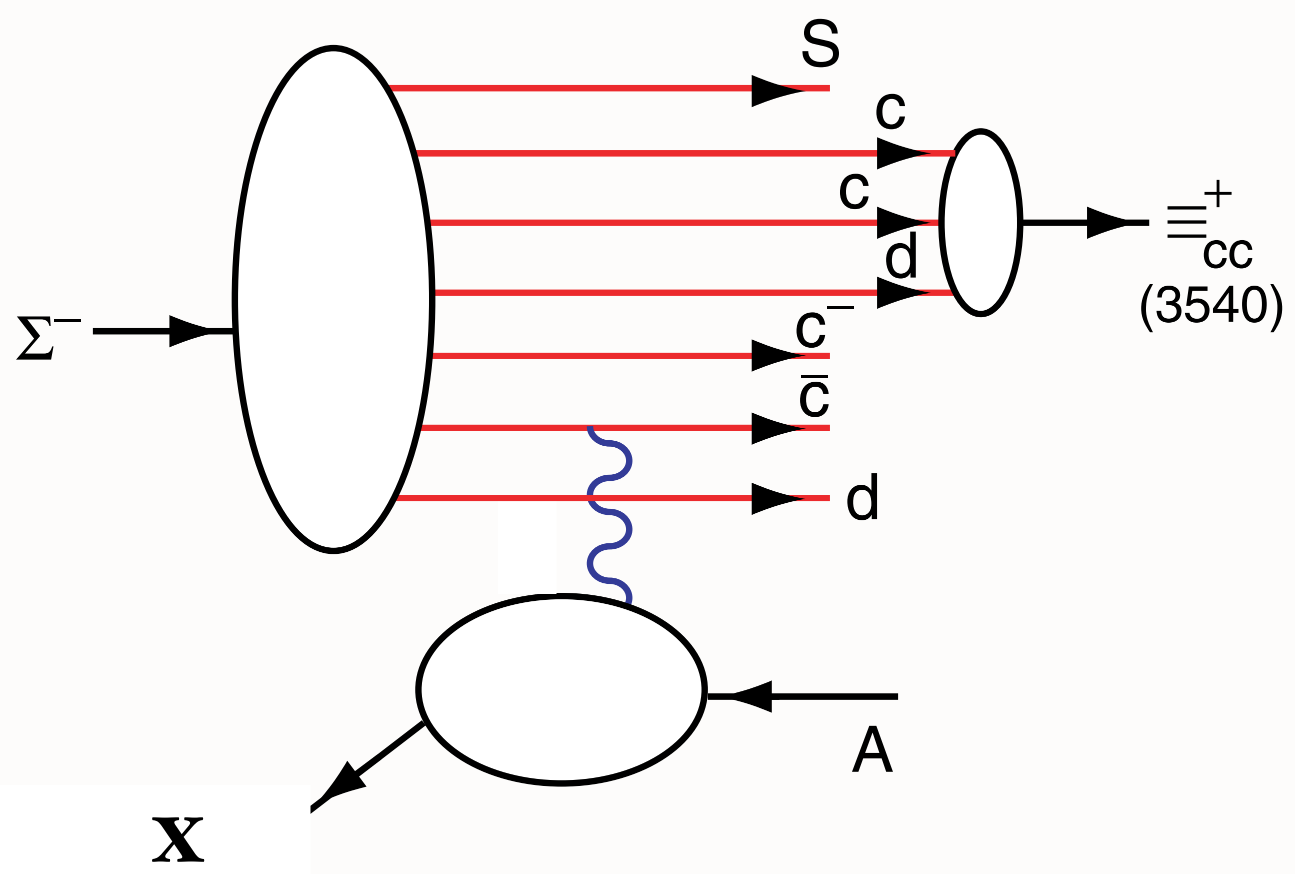
$\pi A \rightarrow J/\psi J/\psi X$

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

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

Excludes PYTHIA 'color drag' model



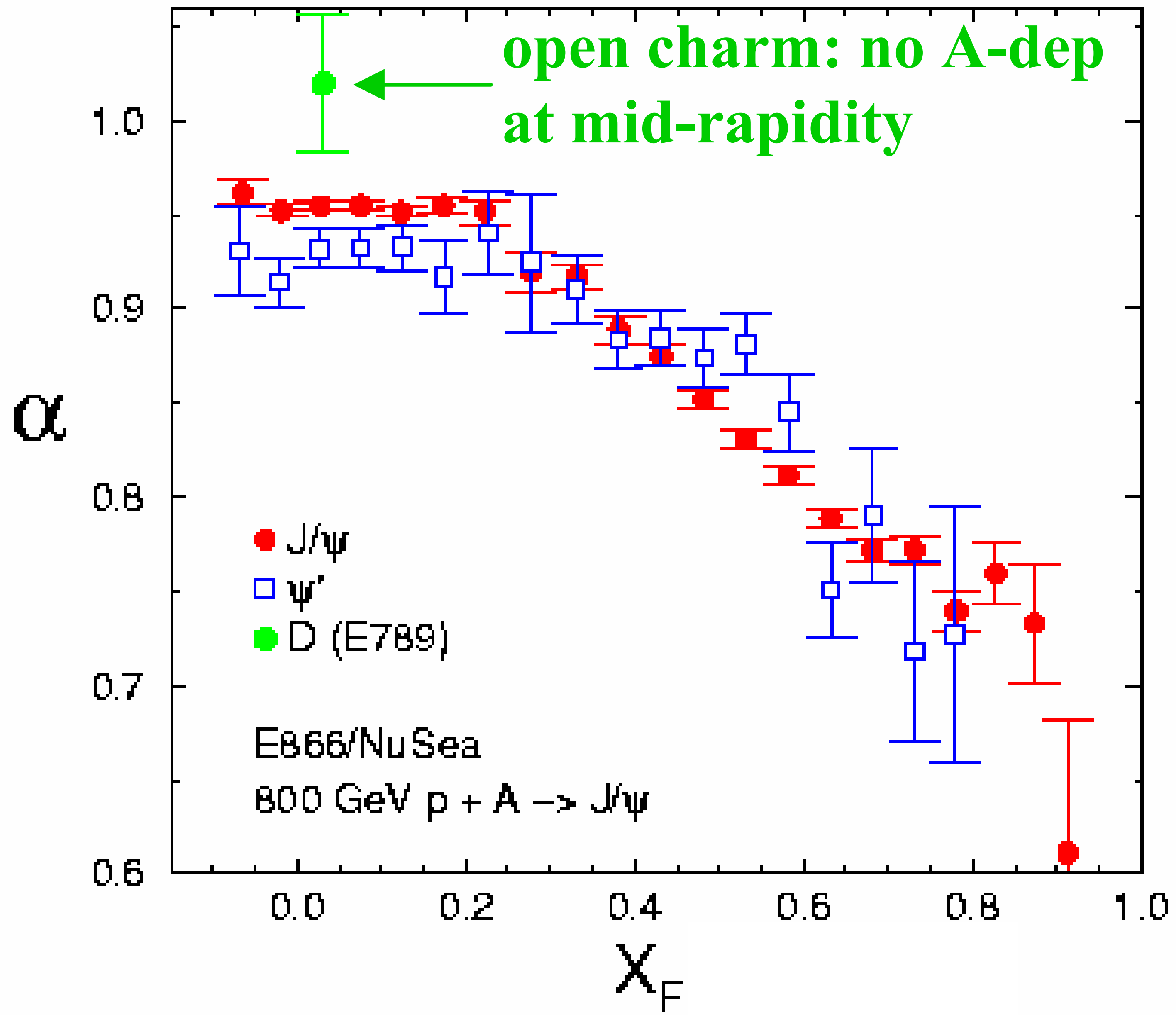
Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

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!

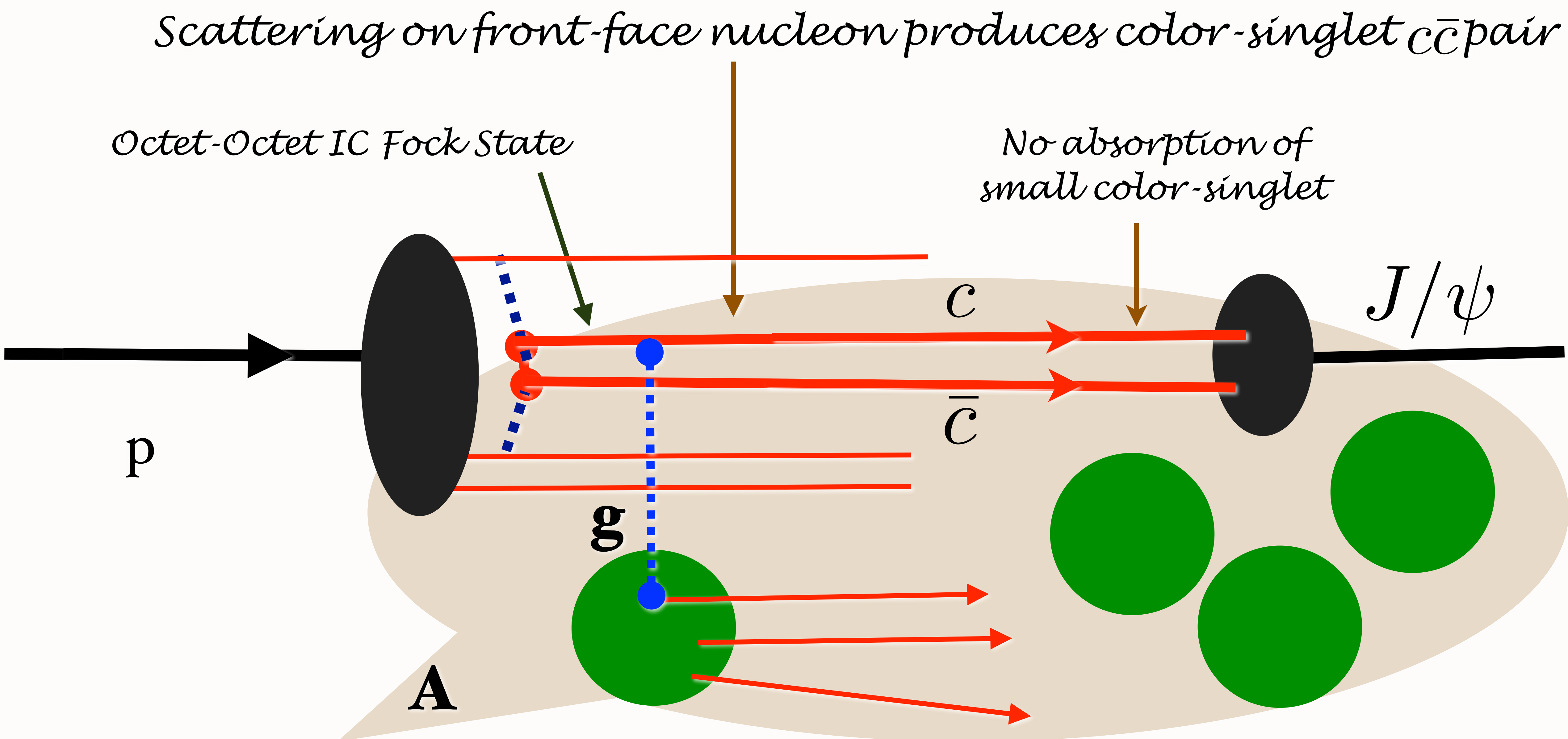
Violation of factorization in charm hadroproduction.
P. Hoyer, **M. Vanttinen** (**Helsinki U.**), **U. Sukhatme** (**Illinois U., Chicago**). **HU-TFT-90-14, May 1990. 7pp.**

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

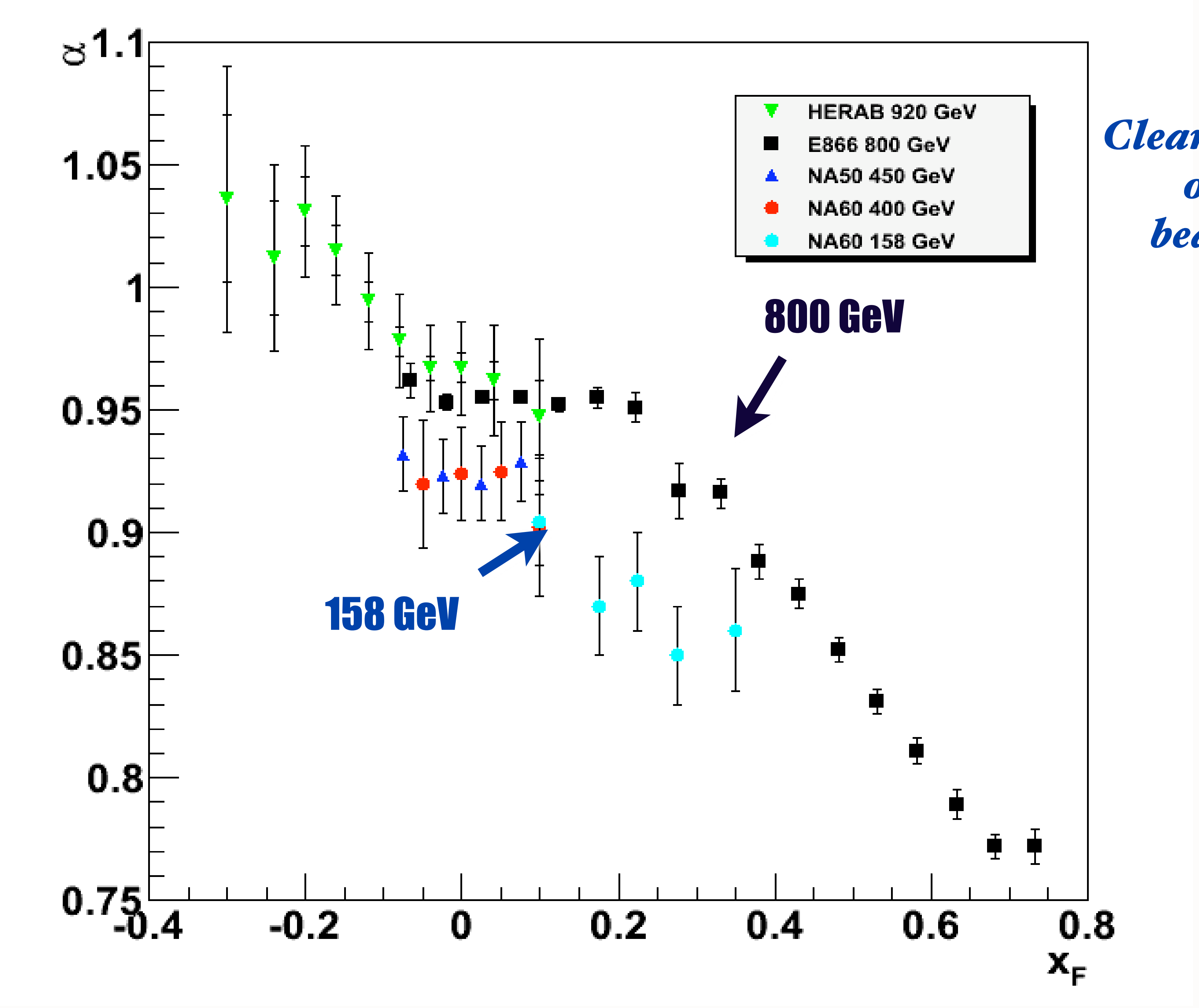


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

NA60 pA data @ 158GeV

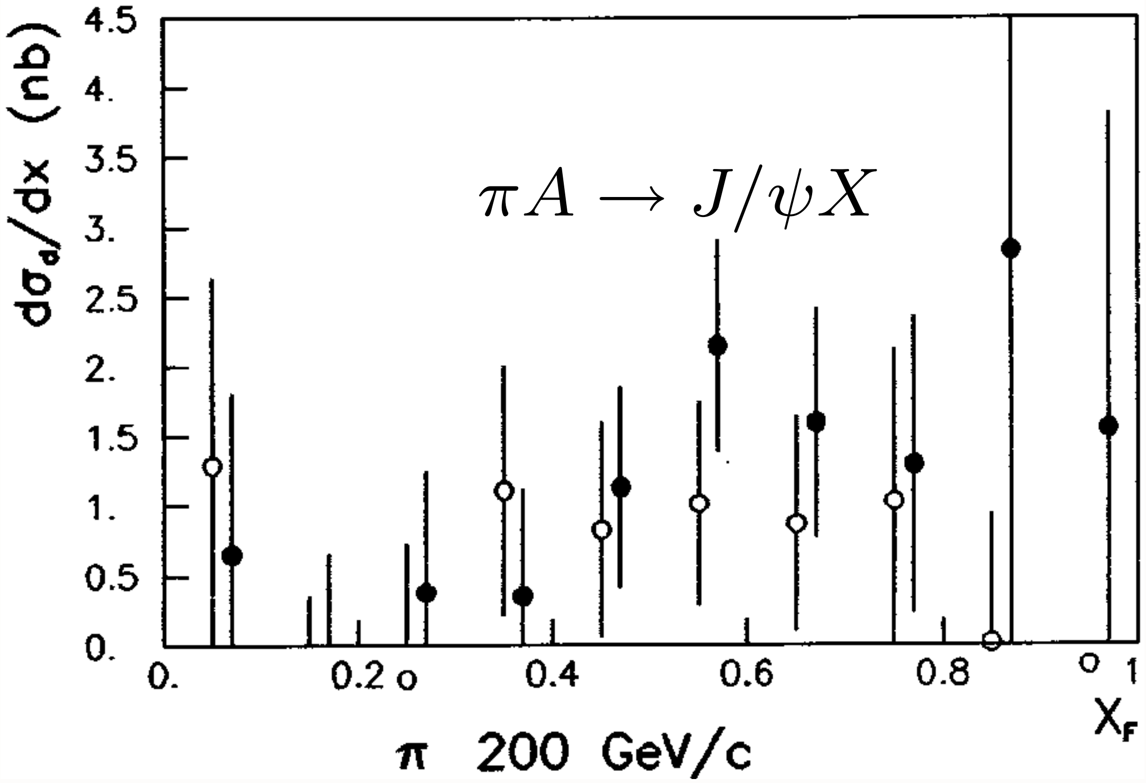
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) \propto A^{\alpha}$$

$\alpha(x_F)$



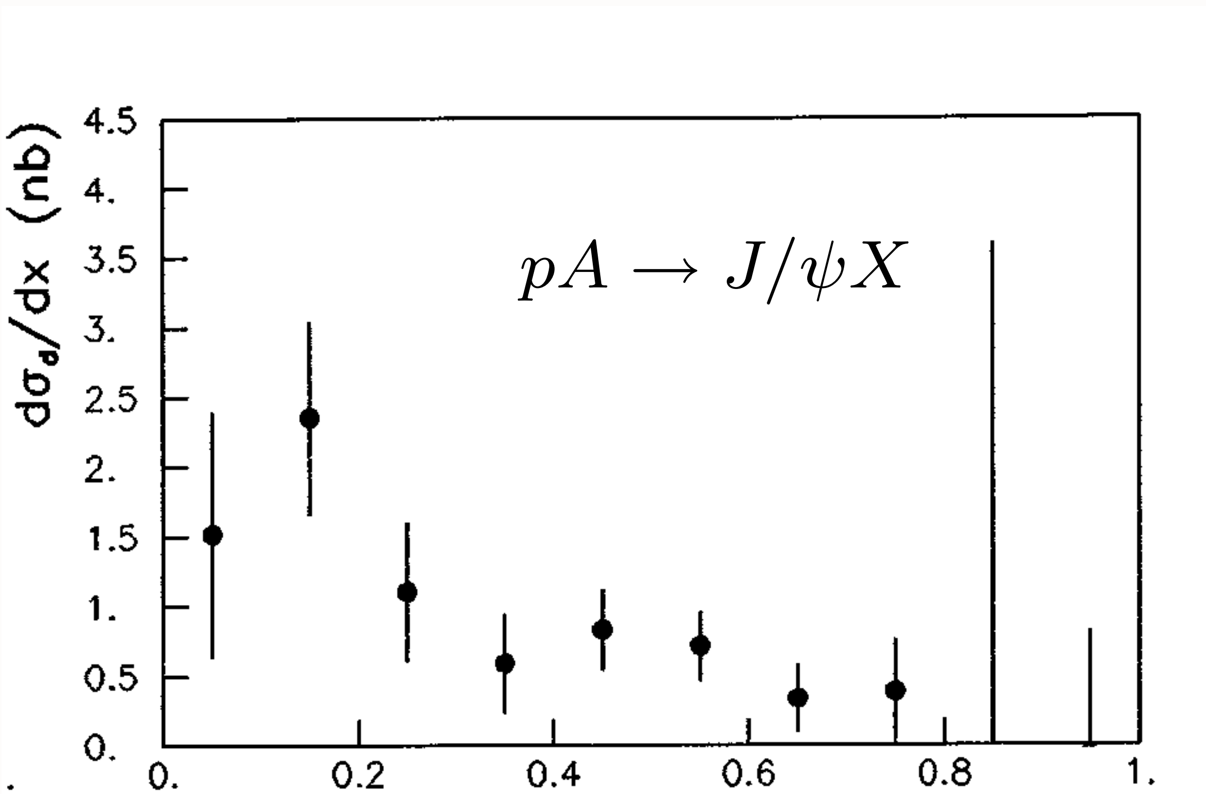
Clear dependence on x_F and beam energy

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



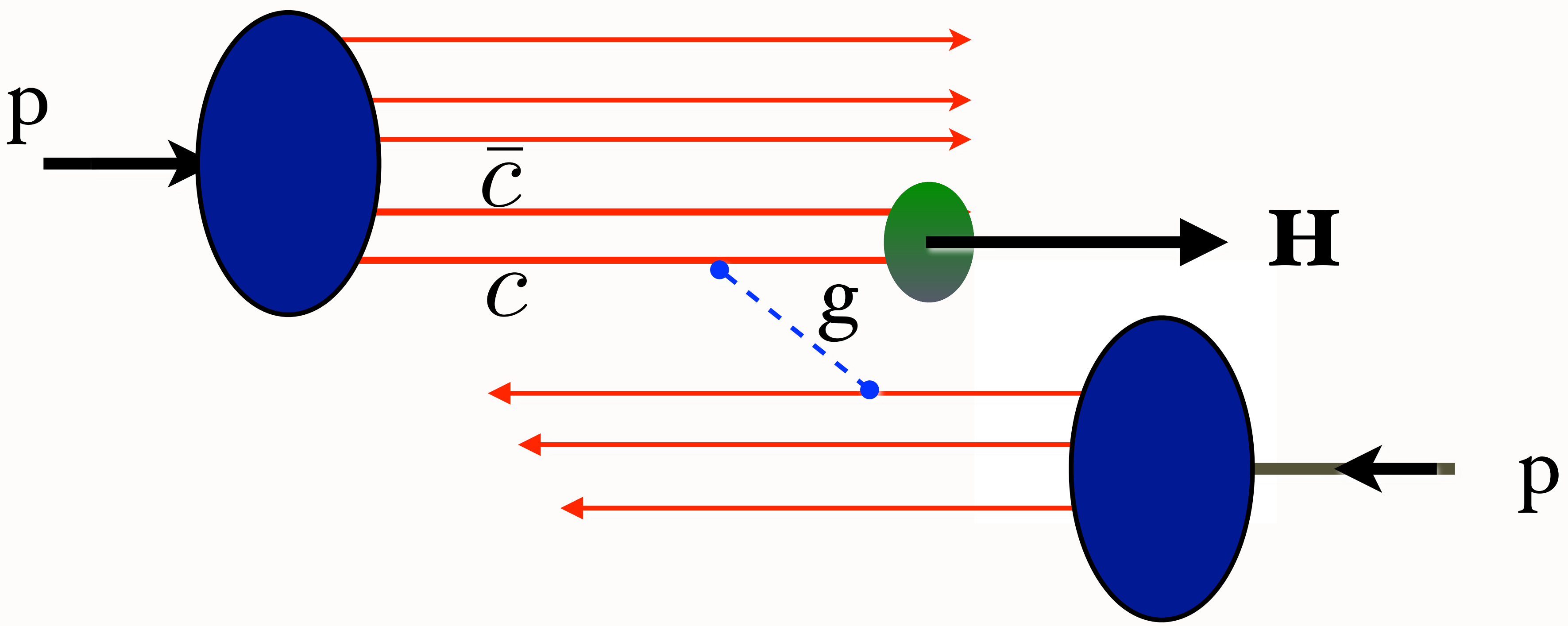
p 200 GeV/c

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



$$pp \rightarrow HX$$

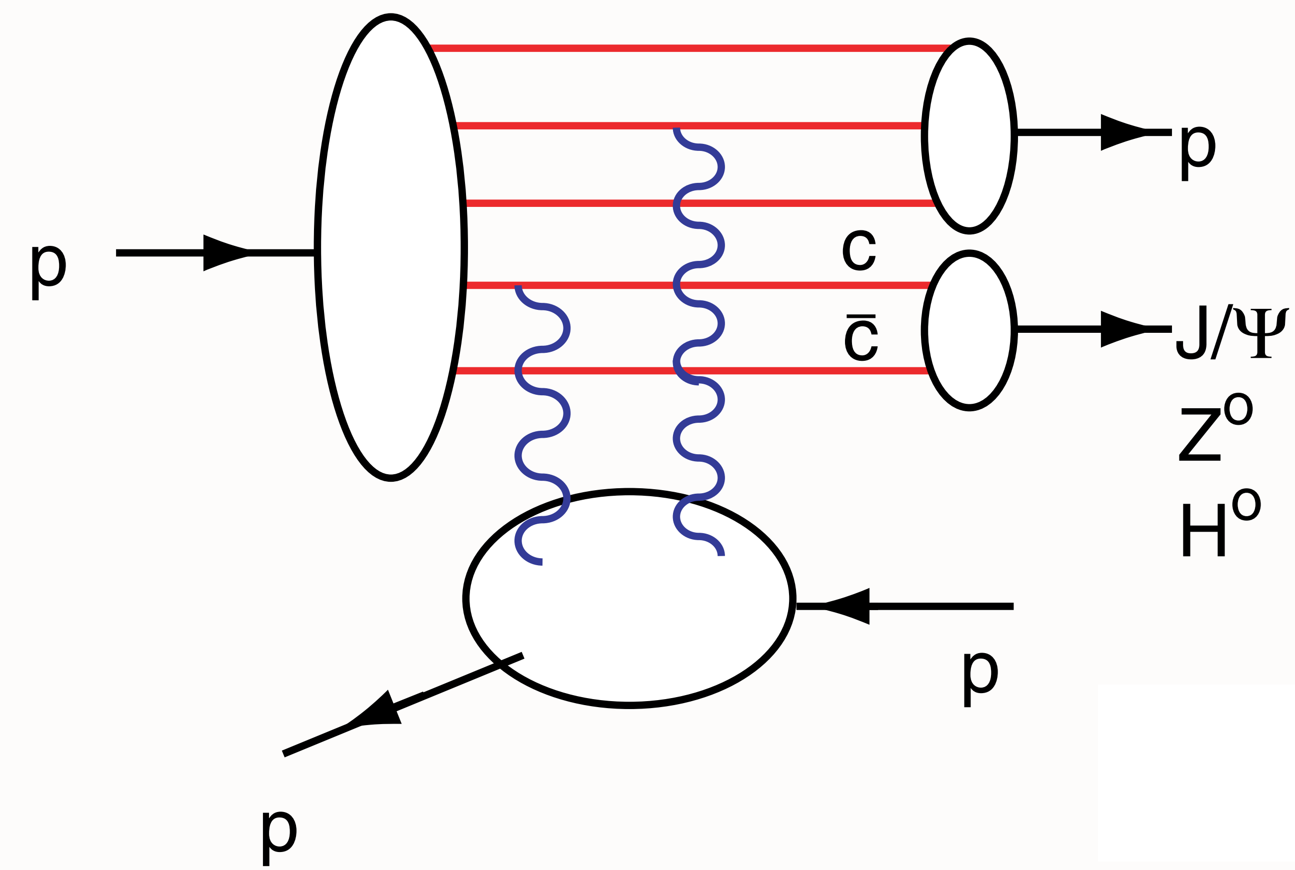
Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$p\,p \rightarrow J/\psi\, p\, p$$

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

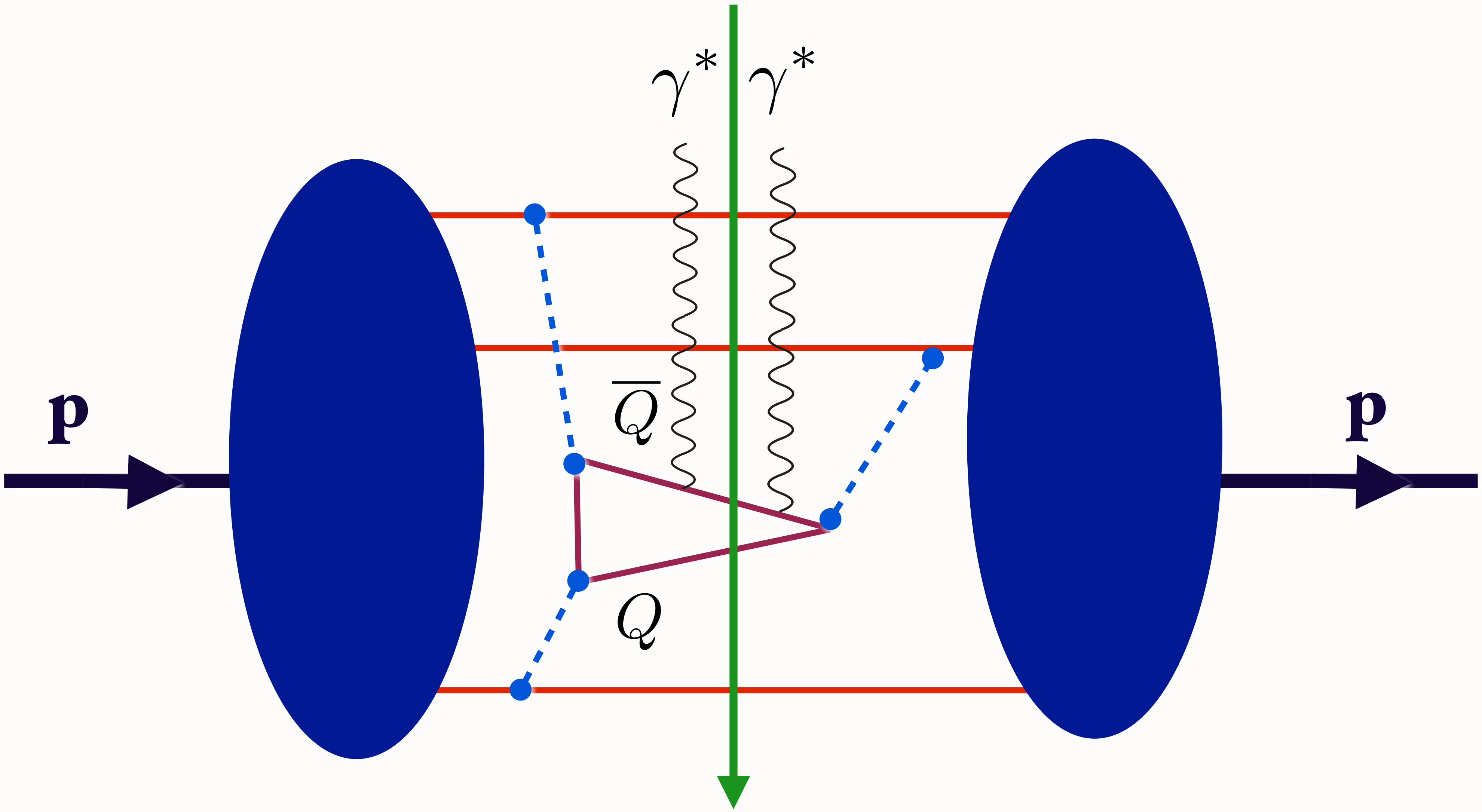
Exclusive Diffractive High-X_F Higgs Production

Kopeliovitch, Schmidt, Soffer, sjb

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

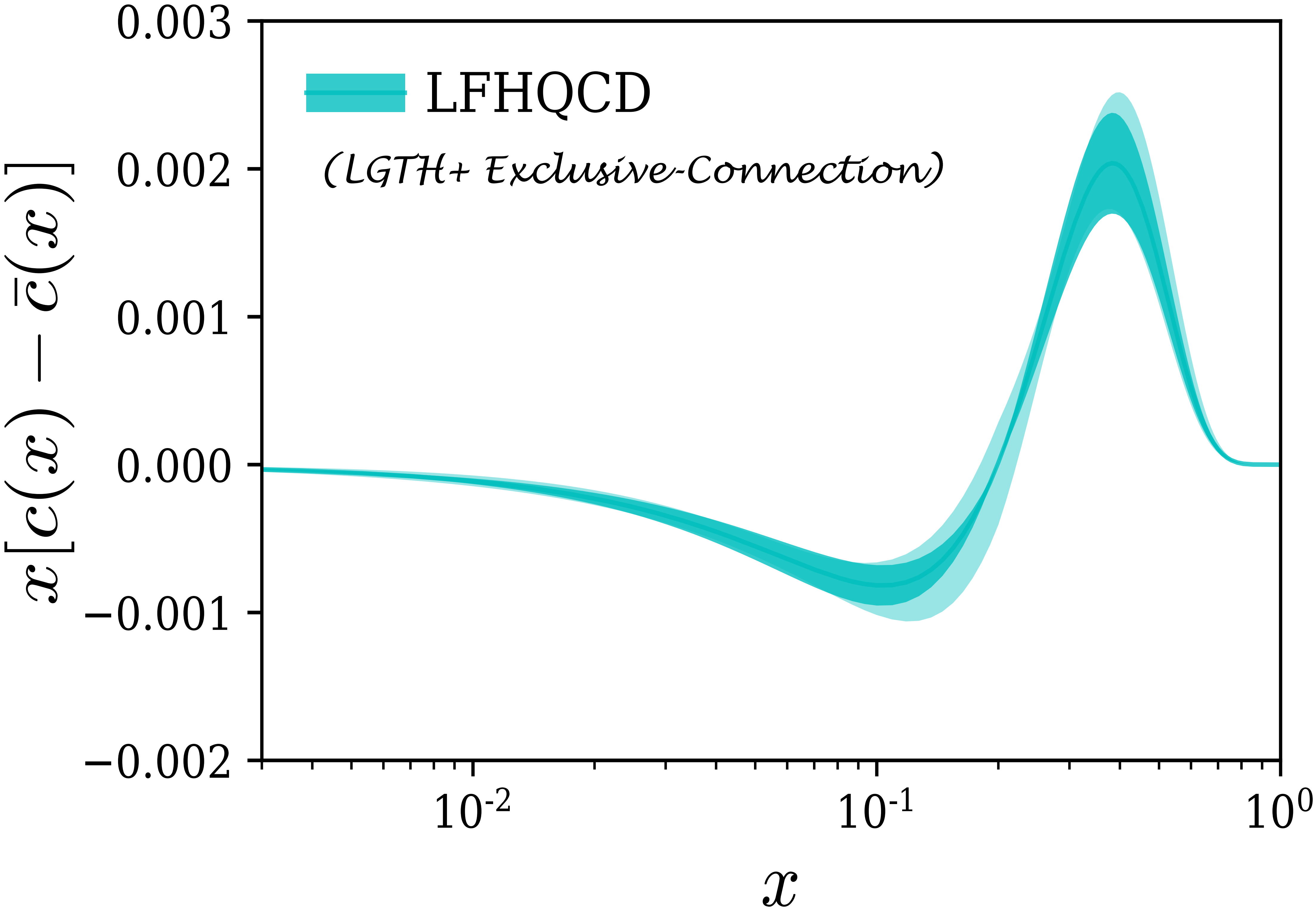
Collision produces color-singlet J/ψ through color exchange

RHIC Experiment



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

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



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%.

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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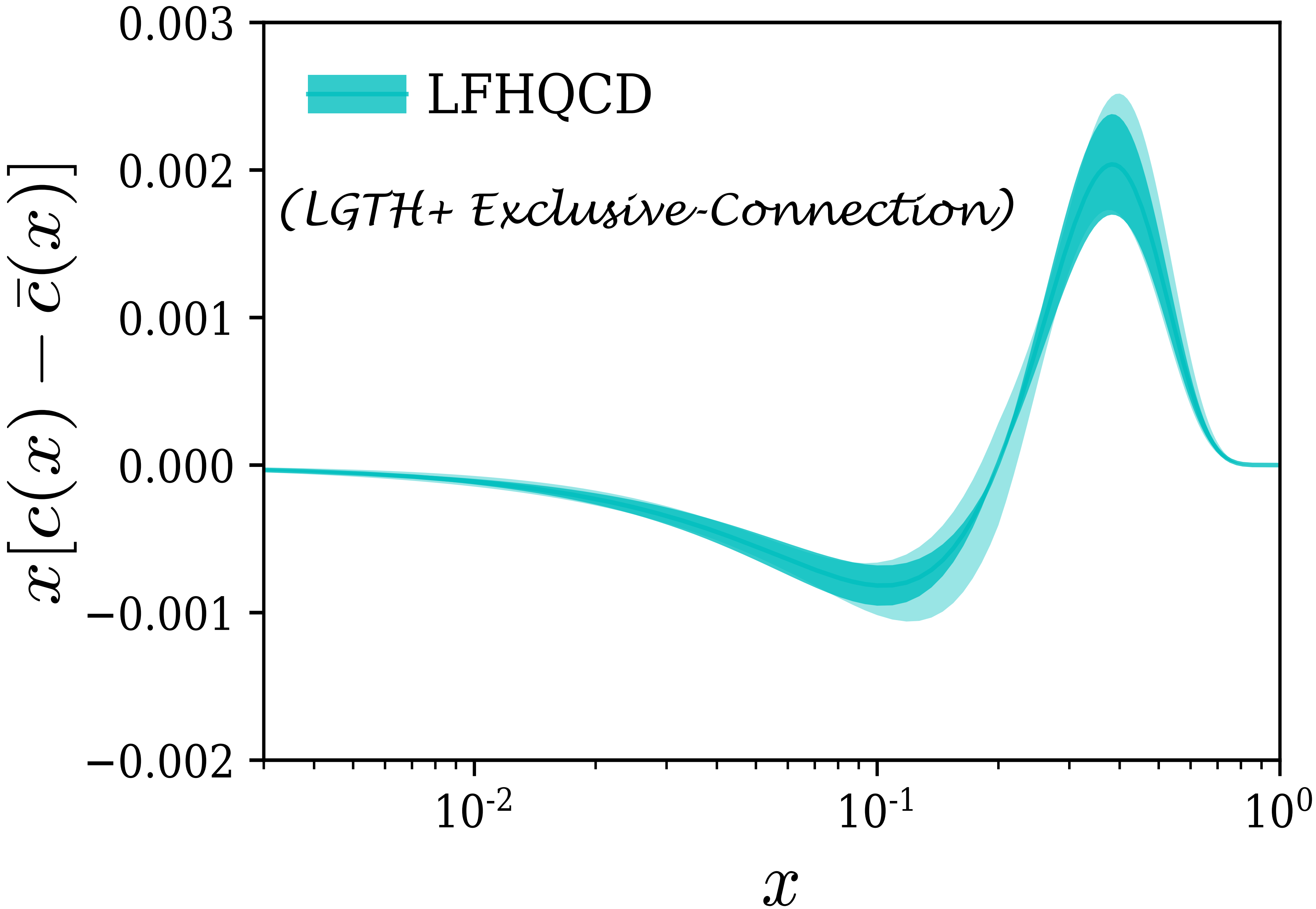
Abstract

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 $0 \leq Q^2 \leq 1.4\ \text{GeV}^2$. 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 $\mu^c_M = -0.00127(38)_{\text{stat}}(5)_{\text{sys}}$, as well as the Pauli form factor, reflects a nontrivial role of the charm sea in the nucleon spin structure. The nonzero $G^c_E(Q^2)$ 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



Predict charm hadron asymmetries

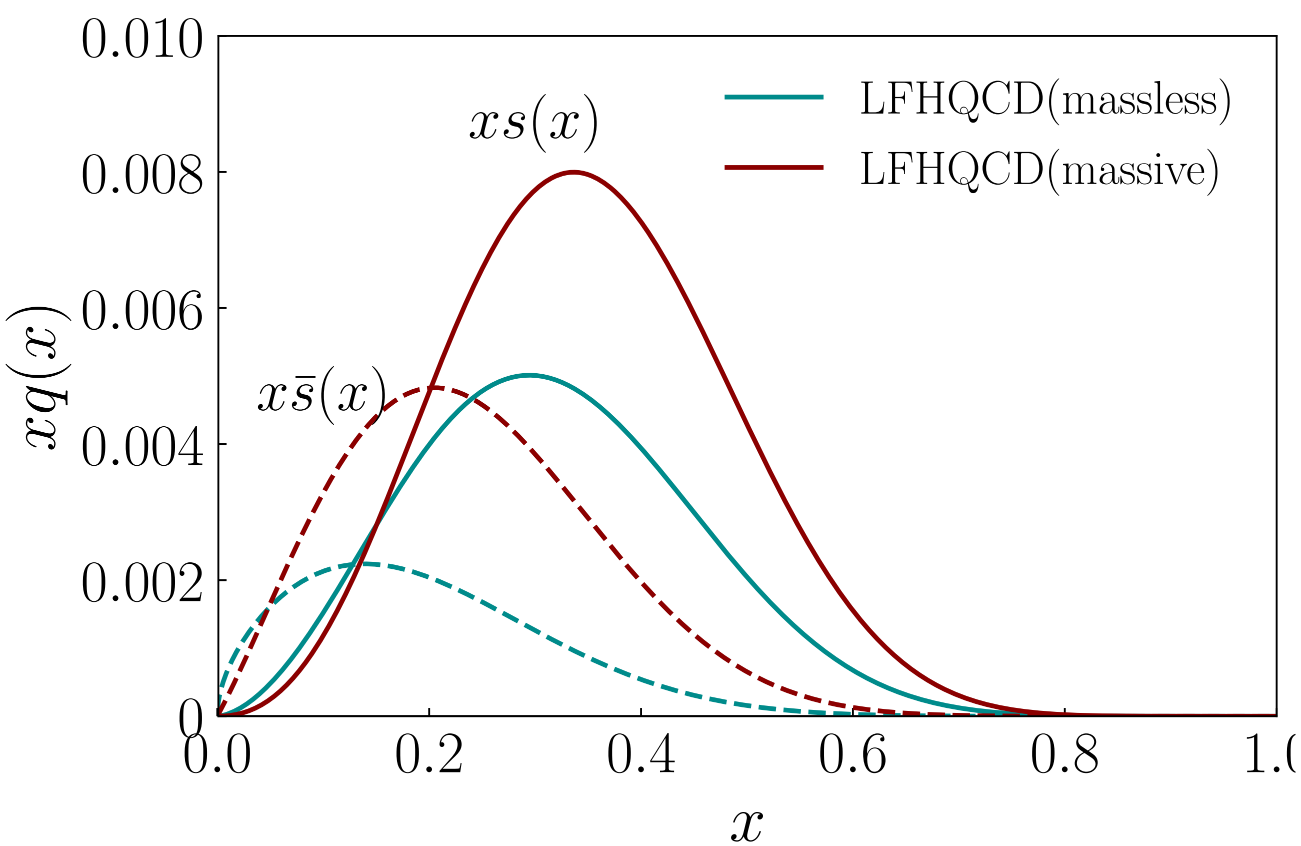
$$\frac{d\sigma}{dx_F\,dp_T^2}(pp \to D^+(c\bar{d})X) > \frac{d\sigma}{dx_F\,dp_T^2}(pp \to D^-(\bar{c}d)X)$$

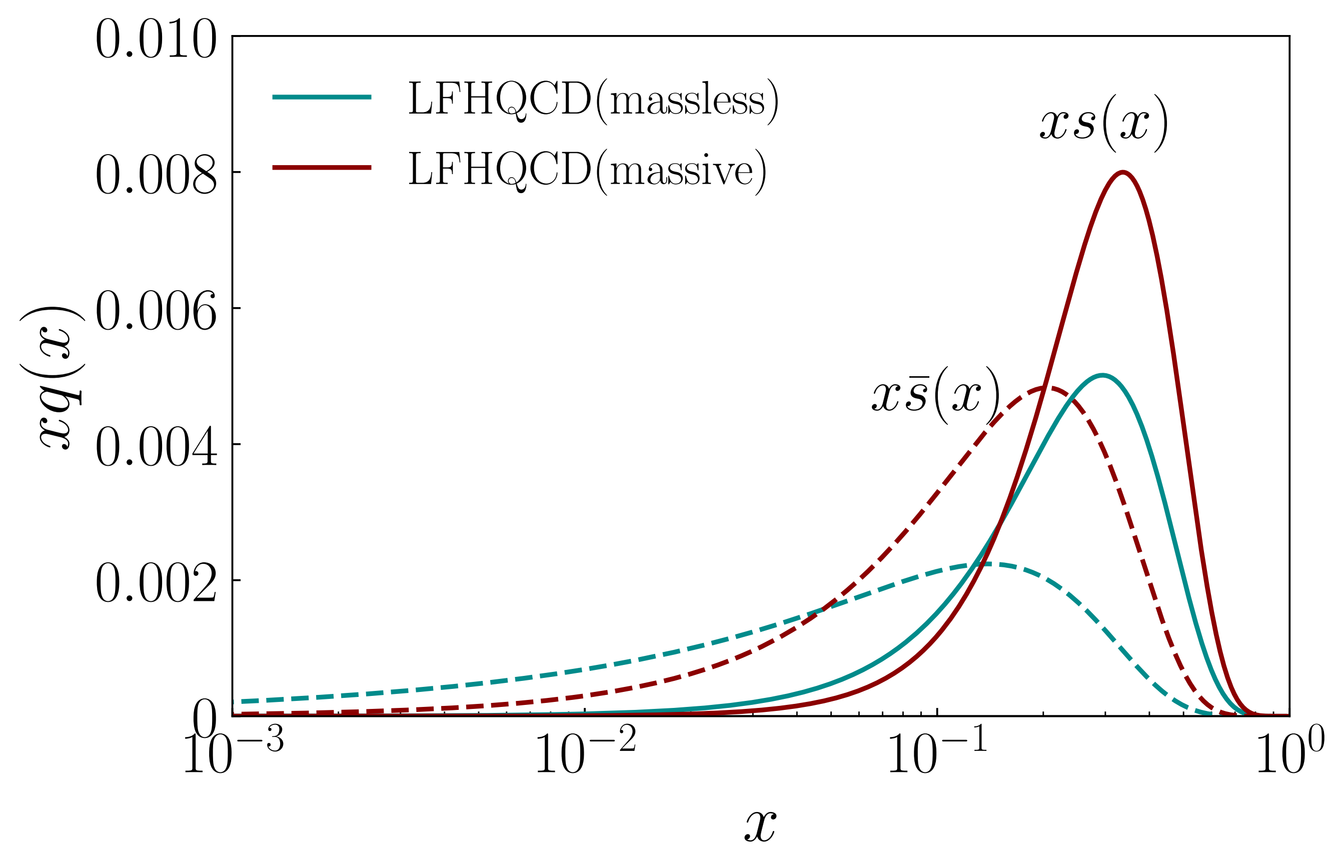
at high p_T and high x_F

Strange and Antistrange Distributions

Input: nonzero lattice axial form factor

Duality with $|K\Lambda>$ meson-nucleon fluctuations





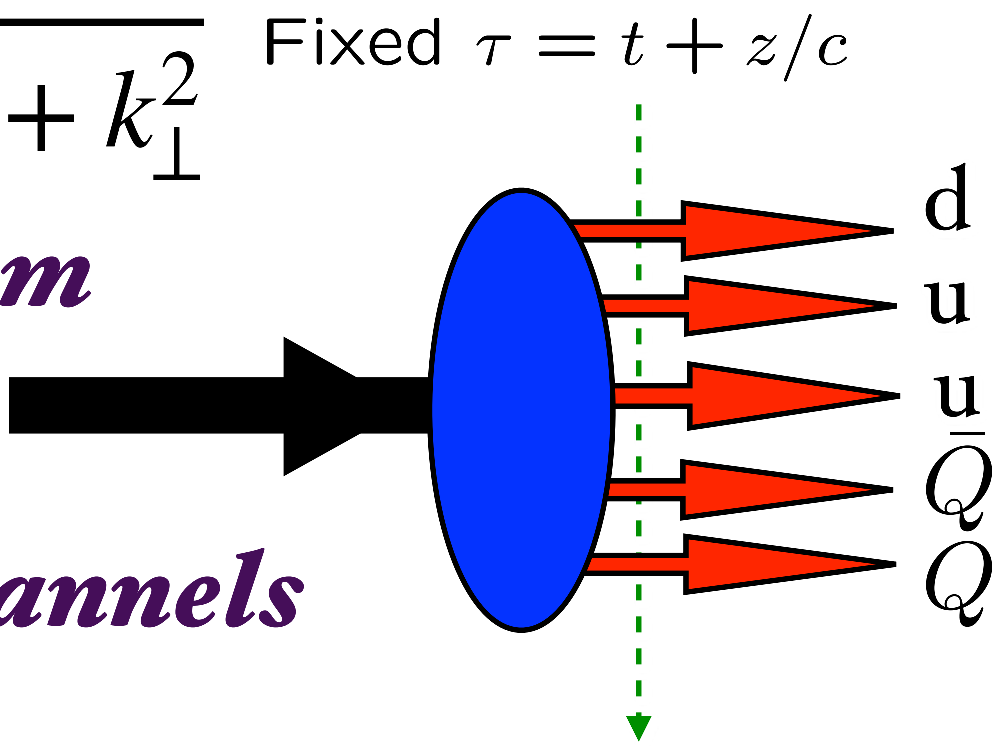
Phys. Rev. D 98, 114004 (2018).

R. S. Sufian, T.Liu, de Teramond, Dosch, Deur, Islam, Ma, sjb

Properties of Non-Perturbative Five-Quark Fock-State

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

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

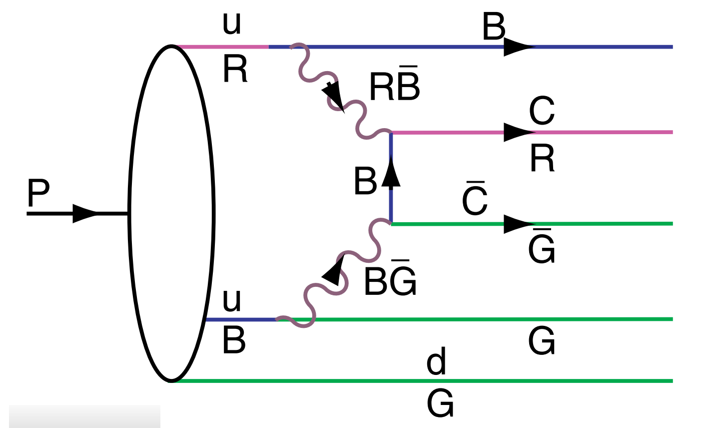


- ***Correlated with proton quantum numbers***
- ***Duality with meson-baryon channels***
- ***Strangeness, charm asymmetry at x > 0.1***

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

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

Intrinsic Heavy-Quark Fock States

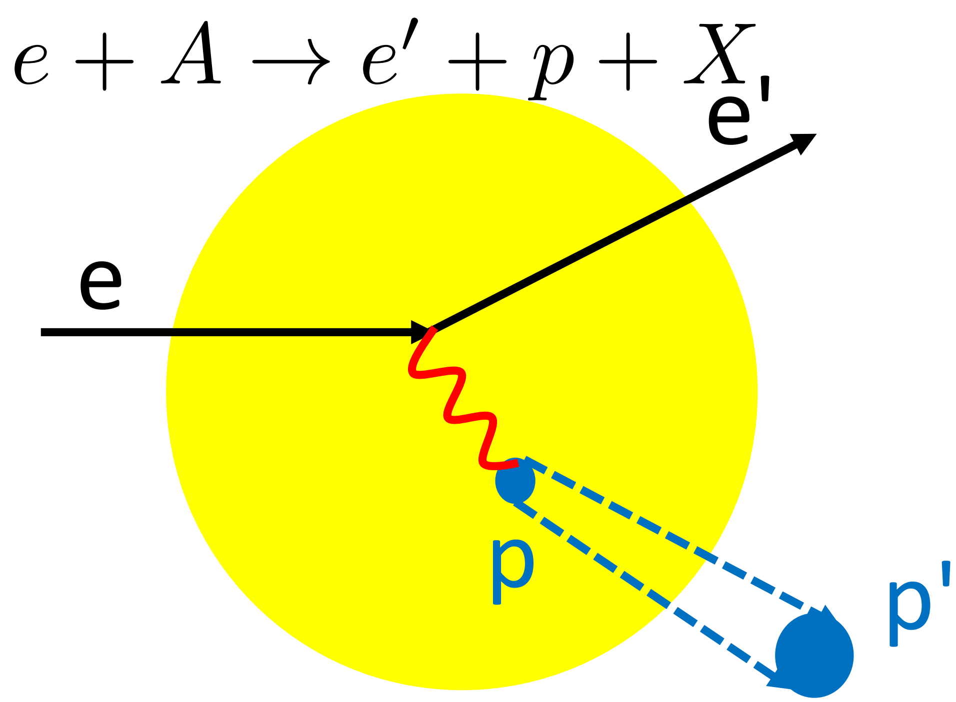


- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production at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

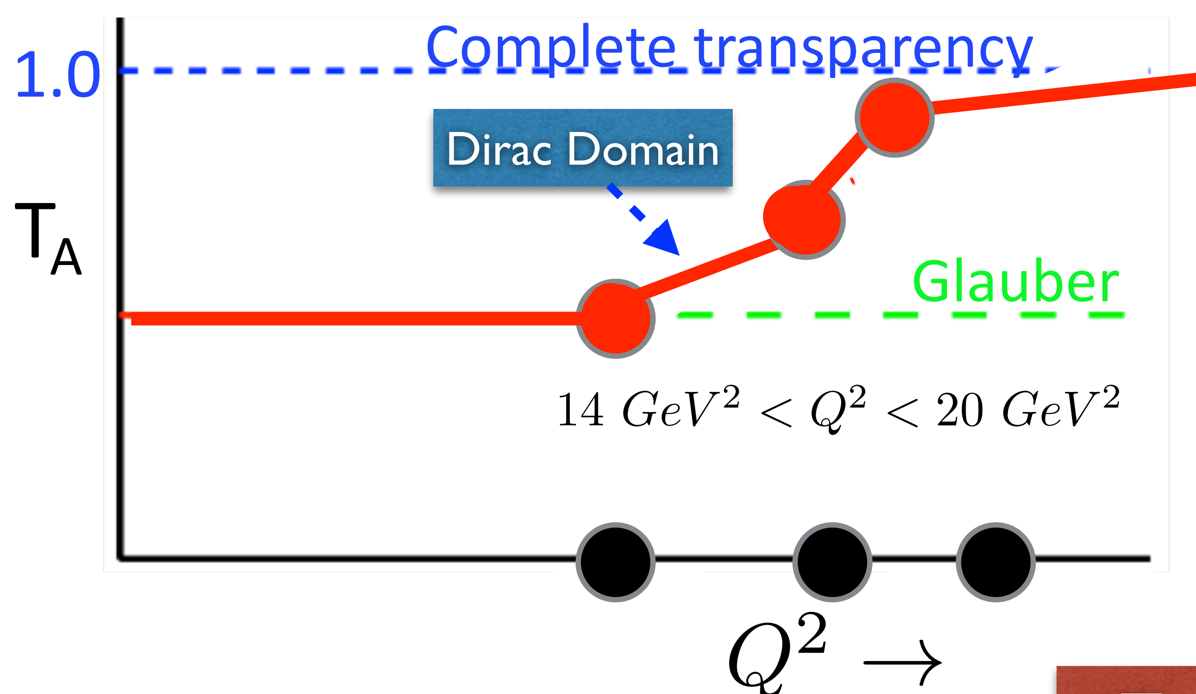
Review: G. Lykasov, et al

A.H. Mueller, sjb

Color transparency: fundamental prediction of QCD



- 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



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

σ_A (nuclear cross section)

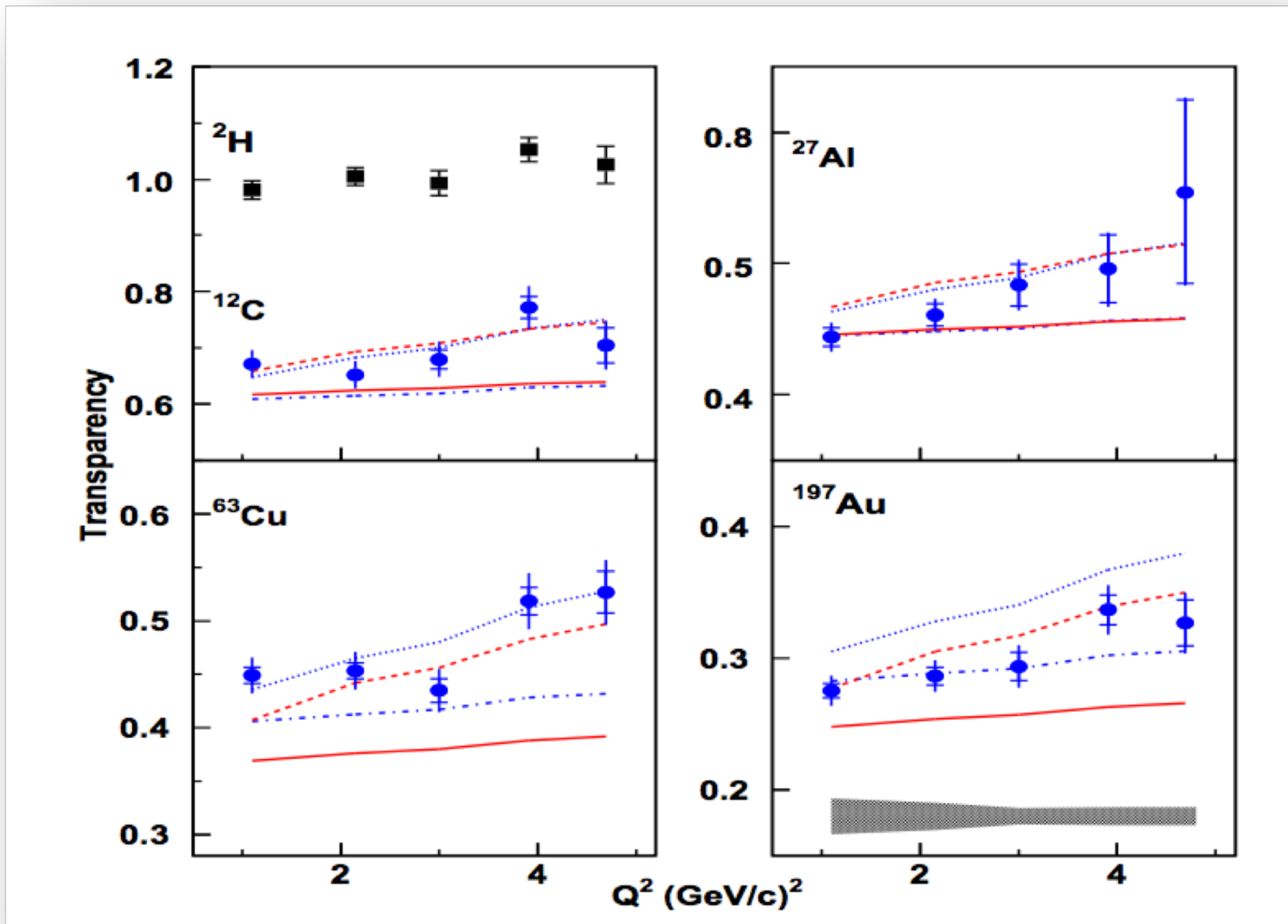
σ_N (free nucleon cross section)

Two-Stage Color Transparency for Proton

Color Transparency verified for π^+ and ρ electroproduction

Hall C E01-107 pion electro-production

A(e,e'π^+)

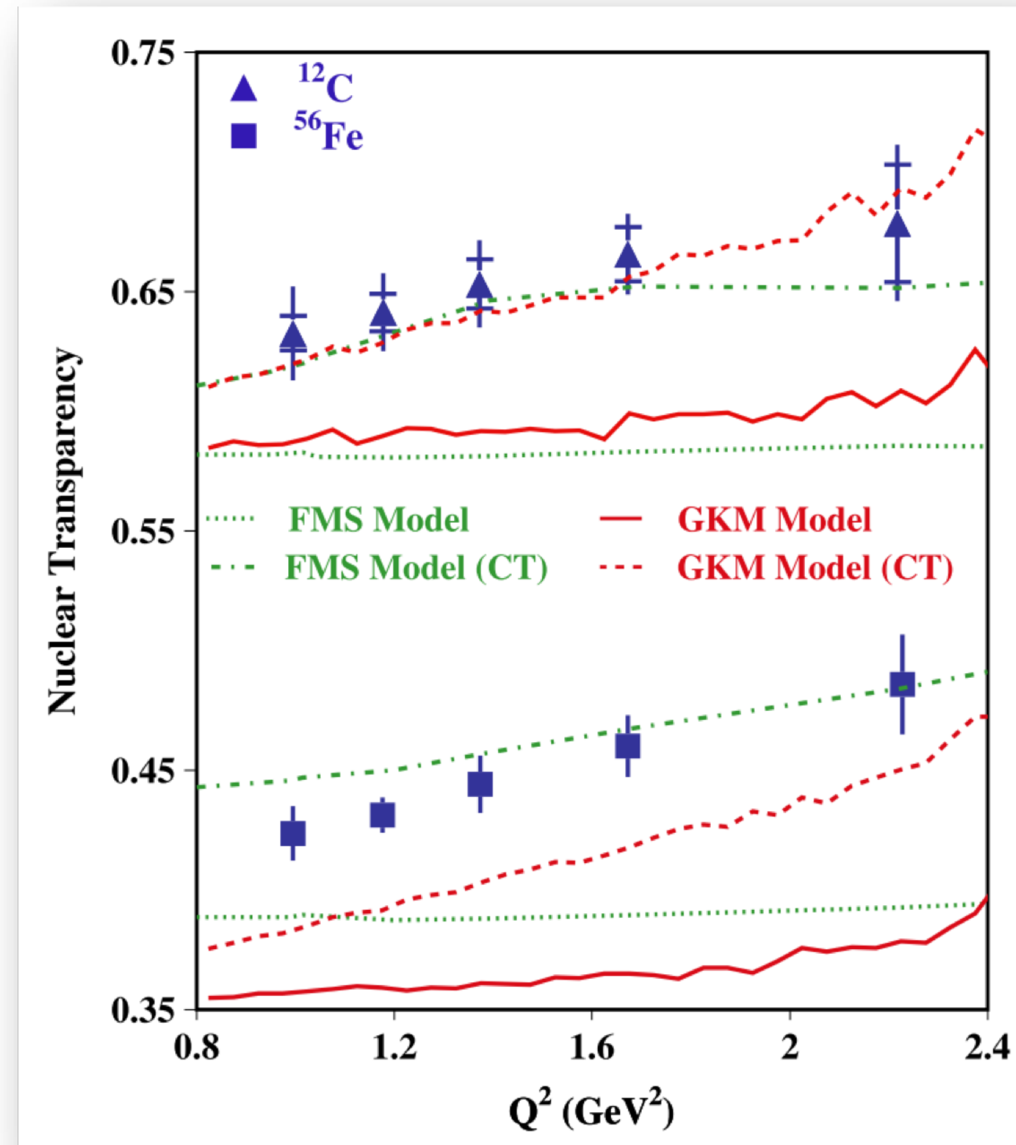


B.Clasie *et al.* PRL 99:242502 (2007)

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

CLAS E02-110 rho electro-production

A(e,e'ρ^0)



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

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

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

$$F(q^2) =$$

G. de Teramond, sjb

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

$$\sum_i x_i = 1$$

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

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

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:

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

For large Q2 :

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

Drell-Yan-West Formula in Impact Space

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

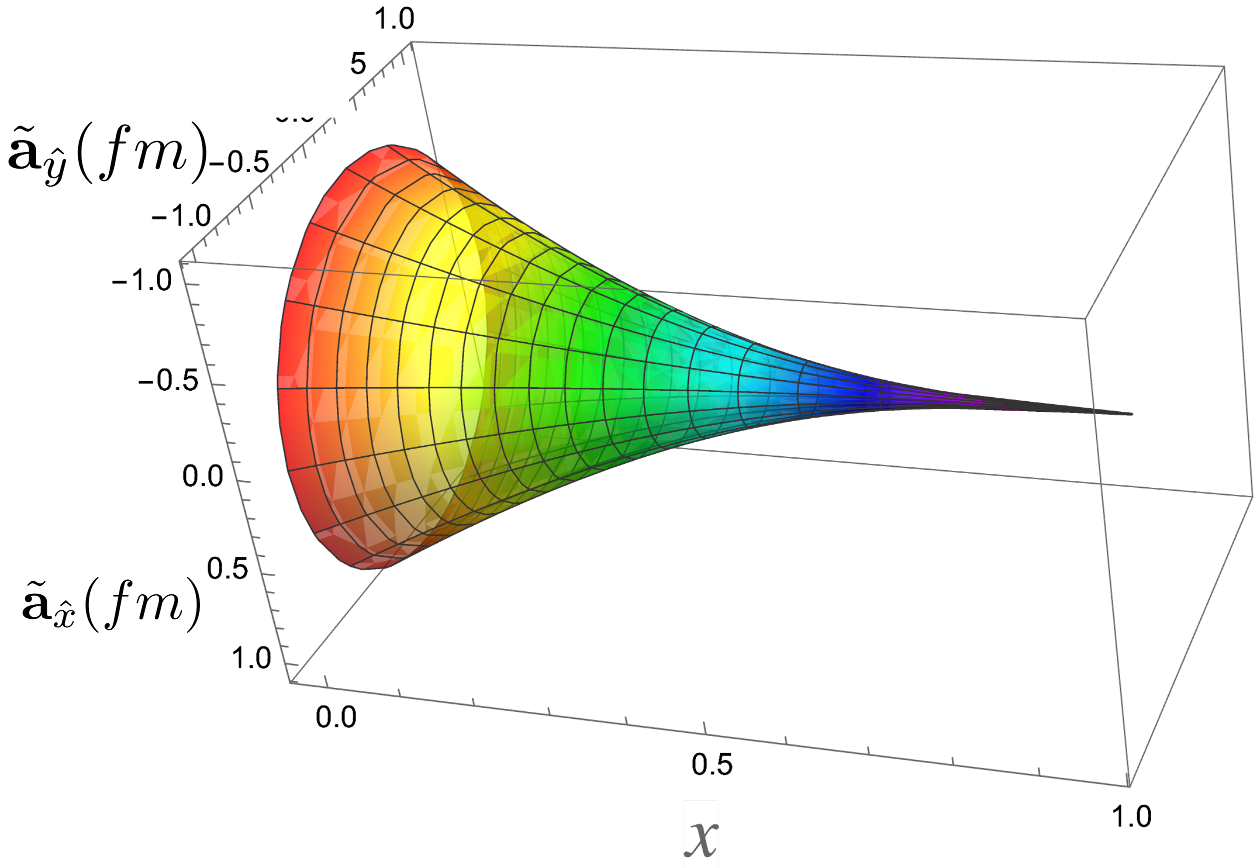
$$\sum_j e_j \psi_n^*(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\psi_n(x_i, \mathbf{k}_{\perp i}, \lambda_i),$$

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

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

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

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



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

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)

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

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

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

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

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

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

$$M_0 = m_\rho$$

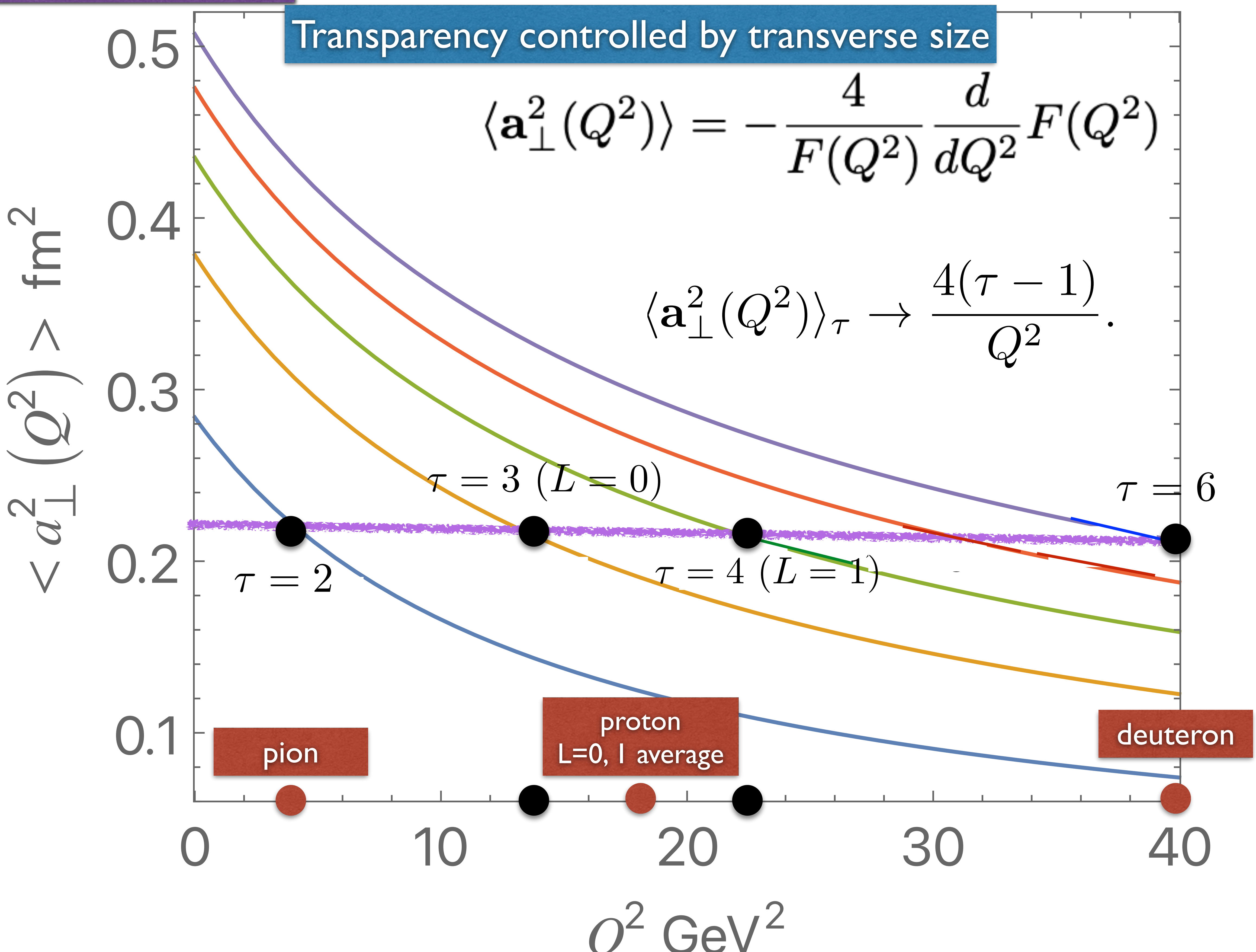
$$\sqrt{\lambda} = \kappa = \frac{m_\rho}{\sqrt{2}} = 0.548\ GeV$$

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

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

Transparency scale Q increases with twist

Light-Front Holography



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

Two-Stage Color Transparency

$$14\ GeV^2 < Q^2 < 20\ GeV^2$$

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).

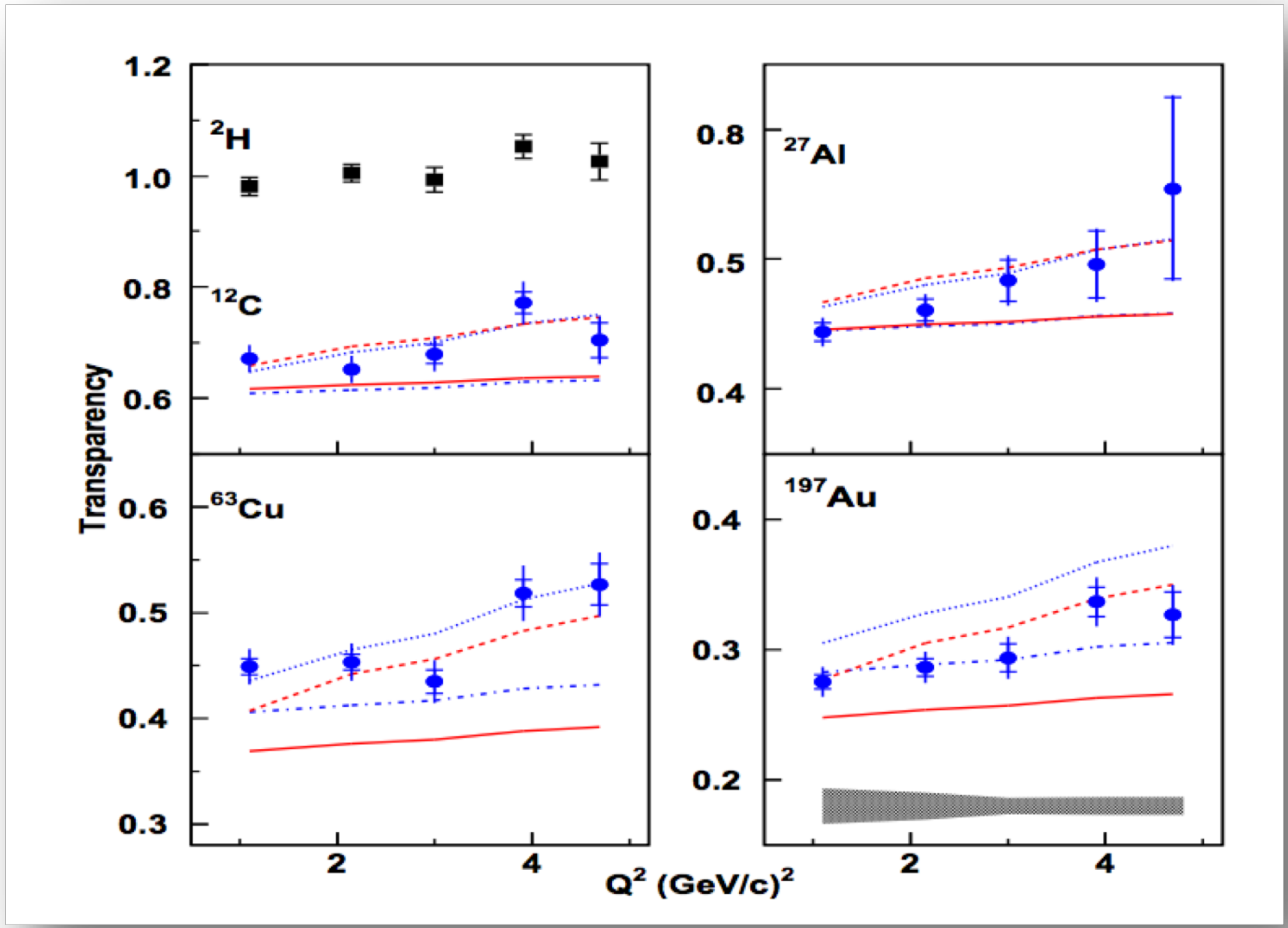
The $ep \to e'p'$ cross section will have the same angular and Q^2 dependence as scattering of the electron on an unphysical proton which has no Pauli form factor.

$$Q^2 > 20\ GeV^2$$

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

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

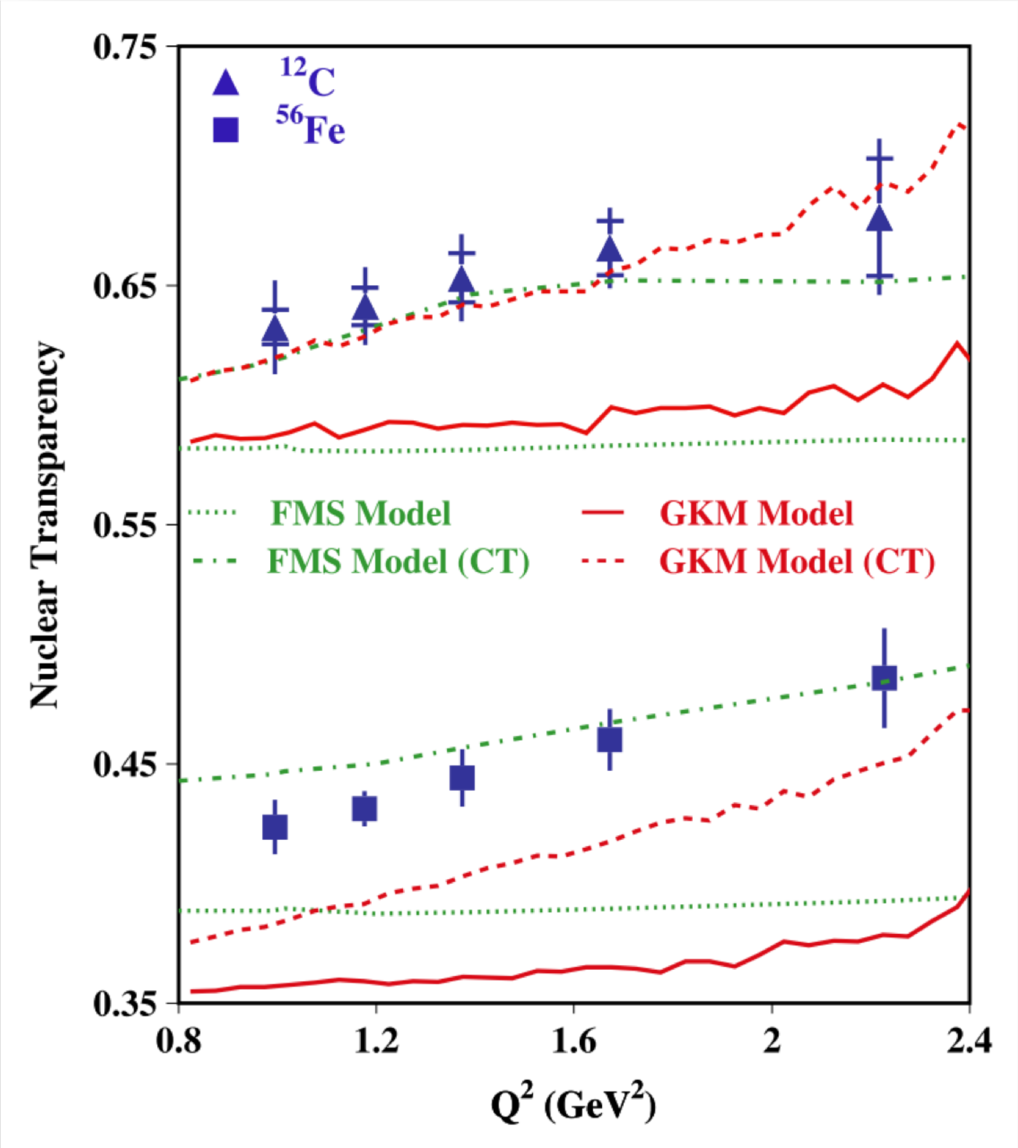


B.Clasie *et al.* PRL 99:242502 (2007)

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)

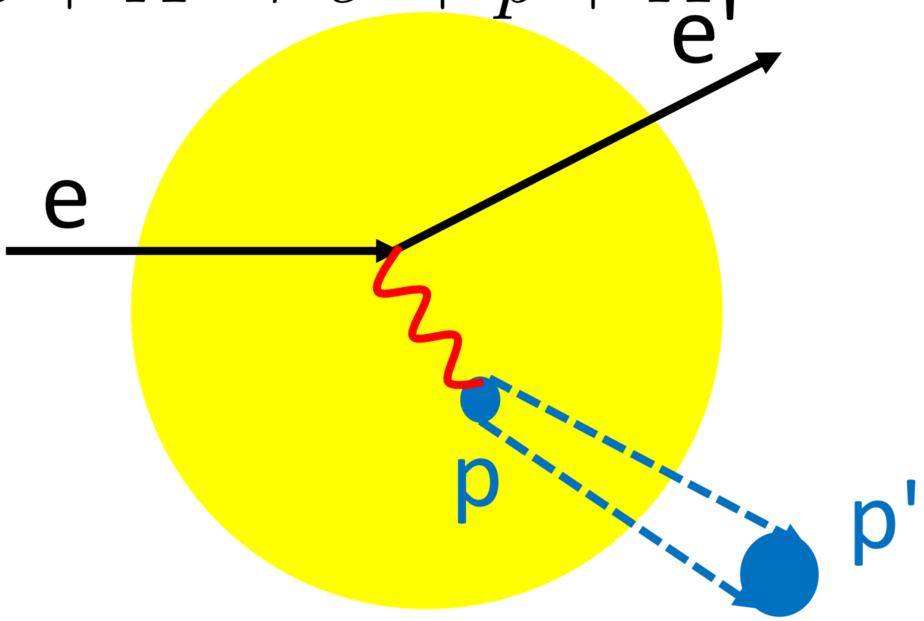
$$< a_\perp^2(Q^2 = 4\ GeV^2) >_{\tau=2} \simeq < a_\perp^2(Q^2 = 14\ GeV^2) >_{\tau=3} \simeq < a_\perp^2(Q^2 = 22\ GeV^2) >_{\tau=4} \simeq 0.24\ fm^2$$

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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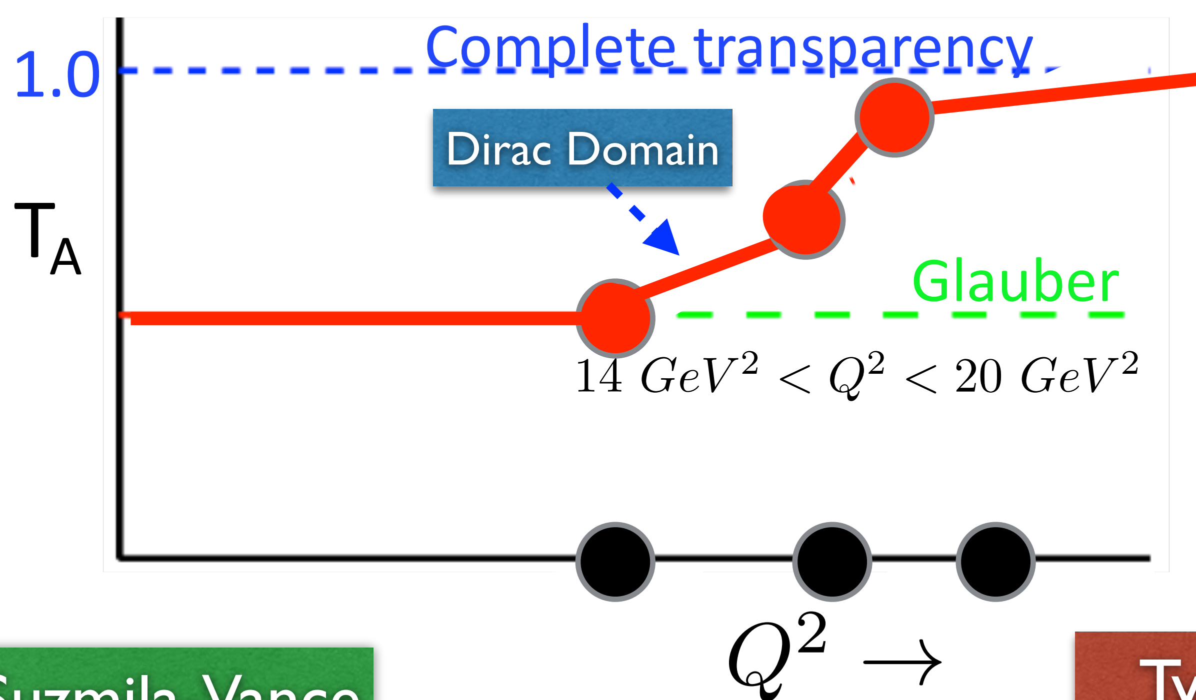


$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$

(nuclear cross section)

(free nucleon cross section)

Holly Suzmila-Vance

Two-Stage Color Transparency for Proton

Color Transparency and Light-Front Holography

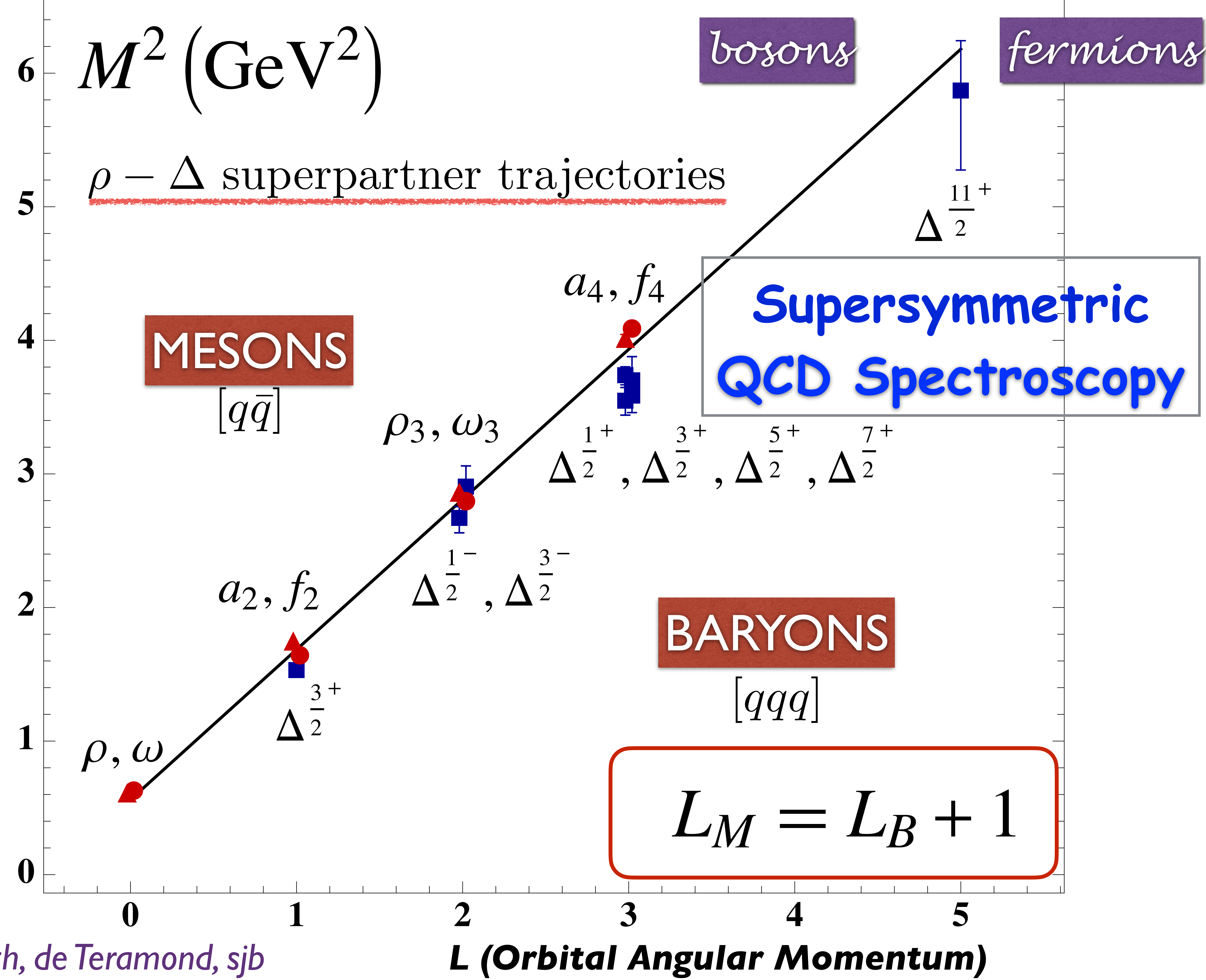
- Essential prediction of QCD
- LF Holography: Spectroscopy, dynamics, structure
- Transverse size predicted by LF Holography as a function of Q
- Q scale for CT increases with twist, number of constituents
- Two-Stage Proton Transparency: Equal probability L=0,1
- No contradiction with present experiments

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

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



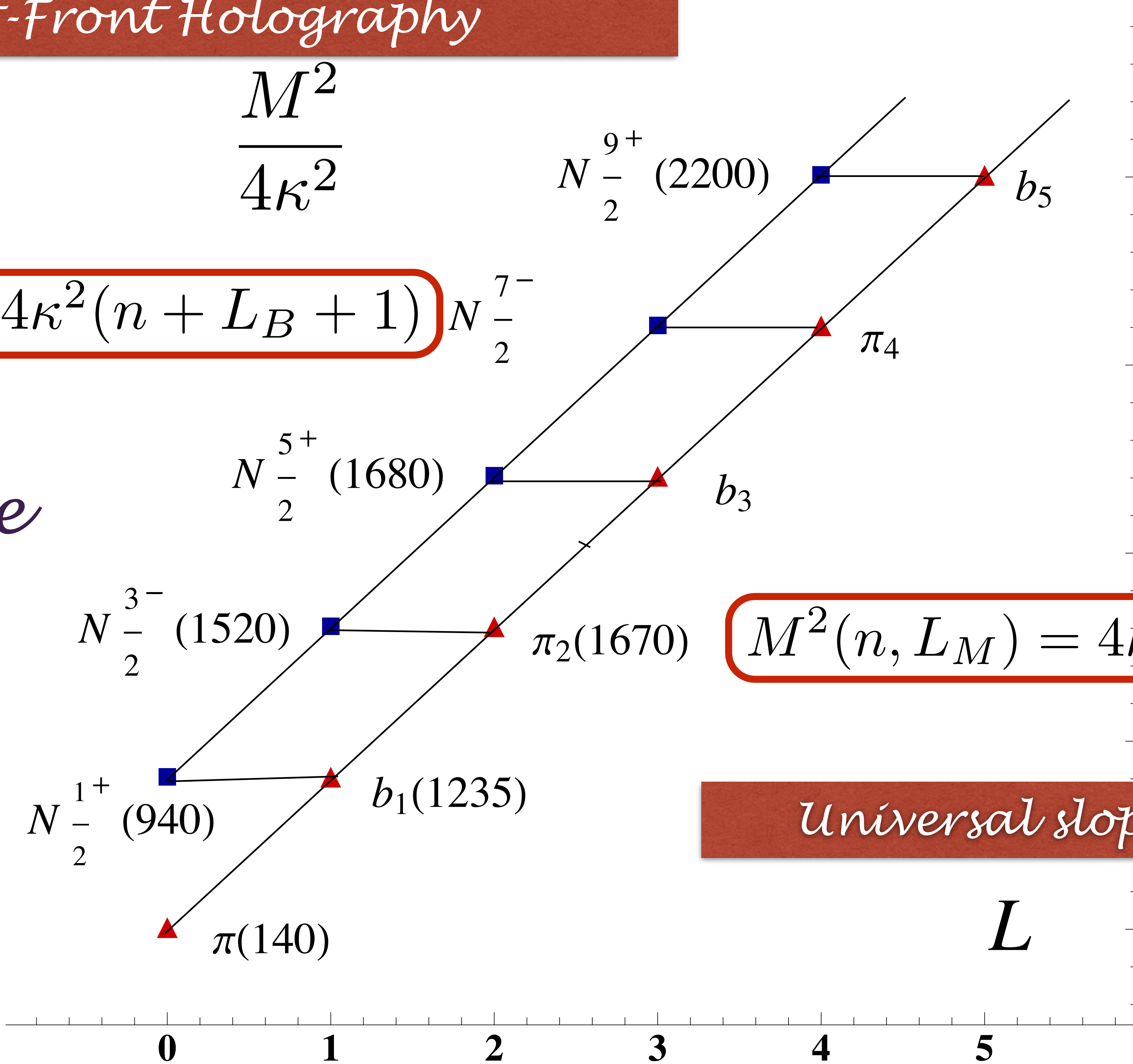
Dosch, de Teramond, sjb

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

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

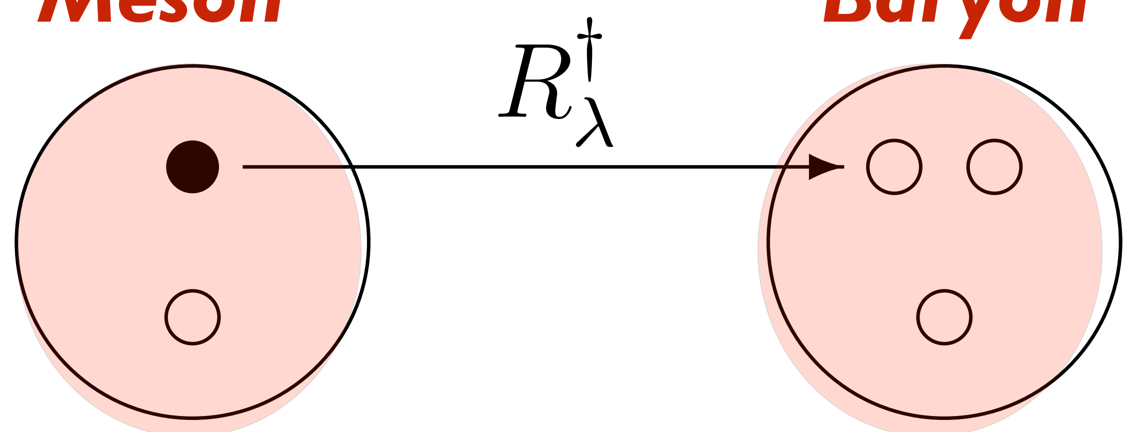
Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

Superconformal Algebra

Four-Plet Representations

Bosons, Fermions with Equal Mass!

Meson **Baryon**



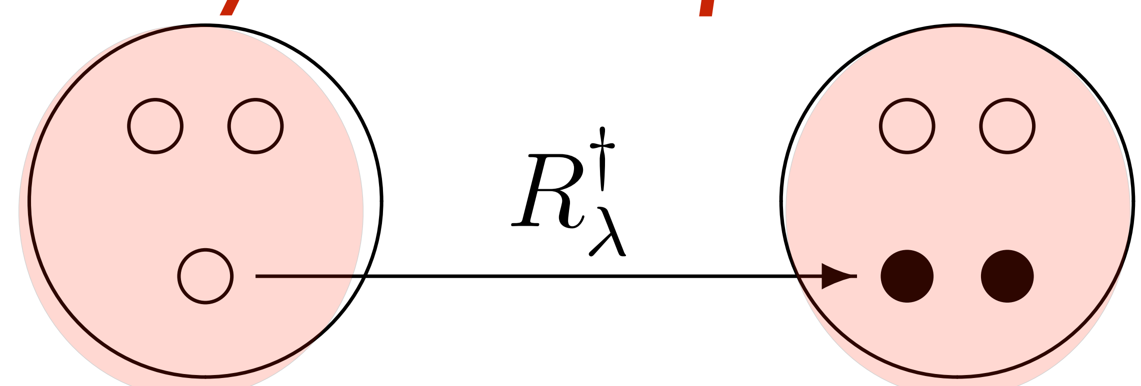
$\phi_M, \ L_B + 1$ $\psi_{B+}, \ L_B$

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

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

Baryon

Tetraquark: diquark + antidiquark



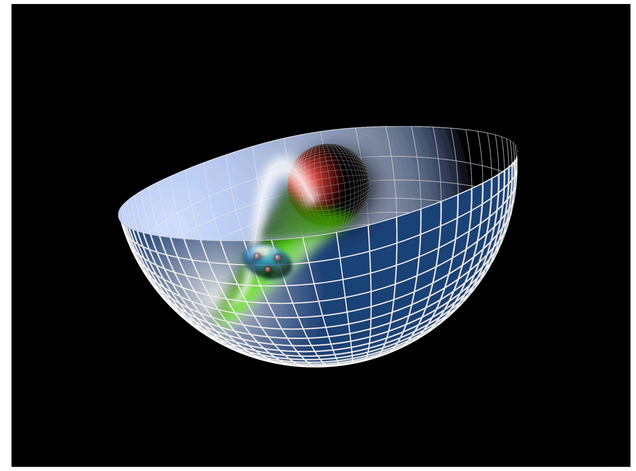
$\psi_{B-}, \ L_B + 1$ $\phi_T, \ L_B$

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

$3_C \to 3_C$

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

de Tèramond, Dosch, sjb



AdS/QCD Soft-Wall Model

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

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

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

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*

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

- *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*

de Téramond, Dosch, Lorcé, sjb

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

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

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

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

S=1/2, P=+

Meson Equation

$$\lambda = \kappa^2$$

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

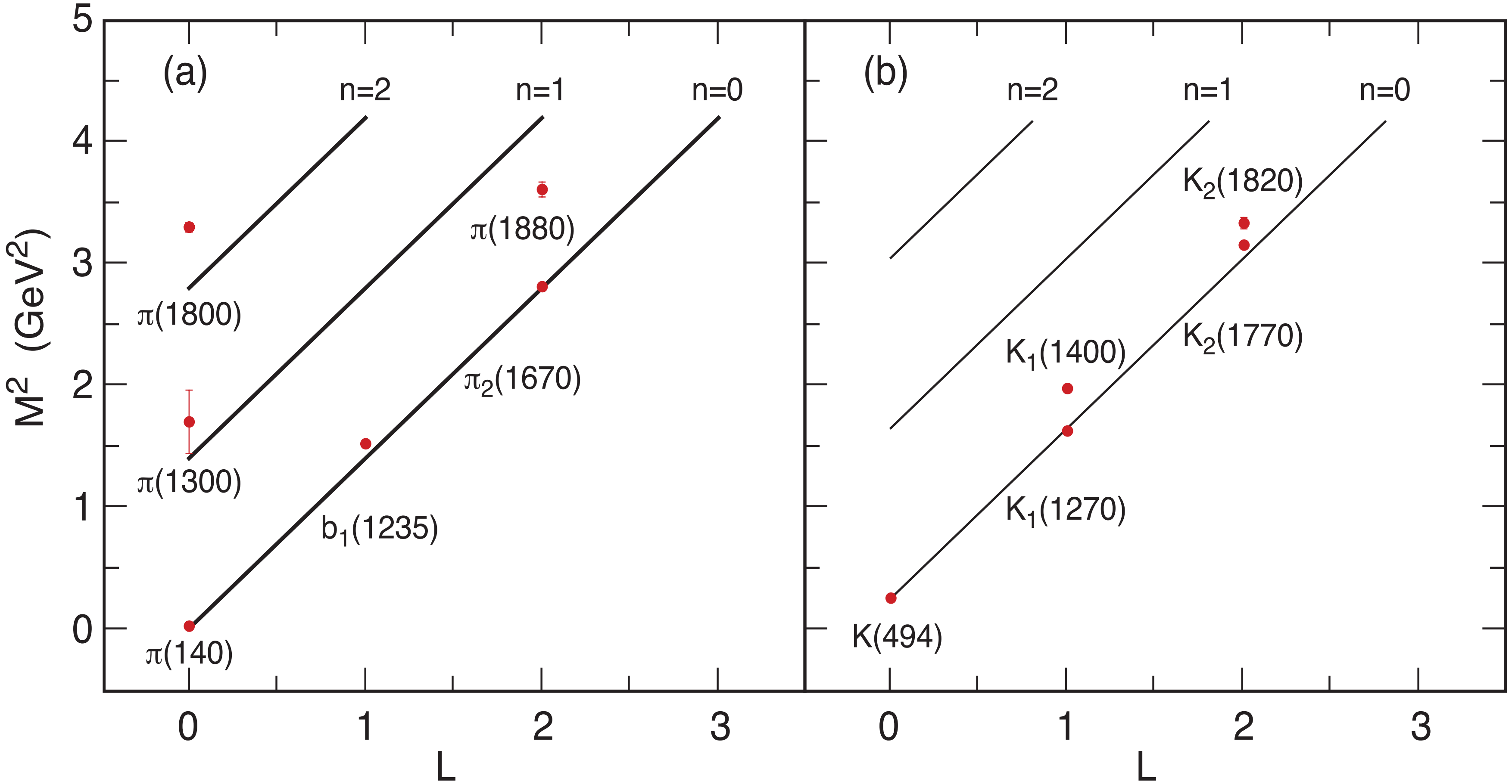
S=0, P=+

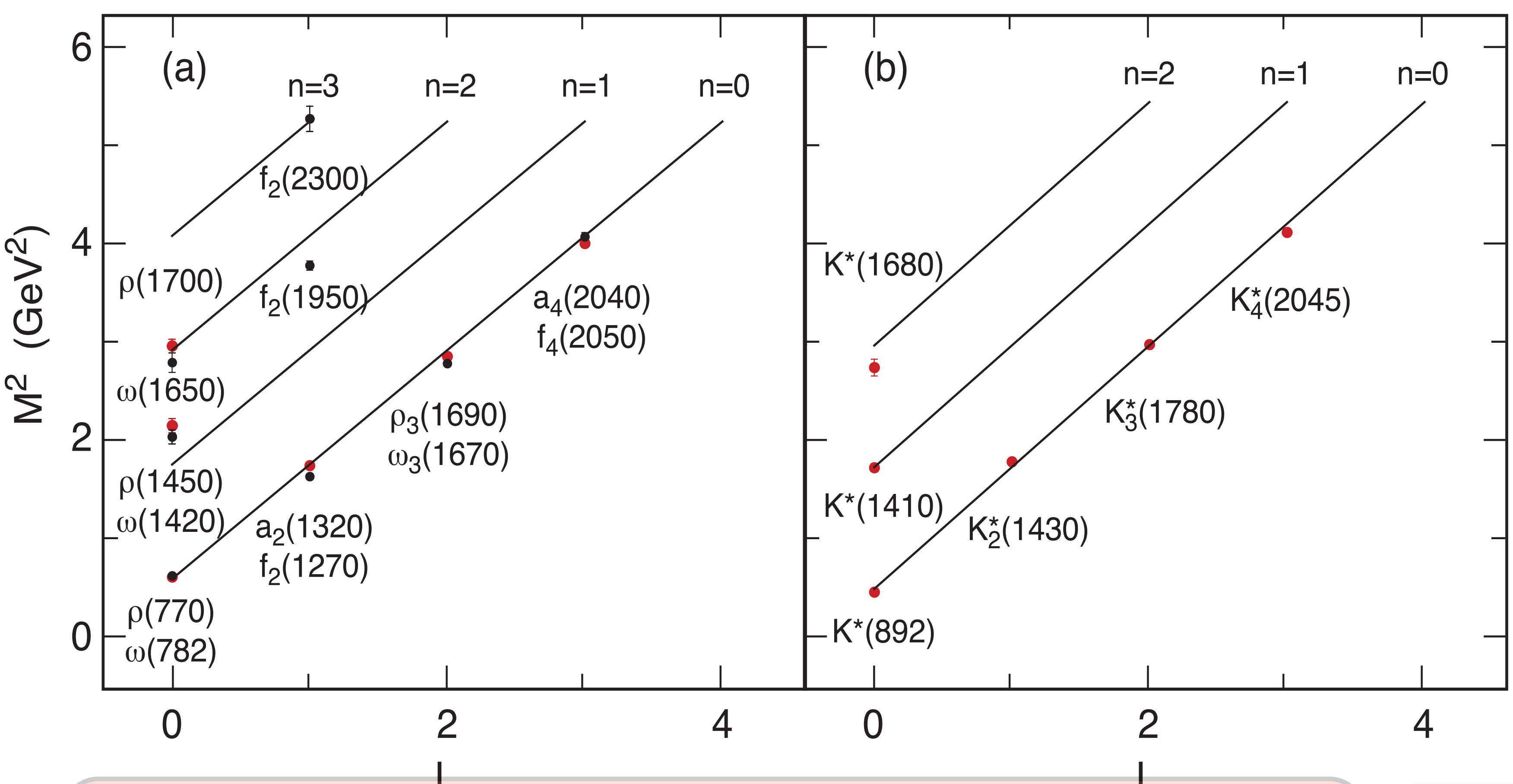
$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

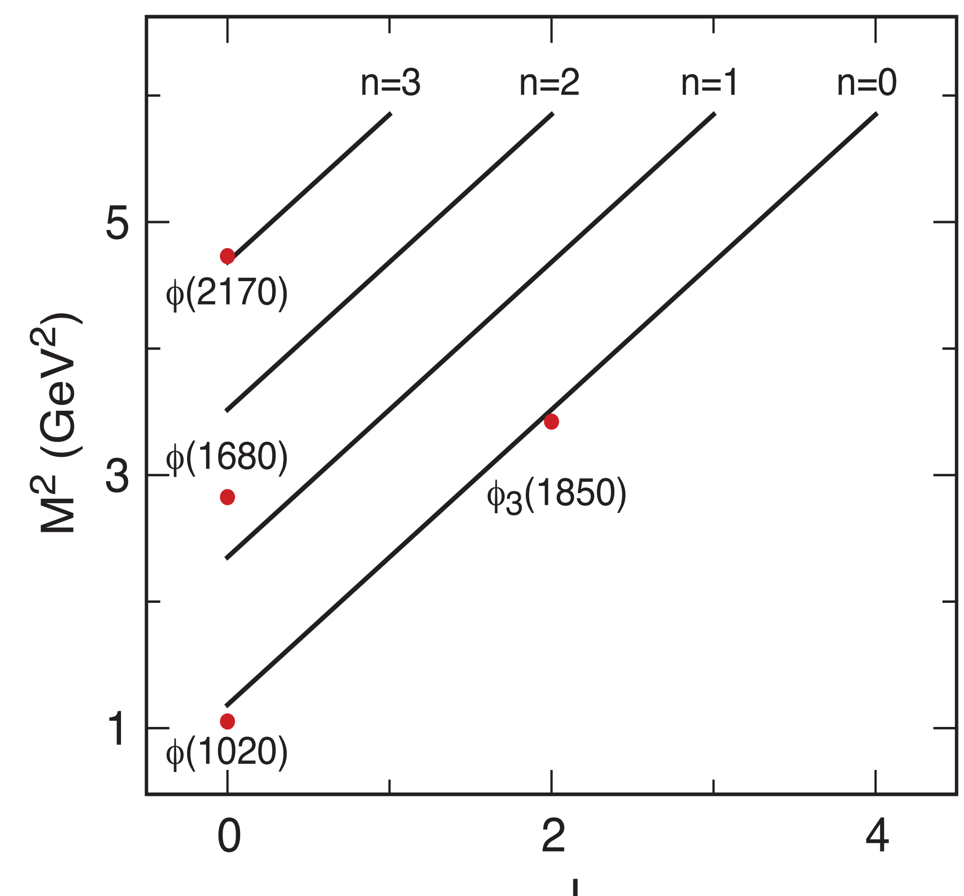
Same κ *!*

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

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





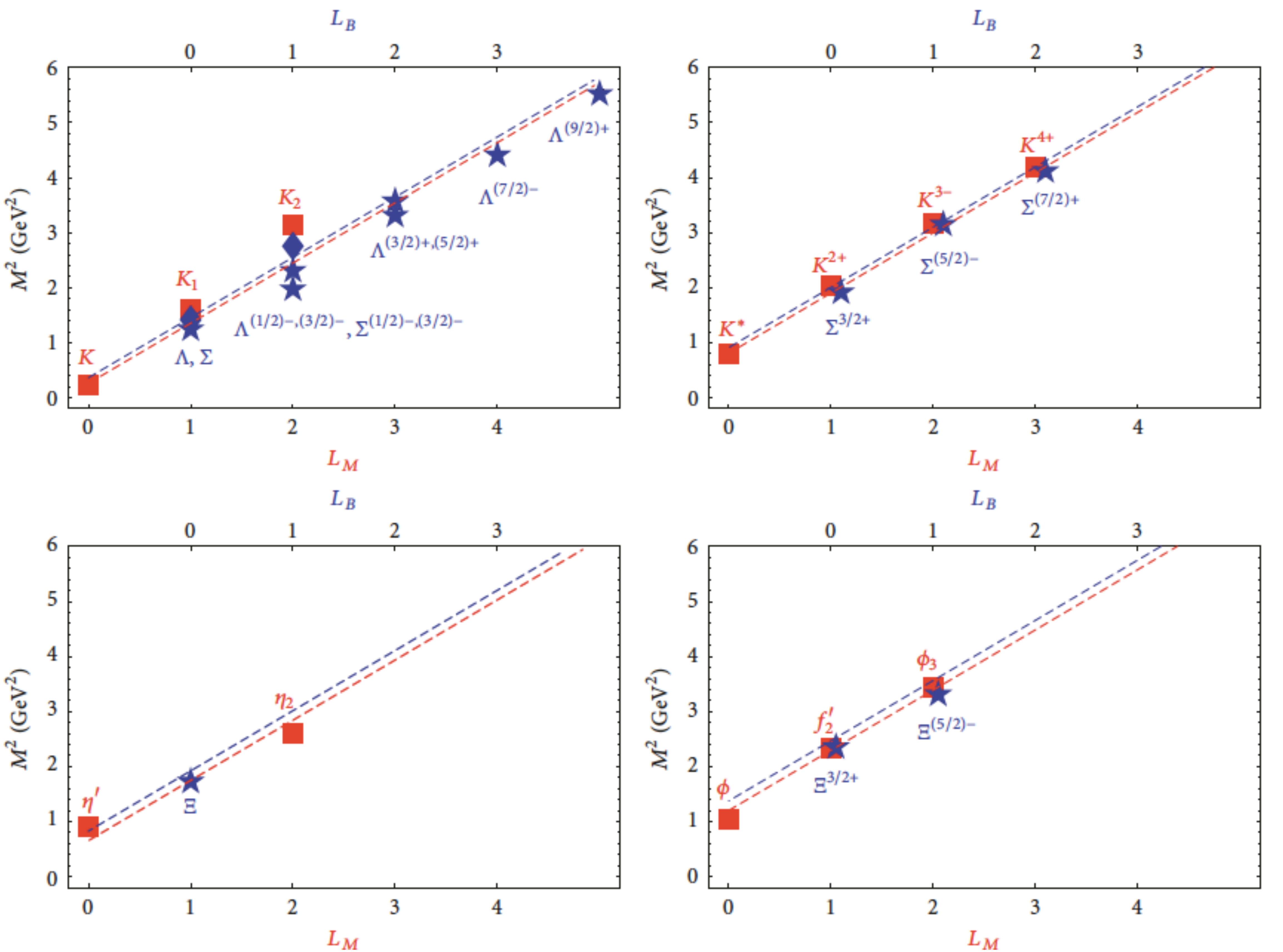


$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

Equal Slope in n and L

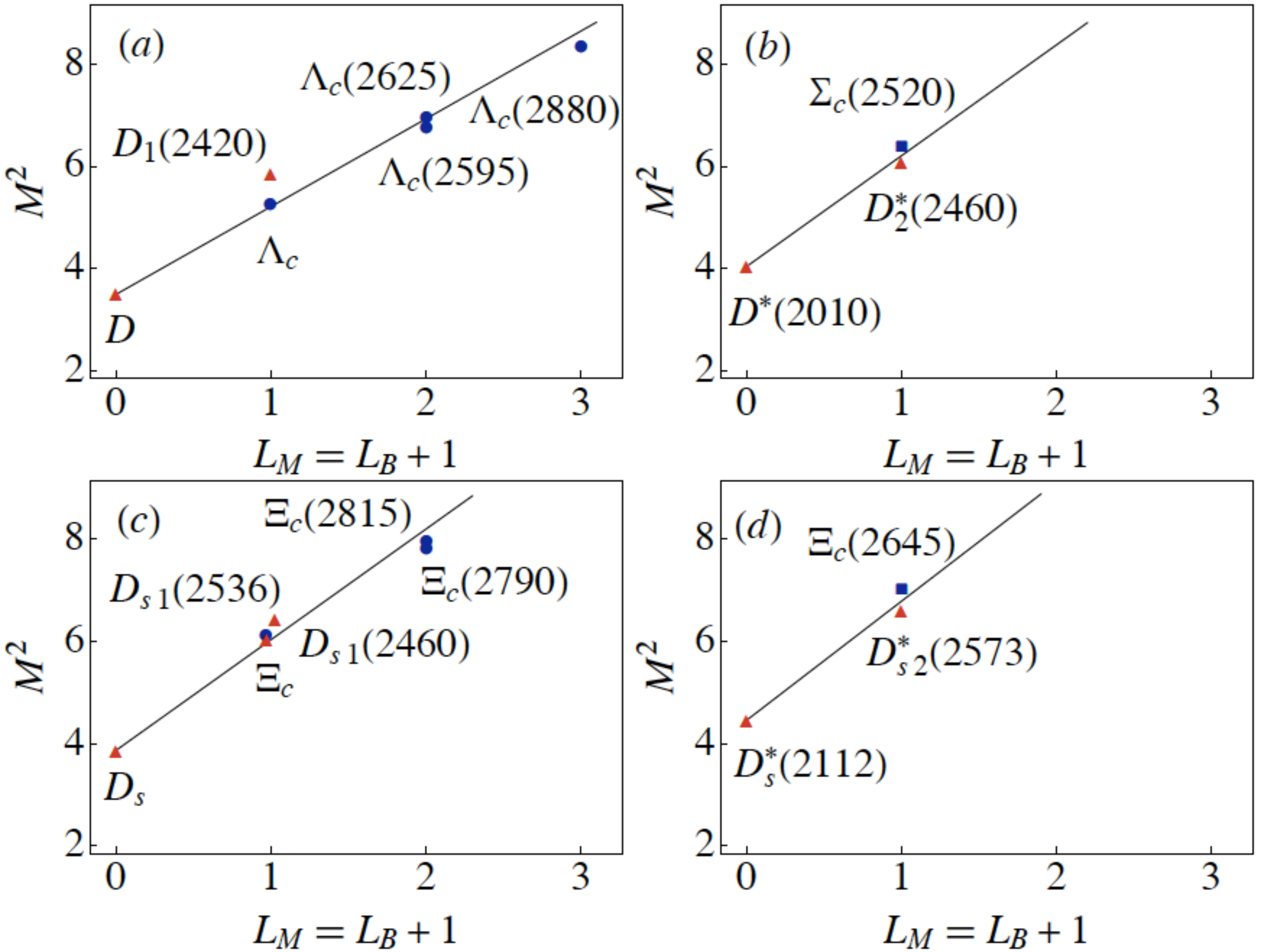
de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum

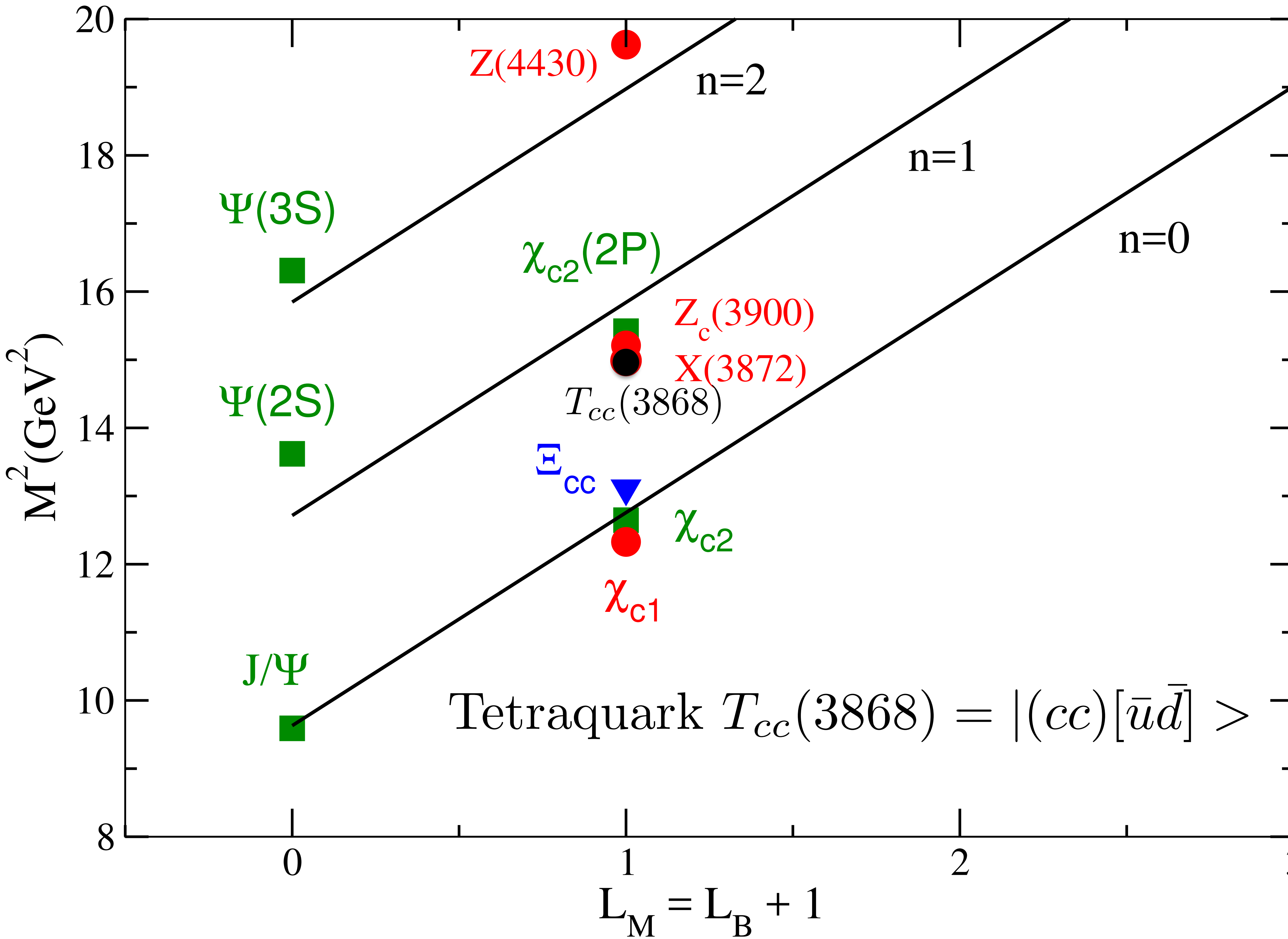


de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



Heavy charm quark mass does not break supersymmetry



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

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***

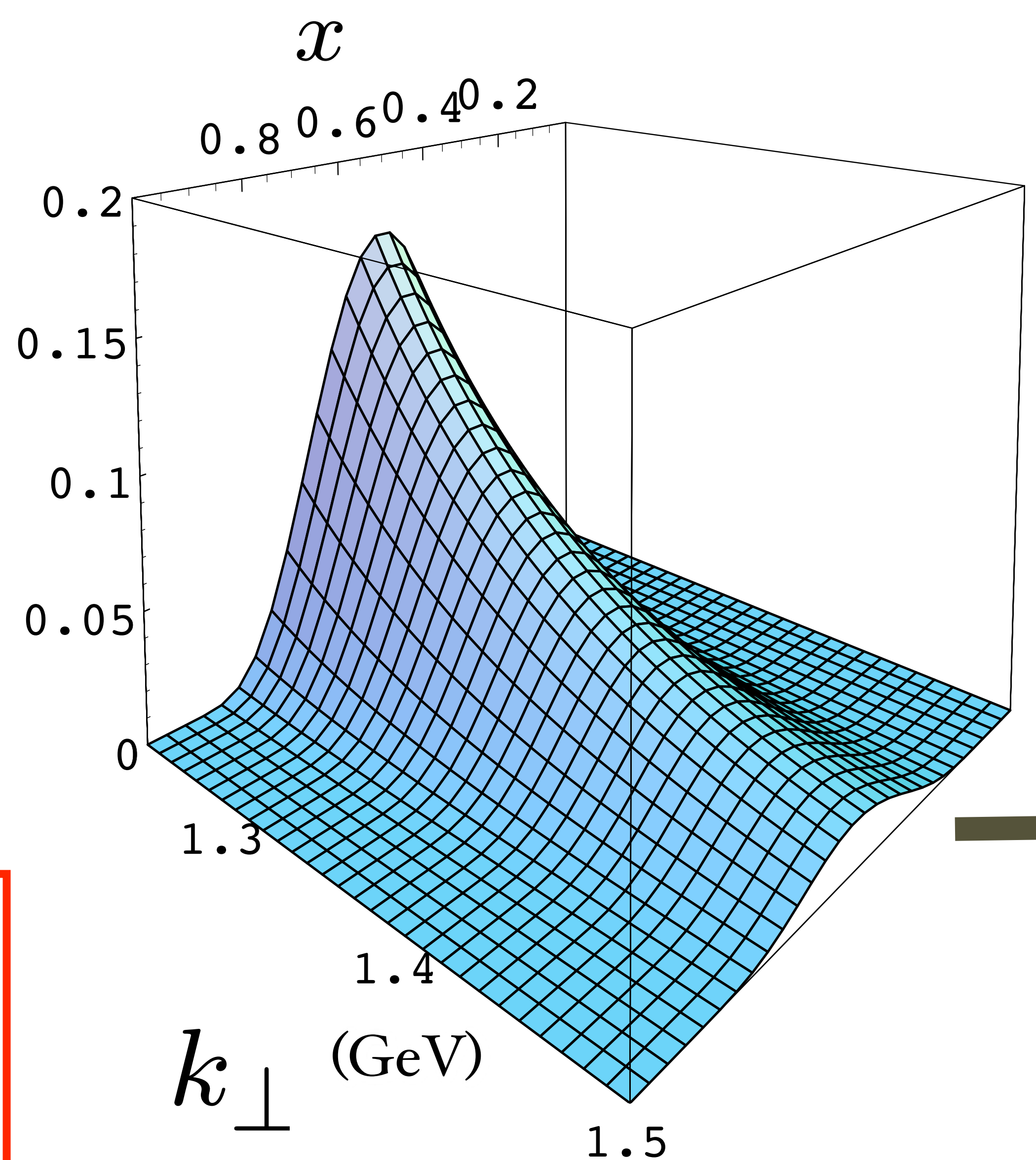
$$\Delta\mathcal{M}^2_{spin} = 2\kappa^2(L + 2S + B - 1)$$

hyperfine spin-spin

Prediction from AdS/QCD: Meson LFWF

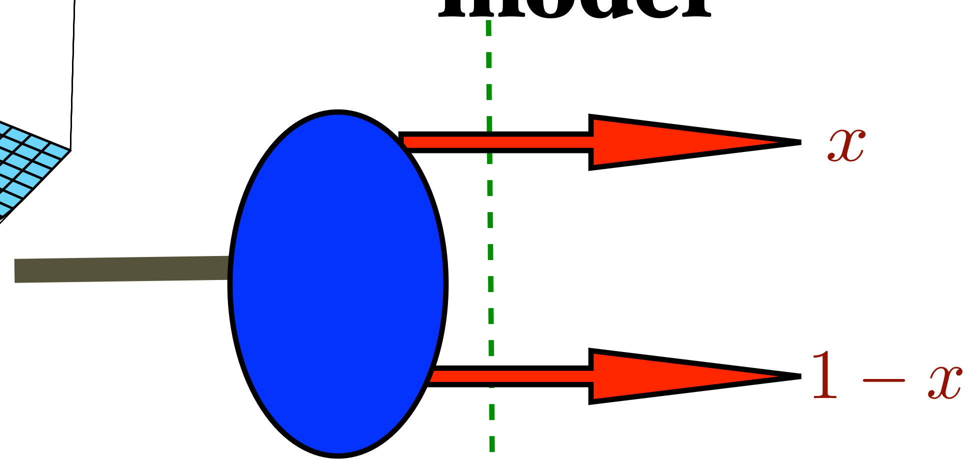
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

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

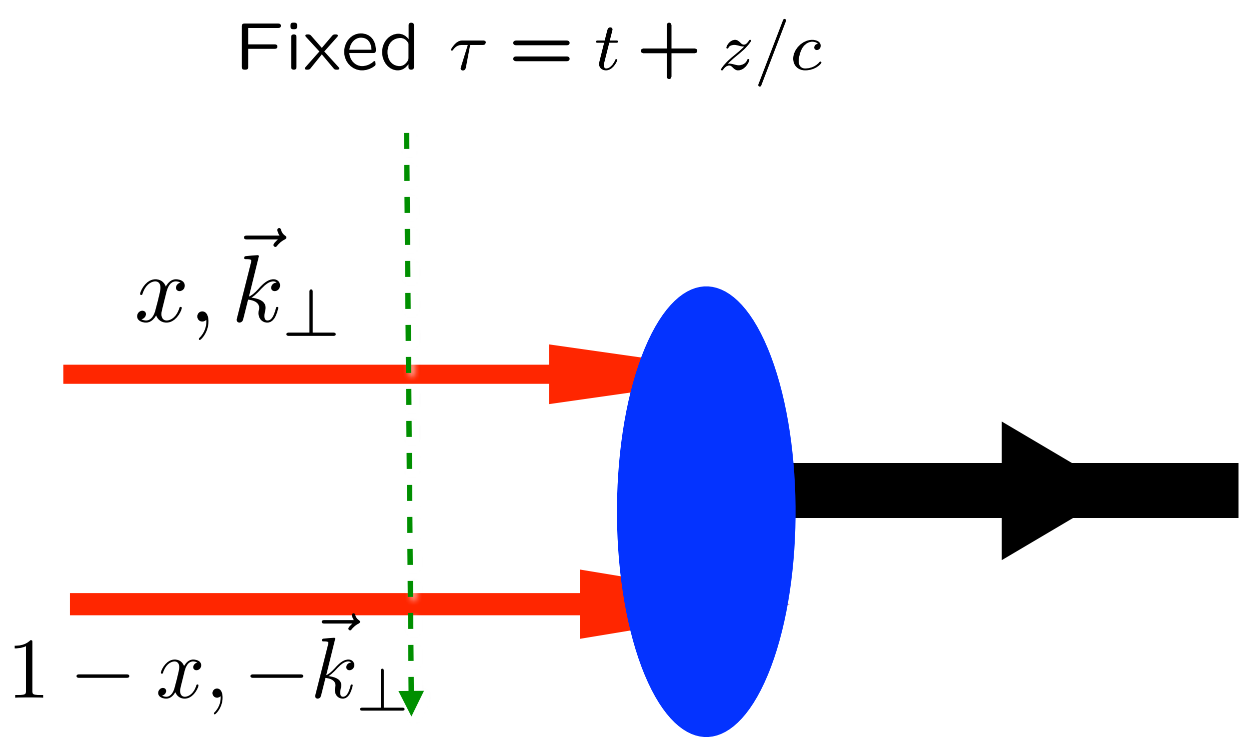
$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

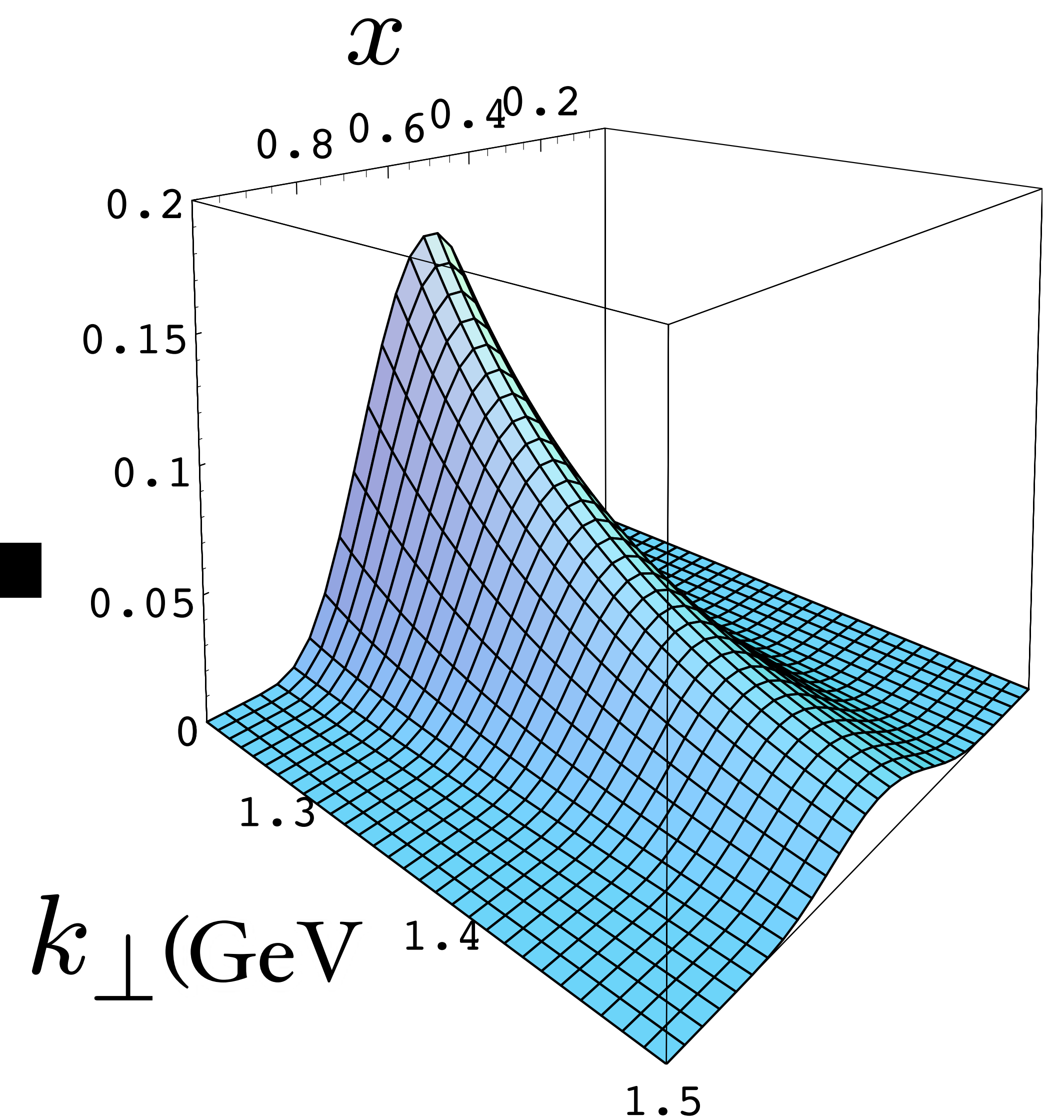
Same as DSE! **C. D. Roberts et al.**

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

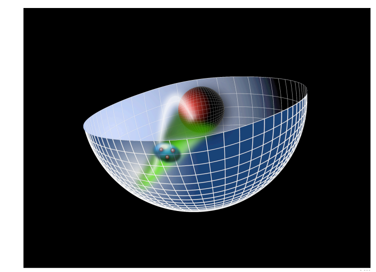
Proceeds in LF time τ within casual horizon
Instant time violates causality

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)*



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

- *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* $U(\zeta^2) = \kappa^4 \zeta^2$

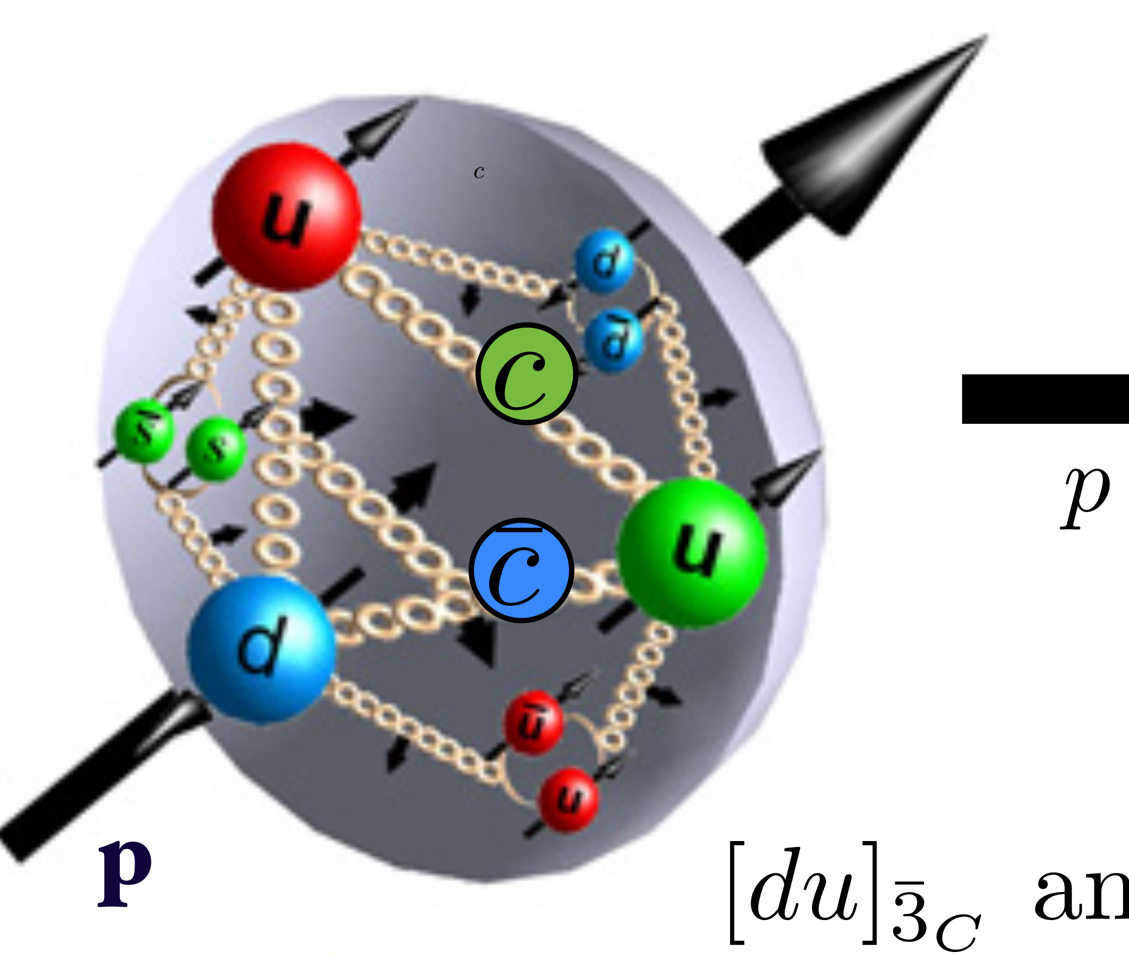
- *Superconformal Algebra: Mass Degenerate 4-Plet:*

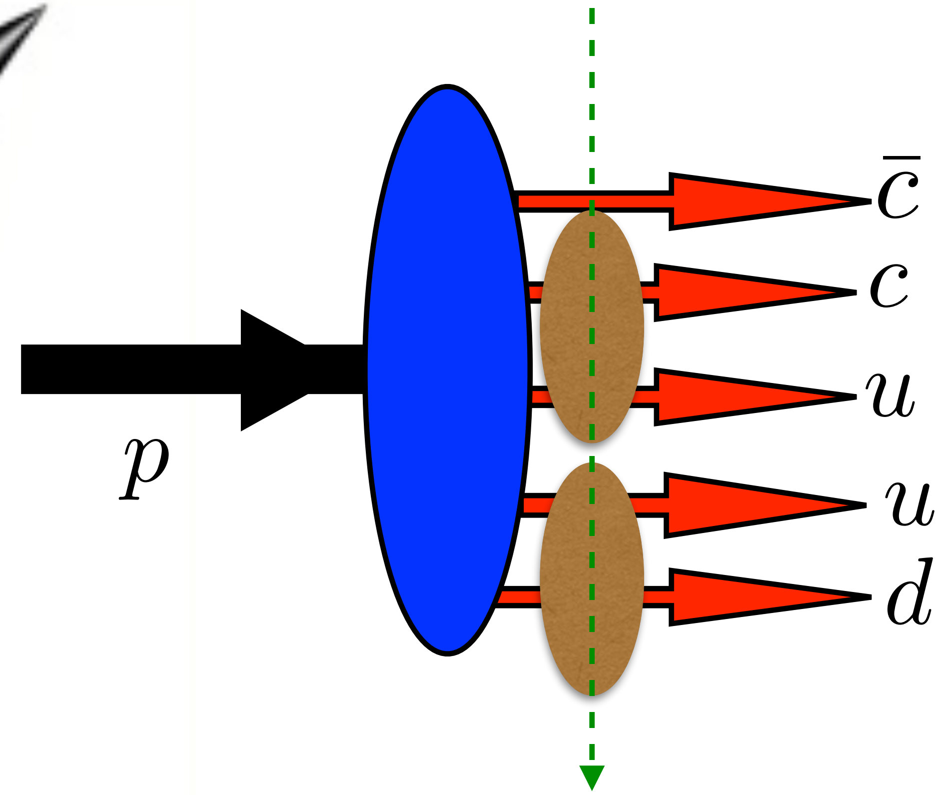
$$\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]$$

Color confinement potential from AdS/QCD

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

Fixed $\tau = t + z/c$





Intrinsic Charm

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

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

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

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

Other Issues for Precision QCD

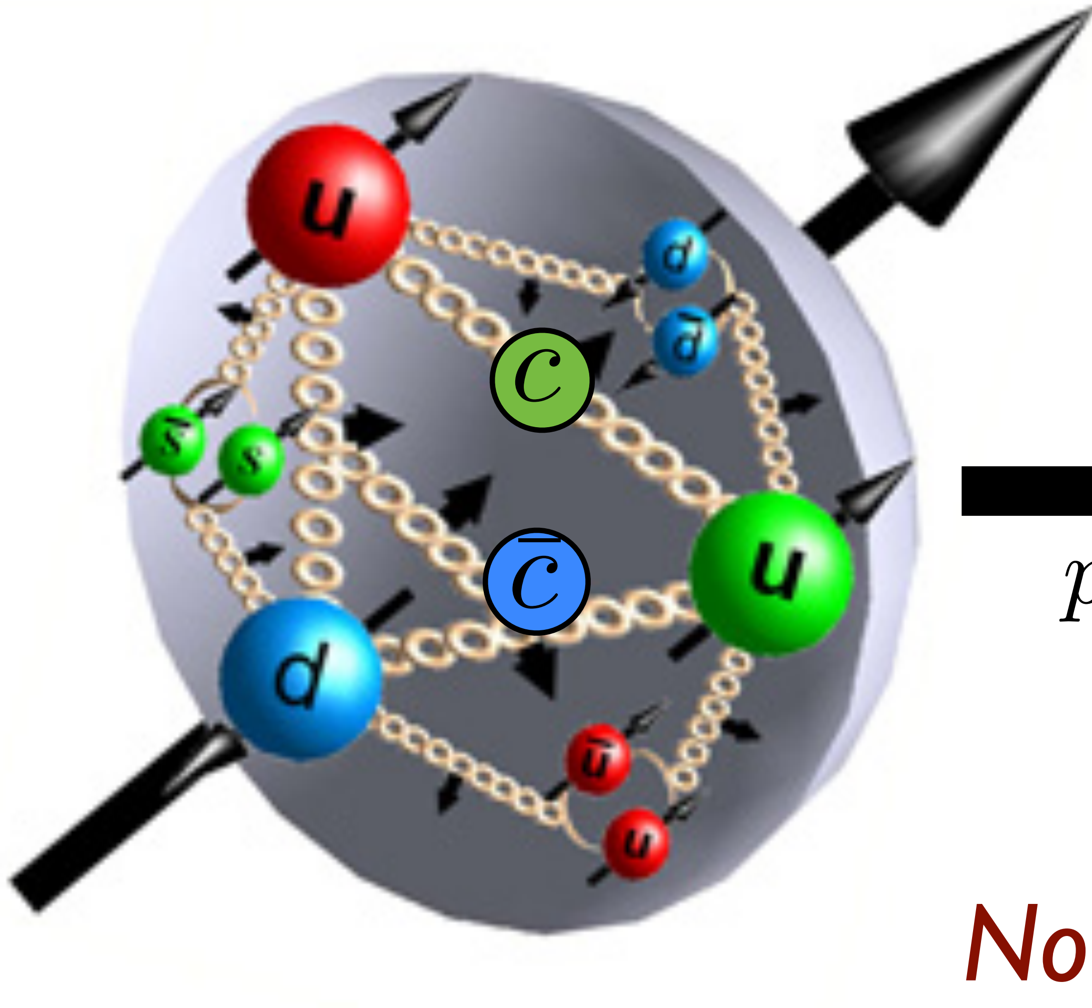
- Elimination of renormalization scale ambiguities
  PMC: Principle of Maximum Conformality

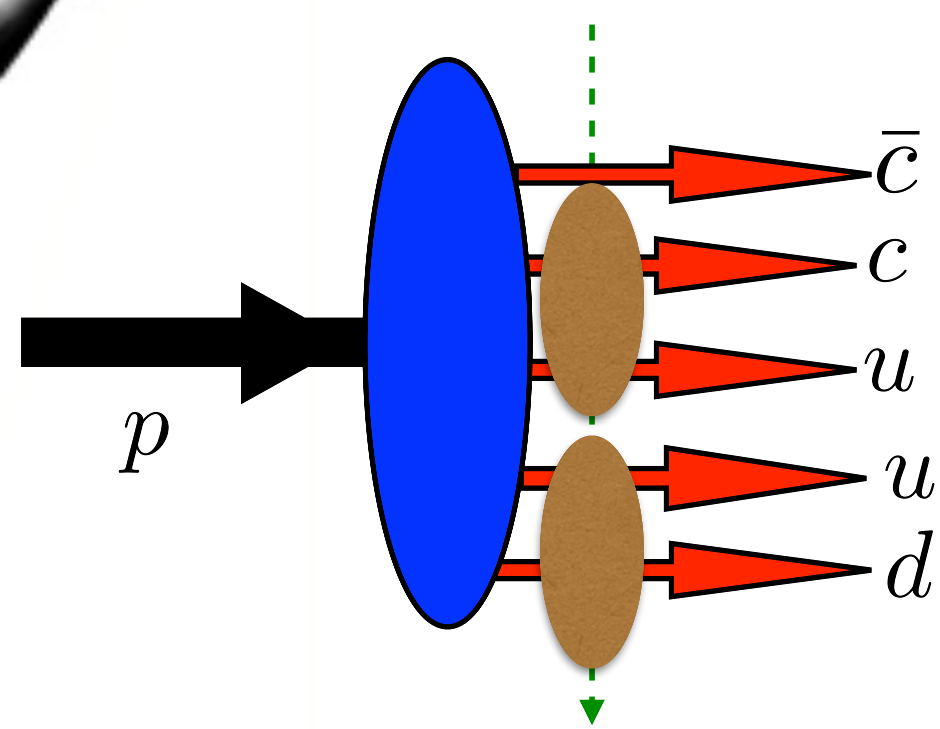
- Diffractive processes and violation of the OPE

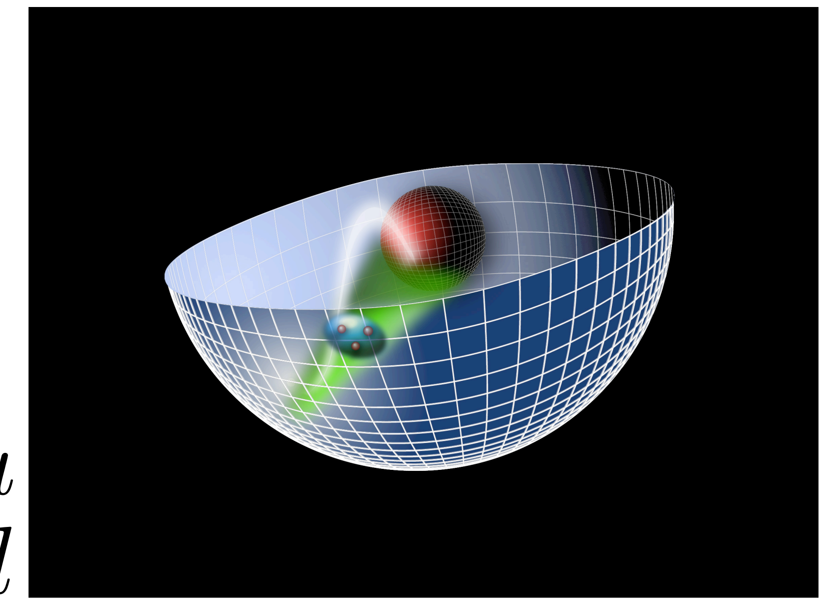
- Validity of the Momentum Sum Rule

- Shadowing and Anti-Shadowing of Nuclear PDFs

Intrinsic Heavy Quark Phenomena
A Novel Property of QCD







Non-perturbative QCD

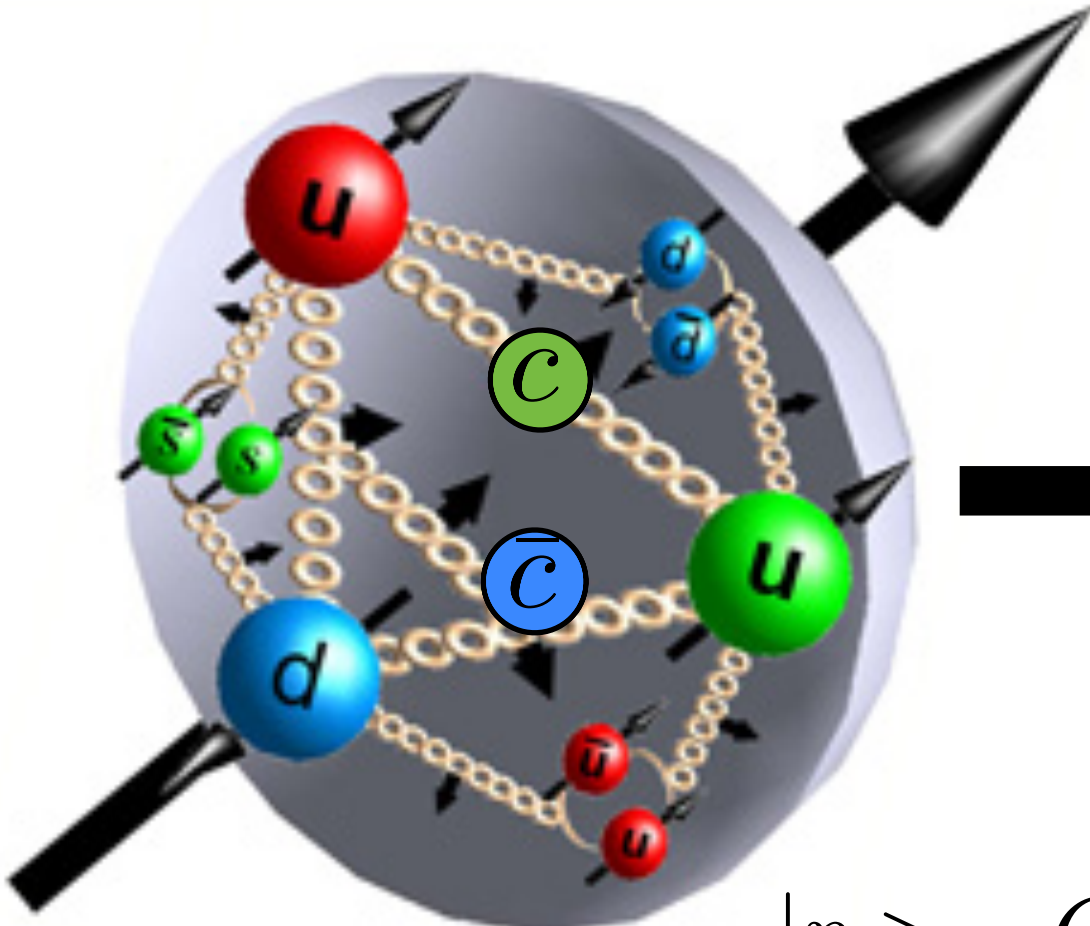
$$|p> = C_{valence}|u[ud]> + C_{intrinsic}|\bar{c}[cu][ud]>$$

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

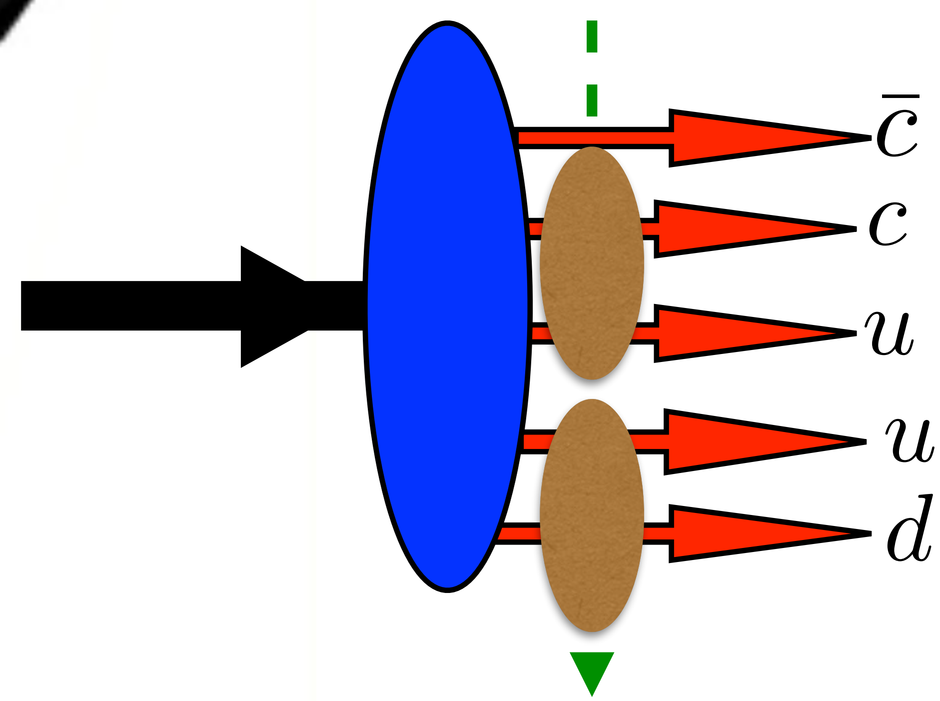
$c(x) \neq \bar{c}(x)$

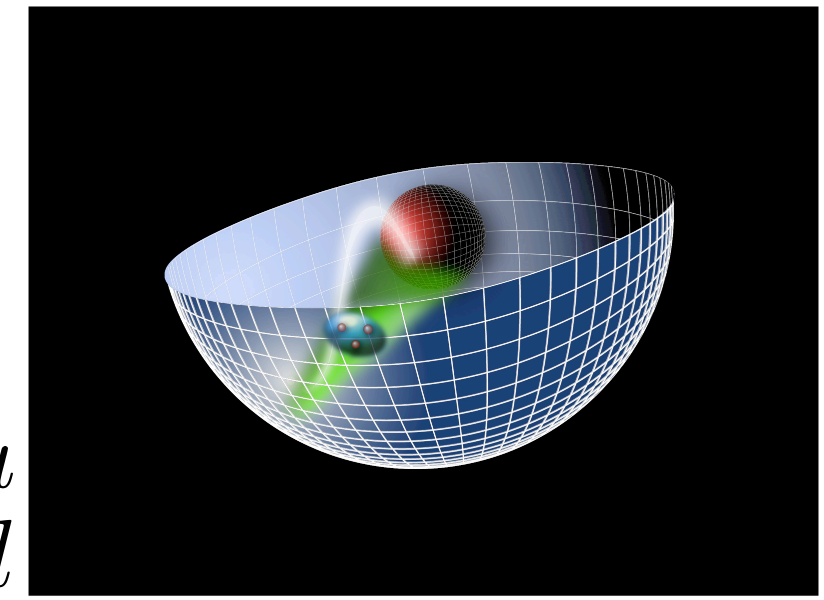
$\bar{c}(x)$ carries proton spin in the $|[ud][uc]\bar{c}>$ intrinsic charm Fock state.

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

High x_F, $P_{uudQ\bar{Q}} \propto \frac{1}{M_Q^2}$

Implications of LHCb measurements and future prospects

Implications of LHCb Measurements and Future Prospects

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

October 21, 2021