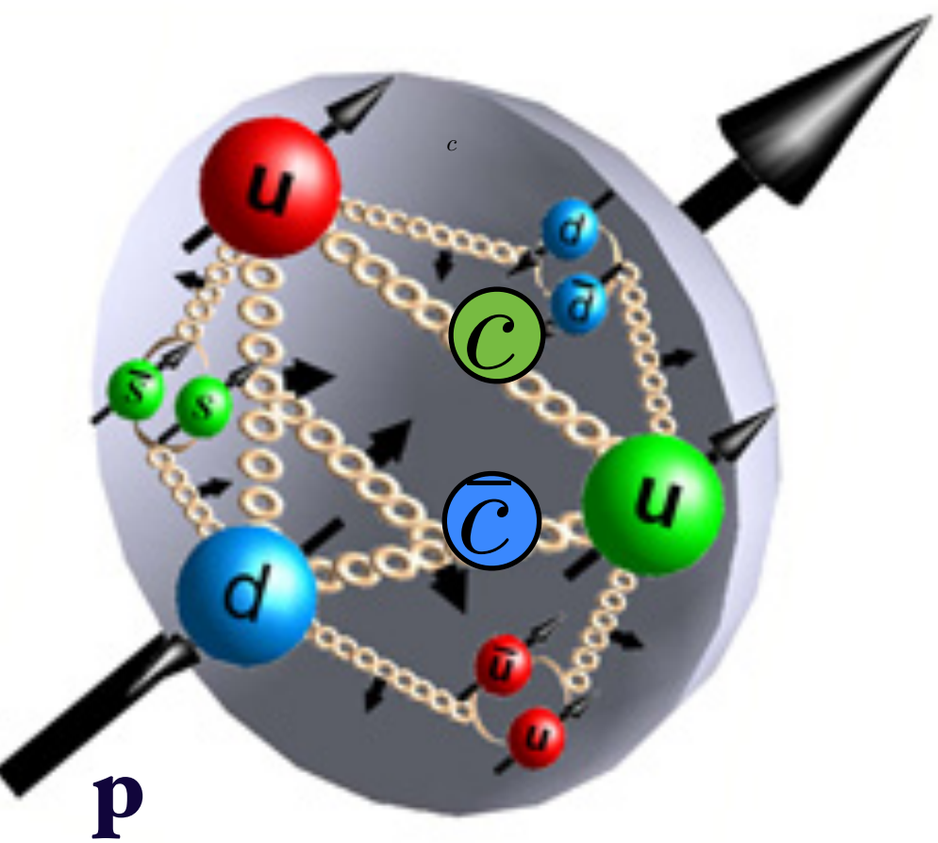
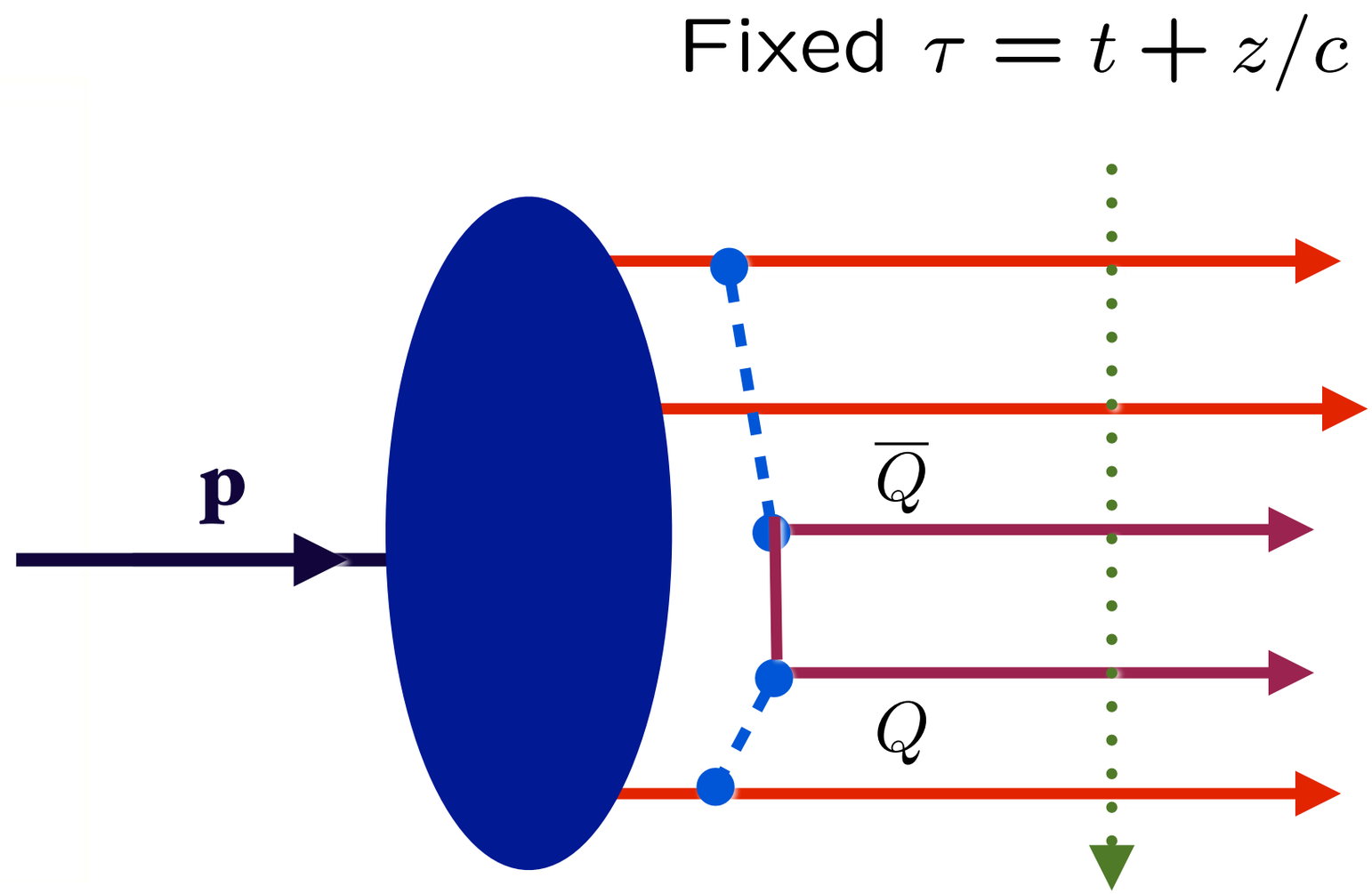
Novel Features of Quarkonium and Tetraquark Physics





QWG

QWG2016

June 8, 2016

Stan Brodsky

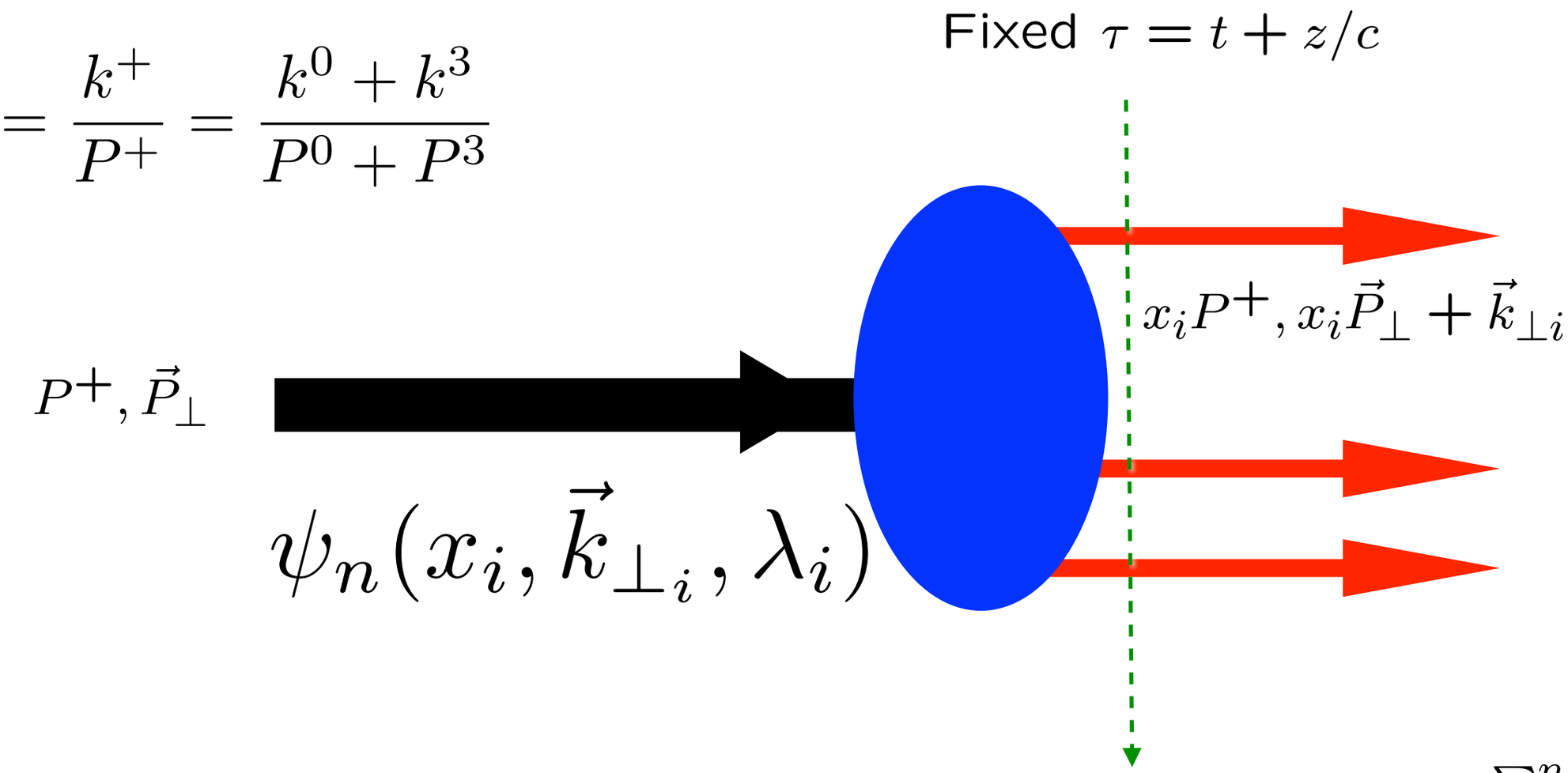
SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY 1891

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

Eigenstate of LF Hamiltonian

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



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

$\sum_i^n x_i = 1$

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

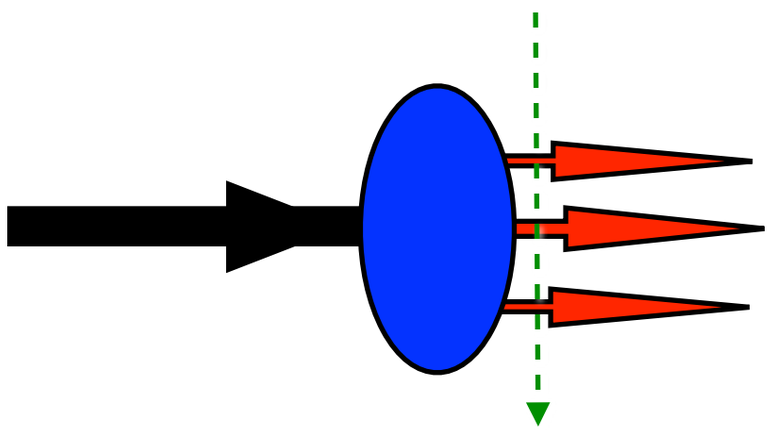
Invariant under boosts! Independent of P^μ

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

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

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



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

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

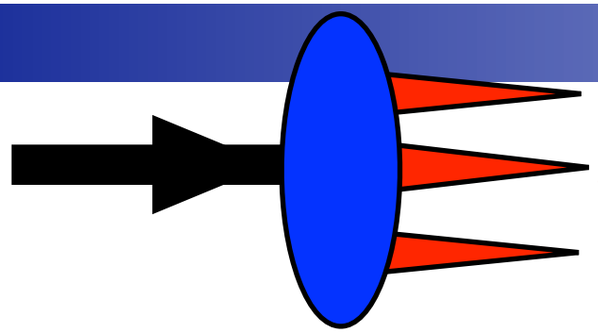
Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

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

• Light Front Wavefunctions:



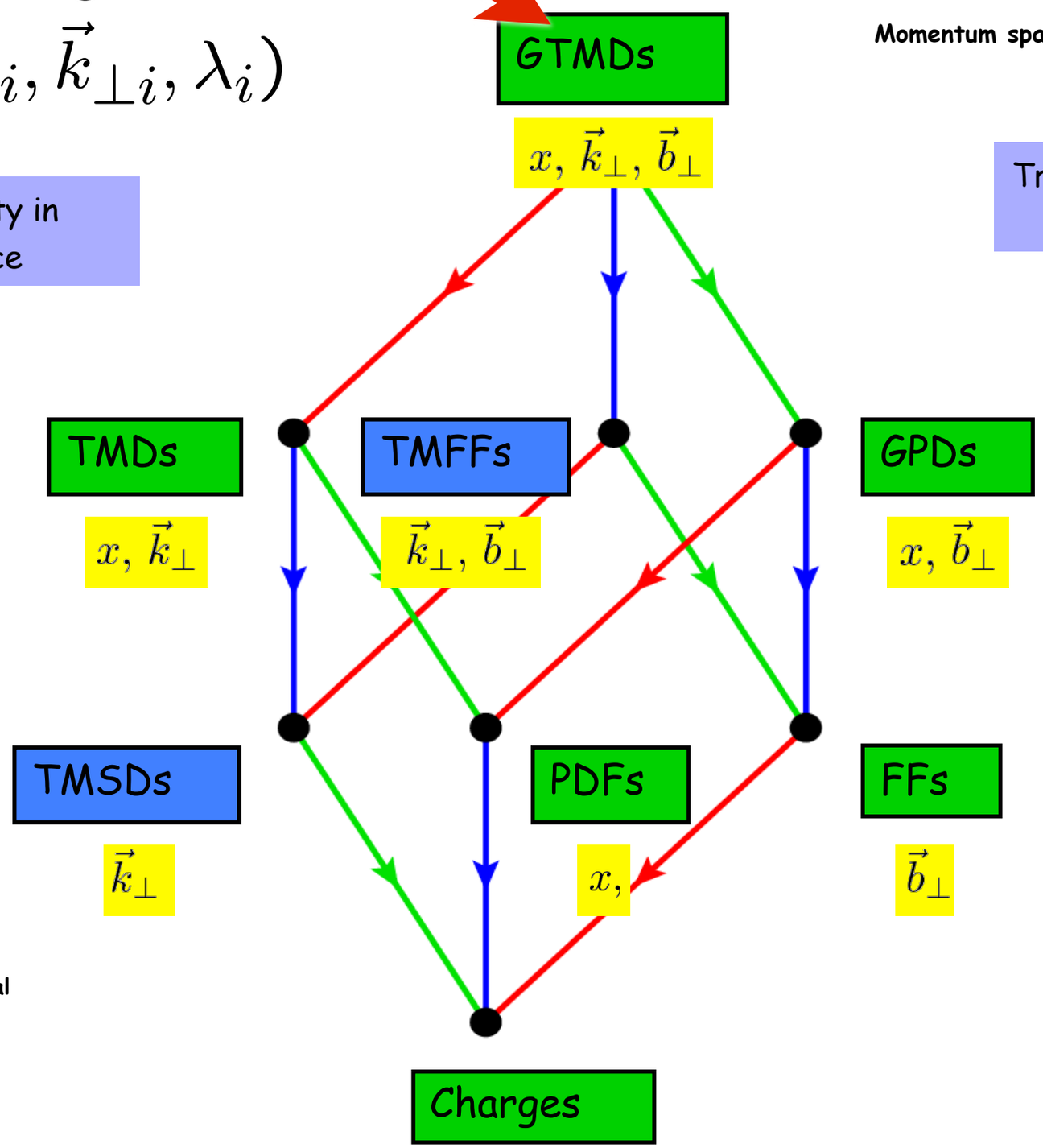
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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

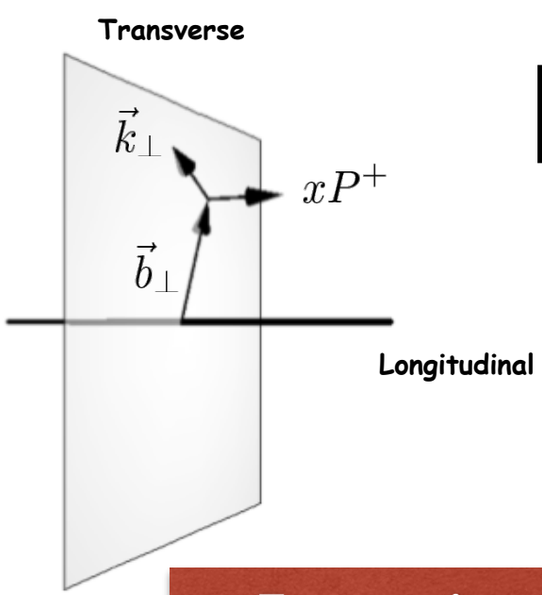
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in momentum space

Transverse density in position space



Lorce, Pasquini



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

$\int \mathrm{d}x$

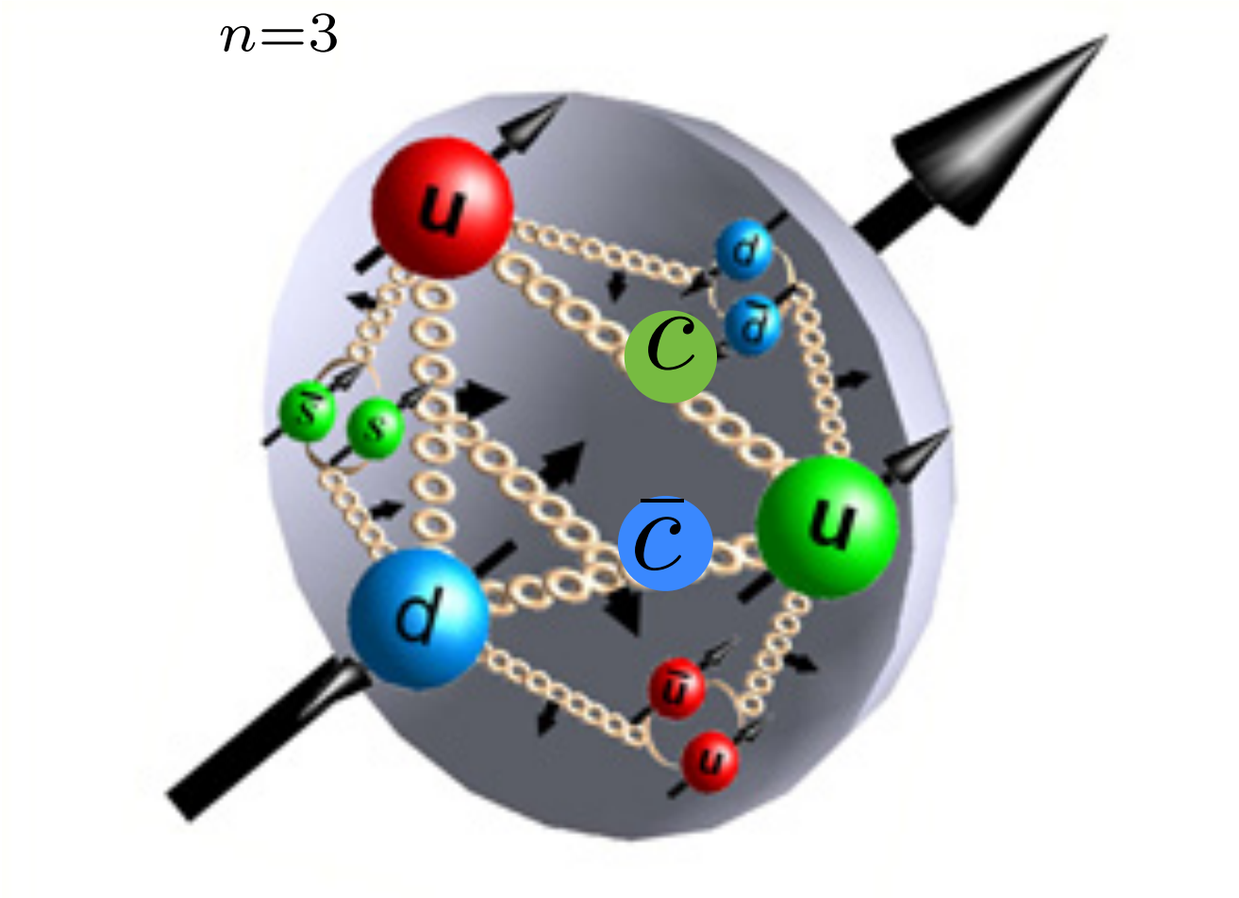
$\int \mathrm{d}^2 k_\perp$

+ Factorization-Breaking Lensing Corrections: Sivers, T-odd

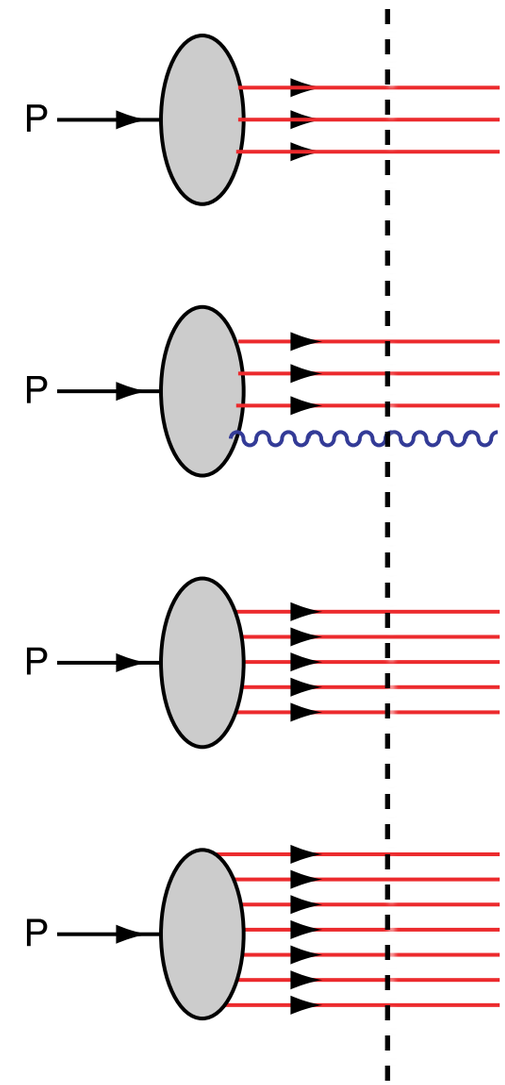
Wavefunction at fixed LF time: Arbitrarily Off-Shell in Invariant Mass

Eigenstate of LF Hamiltonian : all Fock states contribute

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



Higher Fock States of the Proton



Fixed LF time

Do heavy quarks exist in the proton at high x?

Conventional wisdom:

Heavy quarks generated only at low x via DGLAP evolution from gluon splitting

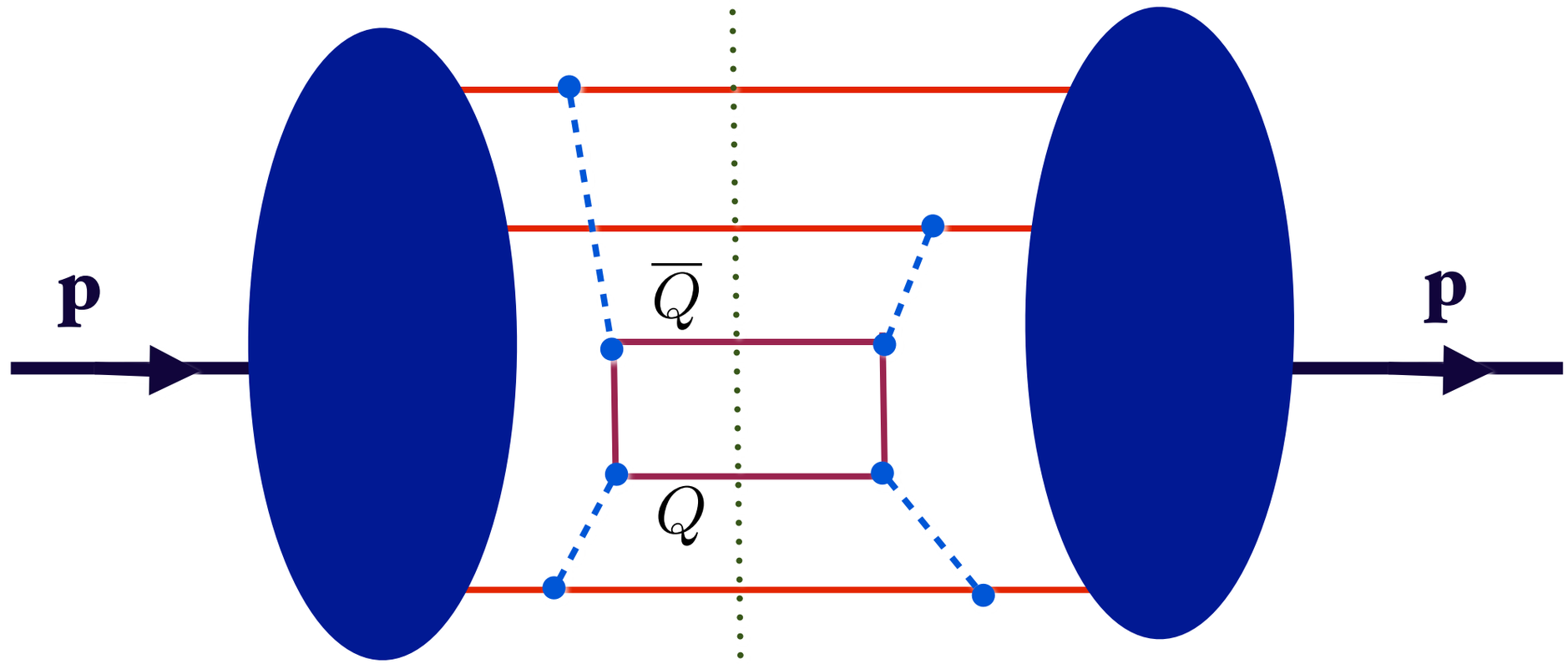
$$s(x,\mu_F^2) = c(x,\mu_F^2) = b(x,\mu_F^2) \equiv 0$$

$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

Fixed LF time

Proton Self Energy
Intrinsic Heavy Quarks



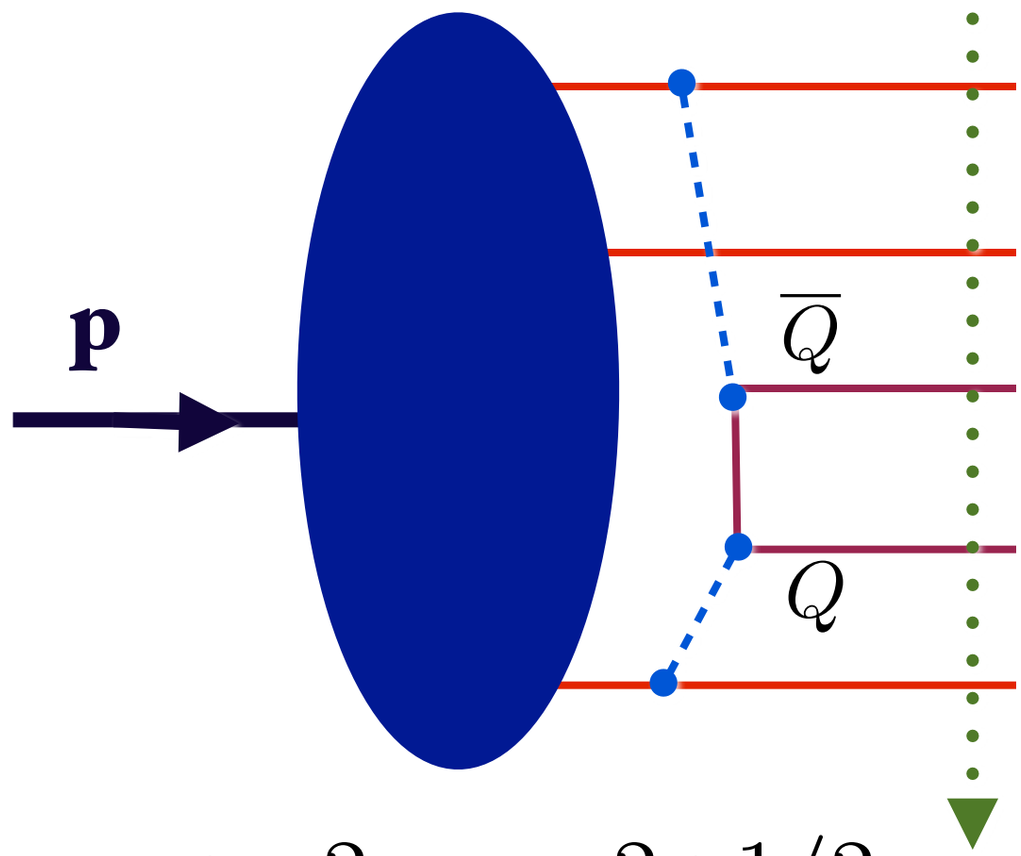
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Rigorous OPE Analysis

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

Fixed LF time

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts
Intrinsic Heavy
Quarks at high x!

Minimal off-shellness

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

Equal rapidity

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

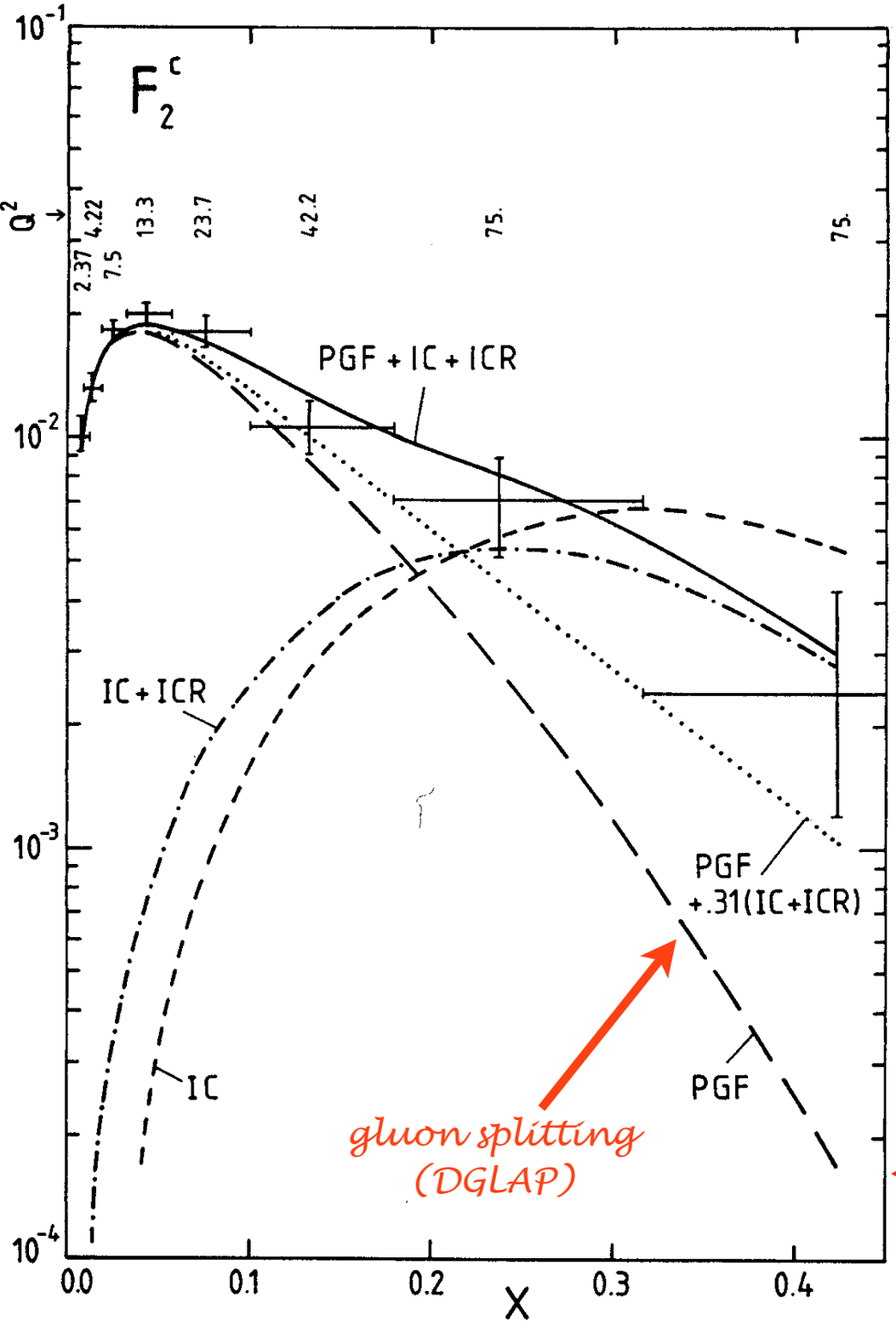
$$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Rigorous OPE
Analysis

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

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).

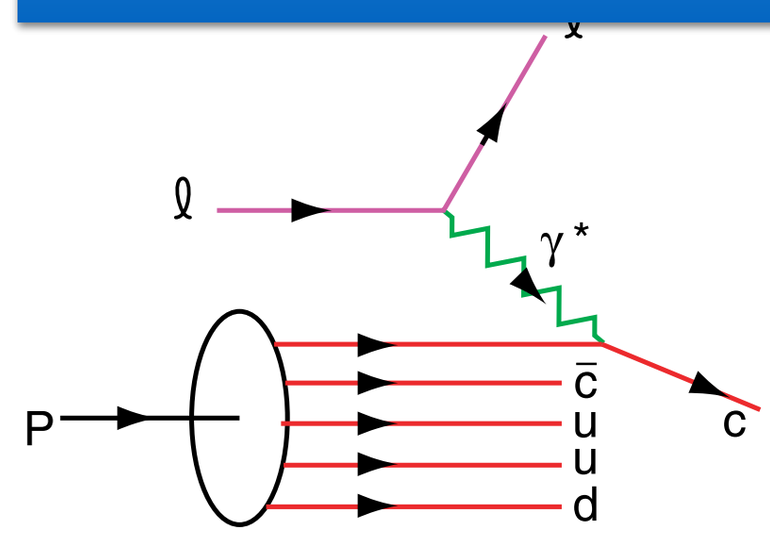


Evidence for Intrinsic Charm

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

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

factor of 30 !



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

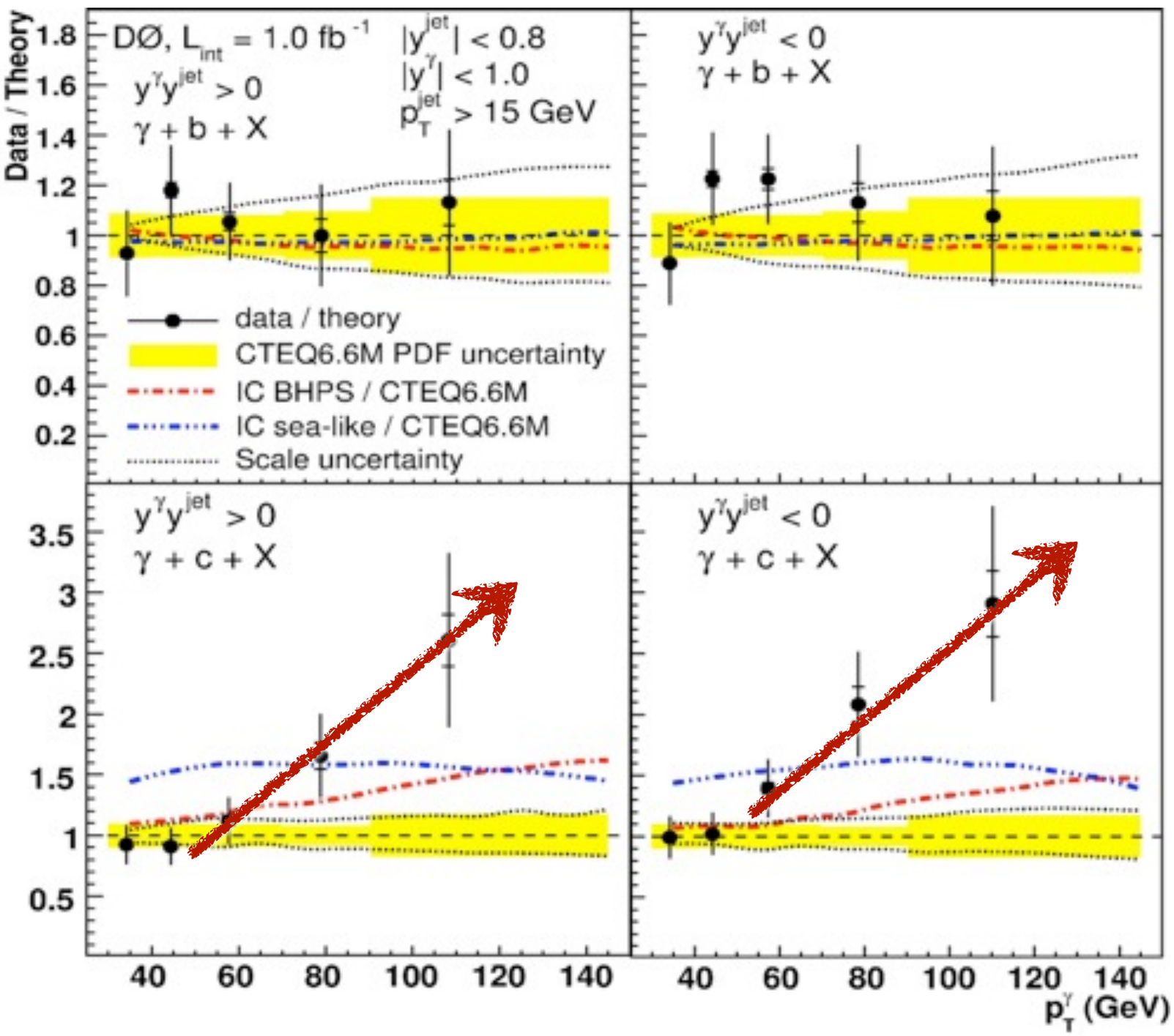
Two Components (separate evolution):

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

D0

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

$$gc \to \gamma c$$

Signal for significant intrinsic charm

Mesropian, Bandurin

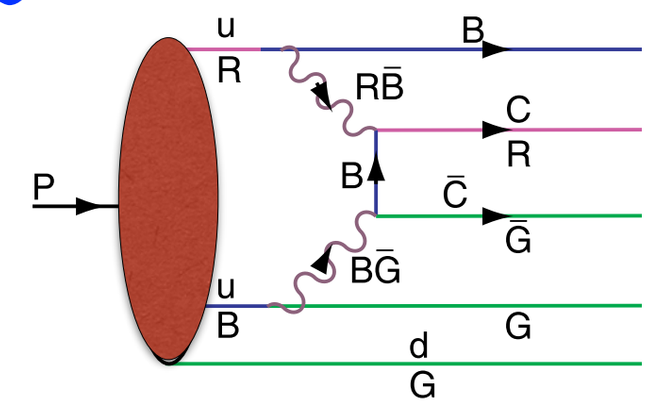
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

LHC: $pp \to Z^0 c X$

Boettcher, Ilten, Williams

Hoyer, Peterson, Sakai, sjb

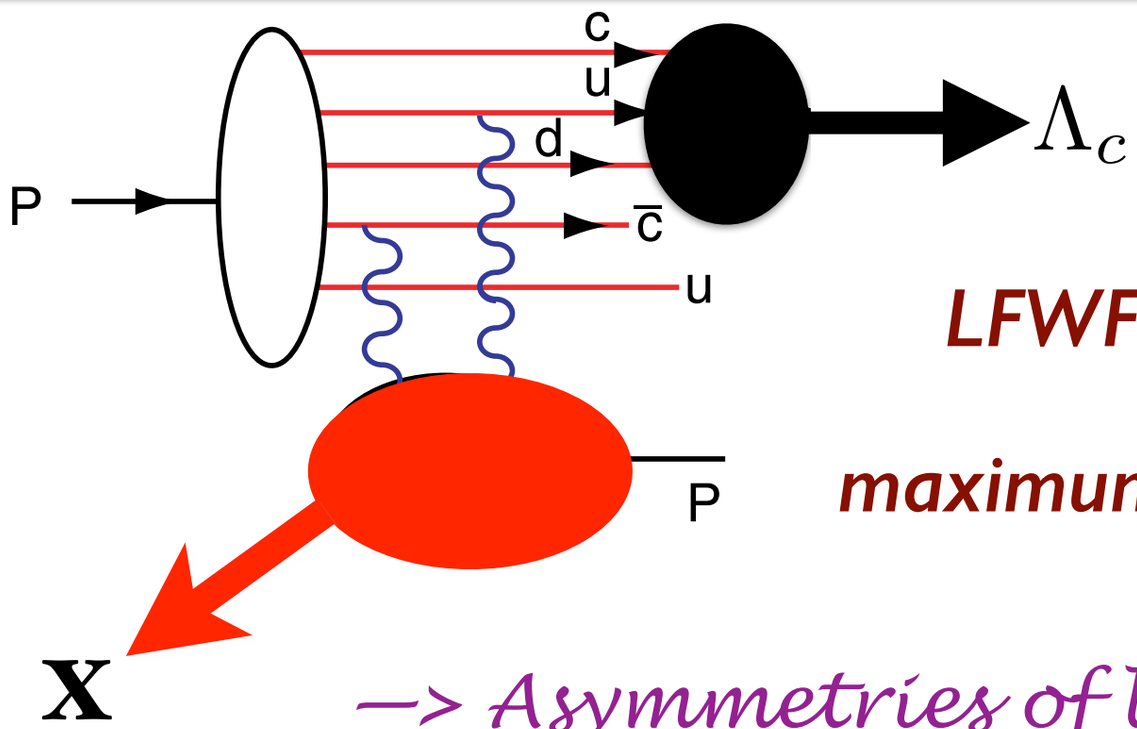
Intrinsic Heavy-Quark Fock



- **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 (Kopeliovich, Schmidt, Soffer, sjb)**
- **Underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)**

Coalesece of comovers produces high x_F heavy hadrons

High x_F hadrons combine most of the comovers, fewest spectators



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

LFWF maximum at equal rapidity

maximum at minimal invariant mass

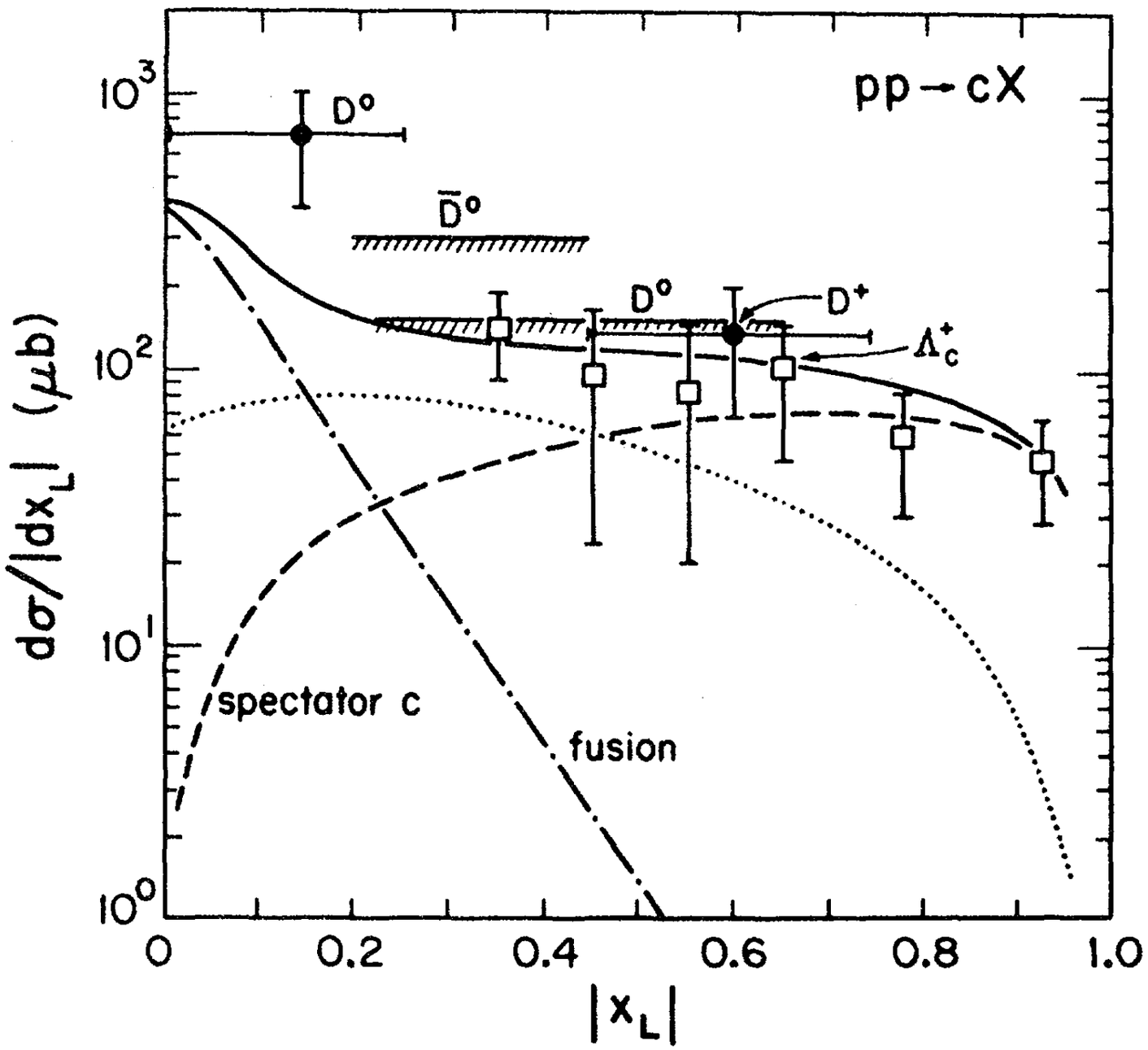
—> Asymmetries of leading hadrons

Spectator counting rules

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

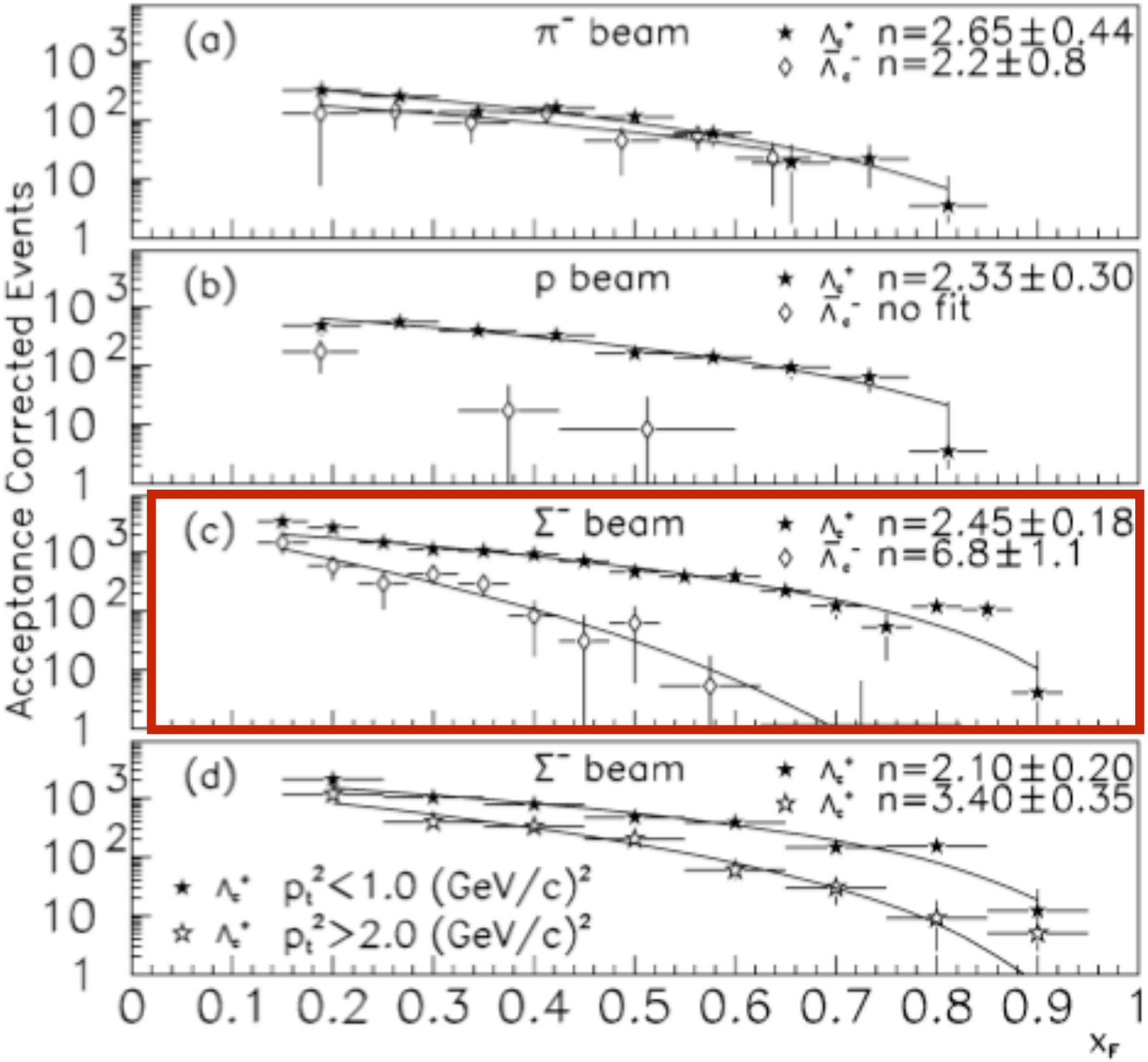
Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

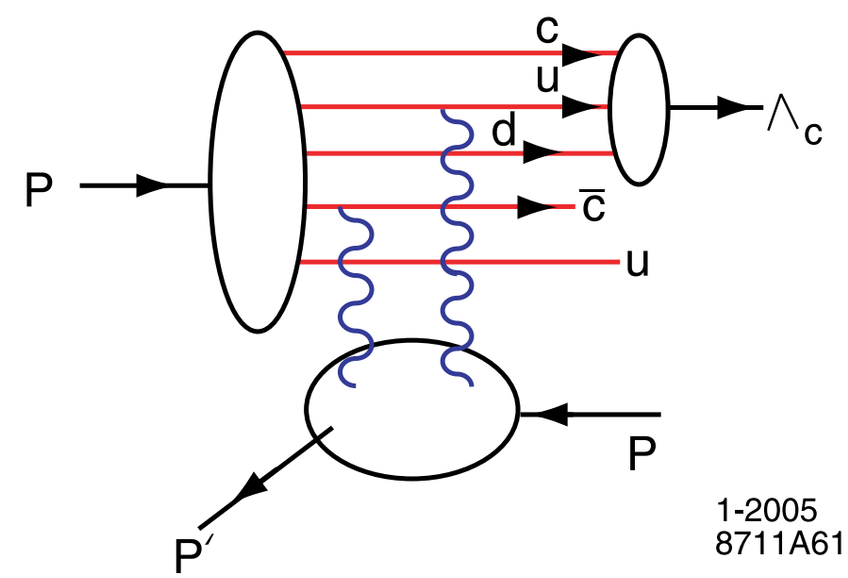
Vogt, sjb



Barger, Halzen, Keung

Evidence for charm at large x





$$p(uudc\bar{c}) \rightarrow \Lambda_c(cud)$$

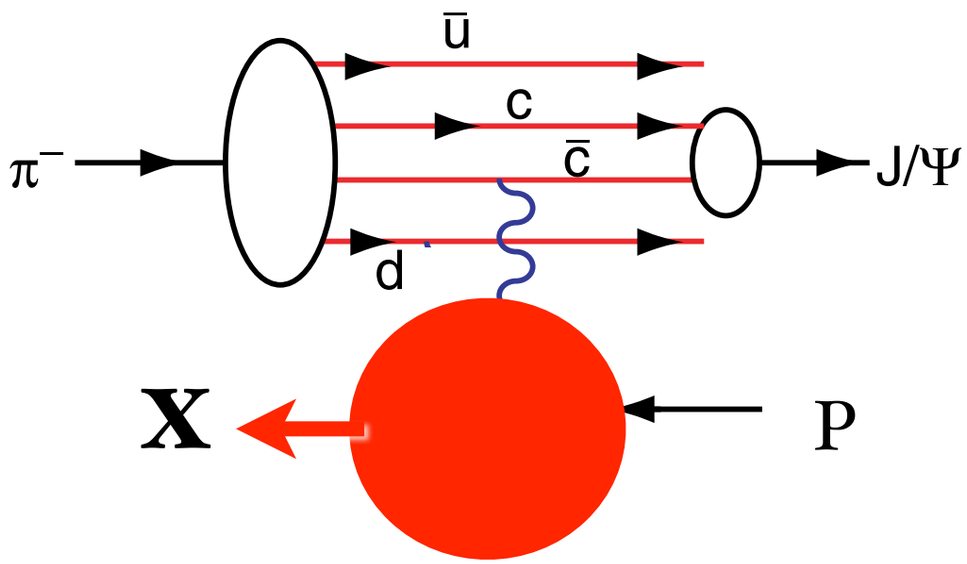
$$n_s = 2$$

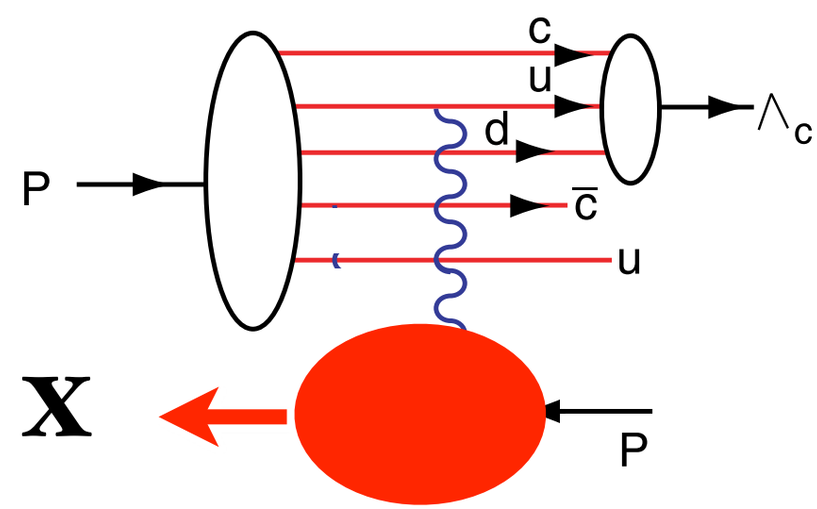
Phase space gives minimum power p

$$(1 - x_F)^p, p = n_s - 1$$

$$\Sigma^-(sddc\bar{c})A \rightarrow \Lambda_c(cdu)X \text{ vs. } \Sigma^-(sddc\bar{c})A \rightarrow \bar{\Lambda}_c(\bar{c}\bar{d}\bar{u})X$$

Coalesece of comovers produces high x_F heavy hadrons





Spectator counting rules

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

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

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

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

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

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

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

Explain Tevatron anomalies: $p\bar{p} \to \gamma c X, Z c X$

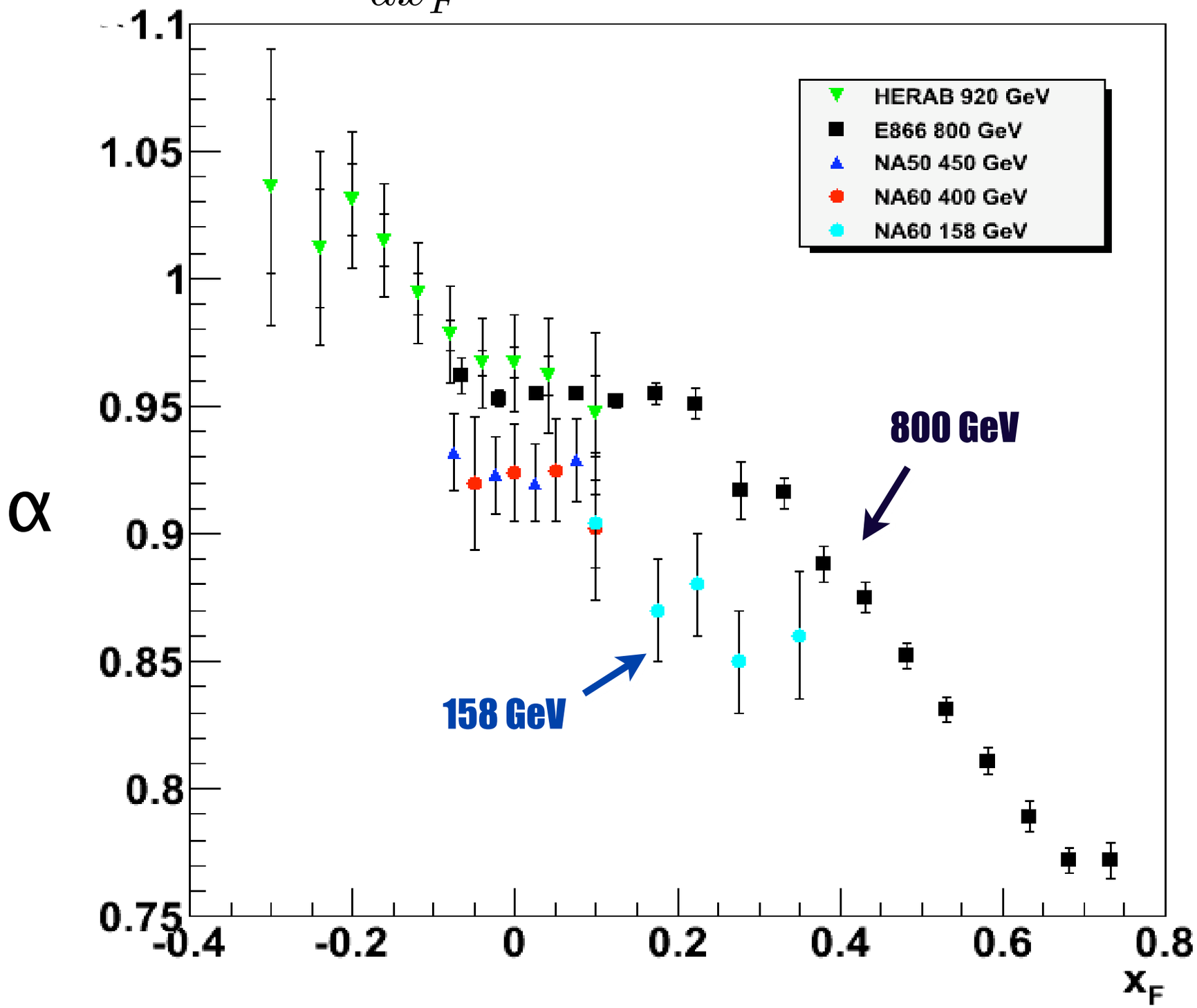
Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

NA60 pA data @ 158GeV

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



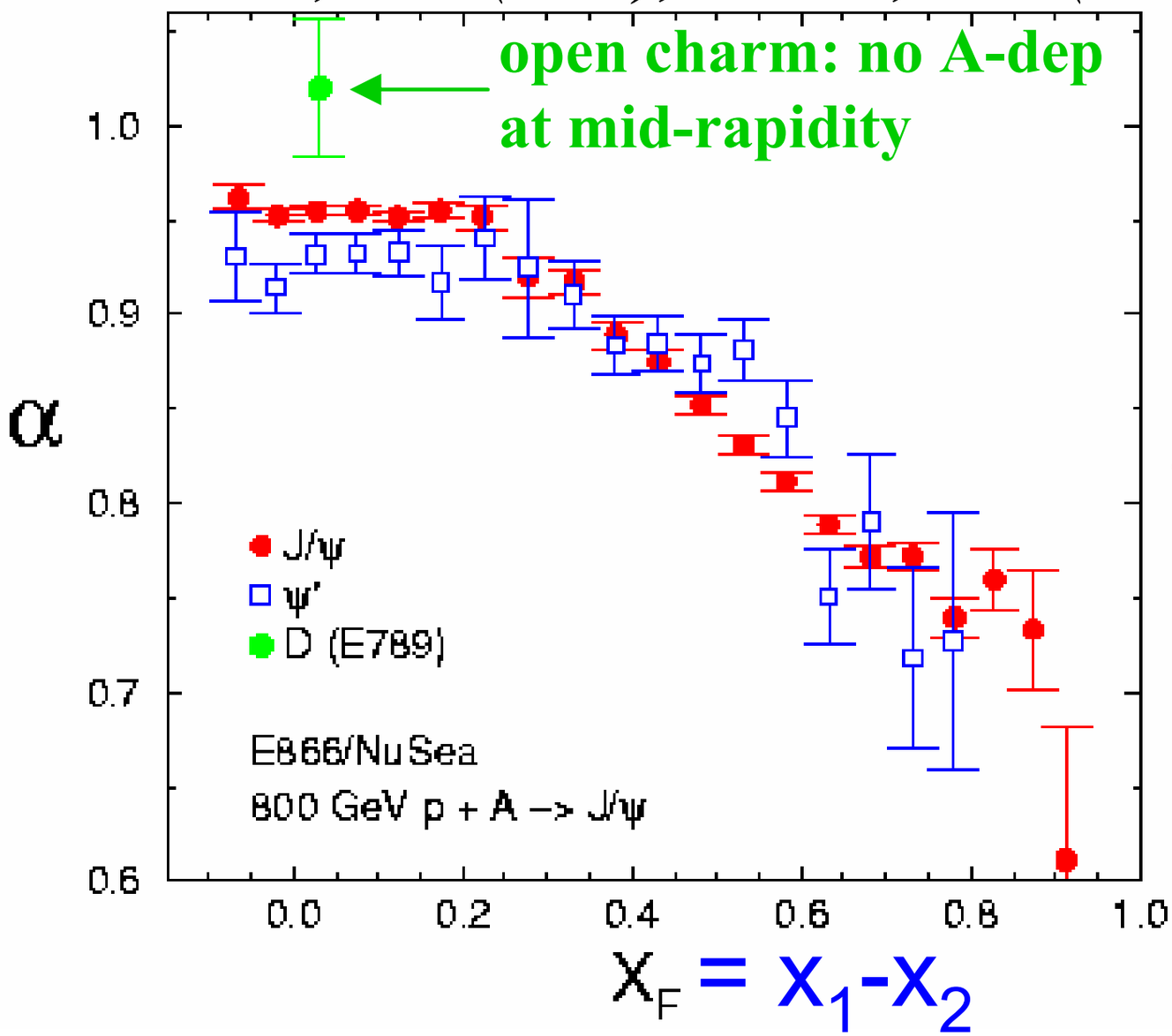
Clear dependence on x_F and beam energy

Dramatic change in nuclear dependence

M. Leitch

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

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



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

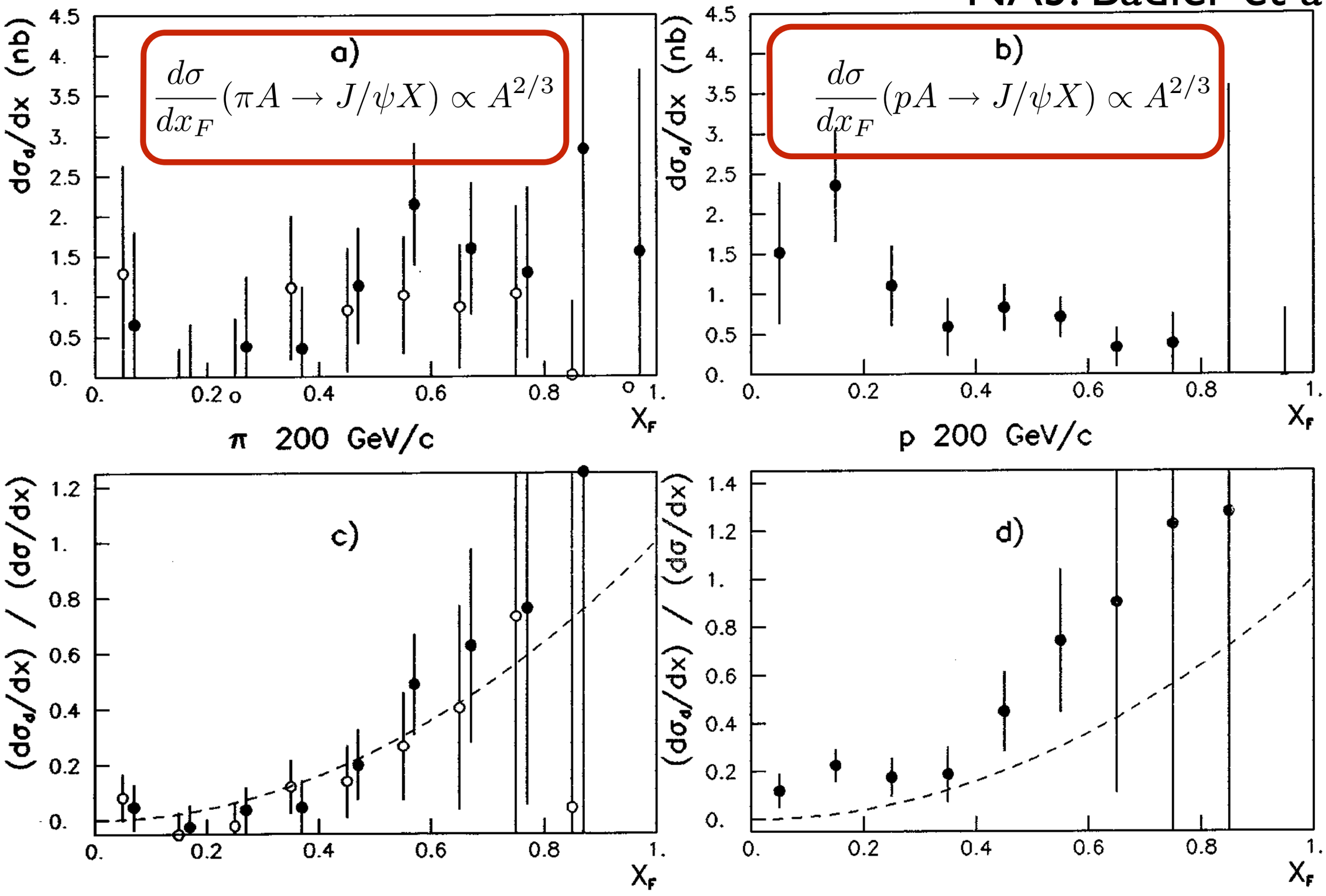
Remarkably Strong Nuclear Dependence for Fast Charmonium

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.
Published in Phys.Lett.B246:217-220,1990

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

NA3: Badier et al.



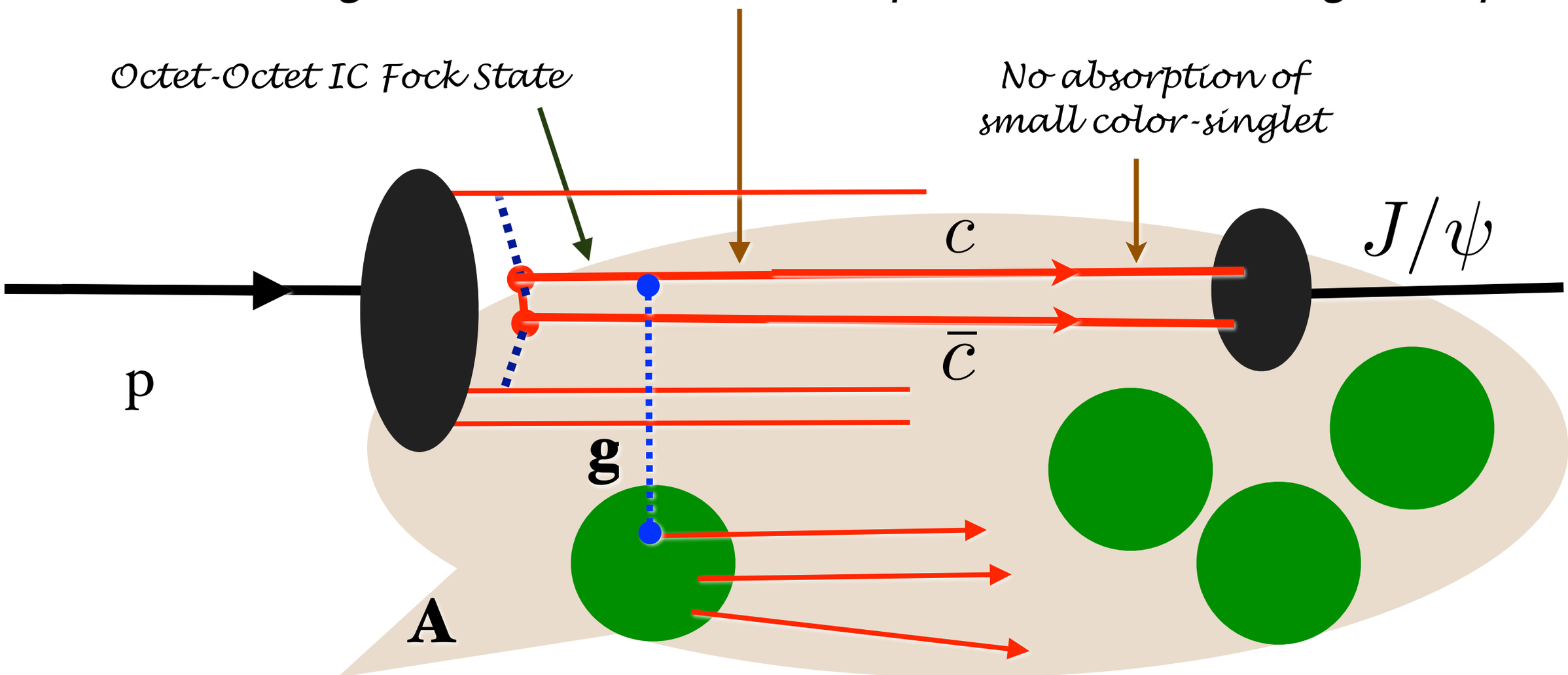
Flat x_F distribution explained by IC

High x_F

Color-Opaque IC Fock state interacts on nuclear front surface

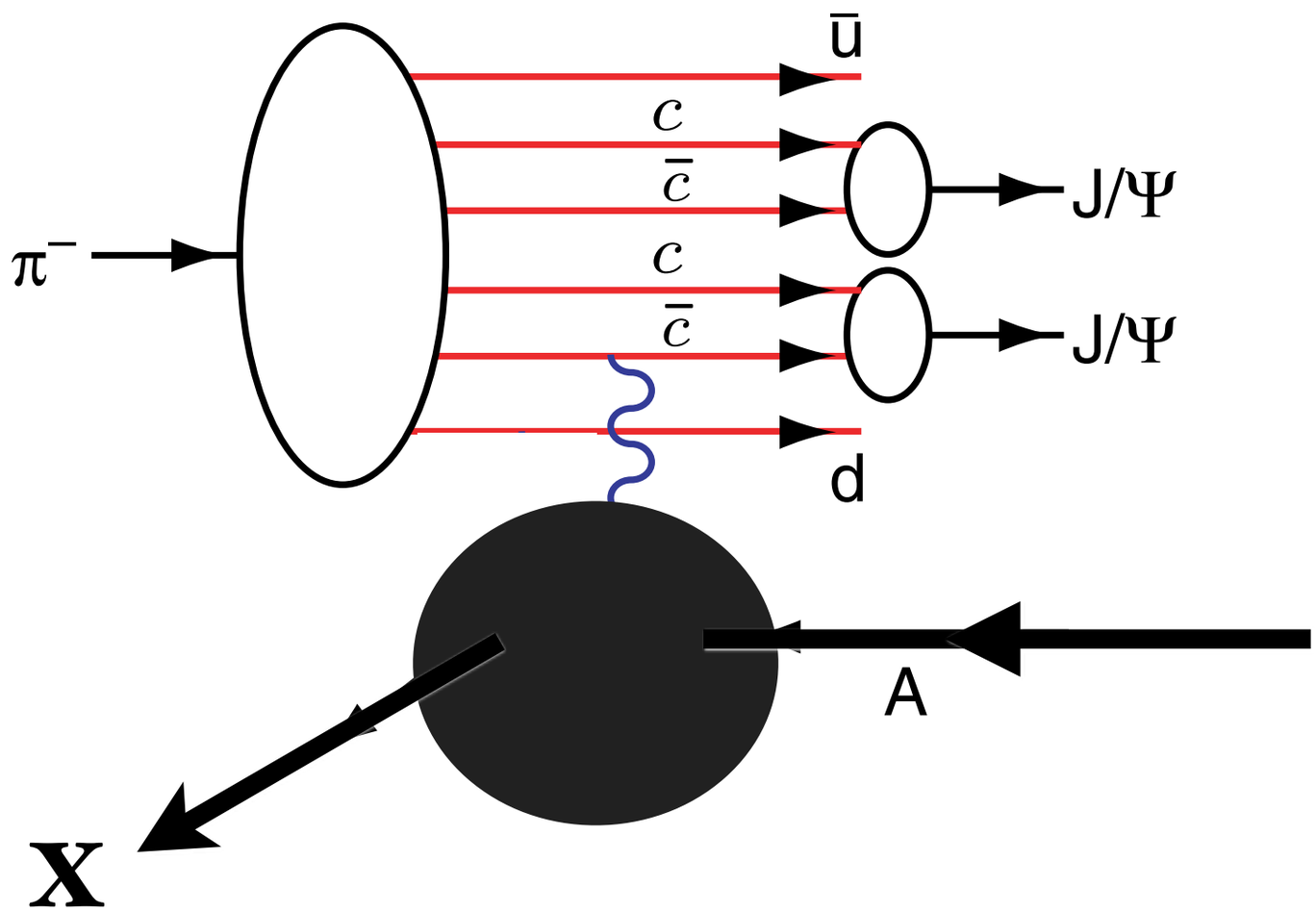
Kopeliovich, Schmidt, Soffer, sjb

Scattering on front-face nucleon produces color-singlet $c\bar{c}$ pair



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

Production of Two Charmonia at High x_F



NA3: All events at high $x_F = x_\psi + x_\psi$!

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

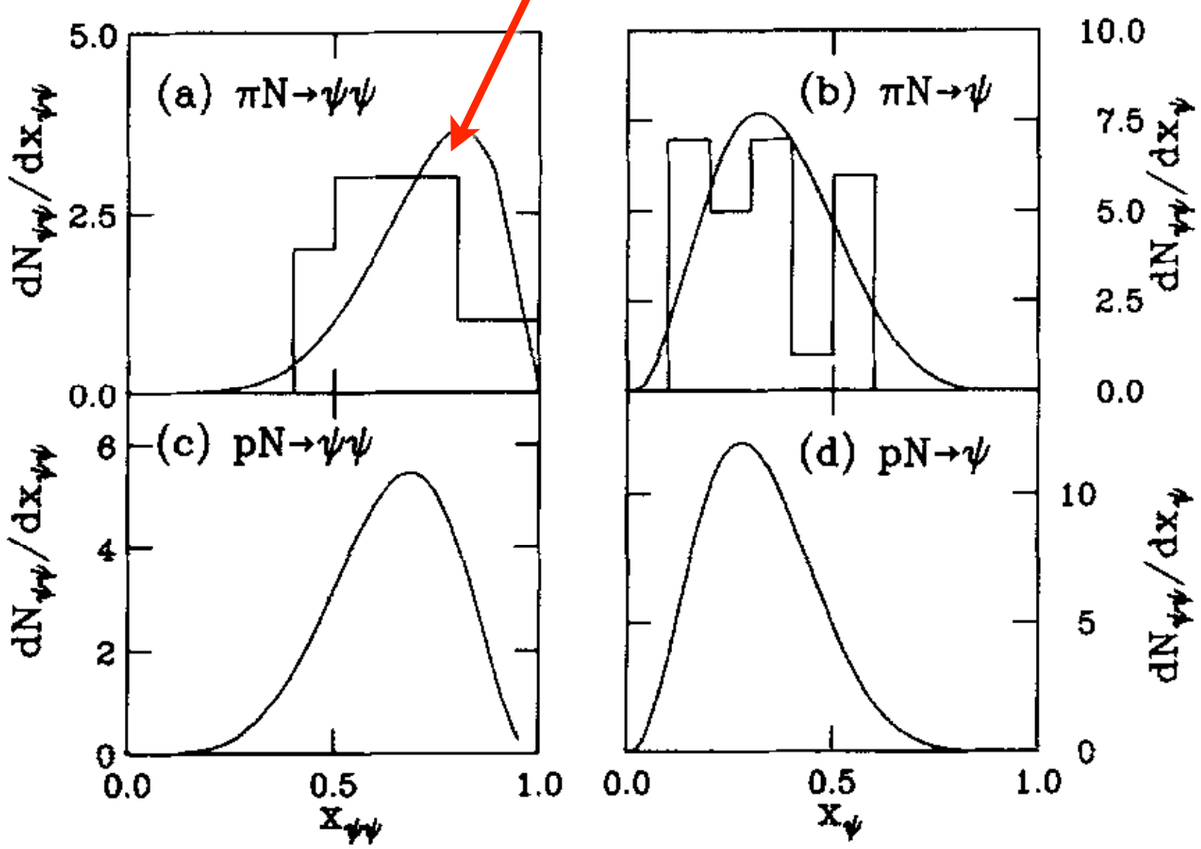


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized 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

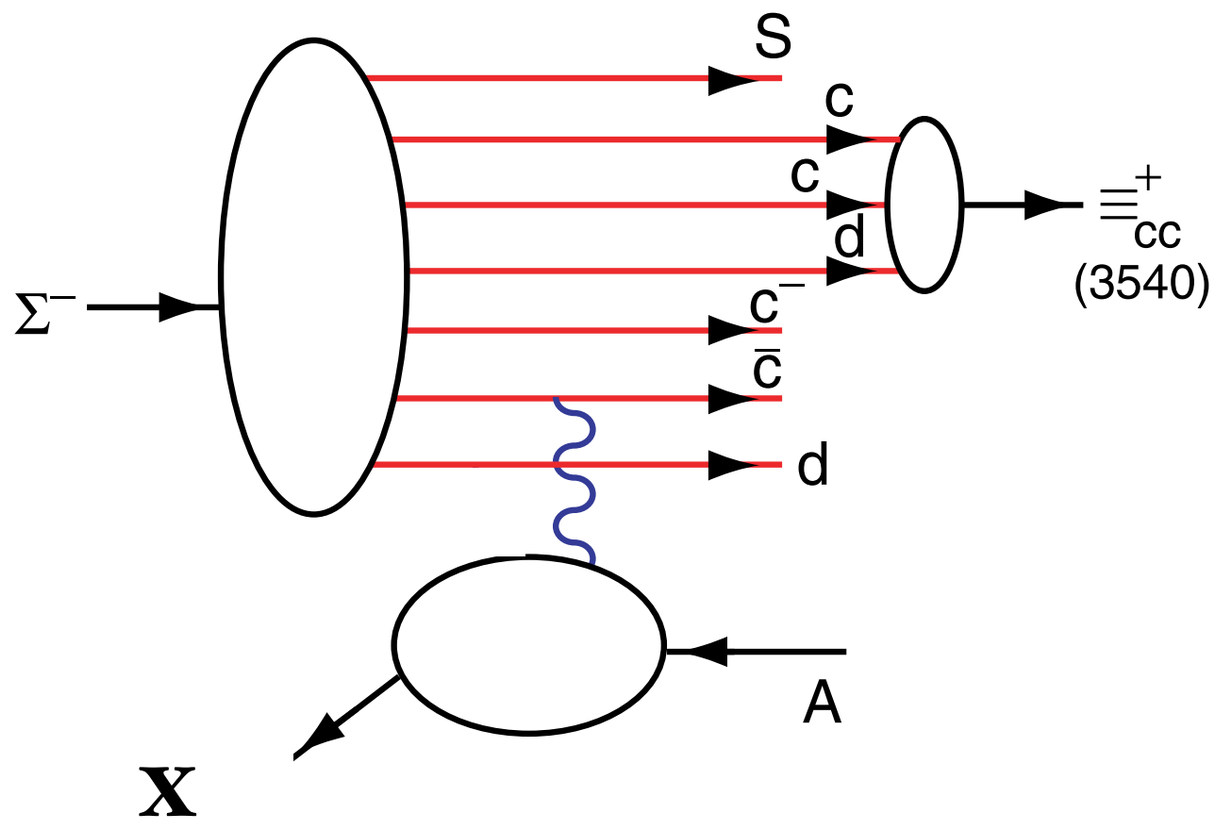
Excludes PYTHIA 'color drag' model

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

R. Vogt, sjb

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

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



Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Why is Intrinsic Heavy Quark Phenomena Important?

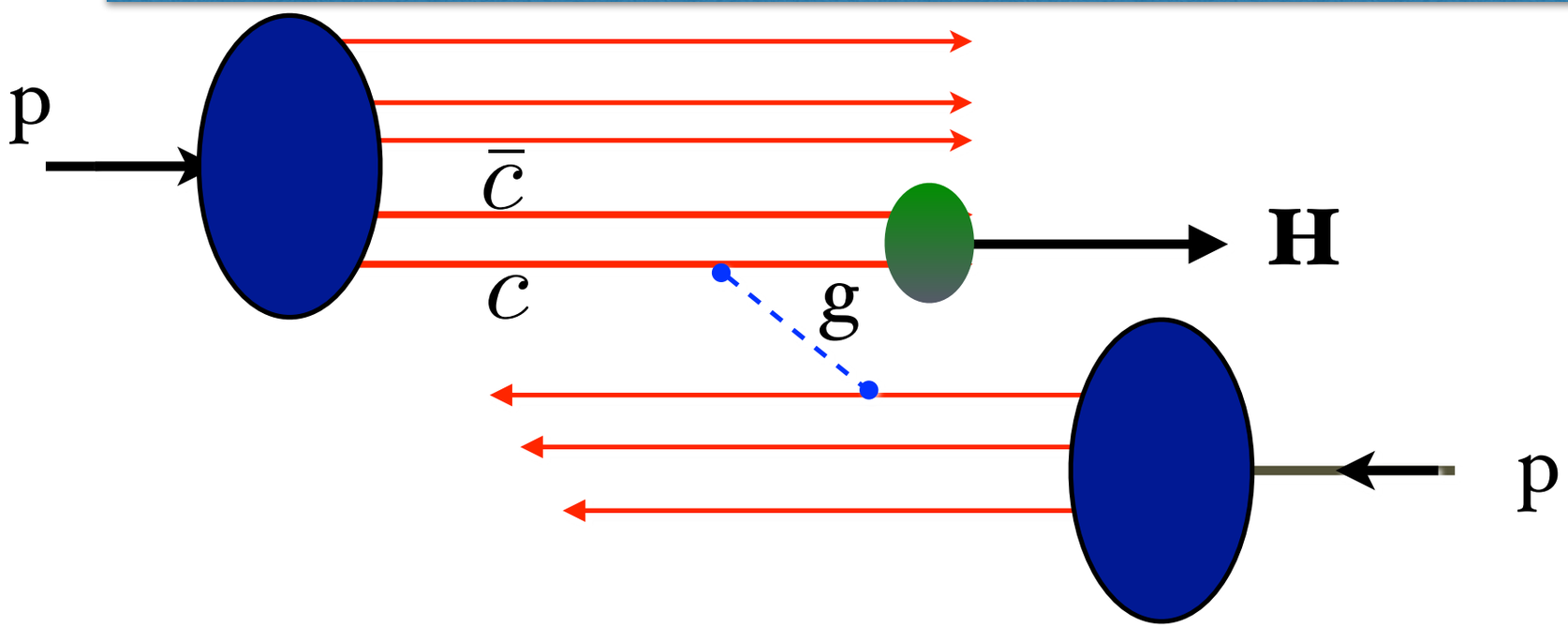
- ***Test Fundamental QCD predictions OPE, Non-Abelian QCD***

  Non-Abelian: $P_{Q\bar{Q}} \propto \frac{1}{M^2_{Q\bar{Q}}}$ Abelian: $P_{Q\bar{Q}} \propto \frac{1}{M^4_{Q\bar{Q}}}$

- ***Test non-perturbative effects***
- ***Important for correctly identifying the gluon distribution***
- ***High-x_F open and hidden charm and bottom; discover exotic states***
- ***Explain anomalous high pT charm jet + γ data at Tevatron***
- ***Important source of high energy ν at IceCube***

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$$pp \to HX$$

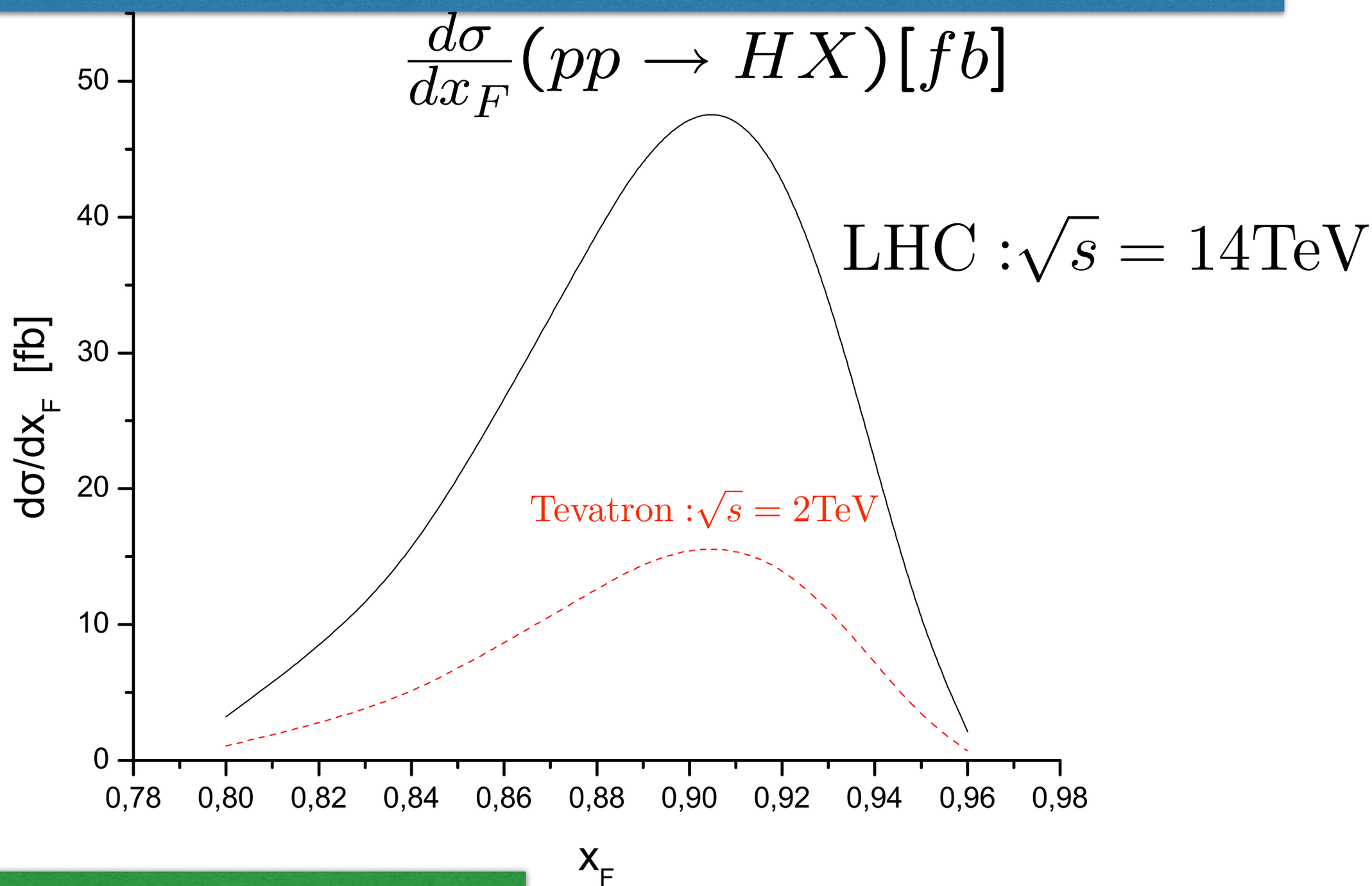
Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs at the LHC

AFTER: Higgs production at threshold!

Intrinsic Heavy Quark Contribution to High x_F Inclusive Higgs Production



Need High x_F Acceptance

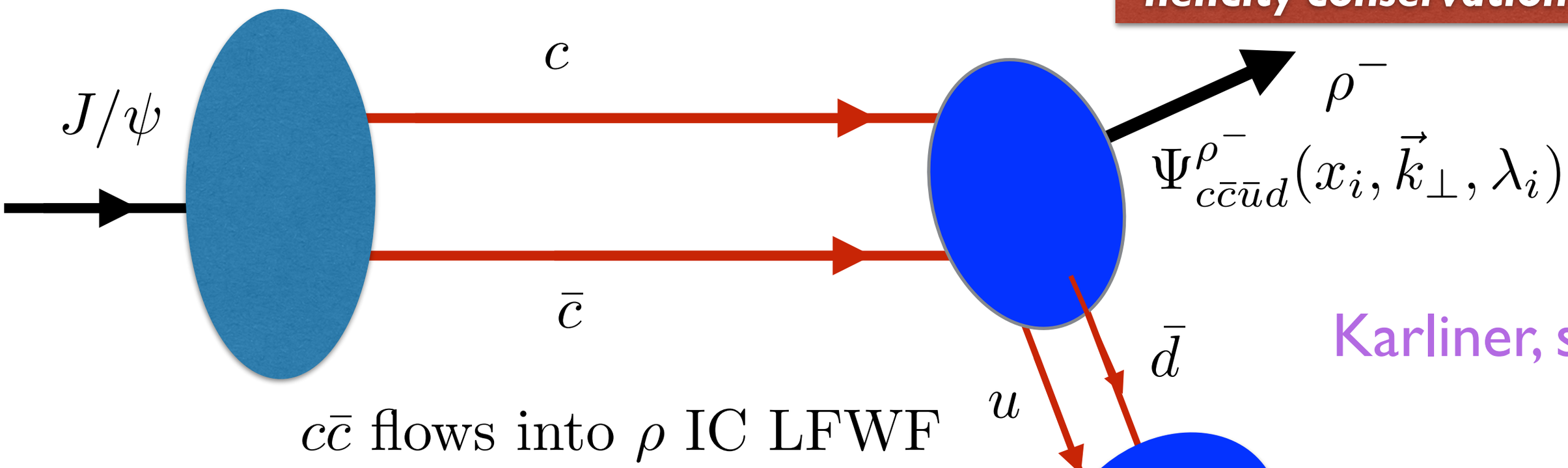
Most practical: Higgs to 4 muons

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

J/Ψ to ρ π Puzzle

$$\frac{\Gamma(\psi(2S) \to \rho\pi))/\Gamma_{\rm tot}}{\Gamma(J/\psi \to \rho\pi))/\Gamma_{\rm tot}} = \frac{3.2 \pm 1.2 \times 10^{-5}}{1.69 \pm 0.15 \times 10^{-2}} \simeq 0.2\%.$$

Not 13%
VP decay violates hadron helicity conservation

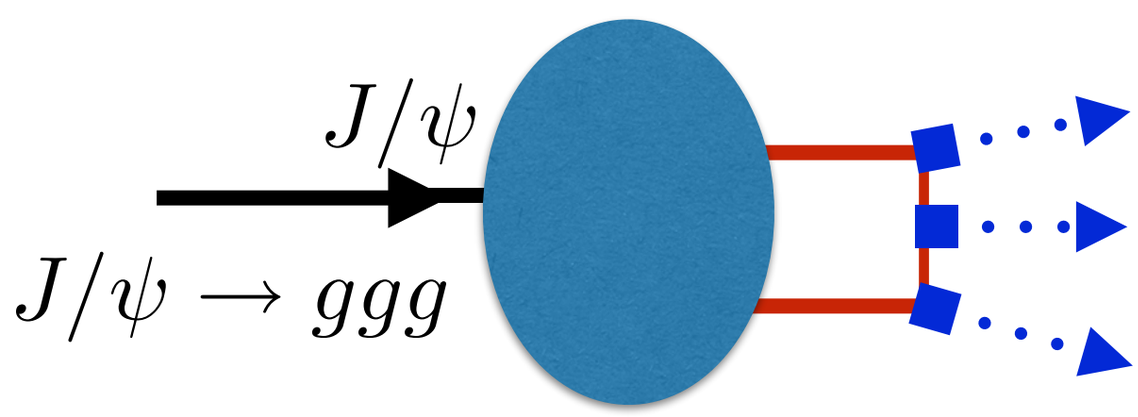


Karliner, sjb

$c\bar{c}$ flows into ρ IC LFWF

Suppressed for $\psi' \to \rho\pi$ because of node

Not OZI

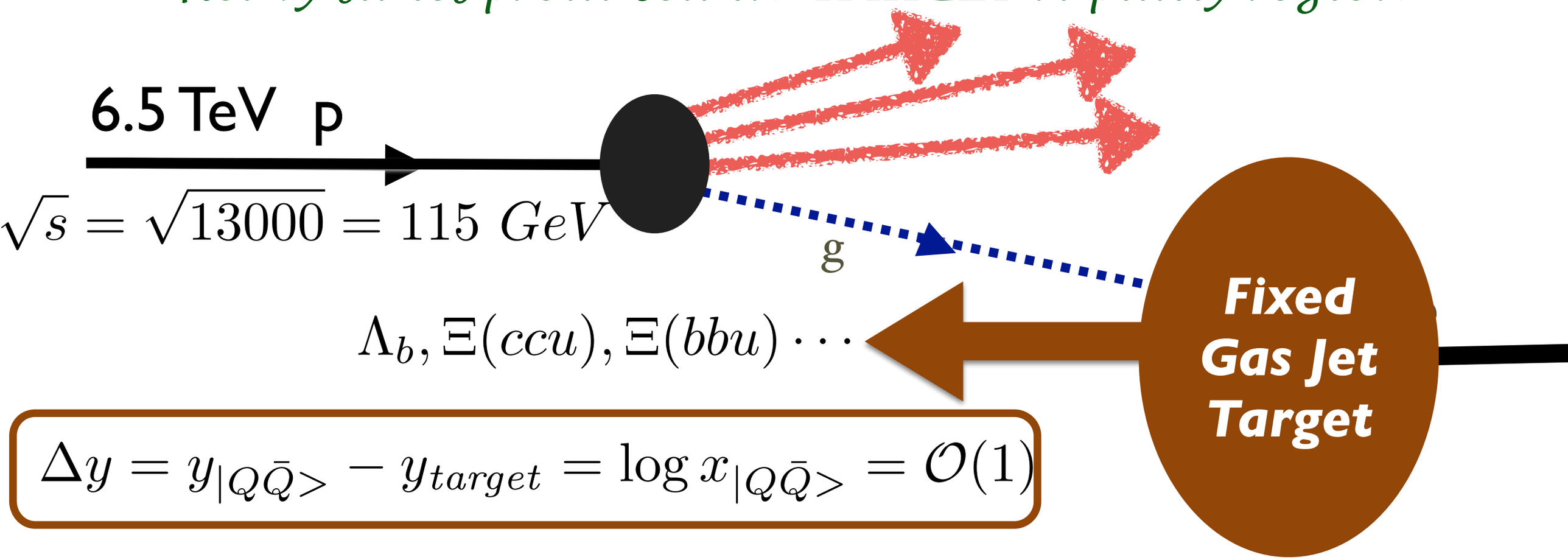


Excitation of Intrinsic Heavy Quarks in a Fixed Target

Amplitude maximal at minimal invariant mass, in target rapidity domain!

$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}} \qquad \frac{d\sigma}{dy_{J/\psi}}(pA \to J/\psi X)$$

Heavy states produced in **TARGET** *rapidity region*



$$\Delta y = y_{|Q\bar{Q}>} - y_{target} = \log x_{|Q\bar{Q}>} = \mathcal{O}(1)$$

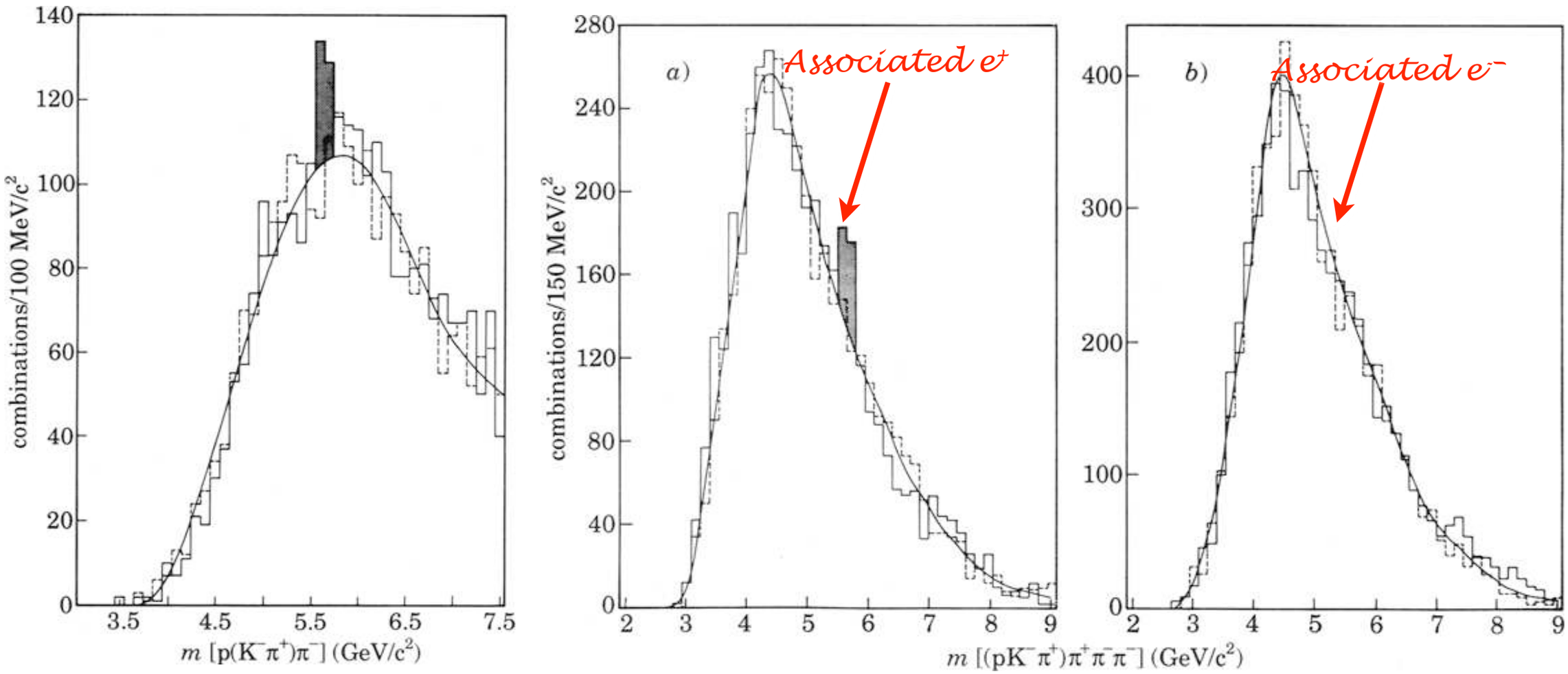
Produce $J/\psi, \Upsilon, \Lambda_c, \Lambda_b, |ccu>, |cud\bar{c}>, |cuuddd u\bar{c}>, \cdots$

Test at LHCb!!

discussions with M. Williams

$pp \to \Lambda_b(bud)B(\bar{b}q)X$ at large x_F $\quad \sqrt{s} = 63\ GeV$

CERN-ISR R422 (Split Field Magnet), 1988/1991



$\Lambda_b^0 \to pD^0\pi^-$ $\qquad$ $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

Il Nuovo Cimento 104, 1787

Discovery of Λ_b; Associated Production; Evidence for Intrinsic $b\bar{b}$

Create Λ_b at rest at LHCb at $\sqrt{s} = \sqrt{13000} = 115\ GeV$

JLab 12 GeV: An Exotic Charm Factory!

$$\gamma^* p \to J/\psi + p \text{ threshold}$$
$$\text{at } \sqrt{s} \simeq 4 \text{ GeV}, \; E_{\text{lab}}^{\gamma^*} \simeq 7.5 \text{ GeV}.$$

Produce $[J/\psi + p]$ bound state

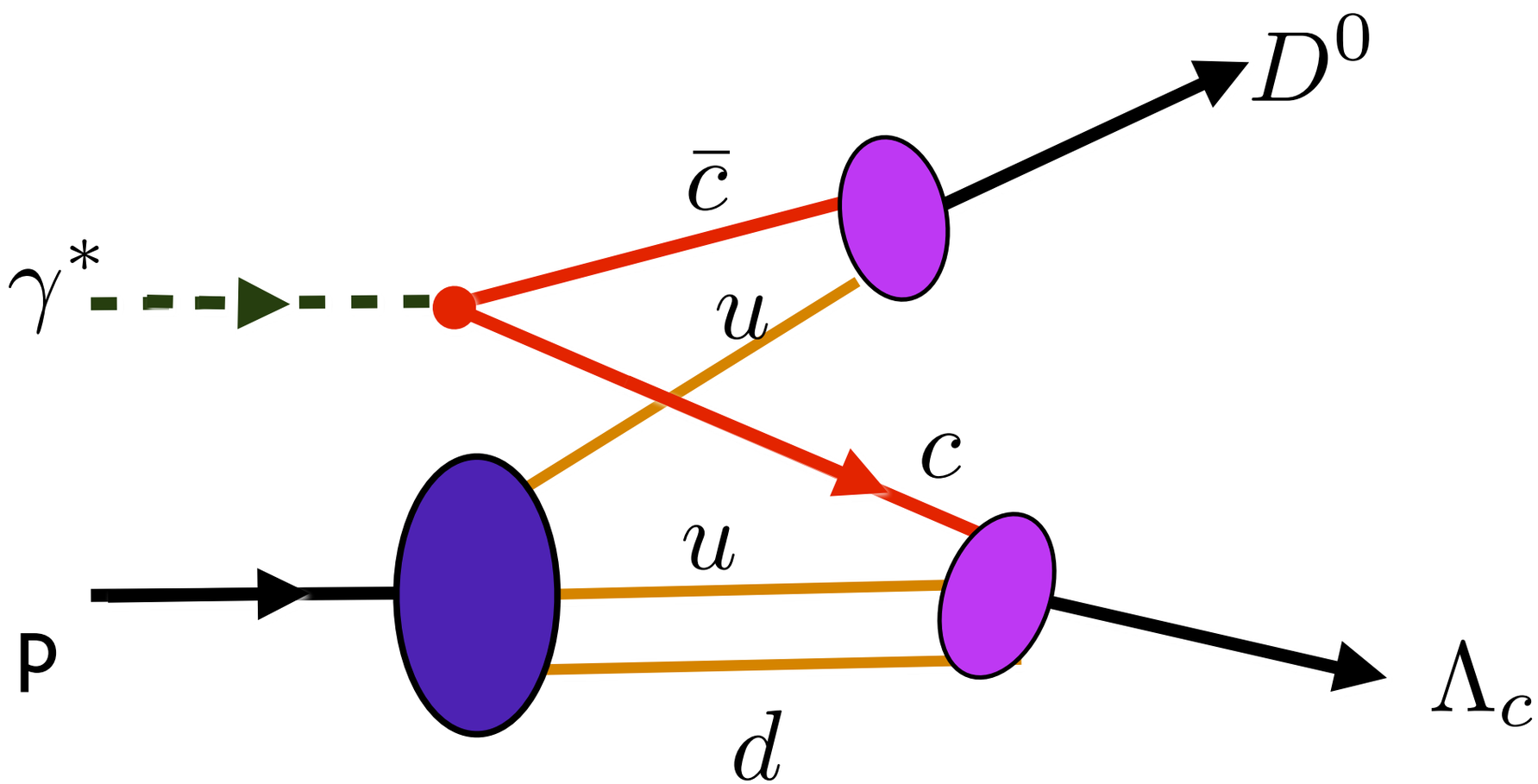
$$|uudc\bar{c}>$$

$$\gamma^* d \to J/\psi + d \text{ threshold}$$
$$\text{at } \sqrt{s} \simeq 5 \text{ GeV}, \; E_{\text{lab}}^{\gamma^*} \simeq 6 \text{ GeV}.$$

Produce $[J/\psi + d]$ nuclear-bound quarkonium state

$$|uuddduc\bar{c}>$$

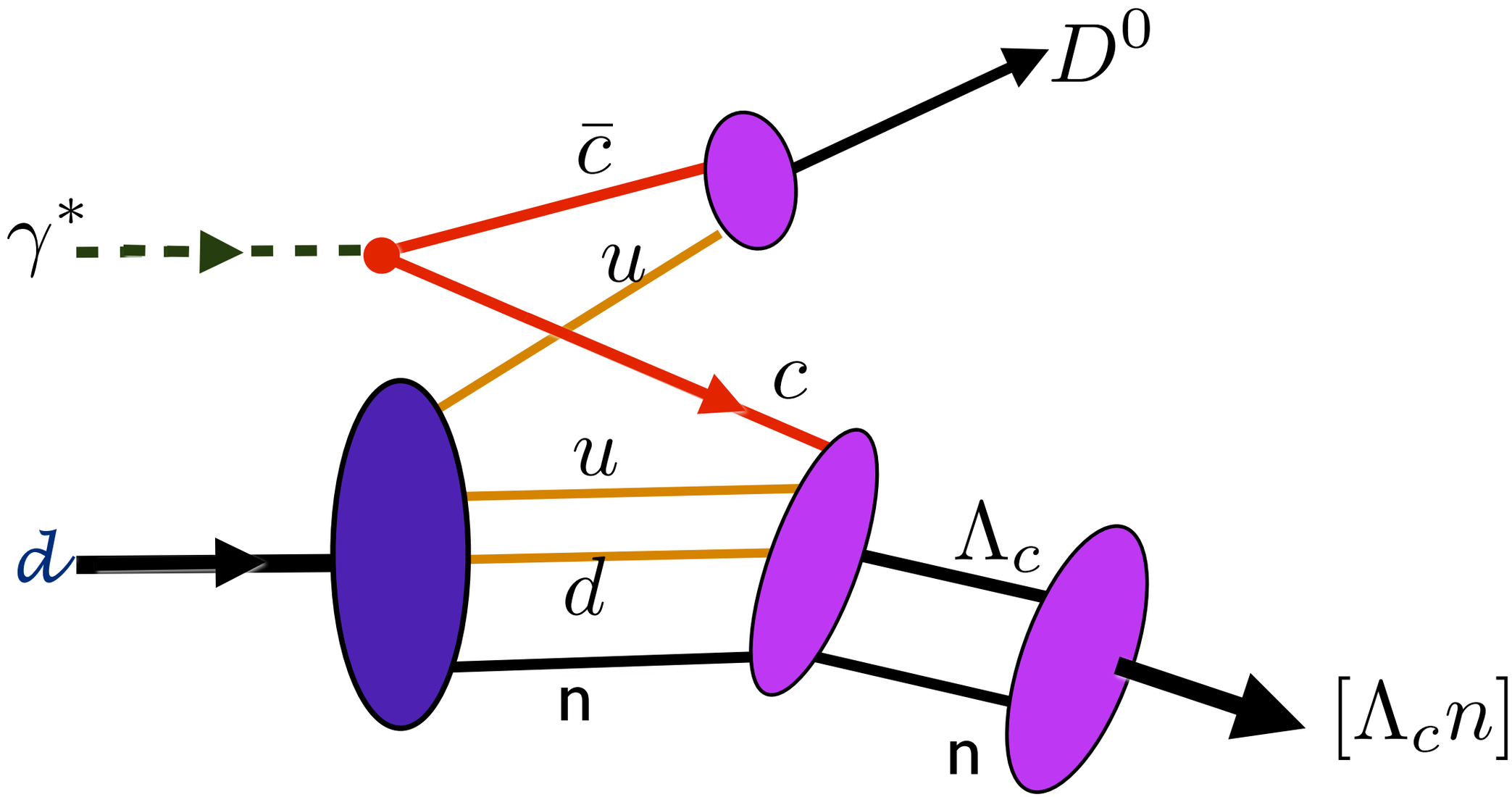
Exclusive Open Charm and Bottom Production



$$\gamma^* p \to \overline{D}^0(\bar{c}u)\Lambda_c(cud)$$

c and u quark interchange

Nuclear binding at low relative velocity

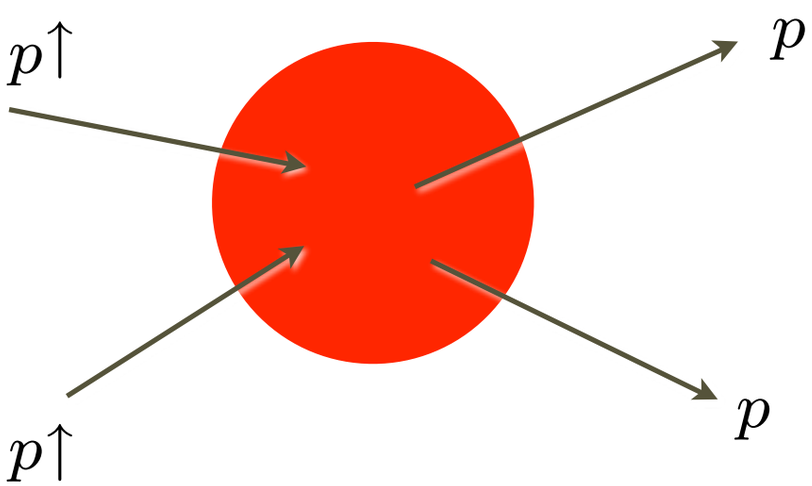


$$\gamma^* d \to \overline{D}^0(\bar{c}u)[\Lambda_c n](cududd)$$

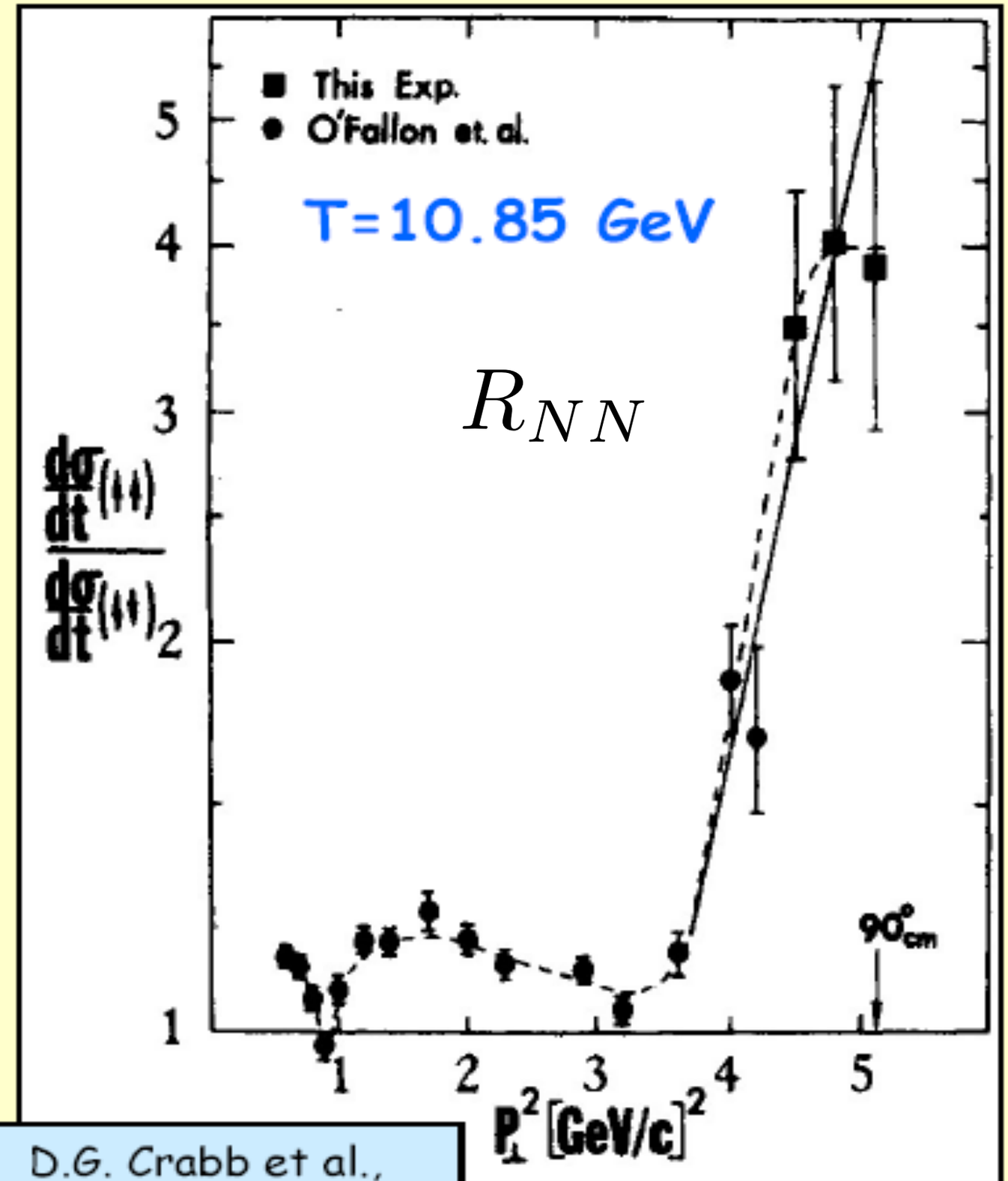
Possible charmed B= 2 nucleus

Krisch, Crabb, et al

Unexpected spin-spin correlation in pp elastic scattering

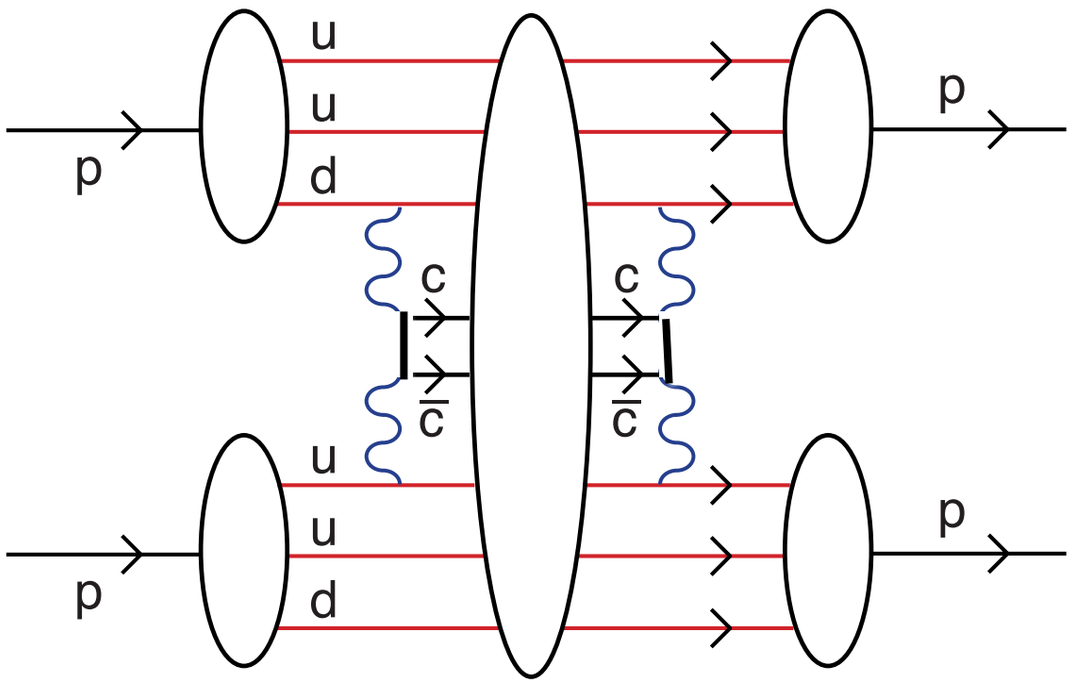


polarizations normal to scattering plane



D.G. Crabb et al., PRL 41, 1257 (1978)

$$A_{nn} = 1!$$



QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

Production of uud $\bar{c}$ c uud octoquark resonance

J=L=S=1, C=-, P=- state

8 quarks in S-wave: odd parity

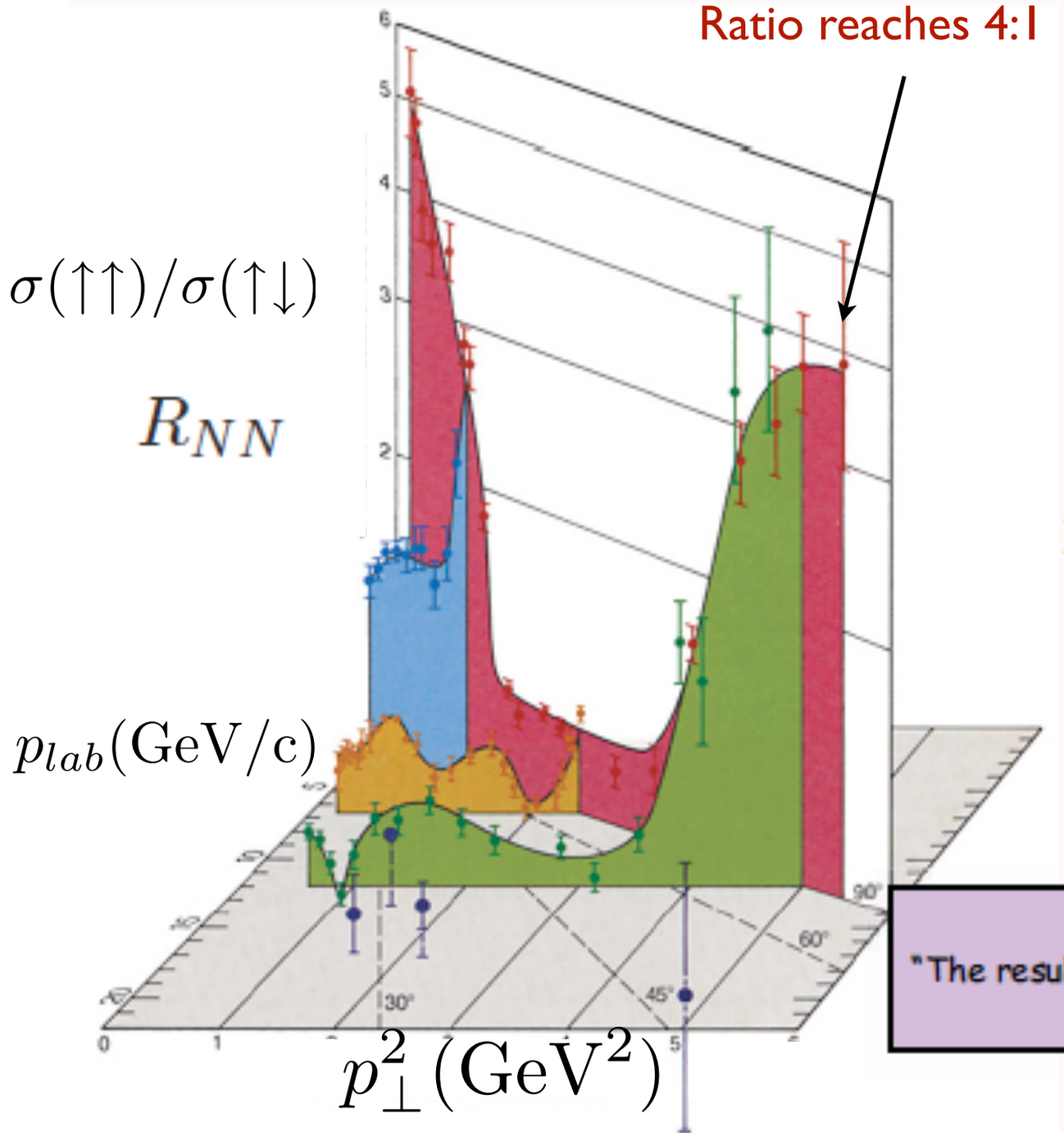
$$|uud\ uud\ c\bar{c}\rangle$$

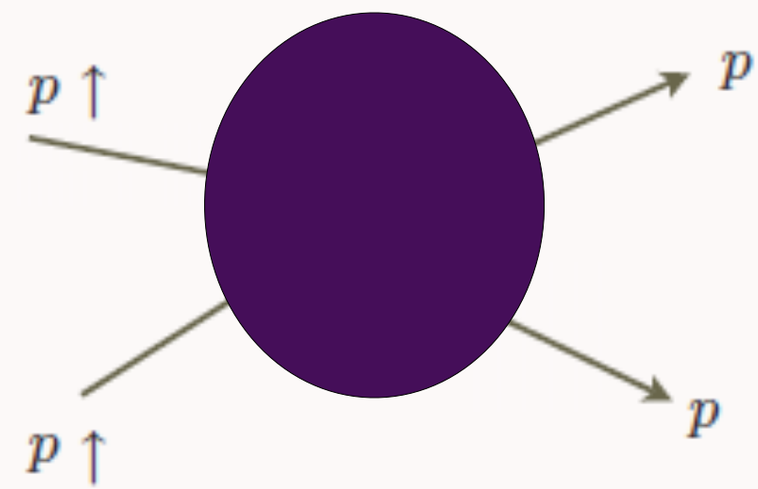
B=2 Octoquark

$$\sigma(pp \to c\bar{c}X) \simeq 1\ \mu b \text{ at threshold}$$

$$\sigma(\gamma p \to c\bar{c}X) \simeq 1\ nb \text{ at threshold}$$

Spin Correlations in Elastic $p - p$ Scattering





polarization normal to scattering plane

$$|uud\ uud\ c\bar{c}\rangle$$

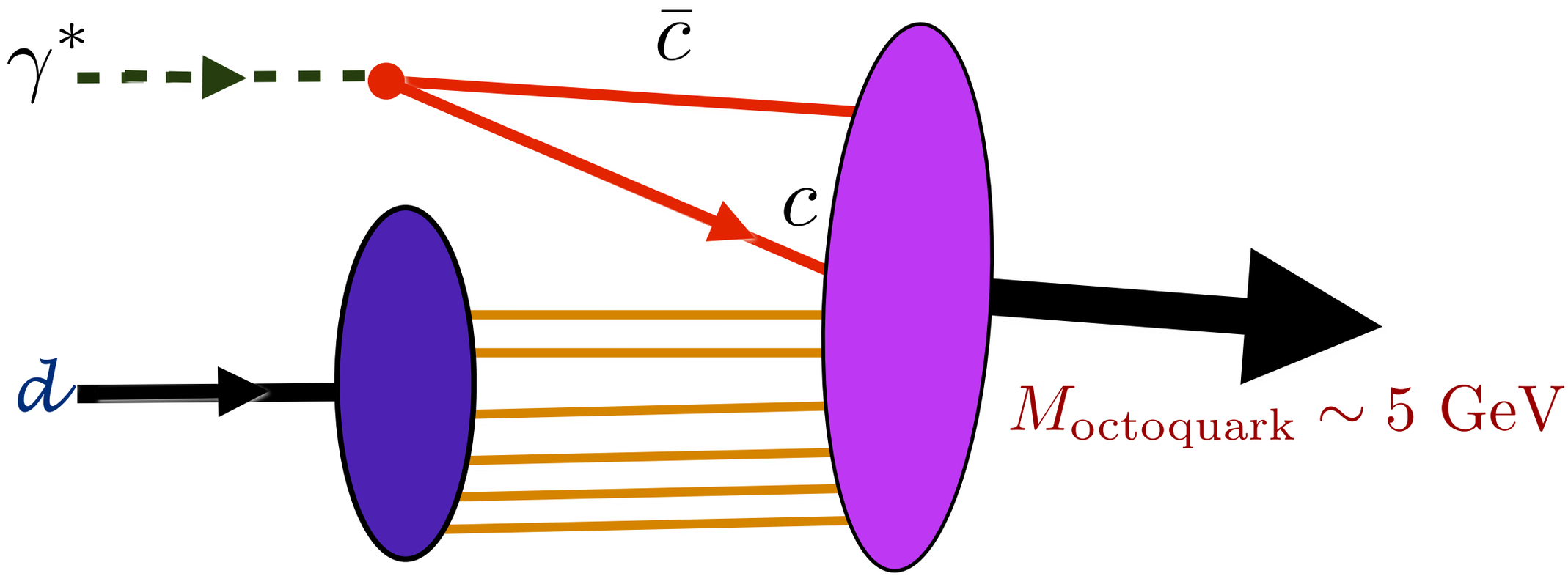
B=2 Octoquark

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

Large R_{NN} in $pp \to pp$ explained by $B = 2, J = L = 1$ $|uuduudc\bar{c}>$ resonance at $\sqrt{s} \sim 5$ GeV

de Teramond and sjb

Octoquark Production at Threshold

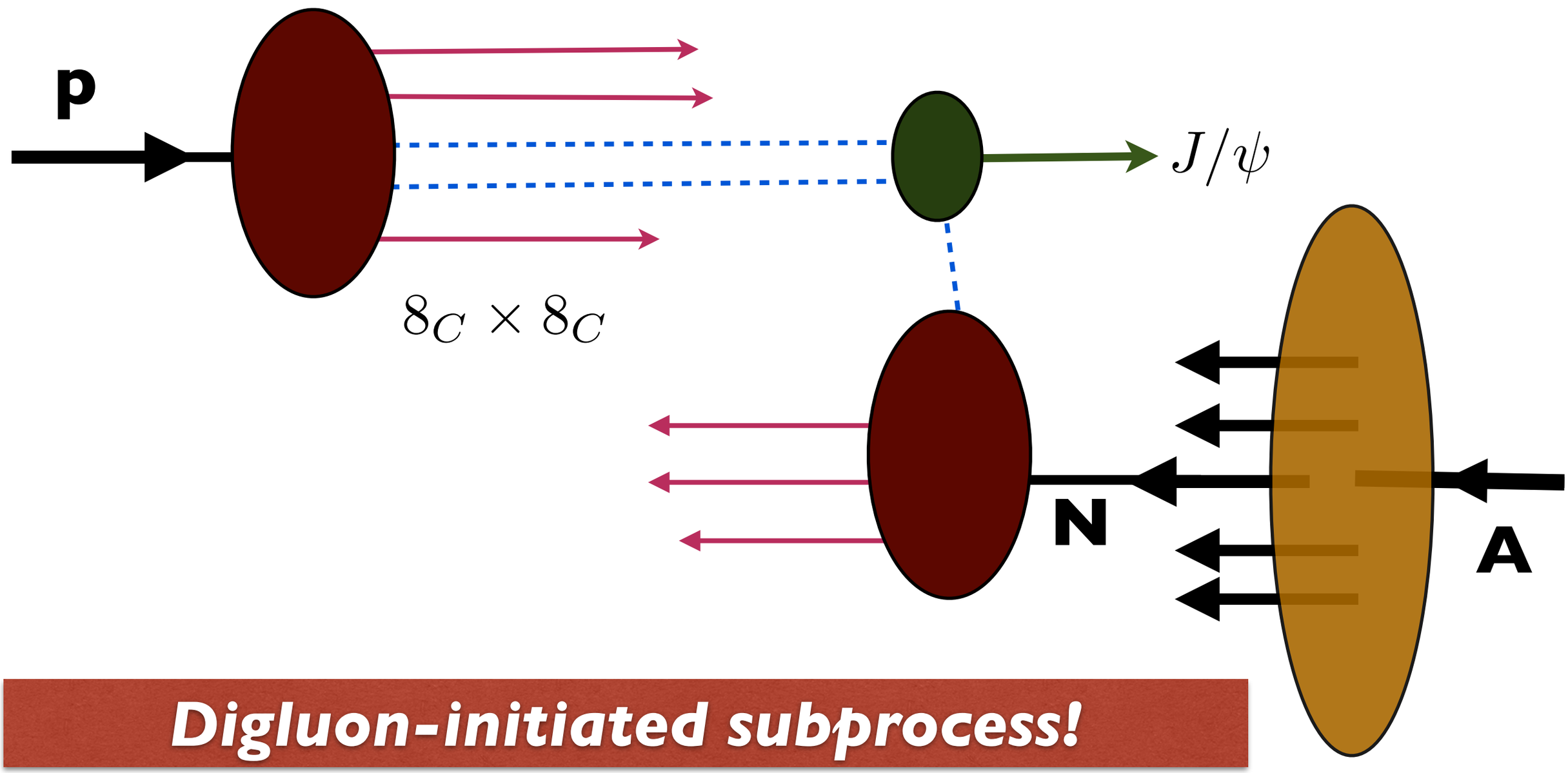


$$\gamma^* d \to |uududdc\bar{c}>$$

Explains Krisch Effect!

$$pA \to J/\psi X$$

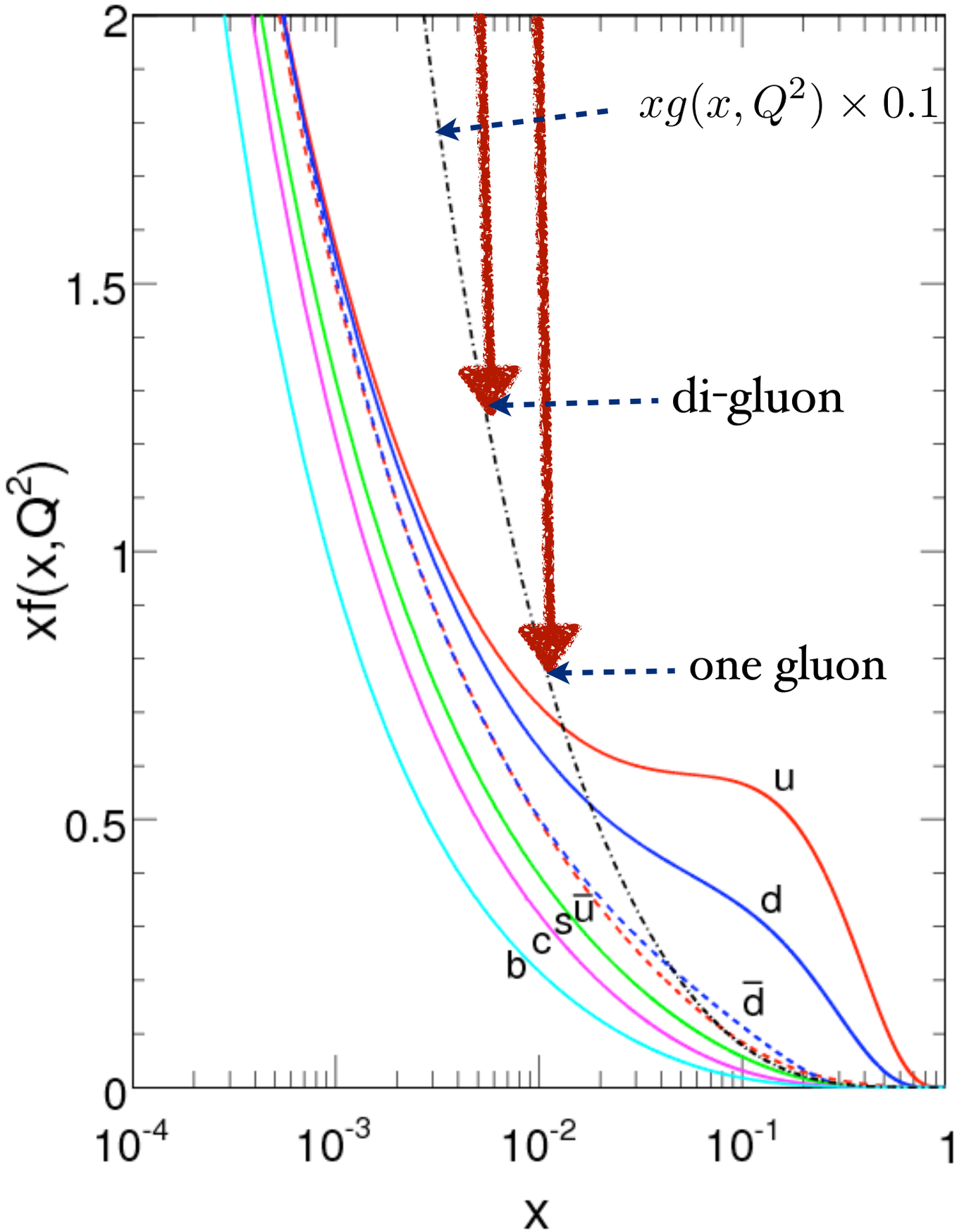
$$(gg)_{8_C} + g_{8_C} \to J/\psi$$



Digluon-initiated subprocess!

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

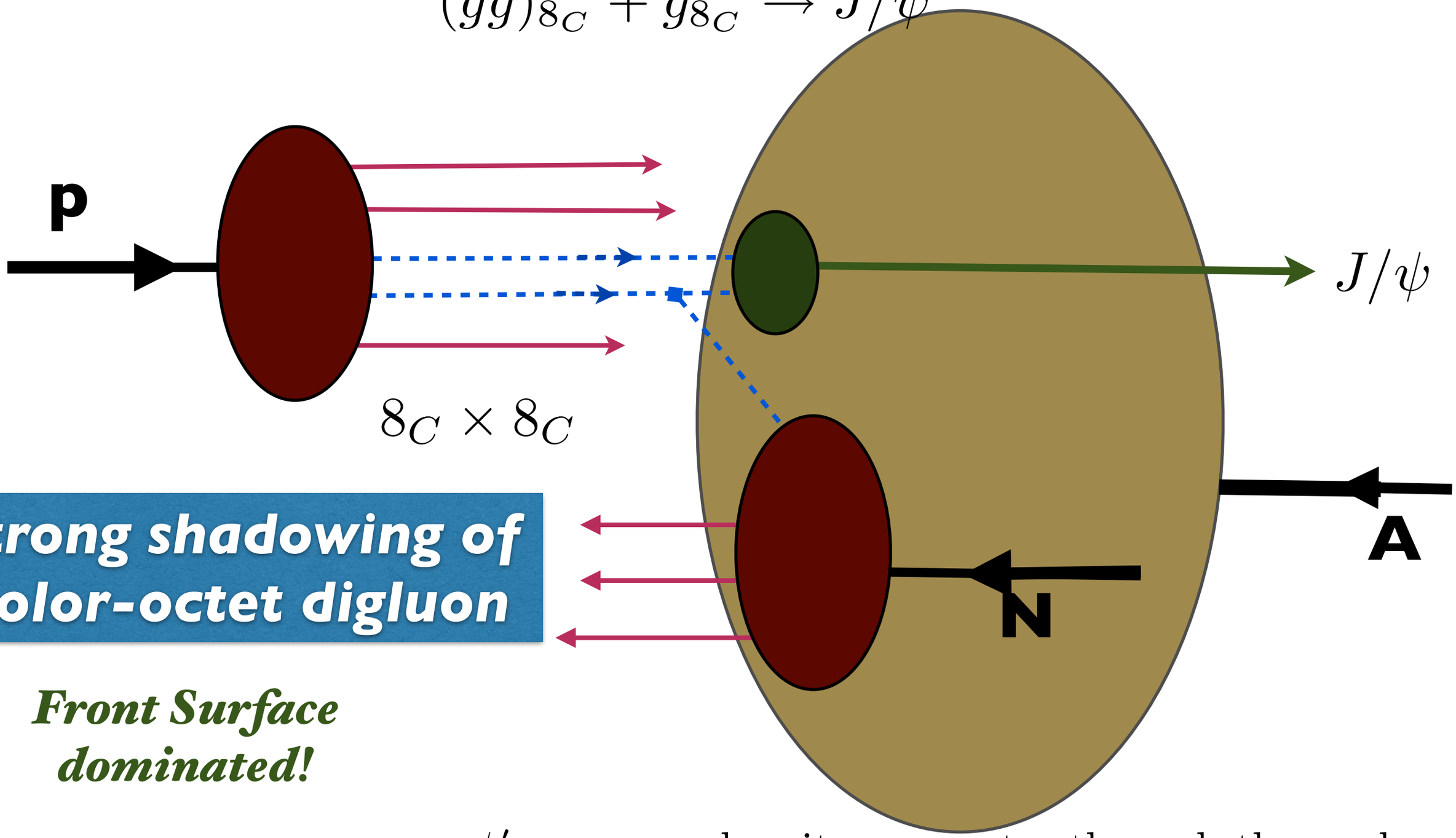
Two gluons at $g(0.005) \sim \frac{13}{0.005} = 2600$ vs. one gluon at $g(0.01) \sim \frac{8}{0.01} = 800$



Forward rapidity y ~4

$$pA \to J/\psi X$$

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



Strong shadowing of color-octet digluon

Front Surface dominated!

ψ' suppressed as it propagates through the nucleus

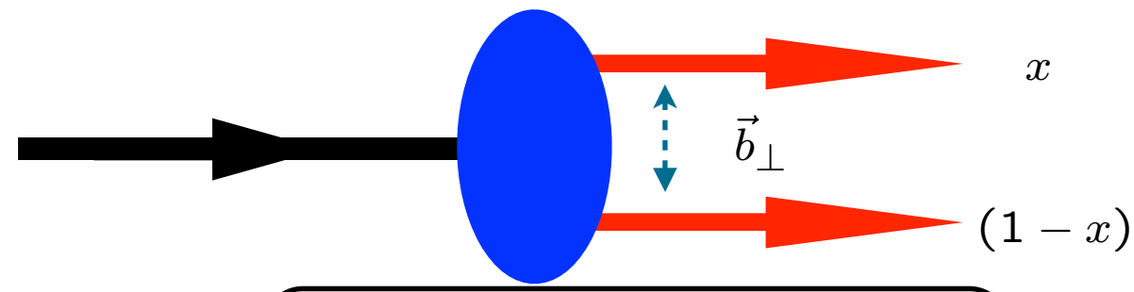
Digluon-initiated subprocess!

Crossing: Diffractive & pomeron exchange

Light-Front QCD

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

Fixed $\tau = t + z/c$



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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

Effective two-particle equation

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

Azimuthal Basis

$$\zeta, \phi$$

$$m_q = 0$$

AdS/QCD:

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

Confining AdS/QCD potential!

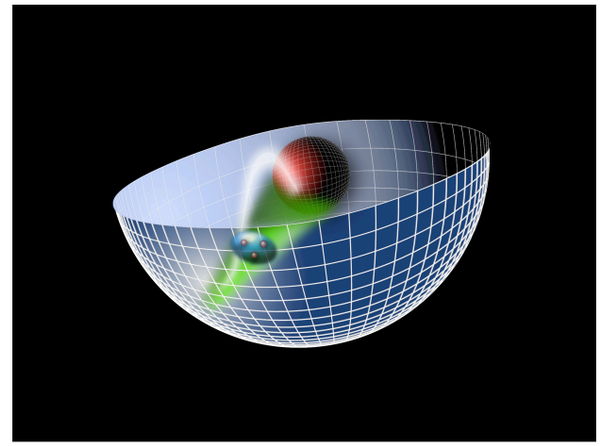
Semiclassical first approximation to QCD

Sums an infinite # diagrams

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent fundamental mass scale
κ



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

Light-Front Holography

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

Light-Front Schrödinger Equation

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

Unique Confinement Potential!

Conformal Symmetry of the action

$$\kappa \simeq 0.6\ GeV$$

Confinement scale:
(m_q=0)

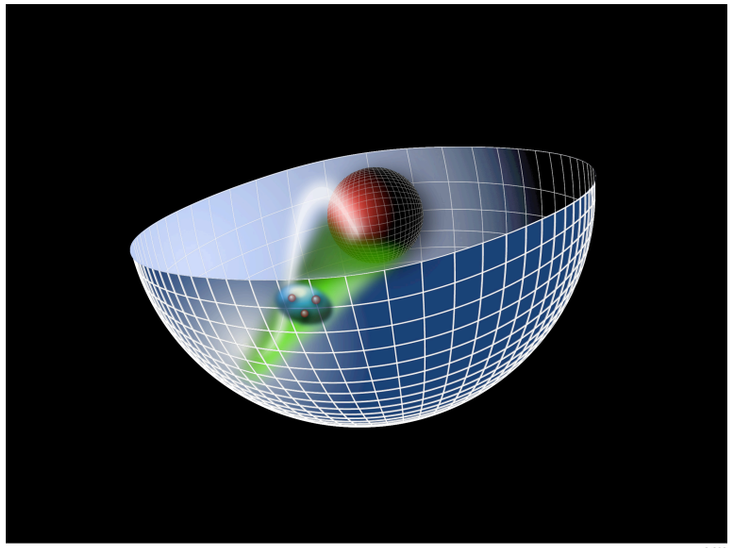
$$1/\kappa \simeq 1/3\ fm$$

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

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

AdS5: Conformal Template for QCD

$\phi(z)$

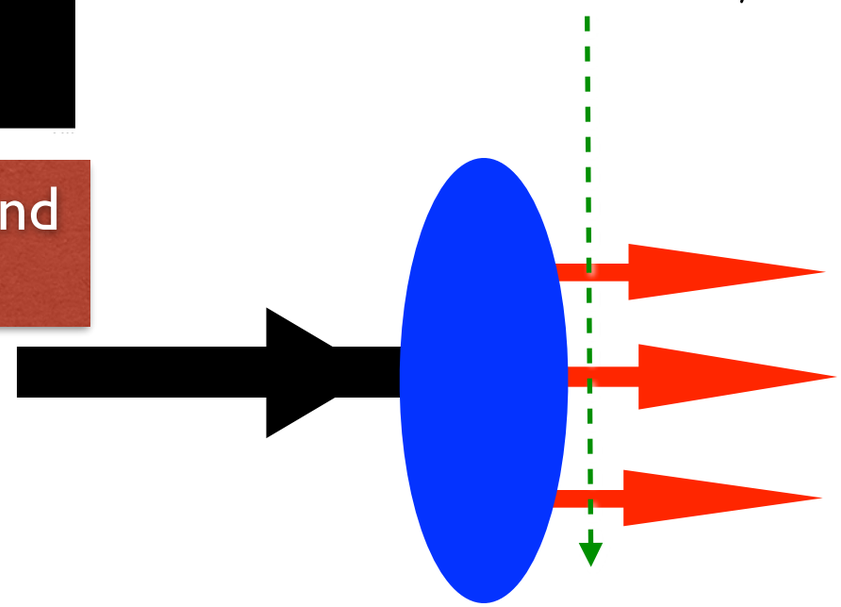


with Guy de Teramond and Hans Guenter Dosch

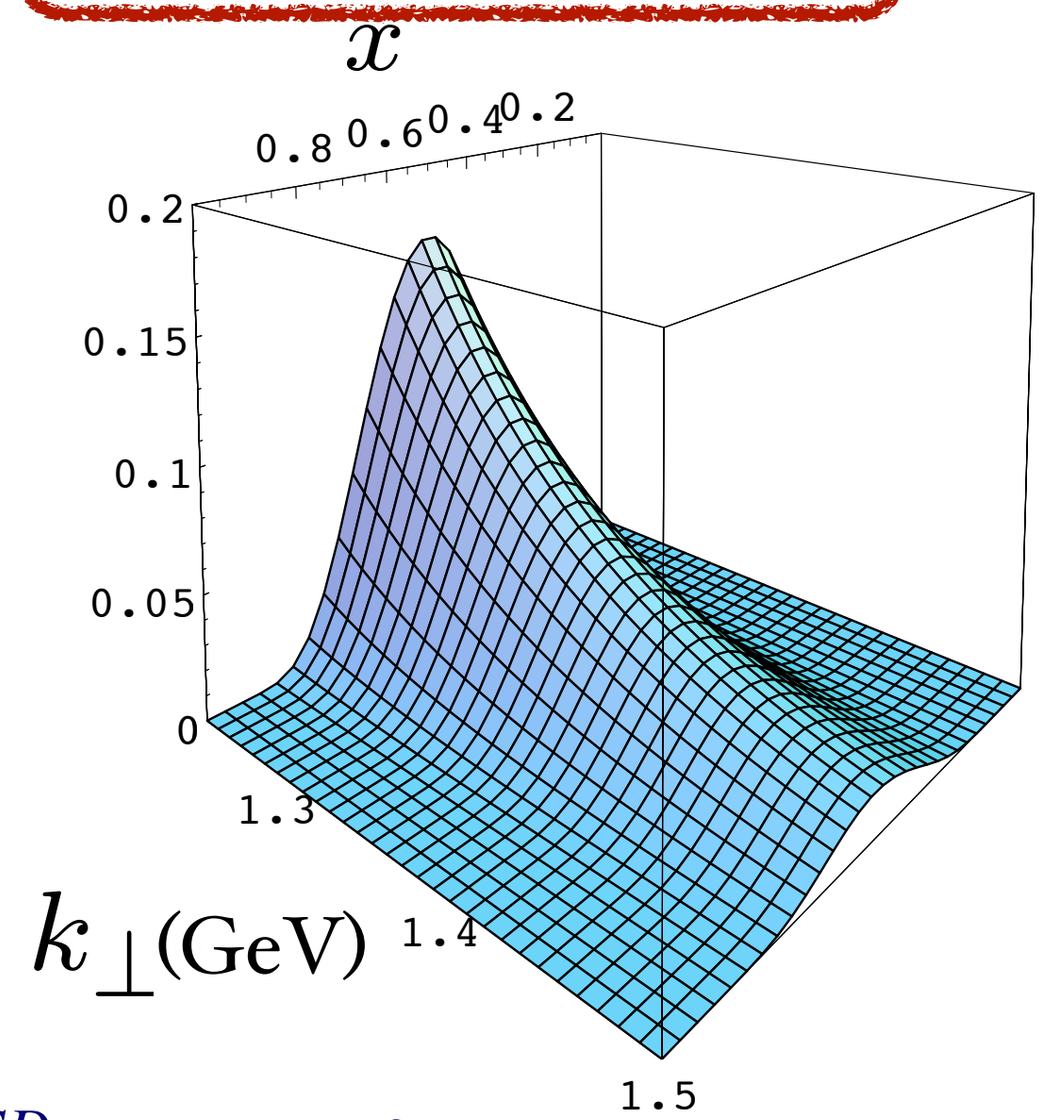
- *Light-Front Holography*

Duality of AdS$_5$ with LF Hamiltonian Theory

Fixed $\tau = t + z/c$



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



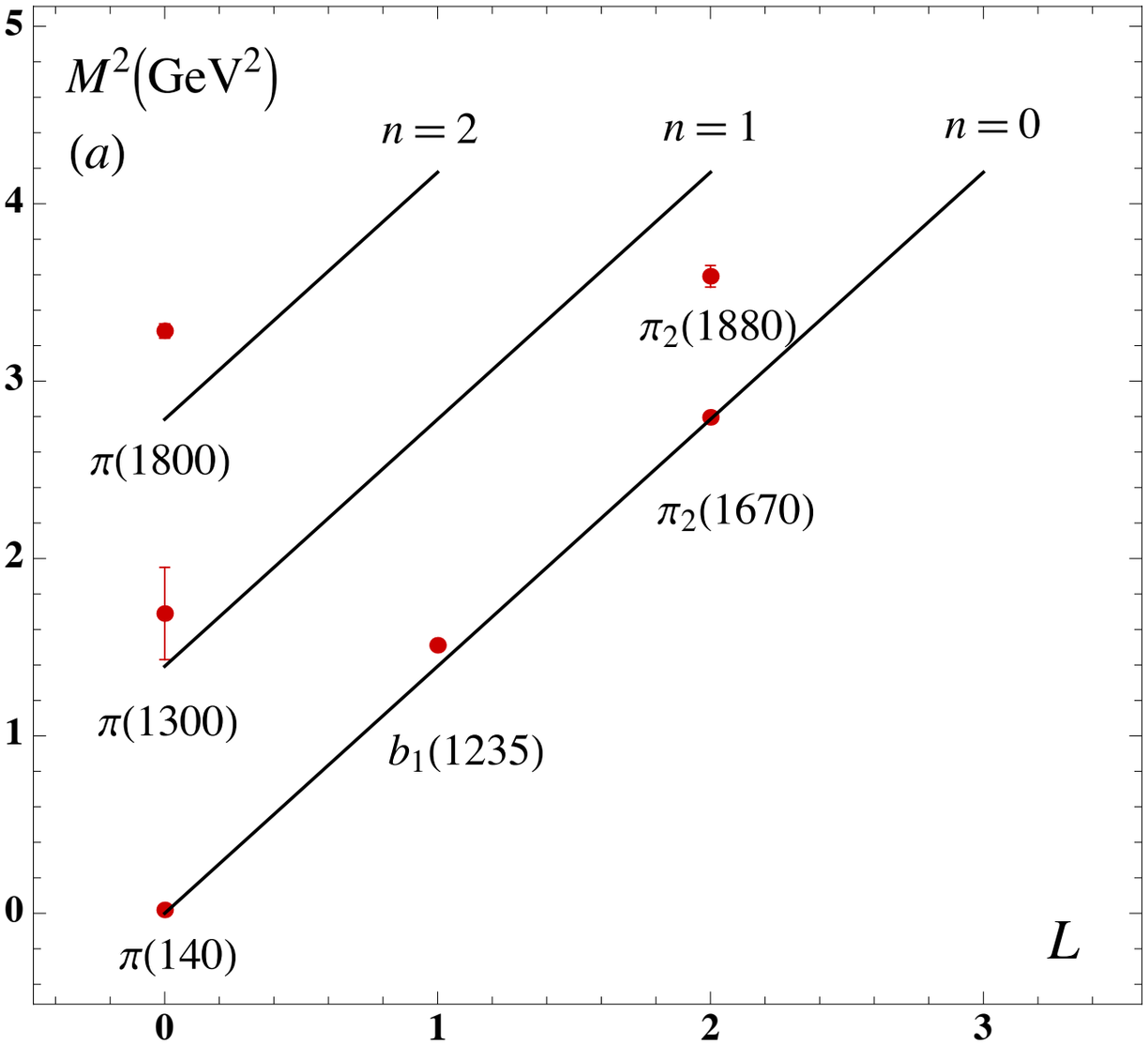
- *Light Front Wavefunctions:*

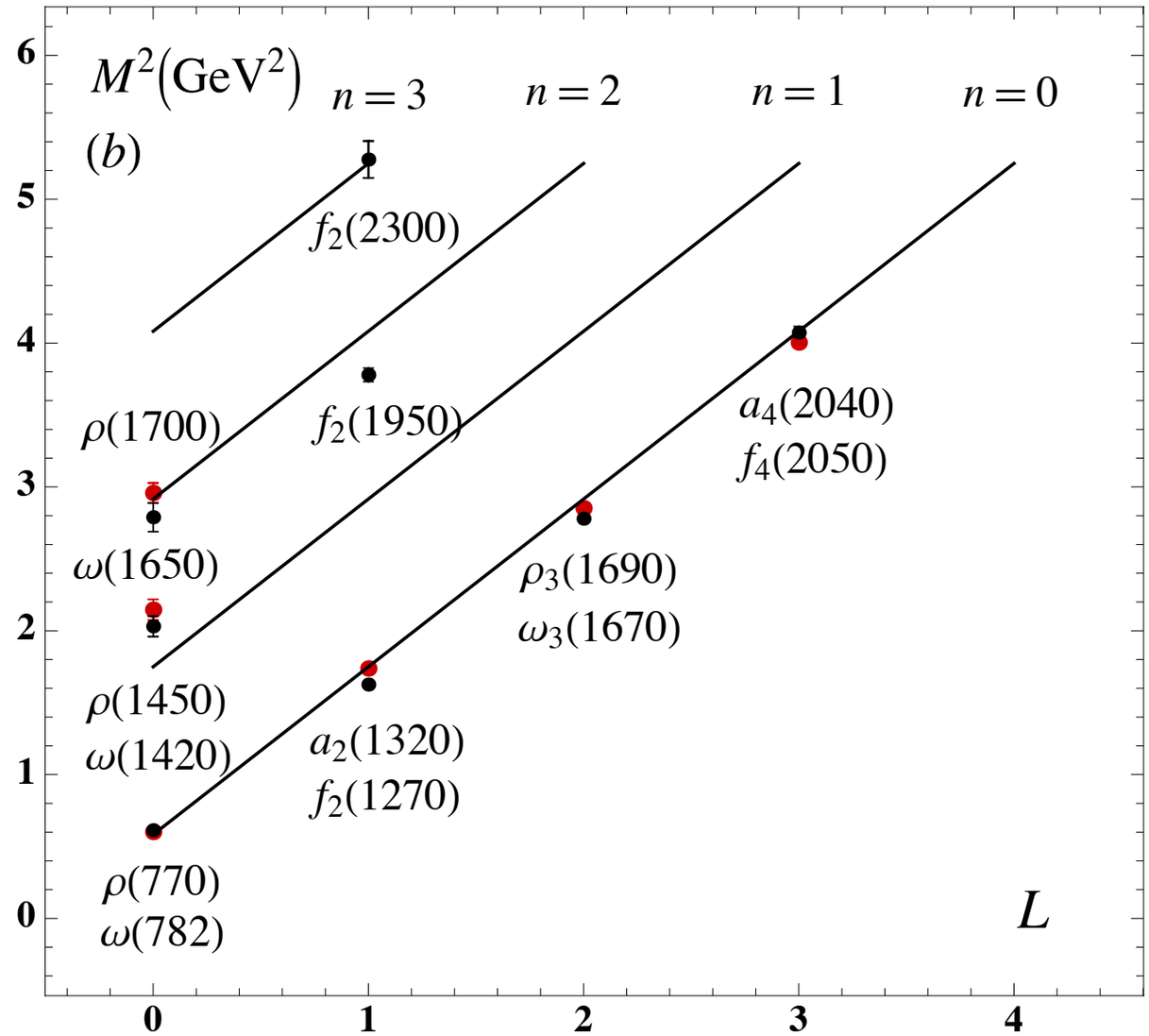
Light-Front Schrödinger Equation
Spectroscopy and Dynamics

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

$$m_u = m_d = 0$$

de Tèramond, Dosch, sjb





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

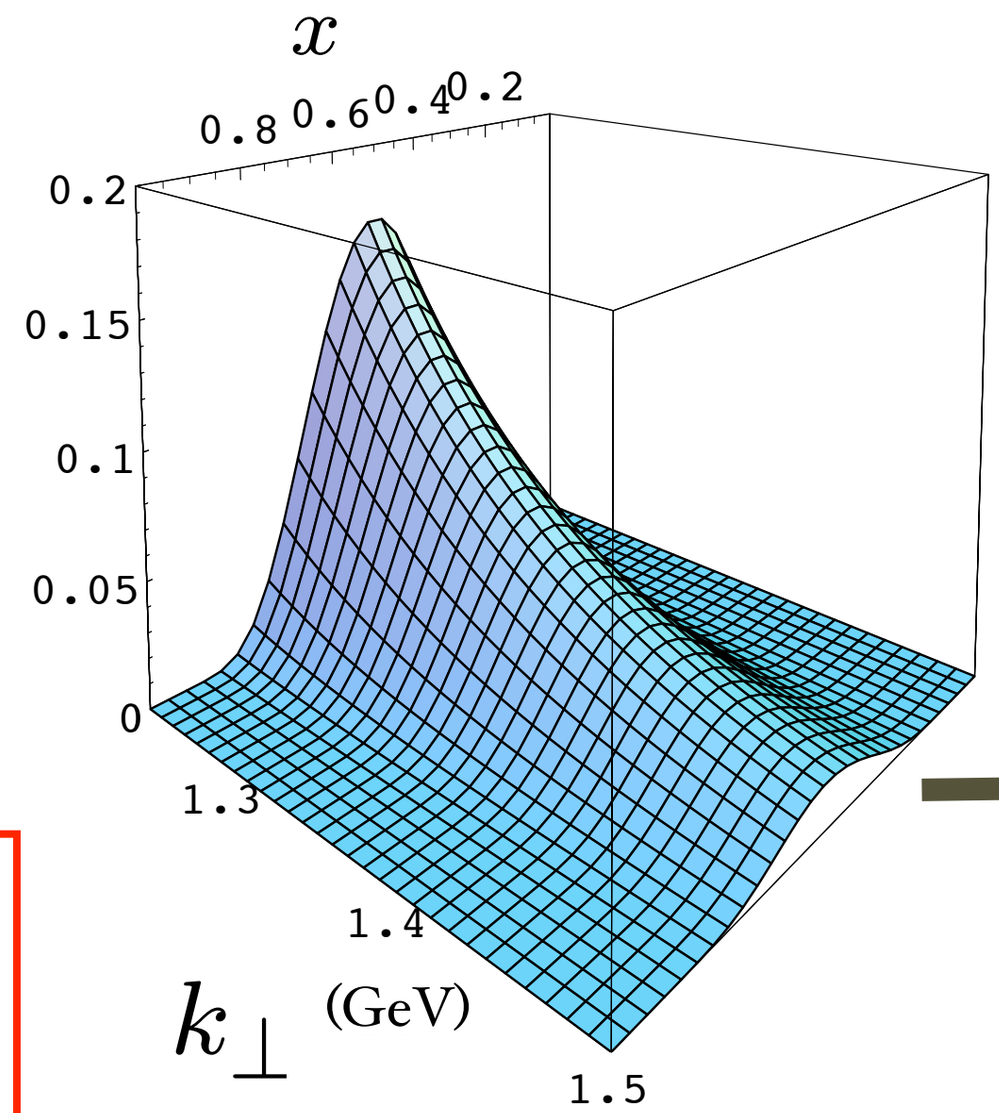
Same slope in n and L!

Super-Conformal Algebra and QCD

- **QCD Lagrangian is conformally invariant**
- **Broken by quantum corrections and quark masses**
- **Mathematical representations of conformal group: AdS5 and Superconformal algebra**
- **AdS5 - Dilaton, soft wall model breaks conformal symmetry : Confinement potential, spectroscopy, LFWFs, distribution amplitude at $\alpha_s(Q^2)$ all scales**
- **Superconformal algebra: Conformal symmetry is broken by dAFF mechanism: Confinement potential, supersymmetric meson-baryon relations; diquark clusters, tetraquarks**

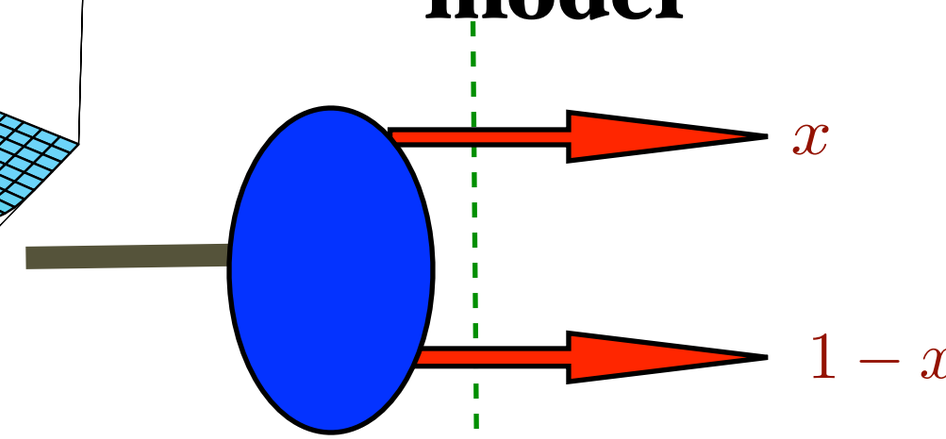
Prediction from AdS/QCD: Meson LFWF

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

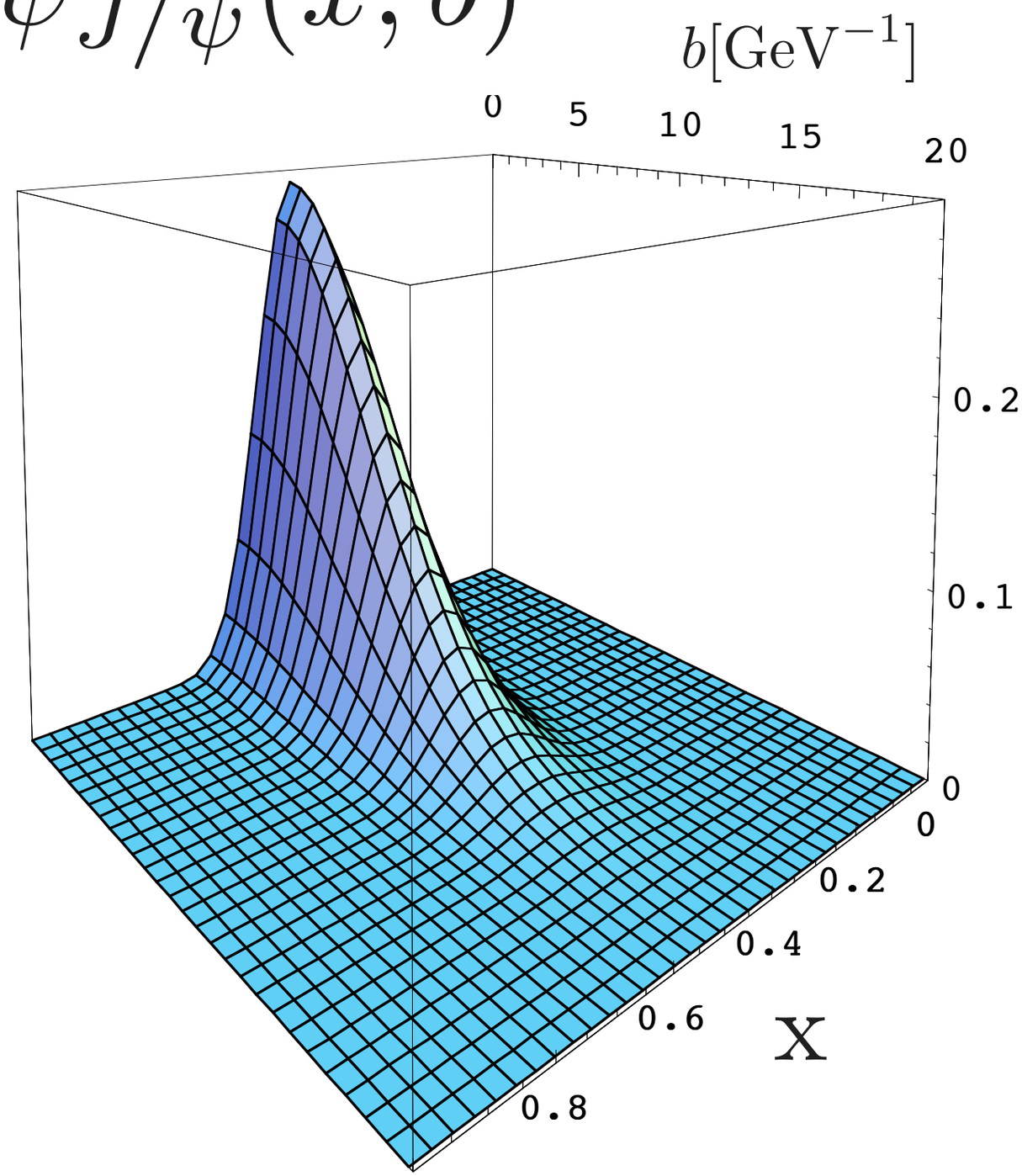
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

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

Provides Connection of Confinement to Hadron Structure

J/ψ

$\psi_{J/\psi}(x, b)$



LFWF peaks at

$$x_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

where

$$m_{\perp i} = \sqrt{m^2 + k_\perp^2}$$

minimum of LF energy denominator

$$\kappa = 0.375 \text{ GeV}$$

$$m_a = m_b = 1.25 \text{ GeV}$$

Connection to the Linear Instant-Form Potential

$$U(\zeta^2) = \kappa^4 \zeta^2 \leftrightarrow V(r) = \sigma r$$

- Compare invariant mass in the instant-form in the hadron center-of-mass system $\mathbf{P} = 0$,

$$M^2_{q\bar{q}} = 4\, m_q^2 + 4\mathbf{p}^2$$

with the invariant mass in the front-form in the constituent rest frame, $\mathbf{k}_q + \mathbf{k}_{\bar{q}} = 0$

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

obtain

$$U = V^2 + 2\sqrt{\mathbf{p}^2 + m_q^2}\, V + 2\, V \sqrt{\mathbf{p}^2 + m_q^2}$$

where $\mathbf{p}_\perp^2 = \frac{\mathbf{k}_\perp^2}{4x(1-x)}$, $p_3 = \frac{m_q(x-1/2)}{\sqrt{x(1-x)}}$, and V is the effective potential in the instant-form

- For small quark masses a linear instant-form potential V implies a harmonic front-form potential U and thus linear Regge trajectories

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

Haag, Lopuszanski, Sohnius (1974)

Fubini and Rabinovici

de Teramond Dosch, Lorce, sjb

Superconformal Quantum Mechanics

1+1

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

two anti-commuting fermionic operators

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

Realization as Pauli Matrices

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

(Conformal)

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

Introduce new spinor operators

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

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

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

Superconformal Quantum Mechanics

Baryon Equation

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

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

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

S=1/2, P=+

both chiralities

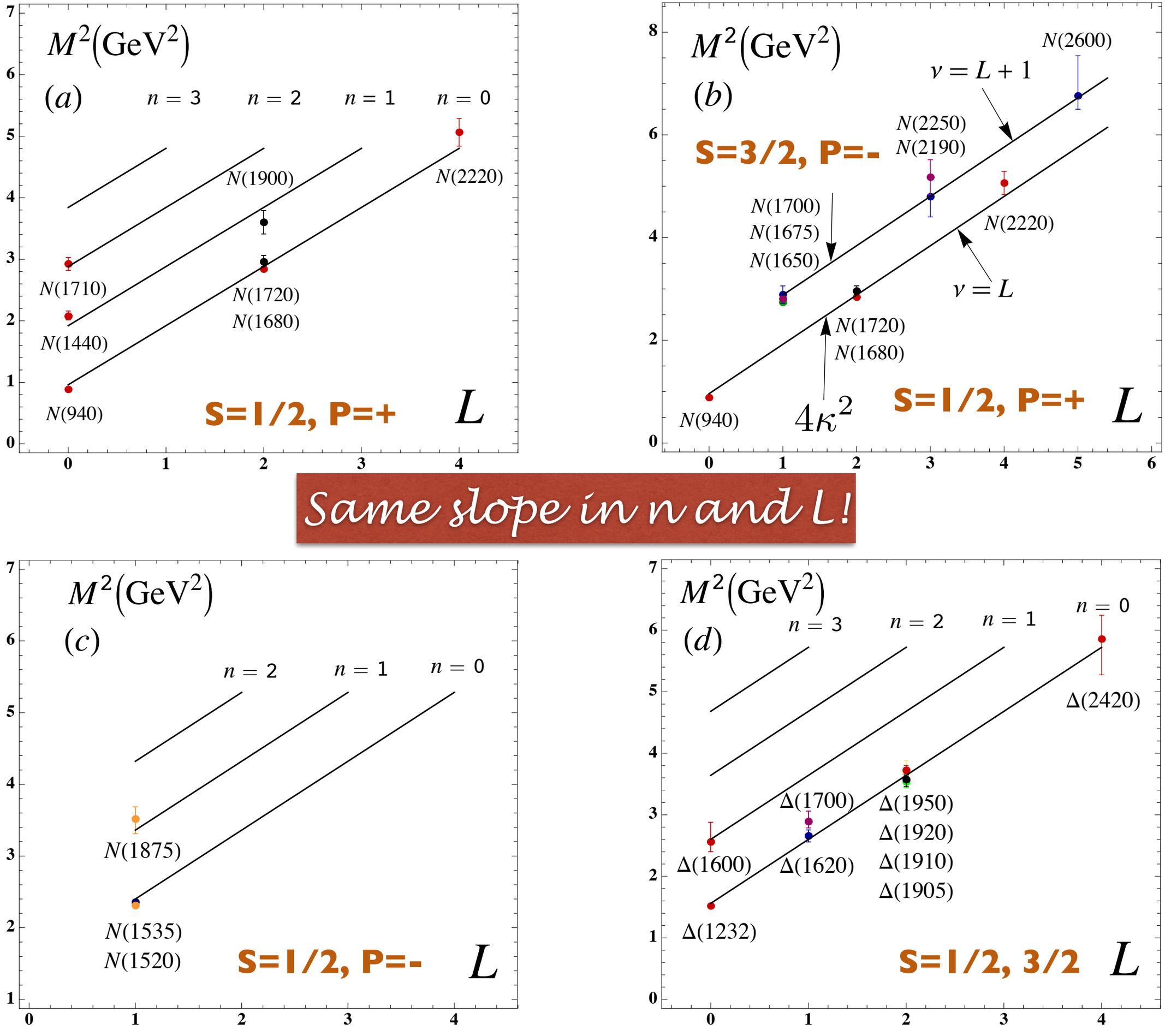
Meson Equation

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

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

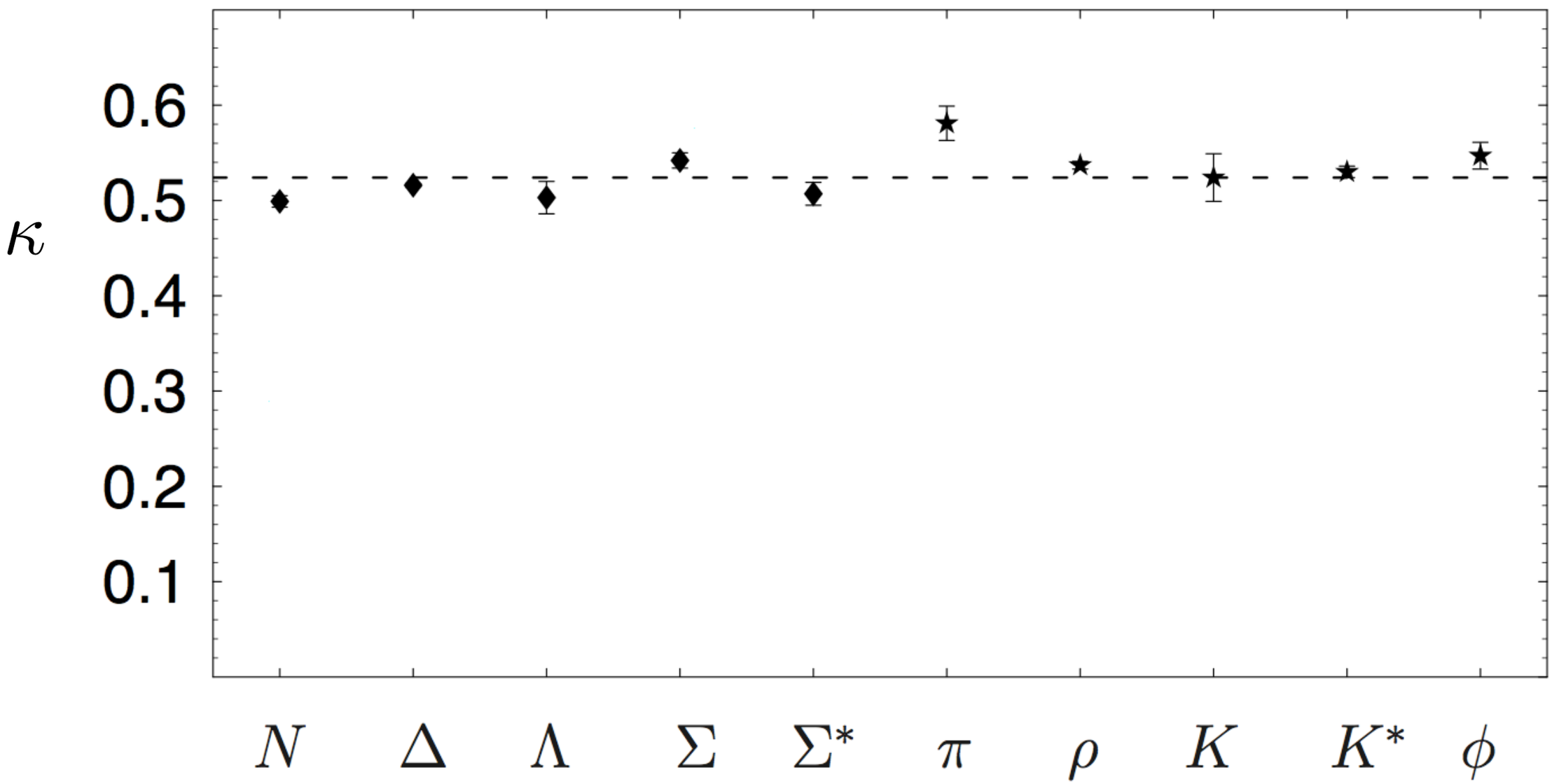
S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

Meson-Baryon Degeneracy for $L_M=L_B+1$ $\lambda_M^2=\lambda_B^2=\kappa^4$


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

Dosch, de Teramond, Lorce, sjb

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



Fit to the slope of Regge trajectories, including radial excitations

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

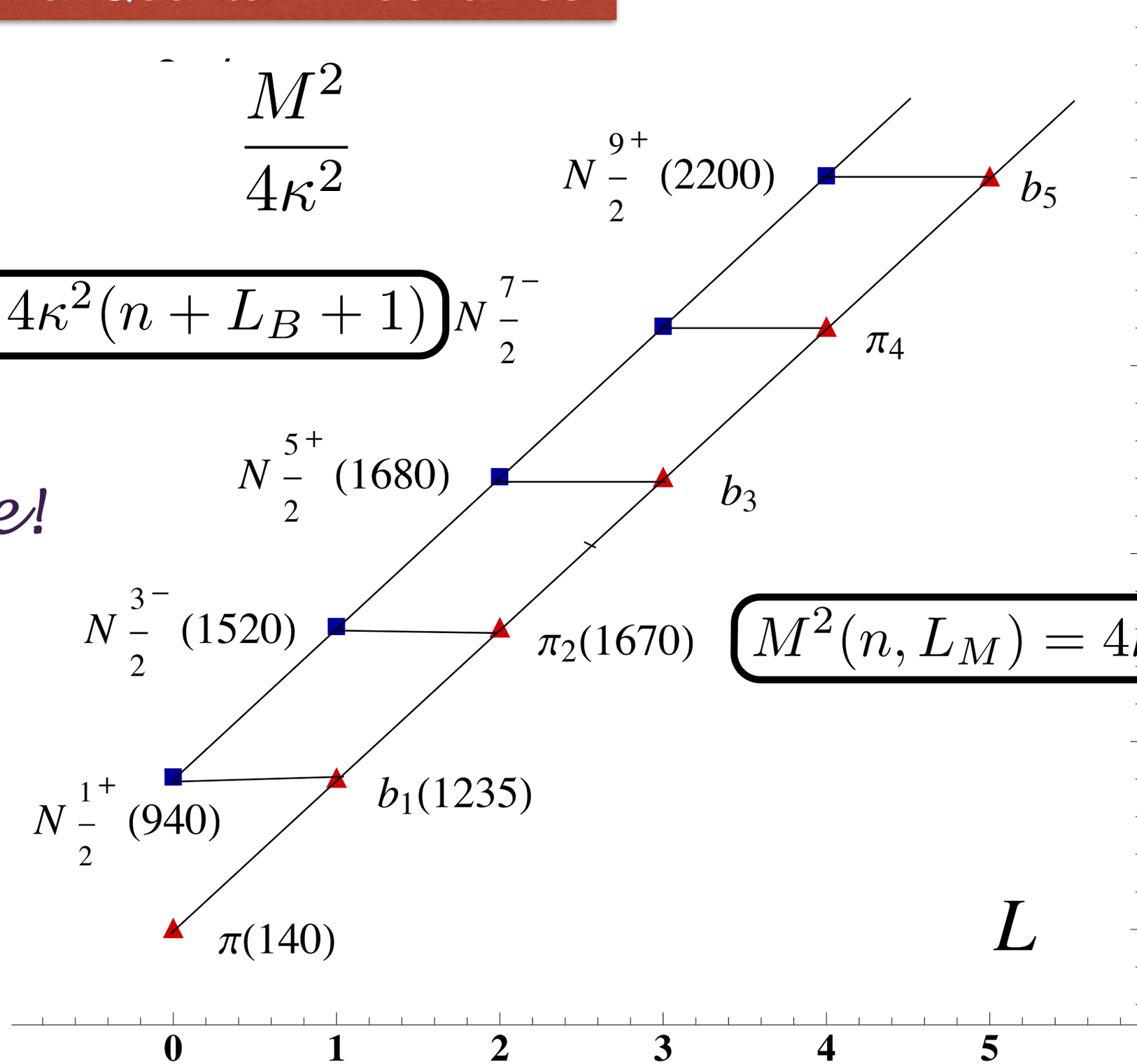
Superconformal Quantum Mechanics

de Tèramond, Dosch, sjb

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

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

Same slope!

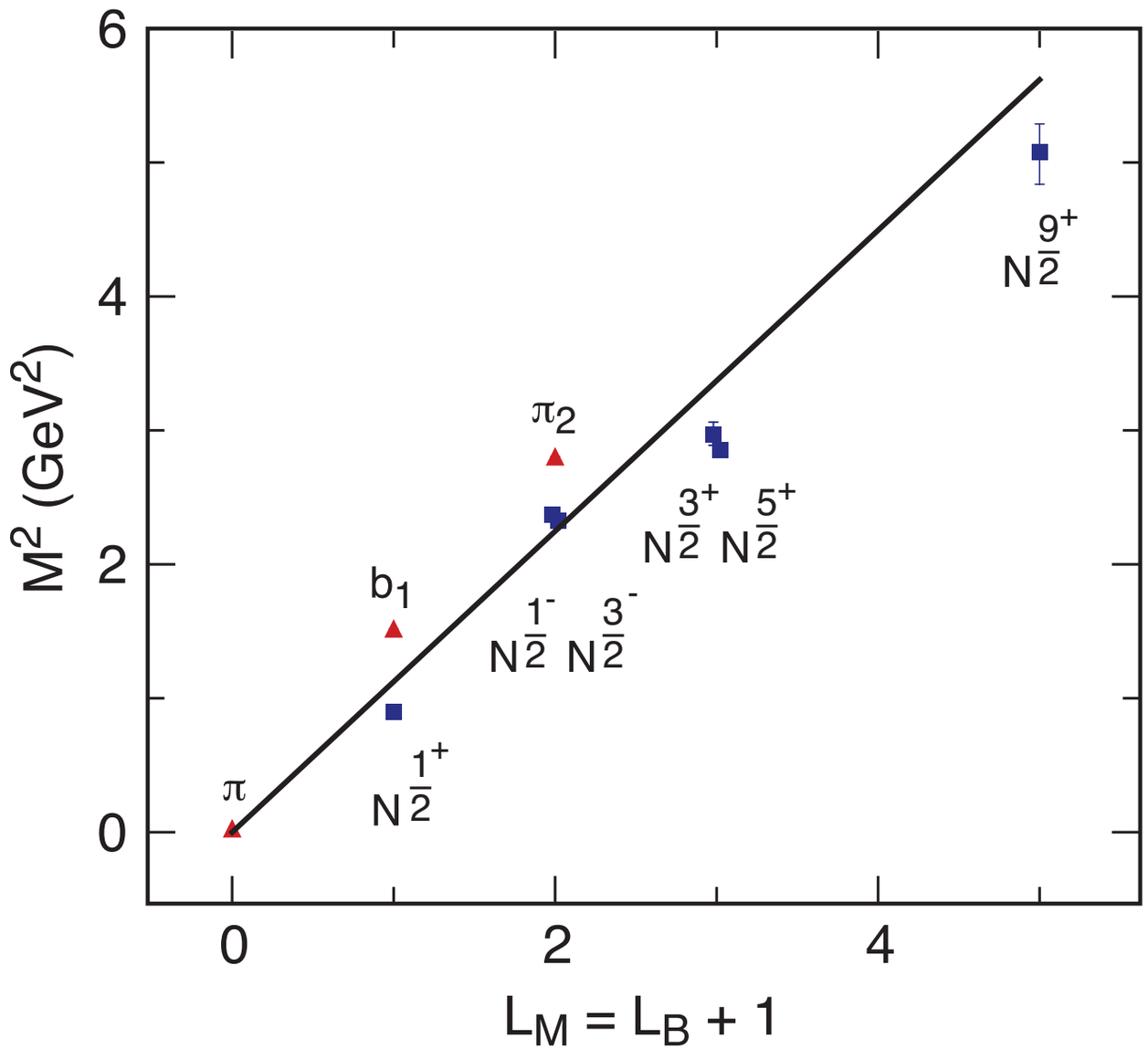


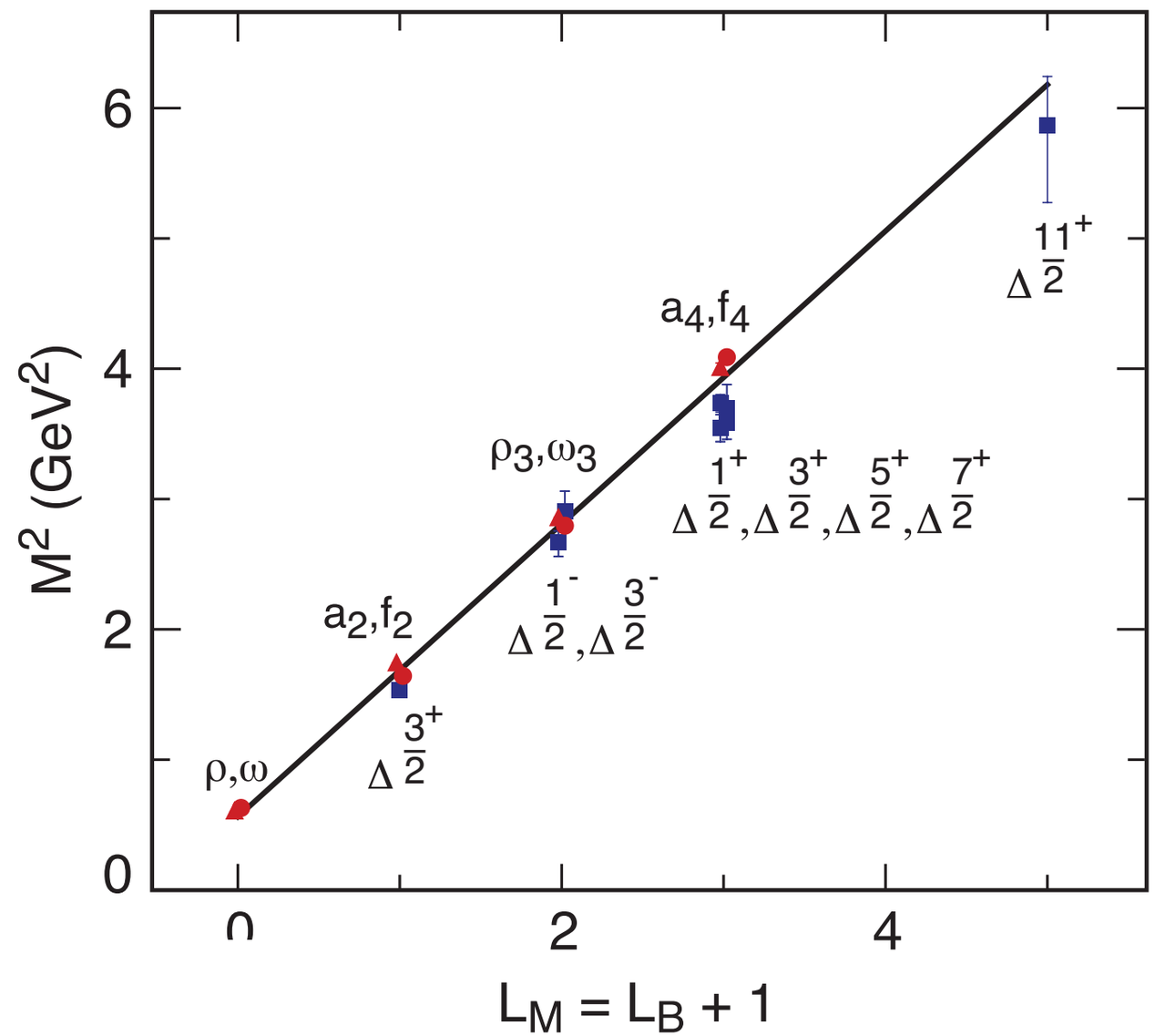
$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

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

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

Solid line: κ = 0.53 GeV





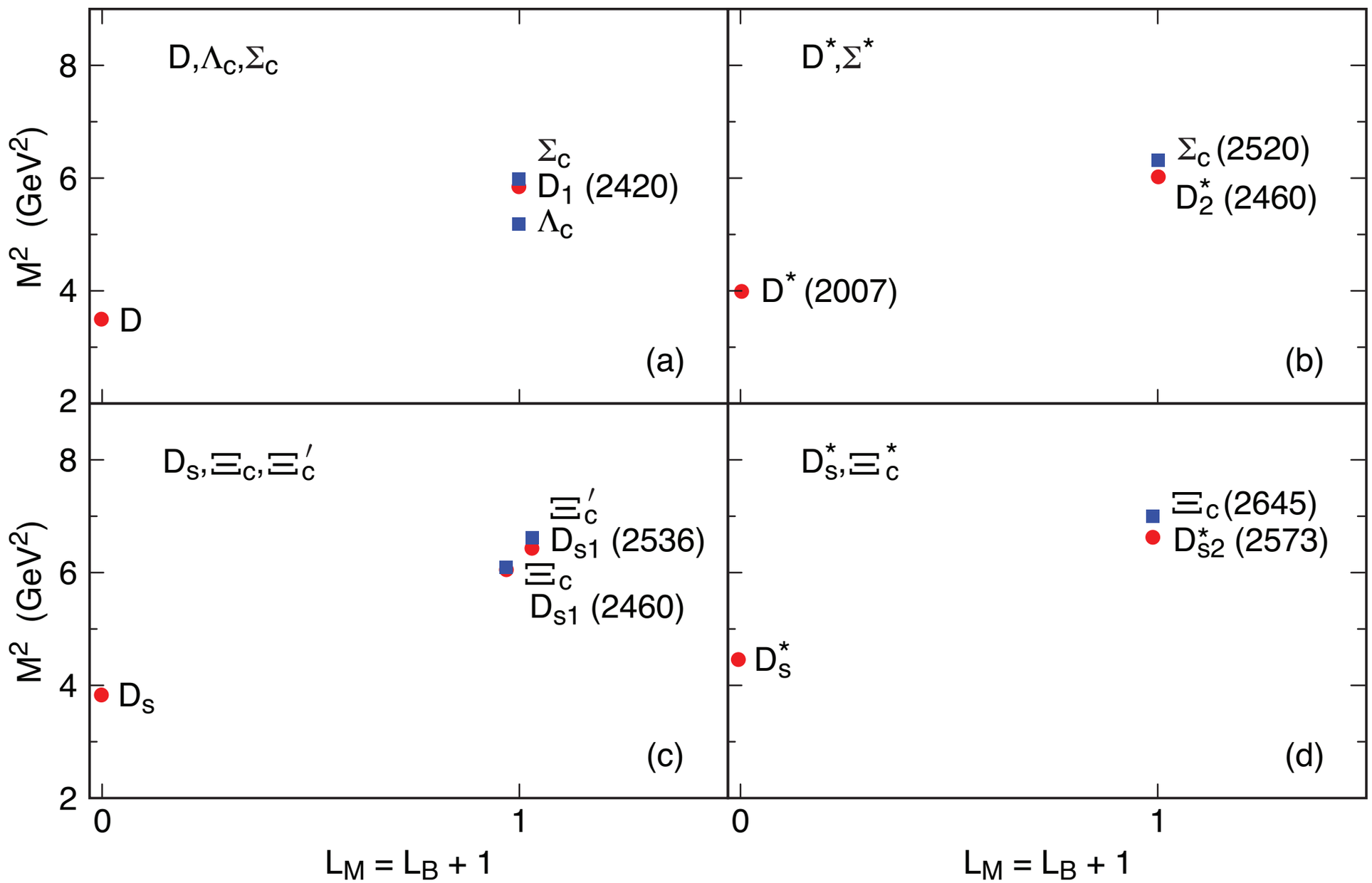
Superconformal meson-nucleon partners

de Tèramond, Dosch, sjb

Dosch, de Teramond, sjb

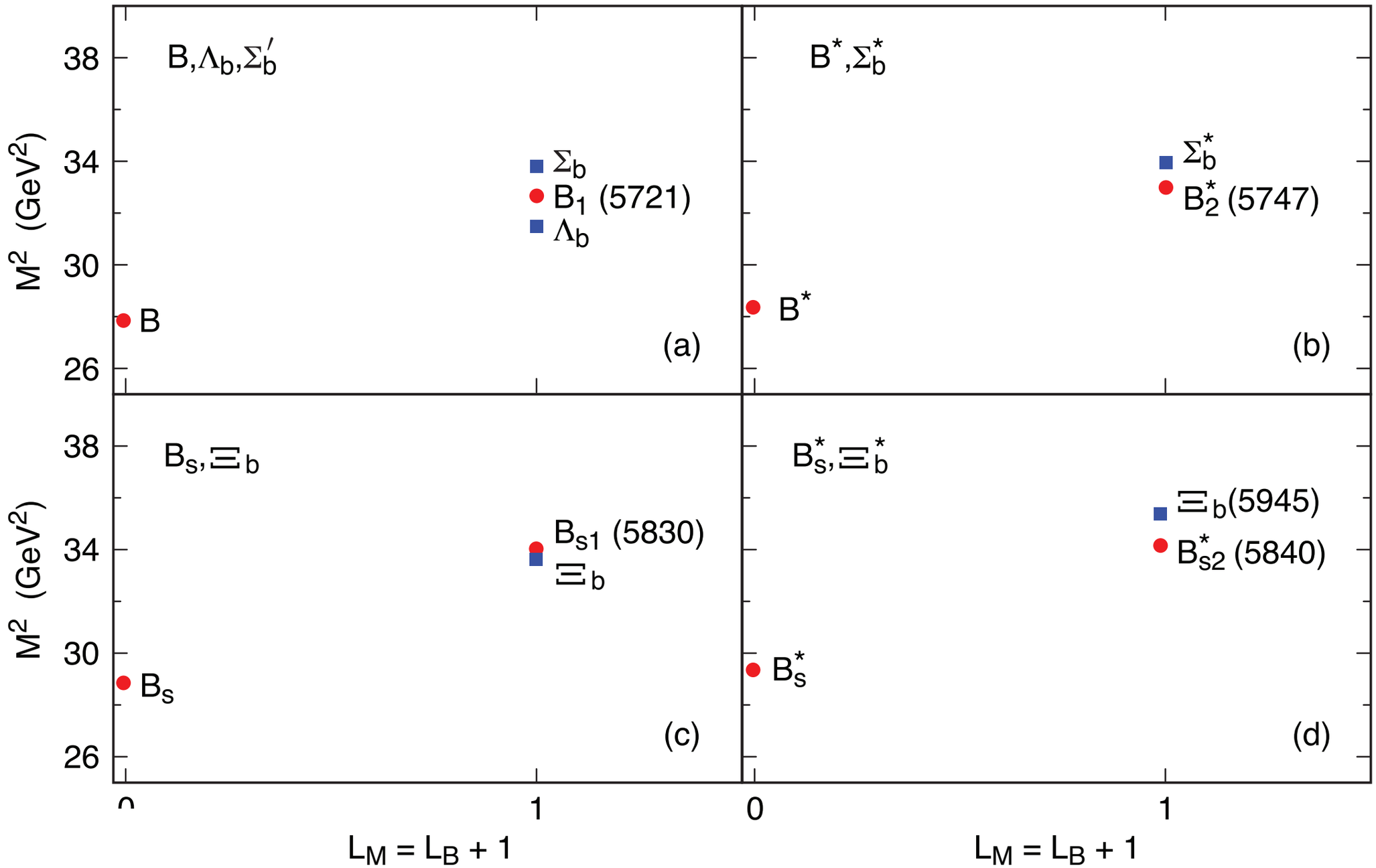
Supersymmetry across the light and heavy-light spectrum

- Introduction of quark masses breaks conformal symmetry without violating supersymmetry



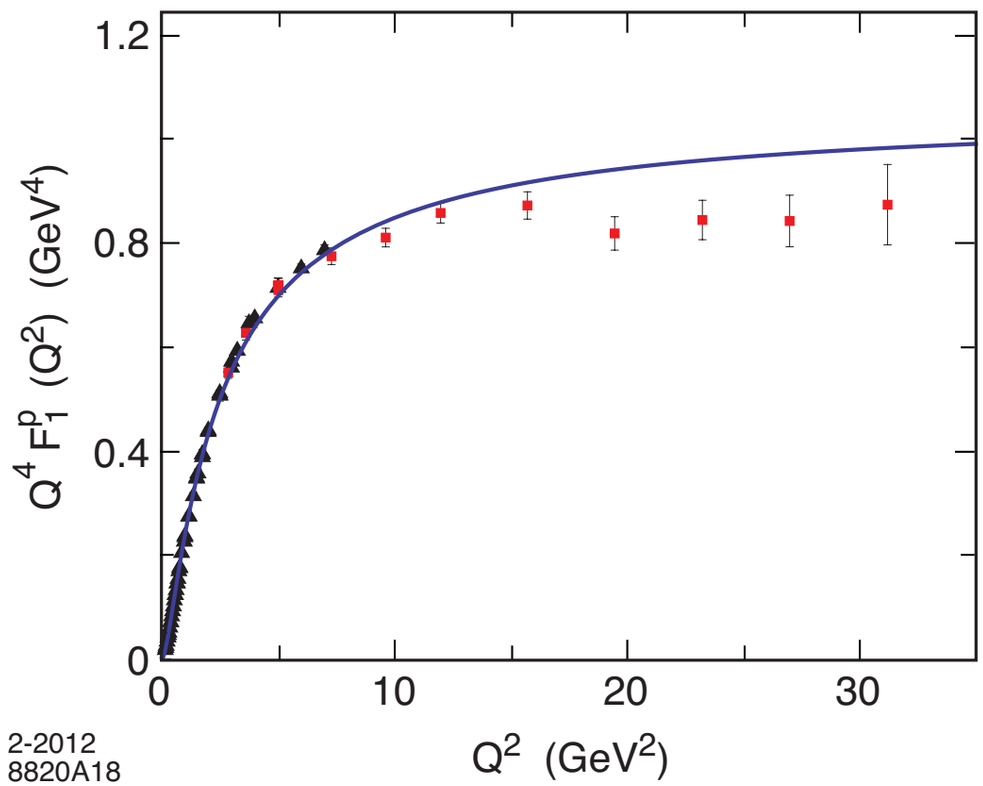
Dosch, de Teramond, sjb

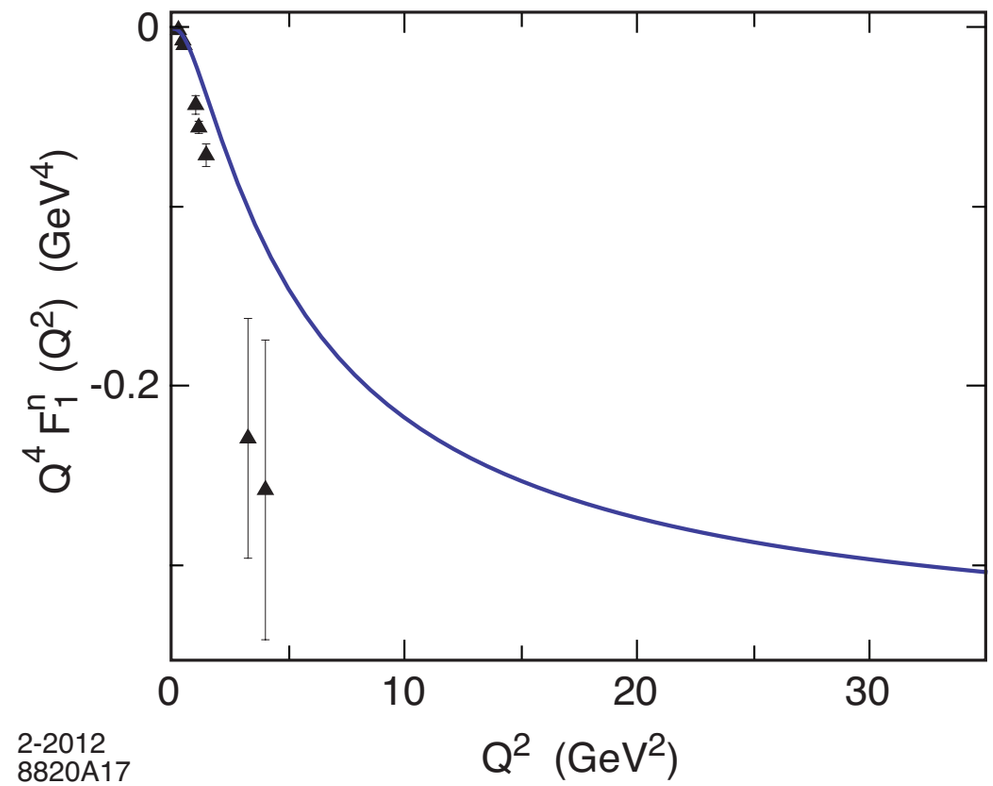
Supersymmetry across the light and heavy-light spectrum

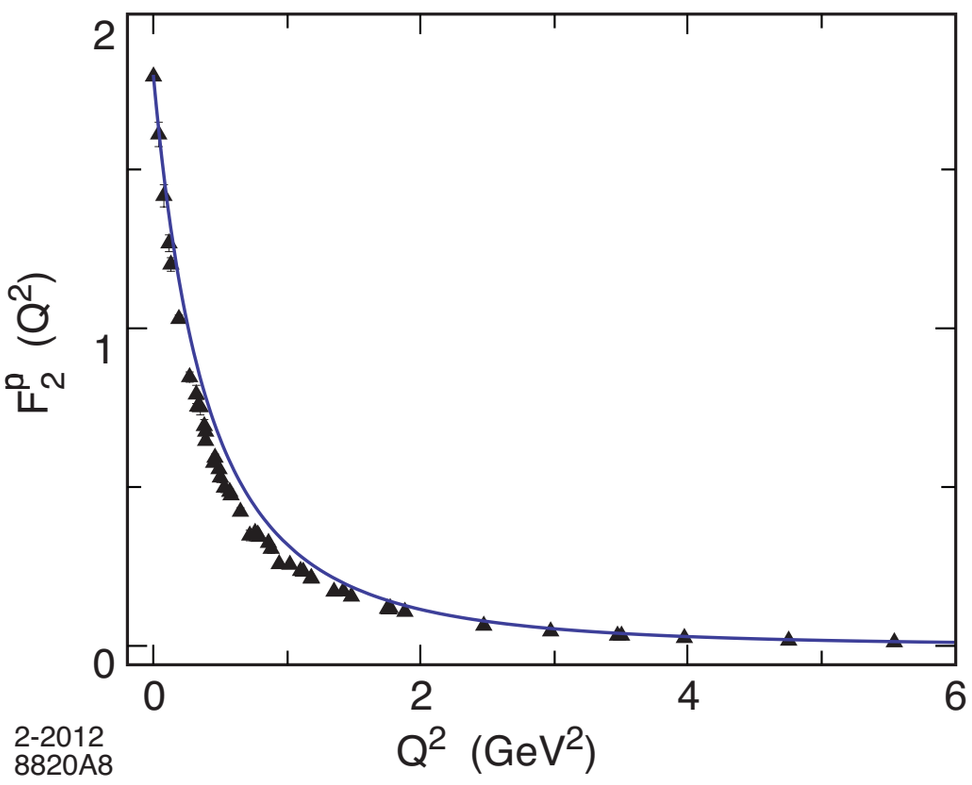


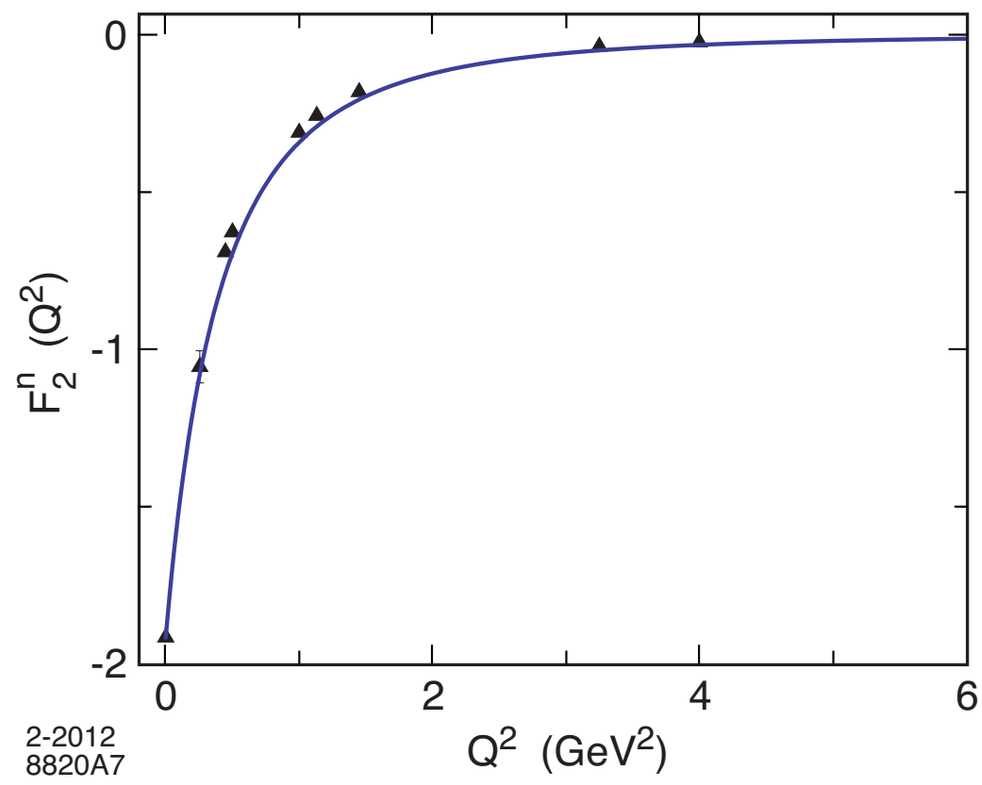
Supersymmetric relations for mesons and baryons with b quarks

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



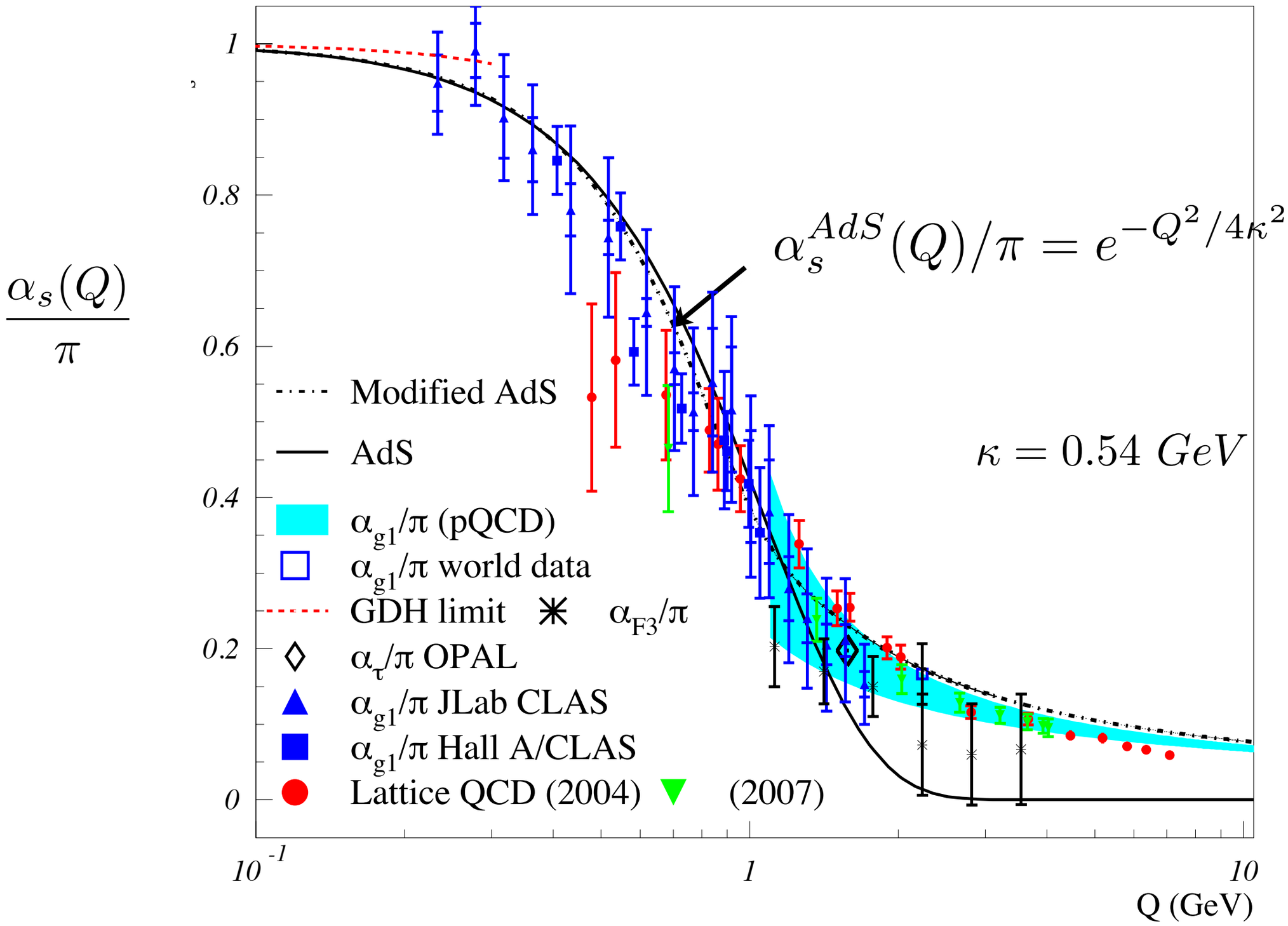






Analytic predictions; Counting rules obeyed

Analytic, defined at all scales, IR Fixed Point



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

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

Deur, de Teramond, sjb

Deur, de Tèramond, sjb

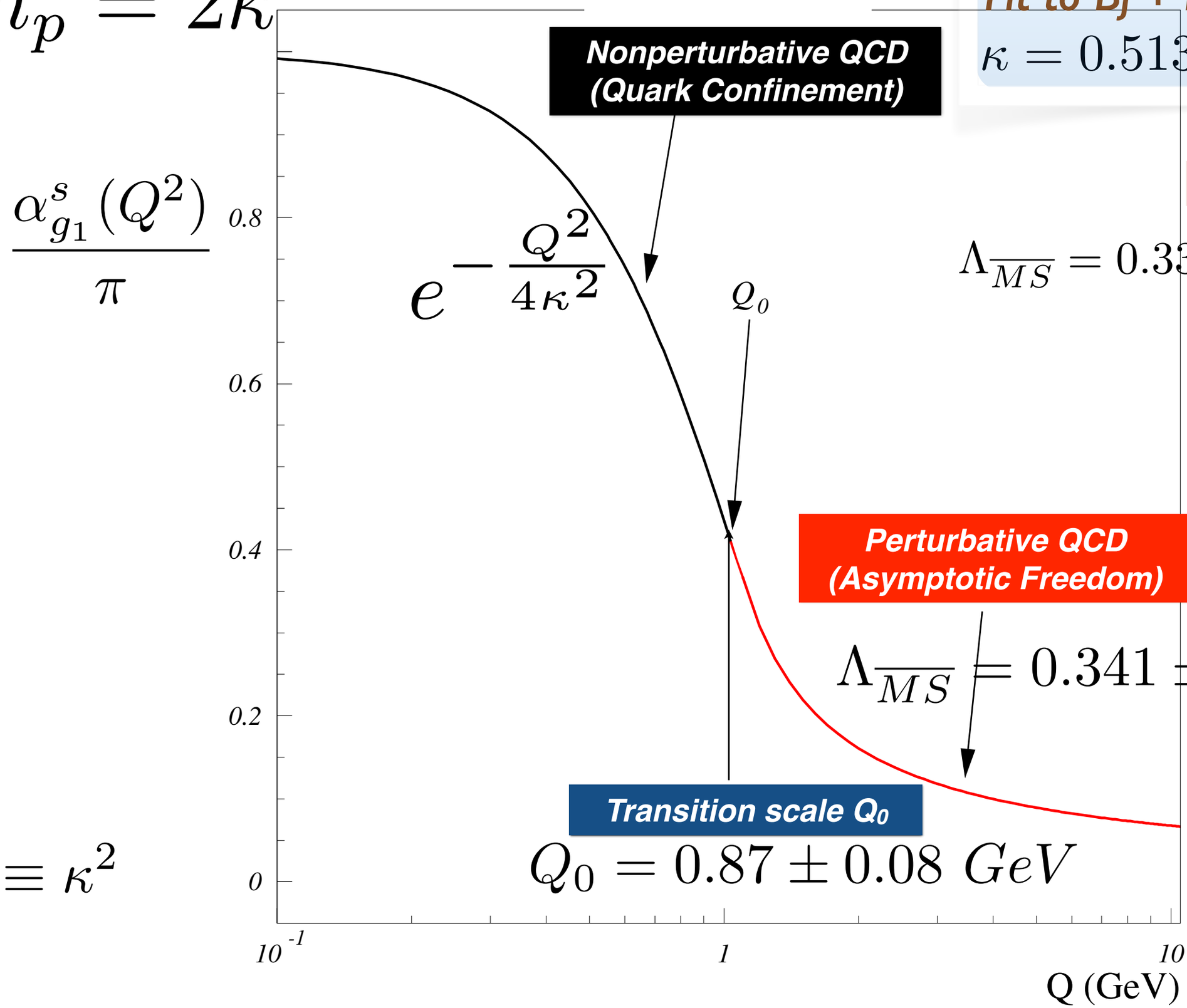
$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

All-Scale QCD Coupling

Fit to Bj + DHG Sum Rules:

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



Expt:

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

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

$\overline{MS}$ scheme

Features of AdS/QCD Superconformal Equations

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

- **Boost Invariant**
- **Trivial LF vacuum! No condensate, but consistent with GMOR**
- **Massless Pion**
- **Hadron Eigenstates (even the pion) have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

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

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

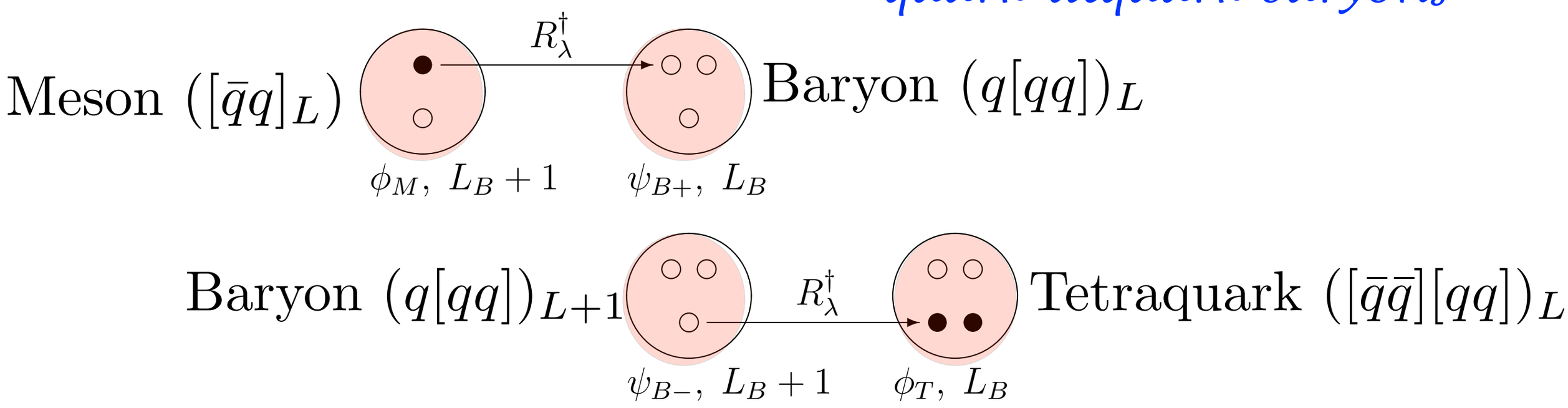
No mass -degenerate parity partners!

Superconformal algebra

2 X 2 Matrix Representations: Mass-Degenerate Hadronic Eigensolutions

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

quark-diquark baryons



diquark-diquark tetraquarks

de Tèramond, Dosch, Lorce, sjb

New World of Tetraquarks

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

Bound!

- Diquark: Color-Confined Constituents: Color $\bar{3}_C$
- Diquark-Antidiquark bound states $\bar{3}_C \times 3_C = 1_C$

$$\sigma(TN) \simeq 2\sigma(pN) - \sigma(\pi N)$$

$$2\big[\sigma([\{qq\}N) + \sigma(qN)\big] - [\sigma(qN) + \sigma(\bar{q}N)] = [\sigma(\{qq\}N) + \sigma(\{qq\}N)]$$

Candidates $f_0(980) I = 0, J^P = 0^+$, partner of proton

$a_1(1260) I = 0, J^P = 1^+$, partner of $\Delta(1233)$

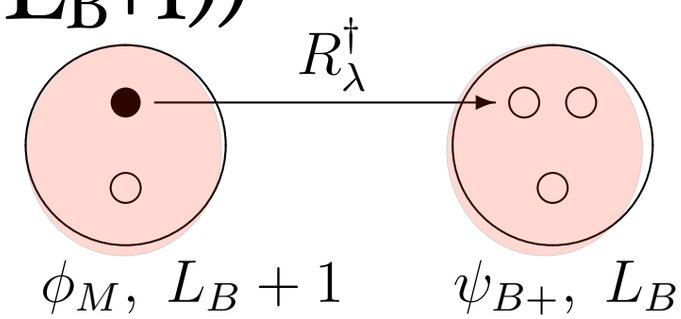
de Tèramond, Dosch, Lorce, sjb

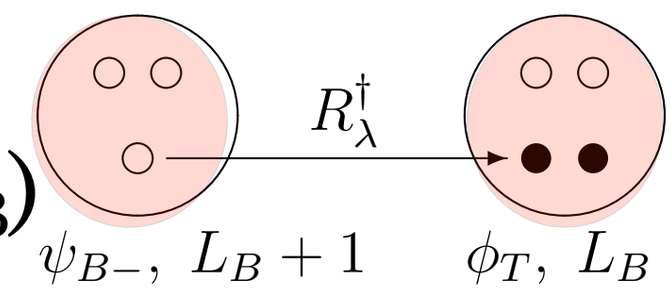
Superconformal Algebra

2X2 Hadronic Multiplets

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

- quark-antiquark meson ($L_M = L_B+1$))
- quark-diquark baryon (L_B)
- quark-diquark baryon (L_B+1)
- diquark-antidiquark tetraquark ($L_T = L_B$)
- Universal Regge slopes $\lambda = \kappa^2$





$$M_H^2/\lambda = \overbrace{\underbrace{(2n + L_H + 1)}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential}}^{\text{contribution from 2-dim light-front harmonic oscillator}} + \overbrace{2(L_H + s) + 2\chi}^{\text{contribution from AdS and superconformal algebra}} + < \sum_i \frac{m_i^2}{x_i} >$$

$$\chi(mesons) = -1 \qquad \chi(baryons, tetraquarks) = +1$$

de Tèramond, Dosch, Lorce, sjb

Diquark Clusters: Building Blocks of Exotic Hadrons

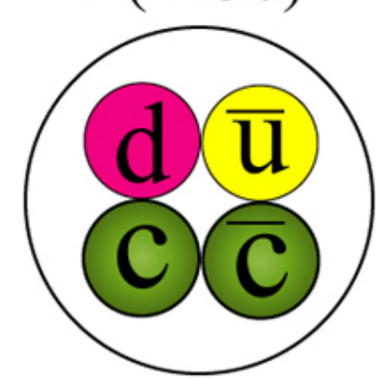
$$[qq]_{\bar{3}C}, [\bar{q}\bar{q}]_{3C},$$

- Diquarks: Spin S=0, 1, all L
- Tetraquarks: $([qq][\bar{q}\bar{q}])$ Spin S =0,1,2, all L
- Regge trajectories, universal slope for mq=0
- All flavors possible $([cu][\bar{c}\bar{u}])$
- Pentaquarks $\left[([qq]_{\bar{3}_C}\bar{q}_{\bar{3}_C})_{3_C}[qq]_{\bar{3}_C}\right]_{1C}$
- Hexaquarks, Octoquarks! $(uuduudc\bar{c})$

diquark-diantiquark

Lebed, Hwang, sjb

Z(4430)



Complete Regge spectrum in n, L

Belle, BaBar:

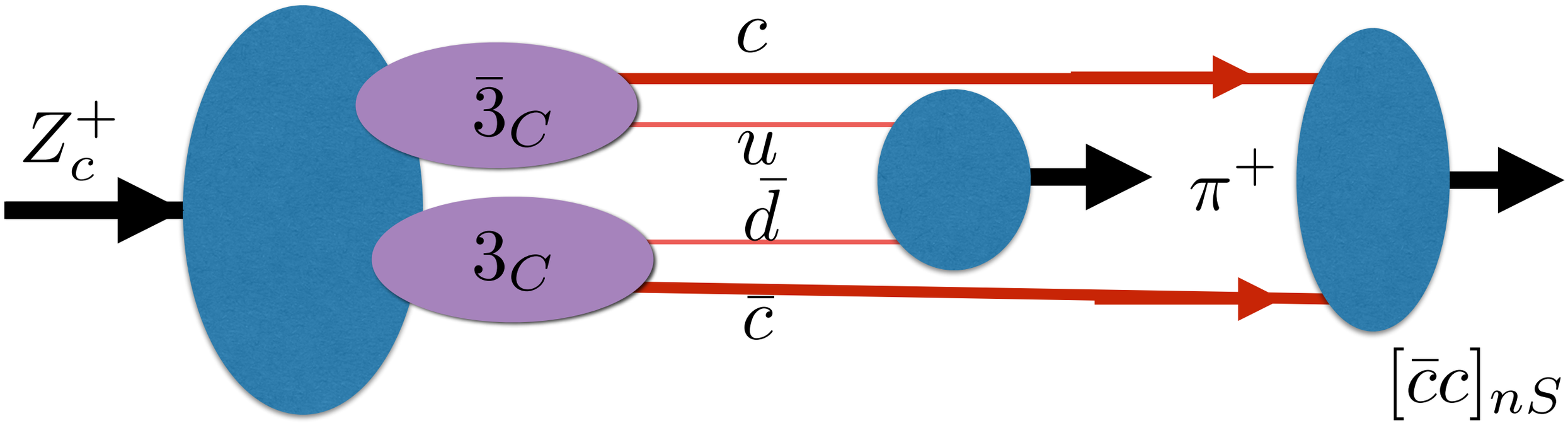
$$\mathcal{B}\left(B^0 \to K^+ Z(4430)^-\right) \times \mathcal{B}\left(Z(4430)^- \to \psi(2S)\pi^-\right) = \left(6.0^{+1.7+2.5}_{-2.0-1.4}\right) \times 10^{-5}.$$

$$\mathcal{B}\left(B^0 \to K^+ Z(4430)^-\right) \times \mathcal{B}\left(Z(4430)^- \to J/\psi\,\pi^-\right) = \left(5.4^{+4.0+1.1}_{-1.0-0.6}\right) \times 10^{-6}.$$

Surprising Result:

Dominance of large size $\psi'(2S)$ vs. J/ψ decays

Diquark Anti-diquark Model



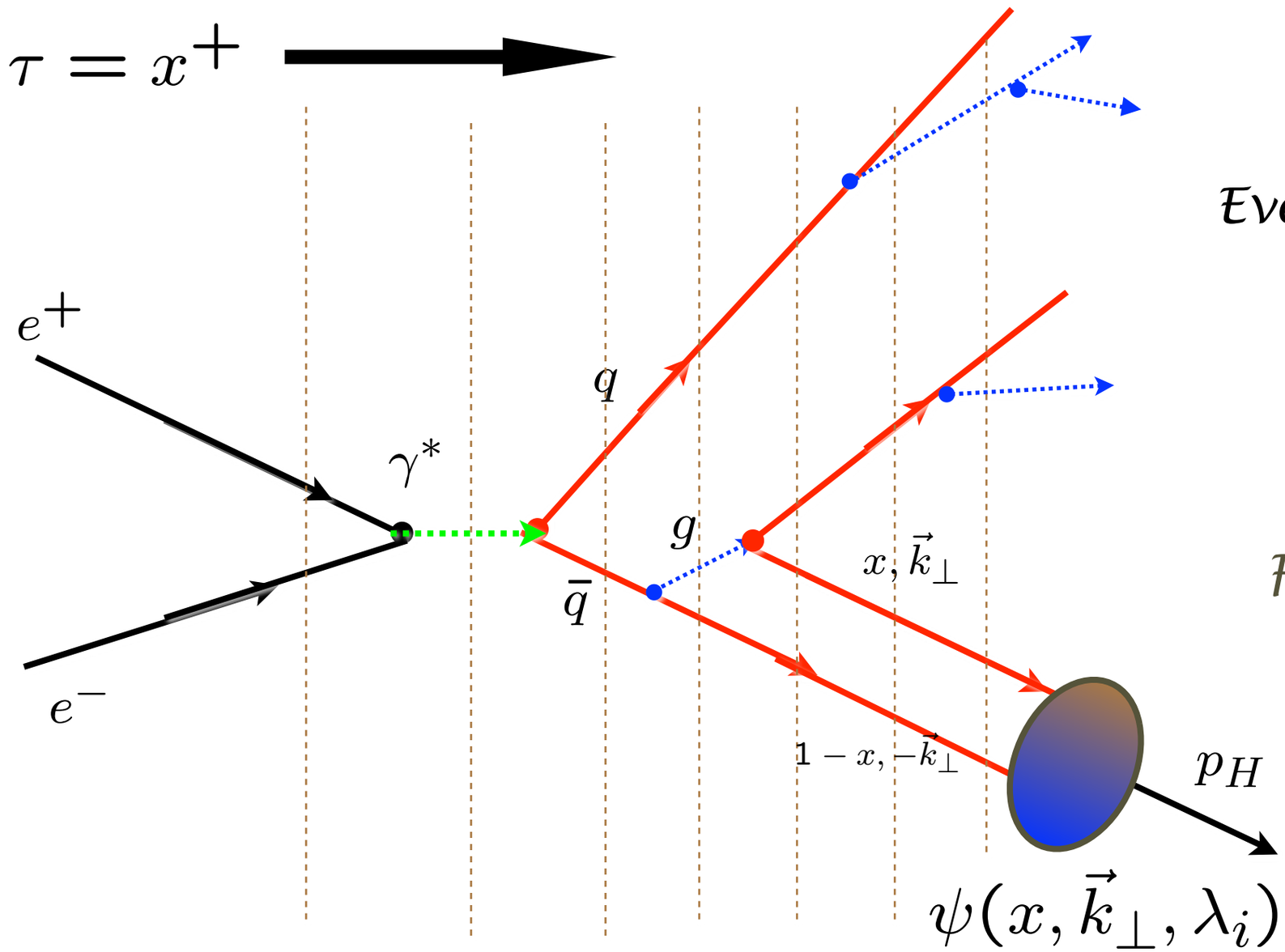
$$Z_c^+([cu]_{\bar{3}C}[\bar{c}\bar{d}]_{3C}) \to \pi^+\psi'$$

Formation of charmonium at large separation:

Dominance of overlap with large-size Ψ' vs J/Ψ decays

Lebed, Hwang, sjb

Hadronization at the Amplitude Level



Event amplitude generator

Cluster Factorization

Capture if $\zeta^2 = x(1-x)b_\perp^2 > \frac{1}{\Lambda_{QCD}^2}$

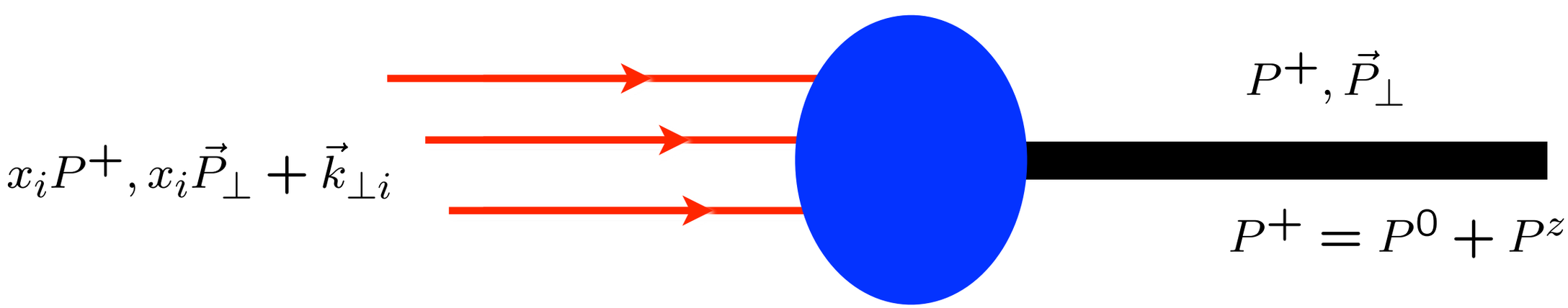
i.e.,

$\mathcal{M}^2 = \frac{k_\perp^2}{x(1-x)} < \Lambda_{QCD}^2$

AdS/QCD Hard Wall Confinement:

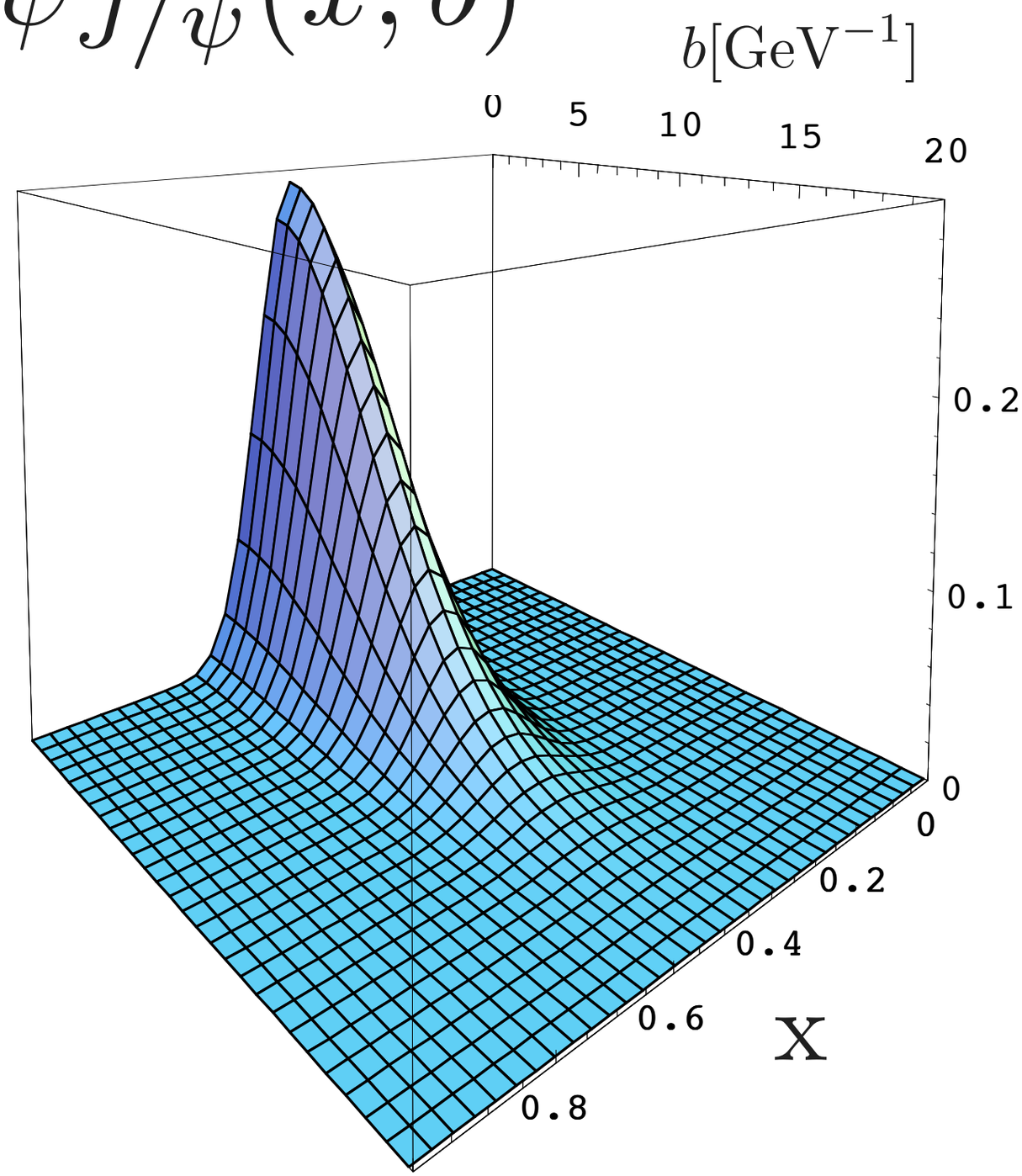
Features of LF T-Matrix Formalism
"Event Amplitude Generator"

- **Same principle as antihydrogen production: off-shell coalescence**
- **coalescence to hadron favored at equal rapidity, small transverse momenta**
- **leading heavy hadron production: D and B mesons produced at large z**
- **hadron helicity conservation if hadron LFWF has L^z =0**
- **Baryon AdS/QCD LFWF has aligned and anti-aligned quark spin**



J/ψ

$\psi_{J/\psi}(x, b)$



LFWF peaks at

$$x_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

where

$$m_{\perp i} = \sqrt{m^2 + k_\perp^2}$$

minimum of LF energy denominator

$$\kappa = 0.375 \text{ GeV}$$

$$m_a = m_b = 1.25 \text{ GeV}$$

Summary

- Light-Front: Rigorous Frame-Independent Bound State Formalism
- Unique Confinement Potential from AdS/QCD
- Meson-Baryon Spectroscopy, Supersymmetry
- Tetraquark partners of meson and baryons
- Intrinsic Heavy Quark LF Fock States:
- High x, target rapidity at LHCb
- Digluon-initiated reactions
- Octoquark
- Running coupling at all scales
- J/\psi to rho pi puzzle

Fundamental Hadronic Features of Hadrons

- Partition of the Proton's Mass: Potential vs. Kinetic Contributions

Virial Theorem

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

Equal L=0,1

- Color Confinement $U(\zeta^2) = \kappa^4\zeta^2$
- Role of Quark Orbital Angular Momentum in the Proton
- Quark-Diquark Structure
- Quark Mass Contribution $\Delta M^2 =< \frac{m_q^2}{x} >$ *from the Yukawa coupling to the Higgs zero mode*
- Baryonic Regge Trajectory $M^2_{\text{p}}(n, L_B) = 4\kappa^2(n + L_B + 1)$
- Mesonic Supersymmetric Partners $L_M = L_B + 1$
- Proton Light-Front Wavefunctions and Dynamical Observables

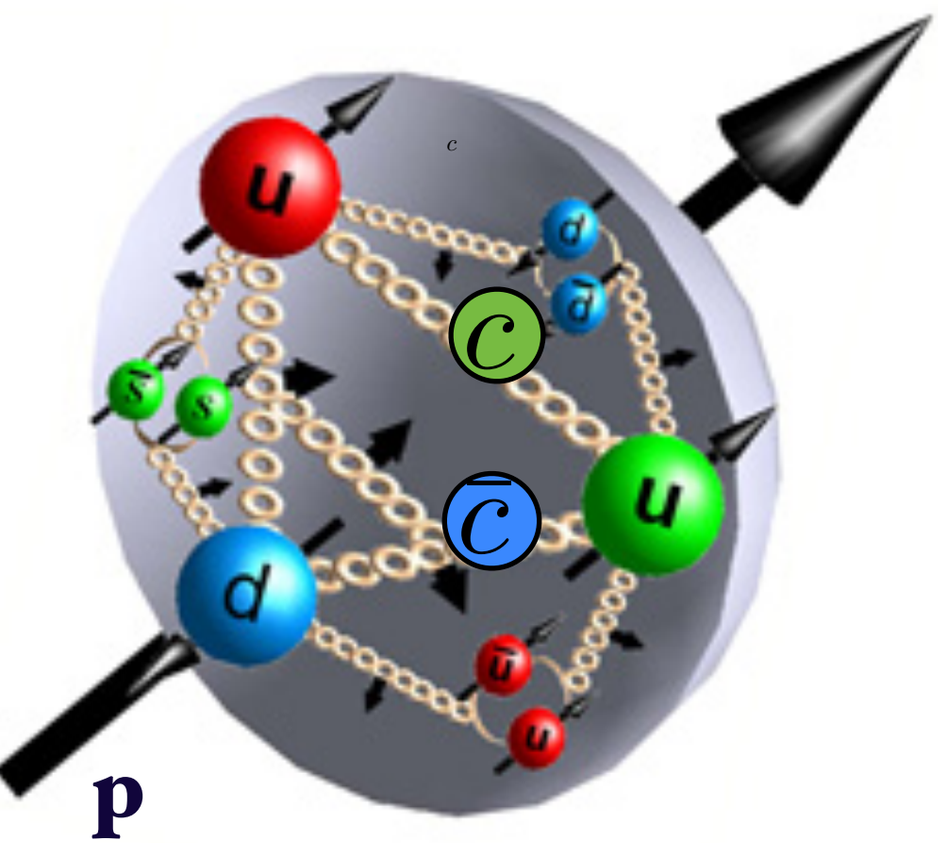
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

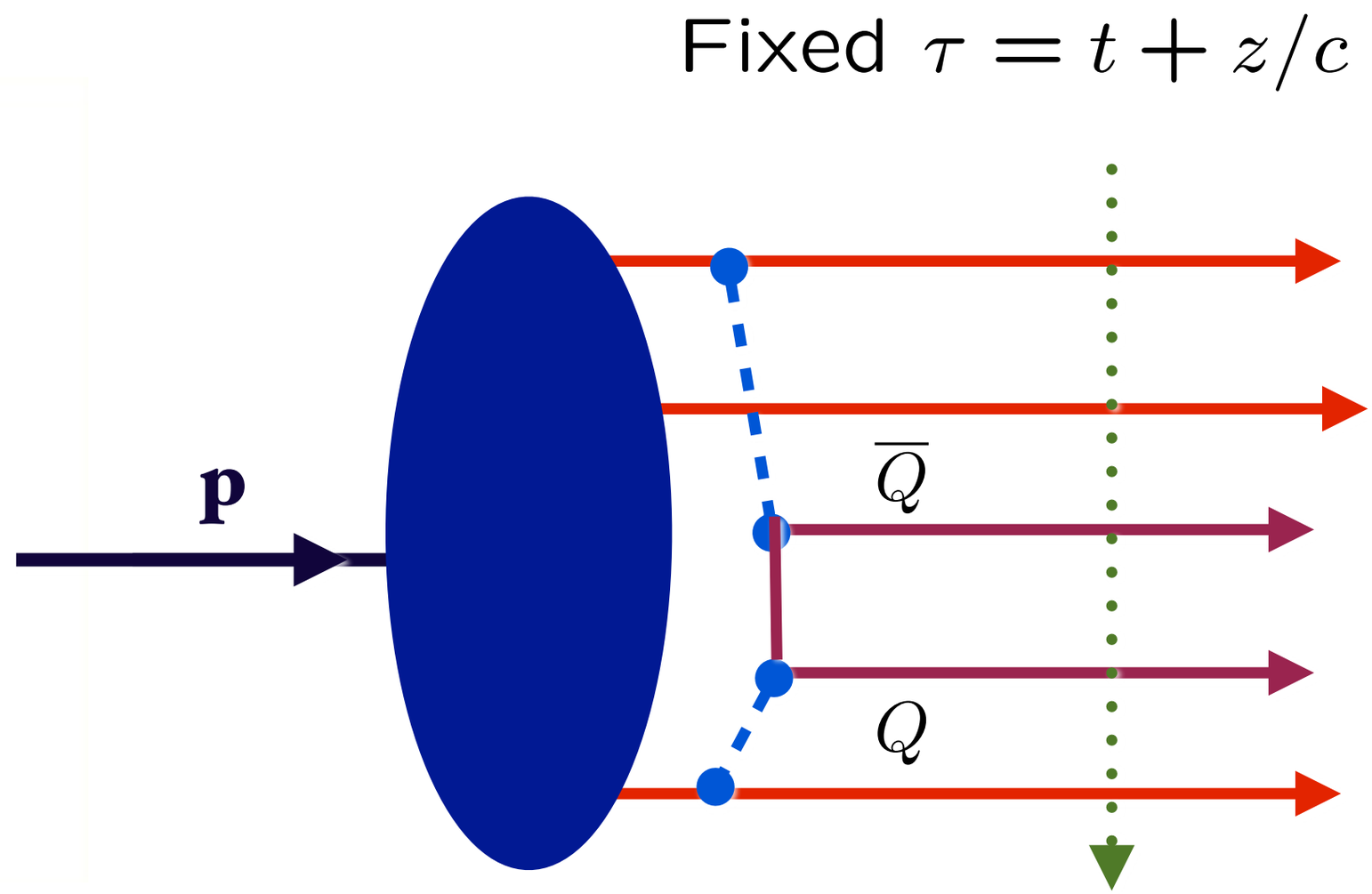
- Form Factors, Distribution Amplitudes, Structure Functions
- Non-Perturbative - Perturbative QCD Transition $Q_0 = 0.87 \pm 0.08\ GeV\ \overline{MS}\ scheme$
- Dimensional Transmutation: $m_p \simeq 3.21\ \Lambda_{\overline{MS}}$ $m_\rho \simeq 2.2\ \Lambda_{\overline{MS}}$

QCD Myths

- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- Heavy quarks only from gluon splitting
- Renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- QCD gives 10^{42} to the cosmological constant
- Colliding Pancakes

Novel Features of Quarkonium and Tetraquark Physics





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