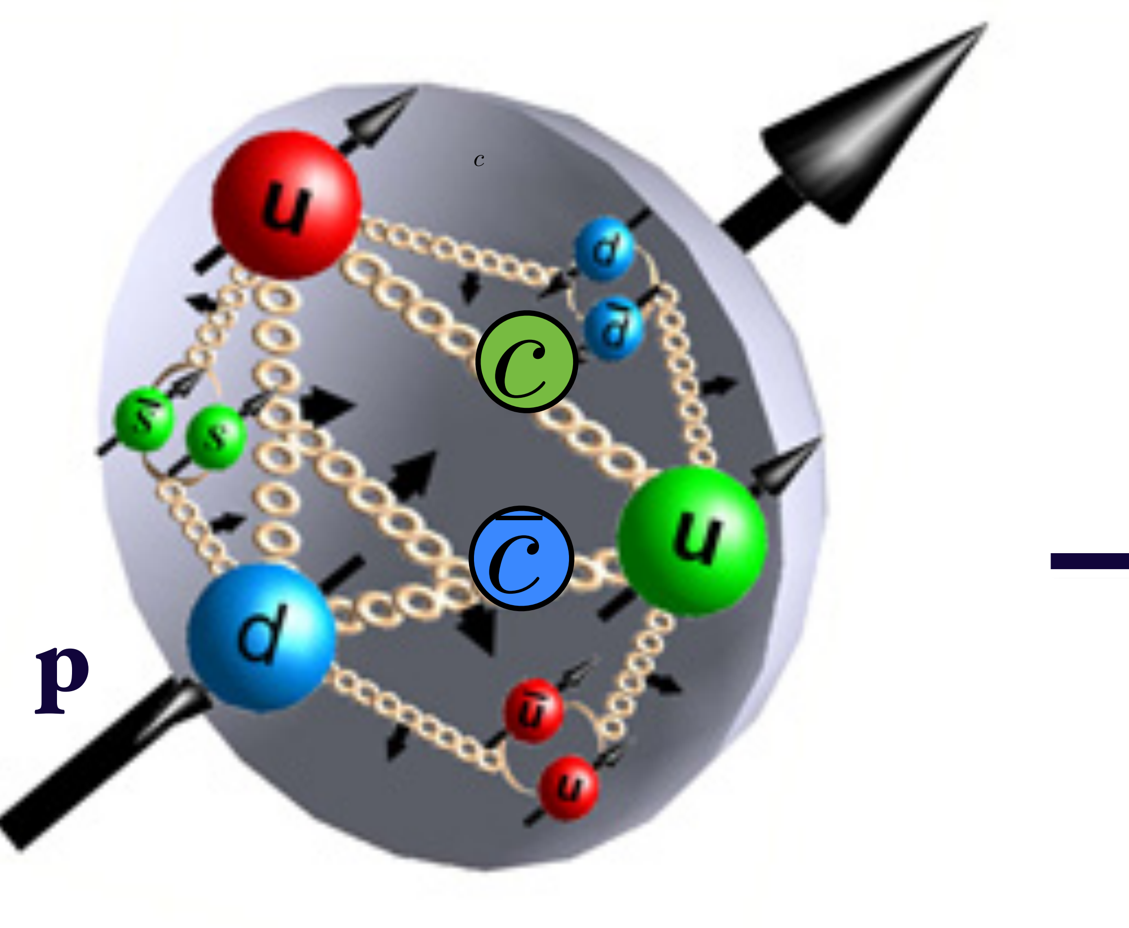
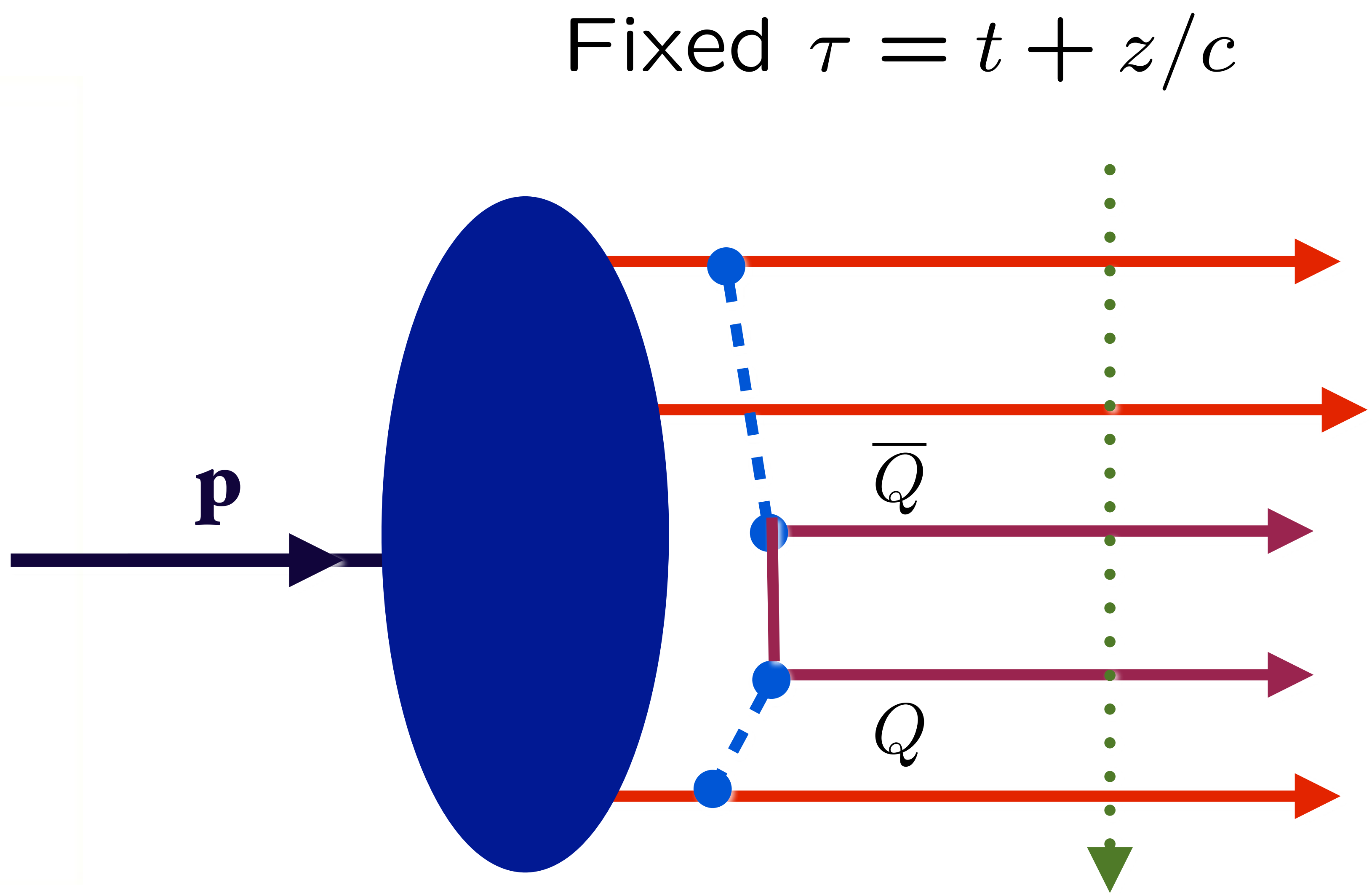
Novel QCD Physics of Heavy Quark Hadroproduction





Scientific Program:
Heavy-Quark Hadroproduction from Collider to Astroparticle Physics

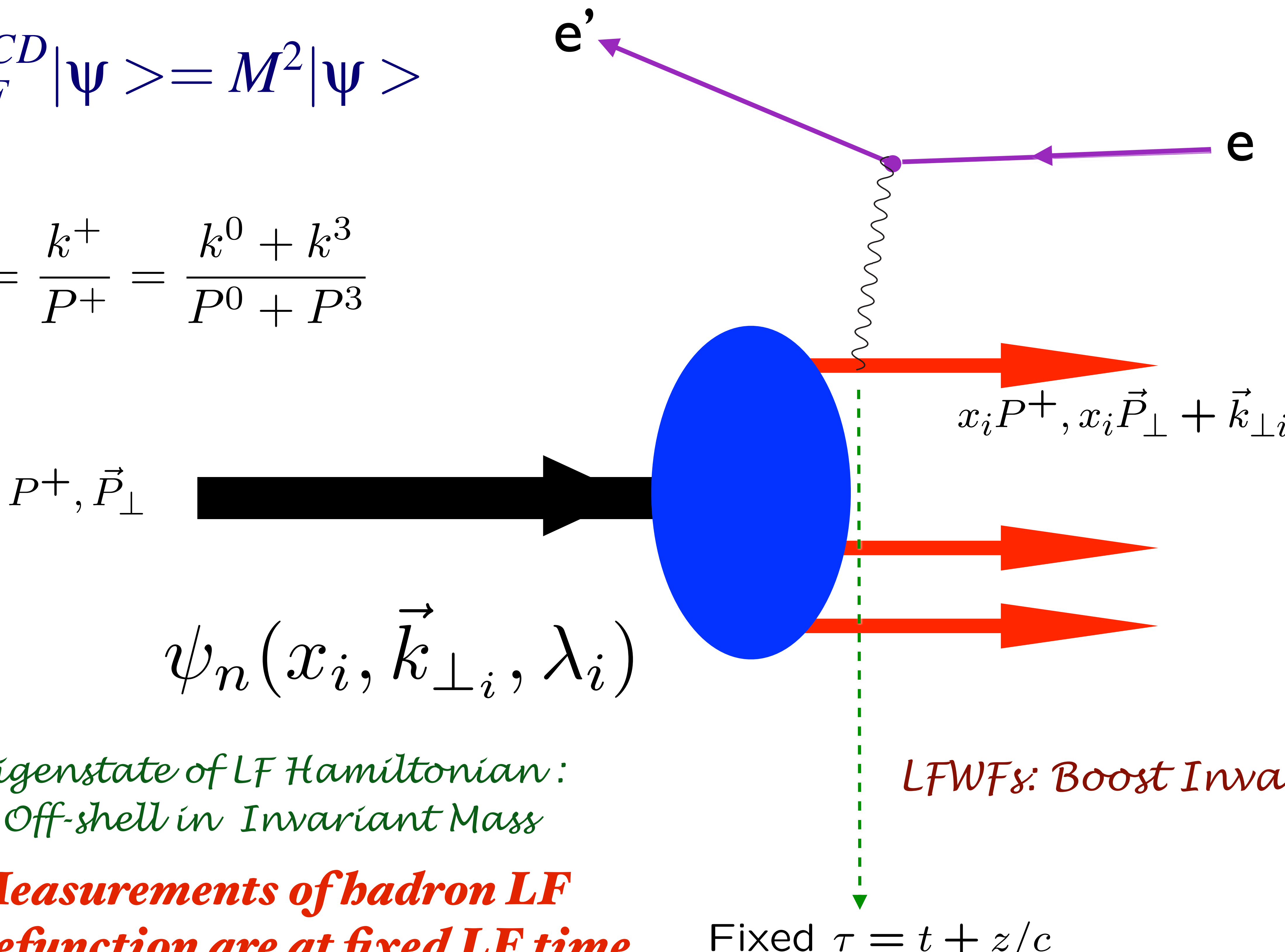
Mainz Institute for Theoretical Physics

October 9, 2019

Stan Brodsky
SLAC National Accelerator Laboratory

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

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



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

Eigenstate of LF Hamiltonian :
Off-shell in Invariant Mass

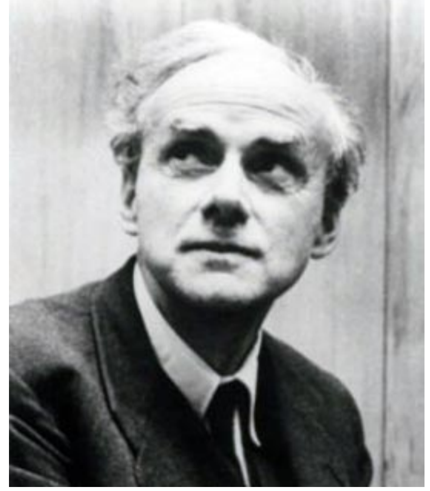
LFWFs: Boost Invariant

Measurements of hadron LF wavefunction are at fixed LF time

Like a flash photograph

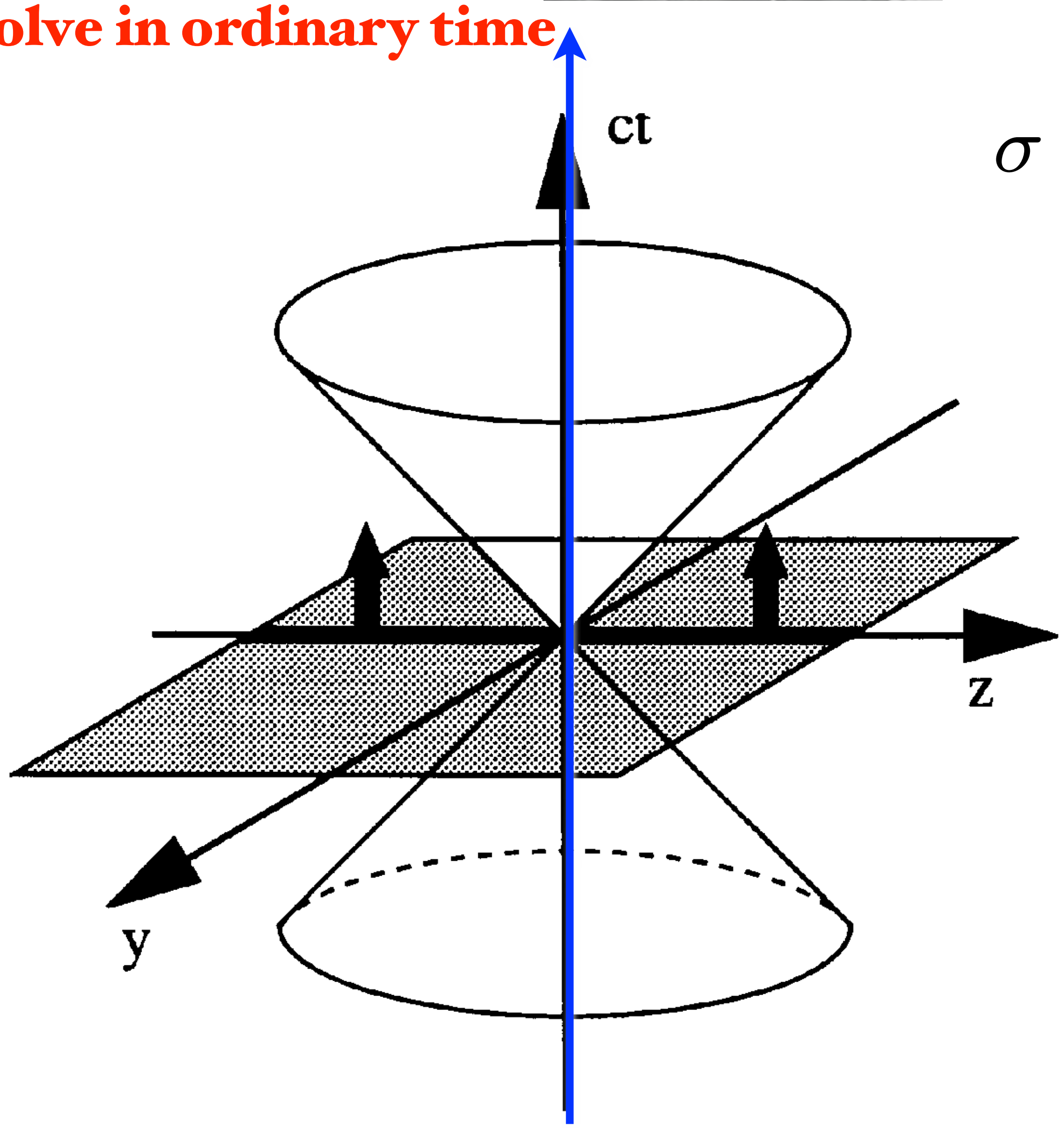
$$x_{bj} = x = \frac{k^+}{P^+}$$

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



Dirac's Amazing Idea:
The "Front Form"

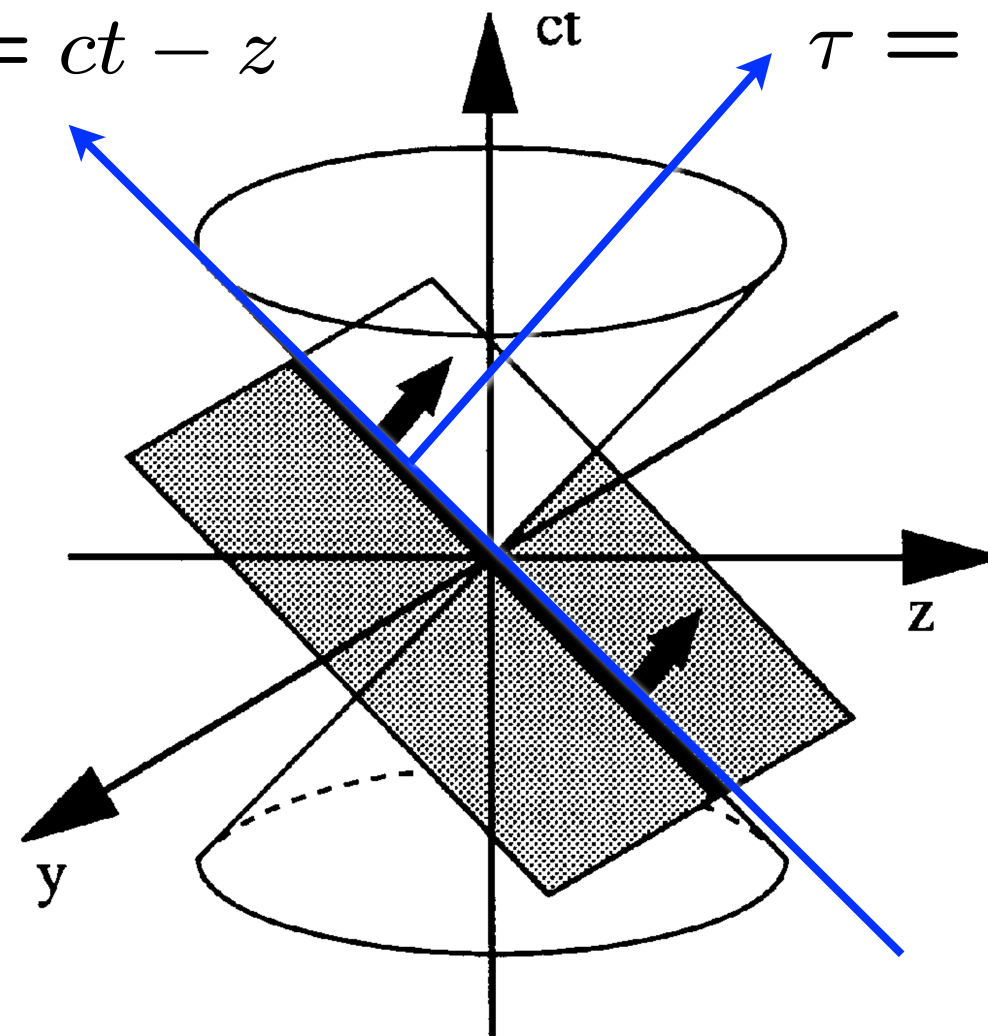
Evolve in ordinary time



Instant Form

Evolve in light-front time!

$\sigma = ct - z$ $\quad$ $\tau = t + z/c$



Front Form

Casual, Boost Invariant!

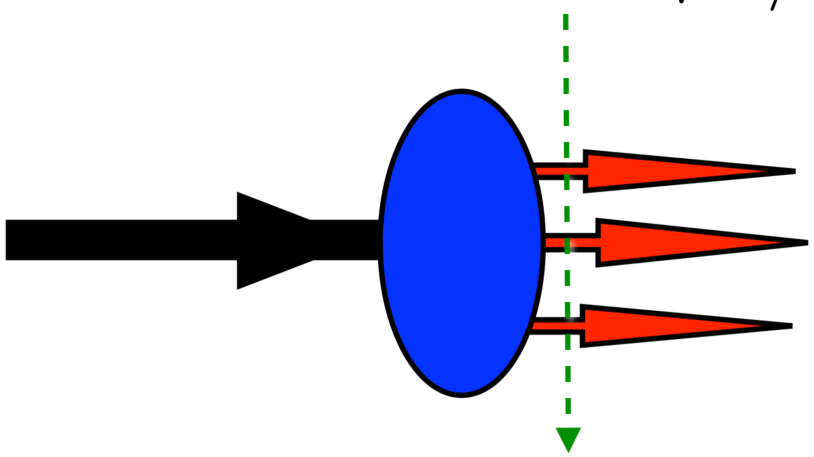
- ***Trivial LF Vacuum (up to zero modes)***

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

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

Fixed $\tau = t + z/c$



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

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

Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

LF Wavefunction: off-shell in invariant mass

LF time uncertainty relation

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

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

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

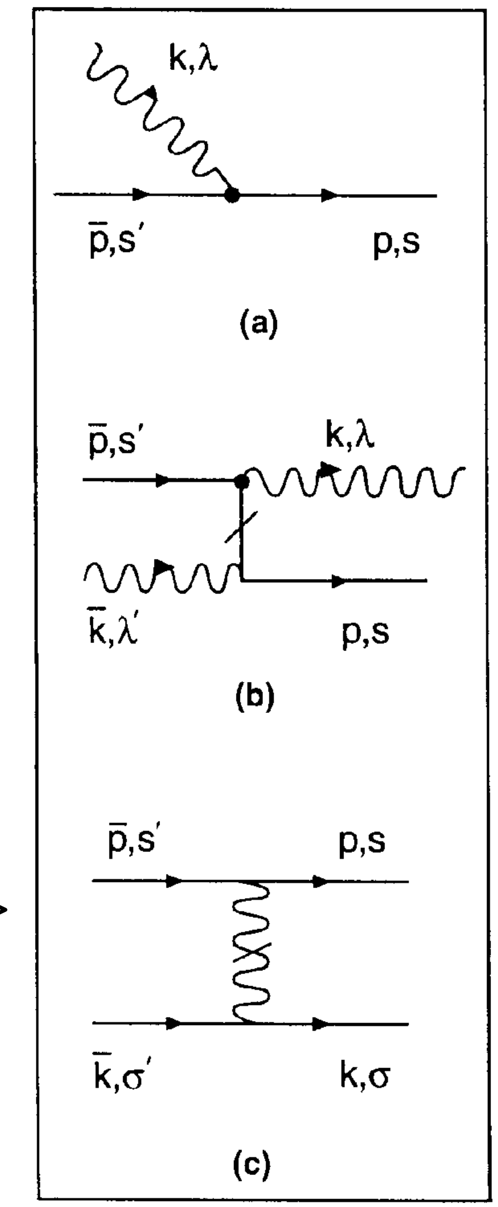
$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

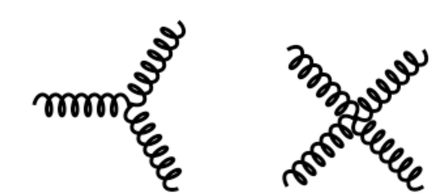
H^{int}_{LF}: Matrix in Fock Space

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

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

Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



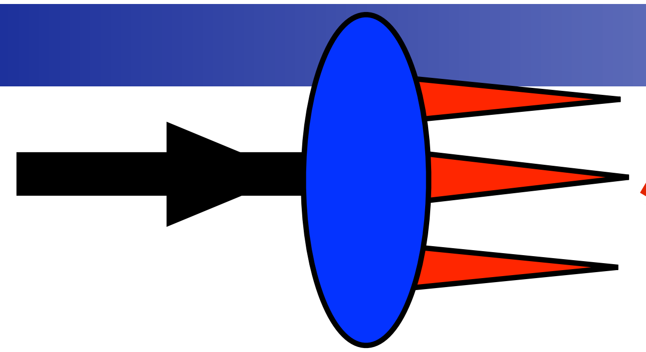


H^{int}_{LF}

LFWFs: Off-shell in P-

$$P^- P^+ - P^2_\perp = M^2$$

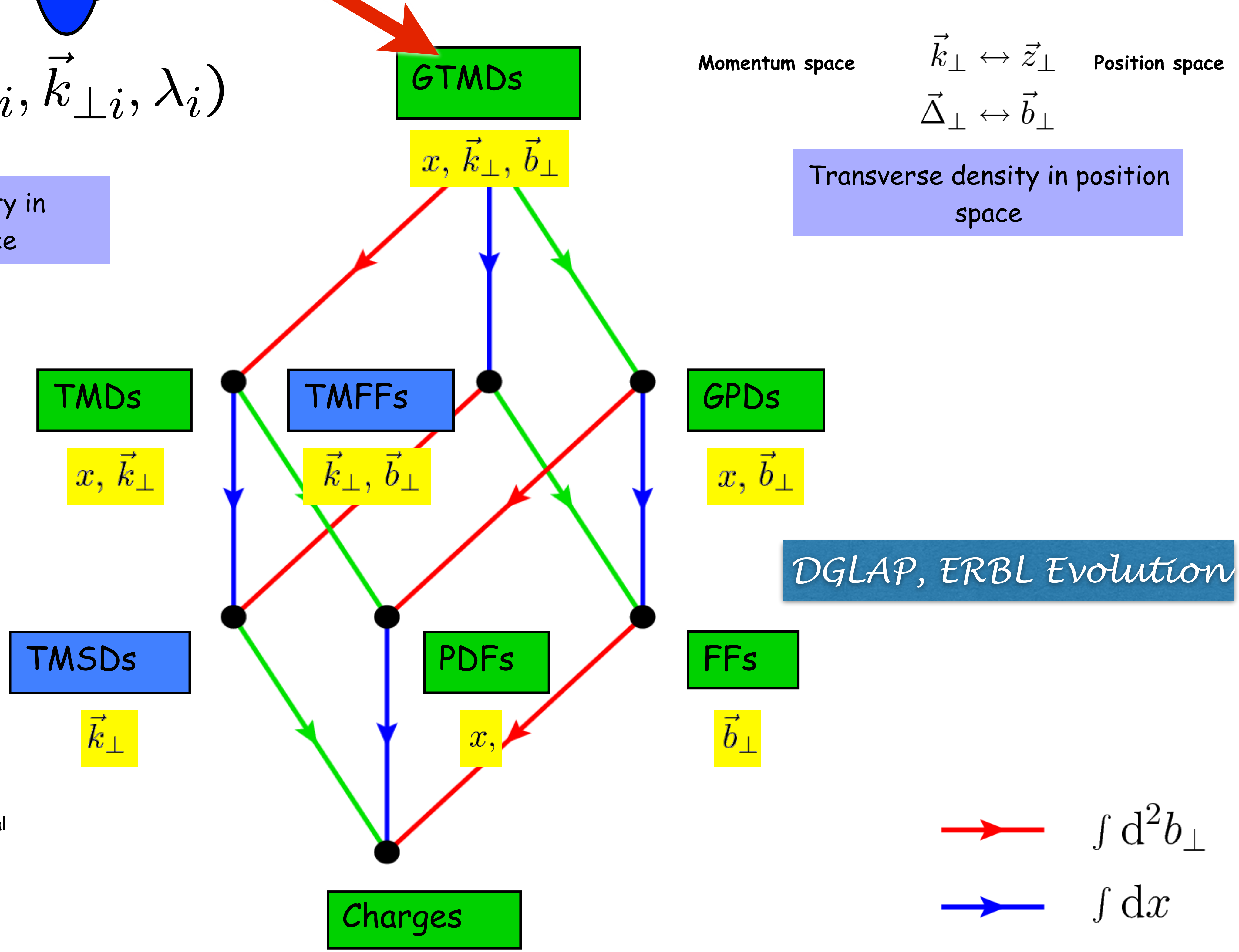
• Light Front Wavefunctions:

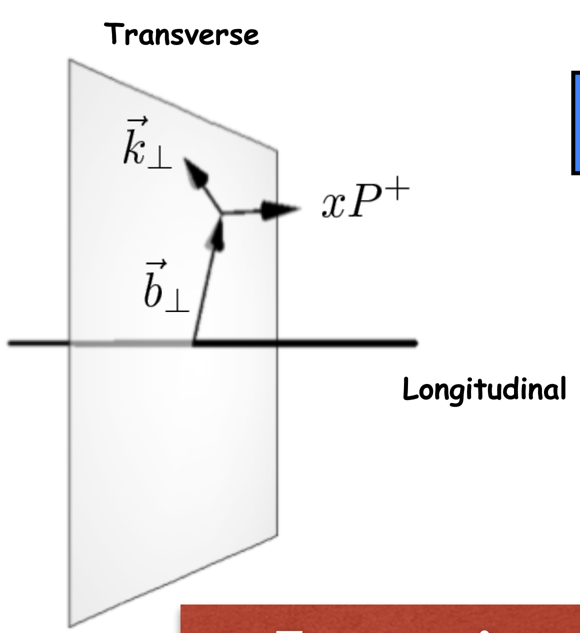


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Transverse density in momentum space

Lorce, Pasquini

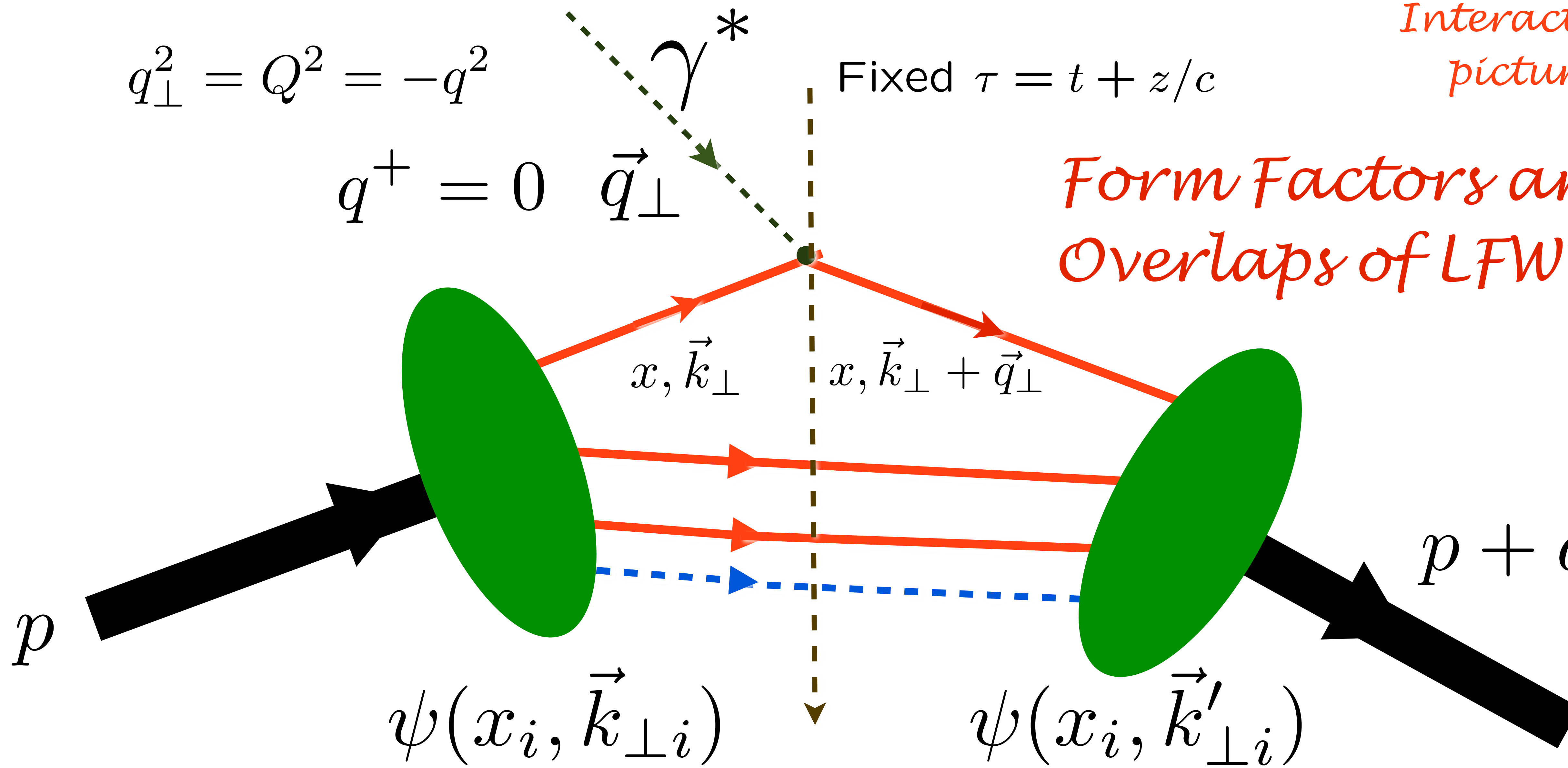




+ Factorization-Breaking Lensing Corrections: Sivers, T-odd

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

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

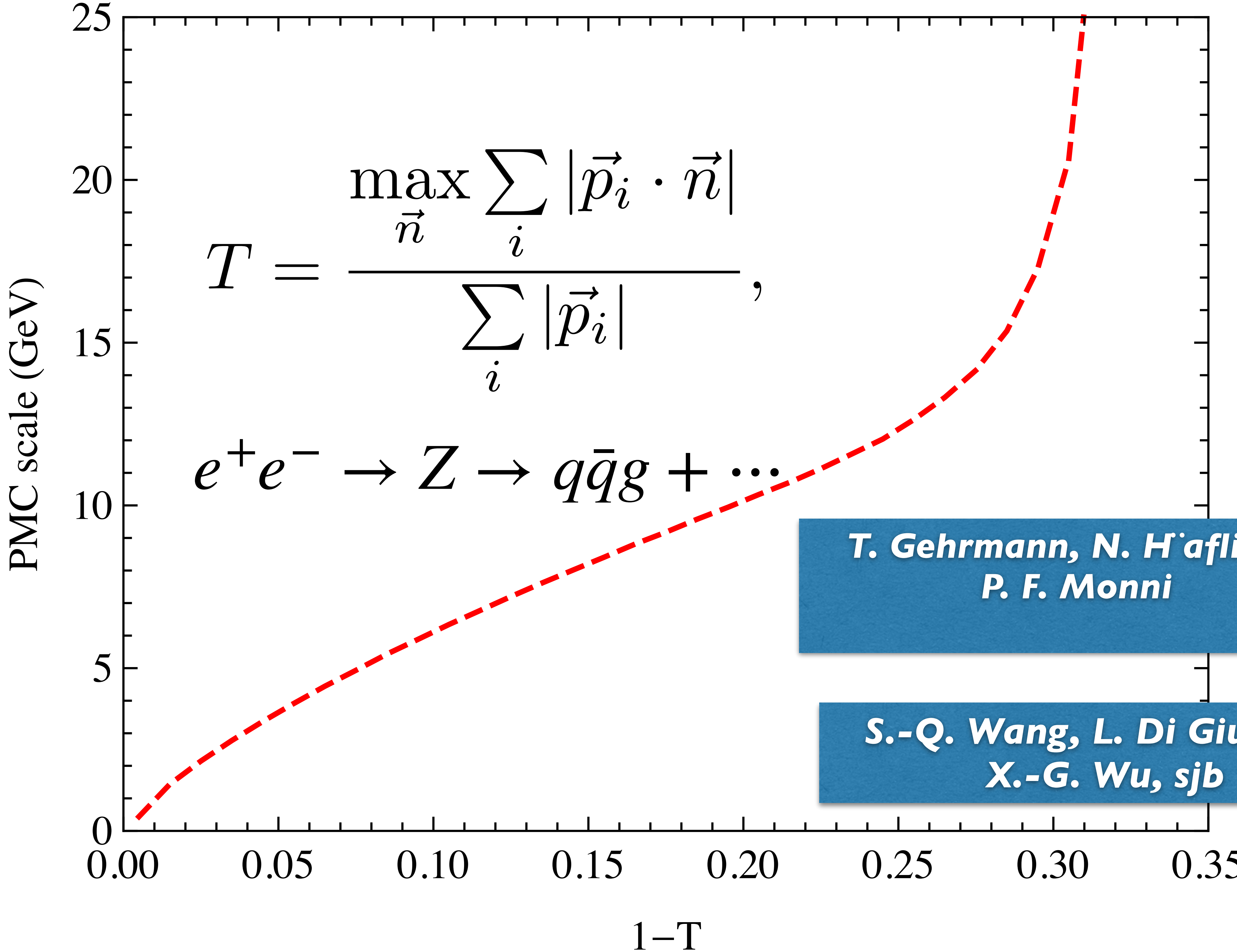
Challenge: Compute Hadron Structure, Spectroscopy, and Dynamics from QCD!

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

- *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*
- *Massless Pion! (Quark Anti-Quark Bound State)*
- *QCD Coupling at all Scales* $\alpha_s(Q^2)$
- *Eliminate Scale Uncertainties and Scheme Dependence*
- *Heavy Quark Distributions*

Renormalization scale depends on the thrust!

Not constant !



T. Gehrmann, N. H˙afliger, P. F. Monni

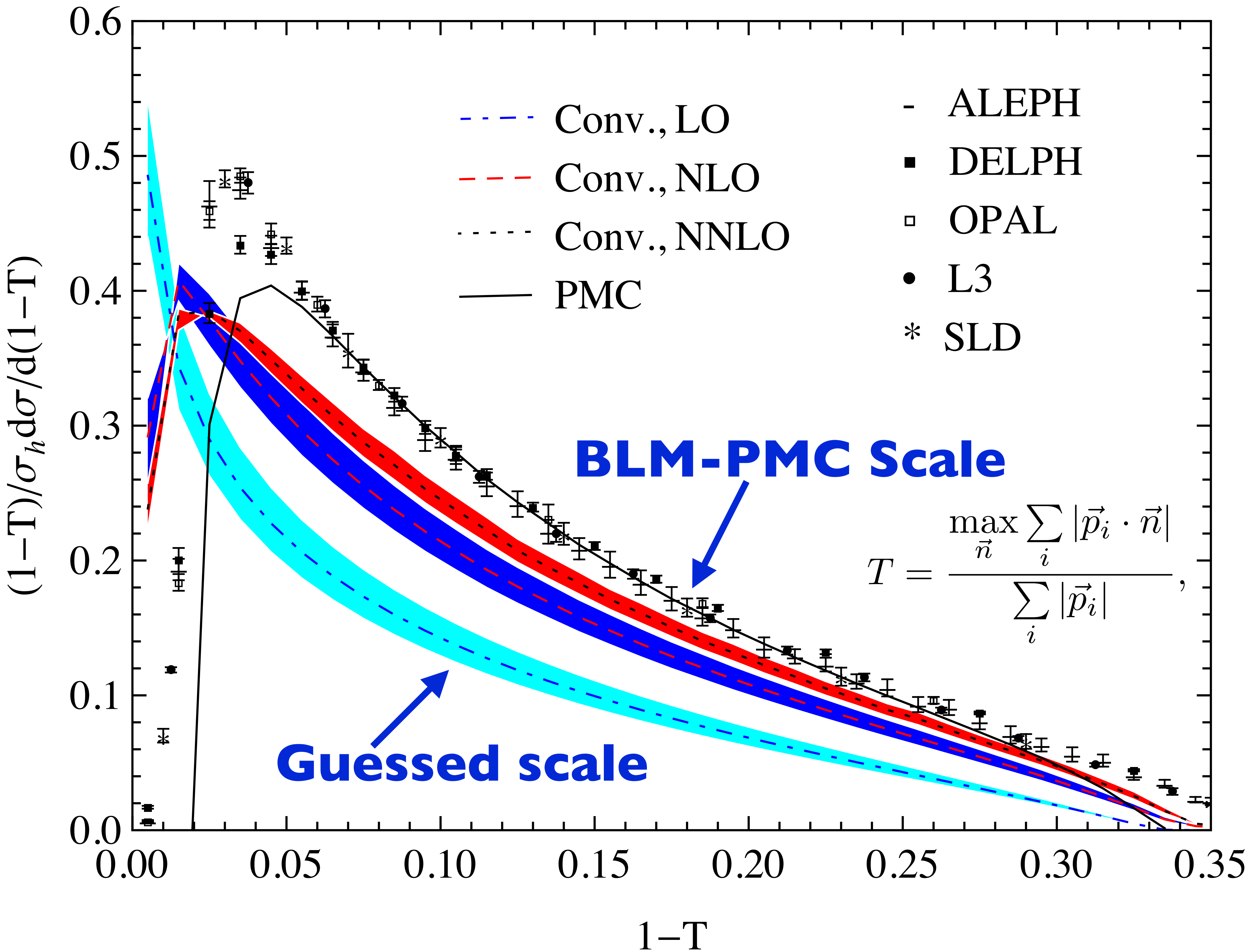
S.-Q. Wang, L. Di Giustino, X.-G. Wu, sjb

Principle of Maximum Conformality (PMC)

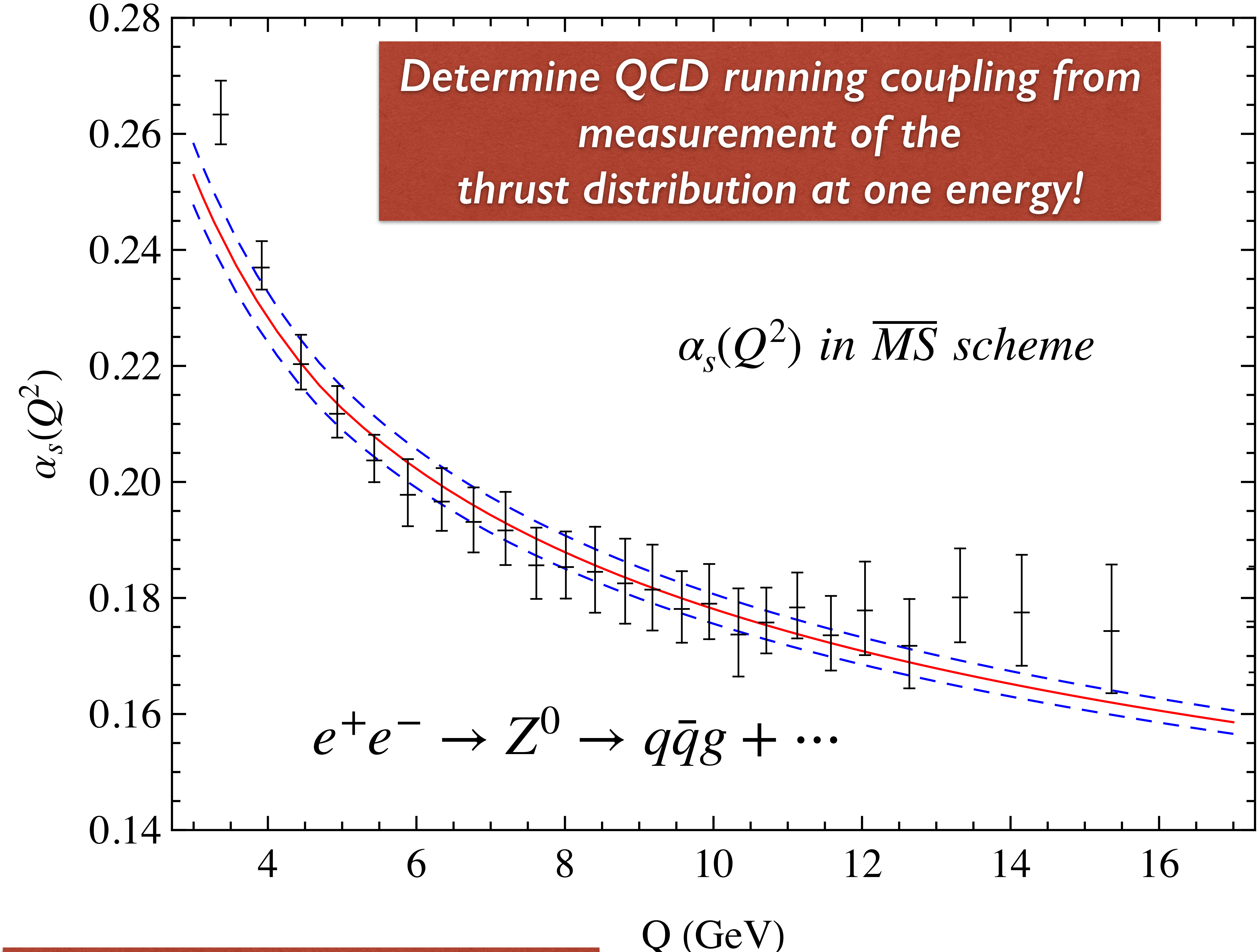
T. Gehrmann, N. H˙afliger, P. F. Monni

S.-Q. Wang, L. Di Giustino, X.-G. Wu, sjb

$$e^+e^- \to Z^* \to X$$

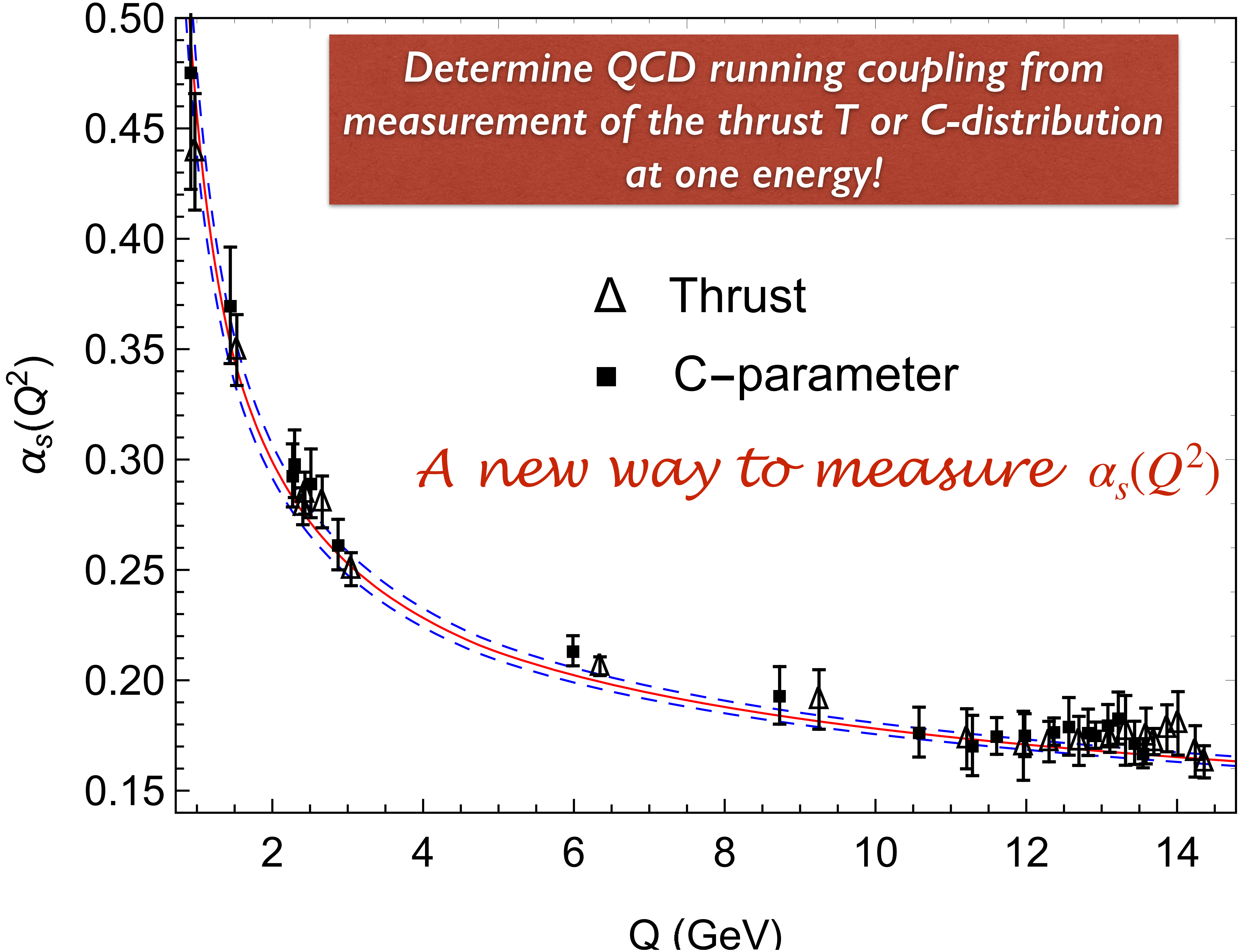


Principle of Maximum Conformality (PMC)



S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB

$e^+e^- \to Z^0 \to q\bar{q}g + \cdots \quad \alpha_s(Q^2)$ *in* $\overline{MS}$ *scheme*



S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB

Set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

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

↓

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

↓

$Identify\ \{\beta_i^R\}-terms\ using\ n_f-terms$

$through\ the\ PMC-BLM\ correspondence\ principle$

or R_δ scheme dependence

↓

$Shift\ scale\ of\ \alpha_s\ to\ \mu_R^{\rm PMC}\ to\ eliminate\ \{\beta_i^R\}-terms$

↓

$Conformal\ Series$

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

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at $N_C=0$

Eliminates unnecessary systematic uncertainty

Scale fixed at each order

δ-Scheme automatically identifies β-terms!

Principle of Maximum Conformality

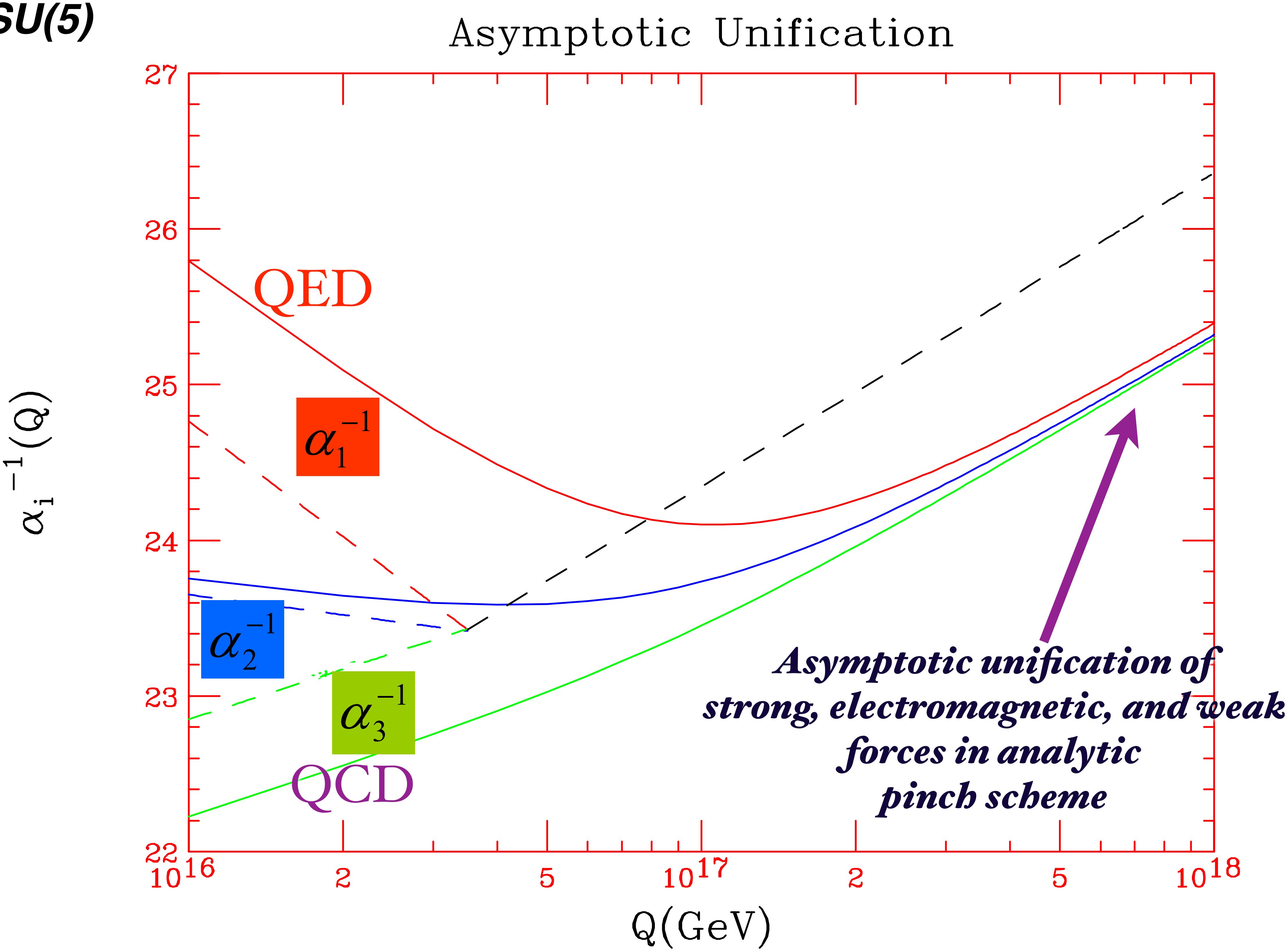
Xing-Gang Wu, Matin Mojaza Leonardo di Giustino, SJB

Features of BLM/PMC

- *Predictions are scheme-independent at every order*
- *Matches conformal series*
- *No n! Renormalon growth of pQCD series*
- *New scale appears at each order; n_F determined at each order - matches virtuality of quark loops*
- *Multiple Physical Scales Incorporated (Hoang, Kuhn, Tuebner, sjb)*
- *Rigorous: Satisfies all Renormalization Group Principles*
- *Realistic Estimate of Higher-Order Terms*
- *Reduces to standard QED scale* $N_C \to 0$
- *GUT: Must use the same scale setting procedure for QED, QCD*
- *Eliminates unnecessary theory error*
- *Maximal sensitivity to new physics*
- *Commensurate Scale Relations between observables: Generalized Crewther Relation (Kataev, Lu, Rathsman, sjb)*
- *PMC Reduces to BLM at NLO: Example: BFKL intercept* (Fadin, Kim, Lipatov, Pivovarov, sjb)

Supersymmetric SU(5)

Binger, sjb



Must Use Same Scale-Setting Procedure! BLM/PMC

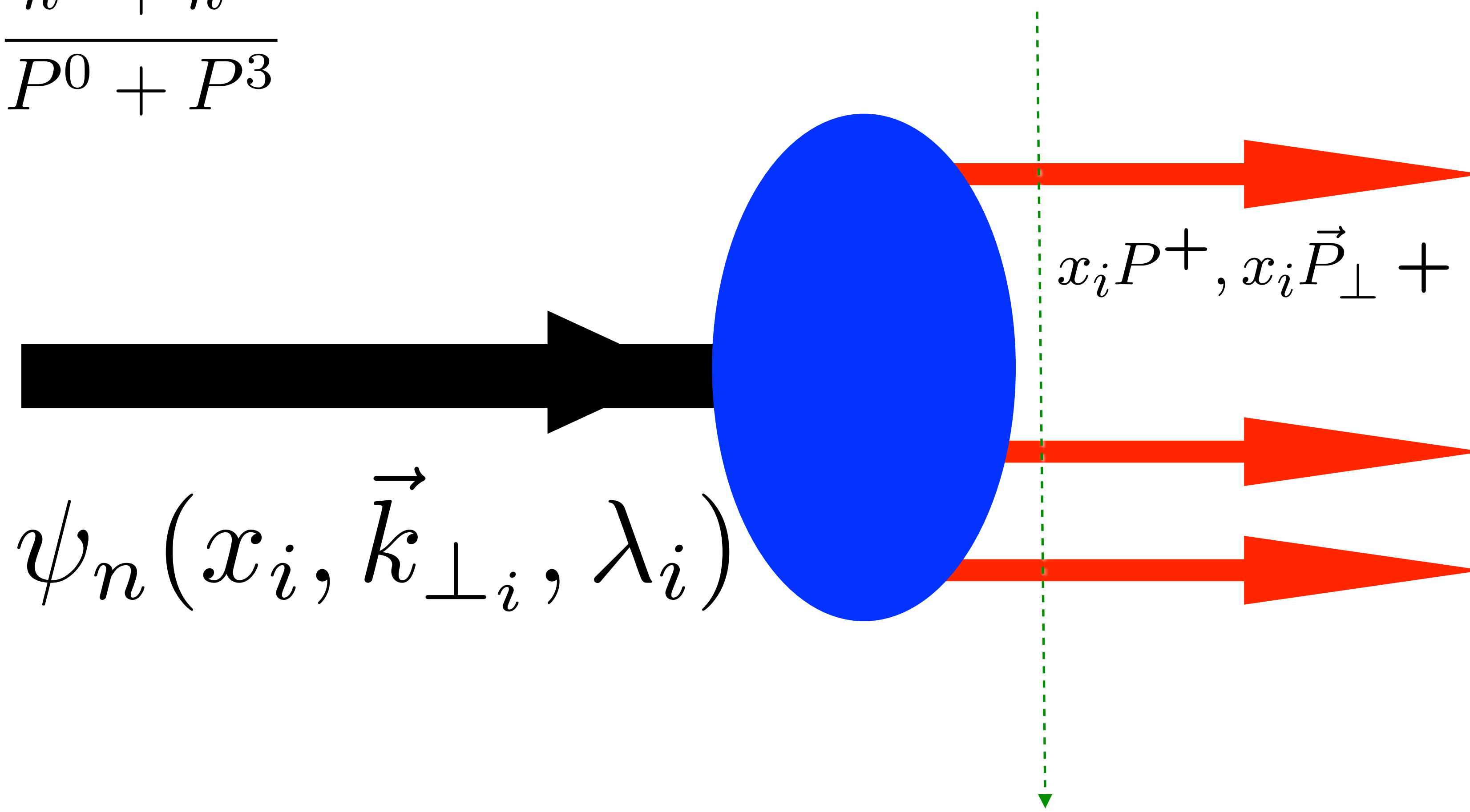
Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of LF Hamiltonian : Off-shell in Invariant Mass

Fixed $\tau = t + z/c$

Fixed LF time

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

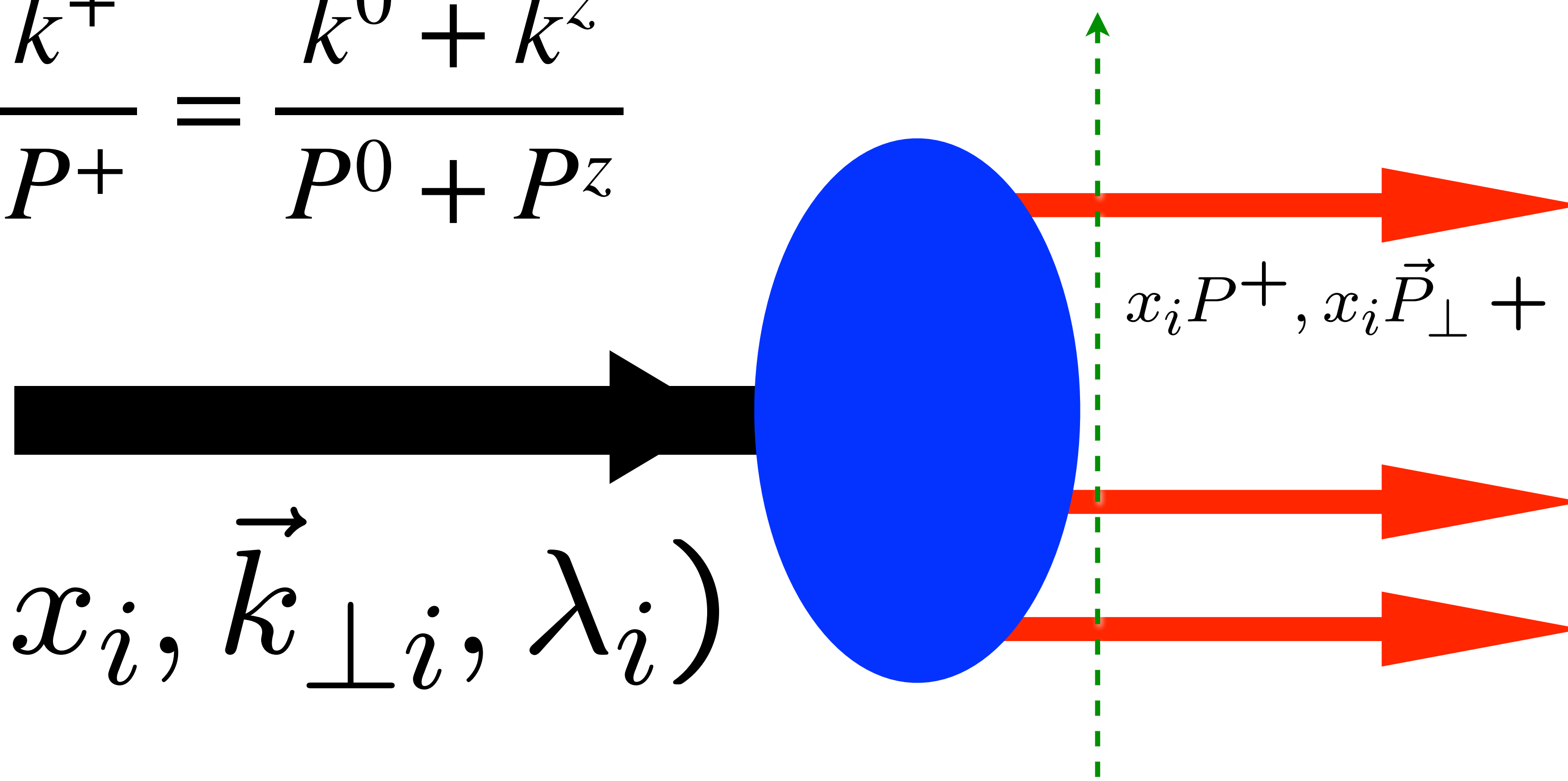
Sum Rules

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

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

Fixed $\tau = t + z/c$

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



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

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

$\sum_i^n x_i = 1$

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

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

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions: Off-Shell in Invariant Mass

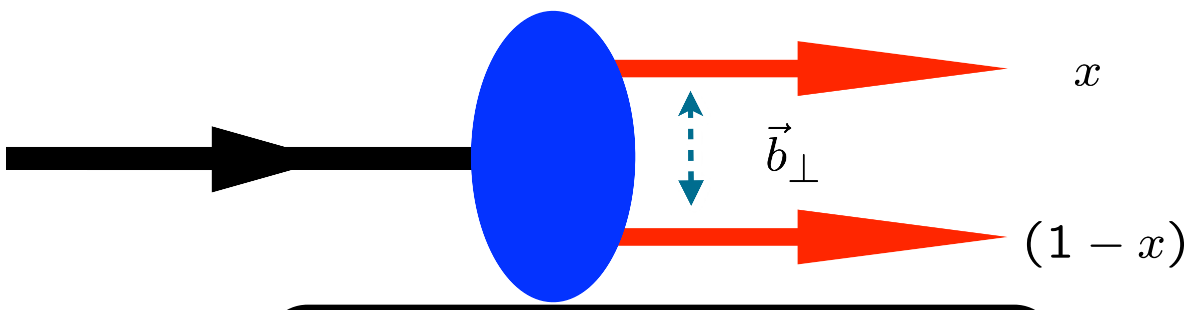
$$\mathscr{M}_n^2 = (\sum_{i=1}^n k^\mu)^2 = \sum_{i=1}^n \frac{k_{\perp i}^2 + m_i^2}{x_i}$$

$$M^2 - \mathscr{M}_n^2 < 0$$

Light-Front QCD

Fixed $\tau = t + z/c$

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



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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

Effective two-particle equation

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

Azimuthal Basis ζ, ϕ

Single variable Equation

$m_q = 0$

AdS/QCD:

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

Confining AdS/QCD potential!

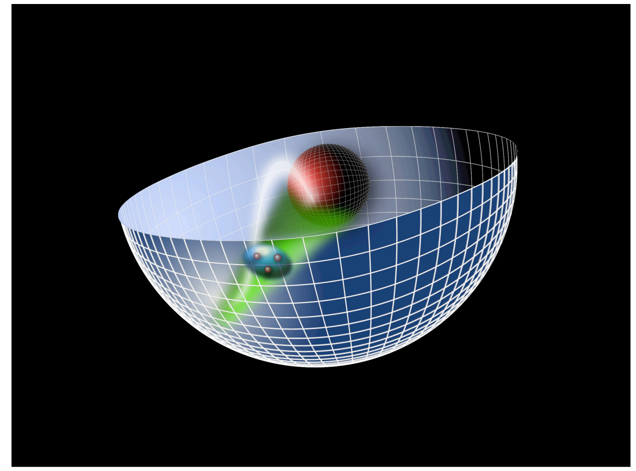
Semiclassical first approximation to QCD

Sums an infinite # diagrams

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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



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

Light-Front Holography

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

Light-Front Schrödinger Equation

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

Single variable ζ

Unique
Confinement Potential!

Conformal Symmetry
of the action

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

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

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

GeV units external to QCD: Only Ratios of Masses Determined de Téramond, Dosch, Lorcé, sjb

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

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

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

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

S=1/2, P=+

Meson Equation

$$\lambda=\kappa^2$$

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

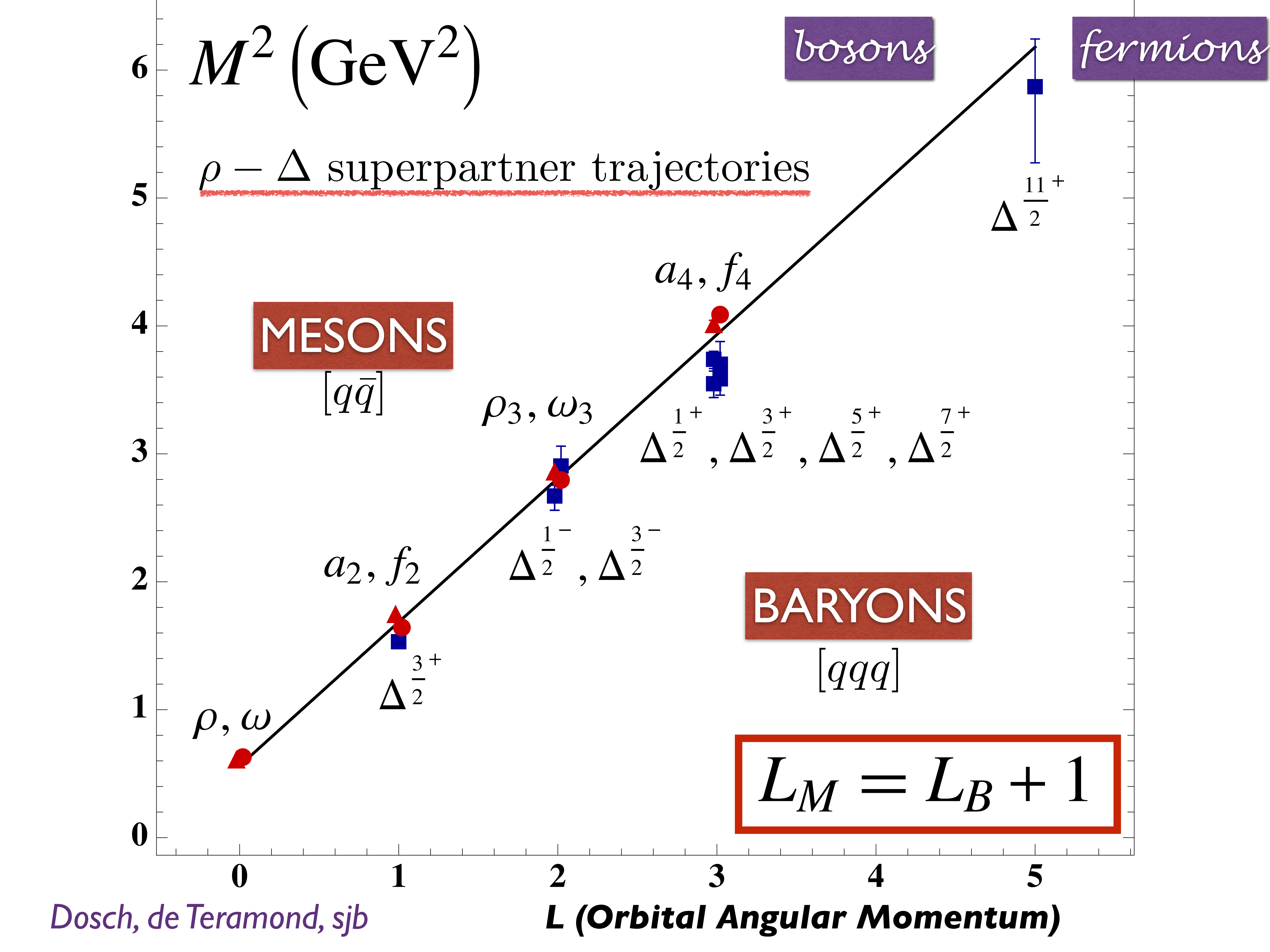
$$M^2(n,L_M)=4\kappa^2(n+L_M)$$

S=0, P=+

Same κ!

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

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

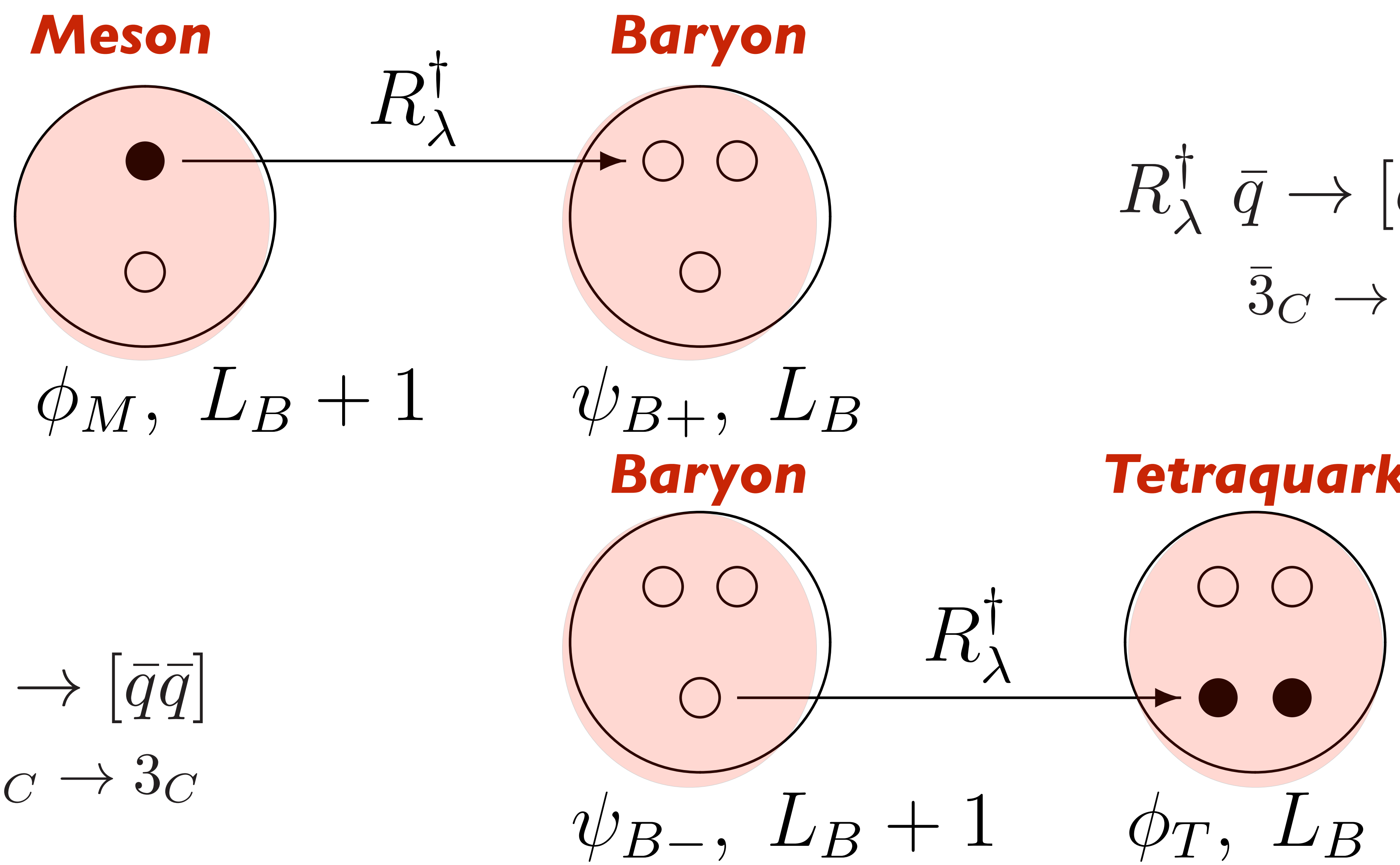


$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
MESONS
$[q\bar{q}]$
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta^{\frac{3}{2}^+}$
$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$
$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$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

Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



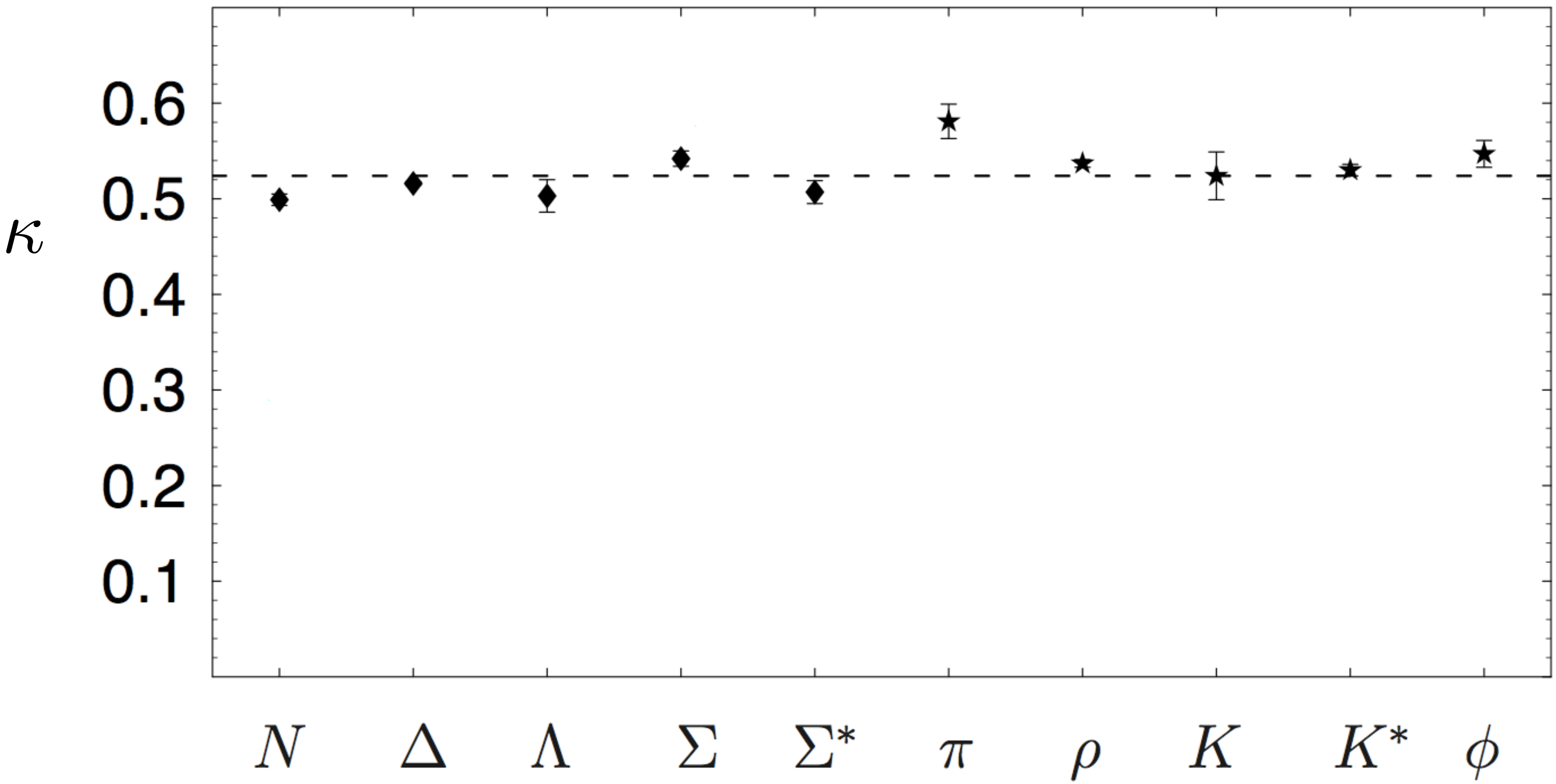
$$R_\lambda^\dagger \ \bar{q} \to [qq]$$
$$\bar{3}_C \to \bar{3}_C$$

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

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

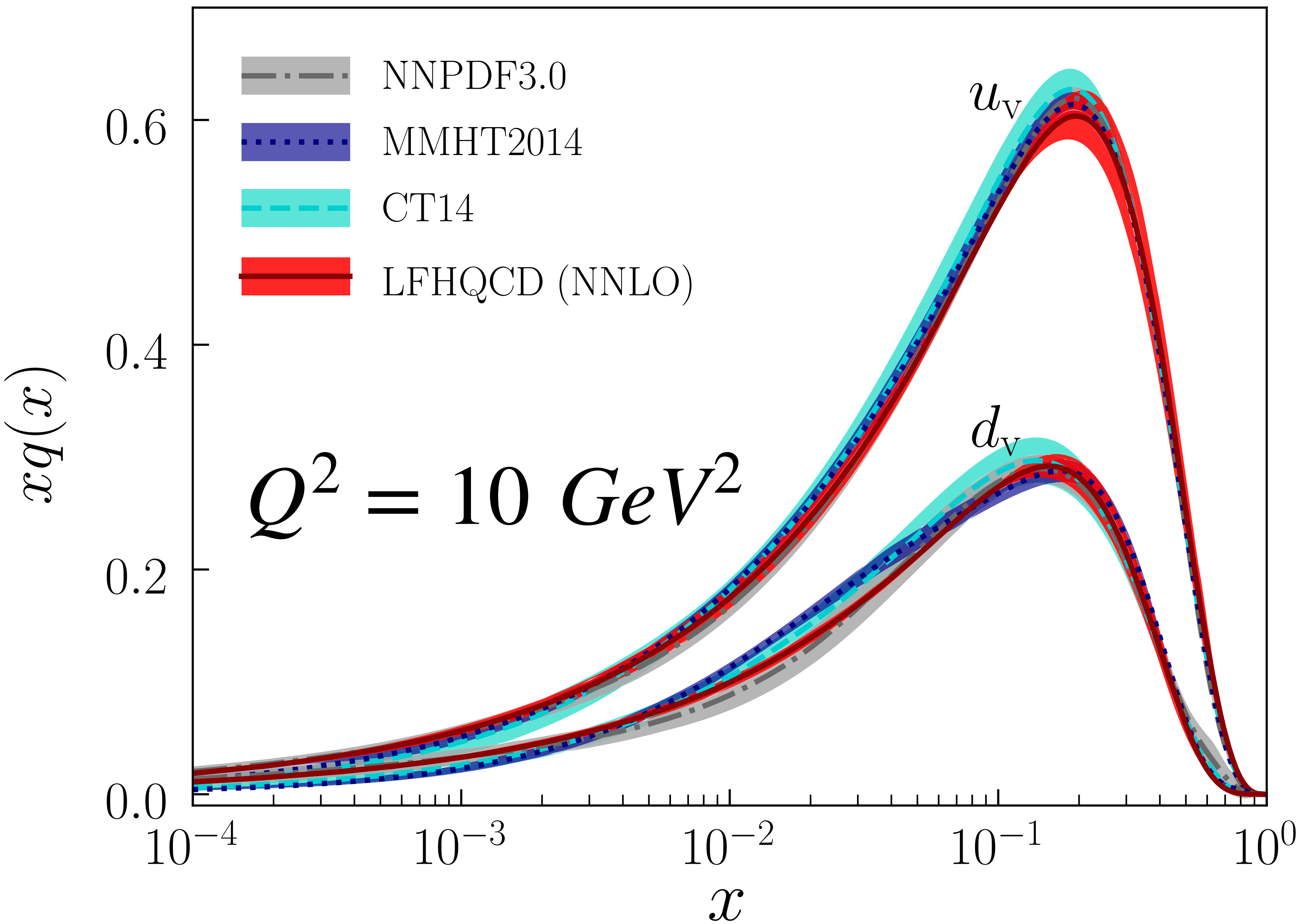
Dosch, de Teramond, Lorce, sjb

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



Fit to the slope of Regge trajectories, including radial excitations

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



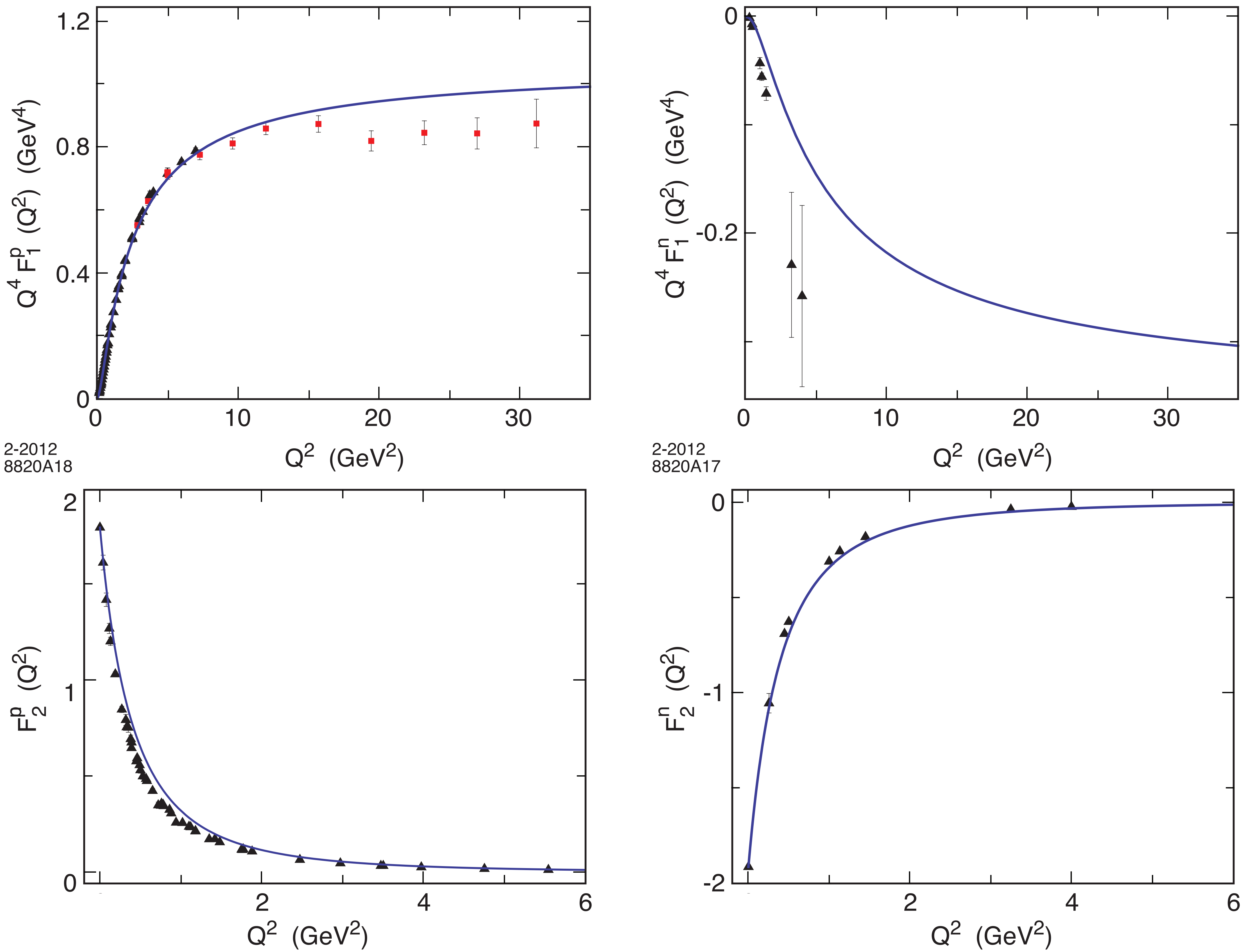
Comparison for $xq(x)$ in the proton from LFHQCD (red bands) and global fits: MMHT2014 (blue bands) [5], CT14 [6] (cyan bands), and NNPDF3.0 (gray bands) [77]. LFHQCD results are evolved from the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV.

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

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

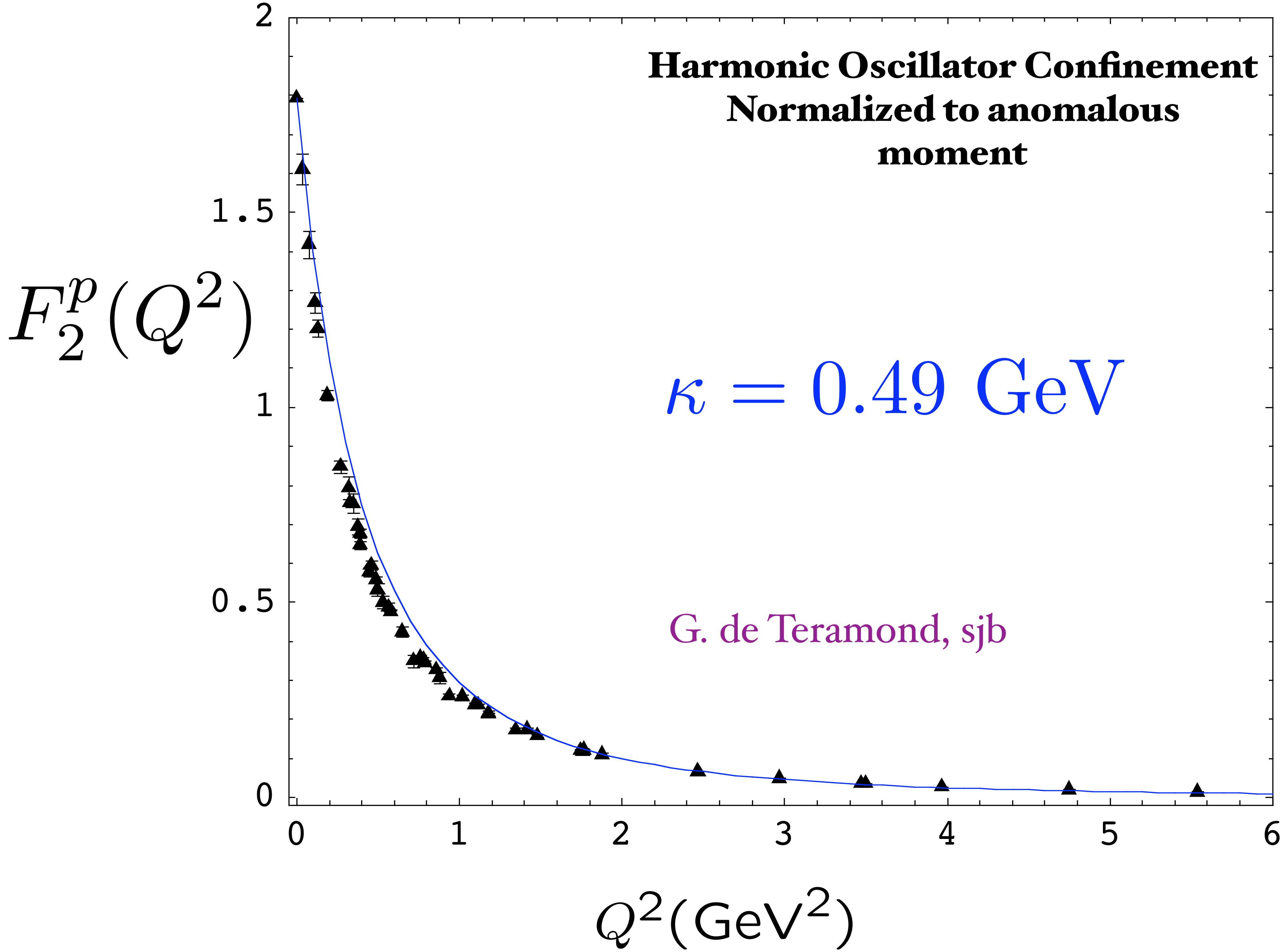
PHYSICAL REVIEW LETTERS 120, 182001 (2018)

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

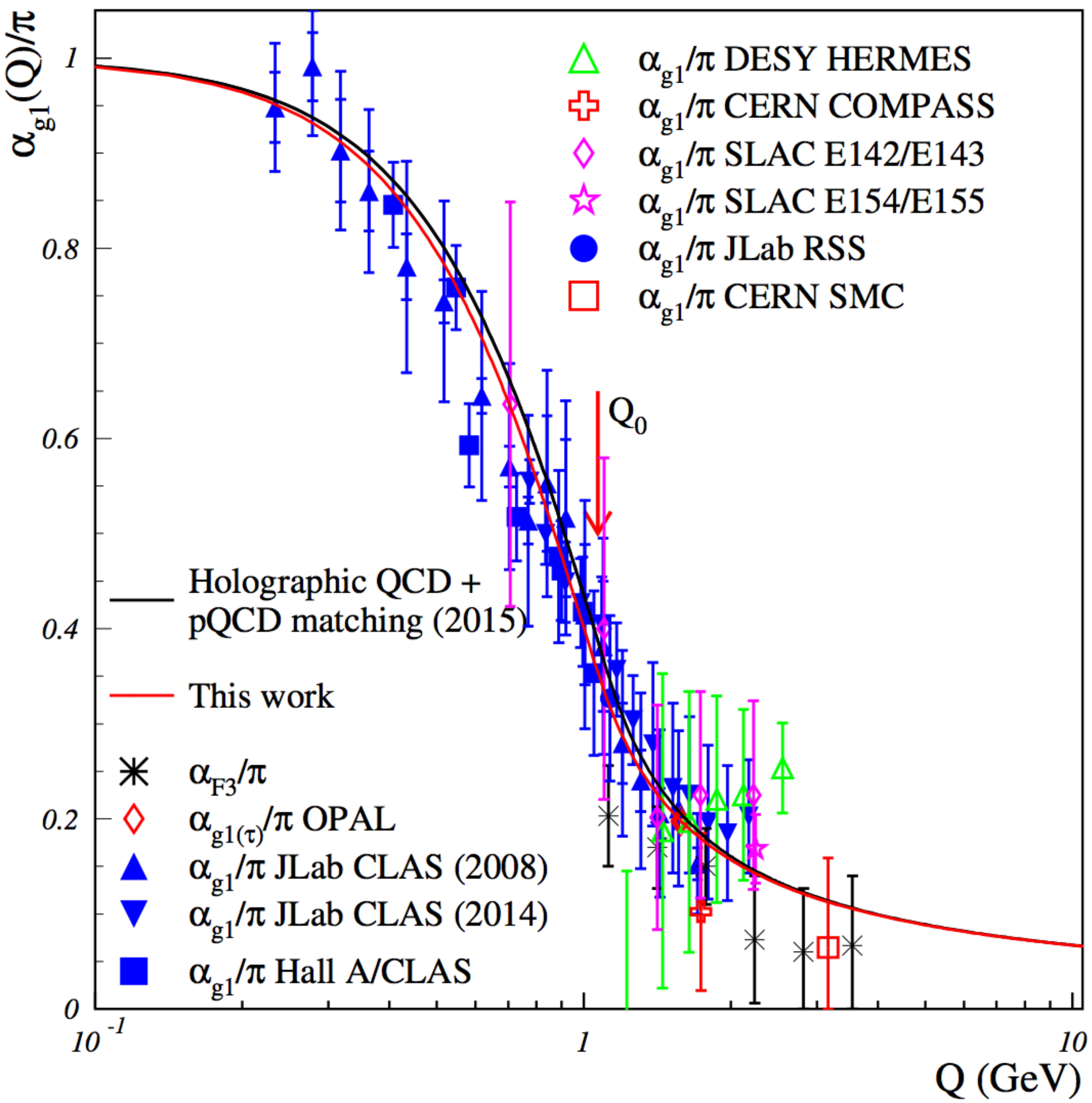


Spacelike Pauli Form Factor

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



Running Coupling from AdS/QCD



Bjorken sum rule:

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

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

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

Imposing continuity for α and its first derivative

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

Analytic, defined at all scales, IR Fixed Point

Bjorken sum rule defines effective charge

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

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

- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal β_0, β_1***

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

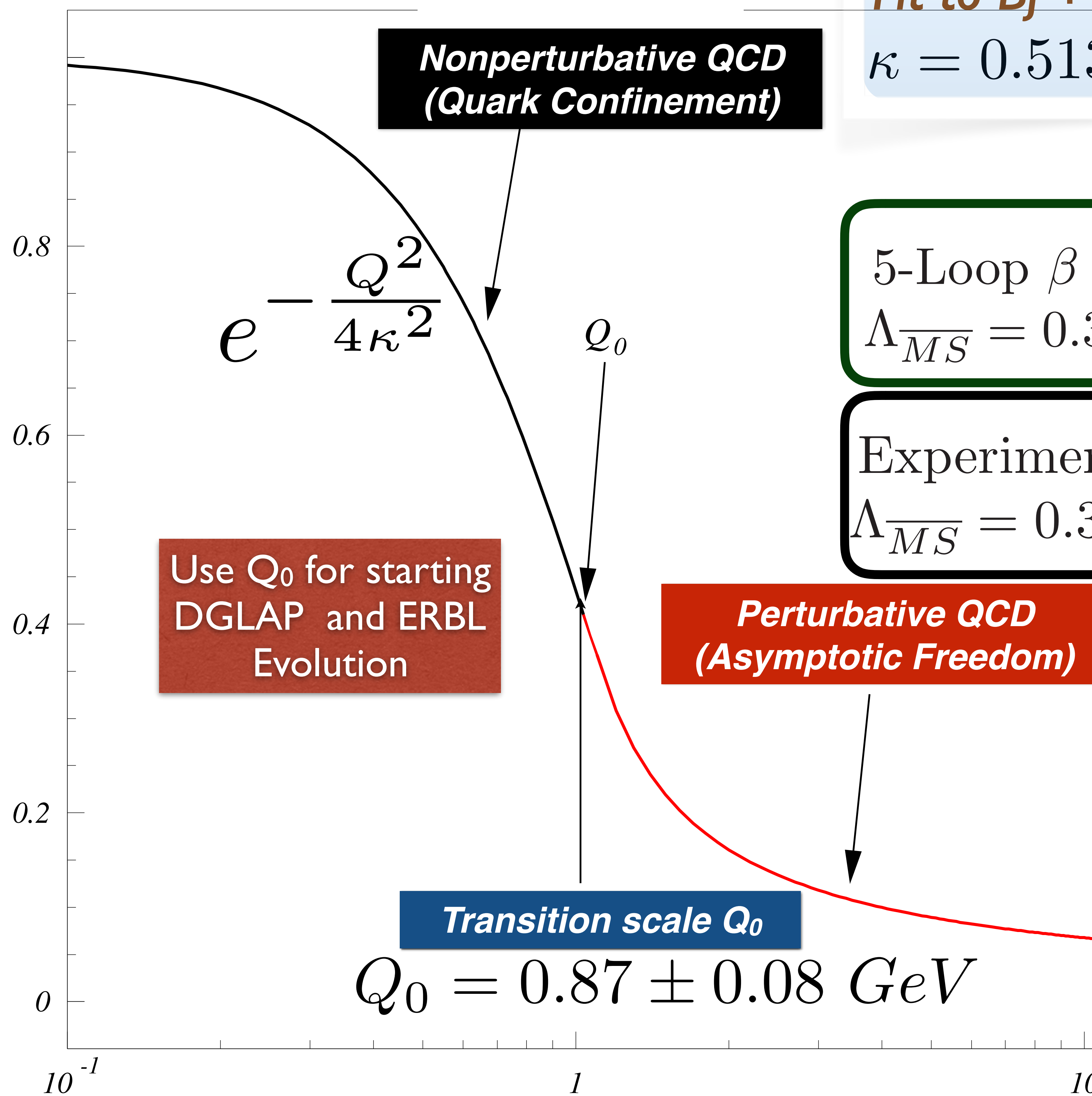
$m_p = 2\kappa$

All-Scale QCD Coupling

Deur, de Tèramond, sjb

Fit to Bj + DHG Sum Rules:
$\kappa = 0.513 \pm 0.007\ GeV$

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



5-Loop β Prediction:
$\Lambda_{\overline{MS}} = 0.339 \pm 0.019\ GeV$

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

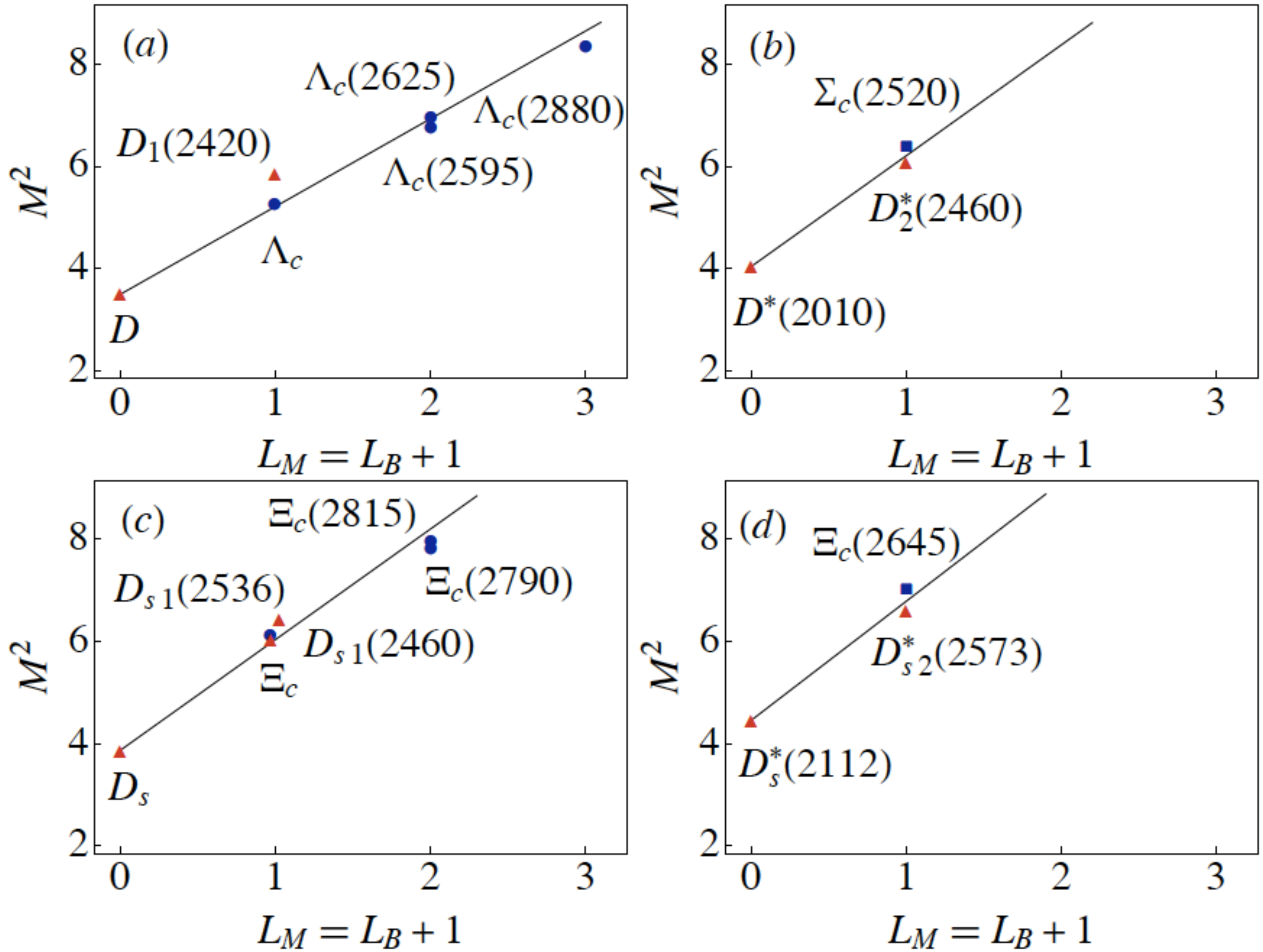
$\lambda \equiv \kappa^2$

$\overline{MS}$ scheme

Reverse Dimensional Transmutation!

de Téramond, Dosch, Nielsen, sjb

Supersymmetry across the light and heavy-light spectrum



Heavy charm quark mass does not break supersymmetry

Meson Spectrum in Soft Wall Model

Massless pion!

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

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

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

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

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

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

- Eigenvalues

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

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

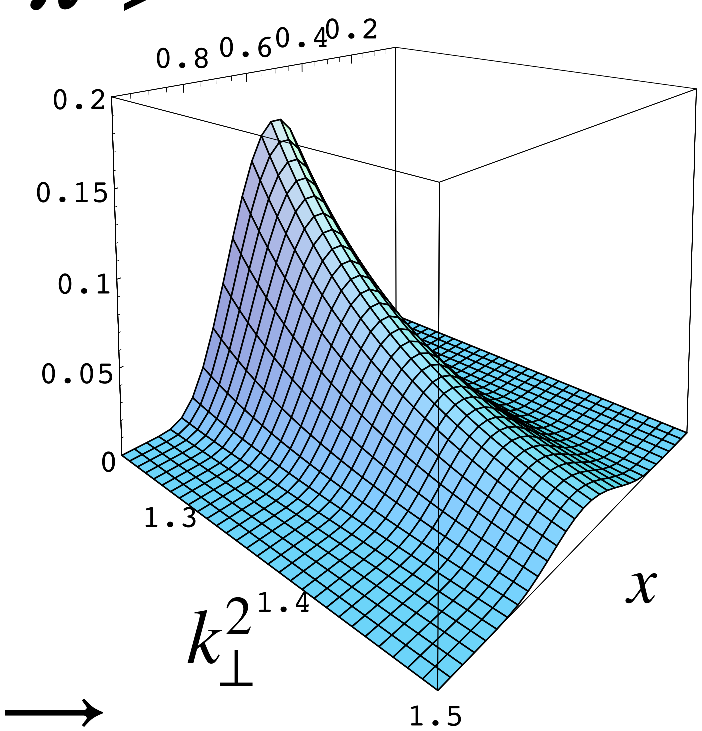
G. de Teramond, H. G. Dosch, sjb

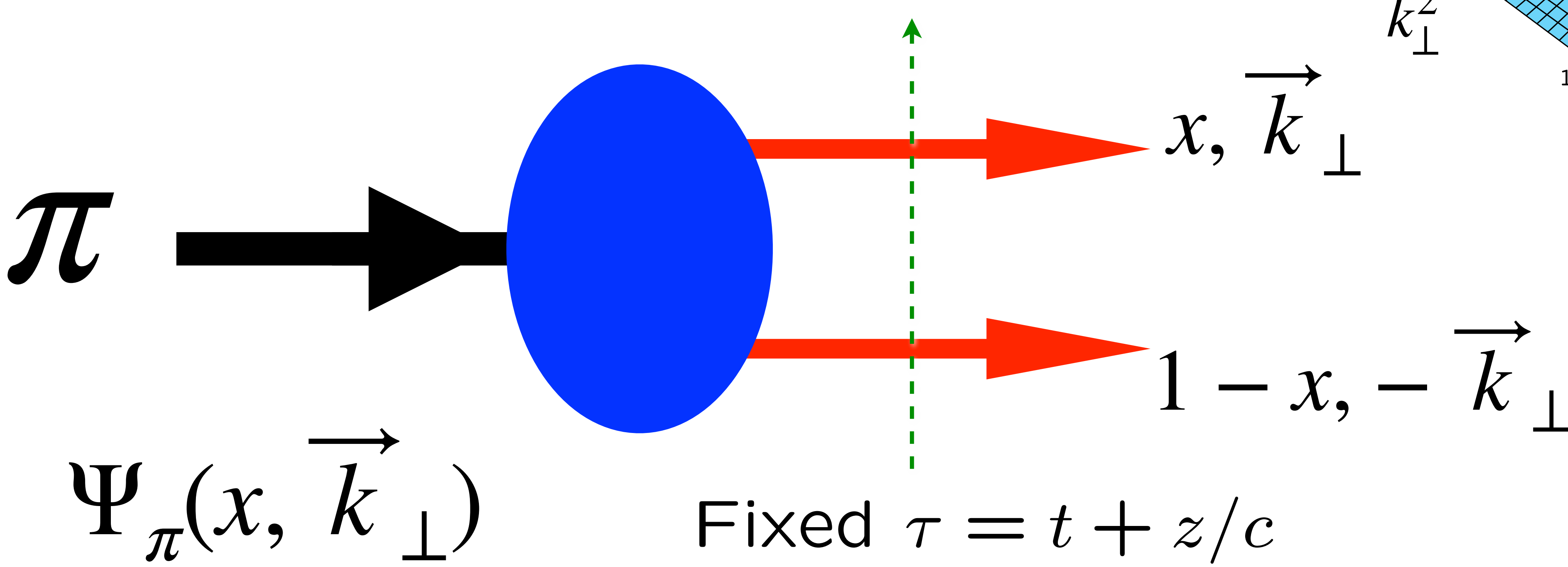
The Pion's Valence Light-Front Wavefunction

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

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

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

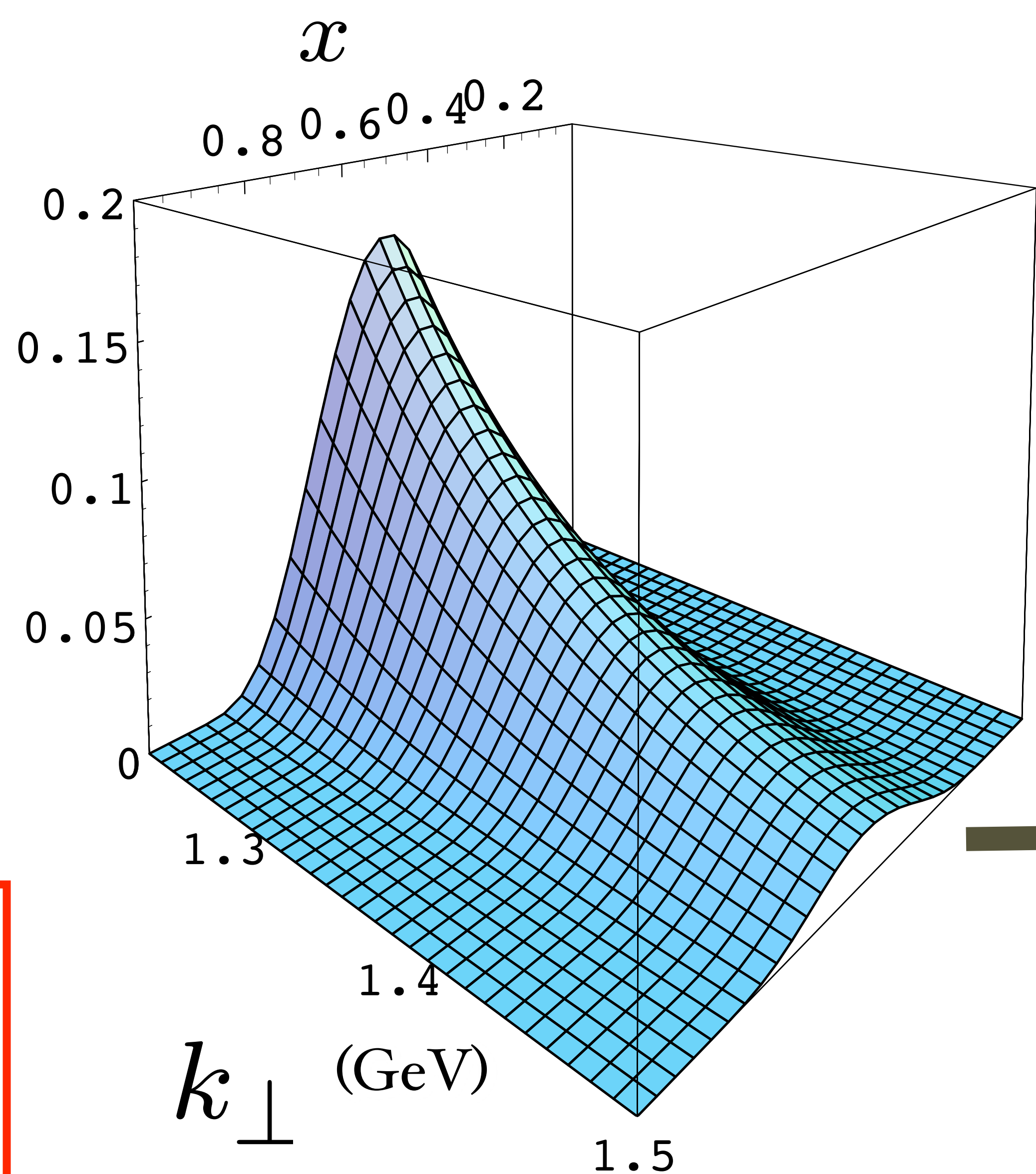




Prediction from AdS/QCD: Meson LFWF

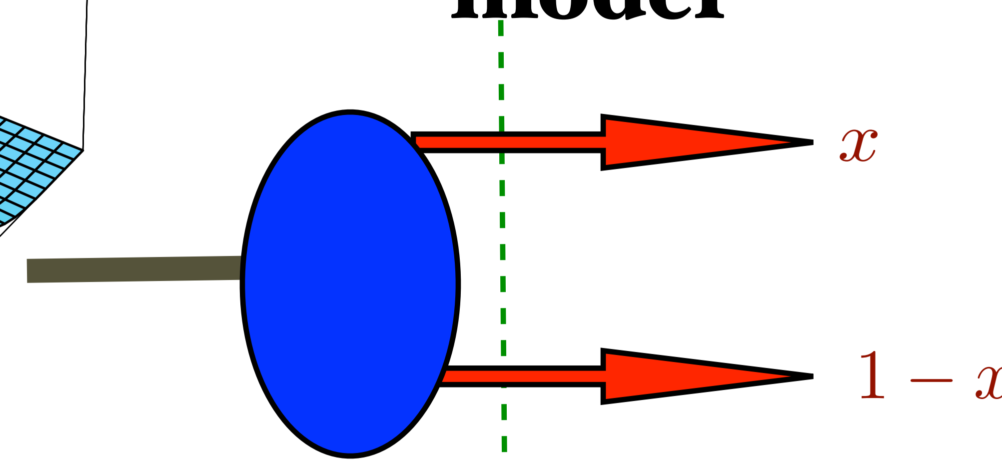
de Teramond, Cao, sjb

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



$k_\perp$

"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

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

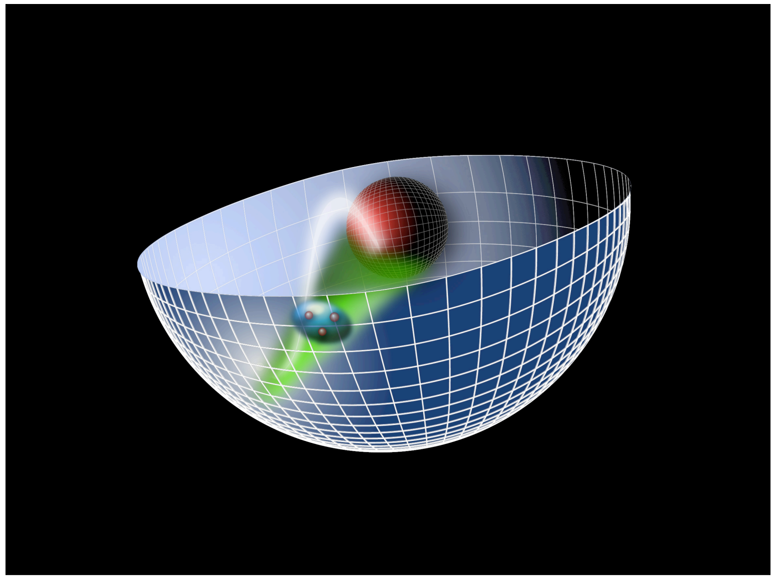
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

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

Provides Connection of Confinement to Hadron Structure

$\phi(z)$

AdS5: Conformal Template for QCD

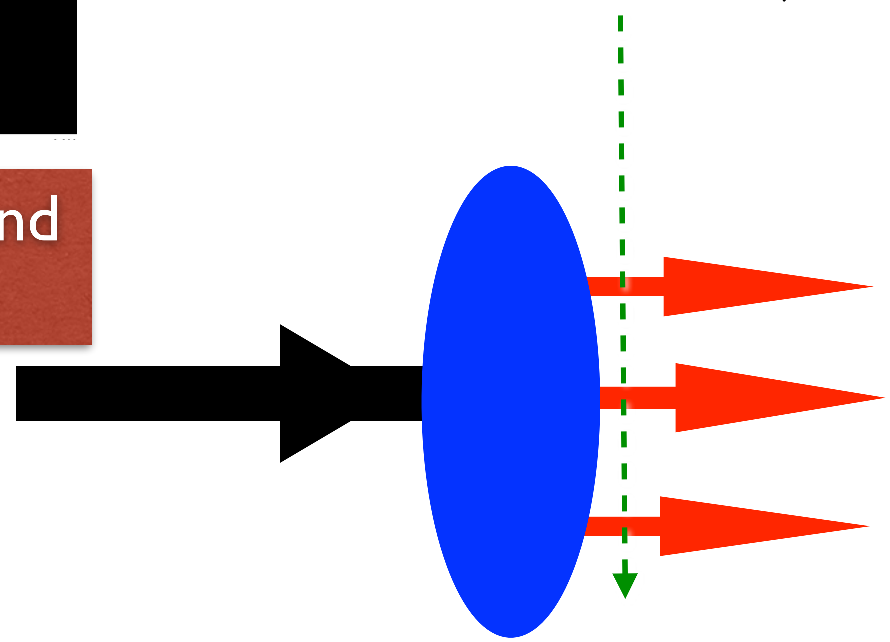


with Guy de Teramond and Hans Guenter Dosch

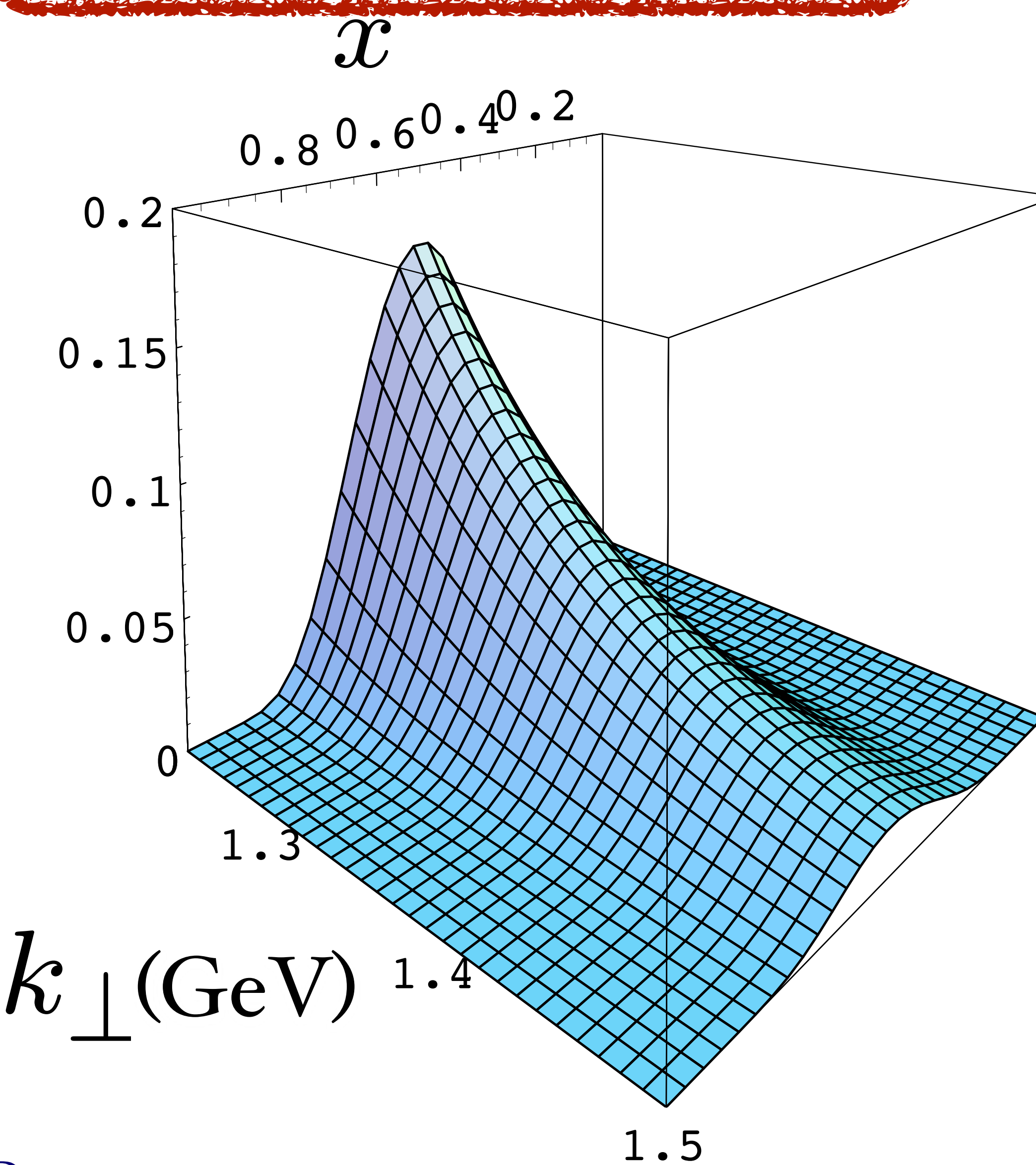
- *Light-Front Holography*

Duality of AdS₅ with LF Hamiltonian Theory

Fixed $\tau = t + z/c$



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



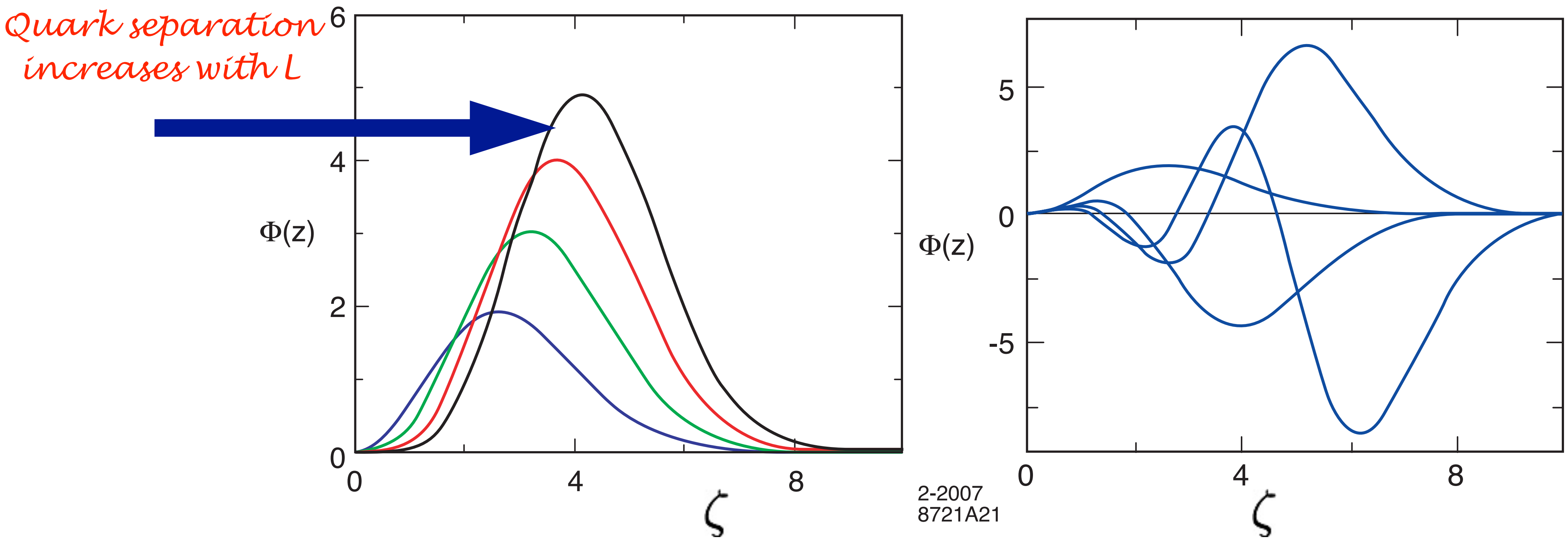
$k_\perp$(GeV)

- *Light Front Wavefunctions:*

Light-Front Schrödinger Equation

Spectroscopy and Dynamics

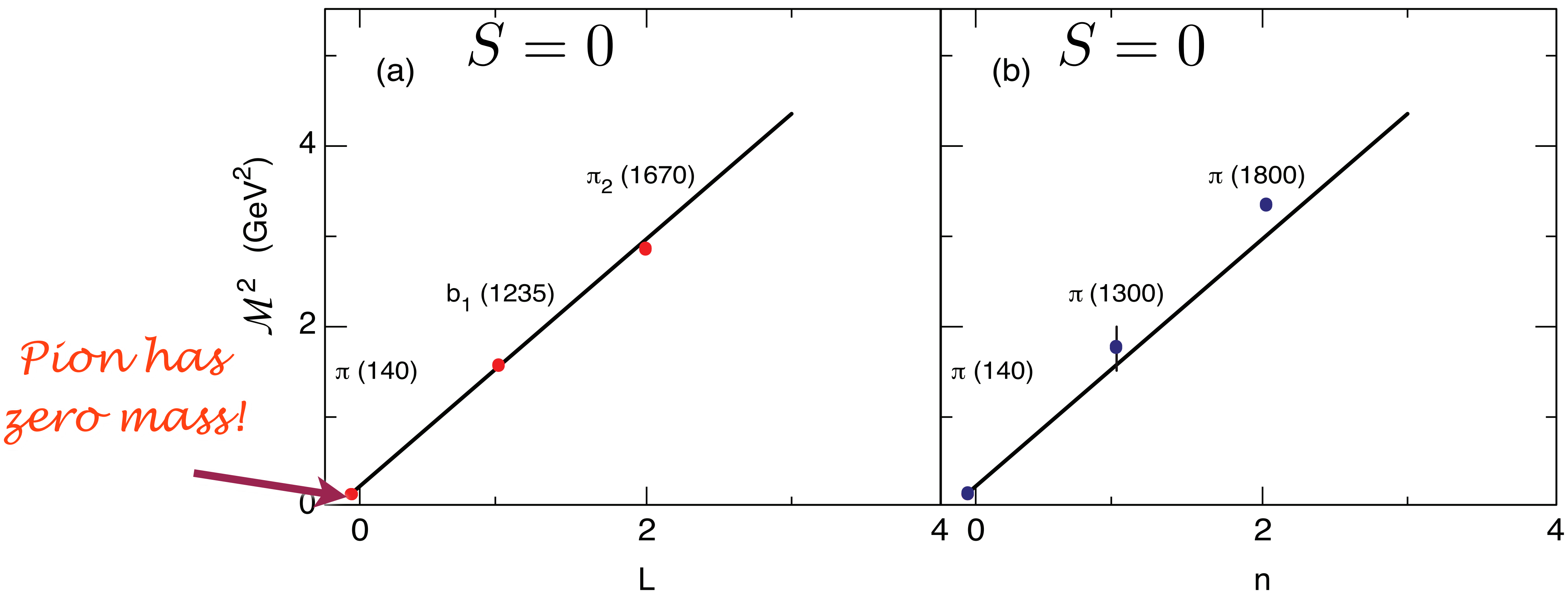
$$H^{QCD}_{LF}|\psi> = M^2|\psi>$$



Soft Wall Model

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

Same slope in n and L!

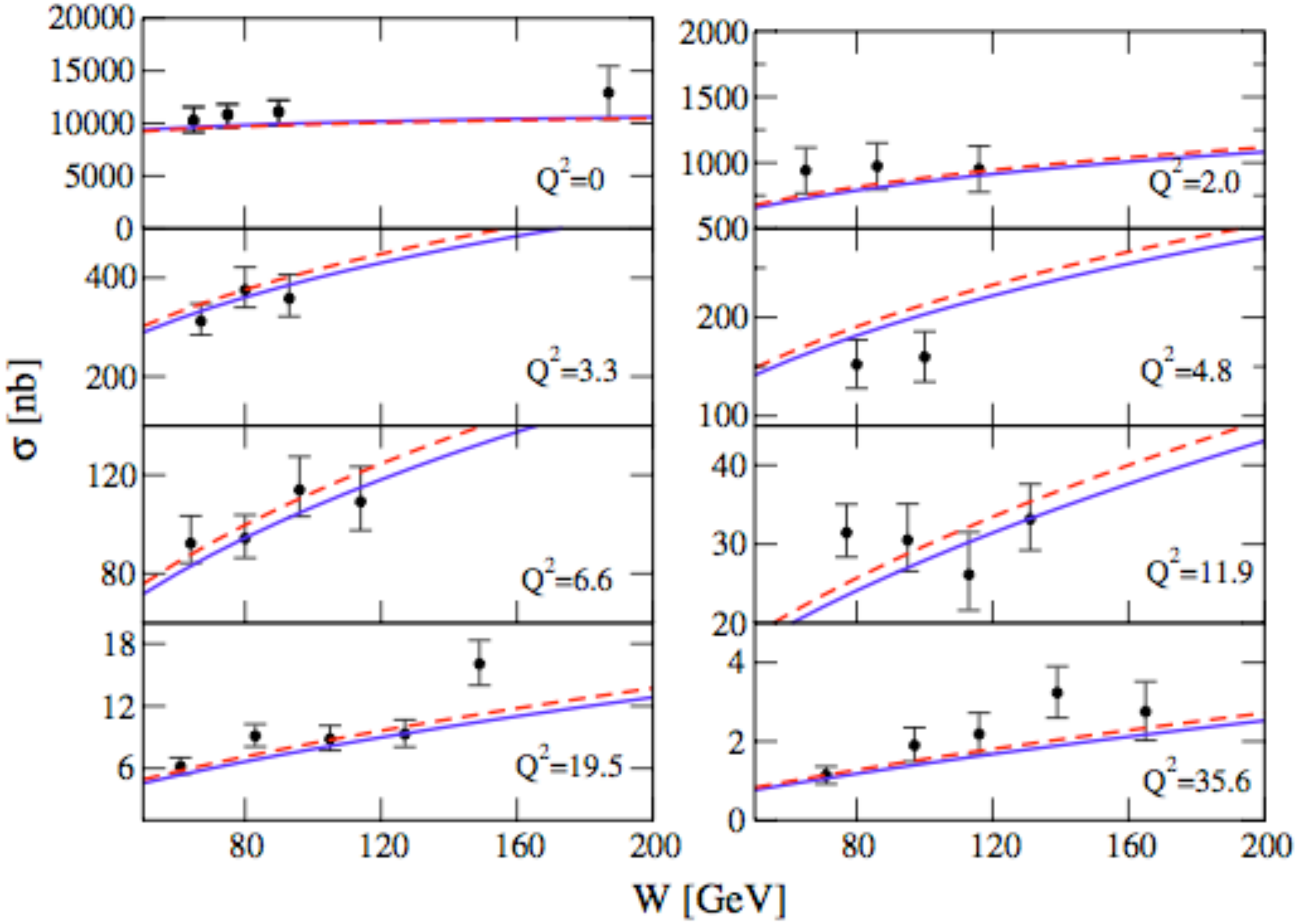


$m_q = 0$

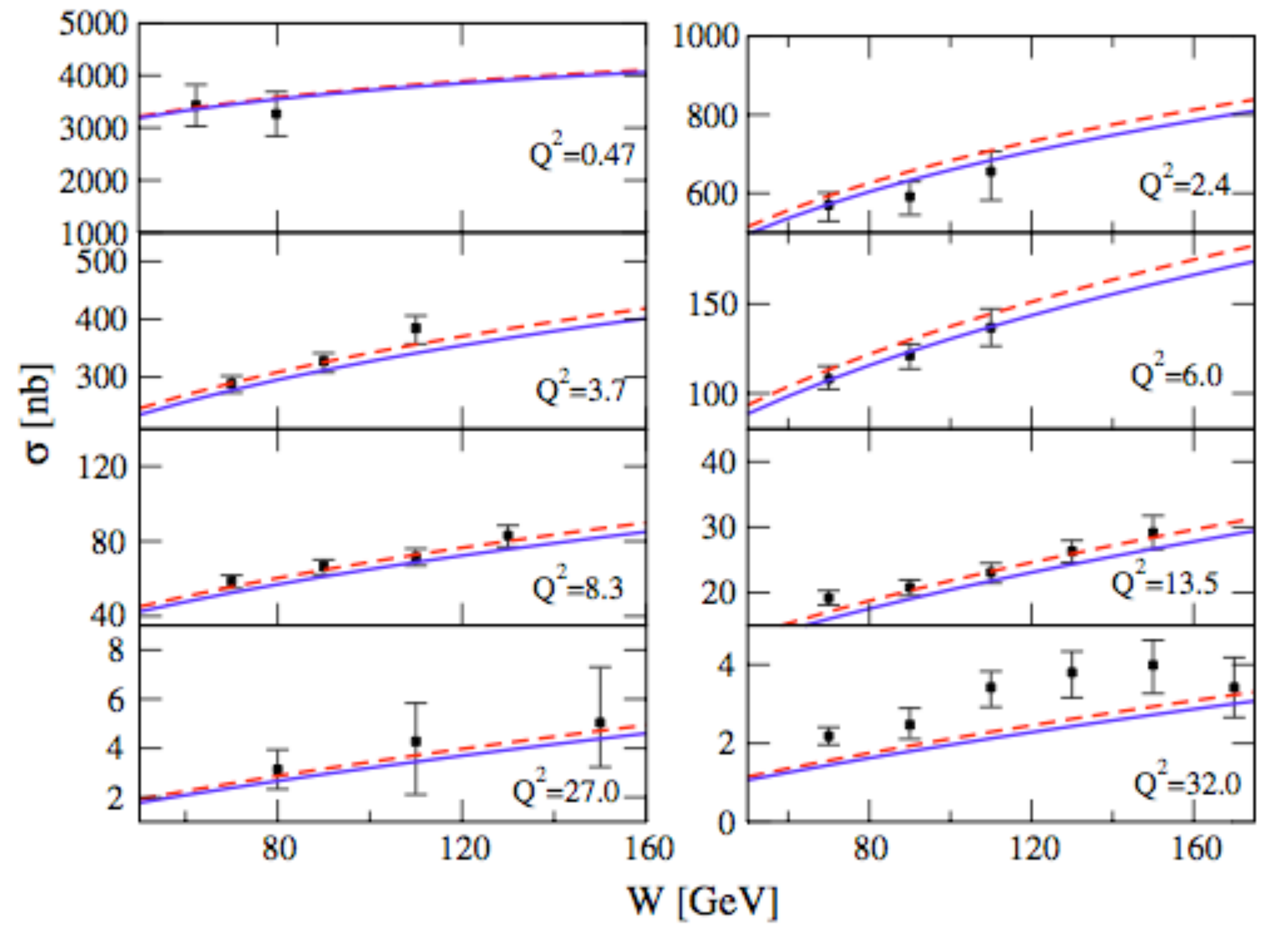
Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

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

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



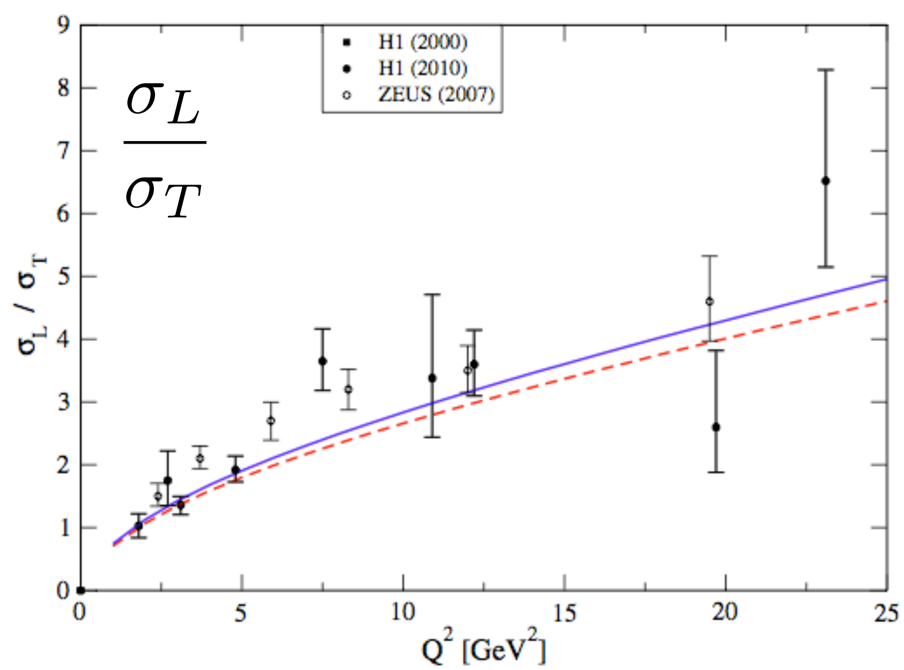
(a) H1



(b) ZEUS

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

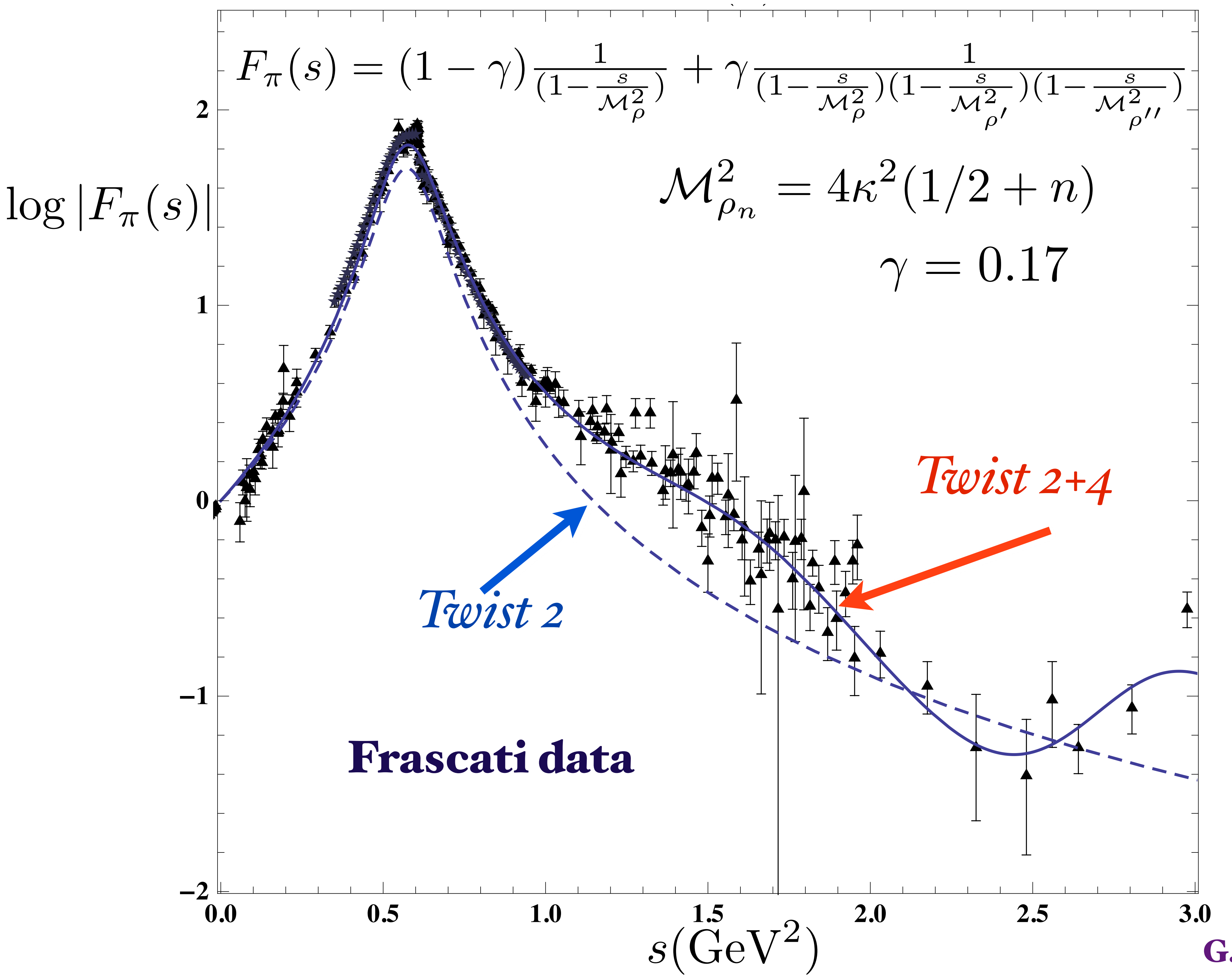
$$\gamma^* p \to \rho^0 p'$$



$$\frac{\sigma_L}{\sigma_T}$$

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

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



Prescription for Timelike poles :

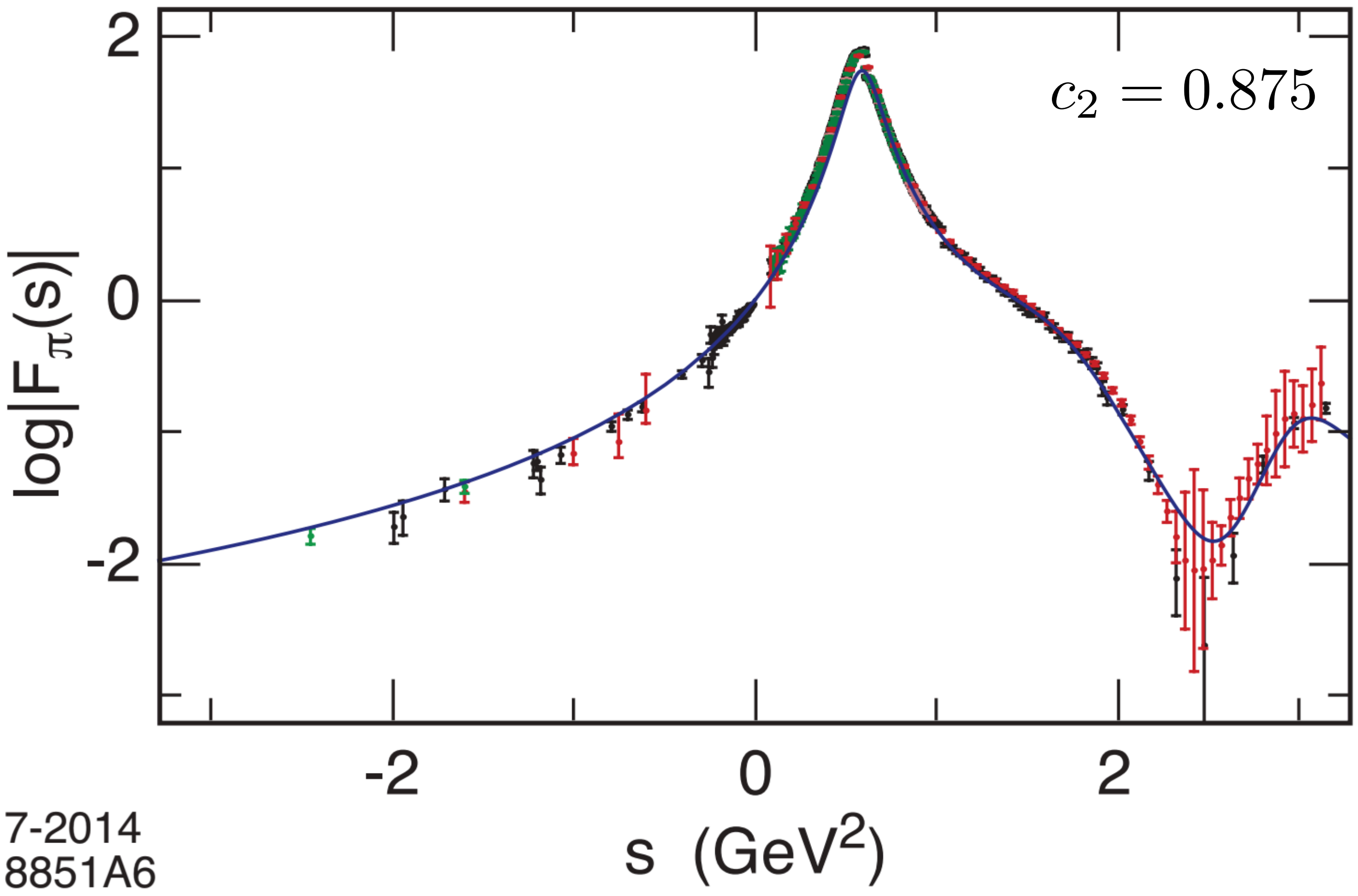
$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb

Pion EM Form Factor

Pion form factor compared with data

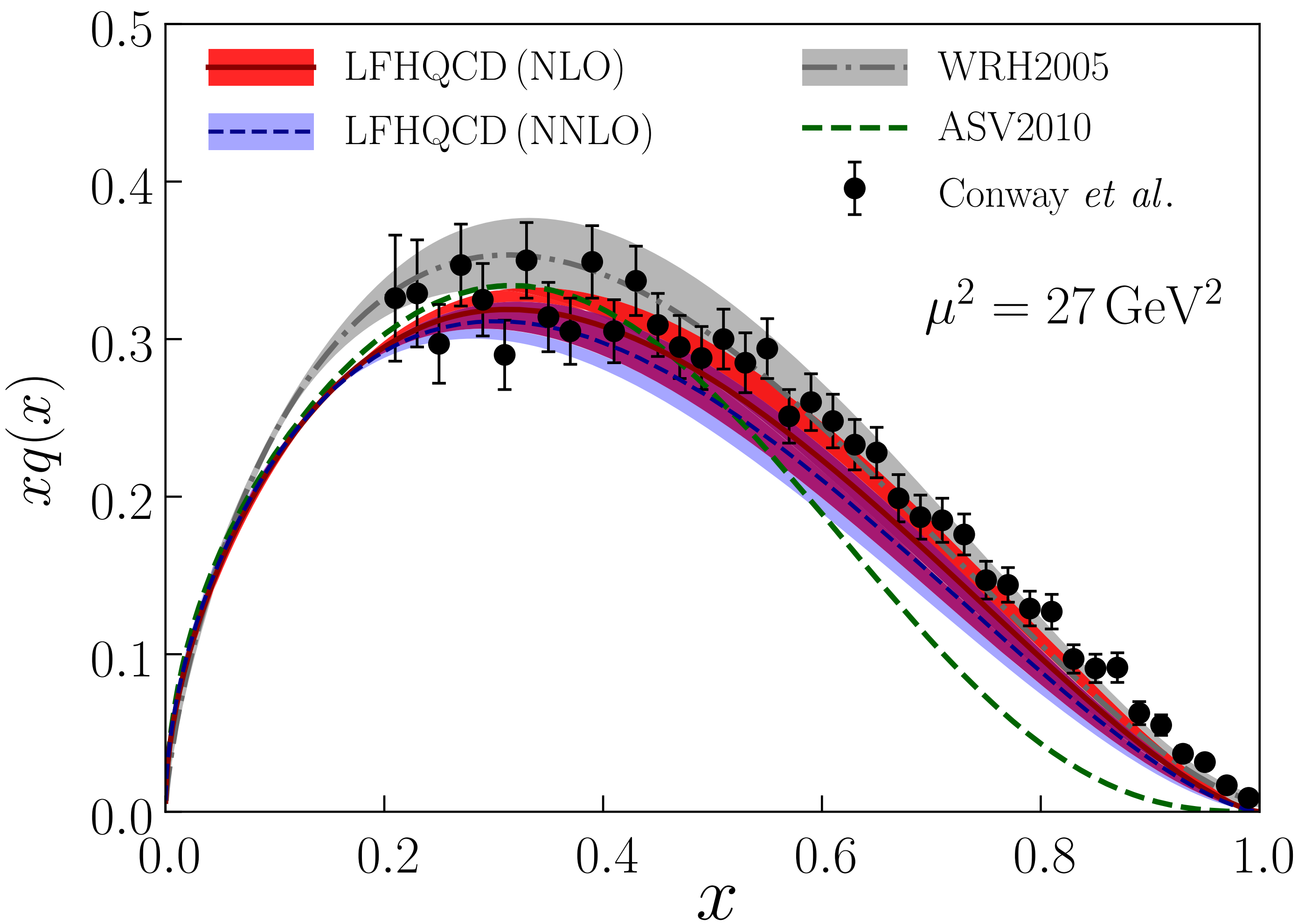


$$F_\pi(t) = \sum_\tau P_\tau F_\tau(t) \qquad \sum_\tau P_\tau = 1$$

Truncated at twist-$\tau = 4$

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

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



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

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

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

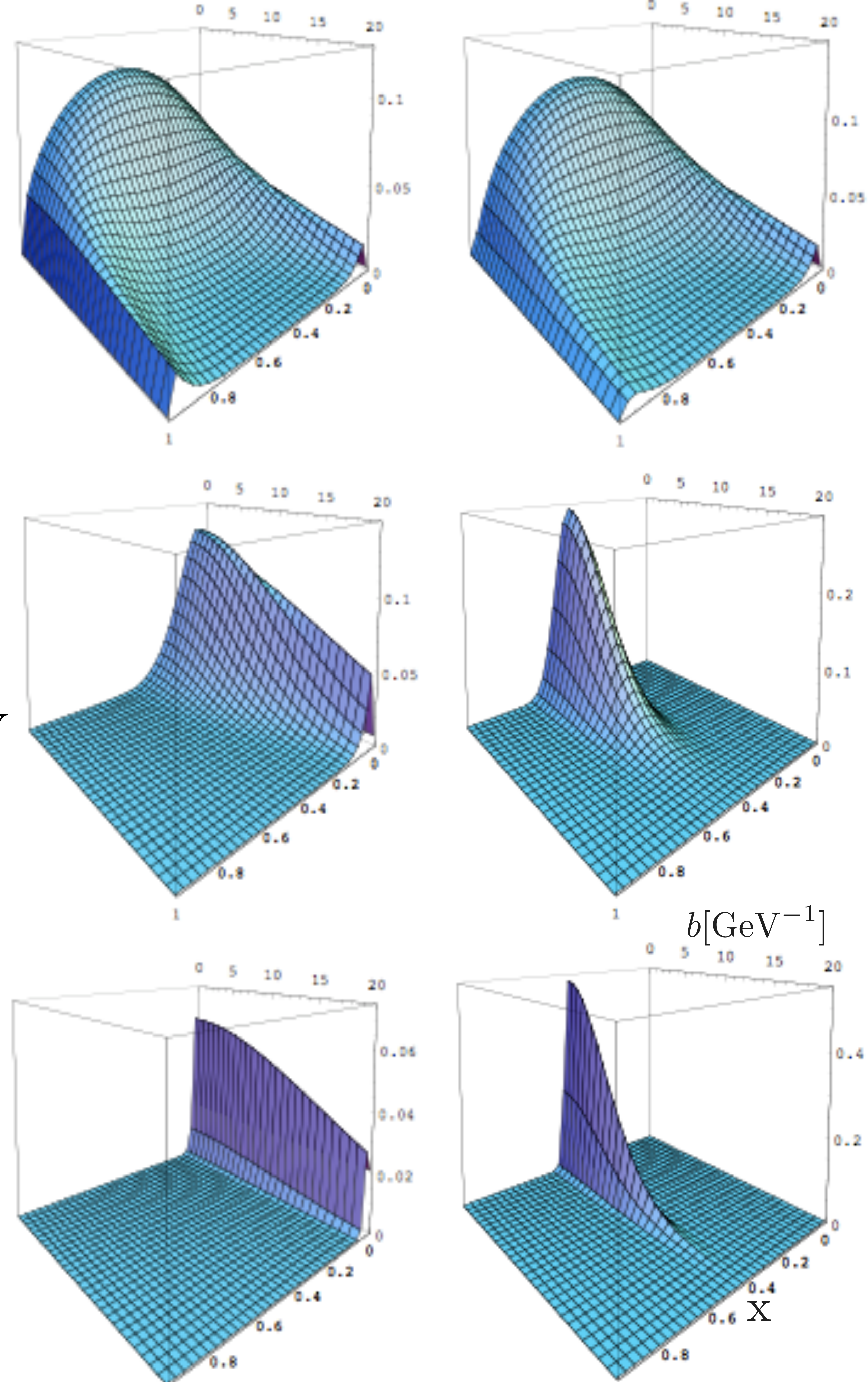
PHYSICAL REVIEW LETTERS 120, 182001 (2018)

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

$m_u = 2\ MeV$
$m_d = 5\ MeV$

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

$m_s = 95\ MeV$



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

$m_c = 1.25\ GeV$

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

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

$m_b = 4.2\ GeV$

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

$\kappa = 375\ MeV$

Polarized PDFs

Spin-aligned and spin-antialigned distributions:

$$q_{\uparrow/\downarrow}(x) = \frac{1}{2}[q(x) \pm \Delta q(x)]$$

Large x limit:

$$q_{\uparrow}(x) \to c_{\tau} q_{\tau}(x) \sim (1-x)^{2\tau-3}$$

$$q_{\downarrow}(x) \to c_{\tau+1} q_{\tau+1}(x) \sim (1-x)^{2\tau-1}$$

Two helicity states tend to a pure contribution from one component.

E.g.: for valence state, τ=3

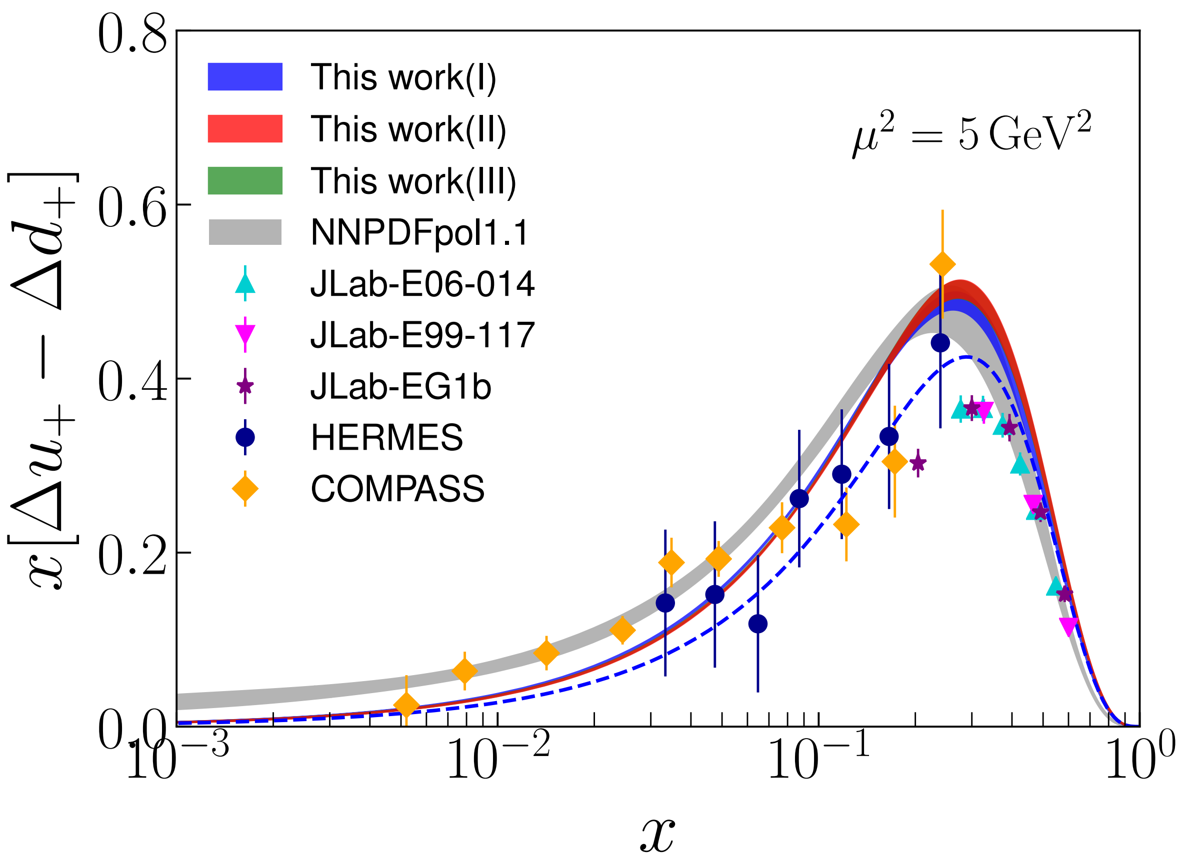
$$q_{\uparrow}(x) \sim (1-x)^{3} \qquad q_{\downarrow}(x) \sim (1-x)^{5}$$

Consistent with pQCD up to logarithmic corrections.

T. Liu, R.S. Suffian, G. De Tèramond, H.G. Dosch, A Deur, sjb

https://arxiv.org/abs/1909.13818

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

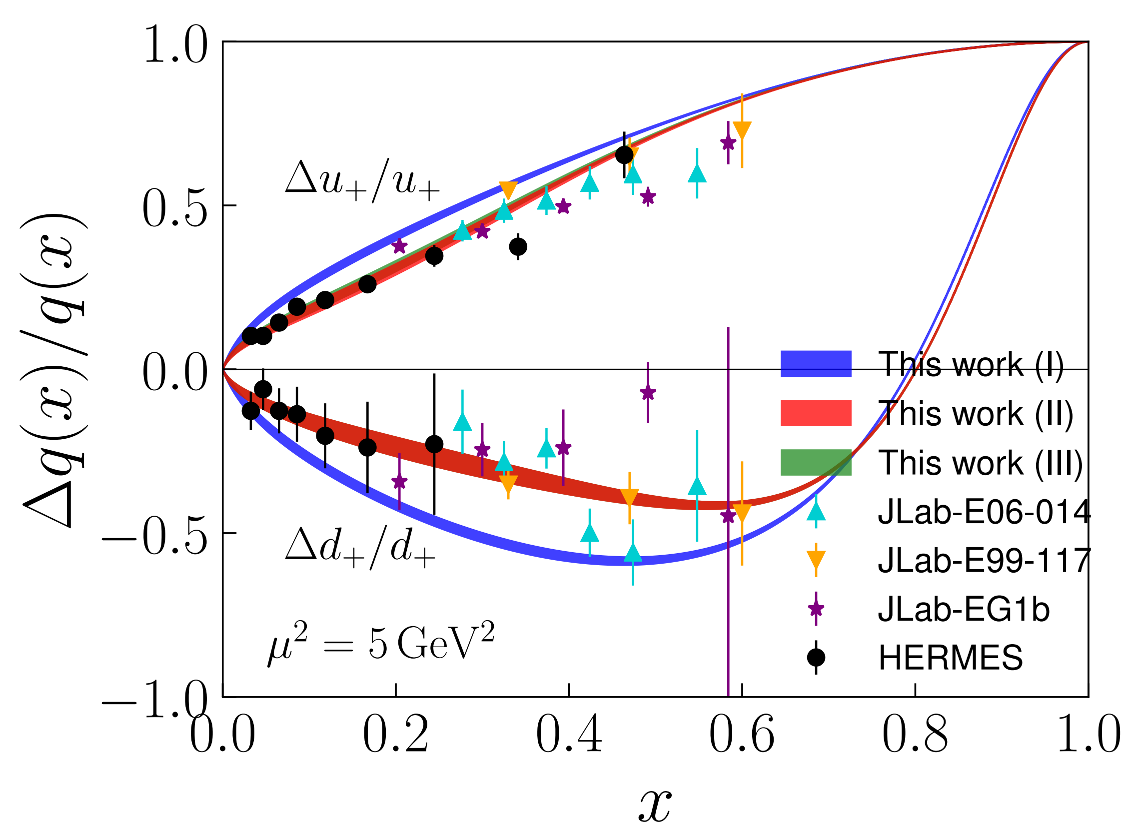


Polarized distributions for the

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

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

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

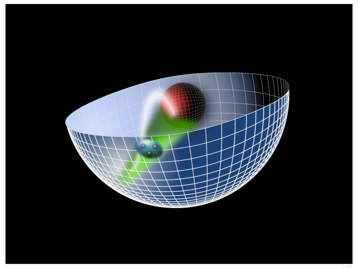


LFHQCD: Underlying Principles

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

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

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



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

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

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

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

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

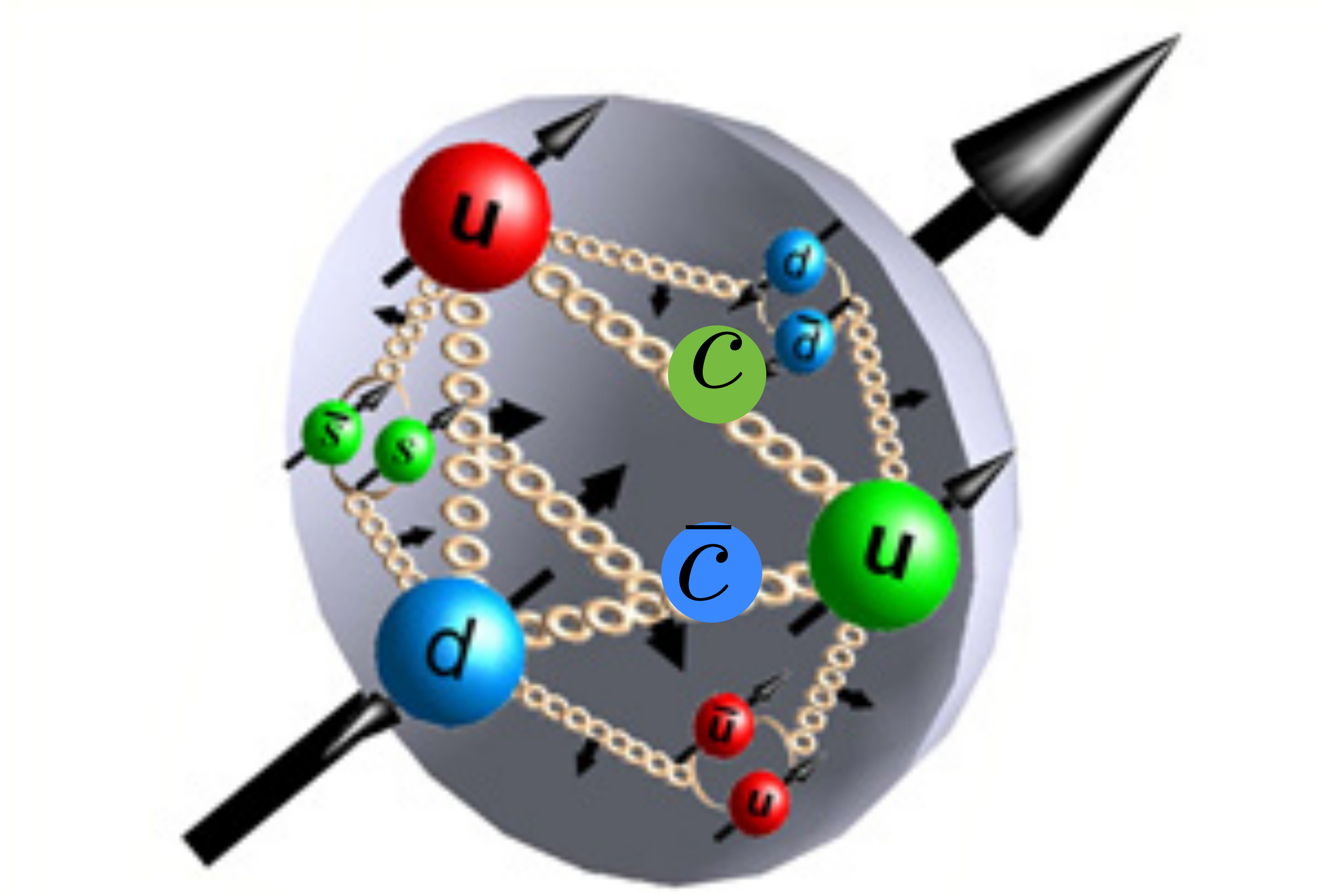
$$\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]$$

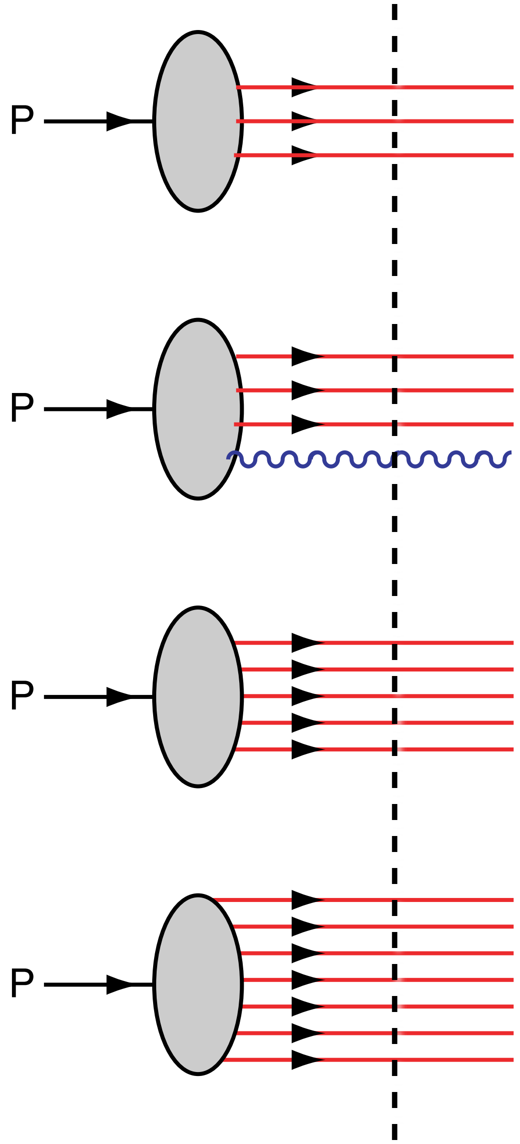
Wavefunction at fixed LF time: Arbitrarily Off-Shell in Invariant Mass

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

Higher Fock States of the Proton:

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





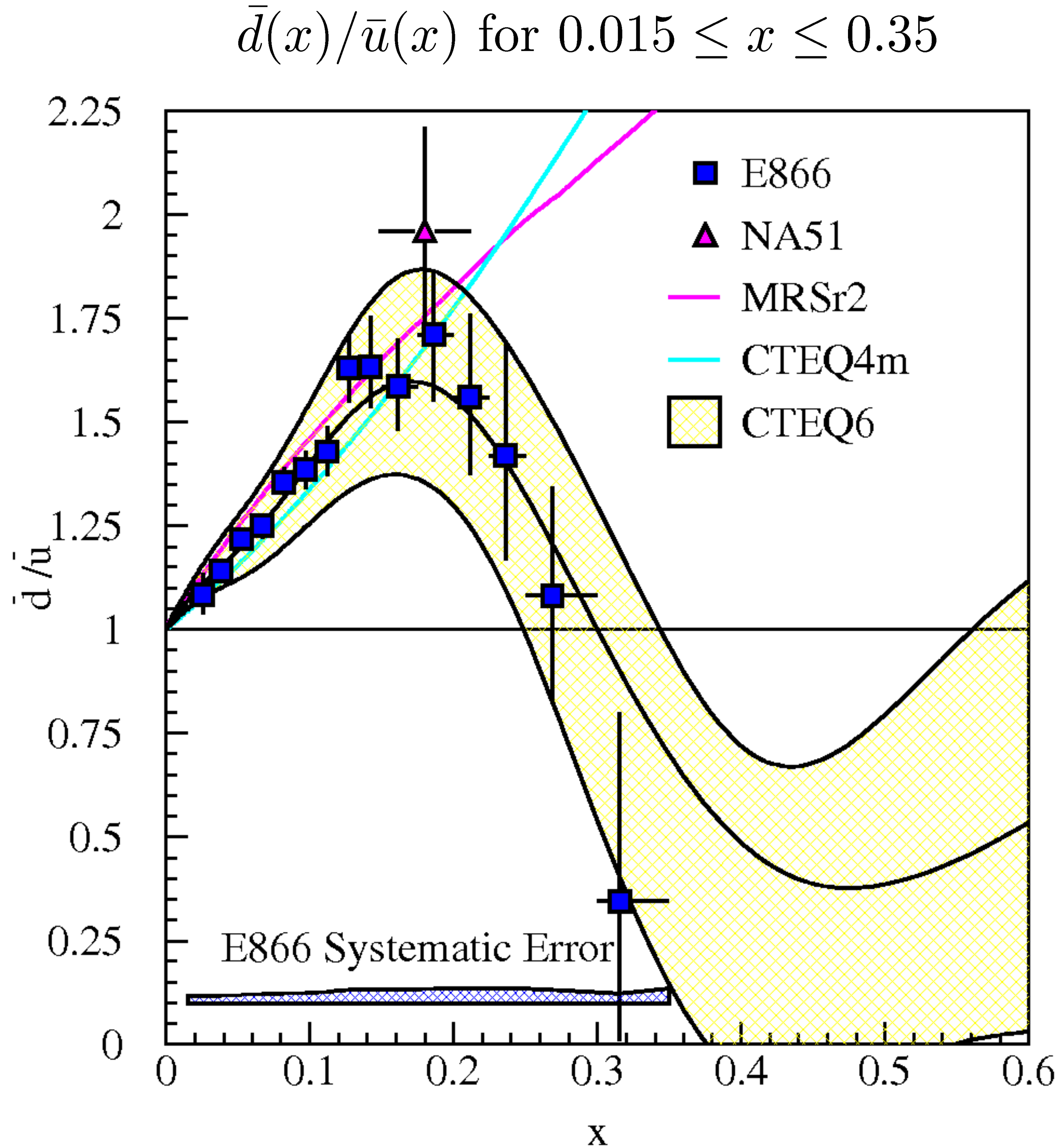
Eigenstate of LF Hamiltonian : all Fock states contribute
Off-shell in invariant mass

■ E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$

Interactions of quarks at same rapidity in 5-quark Fock state

Intrinsic sea quarks



Do heavy quarks exist in the proton at high x?

Conventional wisdom: impossible!

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

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

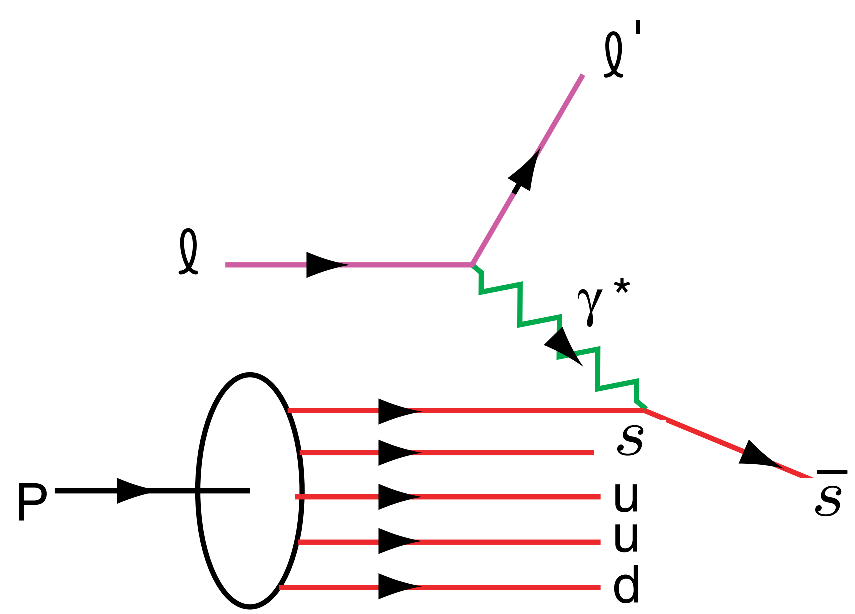
$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

Measure strangeness distribution in Semi-Inclusive DIS at JLab

$$\text{Is } s(x) = \bar{s}(x)?$$

- **Non-symmetric strange and antistrange sea?**
- **Non-perturbative physics; e.g** $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- **Important for interpreting NuTeV anomaly** **B. Q. Ma, sjb**

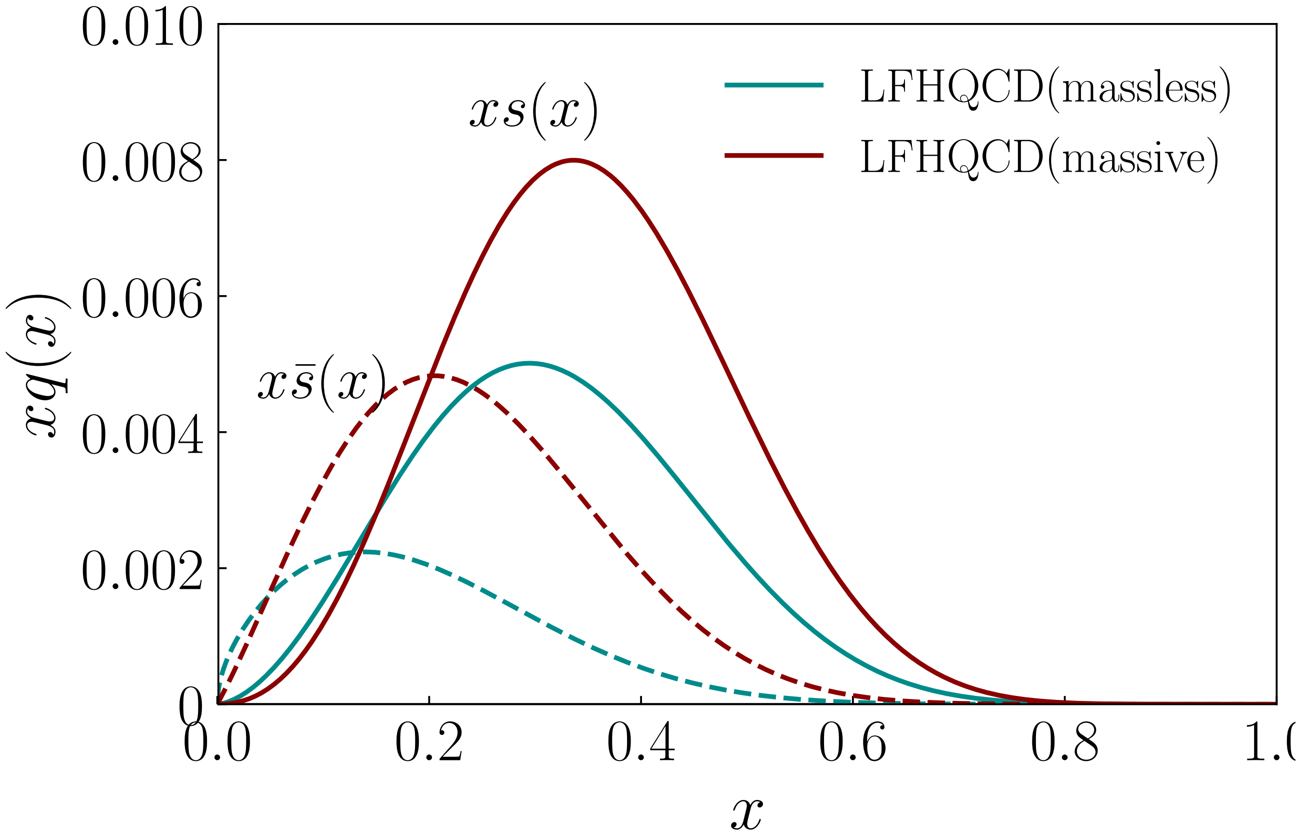


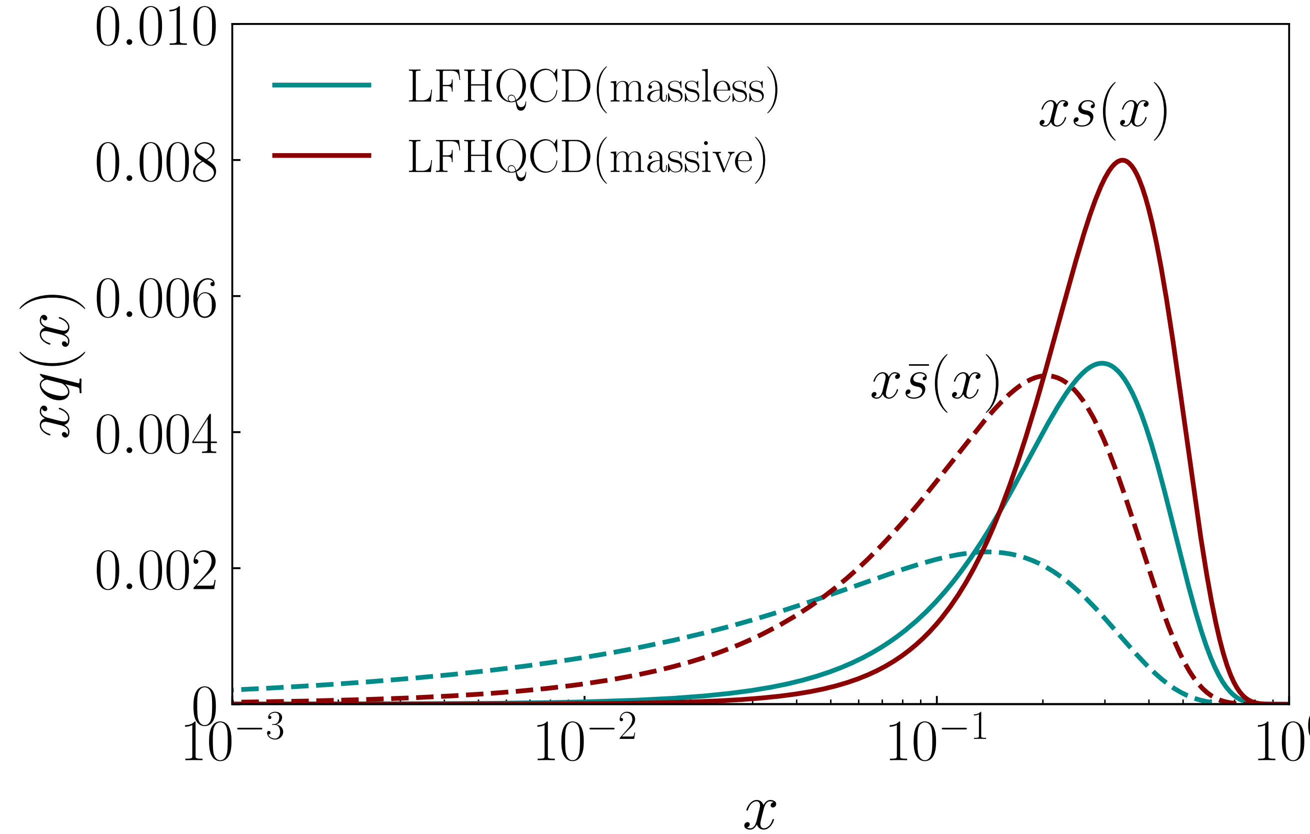
Tag struck quark flavor in semi-inclusive DIS $ep \to e' K^+ X$

Strange and Antistrange Distributions

Input: nonzero lattice axial form factor

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



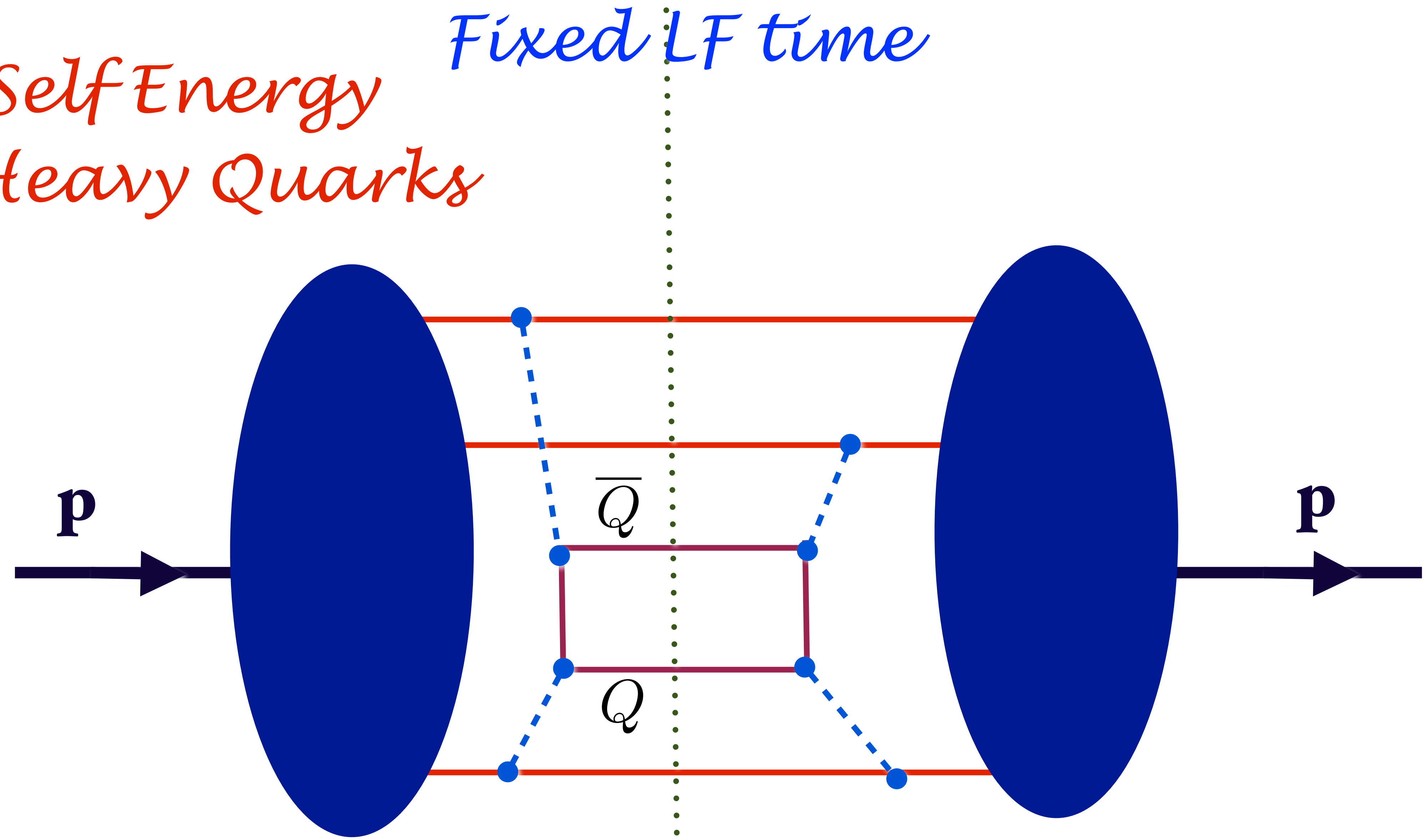


Phys. Rev. D 98, 114004 (2018).

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

Hoyer, Peterson, Sakai, sjb

Proton Self Energy
Intrinsic Heavy Quarks



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

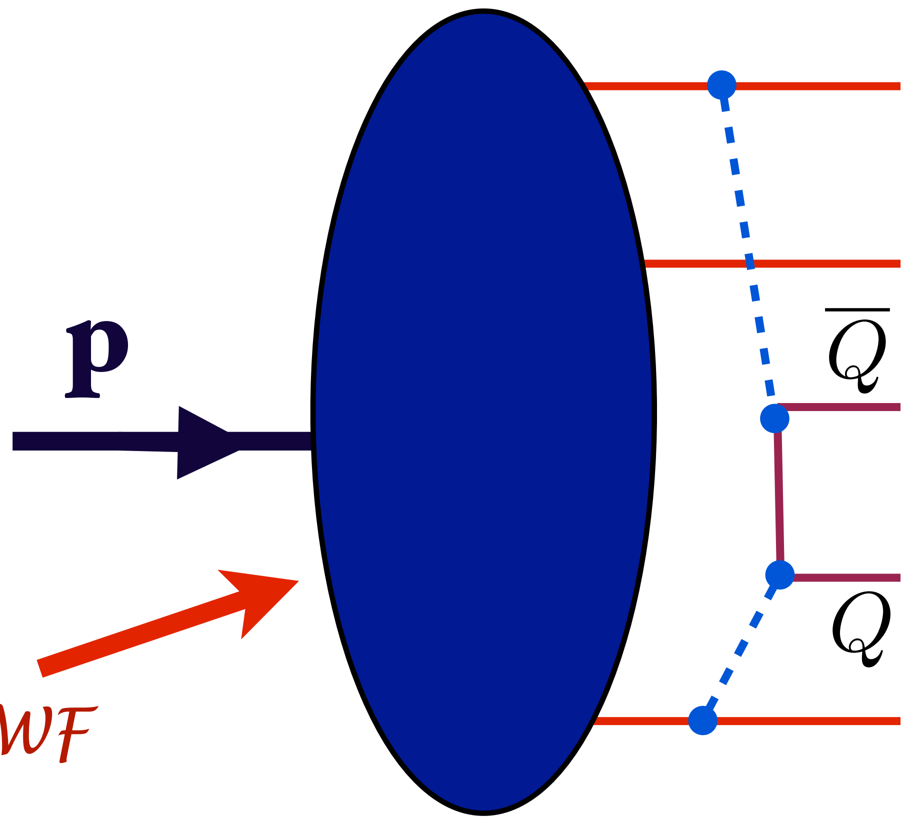
Rigorous OPE Analysis

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

Fixed LF time

Proton 5-quark Fock State :
Intrinsic Heavy Quarks

$g \to Q\bar{Q}$ at low x: High $\mathcal{M}^2$



Use AdS/QCD LFWF

QCD predicts Intrinsic Heavy Quarks at high x!

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

Minimal off-shellness!

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

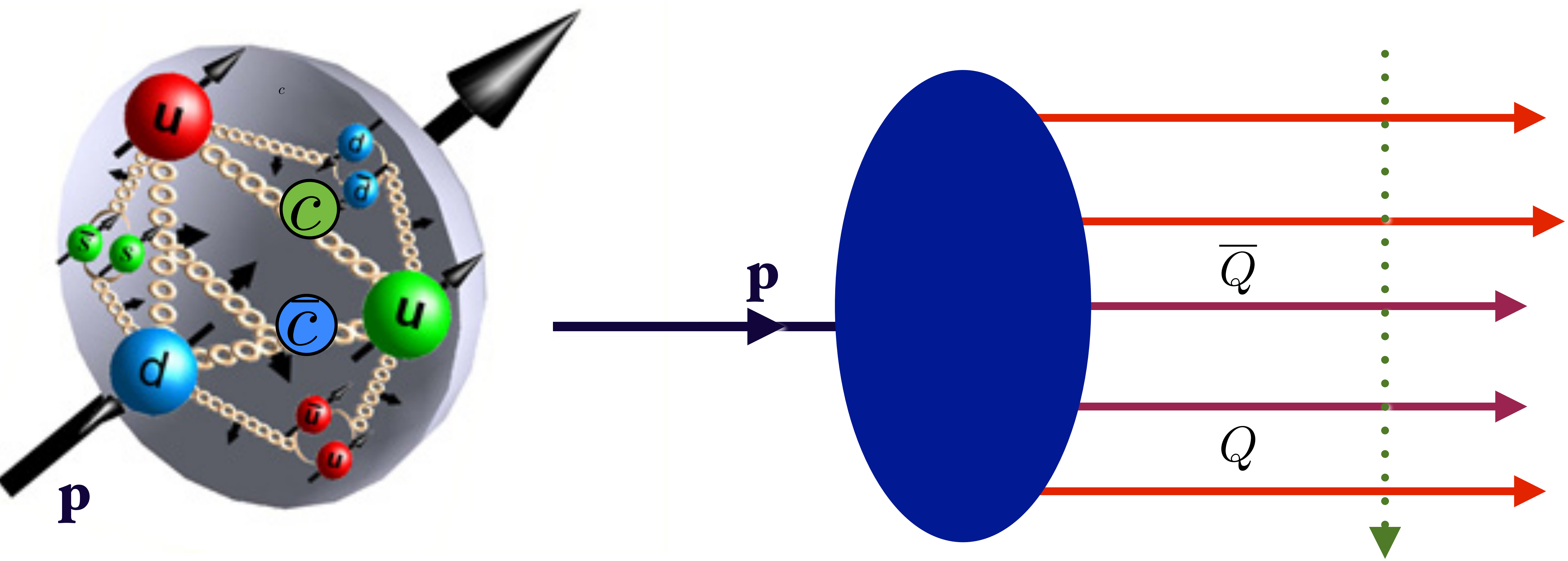
Probability (QCD) $\propto \frac{1}{M_Q^2}$

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

Color confinement potential from AdS/QCD

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

Fixed $\tau = t + z/c$

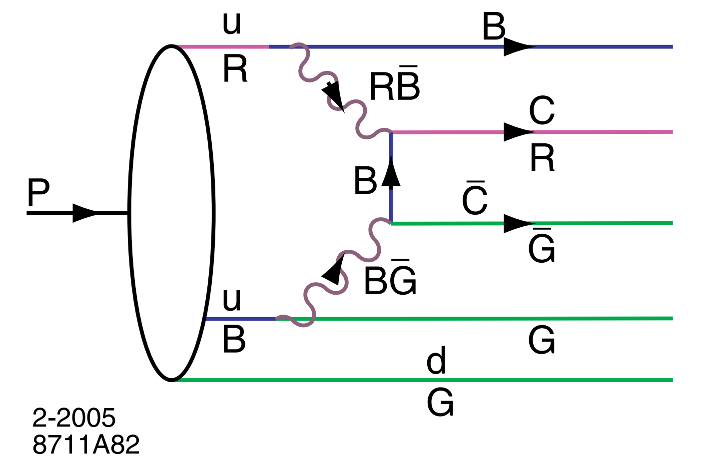


$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}} \, e^{-\mathcal{M}_n^2/2\kappa^2} \, \Pi_{j=1}^{n} \frac{1}{\sqrt{x_j}}$$

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

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

Intrinsic Heavy-Quark Fock States



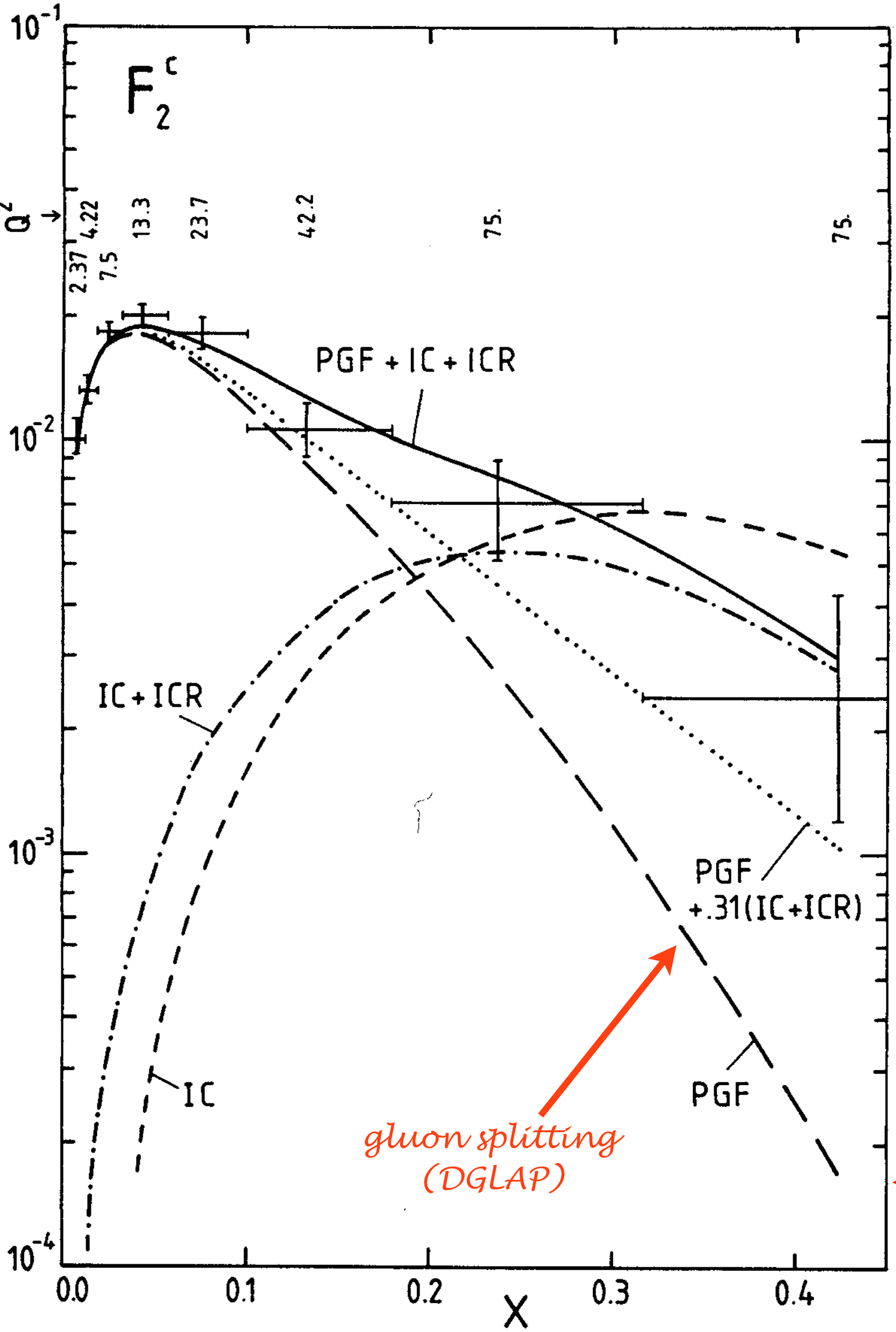
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production at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

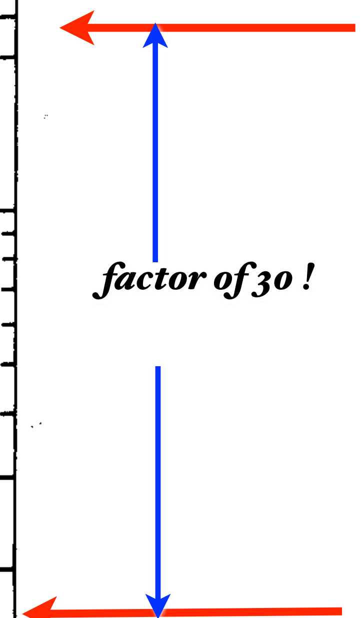
Measurement of Charm Structure Function!

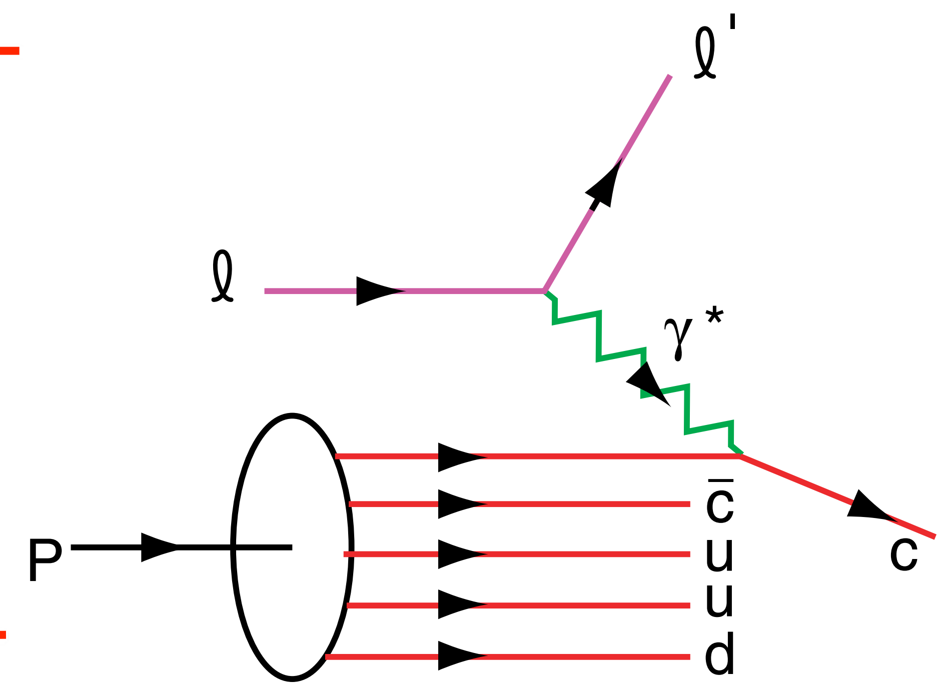
J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm

Hoyer, Peterson, Sakai, sjb







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

Two Components (separate evolution):

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

Measurement of Charm Structure Function!

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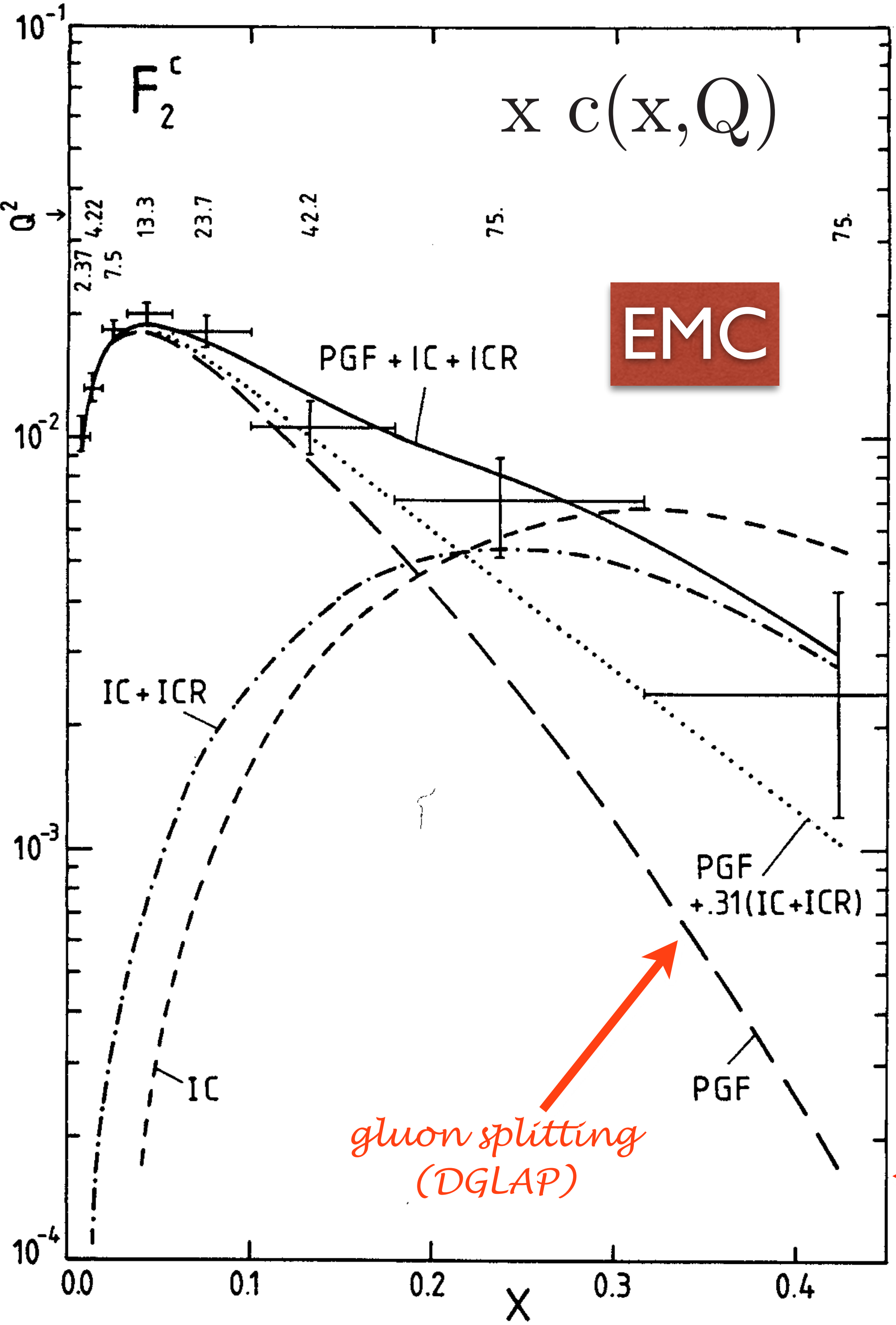
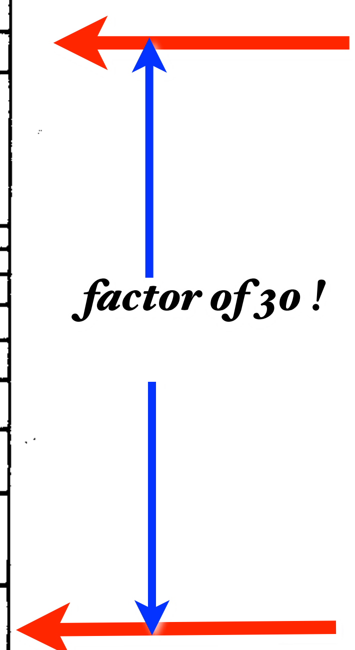
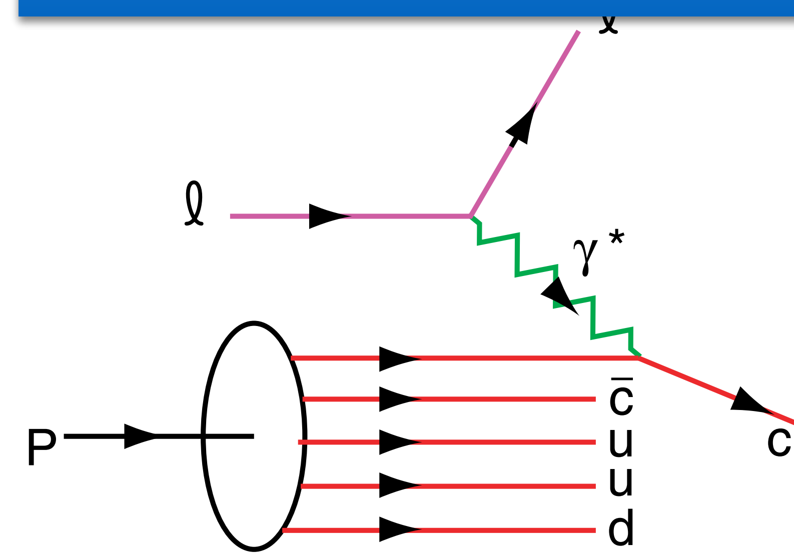




Evidence for Intrinsic Charm

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

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



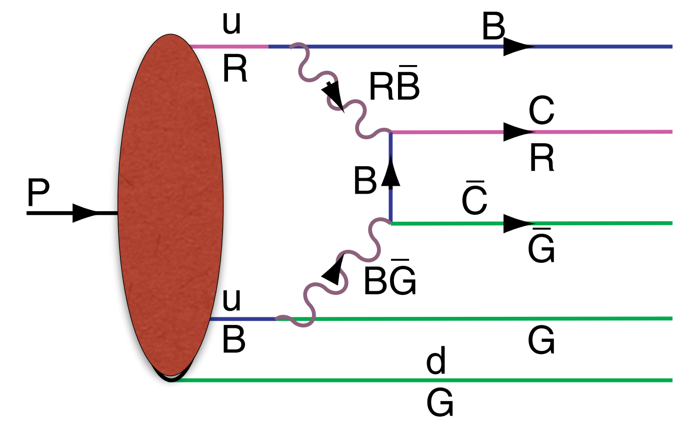
DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

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

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock states



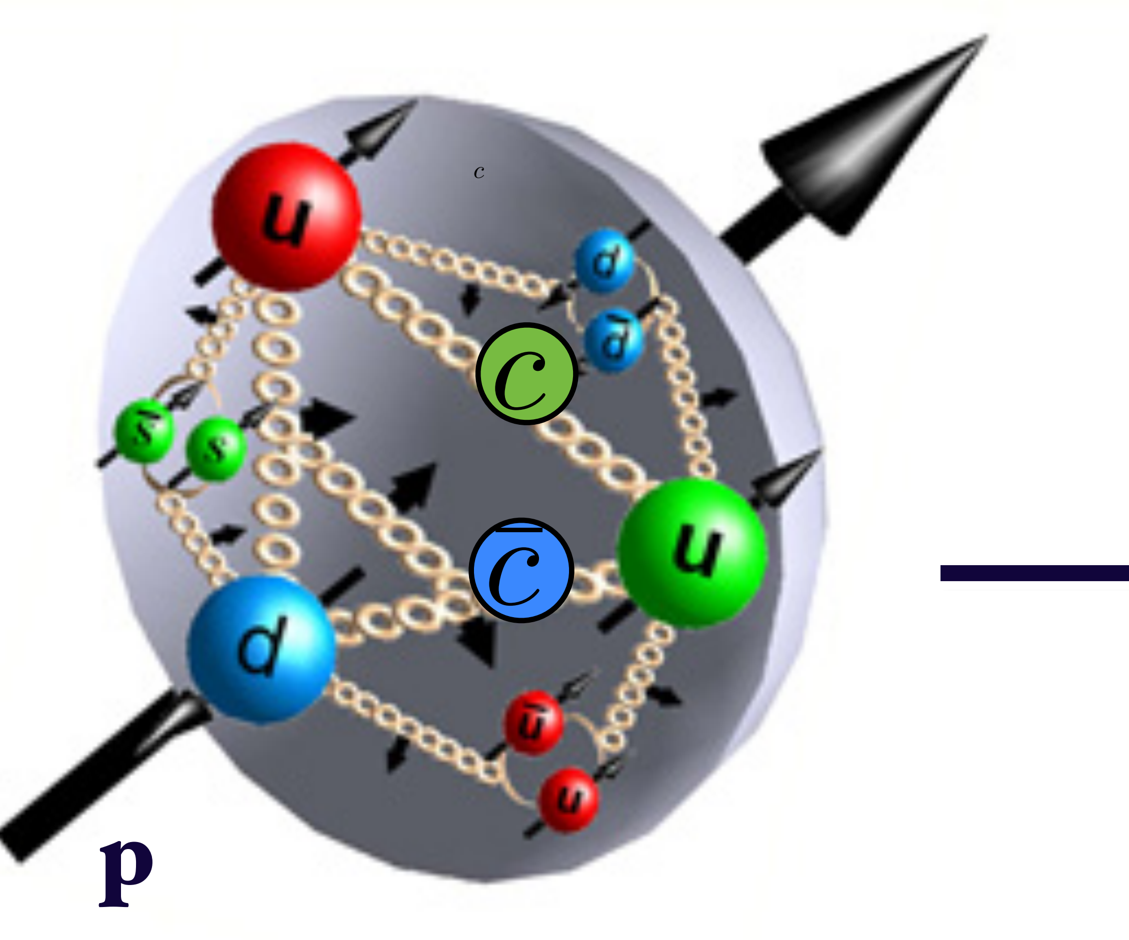
- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs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

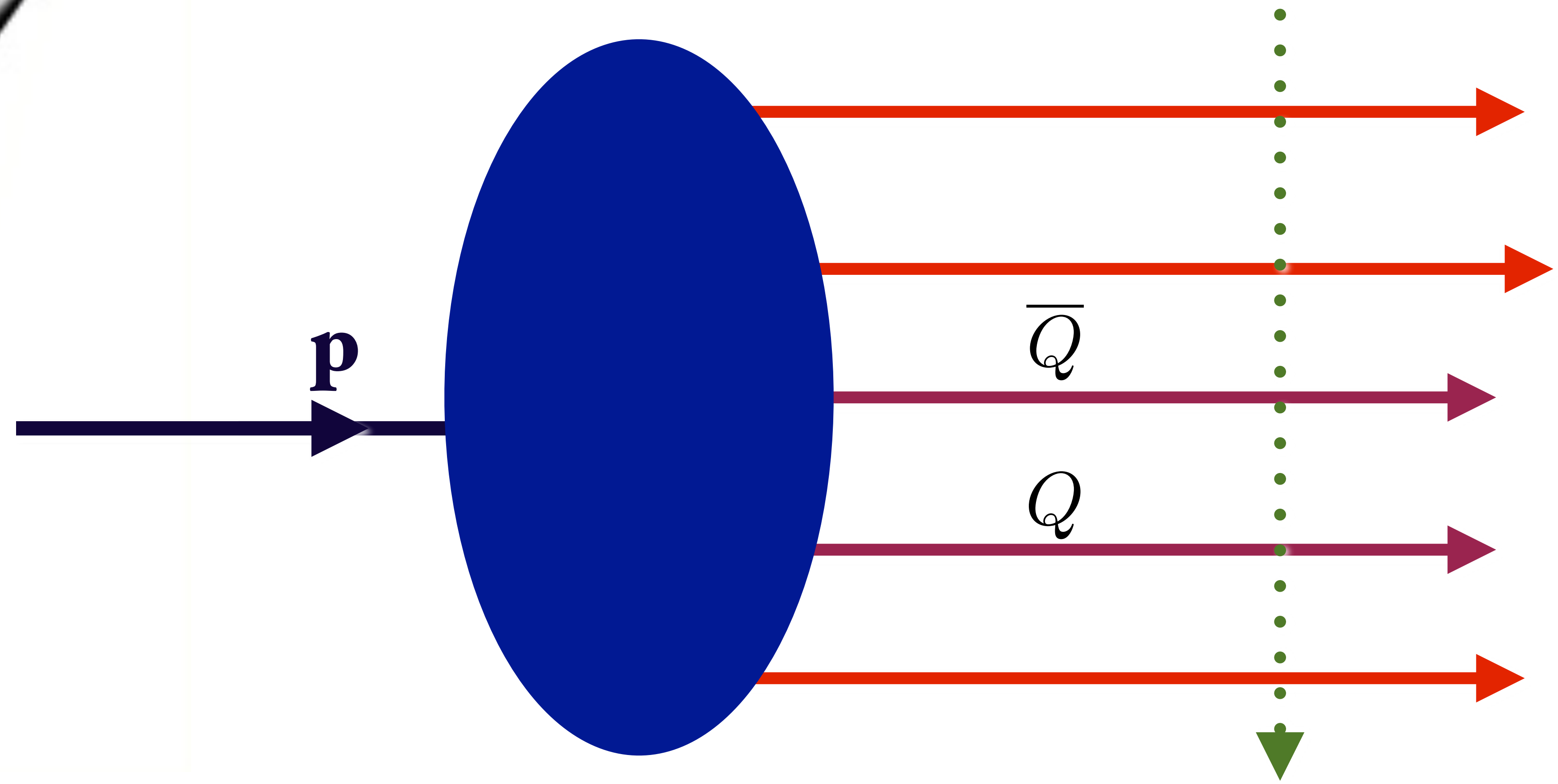
OPE: Collins, S. Ellis, Gunion, Mueller, sjb
Franz, Goecke, M. Polyakov,

Color confinement potential from AdS/QCD

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

Fixed $\tau = t + z/c$





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

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

Minimally Off-Shell

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

Properties of Color-Confining LFWF

- minimal $\quad \mathcal{M}_n^2 = \sum_{i=1}^{n} (\frac{k_\perp^2 + m^2}{x})_i$
- Maximum when $\quad x_i = \propto \;\; m_{\perp i} = \sqrt{m_i^2 + k_{\perp i}^2}$
- Maximum overlap at matching rapidity

$$y = \frac{1}{2} \log \frac{k^+}{k^-} = \log \frac{x P^+}{m_\perp}$$

Frame independent $\quad \Delta y = y_a - y_b = \log \frac{x_a}{m_{\perp a}} - \log \frac{x_b}{m_{\perp b}}$

Relative to proton $\quad \Delta y = y_H - y_p = \log \frac{x_H}{m_{\perp H}/m_p}$

Feynman: Correlations with proton Δy < 2

Properties of Non-Perturbative Five-Quark Fock-State

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

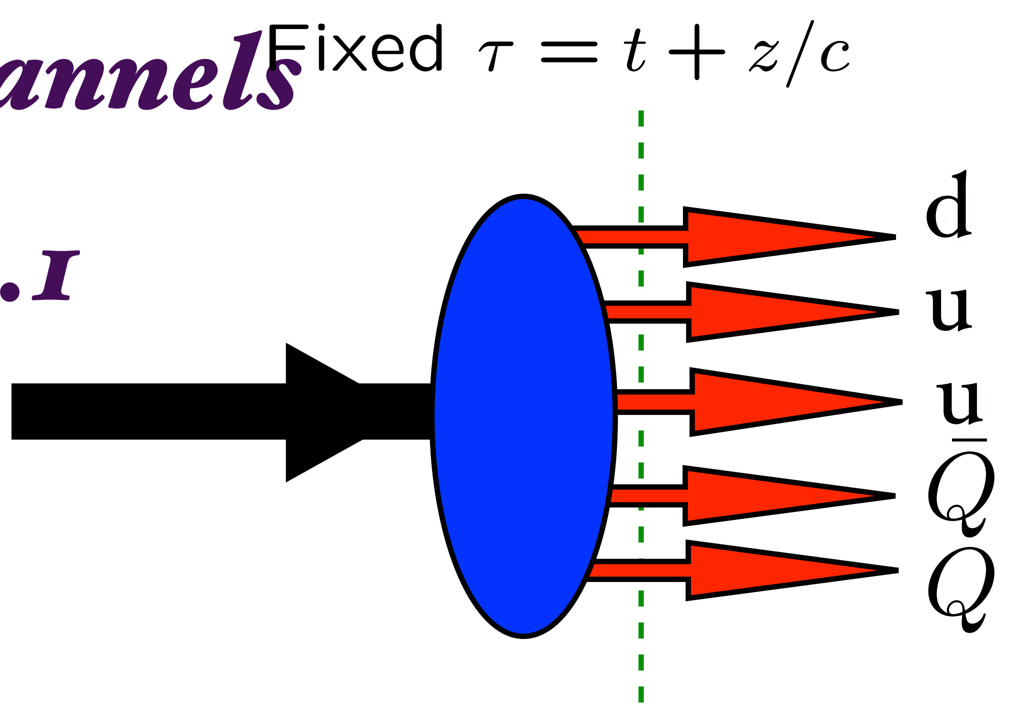
- ***Heavy quarks have most of the LF momentum*** $<x_Q> \propto \sqrt{m_Q^2 + k_\perp^2}$

- ***Correlated with proton quantum numbers***

- ***Duality with meson-baryon channels***

- ***strangeness asymmetry at x > 0.1***

- ***Maximally energy efficient***



Heavy quark mass expansion and intrinsic charm in light hadrons.

M. Franz (Ruhr U., Bochum), Maxim V. Polyakov (Ruhr U., Bochum & St. Petersburg, INP), K. Goeke (Ruhr U., Bochum).

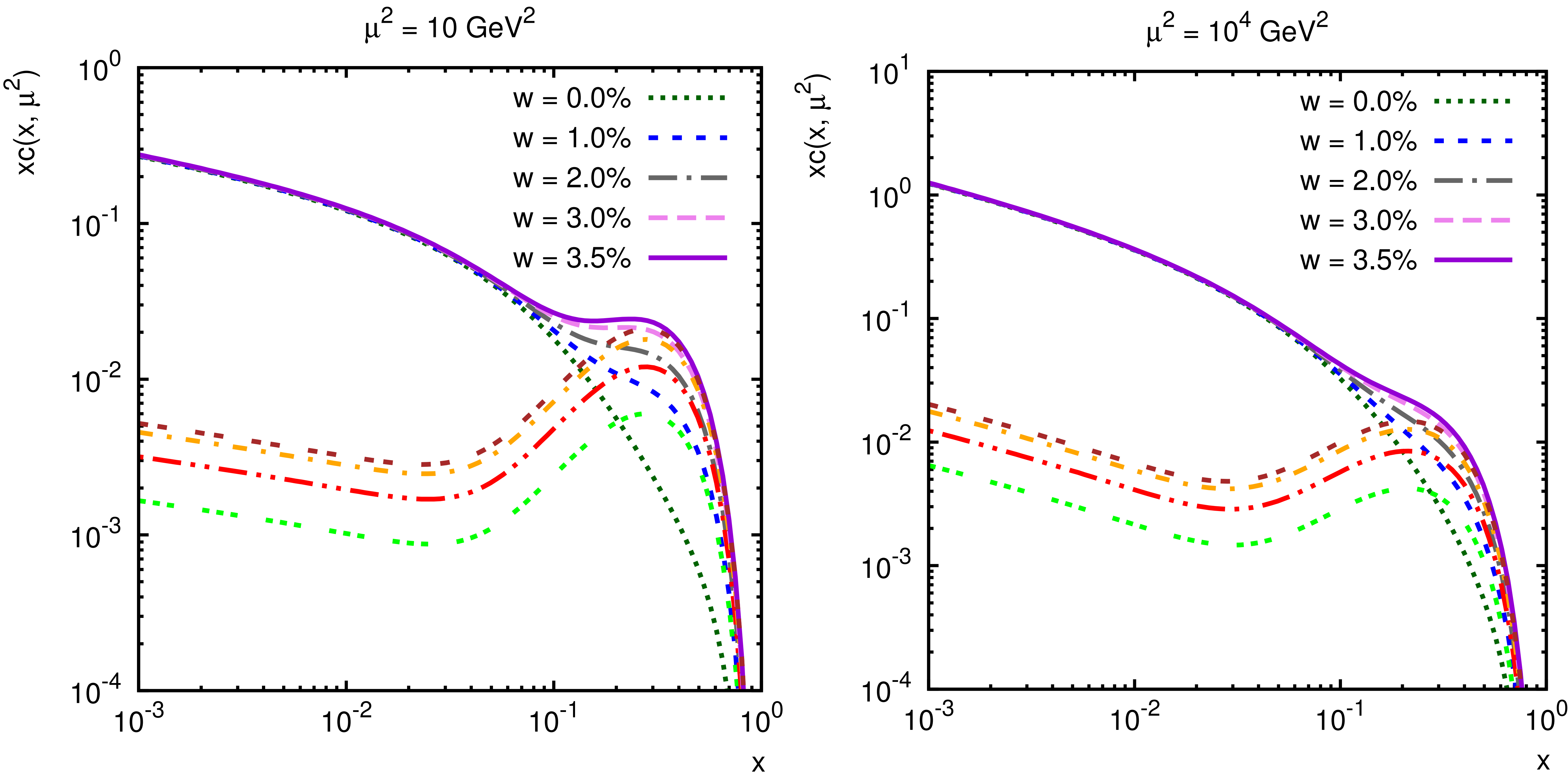
Feb 2000

Phys.Rev. D62 (2000) 074024
e-Print: **hep-ph/0002240**

Abstract: We review the technique of heavy quark mass expansion of various operators made of heavy quark fields using a semiclassical approximation. It corresponds to an operator product expansion in the form of series in the inverse heavy quark mass. This technique applied recently to the axial current is used to estimate the charm content of the η, η' mesons and the intrinsic charm contribution to the proton spin. The derivation of heavy quark mass expansion for $\bar{Q}\gamma_5 Q$ is given here in detail and the expansions of the scalar, vector and tensor current and of a contribution to the energy-momentum tensor are presented as well. The obtained results are used to estimate the intrinsic charm contribution to various observables.

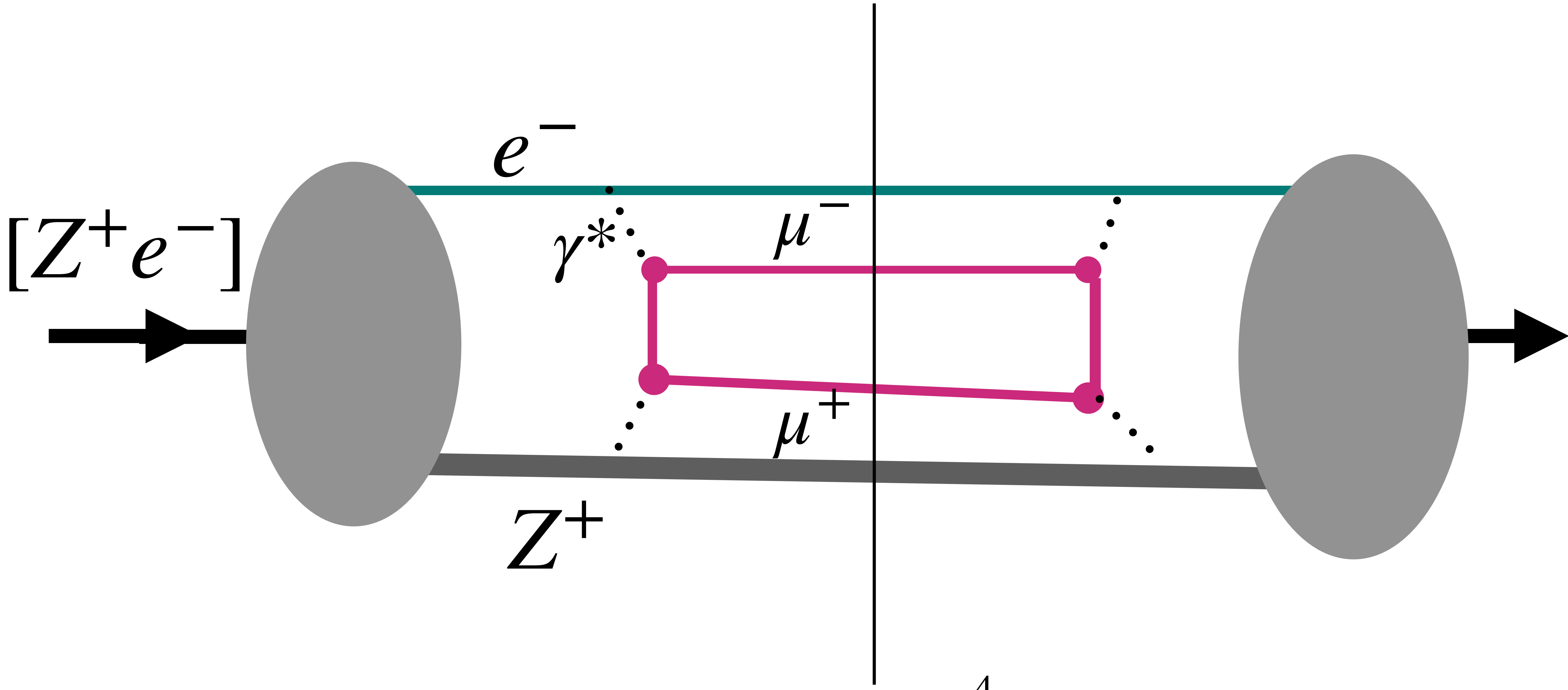
Bednyakov, Lykasov, Smiesko, Tokar, sjb

$$xc(x, \mu^2)$$



$$w = P_{c\bar{c}}^{intrinsic}$$

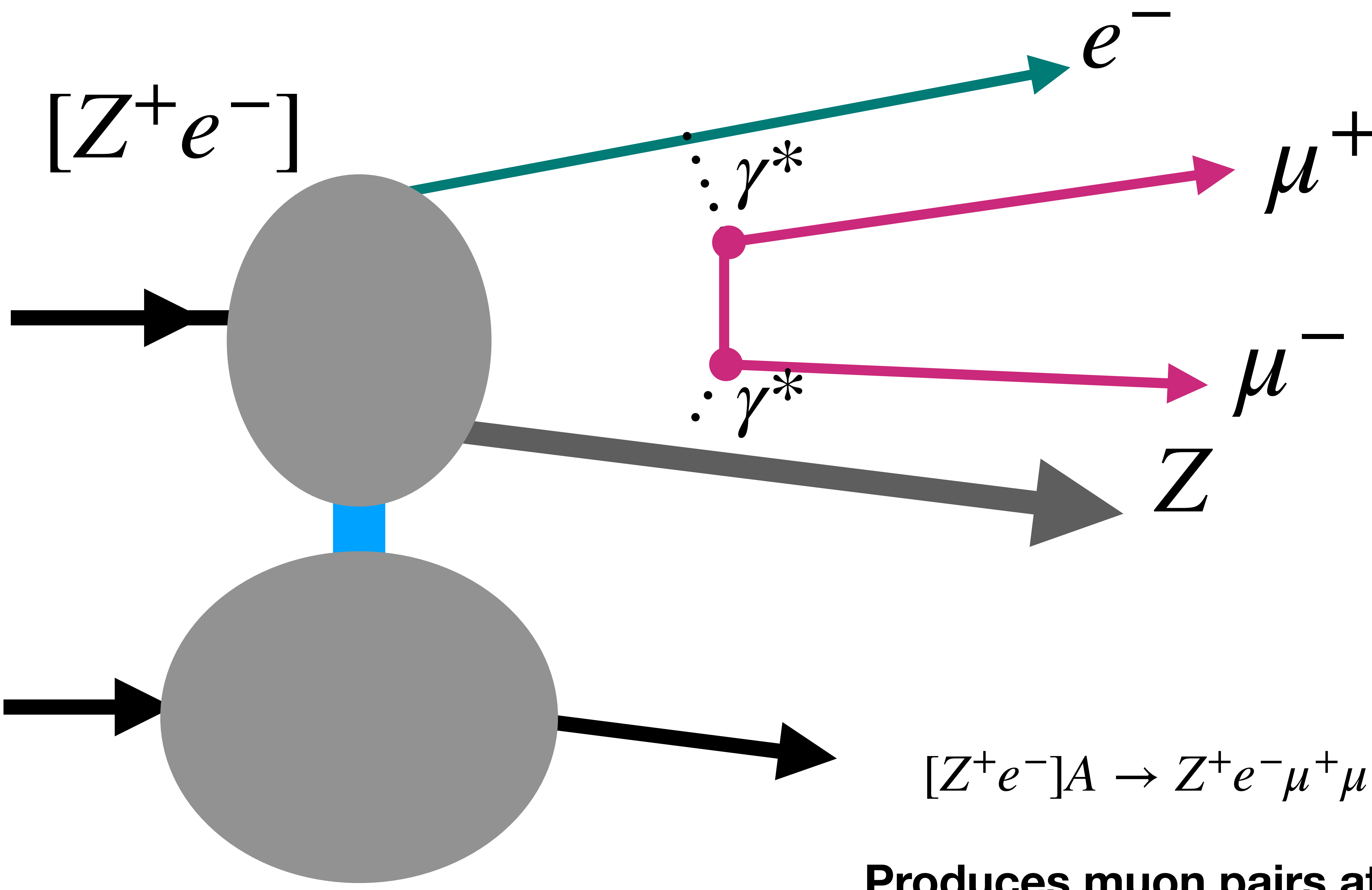
Intrinsic Muons in Electronic Atomic Self Energy



$$\mathcal{M} \propto (Z\alpha^2)\frac{\kappa_B^4}{m_\mu^4}$$

$$\text{Bohr momentum } \kappa_B = Z\alpha m_\mu$$

Intrinsic Muons Produced from Dissociation of Electronic Atoms

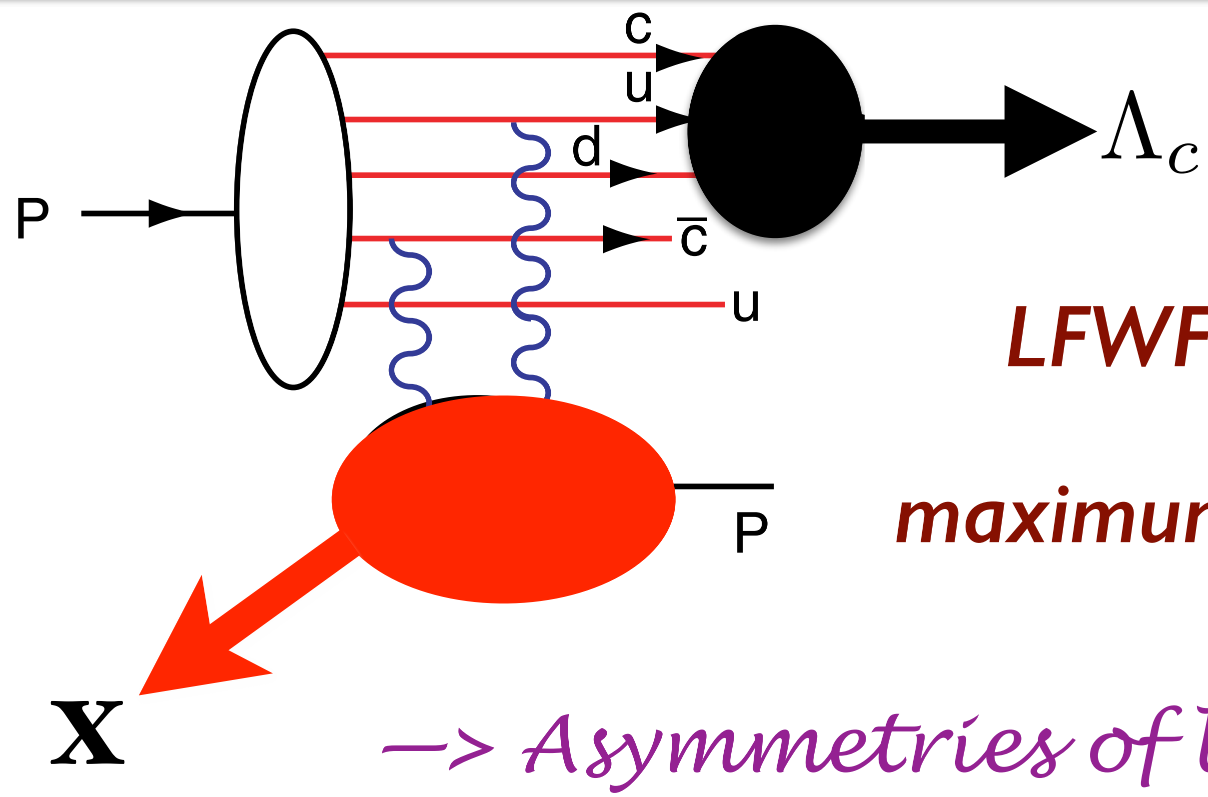


$$[Z^+e^-]A \to Z^+e^-\mu^+\mu^-A'$$

Produces muon pairs at high x_F

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

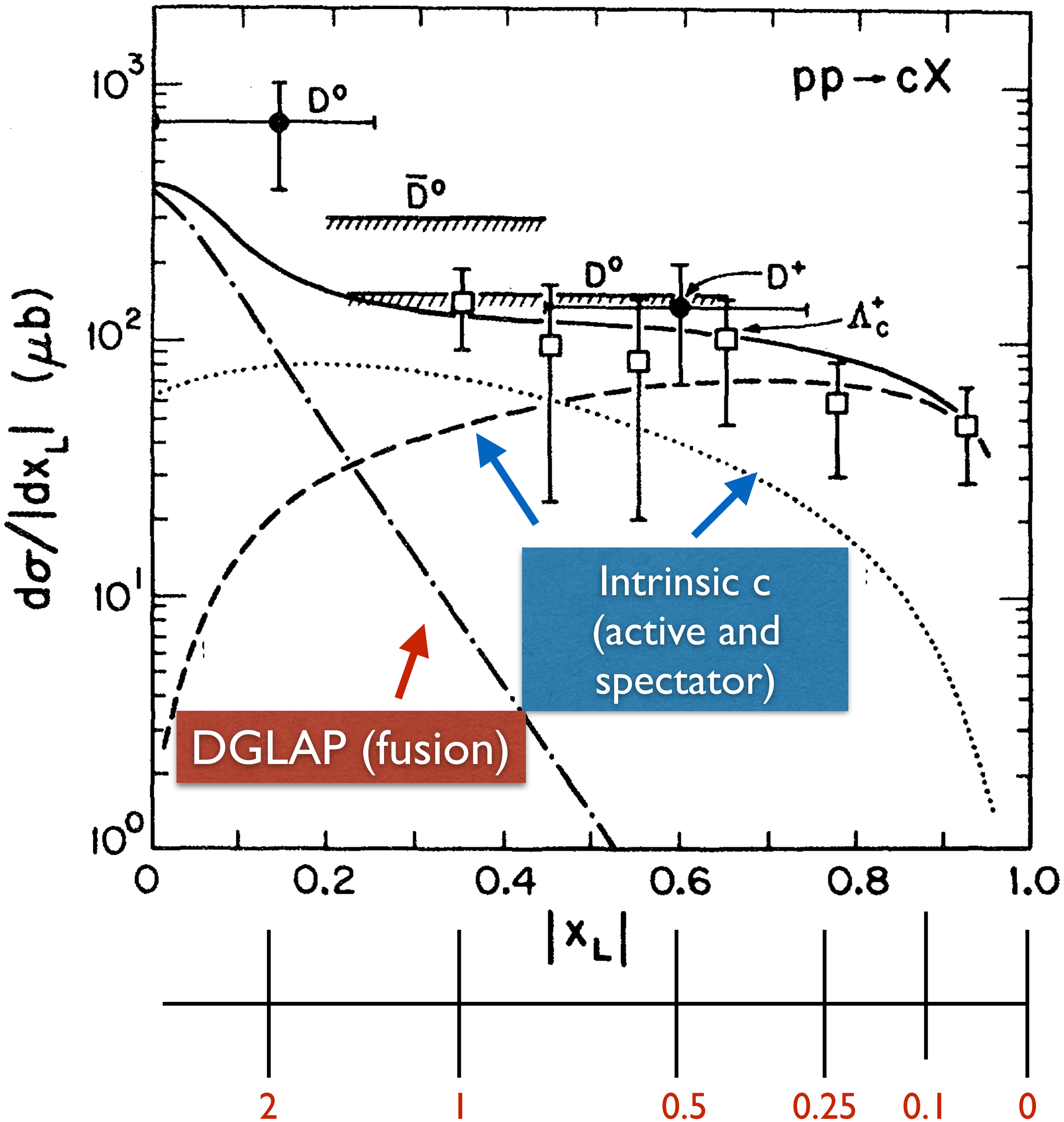
Spectator counting rules

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

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

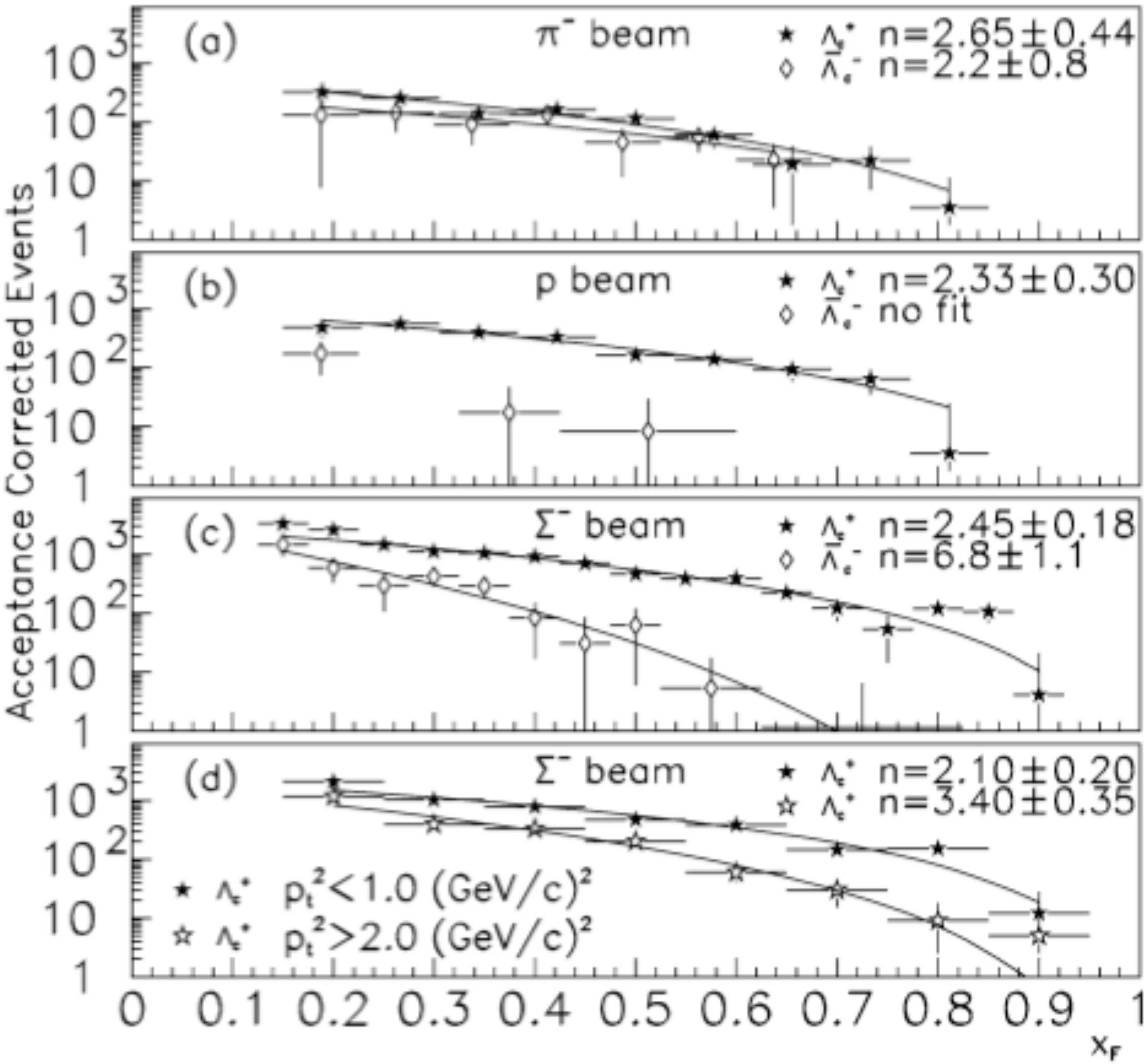
Vogt, sjb

Barger, Halzen, Keung
PRD 25 (1981)



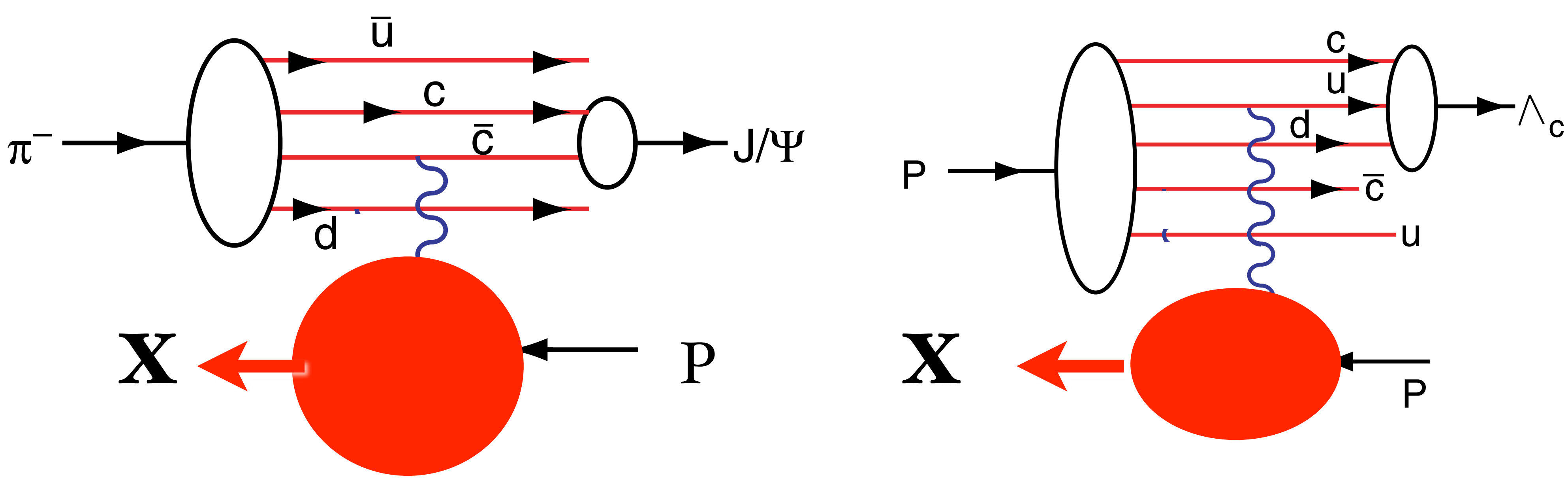
$\Delta y = \log x$

SELEX Collaboration / Physics Letters B 528 (2002) 49–57



Large xF production close to the maximum allowed by phase space!

Coalescence 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

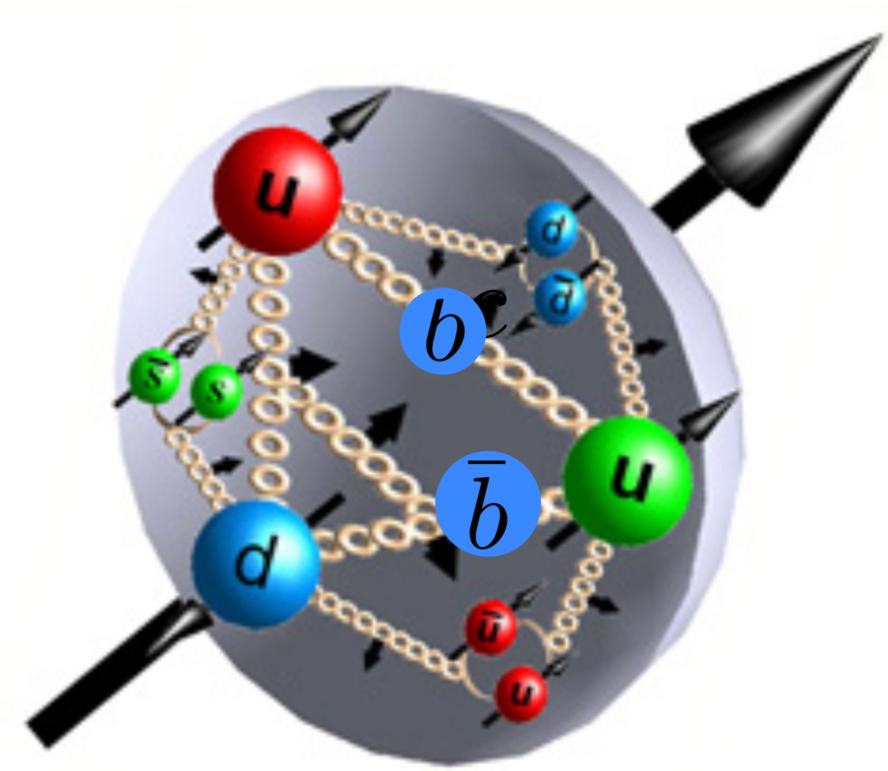
27 May 1991

CM-P00063074

THE Λ_b^o BEAUTY BARYON PRODUCTION IN PROTON-PROTON INTERACTIONS AT $\sqrt{s}$=62 GeV: A SECOND OBSERVATION

G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli,
F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti,
G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari,
G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

CERN, Geneva, Switzerland
Dipartimento di Fisica dell'Università, Bologna, Italy
Dipartimento di Fisica dell'Università, Cosenza, Italy
Istituto di Fisica dell'Università, Palermo, Italy
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto Nazionale di Fisica Nucleare, LNF, Frascati, Italy



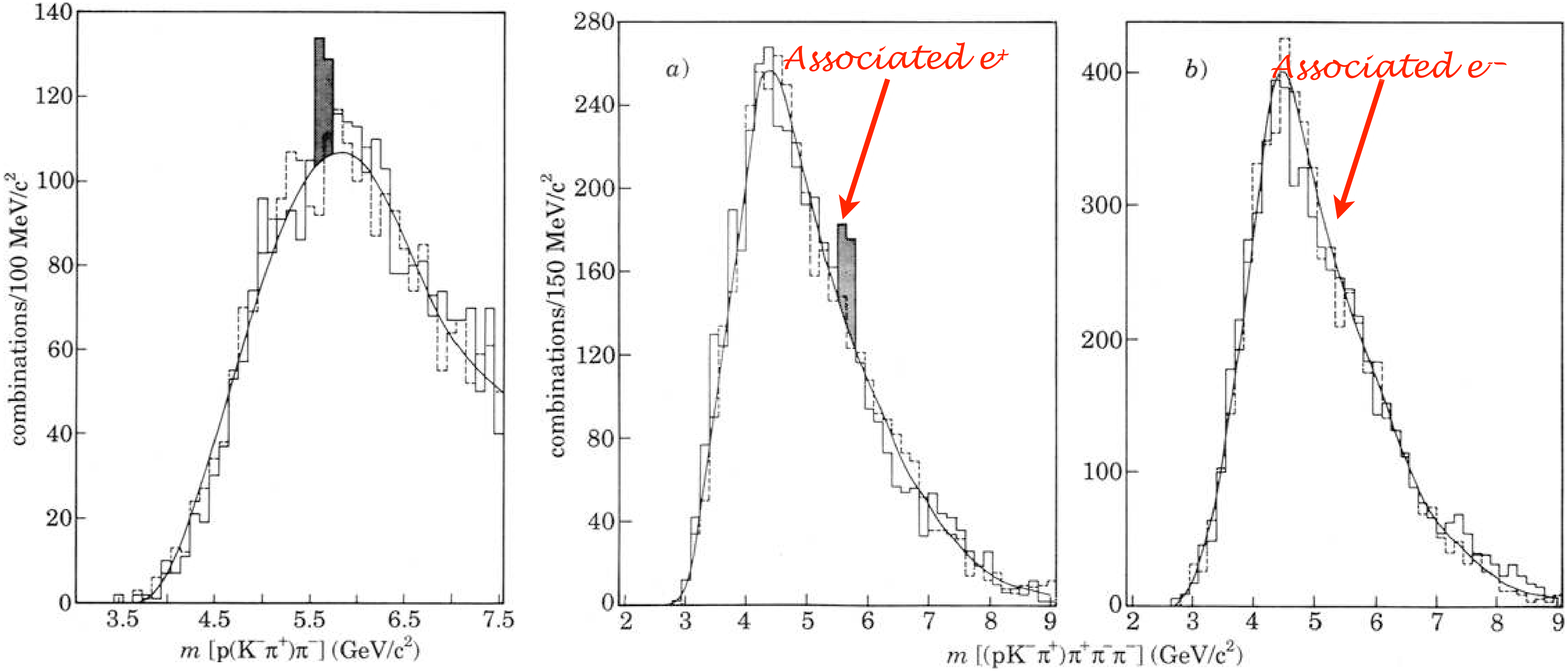
Abstract

Another decay mode of the Λ_b^o (open-beauty baryon) state has been observed: $\Lambda_b^o \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \rightarrow pD^o\pi^-$, are reported. These results confirm our previous findings on Λ_b^o production at the ISR. The mass value (5.6 GeV/c^2) is found to be in good agreement with theoretical predictions. The production mechanism is found to be "leading".

First Evidence for Intrinsic Bottom!

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

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



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

Il Nuovo Cimento 104, 1787

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

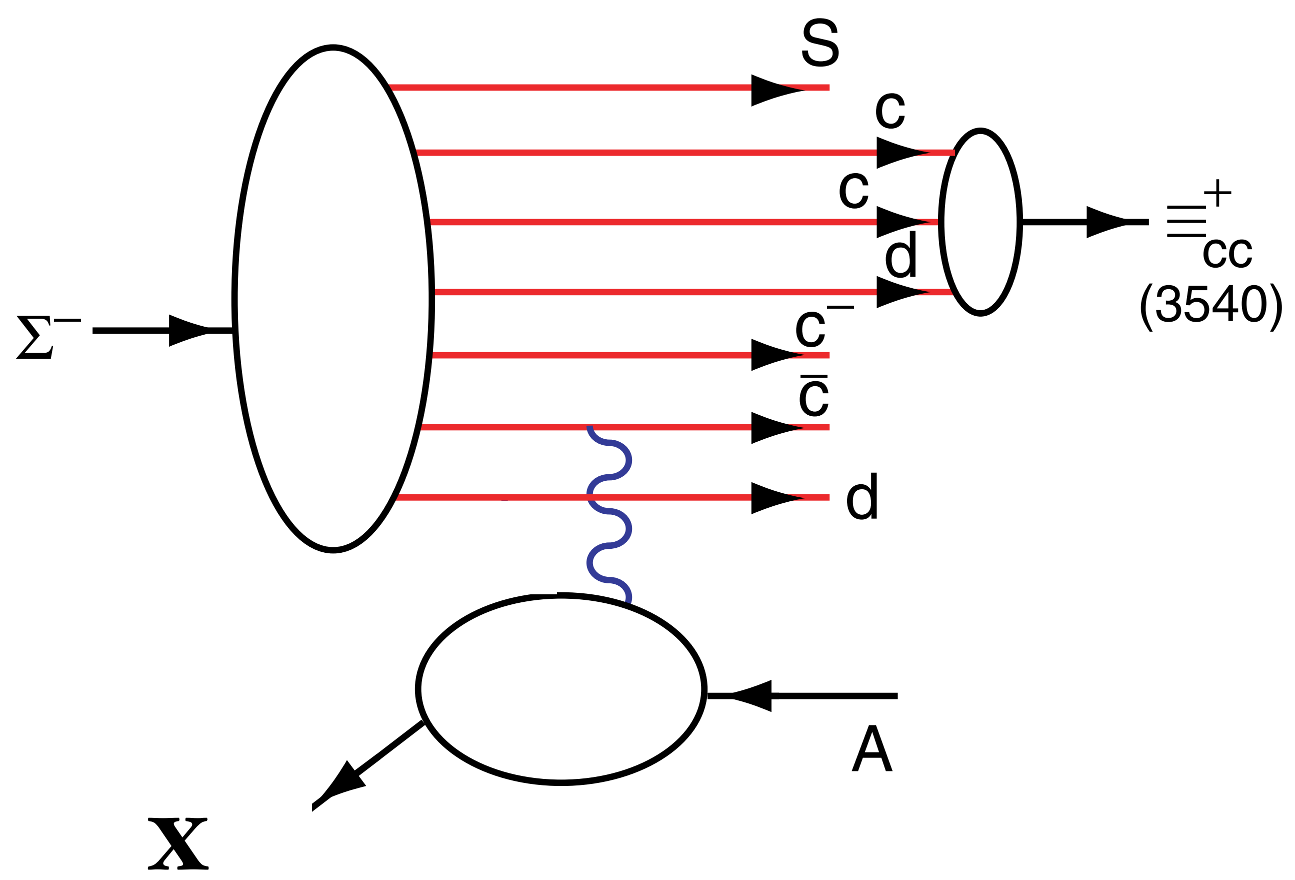
Create Λ_b at rest at LHCb at $\sqrt{s} = \sqrt{13000} = 115\ GeV$

Λ_b^0 MASS

$m_{\Lambda_b^0}$

INSPI

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5619.51 ± 0.23	**OUR AVERAGE**				
5619.30 ±0.34		[1] AAIJ	2014AA	LHCB	$p\,p$ at 7 TeV
5620.15 ±0.31 ±0.47		[2] AALTONEN	2014B	CDF	$p\,\overline{p}$ at 1.96 TeV
5619.7 ±0.7 ±1.1		[2] AAD	2013U	ATLS	$p\,p$ at 7 TeV
5619.44 ±0.13 ±0.38		[2] AAIJ	2013AV	LHCB	$p\,p$ at 7 TeV
5621 ±4 ±3		[3] ABE	1997B	CDF	$p\,\overline{p}$ at 1.8 TeV
5668 ±16 ±8	4	[4] ABREU	1996N	DLPH	$e^+\,e^- \rightarrow Z$
5614 ±21 ±4	4	[4] BUSKULIC	1996L	ALEP	$e^+\,e^- \rightarrow Z$
*** We do not use the following data for averages, fits, limits, etc ***					
5619.19 ±0.70 ±0.30		[2] AAIJ	2012E	LHCB	Repl. by AAIJ 2013AV
5619.7 ±1.2 ±1.2		[5] ACOSTA	2006	CDF	Repl. by AALTONEN 2014B
not seen		[6] ABE	1993B	CDF	Repl. by ABE 1997B
5640 ±50 ±30	16	[7] ALBAJAR	1991E	UA1	$p\,\overline{p}$ 630 GeV
$5640\,^{+100}_{-210}$	52	BARI	1991	SFM	$\Lambda_b^0 \rightarrow pD^0\pi^-$
$5650\,^{+150}_{-200}$	90	BARI	1991	SFM	$\Lambda_b^0 \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$



Production of a Double-Charm Baryon

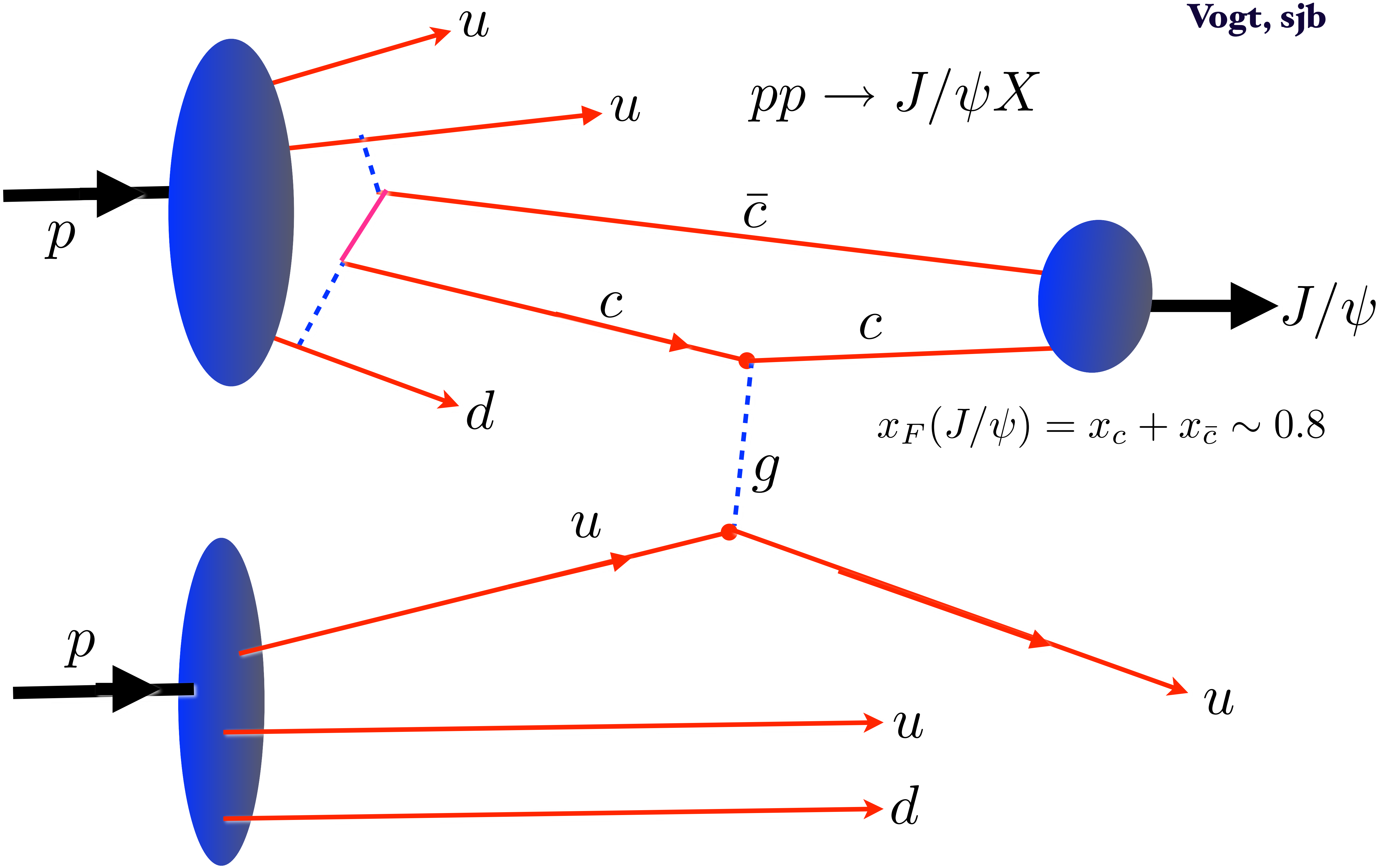
SELEX high x_F $\quad < x_F >= 0.33$

Intrinsic Heavy Quark Contribution to Quarkonium Hadroproduction at High x_F

Lansberg, sjb

Vogt, sjb

$$pp \rightarrow J/\psi X$$



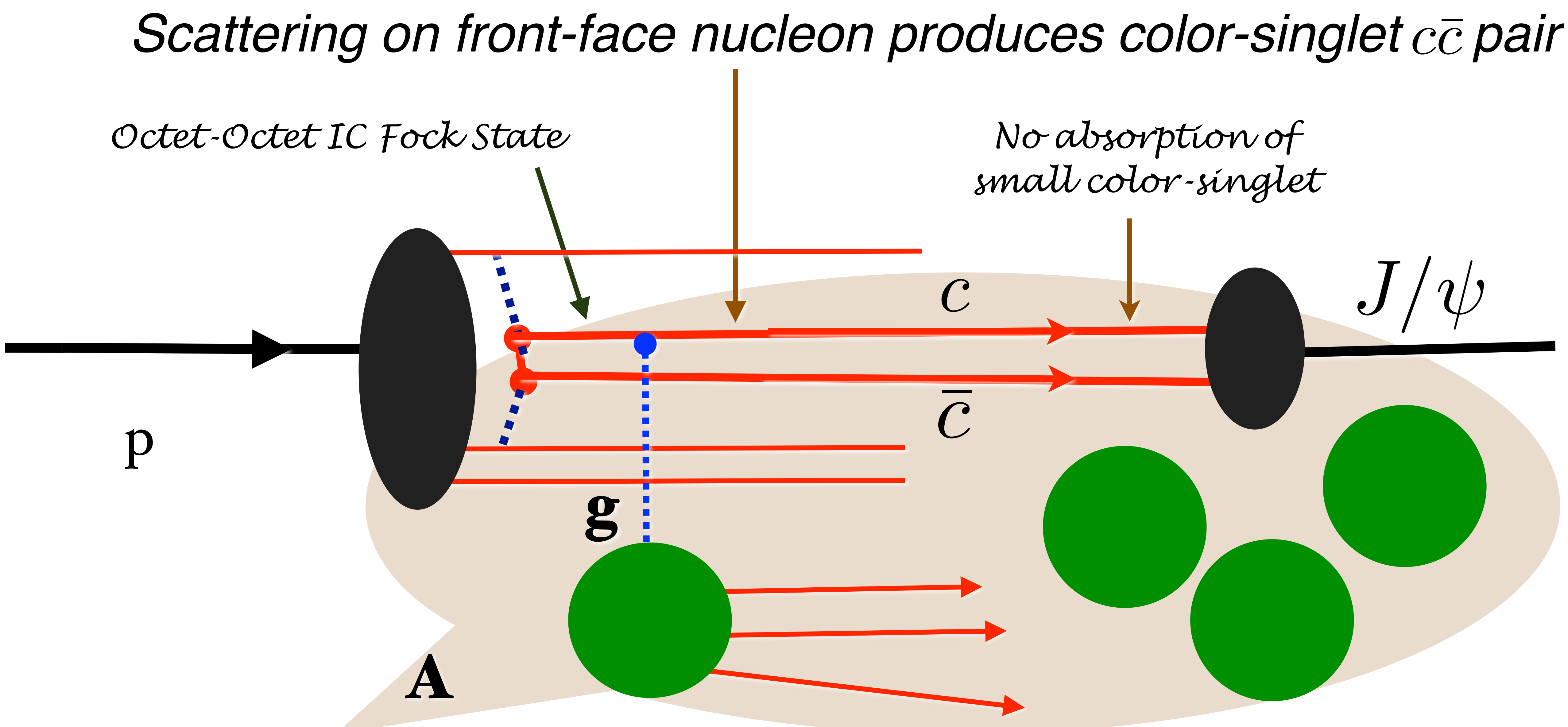
$$x_F(J/\psi) = x_c + x_{\bar{c}} \sim 0.8$$

Maximal Wavefunction Strength at Minimal Invariant Mass : Equal Rapidity

$$x_i \propto \frac{m_{\perp i}}{\sum_j m_{\perp j}}$$

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

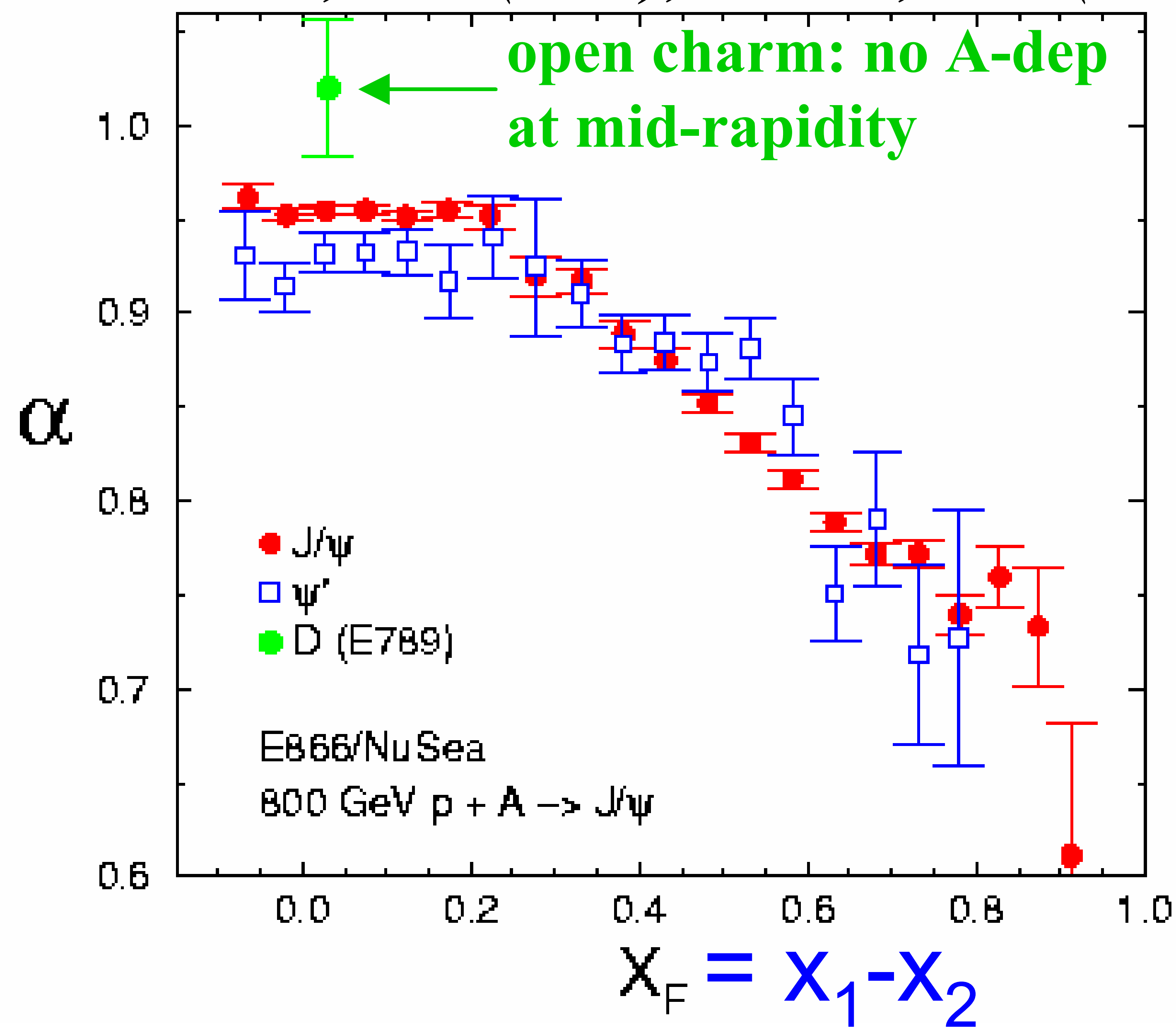


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

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

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

M. Leitch



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

Remarkably Strong Nuclear Dependence for Fast Charmonium

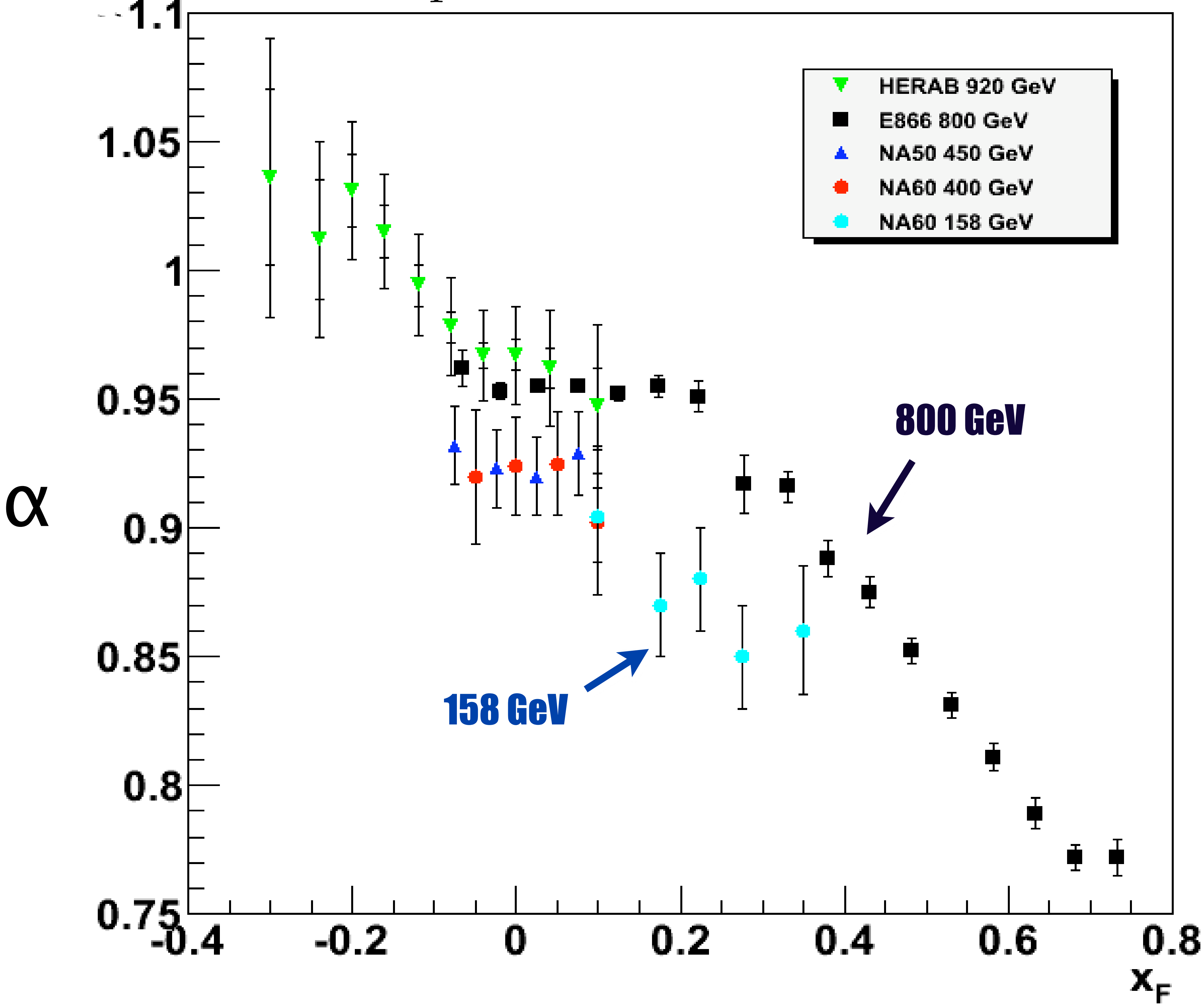
Violation of PQCD Factorization

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

NA60 pA data @ 158GeV

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



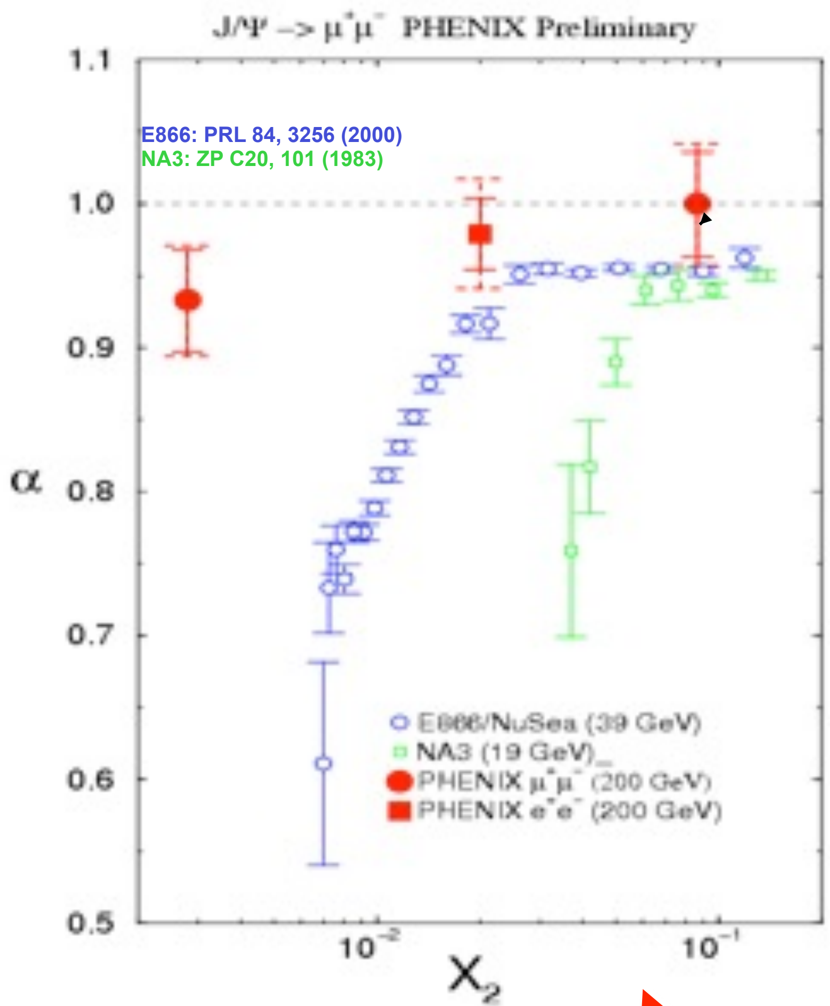
Clear dependence on x_F and beam energy

Dramatic change in nuclear dependence

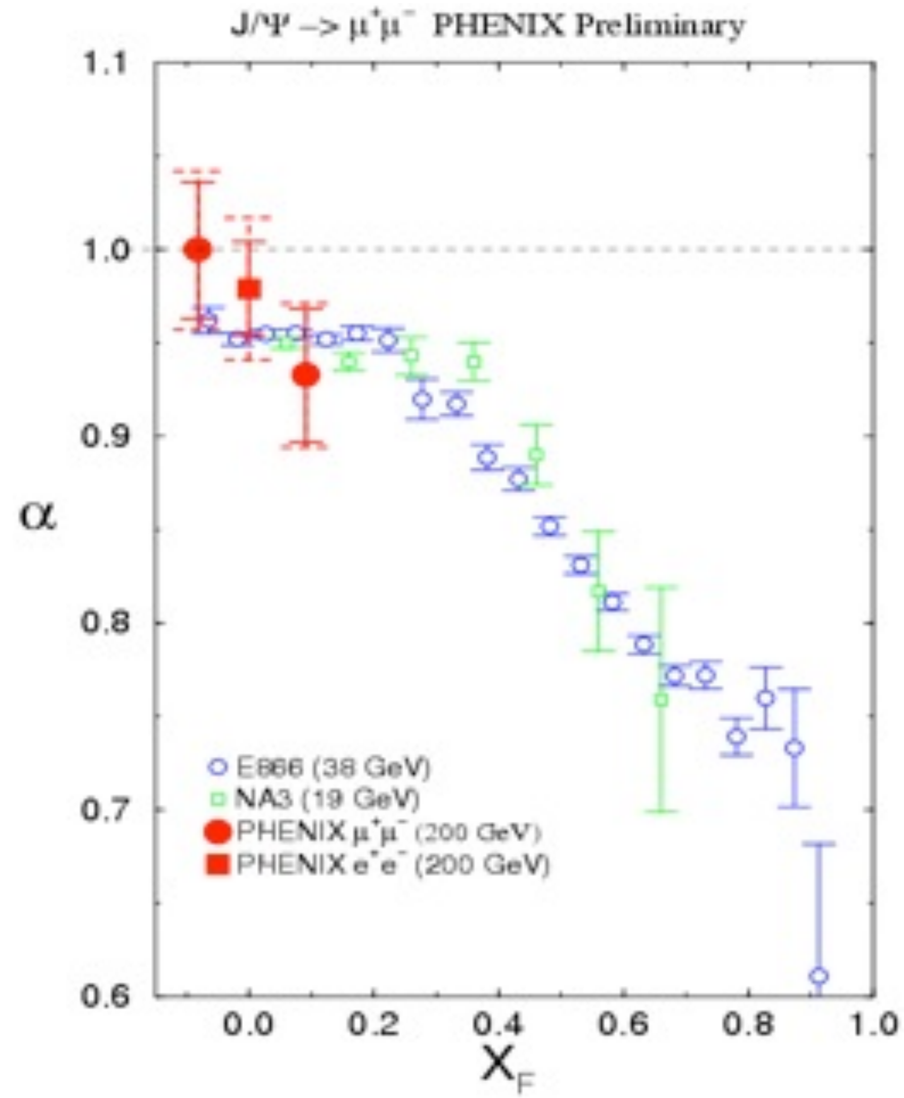
J/ψ nuclear dependence versus rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001



Huge "absorption" effect

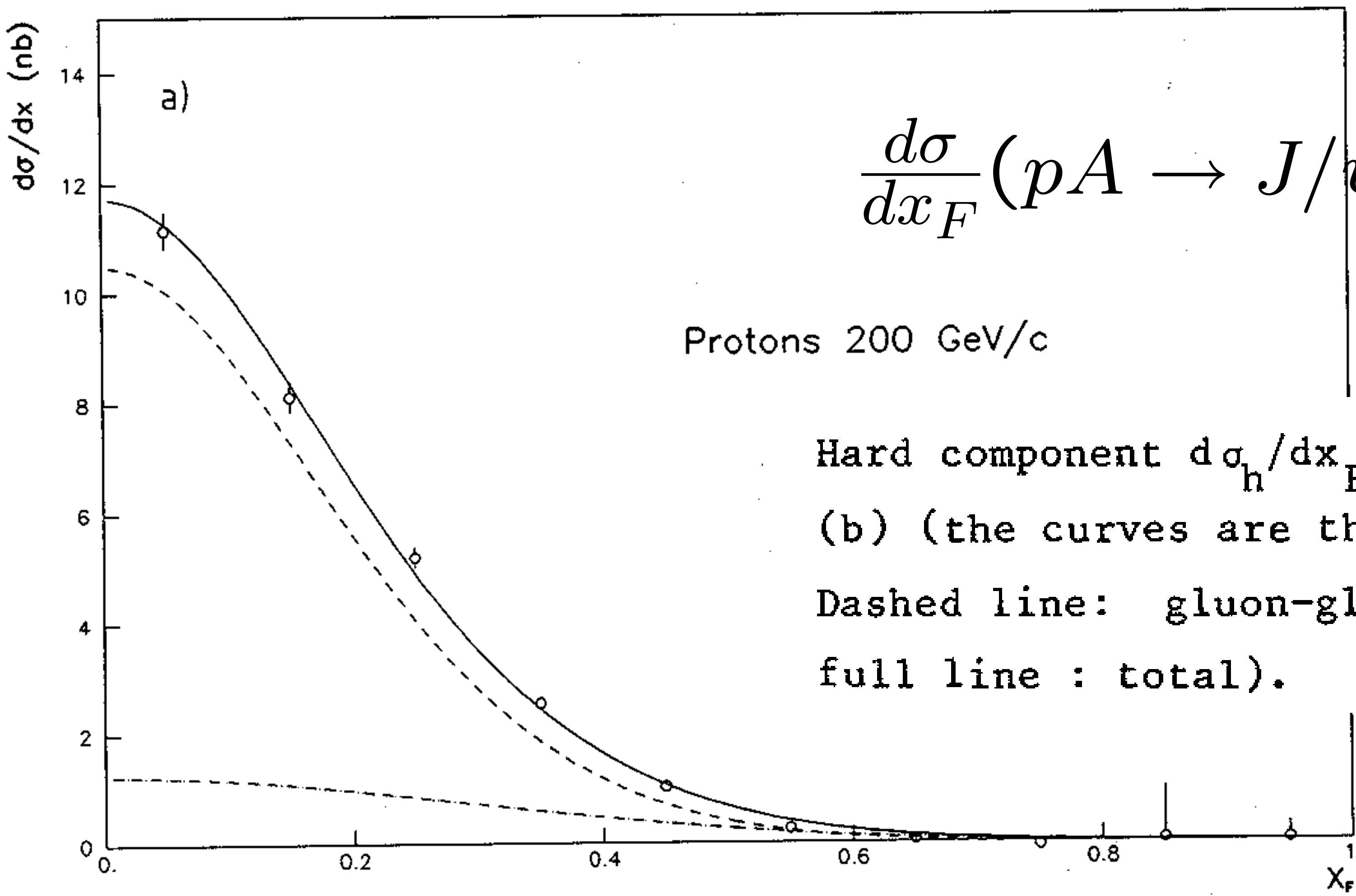
Violates PQCD factorization!

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

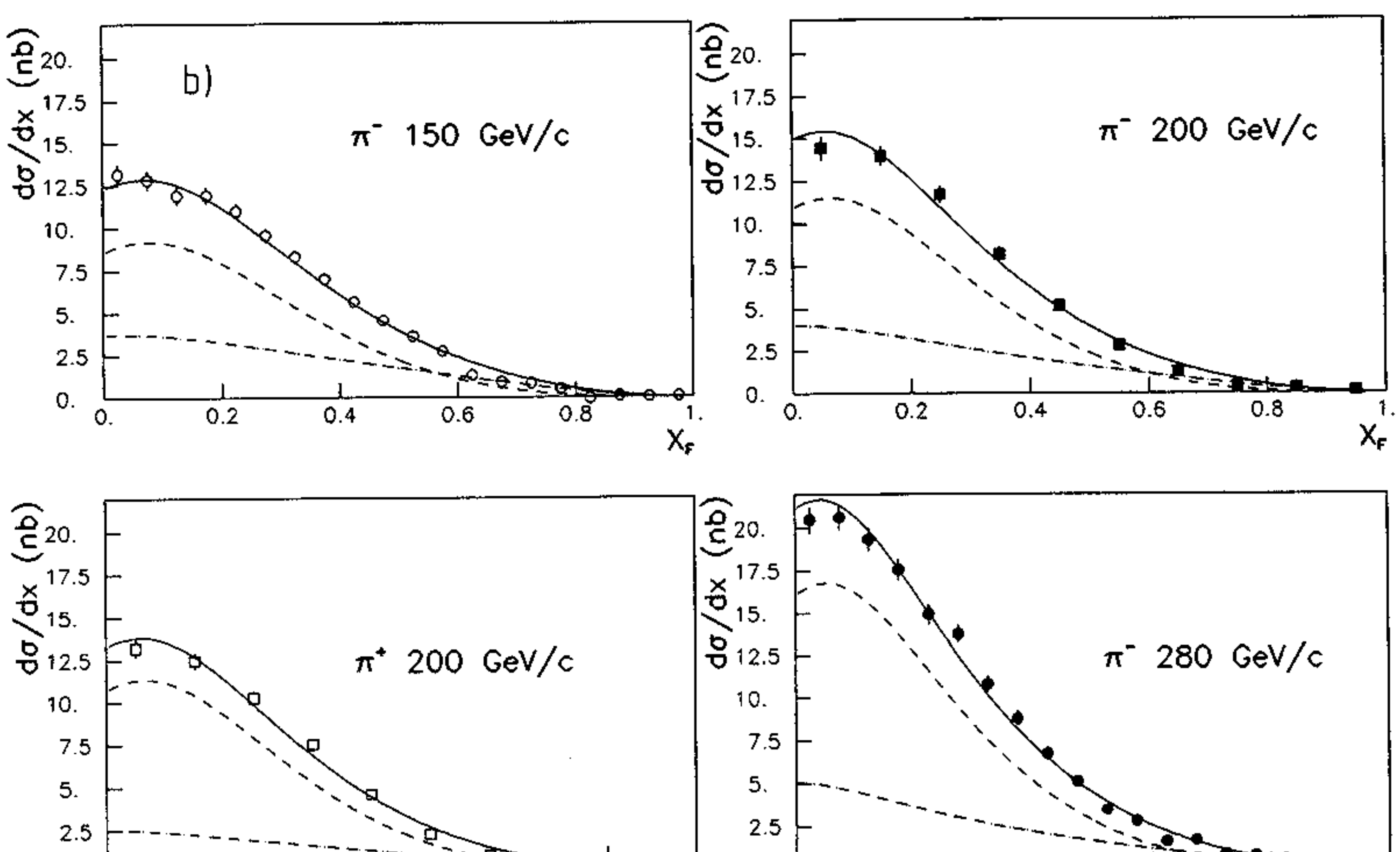
Hoyer, Sukhatme, Vanttinen

Violates PQCD Factorization: $A^\alpha(x_F)$ not $A^\alpha(x_2)$

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

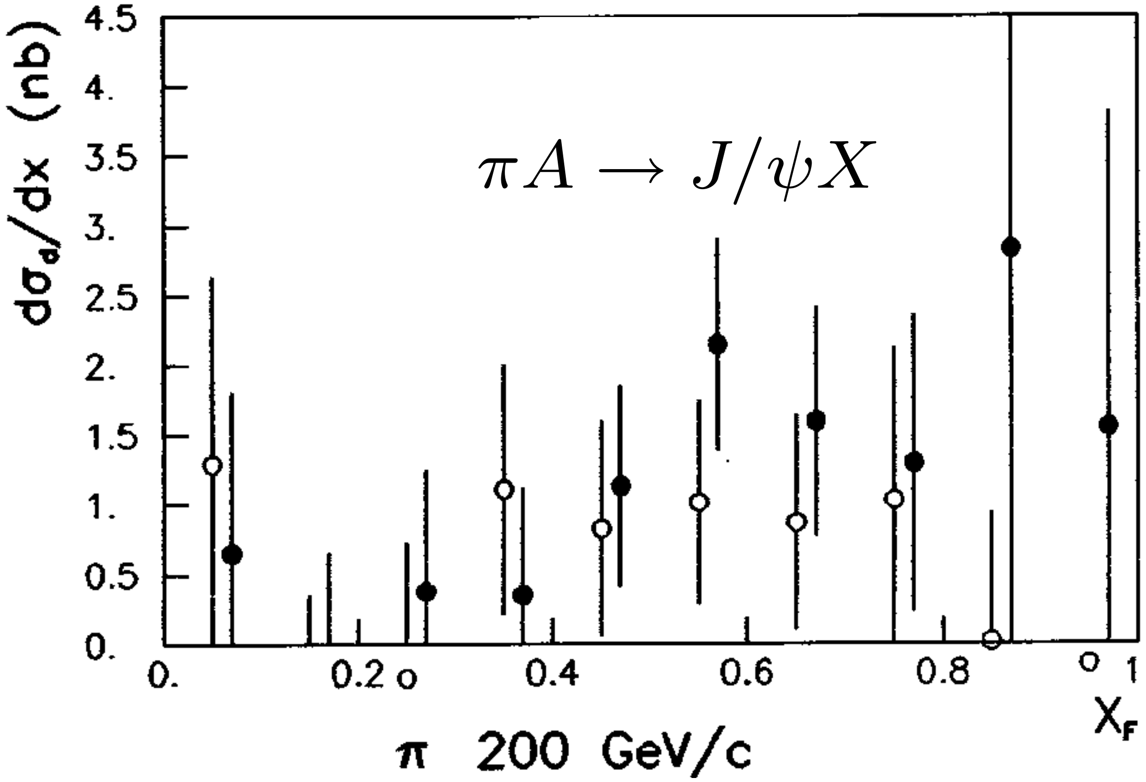


Hard component $d\sigma_h/dx_F$ for incident protons (a) and pions (b) (the curves are the result of the fit described in the text. Dashed line: gluon-gluon fusion; dash-dotted line : $q\bar{q}$ fusion; full line : total).

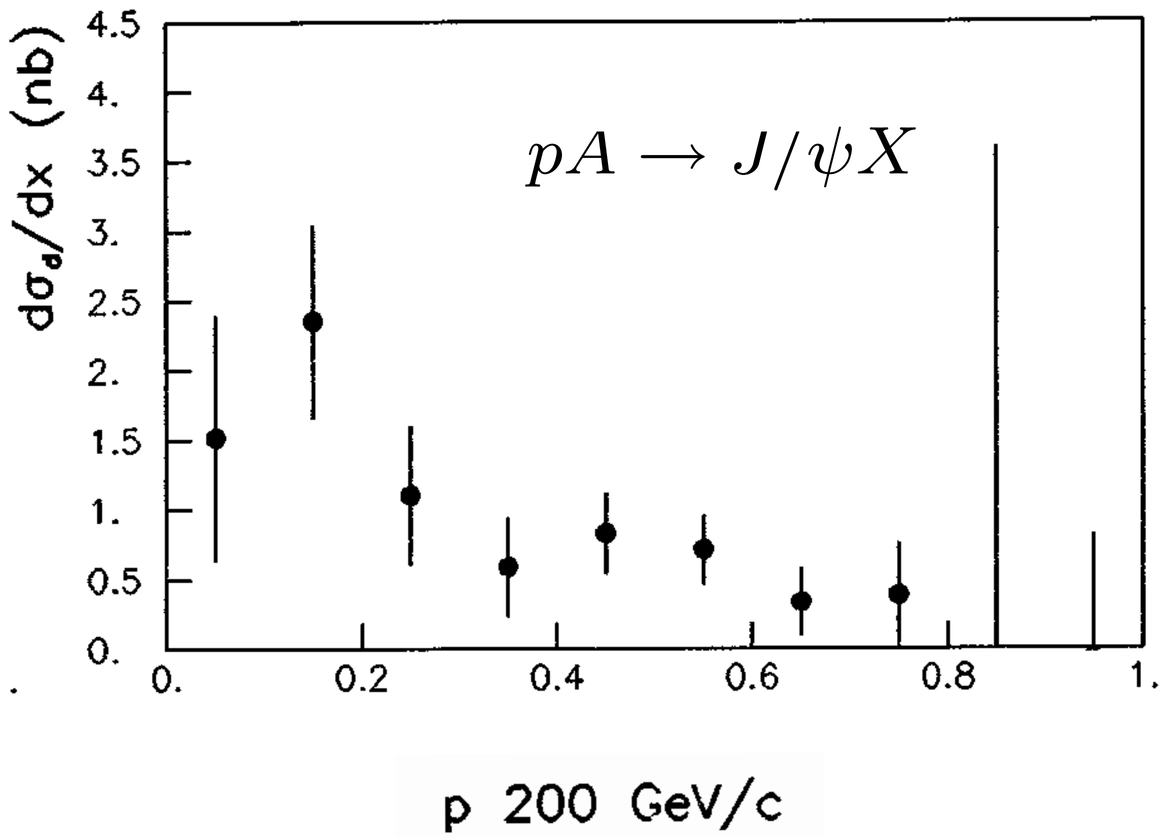


A^1 component consistent with sum of gg and $\bar{q}q$ fusion

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



$A^{2/3}$ component



J. Badier et al, NA3

Excess beyond conventional PQCD subprocesses

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

Excludes `color drag' model

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

R. Vogt, sjb

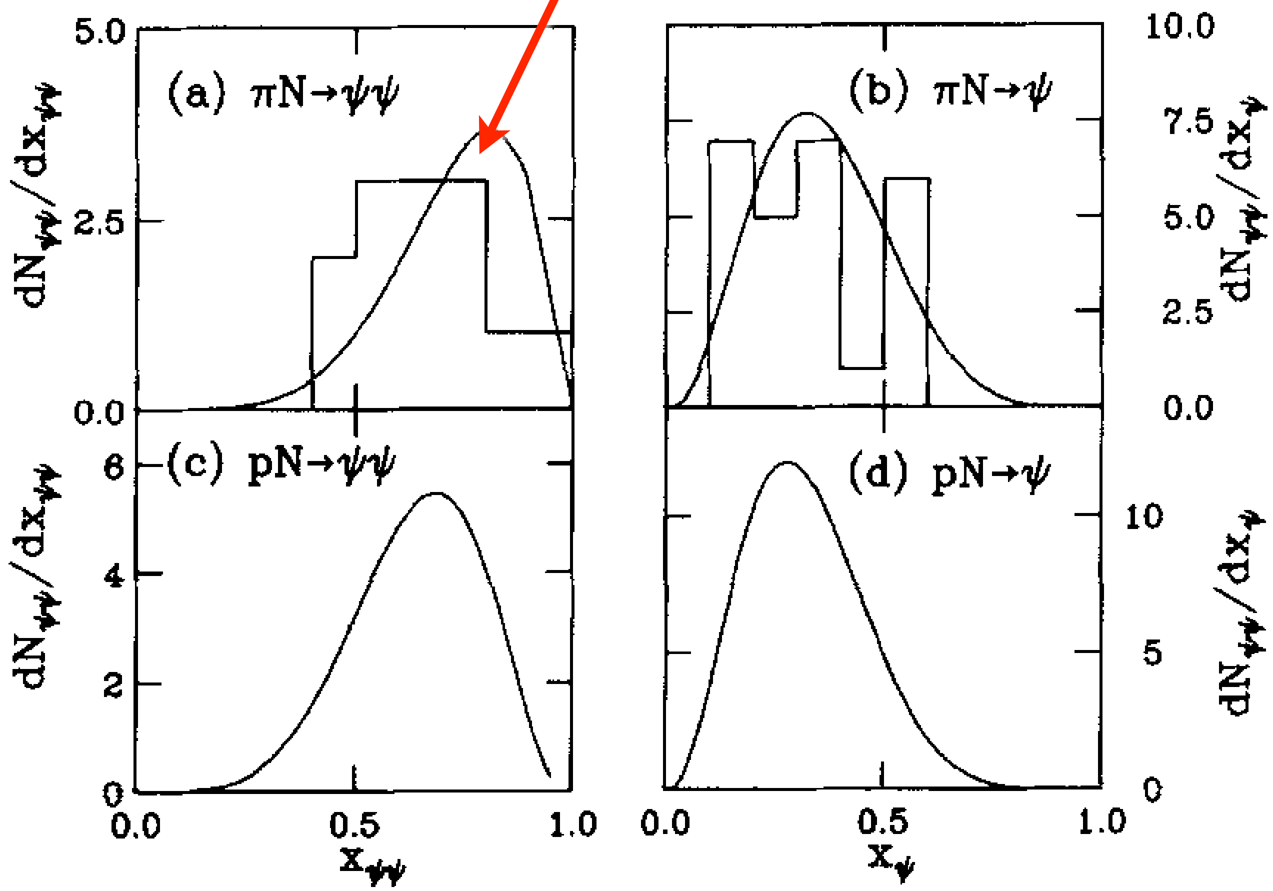


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

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

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

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

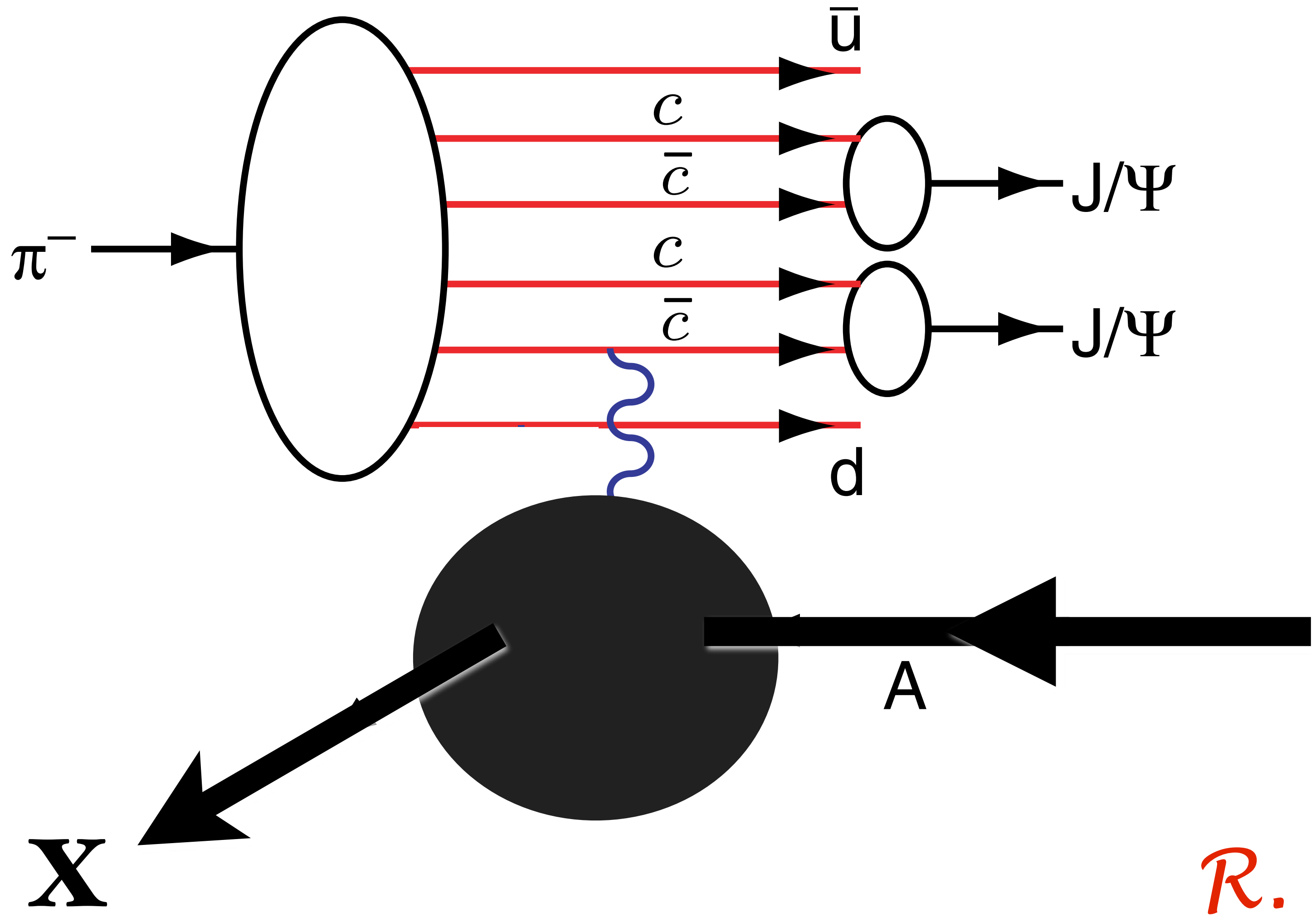
Color Opaqueness

- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in B decay (Gardner, SJB)

Higgs production at x_F = 0.8

Cannot be explained by Color Drag Model



R. Vogt, sjb

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

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

Rules out color drag (Pythia)

- 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

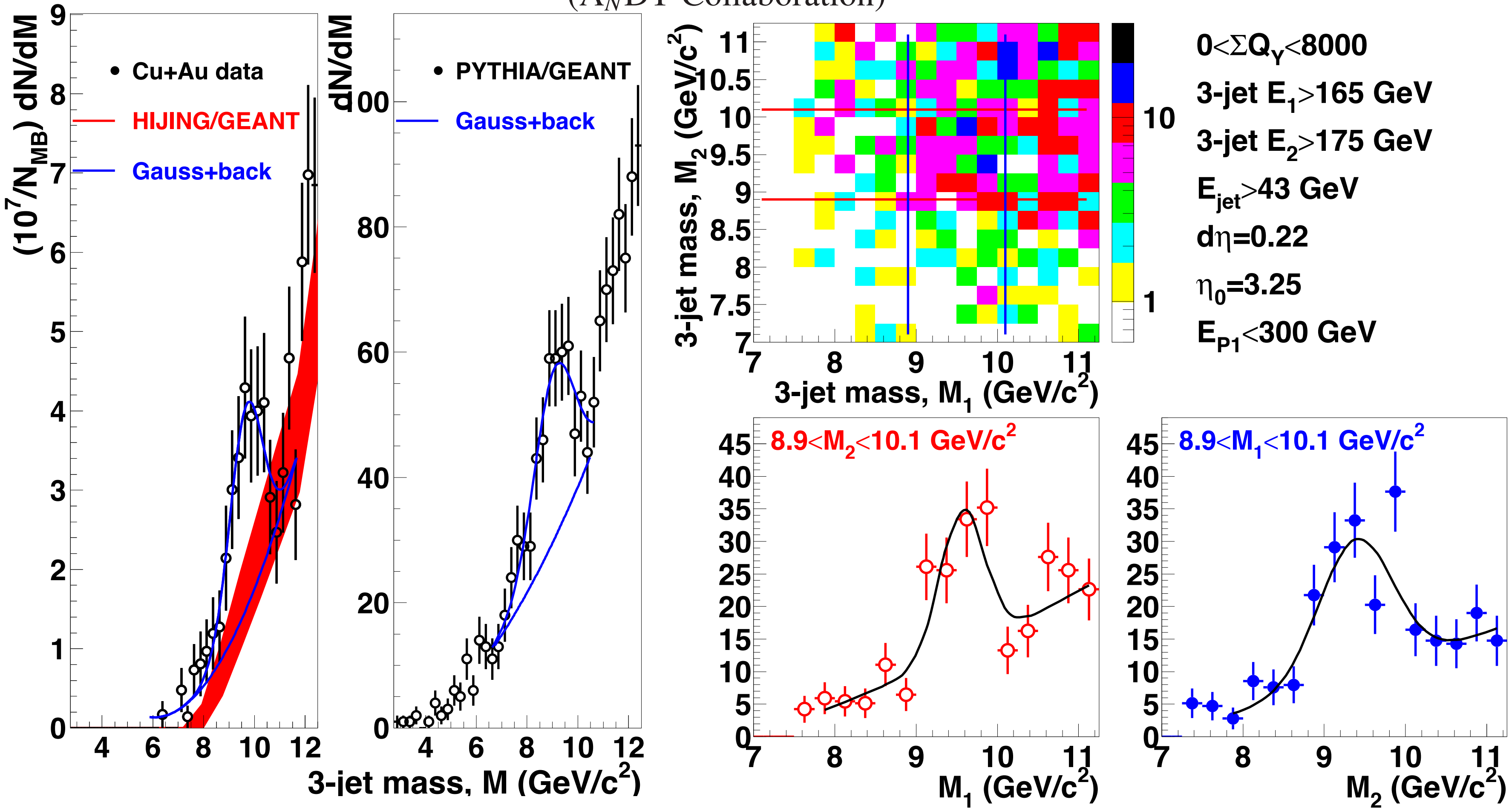
Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

Observation of Feynman scaling violations and evidence for a new resonance at RHIC

L. C. Bland[a], E. J. Brash[b], H. J. Crawford[c], A.A. Derevschikov[d], K. A. Drees[a], J. Engelage[c], C. Folz[a], E. G. Judd[c], X. Li[e,a], N. G. Minaev[d], R. N. Munroe[b], L. Nogach[d], A. Ogawa[a], C. Perkins[c], M. Planinic[f], A. Quintero[i], G. Schnell[g,h], P. V. Shanmuganathan[j], G. Simatovic[f,a], B. Surrow[i], T. G. Throwe[a], A. N. Vasiliev[d]

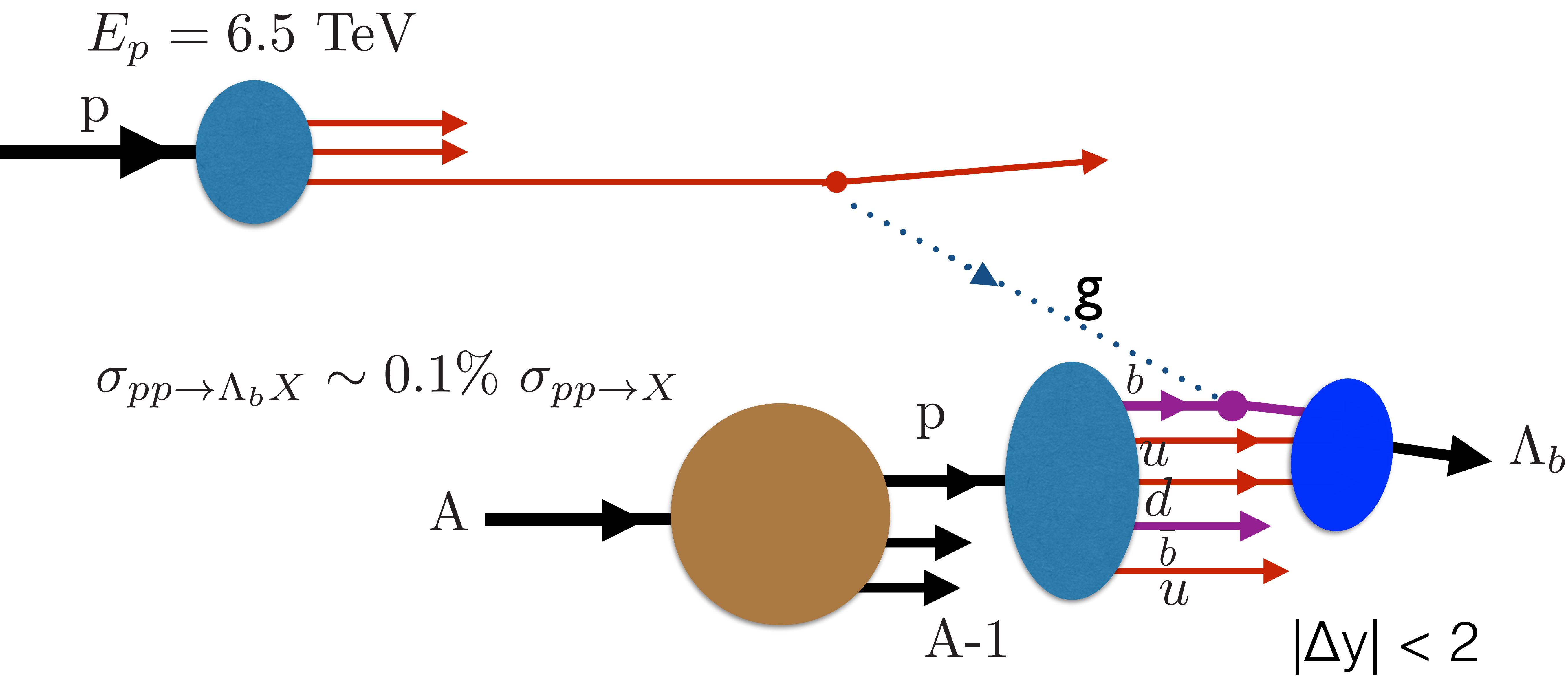
(A_NDY Collaboration)*



Evidence for $\Upsilon(1S)$ via its decay to three jets. (left pair) Inclusive forward production from Cu+Au collisions overlayed with HIJING/GEANT simulation. A 5.2σ peak is observed in the data. Comparison is to PYTHIA/GEANT p+p simulations at $\sqrt{s}$ = 1200 GeV, using the Perugia 0 tune. (right) $\sim 5\sigma$ evidence for forward pair $\Upsilon(1S)$ production. All Cu+Au distributions have vertical axes scaled as $10^7/N_{MB}$.

$A_N DY/RHIC$: Observe single and double $\Upsilon(1S)$ Production at high rapidity in Cu+Au collisions

$$pA \to \Lambda_b X$$

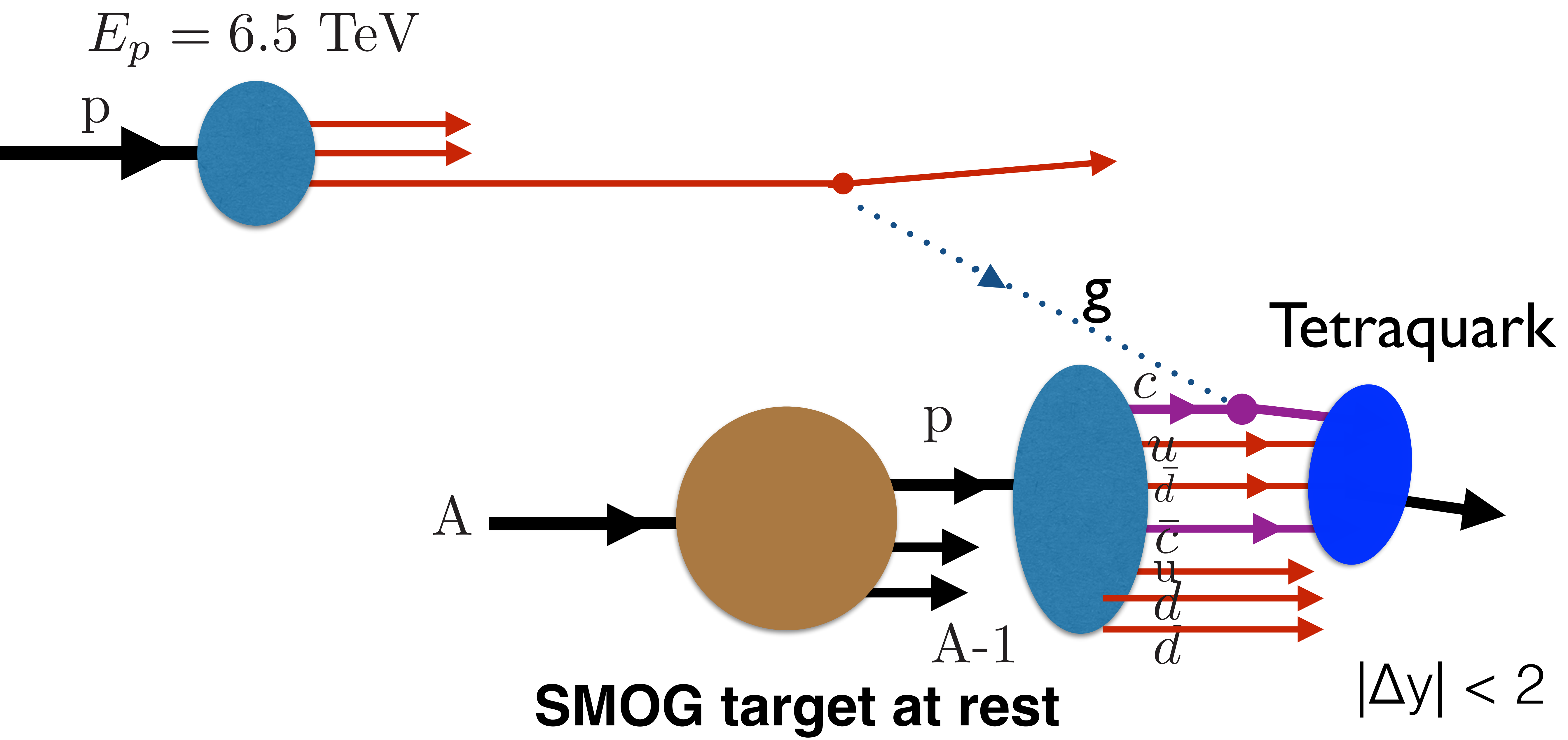


SMOG target at rest

Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Quarkonium produced nearly at rest — has small rapidity in target rest frame

$$pA \to Tetraquark(|cu\bar{c}\bar{d}>)X$$



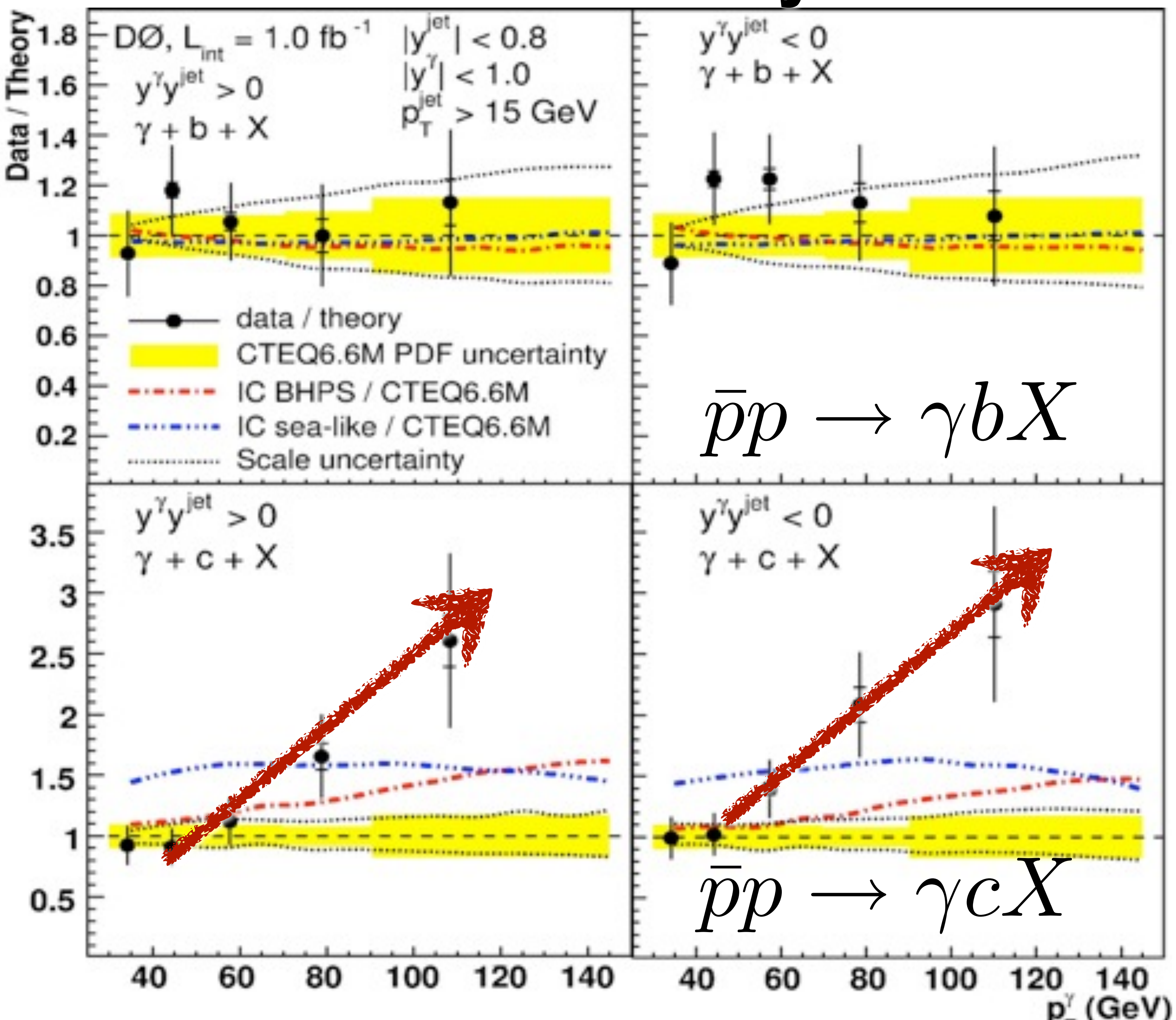
Intrinsic heavy quark probability in the nucleon maximal at minimum off-shellness

Tetraquark produced nearly at rest — has small rapidity in target rest frame

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

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

Data/Theory



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

Ratio insensitive to gluon PDF, scales

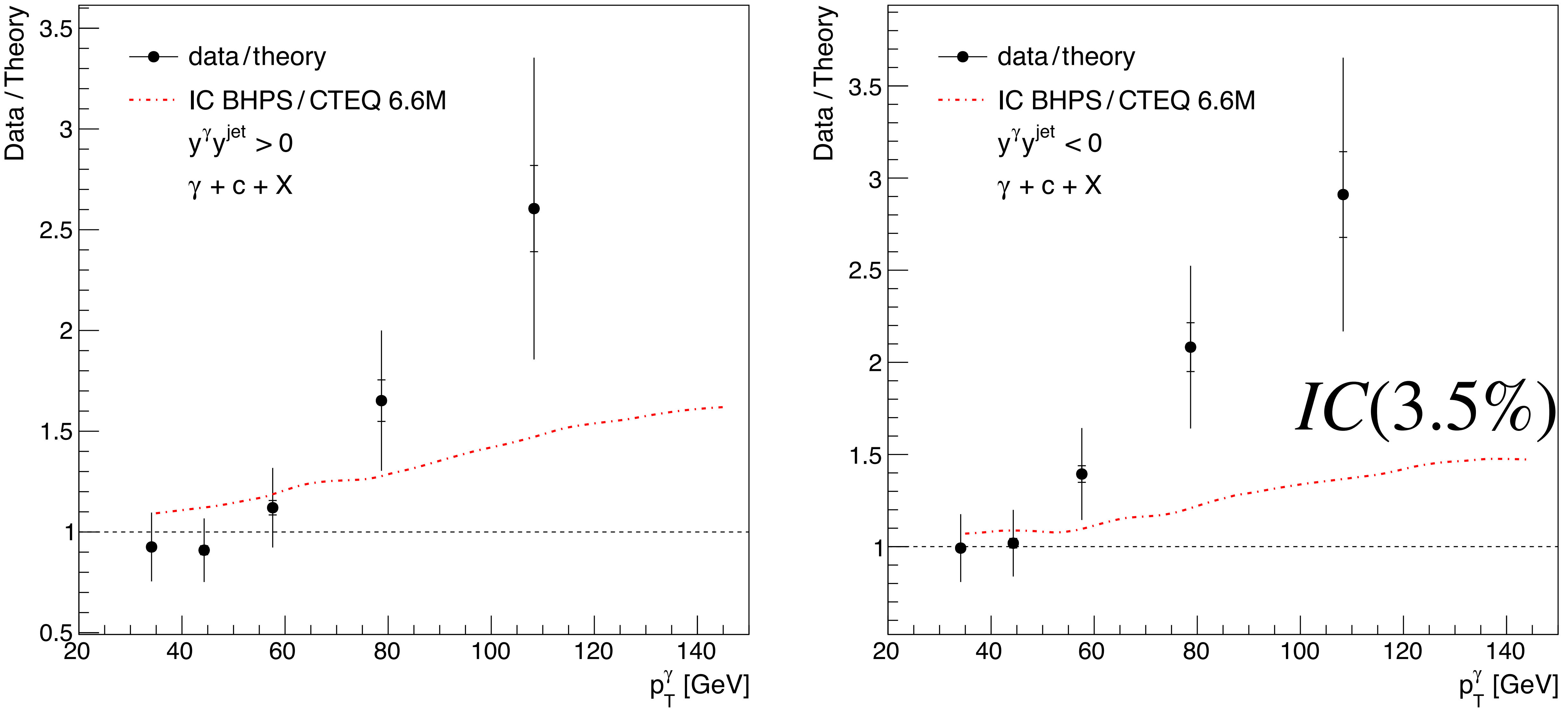
Signal for significant IC at x > 0.1

Consistent with EMC measurement of charm structure function at high x

Production of Prompt Photon and c or b-jet in Hard pp Collisions

$p\bar{p} \rightarrow \gamma c X$

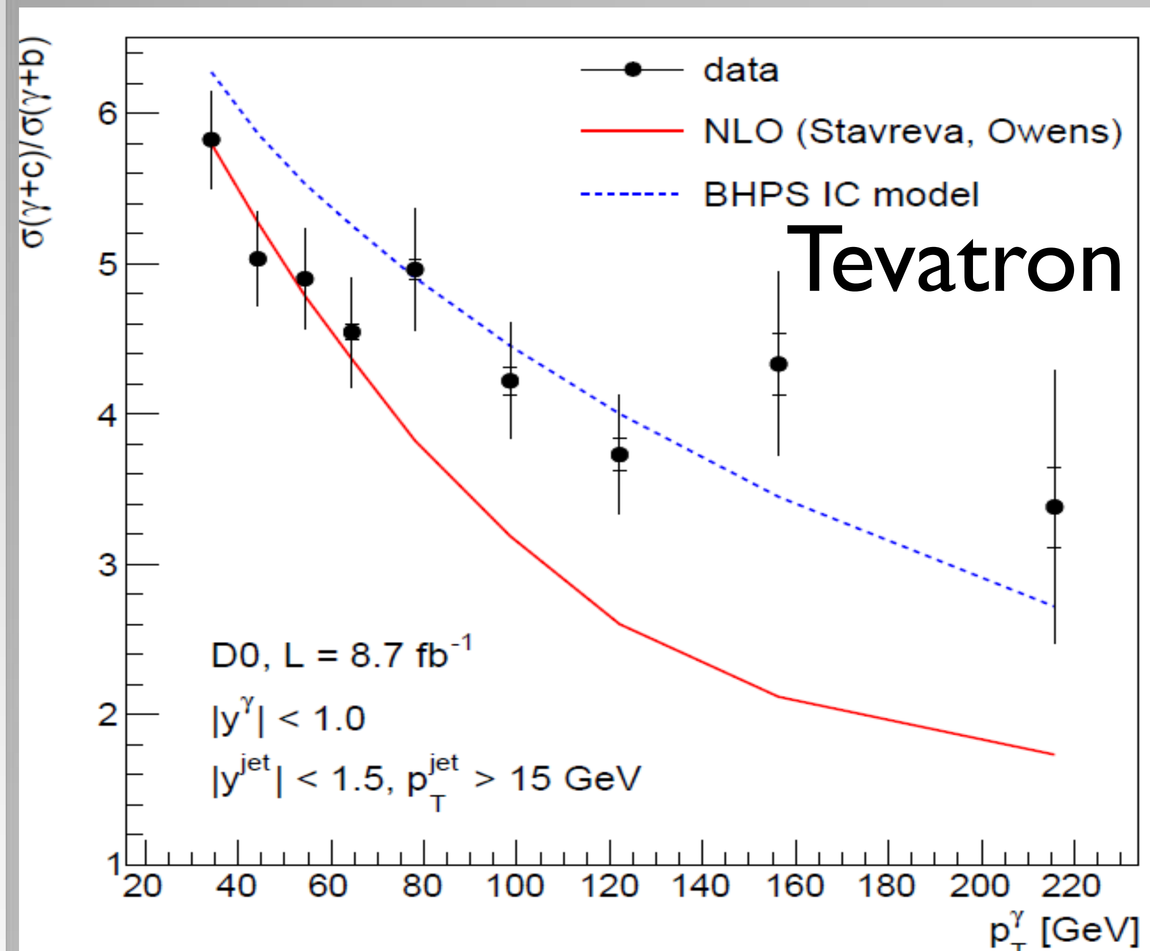
Juraj Smieško

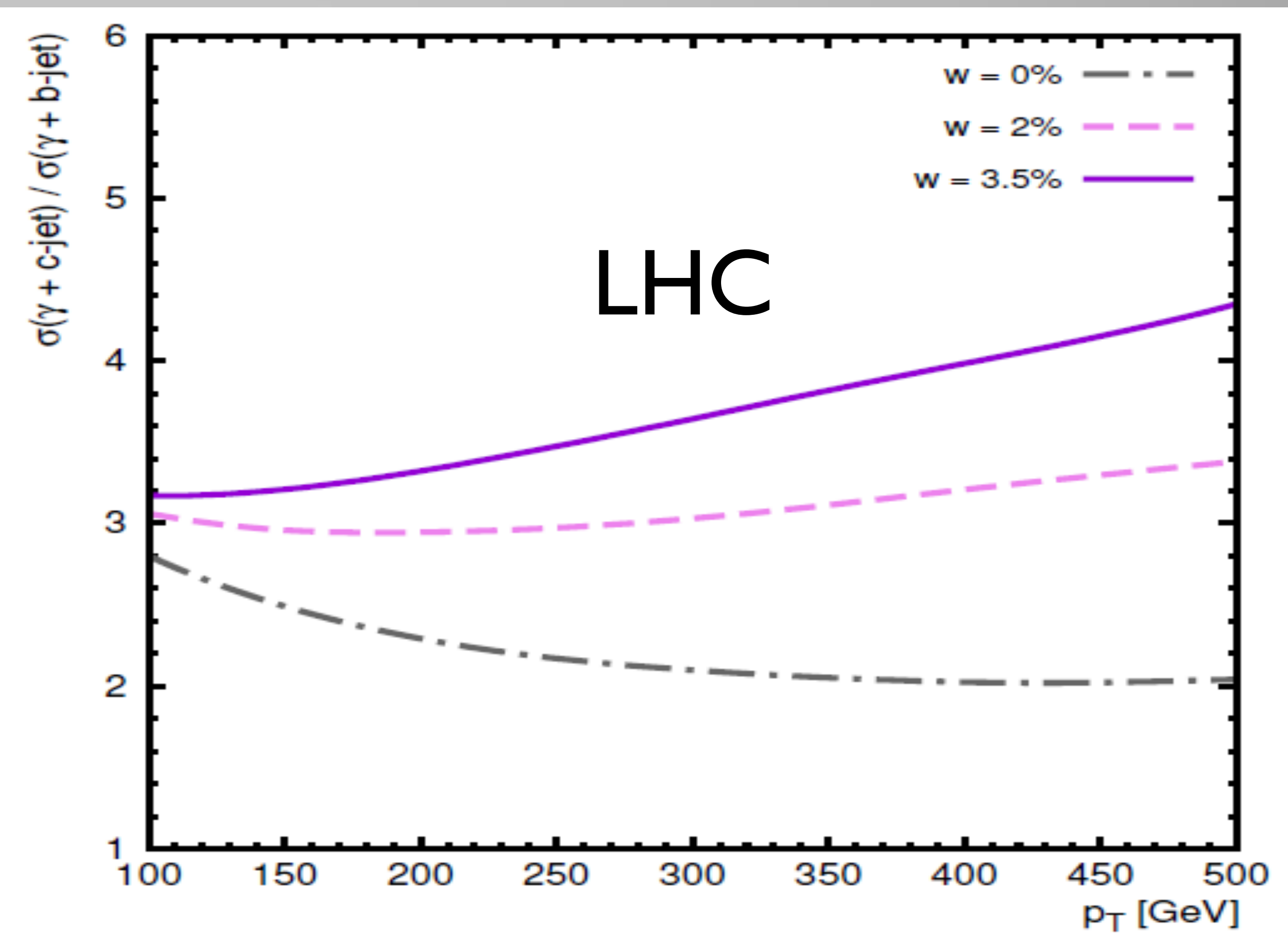


The data-to-theory ratio [8] for the processes $p\bar{p} \longrightarrow \gamma + c + X$, when $y^{\gamma}y^{\text{jet}} > 0$ (left) and the same ratio, when $y^{\gamma}y^{\text{jet}} < 0$ (right) at $\sqrt{s} = 1.96$ TeV. The dash-dotted line is the calculation of this ratio using the BHPS IC model with the IC probability about 3.5 %.

R=σ(γ + c)/σ(γ + b) for p bar{p} -> γ + Q at $s^{1/2}$ = 1.98 TeV (left)

R=σ(γ + c)/σ(γ + b) for p p -> γ + Q at $s^{1/2}$ = 8 TeV (right)





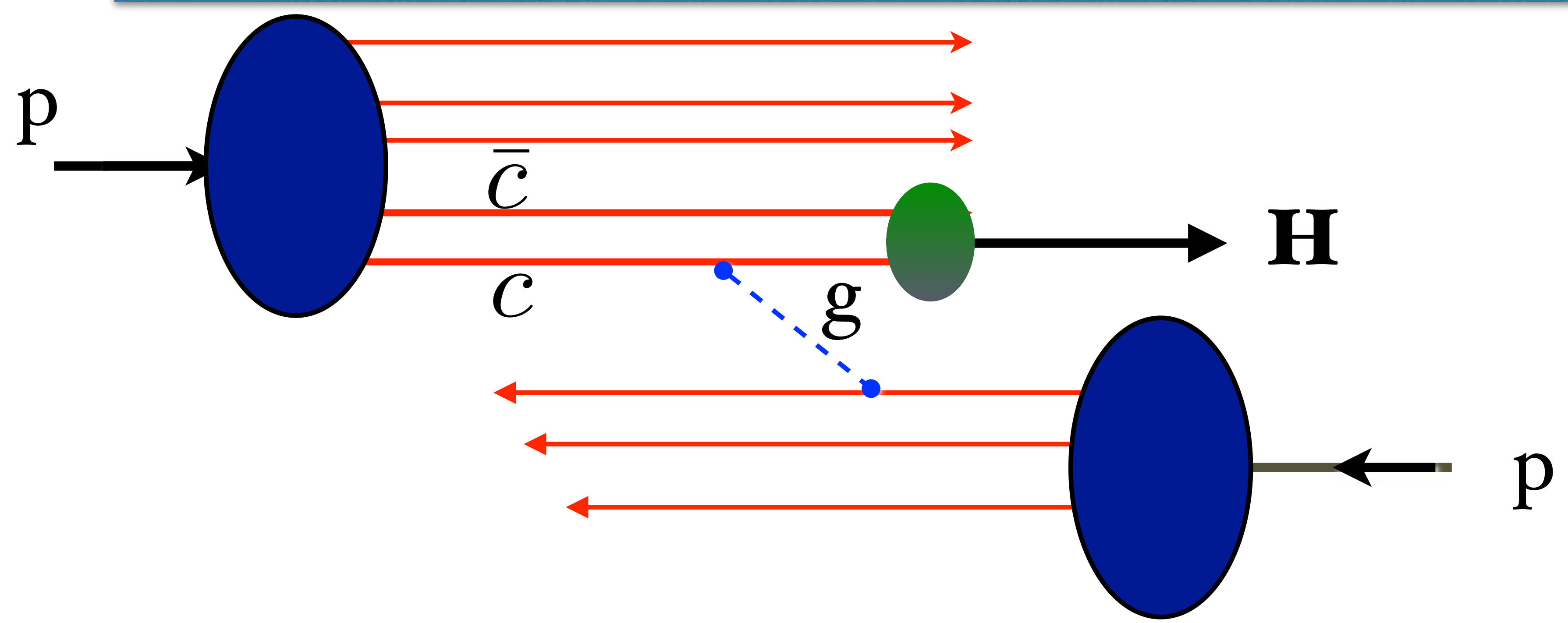
V.M.Abazov, et al. (D0) Phys.Lett. B719 (2013) 354 .

A.V.Lipatov, G.I.Lykasov, Yu.Yu.Stepanenko, V.A.Bednyakov, Phys.Rev. D94 , 053011 (2016) ; S.J.Brodsky, V.A.Bednyakov, G.I.Lykasov, J.Smiesko, S.Tokar, arXiv:1612.01351 , Prog. Part.Nucl.Phys. in press

$$\frac{\sigma(pp\rightarrow\gamma cX)}{\sigma(pp\rightarrow\gamma bX)}$$

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$$pp \rightarrow H X$$

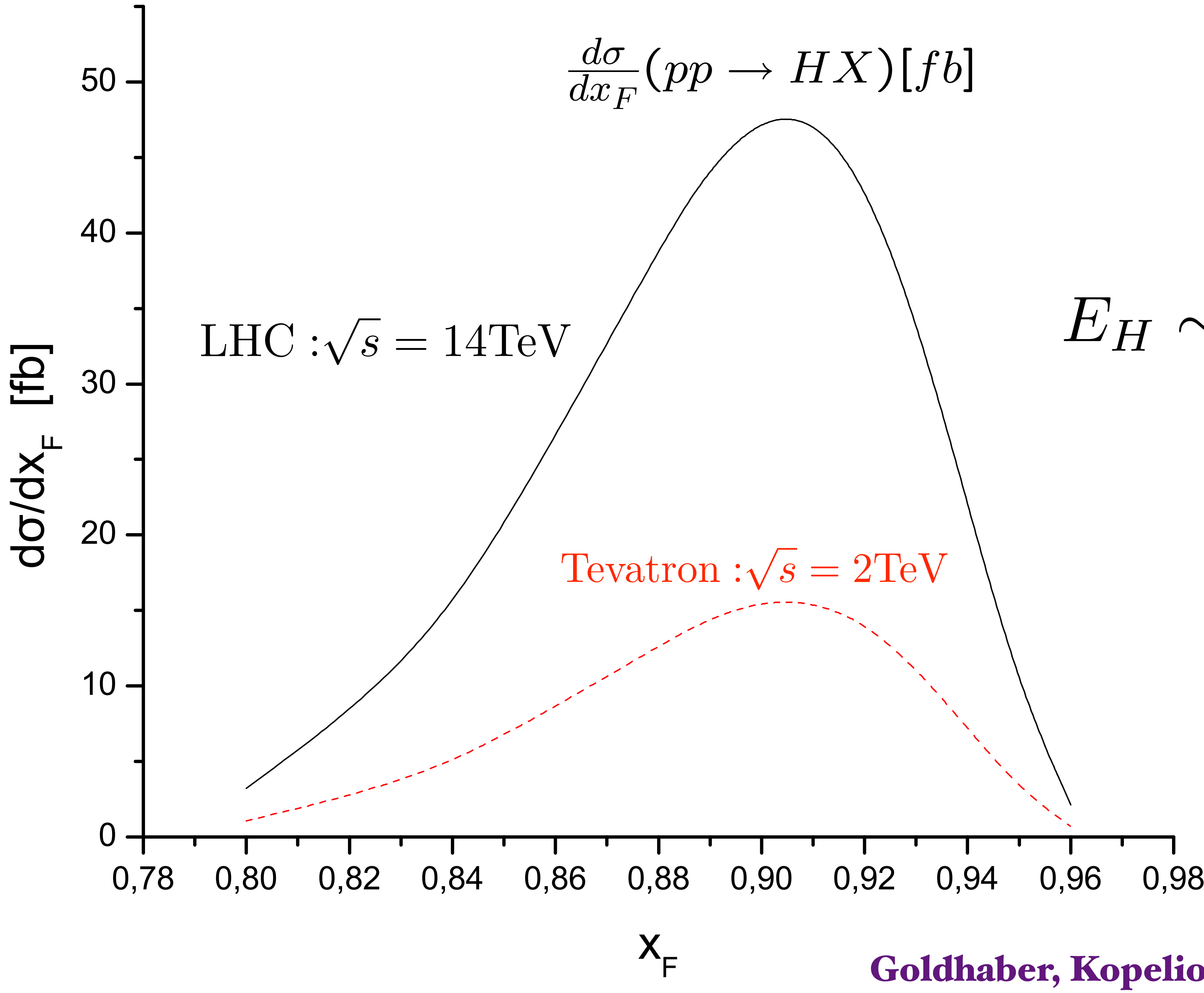
Also: intrinsic strangeness, bottom, top

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 Inclusive Higgs Production



$$E_H \sim 0.9 E_p$$

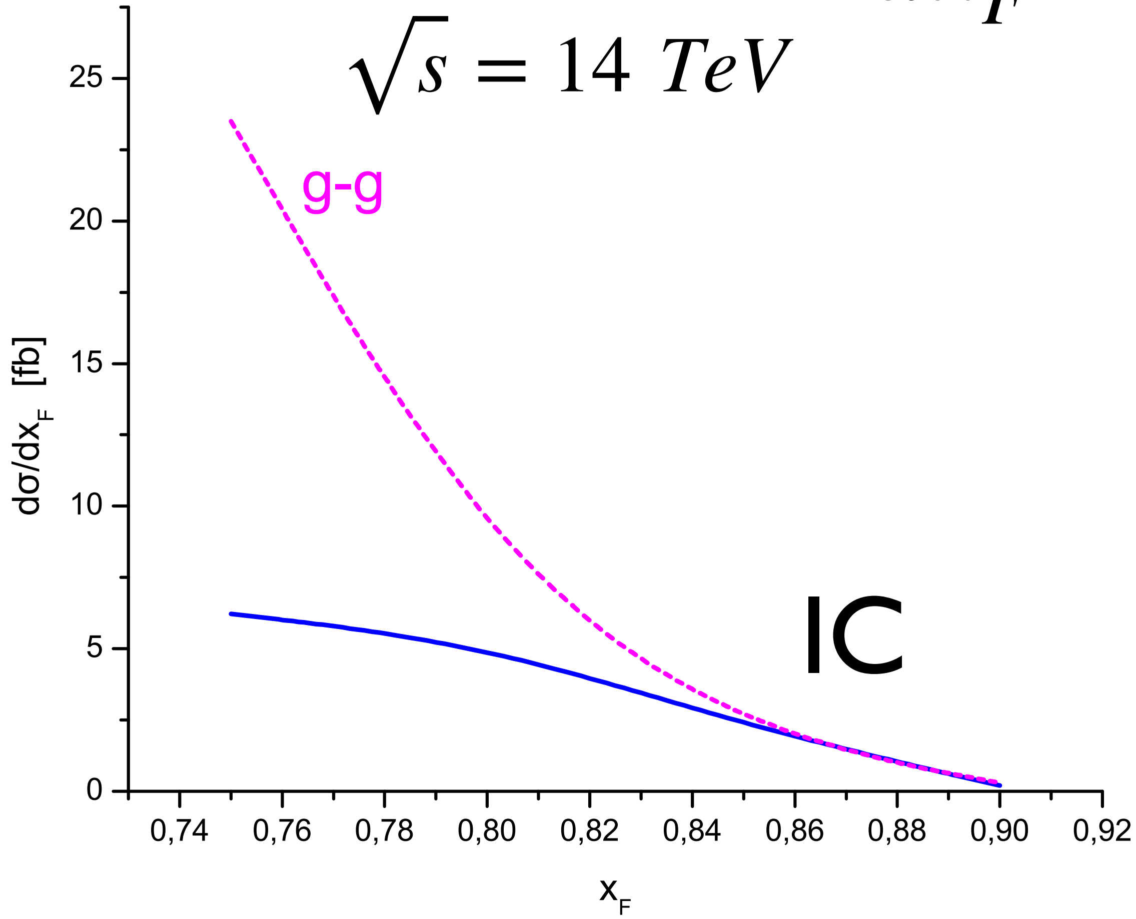
Goldhaber, Kopeliovich, Schmidt, sjb

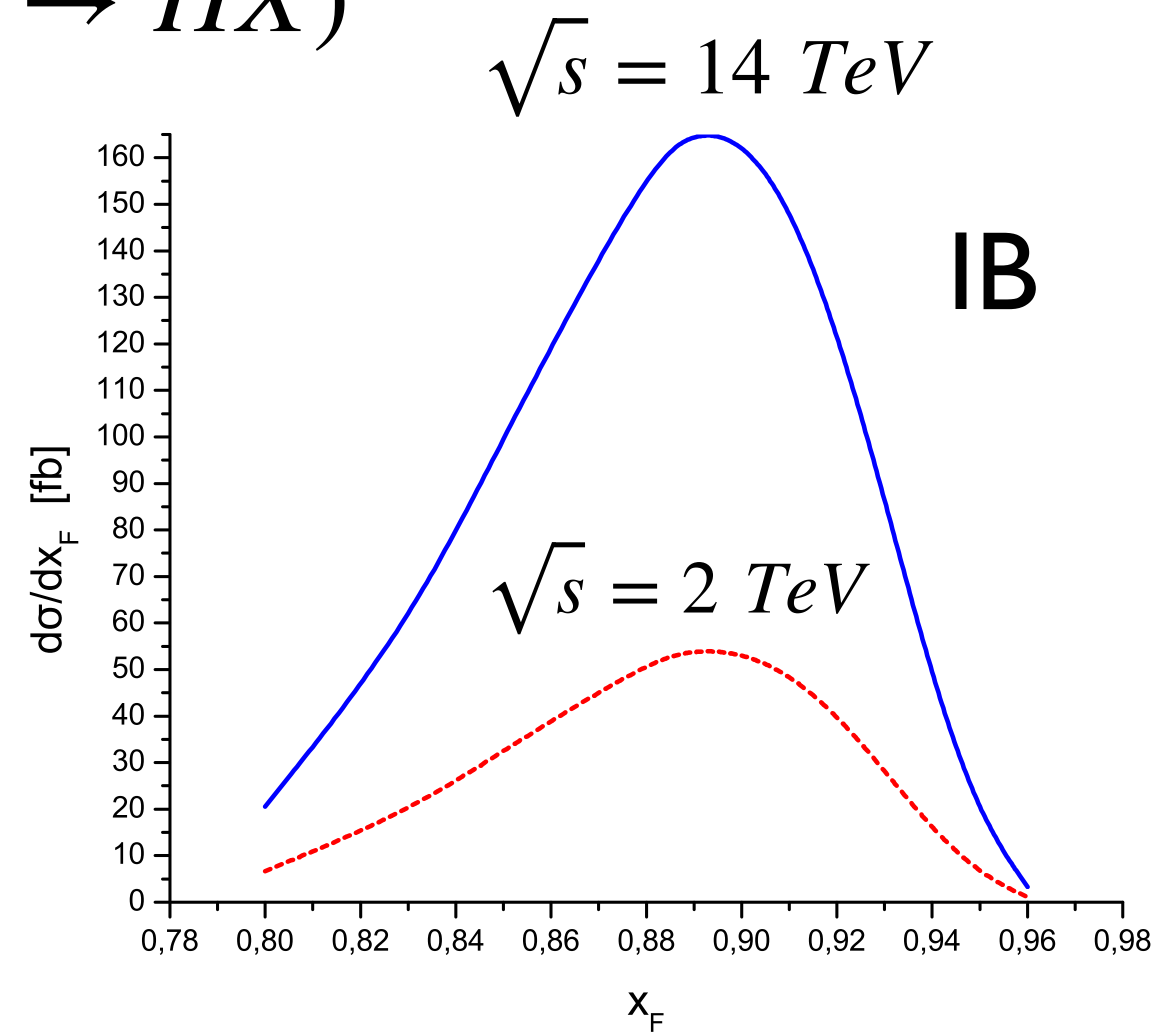
$$\text{Measure } H \to ZZ^* \to \mu^+\mu^-\mu^+\mu^-.$$

Inclusive Production of Higgs Boson and Intrinsic Charm and Bottom in Proton

Juraj Smieško

$$\frac{d\sigma}{dx_F}(pp \to HX)$$

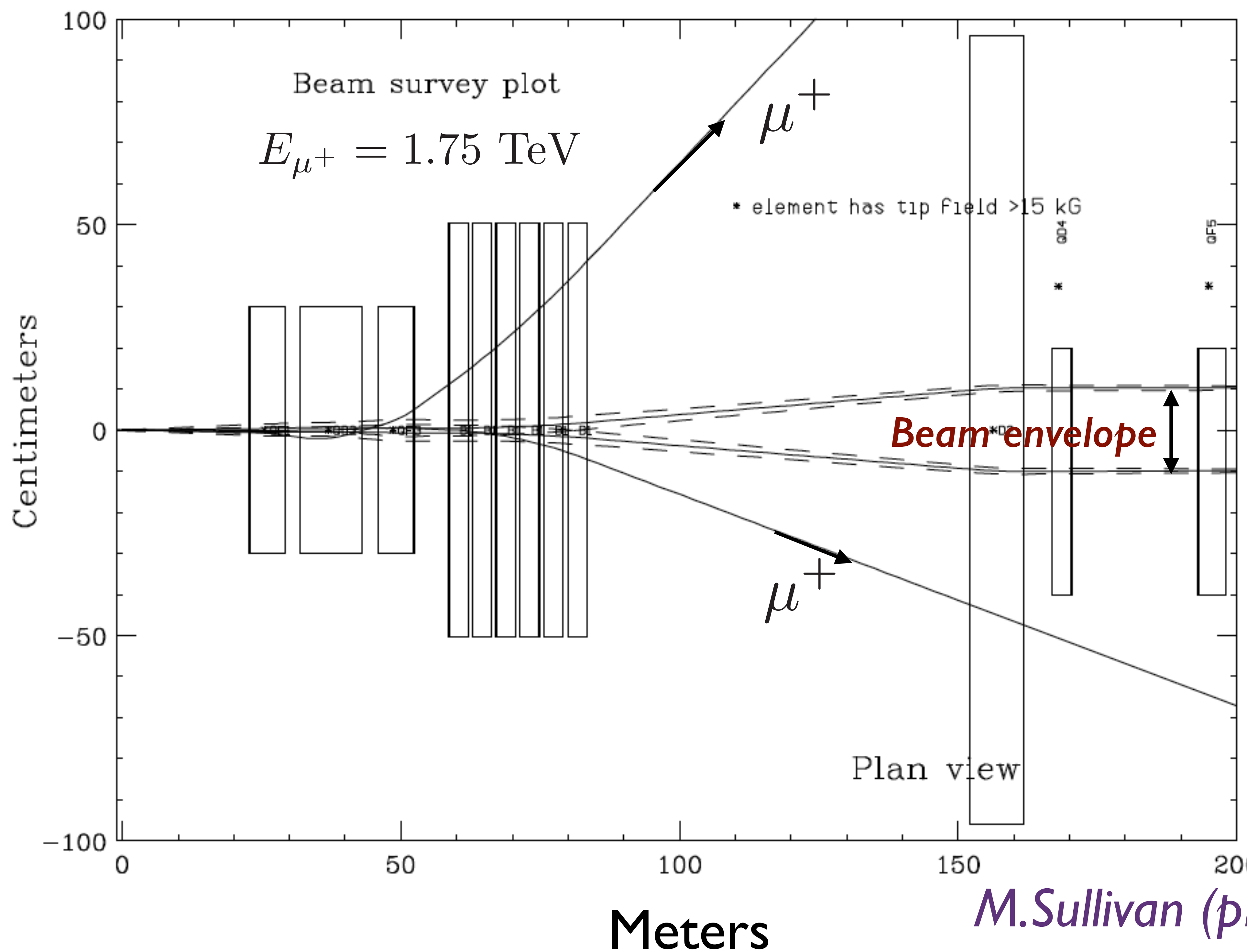




The x_F-distribution of the Higgs boson produced in pp collision at the LHC energy $\sqrt{s}$ = 14 TeV due to the non-perturbative intrinsic charm with the probability about 1 % (solid line). The dashed line corresponds to the Higgs boson production from the gluon-gluon fusion (top). The same distribution due to the non-perturbative IB at the LHC energy $\sqrt{s}$ = 14 TeV (solid line) and the TEVATRON energy $\sqrt{s}$ = 2 TeV (dashed line, bottom) [25].

Use LHC Magnetic Field as Downstream Muon Spectrometer

$$pp \to HX \to \mu^+\mu^-\mu^+\mu^- X$$



M.Sullivan (preliminary)

Measure exotic events at SMOG@LHCb such as

$$pA \to \Upsilon + J/\psi X \to \mu^+\mu^-\mu^+\mu^- X$$

Why is Intrinsic Heavy Quark Phenomena Important?

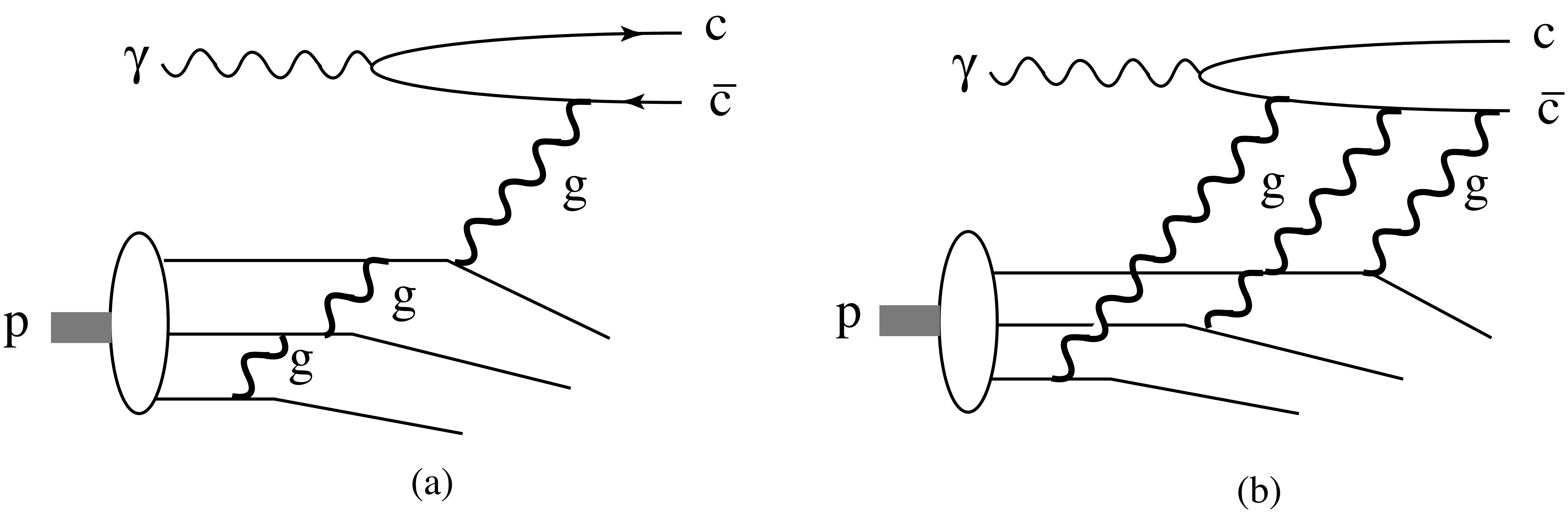
- ***Test Fundamental QCD predictions OPE, Non-Abelian QCD***

  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***

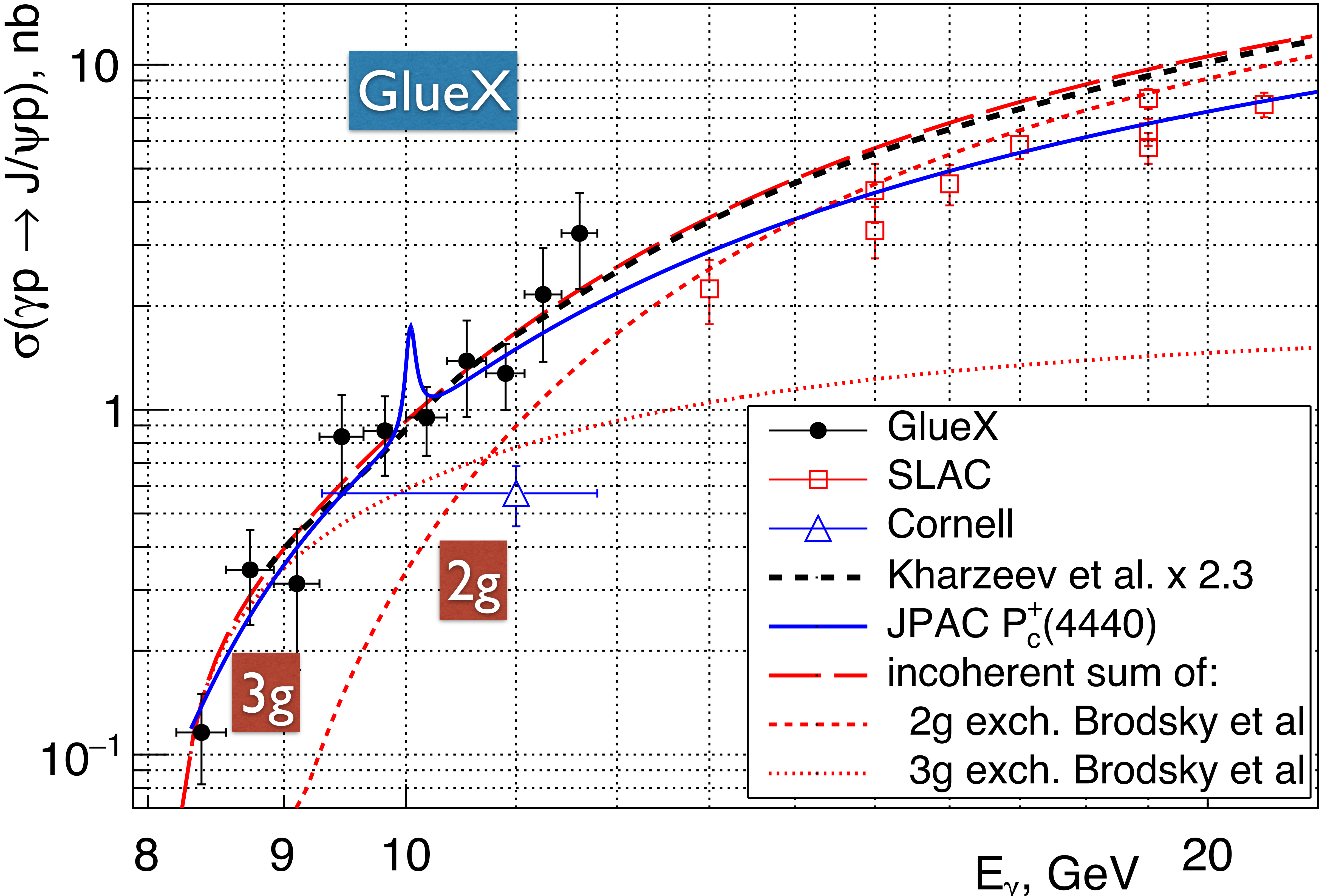
Photoproduction of charm near threshold

S. J. Brodsky,[1] E. Chudakov,[2] P. Hoyer,[3] J.M. Laget,[4]



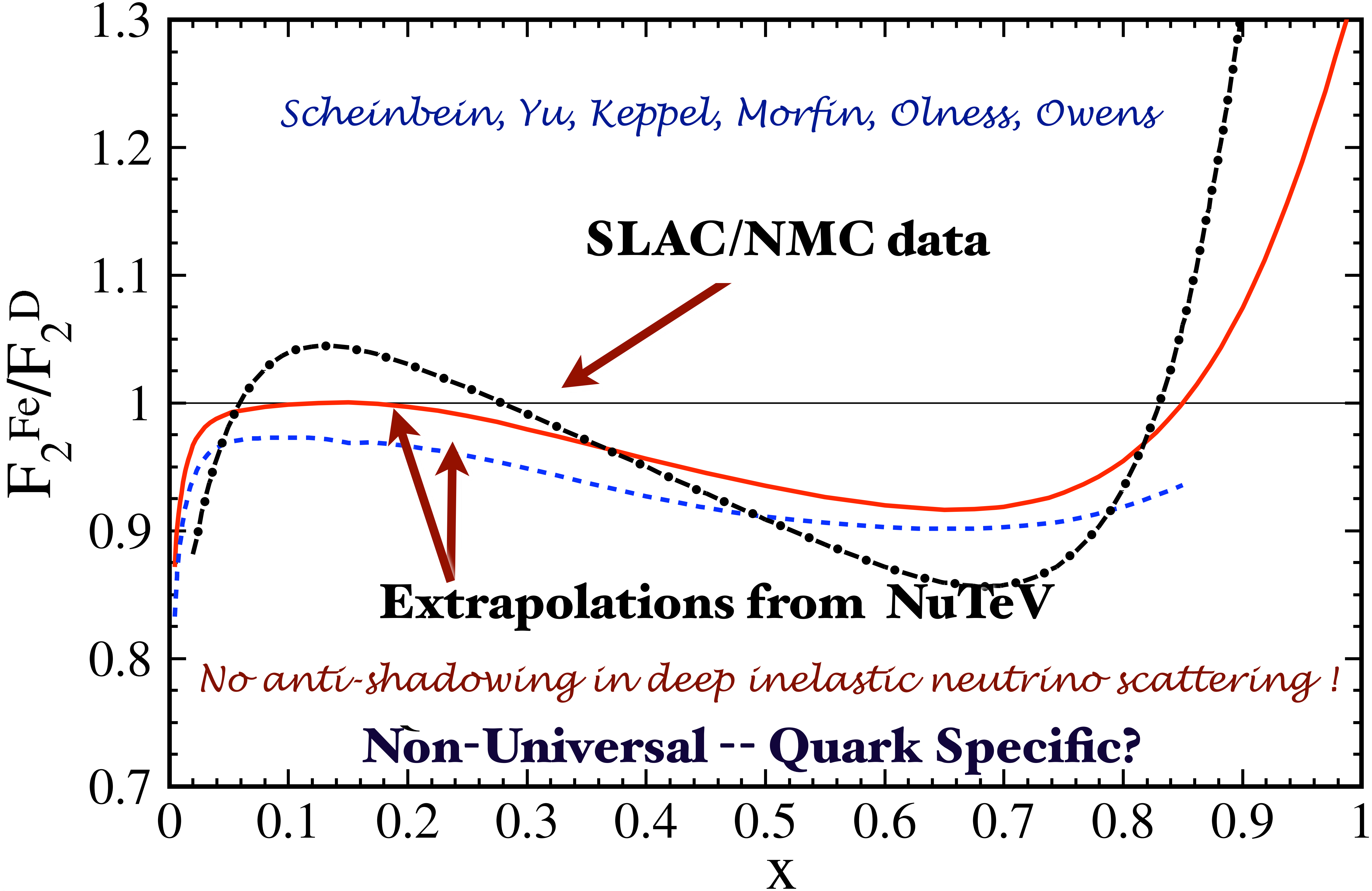
Another aspect of IC

First measurement of near-threshold J/ψ exclusive photoproduction off the proton



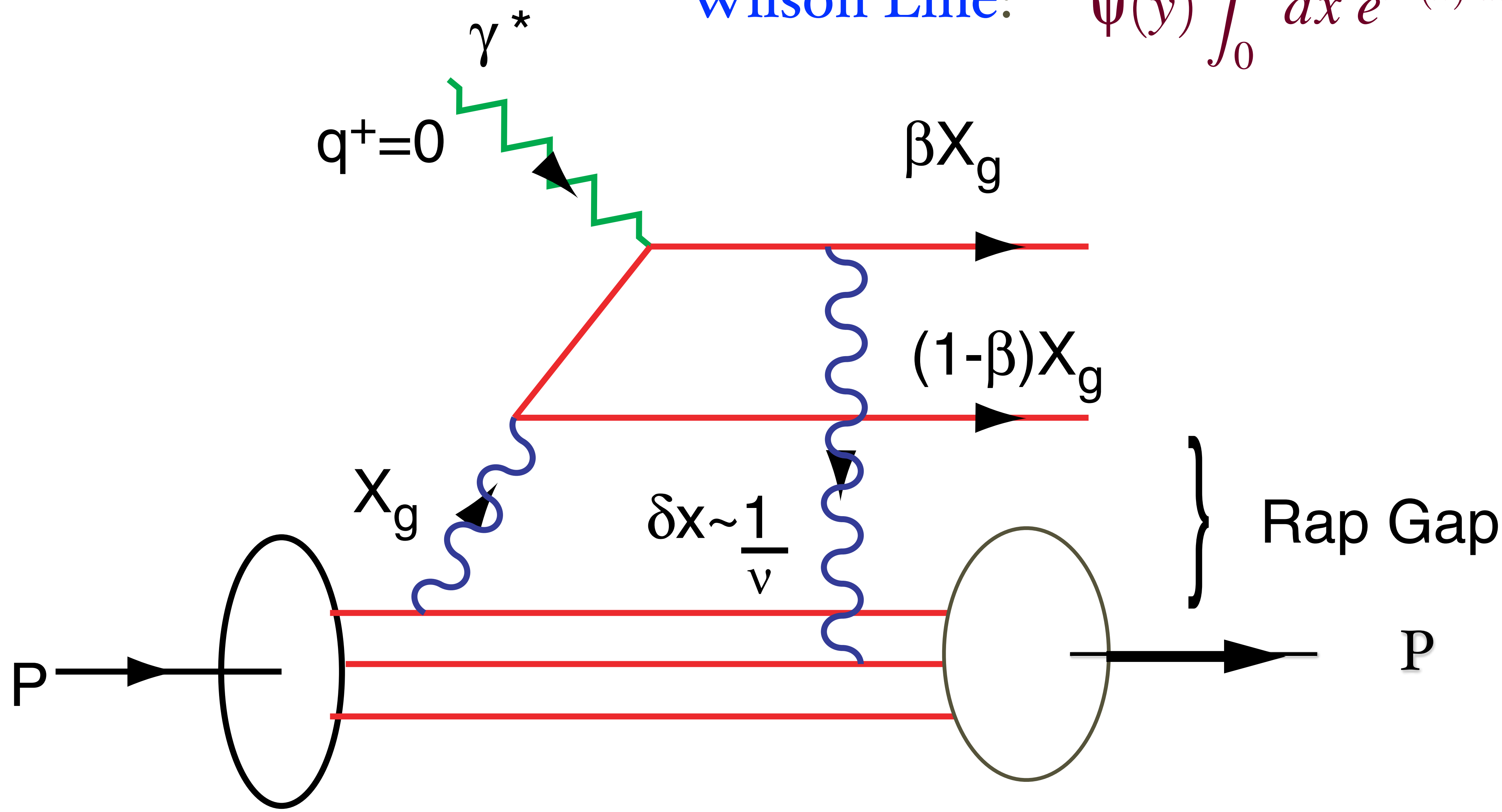
GlueX results for the J/ψ total cross section vs beam energy, compared to the Cornell [15] and SLAC [16] data, the theoretical predictions [11, 13], and the JPAC model [6] corresponding to $\mathcal{B}(P_c^+(4440) \to J/\psi p) = 1.6\%$ for the $J^P = 3/2^-$ case as discussed in the text. All curves are fitted/scaled to the GlueX data only. For our data the quadratic sums of statistical and systematic errors are shown; the overall normalization uncertainty is 27%.

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

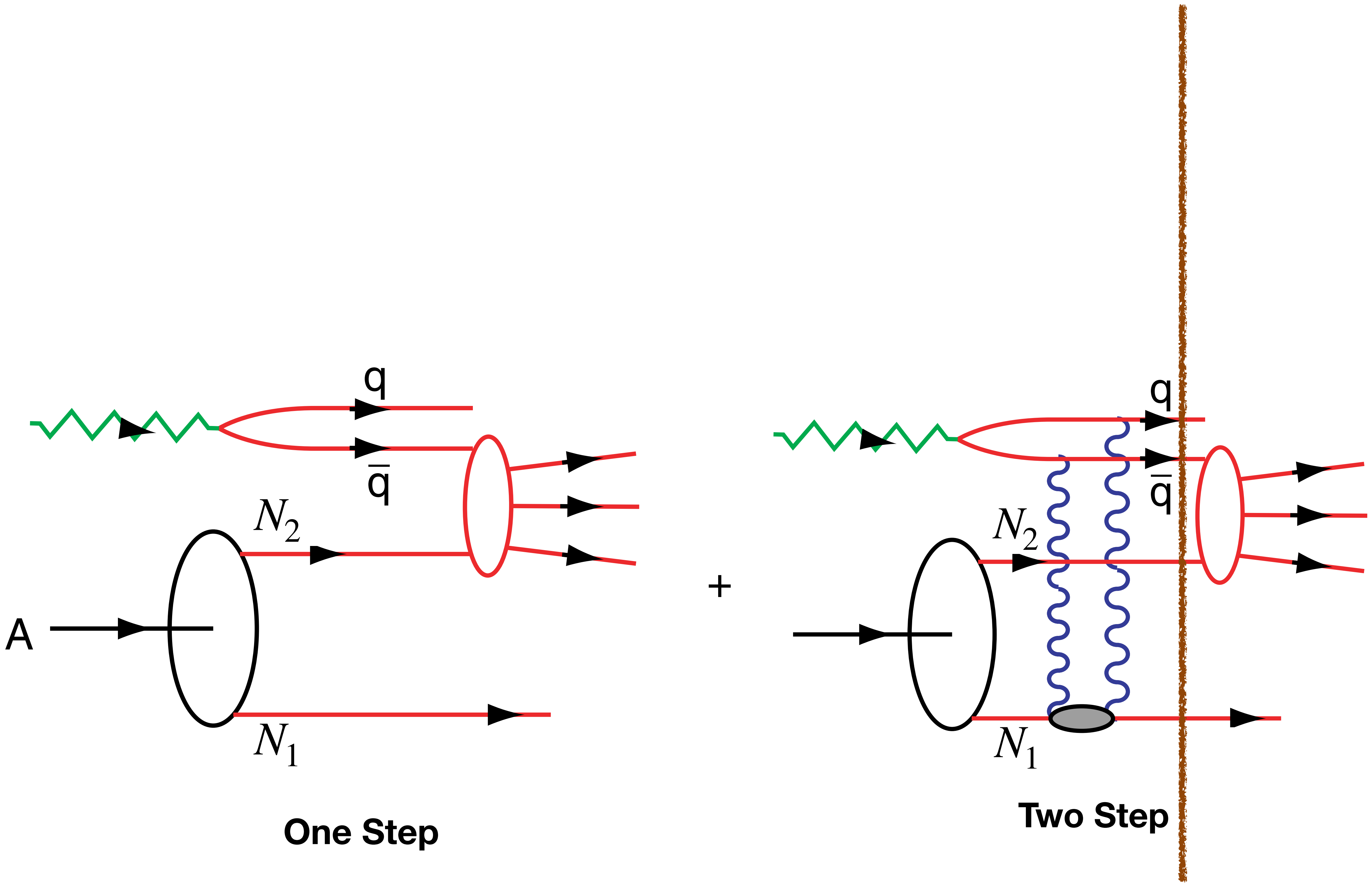


QCD Mechanism for Rapidity Gaps

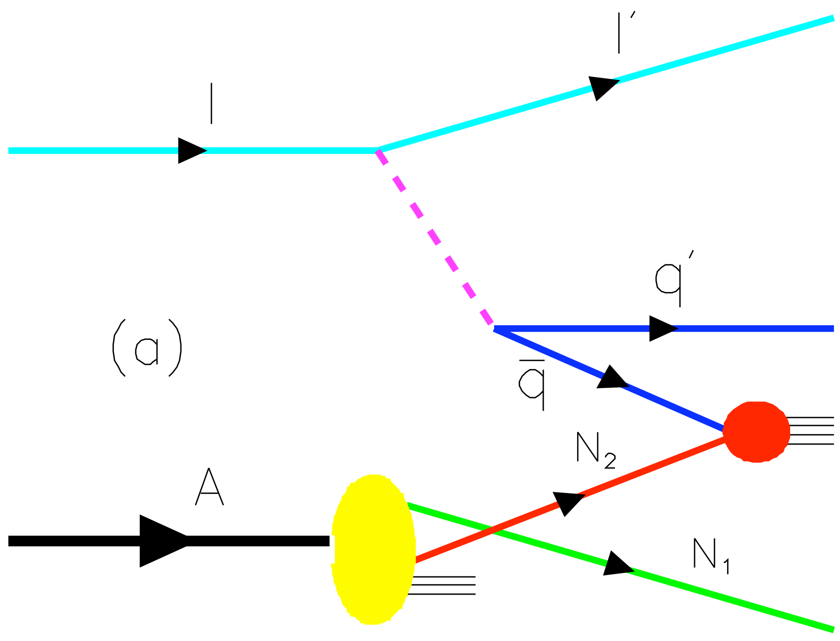
Wilson Line: $\overline{\psi}(y)\int_0^y dx\, e^{iA(x)\cdot dx}\,\psi(0)$



Reproduces lab-frame color dipole approach
DDIS: Input for leading twist nuclear shadowing

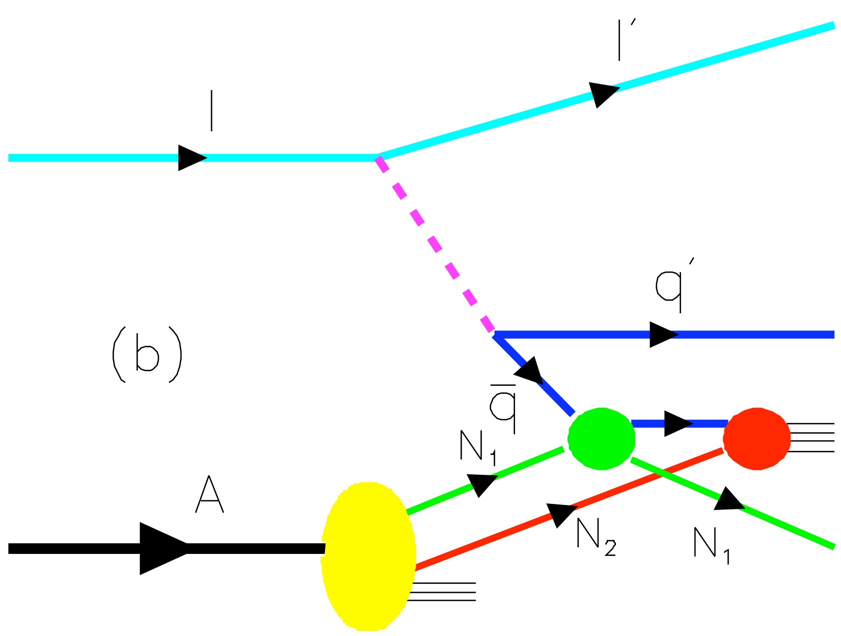


Glauber Cut:
On-Shell Propagation



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

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

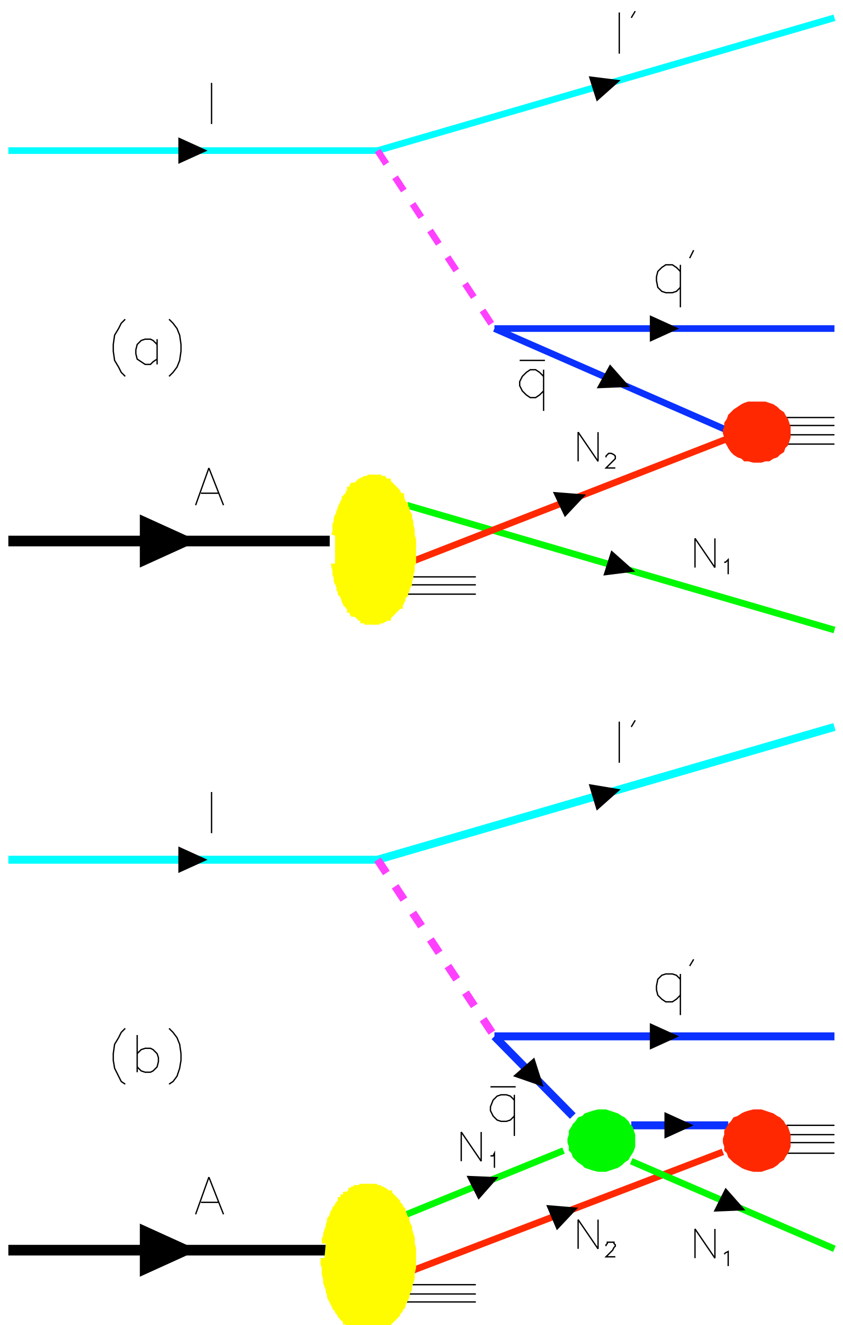


If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

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

Diffraction via Pomeron gives destructive interference!

Shadowing



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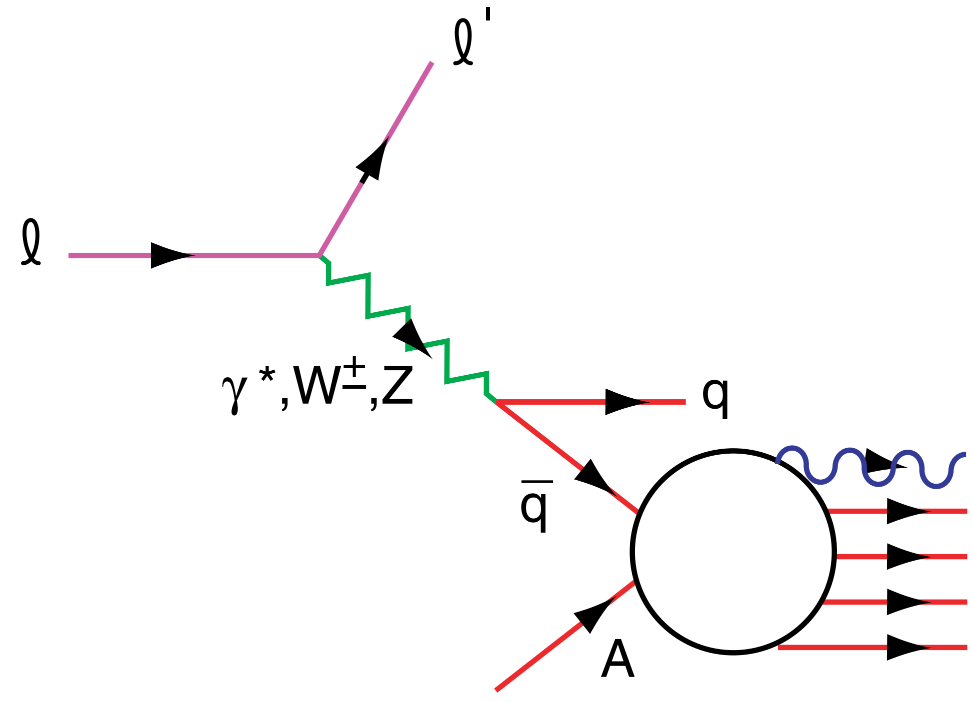
Diffraction via Reggeon Exchange gives constructive interference!

Anti-shadowing

H. Lu, sjb

Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$



Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$

Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x}_{bj}$ at small x_{bj}.

Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

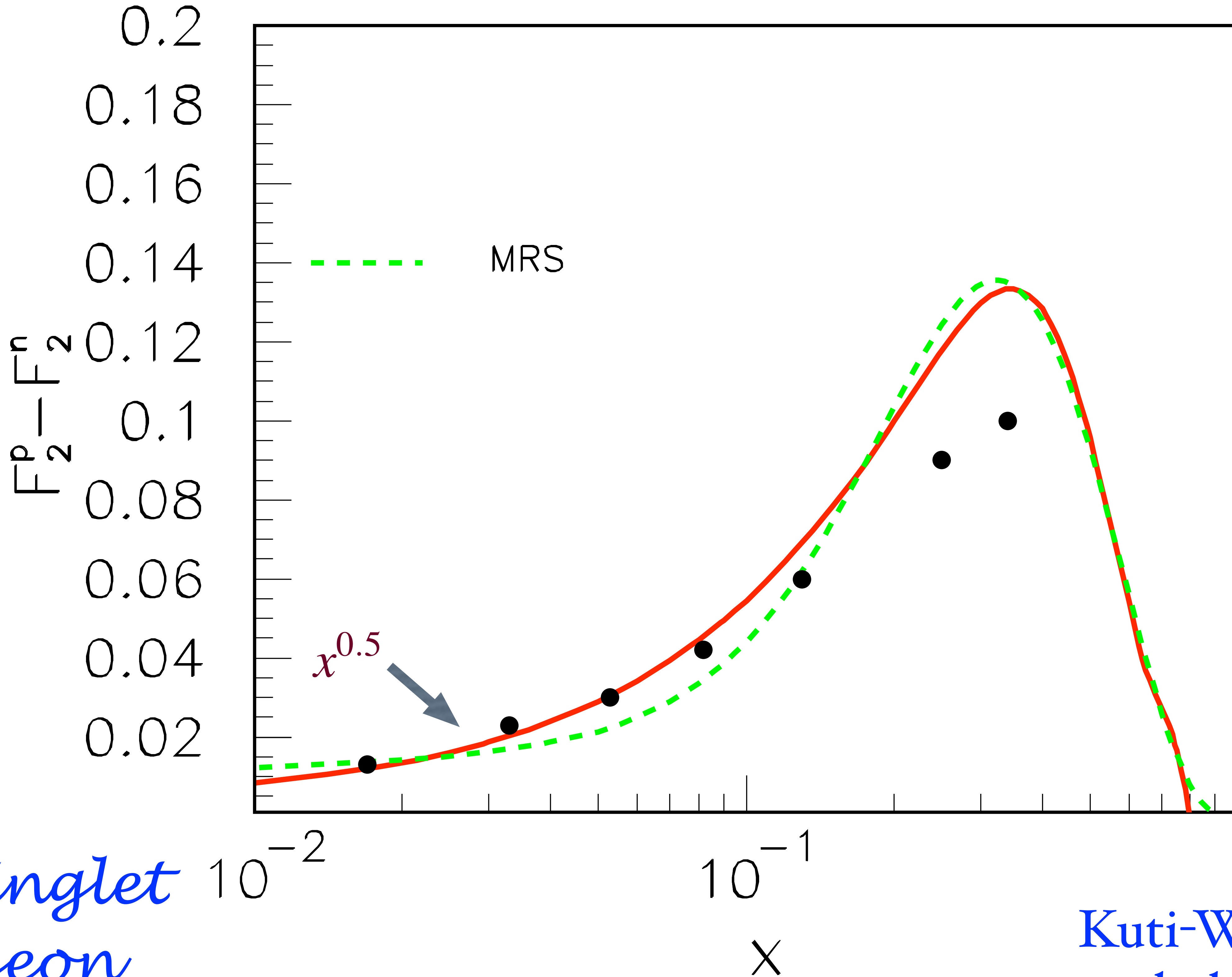
Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb

Regge dependence of structure functions in LFHQCD:

Guy F. de Téramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, S. J. Brodsky, and Alexandre Deur (HLFHS Collaboration) Phys. Rev. Lett. 120, 182001 –2018



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Phase of two-step amplitude relative to one step:

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

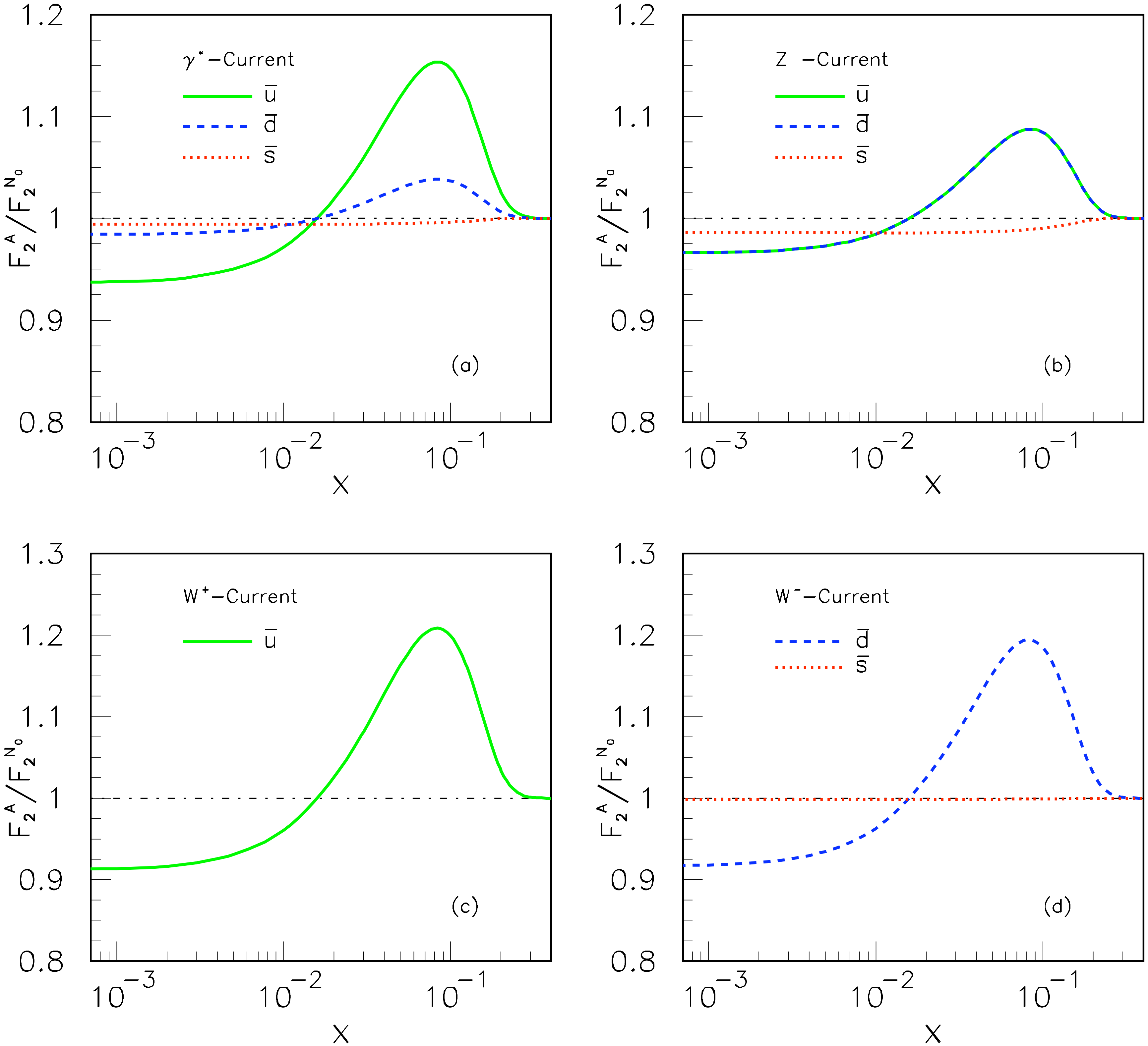
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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

Critical tests: Tagged SIDIS, Drell-Yan



Schmidt, Yang; sjb

Modifies NuTeV extraction of

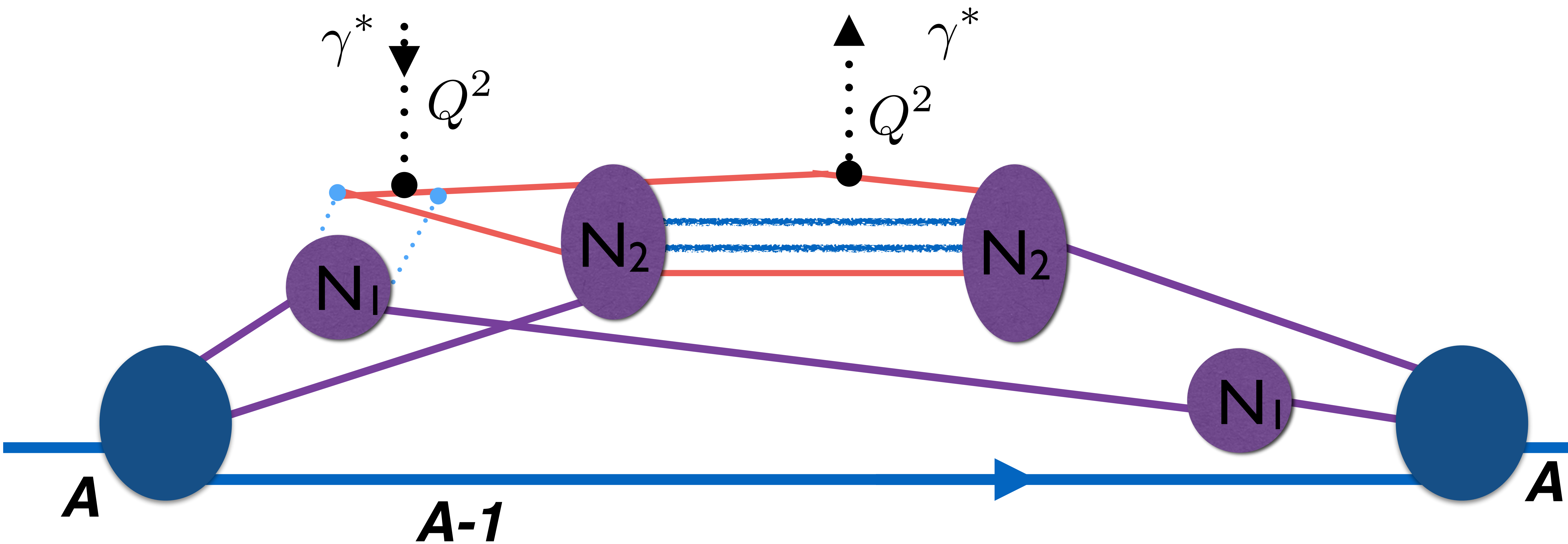
$\sin^2\theta_W$

Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

$$q^+ = 0 \quad q_\perp^2 = Q^2 = -q^2$$

Illustrates the LF time sequence



Front-Face Nucleon N_1 struck — *Front-Face Nucleon N_1 not struck*

One-Step / Two-Step Interference

Study Double Virtual Compton Scattering $\gamma^* A \rightarrow \gamma^* A$

Cannot reduce to matrix element of local operator! No Sum Rules!

Liuti, Schmidt sjb

S. Liuti, I. Schmidt, sjb

- Unlike shadowing, anti-shadowing from Reggeon exchange is flavor specific;
- Each quark and anti-quark will have distinctly different constructive interference patterns
- The flavor dependence of antishadowing explains why anti- shadowing is different for electron (neutral electro- magnetic current) vs. neutrino (charged weak current) DIS reactions.
- Test of the explanation of antishadowing: Bjorken-scaling leading-twist charge exchange DDIS reaction $\gamma^* p \to n X^+$ with a rapidity gap due to I=1 Reggeon exchang
- The finite path length due to the on-shell propagation of V^0 between N_1 and N_2 contributes a finite distance $(\Delta z)^2$ between the two virtual photons in the DVCS amplitude.

The usual "handbag" diagram where the two $J^\mu(x)$ and $J^\nu(0)$ currents acting on an uninterrupted quark propagator are replaced by a local operator $T^{\mu\nu}(0)$ as $Q^2 \to \infty$, is inapplicable in deeply virtual Compton scattering from a nucleus since the currents act on different nucleons.

$$\Delta z^2 \text{ does not vanish as } \frac{1}{Q^2}.$$

OPE and Sum Rules invalid for nuclear pdfs

Invariance Principles of Quantum Field Theory

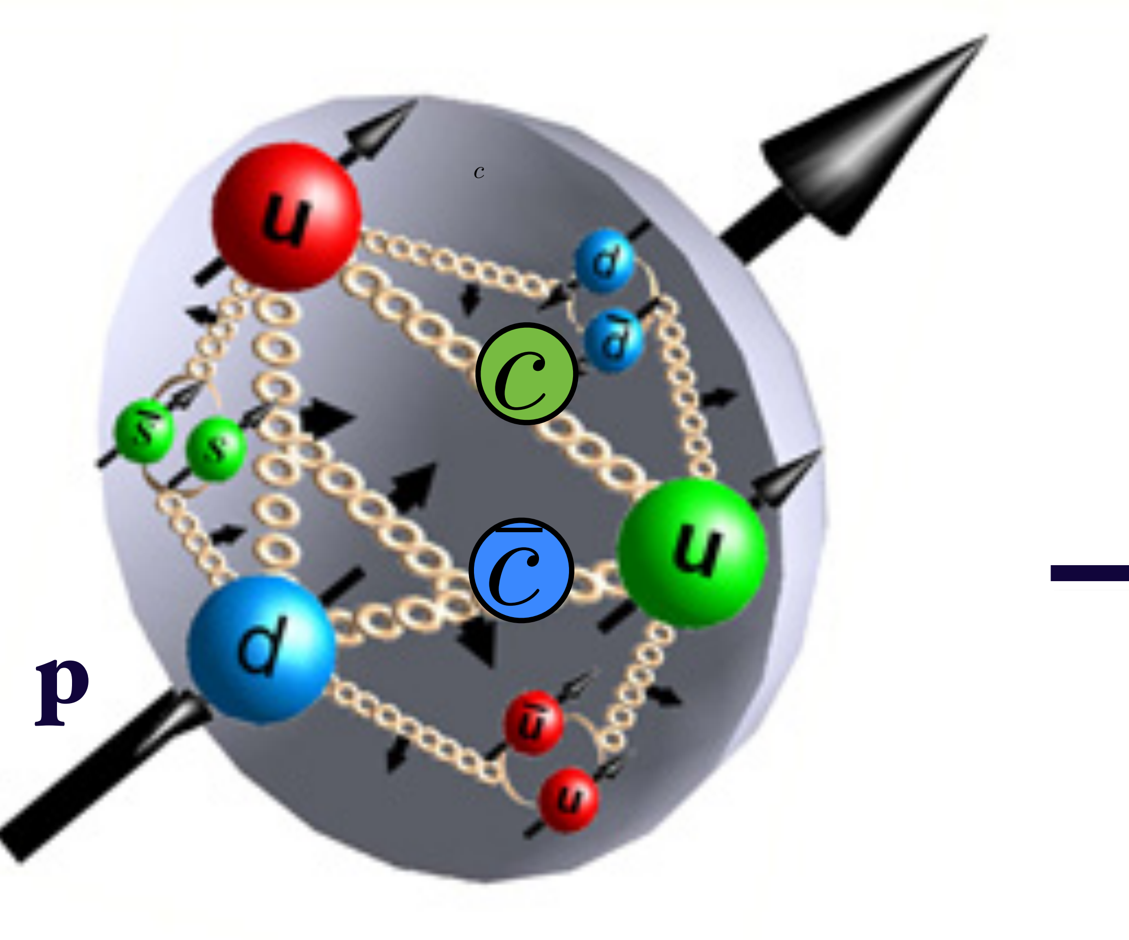
- *Polncarè Invariance: Physical predictions must be independent of the observer's Lorentz frame: Front Form*
- *Causality: Information within causal horizon: Front Form*
- *Gauge Invariance: Physical predictions of gauge theories must be independent of the choice of gauge*
- *Scheme-Independence: Physical predictions of a renormalizable theory must be independent of the choice of the renormalization scheme —Principle of Maximum Conformality (PMC)*
- *Mass-Scale Invariance:*
  Conformal Invariance of the Action (DAFF)

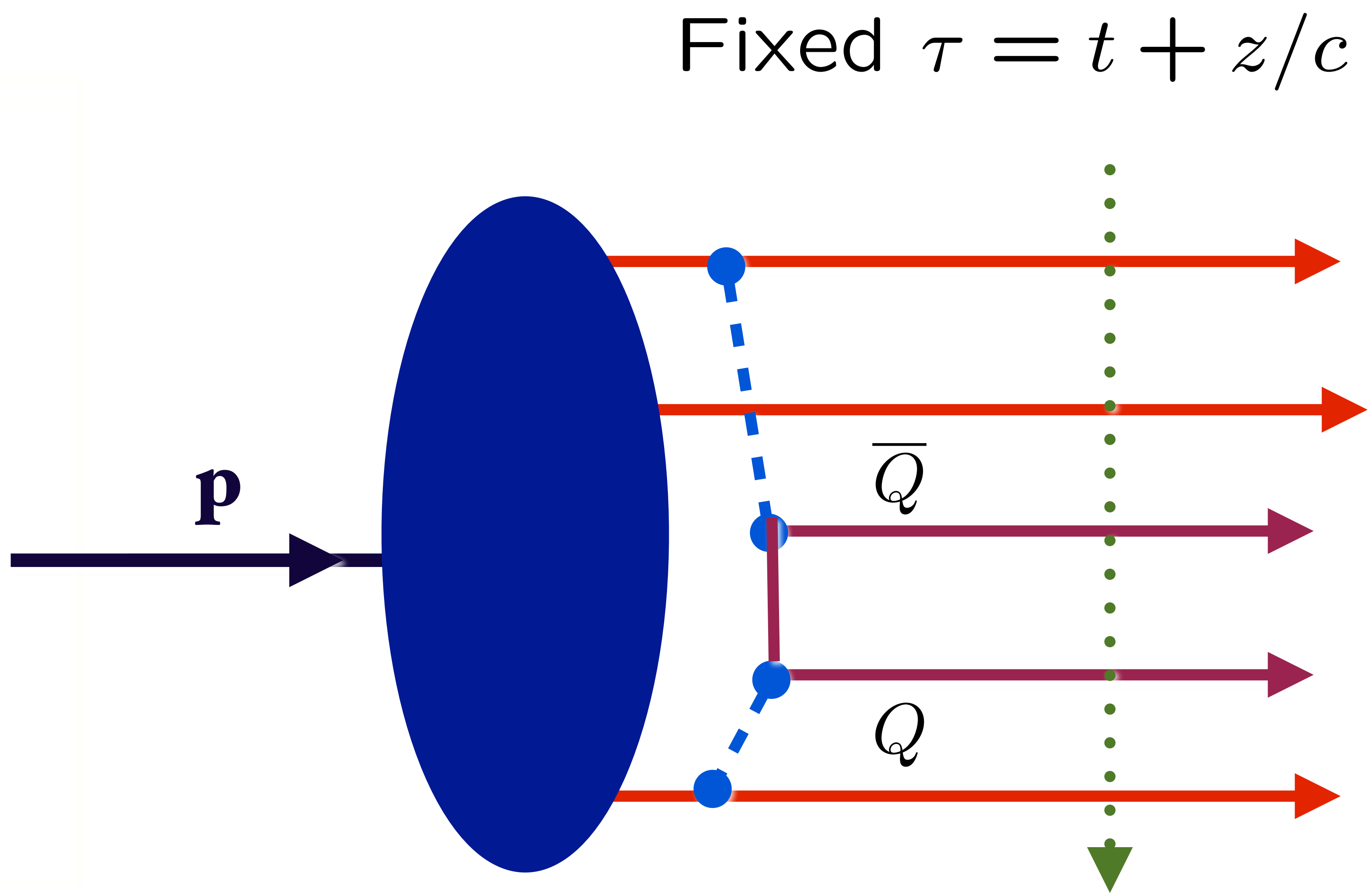
Challenge: Compute Hadron Structure, Spectroscopy, and Dynamics from QCD!

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

- 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
- Massless Pion: Quark Anti-Quark Bound State
- QCD Coupling at all Scales $\alpha_s(Q^2)$
- Eliminate Scale Uncertainties and Scheme Dependence
- Heavy Quark Distributions

Novel QCD Physics of Heavy Quark Hadroproduction





Scientific Program:

Heavy-Quark Hadroproduction from Collider to Astroparticle Physics

Mainz Institute for Theoretical Physics

October 9, 2019

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY