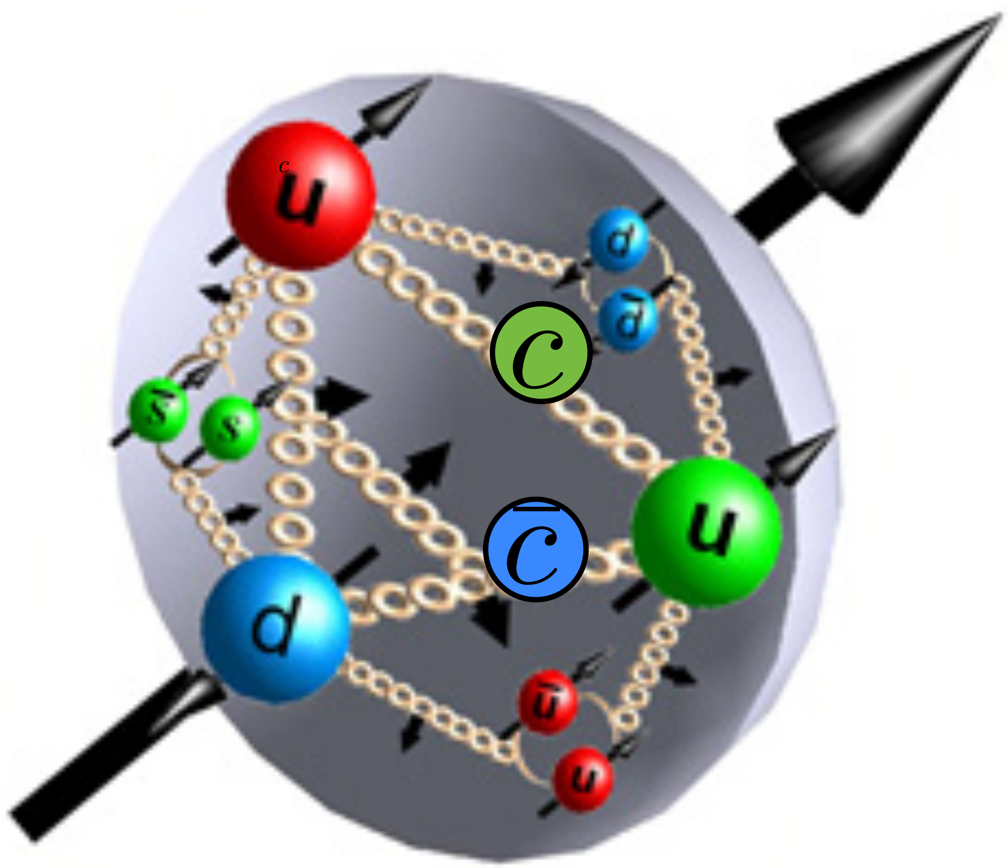
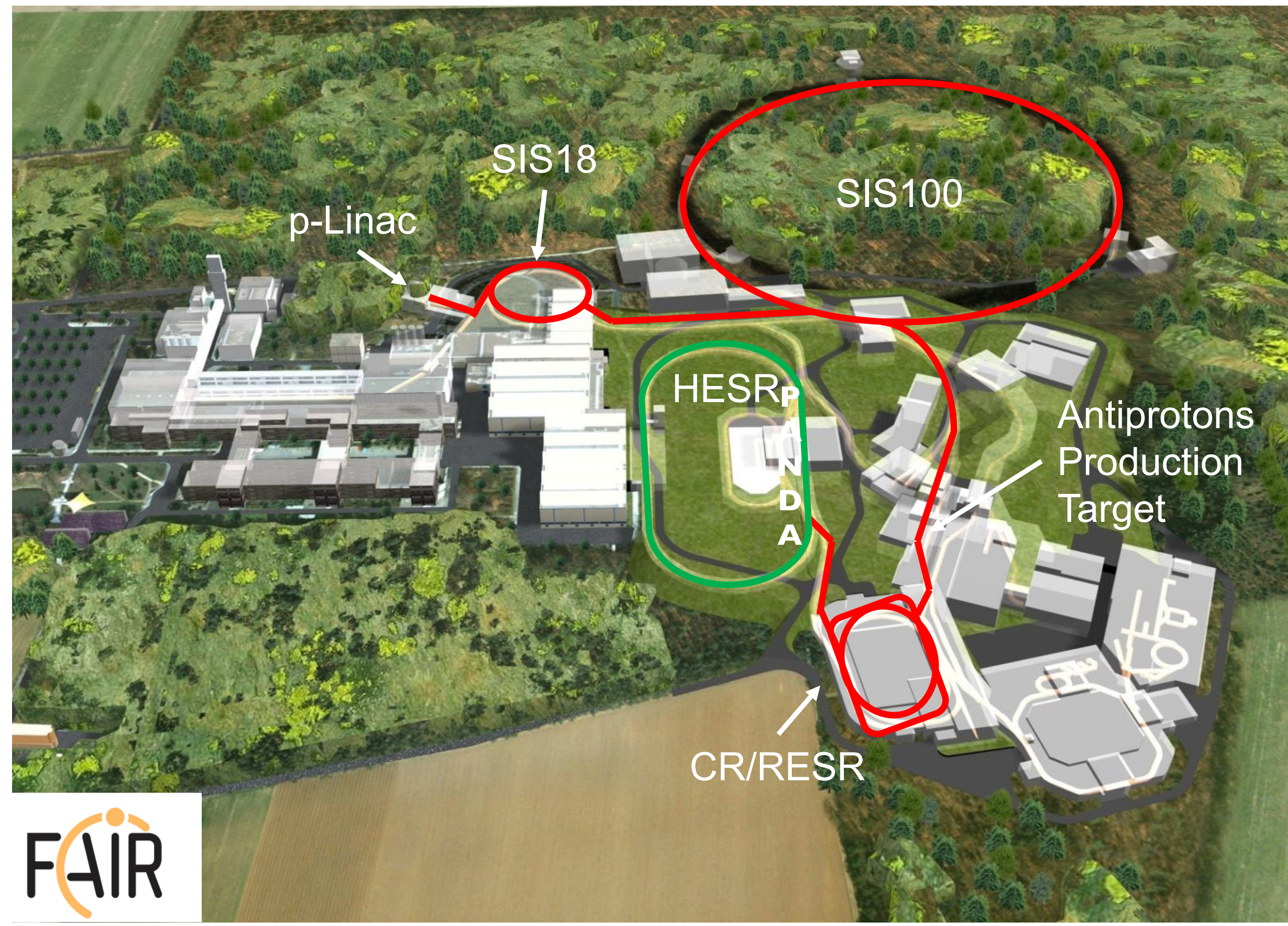
Novel Tests of QCD at FAIR



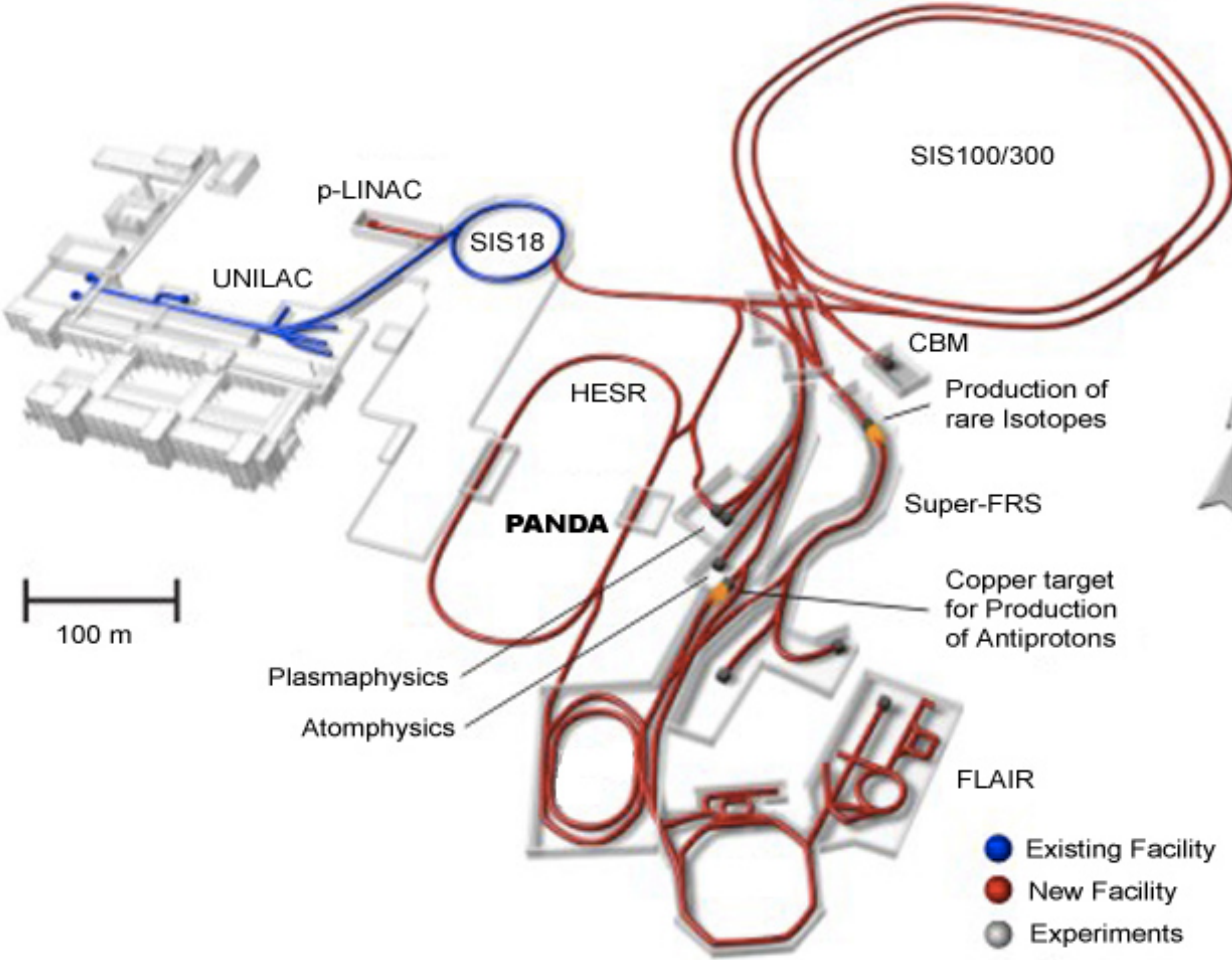


International Conference on Science and Technology for FAIR in Europe October 13-17, 2014

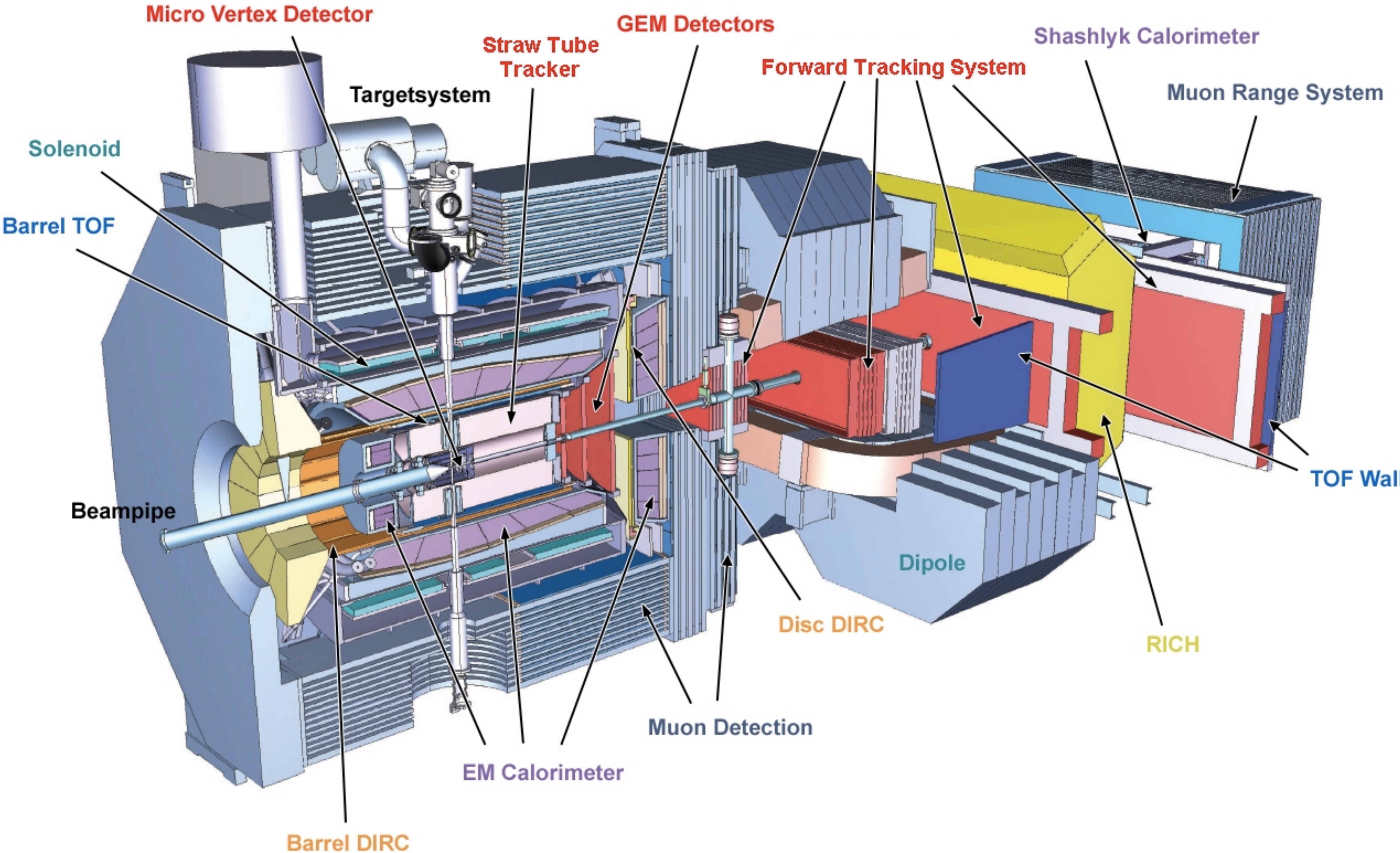
Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY


SIS100/300
p-LINAC
SIS18
UNILAC
CBM
HESR
Production of
rare Isotopes
N
Super-FRS
PANDA
100 m
Copper target
for Production
of Antiprotons
Plasmaphysics
Atomphysics
FLAIR
Existing Facility
New Facility
Experiments

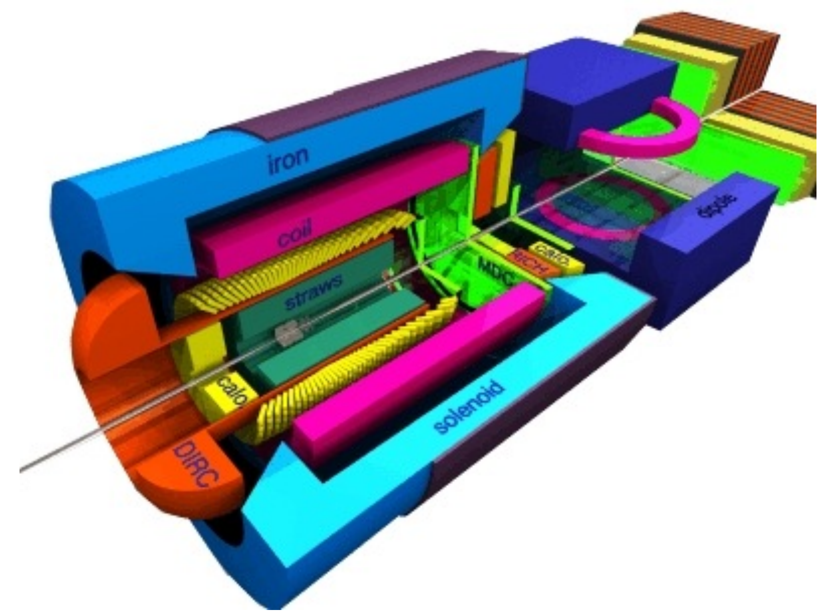
PANDA



Micro Vertex Detector
GEM Detectors
Straw Tube
Tracker
Shashlyk Calorimeter
Forward Tracking System
Muon Range System
Targetsystem
Solenoid
Barrel TOF
TOF Wall
Beampipe
Dipole
Disc DIRC
RICH
Muon Detection
EM Calorimeter
Barrel DIRC

Proton–ANtiproton in DArmstadt (PANDA)

- Anti-Protons from HESR
- E_{max} = 15 GeV
- Pellet or Gas Jet Targets
- Resolution 10^{-4} to 10^{-5}
- $L_{max} = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$

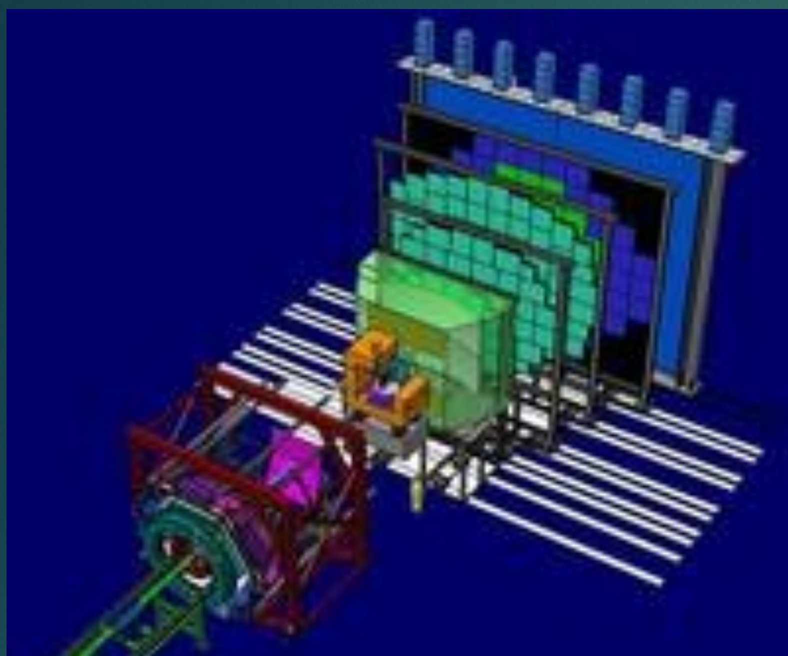


FAIR

Experimental highlights

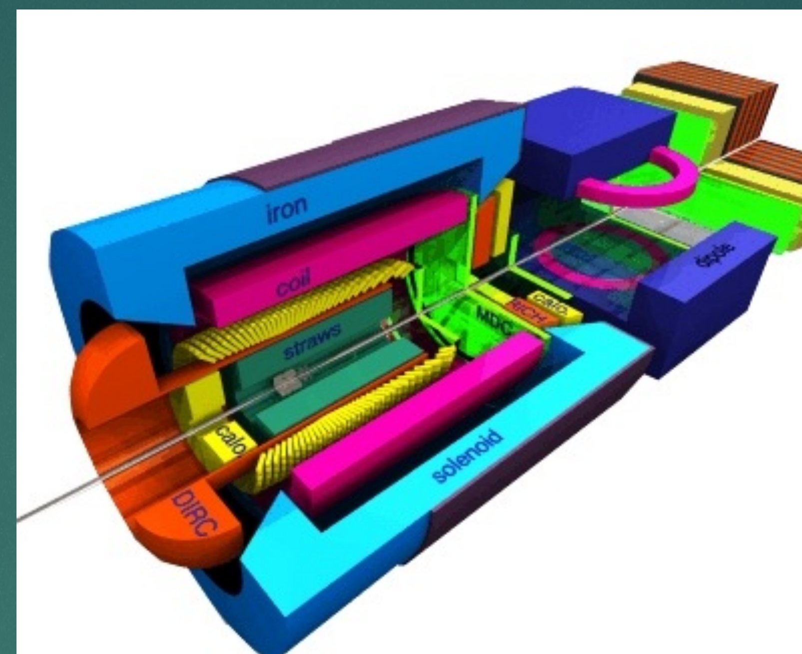
HIDETO EN'YO

Impressive array of diverse, fundamental physics



Compressed **B**aryonic **M**atter

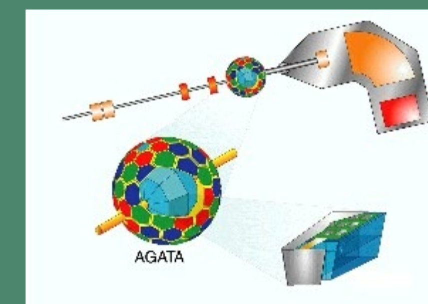
- QCD chiral symmetry breaking/restoration
- EOS at high baryon density
- Origin of hadron masses
- Quark confinement
- Physics of neutron stars

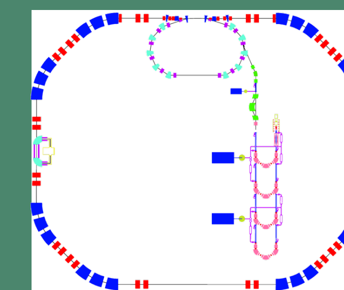


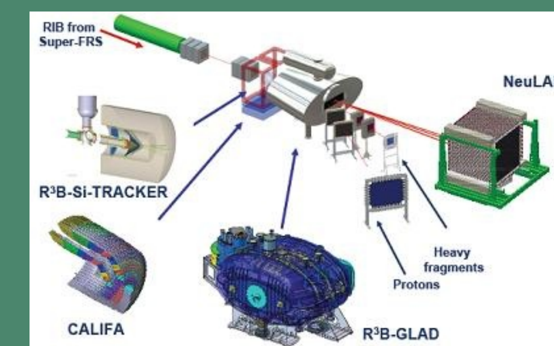
PANDA

Anti**p**roton **An**nihilation at **Da**rmstadt)

- Glueballs and Hybrids
- Charm in Nuclei
- Charmonium
- Hyper nuclei
- D- meson Physics







NUclear **ST**ructure, **A**strophysics and **R**eactions

- **Super FRS**
- DESPEC/HISPEC ELISe
- EXL ILIMA
- LaSpec MATS
- R3B

Novel Tests of QCD at GSI-FAIR

- Drell-Yan: Breakdown of pQCD Factorization
- Violation of Lam-Tung Relation
- Double Drell-Yan Reactions $\bar{p}p \to \mu^+\mu^-\mu^+\mu^- X$
- Higher Twist Effects at High x_F
- Non-Universal Anti-Shadowing
- Diffractive Drell-Yan Reactions $\bar{p}p \to \mu^+\mu^- p$
- Exclusive Processes

QED Lagrangian

$$\mathcal{L}_{QED} = -\frac{1}{4} Tr(F^{\mu\nu} F_{\mu\nu}) + \sum_{\ell=1}^{n_\ell} i \bar{\Psi}_\ell D_\mu \gamma^\mu \Psi_\ell + \sum_{\ell=1}^{n_\ell} m_\ell \bar{\Psi}_\ell \Psi_\ell$$

$$iD^\mu = i\partial^\mu - eA^\mu \qquad F^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu$$

Yang Mills Gauge Principle: Phase Invariance at Every Point of Space and Time

Scale-Invariant Coupling
Renormalizable
Nearly-Conformal
Landau Pole

QCD Lagrangian

gluon dynamics — quark kinetic energy + quark-gluon dynamics — mass term

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \qquad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

Yang Mills Gauge Principle: Color Rotation and Phase Invariance at Every Point of Space and Time

Scale-Invariant Coupling
Renormalizable
Nearly-Conformal
Asymptotic Freedom
Color Confinement

QCD Lagrangian

gluon dynamics

quark kinetic energy + quark-gluon dynamics

mass term

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \qquad [D^\mu, D^\nu] = igG^{\mu\nu}$$

$\lim N_C \to 0$ at fixed $\alpha = C_F \alpha_s, n_\ell = n_F / C_F$

Analytic limit of QCD: Abelian Gauge Theory

$$C_F = \frac{N_C^2 - 1}{2N_C}$$

QCD → **QED**

P. Huet, sjb

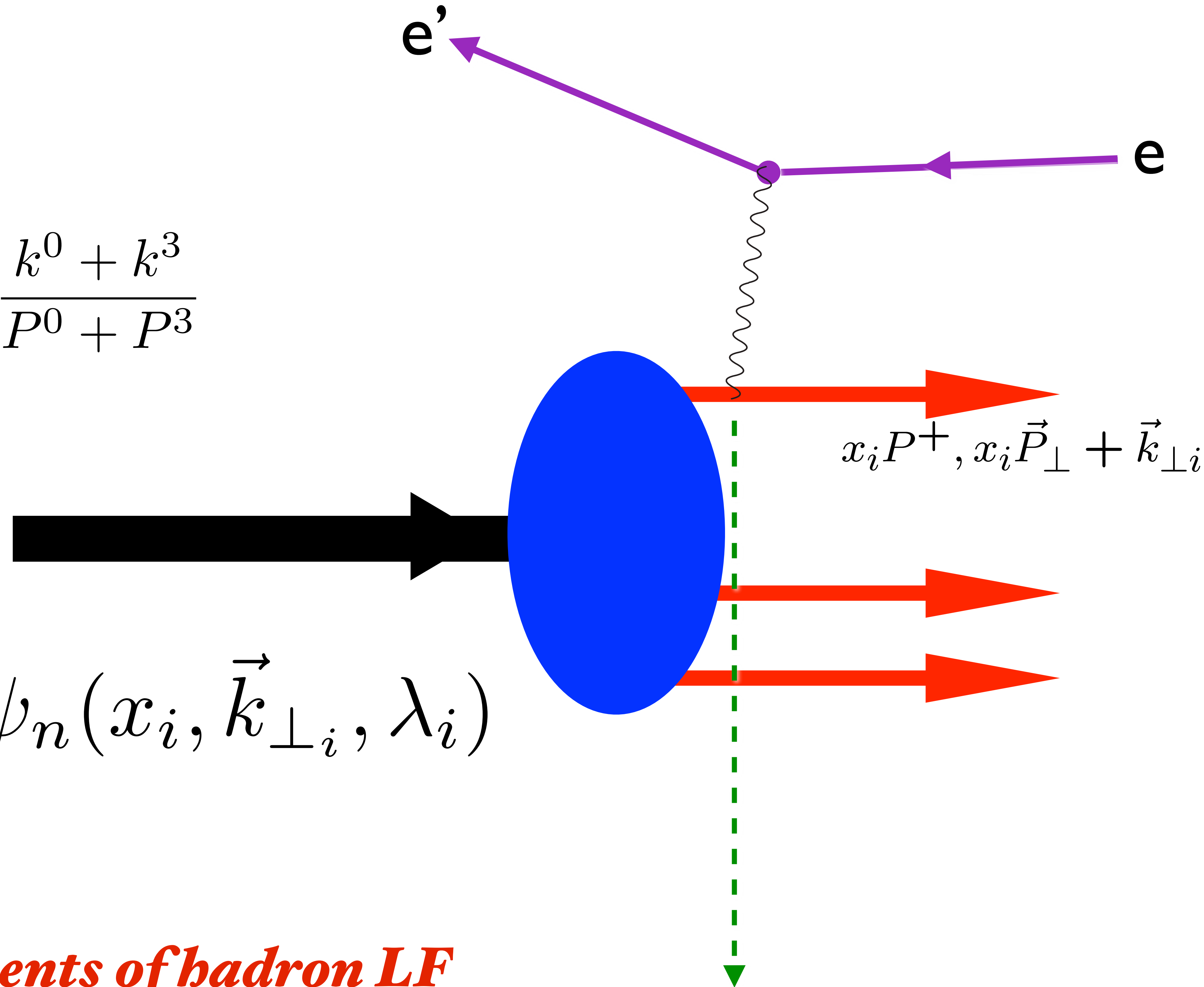
QED: Underlies Atomic Physics, Molecular Physics, Chemistry, Electromagnetic Interactions ...

QCD: Underlies Hadron Physics, Nuclear Physics, Strong Interactions, Jets

Theoretical Tools

- **Feynman diagrams and perturbation theory**
- **Bethe Salpeter Equation, Dyson-Schwinger Equations**
- **Lattice Gauge Theory**
- **Frame-Independent Light-Front Dynamics**
- **Light-Front Holography & AdS/QCD !**

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



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

Measurements of hadron LF wavefunction are at fixed LF time

Like a flash photograph

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

Each element of flash photograph illuminated along the light front **at a fixed**

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

Evolve in LF time

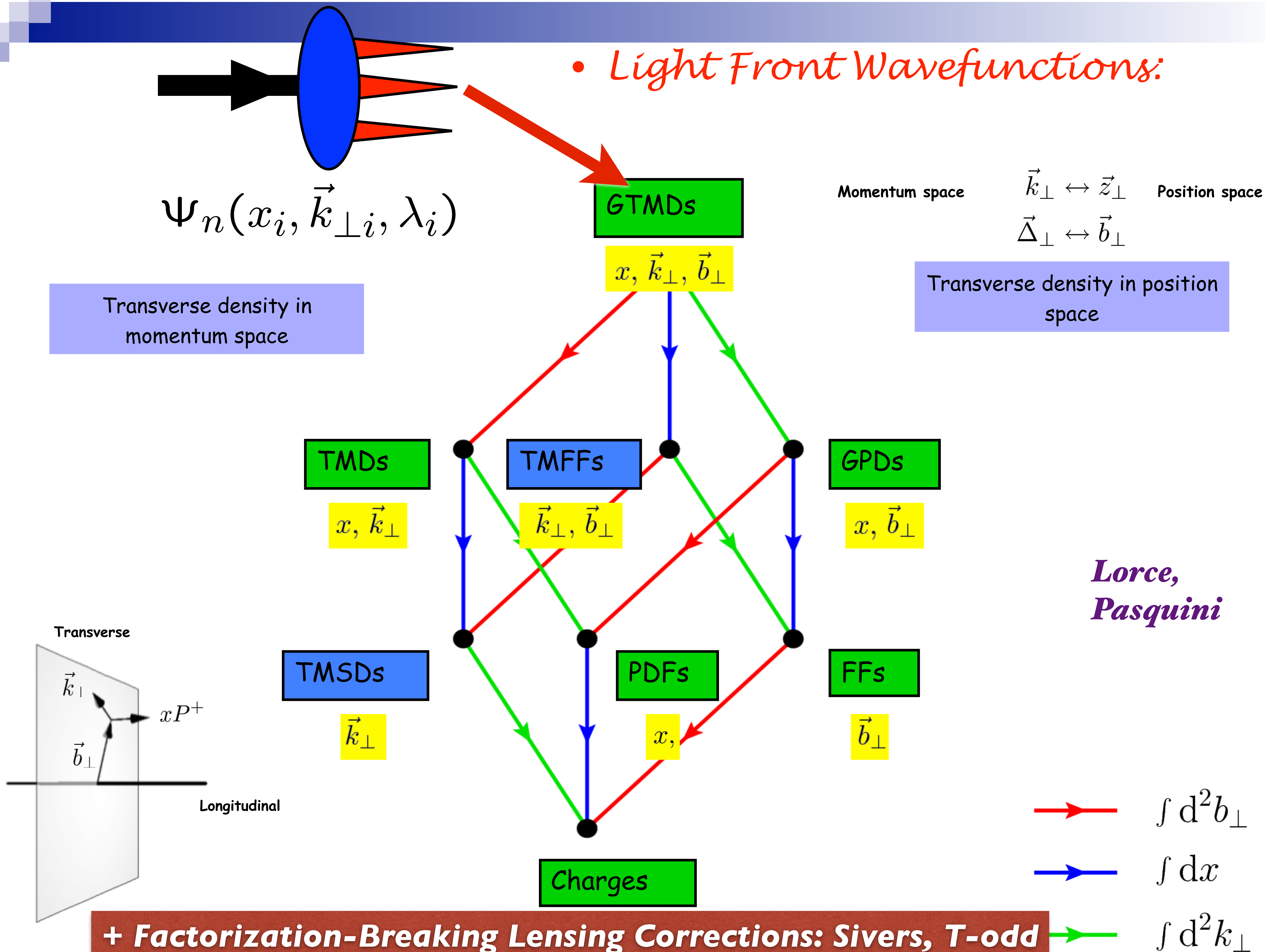
$$P^- = i\frac{d}{d\tau}$$

Eigenvalue

$$P^- = \frac{\mathcal{M}^2 + \vec{P}_\perp^2}{P^+}$$

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

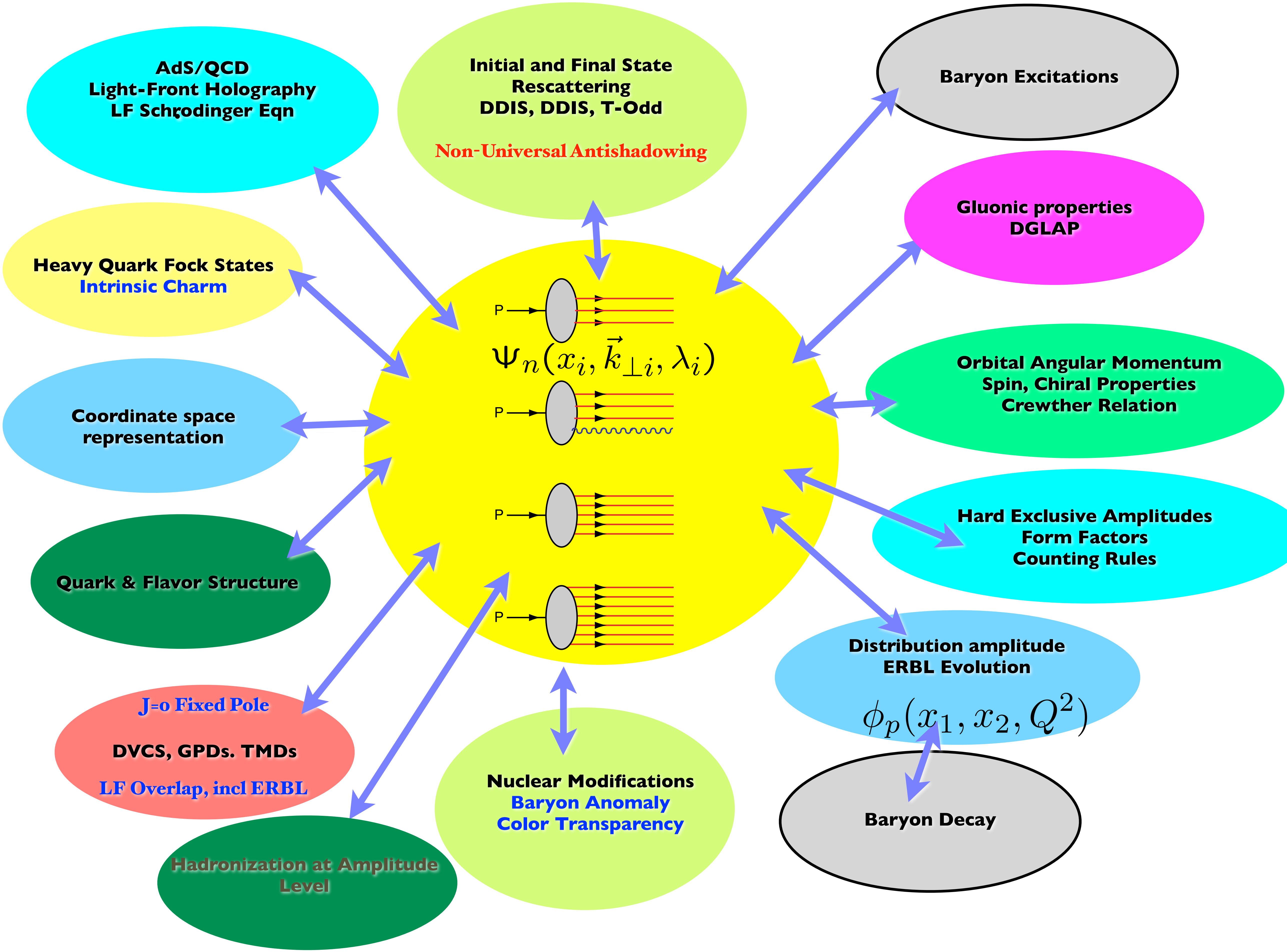
- *Light Front Wavefunctions:*



Lorce, Pasquini

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

QCD and the LF Hadron Wavefunctions



- **LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics**

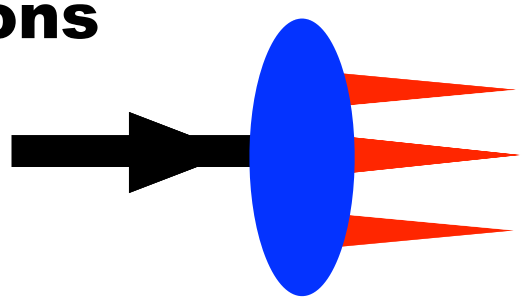
- **LFWFs=Hadron Eigensolutions: Direct Connection to QCD Lagrangian**

- **Relativistic, frame-independent: no boosts, no disc contraction, Melosh built into LF spinors**

- **Hadronic observables computed from LFWFs: Form factors, Structure Functions, Distribution Amplitudes, GPDs, TMDs, Weak Decays, ... modulo `lensing' from ISIs, FSIs**

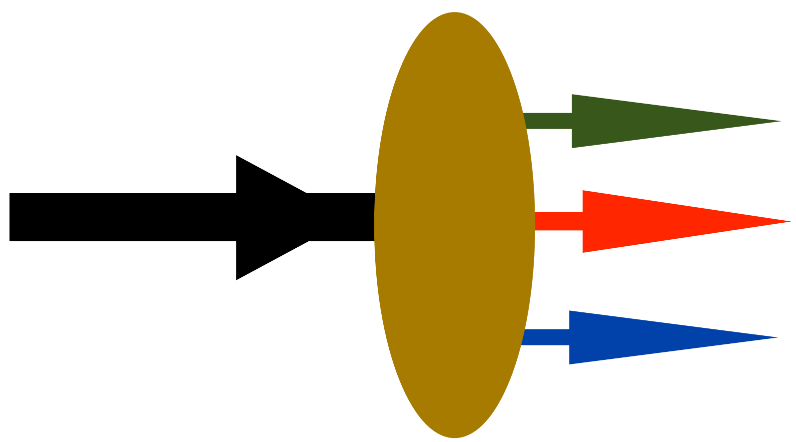
- **Cannot compute current matrix elements using instant form from eigensolutions alone -- need to include vacuum currents!**

- **Hadron Physics without LFWFs is like Biology without DNA!**



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

- *Hadron Physics without LFWFs is like Biology without DNA!*



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

Advantages of the Dirac's Front Form for Hadron Physics

- **Measurements are made at fixed τ**
- **Causality is automatic**
- **Structure Functions are squares of LFWFs**
- **Form Factors are overlap of LFWFs**
- **LFWFs are frame-independent -- no boosts!**
- **No dependence on observer's frame**
- **LF Holography: Dual to AdS space**
- **LF Vacuum trivial -- no condensates!**
- **Profound implications for Cosmological Constant**

Angular Momentum on the Light-Front

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State!

LF Spin Sum Rule

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Orbital angular momentum is a property of Light-Front Wavefunctions

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

Light-Front Schrödinger Equation

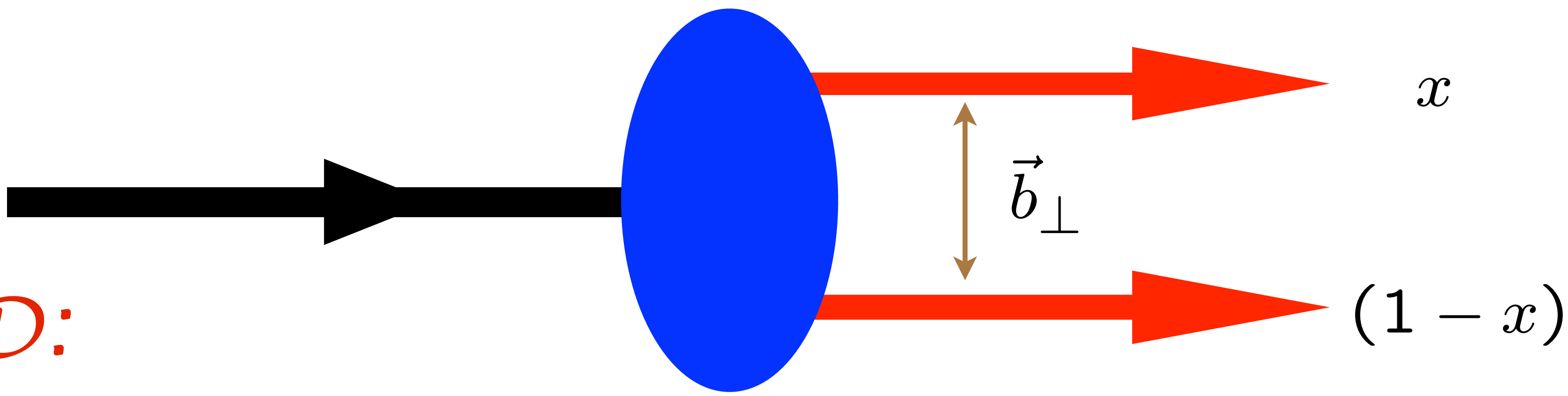
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

$$\left[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{\zeta^2} + U(\zeta, S, L)\right] \psi_{LF}(\zeta) = M^2 \, \psi_{LF}(\zeta)$$

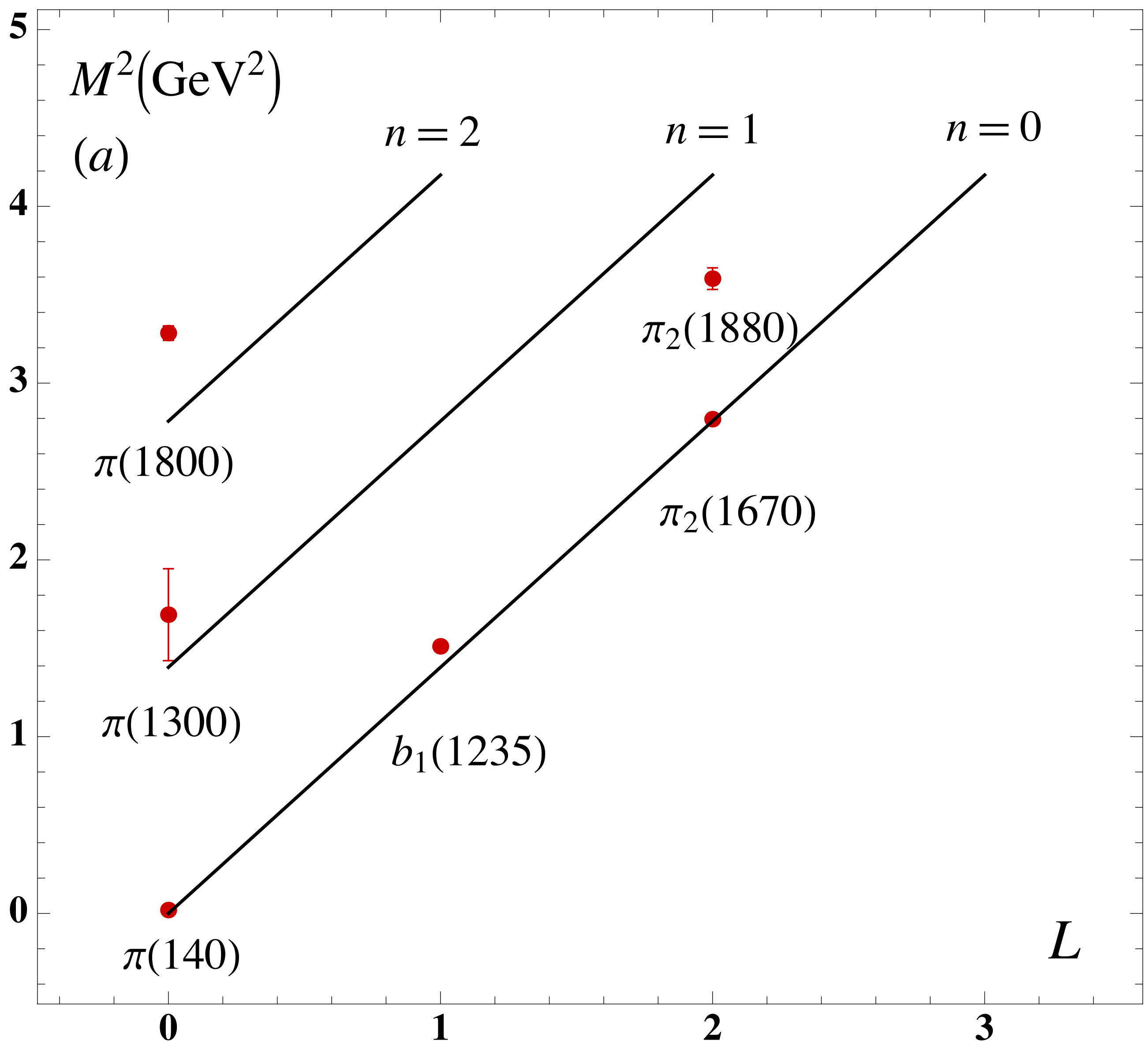
$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2 .$$

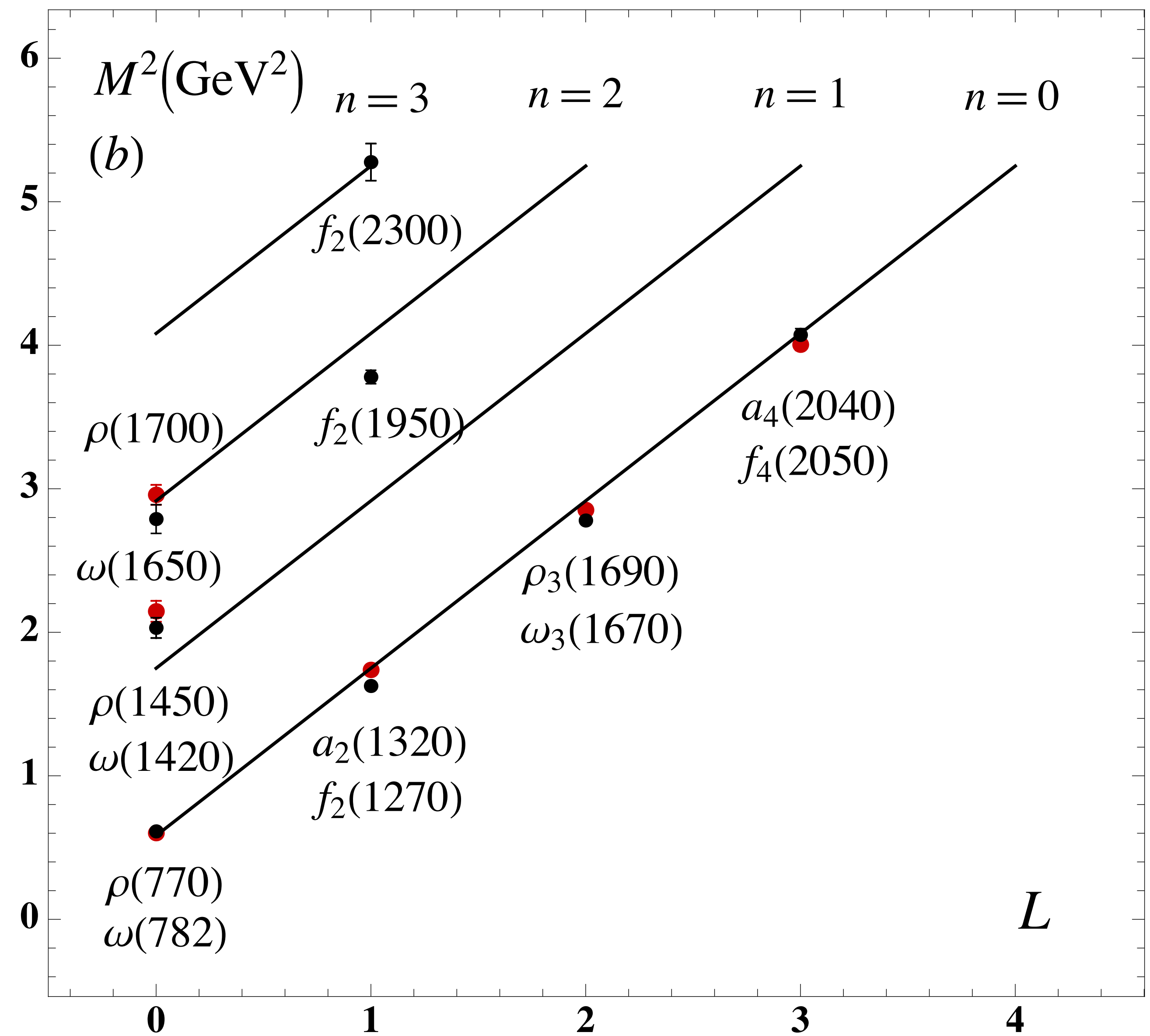


AdS/QCD:

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

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

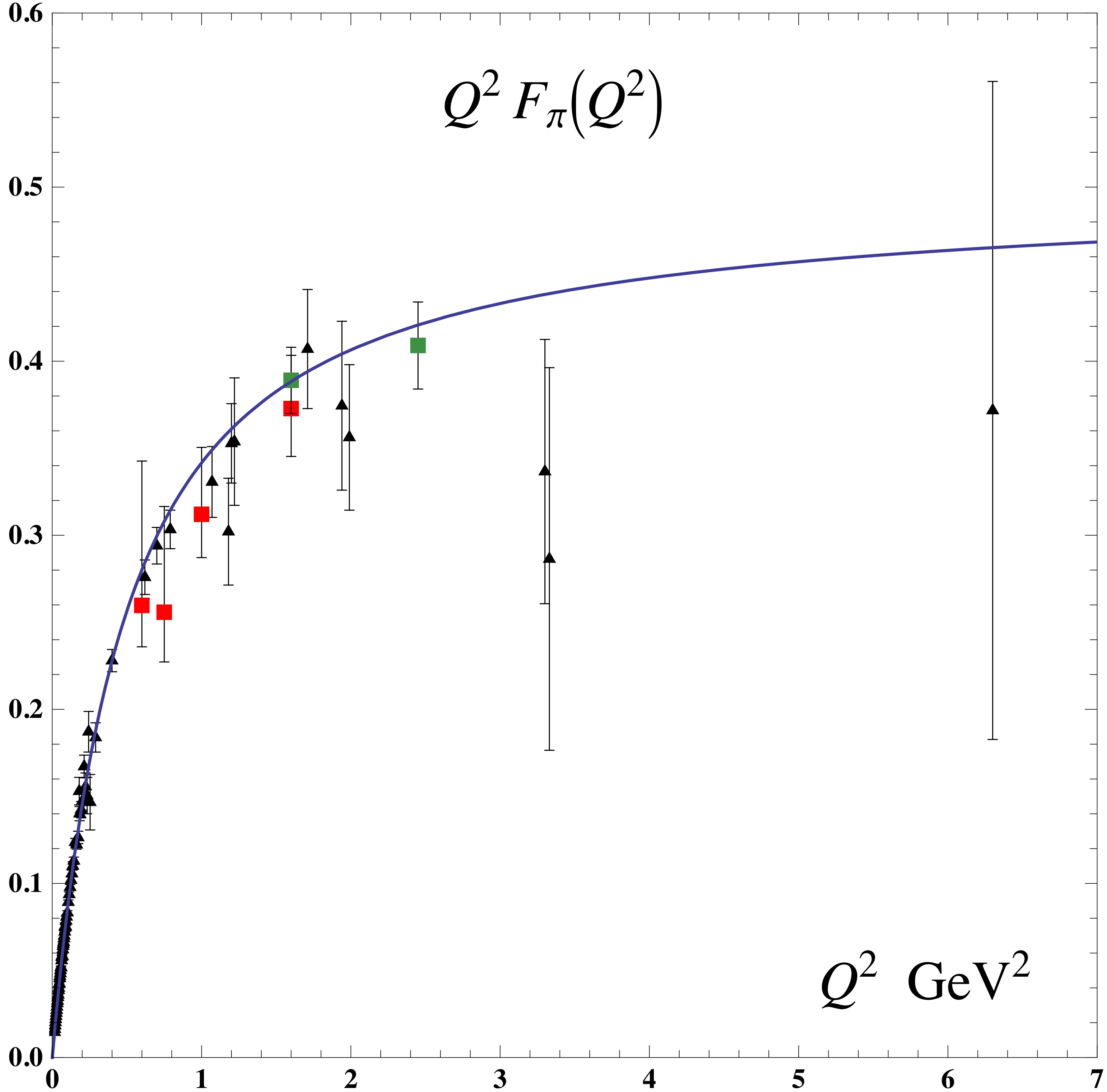




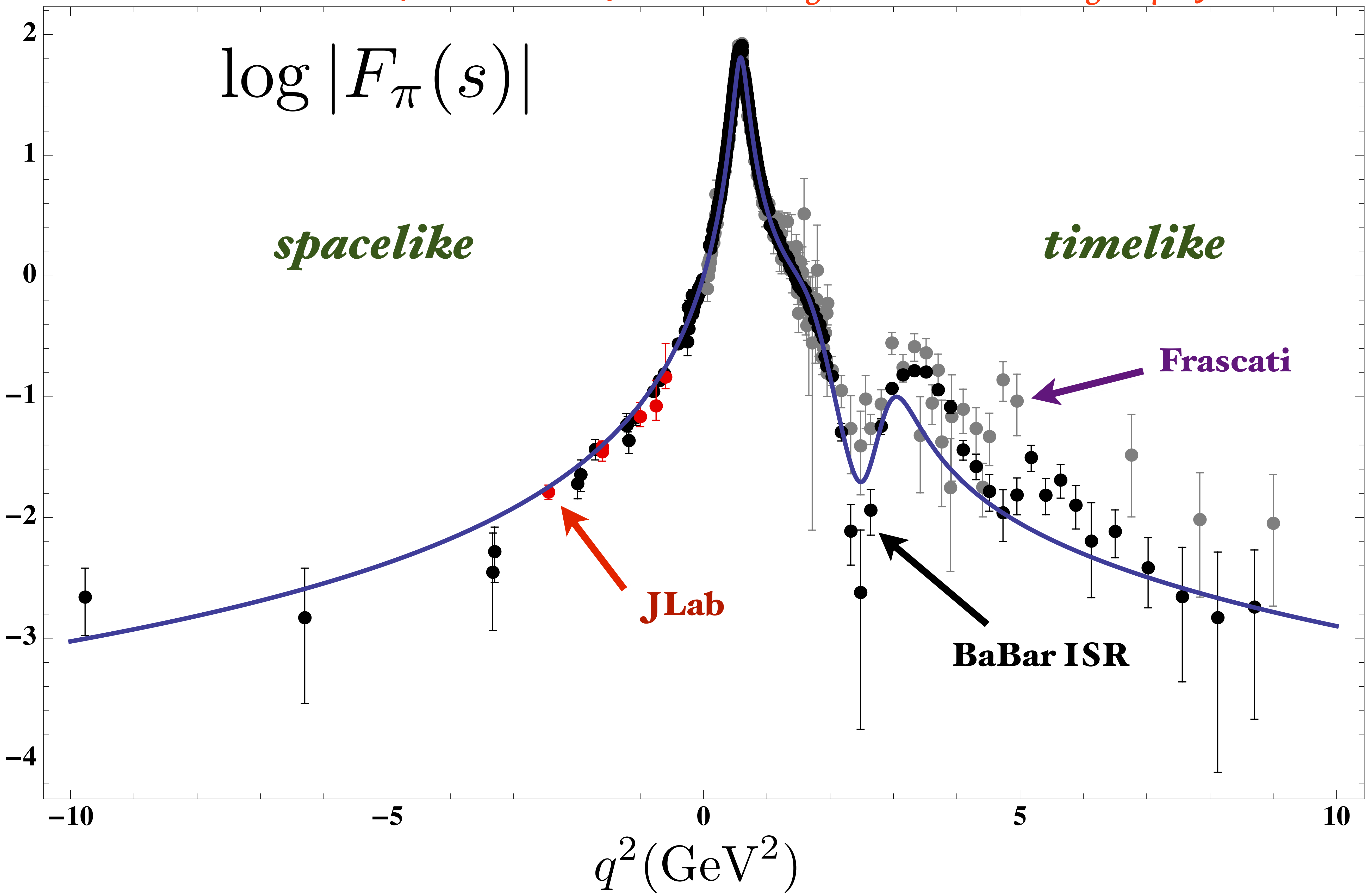
Massless pion in Chiral Limit!

Same slope in n and L!

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



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

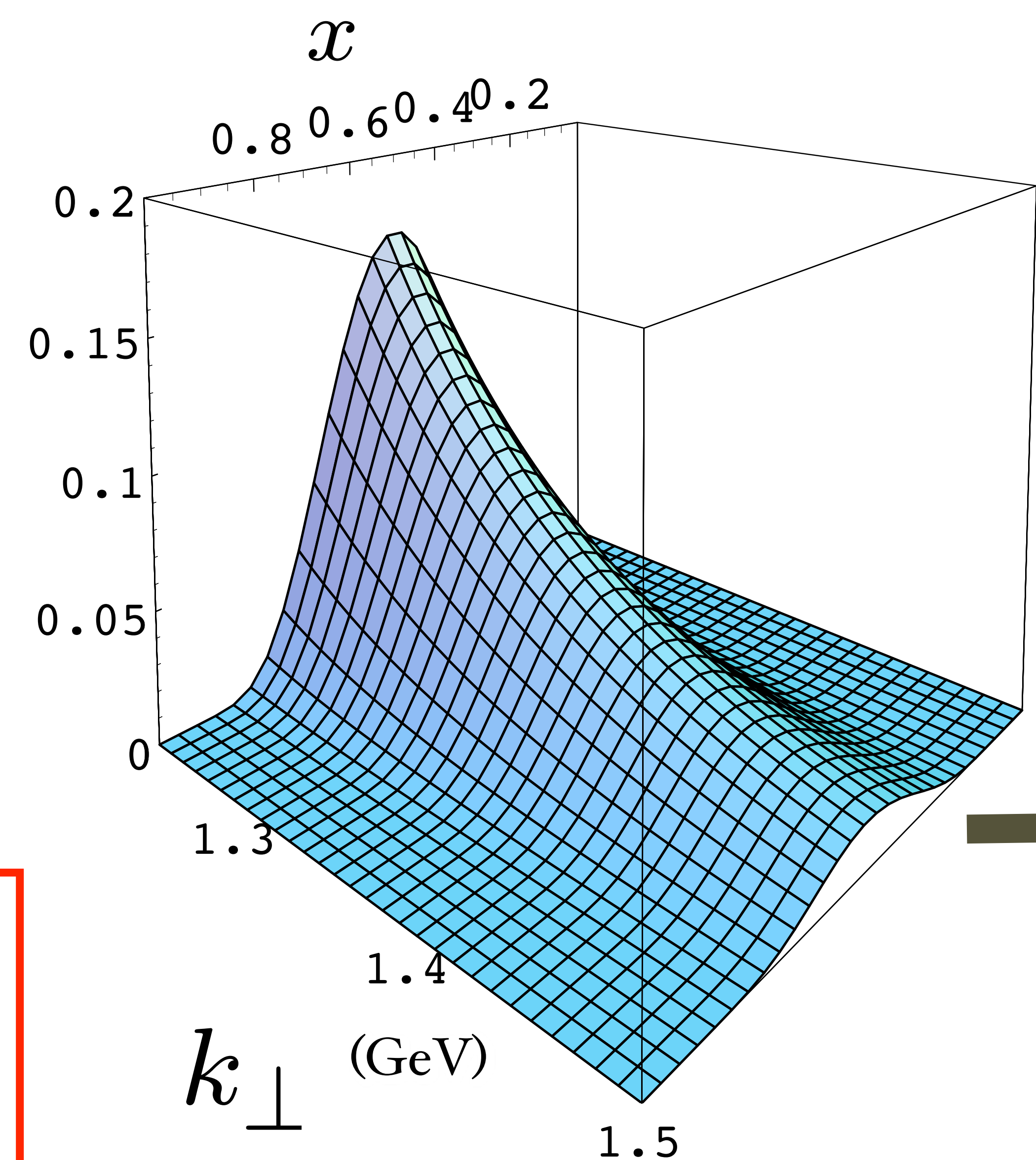


Dressed AdS/QCD Current

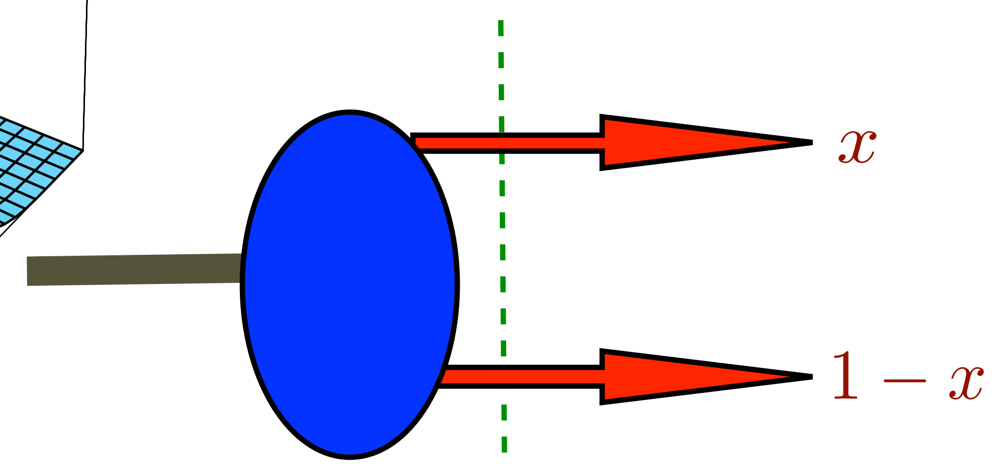
Prediction from AdS/QCD: Meson LFWF

de Teramond, Cao, sjb

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



"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

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

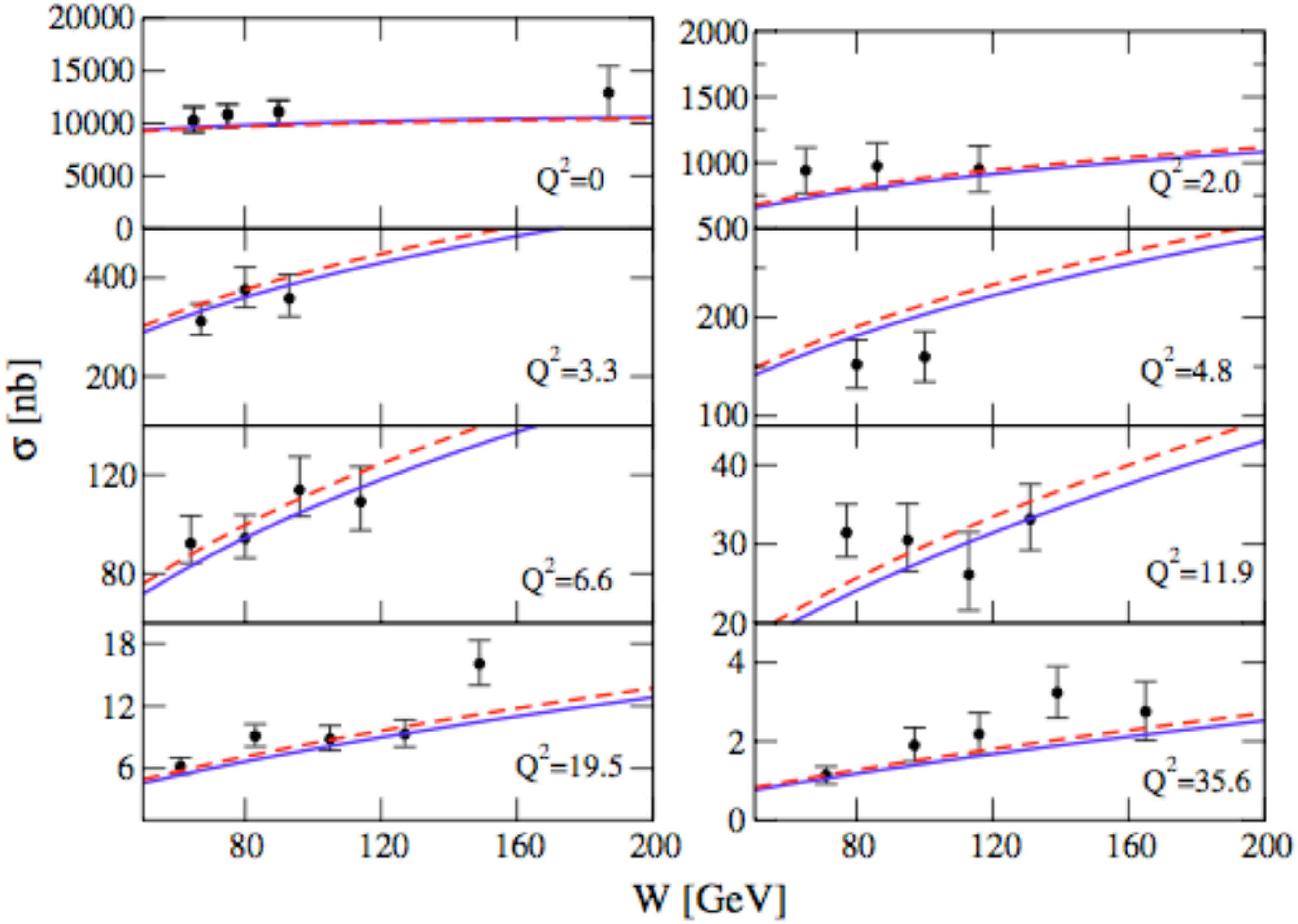
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

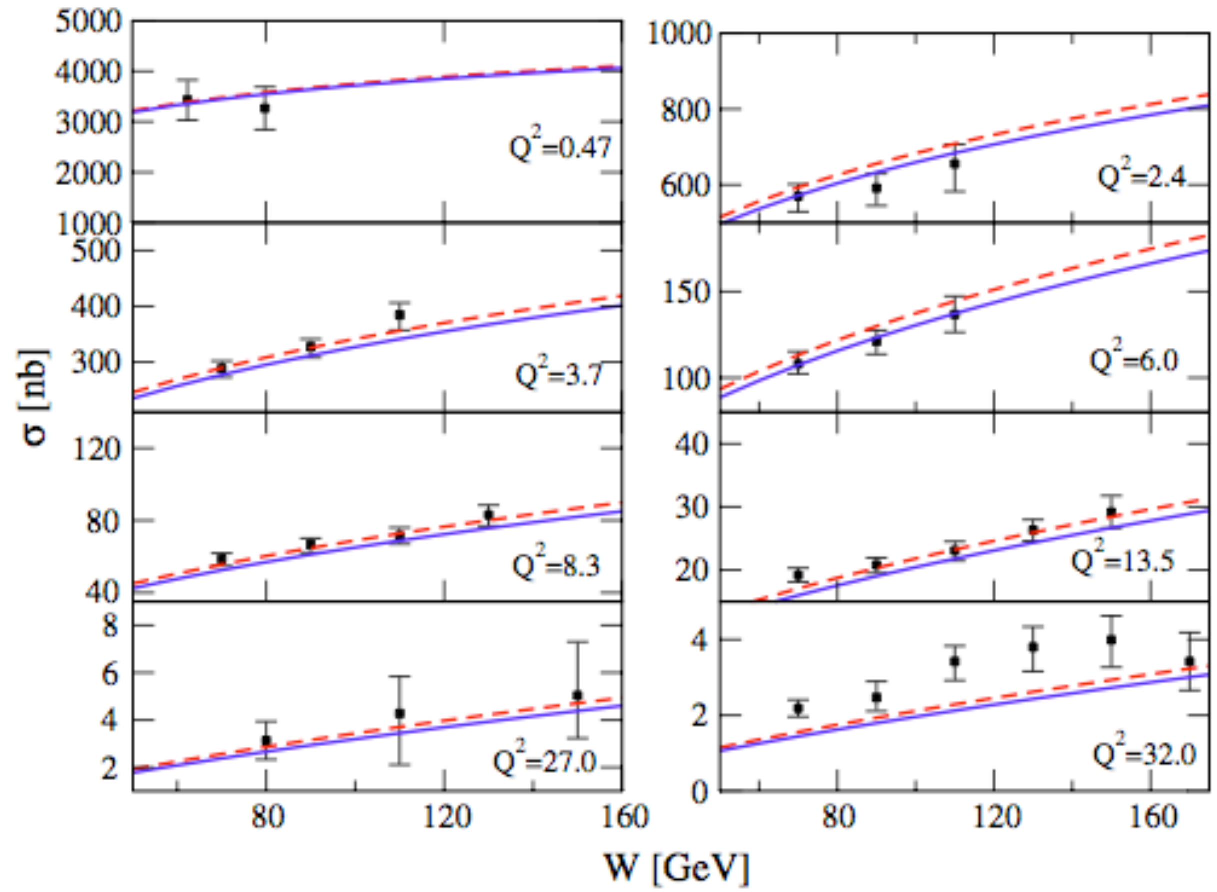
$$f_\pi = \sqrt{P_{q\bar{q}}} \frac{\sqrt{3}}{8} \kappa = 92.4 \text{ MeV}$$

Provides Connection of Confinement to Hadron Structure

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

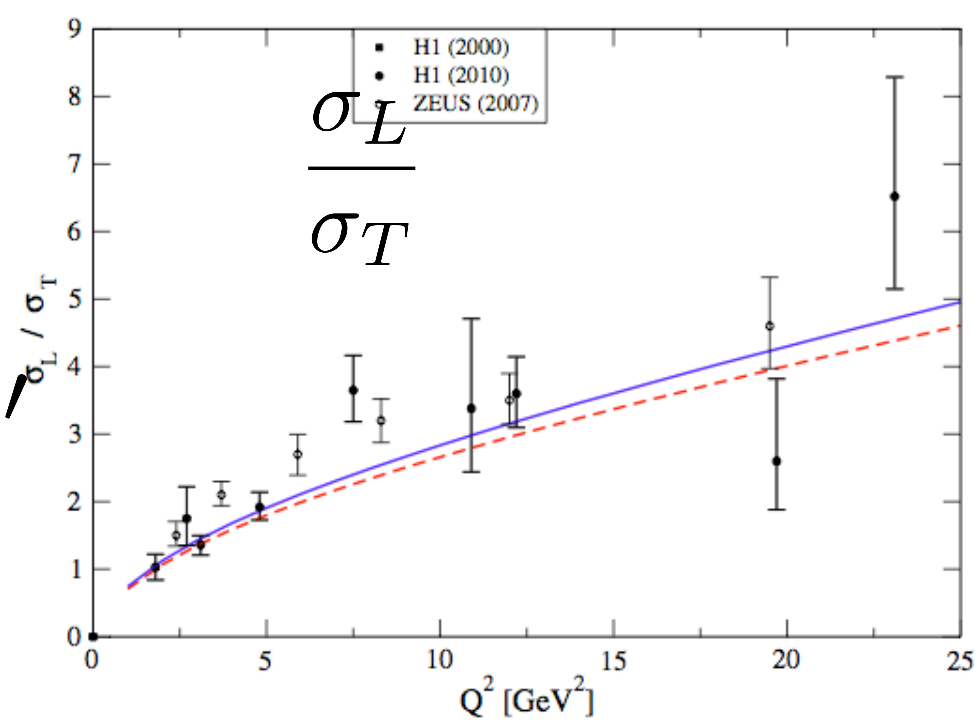




(b) ZEUS

J. R. Forshaw,
R. Sandapen

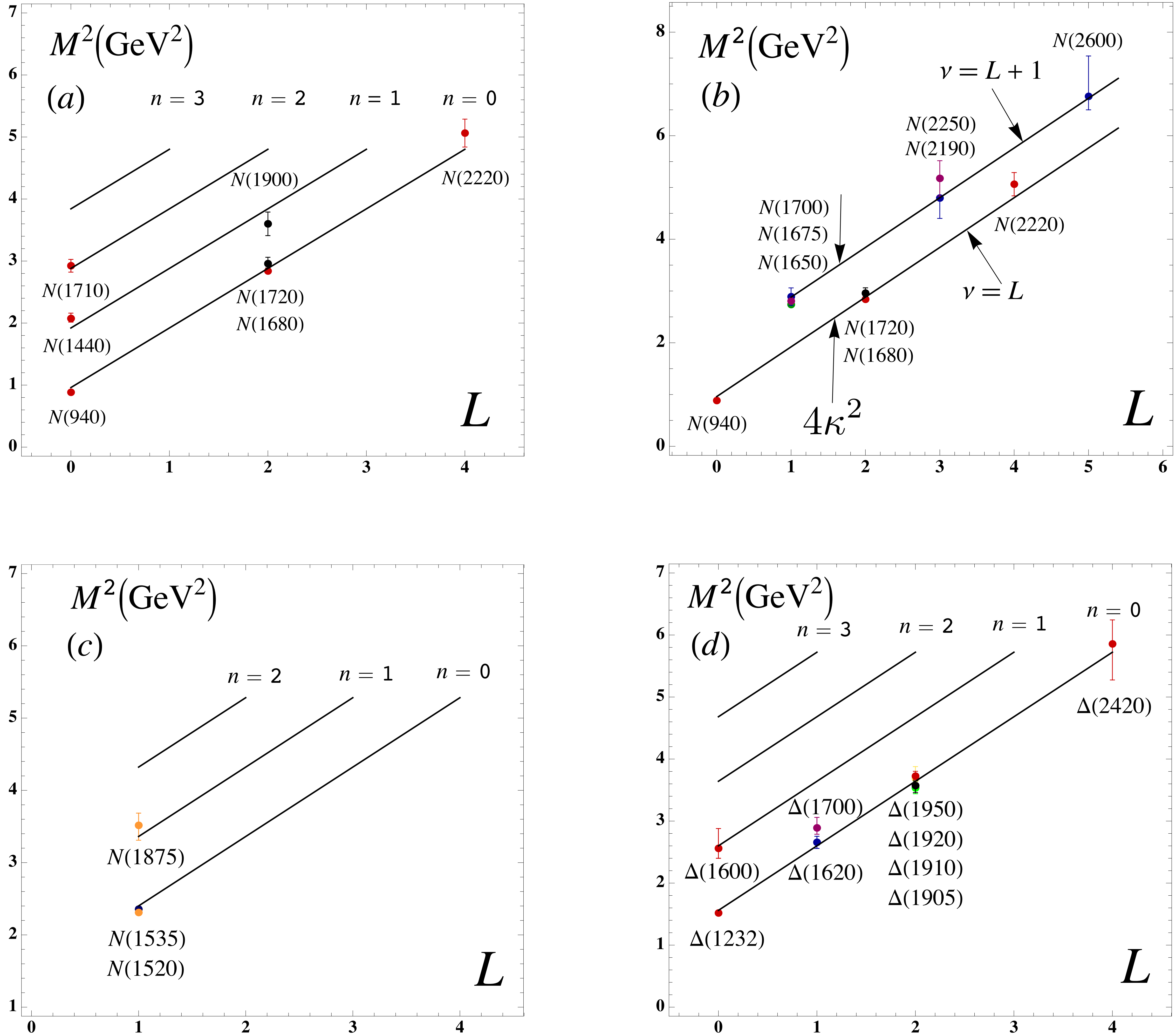
$$\gamma^* p \to \rho^0 p'$$



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

Prediction from Light-Front Holography

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



M²(GeV²)
(a)
n = 3
n = 2
n = 1
n = 0
N(1900)
N(2220)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
L
M²(GeV²)
(b)
ν = L + 1
N(2600)
N(2250)
N(2190)
N(1700)
N(1675)
N(1650)
N(2220)
ν = L
N(1720)
N(1680)
N(940)
4κ²
L
M²(GeV²)
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
L
M²(GeV²)
(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)
L

- Compute Dirac proton form factor using SU(6) flavor symmetry

$$F_1^p(Q^2) = R^4 \int \frac{dz}{z^4} V(Q,z) \Psi_+^2(z)$$

- Nucleon AdS wave function

$$\Psi_+(z) = \frac{\kappa^{2+L}}{R^2} \sqrt{\frac{2n!}{(n+L)!}} z^{7/2+L} L_n^{L+1}\left(\kappa^2 z^2\right) e^{-\kappa^2 z^2/2}$$

- Normalization $\quad (F_1{}^p(0) = 1, \quad V(Q=0,z) = 1)$

$$R^4 \int \frac{dz}{z^4} \Psi_+^2(z) = 1$$

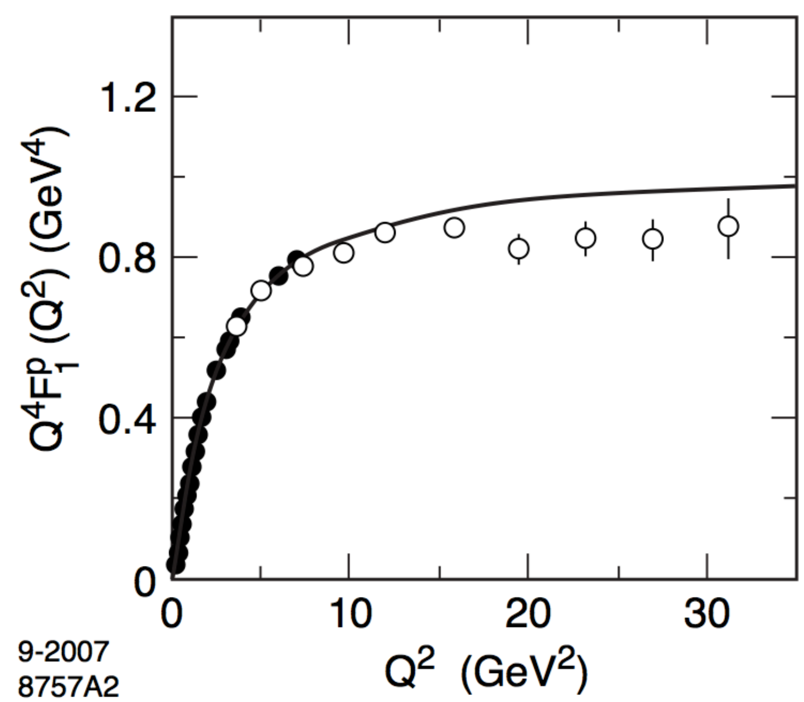
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

$$V(Q,z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \, x^{\frac{Q^2}{4\kappa^2}} e^{-\kappa^2 z^2 x/(1-x)}$$

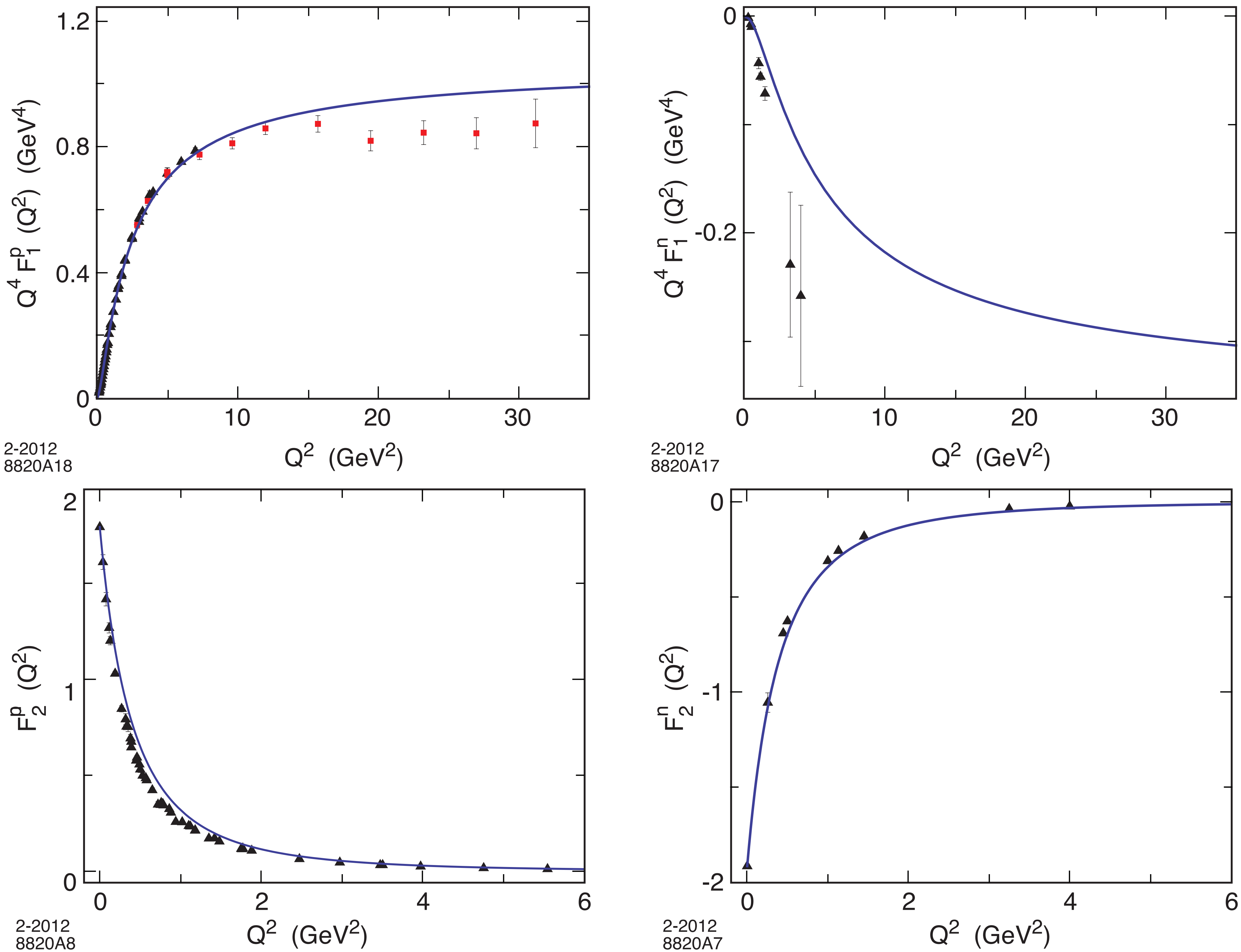
- Find

$$F_1^p(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}$$

with $\mathcal{M}_{\rho_n}{}^2 \to 4\kappa^2(n+1/2)$

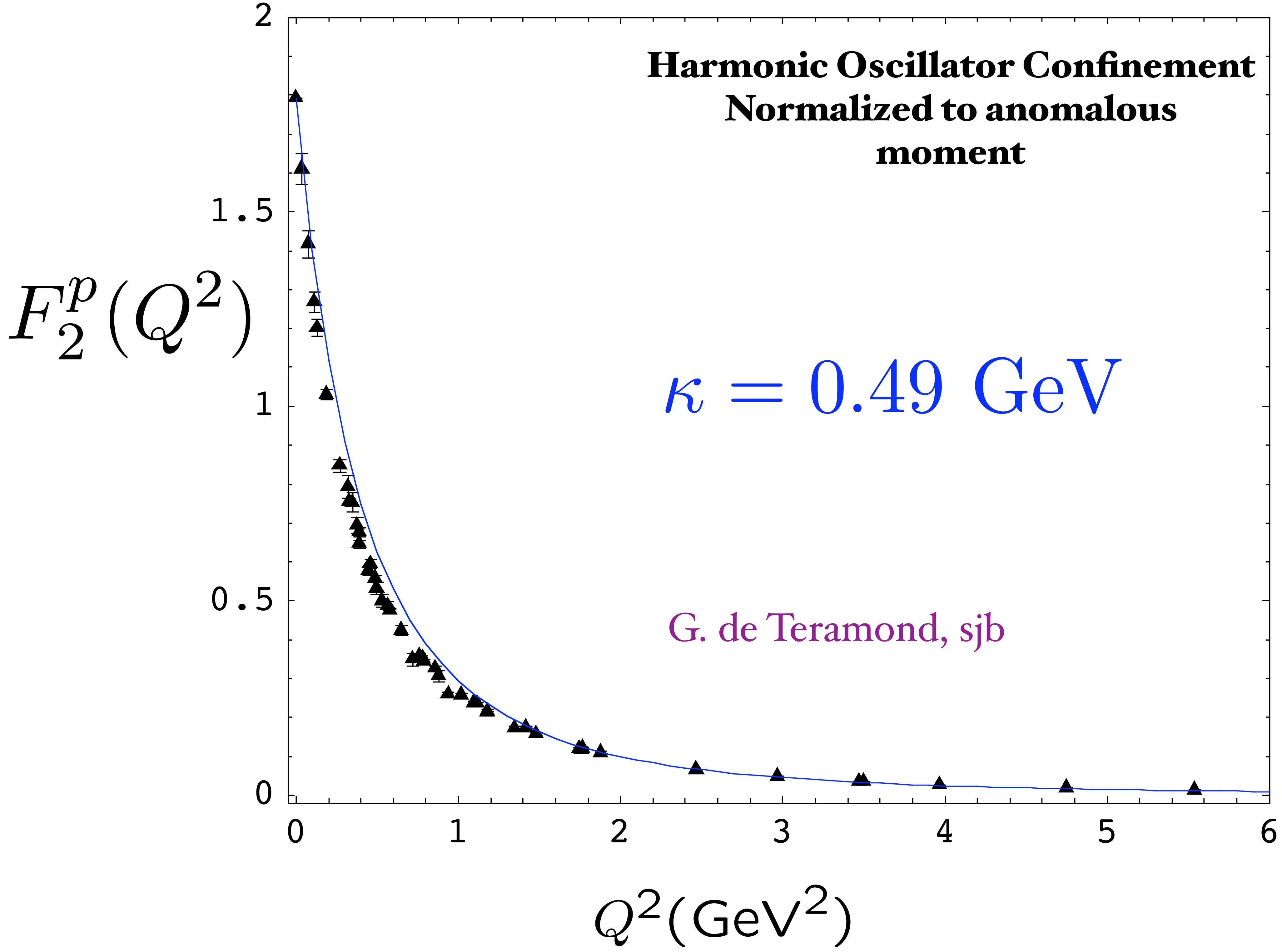


Using $SU(6)$ flavor symmetry and normalization to static quantities



Spacelike Pauli Form Factor

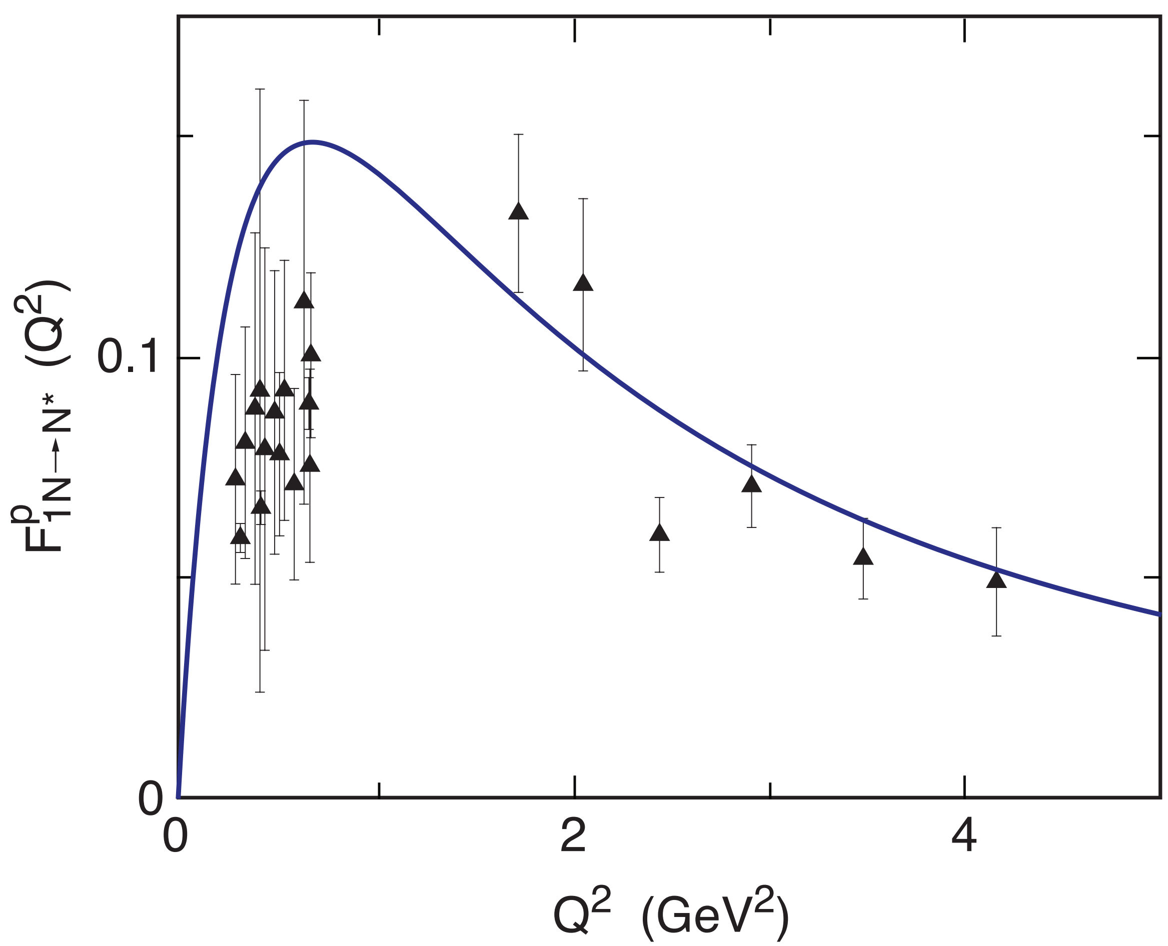
From overlap of $L = 1$ and $L = 0$ LFWFs



Nucleon Transition Form Factors

$$F^p_{1\,N\to N^*}(Q^2) = \frac{\sqrt{2}}{3}\frac{\frac{Q^2}{\mathcal{M}^2_\rho}}{\left(1+\frac{Q^2}{\mathcal{M}^2_\rho}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho'}}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho''}}\right)}.$$

AdS\QCD Light-Front Holography



G. de Teramond, sjb

Proton transition form factor to the first radial excited state. Data from JLab

QCD Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \cancel{\sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f}$$

$$iD^\mu = i\partial^\mu - gA^\mu \qquad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

Classical Chiral Lagrangian is Conformally Invariant

Where does the QCD Mass Scale Λ_{QCD} come from?

How does color confinement arise?

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

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

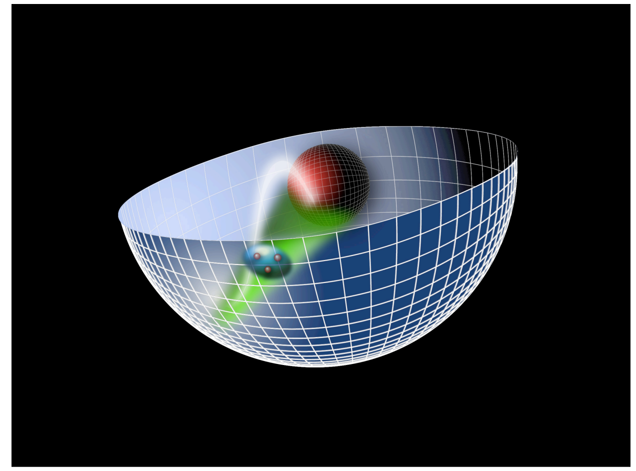
Unique confinement potential!

de Tèramond, Dosch, sjb

AdS/QCD Soft-Wall Model

Single scheme-independent fundamental mass scale

κ



Light-Front Holography

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

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

Light-Front Schrödinger Equation

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

Unique Confinement Potential!

Conformal Symmetry of the action

Confinement scale:

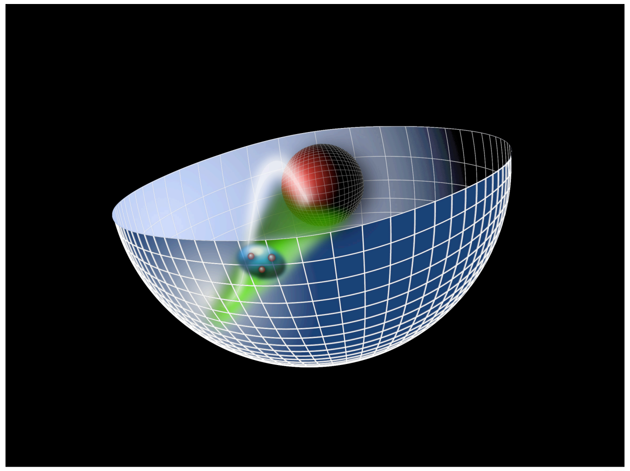
(m_q=0)

$$\kappa \simeq 0.6\ GeV$$

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

- **de Alfaro, Fubini, Furlan:** ***Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!***

de Teramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

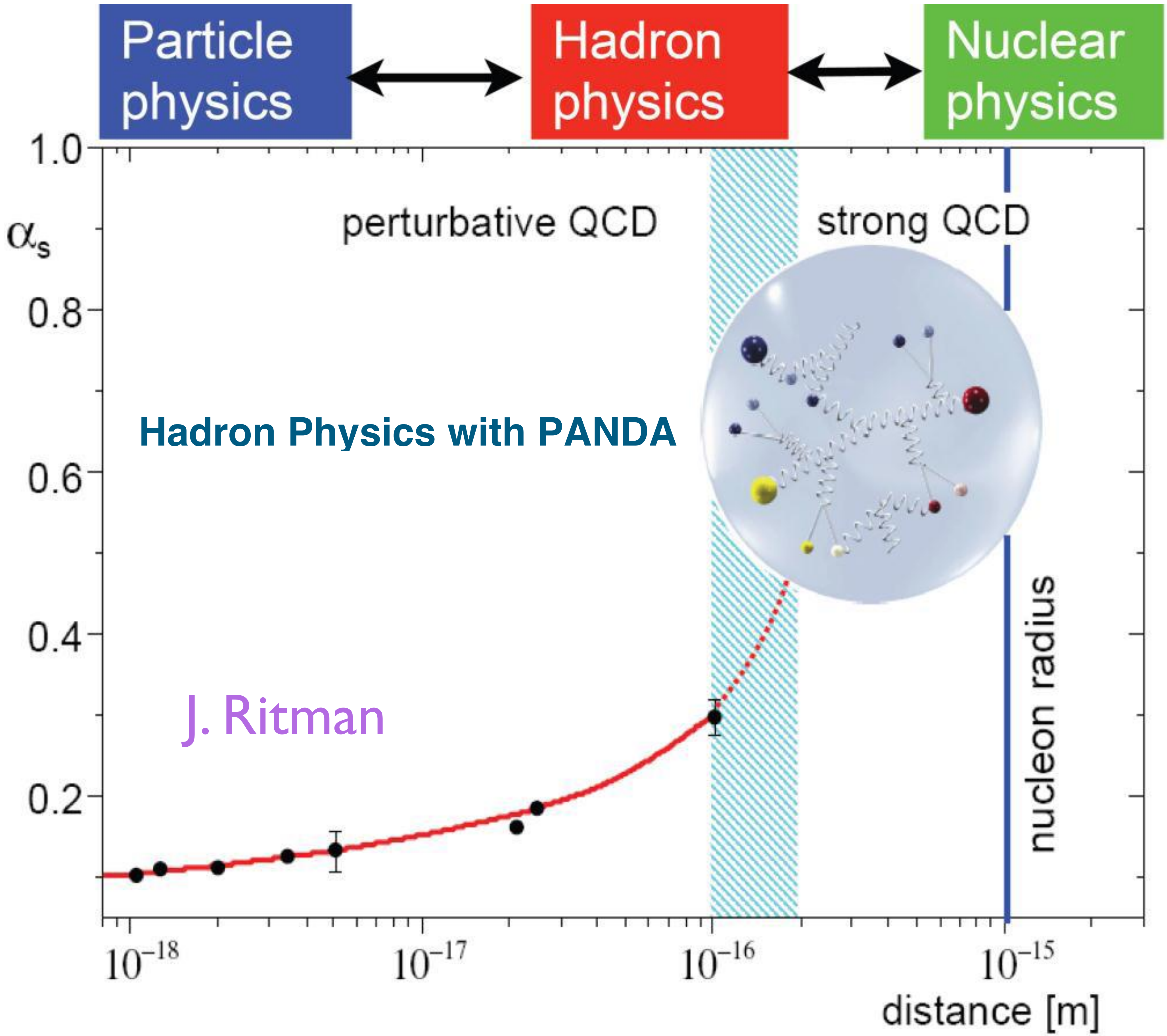
Light-Front Holography

Semi-Classical Approximation to QCD

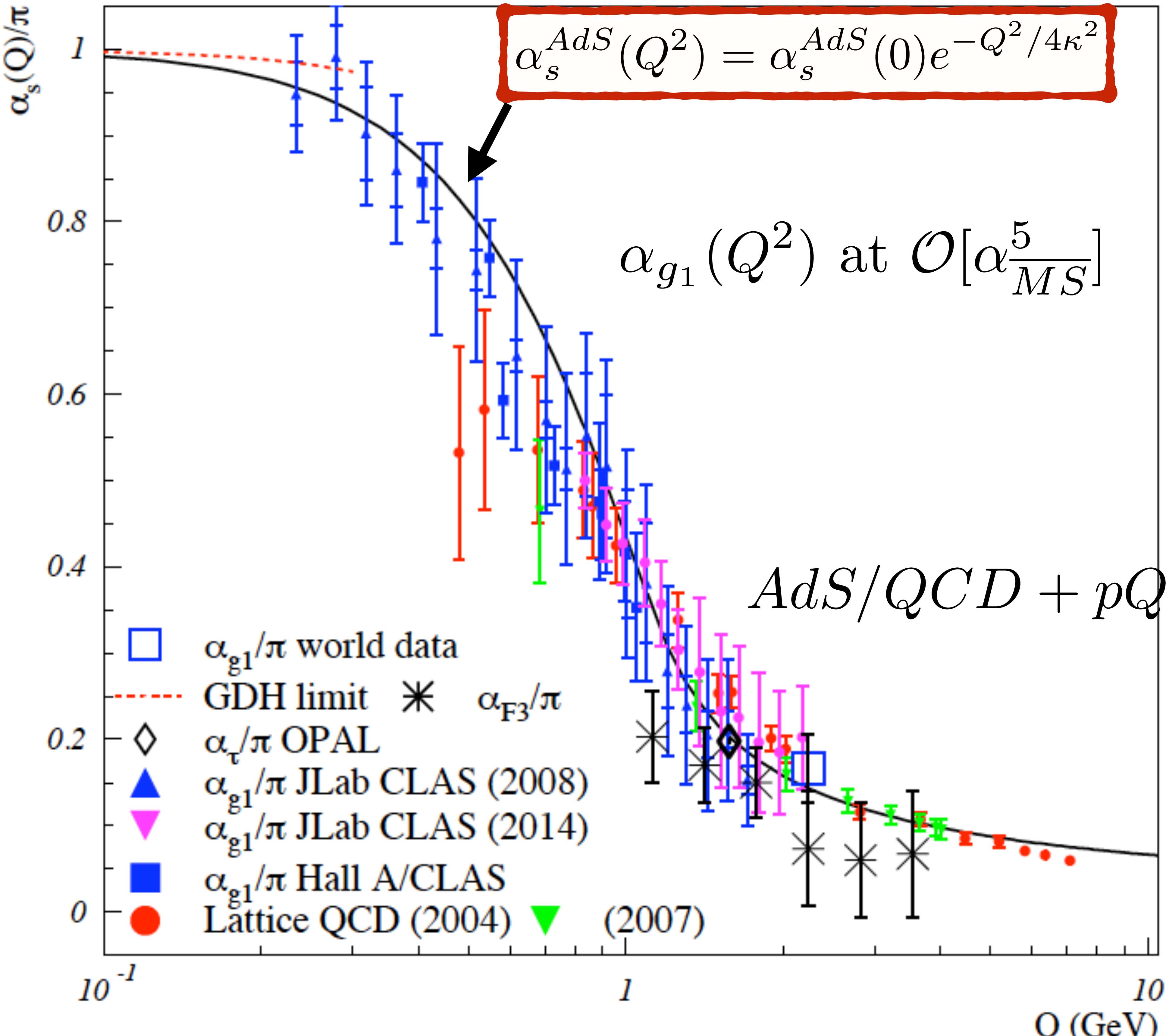
Relativistic, frame-independent
Unique color-confining potential
Zero mass pion for massless quarks
Regge trajectories with equal slopes in n and L
Light-Front Wavefunctions

Conformal Symmetry
of the action

Light-Front Schrödinger Equation


Particle physics
Hadron physics
Nuclear physics
1.0
0.8
0.6
0.4
0.2
αs
perturbative QCD
strong QCD
Hadron Physics with PANDA
J. Ritman
nucleon radius
10^−18
10^−17
10^−16
10^−15
distance [m]

$$\Lambda_{\overline{MS}} = 0.5983\kappa = 0.5983\frac{m_\rho}{\sqrt{2}} = 0.4231 m_\rho = 0.328\ GeV$$



Deur,
de Teramond, sjb

Predict $\Lambda_{\overline{MS}}$ from m_p or m_ρ!

Exclusive Processes: New Level of Testing QCD at GSI-FAIR

- Sensitivity to fundamental features of hadron dynamics, light-front wavefunctions, confinement mechanism, nonpertubative QCD
- Scattering and production mechanisms
- Gluon exchange (Zweig Rule) vs Quark Exchange
- QCD and Hadronization at the Amplitude Level
- Origin of Fundamental Mass Scale of QCD

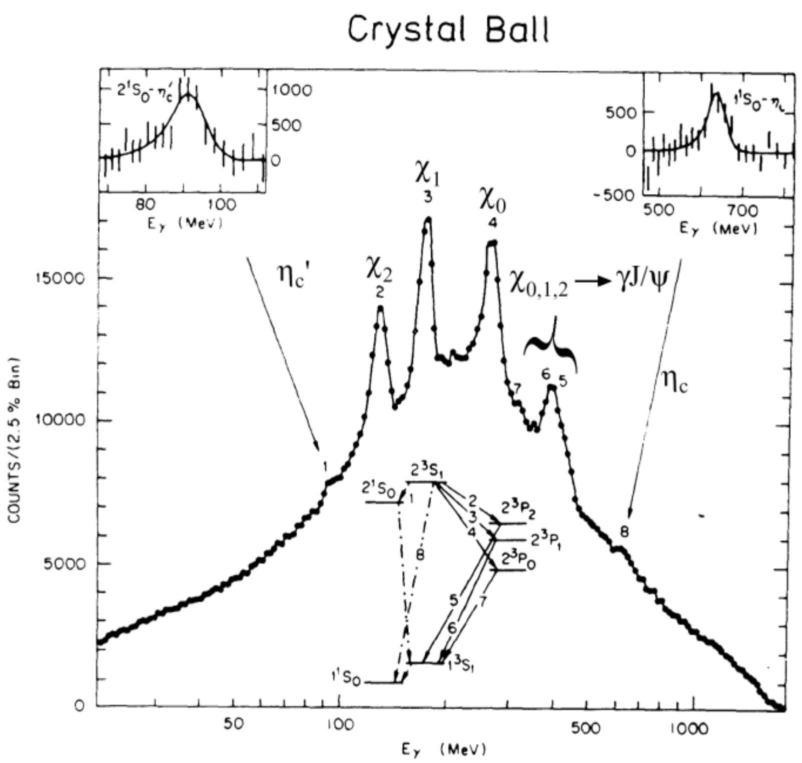
PANDA: Remarkable Laboratory for **Exclusive** Hadronic Processes

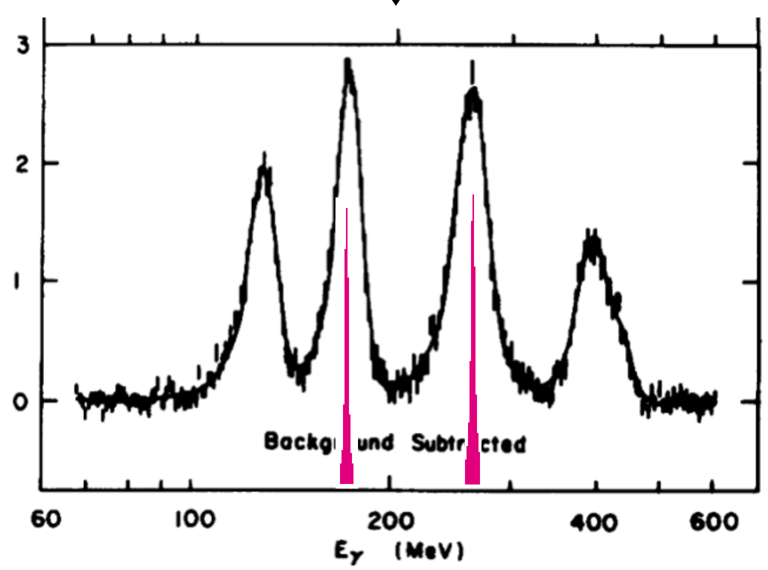
$$\bar{p}p \to \ell\bar{\ell}, \gamma\gamma, \gamma\pi^0, pp, K^+K^-, J/\psi, \eta_c\eta_c, Z_c^+\pi^-, \cdots$$

- ***Test Fundamental Theorems of QCD***
- ***High p_T: Rigorous Factorization Theorems: Convolution of Hadron Distribution Amplitudes and Hard Scattering Amplitudes***
- ***Counting Rules;***
- ***Hadron Helicity Conservation***
- ***Color Transparency***
- ***Hadronization at the Amplitude Level***
- ***Color Confinement, Hadron Structure, Production Mechanisms***
- ***Creation of Heavy Flavors, Open and Hidden Charm, Exotic States, Gluonium***

High Mass/Width Resolution

Panda: 50 KeV Resolution





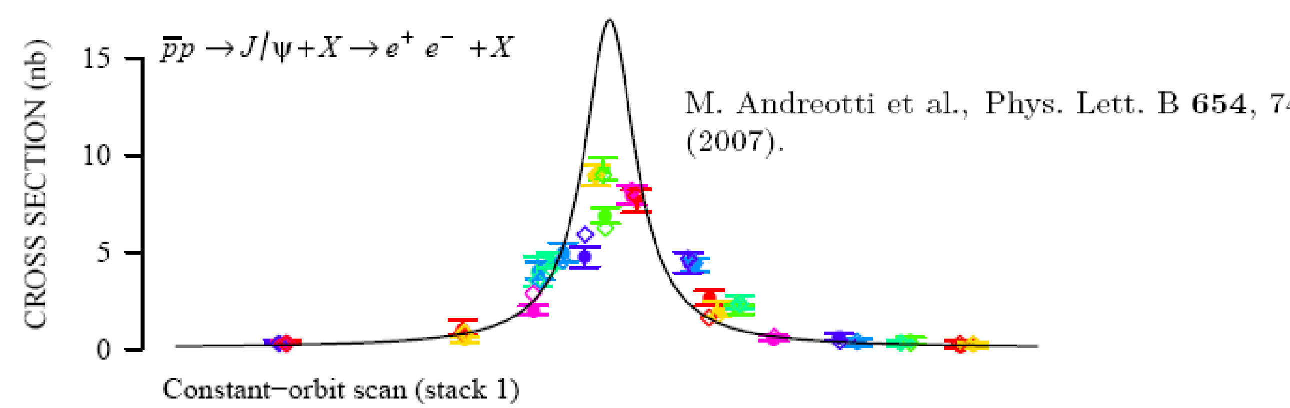
$$e^+e^- \rightarrow \psi' \rightarrow \gamma\chi_{1,2} \rightarrow \gamma(\gamma J/\psi) \rightarrow \gamma\gamma e^{'} e$$

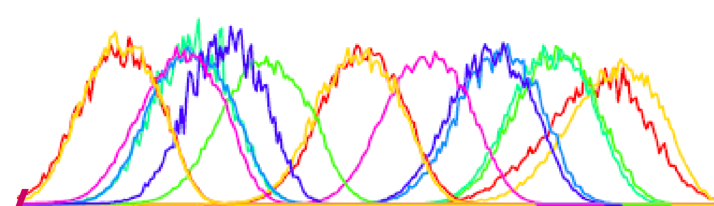
- Invariant mass reconstruction depends
- on the detector resolution ≈ 10 MeV

Formation:

$$\bar{p}p \rightarrow \chi_{1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^-$$

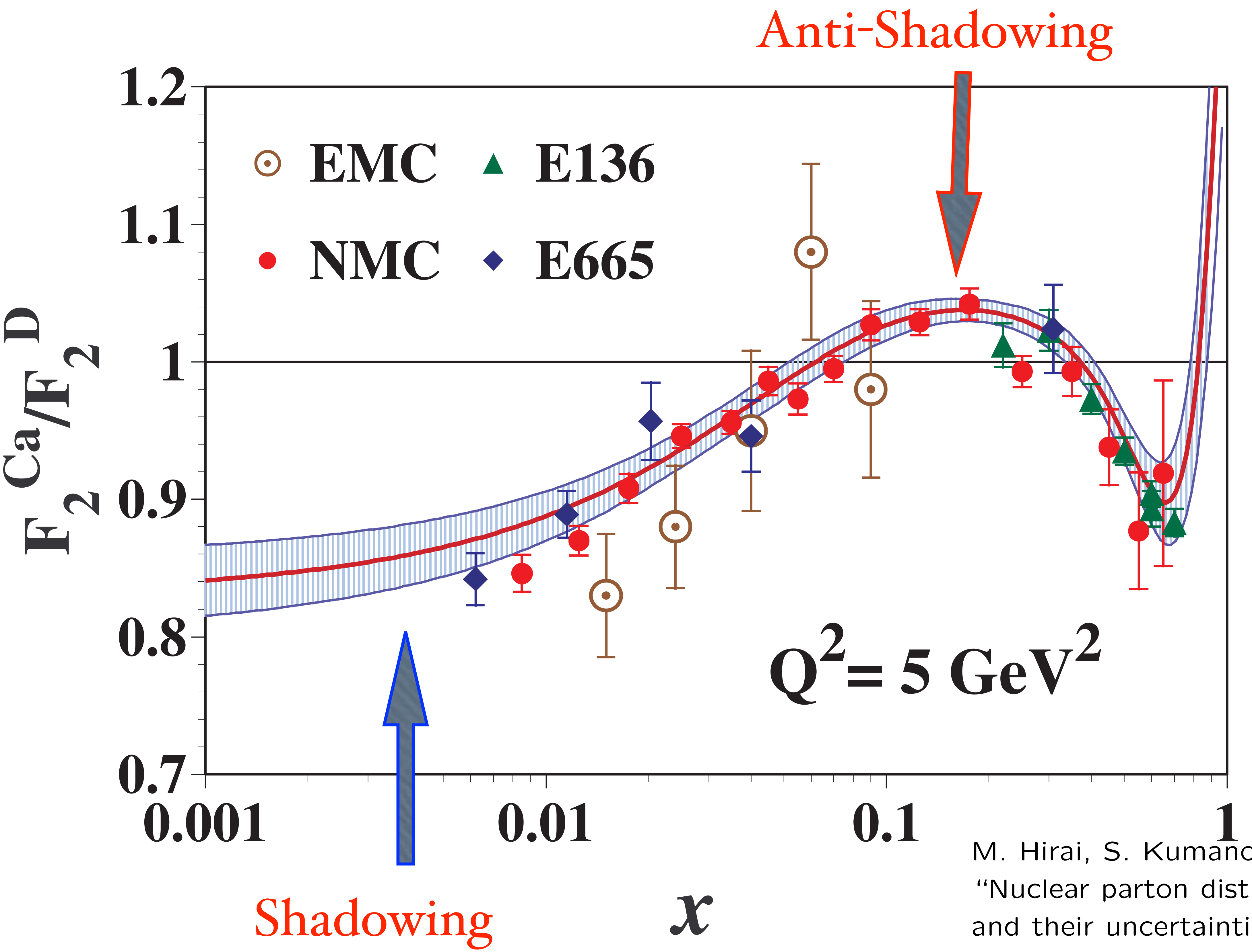
Resonance scan: resolution depends on the beam resolution



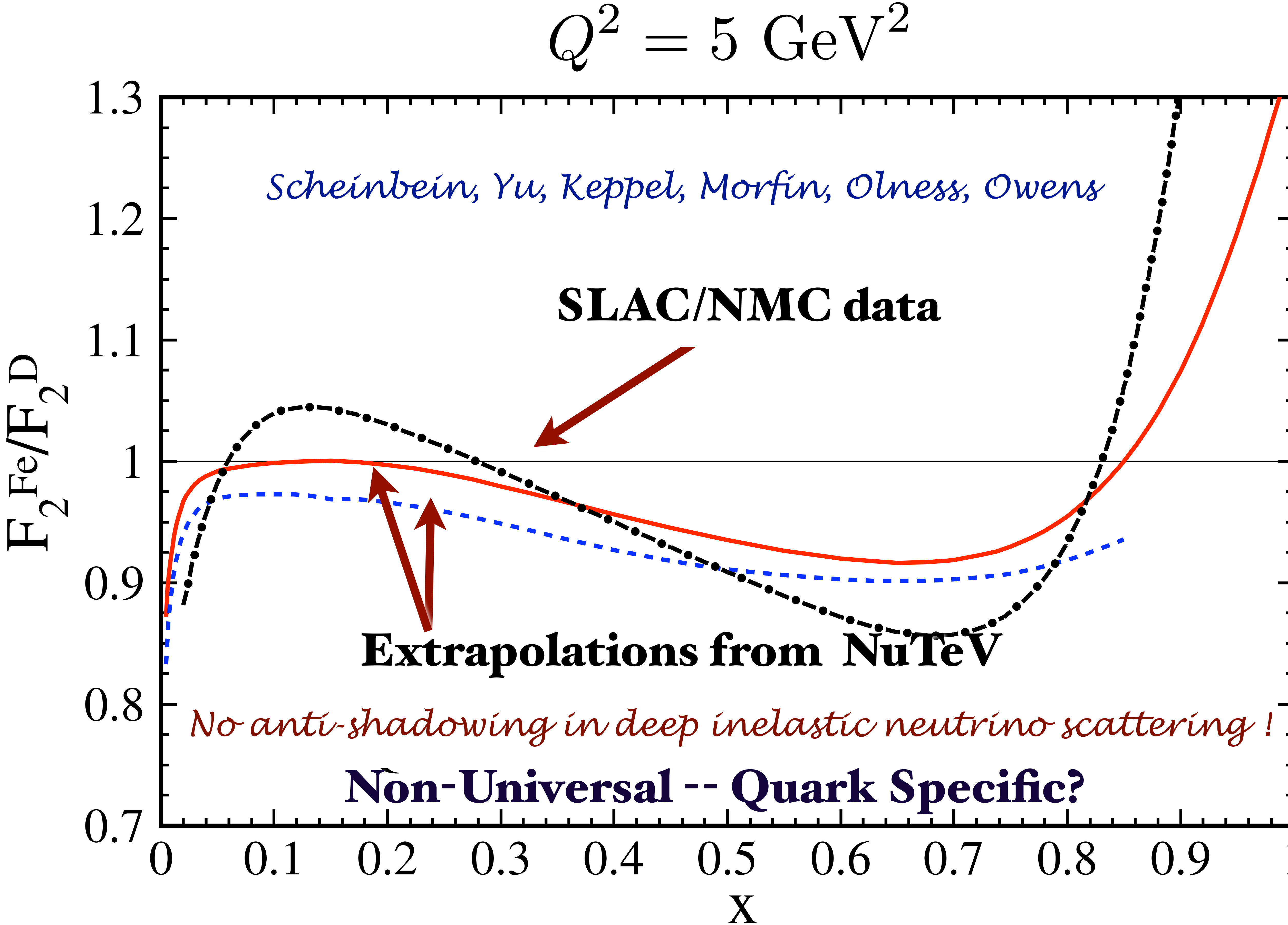


E760@Fermilab ≈ 240 keV

PANDA ≈ 50 keV



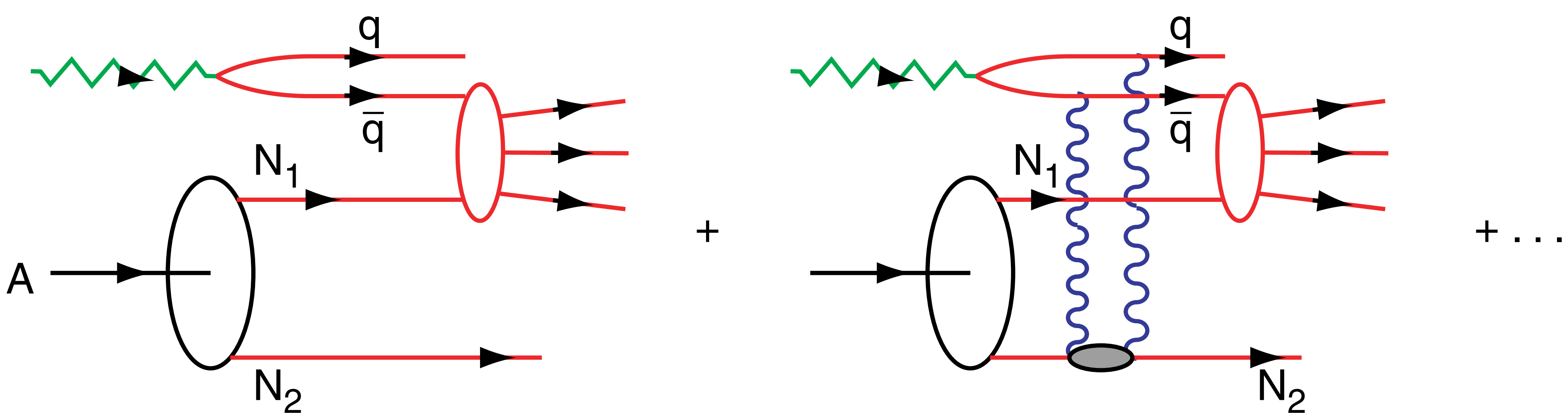
M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].



$Q^2 = 5\ \text{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
Non-Universal -- Quark Specific?
F_2^{Fe}/F_2^{D}
x
1.3
1.2
1.1
1
0.9
0.8
0.7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Stodolsky
Pumplin, sjb
Gribov

Nuclear Shadowing in QCD



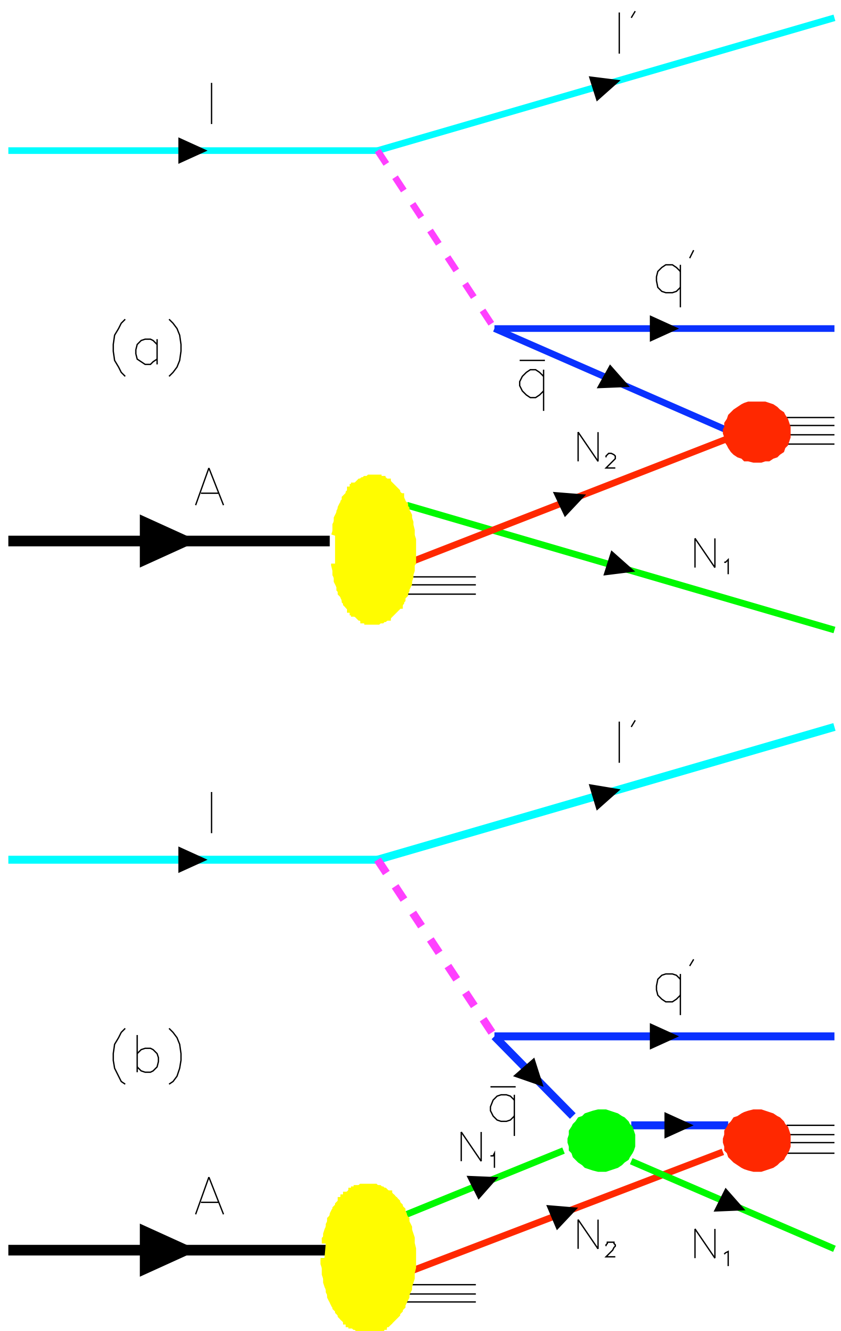
Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

Diffraction via Reggeon gives constructive interference!

Anti-shadowing not universal



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 $\bar{q}$ flux reaching N_2.

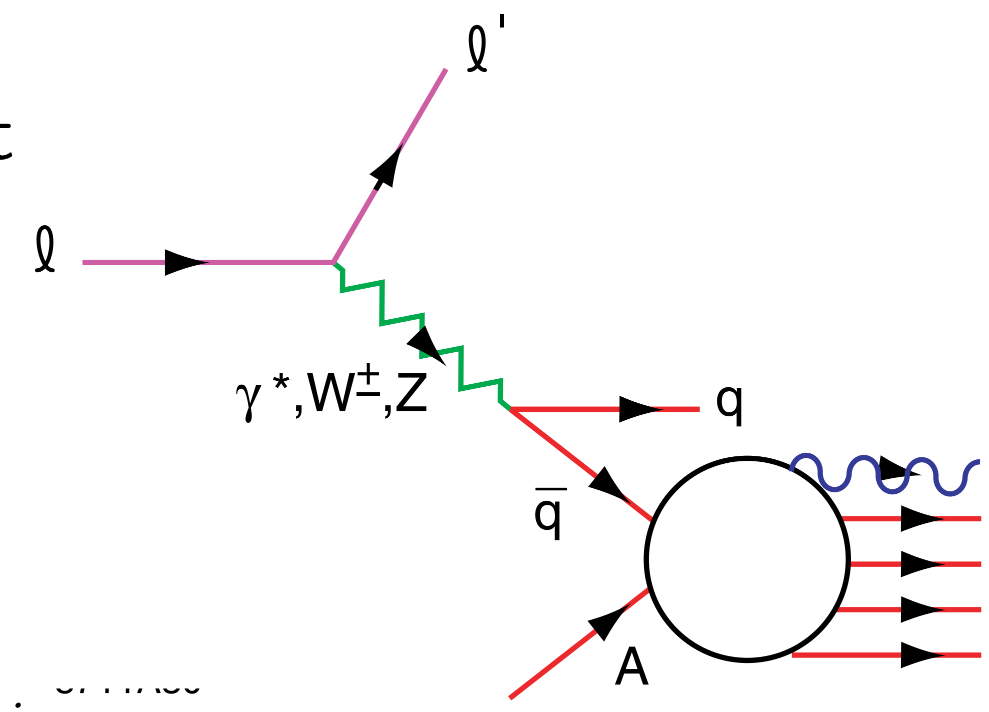
$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Diffraction via Pomeron gives destructive interference!

Shadowing

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

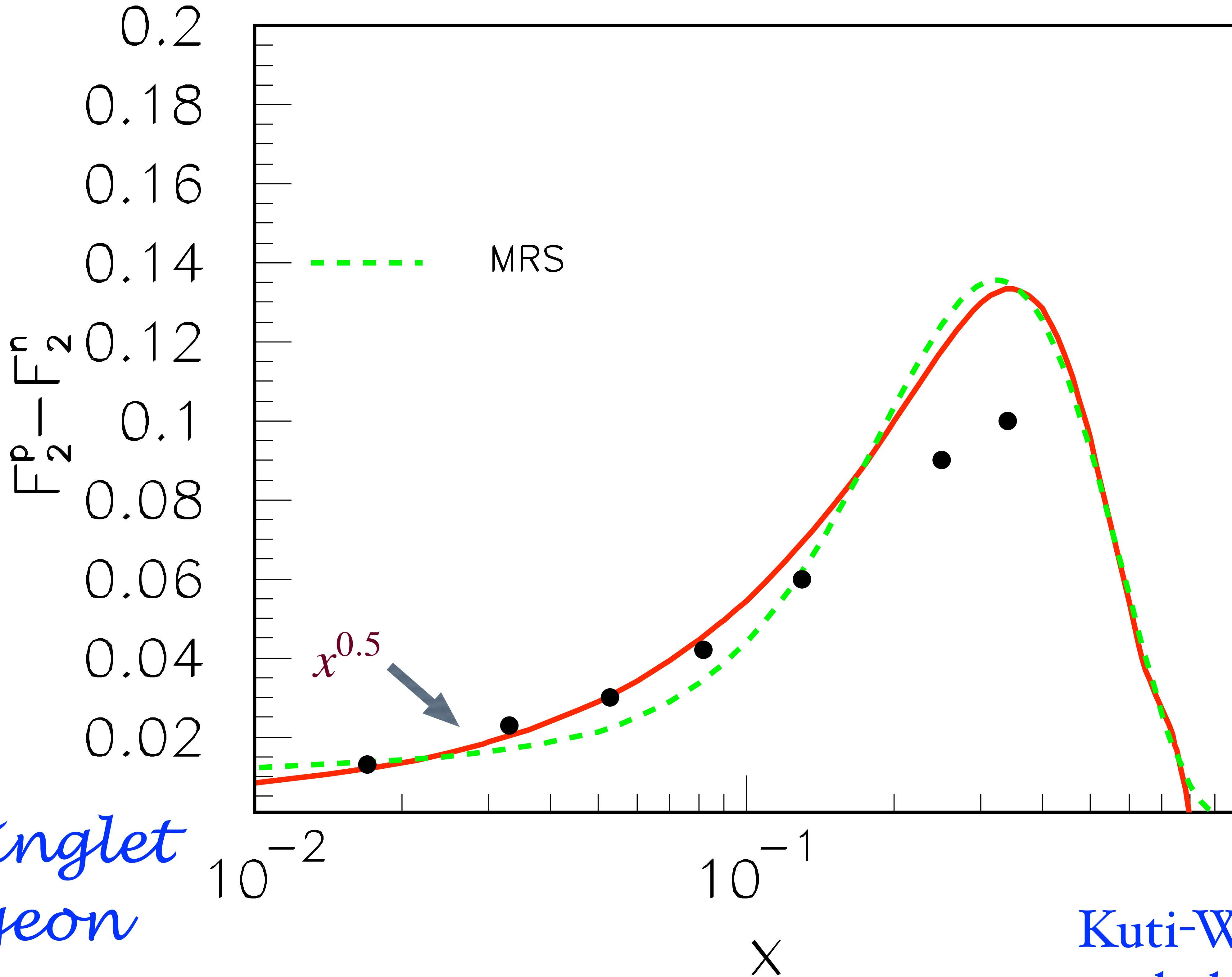
Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

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

Landshoff, Polkinghorne, Short

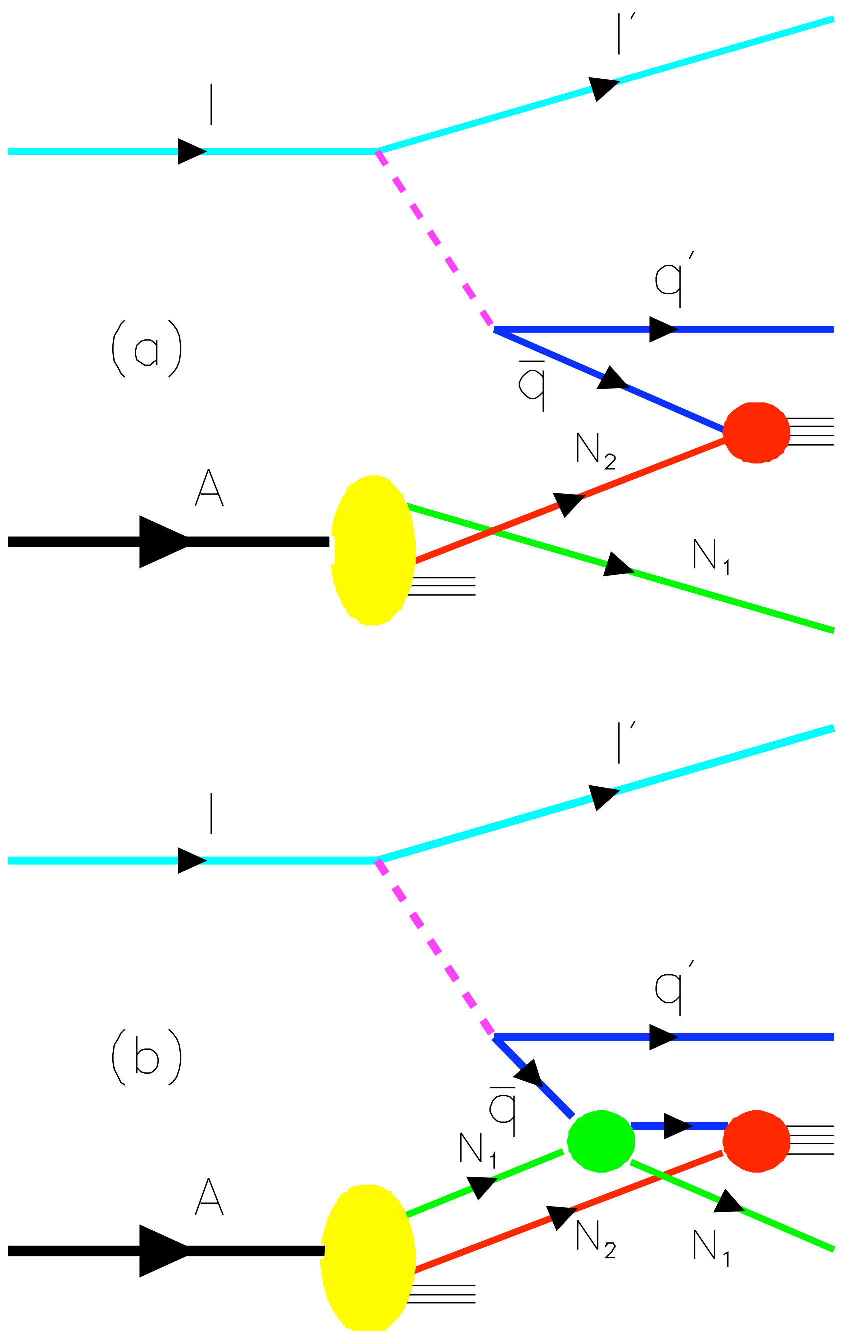
Close, Gunion, sjb

Schmidt, Yang, Lu, sjb



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior



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

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

Regge

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 $\bar{q}$ flux reaching N_2.~~

constructive in phase

thus increasing the flux reaching N_2

Reggeon DDIS produces nuclear flavor-dependent anti-shadowing

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

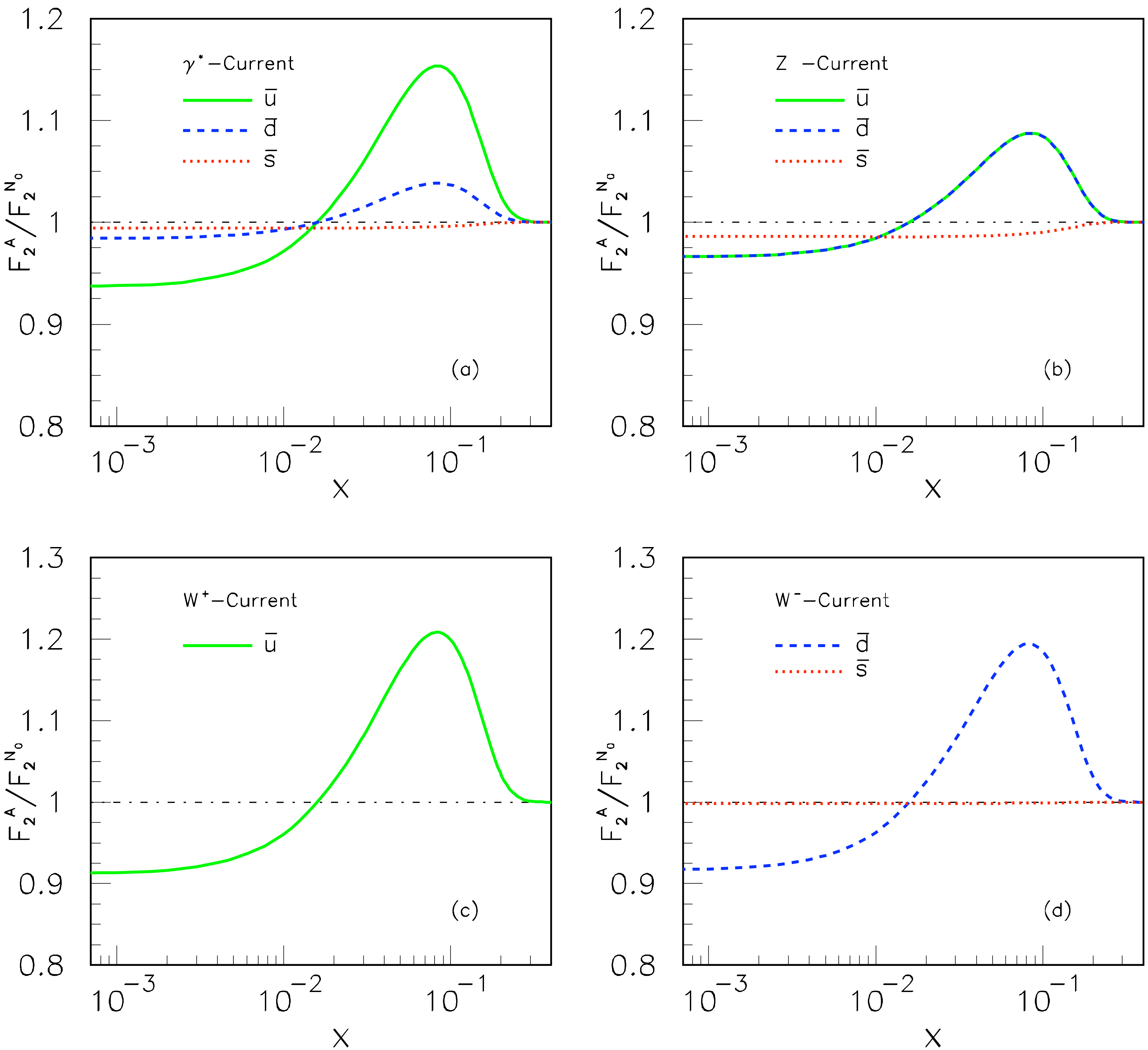
Depends on quark flavor!

Thus antishadowing is not universal

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

Critical test: Tagged Drell-Yan at PANDA

$$\bar{p}A \rightarrow \mu^+\mu^- X$$



Schmidt, Yang; sjb

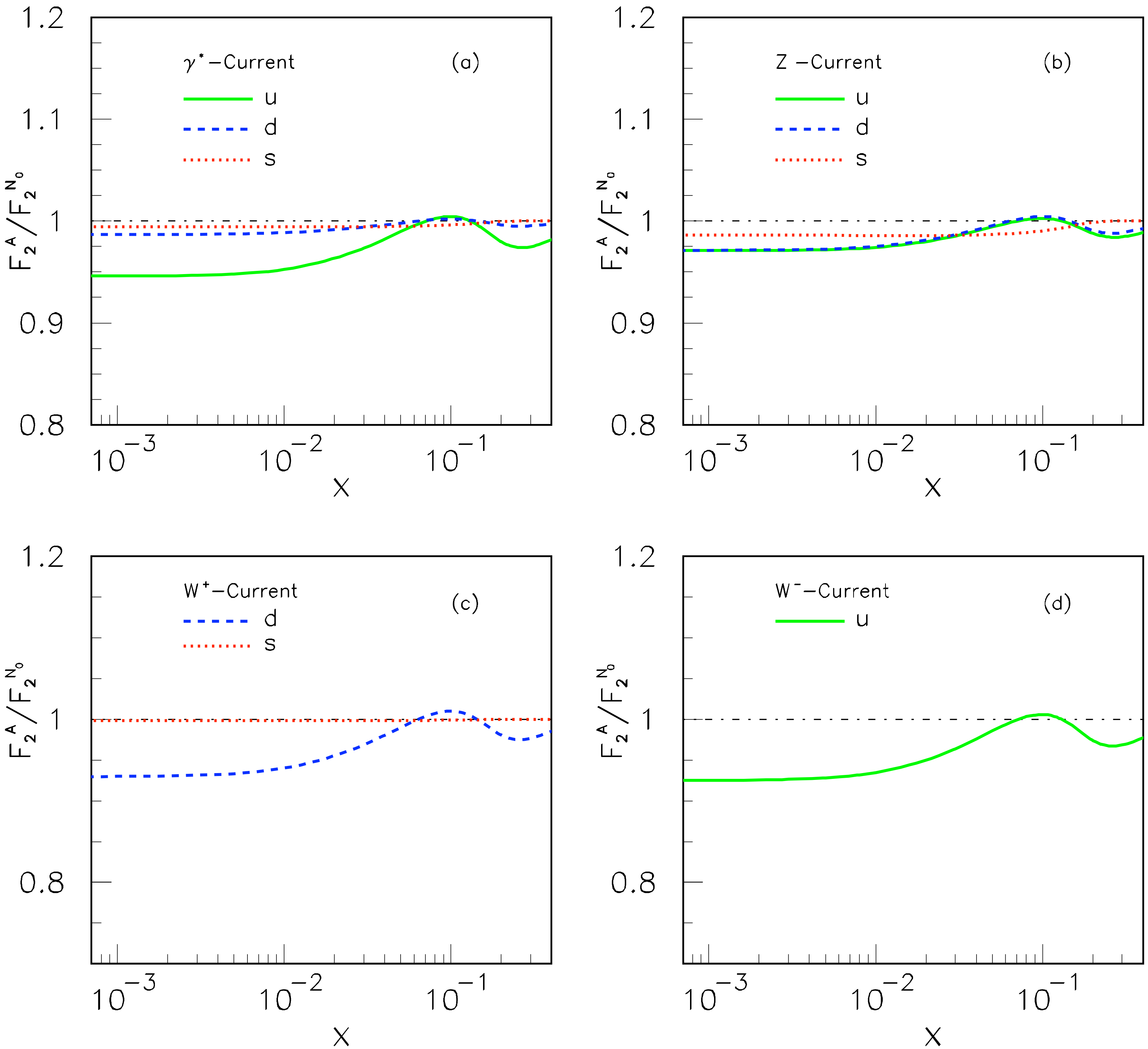
Modifies NuTeV extraction of

$\sin^2 \theta_W$

Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

Shadowing and Antishadowing of DIS Structure Functions



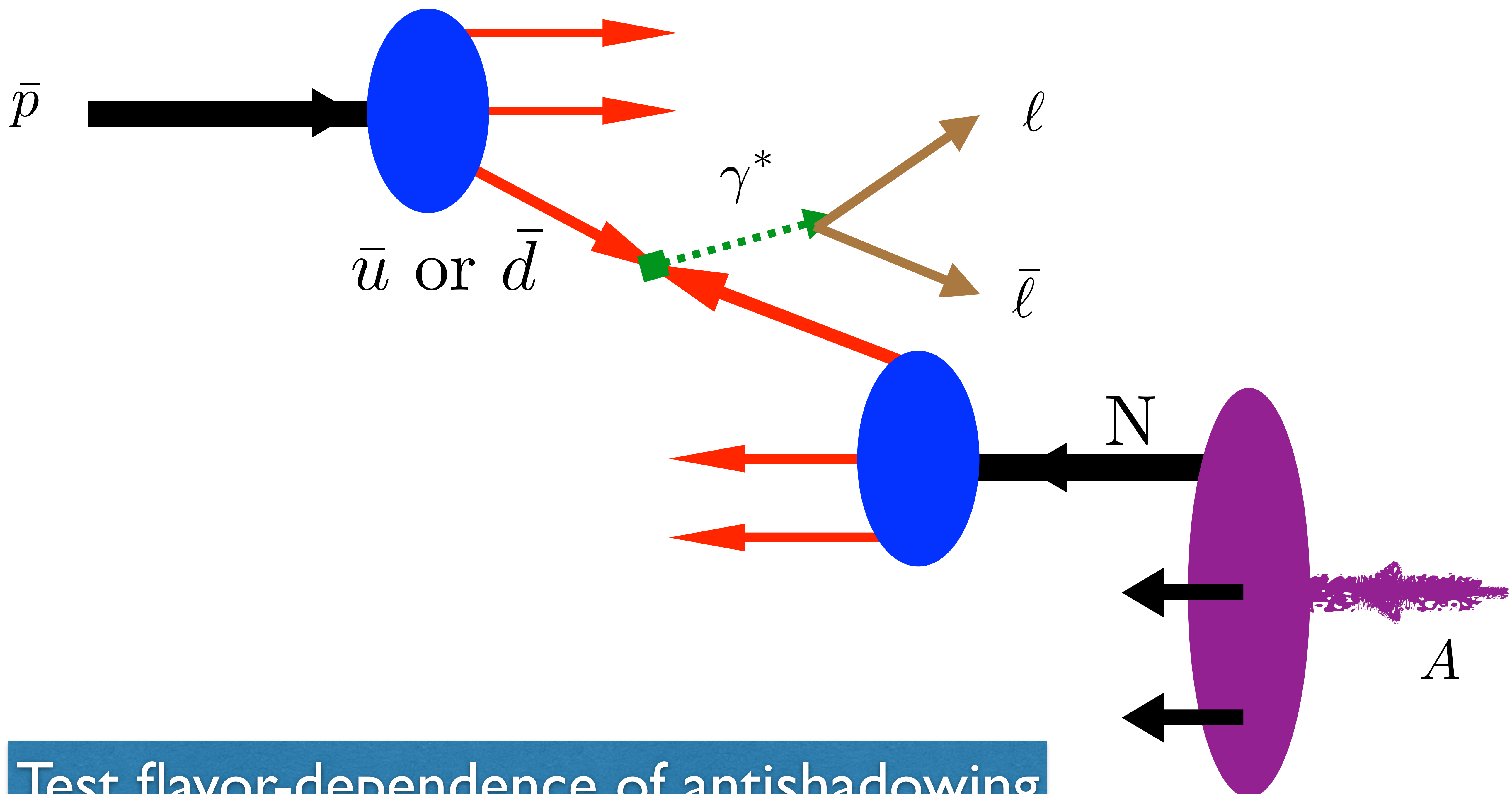
S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Modifies NuTeV extraction of

$$\sin^2\theta_W$$

Test in flavor-tagged lepton-nucleus collisions

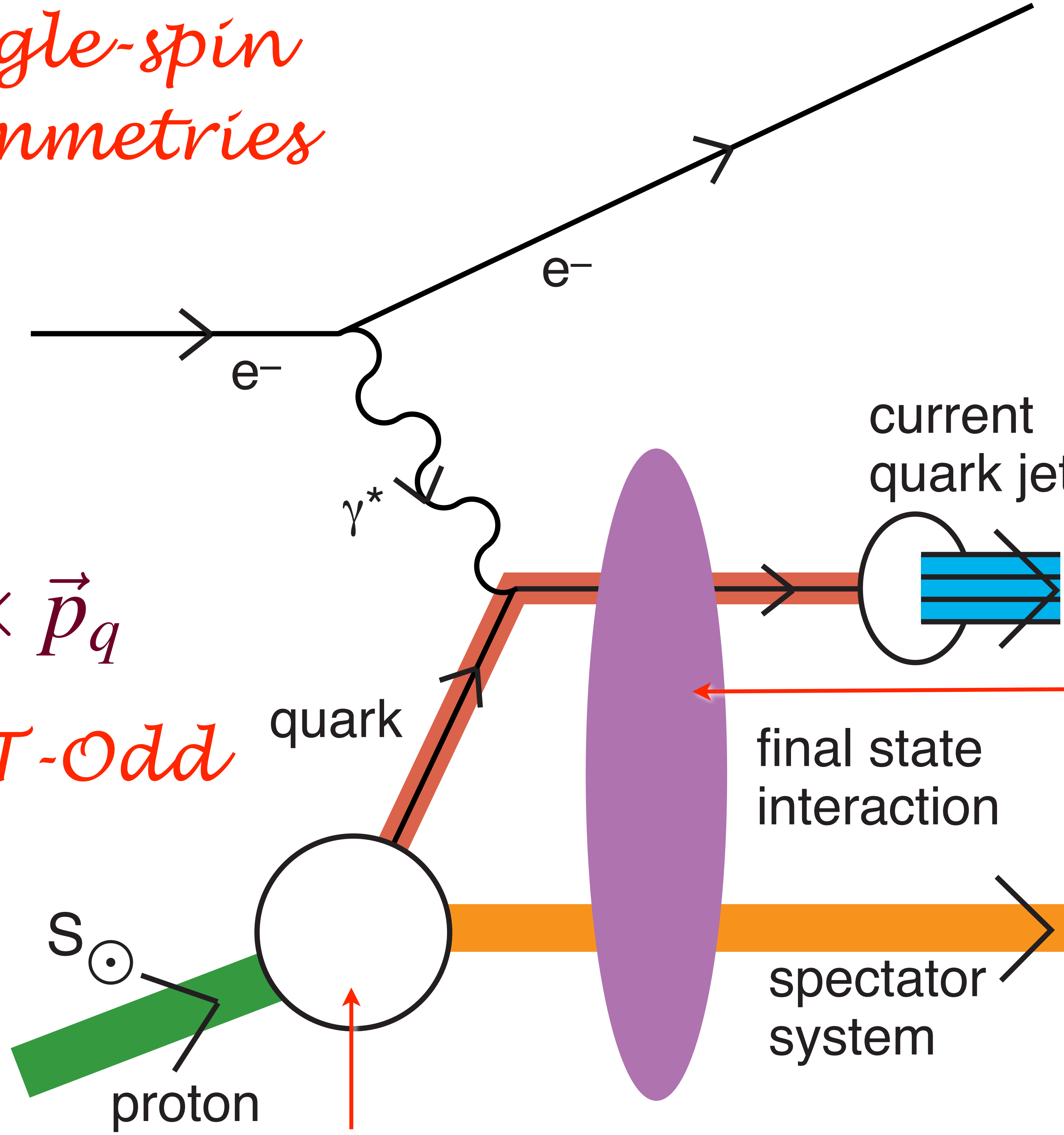
Tag forward fragments compare nuclear targets



Test flavor-dependence of antishadowing

Leading-Twist Sivers Effect

Single-spin asymmetries



Hwang, Schmidt, sjb

Collins, Burkardt
Ji, Yuan

$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo- T-Odd

QCD S- and P-
Coulomb Phases
--Wilson Line

Light-Front Wavefunction
S and P- Waves

Analog of QED FSIs

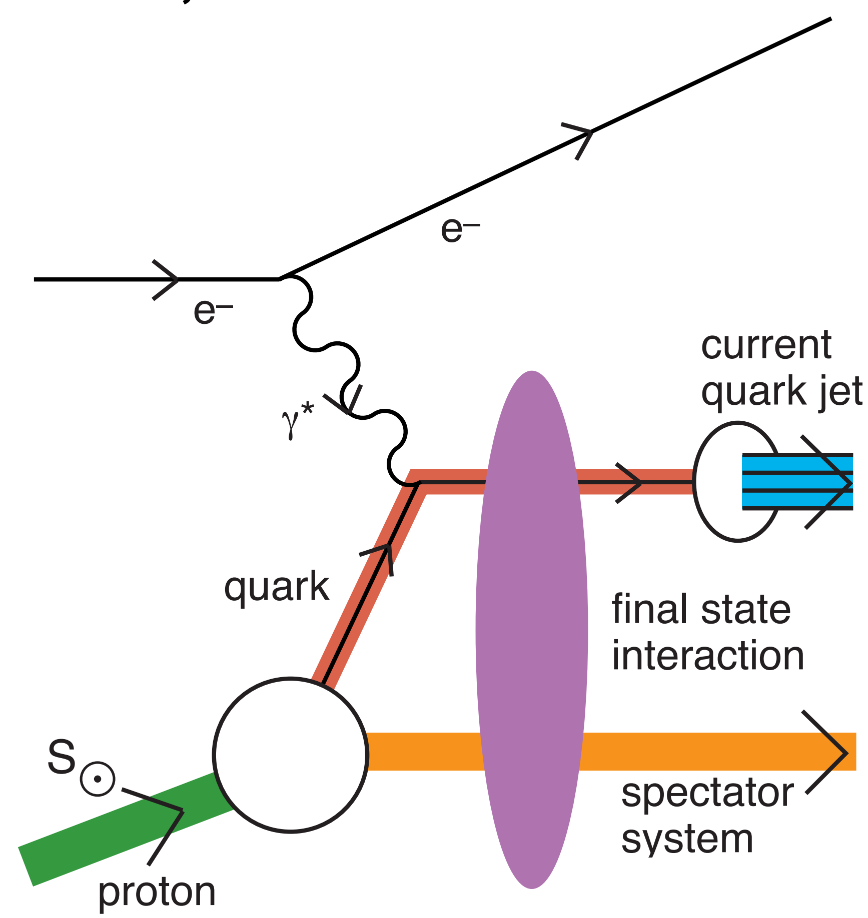
Breakdown of pQCD Factorization Theorems

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

Hwang, Schmidt, sjb
Collins

- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves;**
- **Wilson line effect -- lc gauge prescription**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**
- **Sign Change for SSA for Drell-Yan lepton-pair production**



Mulders, Boer   Qiu, Sterman

Pasquini, Xiao, Yuan, sjb

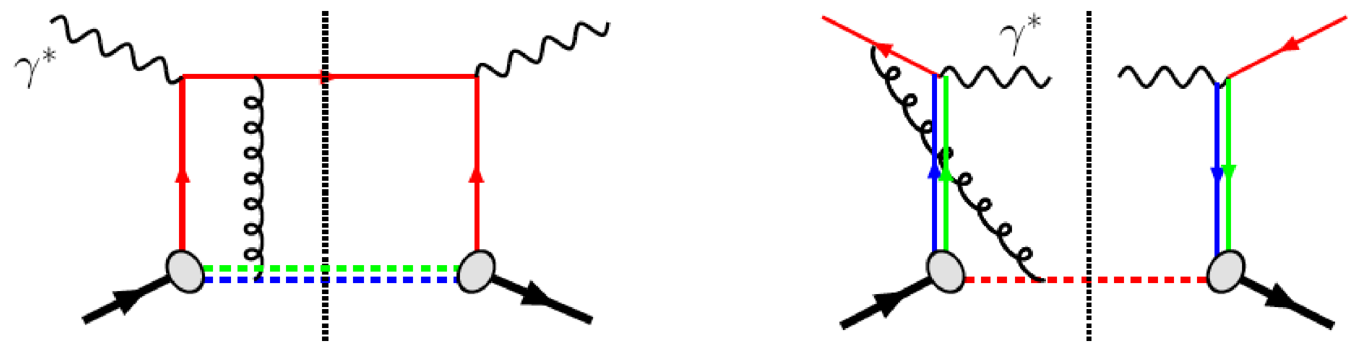
Dae Sung Hwang, Yuri V. Kovchegov,
Ivan Schmidt, Matthew D. Sievert, sjb

Hwang, Schmidt, sjb

Color interactions in QCD:

Collins

- Non-universality of Sivers Function (DIS vs. DY)
- Critical test of TMD Factorization



Attractive FSI
DIS

Repulsive FSI
Drell-Yan

Sivers$_{\text{DIS}}$ = - Sivers$_{\text{DY/W/Z0/}\gamma}$

Both PHENIX and STAR installing upgrades for 2015 for direct photon DY measurement at forward rapidity

Will explore in future 500 GeV Runs

STAR also plans TMD evolution studies using W's

Opportunities at PANDA: Drell Yan sector for future precision studies

Abhay Deshpande

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

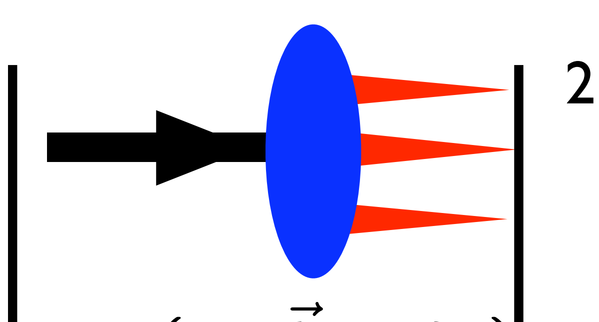
Hwang, Schmidt, sjb,

Mulders, Boer

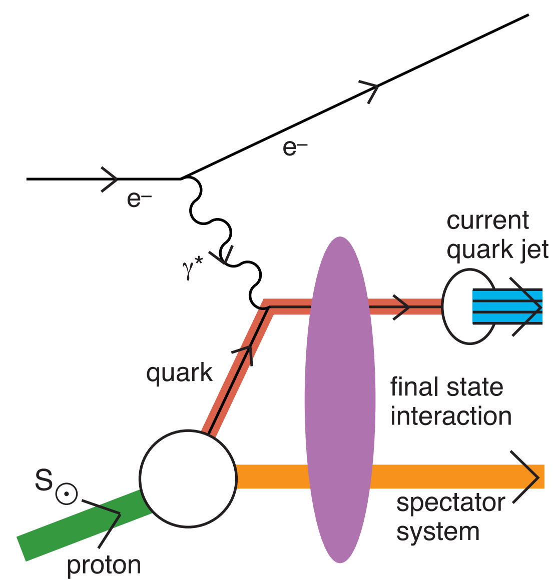
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb

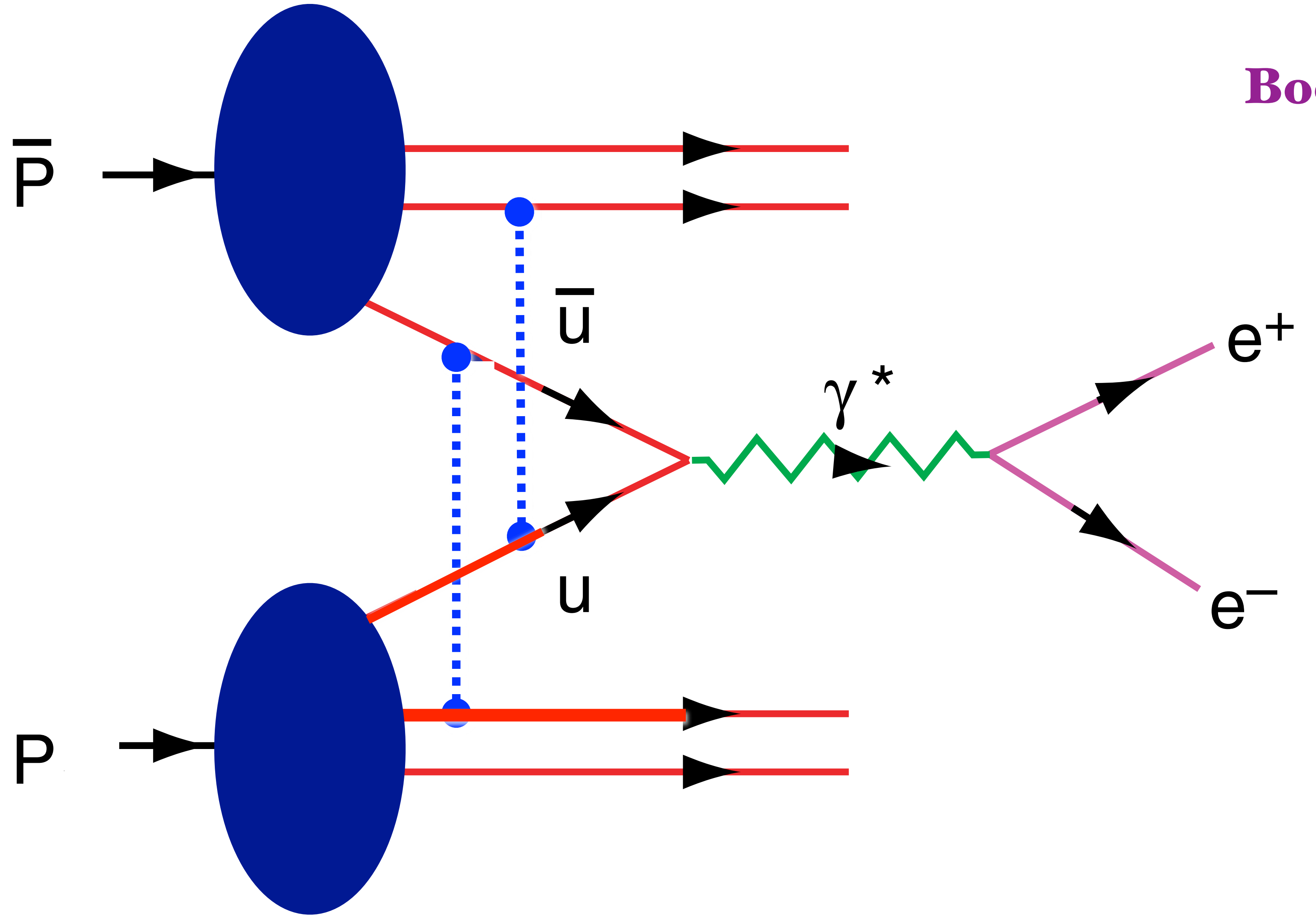


$$\left|\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\right|^2$$



Example of Leading-Twist Lensing Correction

Boer, Hwang, sjb



DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

$$h_1^\perp(x_1, \boldsymbol{p}_\perp^2) \times \bar{h}_1^\perp(x_2, \boldsymbol{k}_\perp^2)$$

Double Initial-State Interactions generate anomalous $\cos 2\phi$

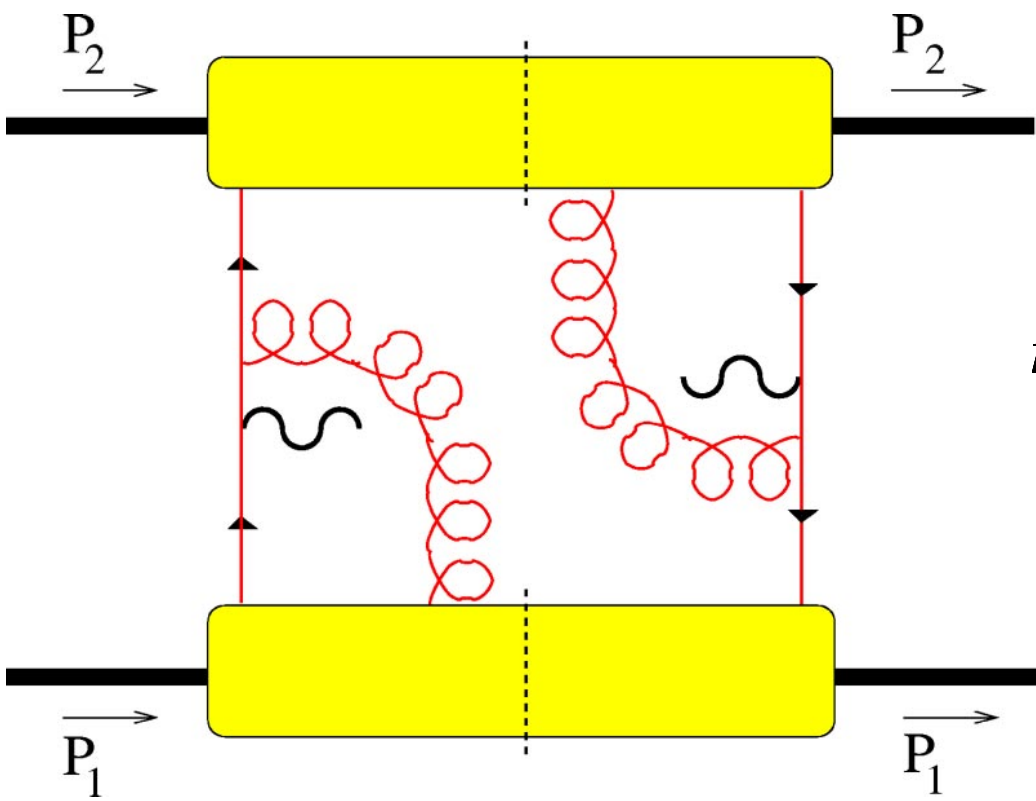
Drell-Yan planar correlations

Boer, Hwang, sjb

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

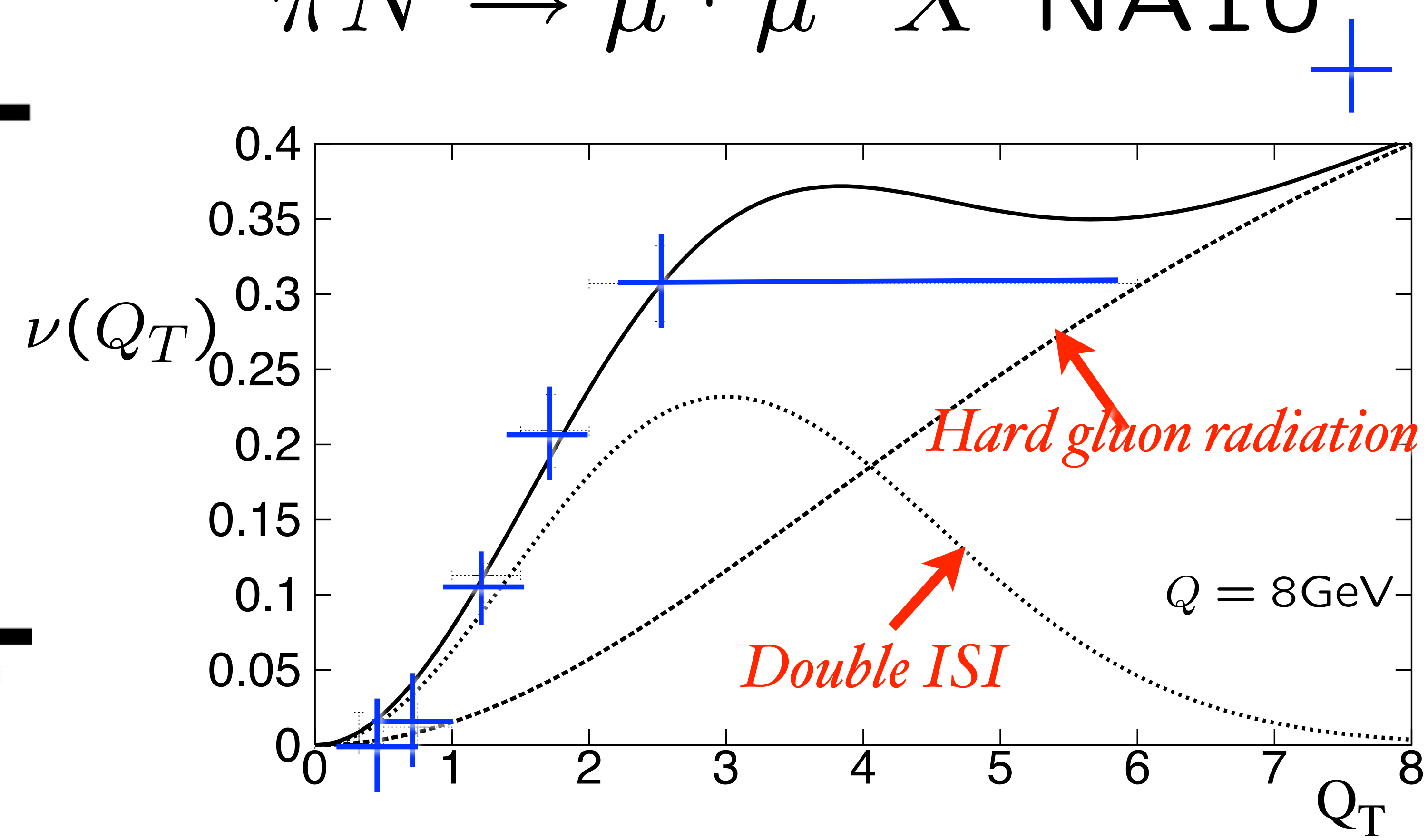
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^\perp(\pi)\, h_1^\perp(N)$$



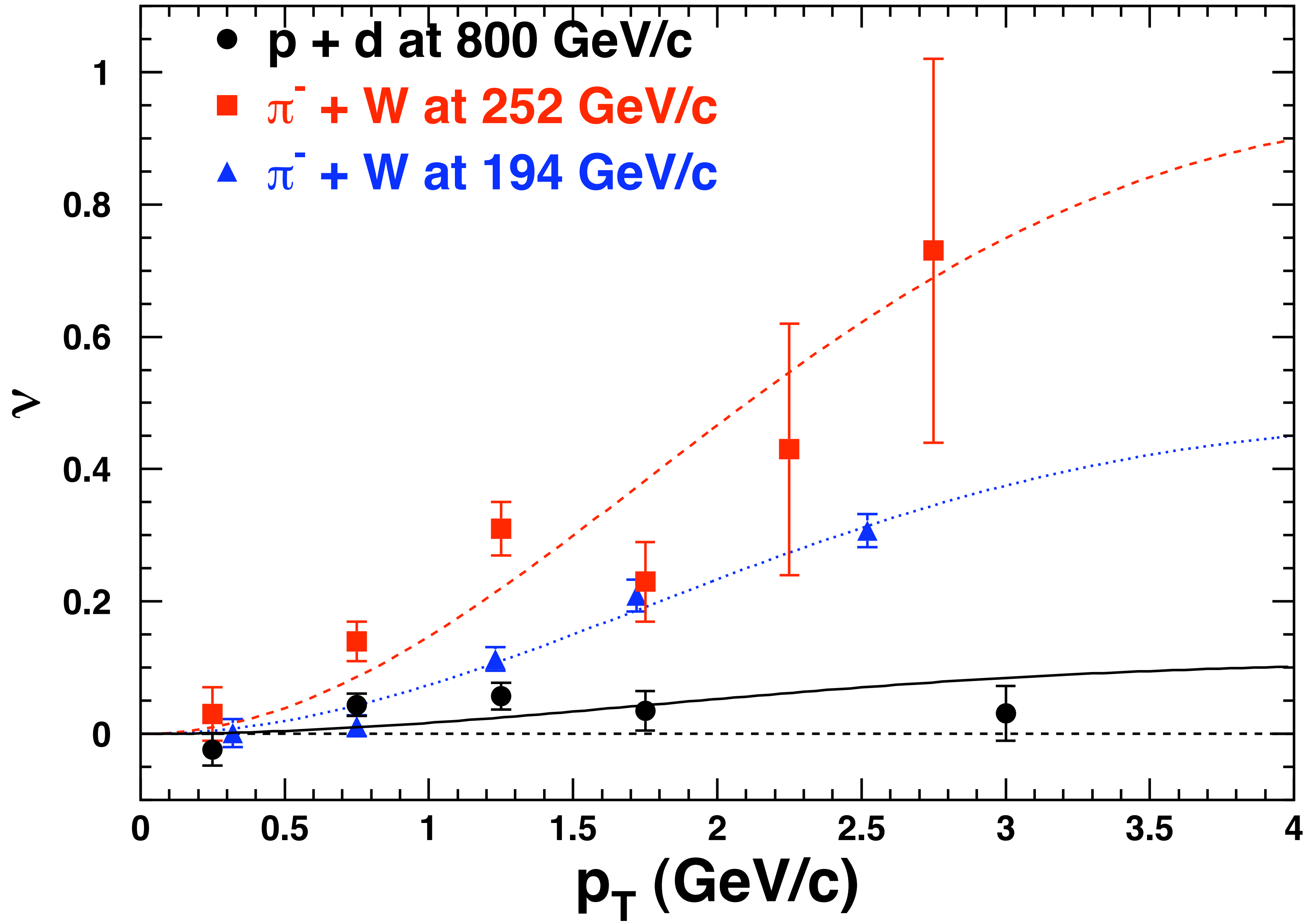
Violates Lam-Tung relation!

$\pi N \to \mu^+\mu^- X$ NA10



Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)



Huge Effect in $\pi W \to \mu^+\mu^- X$

Negligible Effect $pd \to \mu^+\mu^- X$

Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Exclusive Processes at PANDA

- Detailed tests of QCD hadronization at the amplitude level
- Fundamental production and dynamical mechanisms
- Rigorous Scaling Laws at fixed t/s.
- Regge Trajectories become flat at large momentum transfer
- Exclusive Amplitudes: convolution of light front wavefunctions
- Probe color confinement, fundamental QCD scale.
- Color transparency measures color dipole size

Time-like and Space-like EM Form Factors

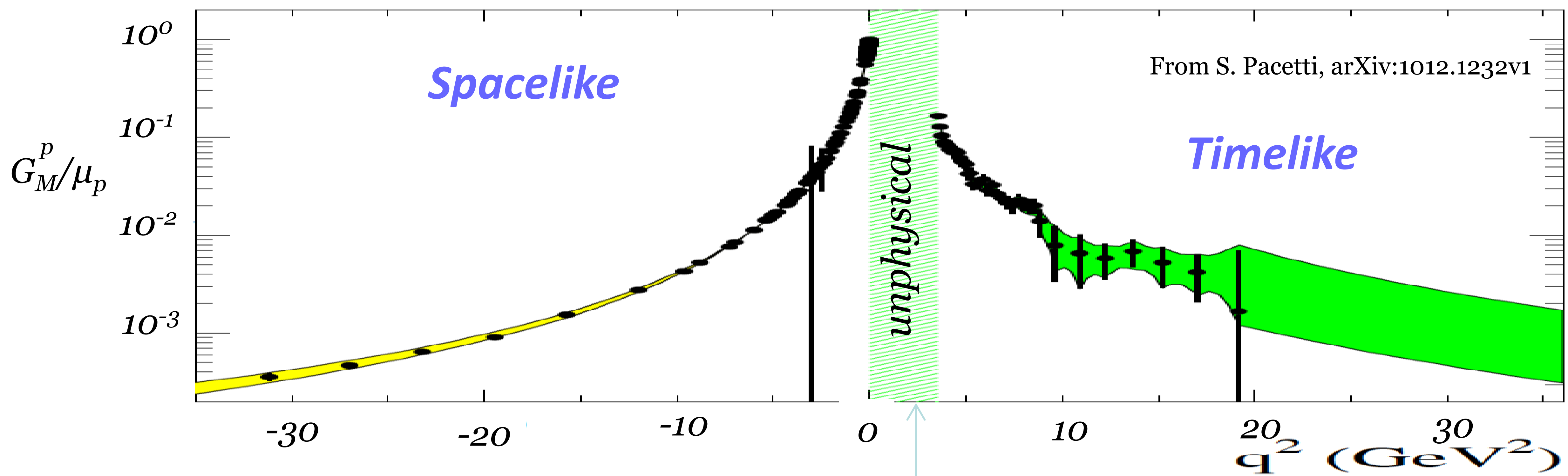
electron scattering

annihilation $\bar{p}p \leftrightarrow e^+e^-$

$q^2 > 4m_p^2$

e^- scattering (Jlab…. A2/Mainz)

$e^+e^- \leftrightarrow \bar{p}p$ (BES, Novosibirsk, PANDA)



Dispersion relations:

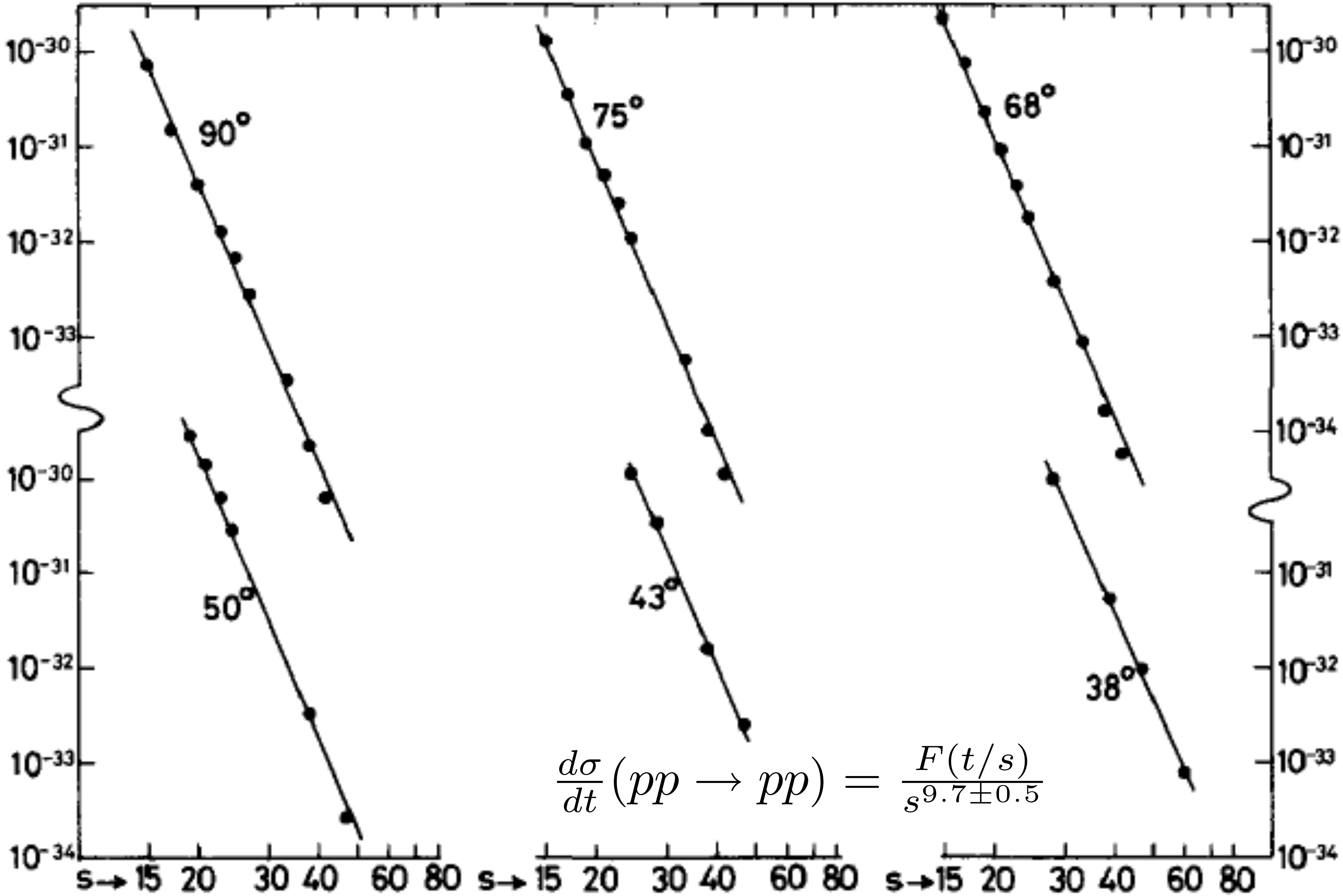
$q^2 < 0$

$$G(q^2) = \frac{1}{\pi}\left[\int_{4m_\pi^2}^{4m_p^2} \frac{\text{Im}\,G(s)\,ds}{s-q^2} + \int_{4m_p^2}^{\infty} \frac{\text{Im}\,G(s)\,ds}{s-q^2}\right]$$

QCD Prediction:

$$\frac{d\sigma}{dt}(pp \to pp) = \frac{F(t/s)}{s^{10}}$$

$N = 4 \times 3 = 12, n = N - 2 = 10$



$$\frac{d\sigma}{dt}(pp \to pp) = \frac{F(t/s)}{s^{9.7 \pm 0.5}}$$

Fixed CM angle scaling

$$\frac{d\sigma}{dt}(A + B \to C + D) = \frac{F(t/s)}{s^{N-2}}$$

Farrar, sjb
Matveev, Muradyan, Tavkhelidze

AdS/QCD: Polchinski and Strassler

$$N = N_A + N_B + N_C + N_D$$

$$s^2 \frac{d\sigma}{dt}(pp \to pp) = \frac{F(t/s)}{s^8} \quad \Longleftrightarrow \quad s^2 \frac{d\sigma}{dt}(\bar{p}p \to \bar{p}p) = \frac{F(t/u)}{u^8}$$

$$s \leftrightarrow u$$

$$\frac{d\sigma}{dt}(\bar{p}p \to \bar{\Lambda}\Lambda) = \frac{F(t/s)}{s^{10}}$$

$$\frac{d\sigma}{dt}(\bar{p}p \to K^- K^+) = \frac{F(t/s)}{s^8}$$

Brodsky and Farrar, Phys. Rev. Lett. 31 (1973) 1153
Matveev et al., Lett. Nuovo Cimento, 7 (1973) 719

Quark Counting Rules for Exclusive Processes

- Power-law fall-off of the scattering rate reflects degree of compositeness
- The more composite -- the faster the fall-off
- Power-law counts the number of quarks and gluon constituents
- Form factors: probability amplitude to stay intact

$$F_H(Q) \propto \frac{1}{(Q^2)^{n-1}}$$

n = # elementary constituents

True for Hadrons and Atoms

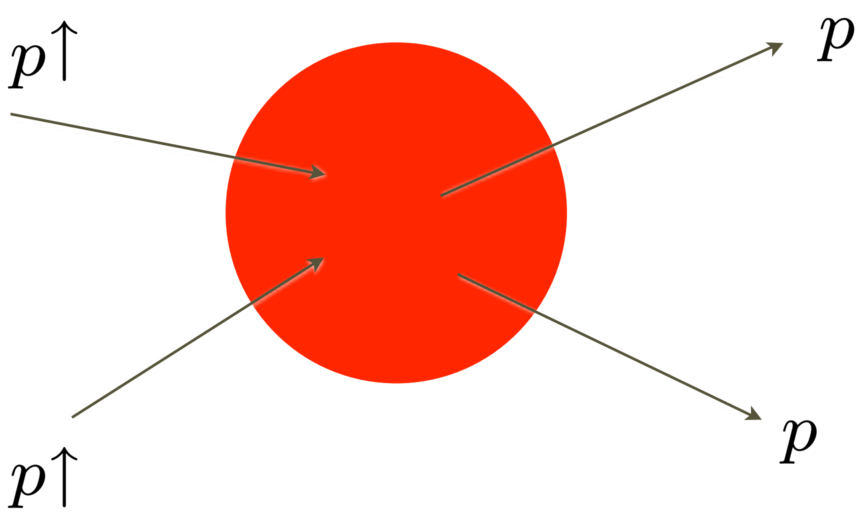
$$M(\bar{p}p \to \bar{p}p) = \sum_i M_{\text{Resonances}} + M_{\text{QCD Background}}$$

$$= \sum_i \frac{P_i^J(cos\theta_{CM}, \phi)}{s - M^2 + i\sqrt{s}\Gamma_i} + \frac{C}{t^4 s^4}$$

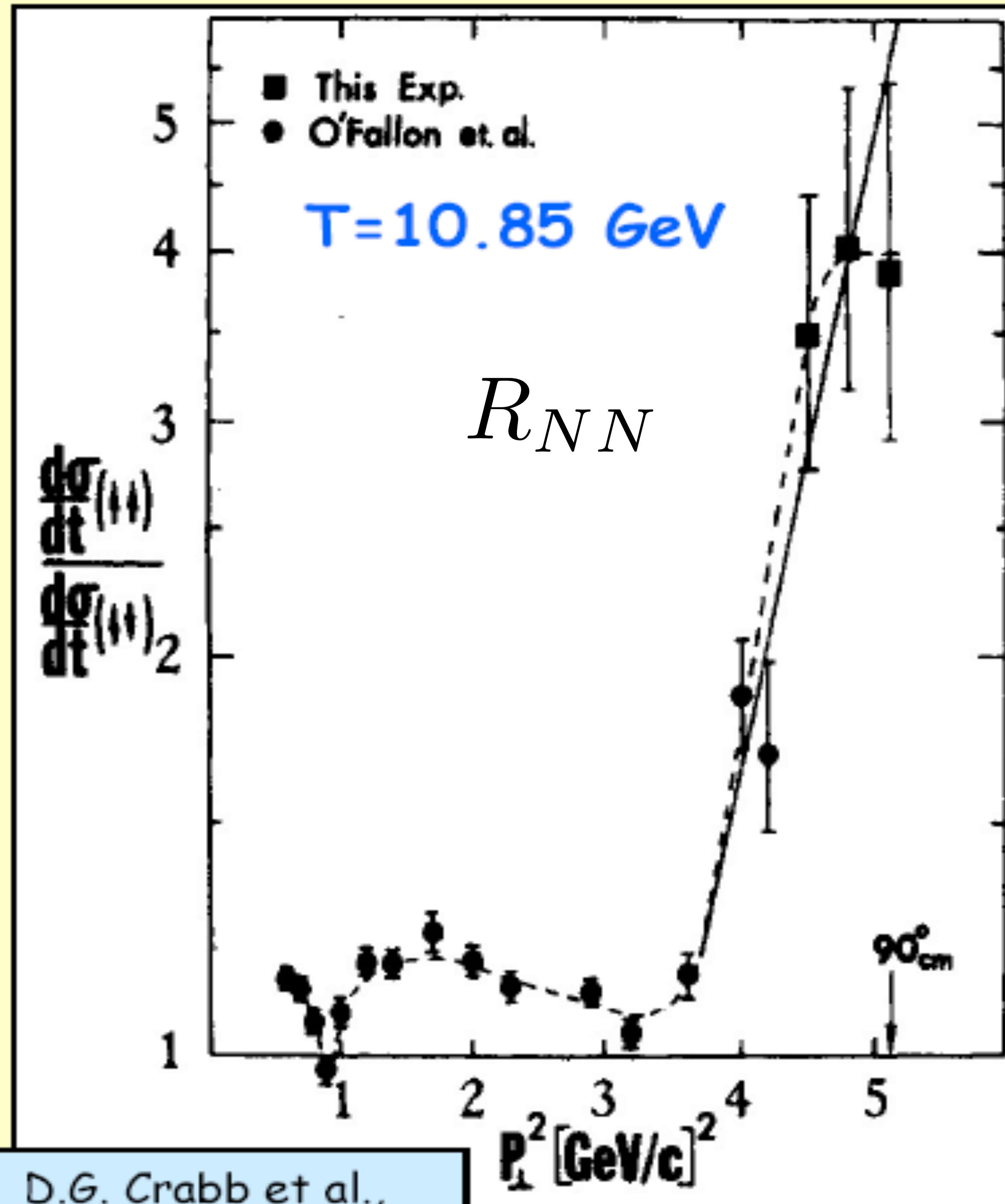
- ***pQCD Quark Counting Rules*** $\frac{d\sigma}{dt}(A + B \to C + D) = \frac{F_{A+B\to C+D}(t/s)}{s^{n_A+n_B+n_C+n_D-2}}$
- ***Crossing Relations***
- ***Hadron-Helicity Conservation***
- ***Quark Interchange dominates Gluon Exchange***
- *Color Transparency*
- ***Interference Patterns; Charm Threshold***

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)

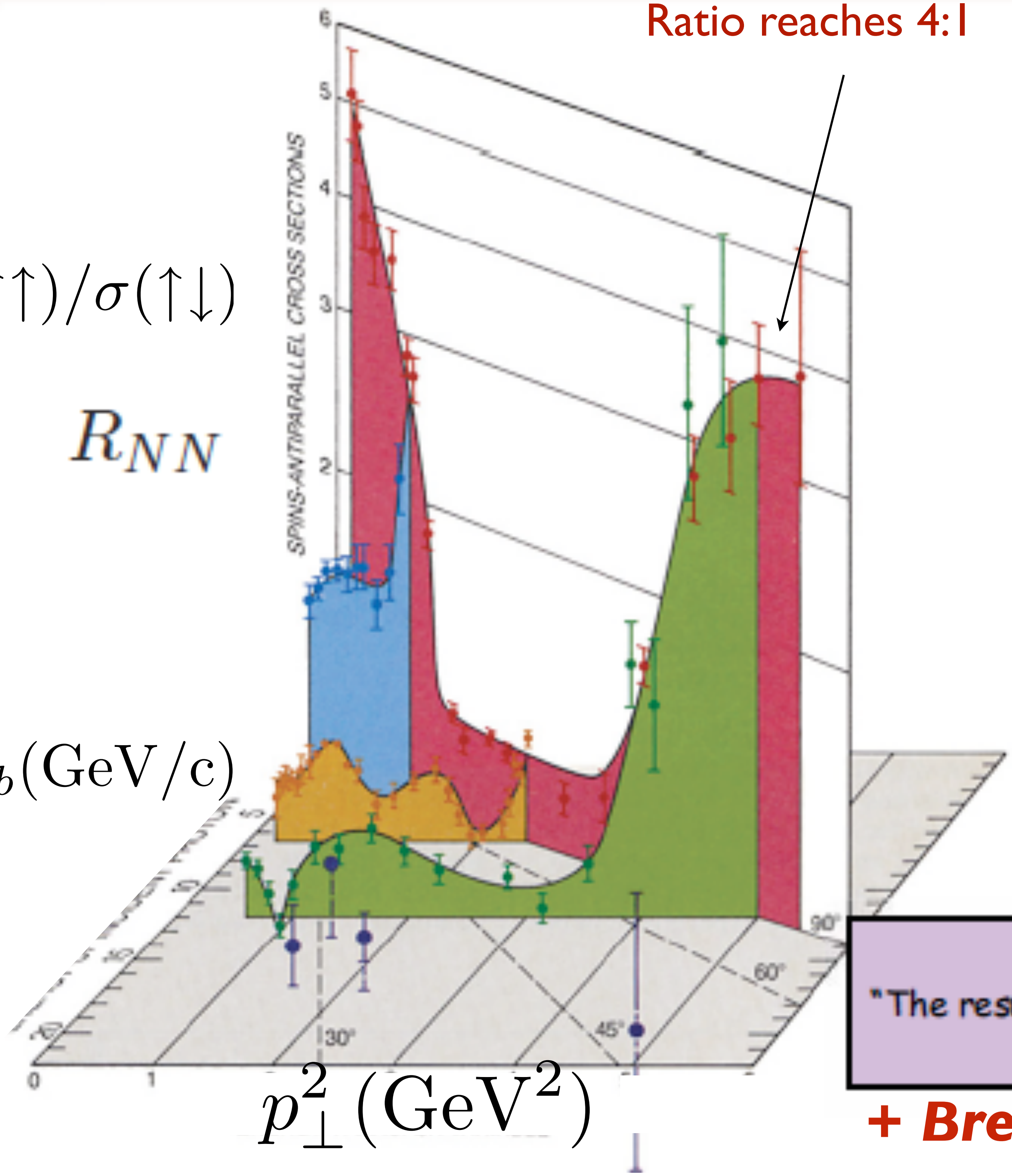
Spin Correlations in Elastic $p-p$ Scattering

Ratio reaches 4:1

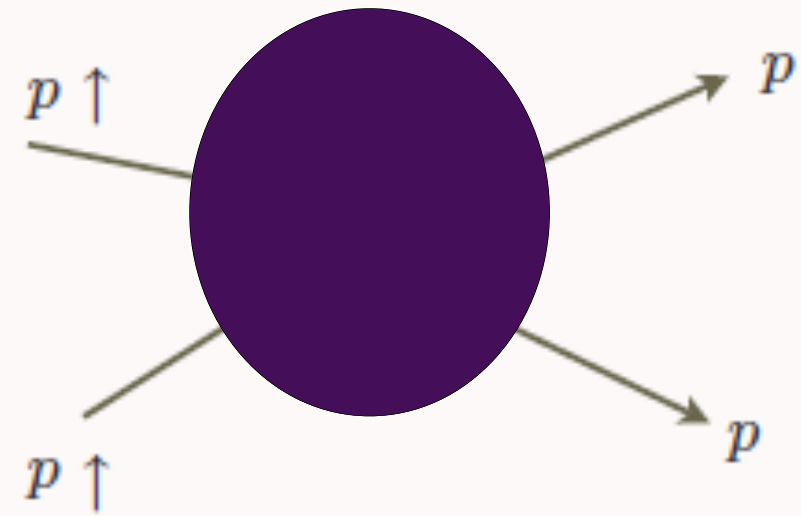
$\sigma(\uparrow\uparrow)/\sigma(\uparrow\downarrow)$

R_{NN}

$p_{lab}(\mathrm{GeV/c})$



$p_\perp^2\,(\mathrm{GeV}^2)$



polarization normal to scattering plane

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

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

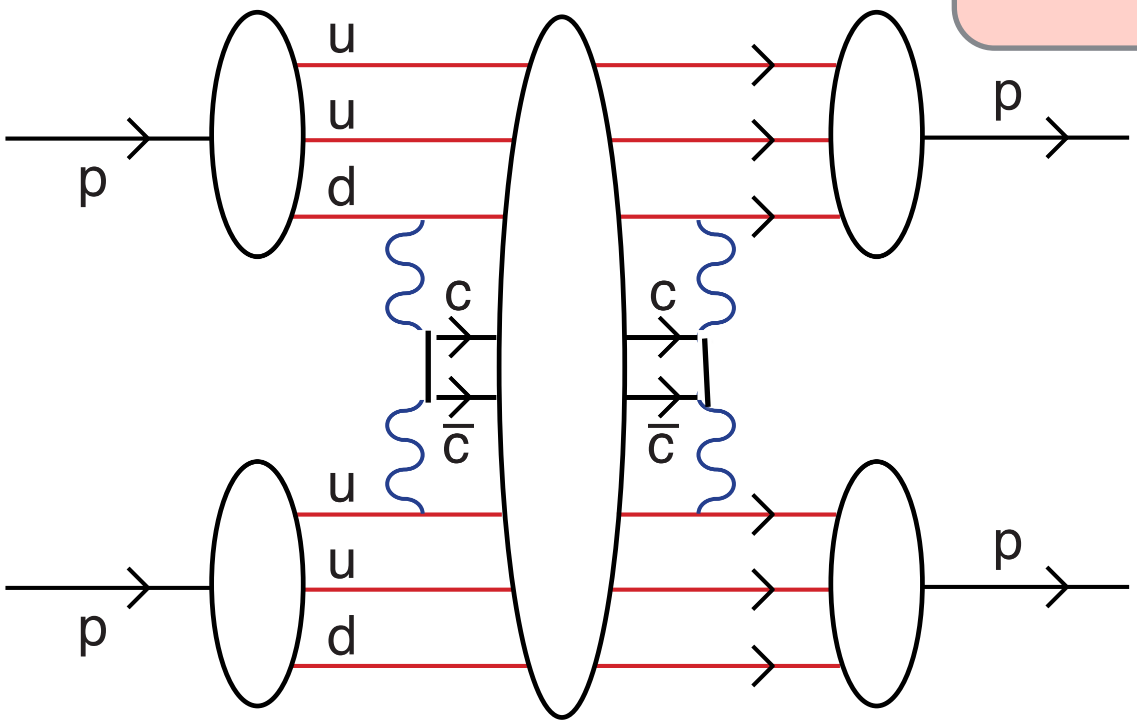
+ Breakdown of Color Transparency!

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

$A_{nn} = 1!$

Possible: Octoquark resonance $uud\bar{u}\bar{u}\bar{d}c\bar{c}$ in $\bar{p}p \to \bar{p}p$ at $\sqrt{s} = 5\ GeV$



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

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

QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

8 quarks in S-wave: odd parity

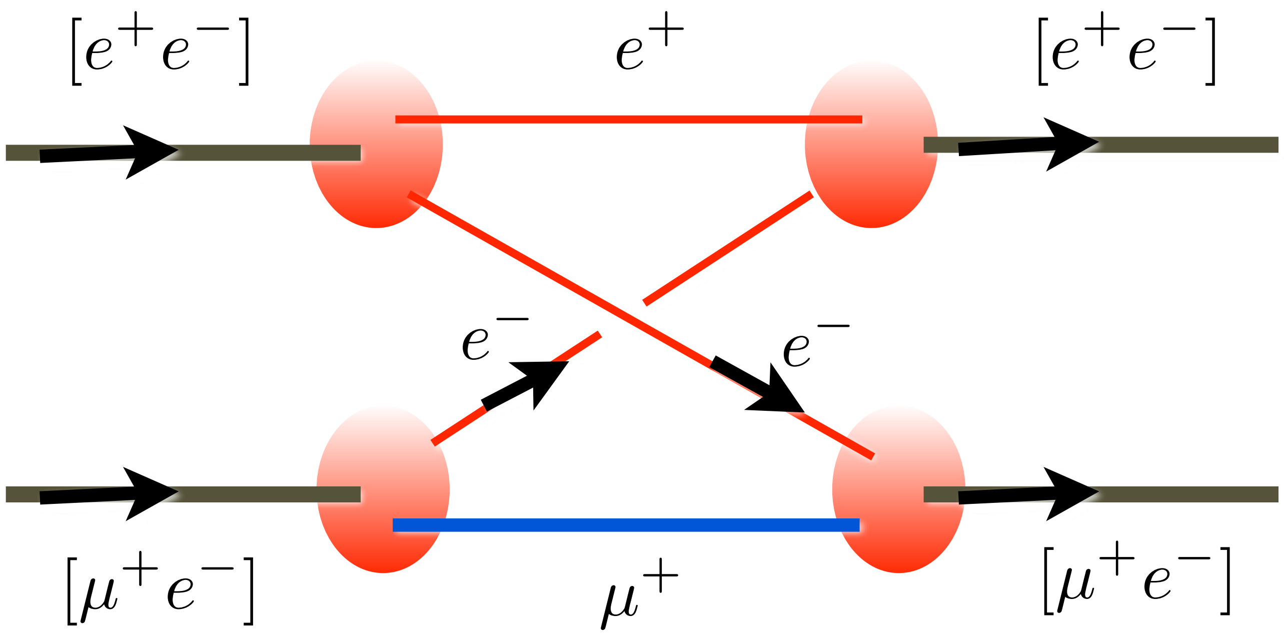
Hebecker, Kuhn, sjb

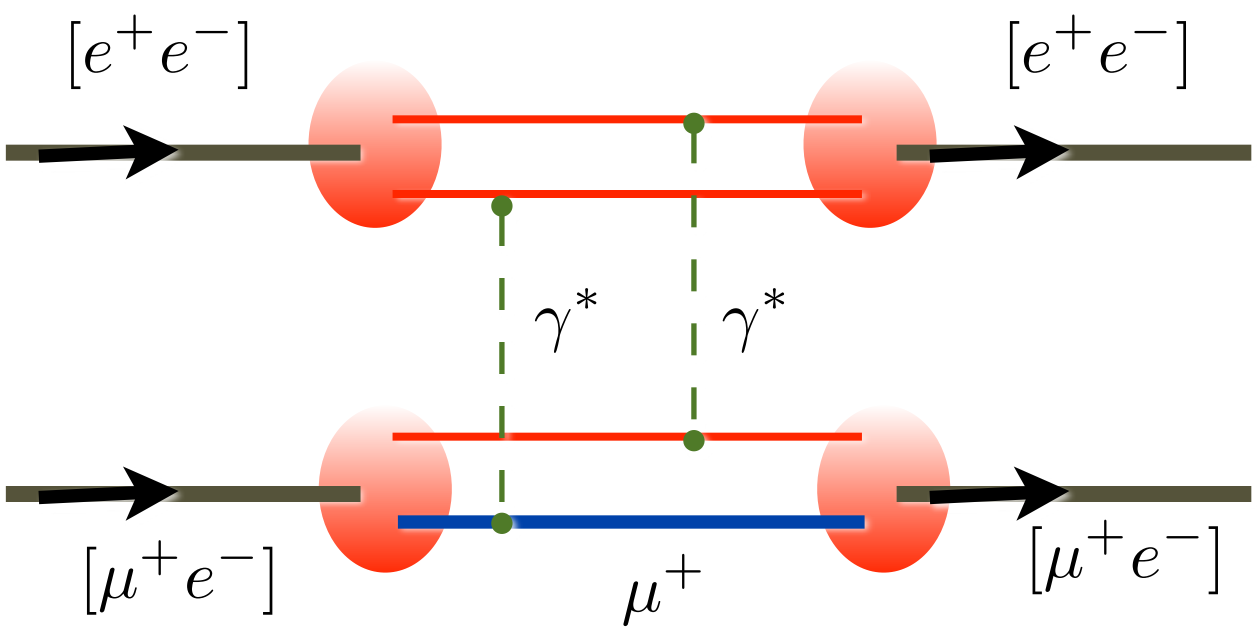
S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

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

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

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





Constituent Interchange

Spin exchange in atom-atom scattering

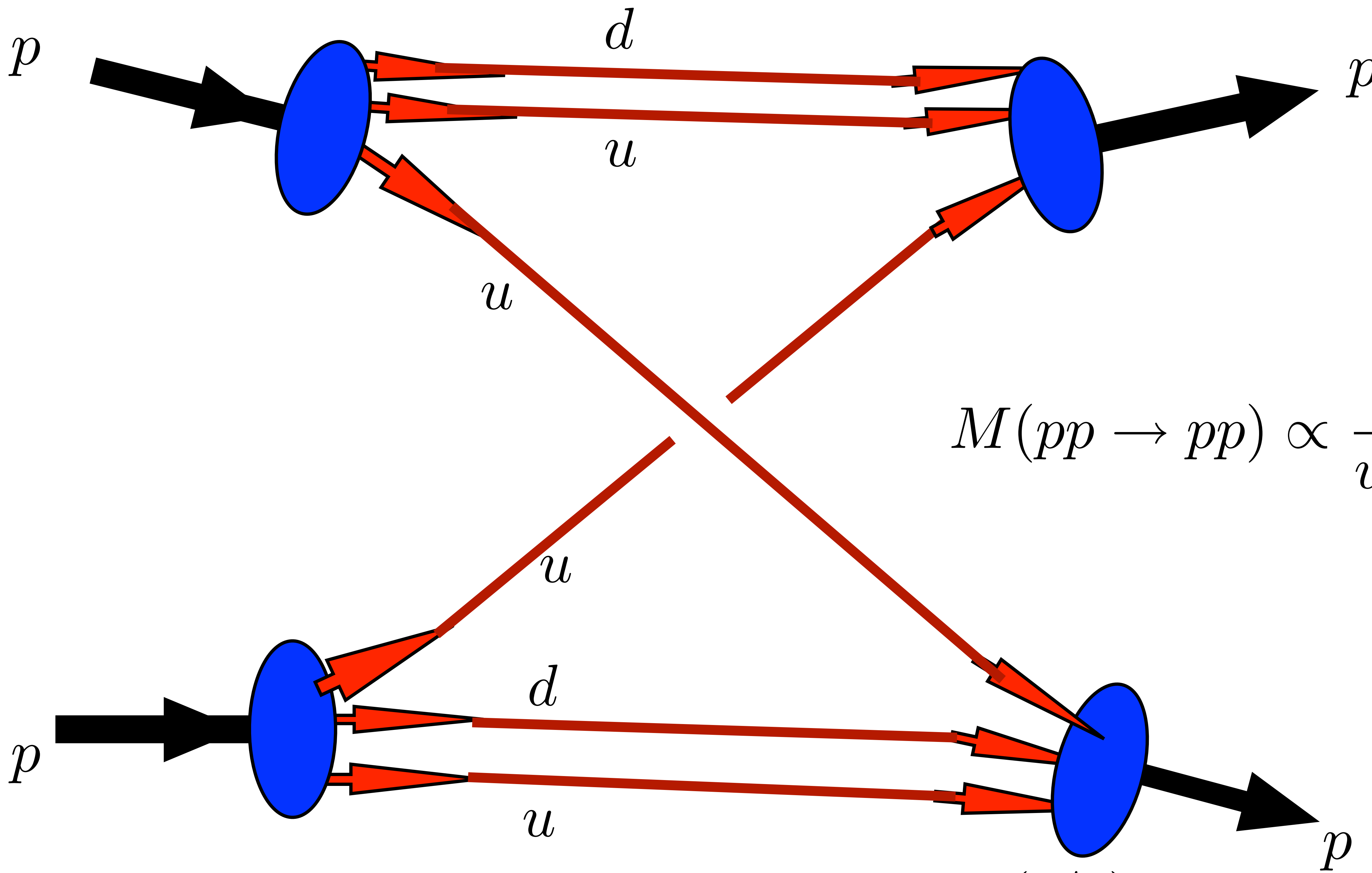
Two-Photon Exchange (Van der Waal)

$$\frac{d\sigma}{dt} = \frac{|M(s,t)|^2}{s^2}$$

$$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$$

$$M(s,t)_{\text{gluonexchange}} \propto sF(t)$$

$$pp \longrightarrow pp$$



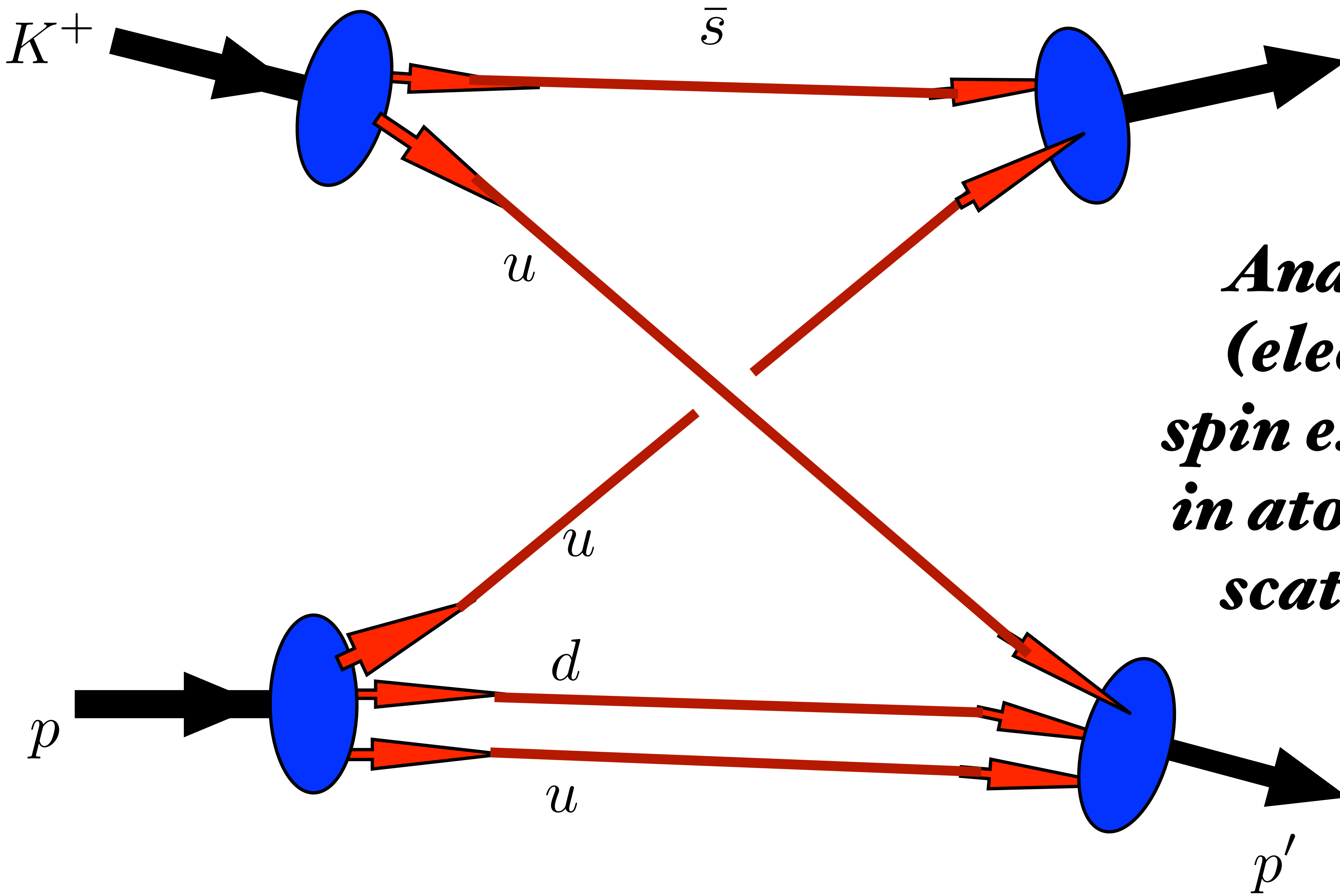
$$M(pp \to pp) \propto \frac{1}{u^2}\frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(pp \to pp) \propto \frac{1}{s^2 t^4 u^4} = \frac{F(t/s)}{s^{10}}$$

Quark Interchange

Blankenbecler, Gunion, sjb

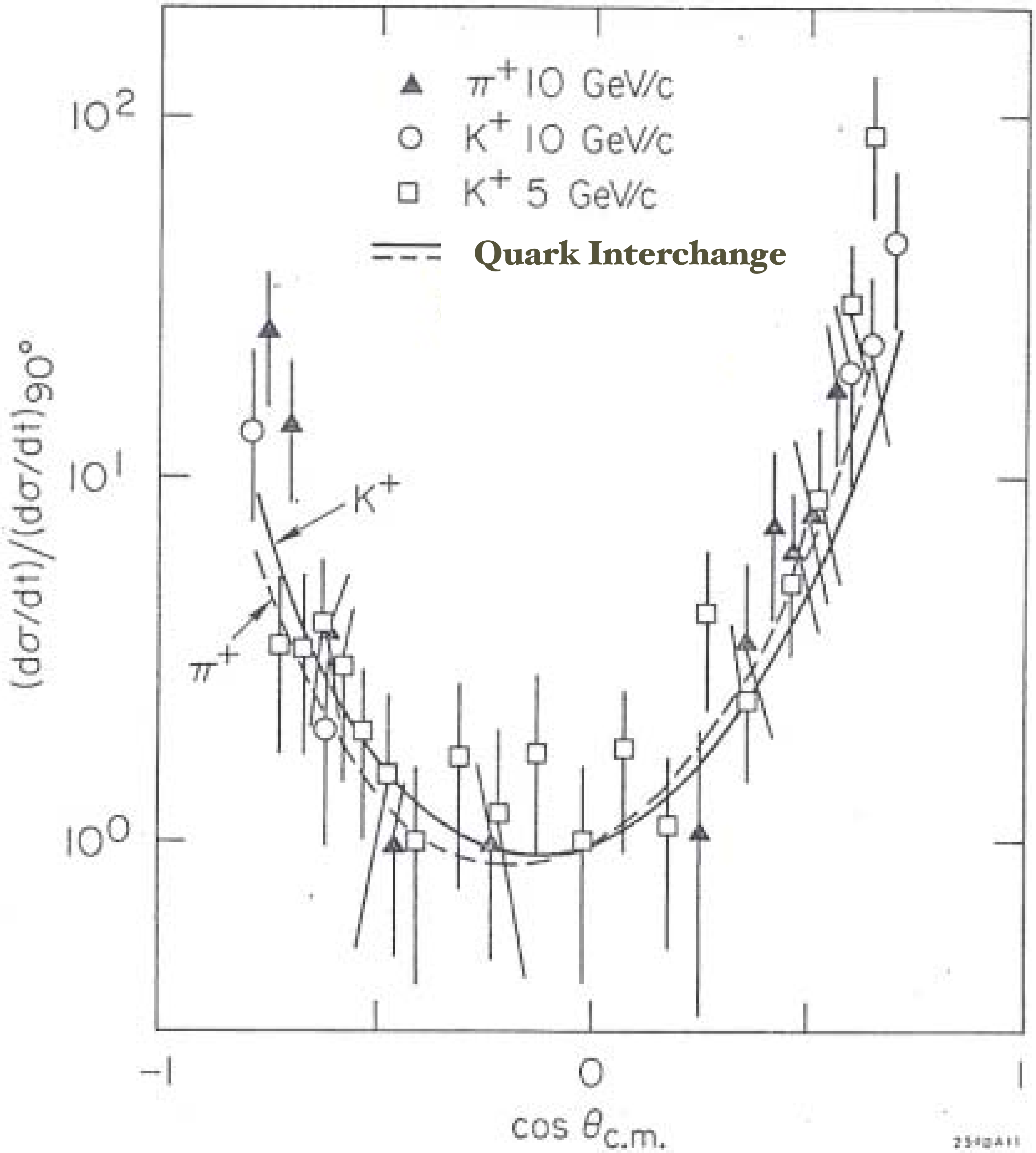
$$K^+ p \to K^+ p$$



Analog of (electron) spin exchange in atom atom scattering

Constituent Interchange

Blankenbecler, Gunion, sjb

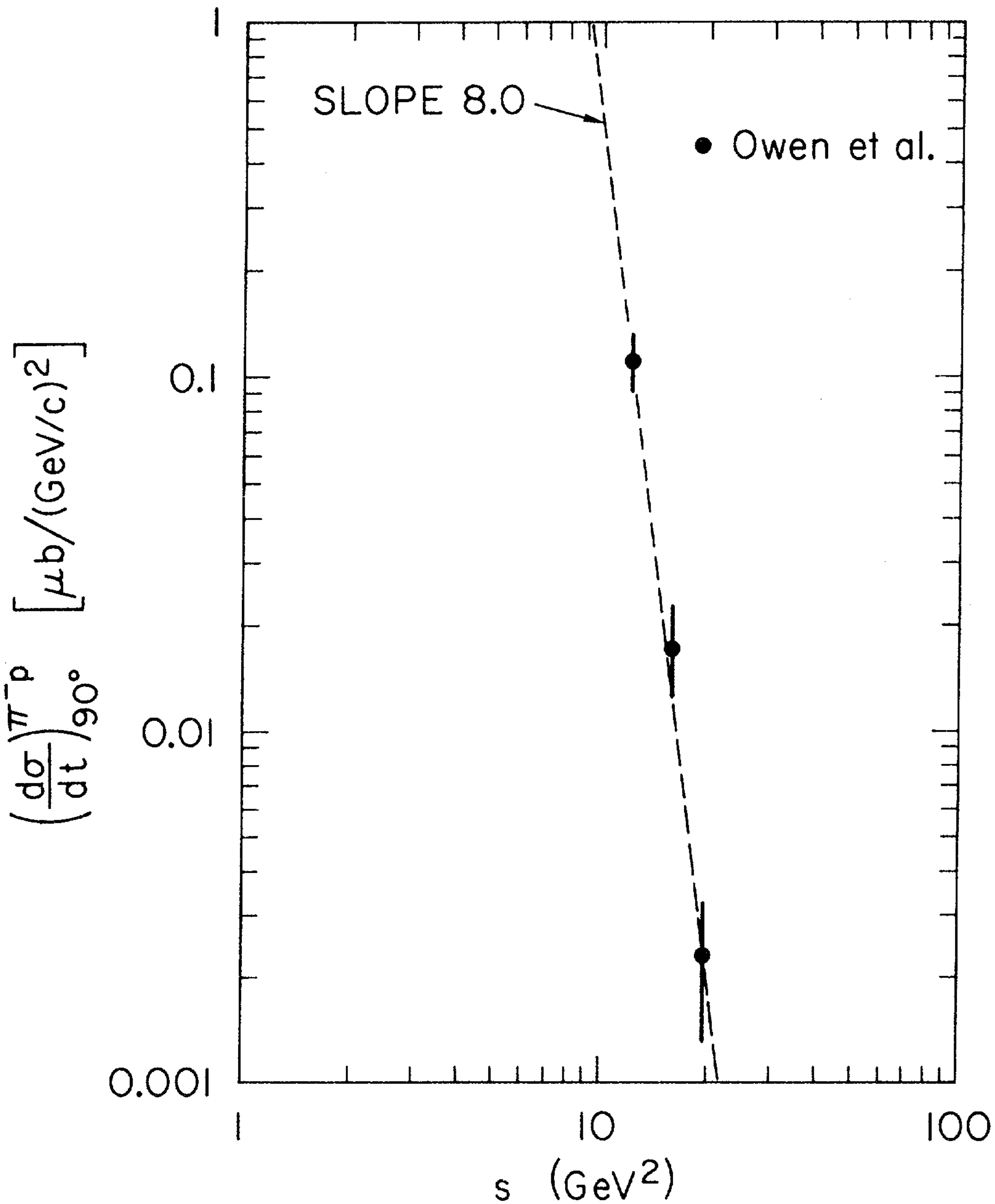


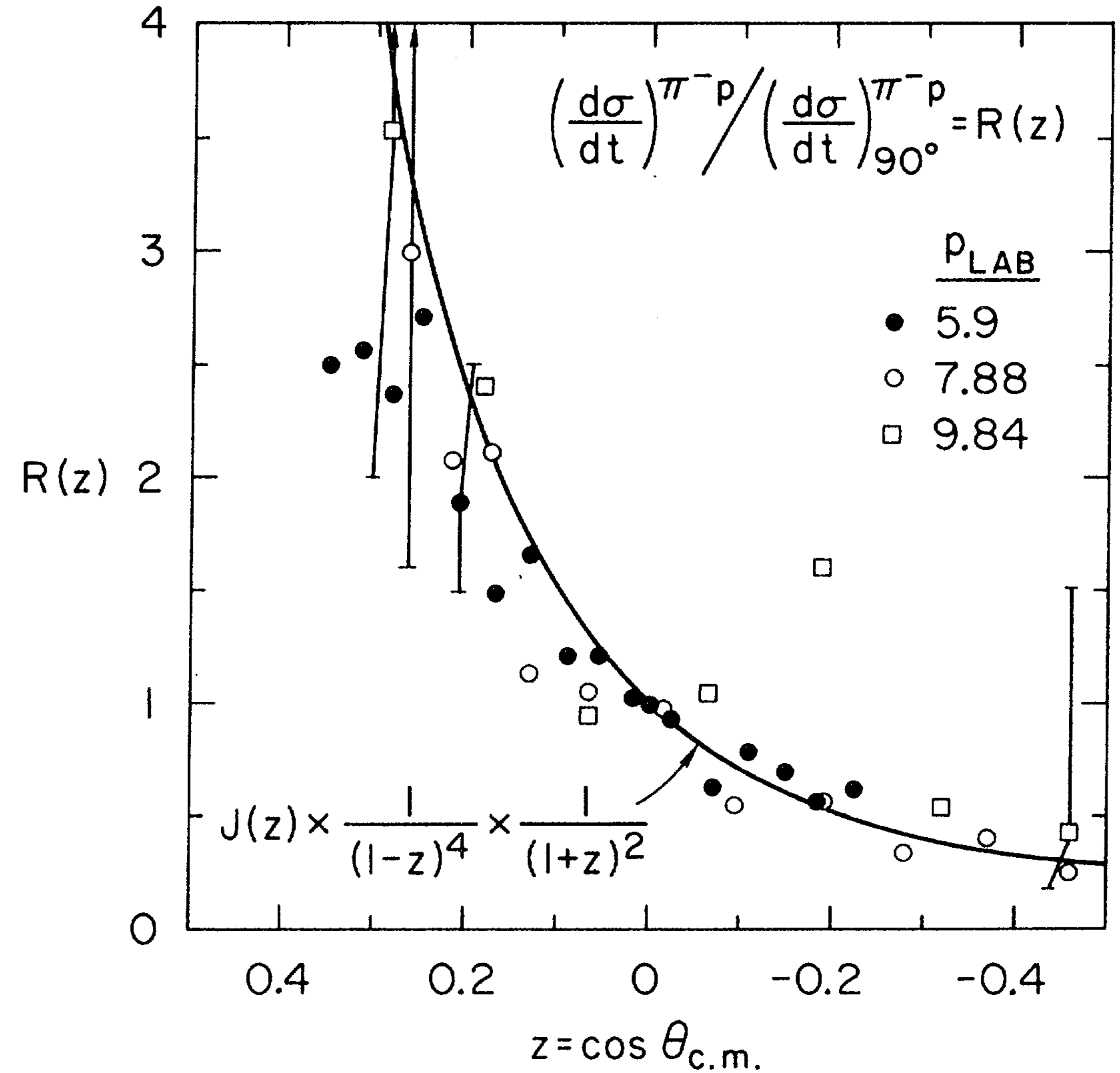
$$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$$

Non-linear Regge behavior:

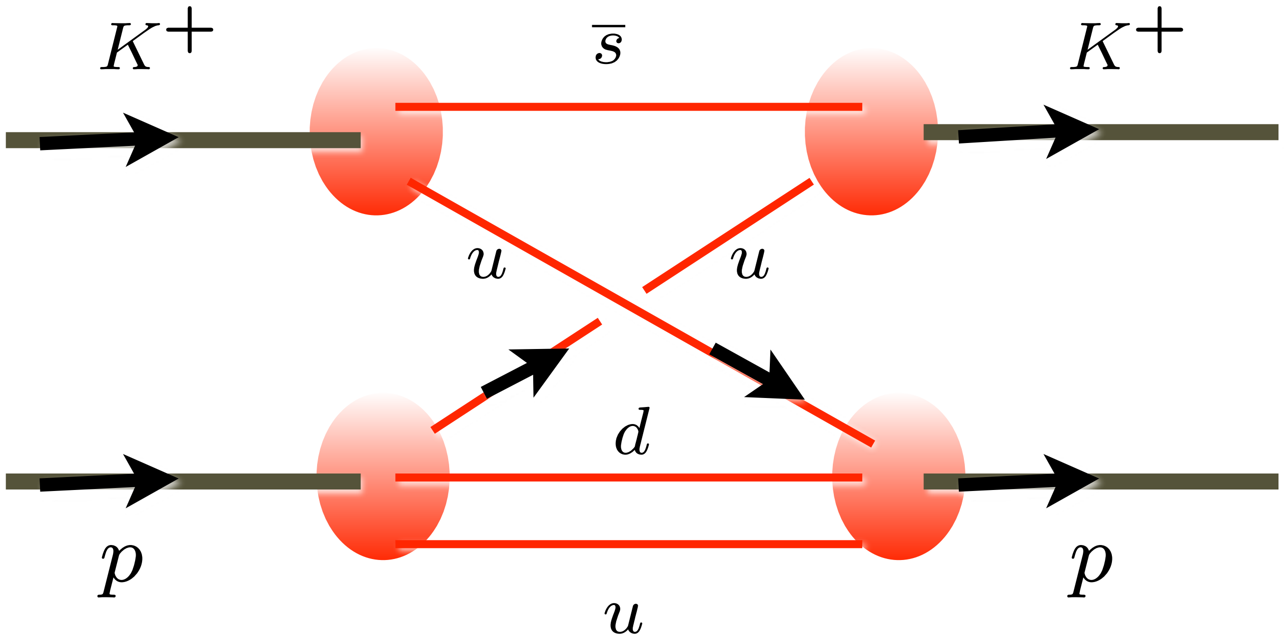
$$\alpha_R(t) \to -1$$

Quark interchange description of pion-proton scattering





Blankenbecler, Gunion, sjb



$$\frac{d\sigma}{dt} = \frac{|M(s,t)|^2}{s^2}$$

$$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$$

$$q_\perp^2 = -t$$

$$r_\perp^2 = -u$$

$$M(s,t)_{A+B\to C+D}$$

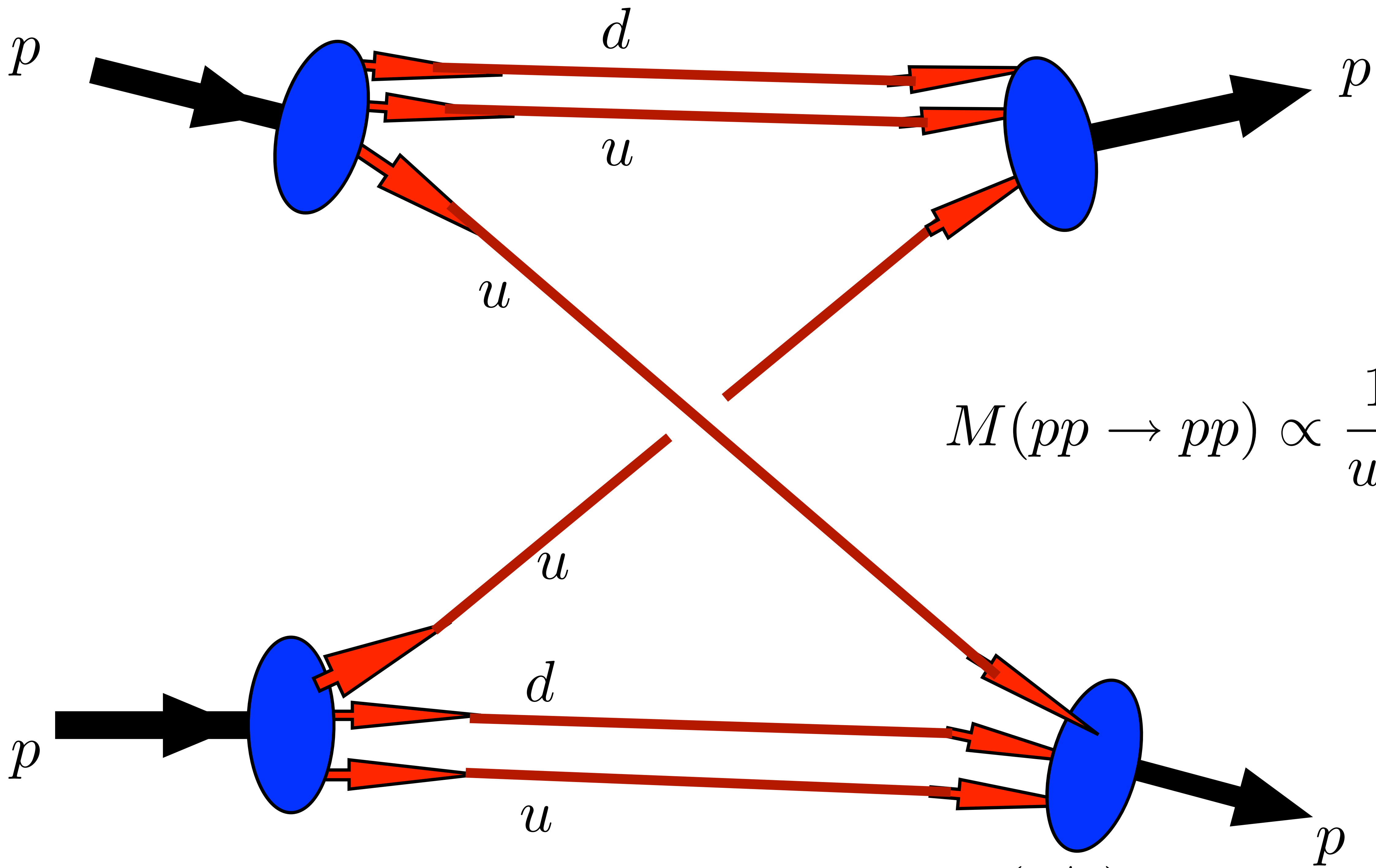
$$= \frac{1}{2(2\pi)^3} \int d^2k \int_0^1 \frac{dx}{x^2(1-x)^2} \Delta \psi_C(\vec{k}_\perp - x\vec{r}_\perp, x) \psi_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) \psi_A(\vec{k}_\perp - x\vec{r}_\perp + (1-x)\vec{q}_\perp, x) \psi_B(\vec{k}_\perp, x)$$

$$\Delta = s - \sum_i \frac{k_{\perp i}^2 + m_i^2}{x_i}$$

Product of four frame-independent light-front wavefunctions

Agrees with electron exchange in atom-atom scattering in nonrelativistic limit

$$pp \rightarrow pp$$



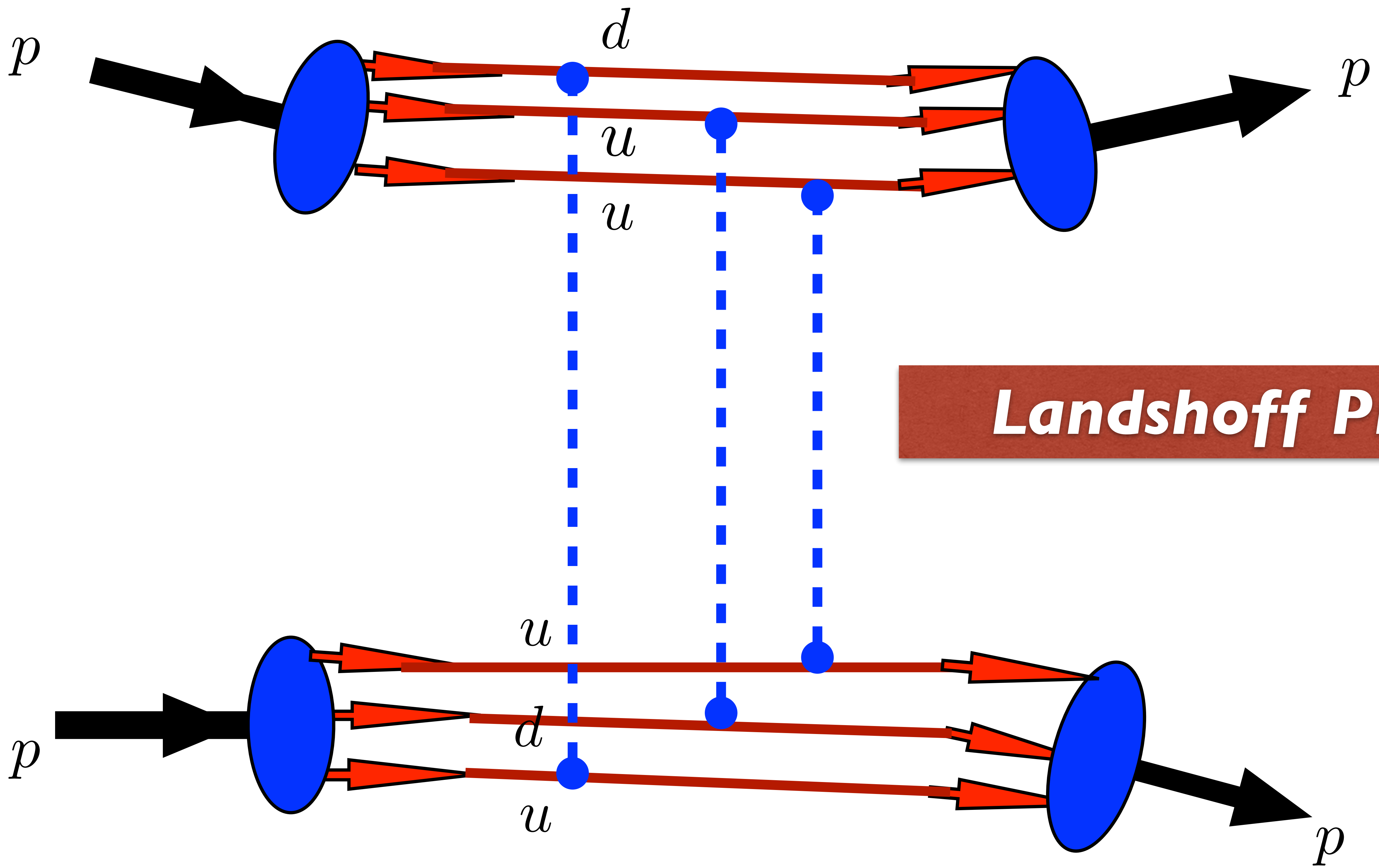
$$M(pp \rightarrow pp) \propto \frac{1}{u^2} \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(pp \rightarrow pp) \propto \frac{1}{s^2 t^4 u^4} = \frac{F(t/s)}{s^{10}}$$

Quark Interchange

Blankenbecler, Gunion, sjb

$$pp \to pp$$



Landshoff Pinch

Gluon exchange: wrong energy and angle dependence

Comparison of Exclusive Reactions at Large t

B. R. Baller,[a] G. C. Blazey,[b] H. Courant, K. J. Heller, S. Heppelmann,[c] M. L. Marshak, E. A. Peterson, M. A. Shupe, and D. S. Wahl[d]
University of Minnesota, Minneapolis, Minnesota 55455

D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi
Brookhaven National Laboratory, Upton, New York 11973

and

S. Gushue[e] and J. J. Russell
Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747
(Received 28 October 1987; revised manuscript received 3 February 1988)

Cross sections or upper limits are reported for twelve meson-baryon and two baryon-baryon reactions for an incident momentum of 9.9 GeV/c, near 90° c.m.: $\pi^{\pm}p \rightarrow p\pi^{\pm}, p\rho^{\pm}, \pi^{+}\Delta^{\pm}, K^{+}\Sigma^{\pm}, (\Lambda^0/\Sigma^0)K^0$; $K^{\pm}p \rightarrow pK^{\pm}$; $p^{\pm}p \rightarrow pp^{\pm}$. By studying the flavor dependence of the different reactions, we have been able to isolate the quark-interchange mechanism as dominant over gluon exchange and quark-antiquark annihilation.

$\pi^{\pm}p \rightarrow p\pi^{\pm}$,

$K^{\pm}p \rightarrow pK^{\pm}$,

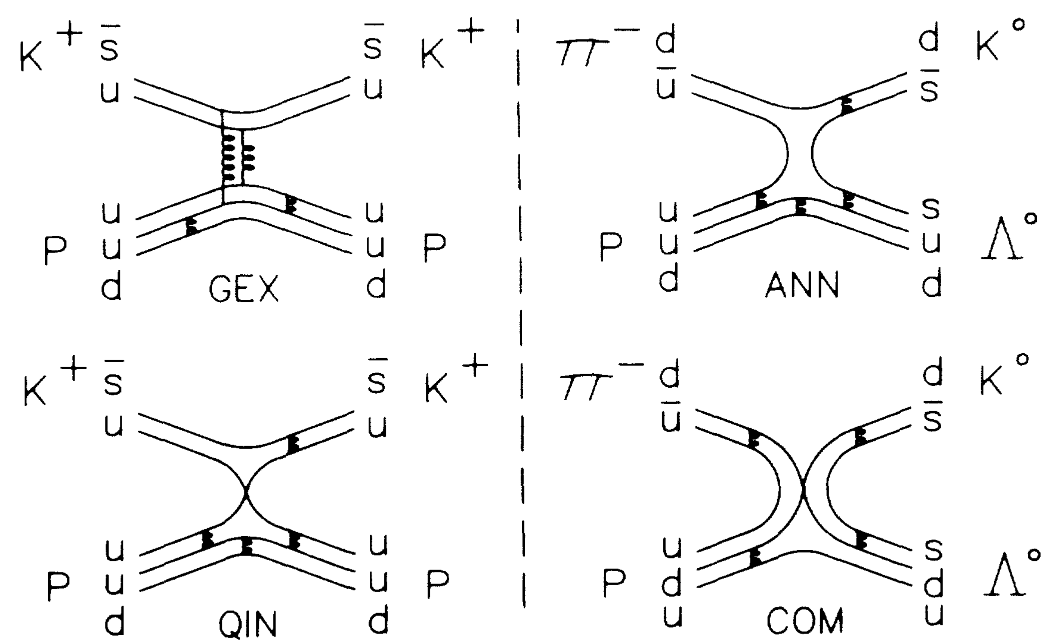
$\pi^{\pm}p \rightarrow p\rho^{\pm}$,

$\pi^{\pm}p \rightarrow \pi^{+}\Delta^{\pm}$,

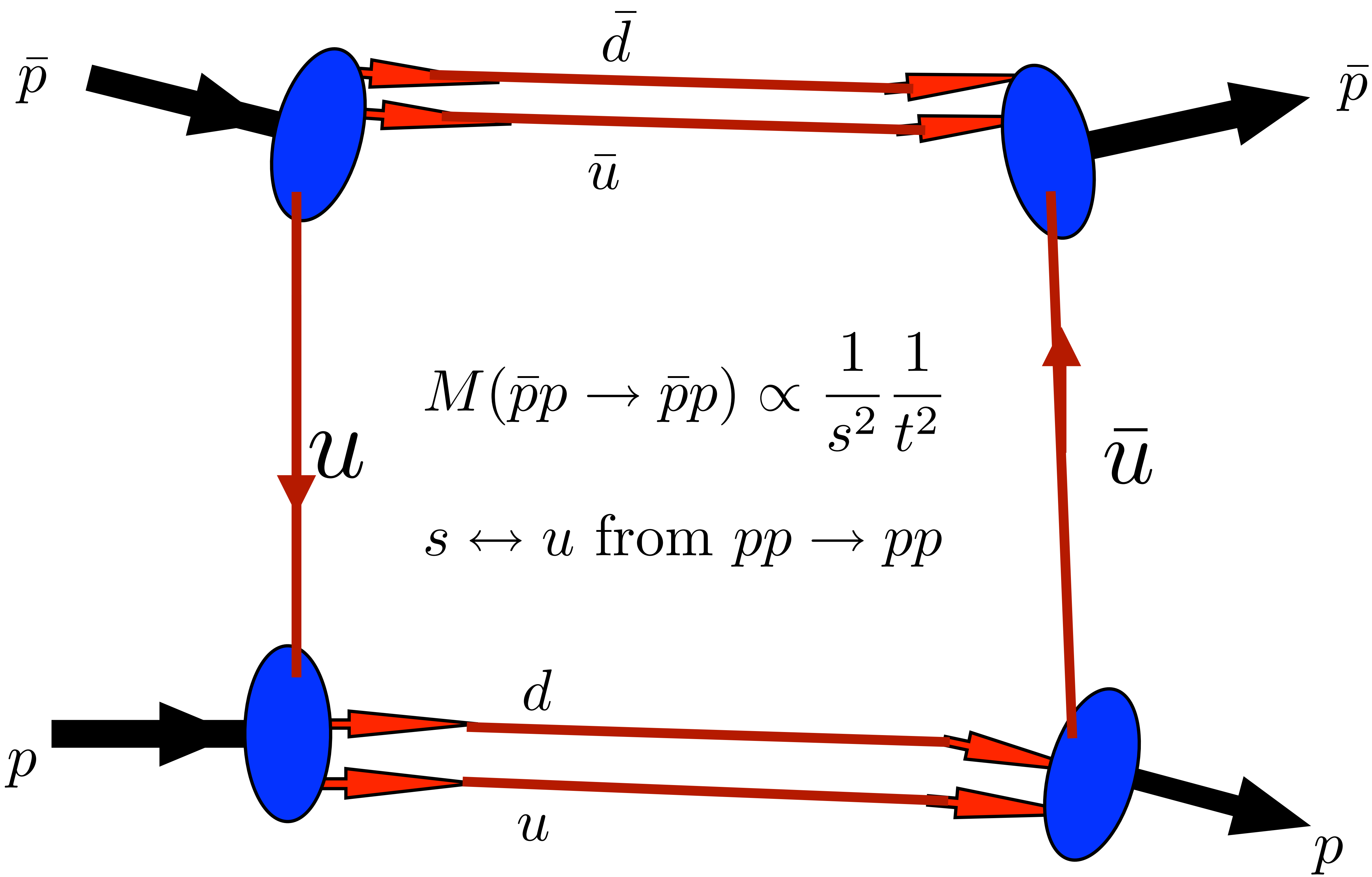
$\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}$,

$\pi^{-}p \rightarrow \Lambda^0K^0, \Sigma^0K^0$,

$p^{\pm}p \rightarrow pp^{\pm}$.



$$\bar{p}p \to \bar{p}p$$



$$M(\bar{p}p \to \bar{p}p) \propto \frac{1}{s^2}\frac{1}{t^2}$$

$s \leftrightarrow u$ from $pp \to pp$

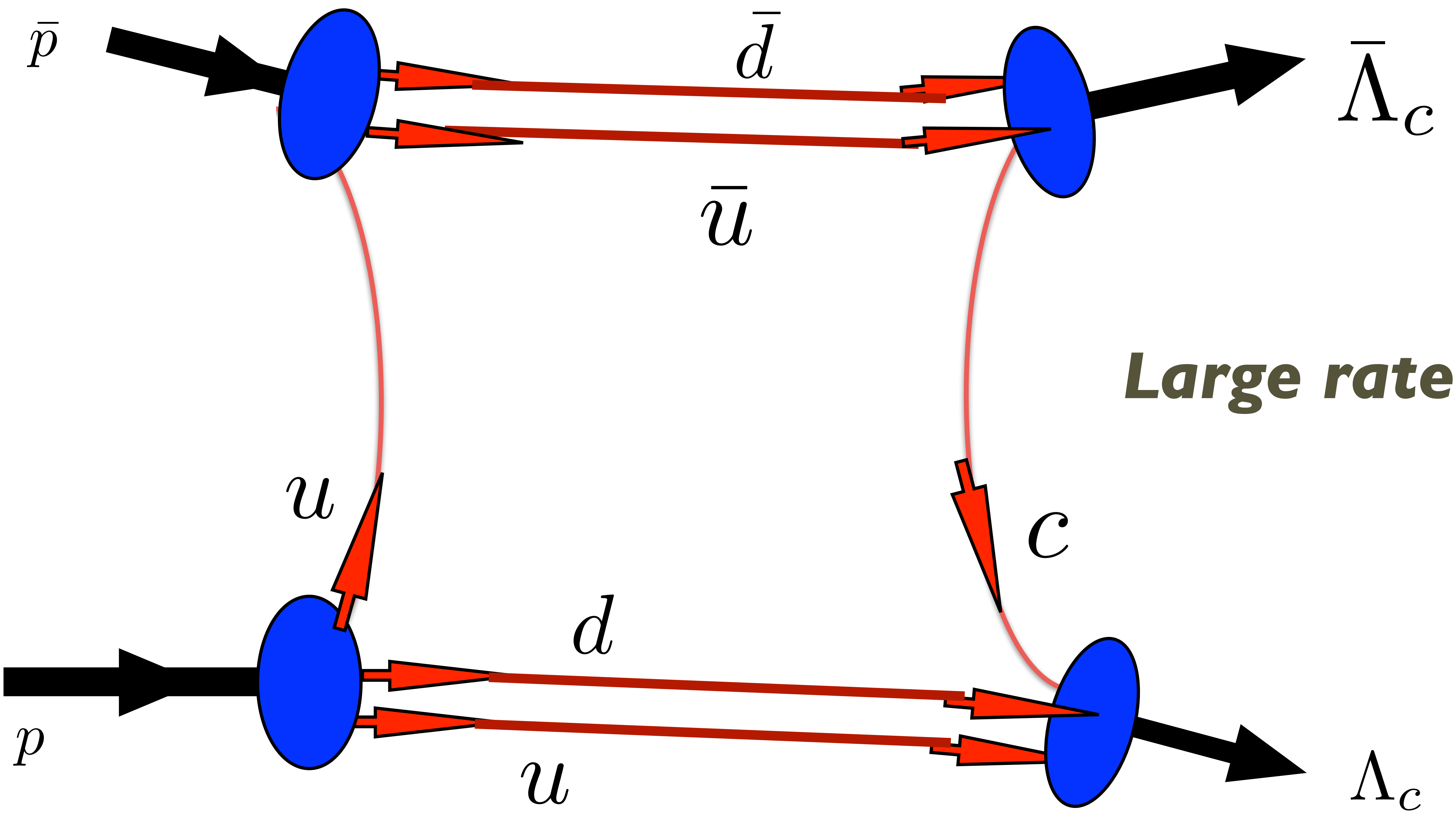
$$\frac{d\sigma}{dt}(\bar{p}p \to \bar{p}p) \propto \frac{1}{s^6}\frac{1}{t^4} = \frac{F(t/s)}{s^{10}}$$

Crossing of Quark Interchange

$$s^2\frac{d\sigma}{dt}(\bar{p}p \to K^-K^+) = \frac{\sigma_0\alpha^2}{2s^6}\frac{(1+z)}{(1-z)^3}$$

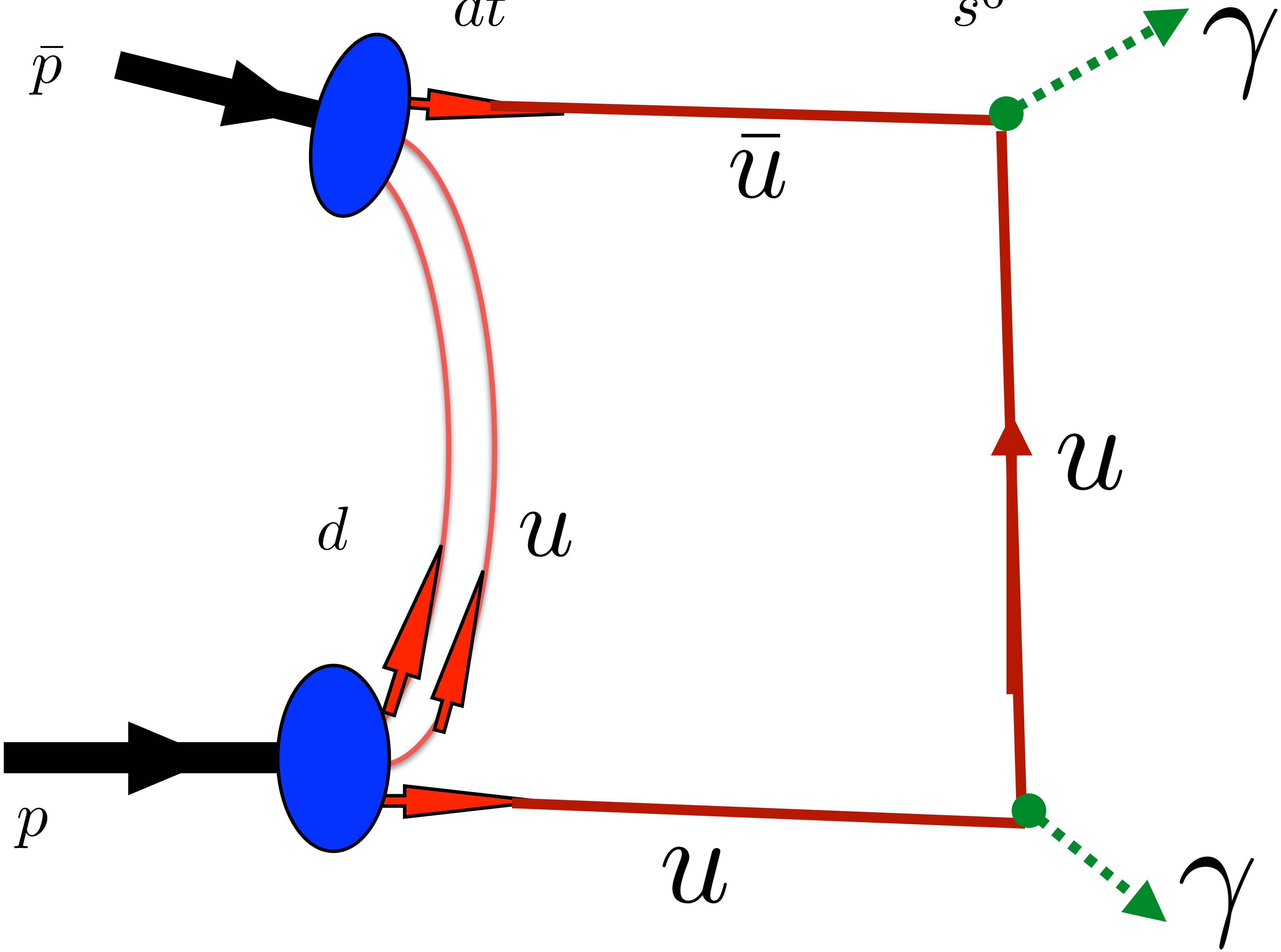
$$\frac{d\sigma}{dt}(K^-p \to K^-p)\Big/\frac{d\sigma}{dt}(\bar{p}p \to K^-K^+) = 2(1-z)^{-1}\,.$$

$\bar{p}p \rightarrow \Lambda_c \bar{\Lambda}_c$

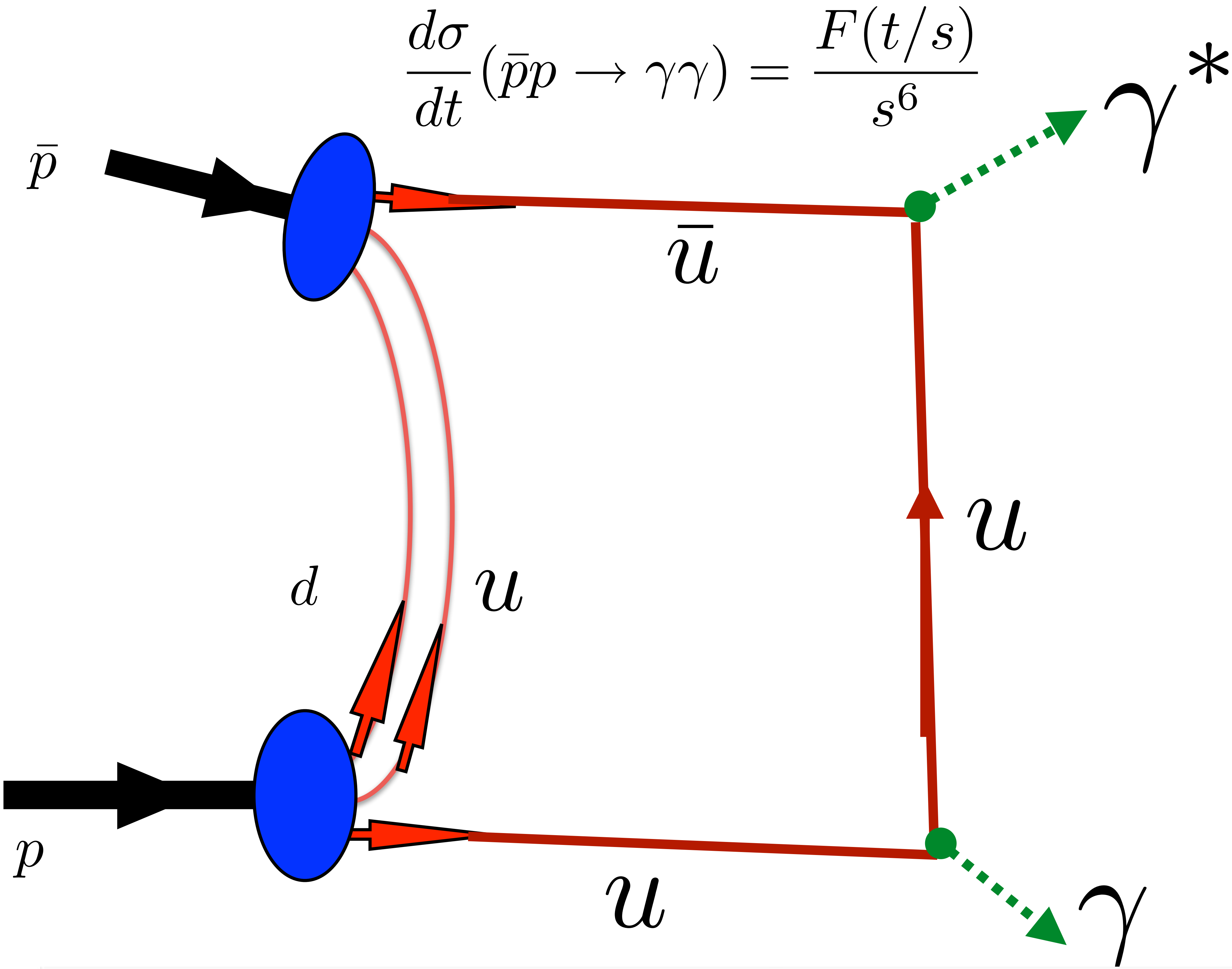


Crossing of Constituent Interchange

$$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma) = \frac{F(t/s)}{s^6}$$

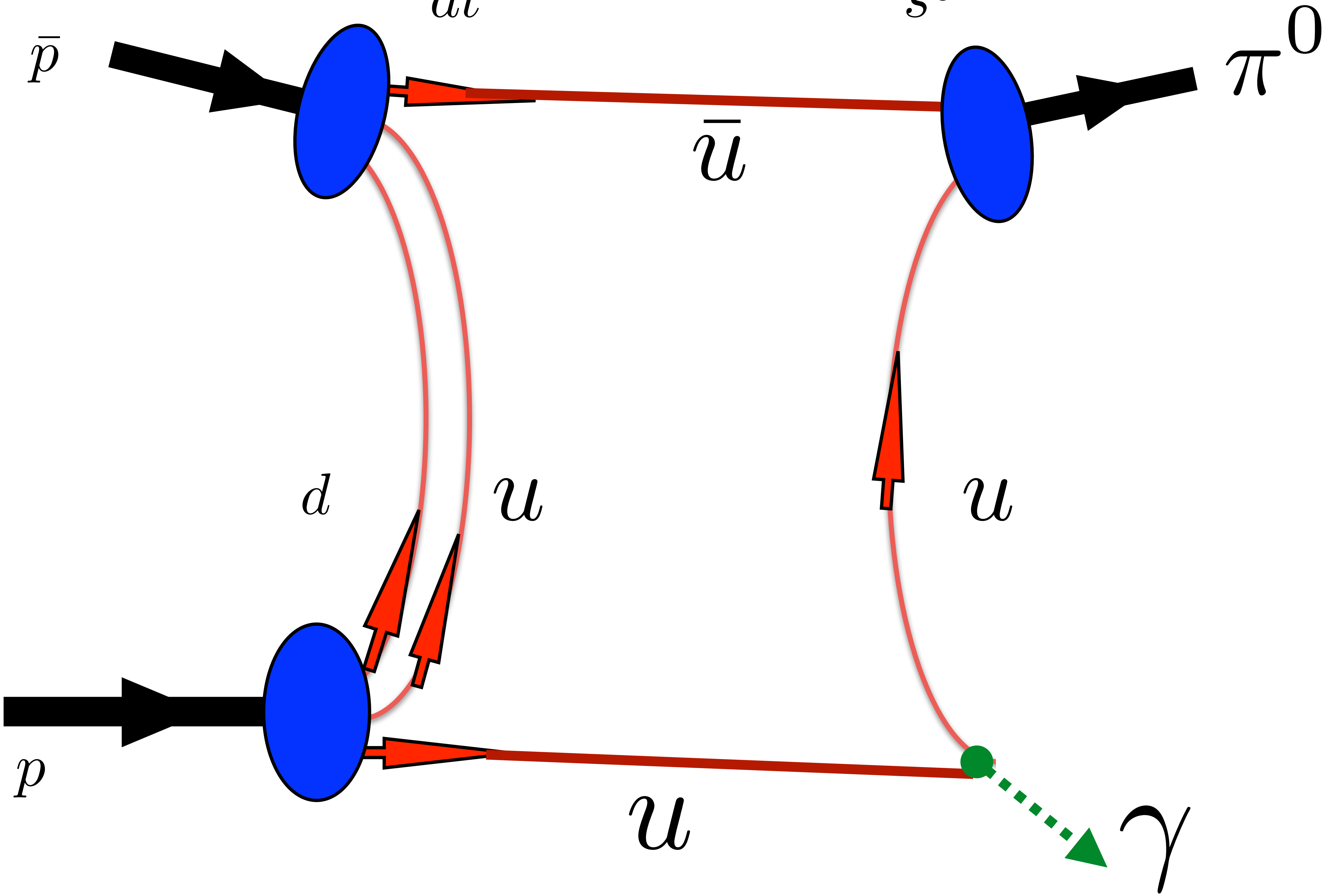


Handbag diagram $\bar{p}p \to \gamma\gamma, \gamma^*\gamma^*$



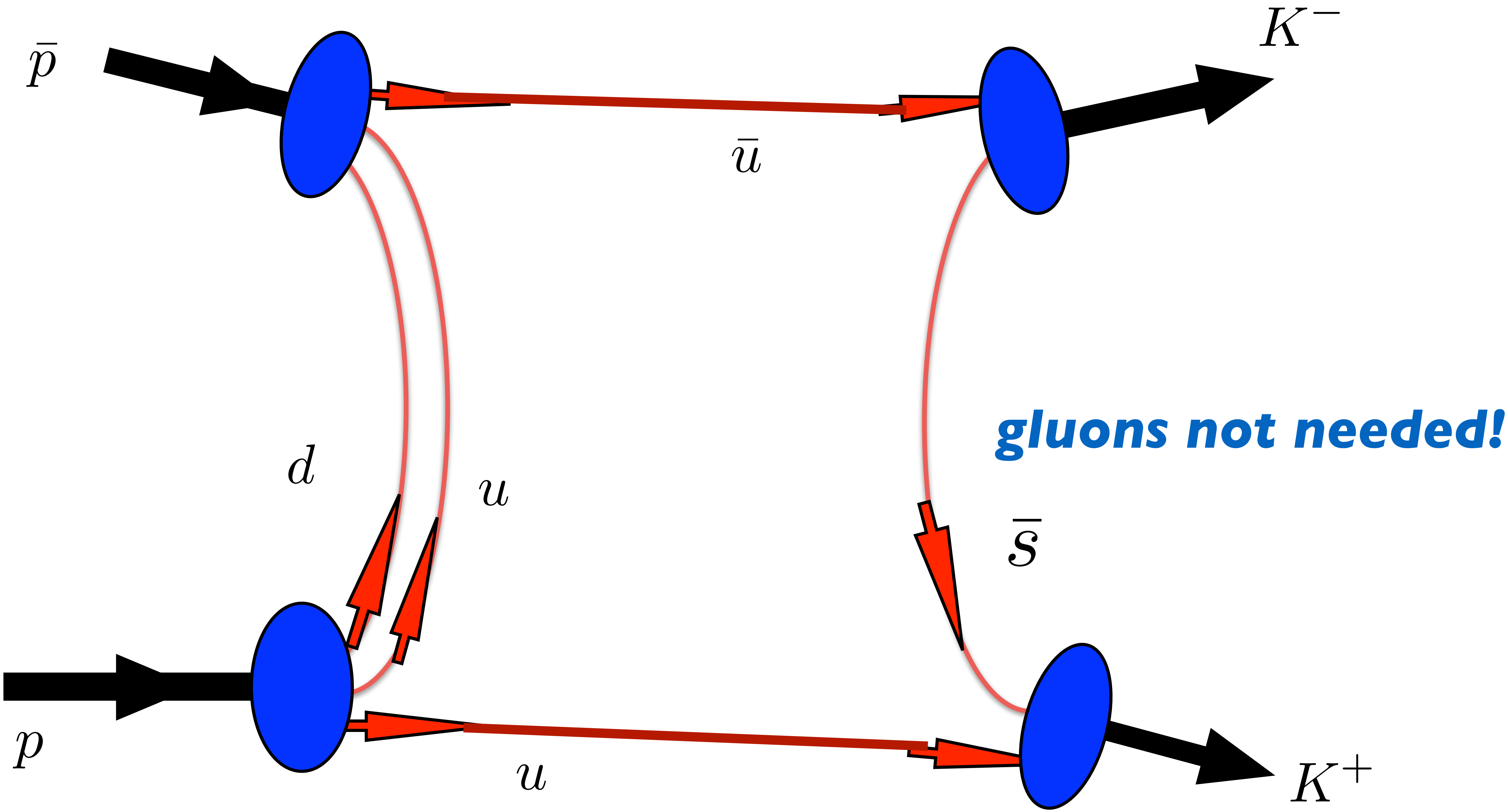
$\bar{p}p \to \gamma$ transition form factor!

$$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma) = \frac{F(t/s)}{s^6}$$



"Handbag" diagram

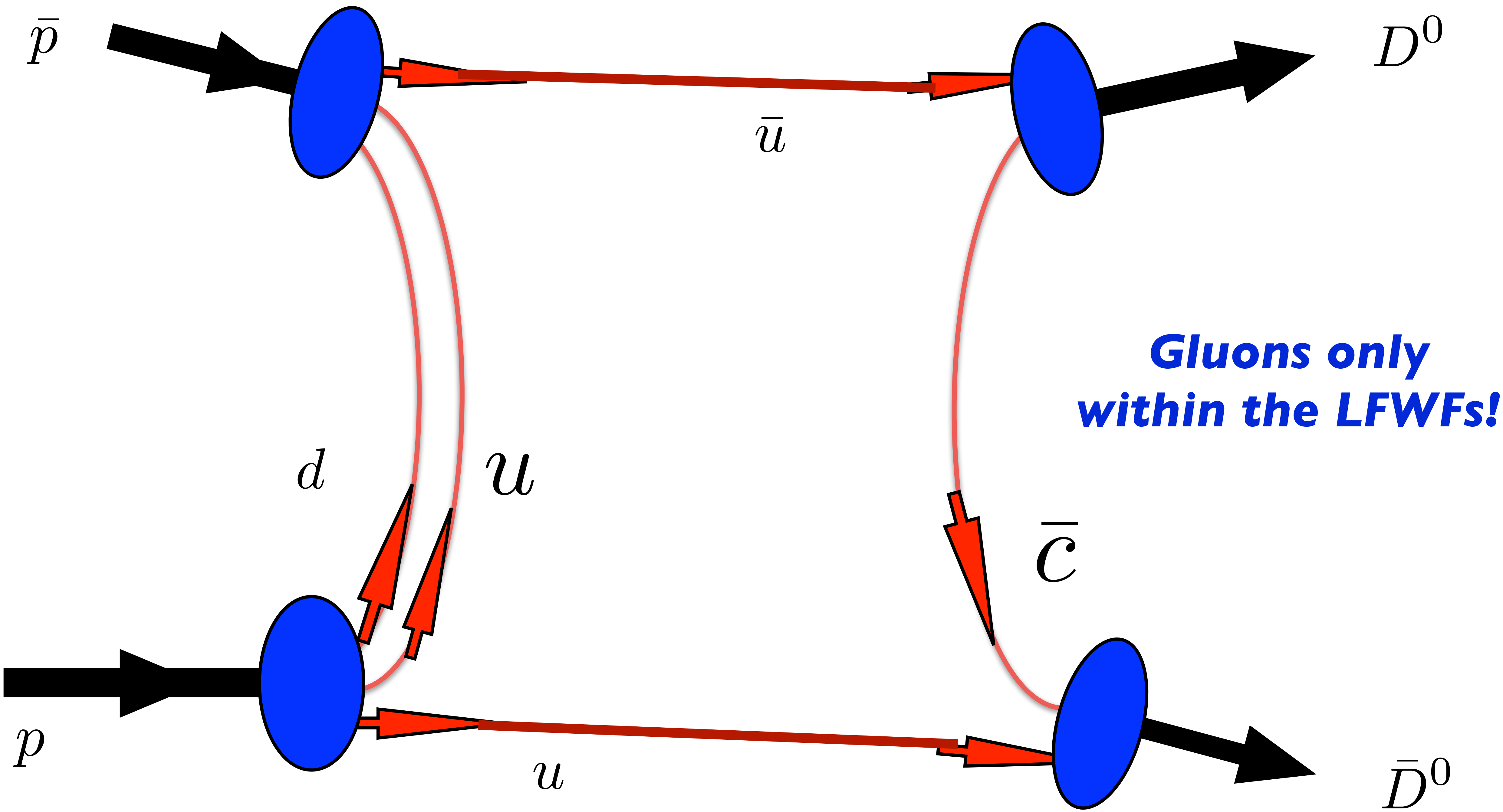
$$\bar{p}p \to K^+K^-$$



Crossing of Constituent Interchange

Blankenbecler, Gunion, sjb

$$\bar{p}p \rightarrow D^0\,\bar{D}^0$$

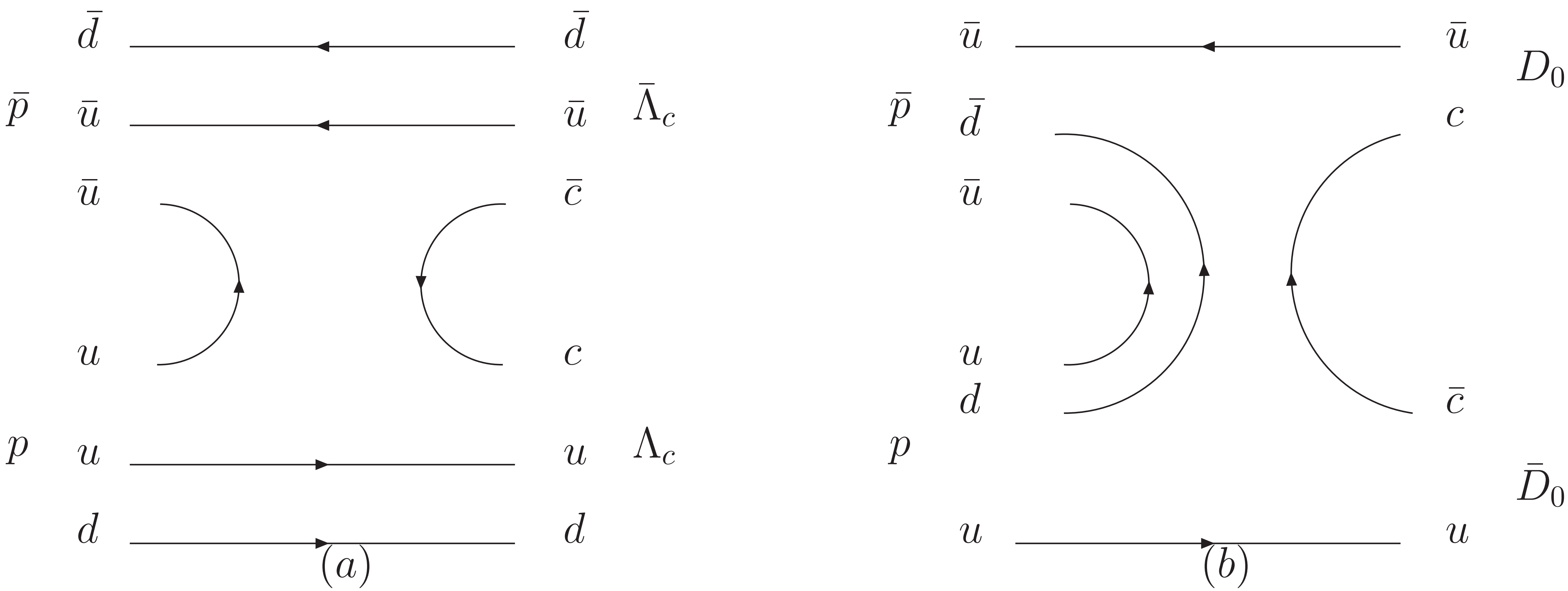


Crossing of Constituent Interchange

Also $\bar{p}p \rightarrow Z_c^- Z_c^+$, etc.

How much charm can $\overline{P}ANDA$ produce?

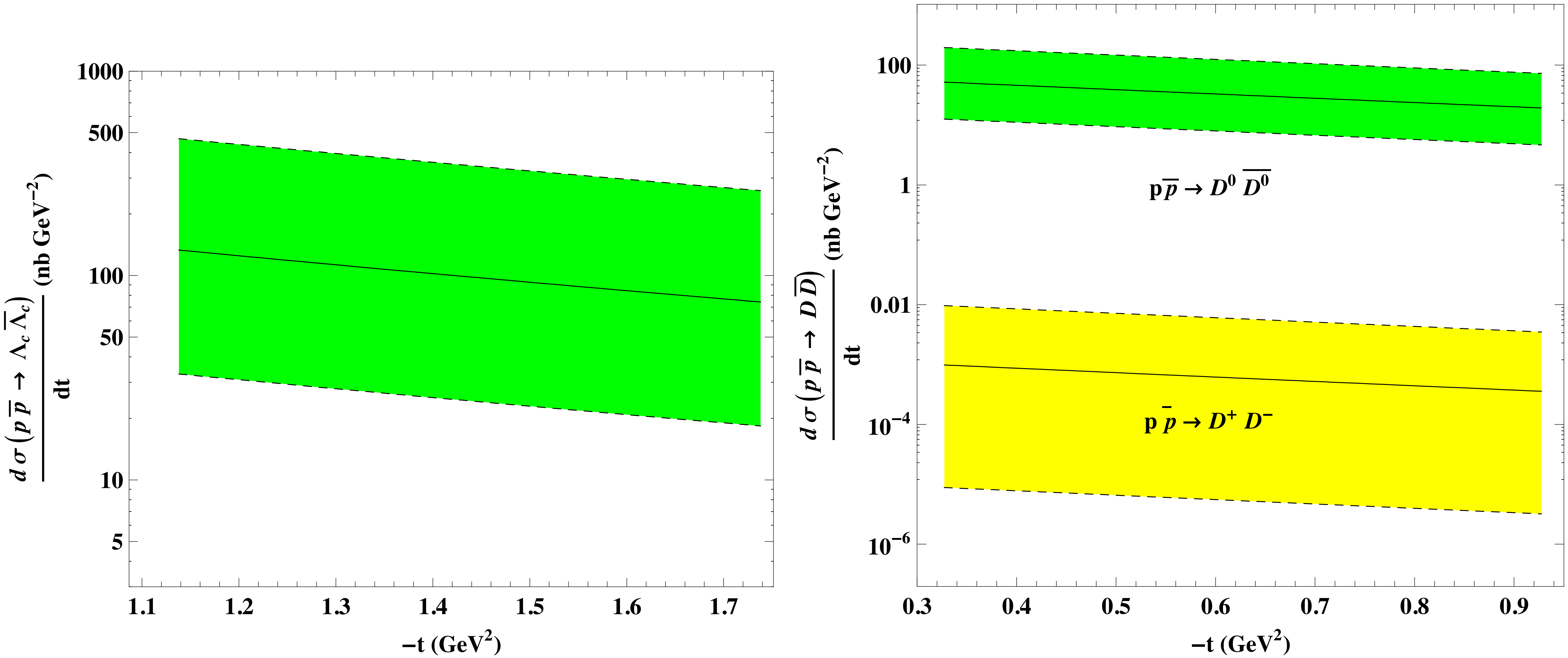
A. Khodjamirian, Ch. Klein, Th. Mannel and Y.-M. Wang



Regge exchange model

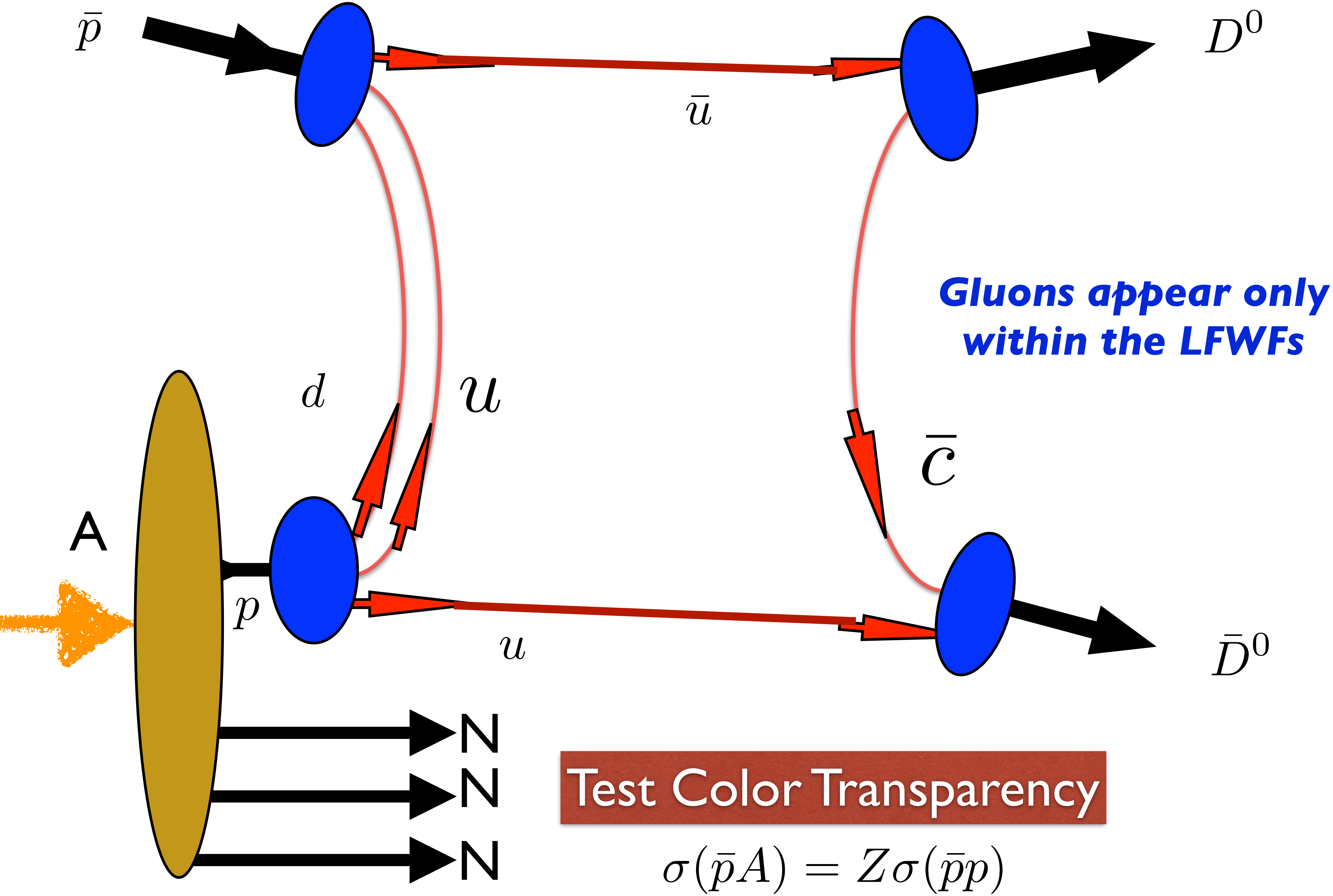
How much charm can $\overline{P}ANDA$ produce?

A. Khodjamirian, Ch. Klein, Th. Mannel and Y.-M. Wang



Differential cross sections of $p\bar{p} \to \Lambda_c\bar{\Lambda}_c$, and $p\bar{p} \to D\bar{D}$ at $p_{lab} = 15\,\mathrm{GeV}$ calculated in QGS model. The dashed lines indicate the uncertainties caused by LCSR estimates of strong couplings.

$\bar{p}p \rightarrow D^0 \bar{D}^0$

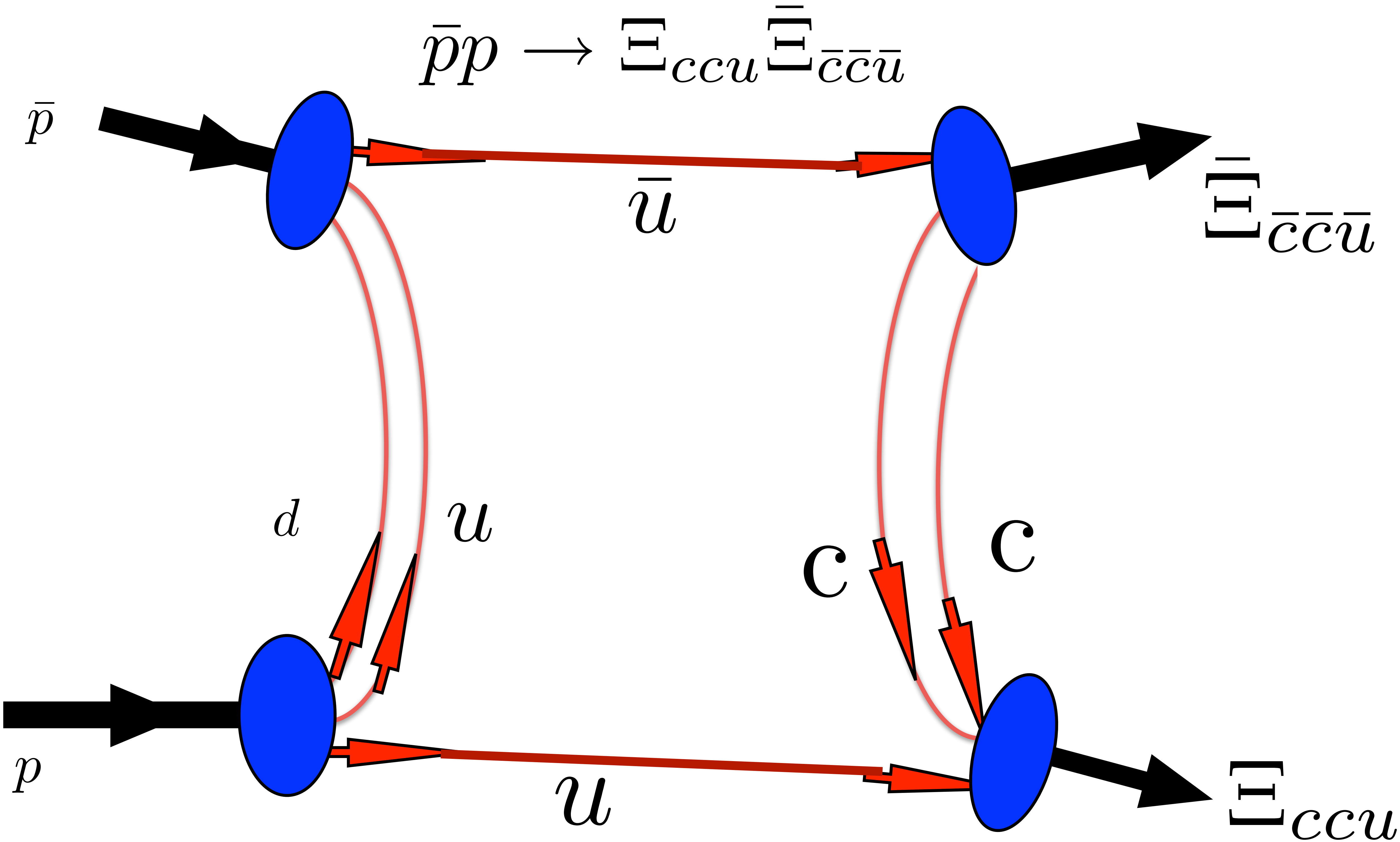


Color Transparency

Bertsch, Gunion, Goldhaber, sjb

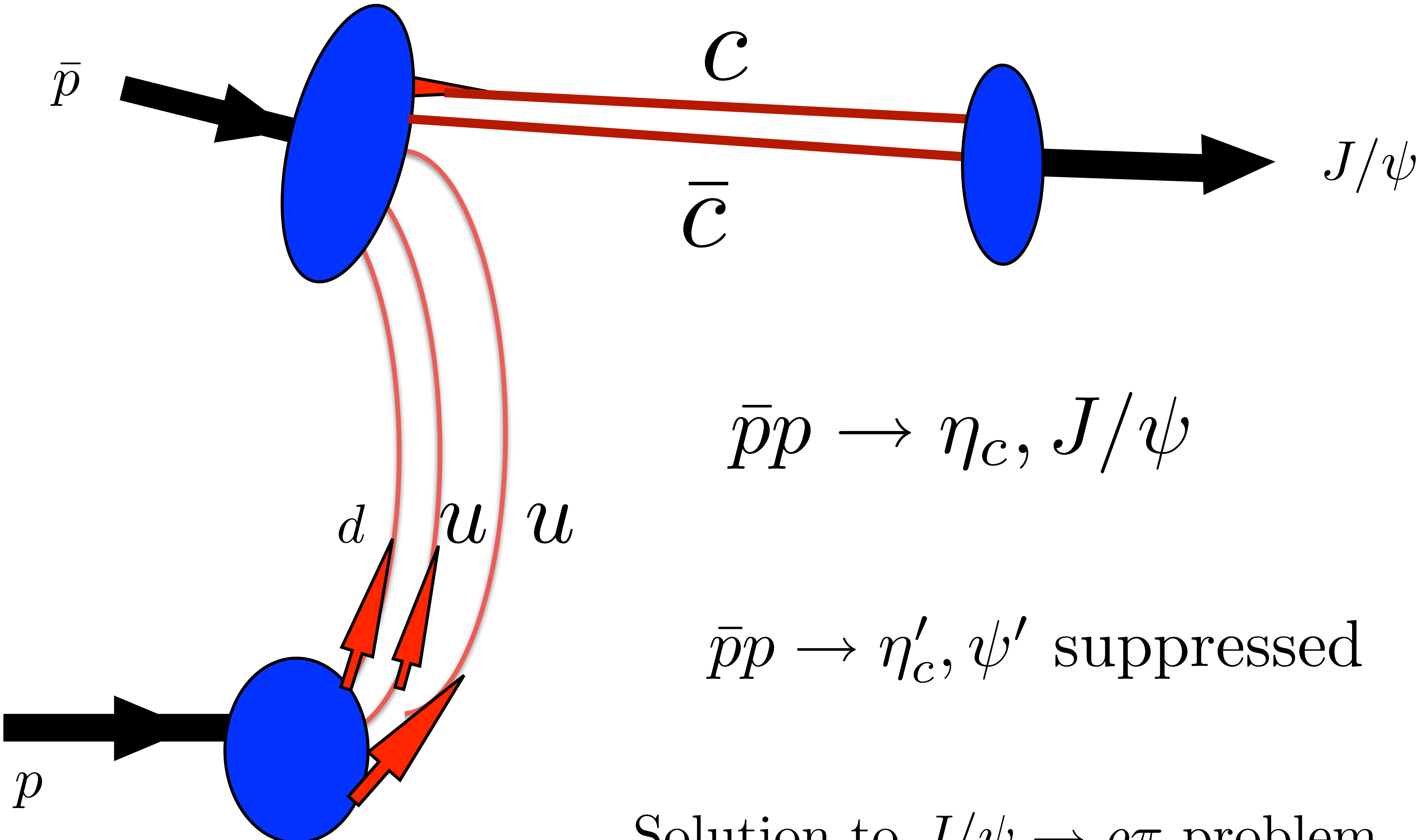
A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets



Production of Double-Charm Baryons!

Alternative to OZI 3-gluon annihilation



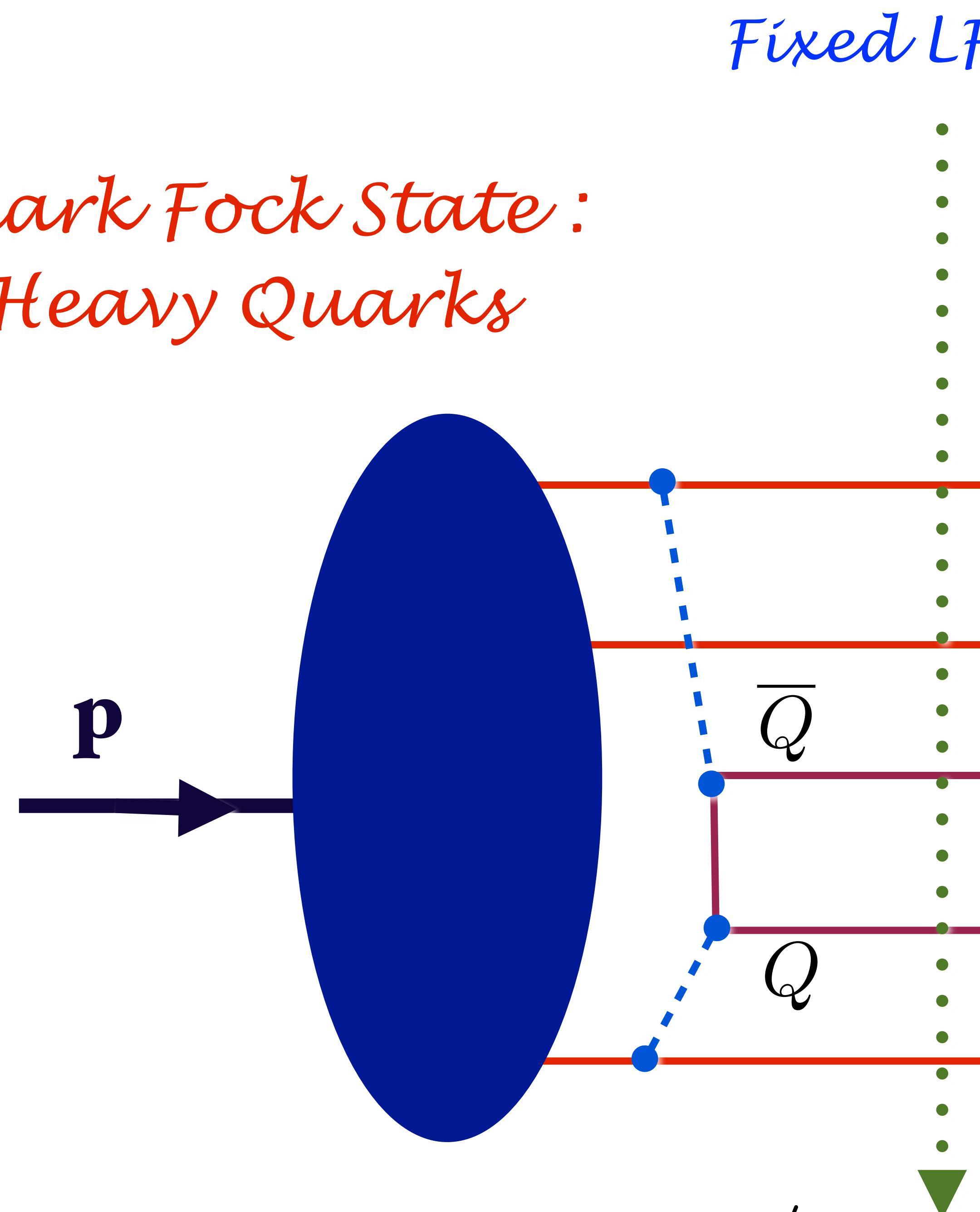
$$\bar{p}p \to \eta_c, J/\psi$$

$\bar{p}p \to \eta'_c, \psi'$ suppressed

Solution to $J/\psi \to \rho\pi$ problem

Production of Quarkonium from |uud $\bar{c}$ c>
Intrinsic Charm Fock state

Proton 5-quark Fock State : Intrinsic Heavy Quarks



Rigorous prediction of QCD

Intrinsic Heavy Quarks at high x!

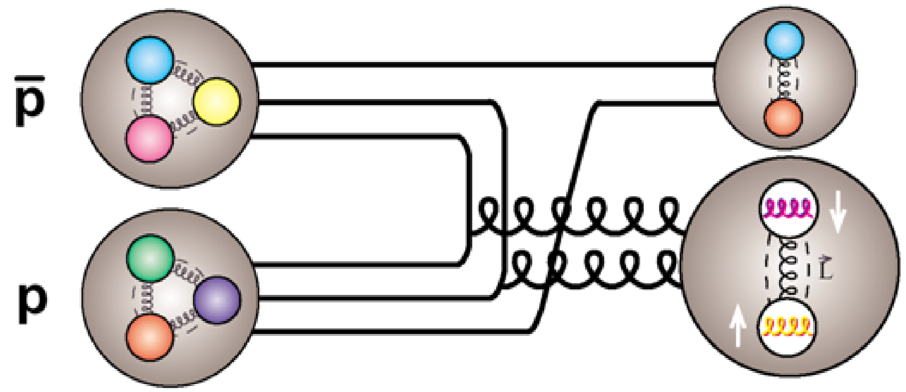
Minimal off-shellness

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

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

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

Exotics production in $\bar{p}p$ collisions via OZI

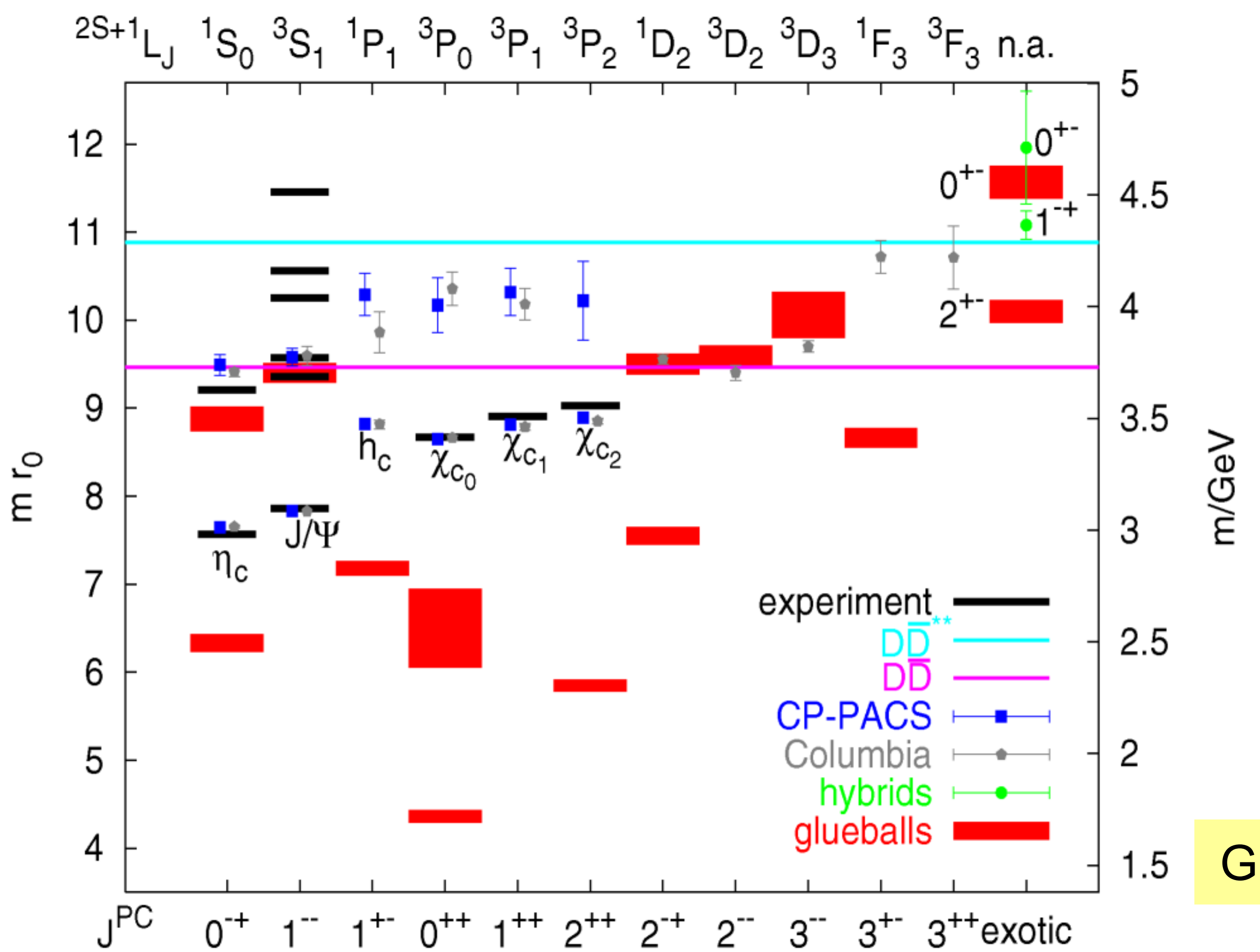


- Production: all J^{PC} accessible

Hybrids

Gluon	1^{-+}	1^{+-}
$^1S_0$, 0^{-+}	1^{++}	1^{--}
$^3S_1$, 1^{--}	0^{+-}	0^{-+}
	1^{+-}	1^{-+}
	2^{+-}	2^{-+}

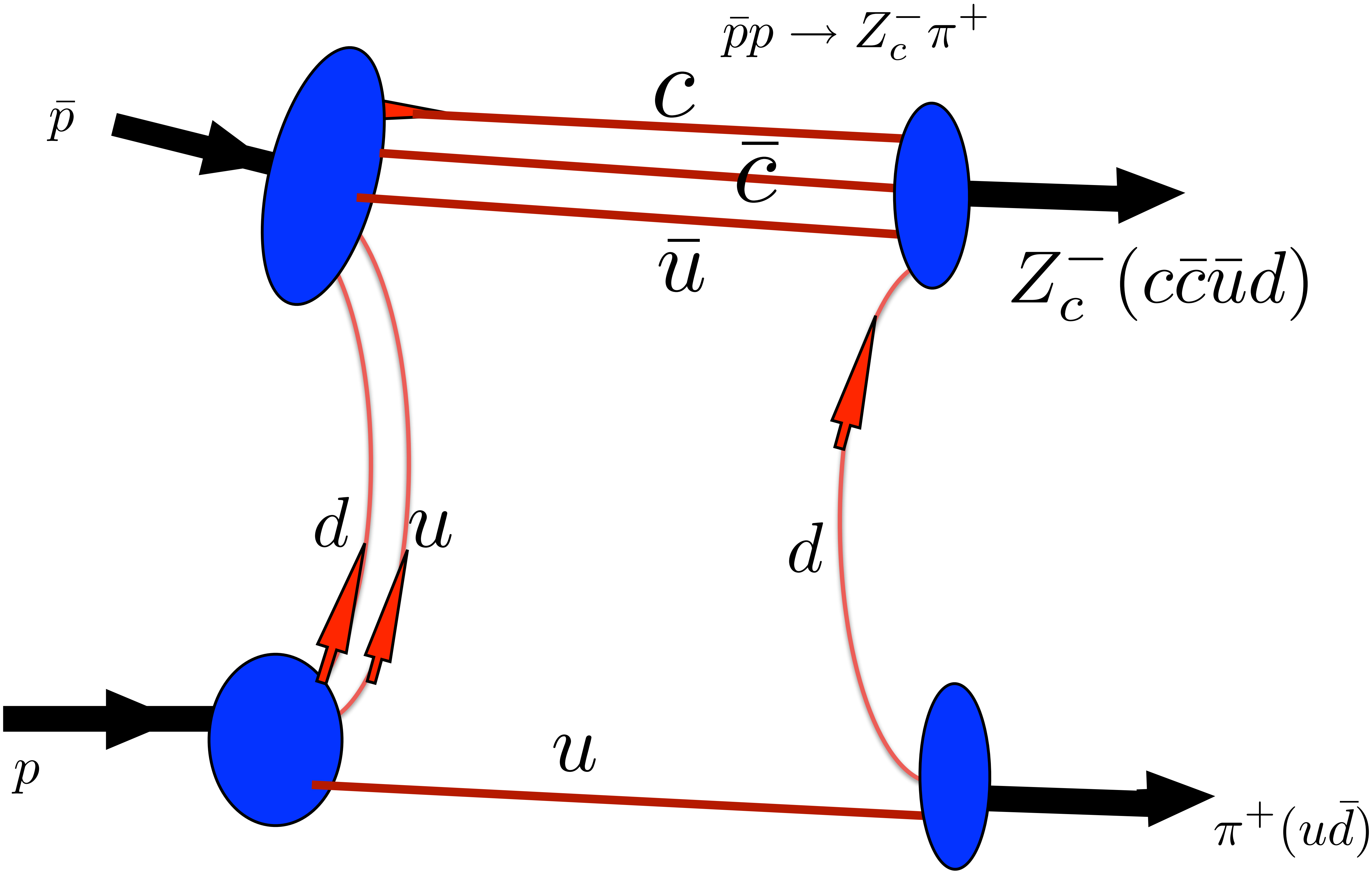
J^{PC} exotic



Exotic J^{PC} would be clear signal

G.Bali, EPJA 1 (2004) 1 (PS)

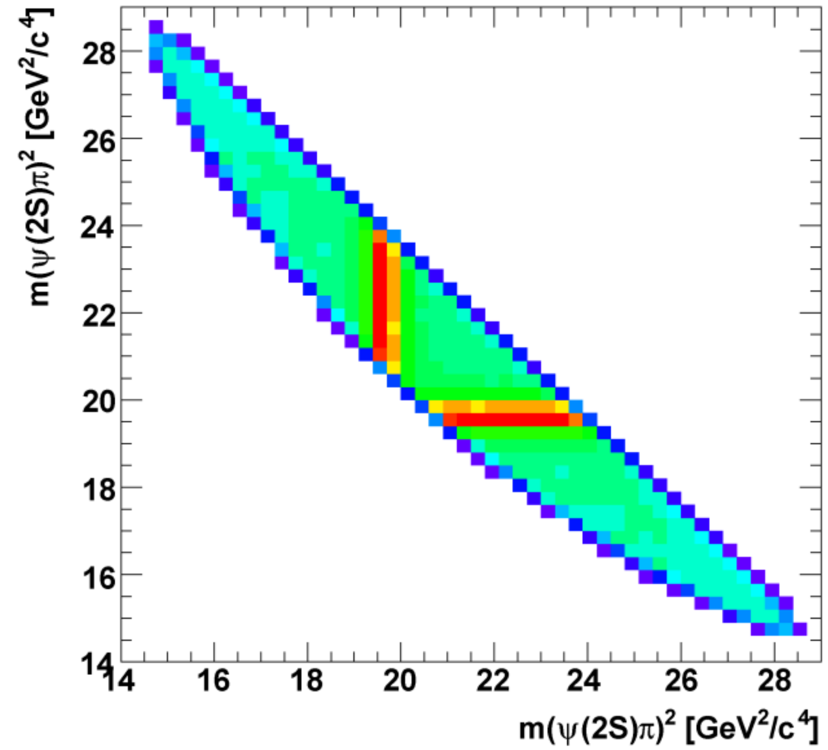
Ritman

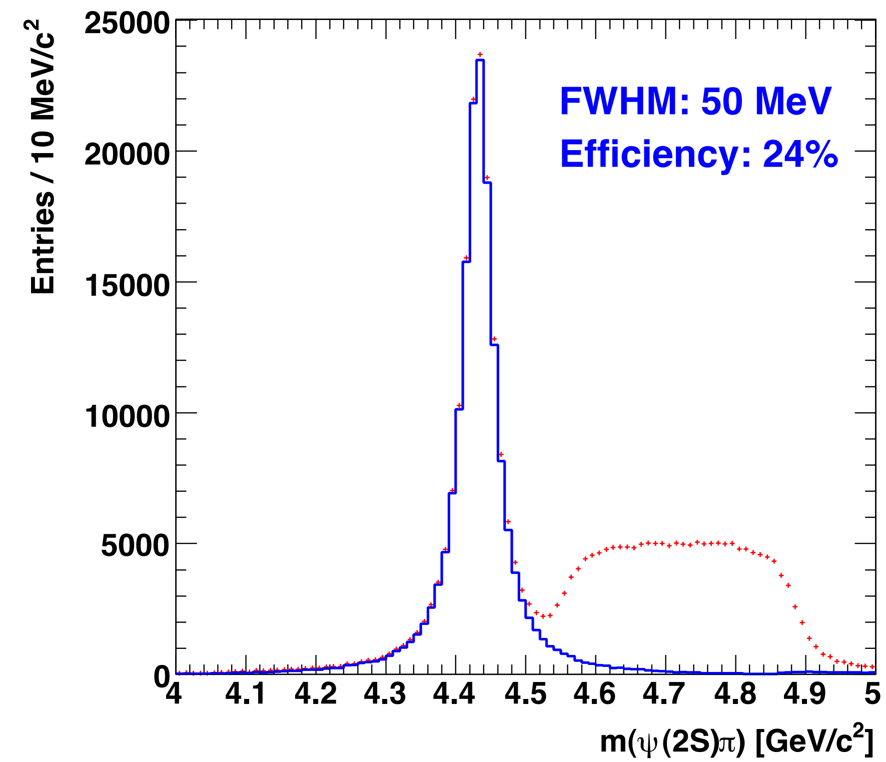


Production of Exotic Quarkonium from |uud c c> Fock state

Non-$q\bar{q}$ Mesons: Charged $c\bar{c}$-like States

- Planned studies with PANDA
  - *production* in $p\bar{p}$:
    $\bar{p}p \rightarrow Z(4430)^{\pm}\,\pi^{\mp}$
    $Z(4430)^{\pm} \rightarrow \psi(2S)\,\pi^{\pm}\,x$
  - *formation* in $\bar{p}n$:
    $\bar{p}d \rightarrow Z(4430)^{-}\,p_{spectator}$
    $\rightarrow \psi(2S)\,\pi^{-}\,p_{spectator}$
    must reconstruct the spectator proton
    reduced mass resolution

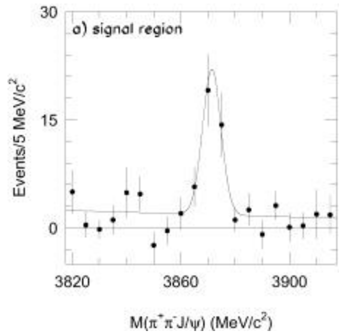




J. Ritman

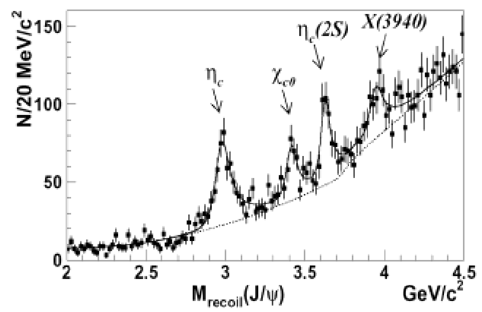
X(3872)

PRL 91,262001 (2003)



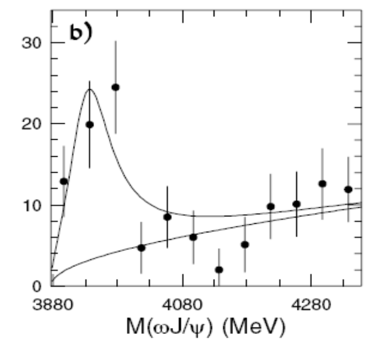
X(3940)

PRL 98,082001 (2007)



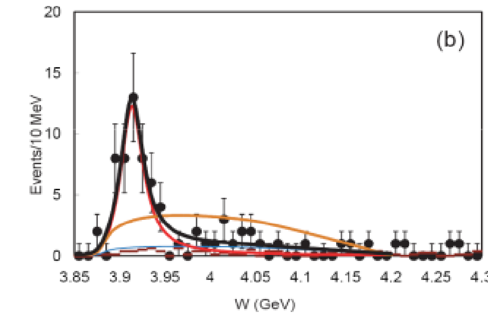
Y(3940)

PRL 94,182002 (2005)



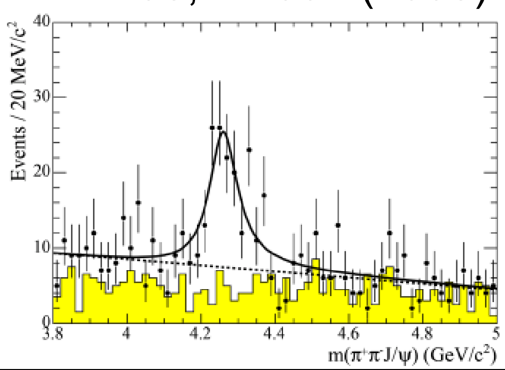
X(3915)

PRL 104,092001 (2010)



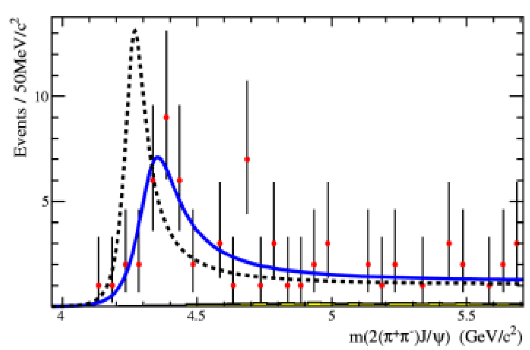
Y(4260)

PRL 95,142001 (2005)



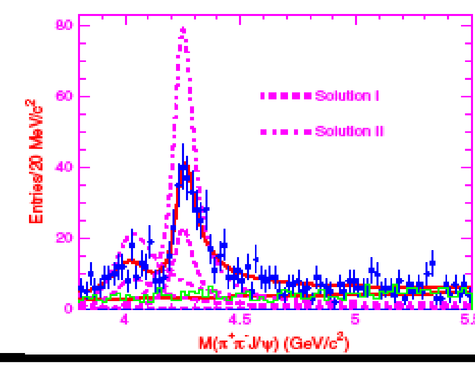
Y(4350)

PRL 98,212001 (2007)



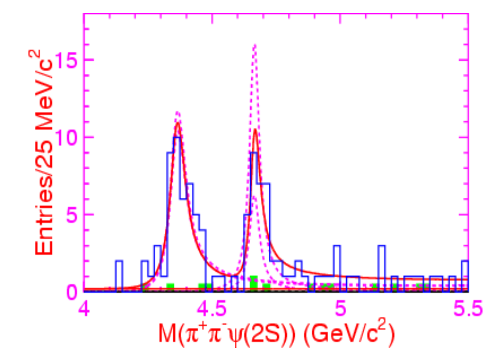
Y(4008)

PRL 99,182004 (2007)



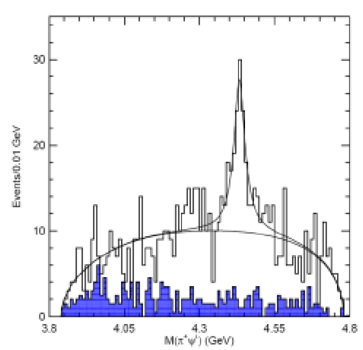
Y(4660)

PRL 99,142002 (2007)



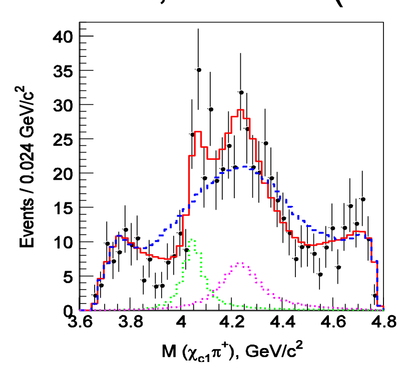
Z(4430)$^-$

PRL 100,142001 (2008)



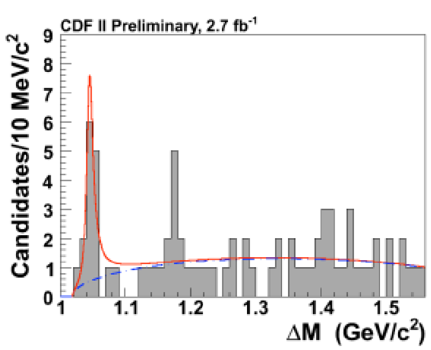
Z_1^- & Z_2^-

PRD 78,072004 (2008)



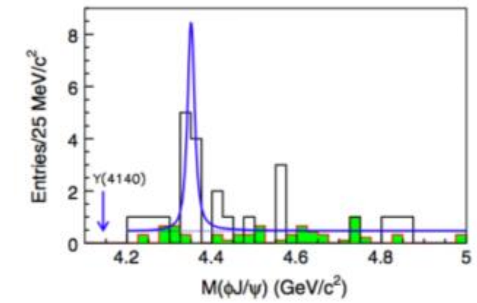
Y(4140)

PRL 102,242002 (2009)



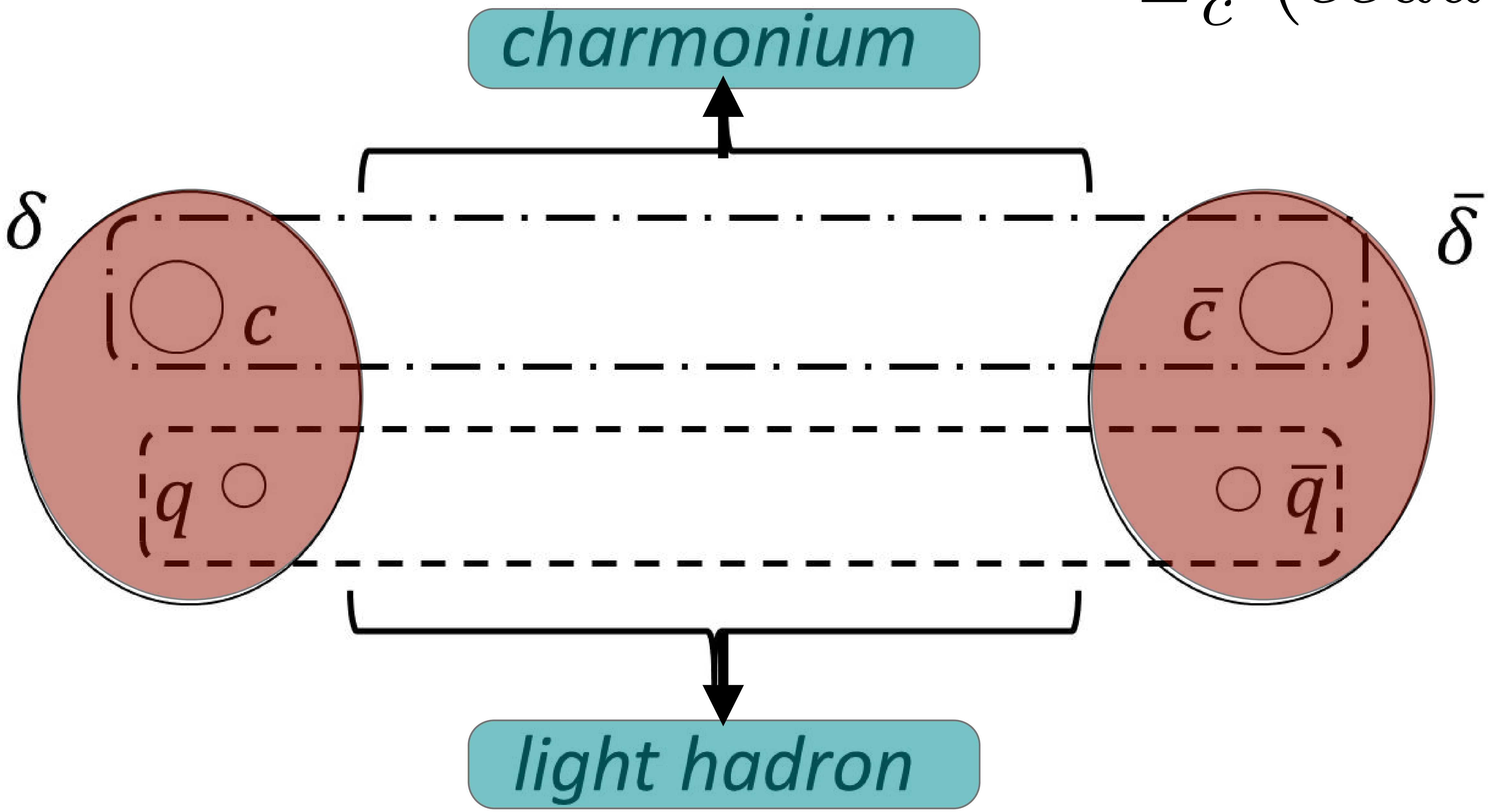
X(4350)

PRL 104,112004 (2010)



Ritman

$Z_c^+(c\bar{c}u\bar{d})$



$Z_c^+([cu][\bar{c}\bar{d}]) \rightarrow \pi^+\psi'$

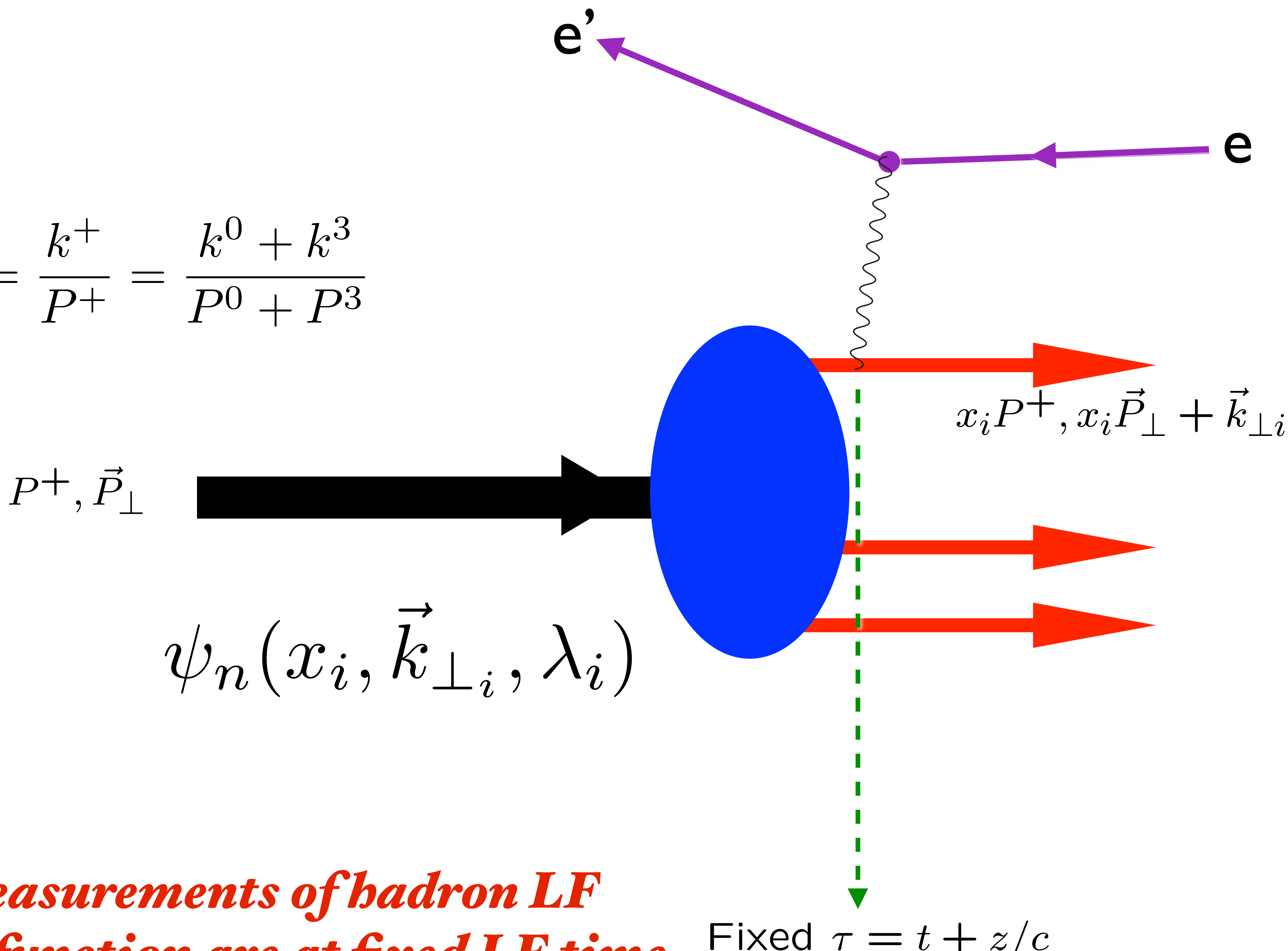
Diquark-Diquark

Annihilation at large separation:

Dominance of large size Ψ' vs J/Ψ decays

Lebed, Hwang, sjb

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



Measurements of hadron LF wavefunction are at fixed LF time

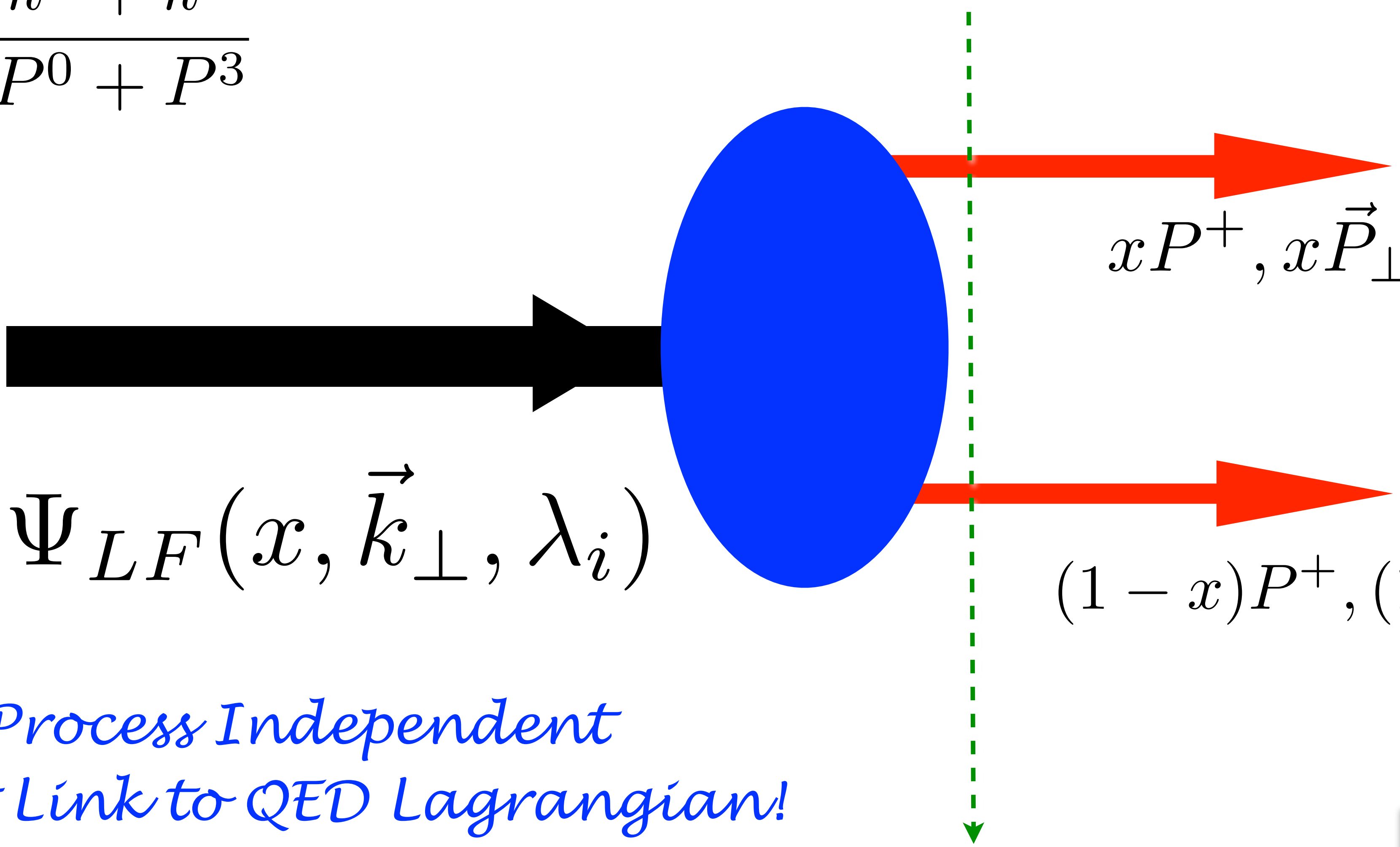
$$x_{bj} = x = \frac{k^+}{P^+}$$

Like a flash photograph

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

Fixed $\tau = t + z/c$

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



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

$xP^+, x\vec{P}_\perp + \vec{k}_\perp$

$(1-x)P^+, (1-x)\vec{P}_\perp - \vec{k}_\perp$

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

Process Independent

Direct Link to QED Lagrangian!

Cannot measure wavefunction at one instant time

Invariant under boosts! Independent of P^μ

Measure wavefunctions of moving atoms, nuclei, hadrons at fixed LF time: Laser Interactions, Compton scattering, Electron Scattering

Light-Front QCD

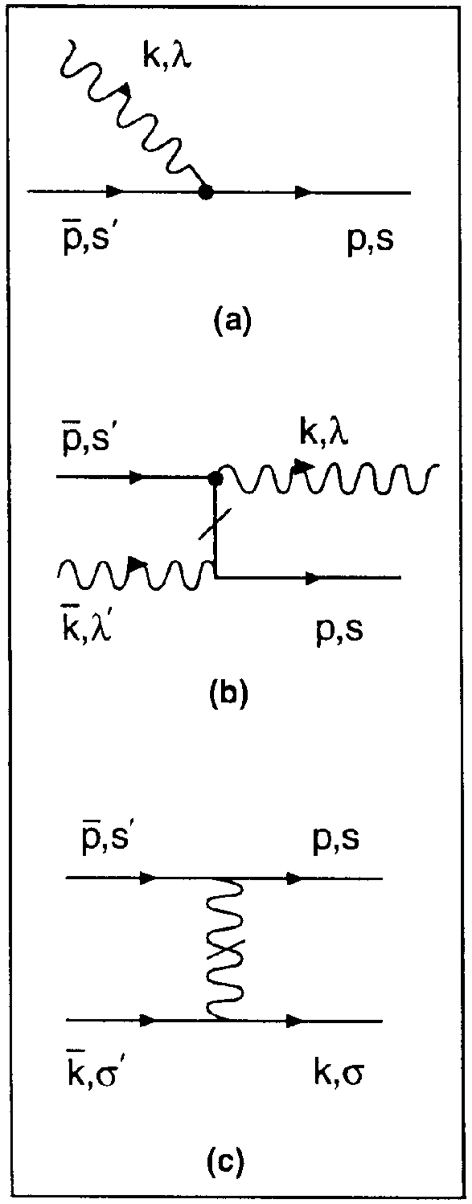
Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

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

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

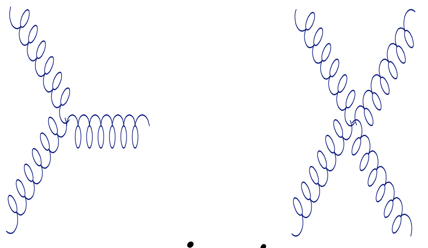
H^{int}_{LF}: Matrix in Fock Space



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

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

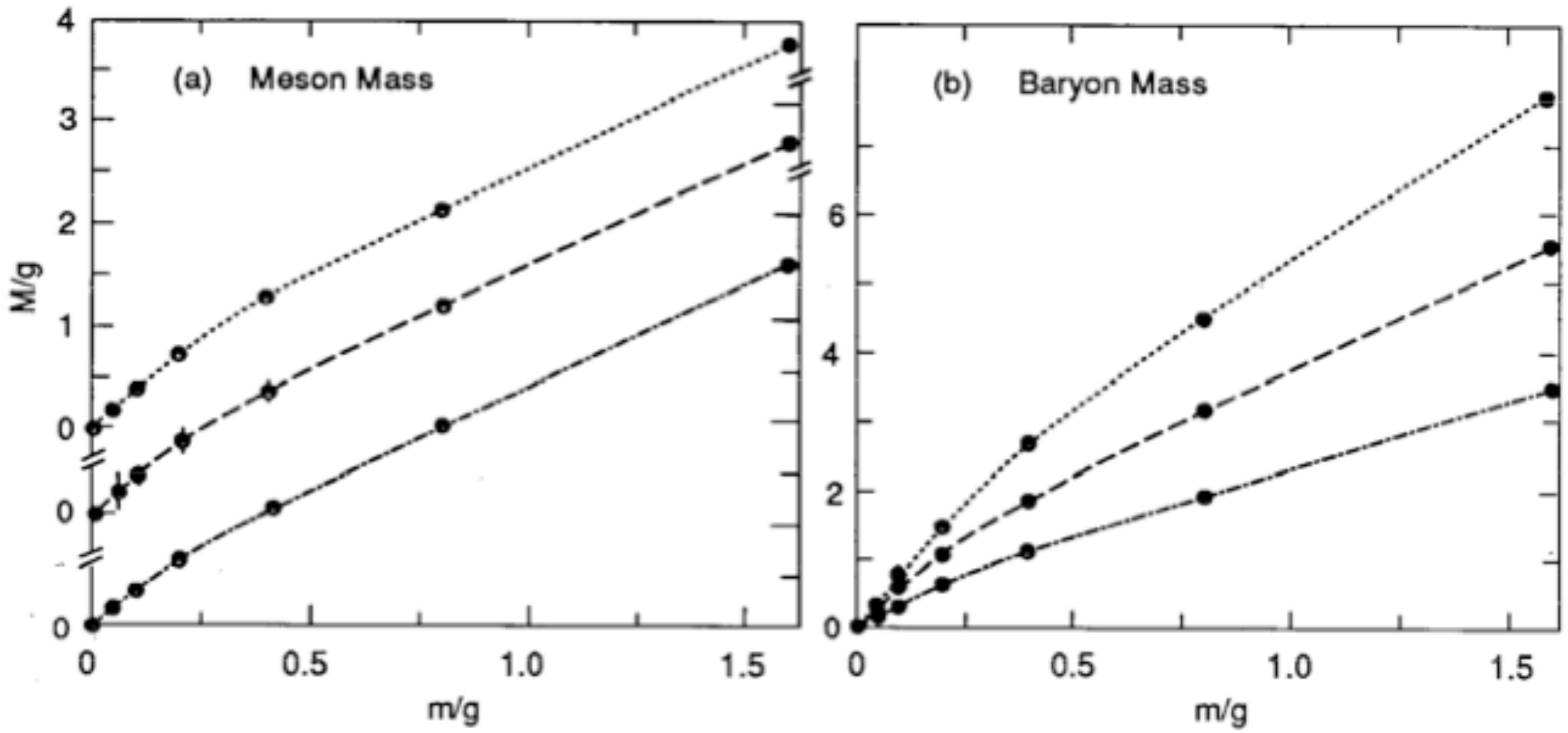
Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



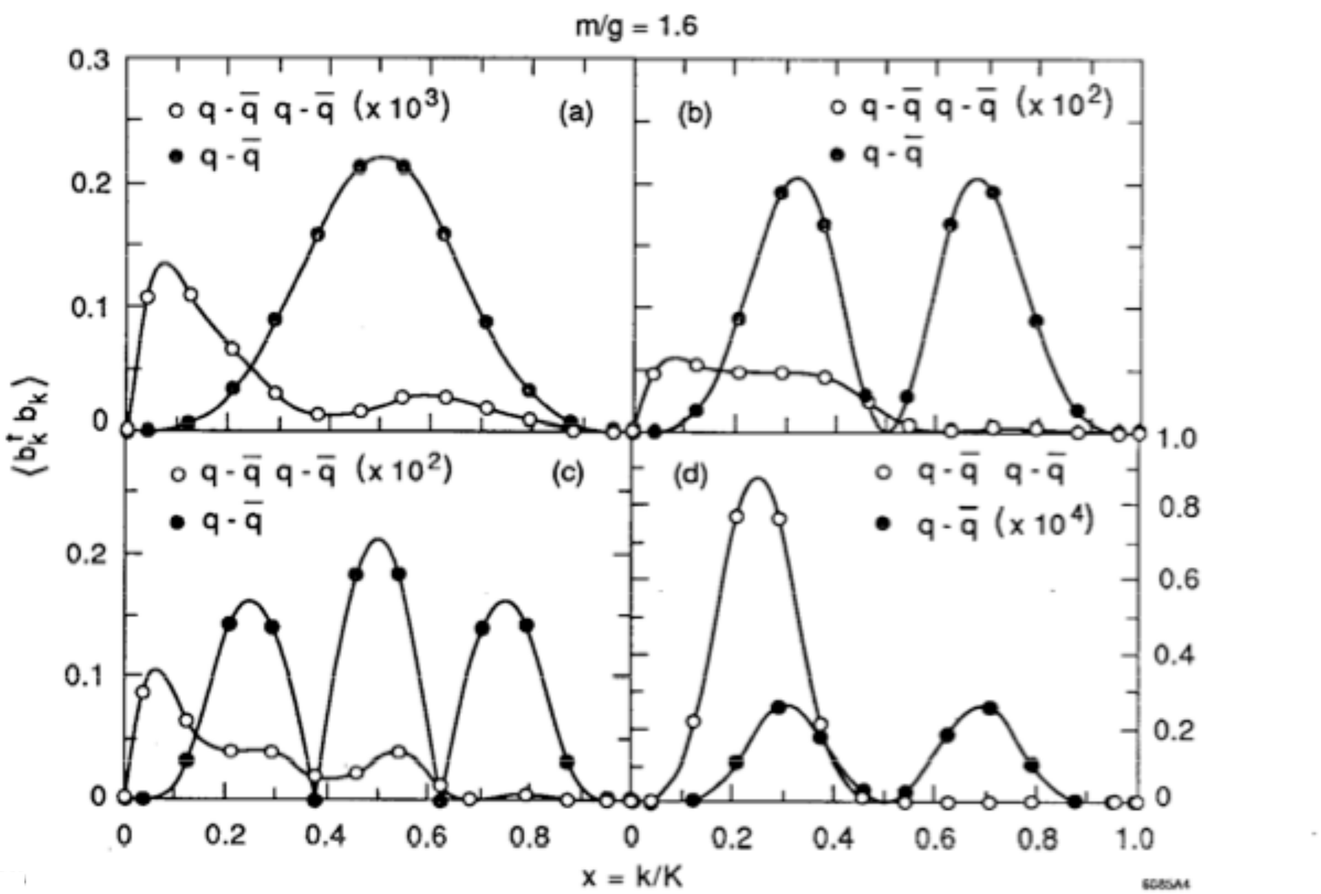
H^{int}_{LF}

LFWFs: Off-shell in P- and invariant mass

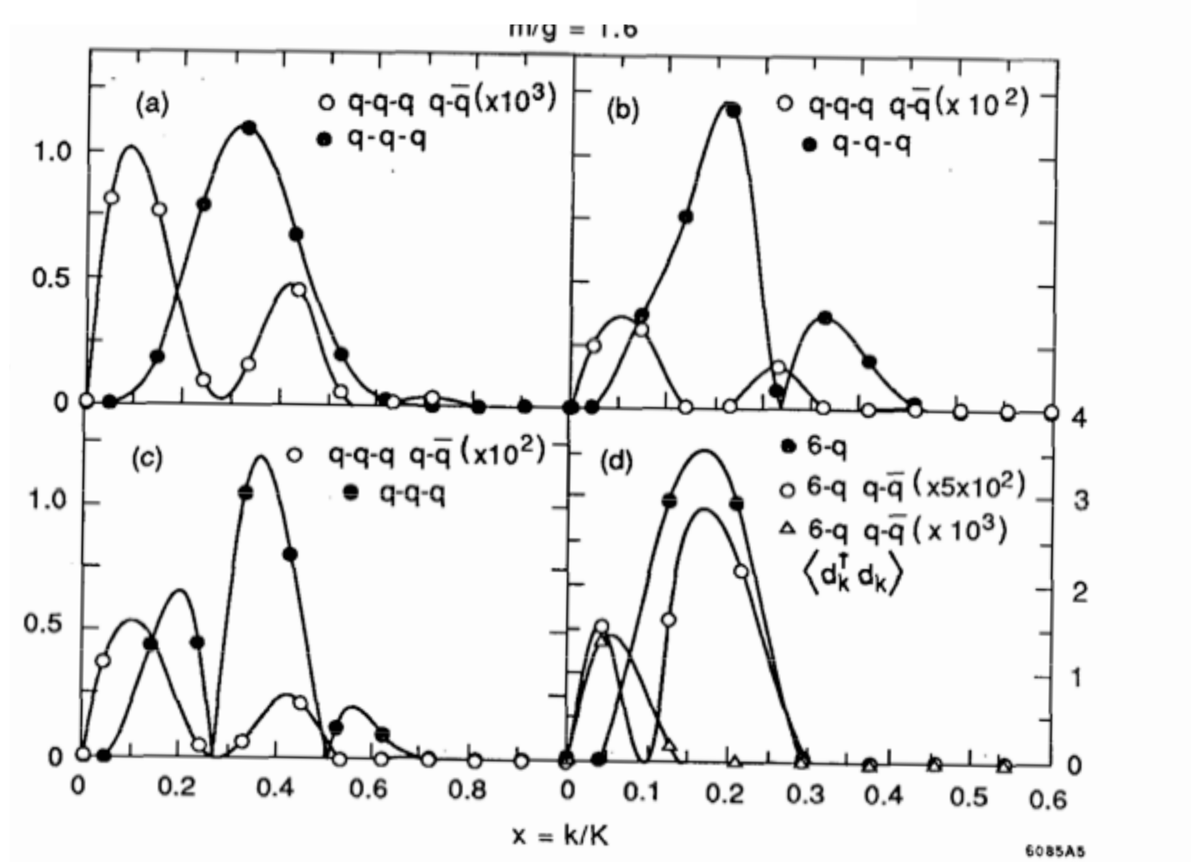
DLCQ: Solve QCD(1+1) for any quark mass and flavors



Extrapolated masses for $N = 2, 3$ and 4 meson and baryon.

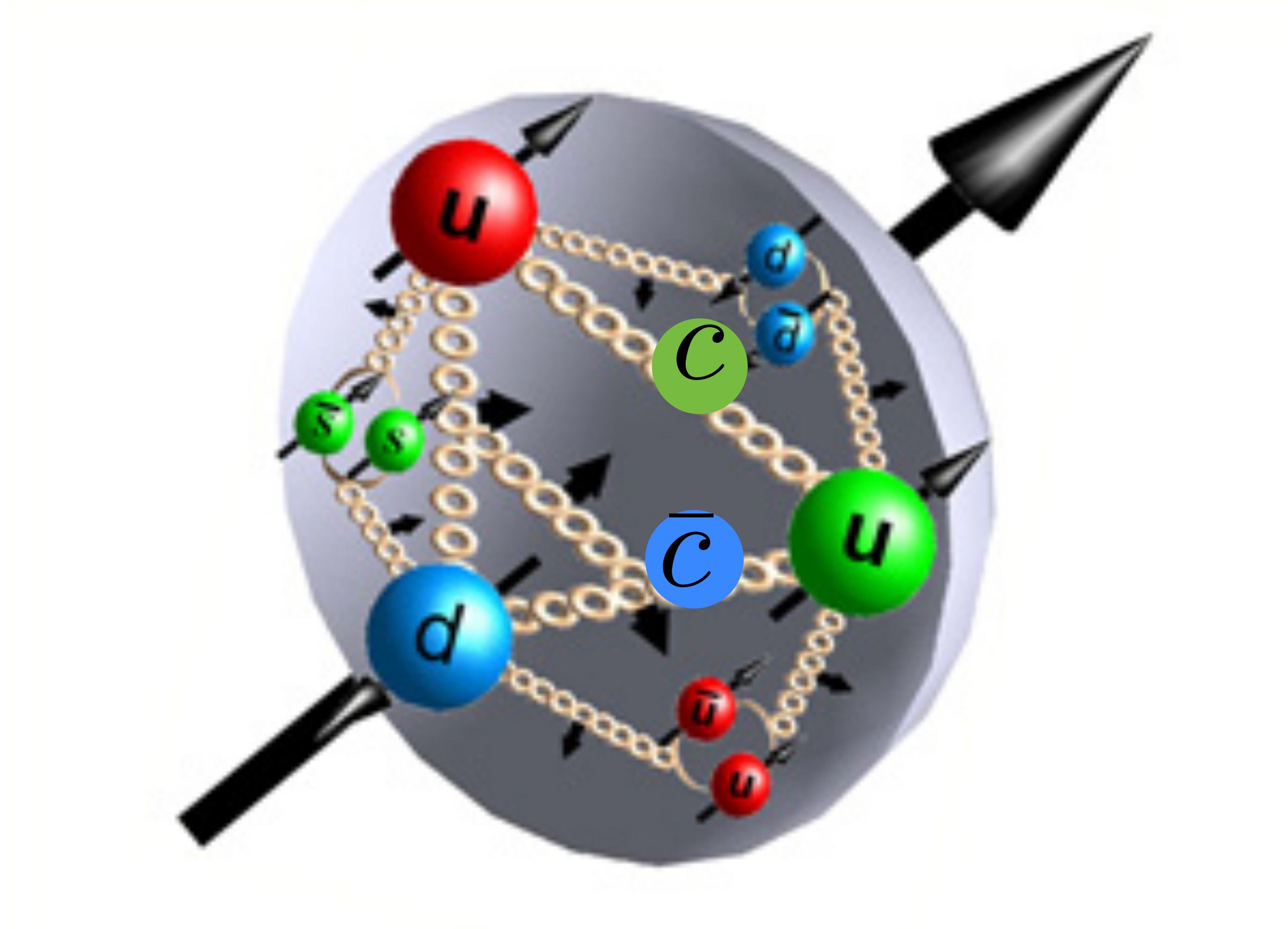


a-c) First three states in $N = 3$ meson spectrum for $m/g = 1.6$, 2K=24. d) Eleventh state.

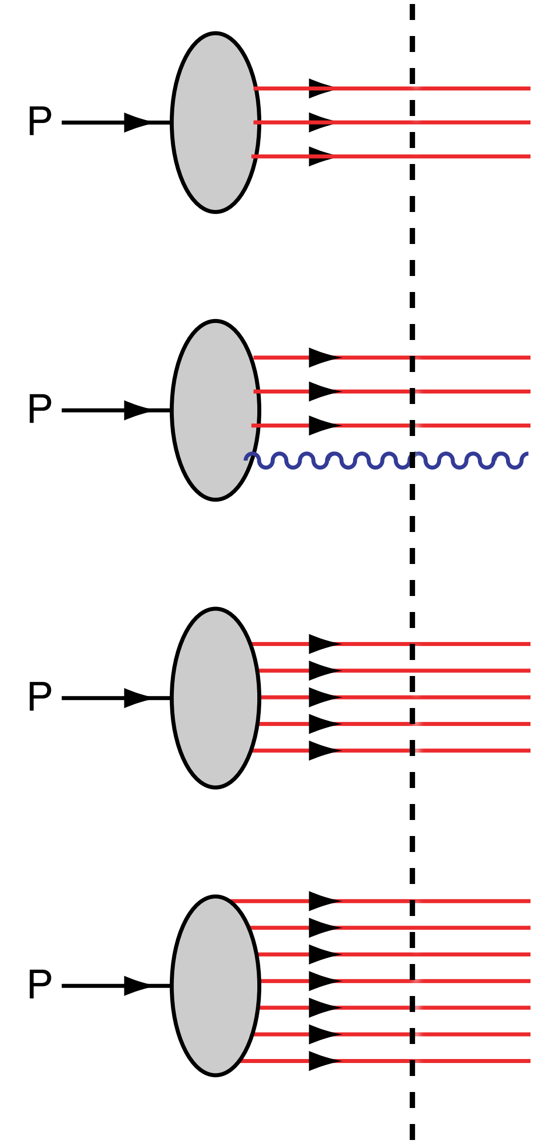


a-c) First three states in $N = 3$ baryon spectrum, 2K=21. d) First $B = 2$ state.

Hornbostel, Pauli, sjb



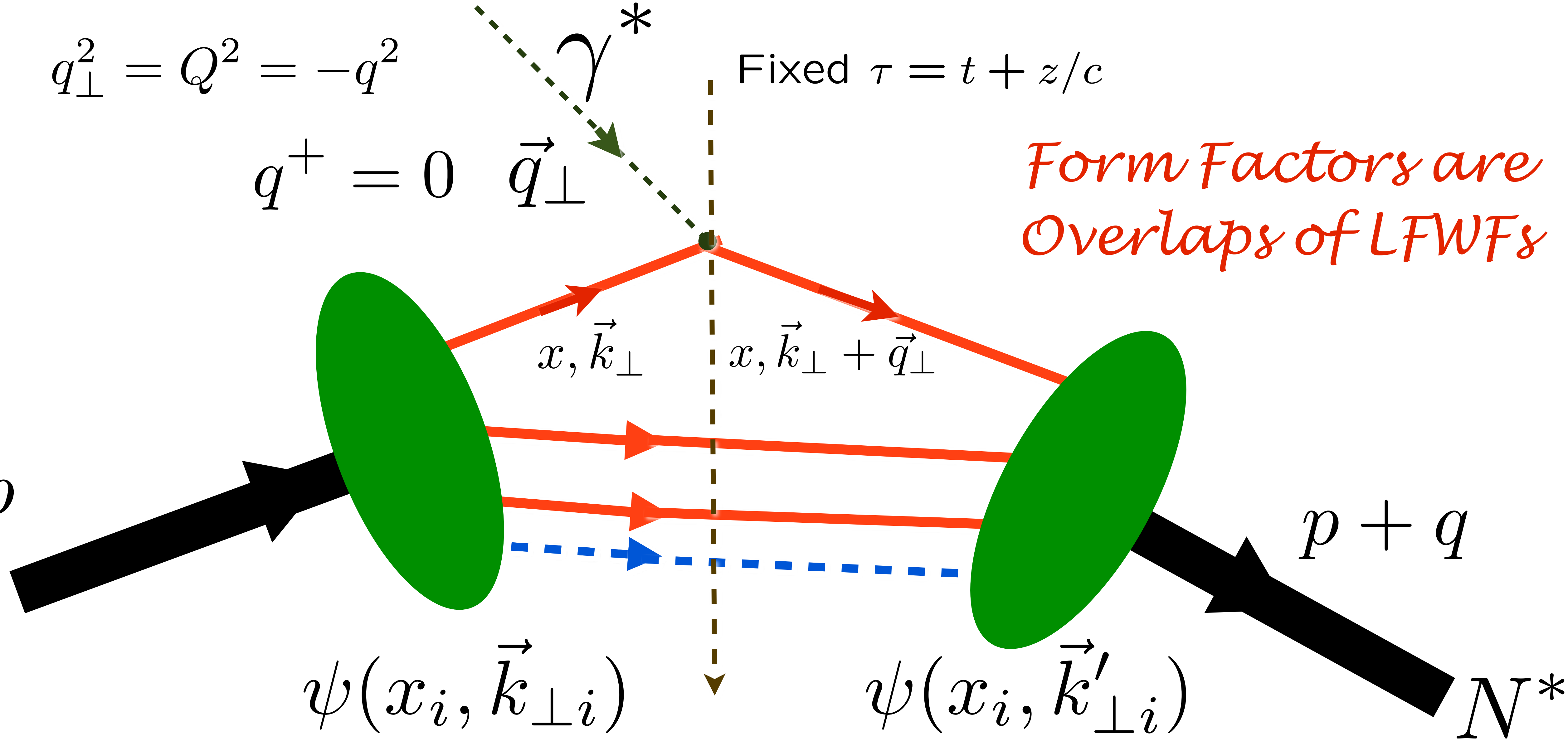
Higher Fock States of the Proton



Fixed LF time

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

Interaction picture



Form Factors are Overlaps of LFWFs

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

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

Drell &Yan, West
Drell, sjb
Exact LF formula

Sum over Fock states

Exact LF Formula for Pauli Form Factor

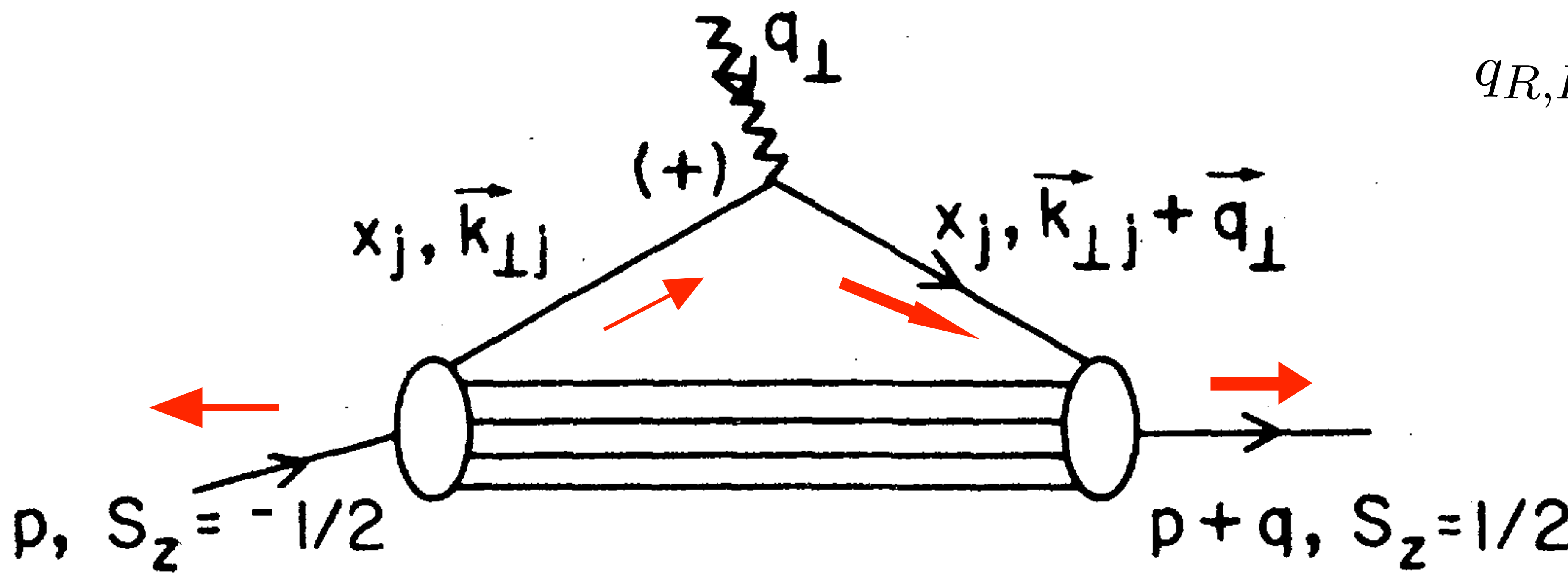
Drell, sjb

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

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

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

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

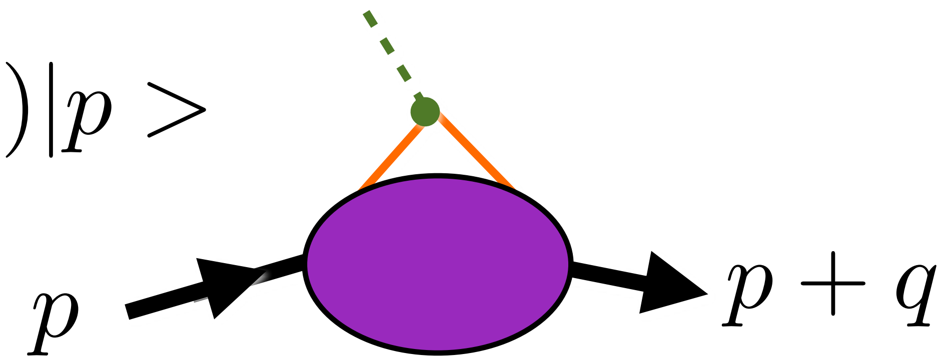


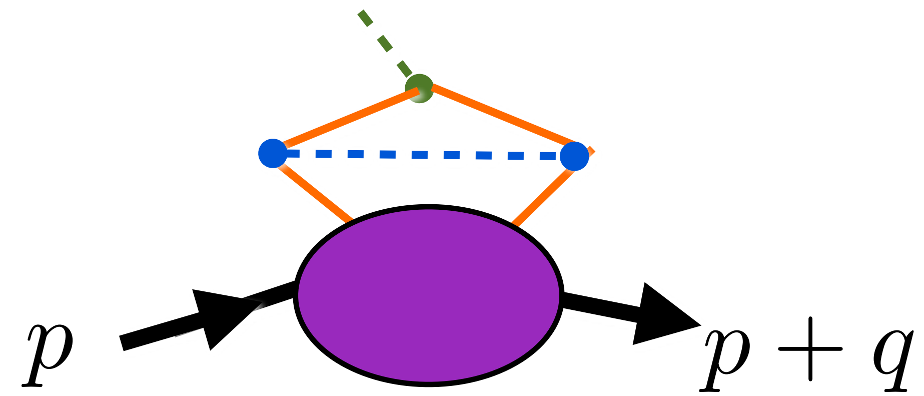
Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

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

Calculation of proton form factor in Instant Form

$< p + q | J^{\mu}(0) | p >$





- **Need to boost proton wavefunction: p to p+q.**
  Extremely complicated dynamical problem.
  Particle number changes

- **Need to couple to all currents arising from vacuum!!**
  Remain even after normal-ordering

- **Instant-form WFs insufficient to calculate form factors**

- **Each time-ordered contribution is frame-dependent**

- **Normal order; Divide by disconnected vacuum diagrams**

Light-Front QCD

- Light-Front Wavefunctions are frame-independent
- Measurements are at fixed LF time
- No Boost of Colliding Hadrons
- Boosting an instant-form wavefunctions dynamical problem -- extremely complicated even in QED
- Light-Front Vacuum same as vacuum of free Hamiltonian—(up to $k^+=0$ modes; e.g. Higgs VEV is zero mode)
- Causal commutators using LF time; no normal-ordering needed
- Cluster decomposition theorem
- Zero anomalous gravitomagnetic moment
- Few LF τ-ordered diagrams since all $k^+ > 0$, J^z conserved
- Instant-Form Vacuum infinitely complex even in QED
- n! time-ordered diagrams in Instant Form

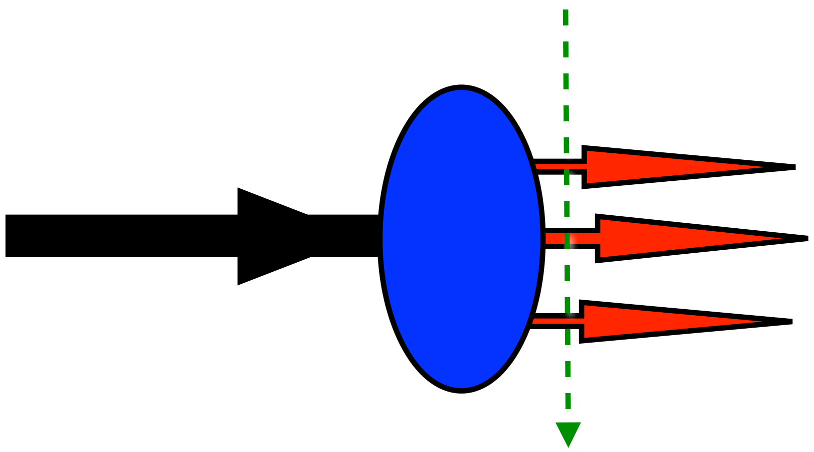
Recursion relations and scattering amplitudes in the light-front formalism

C.A. Cruz-Santiago, A.M. Stasto

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

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

Direct connection to QCD Lagrangian

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

Goal: an analytic first approximation to QCD

- As Simple as Schrödinger Theory in Atomic Physics
- Relativistic, Frame-Independent, Color-Confining
- Confinement in QCD -- What sets the QCD mass scale?
- QCD Coupling at all scales
- Hadron Spectroscopy
- Light-Front Wavefunctions
- Form Factors, Structure Functions,Hadronic Observables
- Constituent Counting Rules
- Hadronization at the Amplitude Level
- Insights into QCD Condensates

QED atoms: positronium and muonium

$$H_{QED}$$

$$(H_0 + H_{int}) \; |\Psi > = E \; |\Psi >$$

Coupled Fock states

$$[-\frac{\Delta^2}{2m_{\rm red}} + V_{\rm eff}(\vec{S}, \vec{r})] \; \psi(\vec{r}) = E \; \psi(\vec{r})$$

Effective two-particle equation

Includes Lamb Shift, quantum corrections

$$[-\frac{1}{2m_{\rm red}} \frac{d^2}{dr^2} + \frac{1}{2m_{\rm red}} \frac{\ell(\ell+1)}{r^2} + V_{\rm eff}(r, S, \ell)] \; \psi(r) = E \; \psi(r)$$

Spherical Basis r, θ, ϕ

$$V_{eff} \to V_C(r) = -\frac{\alpha}{r}$$

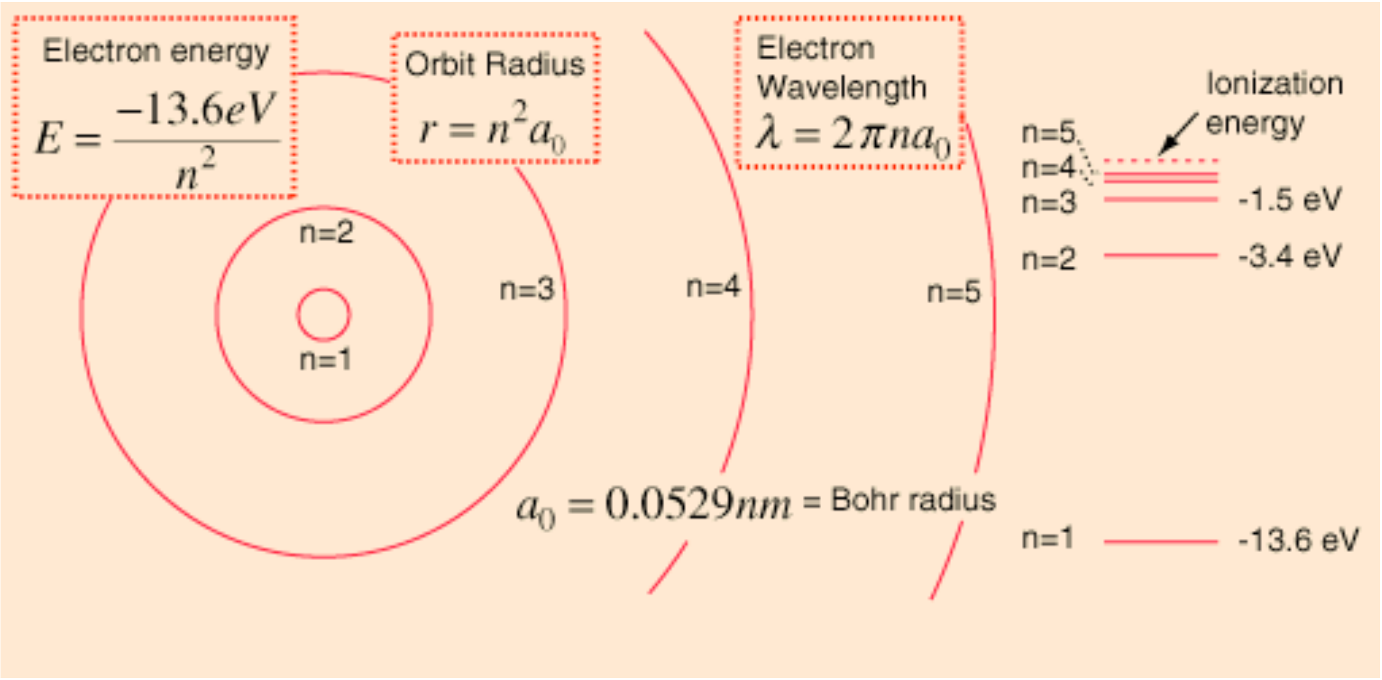
Coulomb potential

Bohr Spectrum

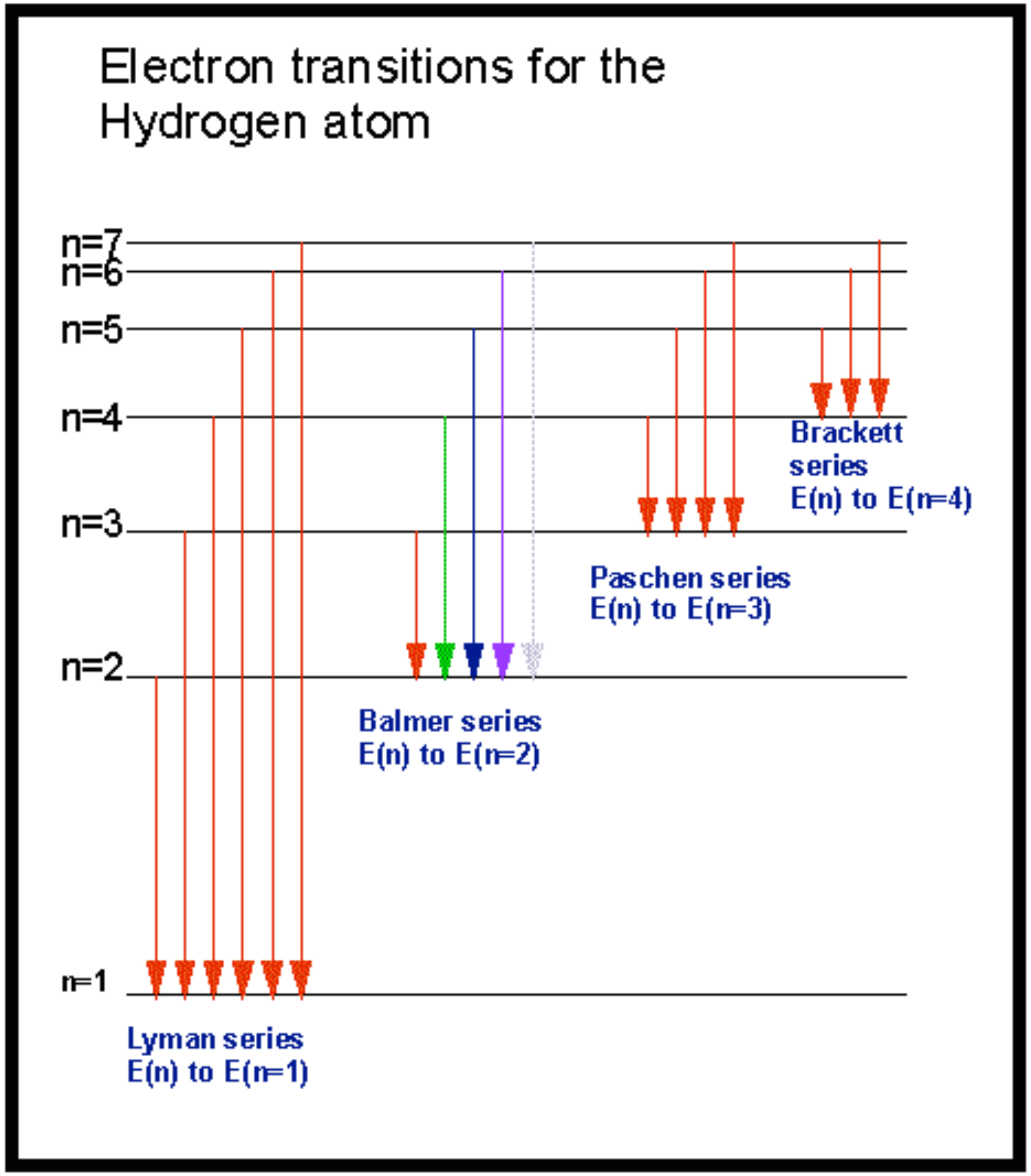
Semiclassical first approximation to QED

Schrödinger Eq.

Bohr Atom



Electron energy
$E = \frac{-13.6eV}{n^2}$
Orbit Radius
$r = n^2 a_0$
Electron Wavelength
$\lambda = 2\pi n a_0$
Ionization energy
n=5
n=4
n=3
-1.5 eV
n=2
-3.4 eV
n=1
-13.6 eV
n=2
n=1
n=3
n=4
n=5
$a_0 = 0.0529nm$ = Bohr radius

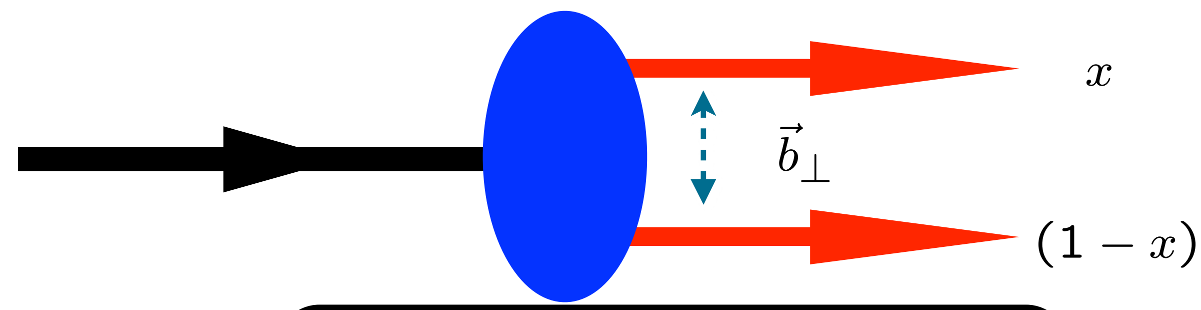


Electron transitions for the Hydrogen atom
n=7
n=6
n=5
n=4
n=3
n=2
n=1
Brackett series
E(n) to E(n=4)
Paschen series
E(n) to E(n=3)
Balmer series
E(n) to E(n=2)
Lyman series
E(n) to E(n=1)

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

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

Effective two-particle equation

$$\left[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1 + 4L^2}{4\zeta^2} + U(\zeta, S, L)\right] \psi_{LF}(\zeta) = M^2 \; \psi_{LF}(\zeta)$$

Azimuthal Basis

ζ, ϕ

AdS/QCD:

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

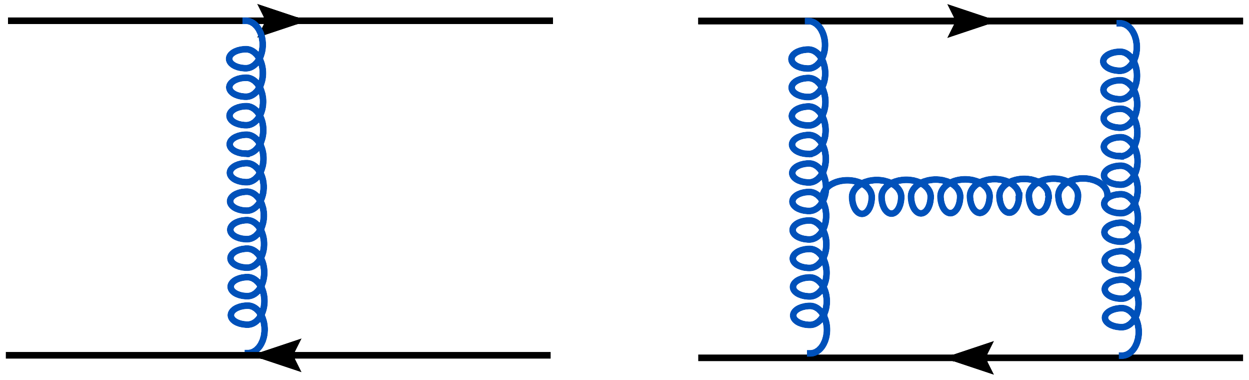
Confining AdS/QCD effective potential

Semiclassical first approximation to QCD

Heavy Quark Potential is IR Divergent in QCD

$$V(Q^2) = -\frac{(4\pi)^2 C_F}{Q^2} a(Q^2) \Big[1 + (c_{2,0} + c_{2,1} N_f) a(Q^2) + (c_{3,0} + c_{3,1} N_f + c_{3,2} N_f^2) a(Q^2)^2$$
$$+ (c_{4,0} + c_{4,1} N_f + c_{4,2} N_f^2 + c_{4,3} N_f^3) a(Q^2)^3 + 8\pi^2 C_A^3 \ln \frac{\mu_{IR}^2}{Q^2} a(Q^2)^3 \Big]$$

Smirnov, Smirnov, Steinhauser, 2010



$$\log \kappa^2 \zeta^2$$

Summation of H graphs: confining potential

Confinement eliminates IR divergences
Self-consistent mass scale κ

Light-Front Schrödinger Equation

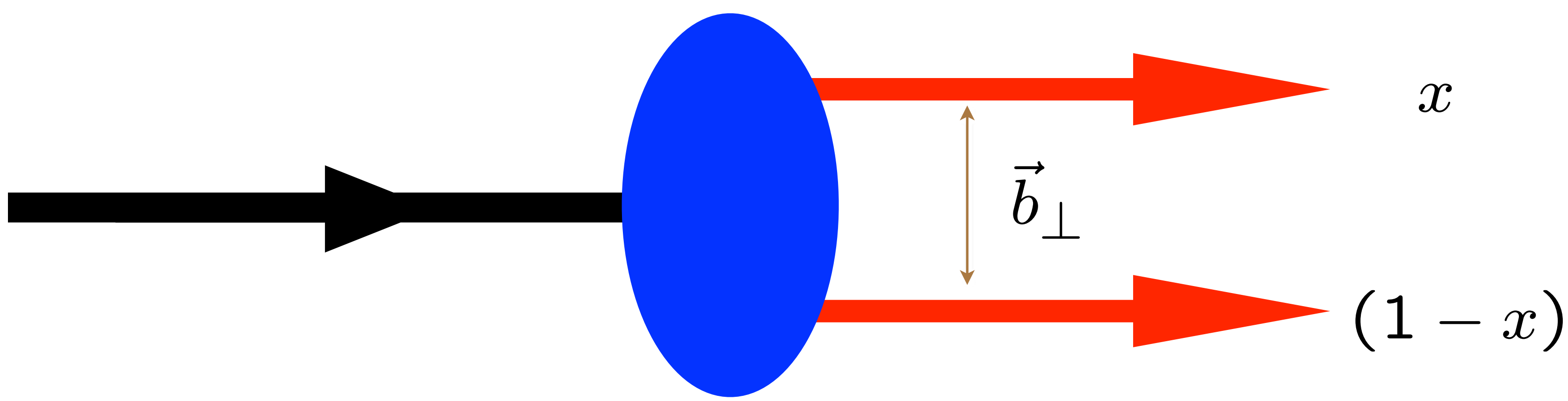
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

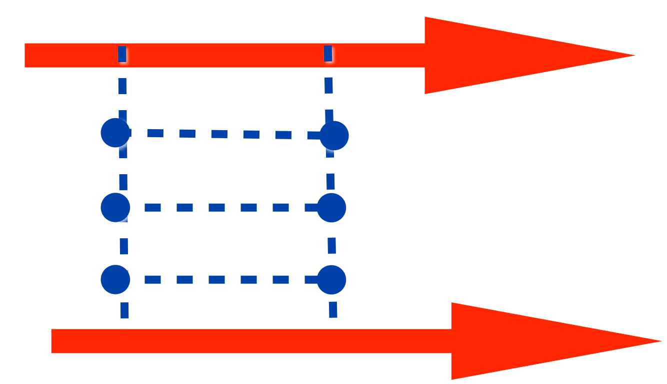
Frame Independent!

$$\left[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{4\zeta^2} + U(\zeta, S, L)\right] \psi_{LF}(\zeta) = M^2 \, \psi_{LF}(\zeta)$$

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



U is the confining QCD potential
Conjecture: 'H'-diagrams generate



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

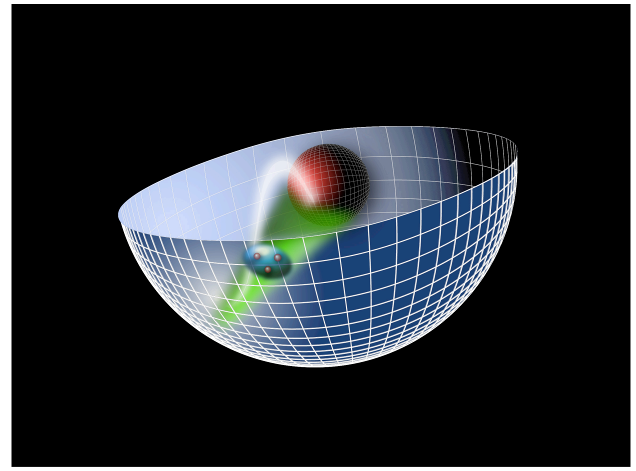
Sum powers of $\log \kappa^2 \zeta^2$

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent fundamental mass scale

κ



Light-Front Holography

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

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

Light-Front Schrödinger Equation

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

Unique Confinement Potential!

Conformal Symmetry of the action

Confinement scale:

(m_q=0)

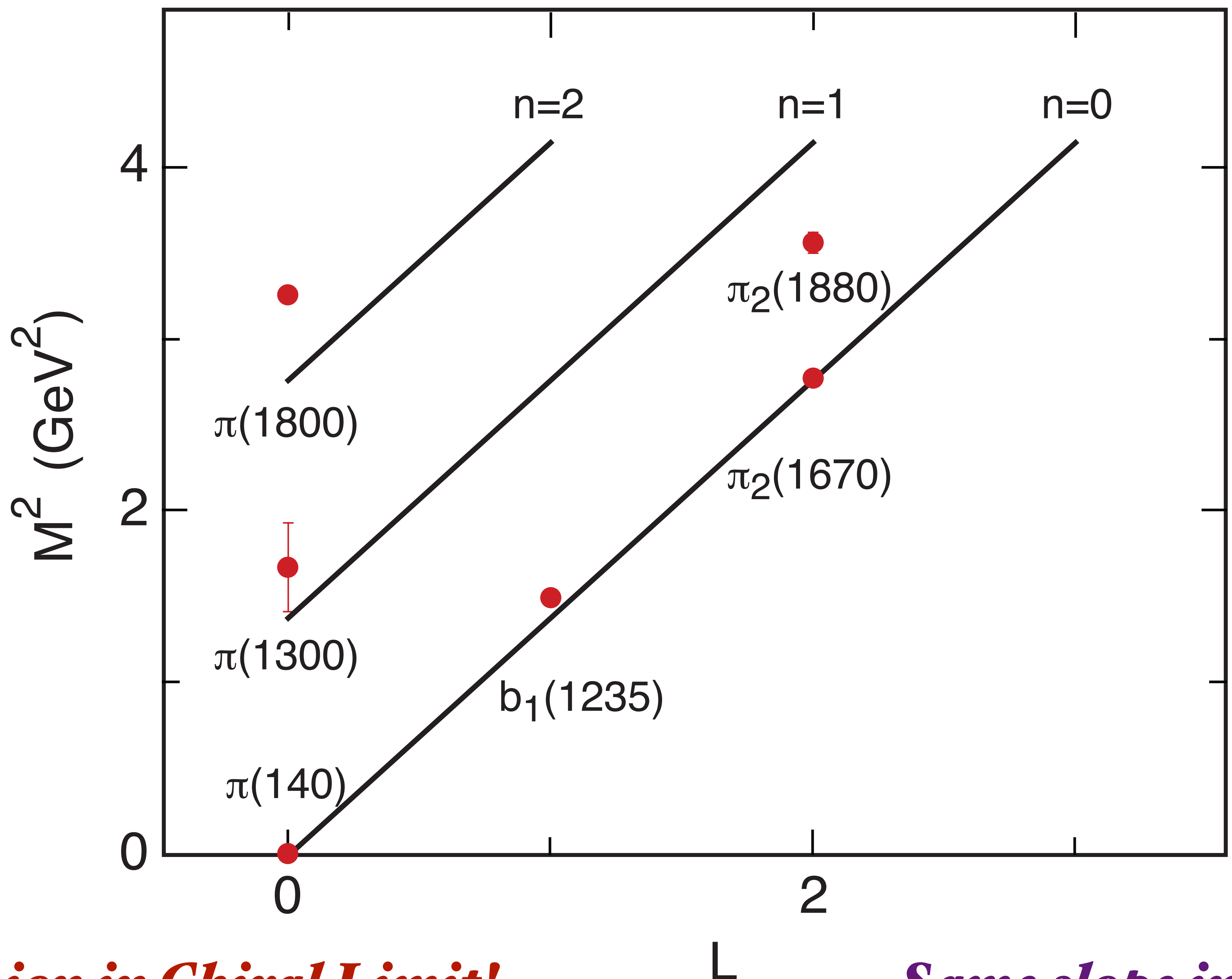
$$\kappa \simeq 0.6\ GeV$$

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

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

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

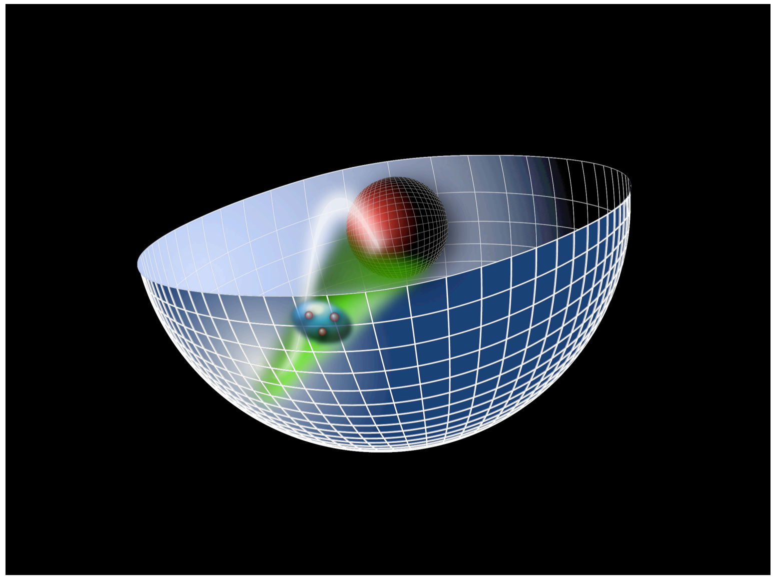
$$\mathcal{M}^2_{n,L,S} = 4\kappa^2(n + L + S/2)$$



Massless pion in Chiral Limit!

Same slope in n and L!

$\phi(z)$

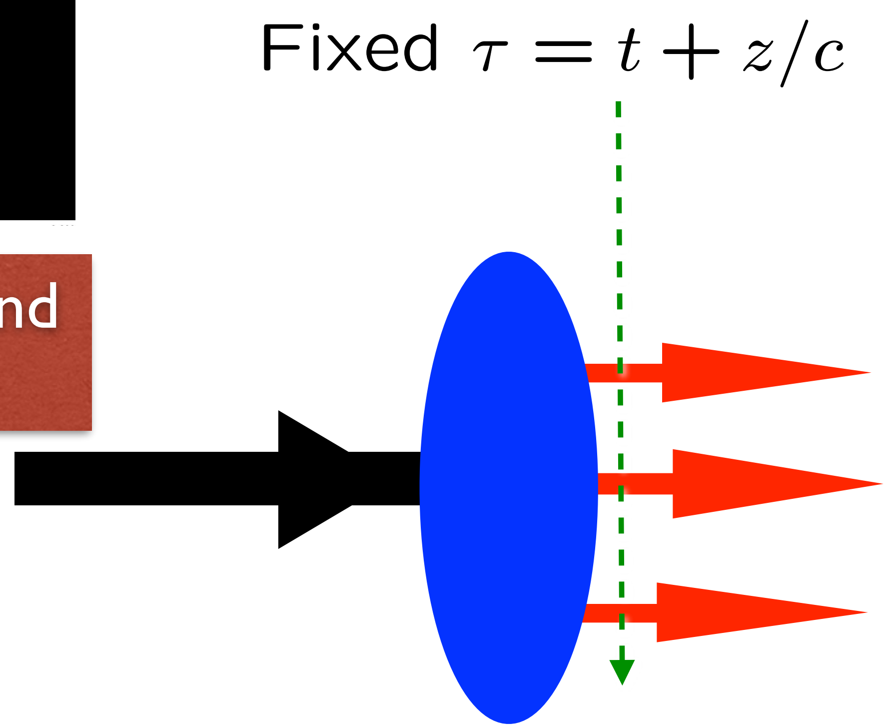


AdS5: Conformal Template for QCD

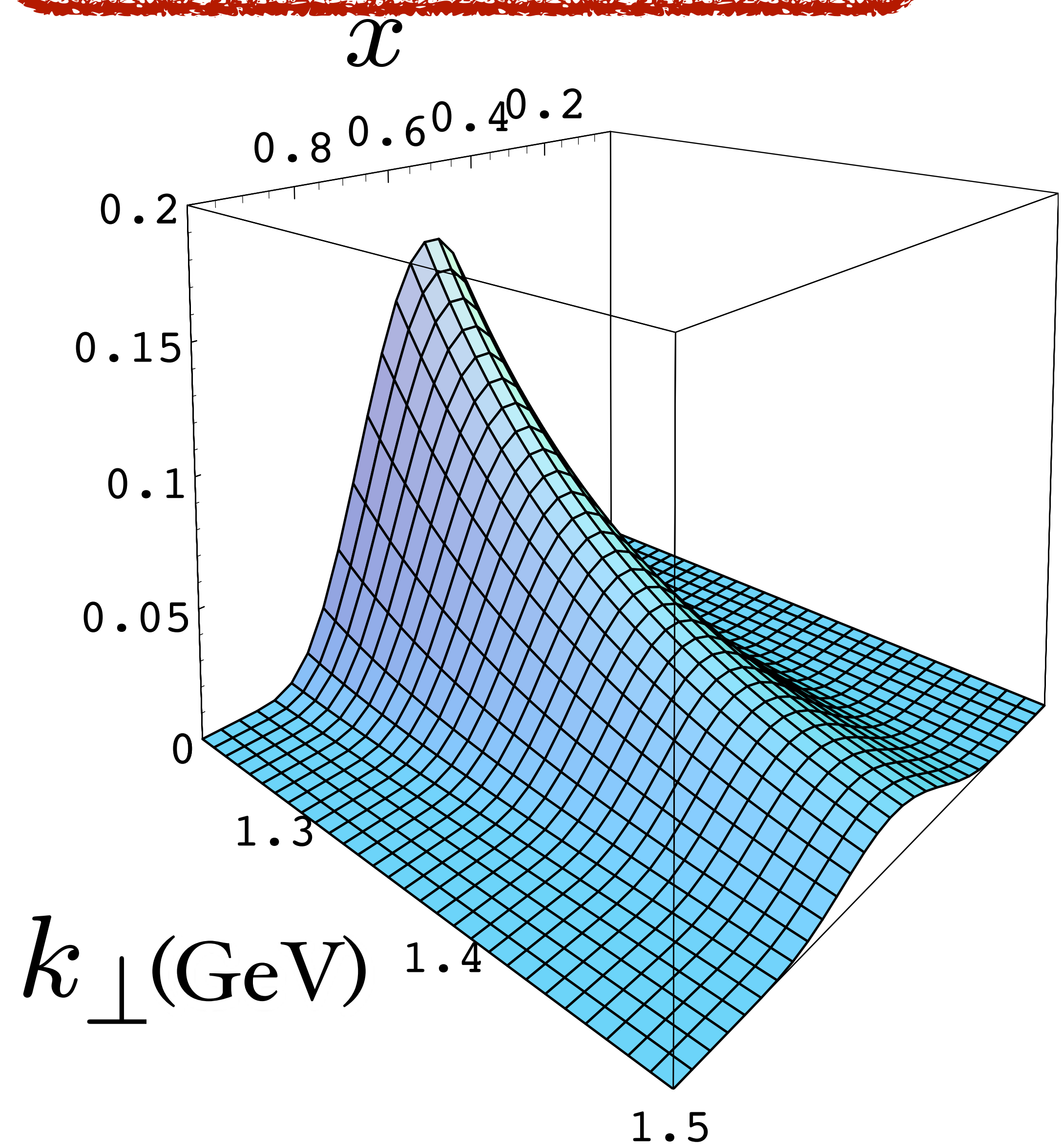
- *Light-Front Holography*

Duality of AdS$_5$ with LF Hamiltonian Theory

with Guy de Teramond and Hans Guenter Dosch



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

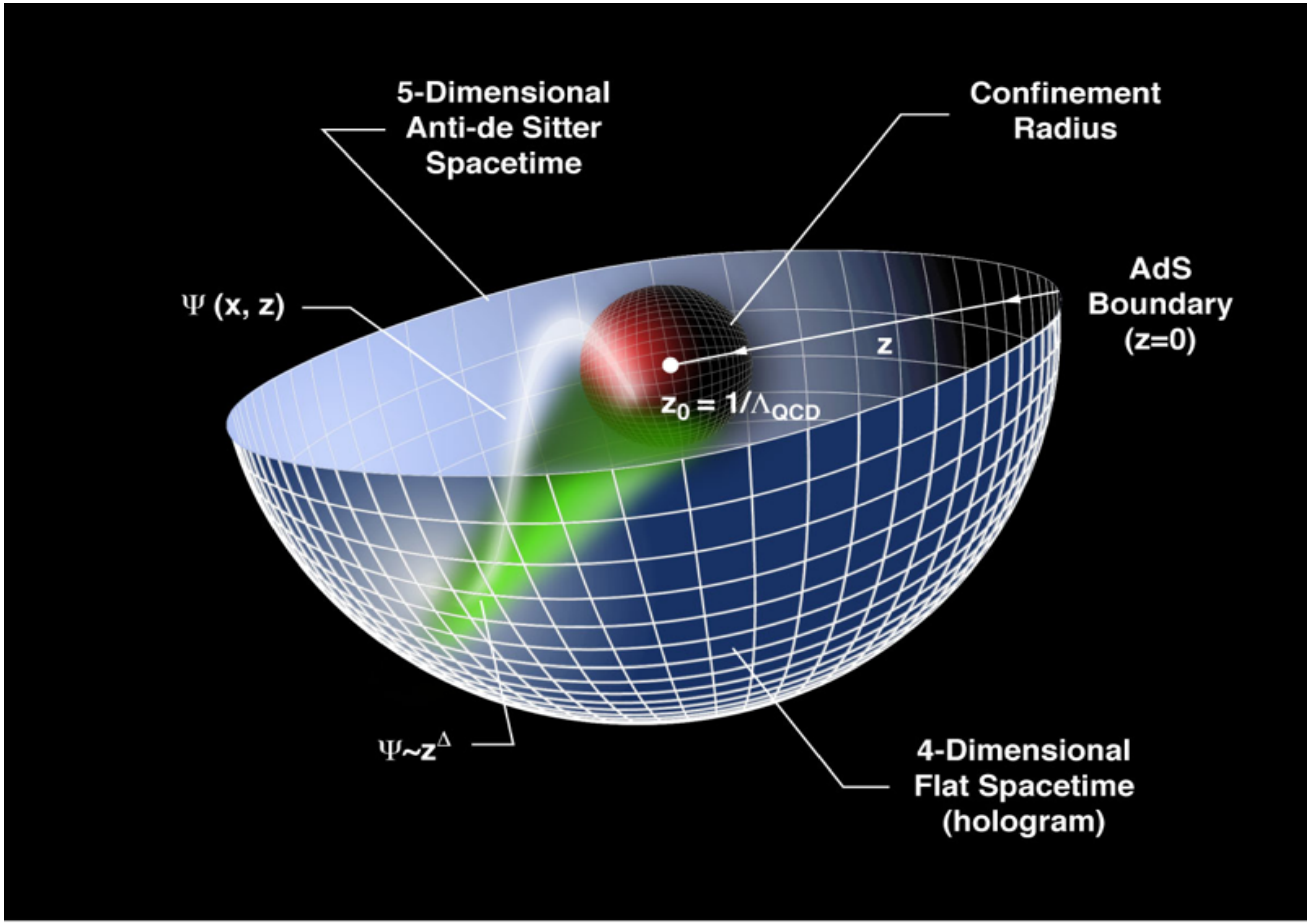


- *Light Front Wavefunctions:*

Light-Front Schrödinger Equation

Spectroscopy and Dynamics

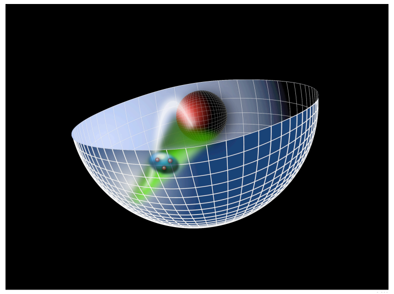
Applications of AdS/CFT to QCD



Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

AdS/CFT



- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2),$$

invariant measure

$x^\mu \to \lambda x^\mu, \; z \to \lambda z$, maps scale transformations into the holographic coordinate z.

- AdS mode in z is the extension of the hadron wf into the fifth dimension.

- Different values of z correspond to different scales at which the hadron is examined.

$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$

$x^2 = x_\mu x^\mu$: invariant separation between quarks

- The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.

Dilaton-Modified AdS/QCD

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

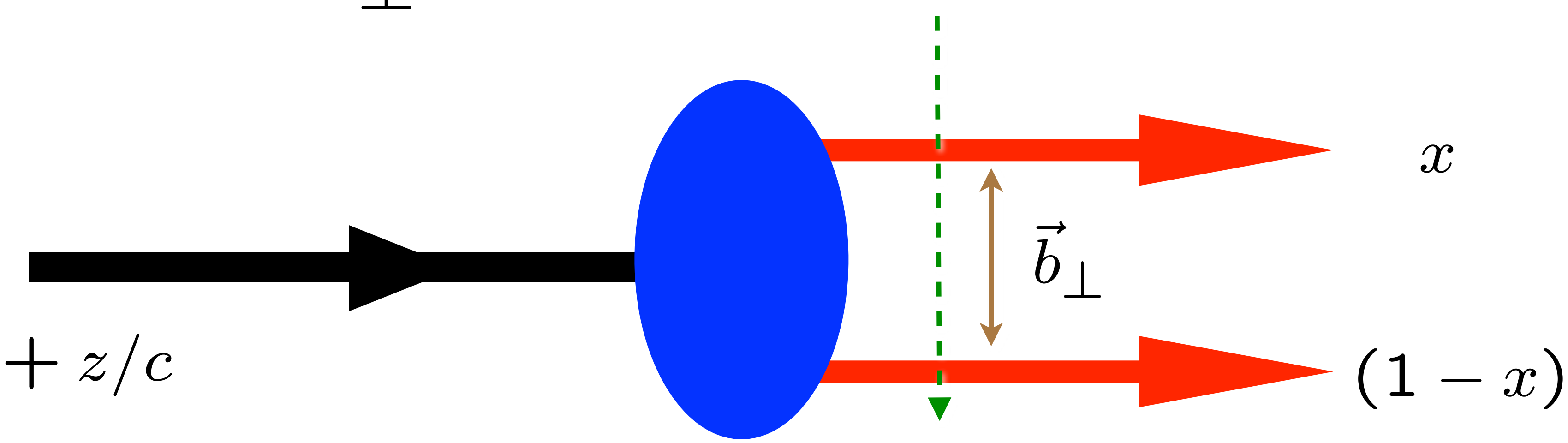
- **Soft-wall dilaton profile breaks conformal invariance** $e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- **Color Confinement**
- **Introduces confinement scale** κ
- **Uses AdS_5 as template for conformal theory**

de Tèramond, Dosch, sjb

$LF(3+1) \quad \longleftrightarrow \quad AdS_5$

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

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



Fixed $\tau = t + z/c$

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

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

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

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

Positive-sign dilaton

- Dosch, de Teramond, sjb

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

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

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

Derived from variation of Action for Dilaton-Modified AdS_5

Identical to Light-Front Bound State Equation!

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

Meson Spectrum in Soft Wall Model

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

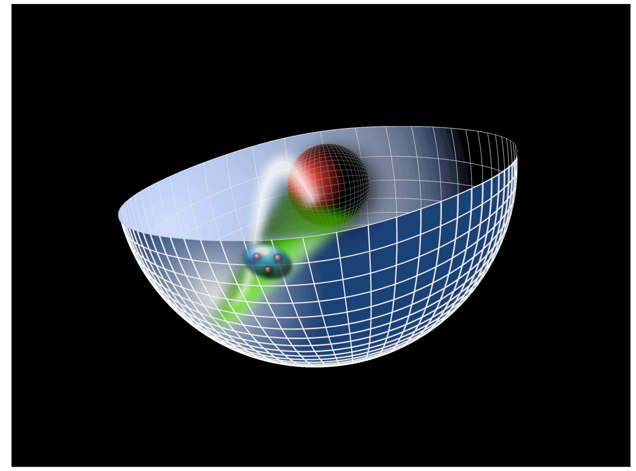
$$\mathcal{M}^2_{n,J,L} = 4\kappa^2 \left(n + \frac{J+L}{2}\right)$$

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

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

Single scheme-independent fundamental mass scale
κ



Light-Front Holography

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

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

Light-Front Schrödinger Equation

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

Unique
Confinement Potential!

Conformal Symmetry
of the action

Confinement scale:

$$\kappa \simeq 0.6\ GeV$$

(m_q=0)

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

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Scale can appear in Hamiltonian and EQM
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- **Soft-wall dilaton profile breaks conformal invariance** $e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- **Color Confinement**
- **Introduces confinement scale** κ
- **Uses AdS_5 as template for conformal theory**

- de Alfaro, Fubini, Furlan

$$G|\psi(\tau) >= i\frac{\partial}{\partial\tau}|\psi(\tau) >$$

$$G = uH + vD + wK$$

New term

$$G = H_\tau = \frac{1}{2}\left(-\frac{d^2}{dx^2} + \frac{g}{x^2} + \frac{4uw - v^2}{4}x^2\right)$$

Retains conformal invariance of action despite mass scale!

$$4uw - v^2 = \kappa^4 = [M]^4$$

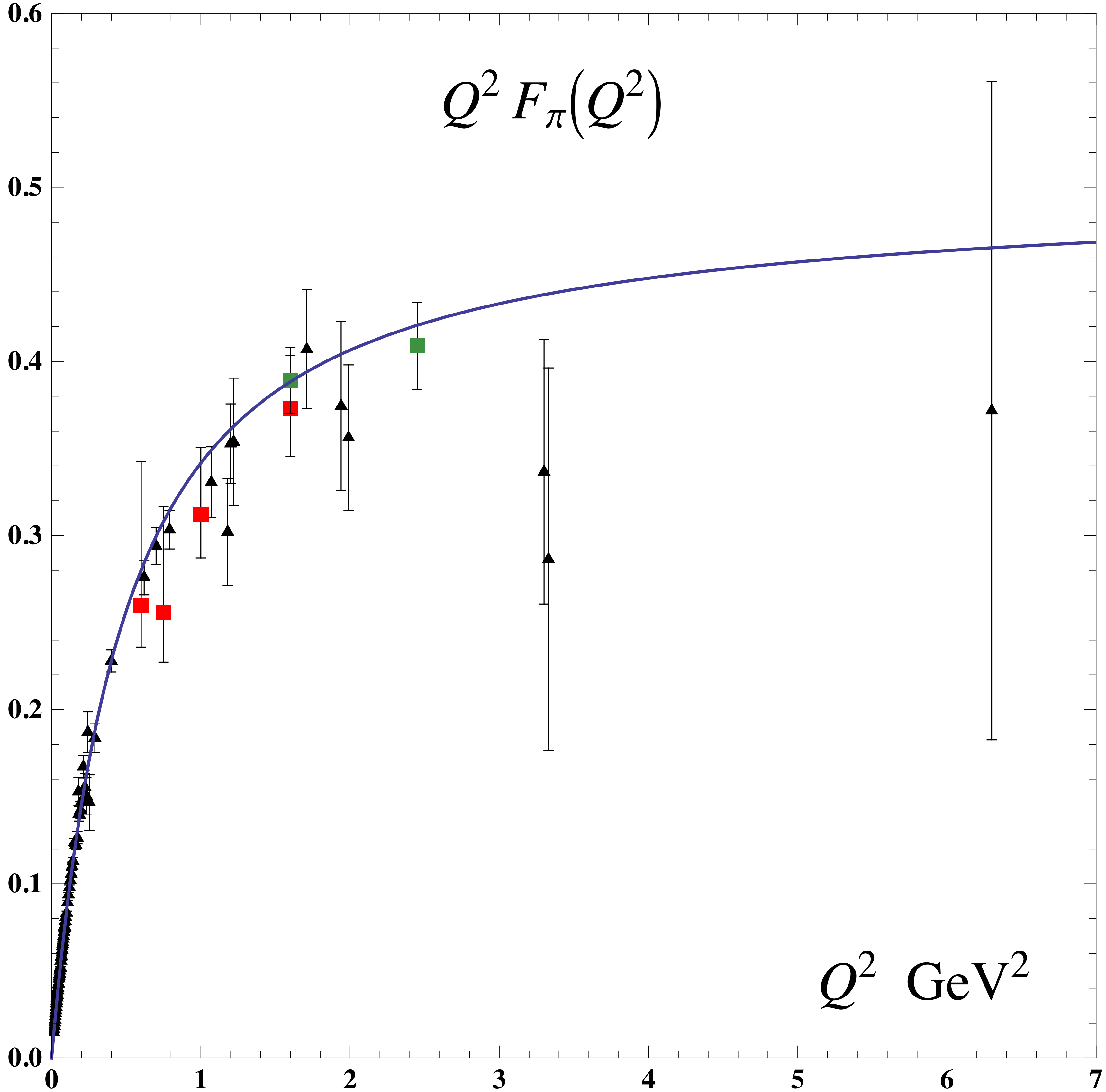
Identical to LF Hamiltonian with unique potential and dilaton!

- Dosch, de Teramond, sjb

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

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

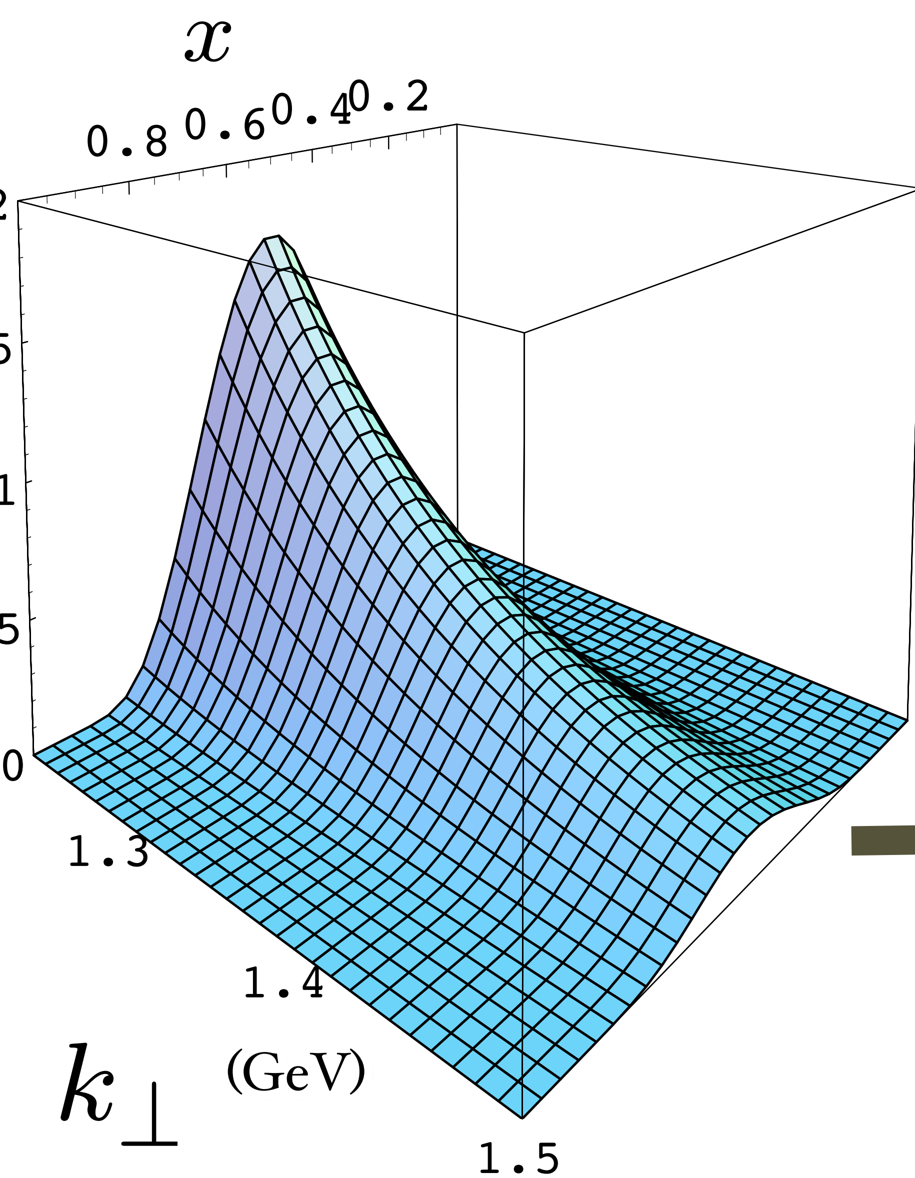
Pion Form Factor from AdS/QCD and Light-Front Holography



Dressed AdS/QCD Current

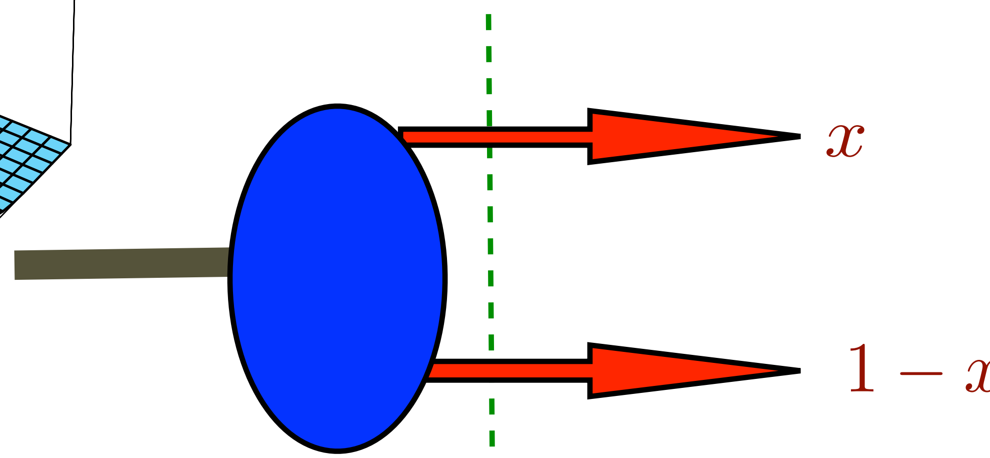
Prediction from AdS/QCD: Meson LFWF

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

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

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

$$b_\perp^2 \propto \frac{1}{(1-x)} \text{ at } x \sim 1$$

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

Connection of Confinement to Hadron Structure

de Teramond,sjb
See also Leutwyler, Stern

- We write the Dirac equation

$$(\alpha\Pi(\zeta) - \mathcal{M})\,\psi(\zeta) = 0,$$

in terms of the matrix-valued operator Π

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu + \frac{1}{2}}{\zeta}\gamma_5 - \kappa^2\zeta\gamma_5\right),$$

and its adjoint $\Pi^\dagger$, with commutation relations

$$\left[\Pi_\nu(\zeta), \Pi^\dagger_\nu(\zeta)\right] = \left(\frac{2\nu + 1}{\zeta^2} - 2\kappa^2\right)\gamma_5.$$

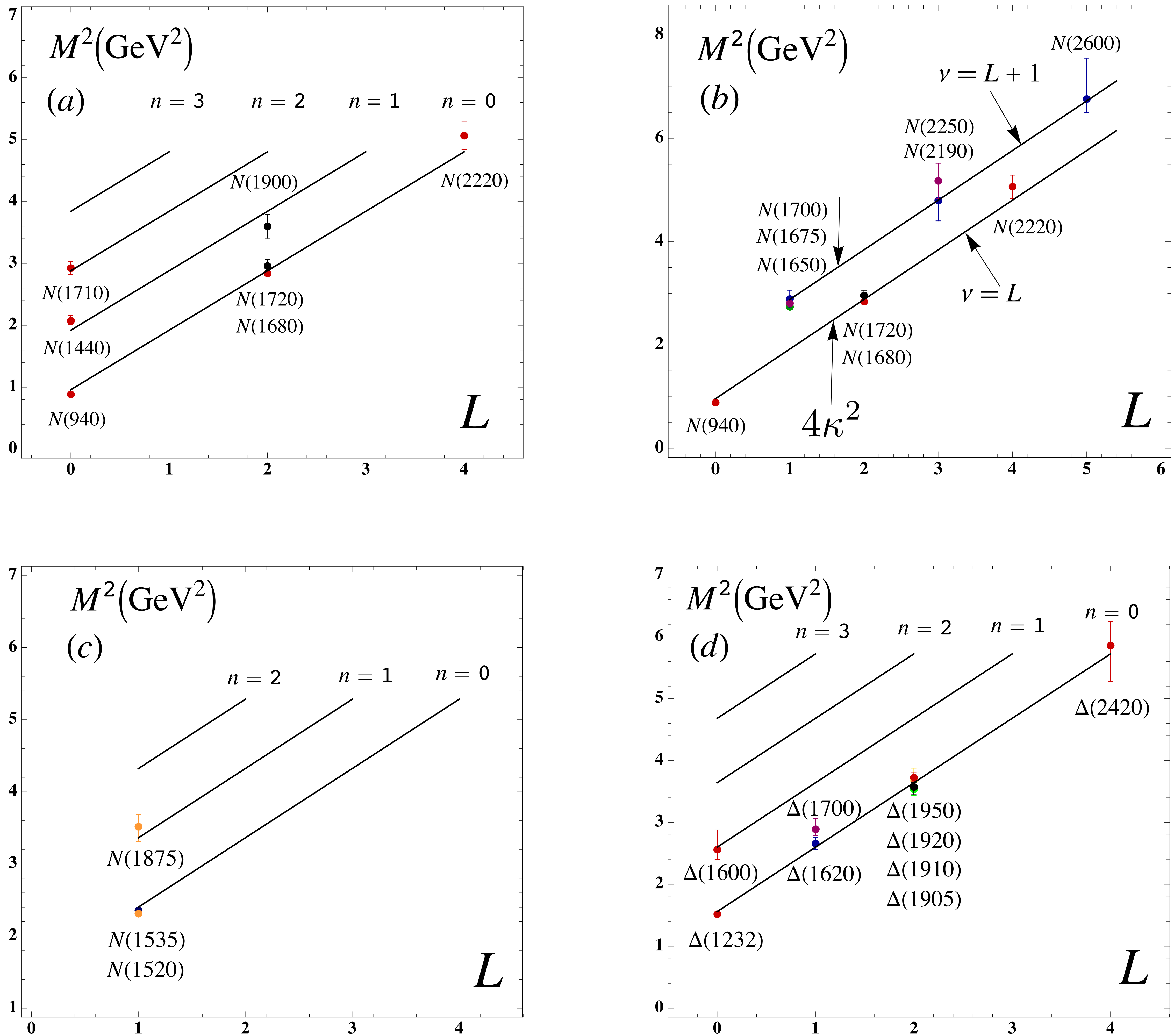
- Solutions to the Dirac equation

$$\psi_+(\zeta) \sim z^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L^\nu_n(\kappa^2\zeta^2),$$
$$\psi_-(\zeta) \sim z^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L^{\nu+1}_n(\kappa^2\zeta^2).$$

$$\nu = L + 1$$

- Eigenvalues

$$\mathcal{M}^2 = 4\kappa^2(n + \nu + 1).$$



$M^2(\mathrm{GeV}^2)$
(a)
n = 3
n = 2
n = 1
n = 0
N(1900)
N(2220)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
L
$M^2(\mathrm{GeV}^2)$
(b)
$\nu = L + 1$
N(2600)
N(2250)
N(2190)
N(1700)
N(1675)
N(1650)
N(2220)
$\nu = L$
N(1720)
N(1680)
N(940)
$4\kappa^2$
L
$M^2(\mathrm{GeV}^2)$
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
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)
L

Table 1: $SU(6)$ classification of confirmed baryons listed by the PDG. The labels S, L and n refer to the internal spin, orbital angular momentum and radial quantum number respectively. The $\Delta\frac{5}{2}^-(1930)$ does not fit the $SU(6)$ classification since its mass is too low compared to other members **70**-multiplet for $n = 0$, $L = 3$.

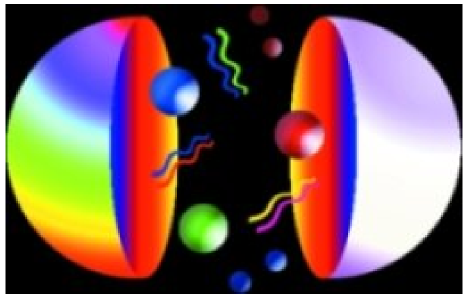
$SU(6)$	S	L	n	Baryon State
56	$\frac{1}{2}$	0	0	$N\frac{1}{2}^+(940)$
	$\frac{1}{2}$	0	1	$N\frac{1}{2}^+(1440)$
	$\frac{1}{2}$	0	2	$N\frac{1}{2}^+(1710)$
	$\frac{3}{2}$	0	0	$\Delta\frac{3}{2}^+(1232)$
	$\frac{3}{2}$	0	1	$\Delta\frac{3}{2}^+(1600)$
70	$\frac{1}{2}$	1	0	$N\frac{1}{2}^-(1535)$ $N\frac{3}{2}^-(1520)$
	$\frac{3}{2}$	1	0	$N\frac{1}{2}^-(1650)$ $N\frac{3}{2}^-(1700)$ $N\frac{5}{2}^-(1675)$
	$\frac{3}{2}$	1	1	$N\frac{1}{2}^-$ $N\frac{3}{2}^-(1875)$ $N\frac{5}{2}^-$
	$\frac{1}{2}$	1	0	$\Delta\frac{1}{2}^-(1620)$ $\Delta\frac{3}{2}^-(1700)$
56	$\frac{1}{2}$	2	0	$N\frac{3}{2}^+(1720)$ $N\frac{5}{2}^+(1680)$
	$\frac{1}{2}$	2	1	$N\frac{3}{2}^+(1900)$ $N\frac{5}{2}^+$
	$\frac{3}{2}$	2	0	$\Delta\frac{1}{2}^+(1910)$ $\Delta\frac{3}{2}^+(1920)$ $\Delta\frac{5}{2}^+(1905)$ $\Delta\frac{7}{2}^+(1950)$
70	$\frac{1}{2}$	3	0	$N\frac{5}{2}^-$ $N\frac{7}{2}^-$
	$\frac{3}{2}$	3	0	$N\frac{3}{2}^-$ $N\frac{5}{2}^-$ $N\frac{7}{2}^-(2190)$ $N\frac{9}{2}^-(2250)$
	$\frac{1}{2}$	3	0	$\Delta\frac{5}{2}^-$ $\Delta\frac{7}{2}^-$
56	$\frac{1}{2}$	4	0	$N\frac{7}{2}^+$ $N\frac{9}{2}^+(2220)$
	$\frac{3}{2}$	4	0	$\Delta\frac{5}{2}^+$ $\Delta\frac{7}{2}^+$ $\Delta\frac{9}{2}^+$ $\Delta\frac{11}{2}^+(2420)$
70	$\frac{1}{2}$	5	0	$N\frac{9}{2}^-$ $N\frac{11}{2}^-$
	$\frac{3}{2}$	5	0	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

PDG 2012

Fermionic Modes and Baryon Spectrum

[Hard wall model: GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Soft wall model: GdT and S. J. Brodsky, (2005), arXiv:1001.5193]



From Nick Evans

- Nucleon LF modes

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

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

- Normalization

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

Chiral Symmetry of Eigenstate!

- Eigenvalues

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

Chiral Features of Soft-Wall AdS/QCD Model

- **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!

AdS/QCD and Light-Front Holography

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

- **Zero mass pion for m_q =0 (n=J=L=0)**
- **Regge trajectories: equal slope in n and L**
- **Form Factors at high Q^2: Dimensional counting** $[Q^2]^{n-1} F(Q^2) \to \mathrm{const}$
- **Space-like and Time-like Meson and Baryon Form Factors**
- **Running Coupling for NPQCD** $\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$
- **Meson Distribution Amplitude** $\phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$

Connection to the Linear Instant-Form Potential

- 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

Connection to the Linear Instant-Form Potential

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

⇕

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

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

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***

Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS_5 space in dilaton background $\varphi(z) = \kappa^2 z^2$

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

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$

- Coupling measured at momentum scale Q

$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta \, J_0(\zeta Q) \, \alpha_s^{AdS}(\zeta)$$

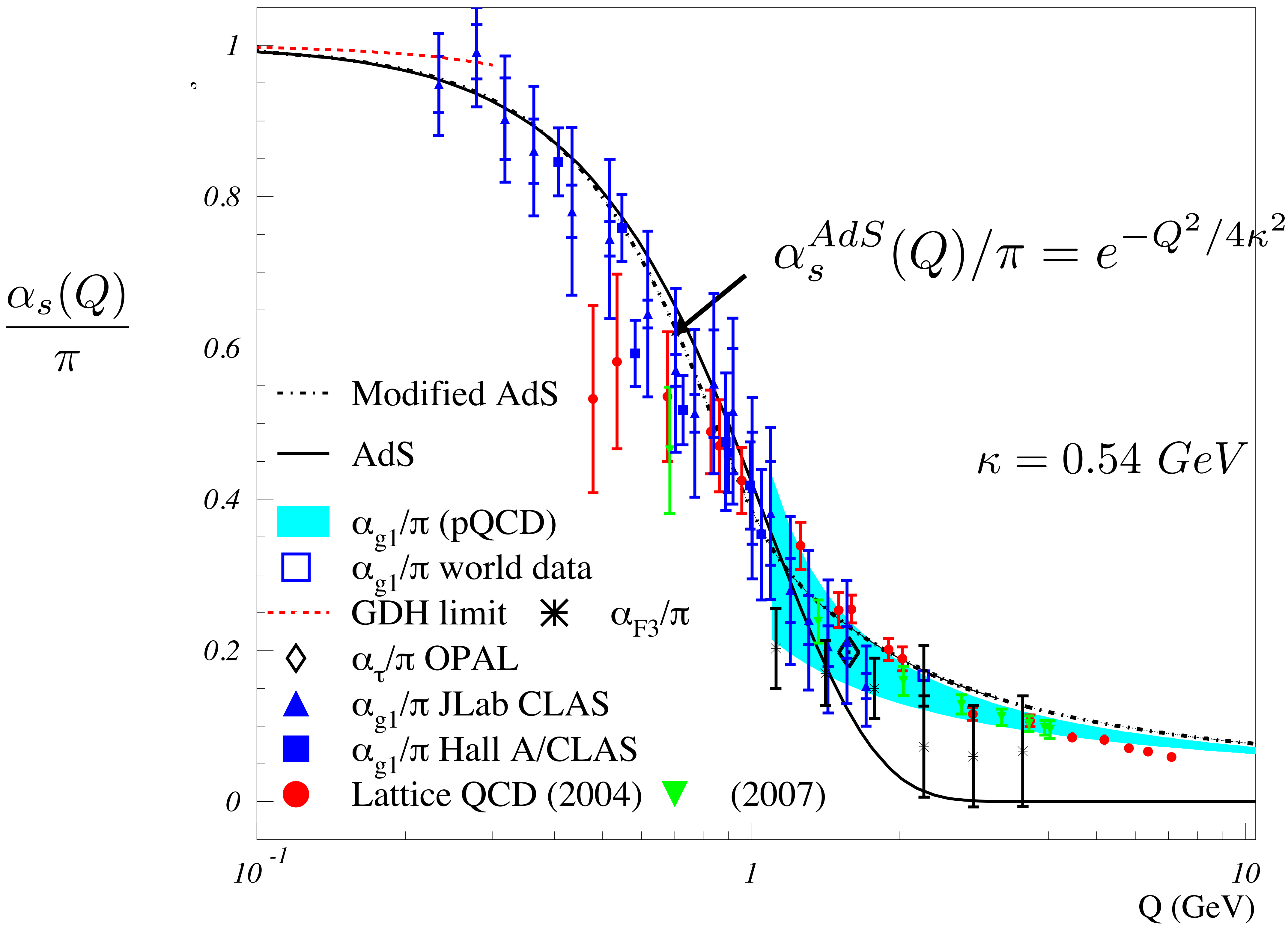
- Solution

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

where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point

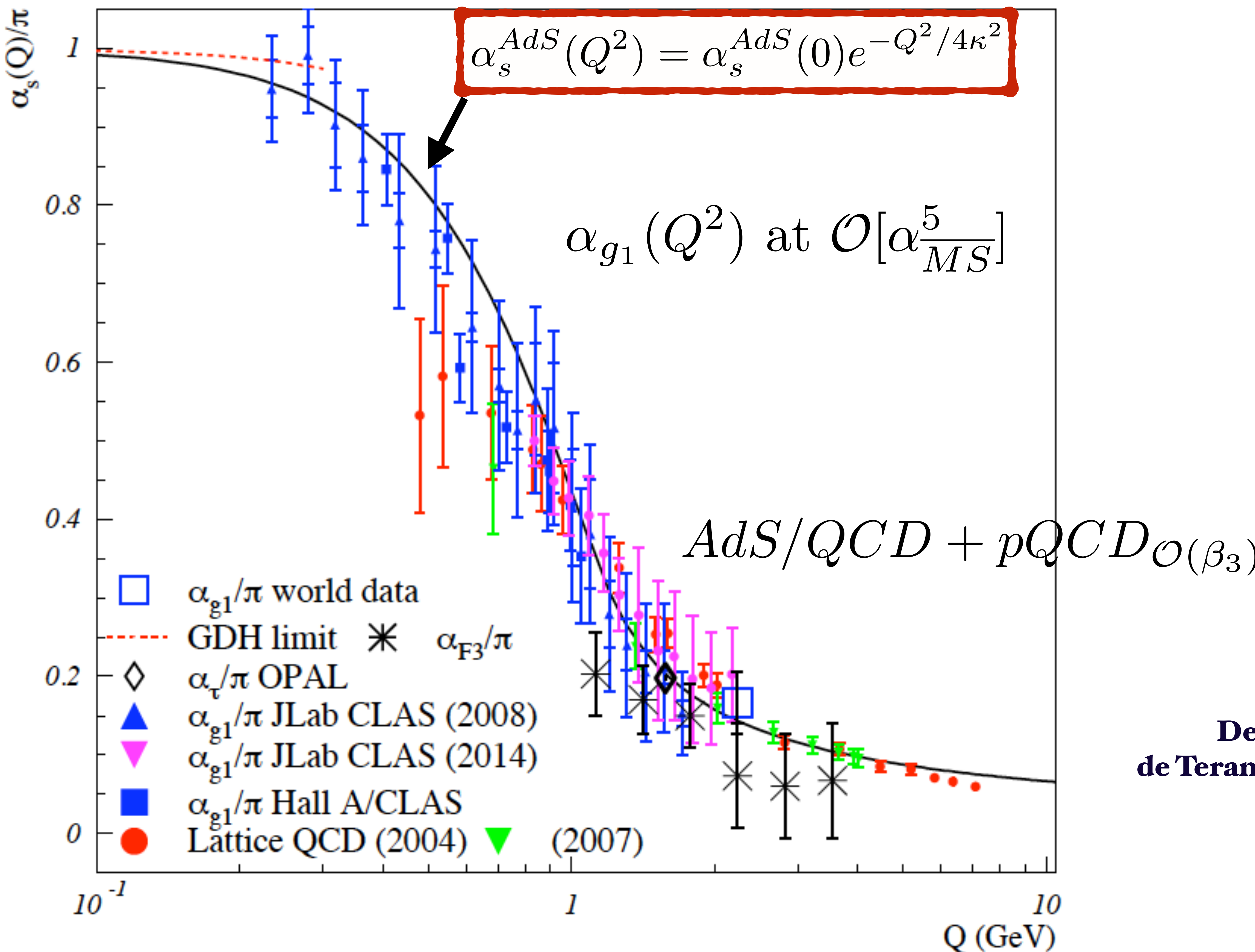


AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

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

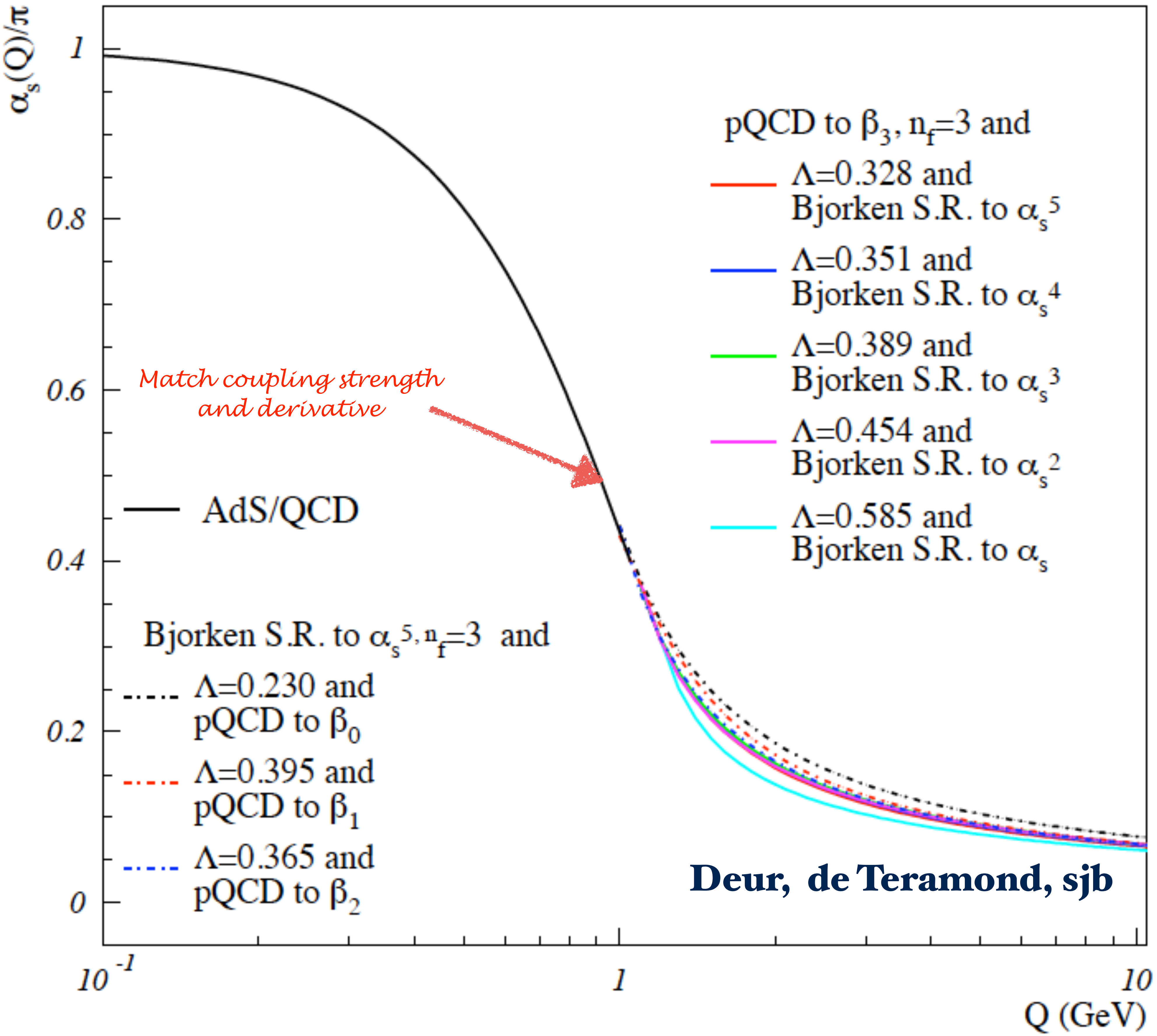
Deur, de Teramond, sjb

$$\Lambda_{\overline{MS}} = 0.5983\kappa = 0.5983\frac{m_\rho}{\sqrt{2}} = 0.4231 m_\rho = 0.328\ GeV$$

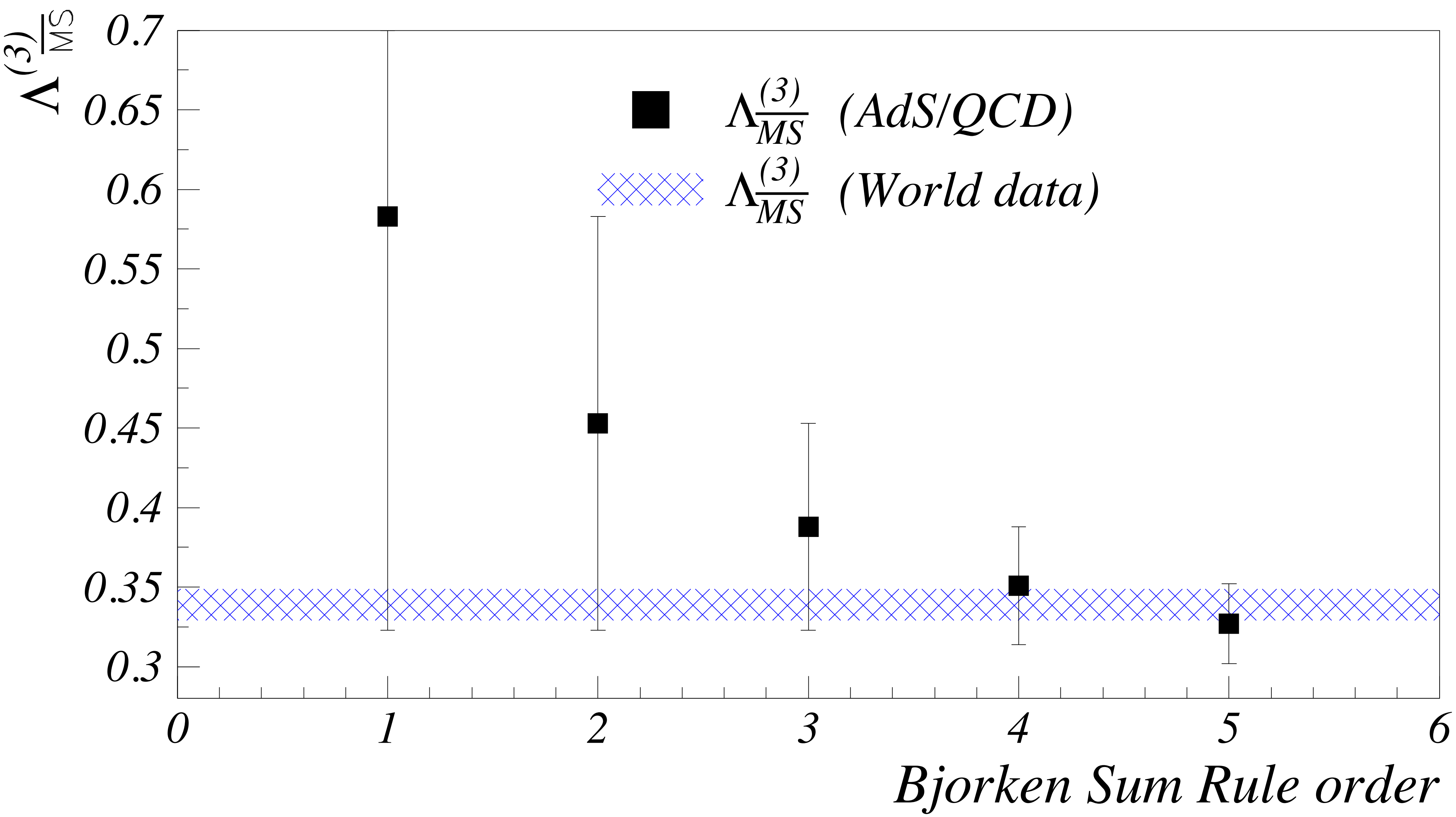


Deur, de Teramond, sjb

$$\Lambda_{\overline{MS}} = 0.5983\kappa = 0.5983\frac{m_\rho}{\sqrt{2}} = 0.4231 m_\rho = 0.328\ GeV$$



Deur, de Teramond, sjb

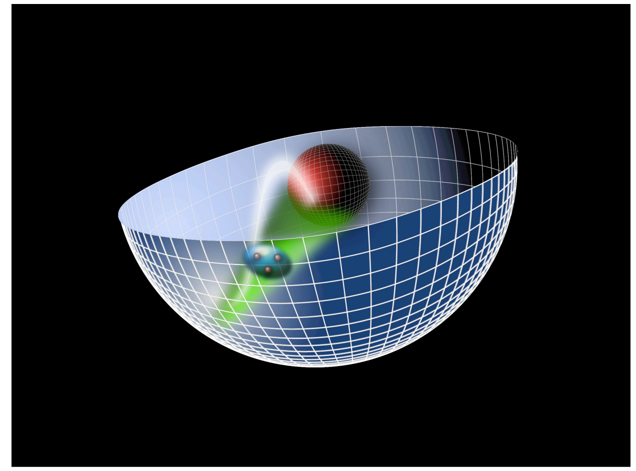


$$\Lambda_{\overline{MS}} = 0.5983\kappa = 0.5983\frac{m_\rho}{\sqrt{2}} = 0.4231 m_\rho = 0.328\ GeV$$

Connect $\Lambda_{\overline{MS}}$ to hadron masses!

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model



Light-Front Holography

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

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

Light-Front Schrödinger Equation

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

Unique Confinement Potential!

Conformal Symmetry of the action

Confinement scale:

$$\kappa \simeq 0.6\ GeV$$

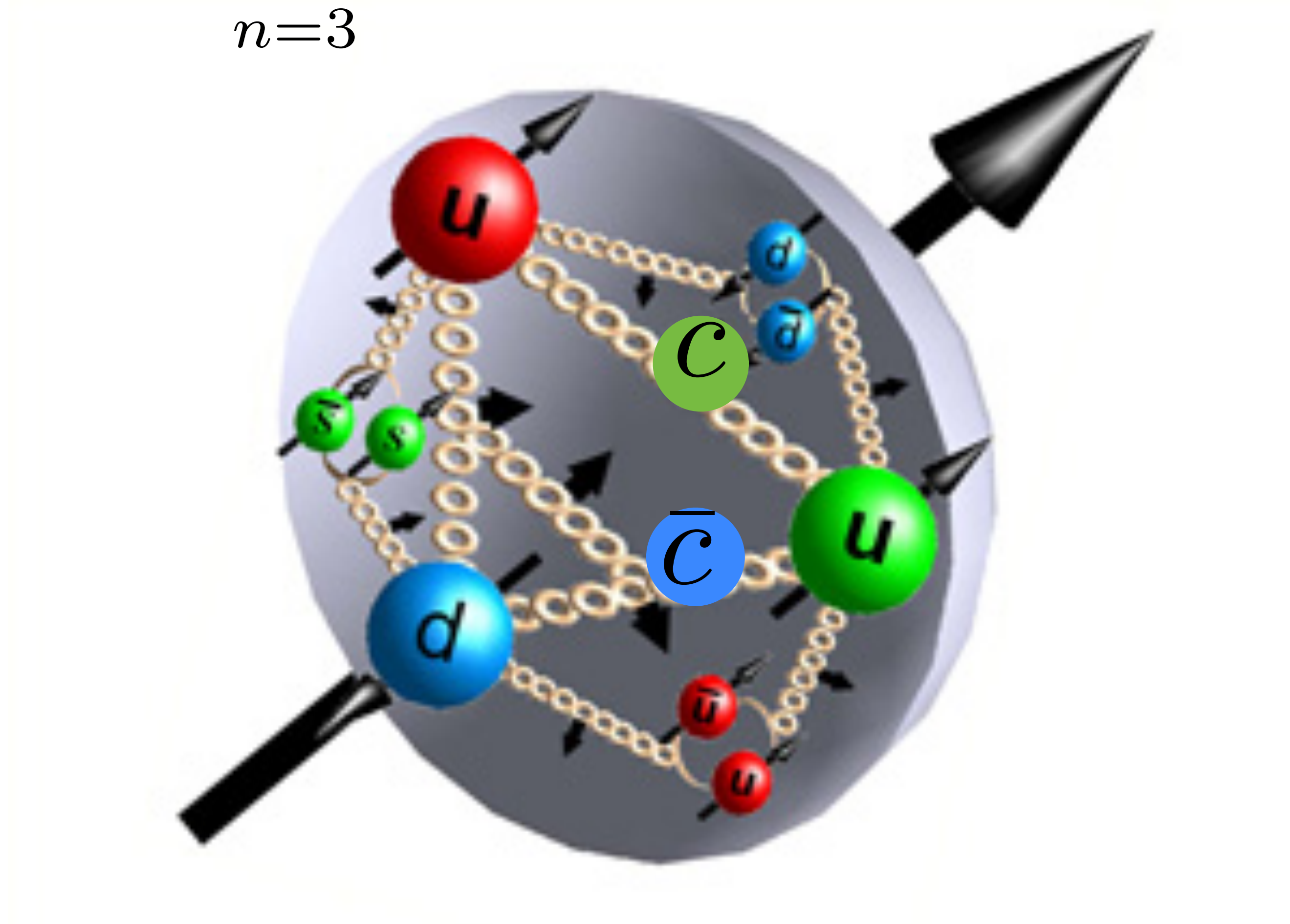
$$1/\kappa \simeq 1/3\ fm$$

- **de Alfaro, Fubini, Furlan:** *Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!*

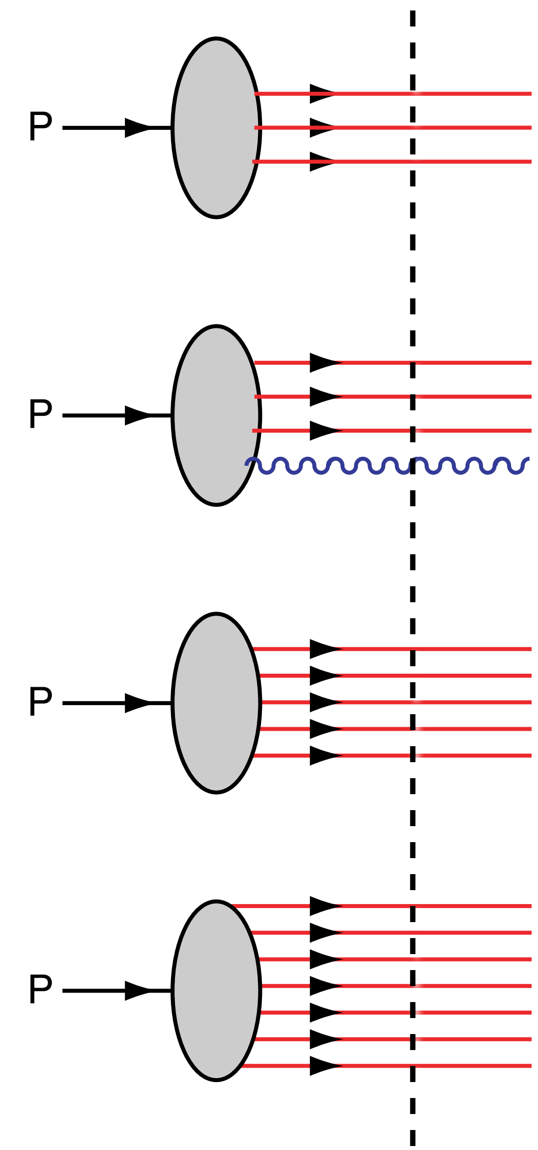
Wavefunction at fixed LF time: Arbitrarily Off-Shell in Invariant Mass

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

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

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

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

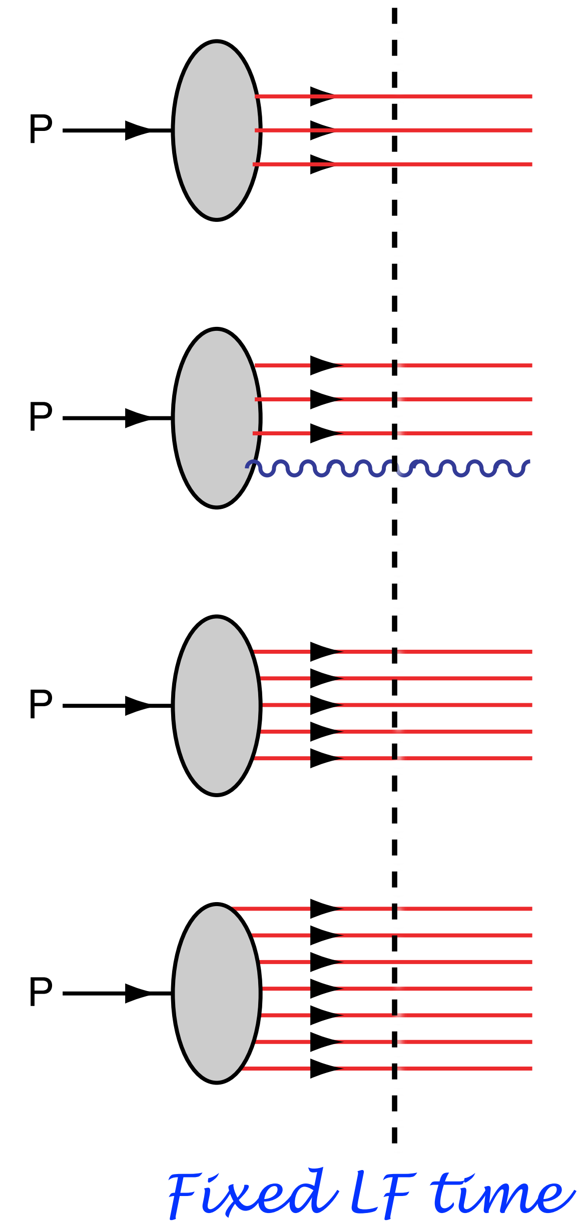
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Intrinsic heavy quarks
s(x), c(x), b(x) at high x !

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

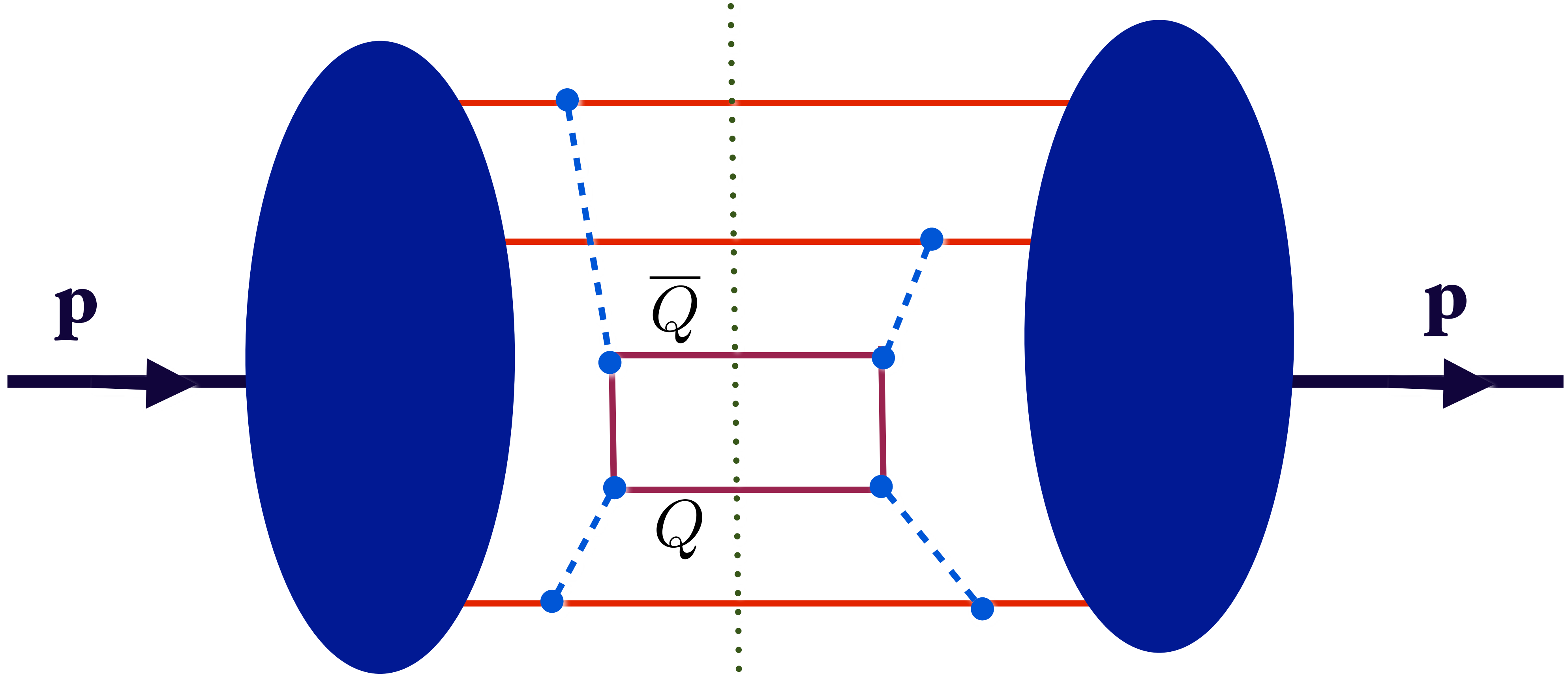
Mueller: gluon Fock states **BFKL Pomeron**

Hidden Color

Fixed LF time

Proton Self Energy
Intrinsic Heavy Quarks

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



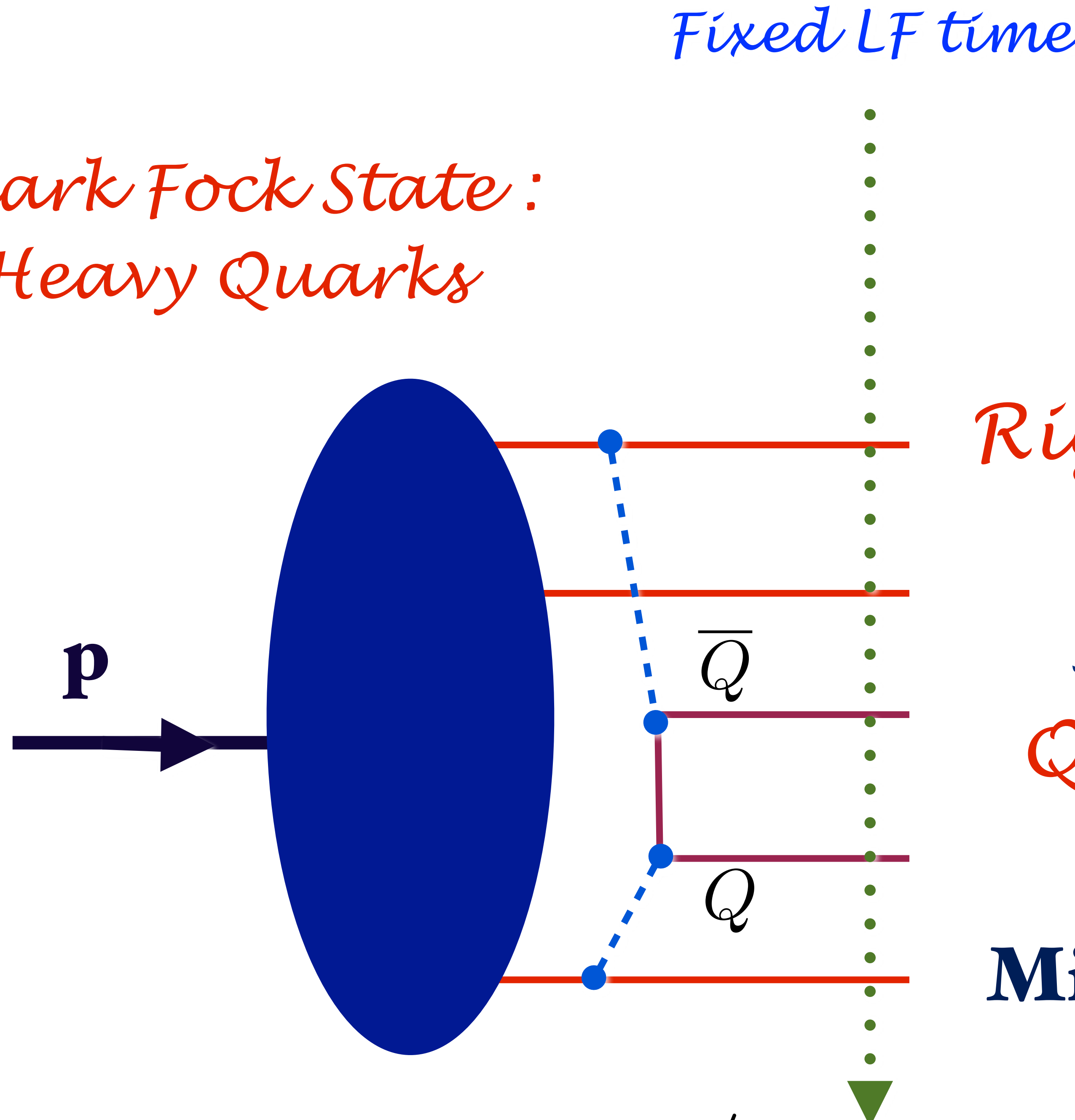
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

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

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

Proton 5-quark Fock State :

Intrinsic Heavy Quarks



Rigorous prediction of QCD

Intrinsic Heavy Quarks at high x!

Minimal off-shellness

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

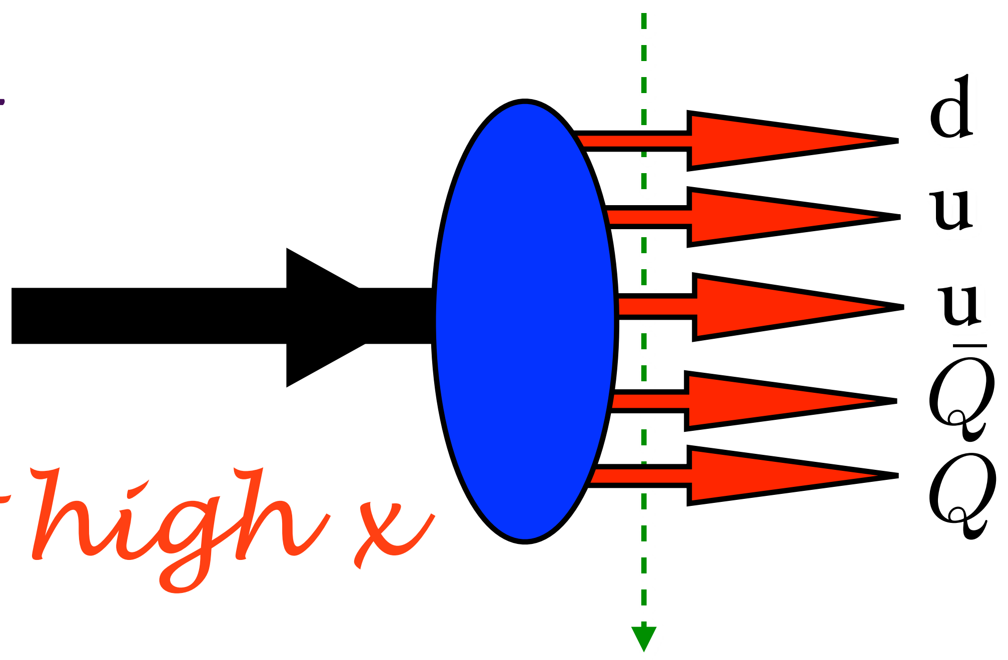
$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Collins, Ellis, Gunion, Mueller, sjb

Polyakov, et al.

Properties of Non-Perturbative Five-Quark Fock-State

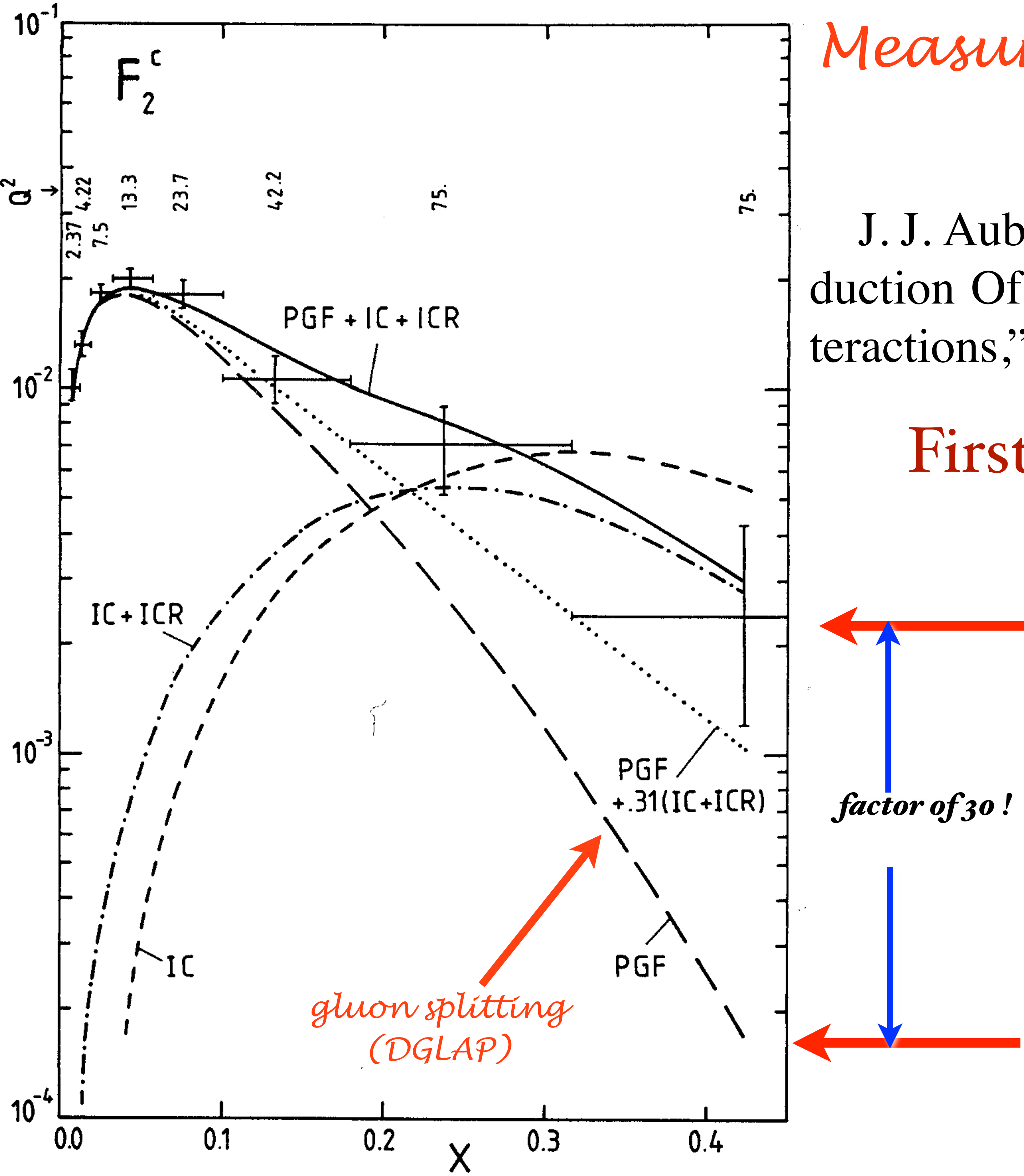
- ***Dominant configuration: same rapidity***
- ***Heavy quarks have most momentum***
- ***Correlated with proton quantum numbers***
- ***Duality with meson-baryon channels***
- ***strangeness asymmetry at $x > 0.1$***
- ***Maximally energy efficient***



Intrinsic Heavy Quarks at high x

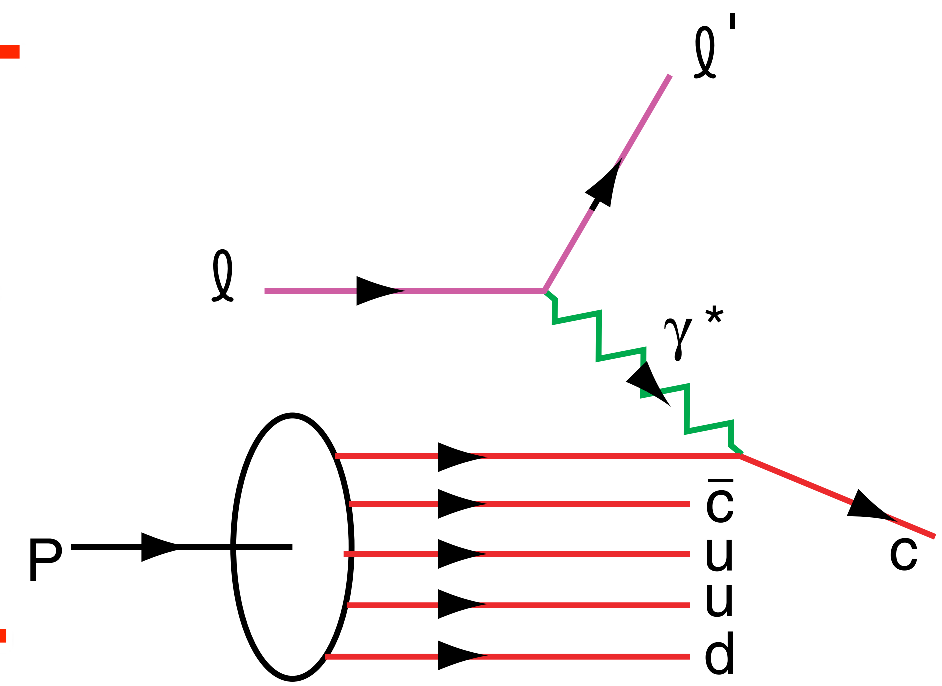
Measurement of Charm Structure Function!

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

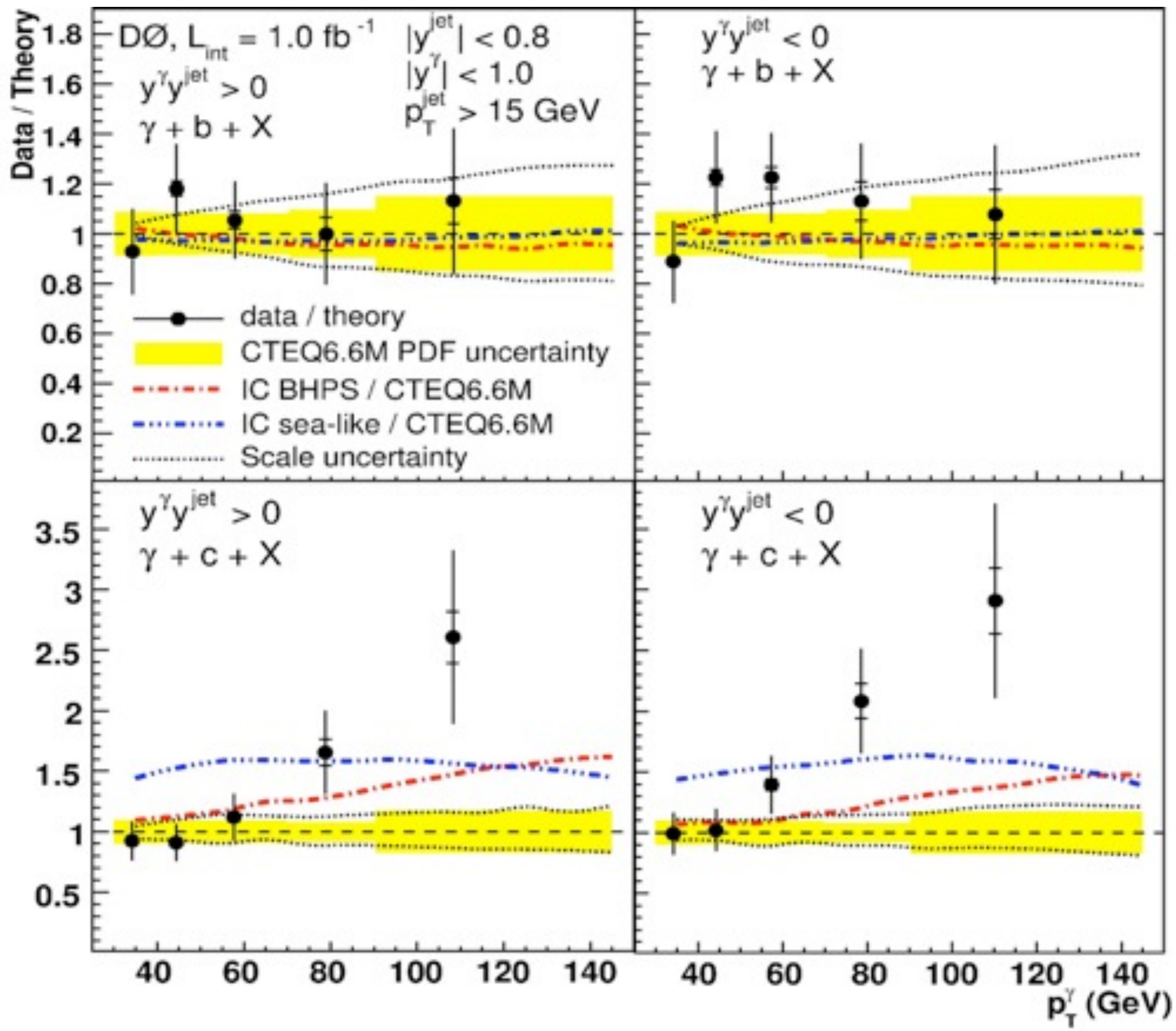
Two Components (separate evolution):

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

D0

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

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

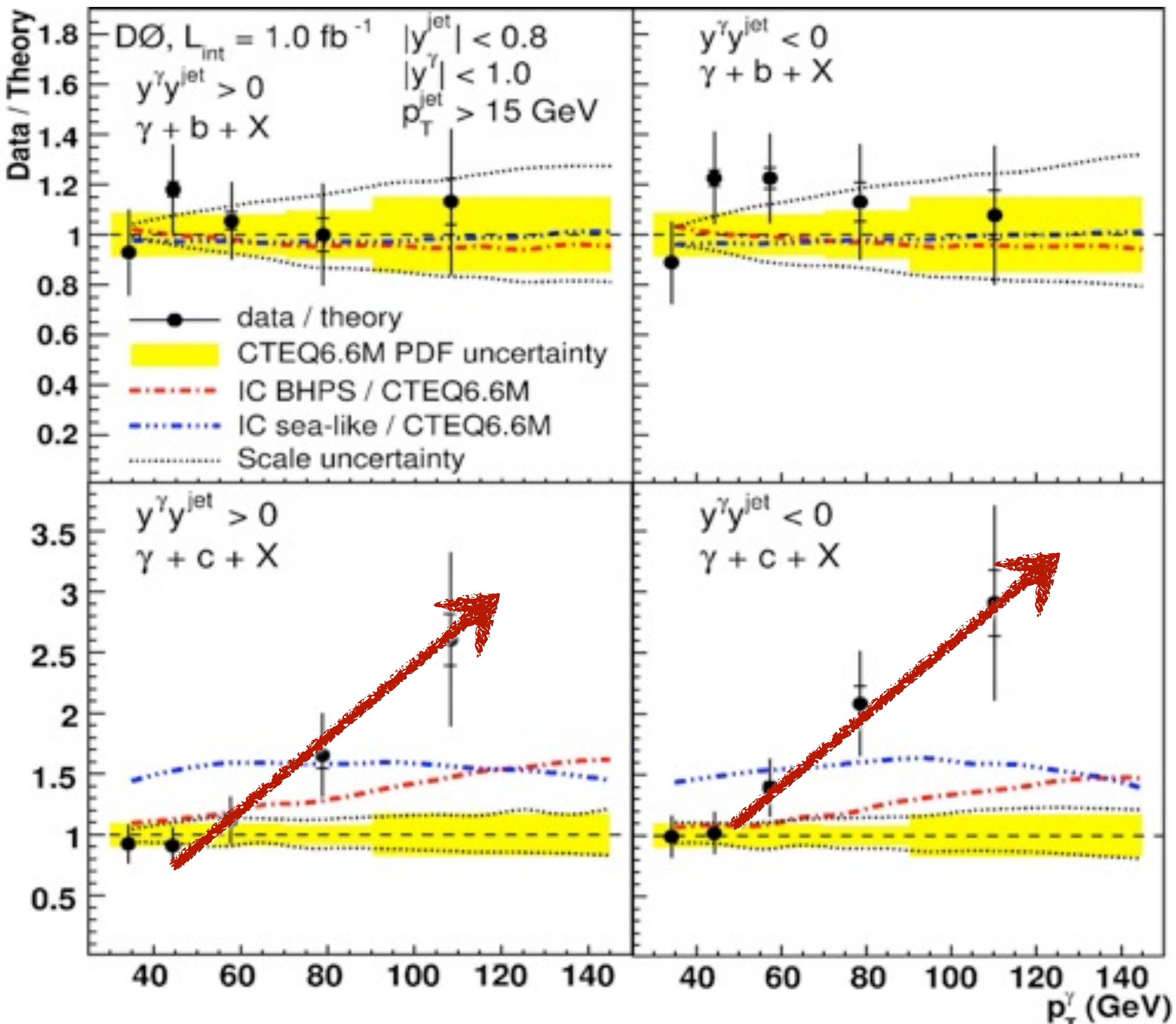


$$\frac{\Delta\sigma(\bar{p}p \rightarrow \gamma c X)}{\Delta\sigma(\bar{p}p \rightarrow \gamma b X)}$$

Ratio is insensitive to gluon PDF, scales

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

$$gc \to \gamma c$$

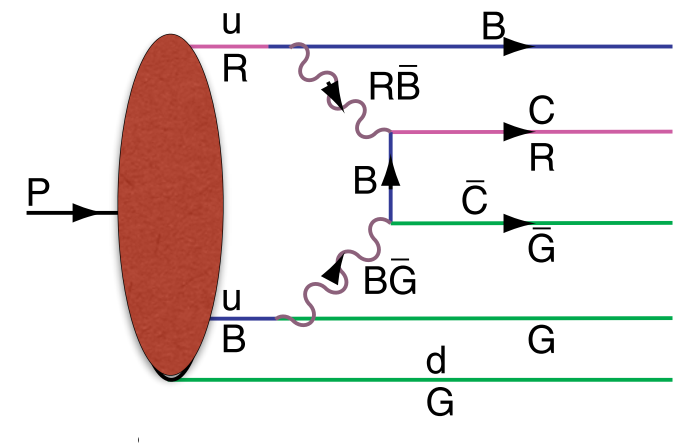
Signal for significant intrinsic charm at x > 0.1 ?

Two Components (separate evolution):

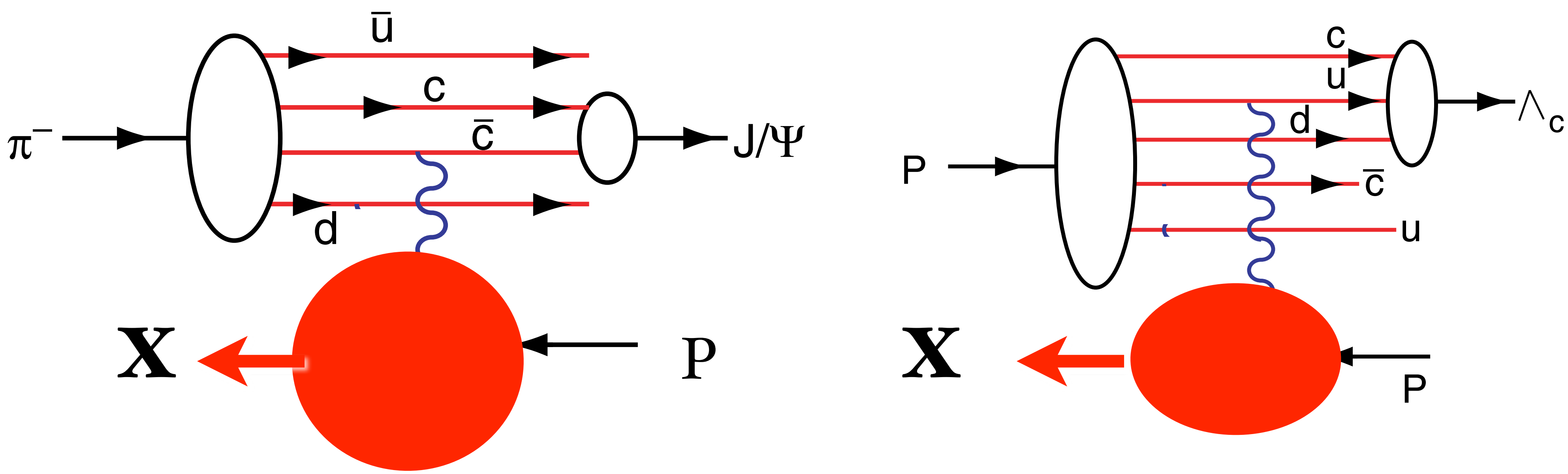
$$c(x, Q^2) = c(x, Q^2)_{\rm extrinsic} + c(x, Q^2)_{\rm intrinsic}$$

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)**



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

- 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

Excludes PYTHIA 'color drag' model!

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

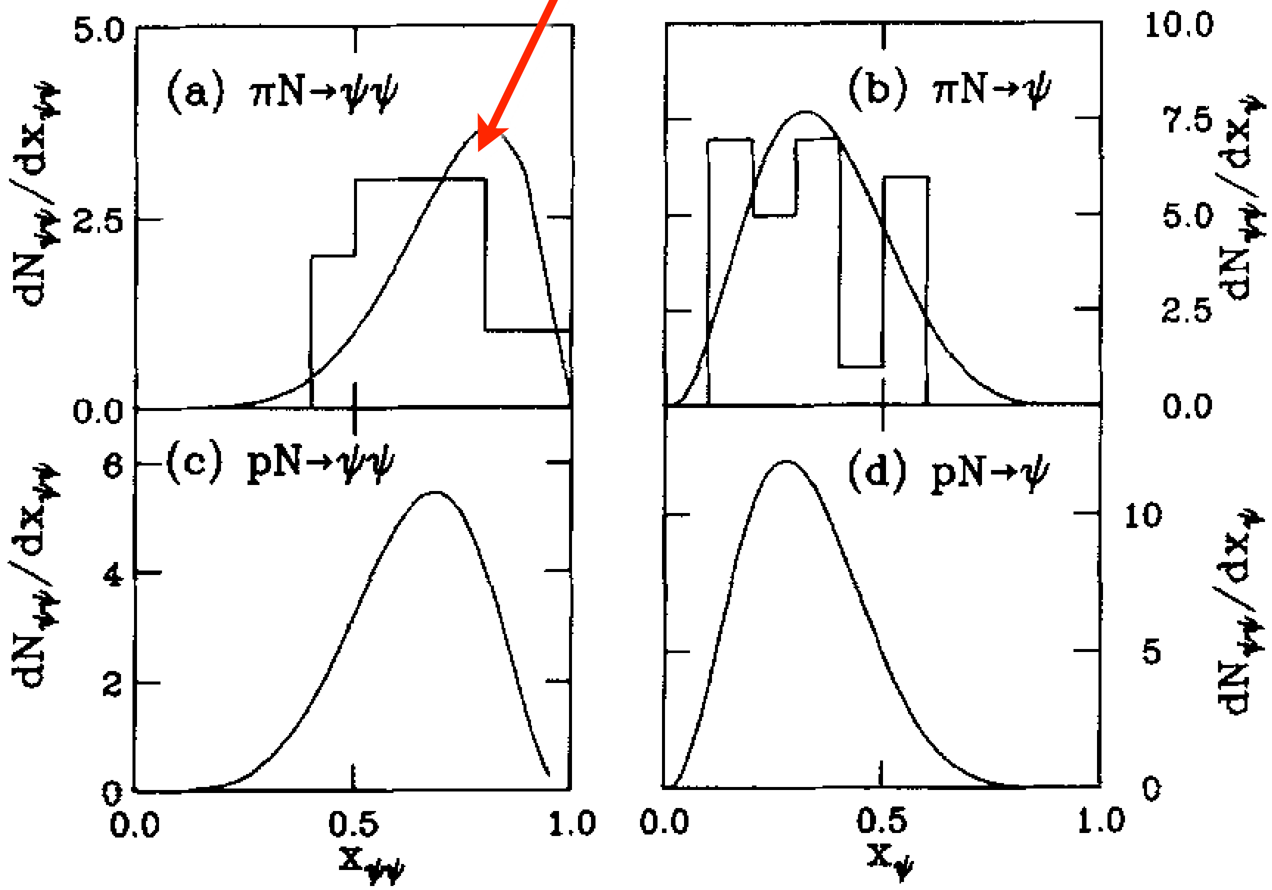


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

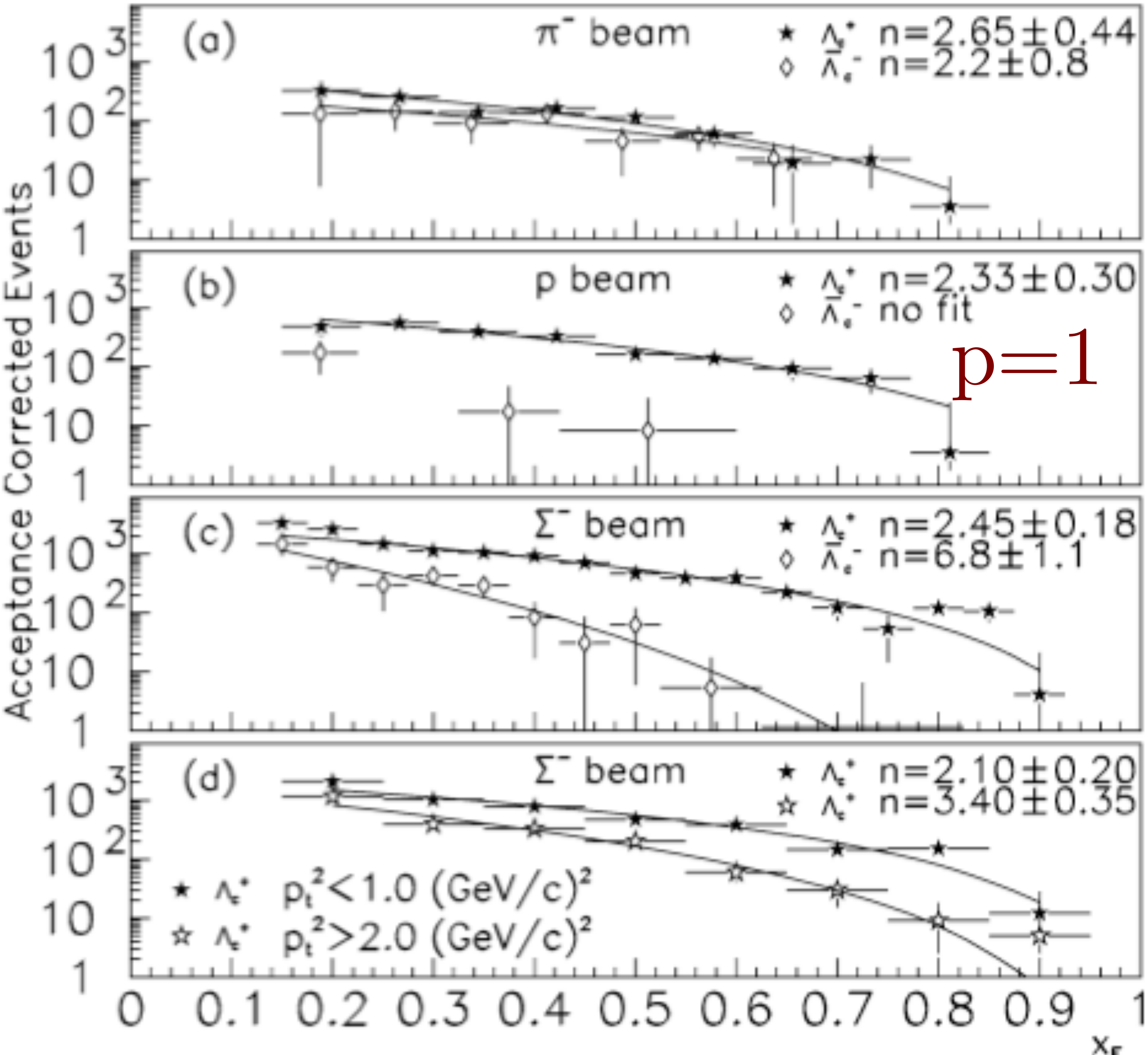
NA3 Data

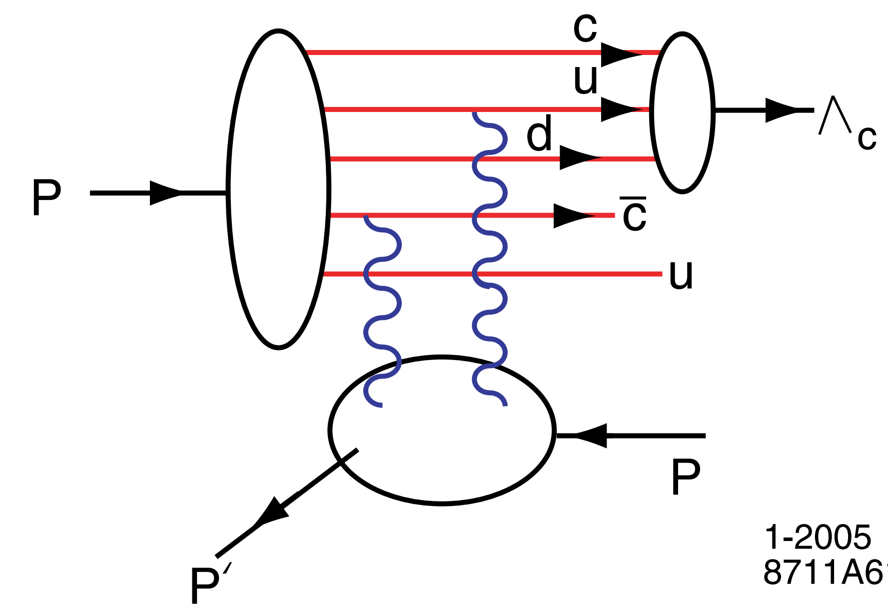
$$\pi A \rightarrow J/\psi J/\psi X$$

R. Vogt, sjb

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

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





$$p(uudc\bar{c})$$

$$\rightarrow \Lambda_c(cud)$$

$$n_s = 2$$

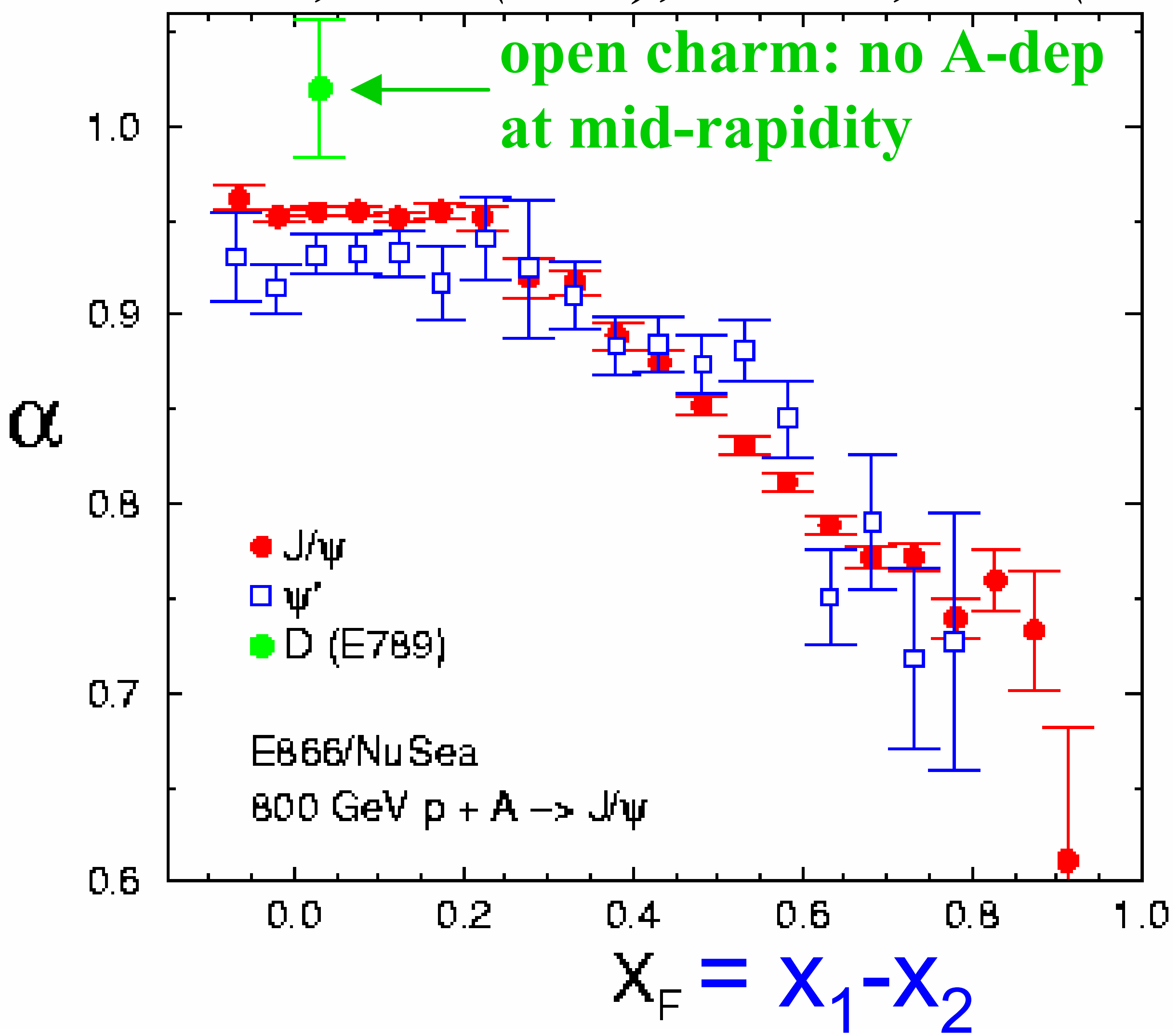
Phase space gives minimum power p

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

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

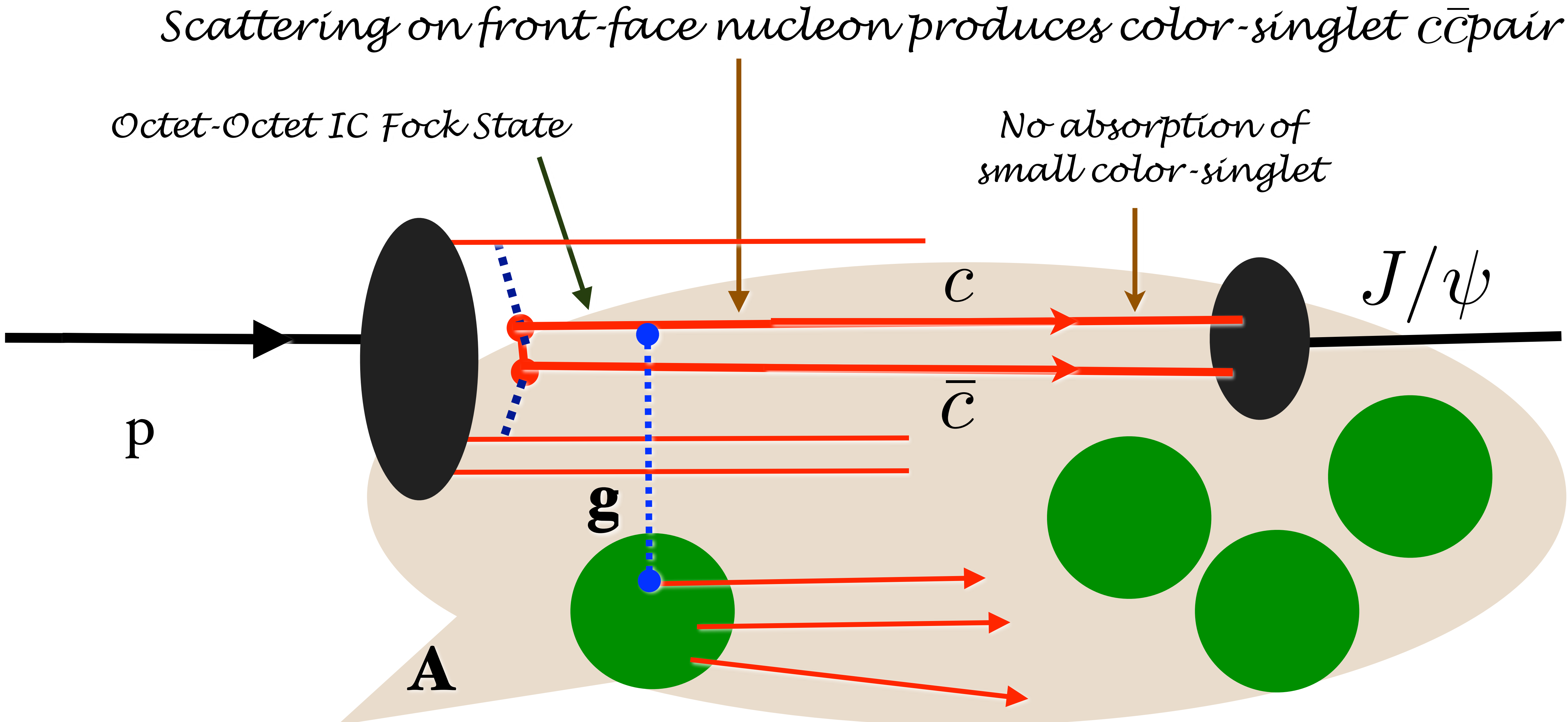
Violation of factorization in charm hadroproduction.
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.
Published in Phys.Lett.B246:217-220,1990

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

High x_F

Color-Opaque IC Fock state interacts on nuclear front surface

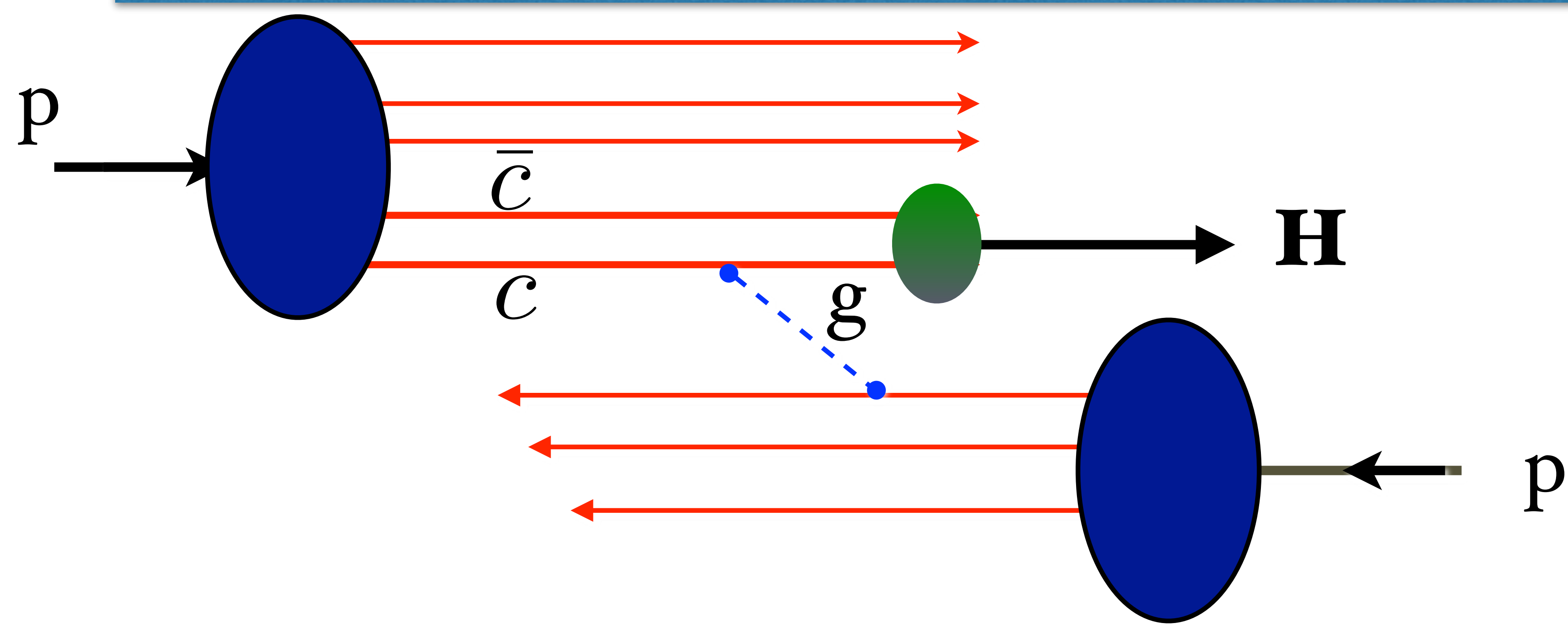
Kopeliovich, Schmidt, Soffer, sjb



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

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$$pp \to HX$$

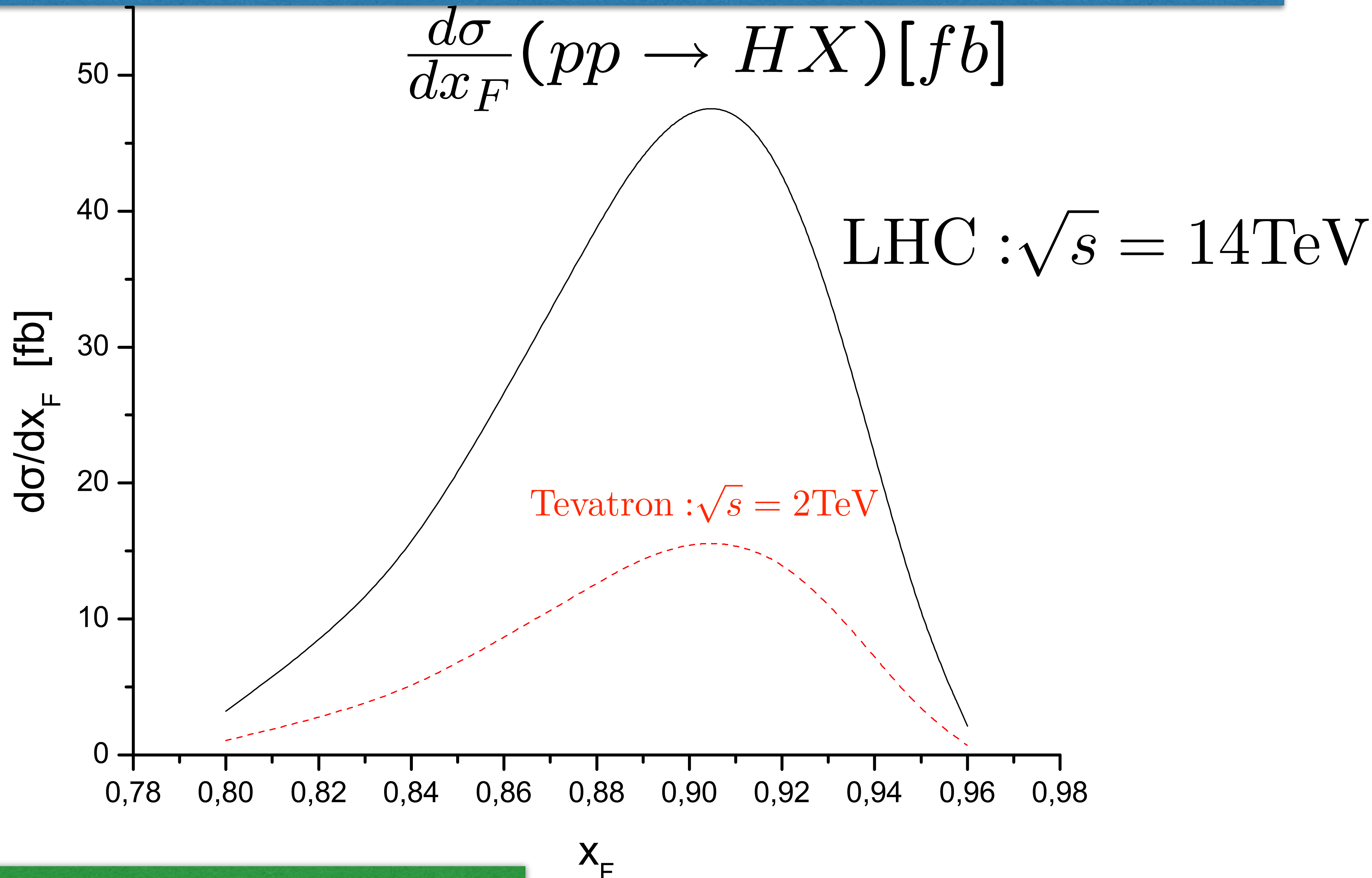
Also: intrinsic strangeness, bottom, top

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

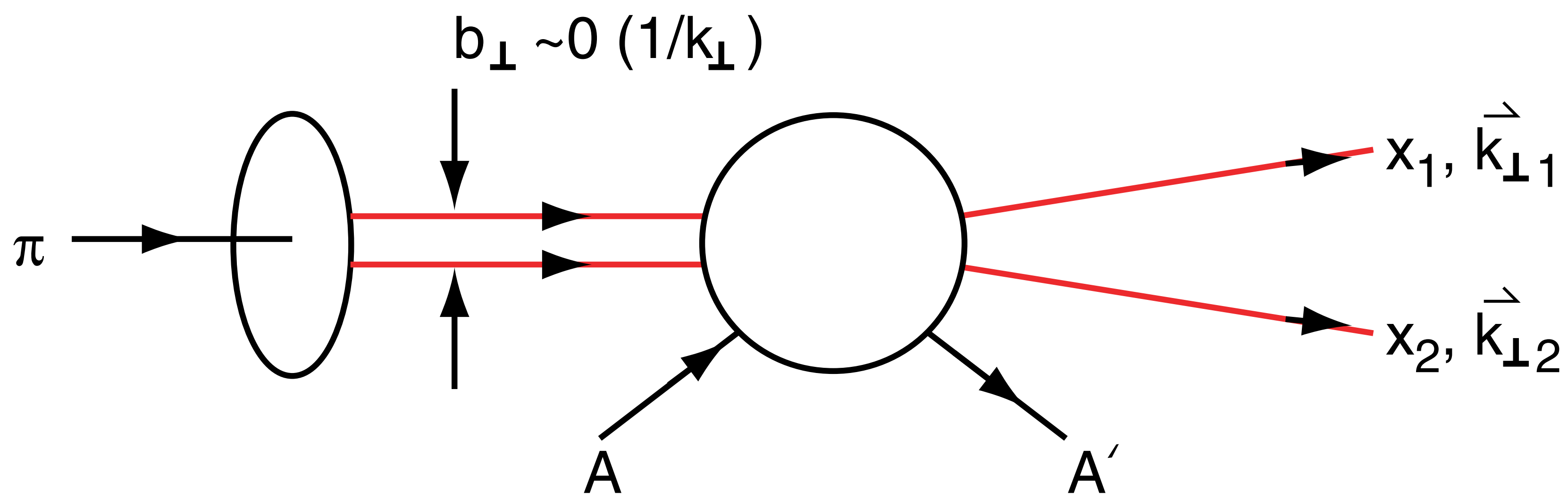
Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Charm at Threshold

- *Intrinsic charm Fock state puts 80% of the proton momentum into the electroproduction process*
- *1/velocity enhancement from FSI*
- *CLEO data for quarkonium production at threshold*
- *Krisch effect shows B=2 resonance*
- *all particles produced at small relative rapidity-- resonance production*
- *Many exotic hidden and open charm resonances will be produced at PANDA (15 GeV) and JLab (11-12 GeV)*

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



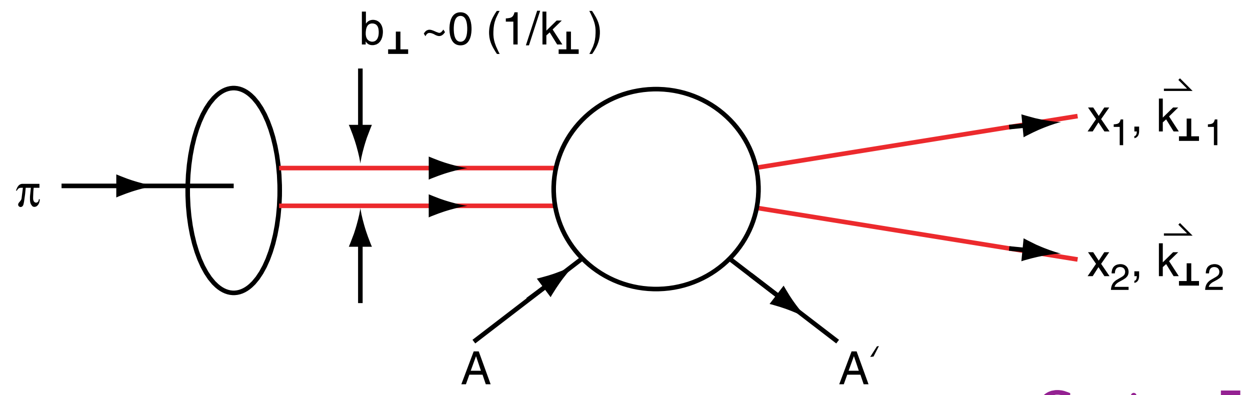
$$M \propto \frac{\partial^2}{\partial^2 k_\perp}\psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

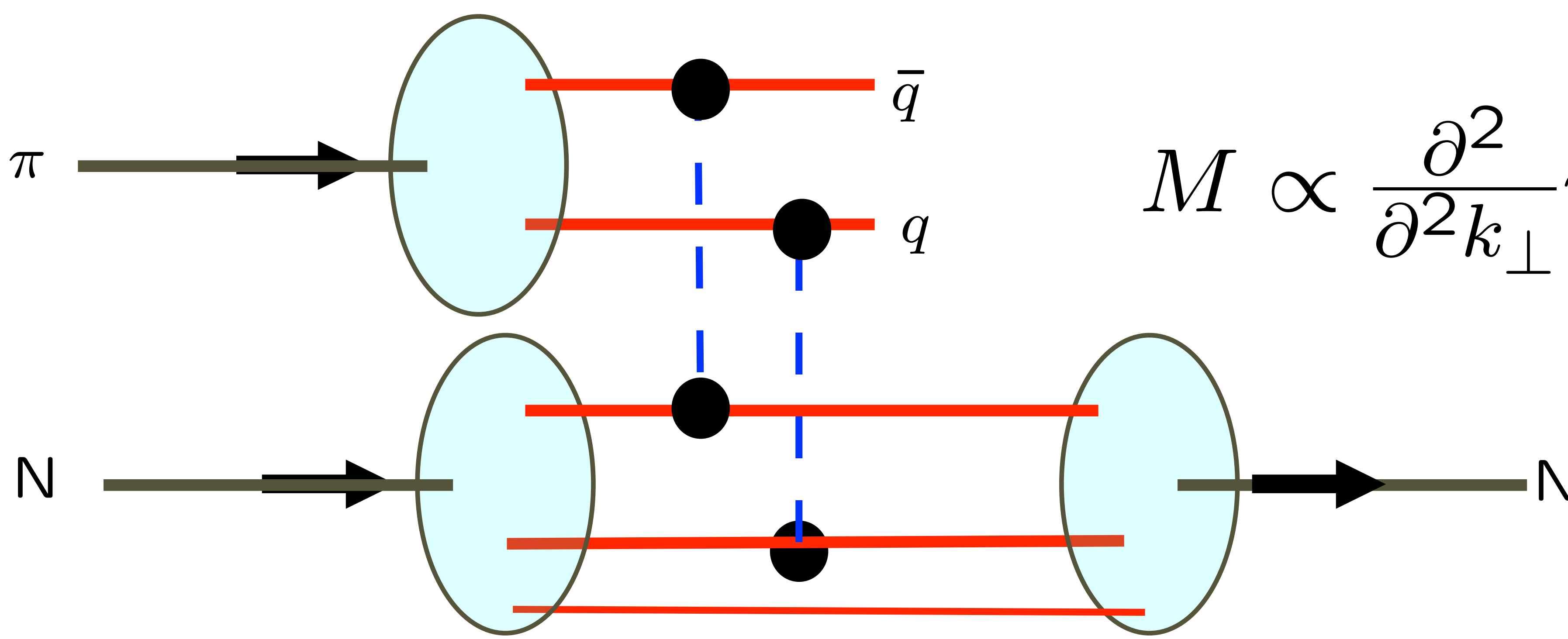
Nucleus left Intact!

E791 FNAL Diffractive DiJet



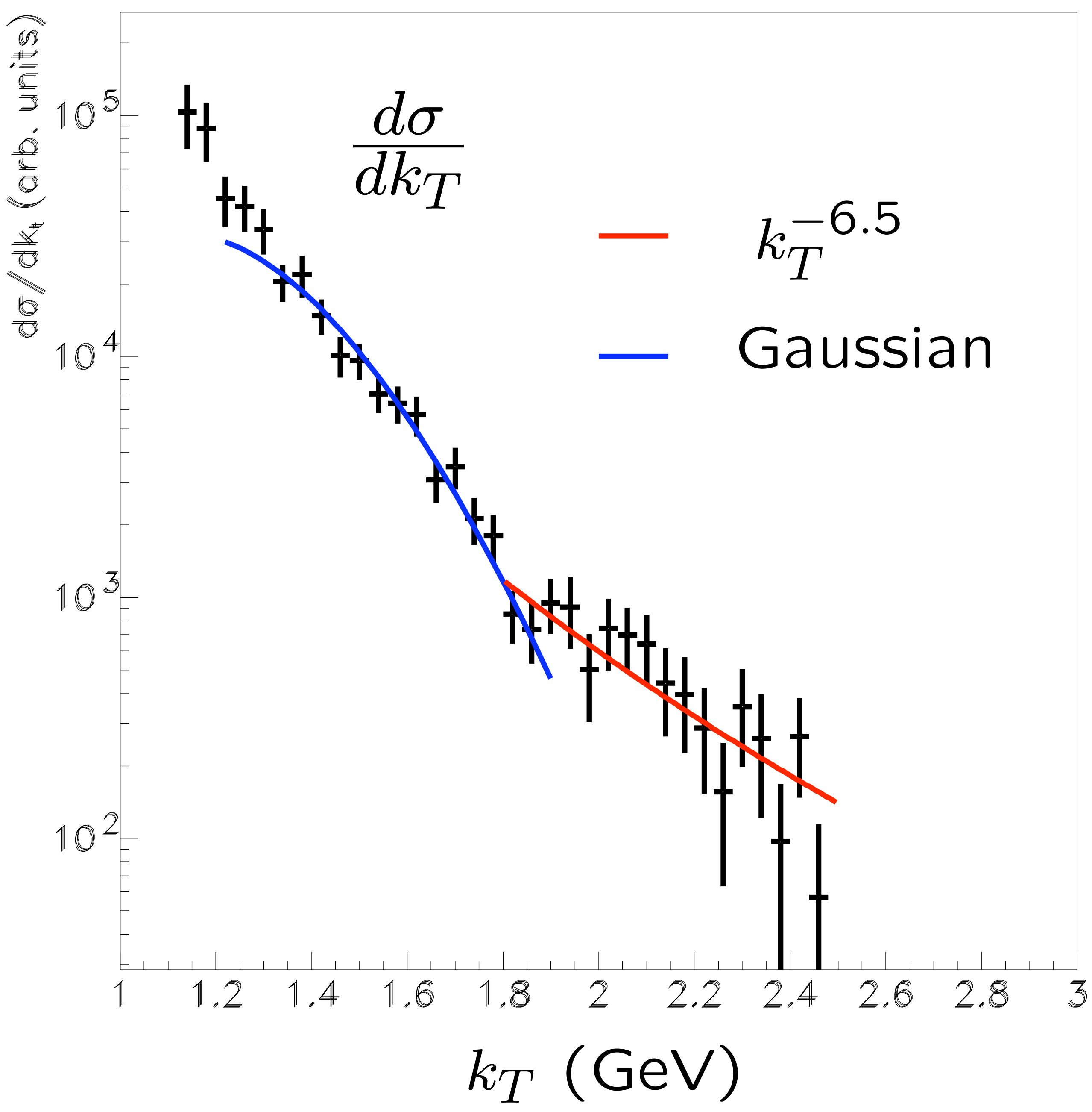
Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

Two-gluon exchange measures the second derivative of the pion light-front wavefunction



$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

E791 Diffractive Di-Jet transverse momentum distribution



Two Components

High Transverse momentum dependence consistent with PQCD, ERBL Evolution

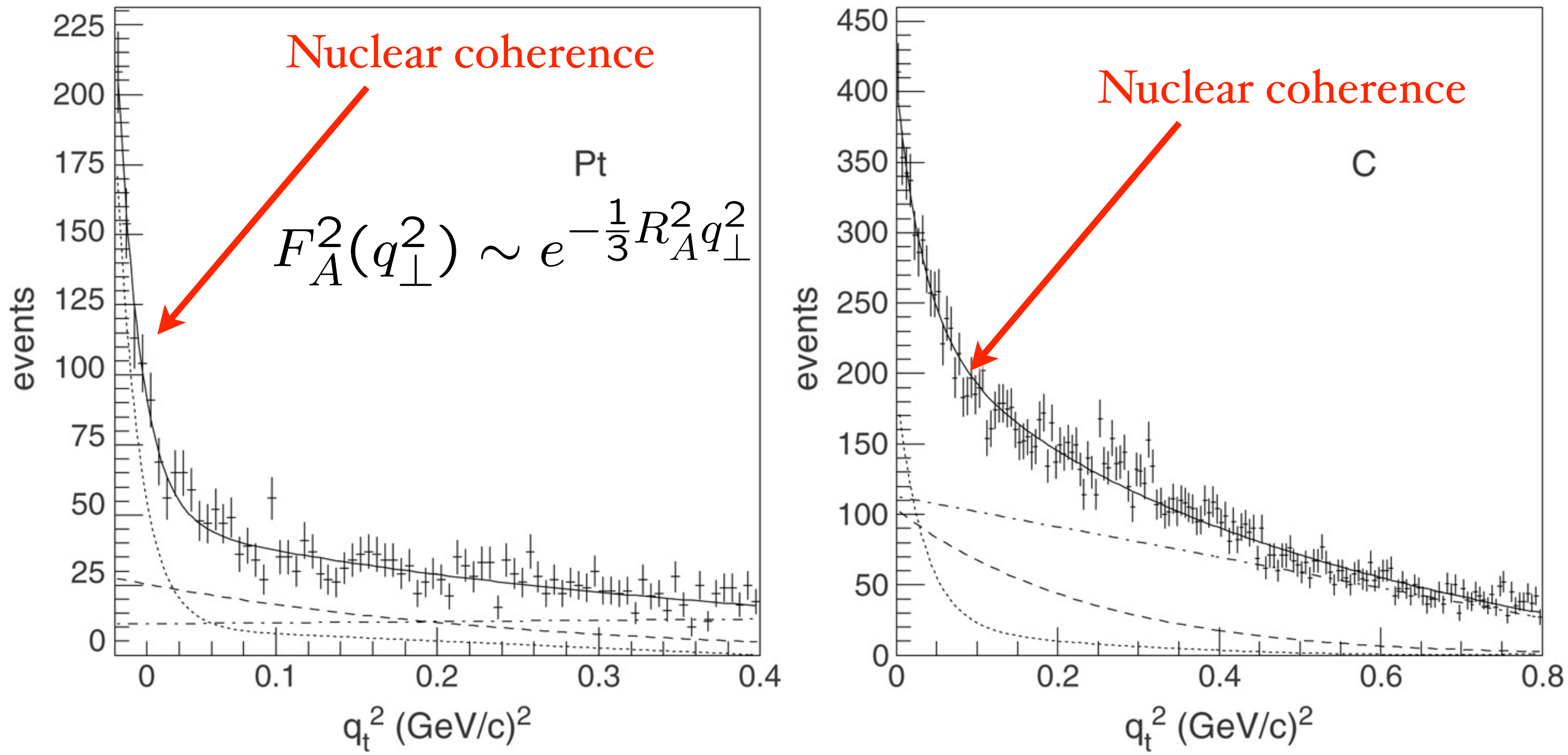
Gaussian component similar to AdS/CFT HO LFWF

- **Fully coherent interactions between pion and nucleons.**
- **Emerging Di-Jets do not interact with nucleus.**

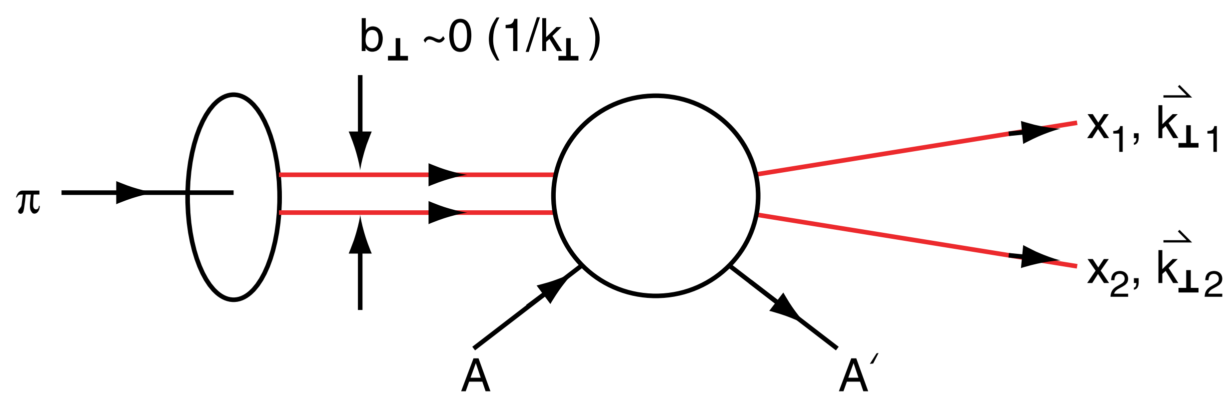
$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0$$

$$\sigma \propto A^{4/3}$$

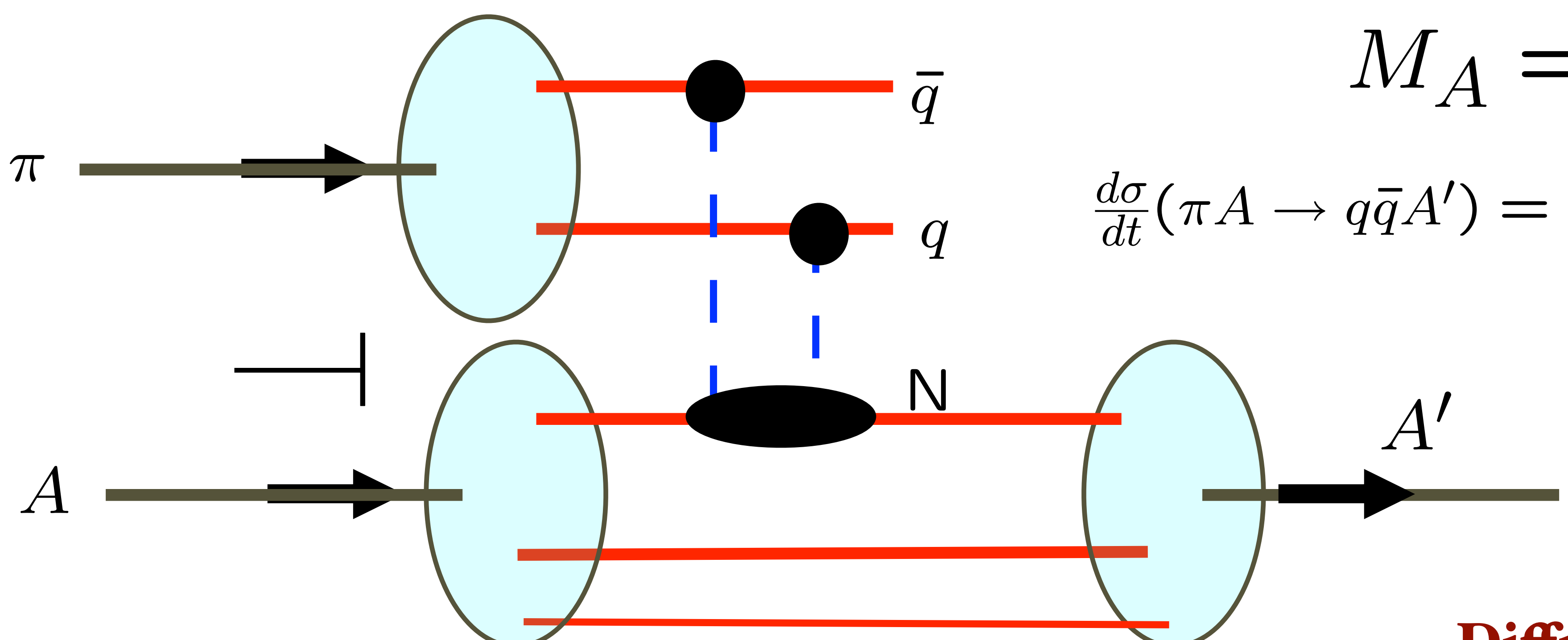


Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller Strikman

Small color-dipole moment pion not absorbed;
interacts with each nucleon coherently
QCD COLOR Transparency



$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F^2_A(t)$$

Target left intact

Diffraction, Rapidity gap

Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	1.64 +0.06 -0.12	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

Ashery E791

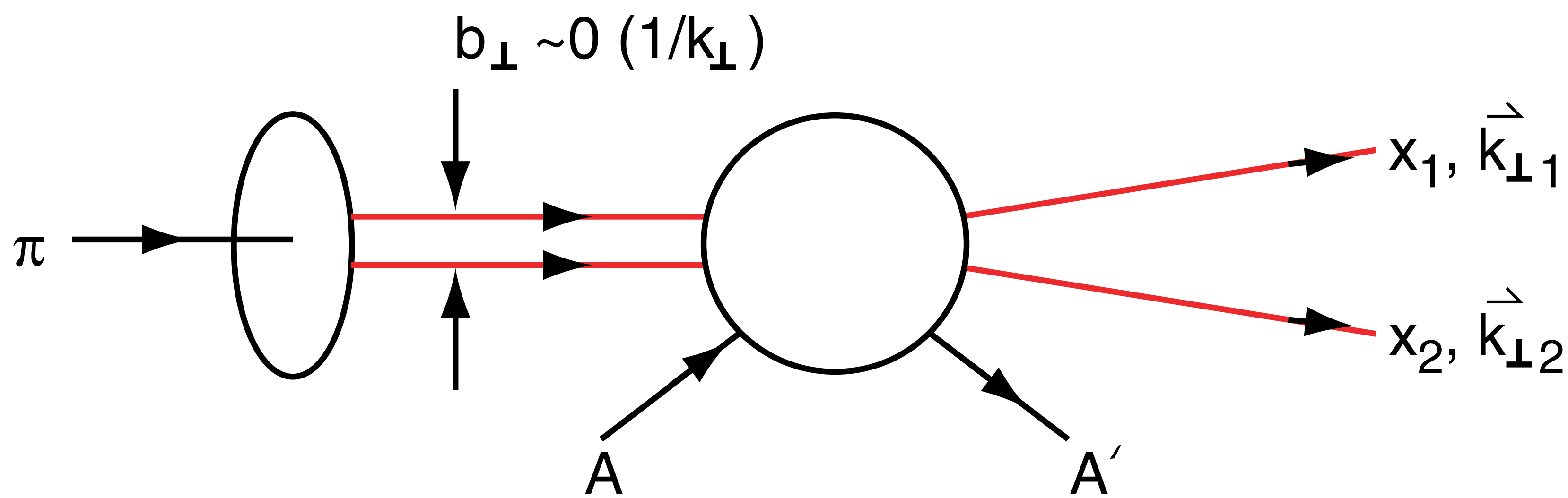
α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus
Nucleus left Intact!

FAIR: Diffractive Dissociation of Antiproton into Quark Jets

F. Wilczek (XXIV Quark Matter 2014)

Quarks (and Glue) at
Frontiers of Knowledge

Challenges, Opportunities

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

Emergent Phenomena

Schizophrenic Protons?

We have two very different pictures of protons, in the lab frame (quark model) and in the infinite momentum frame (parton model). Each is very successful.

How does one proton manage to become the other? Are there intermediate pictures?

Stony Brook University

Abhay Deshpande

F. Wilczek (XXIV Quark Matter 2014)

We have two very different pictures of protons, in the lab frame (quark model) and in the infinite momentum frame (parton model). Each is very successful.

How does one proton manage to become the other? Are there intermediate pictures?

Answer: Light-Front Wavefunctions are independent of the observer's Lorentz frame

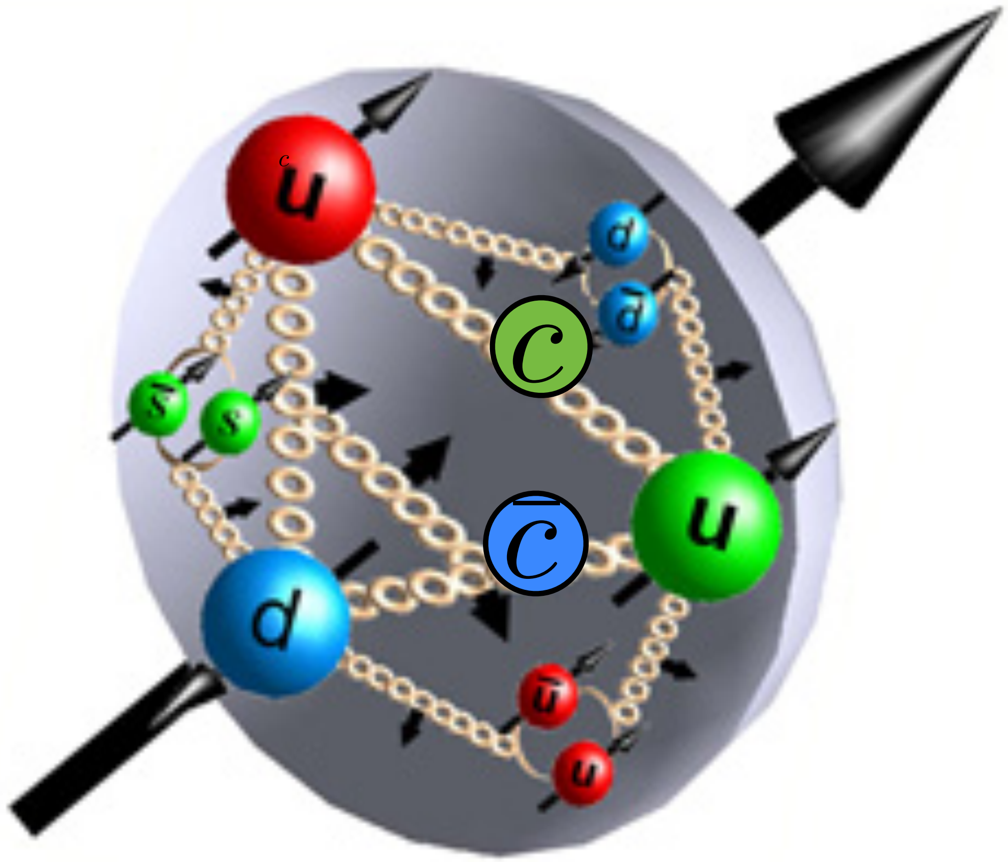
QCD Myths

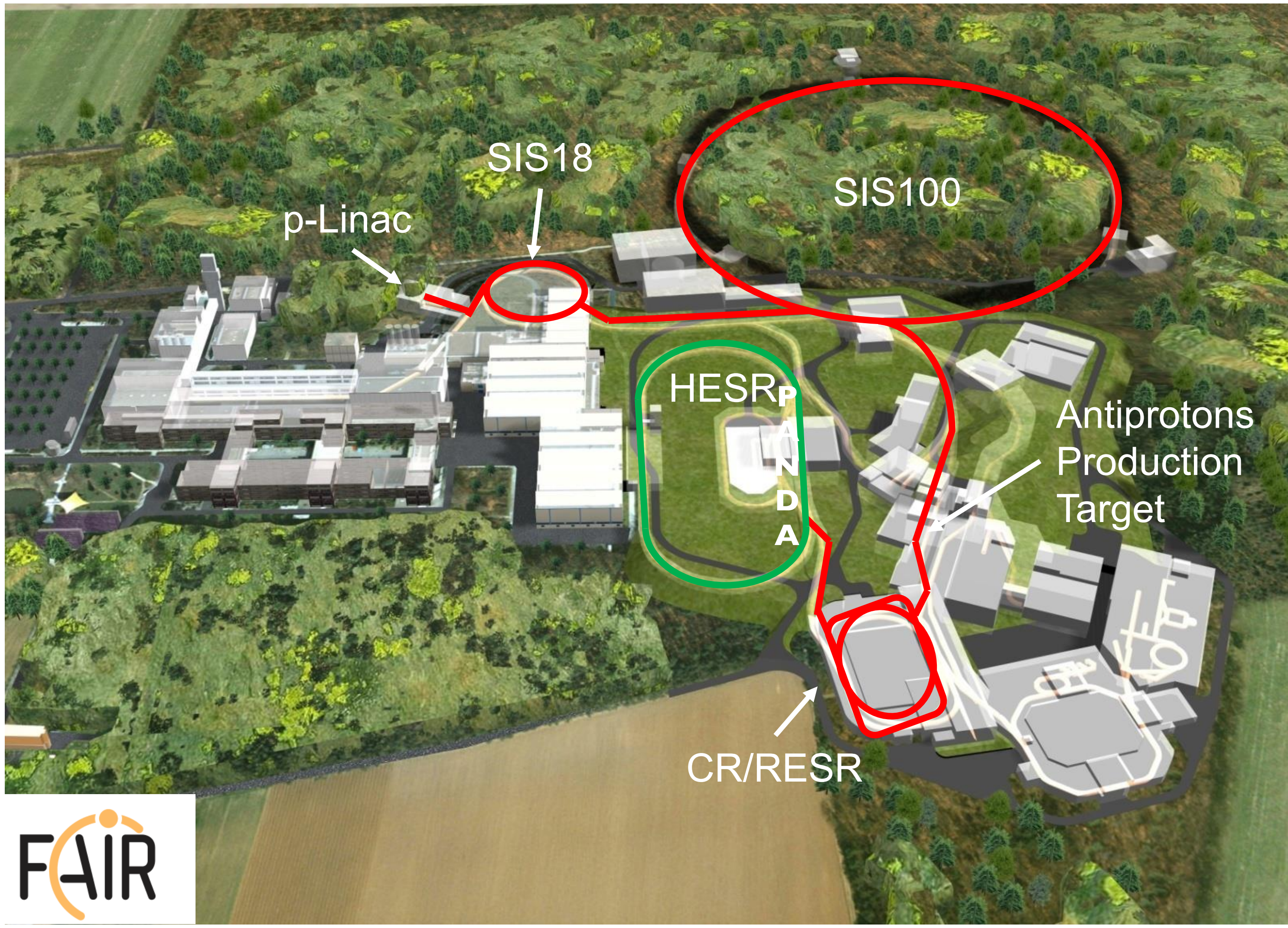
- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- Heavy quarks only from gluon splitting
- Renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- QCD gives 10^{42} to the cosmological constant
- Dynamics always from gluon exchange; Zweig Rule
- Higher Twist always nonleading
- Factorization Theorems Rigorous

Novel Tests of QCD at GSI-FAIR

- Drell-Yan: Breakdown of pQCD Factorization
- Violation of Lam-Tung Relation
- Double Drell-Yan Reactions $\bar{p}p \to \mu^+\mu^-\mu^+\mu^- X$
- Higher Twist Effects at High x_F
- Non-Universal Anti-Shadowing
- Diffractive Drell-Yan Reactions $\bar{p}p \to \mu^+\mu^- p$
- Exclusive Processes $\bar{p}p \to H_A + H_B$
- Crucial tests of fundamental issues in hadron physics

Novel Tests of QCD at FAIR





International Conference on Science and Technology for FAIR in Europe October 13-17, 2014

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

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