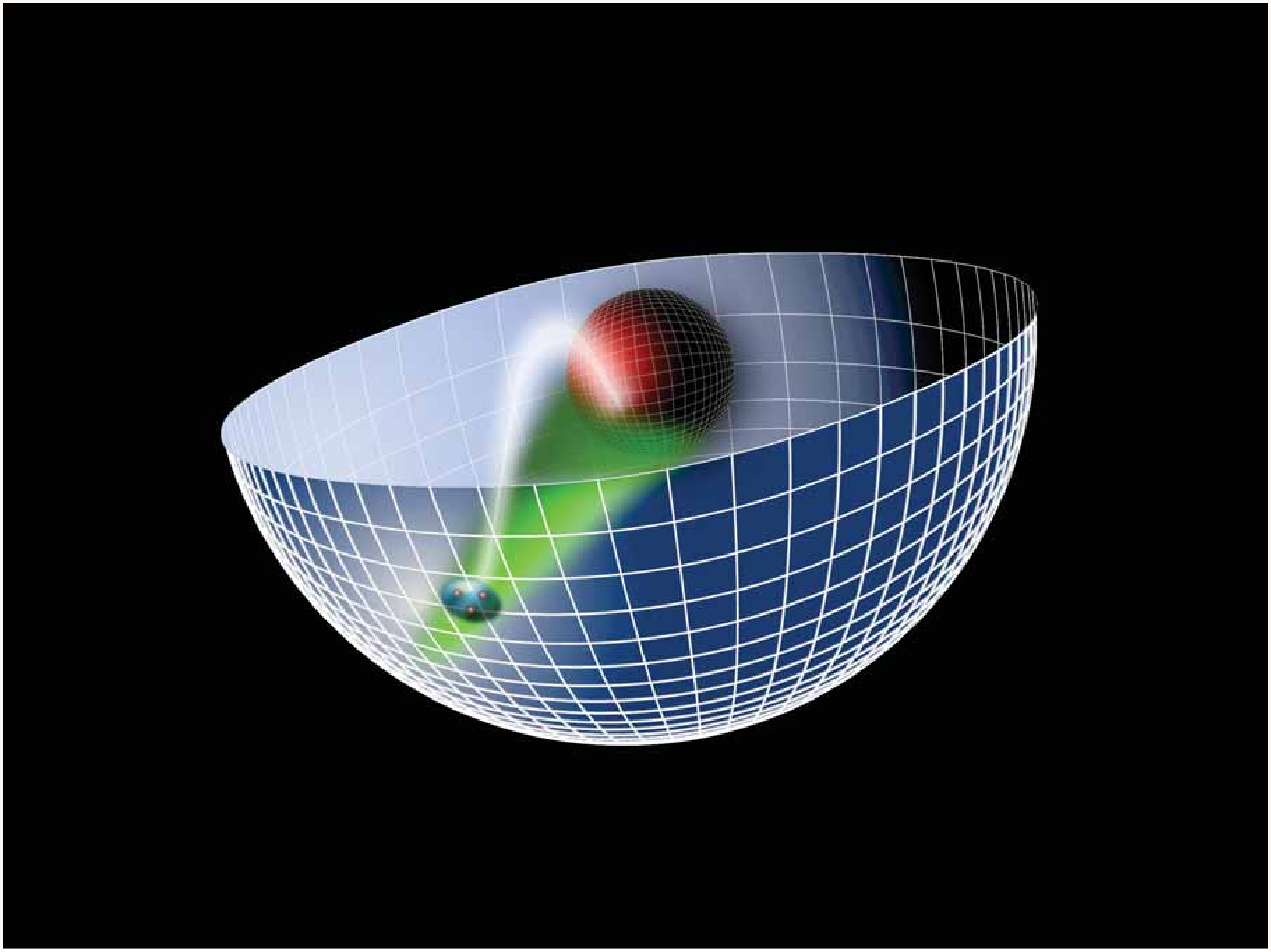
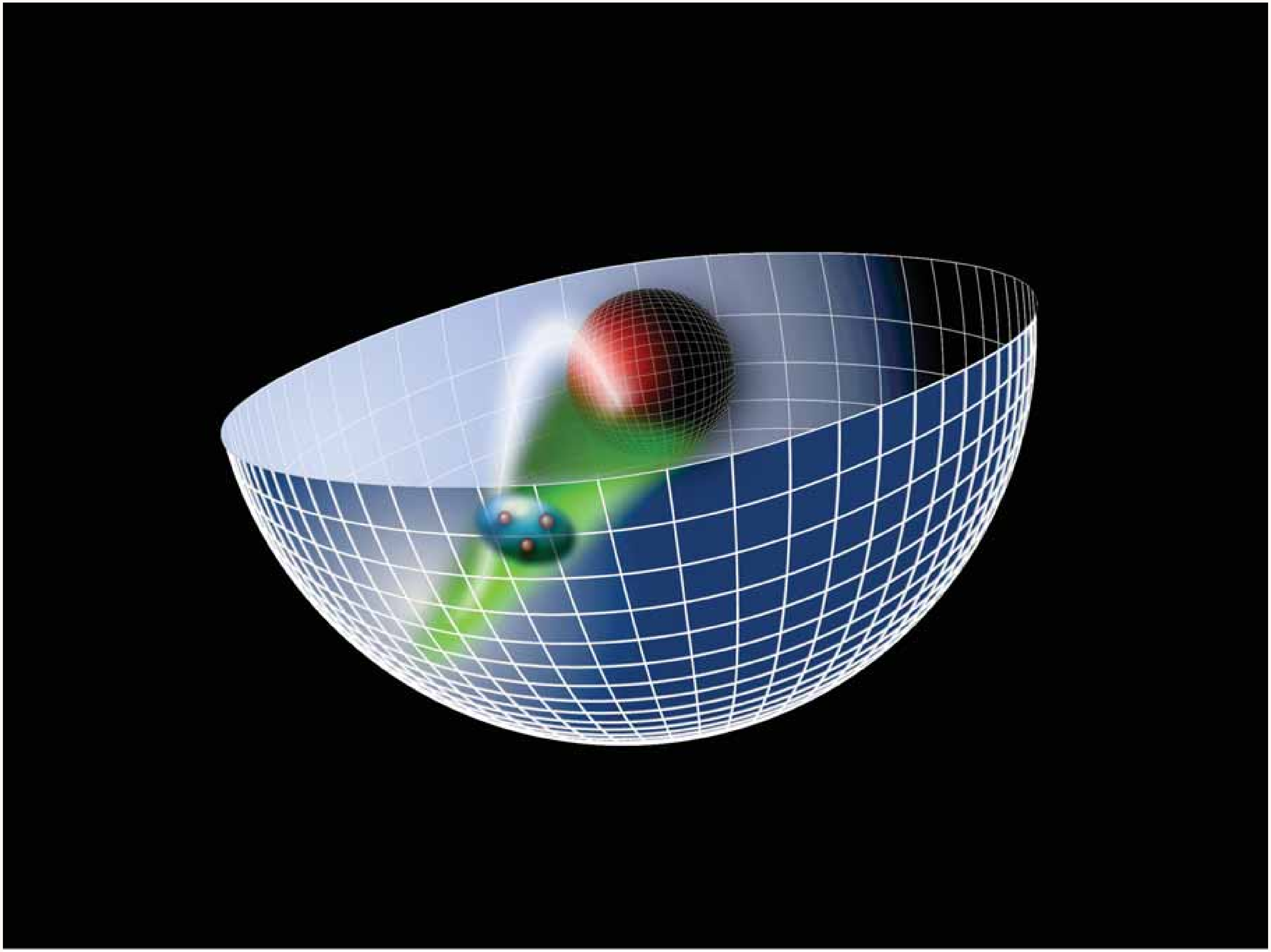
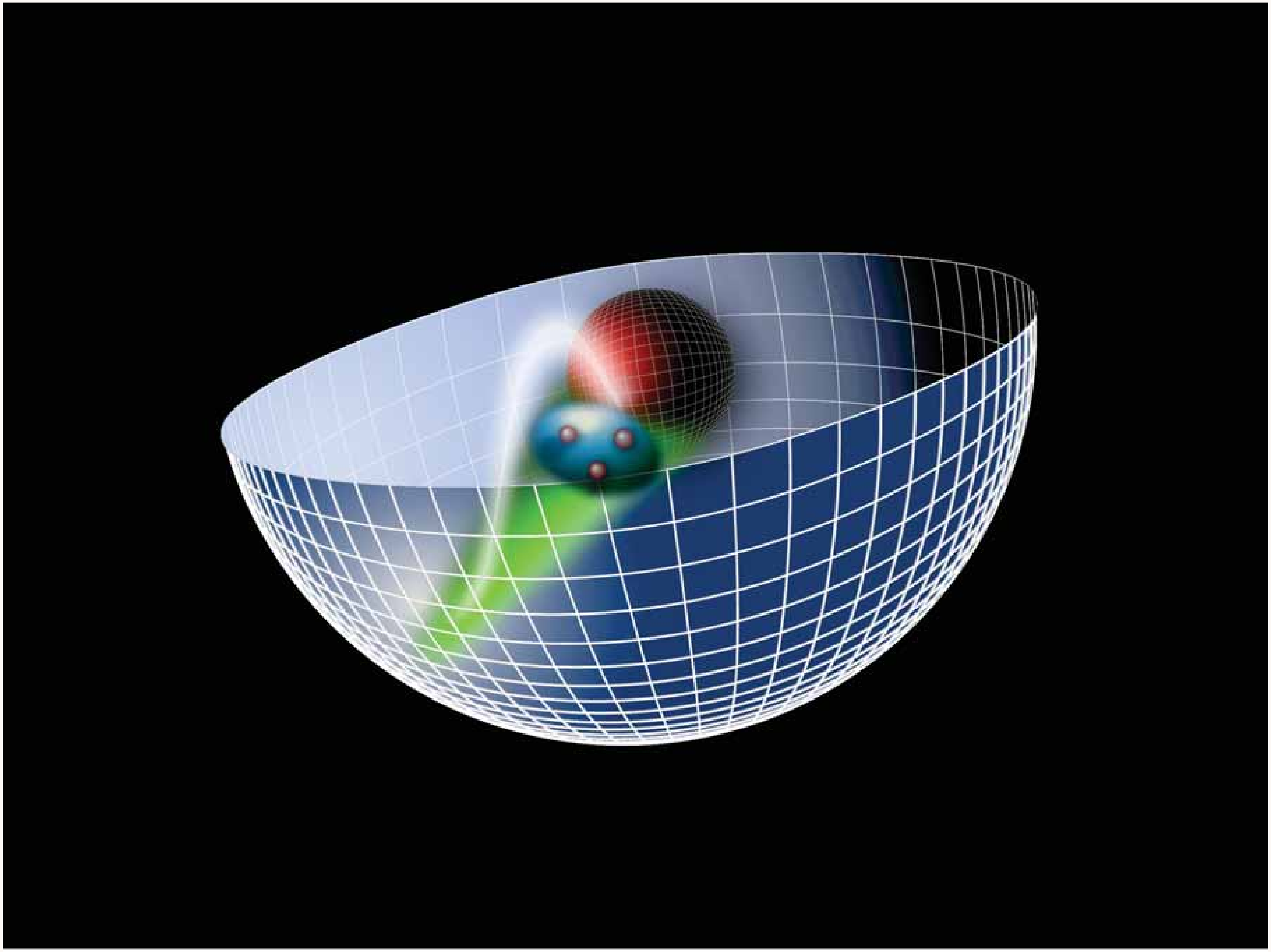






AdS/CFT: Anti-de Sitter Space / Conformal Field Theory

Maldacena:

Map AdS_5 X S_5 to conformal N=4 SUSY

- **QCD is not conformal**; however, it has manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes

- **Conformal window:** $\alpha_s(Q^2) \simeq \text{const at small } Q^2$

- **Use mathematical mapping of the conformal group SO(4,2) to AdS5 space**

- Karch, Katz, Son, Stephanov
- de Teramond, sjb

AdS Schrodinger Equation for bound state of two scalar constituents:

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

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

Derived from variation of Action
Dilaton-Modified AdS_5

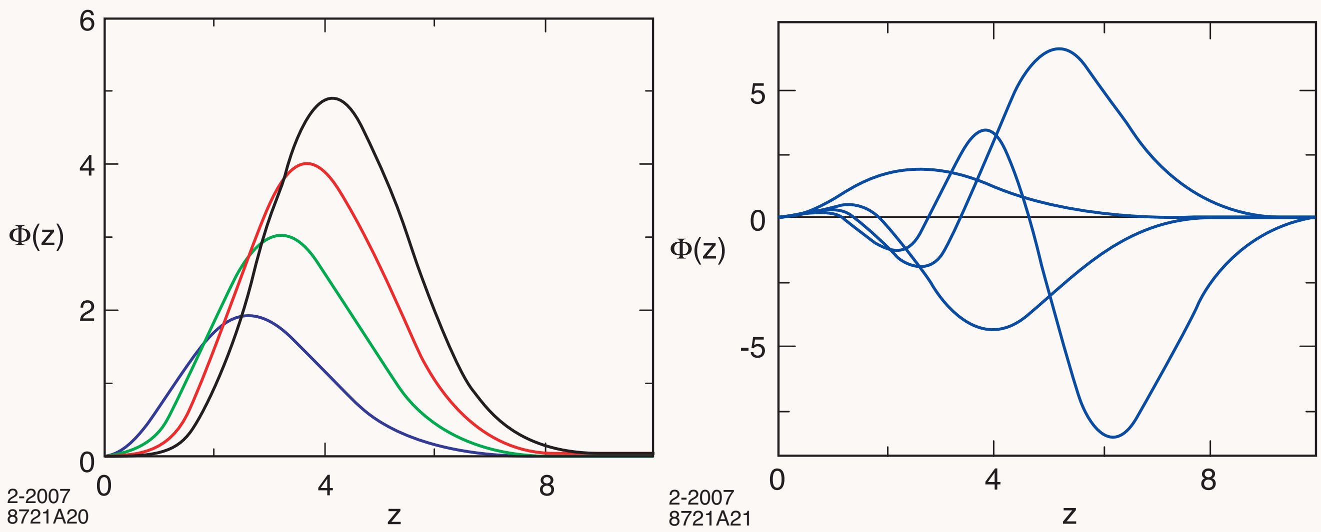
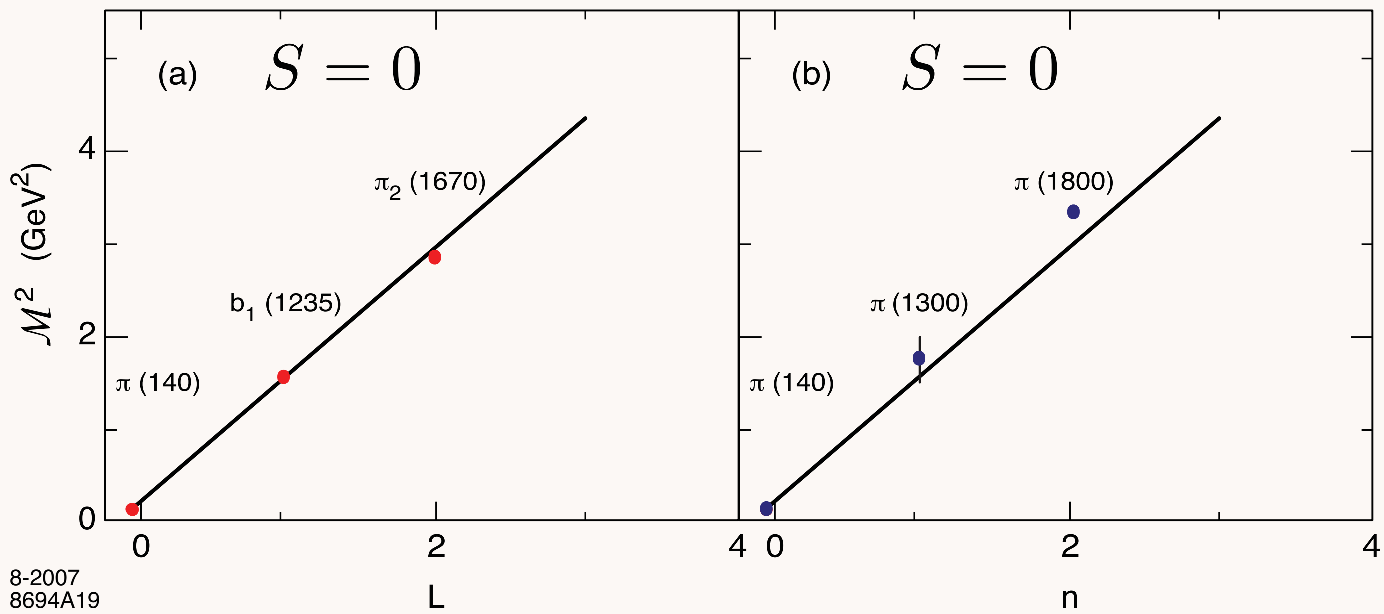


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model



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

Pion mass automatically zero!

$$m_q = 0$$

Higher Spin Bosonic Modes SW

Soft-wall model

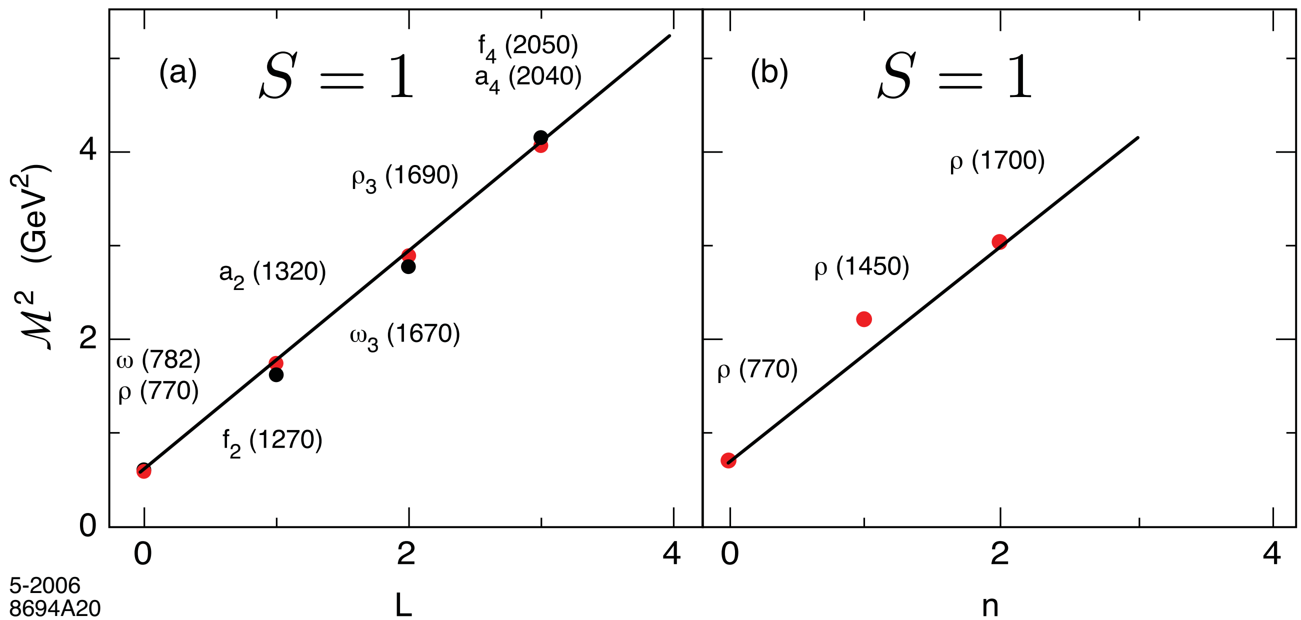
- Effective LF Schrödinger wave equation

$$\left[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + \kappa^4 z^2 + 2\kappa^2(L+S-1)\right]\phi_S(z) = \mathcal{M}^2\phi_S(z)$$

with eigenvalues $\mathcal{M}^2 = 2\kappa^2(2n+2L+S)$.

Same slope in n and L

- Compare with Nambu string result (rotating flux tube): $M_n^2(L) = 2\pi\sigma\,(n+L+1/2)$.

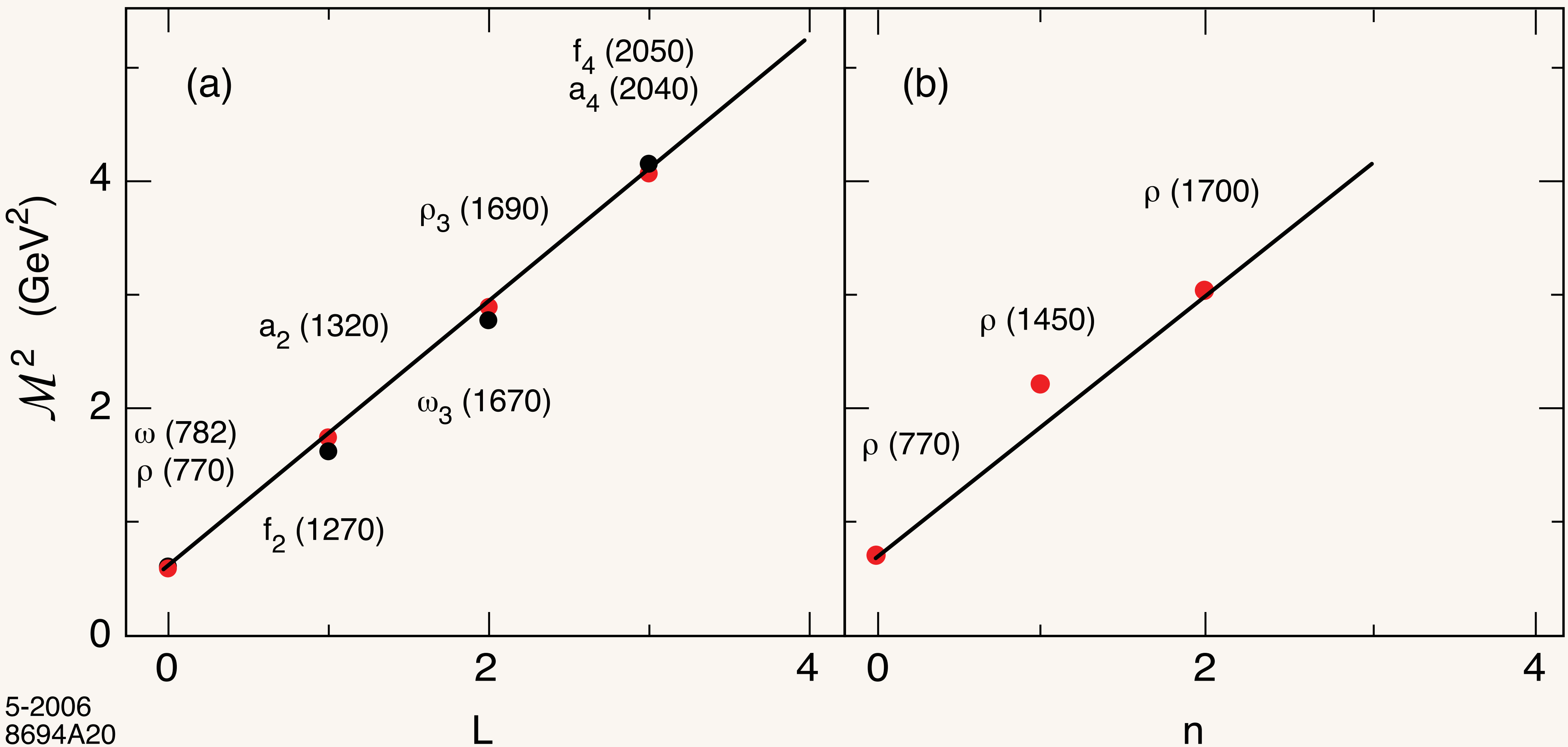


Vector mesons orbital (a) and radial (b) spectrum for $\kappa = 0.54$ GeV.

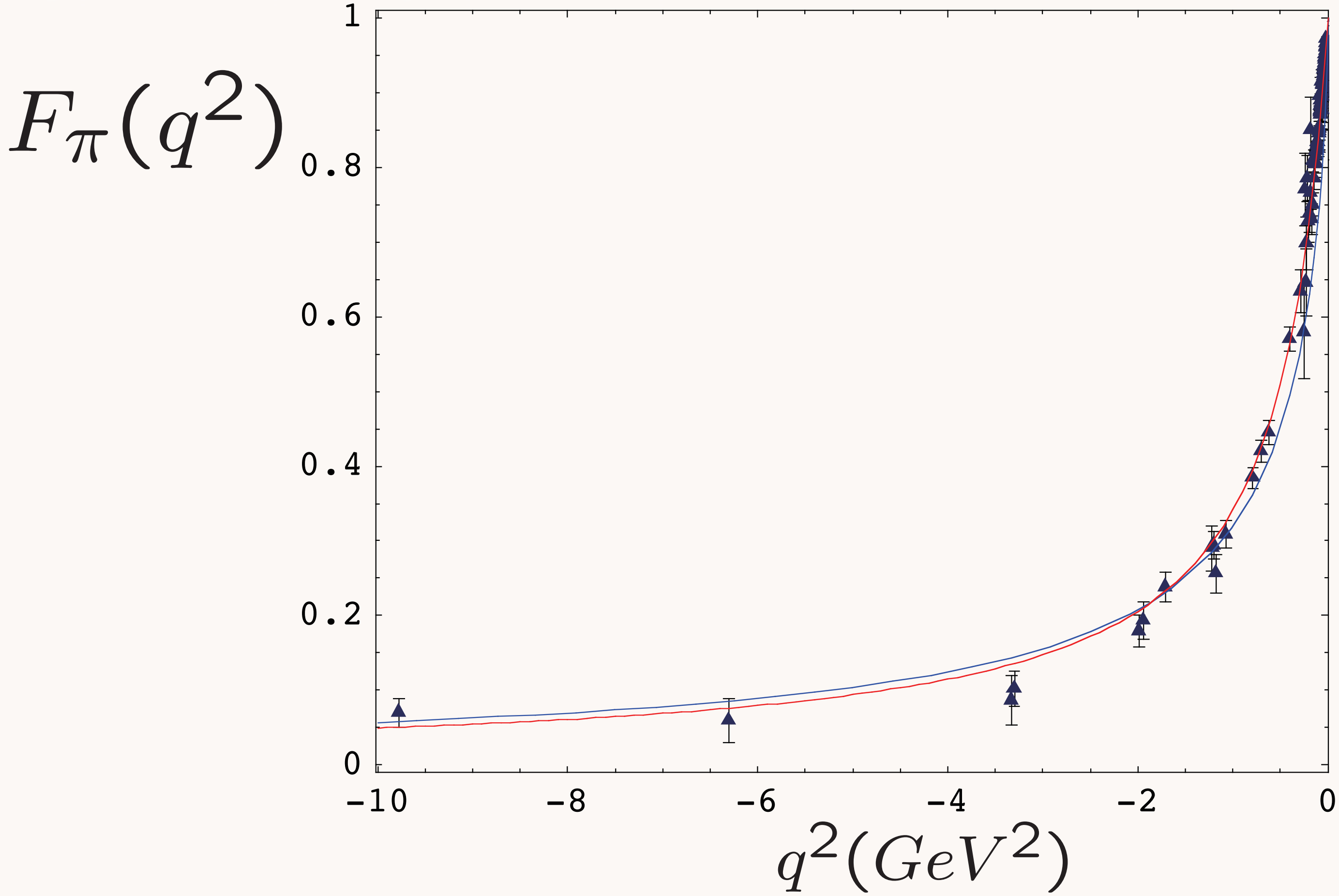
- Glueballs in the bottom-up approach: (HW) Boschi-Filho, Braga and Carrion (2005); (SW) Colangelo, De Facio, Jugeau and Nicotri(2007).

$$\mathcal{M}^2 = 2\kappa^2(2n + 2L + S).$$

$$S = 1$$



Spacelike pion form factor from AdS/CFT



Data Compilation
Baldini, Kloe and Volmer

Soft Wall: Harmonic Oscillator Confinement

Hard Wall: Truncated Space Confinement

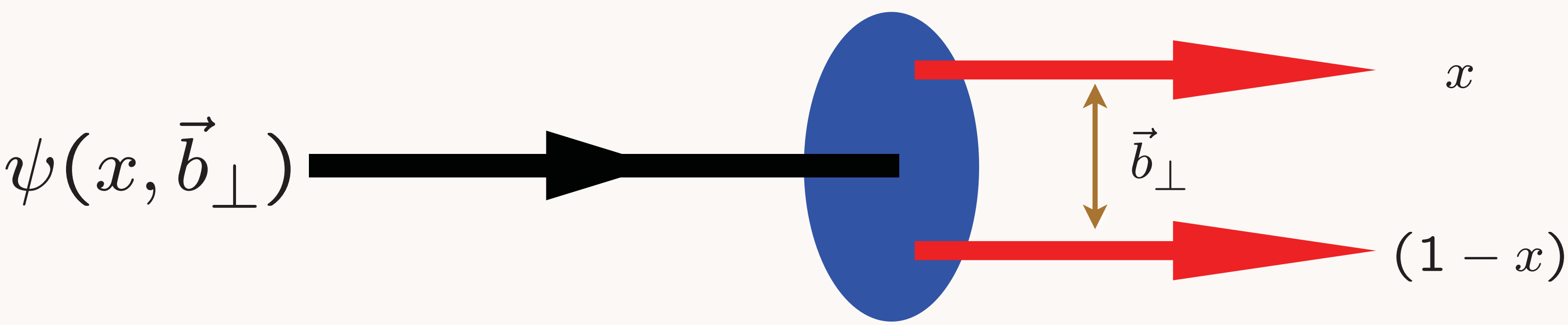
One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

LF(3+1) AdS$_5$

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

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



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

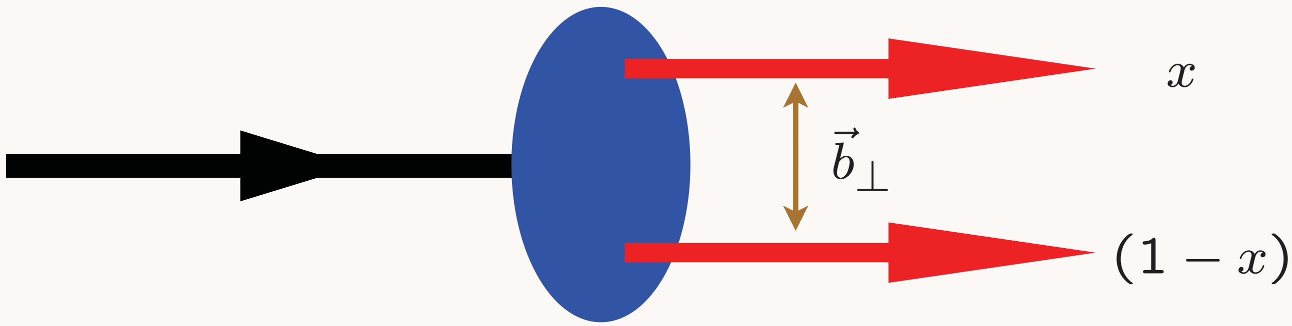
Light-Front Holography: Unique mapping derived from equality of LF and AdS formula for current matrix elements

Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation! *Frame Independent*

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

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



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

G. de Teramond, sjb

"soft-wall" confining potential:

Derivation of the Light-Front Radial Schrodinger Equation directly from LF QCD

$$\mathcal{M}^2 = \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3} \frac{\vec{k}_\perp^2}{x(1-x)} \left|\psi(x,\vec{k}_\perp)\right|^2 + \text{interactions}$$
$$= \int_0^1 \frac{dx}{x(1-x)} \int d^2\vec{b}_\perp \, \psi^*(x,\vec{b}_\perp) \left(-\vec{\nabla}^2_{\vec{b}_{\perp\ell}}\right) \psi(x,\vec{b}_\perp) + \text{interactions}.$$

Change variables $(\vec{\zeta},\varphi),\ \vec{\zeta} = \sqrt{x(1-x)}\vec{b}_\perp$: $\quad \nabla^2 = \frac{1}{\zeta}\frac{d}{d\zeta}\left(\zeta\frac{d}{d\zeta}\right) + \frac{1}{\zeta^2}\frac{\partial^2}{\partial\varphi^2}$

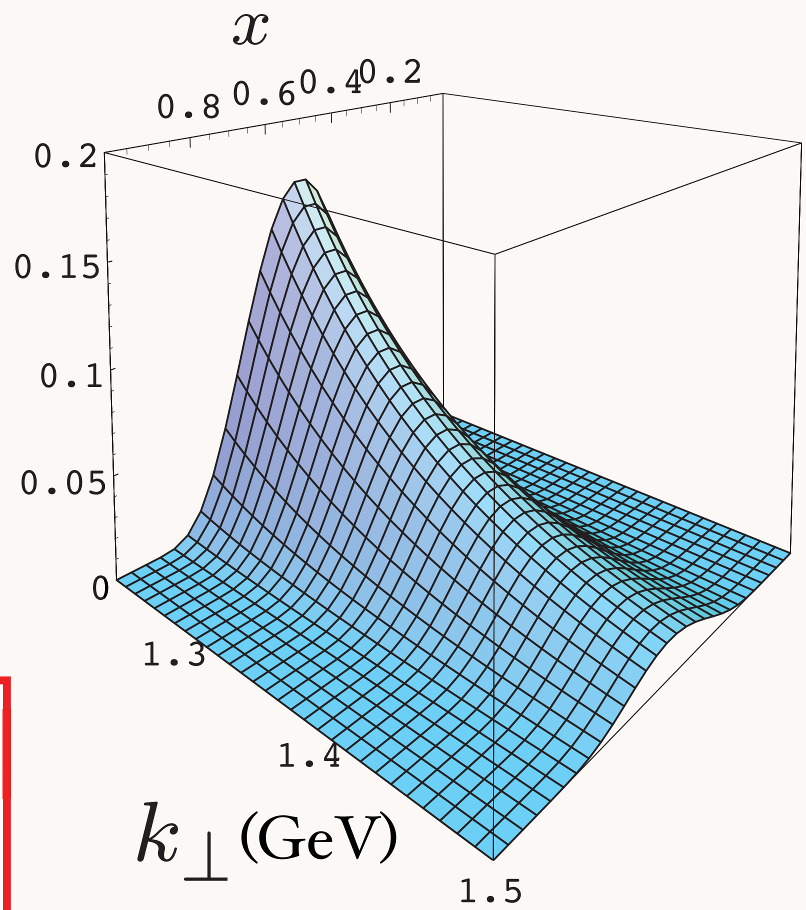
$$\mathcal{M}^2 = \int d\zeta \, \phi^*(\zeta)\sqrt{\zeta}\left(-\frac{d^2}{d\zeta^2} - \frac{1}{\zeta}\frac{d}{d\zeta} + \frac{L^2}{\zeta^2}\right)\frac{\phi(\zeta)}{\sqrt{\zeta}} + \int d\zeta \, \phi^*(\zeta) U(\zeta) \phi(\zeta)$$

$$= \int d\zeta \, \phi^*(\zeta)\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right)\phi(\zeta)$$

Prediction from AdS/CFT: Meson LFWF

de Teramond, sjb

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



$k_\perp$ (GeV)

"Soft Wall" model

$\kappa = 0.375$ GeV

massless quarks

Note coupling
$k_\perp^2, x$

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

$$\phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

Connection of Confinement to TMDs

Features of Soft-Wall AdS/QCD

- Single-variable frame-independent radial Schrodinger equation
- Massless pion (m_q =0)
- Regge Trajectories: universal slope in n and L
- Valid for all integer J & S. Spectrum is independent of S
- Dimensional Counting Rules for Hard Exclusive Processes
- Phenomenology: Space-like and Time-like Form Factors
- LF Holography: LFWFs; broad distribution amplitude
- No large Nc limit
- Add quark masses to LF kinetic energy
- Systematically improvable -- diagonalize H_{LF} on AdS basis

Second Moment of Pion Distribution Amplitude

$$< \xi^2 >= \int_{-1}^{1} d\xi \; \xi^2 \phi(\xi)$$

$$\xi = 1 - 2x$$

Links AdS/QCD and LF to Lattice Gauge Theory

$$< \xi^2 >_\pi = 1/5 = 0.20 \qquad \phi_{asympt} \propto x(1-x)$$

$$< \xi^2 >_\pi = 1/4 = 0.25 \qquad \phi_{AdS/QCD} \propto \sqrt{x(1-x)}$$

Lattice (I) $< \xi^2 >_\pi = 0.28 \pm 0.03$ — Donnellan et al.

Lattice (II) $< \xi^2 >_\pi = 0.269 \pm 0.039$ — Braun et al.

Use AdS/CFT orthonormal LFWFs as a basis for diagonalizing the QCD LF Hamiltonian

- Good initial approximant
- Better than plane wave basis

Pauli, Hornbostel, Hiller, McCartor, sjb

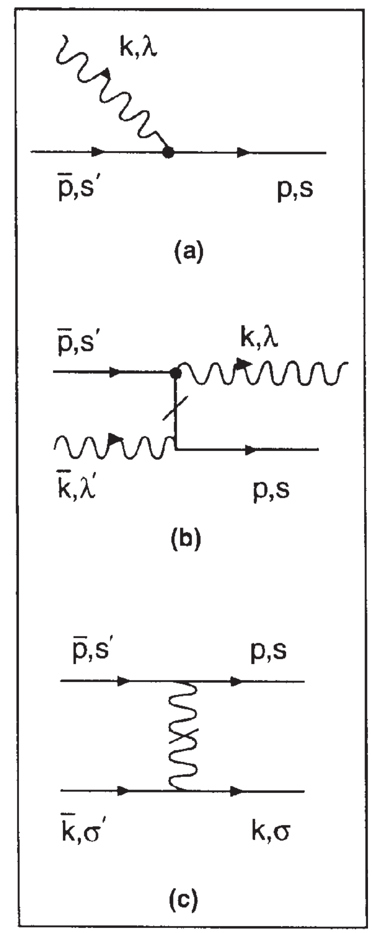
- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion

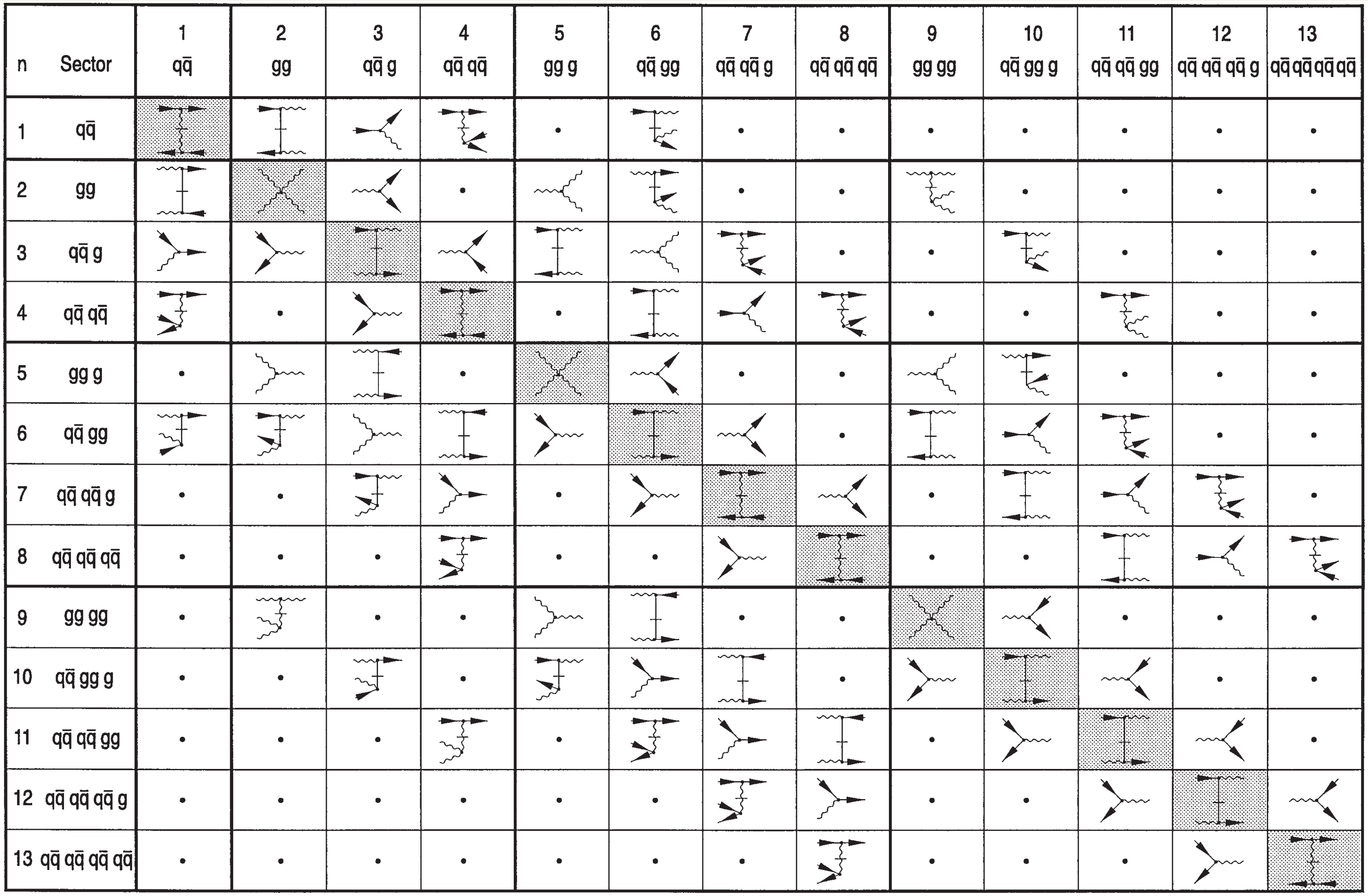
Vary, Harinandrath, Maris, sjb

- Similar to Shell Model calculations

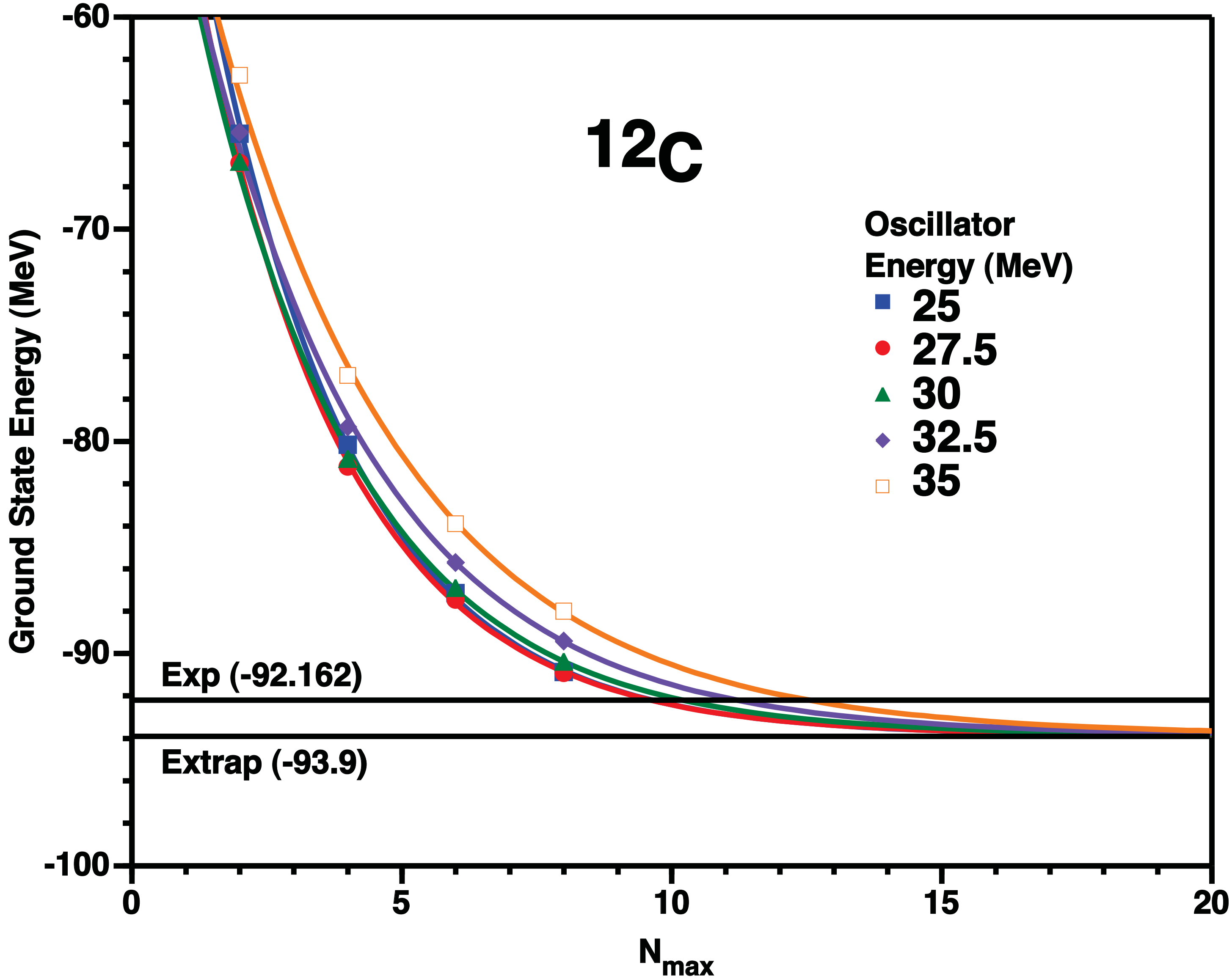
Light-Front QCD Heisenberg Equation

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





Use AdS/QCD basis functions



Application to nuclear physics

J.P. Vary et al

Calculated ground state energy of ^{12}C for $N_{max} = 2-8$ (discrete points) at selected values of $\hbar\Omega$. For each $\hbar\Omega$, the results are fit to an exponential plus a constant, the asymptote, which is constrained to be the same for each curve[5]. We display the experimental ground state energy and the common asymptote.

Recent progress in Hamiltonian light-front QCD

November 2008

SLAC-PUB-13460

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SLAC National Accelerator Laboratory, Stanford University, Menlo Park, California, USA

P. Sternberg, E. G. Ng, C. Yang
Lawrence Berkeley National Laboratory, Berkeley, California, USA

Hamiltonian light-front quantum field theory constitutes a framework for the non-perturbative solution of invariant masses and correlated parton amplitudes of self-bound systems. By choosing light-front gauge and adopting a basis function representation, we obtain a large, sparse, Hamiltonian matrix for mass eigenstates of gauge theories that is solvable by adapting the *ab initio* no-core methods of nuclear many-body theory. Full covariance is recovered in the continuum limit, the infinite matrix limit. We outline our approach and discuss the computational challenges.

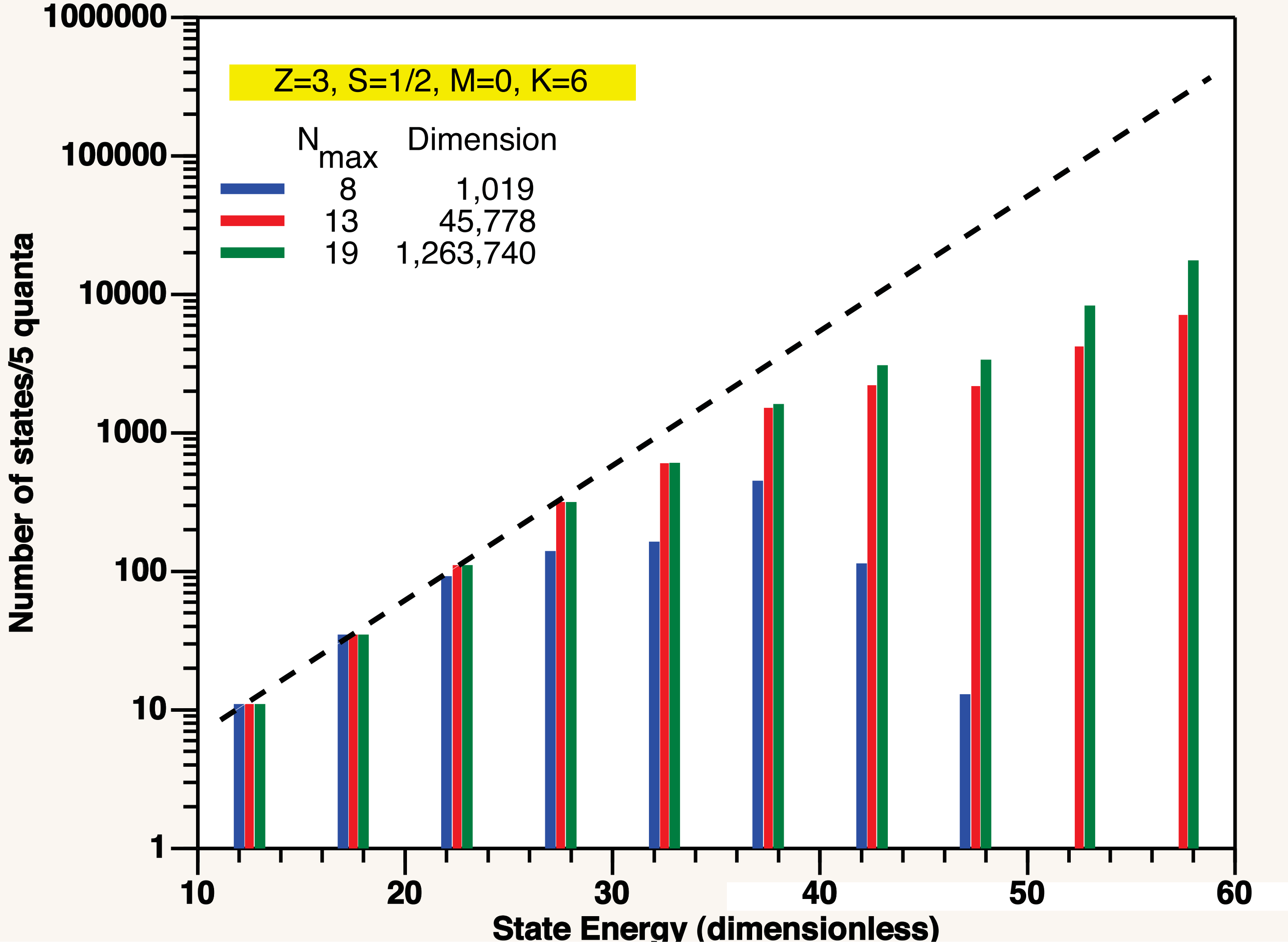
Basis LF Quantization (BFLQ)

Basis LF Quantization (BFLQ)

$$H = H_0 + H_{\text{int}}$$

Massless partons in a 2D harmonic trap solved in basis functions commensurate with the trap:

$$H_0 \equiv 2M_0 P_C^- \equiv \frac{1}{K}\sum_i \frac{1}{x_i}\left[2n_i + |m_i| + 1\right]\hbar\Omega(2M_0)$$



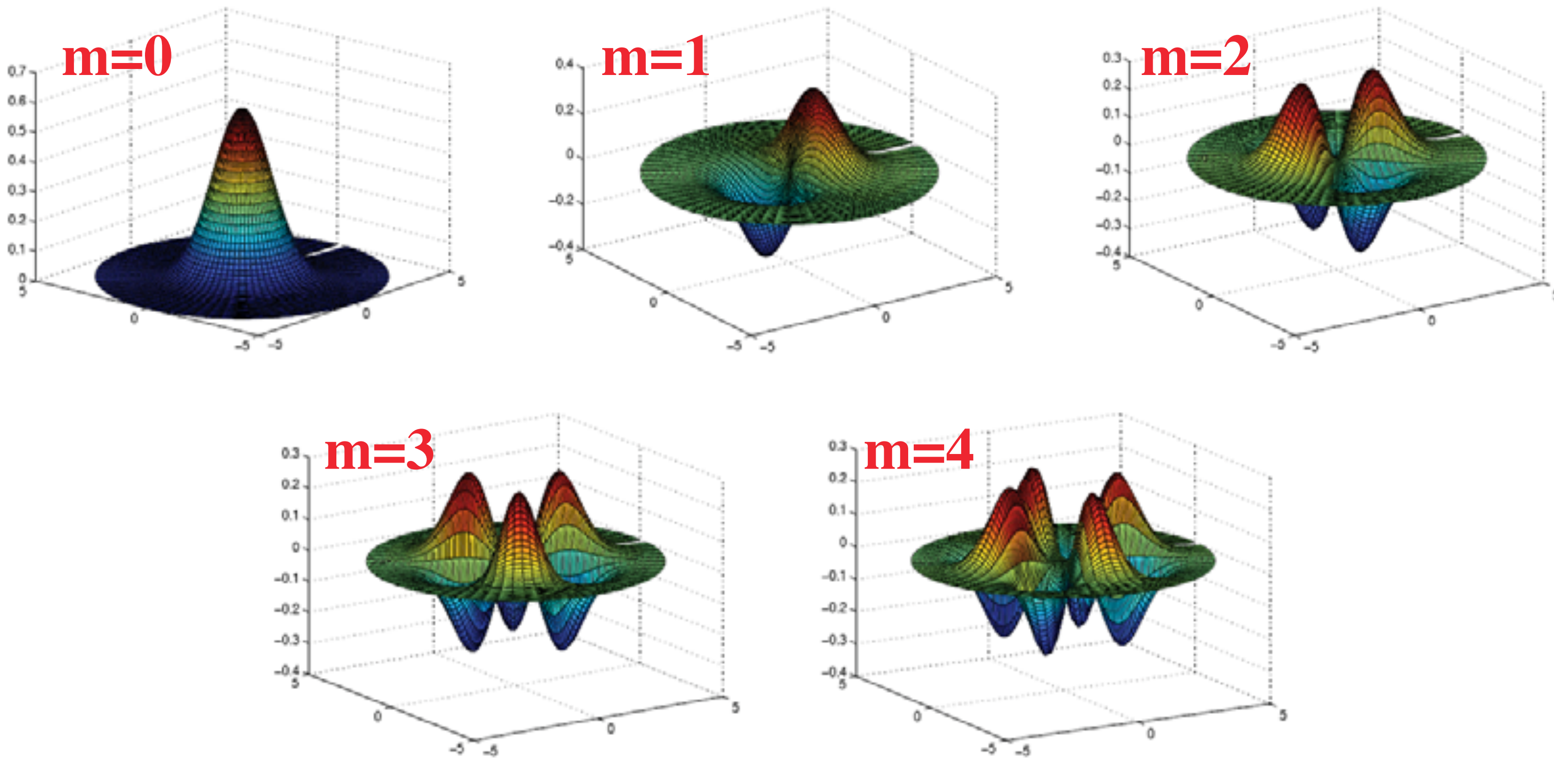
Basis LF Quantization (BFLQ)

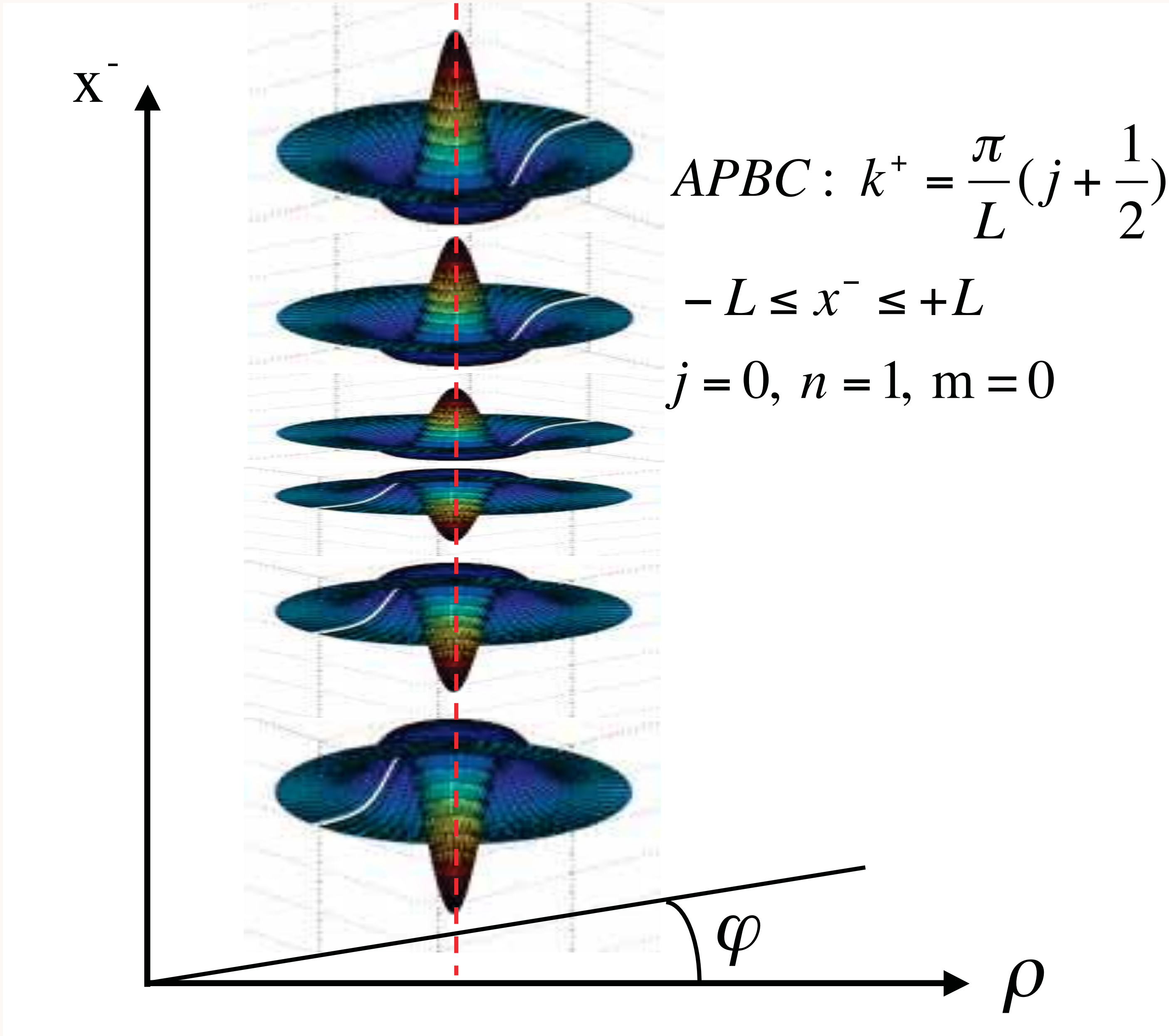
The properly normalized wavefunctions $\Psi_{n,m}(\rho,\phi) = f_{n,m}(\rho)\chi_m(\phi)$ are given by

$$f_{n,m}(\rho) = \sqrt{2\,M\,\Omega}\,\sqrt{\frac{n!}{(n+|m|)!}}\,\mathrm{e}^{-M\,\Omega\,\rho^2/2}\,\left(\sqrt{M\,\Omega}\,\rho\right)^{|m|}\,L_n^{|m|}(M\,\Omega\,\rho^2)$$

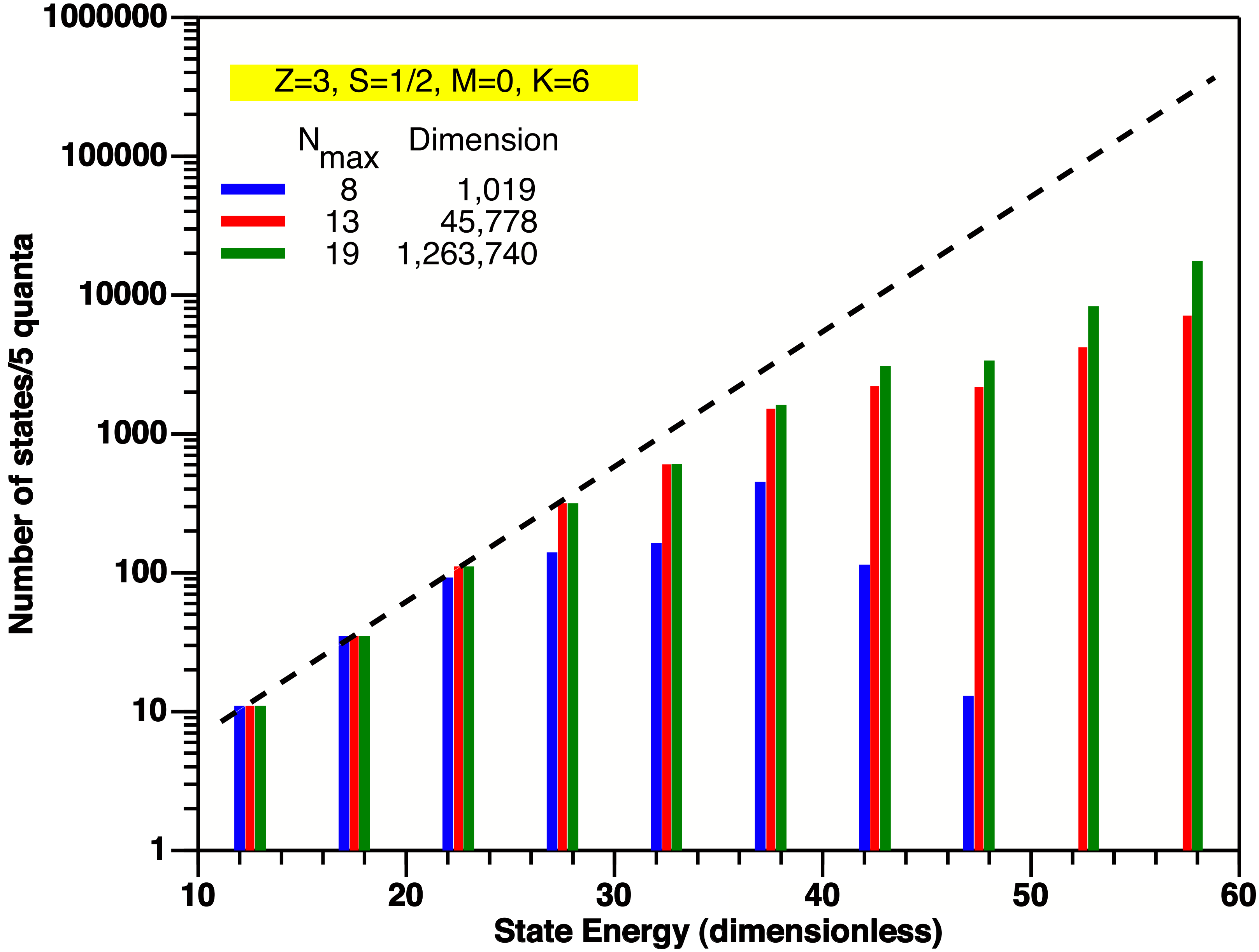
$$\chi_m(\phi) = \frac{1}{\sqrt{2\pi}}\,\mathrm{e}^{i\,m\,\phi}$$

Set of transverse 2D HO modes for n=0





Transverse sections of a 3-D basis function involving a 2-D harmonic oscillator and a longitudinal mode with antiperiodic boundary conditions (APBC).



State density from BLFQ for 3 identical massless fermions confined in a trap for a selection of N_{max} values at fixed $K = 6$. The dimensions of the resulting matrices are presented in the legend. The states are binned in groups of 5 units of energy (quanta) where each parton carries quanta equal to its 2-D oscillator energy divided by its light-front momentum fraction ($x_i = (j_i + 1)/K$). The dashed straight line traces the exponential increase in state density, familiar in many-body theory, when the basis is sufficiently large.

Construct Non-Valence LFWFs

- Start with AdS/QCD Valence LFWF $|q\,q>$

- Construct higher Fock states by applying QCD Interaction Hamiltonian

$$|q\bar{q}g> = \frac{1}{\mathcal{M}^2 - \sum_{j=1}^{3} \frac{k^2_{\perp j} + m^2_j}{x_j}} H^I_{QCD} |q\bar{q}>$$

- Has correct spinors, polarization vectors

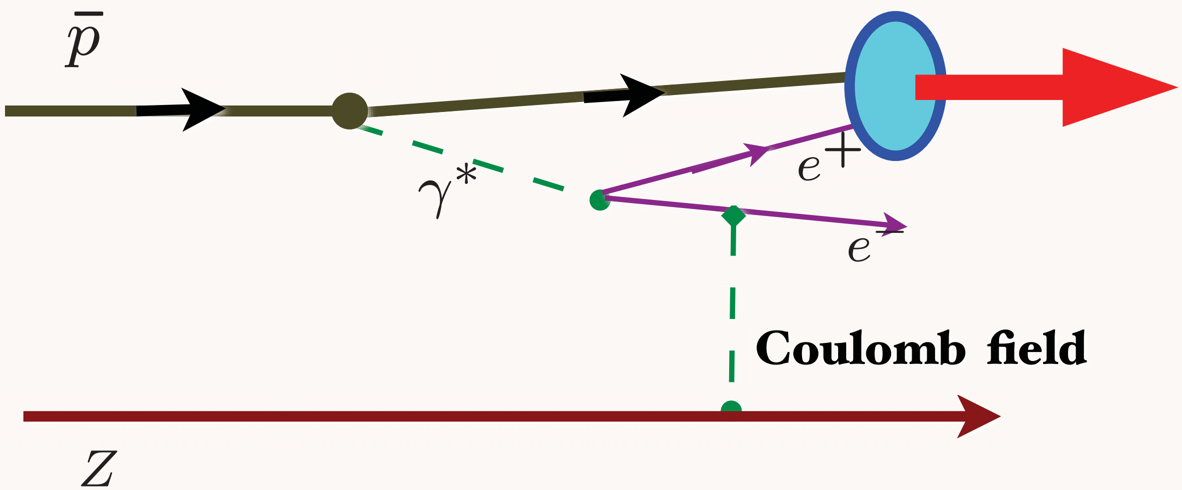
- Color-singlet states

- Optimum basis for diagonalizing QCD LF Hamiltonian

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



$\bar{H}(\bar{p}e^+)$

$b_\perp \leq \frac{1}{m_{red}\alpha}$

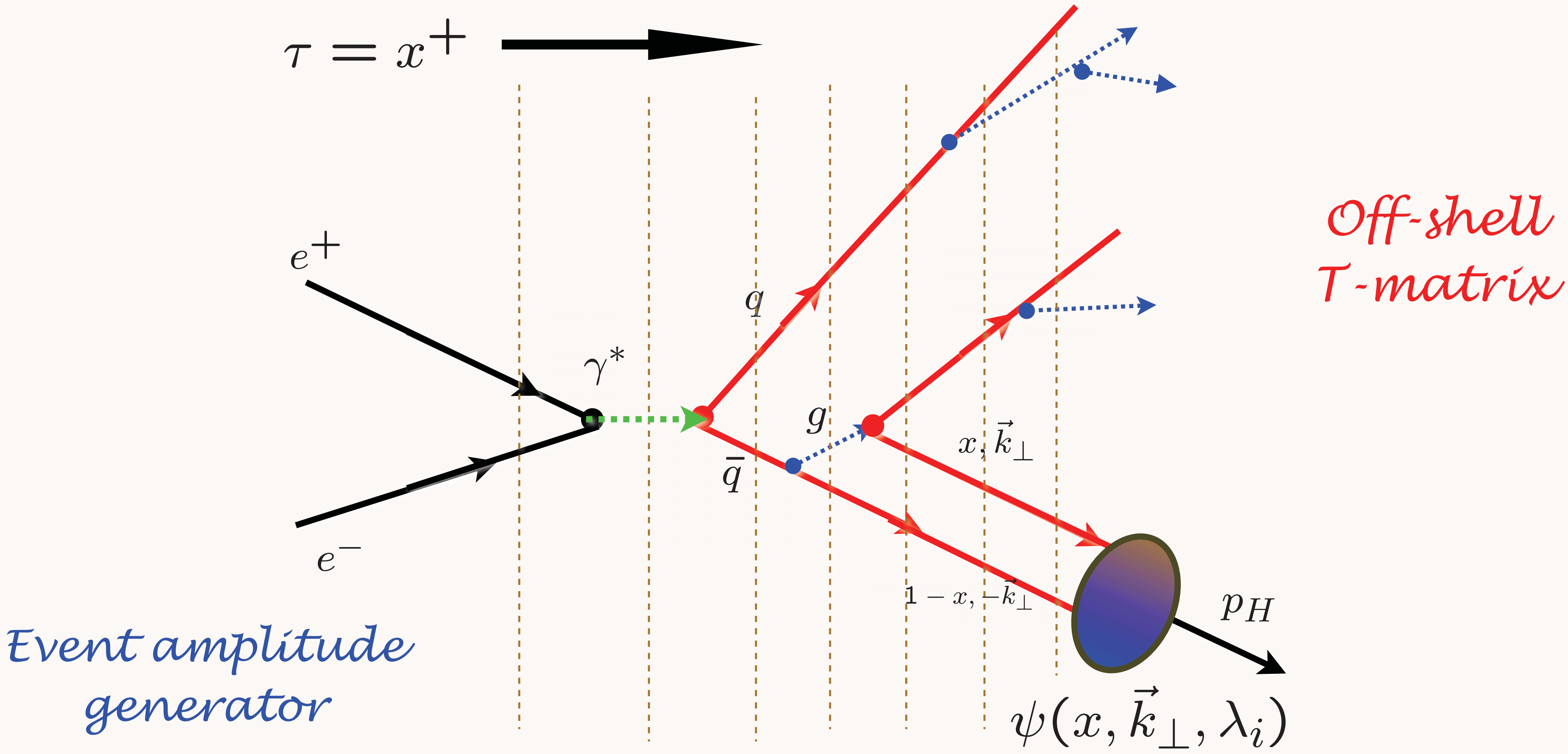
$y_{\bar{p}} \simeq y_{e^+}$

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

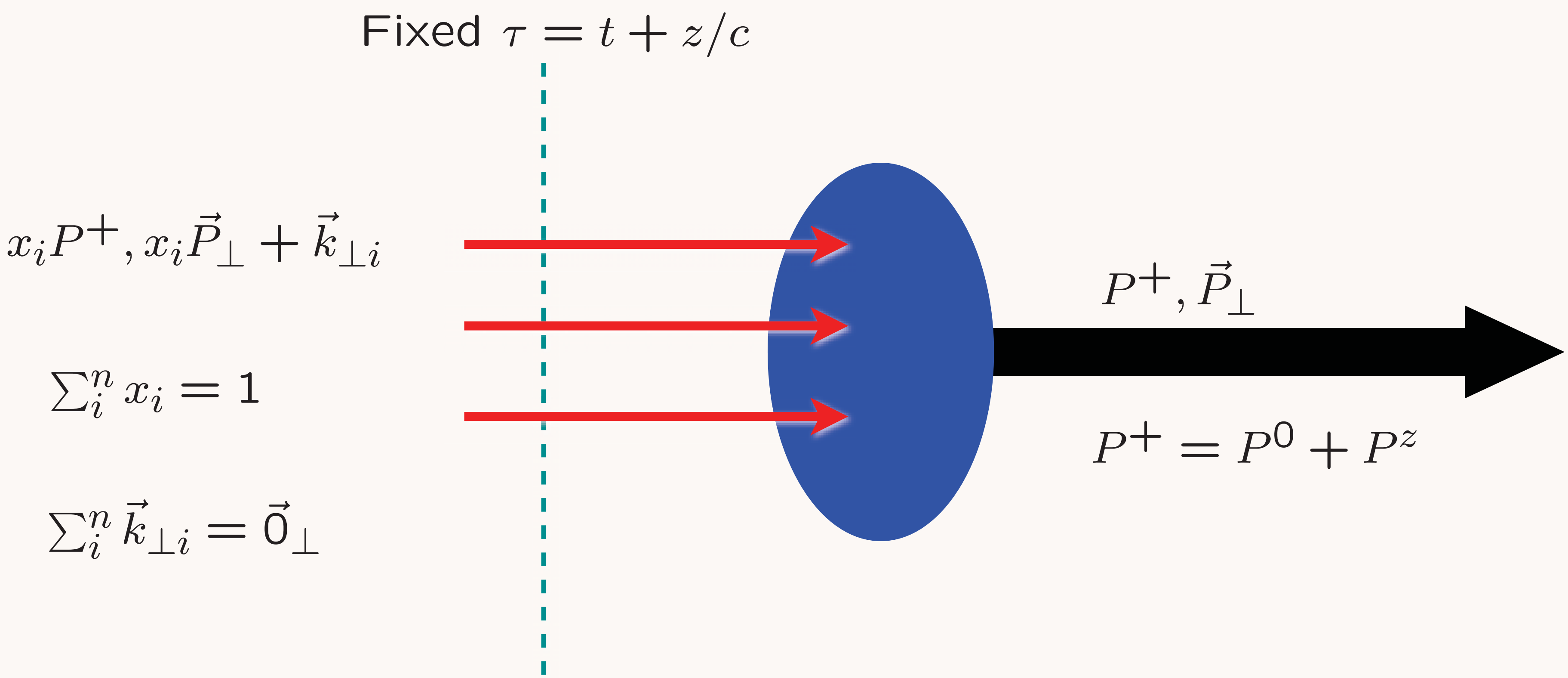
"Hadronization" at the Amplitude Level

Hadronization at the Amplitude Level



Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Light-Front Wavefunctions



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

Invariant under boosts! Independent of P^μ

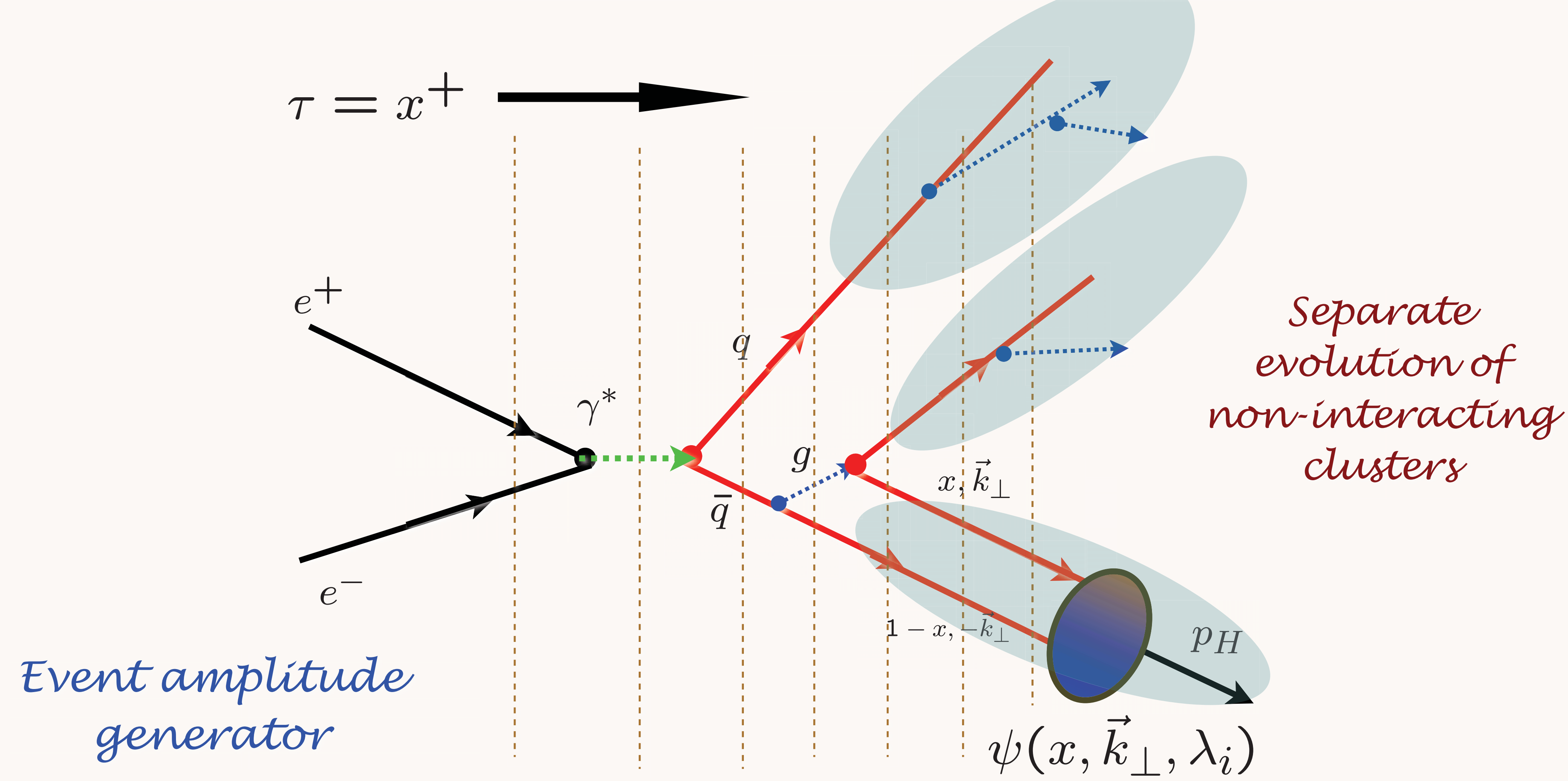
Hadronization at the Amplitude Level

- Rigorous approach to hadron formation
- Off-shell T-matrix for quarks and gluons consistent with confinement
- Light-front wavefunctions put constituents on shell
- Use AdS/QCD model
- Relativistic frame-independent generalization of Lippmann-Schwinger formalism

$$|\psi^{\pm} >= |\phi > + \frac{1}{\mathcal{M}^2_{initial} - H^0_{LF} + i\epsilon} H^I_{QCD} |\psi^{\pm} >$$

- Replaces heuristic probabilistic generators PYTHIA, HERWIG, etc.
- Quantum Mechanical Bose-Einstein, EPR correlators !
- Now conceivable using Exascale Computer capabilities

Hadronization at the Amplitude Level

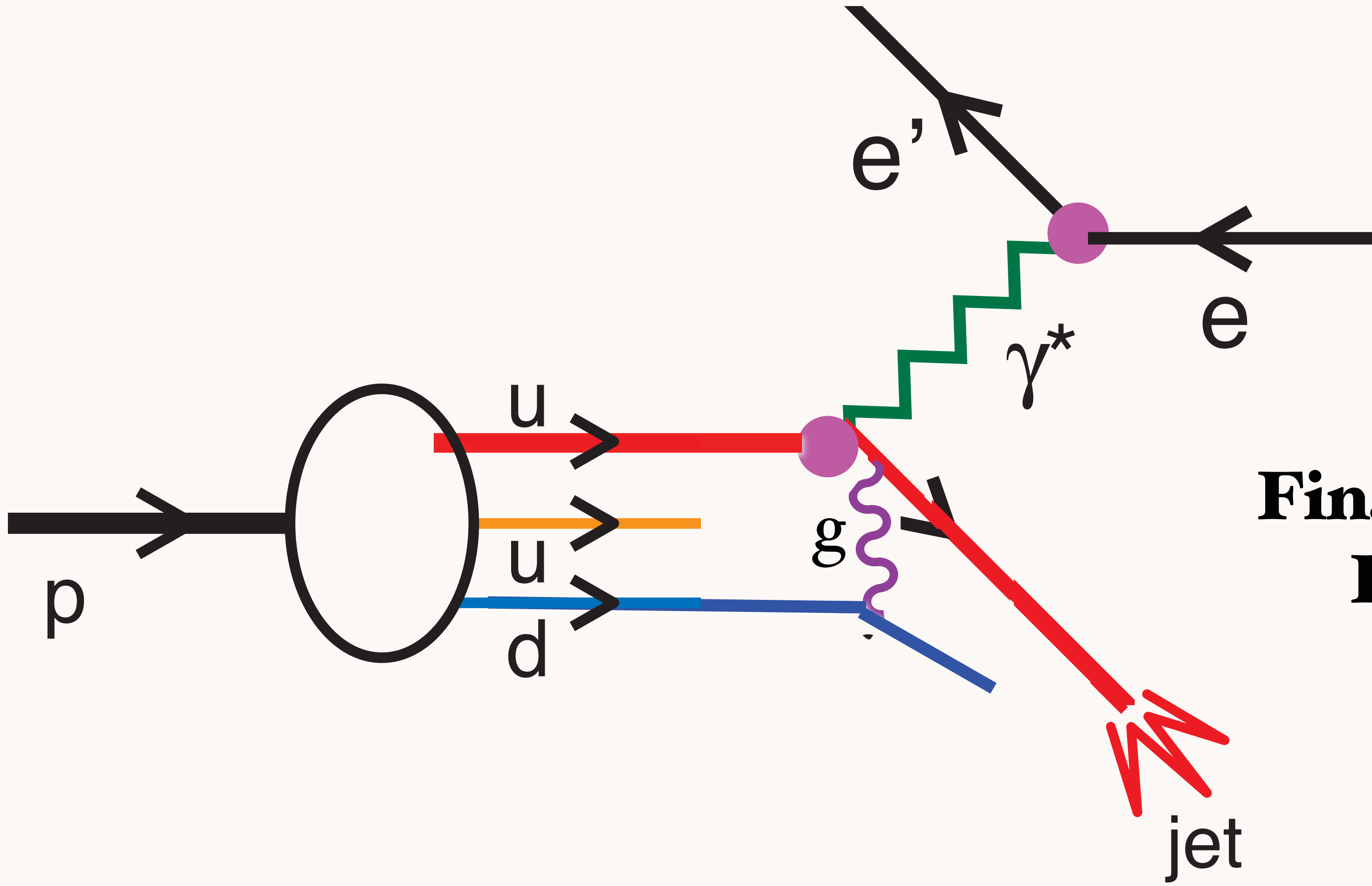


Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Hadronization at Amplitude Level

- Factorization for non-interacting clusters
- Cluster factorization well-matched to parallel processing
- Numerator algebra of cluster amplitude independent of context; format with variable denominators which are set at final stage
- Renormalization using 'alternate denominator' method -- code recognizes divergences and applies counter terms
- Can include rescattering corrections which give single-spin asymmetries, diffraction, shadowing phenomena

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:
Final-state interactions of struck quark can be neglected

Leading Twist Sivers Effect

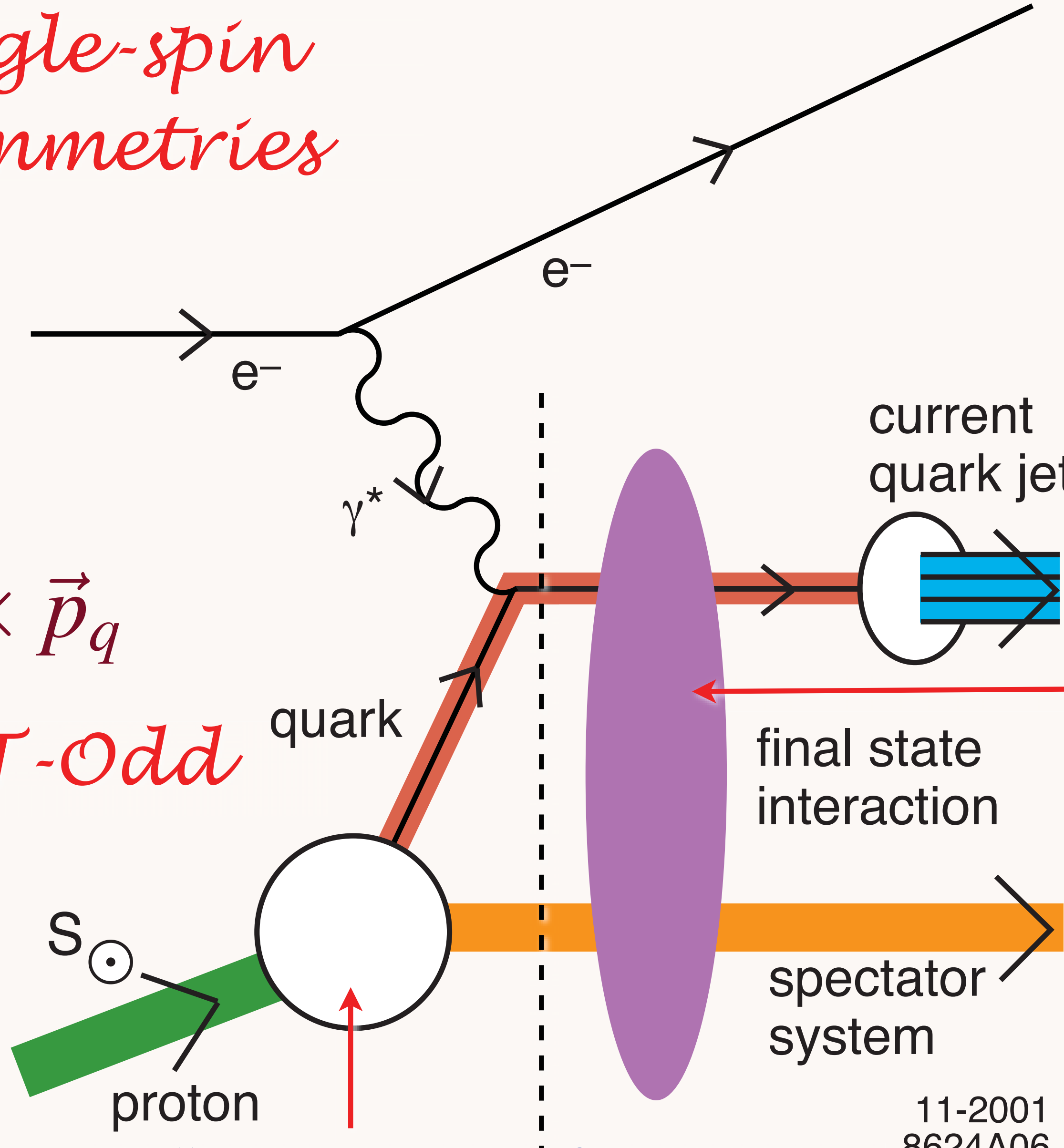
Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

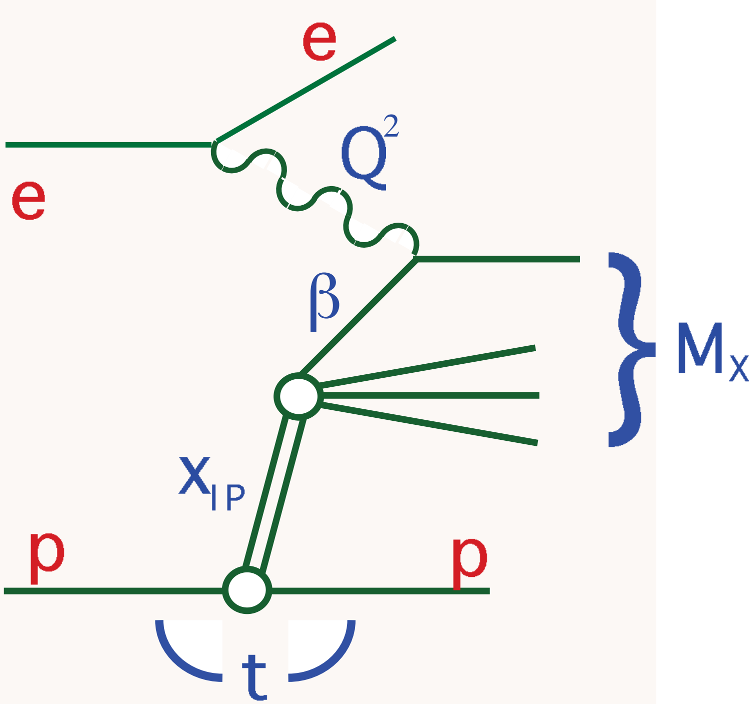
Pseudo-T-Odd

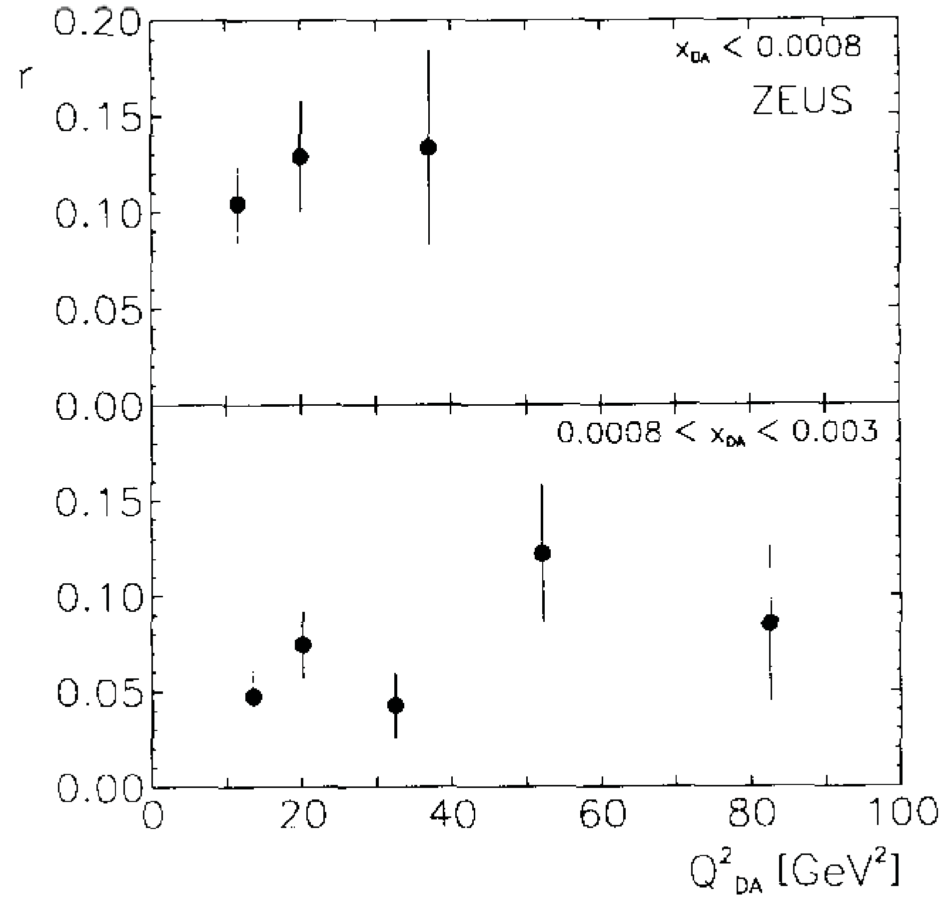


QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

Remarkable observation at HERA





Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

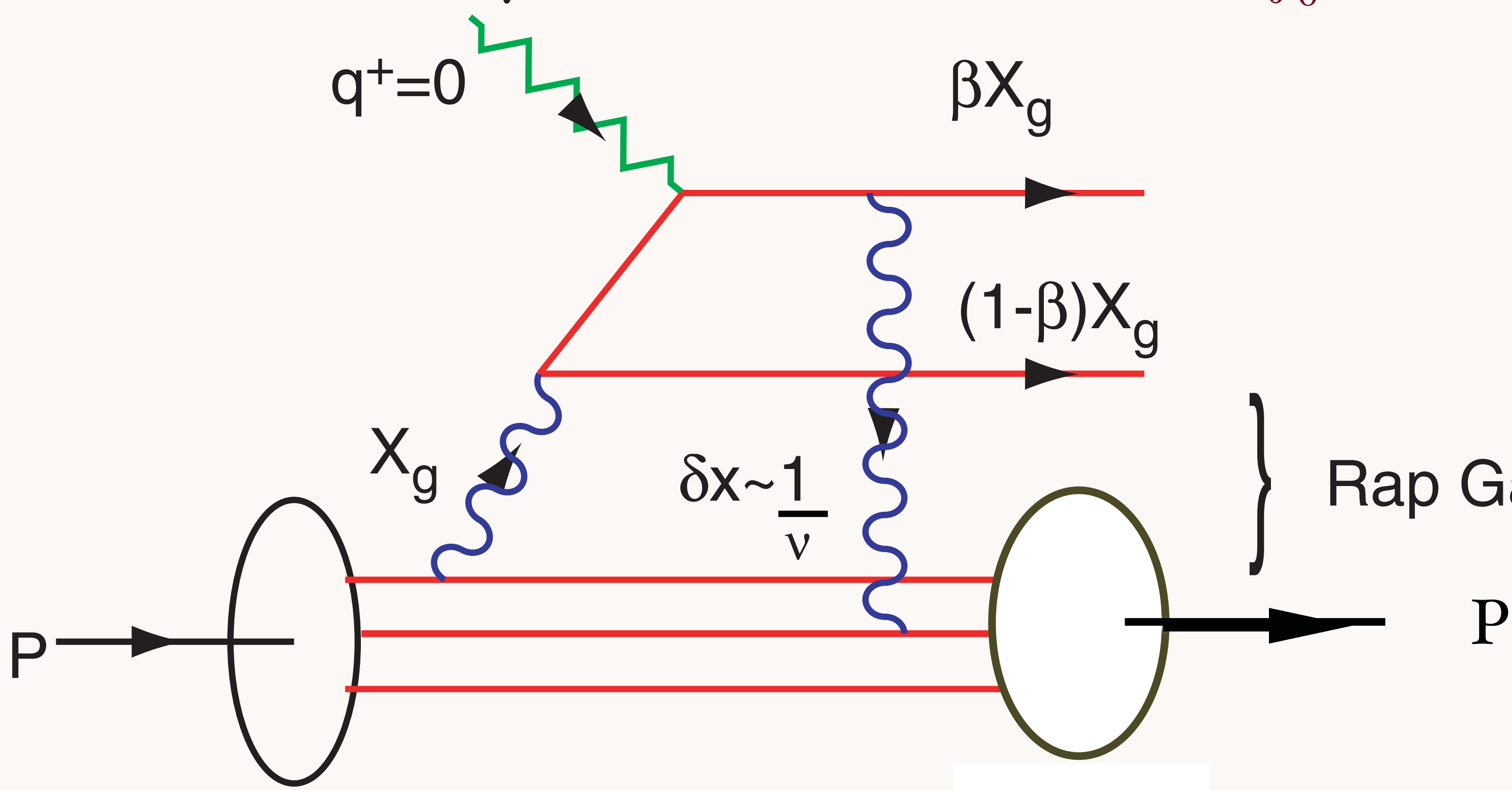
10% to 15% of DIS events are diffractive !

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993).

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

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

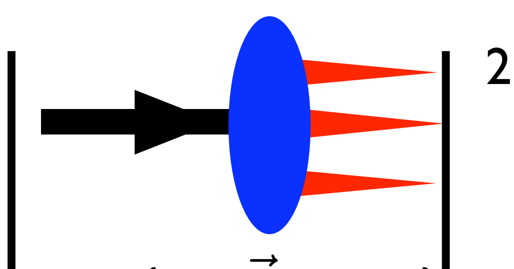


Reproduces lab-frame color dipole approach

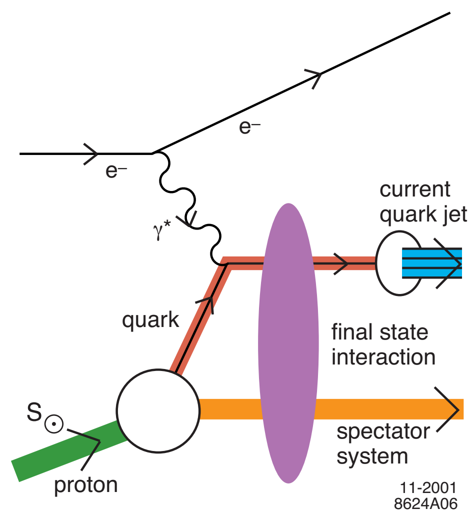
Physics of Rescattering

- Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd single-spin asymmetries,
- Nuclear Shadowing, Non-Universal Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

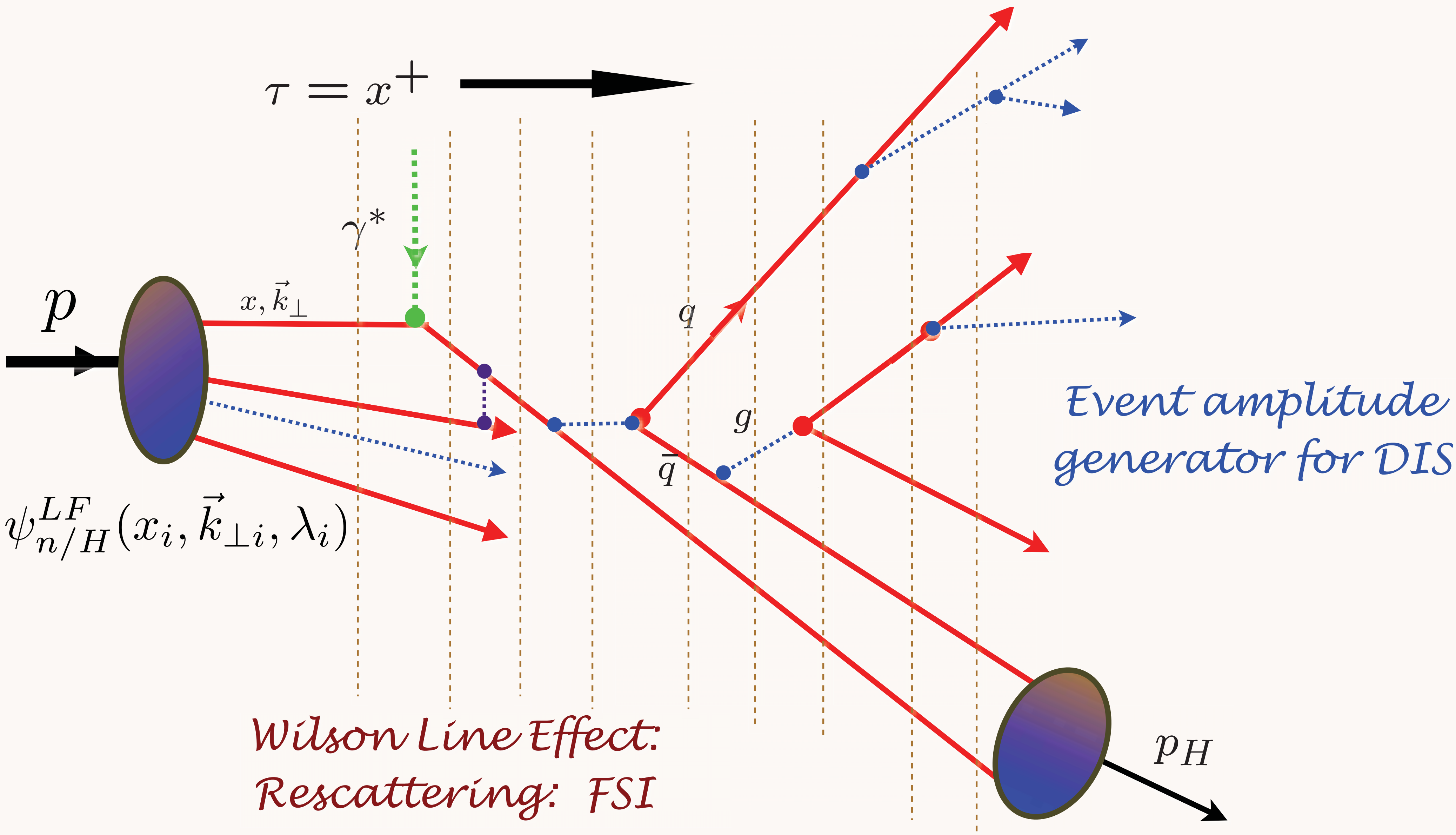
Stationary	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, 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



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



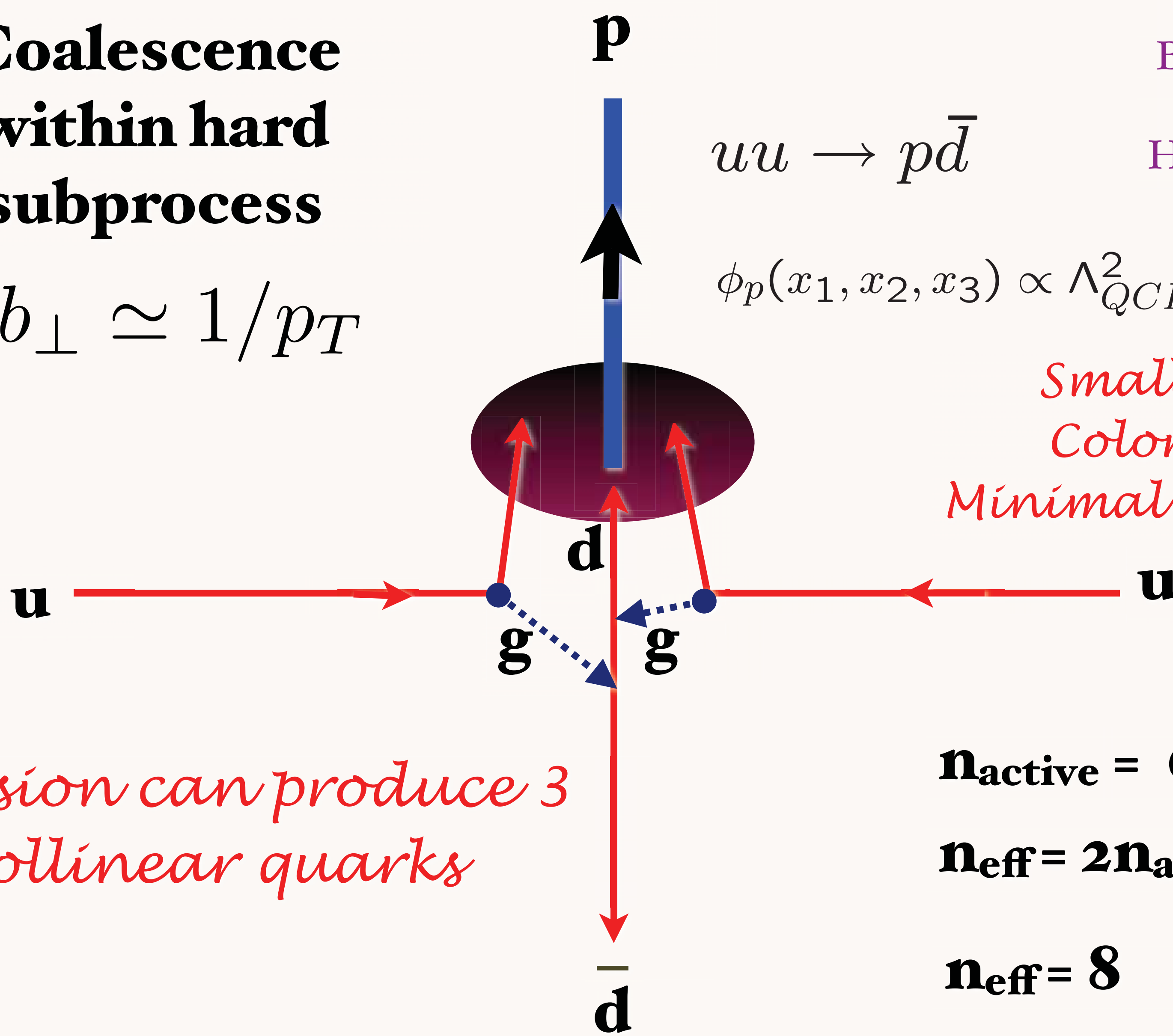
Hadronization at the Amplitude Level



Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

$$b_\perp \simeq 1/p_T$$



$$uu \rightarrow p\bar{d}$$

$$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$$

Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Hoyer, et al: Semi-Exclusive

Sickles, sjb

Small color-singlet
Color Transparent
Minimal same-side energy

Collision can produce 3 collinear quarks

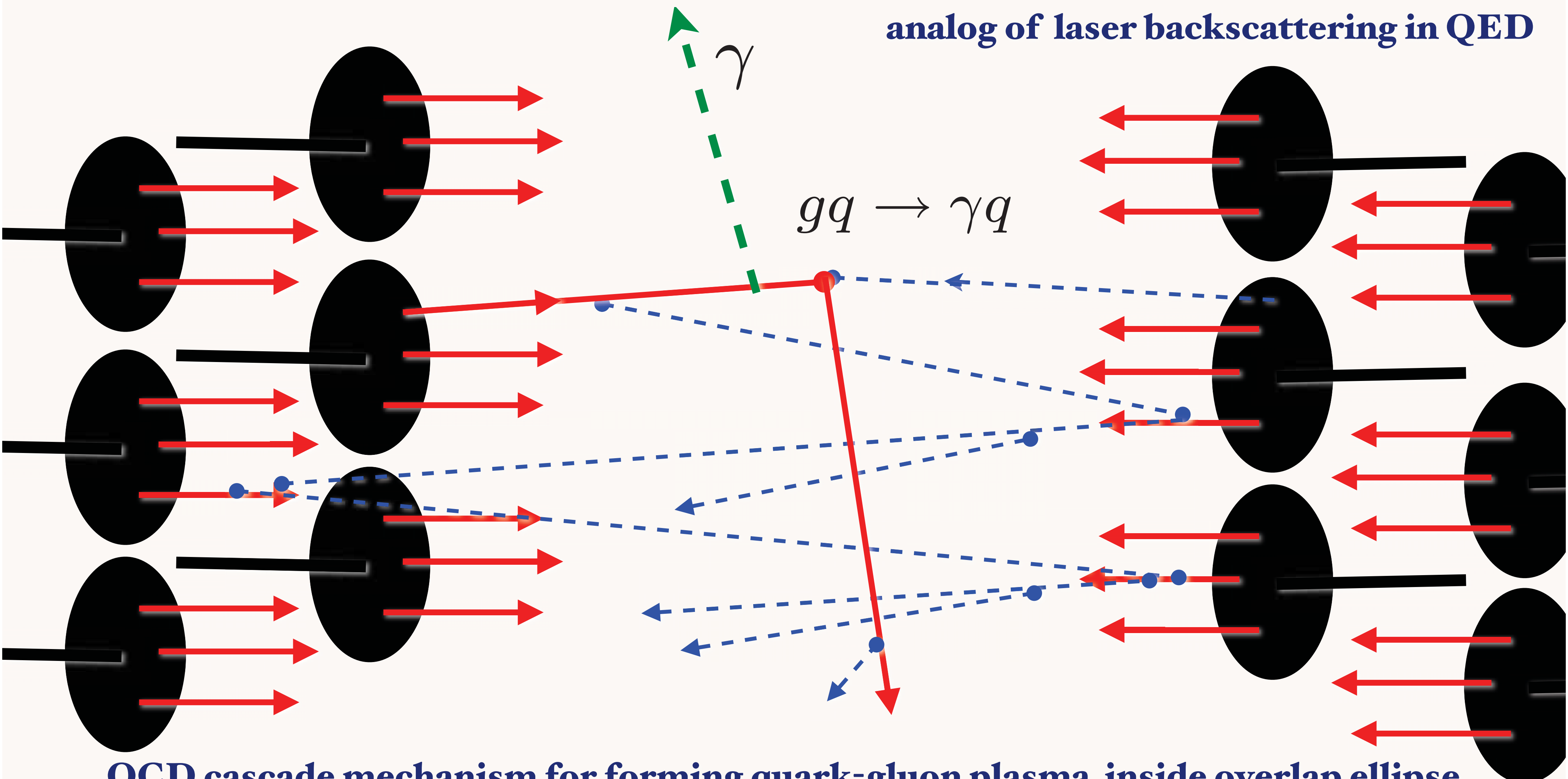
$n_{active} = 6$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

Gluonic Laser

Gluonic bremsstrahlung from initial hard scattering backscatters on nuclear ``mirrors"



QCD cascade mechanism for forming quark-gluon plasma inside overlap ellipse

Coherent

Exascale Simulation of Heavy Ion Collisions

- Dynamical & Quantum Mechanical vs. Statistical
- Retains Quantum Mechanical Coherence $\frac{\eta}{S} \simeq \frac{\hbar}{4\pi}$
- Gluonic Cascade at High Centrality
- Ridge produced from Initial State Inetractions
- RHIC Baryon Anomaly: Allows hadron to be formed directly in hard subprocess -- Color transparency phenomena

Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.
- Relation of spin, momentum, and other distributions to physics of the hadron itself.
- Connections between observables, orbital angular momentum
- Role of FSI and ISIs--Sivers effect

Impact of Exascale Computing on LF QCD

E-flop

10^{18} floating-point calculations per second

- Goal: Nonperturbative Solutions to QCD
- DLCQ and AdS/QCD-generated solutions of QCD(3+1)
- Hadronization at the Amplitude Level
- Computer Simulation of Complex QCD and other quantum field theory processes

http://www.ilcacinc.org/ILCAC-WP-FINAL.pdf

LIGHT-FRONT QUANTUM CHROMODYNAMICS

A framework for analysis of hadron dynamics

White Paper
International Light Cone Advisory Committee

An outstanding goal of physics is to find solutions that describe hadrons in the theory of strong interactions, Quantum Chromodynamics (QCD). For this goal, the light-front Hamiltonian formulation of QCD (LFQCD) is an appealing approach that complements the well-established lattice gauge method. LFQCD offers unique access to the nonperturbative quark and gluon amplitudes for the hadrons which are directly testable in experiments at forefront facilities. We present an overview of the promises and challenges of LFQCD in the context of unsolved issues in QCD that require broadened and accelerated investigations. We identify specific goals of this approach.

The rigorous evaluation of masses and wave functions of hadrons using the light-front Hamiltonian of QCD;

Develop computer codes which implement the regularization and renormalization schemes. Provide a platform-independent, well-documented core of routines that allow investigators to implement different numerical approximations to field-theoretic eigenvalue problems. Consider various quadrature schemes and basis sets, including Discretized Light-Cone Qunatization (DLCQ), finite elements, function expansions, and the complete orthonormal wave functions obtained from AdS/QCD. This will build on the Lanczos-based MPI code developed for nonrelativistic nuclear physics applications and similar codes for Yukawa theory and lower-dimensional supersymmetric Yang-Mills theories.

Solve for hadronic wave functions and masses. Use these wave functions to compute form factors, GPDs, scattering amplitudes, and decay rates. Compare with perturbation theory, lattice QCD, and model calculations, using insights from AdS/QCD, where possible. Study the transition to nuclear degrees of freedom in light nuclei.

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