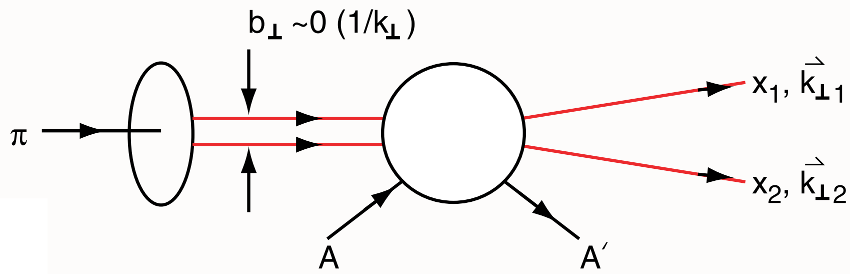
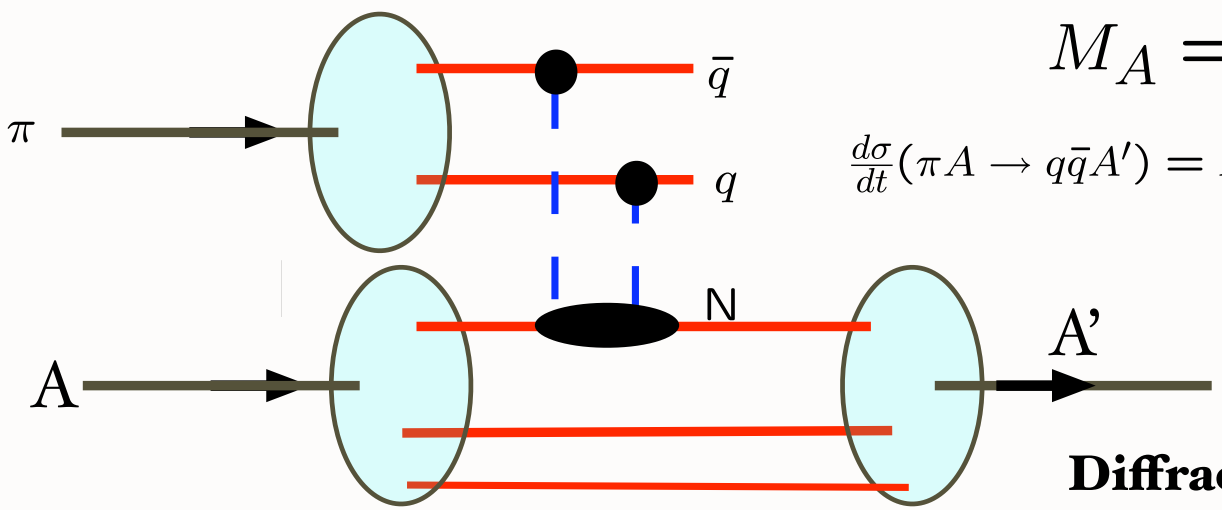
Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller Strikman

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

QCD COLOR Transparency



$$M_A = A\ M_N$$

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

Target left intact

Diffraction, Rapidity gap

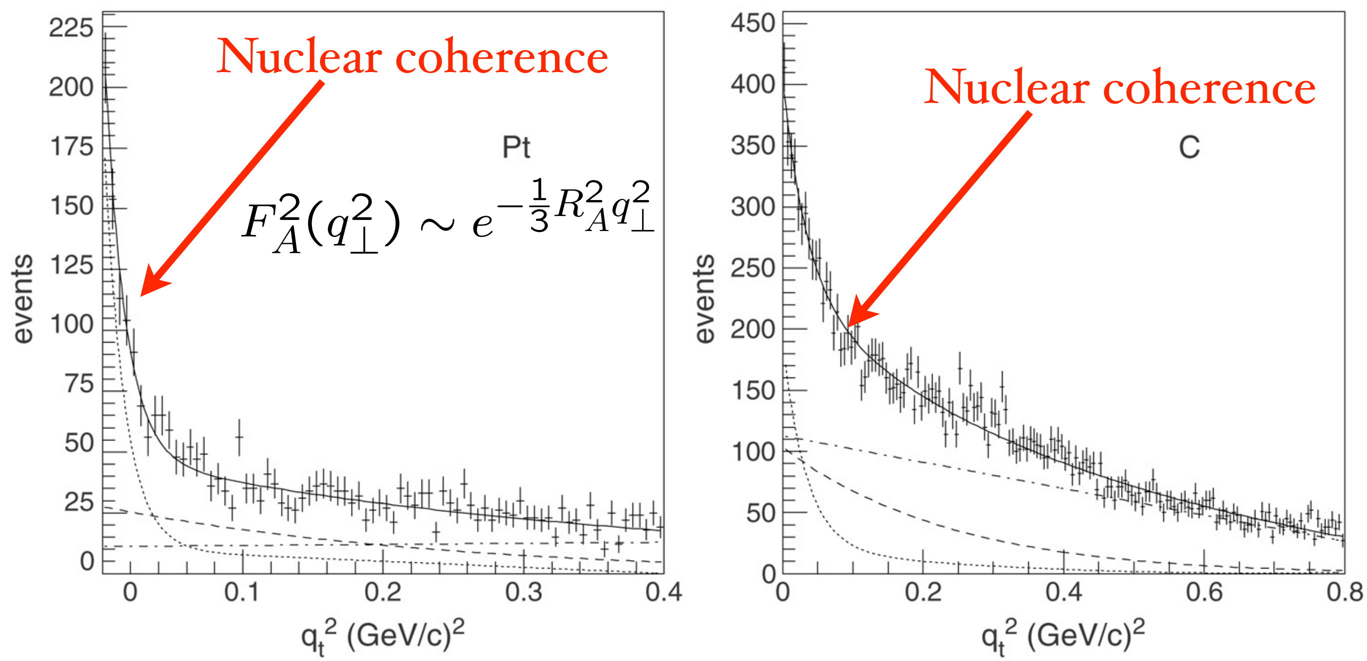
- Fully coherent interactions between pion and nucleons.

- Emerging Di-Jets do not interact with nucleus.

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

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

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



Ashery E791:
Measure pion LFWF in diffractive dijet production
Confirmation of color transparency, gauge theory of strong interactions

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

Theory predictions; Frankfurt, Miller, Strikman

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

α (Incoh.) = 0.70 ± 0.1

Conventional Glauber Theory Ruled Out !

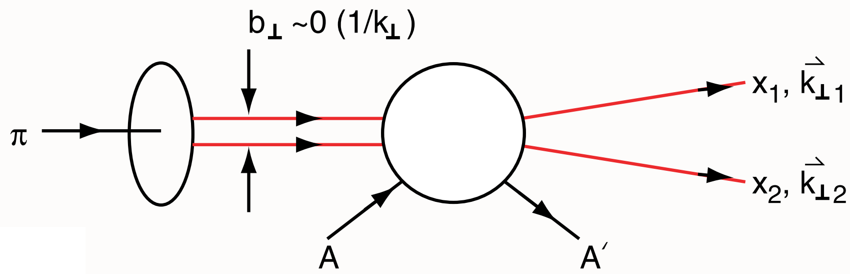
Factor of 7

Color Transparency

A. H. Mueller, sjb
Bertsch, Gunion, Goldhaber, sjb
Frankfurt, Miller, Strikman

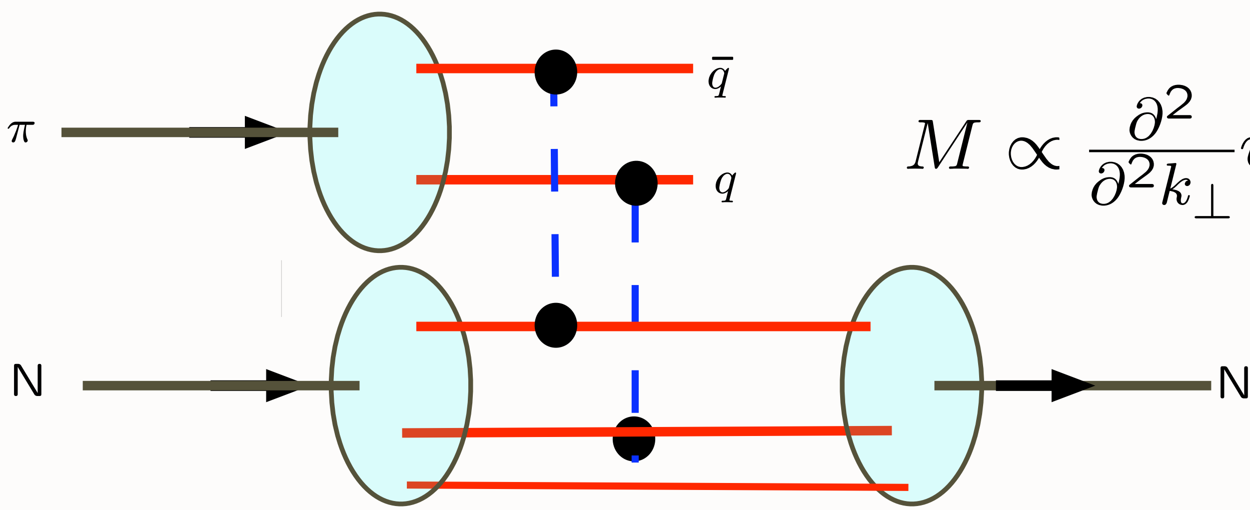
- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

Key Ingredients in Ashery Experiment



Brodsky, Gunion, Frankfurt, Mueller, Strikman
Frankfurt, Miller, Strikman

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

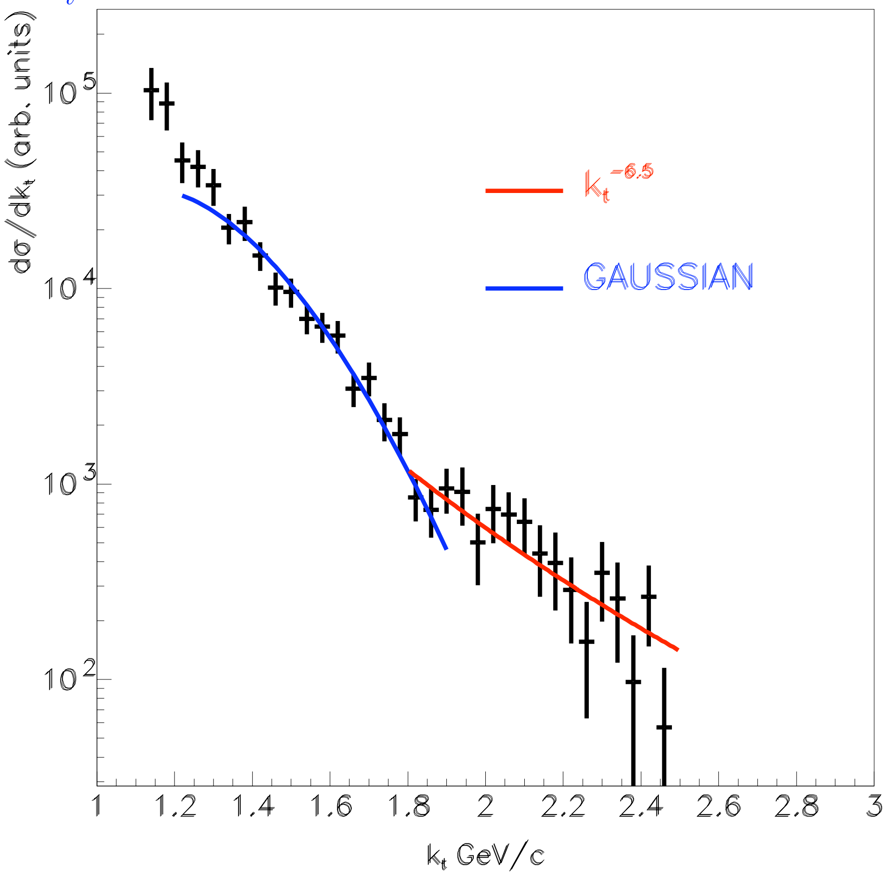


$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

THE k_t DEPENDENCE OF DI-JETS YIELD

$$\frac{d\sigma}{dk_t^2} \propto \left|\alpha_s(k_t^2)G(x,k_t^2)\right|^2 \left|\frac{\partial^2}{\partial k_t^2}\psi(u,k_t)\right|^2$$

With $\psi \sim \frac{\phi}{k_t^2}$, weak $\phi(k_t^2)$ and $\alpha_s(k_t^2)$ dependences and $G(x,k_t^2) \sim k_t^{1/2}$: $\frac{d\sigma}{dk_t} \sim k_t^{-6}$



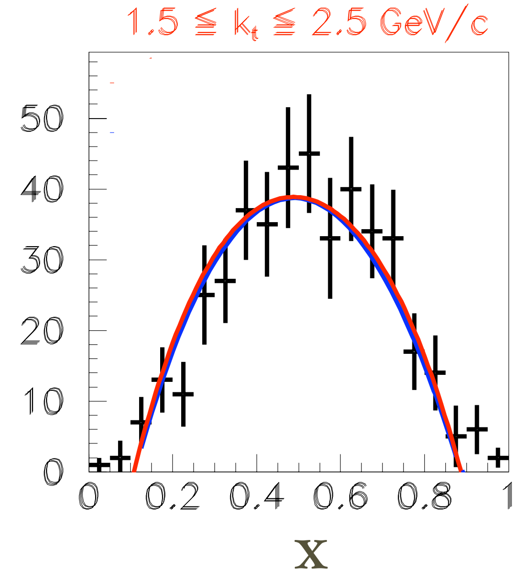
High Transverse momentum dependence consistent with PQCD, ERBL Evolution

Diffractive Dissociation of a Pion into Dijets

$$\pi A \to Jet\,Jet\,A'$$

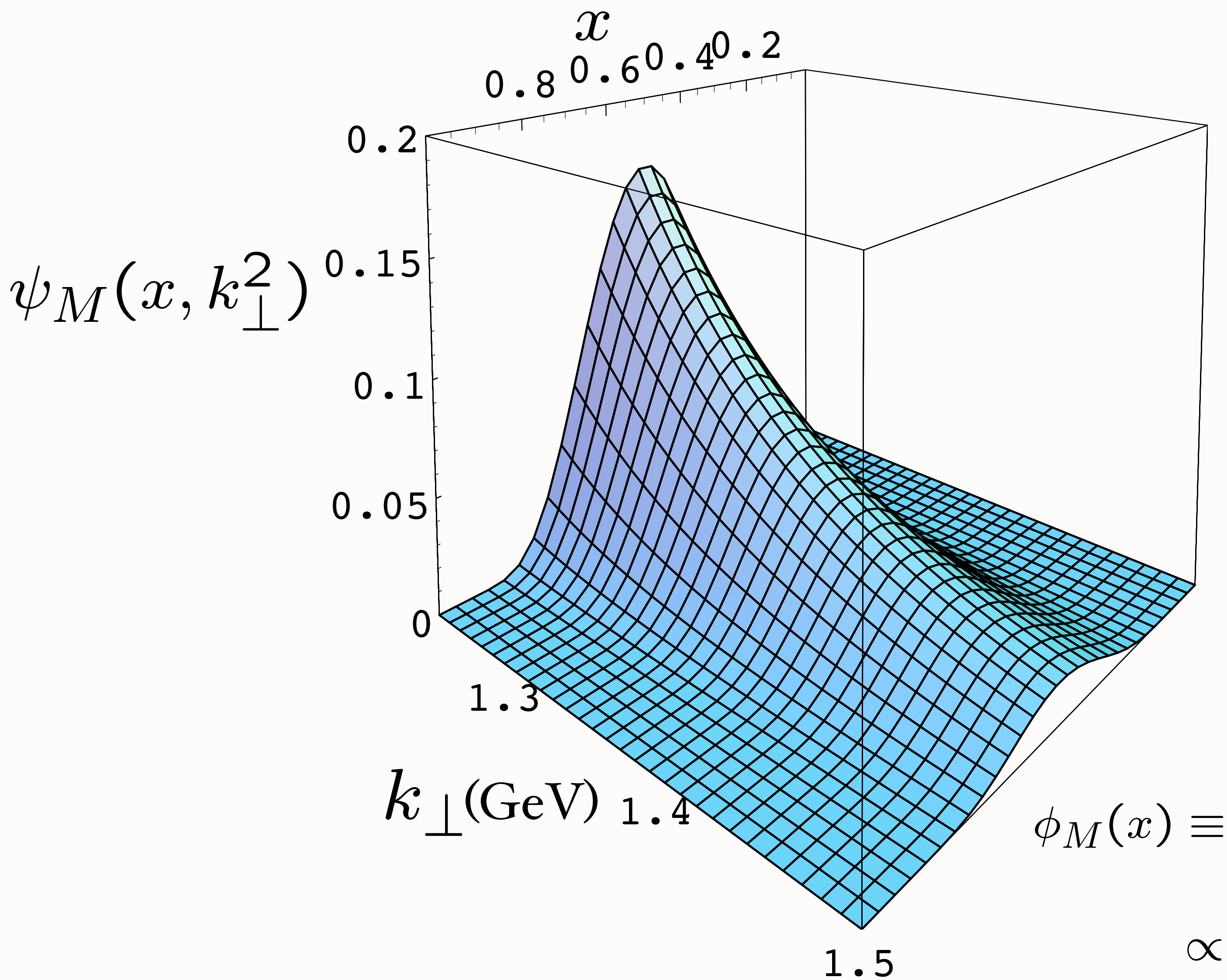
$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_\perp)$$

- E789 Fermilab Experiment Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction



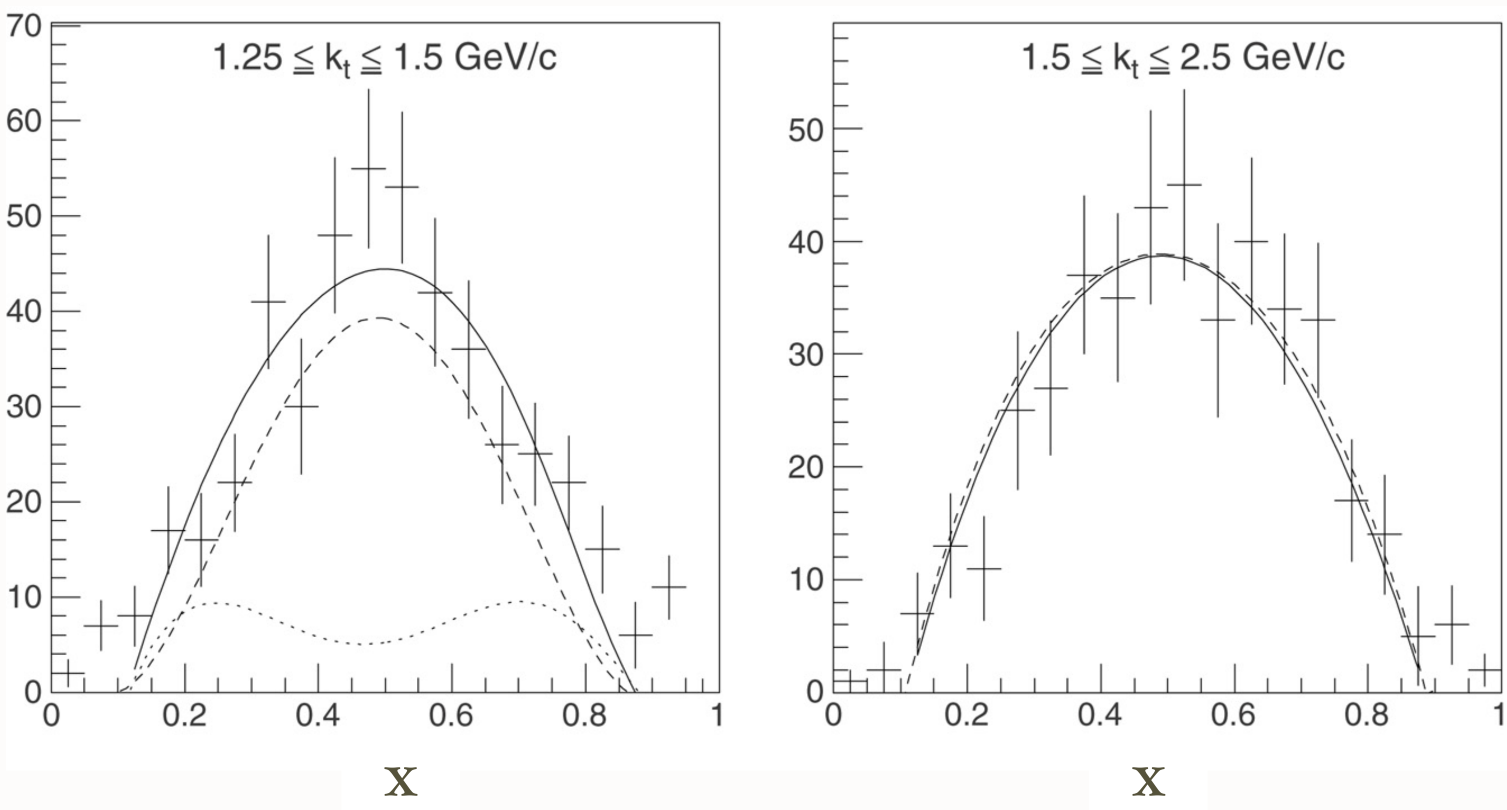
Prediction from AdS/CFT: Meson Light Front WF

de Teramond, sjb



$$\phi_M(x) \equiv \int d^2k_\perp \psi_M(x, \vec{k}_\perp)$$

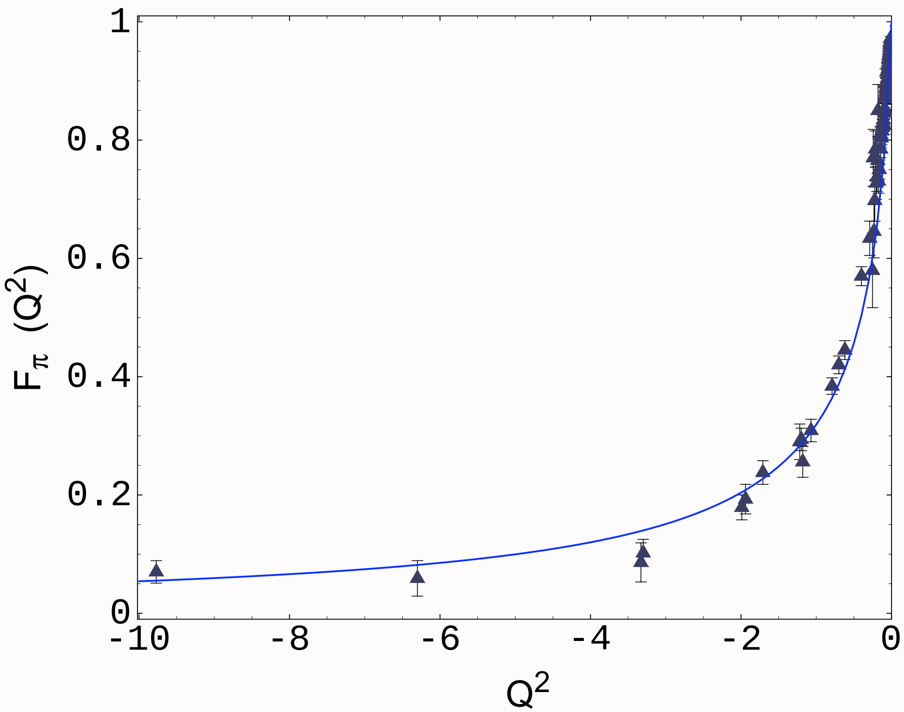
$$\propto f_M \sqrt{x(1-x)}$$



x: distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV/c (left) and for $1.5 \leq k_t \leq 2.5$ GeV/c (right). The solid line is a fit to a combination of the asymptotic and CZ distribution amplitudes. The dashed line shows the contribution from the asymptotic function and the dotted line that of the CZ function.

Change of x distribution at higher jet transverse momentum

ERBL evolution and AdS/CFT

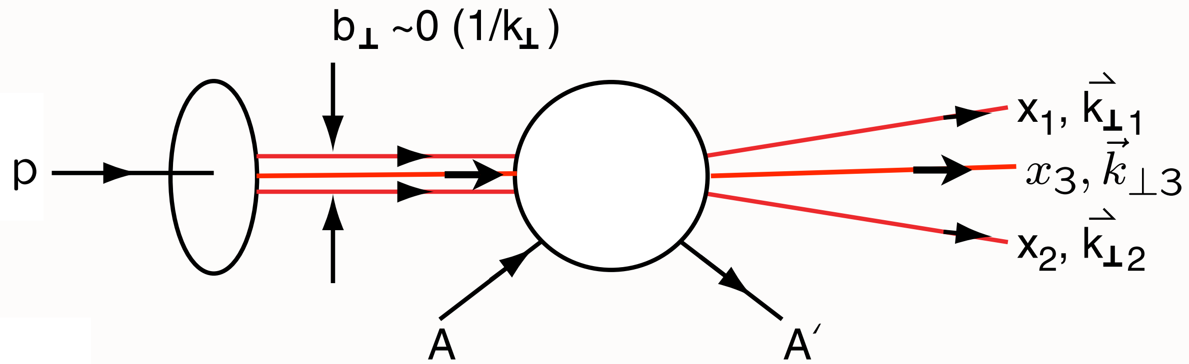


Space-like pion form factor in holographic model for $\Lambda_{QCD} = 0.2$ GeV.

Data Compilation from Baldini, Kloe and Volmer

Diffractive Dissociation of Proton into Quark Jets

Frankfurt, Miller, Strikman



Measure Light-Front Wavefunction of proton

Minimal momentum transfer to nucleus

Nucleus left Intact

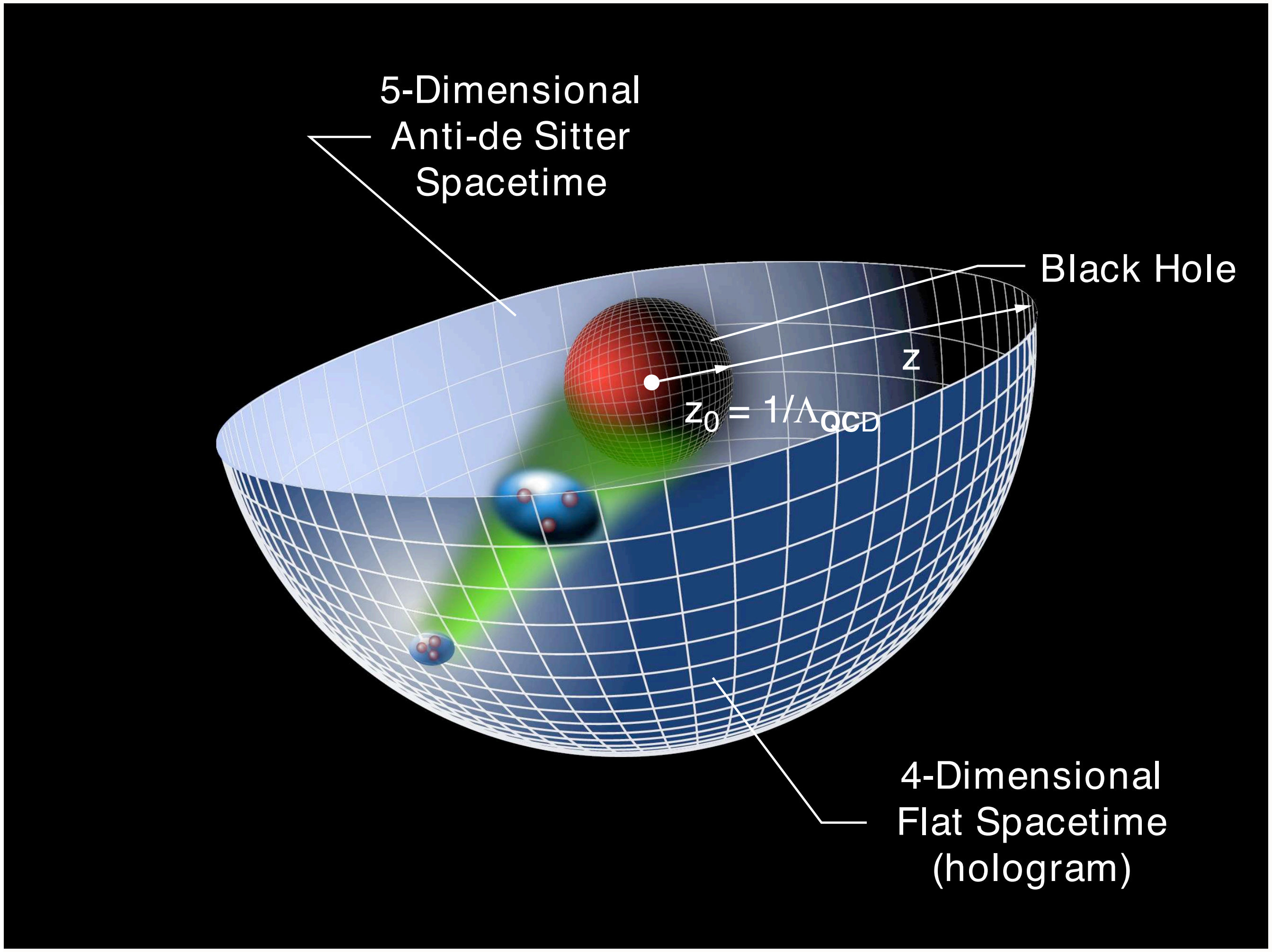
$$M \propto \sum_{ij}^{3} \frac{\partial^2}{\partial \vec{k}_{\perp i} \partial \vec{k}_{\perp j}} \psi_3^p(x_i, \vec{k}_{\perp i})$$

conformal invariance - AdS/CFT

$$\psi_3^p(x_i, \vec{k}_{\perp i}) \simeq \frac{F_p^2}{\mathcal{M}^4} \qquad \mathcal{M}^2 = \sum_i \frac{k_{\perp i}^2}{x_i}$$

LHC with forward acceptance

The Impact of AdS/CFT on QCD Phenomenology



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

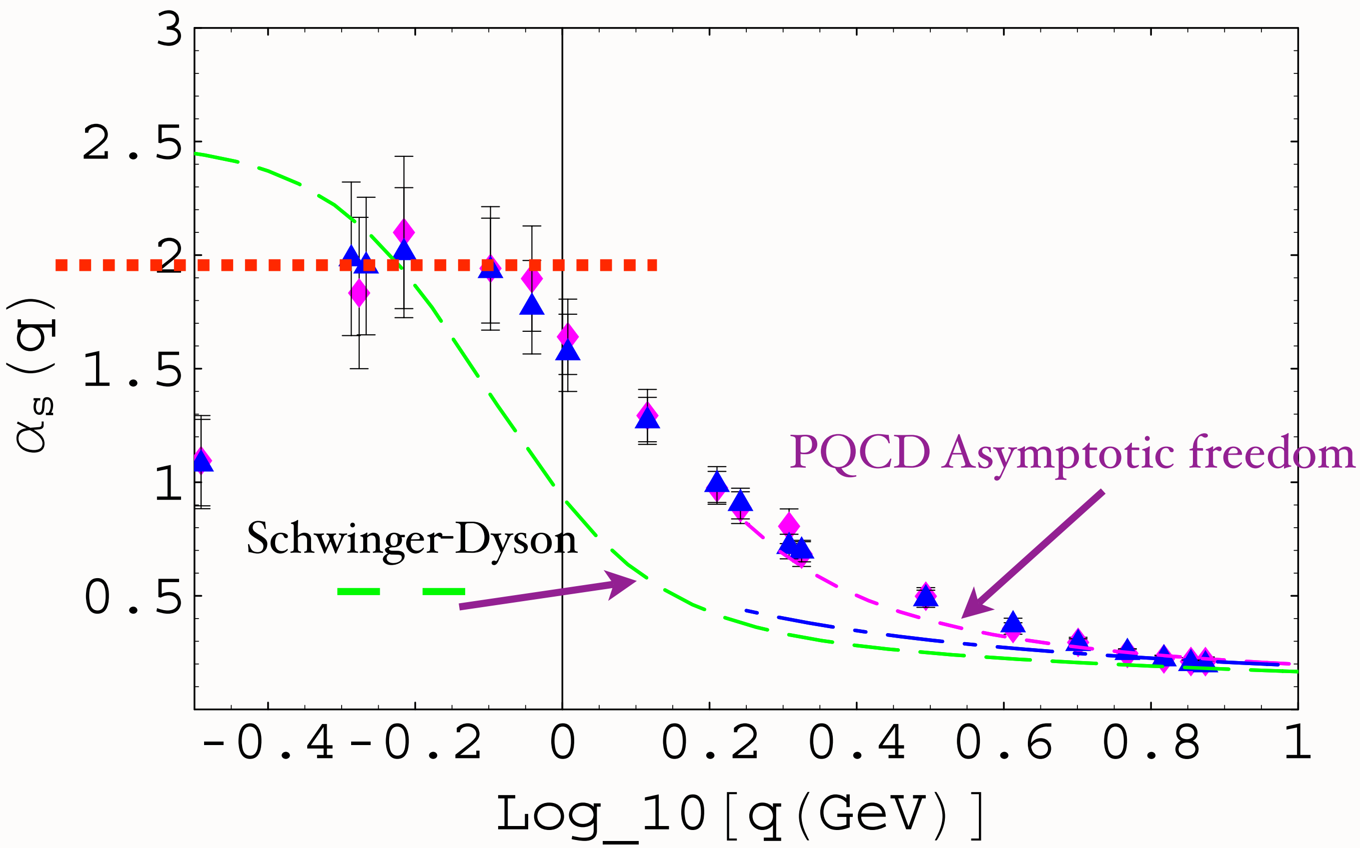
in collaboration with Guy de Teramond

Maldacena:

AdS/CFT: mapping of $AdS_5 \times S_5$ to conformal N=4 SUSY

- QCD not conformal; however, it has some manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes
- IR fixed point? $\alpha_s(Q^2) \simeq \text{const at small } Q^2$
- "Semi-classical" approximation to QCD
- Use mapping of conformal group SO(4,2) to AdS5

Infrared-Finite QCD Coupling?



Shirkov
Gribov
Dokshitser
Siminov
Maxwell

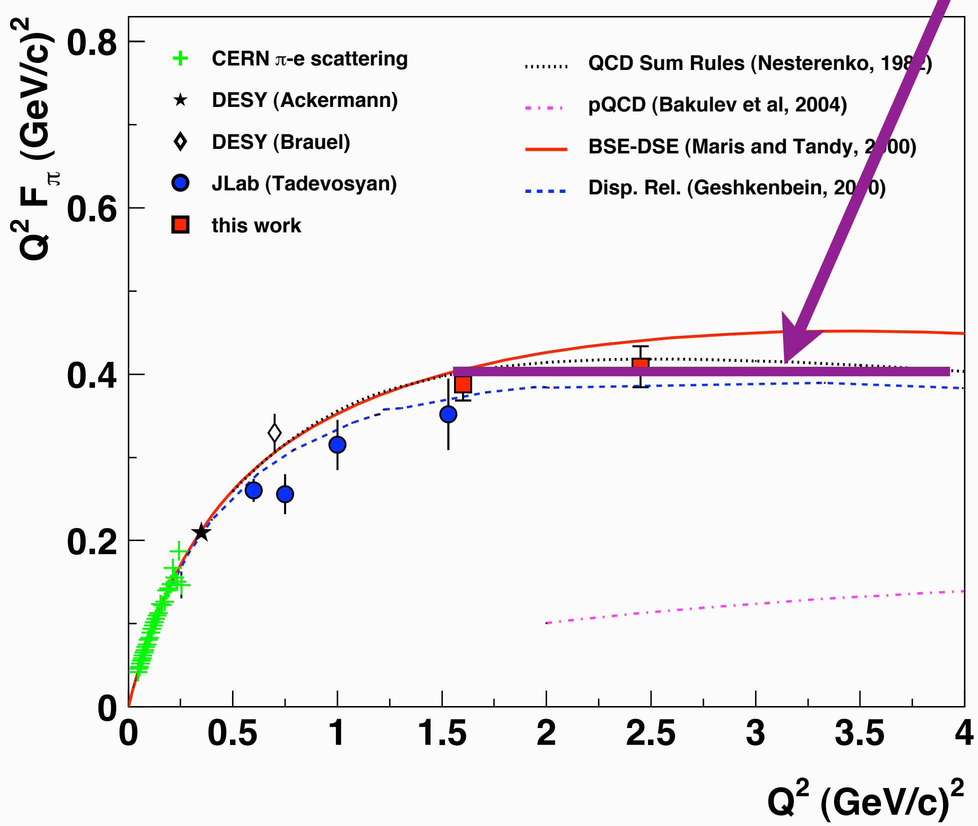
Lattice simulation
(MILC)

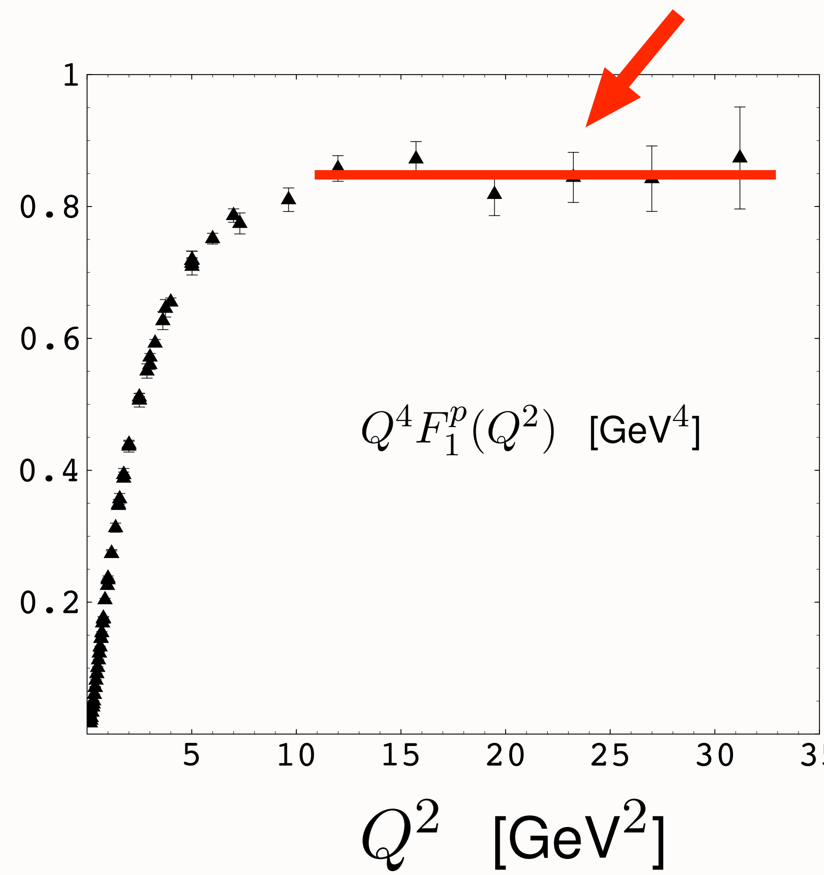
Furui, Nakajima

DSE: Alkofer, Fischer, von Smekal et al.

Conformal behavior: $Q^2 F_\pi(Q^2) \to$ const

$Q^4 F_1(Q^2) \to$ const

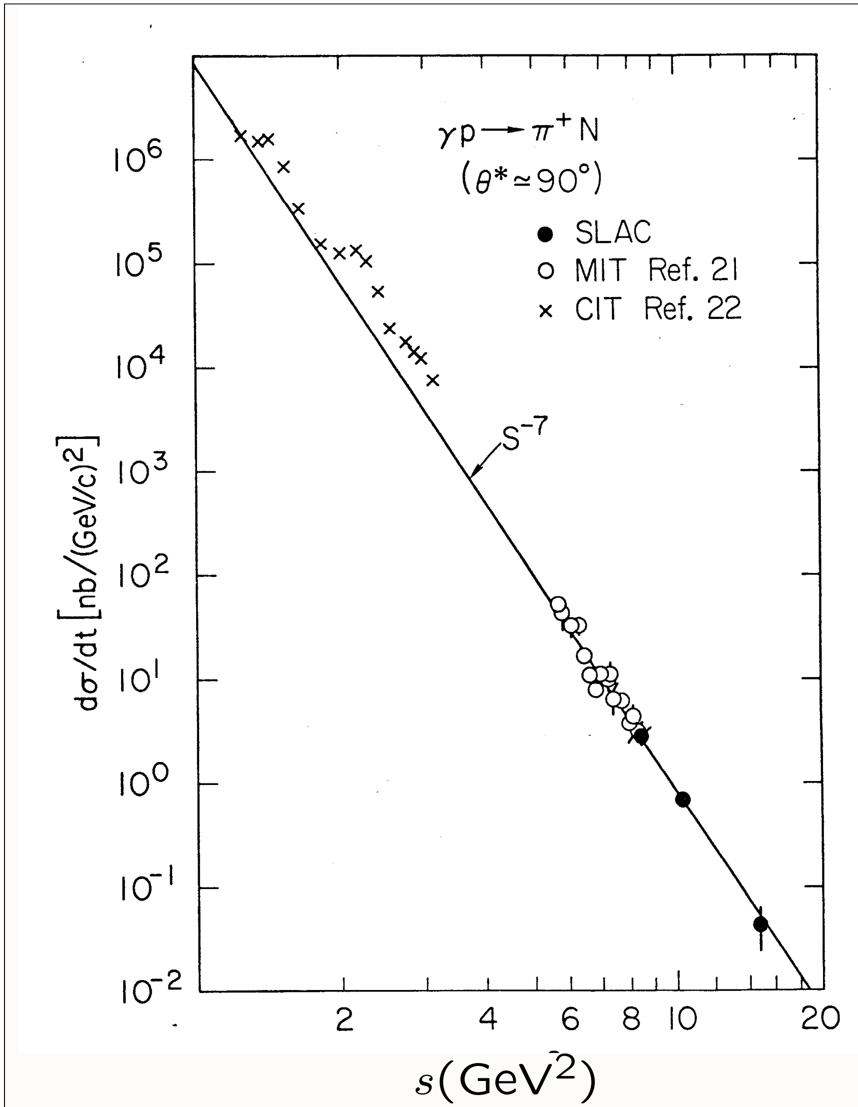


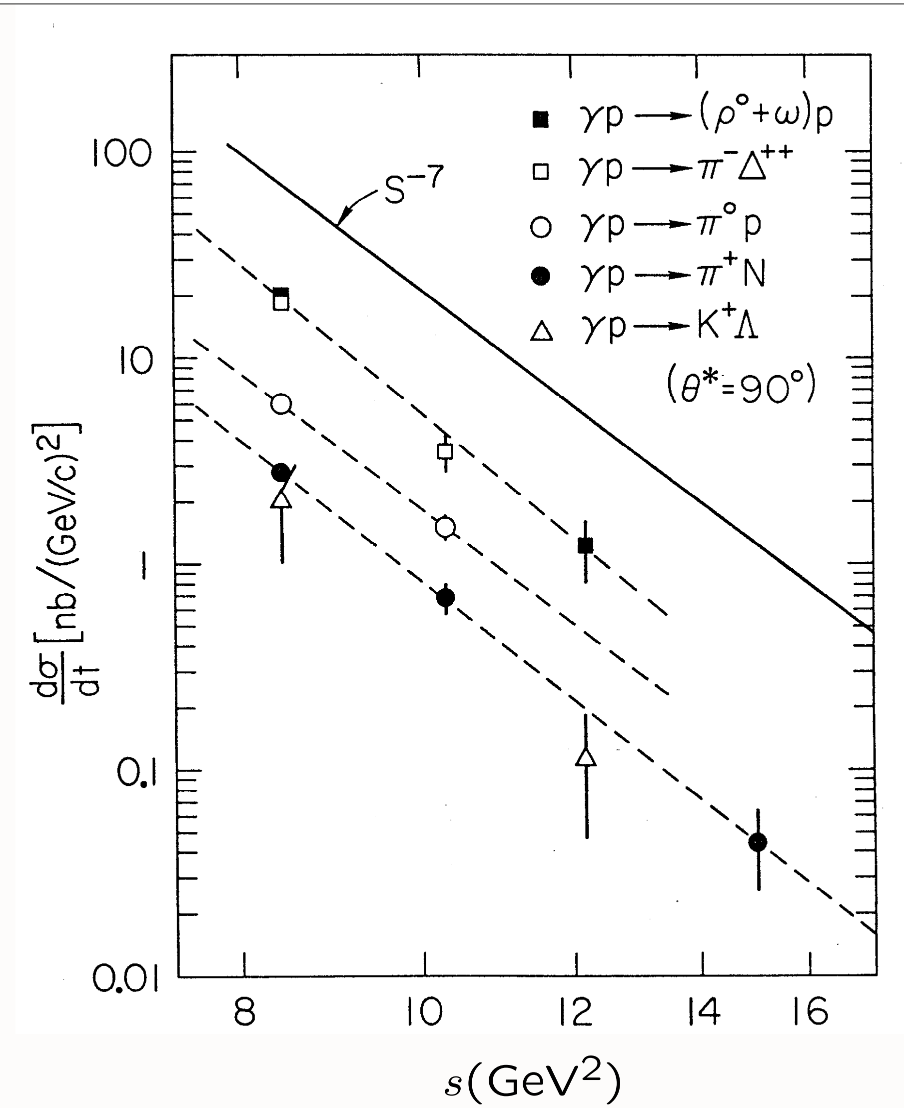


Determination of the Charged Pion Form Factor at Q2=1.60 and 2.45 (GeV/c)2.
By Fpi2 Collaboration (T. Horn *et al.*). Jul 2006. 4pp.
e-Print Archive: **nucl-ex/0607005**

Generalized parton distributions from nucleon form-factor da
M. Diehl (**DESY**) , **Th. Feldmann** (**CERN**) , **R. Jakob**, **P. Kroll** (**W**
DESY-04-146, CERN-PH-04-154, WUB-04-08, Aug 2004. 68pp.
Published in Eur.Phys.J.C39:1-39,2005
e-Print Archive: **hep-ph/0408173**

G. Huber

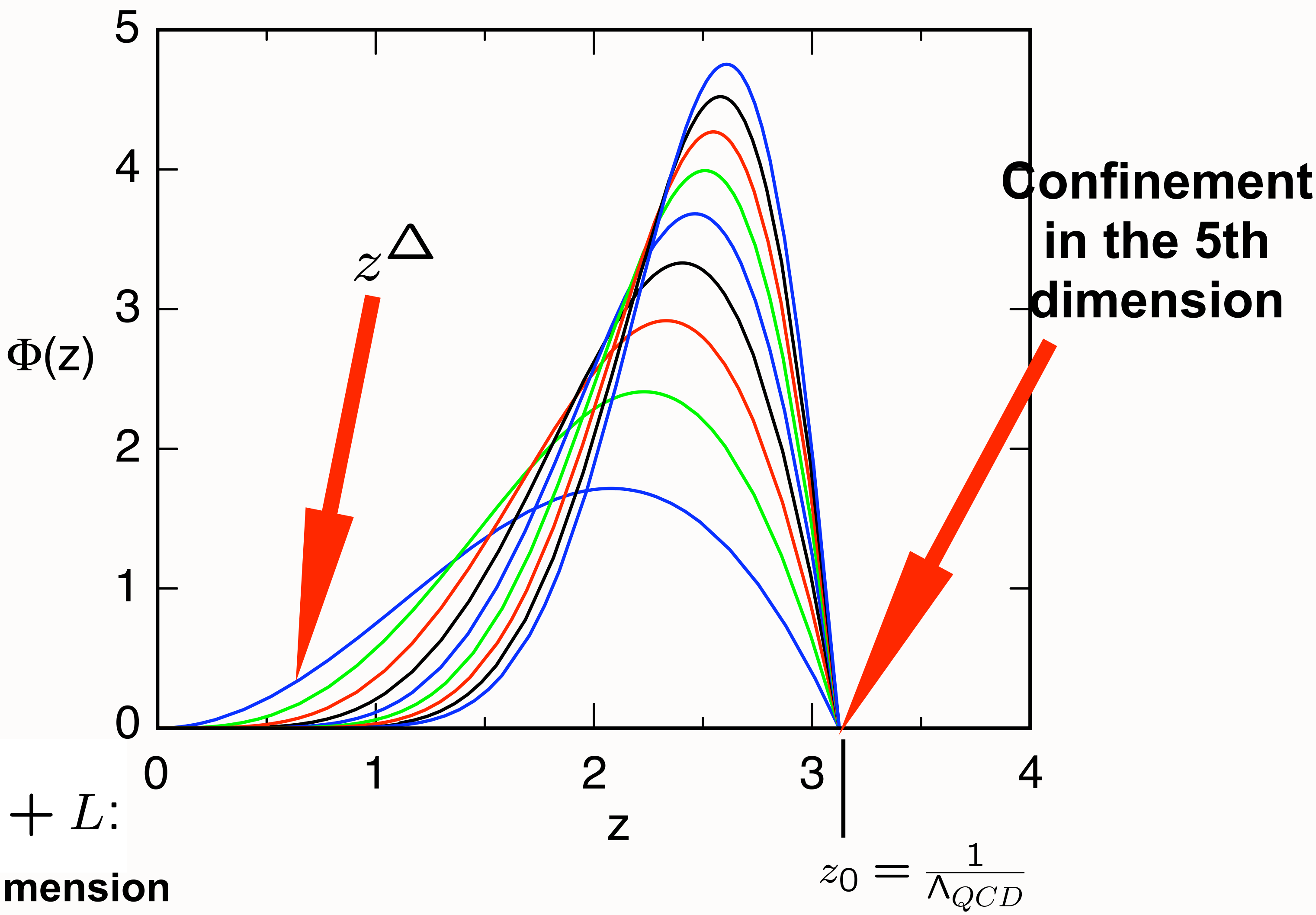




Conformal Invariance:

$$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

Identify hadron by its interpolating operator at z --> 0



$\Delta = 3 + L$:

Twist dimension of baryon

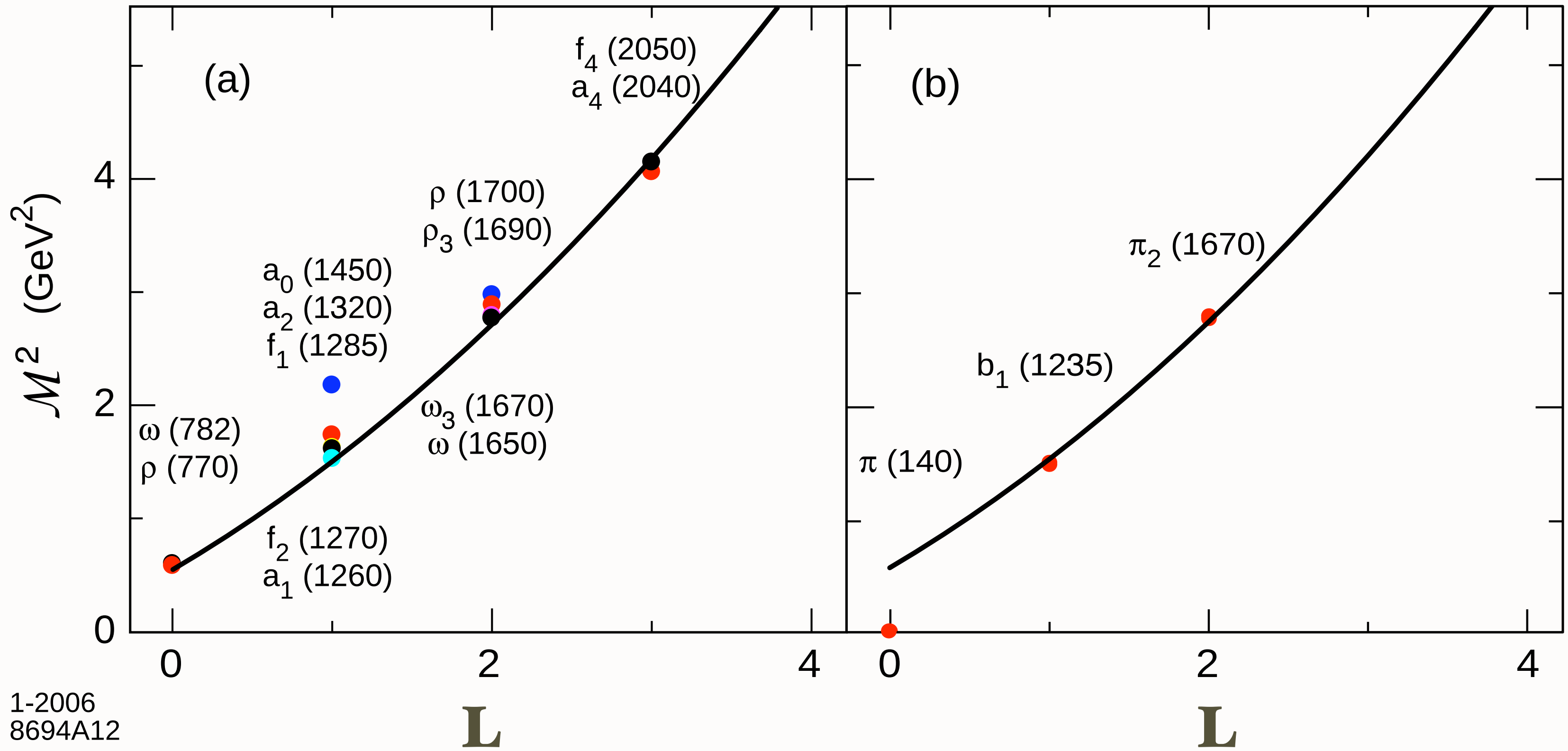
de Teramond, sjb

Guy de Teramond
SJB

AdS/CFT

- Use mapping of conformal group SO(4,2) to AdS5
- Scale Transformations represented by wavefunction $\psi(z)$ in 5th dimension $x_\mu^2 \to \lambda^2 x_\mu^2$ $z \to \lambda z$
- Holographic model: Confinement at large distances and conformal symmetry in interior $0 < z < z_0$
- Match solutions at small z to conformal dimension of hadron wavefunction at short distances $\psi(z) \sim z^\Delta$ at $z \to 0$
- Truncated space simulates "bag" boundary conditions

$$\psi(z_0) = 0 \qquad z_0 = \frac{1}{\Lambda_{QCD}}$$



Light meson orbital spectrum $\Lambda_{QCD} = 0.32 \text{ GeV}$

Guy de Teramond
SJB

Prediction from AdS/QCD

Only one parameter!

Entire light quark baryon spectrum

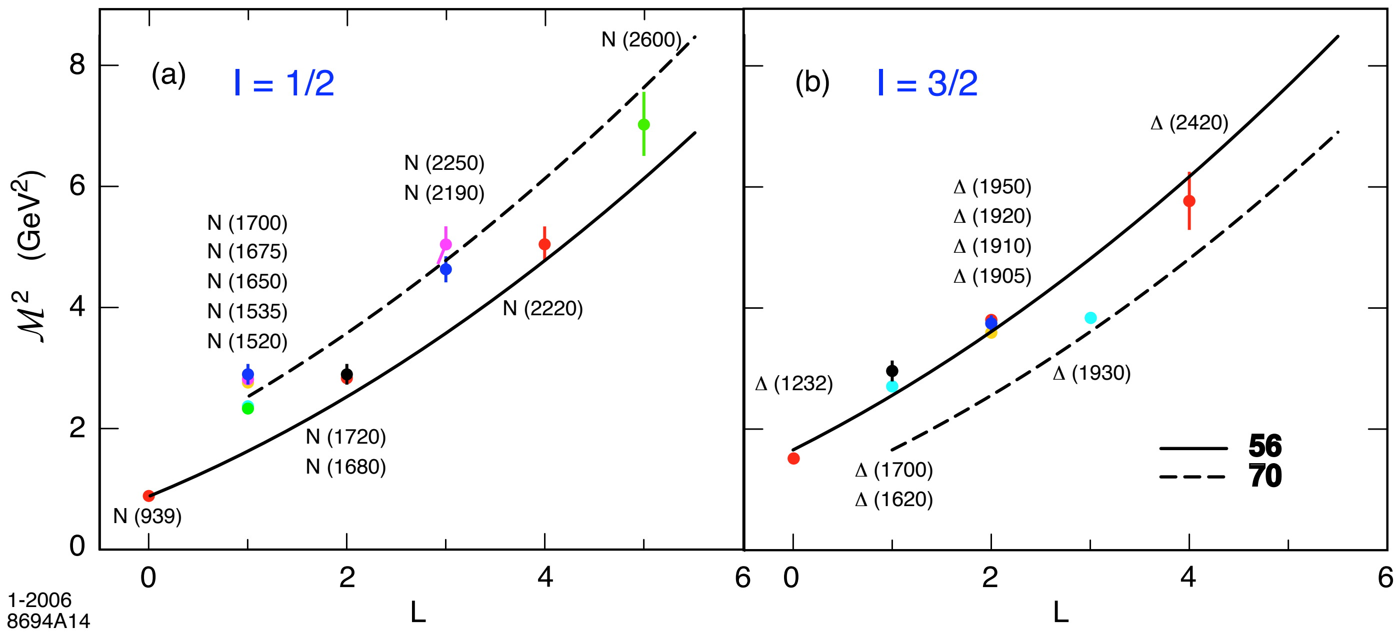


Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The $\mathbf{56}$ trajectory corresponds to L even $P = +$ states, and the $\mathbf{70}$ to L odd $P = -$ states.

Guy de Teramond
SJB

String Theory

AdS/CFT

Mapping of Poincare' and Conformal SO(4,2) symmetries of 3+1 space
to AdS5 space

Goal: First Approximant to QCD

Counting rules for Hard Exclusive Scattering
Regge Trajectories
QCD at the Amplitude Level

AdS/QCD

Conformal behavior at short distances
+ Confinement at large distance

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

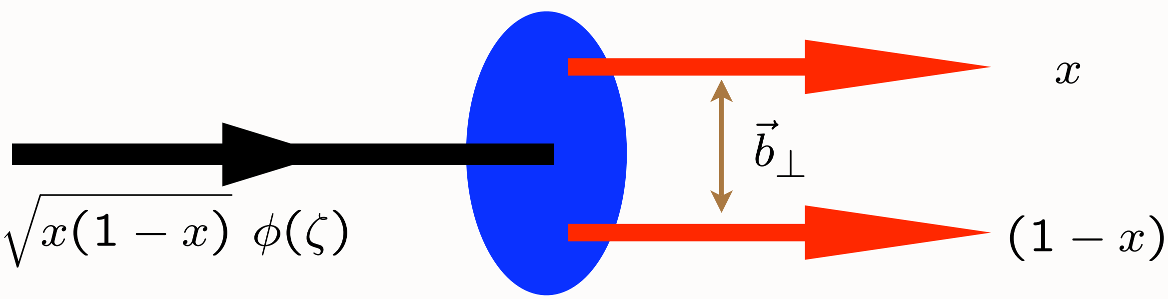
J =0,1,1/2,3/2 plus L

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

Mapping between LF(3+1) and AdS5

LF(3+1)		AdS5
$\psi(x, \vec{b}_\perp)$	$\longleftrightarrow$	$\phi(z)$
$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$	$\longleftrightarrow$	z



$$\psi(x, \vec{b}_\perp) = \sqrt{x(1-x)}\ \phi(\zeta)$$

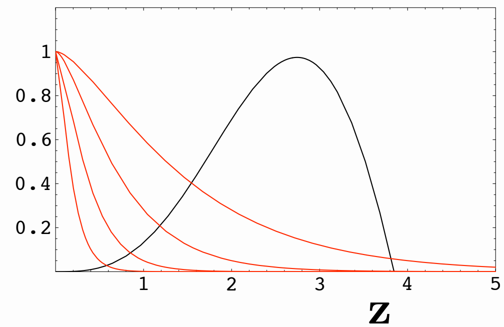
Hadron Form Factors from AdS/CFT

- Propagation of external perturbation suppressed inside AdS.

- At large Q^2 the important integration region is $z \sim 1/Q$.

$$F(Q^2)_{I \to F} = \int \frac{dz}{z^3} \Phi_F(z) J(Q,z) \Phi_I(z)$$

$\mathbf{J}(\mathbf{Q}, \mathbf{z}), \quad \mathbf{\Phi}(\mathbf{z})$



Polchinski, Strassler
de Teramond, sjb

- Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

Dimensional Quark Counting Rules: General result from AdS/CFT

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^{n} \sigma_i$. The twist is equal to the number of partons, $\tau = n$.

Same results using LFWFs.

- Define effective single particle transverse density by (Soper, Phys. Rev. D **15**, 1141 (1977))

$$F(q^2) = \int_0^1 dx \int d^2\vec{\eta}_\perp e^{i\vec{\eta}_\perp \cdot \vec{q}_\perp} \tilde{\rho}(x, \vec{\eta}_\perp)$$

- From DYW expression for the FF in transverse position space:

$$\tilde{\rho}(x, \vec{\eta}_\perp) = \sum_n \prod_{j=1}^{n-1} \int dx_j \, d^2\vec{b}_{\perp j} \, \delta(1 - x - \sum_{j=1}^{n-1} x_j) \, \delta^{(2)}(\sum_{j=1}^{n-1} x_j \vec{b}_{\perp j} - \vec{\eta}_\perp) |\psi_n(x_j, \vec{b}_{\perp j})|^2$$

- Compare with the the form factor in AdS space for arbitrary Q:

$$F(Q^2) = R^3 \int_0^\infty \frac{dz}{z^3} e^{3A(z)} \Phi_{P'}(z) \, J(Q, z) \, \Phi_P(z)$$

- Holographic variable z is expressed in terms of the average transverse separation distance of the spectator constituents $\vec{\eta} = \sum_{j=1}^{n-1} x_j \, \vec{b}_{\perp j}$

$$\boxed{z = \sqrt{\frac{x}{1-x}} \left| \sum_{j=1}^{n-1} x_j \, \vec{b}_{\perp j} \right|}$$

Map AdS/CFT to 3+1 LF Theory

Effective radial equation:

G. de Teramond and sjb

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

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

Effective conformal potential:

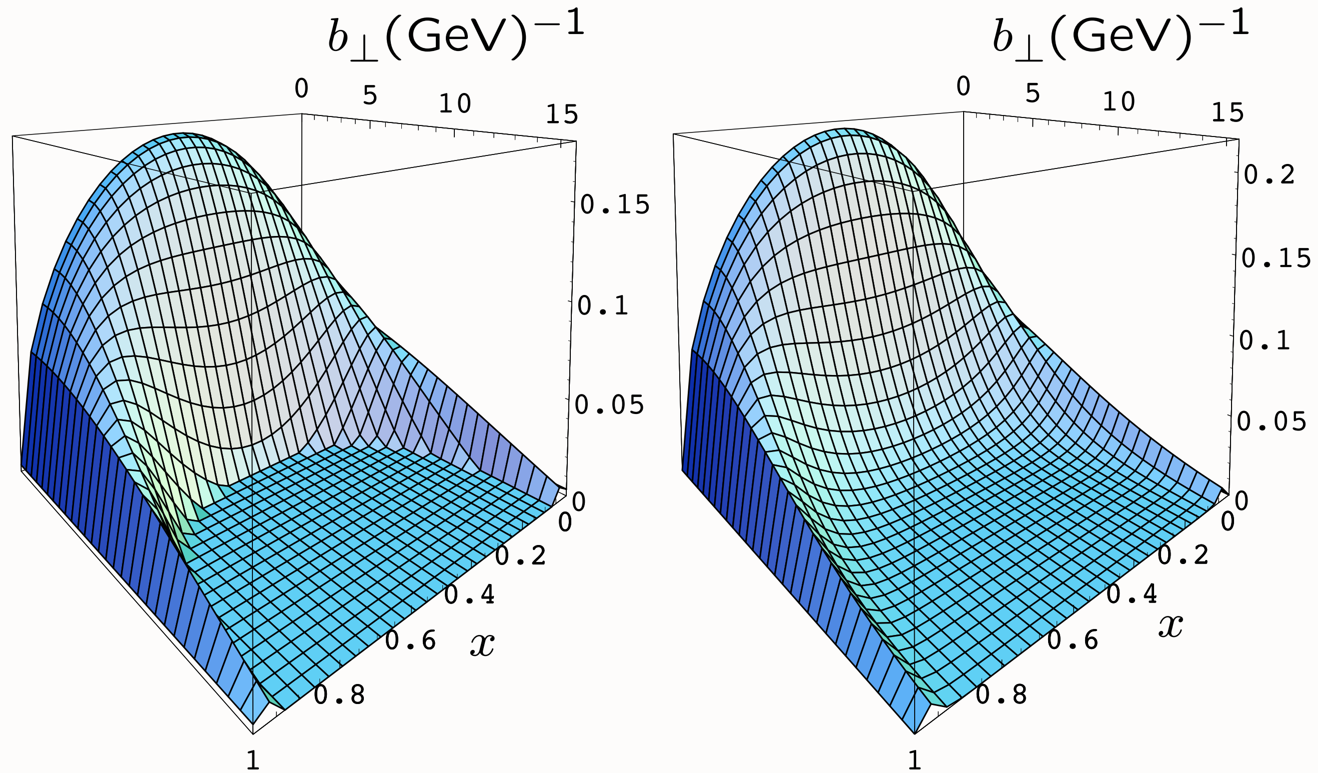
$$V(\zeta) = -\frac{1-4L^2}{4\zeta^2}.$$

General solution:

$$\widetilde{\psi}_{L,k}(x,\vec{b}_\perp) = B_{L,k}\sqrt{x(1-x)}$$

$$J_L\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{L,k}\Lambda_{\mathrm{QCD}}\right)\theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda_{\mathrm{QCD}}^{-2}}{x(1-x)}\right),$$

AdS/CFT Predictions for Meson LFWF $\psi(x, b_\perp)$



Truncated Space ***Harmonic Oscillator***

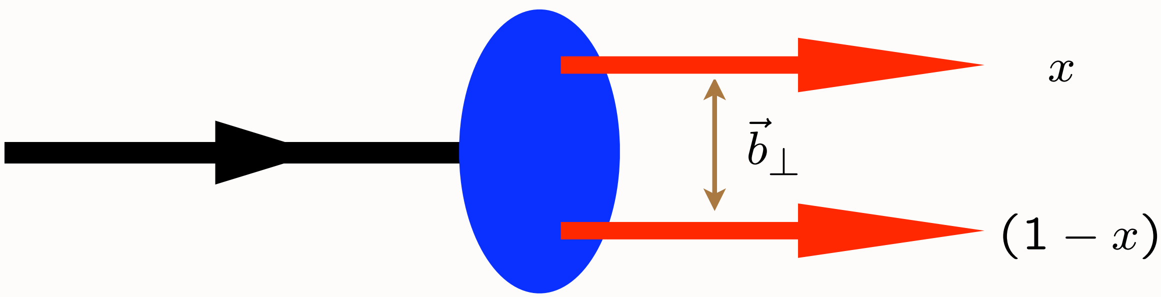
Holography:
Map AdS/CFT to 3+1 LF Theory

Relativistic radial equation: *Frame Independent*

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

G. de Teramond, sjb

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

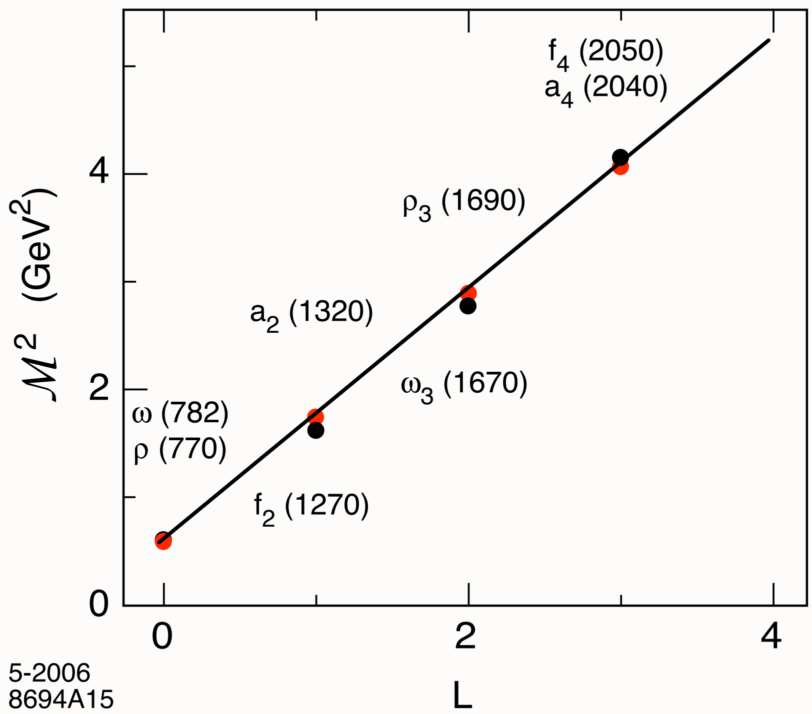


Effective conformal potential:

$$V(\zeta) = -\frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2$$

Karch et al.

add confining potential



$J = L + 1$ vector meson Regge trajectory for $\kappa \simeq 0.54$ GeV

Holographic Harmonic Oscillator Model: Baryons

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

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

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

$$\left(H_{LF} - \mathcal{M}^2\right) \psi(\zeta) = 0, \qquad H_{LF} = \Pi^\dagger \Pi$$

Uncoupled Schrodinger Equations **Harmonic Oscillator Potential!**

$$\left(\frac{d^2}{d\zeta^2} + \frac{1 - 4\nu^2}{4\zeta^2} - \kappa^4 \zeta^2 - 2(\nu+1)\kappa^2 + \mathcal{M}^2\right)\psi_+(\zeta) = 0,$$

$$\left(\frac{d^2}{d\zeta^2} + \frac{1 - 4(\nu+1)^2}{4\zeta^2} - \kappa^4 \zeta^2 - 2\nu\kappa^2 + \mathcal{M}^2\right)\psi_-(\zeta) = 0,$$

Solution

$$\psi_+(\zeta) \sim z^{\frac{1}{2}+\nu} e^{-\kappa^2 \zeta^2/2} L_n^\nu(\kappa^2 \zeta^2),$$

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

Same eigenvalue!

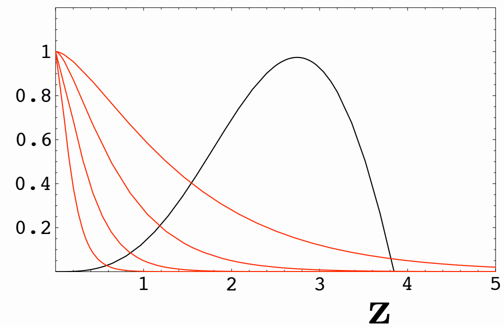
$$\mathcal{M}^2 = 4\kappa^2(n + \nu + 1)$$

Hadron Form Factors from AdS/CFT

- Propagation of external perturbation suppressed inside AdS.
- At large Q^2 the important integration region is $z \sim 1/Q$.

$$F(Q^2)_{I \to F} = \int \frac{dz}{z^3} \Phi_F(z) J(Q,z) \Phi_I(z)$$

$\mathbf{J}(\mathbf{Q},\mathbf{z}), \quad \mathbf{\Phi}(\mathbf{z})$



Polchinski, Strassler
de Teramond, sjb

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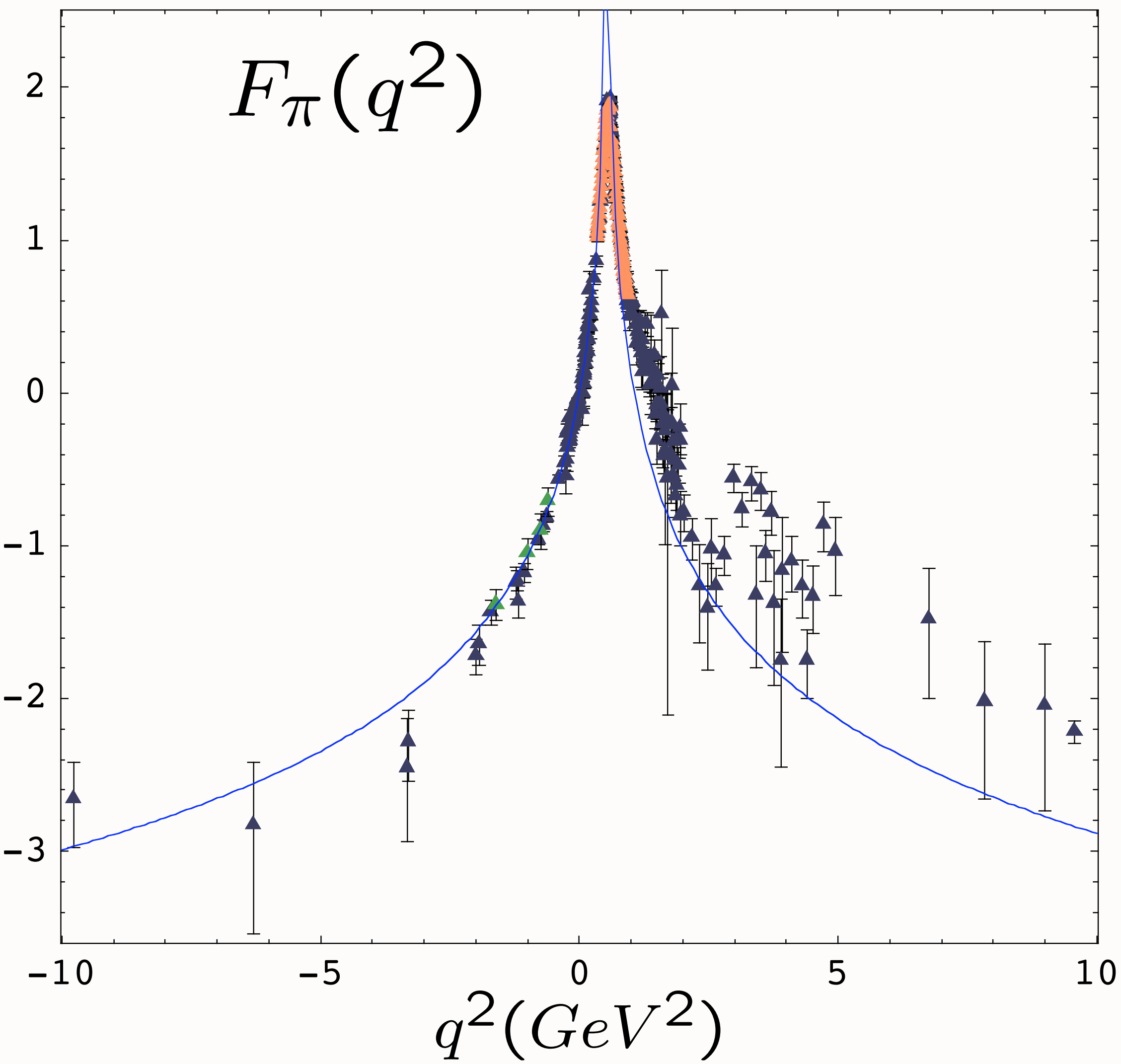
where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^n \sigma_i$. The twist is equal to the number of partons, $\tau = n$.

Same results using LFWFs.

Spacelike and Timelike Pion form factor from AdS/CFT



G. de Teramond, sjb

One parameter - set by pion decay constant

Harmonic Oscillator Confinement Current modified by metric

Baryon Form Factors

- Coupling of the extended AdS mode with an external gauge field $A^\mu(x,z)$

$$ig_5 \int d^4x\, dz\, \sqrt{g}\, A_\mu(x,z)\, \overline{\Psi}(x,z)\gamma^\mu\Psi(x,z),$$

where

$$\Psi(x,z) = e^{-iP\cdot x}\left[\psi_+(z)u_+(P) + \psi_-(z)u_-(P)\right],$$

$$\psi_+(z) = Cz^2 J_1(zM), \qquad \psi_-(z) = Cz^2 J_2(zM),$$

and

$$u(P)_\pm = \frac{1 \pm \gamma_5}{2}\, u(P).$$

$$\psi_+(z) \equiv \psi^\uparrow(z), \quad \psi_-(z) \equiv \psi^\downarrow(z),$$

the LC $\pm$ spin projection along $\hat{z}$.

- Constant C determined by charge normalization:

$$C = \frac{\sqrt{2}\Lambda_{\rm QCD}}{R^{3/2}\left[-J_0(\beta_{1,1})J_2(\beta_{1,1})\right]^{1/2}}.$$

Nucleon Form Factors

- Consider the spin non-flip form factors in the infinite wall approximation

$$F_+(Q^2) = g_+ R^3 \int \frac{dz}{z^3} \, J(Q,z) \, |\psi_+(z)|^2,$$
$$F_-(Q^2) = g_- R^3 \int \frac{dz}{z^3} \, J(Q,z) \, |\psi_-(z)|^2,$$

where the effective charges g_+ and g_- are determined from the spin-flavor structure of the theory.

- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(z)$ and $\psi_-(z)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

- For $SU(6)$ spin-flavor symmetry

$$F_1^p(Q^2) = R^3 \int \frac{dz}{z^3} \, J(Q,z) |\psi_+(z)|^2,$$
$$F_1^n(Q^2) = -\frac{1}{3} R^3 \int \frac{dz}{z^3} \, J(Q,z) \left[|\psi_+(z)|^2 - |\psi_-(z)|^2 \right],$$

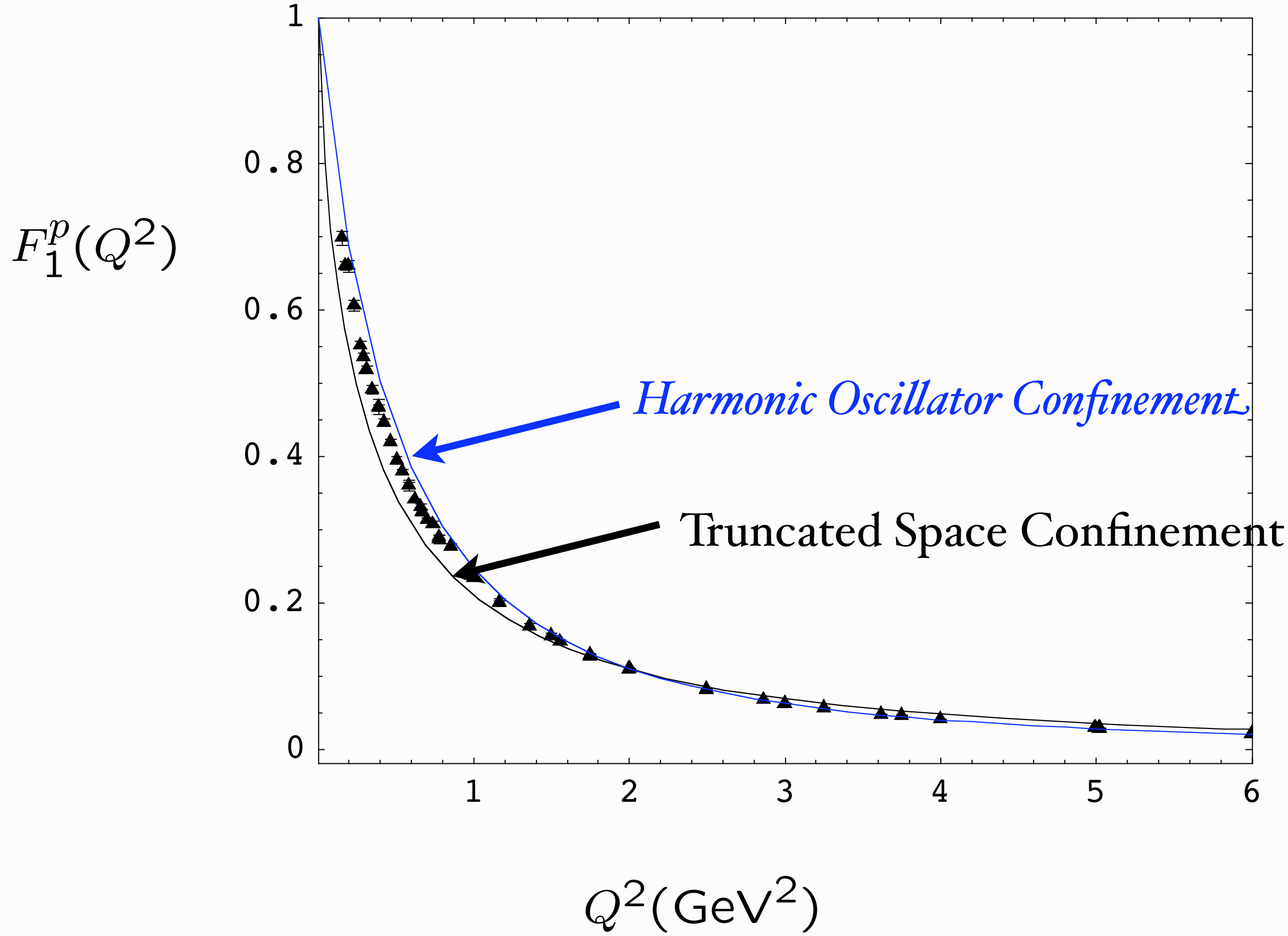
where $F_1^p(0) = 1, \; F_1^n(0) = 0$.

- Large Q power scaling: $F_1(Q^2) \to \left[1/Q^2\right]^2$.

G. de Teramond, sjb

G. de Teramond, sjb

Preliminary



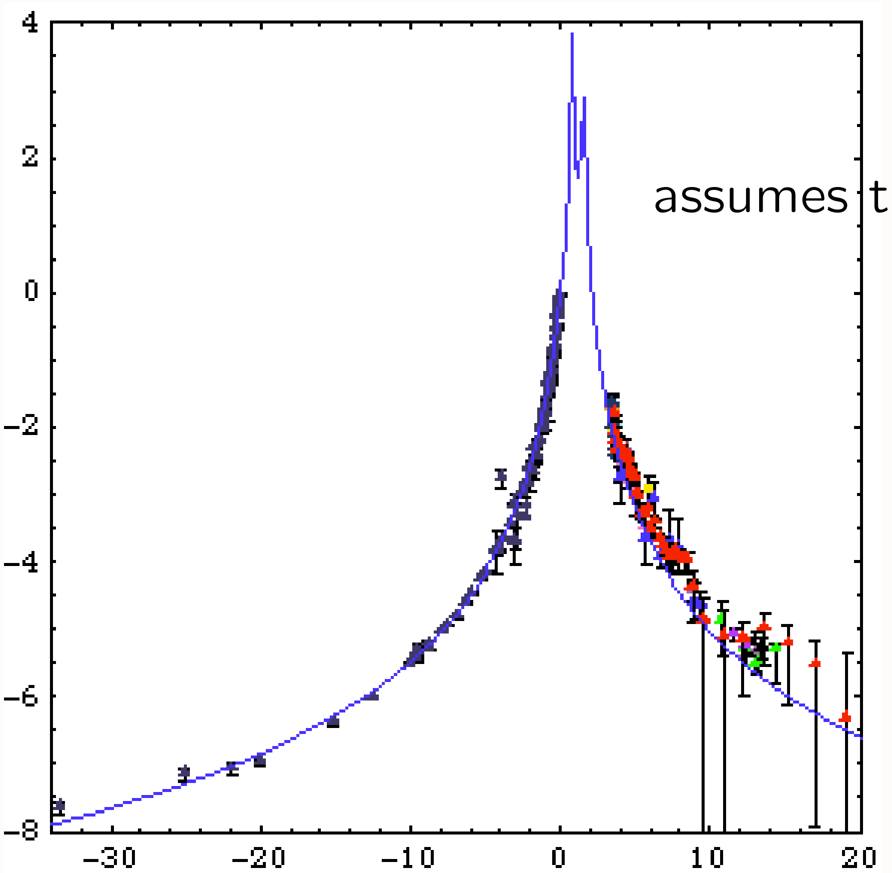
$\kappa = 0.454$ GeV

$\Lambda = 0.2$ GeV

Current modified by metric

$$F_1(Q^2)_{I \to F} = \int \frac{dz}{z^3} \Phi_F^{\uparrow}(z) J(Q,z) \Phi_I^{\uparrow}(z)$$

Spacelike and Timelike Proton Form Factor from AdS/CFT



$G_M^p(q^2)$

assumes timelike $|G_M^p| = |G_E^p|$

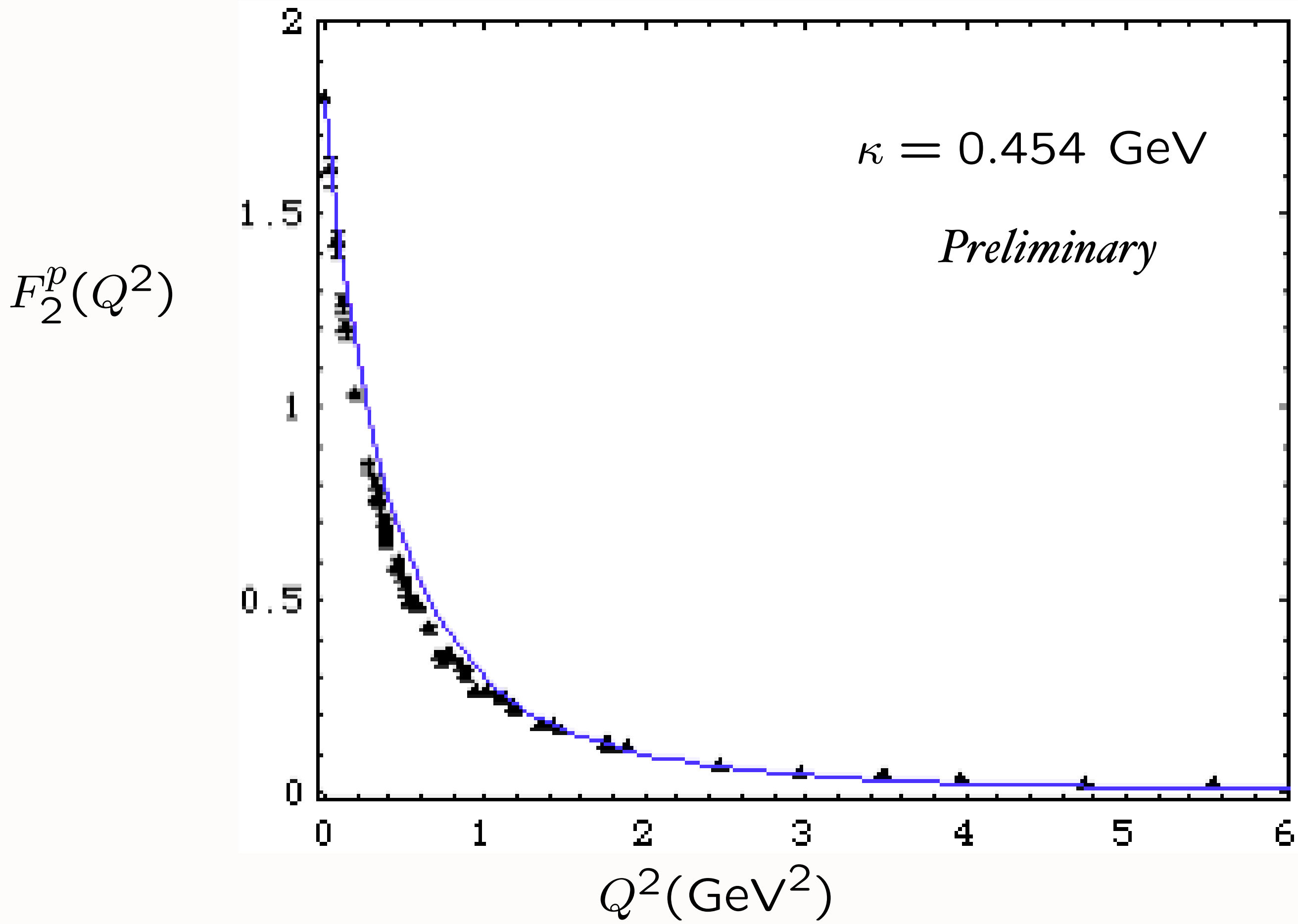
One parameter - set by pion decay constant

Harmonic Oscillator Confinement $q^2(GeV^2)$

G. de Teramond, sjb

$\kappa = 0.424$ GeV

Harmonic Oscillator Confinement

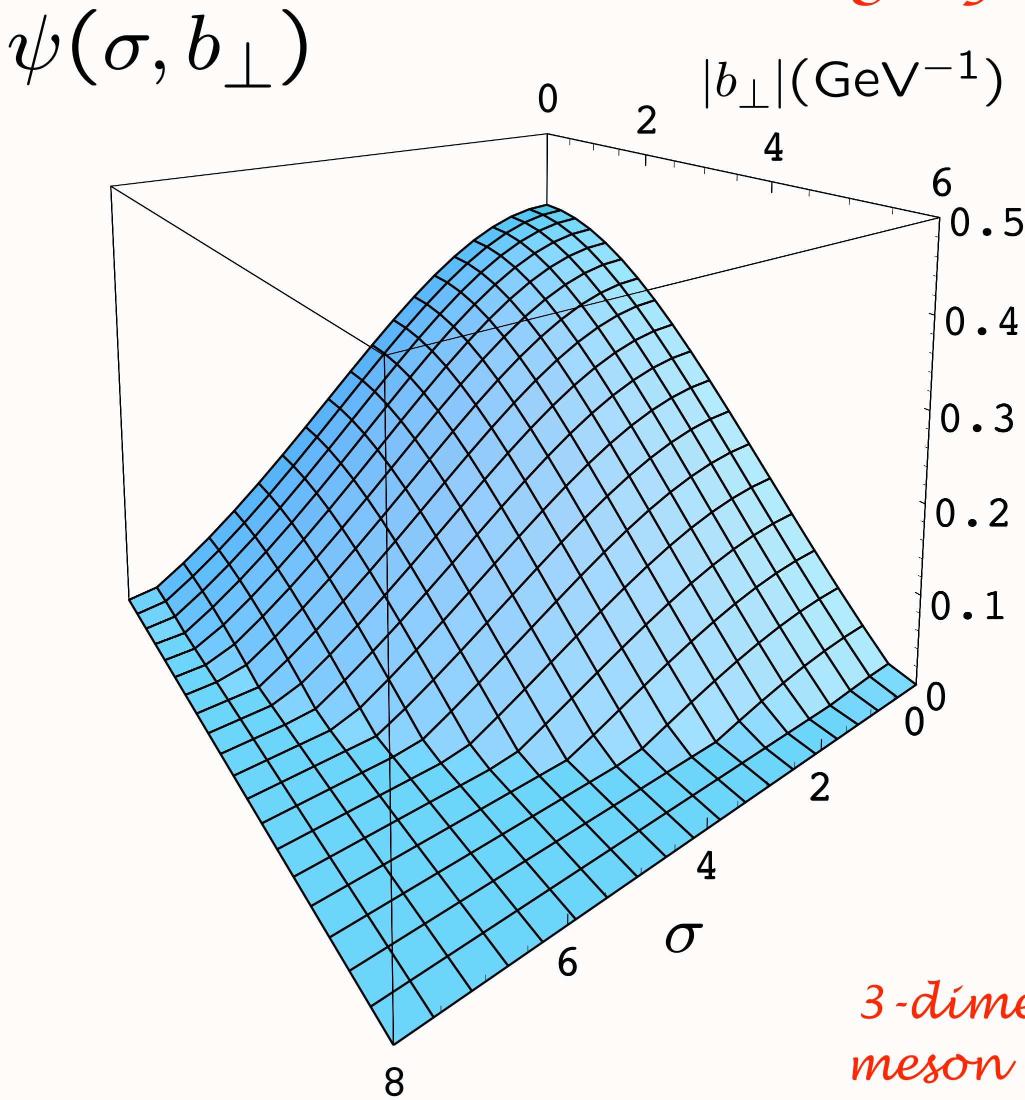


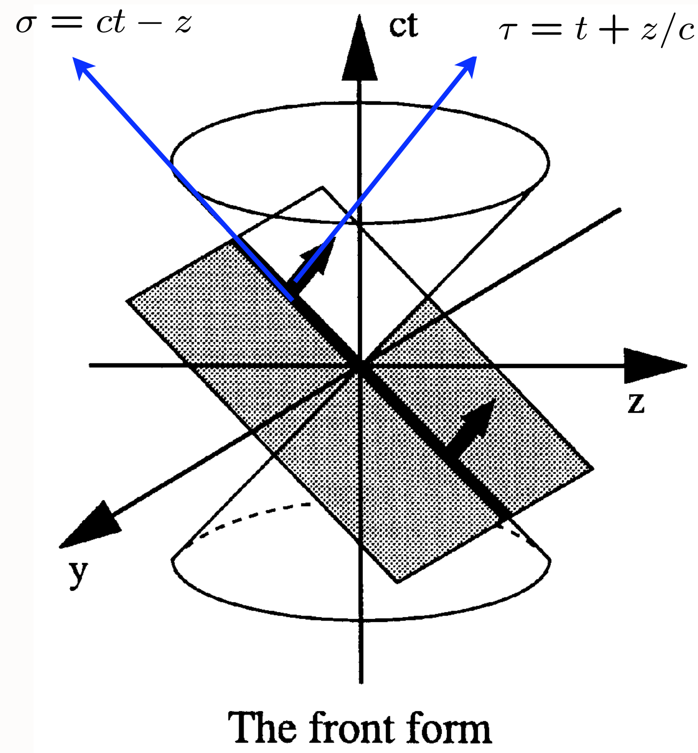
Current modified by metric

$$F_2(Q^2)_{I\to F} = \int \frac{dz}{z^2}\Phi^{\uparrow}_F(z)J(Q,z)\Phi^{\downarrow}_I(z)$$

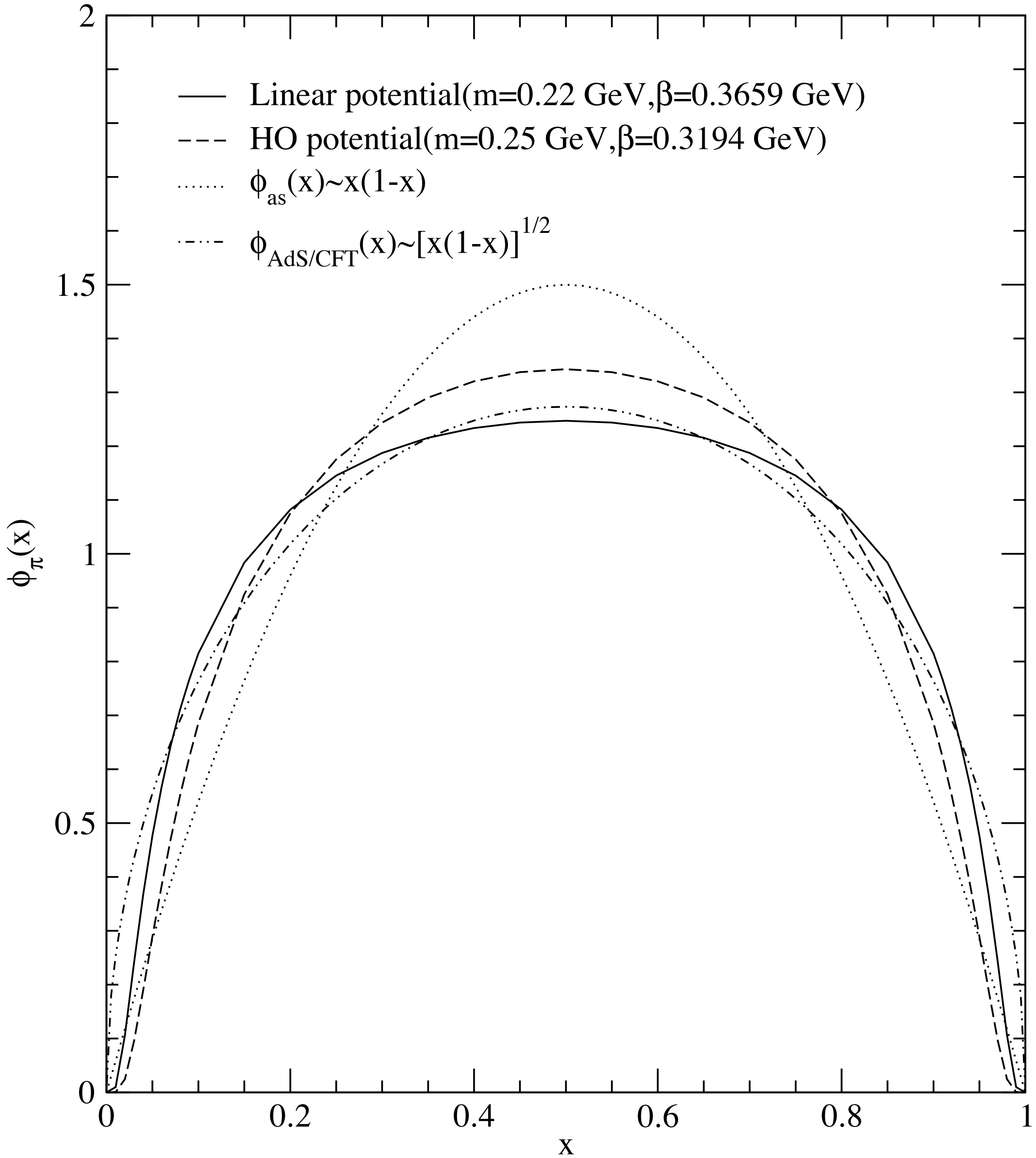
AdS/CFT Holographic Model

G. de Teramond
SJB





3-dimensional photograph:
meson LFWF at fixed LF Time



AdS/CFT:

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

Increases PQCD leading twist prediction for $F_\pi(Q^2)$ by factor 16/9