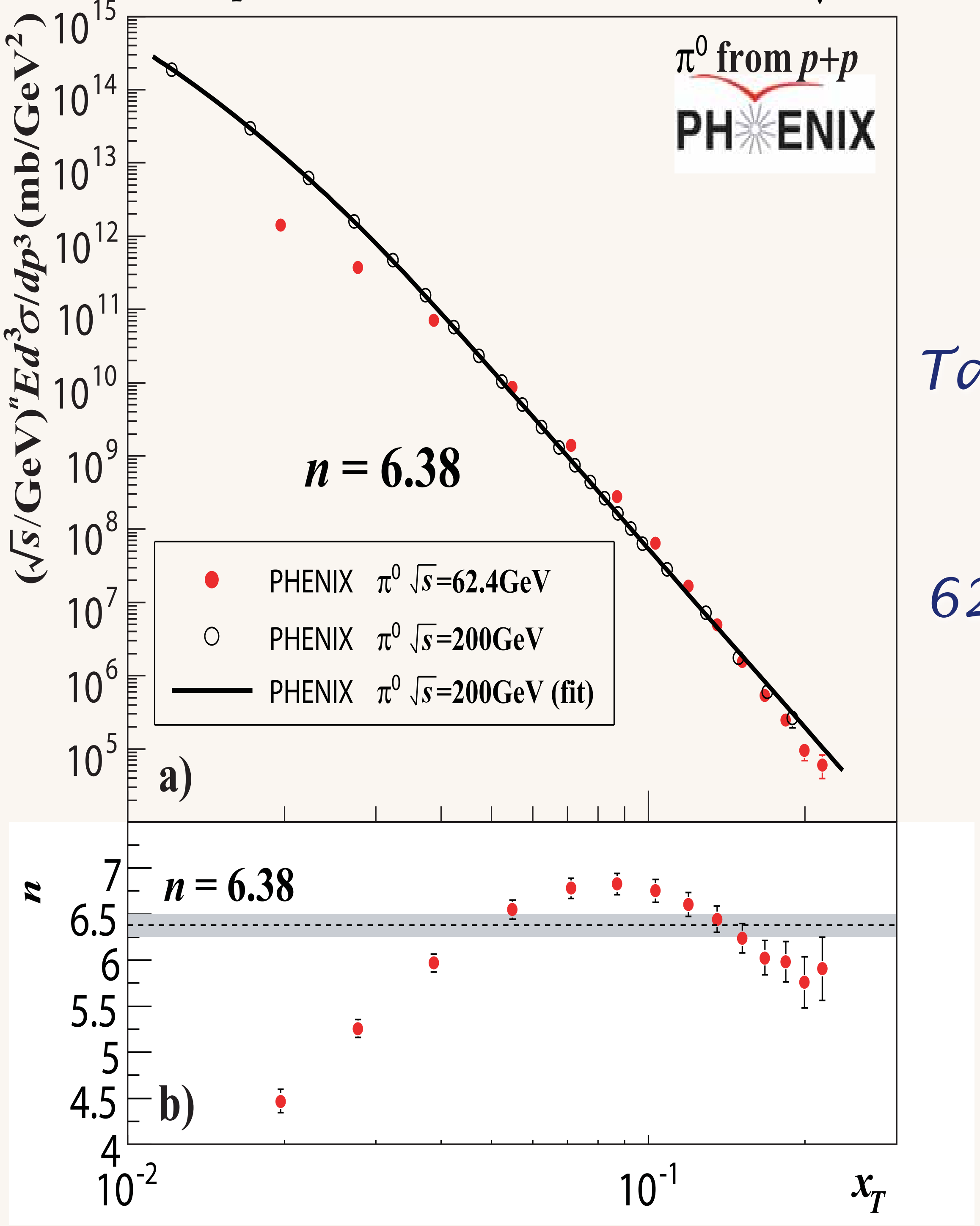
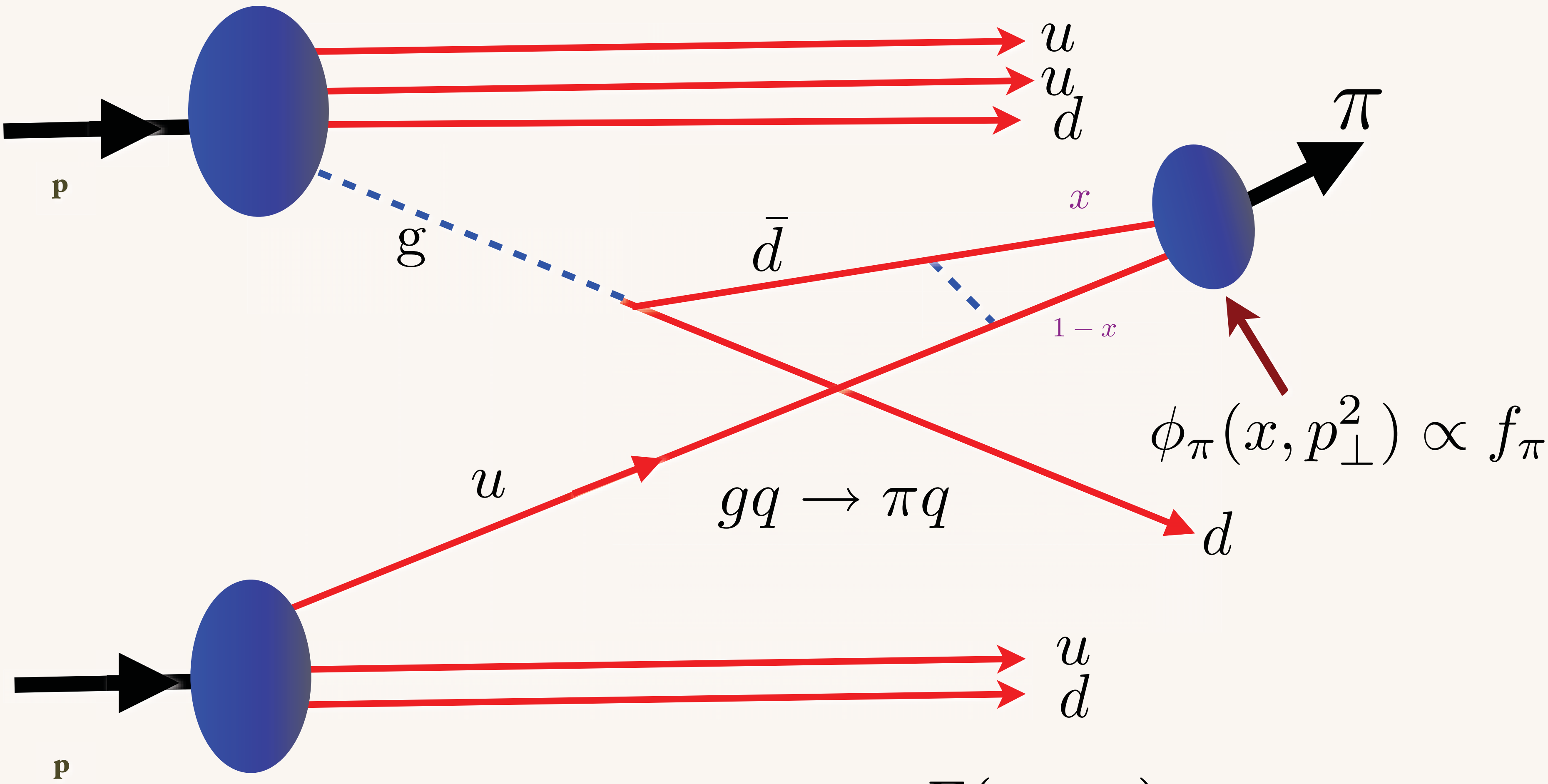
$$\sqrt{s}^{n} E\frac{d\sigma}{d^3p}(pp \to \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}}$$



M. J. Tannenbaum

PHENIX
62.4 and 200
GeV data

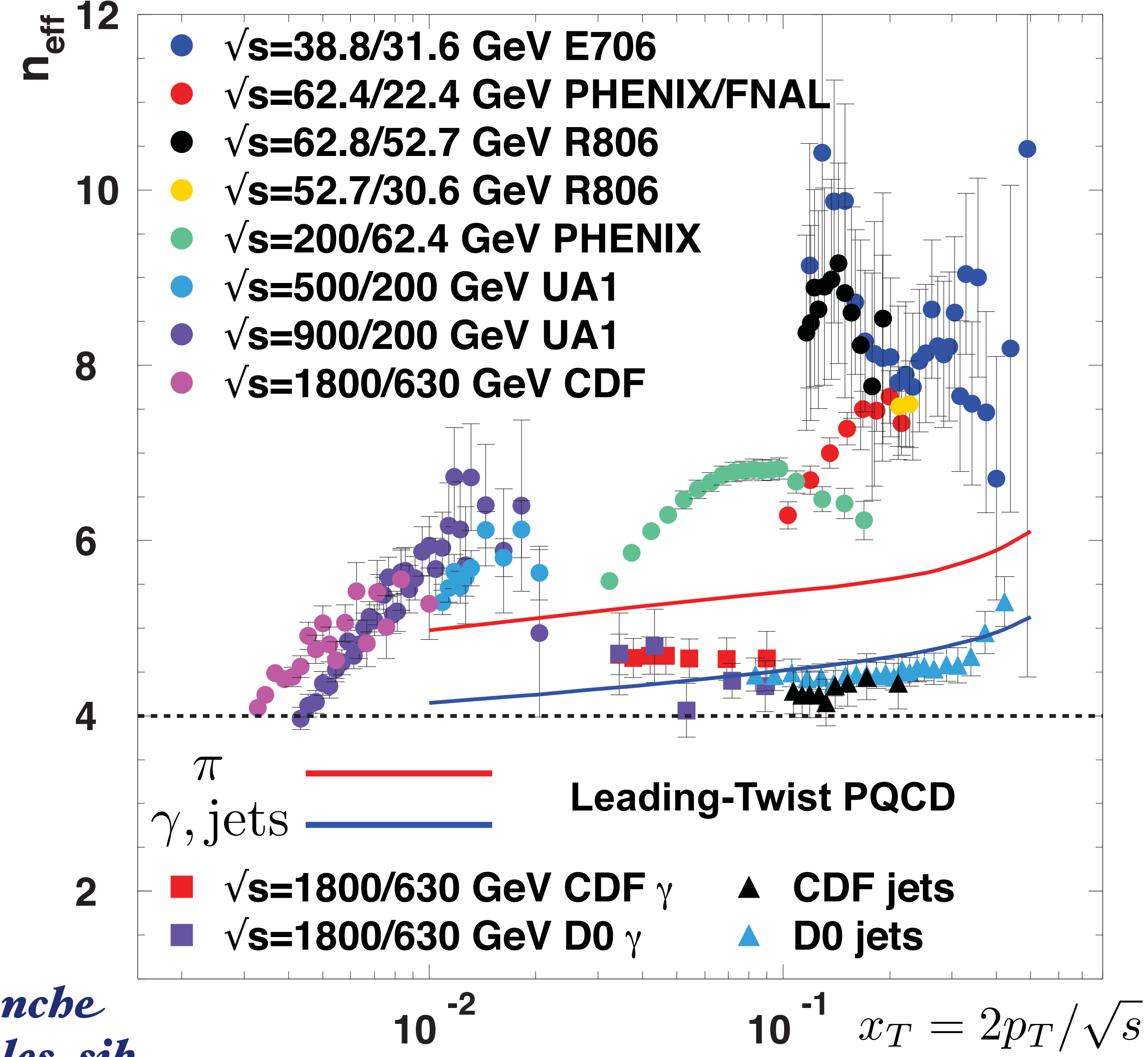
Higher-Twist Contribution to Hadron Production



$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

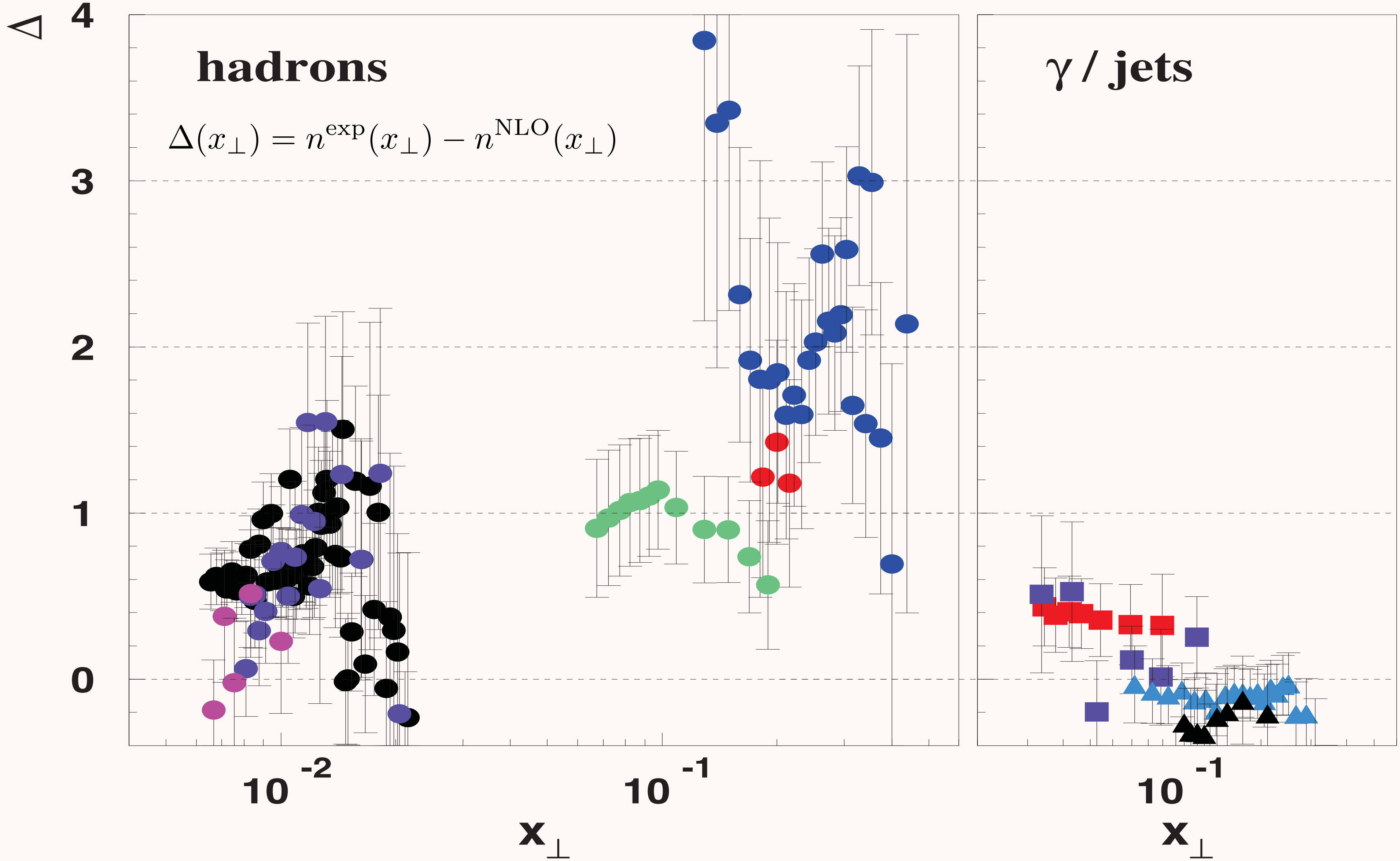
No Fragmentation Function

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{\rm eff}}}$$



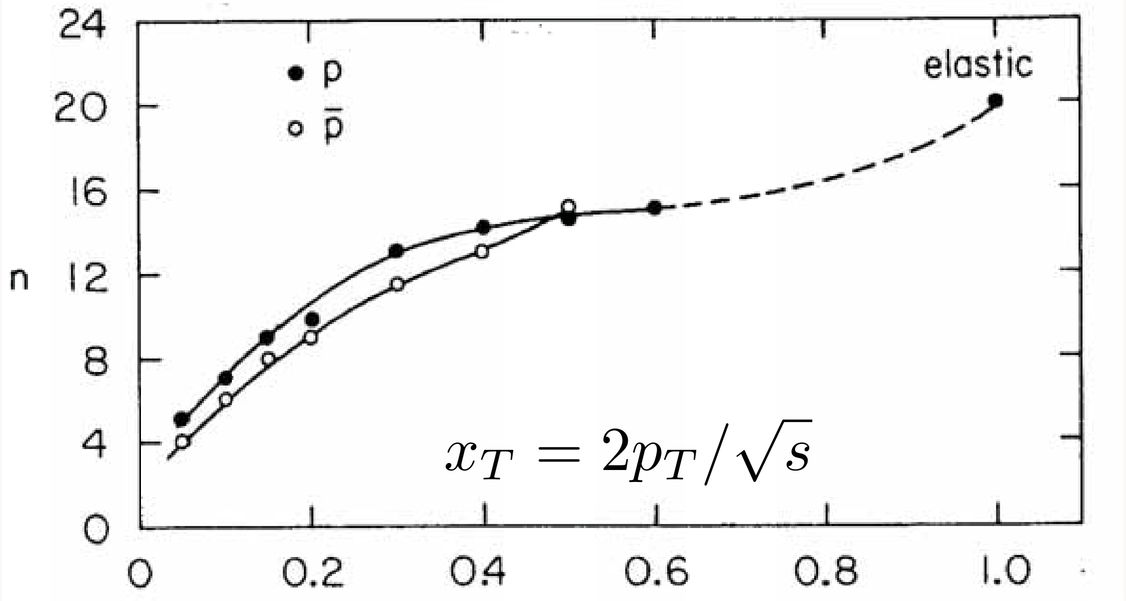
Arleo, Aurenche
Hwang, Sickles, sjb

Arleo, Aurenche Hwang, Sickles, sjb



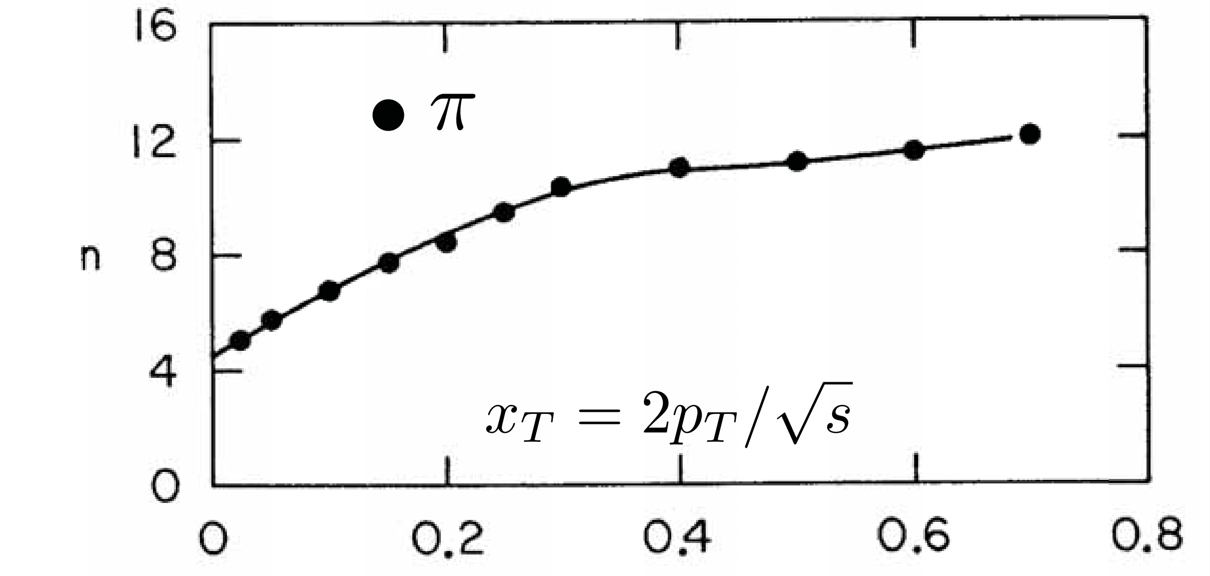
$$n^{\mathrm{exp}}(x_\perp) \equiv -\frac{\ln\left(\sigma^{\mathrm{inv}}(x_\perp, \sqrt{s_1})/\sigma^{\mathrm{inv}}(x_\perp, \sqrt{s_2})\right)}{\ln\left(\sqrt{s_1}/\sqrt{s_2}\right)}$$

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm} = \pi/2)}{p_T^n}$$

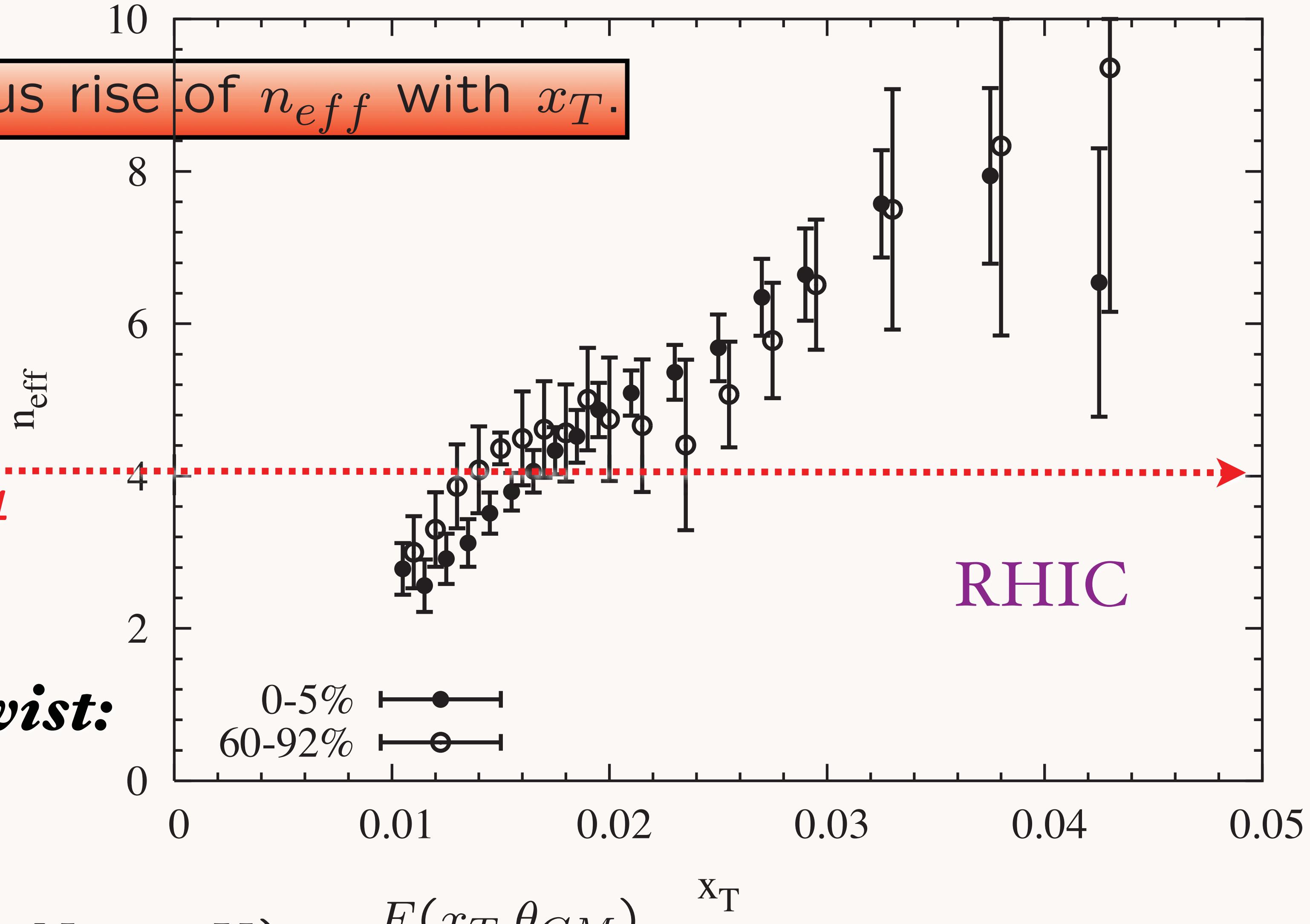


Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available p_T range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.



Continuous rise of n_{eff} with x_T.

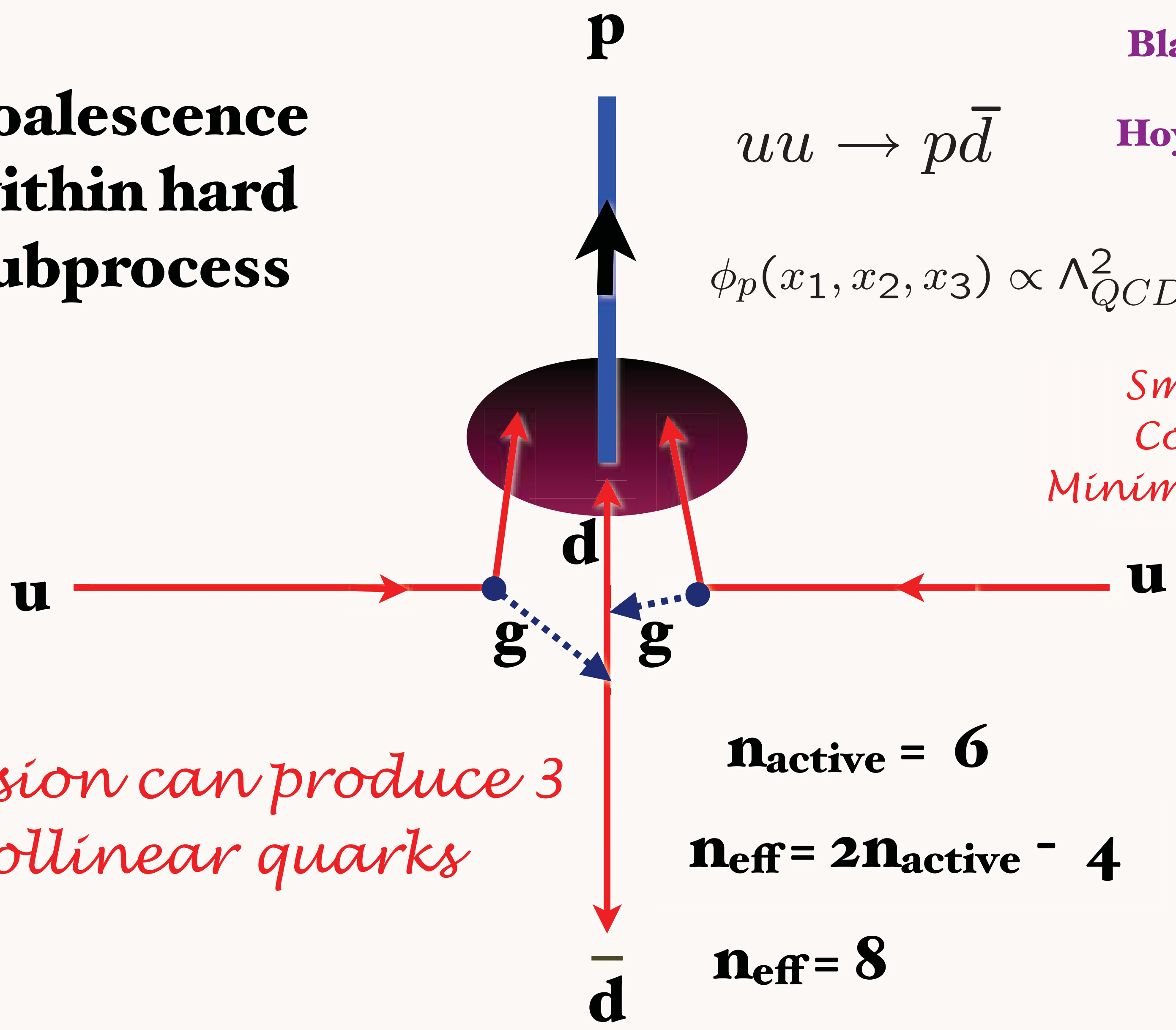
$n_{eff} = 4$

Leading twist:

$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess



$uu \rightarrow p\bar{d}$

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

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

Small color-singlet
Color Transparent
Minimal same-side energy

Collision can produce 3 collinear quarks

$n_{active} = 6$

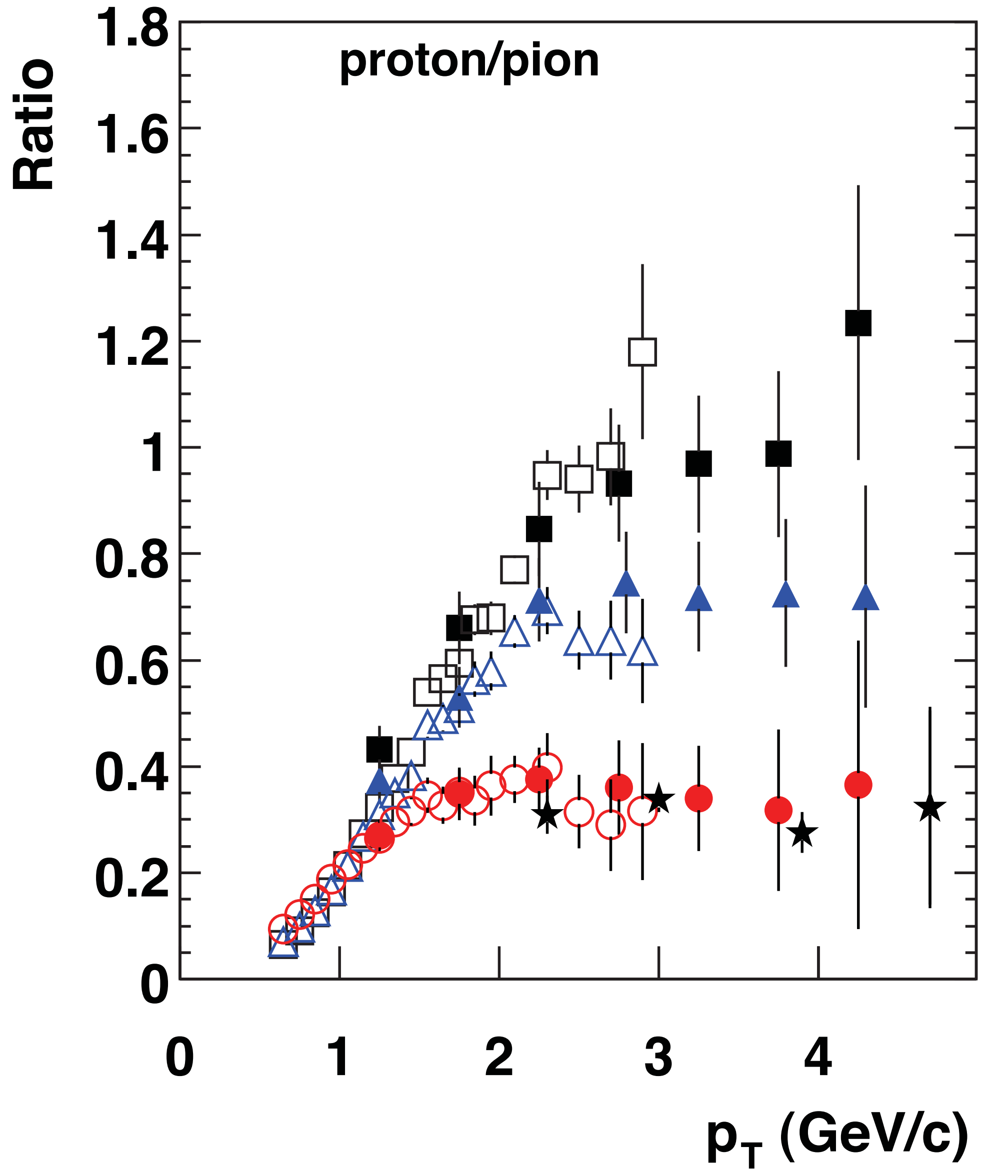
$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

$qq \rightarrow B\bar{q}$

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett*. **91**, 172301 (2003).

Particle ratio changes with centrality!



Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

← **Central**

← **Peripheral**

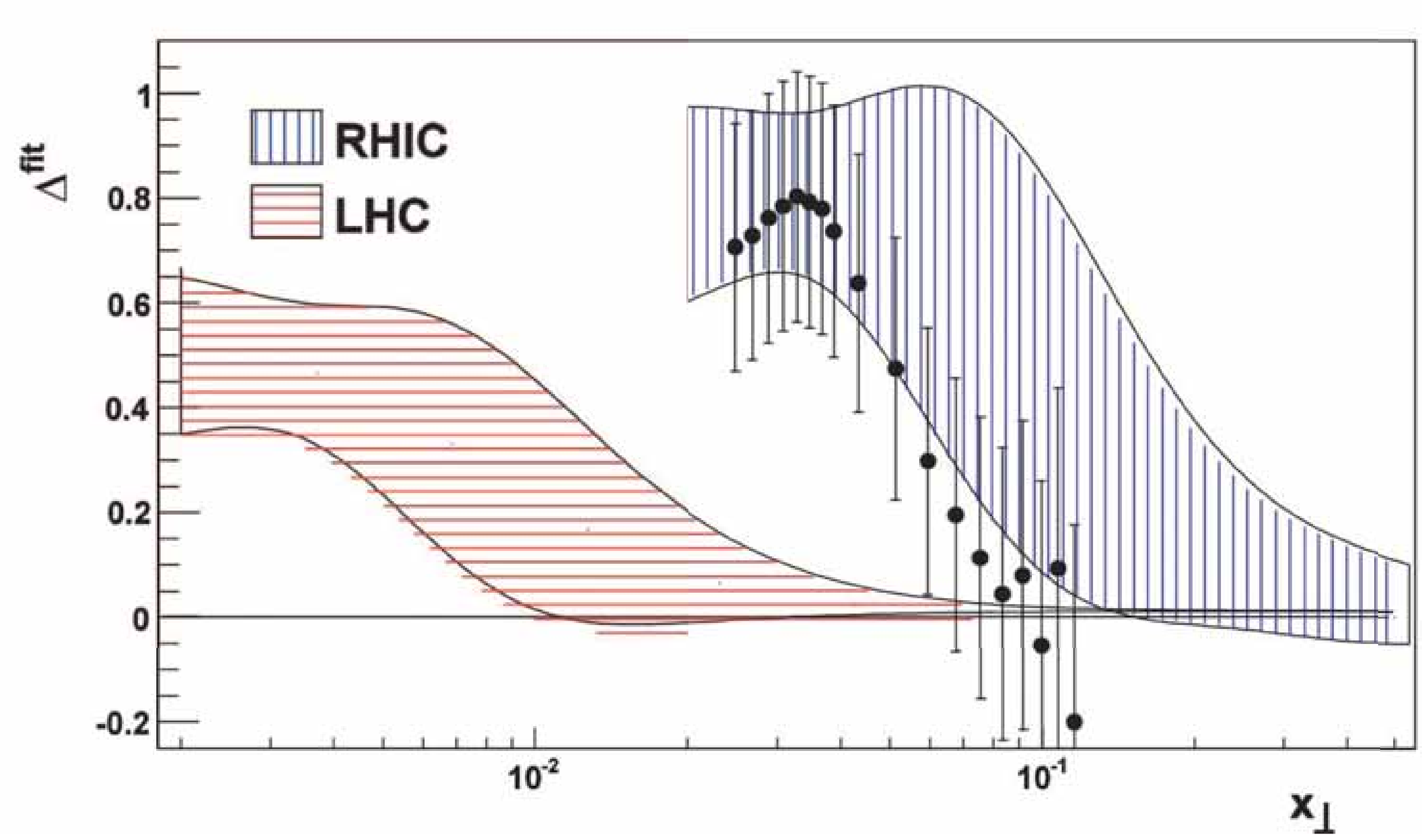
Tannenbaum: Baryon Anomaly:

RHIC/LHC predictions

PHENIX results

Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

[A. Bezilevsky, APS Meeting



- Magnitude of Δ and its $x_\perp$-dependence consistent with predictions

Key QCD Panda Experiment

- Anomalous power behavior at fixed x_T
- Protons more likely to come from direct subprocess than pions
- Protons less absorbed than pions in central nuclear collisions because of **color transparency**
- Predicts increasing proton to pion ratio in central collisions -- seen at RHIC
- Exclusive-inclusive connection at $x_T = 1$

Light-Front Wavefunctions

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

$$\psi(x, k_\perp)$$

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

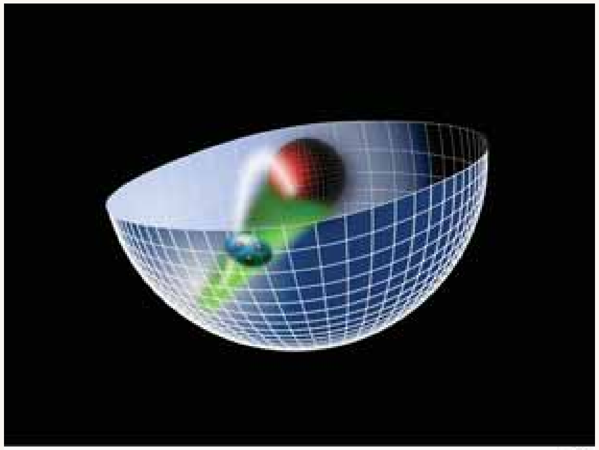
Invariant under boosts. Independent of P^μ

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

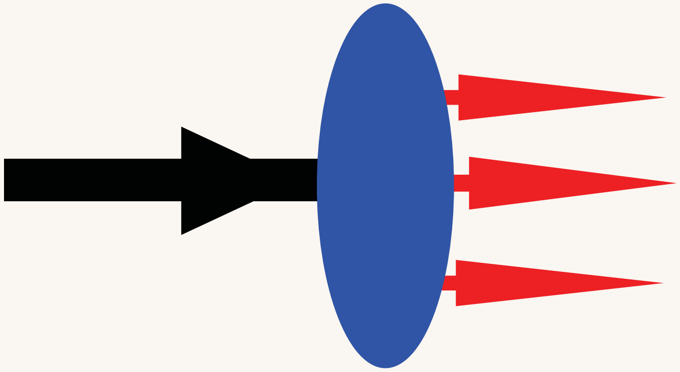
Direct connection to QCD Lagrangian

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

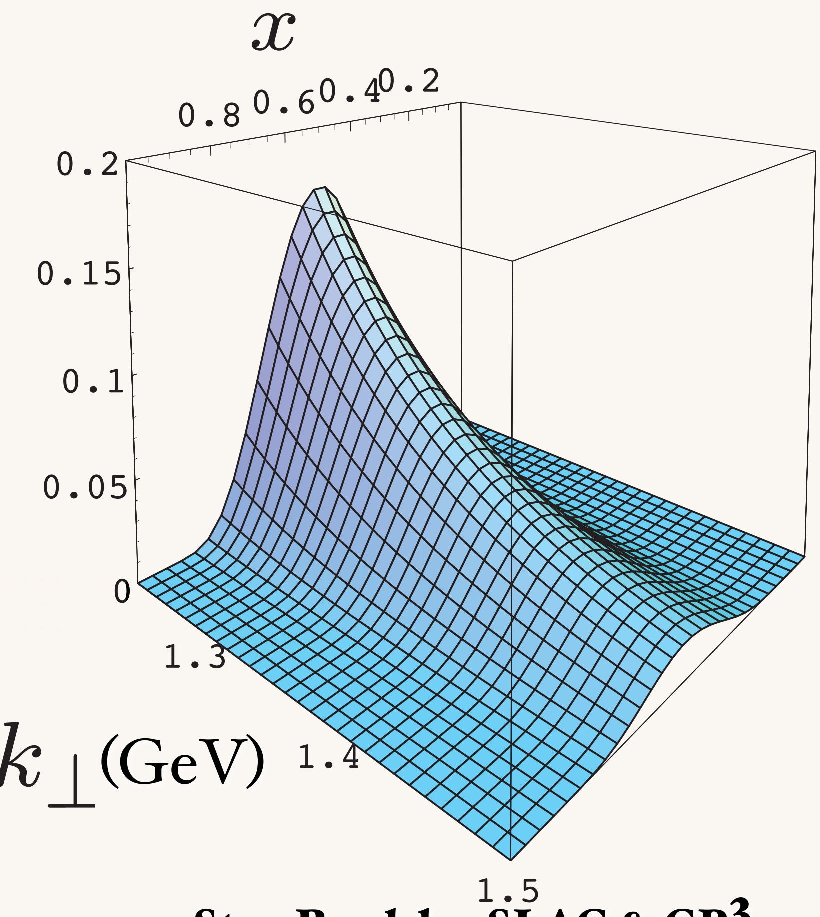
$\phi(z)$



- *Light-Front Holography*



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



- *Light Front Wavefunctions:*

  Schrödinger Wavefunctions of Hadron Physics

Goal:

- **Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**

- **Analogous to the Schrodinger Equation for Atomic Physics**

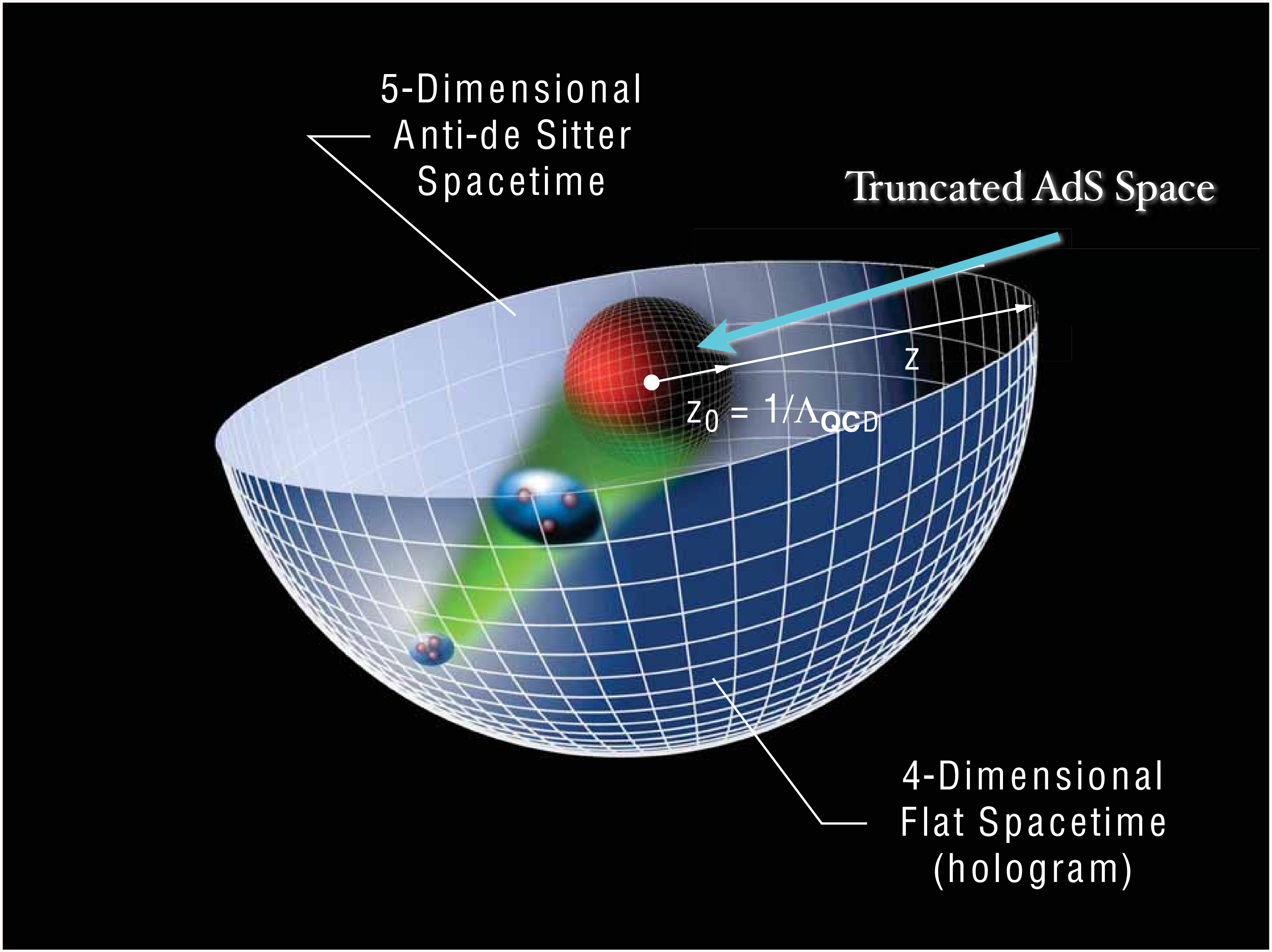
- *AdS/QCD Holographic Model*

Conformal Theories are invariant under the Poincare and conformal transformations with

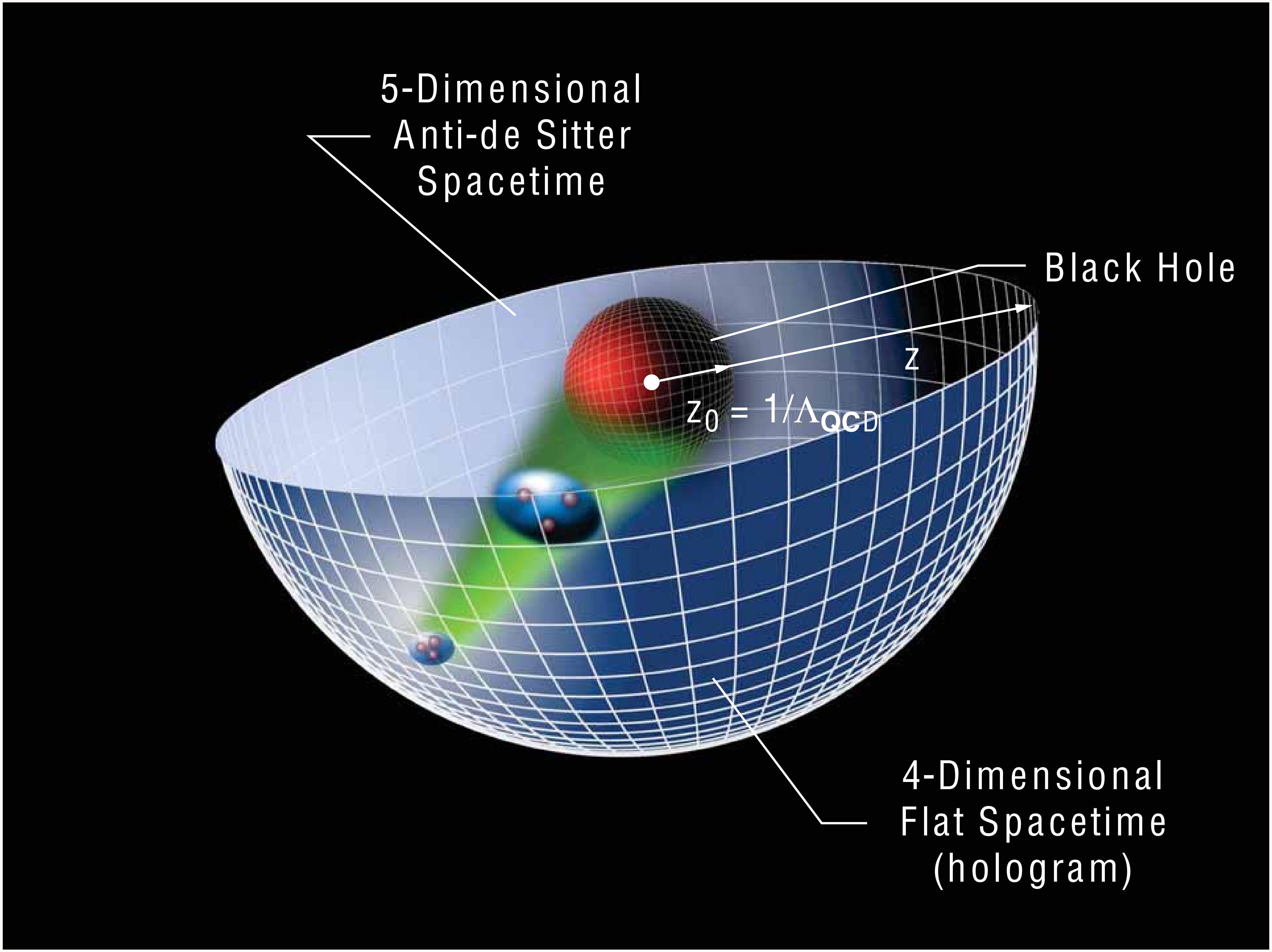
$$\mathbf{M}^{\mu\nu}, \mathbf{P}^{\mu}, \mathbf{D}, \mathbf{K}^{\mu},$$

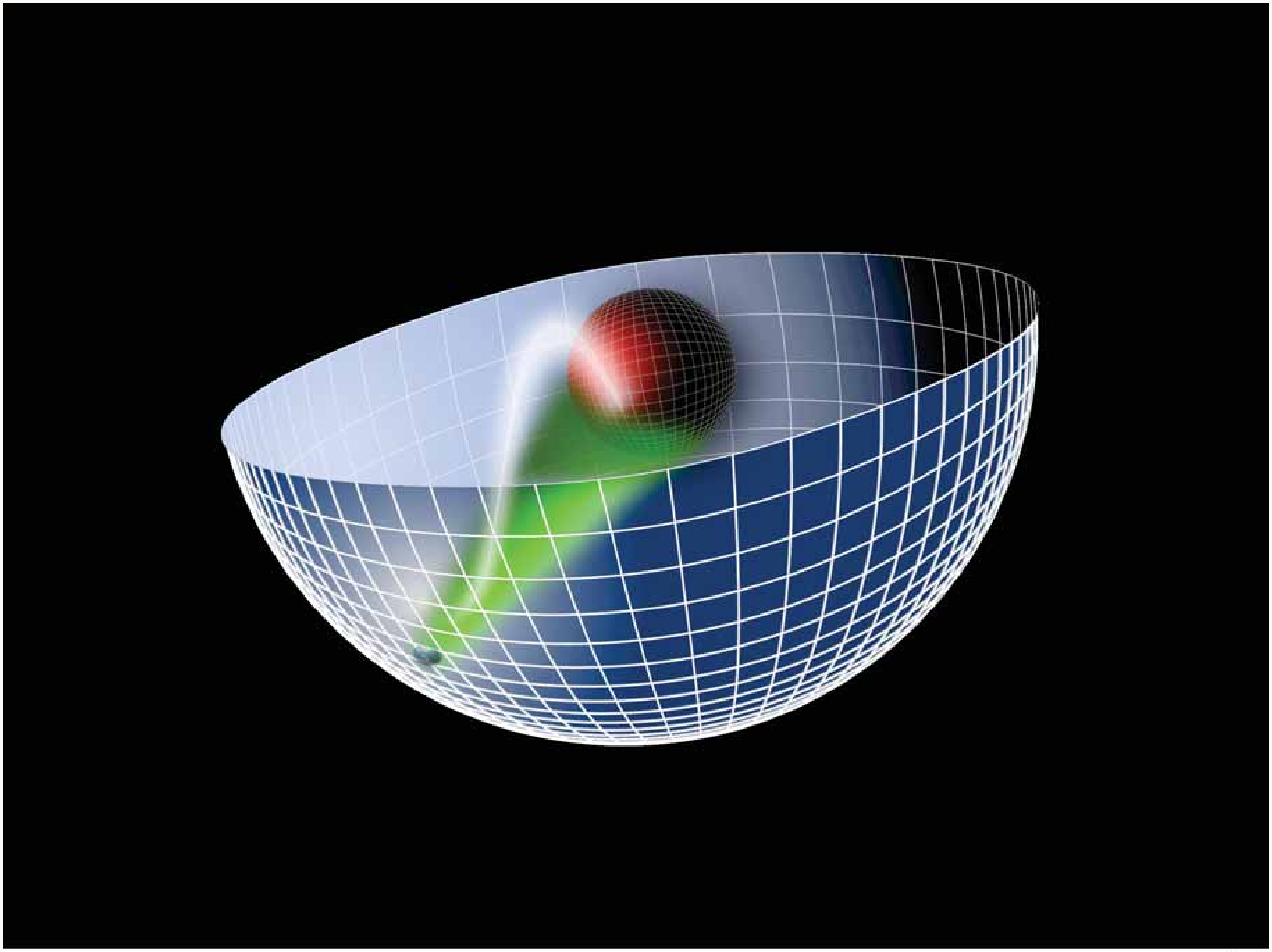
the generators of SO(4,2)

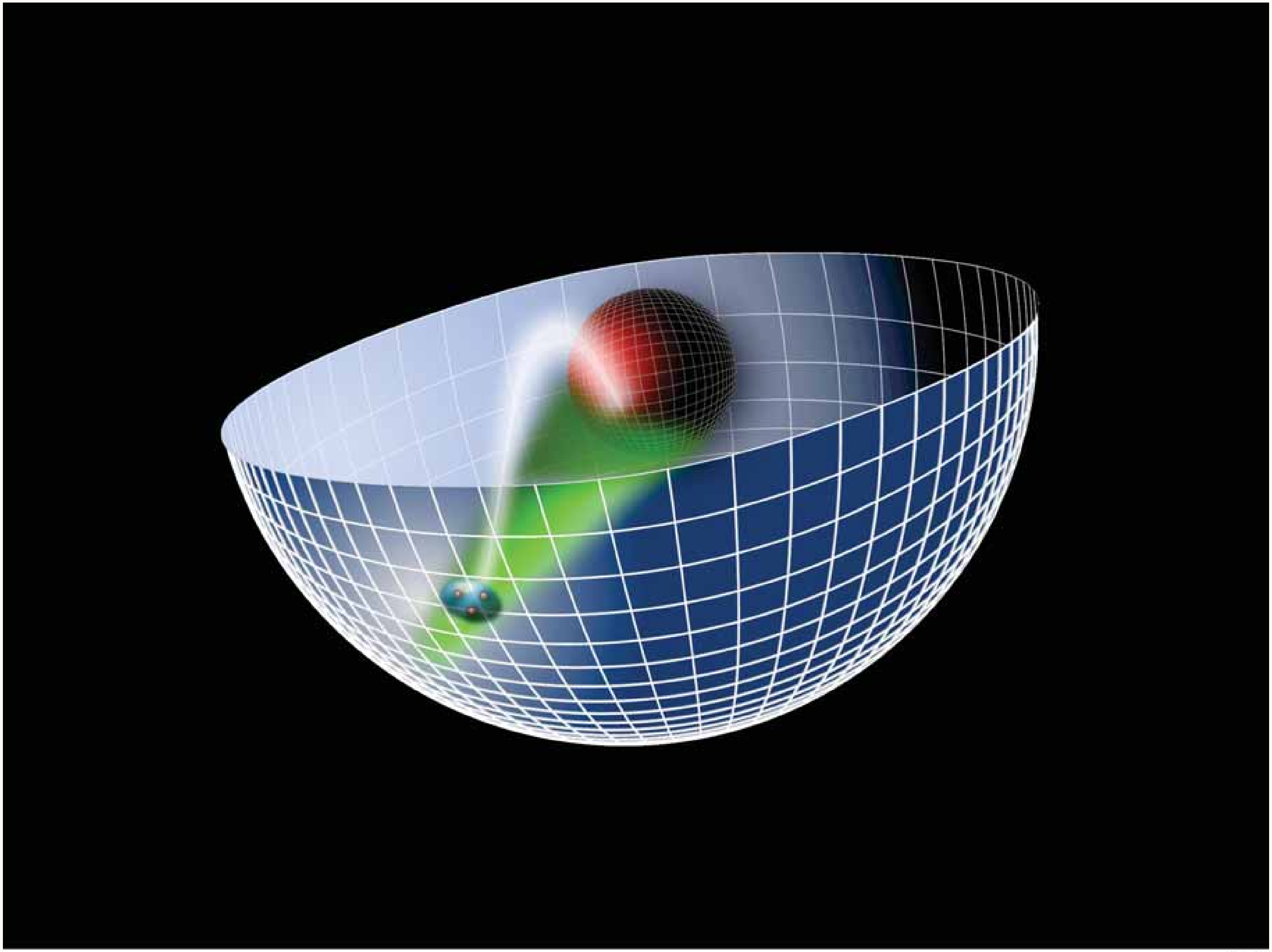
SO(4,2) has a mathematical representation on AdS5

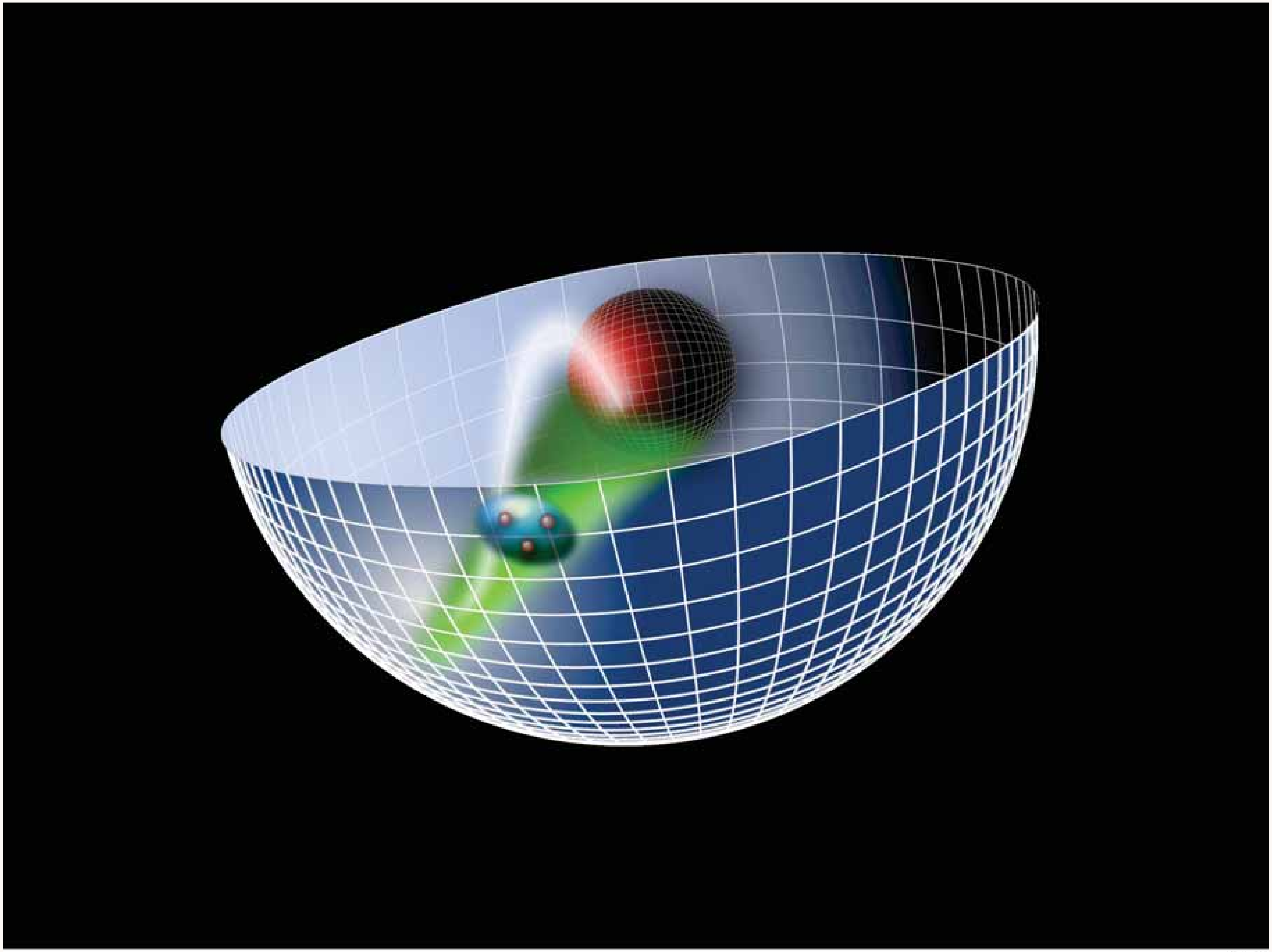


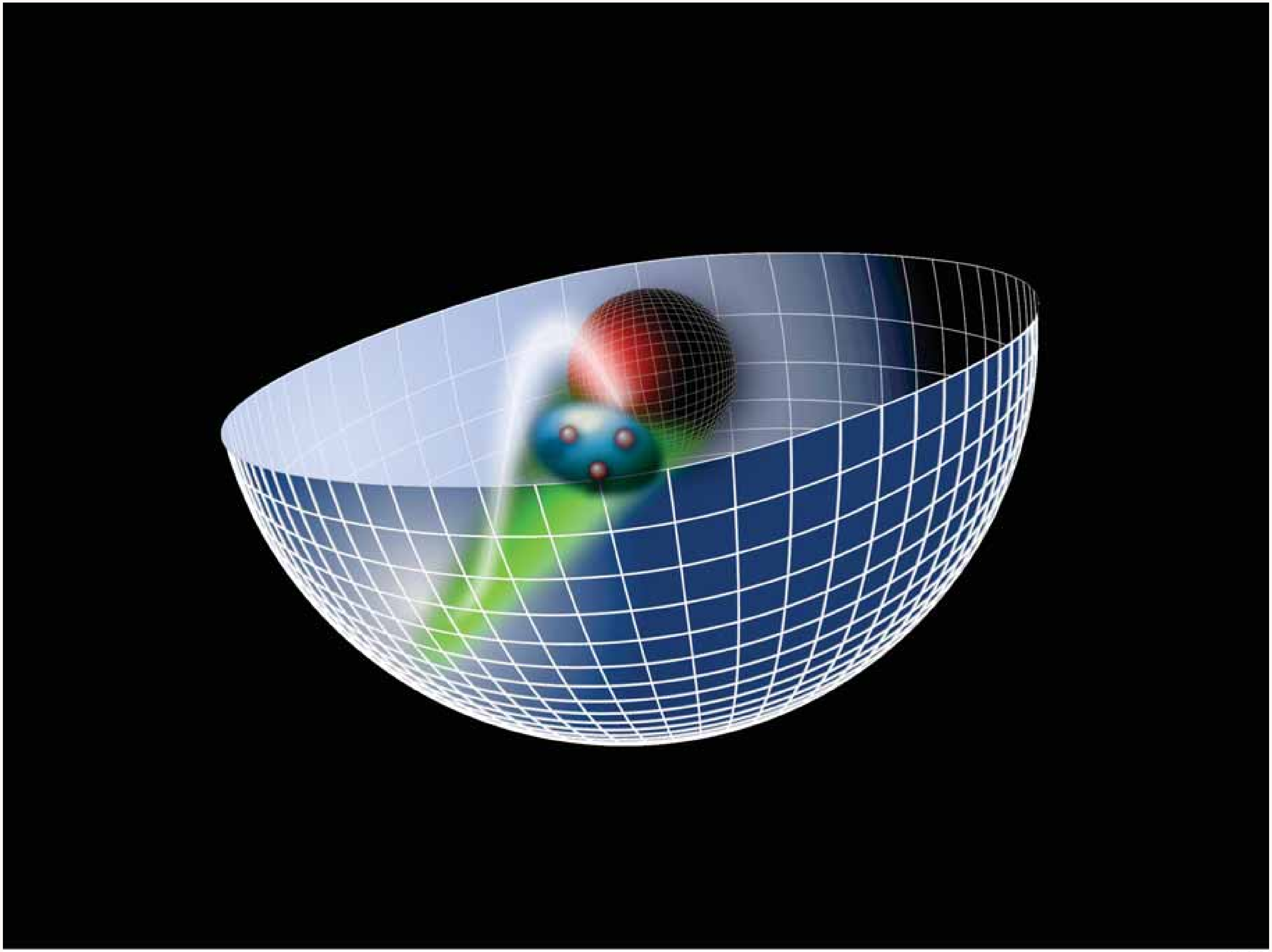
Truncated AdS Space

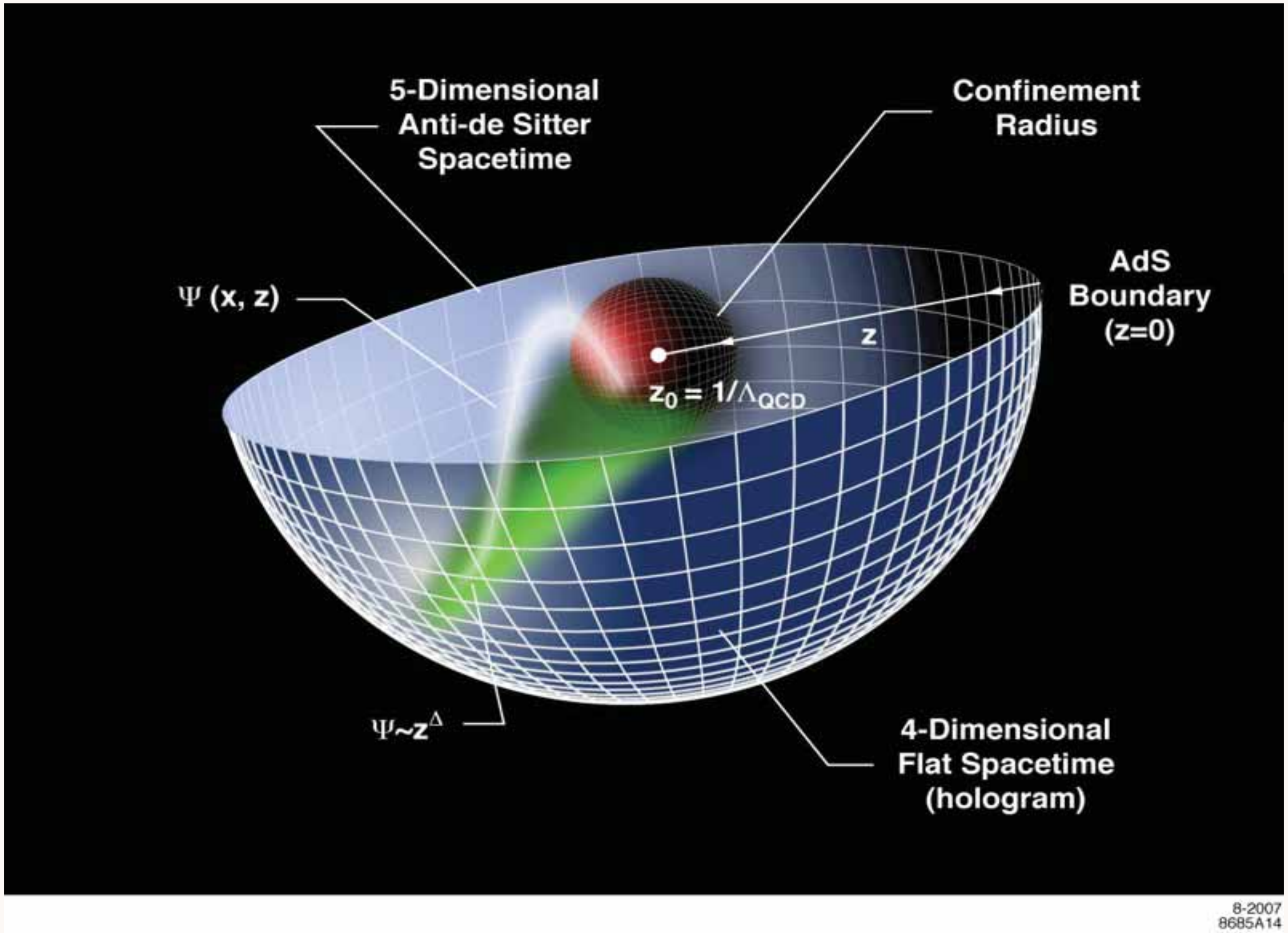

5-Dimensional Anti-de Sitter Spacetime
Black Hole
z
$z_0 = 1/\Lambda_{QCD}$
4-Dimensional Flat Spacetime (hologram)











Guy de Teramond
sjb

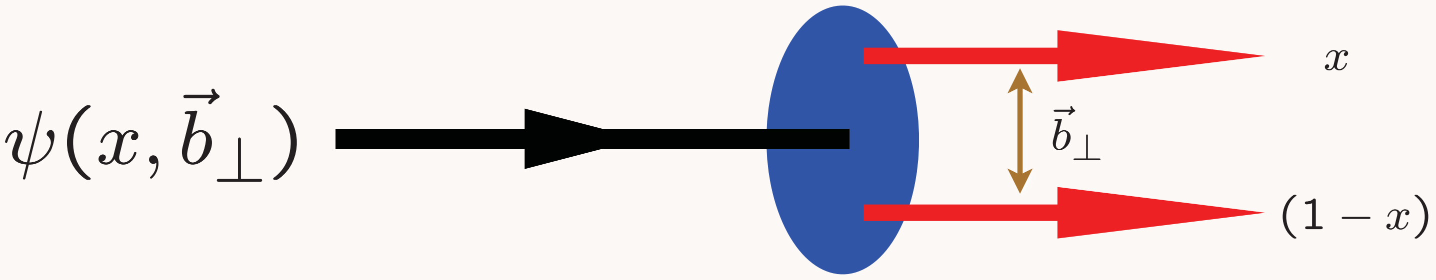
- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\rm QCD}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).
- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).

We consider both holographic models

LF(3+1) **AdS₅**

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

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



$$\psi(x, \vec{b}_\perp) = \sqrt{\frac{x(1-x)}{2\pi\zeta}}\,\phi(\zeta)$$

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

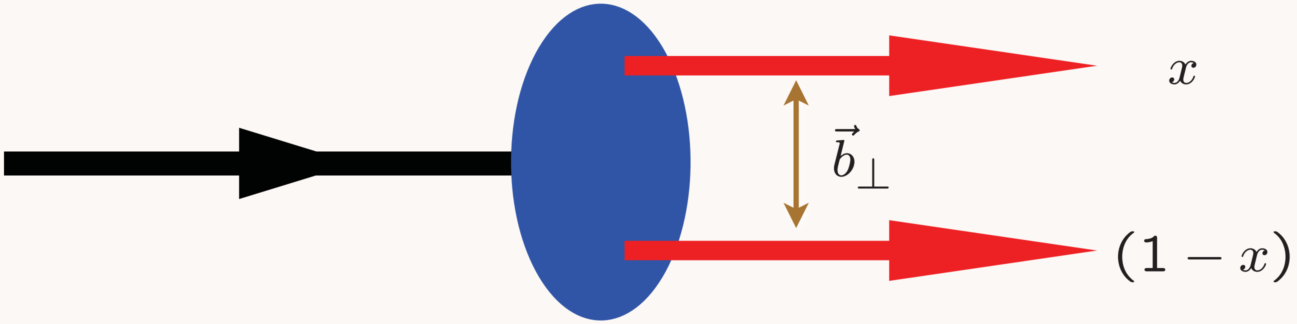
Light-Front Holography:
Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation!

Frame Independent

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

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



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

G. de Teramond, sjb

soft wall
confining potential:

Quark separation increases with L

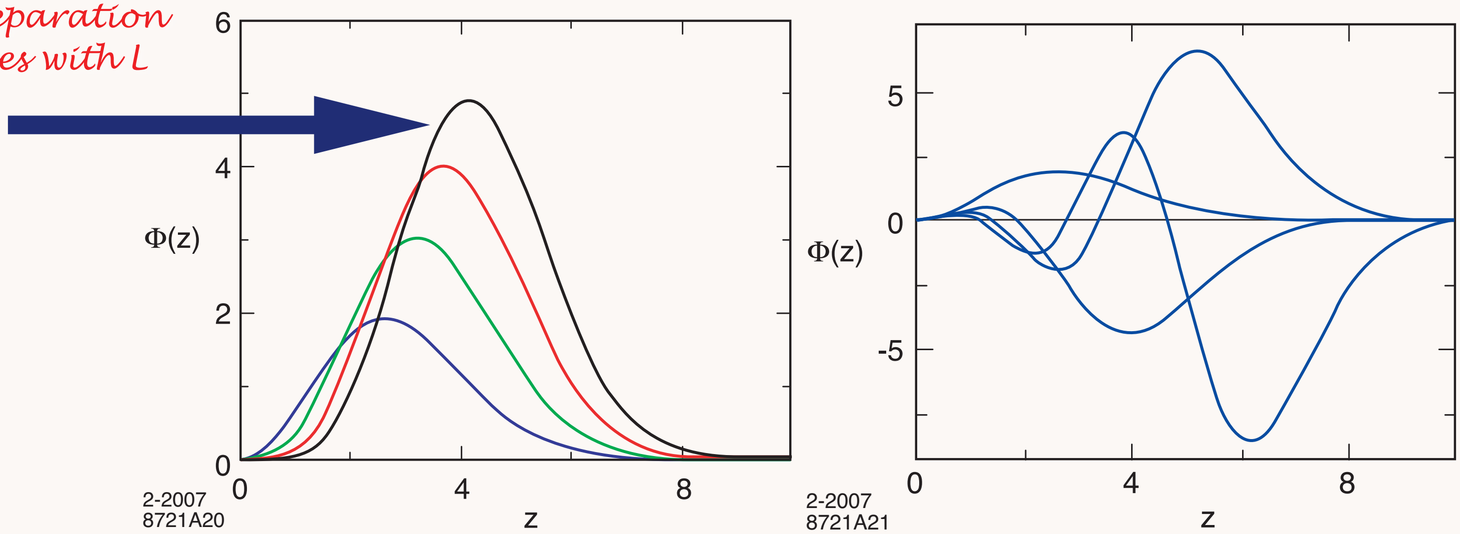


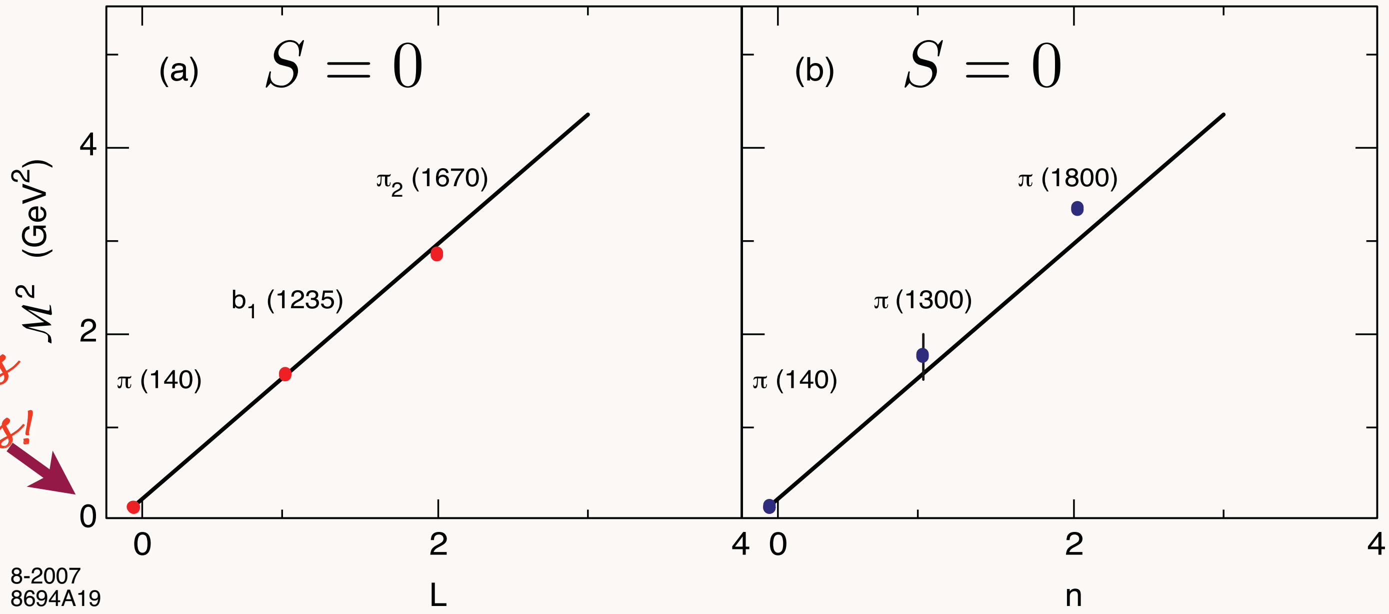
Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Pion mass automatically zero!

$$m_q = 0$$

Pion has zero mass!

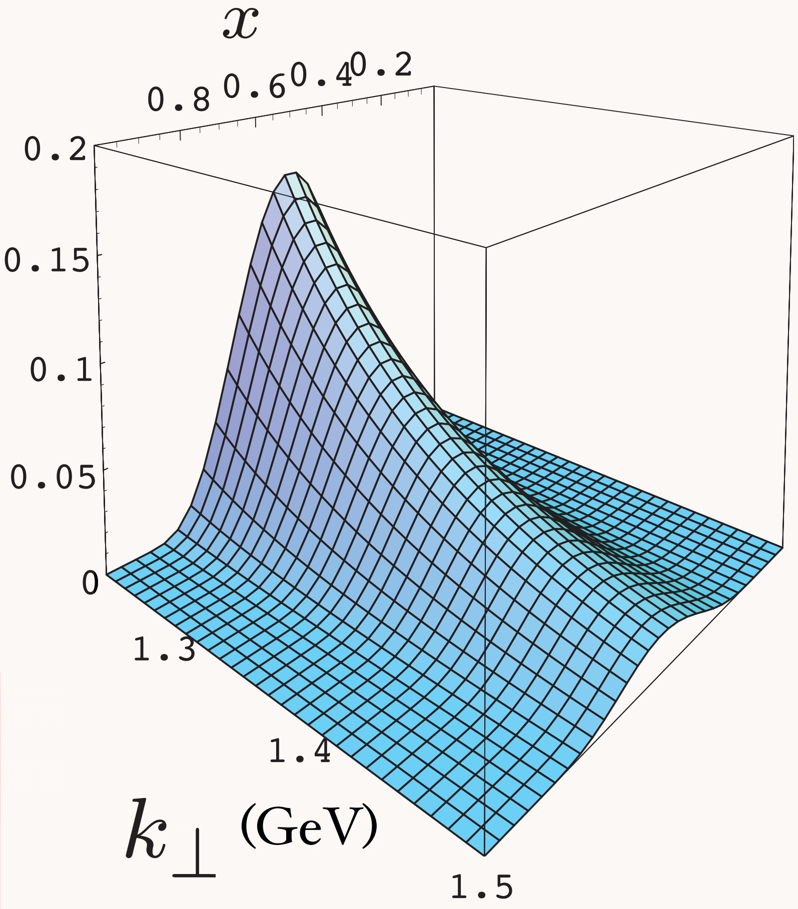


Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

Prediction from AdS/CFT: Meson LFWF

de Teramond, sjb

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



"Soft Wall" model

$\kappa = 0.375$ GeV

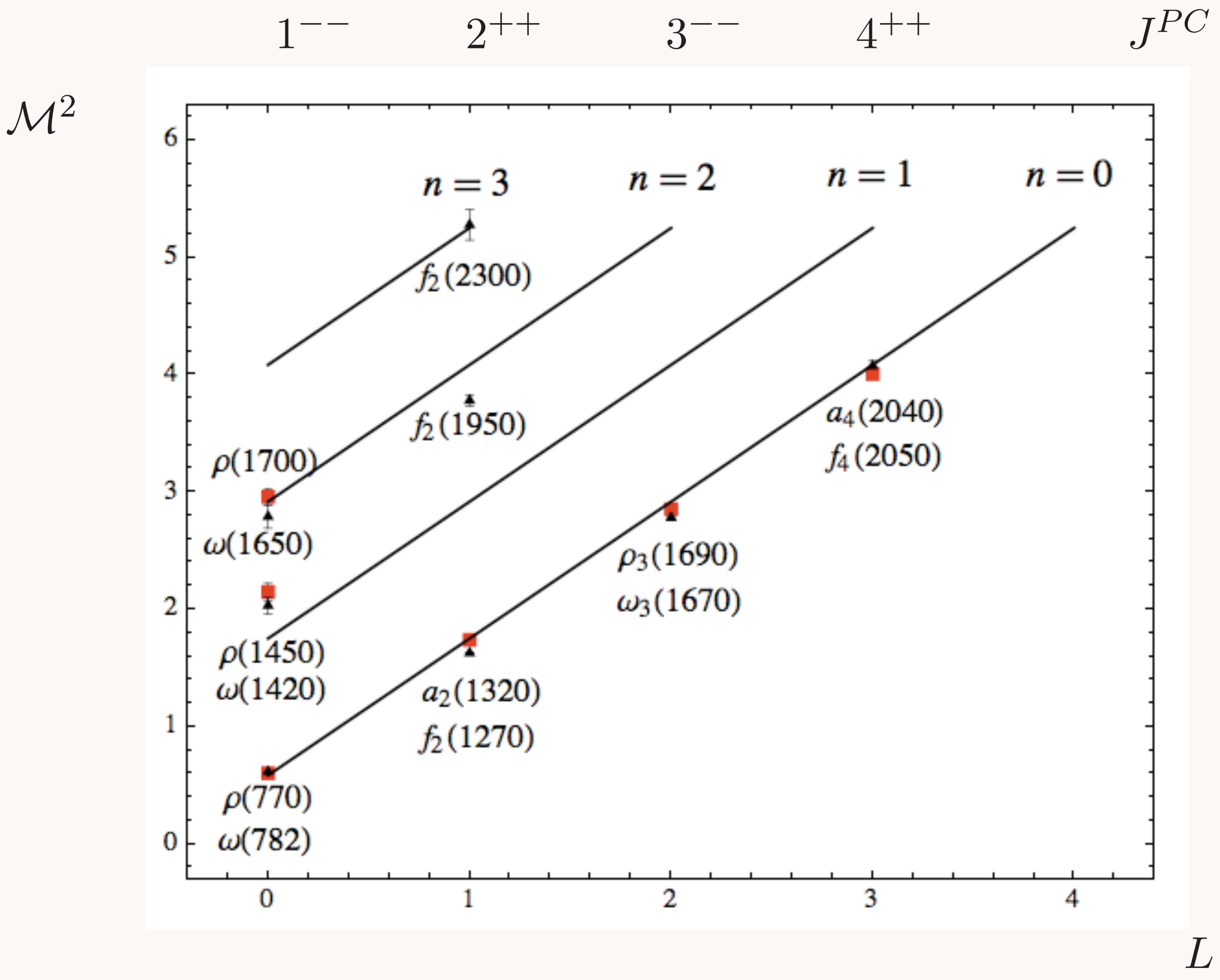
massless quarks

Note coupling

$k_\perp^2, x$

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}} \qquad \phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

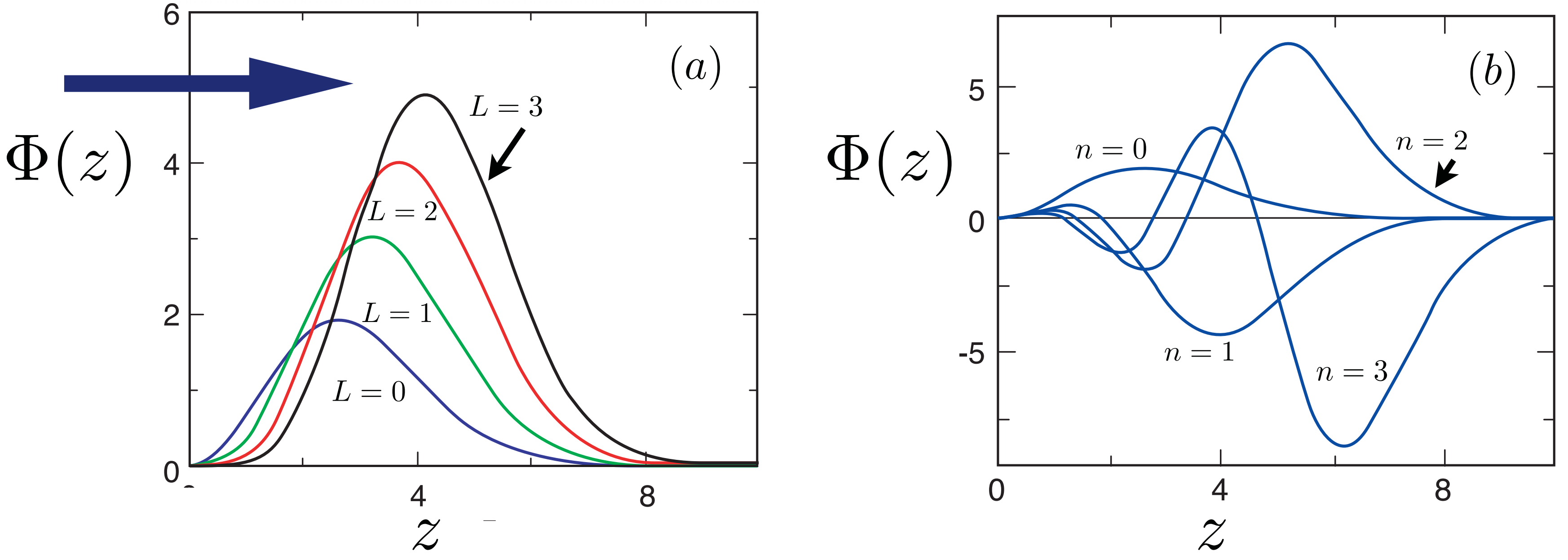
Connection of Confinement to TMDs

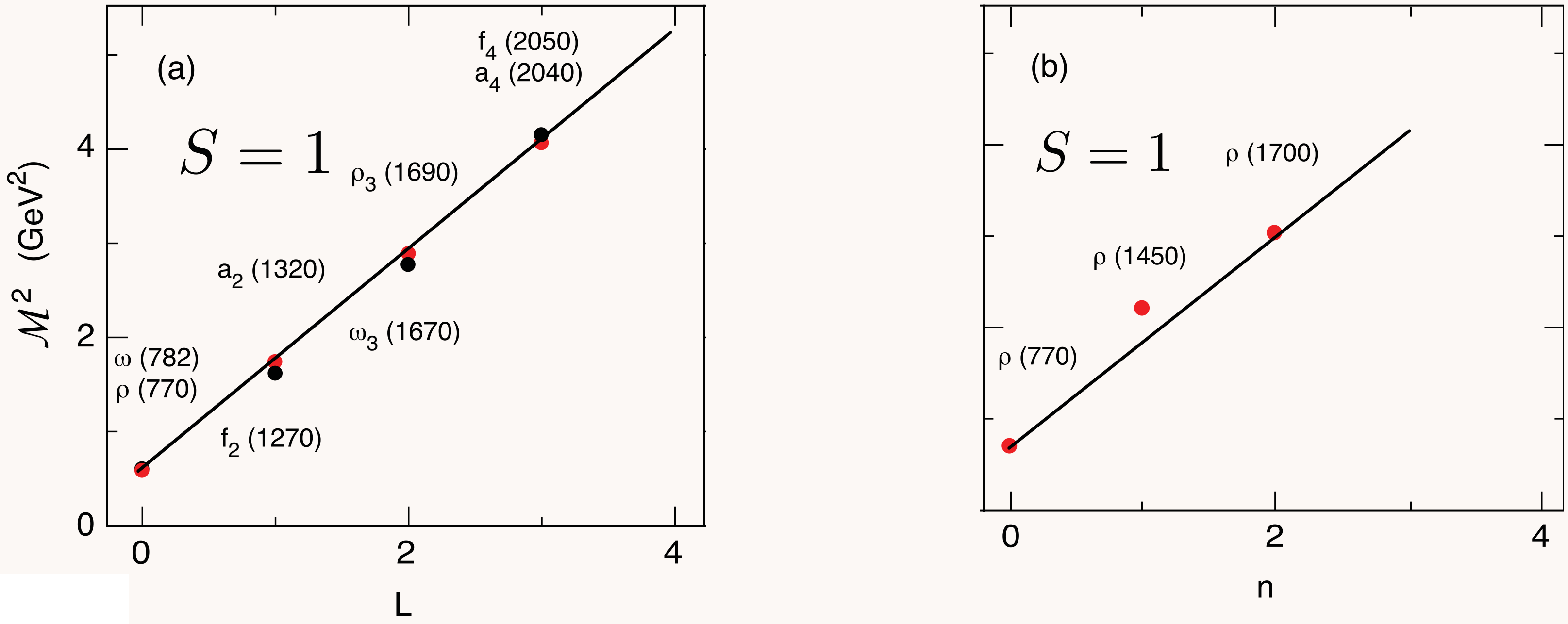


Parent and daughter Regge trajectories for the $I=1$ ρ-meson family (red)

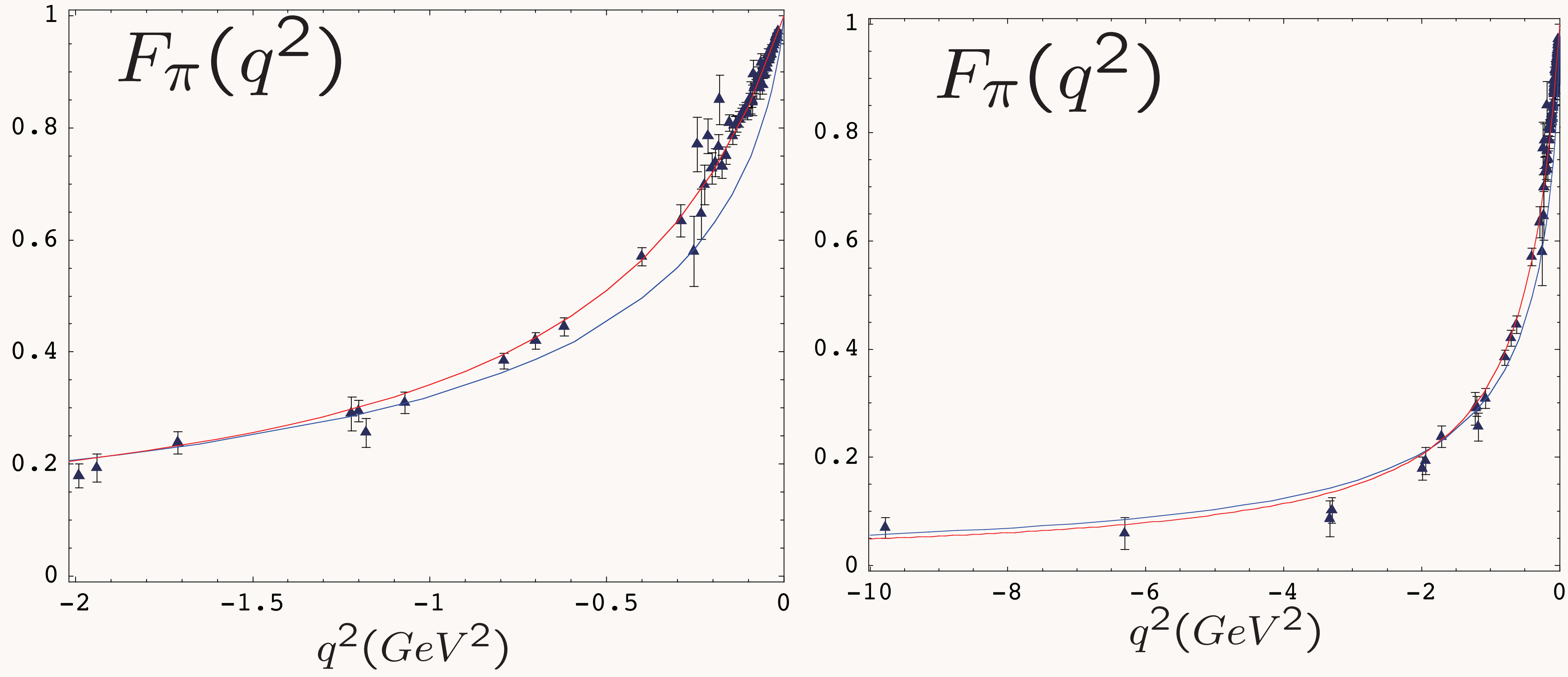
and the $I=0$ ω-meson family (black) for $\kappa = 0.54$ GeV

Quark separation increases with L





Spacelike pion form factor from AdS/CFT



Data Compilation from Baldini, Kloe and Volmer

🟥 Harmonic Oscillator Confinement

🟦 Truncated Space Confinement

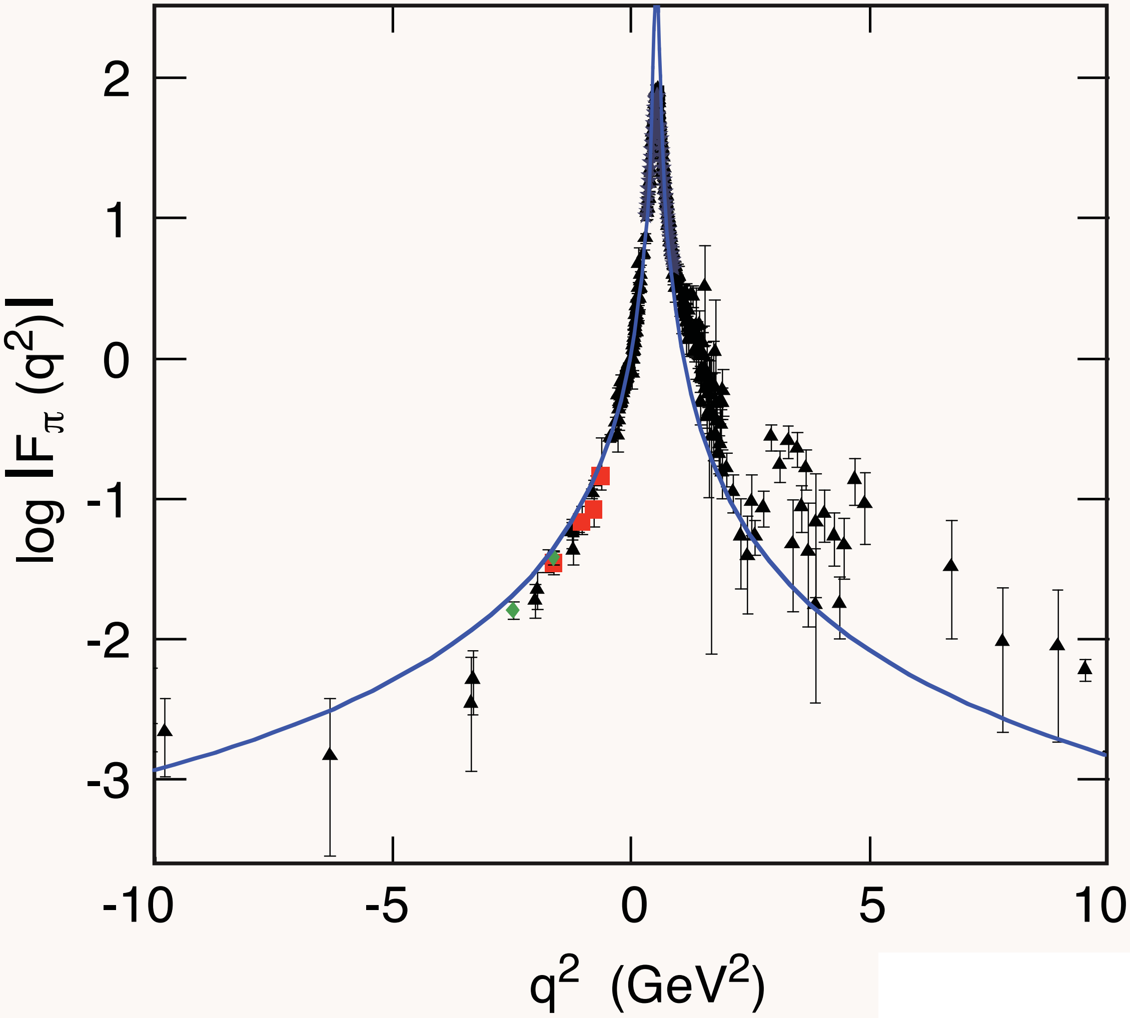
One parameter - set by pion decay constant

G. de Teramond, sjb

- Analytical continuation to time-like region $q^2 \to -q^2$

$$M_\rho = 2\kappa = 750 \text{ MeV}$$

- Strongly coupled semiclassical gauge/gravity limit hadrons have zero widths (stable).

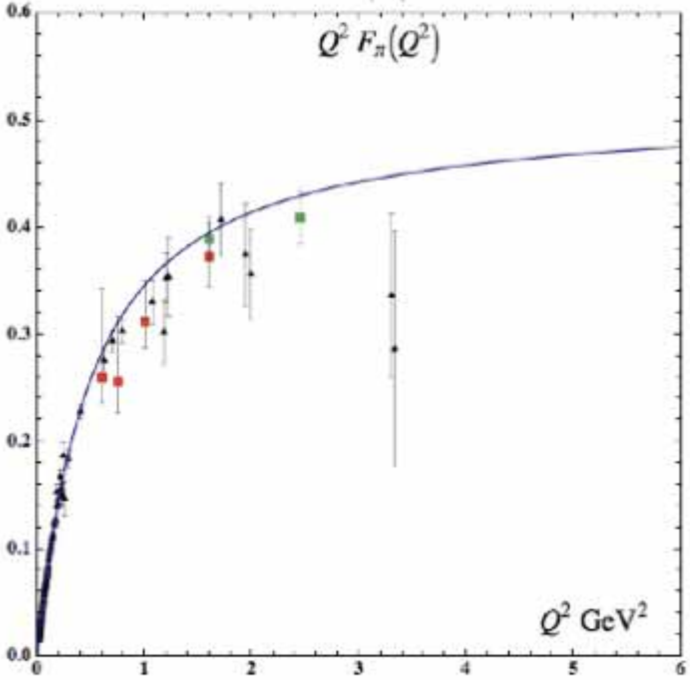


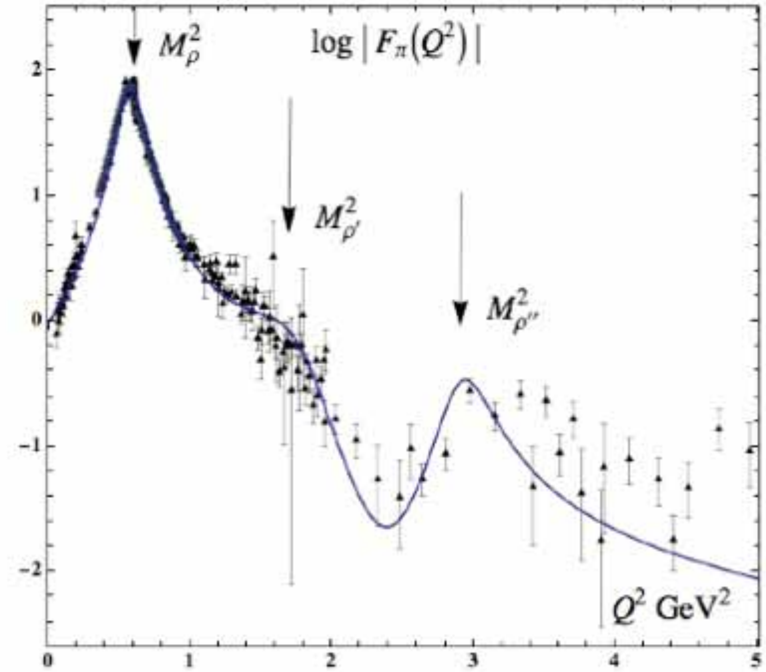
Space and time-like pion form factor for $\kappa = 0.375$ GeV in the SW model.

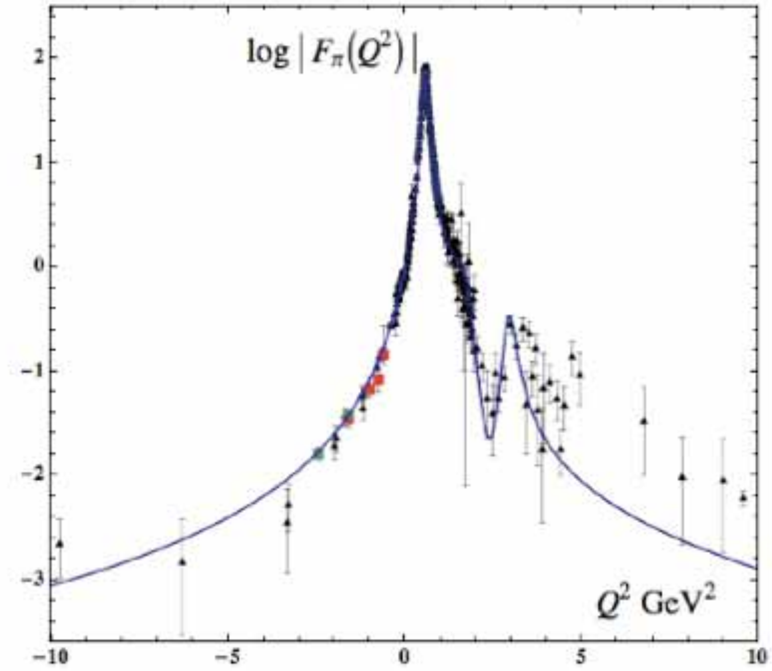
- Vector Mesons: Hong, Yoon and Strassler (2004); Grigoryan and Radyushkin (2007).

Space- and Time Like Pion Form-Factor (HFS)

PRELIMINARY







$$|\pi\rangle = \psi_{q\bar{q}/\pi}|q\bar{q}\rangle + \psi_{q\bar{q}q\bar{q}/\pi}|q\bar{q}q\bar{q}\rangle$$

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

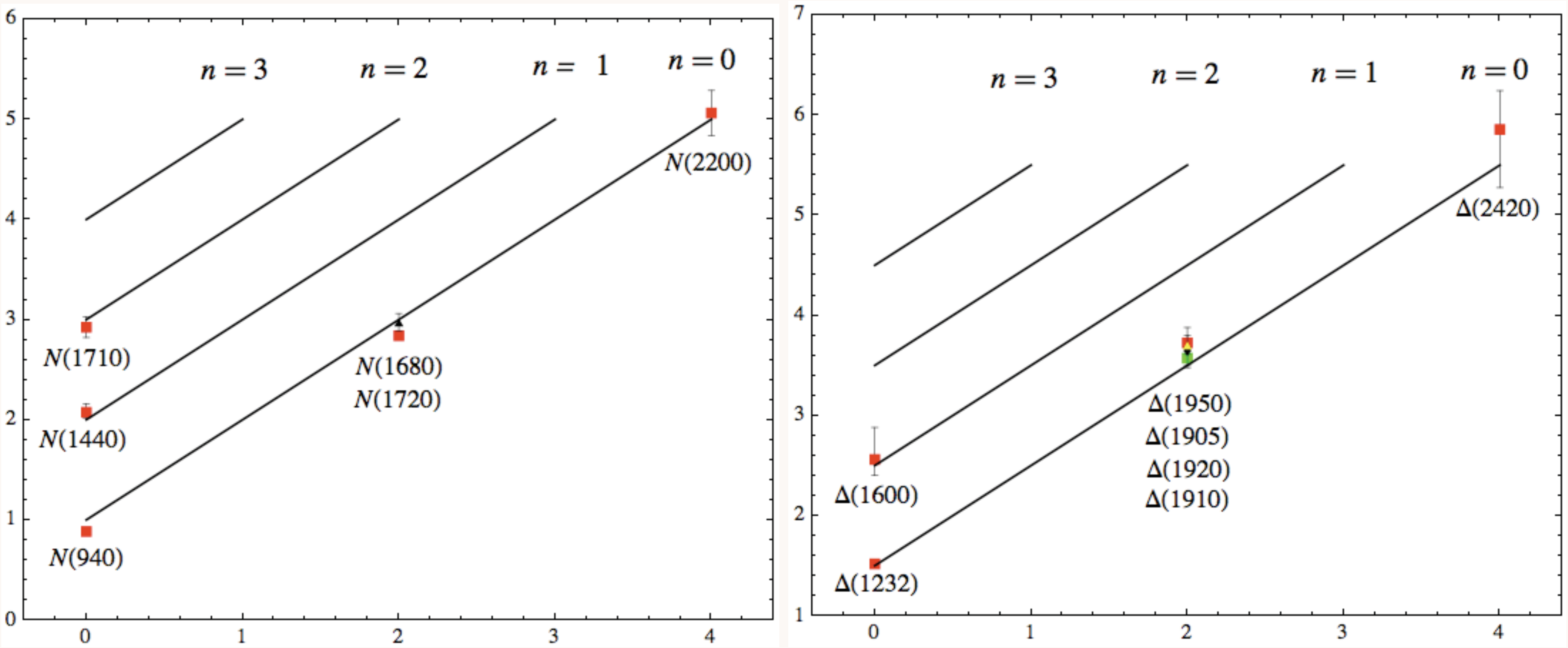
$$\kappa = 0.54 \text{ GeV}$$

$$\Gamma_\rho = 130,\ \Gamma_{\rho'} = 400,\ \Gamma_{\rho''} = 300 \text{ MeV}$$

$$P_{q\bar{q}q\bar{q}} = 13\,\%$$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

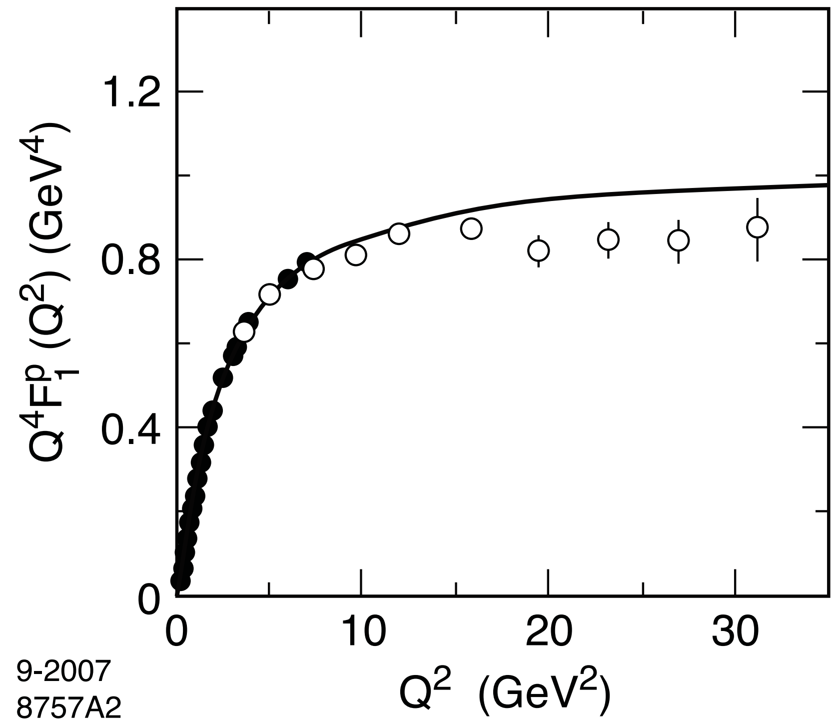
$\mathcal{M}^2$



L

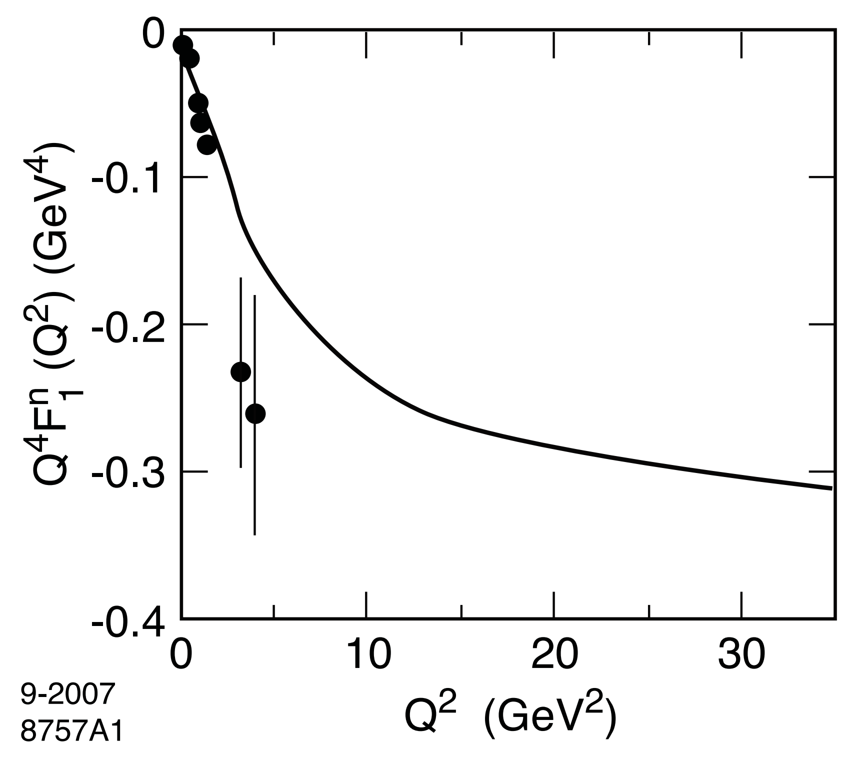
Parent and daughter **56** Regge trajectories for the N and Δ baryon families for $\kappa = 0.5$ GeV

- Scaling behavior for large Q^2: $Q^4 F_1^p(Q^2) \to \text{constant}$ $\boxed{\text{Proton } \tau = 3}$



SW model predictions for $\kappa = 0.424$ GeV. Data analysis from: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

- Scaling behavior for large Q^2: $Q^4 F_1^n(Q^2) \rightarrow \text{constant}$ $\boxed{\text{Neutron } \tau = 3}$

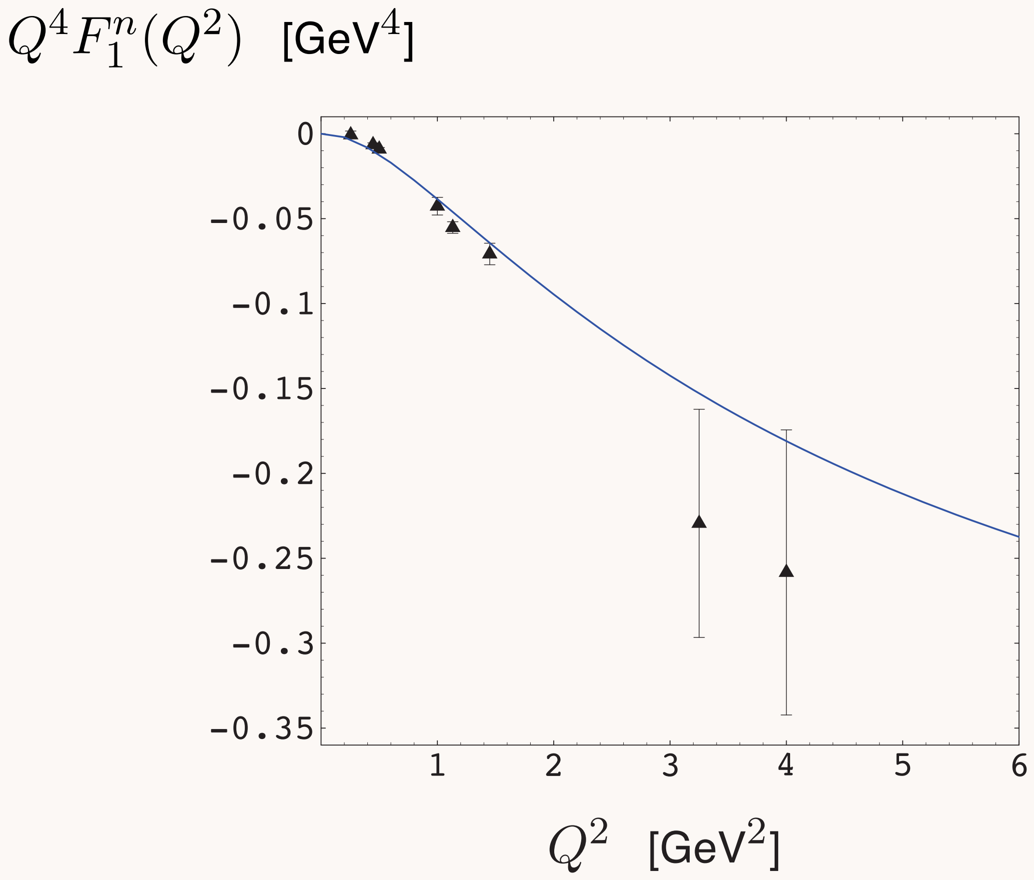


SW model predictions for $\kappa = 0.424$ GeV. Data analysis from M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

Dirac Neutron Form Factor

(Valence Approximation)

Truncated Space Confinement

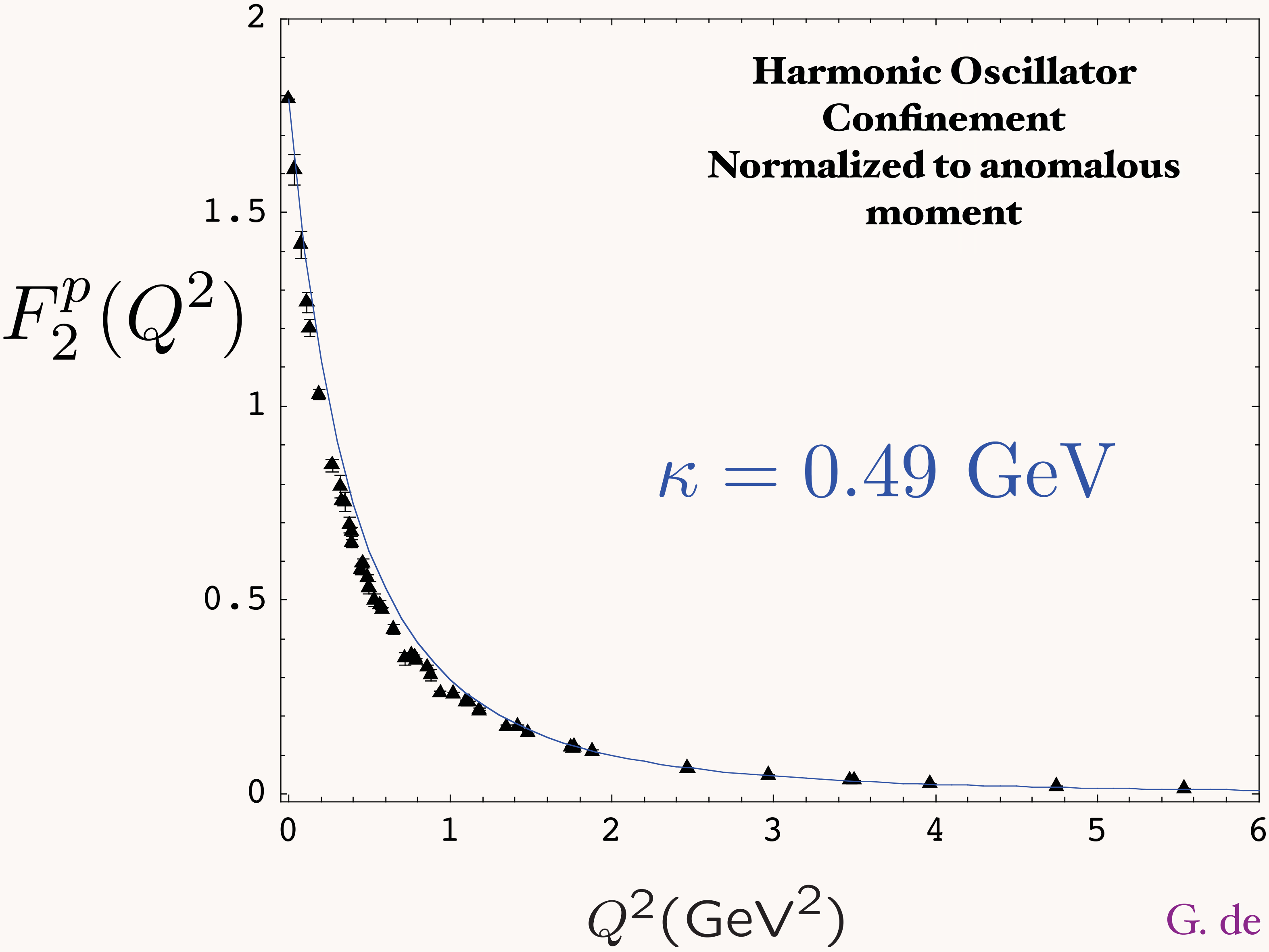


Prediction for $Q^4 F_1^n(Q^2)$ for $\Lambda_{\rm QCD} = 0.21$ GeV in the hard wall approximation. Data analysis from Diehl (2005).

Spacelike Pauli Form Factor

Preliminary

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



Harmonic Oscillator Confinement Normalized to anomalous moment

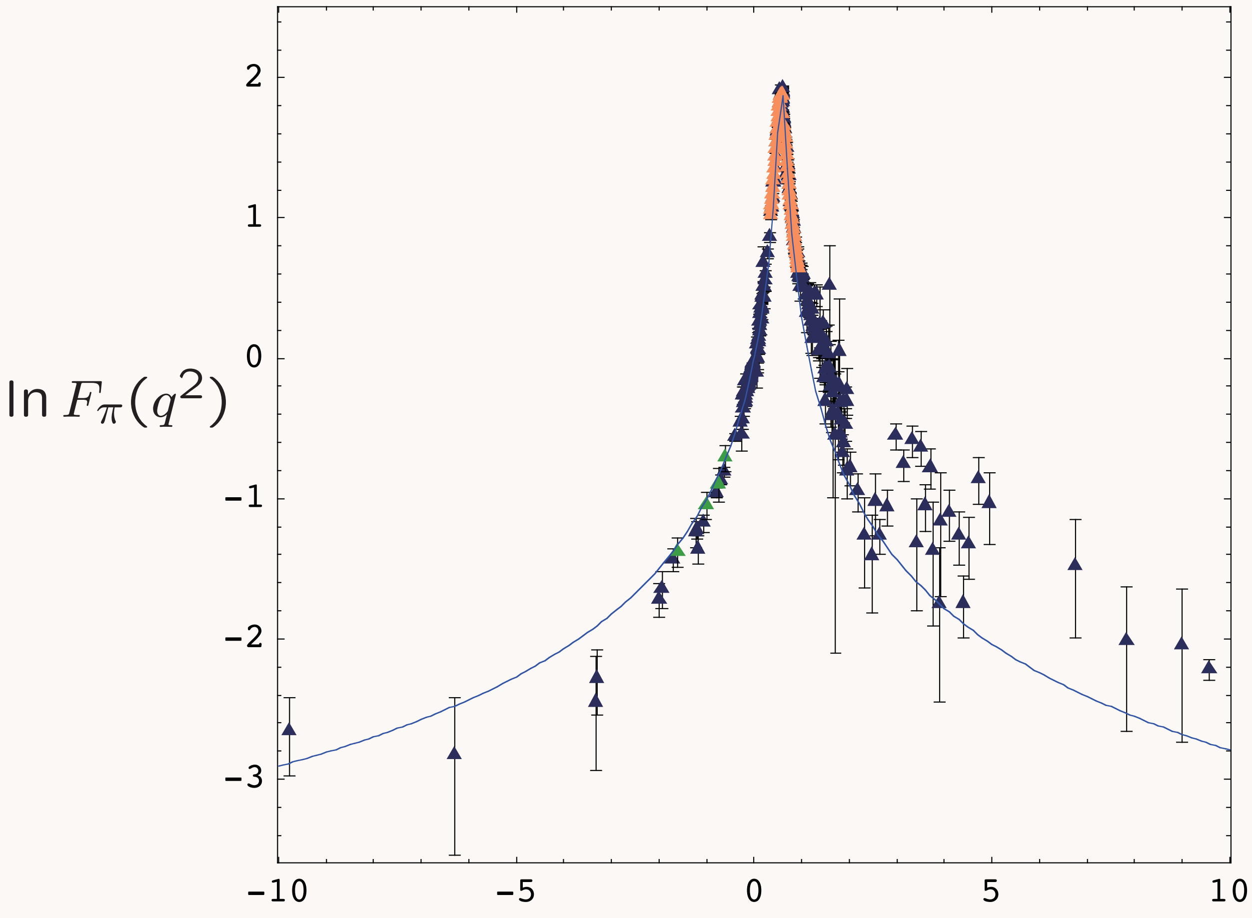
$\kappa = 0.49$ GeV

G. de Teramond, sjb

Spacelike and Timelike Pion form factor from AdS/CFT

G. de Teramond, sjb

$F_\pi(q^2)$



$q^2(GeV^2)$

Harmonic Oscillator Confinement

$\kappa = 0.38\ \text{GeV}$

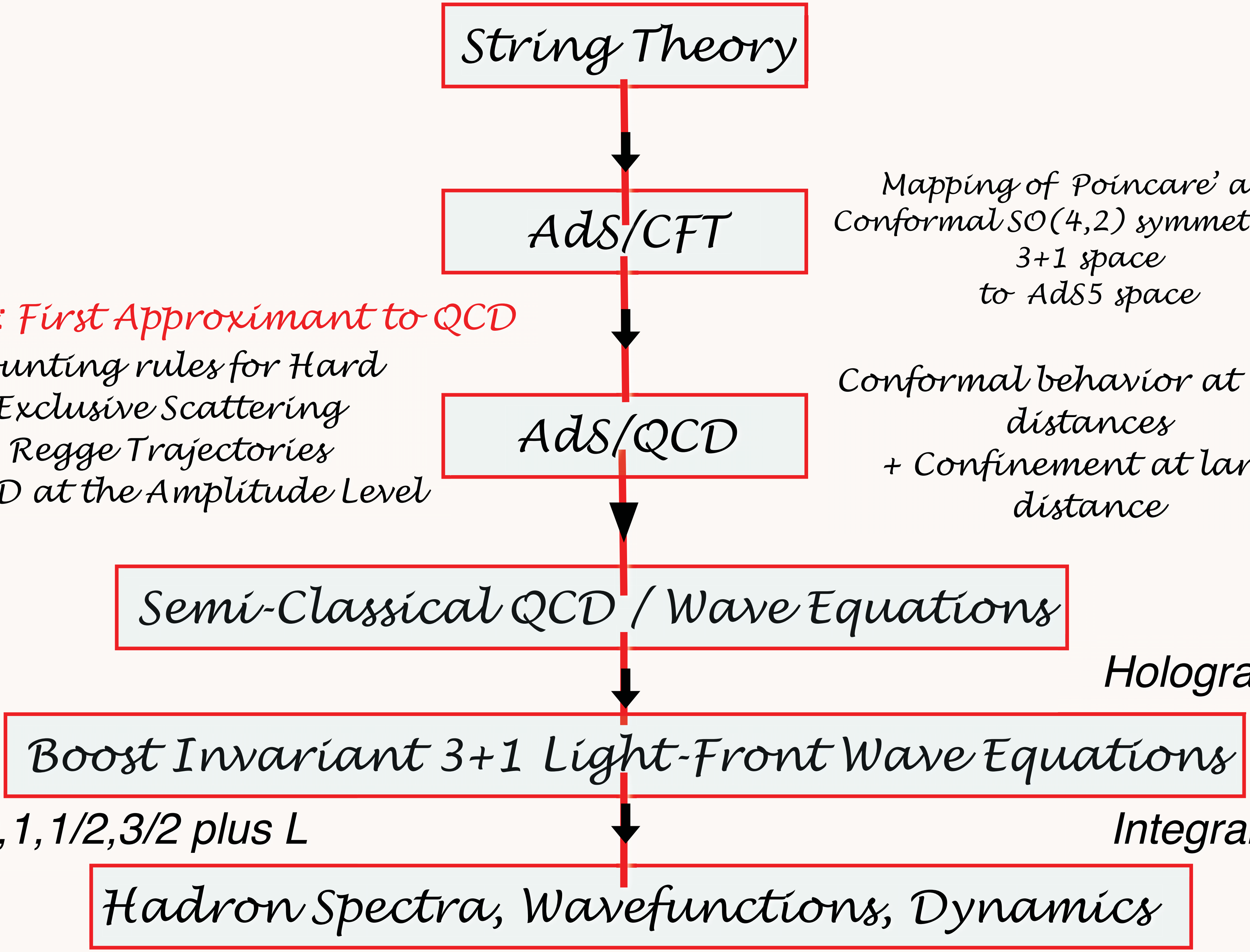
Analytic continue to timelike momenta and introduce width

$$q^2 \to q^2 + i\epsilon \to q^2 + iM\Gamma$$

Fit to height, predict width

$\Gamma_\rho = 111\ \text{MeV}$

$\Gamma_\rho^{exp} = 150.3 \pm 1.6\ \text{MeV}$



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

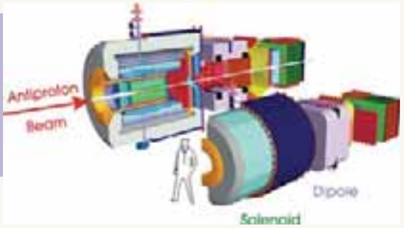
Boost Invariant 3+1 Light-Front Wave Equations

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

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

Key QCD Panda Experiment

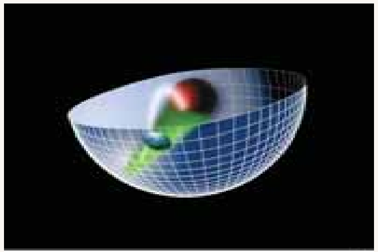


- Analytic form for form factors, GPDs, distribution amplitude
- Matrix elements and LFWFs for baryon scattering amplitudes: Quark Counting Rules!
- Orbital angular momentum in baryon wavefunction for Pauli form factor, SSAs
- Dominance of quark interchange at short distances
- Effective Regge trajectories
- Regge intercepts at negative integers at large t

Features of Soft-Wall AdS/QCD

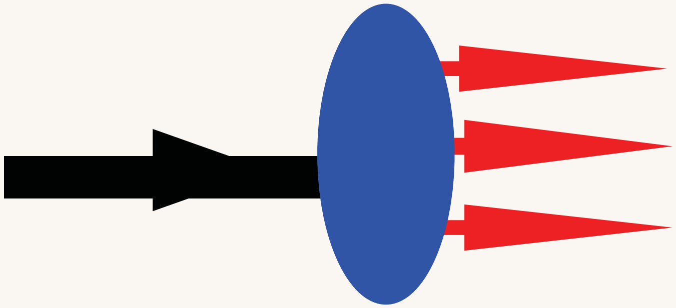
- **Single-variable frame-independent radial Schrodinger equation**
- **Massless pion (m_q =0)**
- **Regge Trajectories: universal slope in n and L**
- **Valid for all integer J & S.**
- **Dimensional Counting Rules for Hard Exclusive Processes**
- **Phenomenology: Space-like and Time-like Form Factors**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

- *Angular Momentum and Spin Phenomena in QCD*
- *Essentials of Spin on the Light Front*
- New Insights from higher space-time dimensions: *AdS/QCD*
- *Light-Front Holography*



- *Light Front Wavefunctions:* analogous to the Schrodinger wavefunctions of atomic physics

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



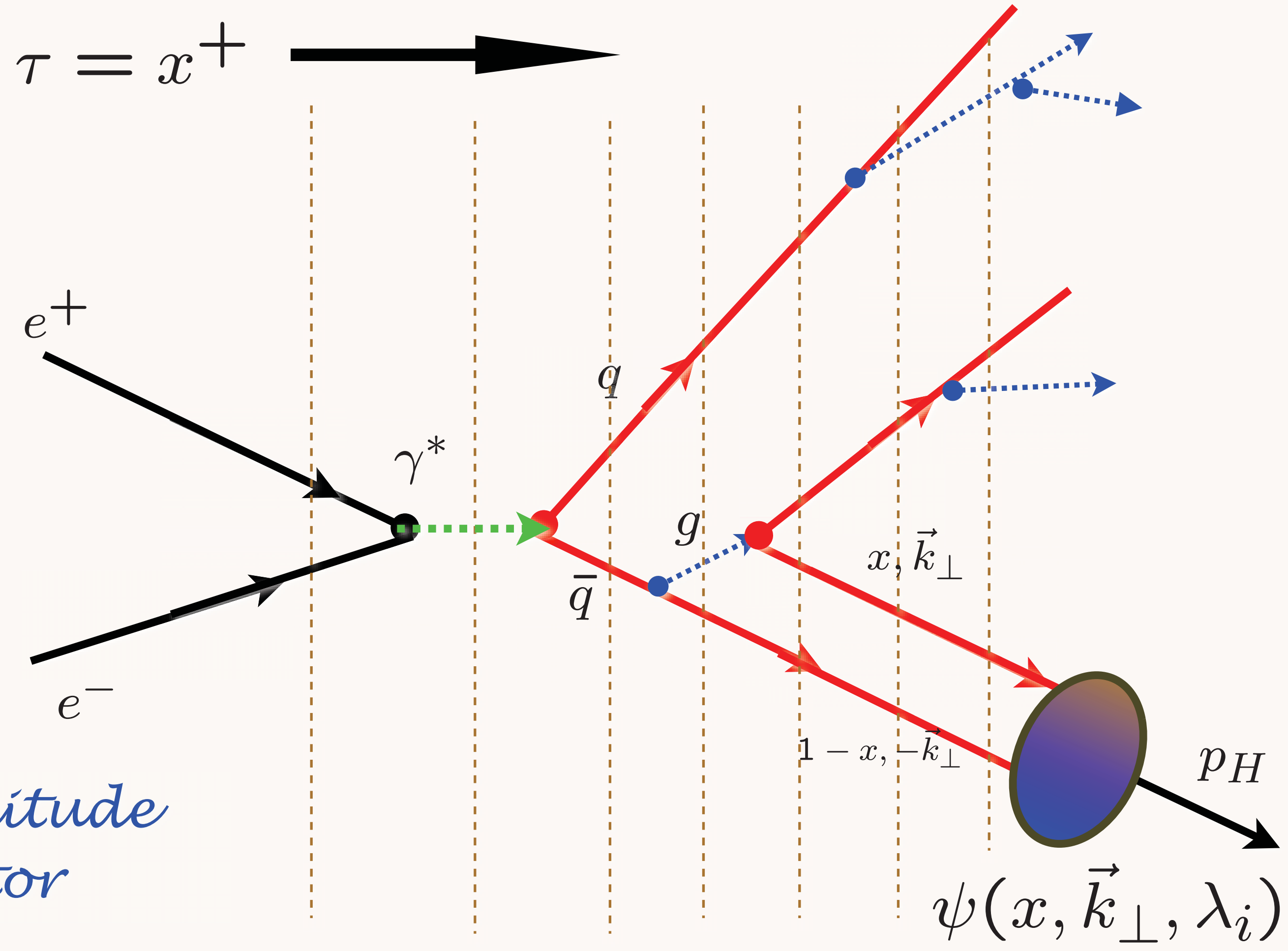
- *Hadronization at the Amplitude Level*

Bochum, June 21, 2010

Novel QCD Physics

Stan Brodsky, SLAC & CP^3

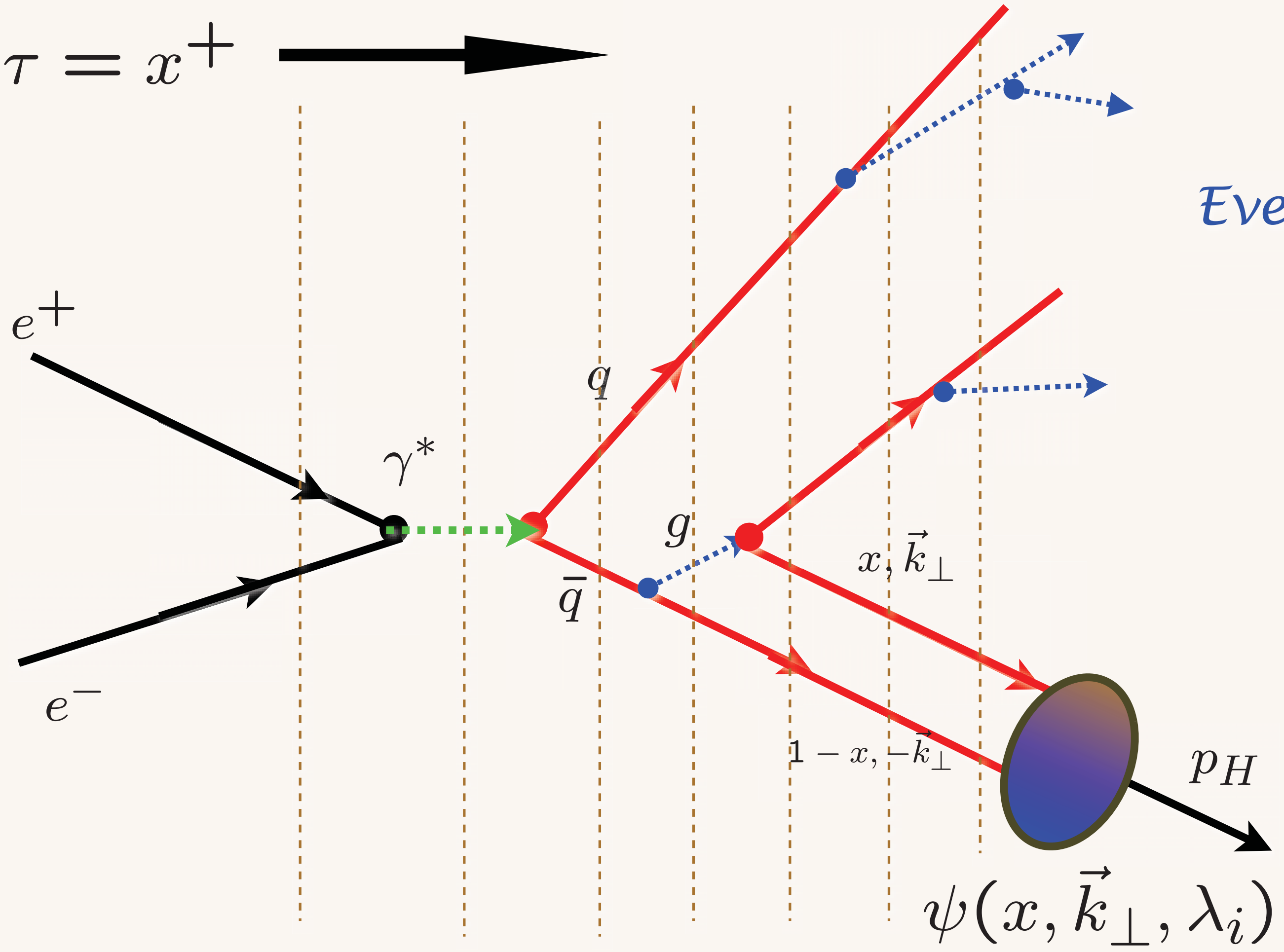
Hadronization at the Amplitude Level



Event amplitude generator

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

Hadronization at the Amplitude Level



Event amplitude generator

AdS/QCD Hard Wall Confinement:

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

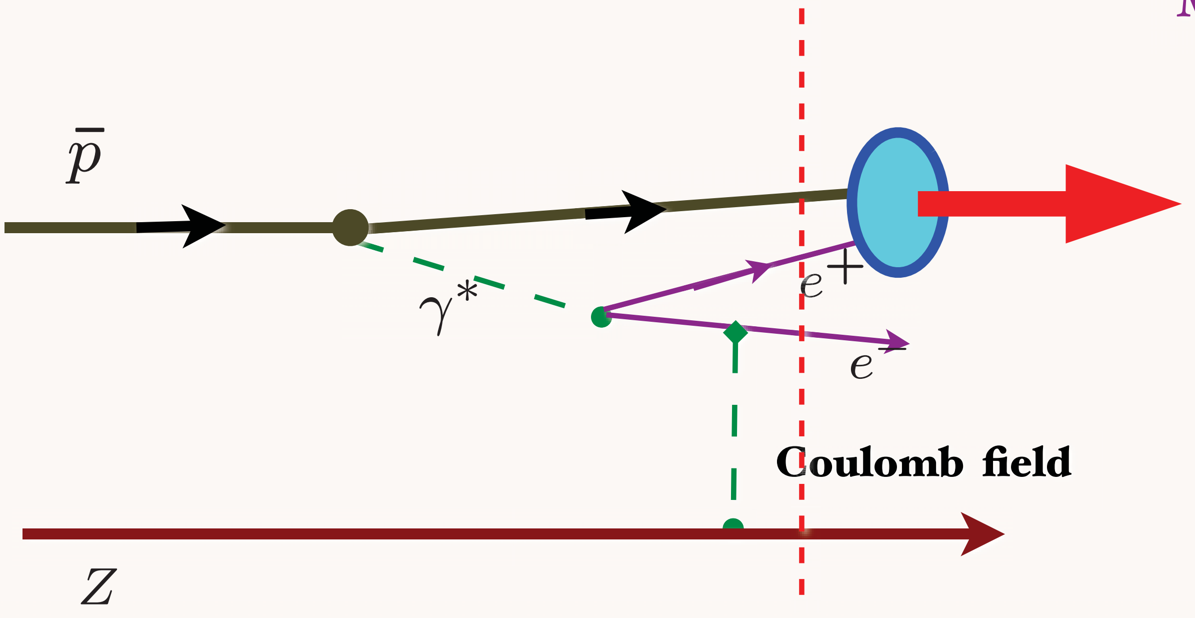
i.e.,

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

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



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

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

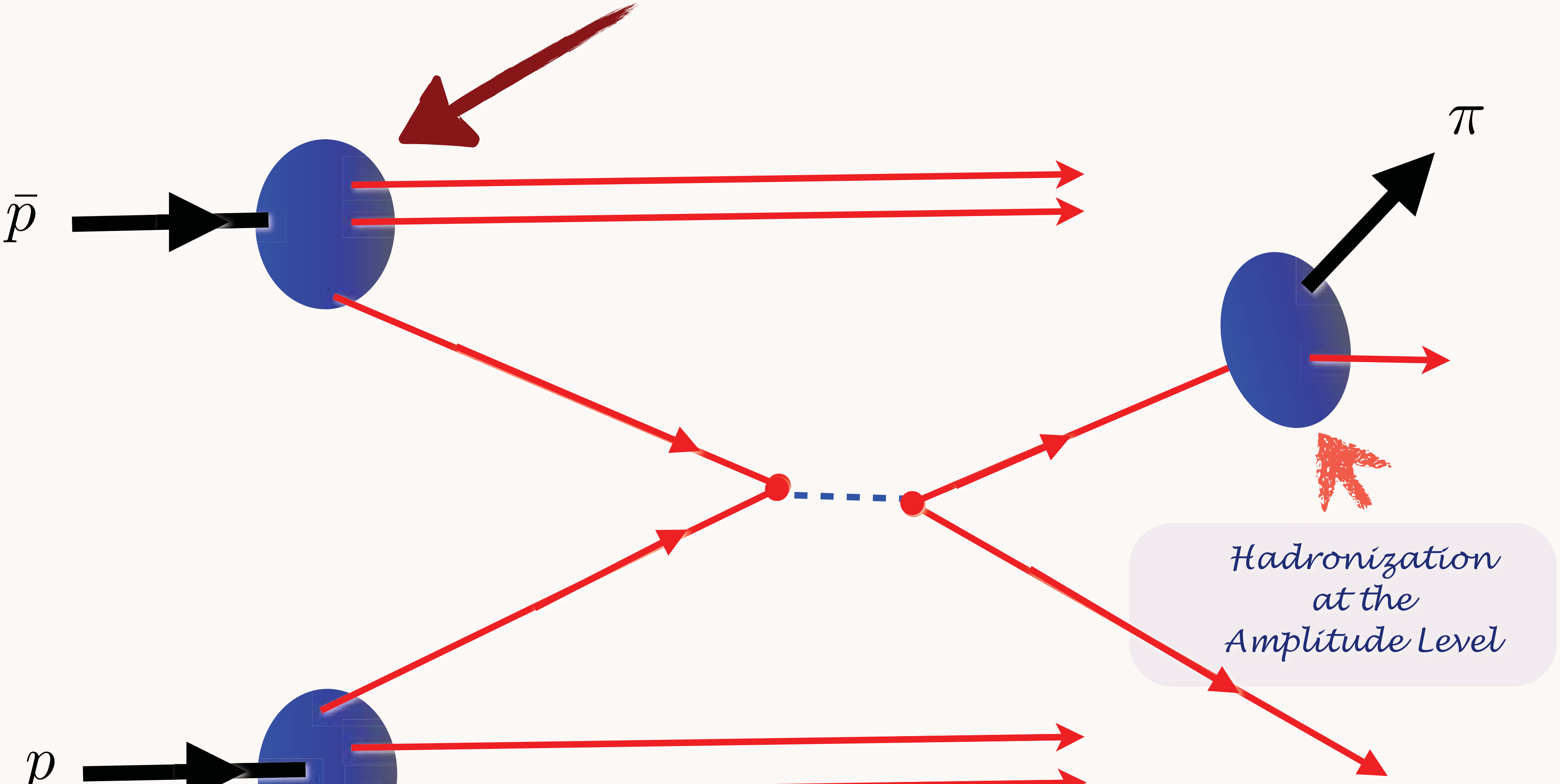
$$y_{\bar{p}} \simeq y_{e^+}$$

Coalescence of off-shell *co-moving positron and antiproton*

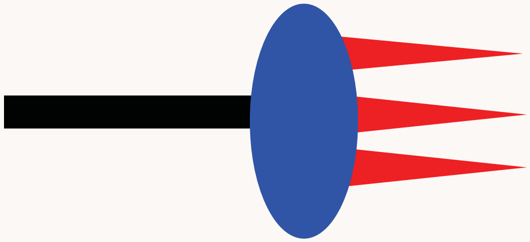
Wavefunction maximal at small impact separation and equal rapidity

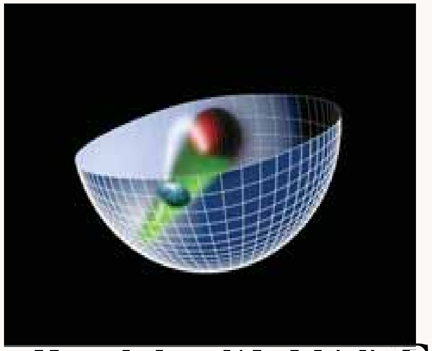
"Hadronization" at the Amplitude Level

Light-Front Wavefunctions from AdS/CFT



Hadronization at the Amplitude Level

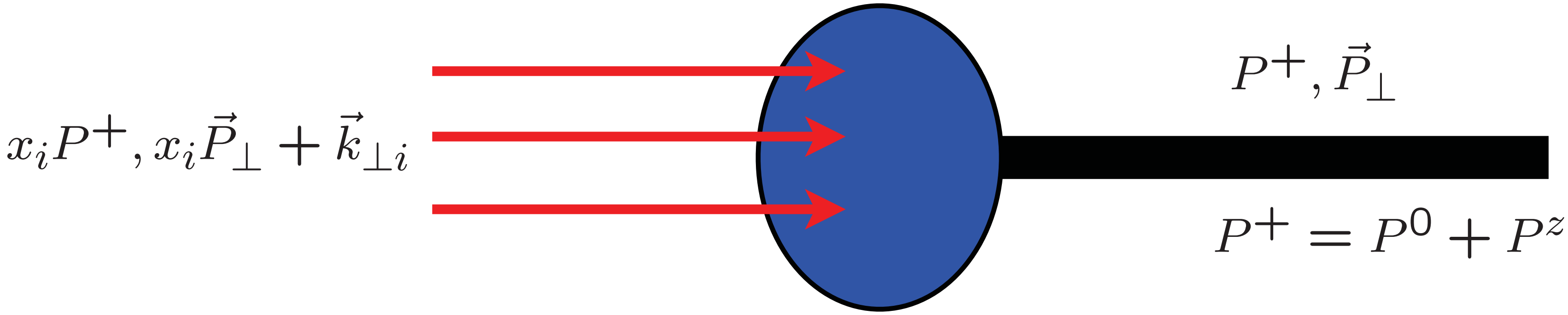




$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

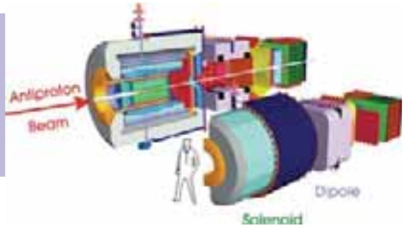
Features of LF T-Matrix Formalism
“Event Amplitude Generator”

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



New Perspectives on QCD Phenomena from AdS/CFT

Key QCD Panda Experiment

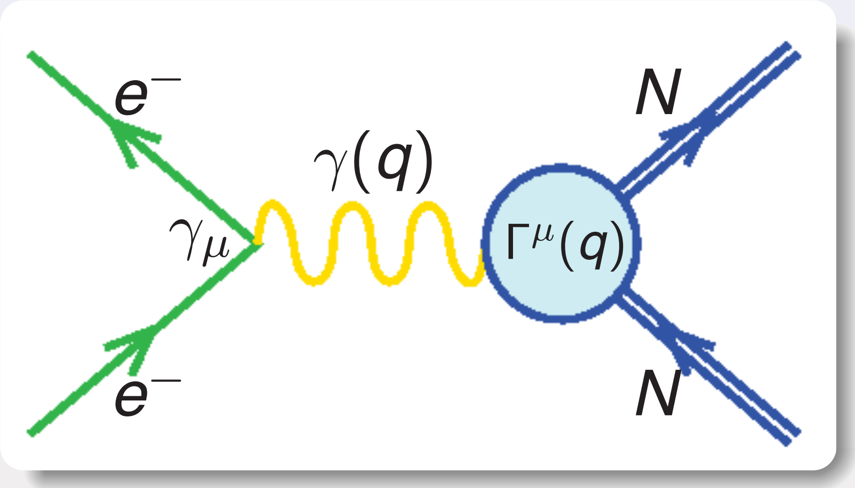


- AdS/CFT: Duality between string theory in Anti-de Sitter Space and Conformal Field Theory
- New Way to Implement Conformal Symmetry
- Holographic Model: Conformal Symmetry at Short Distances, Confinement at large distances
- Remarkable predictions for hadronic spectra, wavefunctions, interactions
- AdS/CFT provides novel insights into the quark structure of hadrons

Novel Dynamical Tests of QCD at PANDA

- Characteristic momentum scale of QCD: 300 MeV
- Many Tests of AdS/CFT predictions possible
- Exclusive channels: Conformal scaling laws, quark-interchange
- $\bar{p}p$ scattering: fundamental aspects of nuclear force
- Color transparency: Coherent color effects
- Nuclear Effects, Hidden Color, Anti-Shadowing
- Anomalous heavy quark phenomena
- Spin Effects: A_N, A_{NN}

Nucleon Form Factors

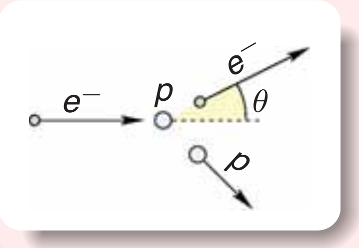


Nucleon current operator (Dirac & Pauli)

$$\Gamma^\mu(q) = \gamma^\mu F_1(q^2) + \frac{i}{2M_N}\sigma^{\mu\nu} q_\nu F_2(q^2)$$

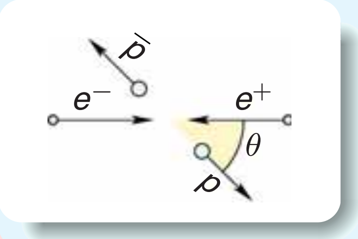
Electric and Magnetic Form Factors

$$G_E(q^2) = F_1(q^2) + \tau F_2(q^2) \qquad \tau = \frac{q^2}{4M_N^2}$$
$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$



Elastic scattering $ep \longrightarrow ep$

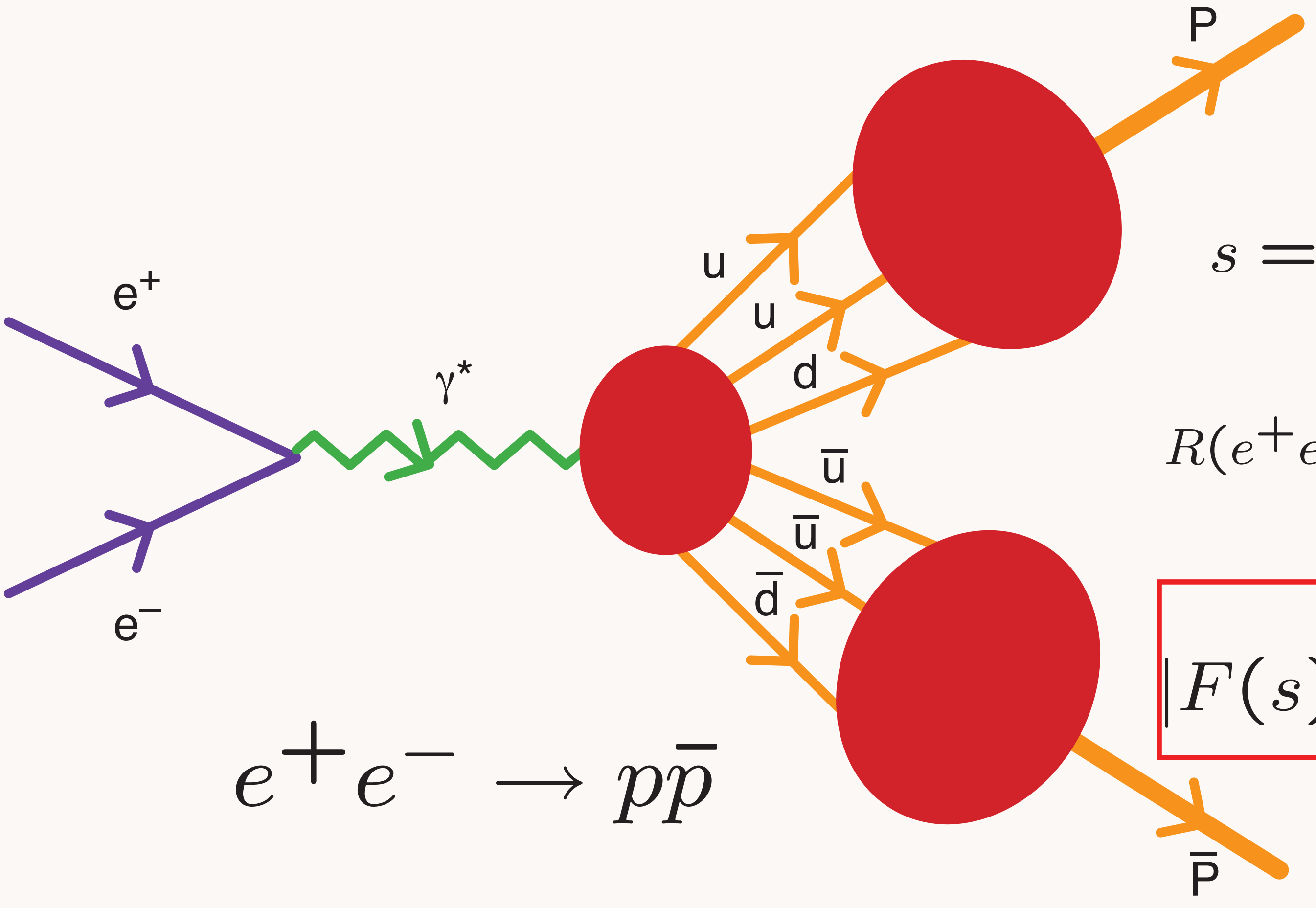
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e' \cos^2\frac{\theta}{2}}{4E_e^3 \sin^4\frac{\theta}{2}}\left[G_E^2 + \tau\left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)G_M^2\right]\frac{1}{1+\tau}$$



Annihilation $e^+e^- \longrightarrow p\bar{p}$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\sqrt{1-1/\tau}}{4q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right]$$

Exclusive Processes



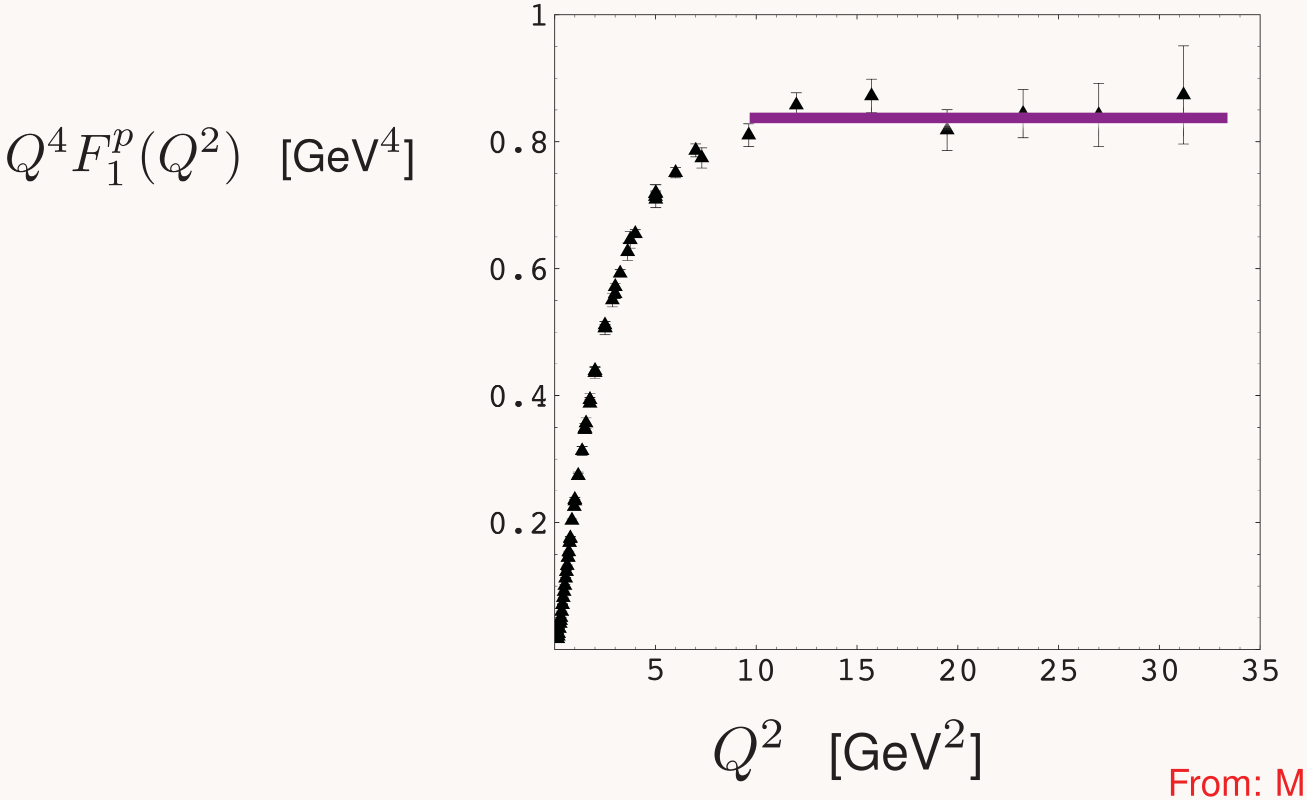
$$e^+e^- \to p\bar{p}$$

$$s = (E_{e^+} + E_{e^-})^2$$

$$R(e^+e^- \to H\bar{H}) \propto |F(s)|^2$$

$$\boxed{|F(s)| \propto [\tfrac{1}{s}]^{n_q-1}}$$

Probability decreases with number of constituents!



$$F_1(Q^2) \sim \left[1/Q^2\right]^{n-1}, \ n = 3$$

measured in electron-proton elastic scattering

From: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

- Phenomenological success of dimensional scaling laws for exclusive processes

$$d\sigma/dt \sim 1/s^{n-2}, \quad n = n_A + n_B + n_C + n_D,$$

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies
Farrar and sjb (1973); Matveev *et al.* (1973).

- Derivation of counting rules for gauge theories with mass gap dual to string theories in warped space (hard behavior instead of soft behavior characteristic of strings) Polchinski and Strassler (2001).

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

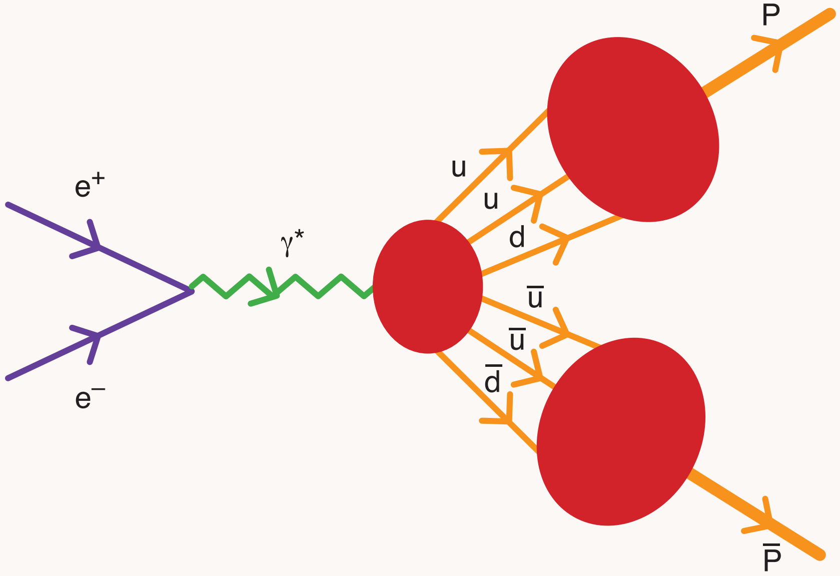
Key QCD Panda Experiment

Lepage; SJB
Efremov, Radyuskin

$$M = \int \prod dx_i dy_i \phi_F(x, \tilde{Q}) \times T_H(x_i, y_i, \tilde{Q}) \phi_I(y_i, Q)$$

- Iterate kernel of LFWFs when at high virtuality; distribution amplitude contains all physics below factorization scale
- Rigorous Factorization Formulae: Leading twist
- Underly Exclusive B-decay analyses
- Distribution amplitude: gauge invariant, OPE, evolution equations, conformal expansions
- BLM scale setting: sum nonconformal contributions in scale of running coupling
- Derive Dimensional Counting Rules/ Conformal Scaling

Timelike proton form factor in PQCD



$$G_M(Q^2) \quad \rightarrow \quad \frac{\alpha_s^2(Q^2)}{Q^4} \sum_{n,m} b_{nm} \left(\log \frac{Q^2}{\Lambda^2}\right)^{\gamma_n^B + \gamma_n^B}$$

$$\times \quad \left[1 + \mathcal{O}\left(\alpha_s(Q^2), \frac{m^2}{Q^2}\right)\right]$$

Lepage and Sjb

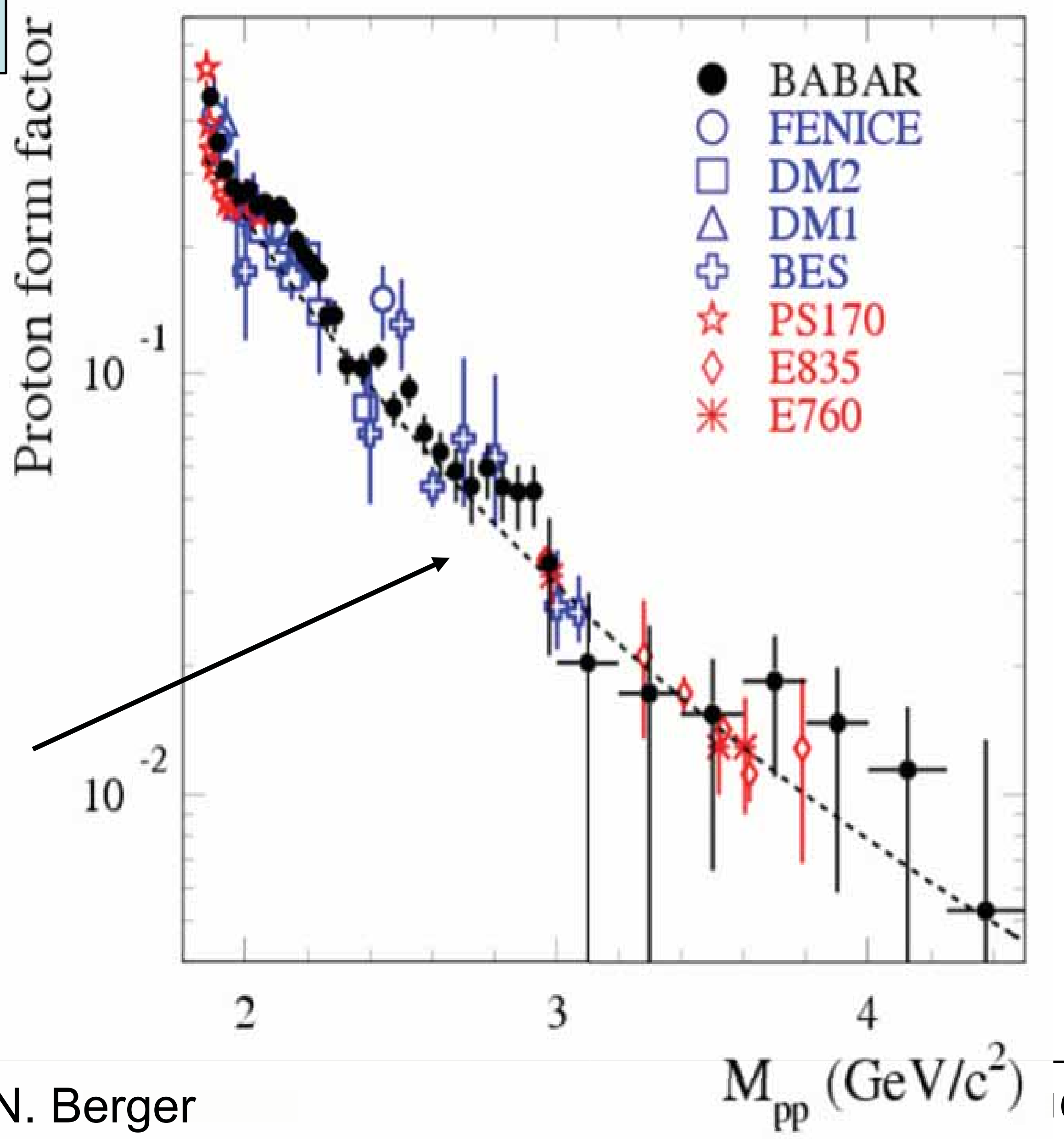
Timelike Proton Form Factor

- Define “Effective” form factor by

$$\sigma = \frac{4\pi\alpha^2\beta C}{3m_{p\bar{p}}^2}|F|^2,\ |F| = \sqrt{|G_M|^2 + \frac{2m_p^2}{m_{p\bar{p}}^2}|G_E|^2}.$$

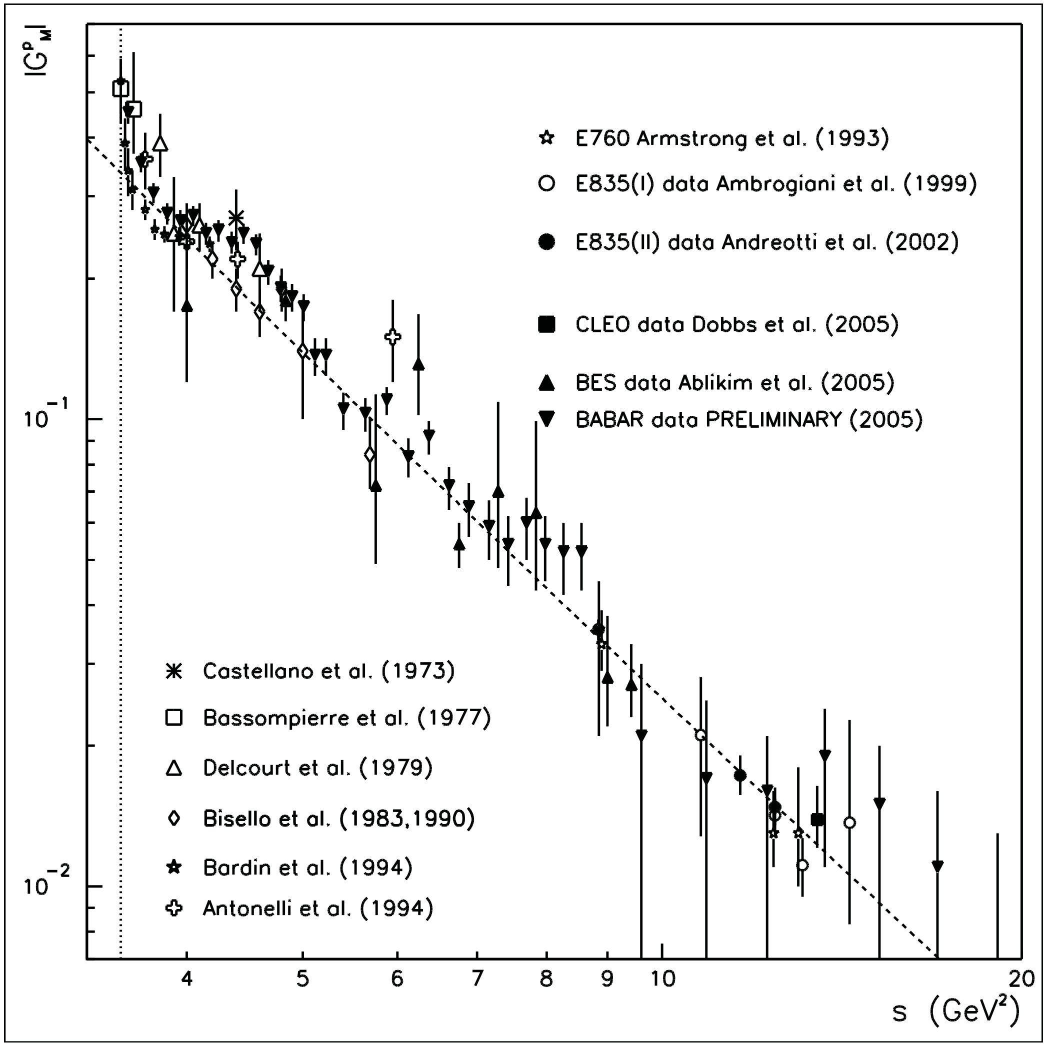
- Peak at threshold, sharp dips at 2.25 GeV, 3.0 GeV.
- Good fit to pQCD prediction for high m_{pp}.

$$F(s) \propto \frac{\log^{-2}\frac{s}{\Lambda^2}}{s^2}$$



Time-like Form Factors

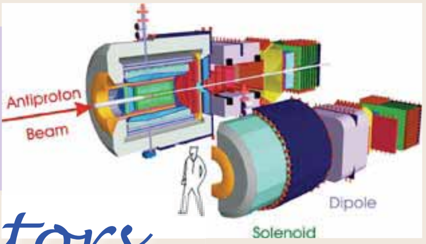
- All data measure absolute cross section $G_E = G_M$
- PANDA will provide independent measurement of G_E and G_M
- widest kinematic range in a single experiment
- Time-like form factors are complex
- precision experiments will reveal these structures



PANDA range

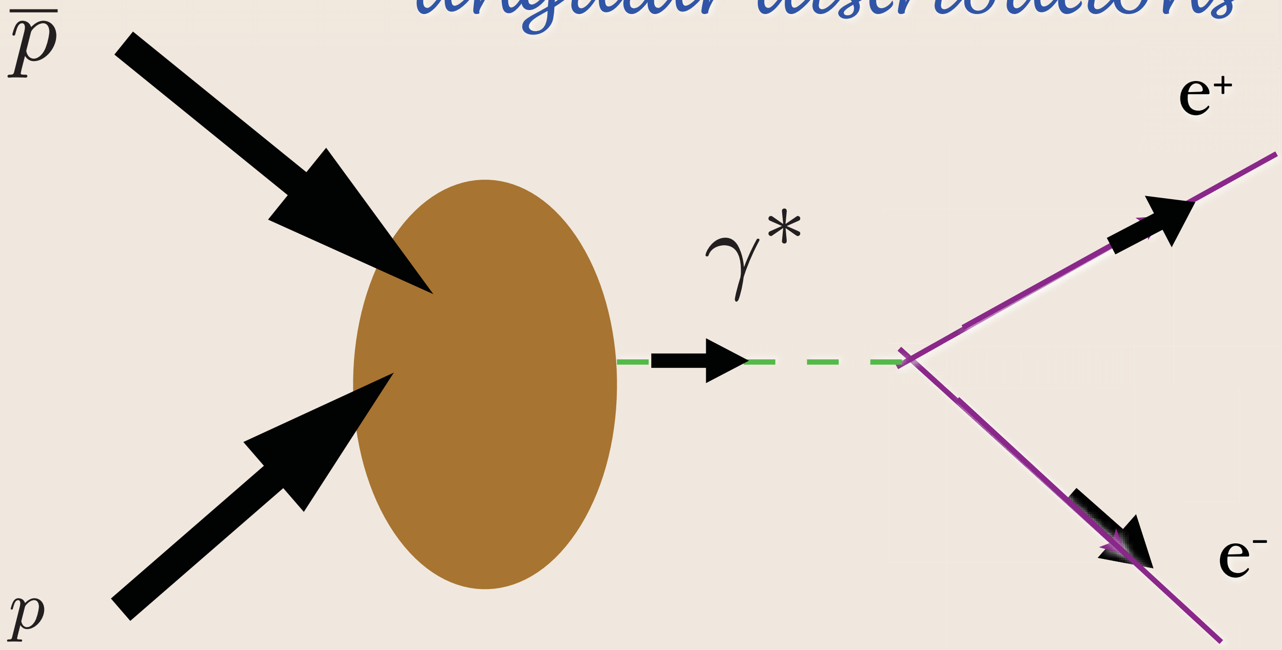
B. Seitz

Key QCD Panda Experiment



Measurement of hadron time-like form factors

angular distributions **Separate F1, F2**



Leading power in QCD

$$F_H(s) \propto [\tfrac{1}{s}]^{n_H - 1}$$

Test QCD Counting Rules

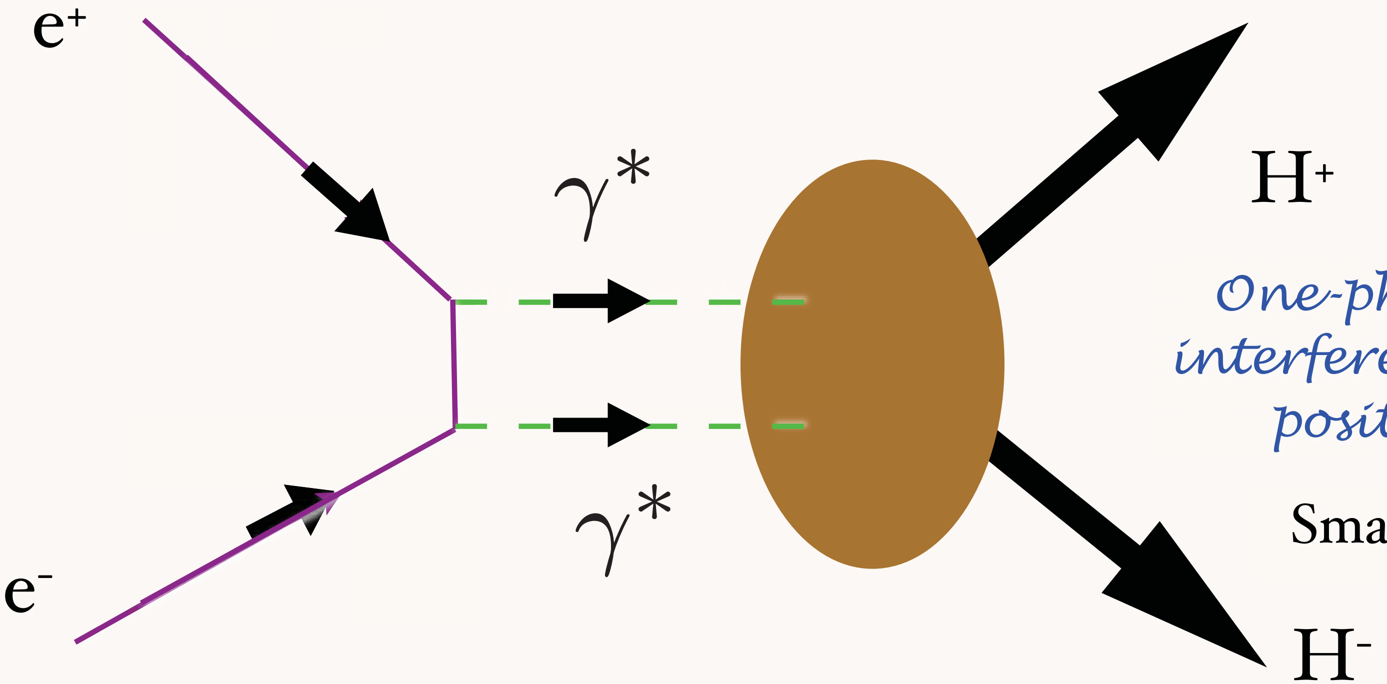
Conformal Symmetry: AdS/CFT

Hadron Helicity Conservation

$$\sum_{\text{initial}} \lambda_H - \sum_{\text{total}} \lambda_H = 0 \,,$$

- Two-photon exchange correction, elastic and inelastic nucleon channels, give significant; interference with one-photon exchange, destroys Rosenbluth method

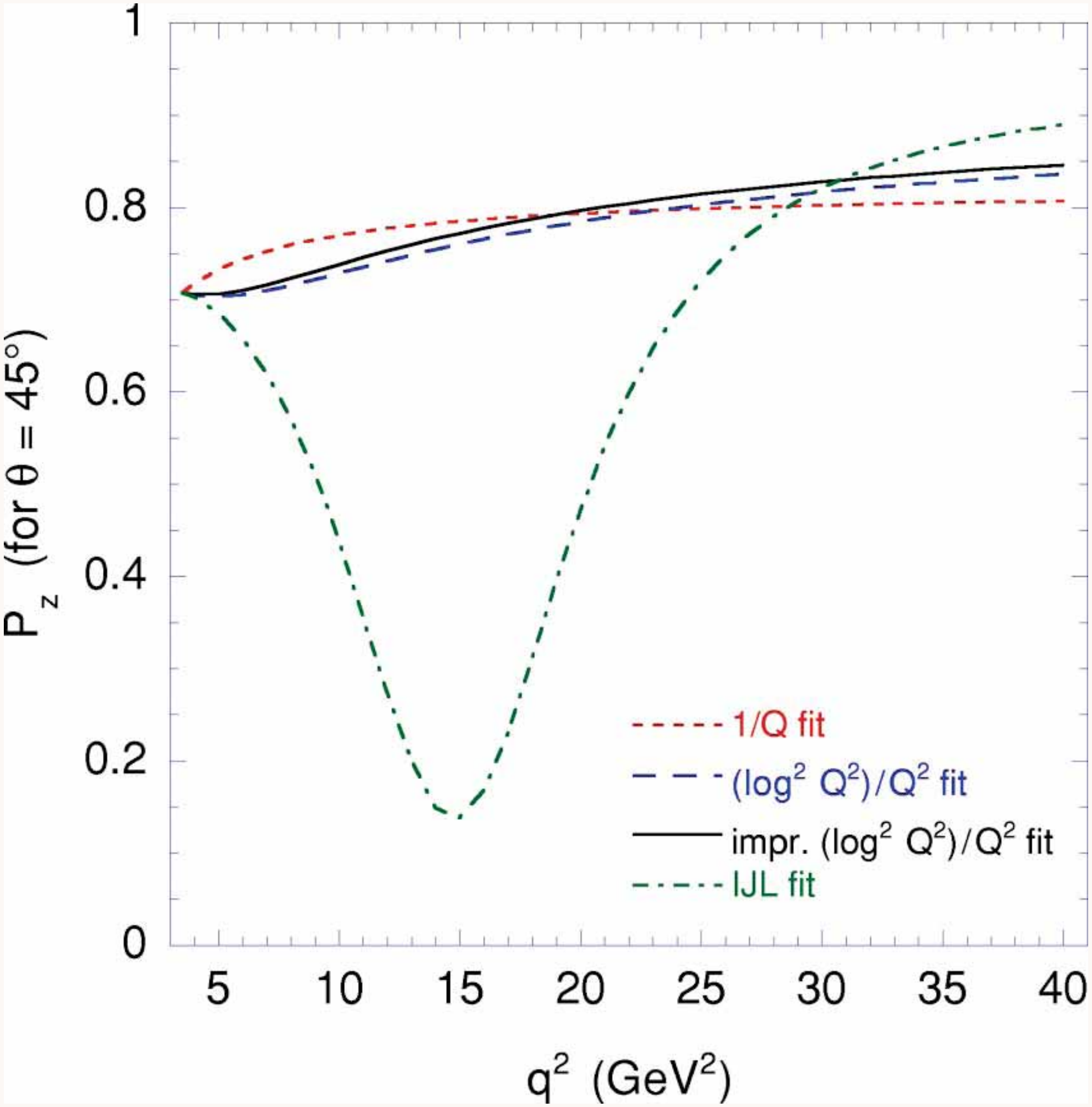
Blunden, Melnitchouk; Afanasev, Chen,Carlson, Vanderhaegen, sjb



One-photon/two-photon interference gives electron-positron asymmetry

Small Effect from Z^o

Single-spin polarization effects and the determination of timelike proton form factors



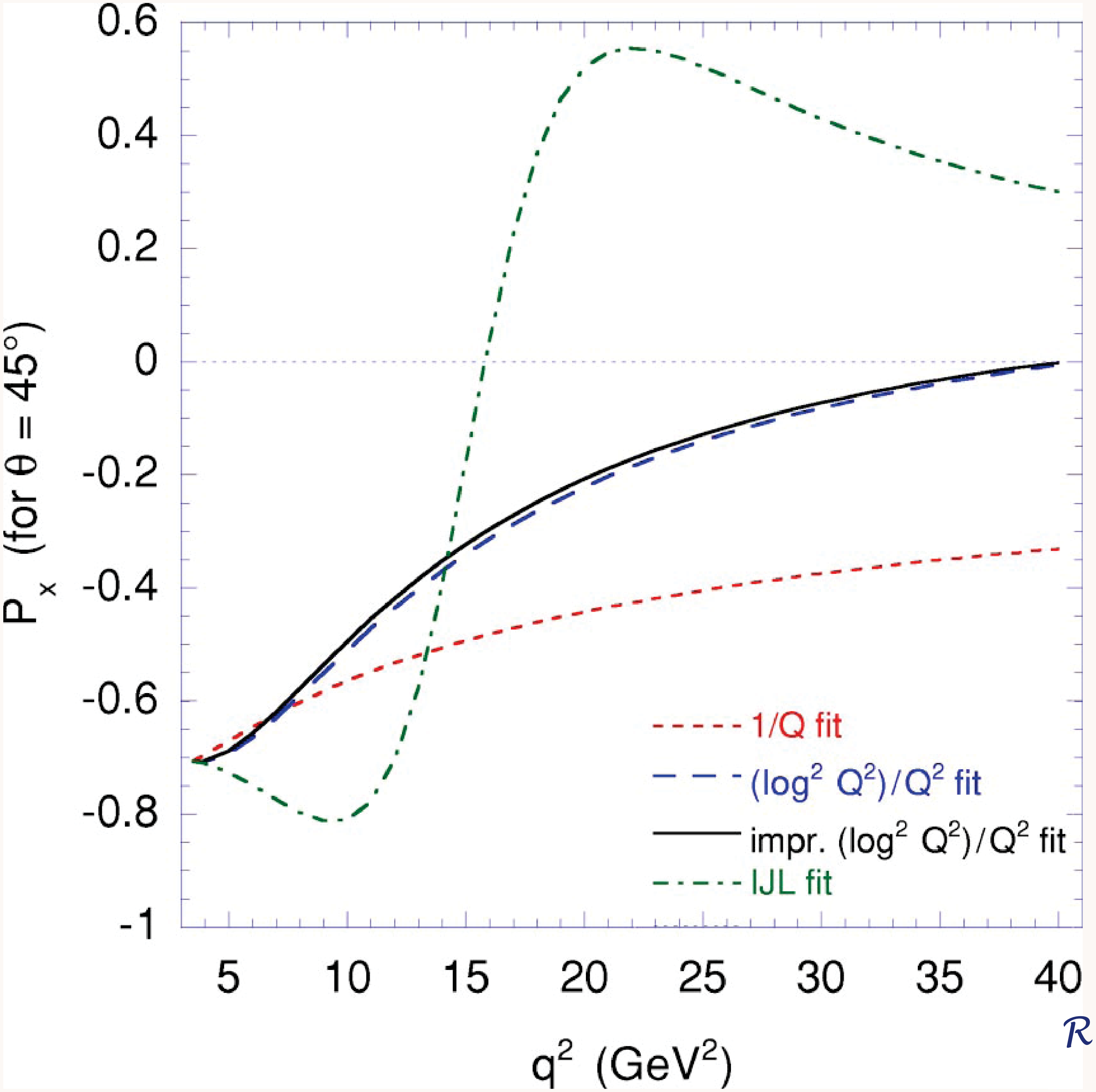
Carlson, Hiller,
Hwang, sjb

$$\mathcal{P}_z = P_e \frac{2\cos\theta |G_M|^2}{D}$$

$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

Requires beam and lepton polarization

Single-spin polarization effects and the determination of timelike proton form factors



Carlson, Hiller, Hwang, sjb

$$\mathcal{P}_x = -P_e \frac{2\sin\theta \,\mathrm{Re}\, G_E^* G_M}{D\sqrt{\tau}}$$

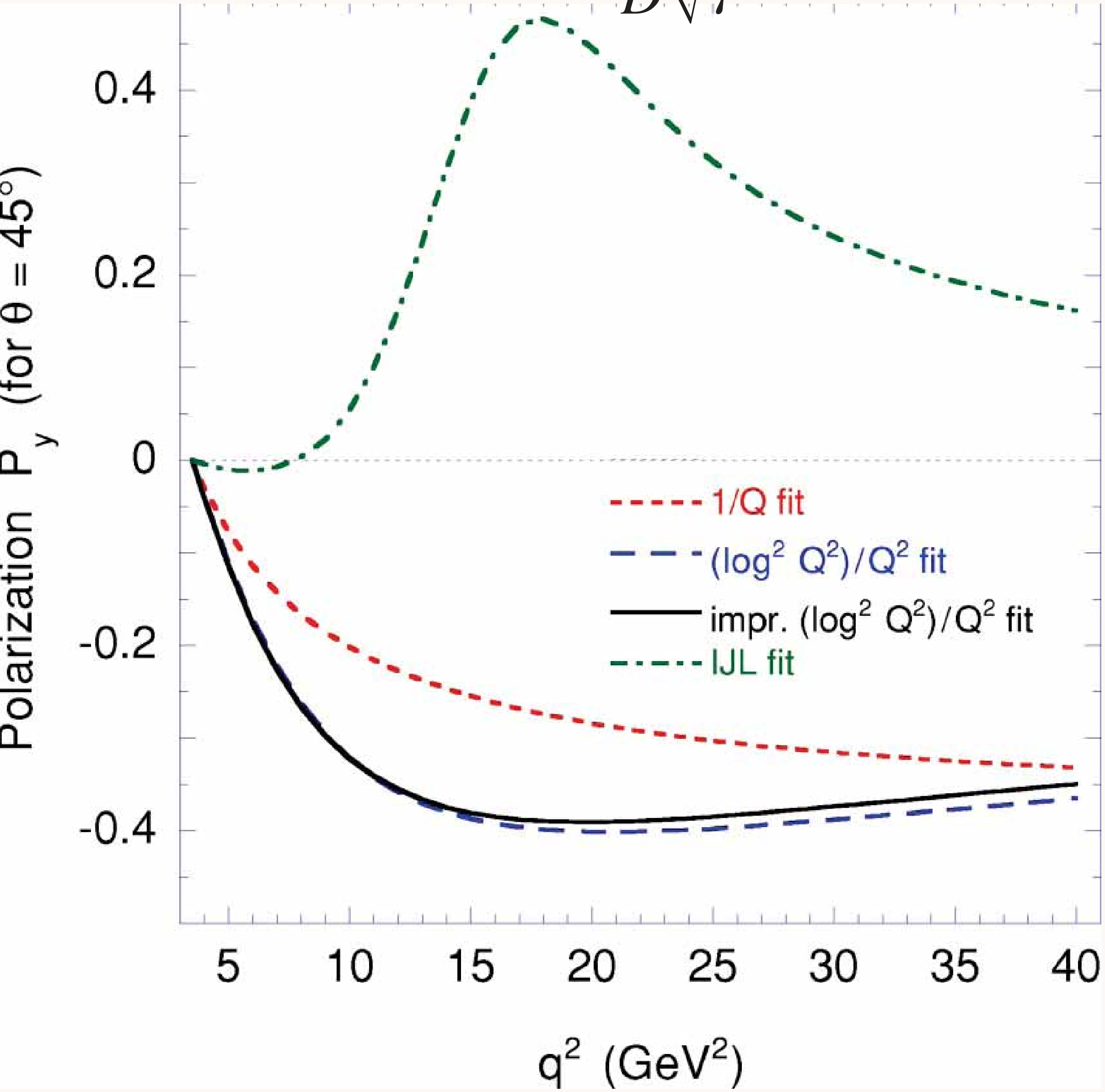
$$D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

Requires beam and lepton polarization

Single-spin polarization effects and the determination of timelike proton form factors

$$\mathcal{P}_y = \frac{\sin 2\theta \, \mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta \, \mathrm{Im}\, F_2^* F_1}{D\sqrt{\tau}}$$

Carlson, Hiller,
Hwang, sjb

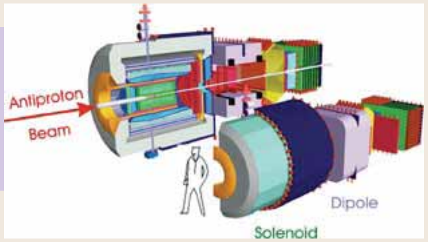


$$D = |G_M|^2(1 + \cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta;$$

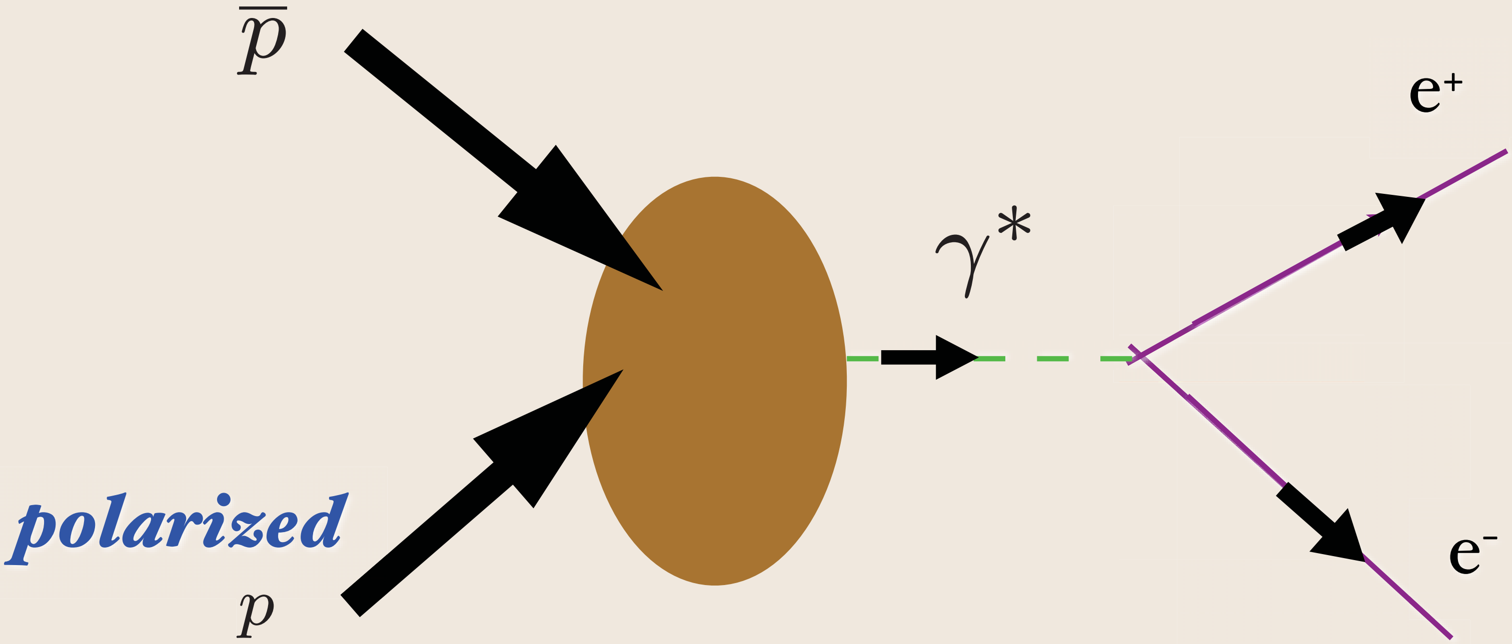
$$\tau \equiv q^2/4m_B^2$$

Measure relative phase of form factors

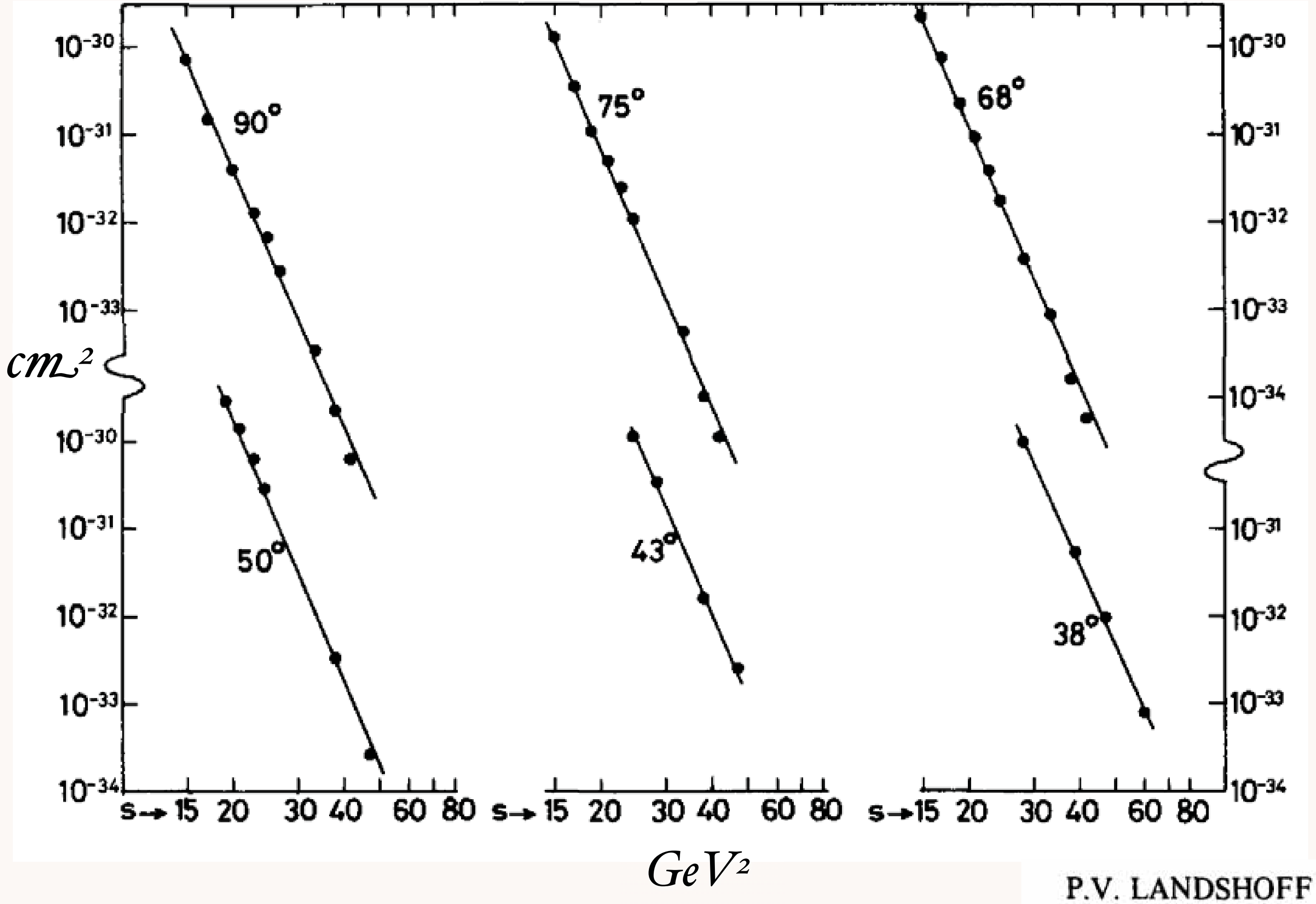
Key QCD Panda Experiment



$$\mathcal{P}_y = \frac{\sin 2\theta \,\mathrm{Im}\, G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta \,\mathrm{Im}\, F_2^* F_1}{D\sqrt{\tau}}$$



Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $n = 4 \times 3 - 2 = 10$



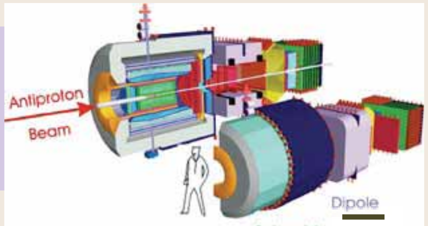
P.V. LANDSHOFF and J.C. POLKINGHORNE

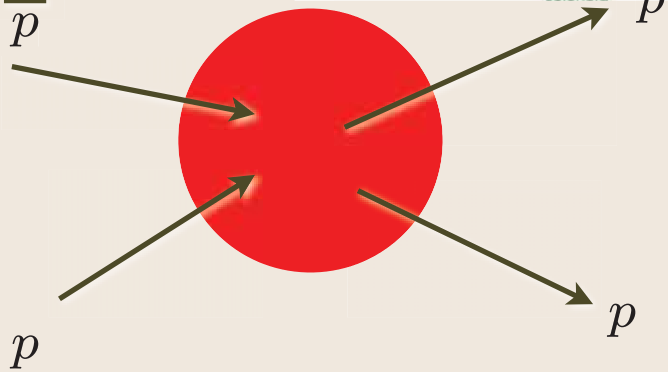
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

Key QCD Panda Experiment





$$\frac{d\sigma}{dt}(\overline{p}p \to \overline{p}p) \text{ at large } p_T$$

Test PQCD AdS/CFT conformal scaling:
twist = dimension - spin = 12

$$\boxed{\frac{d\sigma}{dt}(\overline{p}p \to \overline{p}p) \sim \frac{|F(t/s)|^2}{s^{10}}}$$

$$M(s,t) \sim \frac{F(t/s)}{s^4}$$

Test Quark Interchange Mechanism

$$M \propto \frac{1}{s^2u^2}$$

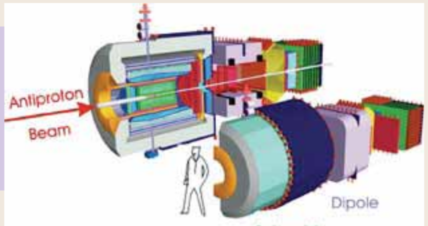
Single-spin asymmetry A_N

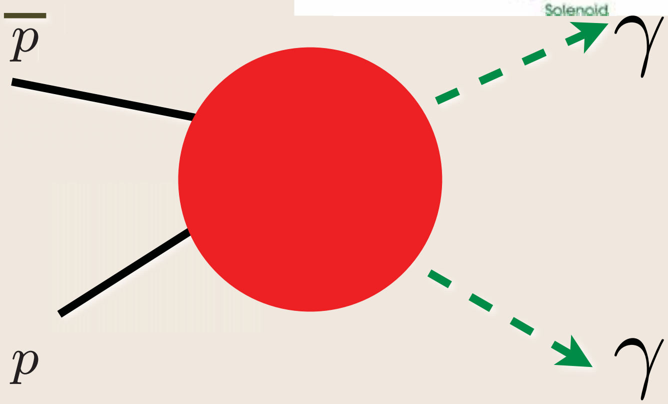
Exclusive Transversity A_{NN}

Test color transparency

Study Fundamental Aspects of Nuclear Force

Key QCD Panda Experiment





$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma)$ at fixed angle, large p_T

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

Tests PQCD and AdS/CFT Conformal Scaling

Handbag Approximation Invalid in PQCD

Single-spin asymmetry A_N

Exclusive Transversity A_{NN}

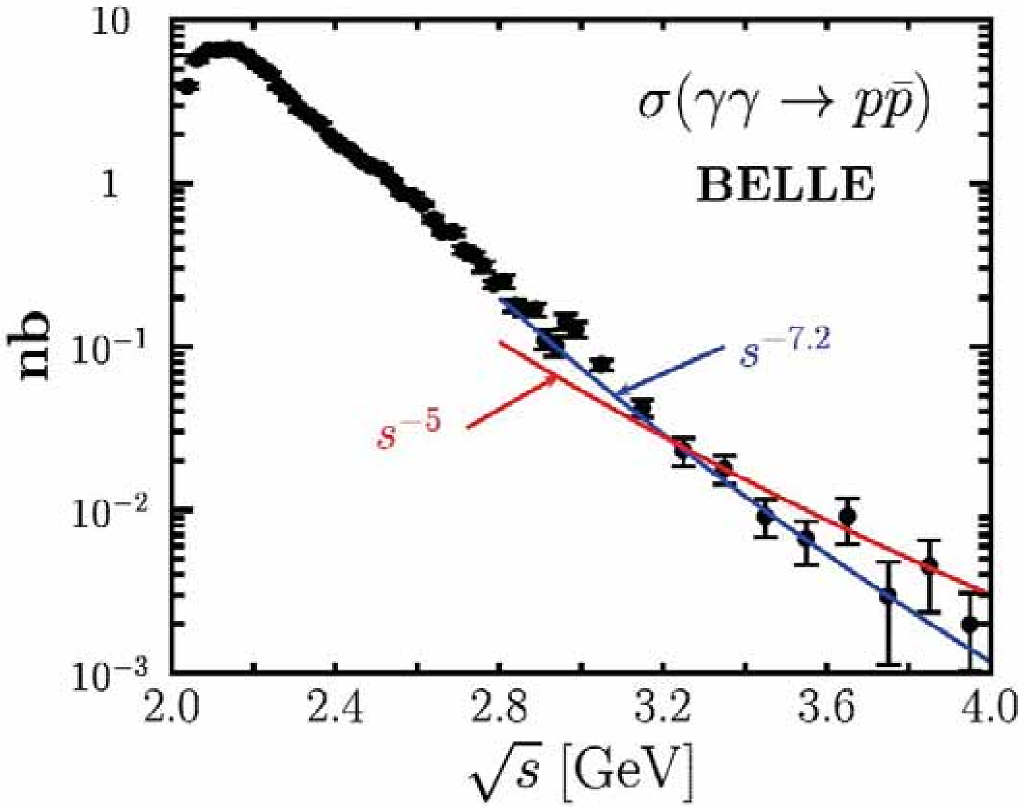
Test color transparency

Recent results from Belle

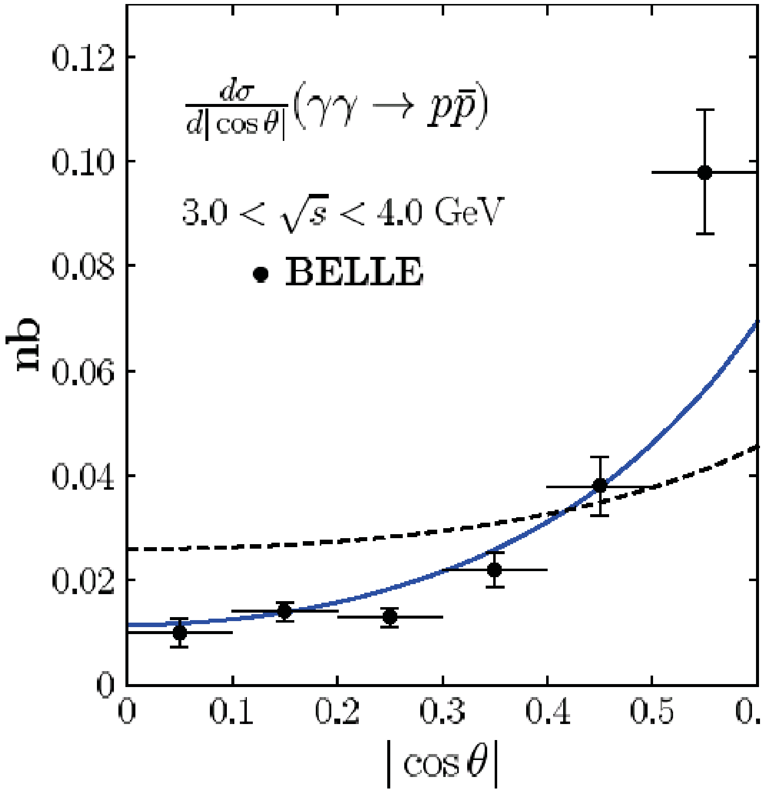
$\boxed{\gamma\gamma \to p\bar{p}}$

PQCD Conformal Scaling for range of θ_{CM}

$$s^5 \Delta\sigma(\gamma\gamma \to \bar{p}p) \simeq \text{const}$$

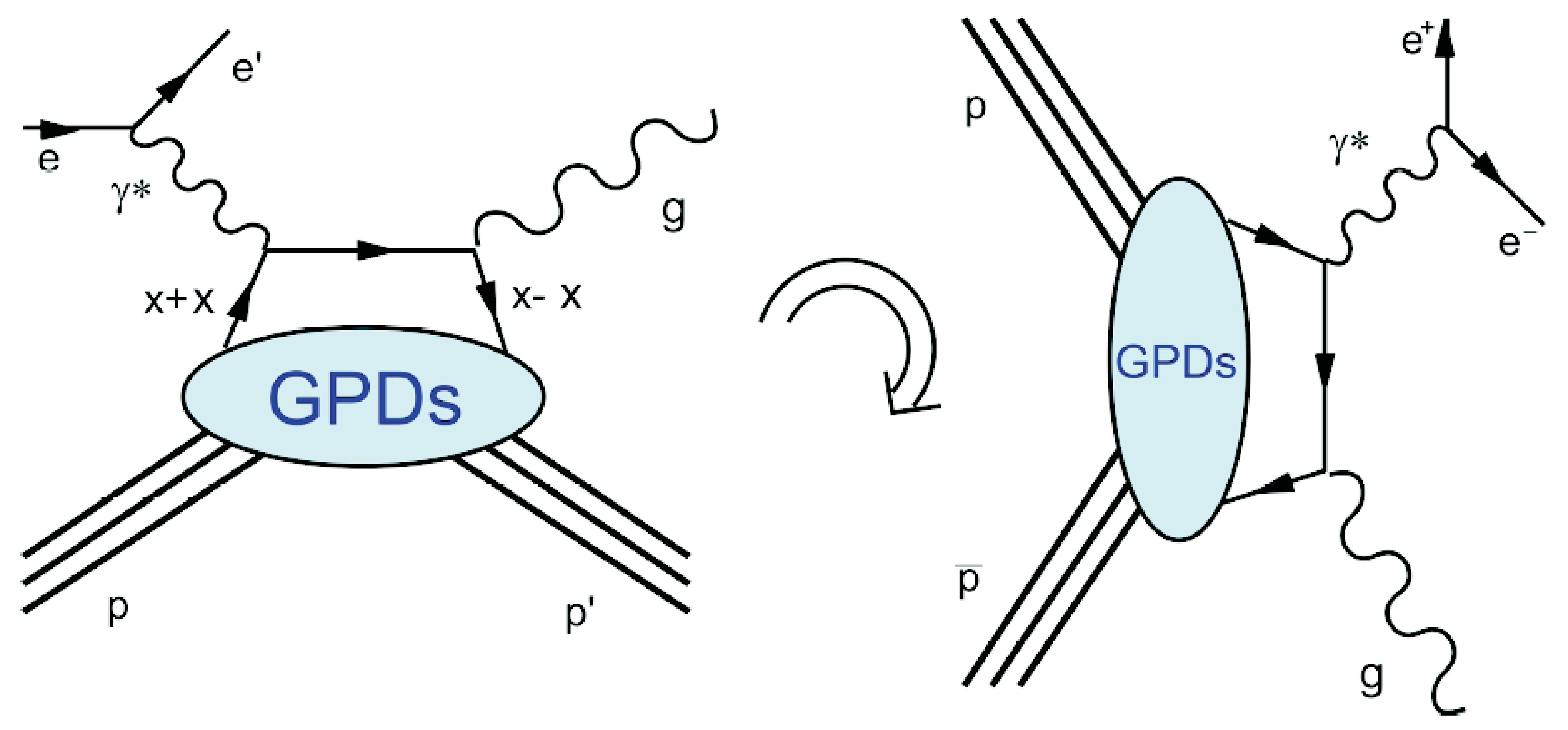


Energy dependence

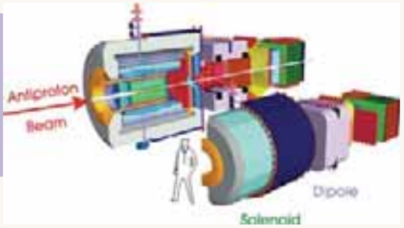


Angular dependence
(GPD curve from Kroll/Schäfer)

Michael Düren

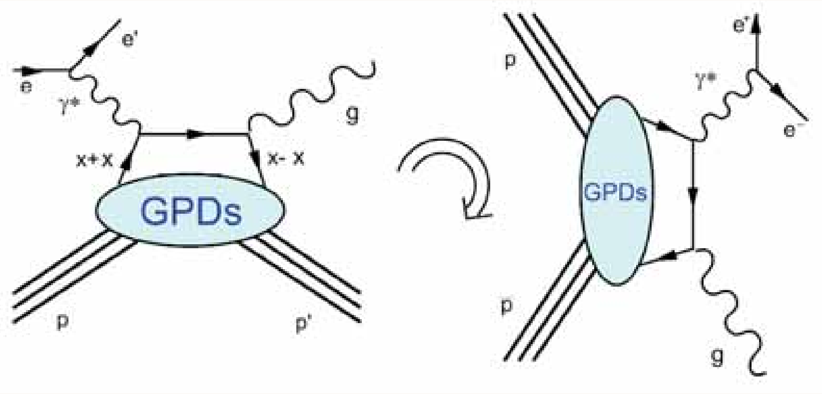

e'
e
γ*
g
x+x
x- x
GPDs
p
p'
p
e+
γ*
e−
GPDs
p̄
g

Key QCD Panda Experiment



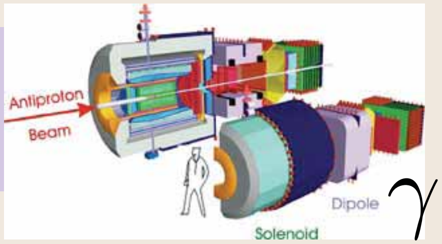
$$\bar{p}p \to \gamma^* \gamma$$

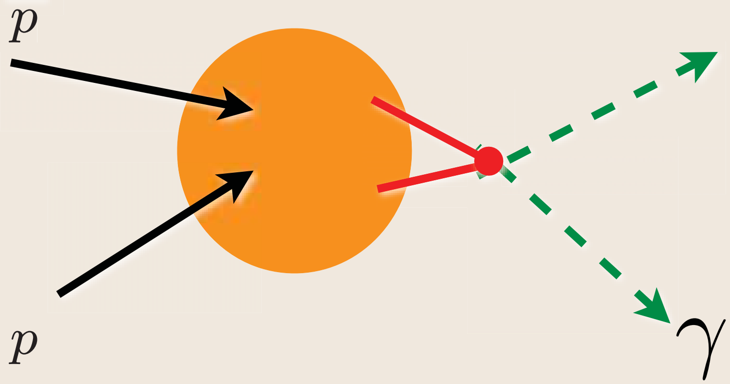
- Test DVCS in Timelike Regime
- J=0 Fixed pole: q^2 independent
- Analytic Continuation of GPDs
- Light-Front Wavefunctions
- charge asymmetry from interference



$$\bar{p}p \to \gamma^* \to \ell^+ \ell^- \to \ell^+ \ell^- \gamma \qquad \bar{p}p \to \bar{p}p\gamma \to \gamma^* \gamma \to \ell^+ \ell^- \gamma$$

Key QCD Panda Experiment





$\frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma)$ at fixed angle, large p_T

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

Local Two-Photon (Seagull) Interaction

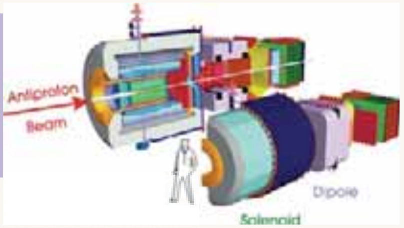
Tests PQCD and AdS/CFT Conformal Scaling

Close, Gunion, sjb
Szczepaniak,
Llanes Estrada, sjb

Angle-Independent J=0 Fixed Pole Contribution:

$$M(\bar{p}p \to \gamma\gamma) = F(s) \propto \frac{1}{s^2} \qquad \frac{d\sigma}{dt}(\bar{p}p \to \gamma\gamma) \propto \frac{1}{s^6}$$

Key QCD Panda Experiment

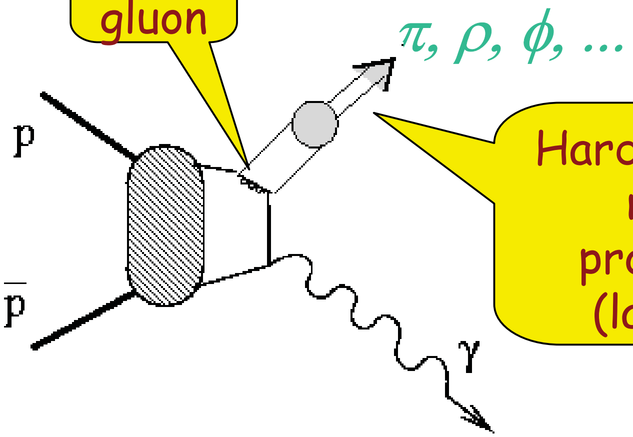


- Effective two-photon contact term
- Seagull for scalar quarks
- Real phase
- $M = s^0 F(t)$
- Independent of Q^2 at fixed t
- <1/x> Moment: Related to Feynman-Hellman Theorem
- Fundamental test of local gauge theory

Damashek, Gilman;
Close, Gunion, sjb
Szepaniack, Lannes Estrada, sjb

Test J=0 Fixed Pole: $s^2\, d\sigma/dt(\gamma\, p \to \gamma\, p) \simeq F^2_0(t)$

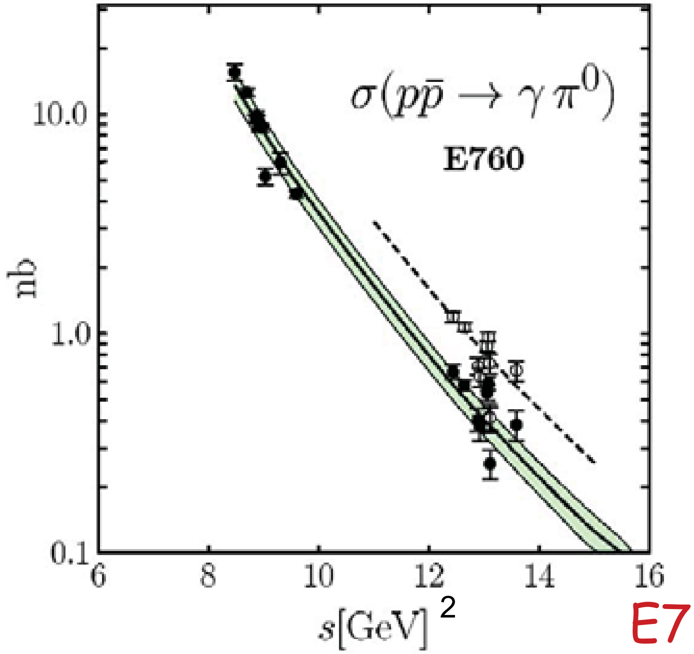
Key QCD Experiment at FAIR



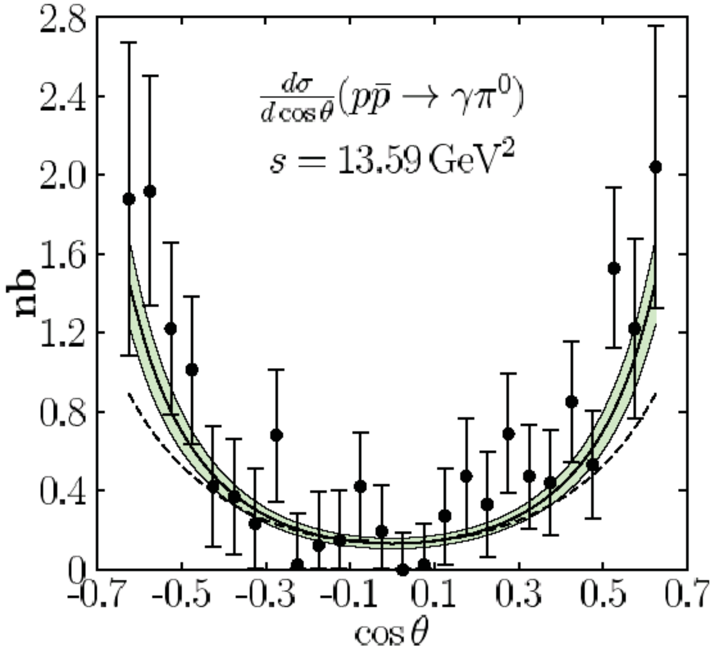
hard gluon

Hard exclusive meson production (large p_T)

- Much larger cross section (compared to $\gamma\gamma$) makes it easier to access!
- 3-γ final state



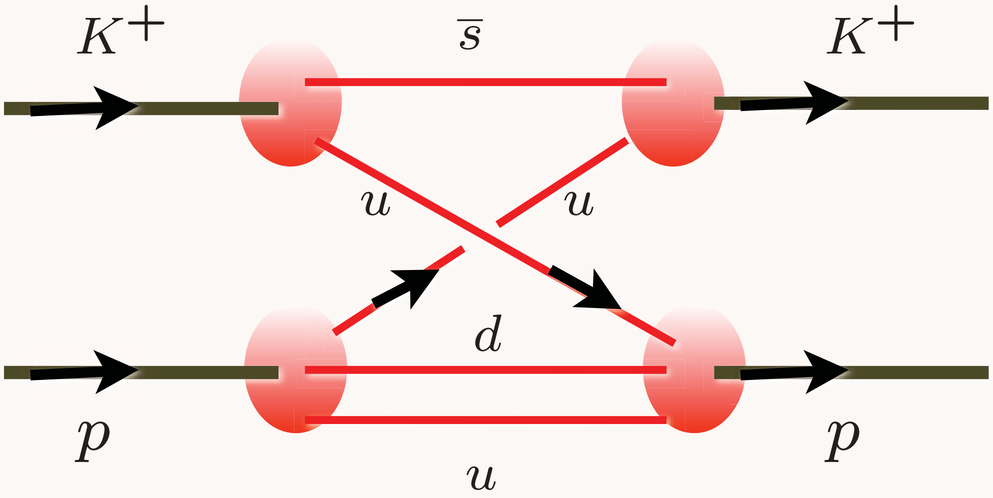
E760 results



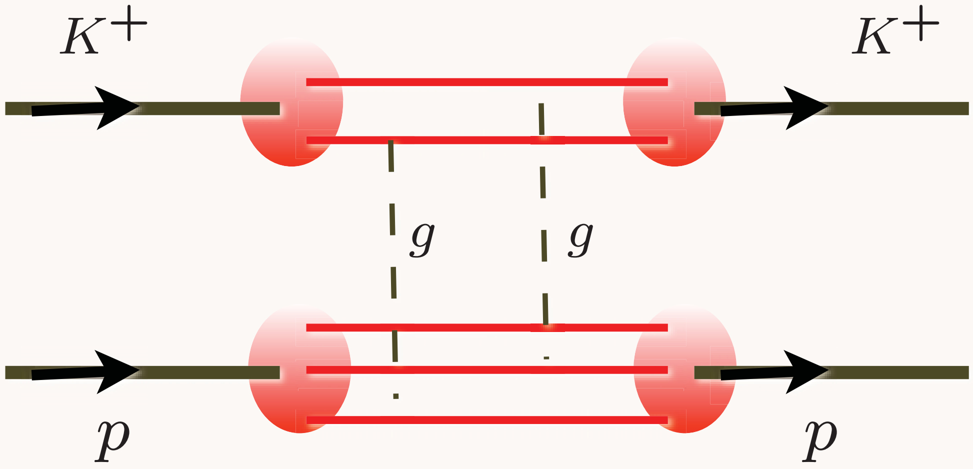
(curve from Kroll/Schäfer)

Michael Düren

CIM: Blankenbecler, Gunion, sjb



Quark Interchange
(Spin exchange in atom-atom scattering)



Gluon Exchange
(Van der Waal -- Landshoff)

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

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

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

MIT Bag Model (de Tar), large N_C, ('t Hooft), AdS/CFT all predict dominance of quark interchange:

Remarkable prediction of AdS/CFT: Dominance of quark interchange

Example: $M(K^+p \to K^+p) \propto \frac{1}{ut^2}$

Exchange of common u quark

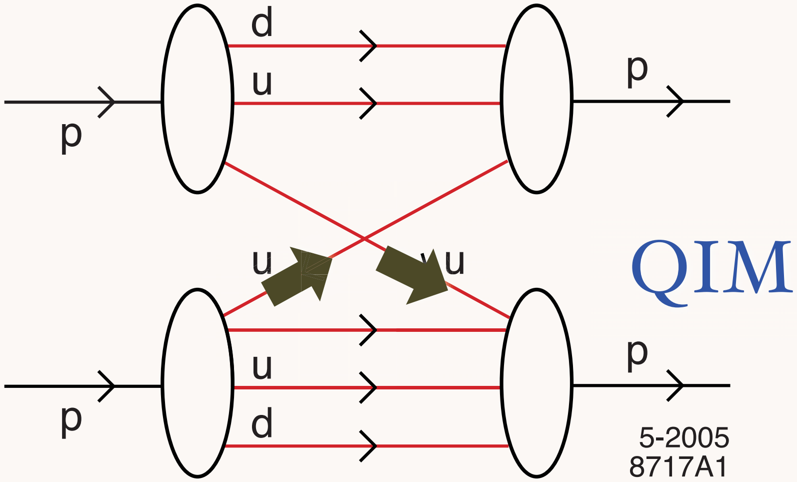
$M_{QIM} = \int d^2k_\perp dx\ \psi^\dagger_C\psi^\dagger_D\Delta\psi_A\psi_B$

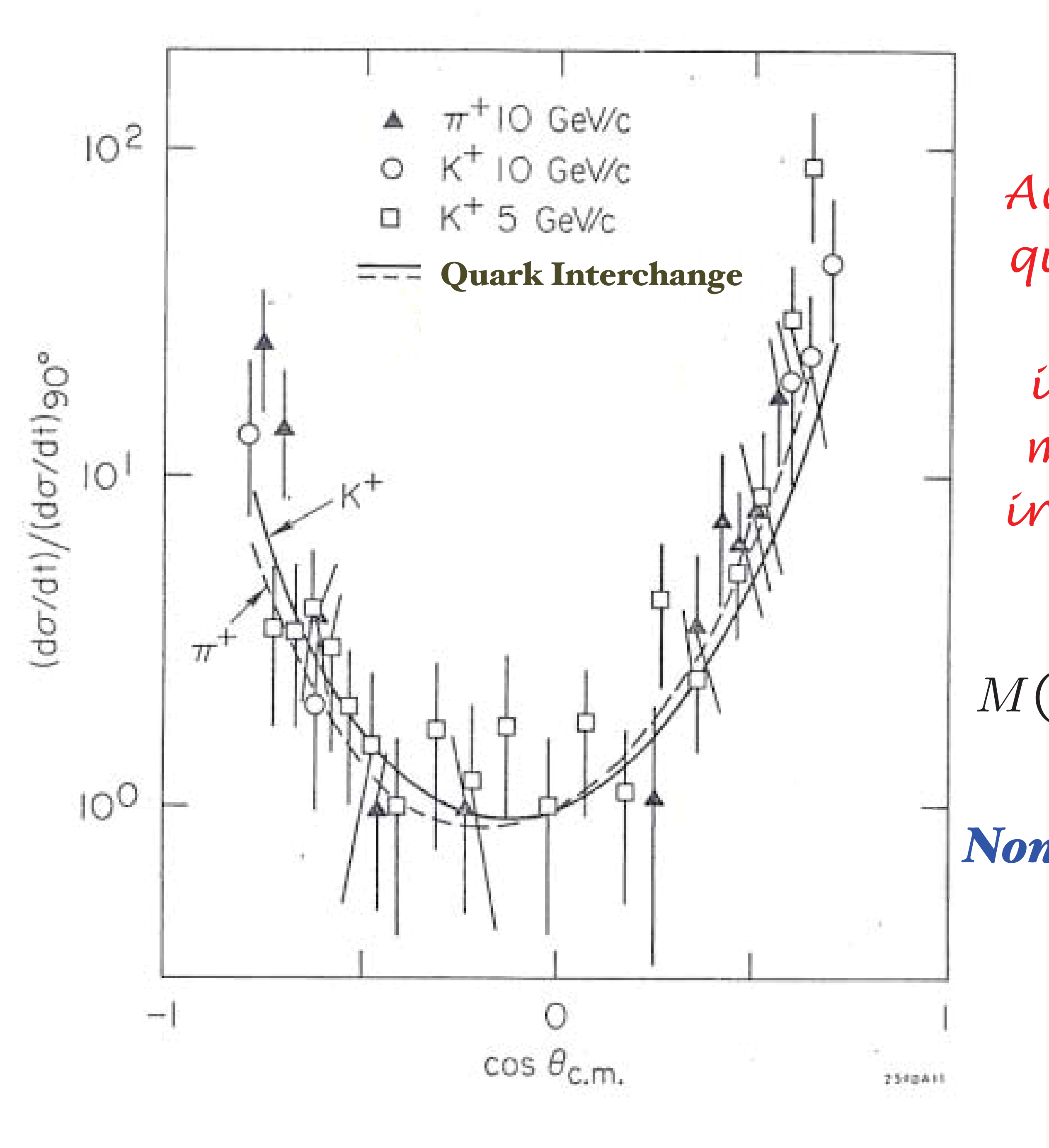
Holographic model (Classical level):

Hadrons enter 5th dimension of AdS_5

Quarks travel freely within cavity as long as separation $z < z_0 = \frac{1}{\Lambda_{QCD}}$

LFWFs obey conformal symmetry producing quark counting rules.





AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions

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

Non-linear Regge behavior:

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

VOLUME 60, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1988

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
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and

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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.

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

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

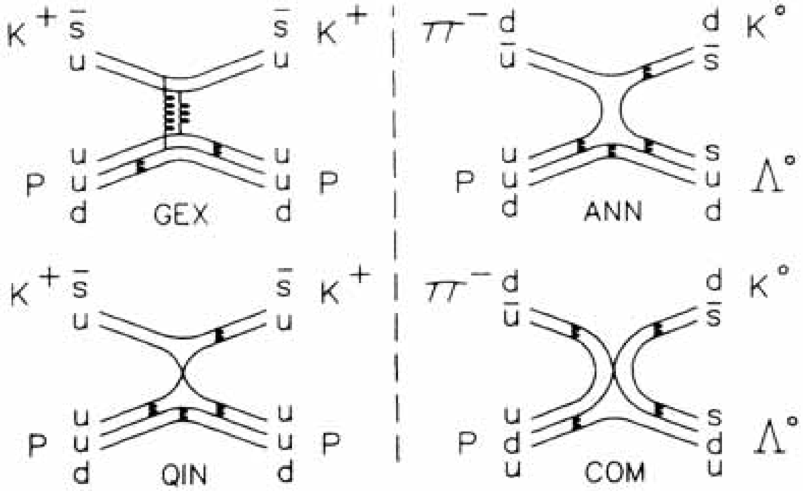
$\pi^{\pm}p \rightarrow p\rho^{\pm}$,

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

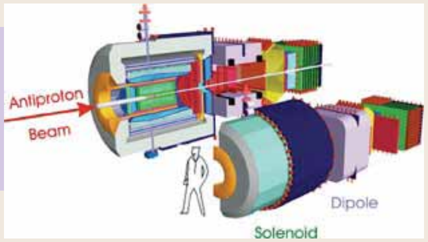
$\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}$,

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

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



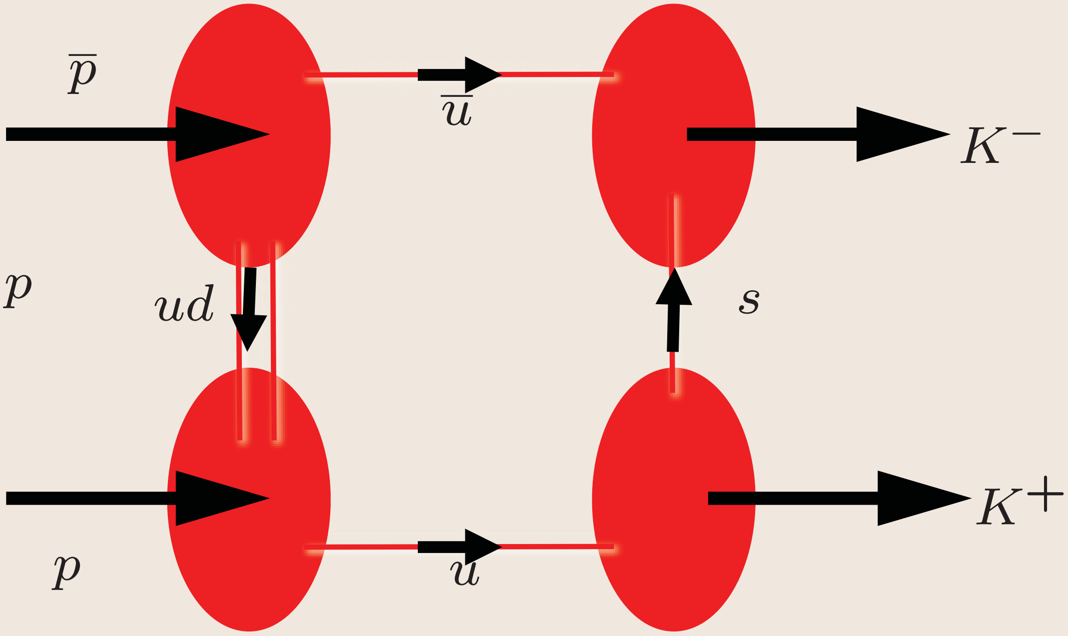
Key QCD Panda Experiment



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

$s \leftrightarrow t$ $t \leftrightarrow u$ crossing of $K^+p \to K^+p$

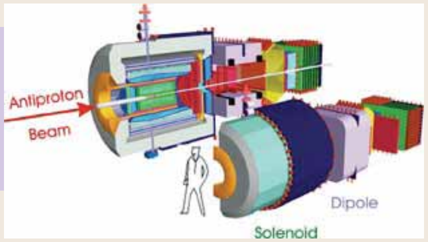
$$M(\bar{p}p \to K^+K^-) \propto \frac{1}{ts^2}$$



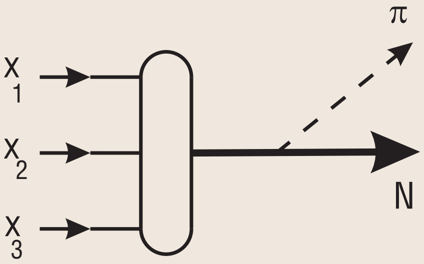
$$\frac{d\sigma}{dt} \propto \frac{1}{s^6t^2}$$

at large t, u

Key QCD Panda Experiment



P. V. Pobylitsa, V. Polyakov
and M. Strikman,
"Soft pion theorems for hard near-threshold
pion production,"
Phys. Rev. Lett. **87**, 022001 (2001)



Small $p\pi$ invariant mass; low relative velocity

Soft-pion theorem relates
near-threshold pion production
to the nucleon distribution amplitude.

$$\boxed{\frac{d\sigma}{dt}(\overline{p}p \to (\pi\overline{p})p) = \frac{F(\theta_{cm})}{s^{10}}}$$

No extra fall-off

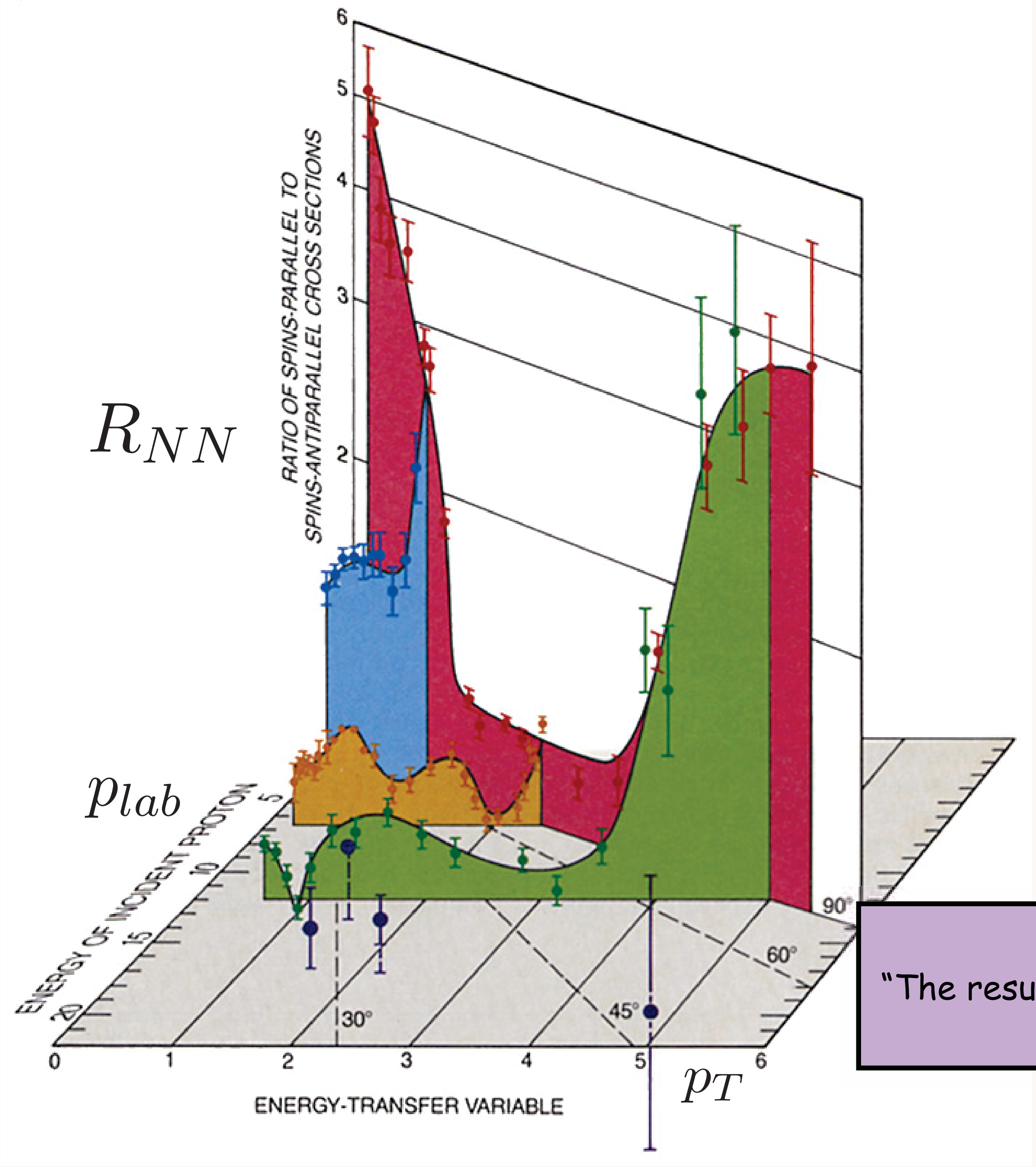
Same scaling as

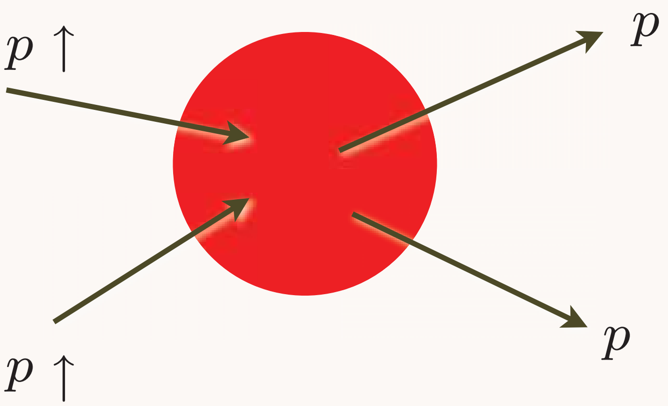
$$\frac{d\sigma}{dt}(\overline{p}p \to \overline{p}p) = \frac{F(\theta_{cm})}{s^{10}}$$

The remarkable anomalies of proton-proton scattering

- Double spin correlations
- Single spin correlations
- Color transparency

Spin Correlations in Elastic $p-p$ Scattering





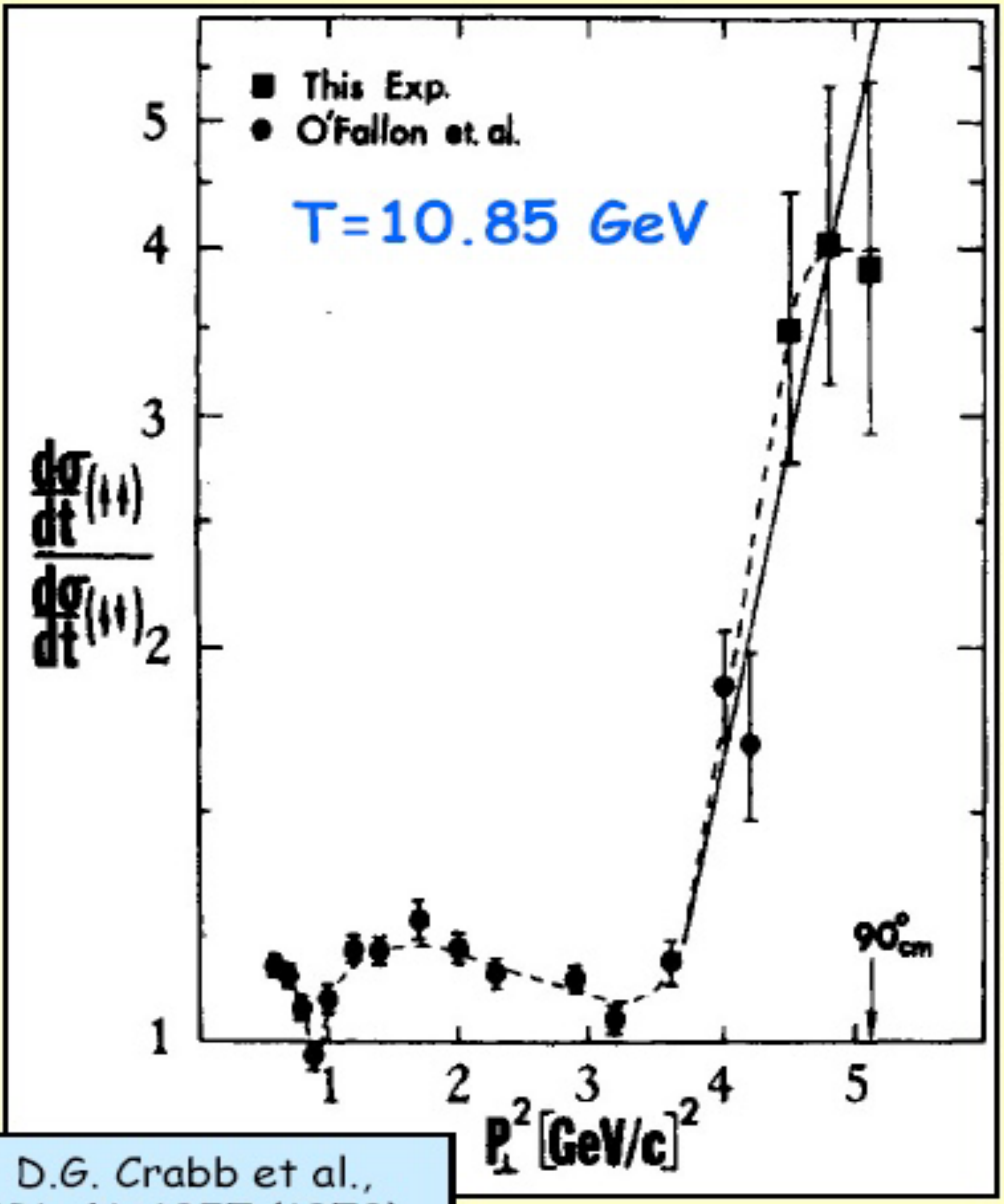
polarization normal to scattering plane

Ratio reaches 4:1 !

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

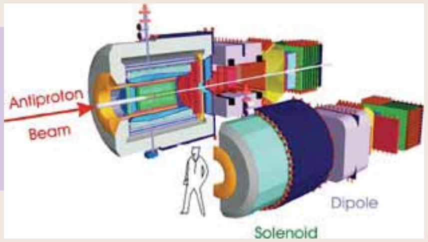
Unexpected spin effects in pp elastic scattering

larger t region can be explored in $p\bar{p}$

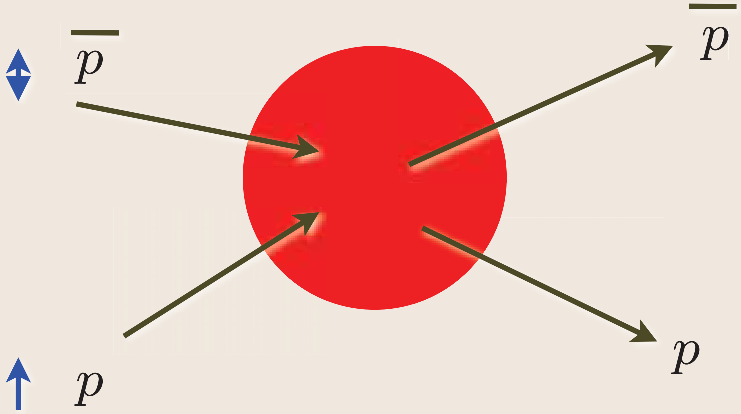


D.G. Crabb et al., PRL 41, 1257 (1978)

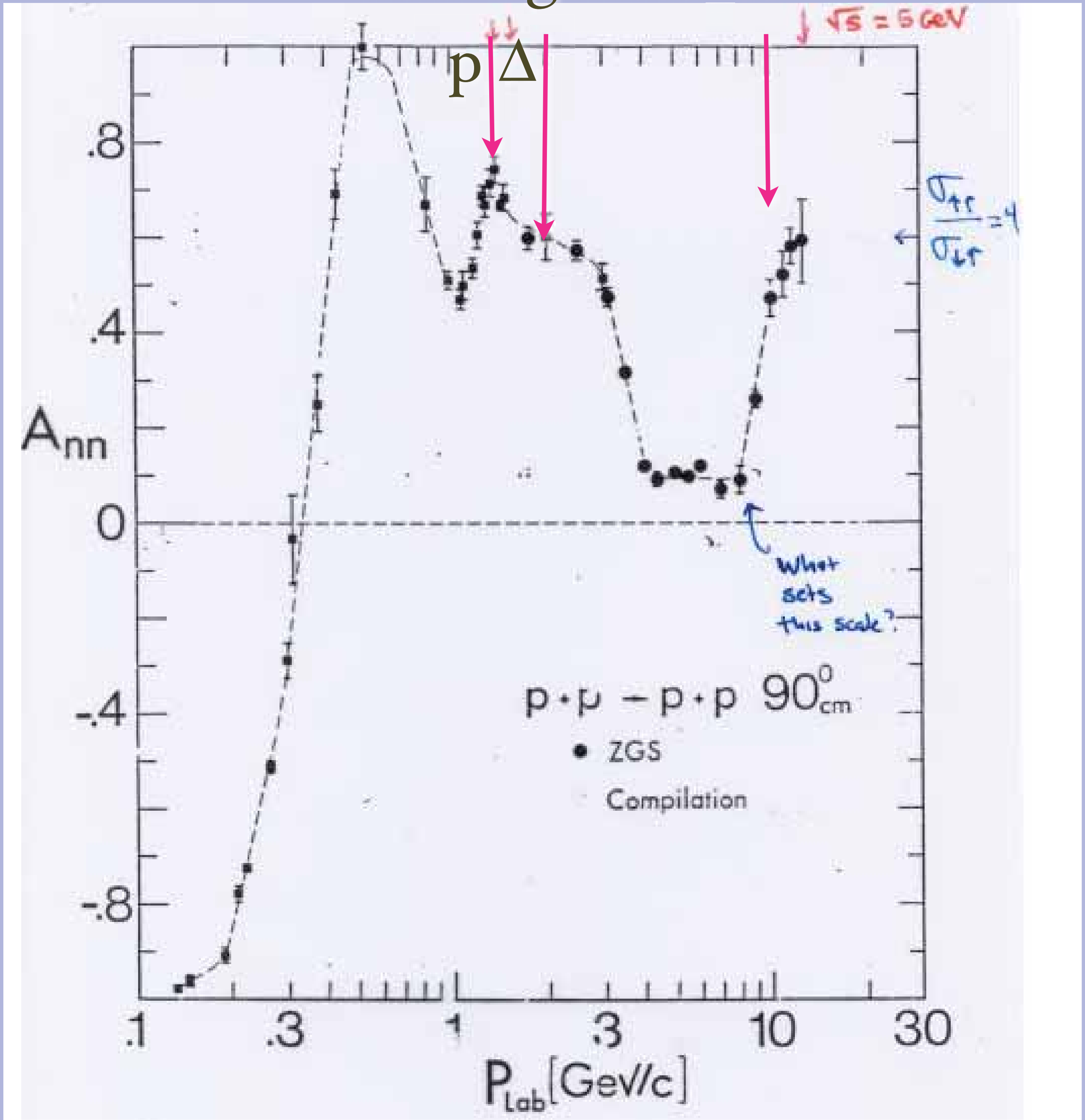
Key QCD Panda Experiment



$$A_{NN} \text{ for } \overline{p}p \rightarrow \overline{p}p$$



Strangeness Charm



"Exclusive Transversity"

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

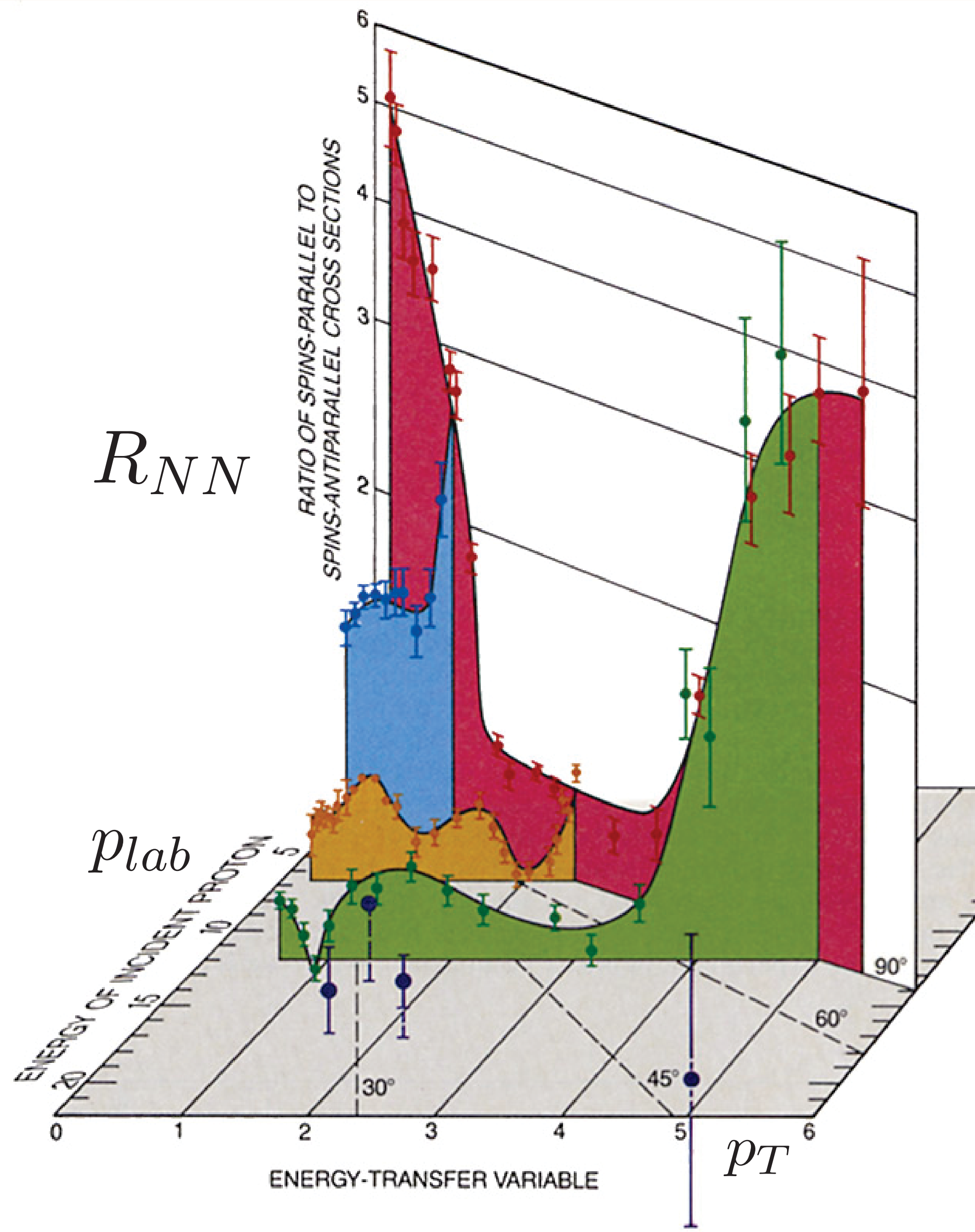
Spin-dependence at large-P_T ($90°_{cm}$):

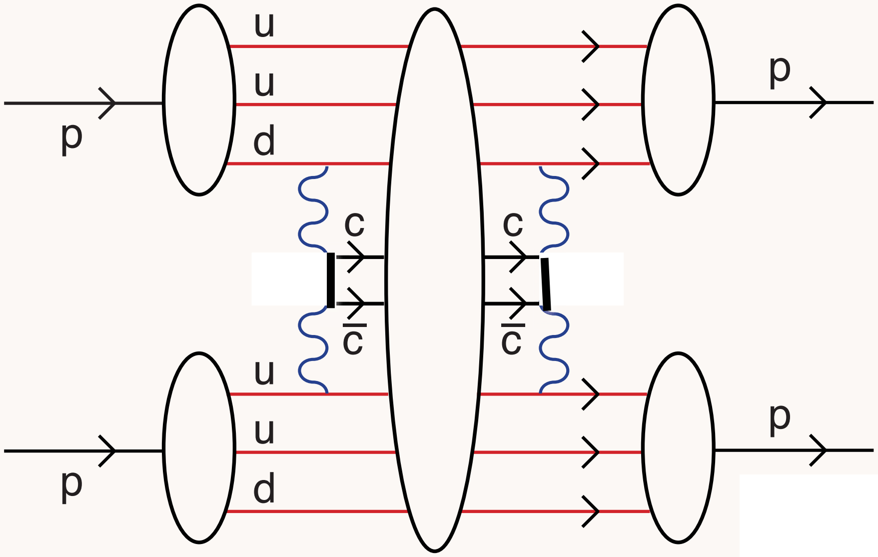
Hard scattering takes place only with spins ↑↑

Coincidence?: Quenching of Color Transparency

Coincidence?: Charm and Strangeness Thresholds

Alternative: Six-Quark Hidden-Color Resonances

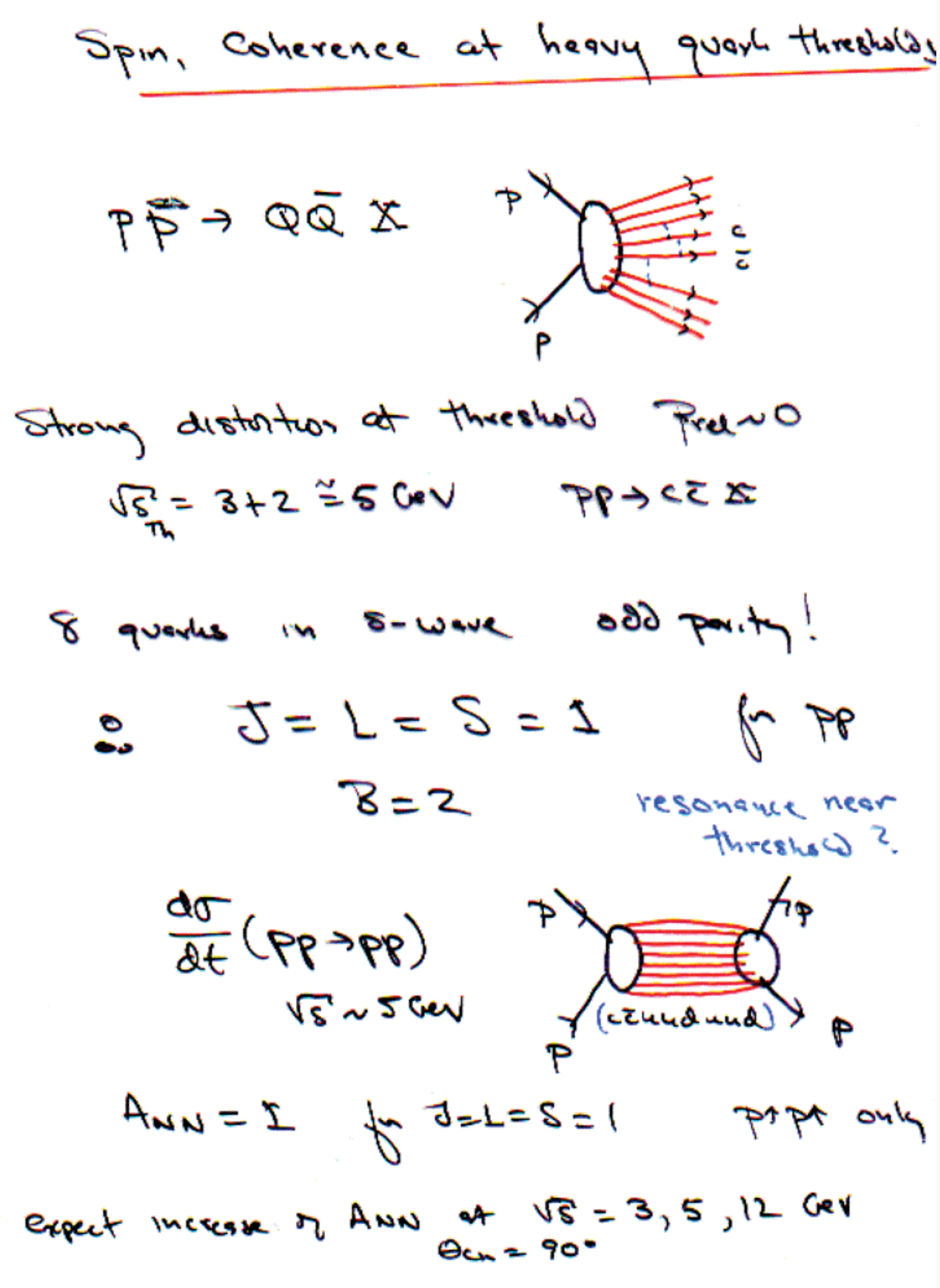




QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

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



Spin, Coherence at heavy quark threshold

$p\overleftrightarrow{p} \to Q\bar{Q}\,X$

Strong distortion at threshold $p_{rel} \sim 0$

$\sqrt{s}_{Th} = 3+2 \simeq 5$ GeV $\quad pp \to c\bar{c}\,X$

8 quarks in S-wave odd parity!

$\therefore \quad J = L = S = 1$ for pp

$B = 2$

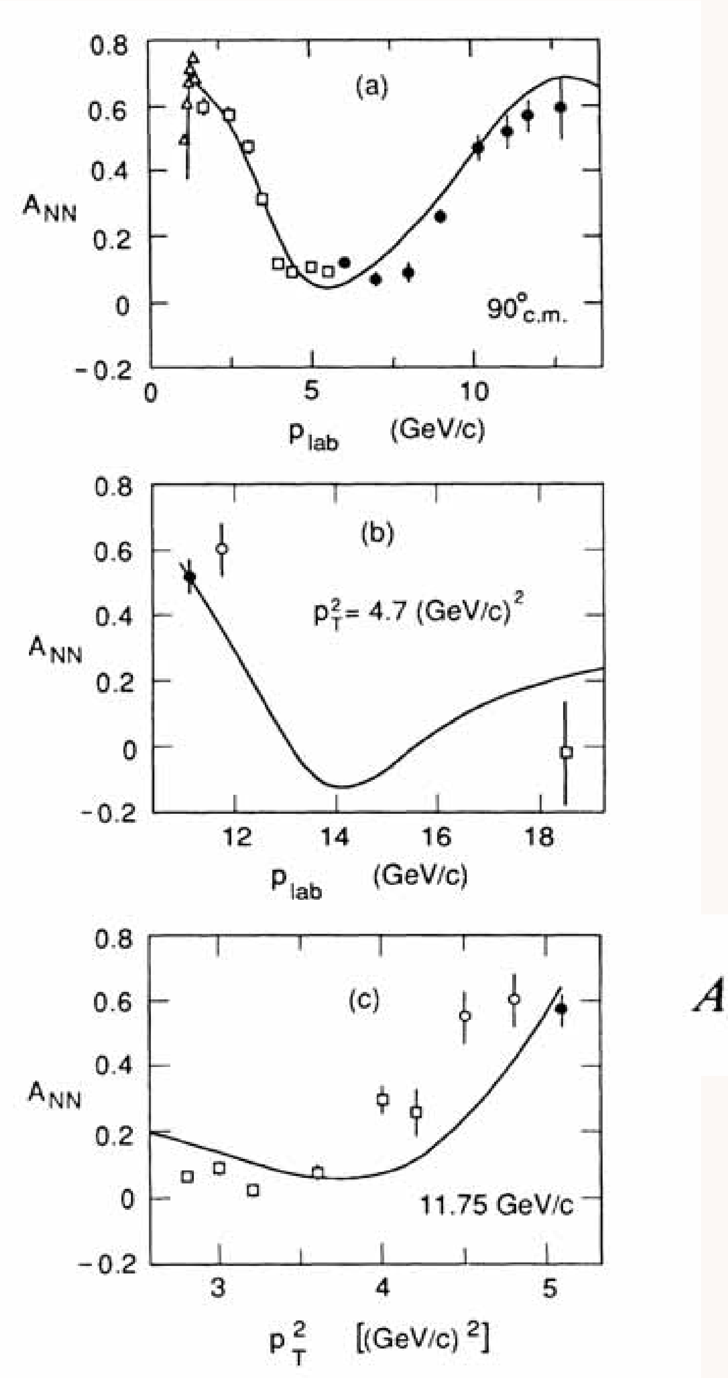
resonance near threshold?

$\frac{d\sigma}{dt}(pp \to pp)$

$\sqrt{s} \sim 5$ GeV

$A_{NN} = 1$ for $J=L=S=1$ $\quad p\uparrow p\uparrow$ only

expect increase of A_{NN} at $\sqrt{s} = 3, 5, 12$ GeV
$\theta_{cm} = 90°$



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).

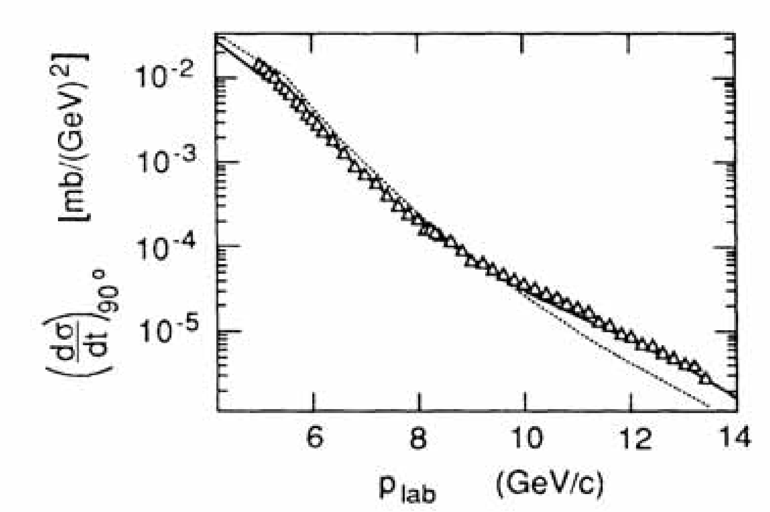
Quark Interchange + 8-Quark Resonance

$|uuduudc\bar{c}>$ Strange and Charm Octoquark!

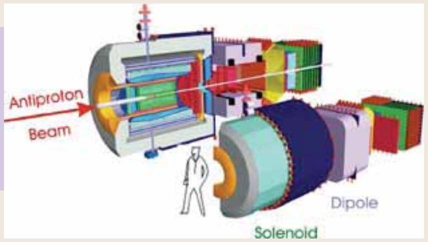
$M = 3$ GeV, $M = 5$ GeV.

$J = L = S = 1,\ B = 2$

$$A_{NN} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)}$$

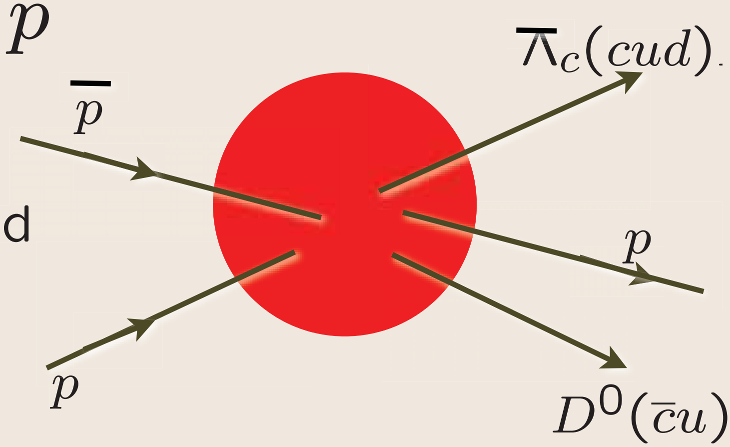


Key QCD Panda Experiment



Open Charm

$$\bar{p}p \to \bar{\Lambda}_c(\overline{cud})D^0(\bar{c}u)p$$



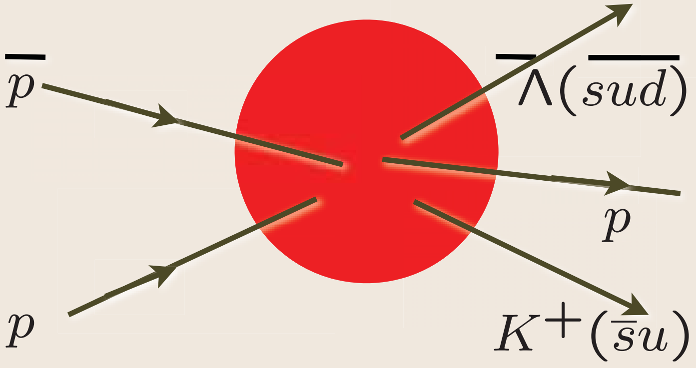
Total open charm cross section at threshold

$$\sigma(pp \to cX) \simeq 1\mu b$$

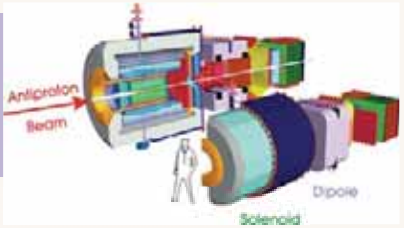
needed to explain Krisch A_{NN}

Compare with strangeness channels

$$pp \to \Lambda(sud)K^+(\bar{s}u)p$$



Key QCD Panda Experiment

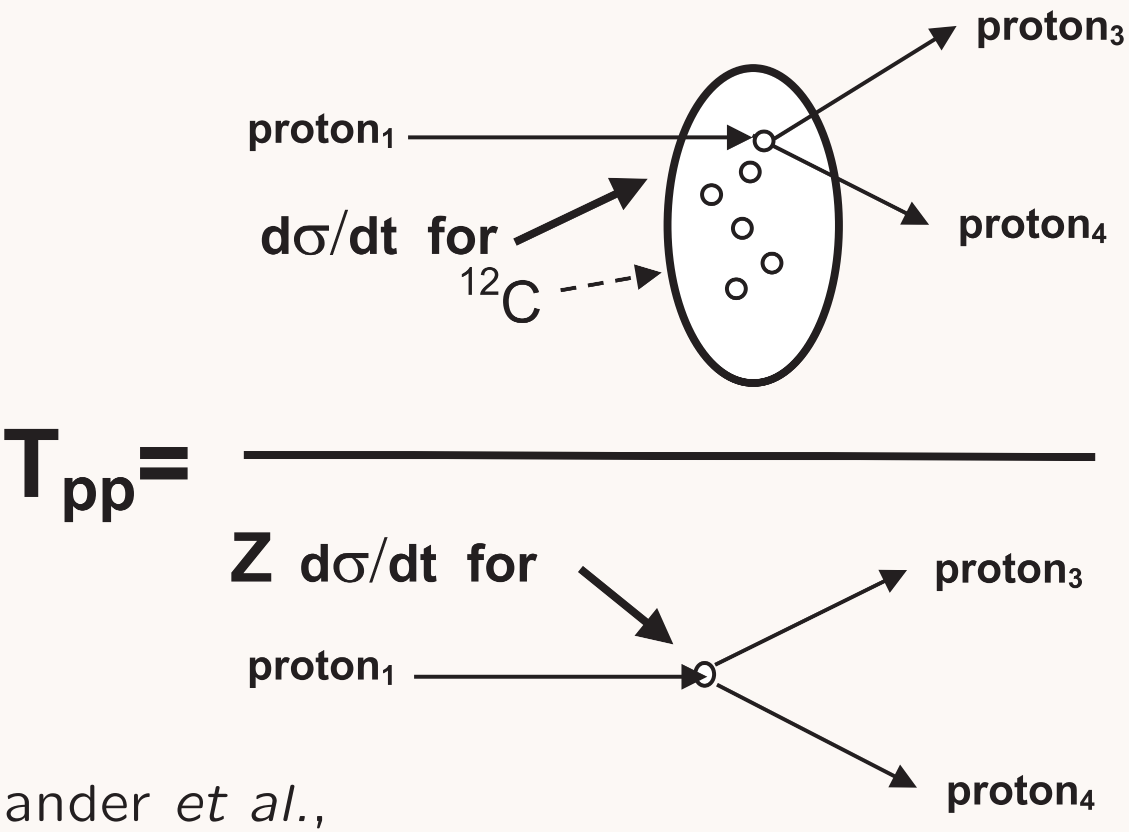


- New QCD physics in proton-proton elastic scattering at the charm threshold
- Anomalously large charm production at threshold!!?
- Octoquark resonances?
- Color Transparency disappears at charm threshold
- Key physics at GSI: second charm threshold

$$\bar{p}p \rightarrow \bar{p}pJ/\psi$$

$$\bar{p}p \rightarrow \bar{p}\Lambda_c D$$

Color Transparency Ratio



proton_3

proton_1

proton_4

$d\sigma/dt$ for ^{12}C

$T_{pp}=$

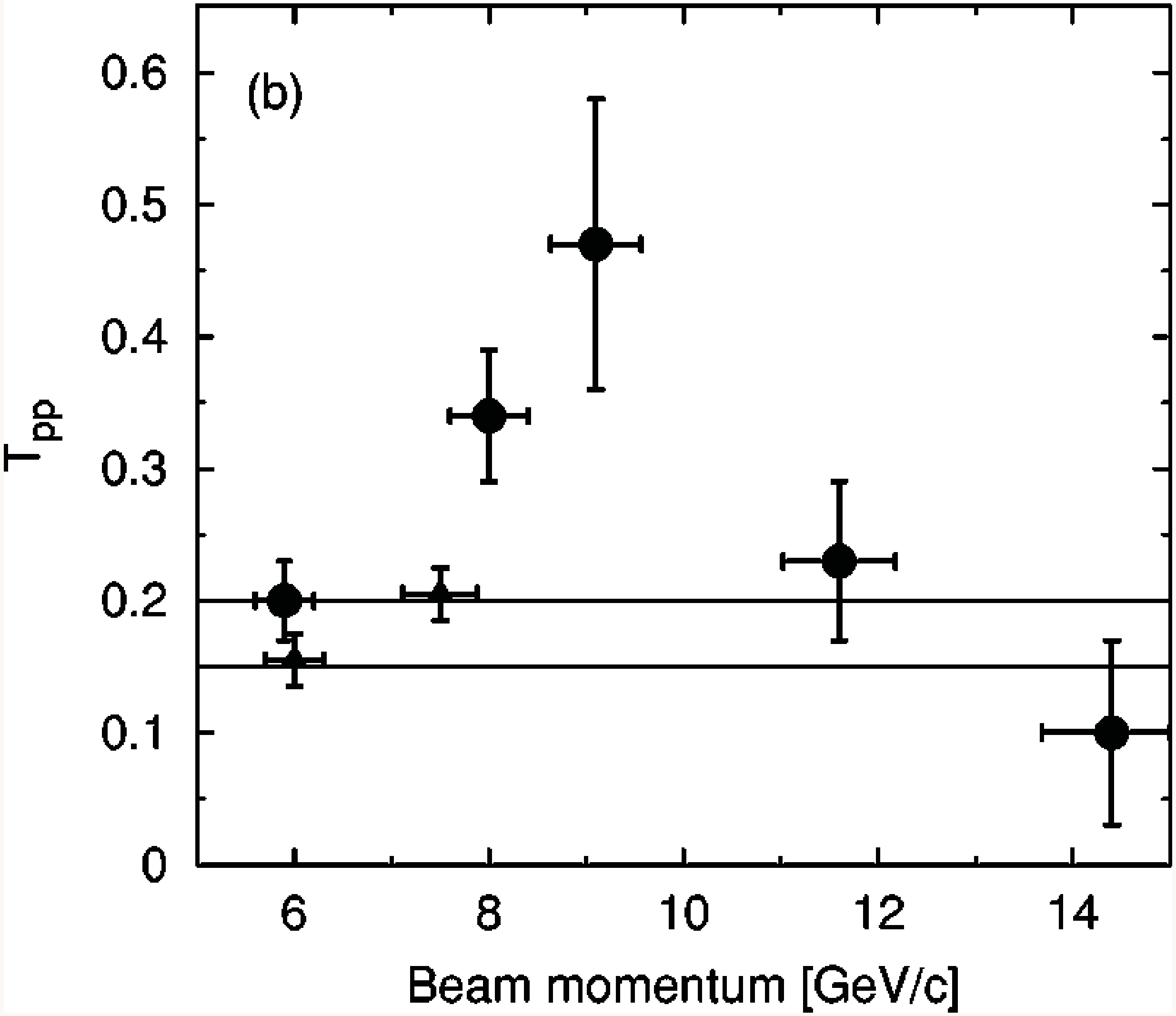
Z $d\sigma/dt$ for

proton_3

proton_1

proton_4

J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

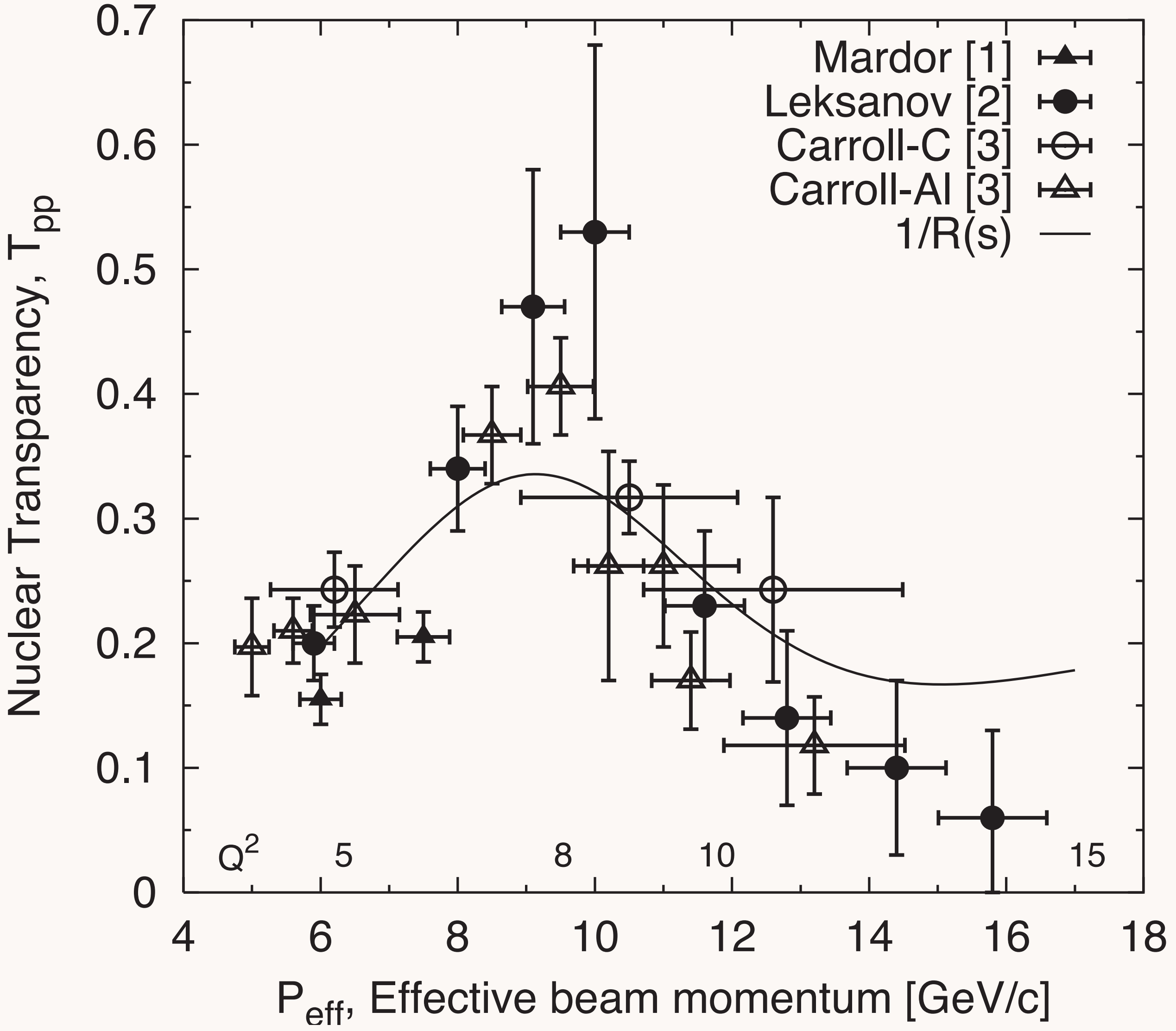


PHYSICAL REVIEW C **70**, 015208 (2004)

Nuclear transparency in $90^{\circ}_{\mathrm{c.m.}}$ quasielastic $A(p,2p)$ reactions

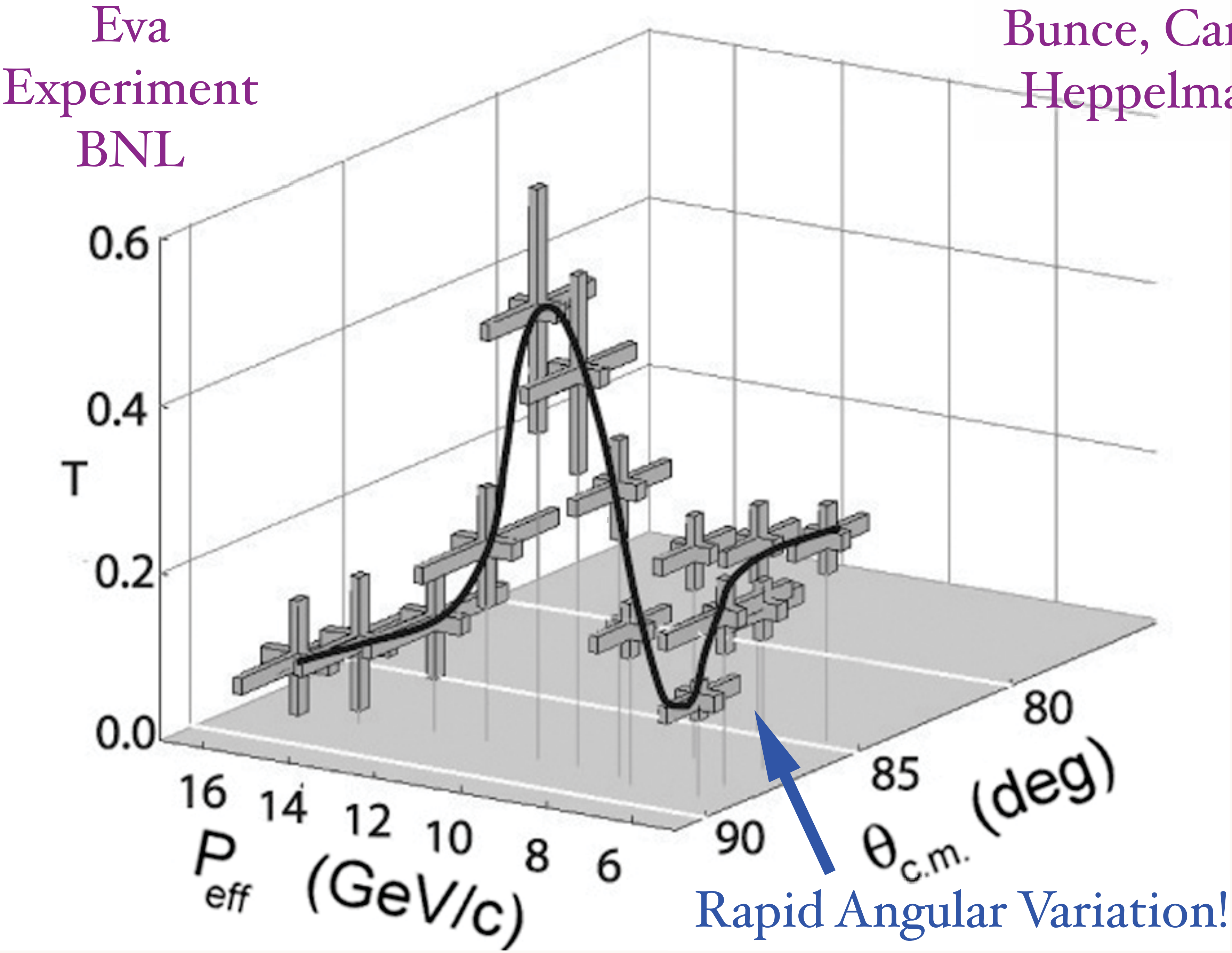
J. Aclander,[7] J. Alster,[7] G. Asryan,[1,*] Y. Averiche,[5] D. S. Barton,[1] V. Baturin,[2,†] N. Buktoyarova,[1,†] G. Bunce,[1]
A. S. Carroll,[1,‡] N. Christensen,[3,§] H. Courant,[3] S. Durrant,[2] G. Fang,[3] K. Gabriel,[2] S. Gushue,[1] K. J. Heller,[3] S. Heppelmann,[2]
I. Kosonovsky,[7] A. Leksanov,[2] Y. I. Makdisi,[1] A. Malki,[7] I. Mardor,[7] Y. Mardor,[7] M. L. Marshak,[3] D. Martel,[4]
E. Minina,[2] E. Minor,[2] I. Navon,[7] H. Nicholson,[8] A. Ogawa,[2] Y. Panebratsev,[5] E. Piasetzky,[7] T. Roser,[1] J. J. Russell,[4]
A. Schetkovsky,[2,†] S. Shimanskiy,[5] M. A. Shupe,[3,‖] S. Sutton,[8] M. Tanaka,[1,¶] A. Tang,[6] I. Tsetkov,[5] J. Watson,[6] C. White,[3]
J-Y. Wu,[2] and D. Zhalov[2]

Color Transparency fails when A_{nn} is large



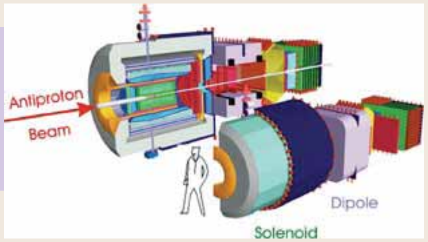
Eva
Experiment
BNL

Bunce, Carroll,
Heppelman...



Rapid Angular Variation!

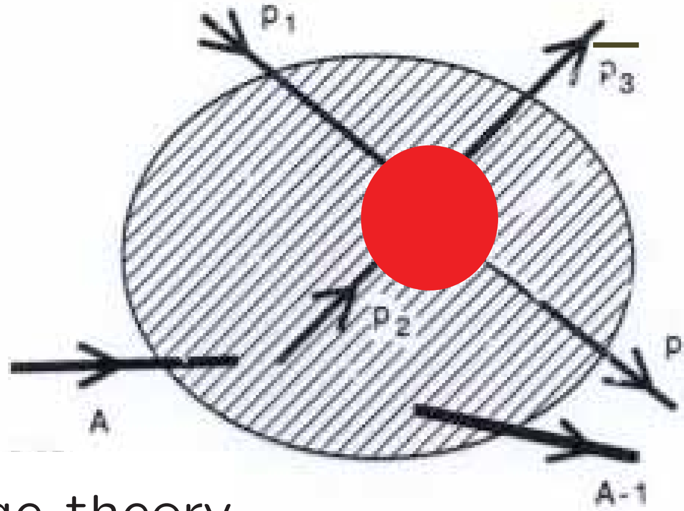
Key QCD Panda Experiment



Test Color Transparency

$$\frac{d\sigma}{dt}(\bar{p}A \to \bar{p}p(A-1)) \to Z \times \frac{d\sigma}{dt}(\bar{p}p \to \bar{p}p)$$

No absorption of small color dipole
at high p_T



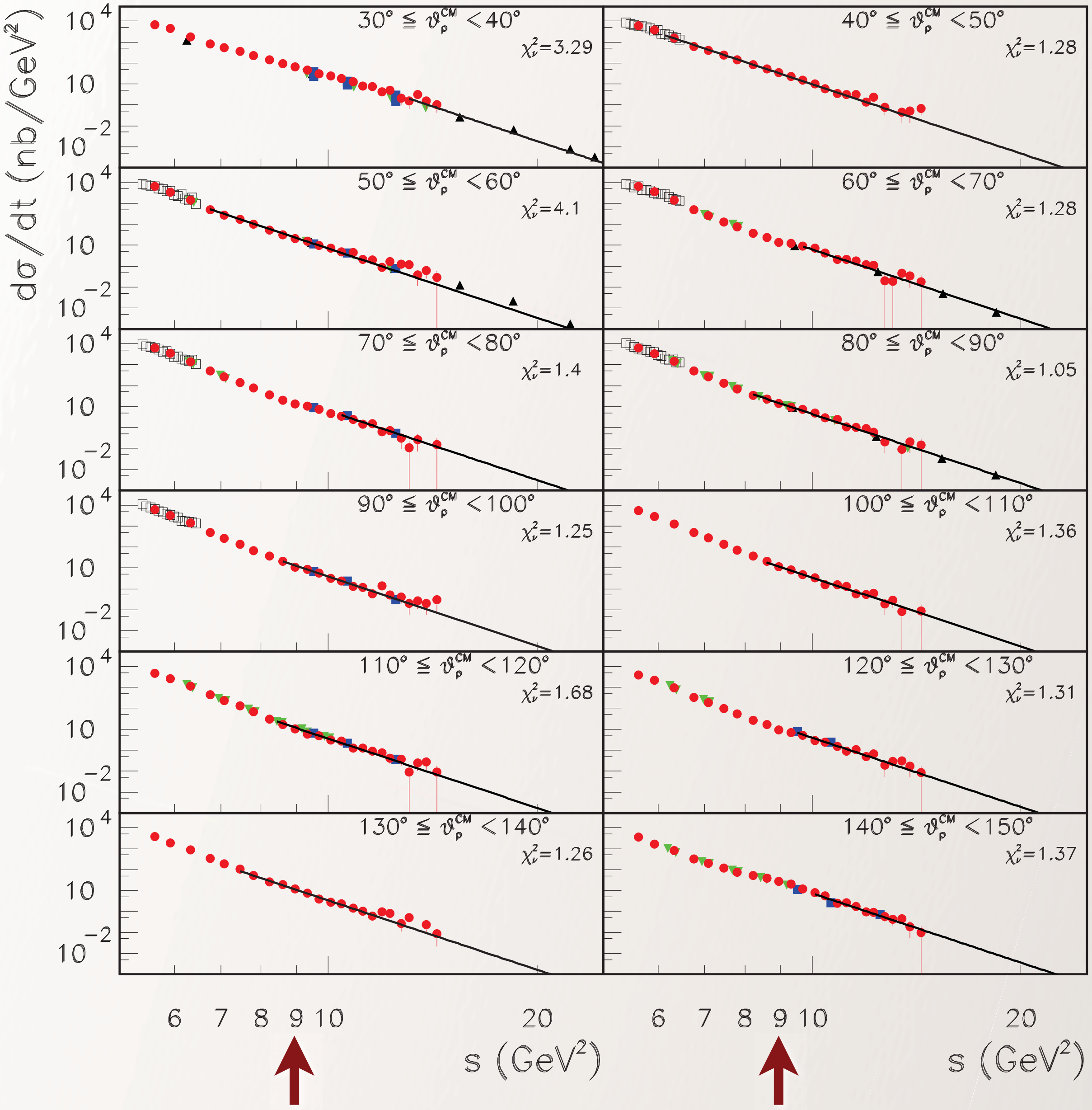
Key test of local gauge theory

Traditional Glauber Theory: $\sigma_A \sim Z^{1/3}\sigma_p$

A.H. Mueller, SJB

Deuteron Photodisintegration and Dimensional Counting

P.Rossi et al, P.R.L. 94, 012301 (2005)



PQCD and AdS/CFT:

$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B\to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np) = F(\theta_{CM})$$

$$n_{tot}-2 = (1+6+3+3)-2 = 11$$

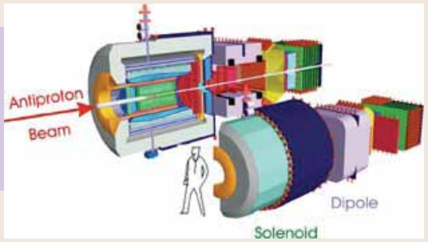
$$\gamma d \to (uuddd us\bar{s}) \to np$$

at $s \simeq 9$ GeV^2

$$\gamma d \to (uuddd uc\bar{c}) \to np$$

at $s \simeq 25$ GeV^2

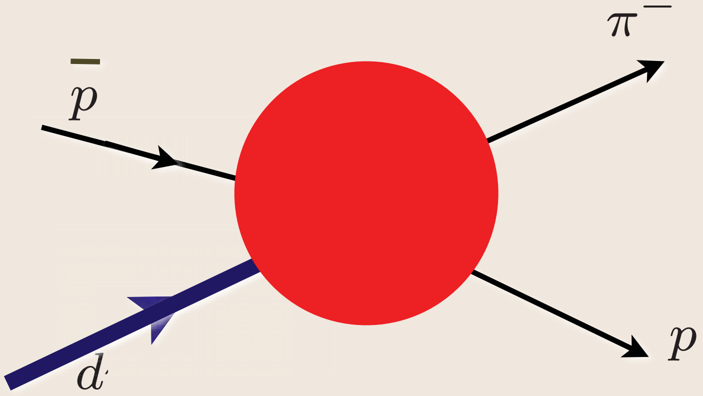
Key QCD Panda Experiment



Test QCD scaling in hard exclusive nuclear amplitudes

Manifestations of Hidden Color in Deuteron Wavefunction

$$\bar{p}d \to \pi^- p$$
$$\bar{p}d \to n\gamma$$
$$\bar{p}d \to \bar{p}d$$



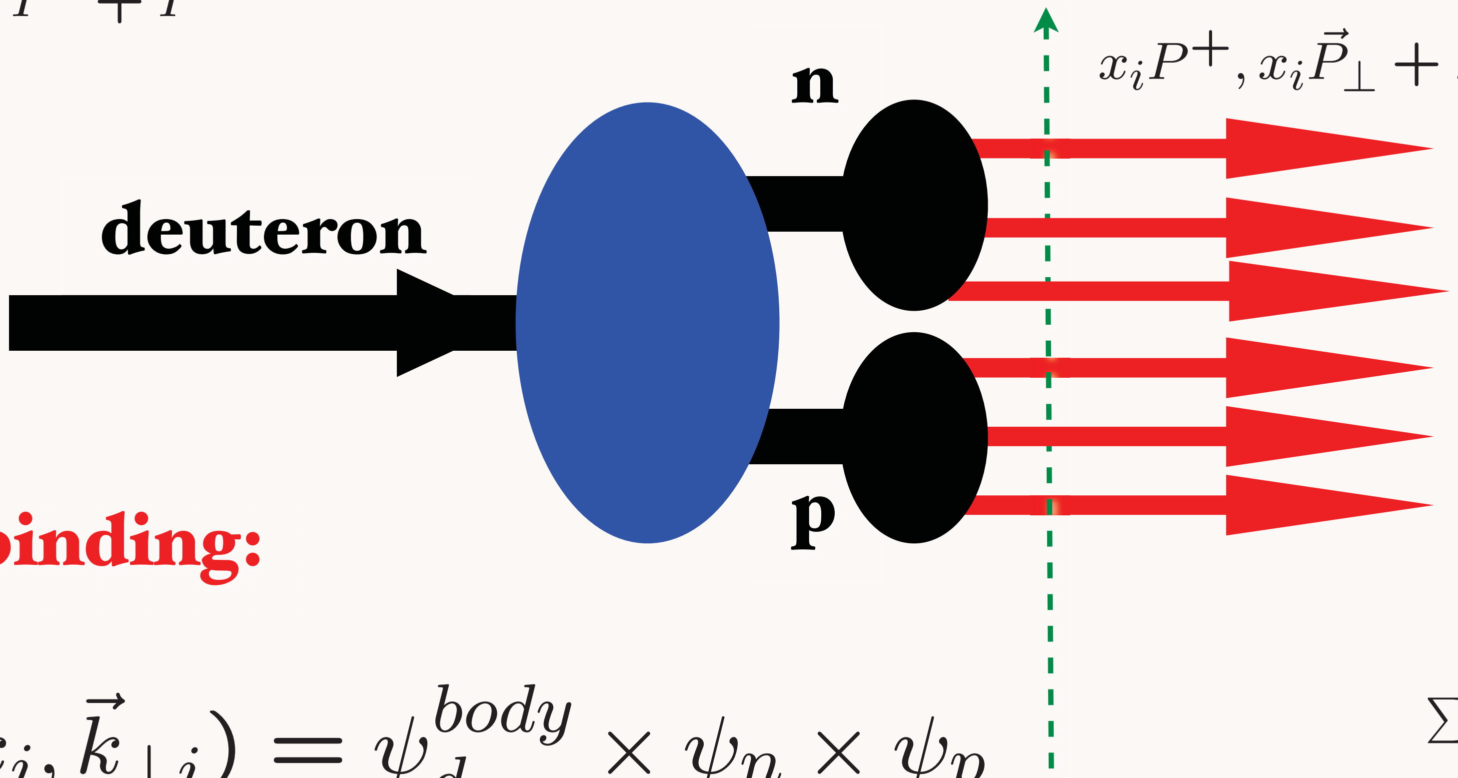
Conformal Scaling, AdS/CFT

$$\boxed{\frac{d\sigma}{dt}(\bar{p}d \to \pi^- p) = \frac{F(\theta_{cm})}{s^{12}}}$$

Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

$P^+ = P^0 + P^z$



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

n

deuteron

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

p

Weak binding:

$$\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$$

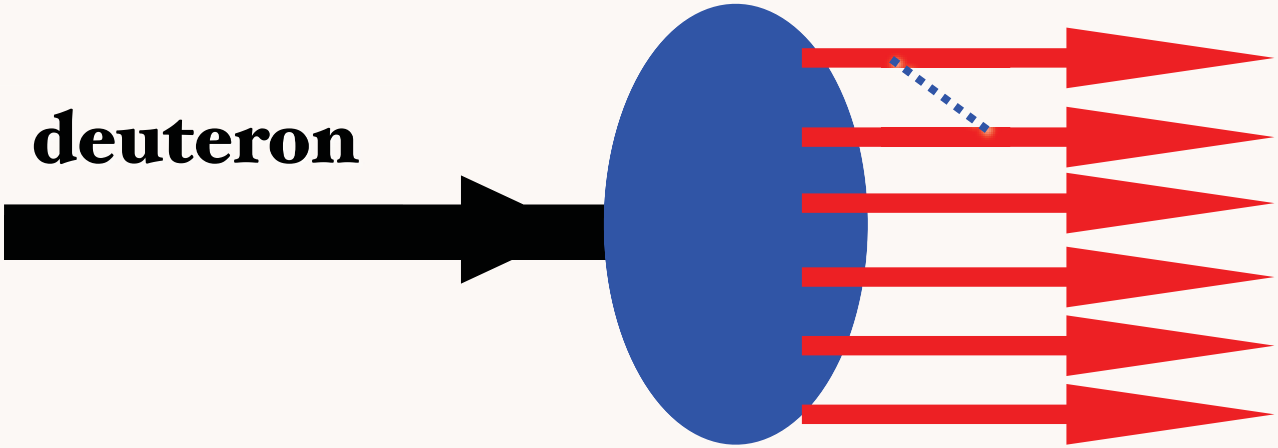
$\Sigma_i^n x_i = 1$

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

Two color-singlet combinations of three 3_C

Evolution of 5 color-singlet Fock states

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



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

$\sum_i^n x_i = 1$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color in QCD Lepage, Ji, sjb

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Ratio = 2/5 for asymptotic wf

QCD Prediction for Deuteron Form Factor

$$F_d(Q^2)=\left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5\sum_{m,n} d_{mn}\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d-\gamma_m^d}\left[1+O\left(\alpha_s(Q^2),\frac{m}{Q}\right)\right]$$

Define “Reduced” Form Factor

$$f_d(Q^2)\equiv\frac{F_d(Q^2)}{F_N{}^2(Q^2/4)}\,.$$

Same large momentum transfer behavior as pion form factor

$$f_d(Q^2)\sim\frac{\alpha_s(Q^2)}{Q^2}\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-(2/5)\,C_F/\beta}$$

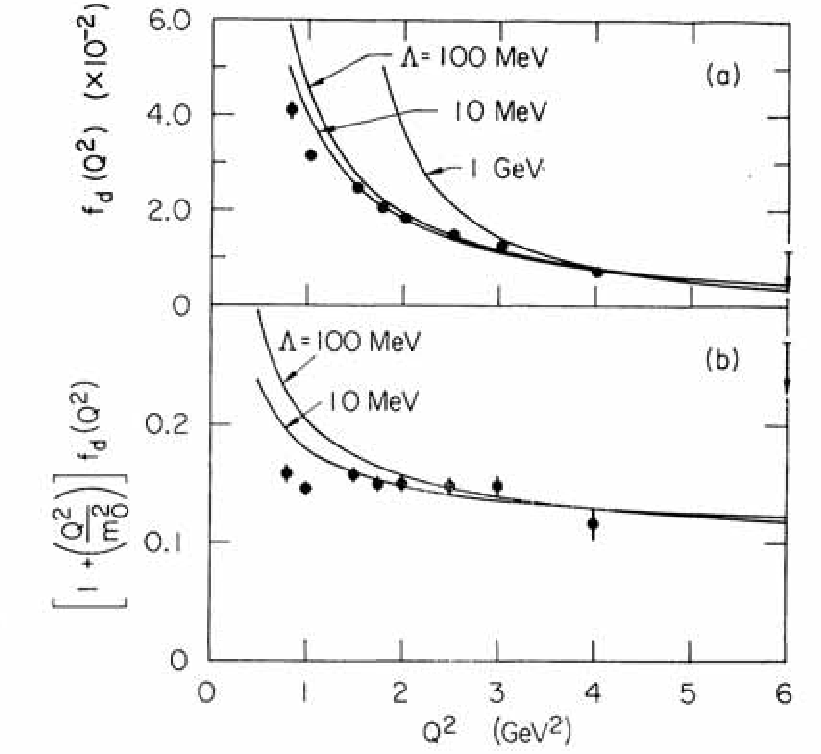
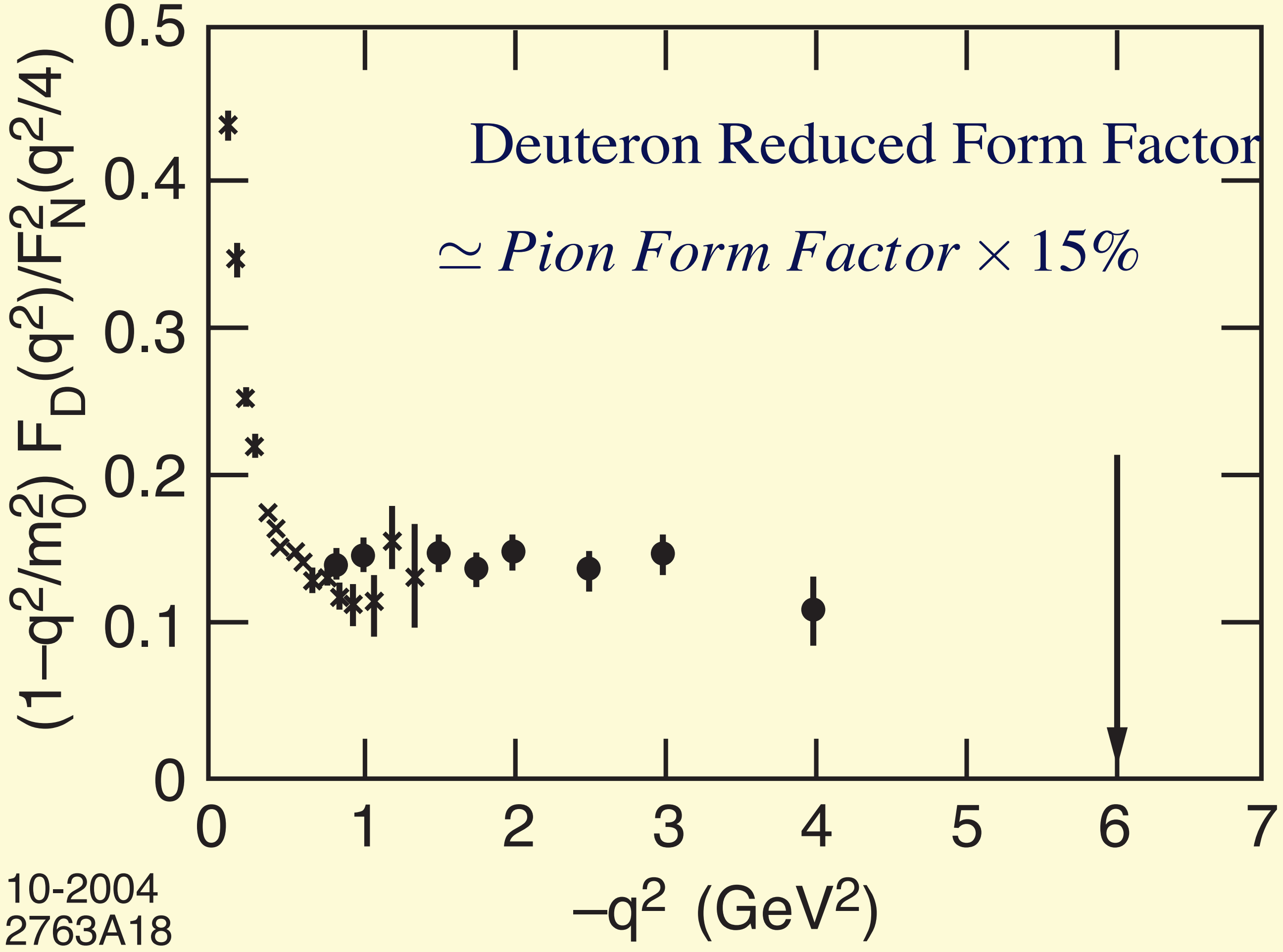


FIG. 2. (a) Comparison of the asymptotic QCD pre
diction $f_d(Q^2)\propto(1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with fin
data of Ref. 10 for the reduced deuteron form factor
where $F_N(Q^2)=[1+Q^2/(0.71\ \text{GeV}^2)]^{-2}$. The normaliz
tion is fixed at the $Q^2=4$ GeV^2 data point. (b) Compa
son of the prediction $[1+(Q^2/m_0^2)]f_d(Q^2)\propto[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with the above data. The value $m_0^2 = 0.28$ GeV^2 is used (Ref. 8).

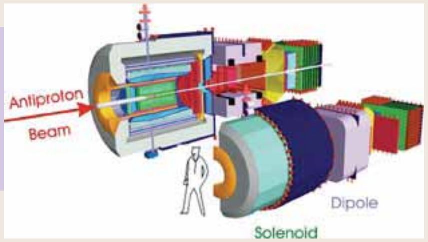


Deuteron Reduced Form Factor

$\simeq$ *Pion Form Factor* $\times$ 15%

- 15% Hidden Color in the Deuteron

Key QCD Panda Experiment



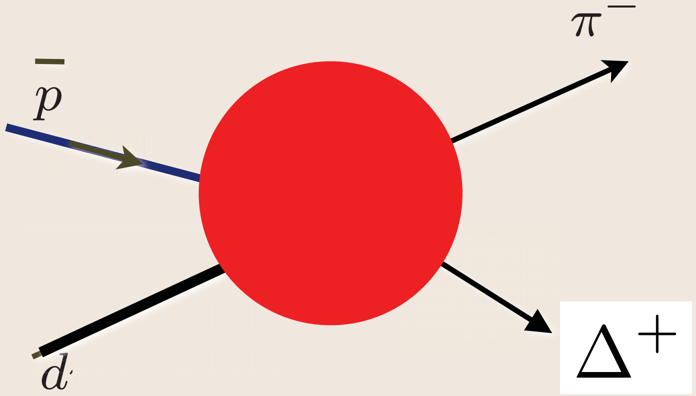
Test QCD scaling in hard exclusive nuclear amplitudes

Manifestations of Hidden Color in Deuteron Wavefunction

$$\bar{p}d \to \pi^- p$$

Ratio predicted to approach 2:5

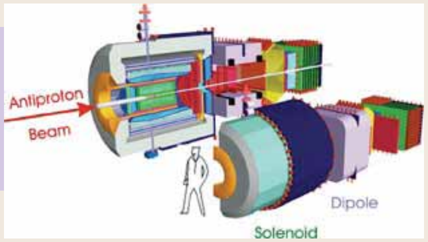
$$\bar{p}d \to \pi^- \Delta^+$$



Conformal Scaling, AdS/CFT

$$\boxed{\frac{d\sigma}{dt}(\bar{p}d \to \pi^- p) = \frac{F(\theta_{cm})}{s^{12}}}$$

Key QCD Panda Experiments



- Diffractive Processes
- Odderon from $\bar{p}$ p and p p difference
- Timelike DVCS
- DVCS: Charge Asymmetry, J=0
- Double lepton pairs
- DVCS: Constraints on GPDs

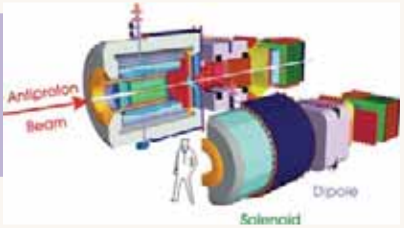
Topics for PANDA in Exclusive Processes

QCD at the Amplitude Level

- Measures of LFWFs, distribution amplitudes, transition distribution amplitudes
- Scaling of Fixed-Angle Amplitudes tests conformal window of QCD
- Quark-Interchange Dominance at large p_T
- Crossing and Analyticity $\bar{p}p \rightarrow \gamma\pi$ vs. $\gamma p \rightarrow \pi p$
- Timelike GPDs from DVCS $\bar{p}p \rightarrow \gamma * \gamma$, charge and spin asymmetry, $J = 0$

Local seagull-like Interactions

- Transition to Regge theory at forward and backward angles
- Regge poles $\alpha_R(t) \rightarrow -1, -2$ at large $-t$.
- Charm and Charmonium at Threshold
- Odderon Tests
- Second Charm Threshold $\bar{p}p \rightarrow \bar{p}pJ/\psi$
- Diffractive Drell-Yan $\bar{p}p \rightarrow \bar{\ell}\ell J/\psi$
- Exclusive A_N, A_{NN}, especially at strange and charm thresholds
- Color Transparency
- Hidden Color of Nuclear Wavefunctions in $\bar{p}d$ reactions
- Exotic $\bar{q}\bar{q}qq$ and gluonium Spectra in $p\bar{p} \rightarrow \gamma M_X$



Heavy Quark Topics for Panda

- Mechanisms for Heavy Hadron and Quarkonium Production Near Threshold
- Tests of Intrinsic Charm
- Quarkonium Attenuation at High x_F
- Non-Universal Anti-Shadowing

- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, rescattering, shadowing, non-universal antishadowing ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities.

—Mark Twain

Looking forward to great physics from PANDA!