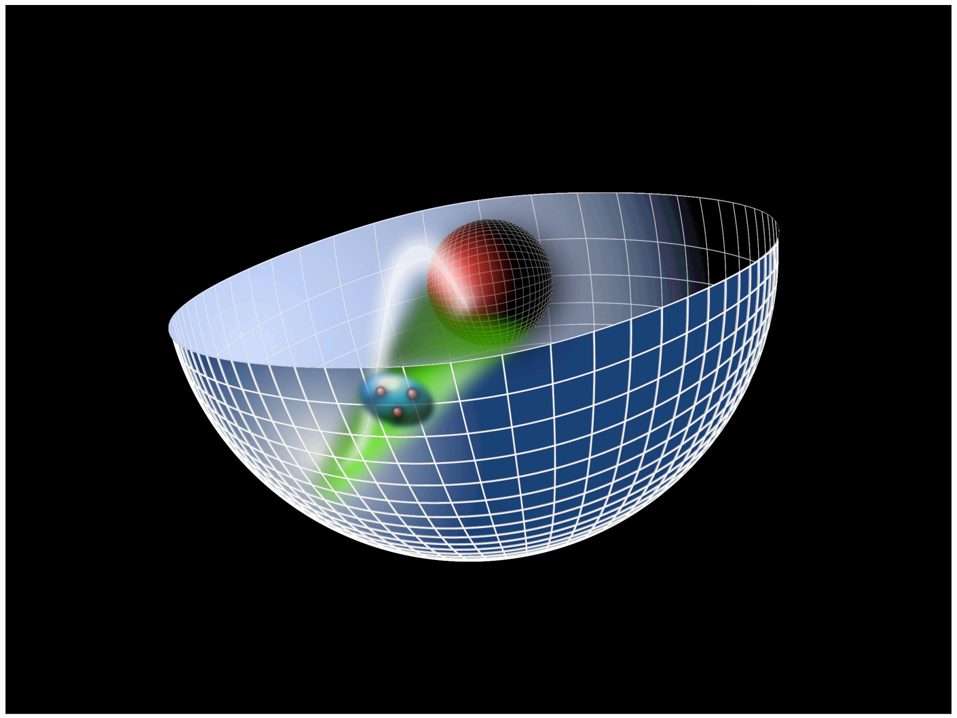
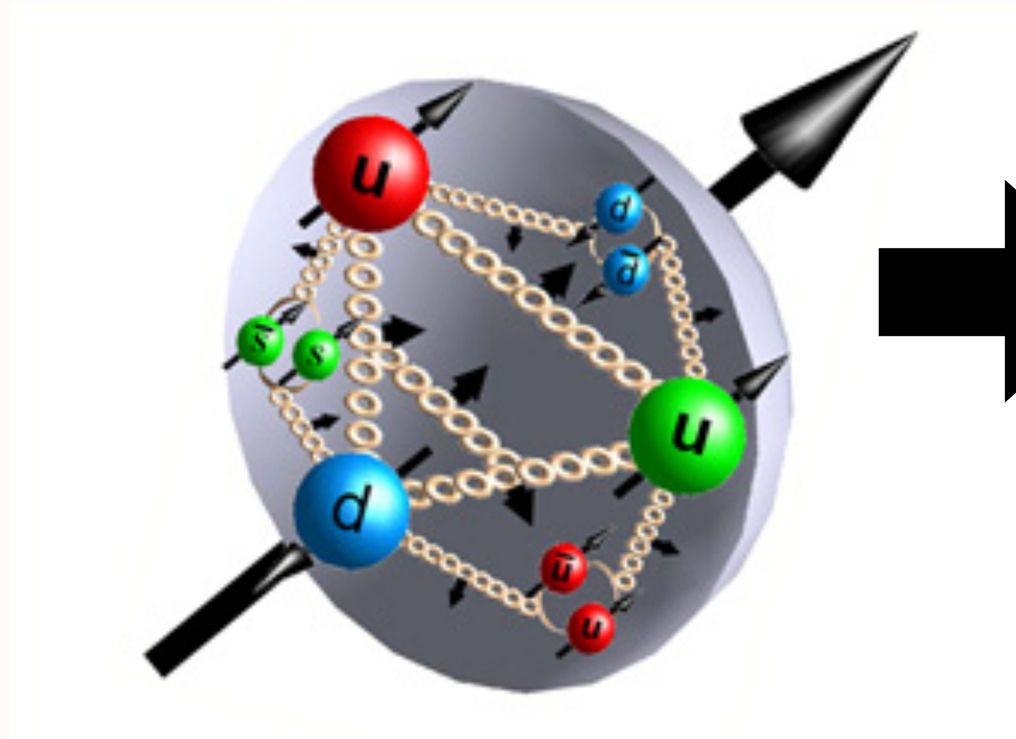
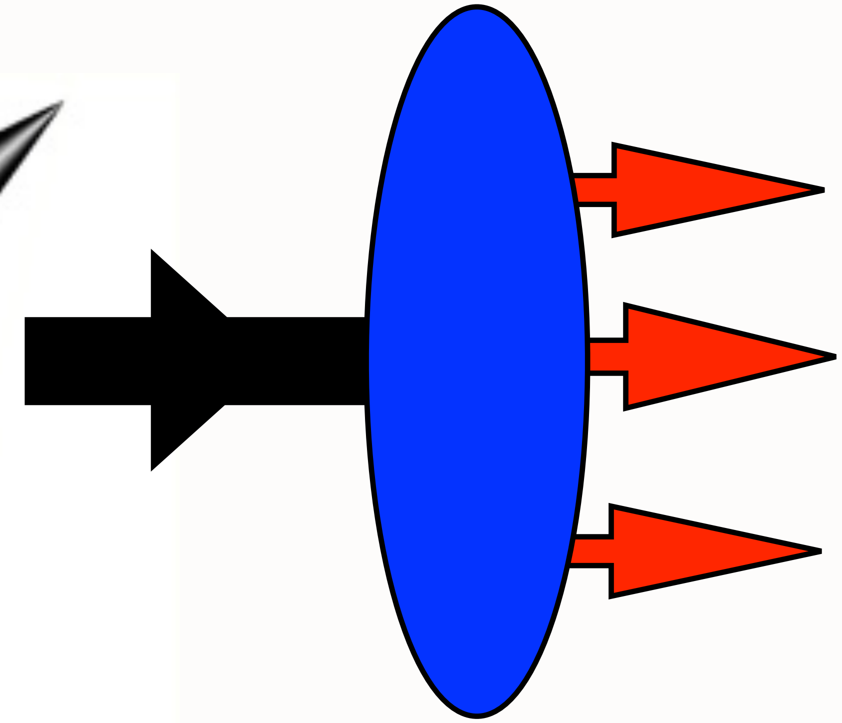
# Light-Front Holography and Novel QCD Phenomena



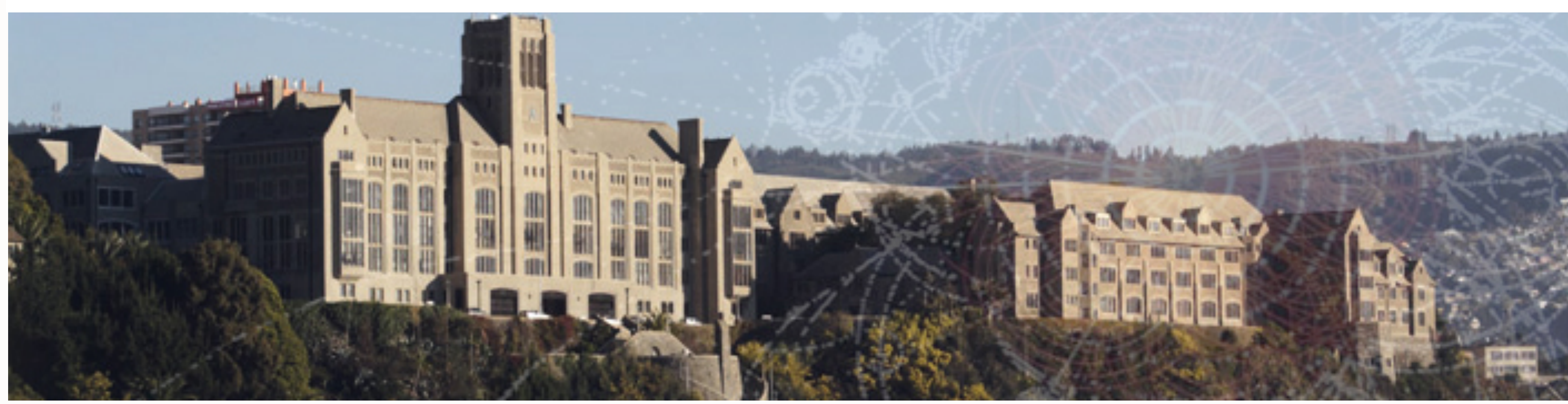


HEP 2012 **High Energy Physics in the LHC Era**

Stan Brodsky

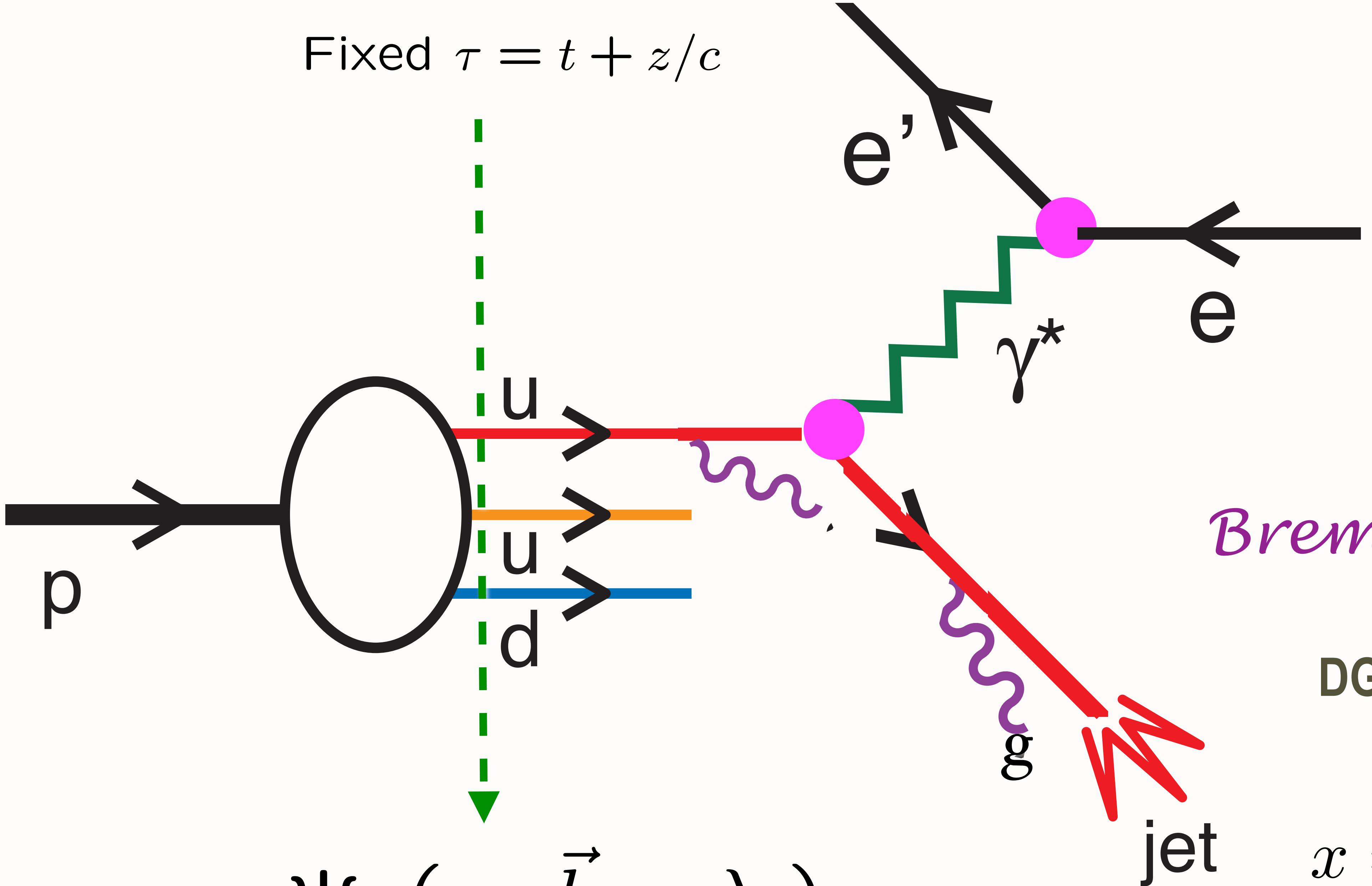
SLAC NATIONAL ACCELERATOR LABORATORY



Valparaíso, Chile

Universidad Técnica Federico Santa María

# Deep Inelastic Electron-Proton Scattering




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

Gluonic Bremmstrahlung

**DGLAP Evolution**

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

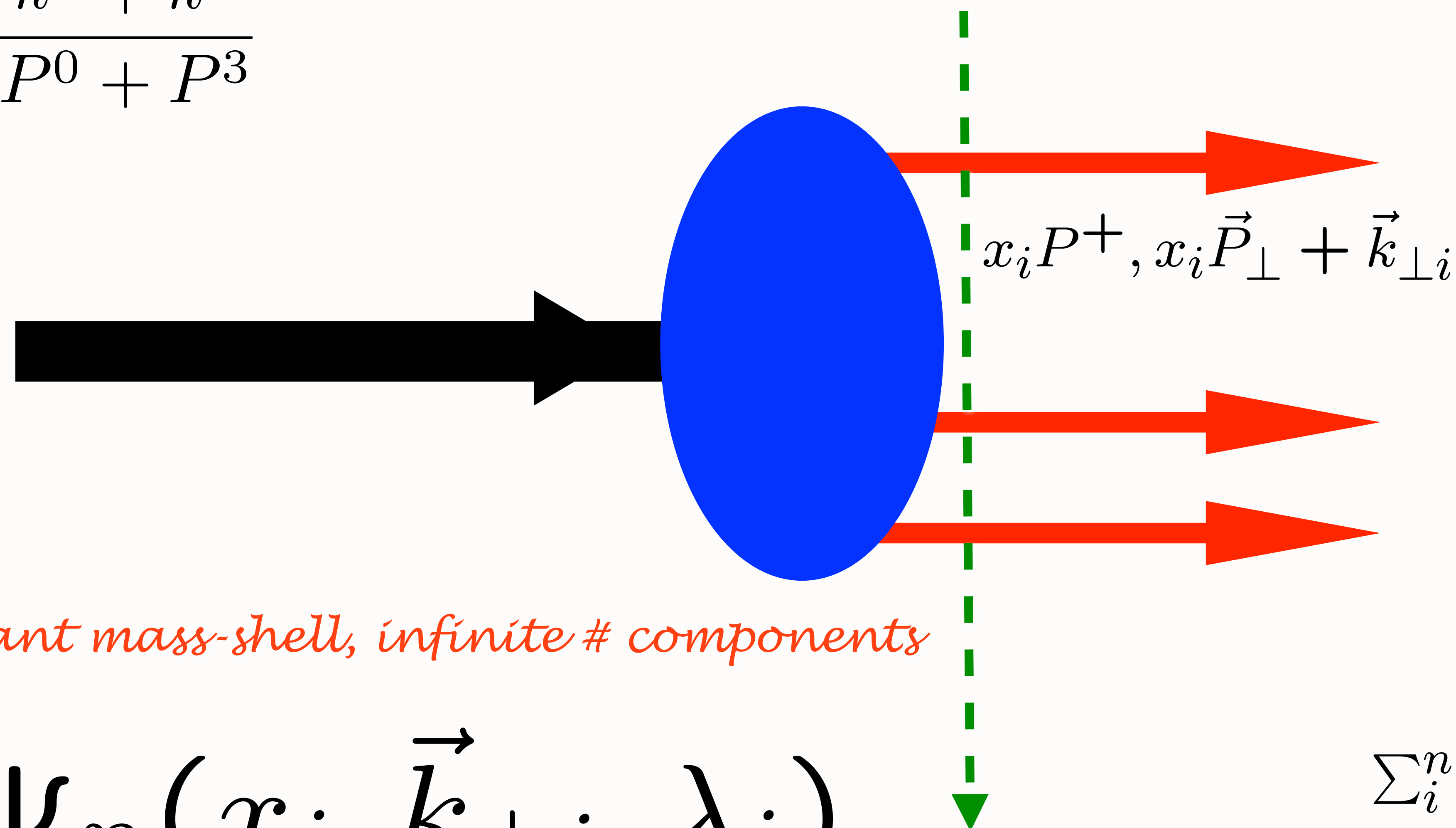
Hadronic Input: Light-Front Wavefunctions

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

Fixed $\tau = t + z/c$

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

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




*LFWFs: off invariant mass-shell, infinite # components*

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

$\sum_i^n x_i = 1$

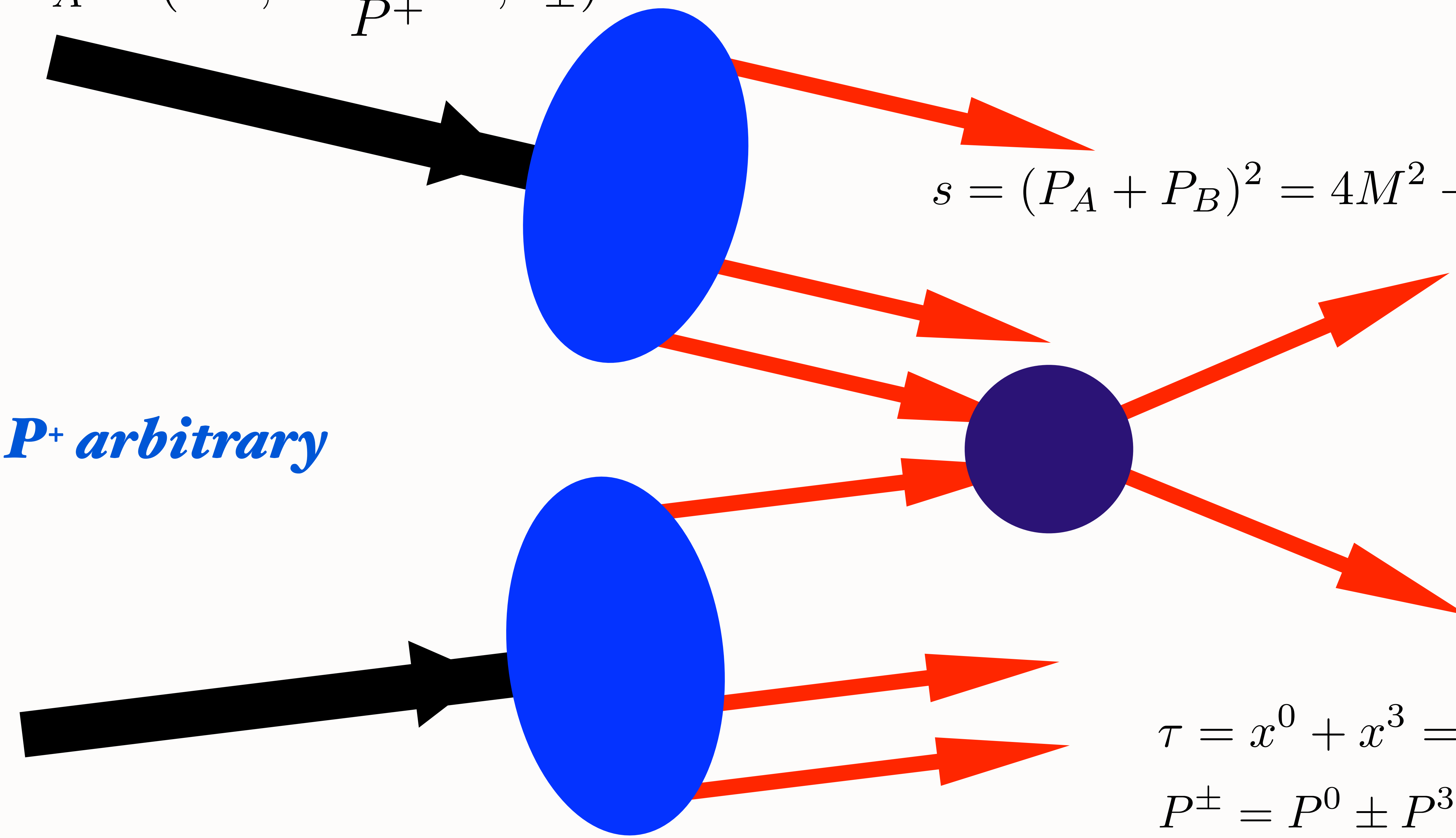
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

*Invariant under boosts! Independent of $P^\mu$*

# Boost-Invariant Light-Front Kinematics

*No pancakes, same physics in every frame*

$$P_A = (P^+, \frac{r_\perp^2 + m^2}{P^+}, \vec{r}_\perp)$$



$$s = (P_A + P_B)^2 = 4M^2 + 4r_\perp^2$$

***P⁺ arbitrary***

$$\tau = x^0 + x^3 = t + z/c$$

$$P^\pm = P^0 \pm P^3$$

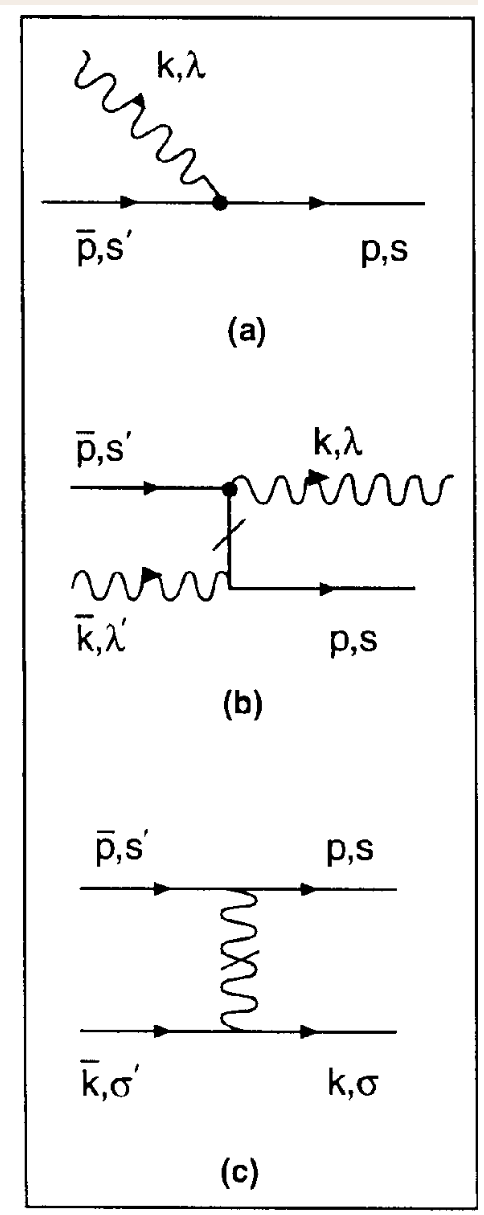
$$P_B = (P_B^+, P_B^-, \vec{P}_{\perp B}) = (P^+, \frac{r_\perp^2 + m^2}{P^+}, -\vec{r}_\perp)$$

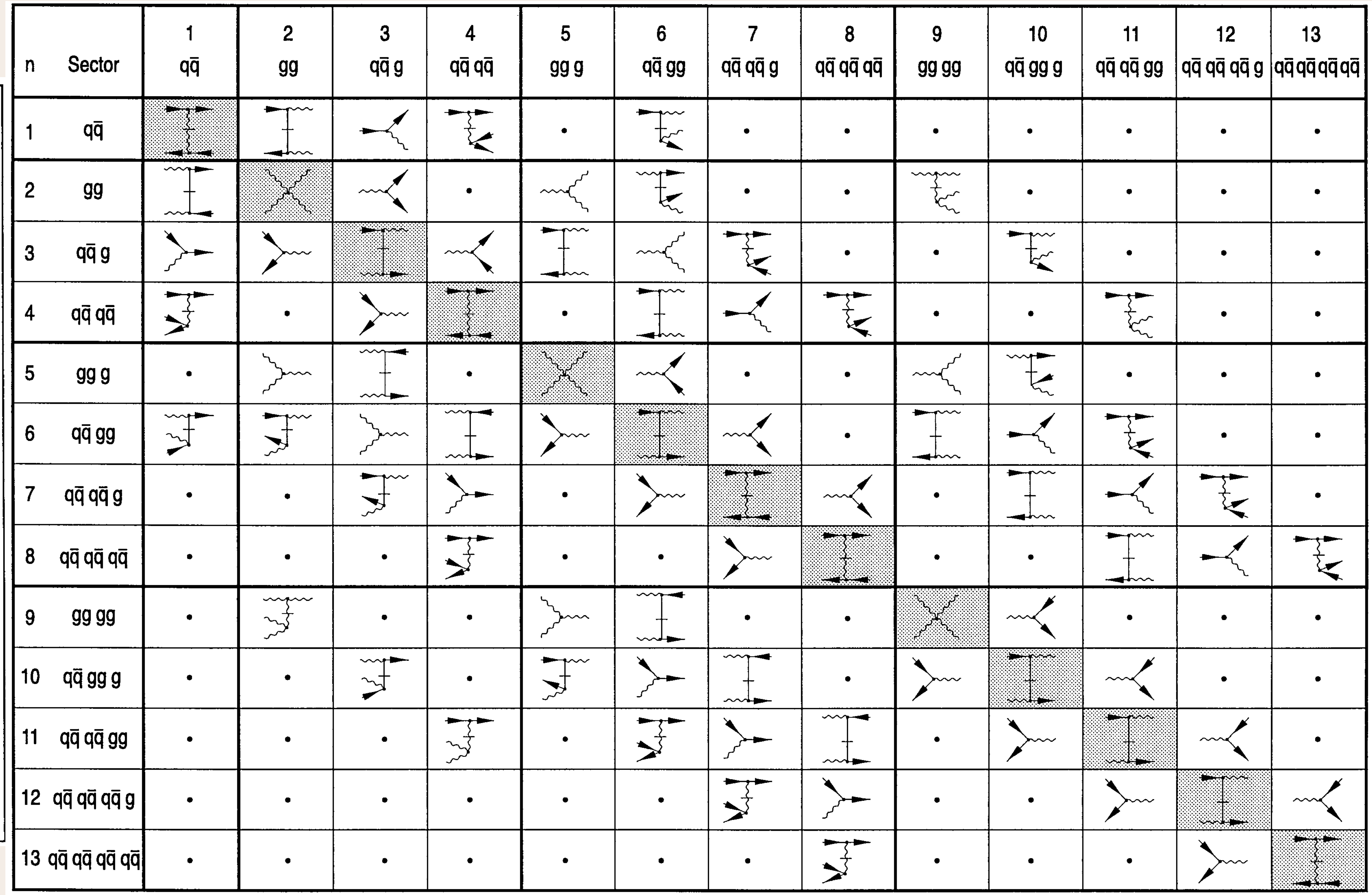
*Light-Front QCD*

*Heisenberg Equation*

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

*Complete solutions*
*QCD(1+1)*
*arbitrary mass, color*



Each element of flash photograph illuminated at same LF time

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

Evolve in LF time

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

Eigenstate -- independent of $\tau$

Causal, Trivial Vacuum

HELEN BRADLEY - PHOTOGRAPHY

# 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 $P^\mu$*

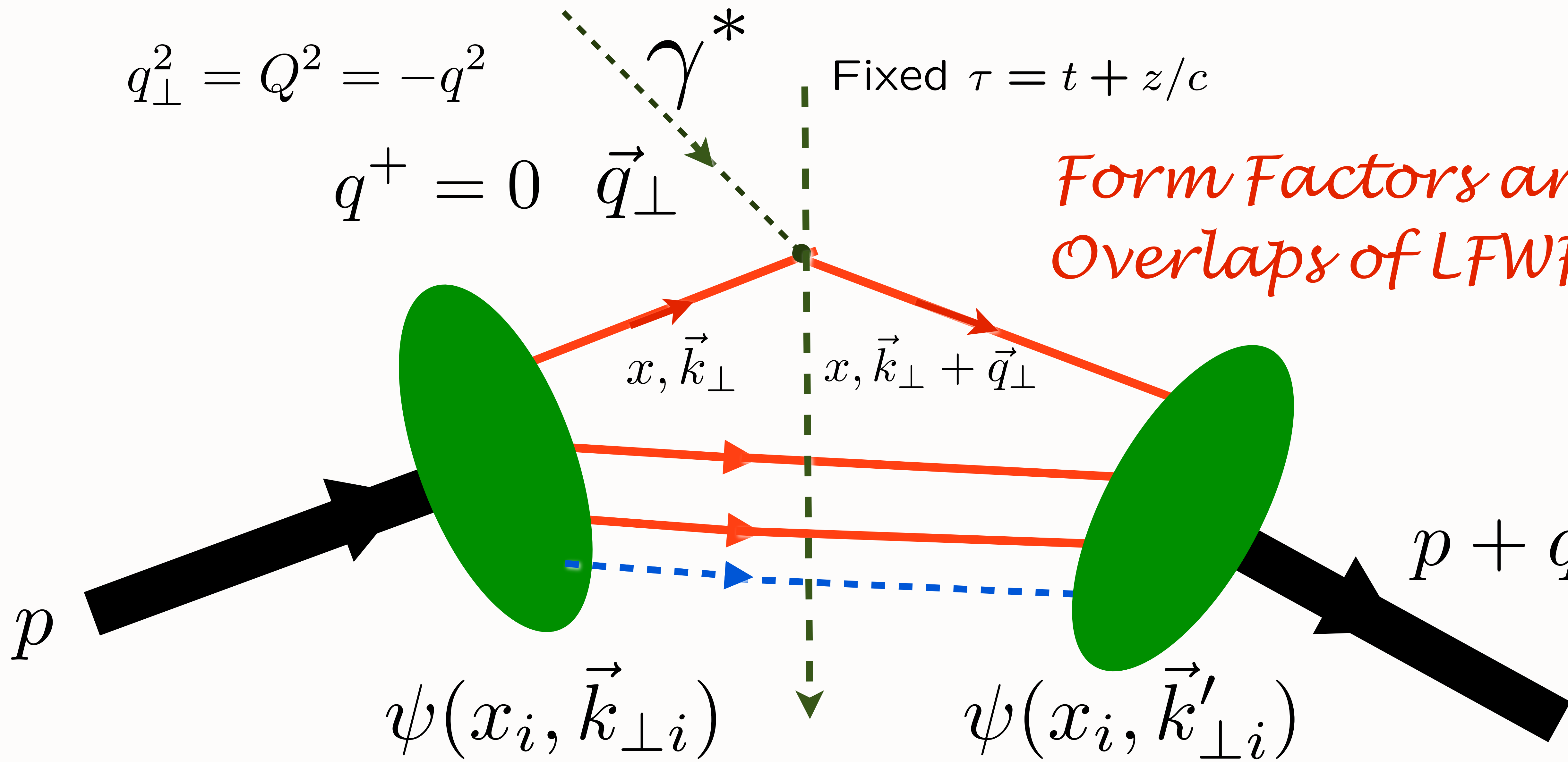
$$H_{LF}^{QCD} |\psi> = M^2 |\psi>$$

*Direct connection to QCD Lagrangian*

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

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

Interaction picture




Form Factors are Overlaps of LFWFs

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

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

**Drell &Yan, West**

# Angular Momentum on the Light-Front

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

Conserved
LF Fock state by Fock State

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

n-1 orbital angular momenta

*Nonzero Anomalous Moment -->Nonzero orbital angular momentum*

# Exact LF Formula for Pauli Form Factor

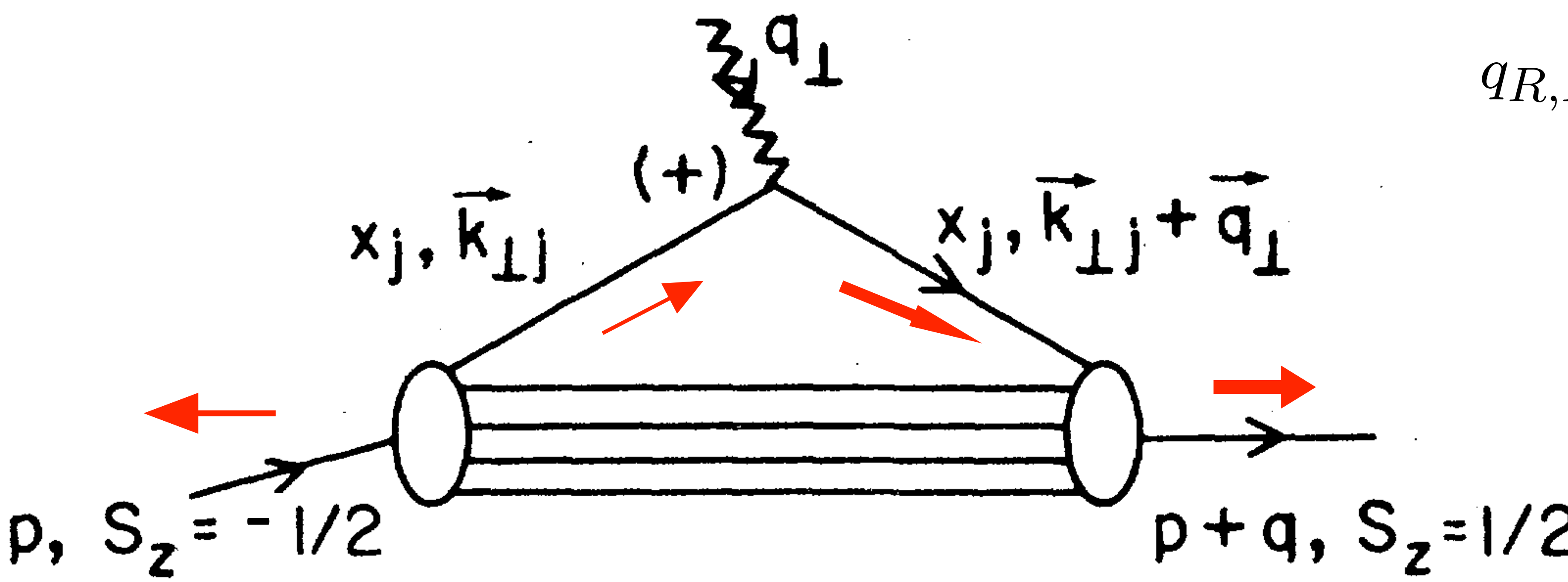
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

**Drell, sjb**

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

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

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

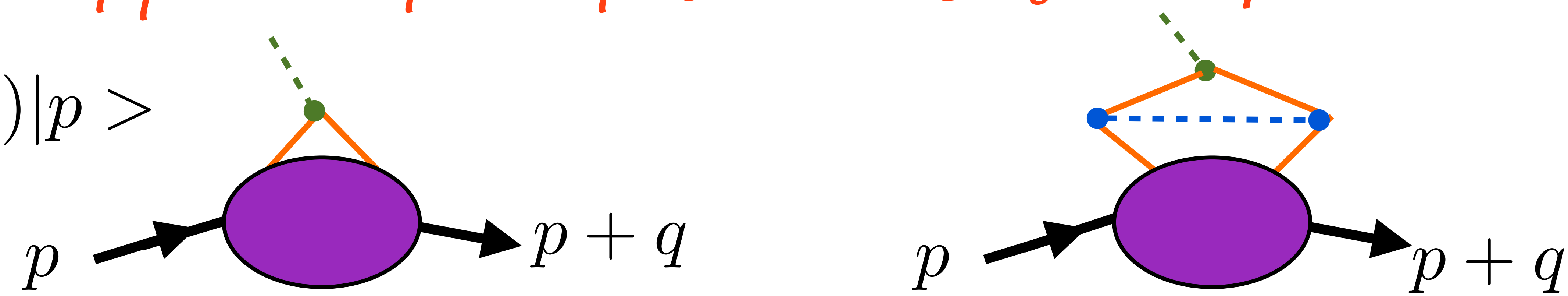



Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

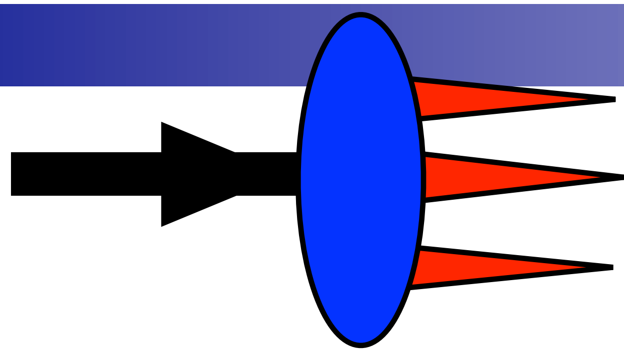
*Nonzero Proton Anomalous Moment -->*
*Nonzero orbital quark angular momentum*

# Calculation of proton form factor in Instant Form

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




- **Need to boost proton wavefunction from p to p+q: Extremely complicated dynamical problem; particle number changes**
- **Need to couple to all currents arising from vacuum!!**
- **Each time-ordered contribution is frame-dependent**
- **States built on normal-ordered acausal vacuum**
- **Divide by disconnected vacuum diagrams**



# • *Light Front Wavefunctions:*

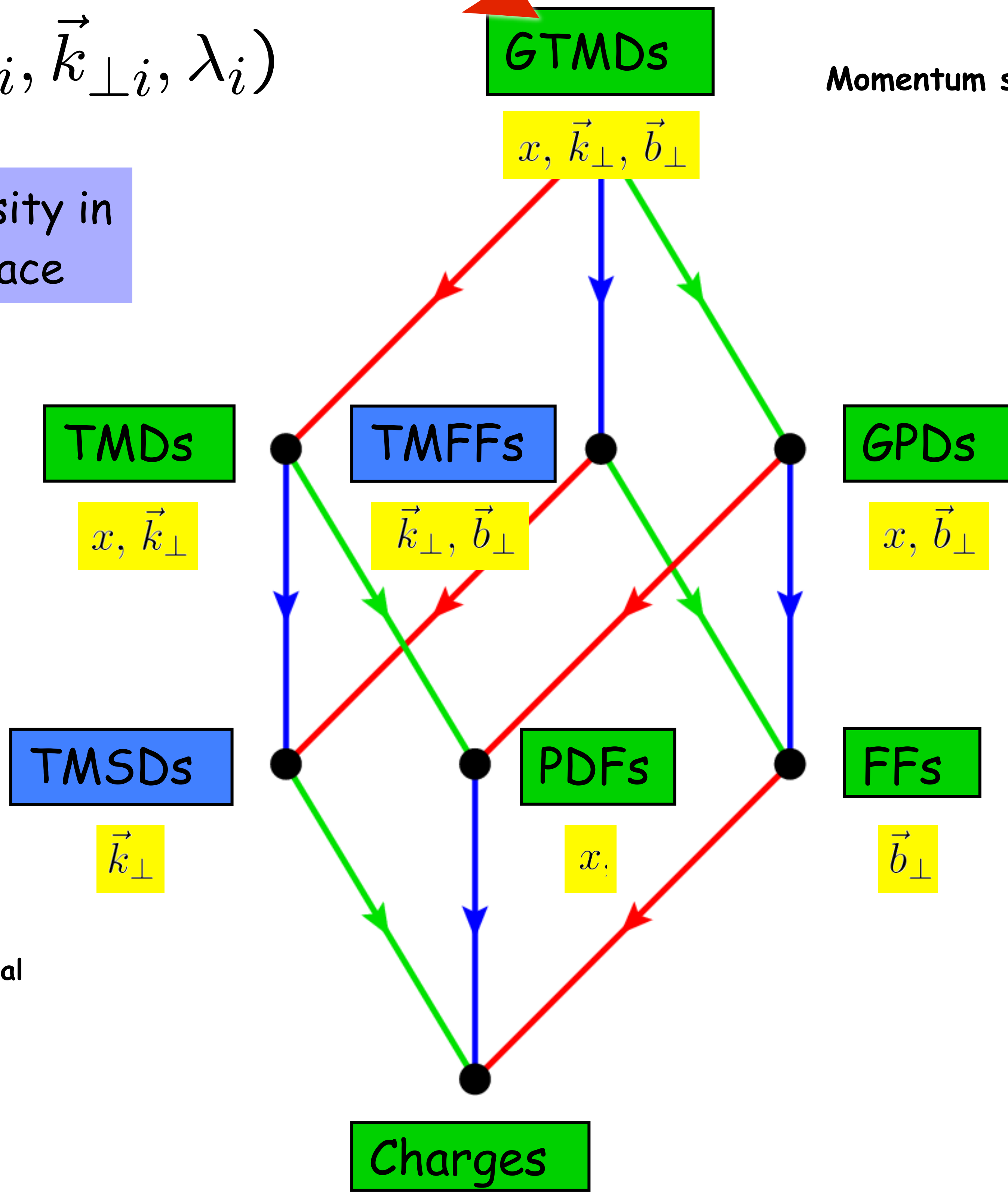
Key Hadronic Input to QCD Observables

Lorce

$\xi = 0$

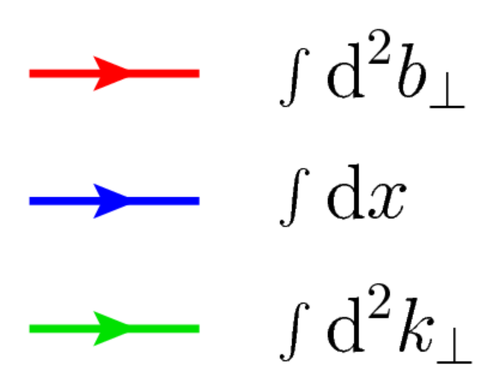
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

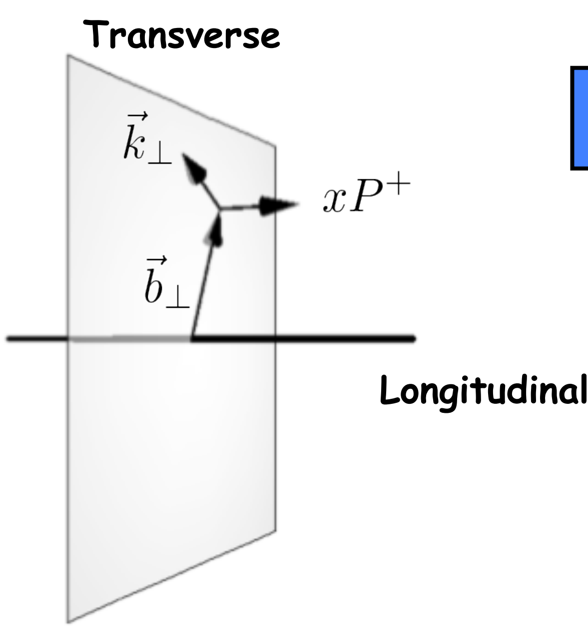
Transverse density in momentum space



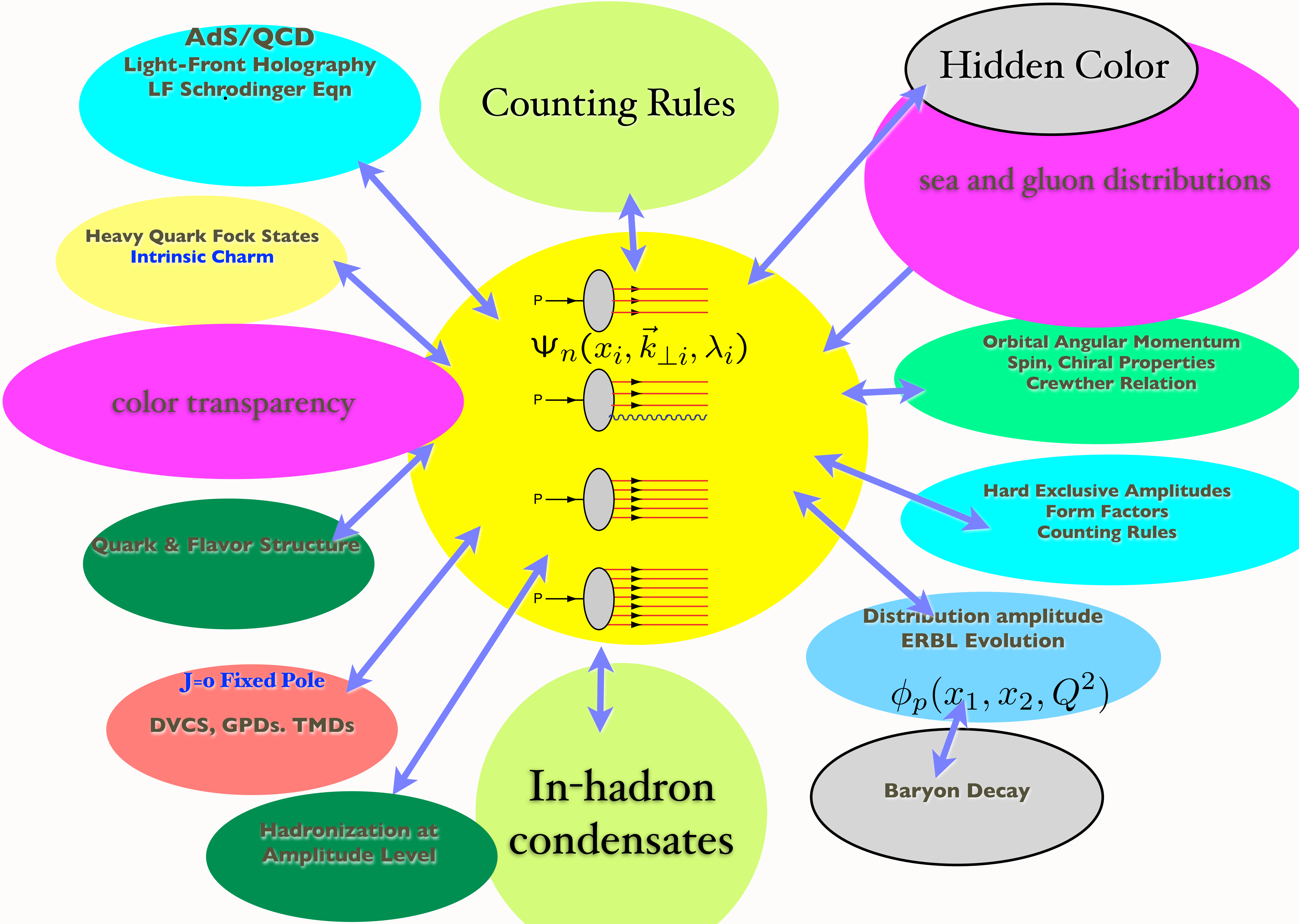

Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ $\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$ Position space

Transverse density in position space



# QCD and the LF Hadron Wavefunctions



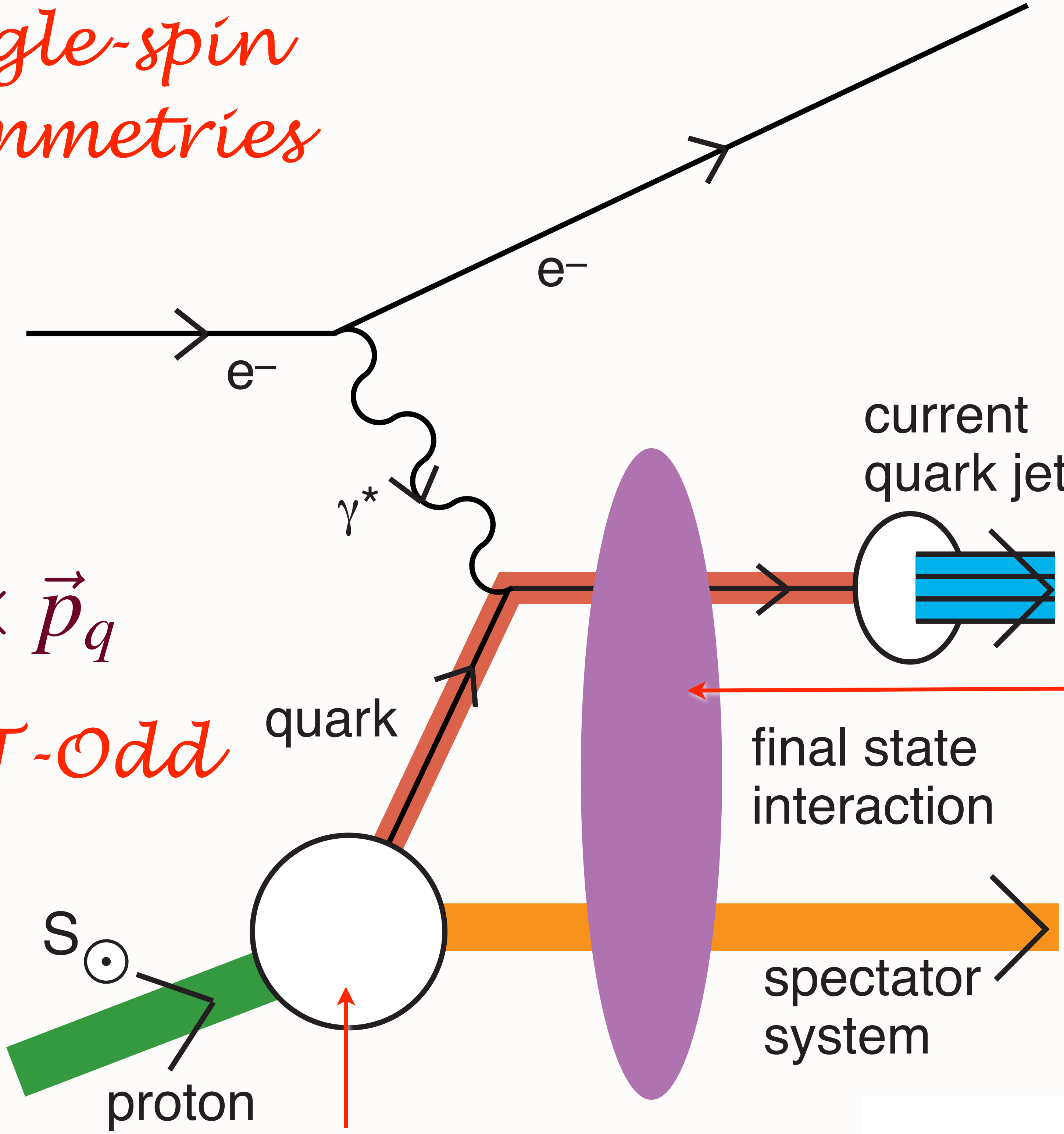
*Single-spin asymmetries*

# Leading-Twist Sivers Effect

*Dae Sung Hwang, Ivan Schmidt, sjb*

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

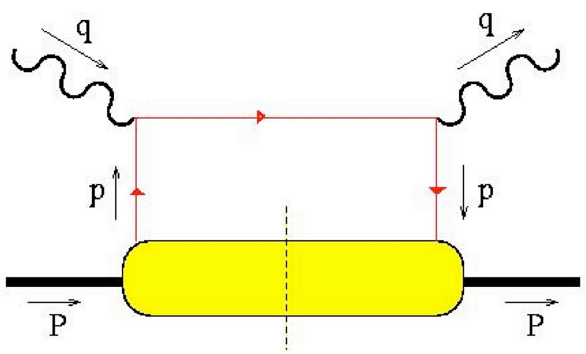
*Pseudo- T-Odd*



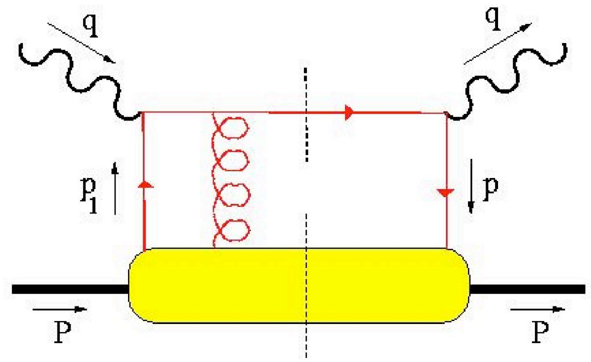

*Light-Front Wavefunction S and P- Waves*

**Lensing Effect:**
*QCD S- and P- Coulomb Phases --Wilson Line*

*Leading-Twist Rescattering Violates pQCD Factorization!*



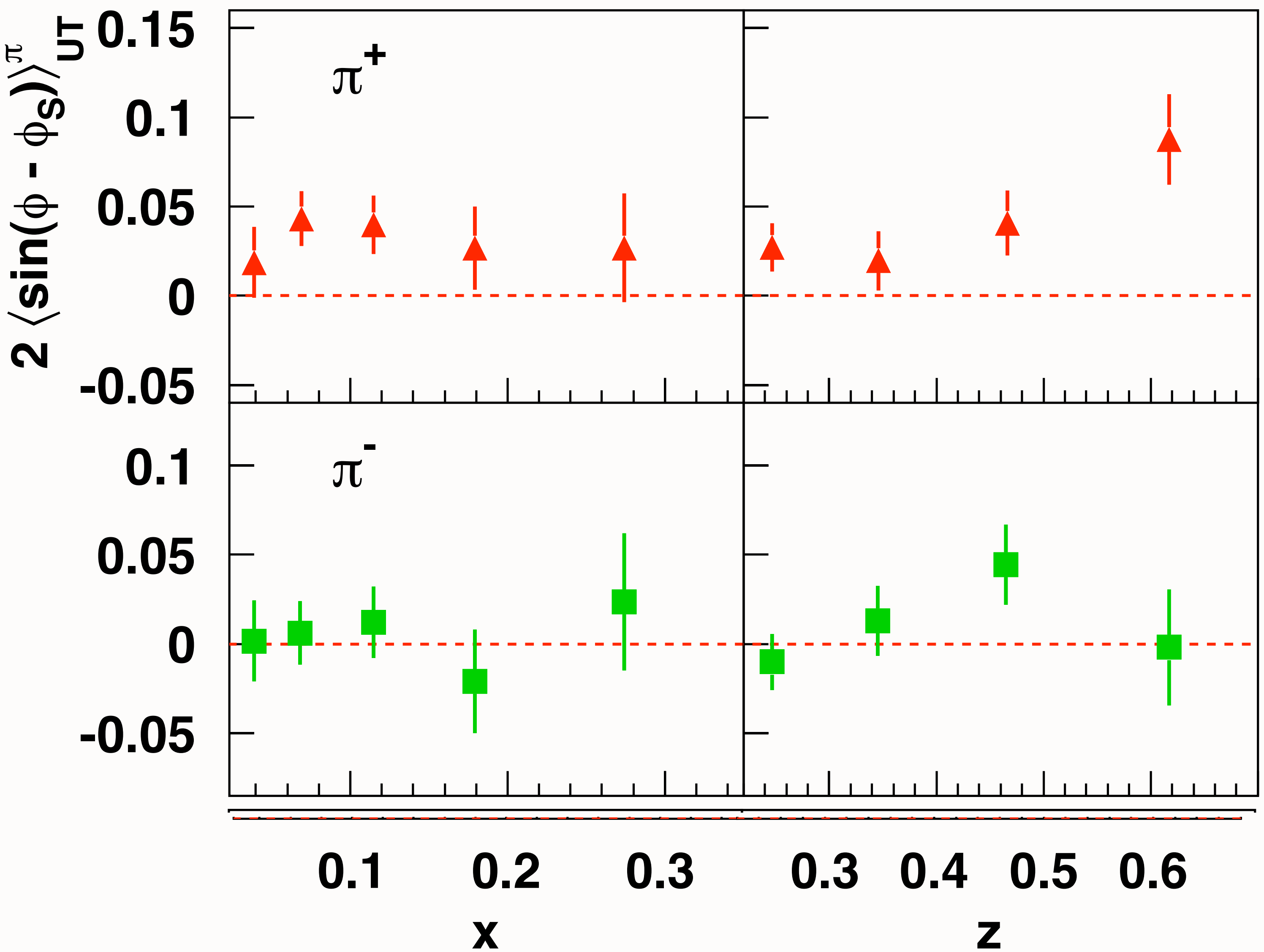

can interfere with




and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

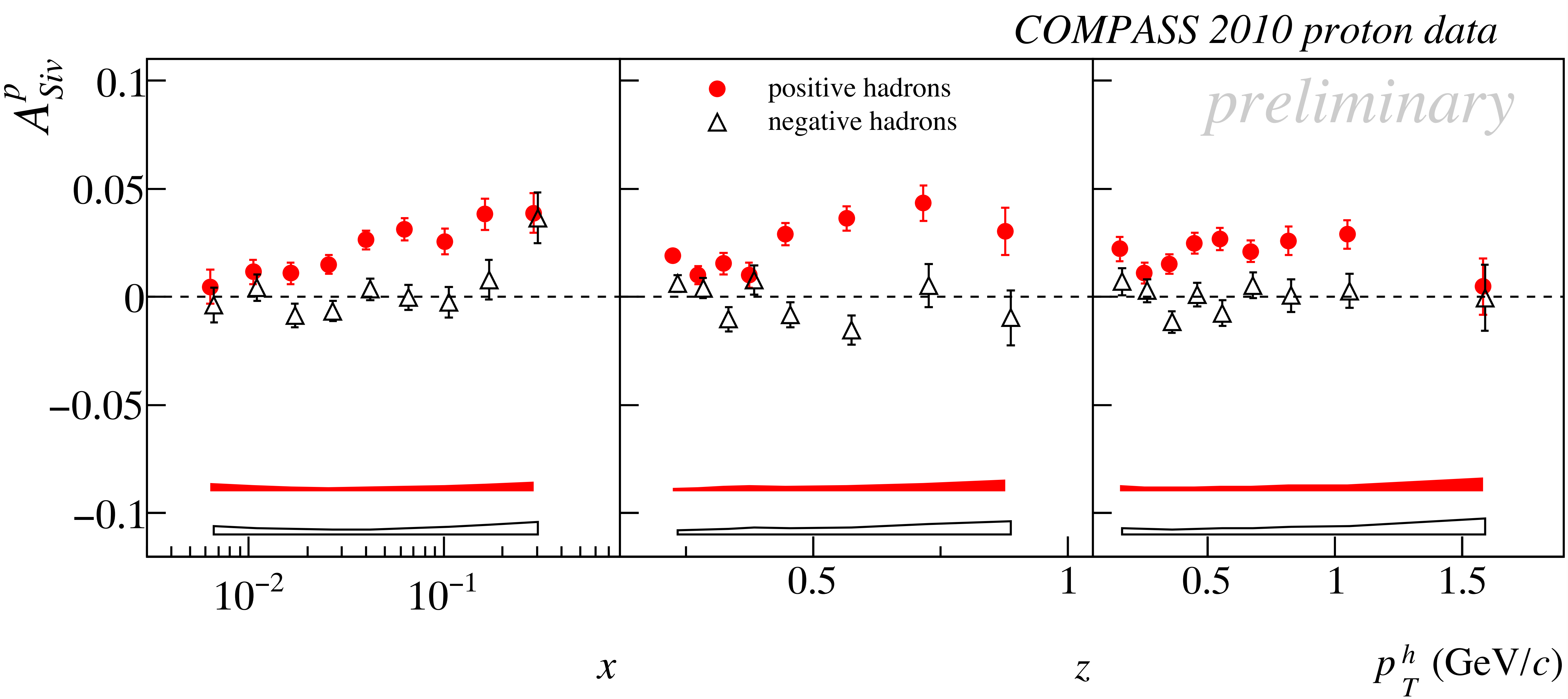
## Sivers asymmetry from HERMES




- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**... Consistent with zero for **π⁻**...

**Gamberg: Hermes data compatible with BHS model**

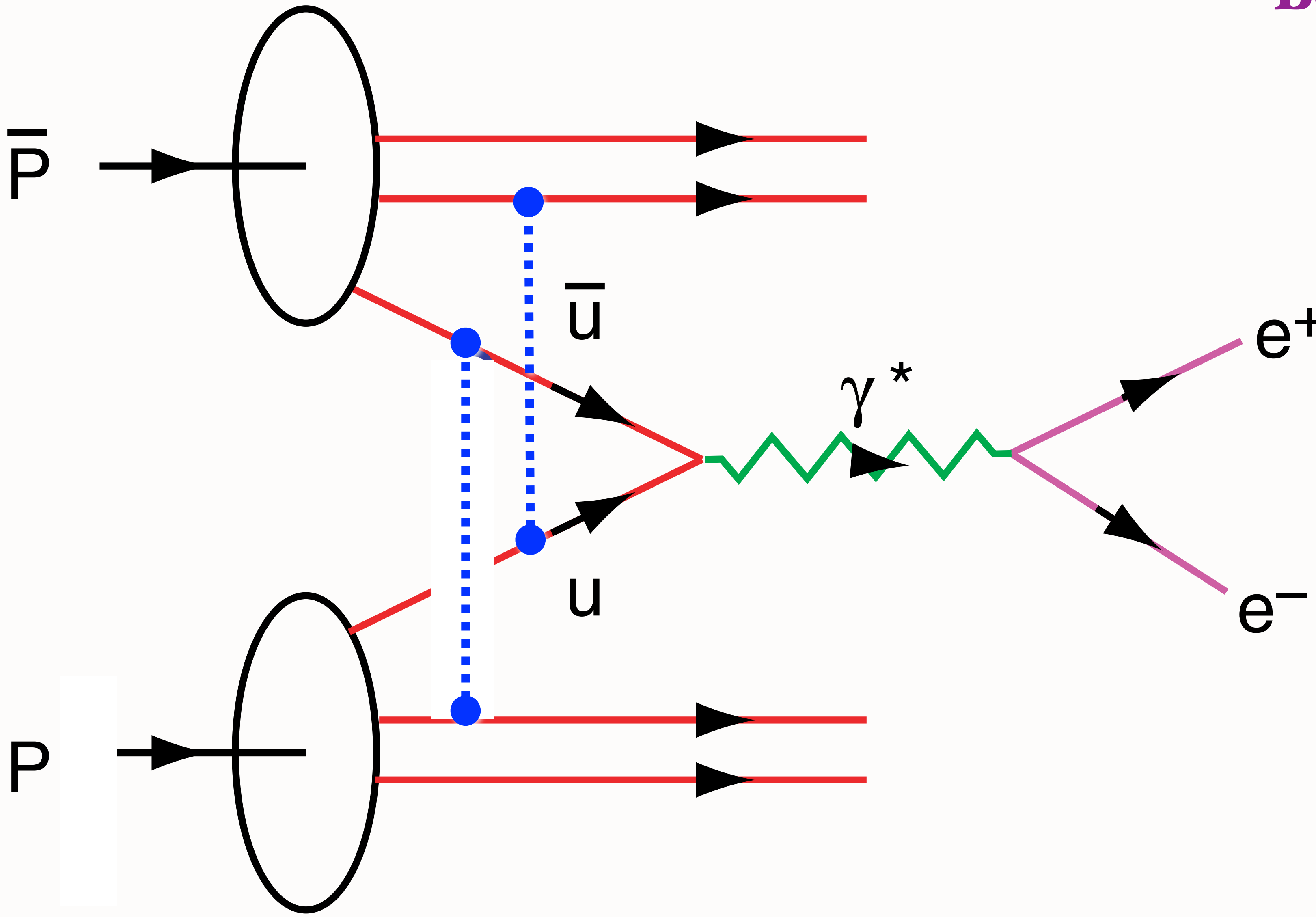
**Schmidt, Lu:**
***Asymmetry ratios should follow quark contributions to anomalous moment***




**Schmidt, Lu:**

***Asymmetry ratios should follow quark contributions to anomalous moment***

Boer, Hwang, sjb




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

Product of Boer - Mulders Functions

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

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

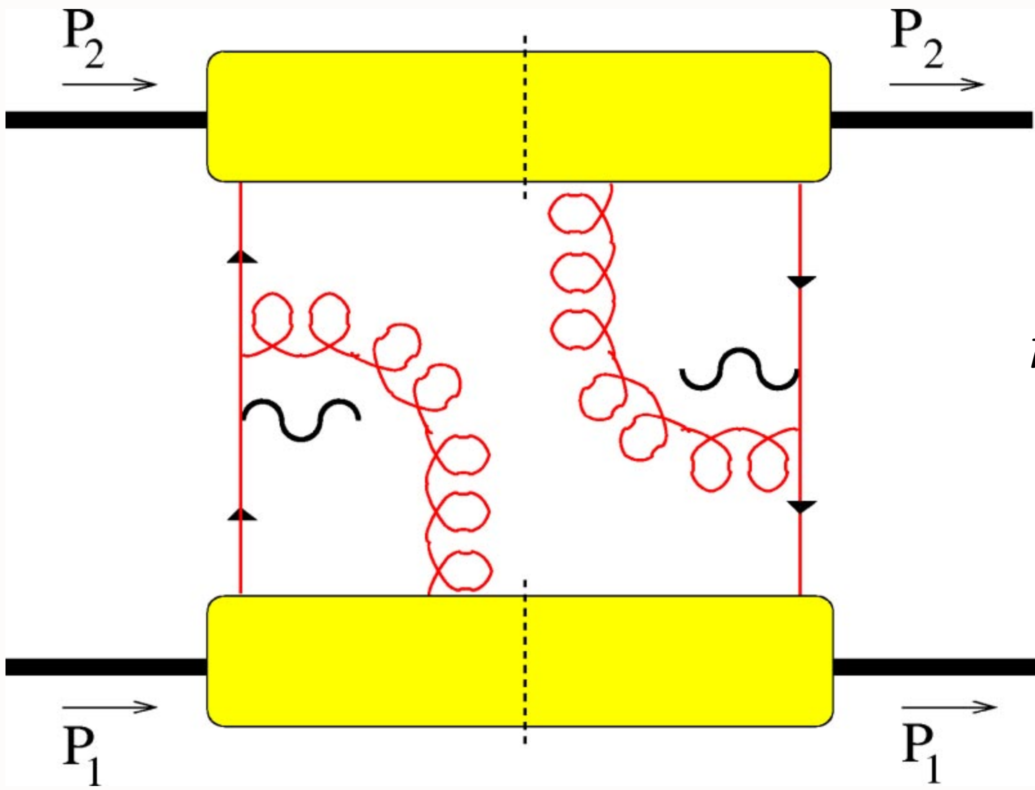
# Drell-Yan planar correlations

Boer, Hwang, sjb

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

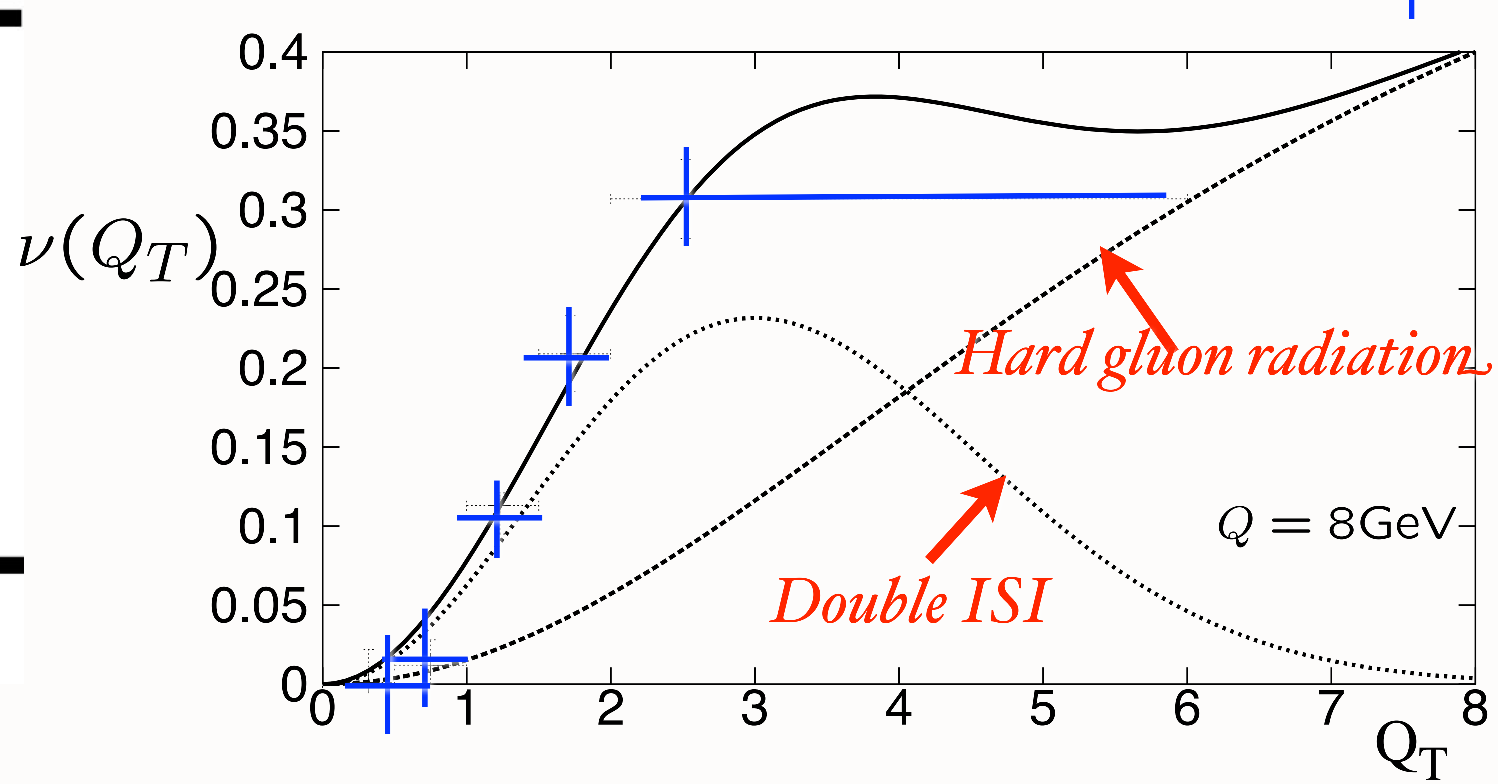
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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




**Violates Lam-Tung relation!**

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

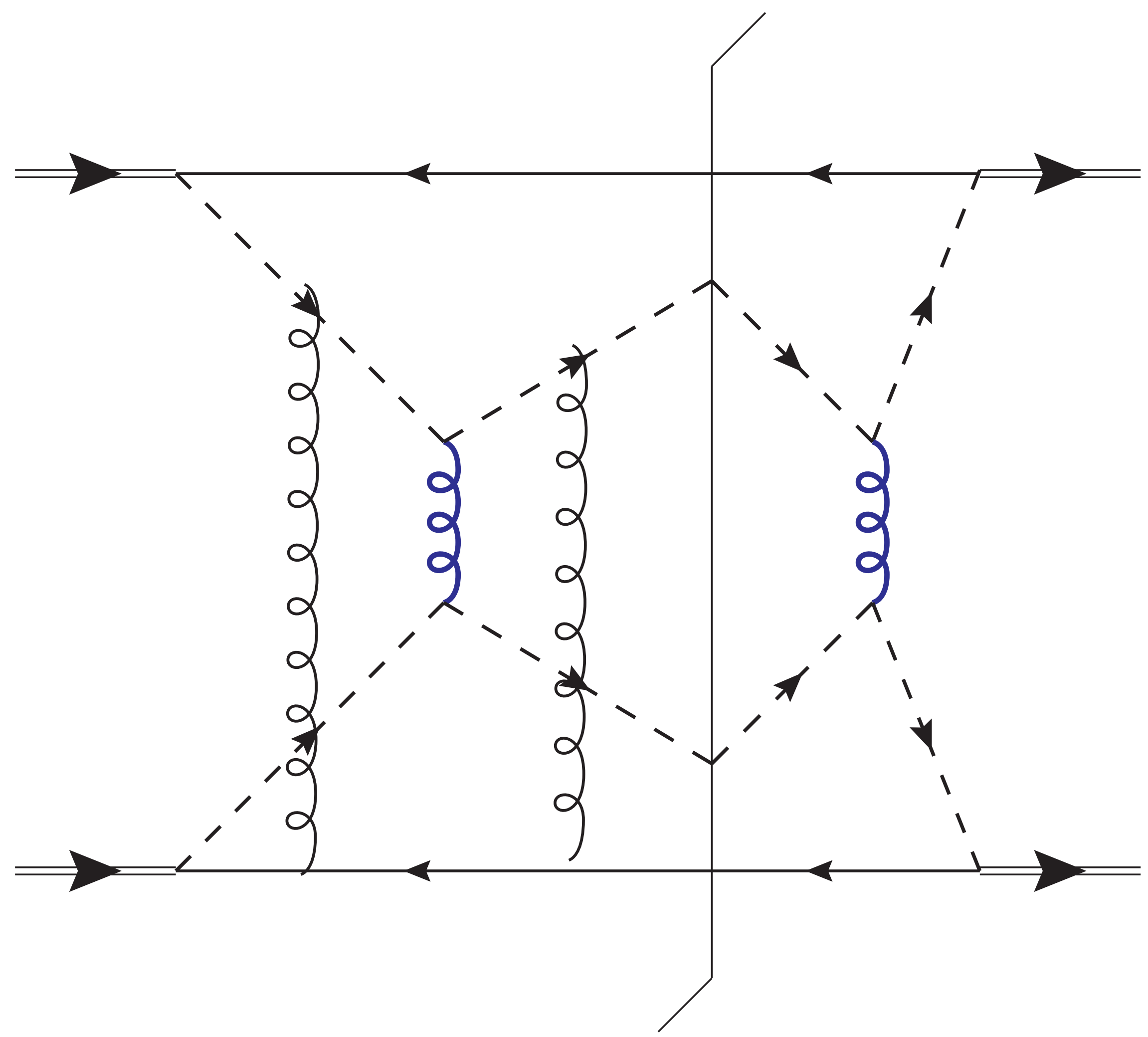



Model: Boer,

# Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

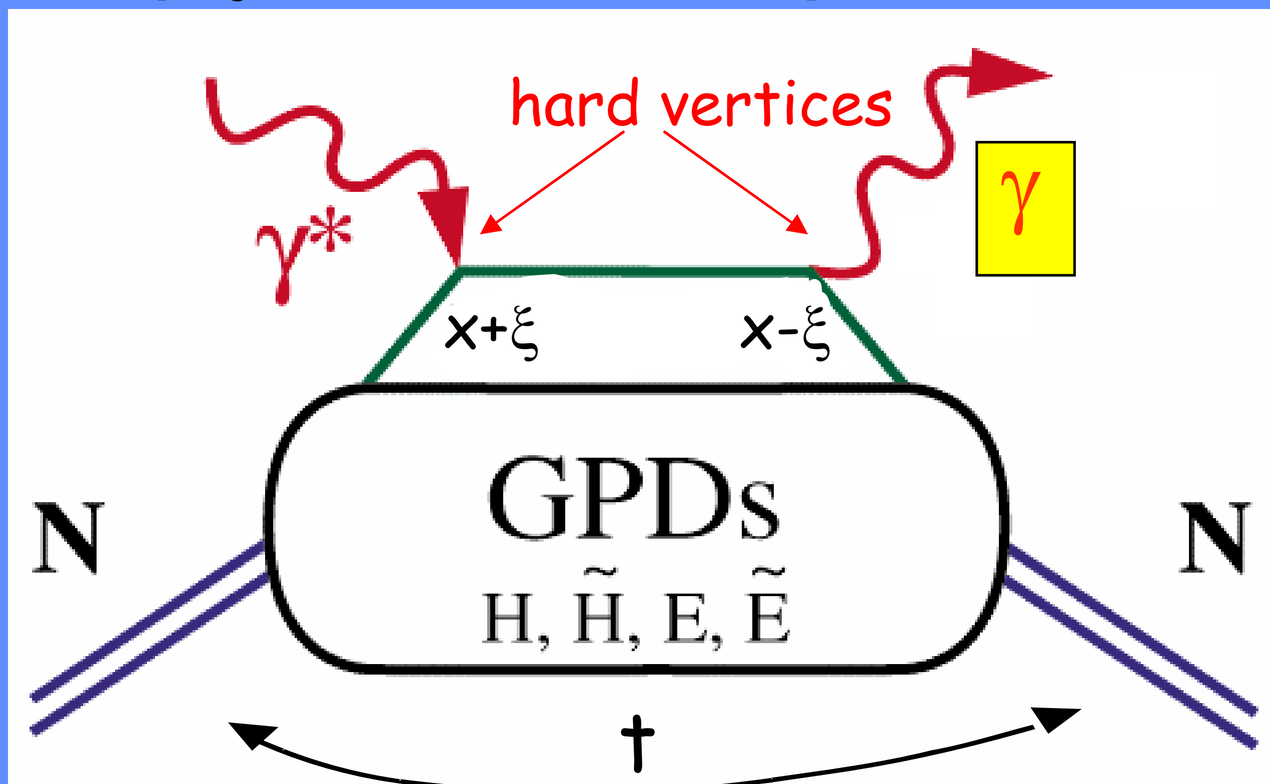
e-Print: **arXiv:0705.2141** [hep-ph]



The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

# GPDs & Deeply Virtual Exclusive Processes
## - New Insight into Nucleon Structure

### Deeply Virtual Compton Scattering (DVCS)




x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

H(x,ξ,t), E(x,ξ,t), . . . "Generalized Parton Distributions"

- Generalized Parton Distributions in gauge/gravity duals

  [Vega, Schmidt, Gutsche and Lyubovitskij, Phys.Rev. D83 (2011) 036001]

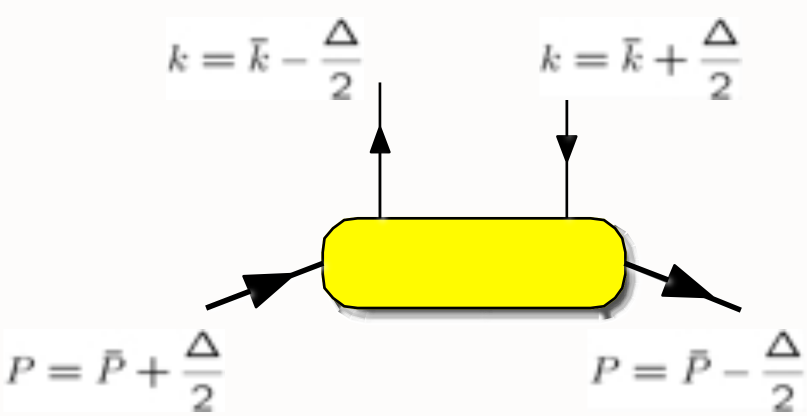
  [Nishio and Watari, arXiv:1105.290]

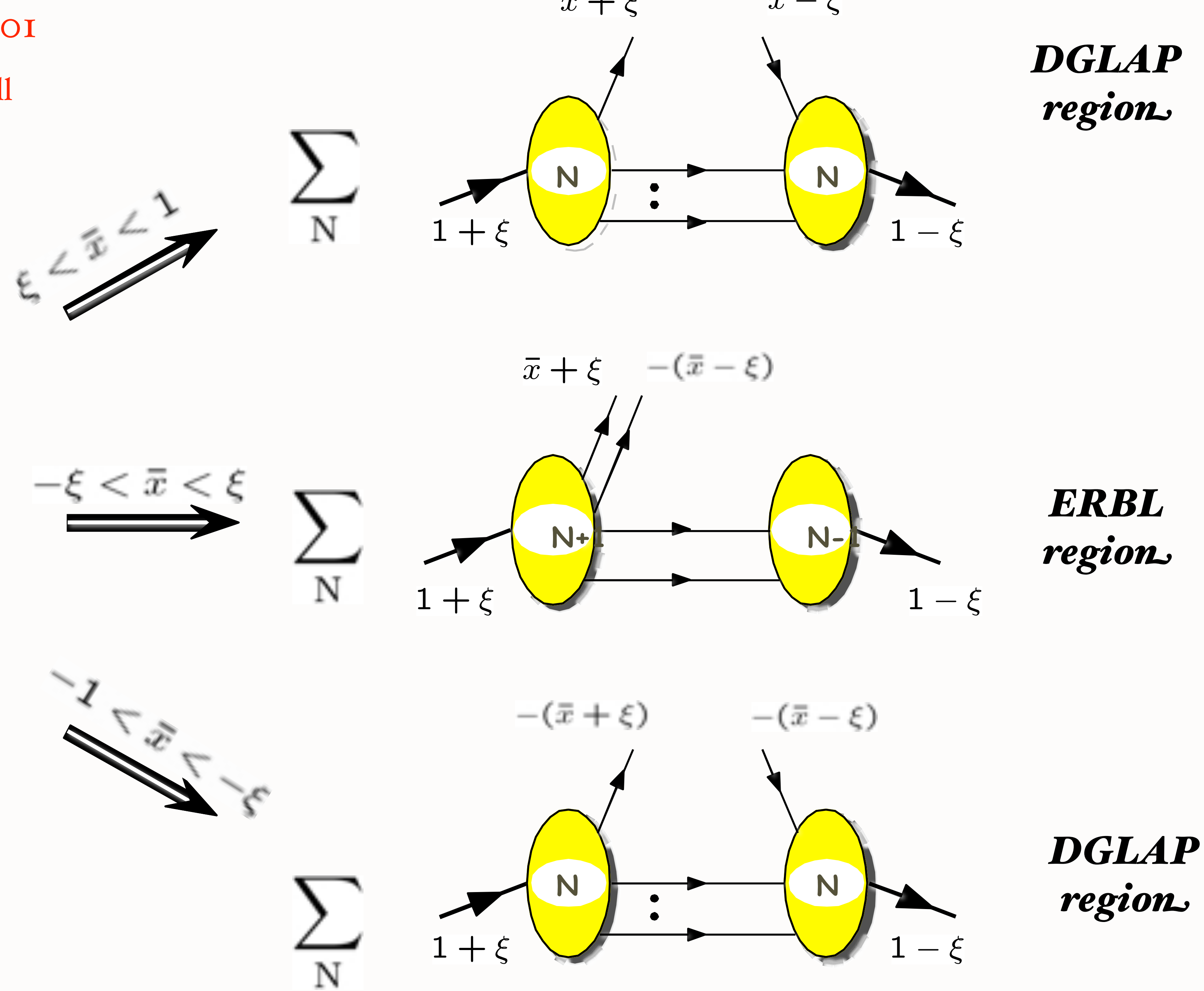
# Light-Front Wave Function Overlap Representation

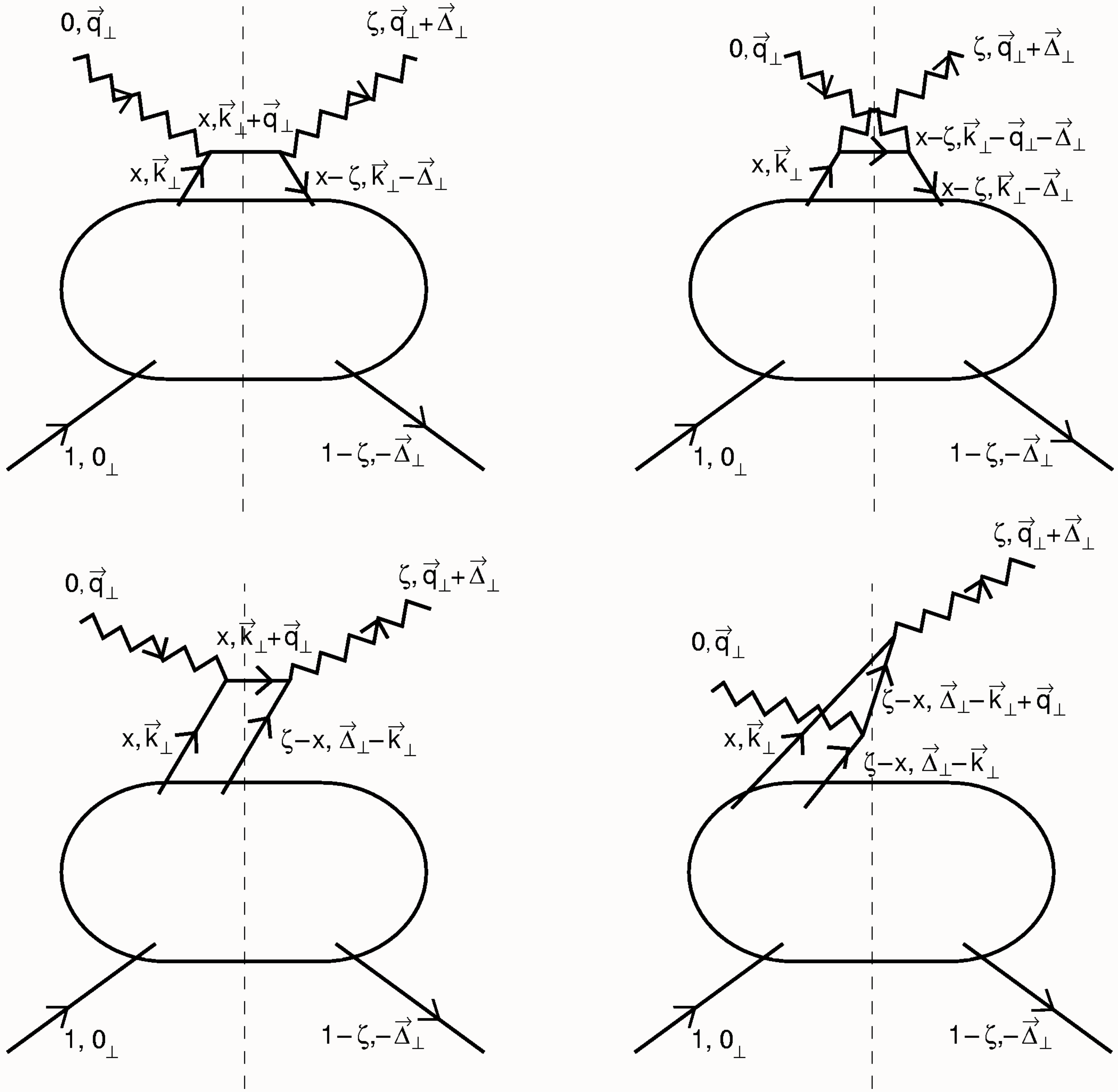
## DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll






# Light-cone wavefunction representation of deeply virtual Compton scattering ☆

Stanley J. Brodsky [a], Markus Diehl [a,1], Dae Sung Hwang [b]

# Example of LFWF representation of GPDs (n => n)

Diehl, Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}}\frac{\Delta^1 - i\Delta^2}{2M} E_{(n\to n)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{2-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3}\, 16\pi^3 \delta\left(1-\sum_{j=1}^{n} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n} \vec{k}_{\perp j}\right)$$

$$\times\, \delta(x-x_1)\, \psi^{\uparrow *}_{(n)}(x'_i, \vec{k}'_{\perp i}, \lambda_i)\, \psi^{\downarrow}_{(n)}(x_i, \vec{k}_{\perp i}, \lambda_i),$$

where the arguments of the final-state wavefunction are given by

$$x'_1 = \frac{x_1-\zeta}{1-\zeta}, \qquad \vec{k}'_{\perp 1} = \vec{k}_{\perp 1} - \frac{1-x_1}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the struck quark,}$$

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the spectators } i = 2, \ldots, n.$$

# Link to DIS and Elastic Form Factors

DIS at $\xi=t=0$

$$H^q(x,0,0)=q(x), \quad -\bar{q}(-x)$$
$$\tilde{H}^q(x,0,0)=\Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int^1 dx \sum_q \left[H^q(x,\xi,t)\right] = F_1(t) \text{ Dirac f.f.}$$
$$\int^1 dx \sum_q \left[E^q(x,\xi,t)\right] = F_2(t) \text{ Pauli f.f.}$$
$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Verified using LFWFs

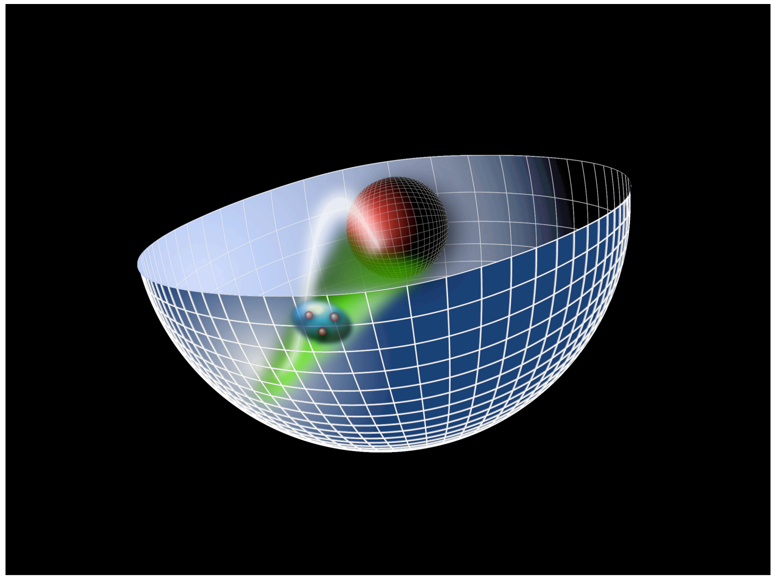
Diehl, Hwang, sjb

Quark angular momentum (Ji's sum rule)

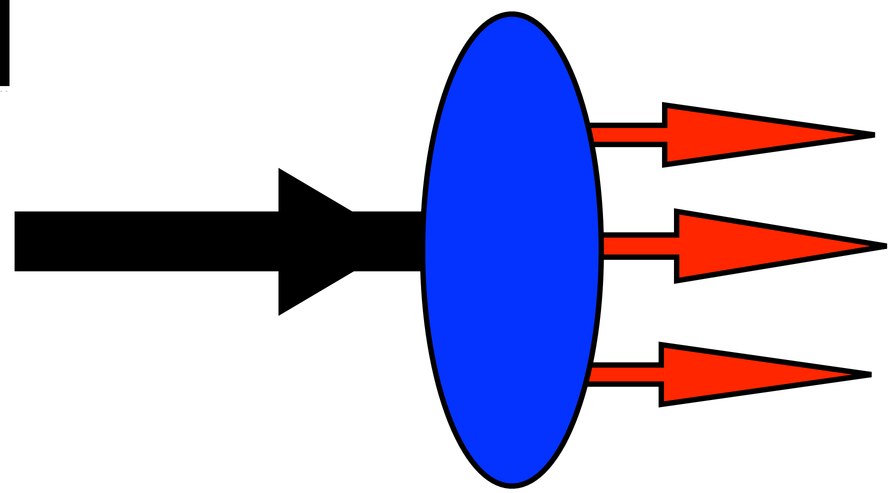
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx\left[H^q(x,\xi,0)+E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

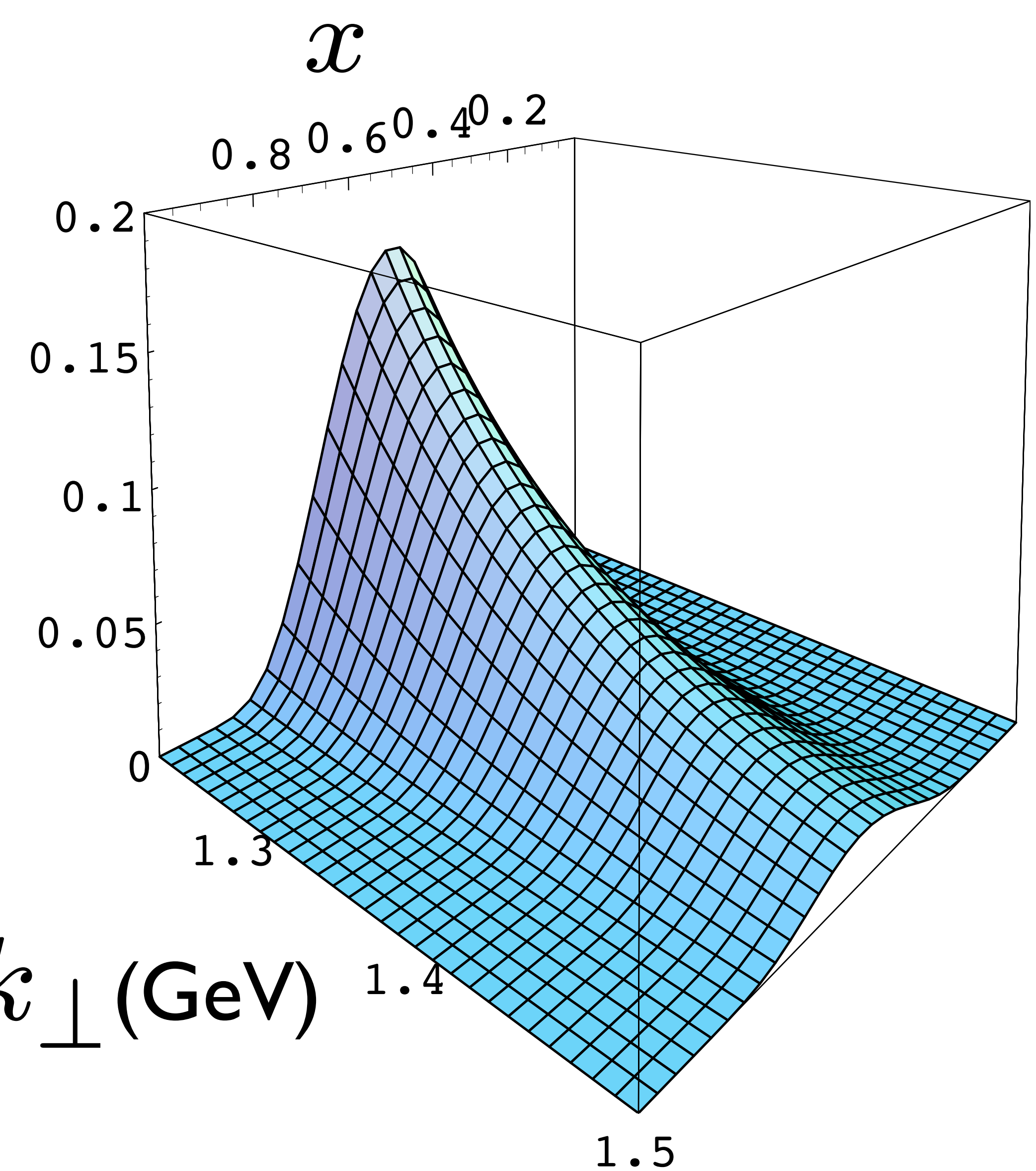
$\phi(z)$



- *Light-Front Holography*



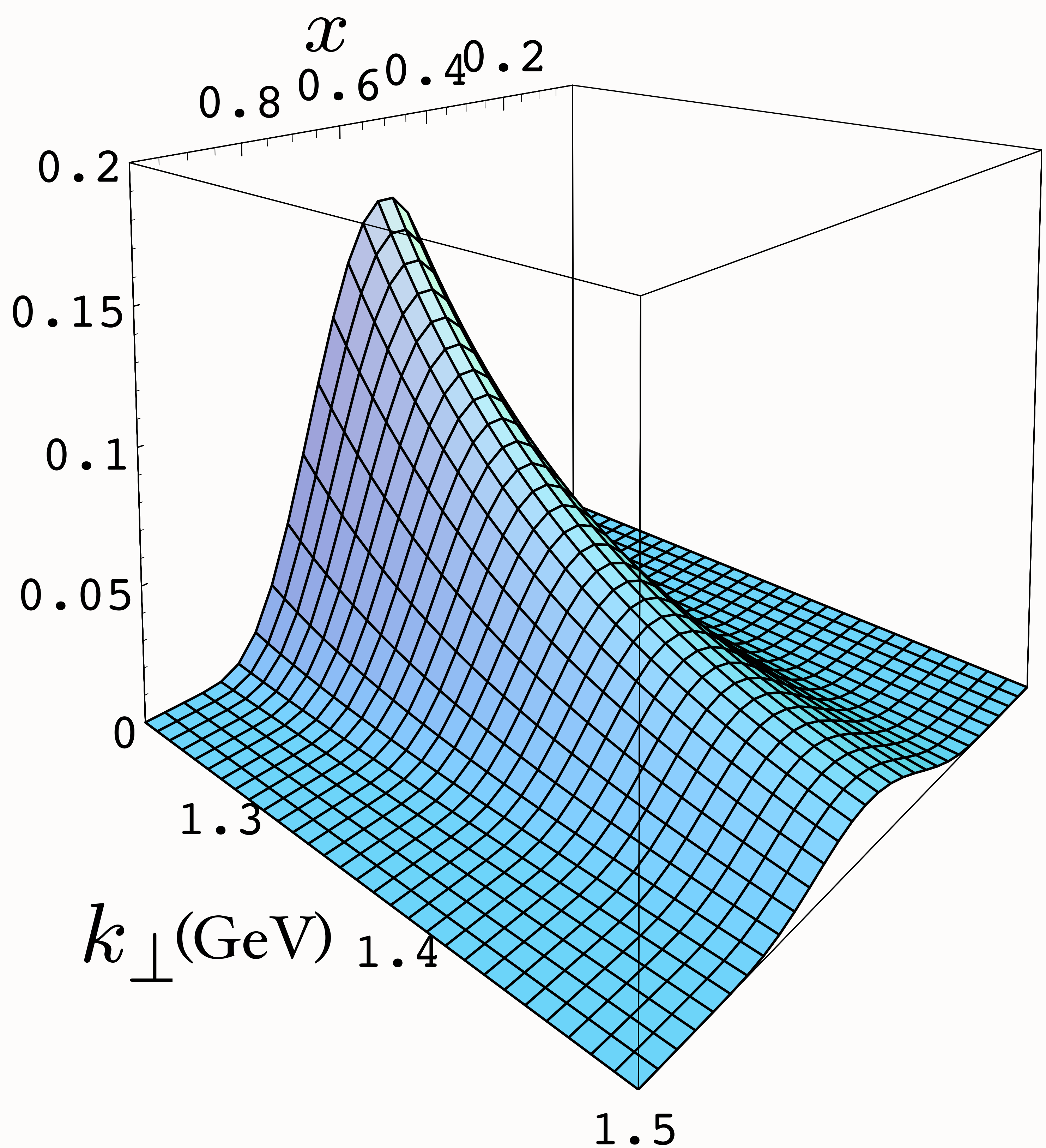
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$




- *Light Front Wavefunctions:*

  Schrödinger Wavefunctions of Hadron Physics

# Prediction from AdS/CFT: Pion Light-Front Wavefunction

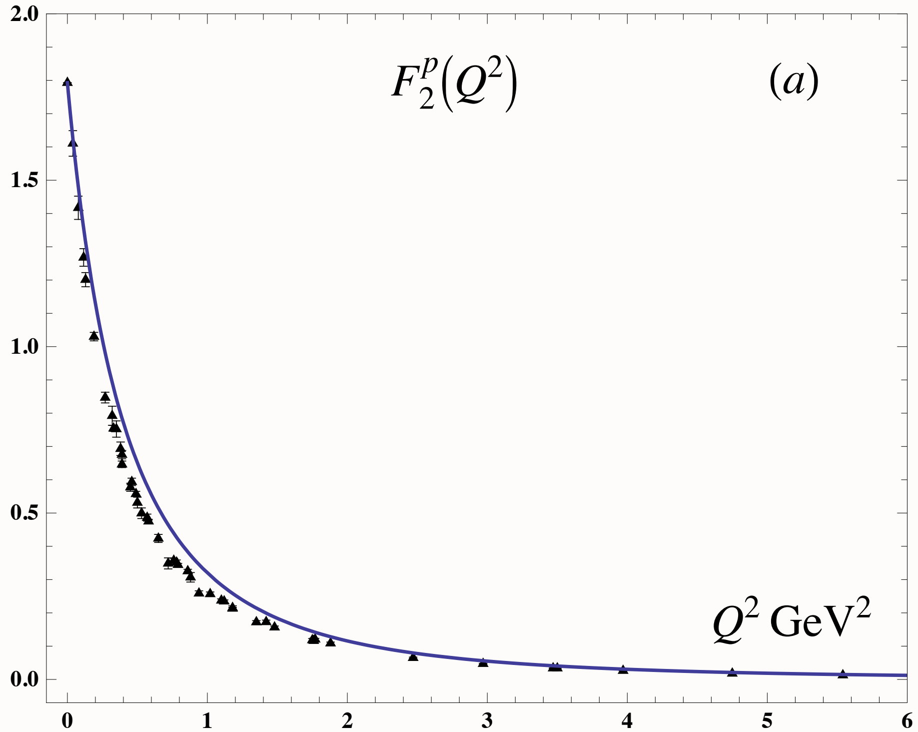


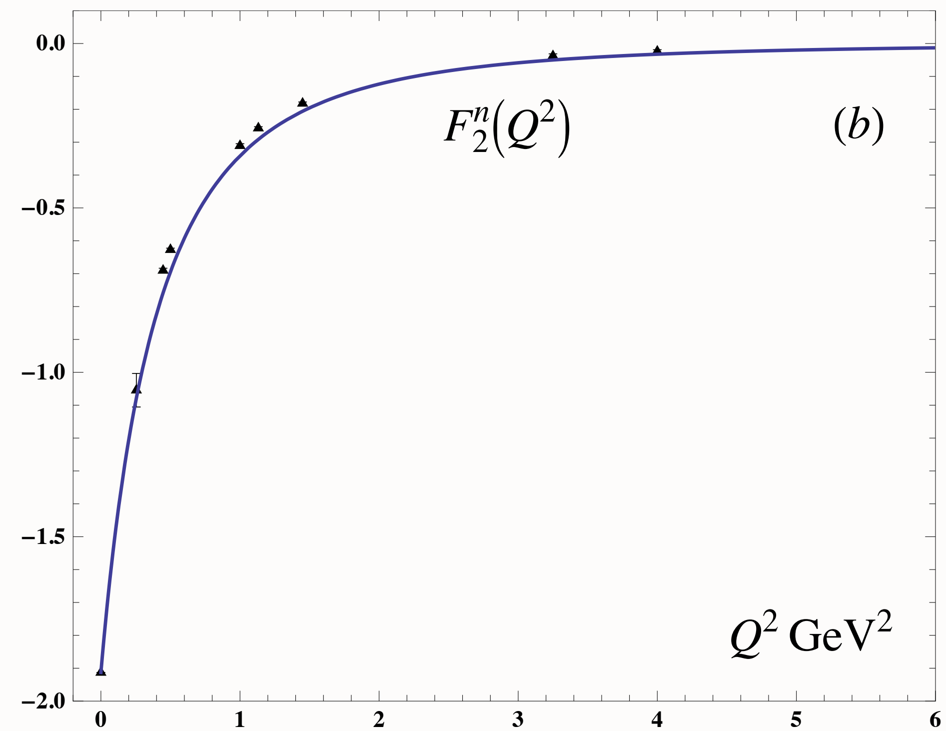

**Soft Wall Model**

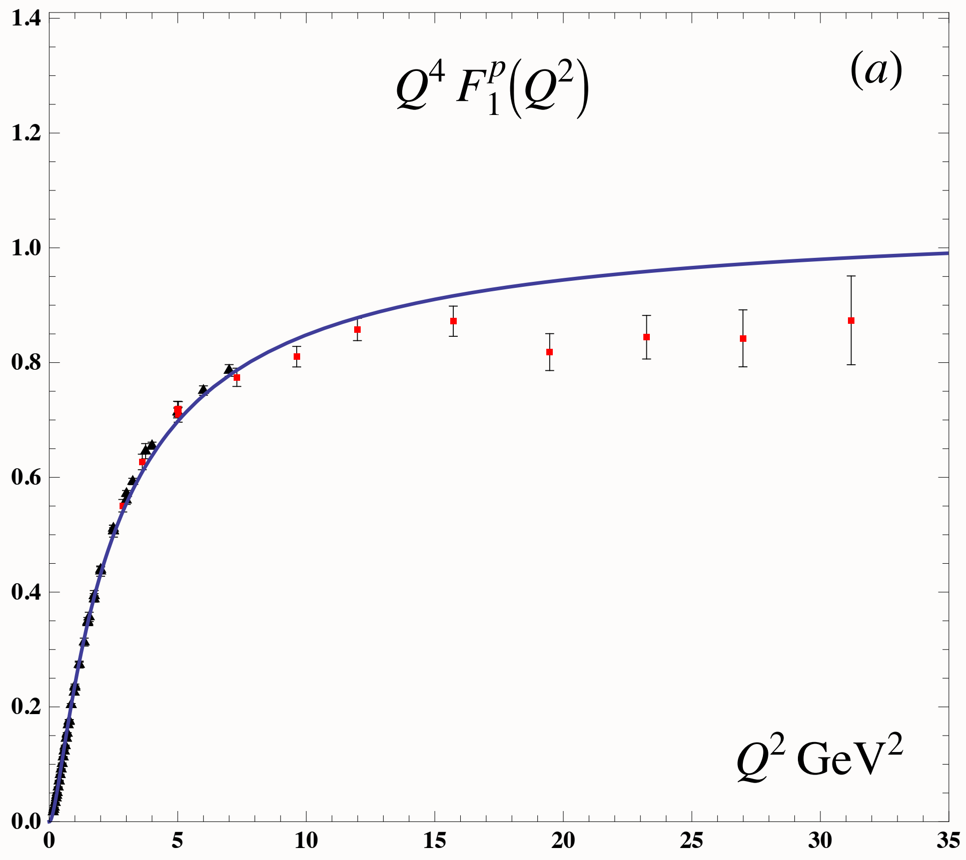
de Teramond, sjb

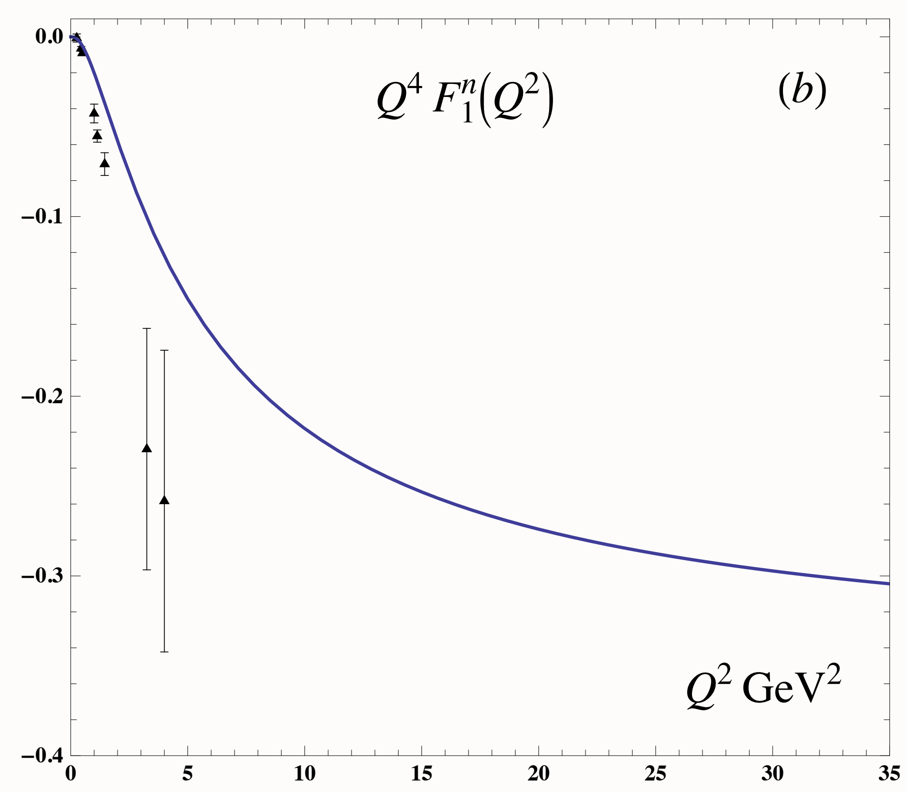
Increases PQCD prediction for $F_\pi(Q^2)$ by 16/9

# Proton and neutron form factors from AdS/QCD -- one parameter



# Some Hadronic Properties from Light Front Holography

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**Abstract.** Using ideas from Light Front Holography, we discuss the calculation of hadronic properties. In this talk I will pay special attention to hadronic masses and the nucleon helicity-independent generalized parton distributions of quarks in the zero skewness case.

**Keywords:** Light Front Holography, Hadron Spectroscopy, Generalized Parton Distributions
**PACS:** 11.10.Kk, 13.40.Gp, 14.40.Be, 14.40.Lb

## Generalized parton distributions in AdS/QCD

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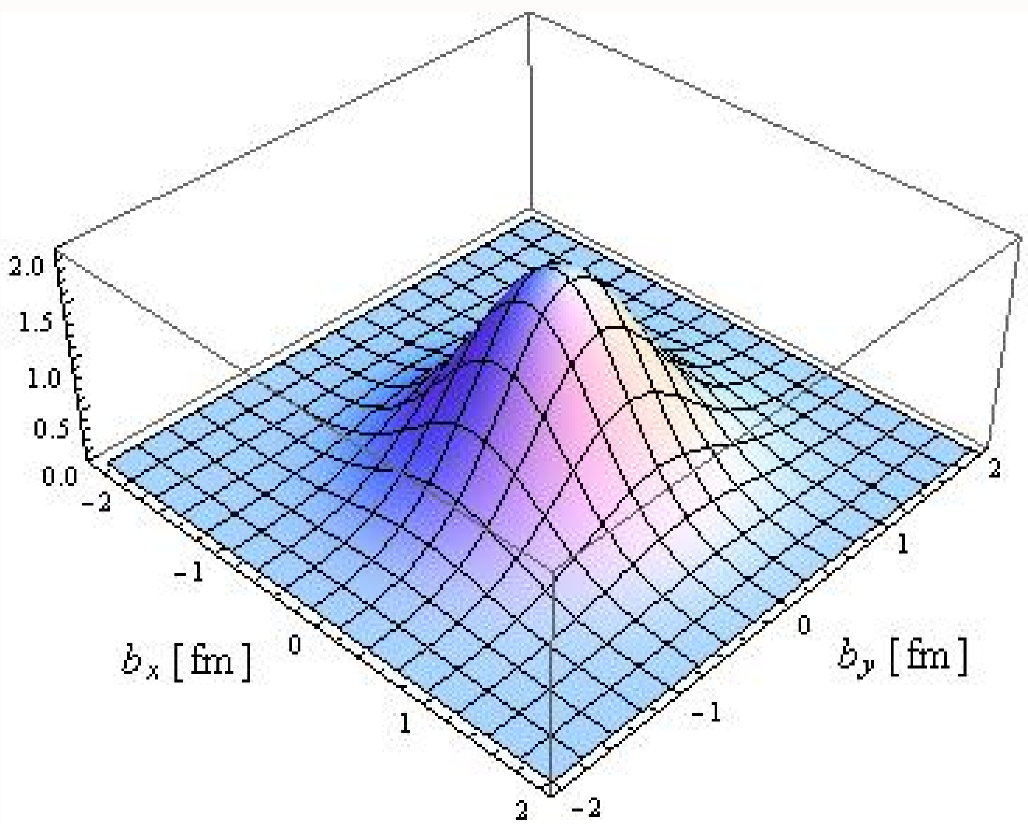
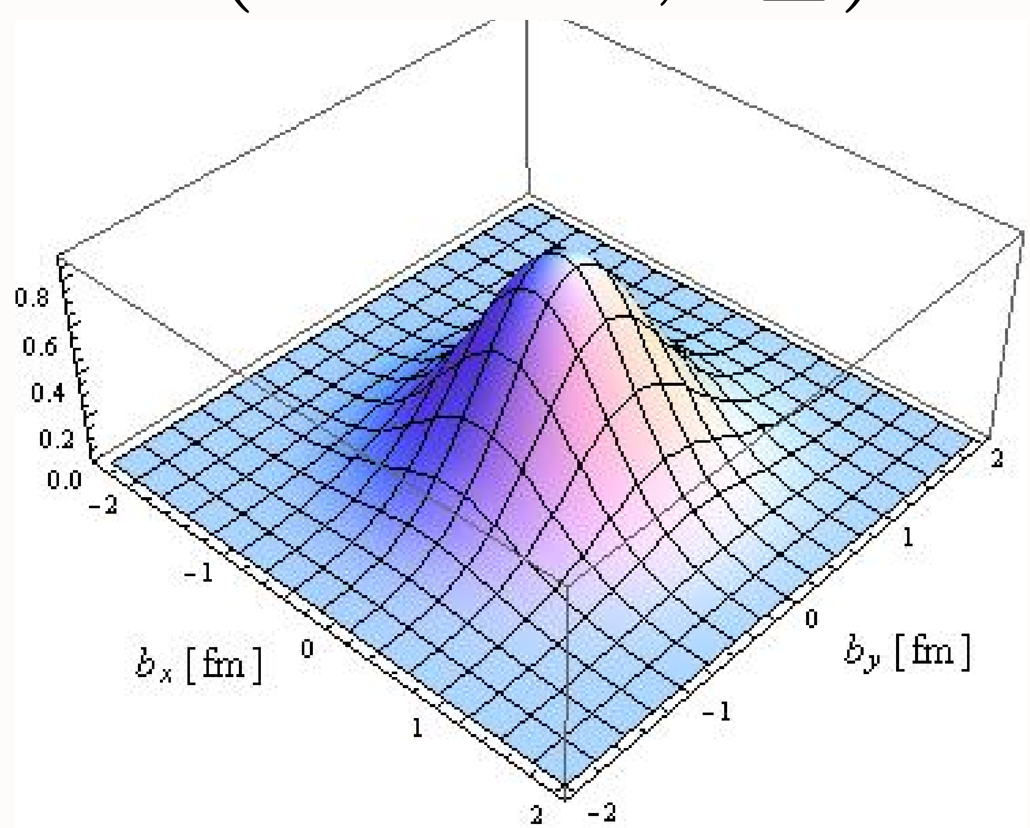
[2] *Institut für Theoretische Physik, Universität Tübingen, Kepler Center for Astro and Particle Physics, Auf der Morgenstelle 14, D–72076 Tübingen, Germany*

(Dated: January 19, 2011)

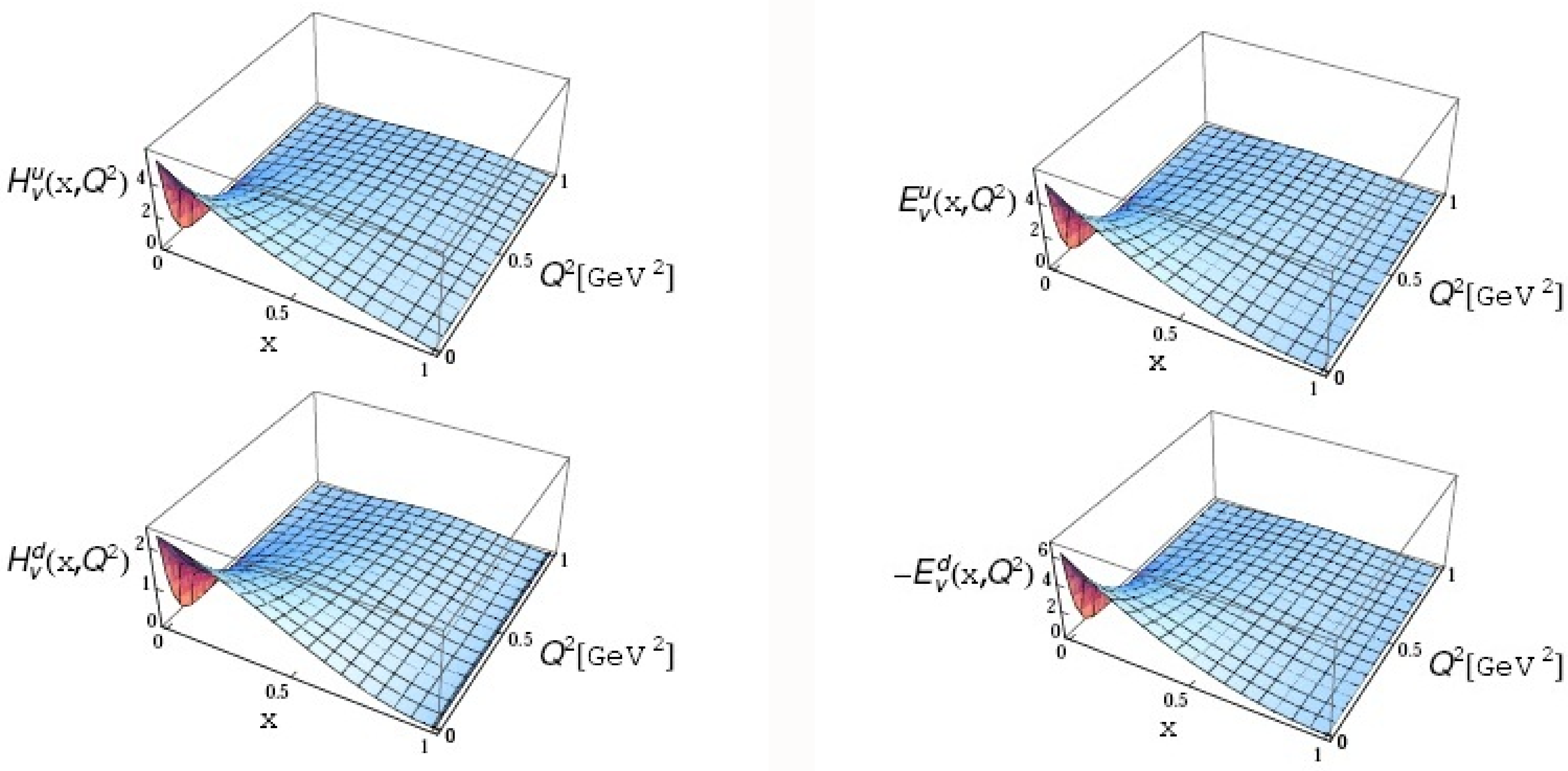
$$u(x = 0.1, \vec{b}_\perp)$$




$$d(x = 0.1, \vec{b}_\perp)$$



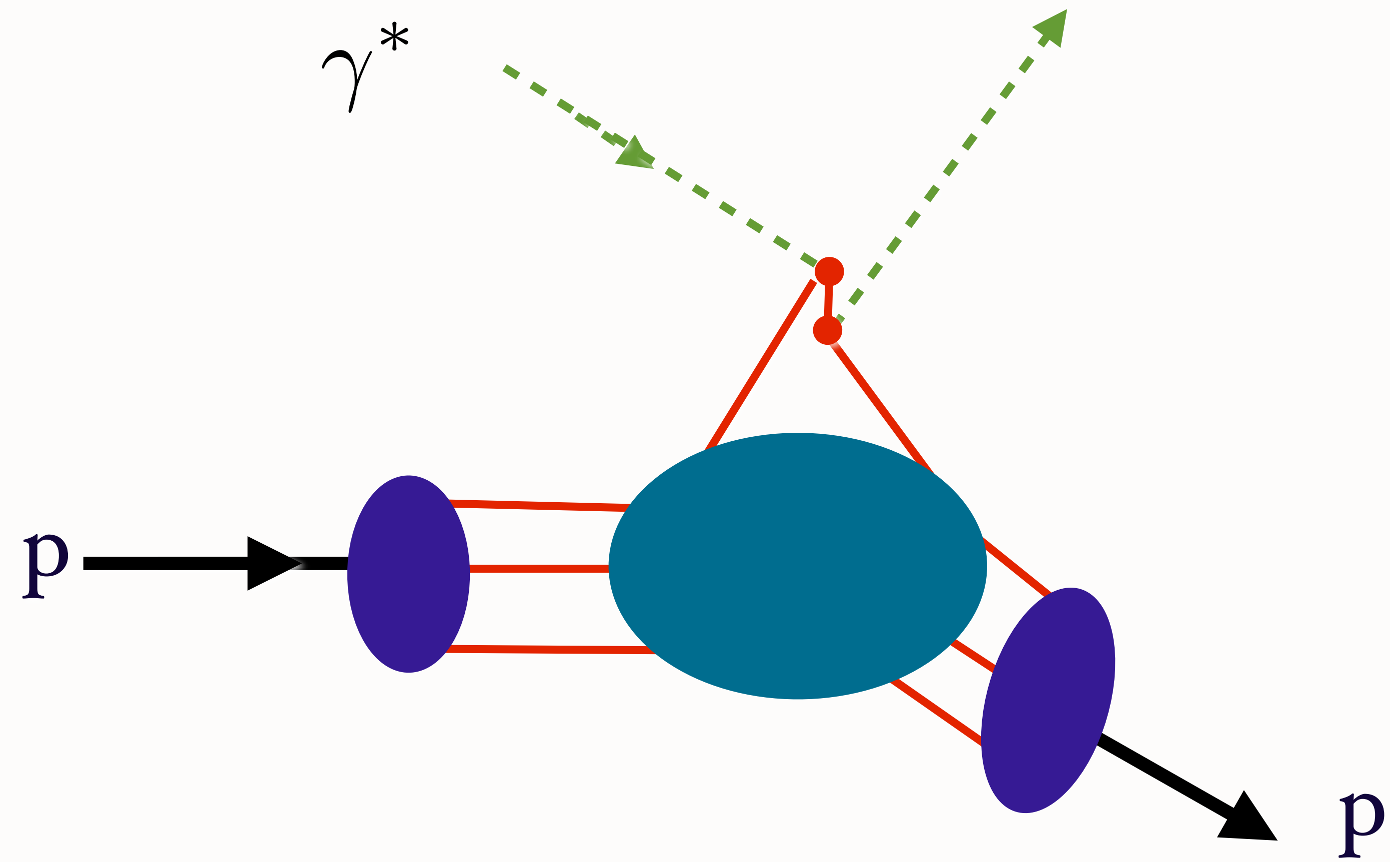
Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt, Alfredo Vega




GPDs $H_v^q(x, Q^2)$ and $E_v^q(x, Q^2)$ calculated in the holographical model.

# Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p$$




*Seagull interaction (instantaneous quark exchange or Z-graph)*

Independent of photon virtuality at fixed t

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

Hard Reggeon Domain

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s_R^{\alpha}(t)\beta_R(t)$$

$$\alpha_R(t) \to 0$$

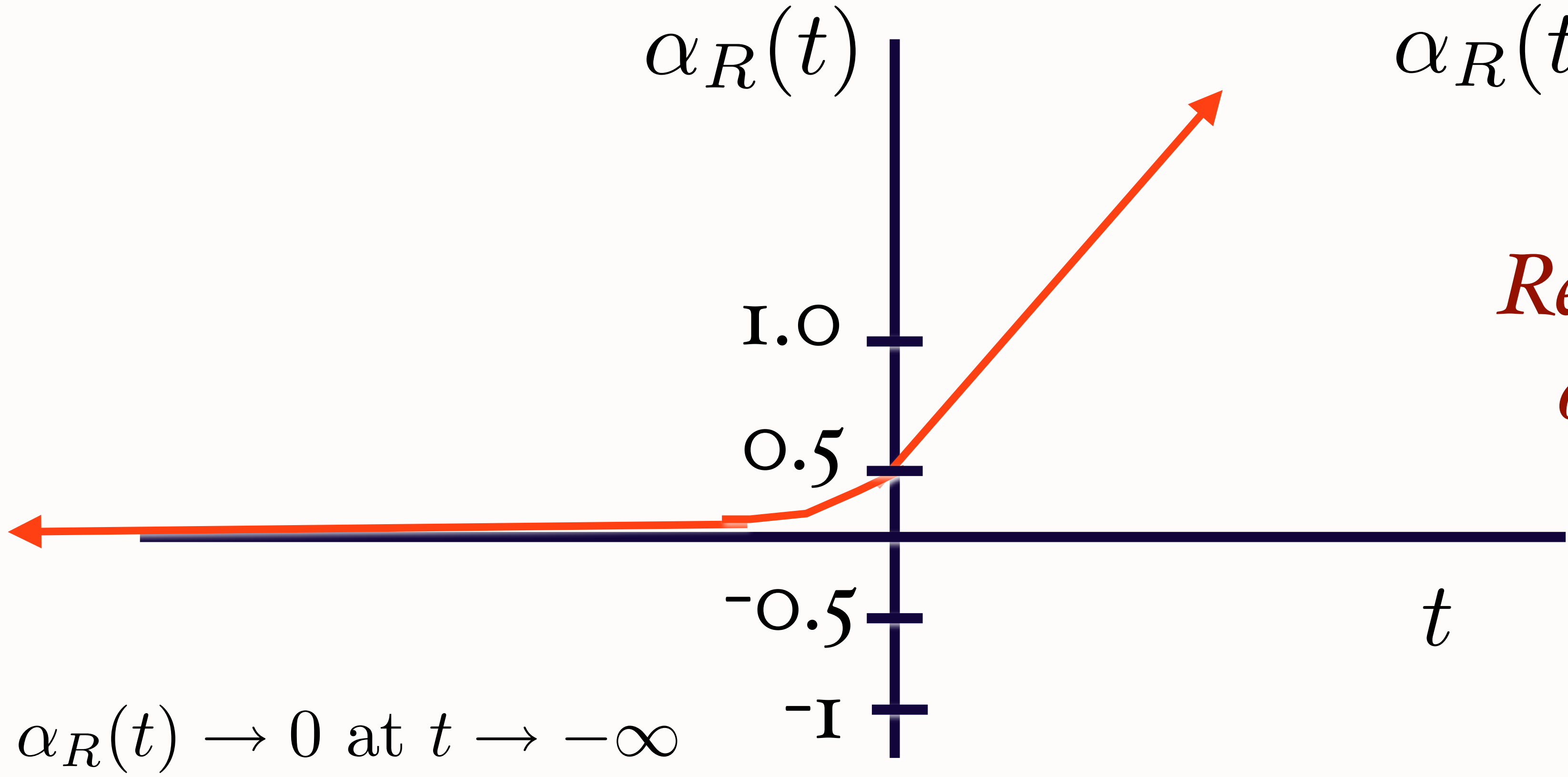
*Reflects elementary coupling of two photons to quarks*

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

# Regge domain

$$T(\gamma^* p \to \gamma p) \sim \sum_R s^{\alpha_R(t)} \beta_R(t) \qquad s >> -t, Q^2$$




$\alpha_R(t) \to 0$ at $t \to -\infty$

J=0 fixed pole

*Reflects elementary coupling of two photons to quarks*

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(\gamma^* p \to \gamma p) \to \frac{1}{s^2}\beta_R^2(t) \sim \frac{1}{s^2 t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{t}{s}, \frac{Q^2}{s}$$

# Fundamental test of QCD

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

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

The Light Front Fock State Wavefunctions

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

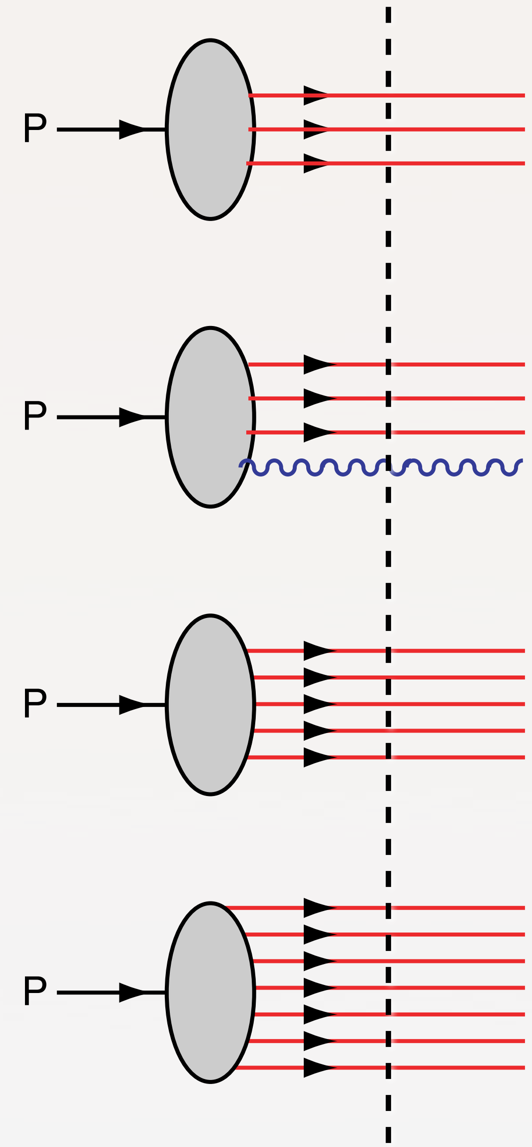
are boost invariant; they are independent of the hadron's energy and momentum $P^\mu$.

The light-cone momentum fraction

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

are boost invariant.

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




*Fixed LF time*

*Coupled. infinite set*

*Intrinsic heavy quarks*

***c(x), b(x) at high x !***

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

**Mueller: gluon Fock states BFKL Pomeron**

*Deuteron: Hidden Color*

# Remarkable Features of Hadron Structure

- Valence quark helicity represents less than half of the proton's spin and momentum
- Significant quark orbital angular momentum!
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$
- Non-symmetric strange and anti-strange sea $\bar{s}(x) \neq s(x)$ $\Delta s(x) \neq \Delta \bar{s}(x)$
- Intrinsic charm and bottom at high x
- Hidden-Color Fock states of the Deuteron

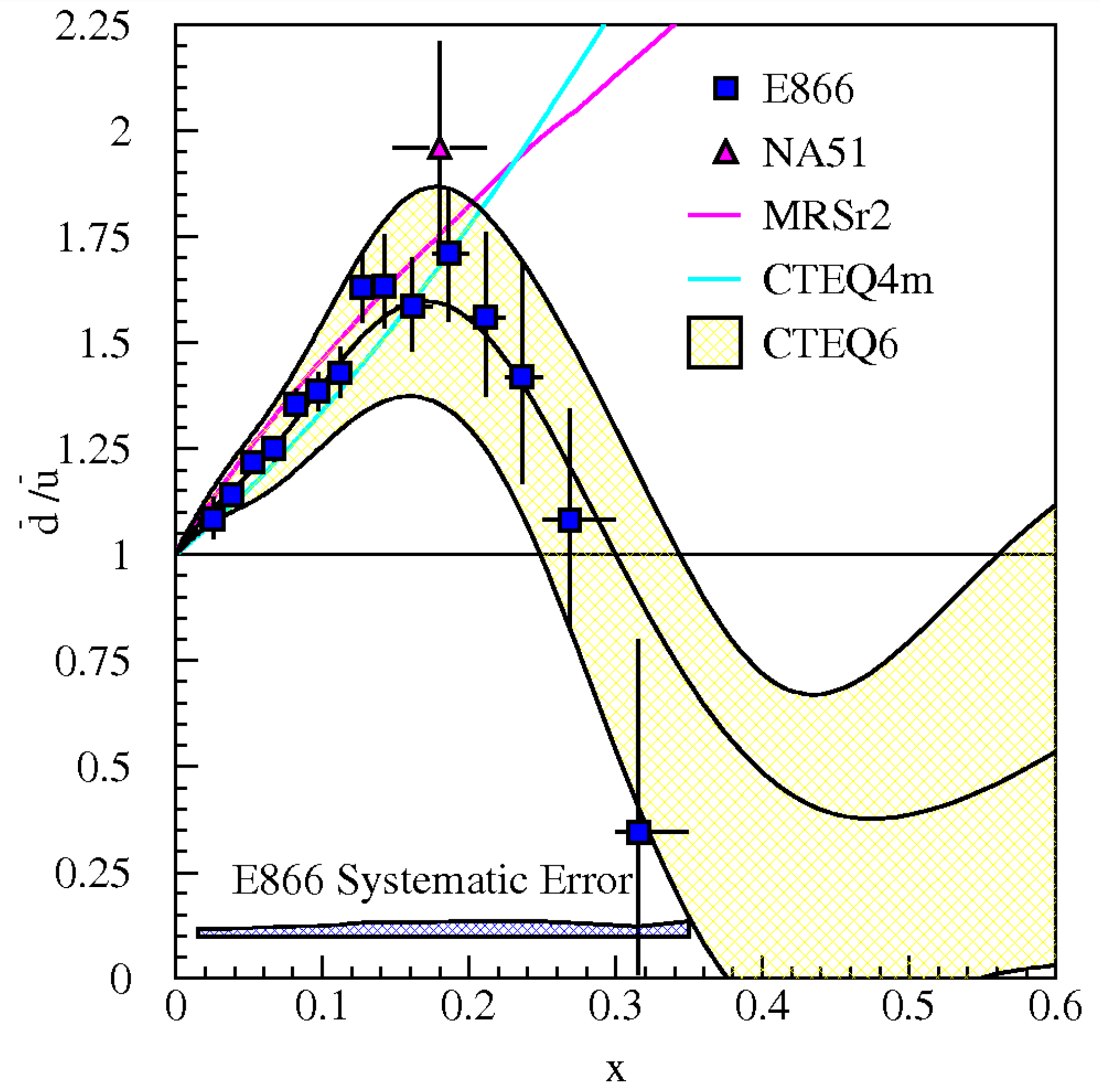
$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$

- E866/NuSea (Drell-Yan)

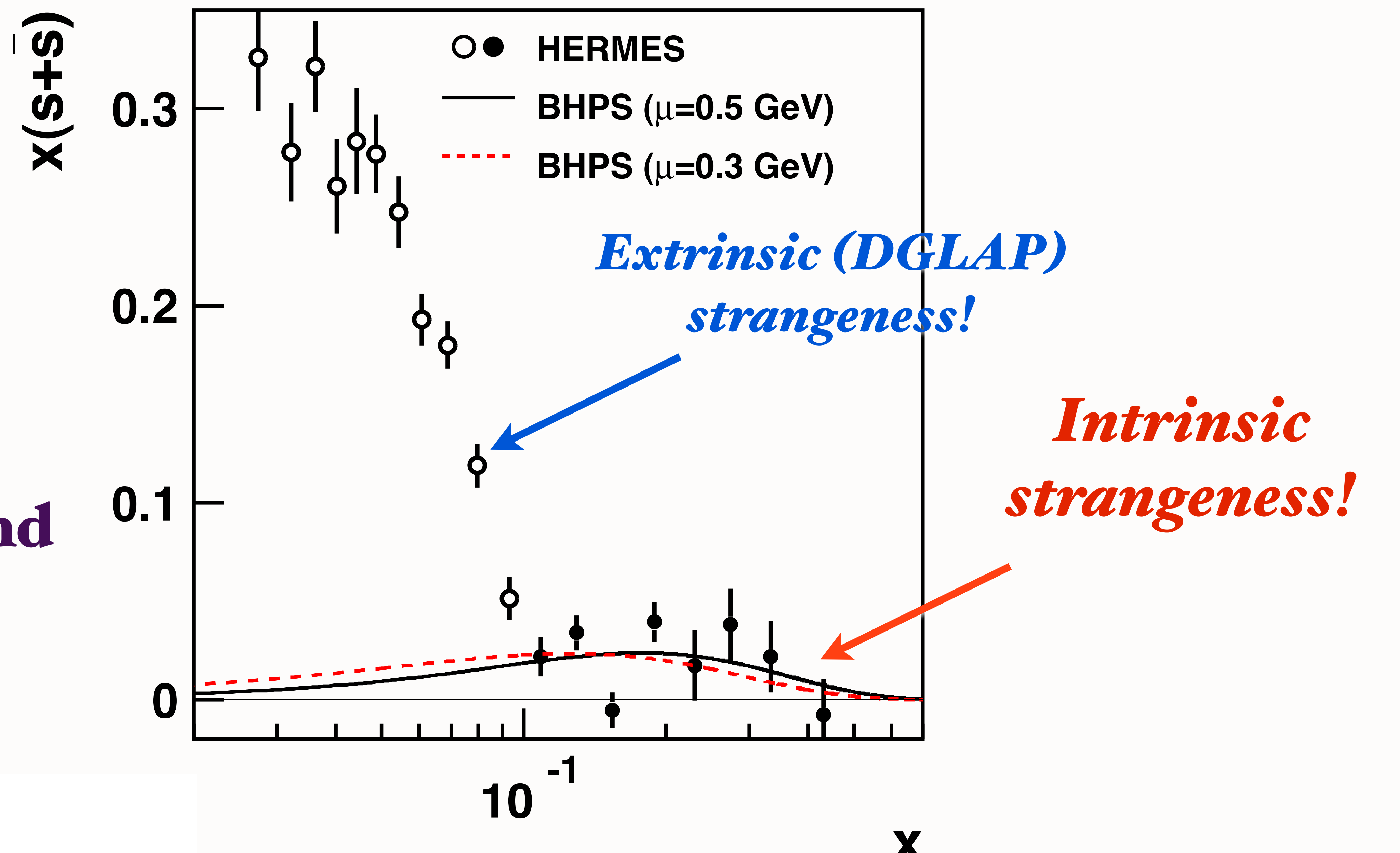
$$\bar{d}(x) \neq \bar{u}(x)$$

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

*Intrinsic glue, sea, heavy quarks*



# HERMES: Two components to $s(x,Q^2)$!

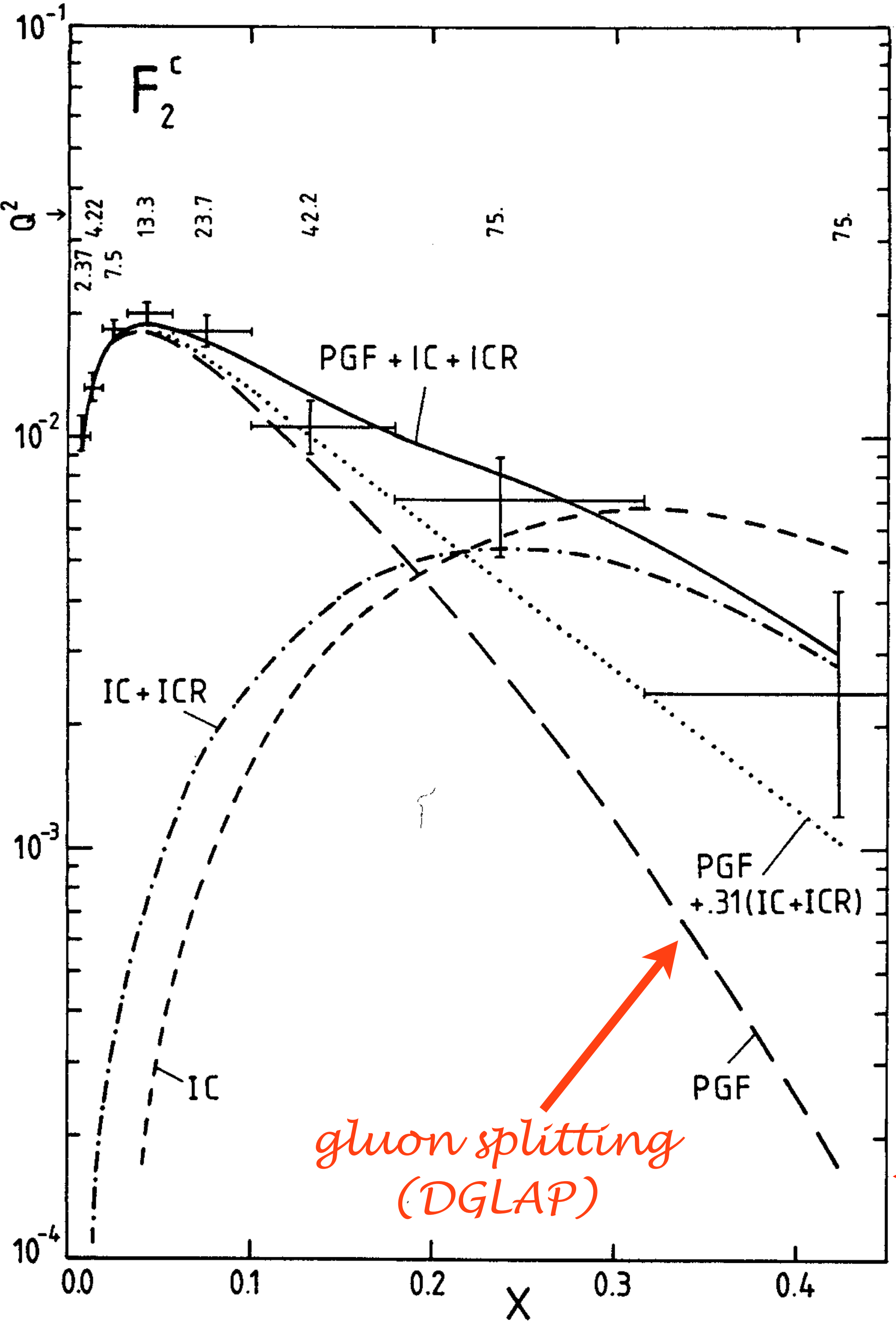



Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV$^2$ using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

**W. C. Chang and J.-C. Peng**

arXiv:1105.2381

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

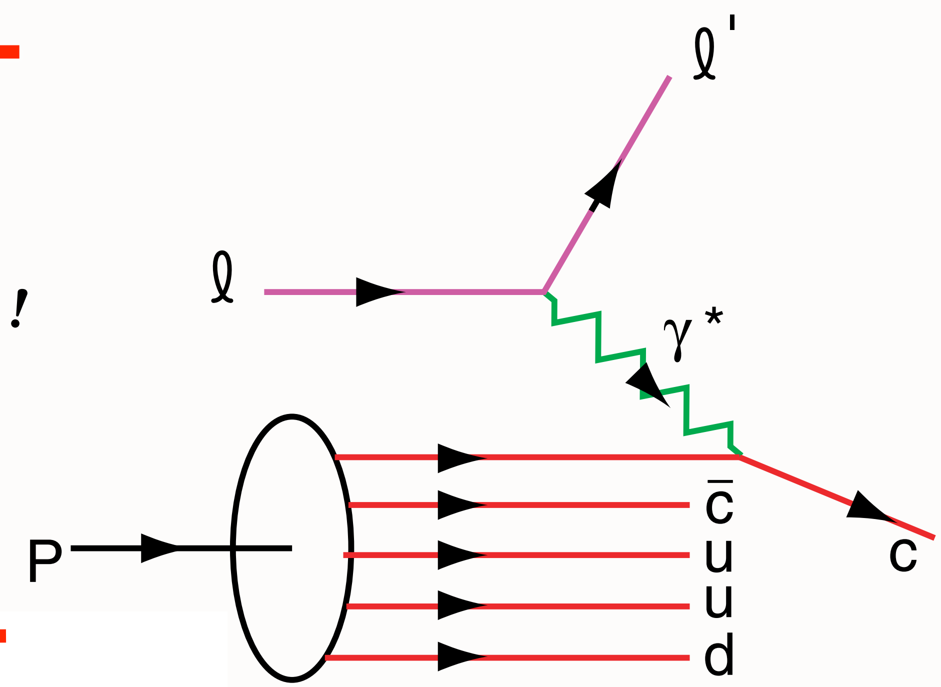



# Measurement of Charm Structure Function

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

## First Evidence for Intrinsic Charm

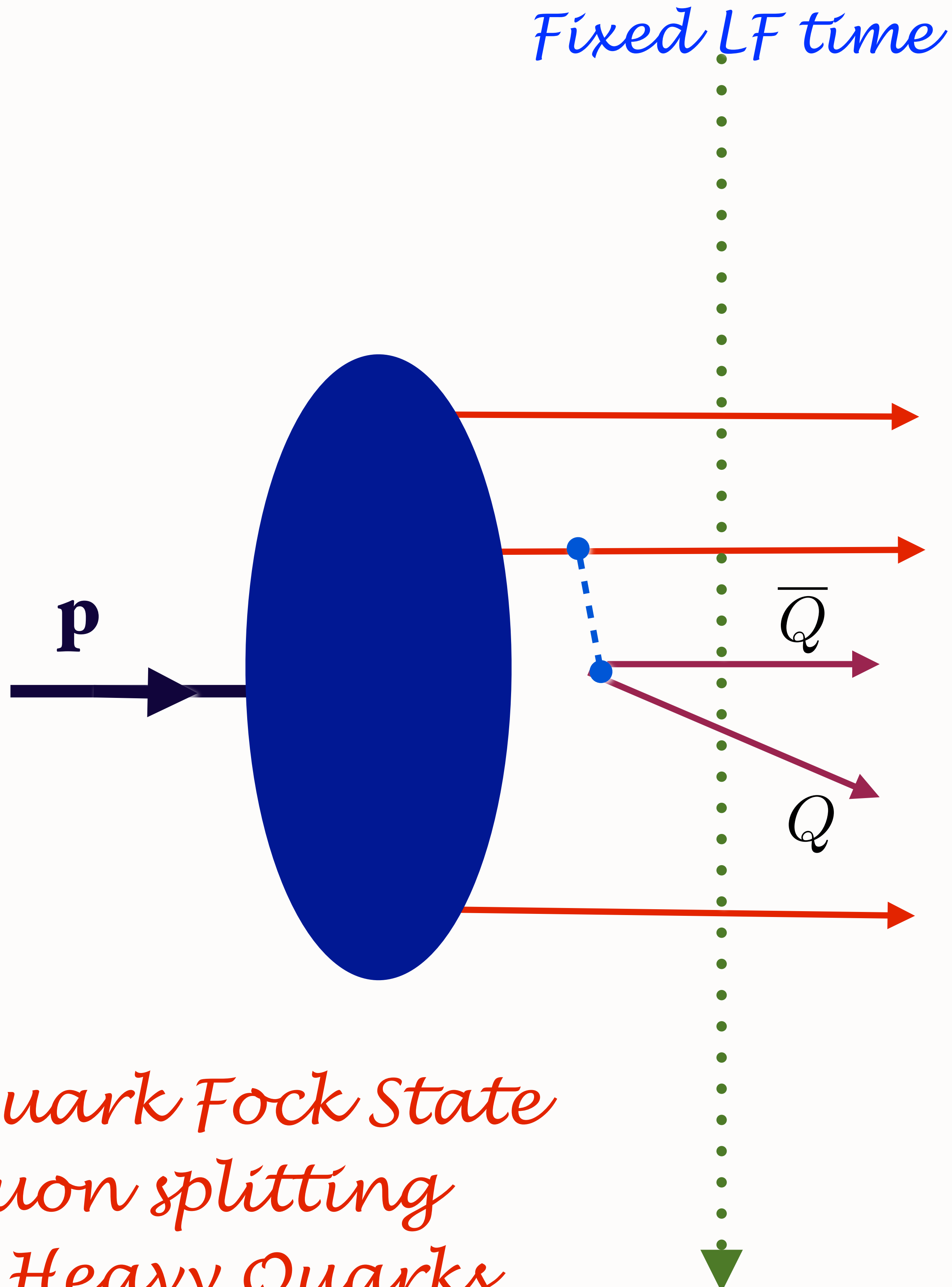
*factor of 30 !*




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

Two Components (separate evolution):

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




Proton 5-quark Fock State
from gluon splitting
Extrinsic Heavy Quarks

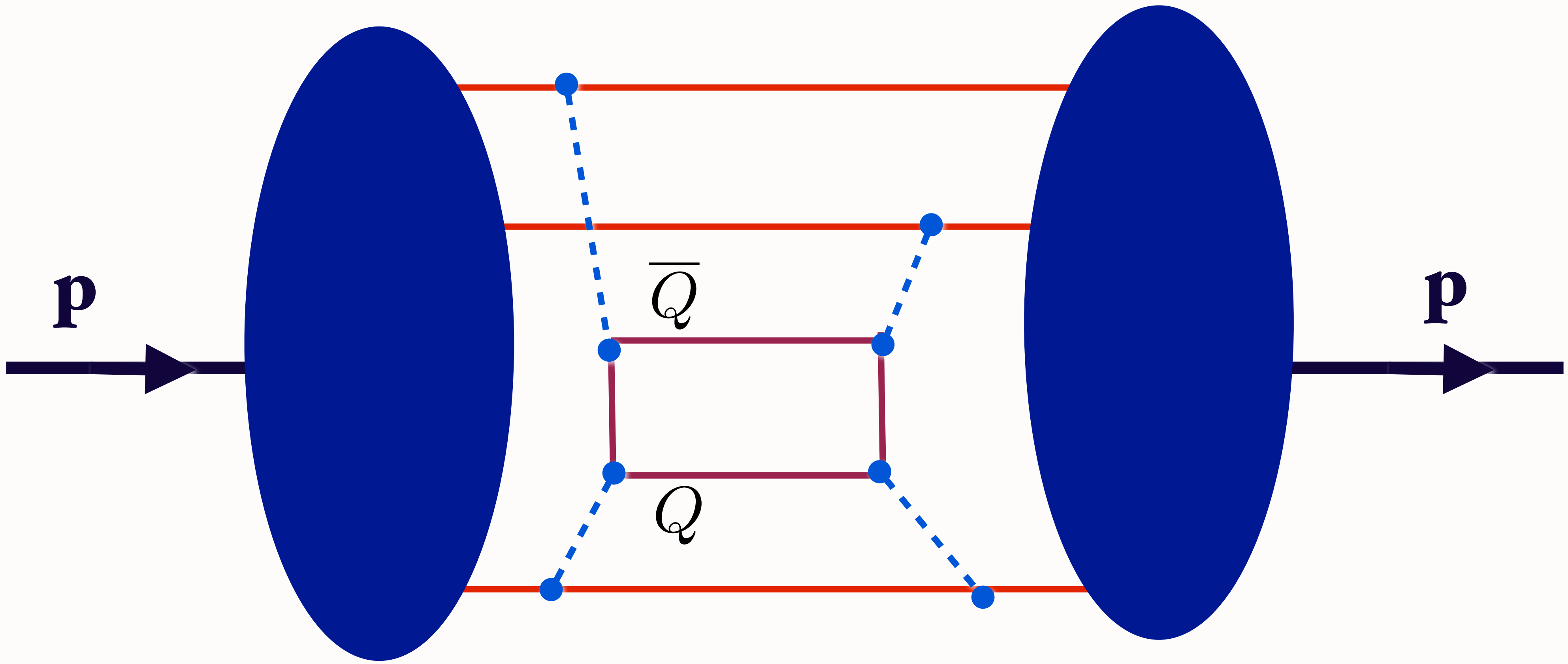
$$c(x, Q^2)_{\text{extrinsic}} \sim (1-x)g(x, Q^2) \sim (1-x)^5$$

# Proton Self Energy

*QCD predicts*

*Intrinsic Heavy Quarks!*

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

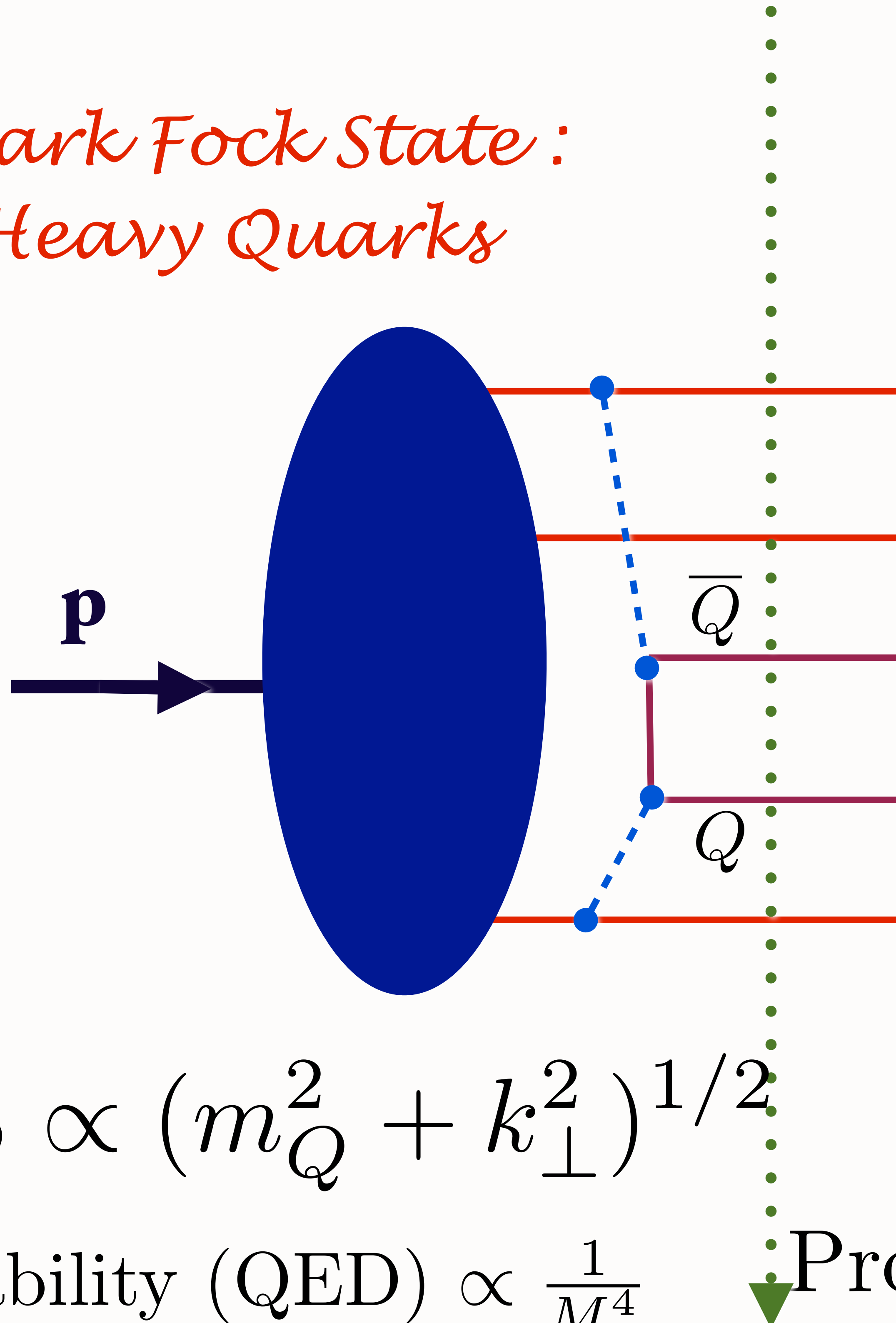



$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

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

Fixed LF time

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



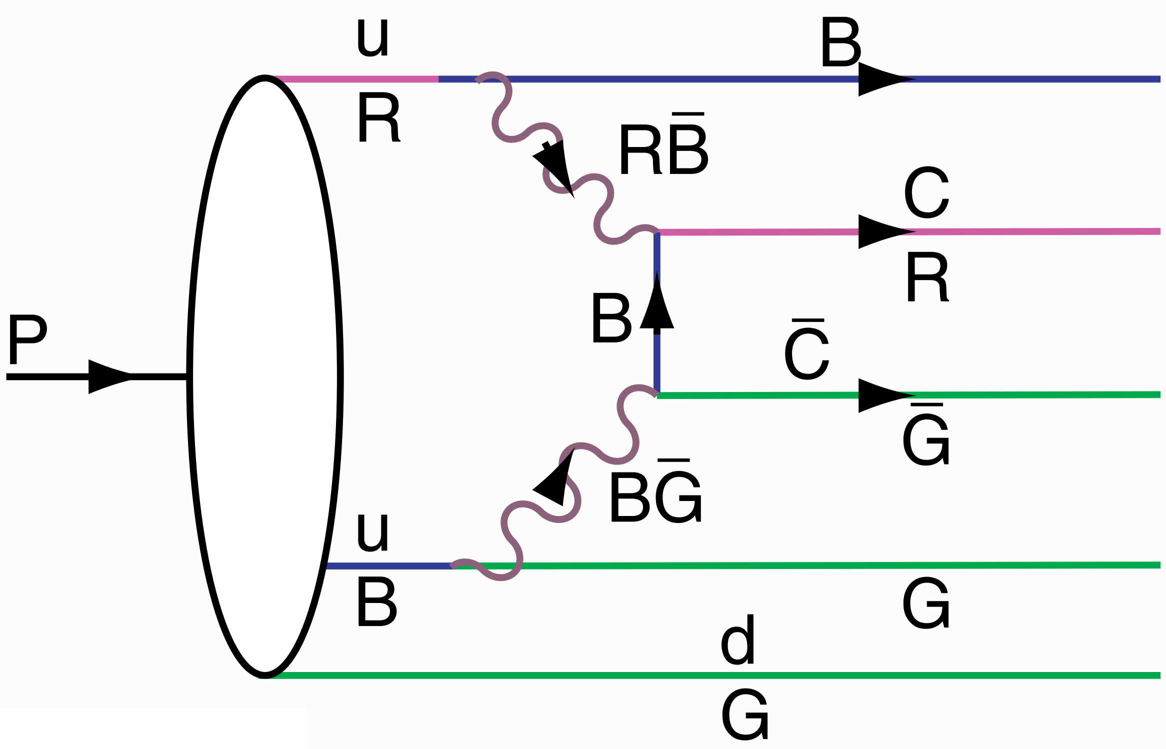

QCD predicts Intrinsic Heavy Quarks at high x!

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

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

**Collins, Ellis, Gunion, Mueller, sjb**
**M. Polyakov**

BHPS: Hoyer, Peterson, Sakai, sjb




$|uudc\bar{c}>$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^->$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

$c\bar{c}$ in Color Octet

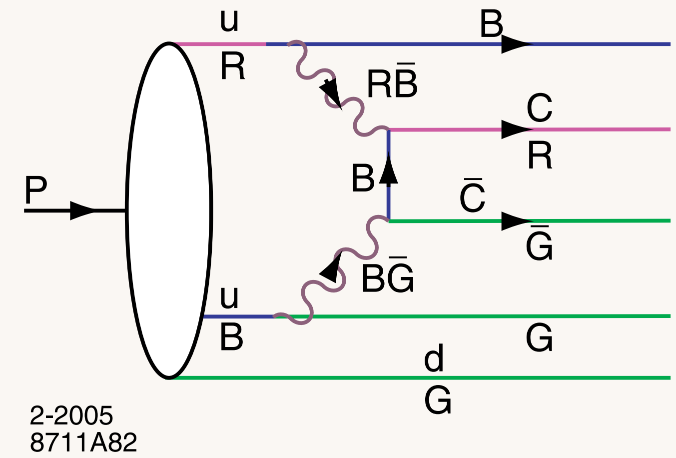
Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

*High x charm!* *Charm at Threshold*

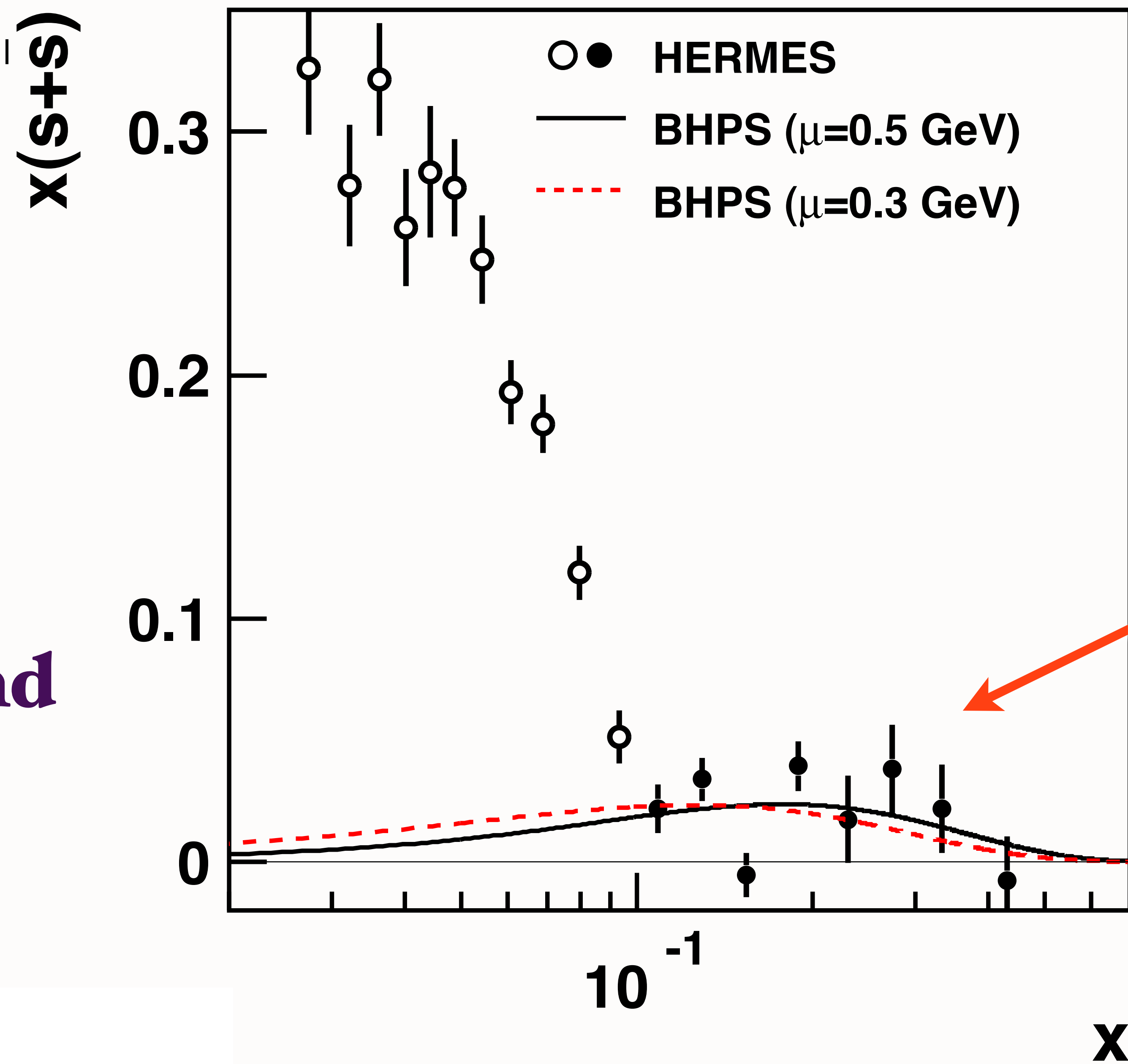
**Action Principle: Minimum KE, maximal potential**

# Intrinsic Heavy-Quark Fock States




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

# HERMES: Two components to s(x,Q²)!




*Intrinsic strangeness!*

**W. C. Chang and J.-C. Peng**

arXiv:1105.2381

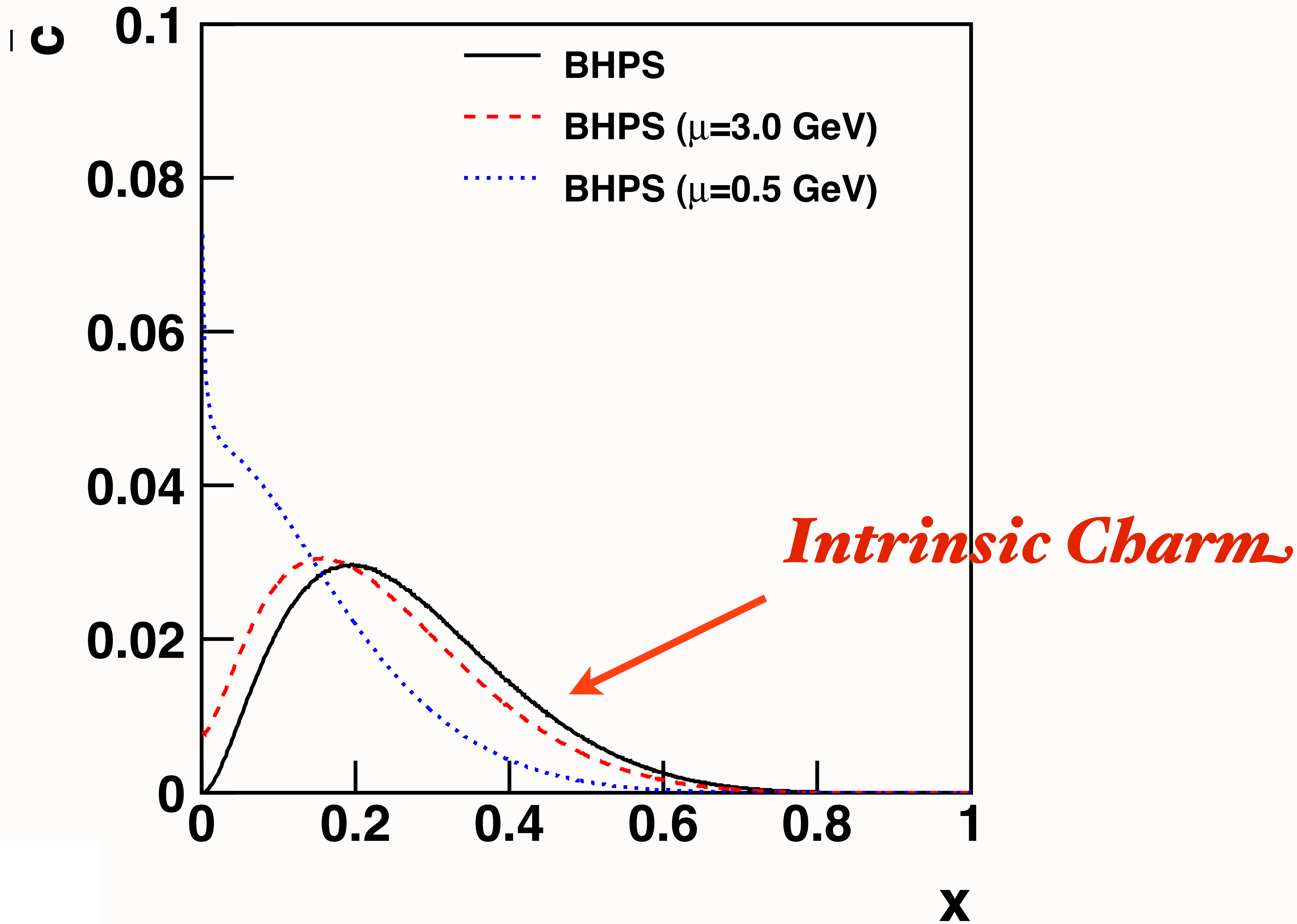
Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV$^2$ using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

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

# Scale intrinsic strangeness by $\frac{1}{m_Q^2}$

W. C. Chang
J.-C. Peng

arXiv:1105.2381

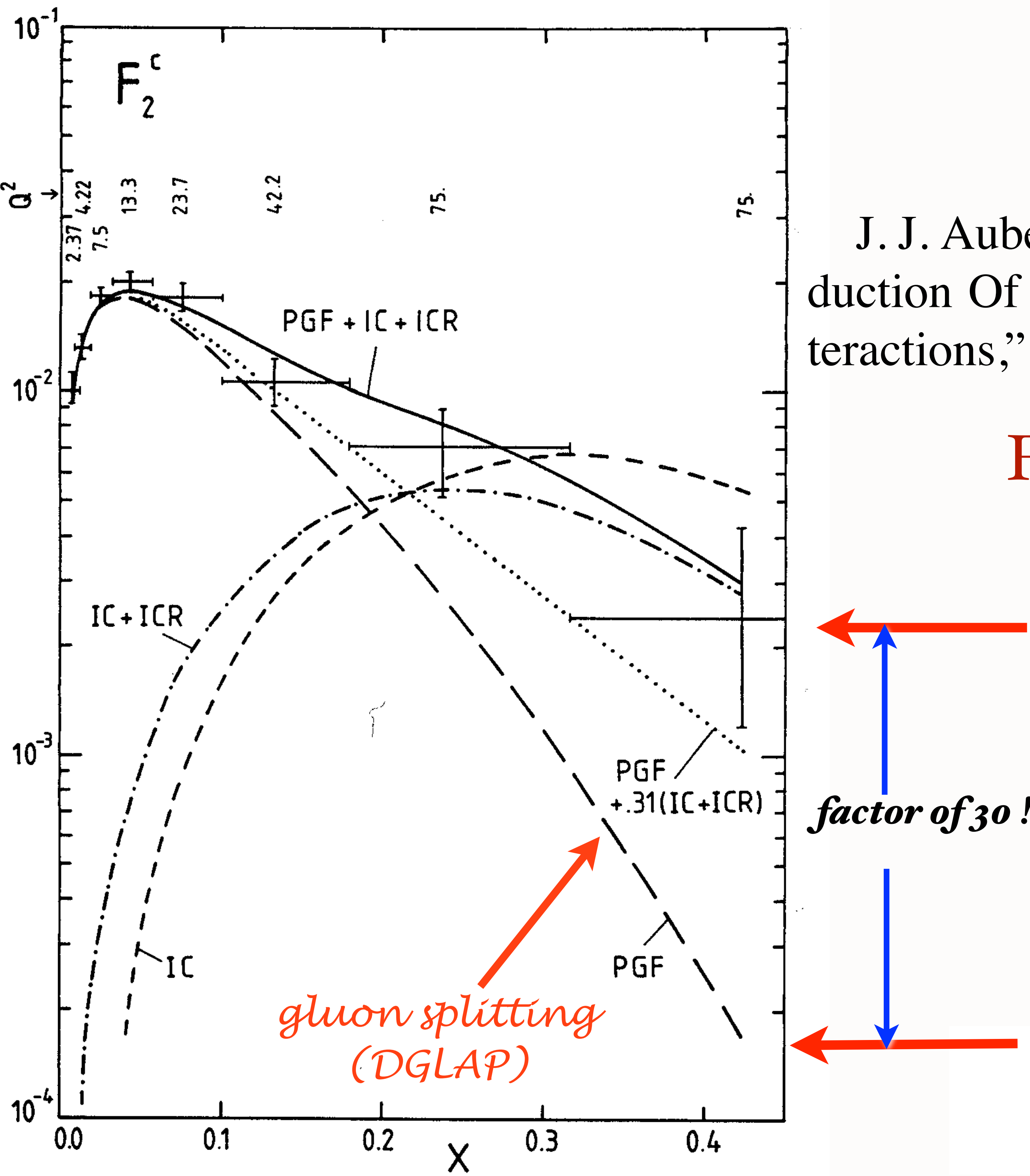


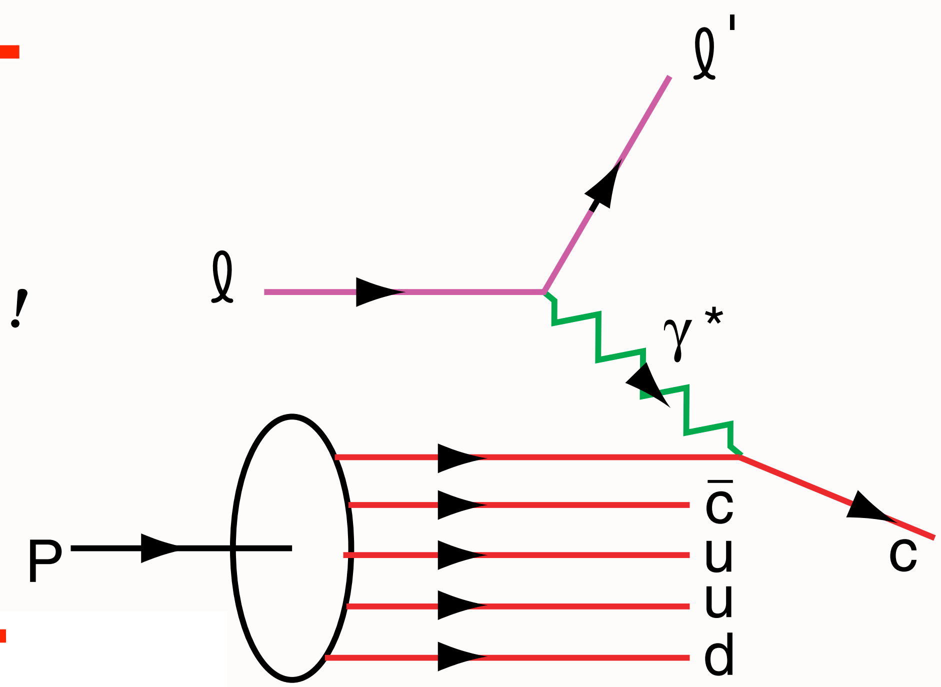

Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 75$ GeV$^2$ using $\mu = 3.0$ GeV, and $\mu = 0.5$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.

# Measurement of Charm Structure Function

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

## First Evidence for Intrinsic Charm

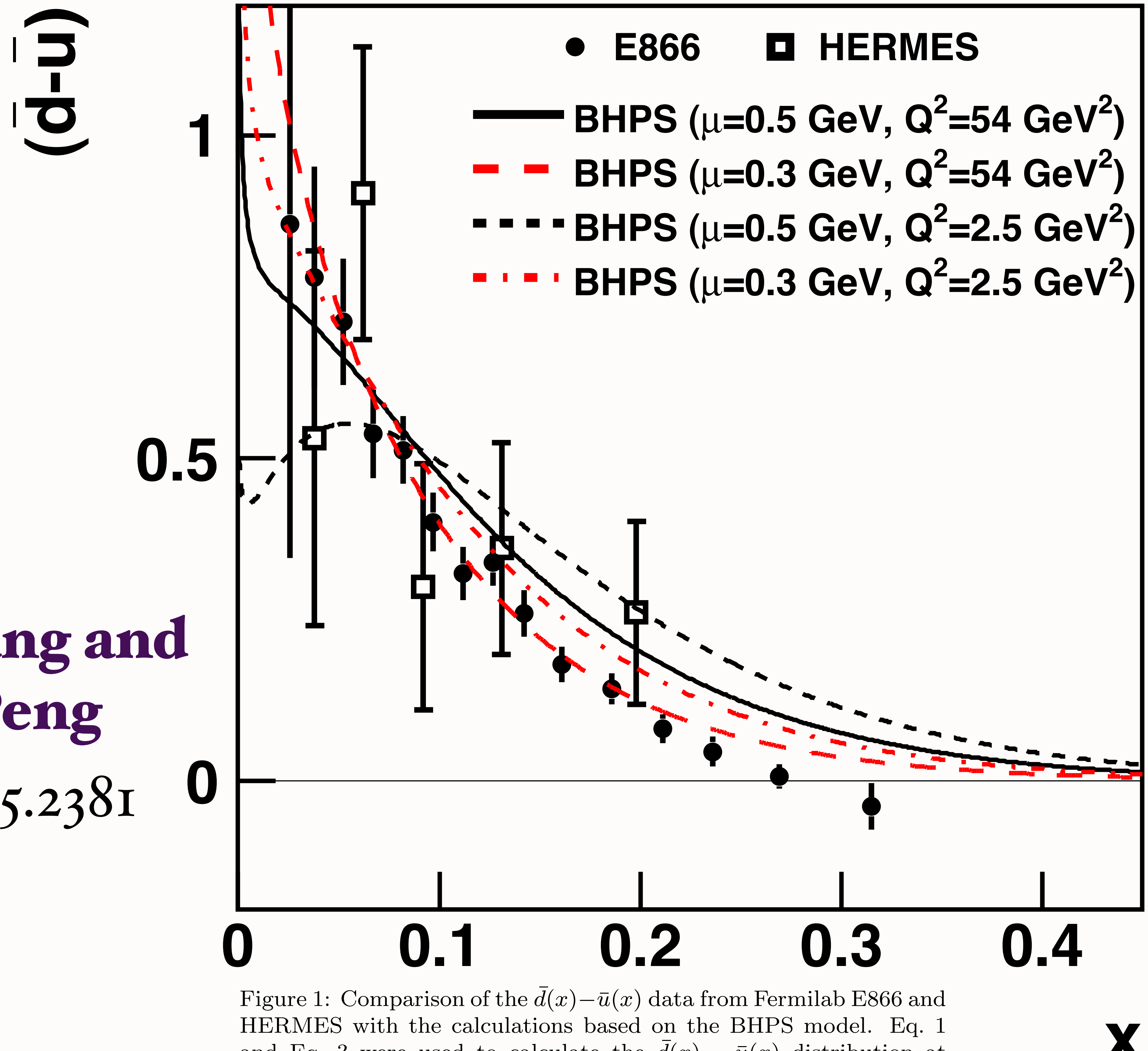



***DGLAP / Photon-Gluon Fusion: factor of 30 too small***

*Two Components (separate evolution):*

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




**W. C. Chang and J.-C. Peng**

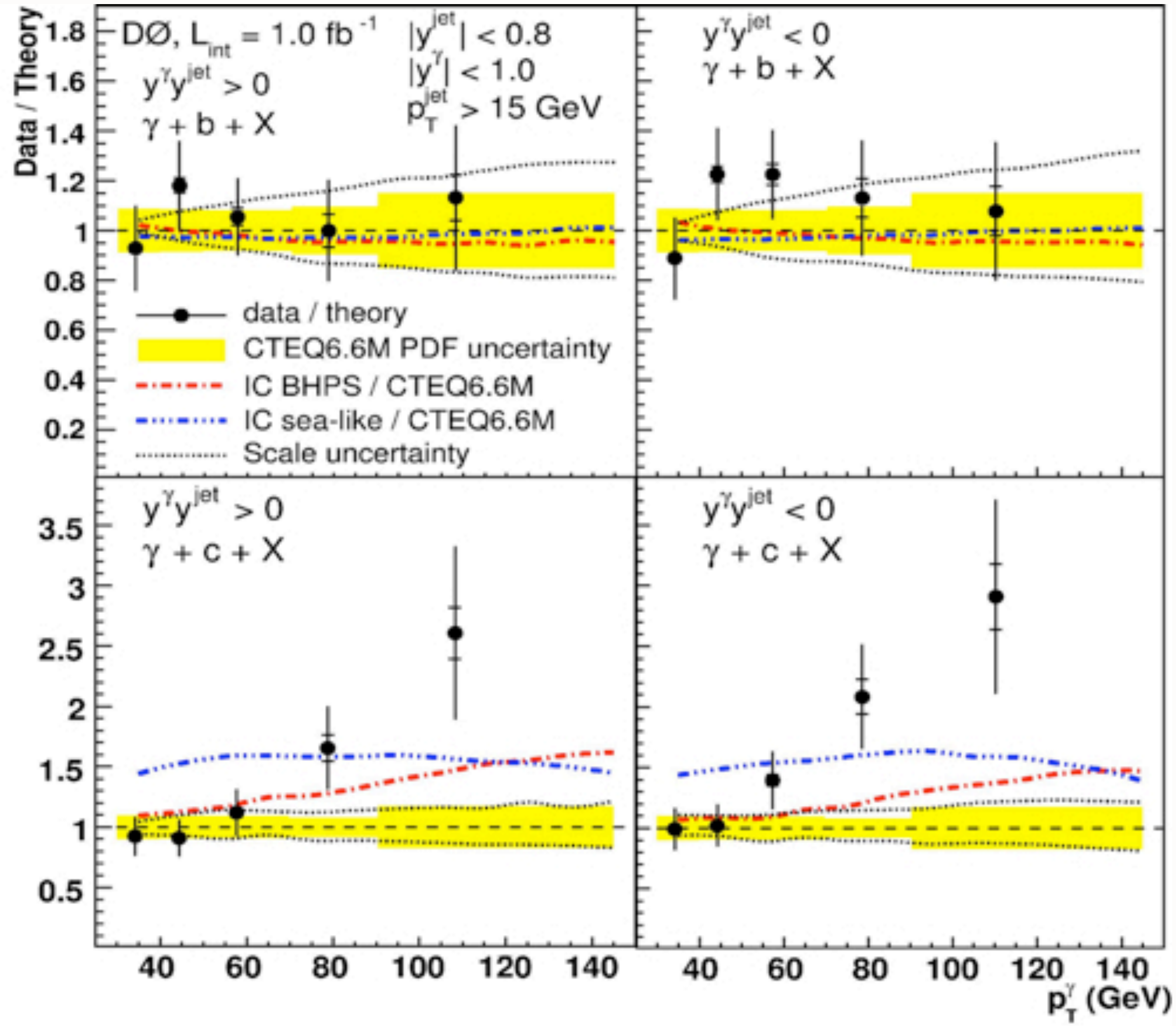
arXiv:1105.2381

Figure 1: Comparison of the $\bar{d}(x)-\bar{u}(x)$ data from Fermilab E866 and HERMES with the calculations based on the BHPS model. Eq. 1 and Eq. 3 were used to calculate the $\bar{d}(x)-\bar{u}(x)$ distribution at the initial scale. The distribution was then evolved to the $Q^2$ of the experiments and shown as various curves. Two different initial scales, $\mu = 0.5$ and 0.3 GeV, were used for the E866 calculations in order to illustrate the dependence on the choice of the initial scale.

# DO

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

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




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

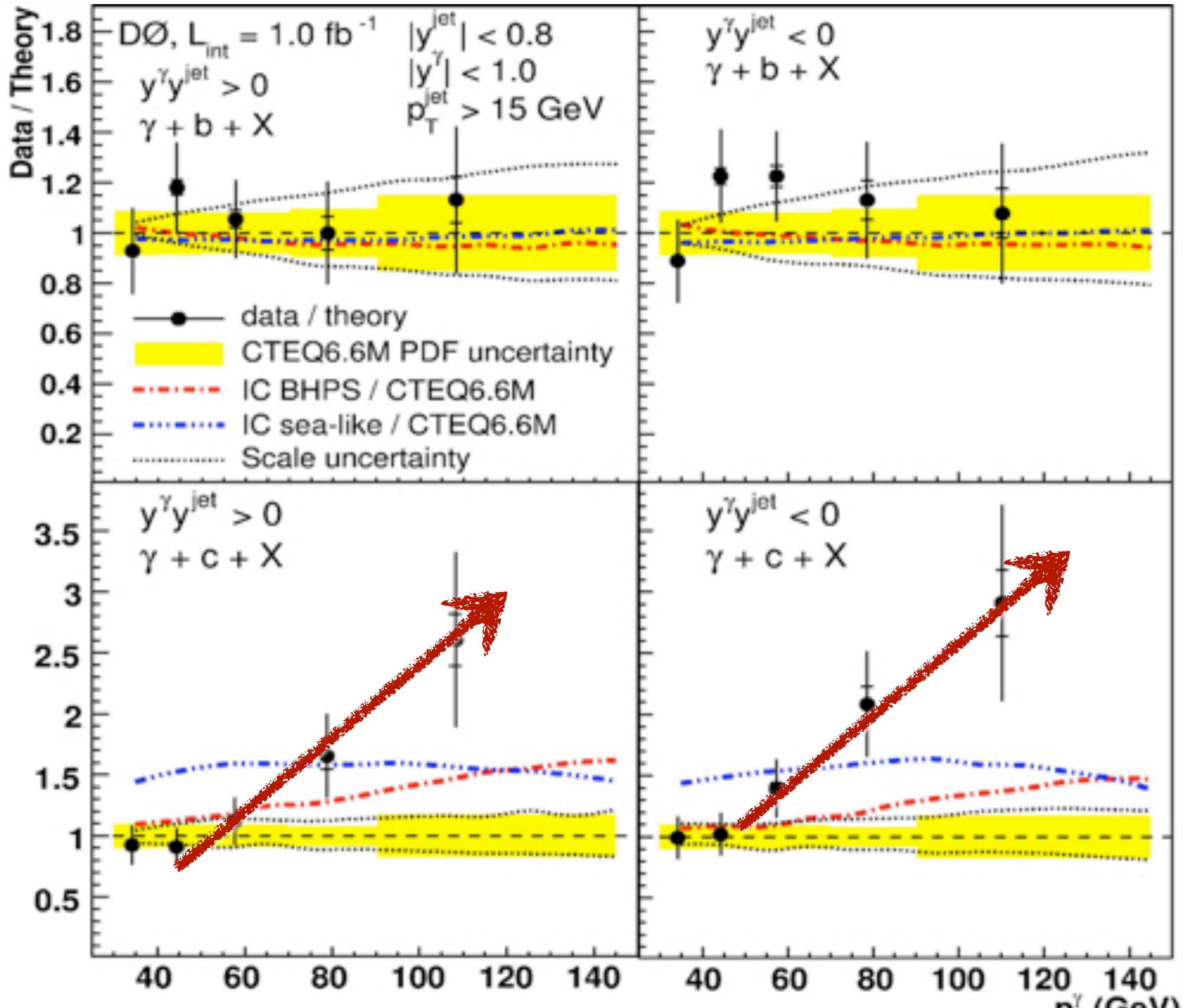
**Ratio is insensitive to gluon PDF, scales**

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

D0

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

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




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

**Ratio is insensitive to gluon PDF, scales**

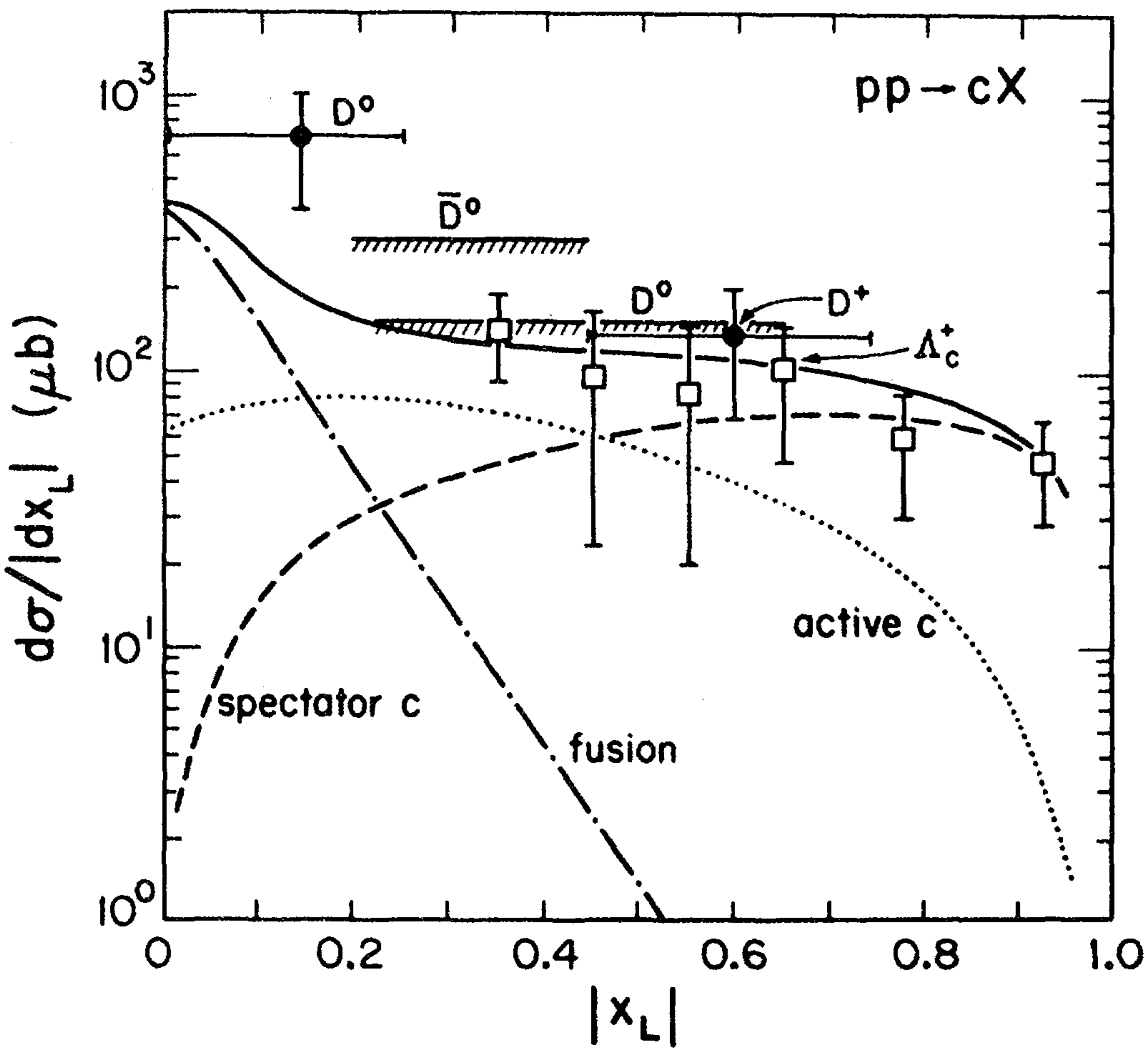
$$gc \to \gamma c$$

**Signal for significant intrinsic charm at x > 0.1 ?**

*Two Components (separate evolution):*

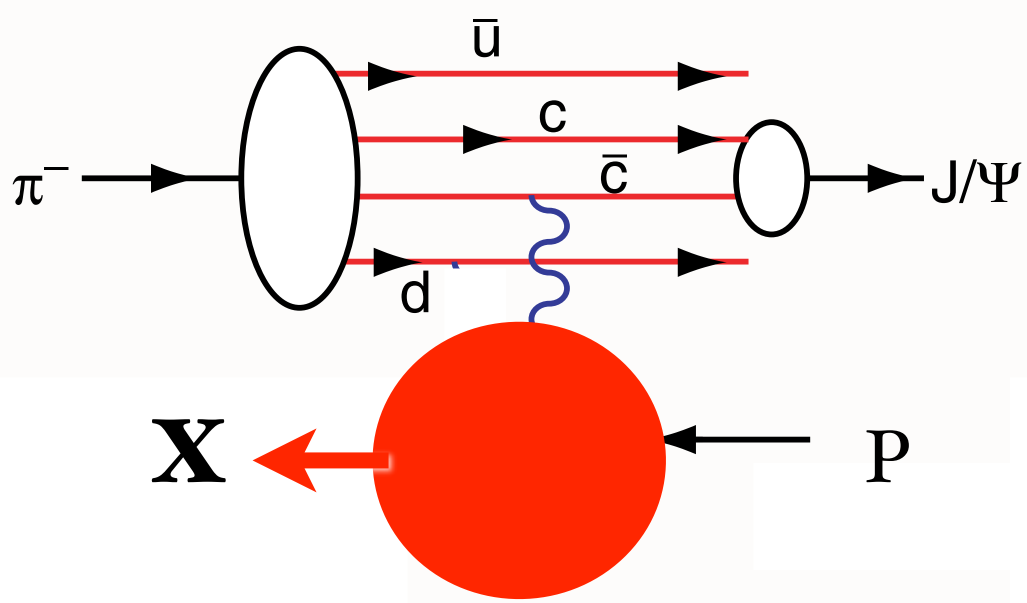
$$c(x, Q^2) = c(x, Q^2)_{\rm extrinsic} + c(x, Q^2)_{\rm intrinsic}$$

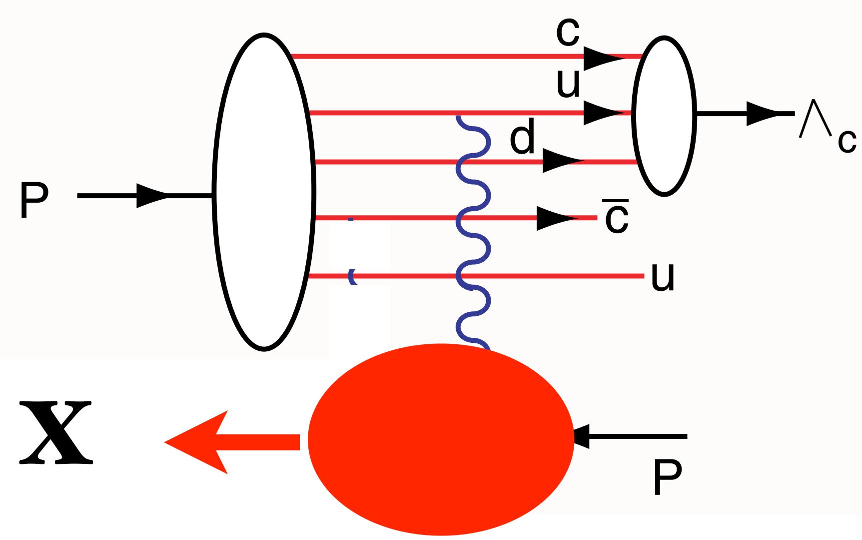
**Need better treatment of DGLAP for intrinsic heavy quarks!**




# Barger, Halzen, Keung

# Leading Hadron Production from Intrinsic Charm




Coalescence of Comoving Charm and Valence Quarks Produce $J/\psi$, $\Lambda_c$ and other Charm Hadrons at High $x_F$

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

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

**CERN NA3**

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

- High $x_F$ $pp \to \Lambda_c X$

**ISR**

- High $x_F$ $pp \to \Lambda_b X$

**Intrinsic Bottom!**
**Zichichi, Cifarelli, et al.**

- High $x_F$ $pp \to \Xi(ccd)X$ (SELEX)

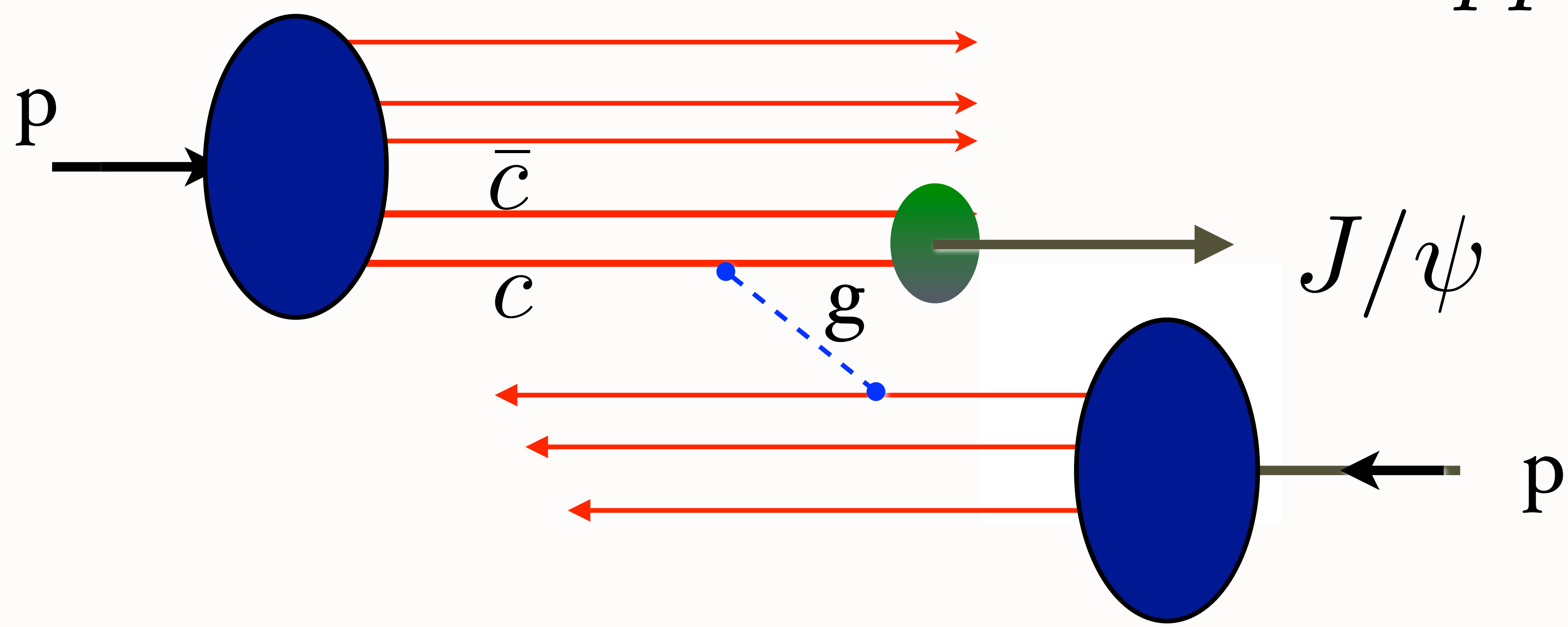
**FermiLab**

**IC Structure Function: Critical Measurement for EIC**

**Many interesting spin, charge asymmetry, spectator effects**

# Intrinsic Charm Mechanism for Inclusive High-$X_F$ Quarkonium Production

$$pp \to J/\psi X$$



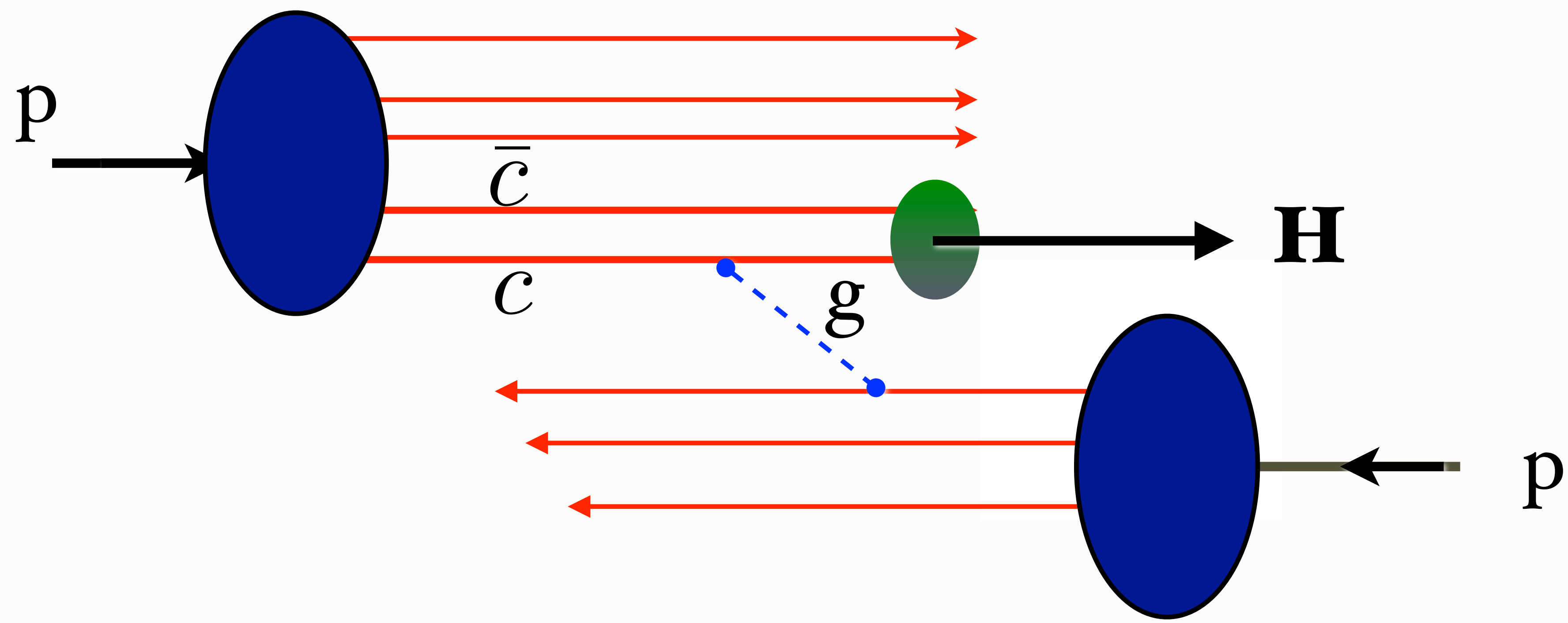

Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

**Quarkonia can have 80% of Proton Momentum!**

*Color-octet IC interacts at front surface of nucleus*

**IC can explains large excess of quarkonia at large $x_F$, A-dependence**

# *Intrinsic Charm Mechanism for Inclusive High-$X_F$ Higgs Production*




$$pp \to HX$$

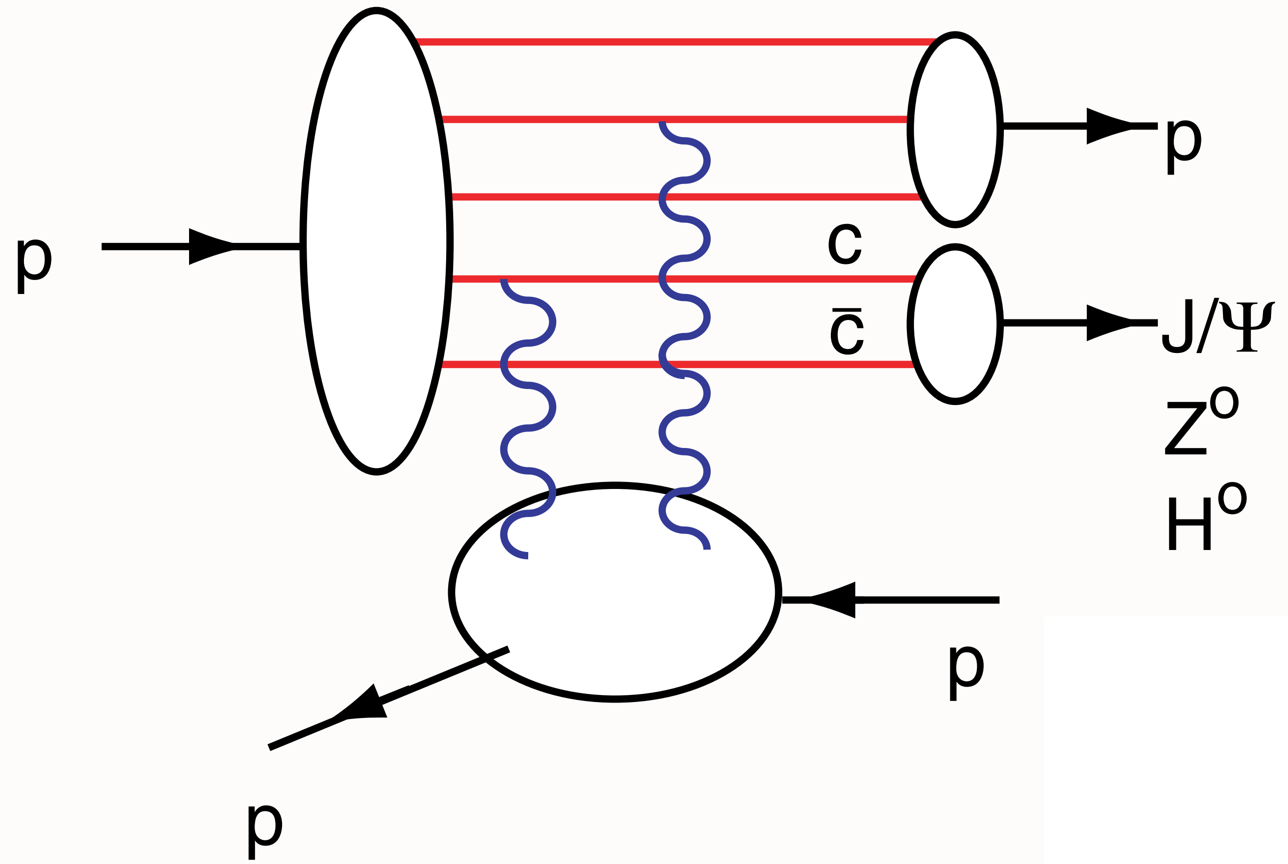
*Goldhaber, Kopeliovich, Schmidt, sjb*

**Also: intrinsic bottom, top**

**Higgs can have 80% of Proton Momentum!**

*New search strategy for Higgs*

# Intrinsic Charm Mechanism for Exclusive Diffraction Production




$$\mathrm{p\,p} \to J/\psi\; p\; p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

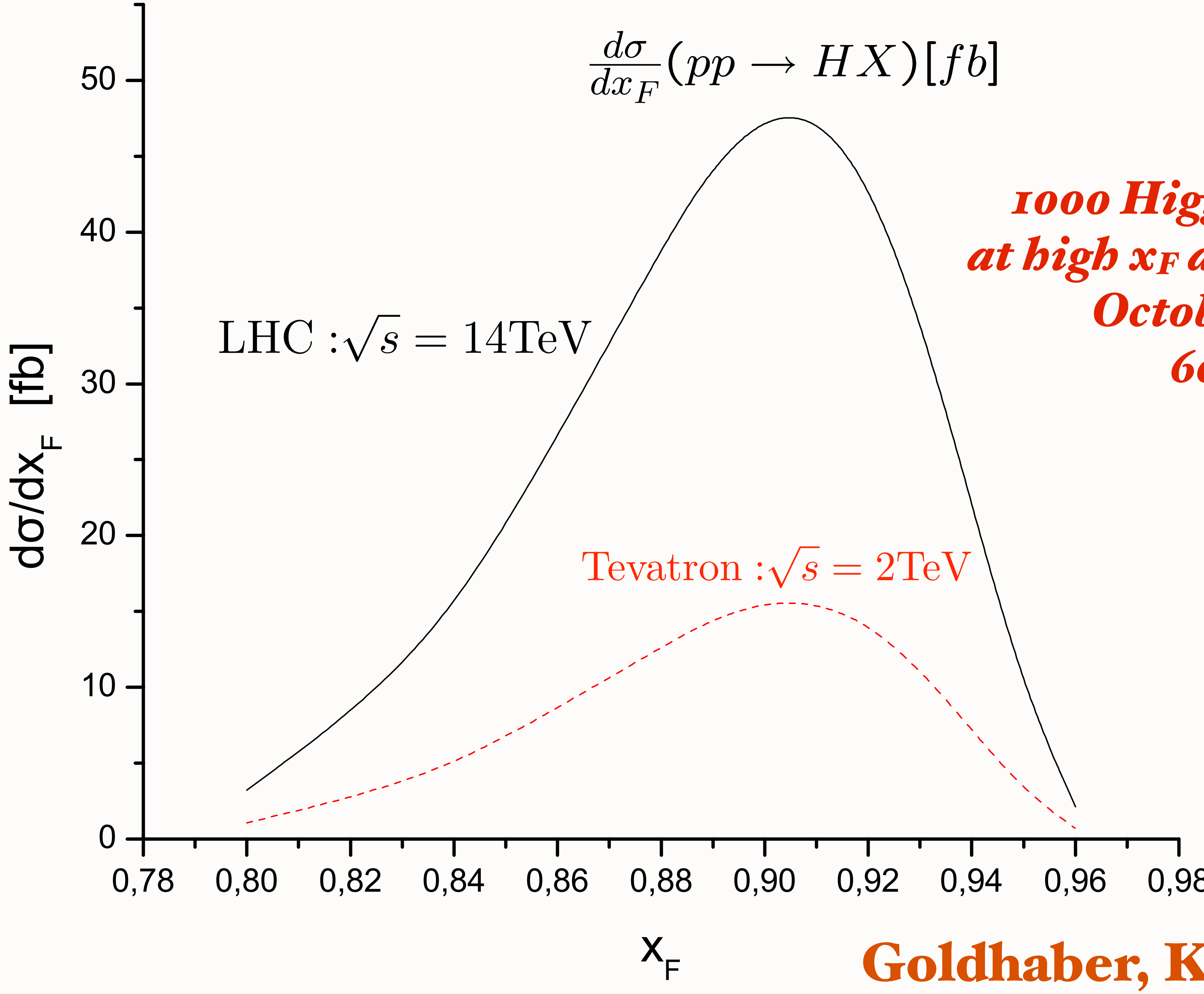
**Exclusive Diffractive**
**High-$X_F$ Higgs Production**

*Kopeliovitch, Schmidt, Soffer, sjb*

Intrinsic $c\bar{c}$ pair formed in color octet $8_C$ in proton wavefunction    Large Color Dipole

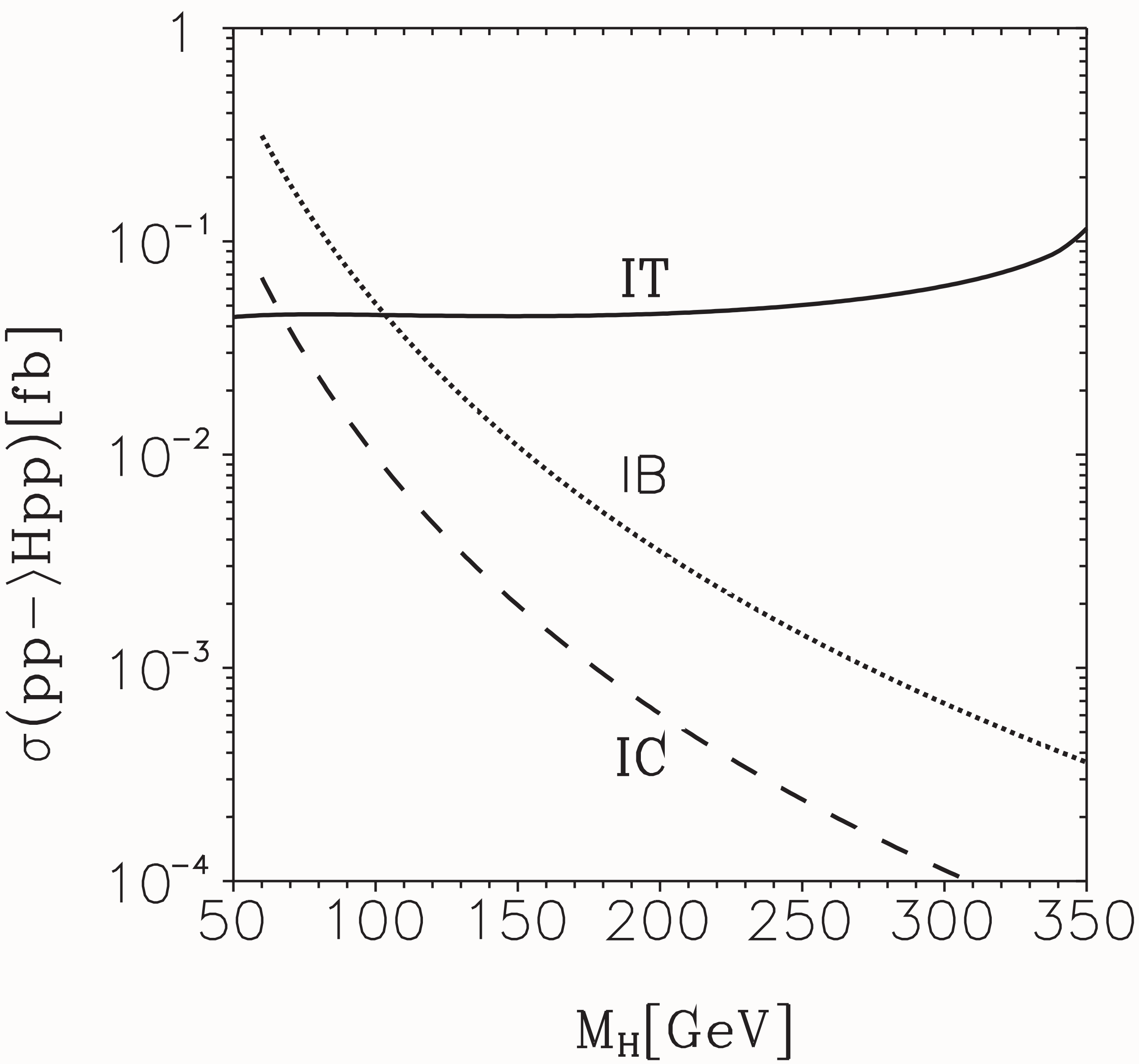
Collision produces color-singlet $J/\psi$ through color exchange

# Intrinsic Bottom Contribution to Inclusive Higgs Production




*1000 Higgs produced at high $x_F$ at the LHC in October, 2012 60 $fb^{-1}$*

**Goldhaber, Kopeliovich, Schmidt, sjb**



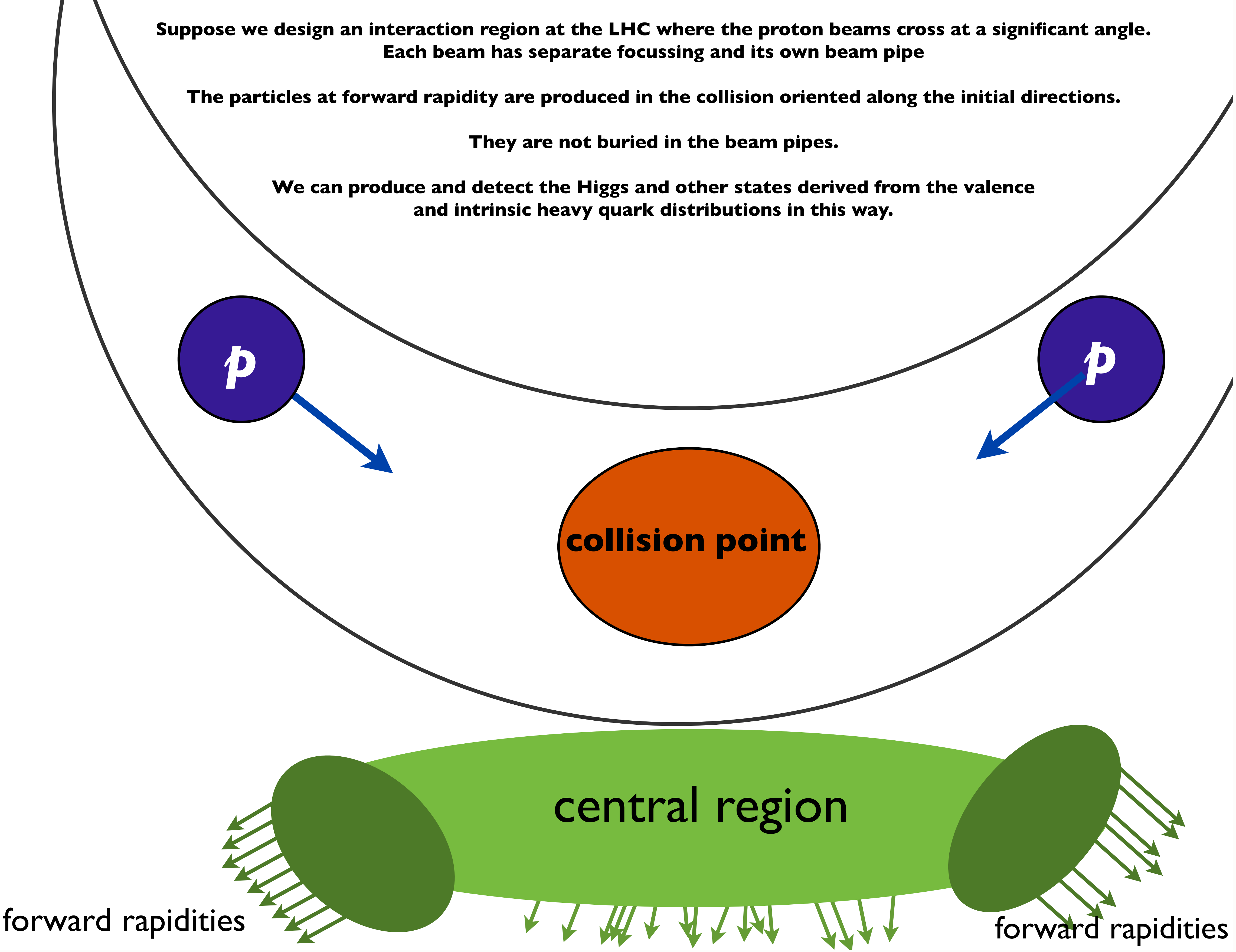

The cross section of the reaction $pp \to Hp + p$ as a function of the Higgs mass. Contributions of IC (dashed line), IB (dotted line), and IT (solid line).

**Suppose we design an interaction region at the LHC where the proton beams cross at a significant angle.**
**Each beam has separate focussing and its own beam pipe**

**The particles at forward rapidity are produced in the collision oriented along the initial directions.**

**They are not buried in the beam pipes.**

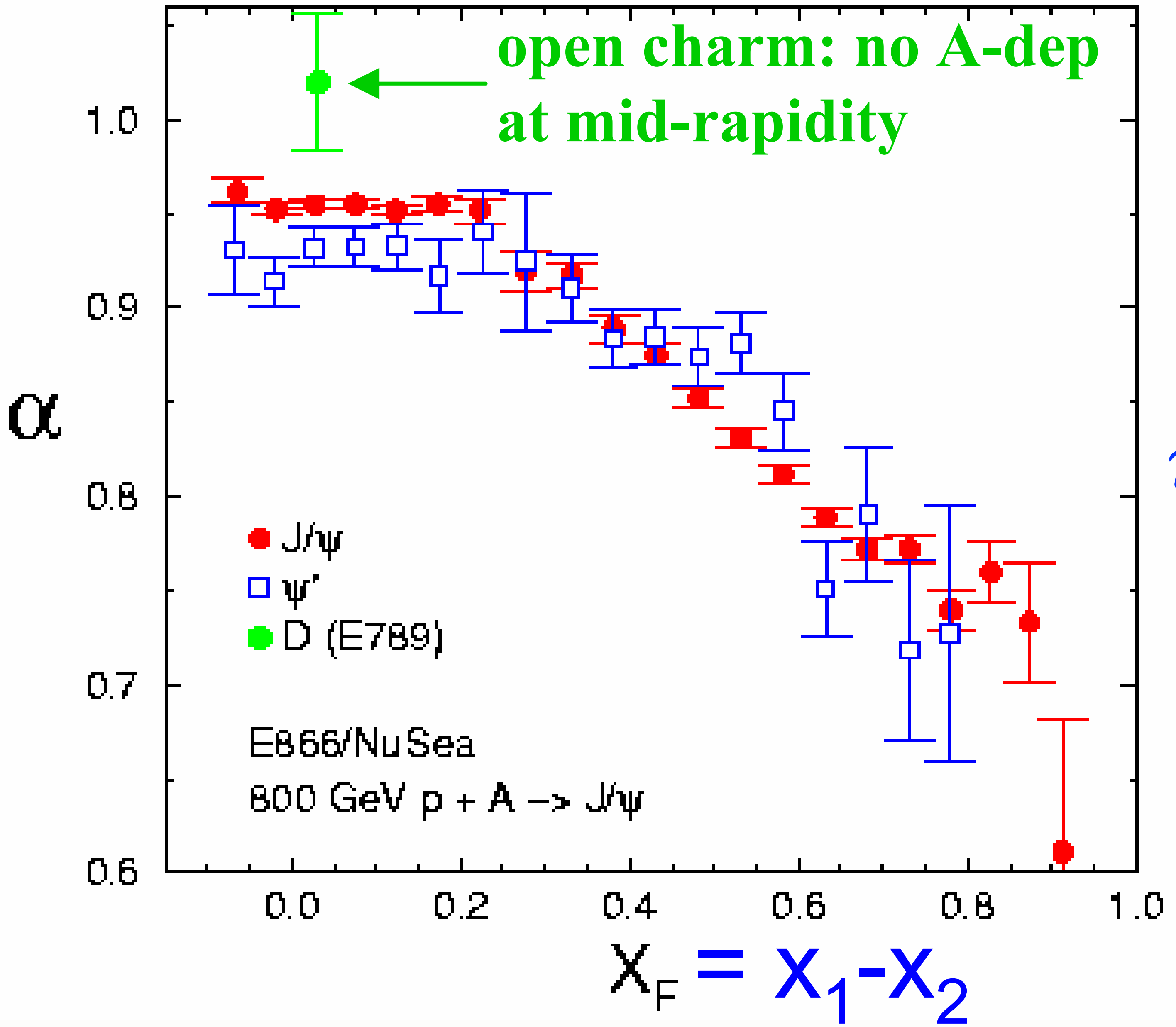
**We can produce and detect the Higgs and other states derived from the valence and intrinsic heavy quark distributions in this way.**



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

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

M. Leitch




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

Remarkably Strong Nuclear Dependence for Fast Charmonium

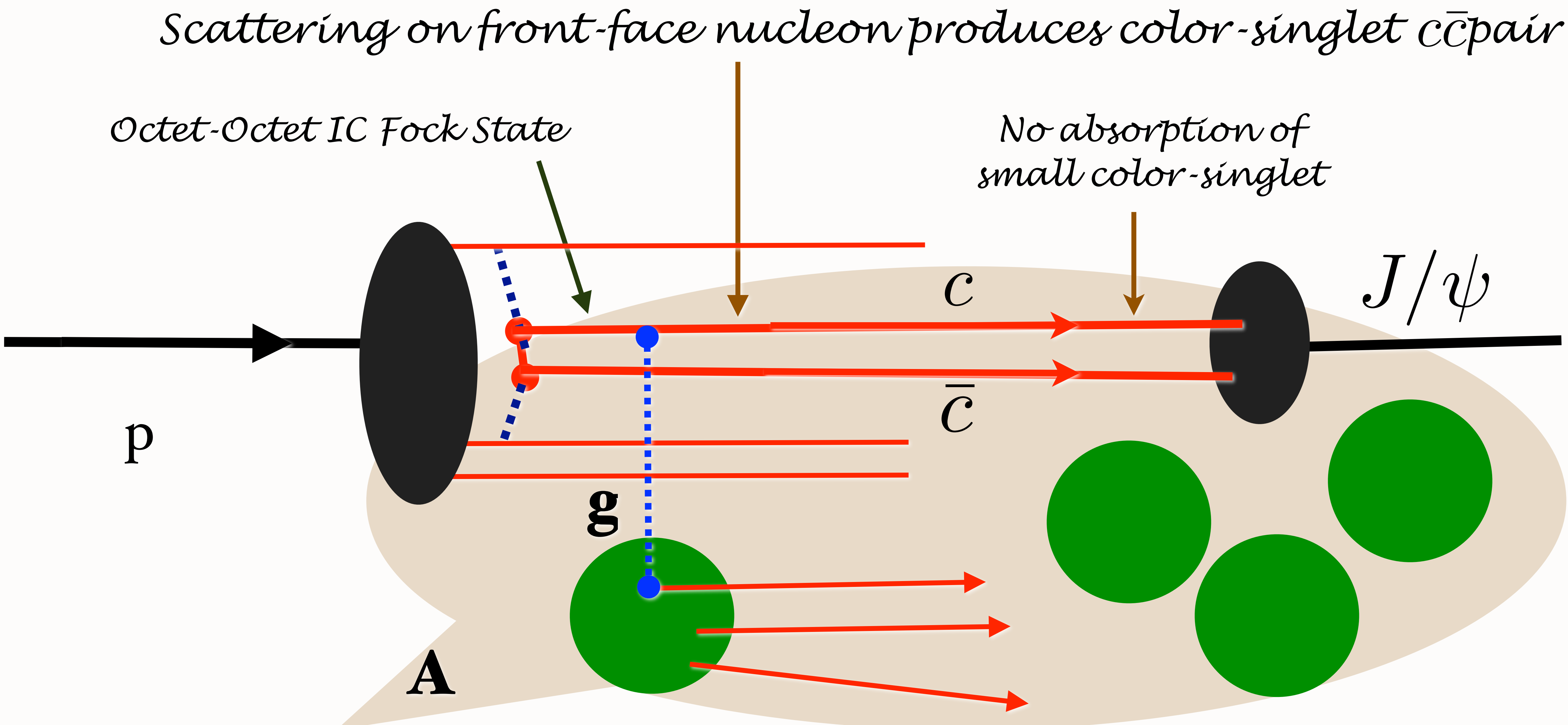
Violation of PQCD Factorization!

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

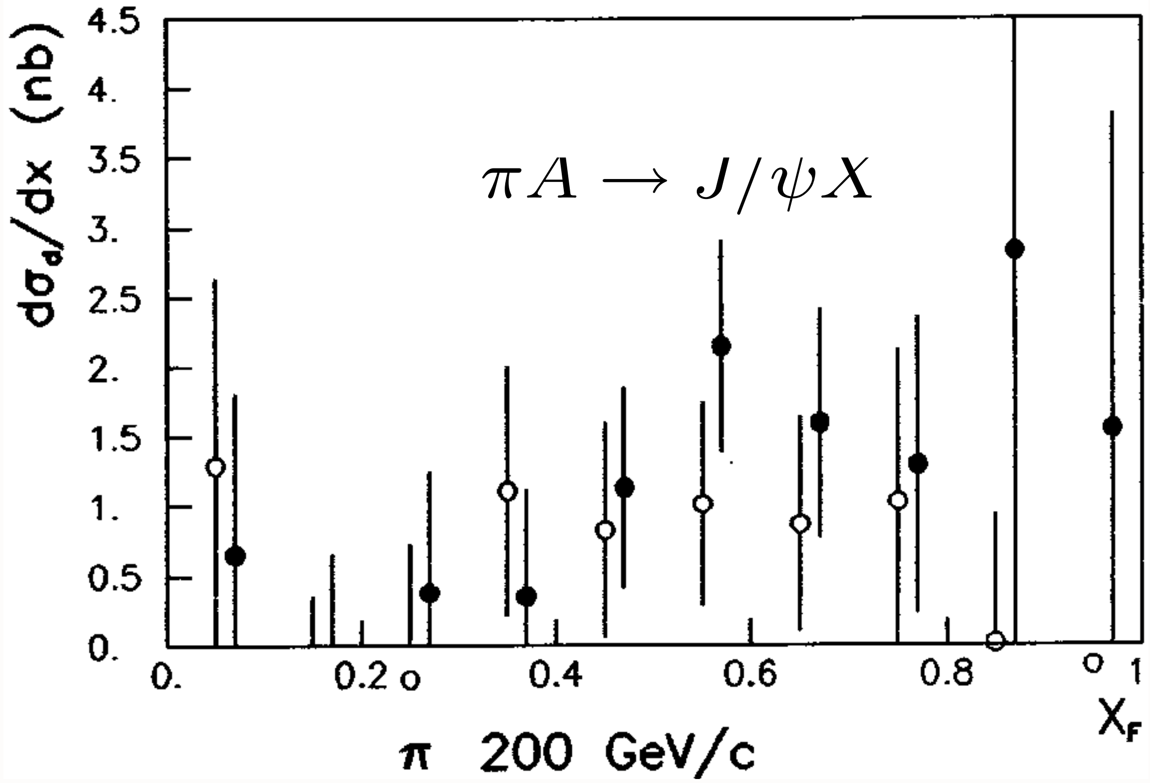
**IC Explains large excess of quarkonia at large $x_F$, A-dependence**

# Color-Opaque IC Fock state interacts on nuclear front surface

**Kopeliovich, Schmidt, Soffer, sjb**

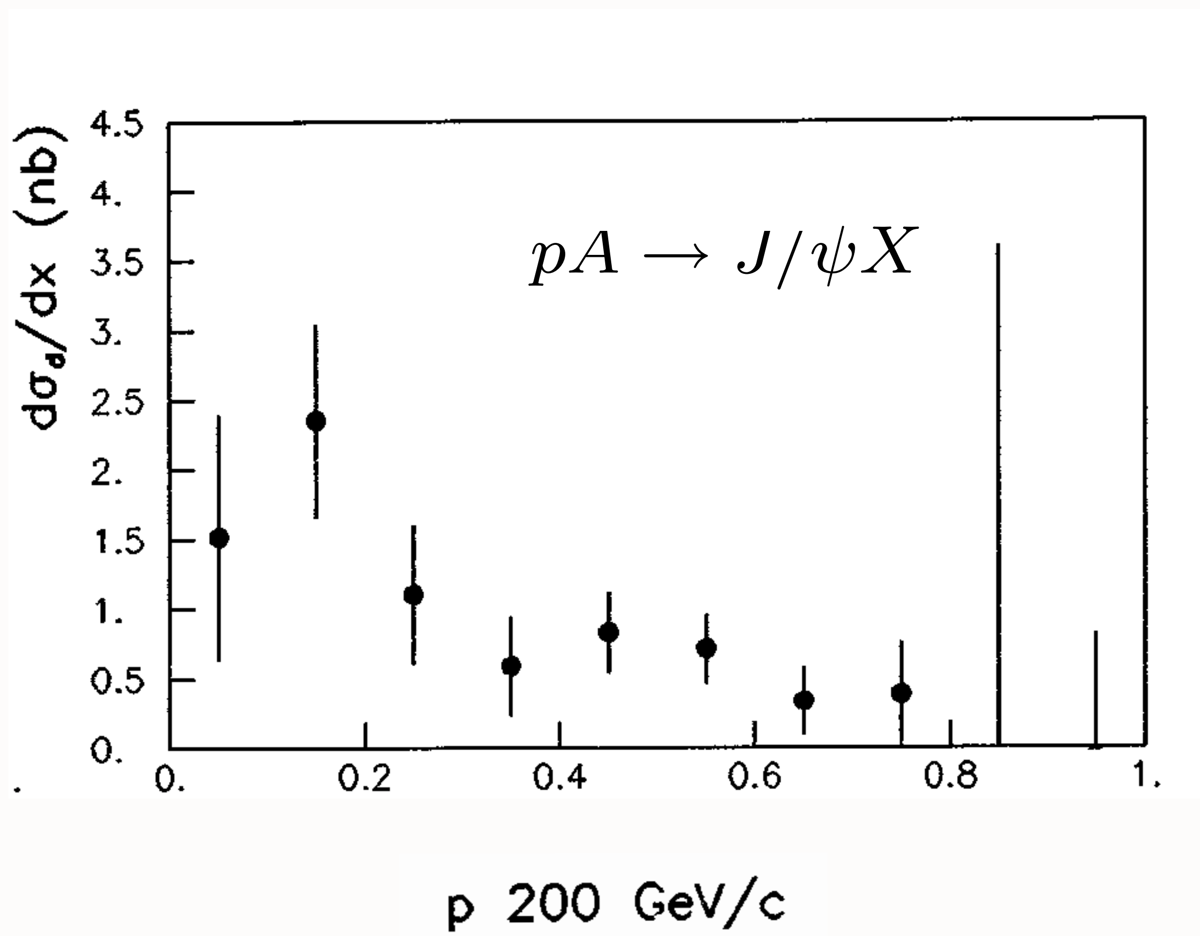



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$




# J. Badier et al, NA3

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_2}{dx_F}$$




## $A^{2/3}$ component

*High $x_F$:*

*Consistent with color-octet intrinsic charm*

**Excess beyond conventional gluon-splitting PQCD subprocesses**

# Why is IQ Important for Flavor Physics?

- **New perspective on fundamental nonperturbative hadron structure**
- **Charm structure function at high x**
- **Dominates high $x_F$ charm and charmonium production**
- **Hadroproduction of new heavy quark states such as ccu, ccd, bcc, bbb, at high $x_F$**
- **Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay** *Gardner, sjb*
- $J/\psi \to \rho\pi$ **puzzle explained** *Karliner , sjb*
- **Novel Nuclear Effects from color structure of IC, Heavy Ion Collisions**
- **New mechanisms for high $x_F$ Higgs hadroproduction**
- **Dynamics of b production: LHCb**
- **Fixed target program at LHC: produce bbb states**

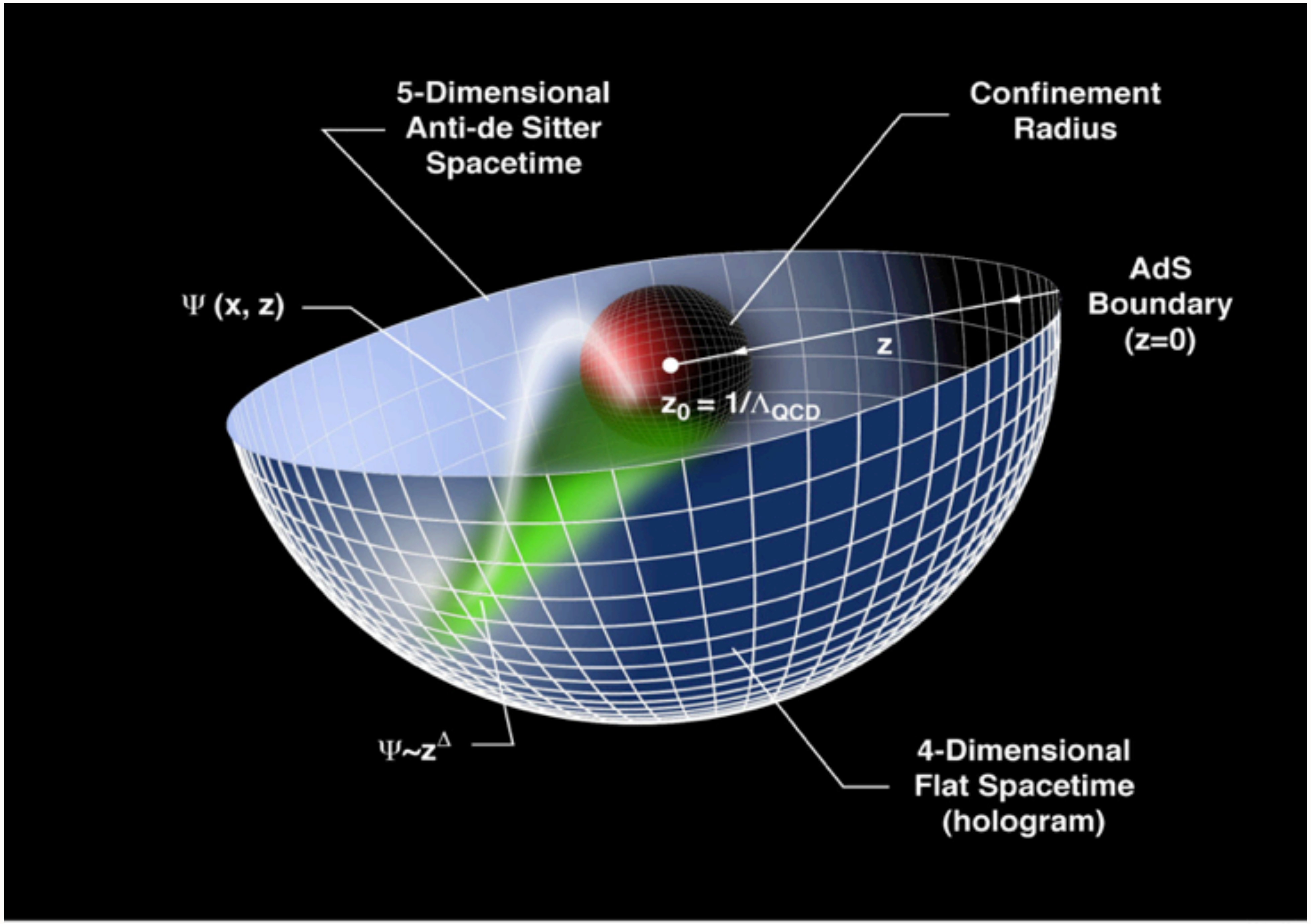
*New Multi-lepton Signals*

# Goal: an analytic first approximation to QCD

- **As Simple as Schrödinger Theory in Atomic Physics**
- **Relativistic, Frame-Independent, Color-Confining**
- **QCD Coupling at all scales**
- **Hadron Spectroscopy**
- **Light-Front Wavefunctions**
- **Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates**
- **Systematically improvable**

**de Teramond, sjb**

# Applications of AdS/CFT to QCD




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

**in collaboration with Guy de Teramond**

# Scale Transformations

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

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

invariant measure

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

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

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

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

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

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

# Soft-Wall Model

$$S = \int d^4x\, dz\, \sqrt{g}\, e^{\varphi(z)} \mathcal{L}, \qquad \varphi(z) = \pm\kappa^2 z^2$$

***Retain conformal AdS metrics but introduce smooth cutoff which depends on the profile of a dilaton background field***

**Karch, Katz, Son and Stephanov (2006)]**

- Equation of motion for scalar field $\mathcal{L} = \frac{1}{2}\left(g^{\ell m}\partial_\ell \Phi \partial_m \Phi - \mu^2 \Phi^2\right)$

$$\left[z^2\partial_z^2 - \left(3 \mp 2\kappa^2 z^2\right) z\, \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2\right] \Phi(z) = 0$$

with $(\mu R)^2 \geq -4$.

- LH holography requires 'plus dilaton' $\varphi = +\kappa^2 z^2$. Lowest possible state $(\mu R)^2 = -4$

$$\mathcal{M}^2 = 0, \quad \Phi(z) \sim z^2 e^{-\kappa^2 z^2}, \quad \langle r^2 \rangle \sim \frac{1}{\kappa^2}$$

A chiral symmetric bound state of two massless quarks with scaling dimension 2:

# Massless pion

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

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

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

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

Derived from variation of Action Dilaton-Modified $AdS_5$

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

**Positive-sign dilaton**

Quark separation increases with L

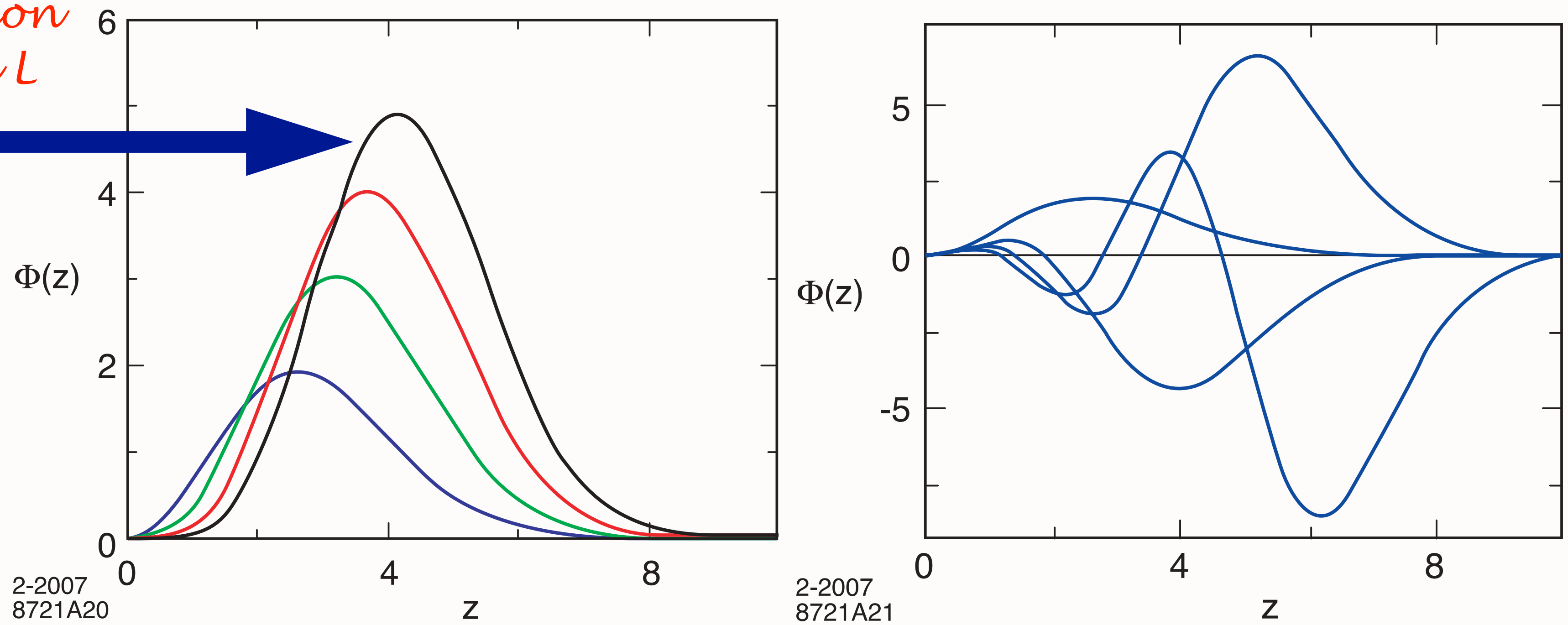
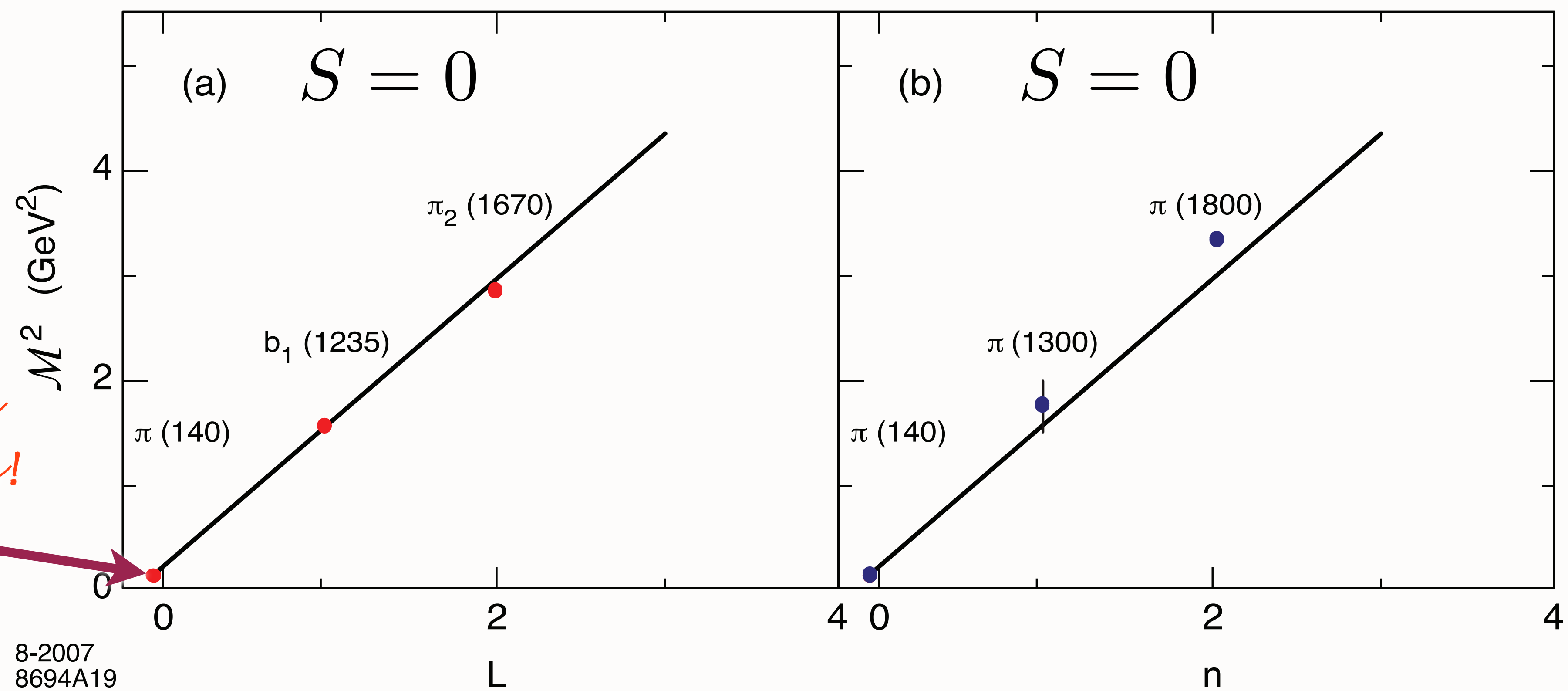



Fig: Orbital and radial AdS modes in the soft wall model for $\kappa = 0.6$ GeV .

# Soft Wall Model

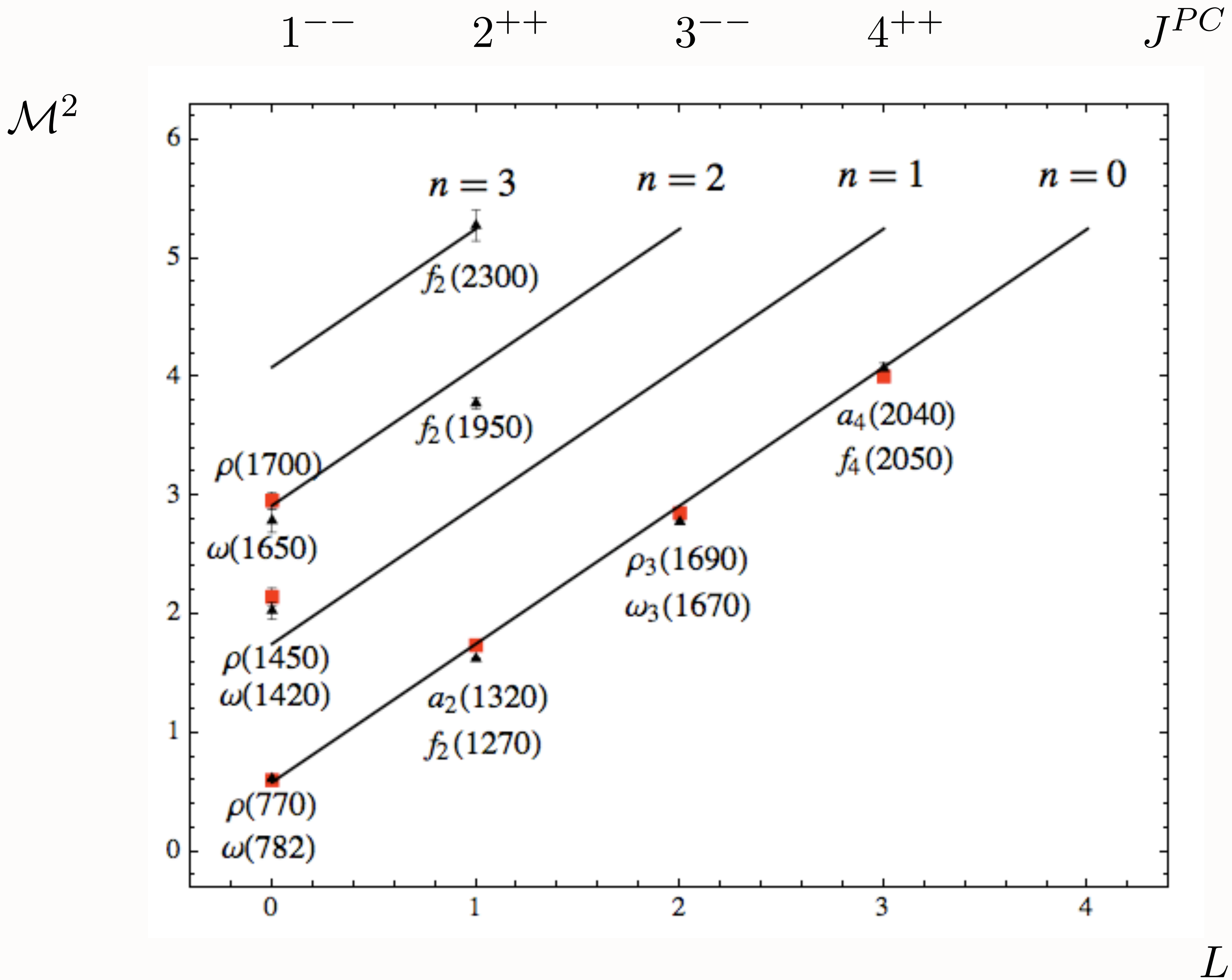
Pion has zero mass!




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

**Pion mass automatically zero!**

$$m_q = 0$$




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

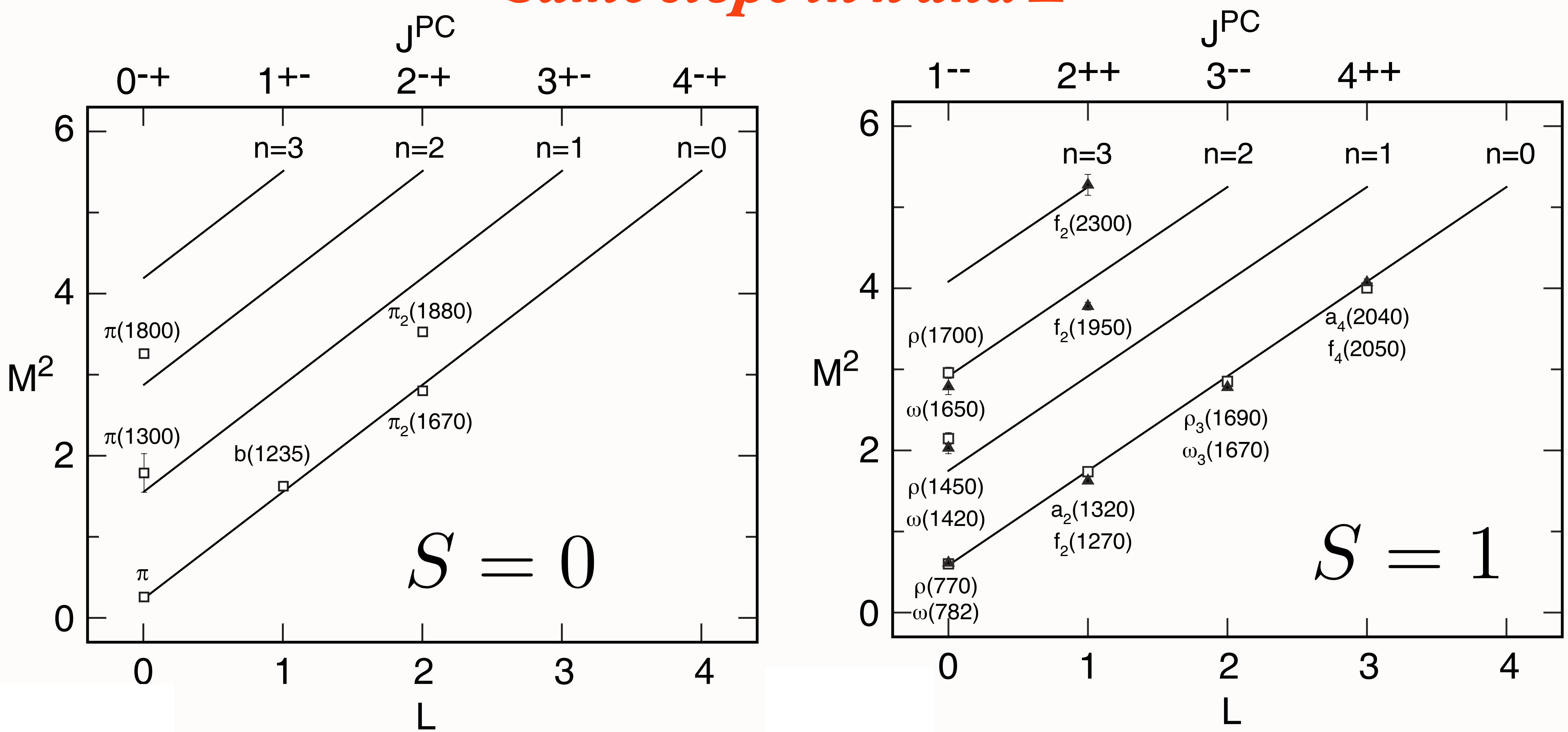
and the $I = 0$ $\omega$-meson family (black) for $\kappa = 0.54$ GeV

# Bosonic Modes and Meson Spectrum

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

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

***Same slope in n and L***




Regge trajectories for the $\pi$ ($\kappa = 0.6$ GeV) and the $I = 1$ $\rho$-meson and $I = 0$ $\omega$-meson families ($\kappa = 0.54$ GeV)

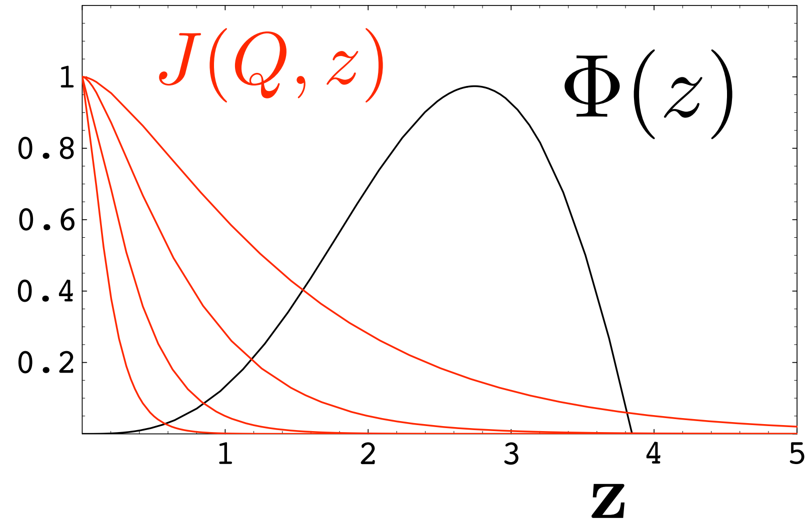
# Hadron Form Factors from AdS/CFT

Propagation of external perturbation suppressed inside AdS.

$$J(Q,z) = zQK_1(zQ)$$

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

High $Q^2$
from
small z ~ 1/Q




Polchinski, Strassler
de Teramond, sjb

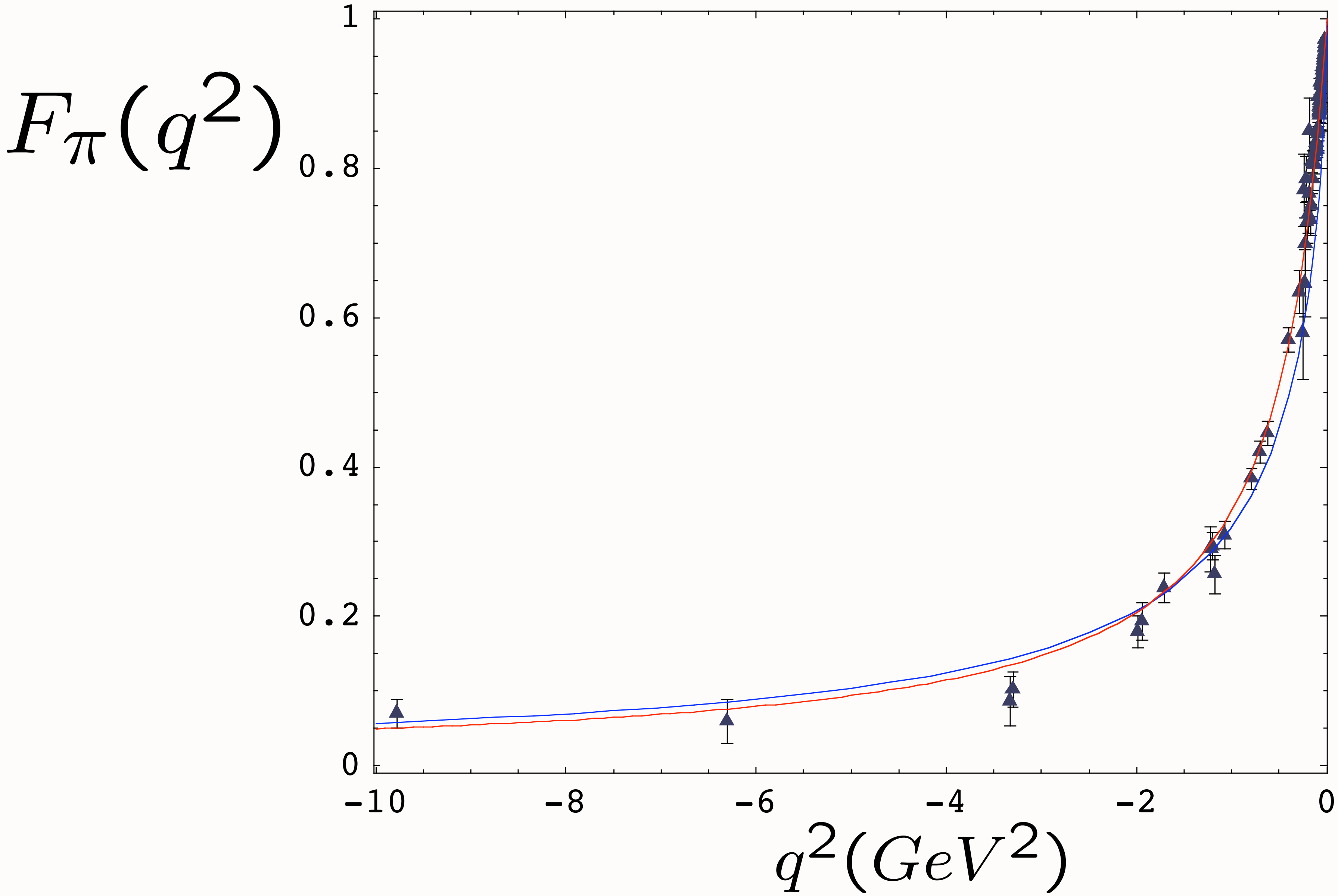
Consider a specific AdS mode $\Phi^{(n)}$ dual to an $n$ partonic Fock state $|n\rangle$. At small $z$, $\Phi$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

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

Dimensional Quark Counting Rules:
General result from
AdS/CFT and Conformal Invariance

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

# 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

# Light-Front Representation of Two-Body Meson Form Factor

- Drell-Yan-West form factor

$$\vec{q}_\perp^{\,2} = Q^2 = -q^2$$

$$F(q^2) = \sum_q e_q \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3}\, \psi^*_{P'}(x, \vec{k}_\perp - x\vec{q}_\perp)\, \psi_P(x, \vec{k}_\perp).$$

- Fourrier transform to impact parameter space $\vec{b}_\perp$

$$\psi(x, \vec{k}_\perp) = \sqrt{4\pi} \int d^2\vec{b}_\perp\, e^{i\vec{b}_\perp\cdot\vec{k}_\perp}\, \widetilde{\psi}(x, \vec{b}_\perp)$$

- Find $(b = |\vec{b}_\perp|)$ :

$$\begin{aligned} F(q^2) &= \int_0^1 dx \int d^2\vec{b}_\perp\, e^{ix\vec{b}_\perp\cdot\vec{q}_\perp} \left|\widetilde{\psi}(x, b)\right|^2 \\ &= 2\pi \int_0^1 dx \int_0^\infty b\, db\, J_0(bqx)\, \left|\widetilde{\psi}(x, b)\right|^2, \end{aligned}$$

**Soper**

## Holographic Mapping of AdS Modes to QCD LFWFs

- Integrate Soper formula over angles:

$$F(q^2) = 2\pi \int_0^1 dx \, \frac{(1-x)}{x} \int \zeta d\zeta J_0\left(\zeta q \sqrt{\frac{1-x}{x}}\right) \tilde{\rho}(x,\zeta),$$

with $\widetilde{\rho}(x,\zeta)$ QCD effective transverse charge density.

- Transversality variable

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

- Compare AdS and QCD expressions of FFs for arbitrary $Q$ using identity:

$$\int_0^1 dx J_0\left(\zeta Q \sqrt{\frac{1-x}{x}}\right) = \zeta Q K_1(\zeta Q),$$

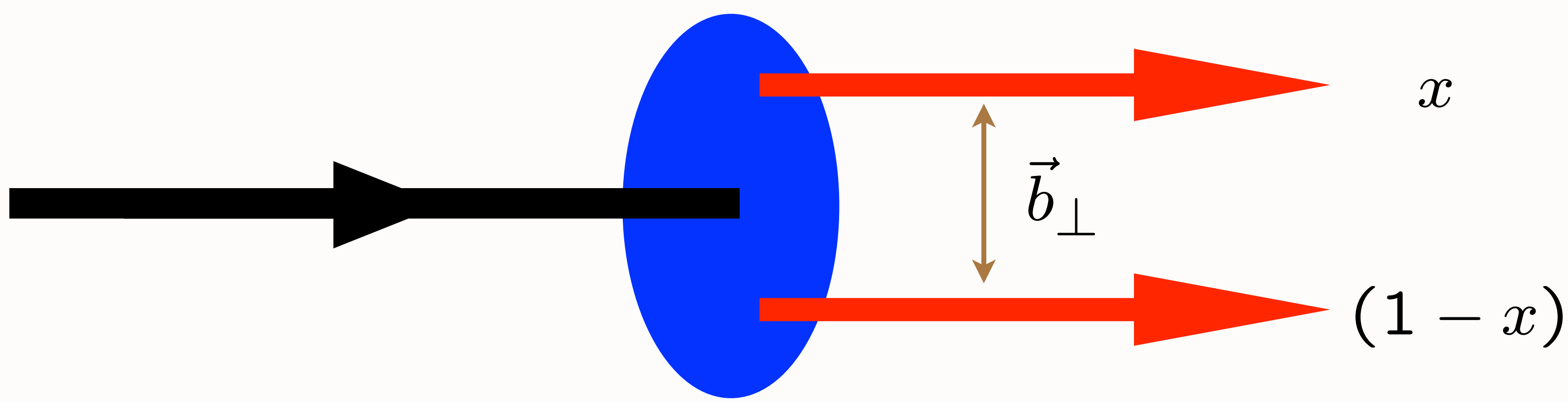
the solution for $J(Q,\zeta) = \zeta Q K_1(\zeta Q)$ !

de Teramond, sjb

$LF(3+1) \longleftrightarrow AdS_5$

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

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




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

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

# Gravitational Form Factor in AdS space

- Hadronic gravitational form-factor in AdS space

$$A_\pi(Q^2) = R^3 \int \frac{dz}{z^3} H(Q^2, z) \left|\Phi_\pi(z)\right|^2,$$

Abidin & Carlson

where $H(Q^2, z) = \frac{1}{2} Q^2 z^2 K_2(zQ)$

- Use integral representation for $H(Q^2, z)$

$$H(Q^2, z) = 2 \int_0^1 x \, dx \, J_0\left(zQ\sqrt{\frac{1-x}{x}}\right)$$

- Write the AdS gravitational form-factor as

$$A_\pi(Q^2) = 2R^3 \int_0^1 x \, dx \int \frac{dz}{z^3} \, J_0\left(zQ\sqrt{\frac{1-x}{x}}\right) \left|\Phi_\pi(z)\right|^2$$

- Compare with gravitational form-factor in light-front QCD for arbitrary $Q$

$$\boxed{\left|\tilde{\psi}_{q\bar{q}/\pi}(x, \zeta)\right|^2 = \frac{R^3}{2\pi} \, x(1-x) \frac{\left|\Phi_\pi(\zeta)\right|^2}{\zeta^4},}$$

*Identical to LF Holography obtained from electromagnetic current*

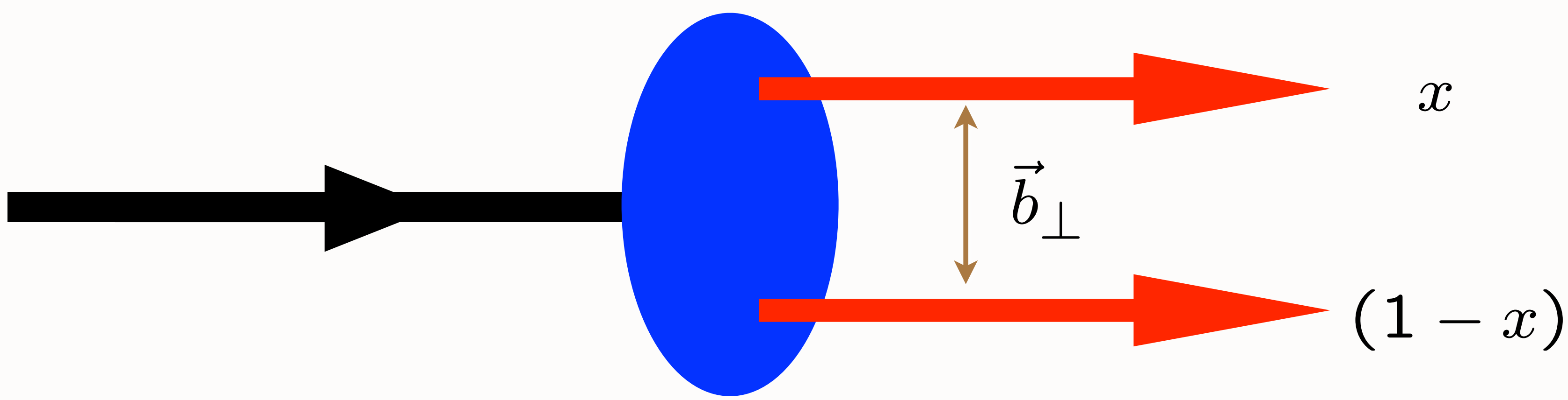
# Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

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

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




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

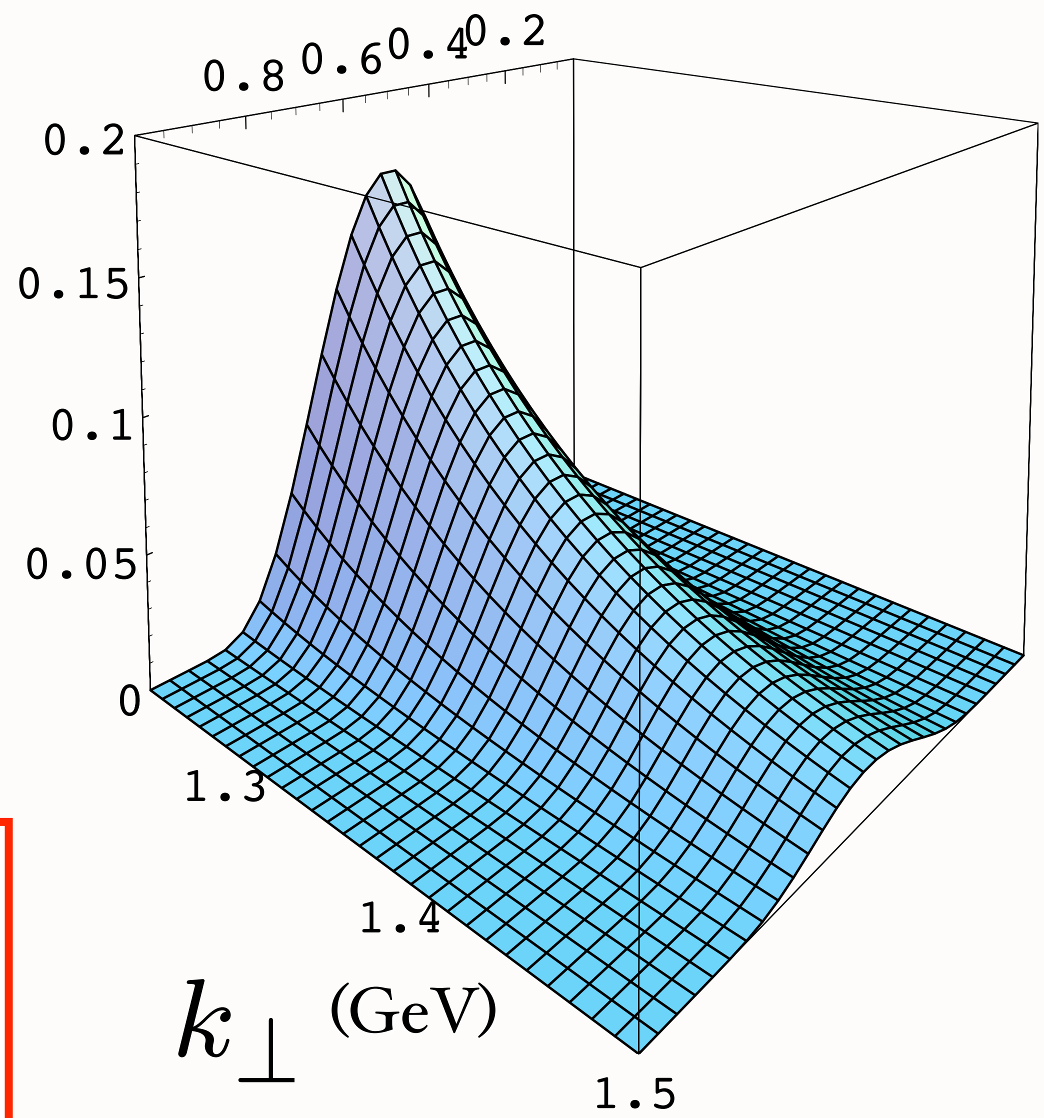
soft wall confining potential:

G. de Teramond, sjb

# 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**

$k_\perp^2, x$

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

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

*Connection of Confinement to TMDs*

$$H_{QED}$$

*QED atoms: positronium and muonium*

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

*Coupled Fock states*

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

*Effective two-particle equation*

**Includes Lamb Shift, quantum corrections**

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

*Spherical Basis* $r, \theta, \phi$

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

*Coulomb potential*

**Bohr Spectrum**

*Semiclassical first approximation to QED*

$$H^{LF}_{QCD}$$

QCD Meson Spectrum

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

Coupled Fock states

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

Effective two-particle equation

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

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

Azimuthal Basis $\zeta, \phi$

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

Semiclassical first approximation to QCD

Confining AdS/QCD potential

**de Teramond, sjb**

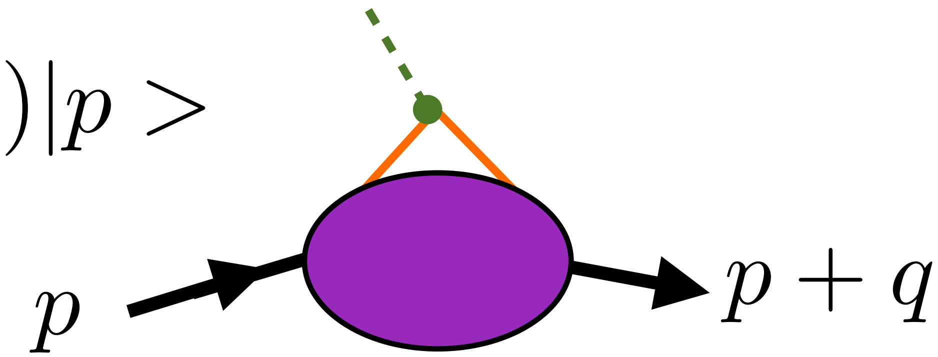
# Light-Front Holography

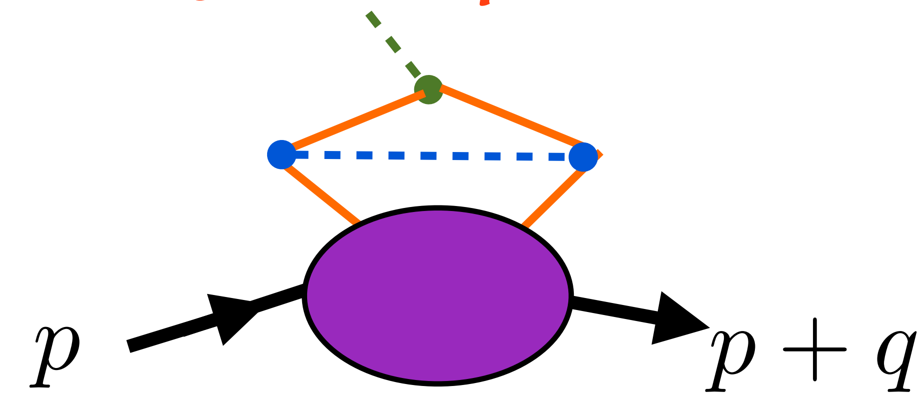
***AdS Space matches 3+1 spacetime at fixed Light-Front Time!***

- *Matching of AdS and LF Expressions for EM and Gravitational Form Factors*
- *Overlap of LFWFs Only -- No Vacuum Currents so cannot match to Instant-Time formula*
- *Matches Equations of LF Hamiltonian Theory*
- *Matches LF Kinetic Energy*
- *Angular Momentum Matches to AdS Mass*

# Calculation of proton form factor in Instant Form

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




- **Need to boost proton wavefunction from p to p+q: Extremely complicated dynamical problem; particle number changes**
- **Need to couple to all currents arising from vacuum!!**
- **Each time-ordered contribution is frame-dependent**
- **States built on normal-ordered acausal vacuum**
- **Divide by disconnected vacuum diagrams**

# Baryons in AdS/QCD

- We write the Dirac equation

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

in terms of the matrix-valued operator $\Pi$

$$\nu = L + 1$$

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

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

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

- Solutions to the Dirac equation

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

- Eigenvalues

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

- Nucleon LF modes

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

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

- Normalization

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

- Eigenvalues

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

- "Chiral partners"

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

- **Δ spectrum identical to Forkel and Klempt, Phys. Lett. B 679, 77 (2009)**

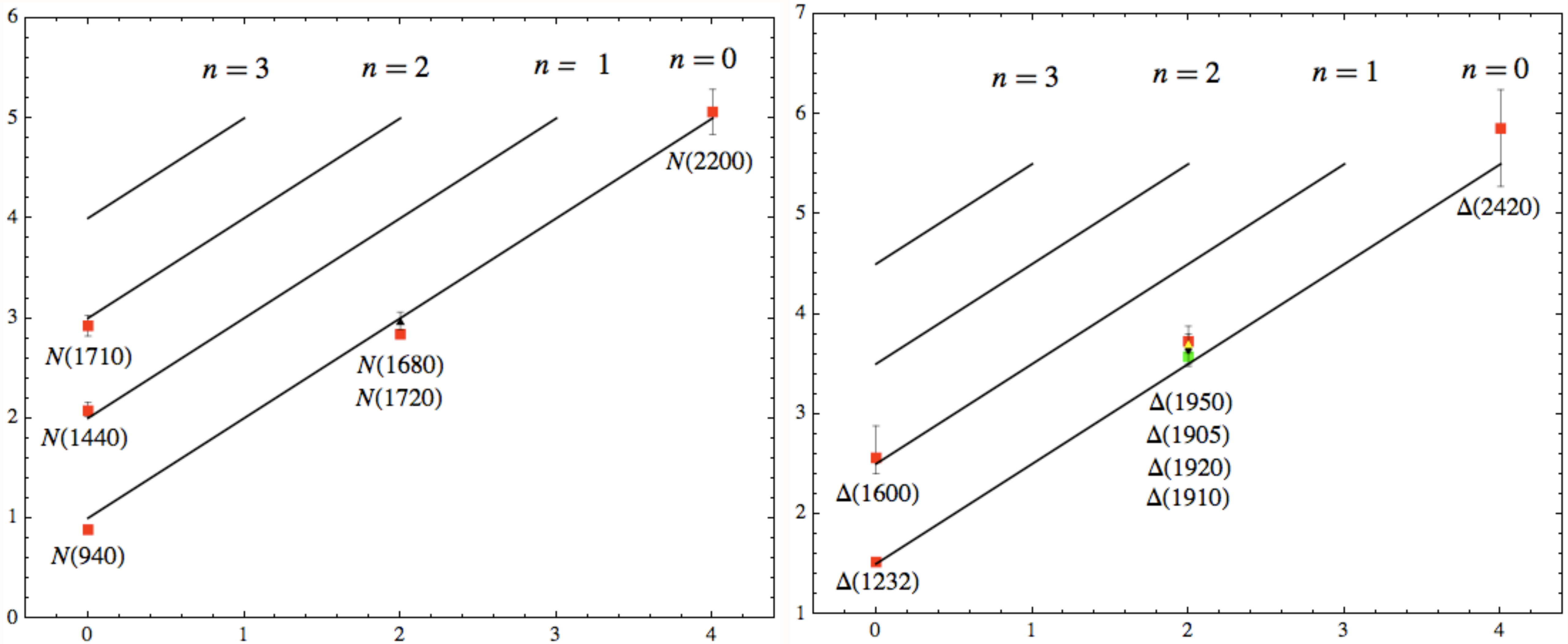
$4\kappa^2$ for $\Delta n = 1$

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

$2\kappa^2$ for $\Delta S = 1$

Same multiplicity of states for mesons and baryons!

$\mathcal{M}^2$




$L$

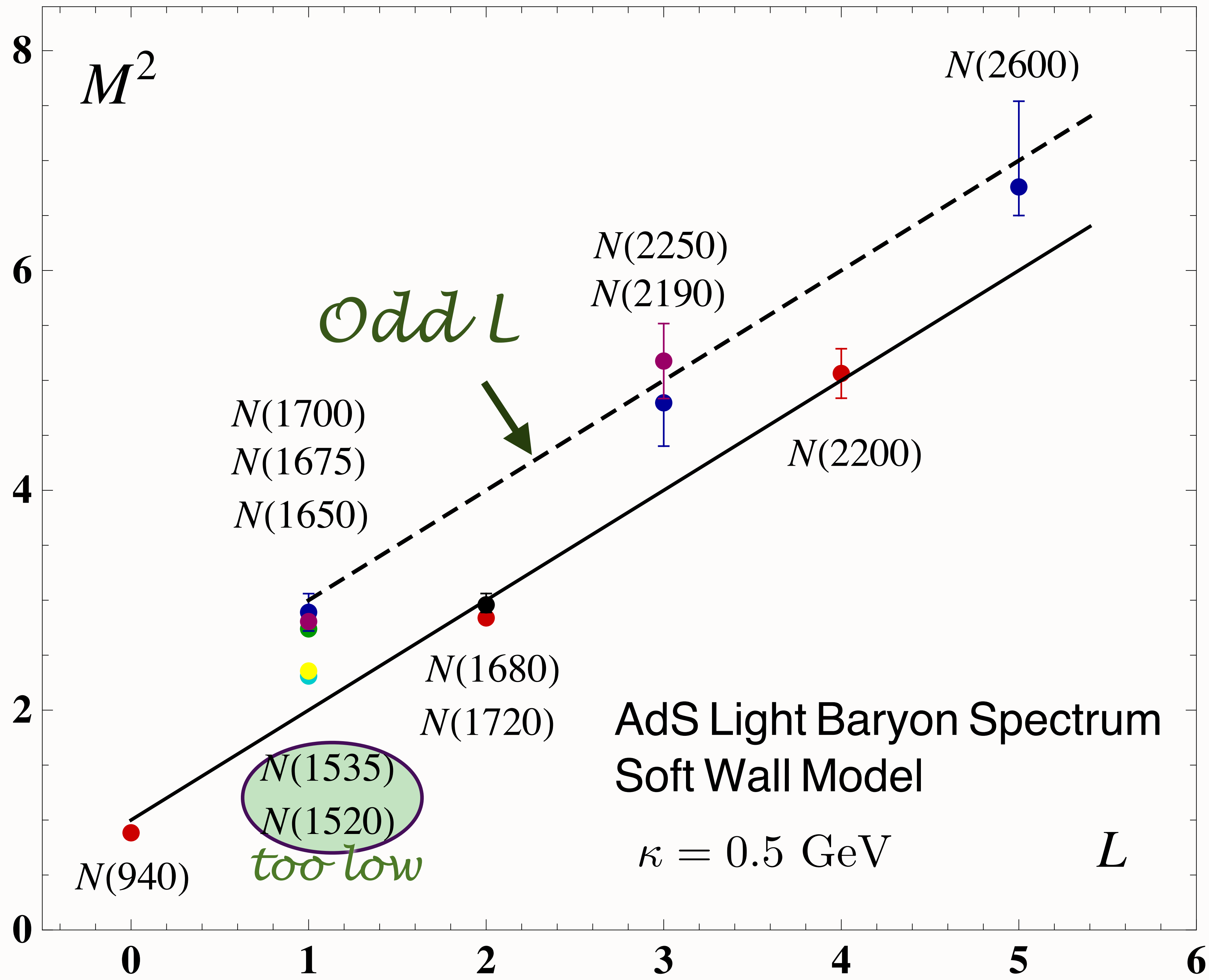
Parent and daughter **56** Regge trajectories for the $N$ and $\Delta$ baryon families for $\kappa = 0.5$ GeV

Positive Parity Nucleons

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

Negative Parity Nucleons

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




$L + 1 = \nu = \mu R - 1/2$ **(even P)**

$L + 1 = \nu = \mu R + 1/2$ **(odd P)**

# Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum.**
- **Massless Pion**
- **Hadron Eigenstates have LF Fock components of different $L^z$**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S_q^z = 0 >$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

Proton spin
carried by quark angular momentum!

## Space-Like Dirac Proton Form Factor

- Consider the spin non-flip form factors

$$F_+(Q^2) = g_+ \int d\zeta\, J(Q,\zeta) |\psi_+(\zeta)|^2,$$
$$F_-(Q^2) = g_- \int d\zeta\, J(Q,\zeta) |\psi_-(\zeta)|^2,$$

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

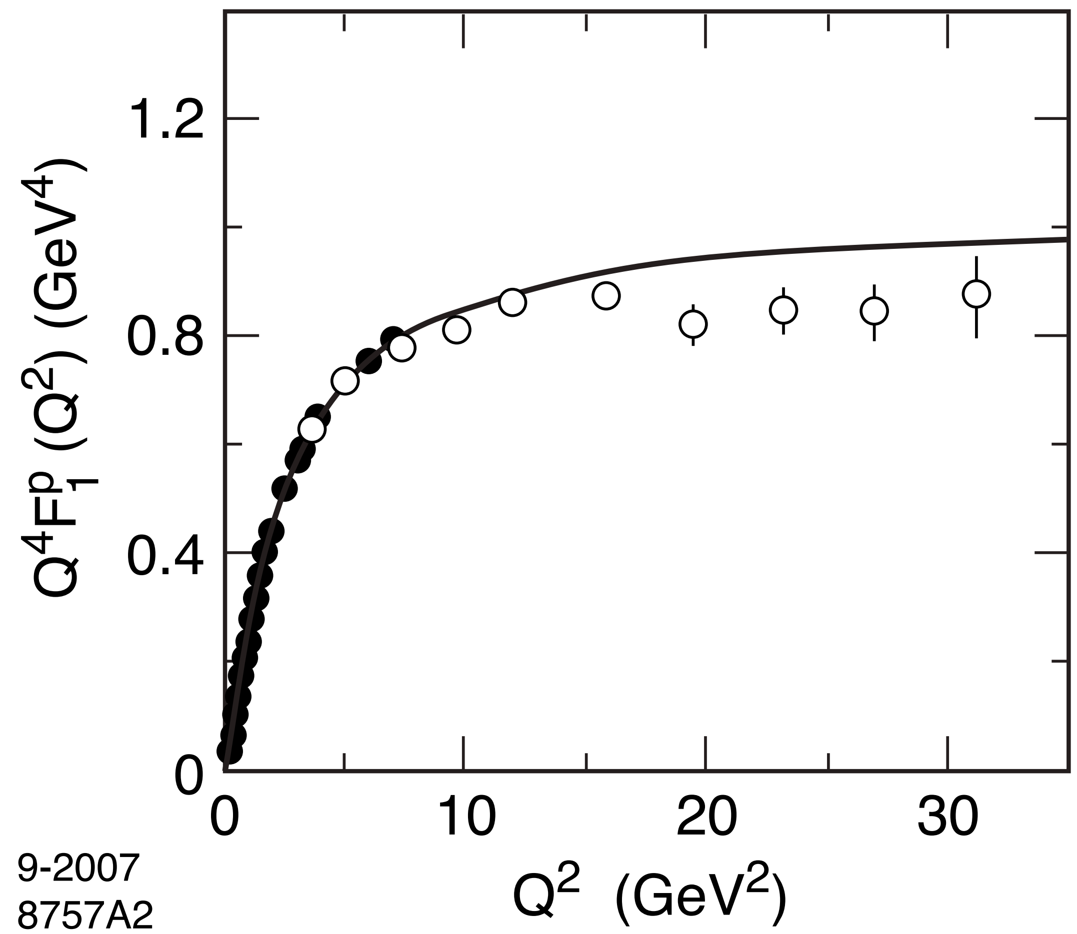
- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(\zeta)$ and $\psi_-(\zeta)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

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

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

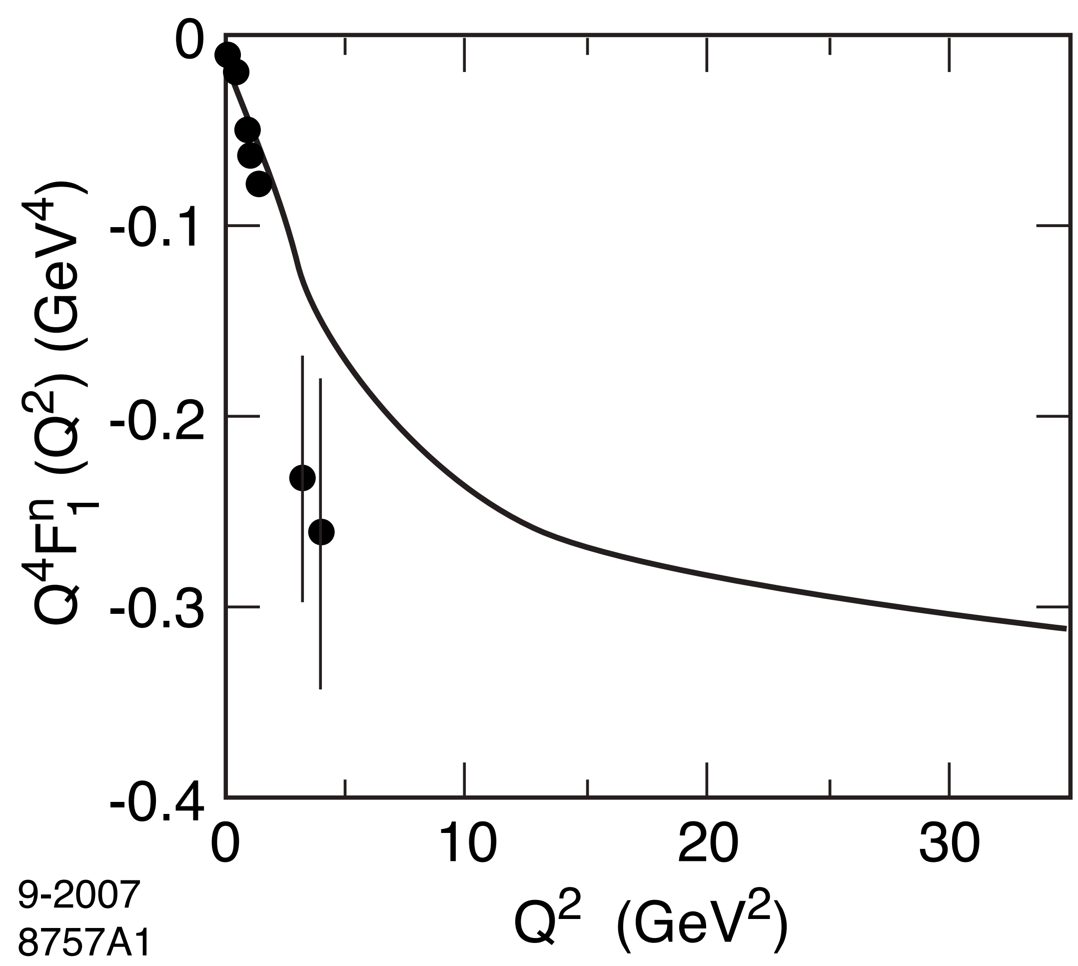
where $F_1^p(0) = 1,\ F_1^n(0) = 0$.

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




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 $Q^2$: $Q^4 F_1^n(Q^2) \to \text{constant}$ $\boxed{\text{Neutron } \tau = 3}$

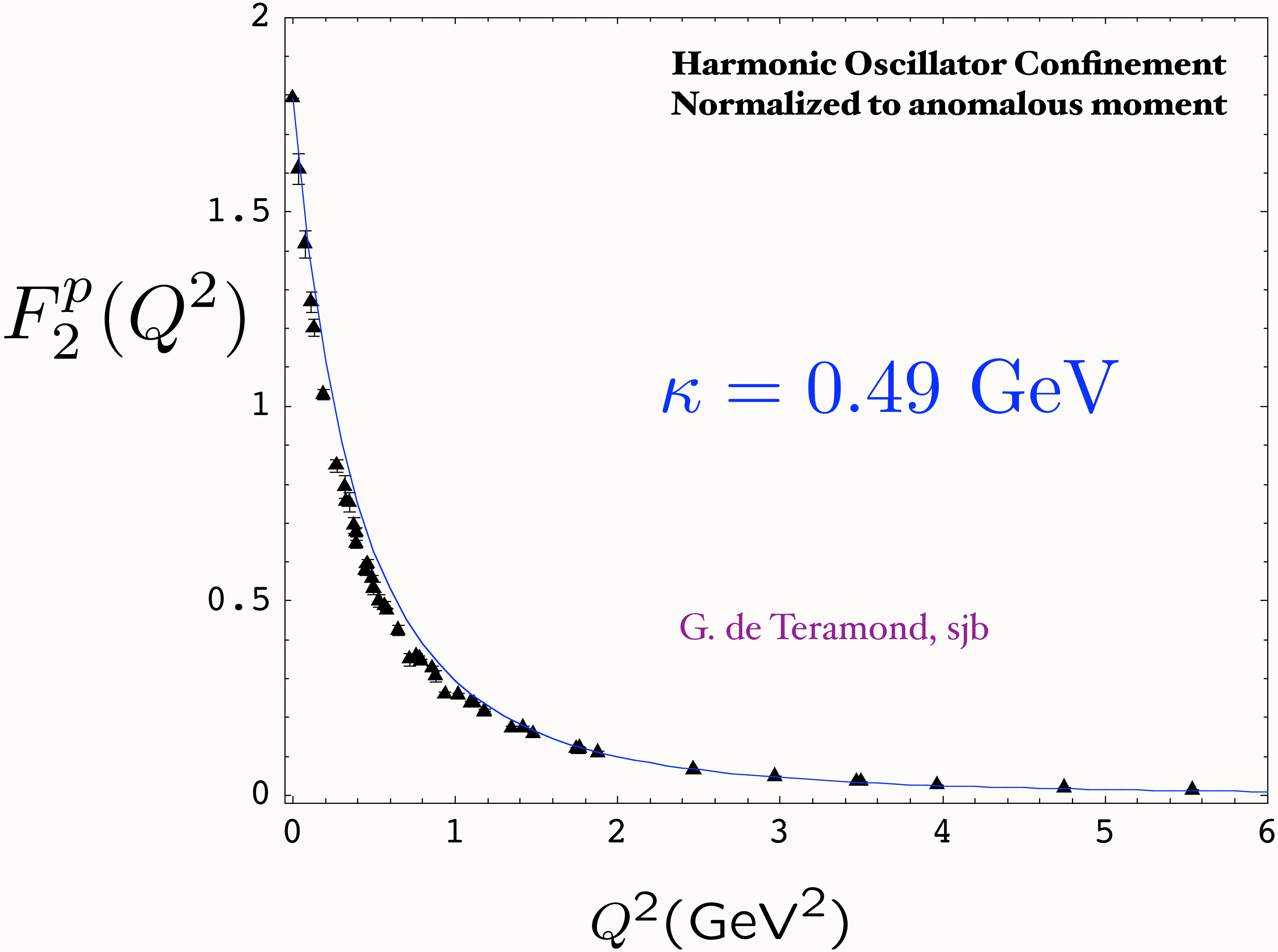



SW model predictions for $\kappa = 0.424$ GeV. Data analysis from M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

# Spacelike Pauli Form Factor

*Preliminary*

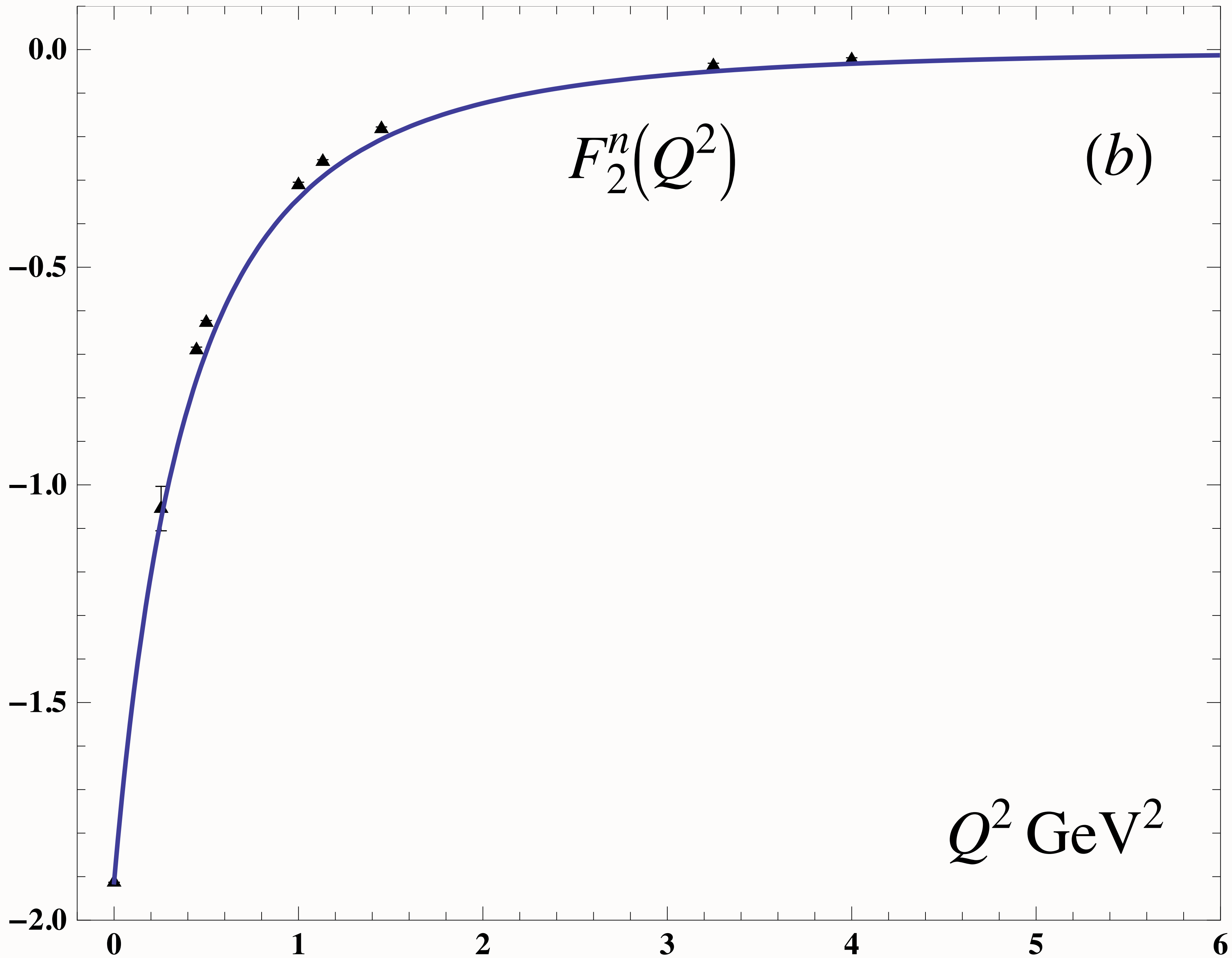
From overlap of $L = 1$ and $L = 0$ LFWFs



# Spacelike Neutron Pauli Form Factor

*Preliminary*

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



## Nucleon Transition Form Factors

- Compute spin non-flip EM transition $N(940) \to N^*(1440)$: $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$
- Transition form factor

$$F_{1\,N\to N^*}^{\,p}(Q^2) = R^4 \int \frac{dz}{z^4}\, \Psi_+^{n=1,L=0}(z) V(Q,z) \Psi_+^{n=0,L=0}(z)$$

- Orthonormality of Laguerre functions $\left(F_{1\,N\to N^*}^{\,p}(0) = 0, \quad V(Q=0,z) = 1\right)$

$$R^4 \int \frac{dz}{z^4}\, \Psi_+^{n',L}(z) \Psi_+^{n,L}(z) = \delta_{n,n'}$$

- Find

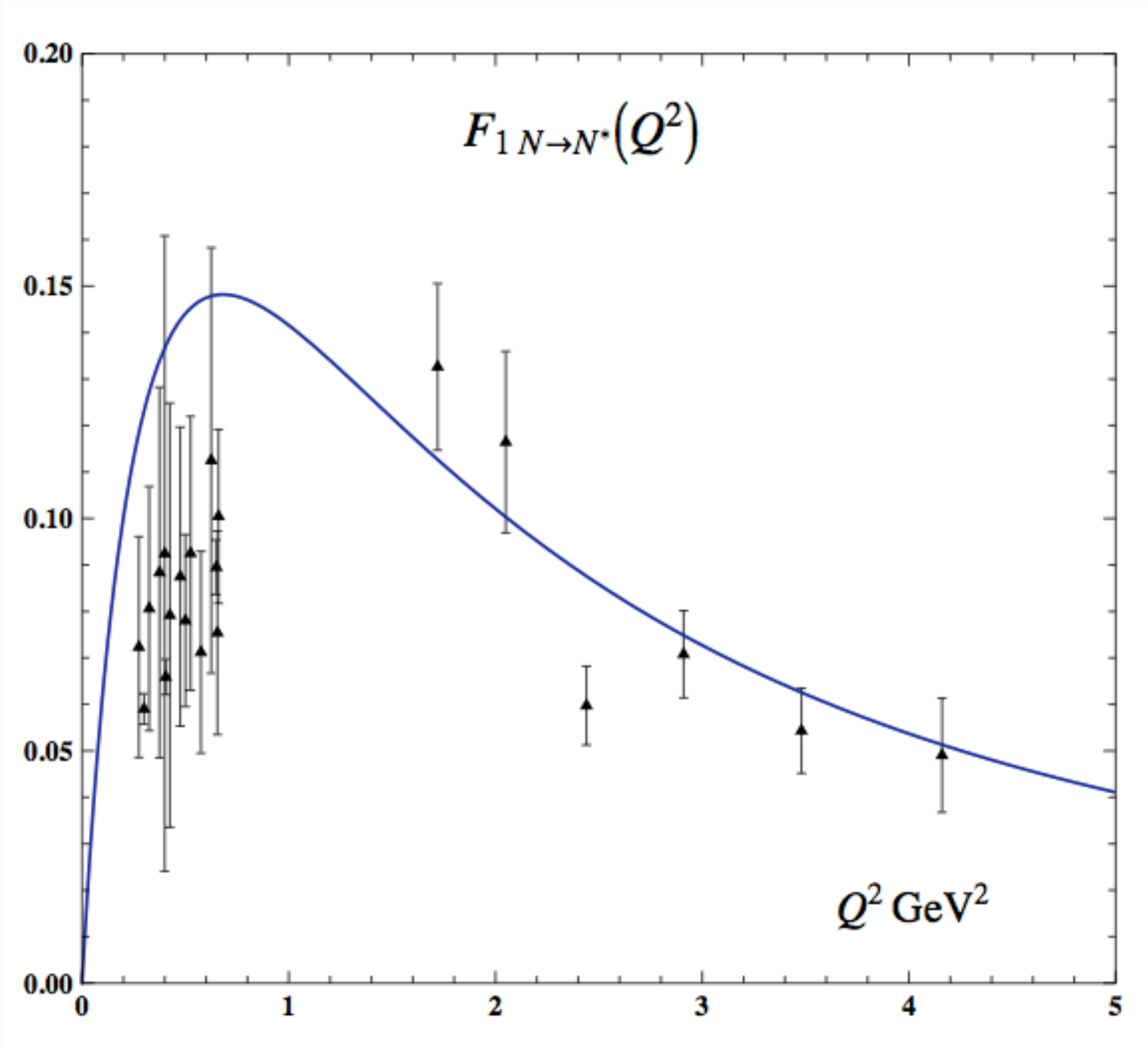
$$F_{1\,N\to N^*}^{\,p}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

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

de Teramond, sjb

*Consistent with counting rule, twist 3*

$$N(940) \to N^*(1440): \quad \Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$$




Data from I. Aznauryan, *et al.* CLAS (2009)

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

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

## Note: Analytical Form of Hadronic Form Factor for Arbitrary Twist

- Form factor for a string mode with scaling dimension $\tau$, $\Phi_\tau$ in the SW model

$$F(Q^2) = \Gamma(\tau) \frac{\Gamma\left(1 + \frac{Q^2}{4\kappa^2}\right)}{\Gamma\left(\tau + \frac{Q^2}{4\kappa^2}\right)}.$$

- For $\tau = N, \quad \Gamma(N + z) = (N - 1 + z)(N - 2 + z) \ldots (1 + z)\Gamma(1 + z)$.

- Form factor expressed as $N - 1$ product of poles

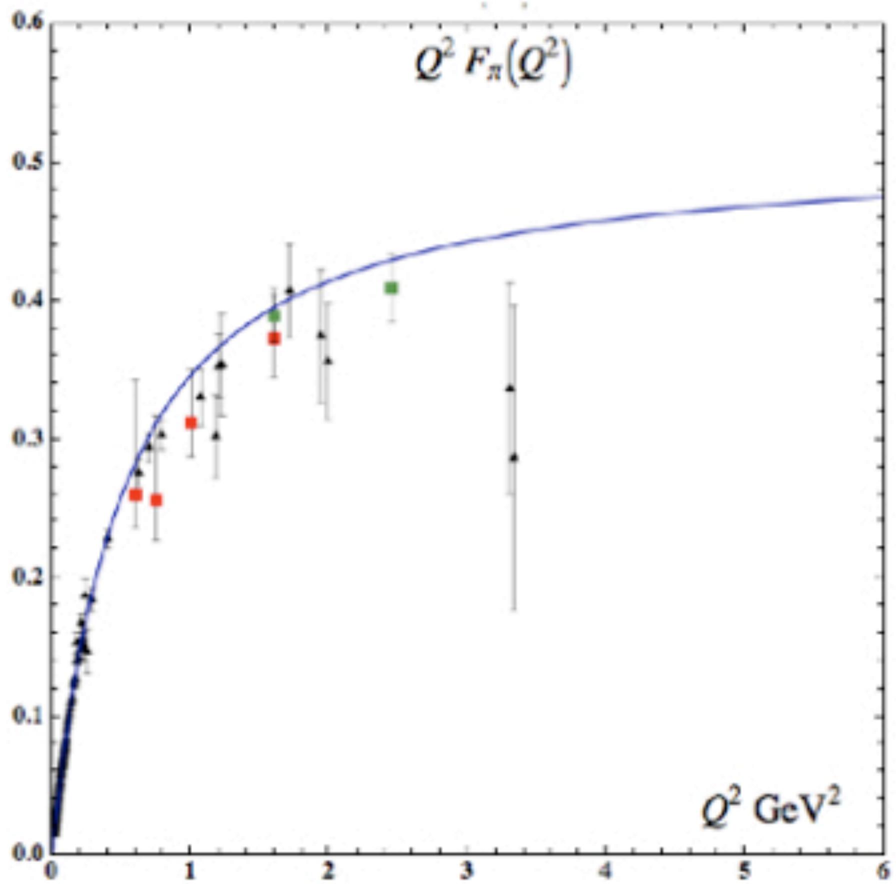
$$\begin{aligned}
F(Q^2) &= \frac{1}{1 + \frac{Q^2}{4\kappa^2}}, \quad N = 2, \\
F(Q^2) &= \frac{2}{\left(1 + \frac{Q^2}{4\kappa^2}\right)\left(2 + \frac{Q^2}{4\kappa^2}\right)}, \quad N = 3, \\
&\cdots \\
F(Q^2) &= \frac{(N-1)!}{\left(1 + \frac{Q^2}{4\kappa^2}\right)\left(2 + \frac{Q^2}{4\kappa^2}\right)\cdots\left(N - 1 + \frac{Q^2}{4\kappa^2}\right)}, \quad N.
\end{aligned}$$

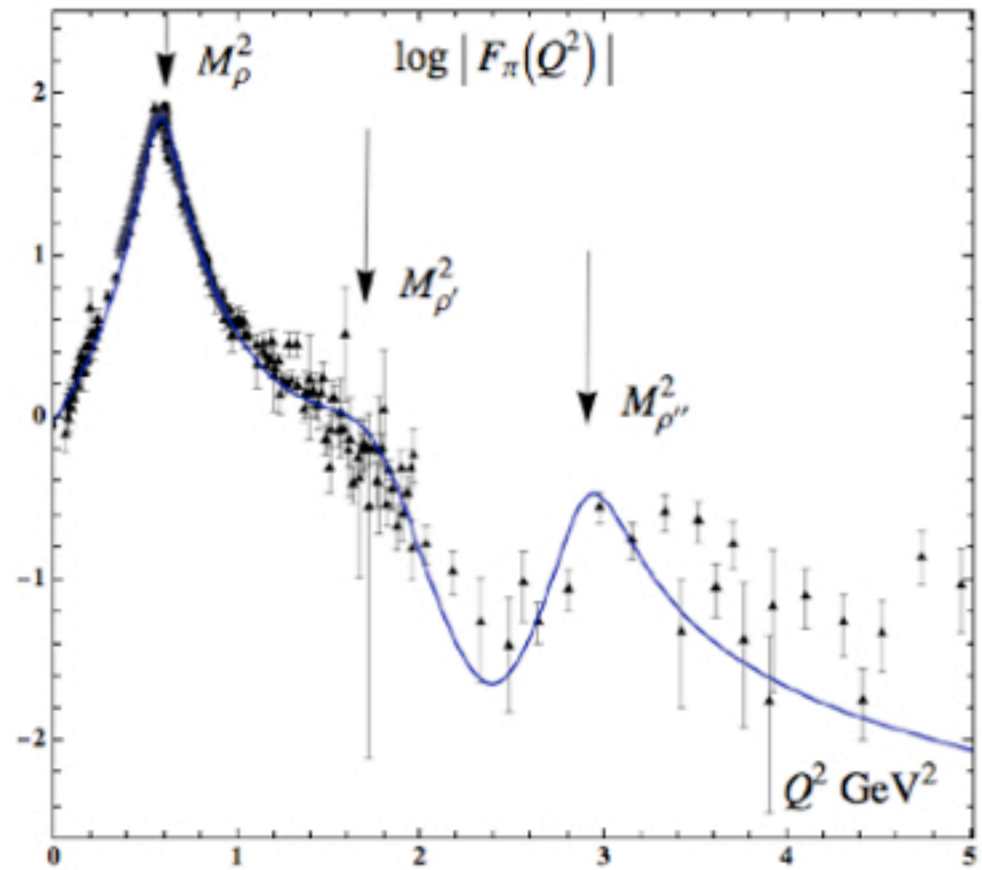
- For large $Q^2$:

$$F(Q^2) \to (N-1)! \left[\frac{4\kappa^2}{Q^2}\right]^{(N-1)}.$$

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

**PRELIMINARY**



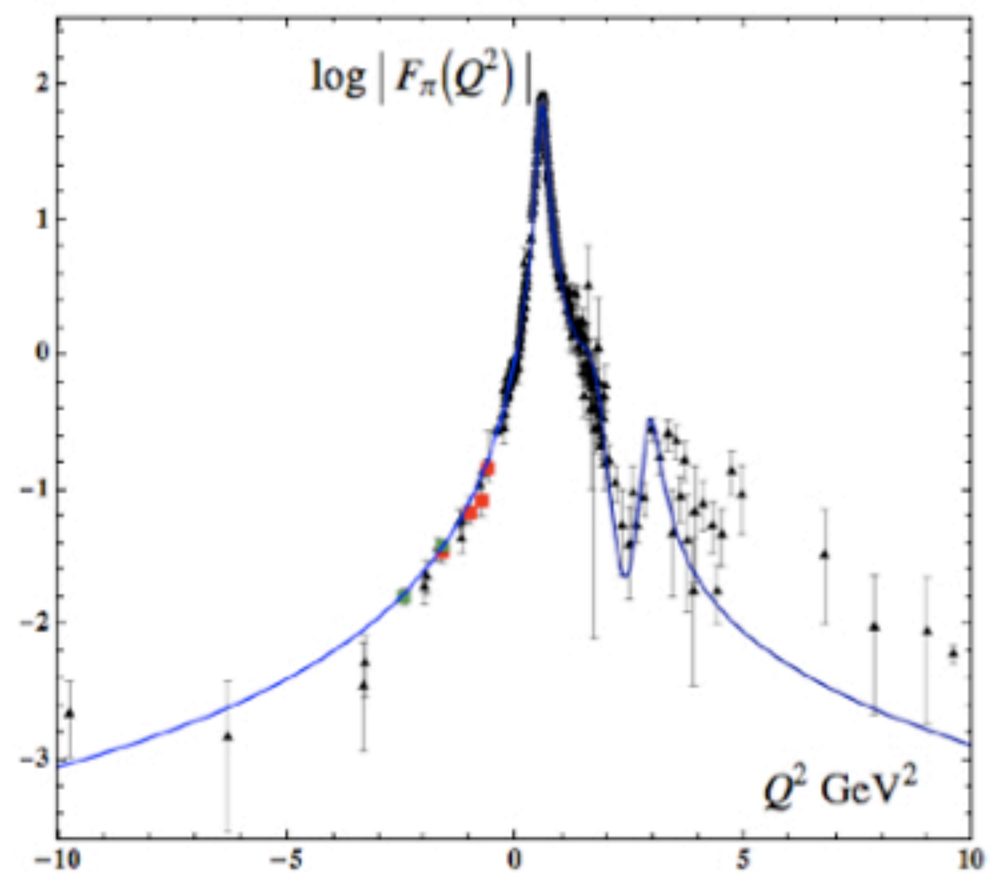

$$|\pi\rangle = \psi_{q\bar{q}/\pi}|q\bar{q}\rangle + \psi_{q\bar{q}q\bar{q}/\pi}|q\bar{q}q\bar{q}\rangle$$

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

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

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

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



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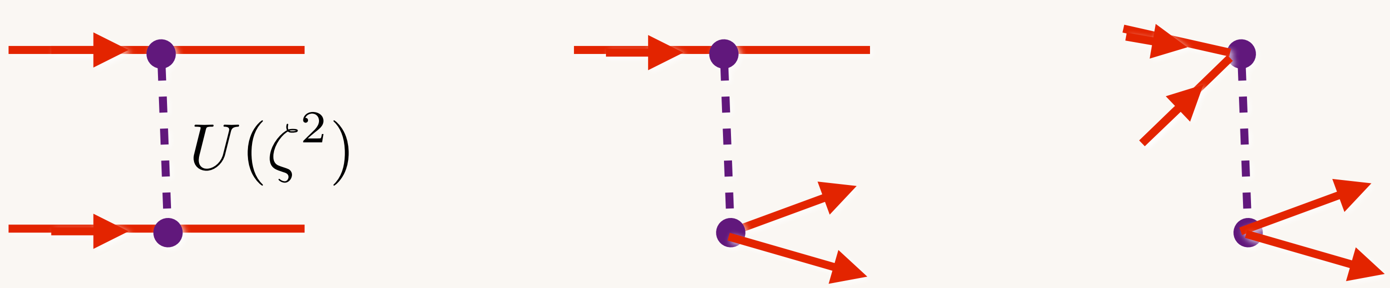
# AdS/QCD predicts Higher Fock States

- Exposed by timelike form factor through dressed current.

- Created by confining interaction

$$P^-_{\text{confinement}} \simeq \kappa^4 \int dx^- d^2\vec{x}_\perp \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+} \frac{1}{(\partial/\partial_\perp)^4} \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+}$$

- Similar to QCD(1+1) in lcg




**de Teramond, sjb**

## Meson Transition Form-Factors

[S. J. Brodsky, Fu-Guang Cao and GdT, arXiv:1005.39XX]

- Pion TFF from 5-dim Chern-Simons structure [Hill and Zachos (2005), Grigoryan and Radyushkin (2008)]

$$\int d^4x \int dz \, \epsilon^{LMNPQ} A_L \partial_M A_N \partial_P A_Q$$
$$\sim (2\pi)^4 \delta^{(4)} \left(p_\pi + q - k\right) F_{\pi\gamma}(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\mu(q) (p_\pi)_\nu \epsilon_\rho(k) q_\sigma$$

- Take $A_z \propto \Phi_\pi(z)/z, \quad \Phi_\pi(z) = \sqrt{2 P_{q\bar q}} \, \kappa \, z^2 e^{-\kappa^2 z^2/2}, \quad \langle \Phi_\pi | \Phi_\pi \rangle = P_{q\bar q}$
- Find $\left(\phi(x) = \sqrt{3} f_\pi x(1-x), \quad f_\pi = \sqrt{P_{q\bar q}} \, \kappa / \sqrt{2}\pi\right)$

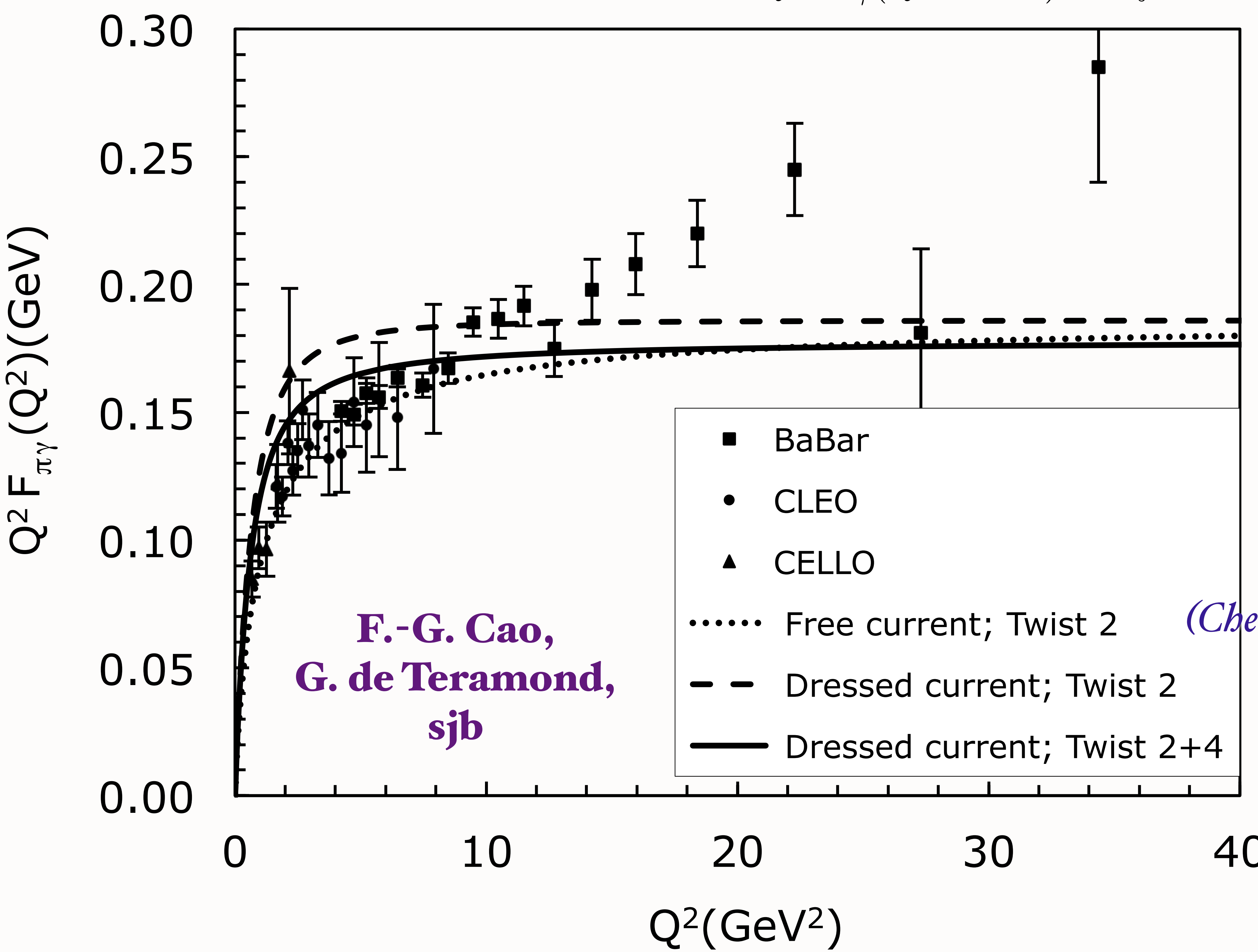
$$Q^2 F_{\pi\gamma}(Q^2) = \frac{4}{\sqrt{3}} \int_0^1 dx \frac{\phi(x)}{1-x} \left[1 - e^{-P_{q\bar q} Q^2 (1-x)/4\pi^2 f_\pi^2 \, x}\right]$$

normalized to the asymptotic DA [$P_{q\bar q} = 1 \rightarrow$ Musatov and Radyushkin (1997)] **G.P. Lepage, sjb**

- Large $Q^2$ TFF is identical to first principles asymptotic QCD result $Q^2 F_{\pi\gamma}(Q^2 \rightarrow \infty) = 2 f_\pi$
- The CS form is local in AdS space and projects out only the asymptotic form of the pion DA

# Photon-to-pion transition form factor

$$Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2f_\pi.$$




*(Chern-Simons)*

# Running Coupling from Modified AdS/QCD

**Deur, de Teramond, sjb**

- Consider five-dim gauge fields propagating in AdS$_5$ space in dilaton background $\varphi(z) = \kappa^2 z^2$

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

- Flow equation

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

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

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

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

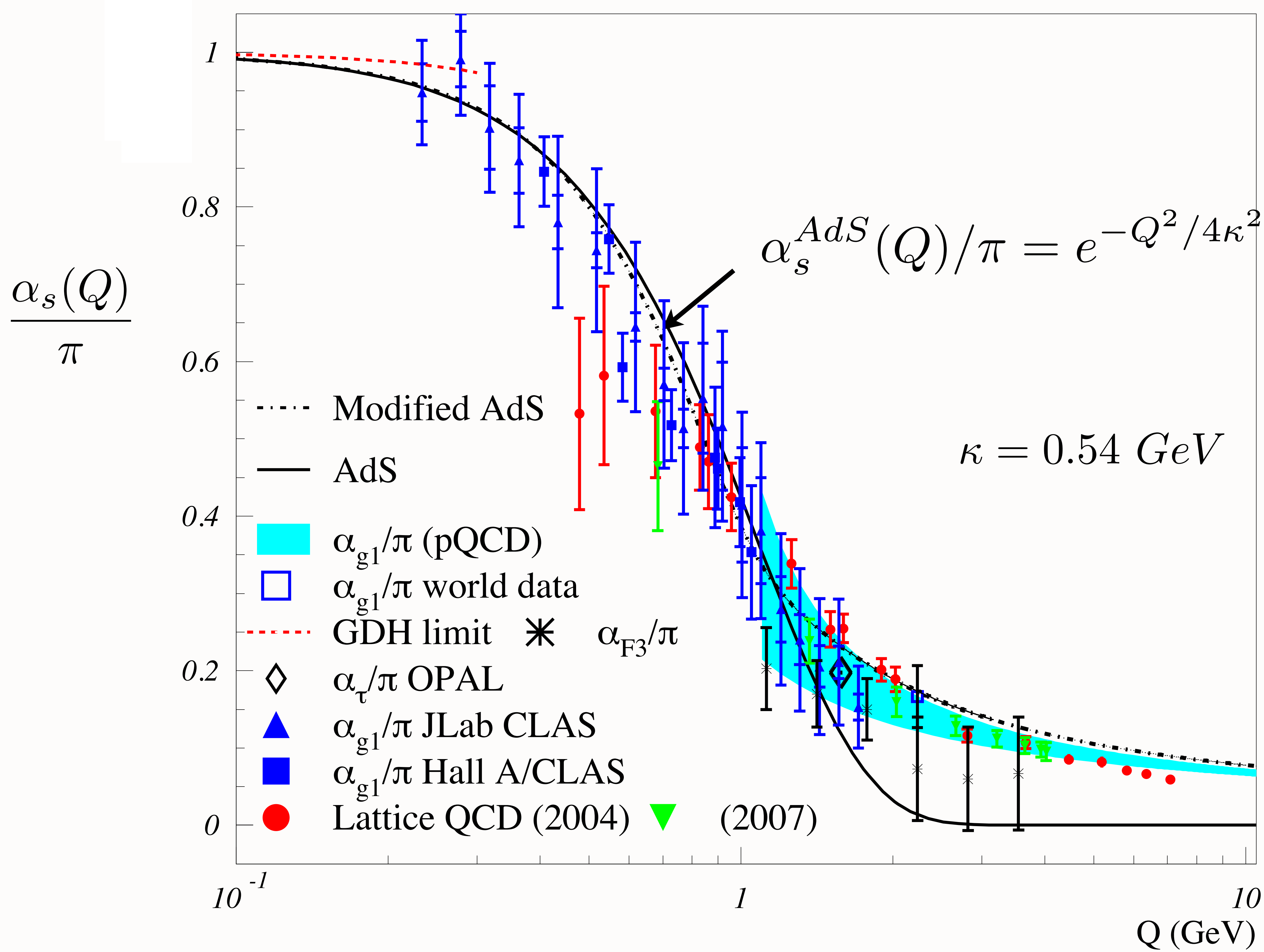
- Solution

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

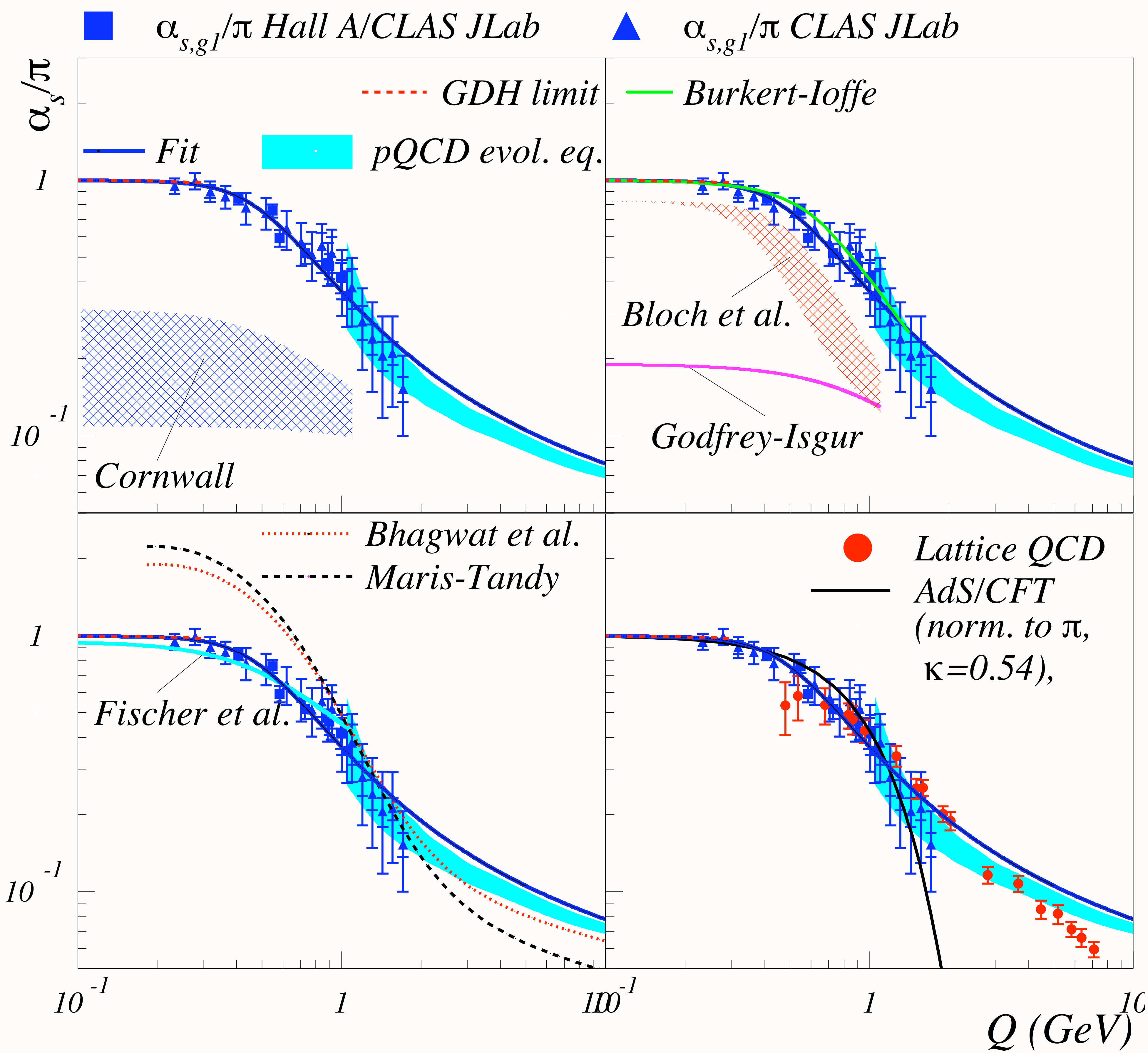
where the coupling $\alpha_s^{AdS}$ incorporates the non-conformal dynamics of confinement

# Running Coupling from Light-Front Holography and AdS/QCD

## Analytic, defined at all scales, IR Fixed Point

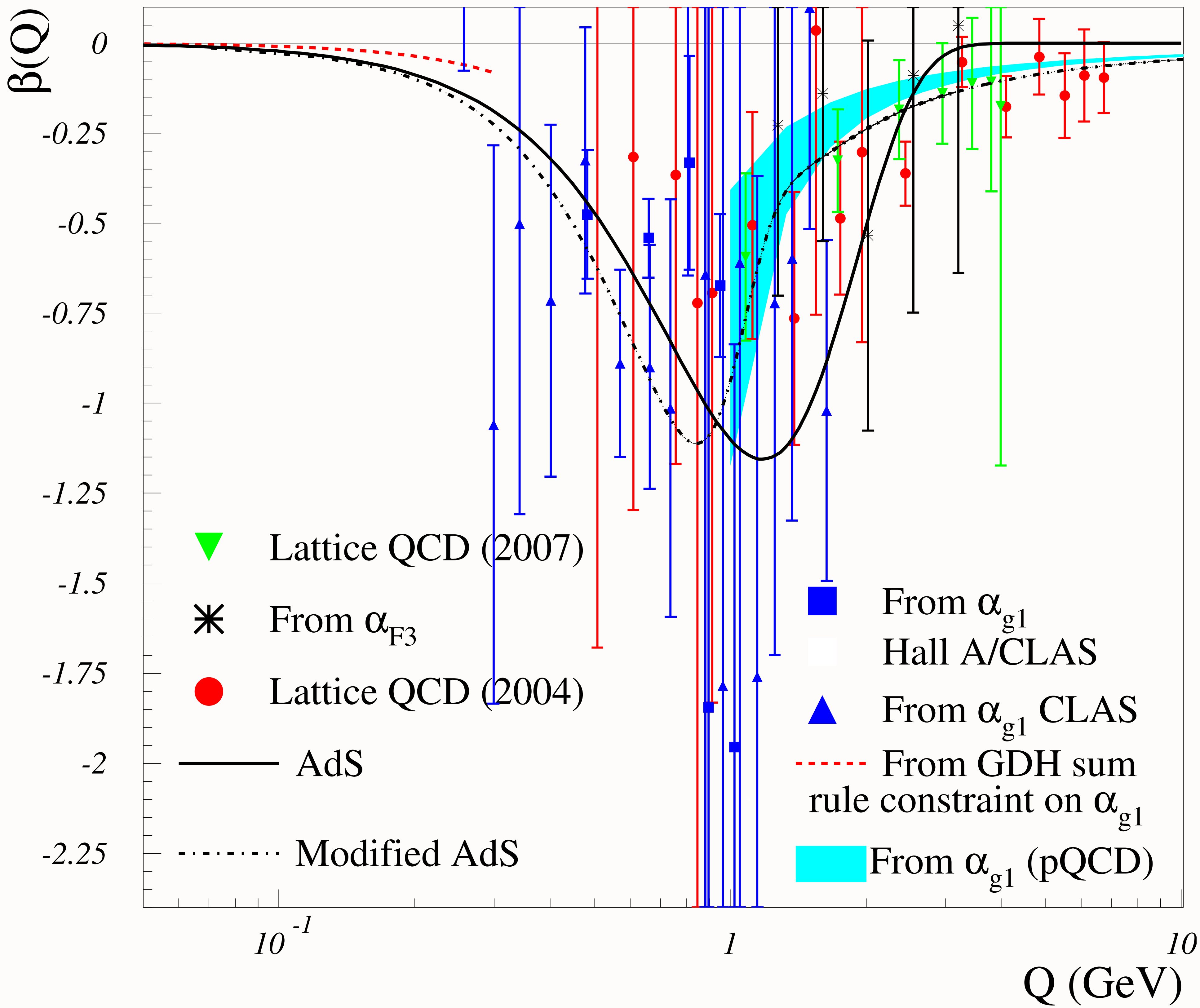



Deur, de Teramond, sjb




Deur, de Teramond, sjb, (preliminary)

$$\beta^{AdS}(Q^2) = \frac{d}{d\log Q^2}\alpha_s^{AdS}(Q^2) = \frac{\pi Q^2}{4\kappa^2}e^{-Q^2/4\kappa^2}$$




**Deur, de Teramond, sjb**

# Features of AdS/QCD LF Holography

- Based on Conformal Scaling of Infrared QCD Fixed Point
- Conformal template: Use isometries of $AdS_5$
- Interpolating operator of hadrons based on twist, superfield dimensions
- Finite $N_c = 3$: Baryons built on 3 quarks -- Large $N_c$ limit not required
- Break Conformal symmetry with dilaton
- Dilaton introduces confinement -- positive exponent
- Origin of Linear and HO potentials: Stochastic arguments (Glazek); General 'classical' potential for Dirac Equation (Hoyer)
- Effective Charge from AdS/QCD at all scales
- Conformal Dimensional Counting Rules for Hard Exclusive Processes

**Bjorken, Kogut, Soper; Blankenbecler, Gunion, sjb; Blankenbecler, Schmidt**

# *Crucial Test of Leading -Twist QCD: Scaling at fixed $x_T$*

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^{n_{\text{eff}}}}$$

$$x_T = \frac{2p_T}{\sqrt{s}}$$

**Parton model: $n_{eff} = 4$**

**As fundamental as Bjorken scaling in DIS**

**scaling law: $n_{eff} = 2\, n_{active} - 4$**

# Dimensional analysis

Scattering amplitude $1\ 2 \cdots \to \ldots n$ has dimension

$$\mathcal{M} \sim [\text{length}]^{n-4}$$

## Consequence

In a conformal theory (no intrinsic scale), scaling of inclusive particle production

$$E\,\frac{d\sigma}{d^3p}(A\ B\ \to C\ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta^{\text{cm}})}{p_\perp^{2n_{\text{active}}-4}}$$

where $n_{\text{active}}$ is the number of fields participating to the hard process

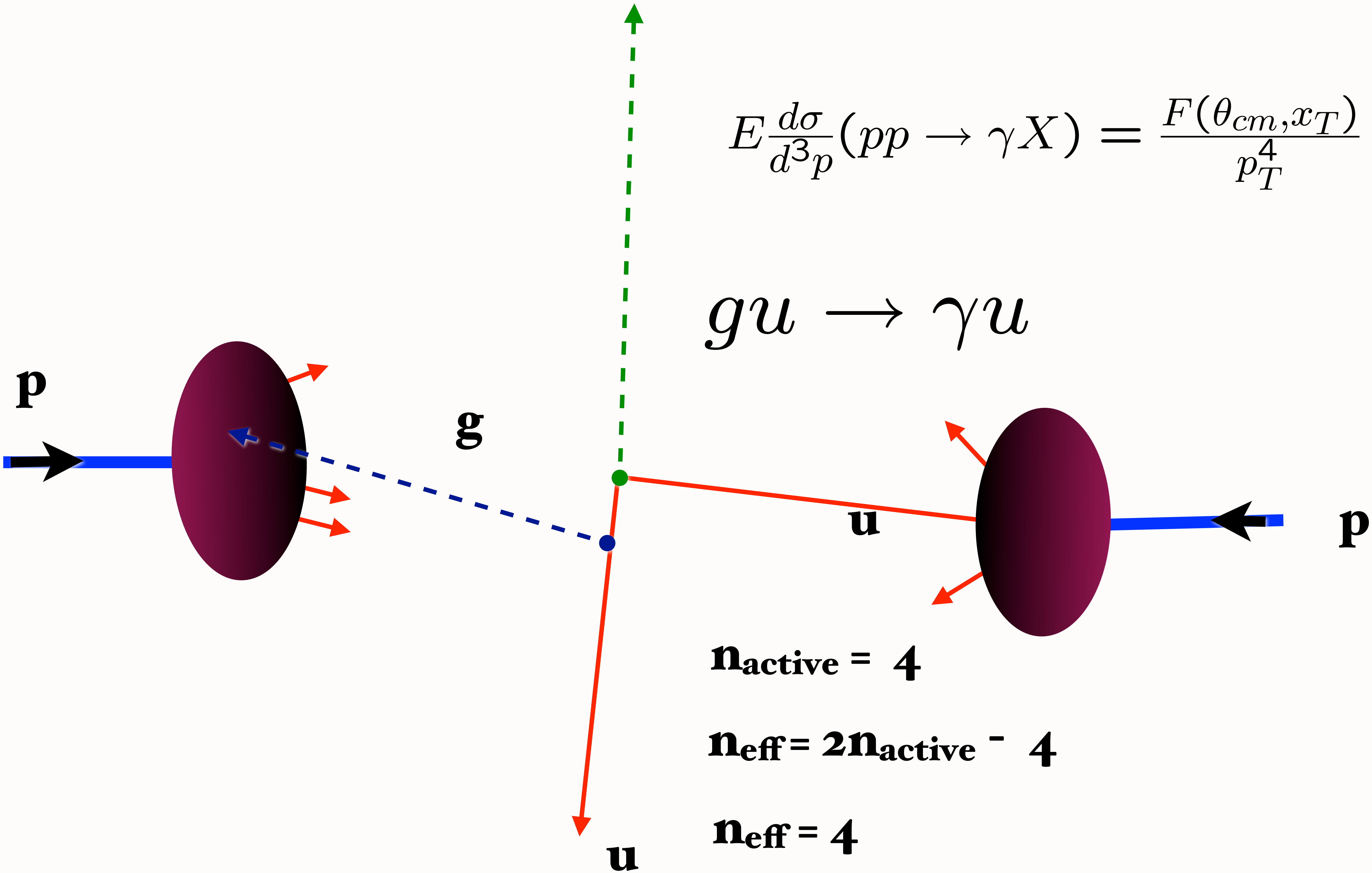
$x_\perp = 2p_\perp/\sqrt{s}$ and $\vartheta^{\text{cm}}$: ratios of invariants

$$n_{active} = 4 \to n_{eff} = 4$$

$$pp \longrightarrow \gamma X$$

$$E\frac{d\sigma}{d^3p}(pp \rightarrow \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$$

$$gu \longrightarrow \gamma u$$




$n_{active} = 4$

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

$n_{eff} = 4$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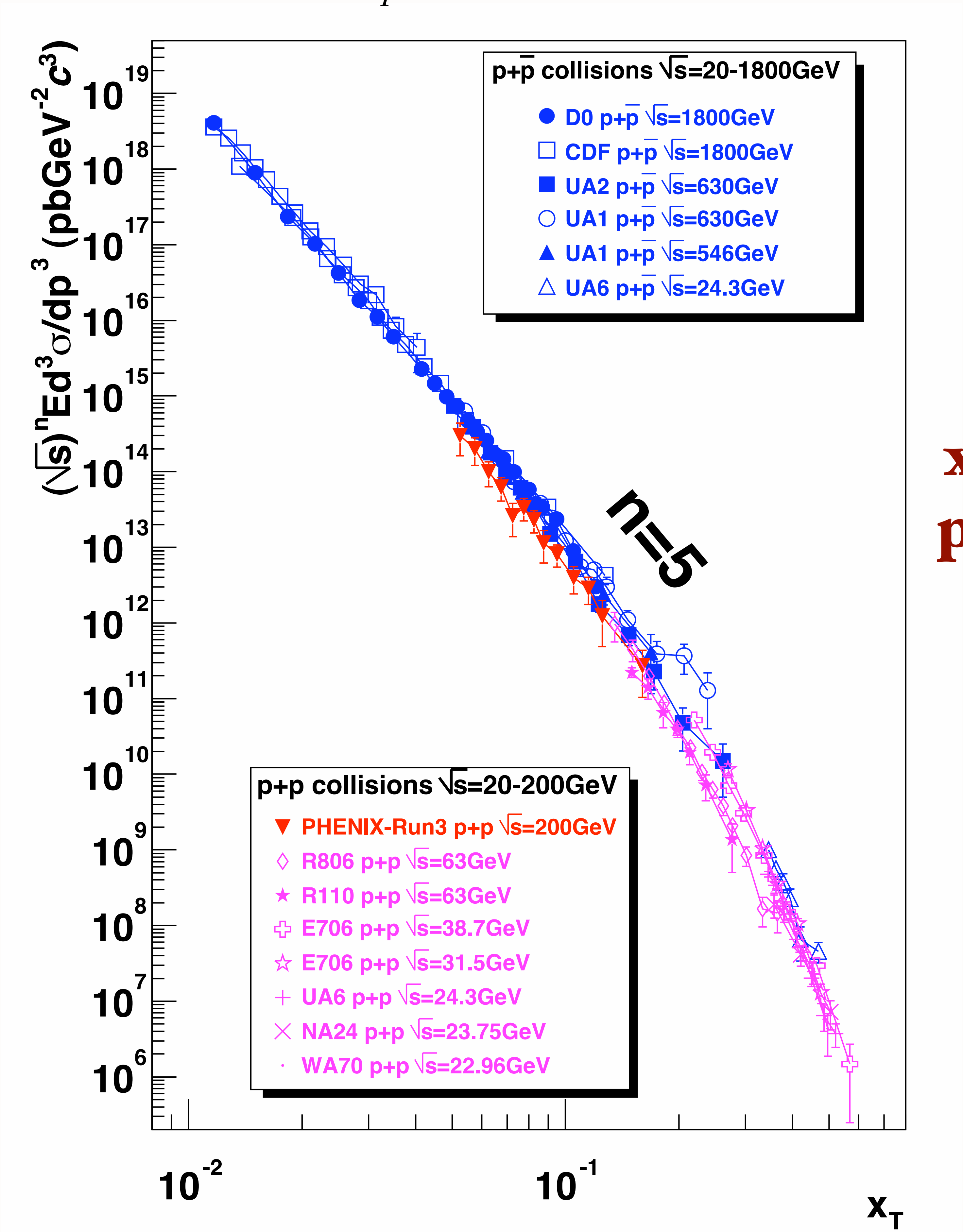
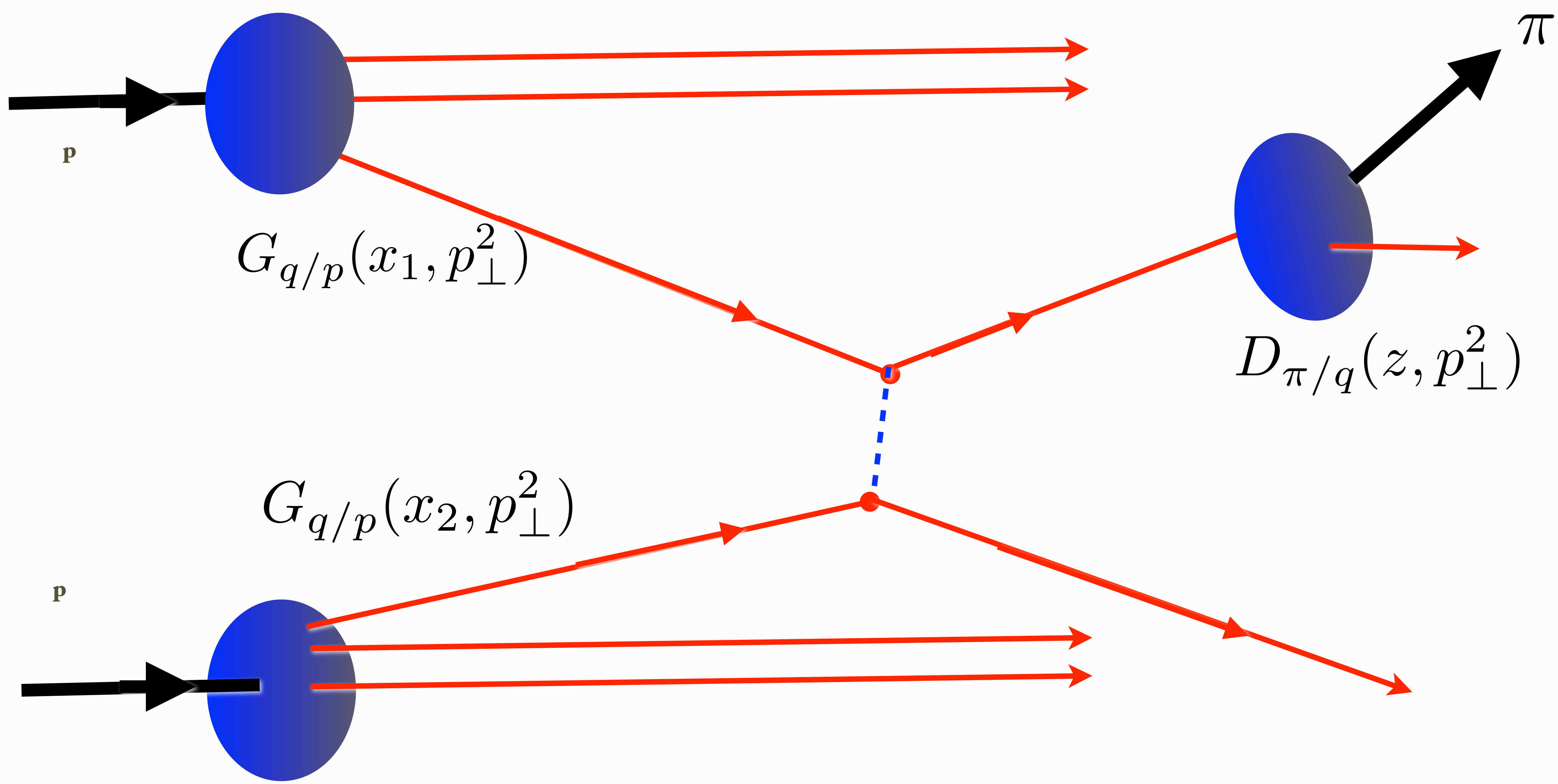
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed $x_T$

Tannenbaum




**$x_T$-scaling of direct photon production: consistent with PQCD**

# Leading-Twist Contribution to Hadron Production

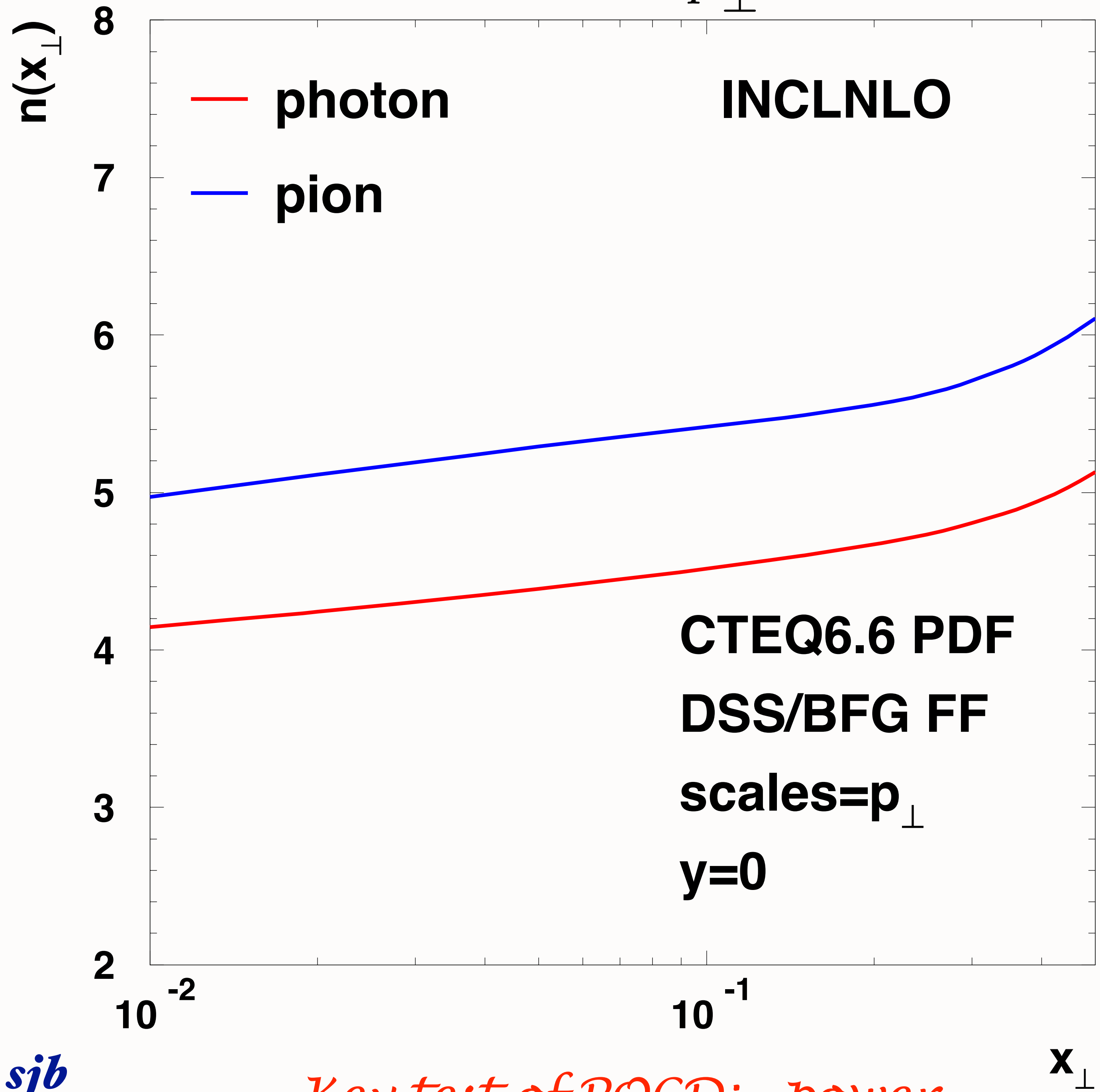



Parton model and Conformal Scaling:

$$\frac{d\sigma}{d^3p/E} = \alpha_s^2 \frac{F(x_\perp, y)}{p_\perp^4}$$

# QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$




$$pp \to \pi X$$

$$pp \to \gamma X$$

$$5 < p_\perp < 20 \; GeV$$

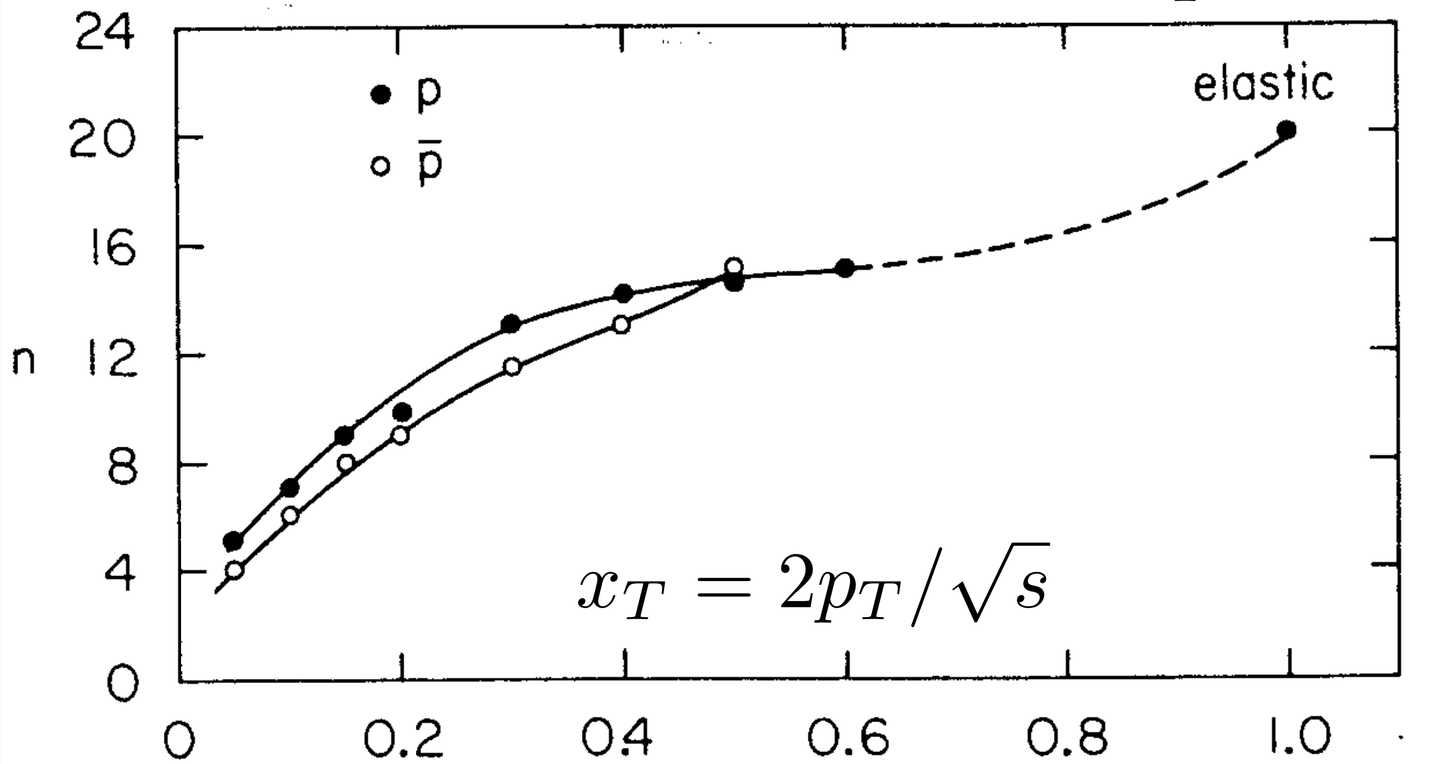
$$70 \; GeV < \sqrt{s} < 4 \; TeV$$

*Arleo, Hwang, Sickles, sjb*

*Pirner, Raufeisen, sjb*

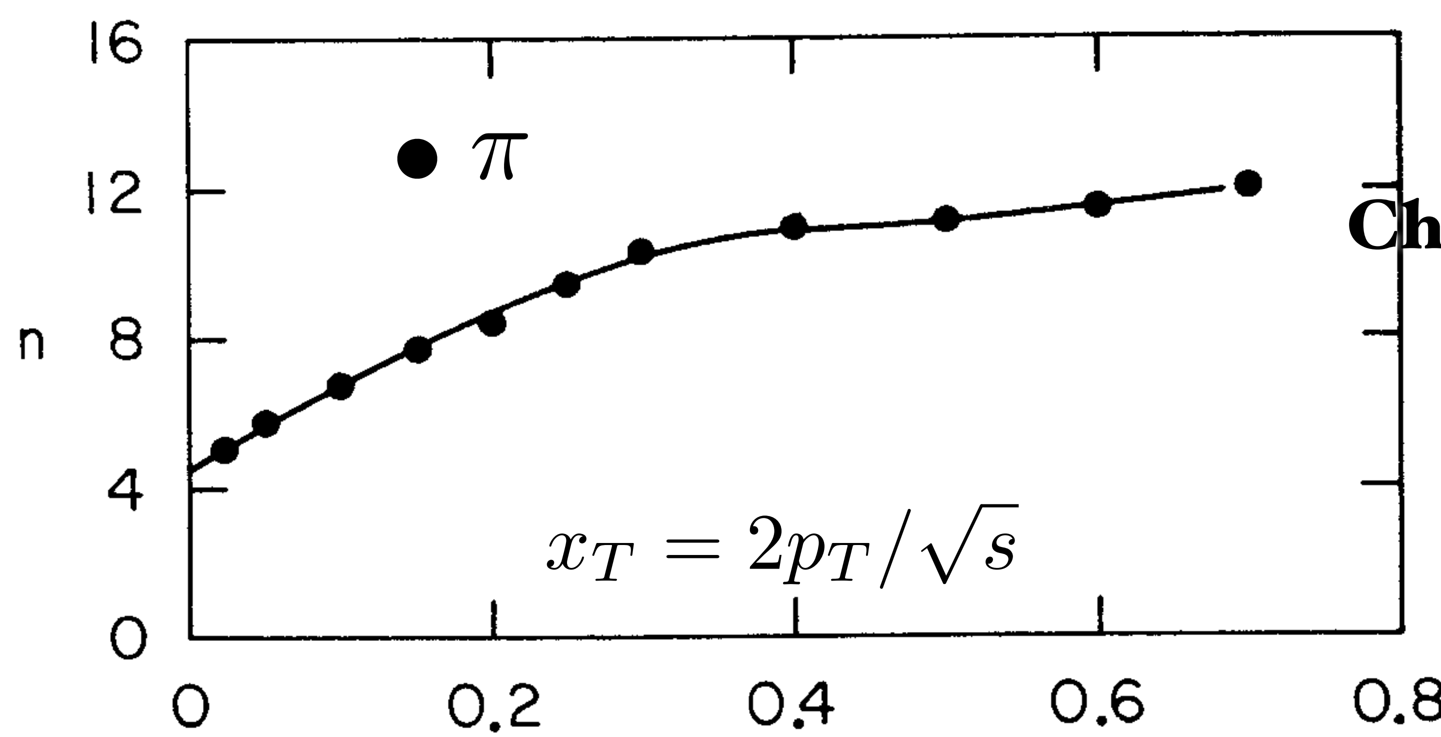
*Key test of PQCD: power-law fall-off at fixed $x_T$*

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



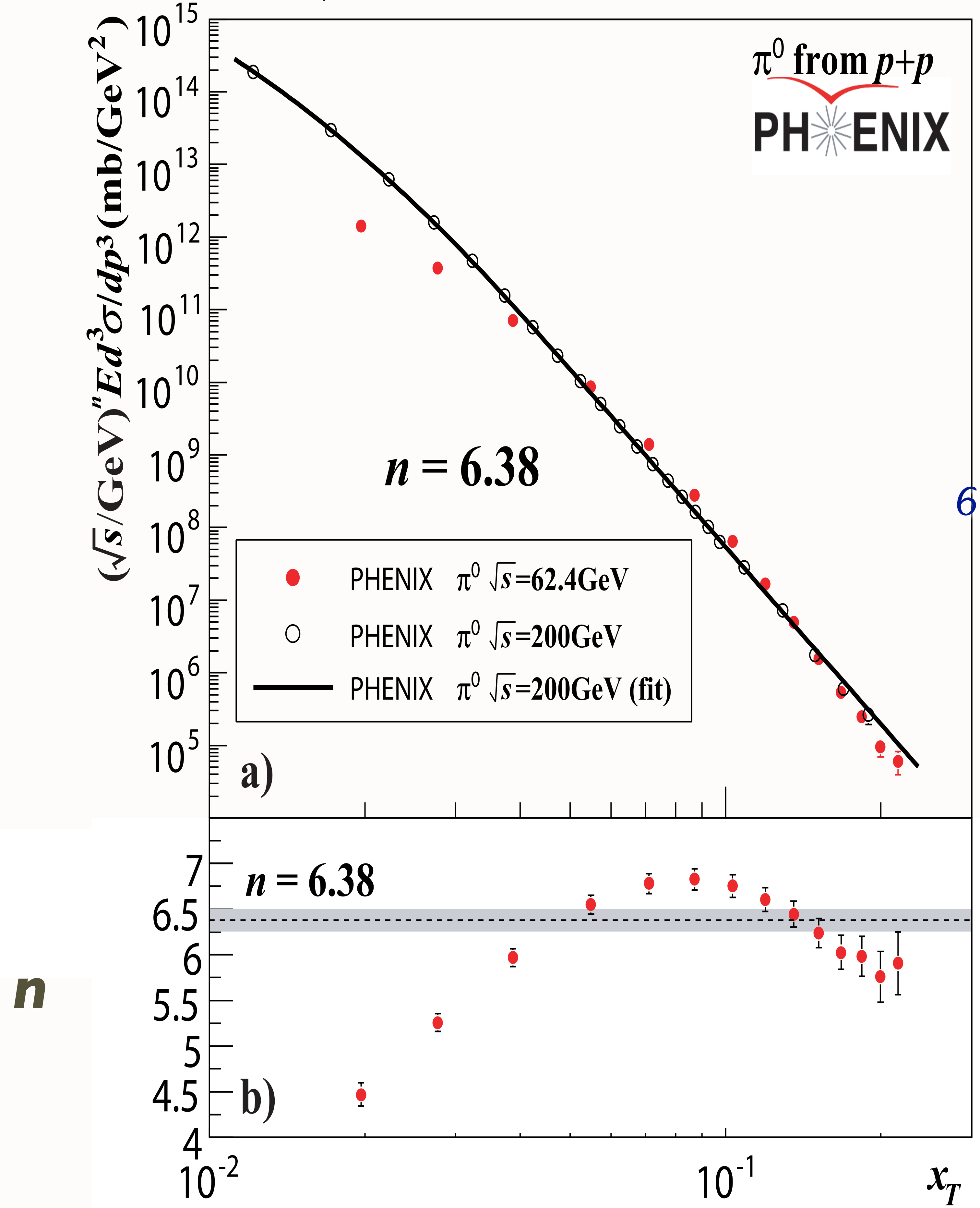

*Clear evidence for higher-twist contributions*

**J. W. Cronin, SSI 1974**




**Chicago-Princeton FNA**

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




M. J. Tannenbaum

PHENIX
62.4 and 200 GeV data

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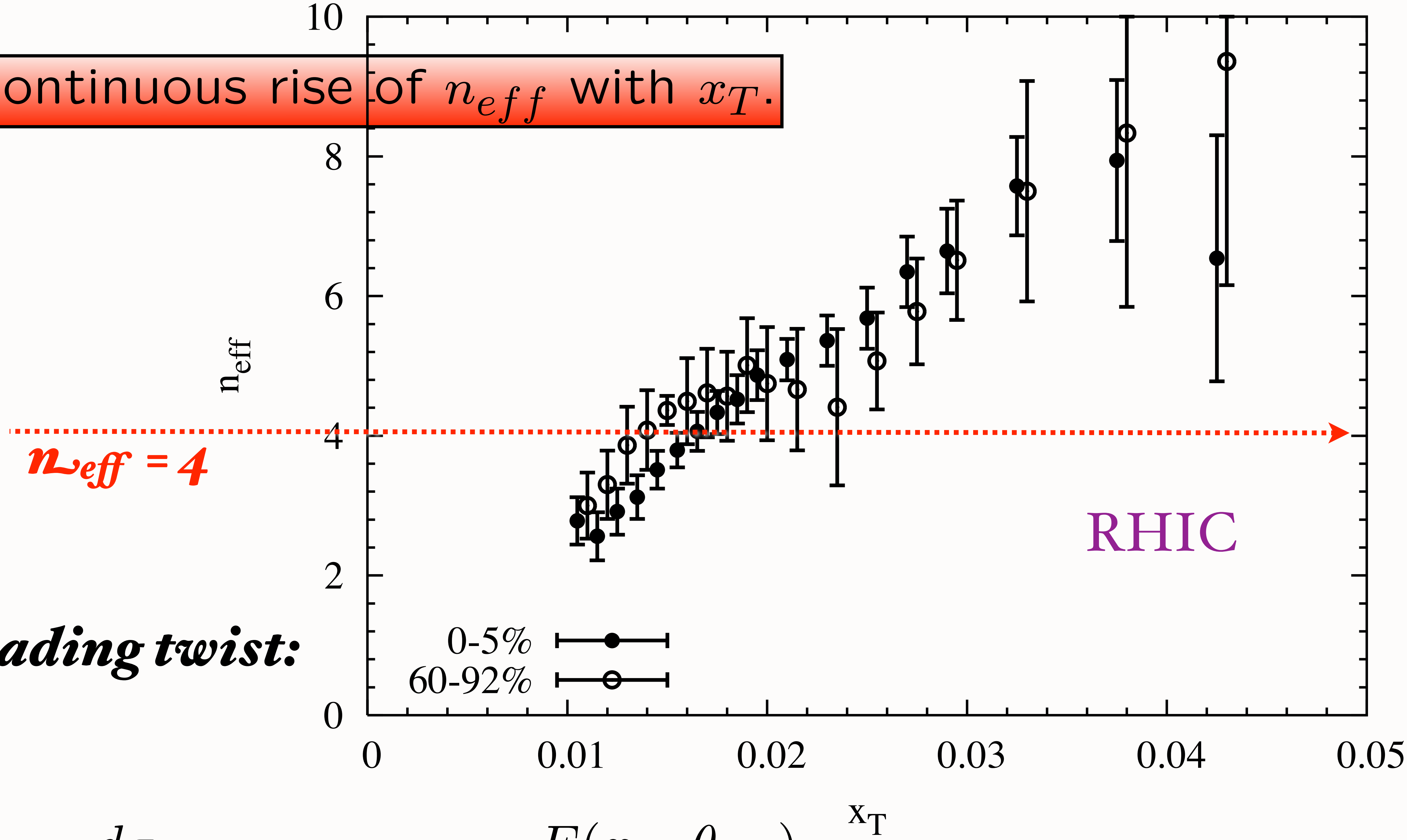
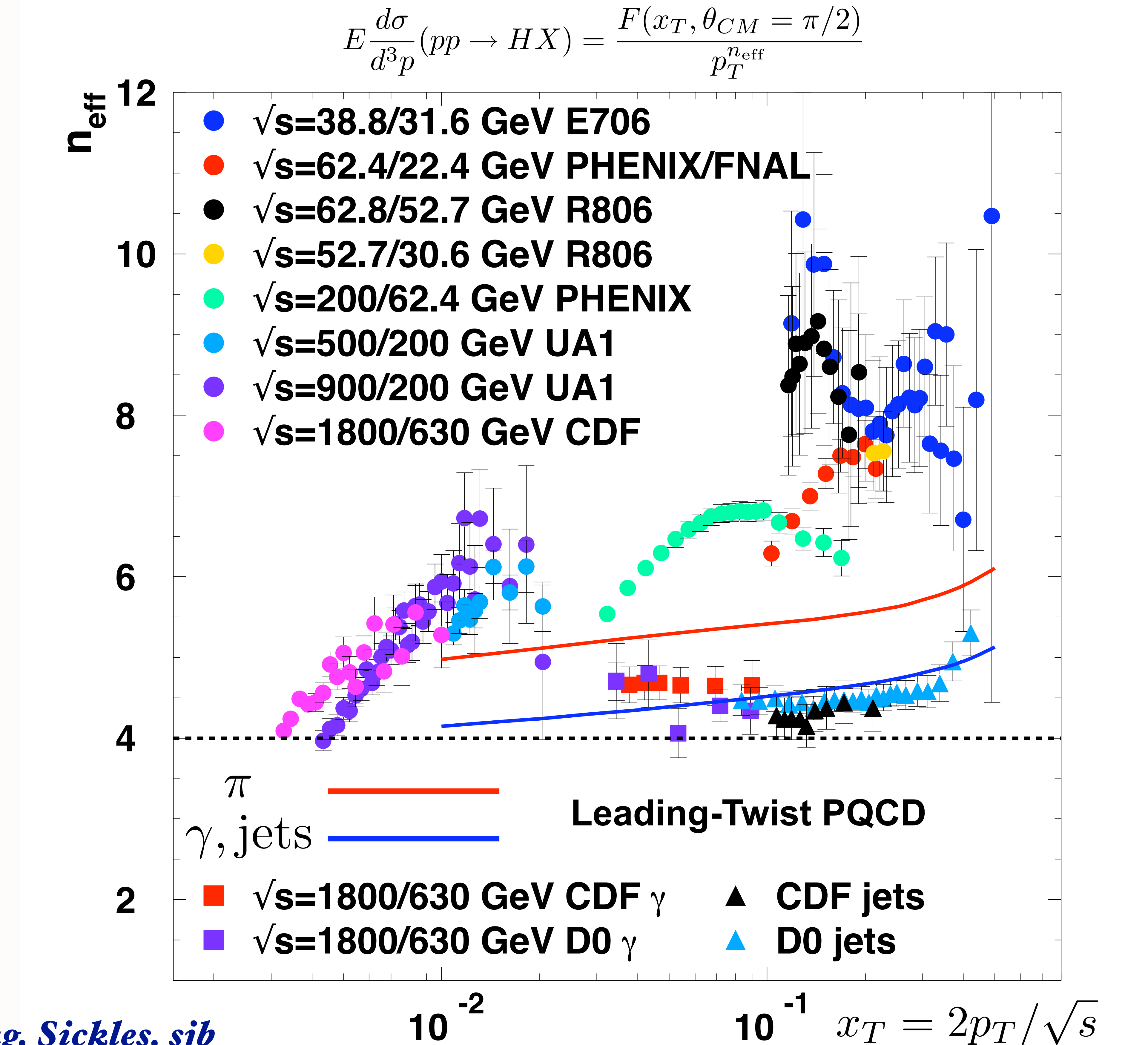
*Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available $p_T$ range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.*

Continuous rise of $n_{eff}$ with $x_T$.



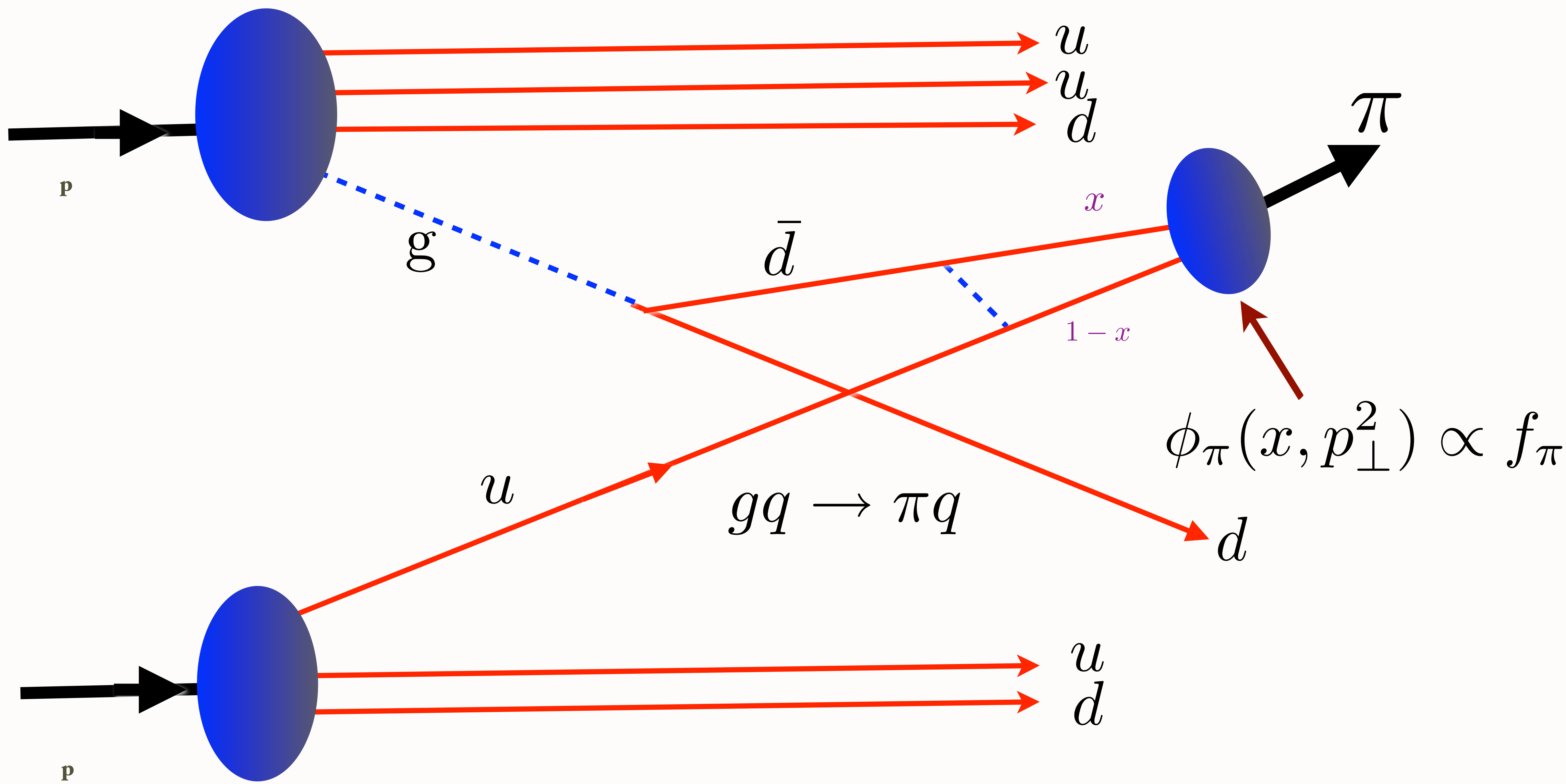

***Leading twist:***

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




*Arleo,Hwang, Sickles, sjb*

# Direct Contribution to Hadron Production

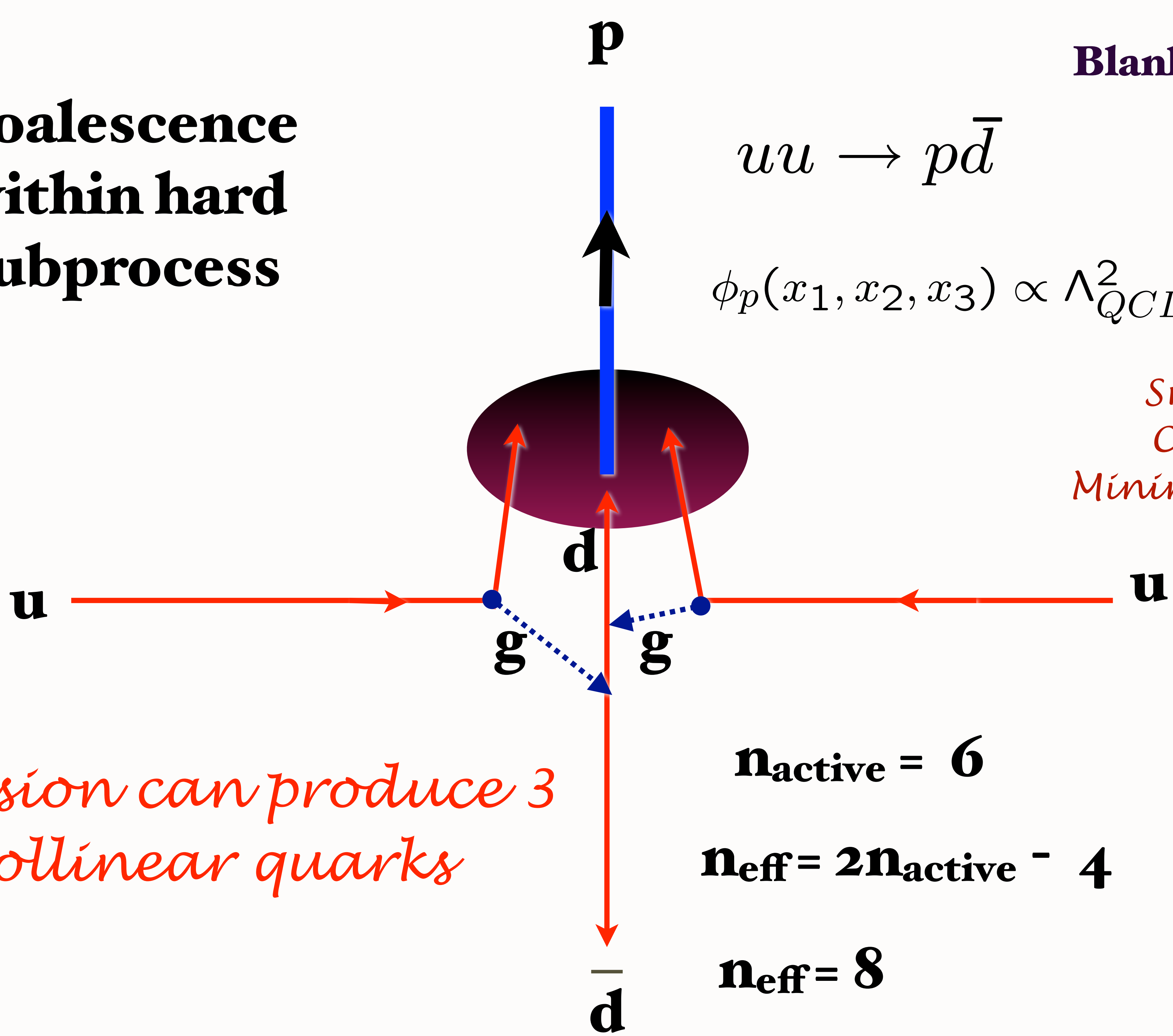



$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

# 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**
**Sickles, Sjb**

*Small color-singlet*
*Color Transparent*
*Minimal same-side energy*

*Collision can produce 3 collinear quarks*

$n_{active} = 6$

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

$n_{eff} = 8$

$qq \rightarrow B\bar{q}$

# Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

2-component toy-model

$$\sigma^{\mathrm{model}}(pp \to \pi\ \mathrm{X}) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

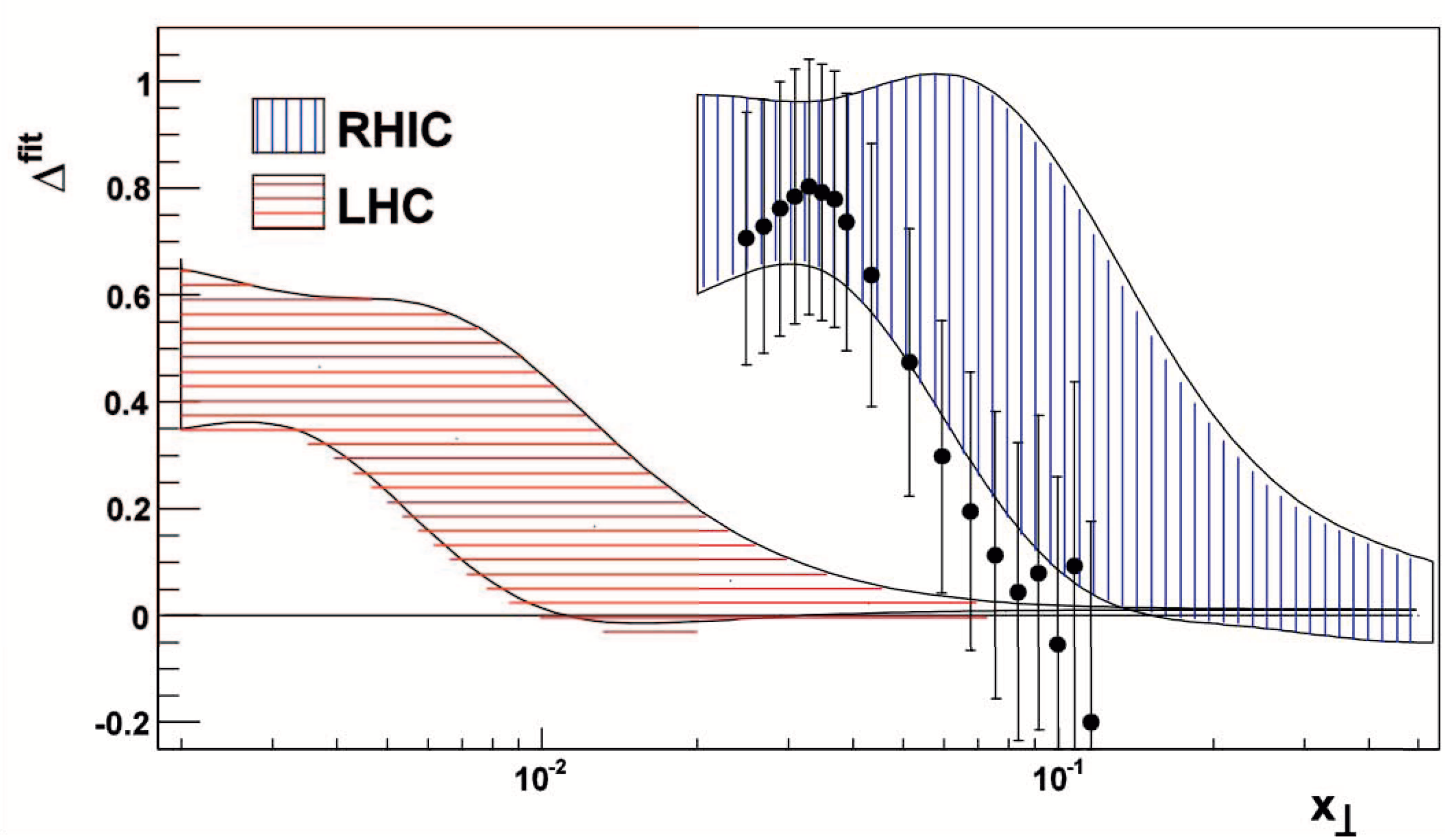
$$\begin{aligned} n_{\mathrm{eff}}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\mathrm{model}}}{\partial \ln p_\perp} + n^{\mathrm{NLO}}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\mathrm{NLO}}(x_\perp, p_\perp) \end{aligned}$$

# RHIC/LHC predictions

## PHENIX results

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

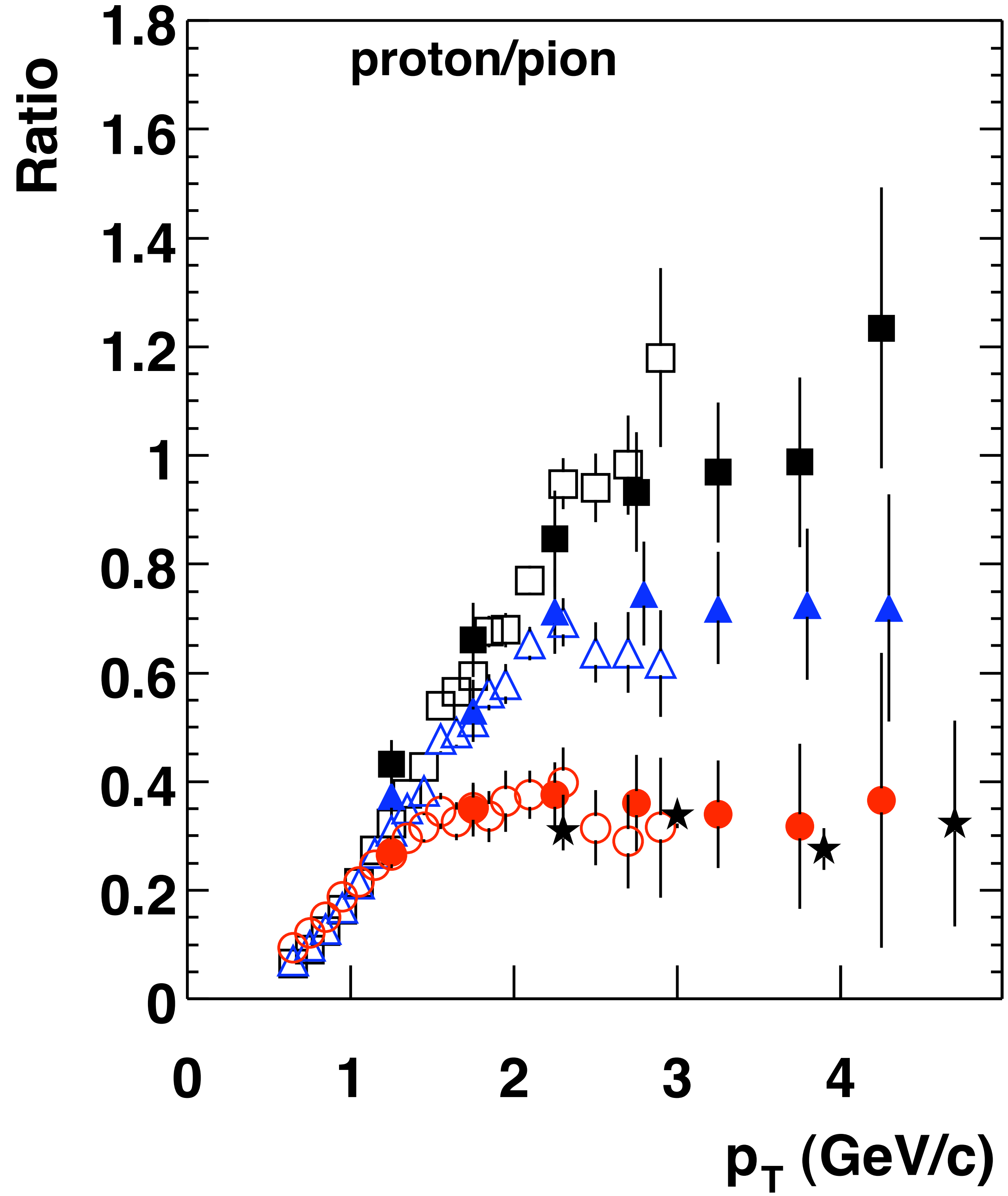
[ A. Bezilevsky, APS Meeting ]




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

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

*Particle ratio changes with centrality!*

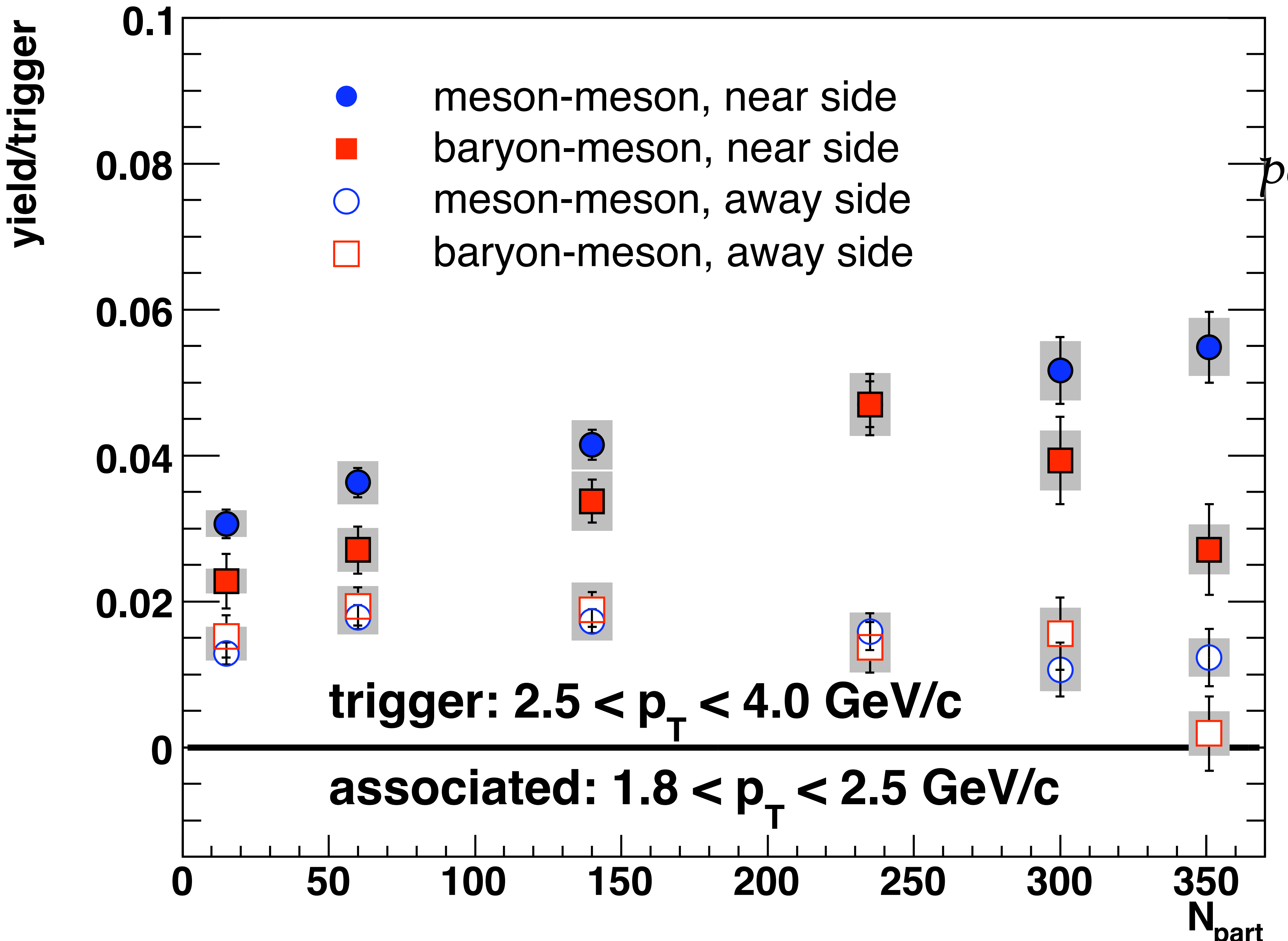



*Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process*

← **Central**

← **Peripheral**

*Tannenbaum: Baryon Anomaly:*

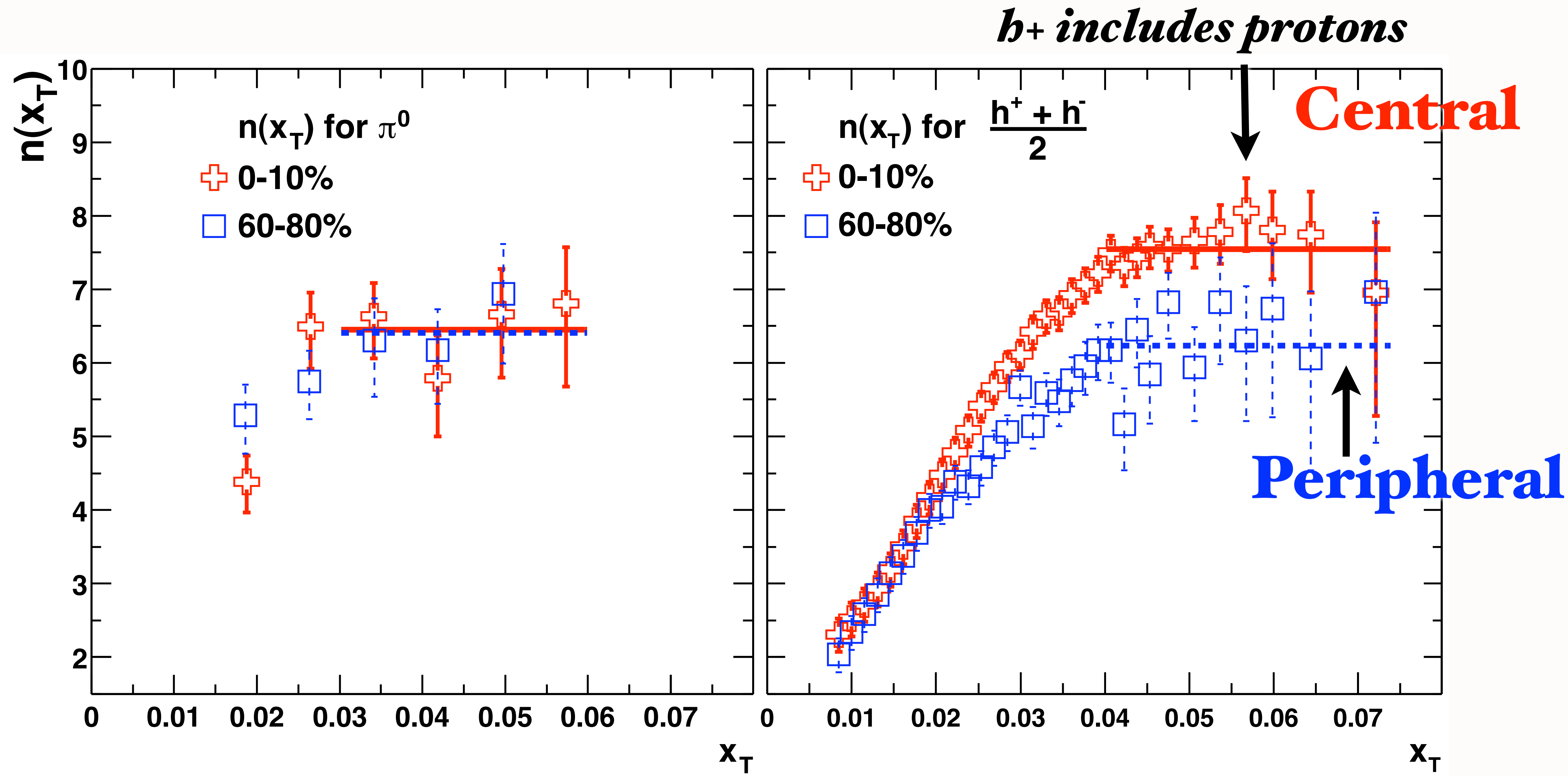



*proton trigger: # same-side particles decreases with centrality*

**Proton production more dominated by color-transparent direct high-$n_{eff}$ subprocesses**

Power-law exponent $n(x_T)$ for $\pi^0$ and $h$ spectra in central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV

S. S. Adler, *et al.*, PHENIX Collaboration, *Phys. Rev.* C **69**, 034910 (2004) [`nucl-ex/0308006`].




Proton power changes with centrality !

Proton production dominated by
color-transparent direct high $n_{eff}$ subprocesses

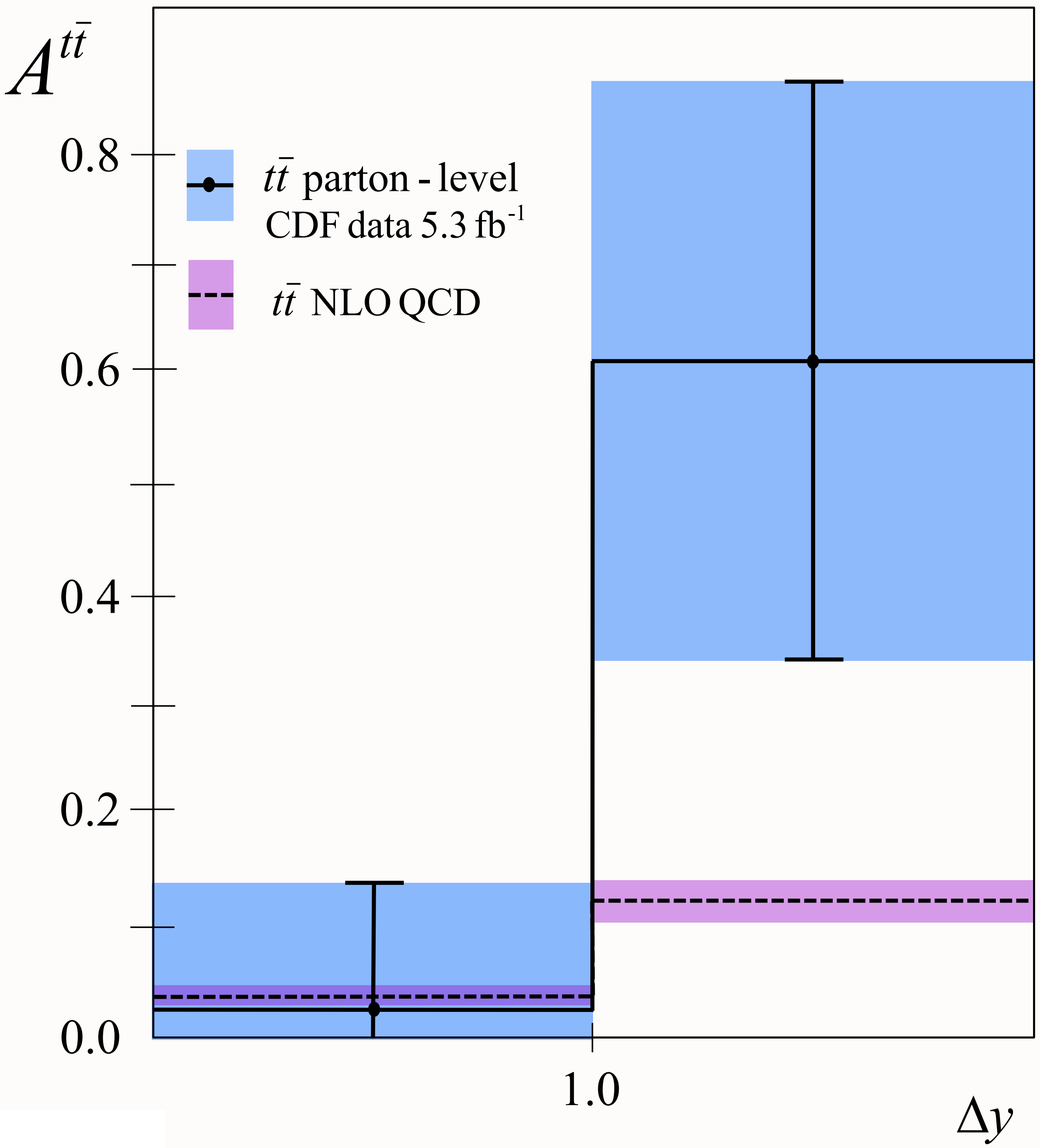
# Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- **Explains anomalous power behavior at fixed $x_T$**
- **Protons more likely to come from direct higher-twist 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**
- **Proton power $n_{eff}$ increases with centrality since leading twist contribution absorbed**
- **Fewer same-side hadrons for proton trigger at high centrality**
- **Exclusive-inclusive connection at $x_T = 1$**

Anne Sickles, sjb

# Higher Twist at the LHC

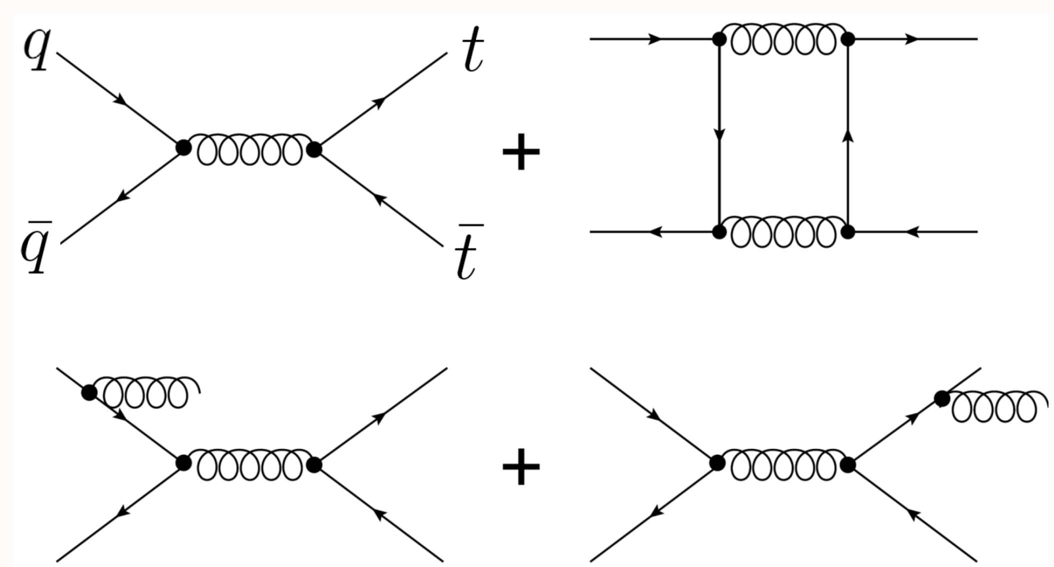
- Fixed $x_T$: powerful analysis of PQCD
- Insensitive to modeling
- Higher twist terms energy efficient since no wasted fragmentation energy
- Evaluate at minimal $x_1$ and $x_2$ where structure functions are maximal
- Higher Twist competitive despite faster fall-off in $p_T$
- Direct processes can confuse new physics searches
- Related to Quarkonium Processes -- Jian-wei Qiu
- Bound-state production: Light-Front Wavefunctions, Distribution amplitudes, ERBL evolution.




Parton level asymmetries at small and large $\Delta y$ compared to SM prediction of MCFM. The shaded bands represent the total uncertainty in each bin. The negative going uncertainty for $\Delta y < 1.0$ is suppressed.

$$A^{t\bar{t}}(\Delta y_i) = \frac{N(\Delta y_i) - N(-\Delta y_i)}{N(\Delta y_i) + N(-\Delta y_i)}$$

Asymmetries in $\Delta y$ are identical to those in the $t$ production angle in the $t\bar{t}$ rest frame. We find a parton-level asymmetry of $A^{t\bar{t}} = 0.158 \pm 0.075$ (stat+sys), which is somewhat higher than, but not inconsistent with, the NLO QCD expectation of $0.058 \pm 0.009$.




Fermilab-Pub-10-525-E

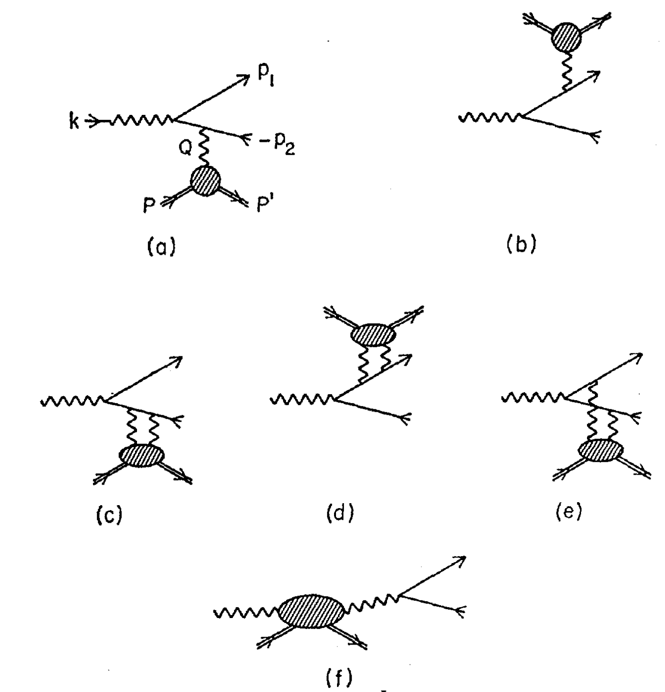
**Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production**

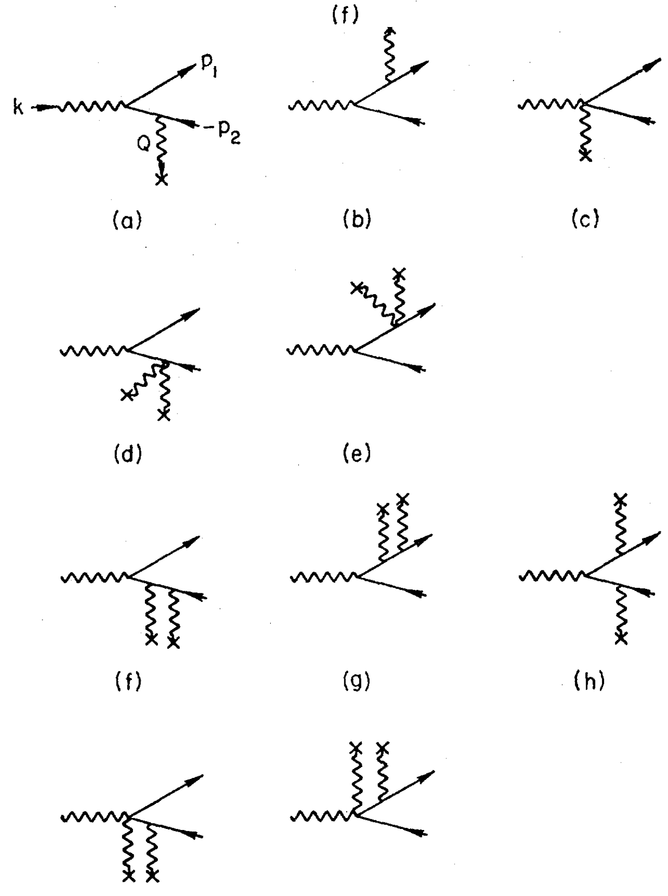
CDF Collaboration

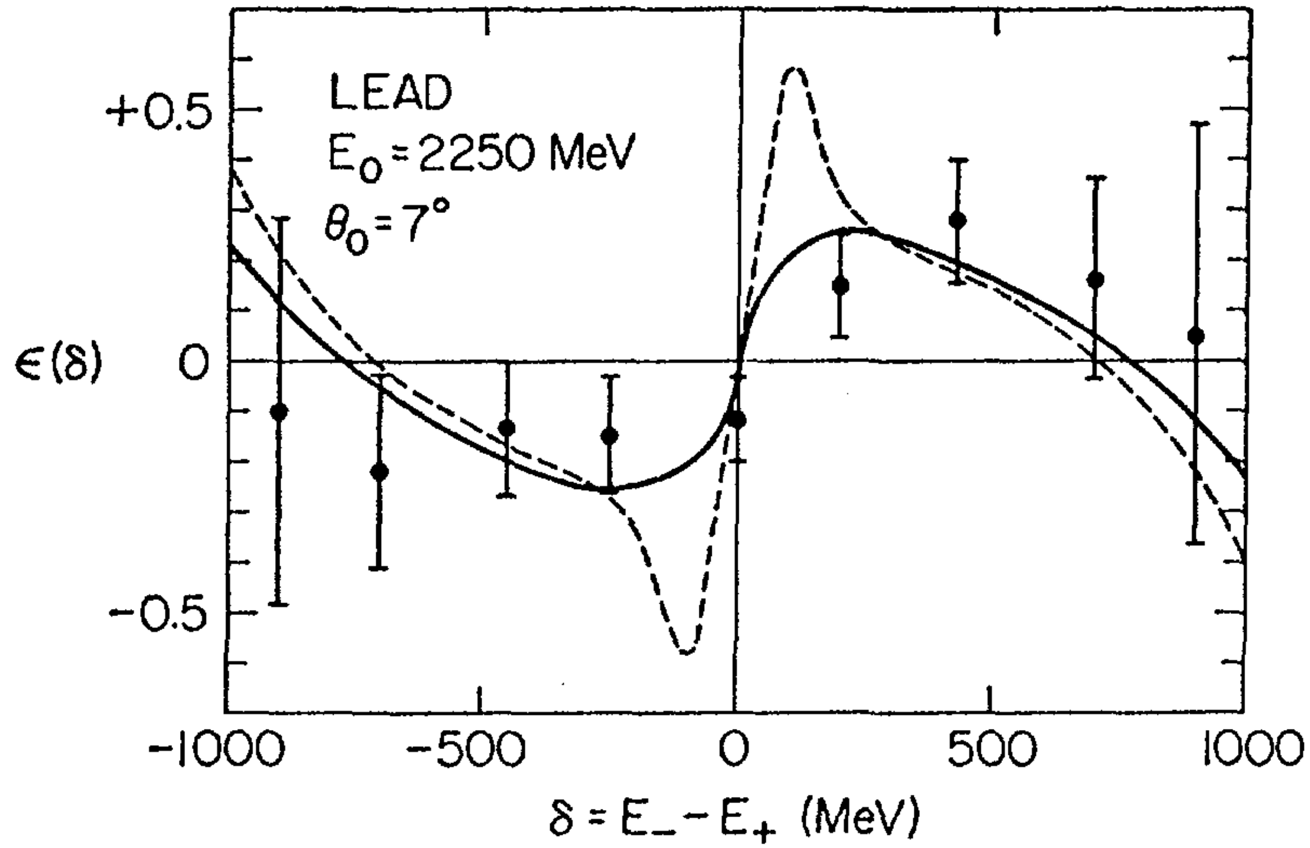
# Second Born Corrections to Wide-Angle High-Energy Electron Pair Production and Bremsstrahlung*

J. Gillespie and sjb

PR 173 1011 (1968)



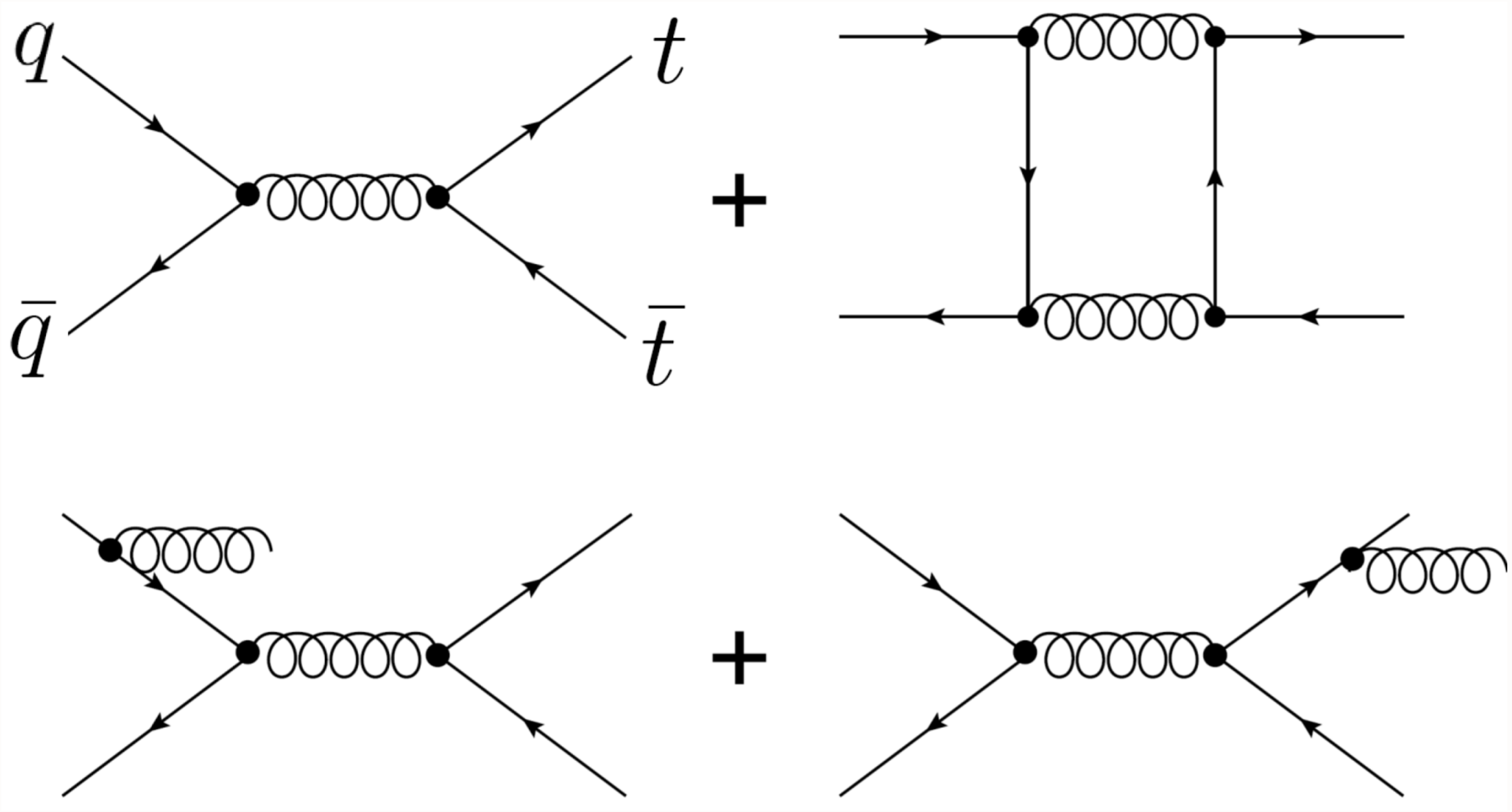




[4] J. G. Asbury, W. K. Bertram, U. Becker, P. Joos, M. Rohde, A. J. S. Smith, S. Friedlander, C. L. Jordan, and S. C. C. Ting, Phys. Rev. **161**, 1344 (1967), and references therein.

$$\mathfrak{R} \equiv \frac{d\sigma_{\text{int}}}{d\sigma_{\text{Born}}} = \tfrac{1}{4} Z\alpha\pi |\mathbf{Q}| \times \left[ \frac{(E_2 - E_1)Q^2 + 2E_2 k\cdot p_2 - 2E_1 k\cdot p_1}{E_1E_2Q^2 + (k\cdot p_1)(k\cdot p_2)} \right] + O(Z\alpha)^3$$

(spin zero, point nucleus). (4.9)




Conventional pQCD approach



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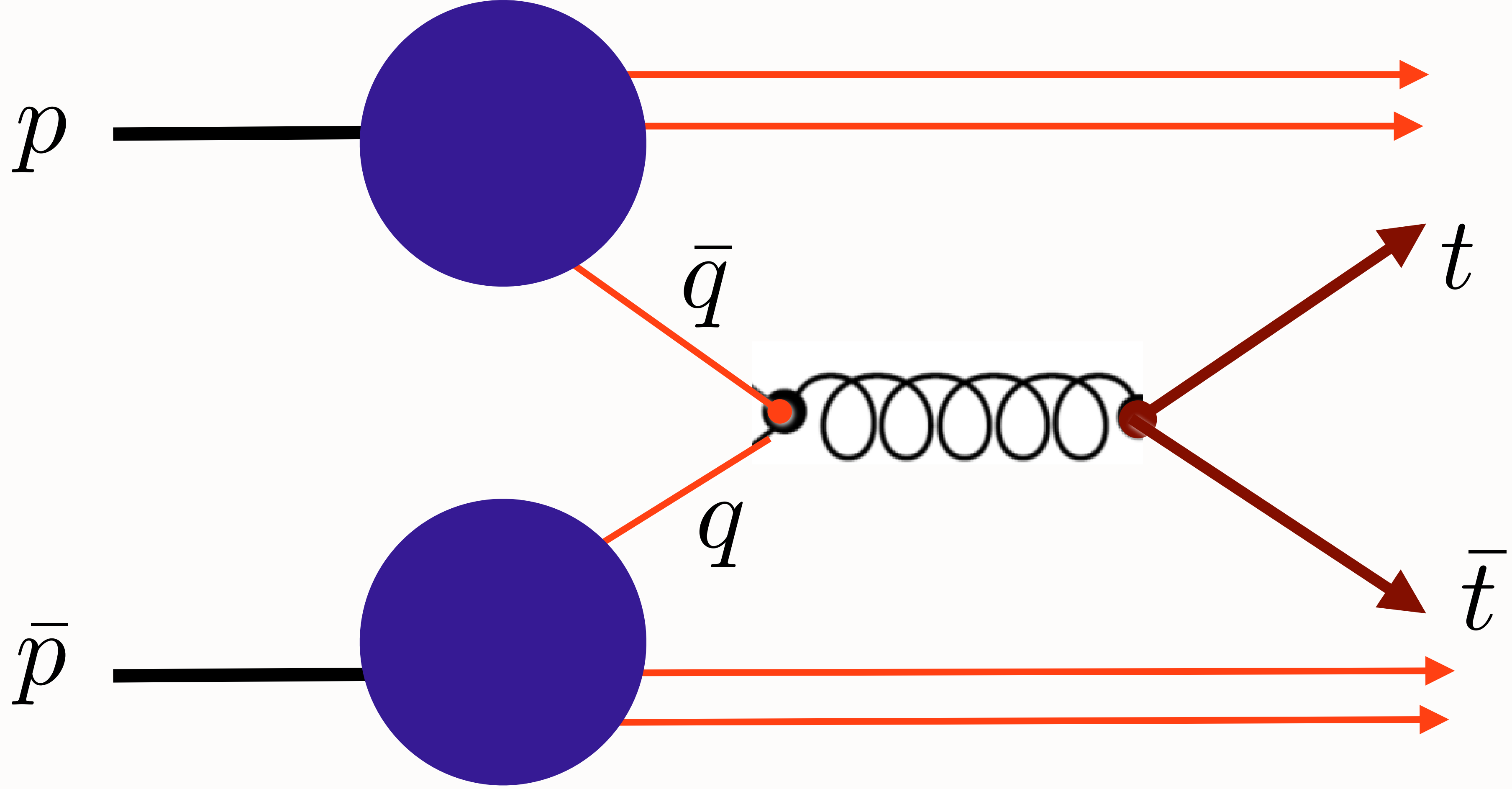
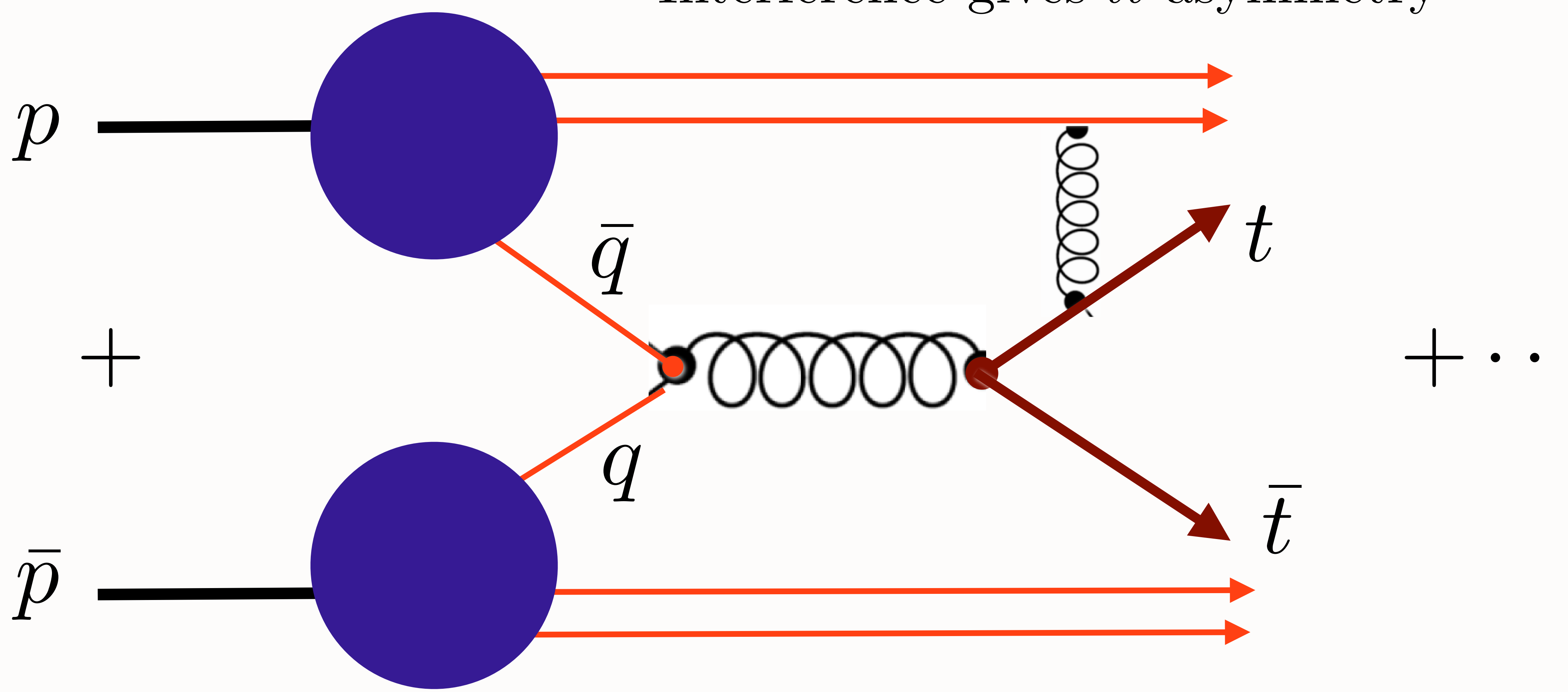



Interference gives $t\bar{t}$ asymmetry





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# QCD Analysis of heavy quark asymmetries

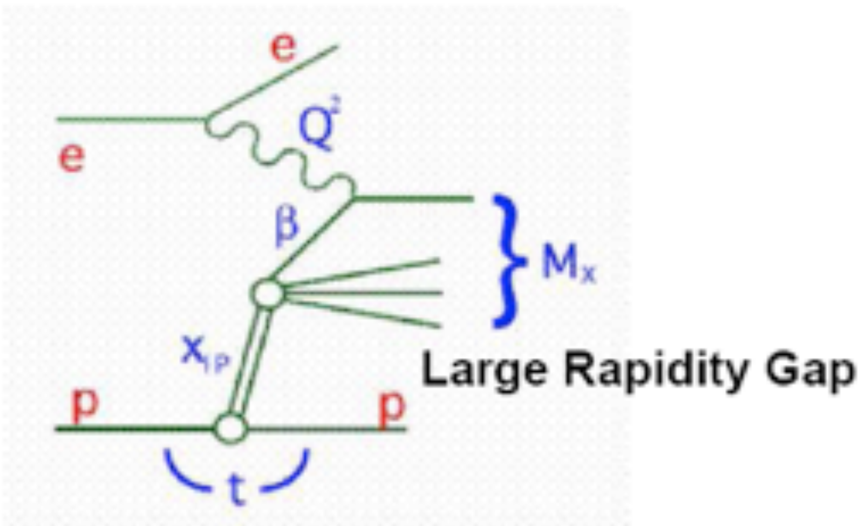
B. von Harling, Y. Zhao, sjb

- **Include Radiation Diagrams**
- **FSI similar to Sivers Effect**

$$\pi Z\alpha \to \pi C_F \alpha_s$$

- **Renormalization scale relatively soft**

# Diffractive Structure Function $F_2^D$




**Diffractive inclusive cross section**

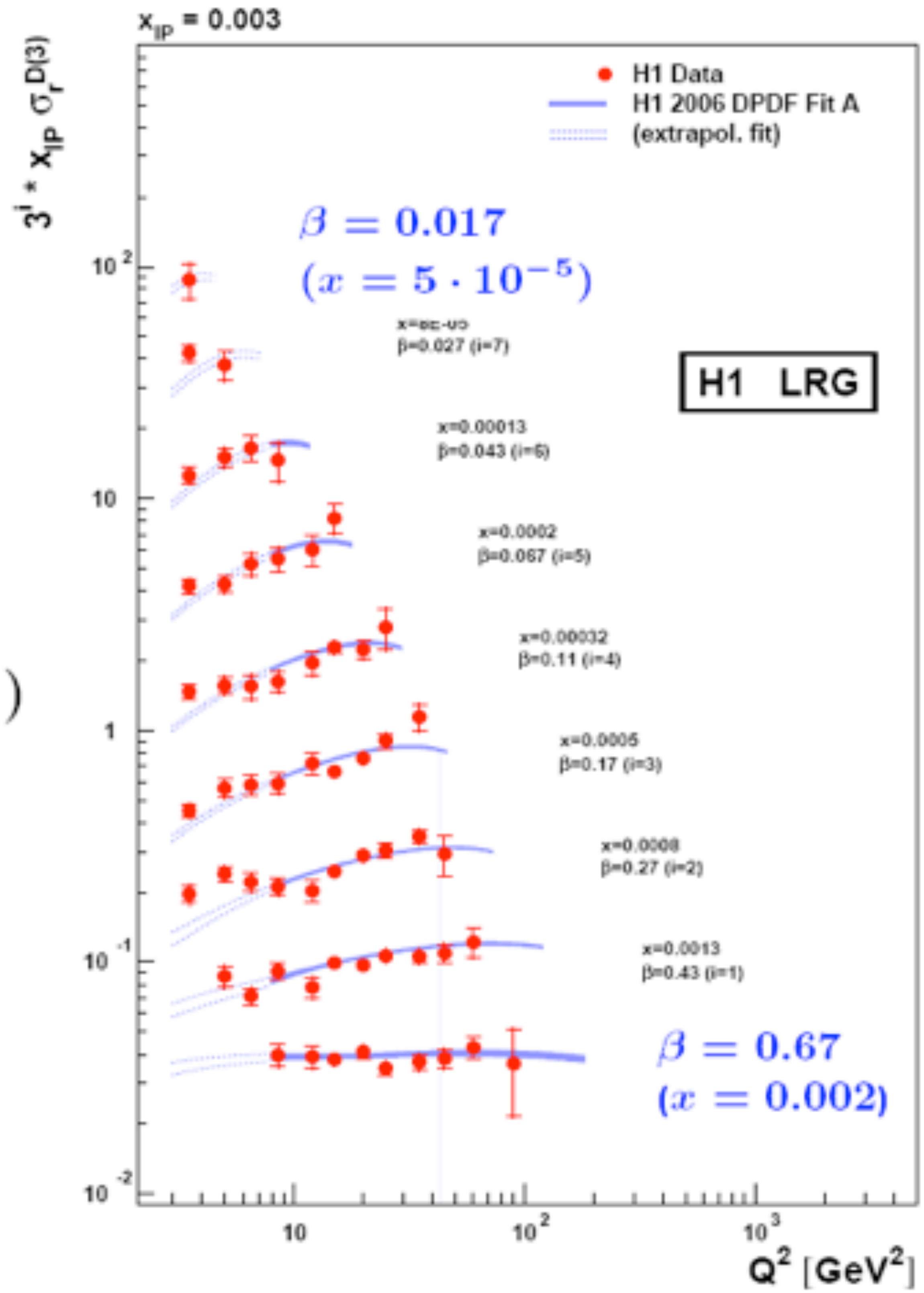
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

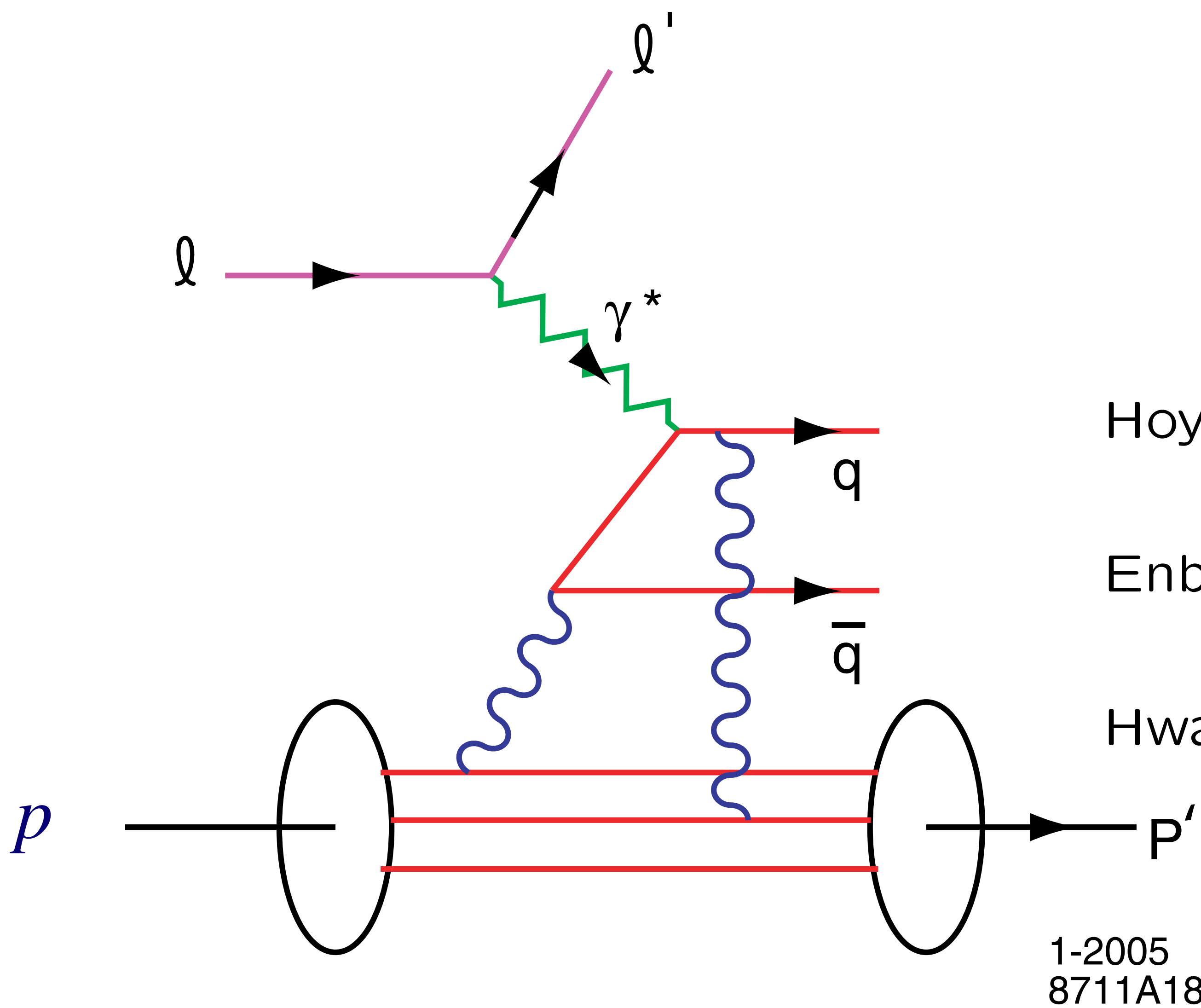
extract DPDF and $xg(x)$ from scaling violation

*Large kinematic domain* $3 < Q^2 < 1600\ \mathrm{GeV}^2$

*Precise measurements* sys 5%, stat 5–20 %



# Final-State Interaction Produces Diffractive DIS



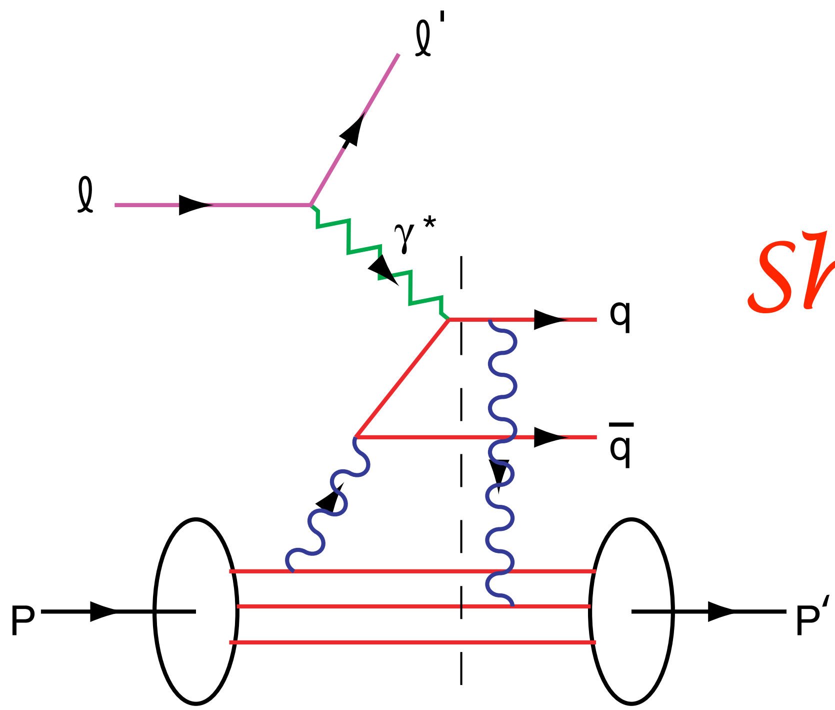

Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

**Low-Nussinov model of Pomeron**




# Shadowing depends on leading-twist DDIS

Hoyer, Marchal, Peigne, Sannino, sjb

***Integration over on-shell domain produces phase i***

***Need Imaginary Phase to Generate Pomeron***

***Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry***

Physics of FSI not in Wavefunction of Target

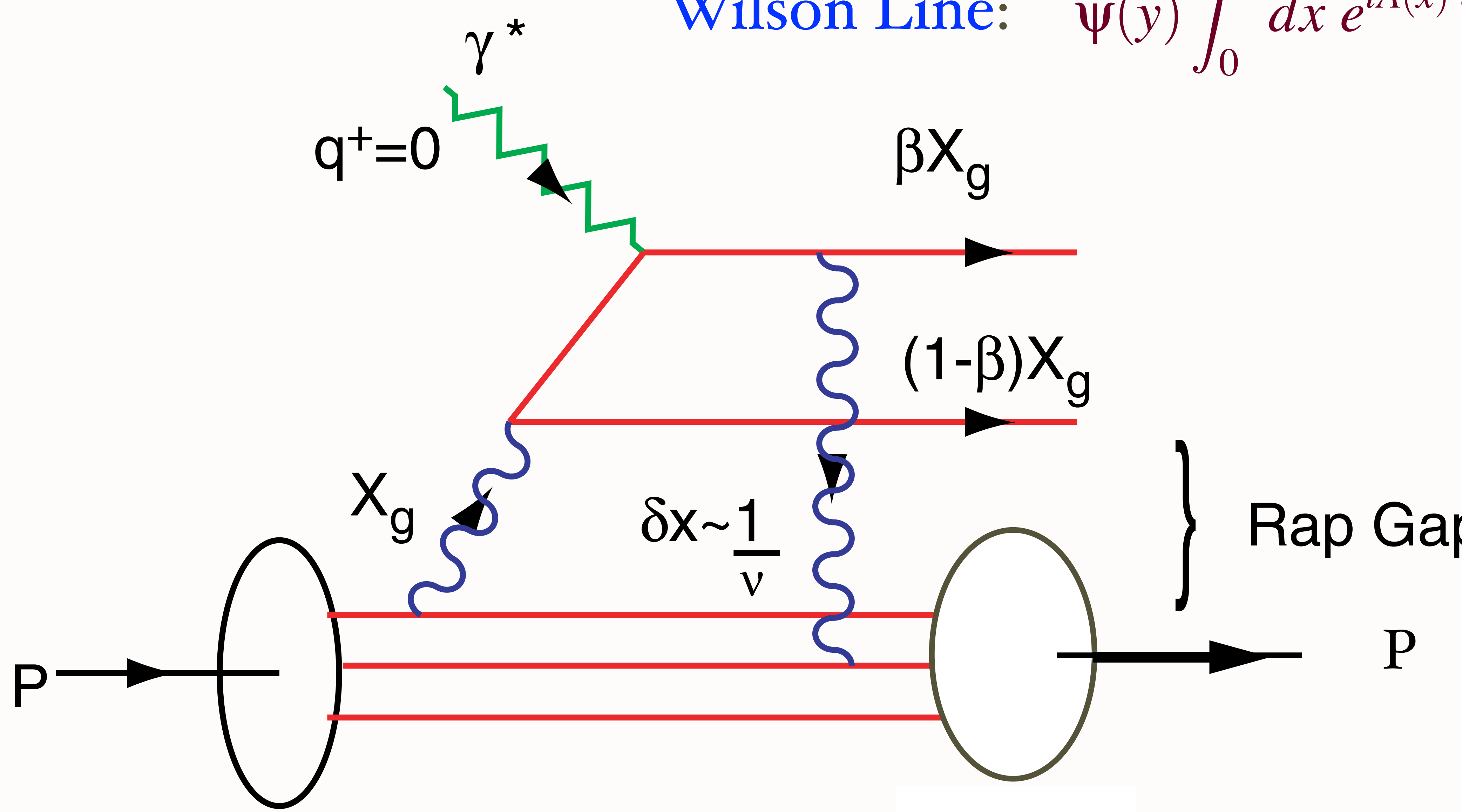
Antishadowing (Reggeon exchange) is not universal!

Schmidt, Yang, sjb

Hoyer, Marchal, Peigne, Sannino, sjb

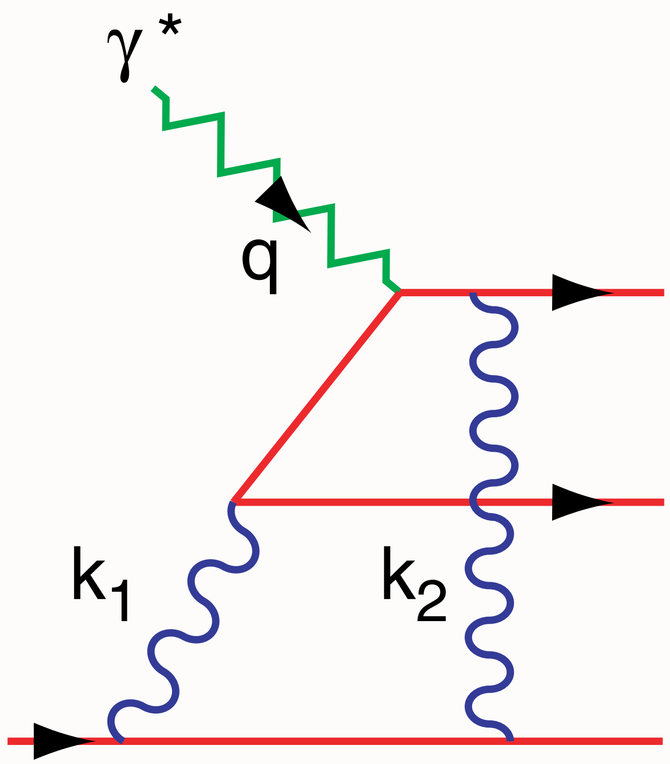
# QCD Mechanism for Rapidity Gaps

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

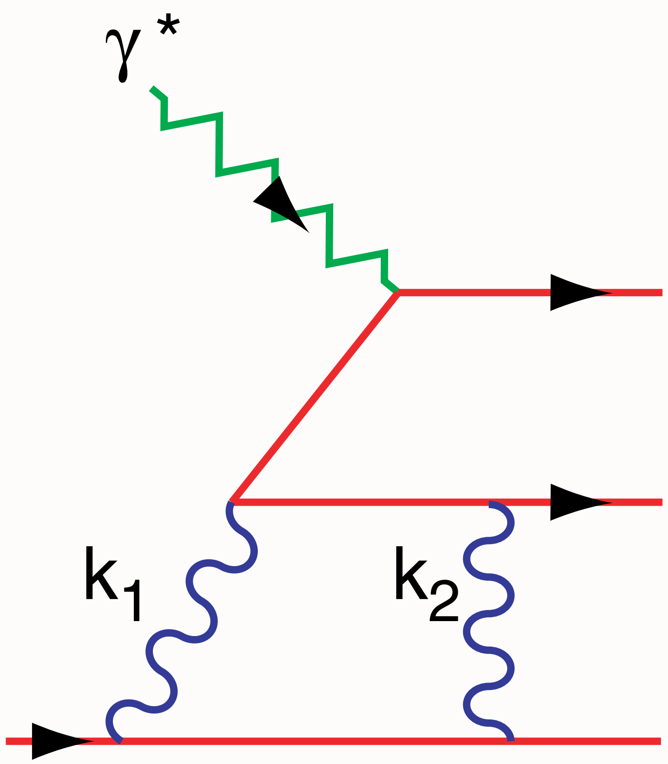



**Reproduces lab-frame color dipole approach**

# Final State Interactions in QCD




Feynman Gauge



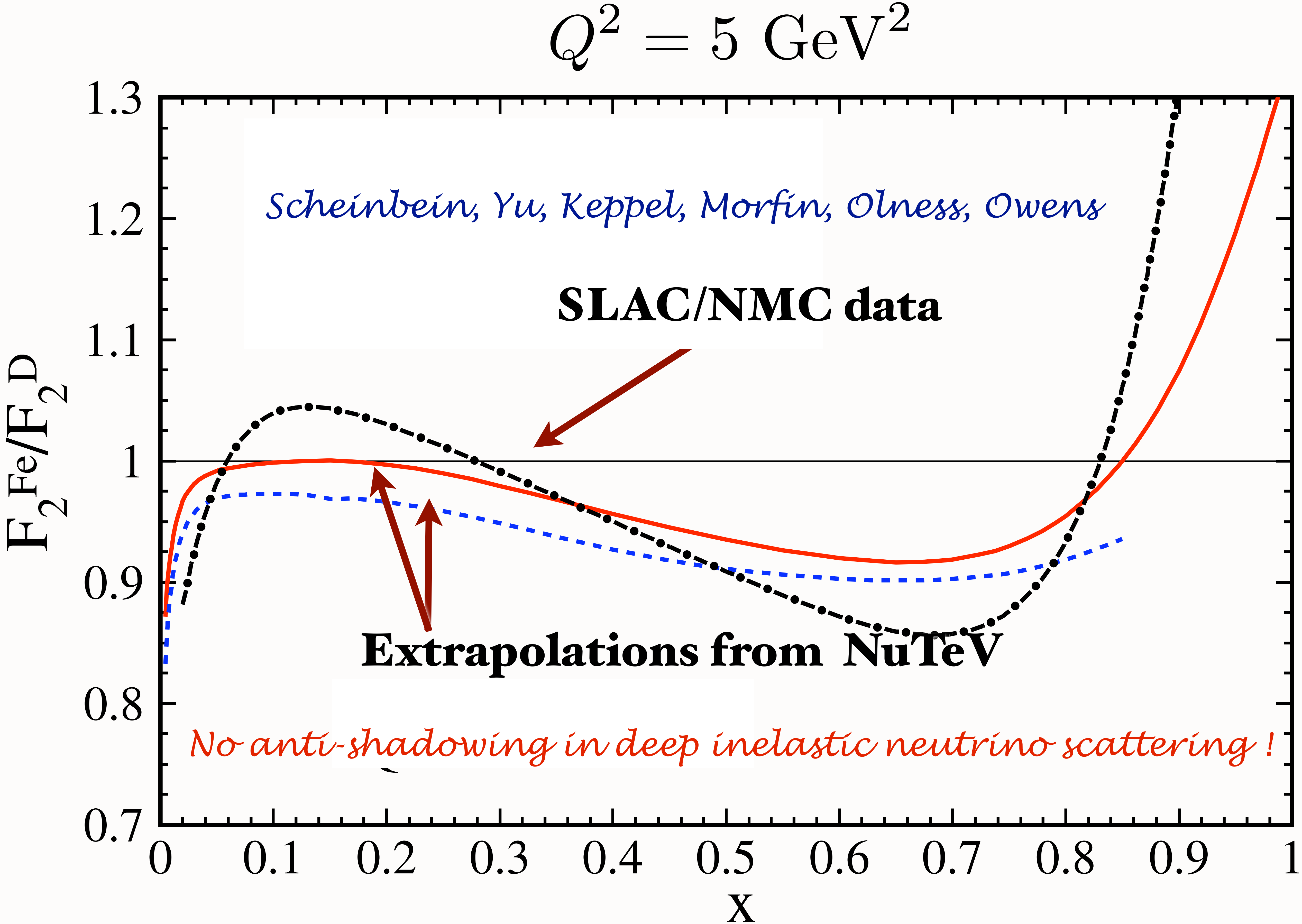

Light-Cone Gauge

*Result is Gauge Independent*

# Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!

  Not square of LFWFs
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon


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

# *Shadowing and Antishadowing in Lepton-Nucleus Scattering*

- Shadowing: Destructive Interference of Two-Step and One-Step Processes *Pomeron Exchange*

- Antishadowing: Constructive Interference of Two-Step and One-Step Processes! *Reggeon and Odderon Exchange*

- Antishadowing is Not Universal! Electromagnetic and weak currents: different nuclear effects !

Jian-Jun Yang

Ivan Schmidt

Hung Jung Lu

sjb

*Can explain NuTeV result!*

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

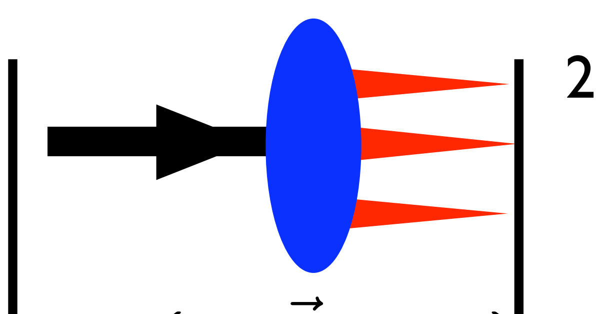
**Hwang, Schmidt, sjb,**

**Mulders, Boer**

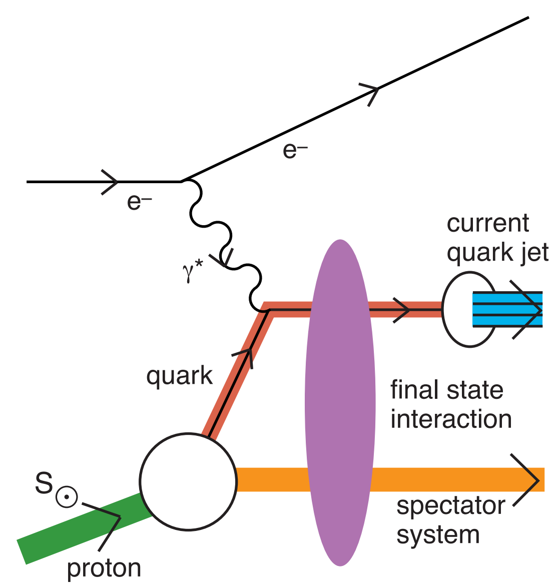
**Qiu, Sterman**

**Collins, Qiu**

**Pasquini, Xiao, Yuan, sjb**



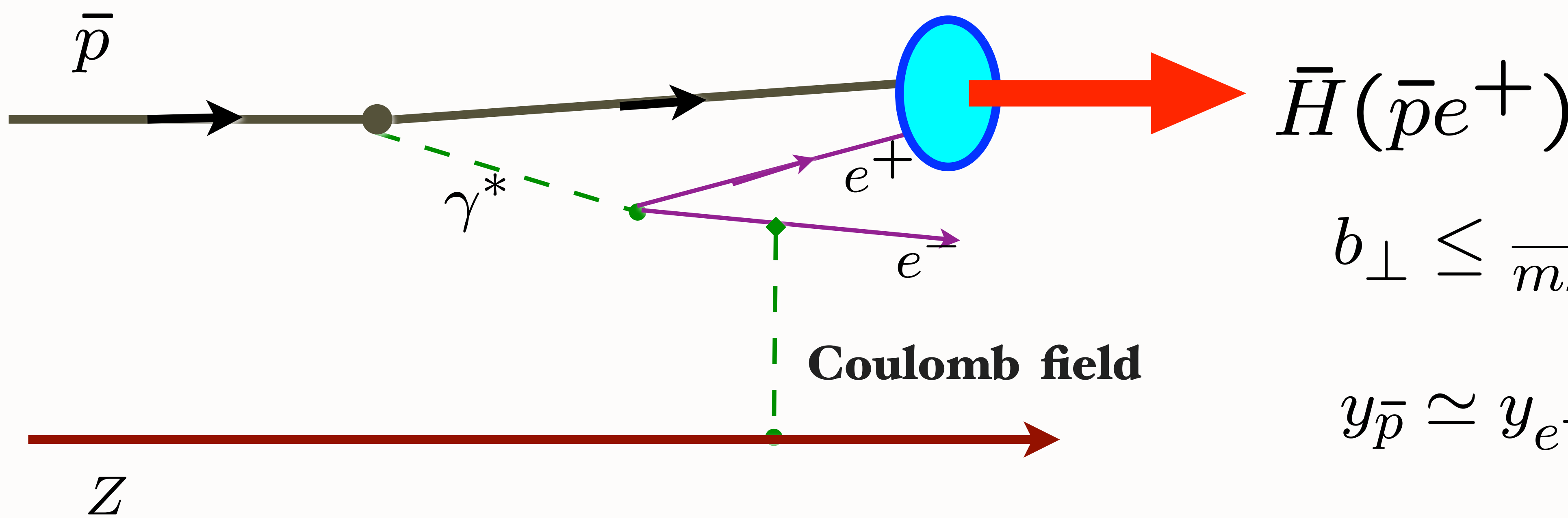

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



# Formation of Relativistic Anti-Hydrogen

**Measured at CERN-LEAR and FermiLab**

Munger, Schmidt, sjb




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

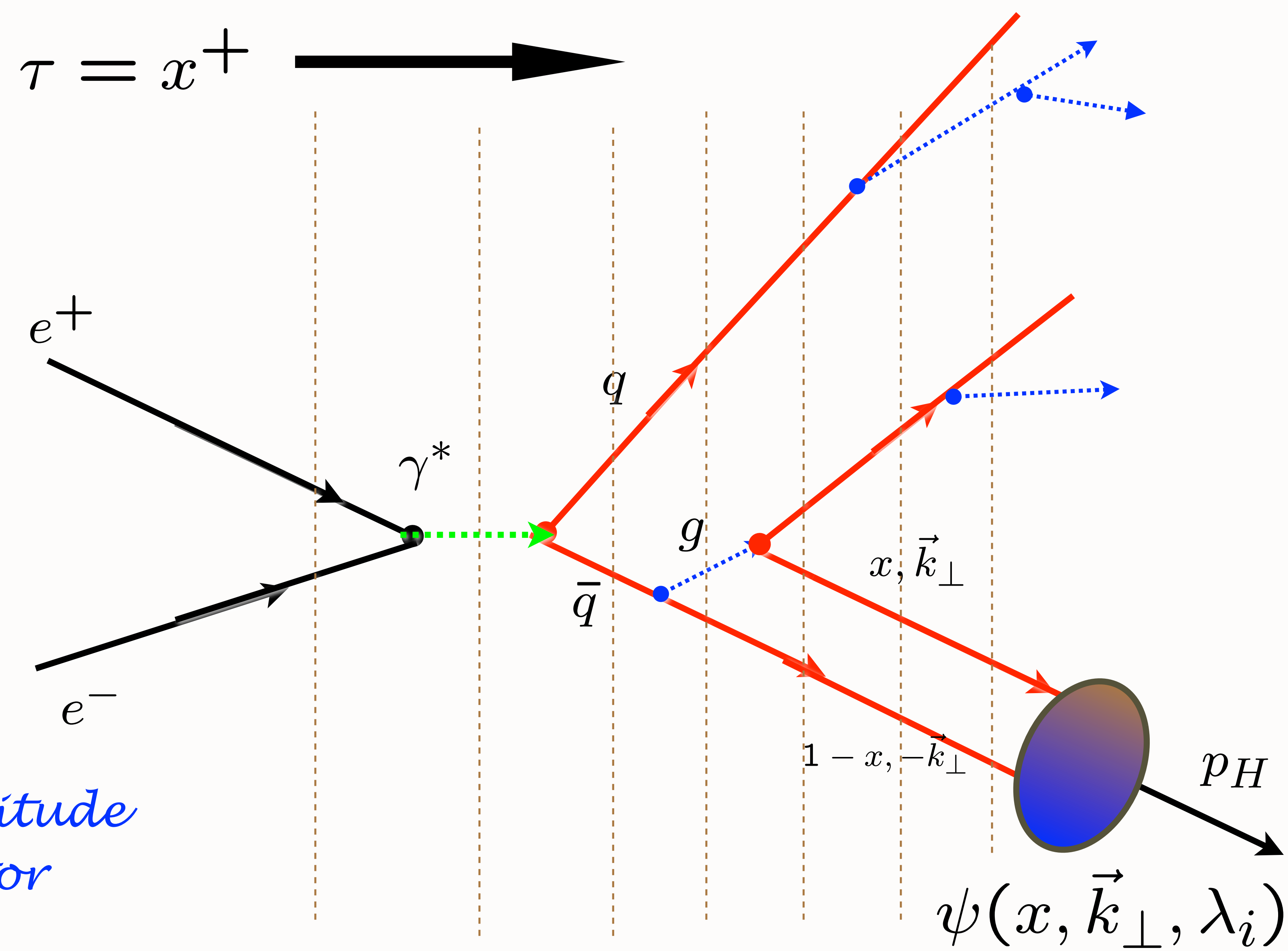
$$y_{\bar{p}} \simeq y_{e^+}$$

*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

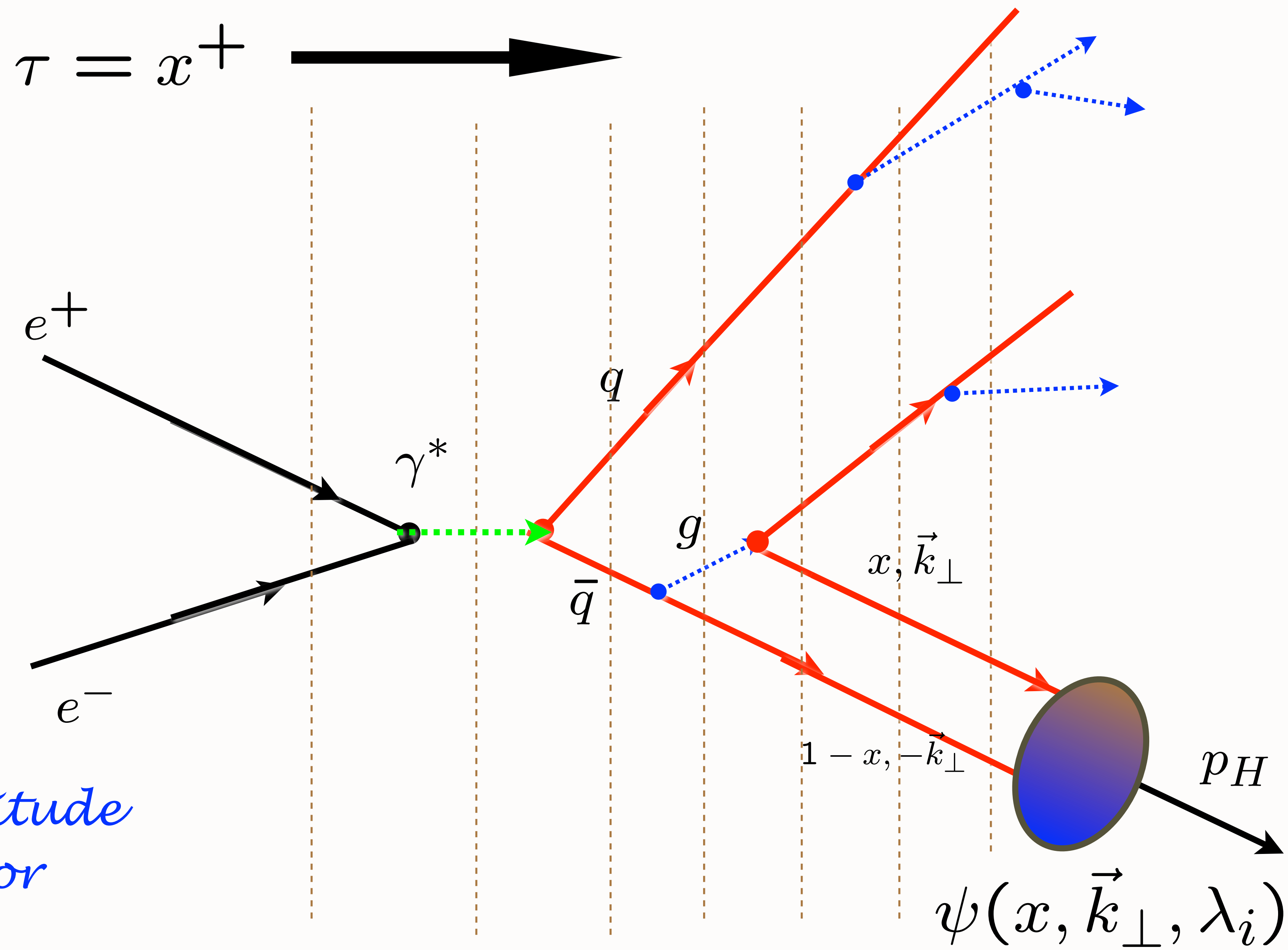



*Event amplitude generator*

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

*Similar method for hadronization in DIS*

# Hadronization at the Amplitude Level

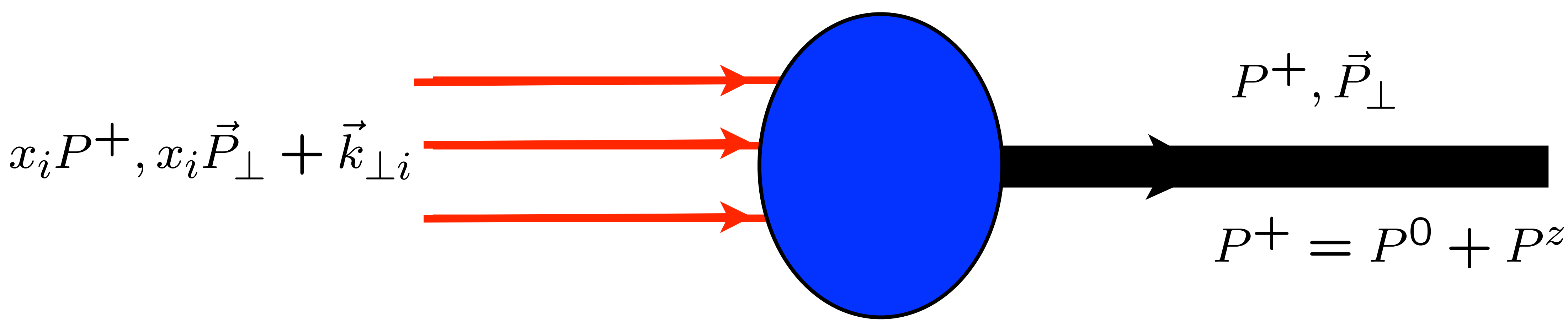



Event amplitude generator

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

# Features of LF T-Matrix Formalism
# "Event Amplitude Generator"

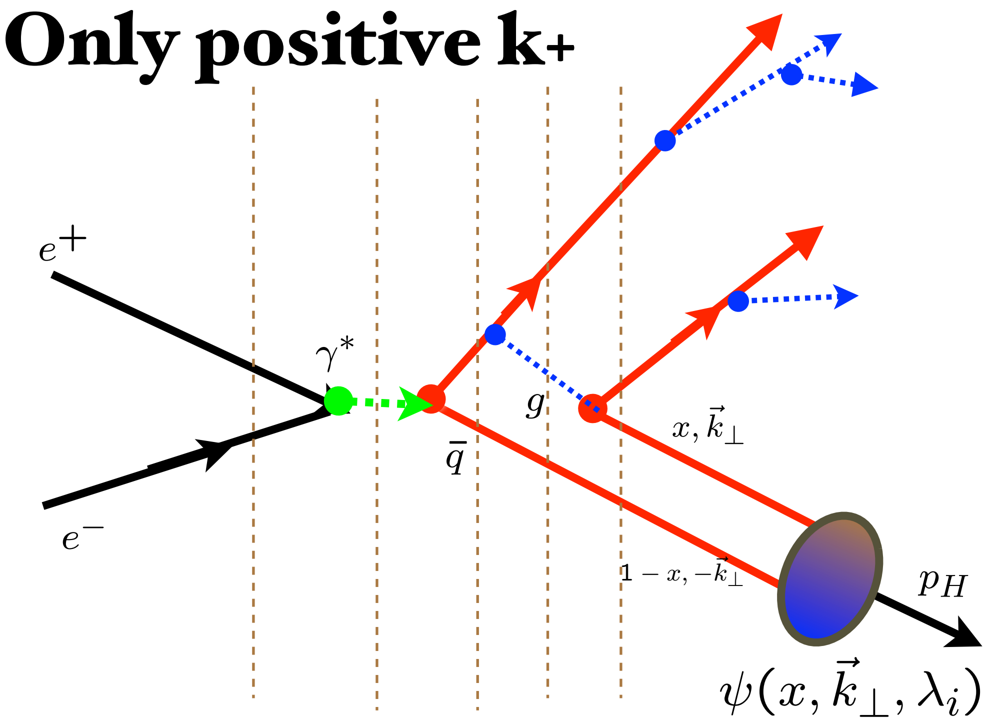
- **Same principle as antihydrogen production: off-shell coalescence**
- **coalescence to hadron favored at equal rapidity, small transverse momenta**
- **leading heavy hadron production: D and B mesons produced at large z**
- **hadron helicity conservation if hadron LFWF has $L^z = 0$**
- **Baryon AdS/QCD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



# Need Off -Shell T-Matrix

## *Event amplitude generator*

- **Quarks and Gluons Off-Shell**
- **LFPth: Minimal Time-Ordering Diagrams-Only positive k+**
- **$J^z$ Conservation at every vertex**
- **Frame-Independent**
- **Cluster Decomposition** Chueng Ji, sjb
- **"History"-Numerator structure universal**
- **Renormalization- alternate denominators**
- **LFWF takes Off-shell to On-shell**
- **Tested in QED: g-2 to three loops**




Roskies, Suaya, sjb

# "One of the gravest puzzles of theoretical physics"

**DARK ENERGY AND THE COSMOLOGICAL CONSTANT PARADOX**

A. ZEE

*Department of Physics, University of California, Santa Barbara, CA 93106, USA*
*Kavil Institute for Theoretical Physics, University of California,*
*Santa Barbara, CA 93106, USA*
*zee@kitp.ucsb.edu*

$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

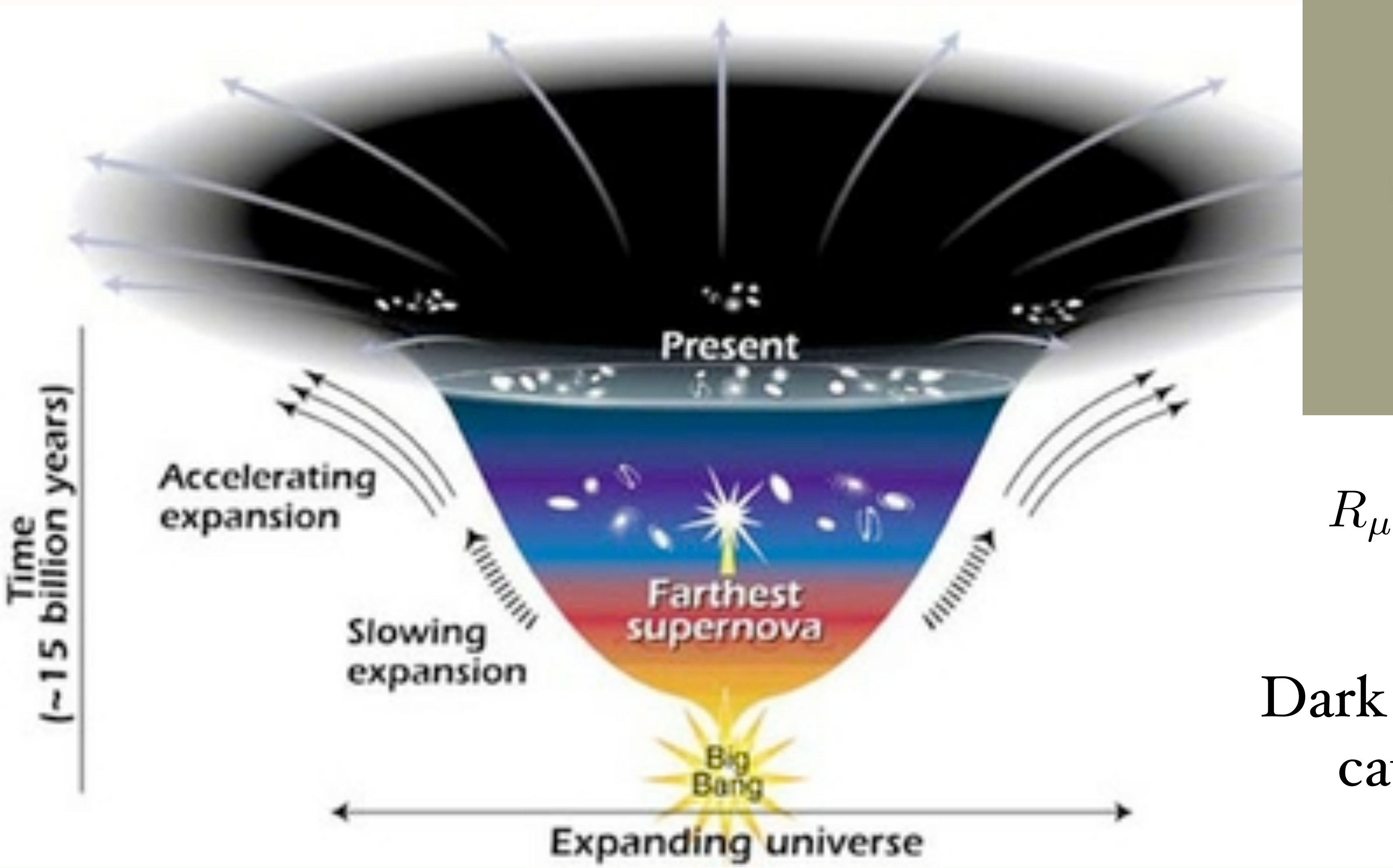
$$\Omega_\Lambda = 0.76(expt)$$

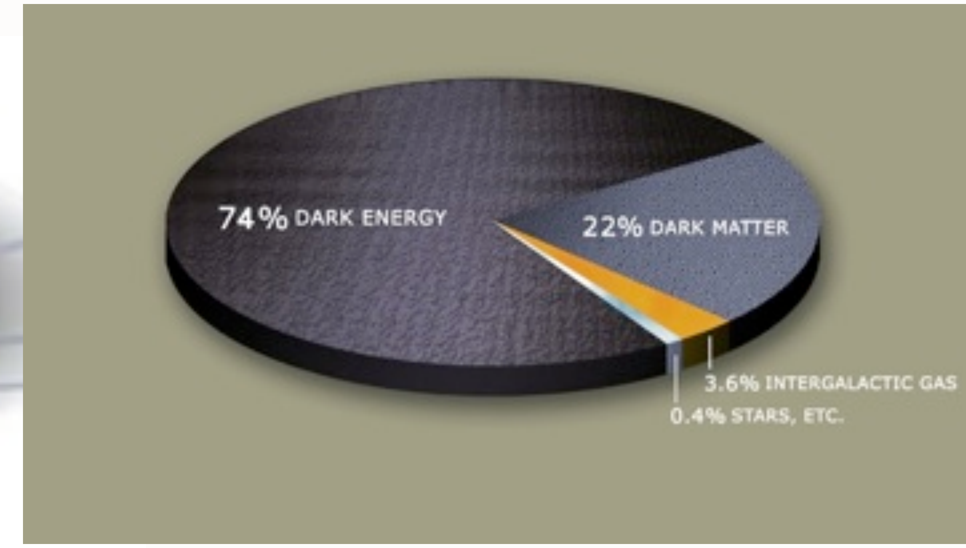
$$(\Omega_\Lambda)_{QCD} \propto < 0|q\bar{q}|0 >^4$$

*QCD Problem Solved if quark and gluon condensates reside within hadrons, not vacuum!*

**R. Shrock, sjb** Proc.Nat.Acad.Sci. 108 (2011) 45-50 "Condensates in Quantum Chromodynamics and the Cosmological Constant"

**C. Roberts, R. Shrock, P. Tandy, sjb** Phys.Rev. C82 (2010) 022201 "New Perspectives on the Quark Condensate"




$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = (8\pi G_N) T_{\mu\nu}$$

↑

Dark energy/cosmological constant
causes accelerating expansion

$$\frac{1}{a}\frac{d^2}{dt^2} a = \Lambda/3 = (8\pi) G_N \rho_\Lambda / 3$$

*If the vacuum energy $\rho$ is due to QCD condensates*

$$\rho_\Lambda^{\rm QCD} \simeq M_{\rm QCD}^4 \simeq 10^{45} \rho_\Lambda^{\rm obs} \, !$$

$$\Omega_\Lambda = \frac{\rho_\Lambda^{\rm obs}}{\rho_c} \simeq 0.76 \qquad \rho_c = \frac{3H_0^2}{8\pi G_N}$$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# *Gell-Mann Oakes Renner Formula in QCD*

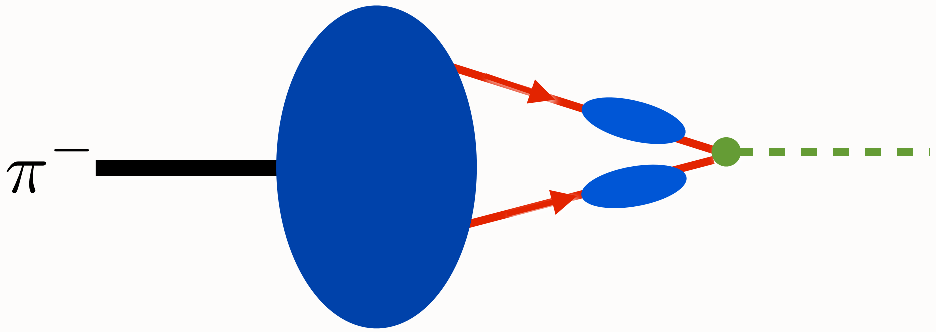
$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi^2} < 0|\bar{q}q|0 >$$

**current algebra: effective pion field**

$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi} < 0|i\bar{q}\gamma_5 q|\pi >$$

**QCD: composite pion Bethe-Salpeter Eq.**

*vacuum condensate actually is an "in-hadron condensate"*




$$< 0|\bar{q}\gamma_5 q|\pi >$$

Maris, Roberts, Tandy



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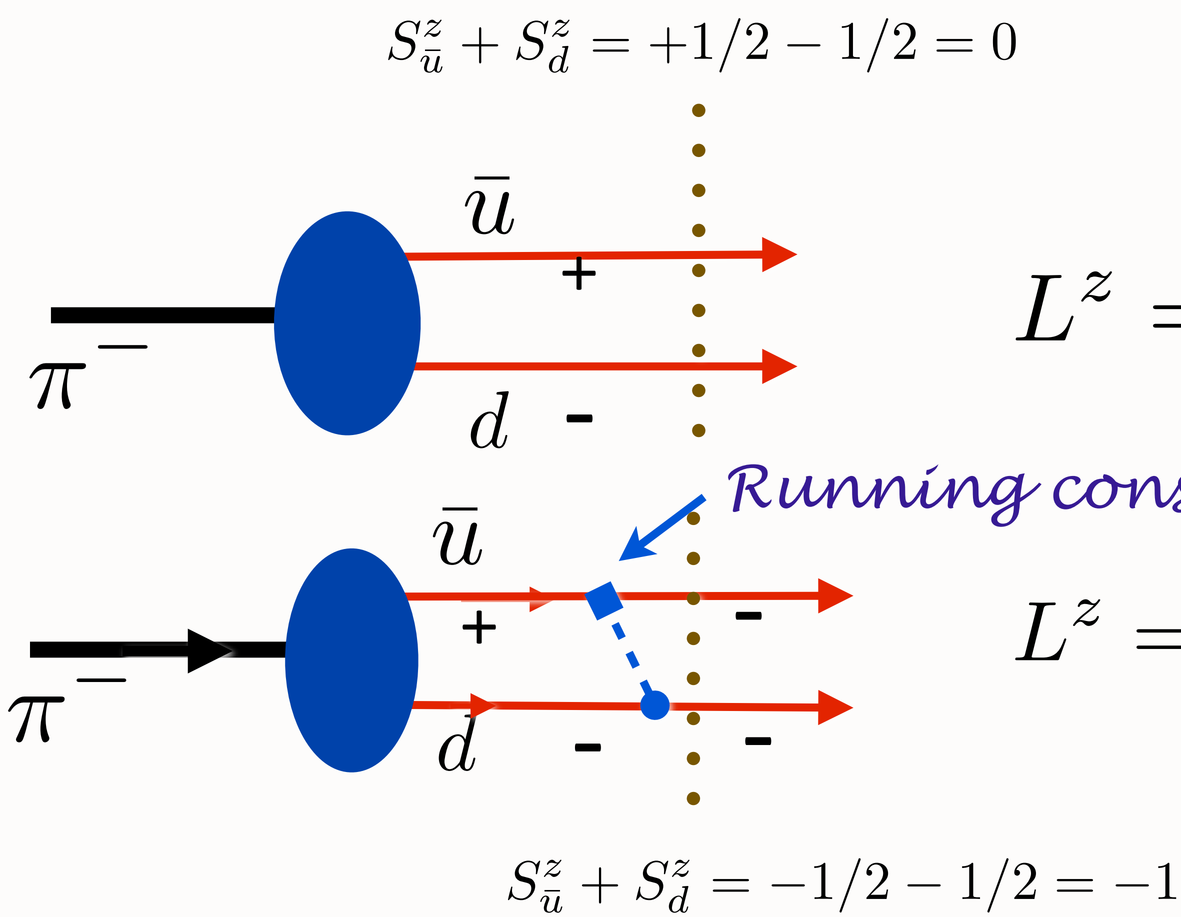
# Light-Front Pion Valence Wavefunctions




**Couples to**

$$L^z = 0, S^z = 0 \quad < \pi|\bar\gamma^\mu q \gamma_5 q|0 > \sim f_\pi$$

$$L^z = +1, S^z = -1 \quad < \pi|\bar q \gamma_5 q|0 > \sim \rho_\pi$$

***Angular Momentum Conservation***

$$J^z = \sum_i^n S^z_i + \sum_i^{n-1} L^z_i$$

PHYSICAL REVIEW C **82**, 022201(R) (2010)

# New perspectives on the quark condensate

Stanley J. Brodsky,[1,2] Craig D. Roberts,[3,4] Robert Shrock,[5] and Peter C. Tandy[6]
[1] *SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94309, USA*
[2] *Centre for Particle Physics Phenomenology: CP[3]-Origins, University of Southern Denmark, Odense 5230 M, Denmark*
[3] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4] *Department of Physics, Peking University, Beijing 100871, China*
[5] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[6] *Center for Nuclear Research, Department of Physics, Kent State University, Kent, Ohio 44242, USA*
(Received 25 May 2010; published 18 August 2010)

We show that the chiral-limit vacuum quark condensate is qualitatively equivalent to the pseudoscalar meson leptonic decay constant in the sense that they are both obtained as the chiral-limit value of well-defined gauge-invariant hadron-to-vacuum transition amplitudes that possess a spectral representation in terms of the current-quark mass. Thus, whereas it might sometimes be convenient to imagine otherwise, neither is essentially a constant mass-scale that fills all spacetime. This means, in particular, that the quark condensate can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wave functions.

QCD: Zero Contribution to Dark Energy, Cosmological Constant!

# “One of the gravest puzzles of theoretical physics”

DARK ENERGY AND
THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE

*Department of Physics, University of California, Santa Barbara, CA 93106, USA*
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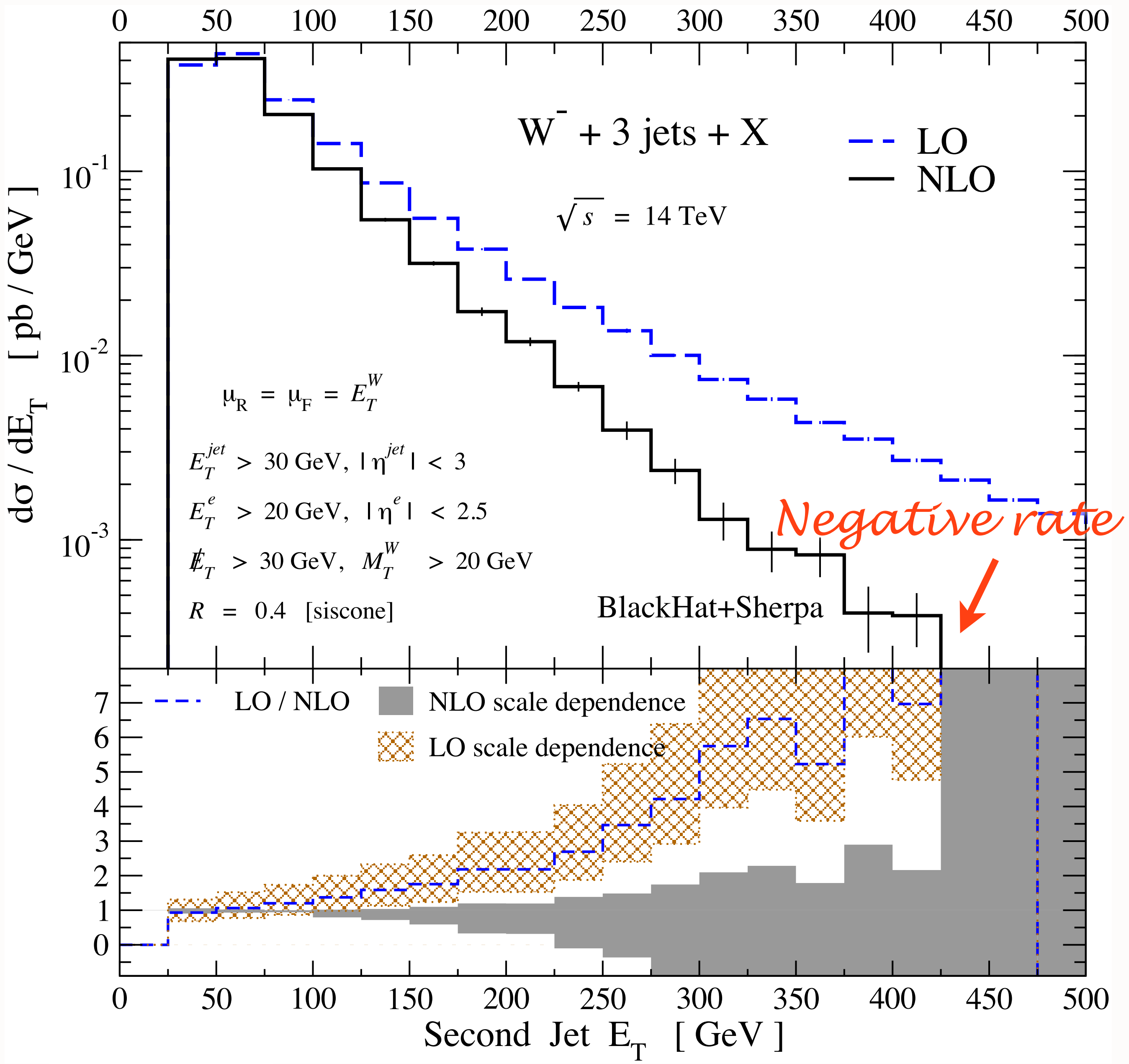
# Goals

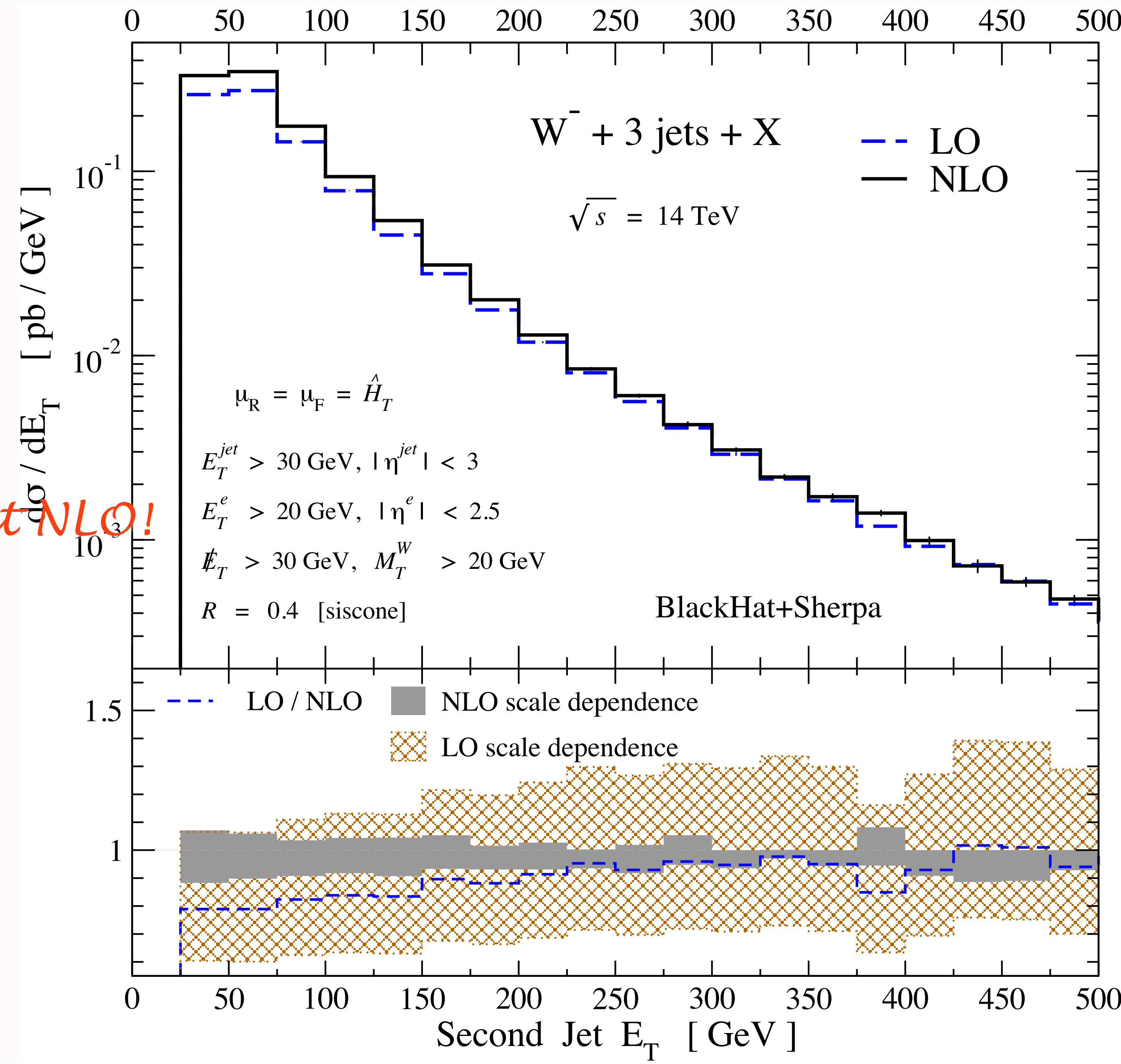
- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$ at all scales
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Relate renormalization schemes without ambiguity
- Maximize sensitivity to new physics at the colliders

# Next-to-Leading Order QCD Predictions for W + 3-Jet Distributions at Hadron Colliders

***Black Hat***

$$\mu_R = \mu_F = E_T^W \qquad\qquad \mu_R = \mu_F = \hat{H}_T$$




**. F. Berger, Z. Bern, L. J. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, H. Ita, D. A. Kosower, and D. Maître**

# Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

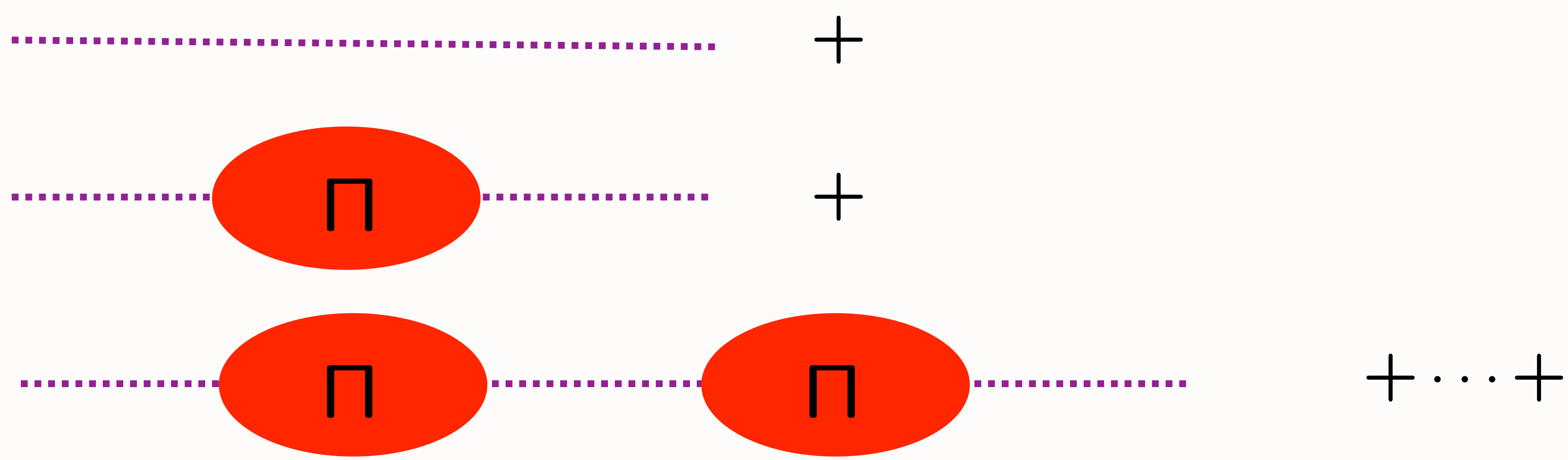

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

**Gell-Mann--Low Effective Charge**

# QED Effective Charge

$$\alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)}$$

*All-orders lepton-loop corrections to dressed photon propagator*

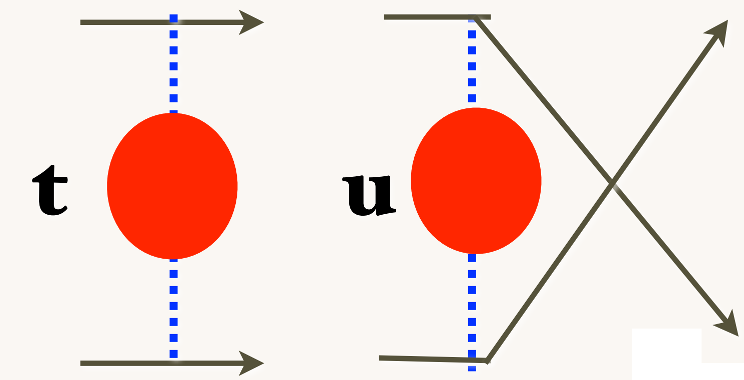



$$\alpha(t) = \frac{\alpha(t_0)}{1 - \Pi(t, t_0)} \qquad \Pi(t, t_0) = \frac{\Pi(t) - \Pi(t_0)}{1 - \Pi(t_0)}$$

***Initial*** **scale $t_0$ is arbitrary -- Variation gives RGE Equations**
**Physical renormalization scale $t$ not arbitrary!**

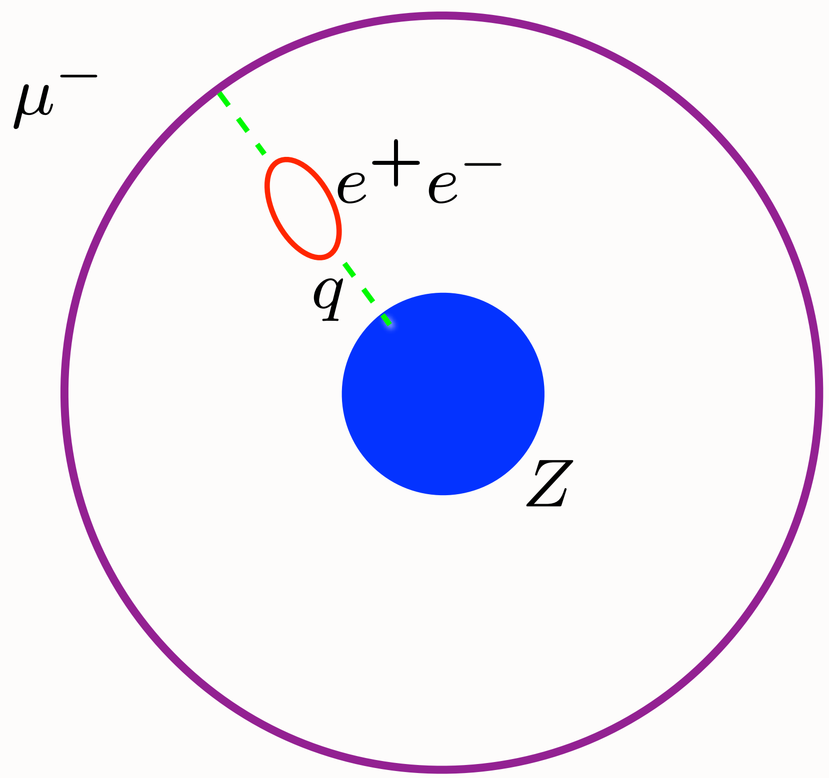
# Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$




- Two separate physical scales: t, u = photon virtuality
- Gauge Invariant. Dressed photon propagator
- Sums all vacuum polarization, non-zero beta terms into running coupling. This is the purpose of the running coupling!
- If one chooses a different initial scale, one must sum an infinite number of graphs -- but always recover same result!
- Number of active leptons correctly set
- Analytic: reproduces correct behavior at lepton mass thresholds
- No renormalization scale ambiguity!

# Another Example in QED: Muonic Atoms



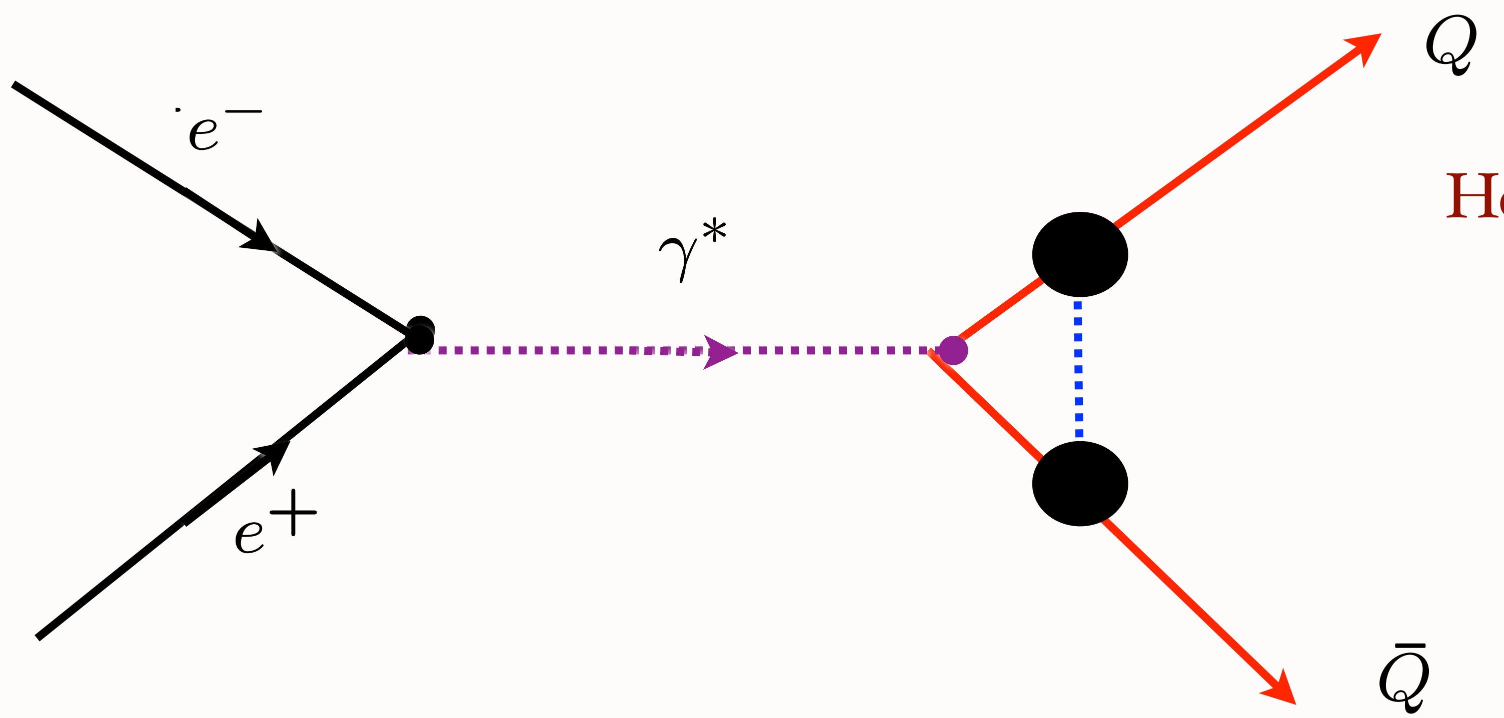

$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

$$\mu_R^2 \equiv q^2$$

$$\alpha_{QED}(q^2) = \frac{\alpha_{QED}(0)}{1-\Pi(q^2)}$$

**Scale is unique: Tested to ppm**

Gyulassy: Higher Order VP verified to 0.1% precision in $\mu$ Pb




Hoang, Kuhn, Teubner, sjb

$$F_1 + F_2 = [1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}] \times [1 + \frac{\pi\alpha_s(sv^2)}{4v}]$$

**Angular distributions of massive quarks close to threshold.**

*Example of Multiple BLM Scales*

**Need QCD coupling at small scales at low relative velocity v**

# Relation between scales of the Gell-Mann--Low and $\overline{\text{MS}}$ schemes

$$\log \frac{\mu_0^2}{m_\ell^2} = 6 \int_0^1 x(1-x) \log \frac{m_\ell^2 + Q_0^2 x(1-x)}{m_\ell^2}$$

$$\log \frac{\mu_0^2}{m_\ell^2} = \log \frac{Q_0^2}{m_\ell^2} - 5/3$$

$$\boxed{\mu_0^2 = Q_0^2 \; e^{-5/3}} \quad \text{when } Q_0^2 >> m_\ell^2$$

**D. S. Hwang, sjb**

**M. Binger**

*Can use $\overline{\text{MS}}$ scheme in QED; answers are scheme independent*
*Analytic extension: coupling is complex for timelike argument*

# QCD Observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

**Scale-Free Conformal Series**

**Running Coupling Effects**

**Higher Twist from Hadron Dynamics**

**Intrinsic Heavy Quarks**

**Light by Light Loops**

***BLM: Absorb β terms into running coupling***

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

# The Renormalization Scale Problem

- No renormalization scale ambiguity in QED
- Gell Mann-Low QED Coupling defined from physical observable
- Sums all Vacuum Polarization Contributions
- Recover conformal series
- Renormalization Scale in QED scheme: Identical to Photon Virtuality
- Analytic: Reproduces lepton-pair thresholds -- number of active leptons set
- Examples: muonic atoms, g-2, Lamb Shift
- Time-like and Space-like QED Coupling related by analyticity
- Uses Dressed Skeleton Expansion
- Results are scheme independent!
- *Predictions for physical observables cannot be scheme dependent*

# Features of BLM Scale Setting

**On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.**

Lepage, Mackenzie, sjb Phys.Rev.D28:228,1983

- "Principle of Maximum Conformality" Di Giustino, Wu, sjb
- All terms associated with nonzero beta function summed into running coupling
- Standard procedure in QED
- Resulting series identical to conformal series
- Renormalon n! growth of PQCD coefficients from beta function eliminated!
- Scheme Independent!!!
- In general, BLM/PMC scales depend on all invariants
- Single Effective PMC scale at NLO

# Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Conformal Template
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[ 1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[ g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[ 1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648}f^2\right\}.$$

# Eliminate MSbar, Find Amazing Simplification

Lu, Kataev, Gabadadze, Sjb

# Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

$$\sqrt{s^*} \simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

*Nonconformal terms set relative scales (BLM)*

*No renormalization scale ambiguity!*

**Both observables go through new quark thresholds at commensurate scales!**

# Myths concerning scale setting

- Renormalization scale "unphysical": No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess $\mu_R = Q$ with an arbitrary range $Q/2 < \mu_R < 2Q$
- Factorization scale should be taken equal to renormalization scale $\mu_F = \mu_R$

**These assumptions are untrue in QED and thus they cannot be true for QCD**

**Clearly heuristic. Wrong in QED. Scheme dependent!**

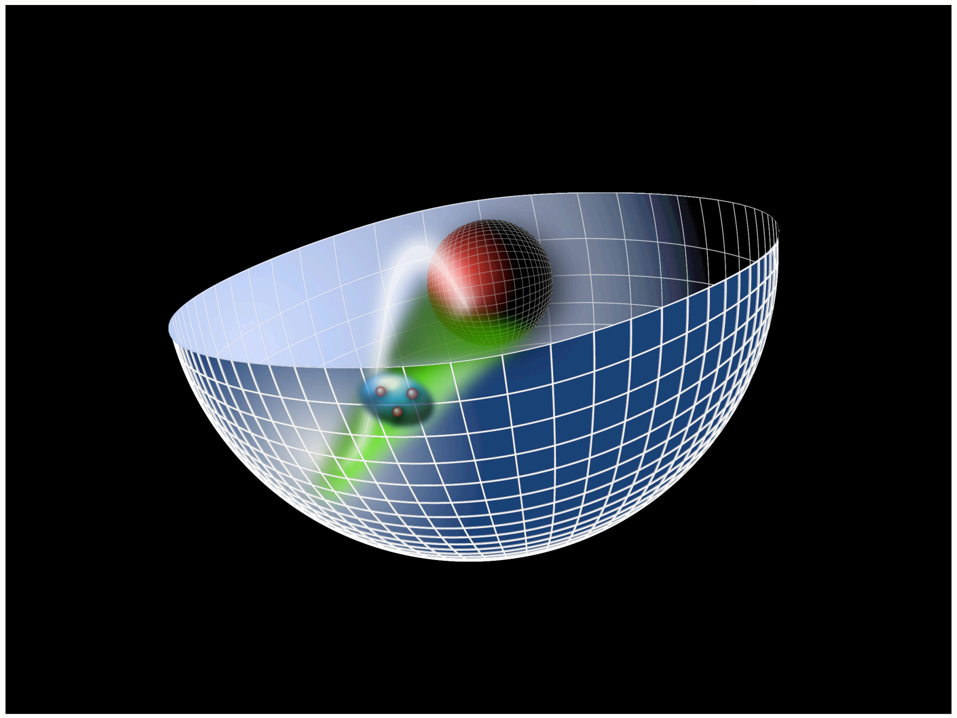
# QCD Myths

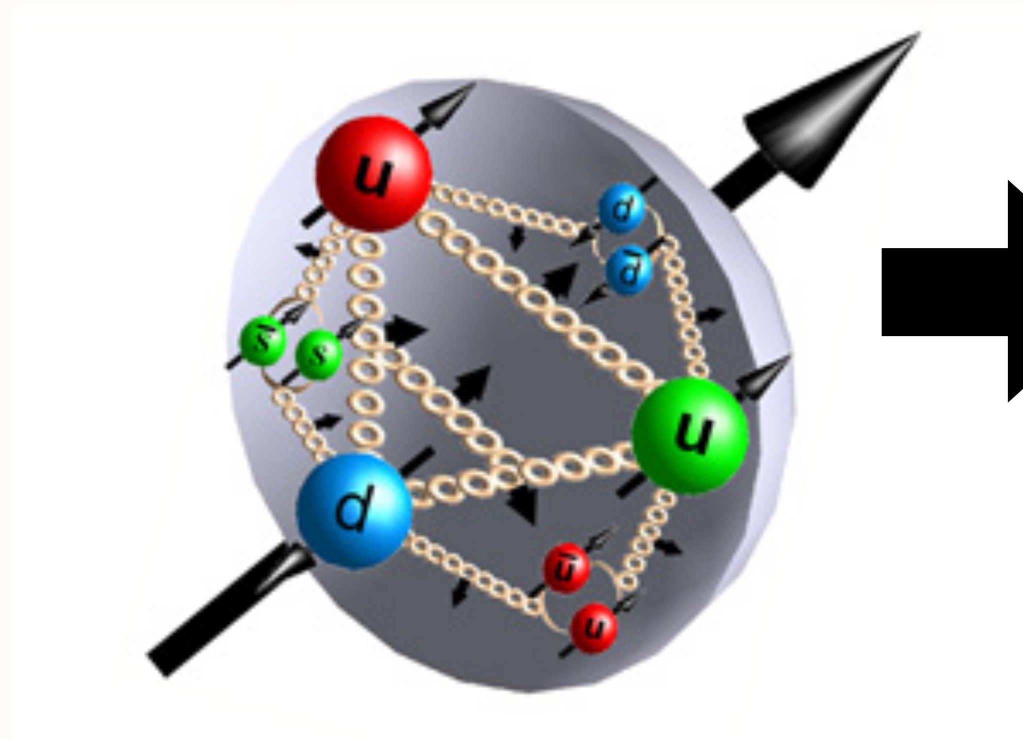
- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- heavy quarks only from gluon splitting
- renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- Infrared Slavery
- Nuclei are composites of nucleons only
- Real part of DVCS arbitrary

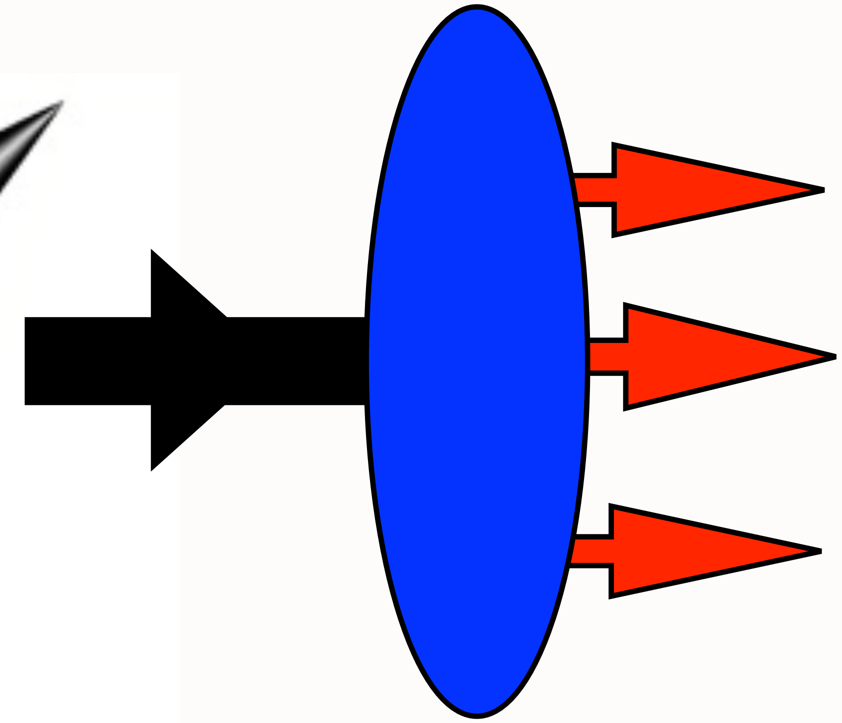
# Fixed-Target Physics with the LHC Beams

- 7 TeV proton beam, nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations!
- Single-Spin Asymmetries, Transversity Studies, $A_N$
- High-$x_F$ Dynamics at Forward and Backward Rapidities
- High $x_F$ Nuclear Anomalies
- Production of ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System

# Light-Front Holography and Novel QCD Phenomena







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**High Energy Physics in the LHC Era**

HEP 2012

Universidad Técnica Federico Santa María