

Comparison of Exclusive Reactions at Large t

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

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

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

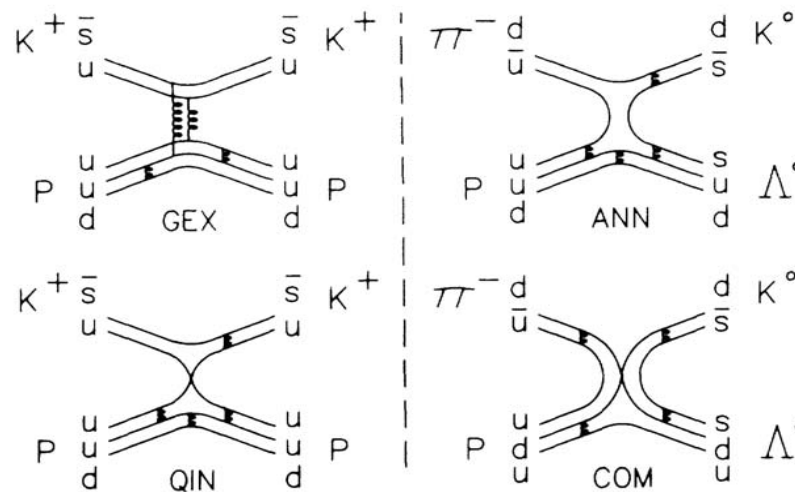
$$\pi^\pm p \rightarrow p\rho^\pm,$$

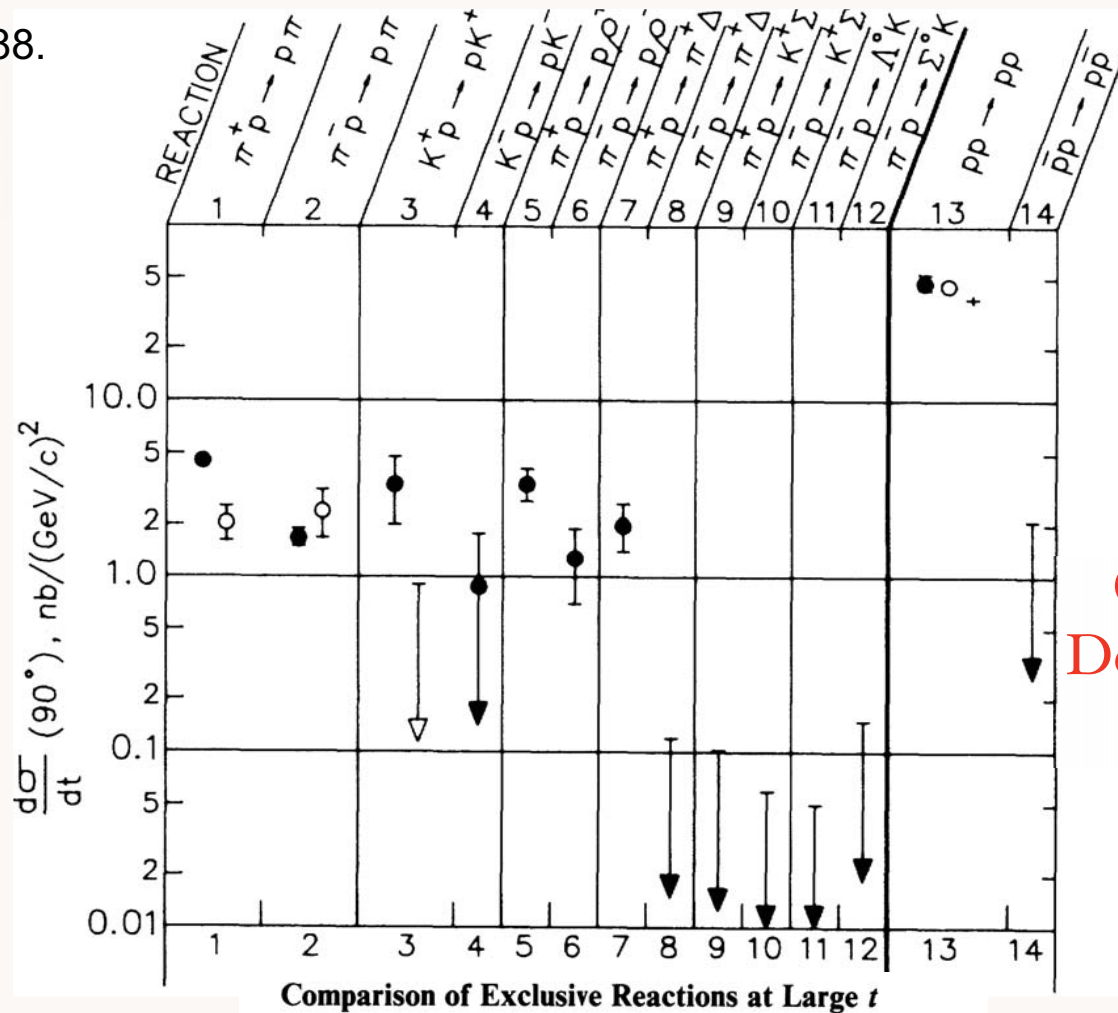
$$\pi^\pm p \rightarrow \pi^+\Delta^\pm,$$

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

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

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





Quark Interchange:
 Dominant Dynamics at
 large t, u

Relative Rates Correct

The cross section and upper limits (90% confidence level) measured by this experiment are indicated by the filled circles and arrowheads. Values from this experiment and from previous measurements represent an average over the angular region of $-0.05 < \cos\theta_{c.m.} < 0.10$. The other measurements were obtained from the following references: $\pi^+ p$ and $K^+ p$ elastic, Ref. 5; $\pi^- p \rightarrow p \pi^-$, Ref. 6; $pp \rightarrow pp$, Ref. 7; Allaby, open circle; Akerlof, cross. Values for the cross sections [(Reaction), cross section in nb/(GeV/c)²] are as follows: (1), 4.6 ± 0.3; (2), 1.7 ± 0.2; (3), 3.4 ± 1.4; (4), 0.9 ± 0.7; (5), 3.4 ± 0.7; (6), 1.3 ± 0.6; (7), 2.0 ± 0.6; (8), < 0.12; (9), < 0.1; (10), < 0.06; (11), < 0.05; (12), < 0.15; (13), 48 ± 5; (14), < 2.1.



Why is quark-interchange dominant over gluon exchange?

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

Exchange of common u quark

$$M_{QIM} = \int d^2k_{\perp} dx \psi_C^{\dagger} \psi_D^{\dagger} \Delta \psi_A \psi_B$$

Holographic model (Classical level):

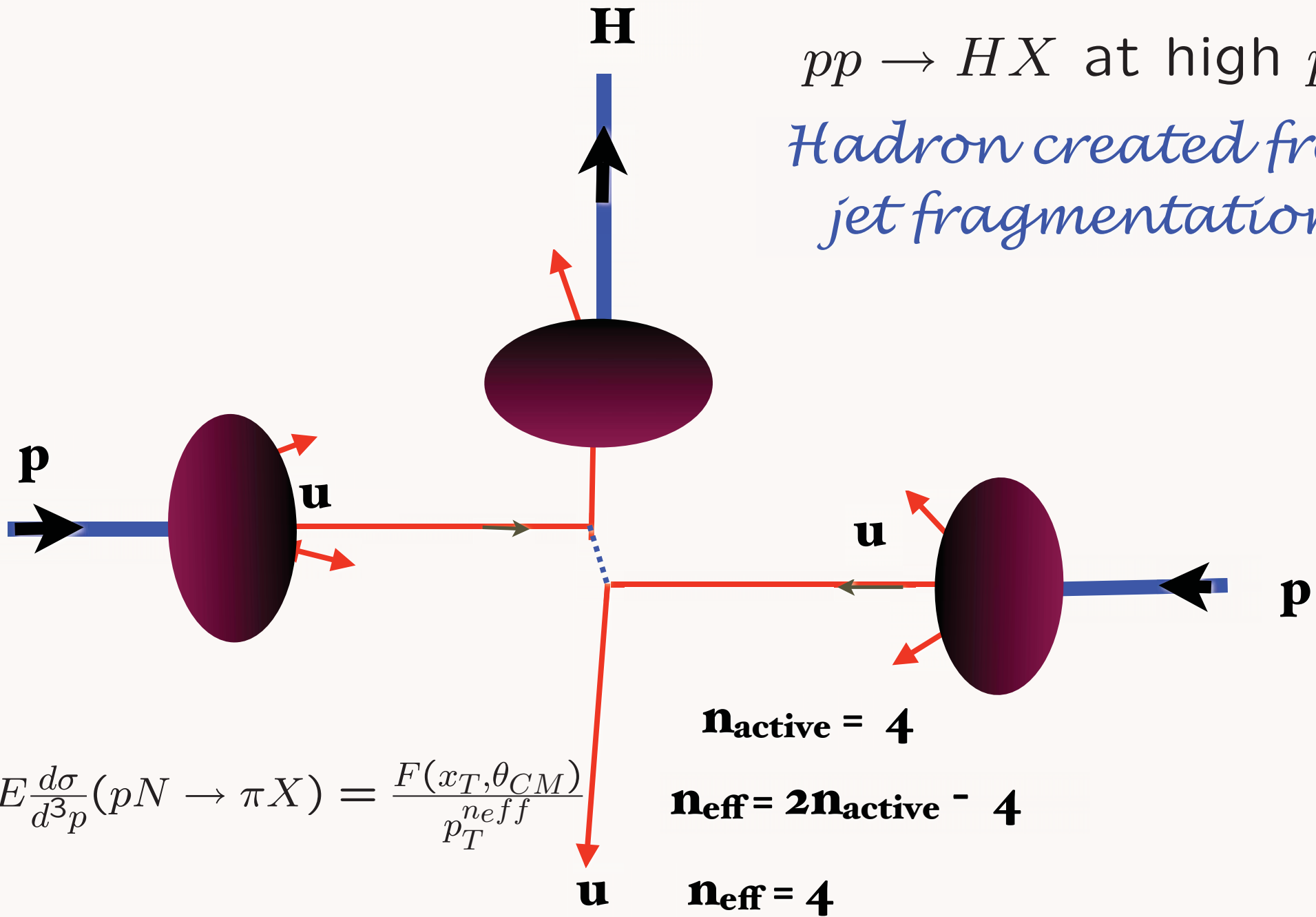
Hadrons enter 5th dimension of AdS_5

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

LFWFs obey conformal symmetry producing quark counting rules.



$pp \rightarrow HX$ at high p_T
Hadron created from jet fragmentation



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

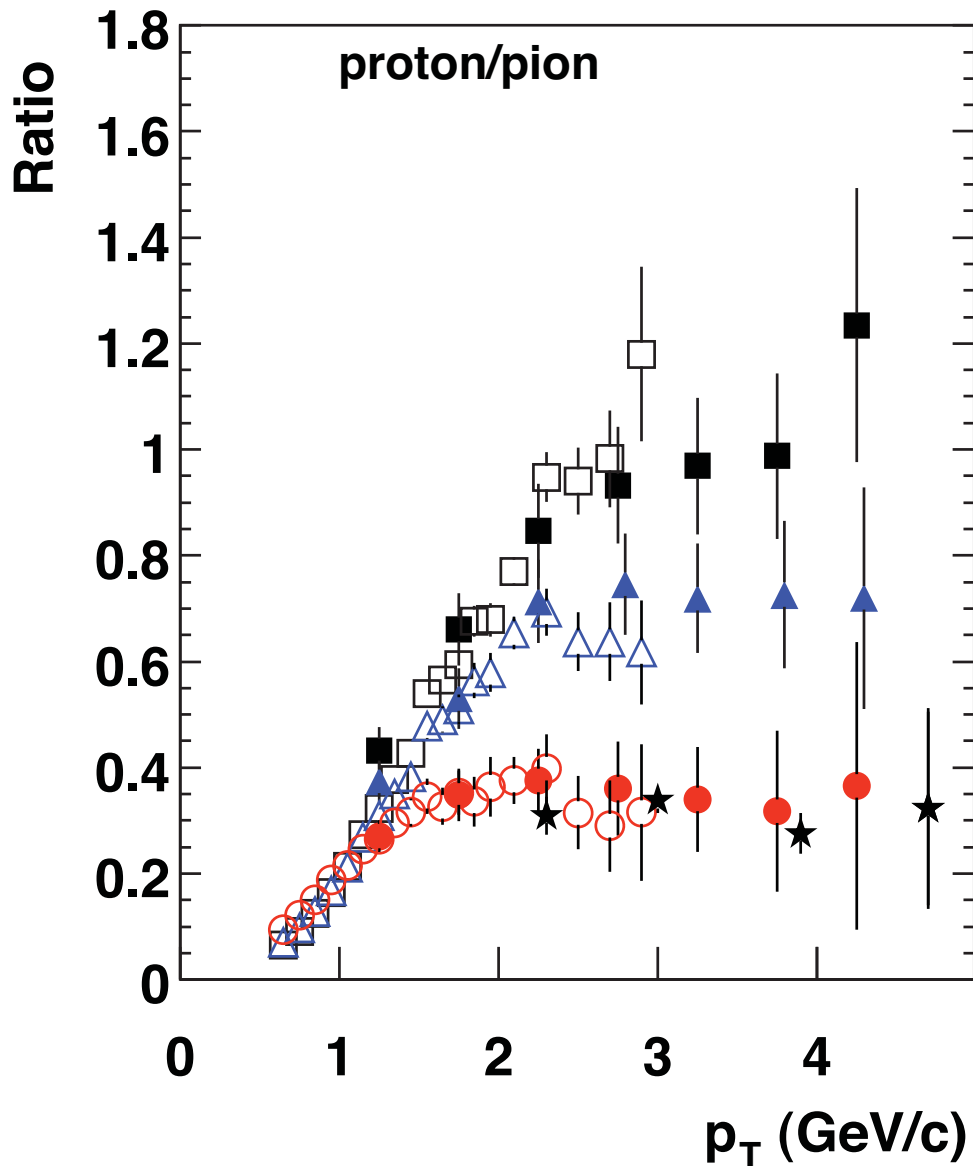
$$\mathbf{n}_{active} = 4$$

$$\mathbf{n}_{eff} = 2\mathbf{n}_{active} - 4$$

$$\mathbf{n}_{eff} = 4$$



Particle ratio changes with centrality!



A. Sickles and sjb

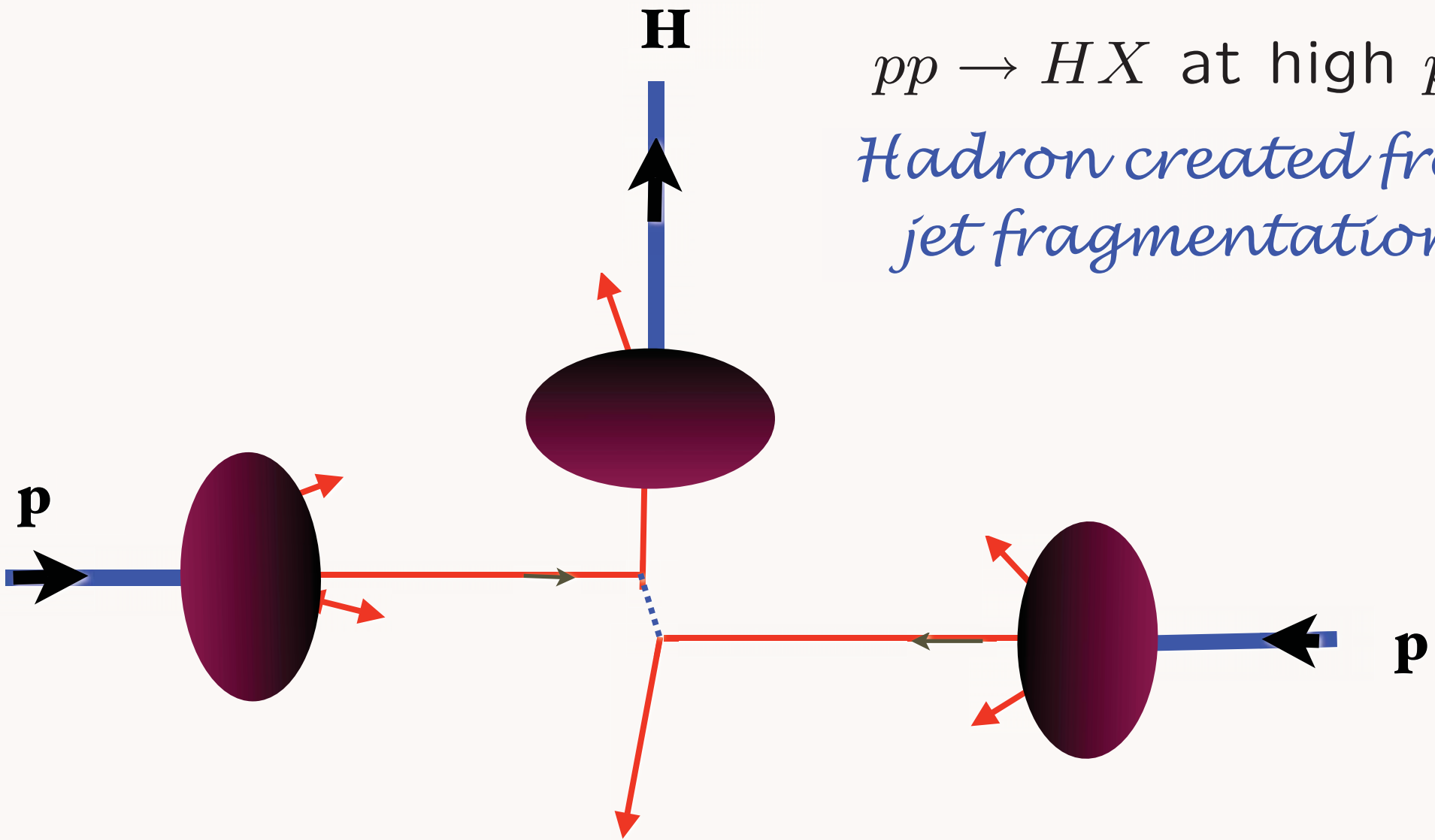
← **Central**

- ■ Au+Au 0-10%
 - △ ▲ Au+Au 20-30%
 - ● Au+Au 60-92%
 - ★ p+p, $\sqrt{s} = 53$ GeV, ISR
- $\pi^\pm \pi^0$

← **Peripheral**

*Protons less absorbed
in nuclear collisions than pions!*

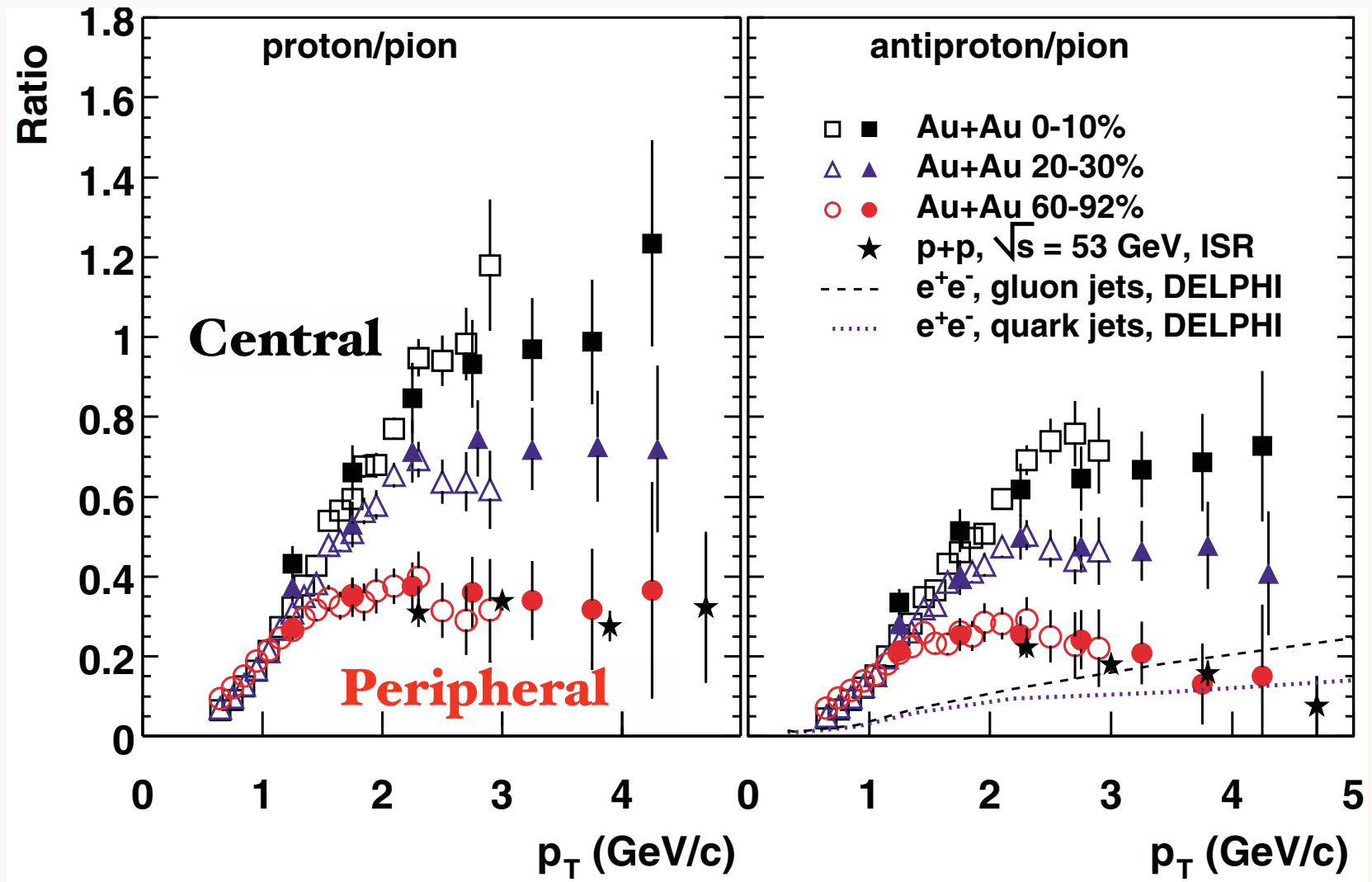




PQCD Factorization : p/π ratio universal.
Same as $e^+e^- \rightarrow HX$.



Particle ratios change with centrality!



PQCD Factorization : p/π ratio universal.
Same as $e^+e^- \rightarrow HX$.

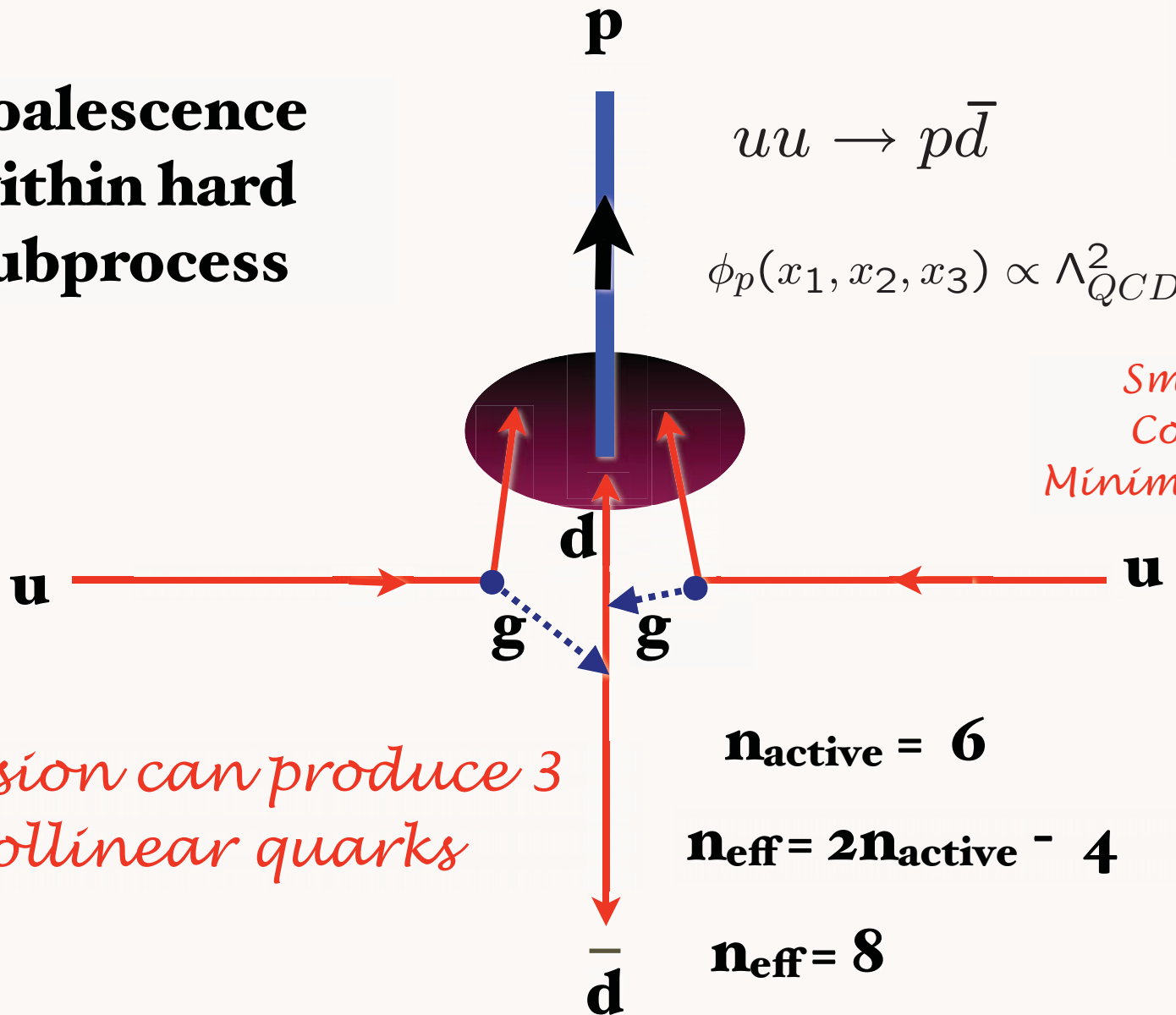
AdS/QCD



Baryon can be made directly within hard subprocess

**Coalescence
within hard
subprocess**

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



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

*Collision can produce 3
collinear quarks*

$n_{\text{active}} = 6$

$qq \rightarrow B\bar{q}$

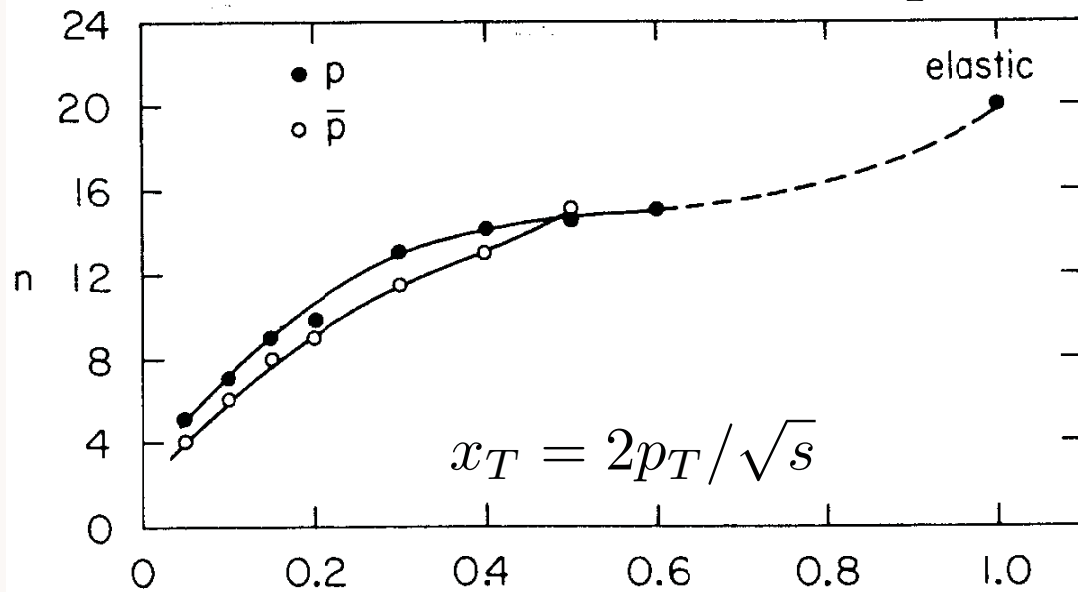
$n_{\text{eff}} = 2n_{\text{active}} - 4$

$n_{\text{eff}} = 8$

AdS/QCD

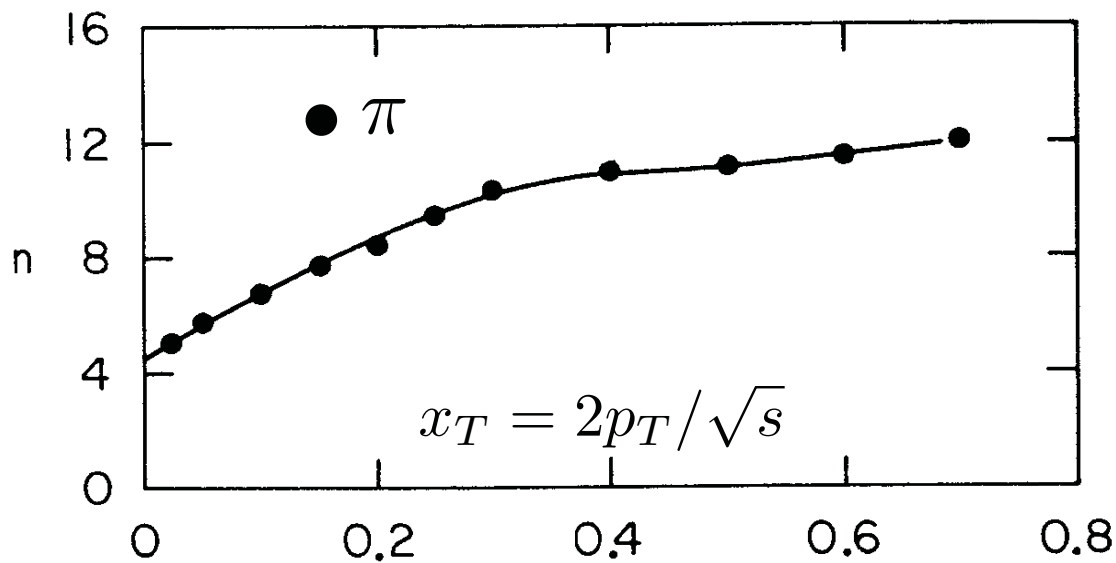


$$E \frac{d\sigma}{d^3p} (pp \rightarrow HX) = \frac{F(x_T, \theta_{cm} = \pi/2)}{p_T^n}$$



Clear evidence for higher-twist contributions

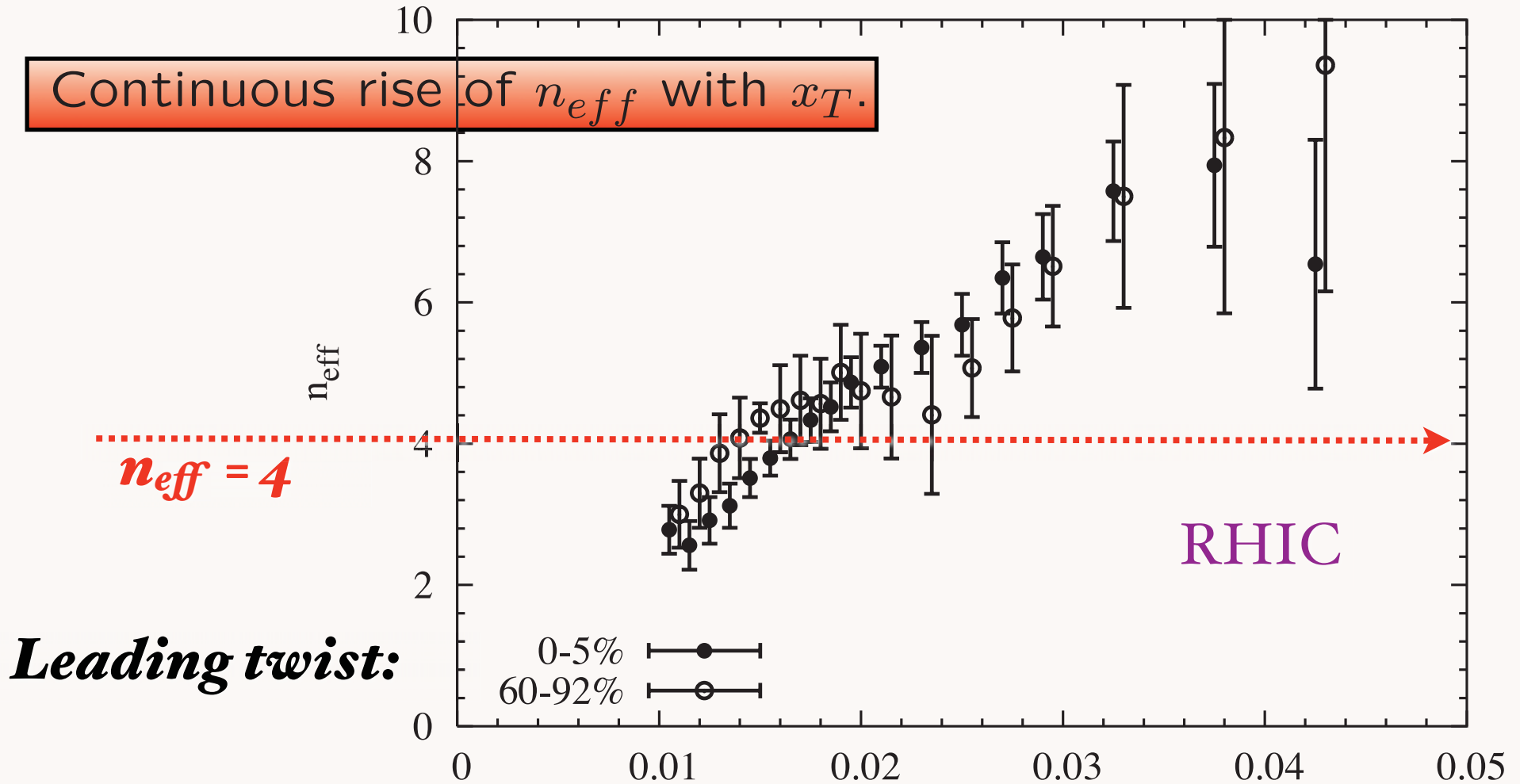
J. W. Cronin, SSI 1974



AdS/QCD



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.



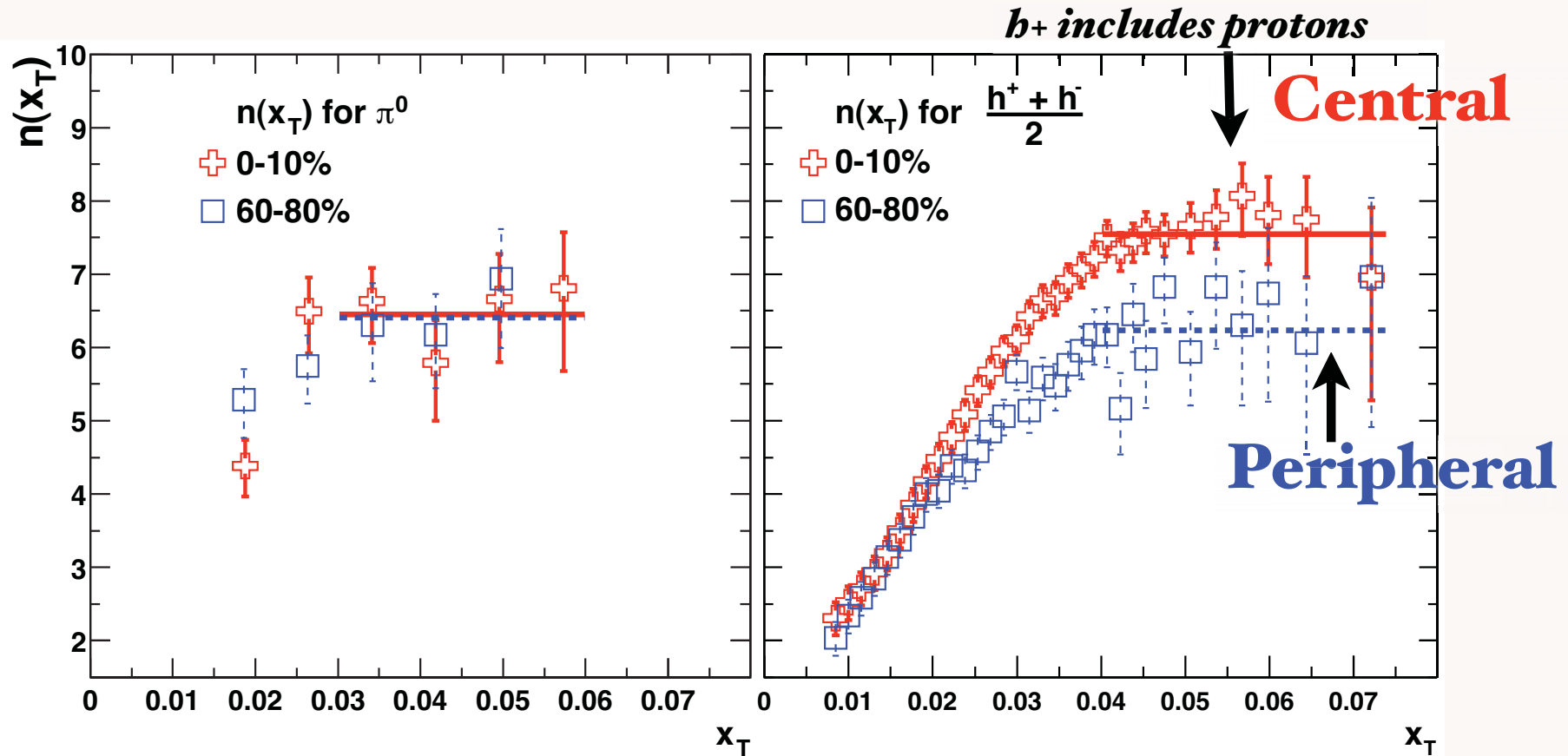
$$E \frac{d\sigma}{d^3p} (pN \rightarrow pX) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} x_T$$

AdS/QCD



Power-law exponent $n(x_T)$ for π^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 production dominated by color-transparent direct high n_{eff} subprocesses



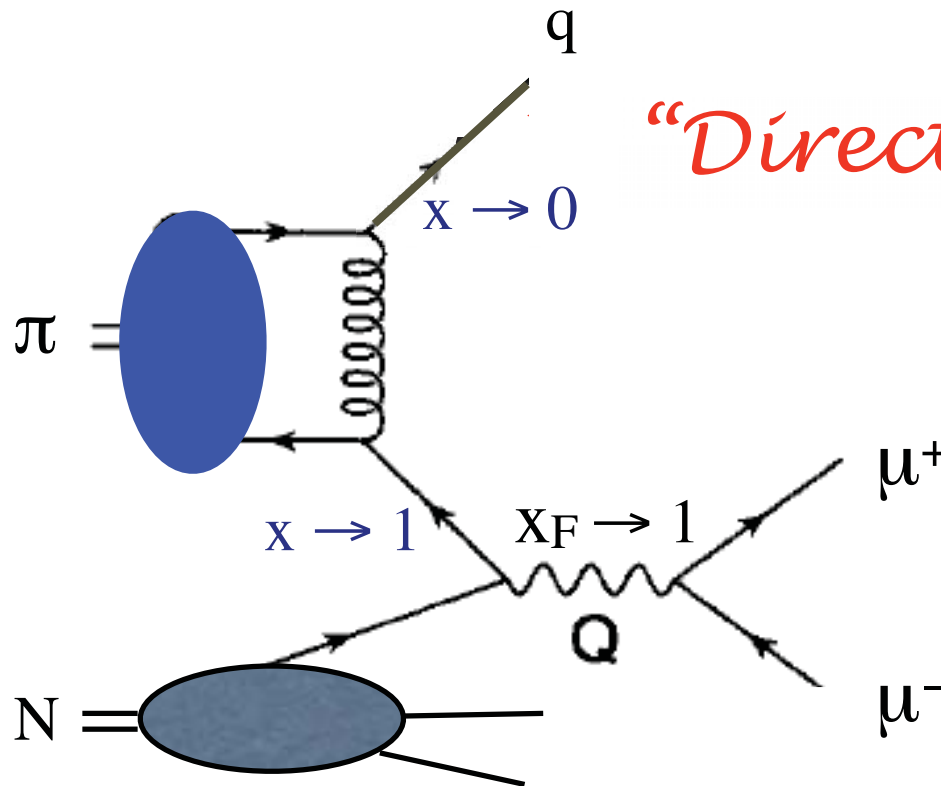
Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- 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 $x_T = 1$

$$\pi N \rightarrow \mu^+ \mu^- X \text{ at high } x_F$$

In the limit where $(1-x_F)Q^2$ is fixed as $Q^2 \rightarrow \infty$

Entire pion wf
contributes to
hard process



“Direct” Subprocess

Virtual photon is
longitudinally
polarized

Berger and Brodsky, PRL 42 (1979) 940



$\pi^- N \rightarrow \mu^+ \mu^- X$ at 80 GeV/c

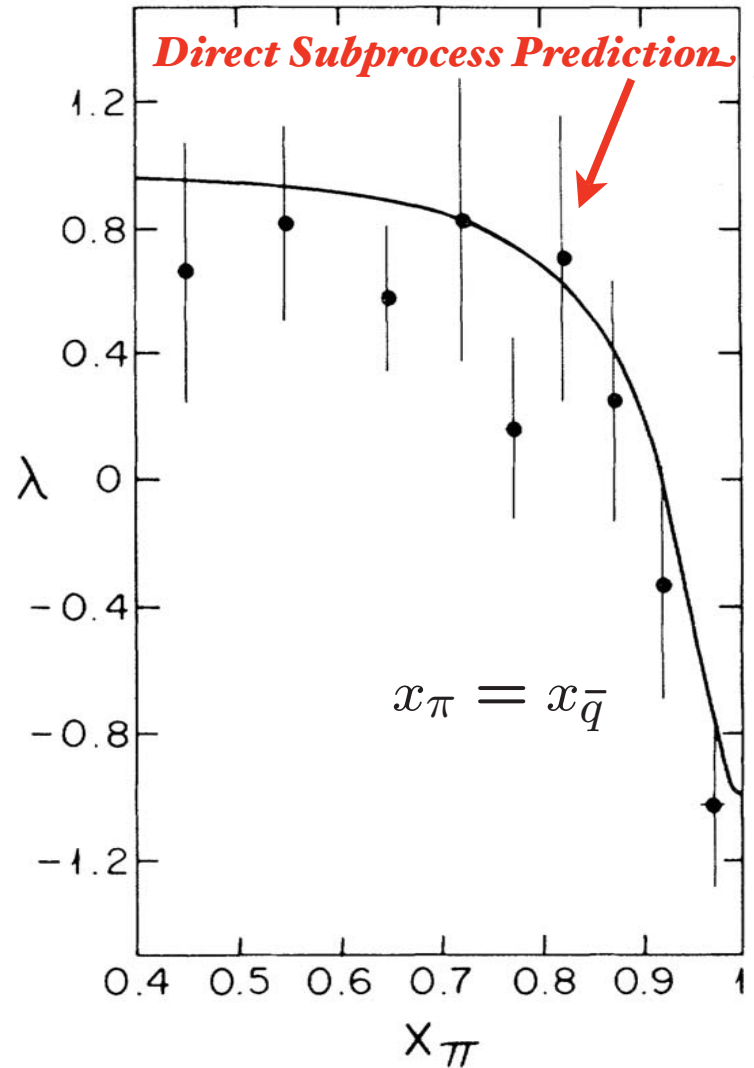
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi.$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1 - x_\pi)^2 (1 + \cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

$$\langle k_T^2 \rangle = 0.62 \pm 0.16 \text{ GeV}^2/c^2$$

*Dramatic change in
angular distribution at
large x_F*

**Example of a higher-twist
direct subprocess**



Chicago-Princeton
Collaboration

Phys.Rev.Lett.55:2649,1985



University of Southern Denmark
Odense May 5, 2008

AdS/QCD

158

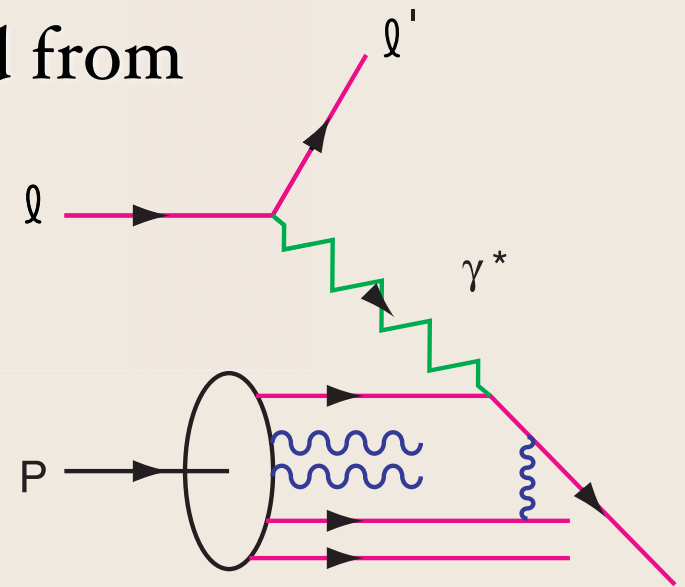
Stan Brodsky, SLAC/IPPP

Hadron Dynamics at the Amplitude Level

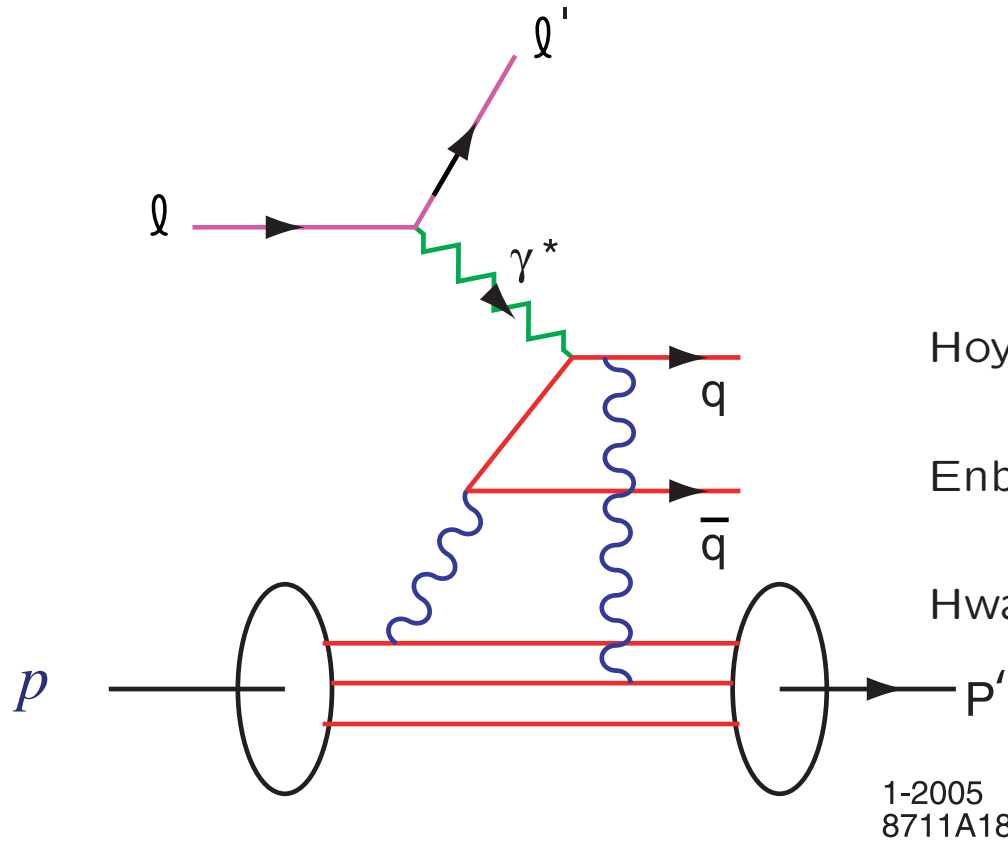
- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes.
- Relation of spin, momentum, and other distributions to physics of the hadron itself.
- Connections between observables, orbital angular momentum
- Role of FSI and ISIs--Sivers effect

- Quarks Reinteract in Final State
- Analogous to Coulomb phases, but not unitary
- Observable effects: DDIS, SSI, shadowing, antishadowing
- Structure functions cannot be computed from LFWFs computed in isolation
- Wilson line not 1 even in lcg

Hoyer, Marchal, Peigne, Sannino, sjb



Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM)

Enberg, Hoyer, Ingelman, SJB

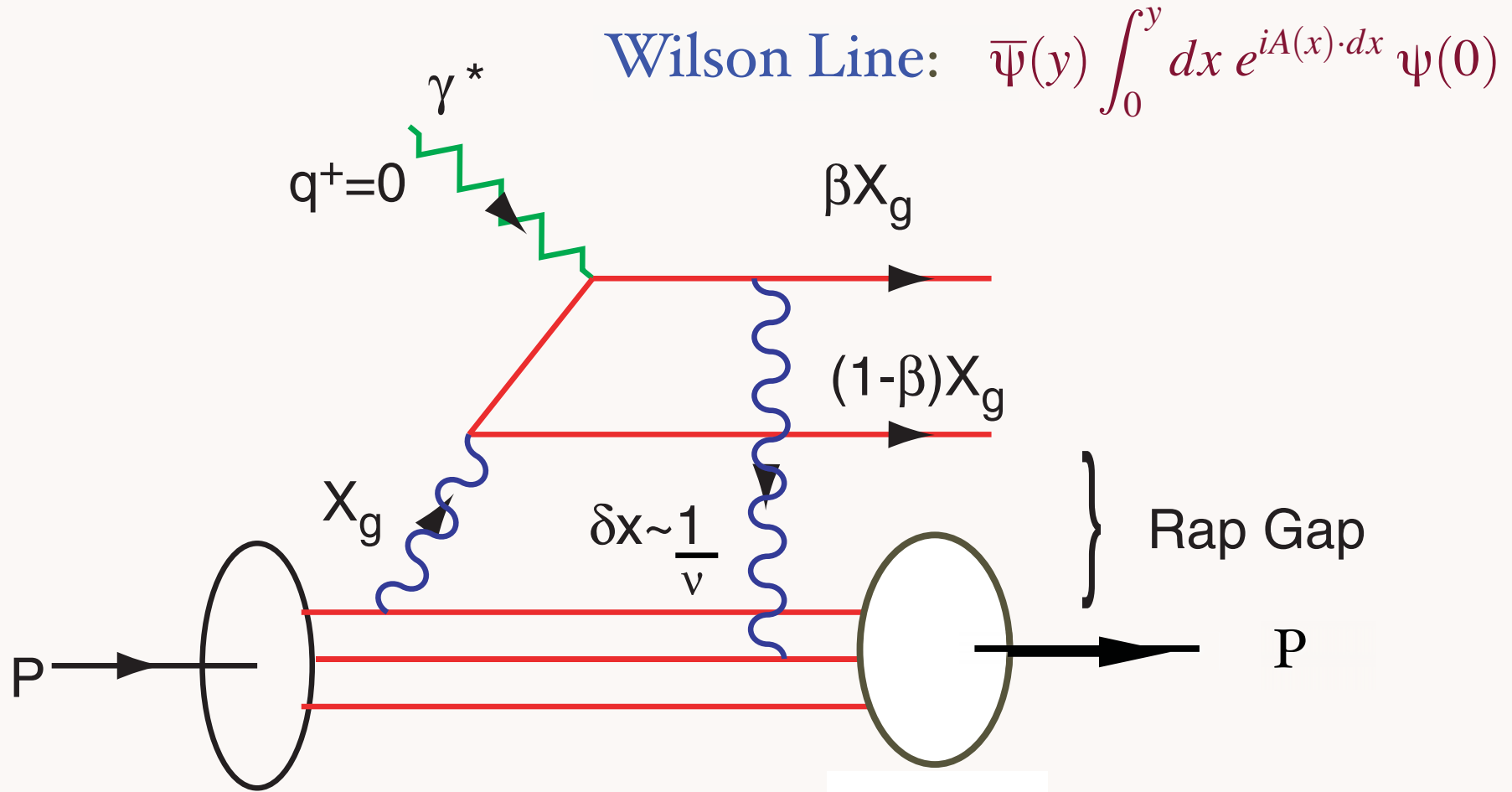
Hwang, Schmidt, SJB

1-2005
8711A18

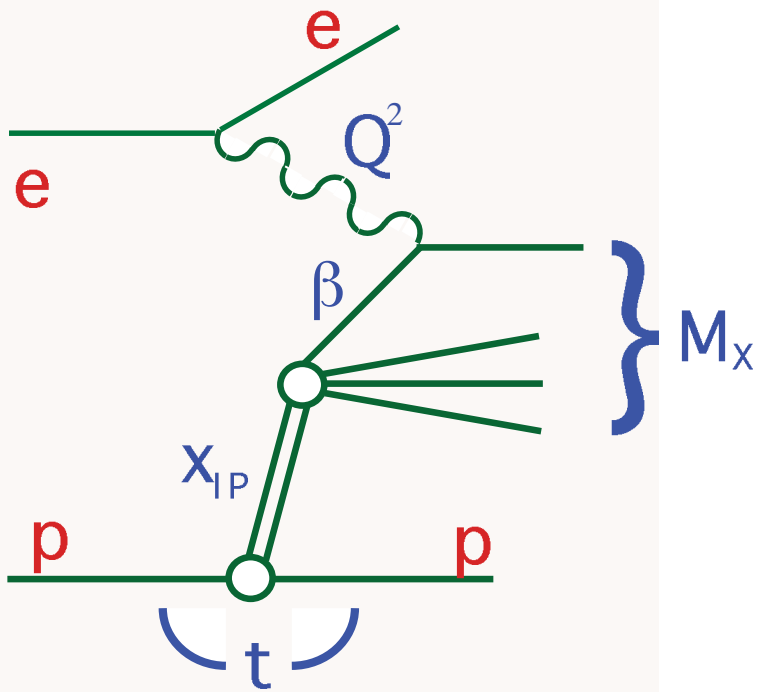
Low-Nussinov model of Pomeron



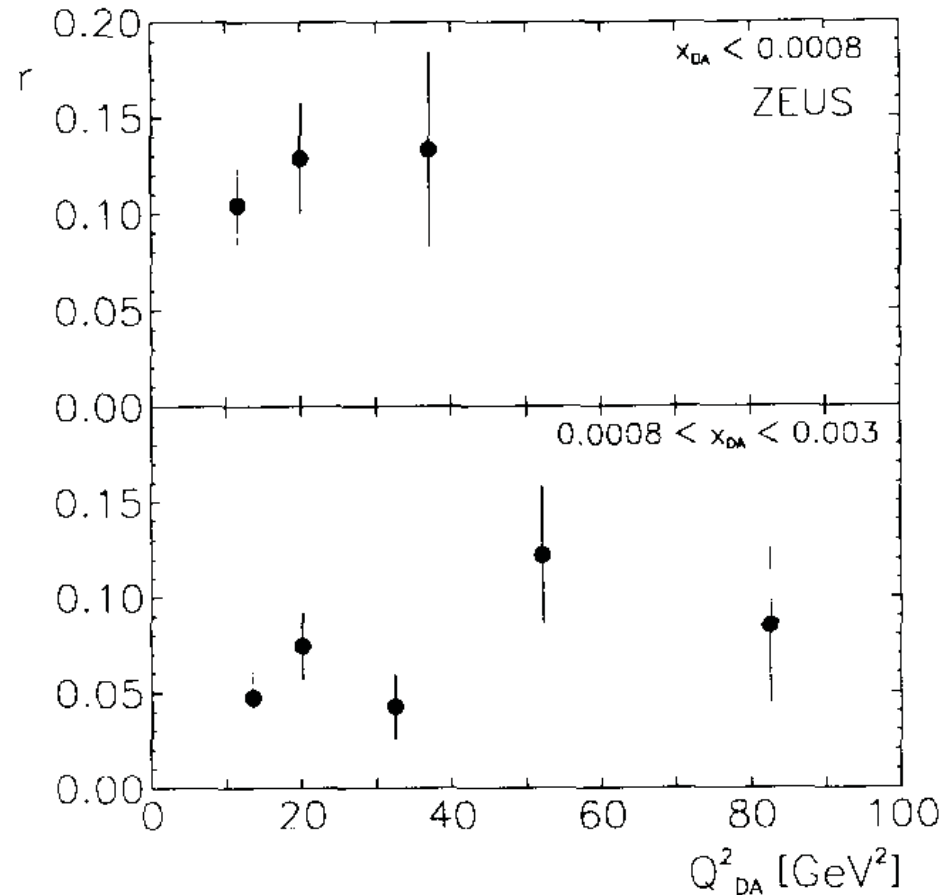
QCD Mechanism for Rapidity Gaps



Reproduces lab-frame color dipole approach



10% of DIS
events are
diffractive !



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

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

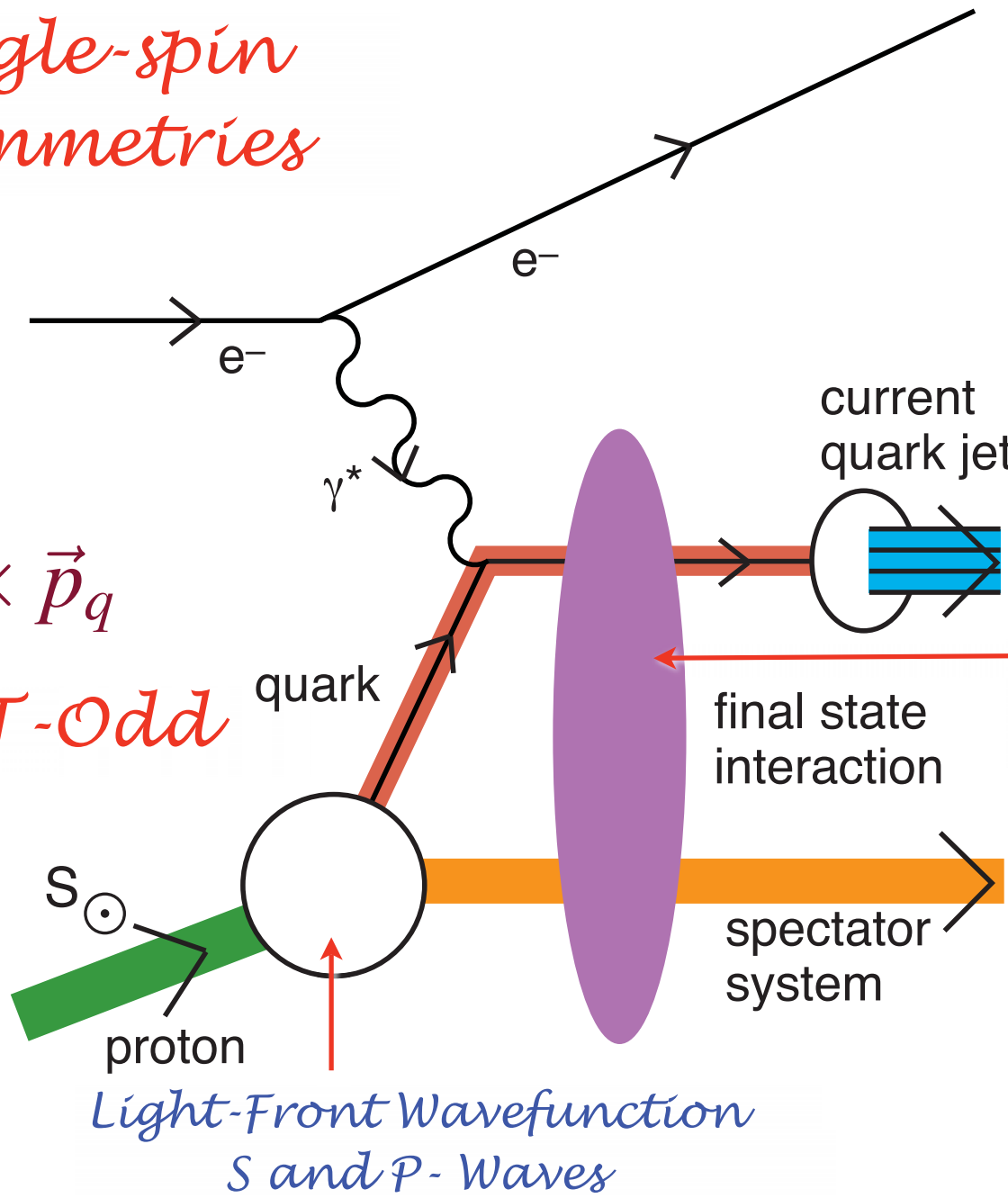


Single-spin asymmetries

Leading-Twist Sivers Effect

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

Pseudo-T-Odd



QCD S- and P-Coulomb Phases

*Light-Front Wavefunction
S and P-Waves*

D. S. Hwang,
I. A. Schmidt,
sjb



Final State Interactions Produce T-Odd (Sivers Effect)

- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment)

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

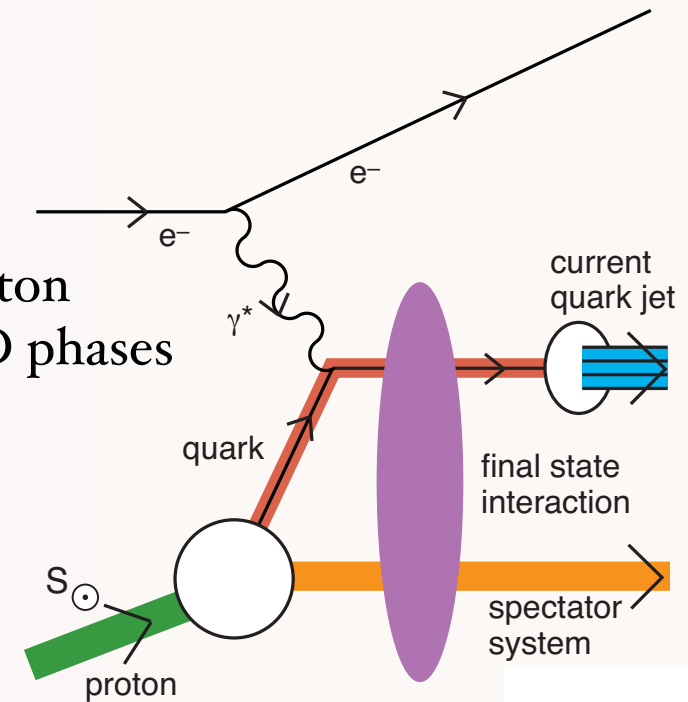
Hwang, Schmidt, sjb;
Burkardt



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

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark!
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Unexpected QCD Effect -- thought to be zero!
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD Coulomb phase at soft scale
- Measure in jet trigger or leading hadron
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment: $B(0) = 0$)

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



Double Initial-State Interactions

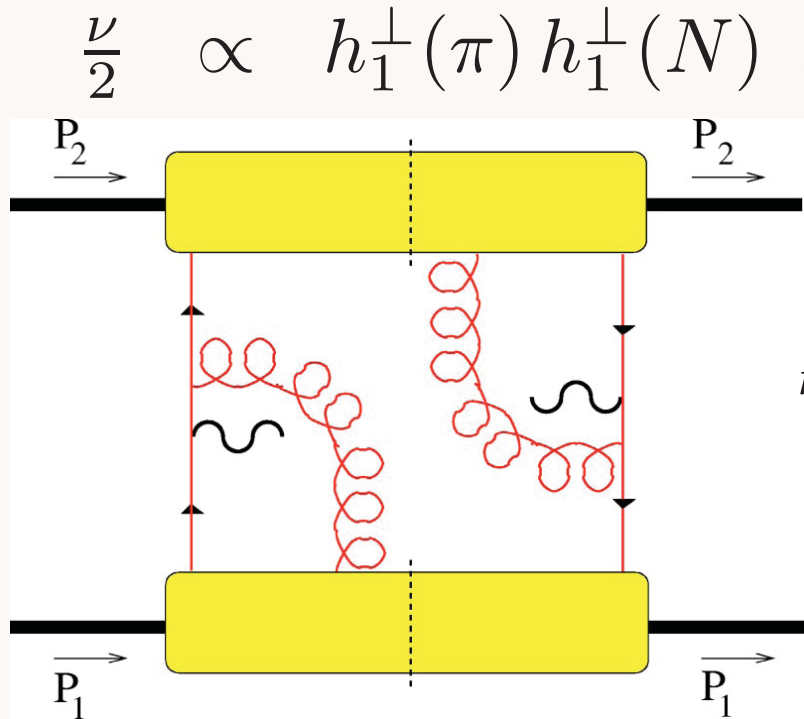
generate anomalous $\cos 2\phi$

Boer, Hwang, sjb

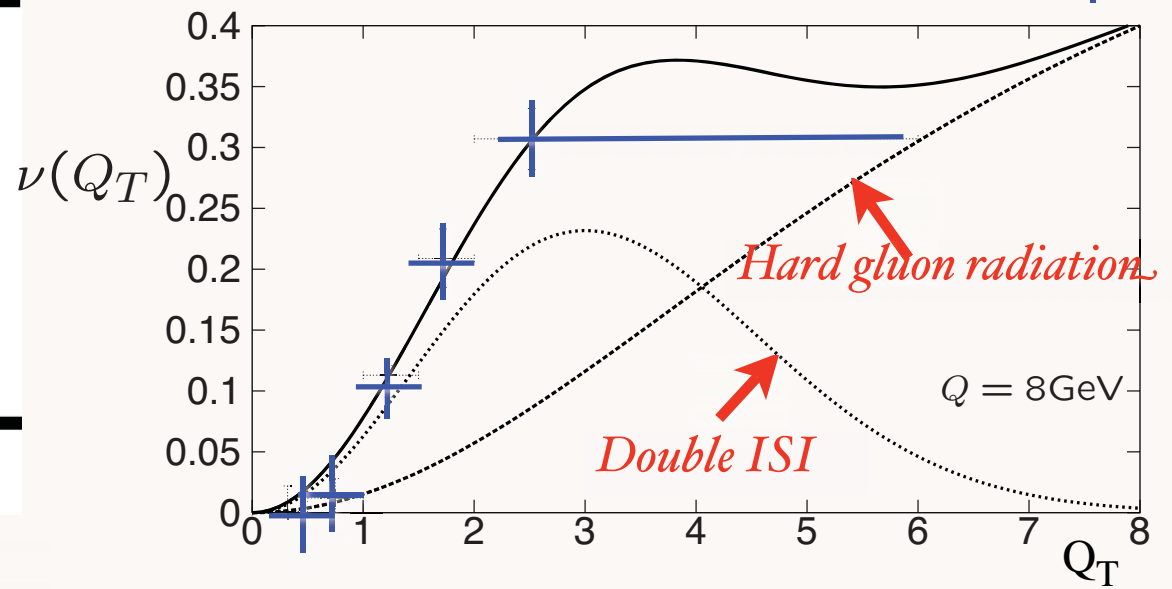
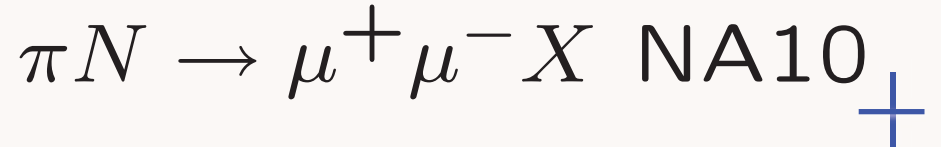
Drell-Yan planar correlations

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

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



Violates Lam-Tung relation!



Model: Boer,



Novel Manifestations of QCD

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

Mark Twain

- Quark-Gluon Plasma -- New Phenomena in Ion-Ion Collisions at RHIC and the LHC
- Connections to Early-Universe and Supernovae
- “Intrinsic Charm and Bottom” high momentum quarks in proton wavefunction
- “Hidden Color” Degrees of Freedom in QCD
- “Color Transparency”
- Color Confinement !

Physics of Rescattering

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- $DY \cos 2\phi$ distribution at leading twist from double ISI-- not given by PQCD factorization -- breakdown of factorization!
- Wilson Line Effects not 1 even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments
- Corrections to Handbag Approximation in DVCS!

Hoyer, Marchal, Peigne, Sannino, sjb

Novel Diffractive Phenomena and New Insights Into QCD from AdS/CFT

- Initial-state and final-state interactions from gluon-exchange, neglected in the parton model, have a profound effect on QCD hard-scattering reactions --
- Leading-twist single-spin asymmetries
- Diffractive deep inelastic scattering
- Diffractive hard hadronic reactions
- Nuclear shadowing and antishadowing
- New “Exclusive Diffractive Mechanism” for high x_F Higgs Production

Features of Light-Front Formalism

- *Hidden Color* Nuclear Wavefunction
- *Color Transparency, Opaqueness*
- *Intrinsic glue, sea quarks, intrinsic charm*
- Simple proof of Factorization theorems for hard processes (Lepage, sjb)
- *Direct mapping to AdS/CFT* (de Teramond, sjb)
- New Effective LF Equations (de Teramond, sjb)
- Light-Front Amplitude Generator

Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes that underlie structure functions, GPDs, exclusive processes.
- Relation of transversity and other distributions to physics of the hadron itself.
- Connections between observables
- GPDs are not densities or probability distributions
- Parton number not conserved: $n=n'$ & $n=n'+2$ at nonzero skewness
- orbital angular momentum
- Role of FSI and ISIs--Sivers effect

String Theory



AdS/CFT

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

Goal: First Approximant to QCD

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

AdS/QCD

Conformal behavior at short distances + Confinement at large distance

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

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

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

AdS/QCD



New Perspectives on QCD Phenomena from AdS/CFT

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

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

- Good initial approximant
- Better than plane wave basis Pauli, Hornbostel, Hiller,
McCartor, sjb
- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion Vary, Harinandrath, Maris, sjb
- Similar to Shell Model calculations

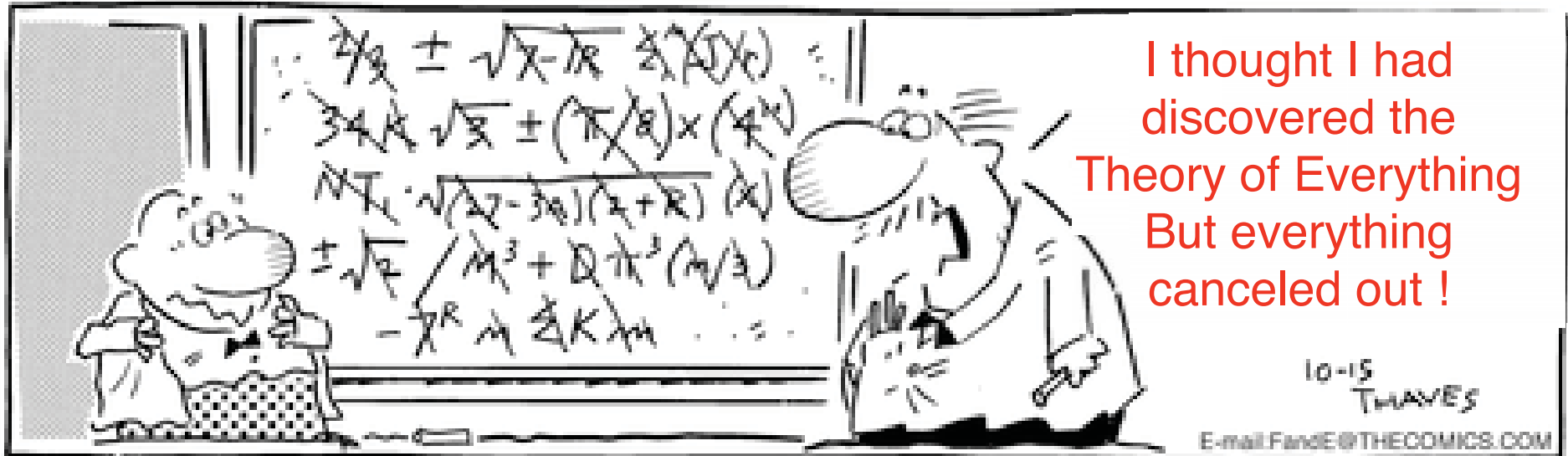
Future QCD Experimental Programs: Hadron and Nuclear Physics

- GSI antiproton storage ring
- JLab 12 GeV electrons
- J-PARC Protons
- e-RHIC: electron/positron - proton/ion collider
- LHC
- ILC
- Super B Factory

A Theory of Everything Takes Place

String theorists have broken an impasse and may be on their way to converting this mathematical structure -- physicists' best hope for unifying gravity and quantum theory -- into a single coherent theory.

Frank and Ernest



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University of Southern Denmark
Odense May 5, 2008

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177

Stan Brodsky, SLAC/IPPP

Light-Front Holography and AdS/QCD Correspondence.

[Stanley J. Brodsky](#), [Guy F. de Teramond](#) . SLAC-PUB-13220, Apr 2008. 14pp.

e-Print: [arXiv:0804.3562](#) [hep-ph]

Light-Front Dynamics and AdS/QCD Correspondence: Gravitational Form Factors of Composite Hadrons.

[Stanley J. Brodsky](#) ([SLAC](#)) , [Guy F. de Teramond](#) ([Ecole Polytechnique, CPHT](#) & [Costa Rica U.](#)) . SLAC-PUB-13192, Apr 2008. 12pp. e-Print: [arXiv:0804.0452](#) [hep-ph]

AdS/CFT and Light-Front QCD.

[Stanley J. Brodsky](#), [Guy F. de Teramond](#) . SLAC-PUB-13107, Feb 2008. 38pp.

Invited talk at International School of Subnuclear Physics: 45th Course: Searching for the "Totally Unexpected" in the LHC Era, Erice, Sicily, Italy, 29 Aug - 7 Sep 2007.

e-Print: [arXiv:0802.0514](#) [hep-ph]

AdS/CFT and Exclusive Processes in QCD.

[Stanley J. Brodsky](#), [Guy F. de Teramond](#) . SLAC-PUB-12804, Sep 2007. 29pp. [Temporary entry](#)

e-Print: [arXiv:0709.2072](#) [hep-ph]

Light-Front Dynamics and AdS/QCD Correspondence: The Pion Form Factor in the Space- and Time-Like Regions.

[Stanley J. Brodsky](#) ([SLAC](#)) , [Guy F. de Teramond](#) ([Costa Rica U.](#) & [SLAC](#)) . SLAC-PUB-12554, SLAC-PUB-12544, Jul 2007. 20pp.

Published in **Phys.Rev.D77:056007,2008.**

e-Print: [arXiv:0707.3859](#) [hep-ph]



AdS/CFT and QCD

Bottom-Up Approach

- Nonperturbative derivation of dimensional counting rules of hard exclusive glueball scattering for gauge theories with mass gap dual to string theories in warped space:
Polchinski and Strassler, hep-th/0109174.
- Deep inelastic structure functions at small x :
Polchinski and Strassler, hep-th/0209211.
- Derivation of power falloff of hadronic light-front Fock wave functions, including orbital angular momentum, matching short distance behavior with string modes at AdS boundary:
Brodsky and de Téramond, hep-th/0310227. *E. van Beveren et al.*
- Low lying hadron spectra, chiral symmetry breaking and hadron couplings in AdS/QCD:
Boschi-Filho and Braga, hep-th/0212207; de Téramond and Brodsky, hep-th/0501022; Erlich, Katz, Son and Stephanov, hep-ph/0501128; Hong, Yong and Strassler, hep-th/0501197; Da Rold and Pomarol, hep-ph/0501218; Hirn and Sanz, hep-ph/0507049; Boschi-Filho, Braga and Carrion, arXiv:hep-th/0507063; Katz, Lewandowski and Schwartz, arXiv:hep-ph/0510388.



- Gluonium spectrum (top-bottom):

Csaki, Ooguri, Oz and Terning, hep-th/9806021; de Mello Kock, Jevicki, Mihailescu and Nuñez, hep-th/9806125; Csaki, Oz, Russo and Terning, hep-th/9810186; Minahan, hep-th/9811156; Brower, Mathur and Tan, hep-th/0003115, Caceres and Nuñez, hep-th/0506051.

- D3/D7 branes (top-bottom):

Karch and Katz, hep-th/0205236; Karch, Katz and Weiner, hep-th/0211107; Kruczenski, Mateos, Myers and Winters, hep-th/0311270; Sakai and Sonnenschein, hep-th/0305049; Babington, Erdmenger, Evans, Guralnik and Kirsch, hep-th/0312263; Nuñez, Paredes and Ramallo, hep-th/0311201; Hong, Yoon and Strassler, hep-th/0312071; hep-th/0409118; Kruczenski, Pando Zayas, Sonnenschein and Vaman, hep-th/0410035; Sakai and Sugimoto, hep-th/0412141; Paredes and Talavera, hep-th/0412260; Kirsh and Vaman, hep-th/0505164; Apreda, Erdmenger and Evans, hep-th/0509219; Casero, Paredes and Sonnenschein, hep-th/0510110.

- Other aspects of high energy scattering in warped spaces:

Giddings, hep-th/0203004; Andreev and Siegel, hep-th/0410131; Siopsis, hep-th/0503245.

- Strongly coupled quark-gluon plasma ($\eta/s = 1/4\pi$):

Policastro, Son and Starinets, hep-th/0104066; Kang and Nastase, hep-th/0410173 ...



1. **“Light-Front Dynamics and AdS/QCD: The Pion Form Factor in the Space- and Time-Like Regions”**
S. J. Brodsky and G. F. de Teramond
arXiv:0707.3859 [hep-ph]
SLAC-PUB-12554(2007) (Submitted to Phys.Rev.D)
2. **“AdS/CFT and QCD”**
S. J. Brodsky and G. F. de Teramond
arXiv:hep-th/0702205
SLAC-PUB-12361(2007)
Invited talk at 2006 International Workshop on the Origin of Mass and Strong Coupling Gauge Theories (SCGT 06), Nagoya, Japan, 21-24 Nov 2006
3. **“Hadronic spectra and light-front wavefunctions in holographic QCD”**
S. J. Brodsky and G. F. de Teramond
Phys. Rev. Lett. **96**, 201601 (2006) [arXiv:hep-ph/0602252]
4. **“Advances in light-front quantization and new perspectives for QCD from AdS/CFT”**
S. J. Brodsky and G. F. de Teramond
Nucl. Phys. Proc. Suppl. **161**, 34 (2006)
Invited talk at Workshop on Light-Cone QCD and Nonperturbative Hadron Physics 2005 (LC 2005), Cairns, Queensland, Australia, 7-15 Jul 2005
5. **“Hadron spectroscopy and wavefunctions in QCD and the AdS/CFT correspondence”**
S. J. Brodsky and G. F. de Teramond
AIP Conf. Proc. **814**, 108 (2006) [arXiv:hep-ph/0510240]
Invited talk at 11th International Conference on Hadron Spectroscopy (Hadron05), Rio de Janeiro, Brazil, 21-26 Aug 2005



6. **“Applications of AdS/CFT duality to QCD”**
S. J. Brodsky and G. F. de Teramond
Int. J. Mod. Phys. A **21**, 762 (2006) [arXiv:hep-ph/0509269]
Invited talk at International Conference on QCD and Hadronic Physics, Beijing, China, 16-20 Jun 2005
7. **“Nearly conformal QCD and AdS/CFT”**
G. F. de Teramond and S. J. Brodsky
arXiv:hep-ph/0507273
SLAC-PUB-11375(2005)
Presented at 1st Workshop on Quark-Hadron Duality and the Transition to pQCD, Frascati, Rome, Italy, 6-8 Jun 2005
8. **“The hadronic spectrum of a holographic dual of QCD”**
G. F. de Teramond and S. J. Brodsky
Phys. Rev. Lett. **94**, 201601 (2005) [arXiv:hep-th/0501022]
9. **“Baryonic states in QCD from gauge / string duality at large $N(c)$ ”**
G. F. de Teramond and S. J. Brodsky
arXiv:hep-th/0409074
SLAC-PUB-10693(2004)
Presented at ECT Workshop on Large N_c QCD 2004, Trento, Italy, 5-9 Jul 2004*
10. **“Light-front hadron dynamics and AdS/CFT correspondence”**
S. J. Brodsky and G. F. de Teramond
Phys. Lett. B **582**, 211 (2004) [arXiv:hep-th/0310227]

