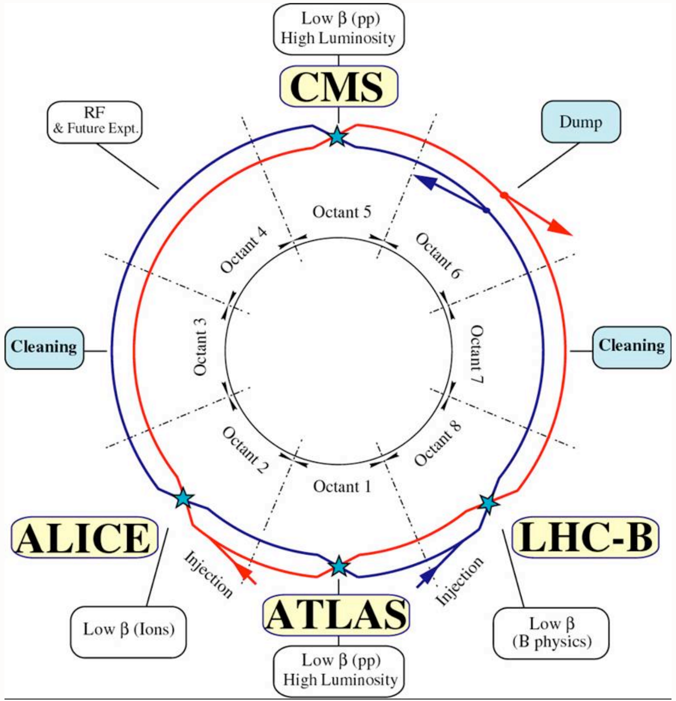
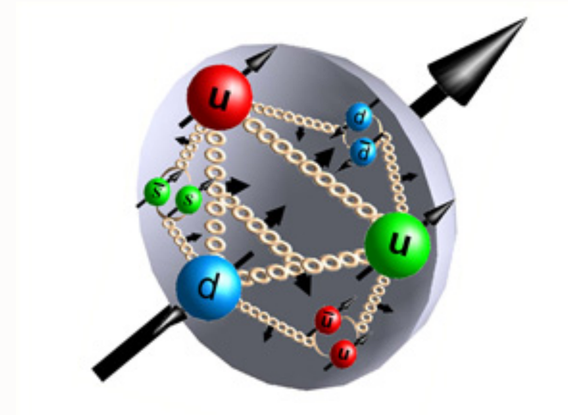
Physics Flagships for AFTER: Fixed Target ExpeRiments @ the LHC

Heavy Quark Physics



AFTER @ LHC



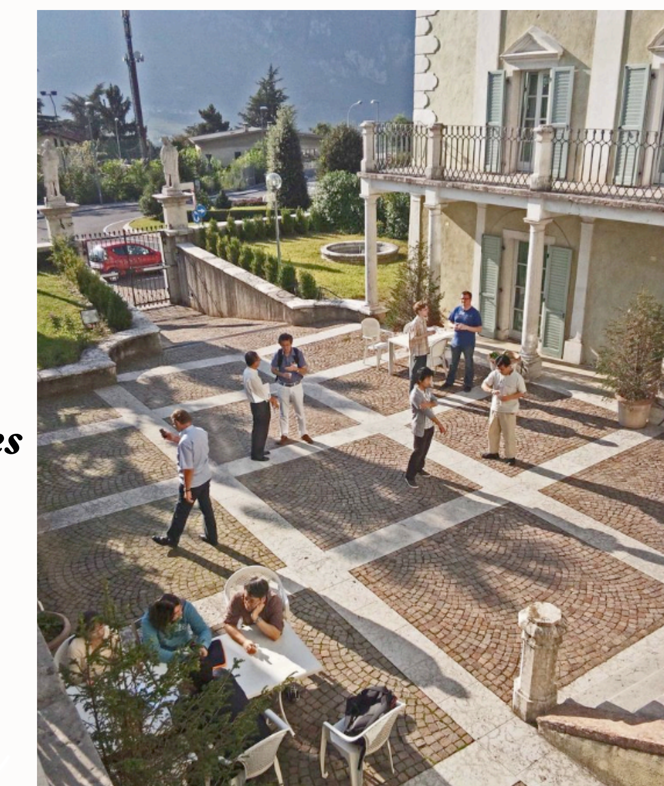
Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

ECT* Workshop

February 4-8, 2013

European Center for Theoretical Studies in Nuclear Physics and Related Areas



Thanks to the France-Stanford Center for Interdisciplinary Studies

Thanks to: J.-P. Lansberg, F. Fleuret

A Compelling Idea for QCD:

Utilize the High-Energy LHC proton and nuclear beams in a fixed-target mode

- *Nuclear and Polarized Targets*

AFTER @ LHC

A Fixed-Target ExpeRiment

- *Study Dynamics at extreme rapidities: $X_F = -1$*

A new hadron physics laboratory for studying and testing QCD

AFTER @ LHC

- *7 TeV proton beam collisions on a proton or nuclear target -- Extract beam with Crystals -*
- *Minimal effects on the collider*
- *Equivalent to Ecm = 115 GeV*
- *Nuclear and Polarized Targets*
- *Nuclear Beams: Produce QGP in Rest Frame of Target Nucleus*
- *Study Dynamics at extreme rapidities:* $X_F = -1$ *New domain!*
- *Secondary Beams -- Even B and D*
- *Diffraction on Nucleons and Nucleus*
- *Cosmic Ray Simulations*

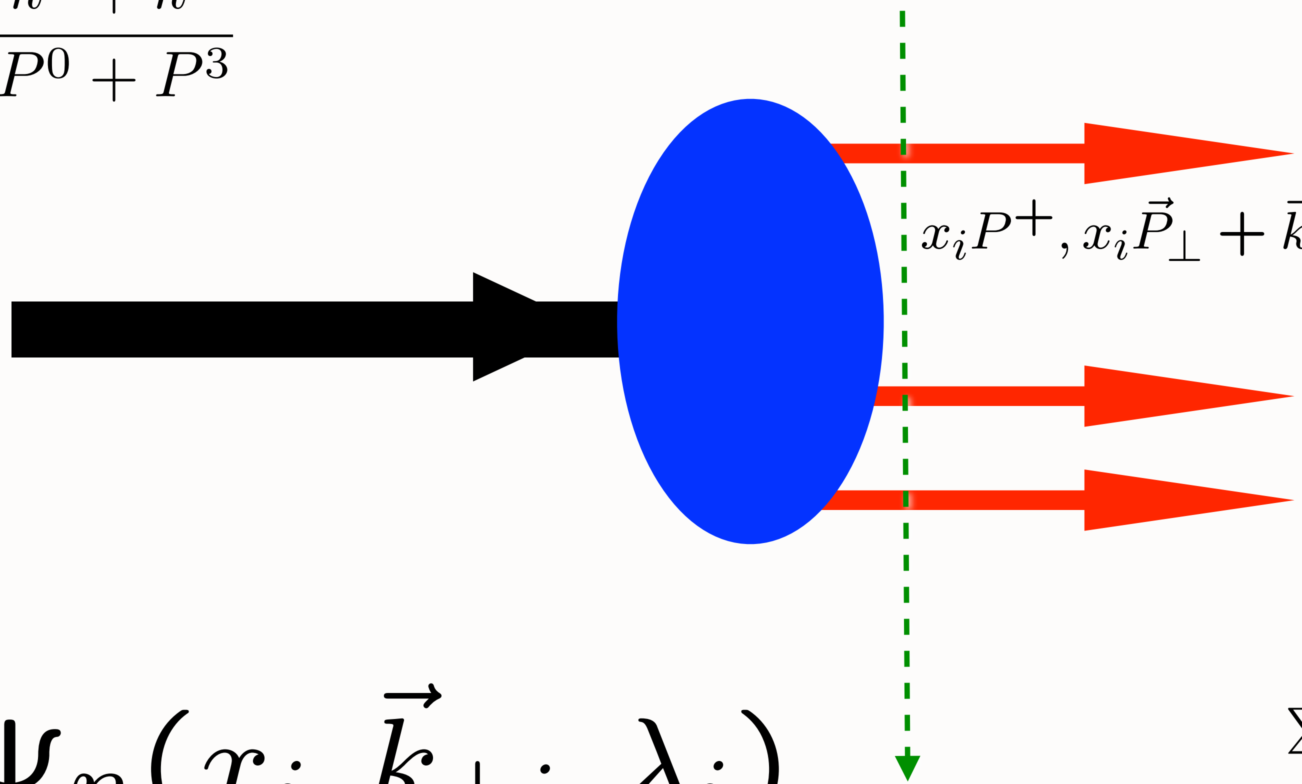
Fixed-Target Physics with the LHC Beams

- 7 TeV proton beam, 3 TeV nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations
- Sterile Neutrinos -- Dark Matter Candidates
- Single-Spin Asymmetries, Transversity Studies, A_N
- High-x_F Dynamics --Correlations, Diffraction
- High-x_F Heavy Quark and quarkonium phenomena
- Production of ccq to ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System: e.g. Ridge Physics at Extreme Rapidities
- Anti-Shadowing: Flavor Specific?
- Higgs at Threshold using nuclear Fermi motion

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

Fixed $\tau = t + z/c$

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



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

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

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Each element of flash photograph illuminated at same LF time

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

Causal, frame-independent

Evolve in LF time

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

Eigenstate -- independent of τ

$$H_{LF} = P^+ P^- - \vec{P}^2_\perp$$

$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

HELEN BRADLEY - PHOTOGRAPHY

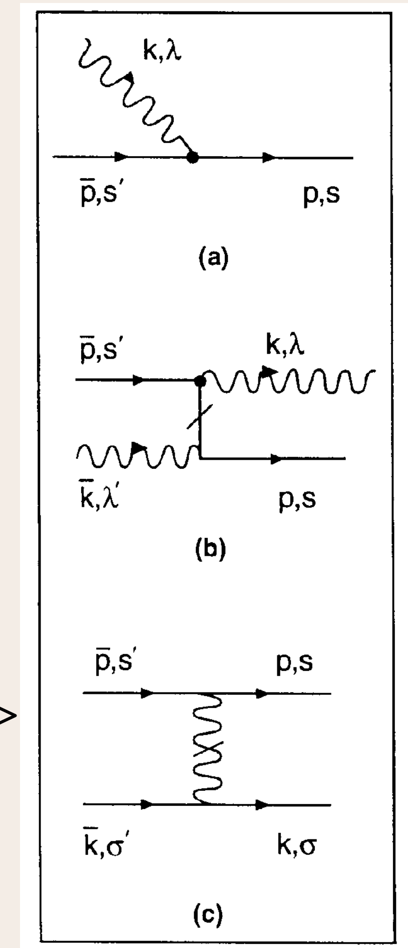
Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$



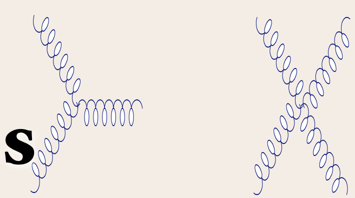
H^{int}_{LF}: Matrix in Fock Space

$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

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

Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions

LFWFs: Off-shell in P- and invariant mass



$$H^{int}_{LF}$$

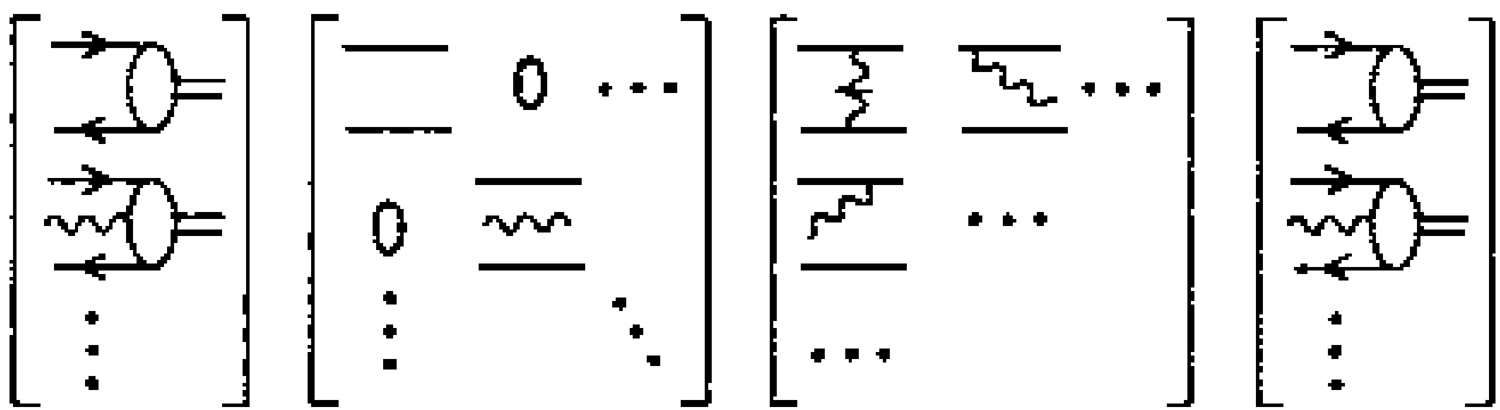
LIGHT-FRONT MATRIX EQUATION

G.P. Lepage, sjb

Rigorous Method for Solving Non-Perturbative QCD!

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i}\right)\begin{bmatrix}\psi_{q\bar{q}/\pi}\\ \psi_{q\bar{q}g/\pi}\\ \vdots\end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\,V\,|q\bar{q}\rangle & \langle q\bar{q}|\,V\,|q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\,V\,|q\bar{q}\rangle & \langle q\bar{q}g|\,V\,|q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}\begin{bmatrix}\psi_{q\bar{q}/\pi}\\ \psi_{q\bar{q}g/\pi}\\ \vdots\end{bmatrix}$$

$$A^+ = 0$$



Minkowski space; frame-independent; no fermion doubling; no ghosts

- ***Light-Front Vacuum = Vacuum of Free Hamiltonian!***

Causal, Frame-Independent ***Possible zero modes***

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

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

The Light Front Fock State Wavefunctions

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

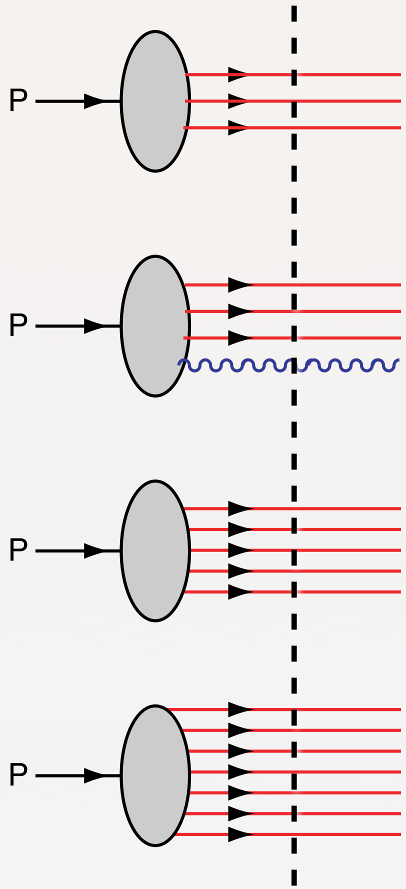
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

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

Hidden Color

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

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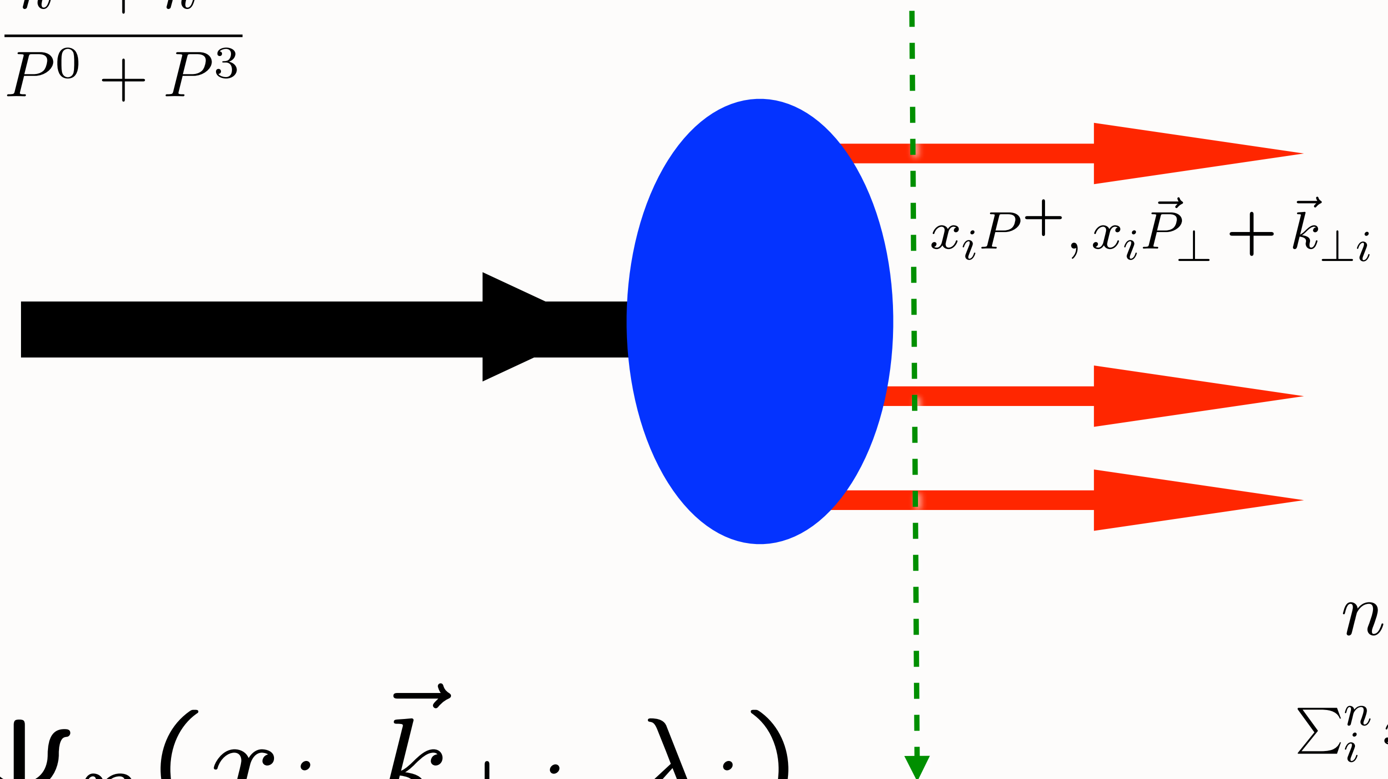
$P^+, \vec{P}_\perp$



$n = 3$

$\sum_i^n x_i = 1$

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

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

Invariant under boosts! Independent of P^μ

Bethe-Salpeter WF integrated over k^-

Measured in DIS

Off-shell amplitude -- arbitrarily off-shell in invariant mass!

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
Every Vertex

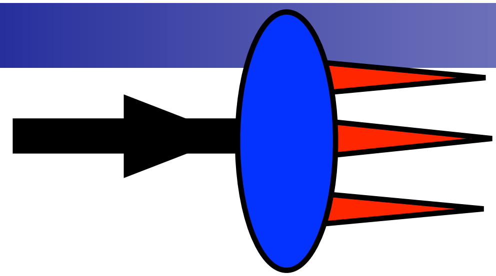
$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Parke-Taylor Amplitudes **Stasto**

Nonzero Anomalous Moment -->Nonzero orbital angular momentum
Drell, sjb

• Light Front Wavefunctions:



Lorce

$\xi = 0$

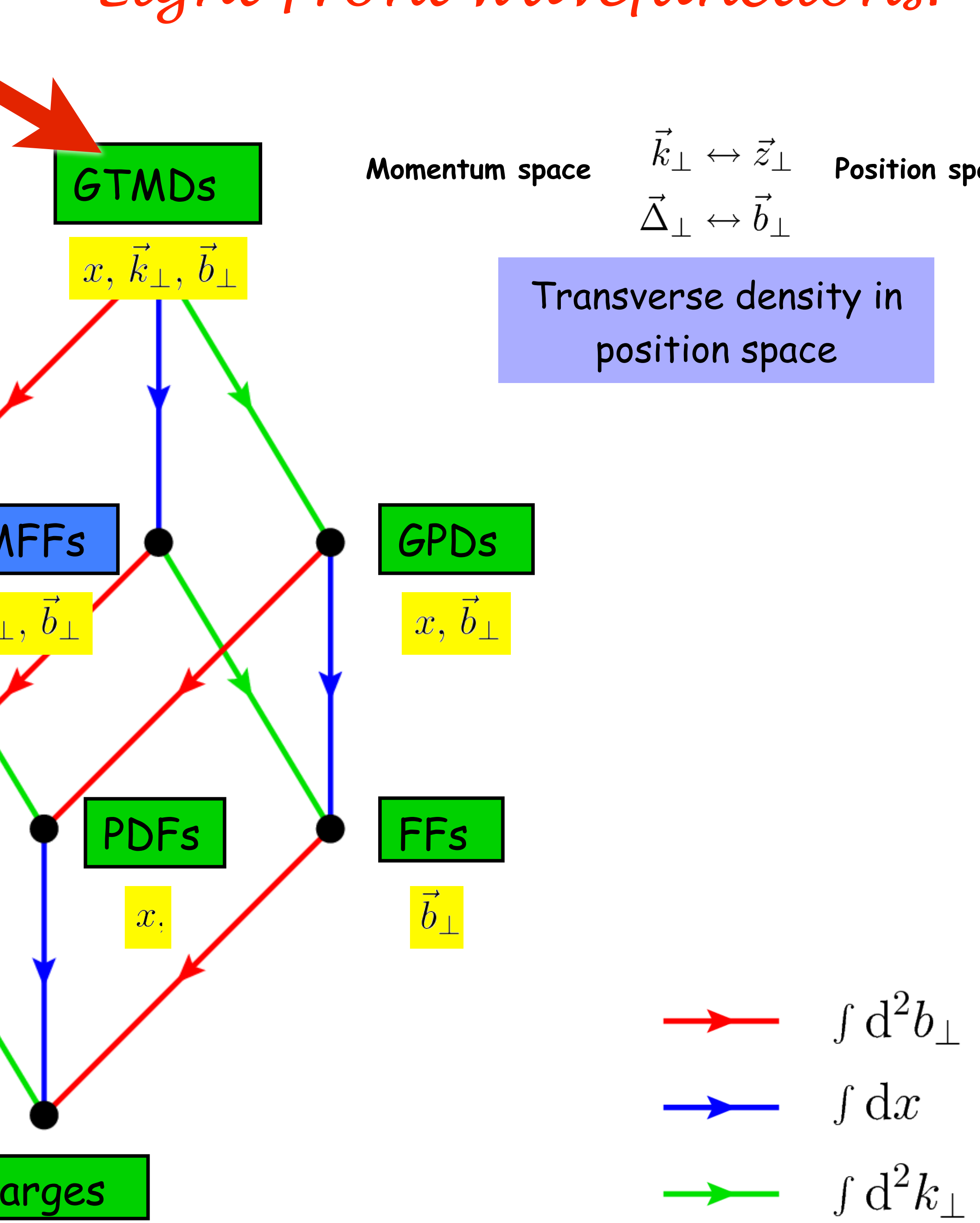
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

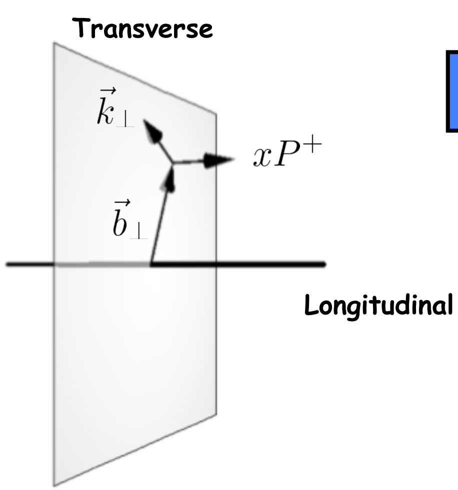
Transverse density in momentum space

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

$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in position space





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

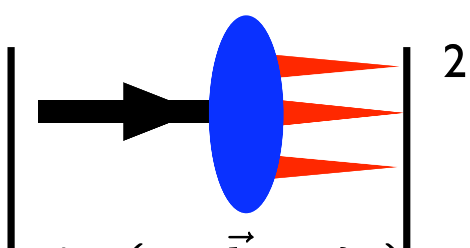
Hwang, Schmidt, sjb,

Mulders, Boer

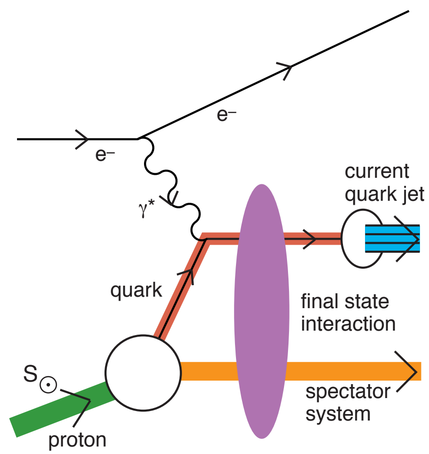
Qiu, Sterman

Collins, Qiu

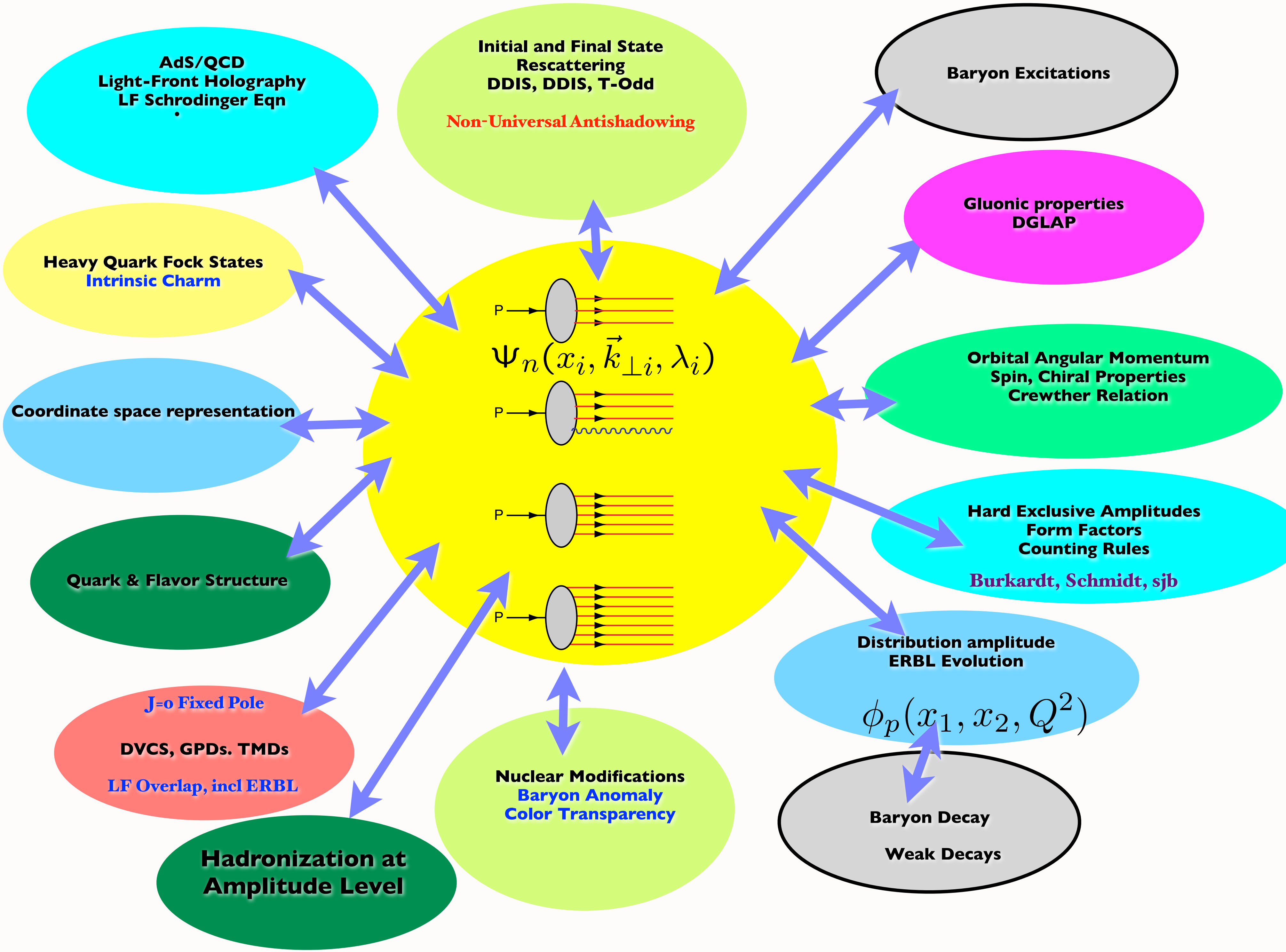
Pasquini, Xiao, Yuan, sjb

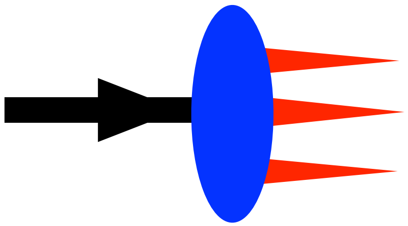


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



QCD and the LF Hadron Wavefunctions





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

- **LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics**

- **LFWFs=Hadron Eigensolutions: Direct Connection to QCD Lagrangian**

- **Relativistic, frame-independent: no boosts, no disc contraction, Melosh built into LF spinors**

- **Hadronic observables computed from LFWFs: Form factors, Structure Functions, Distribution Amplitudes, GPDs, TMDs, Weak Decays, ... modulo `lensing' from ISIs, FSIs**

- **Cannot compute current matrix elements using instant or point form from eigensolutions alone -- need to include vacuum currents!**

- *Hadron Physics without LFWFs is like Biology without DNA!*

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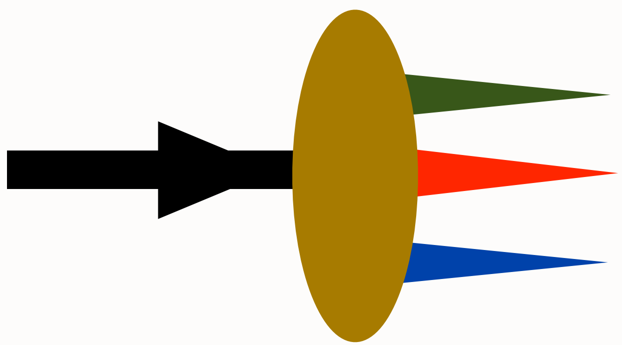


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$$H_{QCD}^{LF}$$

QCD Meson Spectrum

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

Coupled Fock states

$$\left[\frac{\vec{k}_\perp^2 + m^2}{x(1-x)} + V_{\rm eff}^{LF}\right] \psi_{LF}(x, k_\perp) = M^2 \ \psi_{LF}(x, \vec{k}_\perp)$$

Effective two-particle equation

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

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

Azimuthal Basis ζ, ϕ

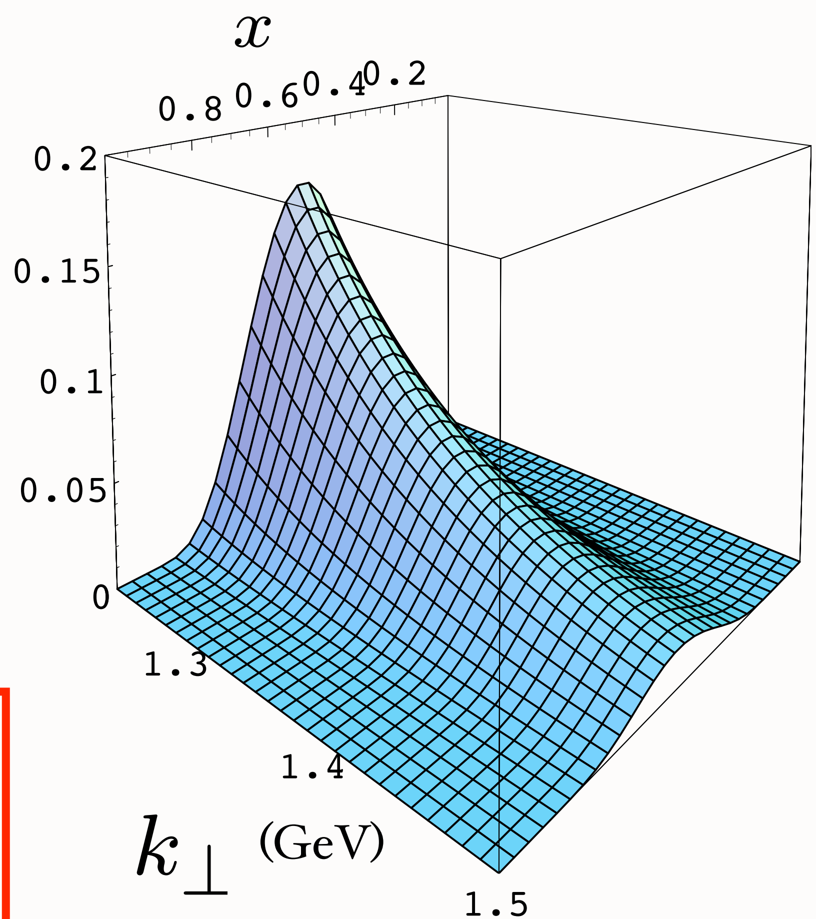
$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2(L + S - 1)$$

Confining AdS/QCD potential

Semiclassical first approximation to QCD

Prediction from AdS/CFT: Meson LFWF

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



de Teramond, sjb

"Soft Wall" model

J. R. Forshaw, R. Sandapen

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

Wavefunctions functions of invariant mass $\frac{k_\perp^2}{x(1-x)}$

PRL **109,** 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

J. R. Forshaw*

Consortium for Fundamental Physics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom

R. Sandapen†

Département de Physique et d'Astronomie, Université de Moncton, Moncton, New Brunswick E1A3E9, Canada

(Received 5 April 2012; published 20 August 2012)

We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive

$$\phi(x, \zeta) = \mathcal{N} \frac{\kappa}{\sqrt{\pi}} \sqrt{x(1-x)} \exp\left(-\frac{\kappa^2 \zeta^2}{2}\right),$$

$$\tilde{\phi}(x, k) \propto \frac{1}{\sqrt{x(1-x)}} \exp\left(-\frac{M_{q\bar{q}}^2}{2\kappa^2}\right),$$

Wavefunctions functions of invariant mass $\frac{k_\perp^2}{x(1-x)}$

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

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

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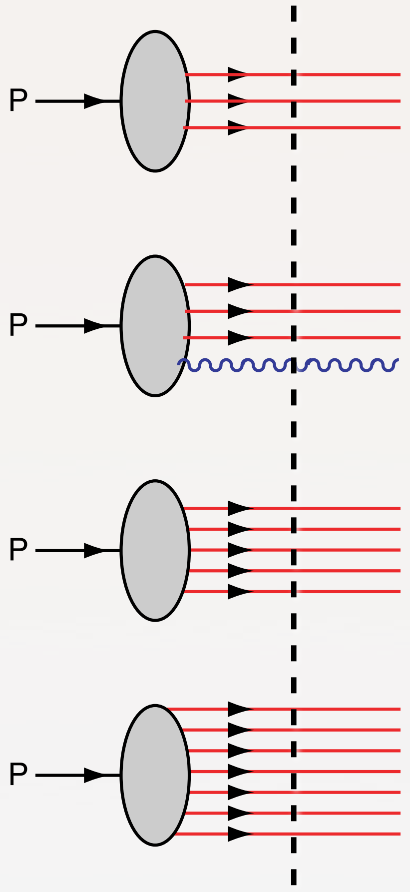


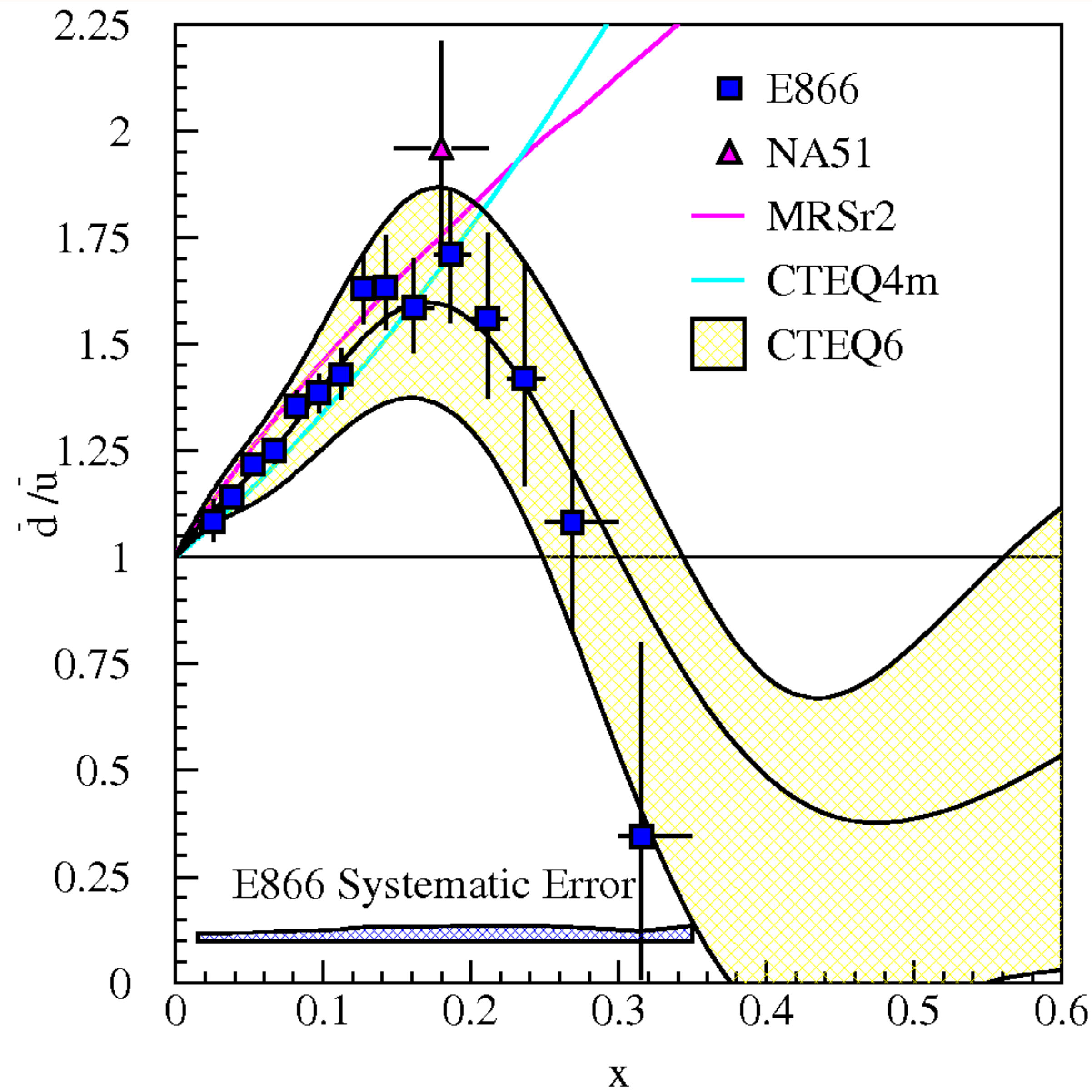
Intrinsic heavy quarks
c(x), b(x) at high x !

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

Hidden Color

Mueller: gluon Fock states BFKL

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



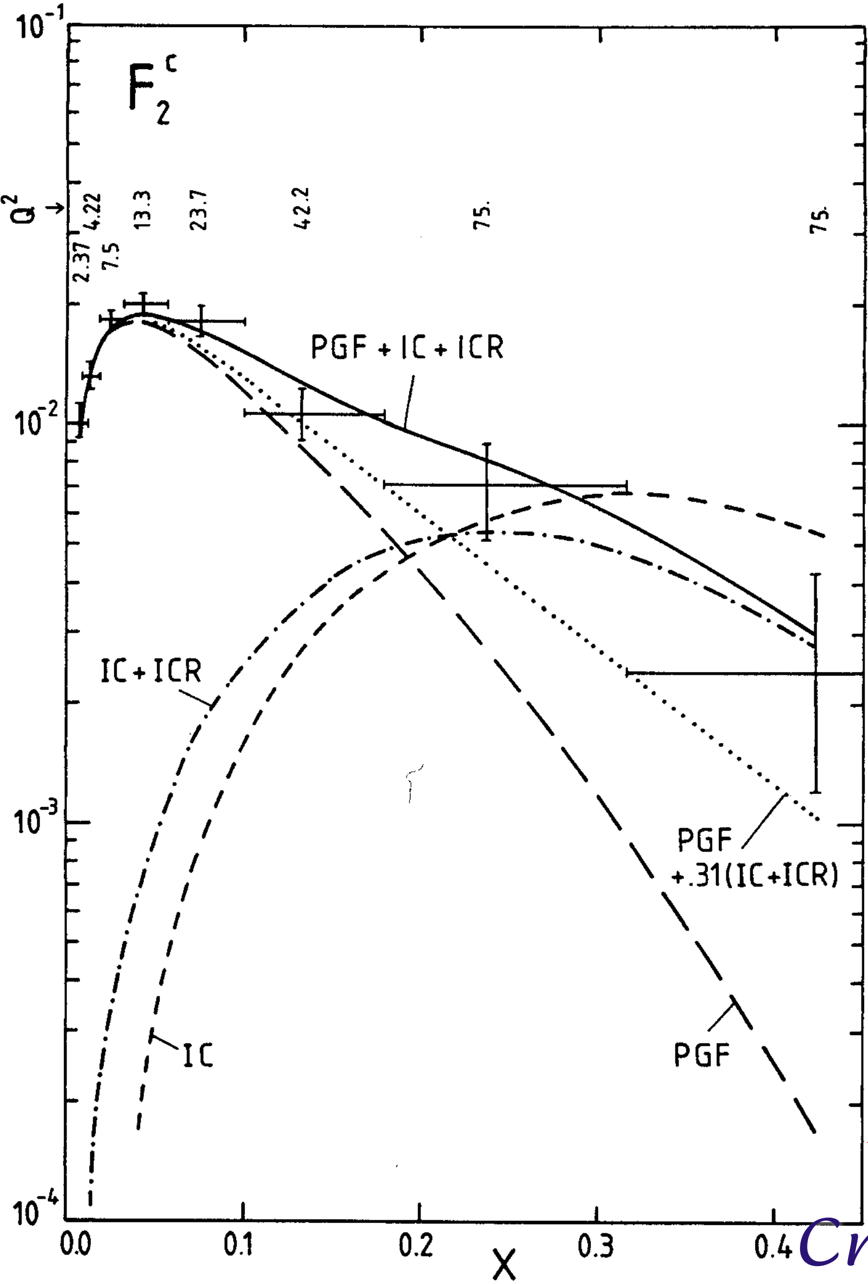
- E866/NuSea (Drell-Yan)

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

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

Intrinsic glue, sea, heavy quarks

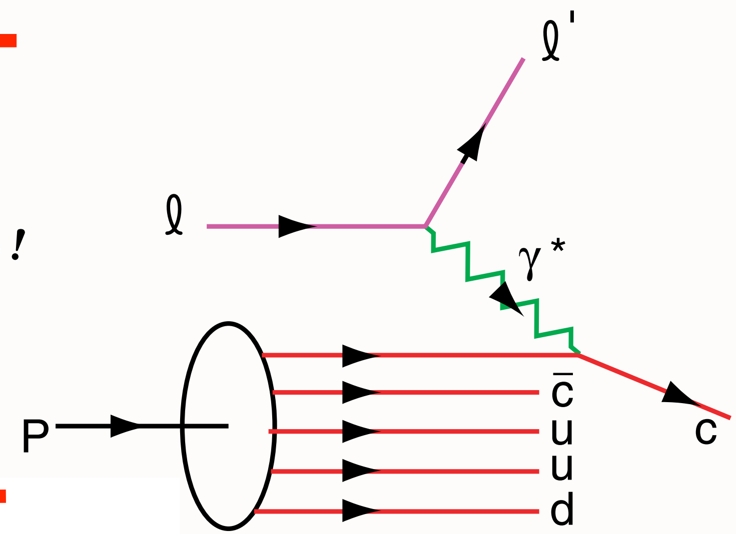
Measurement of Charm Structure Function



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 !



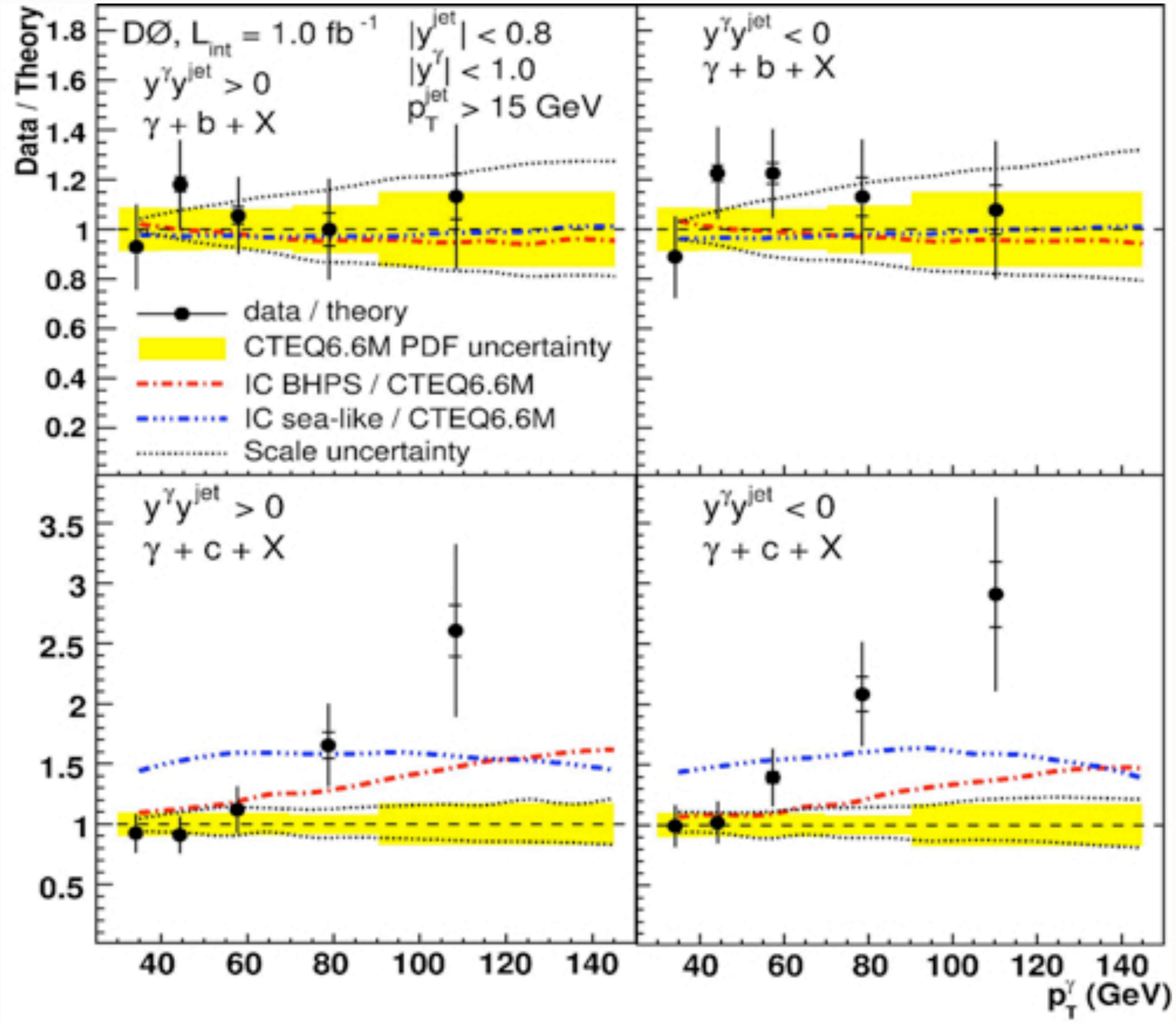
Crucial measurement for COMPASS!

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

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**

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



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

Ratio is insensitive to gluon PDF, scales

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

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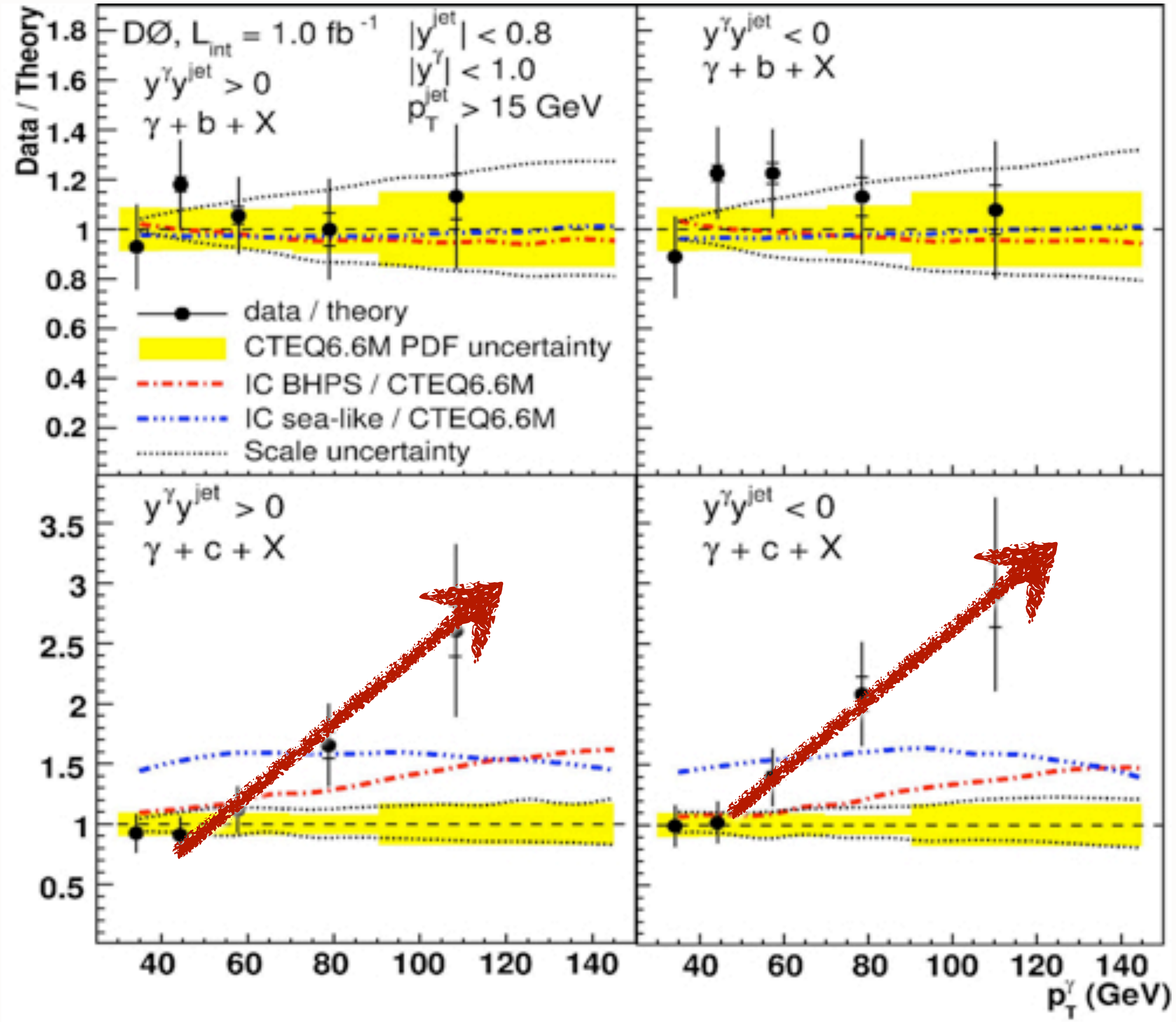


$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

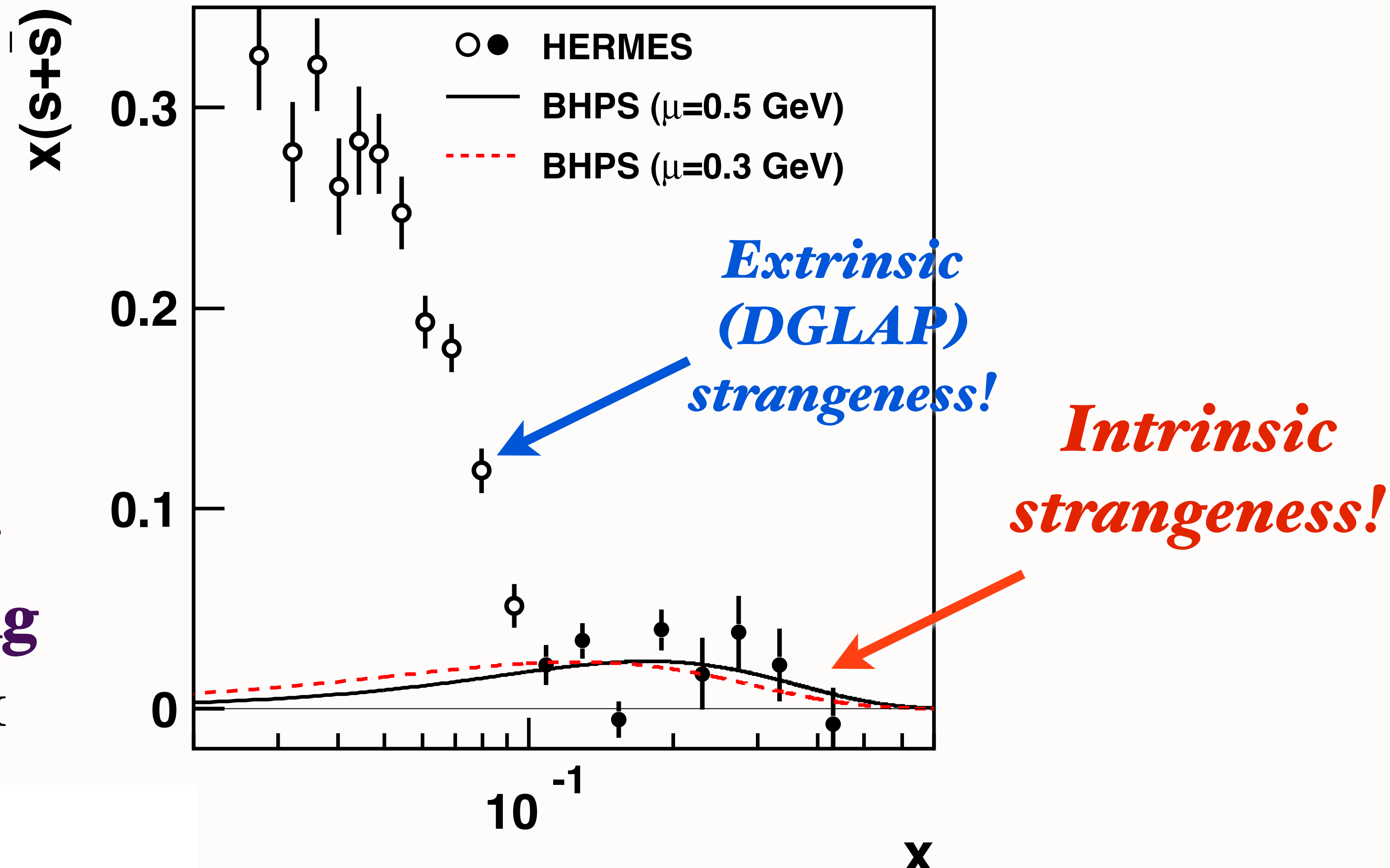
Signal for significant IC at x > 0.1 ?

Need to evolve with massive quark!

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

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.

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

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

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

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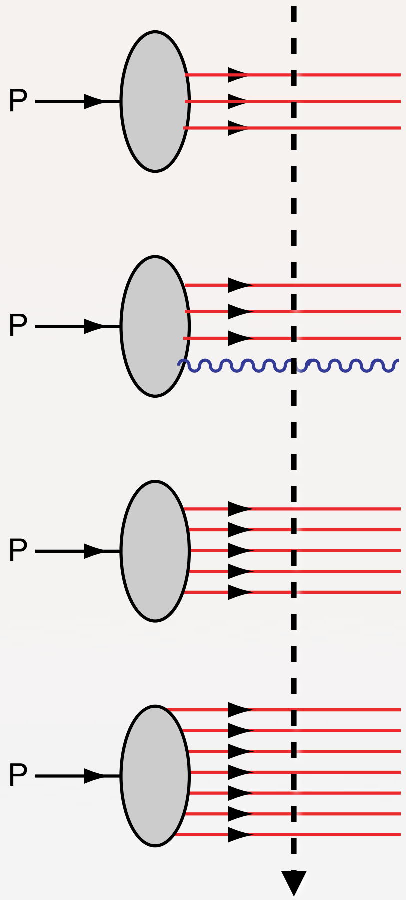

Fixed LF time

Intrinsic heavy quarks

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

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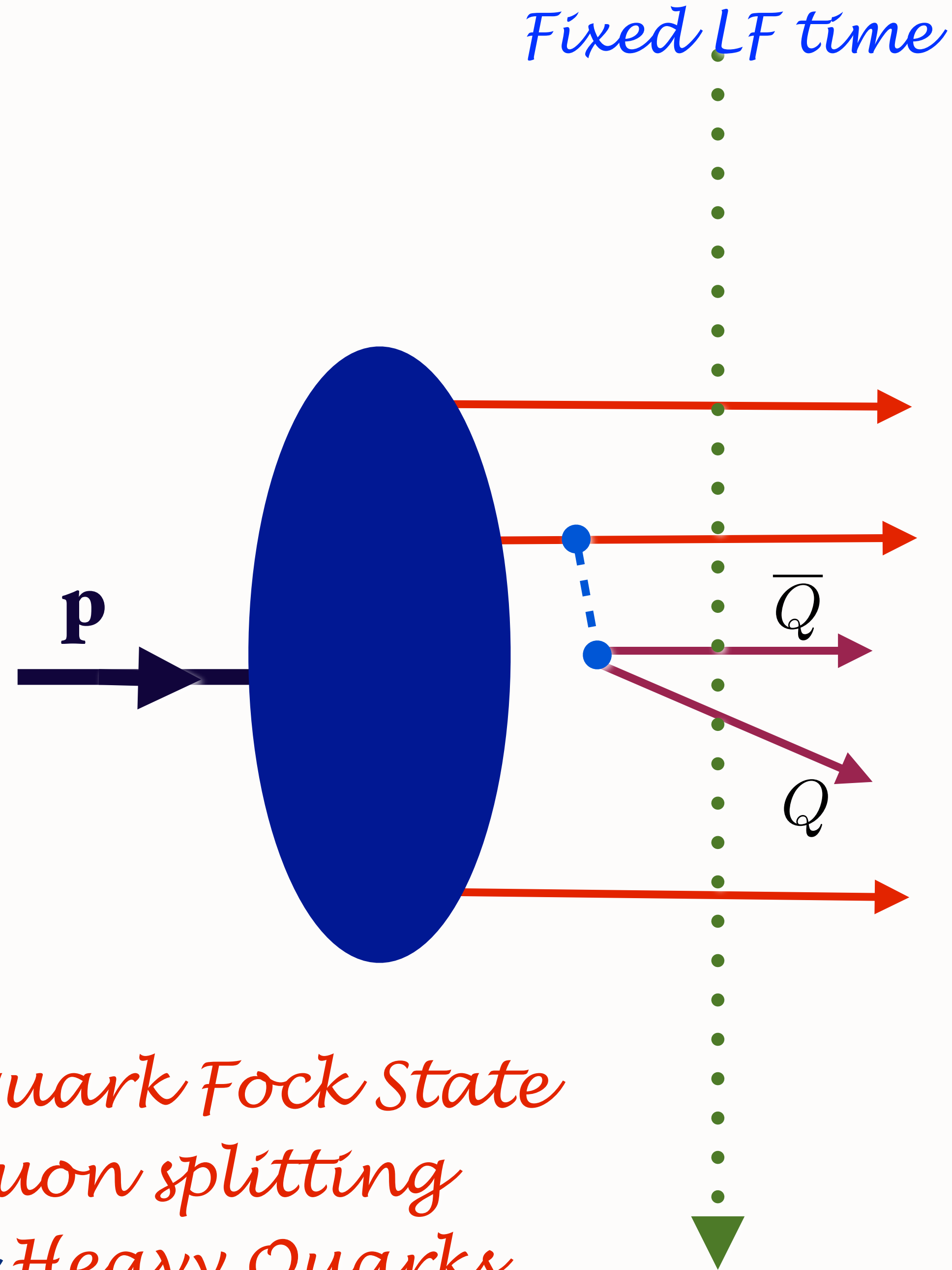
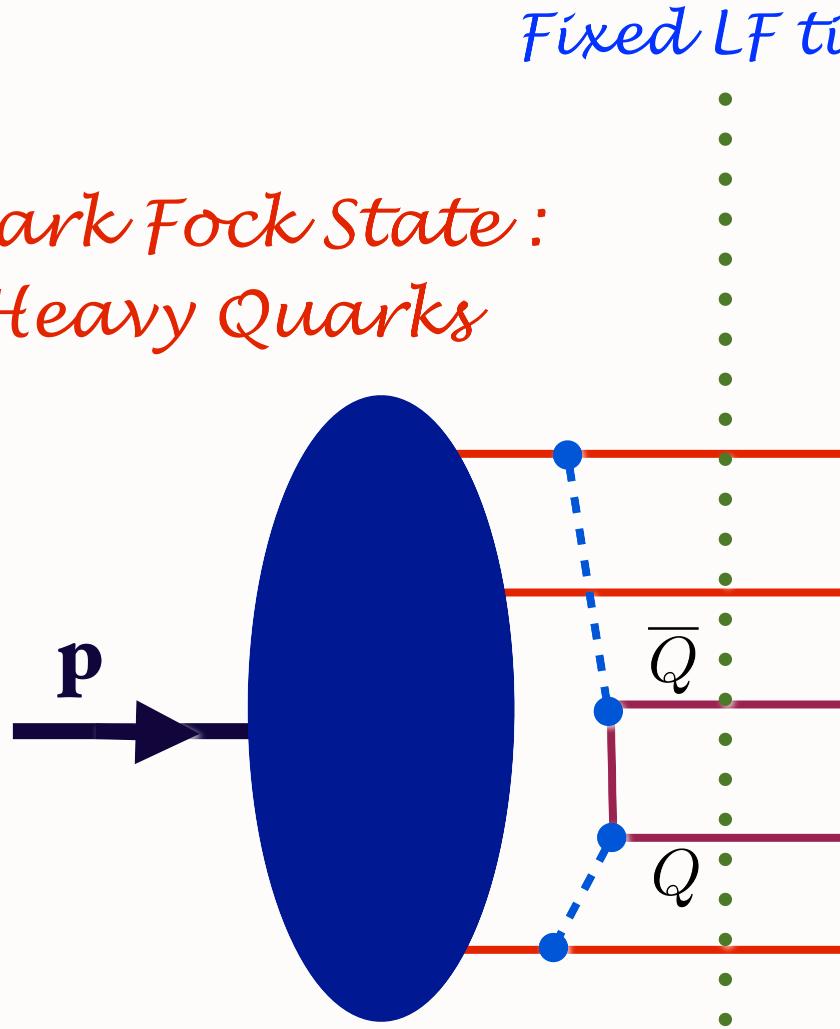


Proton 5-quark Fock State
from gluon splitting
Extrinsic Heavy Quarks

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

Proton 5-quark Fock State : Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

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

Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb

M. Polyakov

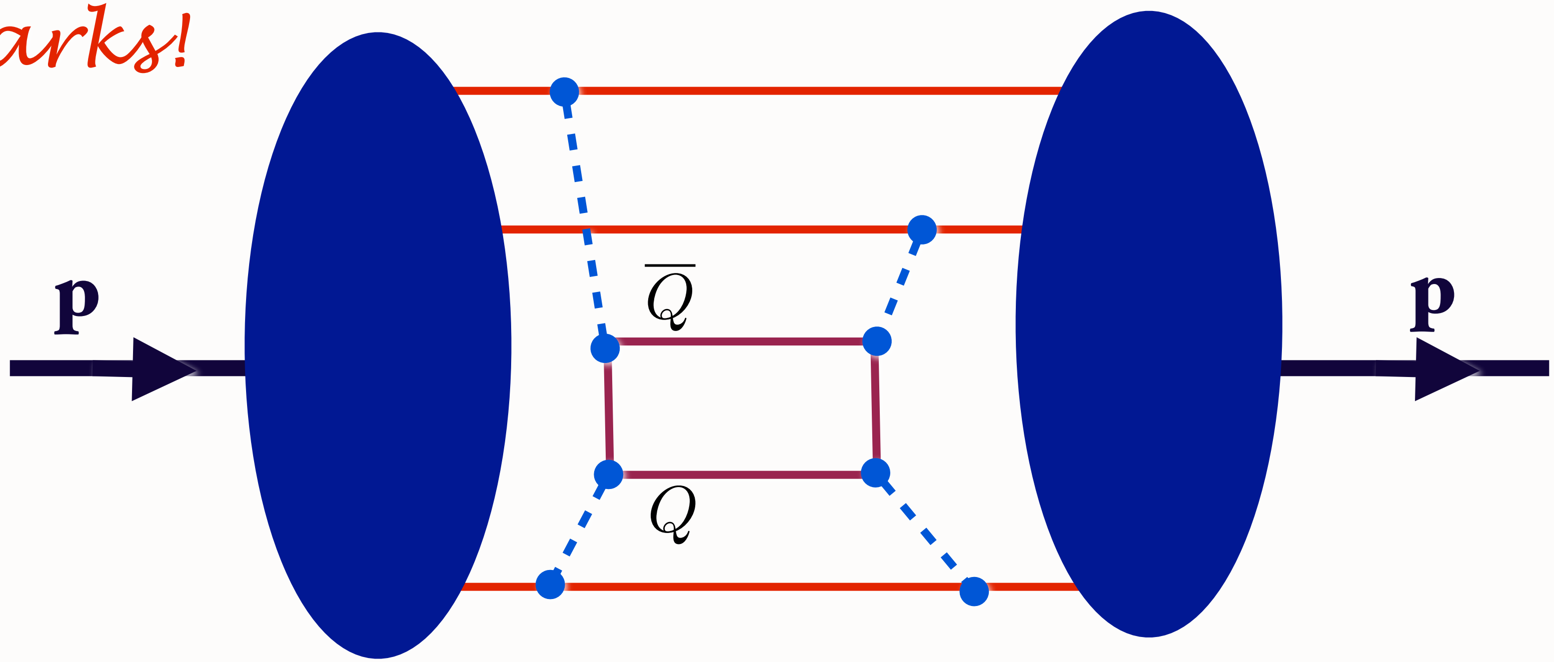
Proton Self Energy

QCD predicts

Intrinsic Heavy

Quarks!

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

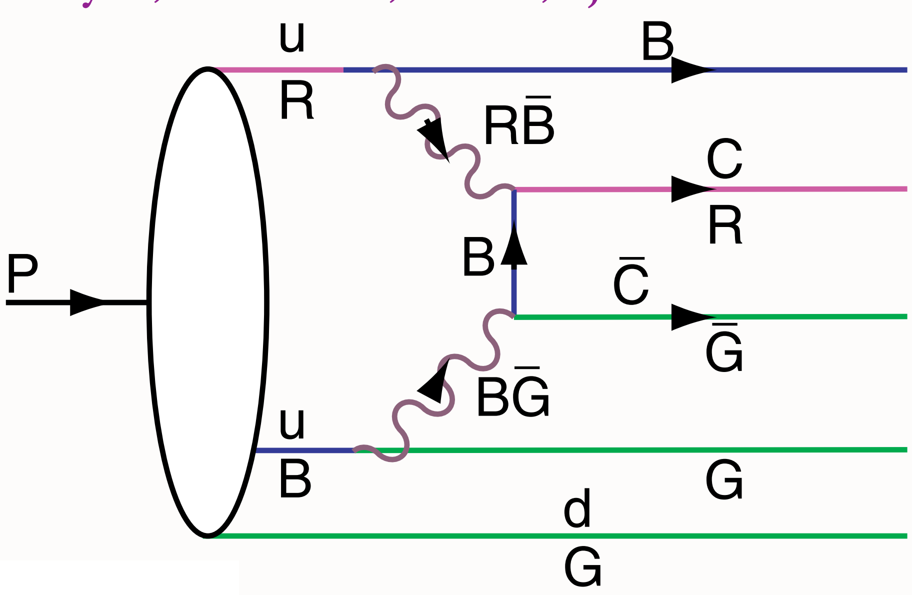


$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

Collins, Ellis, Gunion, Mueller, sjb

M. Polyakov, et al.

Hoyer, Peterson, Sakai, sjb



$|uudcc>$ 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. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

cc 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 CHEVROLETS AT THE SSC

Stanley J. Brodsky

Stanford Linear Accelerator Center, Stanford University, Stanford CA 94305

John C. Collins

Department of Physics, Illinois Institute of Technology, Chicago IL 60616
and
High Energy Physics Division, Argonne National Laboratory, Argonne IL 60439

Stephen D. Ellis

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Department of Physics, Columbia University, New York NY 10027

$$\mathcal{L}_{QCD}^{eff} = -\frac{1}{4} F_{\mu\nu a} F^{\mu\nu a} - \frac{g^2 N_C}{120\pi^2 M_Q^2} D_\alpha F_{\mu\nu a} D^\alpha F^{\mu\nu a} + C \frac{g^2 N_C}{120\pi^2 M_Q^2} F_\mu^{a\nu} F_\nu^{b\tau} F_\tau^{c\mu} f_{abc} + \mathcal{O}(\frac{1}{M_Q^4})$$

Probability of Intrinsic Heavy Quarks ~ $1/M^2_Q$

Published in Snowmass Summer Study 1984:0227 (QCD184:S7:1984)

Heavy quark mass expansion and intrinsic charm in light hadrons.

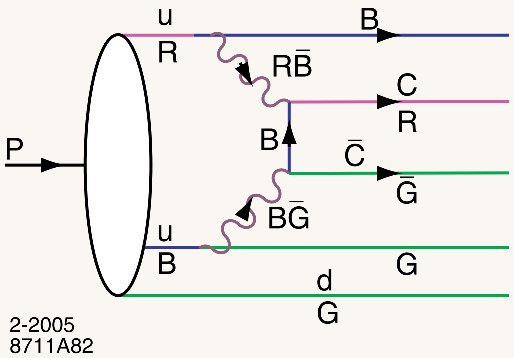
M. Franz (Ruhr U., Bochum), Maxim V. Polyakov (Ruhr U., Bochum & St. Petersburg, INP), K. Goeke (Ruhr U., Bochum).

Feb 2000

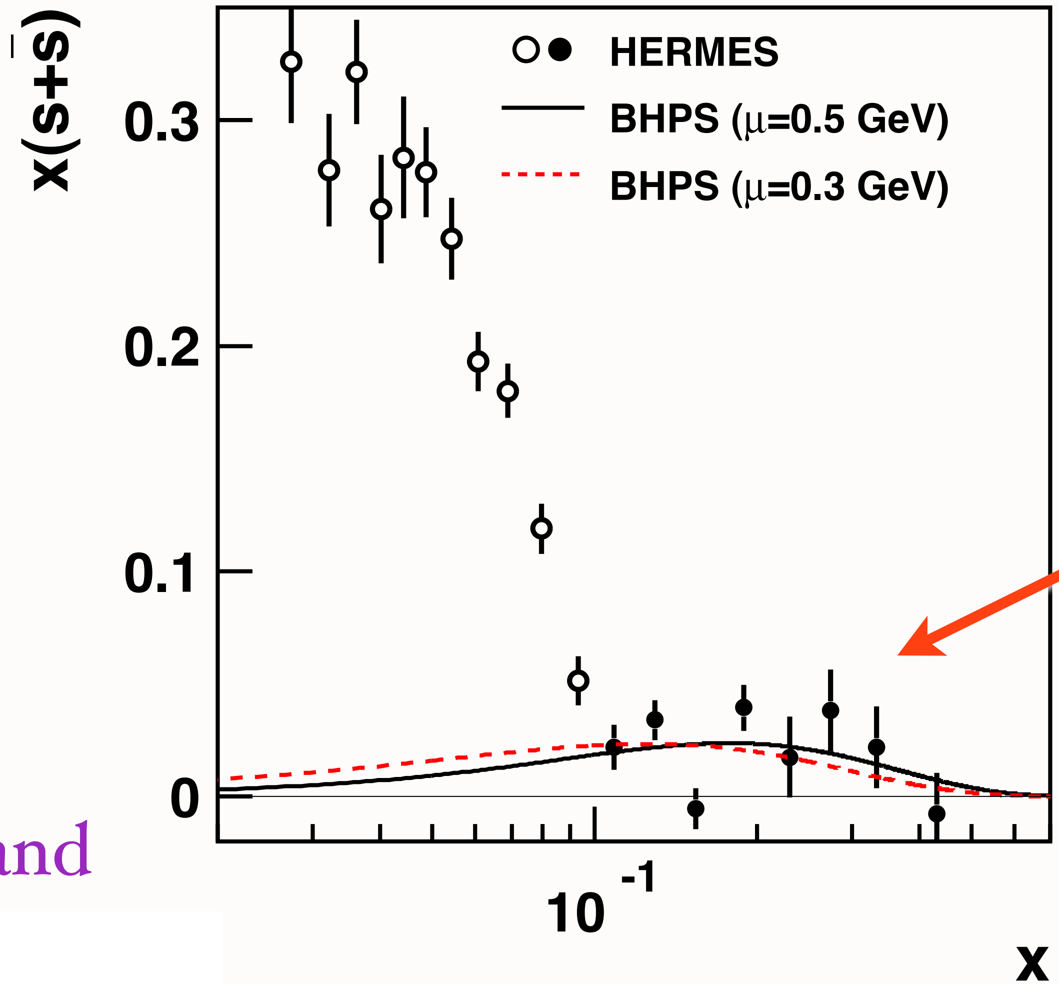
Phys.Rev. D62 (2000) 074024
e-Print: **hep-ph/0002240**

Abstract: We review the technique of heavy quark mass expansion of various operators made of heavy quark fields using a semiclassical approximation. It corresponds to an operator product expansion in the form of series in the inverse heavy quark mass. This technique applied recently to the axial current is used to estimate the charm content of the η, η' mesons and the intrinsic charm contribution to the proton spin. The derivation of heavy quark mass expansion for $\bar{Q}\gamma_5 Q$ is given here in detail and the expansions of the scalar, vector and tensor current and of a contribution to the energy-momentum tensor are presented as well. The obtained results are used to estimate the intrinsic charm contribution to various observables.

Intrinsic Heavy-Quark Fock States



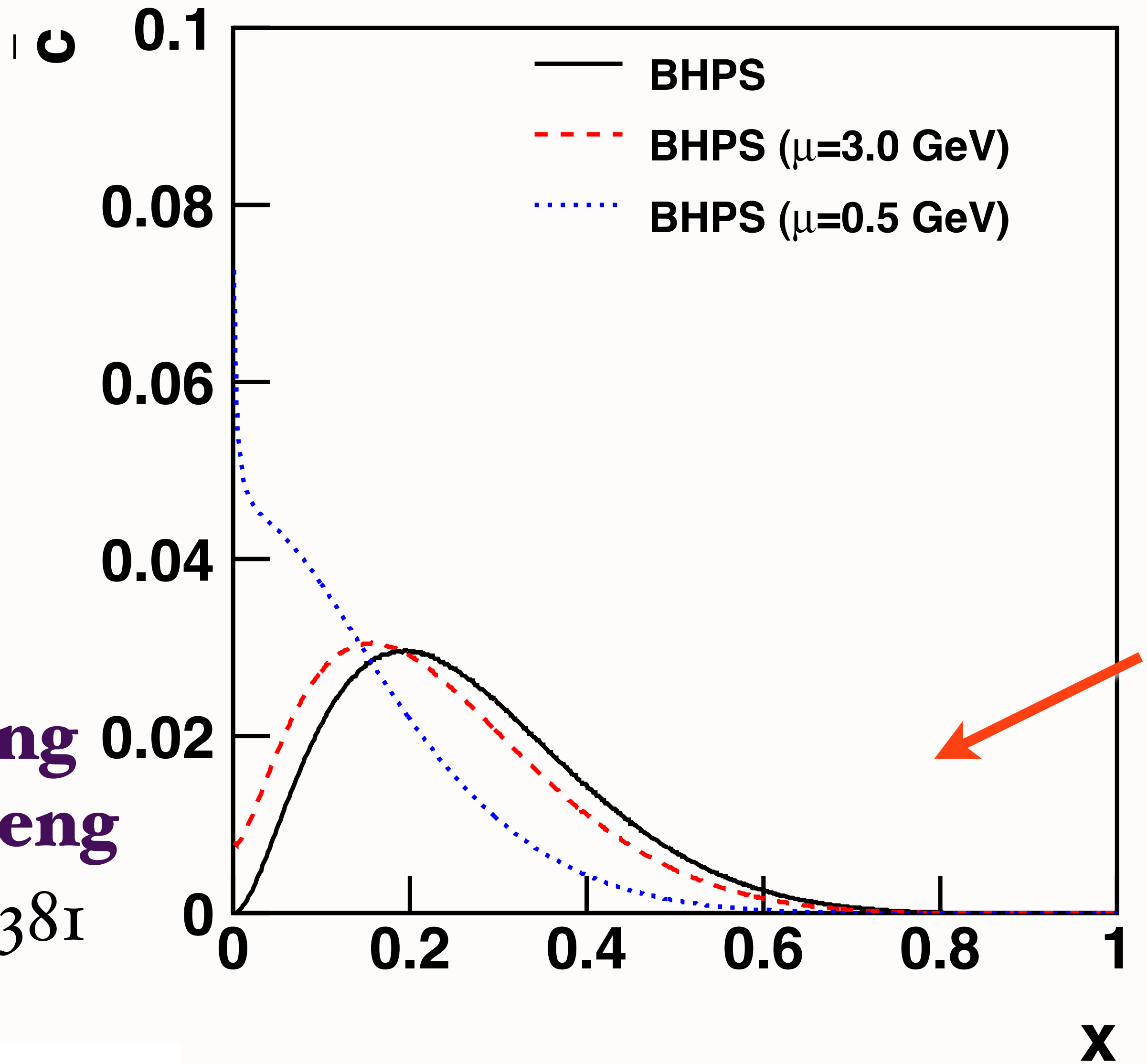
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M^2_Q}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha^2_s P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests



Intrinsic strangeness

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

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.

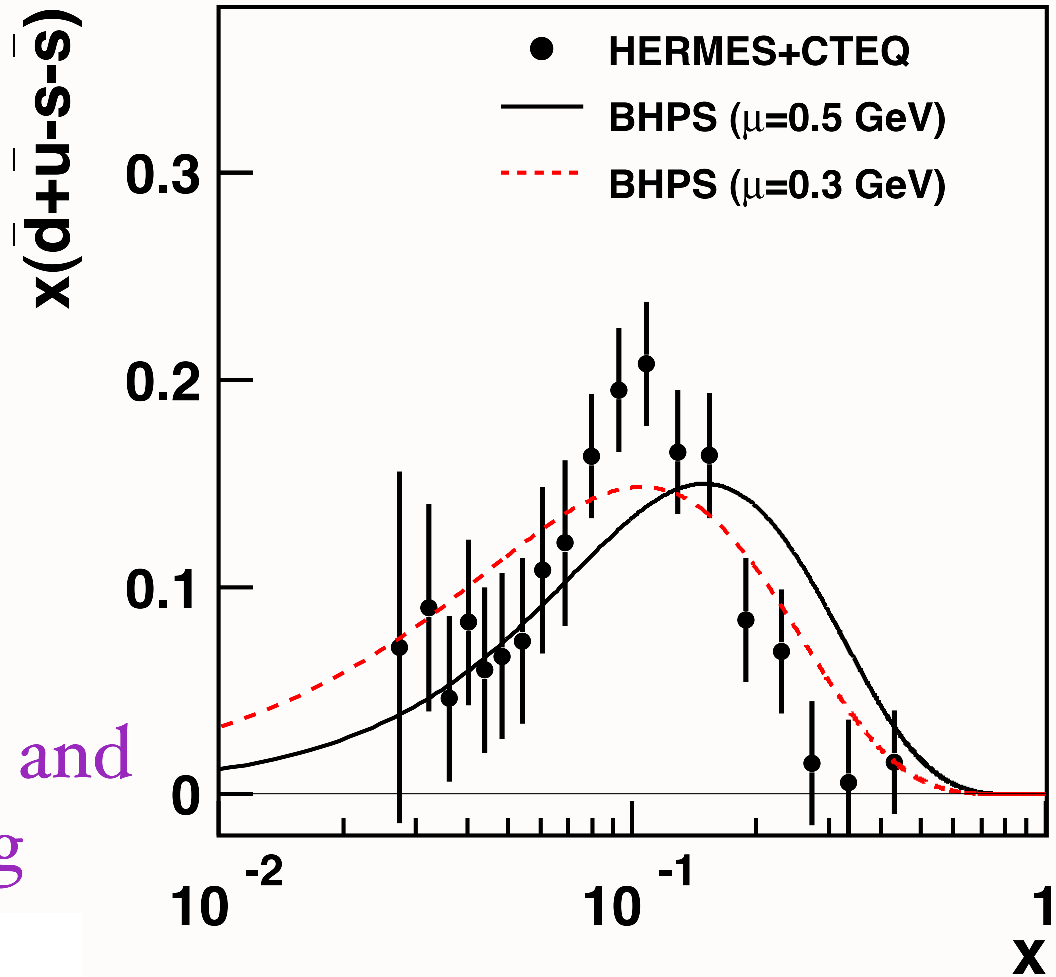


Intrinsic Charm

W. C. Chang and 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 $\mathcal{P}_5^{c\bar{c}} = 0.01$.



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

Comparison of the $x(\bar{d}(x)+\bar{u}(x)-s(x)-\bar{s}(x))$ data with the calculations based on the BHPS model. The values of $x(s(x)+\bar{s}(x))$ are from the HERMES experiment [6], and those of $x(\bar{d}(x)+\bar{u}(x))$ are obtained from the PDF set CTEQ6.6 [11]. 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 normalization of the calculations are adjusted to fit the data.

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

arXiv:1105.2381

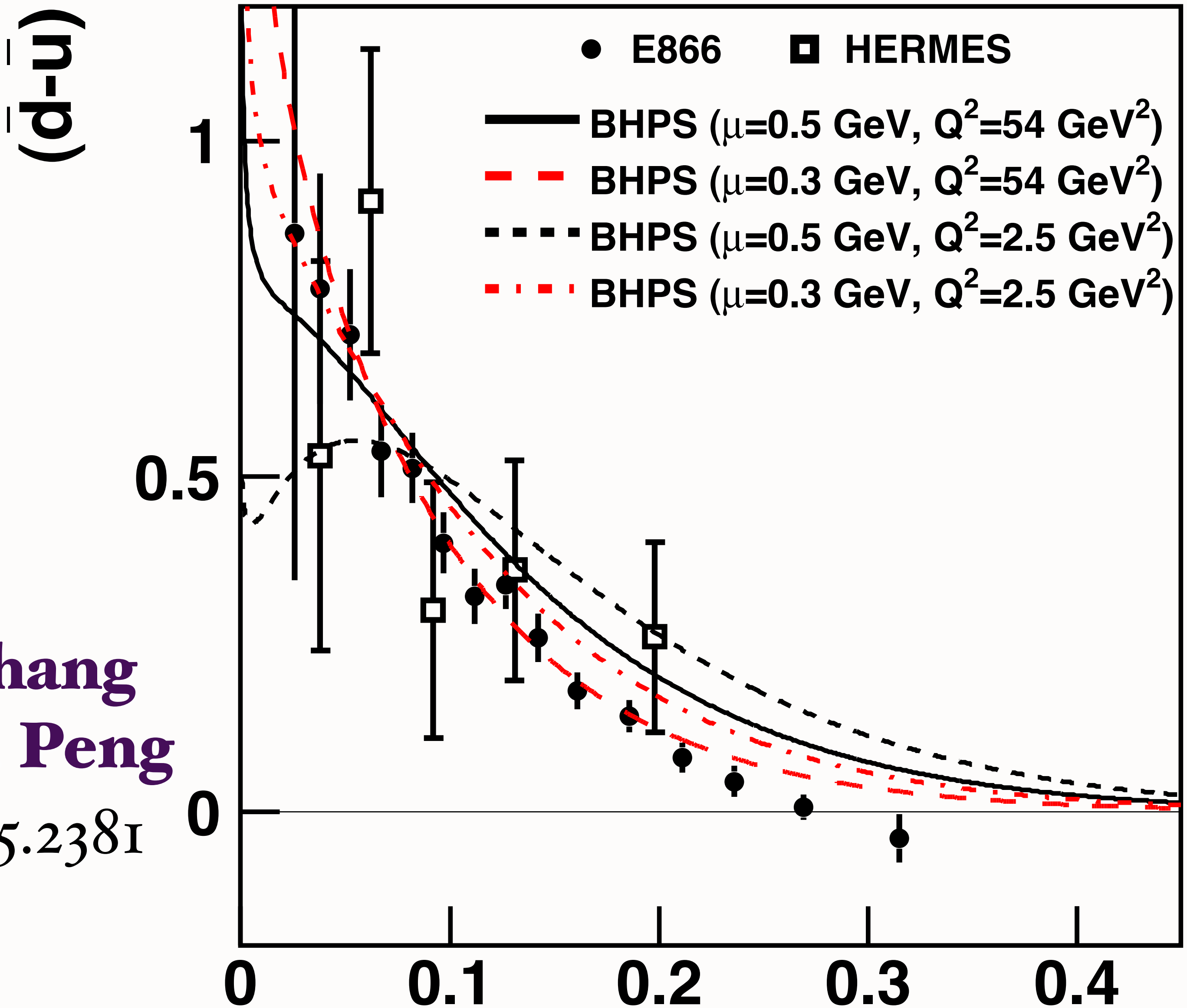
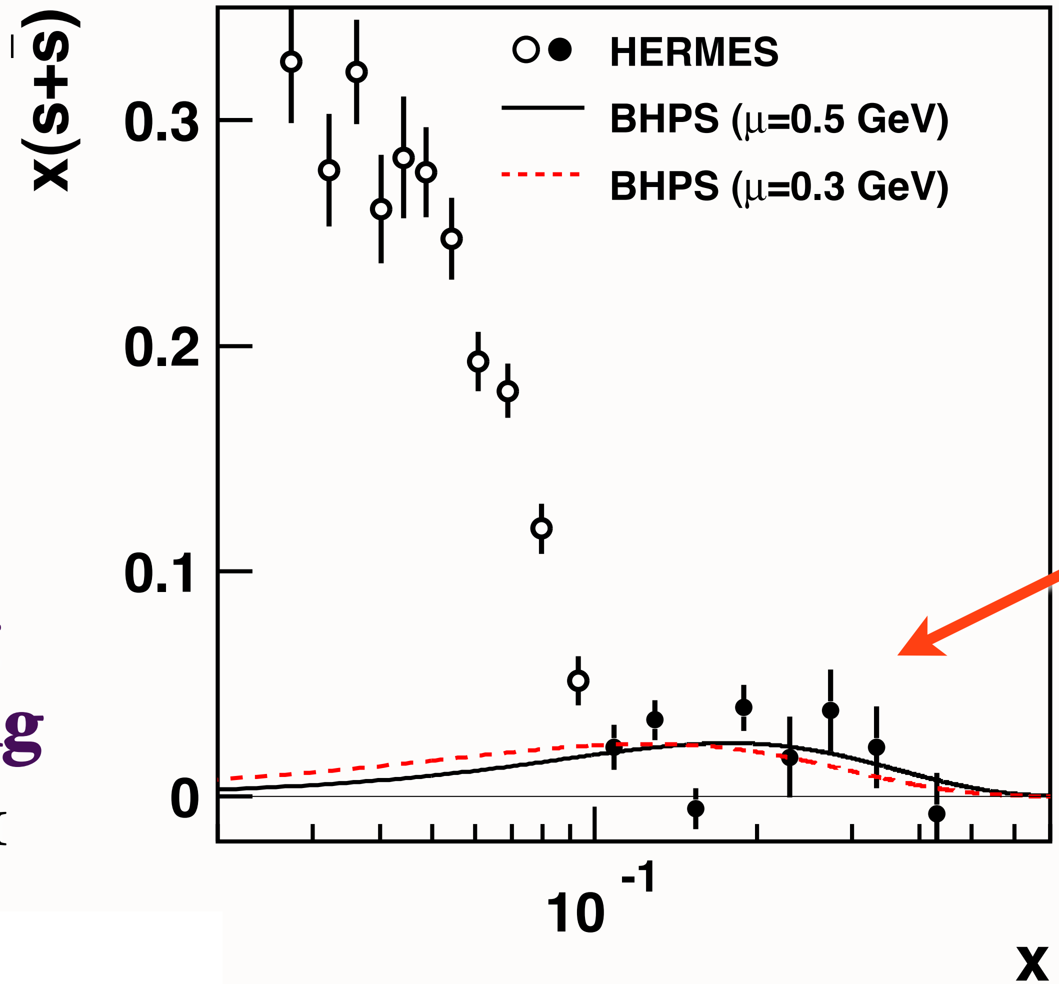


Figure 1: Comparison of the $\bar{d}(x)-\bar{u}(x)$ data from Fermilab E866 and HERMES with the calculations based on the BHPS model. Eq. 1 and Eq. 3 were used to calculate the $\bar{d}(x)-\bar{u}(x)$ distribution at the initial scale. The distribution was then evolved to the Q^2 of the experiments and 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.

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.

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

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

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

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

- High x_F $pp \to \Lambda_c X$

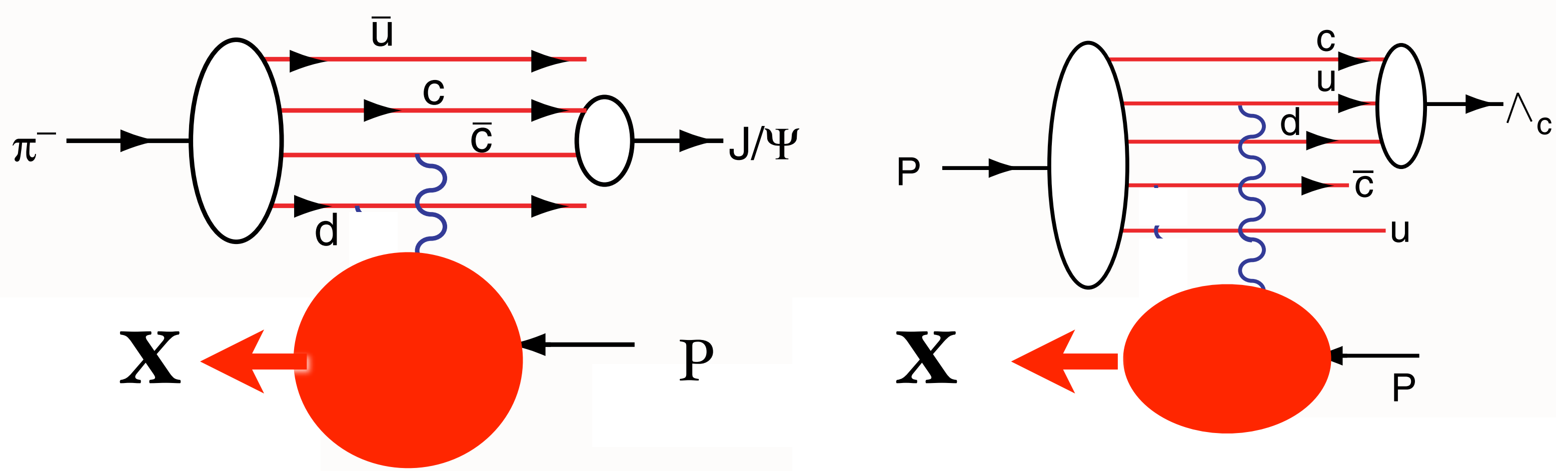
- High x_F $pp \to \Lambda_b X$

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

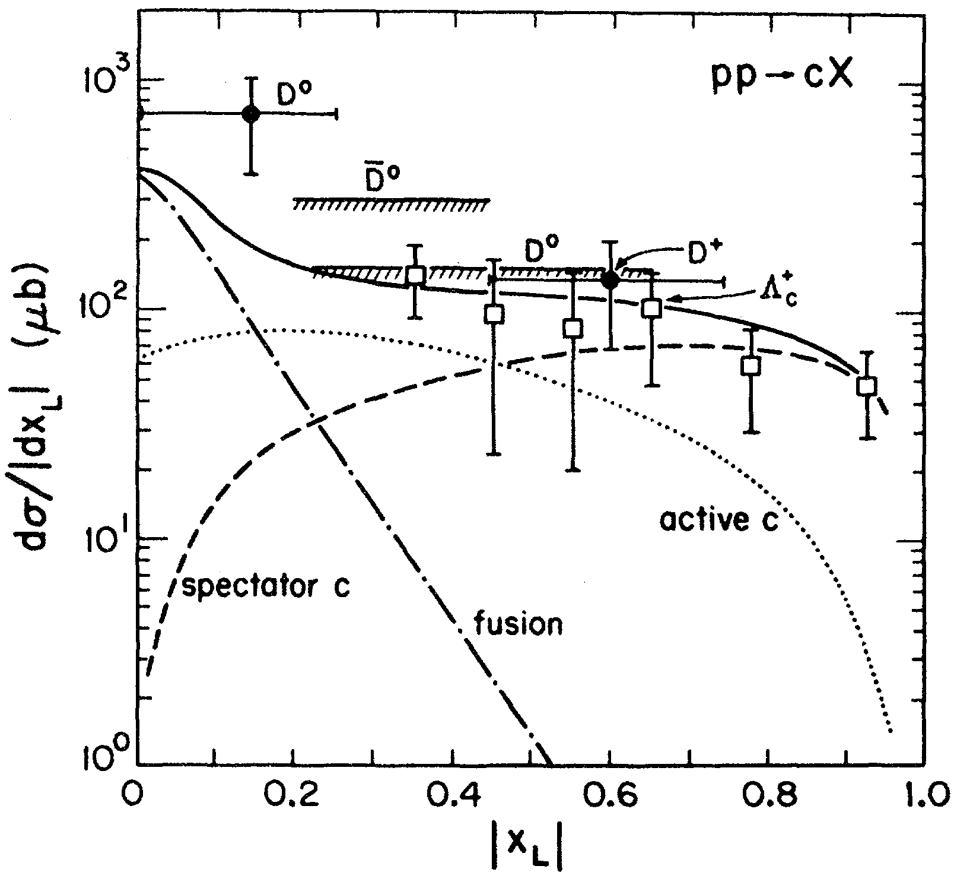
IC Structure Function: Critical Measurement for EIC

Many interesting spin, charge asymmetry, spectator effects

Leading Hadron Production from Intrinsic Charm



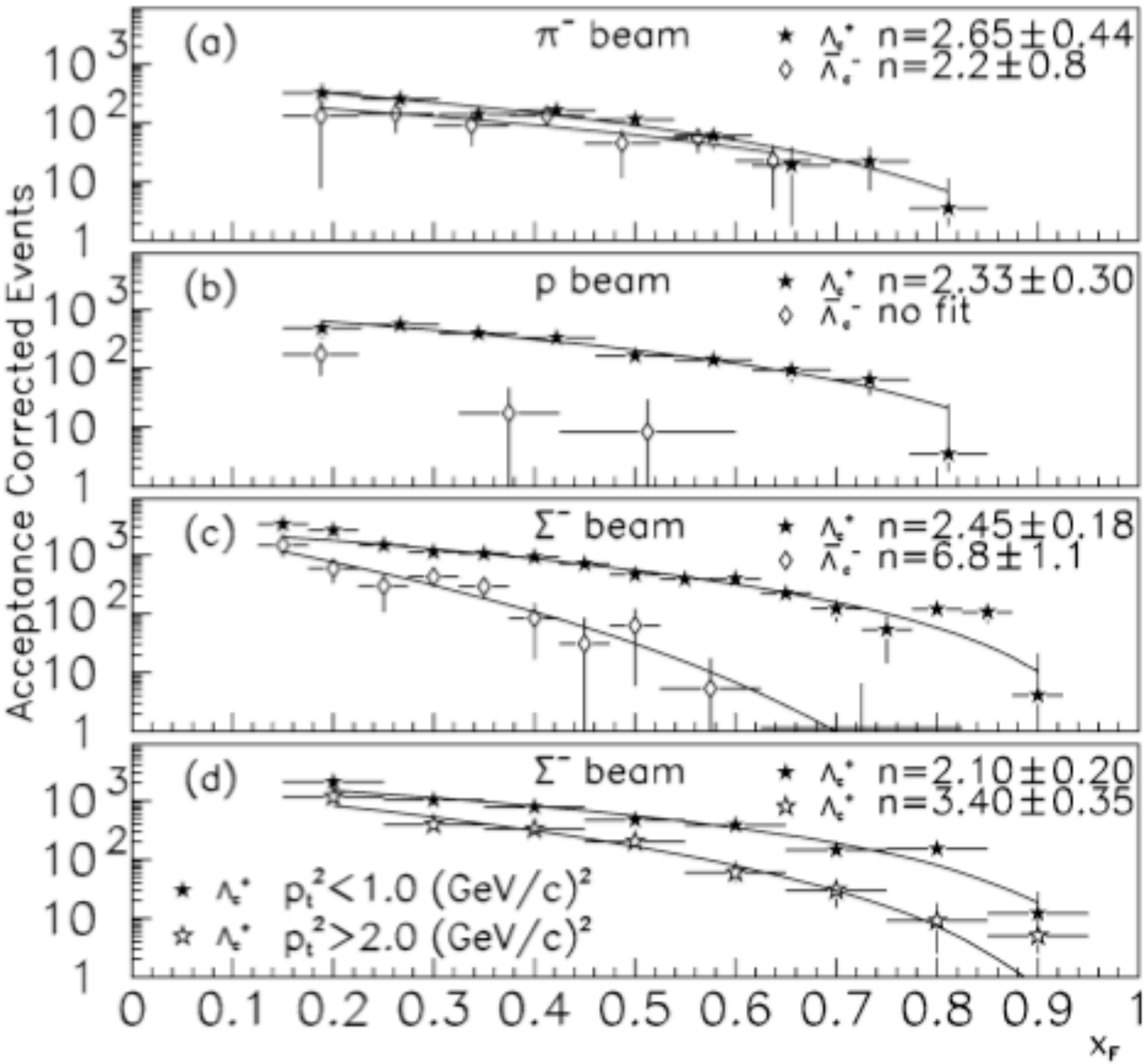
Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F



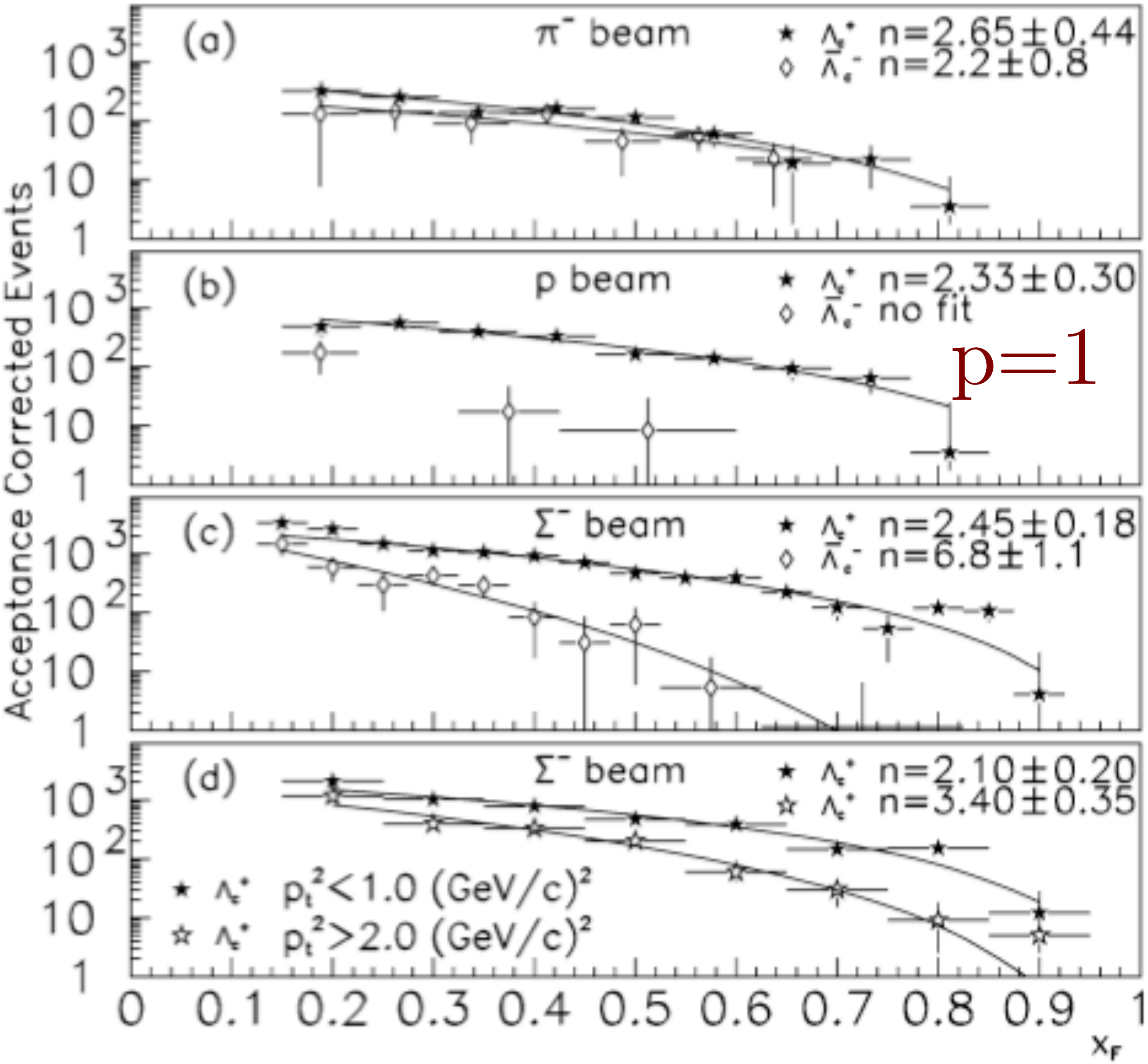
Model similar to Intrinsic Charm

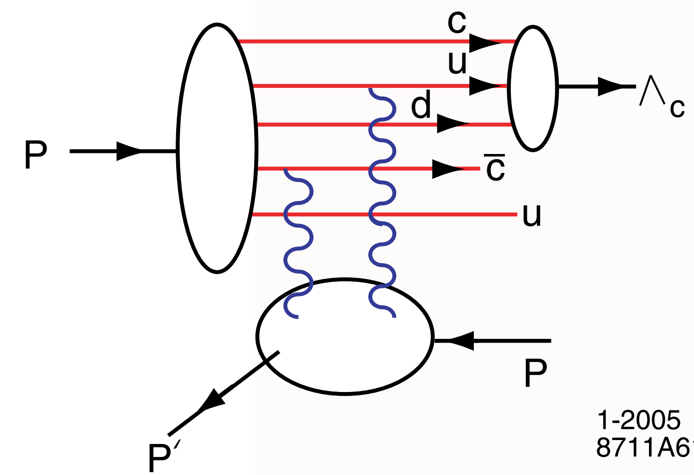
V. D. Barger, F. Halzen and W. Y. Keung, "The Central And Diffractive Components Of Charm Production," Phys. Rev. D 25, 112 (1982).

SELEX Collaboration / Physics Letters B 528 (2002) 49–57



Large xF production close to the maximum allowed by phase space!





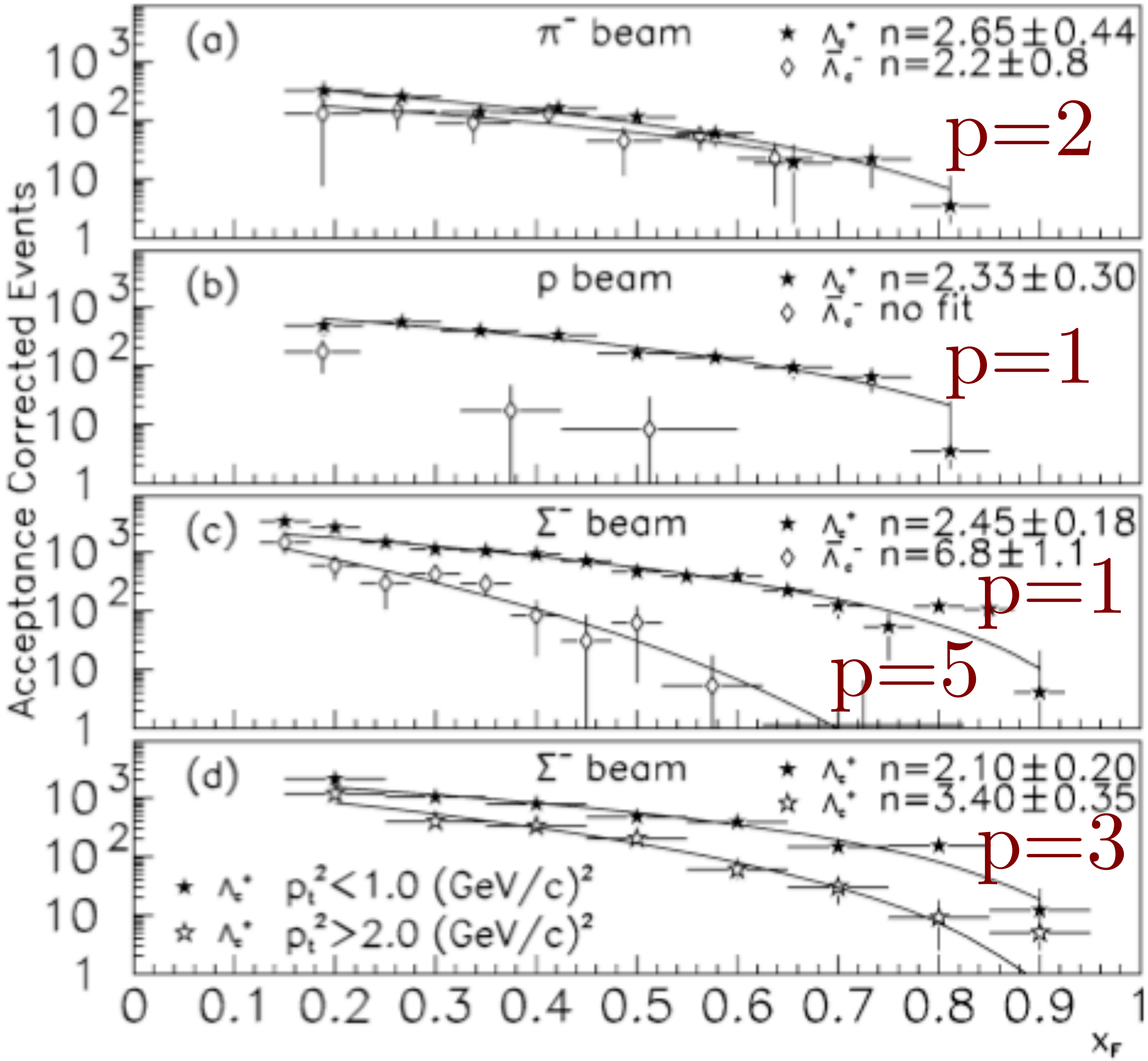
$$p(uudc\bar{c})$$

$$\rightarrow \Lambda_c(cud)$$

$$n_s = 2$$

Phase space gives minimum power p

$$(1-x_F)^p, p = n_s - 1$$



$$(1-x_F)^p, p = n_s - 1$$

$$\pi^-(d\bar{u}) \rightarrow \Lambda_c(cud) \quad \bar{\Lambda}_c(\bar{c}\bar{u}\bar{d})$$

$$n_s = 2 + 1 = 3$$

p=2

$$\Sigma^-(sdd) \rightarrow \Lambda_c(cud)$$

$$n_s = 3 + 1 = 4$$

p=3

$$p(uud) \quad \Sigma^-(sdd) \rightarrow \bar{\Lambda}_c(\bar{c}\bar{u}\bar{d})$$

$$n_s = 4 + 2 = 6$$

p=5

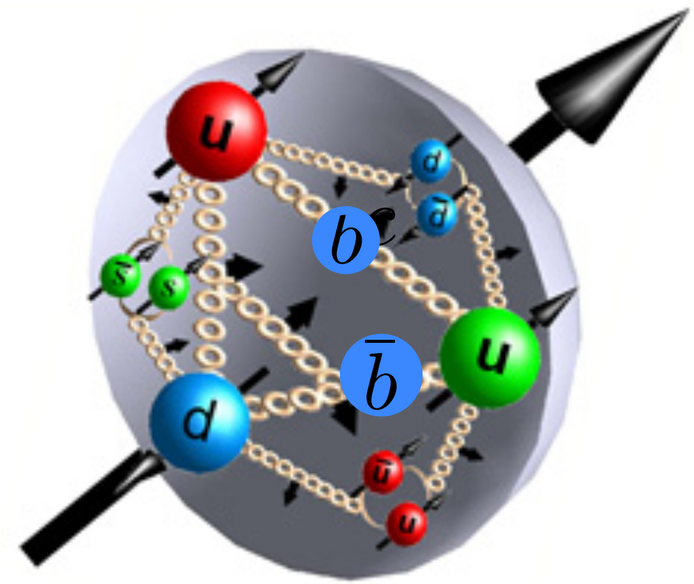
Phase space gives minimum power p

27 May 1991

THE Λ_b^o BEAUTY BARYON PRODUCTION IN PROTON-PROTON INTERACTIONS AT $\sqrt{s}$=62 GeV: A SECOND OBSERVATION

G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli, F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti, G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

CERN, Geneva, Switzerland
Dipartimento di Fisica dell'Università, Bologna, Italy
Dipartimento di Fisica dell'Università, Cosenza, Italy
Istituto di Fisica dell'Università, Palermo, Italy
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto Nazionale di Fisica Nucleare, LNF, Frascati, Italy



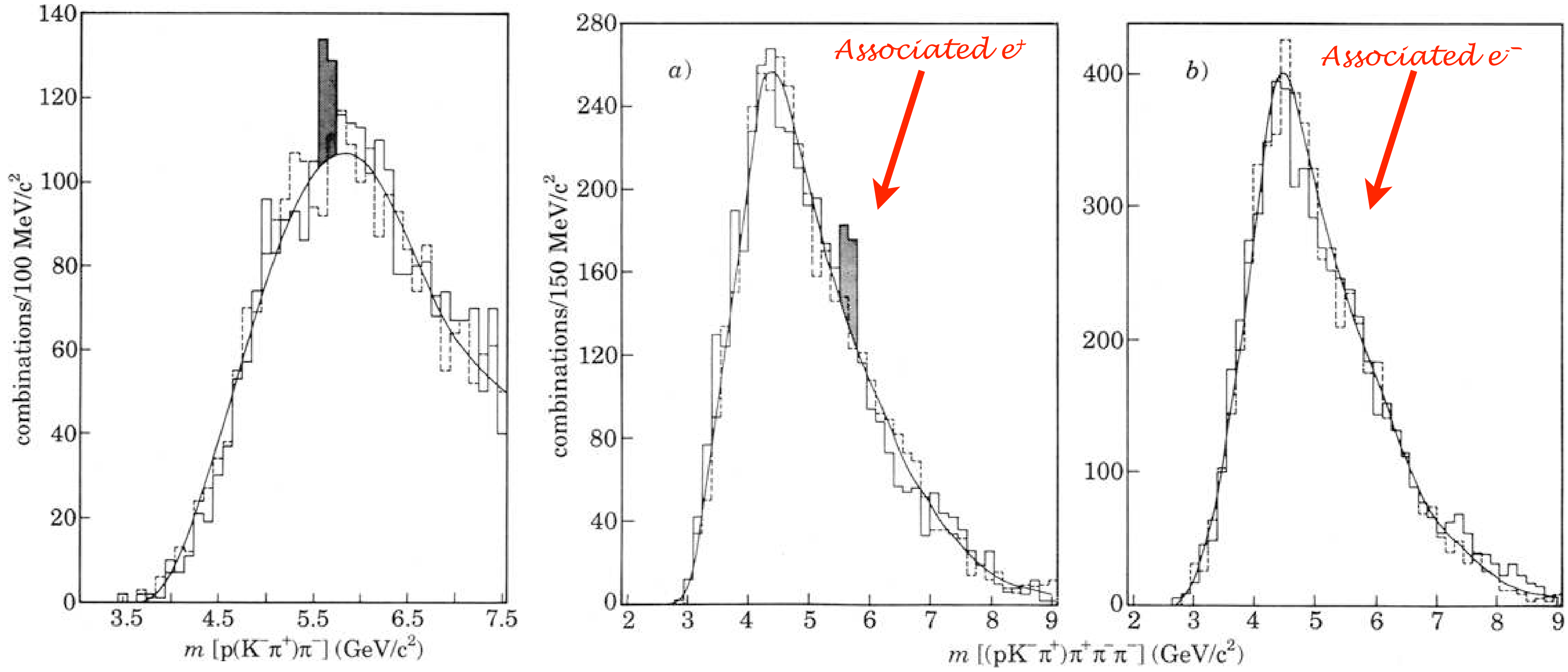
Abstract

Another decay mode of the Λ_b^o (open-beauty baryon) state has been observed: $\Lambda_b^o \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \rightarrow pD^o\pi^-$, are reported. These results confirm our previous findings on Λ_b^o production at the ISR. The mass value (5.6 GeV/c^2) is found to be in good agreement with theoretical predictions. The production mechanism is found to be "leading".

First Evidence for Intrinsic Bottom!

$pp \to \Lambda_b(bud)B(\bar{b}q)X$ at large x_F

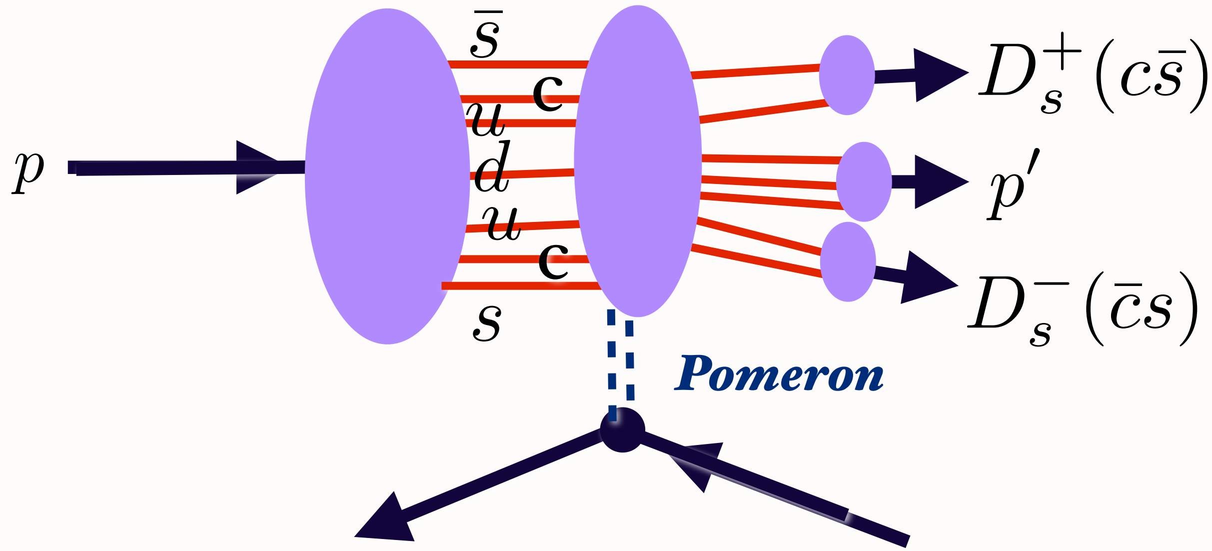
CERN-ISR R422 (Split Field Magnet), 1988/1991



$\Lambda_b^0 \to pD^0\pi^-$ $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

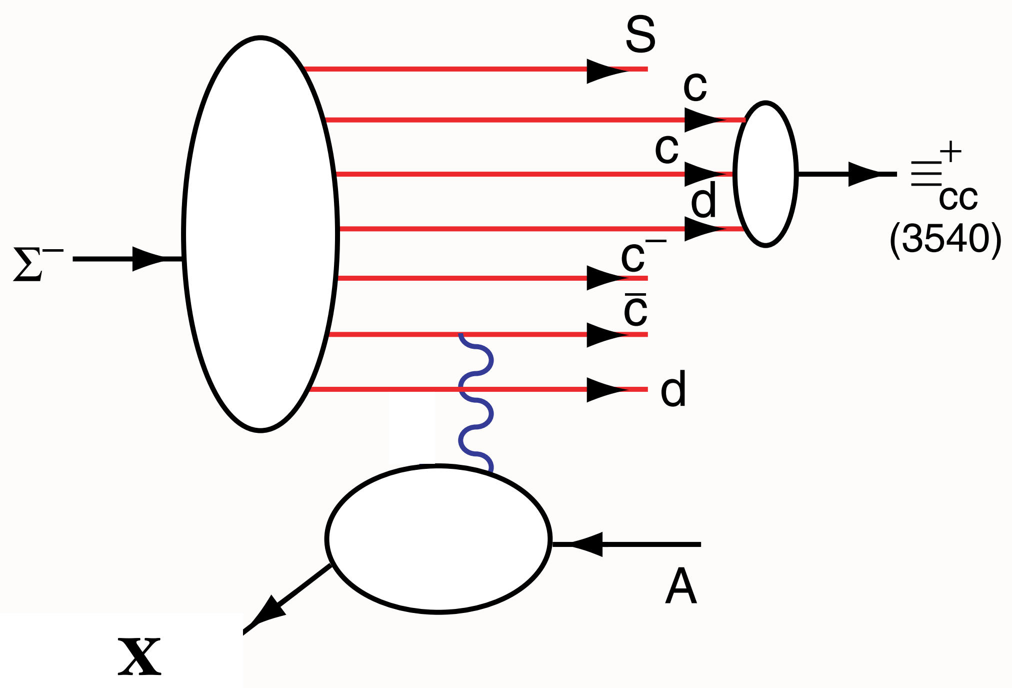
Il Nuovo Cimento 104, 1787

First Evidence for Intrinsic Bottom!



Look for $D_s^-(\bar{c}s)$ vs. $D_s^+(c\bar{s})$ asymmetry

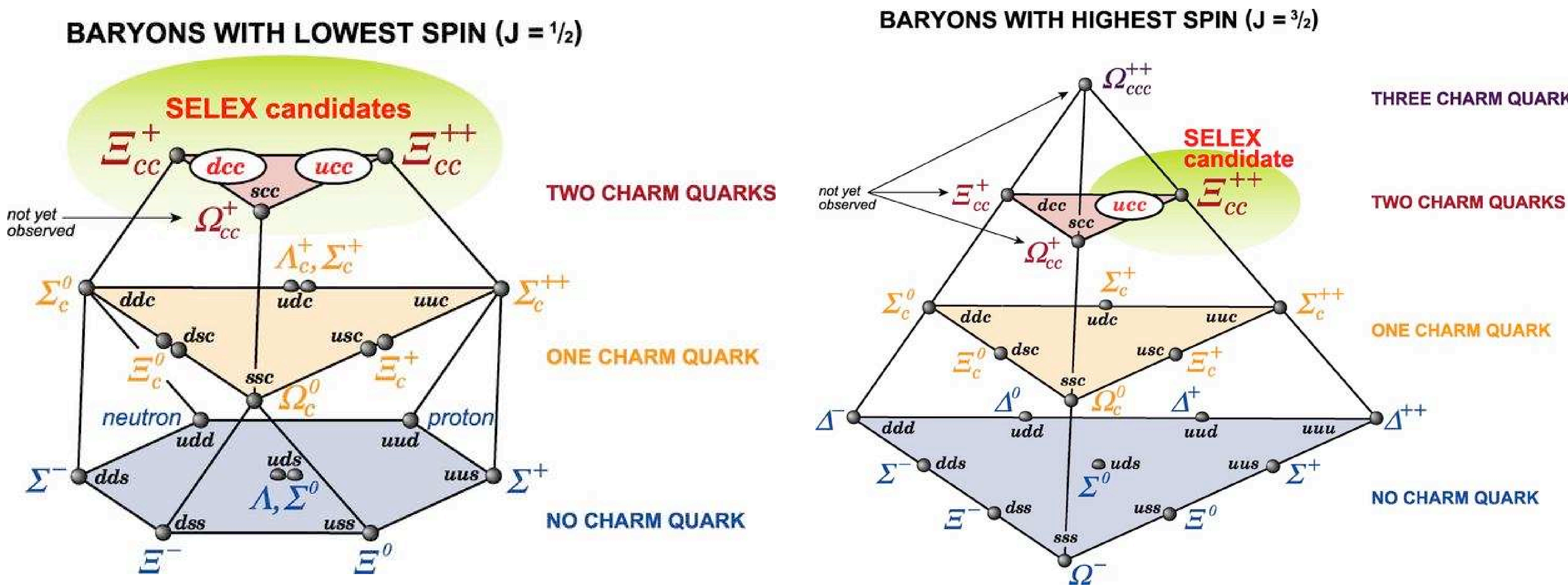
Reflects s vs. $\bar{s}$ asymmetry in proton $|uudc\bar{c}s\bar{s}>$ Fock LF state.



Production of a Double-Charm Baryon

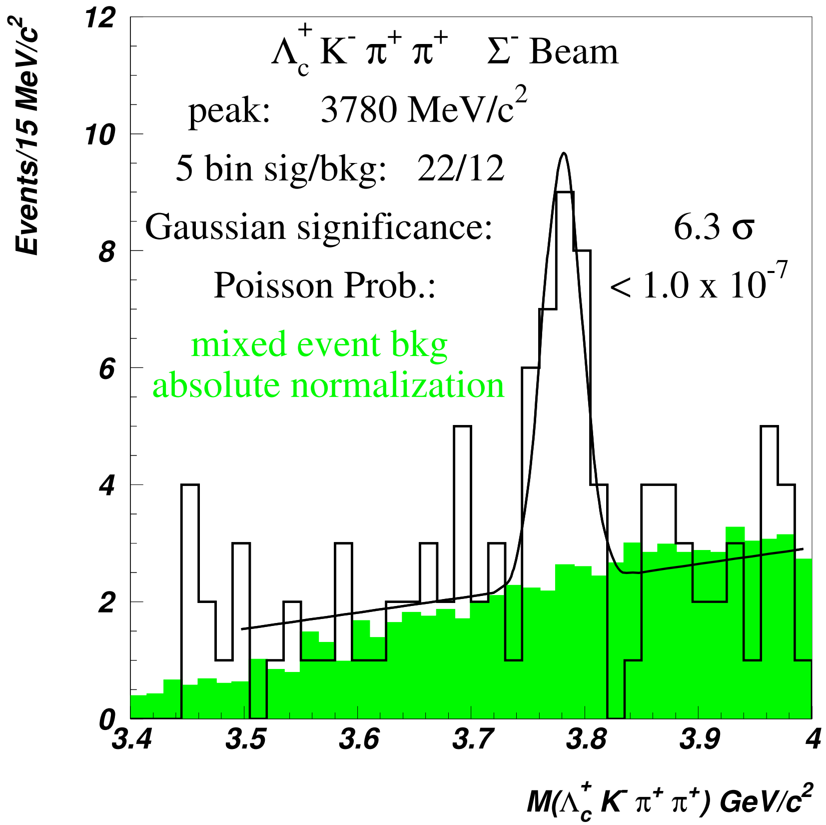
SELEX high x_F $< x_F >= 0.33$

Doubly Charmed Baryons



$\Xi_{cc}(3780)^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

- Re-Analyzed Data
- Restrict to Σ^-–Beam
- Peak wider than Resolution
- Half decay to $\Xi_{cc}^+(3520)$
- Still working on Details

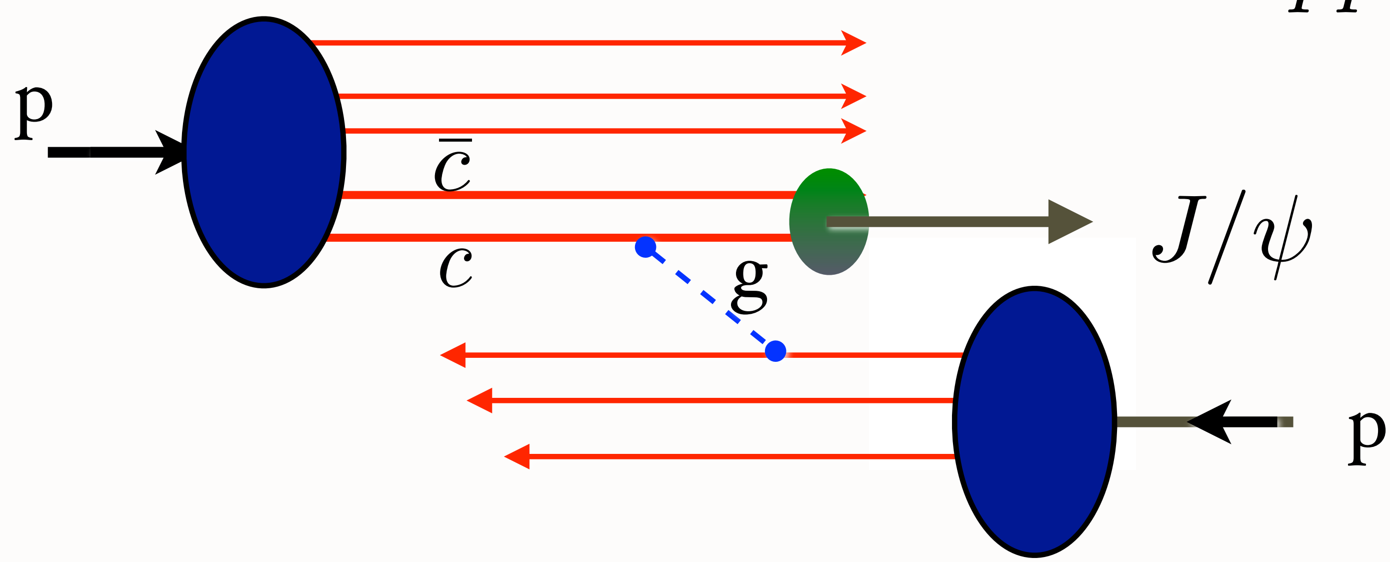


Produce entire set of Heavy Baryons up to bbb

AFTER @ LHC

Intrinsic Charm Mechanism for Inclusive High-X_F Quarkonium Production

$$pp \rightarrow J/\psi X$$



Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

Quarkonia can have 80% of Proton Momentum!

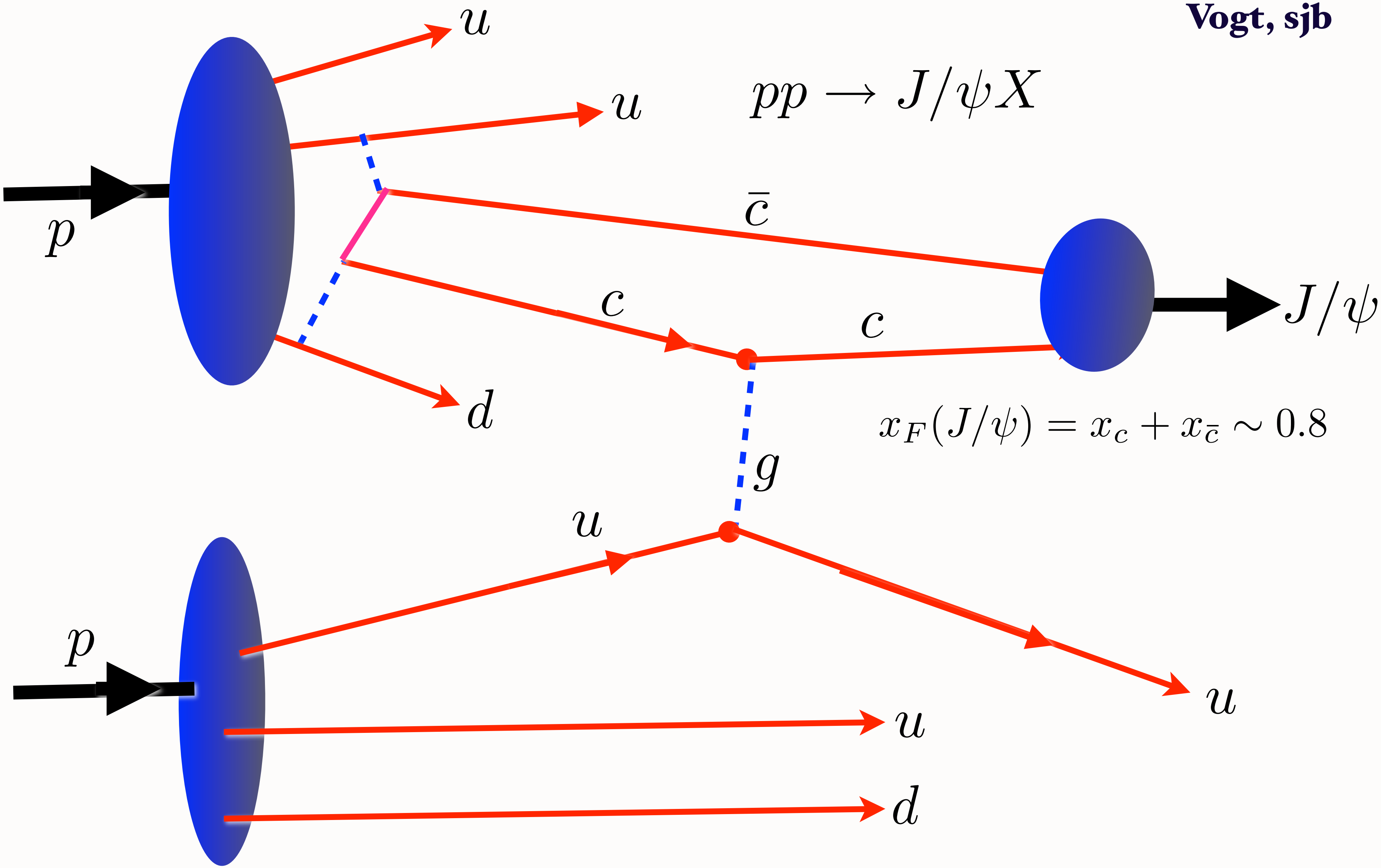
Color-octet IC interacts at front surface of nucleus

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

Intrinsic Heavy Quark Contribution to Quarkonium Hadroproduction at High x_F

Lansberg, sjb

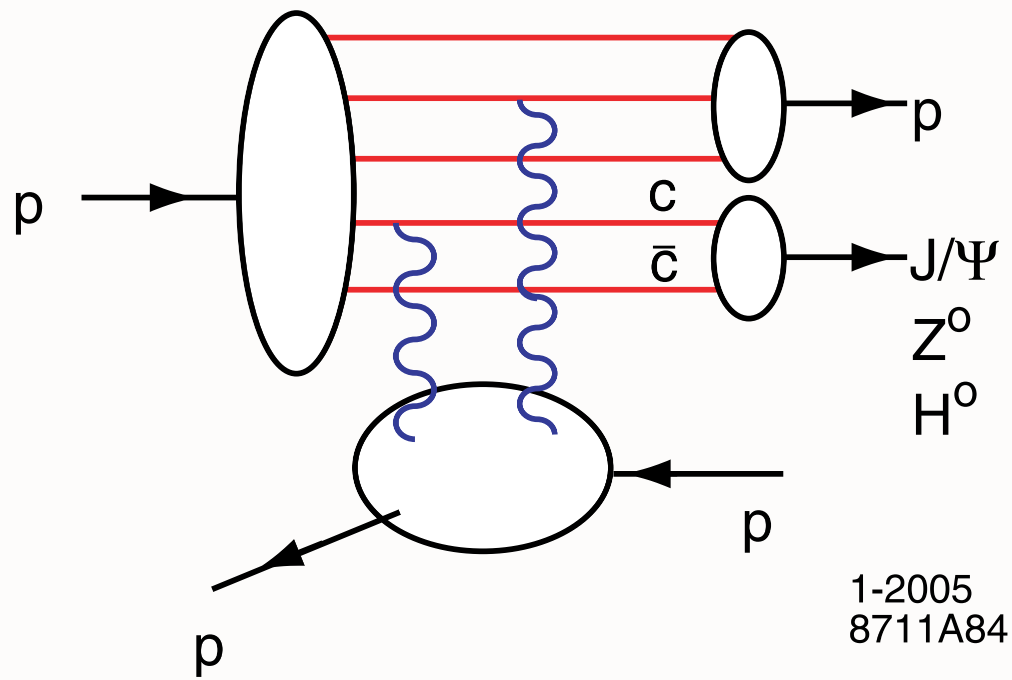
Vogt, sjb



Maximal Wavefunction Strength at Minimal Invariant Mass : Equal Rapidity

$$x_i \propto \frac{m_{\perp i}}{\sum_j m_{\perp j}}$$

Intrinsic Charm Mechanism for Exclusive Diffraction Production



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

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

Exclusive Diffractive High-X_F Higgs Production

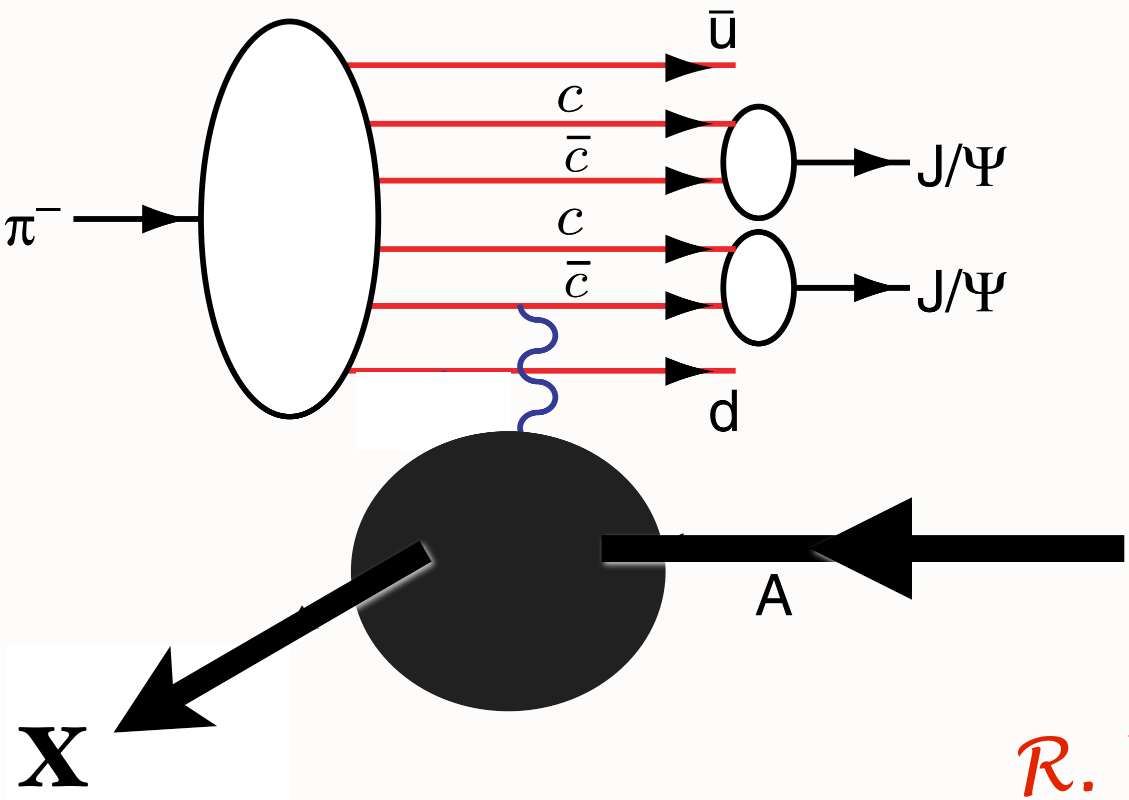
Kopeliovitch, Schmidt, Soffer, sjb

Intrinsic *cc* pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

Production of Two Quarkonia at High x_F



R. Vogt, sjb

All events have $x^F_{\psi\psi} > 0.4$!

Excludes `color drag' model

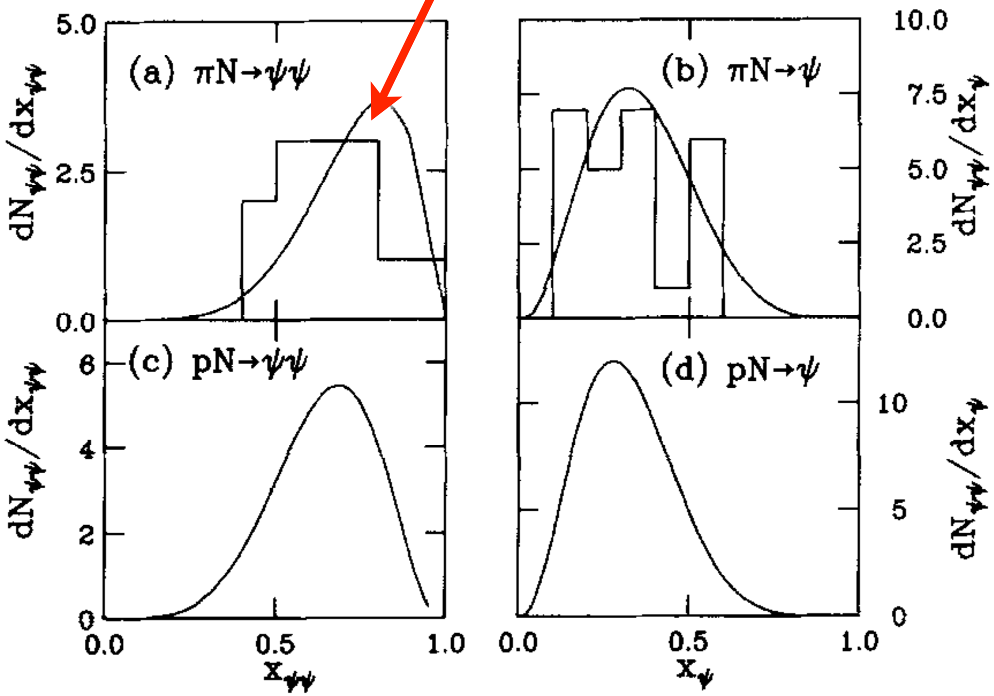


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

$$\pi A \to J/\psi J/\psi X$$

R. Vogt, sjb

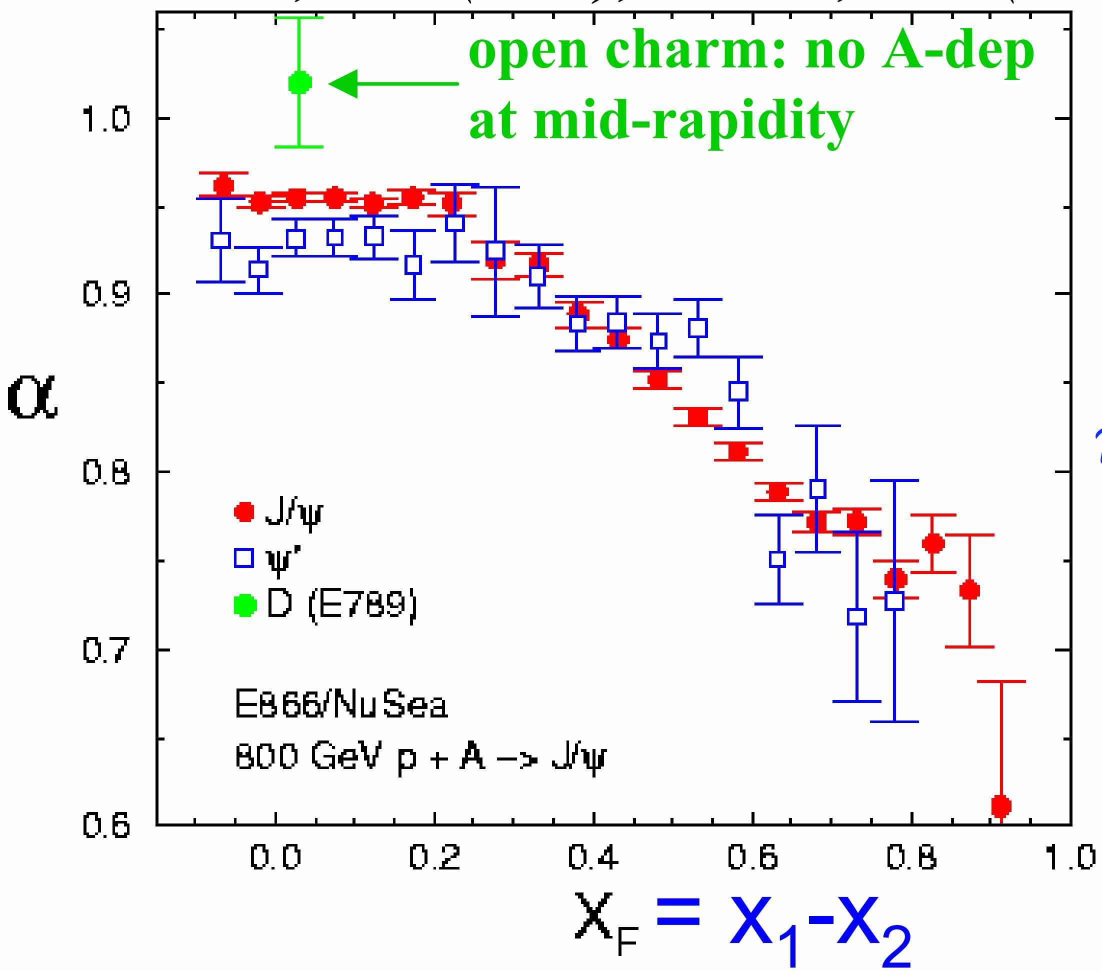
The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

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

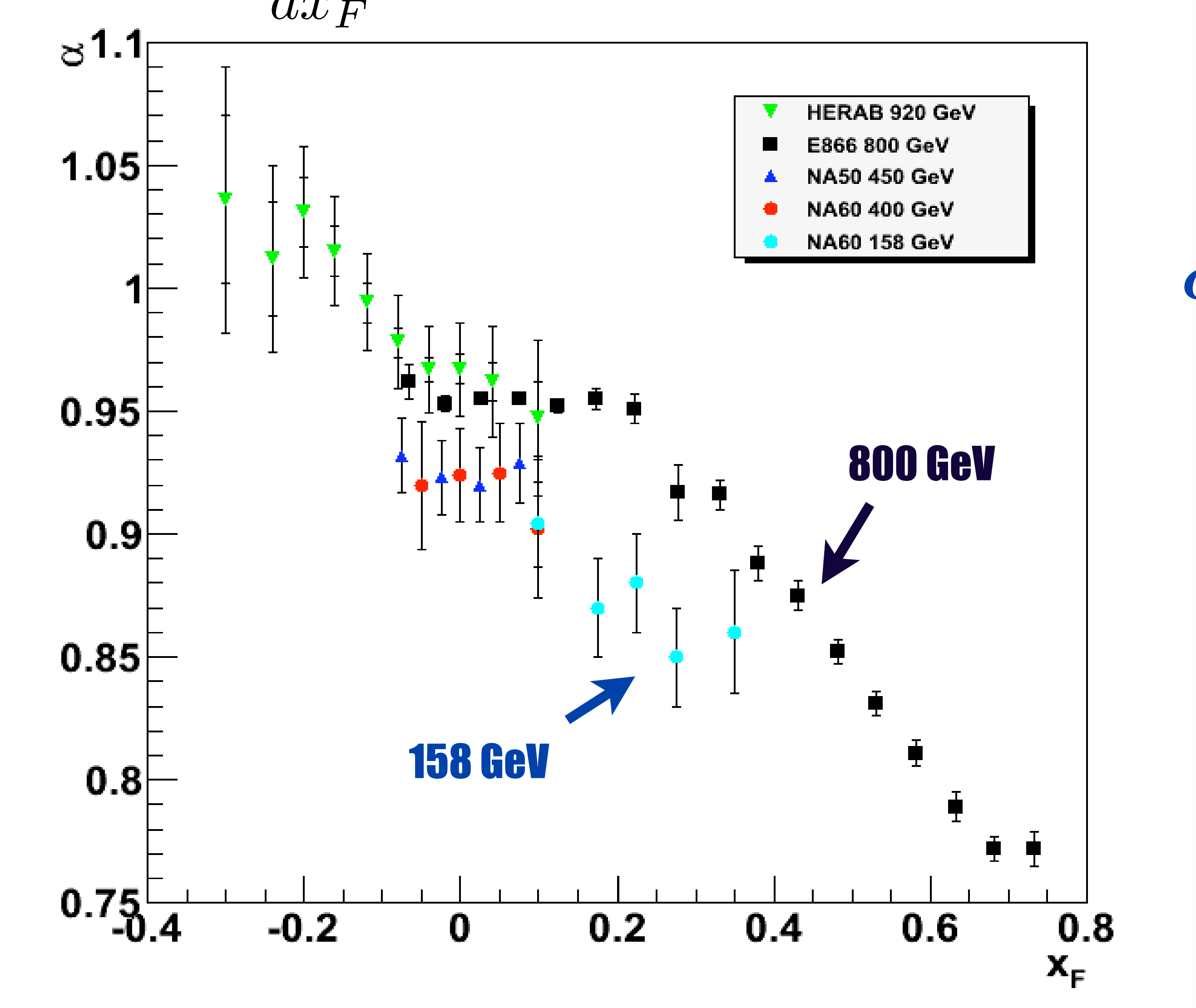
Violation of PQCD Factorization

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

NA60 pA data @ 158GeV

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



Clear dependence on x_F and beam energy

Heavy Quark Anomalies

Nuclear dependence of J/ψ hadroproduction

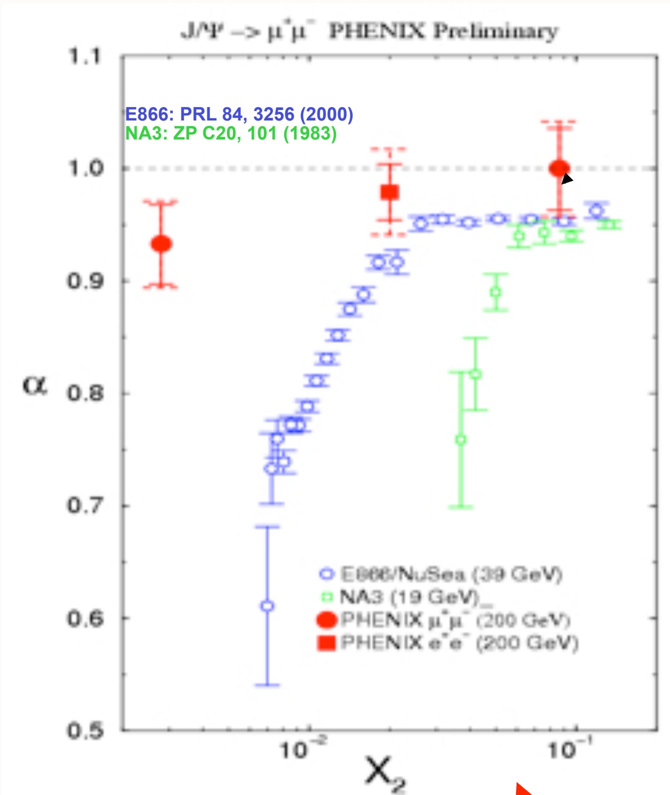
Violates PQCD Factorization: $A^{\alpha}(x_F)$ not $A^{\alpha}(x_2)$

Huge $A^{2/3}$ effect at large x_F

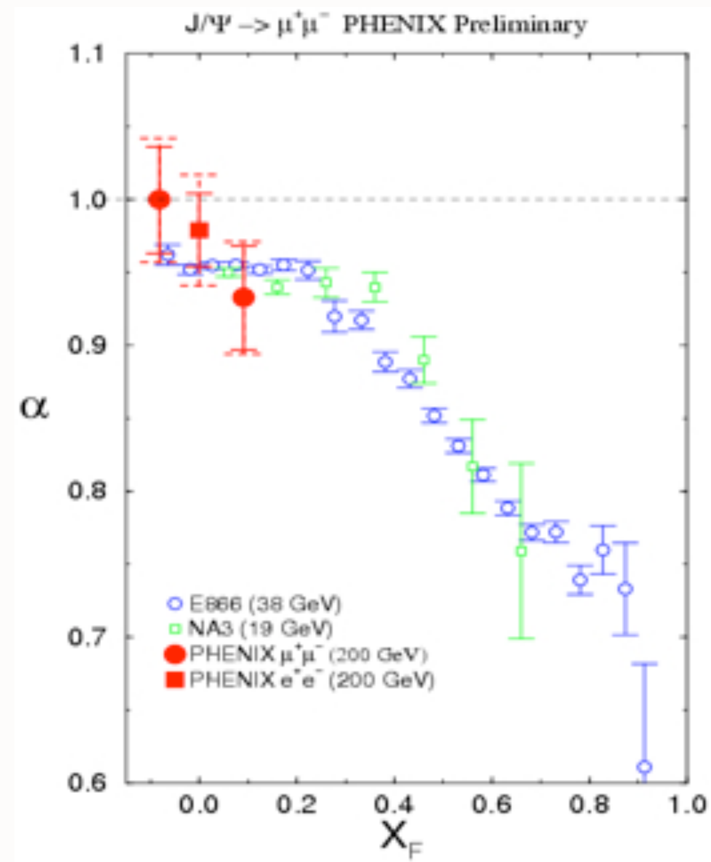
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001



Huge "absorption" effect

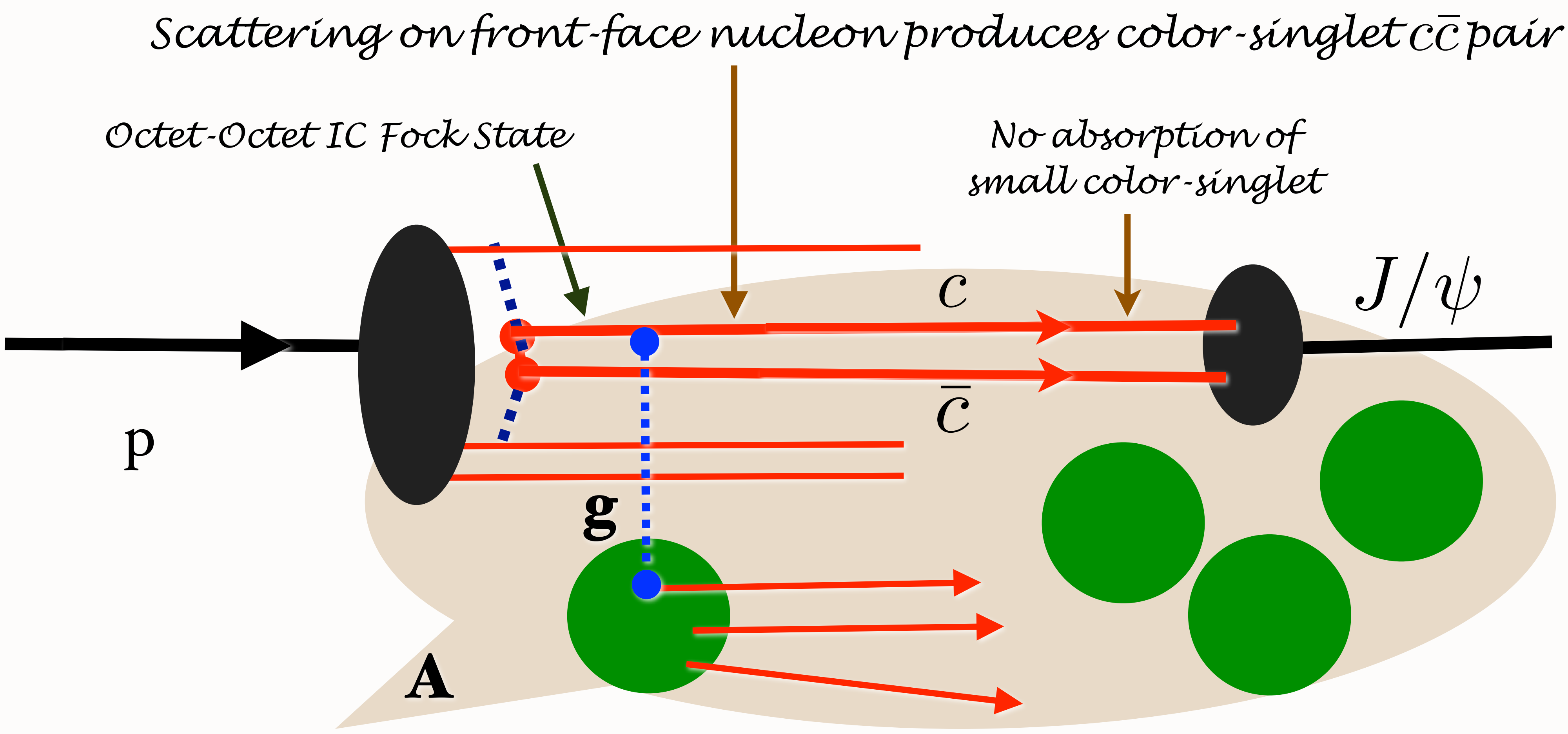
Violates PQCD factorization!

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

Hoyer, Sukhatme, Vanttinen

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

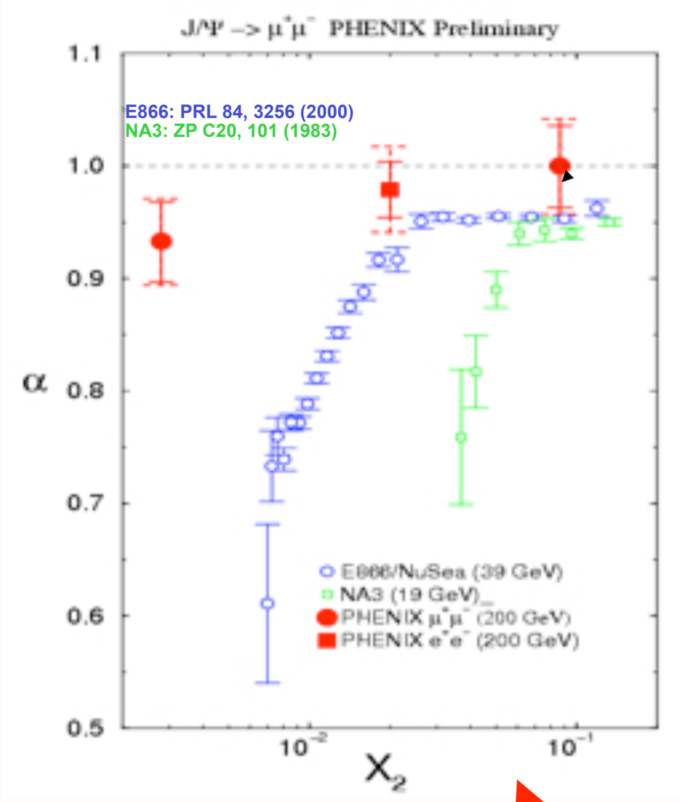


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

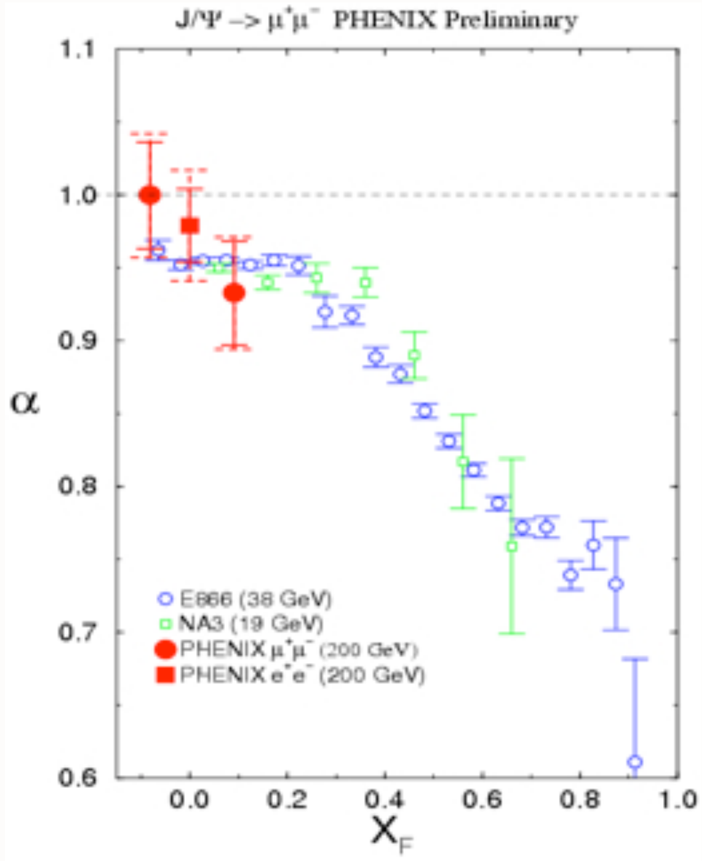
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001



Huge "absorption" effect

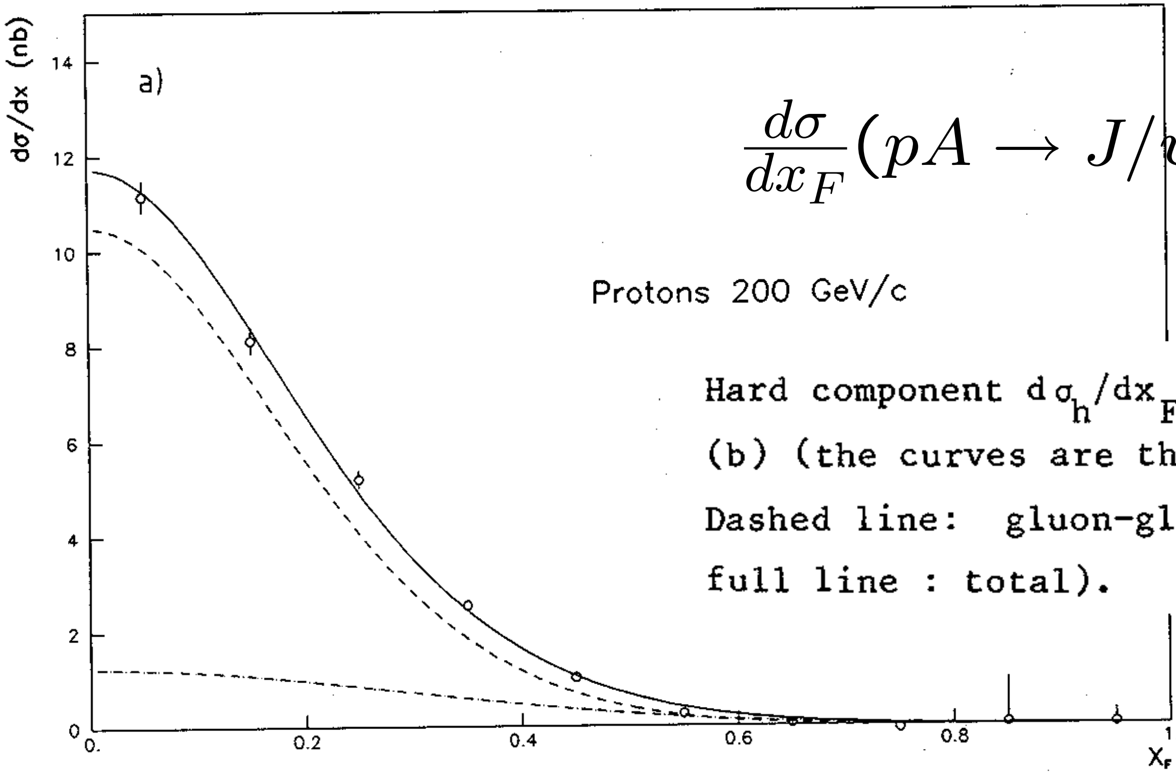
Violates PQCD factorization!

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

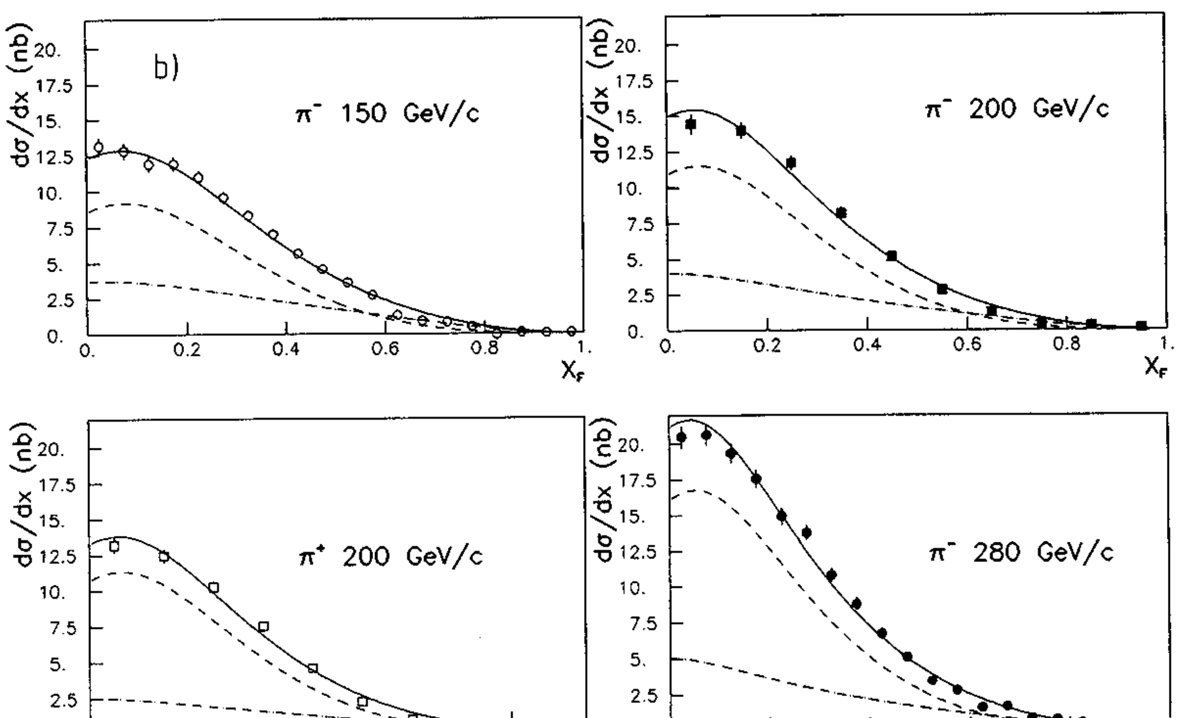
Hoyer, Sukhatme, Vanttinen

Violates PQCD Factorization: $A^{\alpha}(x_F)$ not $A^{\alpha}(x_2)$

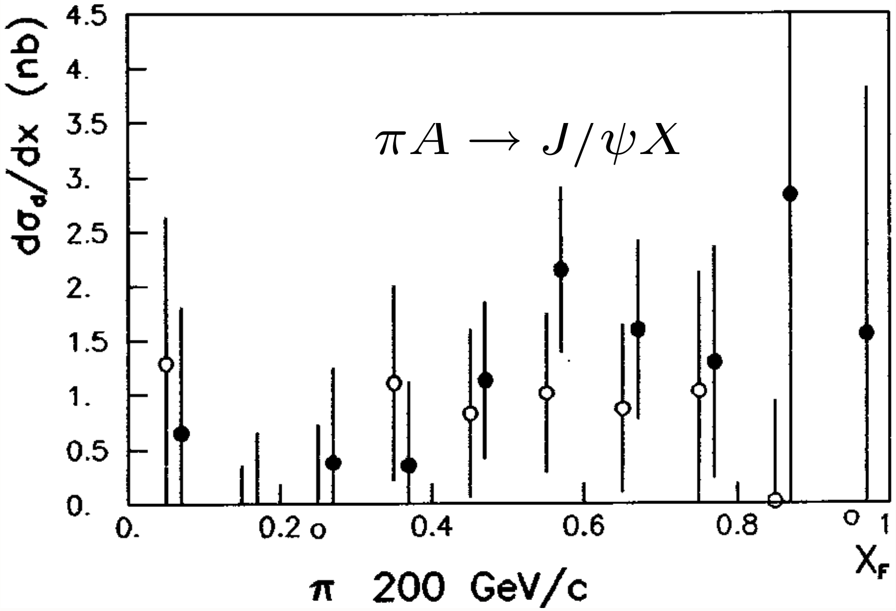
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F}$$



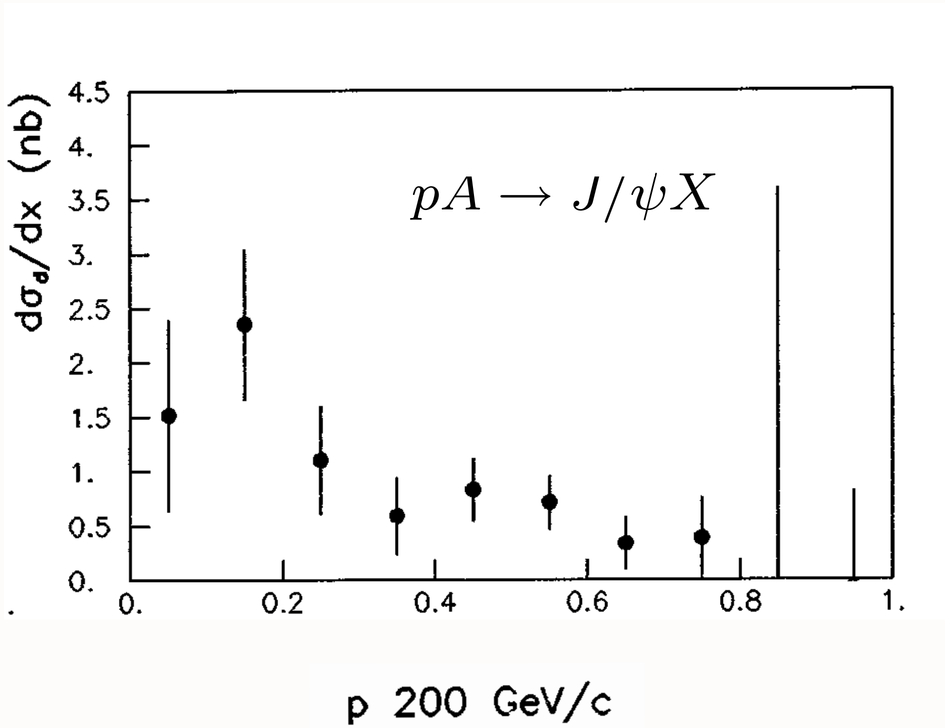
Hard component $d\sigma_h/dx_F$ for incident protons (a) and pions (b) (the curves are the result of the fit described in the text. Dashed line: gluon-gluon fusion; dash-dotted line : $q\bar{q}$ fusion; full line : total).



A^1 component consistent with sum of gg and $\bar{q}q$ fusion



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



$A^{2/3}$ component

J. Badier et al, NA3

Excess beyond conventional PQCD subprocesses

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

Color Opaqueness

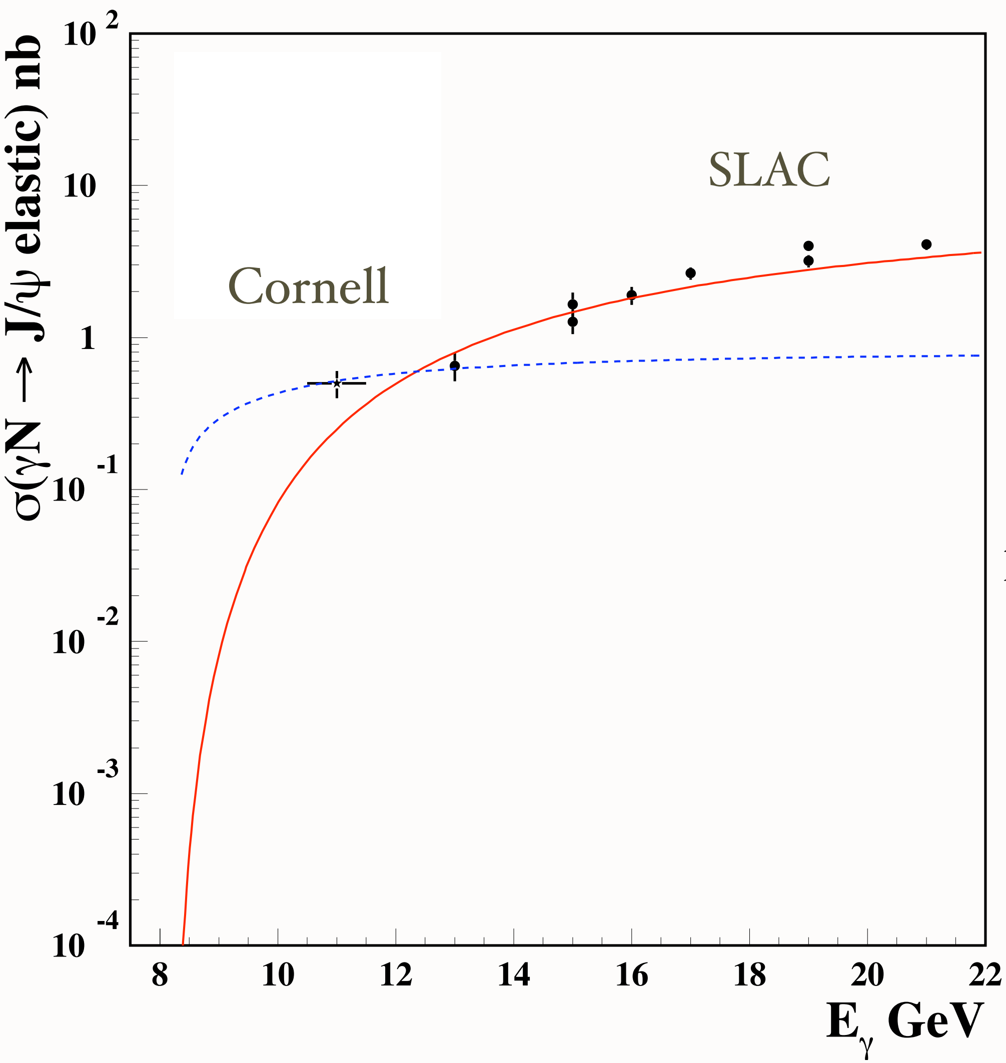
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

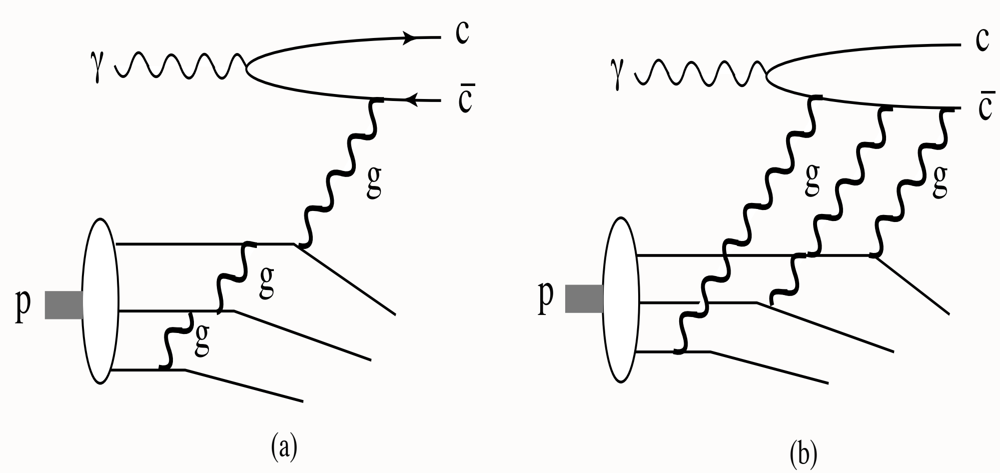
- IC leads to new effects in B decay (Gardner, SJB)

Higgs production at x_F = 0.8

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb





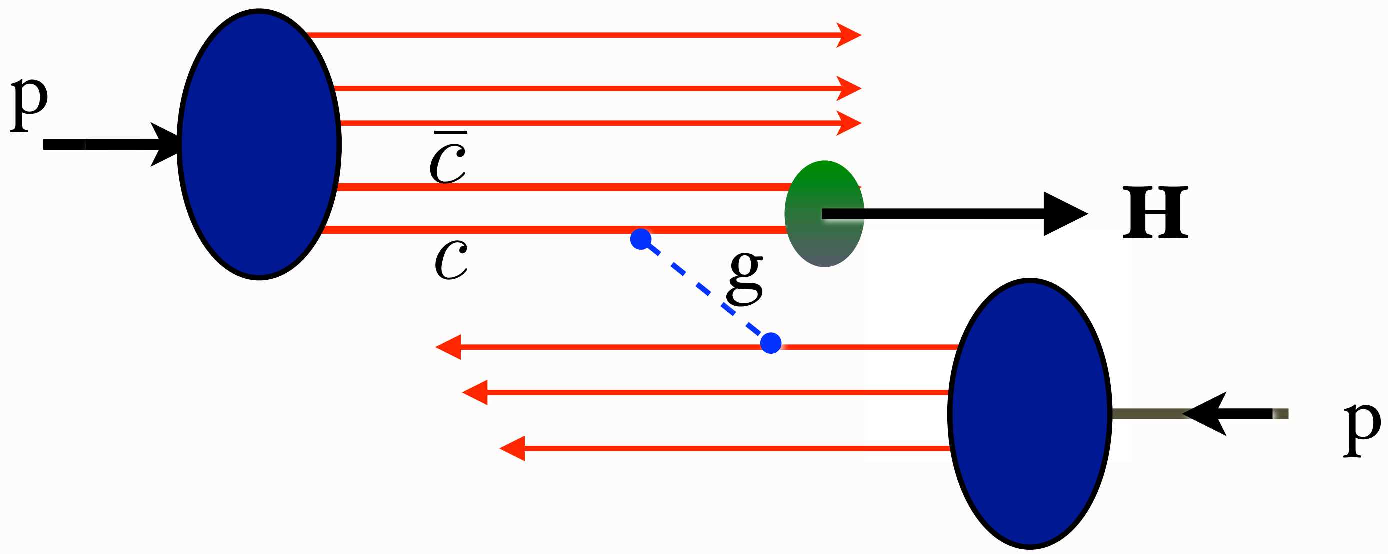
Leading twist contribution

Dominant near threshold

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** *New Multi-lepton Signals*
- **Fixed target program at LHC: produce bbb states**

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



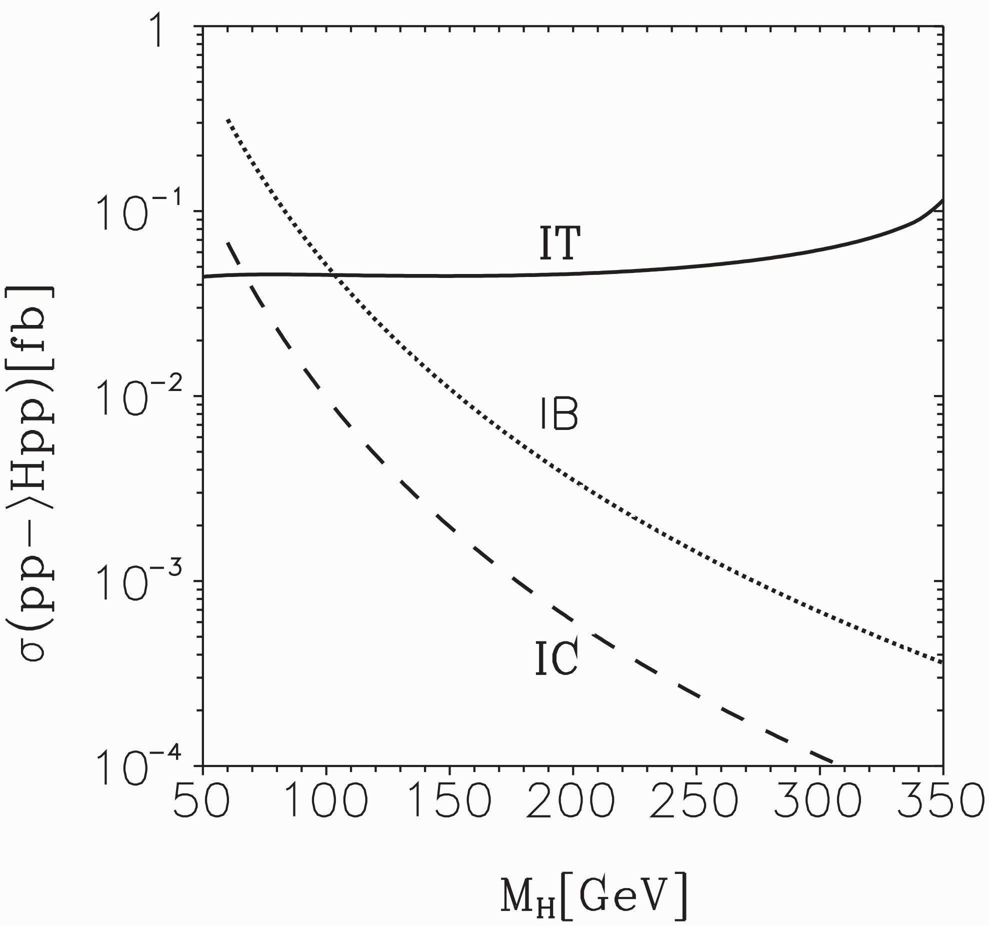
$$pp \to H X$$

Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

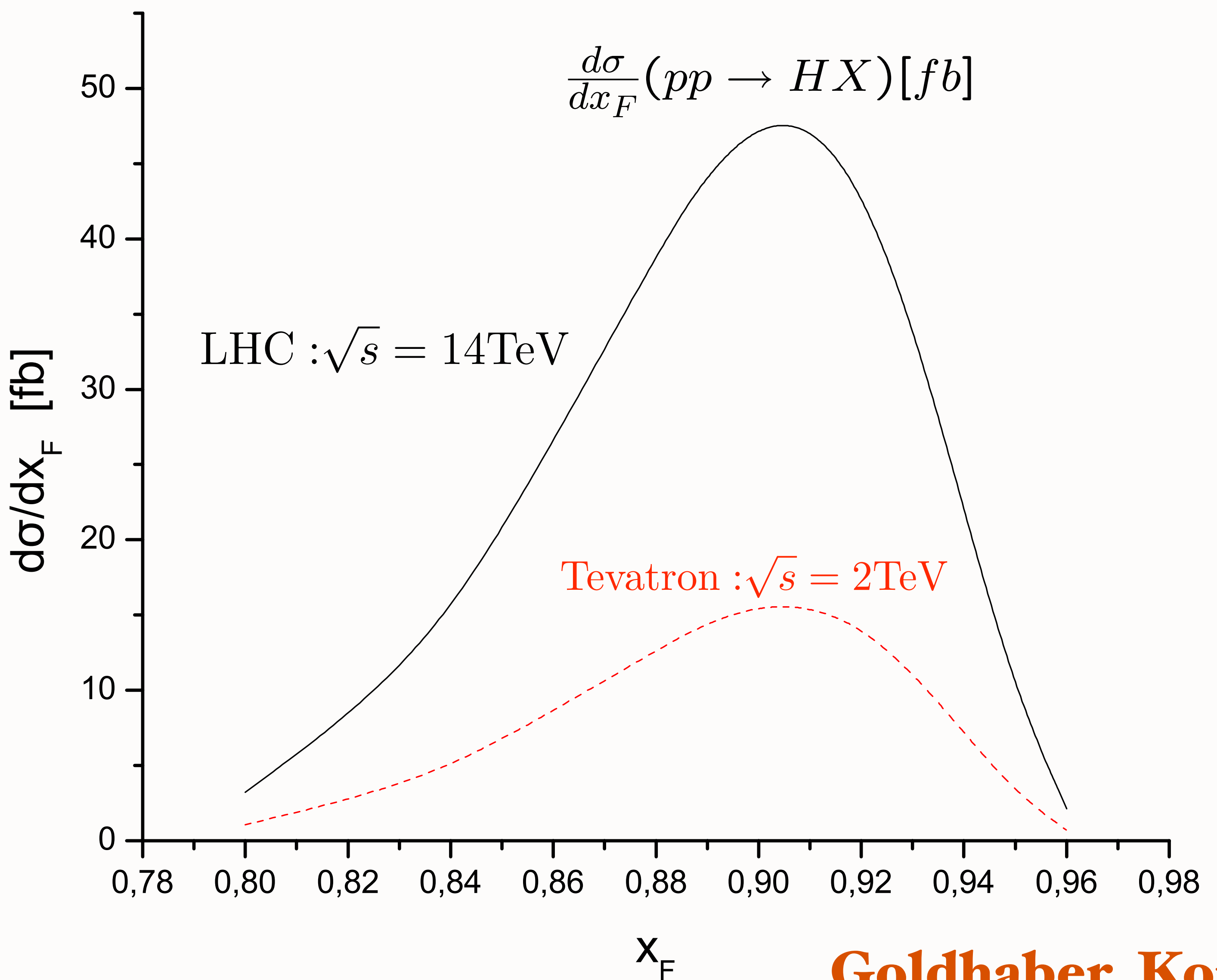
Higgs can have 80% of Proton Momentum!

New search strategy for Higgs



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

Intrinsic Bottom Contribution to Inclusive Higgs Production



Goldhaber, Kopeliovich, Schmidt, sjb

Need for a quarkonium observatory

- To put an end to production controversies (since 1995 !), we need
  - a study of direct J/ψ yield (χ_c only measured in *pp* by CDF and PHENIX)
  - a study of direct $\Upsilon(nS)$ (χ_b only measured in *pp* by CDF (1 point))
  - a study of the polarisation of direct yields
    (at least in 2 frames or 2D distrib.)
  - + probably associated production
- $\chi_{c,b}$ production is badly known, even worse for the η_c
- The latter are **potentially better probes** of glue in *pp*
- LO processes are $gg \to \begin{cases} \chi_{c,b,2} \\ \eta_{c,b} \end{cases}$
- For that, we need
  - high stats
    $\to$ wide acceptance (also help not to bias 1D polarisation analyses)
  - a vertex detector
  - state-of-the-art calorimetry for γ ($\chi_Q \to ^3S_1 + \gamma$, $\eta_c \to \gamma\gamma$)
  - adapted triggers (Big issue for CMS and ATLAS)

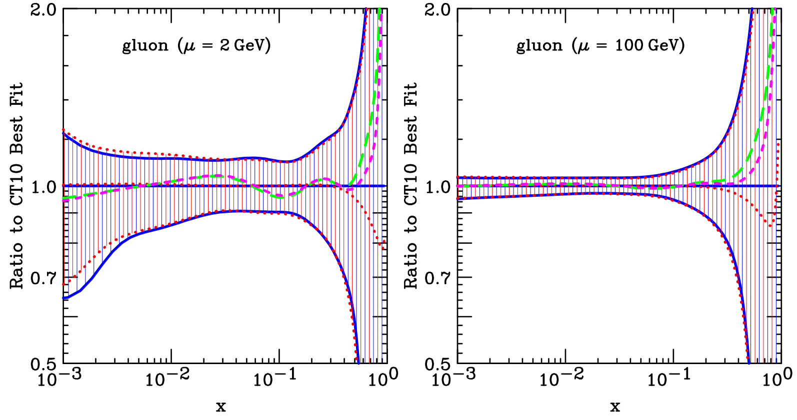
A Fixed Target ExpeRiment: A quarkonium observatory

- Interpolating the world data set:
- Rates expected at RHIC in 2011: J/ψ: 10^6 in *pp*, Υ: 10^4 in *pp*
- 2-3 orders of magnitude higher here

  (RHIC yields are much lower in dAu compared to p*A* here)
- Numbers are for only one unit of *y* about 0
- Unique access in the backward region
- Probe of the (very) large *x* in the target
- AIM/HOPE: Extract $g(x, Q^2)$ with Q^2 as low as 10 GeV^2

  from $x = 10^{-3}$ up to $\simeq$ one

Target	$N_{J/\Psi}$ (y^{-1}) $N_{J/\Psi} = A\mathcal{L}\sigma_\Psi$	N_Υ (y^{-1}) $N_\Upsilon = A\mathcal{L}\sigma_\Upsilon$
	(with branching and per unit of rapidity)	
Liq. H² (1m)	0.6 10^9	10^6
Liq. D²	1.5 10^9	23 10^5
Be	0.2 10^9	2.7 10^5
Cu	0.8 10^9	13 10^5
W	1.7 10^9	27 10^5
Pb	1. 10^9	16 10^5



A Fixed Target ExpeRiment: a quarkonium observatory in *PbA*

Observation of J/ψ sequential suppression seems to be hindered by

- the Cold Nuclear Matter effects: non trivial and
  ... not well-known, after all
- the difficulty to observe directly the excited states
  which would melt before the ground states
  - χ_c never studied in *AA* collisions
  - $\psi(2S)$ not yet studied in *AA* collisions at RHIC and the LHC
- the possibilities for $c\bar{c}$ recombination
  - Open charm studies are difficult where recombination matters most
    i.e. at low P_T
  - Only indirect indications –from the y and P_T dependence of R_{AA}–
    that recombination may be at work
  - CNM effects may show a non-trivial y and P_T dependence too !
  - not clear what v_2 tells us

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- Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay
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- Fixed target program at LHC: produce bbb states

Direct Subprocesses

- Explains Drell Yan polarization at high x_F
- Hadrons produced directly without jet hadronization
- Explains power-laws at fixed x_T
- Energy efficient; minimal x_1,x_2; large rate
- Color Transparent; Explains Baryon-Anomaly in Heavy-Ion collisions; change of power with centrality; depletion of same-side yield

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

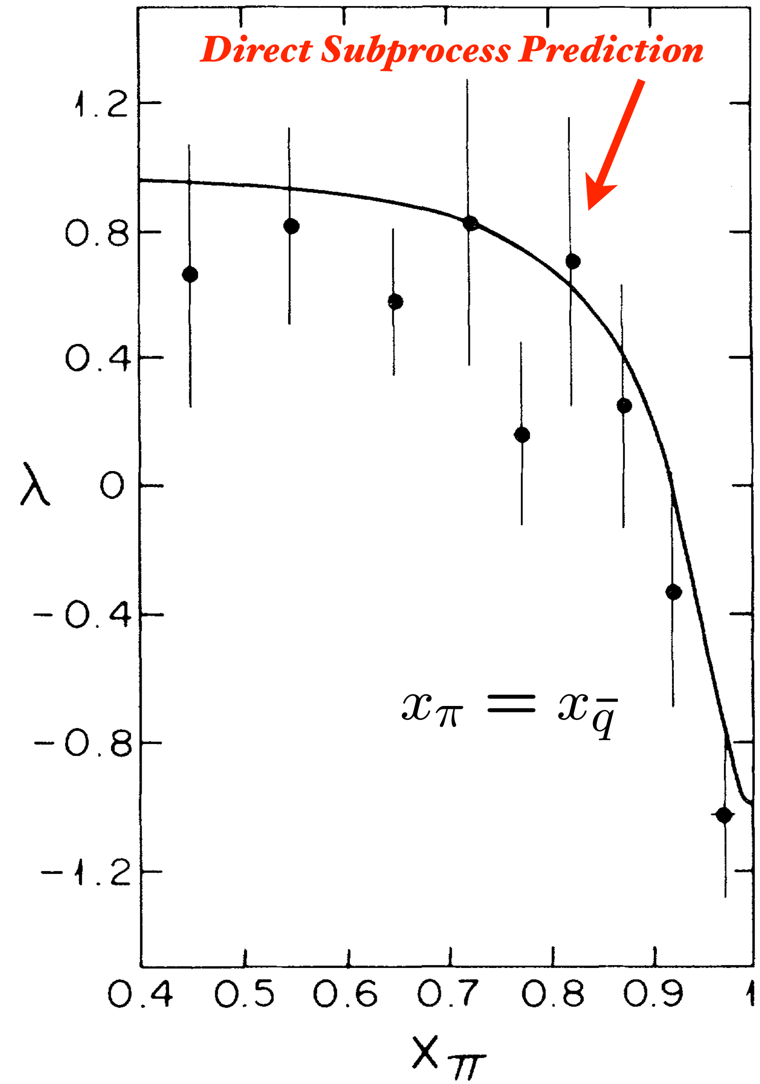
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi .$$

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

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

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F



Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Example of a higher-twist direct subprocess

Many Tests at AFTER

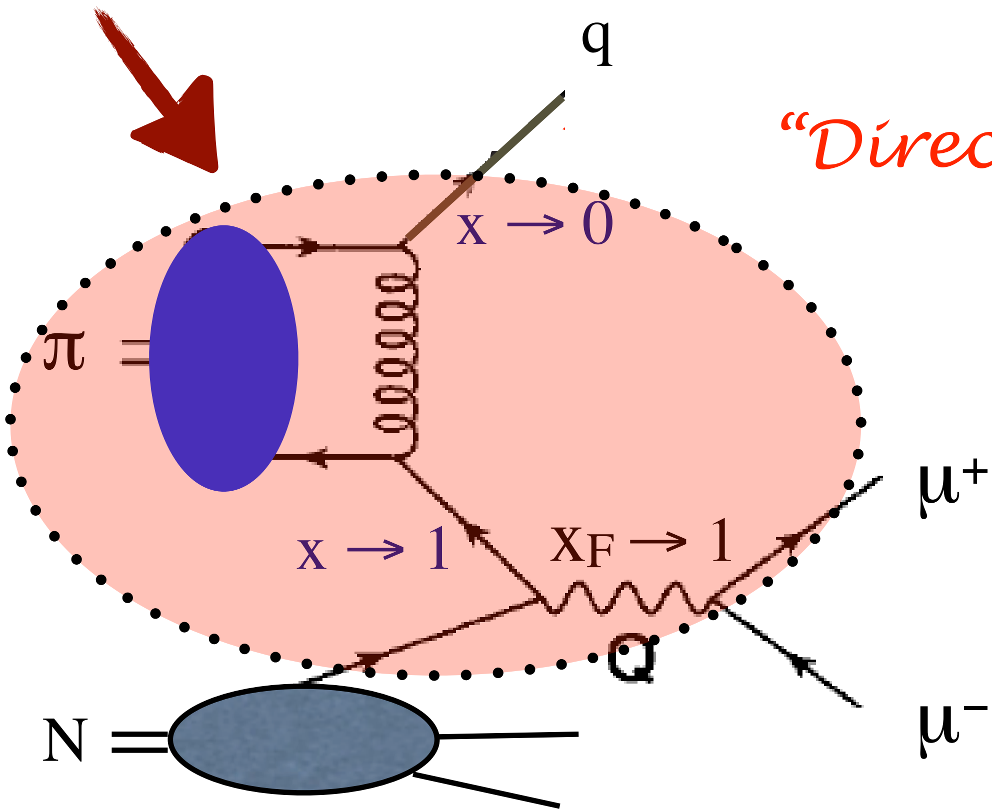
$\pi N \rightarrow \mu^+ \mu^- X$ at high x_F

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

Distribution amplitude from AdS/CFT

"Direct" Subprocess

Entire pion wf contributes to hard process



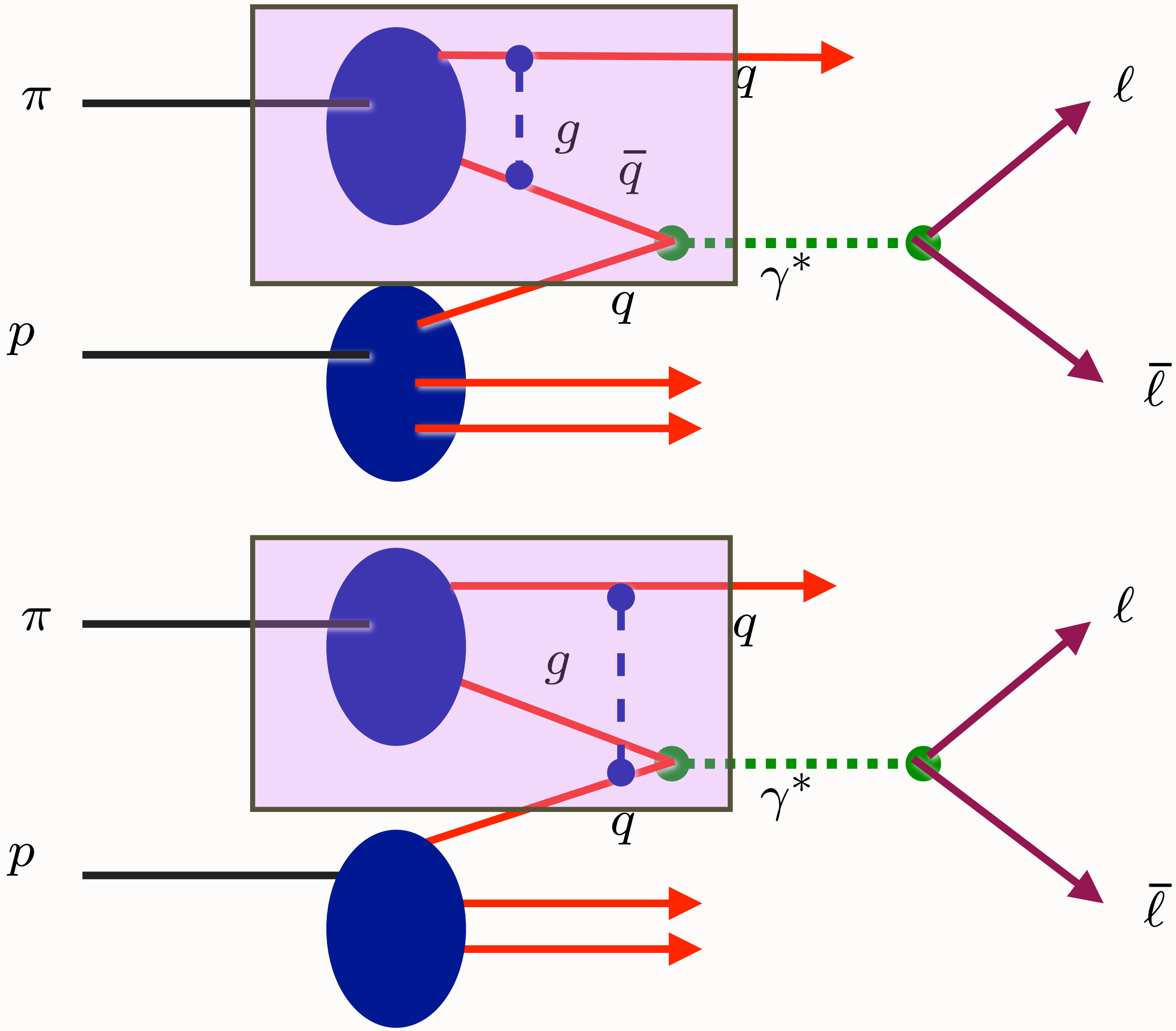
Virtual photon is longitudinally polarized

Similar higher twist terms in jet hadronization at large z

Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

Berger, Lepage, sjb



$$\pi q \to \gamma^* q$$

Initial State Interaction

Pion appears directly in subprocess at large x_F

All of the pion's momentum is transferred to the lepton pair

Lepton Pair is produced longitudinally polarized

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

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

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^{n_{\rm eff}}} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

Parton model: $n_{eff} = 4$

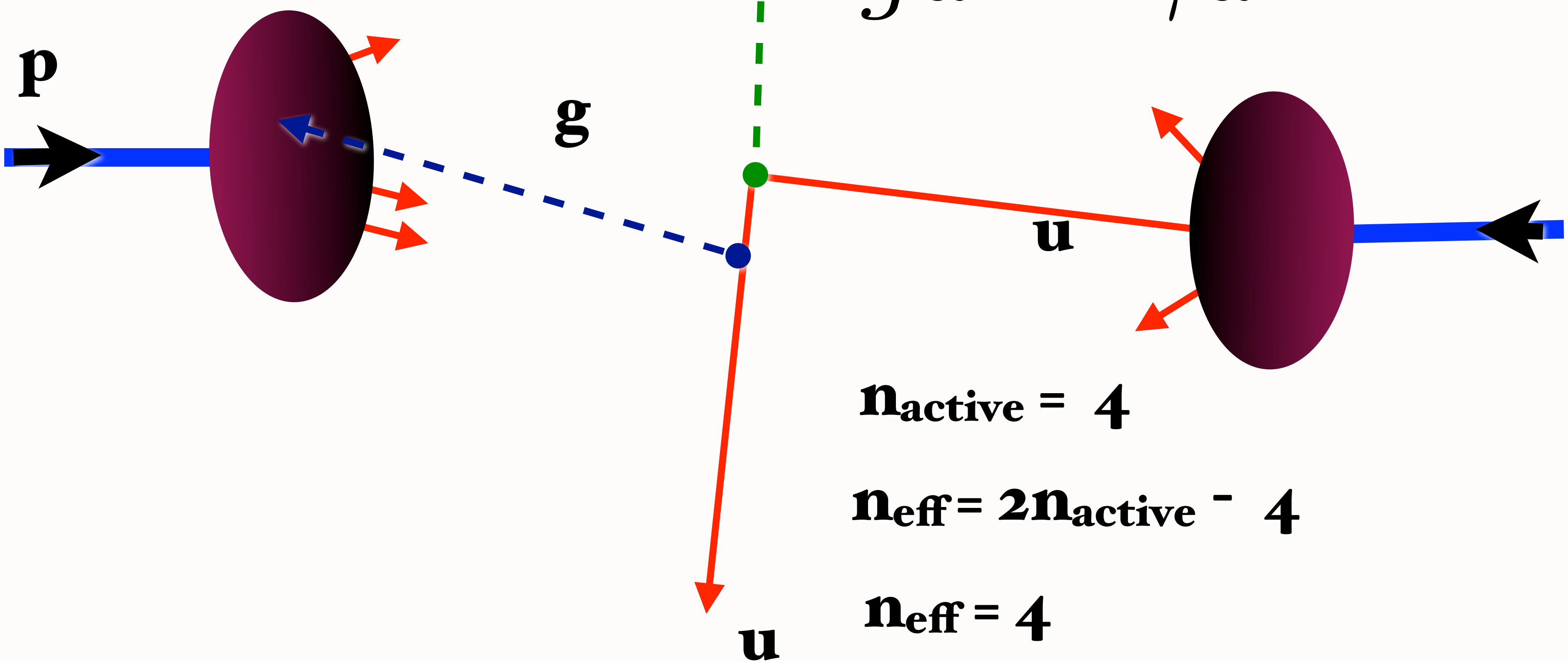
As fundamental as Bjorken scaling in DIS

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

$$pp \rightarrow \gamma X$$

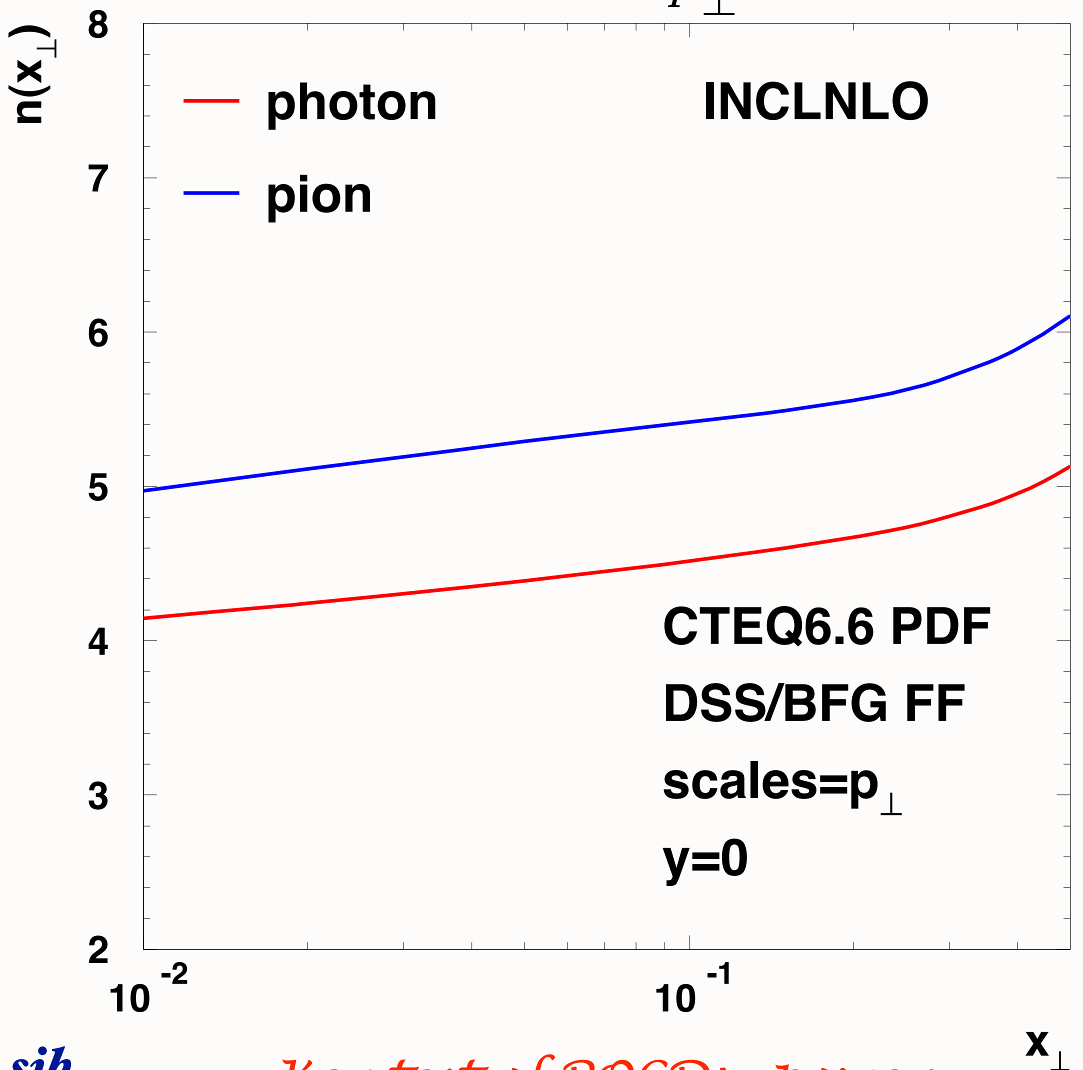
$$E\frac{d\sigma}{d^3p}(pp \rightarrow \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$$

$$gu \rightarrow \gamma u$$



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

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



$$pp \to \pi X$$

$$pp \to \gamma X$$

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

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

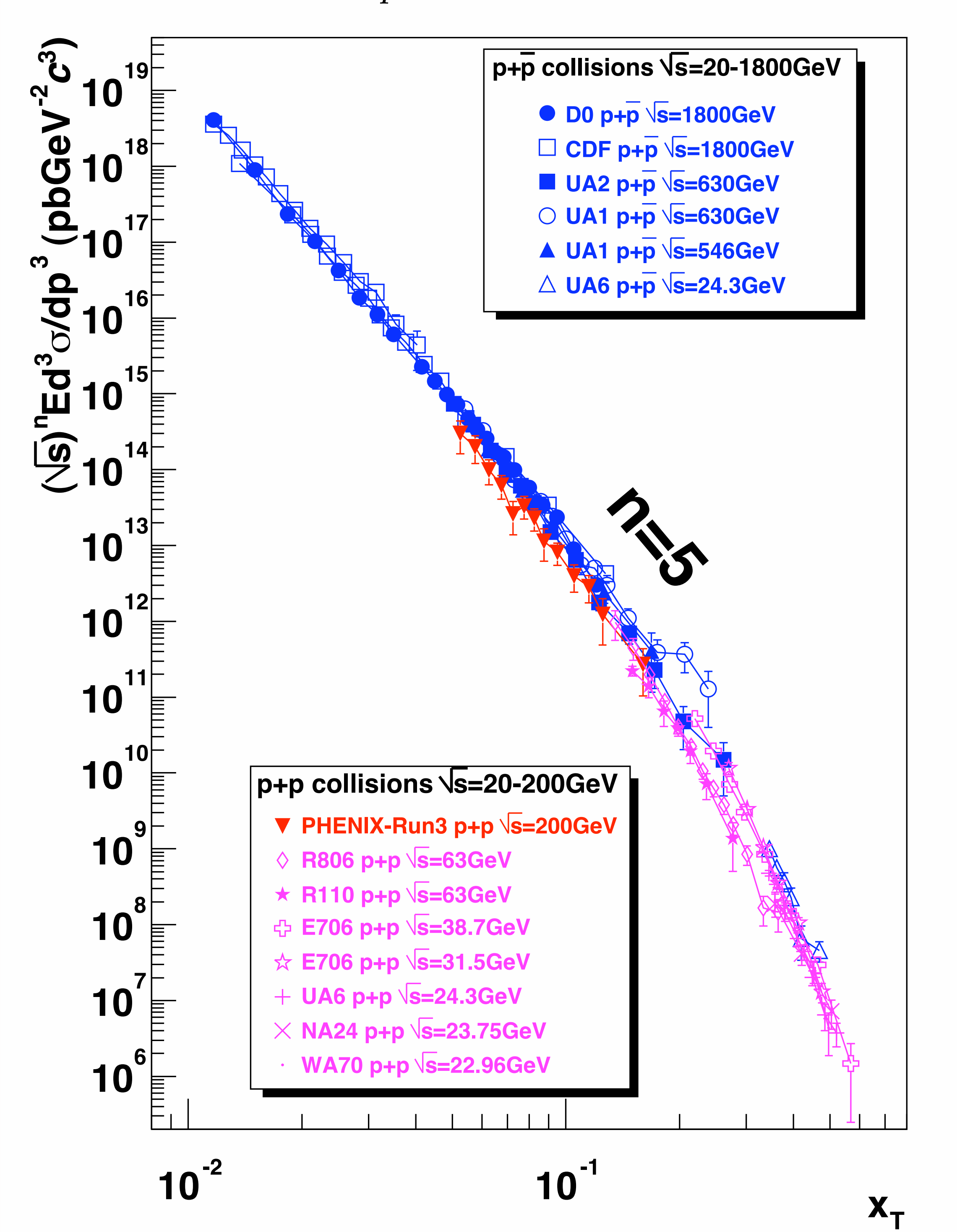
Arleo, Hwang, Sickles, sjb

Pirner, Raufeisen, sjb

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

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

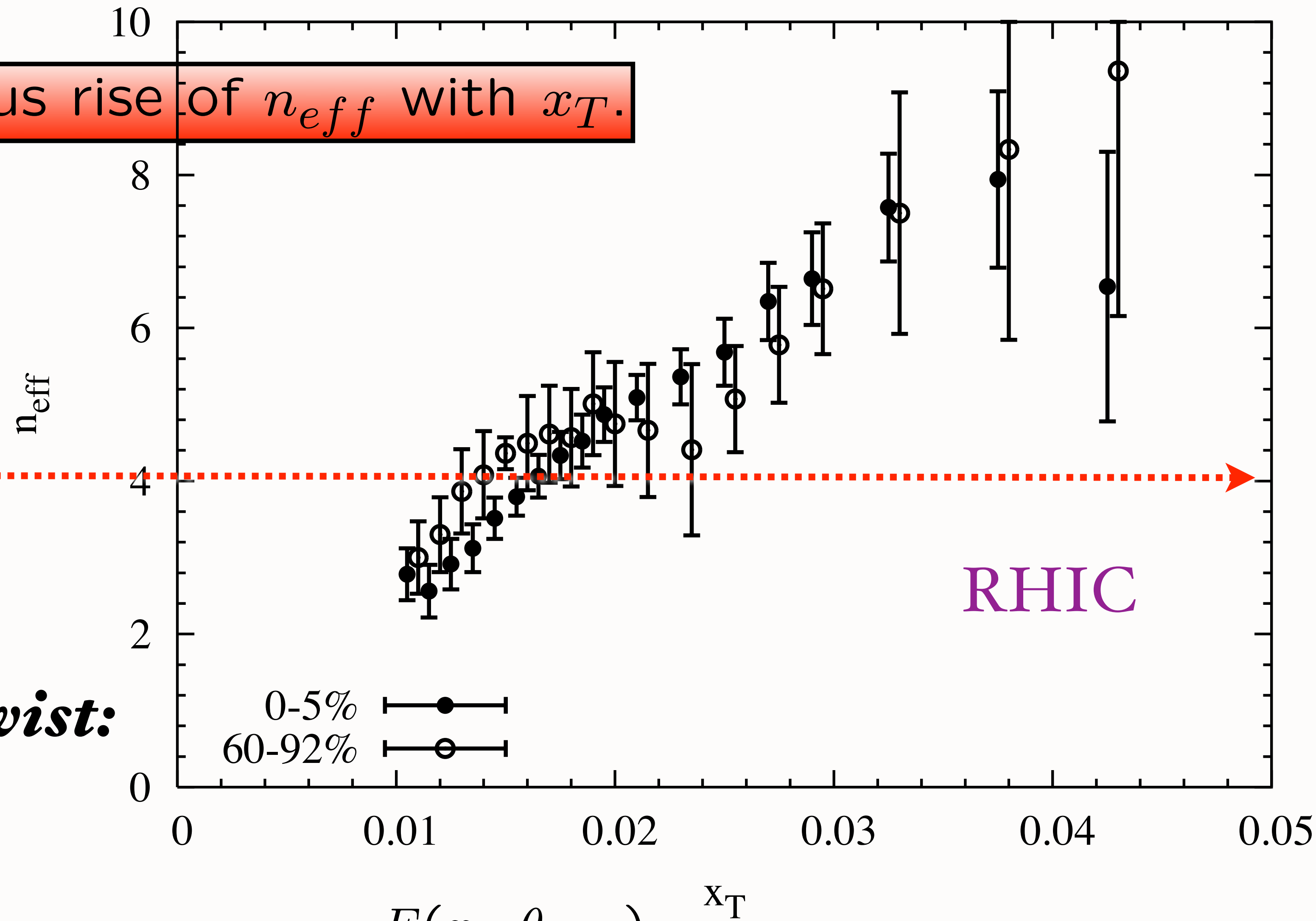
Tannenbaum



x_T-scaling of direct photon production: consistent with PQCD

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

Continuous rise of n_{eff} with x_T.

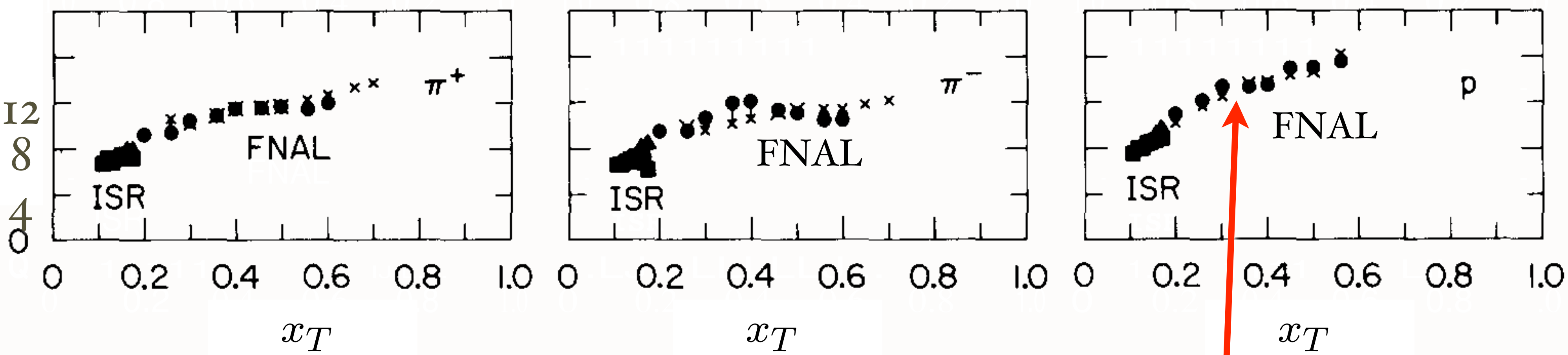


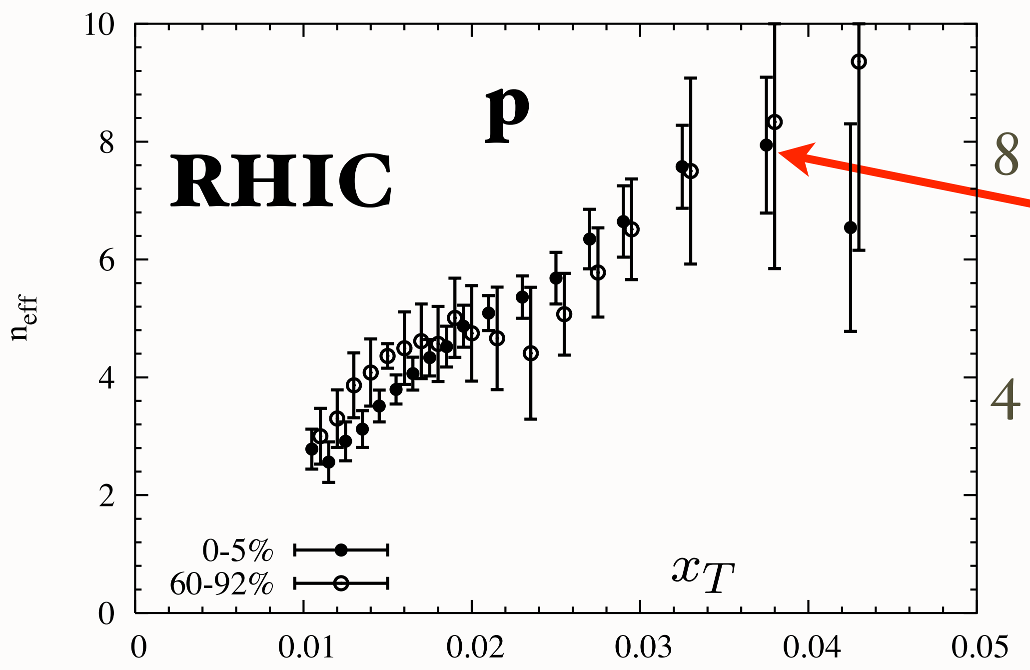
$n_{eff} = 4$

Leading twist:

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

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

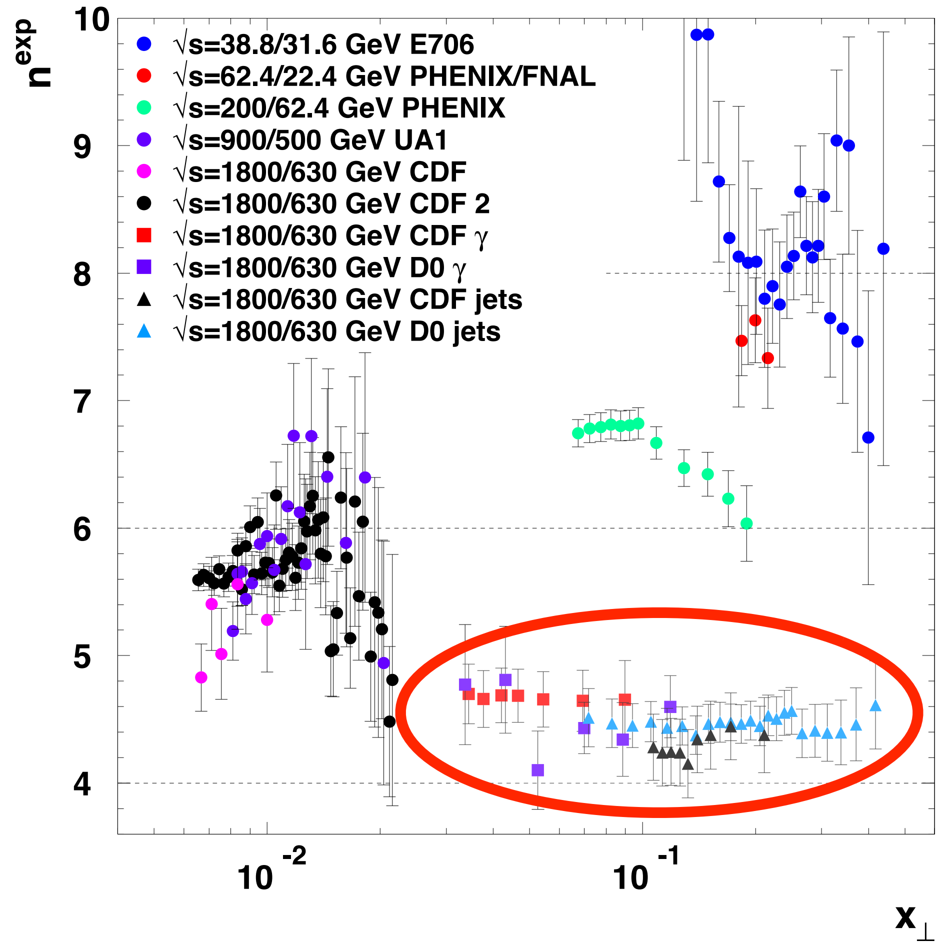




$$E\frac{d\sigma}{d^3p}(pp \rightarrow pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

$$E\frac{d\sigma}{d^3p}(pp \rightarrow pX) = \frac{F(x_T,\theta_{CM})}{p_T^{8}}$$

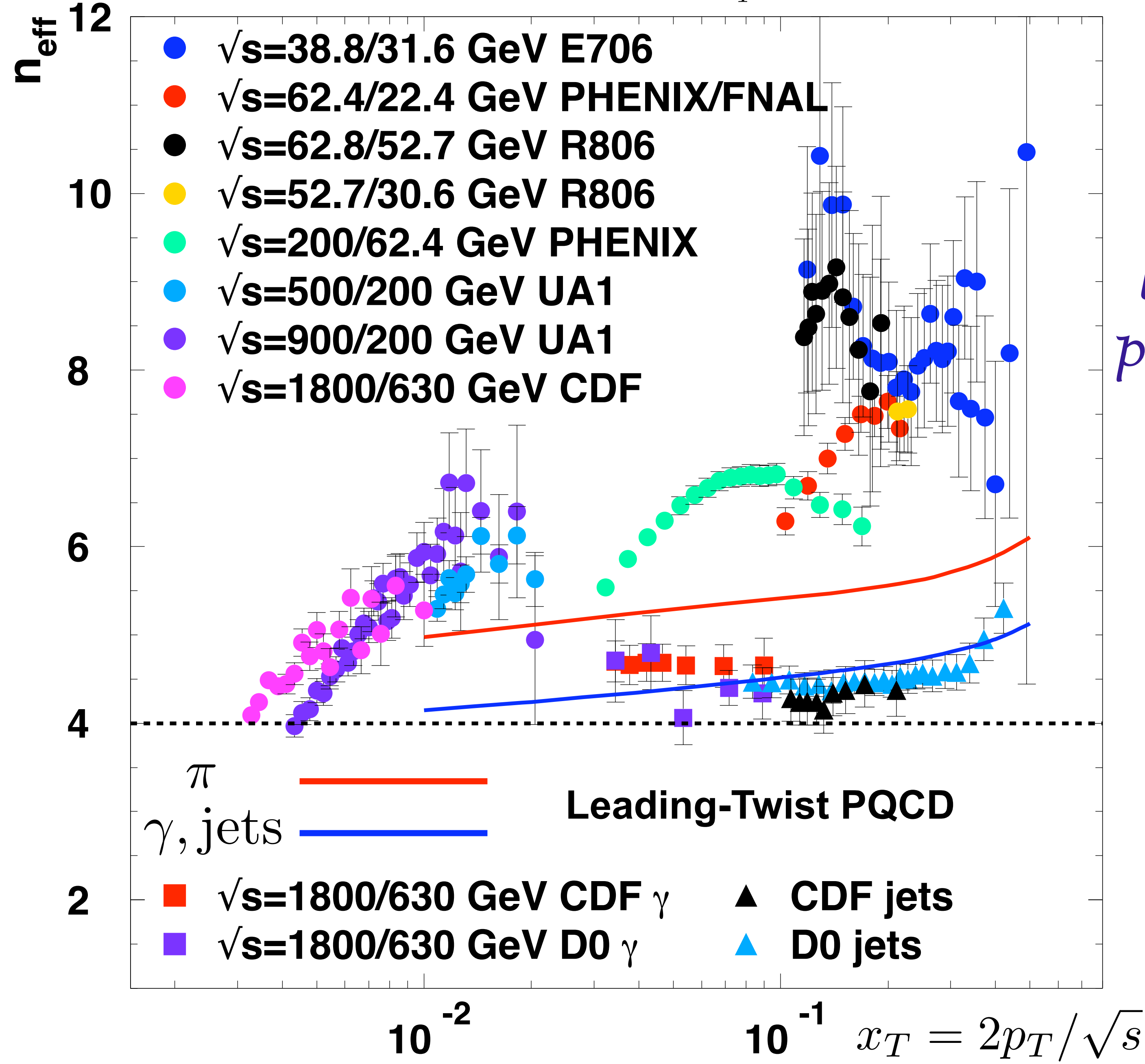
Trend consistent with RHIC at small x_T



Photons and Jets agree with PQCD x_T scaling
Hadrons do not!

- Significant increase of the hadron $n^{\rm exp}$ with $x_\perp$
  - $n^{\rm exp} \simeq 8$ at large $x_\perp$
- Huge contrast with photons and jets !
  - $n^{\rm exp}$ constant and slight above 4 at all $x_\perp$

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

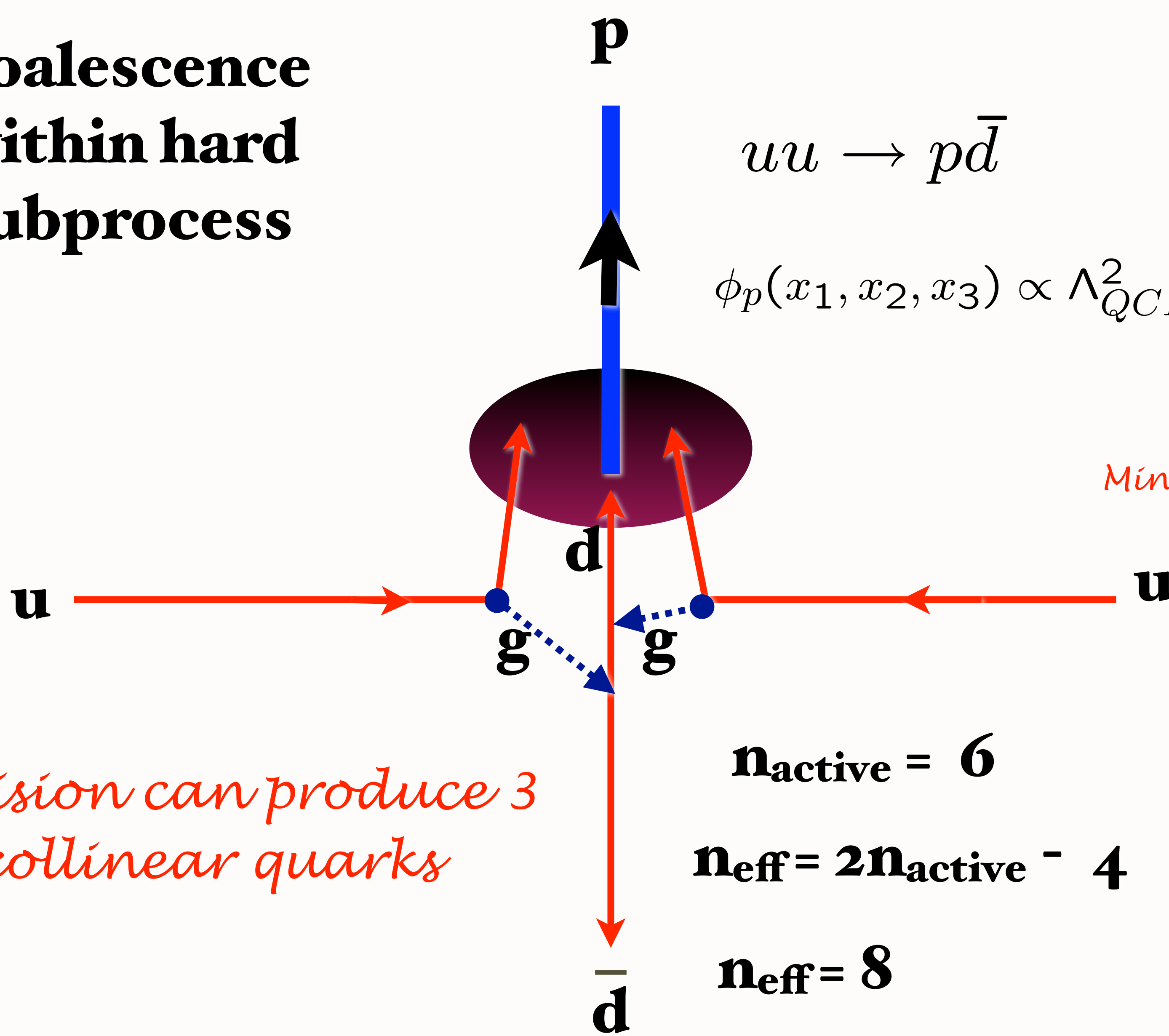


Leading-twist prediction fails at ISR, FNAL, RHIC, CDF!

Arleo, Hwang, Sickles, sjb

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess



$uu \rightarrow p\bar{d}$

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

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

Sickles; sjb

Small color-singlet
Color Transparent
Minimal same-side energy

Explains Baryon anomaly

$qq \rightarrow B\bar{q}$

Collision can produce 3 collinear quarks

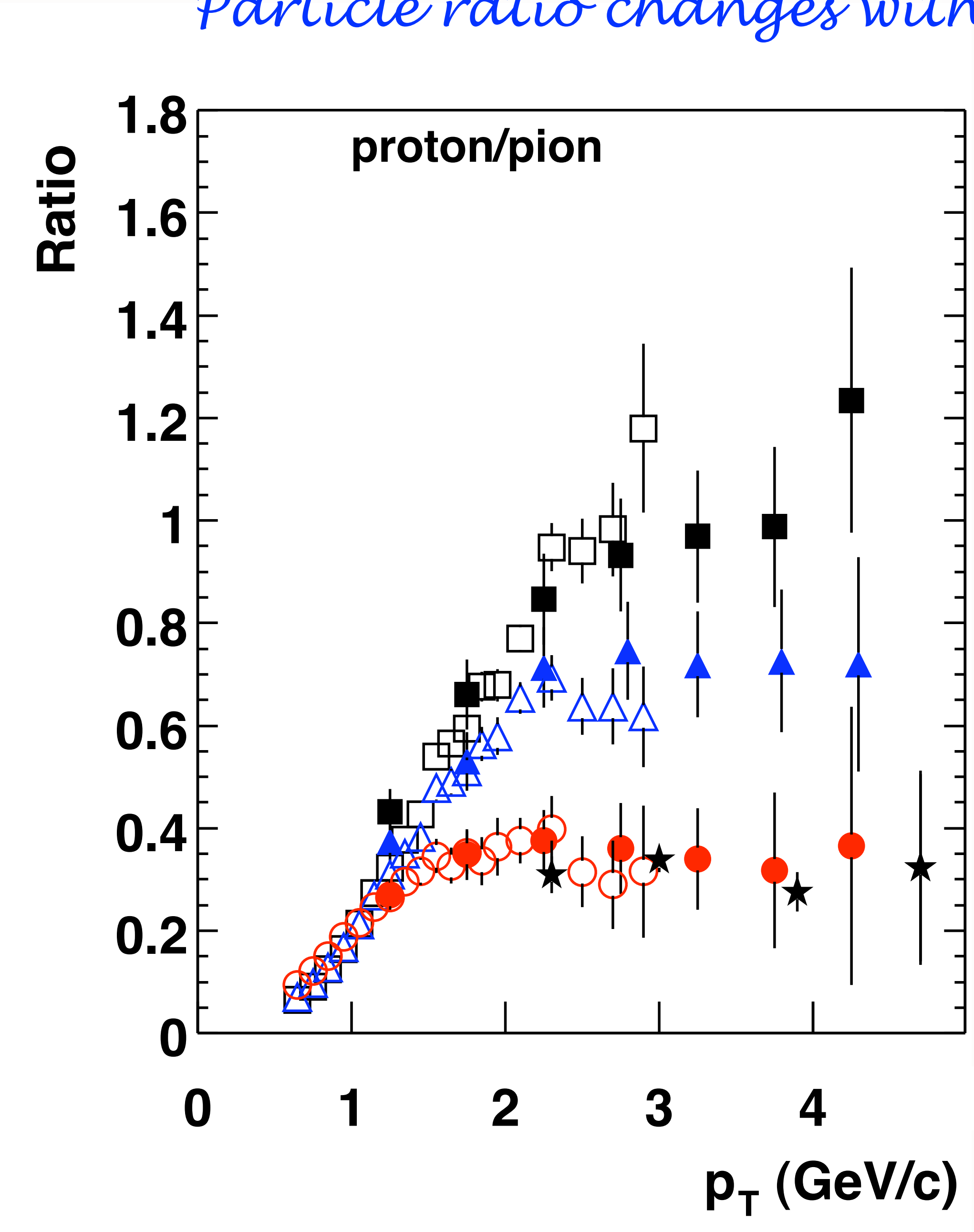
$n_{active} = 6$

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

$n_{eff} = 8$

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:

Higher Twist at the LHC

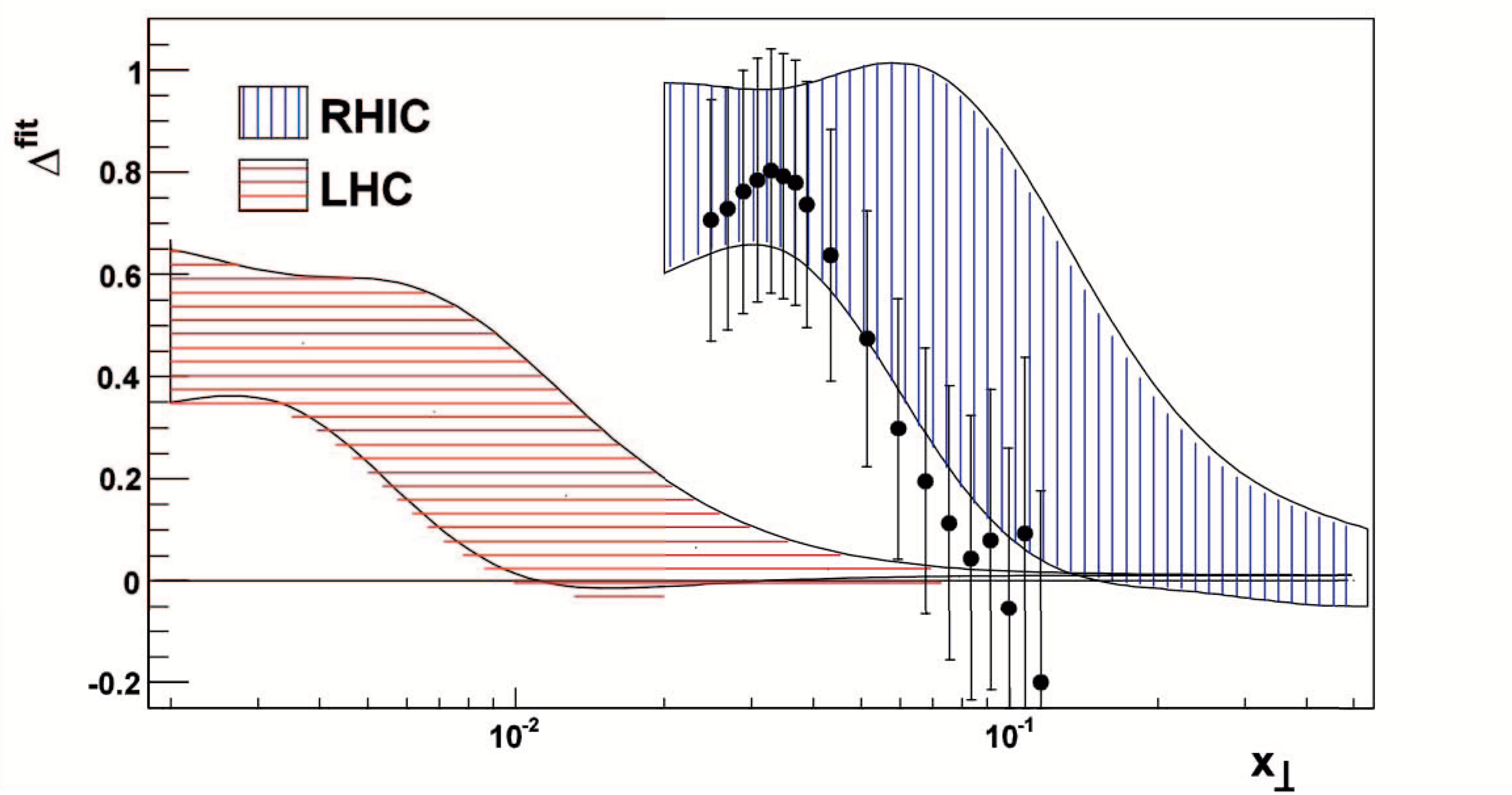
- **Fixed x_T: powerful analysis of PQCD**
- **Insensitive to modeling**
- **Higher twist terms energy efficient since no wasted fragmentation energy**
- **Evaluate at minimal x_1 and x_2 where structure functions are maximal**
- **Higher Twist competitive despite faster fall-off in p_T**
- **Direct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

RHIC/LHC predictions

PHENIX results

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

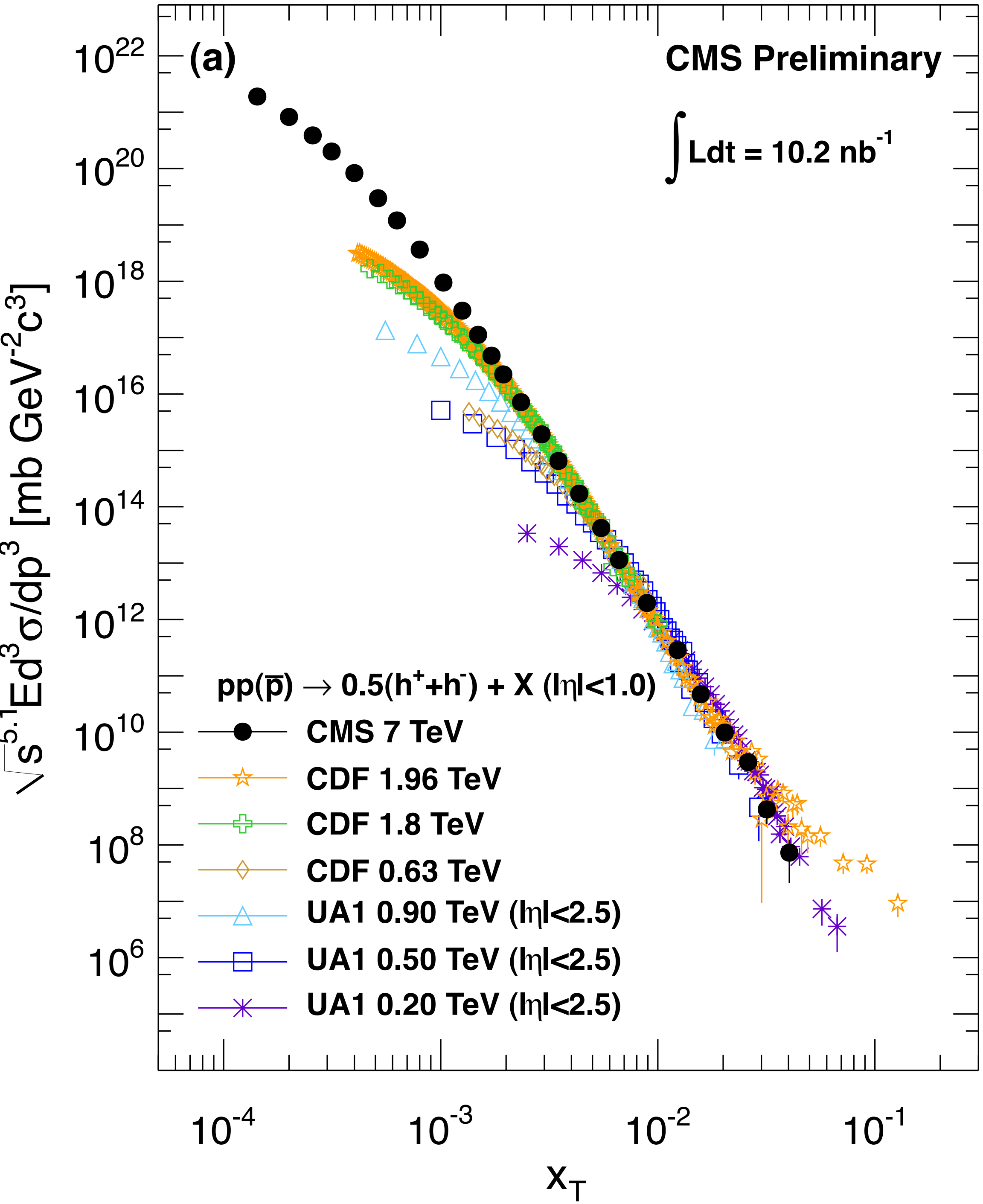
[A. Bezilevsky, APS Meeting]



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

$$\Delta = n_{expt} - n_{PQCD}$$

Arleo, Hwang, Sickles, sjb



Jet-triggered charged particle transverse momentum spectra in pp collisions at 7 TeV

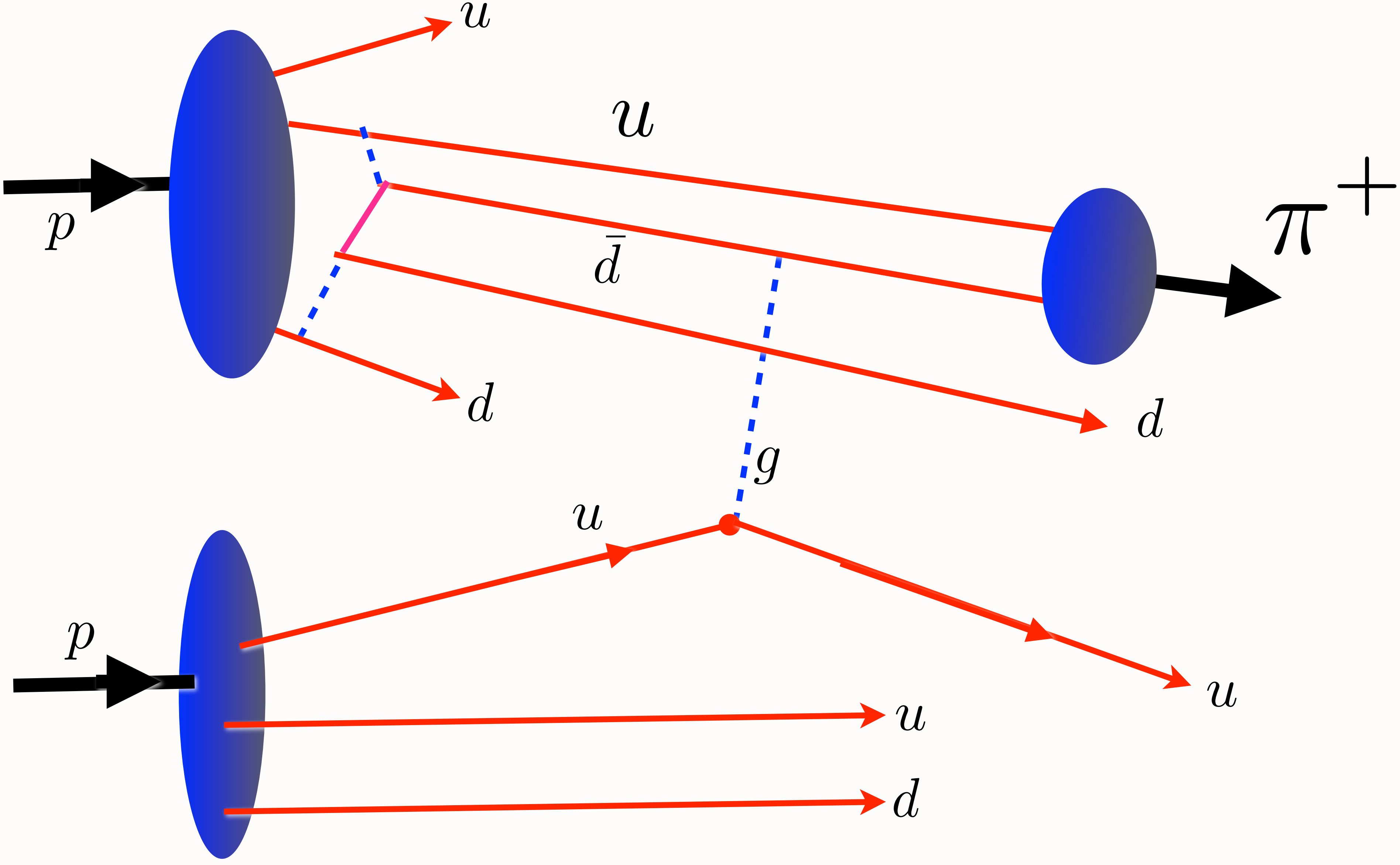
The CMS Collaboration

x_T scaling fails

at the LHC

Inclusive invariant cross sections, scaled by $\sqrt{s}^{5.1}$

Direct pion production at high x_F

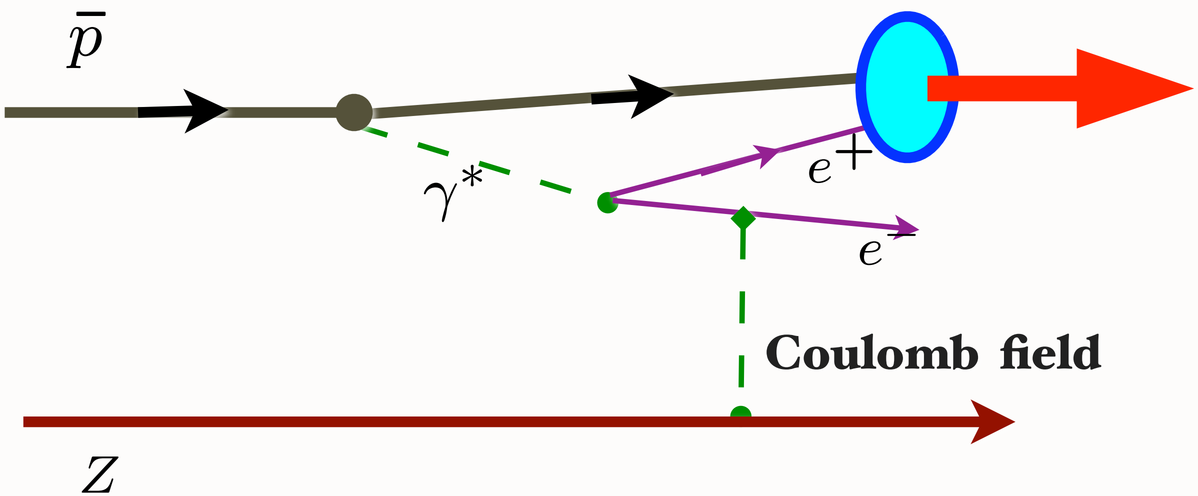


Interference of multi-gluon exchange: Mechanism for large A_N

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



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

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

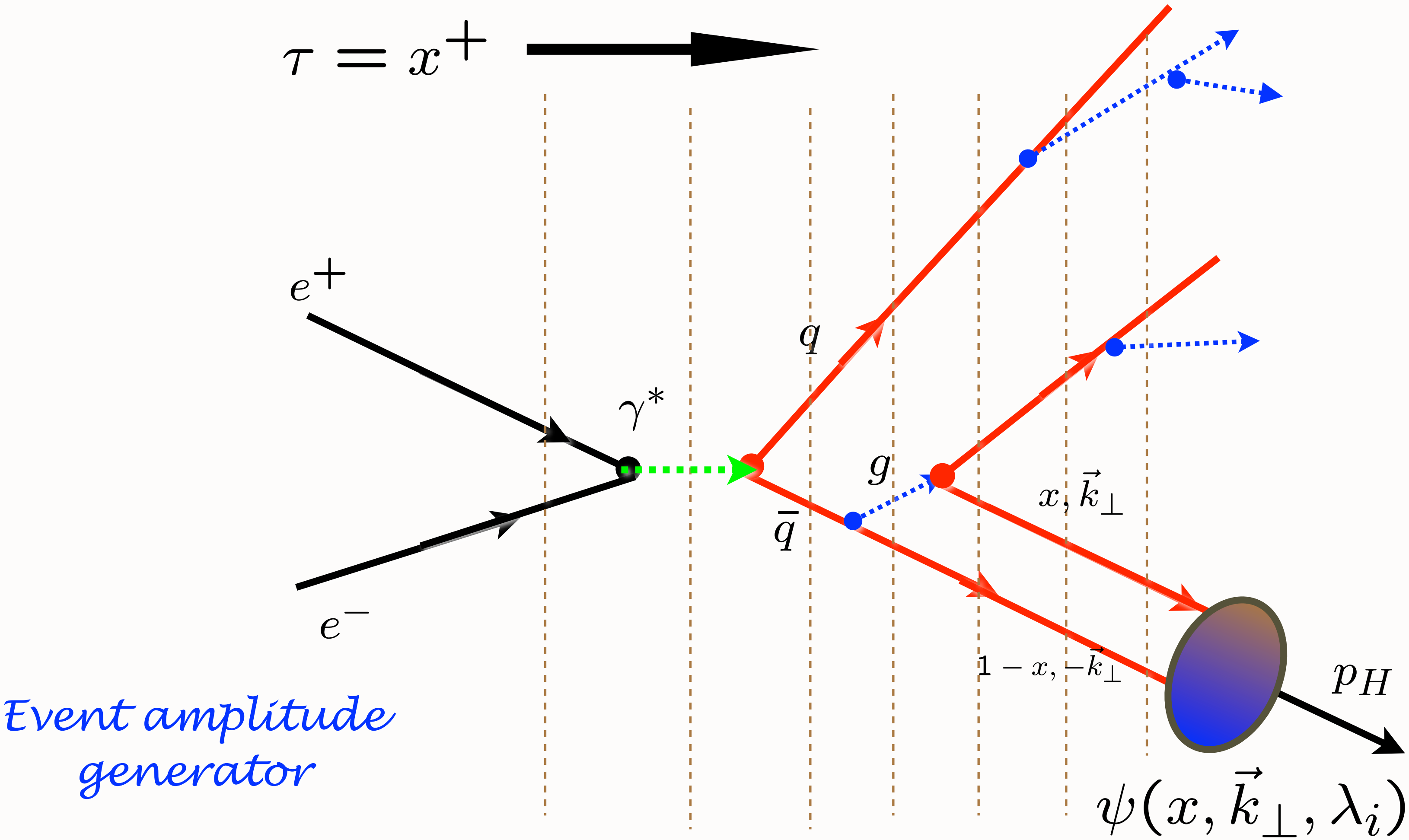
$$y_{\bar{p}} \simeq y_{e^+}$$

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

Wavefunction maximal at small impact separation and equal rapidity

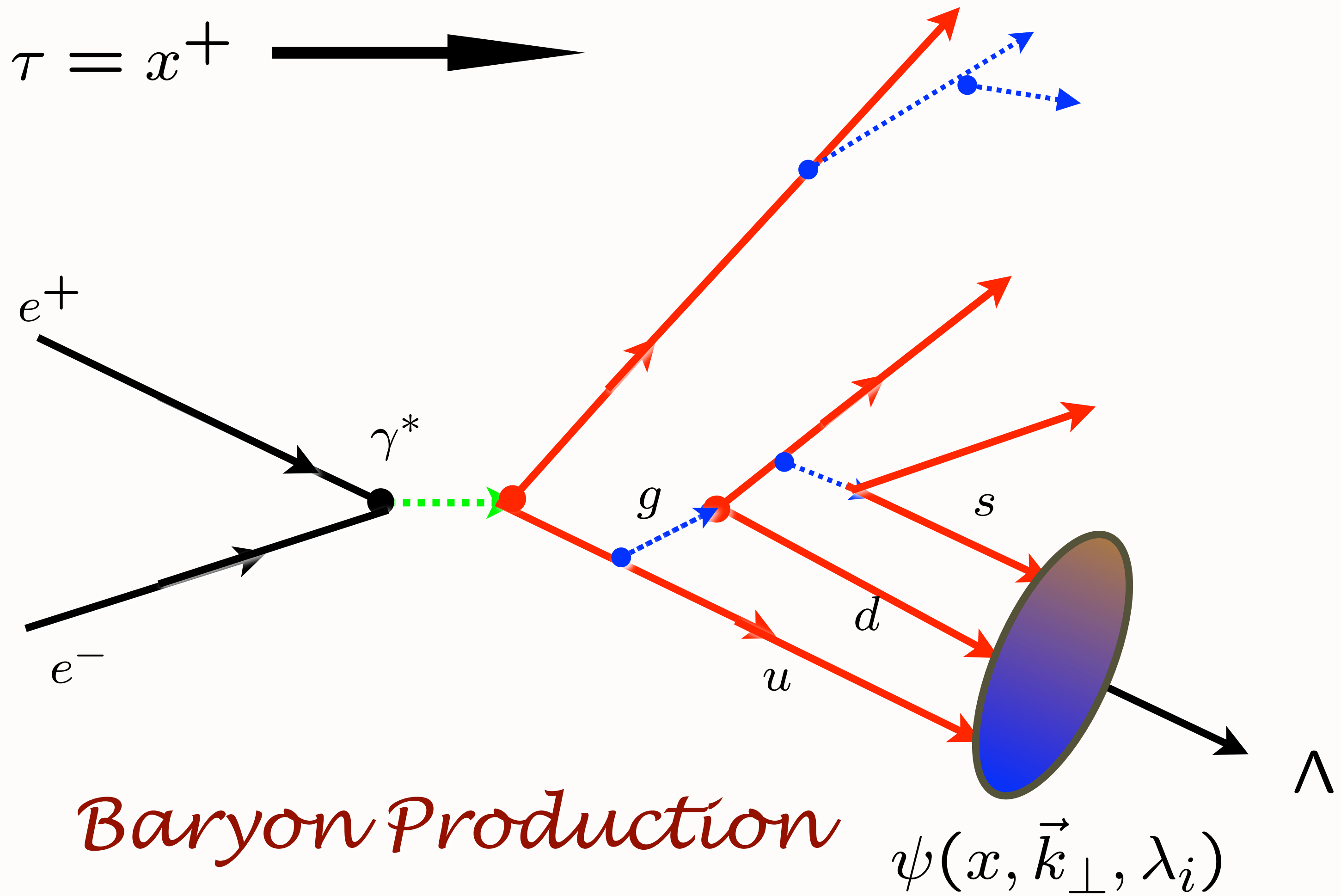
"Hadronization" at the Amplitude Level

Hadronization at the Amplitude Level



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

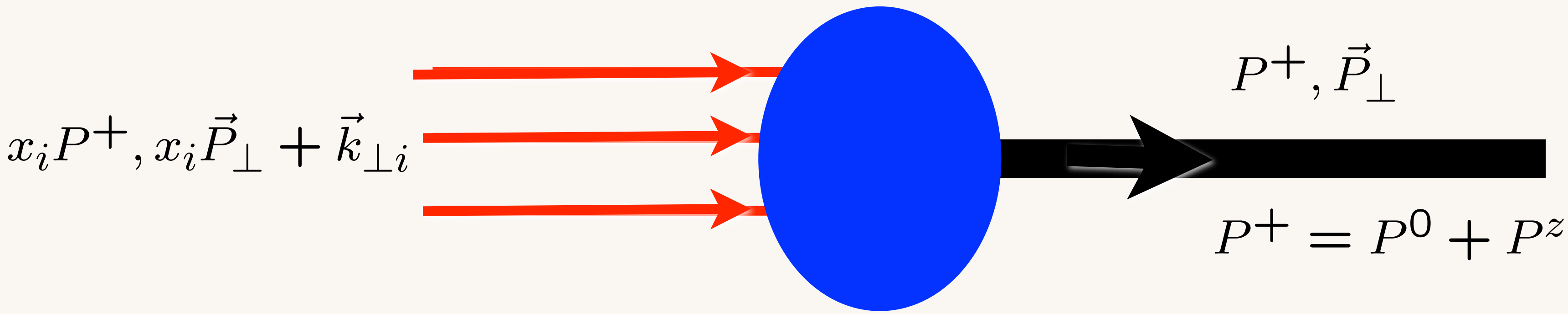
Hadronization at the Amplitude Level



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

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

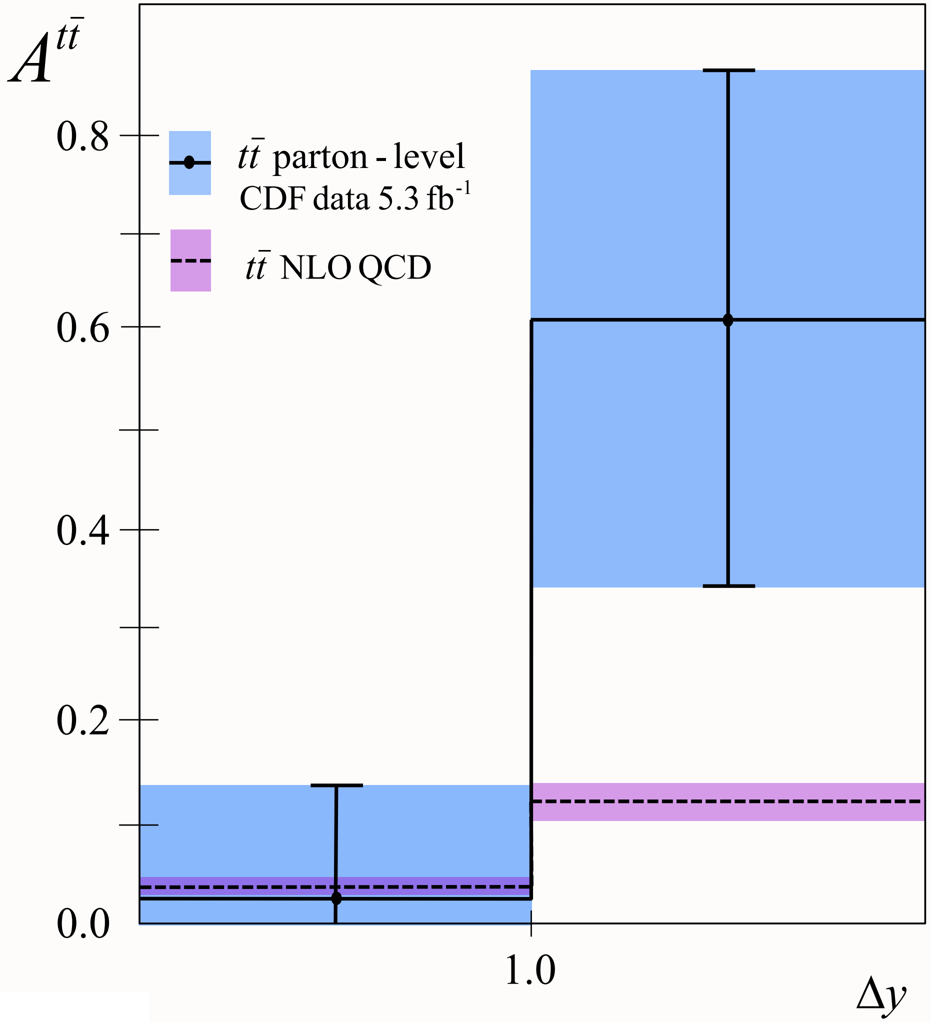
- Same principle as antihydrogen production: off-shell coalescence
- coalescence to hadron favored at equal rapidity, small transverse momenta
- leading heavy hadron production: D and B mesons produced at large z
- hadron helicity conservation if hadron LFWF has $L^z = 0$
- Baryon AdS/QCD LFWF has aligned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



Hot Topics in QCD

- *Intrinsic Heavy Quarks*
- *Breakdown of pQCD Leading-Twist Factorization*
- *Top/anti-Top asymmetry*
- *Non-universal antishadowing*
- *Demise of QCD Vacuum Condensates*
- *Elimination of the QCD Renormalization Scale Ambiguity*
- *AdS/QCD and Light-Front Holography*

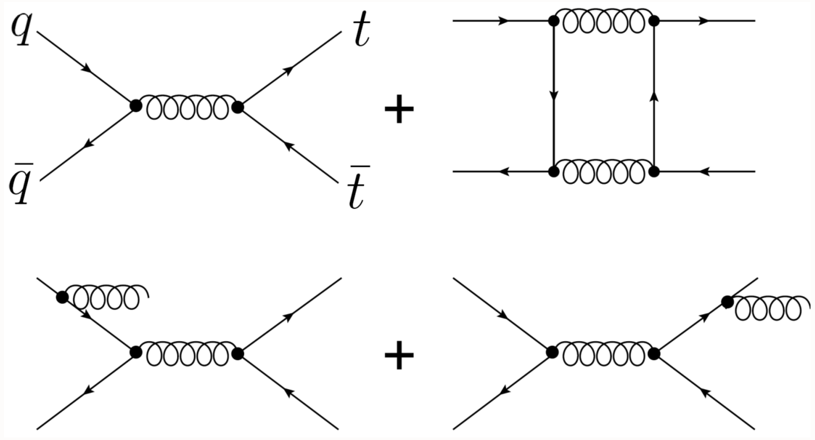
Crucial to Understand QCD to High Precision to Illuminate New Physics



Heavy Quark Asymmetries

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

Asymmetries in Δy 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 ± 0.009.



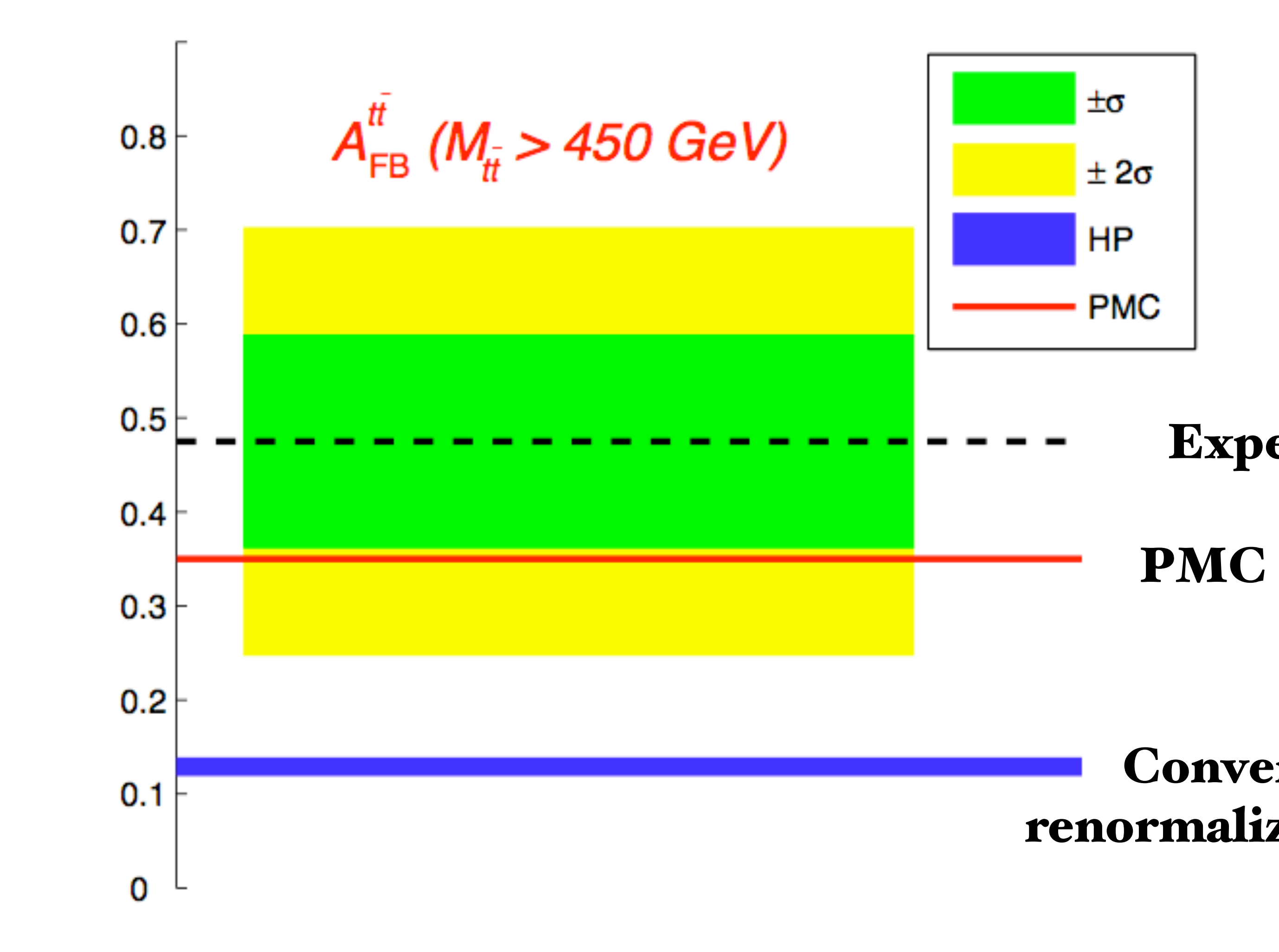
Parton level asymmetries at small and large Δy compared to SM prediction of MCFM. The shaded bands represent the total uncertainty in each bin. The negative going uncertainty for $\Delta y < 1.0$ is suppressed.

Fermilab-Pub-10-525-E

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

CDF Collaboration

Eliminating the Renormalization Scale Ambiguity for Top-Pair Production Using the 'Principle of Maximum Conformality' (PMC)



Xing-Gang Wu
SJB

Experimental asymmetry

PMC Prediction

Conventional: guess for renormalization scale and range

$t\bar{t}$ asymmetry predicted by pQCD NNLO within
1 σ of CDF/D0 measurements using PMC/BLM scale setting

Need to set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

$Choose\ renormalization\ scheme;\ e.g.\ \alpha_s^R(\mu_R^{\rm init})$

↓

$Choose\ \mu_R^{init};\ arbitrary\ initial\ renormalization\ scale$

↓

$Identify\ \{\beta_i^R\} - terms\ using\ n_f - terms$

$through\ the\ PMC - BLM\ correspondence\ principle$

↓

$Shift\ scale\ of\ \alpha_s\ to\ \mu_R^{\rm PMC}\ to\ eliminate\ \{\beta_i^R\} - terms$

↓

$Conformal\ Series$

$Result\ is\ independent\ of\ \mu_R^{\rm init}\ and\ scheme\ at\ fixed\ order$

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

Same as QED Scale Setting

Apply to Evolution kernels, hard subprocesses

Eliminates unnecessary systematic uncertainty

Xing-Gang Wu
Leonardo di Giustino, SJB

Principle of Maximum Conformality

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

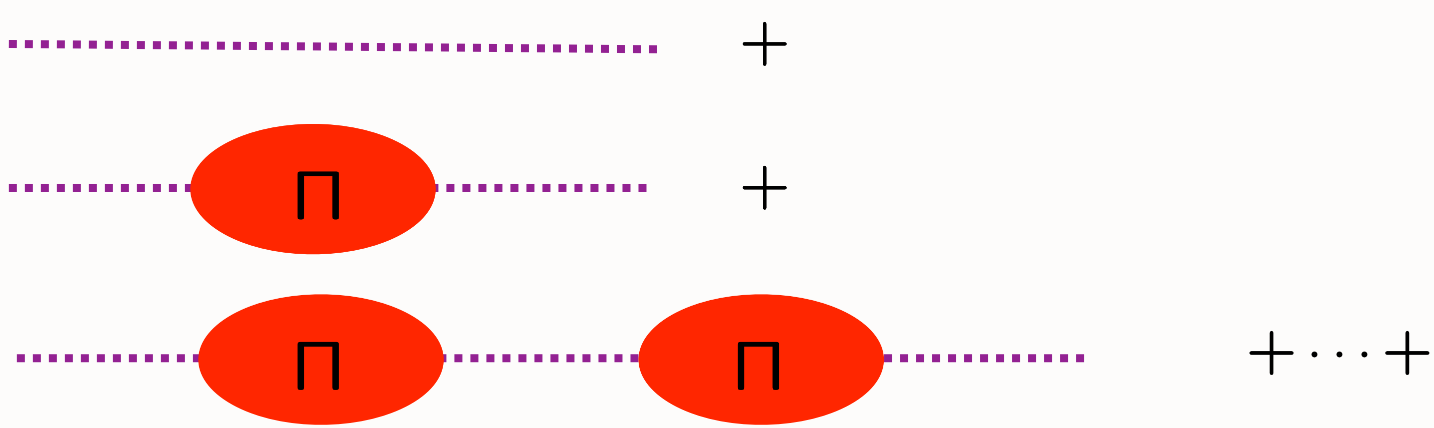
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell-Mann--Low Effective Charge

QED Effective Charge

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

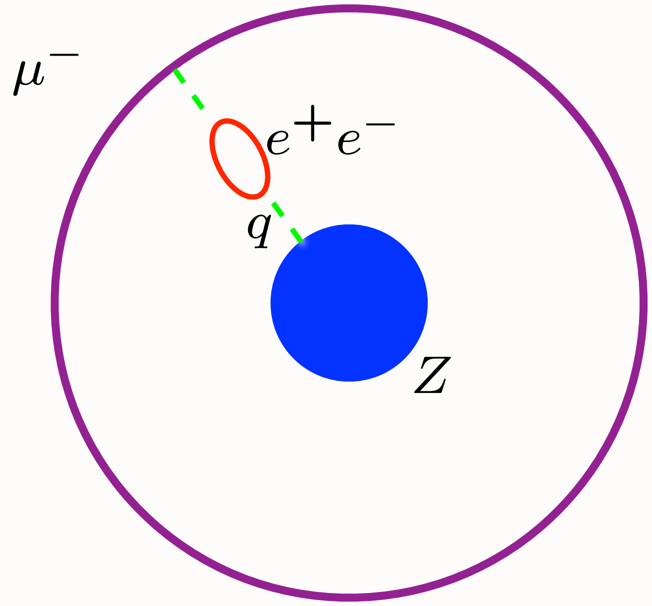
All-orders lepton-loop corrections to dressed photon propagator



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

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

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 μ Pb

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 with an arbitrary range
- Factorization scale should be taken equal to renormalization scale

$$\mu_F = \mu_R$$

Guessing the scale: Wrong in QED. Scheme dependent!

Features of BLM/PMC 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, Mojaza, 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**

QCD Observables

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

Scale-Free Conformal Series

Running Coupling Effects

Higher Twist from Hadron Dynamics

Intrinsic Heavy Quarks

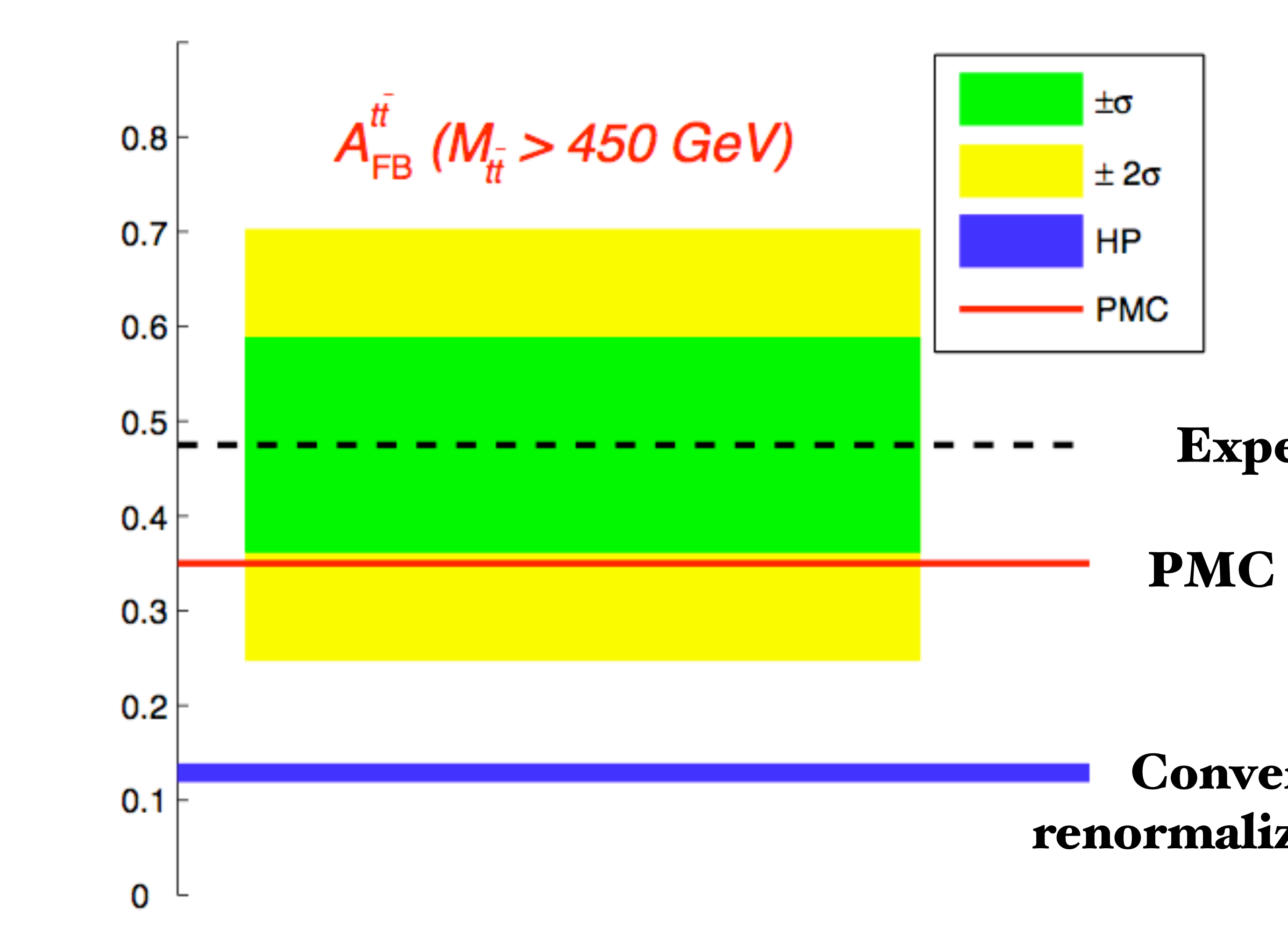
Light by Light Loops

BLM/PMC: Absorb β-terms into running coupling

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

Eliminating the Renormalization Scale Ambiguity for Top-Pair Production Using the 'Principle of Maximum Conformality' (PMC)

Xing-Gang Wu
SJB

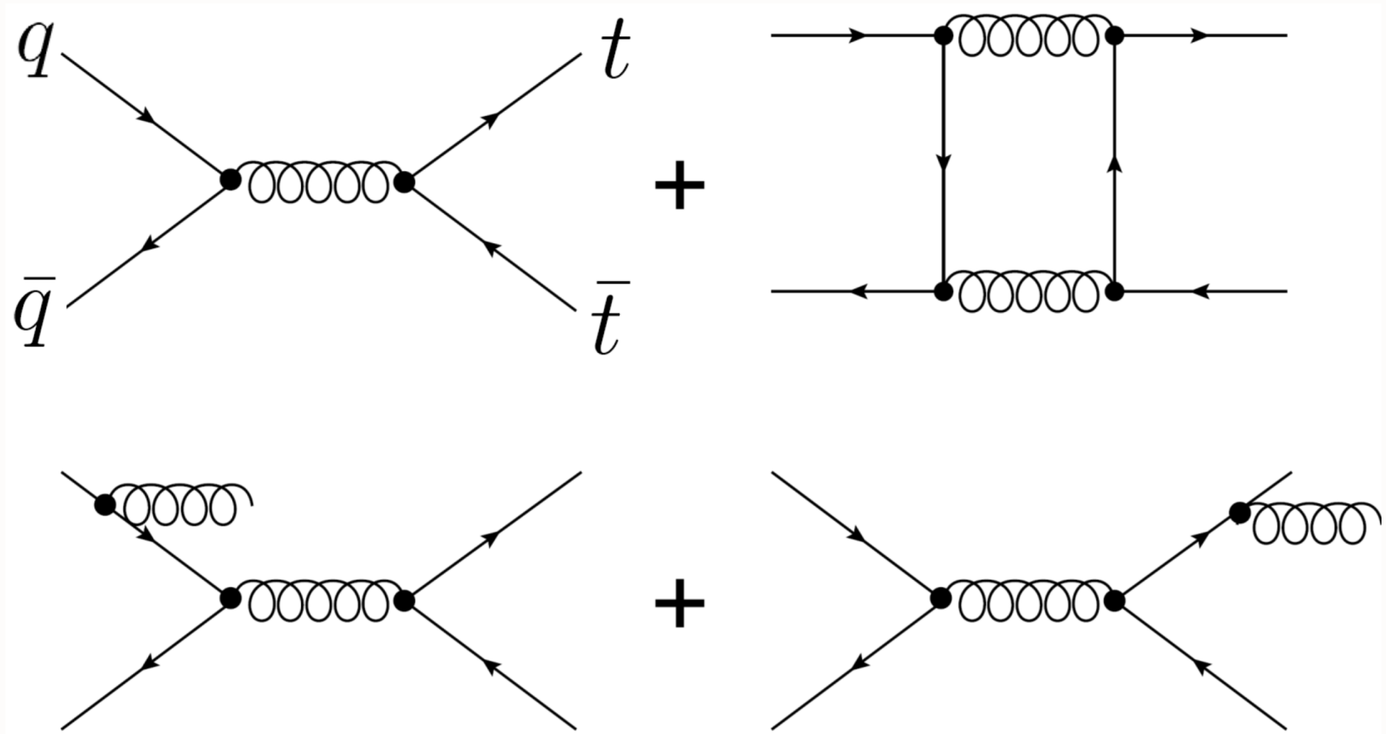


Experimental asymmetry

PMC Prediction

Conventional: guess for renormalization scale and range

$t\bar{t}$ asymmetry predicted by pQCD NNLO within
1 σ of CDF/D0 measurements using PMC/BLM scale setting

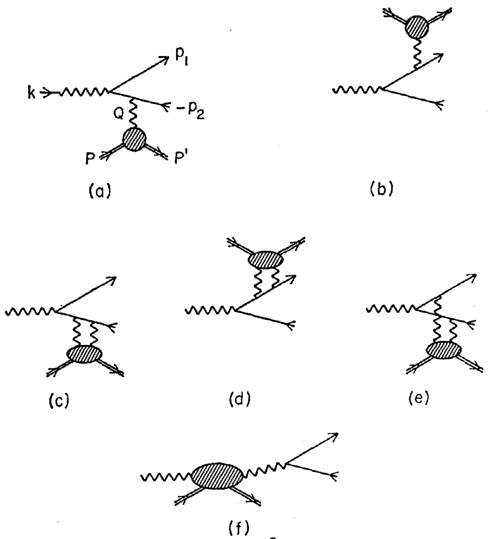


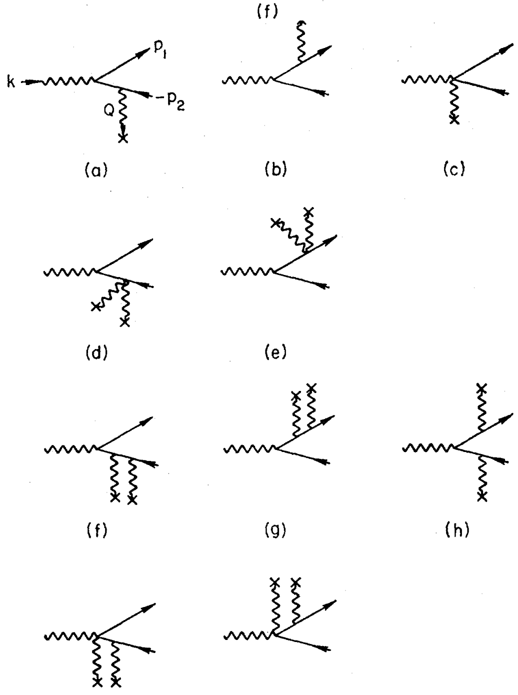
Conventional pQCD approach

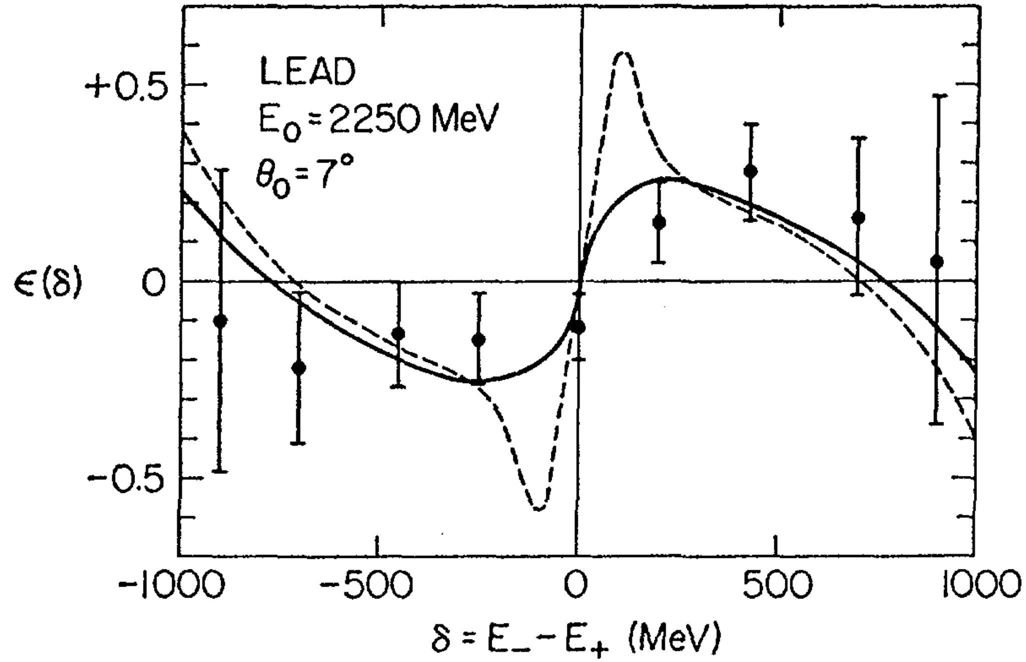
Second Born Corrections to Wide-Angle High-Energy Electron Pair Production and Bremsstrahlung*

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.

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

(spin zero, point nucleus). (4.9)

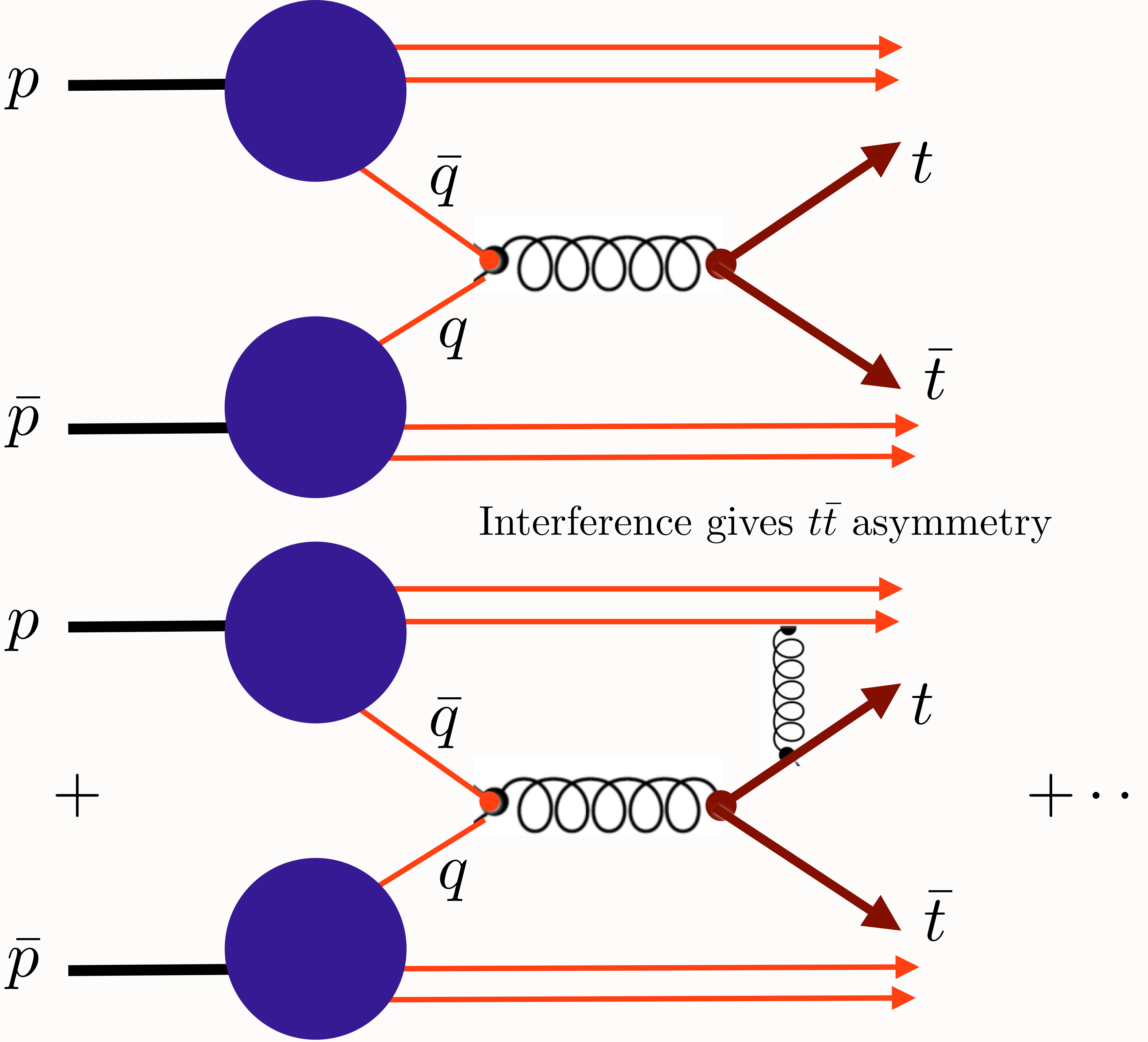
QCD Analysis of heavy quark asymmetries

B. von Harling, Y. Zhao, sjb

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

$$\pi Z\alpha \rightarrow \pi C_F \alpha_s$$

- **Renormalization scale relatively soft**



p
$\bar{q}$
t
q
$\bar{t}$
$\bar{p}$
Interference gives $t\bar{t}$ asymmetry
p
$\bar{q}$
t
$+$
$+\cdots$
q
$\bar{t}$
$\bar{p}$

QCD Analysis of heavy quark asymmetries

B. von Harling, Y. Zhao, sjb

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- **Renormalization scale relatively soft**

$$H_{QCD}^{LF}$$

QCD Meson Spectrum

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

Coupled Fock states

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

Effective two-particle equation

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

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

Azimuthal Basis ζ, ϕ

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

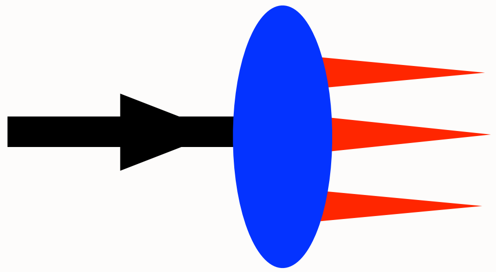
Confining AdS/QCD potential

Semiclassical first approximation to QCD

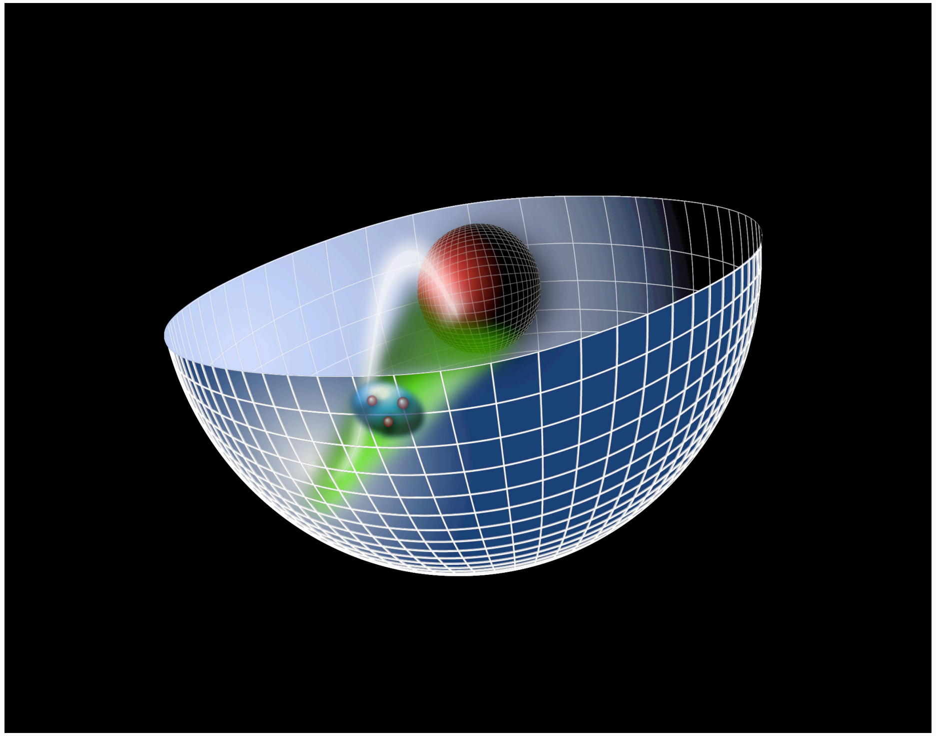
Light-Front Holography and Non-Perturbative QCD

Goal:
Use AdS/QCD duality to construct a first approximation to QCD

Hadron Spectrum
Light-Front Wavefunctions,
Running coupling in IR



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



in collaboration with
Guy de Teramond

Direct Mapping of the 5th Dimension of AdS Space to Physical Space-Time at Fixed Light-Front Time

Light-Front Schrödinger Equation

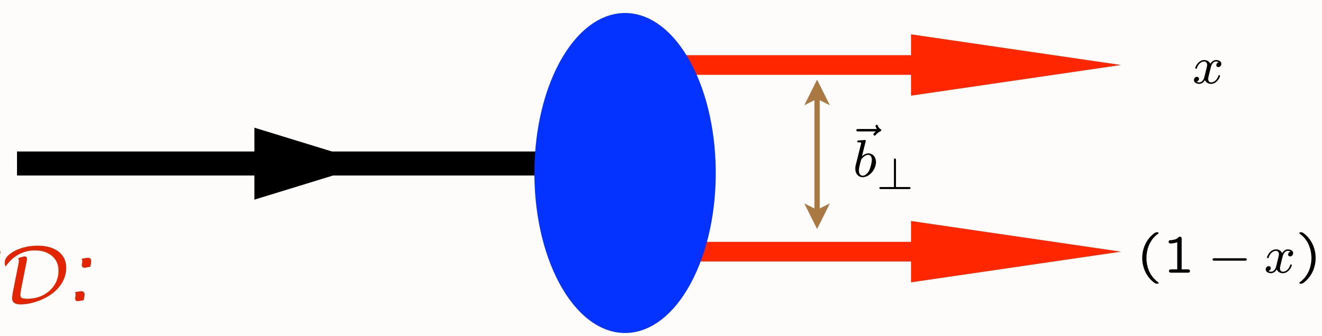
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

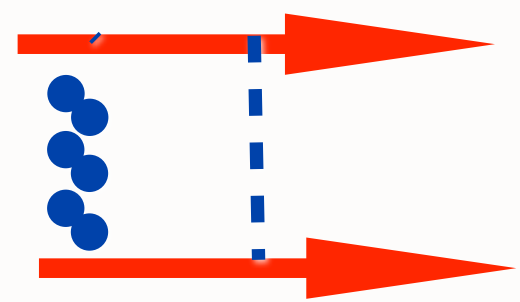
$$[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{\zeta^2} + U(\zeta, S, L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

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



AdS/QCD:

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



U is the exact QCD potential
Conjecture: 'H'-diagrams generate U

Quark separation increases with L

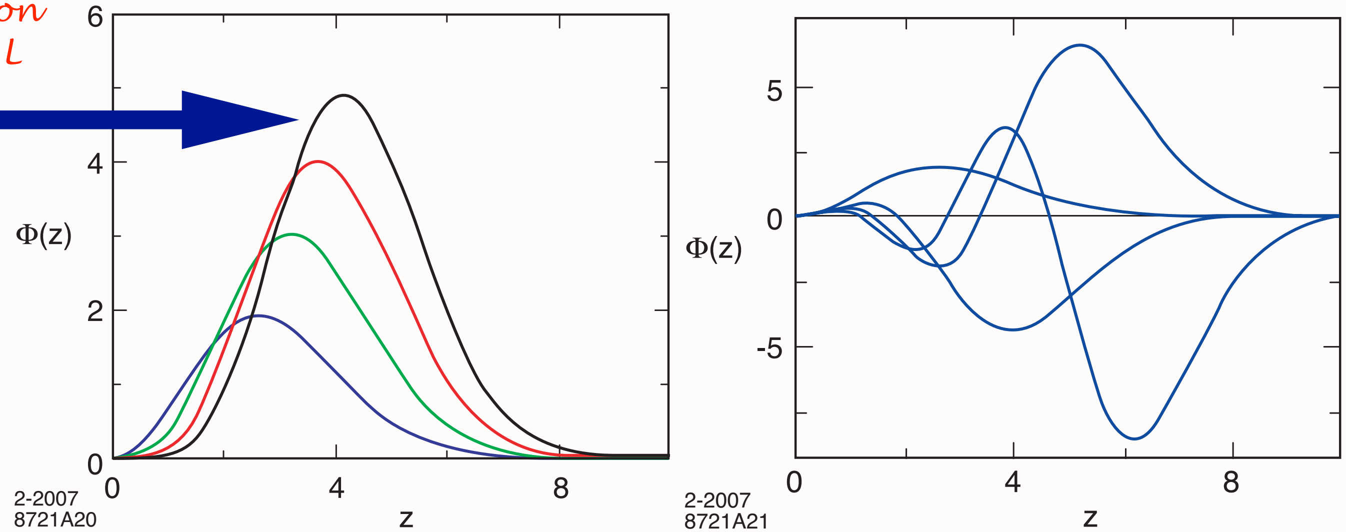
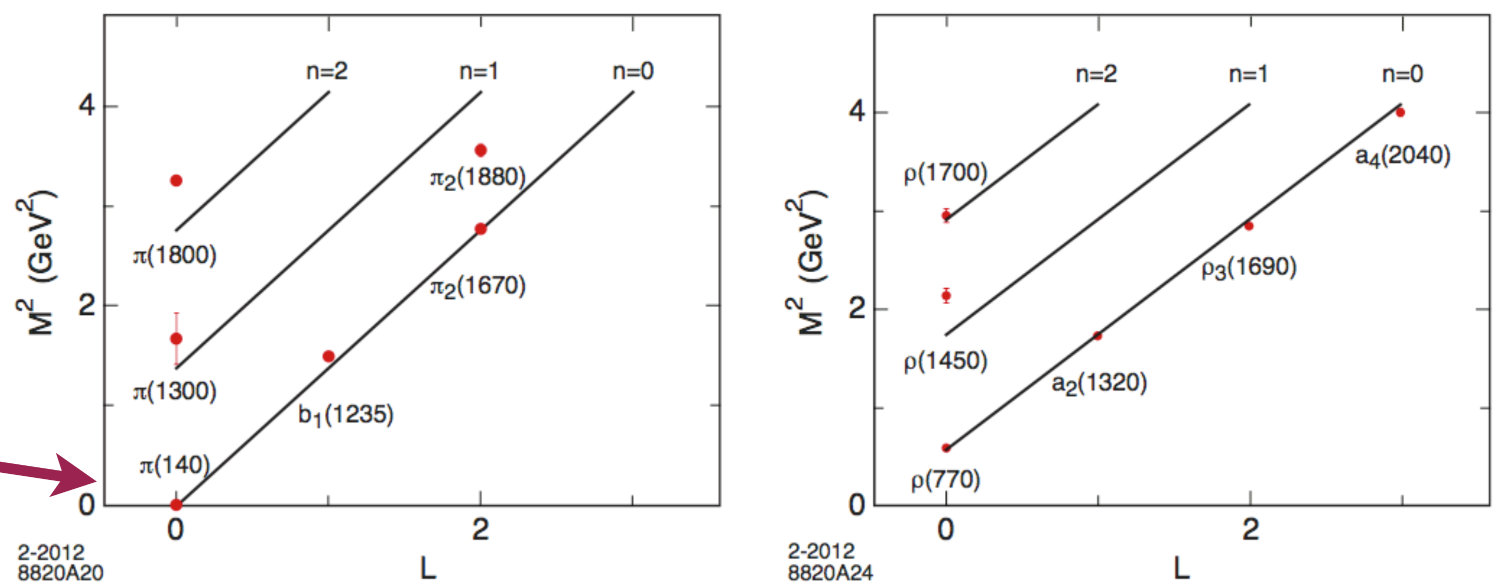


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Pion has zero mass!

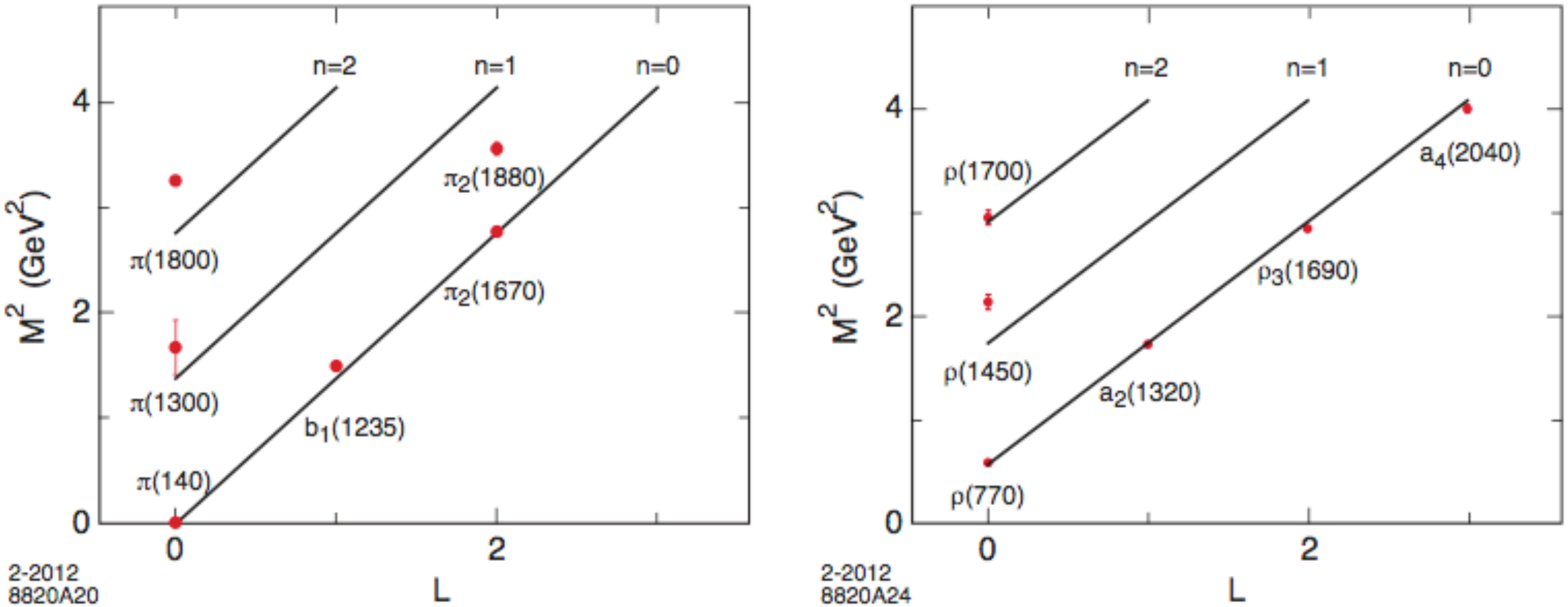


Orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ I=1meson families ($\kappa = 0.54$ GeV)

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

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

Same slope in n and L



I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

- Triplet splitting for the $I = 1, L = 1, J = 0, 1, 2$, vector meson a-states

$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

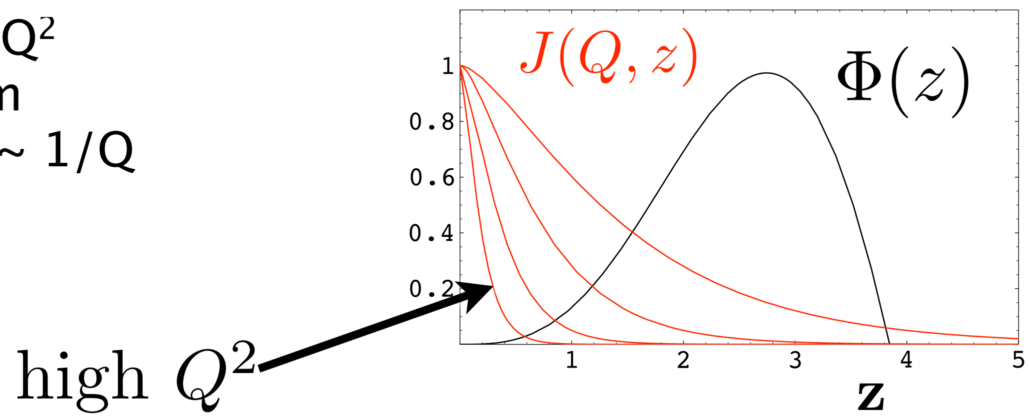
Hadron Form Factors from AdS/CFT

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, Φ 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, $\tau = n$.

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.

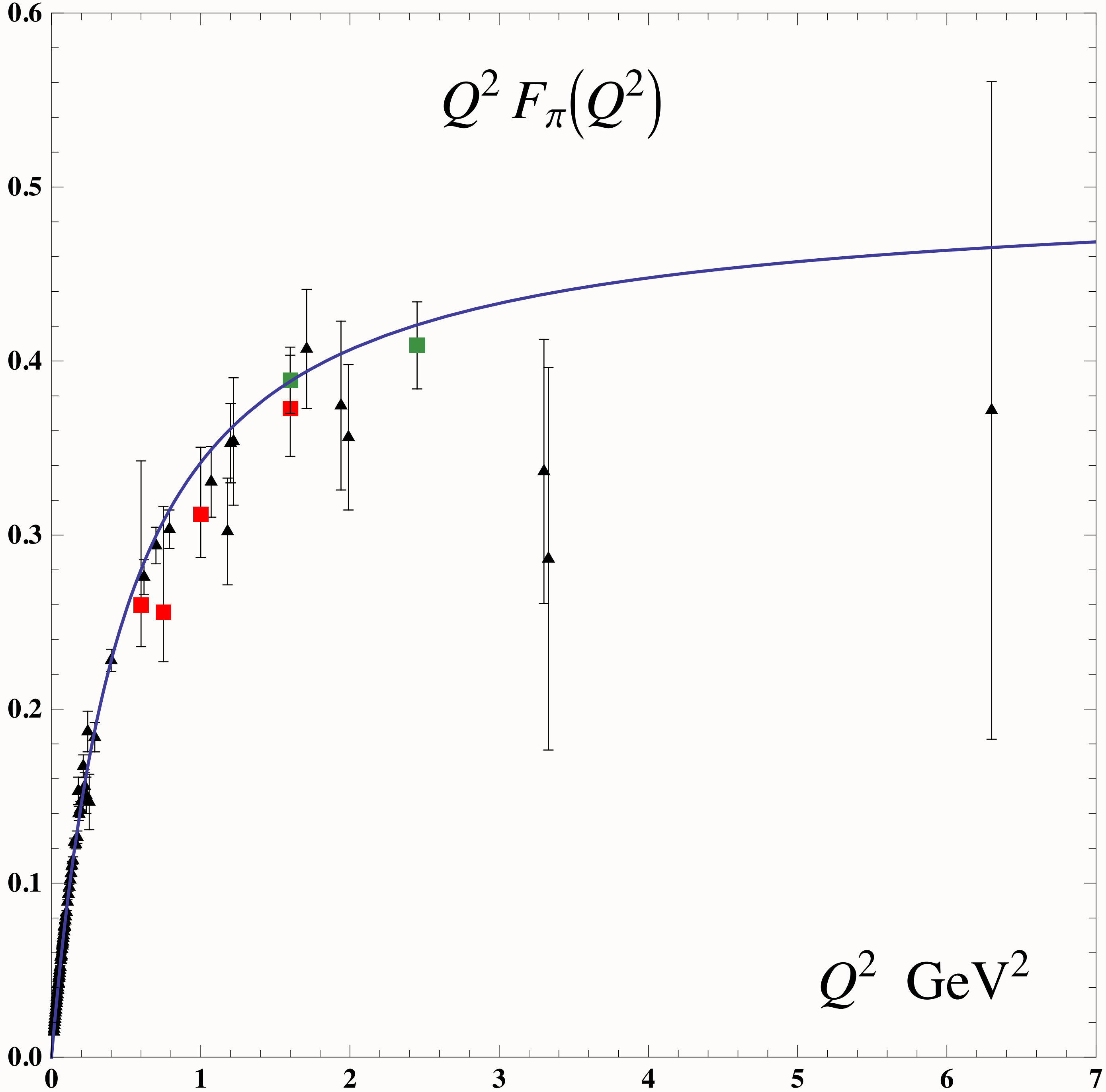
- Transversality variable

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

- 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 $J(Q,\zeta) = \zeta Q K_1(\zeta Q)$!


$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7

Current Matrix Elements in AdS Space (SW)

sjb and GdT
Grigoryan and Radyushkin

- Propagation of external current inside AdS space described by the AdS wave equation

$$\left[z^2\partial_z^2 - z\left(1 + 2\kappa^2 z^2\right)\partial_z - Q^2 z^2\right] J_\kappa(Q,z) = 0.$$

- Solution bulk-to-boundary propagator

$$J_\kappa(Q,z) = \Gamma\left(1 + \frac{Q^2}{4\kappa^2}\right) U\left(\frac{Q^2}{4\kappa^2}, 0, \kappa^2 z^2\right),$$

where $U(a,b,c)$ is the confluent hypergeometric function

$$\Gamma(a)U(a,b,z) = \int_0^\infty e^{-zt} t^{a-1}(1+t)^{b-a-1} dt.$$

Soft Wall Model

- Form factor in presence of the dilaton background $\varphi = \kappa^2 z^2$

$$F(Q^2) = R^3 \int \frac{dz}{z^3}\, e^{-\kappa^2 z^2} \Phi(z) J_\kappa(Q,z) \Phi(z).$$

- For large $Q^2 \gg 4\kappa^2$

$$J_\kappa(Q,z) \to zQK_1(zQ) = J(Q,z),$$

the external current decouples from the dilaton field.

Note: Analytical Form of Hadronic Form Factor for Arbitrary Twist

- Form factor for a string mode with scaling dimension τ, Φ_τ 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 $\tau = N, \quad \Gamma(N+z) = (N-1+z)(N-2+z)\ldots(1+z)\Gamma(1+z).$

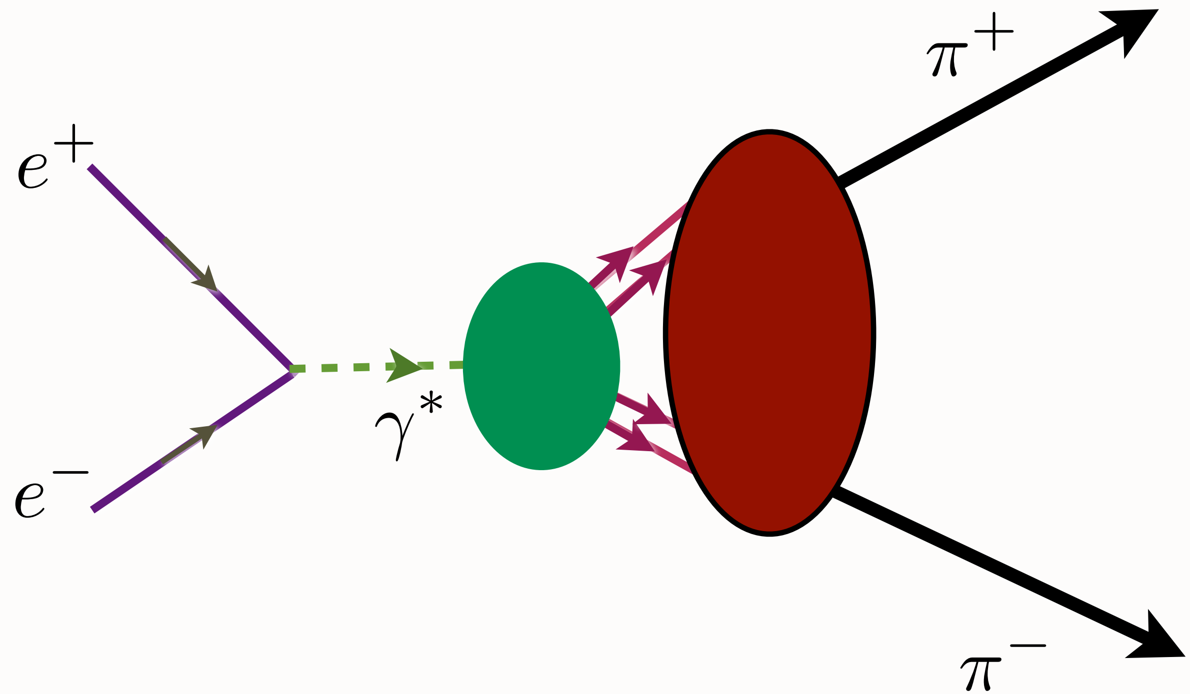
- Form factor expressed as $N-1$ product of poles

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

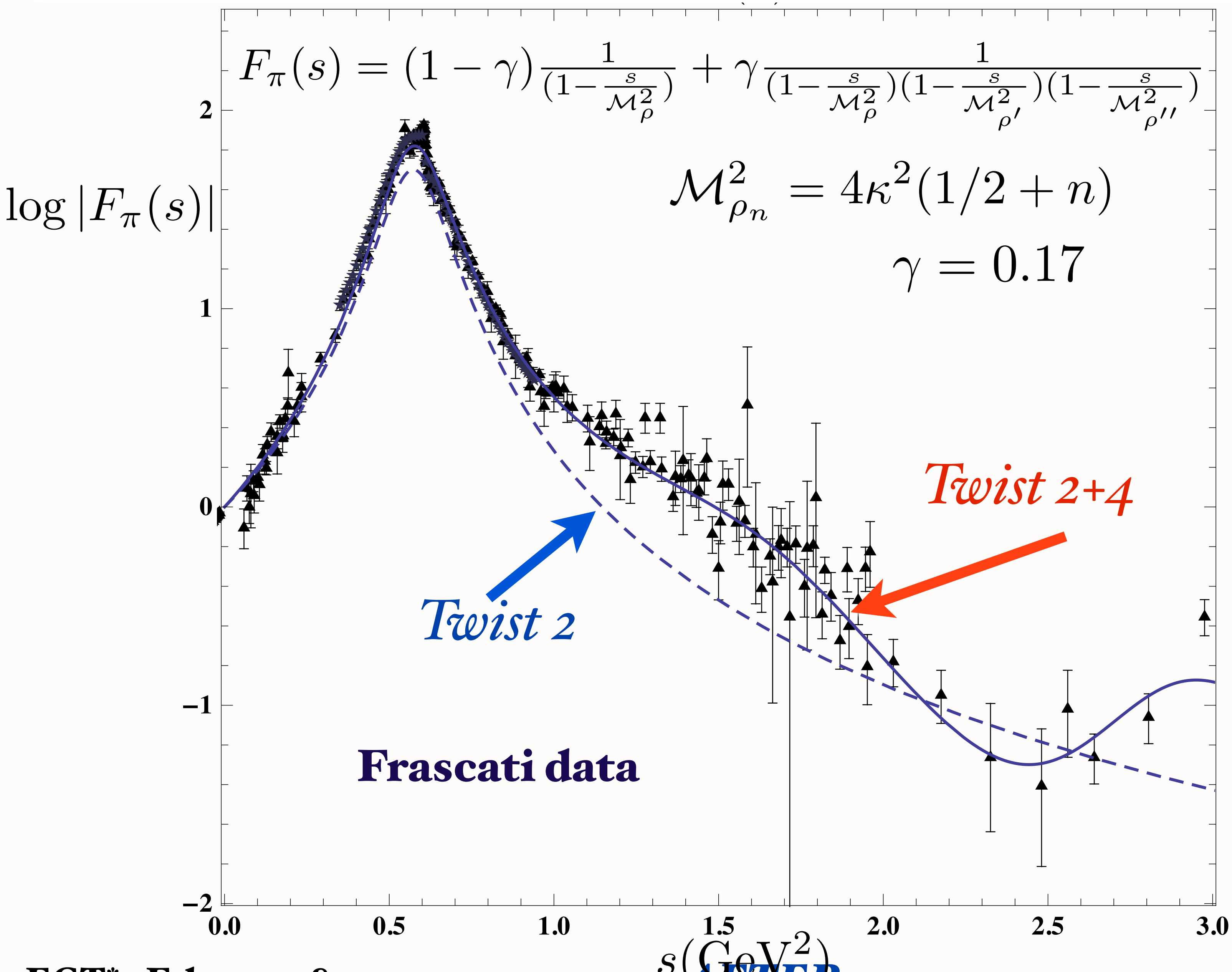
- For large Q^2:

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

Dressed soft-wall current brings in higher Fock states and more vector meson poles



Timelike Pion Form Factor from AdS/QCD and Light-Front Holography



Prescription for Timelike poles :

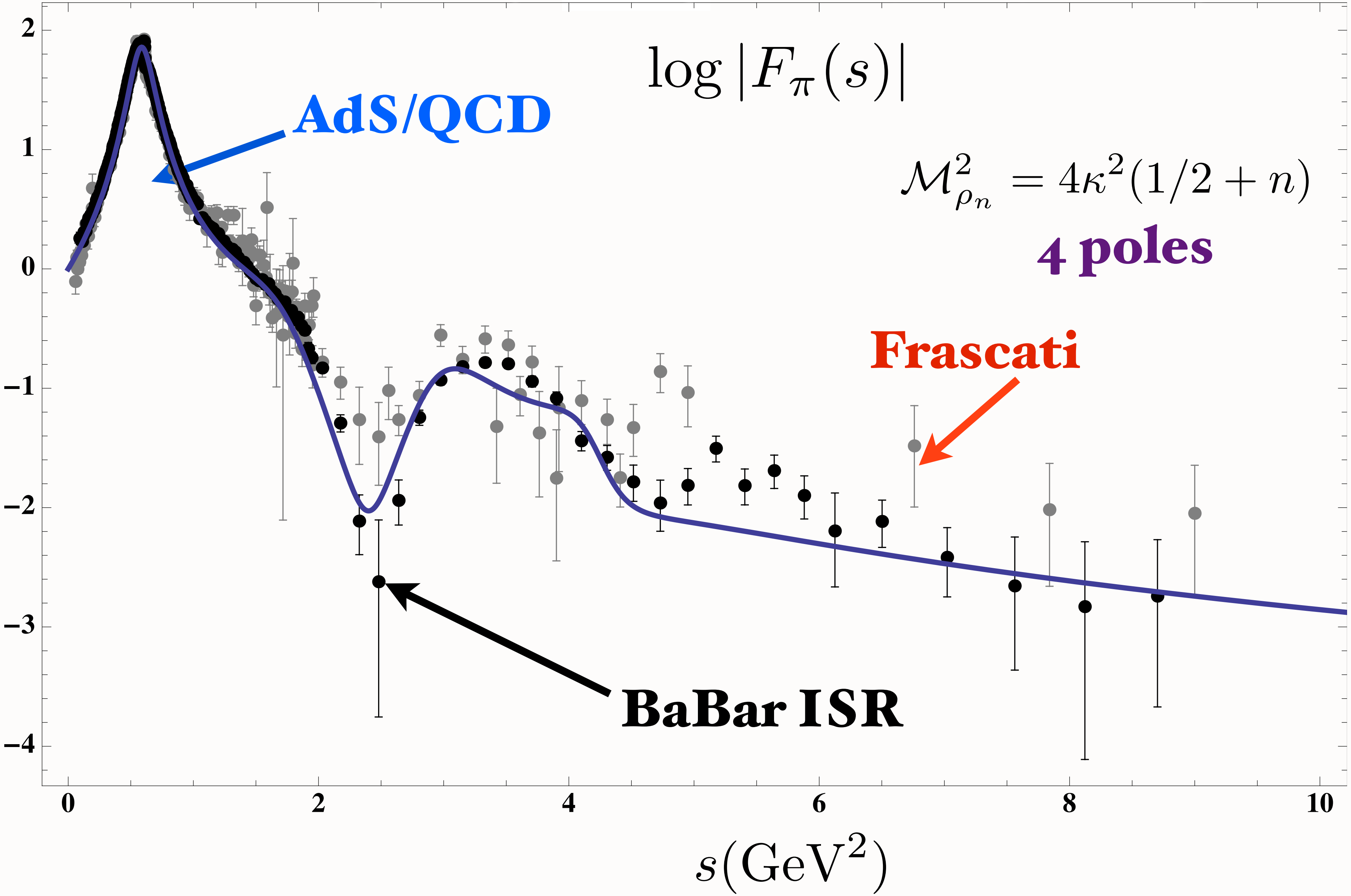
$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

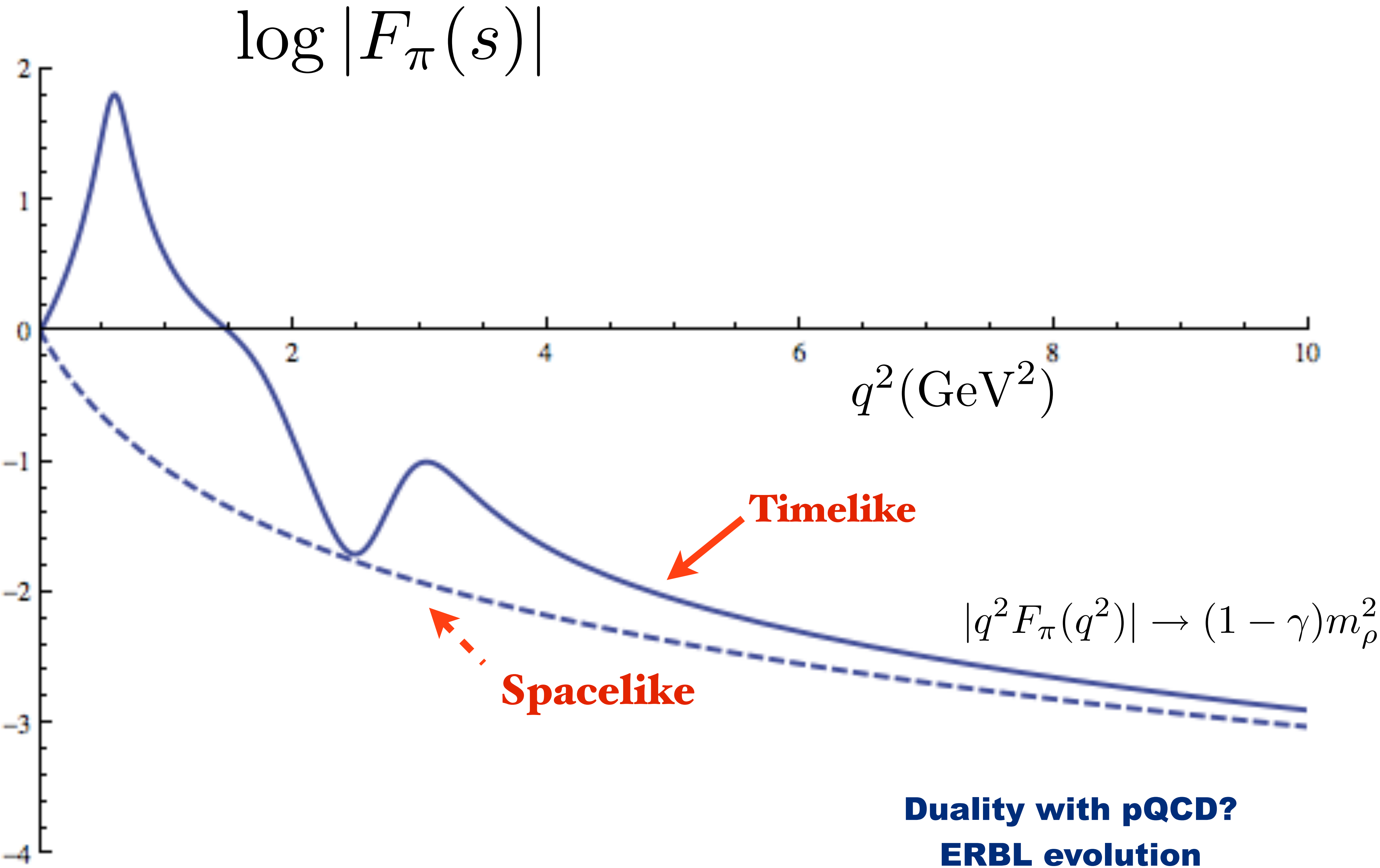
14% four-quark probability

AFTER

G. de Teramond & sjb

Pion Timelike Form Factor (Includes Twist 2 to 5)




$\log|F_\pi(s)|$
2
1
0
−1
−2
−3
−4
2
4
6
8
10
$q^2(\mathrm{GeV}^2)$
Timelike
Spacelike
$|q^2F_\pi(q^2)| \to (1-\gamma)m_\rho^2$
Duality with pQCD?
ERBL evolution

Fixed-Target Physics with the LHC Beams

AFTER @ LHC

- 7 TeV proton beam, 3 TeV nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations
- Sterile Neutrinos -- Dark Matter Candidates
- Single-Spin Asymmetries, Transversity Studies, A_N
- High-x_F Dynamics --Correlations, Diffraction
- High-x_F Heavy Quark and quarkonium phenomena
- Production of ccq to ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System:
  e.g. Ridge Physics at Extreme Rapidities
- Anti-Shadowing: Flavor Specific?
- Higgs at Threshold using nuclear Fermi motion

High x_F at AFTER

- Drell Yan at high x_F
- W, Z
- Structure Functions at High x
- Direct Processes
- Polarization Correlations
- Intrinsic Heavy Quark Studies
- Diffractive Channels
- Proton Diffraction to 3 Jets
- Quarkonium Dynamics
- Open Flavor, B and D

Novel Physics at AFTER,

- **Secondary Beams: Pions Kaons, Muons, even B and D**
- **Pion Exchange: Effective Pion Collisions**
- **Deuteron Target: Hidden Color**
- **Spin-Correlations with Polarized Targets**
- **Huge single spin asymmetries at high xF**
- **pA to Quarkonium -- non-factorizing nuclear dependence**
- **Breakdown of Factorization: Double Boer-Mulders**
- **Photon plus Heavy Quark Anomalies**
- **Shadowing, Antishadowing**
- **Odderon Search**

Fixed Target Physics with the LHC Beams

AFTER @ LHC

- Many Novel QCD Effects never thoroughly investigated
- "Lensing" Effects: Exceptions to Factorization Theorems
- Violation of Scaling Laws
- Dynamic versus Static Structure Functions
- Production of charm, bottom and exotics
- Novel Nuclear Dynamics
- Novel Diffractive Processes
- High Rapidity: Maximal Spin, Flavor Correlations
- High AFTER energy domain well-matched to QCD

Nuclear Collisions with AFTER

- **Nucleus-Nucleus and Proton-Nucleus Scattering in Lab Frame Look at Target Fragmentation Region $x_F=-1$**
- **What happens to Target Nucleus when QGP is formed?**
- **pp pA AA Ridge at extreme rapidity**
- **What are the critical parameters for the onset of QGP**
- **Light-Front Description: Frame-Independent**
- **Use Fool's ISR Frame -- No Lorentz Contraction of LFWF**
- **Energy Loss Studies, LPM, Non-Abelian**
- **Quarkonium Production, Polarization**
- **Open charm, bottom**

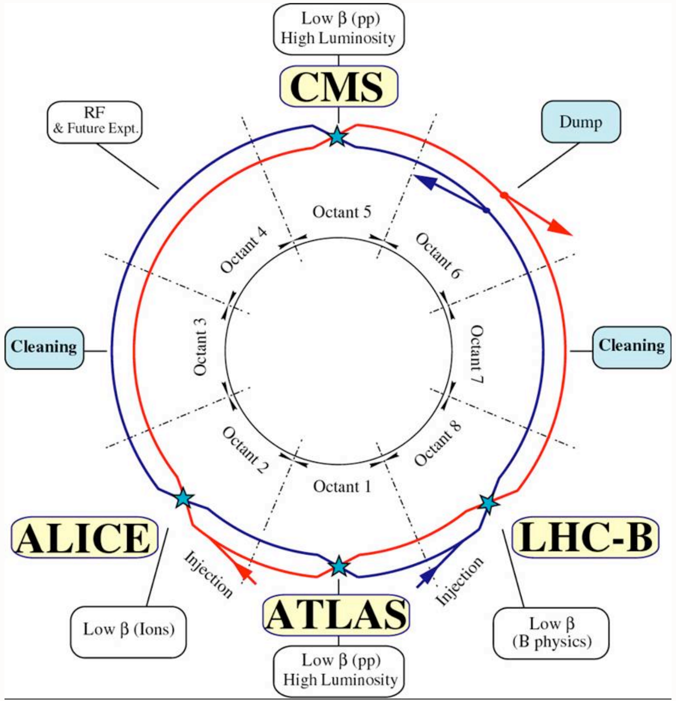
QCD Myths

- 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

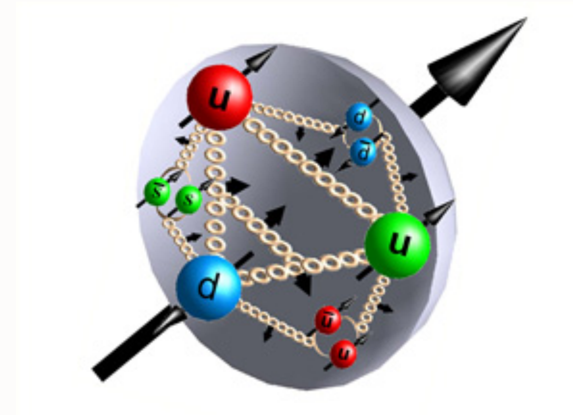
Physics Flagships for **AFTER***:*

F*ixed* **T***arget* **E***xpe***R***iments @ the LHC*

Heavy Quark Physics



AFTER @ LHC



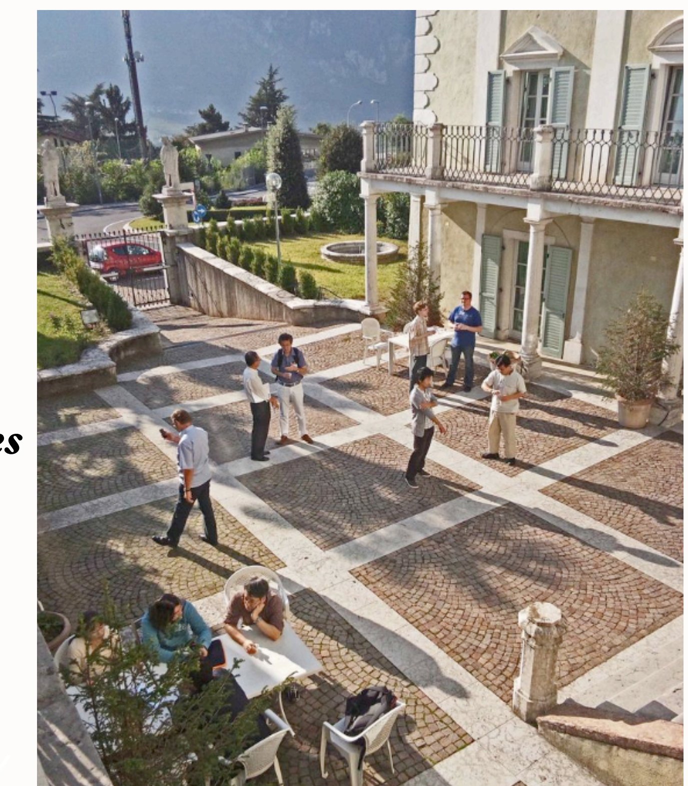
ECT Workshop*

February 4-8, 2013

European Center for Theoretical Studies in Nuclear Physics and Related Areas

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY



Thanks to the France-Stanford Center for Interdisciplinary Studies

Thanks to: J.-P. Lansberg, F. Fleuret