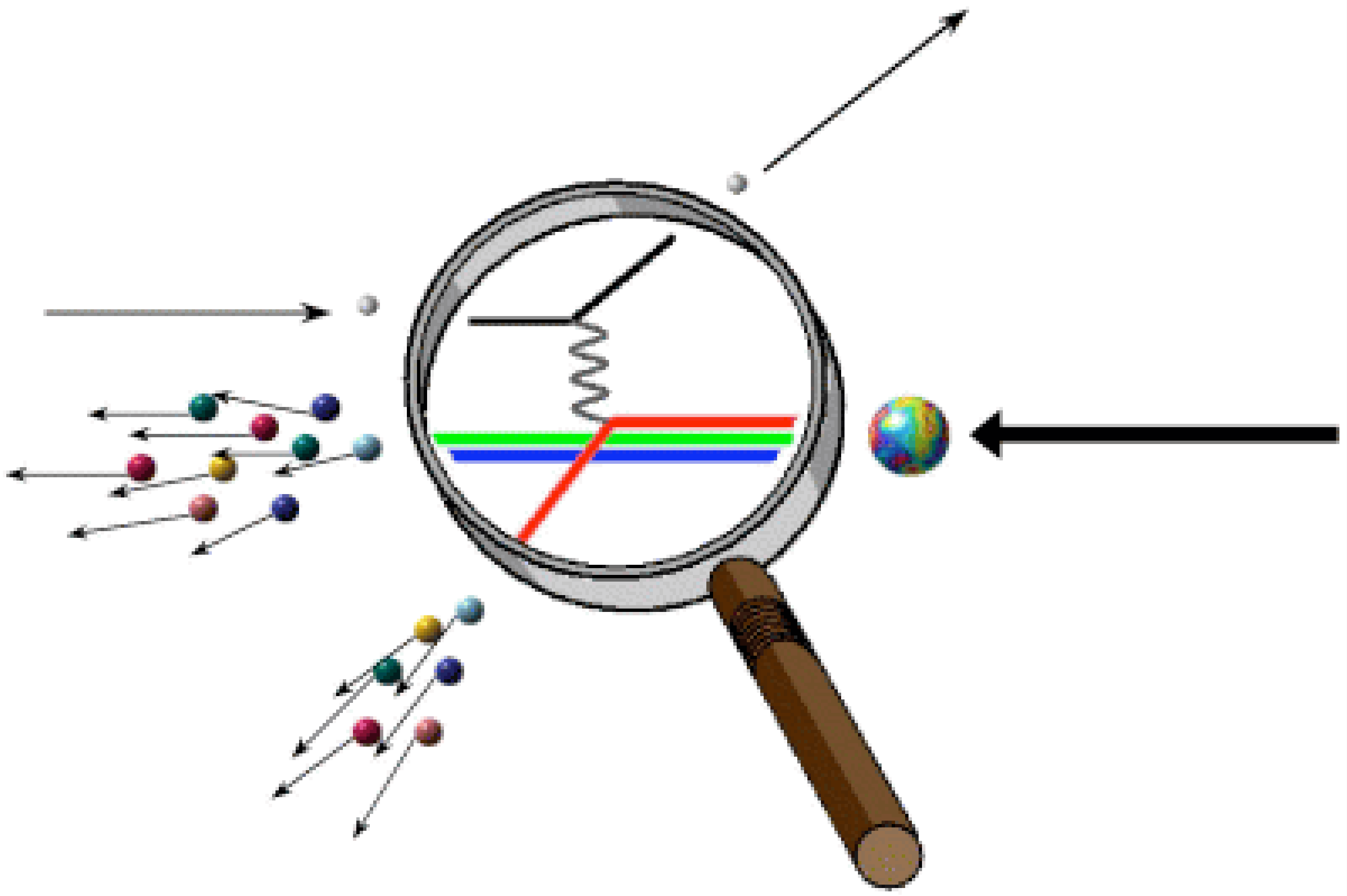
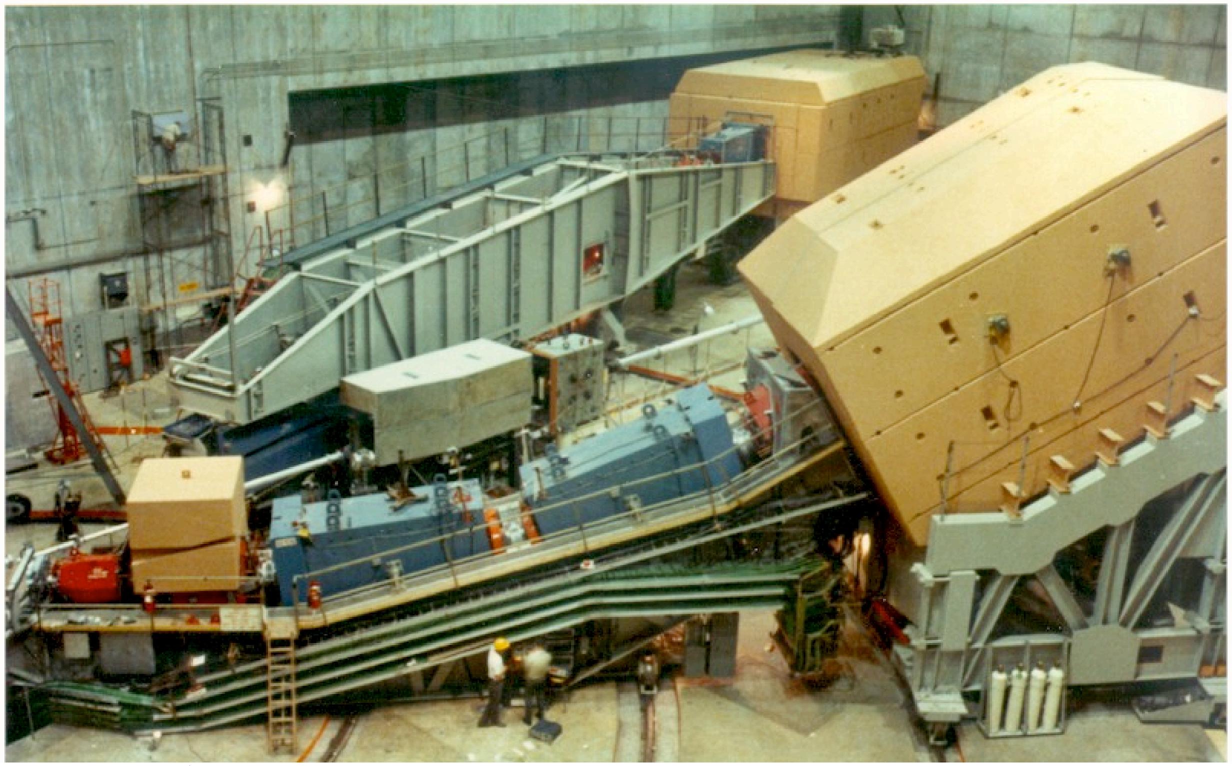
Novel QCD Phenomena at Electron-Proton Colliders

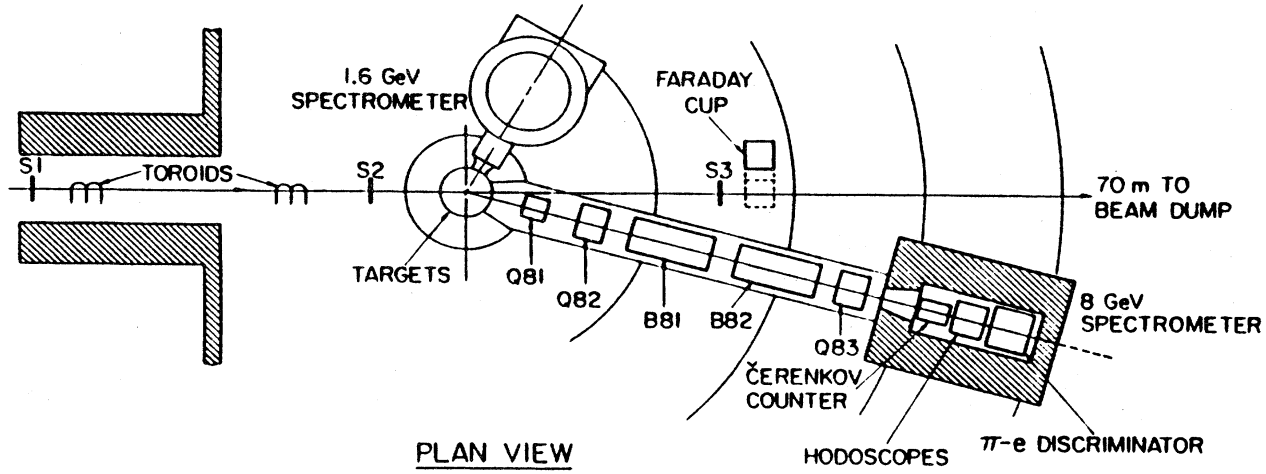
Stan Brodsky, SLAC



SLAC Two-Mile Linear Accelerator



Pief

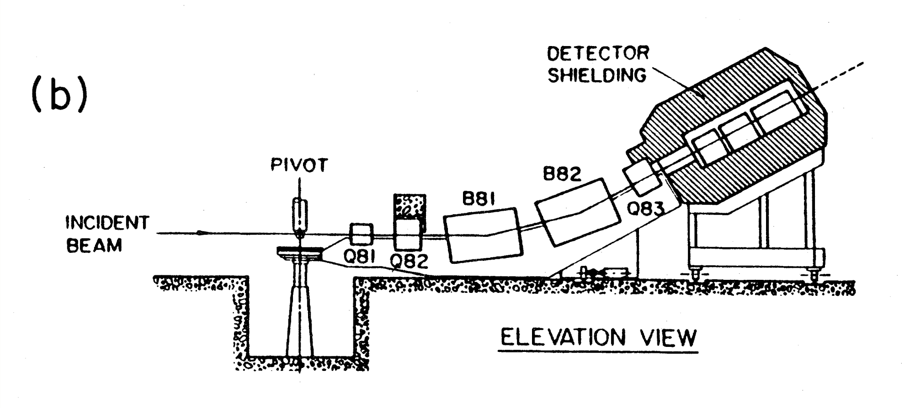


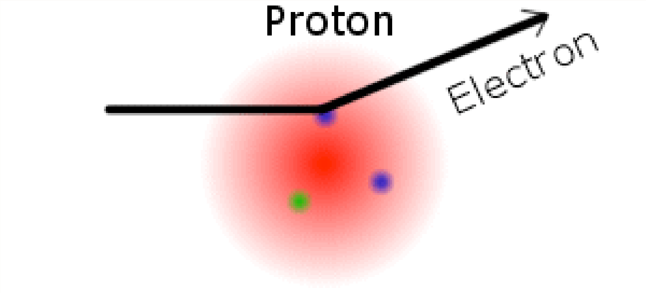
1967 SLAC Experiment:

Scatter 20 GeV/c Electrons on protons
in a Hydrogen Target

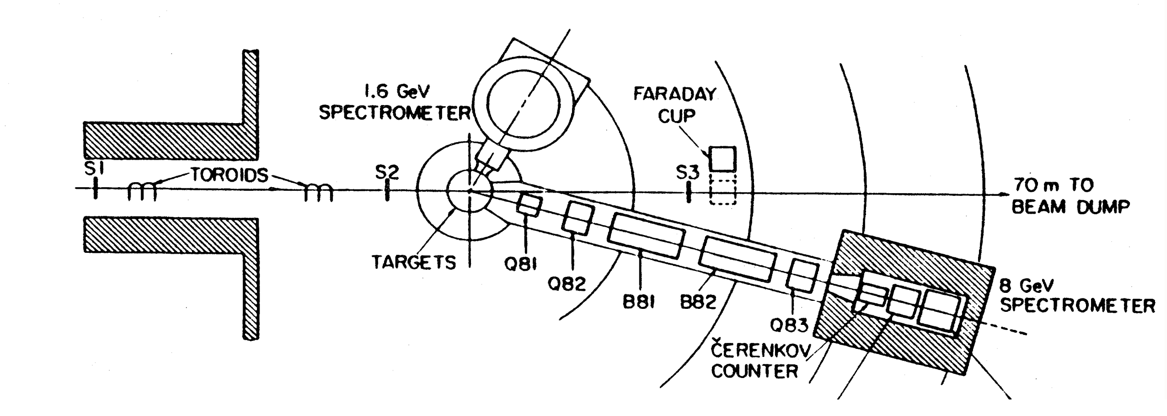
Discovery of the Quark Structure of Matter

$$ep \to e'X$$

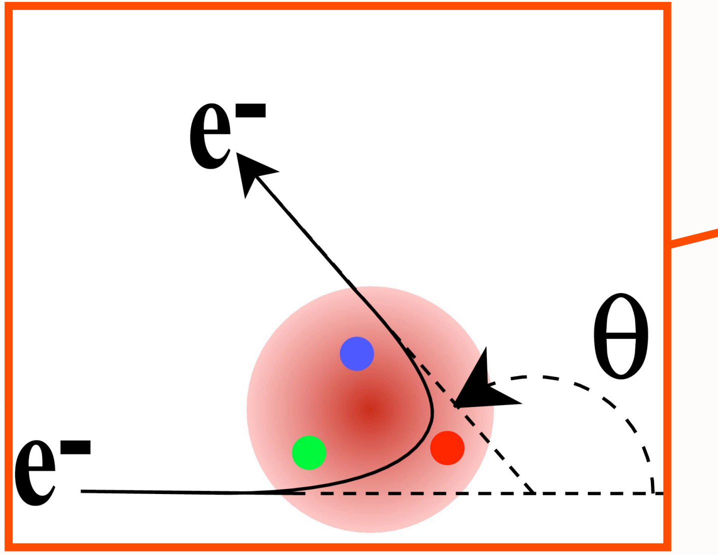




Discovery of quarks!

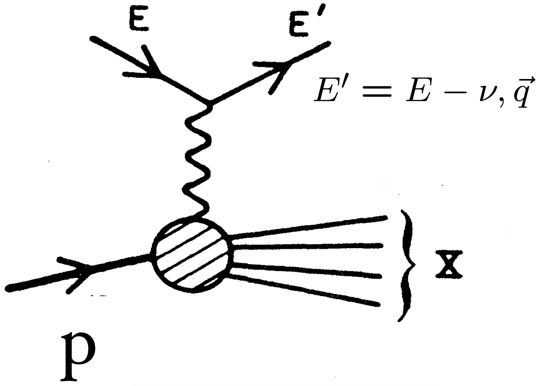


Deep inelastic scattering: Experiments on the proton and the observation of scaling*

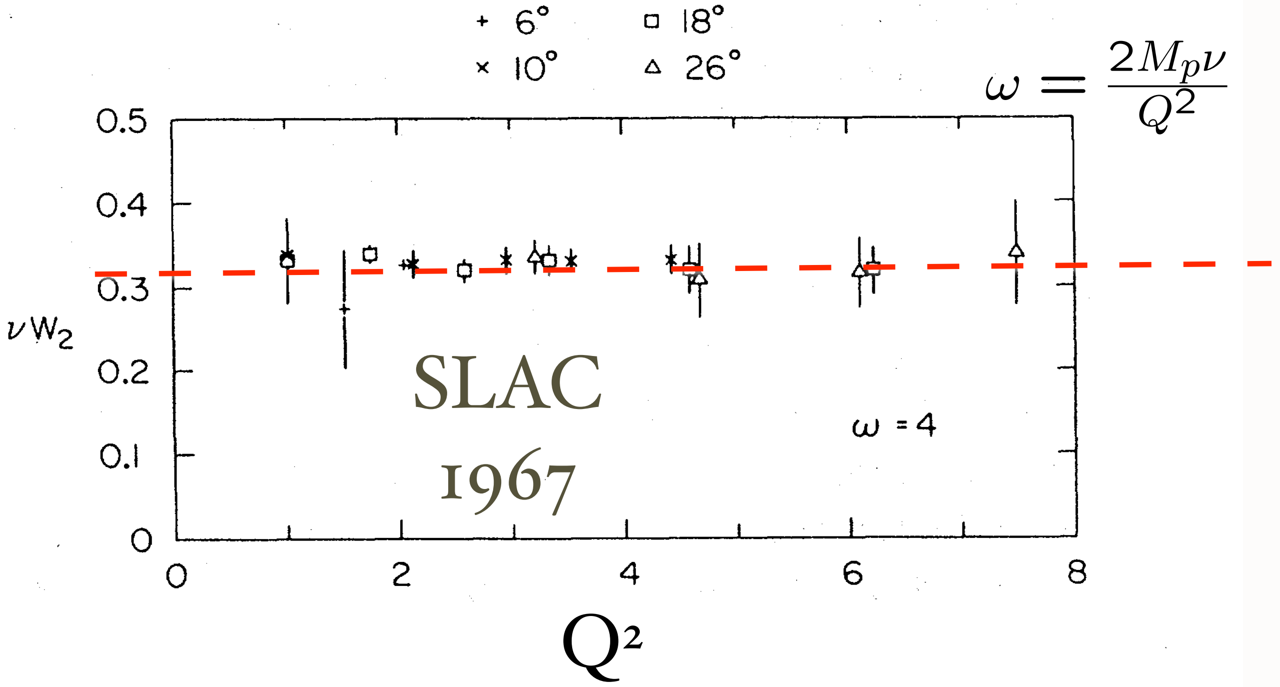


Friedman, Kendall, Taylor: Nobel Prize

$$ep \rightarrow e'X$$



$$Q^2 = \vec{q}^2 - \nu^2$$



$$\omega = \frac{2M_p\nu}{Q^2}$$

No intrinsic length scale !

Measure rate as a function of energy loss ν and momentum transfer Q

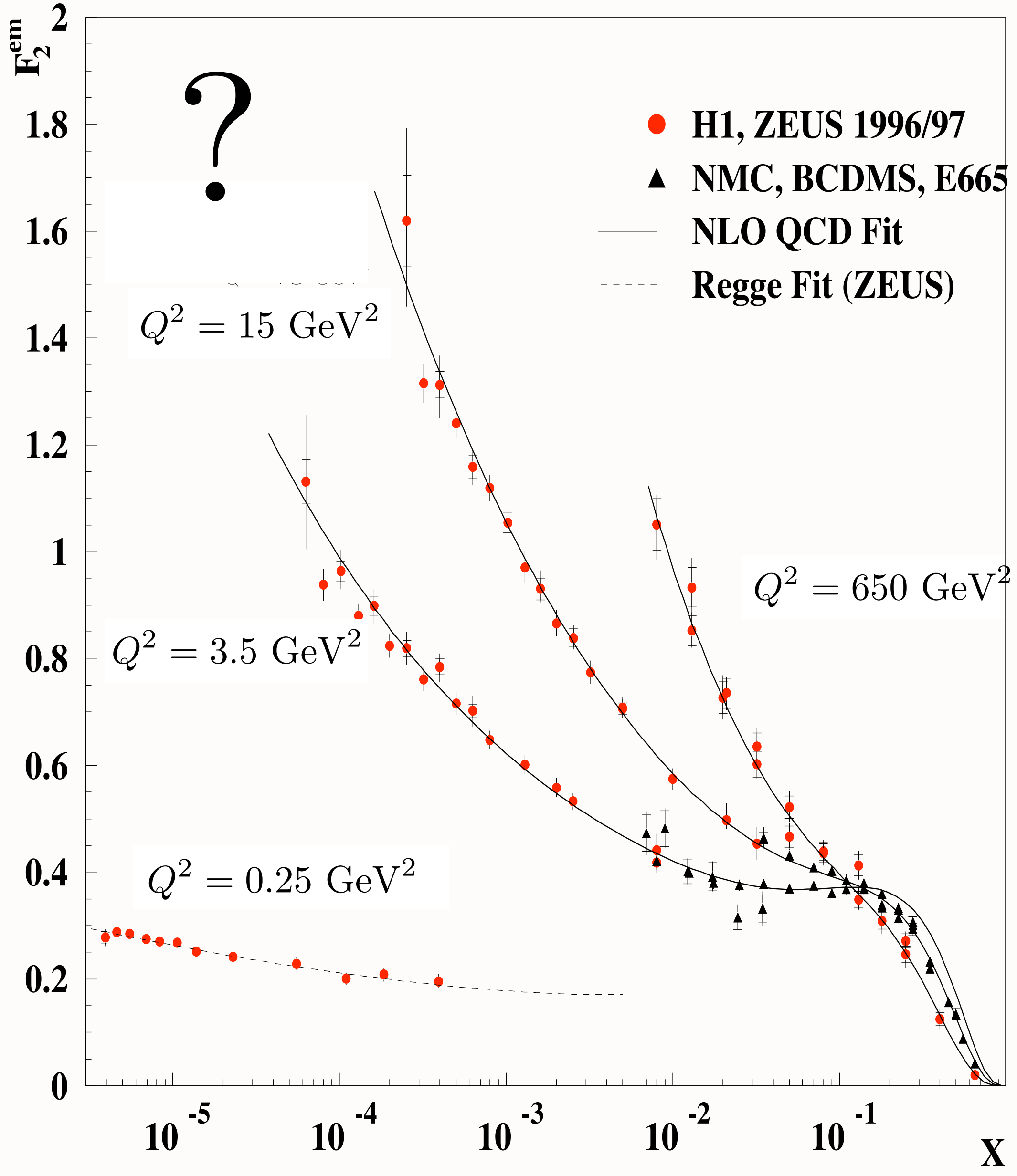
Scaling at fixed $x_{Bjorken} = \frac{Q^2}{2M_p\nu} = \frac{1}{\omega}$

Discovery of Bjorken Scaling

Electron scatters on point-like quarks!

- ***Key Probe of QCD: Lepton-Nucleon, Lepton-Nucleus Scattering***

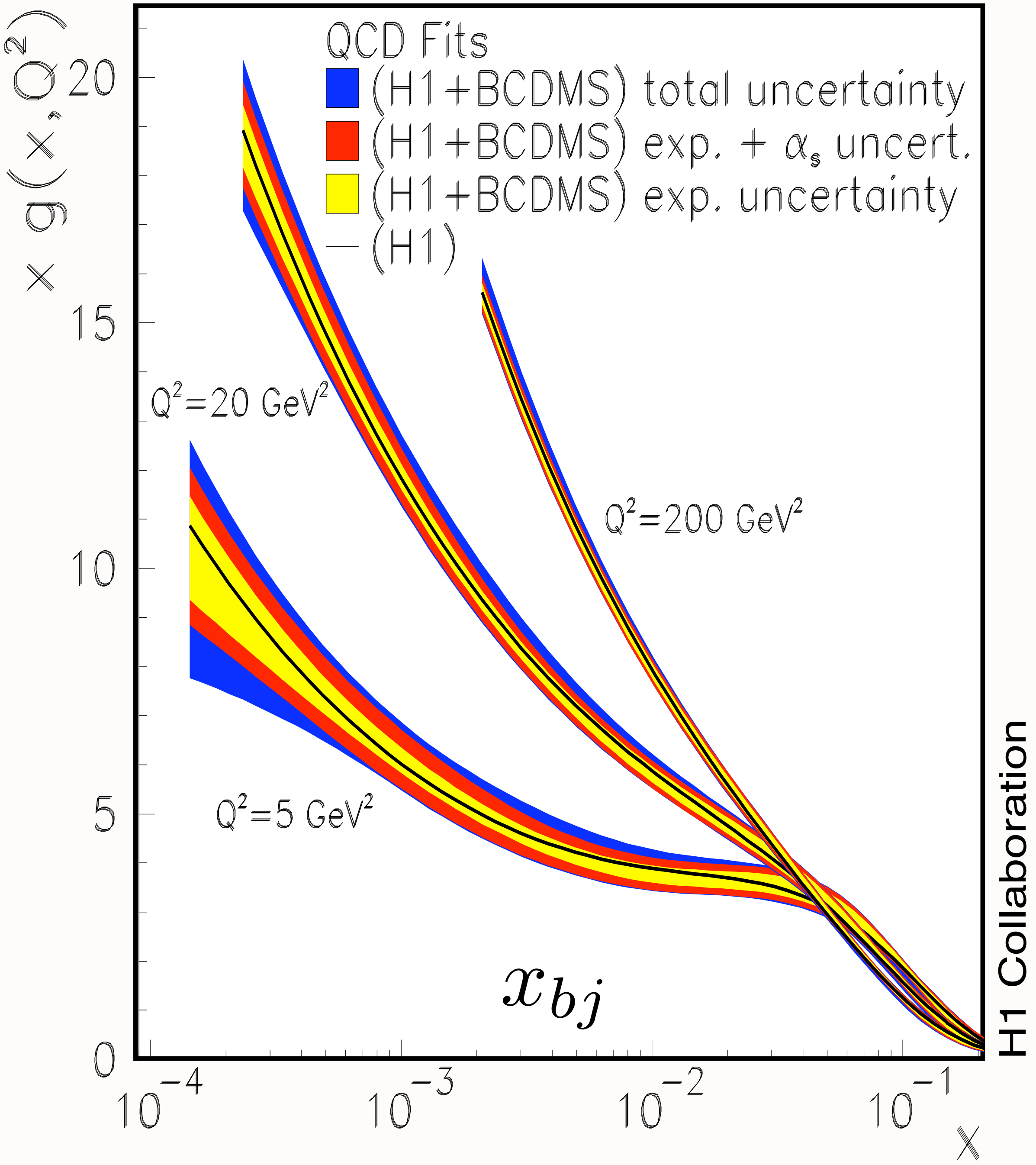
$F_2(x, Q^2)$



Unitarity Bound?

Saturation?

$$xg(x, Q^2)$$



Gluon distribution inferred from charm production, etc.

Two Pictures of High Energy Lepton-Proton Collisions

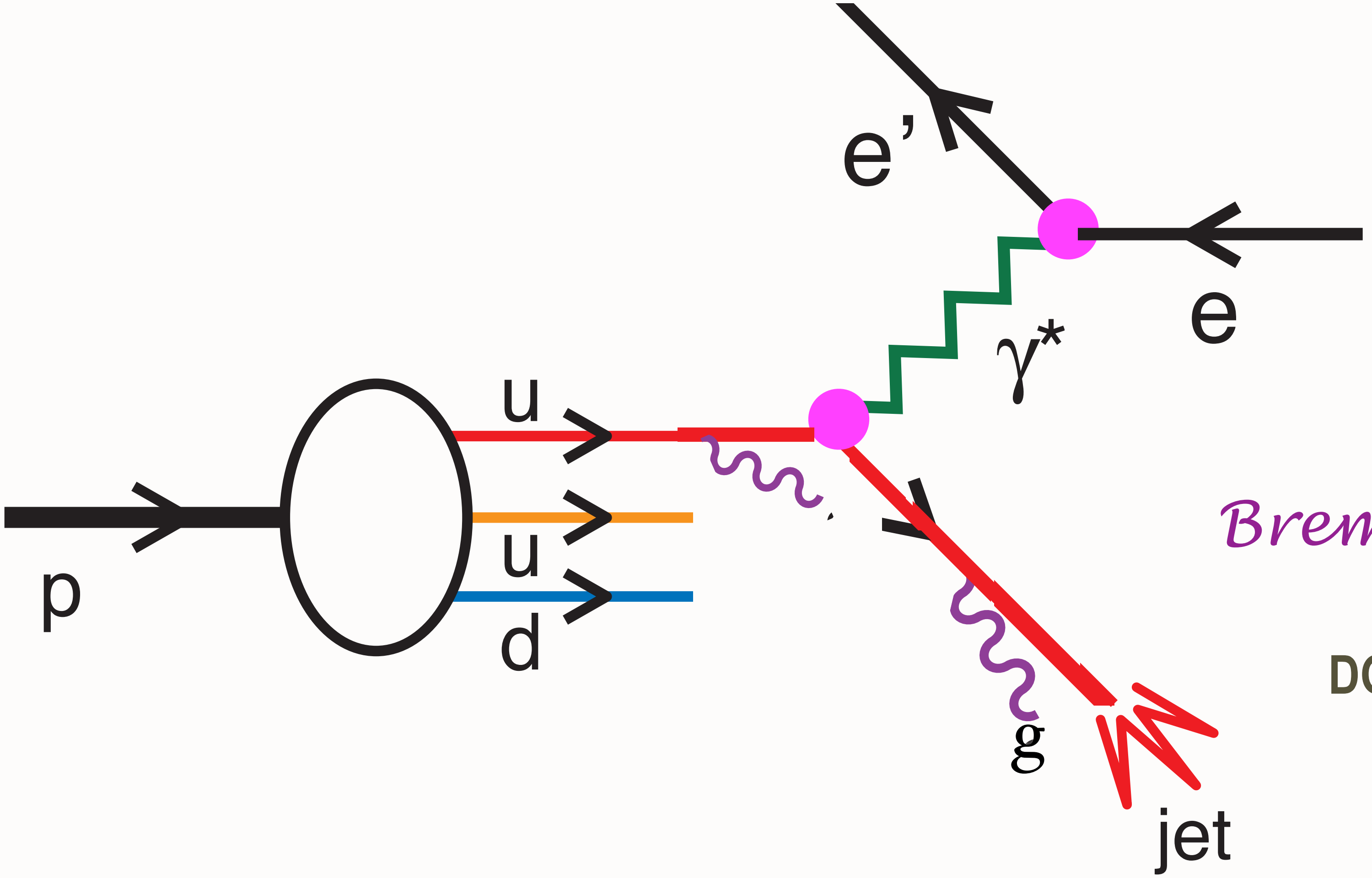
Infinite momentum frame **Parton Model**

Simple Virtual Photon Probes Complex Evolved Proton

Proton Rest Frame **Color-Dipole Model**

Color Dipole of Virtual Photon Scatters on a Complex Static Proton

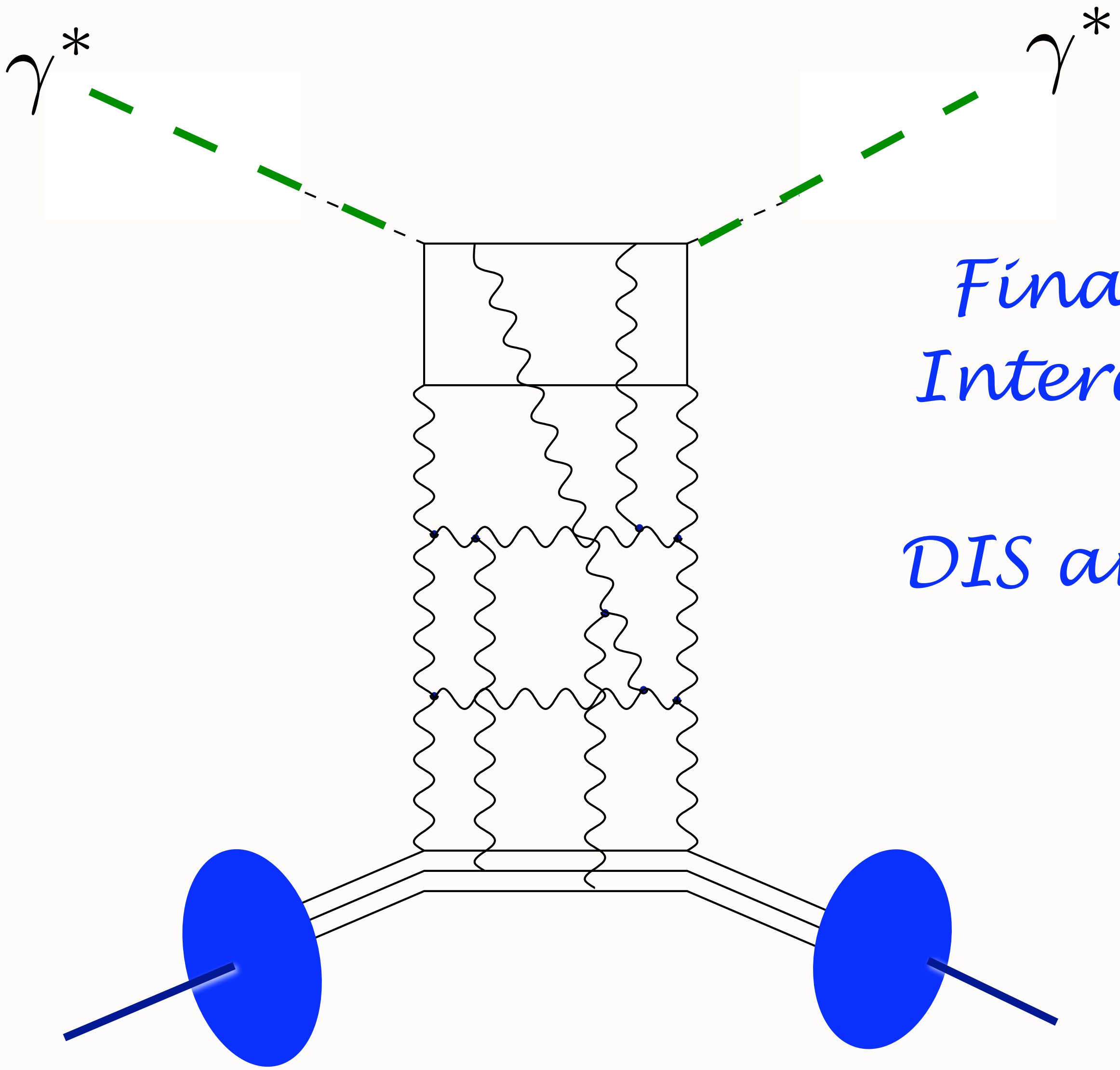
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Simple Virtual Photon Probes Complex Evolved Proton

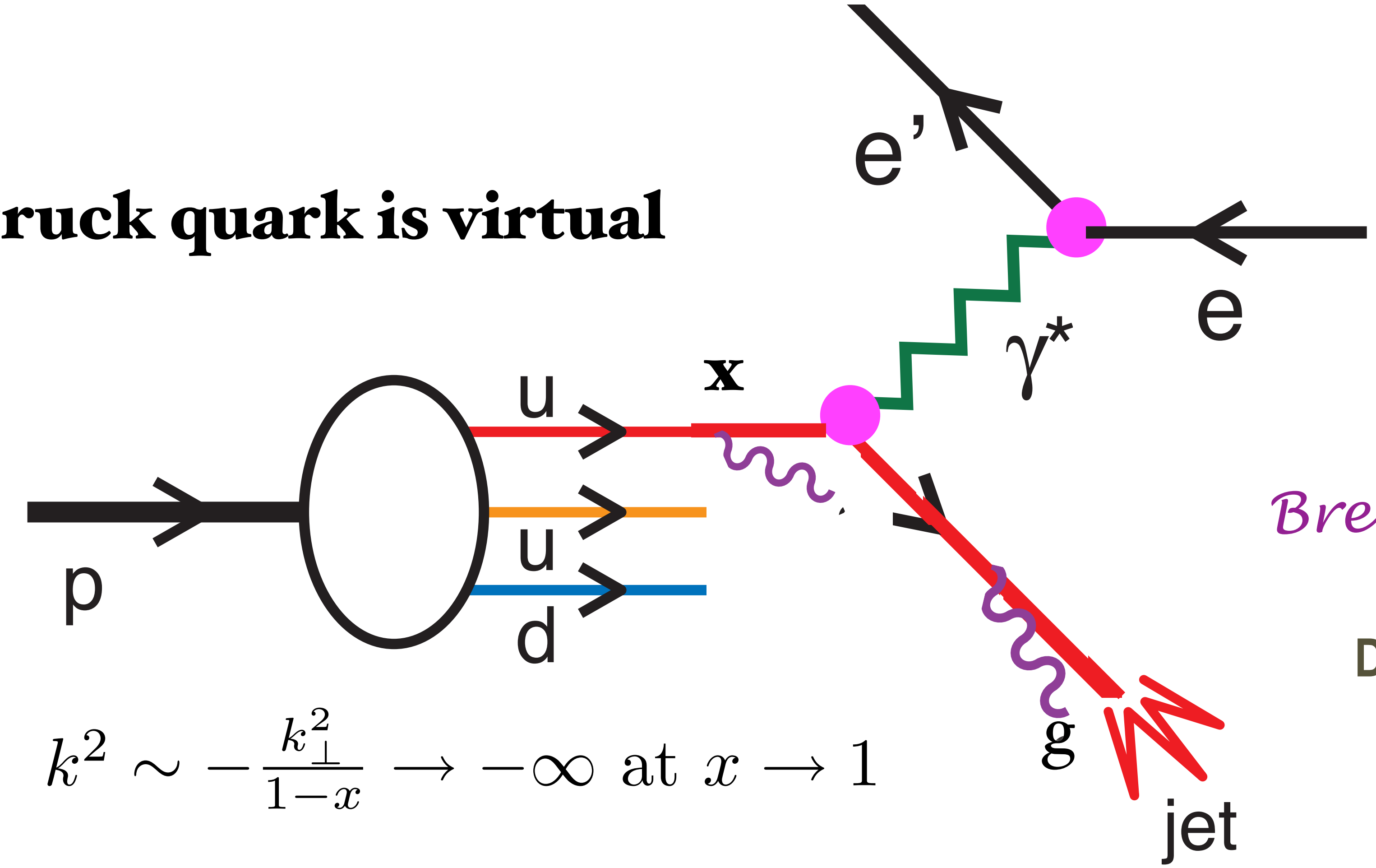


Final-State Interactions!

DIS and DVCS

Deep Inelastic Electron-Proton Scattering

Struck quark is virtual



$$k^2 \sim -\frac{k_\perp^2}{1-x} \rightarrow -\infty \text{ at } x \rightarrow 1$$

Gluonic Bremmstrahlung

DGLAP Evolution

Off-shell Effect: Breakdown of DGLAP at x ~1 !

Modifications from FSI !

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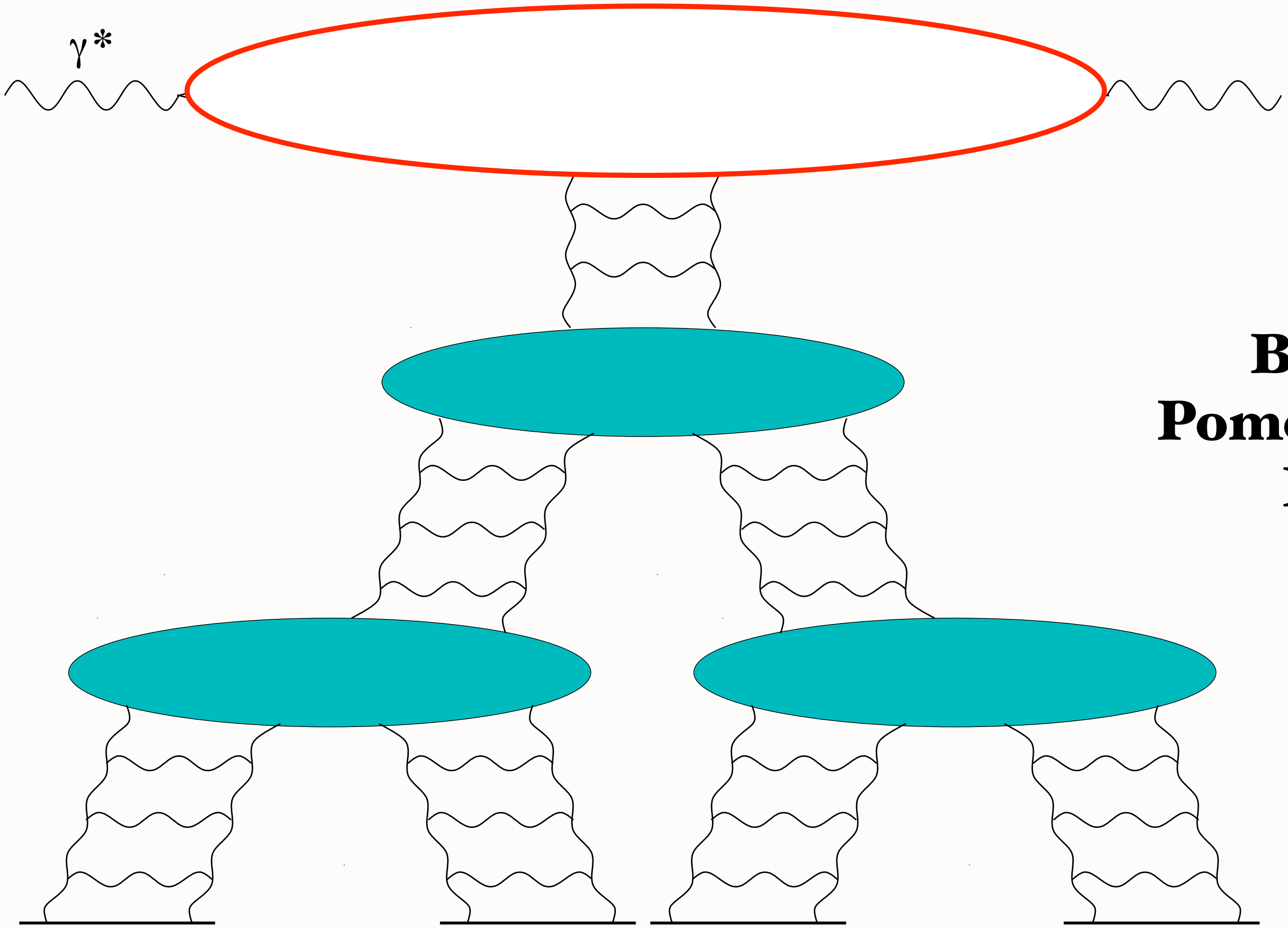
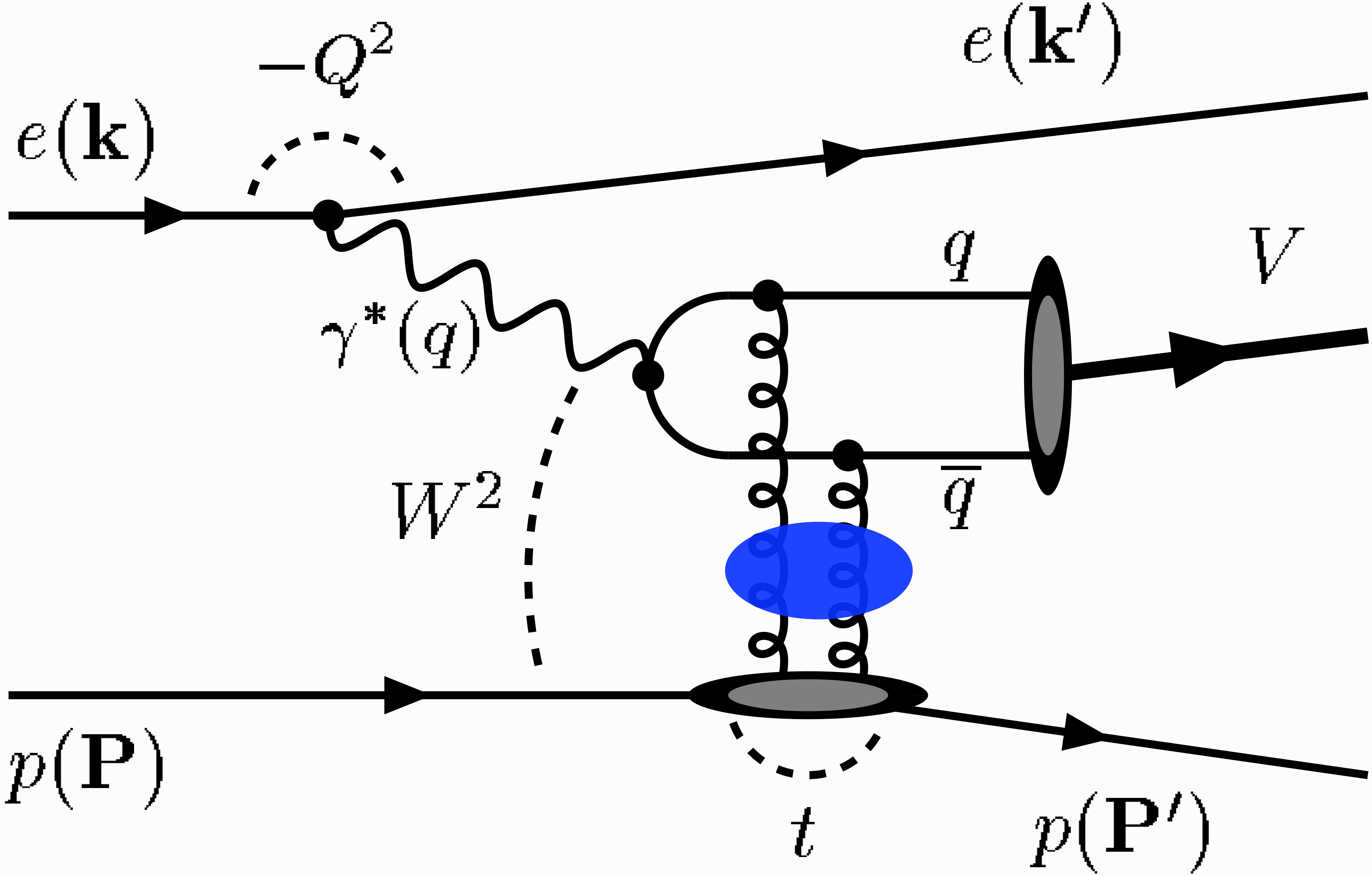


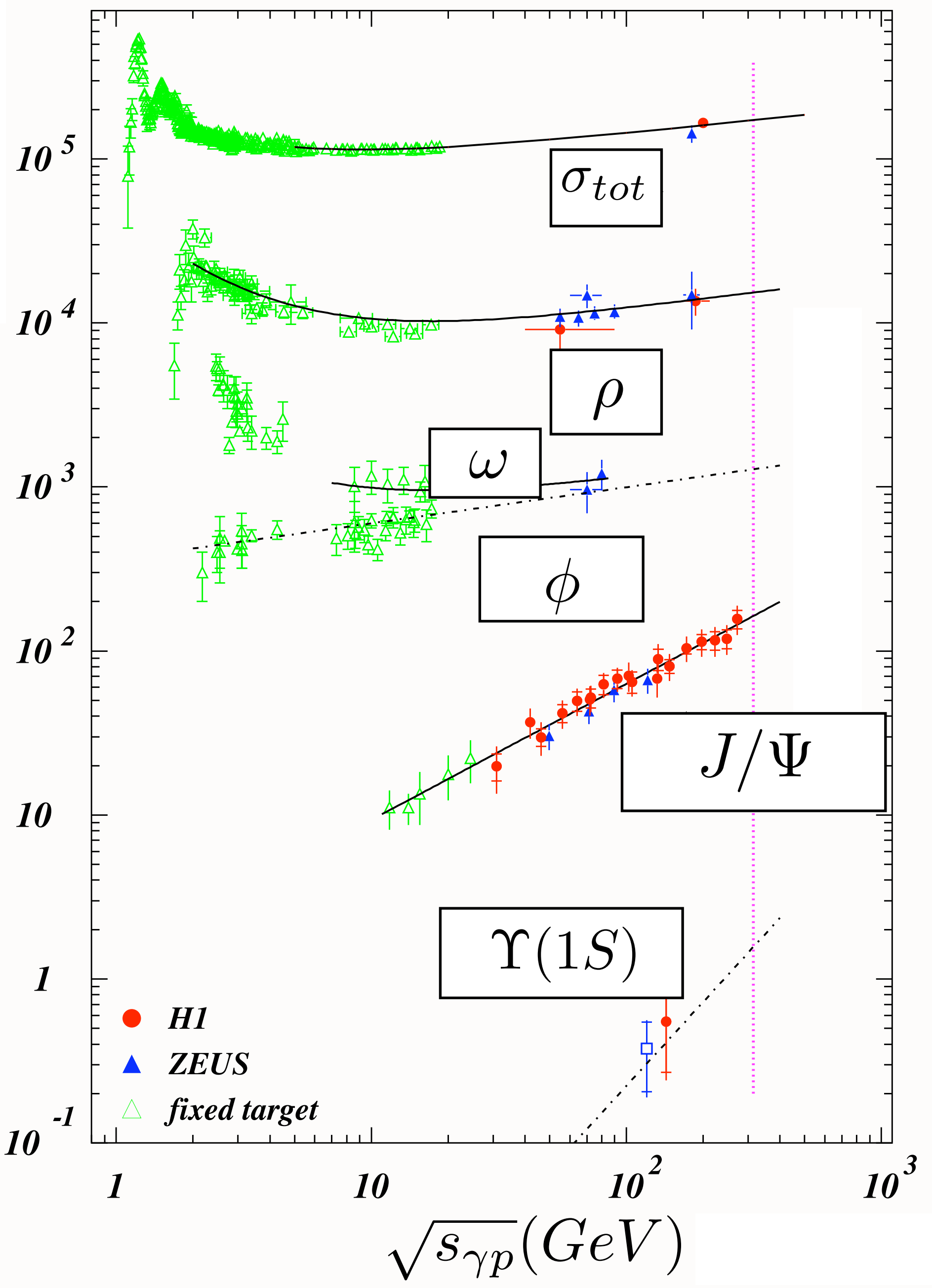
BFKL Hard Pomeron-Odderon Exchange

Color Dipole of Virtual Photon Scatters on a Complex Static Proton



BFKL hard pomeron exchange
\+ BLM NLO scale fixing

$\sigma(\gamma p \to V p)[nb]$



Diffractive Processes

Unitarity Bound?
Saturation?

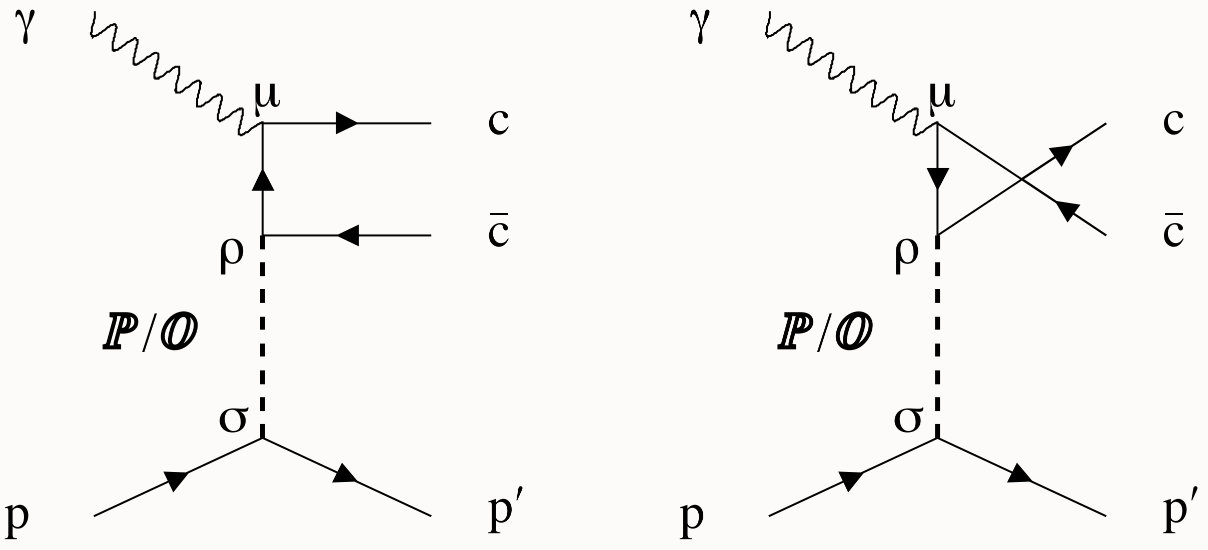
Hard Diffraction

$$\gamma p \to \Upsilon p$$

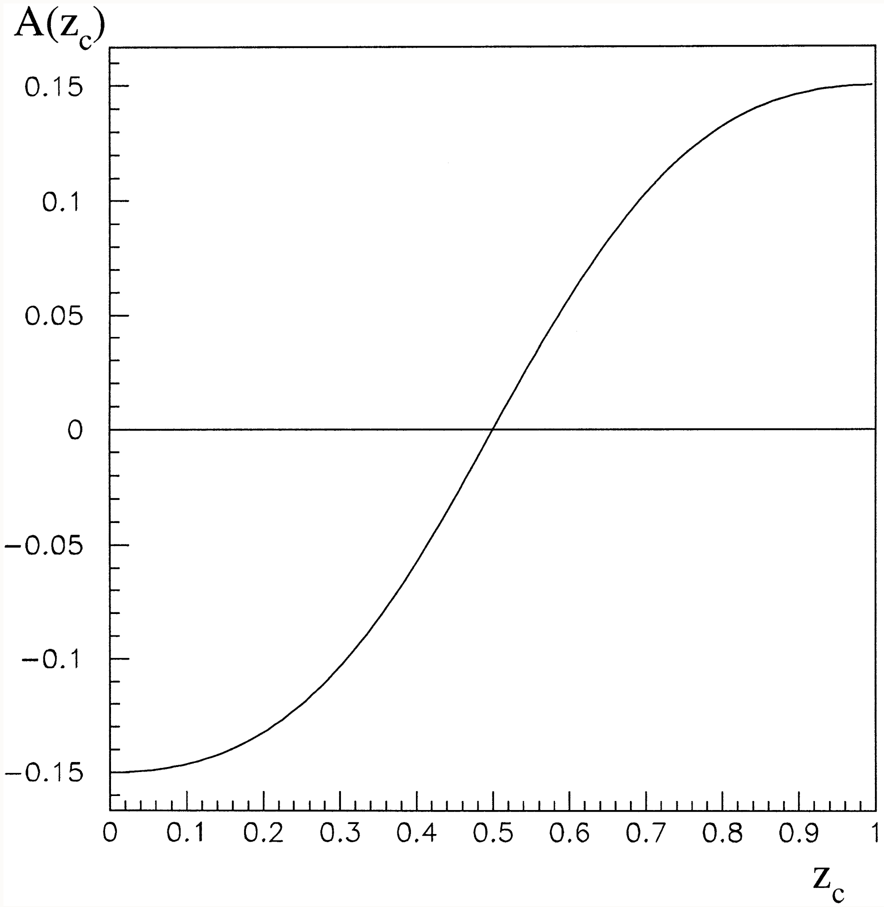
$$\gamma^* p \to \rho p$$

Odderon

$$\gamma^* p \to \pi^0 p$$



Odderon-Pomeron Interference!



$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2\,z_c - 1}{z_c^2 + (1 - z_c)^2}$$

Measure charm asymmetry in photon fragmentation region

Merino, Rathsman, sjb

Three Pictures of High Energy Lepton-Proton Collisions

Infinite momentum frame **Parton Model**

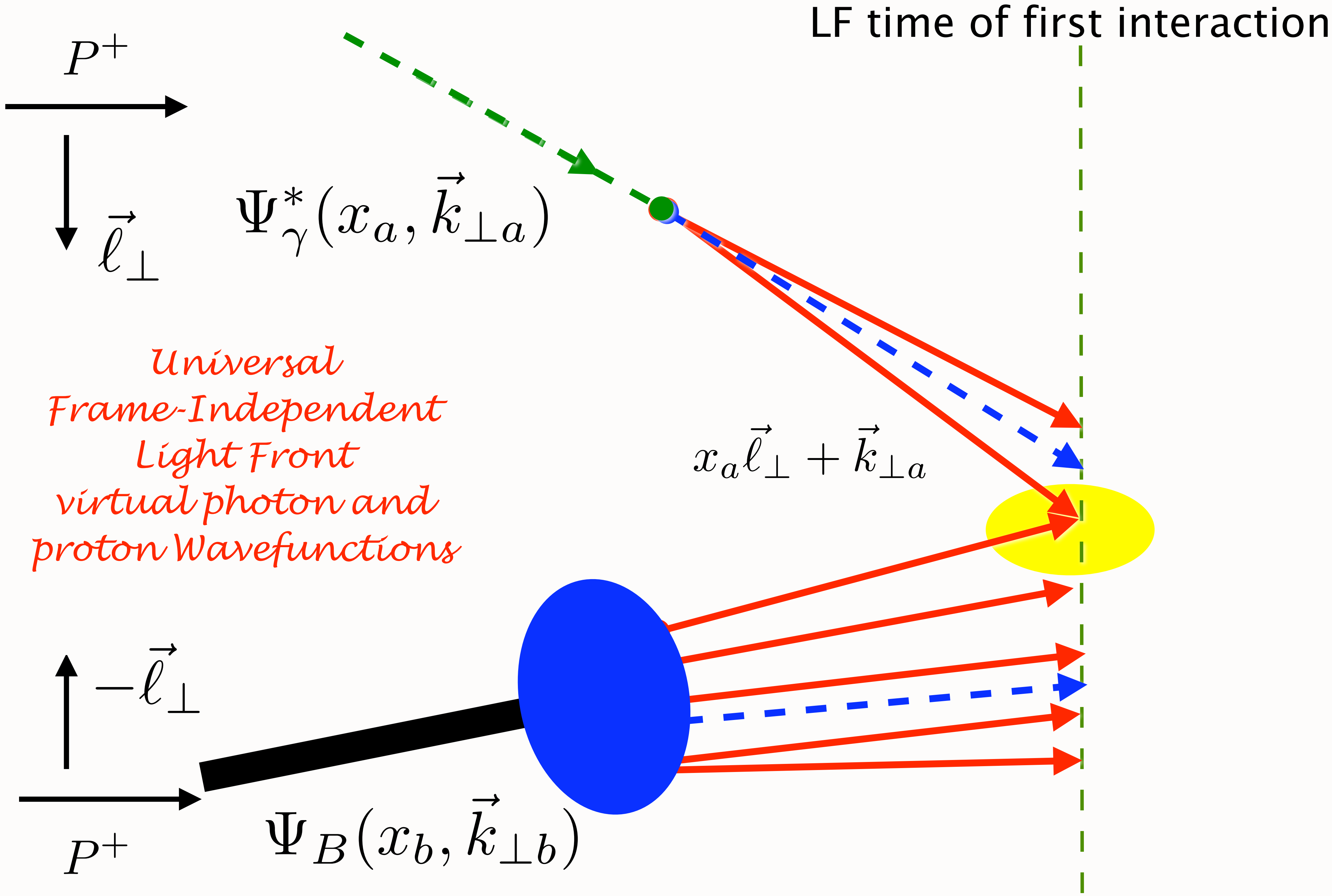
Simple Virtual Photon Probes Complex Evolved Proton

Proton Rest Frame **Color-Dipole Model**

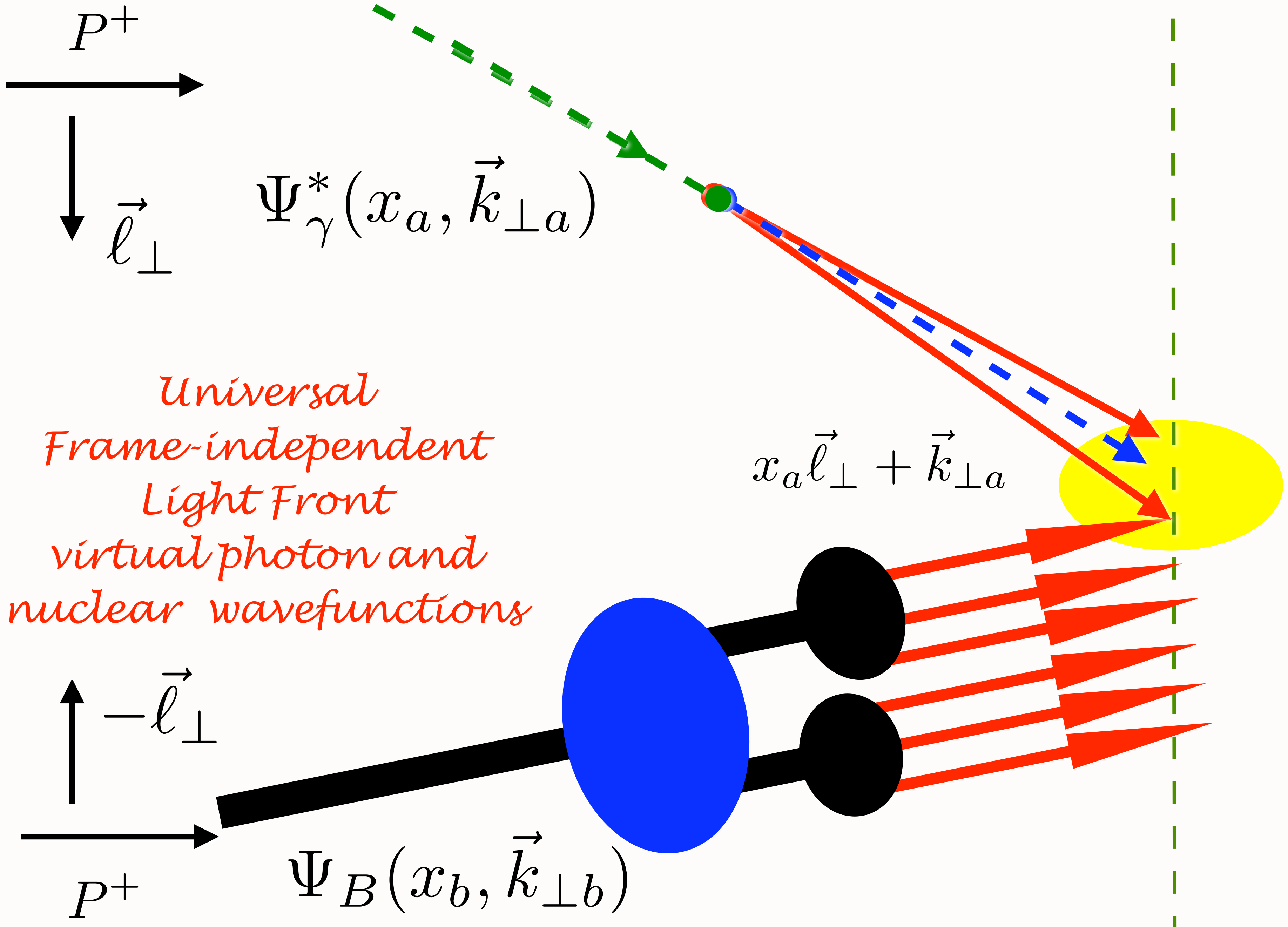
Color Dipole of Virtual Photon Scatters on a Static Proton

Frame-Independent **Light-Front HamiltonianTheory**

Collision of Light-Front Wavefunctions of Virtual Photon and Proton



Universal
Frame-Independent
Light Front
virtual photon and
proton Wavefunctions



Universal
Frame-independent
Light Front
virtual photon and
nuclear wavefunctions

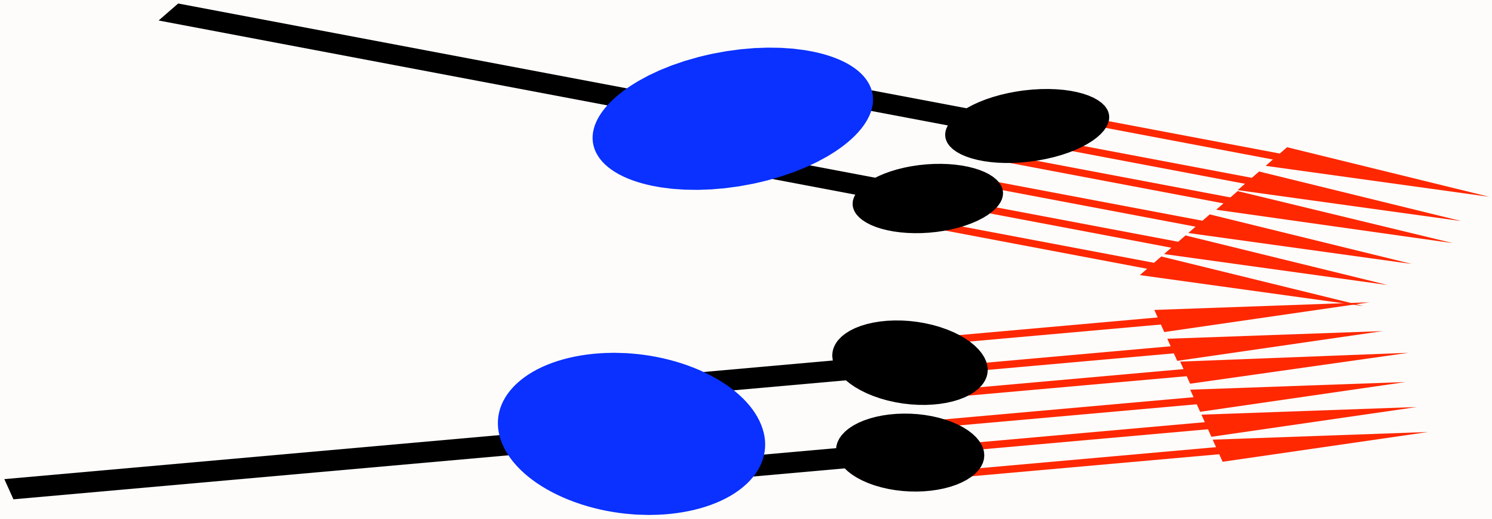
$$p_A = (P^+, \frac{M_A^2 + \ell_\perp^2}{P^+}, \vec{\ell}_\perp)$$

$$p_B = (P^+, \frac{M_B^2 + \ell_\perp^2}{P^+}, -\vec{\ell}_\perp)$$

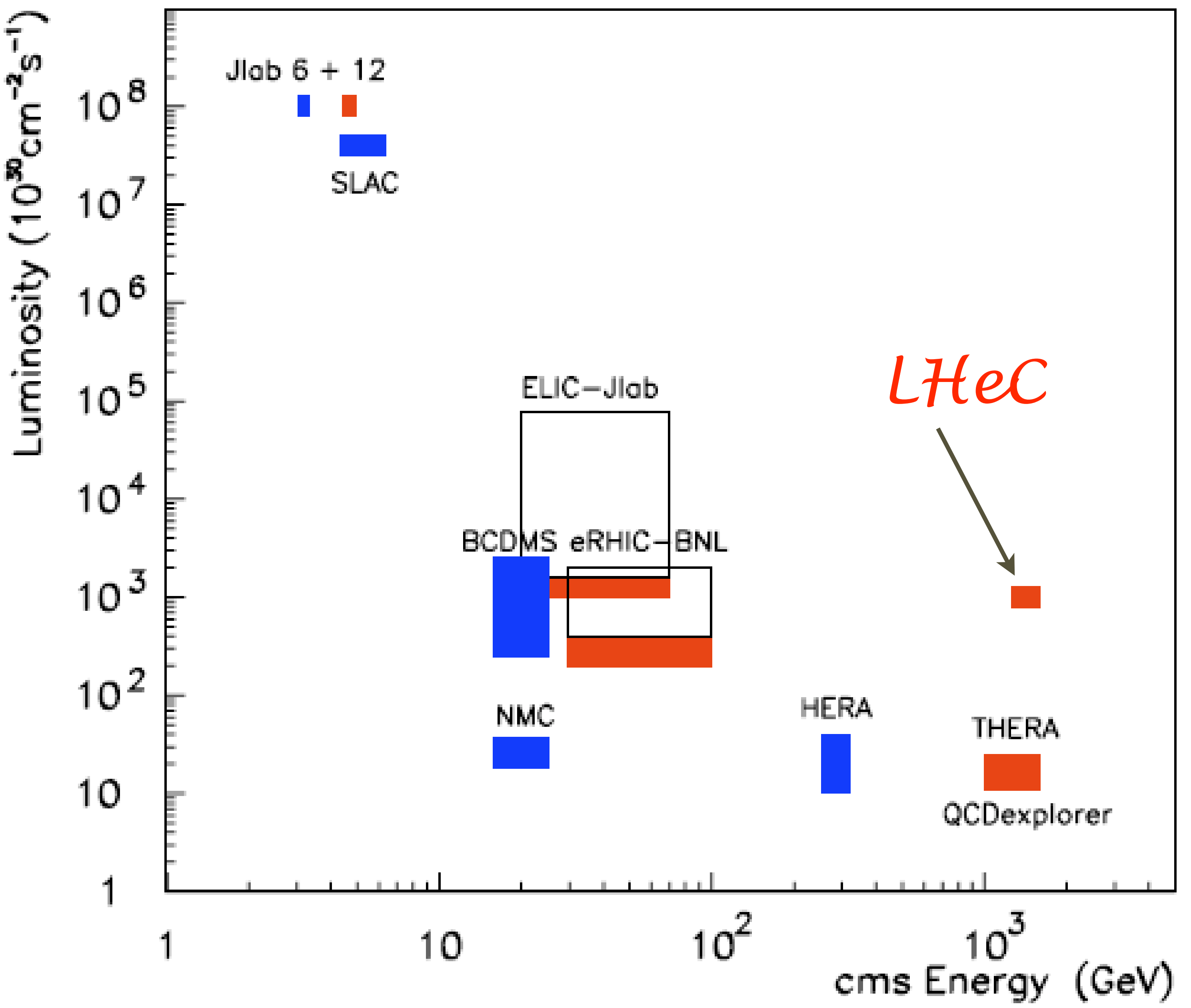
Both beams move along the positive z direction, and $s = (p_A + p_B)^2 = 2M_A^2 + 2M_B^2 + 4\ell_\perp^2$ is represented by the oppositely directed transverse momenta $\pm\vec{\ell}_\perp$ of the colliding nuclei.

Note that the value of P^+ is irrelevant.

As τ progresses, the constituents from A and B each interact as their coordinates σ_i and $\vec{b}_{\perp i}$ overlap.

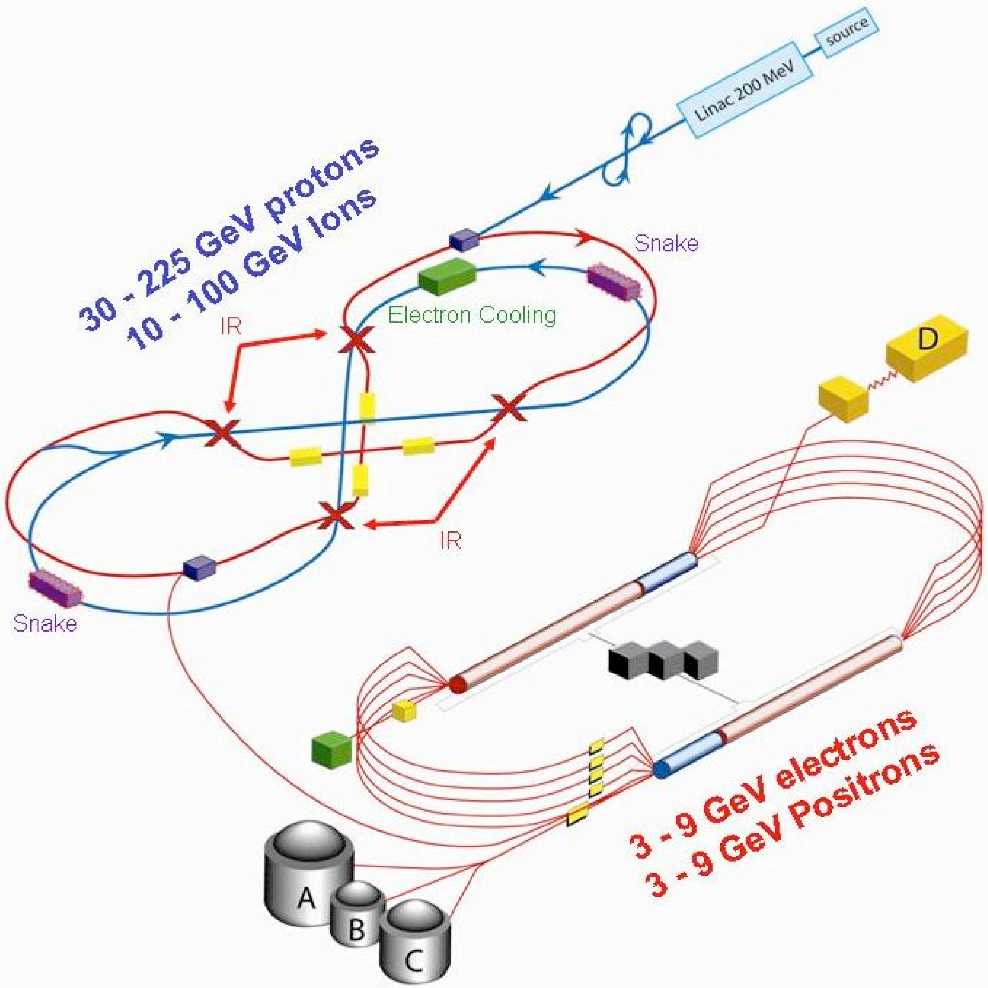


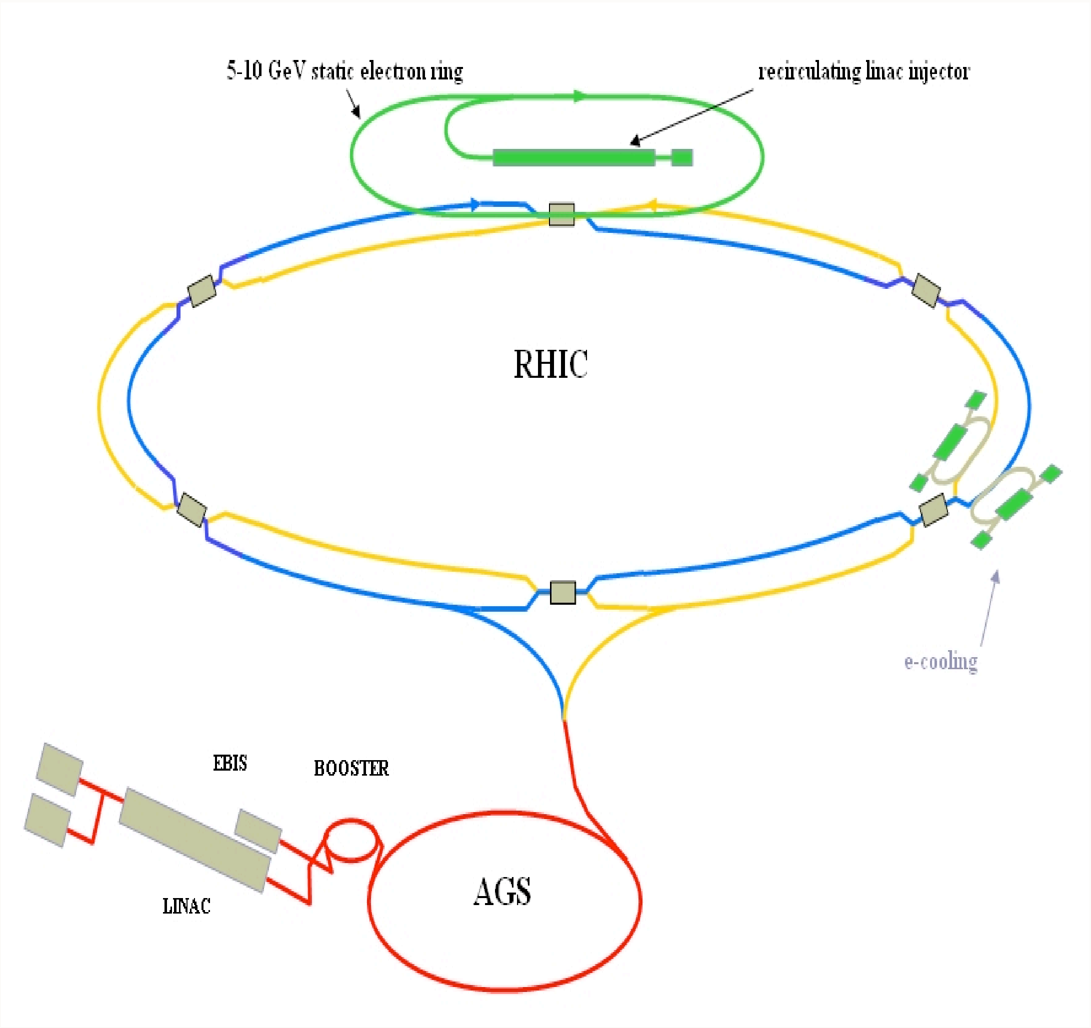
Past and Future ep Facilities



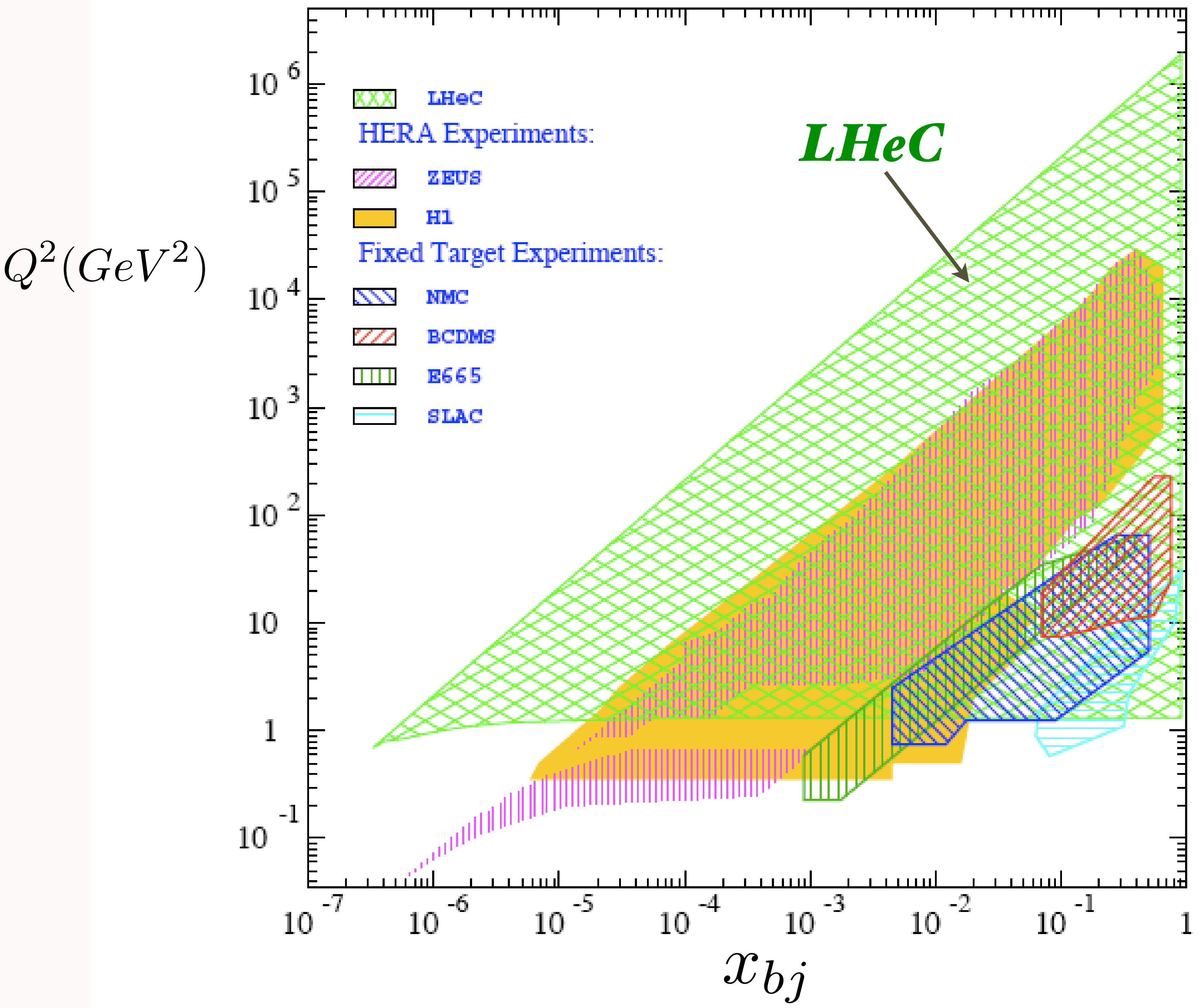
LHeC: $\sqrt{s_{ep}} > 1$ TeV

JLab and BNL Plans

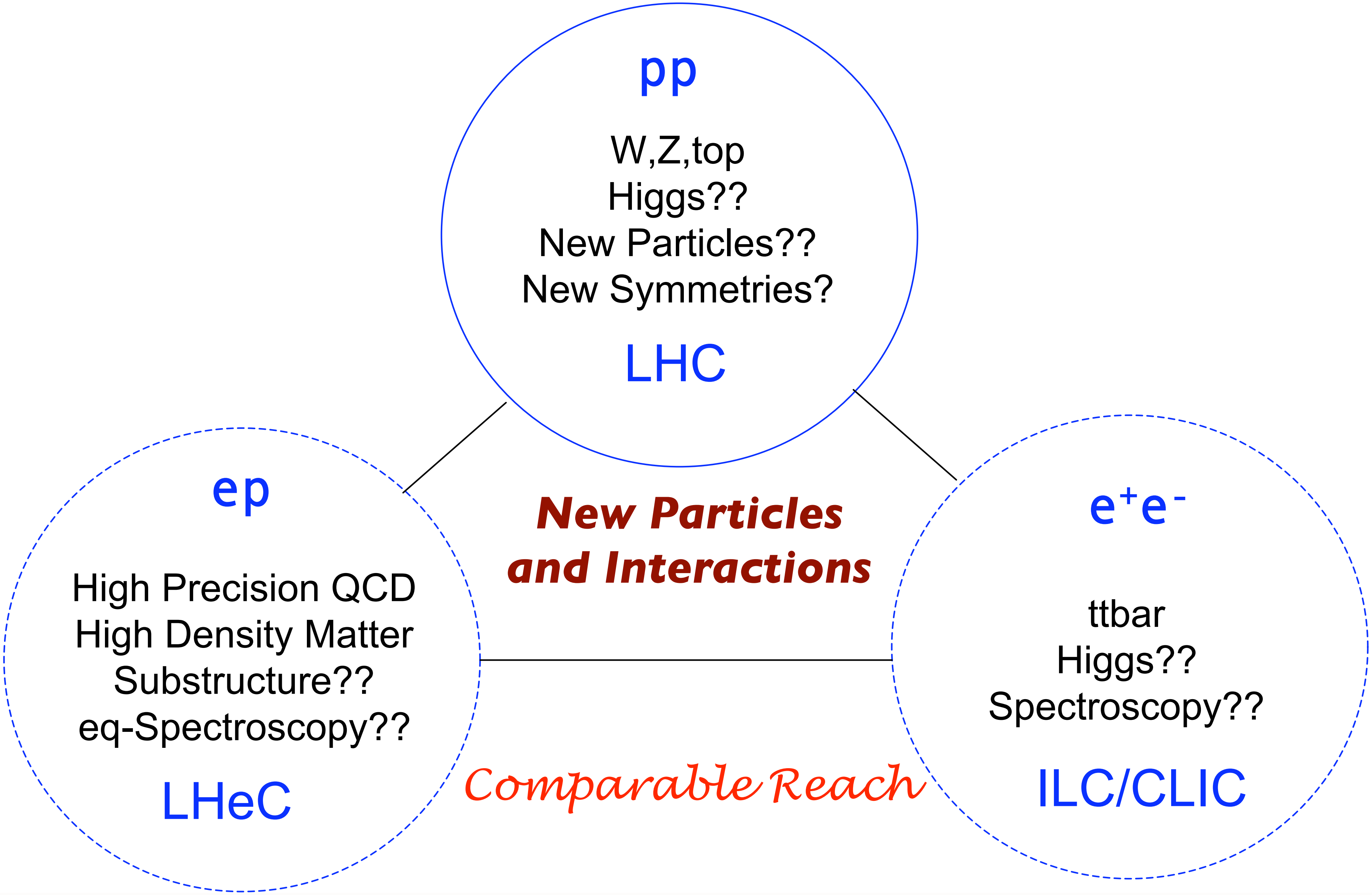




LHeC: $\sqrt{s_{ep}} > 1$ TeV



The TeV Scale [2008-2033..]



pp

W,Z,top
Higgs??
New Particles??
New Symmetries?

LHC

ep

High Precision QCD
High Density Matter
Substructure??
eq-Spectroscopy??

LHeC

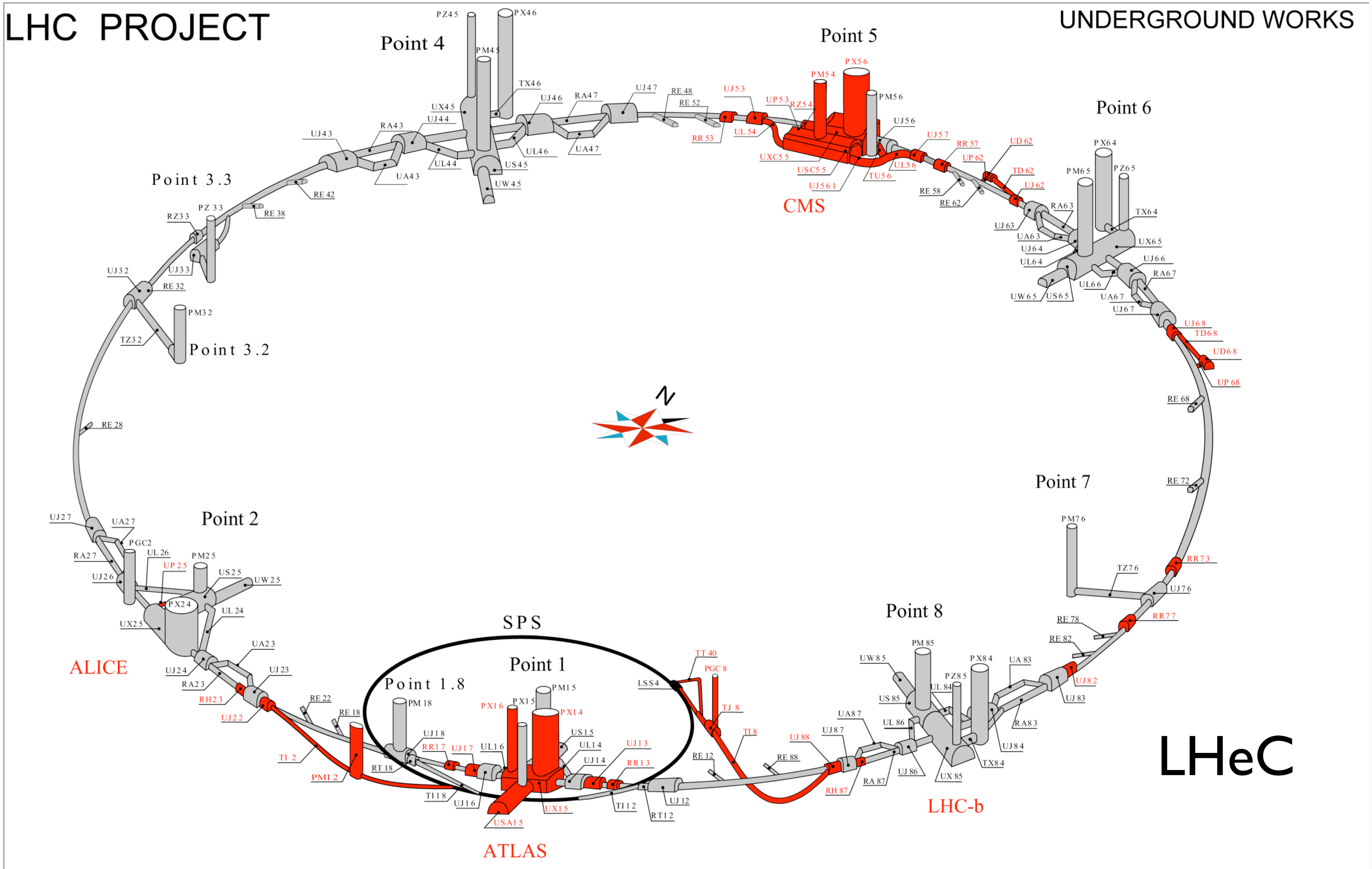
New Particles and Interactions

e^+e^-

ttbar
Higgs??
Spectroscopy??

ILC/CLIC

Comparable Reach

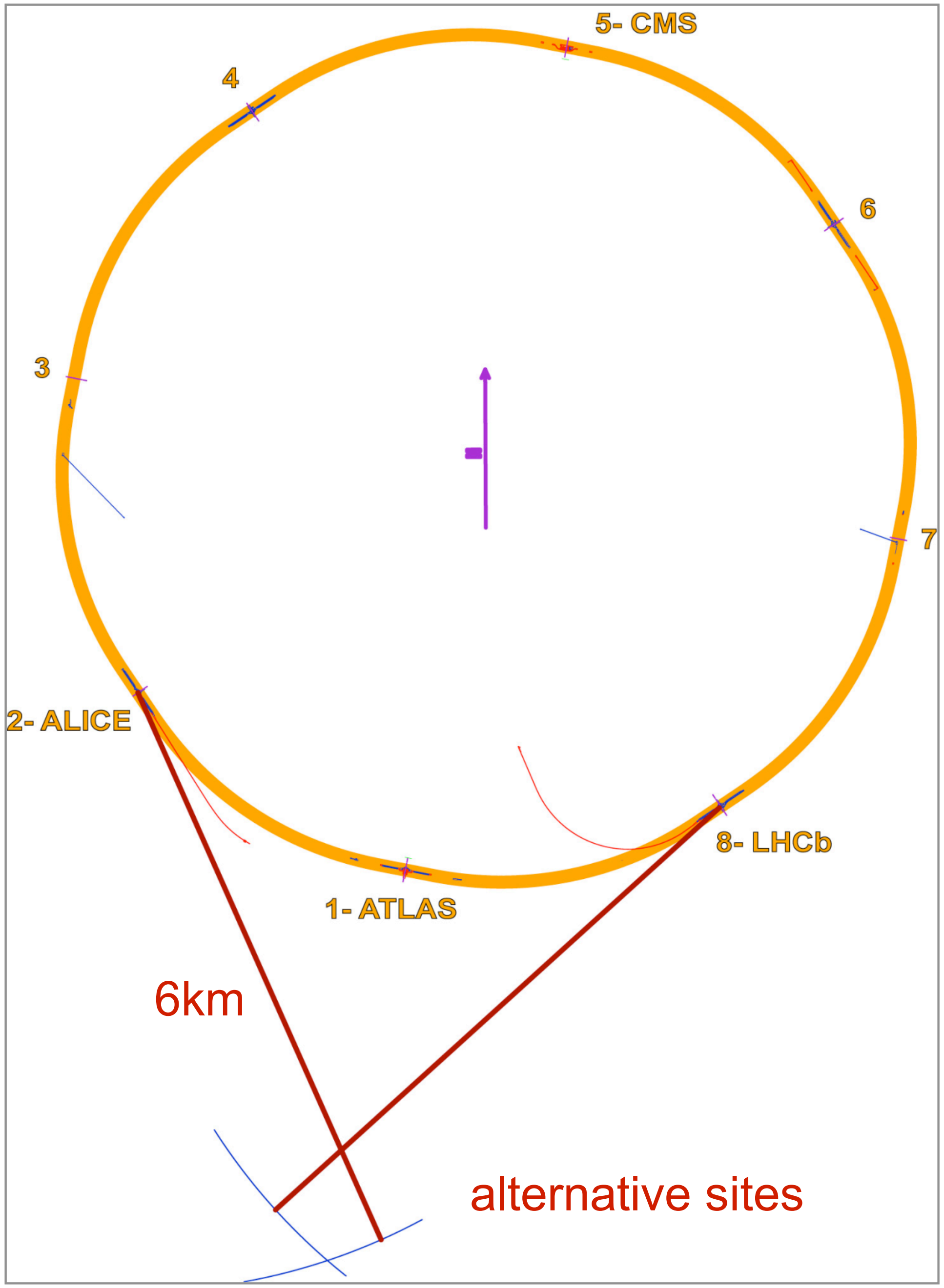


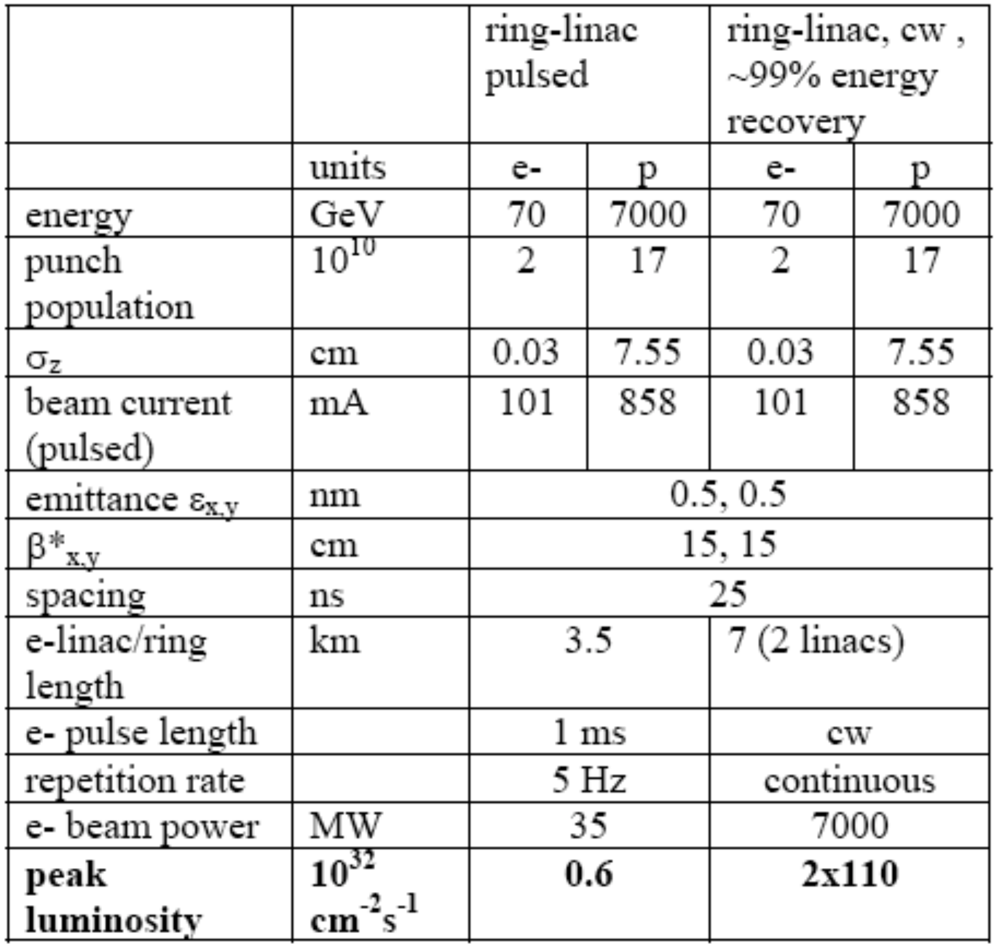
LHeC

An electron ring would have to bypass experiments. P3 and 6, perhaps
An electron linac would be largely decoupled from the LHC. In any case,
an ep/eA interaction region by then would have to be in P2 or/and P8.

▭ Existing Structures
🟥 LHC Project Structures

e± Linac - p/A Ring

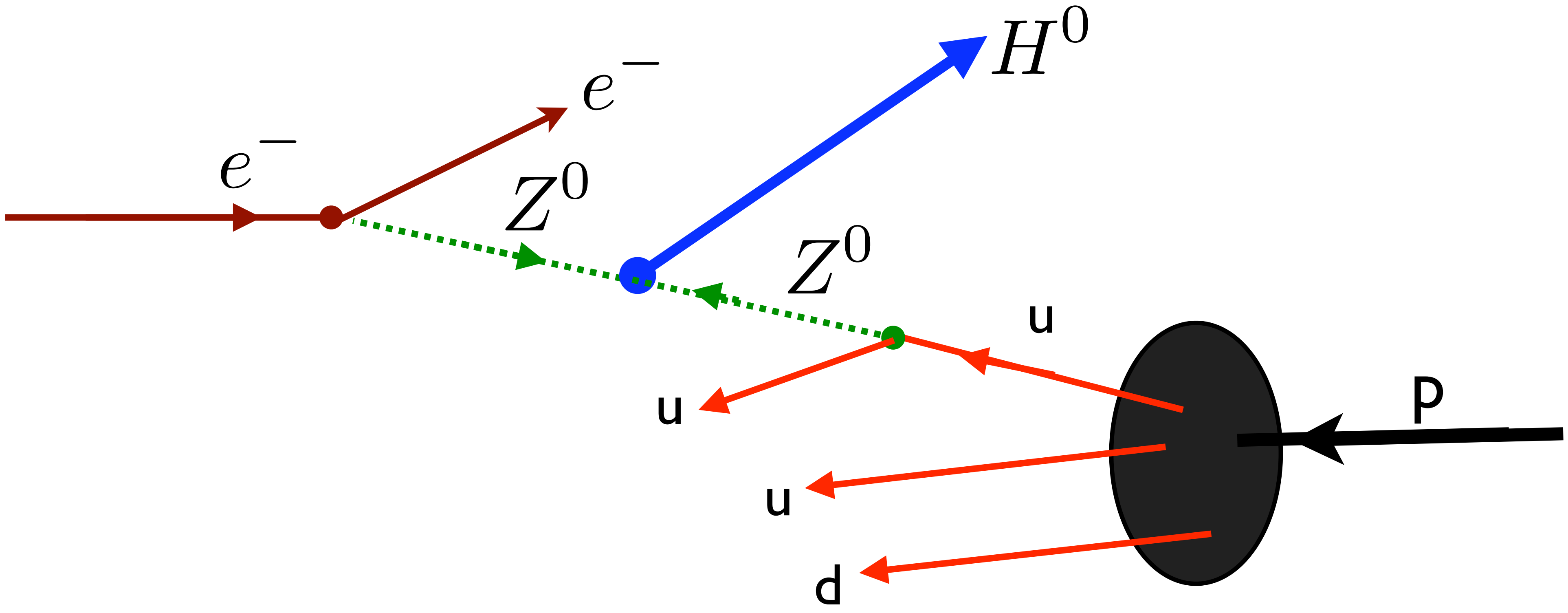




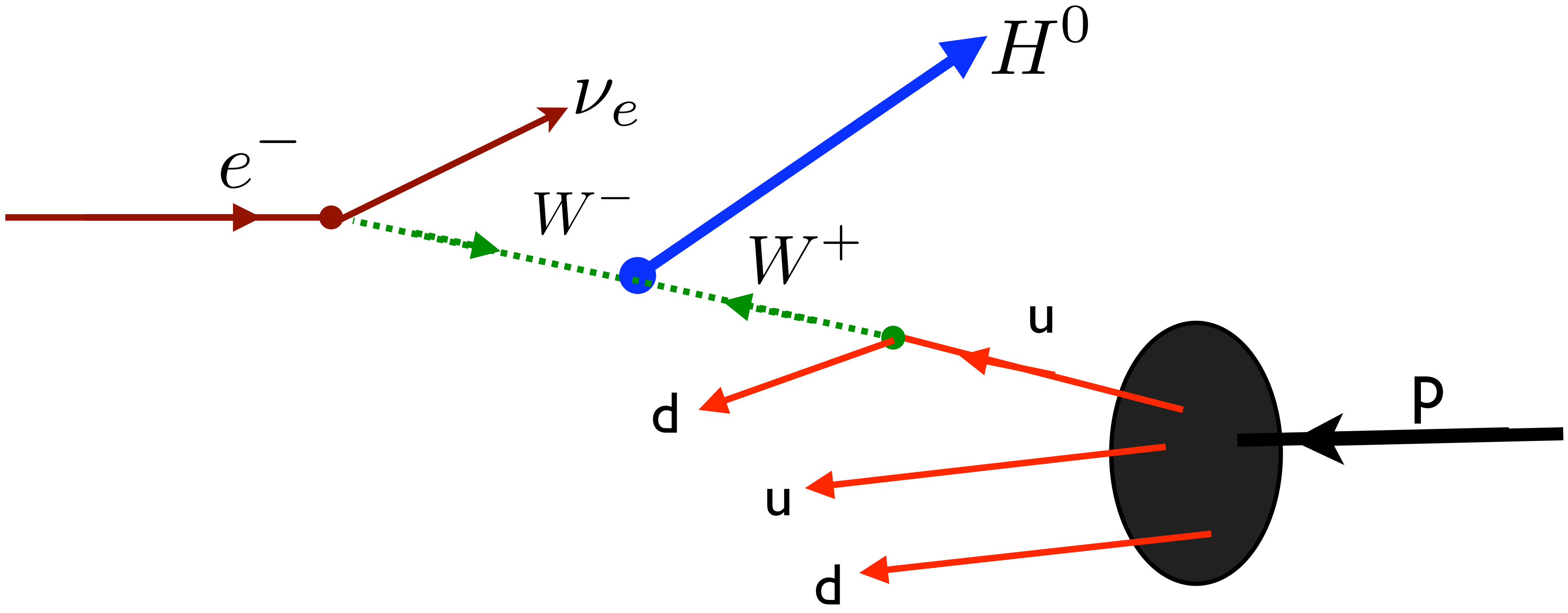
		ring-linac pulsed		ring-linac, cw , ~99% energy recovery	
	units	e-	p	e-	p
energy	GeV	70	7000	70	7000
punch population	10^{10}	2	17	2	17
σ_z	cm	0.03	7.55	0.03	7.55
beam current (pulsed)	mA	101	858	101	858
emittance $\varepsilon_{x,y}$	nm	0.5, 0.5			
$\beta^*_{x,y}$	cm	15, 15			
spacing	ns	25			
e-linac/ring length	km	3.5		7 (2 linacs)	
e- pulse length		1 ms		cw	
repetition rate		5 Hz		continuous	
e- beam power	MW	35		7000	
peak luminosity	**10^{32} cm^{-2}s^{-1}**	**0.6**		**2x110**	

S. Chattopadhyay (Cockcroft), F.Zimmermann (CERN), et al.

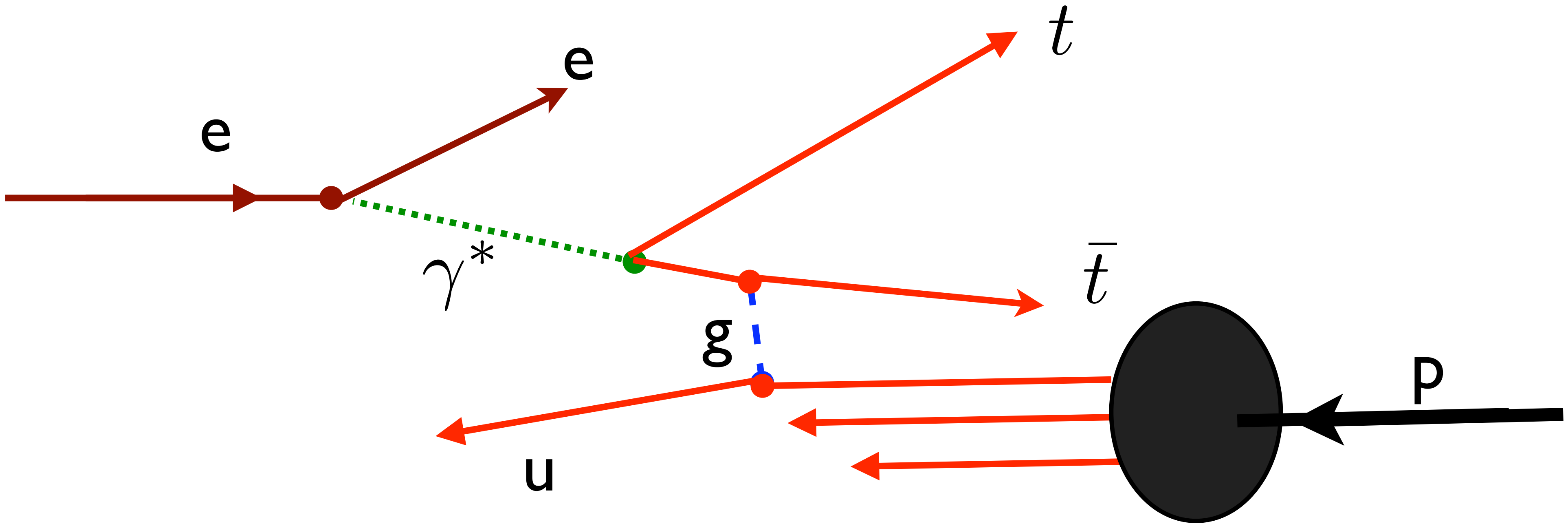
Inclusive Higgs Electroproduction at the LHeC from the Neutral Current



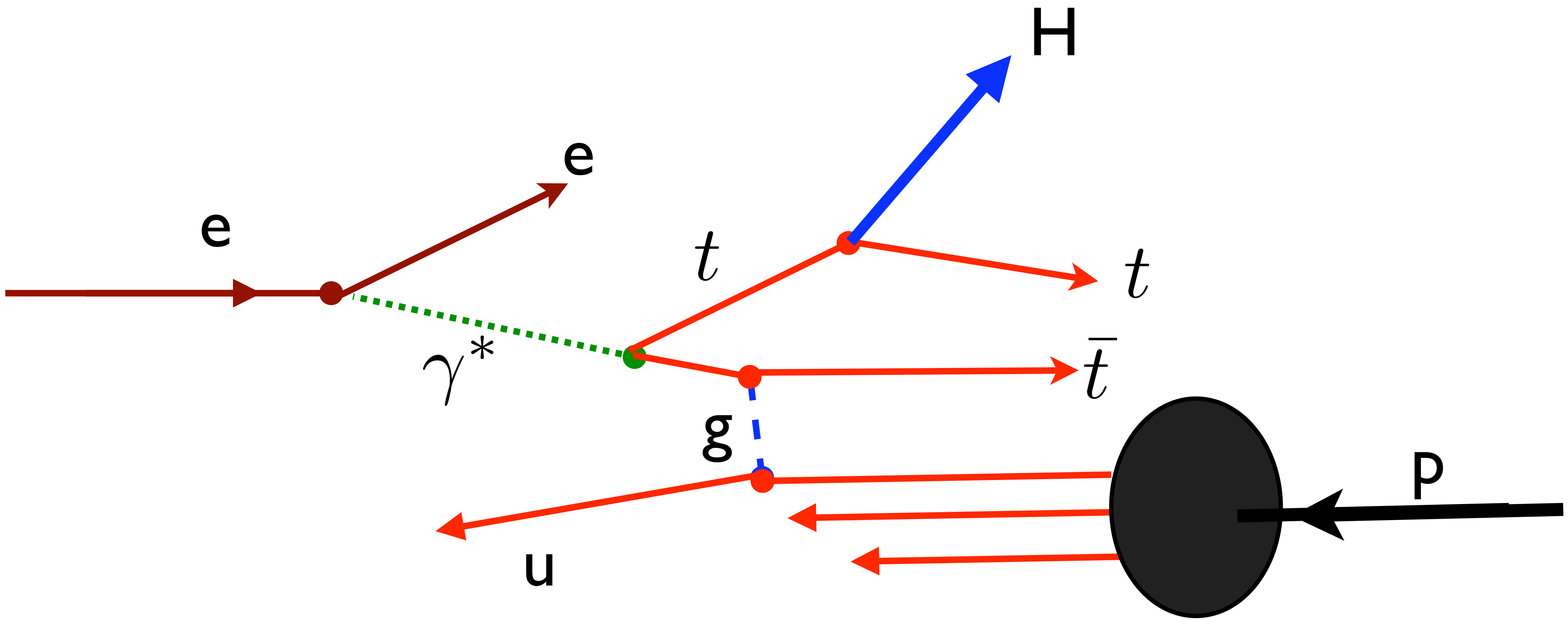
Inclusive Higgs Electroproduction at the LHeC from the Charged Current



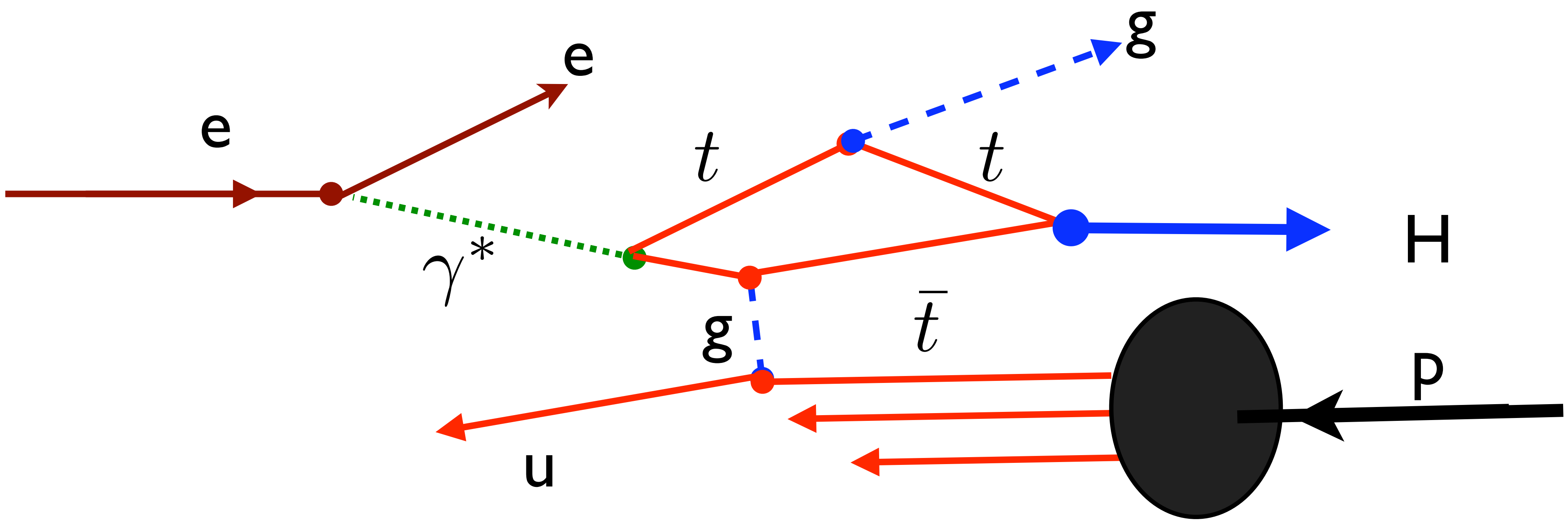
Inclusive Top Electroproduction at the LHeC



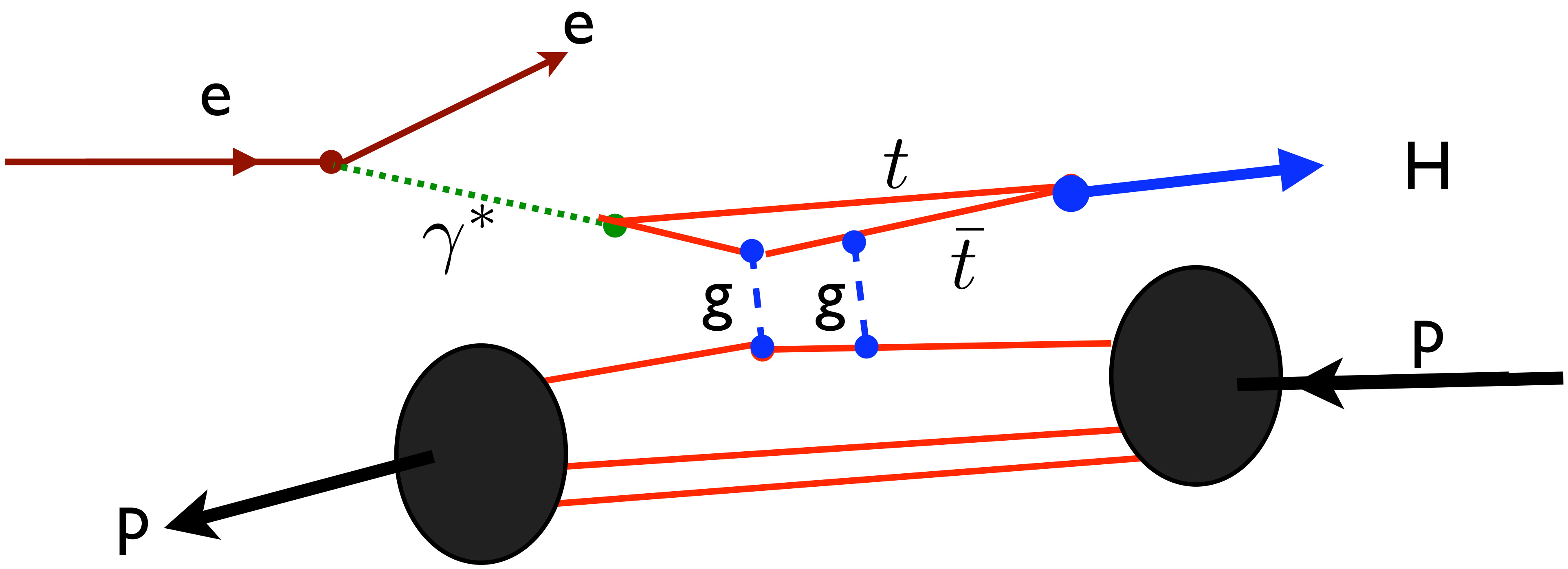
Inclusive Higgs Electroproduction at the LHeC



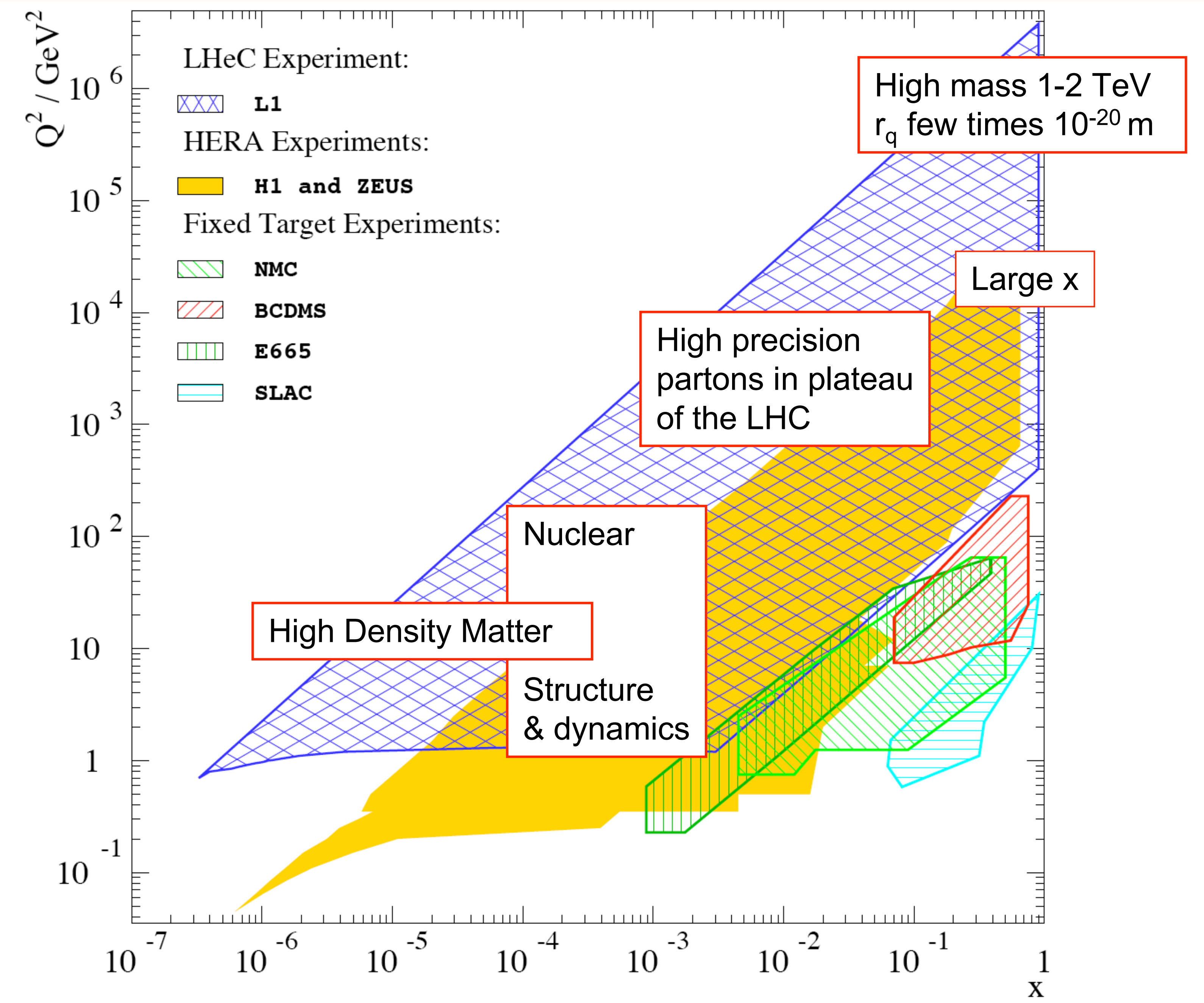
Inclusive Higgs Electroproduction at the LHeC



Diffractive Higgs Electroproduction at the LHeC



Kopeliovich, Schmidt, sjb



High mass 1-2 TeV
r_q few times 10^{-20} m

Large x

High precision partons in plateau of the LHC

Nuclear

High Density Matter

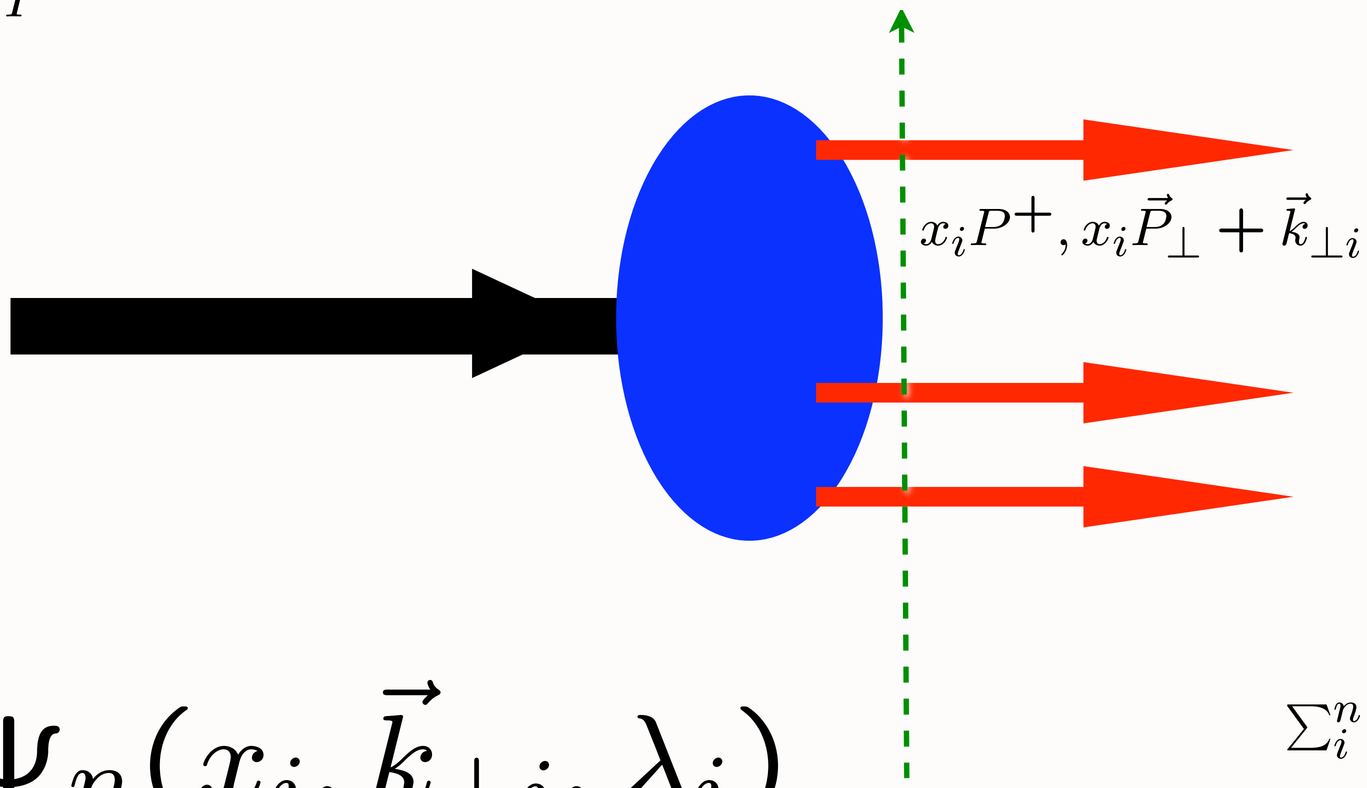
Structure & dynamics

Beyond the Standard Model
High Energy Physics Opportunities

- Leptoquarks: s-and t-channel effects
- SUSY
- Technicolor
- Lepton/quark
- Compositeness

Light-Front Wavefunctions

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



Fixed $\tau = t + z/c$

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

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

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

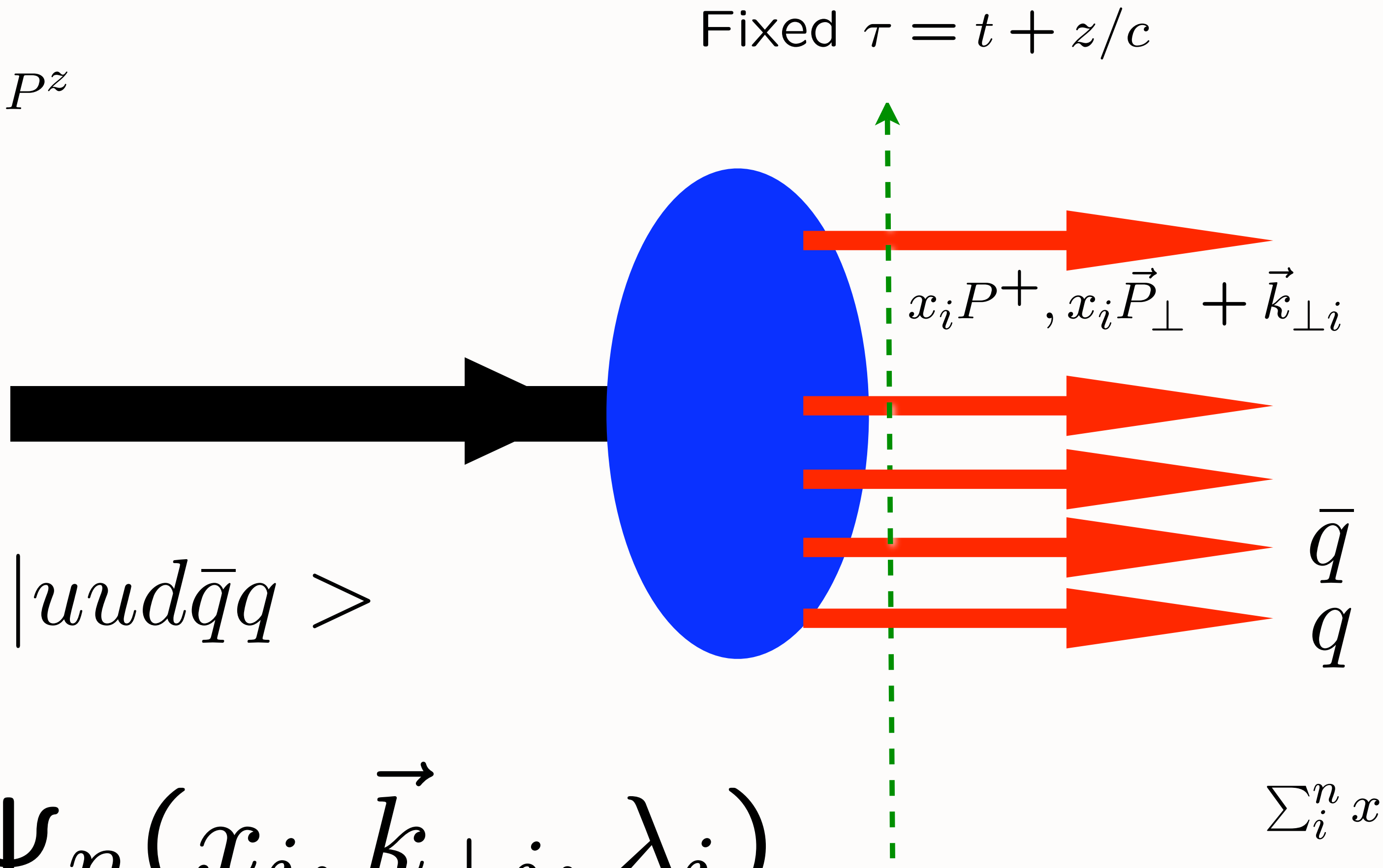
$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions

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



Fixed $\tau = t + z/c$

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

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

$\bar{q}$

q

$|uud\bar{q}q>$

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

$\Sigma_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

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

Conserved
LF Fock state by Fock State

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

n-1 orbital angular momenta

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

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

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

The Light Front Fock State Wavefunctions

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

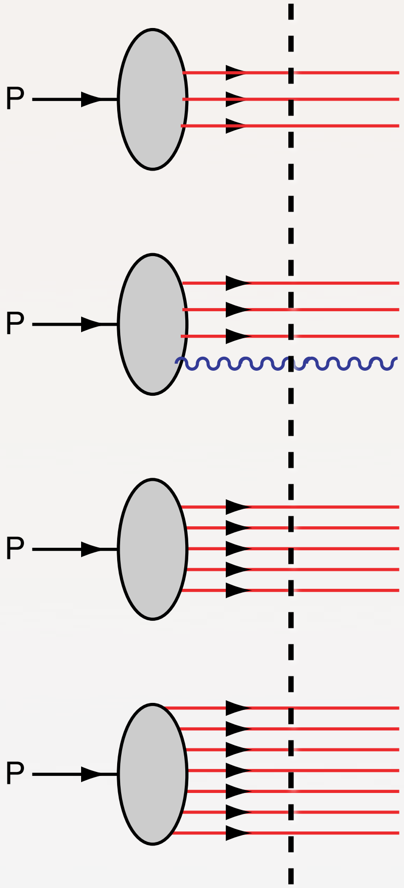
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

$$\boxed{\begin{array}{c}\bar{u}(x) \neq \bar{d}(x) \\ \bar{s}(x) \neq s(x)\end{array}}$$

Mueller: BFKL DYNAMICS

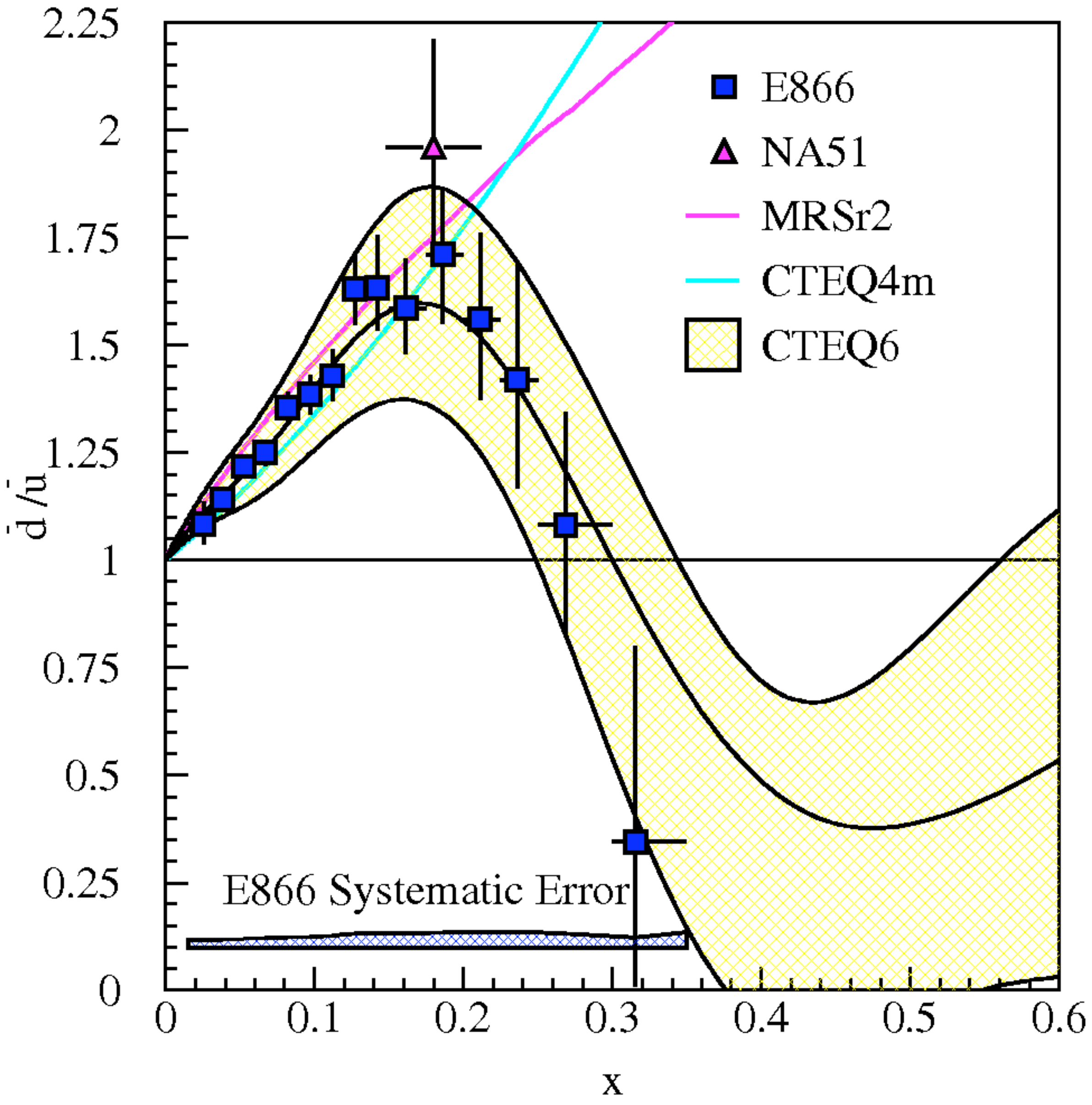
Light Antiquark Flavor Asymmetry

- Naïve Assumption from gluon splitting:

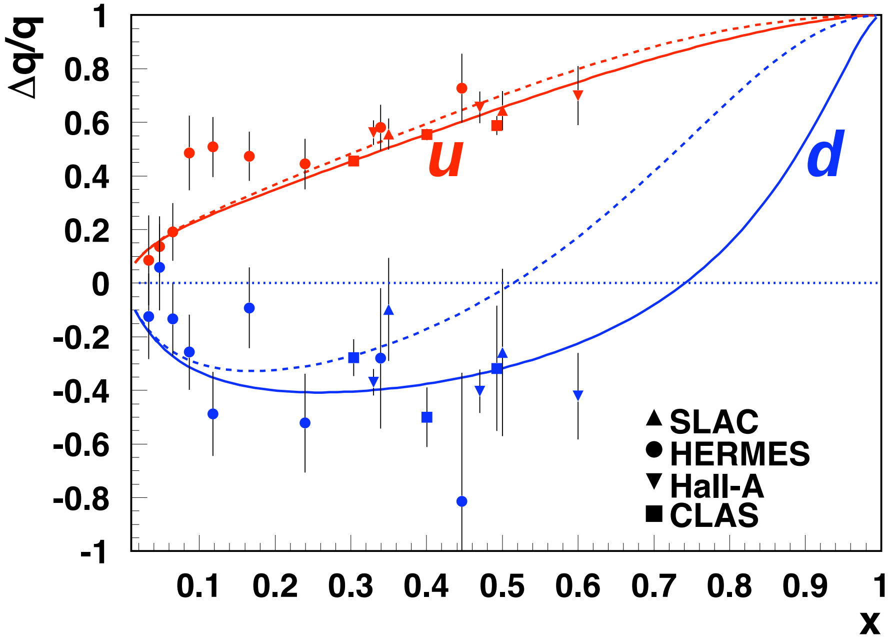
$$\bar{d}(x) = \bar{u}(x)$$

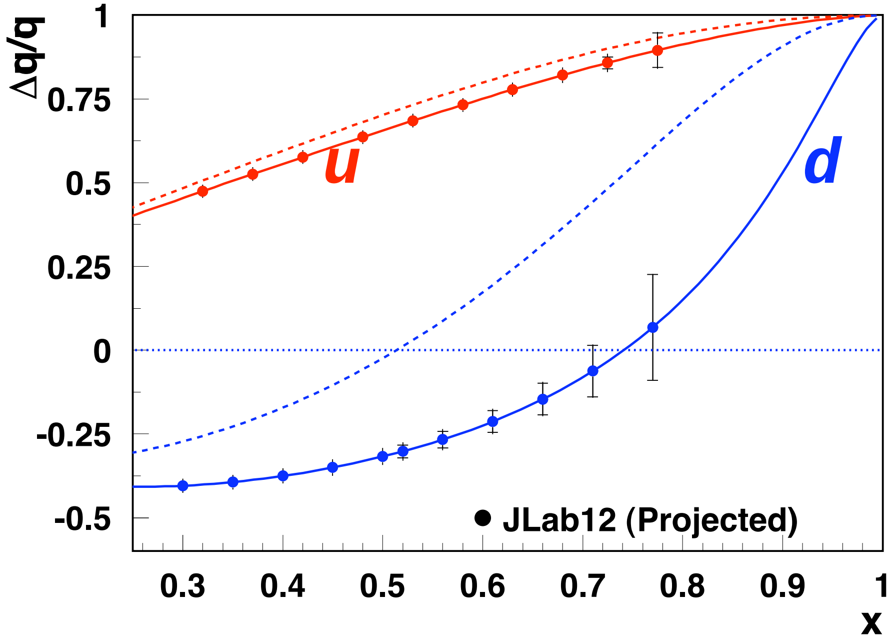
- E866/NuSea (Drell-Yan)

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



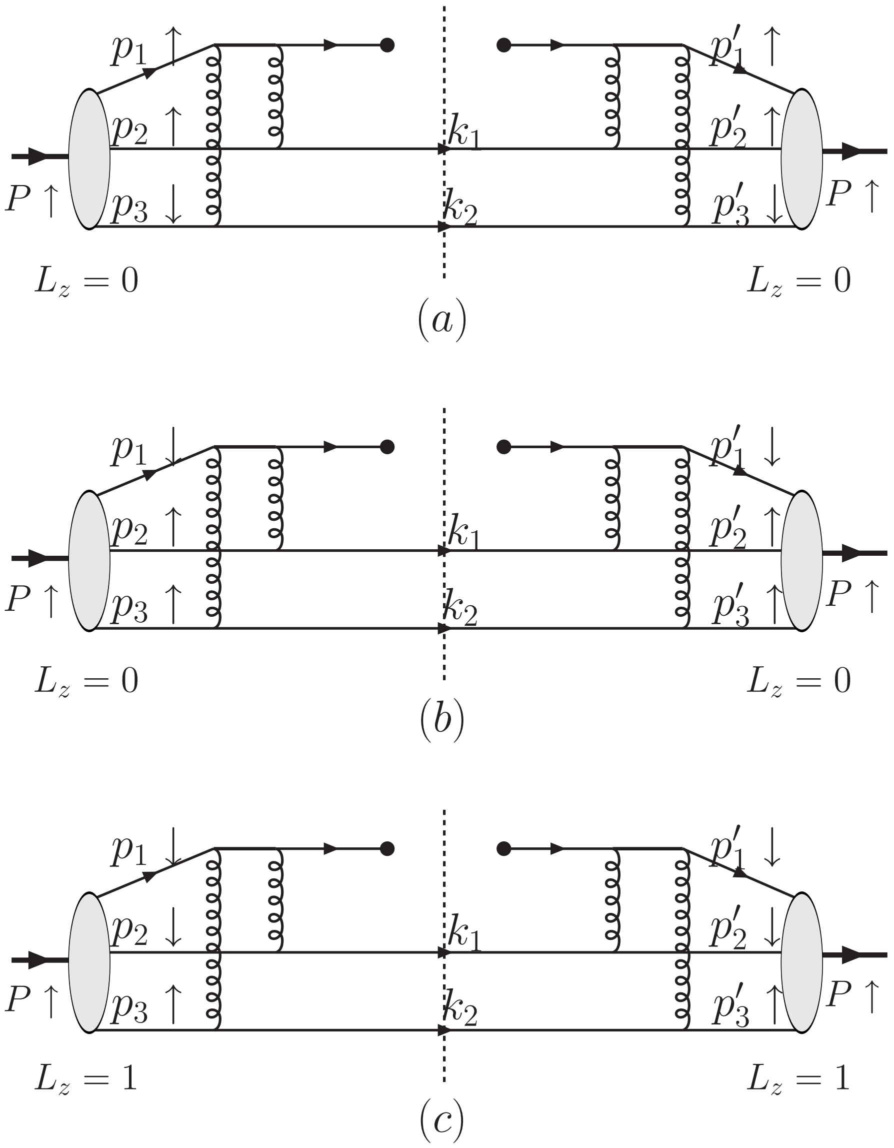
Effect of Orbital Angular Momentum on Valence-Quark Helicity Distributions





Avakian, Deur, Yuan, sjb

Effect of Orbital Angular Momentum on Valence-Quark Helicity Distributions



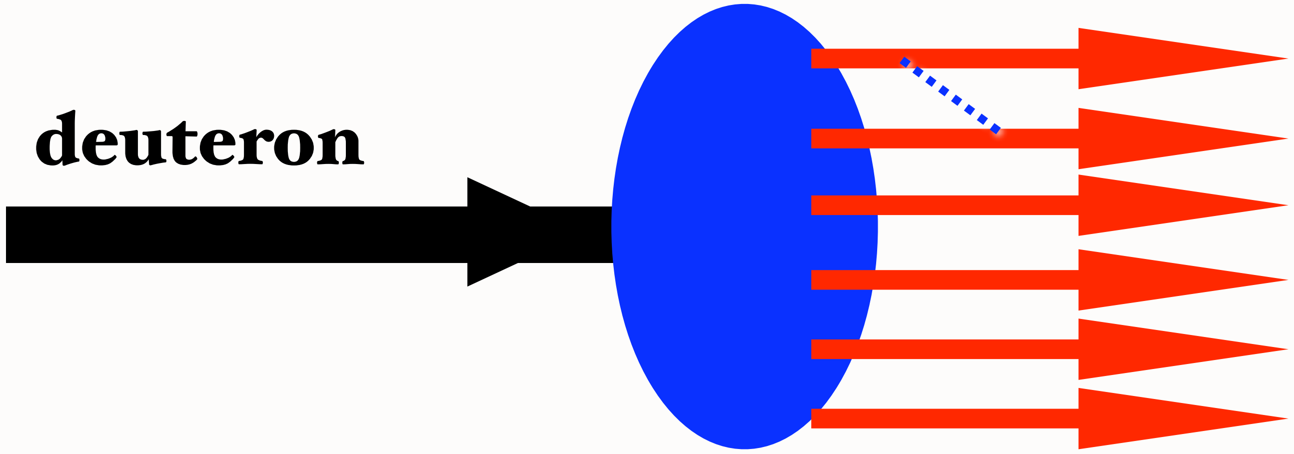
Spectator counting rules at $x \to 1$

Avakian, Deur, Yuan, sjb

Hidden Color of Deuteron

Evolution of 5 color-singlet Fock states

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



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

$\sum_i^n x_i = 1$

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

Ji, Lepage, sjb

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Remarkable Features of Hadron Structure

- Valence quark helicity represents less than half of the proton's spin and momentum
- Non-zero quark orbital angular momentum!
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$relation to meson cloud
- Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$

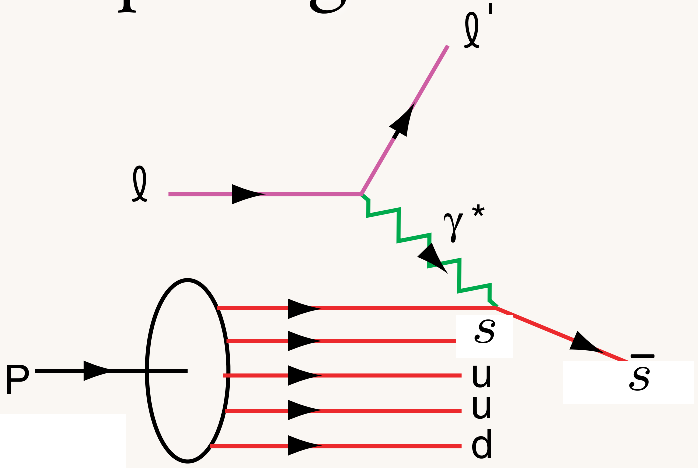
$\Delta s(x) \neq \Delta \bar{s}(x)$

- Intrinsic charm and bottom at high x
- Hidden-Color Fock states of the Deuteron

Measure strangeness distribution from DIS at EIC

$$\bar{s}(x) \neq s(x) \qquad ep \to e'KX$$

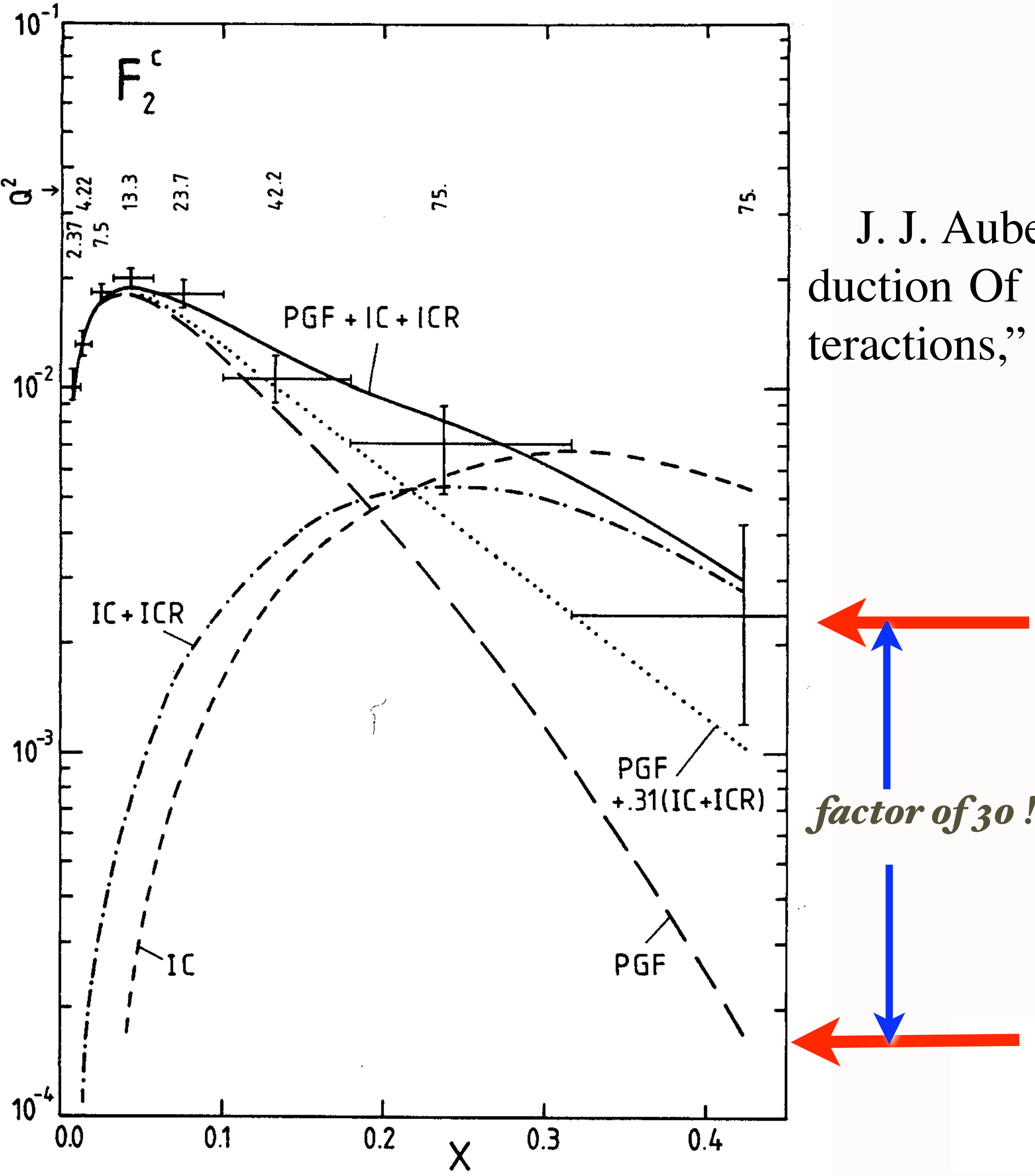
- Non-symmetric strange and antistrange sea
- Non-perturbative input; e.g $|uuds\bar{s}> \simeq |\Lambda(uds)K^{+}(\bar{s}u)>$
- Crucial for interpreting NuTeV anomaly

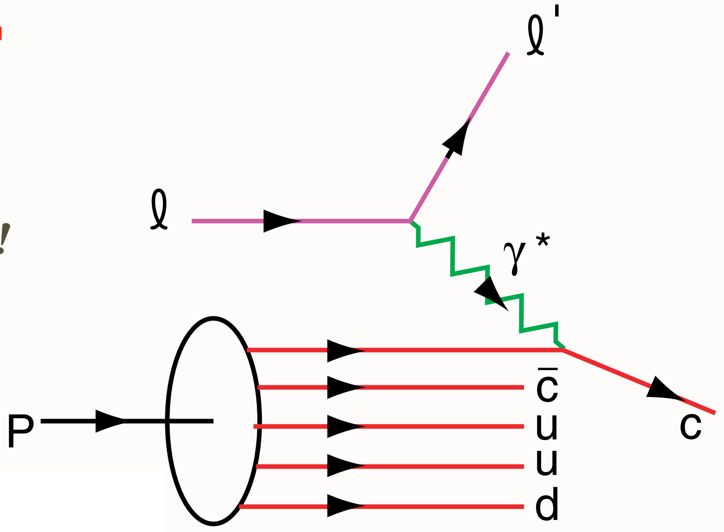


Measurement of Charm Structure Function

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

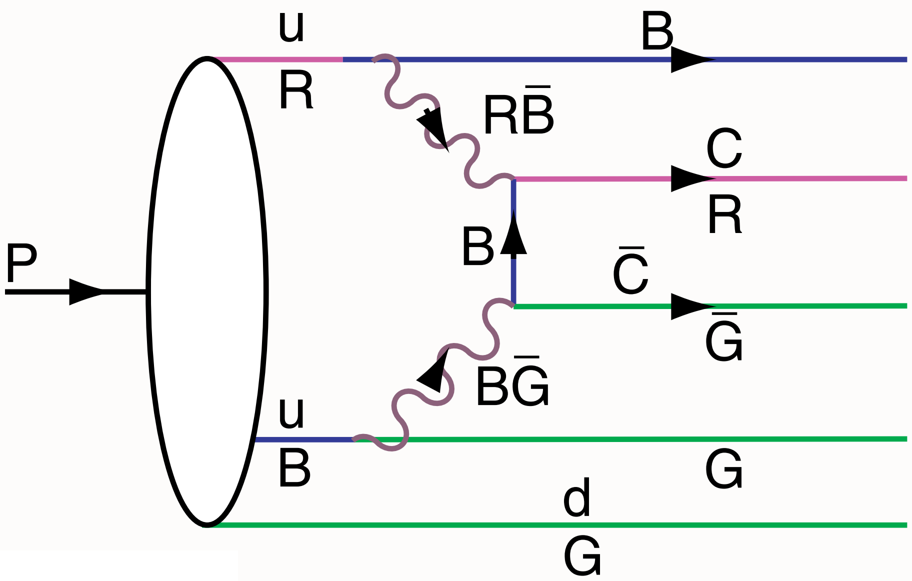
First Evidence for Intrinsic Charm





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

Hoyer, Peterson, Sakai, sjb



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

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

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

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

OPE derivation - M.Polyakov et al.

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

$c\bar{c}$ in Color Octet

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

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

High x charm!

Charm at Threshold

- 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 $pp \to \Lambda_c X$

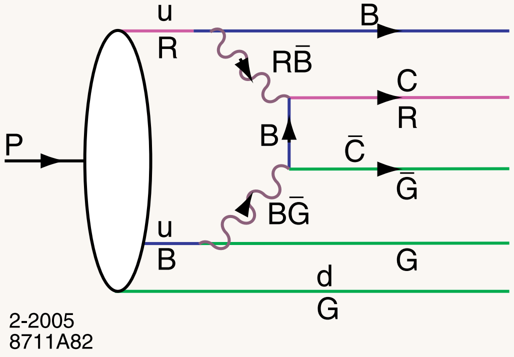
- High x_F $pp \to \Lambda_b X$

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

IC Structure Function: Critical Measurement for EIC

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



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

Use extreme caution when using $\gamma g \to c\bar{c}$ or $gg \to \bar{c}c$ to tag gluon dynamics

Light-Front Wavefunctions

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

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

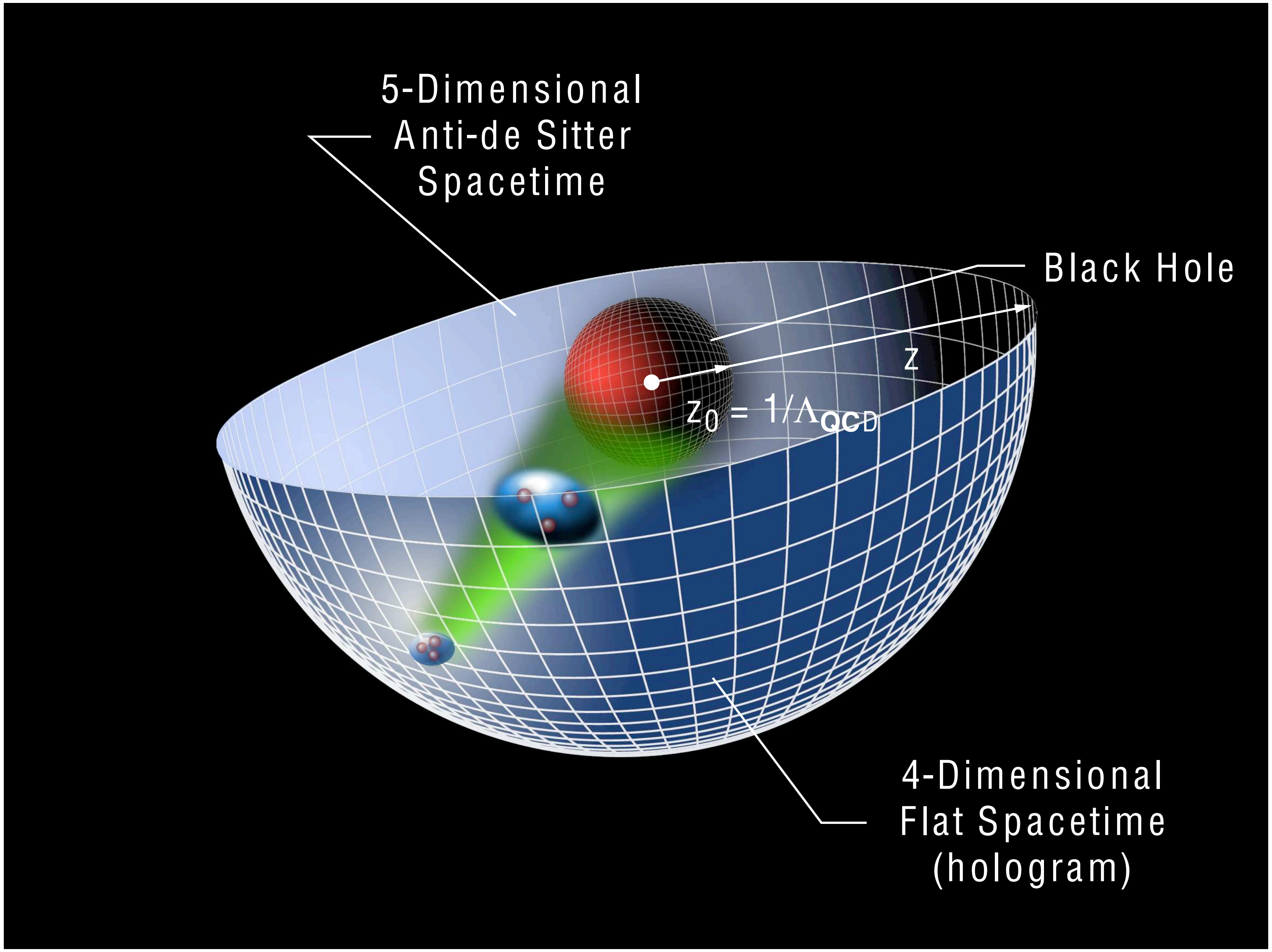
$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

$$\mathrm{H}_{LF}^{QCD}|\psi> = M^2|\psi>$$

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

Applications of AdS/CFT to QCD



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

in collaboration with Guy de Teramond

Goal:

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

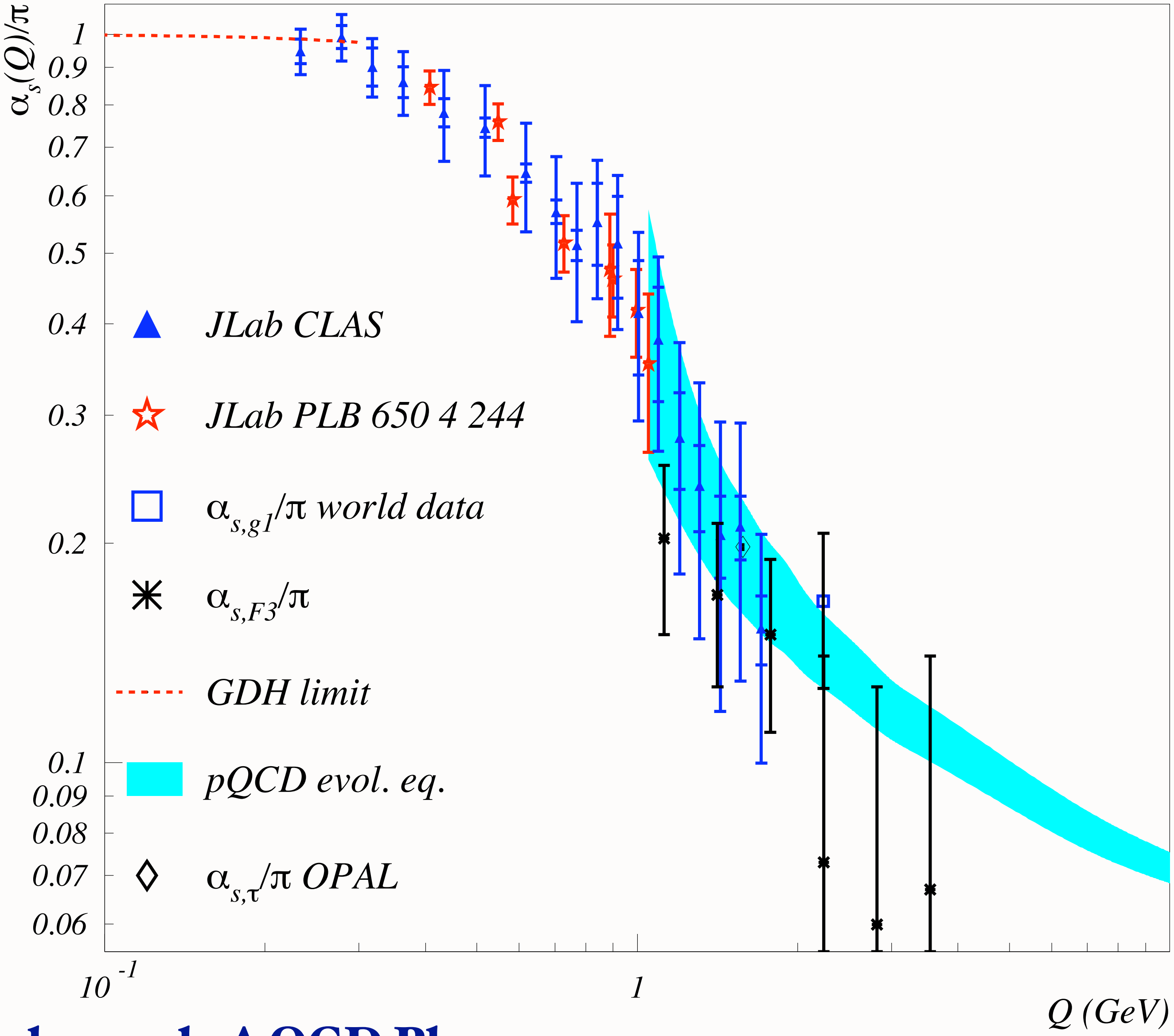
- **Analogous to the Schrodinger Equation for Atomic Physics**

- *AdS/QCD Holographic Model*

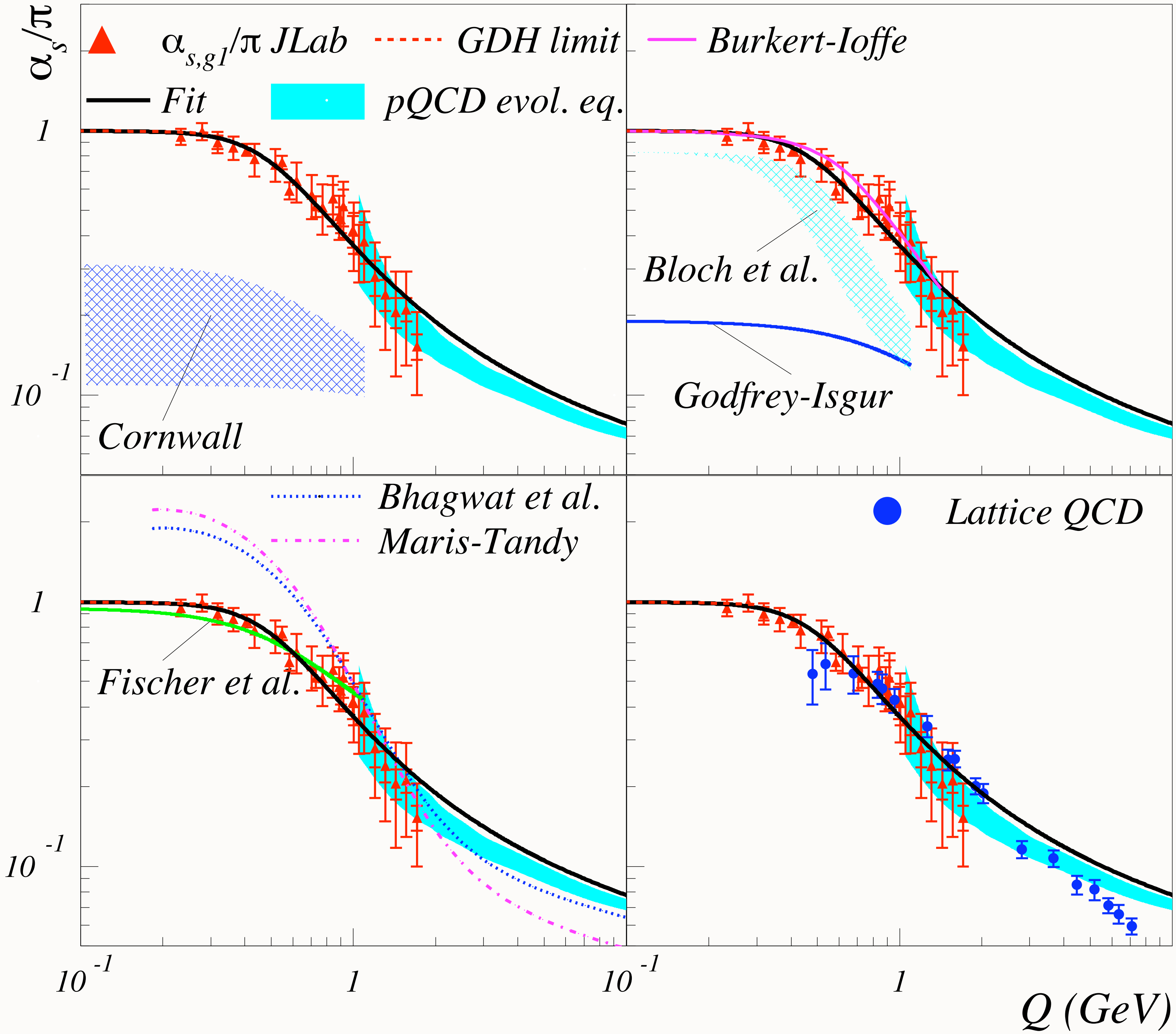
Deur, Korsch, et al: Effective Charge from Bjorken Sum Rule

$$\Gamma_{bj}^{p-n}(Q^2) \equiv \frac{g_A}{6}[1 - \frac{\alpha_s^{g_1}(Q^2)}{\pi}]$$

IR Conformal
Window
--> AdS/QCD



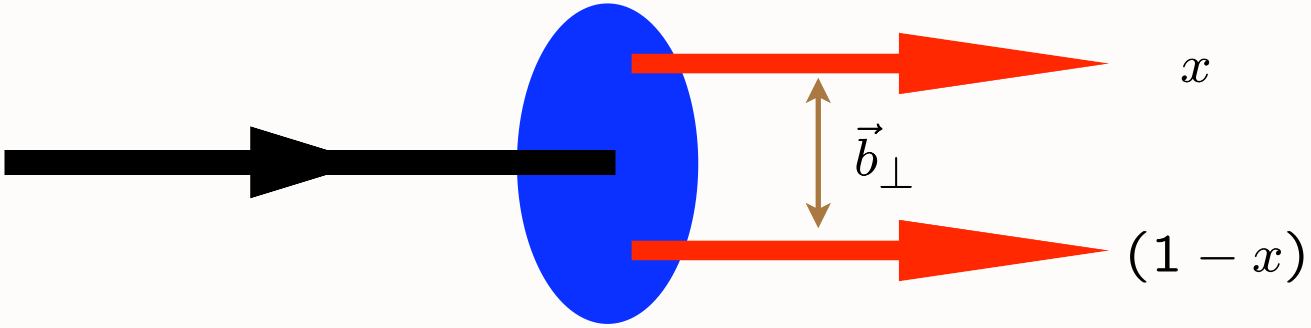
Deur, Korsch, et al.



LF(3+1) AdS5

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

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



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

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

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

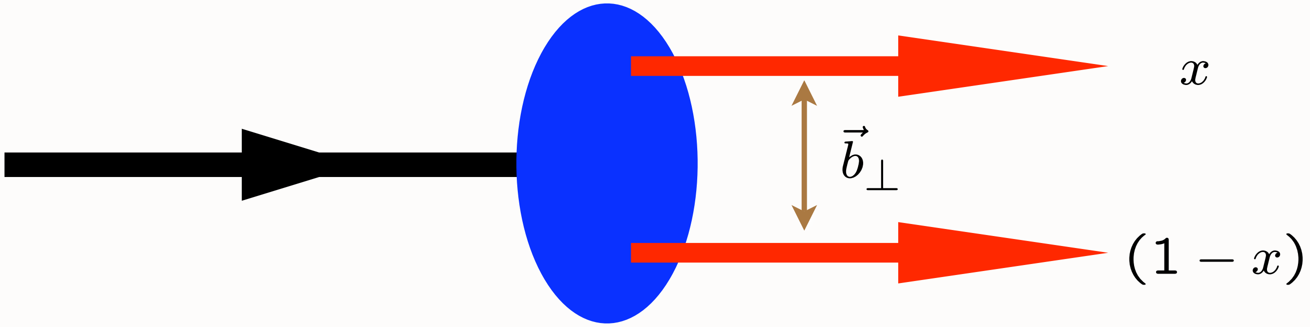
Relativistic LF radial equation

Frame Independent

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

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

G. de Teramond, sjb



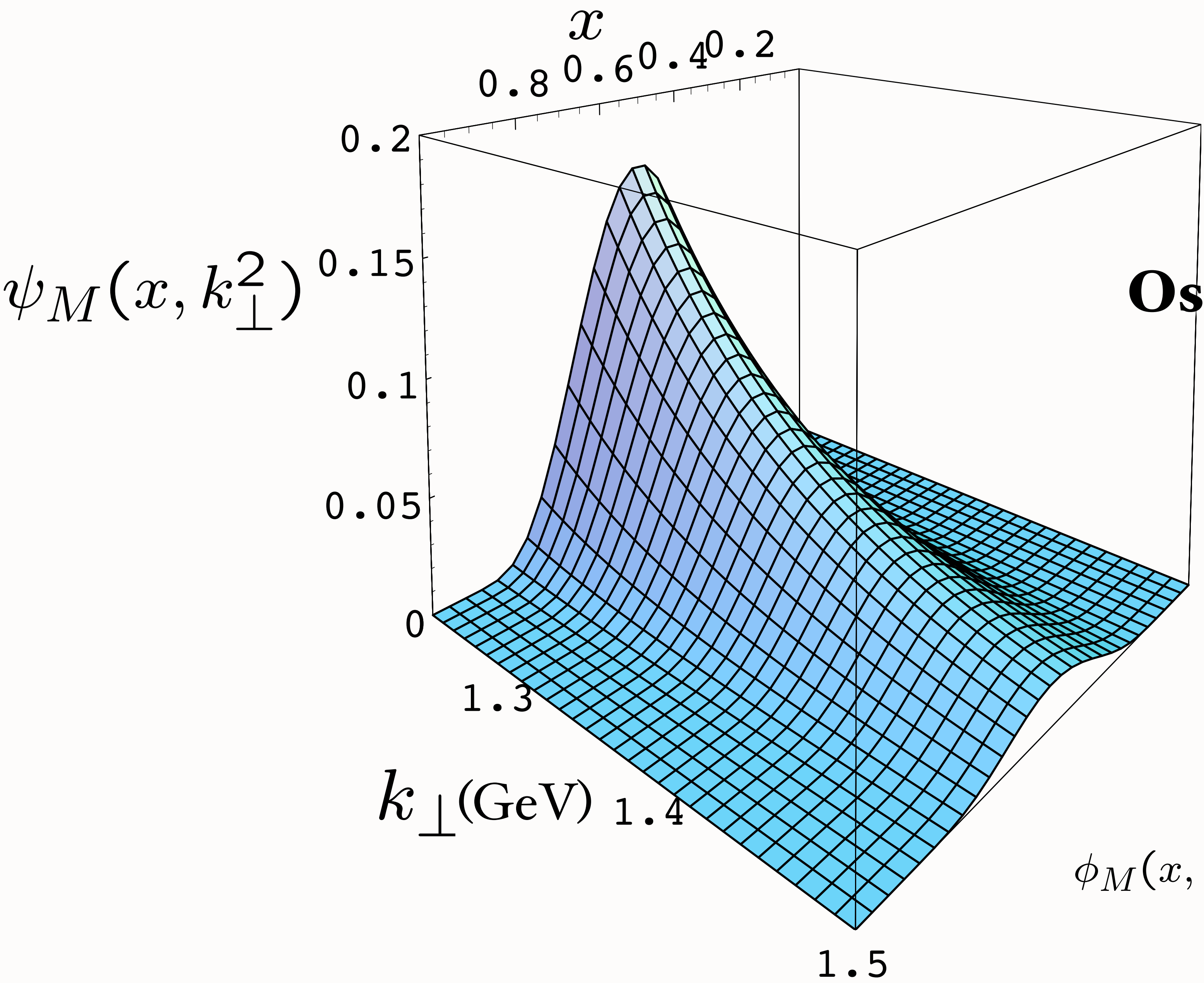
Effective conformal potential:

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

$$+\kappa^4\zeta^2$$

Soft wall harmonic oscillator potential:

Prediction from AdS/CFT: Meson LFWF



Harmonic Oscillator model

de Teramond, sjb

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

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

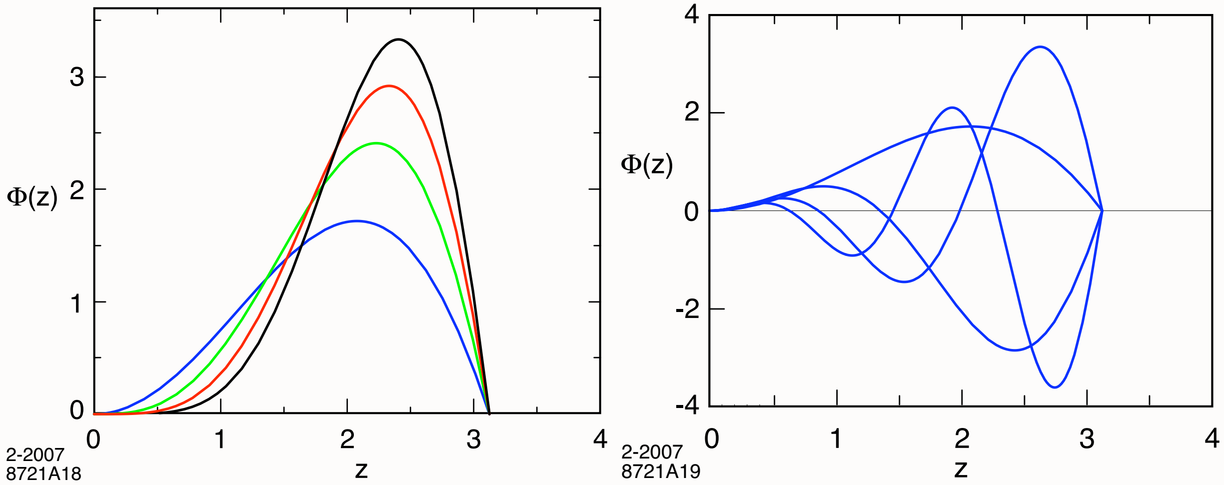


Fig: Orbital and radial AdS modes in the hard wall model for $\Lambda_{\rm QCD}$ = 0.32 GeV .

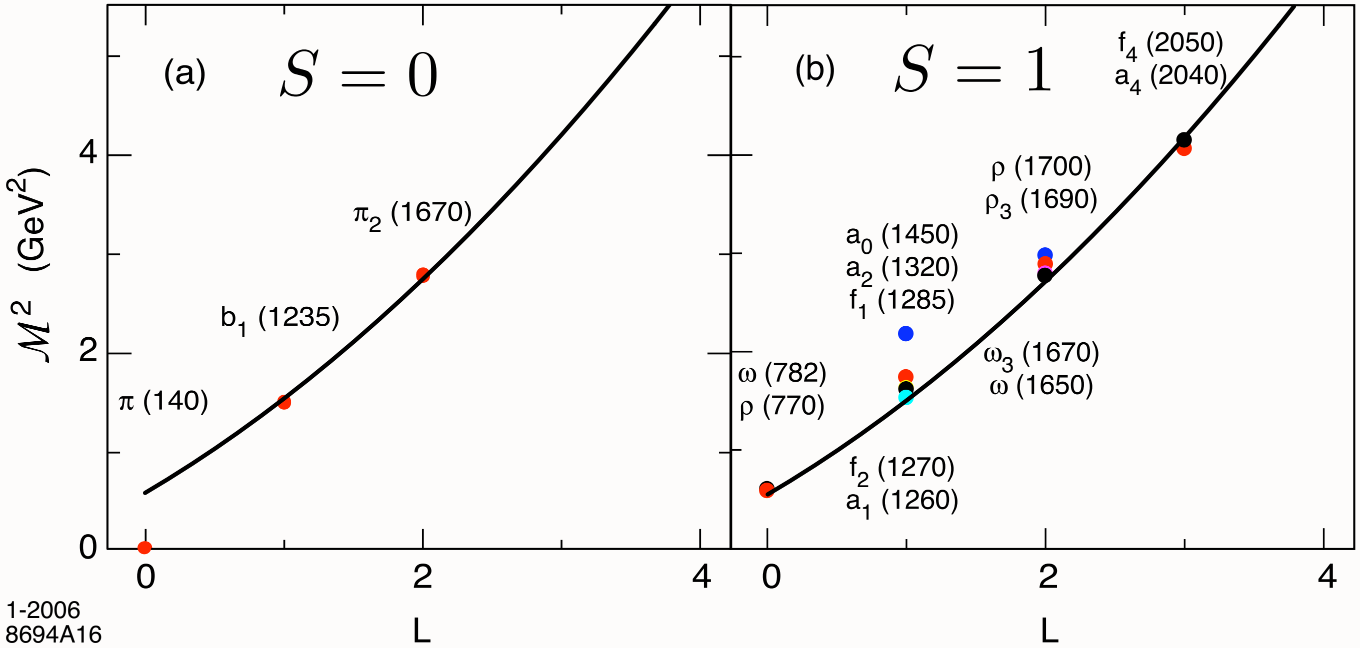
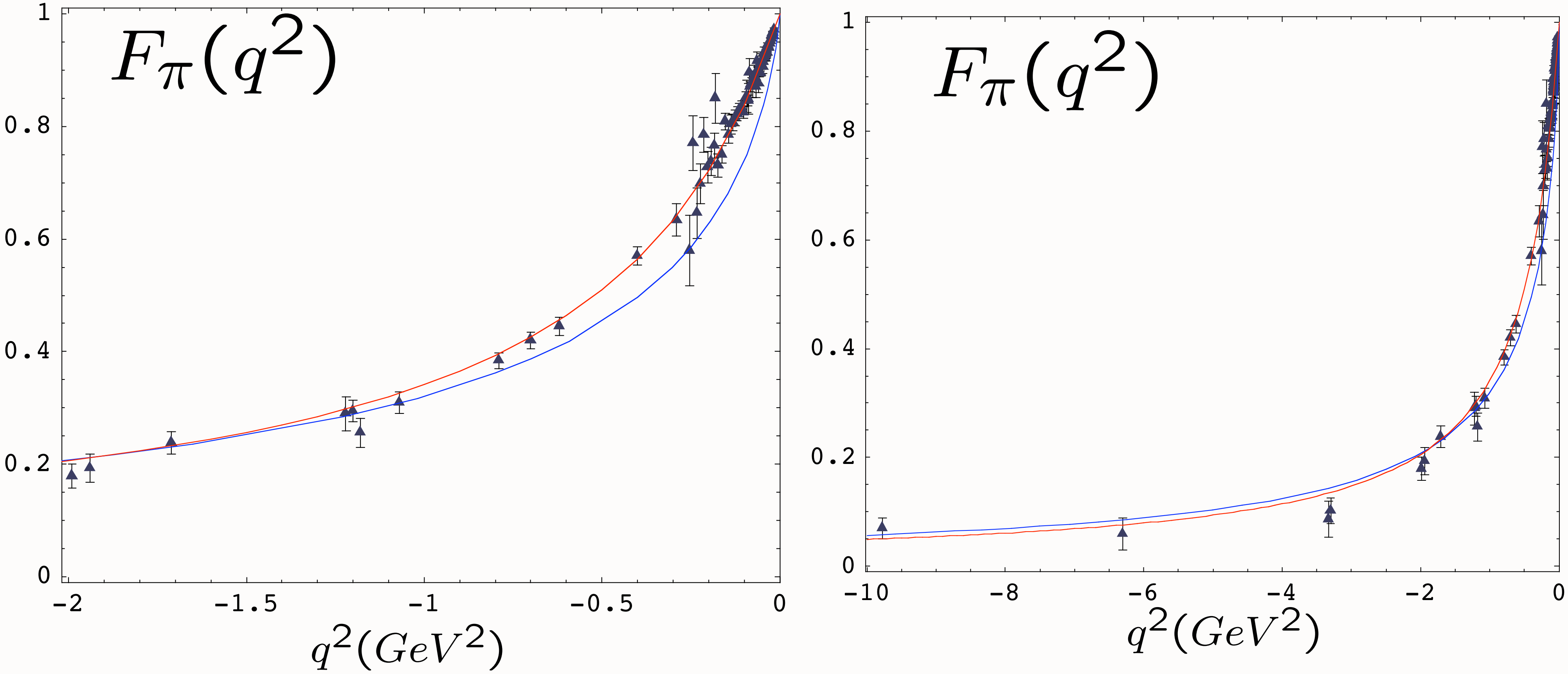


Fig: Light meson and vector meson orbital spectrum $\Lambda_{QCD} = 0.32 \, \mathrm{GeV}$

Spacelike pion form factor from AdS/CFT



Data Compilation from Baldini, Kloe and Volmer

🟥 SW: Harmonic Oscillator Confinement

🟦 HW: Truncated Space Confinement

One parameter - set by pion decay constant

de Teramond, sjb

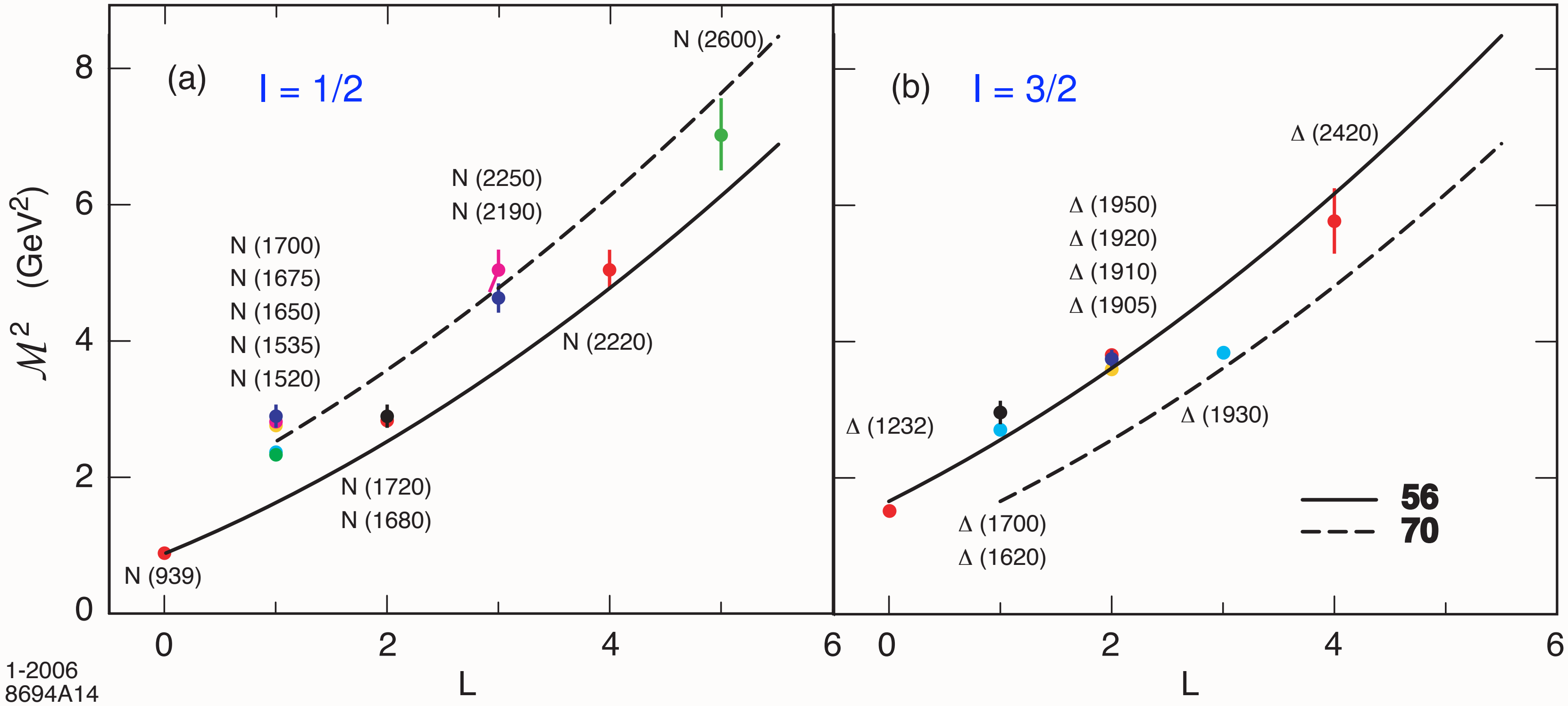
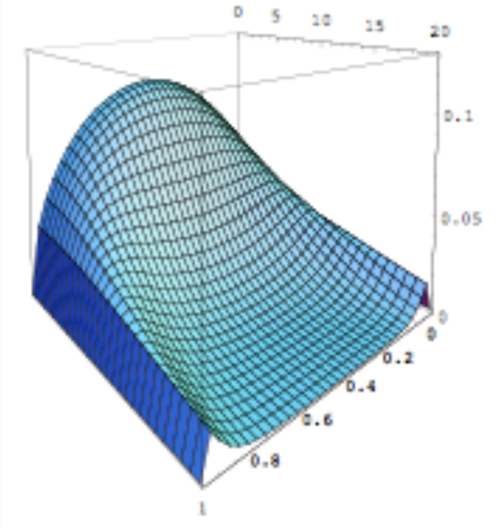
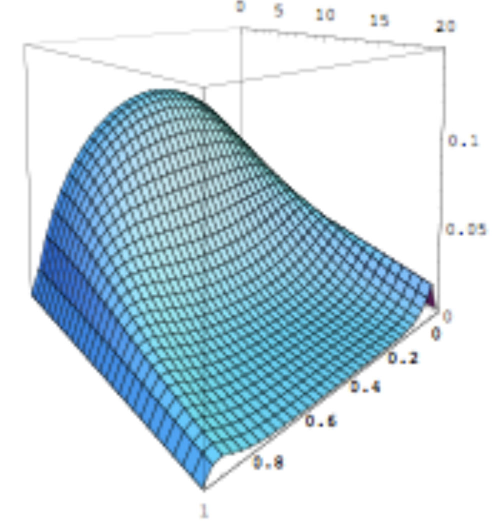


Fig: Light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV in the HW model. The $\mathbf{56}$ trajectory corresponds to L even $P = +$ states, and the $\mathbf{70}$ to L odd $P = -$ states.

$|\pi^+ >= |u\bar{d}>$

$m_u = 2\ MeV$
$m_d = 5\ MeV$



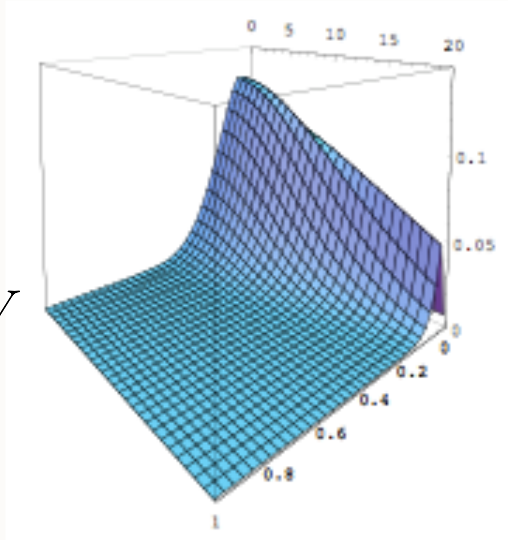


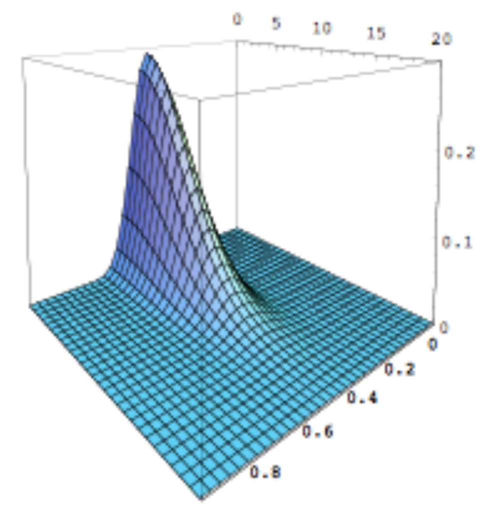
$|K^+ >= |u\bar{s}>$

$m_s = 95\ MeV$

$|D^+ >= |c\bar{d}>$

$m_c = 1.25\ GeV$

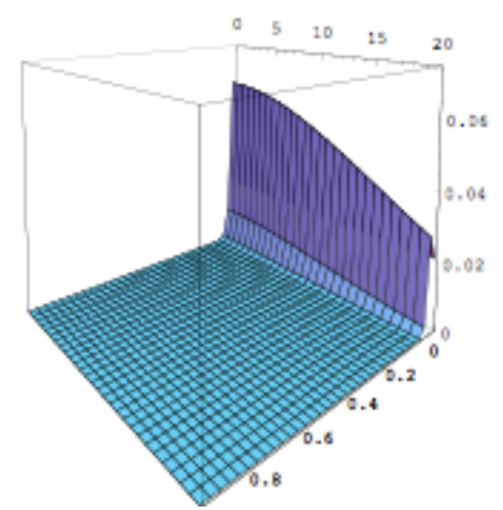


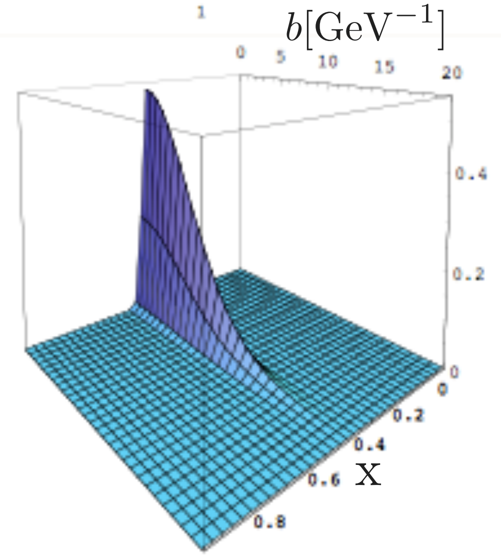


$|\eta_c >= |c\bar{c}>$

$|B^+ >= |u\bar{b}>$

$m_b = 4.2\ GeV$





$|\eta_b >= |b\bar{b}>$

$\kappa = 375\ MeV$

Meson LFWF (L=0) for massive quarks

$$\psi_{\bar{q}q/\pi}(x, \mathbf{k}_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}}\, e^{-\frac{\mathbf{k}_\perp^2 + m^2}{2\kappa^2 x(1-x)}},$$

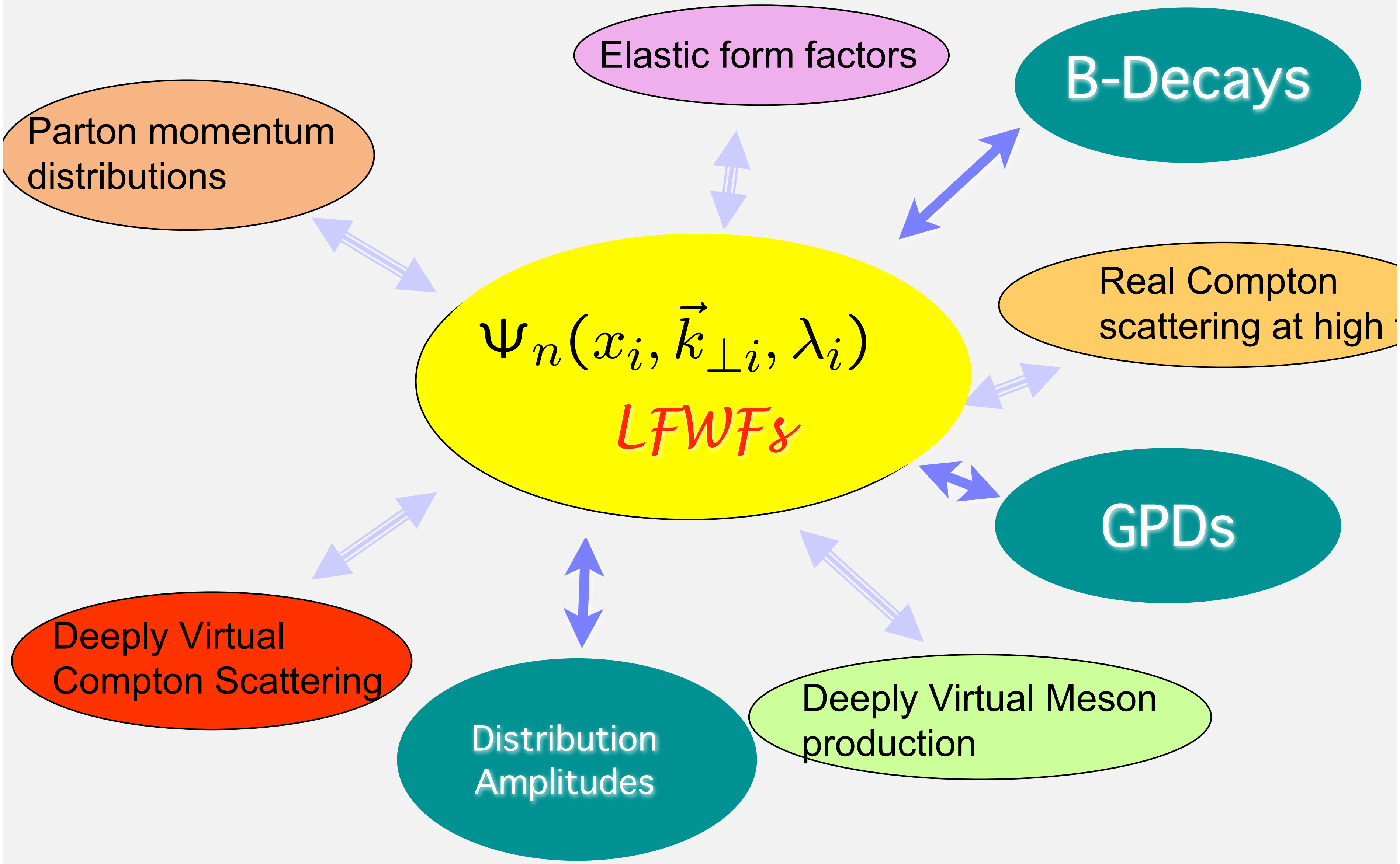
$$\widetilde{\psi}_{q\bar{q}/\pi}(x, \mathbf{b}_\perp) = \frac{\kappa}{\sqrt{\pi}}\sqrt{x(1-x)}\ \exp\left(-\frac{1}{2}\kappa^2 x(1-x)\mathbf{b}_\perp^2 - \frac{m^2}{2\kappa^2 x(1-x)}\right)$$

Key variable for n-parton LFWF with massive quarks:

$$\boxed{\chi^2 = \zeta^2 + \frac{1}{\kappa^4}\sum_{i=1}^{n}\frac{m_i^2}{x_i},}$$

$$\zeta = \sqrt{\frac{x}{1-x}}\left|\sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}\right|$$

A Unified Description of Hadron Structure



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

LFWFs

Elastic form factors

B-Decays

Parton momentum distributions

Real Compton scattering at high

GPDs

Deeply Virtual Compton Scattering

Distribution Amplitudes

Deeply Virtual Meson production

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

Diehl, Hwang, sjb

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

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

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

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

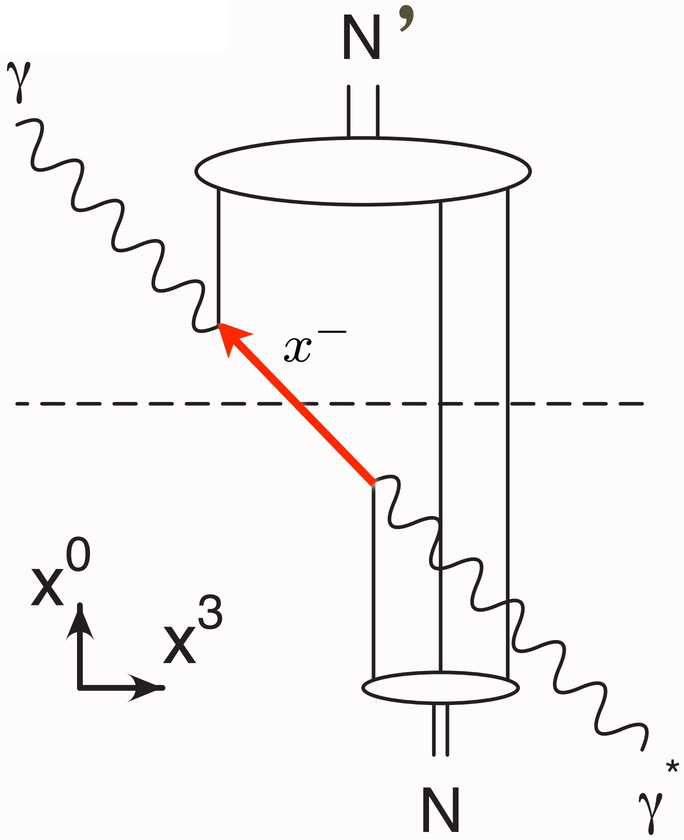
$$x'_1 = \frac{x_1-\zeta}{1-\zeta}, \qquad \vec{k}'_{\perp 1} = \vec{k}_{\perp 1} - \frac{1-x_1}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the struck quark,}$$

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

Space-time picture of DVCS

P. Hoyer

$$\sigma = \tfrac{1}{2} x^- P^+$$



$$x^+ = \mathbf{x}_\perp = 0)$$

The position of the struck quark differs by x^- in the two wave functions

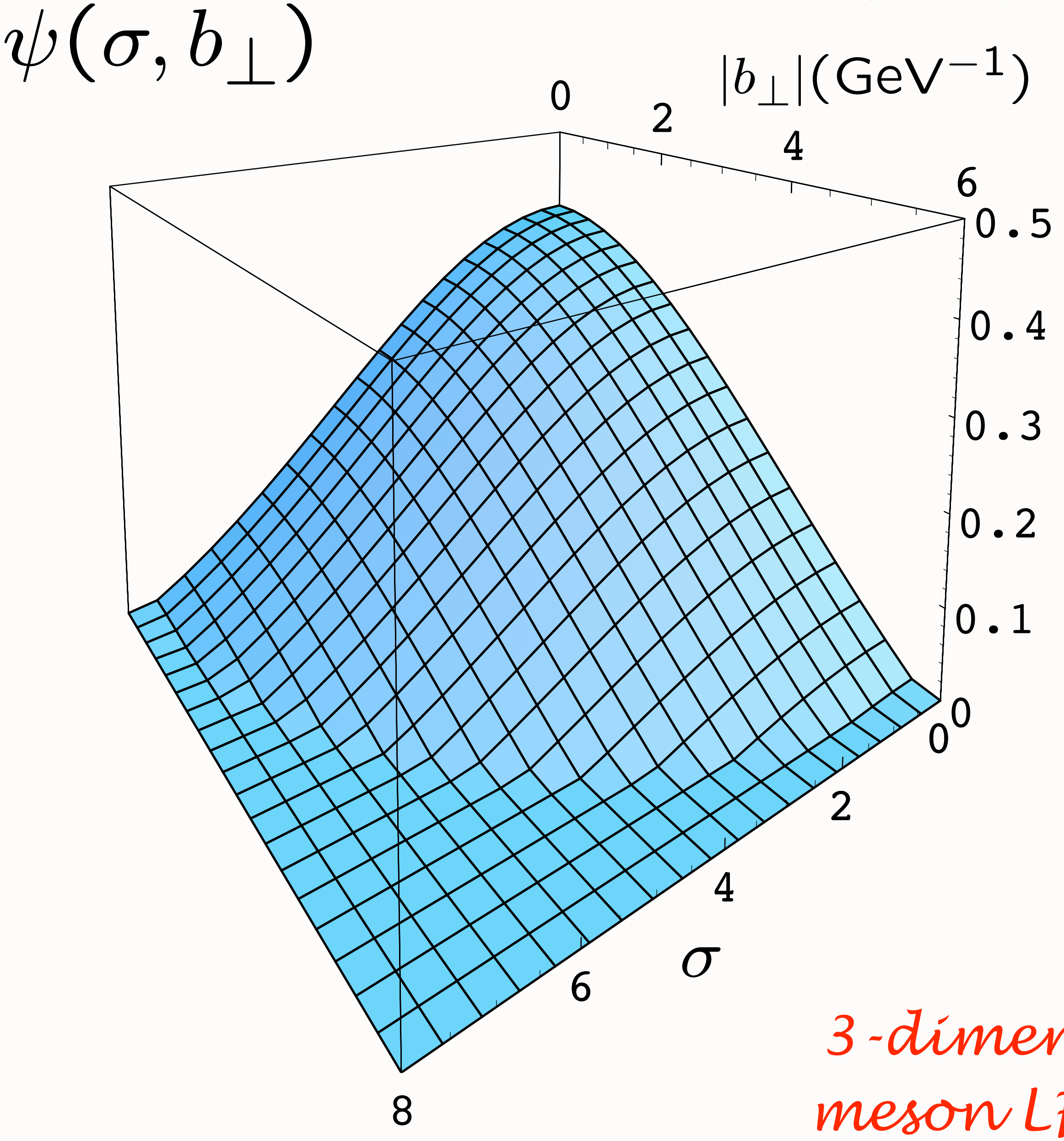
Measure x- distribution from DVCS:
Take Fourier transform of skewness,
the longitudinal momentum transfer

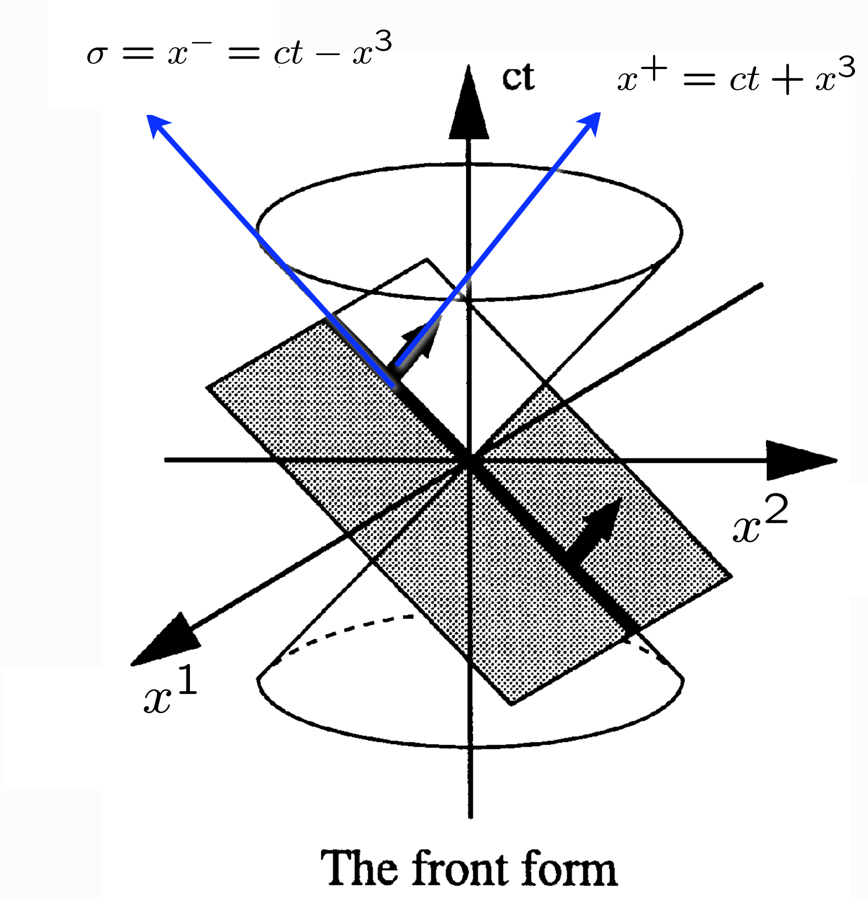
$$\zeta = \frac{Q^2}{2p \cdot q}$$

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

AdS/CFT Holographic Model

G. de Teramond
SJB





The front form

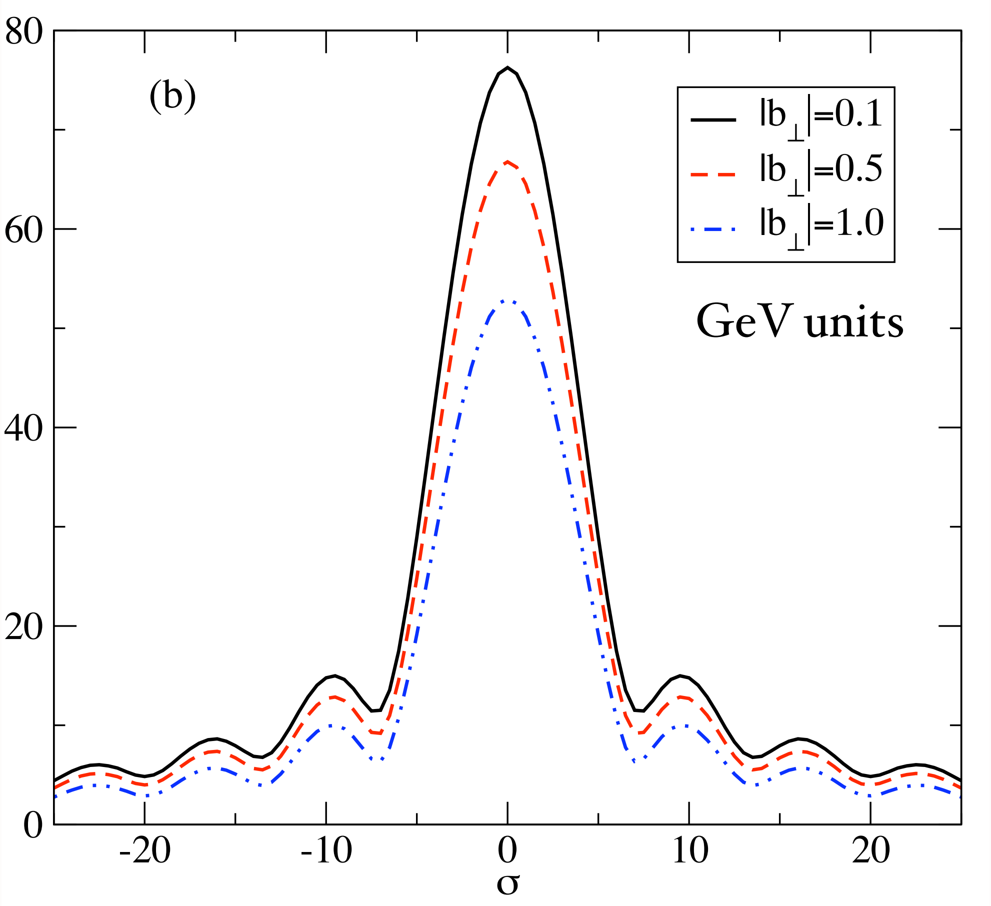
3-dimensional photograph: meson LFWF at fixed LF Time

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

Hadron Optics

$$A(\sigma, b_\perp) = \frac{1}{2\pi}\int d\zeta e^{i\sigma\zeta}\tilde{A}(b_\perp, \zeta)$$

$$\sigma = \tfrac{1}{2}x^- P^+ \qquad \zeta = \frac{Q^2}{2p\cdot q}$$

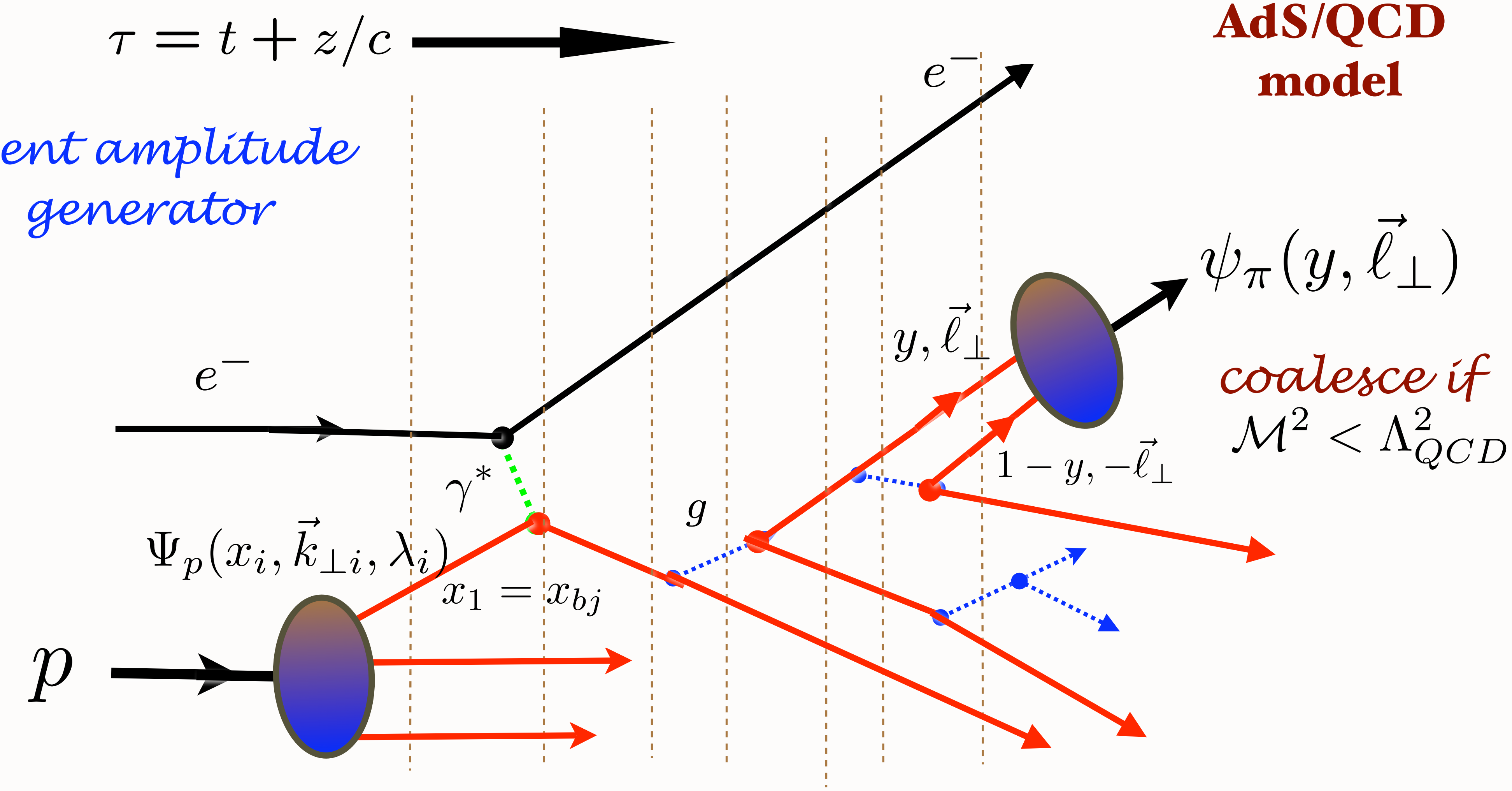


The Fourier Spectrum of the DVCS amplitude in σ space for different fixed values of $|b_\perp|$.

DVCS Amplitude using holographic QCD meson LFWF

$$\Lambda_{QCD} = 0.32$$

Jet Hadronization at the Amplitude Level



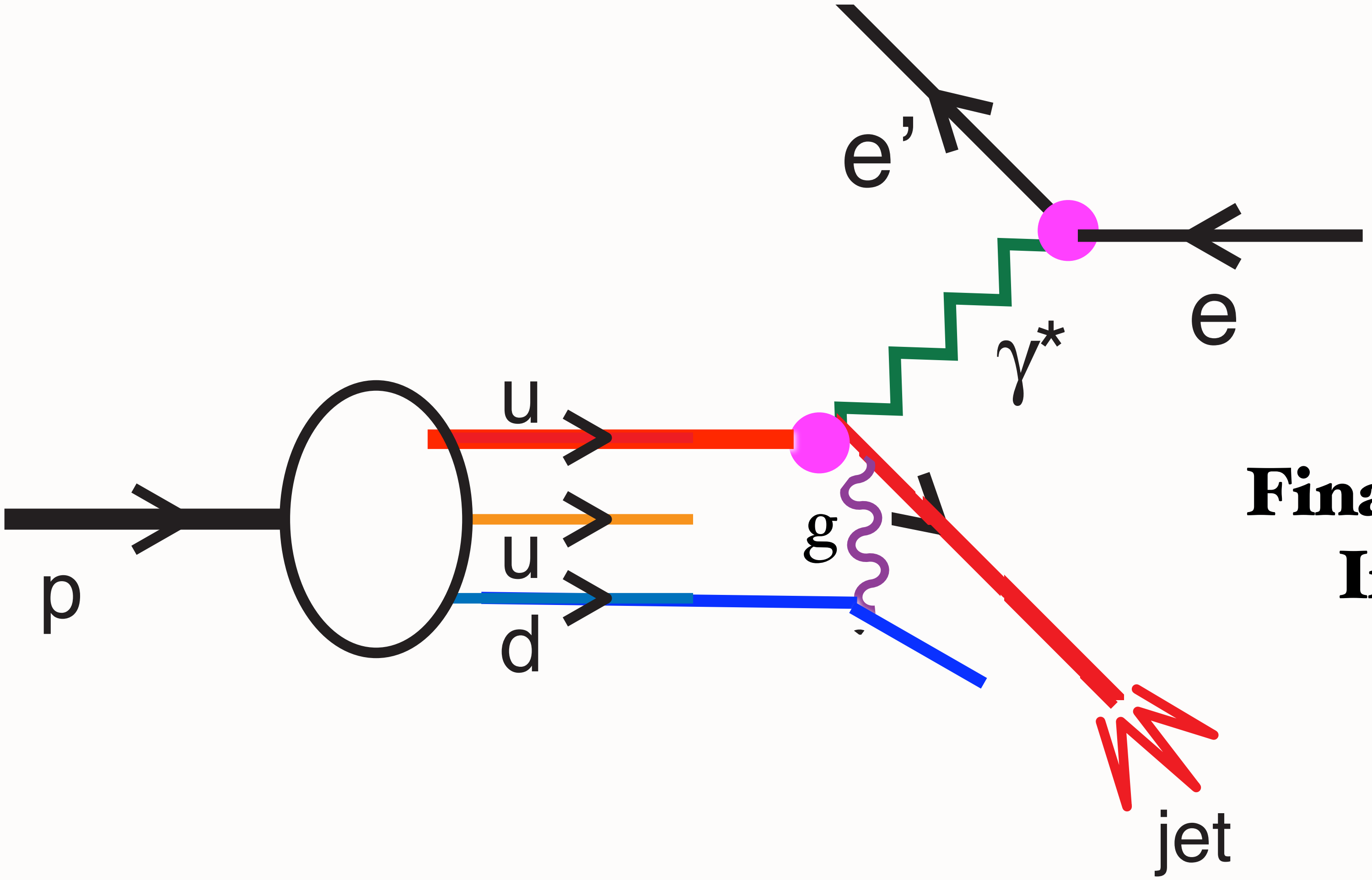
AdS/QCD model

Event amplitude generator

coalesce if $\mathcal{M}^2 < \Lambda^2_{QCD}$

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

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:

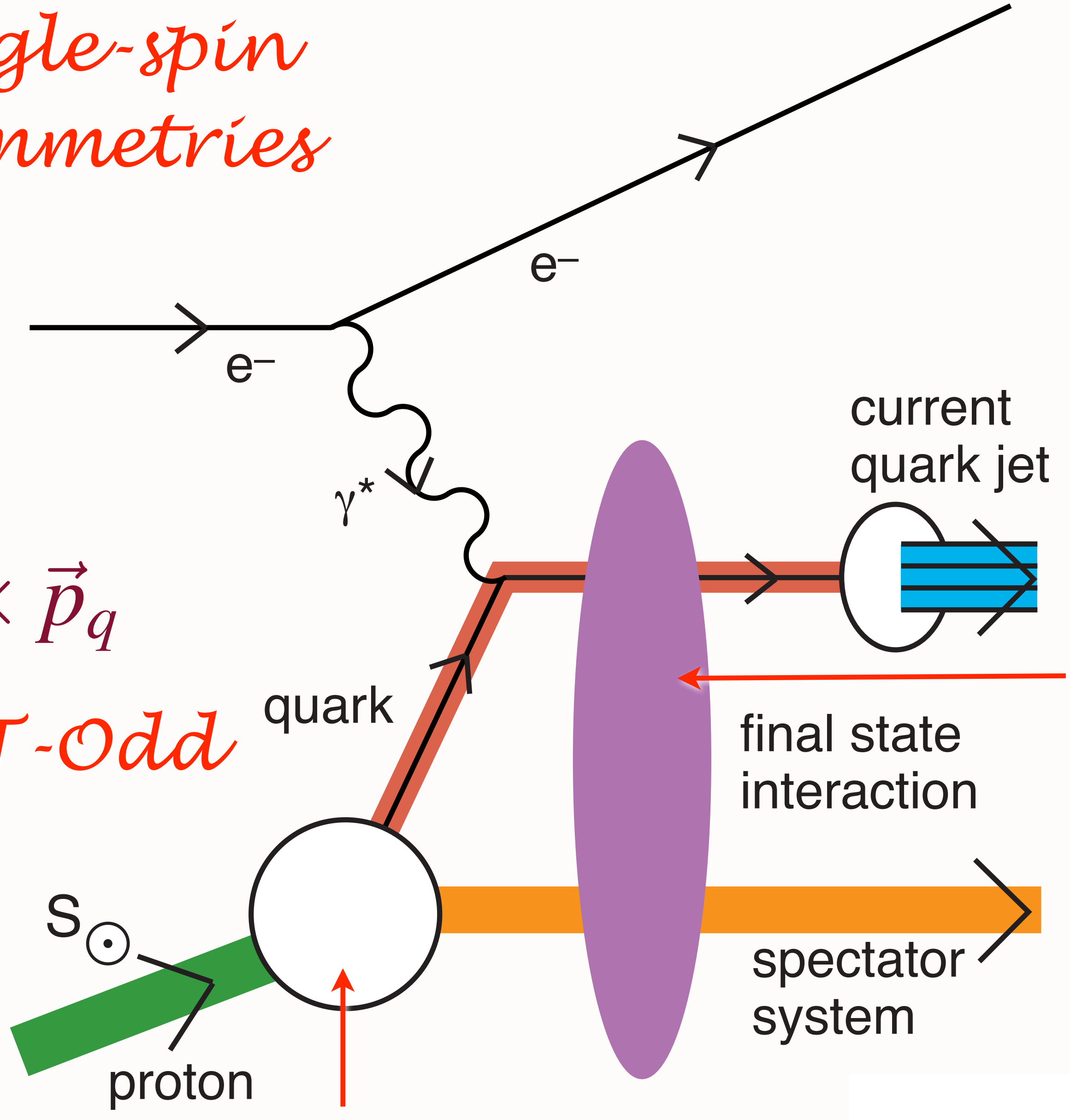
Final-state interactions of struck quark can be neglected

Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt
Ji, Yuan

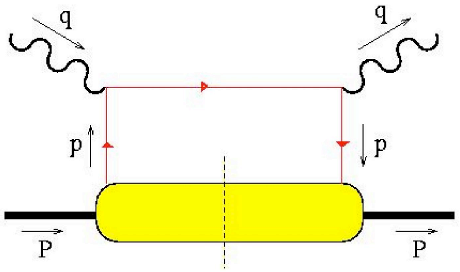


$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$

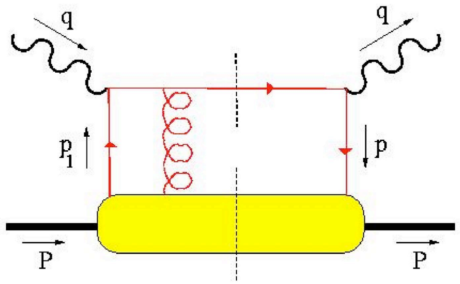
Pseudo-T-Odd

QCD S- and P- Coulomb Phases --Wilson Line

Light-Front Wavefunction
S and P- Waves



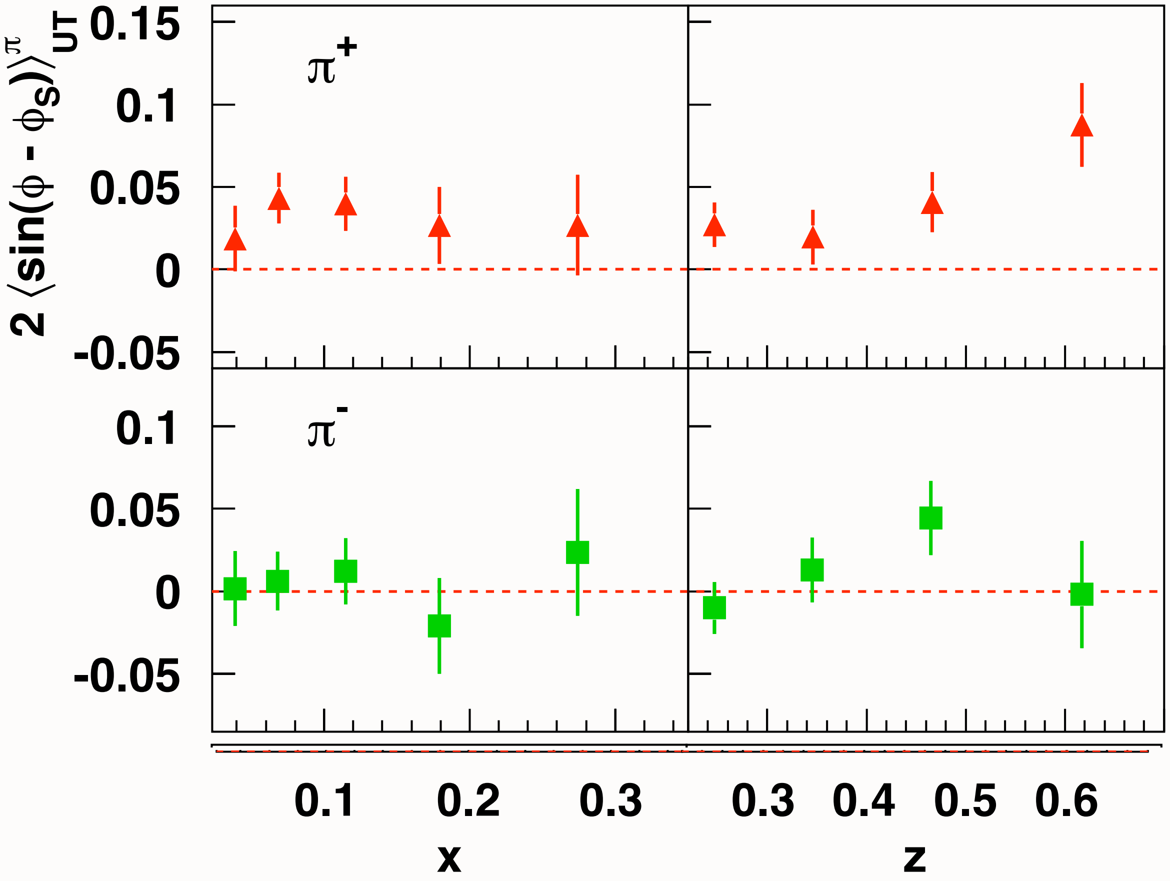
can interfere
with



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

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

Sivers asymmetry from HERMES



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

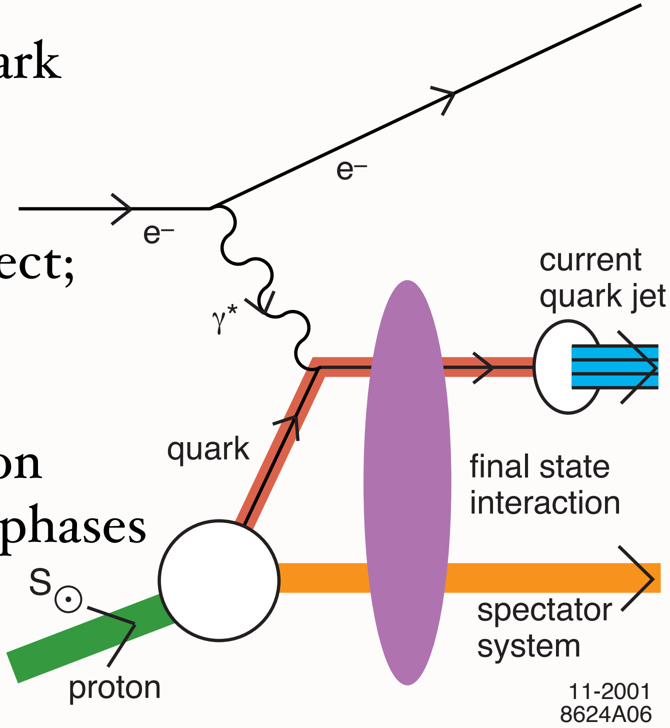
Gamberg: Hermes data compatible with BHS model

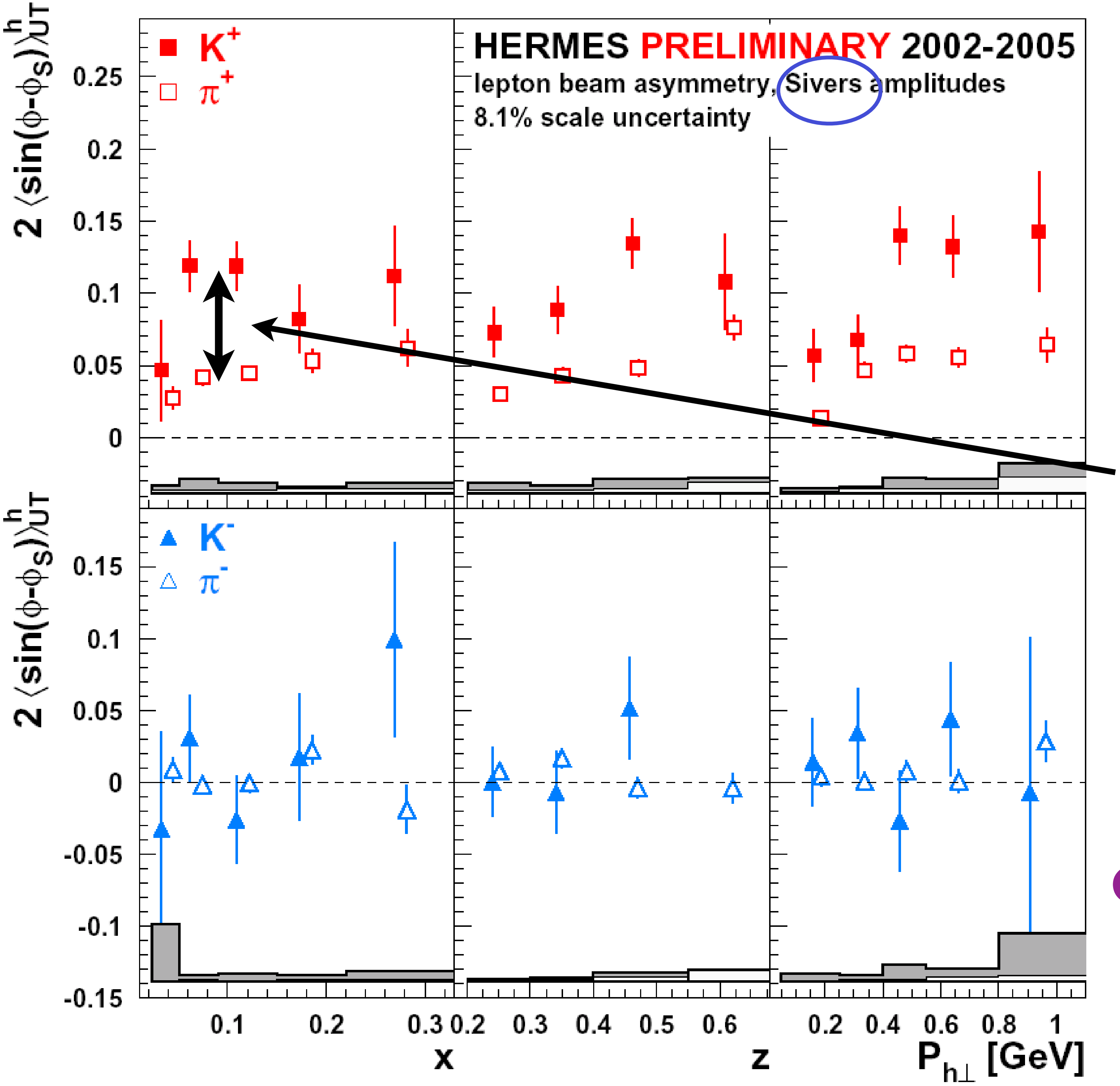
Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

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

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

- 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
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD phase at soft scale!
- New window to QCD coupling and running gluon mass in the IR
- QED S and P Coulomb phases infinite -- difference of phases finite!





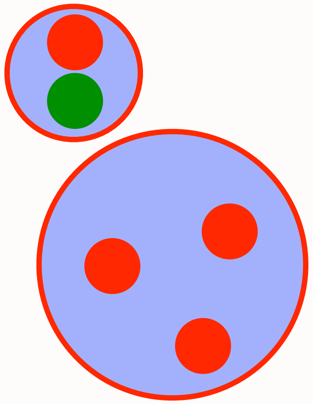
Large K$^+$ asymmetry!

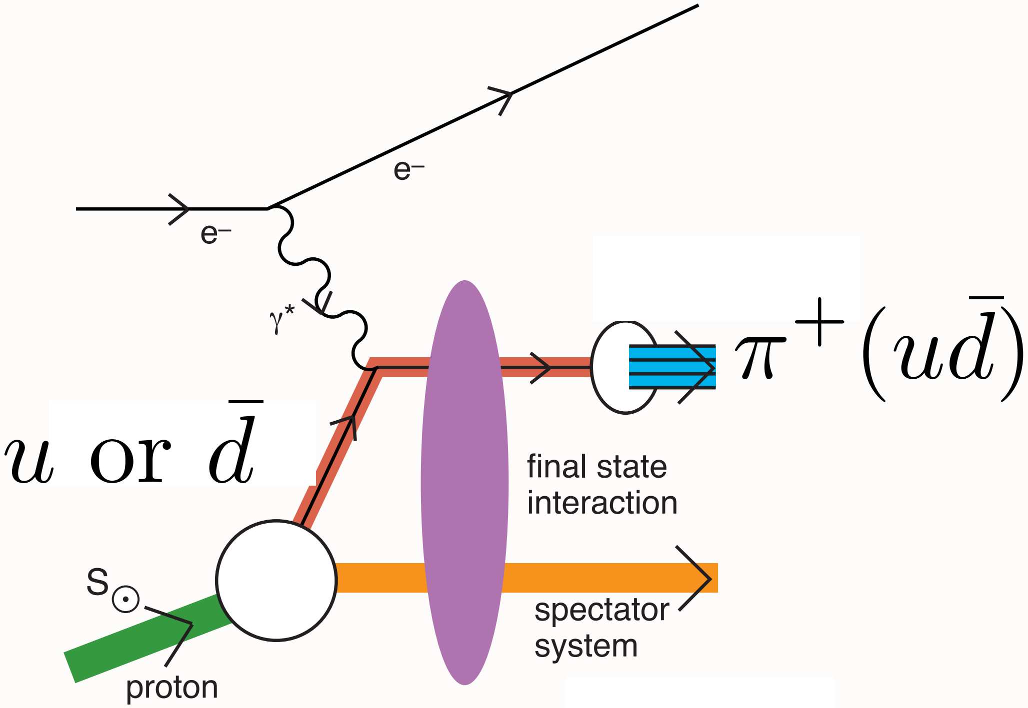
Difference at low x from sea-quark OAM?

Gardner, sjb in progress

Gardner, sjb

Sea quarks carry orbital angular momentum





Sivers effect for $\pi^+(u\bar{d})$ reduced by $L_{\bar{d}}$ at low x

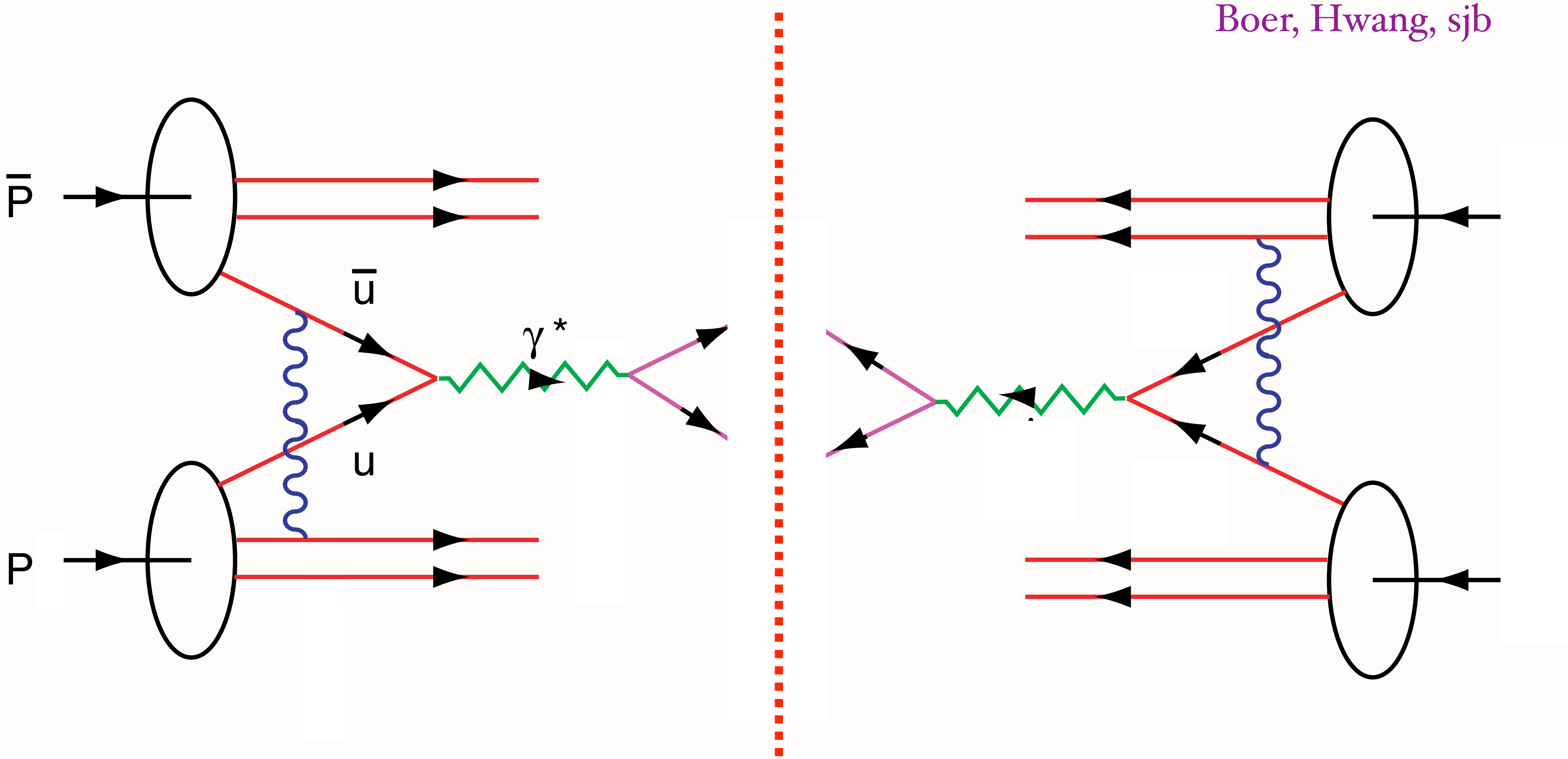
Sivers effect for $\pi^-(d\bar{u})$ reduced by $L_{\bar{u}}$ at low x

Sivers effect for $K^+(u\bar{s})$ increased by $L_{\bar{s}}$!

Physics of Rescattering

- Sivers Amplitude is Imaginary
- Phase comes from FSI
- Cannot be computed from wavefunction of proton in isolation!
- Phase requires QCD coupling in infrared
- Process dependent
- Input from hadron dynamics: Overlap of spin parallel and antiparallel LFWFS
- Same amplitudes which determine Pauli form factor

Boer, Hwang, sjb

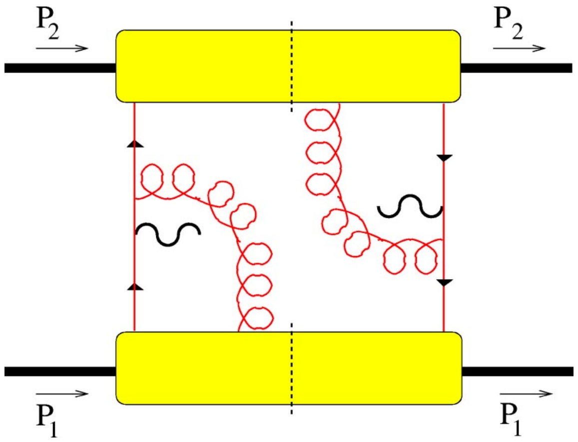


DY $\cos 2\phi$ correlation at leading twist from double ISI

Anomalous effect from Double ISI in Massive Lepton Production

Boer, Hwang, sjb

$\cos 2\phi$ correlation



- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

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

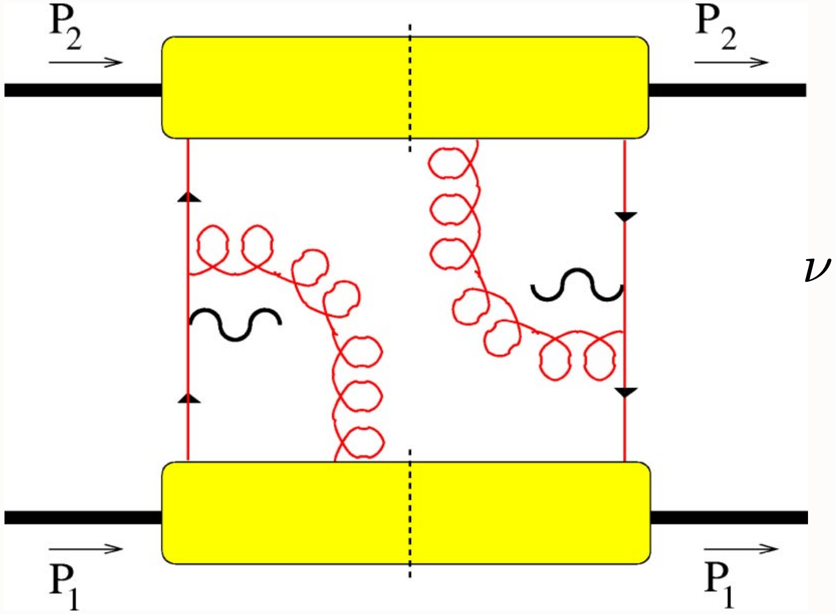
Boer, Hwang, sjb

Drell-Yan planar correlations

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

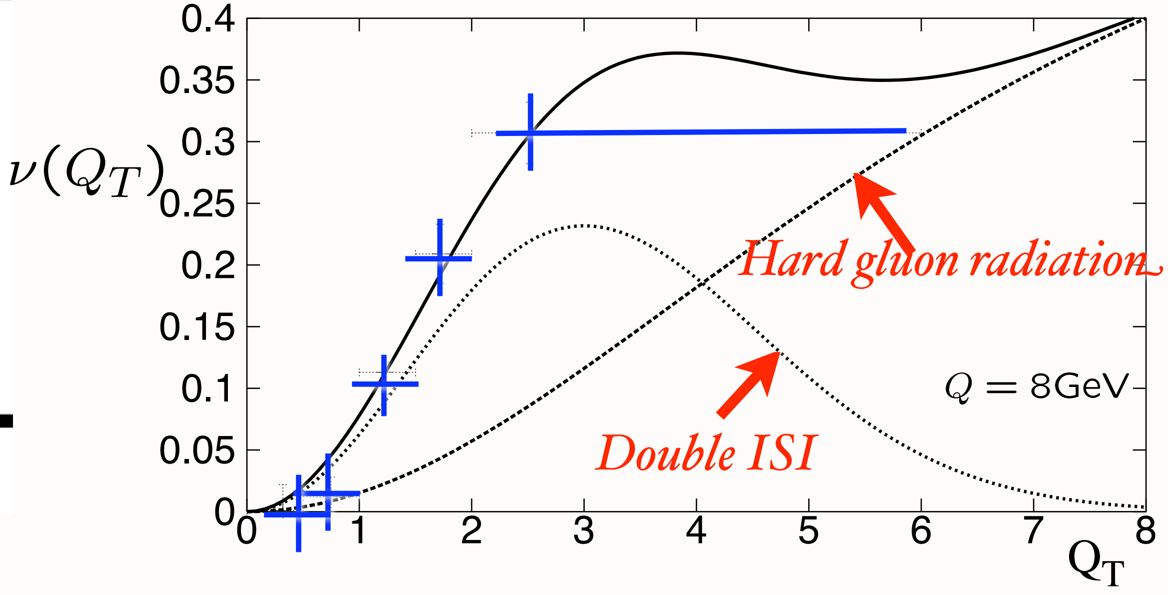
PQCD Factorization (Lam Tung): $1-\lambda-2\nu = 0$

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

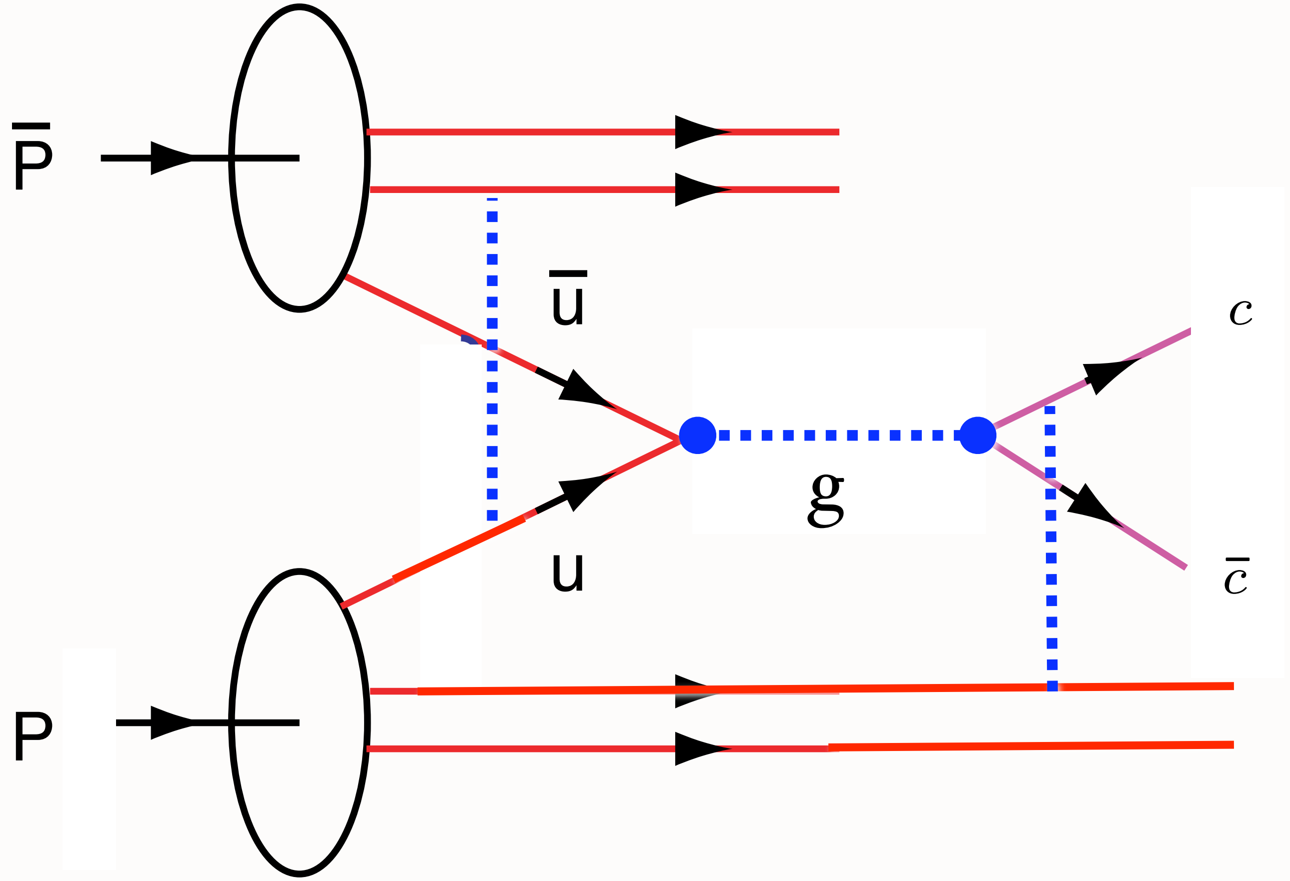


Violates Lam-Tung relation!

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



Model: Boer,

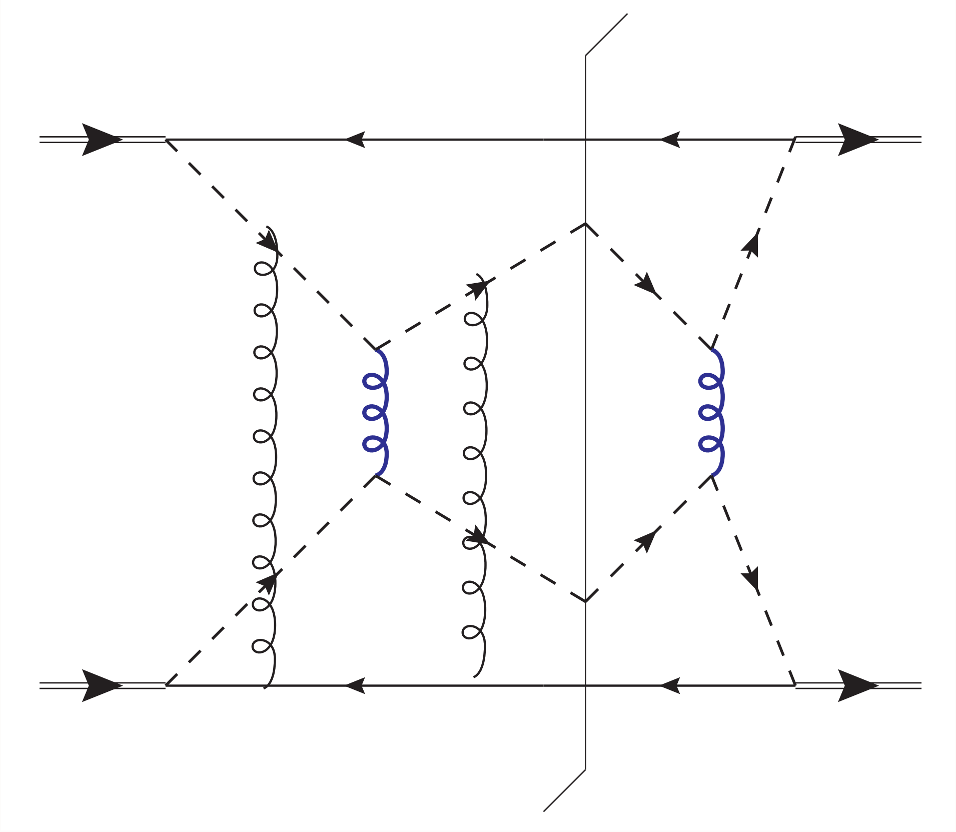


Problem for factorization when both ISI and FSI occur

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

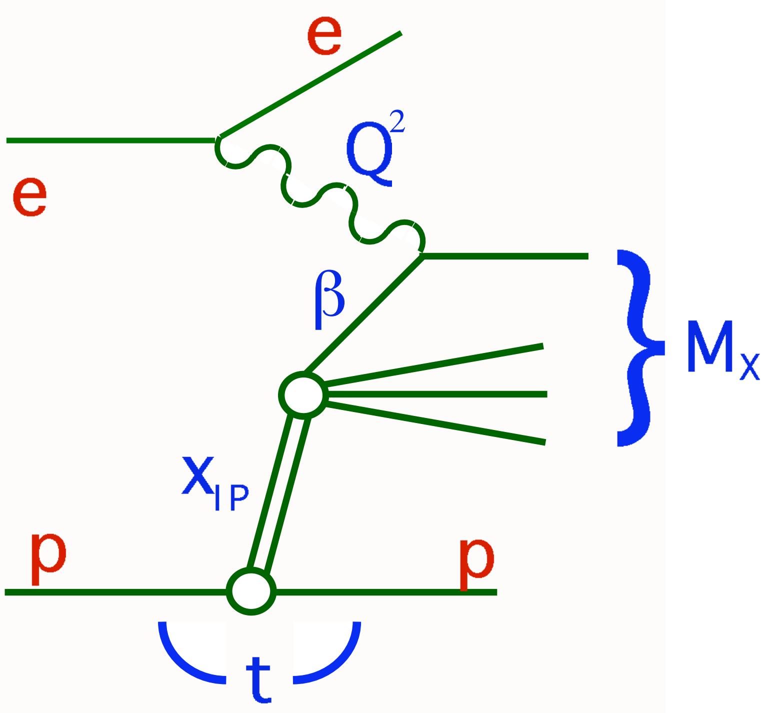
John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

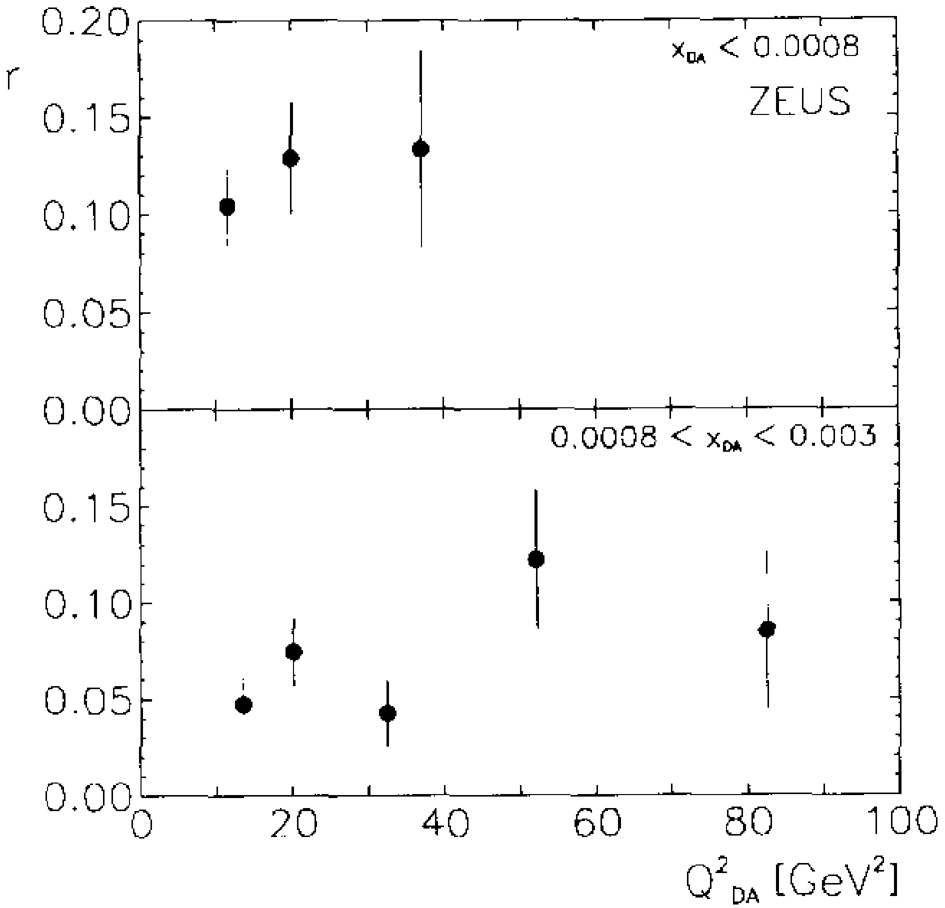
e-Print: **arXiv:0705.2141** [hep-ph]



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

Remarkable observation at HERA





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

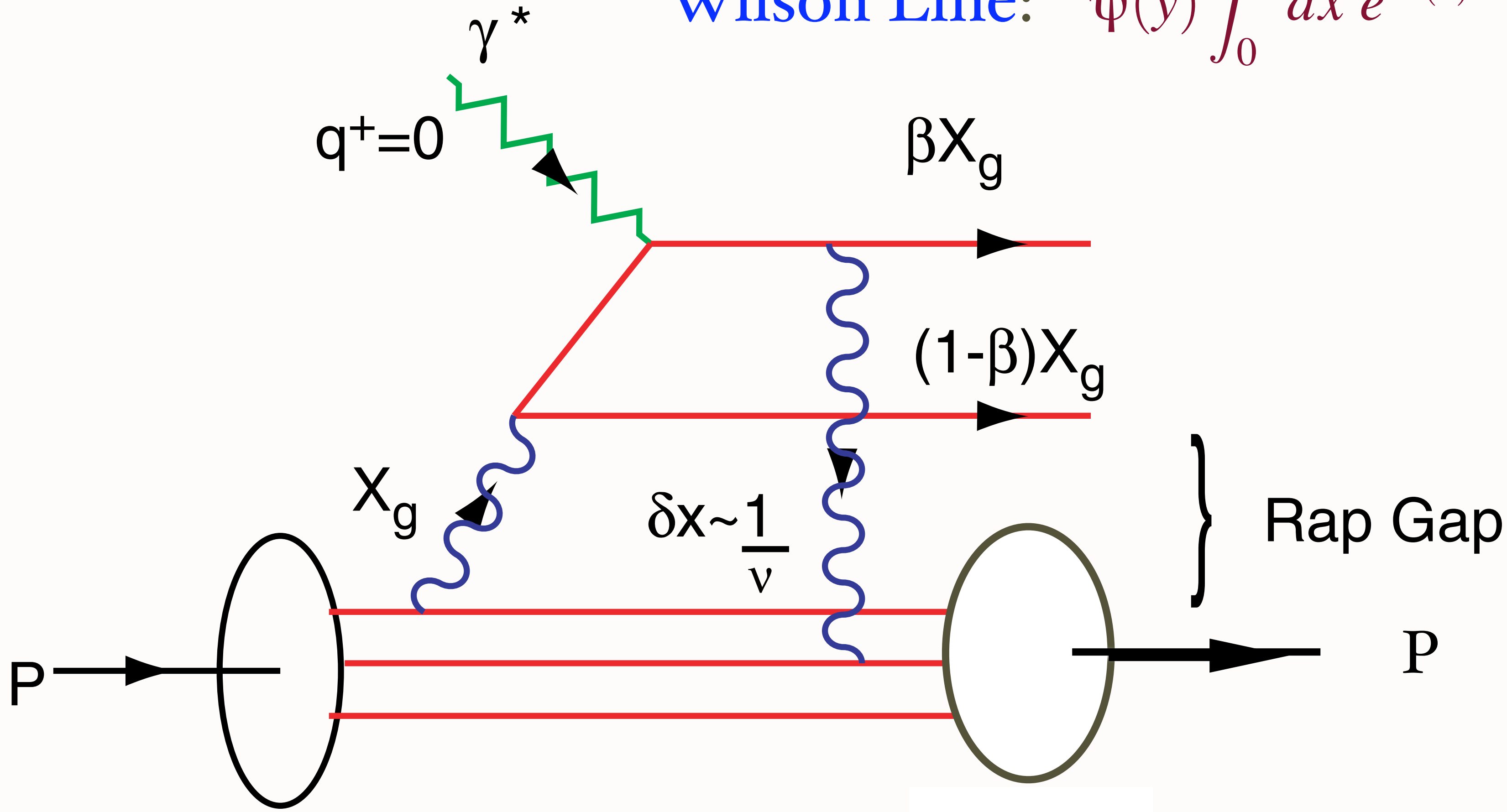
10% to 15% of DIS events are diffractive !

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

Hoyer, Marchal, Peigne, Sannino, sjb

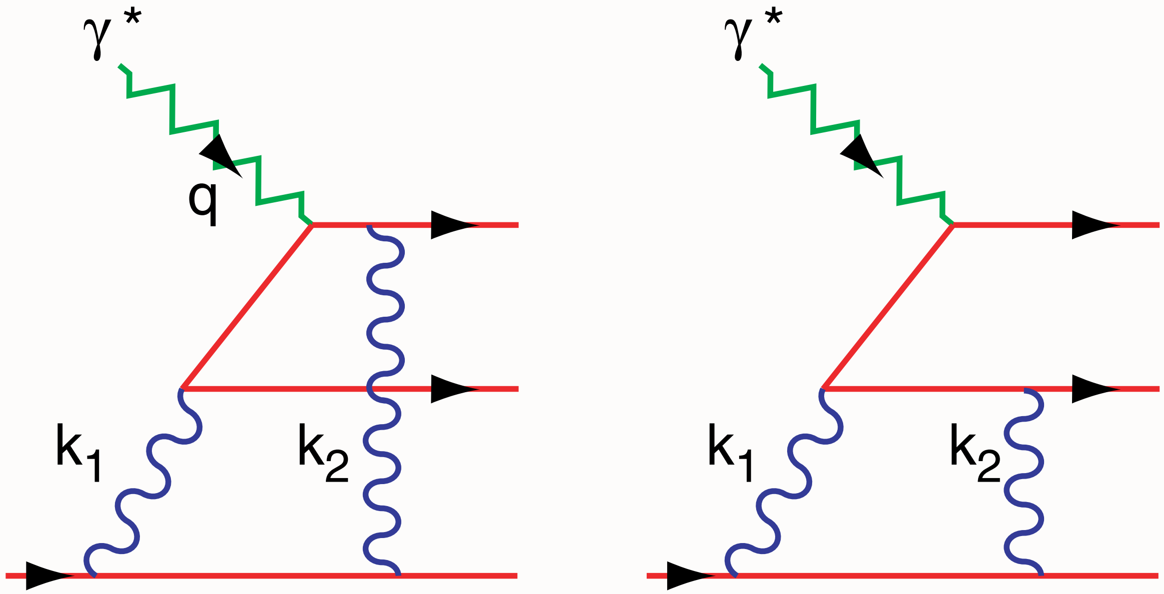
QCD Mechanism for Rapidity Gaps

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



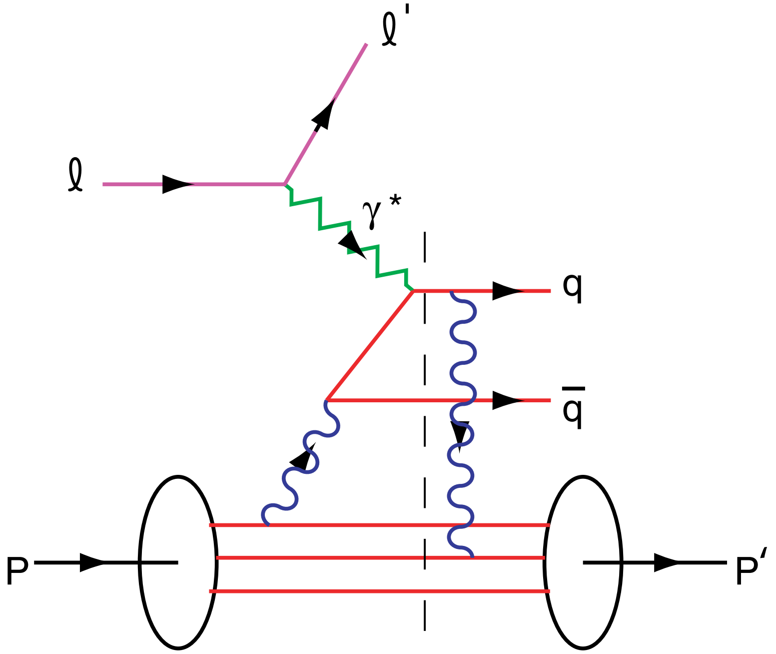
Reproduces lab-frame color dipole approach

Final State Interactions in QCD



Feynman Gauge Light-Cone Gauge

Result is Gauge Independent

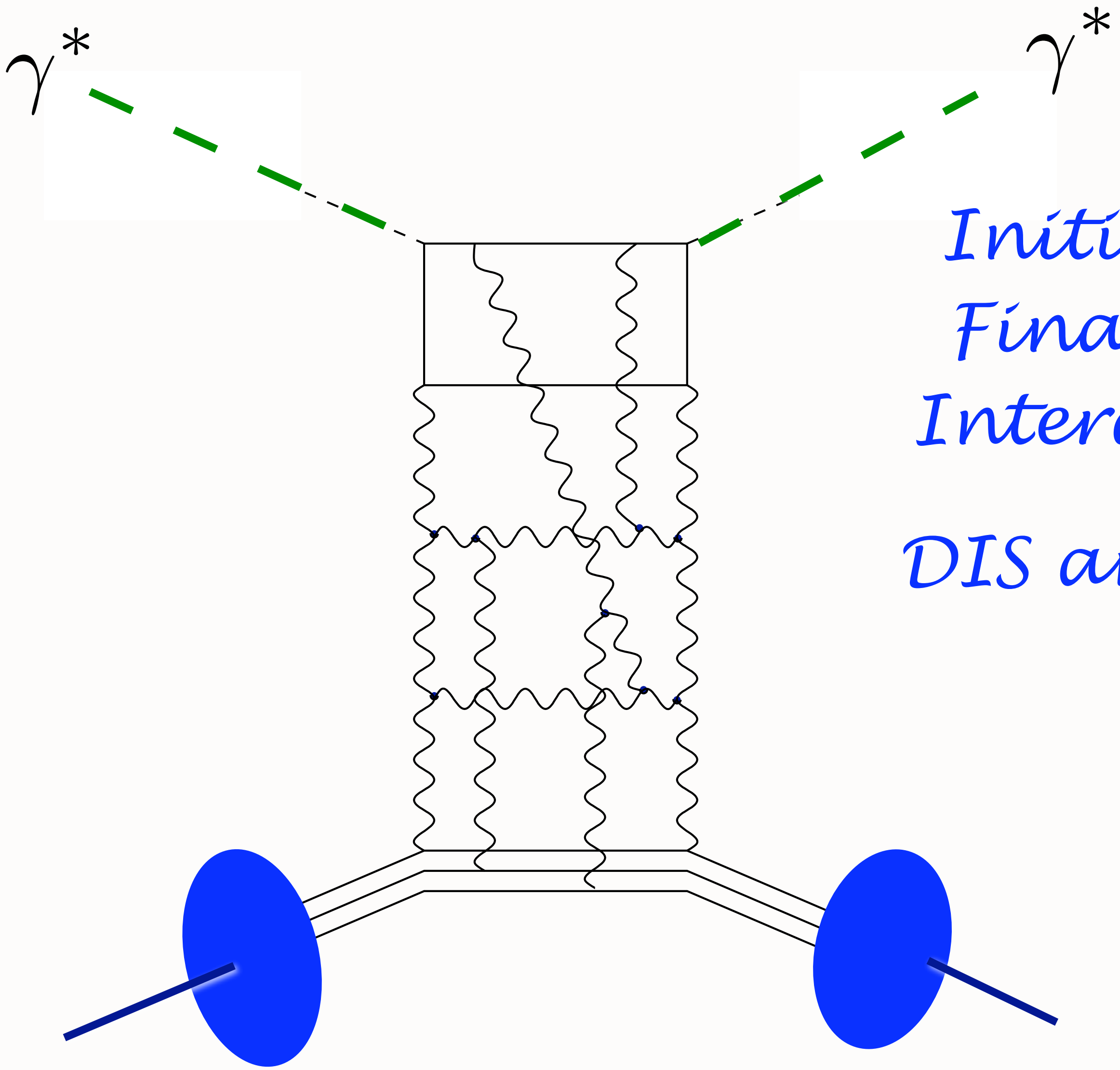


Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target

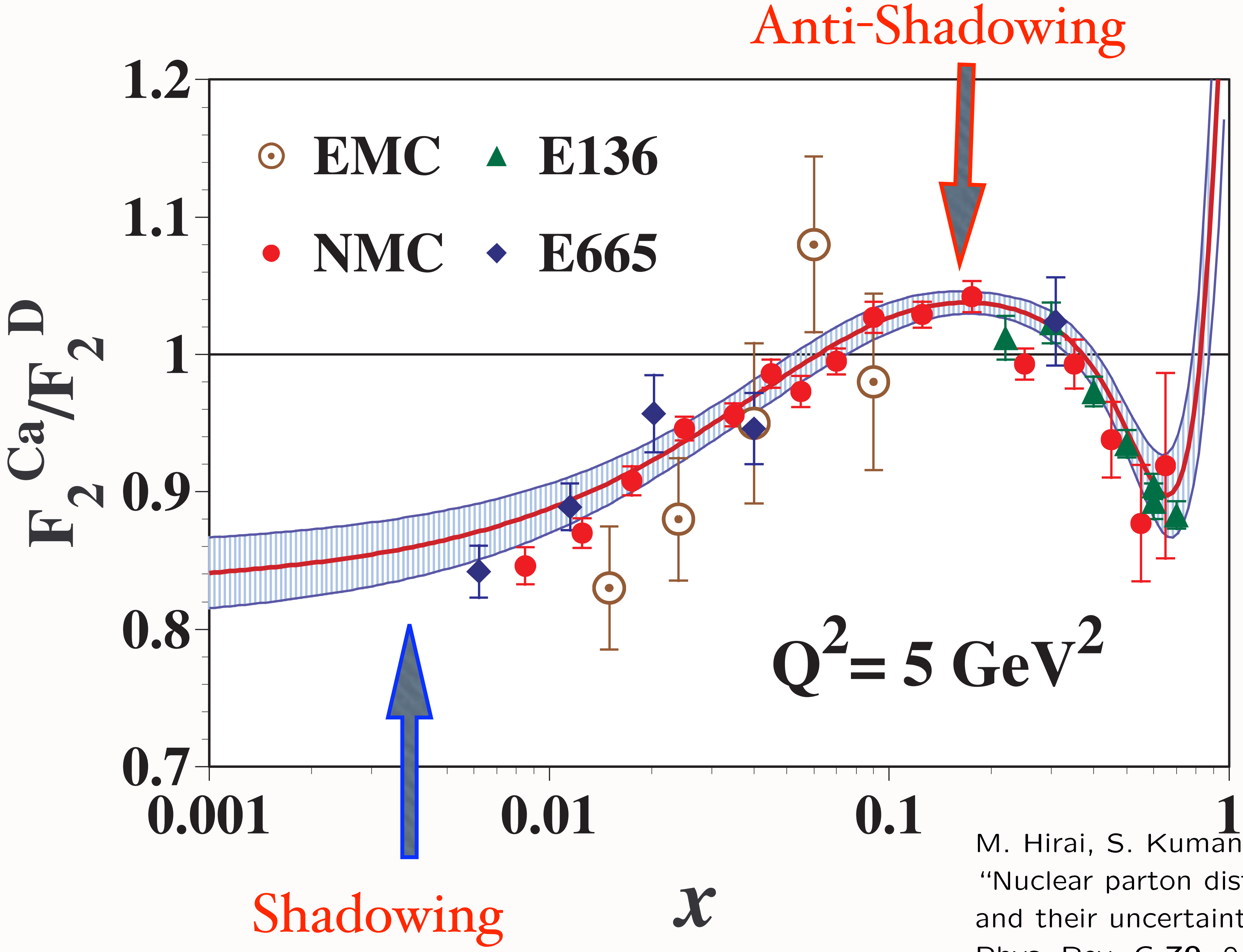


Initial and Final-State Interactions!

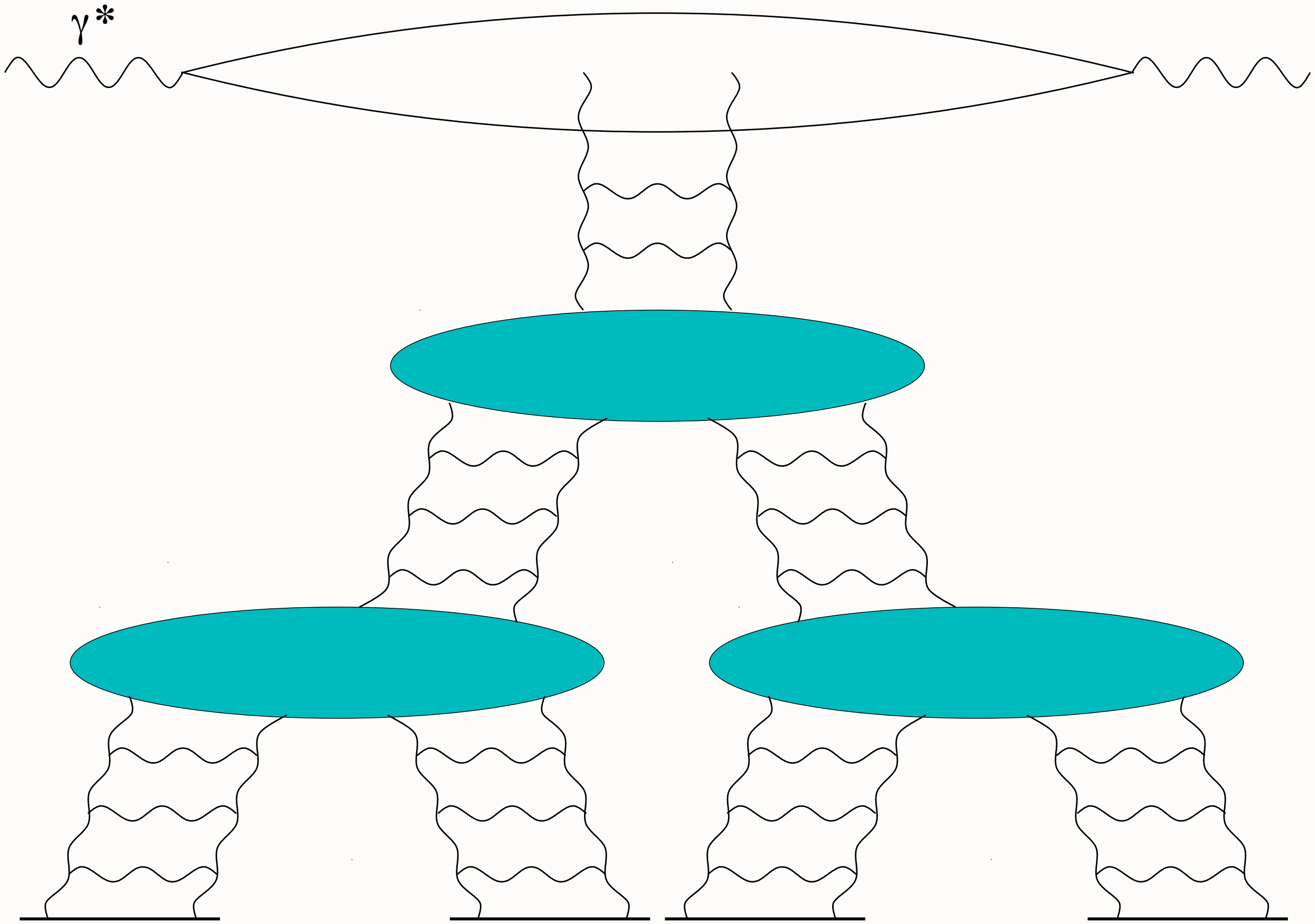
DIS and DVCS

Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon



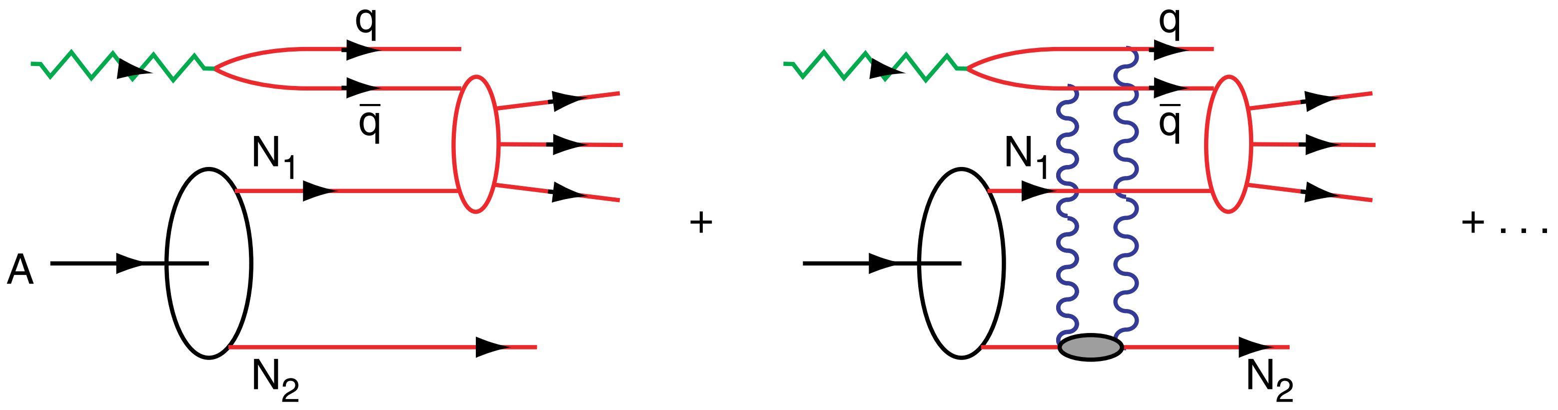
M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].



Multi-scattering in Target

Stodolsky
Pumplin, sjb
Gribov

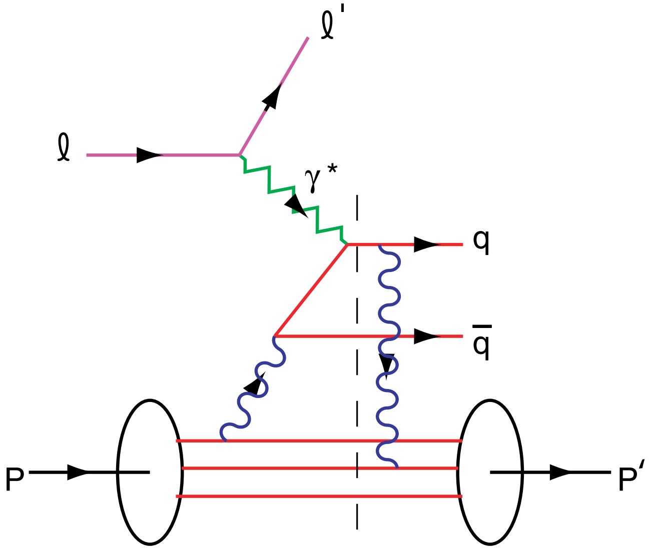
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



Shadowing depends on understanding leading-twist-diffraction in DIS

Integration over on-shell domain produces phase i

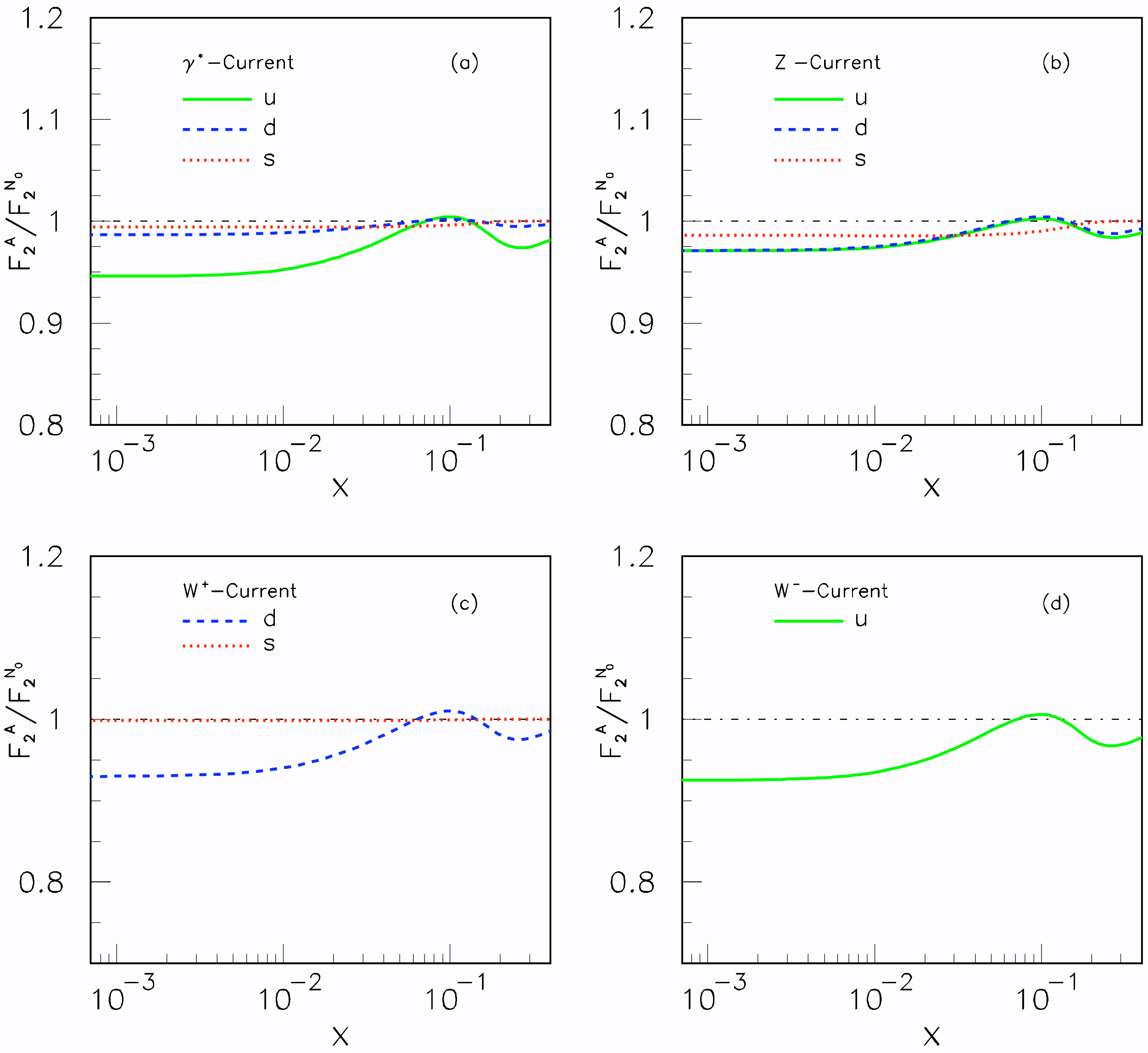
Need Imaginary Phase to Generate Pomeron

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

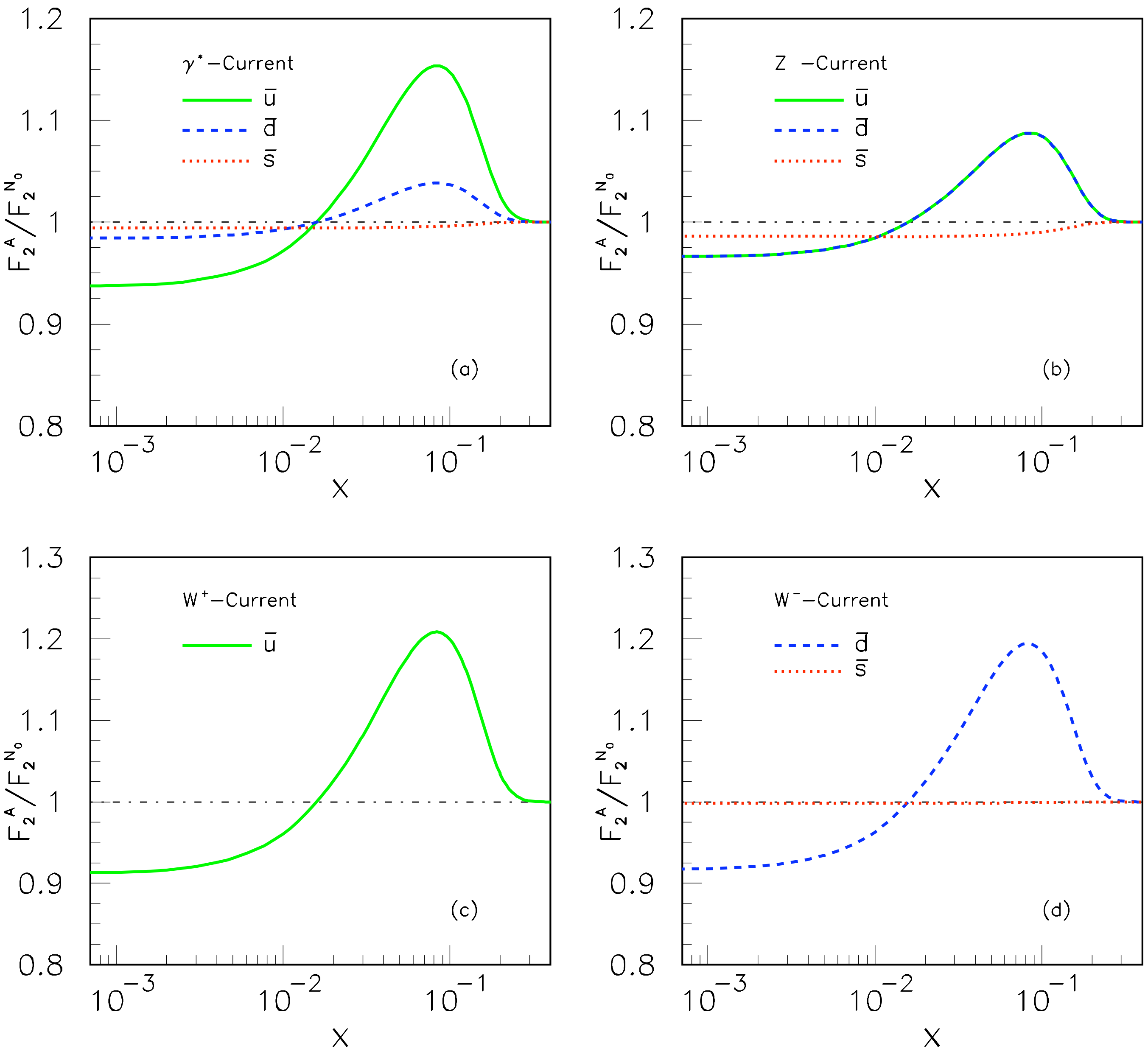
Physics of FSI not in Wavefunction of Target

Antishadowing (Reggeon exchange) is not universal!

Shadowing and Antishadowing of DIS Structure Functions



S. J. Brodsky, I. Schmidt and J. J. Yang, “Nuclear Antishadowing in Neutrino Deep Inelastic Scattering,” Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].



Nuclear Effect not Universal !

Physics of Rescattering

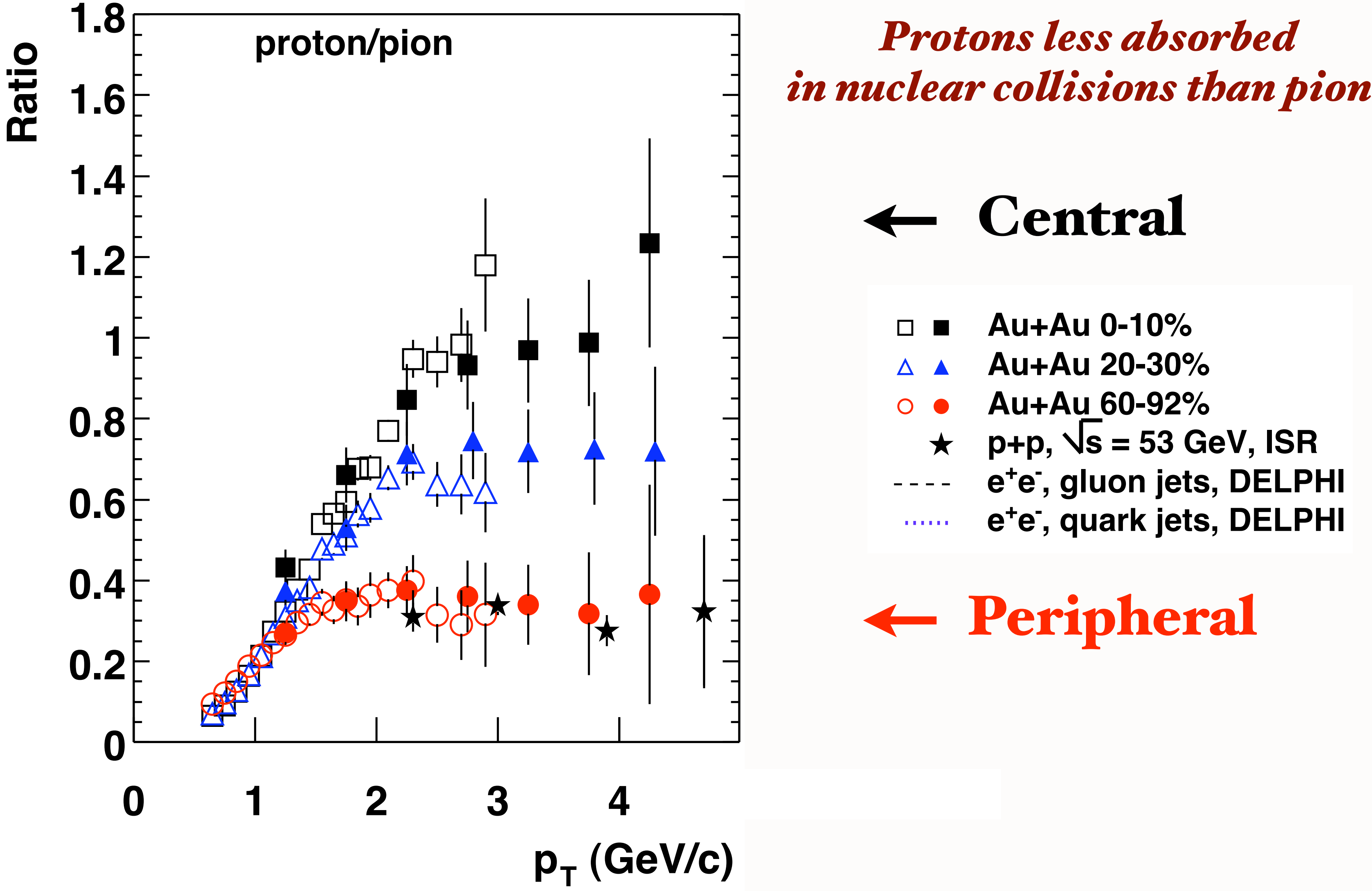
- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY angular distribution at leading twist from double ISI-- not given by PQCD factorization -- 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

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



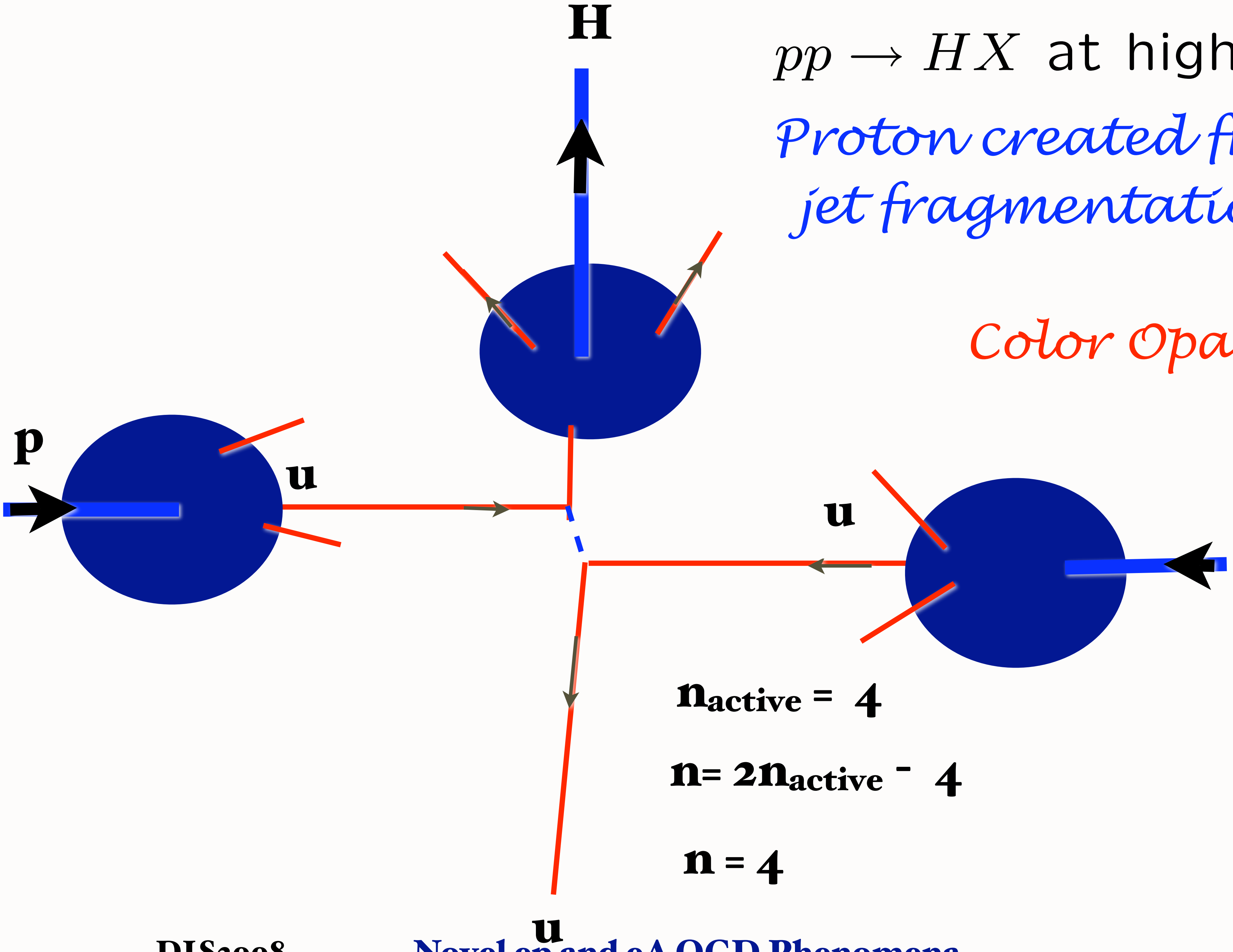
← **Central**

← **Peripheral**

$pp \to HX$ at high p_T

Proton created from jet fragmentation

Color Opaque



$n_{\text{active}} = 4$

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

$n = 4$

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

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

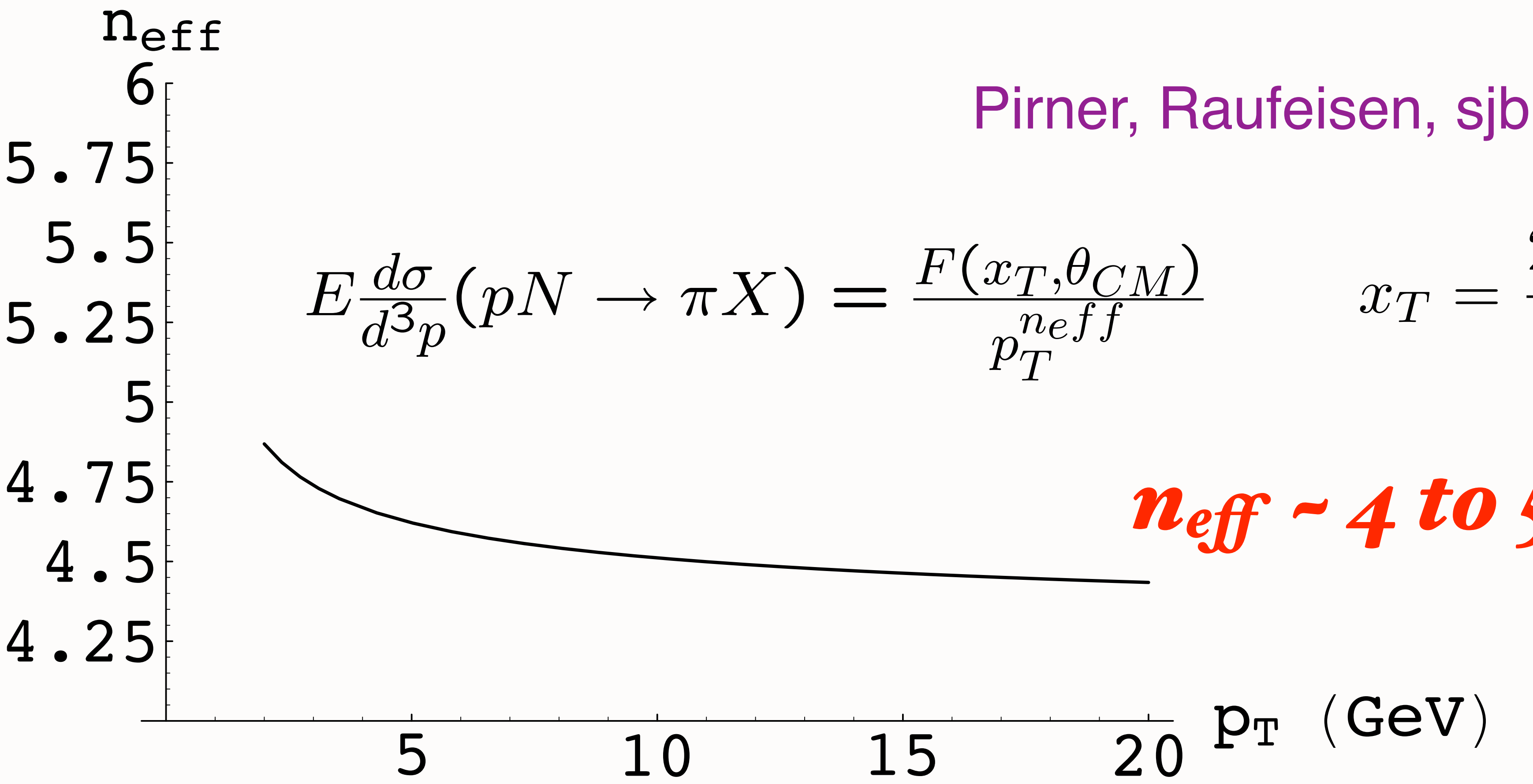
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

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

As fundamental as Bjorken scaling in DIS

Conformal scaling: n_{eff} = 2 n_{active} - 4

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



Pirner, Raufeisen, sjb

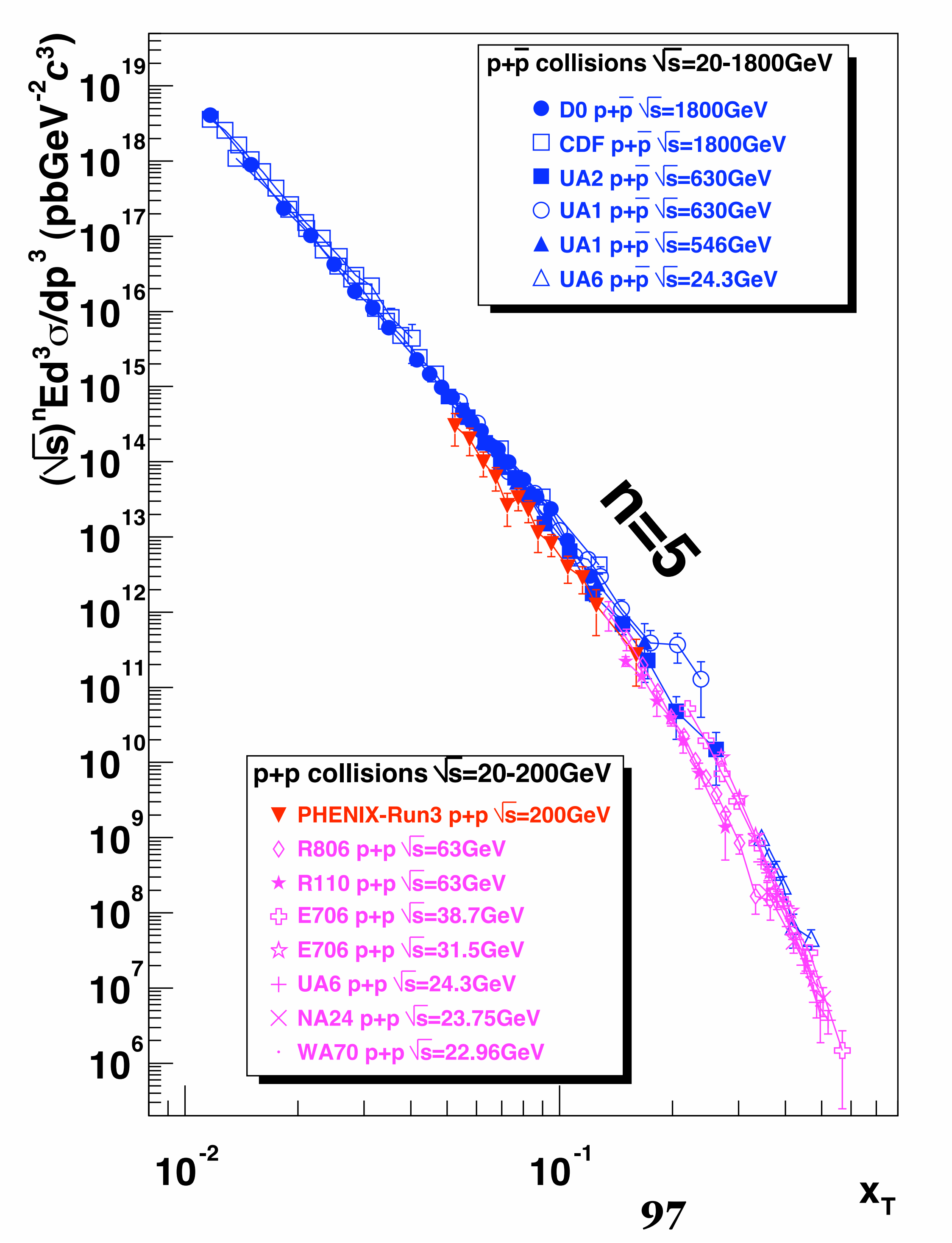
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

n_{eff} ~ 4 to 5

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

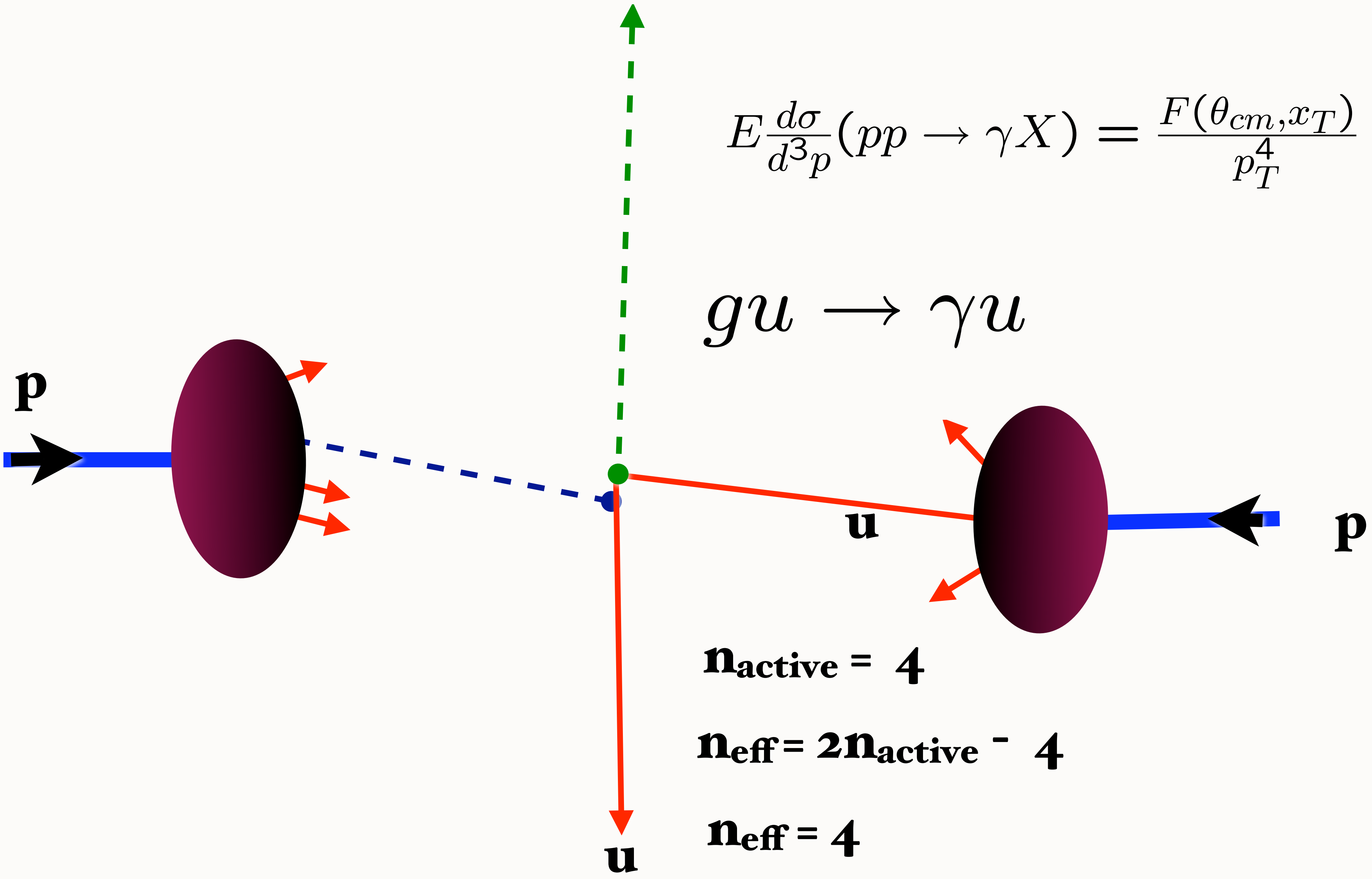
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

Tannenbaum



Scaling of direct photon production consistent with PQCD

$$pp \longrightarrow \gamma X$$



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

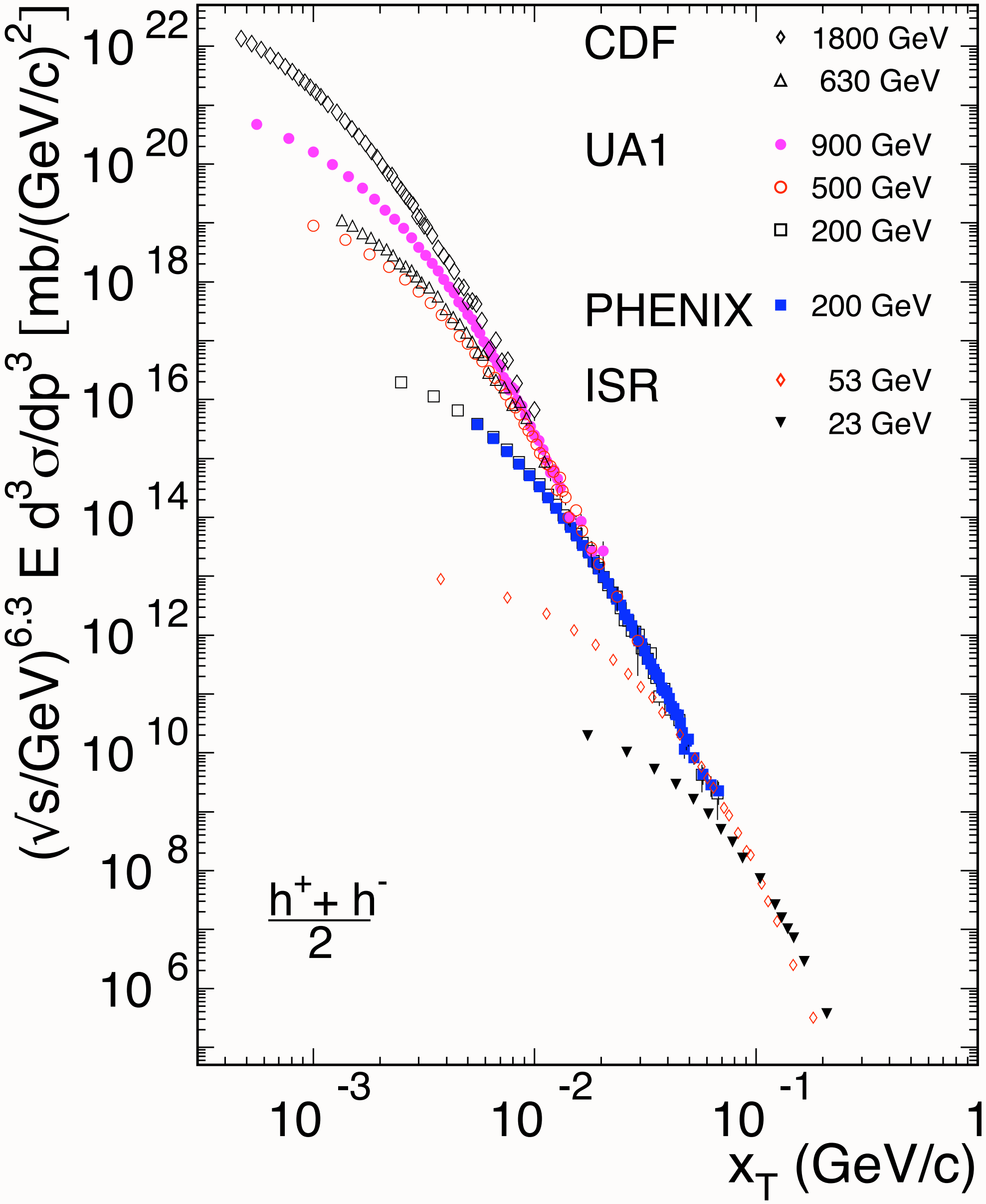
$$gu \longrightarrow \gamma u$$

$n_{active} = 4$

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

$n_{eff} = 4$

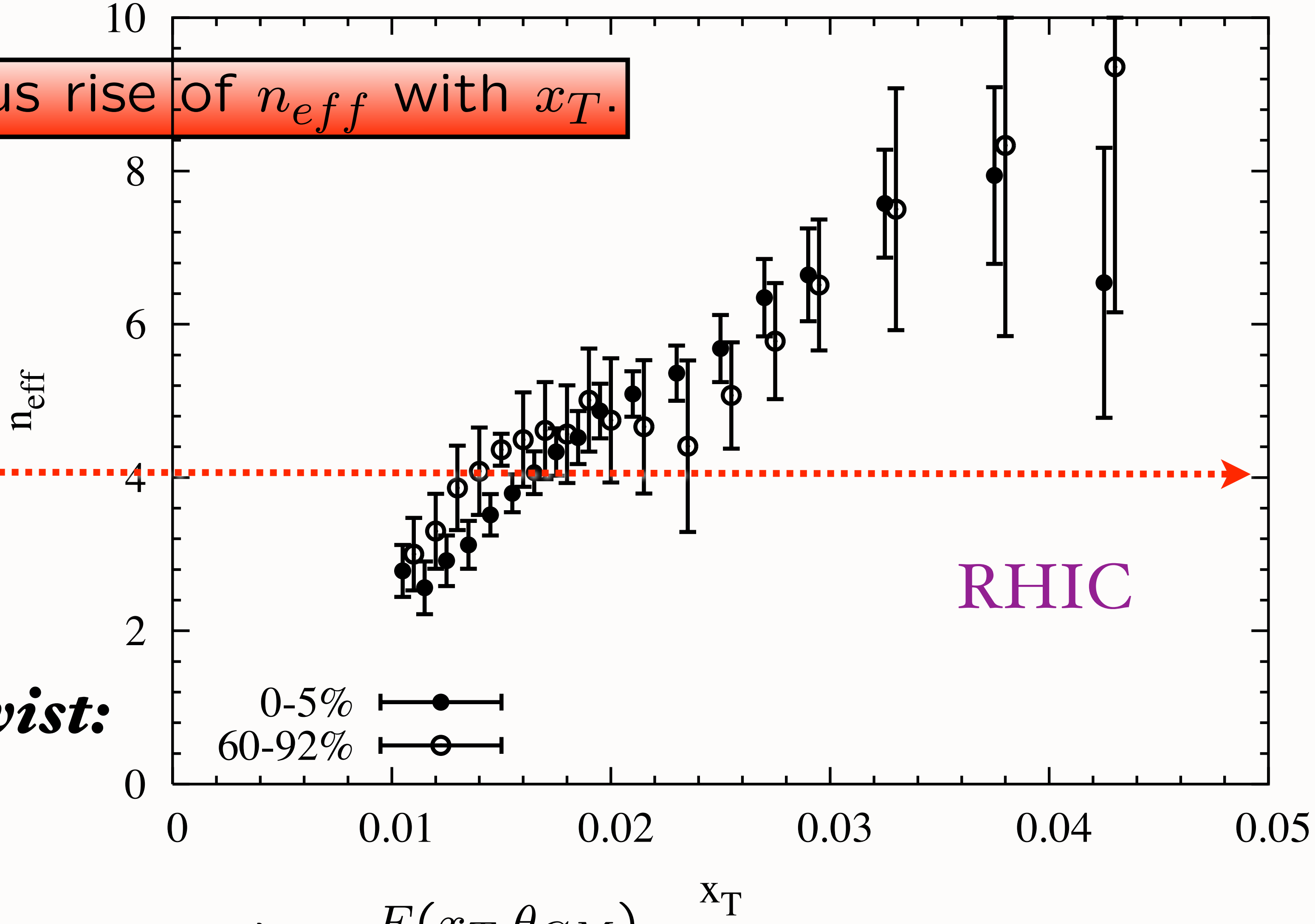
$\sqrt{s}^{6.3} \times E\frac{d\sigma}{d^3p}(pp \rightarrow H^{\pm}X)$ at fixed x_T



Tannenbaum

Scaling inconsistent 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.



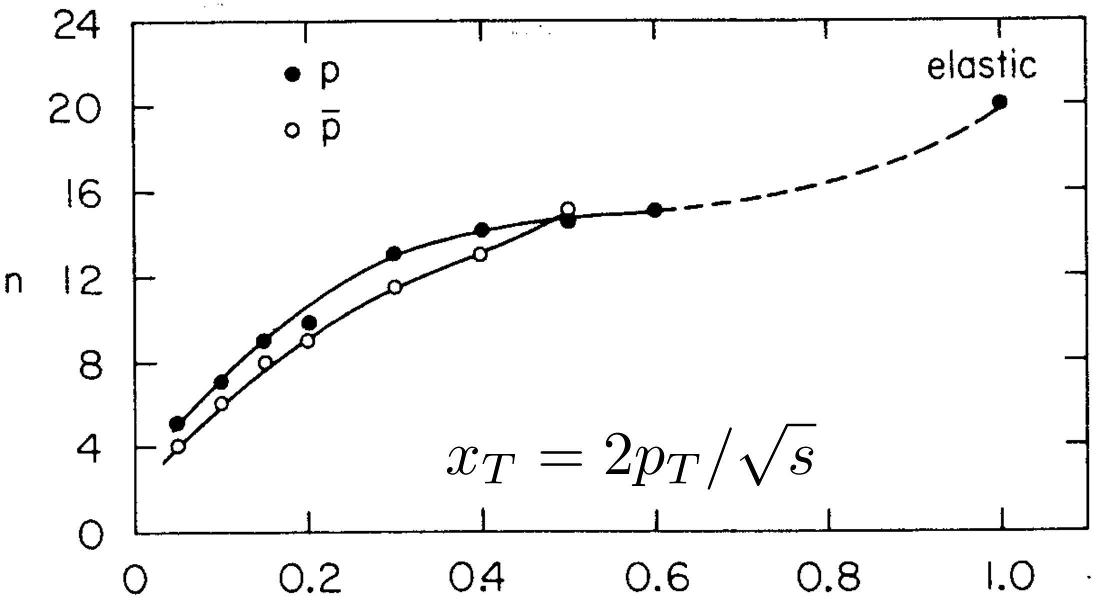
Continuous rise of n_{eff} with x_T.

$n_{eff} = 4$

Leading twist:

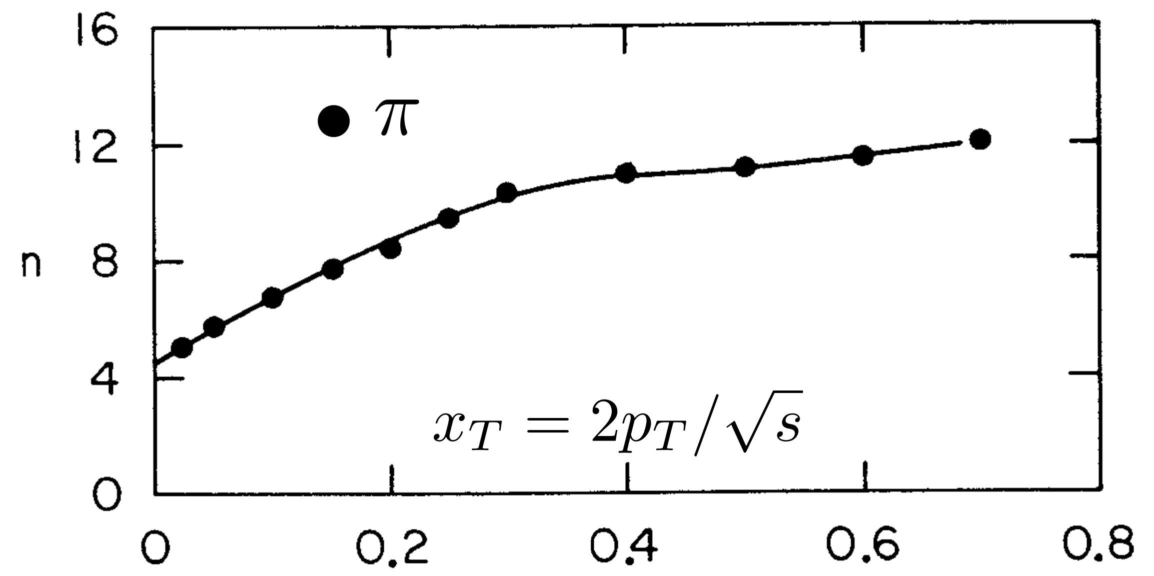
$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}}$$

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

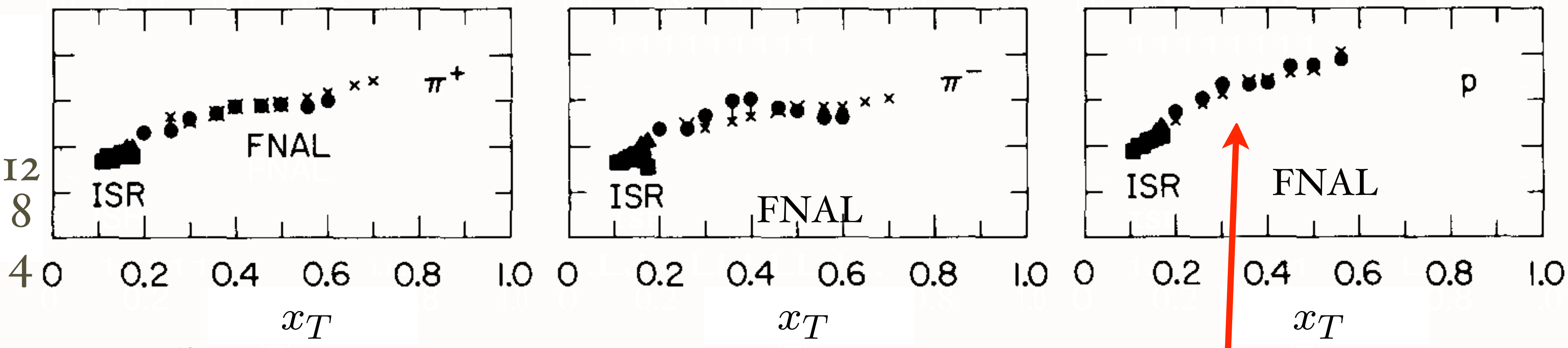


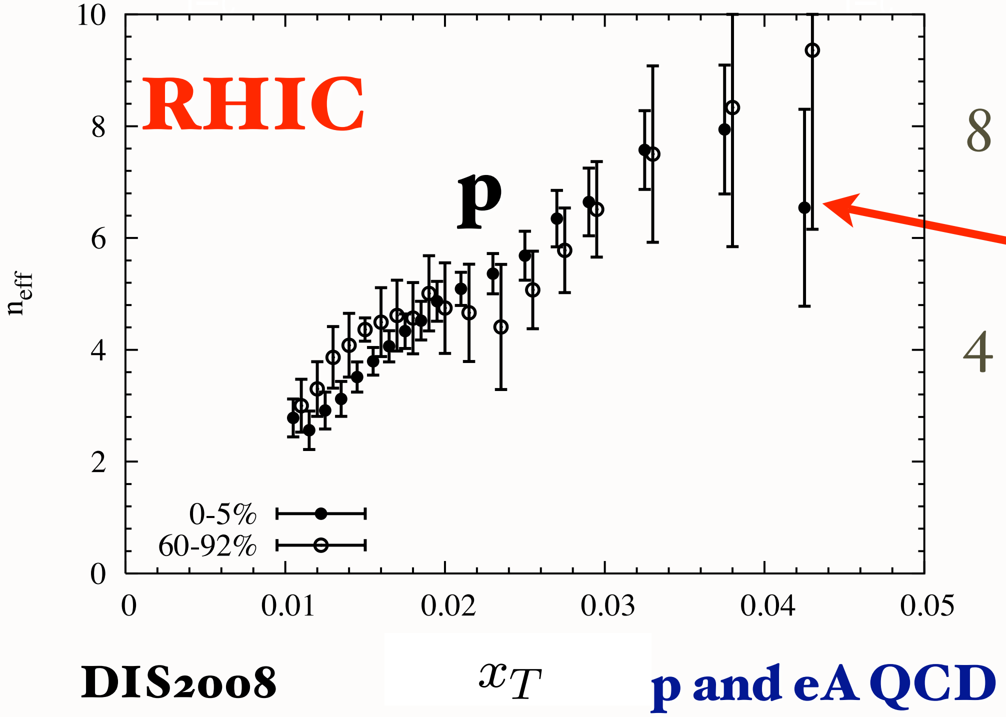
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



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



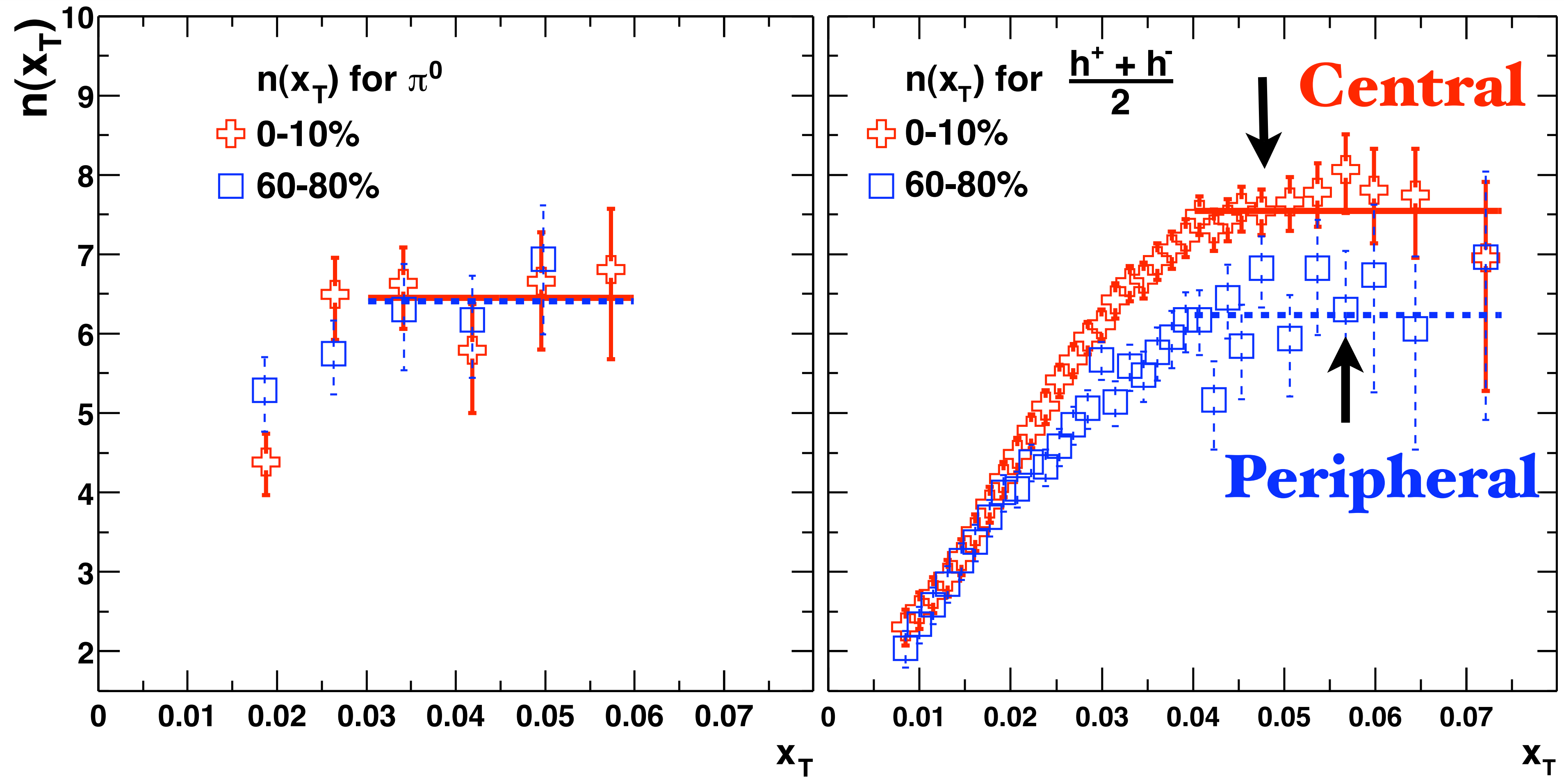


$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

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

Trend consistent with RHIC at small x_T

$\sqrt{s_{NN}} = 130$ and 200 GeV

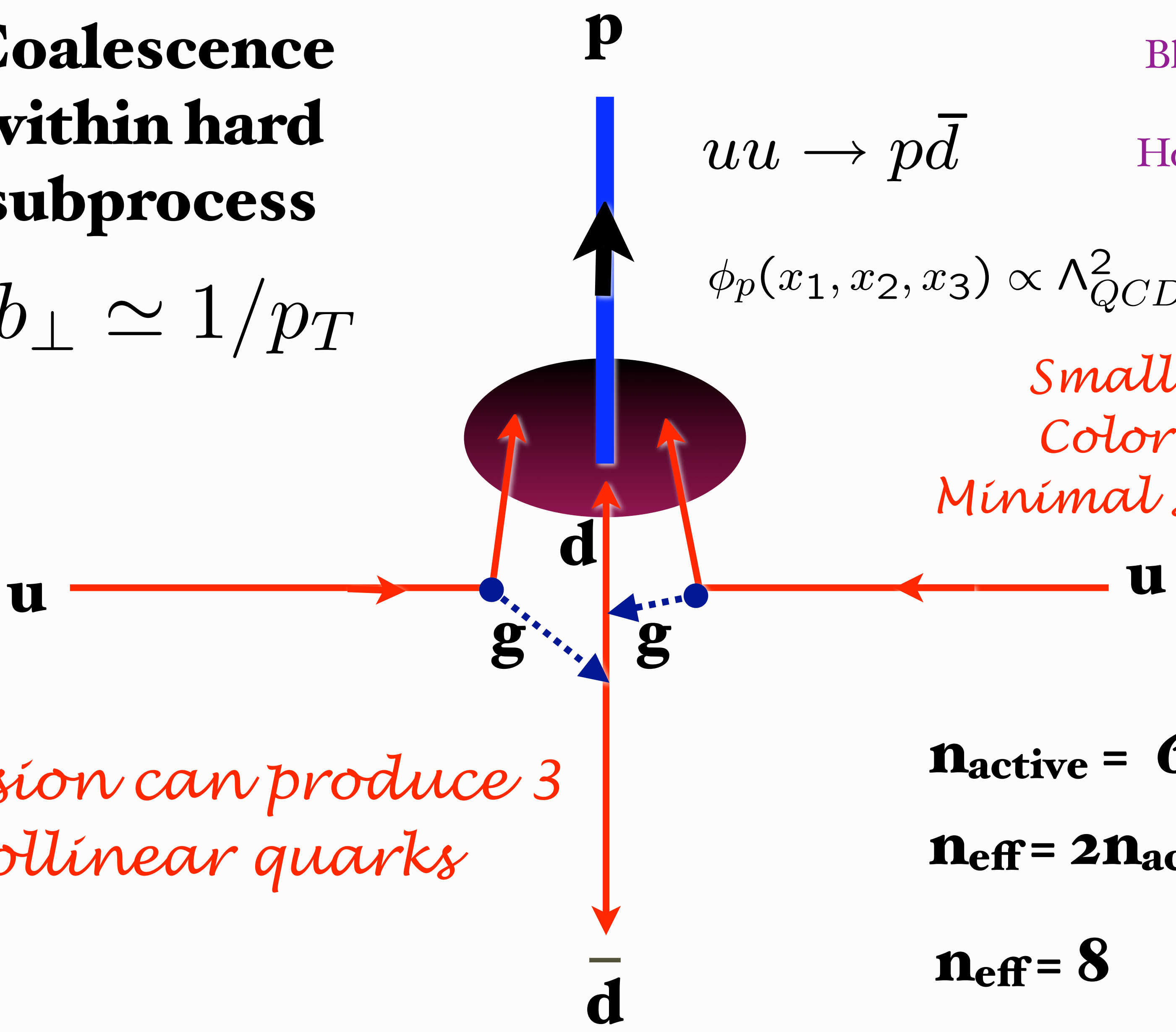


Proton power changes with centrality !

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

$$b_\perp \simeq 1/p_T$$



$$uu \to p\bar{d}$$

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

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

Small color-singlet
Color Transparent
Minimal same-side energy

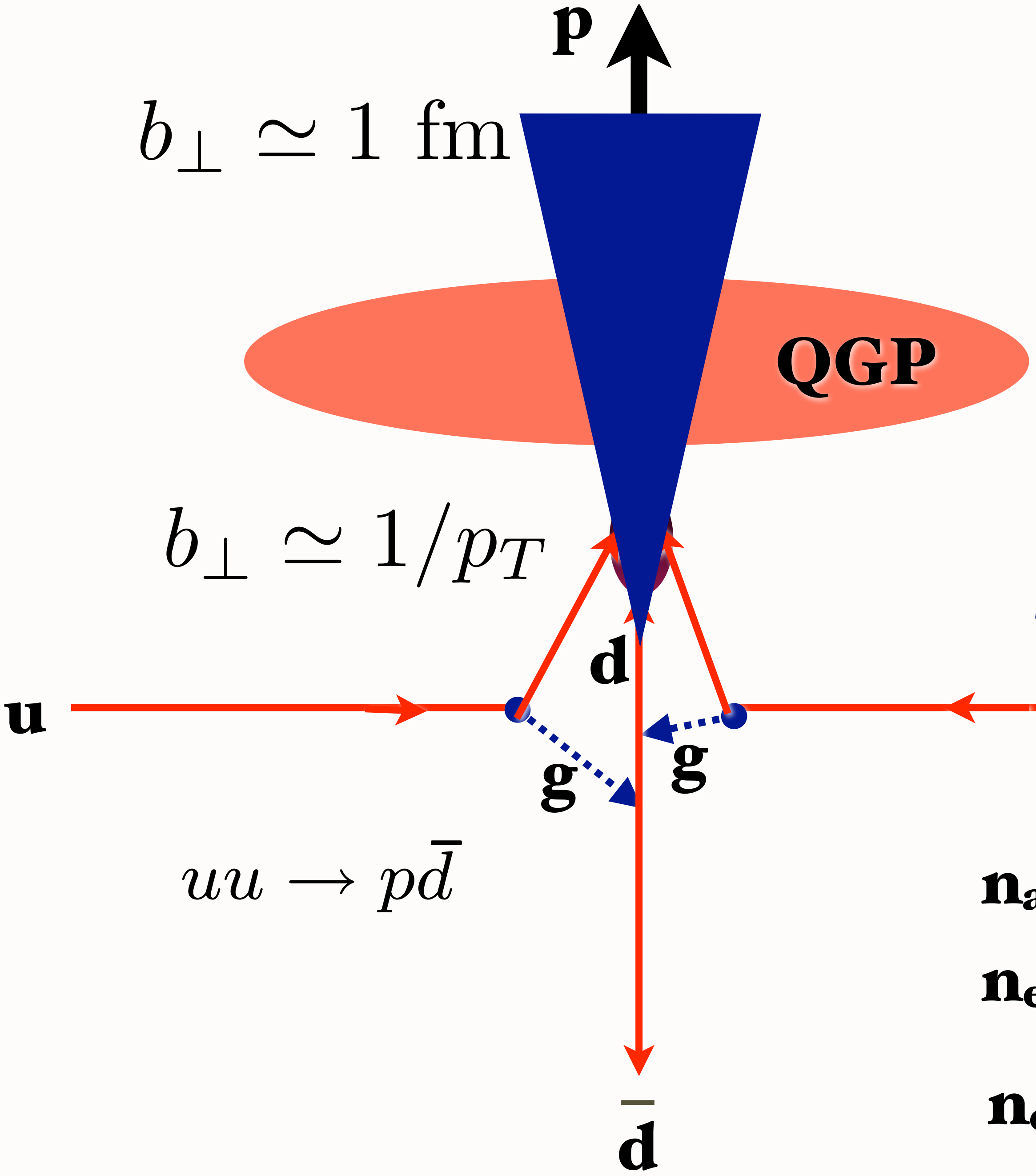
Collision can produce 3 collinear quarks

$n_{active} = 6$

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

$n_{eff} = 8$

Baryon made directly within hard subprocess



Formation Time
proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

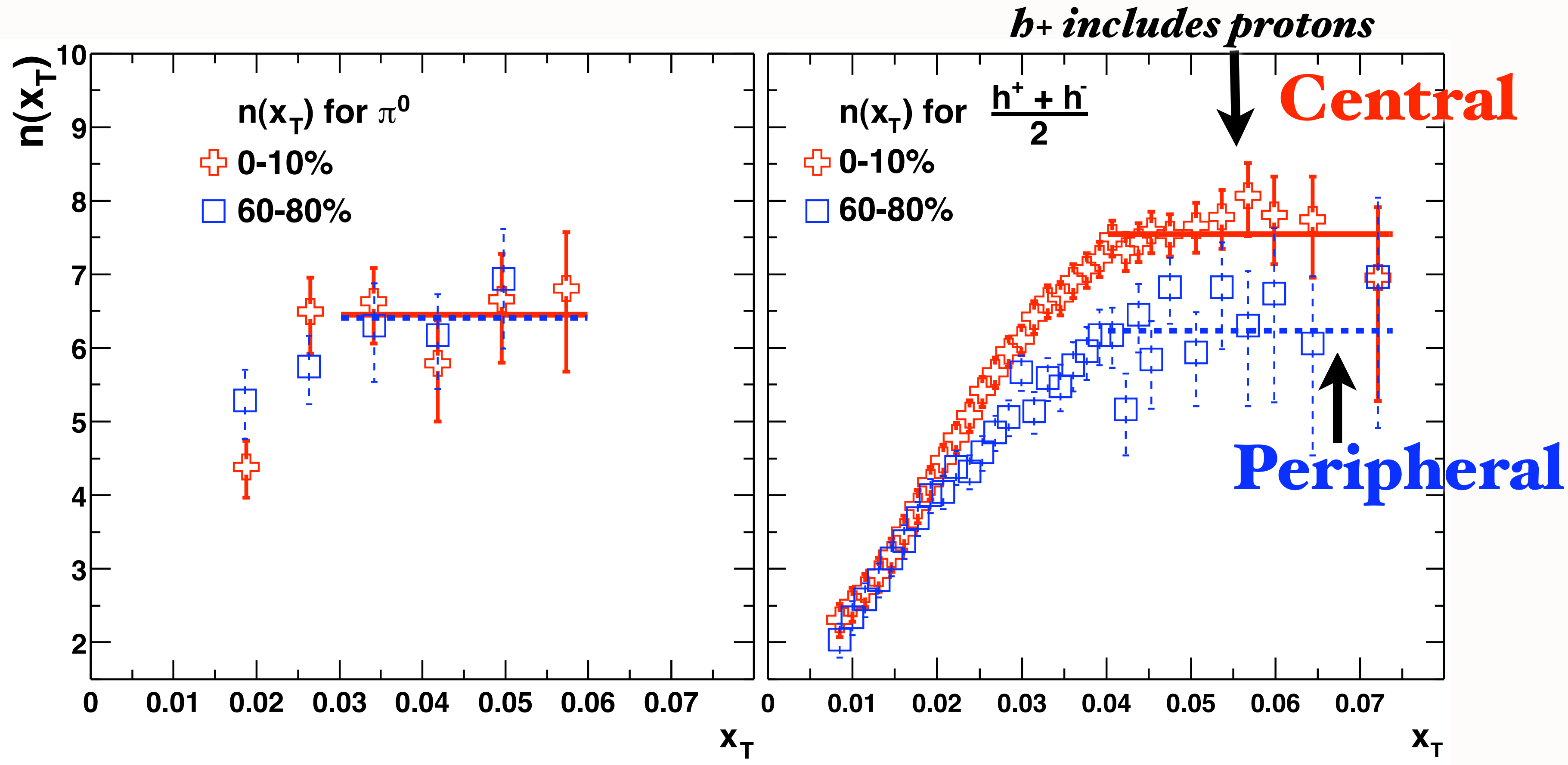
$n_{active} = 6$

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

$n_{eff} = 8$

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`].



h+ includes protons

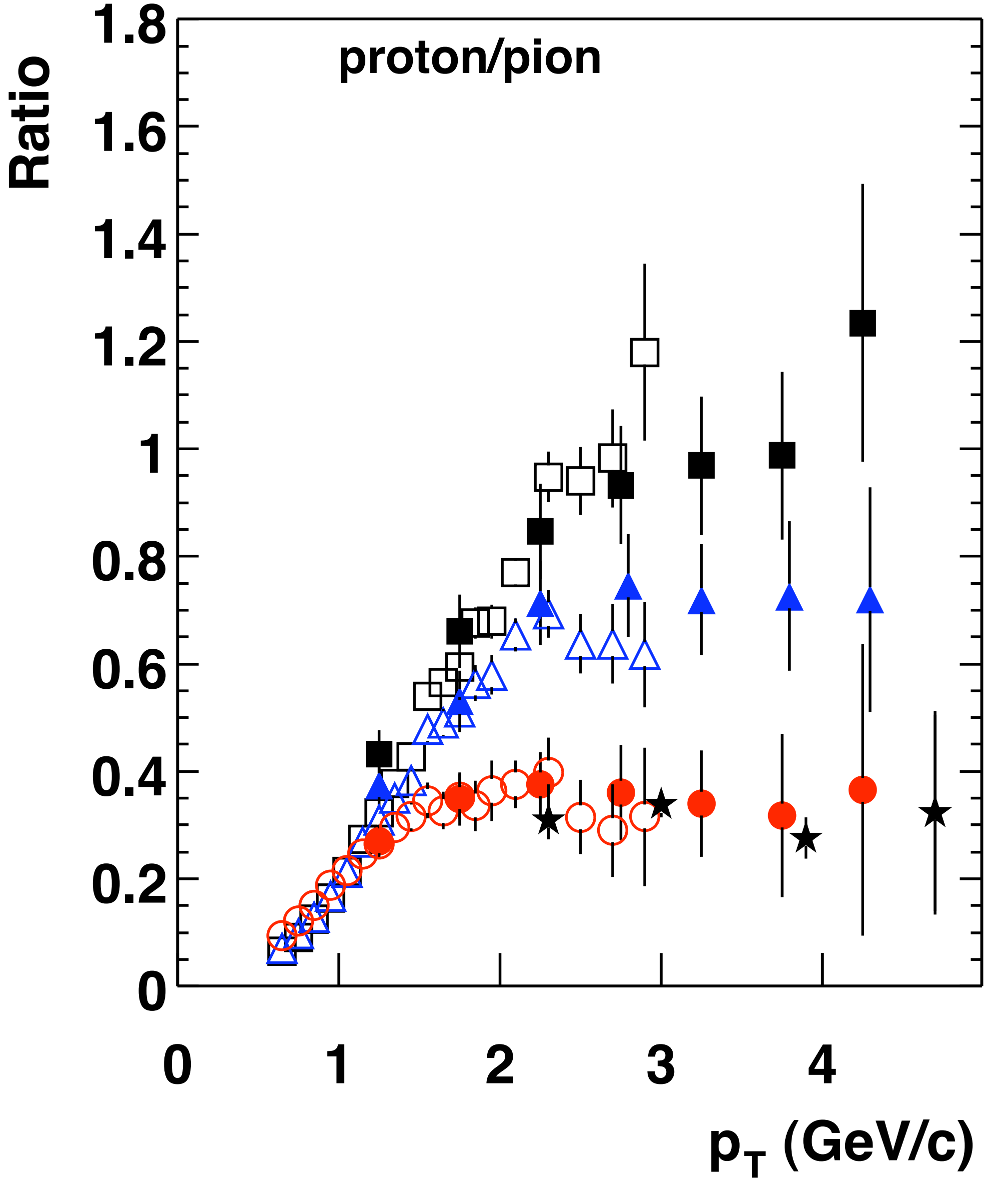
Central

Peripheral

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

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

Particle ratio changes with centrality!

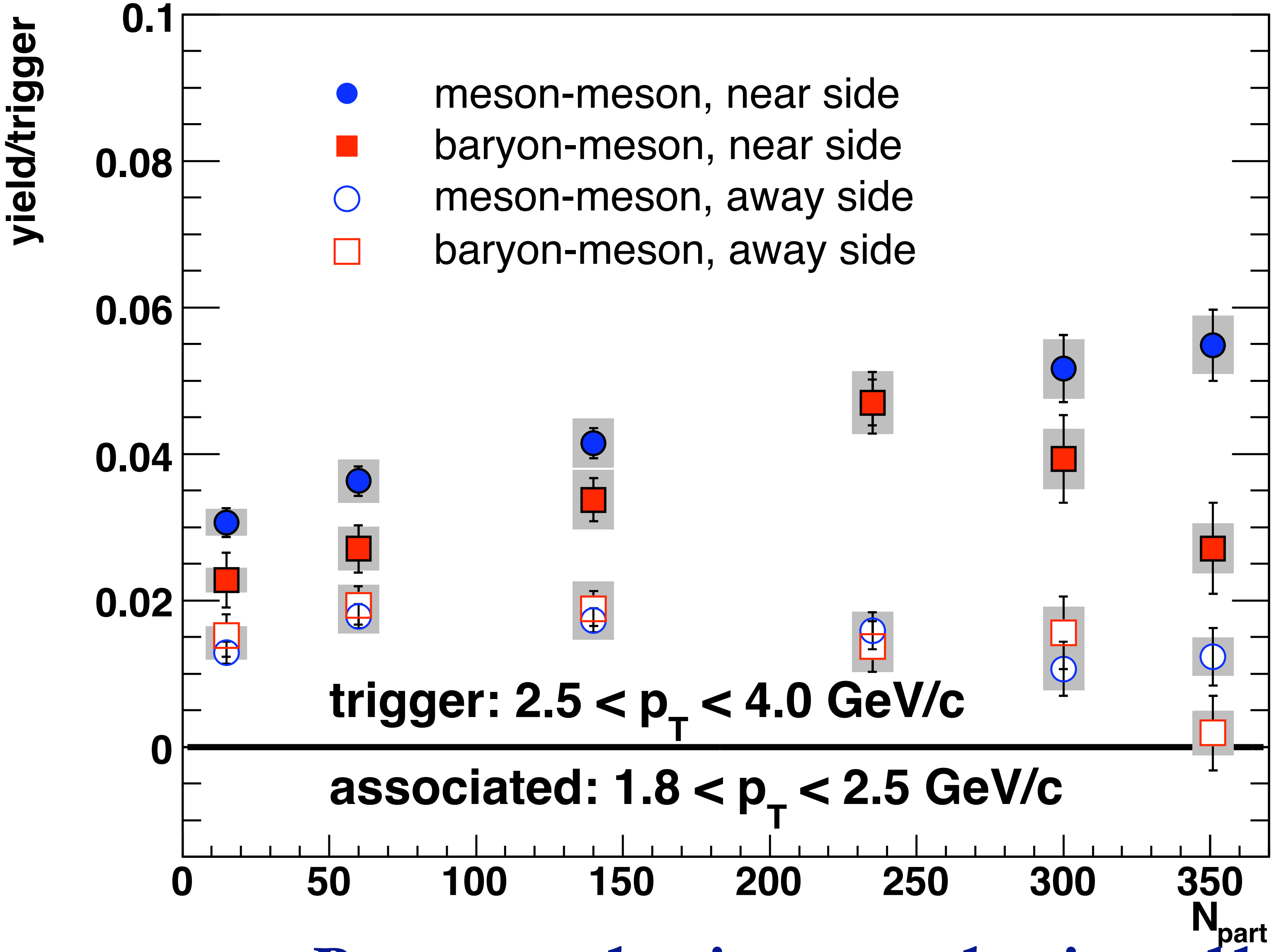


Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

← **Central**

← **Peripheral**

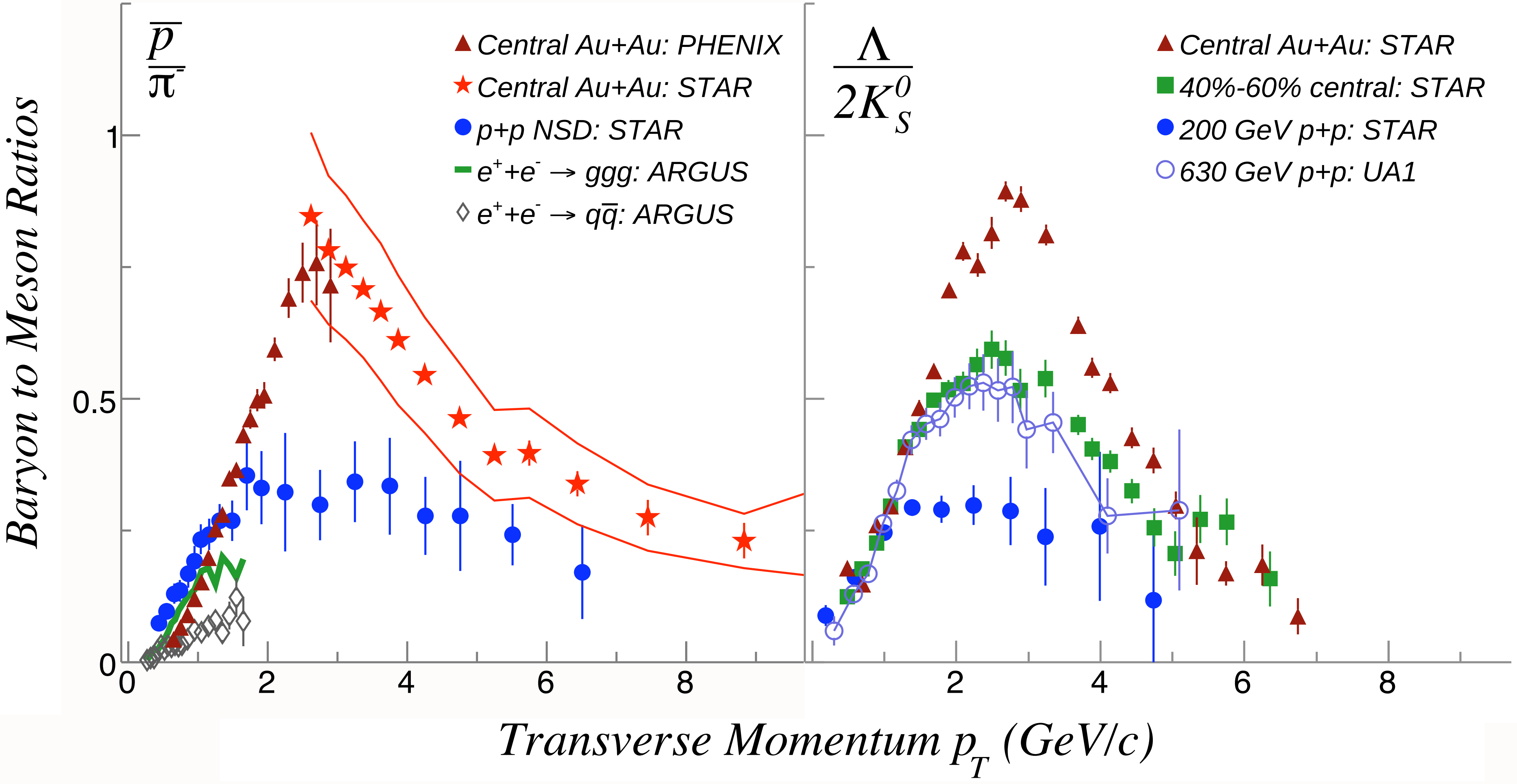
Anne Sickles



proton trigger: # same-side particles decreases with centrality

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

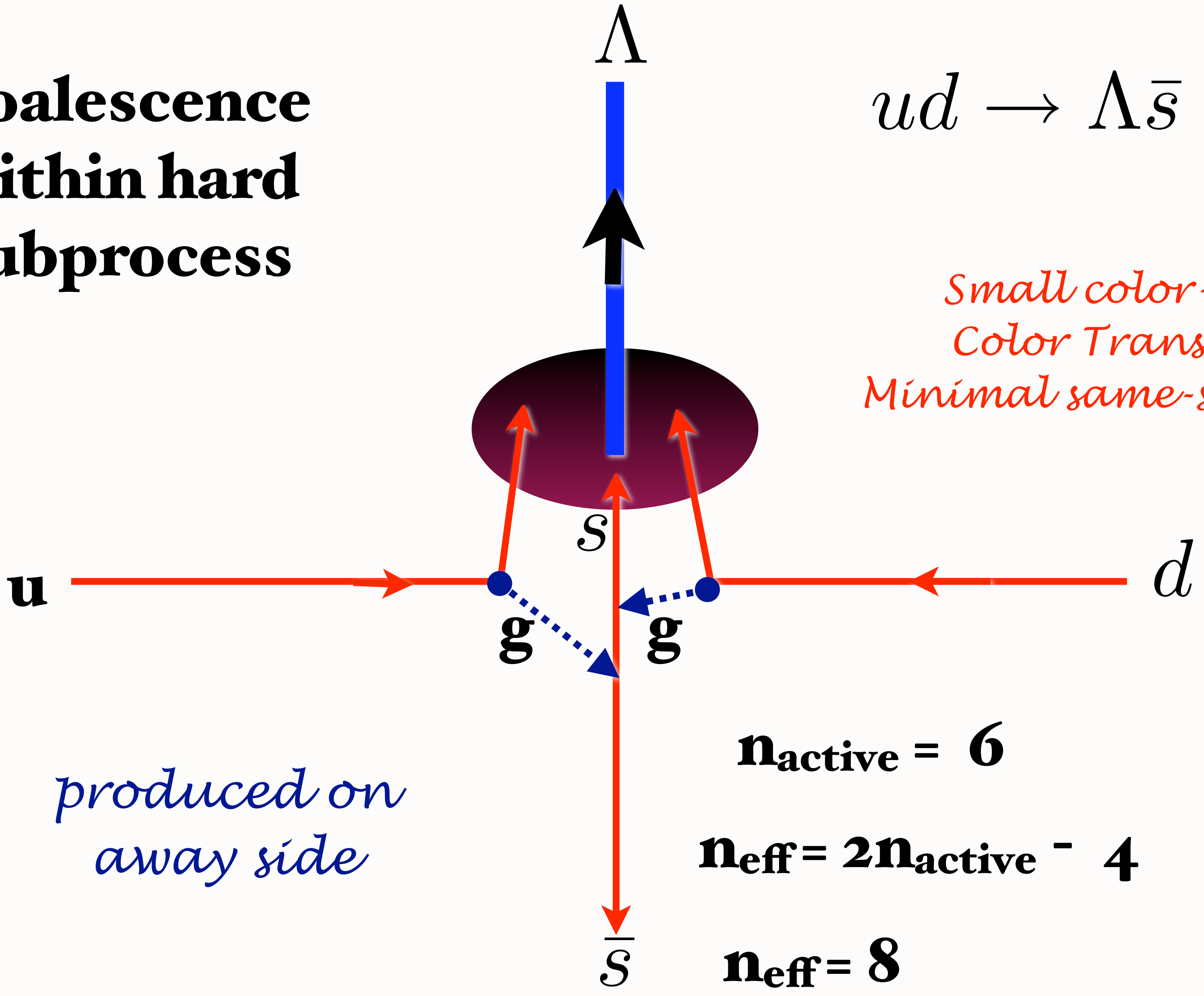
Paul Sorensen



Lambda can be made directly within hard subprocess

Coalescence within hard subprocess

$ud \rightarrow \Lambda\bar{s}$



Small color-singlet
Color Transparent
Minimal same-side energy

$\bar{s}$ produced on away side

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

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

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

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 $x_T = 1$

Role of higher twist in hard inclusive reactions

“Semi-Exclusive

Hoyer, Mueller, Tang, sjb

- **Hadron can be produced directly in hard subprocess as in exclusive reactions**
- **Sum over reactions**
- **Trigger bias: No wasted same-side energy**
- **Exclusive -inclusive connection important at high x_T**
- **Explanation of $n_{eff} = 8, 12$ observed at ISR, Fermilab: Chicago-Princeton experiments**
- **Direct Hadron Production -- color transparency and reduced same side absorption**
- **Critical to plot data at fixed x_T**
- **Interpretation of RHIC data is modified if higher twist subprocesses play an important role**

Conventional wisdom in QCD concerning scale setting

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

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

Electron-Electron Scattering in QED

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

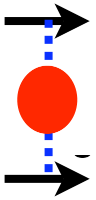
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

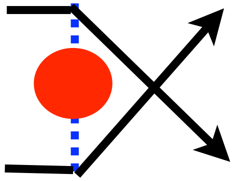
Gell Mann-Low Effective Charge

Electron-Electron Scattering in QED

- No renormalization scale ambiguity!

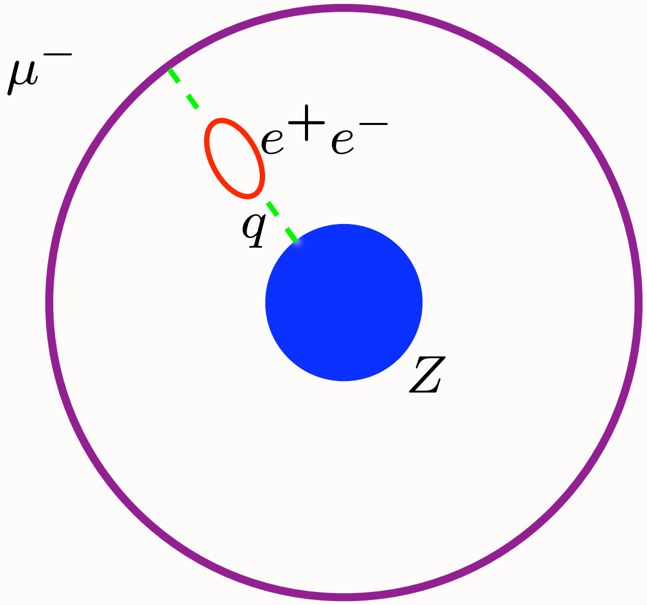
$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$





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

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

Huet, sjb

$$\boxed{\lim N_C \to 0 \text{ at fixed } \alpha = C_F\alpha_s, n_\ell = n_F/C_F}$$

$$\boxed{\text{QCD} \to \text{Abelian Gauge Theory}}$$

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD
must be applicable to QED

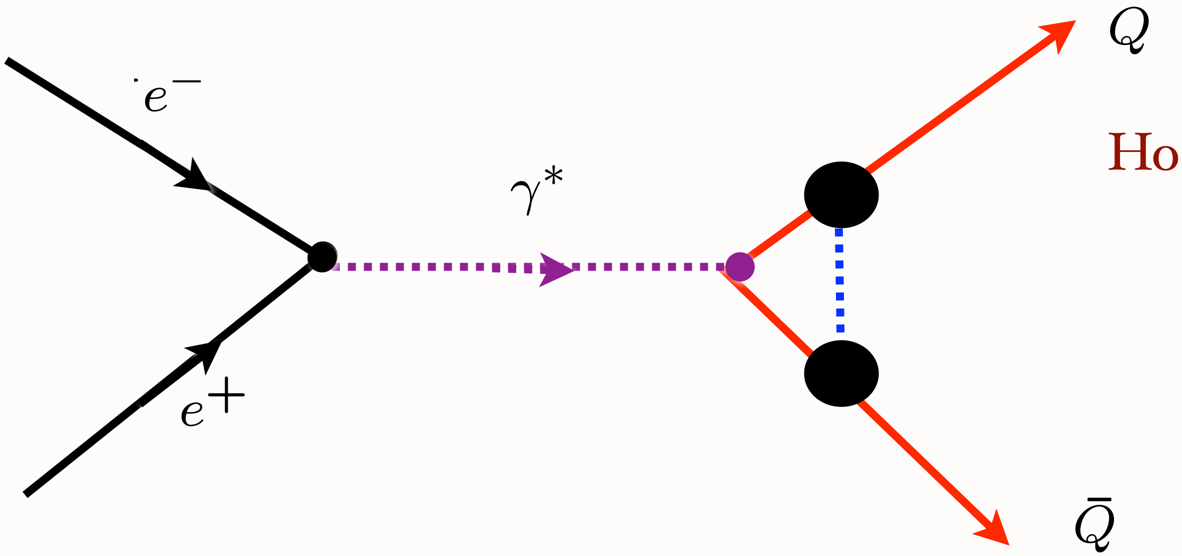
Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb

Phys.Rev.D28:228,1983

- All terms associated with non-zero beta function summed into running coupling
- Identical procedure in QED:
- Correct $\mathbf{N_C = 0}$ limit
- Resulting series identical to conformal series
- Renormalon n! growth of PQCD coefficients from beta function eliminated!
- In general, scale depends on all invariants



Hoang, Kuhn, Teubner, sjb

$$\begin{aligned} F_1 + F_2 &= 1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta} - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi} \\ &\cong \left(1 - 2\,\frac{\alpha(s\,e^{3/4}/4)}{\pi}\right)\left(1 + \frac{\alpha(s\,\beta^2)\,\pi}{4\,\beta}\right) \end{aligned}$$

Example of Multiple BLM Scales

Angular distributions of massive quarks and leptons close to threshold.

Three Pictures of High Energy Lepton-Proton Collisions

Infinite momentum frame **Parton Model**

Simple Virtual Photon Probes Complex Evolved Proton

Proton Rest Frame **Color-Dipole Model**

Color Dipole of Virtual Photon Scatters on a Static Proton

Frame-Independent **Light-Front HamiltonianTheory**

Collision of Light-Front Wavefunctions
of Virtual Photon and Proton

Novel Aspects of QCD in ep scattering

- **Clash of DGLAP and BFKL with unitarity: saturation phenomena; off-shell effects at high x**
- **Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction: Intrinsic c(x,Q), b(x,Q), t(x,Q):**
- **Hidden-Color of Nuclear Wavefunction; antishadowing is quark specific!**
- **polarized u(x) and d(x) at large x; duality**
- **Virtual Compton scattering : DVCS, DVMS, GPDs; J=0 fixed pole reflects elementary source of electromagnetic current**
- **Initial-and Final-State Interactions: leading twist SSA, DDIS**
- **Direct Higher-Twist Processes; Color Transparency**

Novel Aspects of QCD in ep scattering

- Initial and final-state interactions are not power suppressed DIS; Wilson line correction to handbag diagram in DVCS
- Leading-twist Bjorken-scaling single-spin asymmetry; analog of Aharonov-Bohm effect
- Leading-twist Bjorken-scaling Diffractive DIS
- Diffractive Electroproduction; Color Transparency
- DIS at high energy reflects interactions of color-dipole of virtual photon with proton and nucleus: shadowing, saturation:
- Breakdown of parton model concepts: Structure functions are not probability distributions
- Nuclear LFWFS are universal, but the measured nuclear parton distributions are not universal -- antishadowing is flavor-dependent

Challenging Conventional Wisdom

- **Renormalization scale is not arbitrary; multiple scales, unambiguous at given order**
- **Heavy quark distributions do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction**
- **Initial and final-state interactions are not always power suppressed in a hard QCD reaction**
- **LFWFS are universal, but measured nuclear parton distributions are not universal -- antishadowing is flavor dependent**
- **Hadroproduction at large transverse momentum does not derive exclusively from 2 to 2 scattering subprocesses**

- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.
- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, initial and final-state interaction effects, shadowing, antishadowing ...

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

—Mark Twain