The glue that binds us all:

Probing the nature of gluonic matter with an electron-ion collider

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BNL PAC September 13th, 2006

Outline of Talk

- A brief introduction to QCD and the essential role of gluons
- What do we know about gluonic matter ?
- What do we wish to learn about glue ?
- How do we accomplish this ?

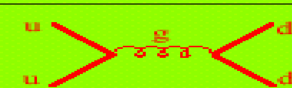
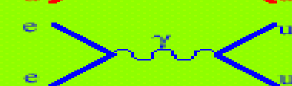
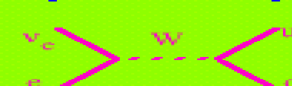
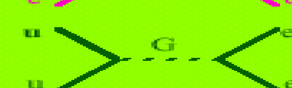
Fundamental particles and their interactions

QUARKS S=1/2		LEPTONS S=1/2		GAUGE BOSONS S=1
Q = −2/3	Q = −1/3	Q = −1	Q = 0	quanta
u u u m=(1-4) 10^{-3}	d d d m=(5-8) 10^{-3}	e m=5.11 10^{-4}	ν_e m<3 10^{-9}	g_1 …… g_8 m< a few 10^{-3}
c c c m=1.0-1.4	s s s m=0.08-0.15	μ m=0.10566	ν_μ m<1.9 10^{-4}	γ m<2 10^{-25}
t t t m=174.3±5.1	b b b m=4.0-4.5	τ m=1.7770	ν_τ m<18.2 10^{-3}	$W^{\pm}$, Z^0 m_W=80.432 ±0.39, m_Z=91.1876 ±0.0021

All masses in GeV units

QCD →

QED ↗

Interaction	exchanged boson	relative strength	example
Strong	Gluon (g)	1	
Electromagnet.	Photon (γ)	$\frac{1}{137}$	
Weak	W^+, W^-, Z^0	10^{-14}	
Gravitation	Graviton (G) ?	10^{-40}	

Quantum Chromodynamics (QCD) in the news…

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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The 2004 Nobel prize in physics

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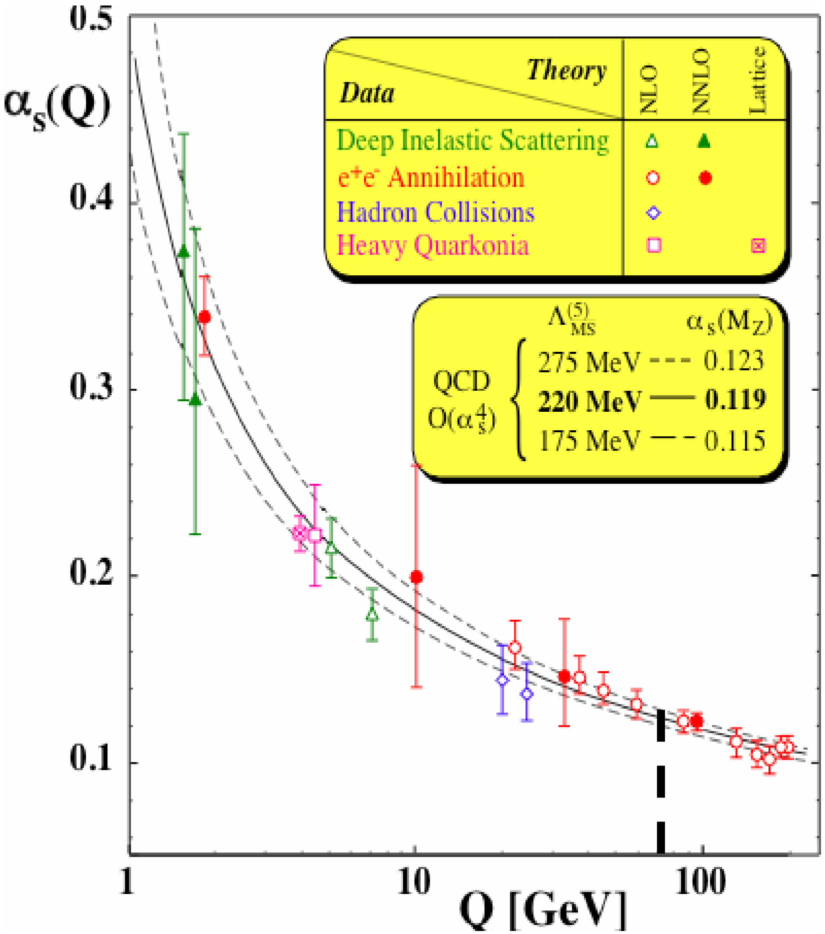
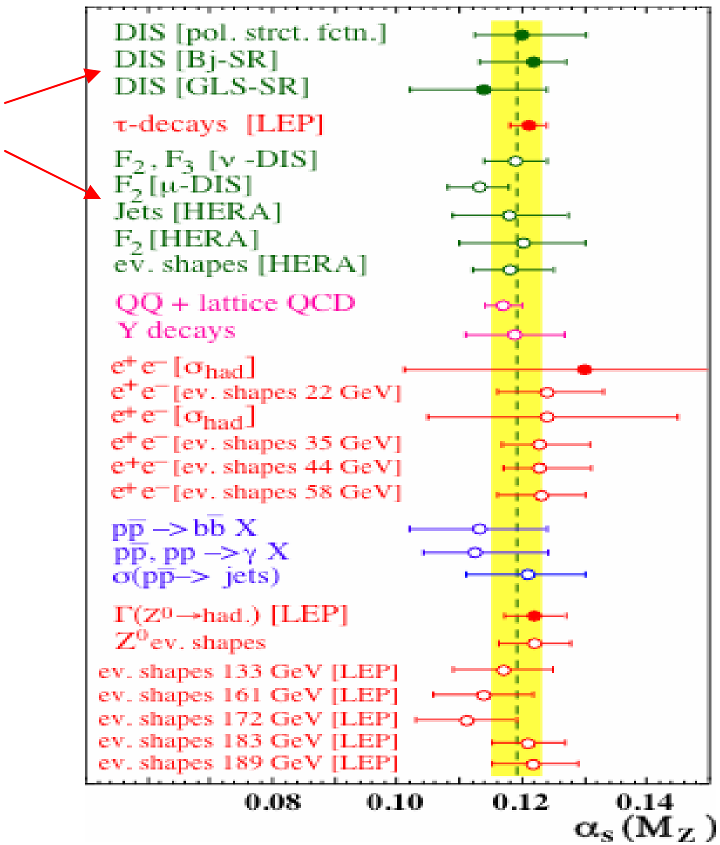
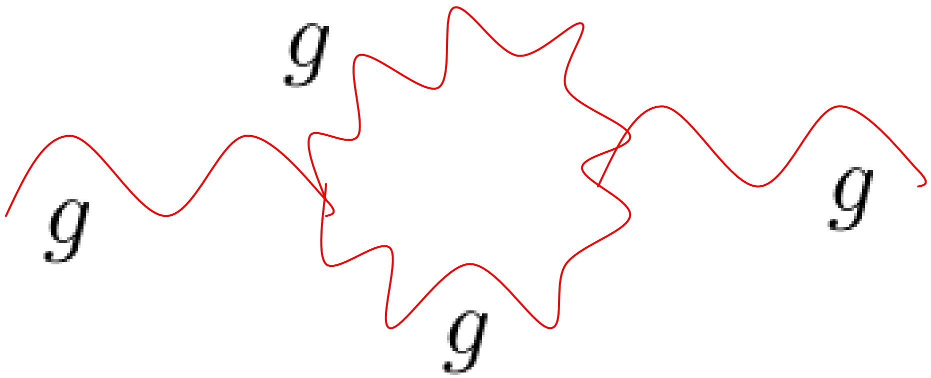
For the discovery of asymptotic freedom in QCD- the theory of the strong interaction…





In QCD, one has “anti-screening” because colored gluons can interact with each other…

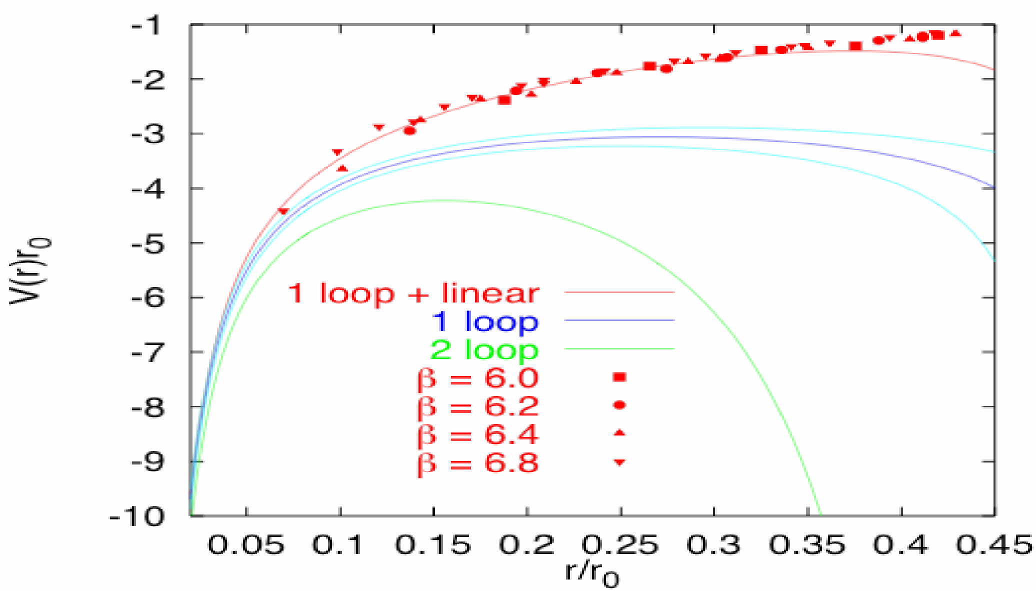


The coupling between color charges gets weaker at high energies- or short distances…

Infrared Slavery

$$V(r) = \sigma r - \frac{e}{r}$$

$\sigma = 425 \text{ MeV}^2 \; ; \; e \approx 0.5$



Potential between static quark-anti-quark pair grows linearly at large distances -

provides intuitive picture of confinement

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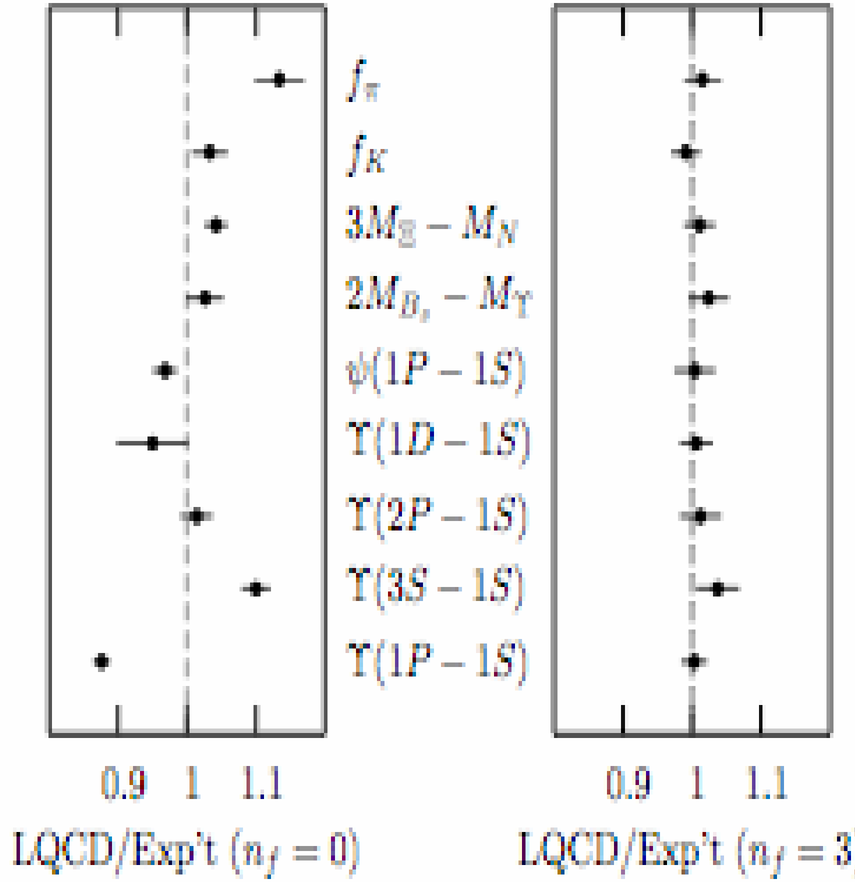
are needed to see this picture.



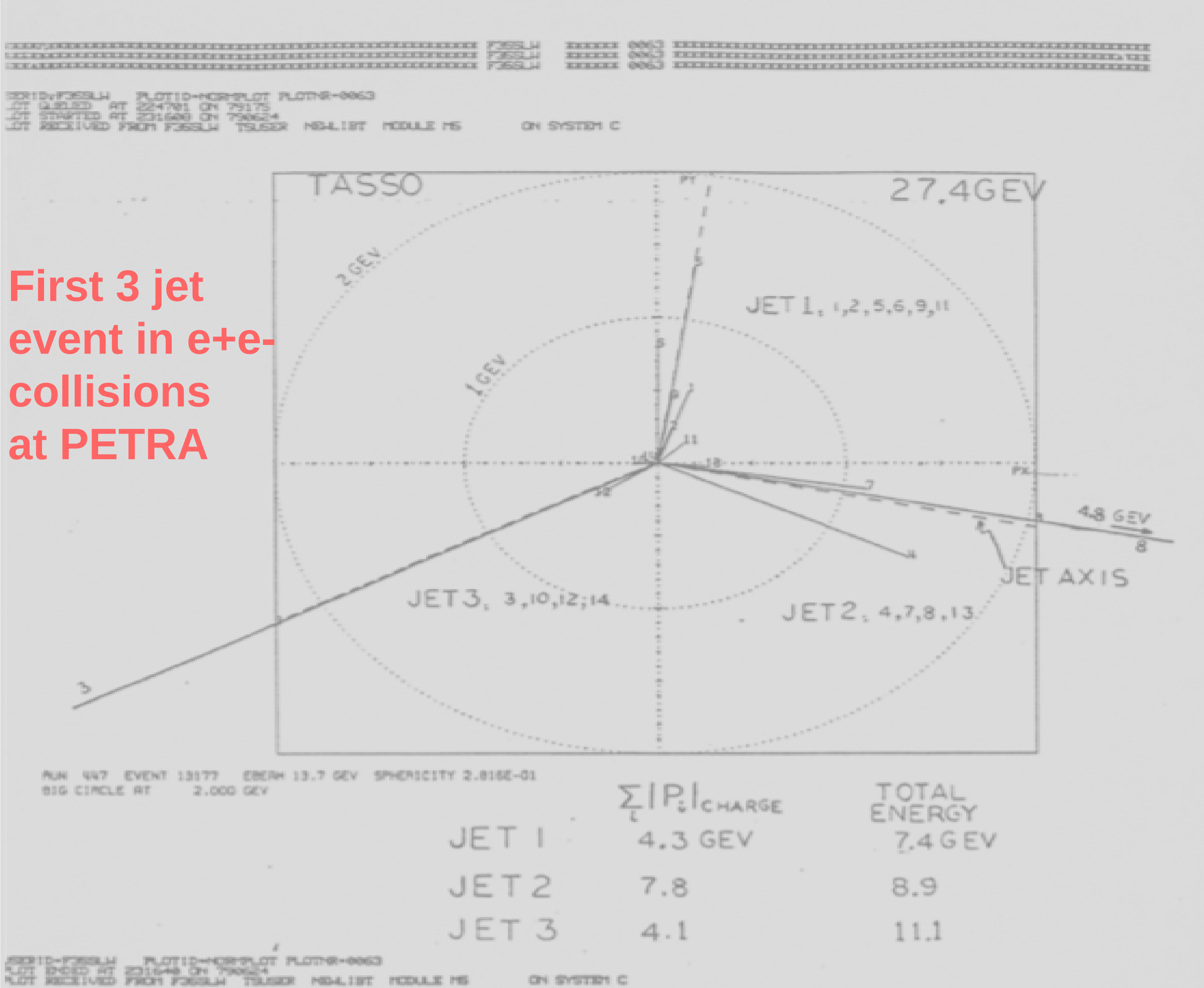
Hep-lat/0304004

QCD explains 99.9% of observable mass of the universe!

(Quenched QCD explains mass spectrum to ~ 10%)

What do we know about gluonic matter ?

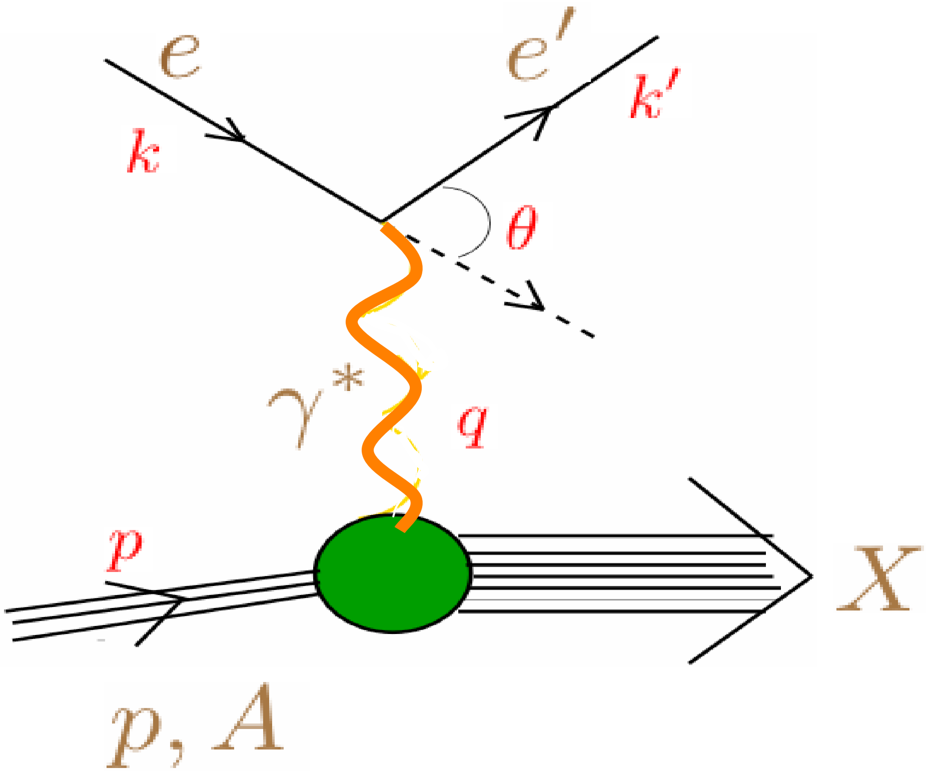
First 3 jet event in e+e- collisions at PETRA



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

DEEPLY INELASTIC SCATTERING

The simplest way to study hadronic structure at short distances…



R. Hofstadter

Kinematic Invariants s Q^2 x_{Bj}

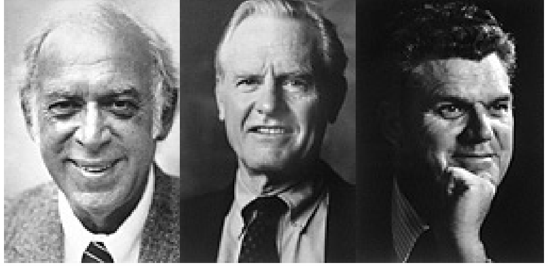
$$x_{\mathrm{Bj}} \approx \frac{Q^2}{s}$$

DIS inclusive cross-section:

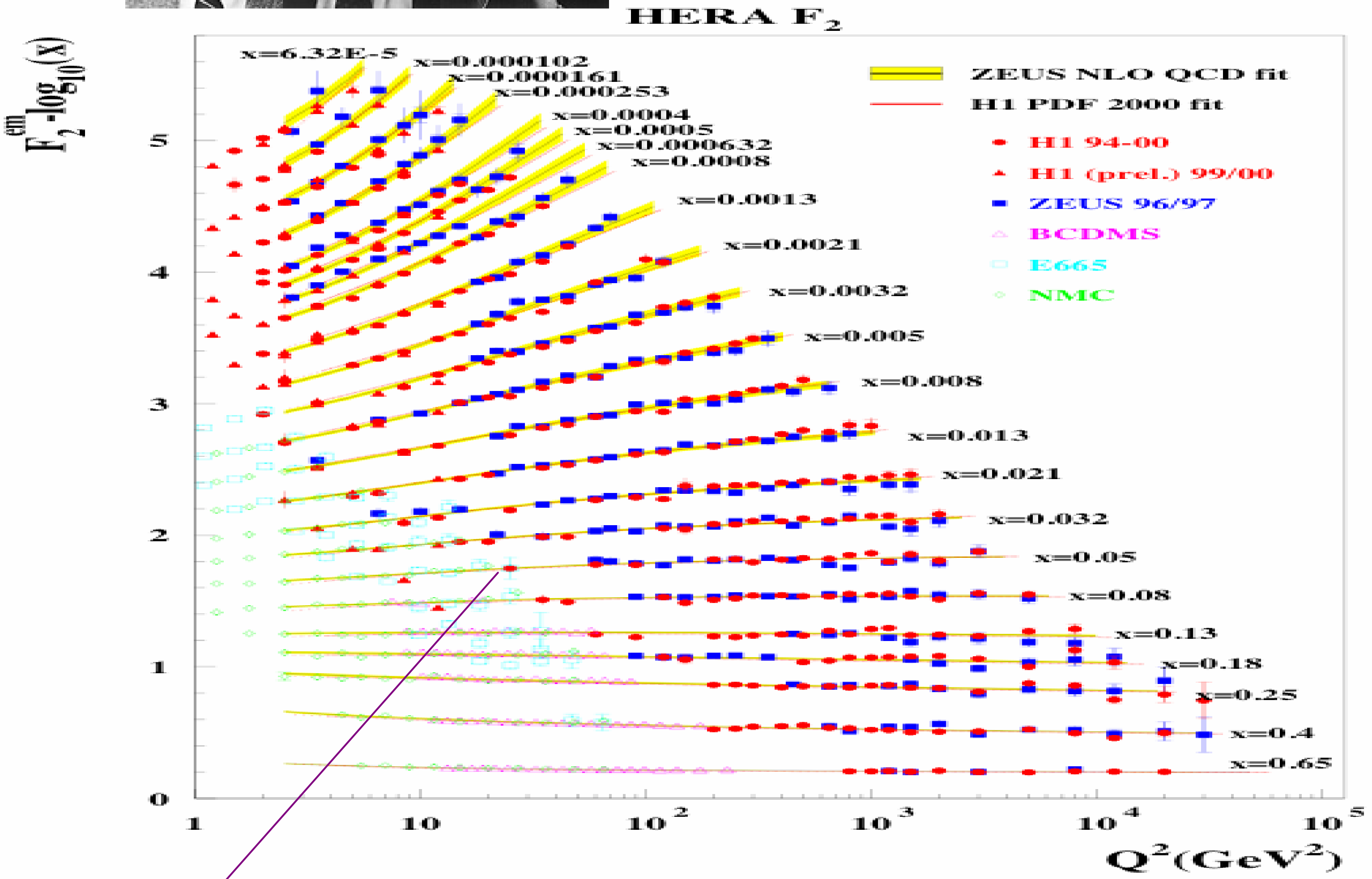
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{\mathrm{em.}}}{xQ^4}\left[y^2 x F_1(x,Q^2) + (1-y)F_2(x,Q^2)\right]$$

Structure functions

Rutherford cross-section



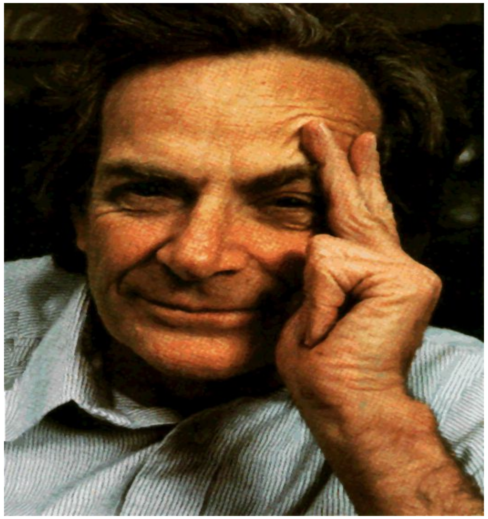
Friedman, Kendall, Taylor



Bj-scaling - apparent scale invariance of structure functions…

DIS in the Bjorken-Feynman picture:

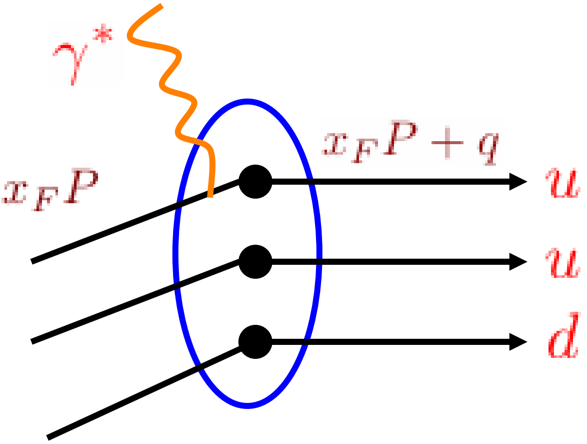
Bjorken

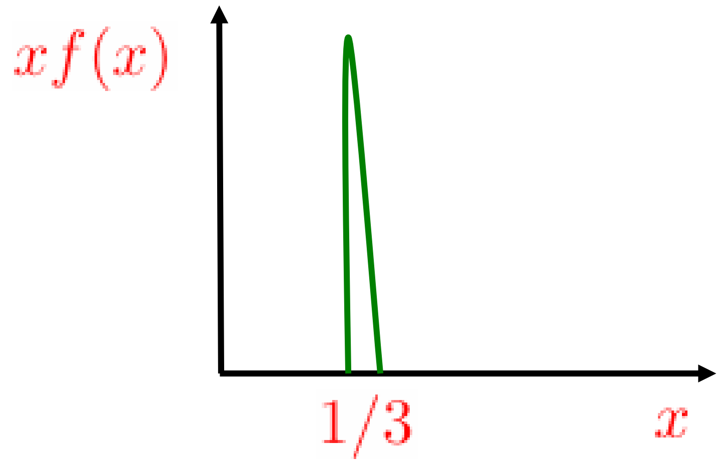


Feynman

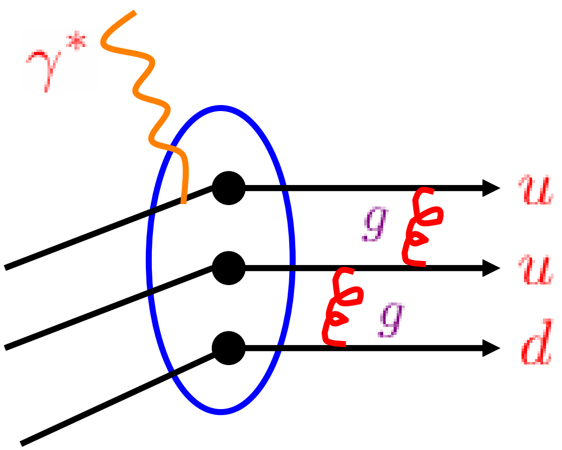
$$Q^2 \to \infty \; ; \; s \to \infty \; ; \; x_{\mathrm{Bj}} = \text{fixed}$$

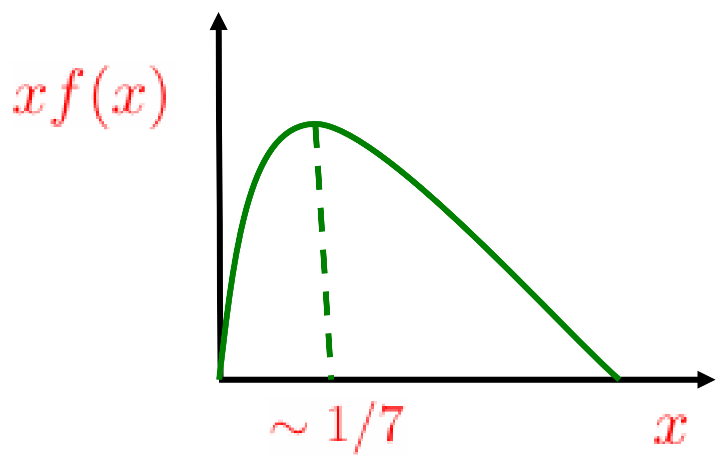
The Hadron at high energies



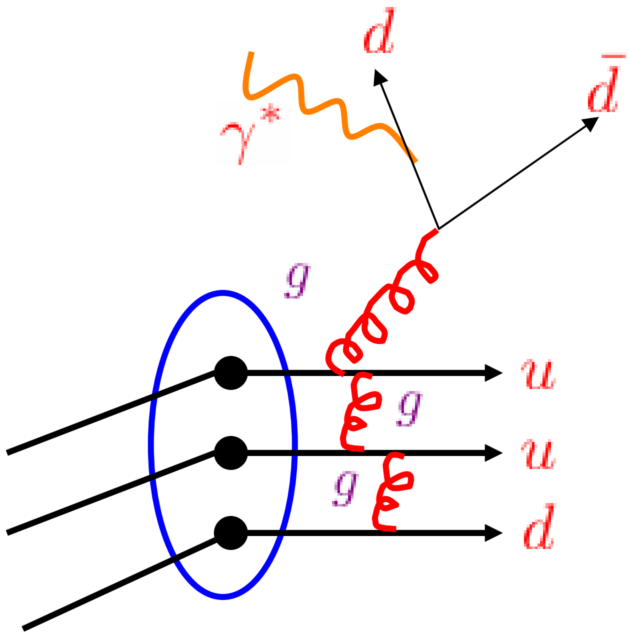


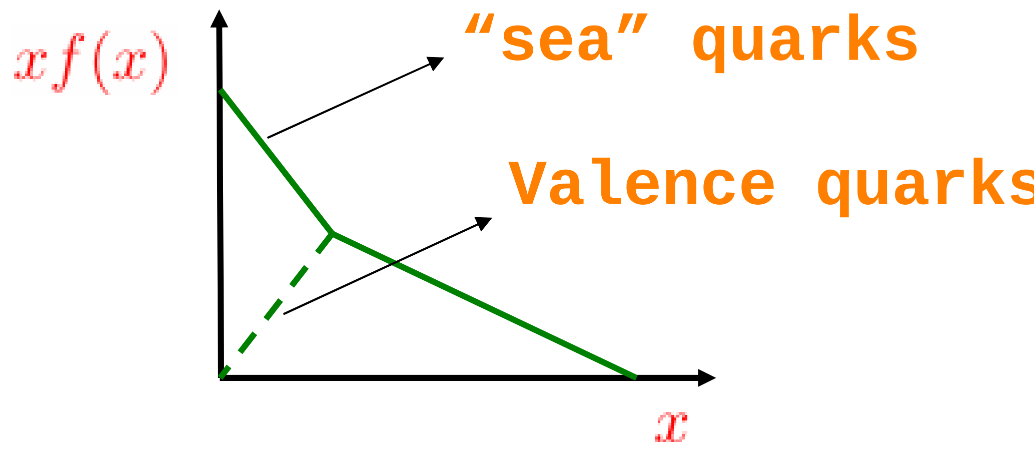
Parton model





QCD-logarithmic corrections





"X"-QCD--RG evolution

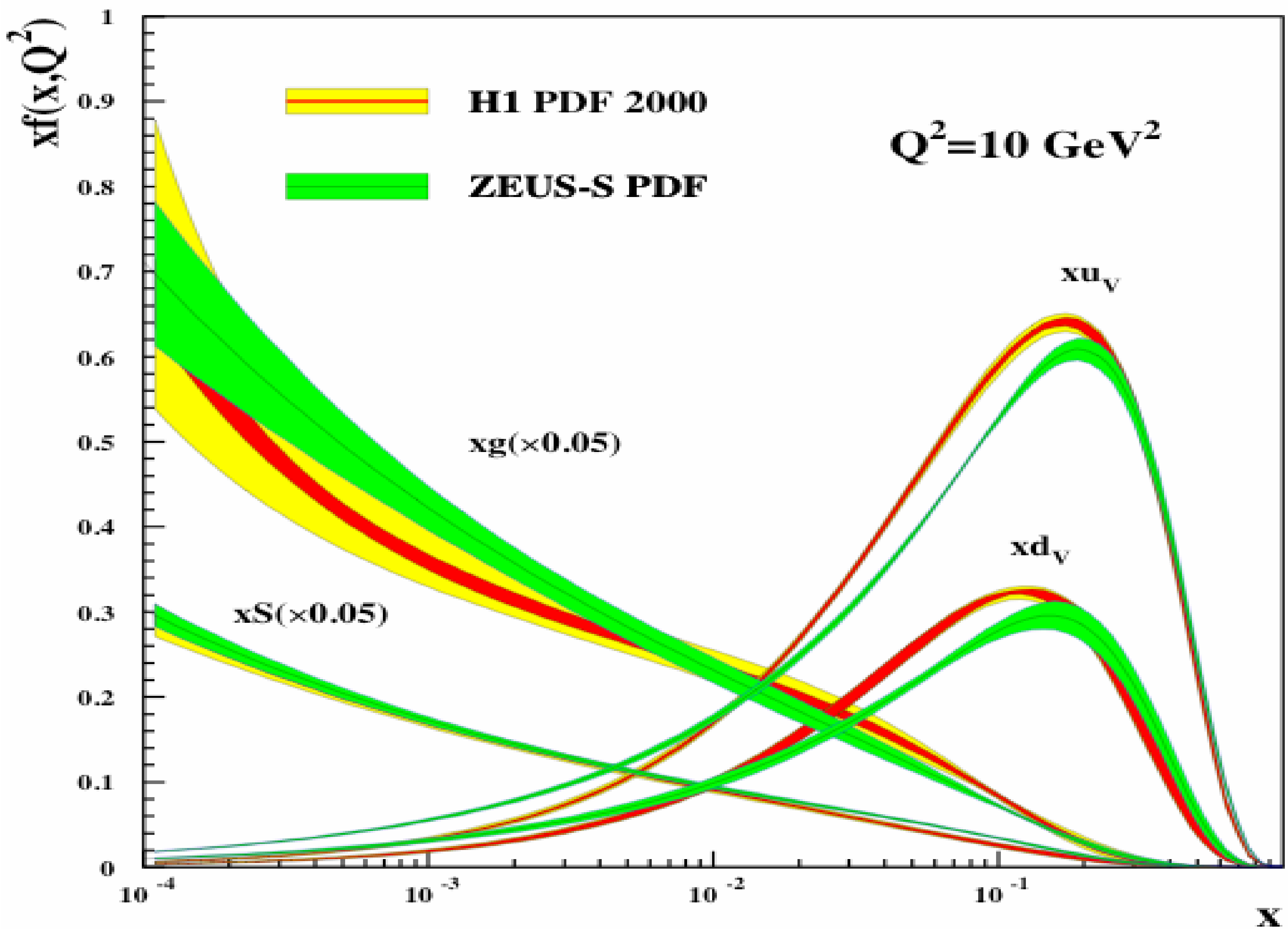
$$\int_0^1 \frac{dx}{x}\left(xq(x) - x\bar{q}(x)\right) = 3$$

# of valence quar

$$\int_0^1 \frac{dx}{x}\left(xq(x) + x\bar{q}(x)\right) \to \infty$$

quarks…

THE HADRON AT HIGH ENERGIES



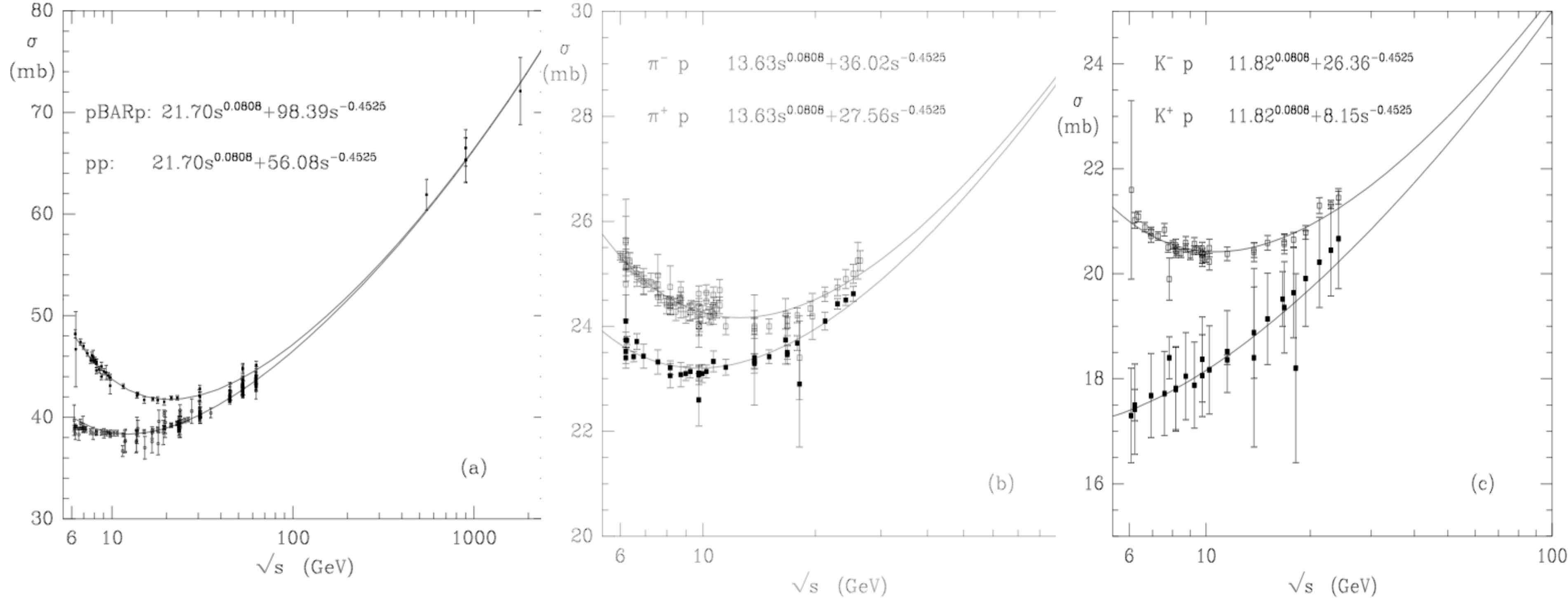
What do we wish to learn about glue ?

a) How do gluons determine the ***structure of hadrons and hadronic interactions*** at high energies ?

b) What is the nature of gluonic matter in nuclear media
-how does it transform into hot and dense matter ?

c) What is the contribution of glue to the spin of the nucleon ?

Total cross-sections



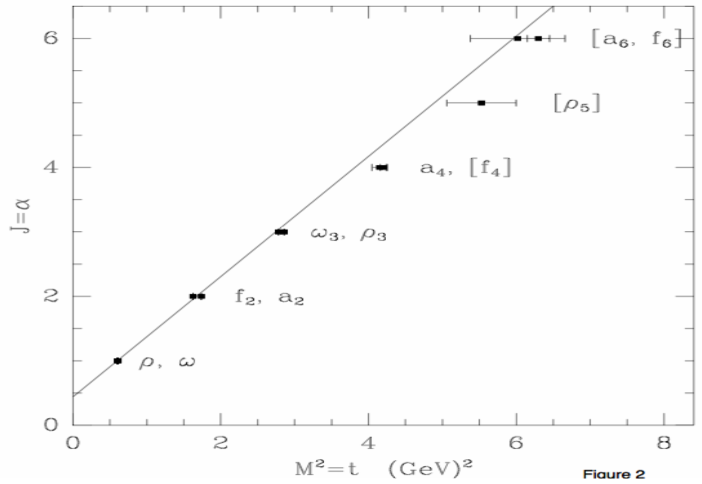
$$\sigma \propto A\, s^{0.0808} + B\, s^{-0.4525}$$

Pomeron exchange **Reggeon exchange**

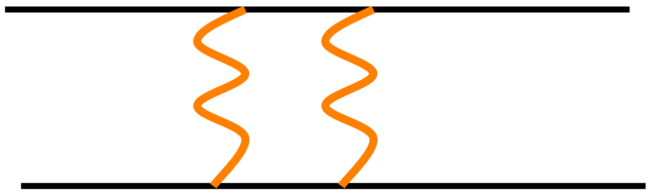
$$\frac{A^{\pi p}}{A^{pp}} \approx \frac{2}{3}$$

=> constituent quark model ?

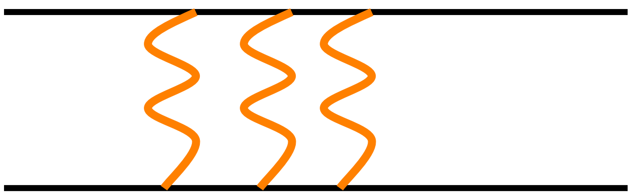
Regge trajectories



Pomeron-color singlet
t-channel glue exchange ?

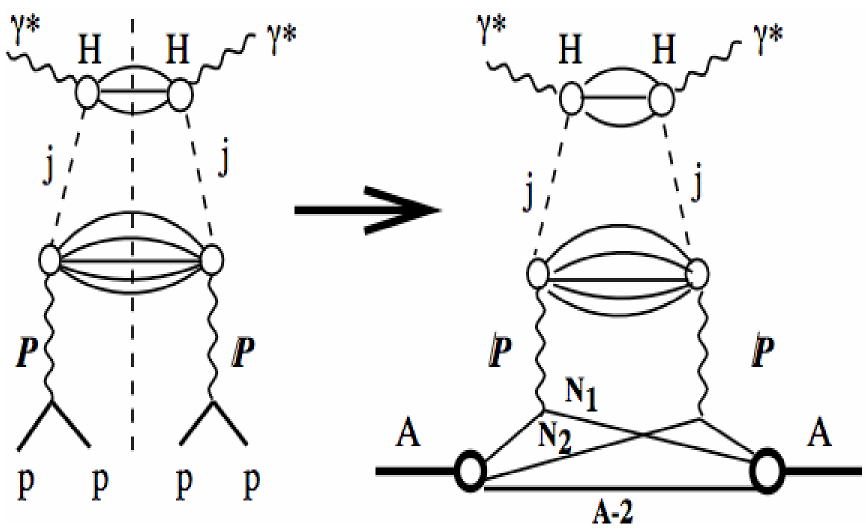


Odderon-color singlet
C-odd partner ?

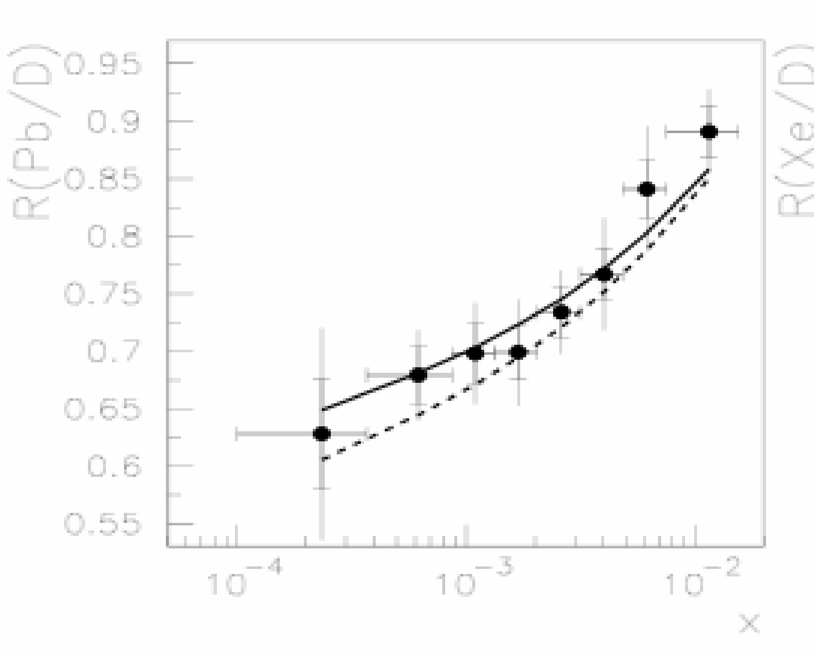


Can these be understood as "universal" quasi-particle excitations of the vacuum ?

How are they modified in nuclei ?



Gribov rules: relation between *diffractive* scattering off nucleons and *nuclear shadowing*



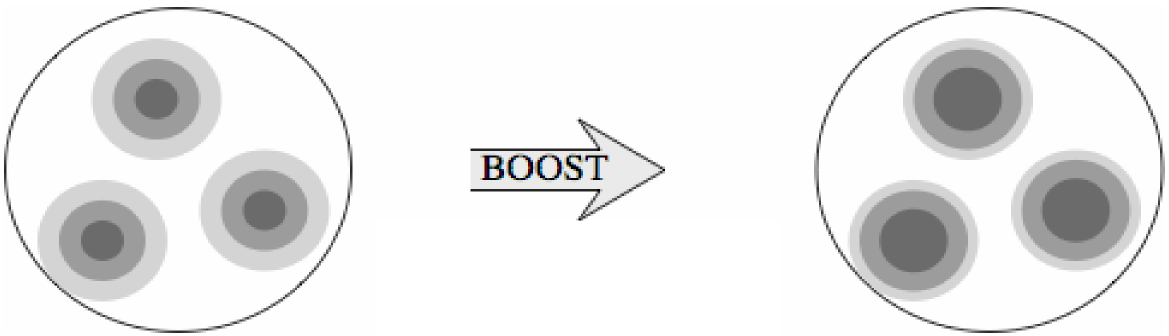
Extensive work on Regge phenomenology but limited understanding in QCD framework

DIS in the Regge-Gribov picture:

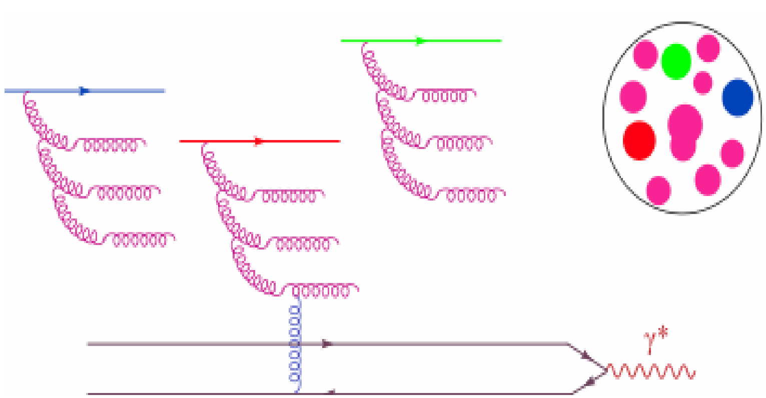
$$x_{\mathrm{Bj}} \to 0 \; ; \; s \to \infty \; ; \; Q^2 = \mathrm{fixed}$$

More relevant for understanding multi-particle production and total cross-sections…

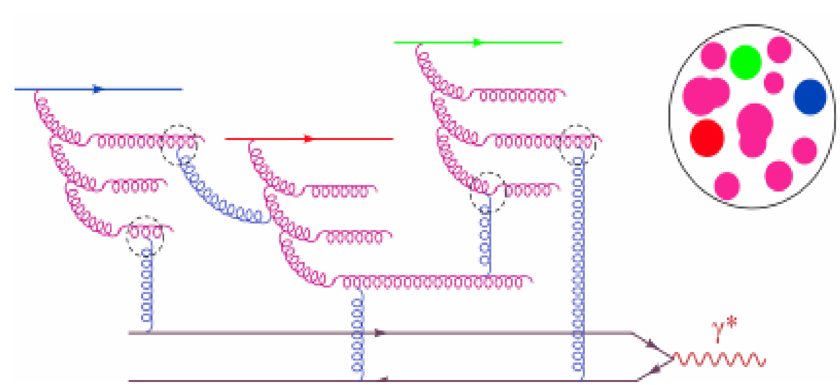
Viewing the hadron in the transverse plane at high energies…



Y_0 ---> Y+Y_0



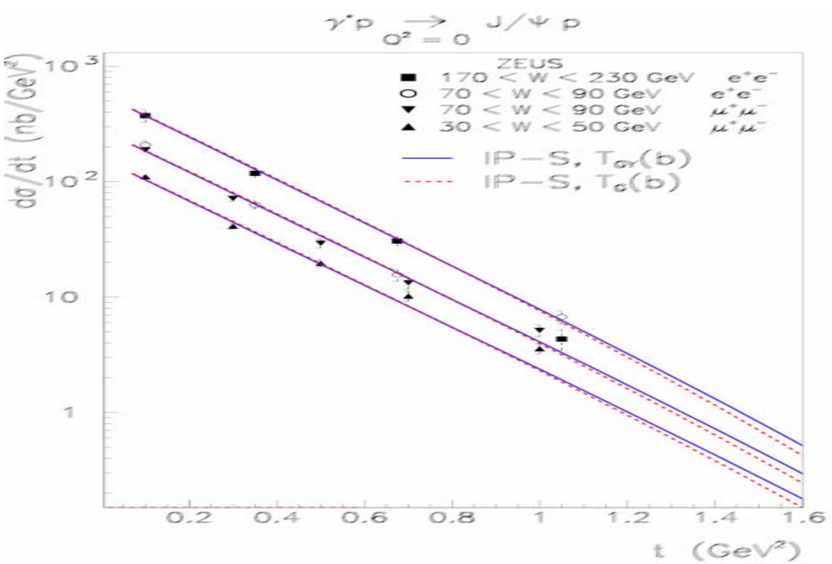
Gluon radiation



Gluon radiation & recombination

- **Overlapping gluon clouds… at large impact parameters, interplay between perturbative (hard Pomeron) and non-perturbative (soft Pomeron) physics…**

- **By studying the "t" dependence of diffractive final states , can we learn more about the transition regime ?**

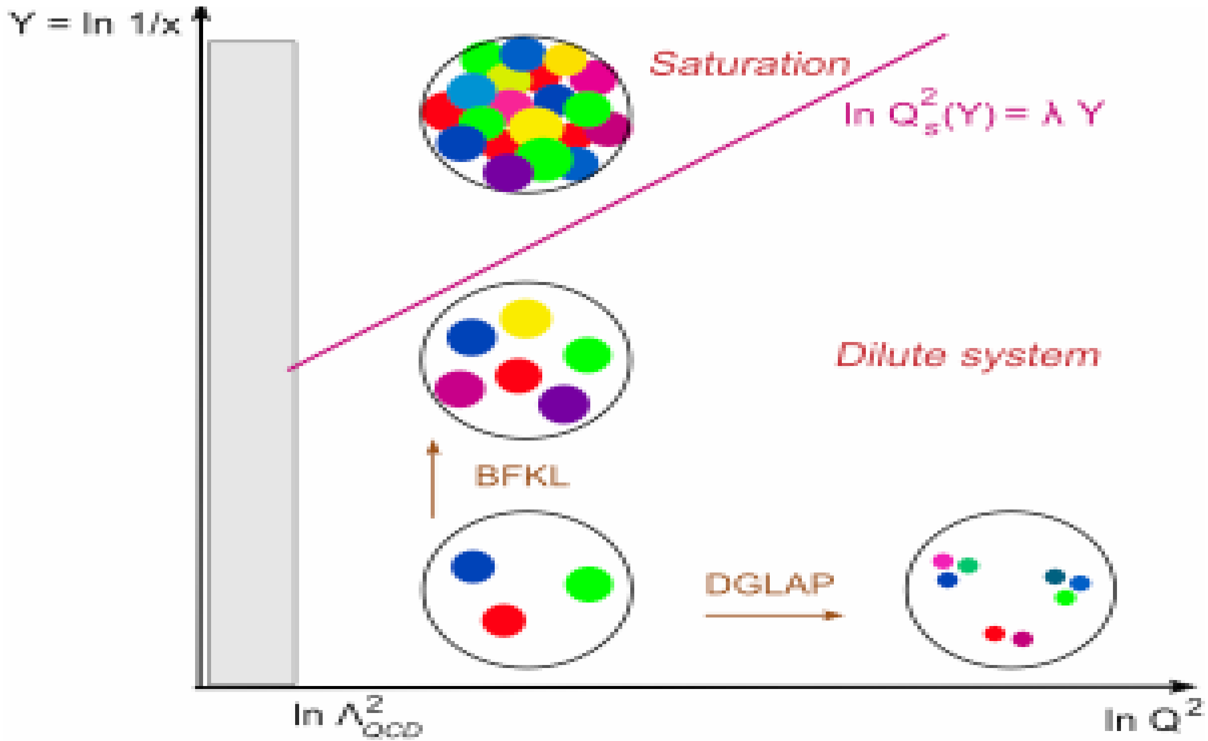


S-matrix:

$$S(x,r,b) \propto 1 - \int d^2\Delta\, e^{-i\Delta\cdot b}\sqrt{\frac{d\sigma}{dt}}$$

$$\Delta^2 = -t$$

Resolving the hadron…

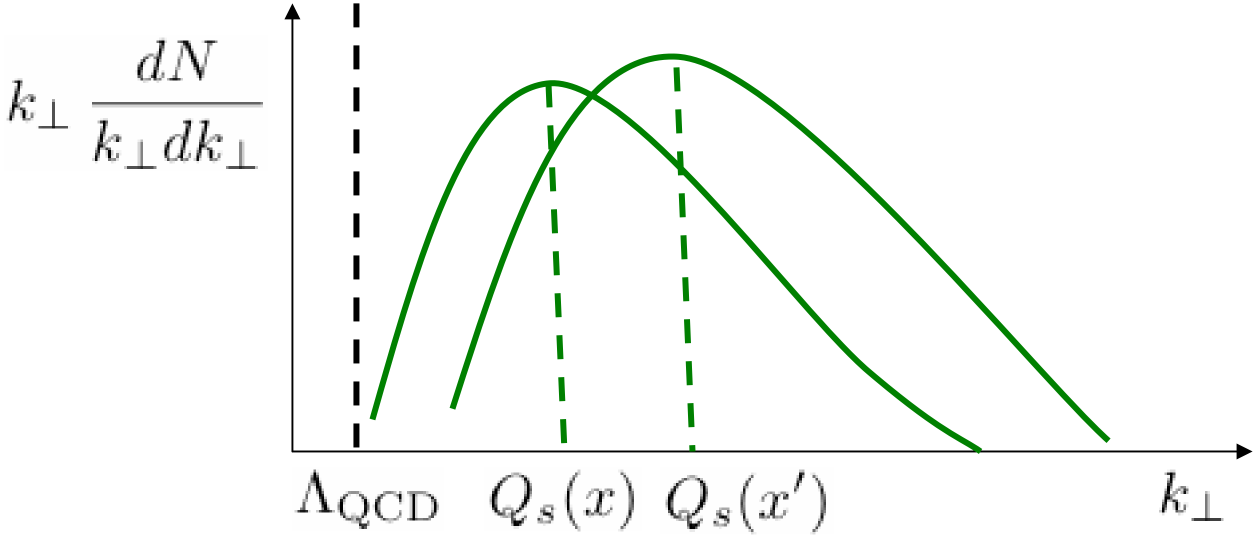


Gluon density saturates at maximal field strength squared:

f = $\dfrac{1}{\alpha_S}$

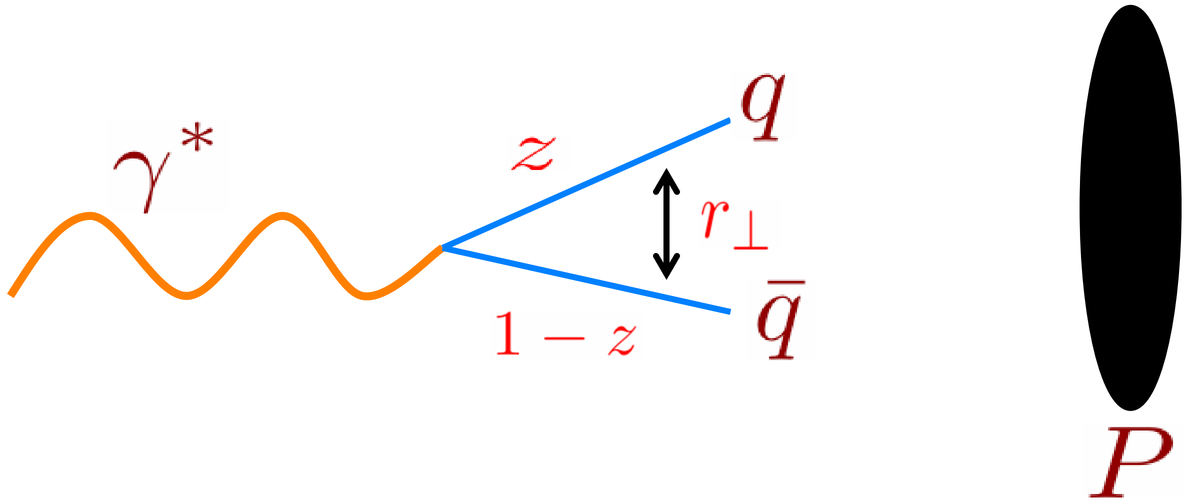
New scale: $Q_s(x,b)$

Hadron at high energies is a Color Glass Condensate



- ✓ **Gluons are colored**
- ✓ **Random sources evolving on time scales much larger than natural time scales-very similar to spin glasses**
- ✓ **Bosons with large occupation** $\sim \frac{1}{\alpha_S}$
- ✓ **Typical momentum of gluons is** Q_s

Golec-Biernat & Wusthoff's model



$$\sigma_{\mathrm{T,L}}^{\gamma^*,P} = \int d^2 r_\perp \int dz \, |\psi_{\mathrm{T,L}}(r_\perp, z, Q^2)|^2 \, \sigma_{q,\bar{q},P}(r_\perp, x)$$

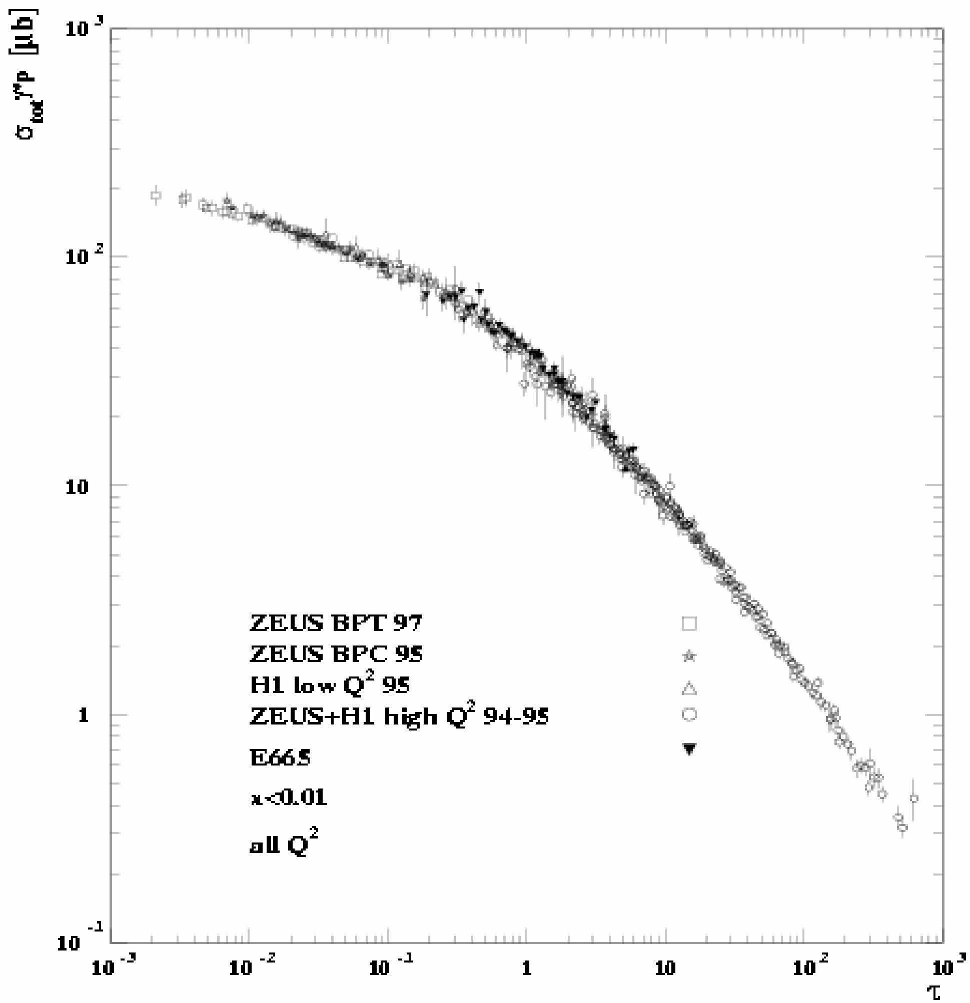
where $\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0 \left[1 - \exp\left(-r_\perp^2 \, Q_s^2(x)\right)\right]$

& $$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

Parameters: $Q_0 = 1\,\mathrm{GeV}\,;\, \lambda = 0.3\,;\, x_0 = 3 \cdot 10^{-4}$

Geometrical scaling at HERA

(Golec-Biernat,Kwiecinski,Stasto)



$\tau = Q^2/Q_s^2$

Saturation models fit HERA inclusive and diffractive data

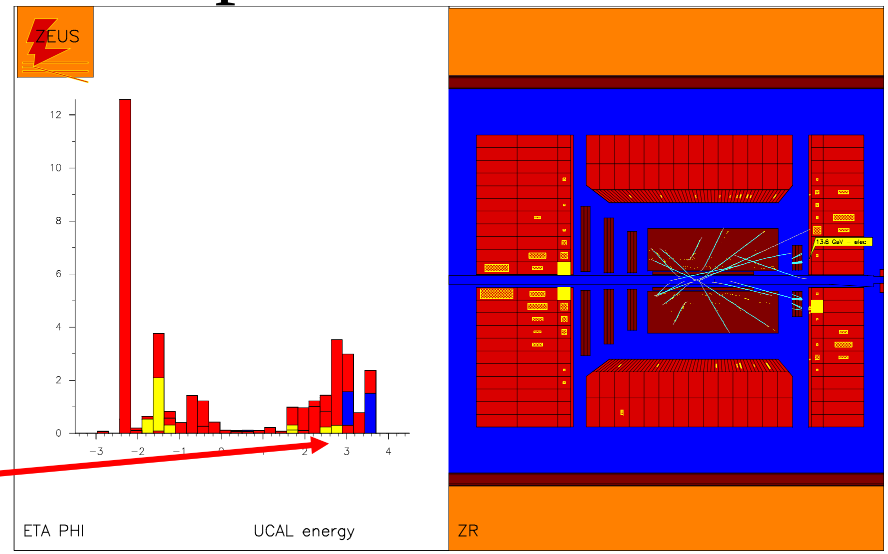
Forshaw and Sandapen, hep-ph/0411337
Kowalski-Teaney hep-ph/0304189

Scaling seen for all x < 0.01 and $0.045 < Q^2 < 450\,\mathrm{GeV}^2$

Diffractive Surprises

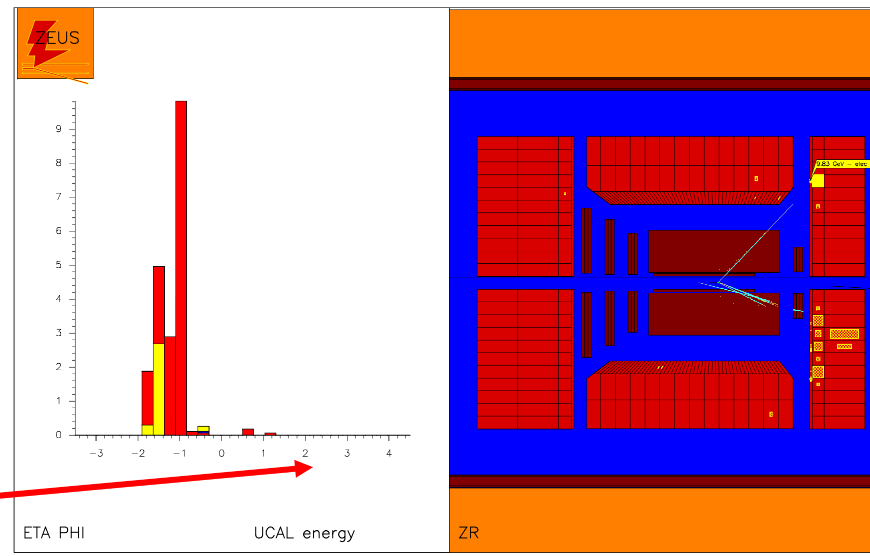
‘Standard DIS event’

Detector activity in proton direction



Diffractive event

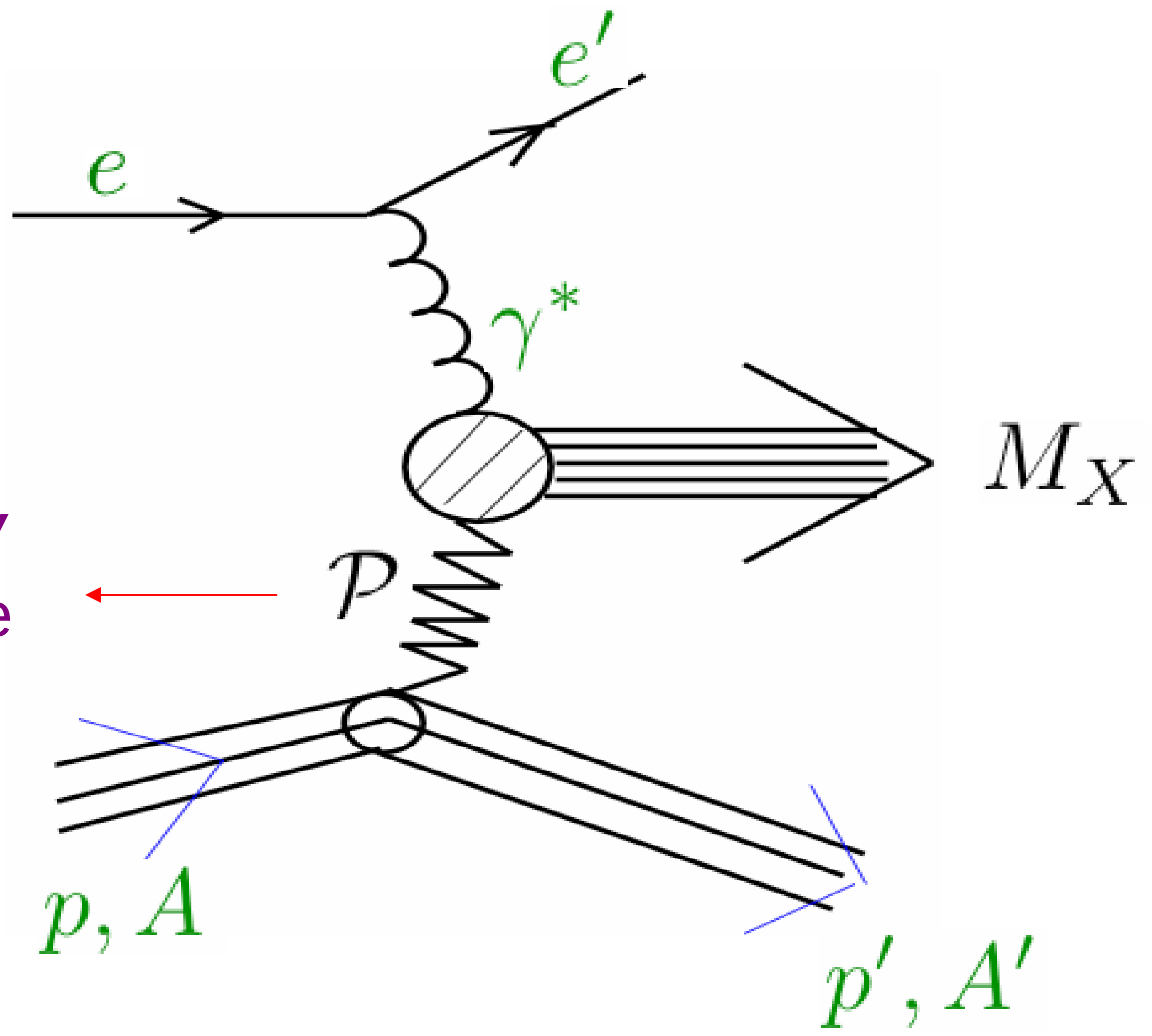
No activity in proton direction



Approximate 10% of events are hard diffractive events!

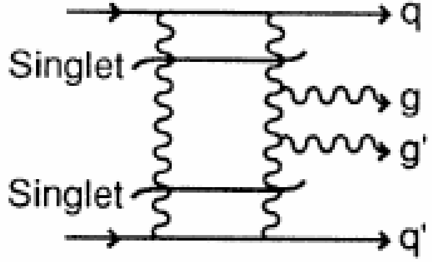
III: Hard diffractive processes

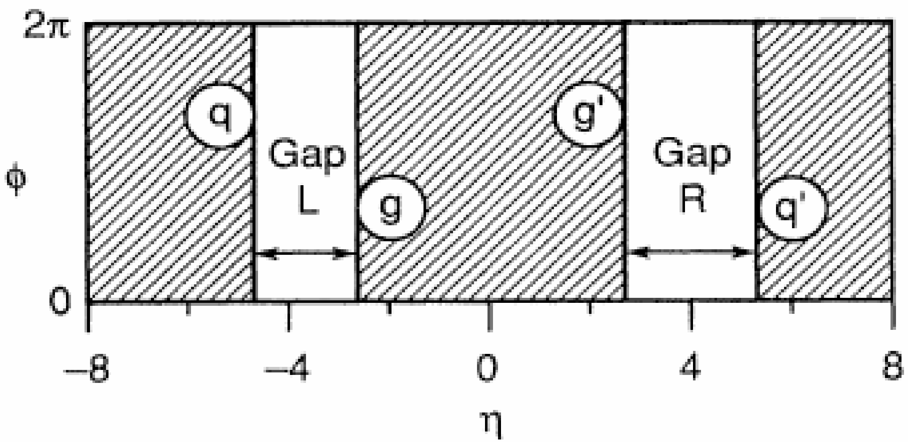
“Pomeron”
exchange



30 % of eRHIC eA events may be hard diffractive events-
Study sizes and distributions of Rapidity Gaps

Lego plots a la Bjorken and Khoze et al.



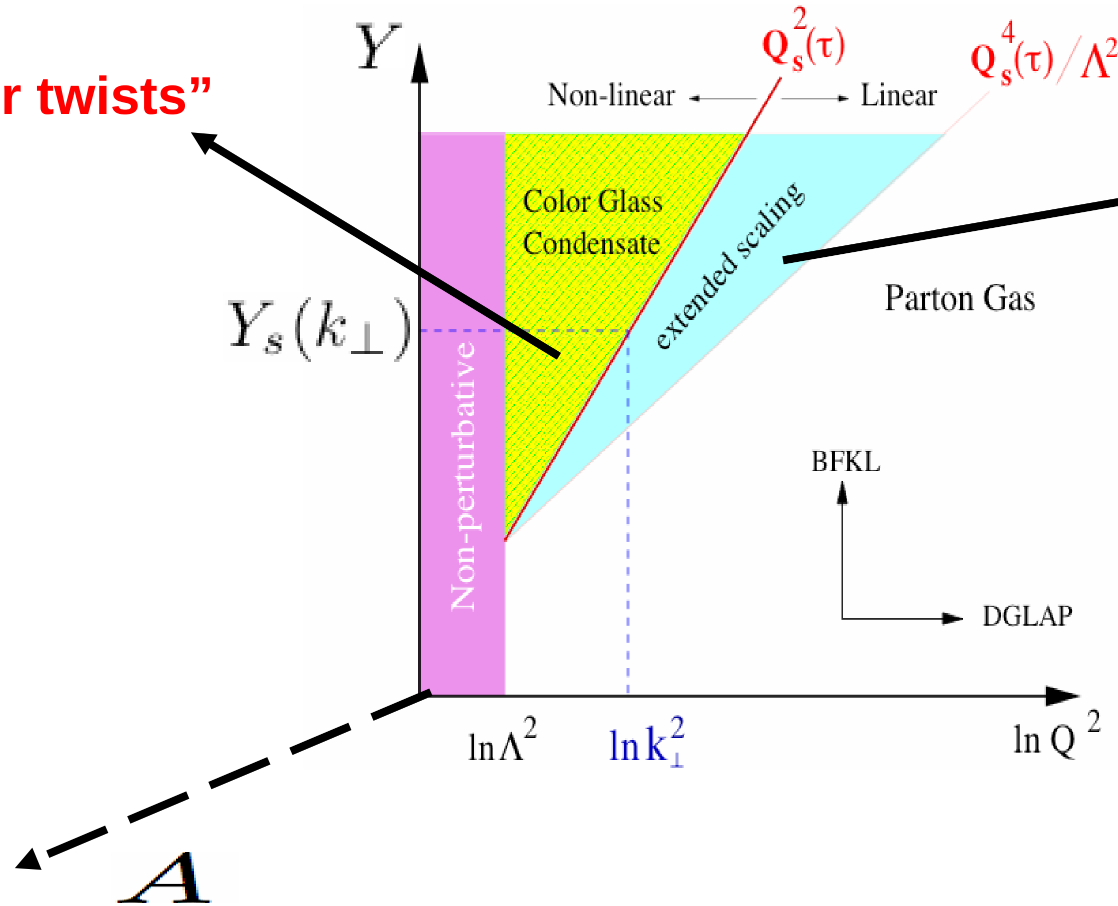


Such multi-gap events can also be studied in DIS

Bj, hep-ph/9601363

Novel regime of QCD evolution at high energies

“Higher twists”



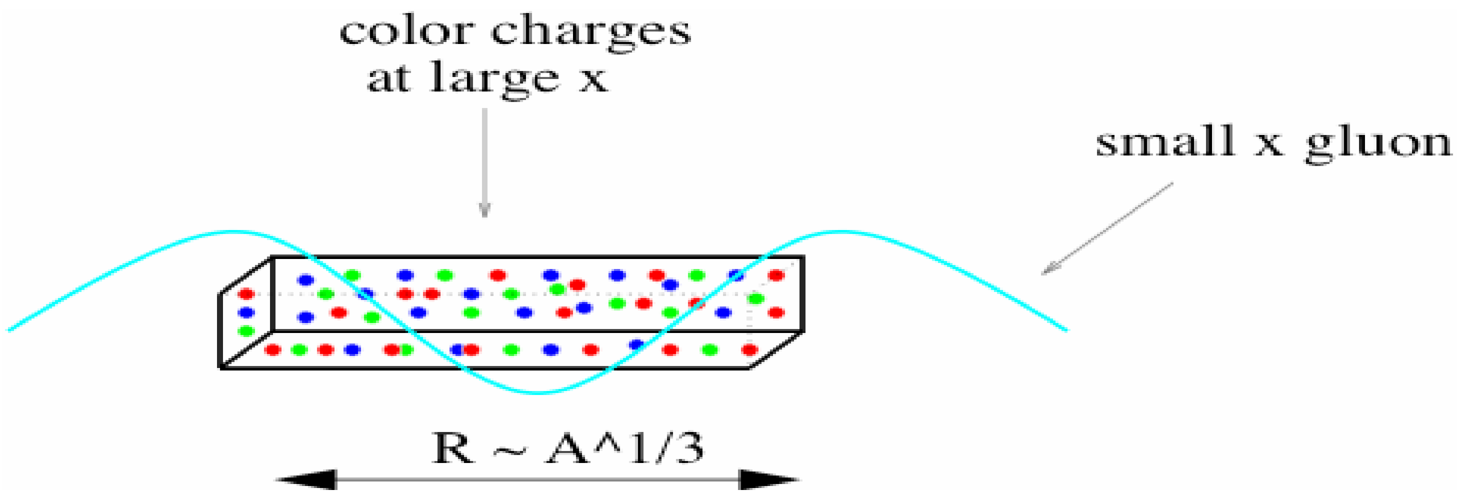
Leading twist shadowing

Novel Renormalization Group equations now allow detailed and controlled studies in the Regge-Gribov limit

The nuclear “oomph” factor!

?

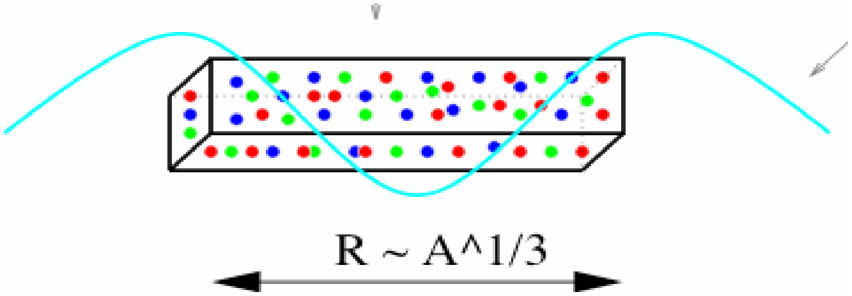
$$Q_s^2 \propto \frac{A^{1/3}}{x^{\delta}}$$



eA at eRHIC $\approx$ same parton density as ep at LHC energies!

Virtual photon coherence length:

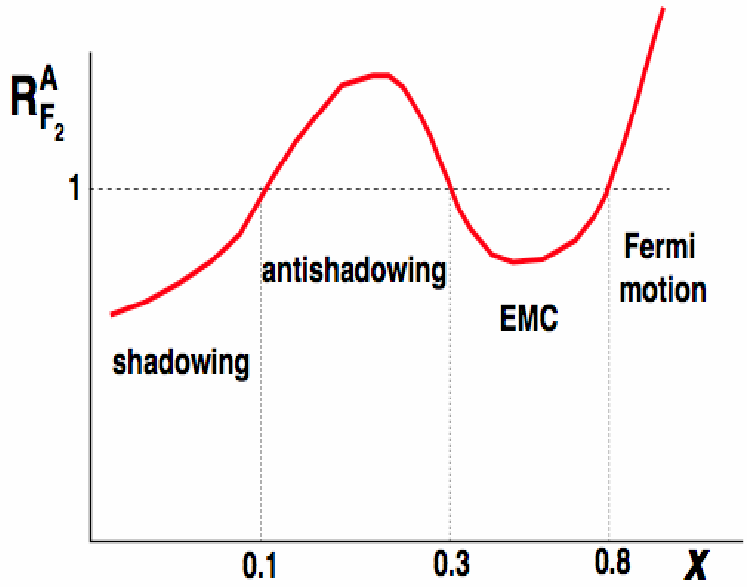
$$l_{\mathrm{coh.}} \propto 1/(2m_n\, x)$$



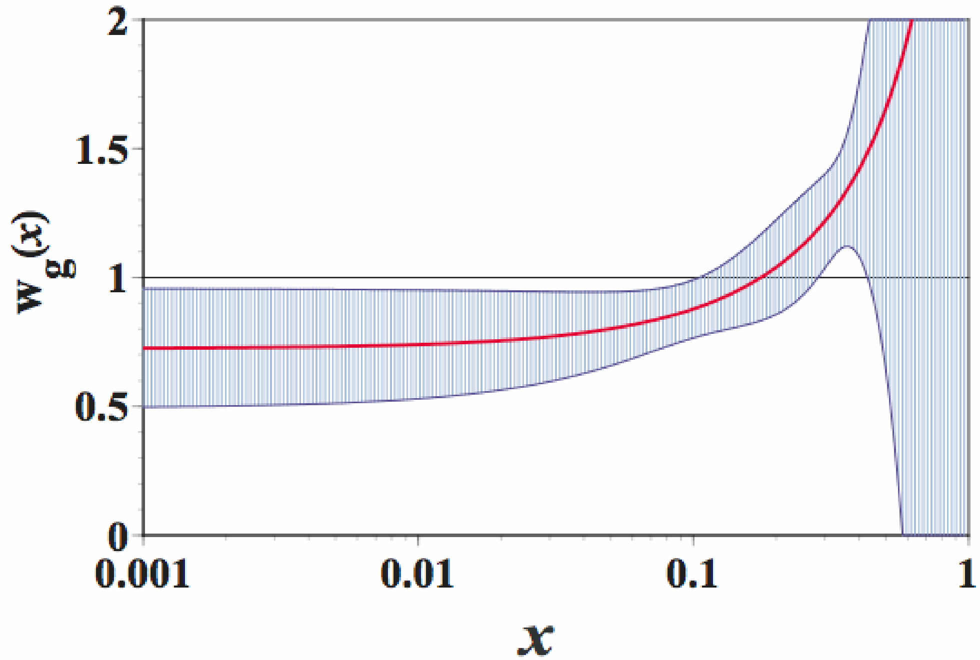
- x_Bj << 0.01 : Photon coherence length exceeds nuclear size
  - study "universal" high parton density effects.

- 0.01 < x_Bj < 0.1: Intermediate length scale between R_p & R_A
  - study medium dependence of final states
  - hadronization in QCD media.

- x_Bj >> 0.1: Photon localized to longitudinal size smaller than nucleon size-EMC and Fermi motion region

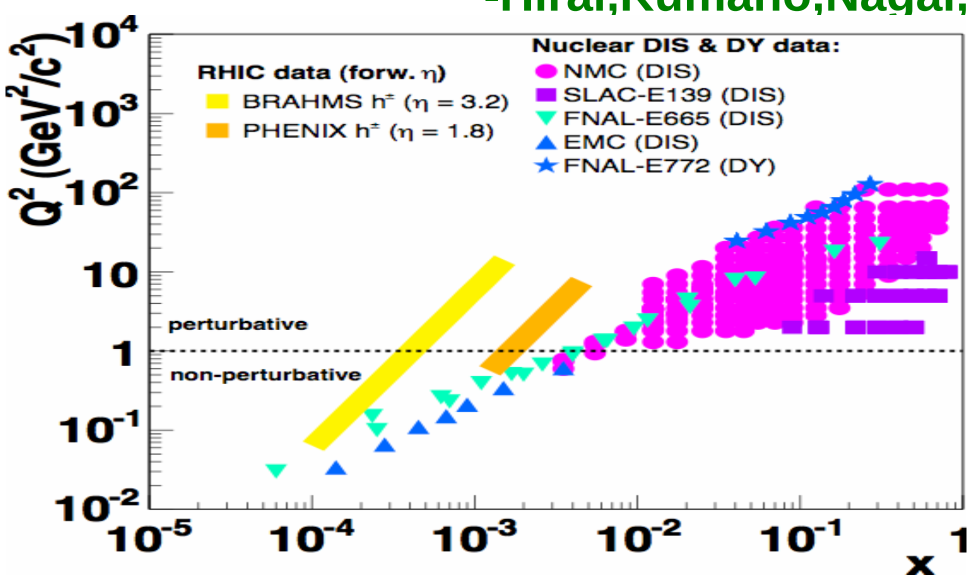


Cartoon of ratio of nuclear structure functions



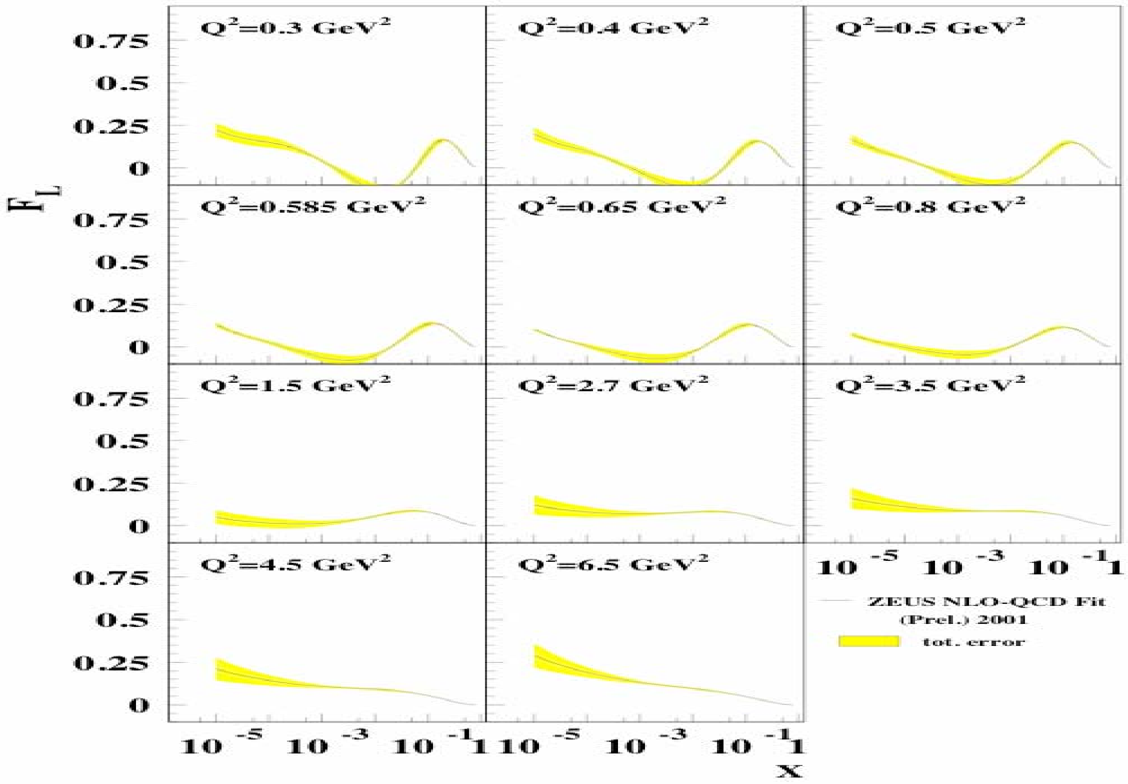
Uncertainity in ratio of Ca to nucleon gluon distributions

-Hirai,Kumano,Nagai, hep-ph/0404093



Armesto

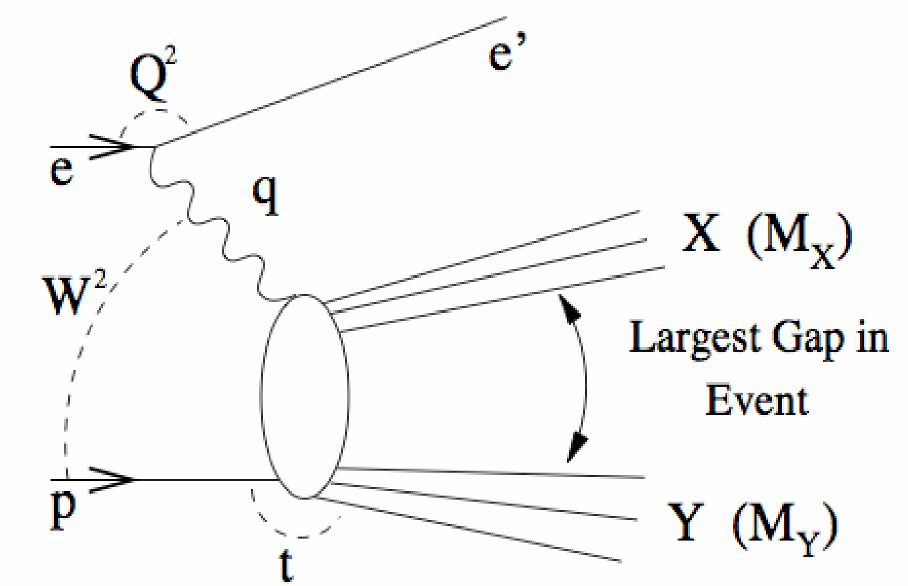
How do we accomplish what we wish to learn about the nature of glue ?



$$F_L \propto \alpha_S \, x \, G(x, Q^2)$$

F_L is a positive definite quantity- more sensitive to higher twists than F_2 ?

- clarify comparision with leading twist NLO pQCD at low x and moderate Q^2



$$R_{A_1,A_2}(\beta, Q^2, x_{\mathcal{P}}) = \frac{F_{2,A_1}^{D(3)}(\beta, Q^2, x_{\mathcal{P}})}{F_{2,A_2}^{D(3)}(\beta, Q^2, x_{\mathcal{P}})}$$

R_{A1,A2} = 1 => Pomeron flux is A -independent
= f(A1,A2) - universal form

Diffractive Vector Meson Production:

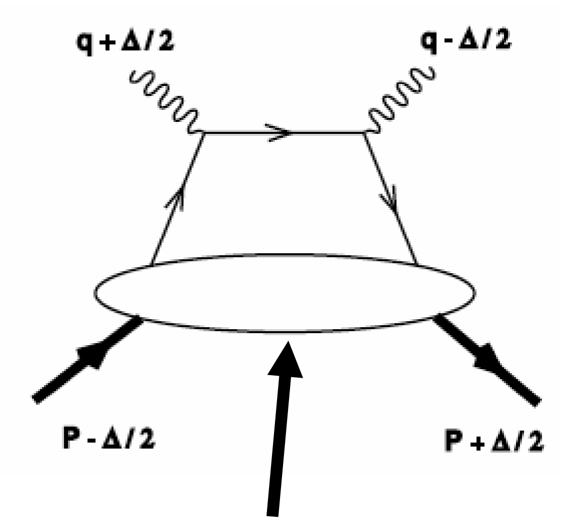
$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* A \to VA) \propto \alpha_S^2 \left[G_A(x, Q^2)\right]$$

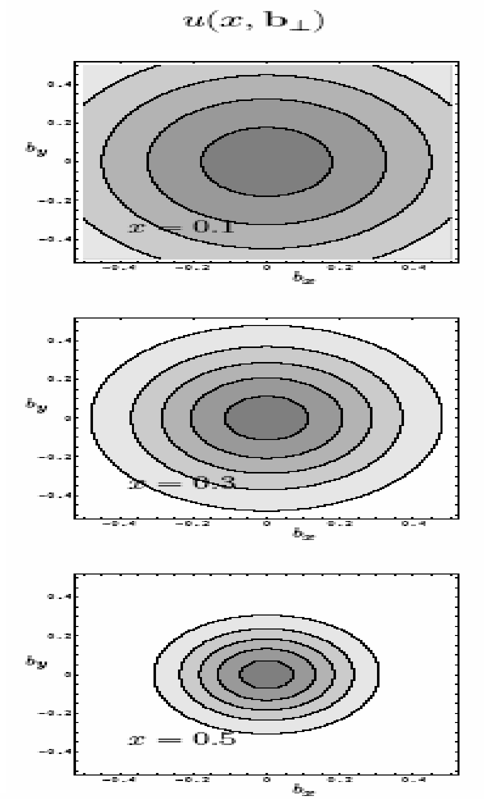
Very sensitive to small x glue!

Brodsky,Gunion,Mueller, Frankfurt,Strikman

“Generalized parton distributions”

“Deeply-virtual Compton scattering”,   exclusive proc.





$$H_q(x,\xi,\Delta^2),\ E_q(x,\xi,\Delta^2)$$

$$J_q = \frac{1}{2} \lim_{\Delta^2 \to 0} \int dx\, x \left[H_q(x,\xi,\Delta^2) + E_q(x,\xi,\Delta^2) \right]$$

$$q(x,\vec{b}_\perp) = \int d^2\Delta_\perp\, \mathrm{e}^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp}\, H_q(x,0,-\Delta_\perp^2)$$

How can we probe glue with a high luminosity lepton-ion collider ?

- ✓ Precision inclusive measurements of structure functions
  -wide sweep from Protons to Uranium

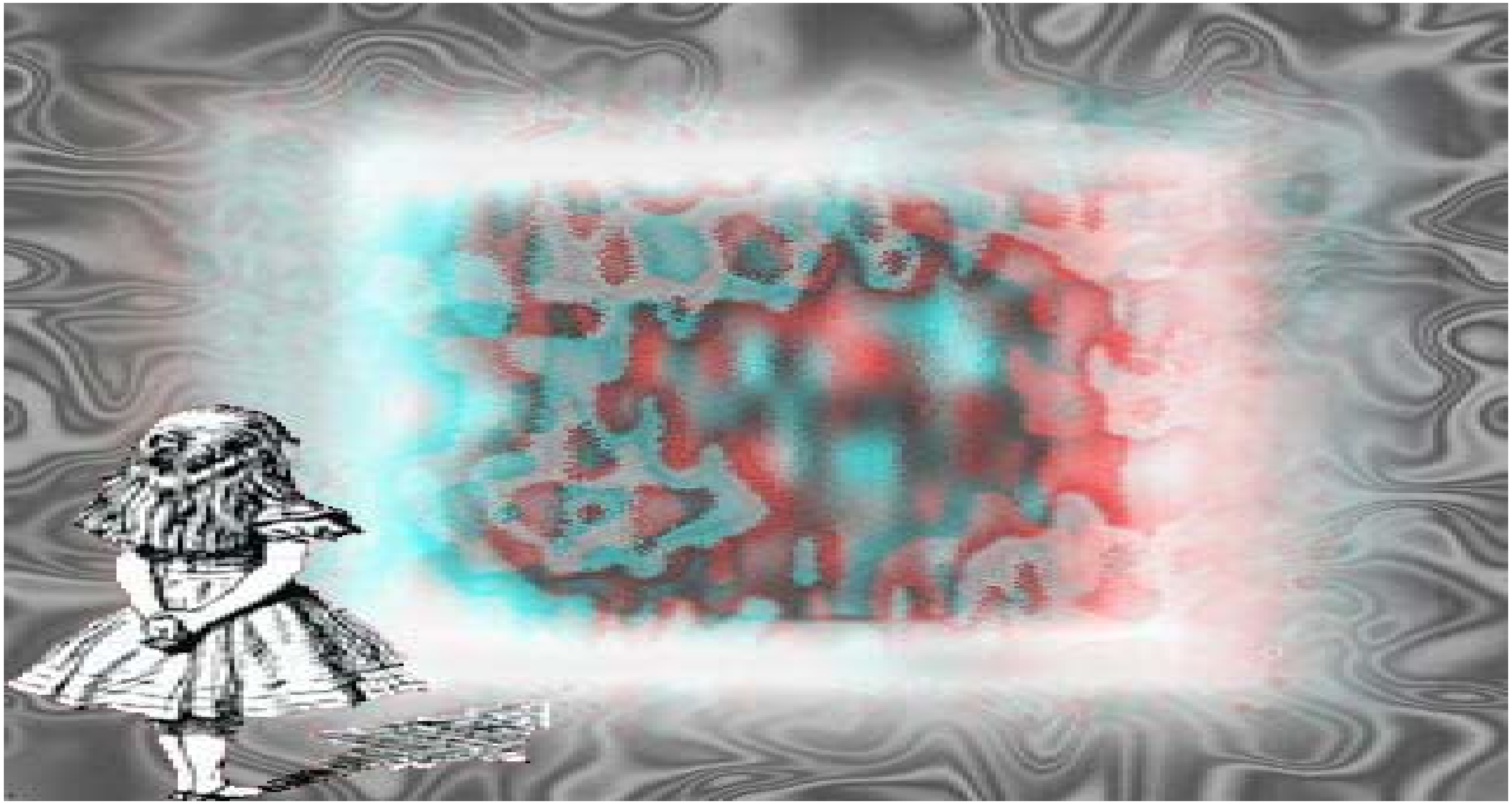
$$F_2^A \quad F_L^A \quad F_{2,Diff.}^A \quad F_{L,Diff.}^A$$

- ✓ Direct (**photon-gluon fusion**) semi-inclusive and exclusive probes of final states

$$\gamma^* A \to \pi, K, \Lambda, \cdots X \; ; \; \gamma^* A \to J/\psi A$$

- ✓ Generalized Parton Distributions (DVCS) $\gamma^* A \to \gamma A$
- ✓ Multiplicity fluctuations and correlations

New insights into old puzzles of the Regge-Gribov limit of QCD:



Great progress in understanding gluonic quasi-particle excitations of the vacuum

Summary

- Gluons exist. They provide much of the observable mass of the universe.
- In hadrons at high energies, they exist as ``wee" excitations of the vacuum- they are numerous and have remarkable collective interactions- Color Glass Condensate
- They control the properties of much of high energy scattering and produce a hot and dense Quark Gluon Plasma in heavy ion collisions

…summary

- They contribute significantly to the spin of the proton

- Very little is known about glue -- especially in nuclei
  .

- A high energy, high luminosity, electron-ion collider is ideally suited to explore this *terra incognita*

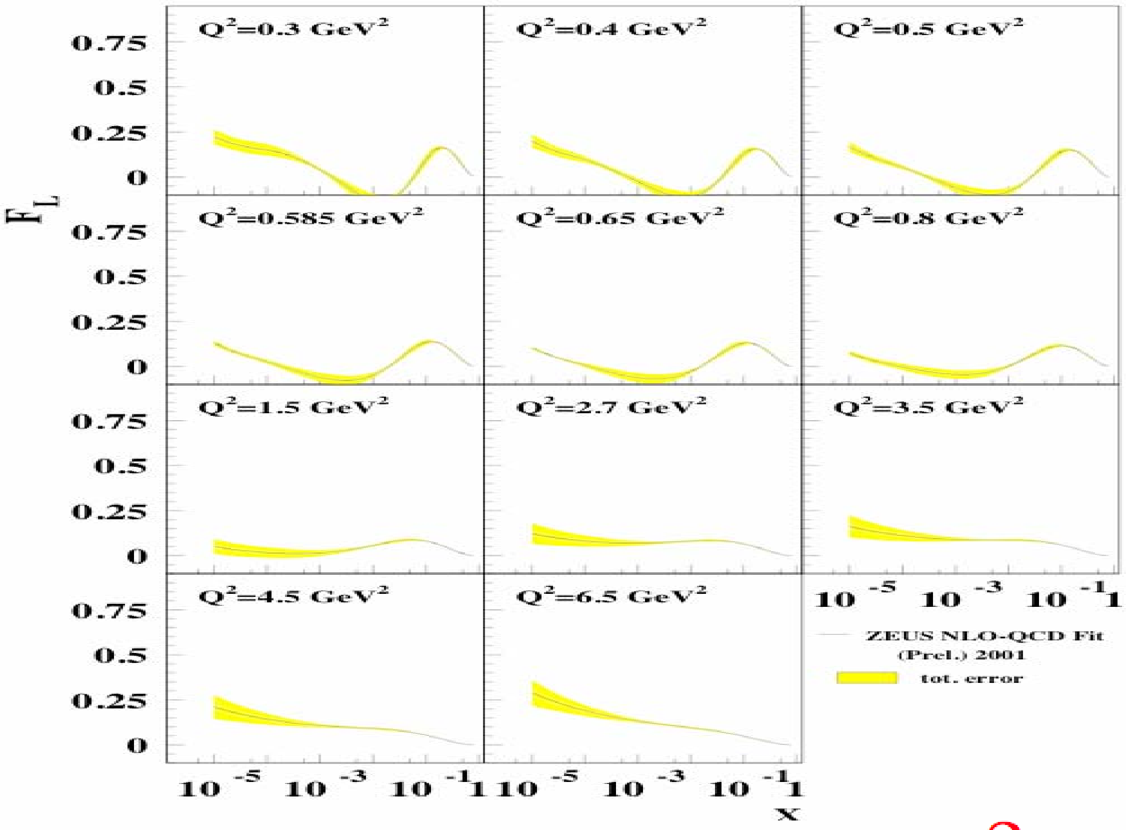
Extra Slides

Principal physics goals of eRHIC

Extend DIS Paradigm for <u>quantitative</u> QCD studies in largely ``terra incognita" small x-large Q^2 regime

Three pronged approach

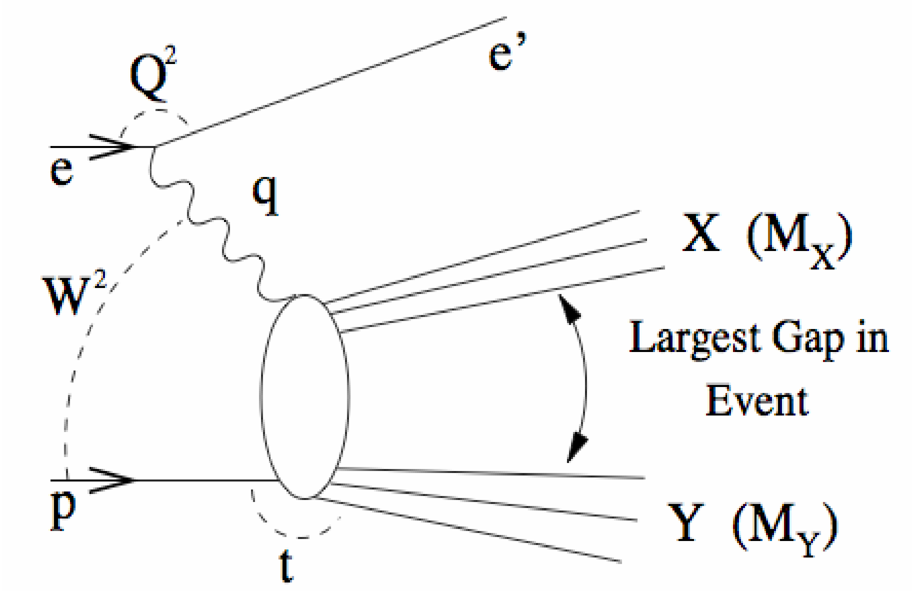
- **High luminosity (~100 times HERA) unpolarized e-p scattering**
- **Polarized e-pol. P - highest energies and collider mode for the first time**
- **First eA collider - detailed map of QCD in nuclear media & very high parton densities.**



$$F_L \propto \alpha_S \, x \, G(x, Q^2)$$

F_L is a positive definite quantity- more sensitive to higher twists than F_2 ?

- clarify comparision with leading twist NLO pQCD at low x and moderate Q^2



$$R_{A_1,A_2}(\beta, Q^2, x_{\mathcal{P}}) = \frac{F_{2,A_1}^{D(3)}(\beta, Q^2, x_{\mathcal{P}})}{F_{2,A_2}^{D(3)}(\beta, Q^2, x_{\mathcal{P}})}$$

R_{A1,A2} = 1 => Pomeron flux is A -independent
= f(A1,A2) - universal form

Diffractive Vector Meson Production:

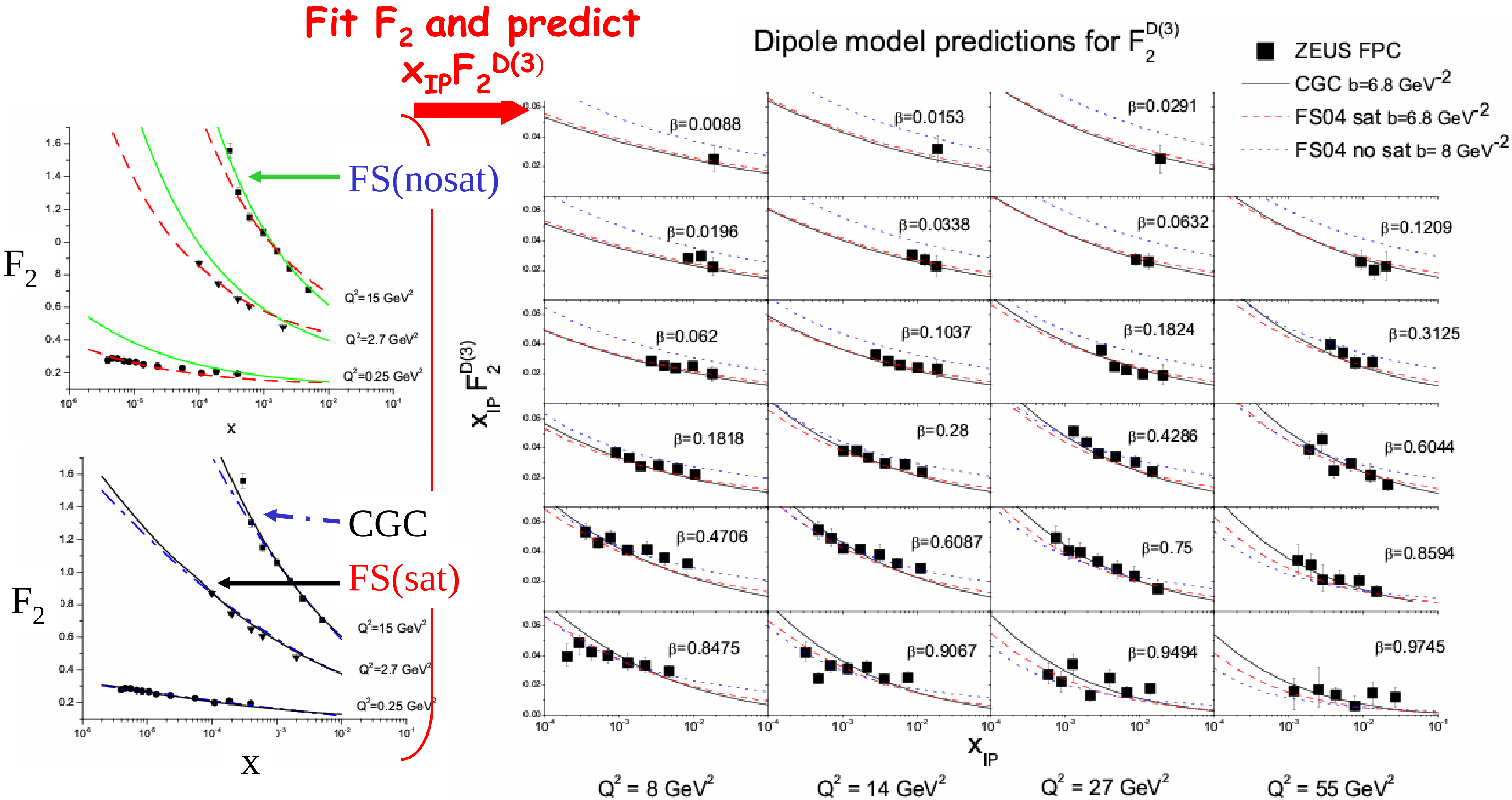
$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* A \rightarrow VA) \propto \alpha_S^2 \left[G_A(x, Q^2)\right]^2$$

Very sensitive to small x glue!

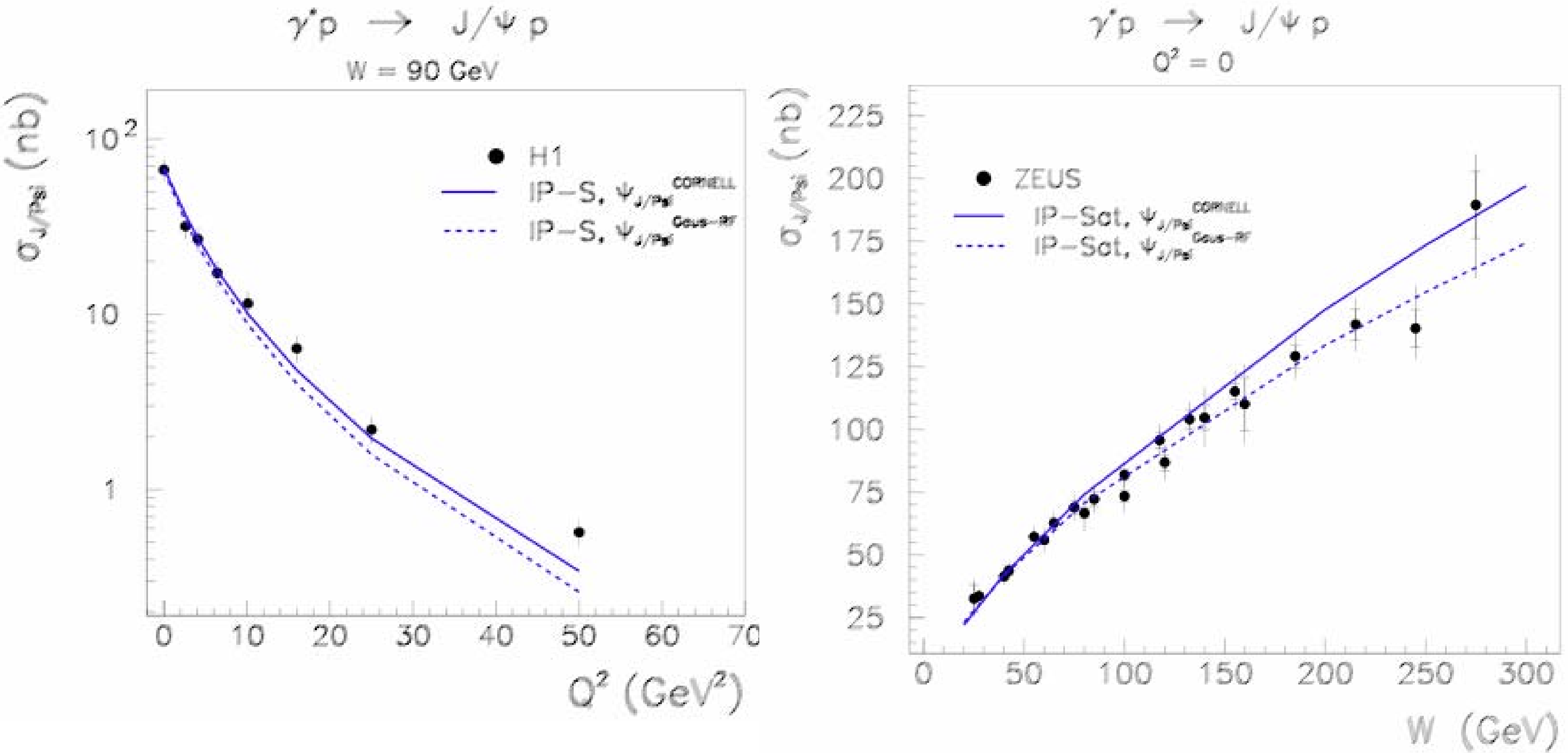
Brodsky,Gunion,Mueller, Frankfurt,Strikman

Comparison with Data

FS model with/without saturation and **IIM CGC model** hep-ph/0411337.



Comparison with Data



Exclusive J/Psi production: Kowalski-Teaney

Complementary physics of pA & eA at RHIC

- Both p/D-A & eA can probe small x region-important to test universal aspects of new physics.

- eA due to independent "lever arms" in x and Q^2 well equipped for precision measurements. Much harder with pA

- eA & pA have important qualitative differences for hard diffractive processes. May be 30-40% of cross-section in eA!

II: Extracting gluon distributions in pA relative to eA

Direct photons

Open charm

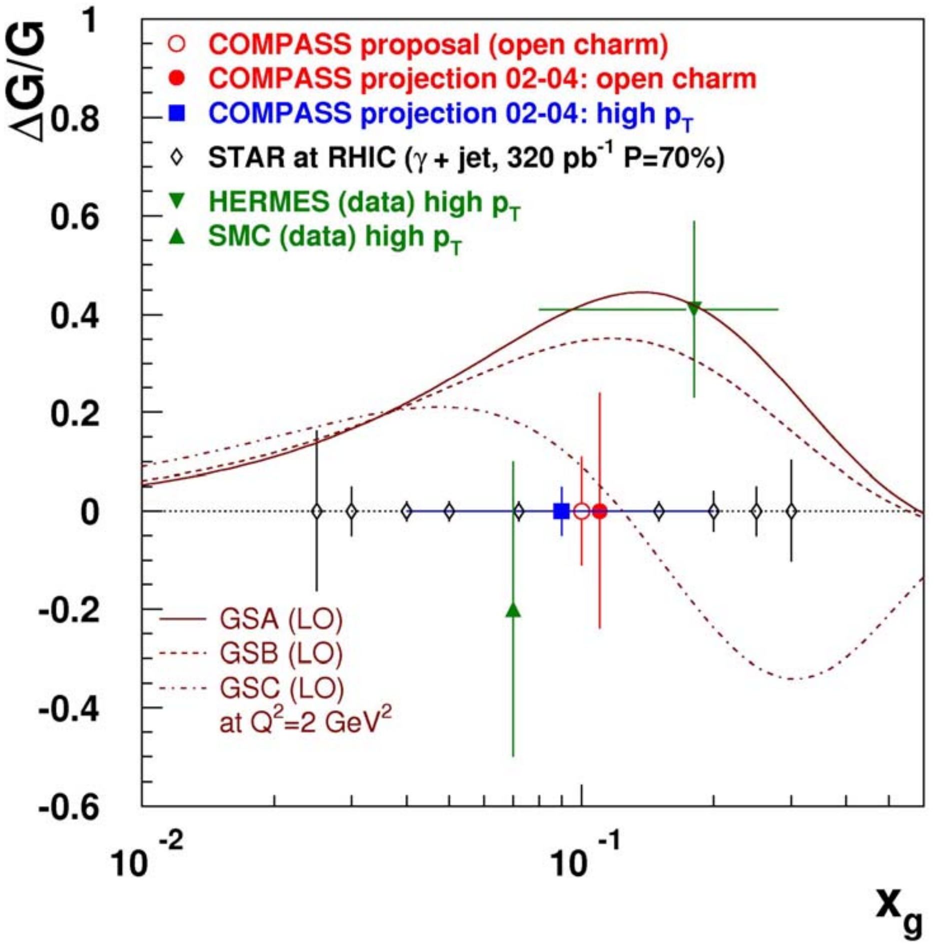
e™ and a
ecompressor
e this picture.

J/ψ

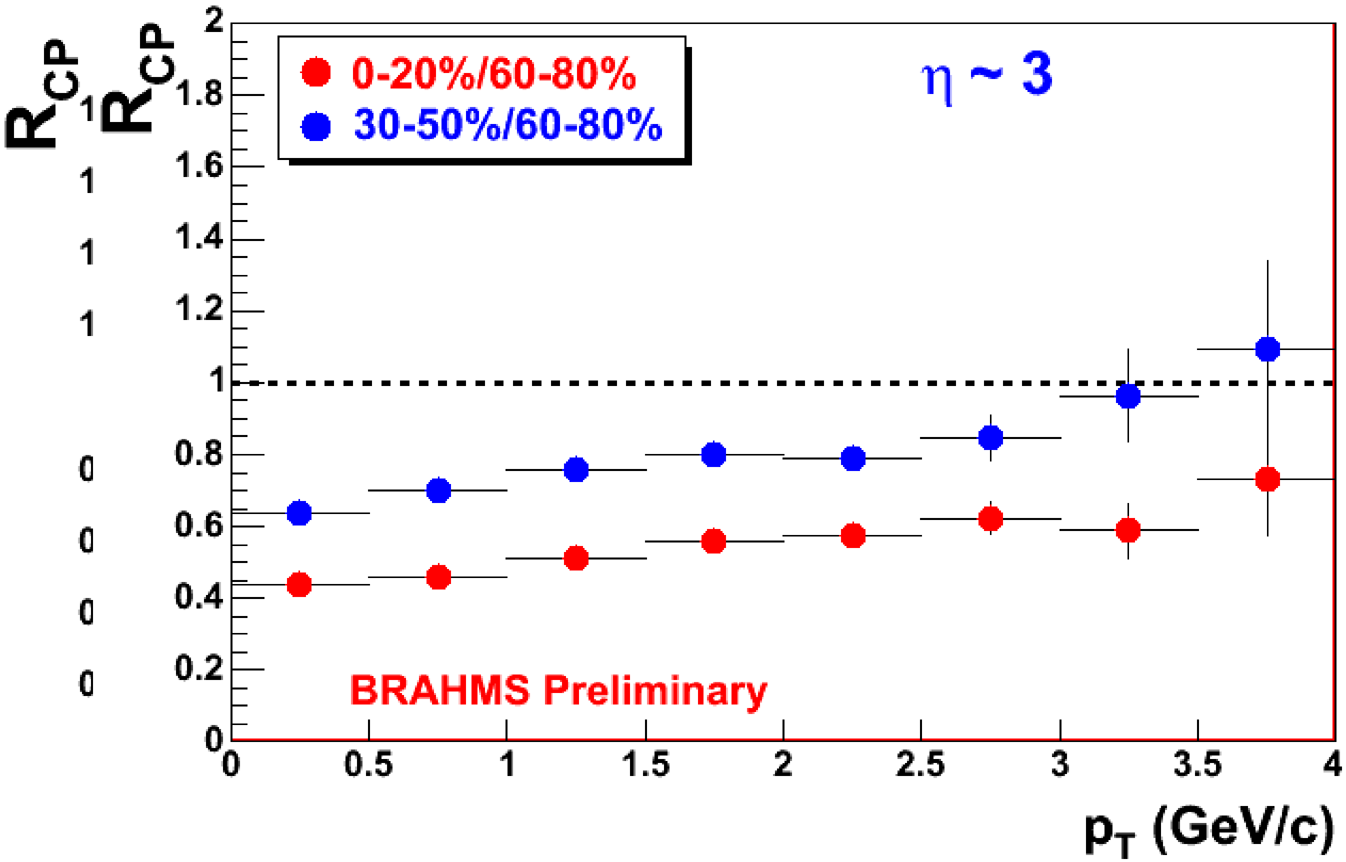
Drell-Yan

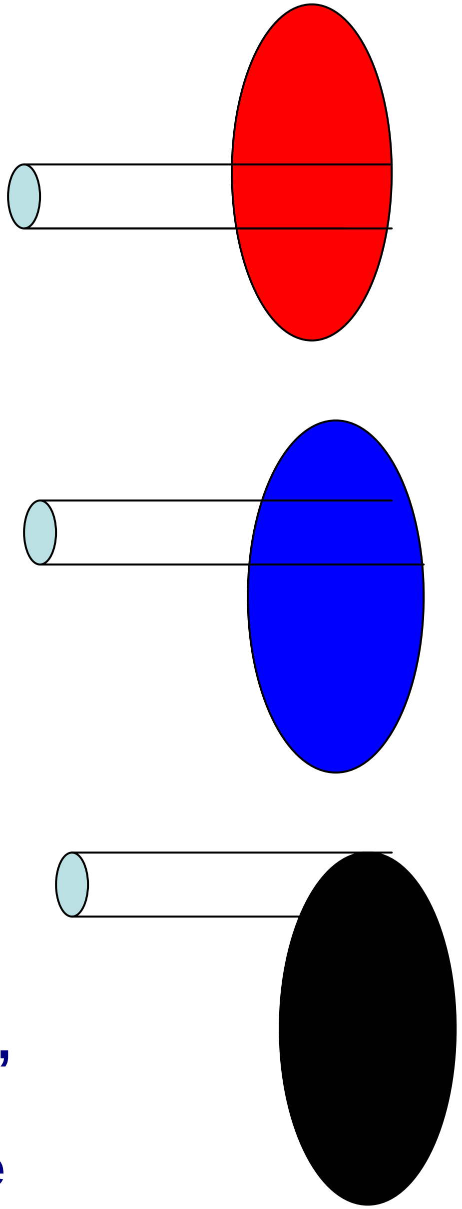
As many channels…but more convolutions, kinematic constraints-limit precision and range.

Direct photons: promising-need wide coverage to go to small x-need simulations at forward rapidity…kt issues to be resolved .



STRONG HINTS FROM RHIC OF NEW PHYSICS



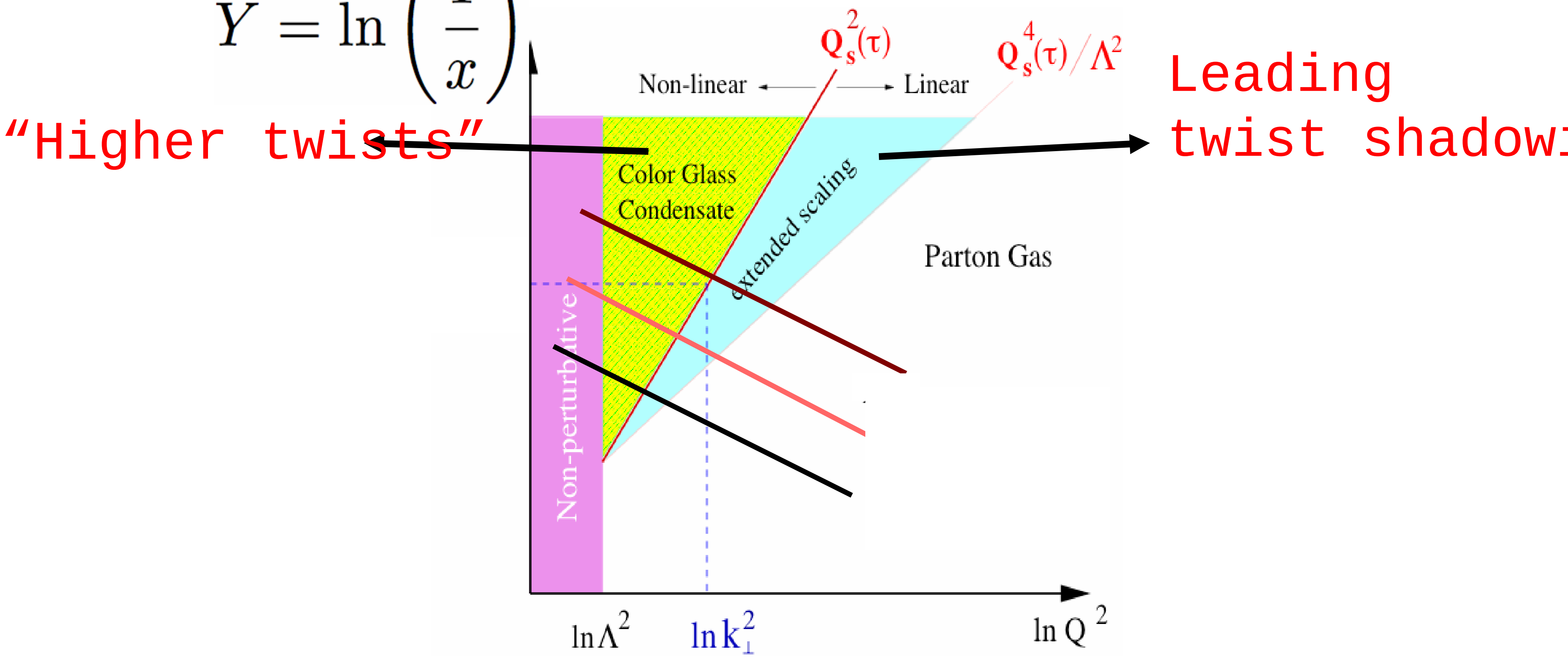


a) Phenomenon was predicted in CGC scenario,

b) Phenomenon well within EIC kinematic range

Novel regime of QCD at high energies

$$Y = \ln\left(\frac{1}{x}\right)$$



- (black line) $Y_{\mathrm{RHIC-central}} = 0 \ (x = 10^{-2}, Q_s = 1.4\,\mathrm{GeV})$
- (pink line) $Y_{\mathrm{RHIC}} = 3, Y_{\mathrm{LHC-central}} = 0 \ (x = 5 \cdot 10^{-4}, Q_s = 2.2\,\mathrm{GeV})$
- (dark red line) $Y_{\mathrm{LHC}} = 3 \ (x = 3 \cdot 10^{-5}, Q_s = 3.4\,\mathrm{GeV})$