The physics of
The Electron Ion Collider

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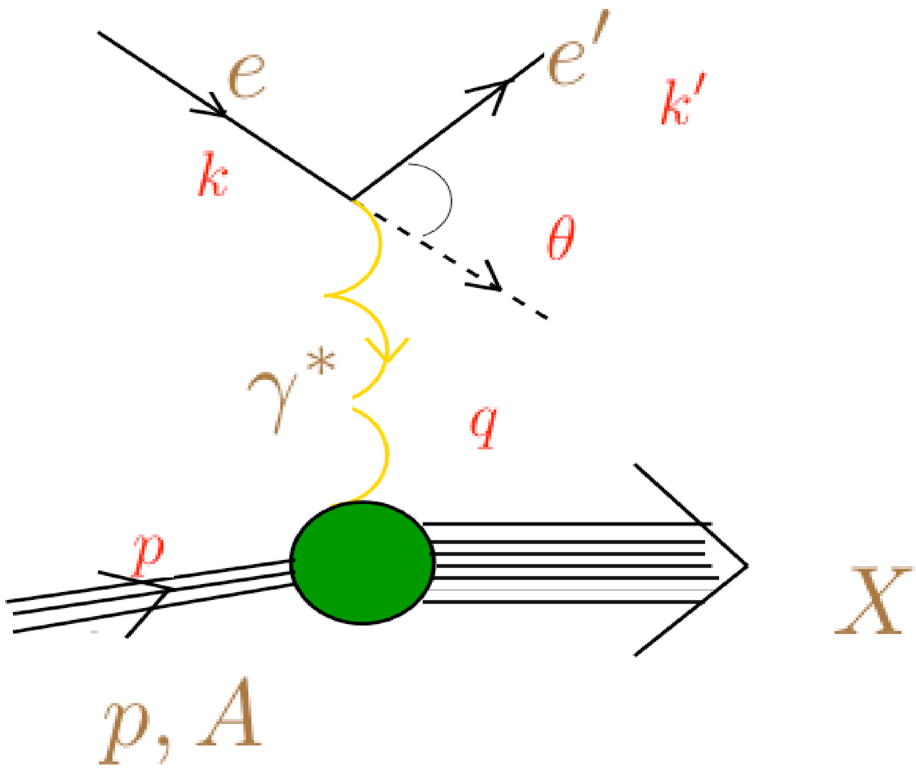
The DIS Paradigm



Kinematics:

$$s = (p+k)^2$$

$$Q^2 = -q^2 = 4E_e E_{e'} \sin^2\left(\frac{\theta}{2}\right)$$

$$x_{\rm Bj} = \frac{Q^2}{2M_p(E_e - E_{e'})} \equiv \frac{Q^2}{2p\cdot q}$$

$$y = \left(1 - \frac{E_{e'}}{E_e}\right) = \frac{p\cdot q}{p\cdot k}$$

$$x\, y \approx \frac{Q^2}{s}$$

Cross-section:

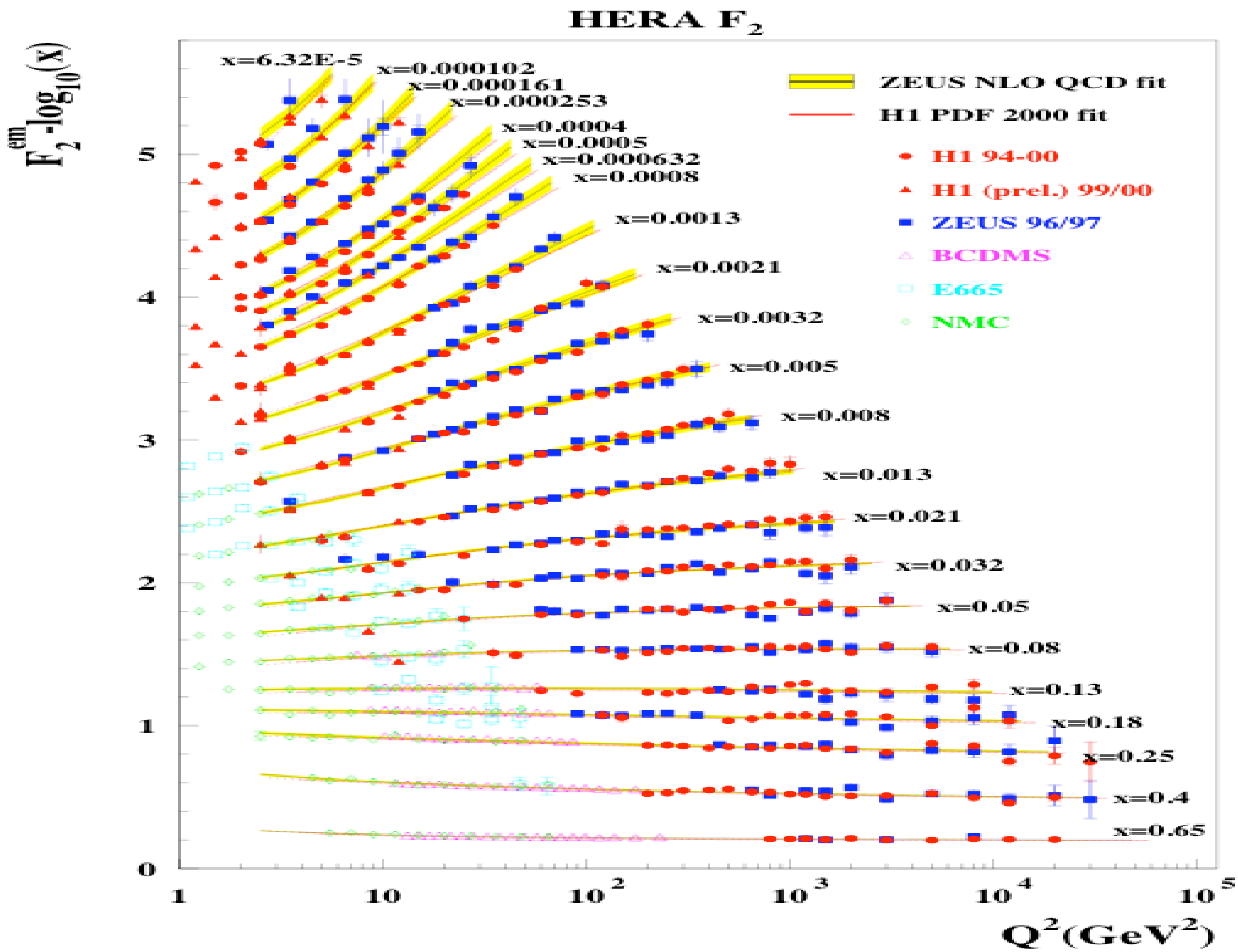
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{\rm em.}}{xQ^4}\left[y^2 x F_1(x,Q^2) + (1-y)F_2(x,Q^2)\right]$$

g_1,...g_5 - polarized structure functions in pol. e - pol. p scattering

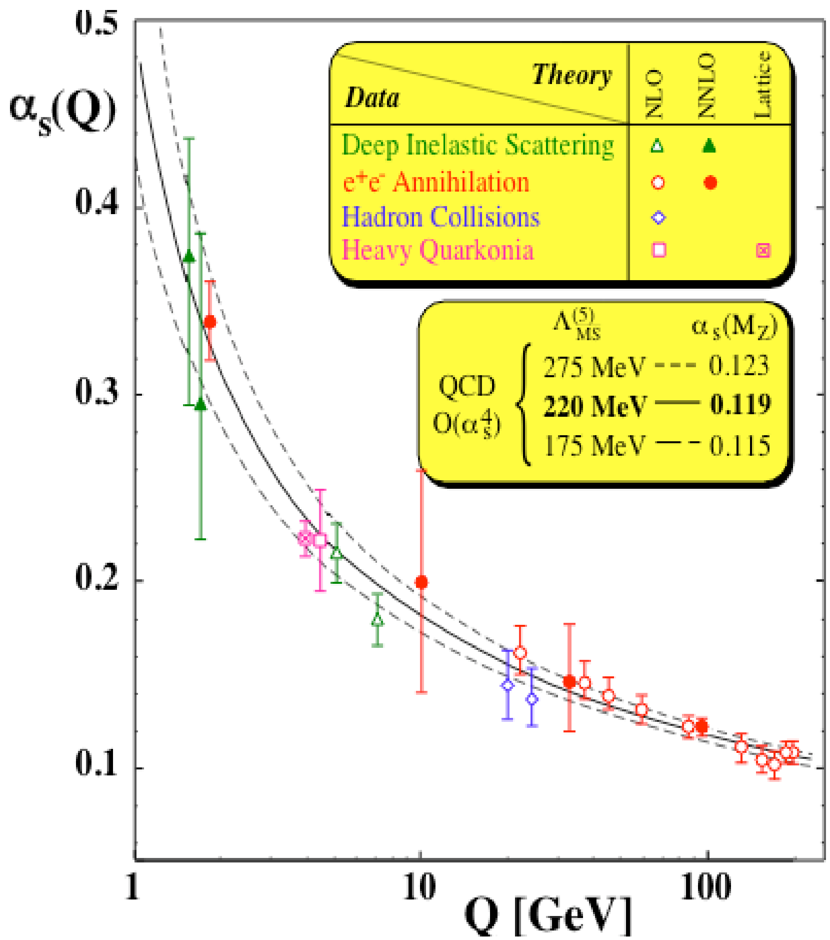
DIS highlights:

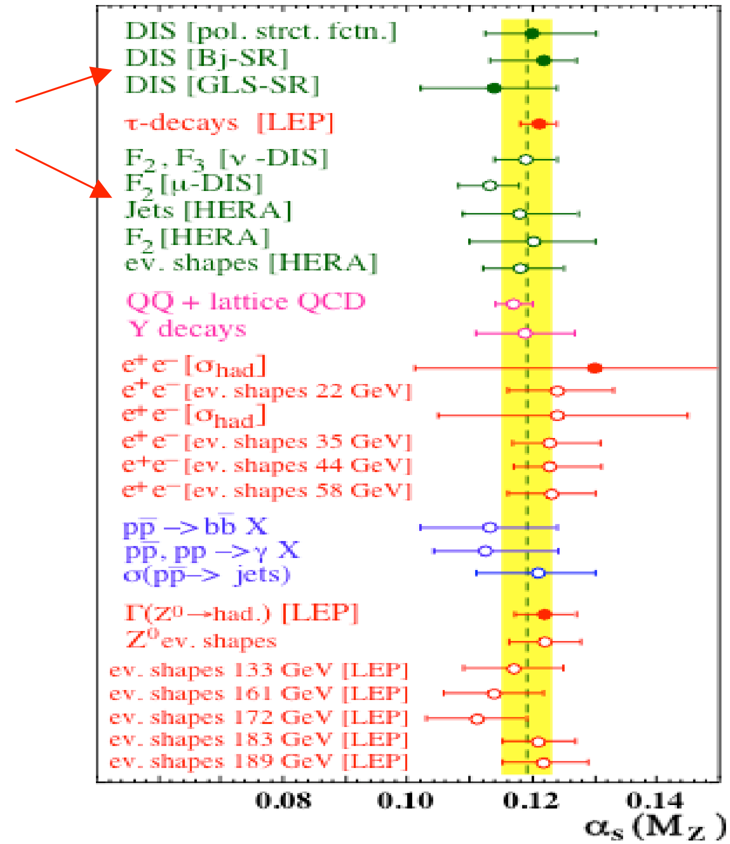
- Bjorken scaling: the parton model.
- Scaling violations: QCD- asymptotic freedom, renormalization group; precision tests of pQCD.
- Rapid growth of gluon density at small x, significant hard diffraction.
- Measurement of polarized structure functions: scaling violations, the “spin crisis”.
- QCD in media: the EMC effect, shadowing, color transparency,..

Scaling violations…

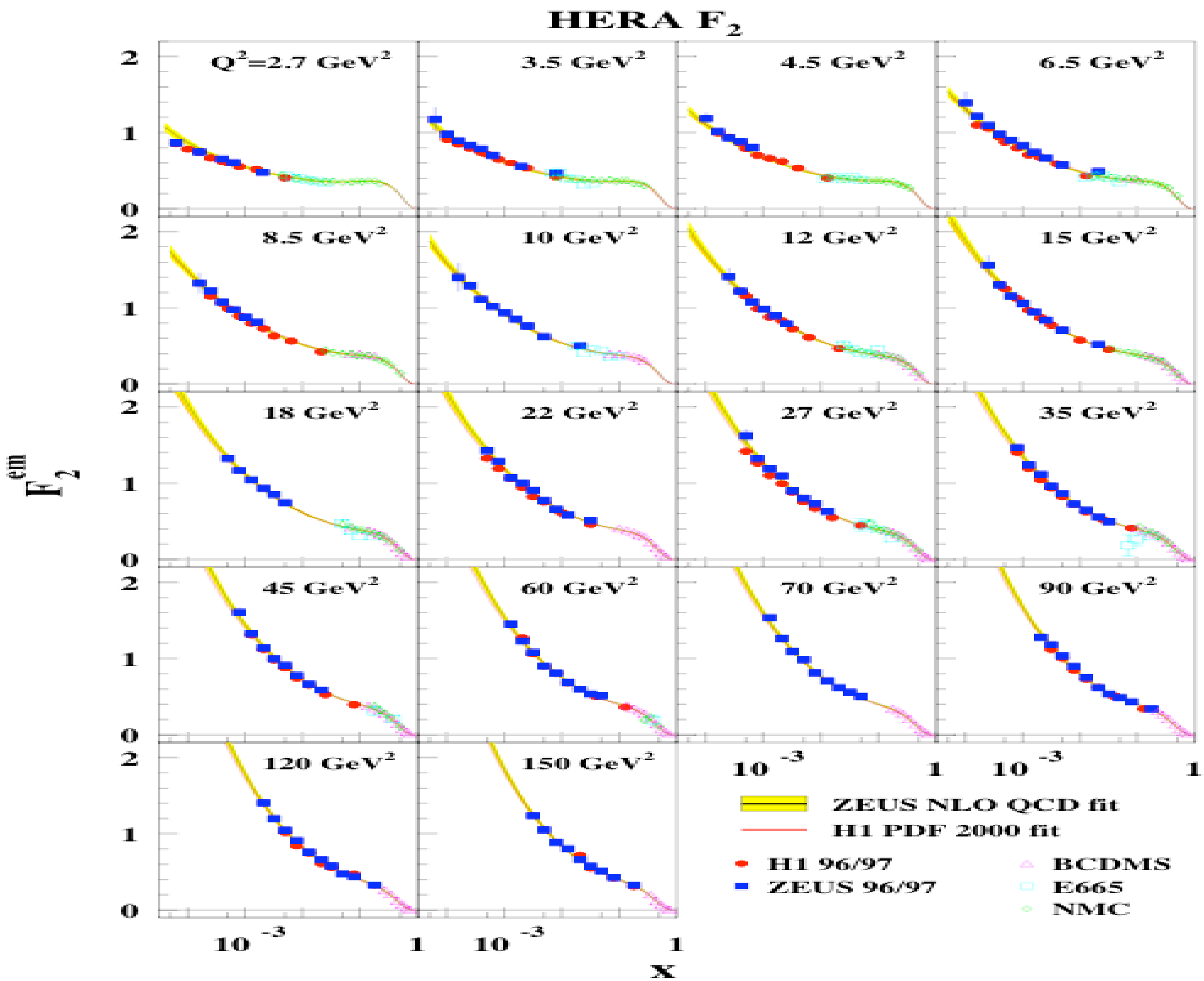


Asymptotic freedom…





RG evolution…



Principal goals of an Electron-Ion Collider

Extend DIS Paradigm for quantitative 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.

Unpolarized e-p scattering

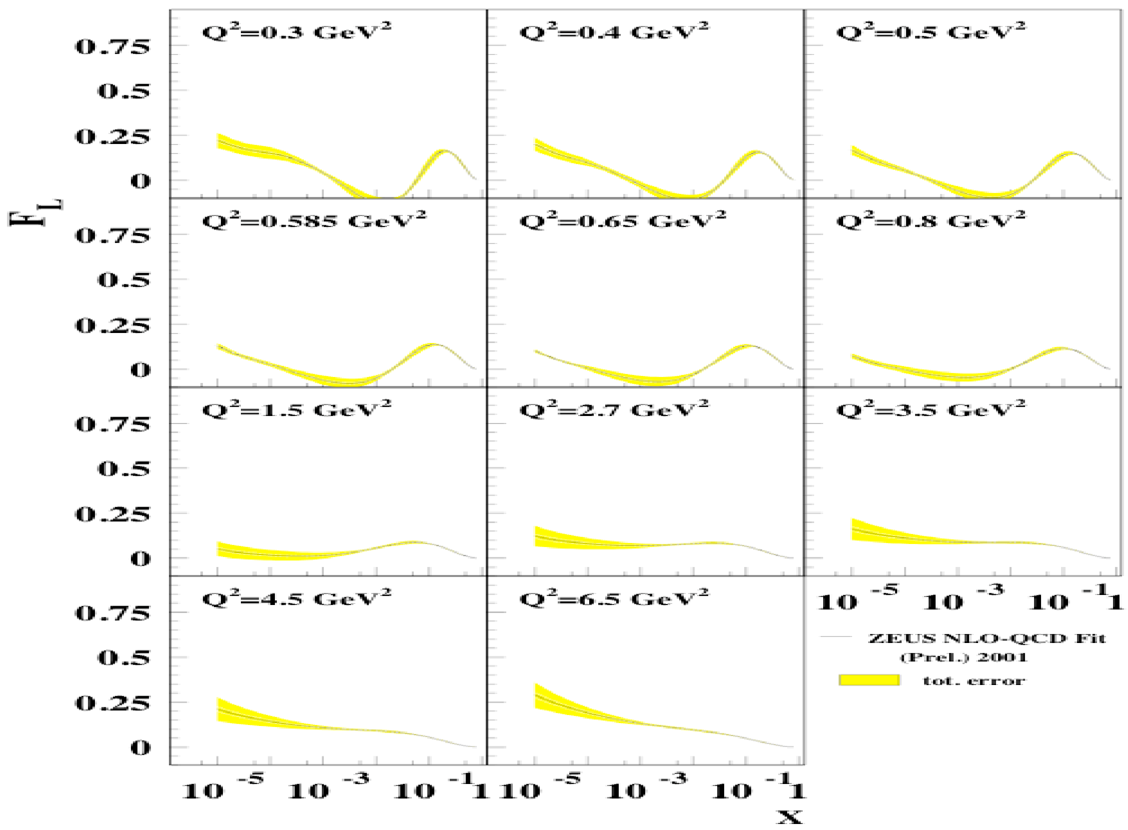
What can we do with luminosity 100 times HERA (albeit factor 3 lower energy) and detectors optimized for small x physics ?

✓ Vary beam energies to measure F_L *independently* for first time in small x region-measure of gluon density. Is more sensitive to higher twists than F_2.

✓ Wider η coverage than HERA-precision studies of diffractive parton dists.-rapidity gaps.

✓ Semi-inclusive (and exclusive!) measurements: DVCS, vector meson production, fluctuations and correlations

✓ Precision α_S tests? Strong constraints on flavor dists.



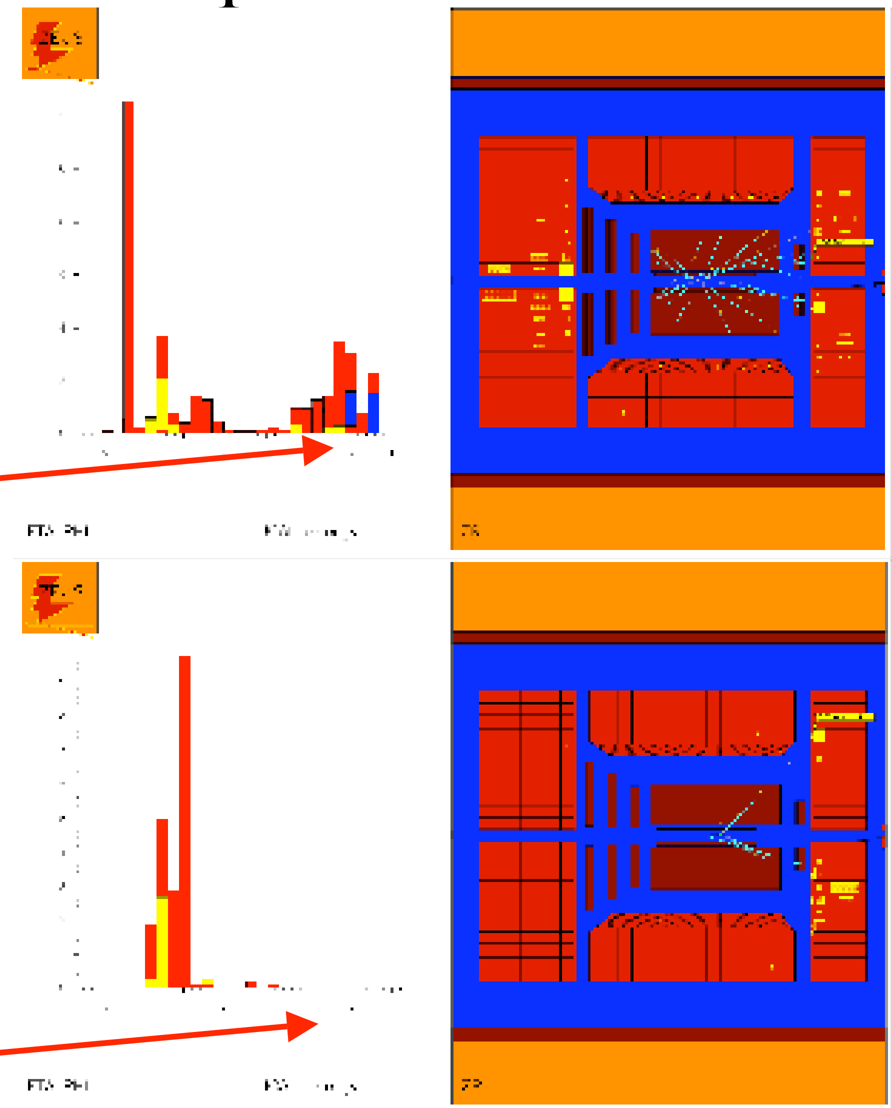
$$F_L \propto \alpha_S x G(x, Q^2)$$

F_L is a positive definite quantity-result hints at problem with leading twist NLO pQCD at low x and moderate Q^2

Diffractive Surprises

‘Standard DIS event’

Detector activity in proton direction



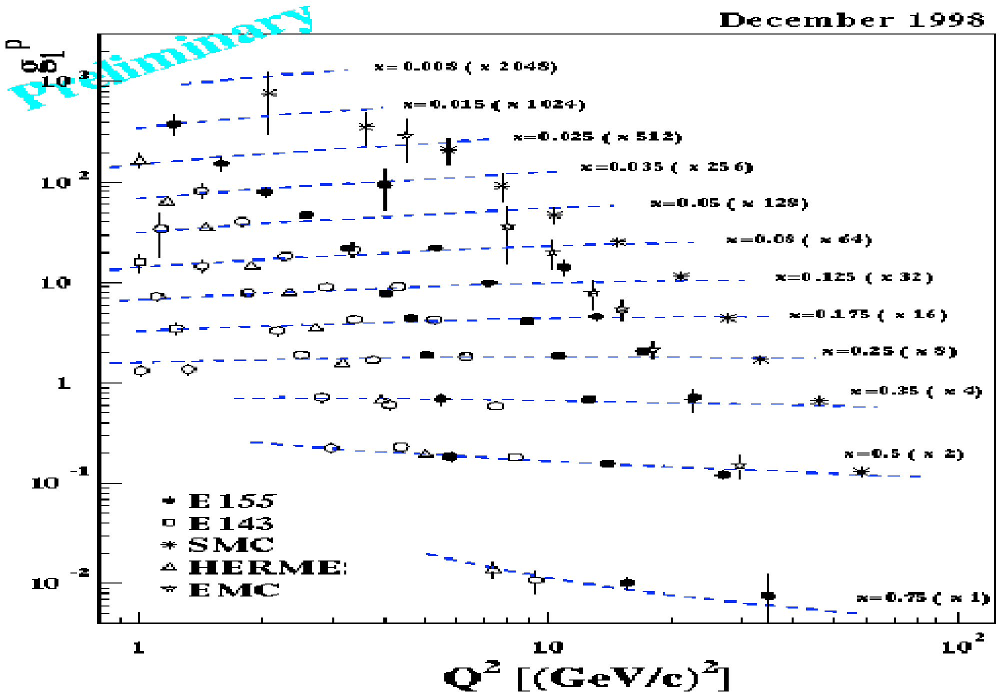
Diffractive event

No activity in proton direction

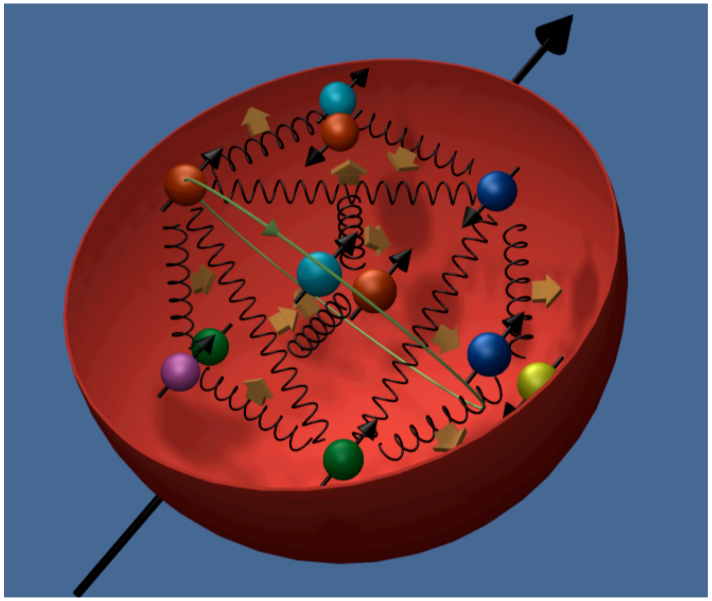
APPROXIMATE 10% OF EVENTS ARE HARD DIFFRACTIVE EVENTS!

pol.e-pol.p scattering

Precision measurements of spin structure functions- Scaling violations-is it DGLAP or are small x-corrections $\alpha_S \ln^2(1/x)$ resummation large?



g_1 measurements, in combination with $\frac{\Delta G(x)}{G}$ from RHIC and eRHIC can constrain -first moment- ΔG critical to resolve spin puzzle-contributions to nucleon spin from quark & gluon spins



Pol. DIS: CERN, SLAC, DESY

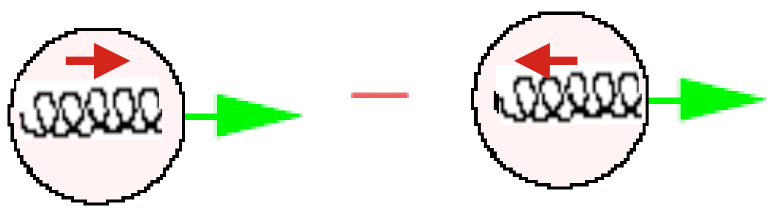
~ 0.1

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

?

$$\langle S_q \rangle = \frac{1}{2}\Delta\Sigma = \frac{1}{2}\int_0^1 dx\, \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x)$$

$\Delta q(x) =$ 

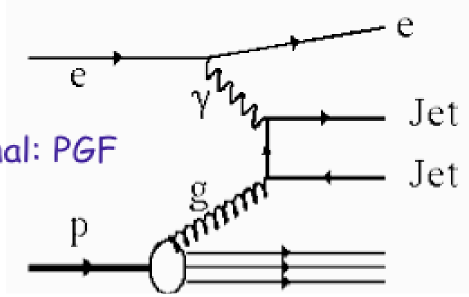
$\Delta g(x) =$ 

$$\langle S_g \rangle = \Delta G = \int_0^1 dx\, \Delta g(x)$$

Theoretical uncertainity from small x extrapolation of Struct. Fns.

→ $\Delta G(x)$ at eRHIC from a) scaling violations, b) direct measurements from photon-gluon fusion processes (di-jets,...)

Signal: PGF

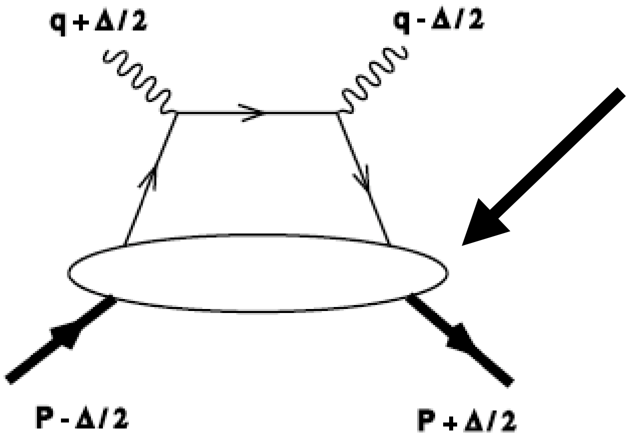


- *Precision measurements of α_S from g_1 scaling violations*
- *First measurement of EW structure function g_5 from $W^{\pm}$ production*
- *Single spin asymmetries-Collins (final-state) and Sivers (initial state) effects.*

- *Generalized parton distributions-hadron micro-surgery…*
- *Transversity-chiral odd twist 2 structure functions*
- *Flavor separation of polarized PDF's through semi-inclusive DIS.*

- **Parton orbital angular momenta from GPD's ?**

“Deeply-virtual Compton scattering”, exclusive proc.



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

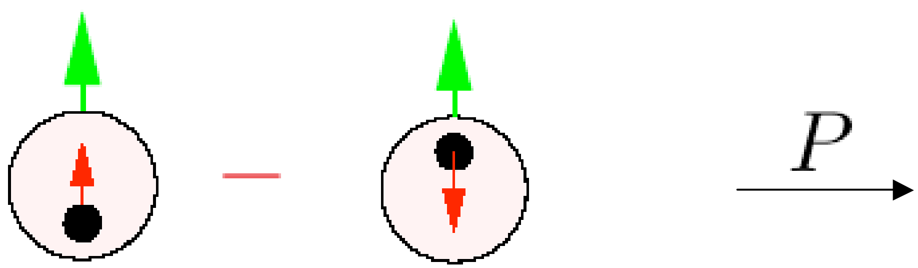
off-forward

“Generalized parton distributions”

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

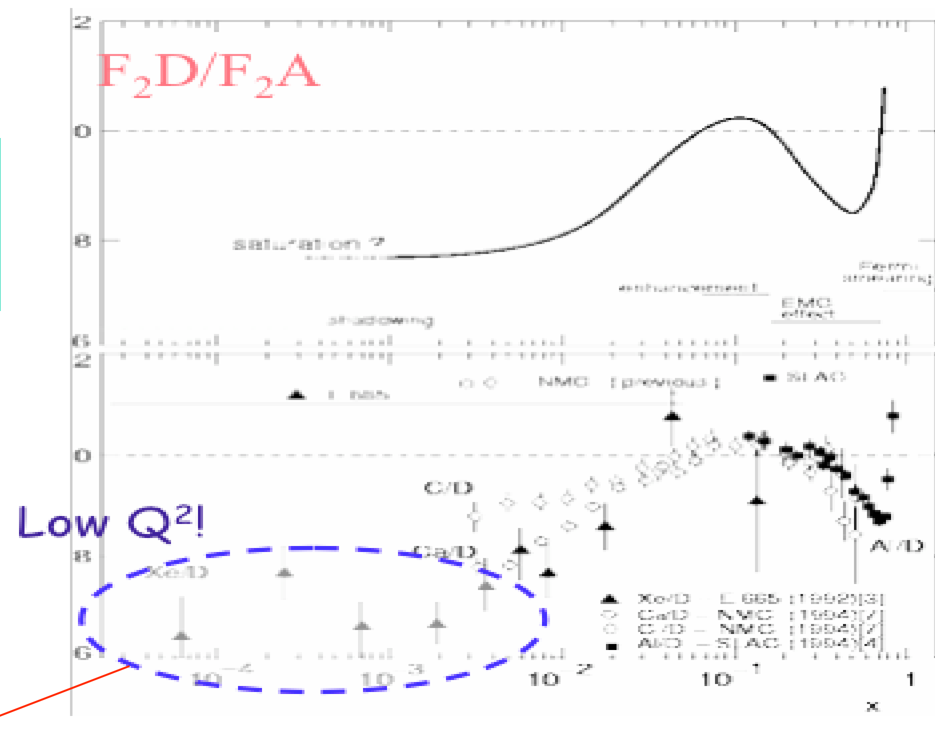
“Transversity”

$$\delta q(x) =$$



electron-nucleus scattering

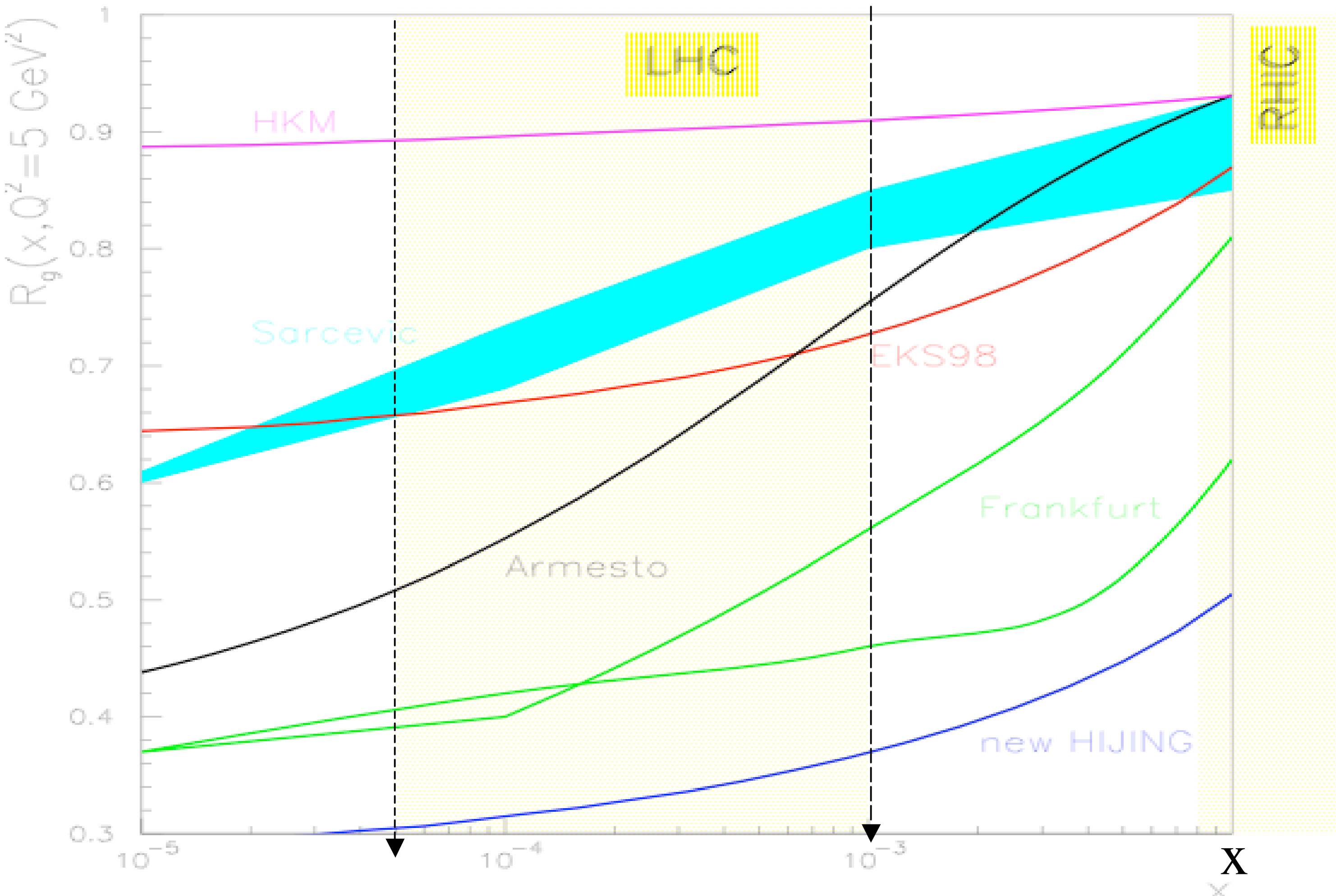
Quantitative studies of QCD in media



Shadowing: EIC will have data with very high statistical accuracy at significantly higher Q^2

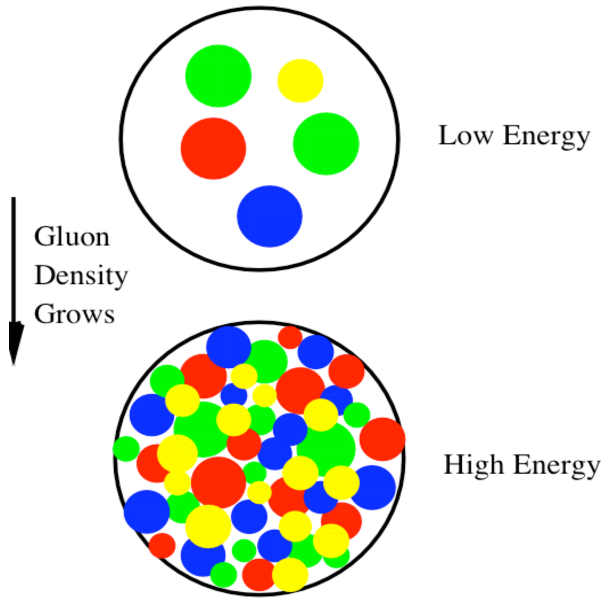
Extract F_2^A ; $G^A(X,Q^2) \propto \frac{\partial F_2^A}{\partial \ln Q^2}$; $F_L^A(x,Q^2)$ for light & heavy nuclei for $Q^2 \approx 10\, Q^2_{\mathrm{fixedtarget}}$ at fixed small x

Ratio of Gluon densities in Lead to Proton at $Q^2 = 5\,\mathrm{GeV}^2$
in x range $10^{-2} - 10^{-5}$



Factor 3 uncertainity in glue => Factor 9 uncertainity in Semi-hard HI-parton cross-sections at LHC!

THE COLOR GLASS CONDENSATE



-Large x

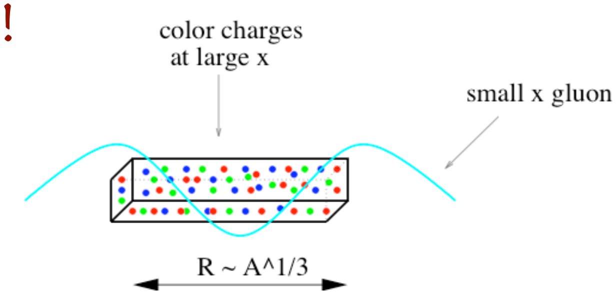
-Small x

Phase space density f grows rapidly at small x

Gluon density saturates at f= $\frac{1}{\alpha_S}$

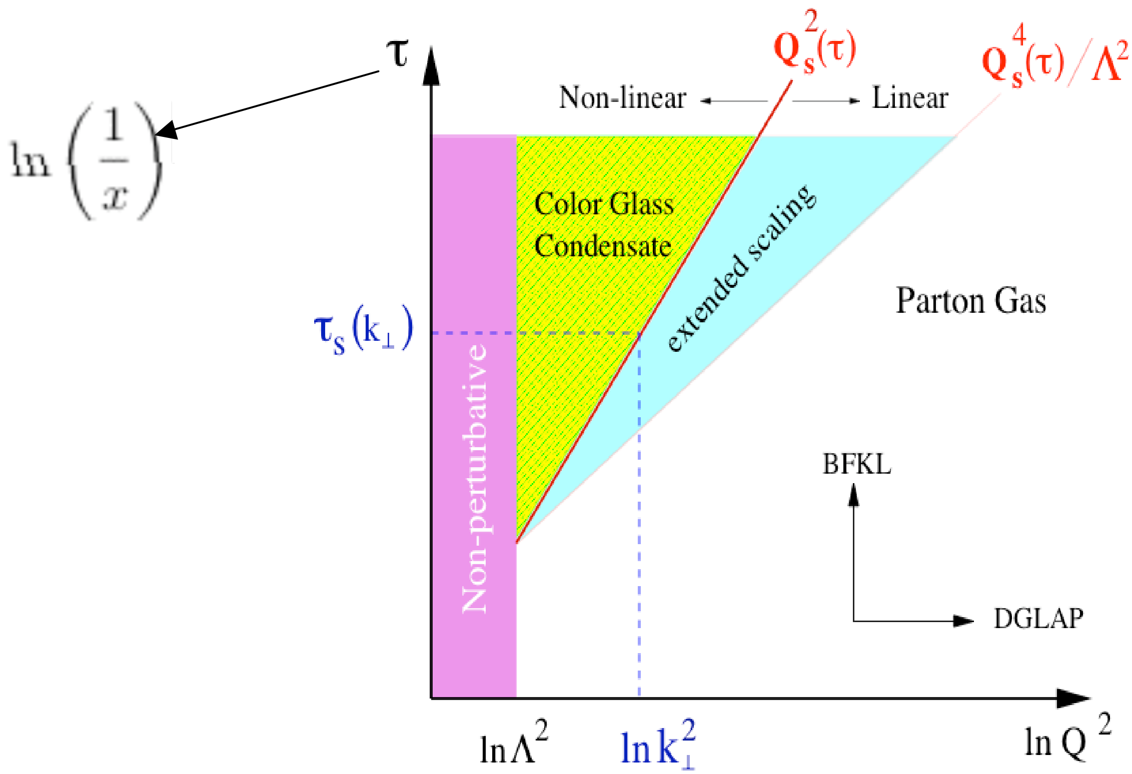
THE NUCLEAR OOMPH FACTOR!

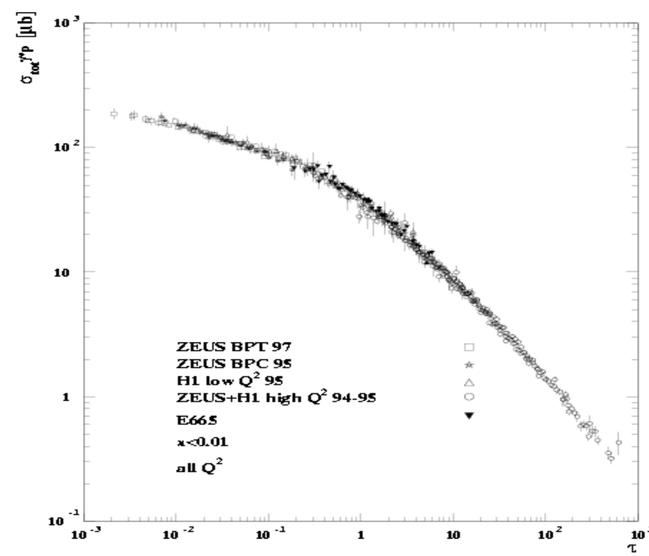
$$\frac{1}{\pi R^2}\frac{dN}{dy} \propto \frac{A^{1/3}}{x^\delta}\ ;\ \delta \sim 0.3$$



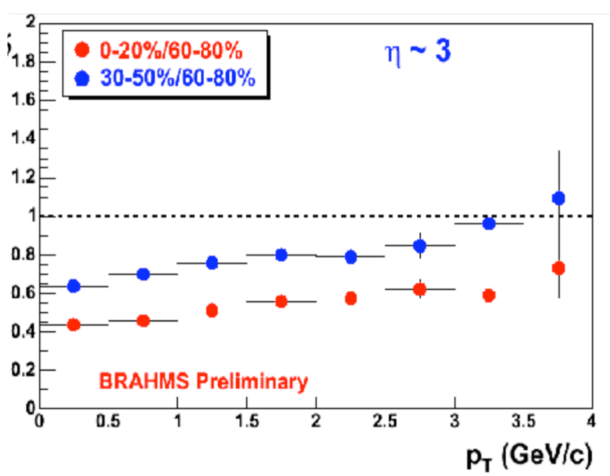
eA at RHIC ≈ same parton density as ep at LHC energies!

Novel regime of QCD evolution at high energies





Geometrical scaling seen at HERA-similar scaling in eA?



Leading candidate to explain non-trivial BRAHMS centrality dependence at forward eta (small x in nucleus)

Phenomenon well within EIC kinematic range

Concluding remarks on eA:

- Very significant progress in theory-novel RG equations-the EIC can test to high precision new phenomena-scaling violations very different from DGLAP.

- Besides inclusive signatures, semi-inclusive measurements (vector mesons, hard diffraction,...) very sensitive to the high parton density state.

- eA & pA needed to test universality of novel degrees of freedom at small x.

- Not least, EIC can extend previous "in-media" studies of fixed target (NMC, HERMES,...) experiments to new kinematic regions in clean collider environment

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.

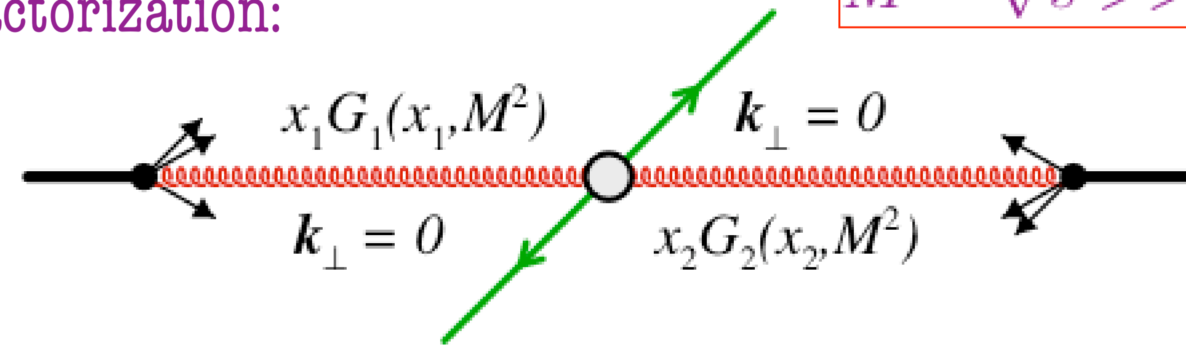
- eA due to independent "lever arms" in x and Q^2 well equipped for precision measurements. Much harder with pA.

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

I: Universality: collinear versus k_t factorization

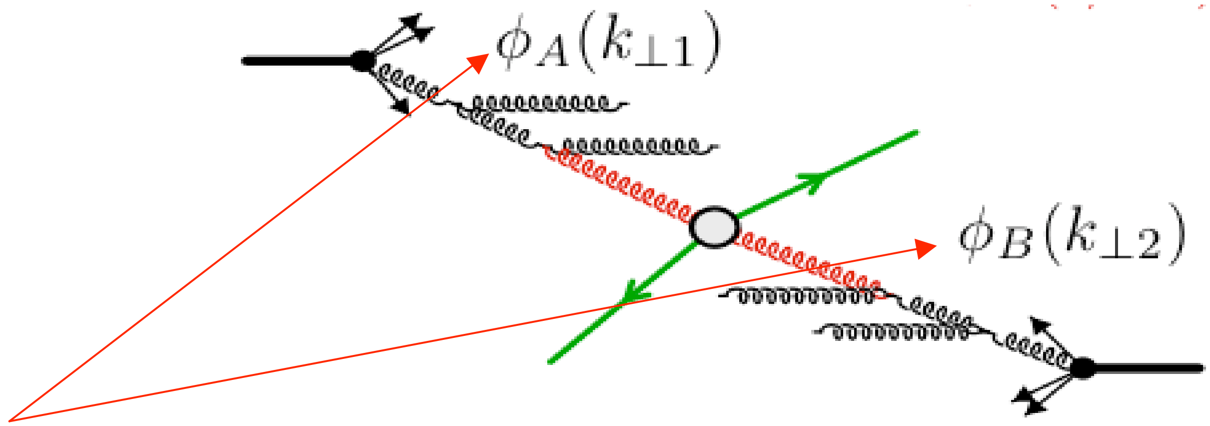
Collinear factorization:

$M \sim \sqrt{s} >> \Lambda_{QCD}$



k_t factorization:

$\Lambda_{QCD} << M << \sqrt{s}$



Are these objects universal? Very important for extraction of "gluon" distributions.

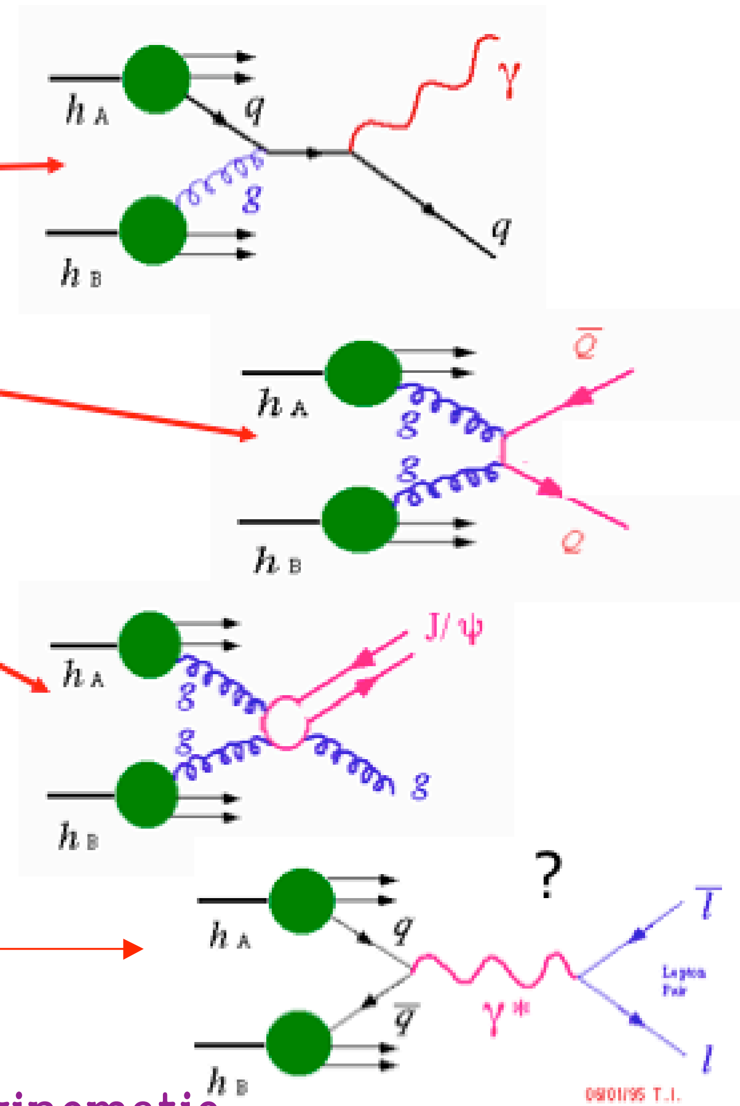
II: Extracting gluon distributions in pA relative to eA

Direct photons

Open charm

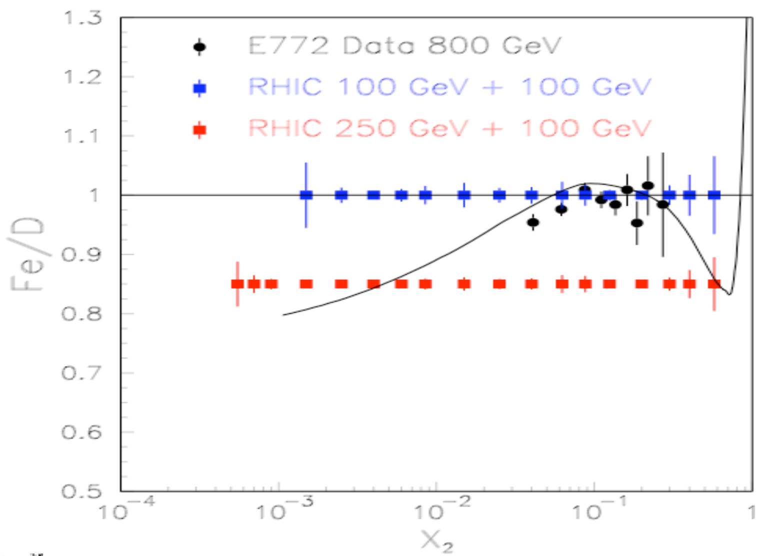
J/ψ

Drell-Yan

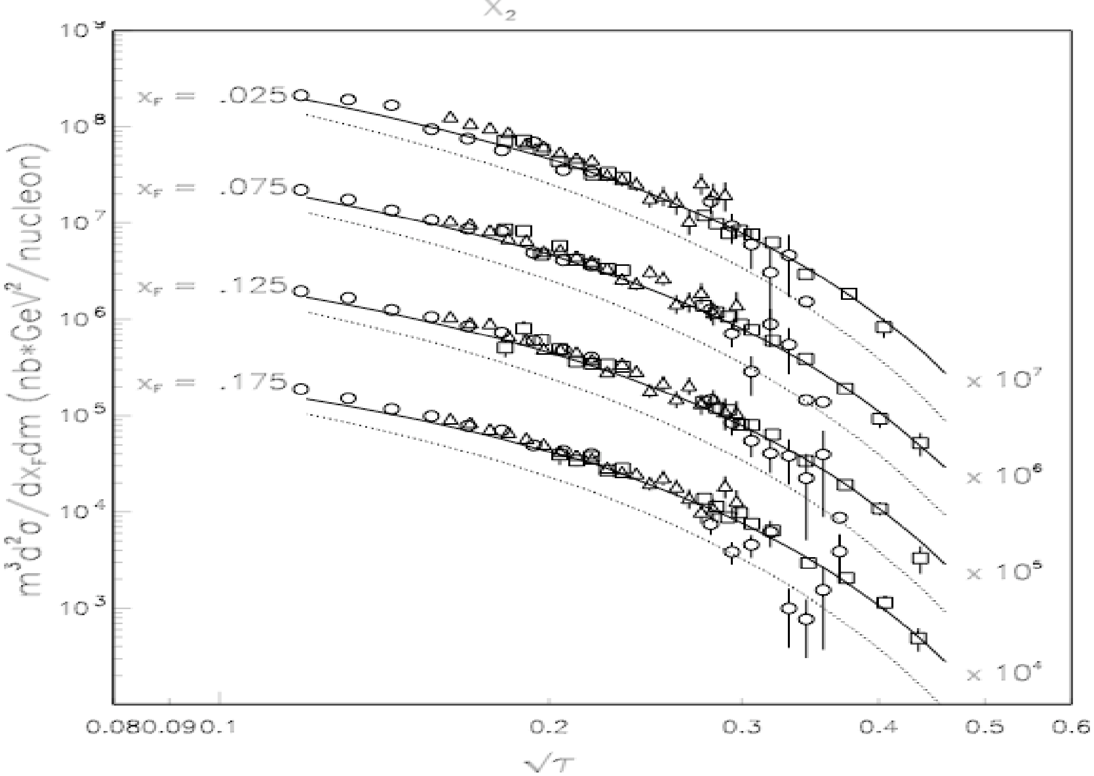


As many channels…but more convolutions, kinematic constraints-limit precision and range.

Drell-Yan



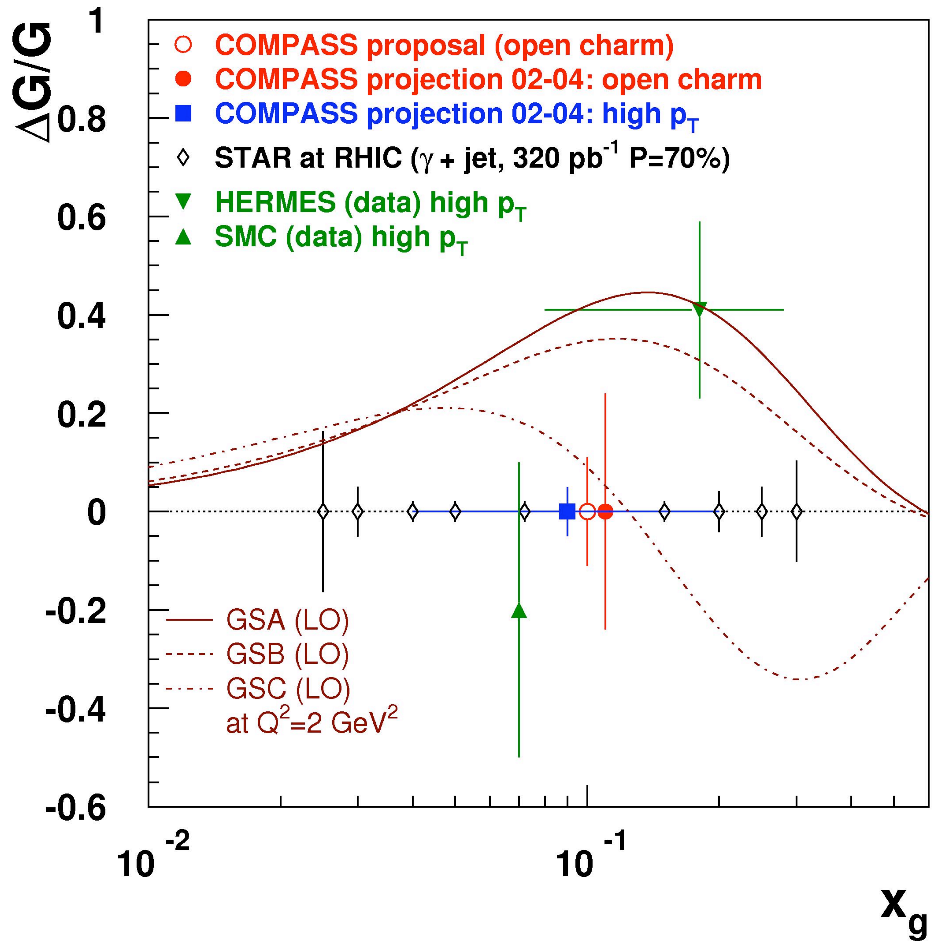
Impressive reach...



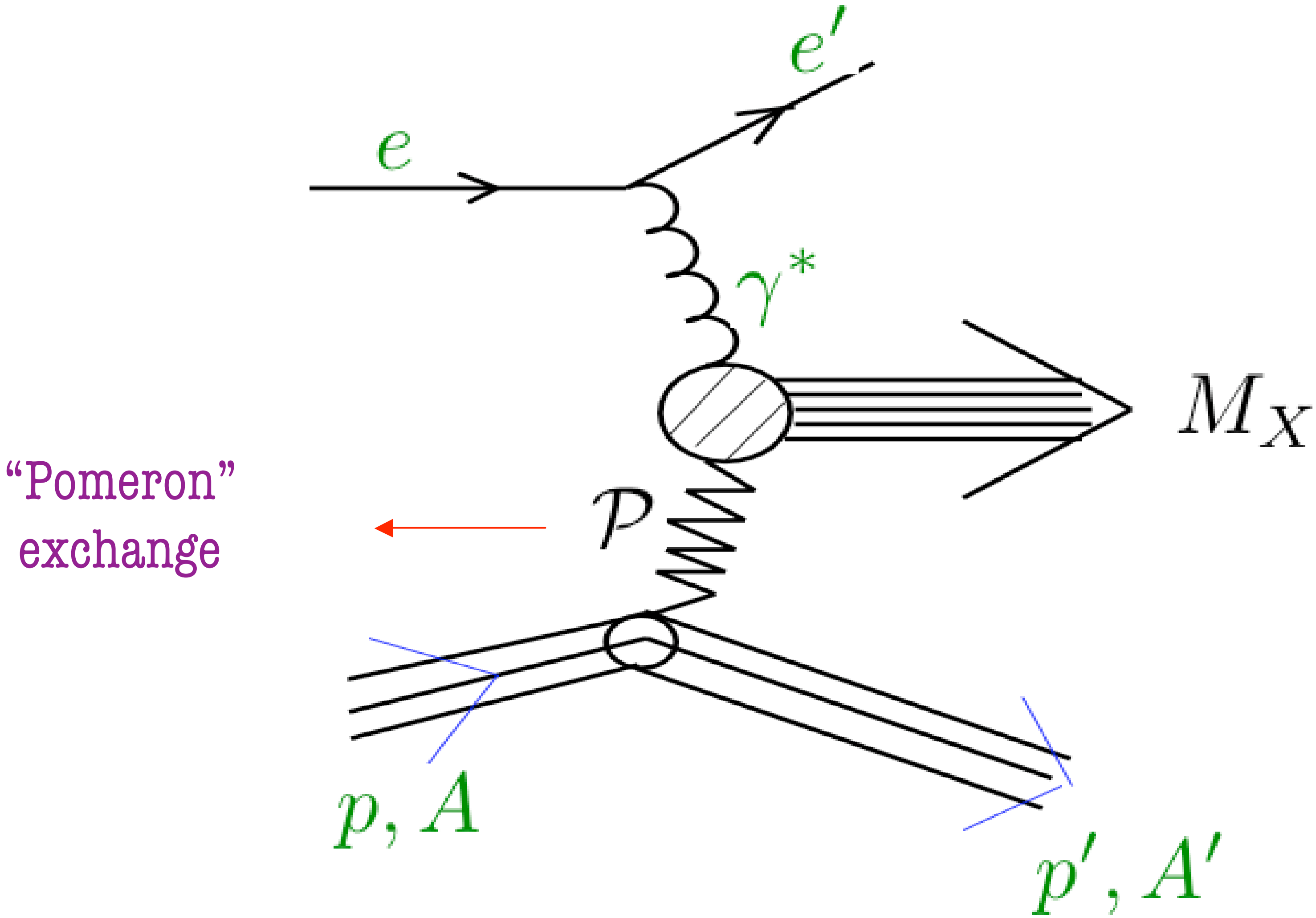
But very difficult to see scaling violations

$$M^2 > 16\, GeV^2$$

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



III: Hard diffractive processes



30-40% of eRHIC events may be hard diffractive events-
Study sizes and distributions of Rapidity Gaps

- Factorization theorems for diffractive parton distributions only hold for Lepton-Hadron processes- NOT for Hadron-Hadron processes.

- Spectator interactions destroy Rapidity Gaps in pA scattering

Study of Rapidity Gaps links the study of CGC physics and confinement-can provide major advance in our understanding.