# Exploring QCD at high energy in DIS off nucleons and nuclei

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# Outline

- What have we learned from HERA.
- High  gluon densities and parton saturation.
- Hints of saturation at HERA and RHIC.
- Why next ep/eA collider? New directions and possibilities.

# Quantum Chromodynamics

QCD Lagrangian:

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu}_{a} + \sum_{\mathrm{flavours}} \bar{q}_a (iD^{\mu}\gamma_{\mu} - m_f)_{ab} q_b$$

Field strength:

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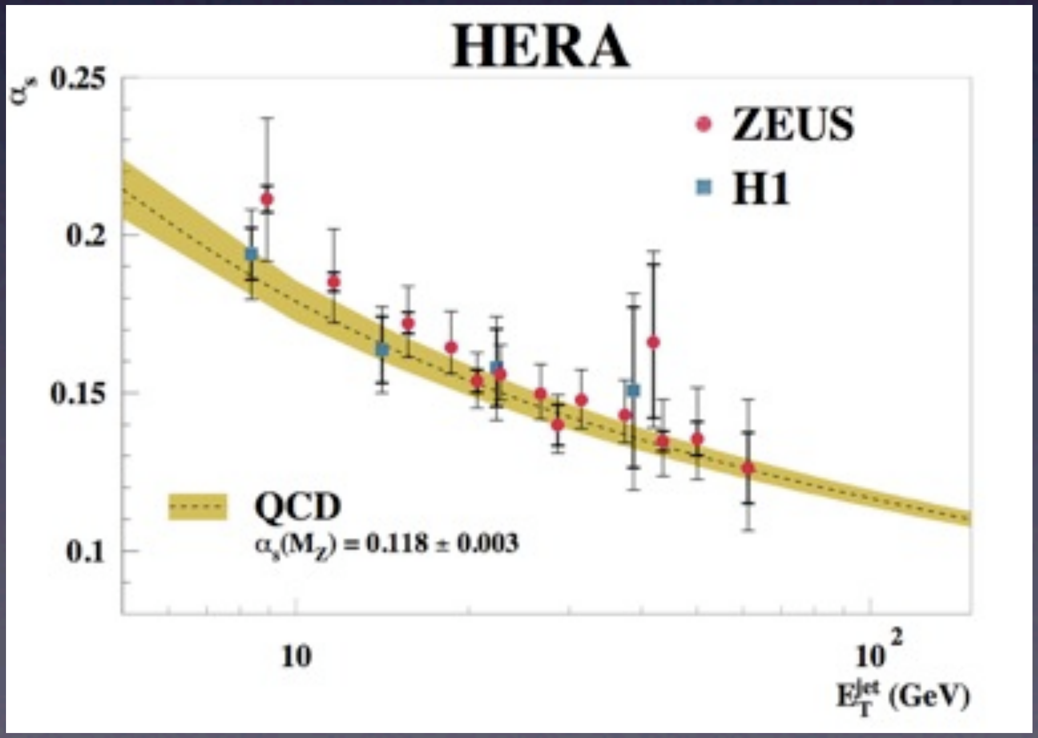


Small scales

Large scales

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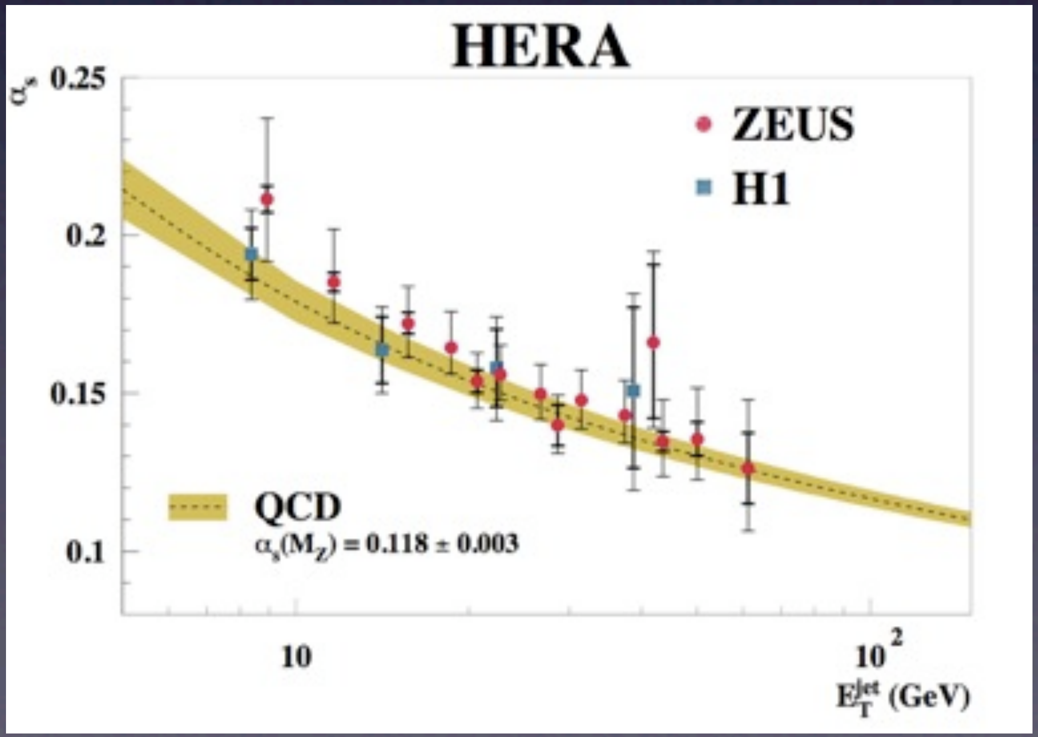


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Large scales

- Rich and very complicated structure due to non-linear interactions of gluons.
- Emergent phenomena: confinement, Regge trajectories, hadron spectrum.
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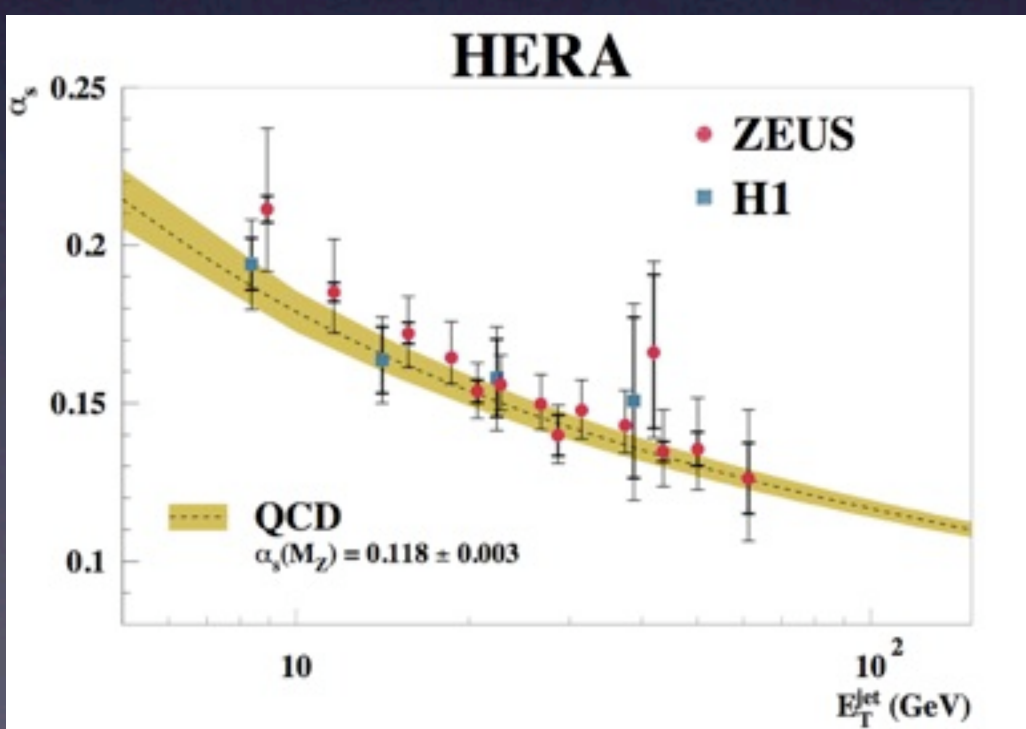


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Understanding of the dynamics of the gluon fields is of fundamental importance.

How do we know that gluons play such an important role at high energies?

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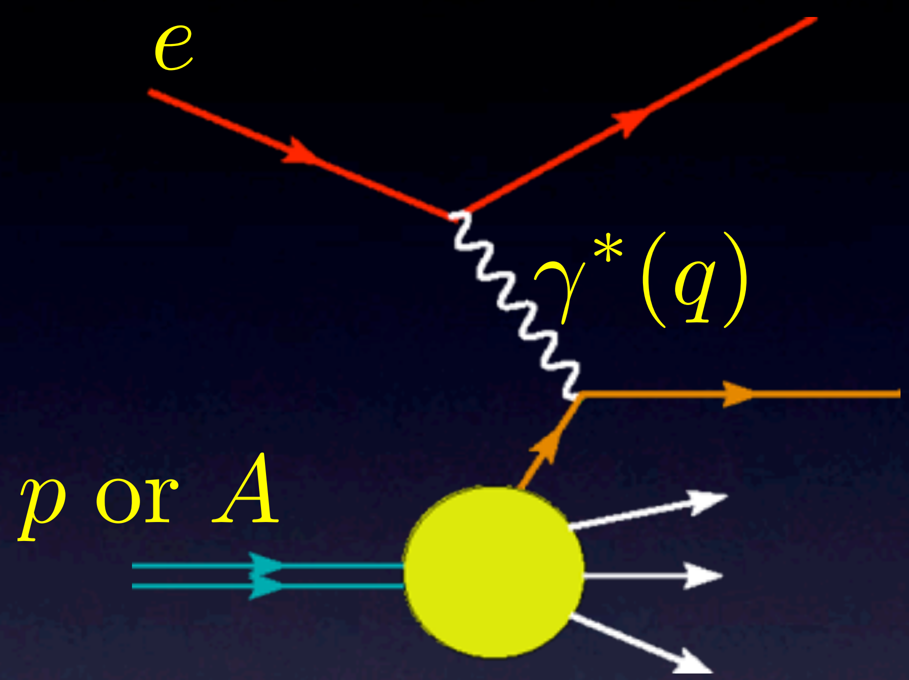

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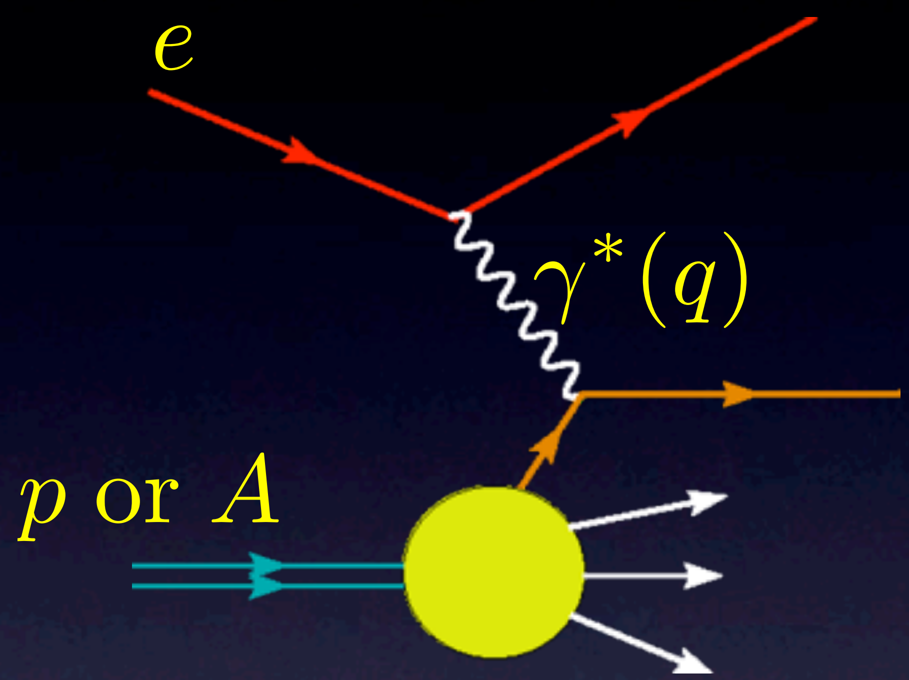


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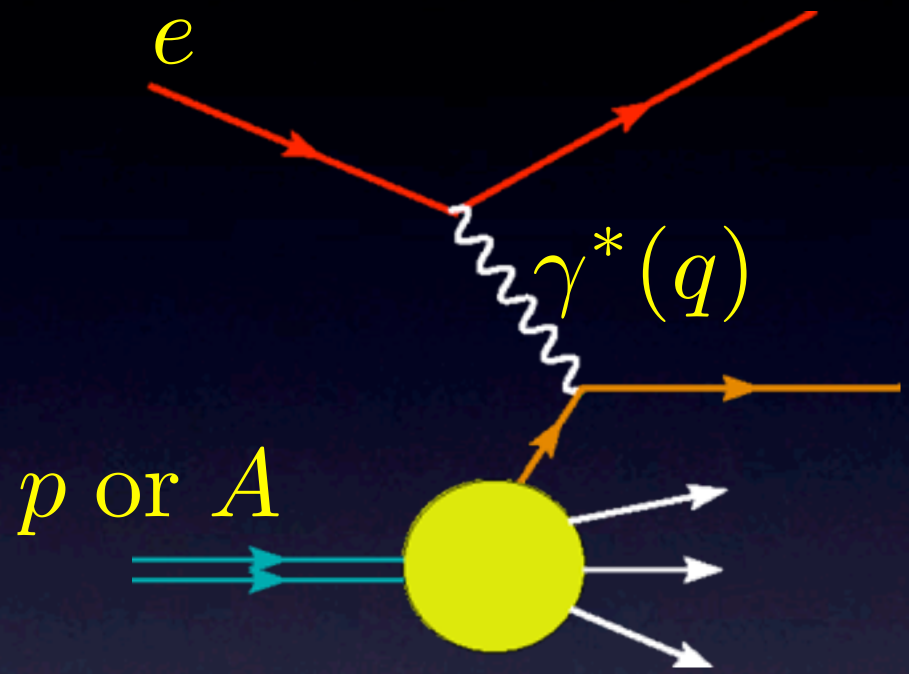


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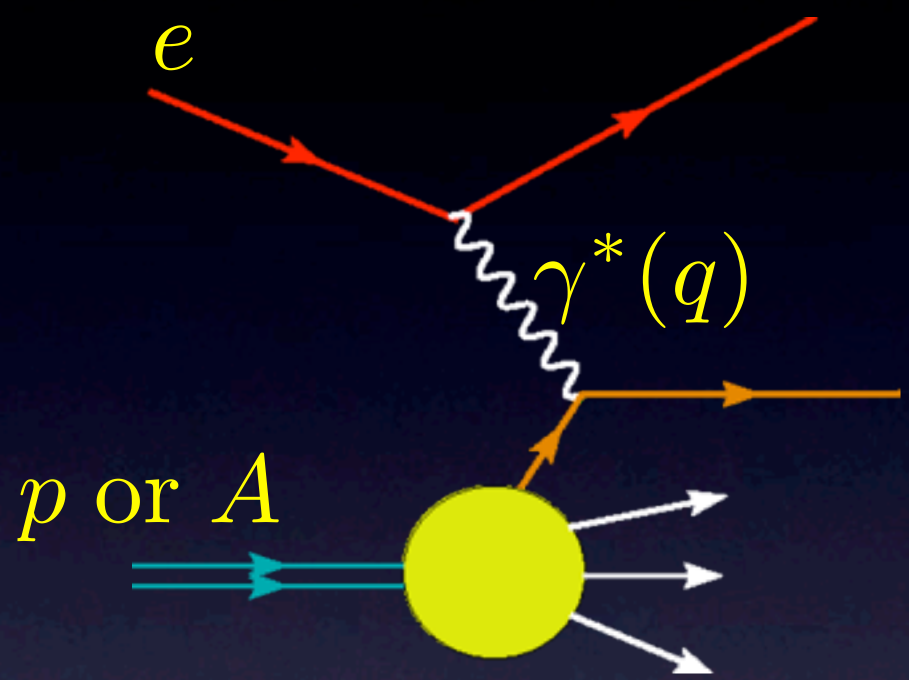


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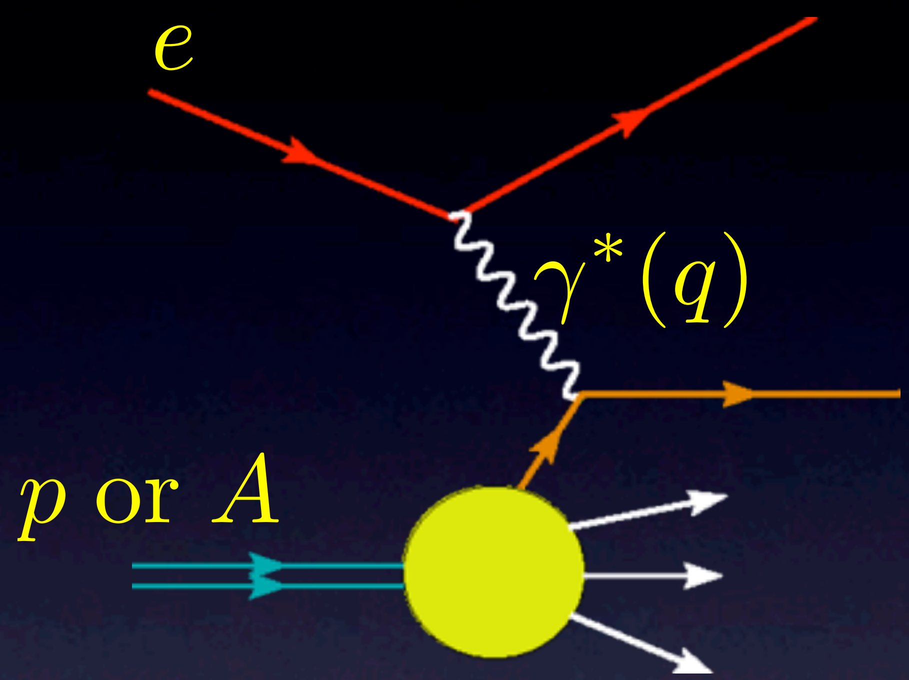


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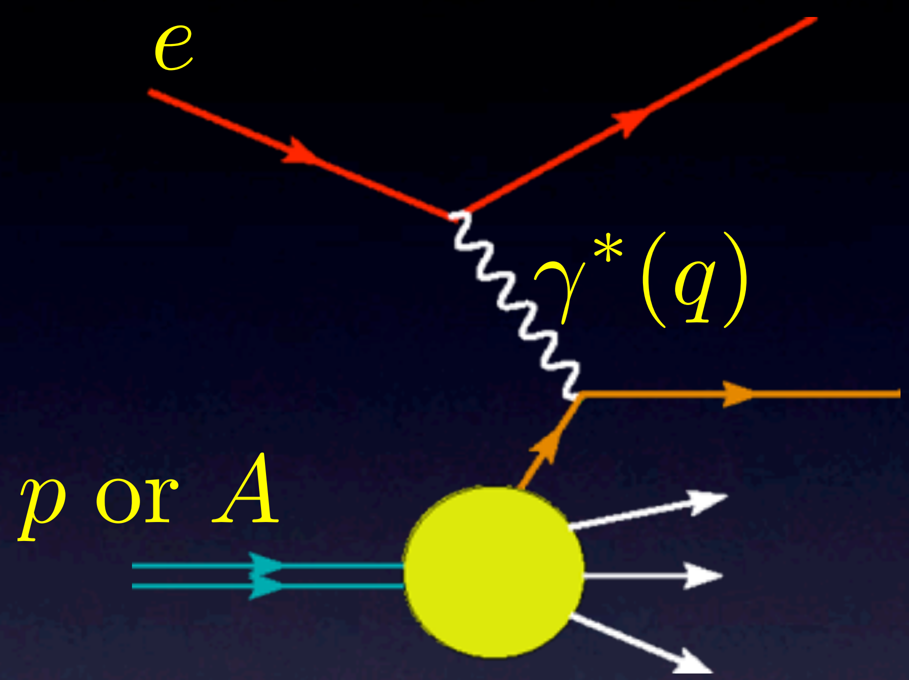


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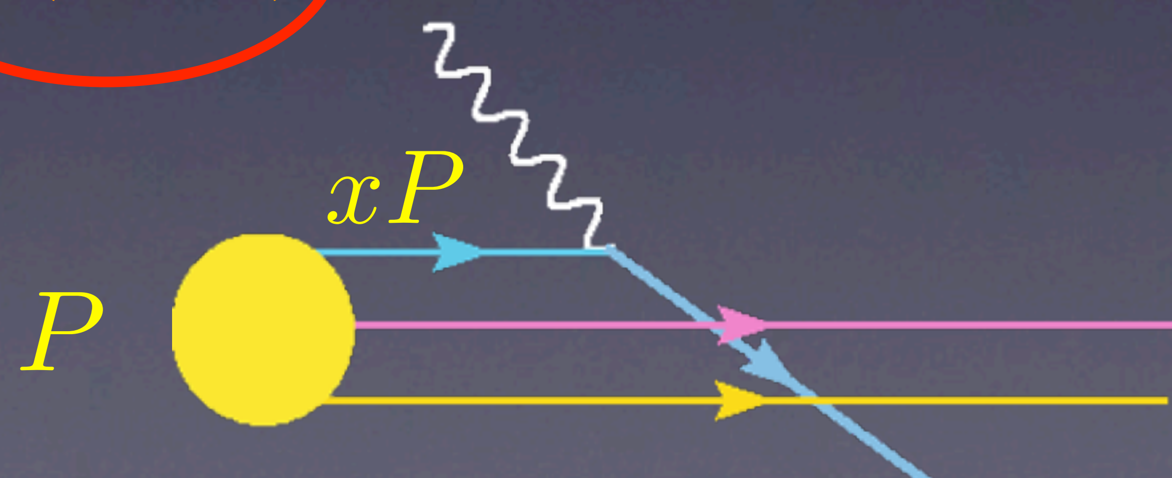
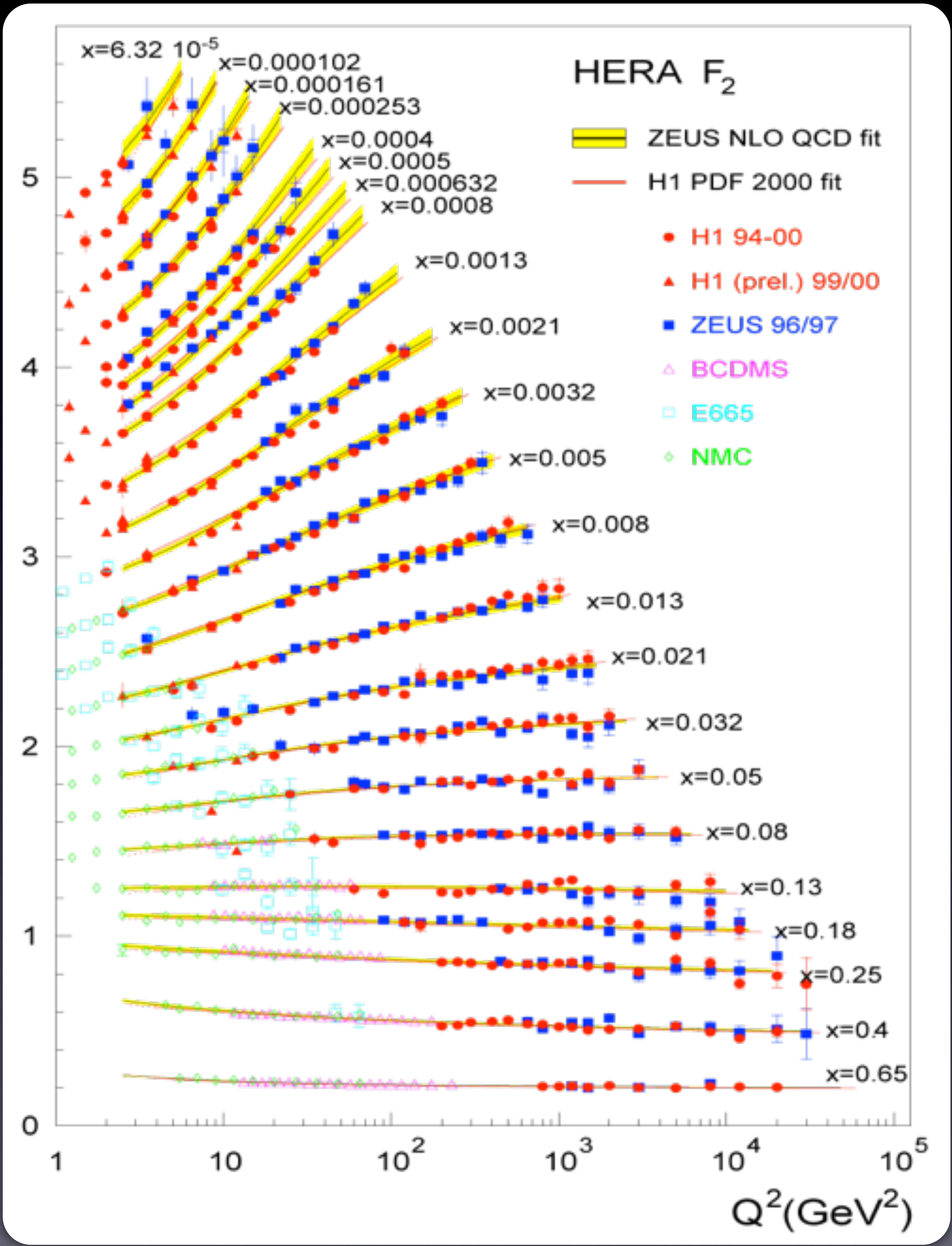



**x** fraction of the longitudinal momentum of the proton carried by the quark

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

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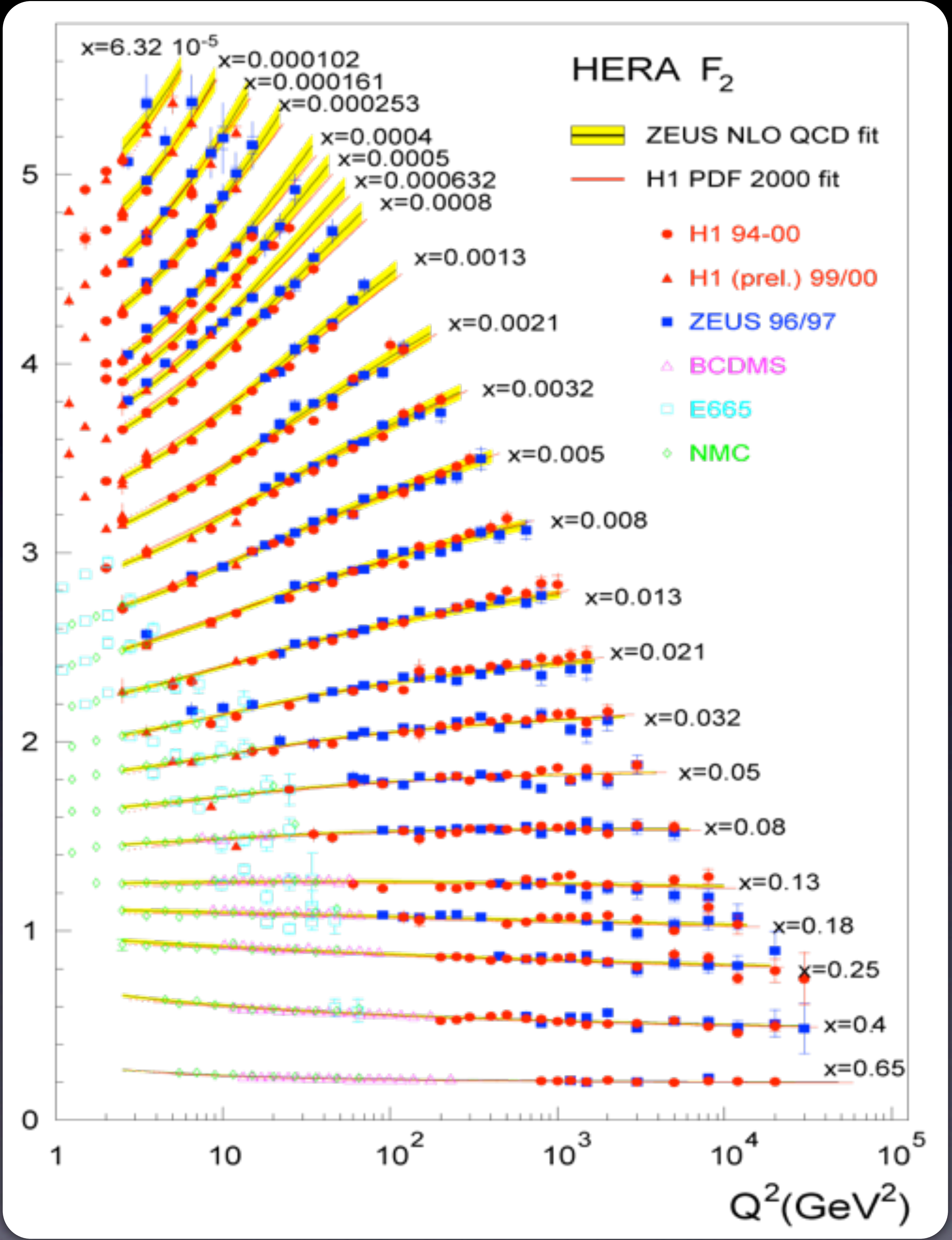


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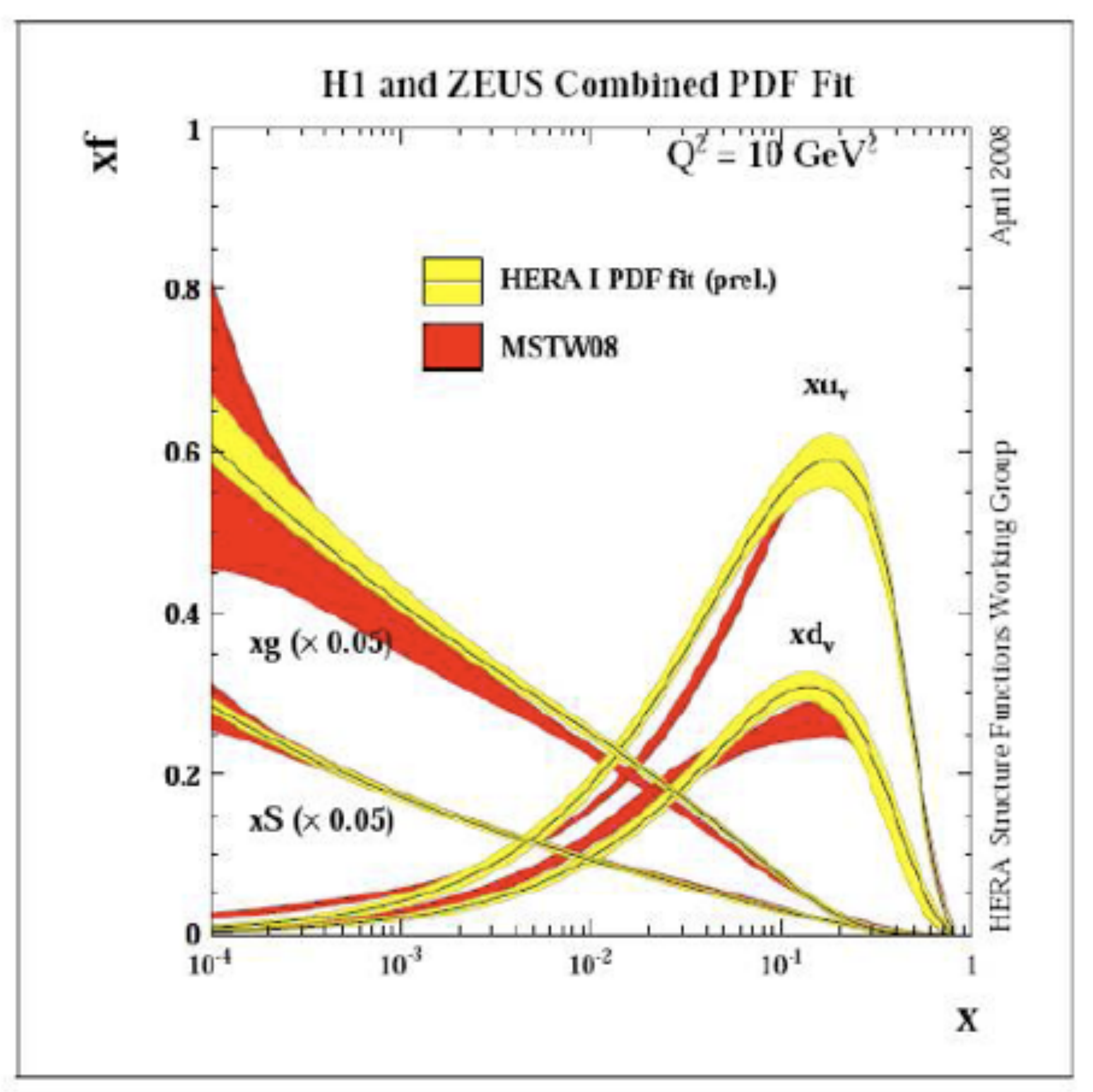

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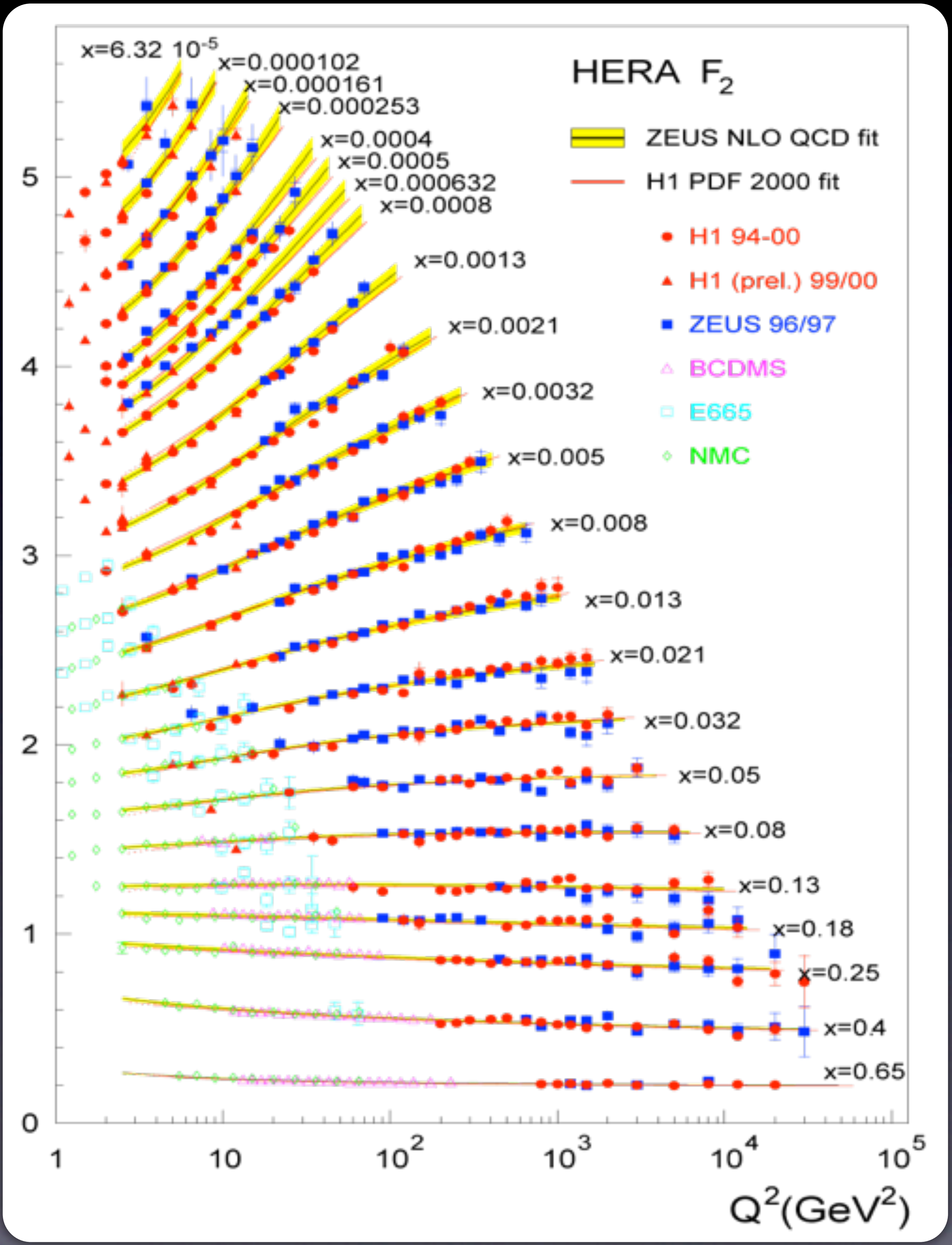
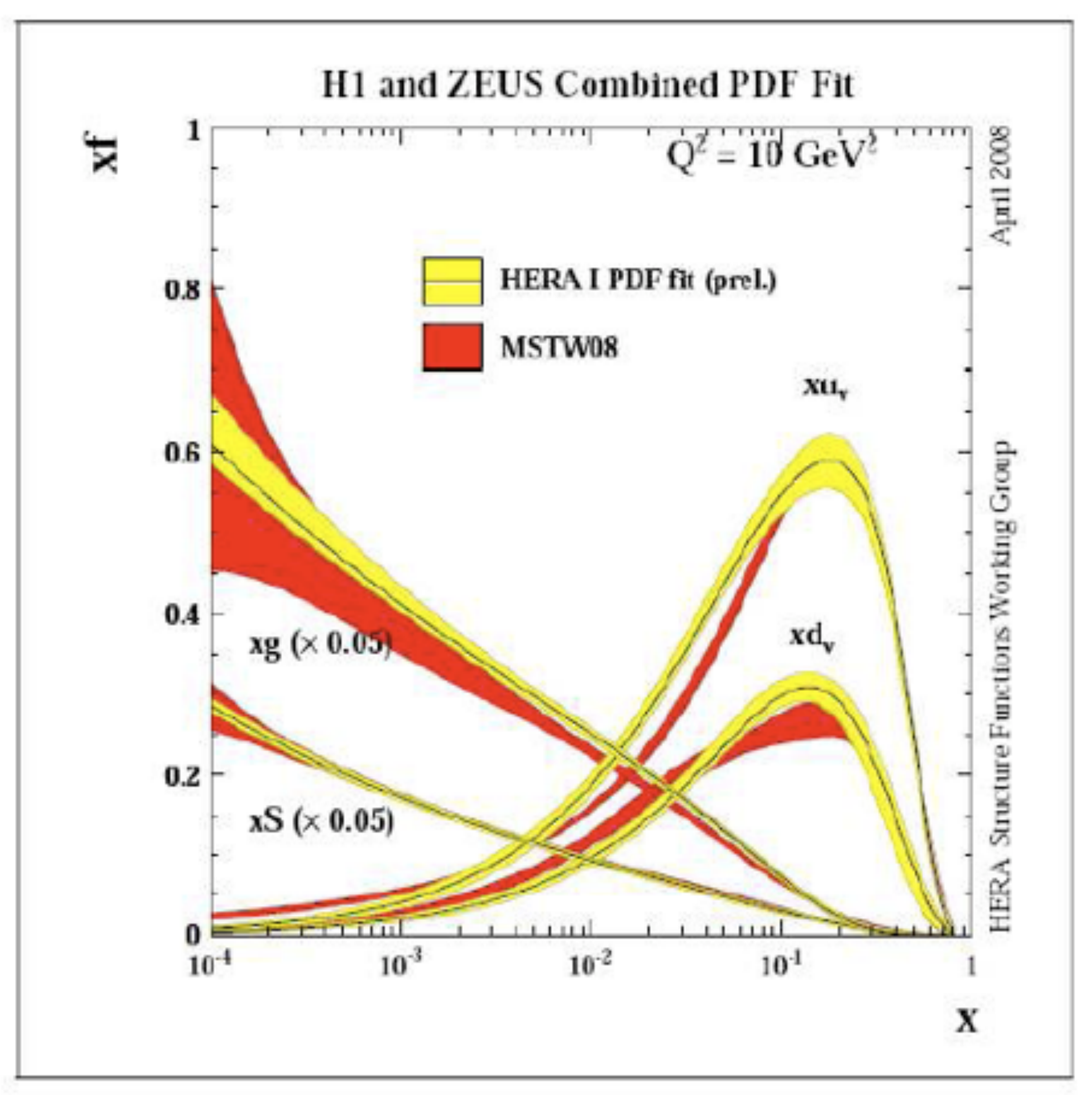



Observation of large scaling violations.

Gluon density dominates at small x!



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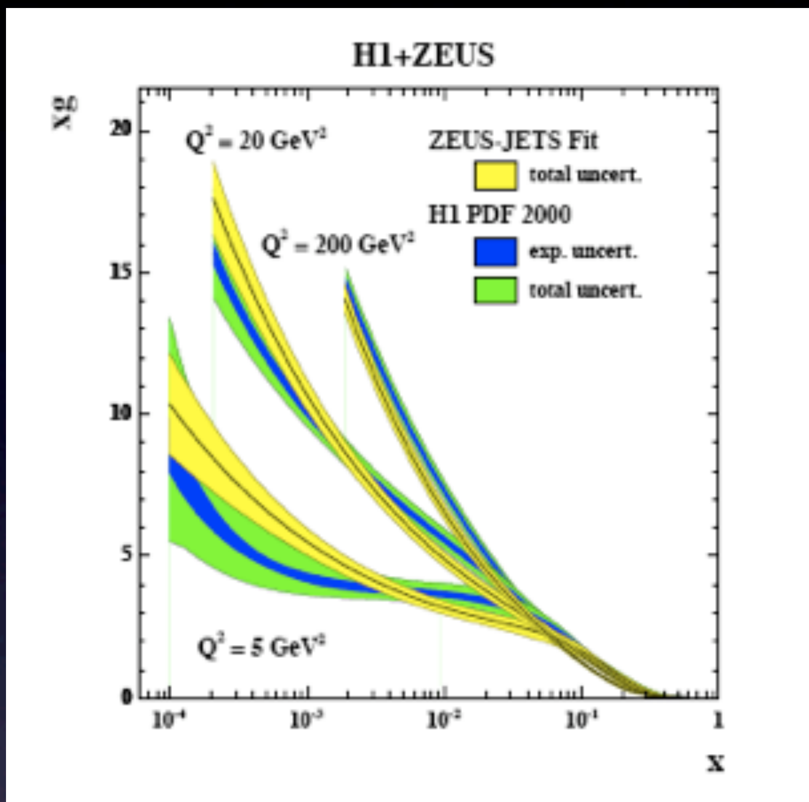

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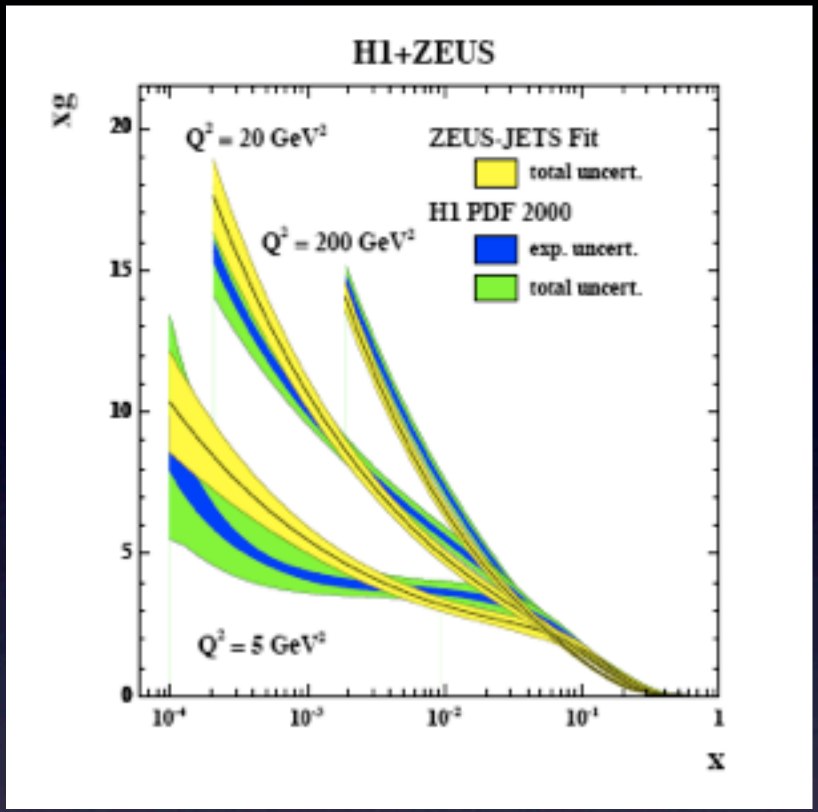


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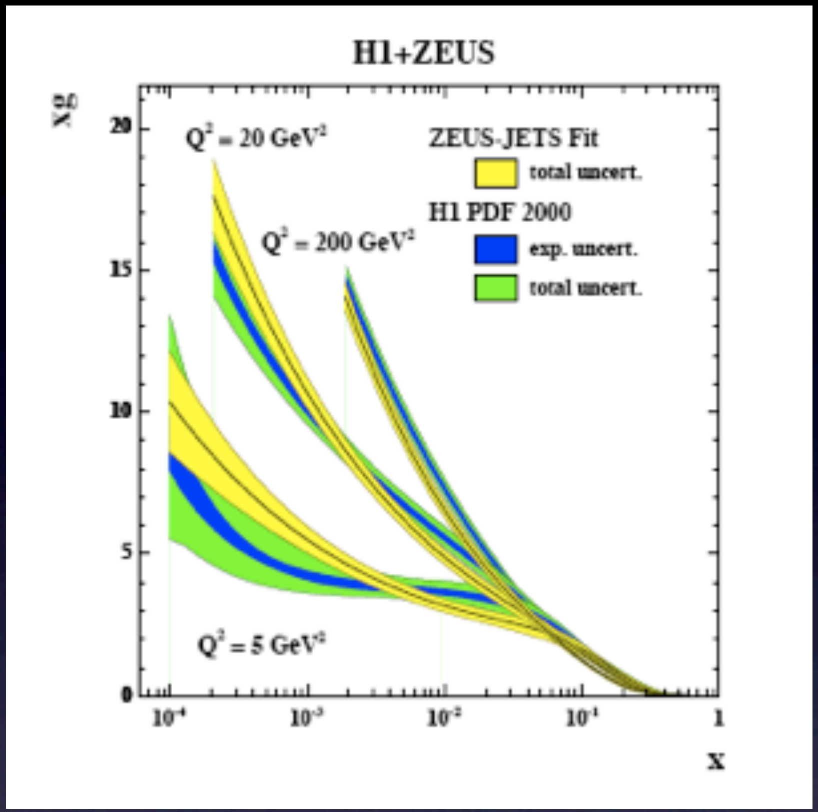


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$$x \sim \frac{Q^2}{s}$$

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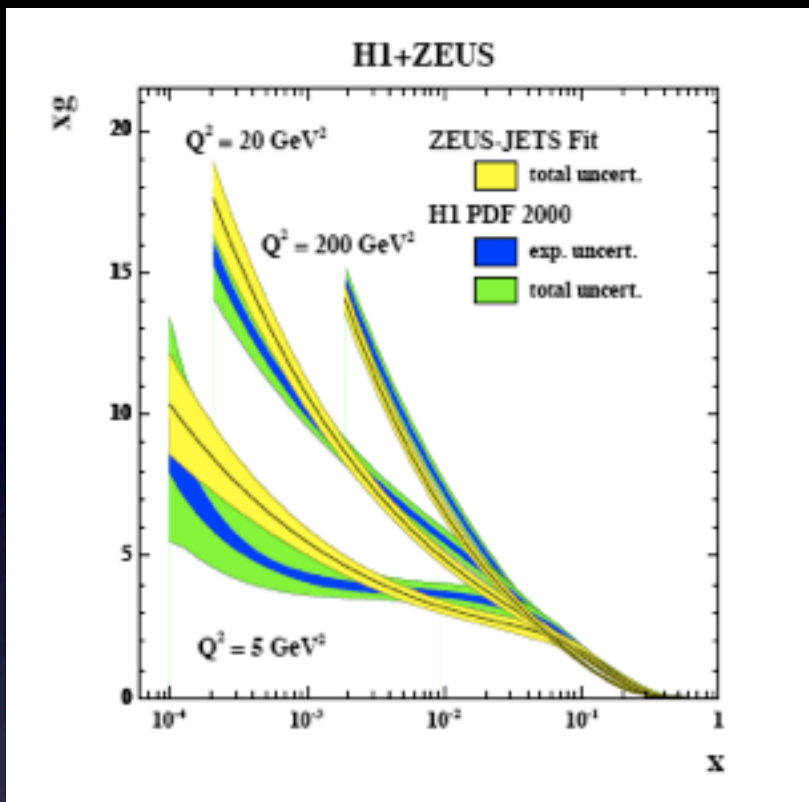


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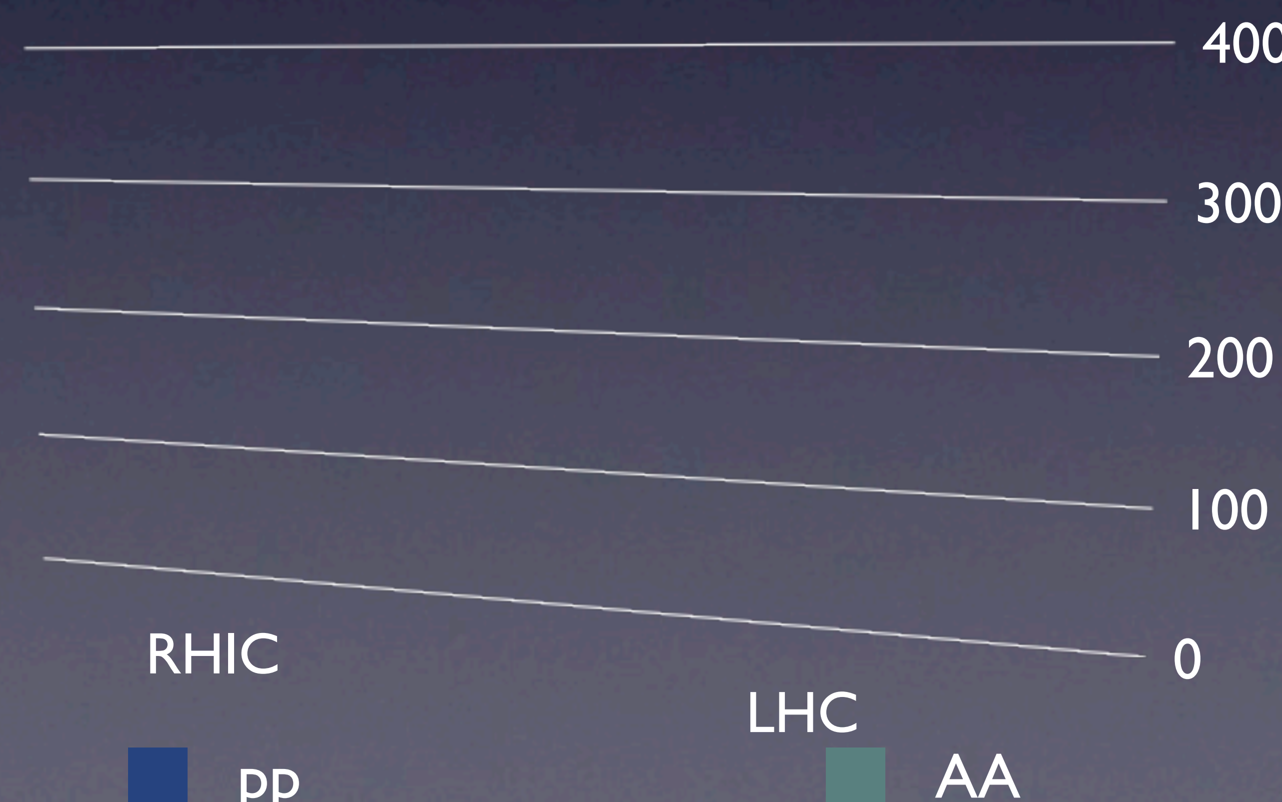

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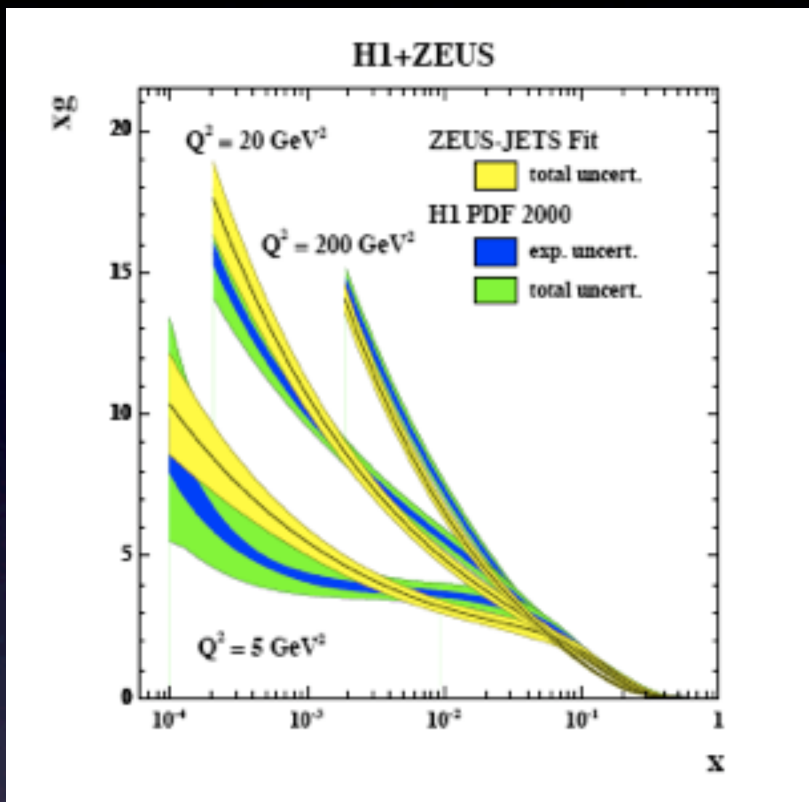


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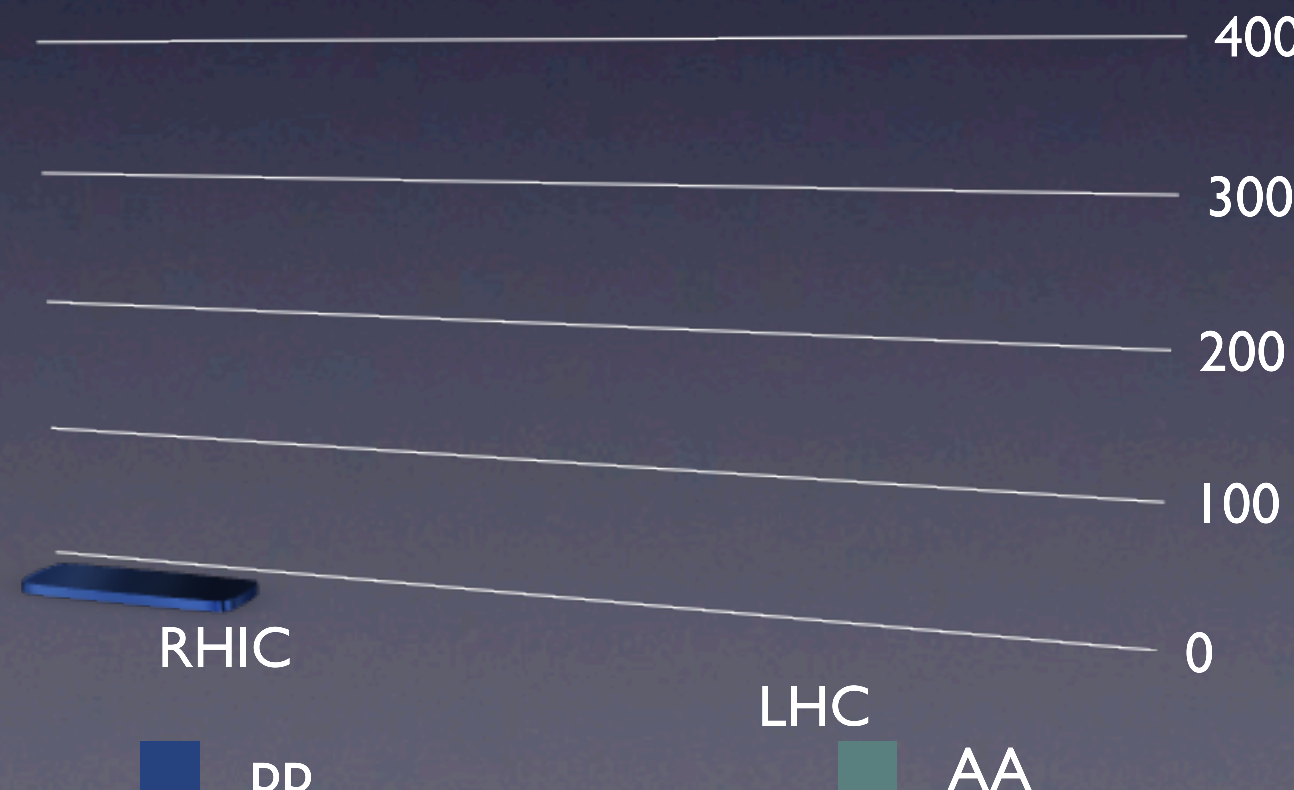

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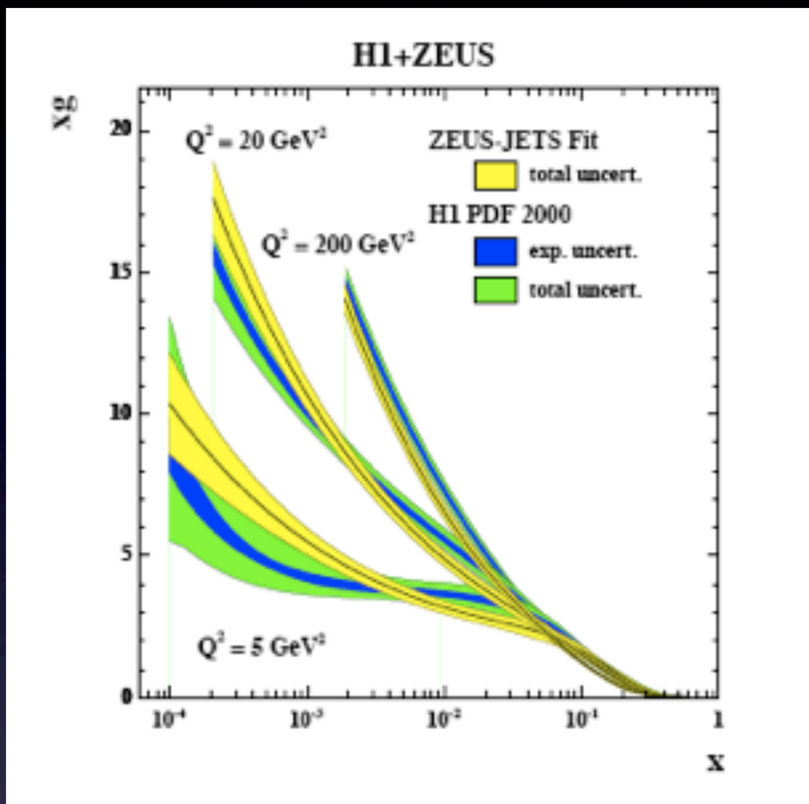


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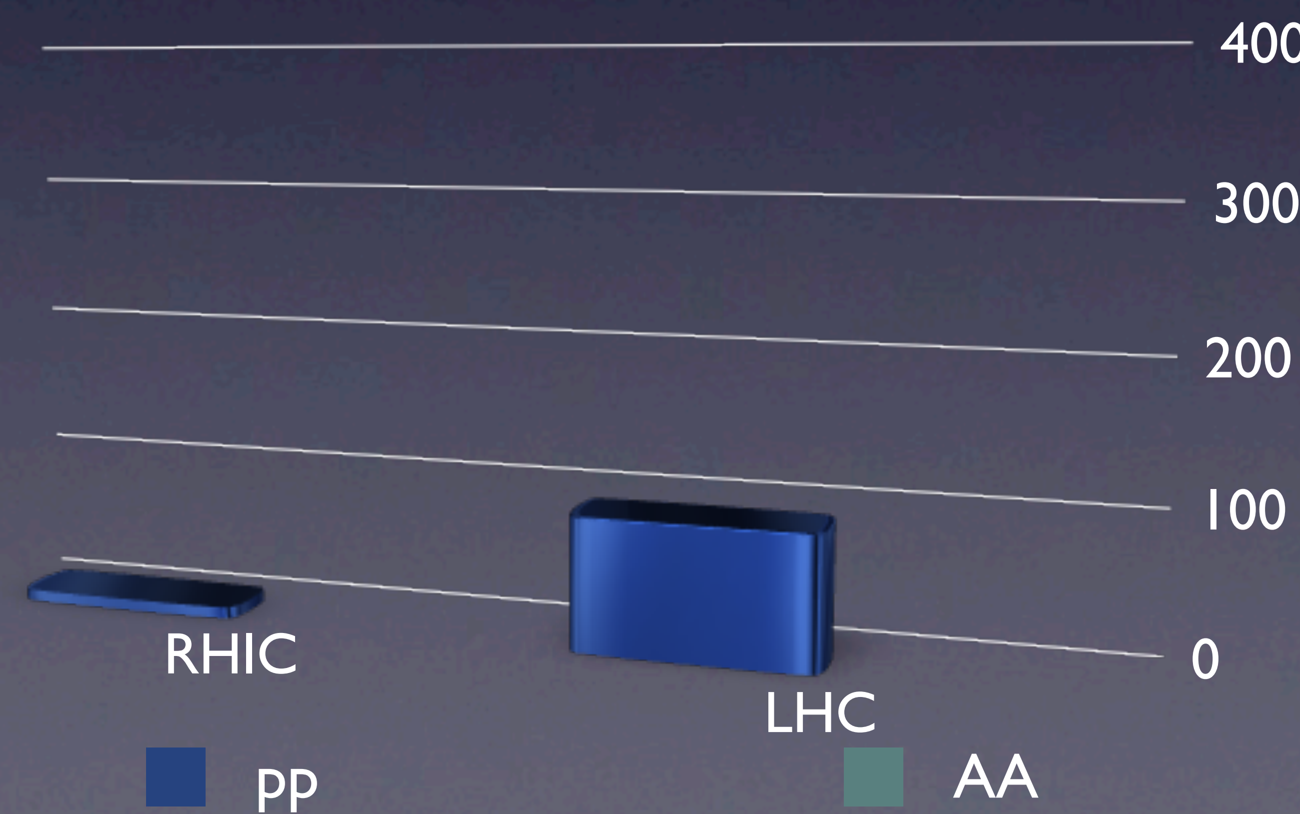

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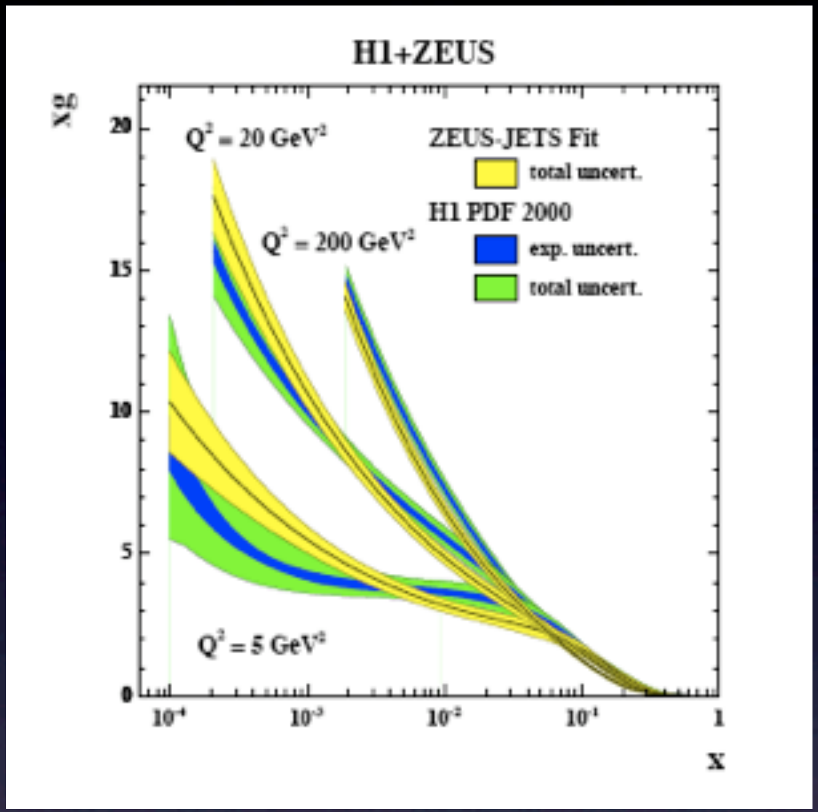


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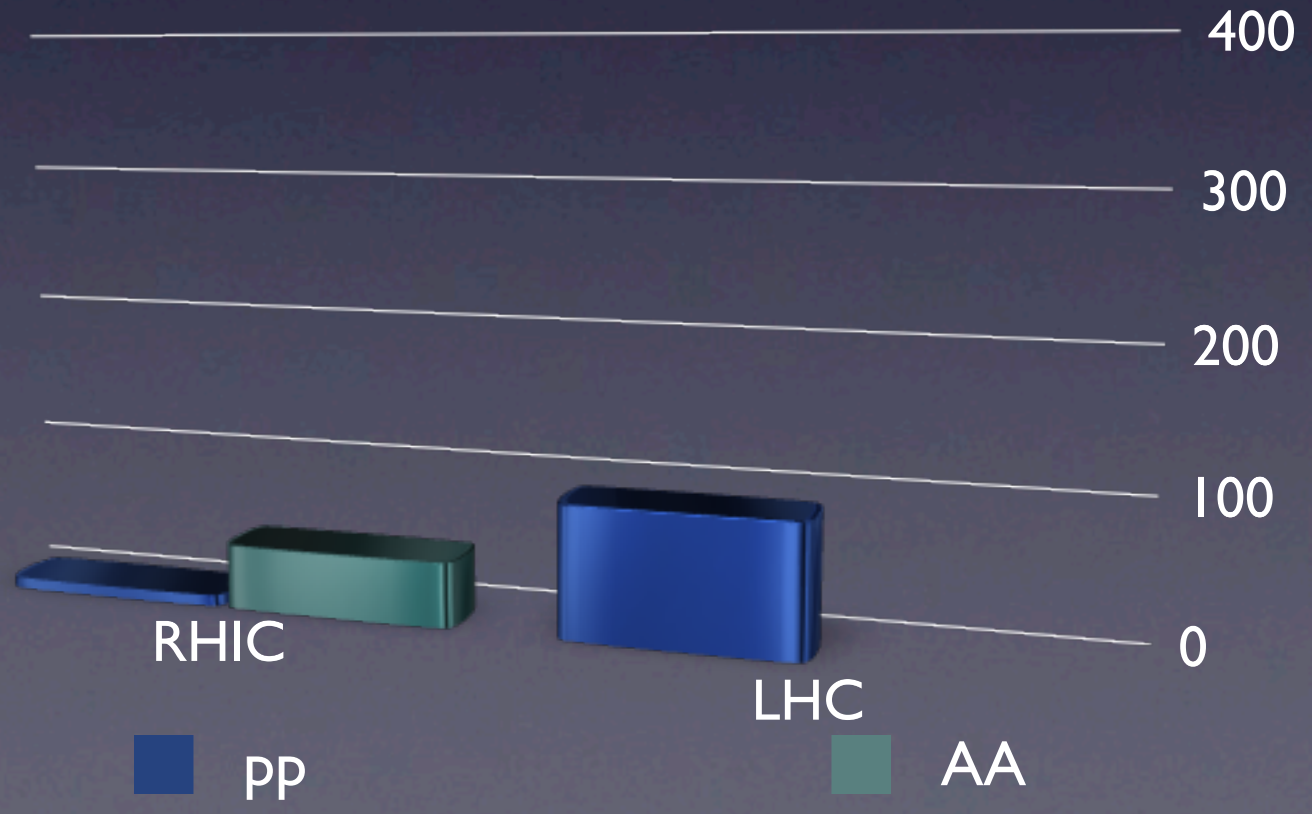

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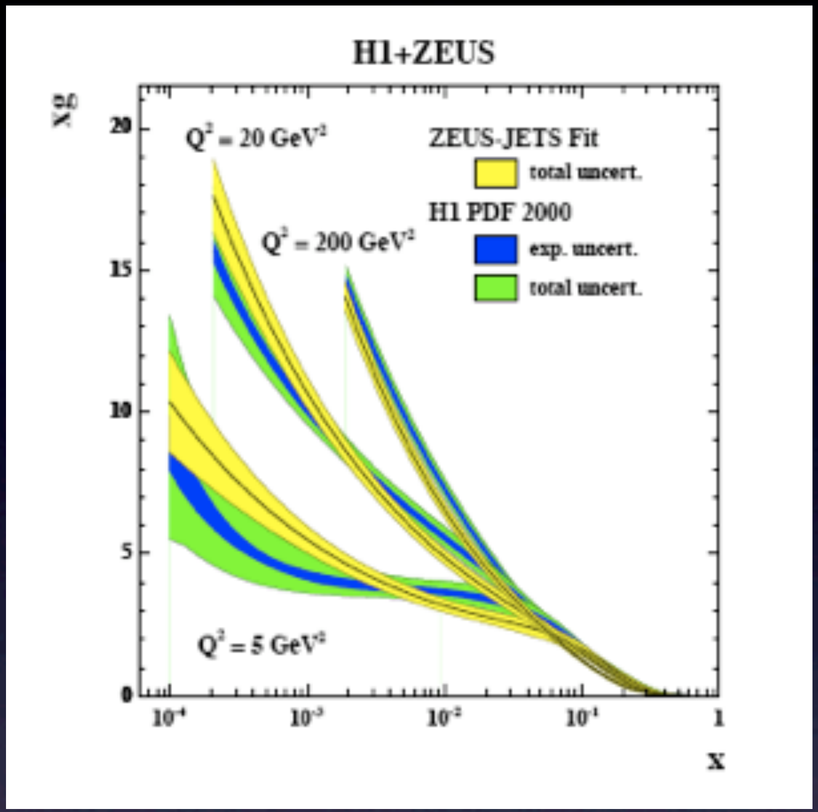


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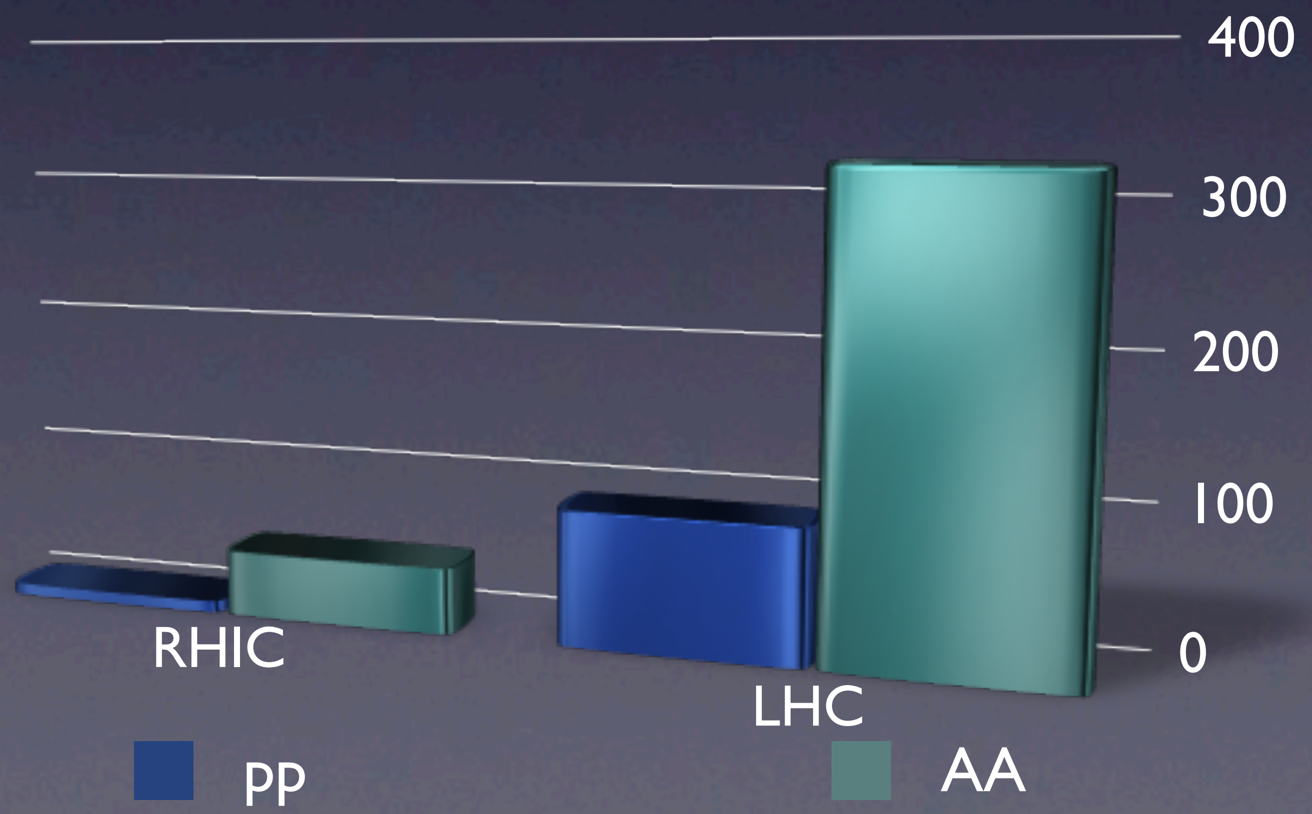

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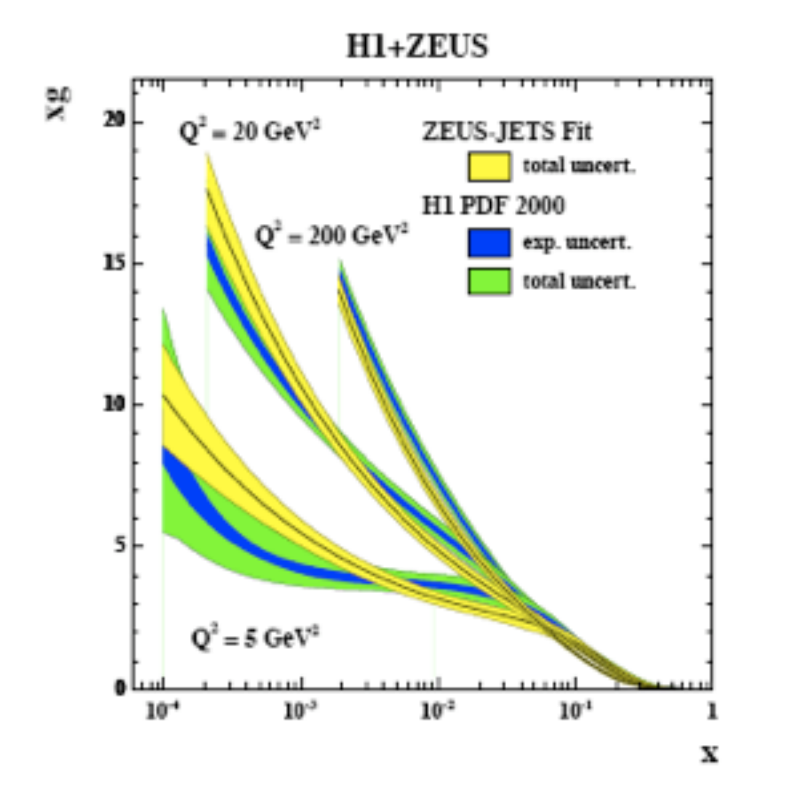


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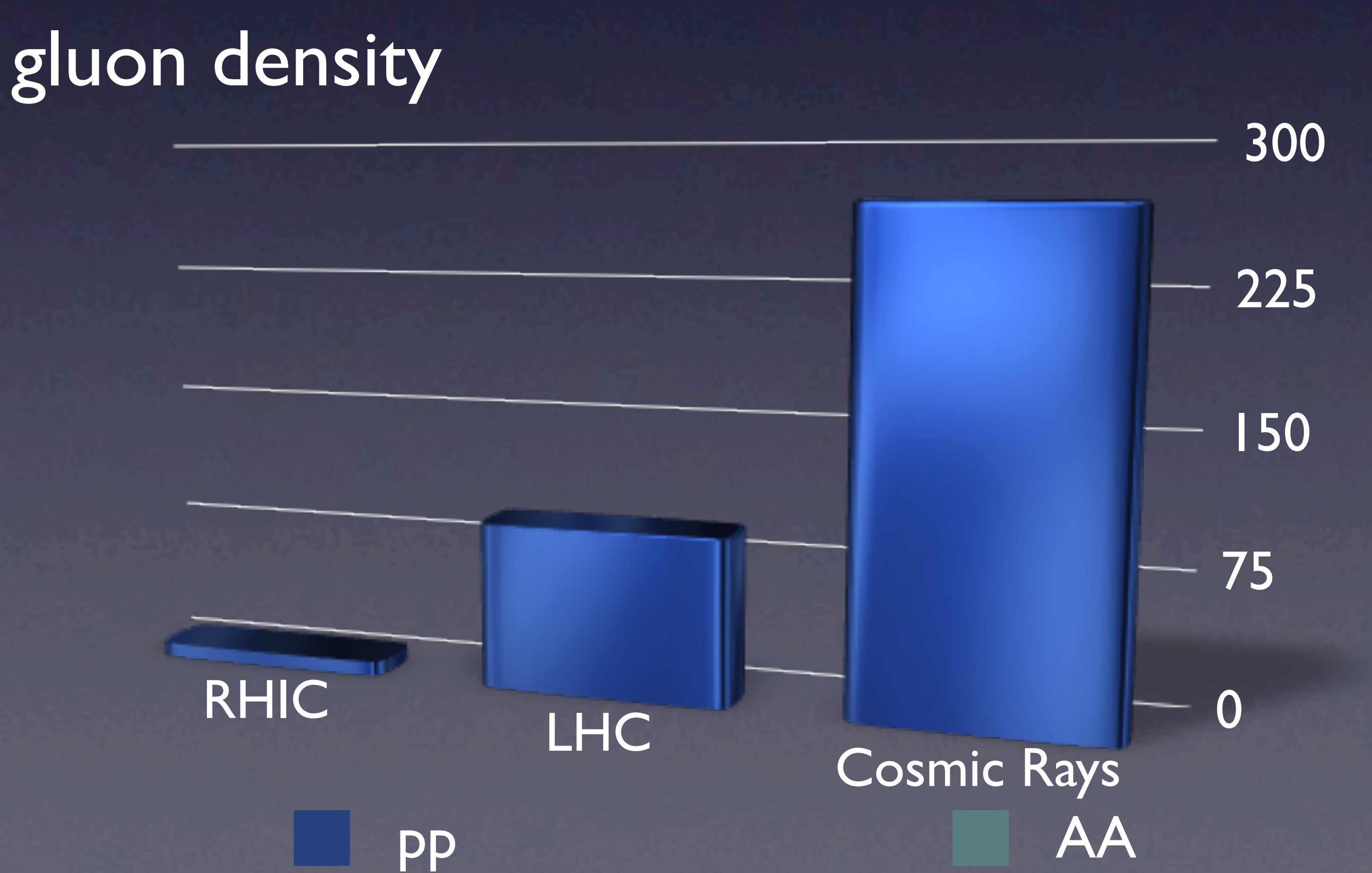



- Increase of the gluon density either via increasing energy or increasing size of the projectile (AA)
- Very small x probed at LHC and Cosmic Ray energies.
- Large gluon densities.

# Why the gluon density grows?

Grows with:

- increasing Q (resolution)
- decreasing x (increasing energy)

DGLAP evolution: in $Q^2$

Increasing photon virtuality, means increasing resolution.
More parton fluctuations resolved.

$$\frac{\partial}{\partial \ln Q^2/\Lambda^2} f_a(x, Q^2) = P_{ab} \otimes f(x, Q^2)$$

splitting function $P_{ab}$ describes splitting of parton b into a

# BFKL evolution: in x

Decreasing x or increasing total energy s. Resolution is fixed.
Opening the kinematic phase space for more parton emissions.

Again linear evolution in density, differential equation in x

$$\frac{df_g(x,k_T^2)}{d\ln 1/x} = \frac{\alpha_s N_c}{\pi} \int d^2k'_T \mathcal{K}(k_T,k'_T)\, f_g(x,k'_T)$$

$\mathcal{K}(k,k')$ branching kernel for gluons

Solution:

$$f_g(x,k_T) \sim x^{-\omega_P}$$

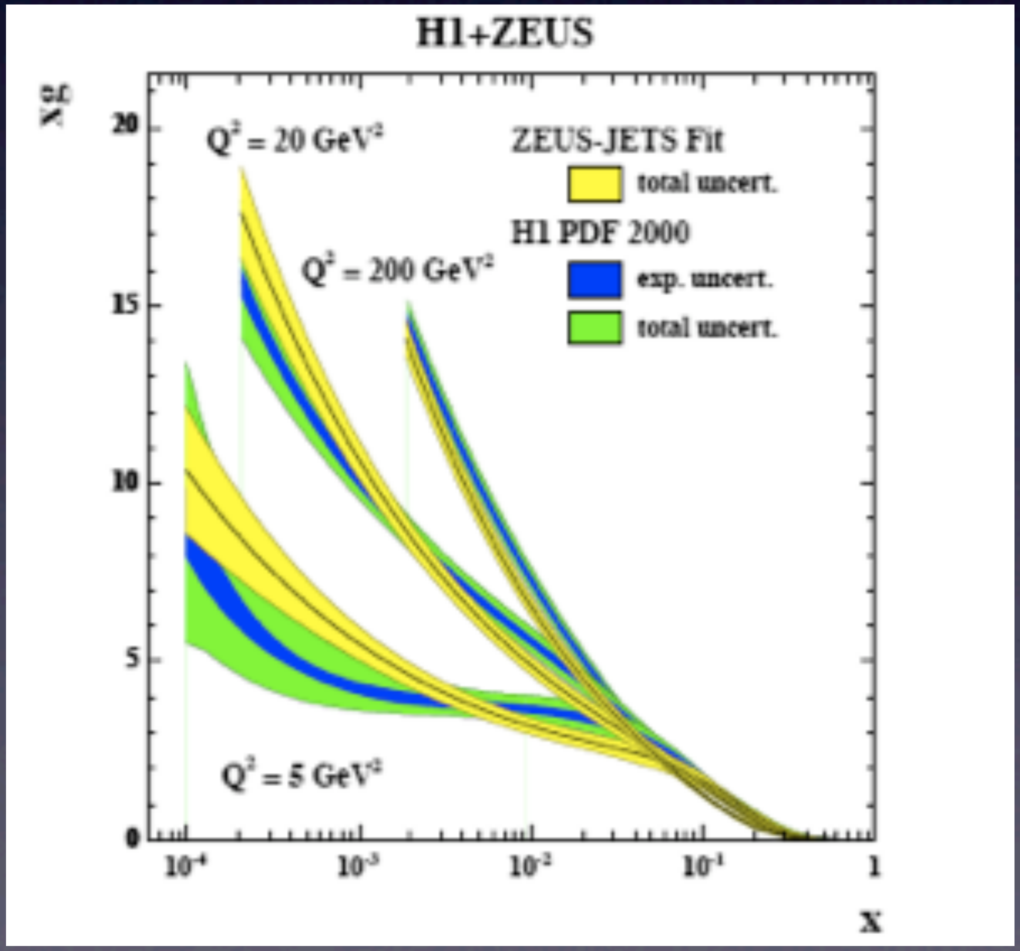
Leading exponent(spin)

$$\omega_P = j-1 = \frac{\alpha_s N_c}{\pi} 4\ln 2$$

Very fast increase of the density with small x!

# Parton Saturation

# Can the gluon density rise forever?
# How fast?



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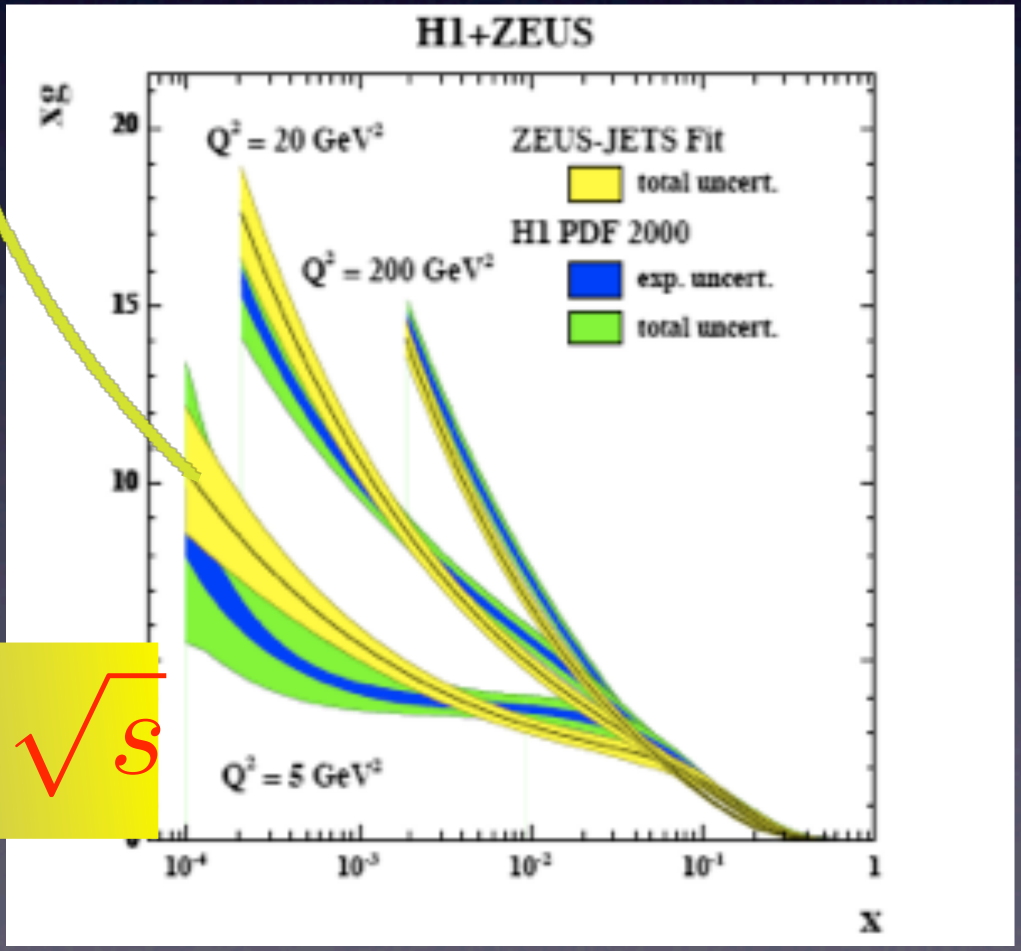


Increase energy $\sqrt{s}$

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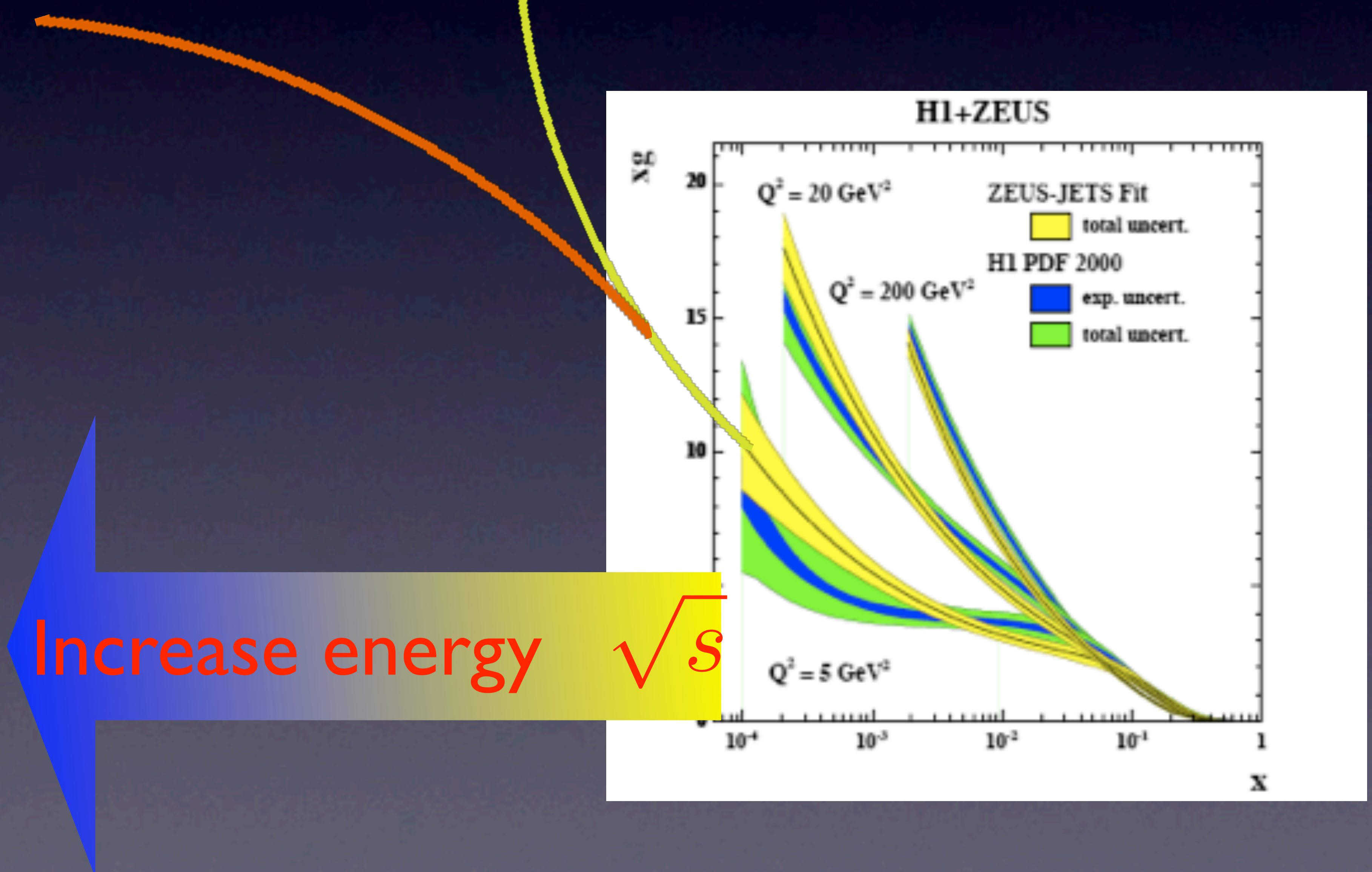

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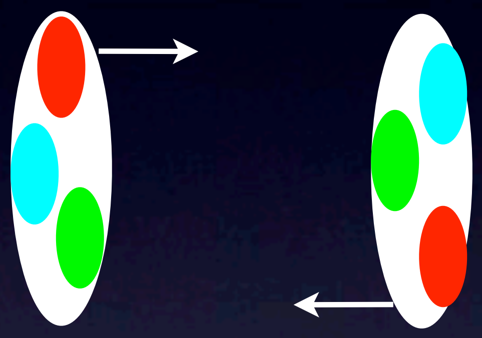

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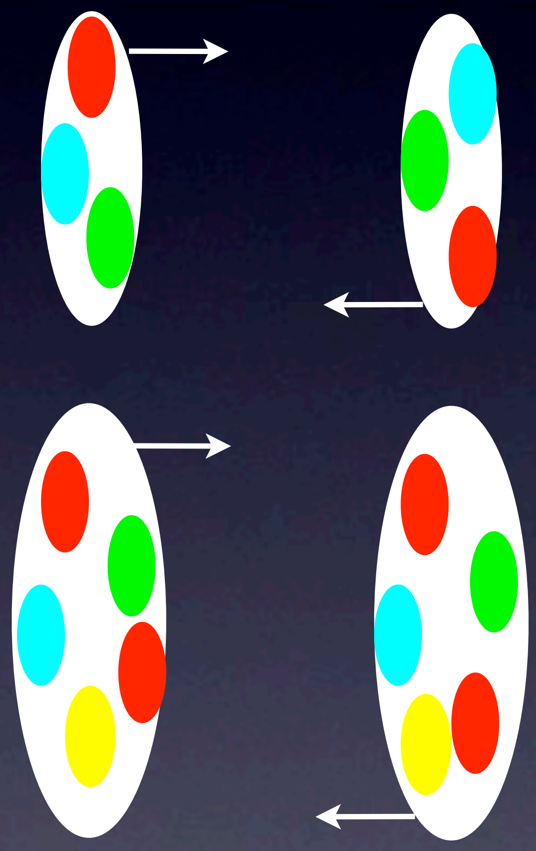

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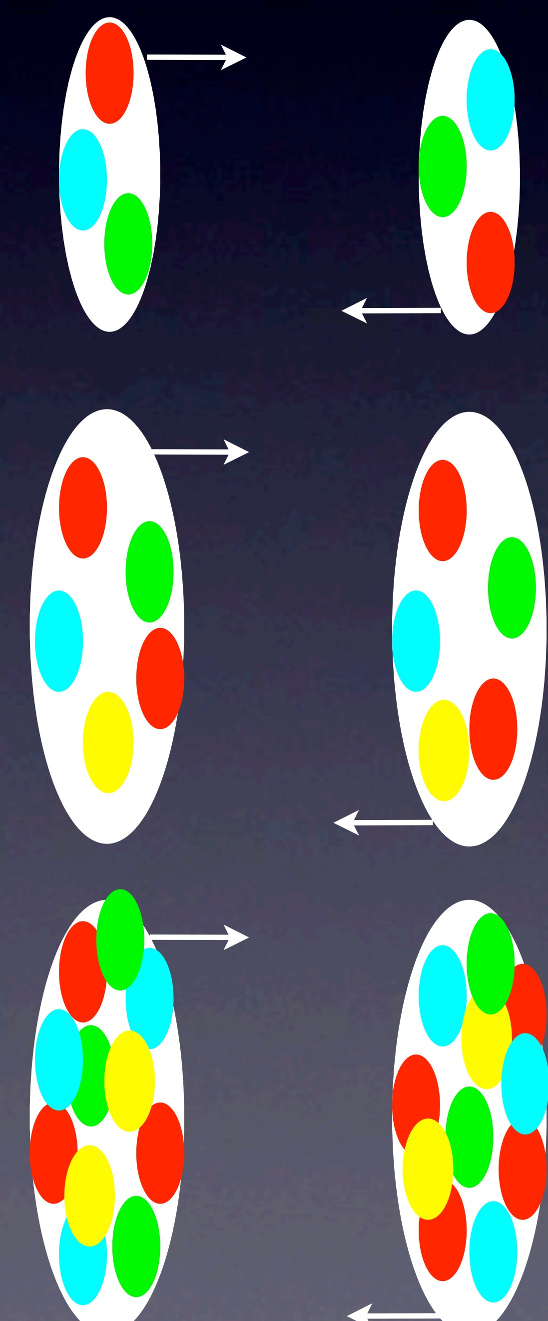
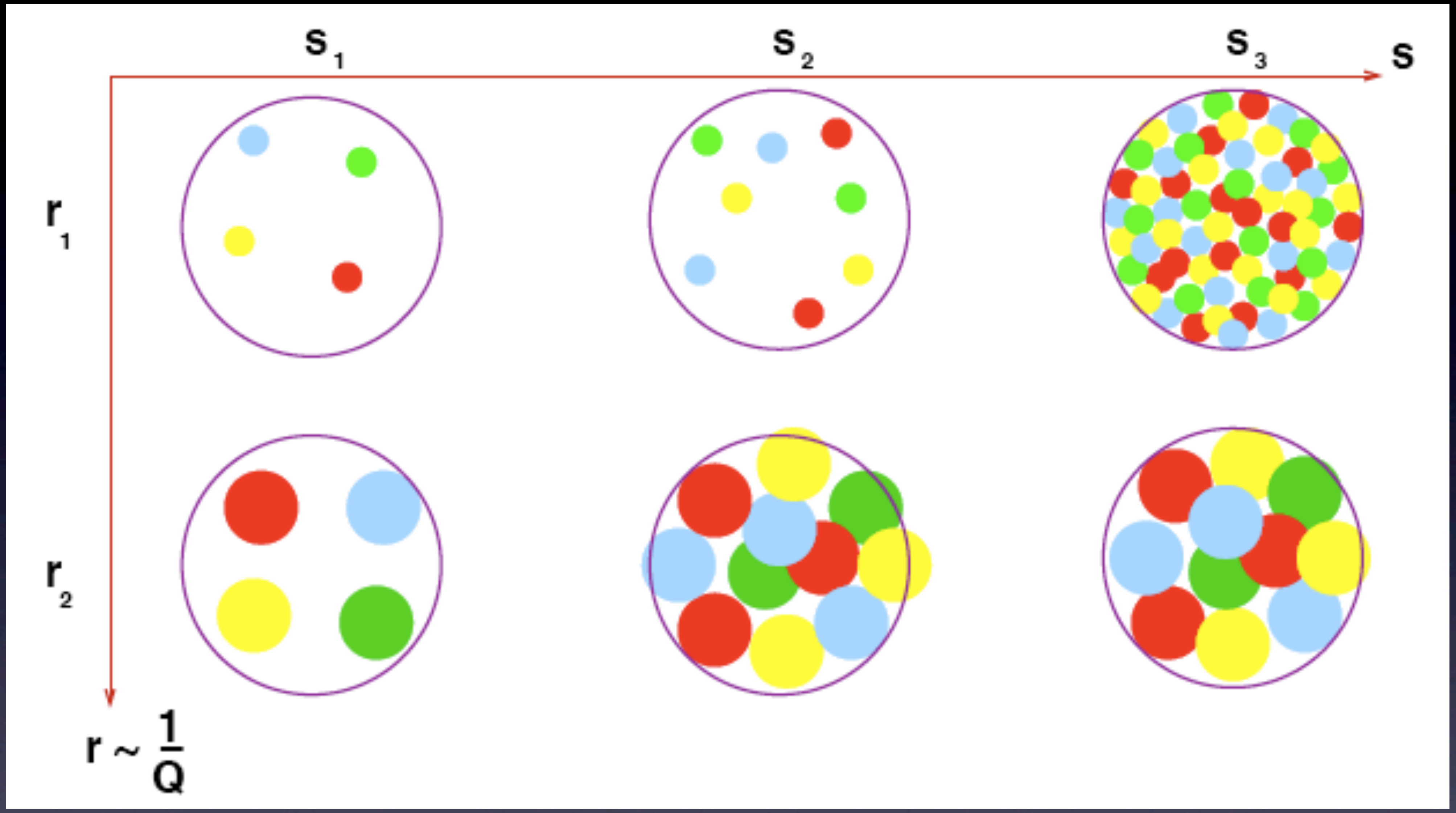
- Increase in the density of the projectile.
- It is limited by the unitarity at fixed impact parameter. Probability of the interaction: $N(b) \leq 1$

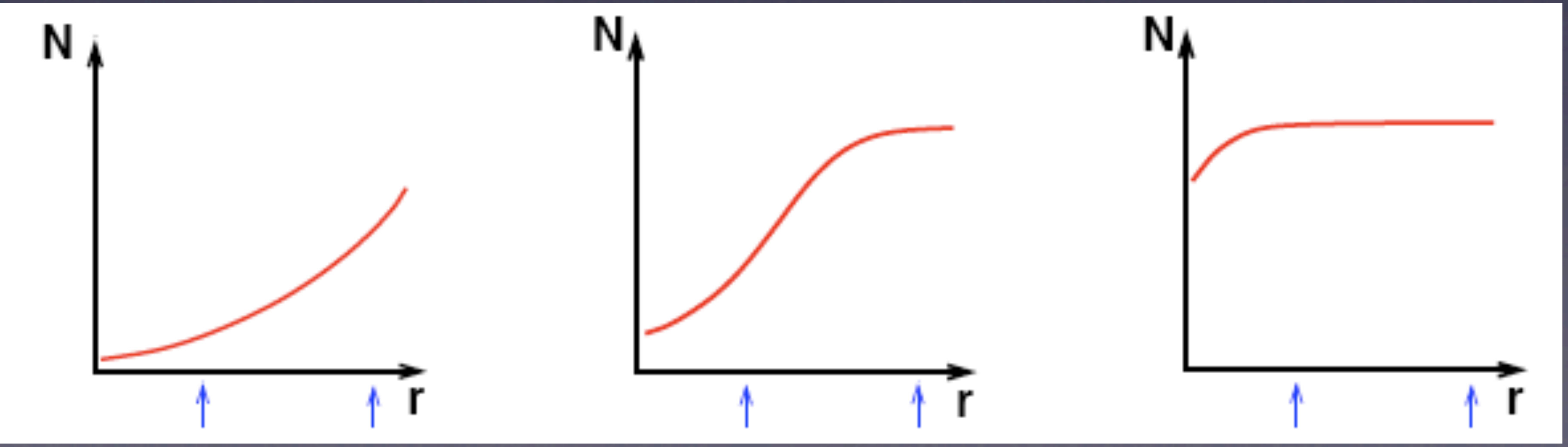


# Parton saturation

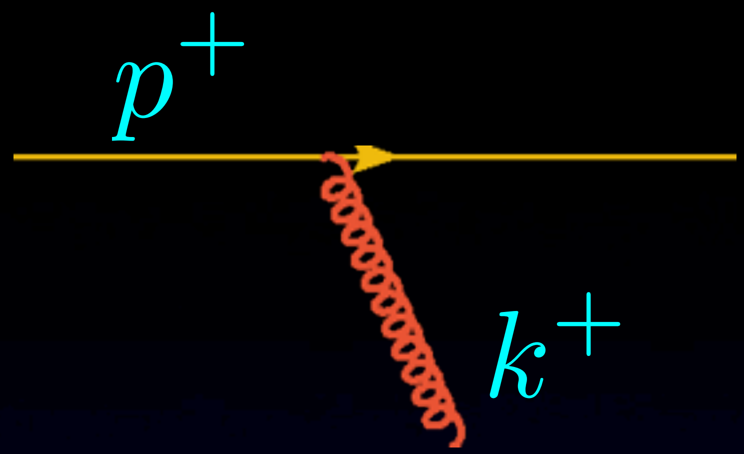
energy of the interaction

size of the probe



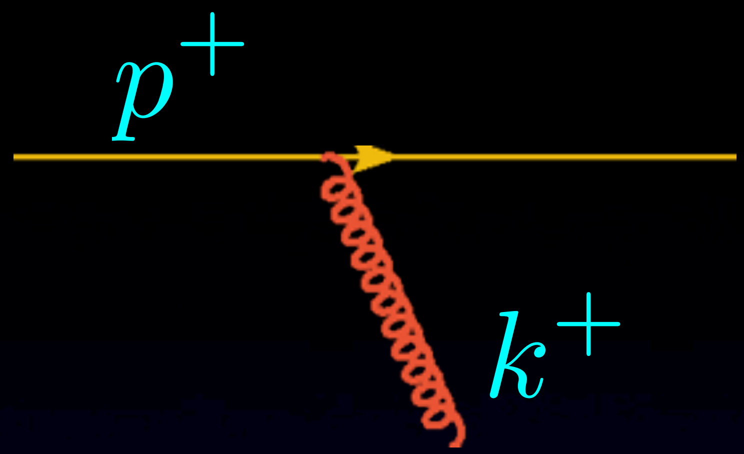



# Microscopic mechanism:




$$p^+ = \frac{1}{\sqrt{2}}(E + p_z)$$

Microscopic mechanism: Single charge (source)

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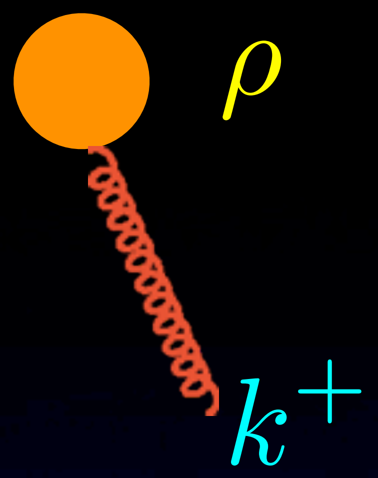

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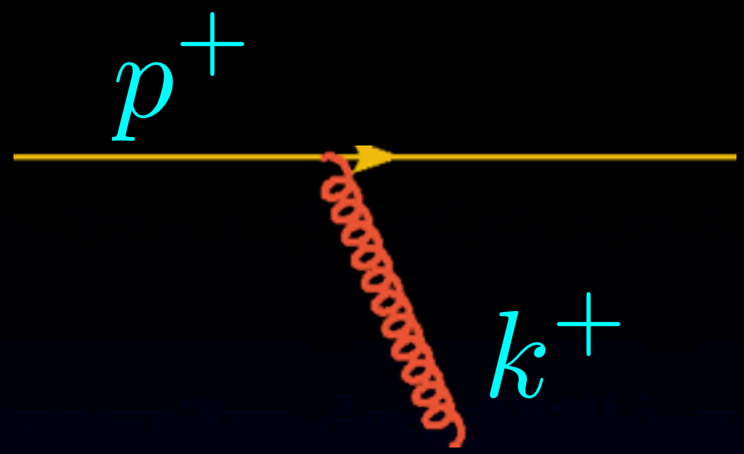


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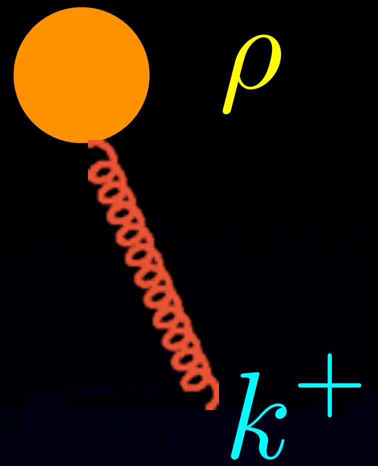


Fast hadron or a nucleus

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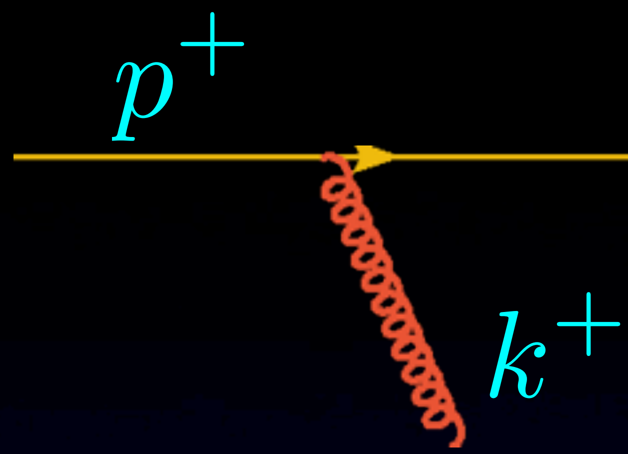


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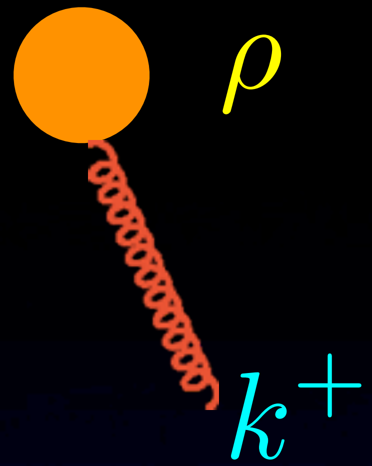


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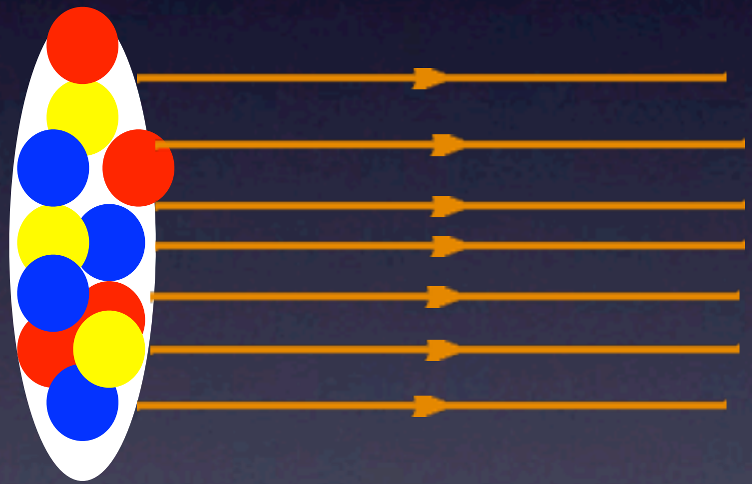

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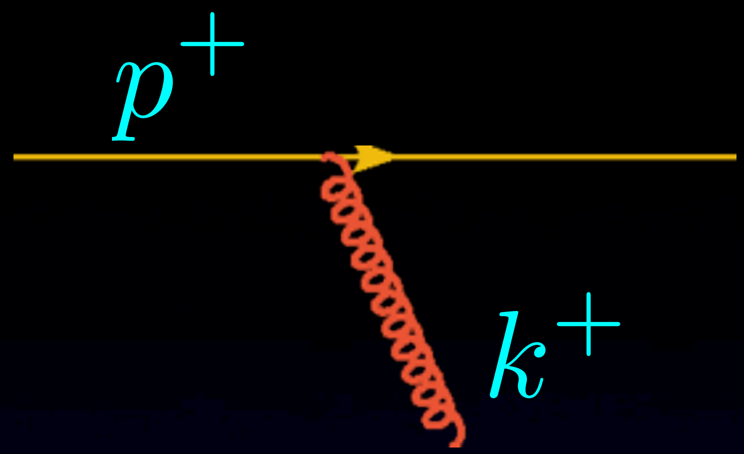


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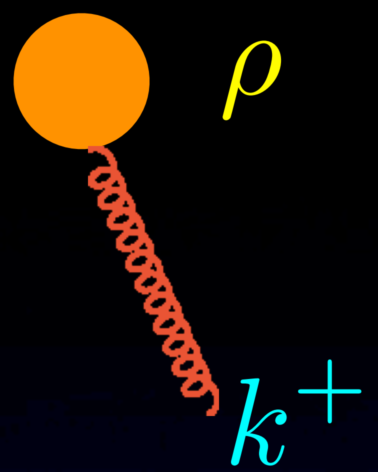
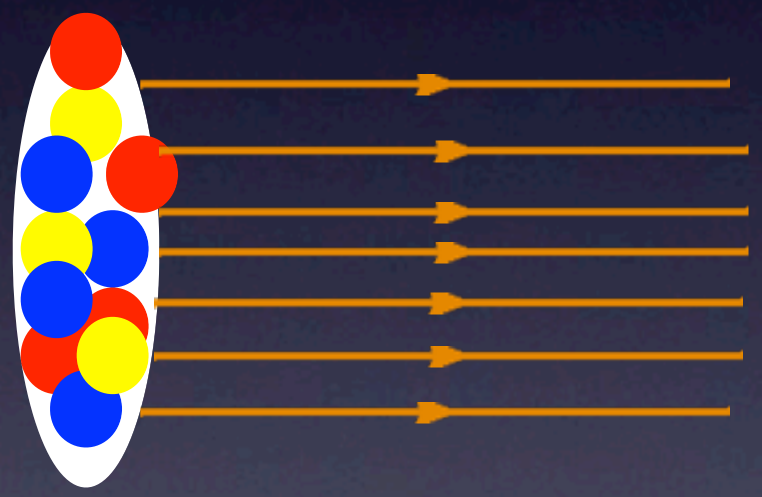
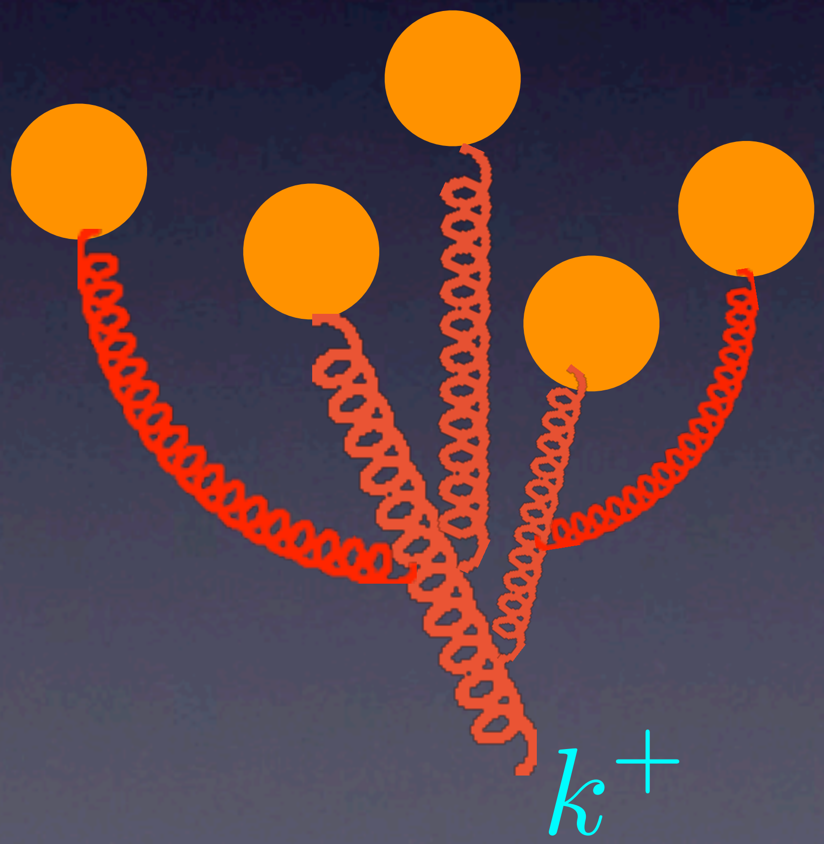



Fast hadron or a nucleus



Many charges (sources)



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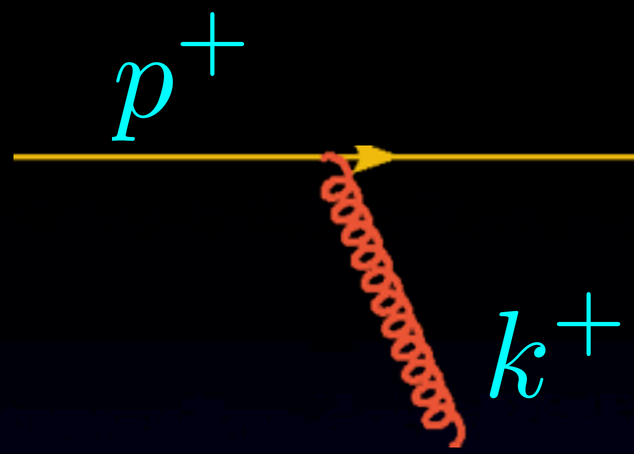
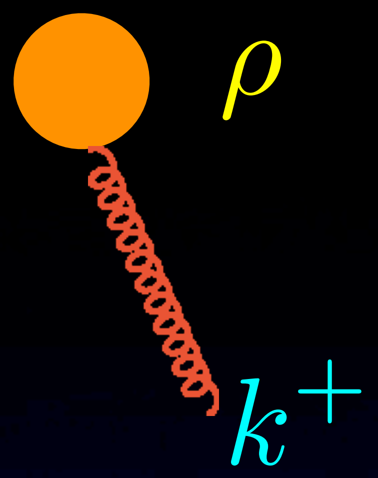



$$p^+ = \frac{1}{\sqrt{2}}(E + p_z)$$

Single charge (source)

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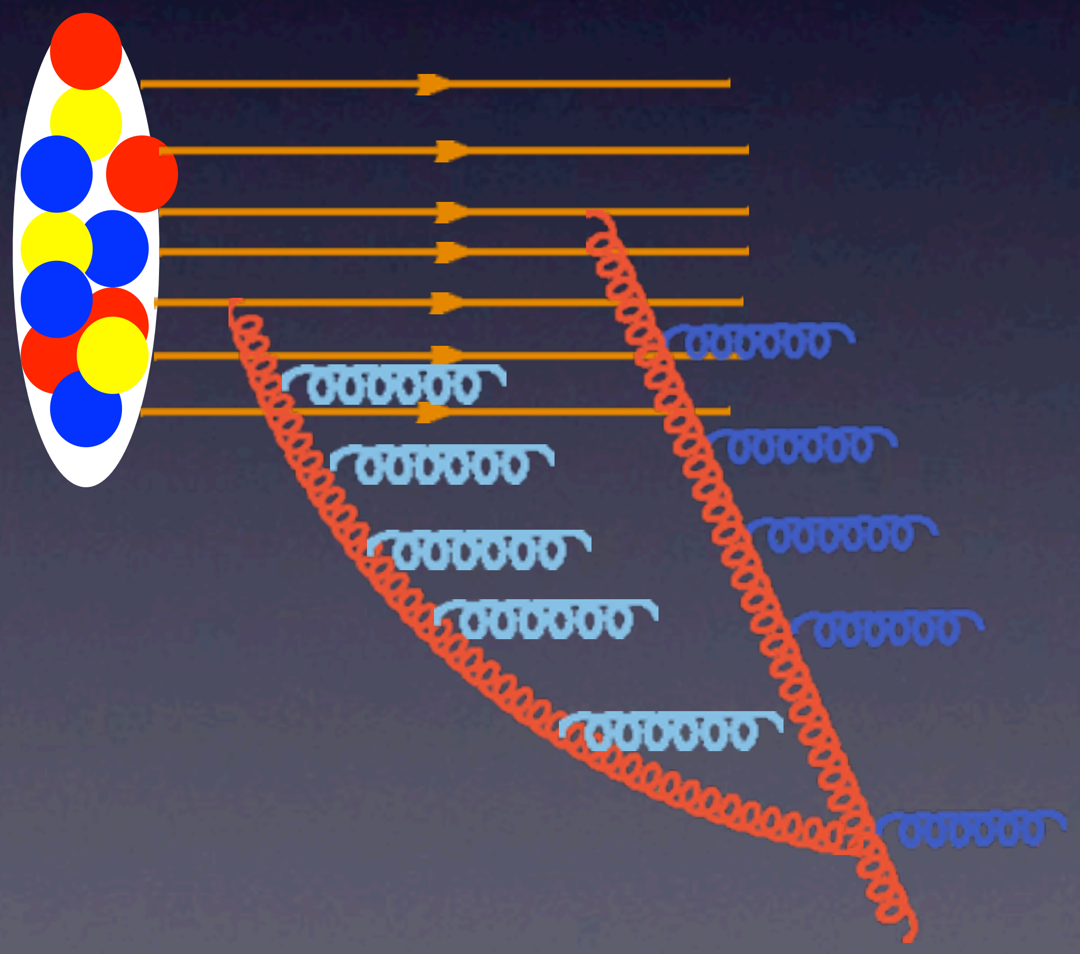

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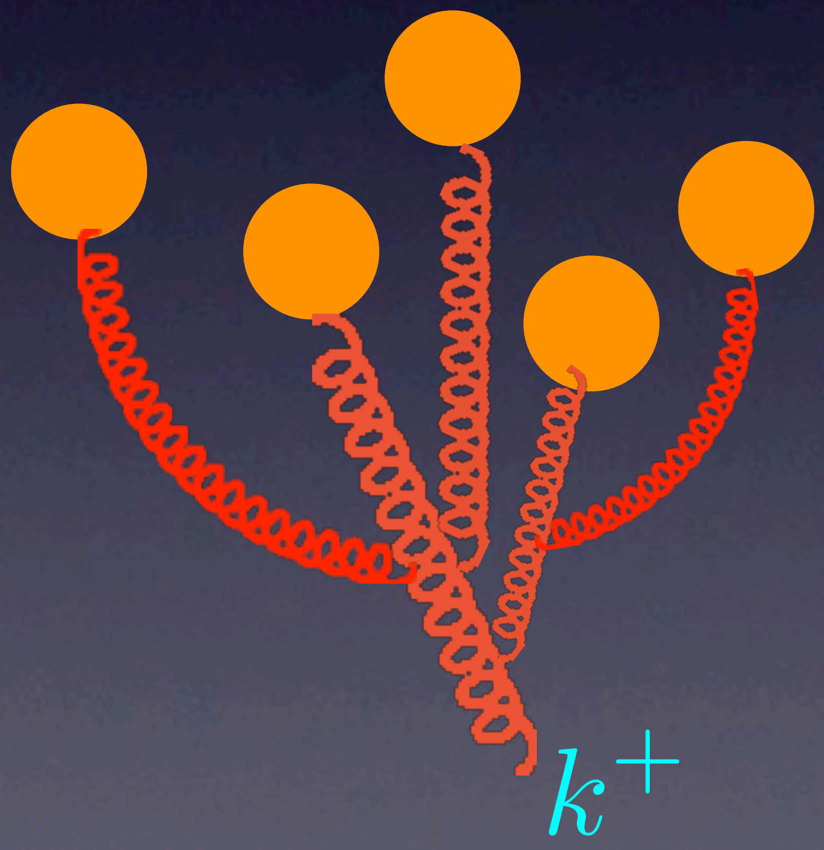

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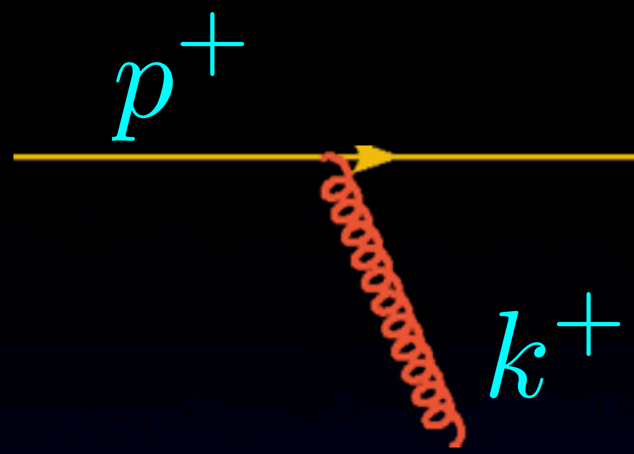


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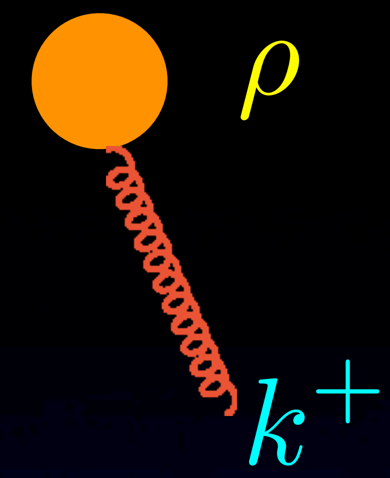


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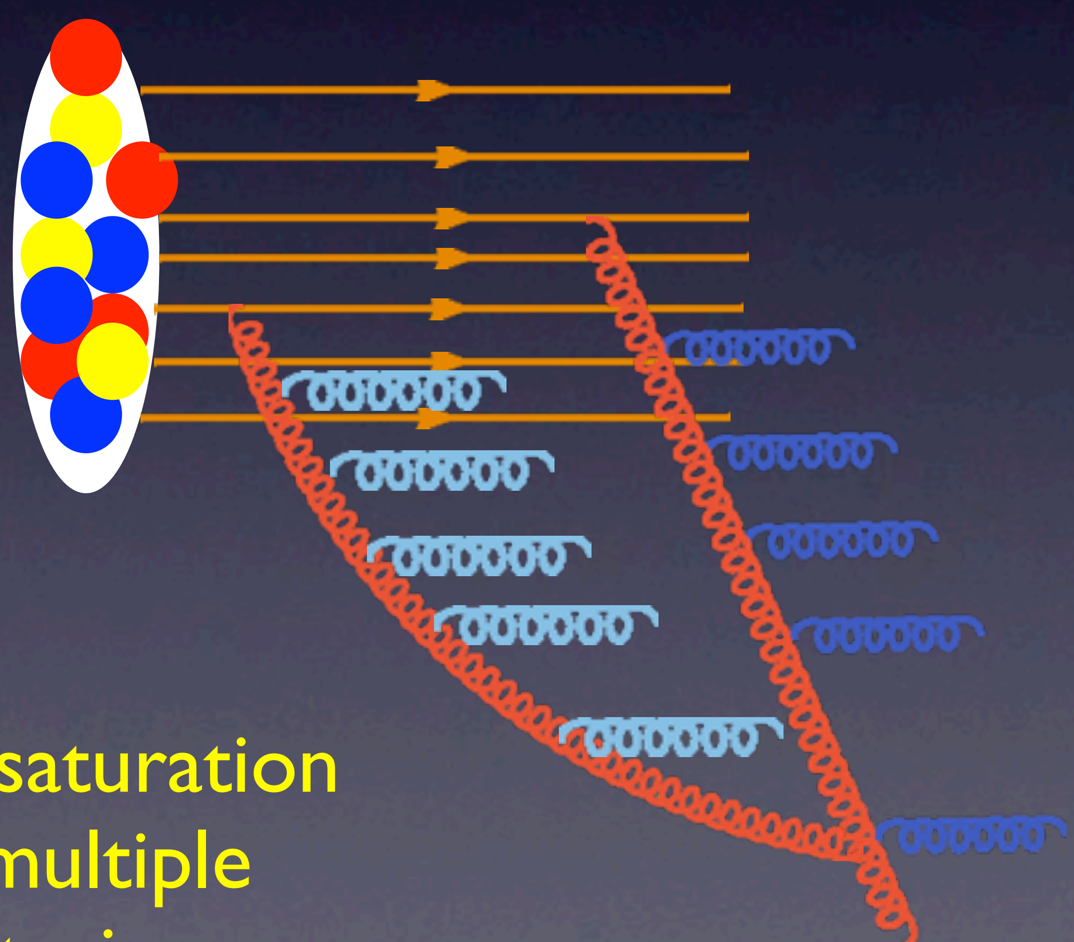

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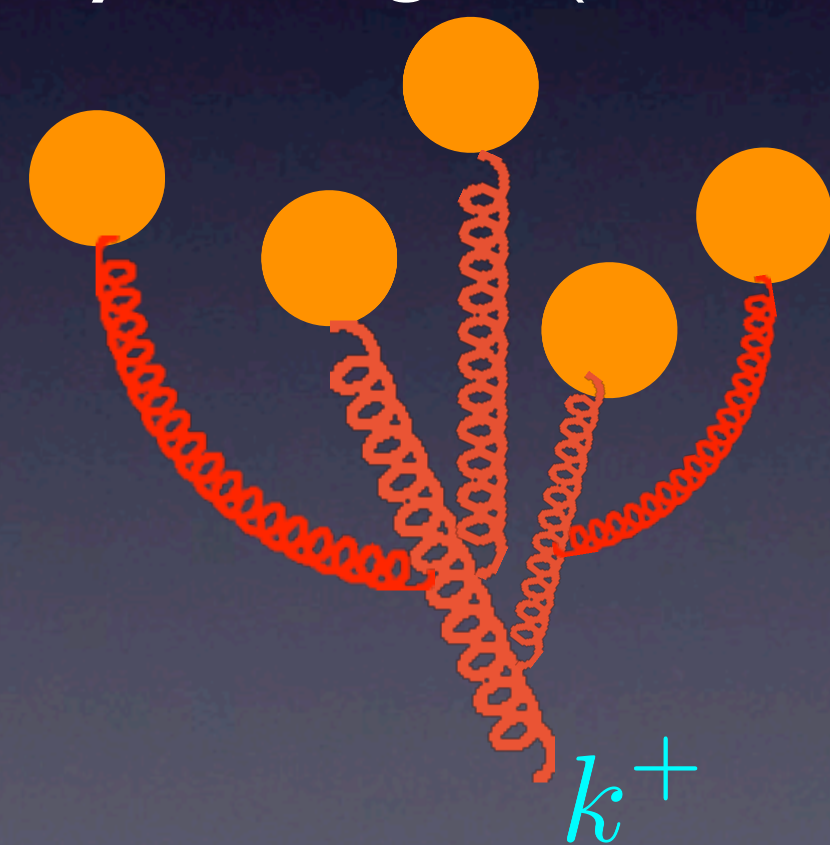


Parton saturation
as a multiple
scattering.

*L.McLerran,R.Venugopalan*

# Multiple scatterings

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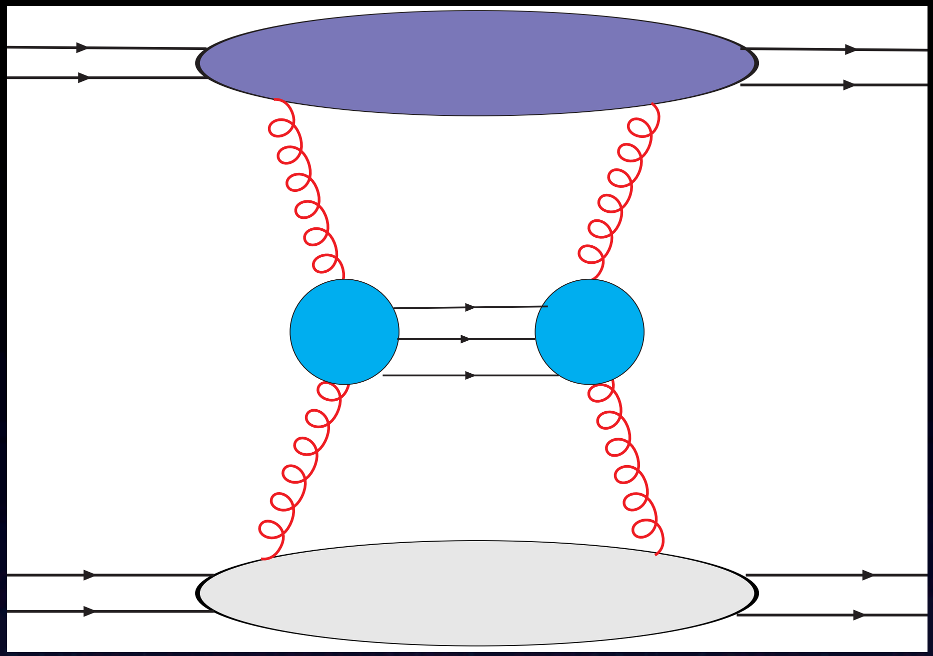
Single scattering: 2-point function, measures gluon density(number).



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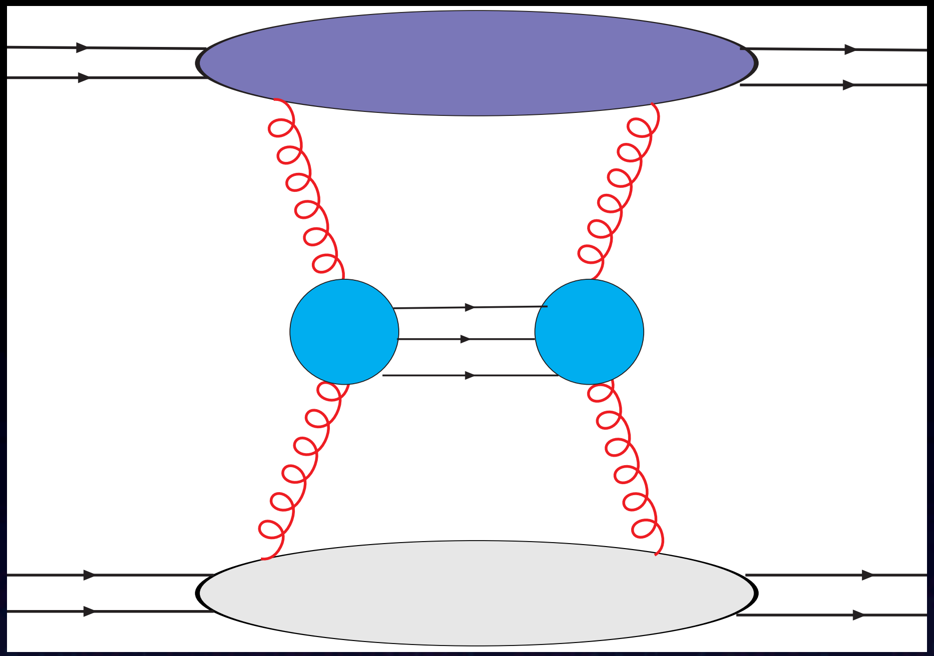
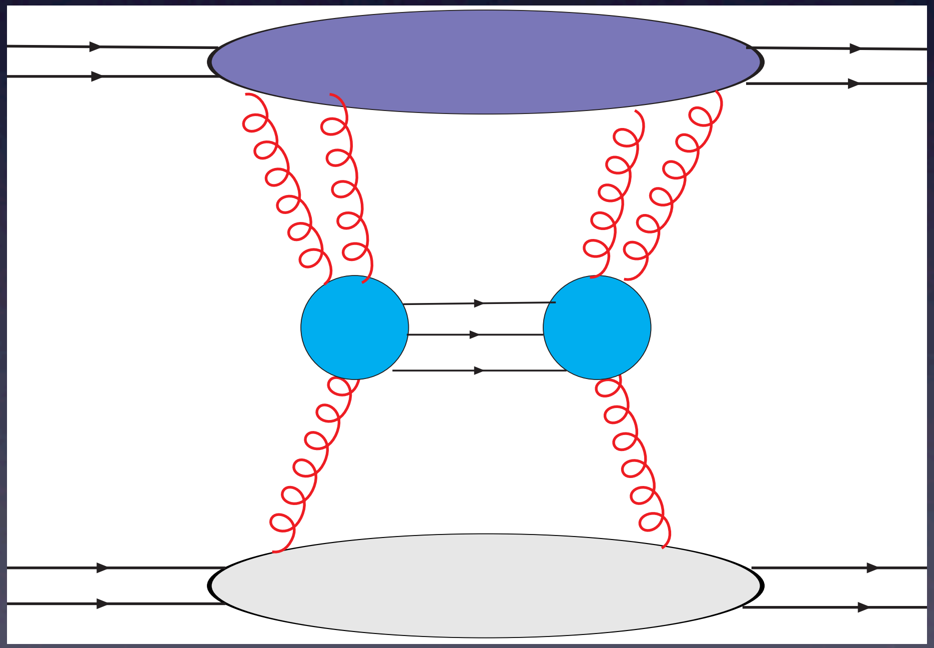


Double scattering: 4-point function, measures correlation.



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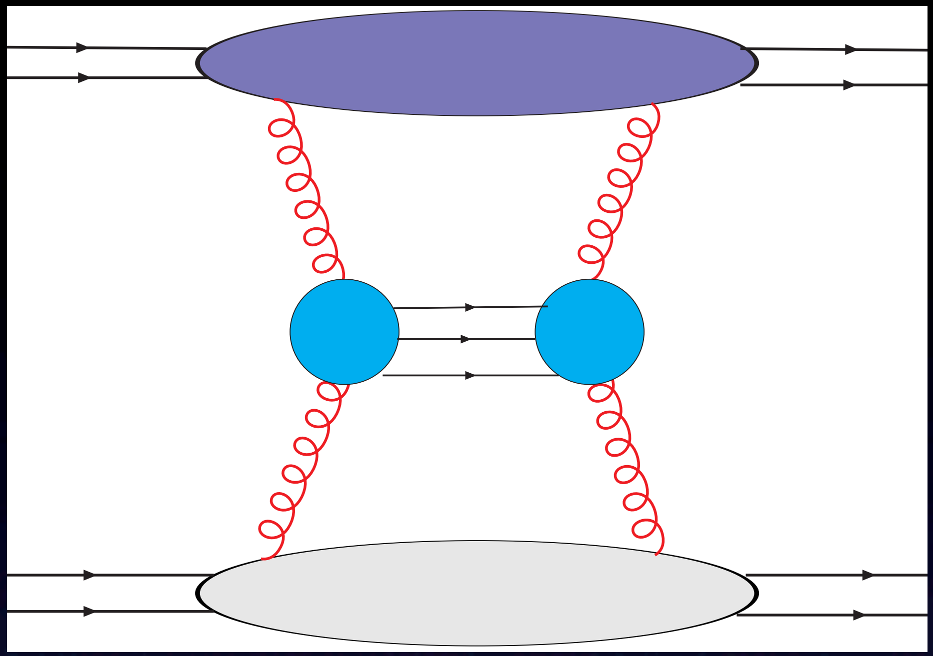

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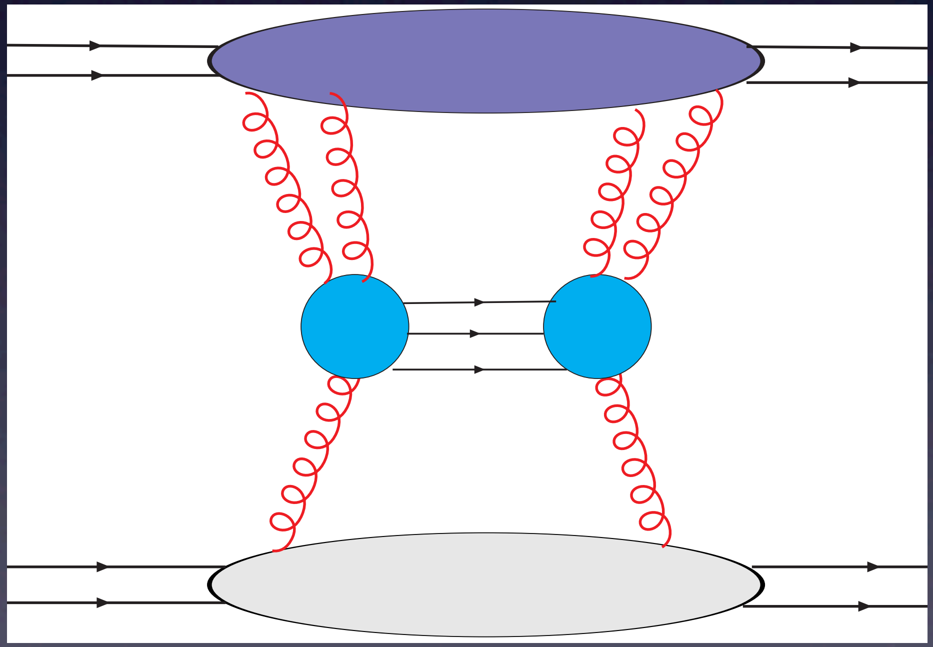

Color Glass Condensate: an effective theory derived from QCD in the limit of high energies and high densities which systematically incorporates higher correlators.

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For small densities in the projectile the evolution equation reduces to the BFKL evolution equation for the gluon density.

# The evolution equation becomes nonlinear in density

$$\frac{df_g(x,k_T^2)}{d\ln 1/x} = \frac{\alpha_s N_c}{\pi} \int d^2k'_T \mathcal{K}(k_T, k'_T)\ f_g(x, k'_T)$$

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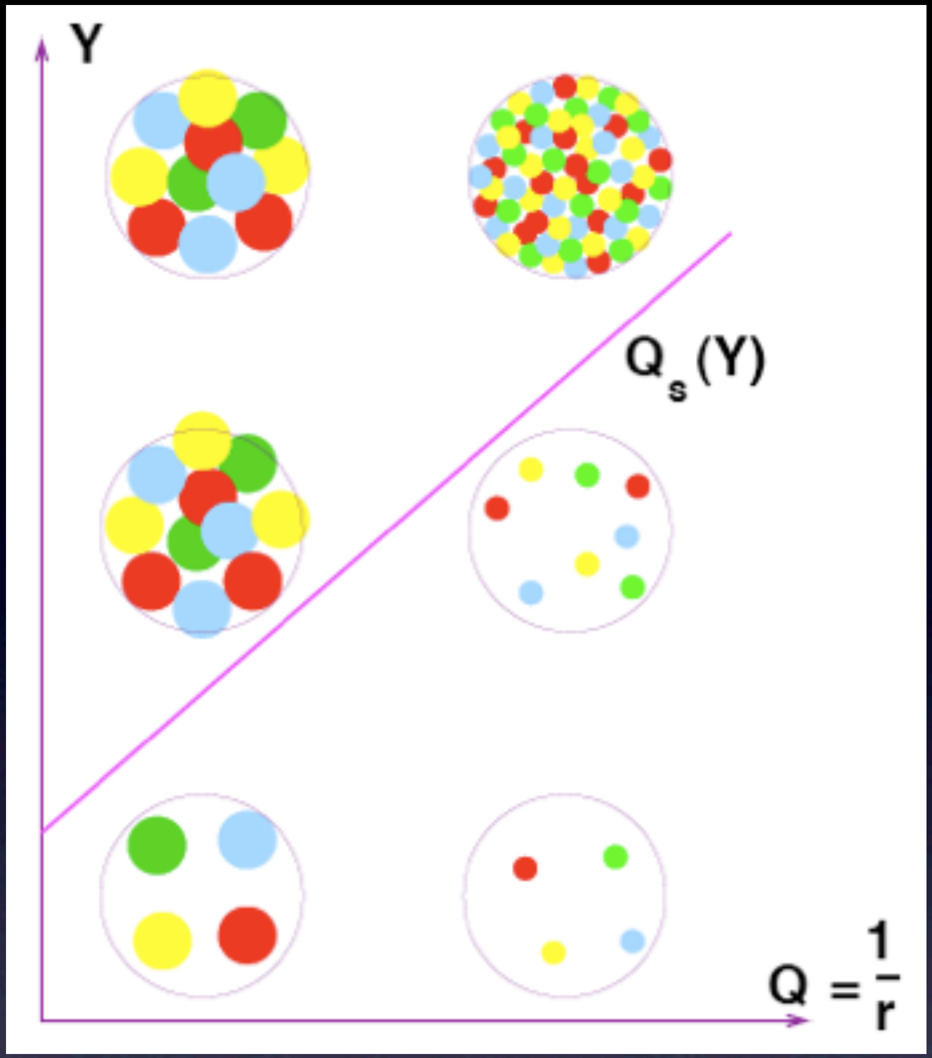
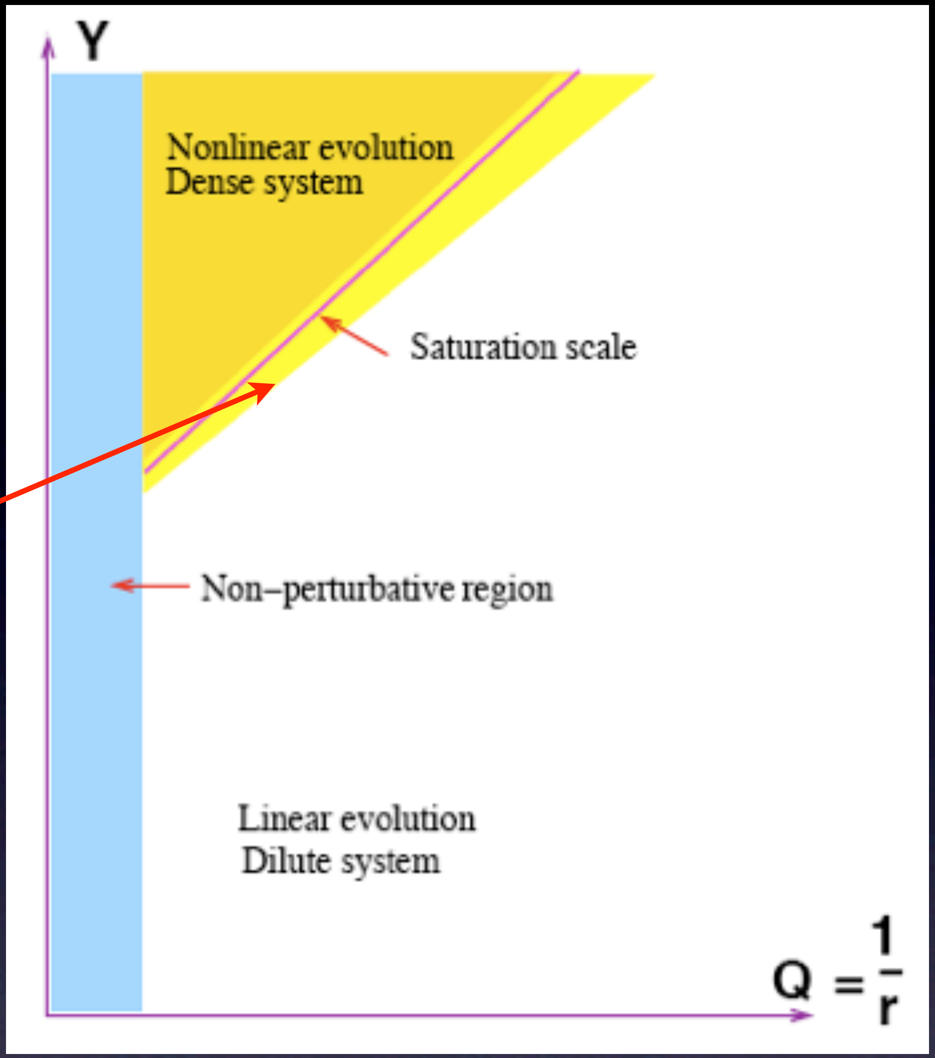
***parton saturation***

# Saturation scale




transition between dilute and dense is rather smooth

extended region of transition




saturation scale $Q_s(x) \sim x^{-\lambda}$ Dynamically generated

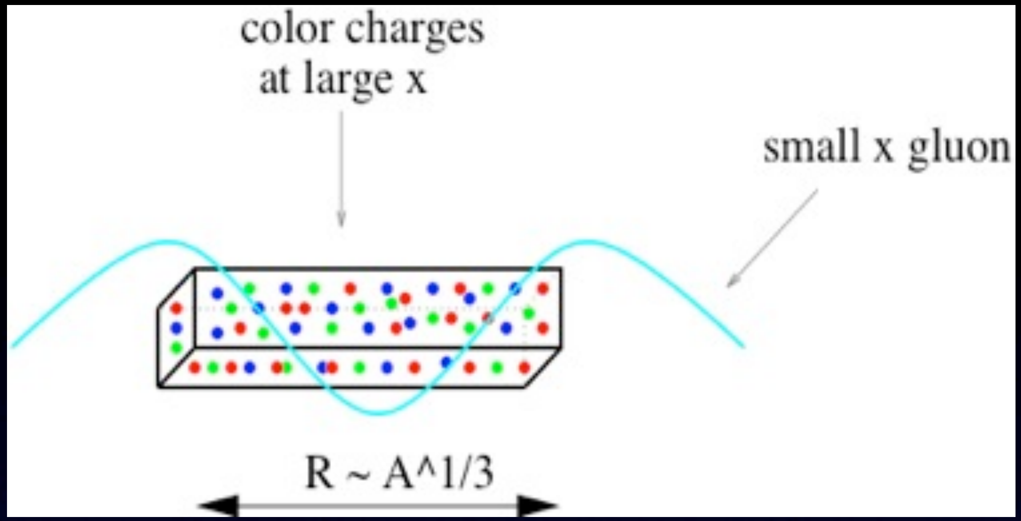
At small x this scale can become large: $Q_s(x) \gg \Lambda_{QCD}$

Note: when running coupling is included, the saturation scale provides a natural regularization of the strong coupling.

# Saturation scale grows with A

- Probes interact over distances $L \sim \dfrac{1}{2m_N x}$

- For $L > 2R_A \sim A^{1/3}$ high-energy probes interact coherently across nuclear size. Very large field strengths.



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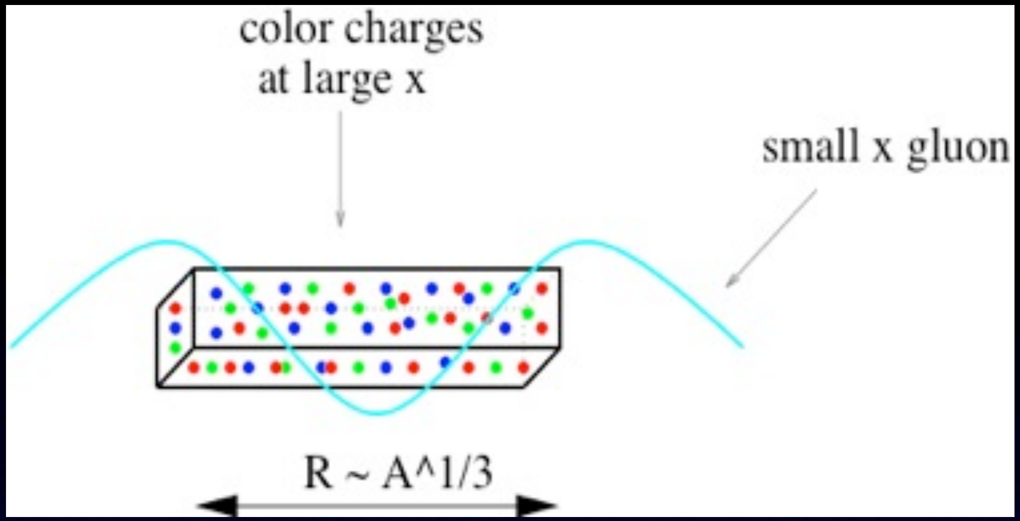


Pocket formula:

$$Q_s^2(x, A) \sim Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

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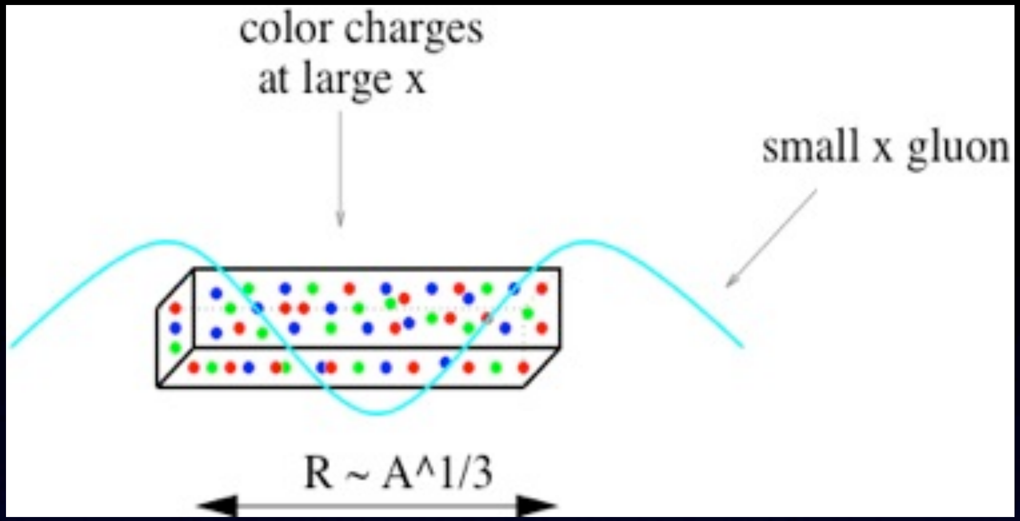


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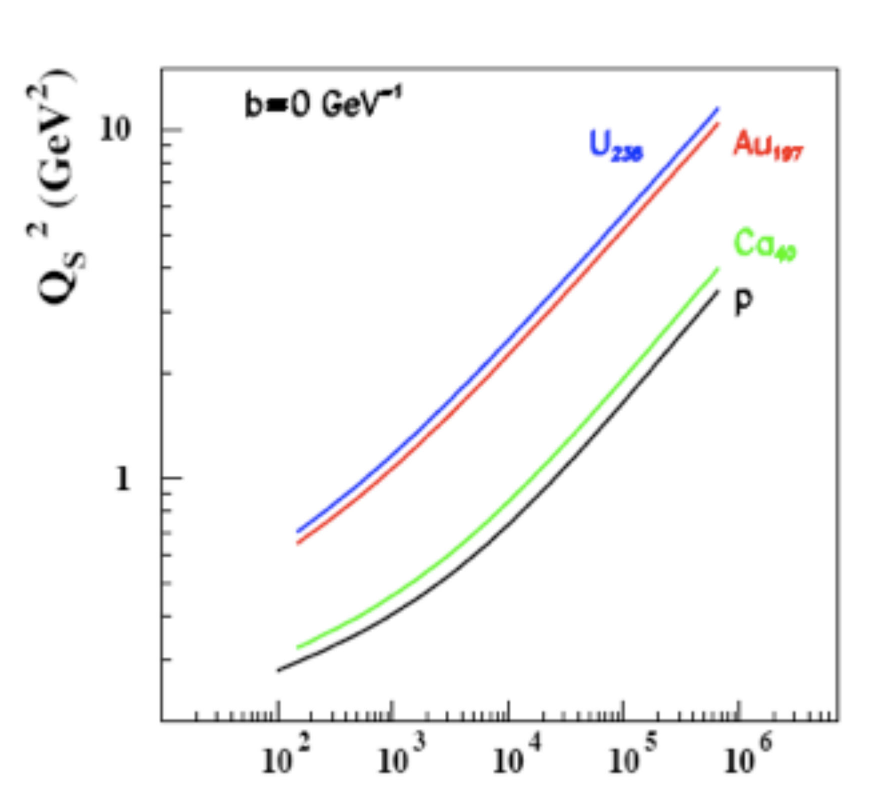
Scattering off nuclei: Saturation is reached for smaller energies due to the enhancement from A.

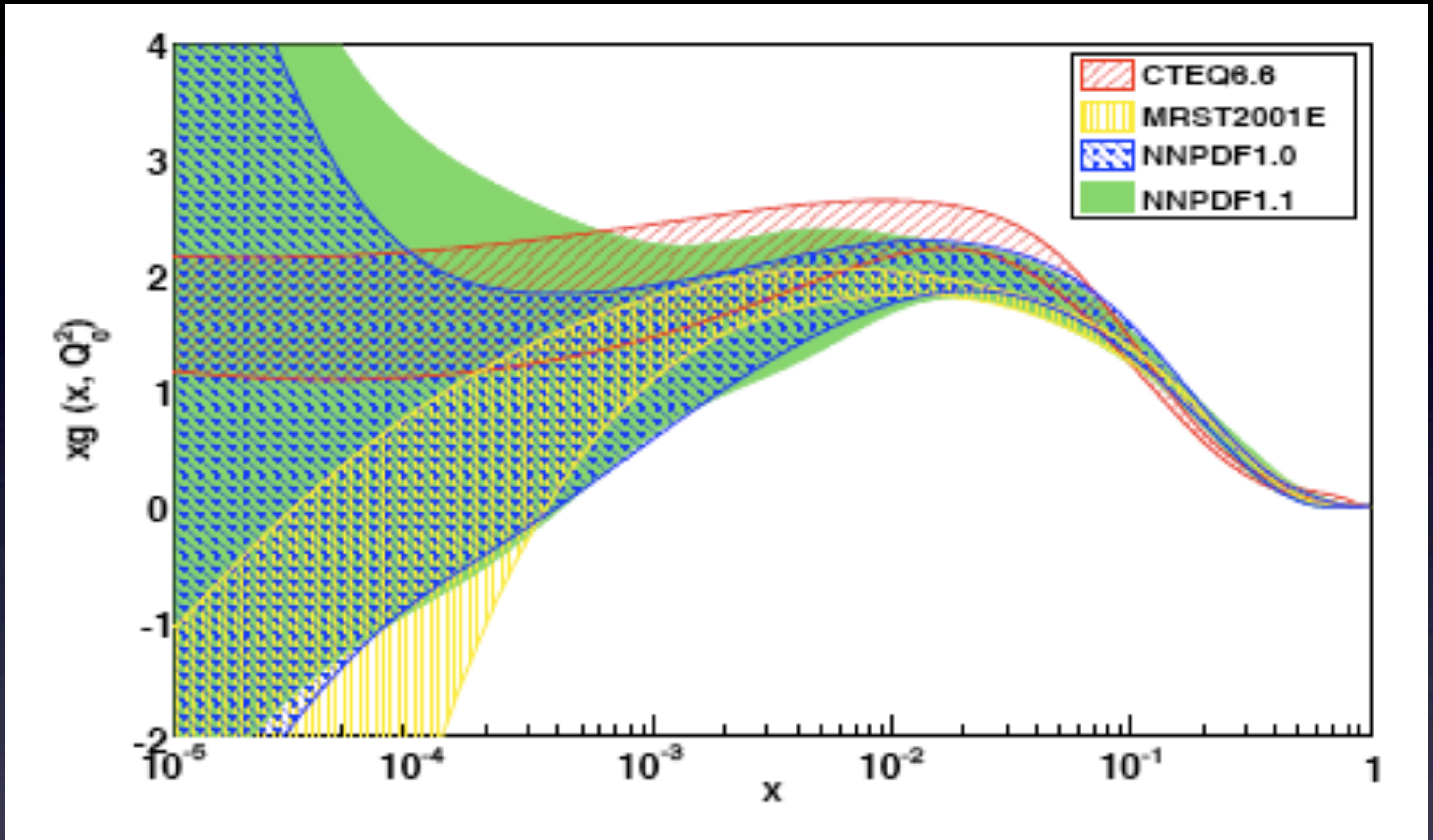



*Kowalski, Teaney*

# Hints of saturation at HERA and RHIC

# Hints of saturation at HERA

## Failure of standard description at low Q and x




Gluon density at small Q and small x.

$$Q^2 = 2\,\mathrm{GeV}^2$$

- Strange behavior of the gluon density for small x and small Q. Gluon density largely unconstrained. Implications for longitudinal structure function.
- Signal of the breakdown of linear DGLAP evolution?
- Higher twist/saturation, or resummation (of higher orders in ln 1/x) effects needed?

# Geometrical scaling vs data

*K.Golec-Biernat, M.Wusthoff*

Saturation model: a few parameter model with a saturation scale and scaling property built in:

$$N(r,x) = N(r^2 Q_s(x)^2)$$

DIS ep

$$\sigma^{\gamma^* p}(Q^2/Q_s^2(x))$$

At small x.

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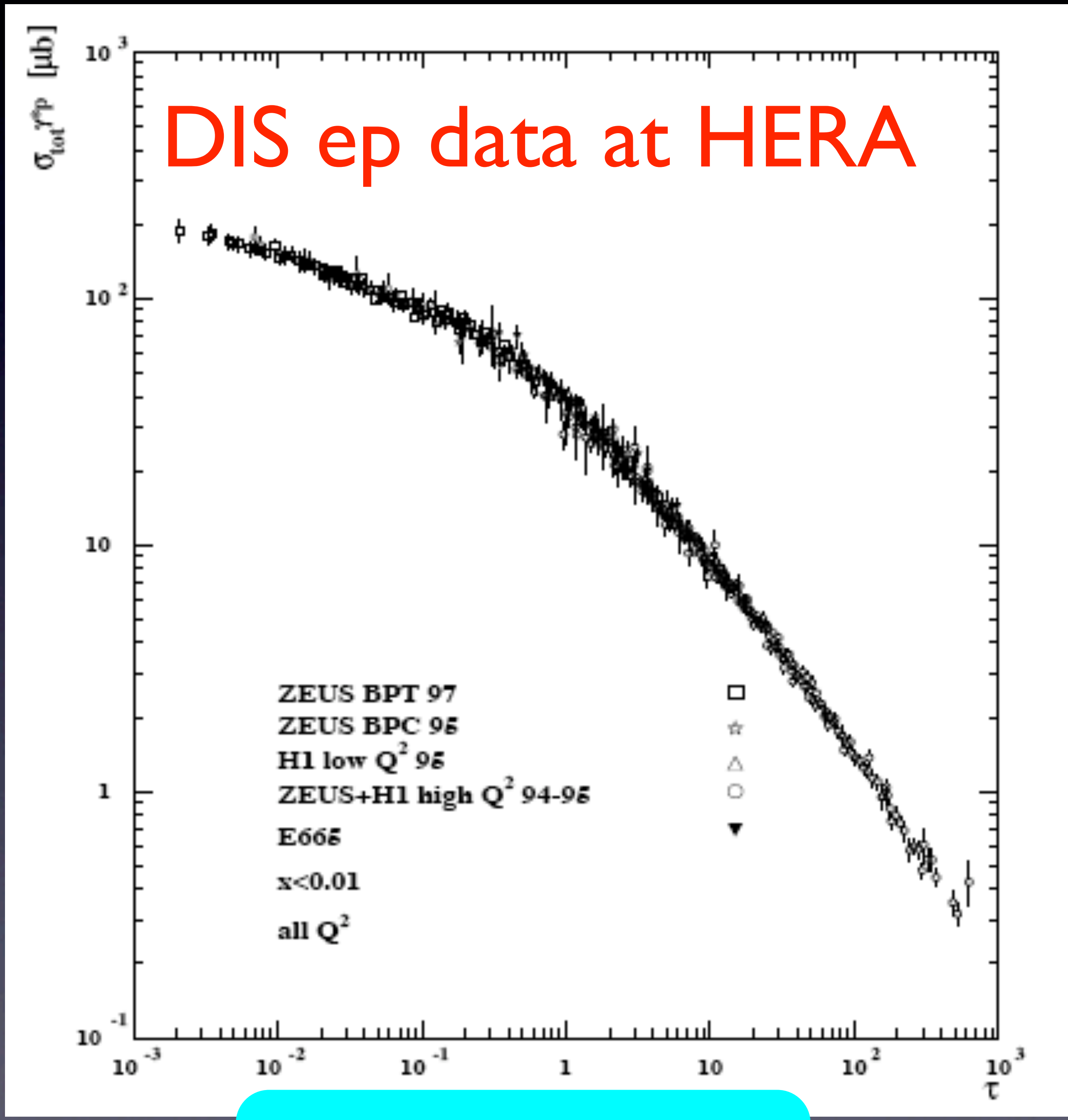


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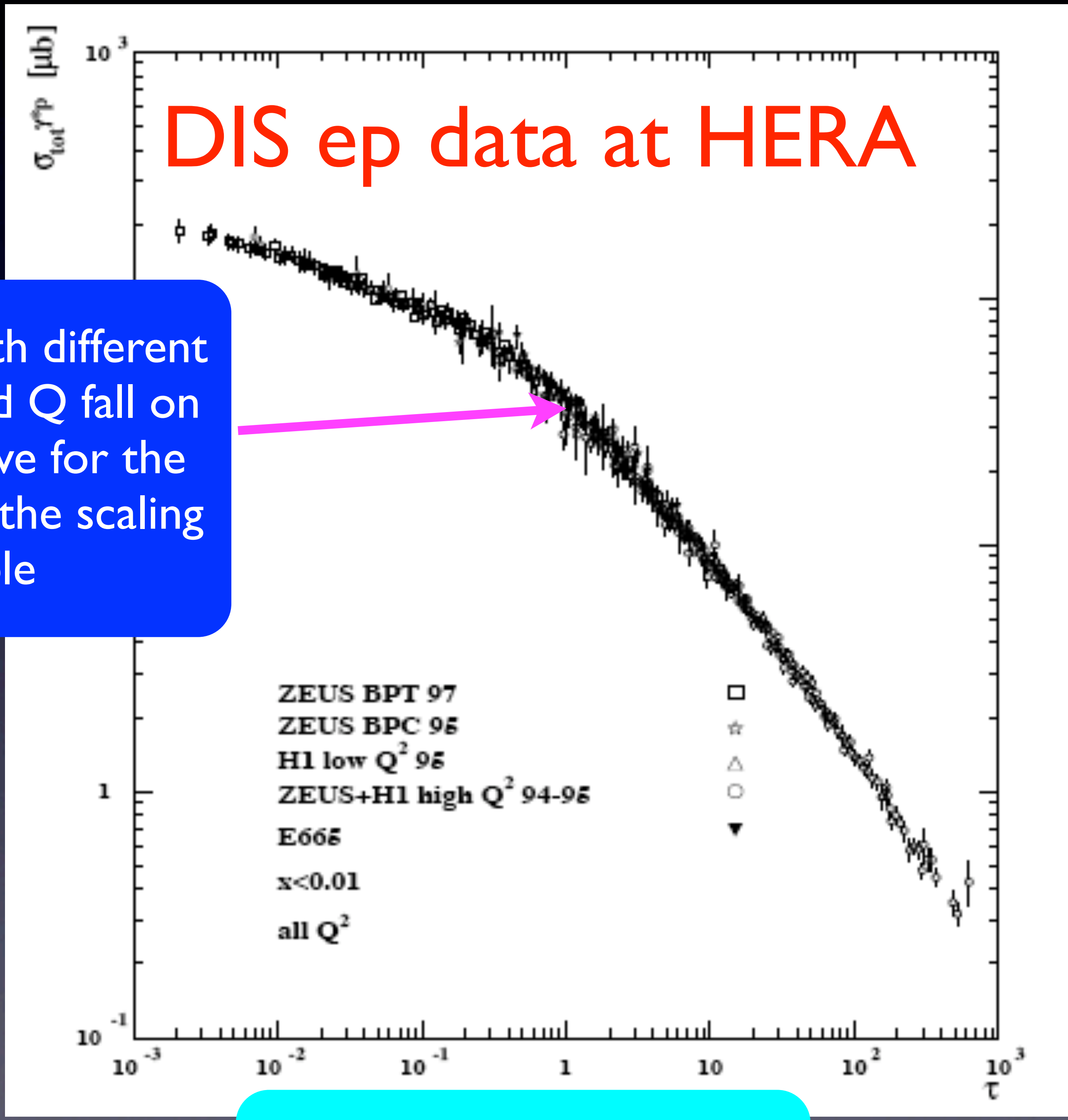


Datapoints with different values of x and Q fall on the same curve for the same value of the scaling variable

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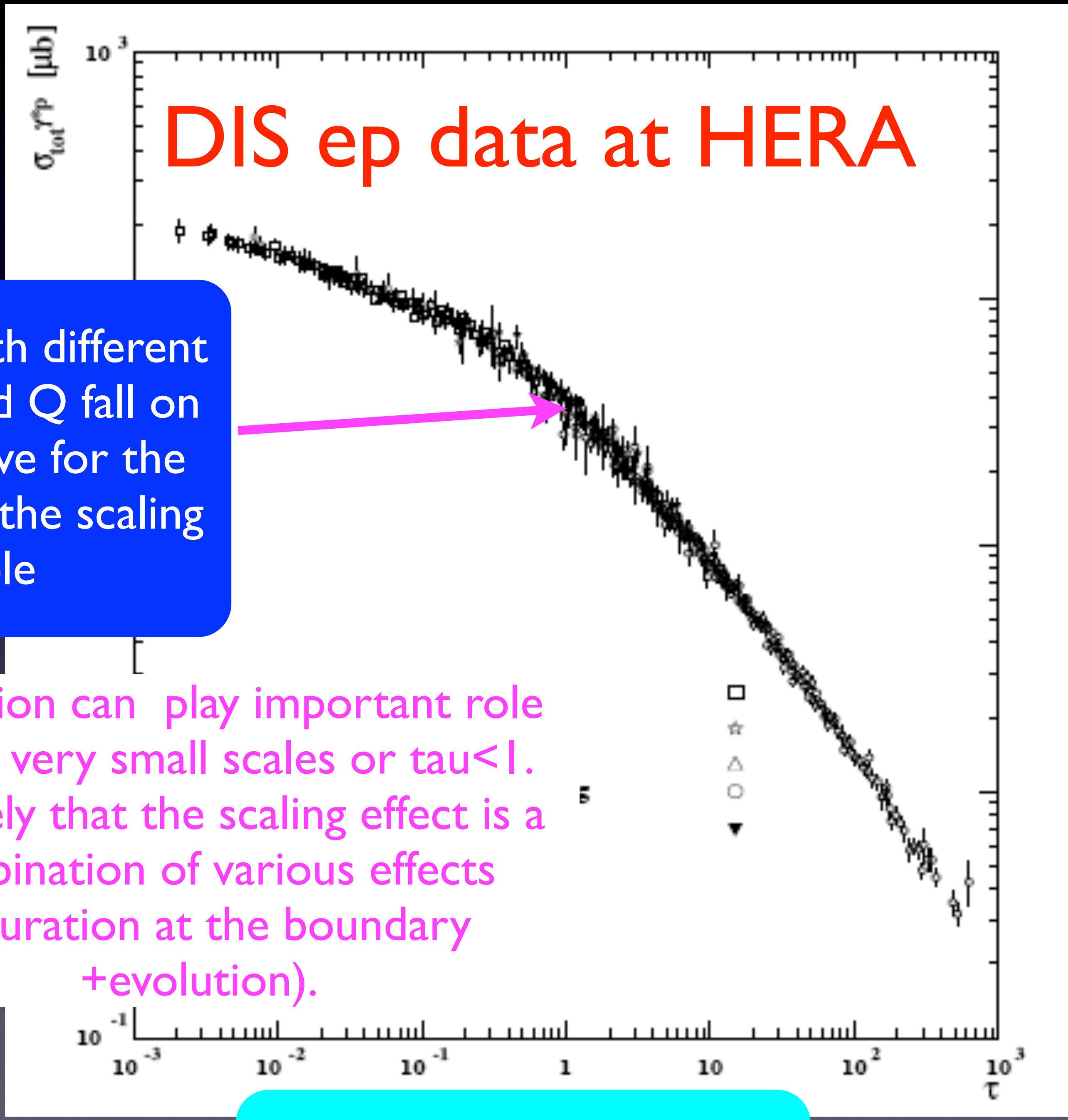
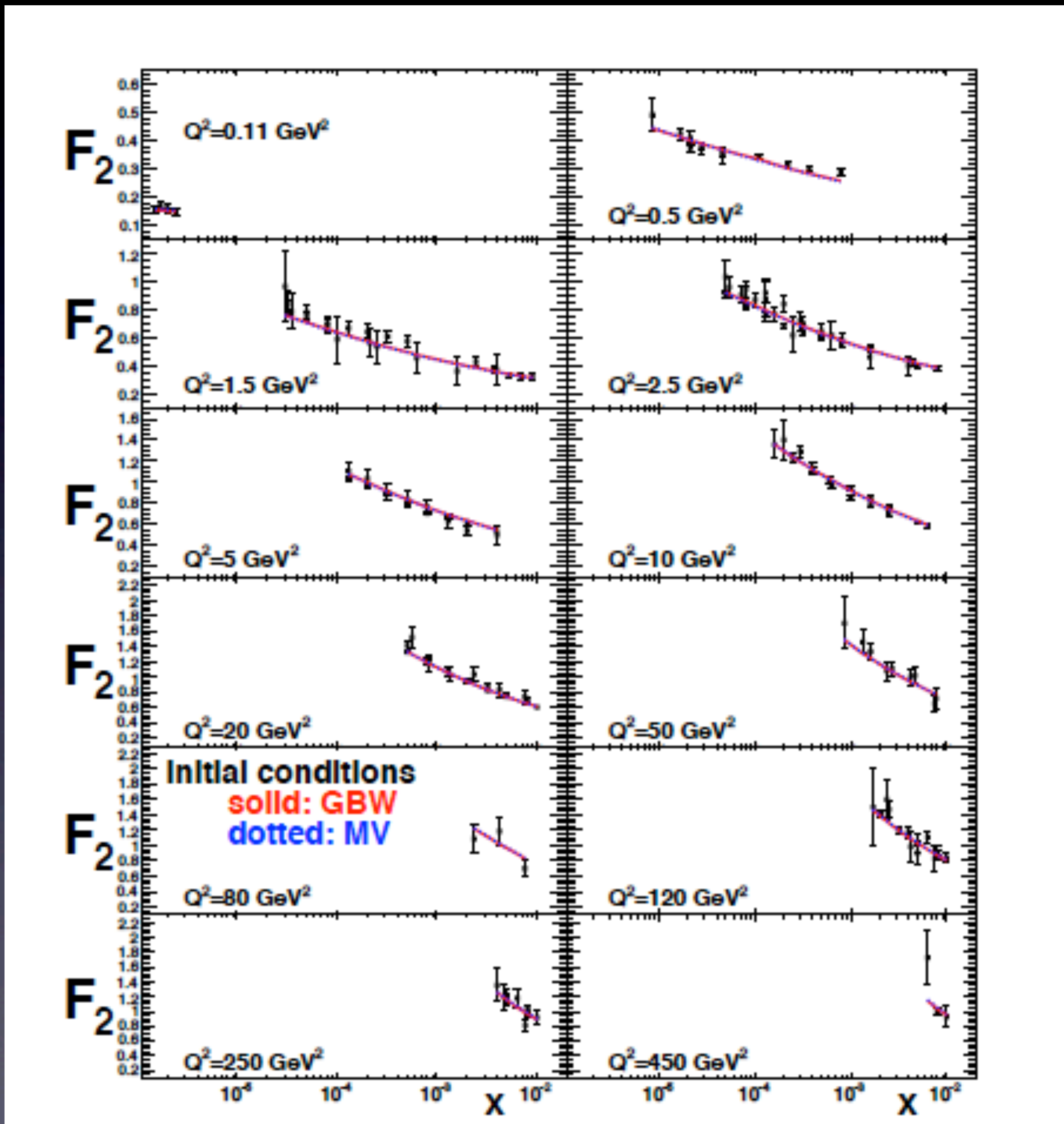



Datapoints with different values of x and Q fall on the same curve for the same value of the scaling variable

Saturation can play important role only at very small scales or tau<1. It is likely that the scaling effect is a combination of various effects (saturation at the boundary +evolution).

$$\tau = Q^2/Q_s^2(x)$$

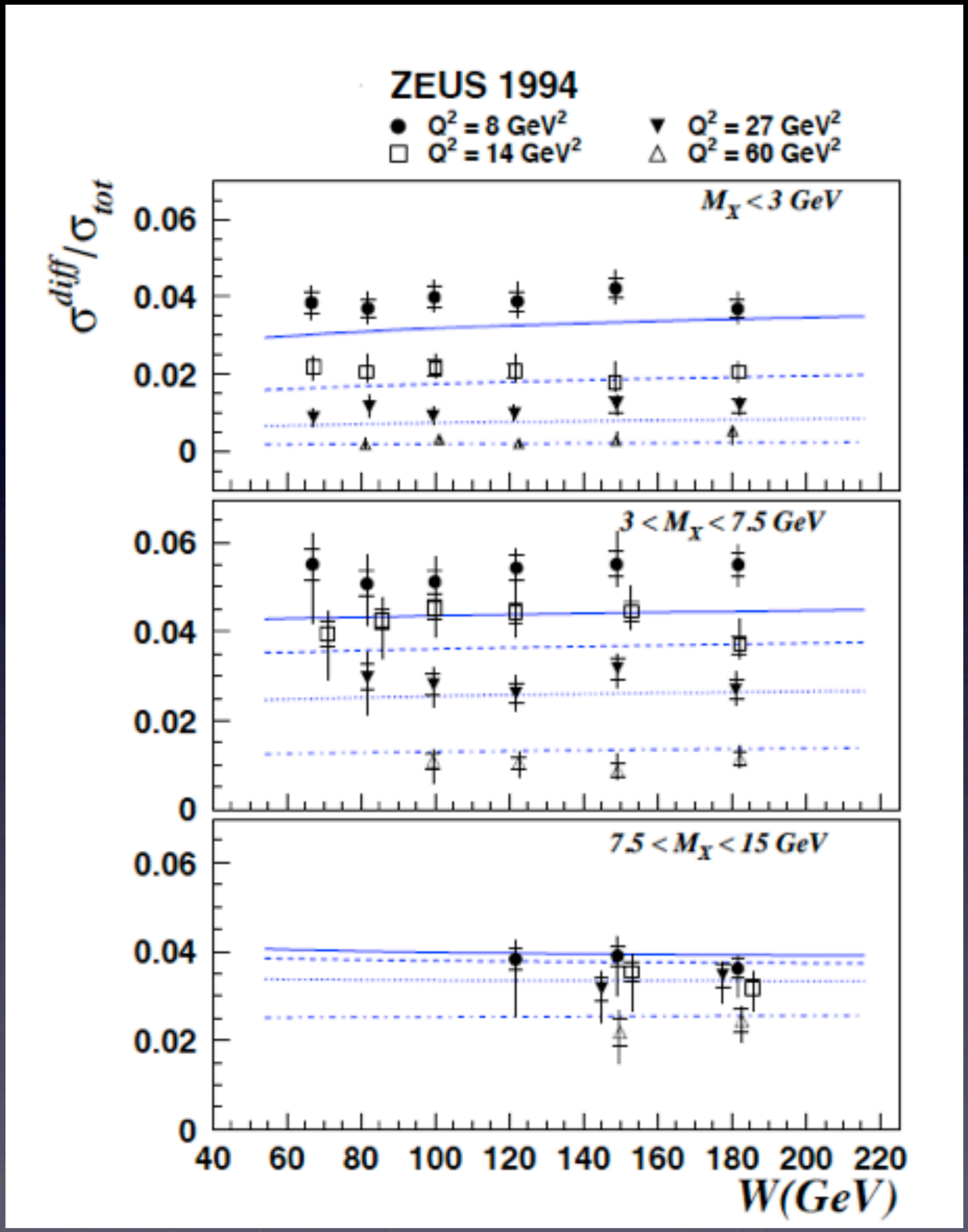
# Description of structure function F2 down to low photon virtualities




- Dipole models which are supplemented by the saturation desciber the experimental data very well.
- Down to very low scales.
- Transition from large to low Q is correctly reproduced by the models which include saturation.

*Albacete, Armesto, Milhano, Salgado*

# Diffractive to inclusive ratio in ep




Naively:

$$\sigma^{incl} \sim xg(x,Q^2)$$

$$\sigma^{diff} \sim xg(x,Q^2)^2$$

Therefore ratio should have non-trivial energy dependence.

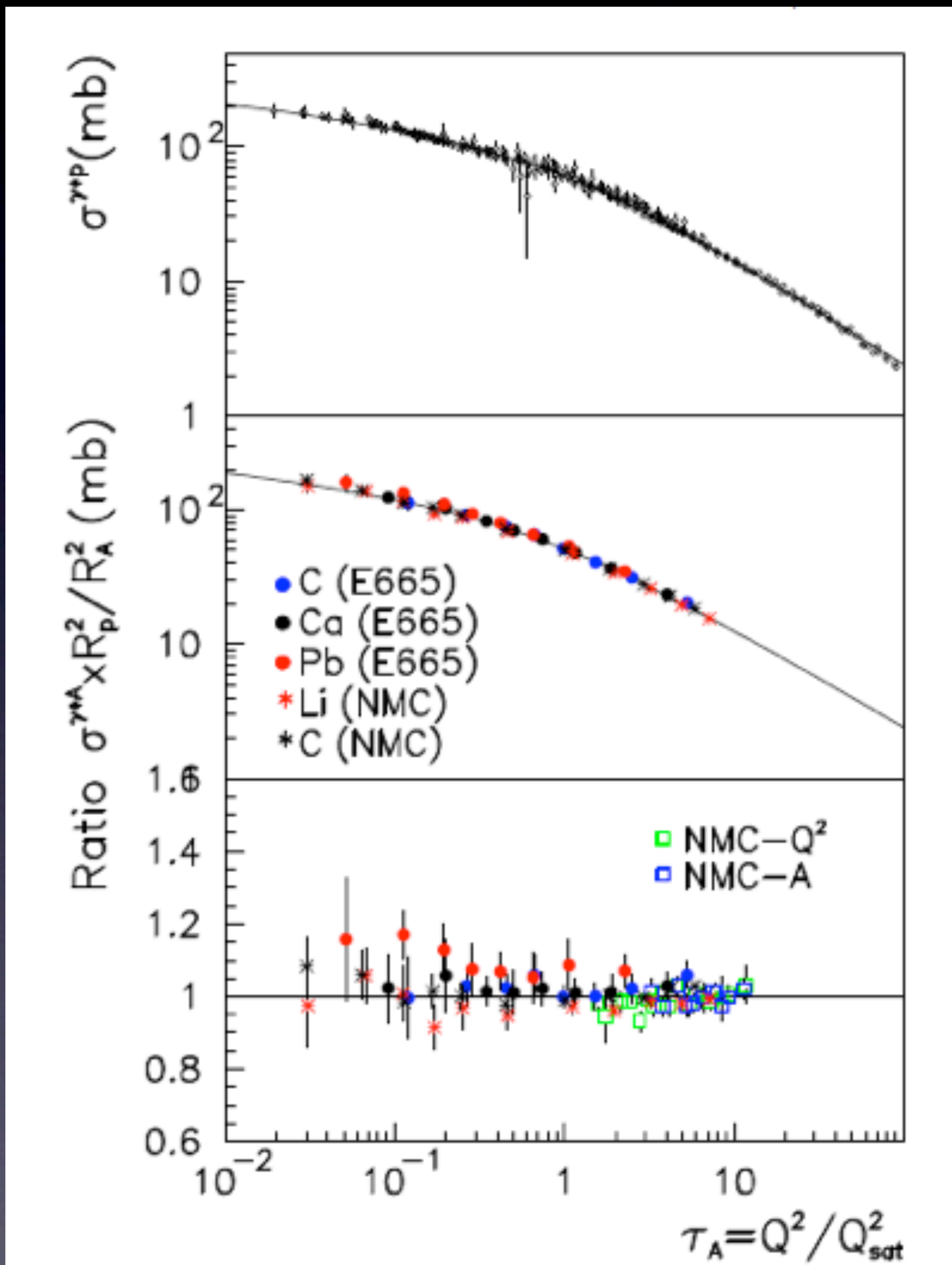
Constant ratio naturally explained in the saturation model.

Is it the same ratio and still constant at higher energy?

*Golec-Biernat, Wuesthoff*

# Hints from RHIC

Multiplicites in AA:




Saturation scale in nuclei

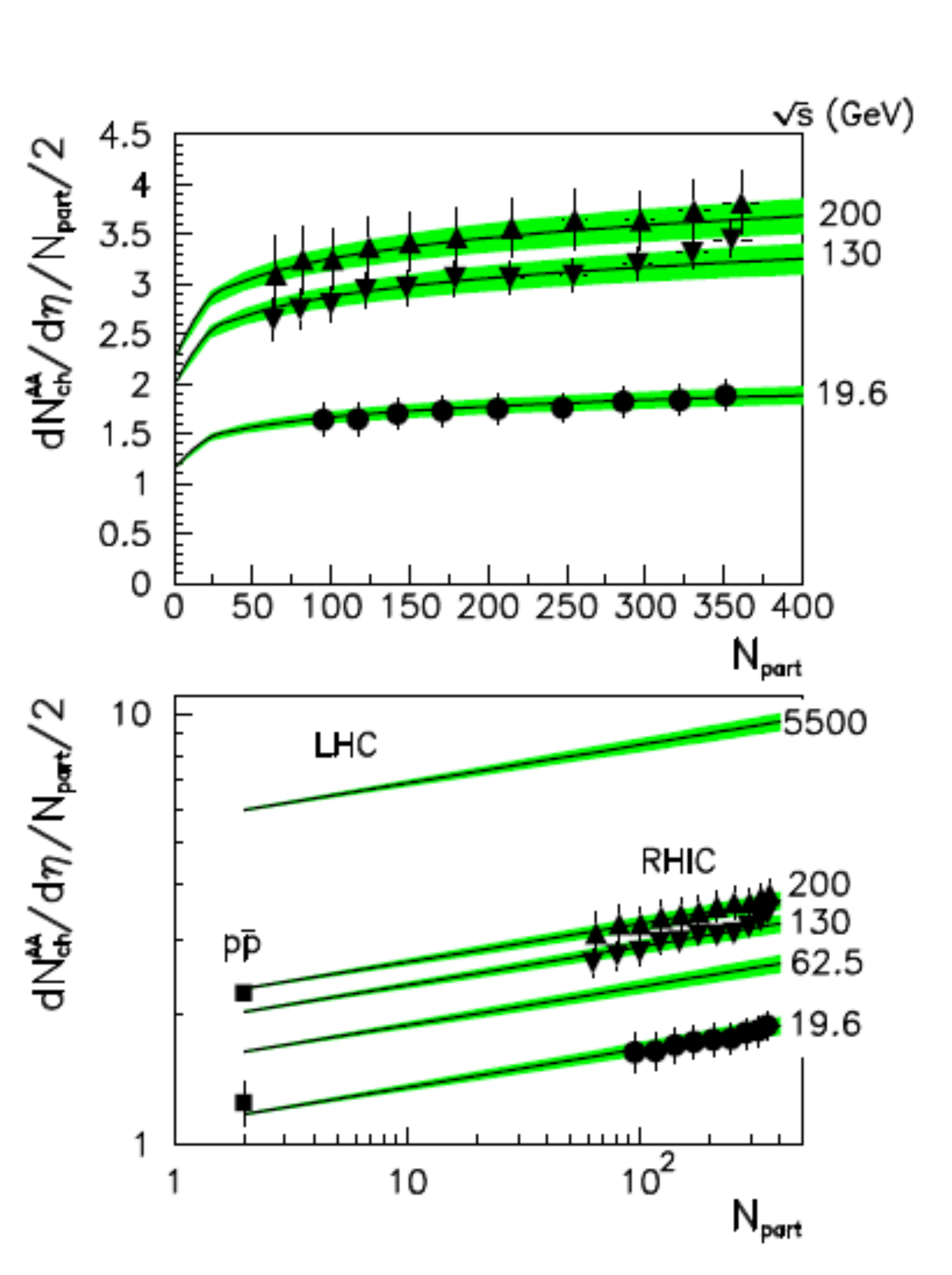
$$Q^2_{s,A}(x) = Q^2_{s,p}(x)\left(A\frac{R_p^2}{R_A^2}\right)^{\delta}$$

Extension of geometric scaling and saturation picture to nuclei.

Very good description of different kinds of nuclei (though limited statistics).

*Nestor Armesto, Carlos A. Salgado, Urs Achim Wiedemann*

# Multiplicites in AA




Nestor Armesto, Carlos A. Salgado, Urs Achim Wiedemann

$$\frac{dN^{AA}}{d\eta}(N_{part}, \sqrt{s})$$

Using CGC type of picture, kt factorization, supplemented by the centrality dependence.

Very good description for range of energies and centralities.

Questions remain: why the description is so good at low energies?

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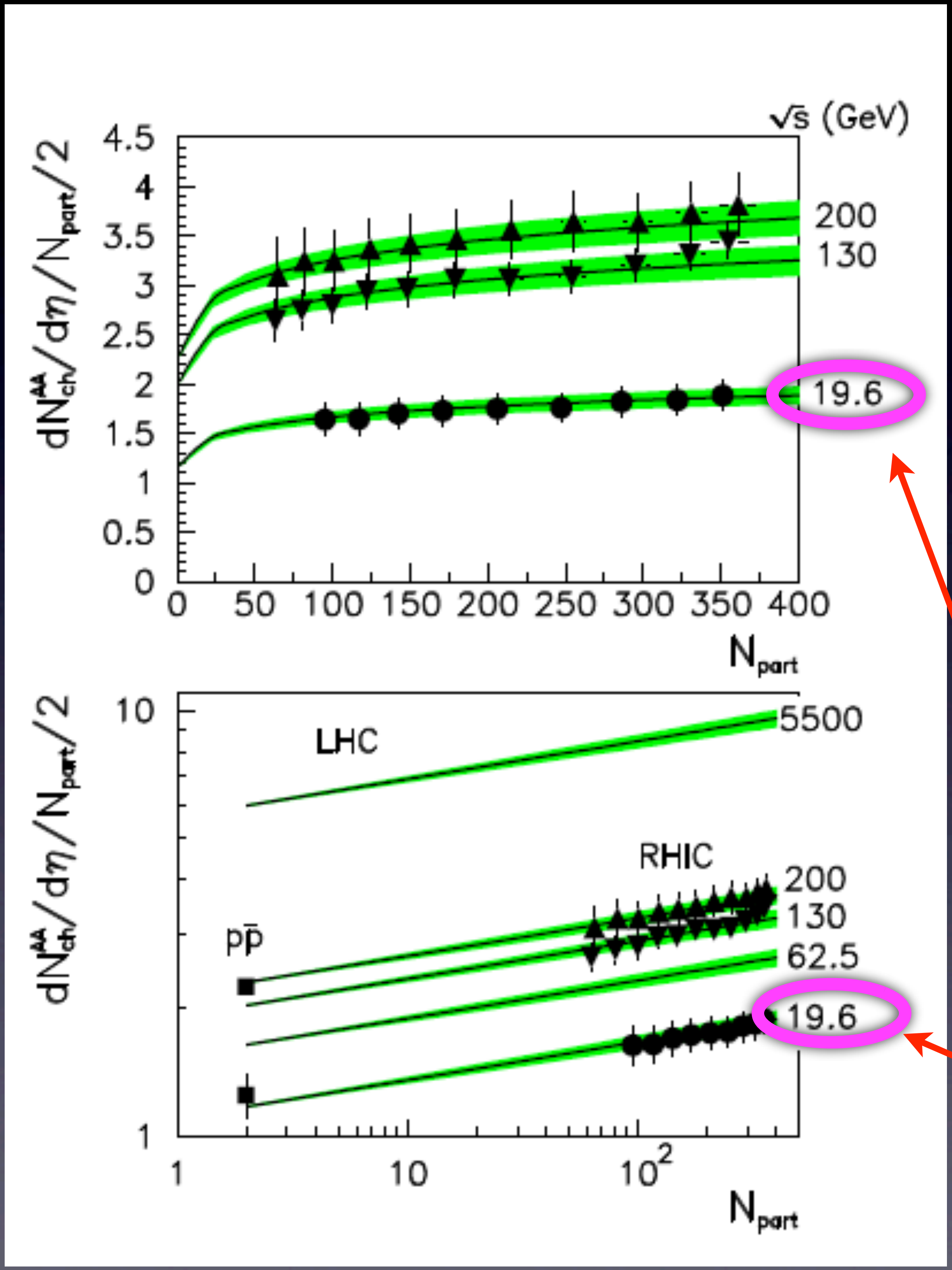


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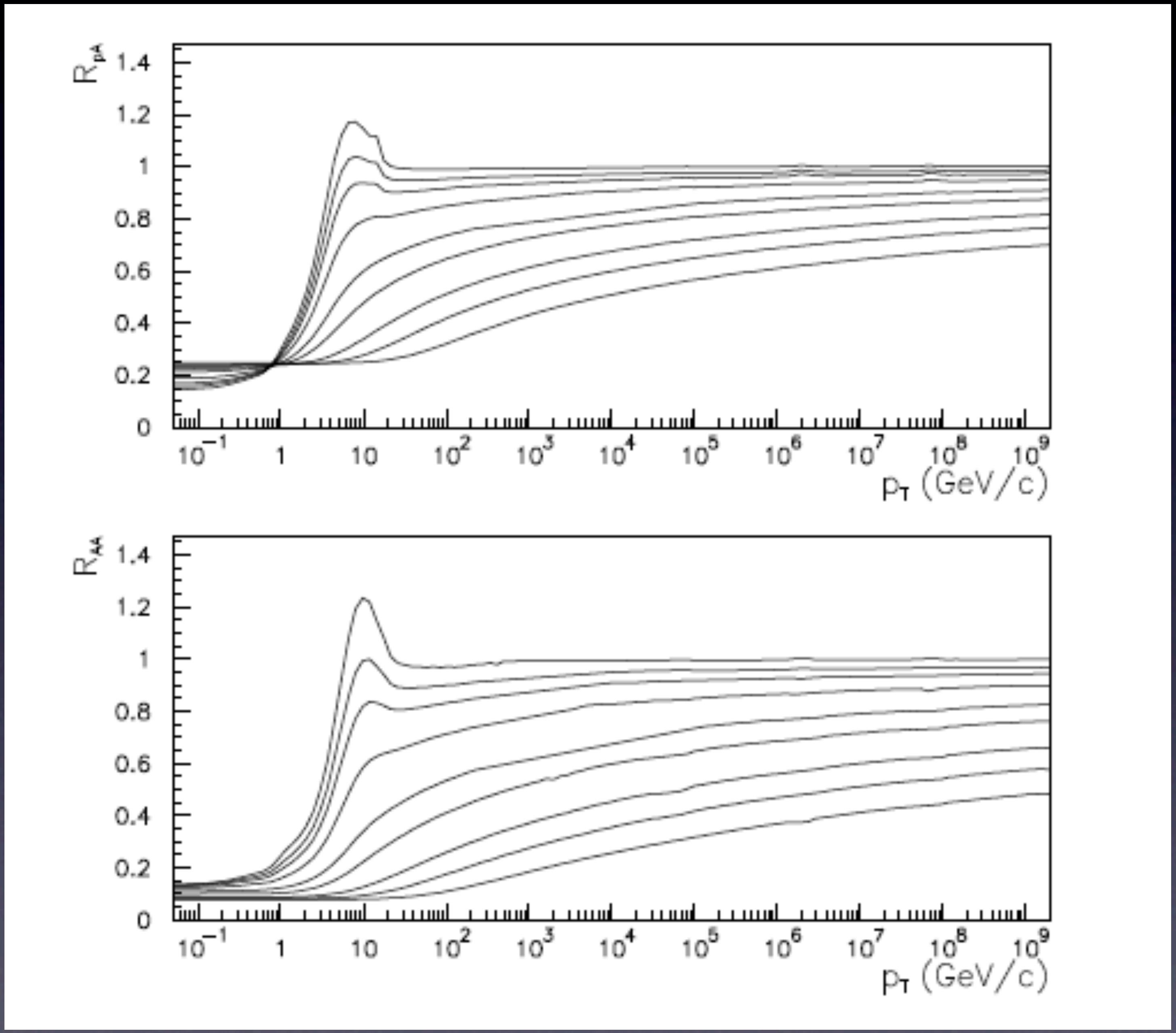
# Disappearance of Cronin enhancement



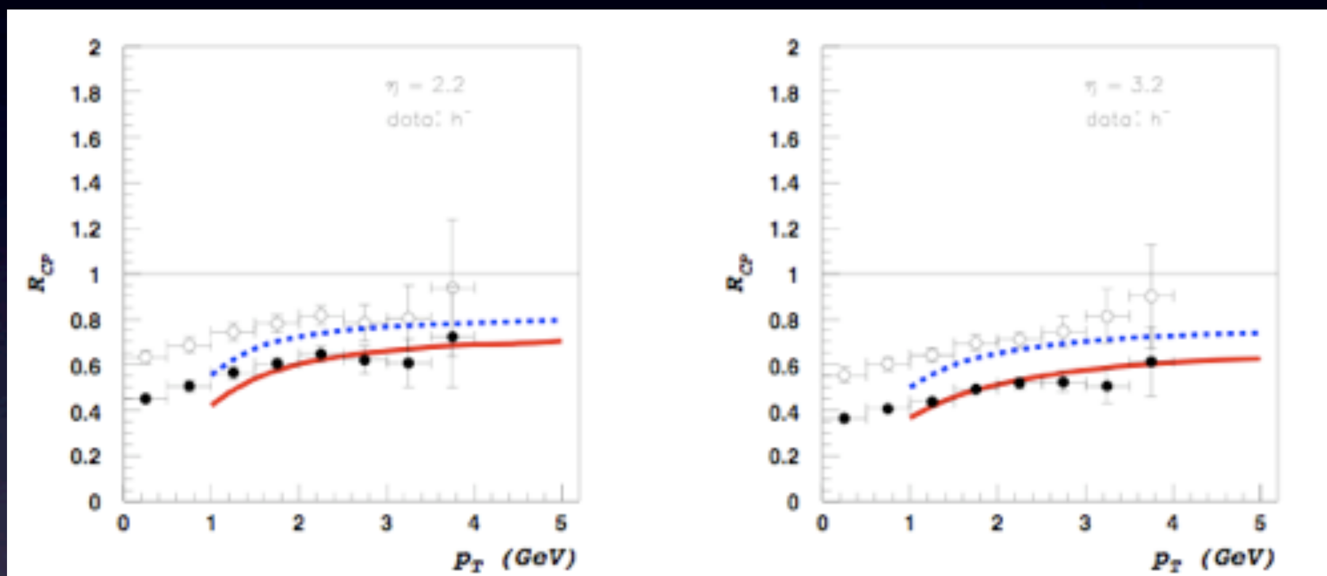

Ratios of pA and AA for particle yields as a function of transverse momenta normalized to pp spectra.

Small x evolution completely washes out the Cronin enhancement at forward rapidities.

*Javier L. Albacete, Nestor Armesto, Alex Kovner, Carlos A. Salgado, Urs Achim Wiedemann*

# Saturation: phenomenology at RHIC

$\eta = 2.2$ $\eta = 3.2$

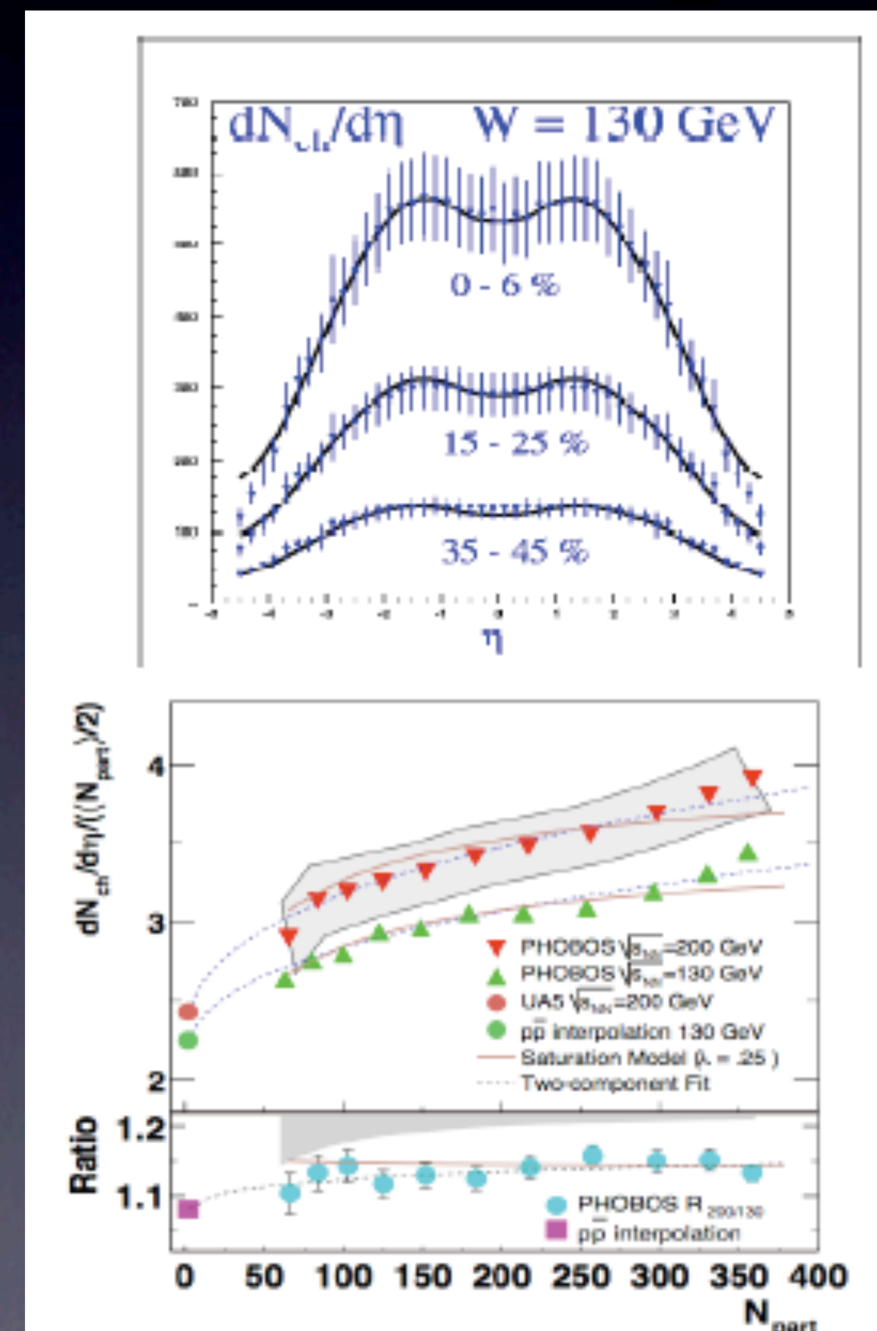



*Kharzeev, Kovchegov, Tuchin*

dAu : suppression of the transverse momentum distribution at forward rapidities

Very good agreement with the data!

Rapidity distributions

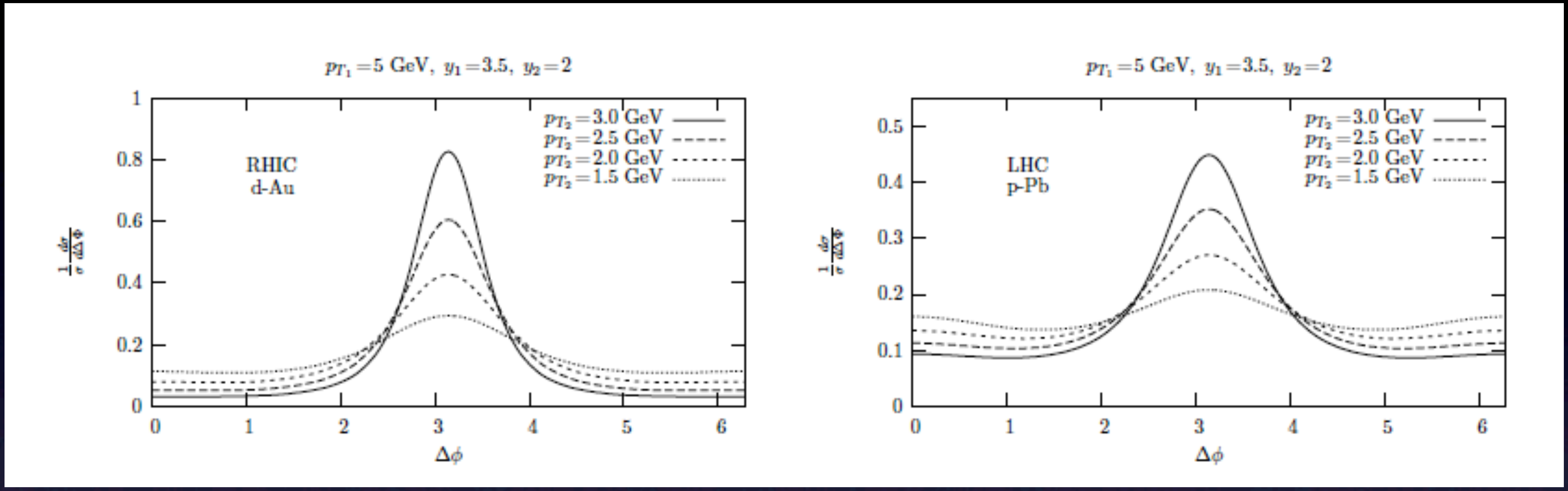



*Kharzeev, Levin, Nardi*

# Two particle correlations in pA/dA

## Predictions from CGC

$pA \rightarrow h_1 h_2 X$




*Cyrille Marquet*

Decreasing pt at fixed rapidity reduces the correlation in azimuthal angle. At LHC smaller values of x can be reached and so the decorrelation is bigger.

Is it really a signal of saturation? Dependence on centrality is crucial. x dependence should come out also from the linear type evolution: enhanced phase space, more emissions, more decorrelation.

Consistent with the signals from RHIC

# Why ep/eA collider?

- Electron as a clean probe of the proton/nucleus.
- Initial state measurement: direct extraction of the parton densities.
- If the energy of electron is changed, longitudinal structure function can be measured: direct constraint on the gluon density.
- Polarized structure functions.

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Polarized option.

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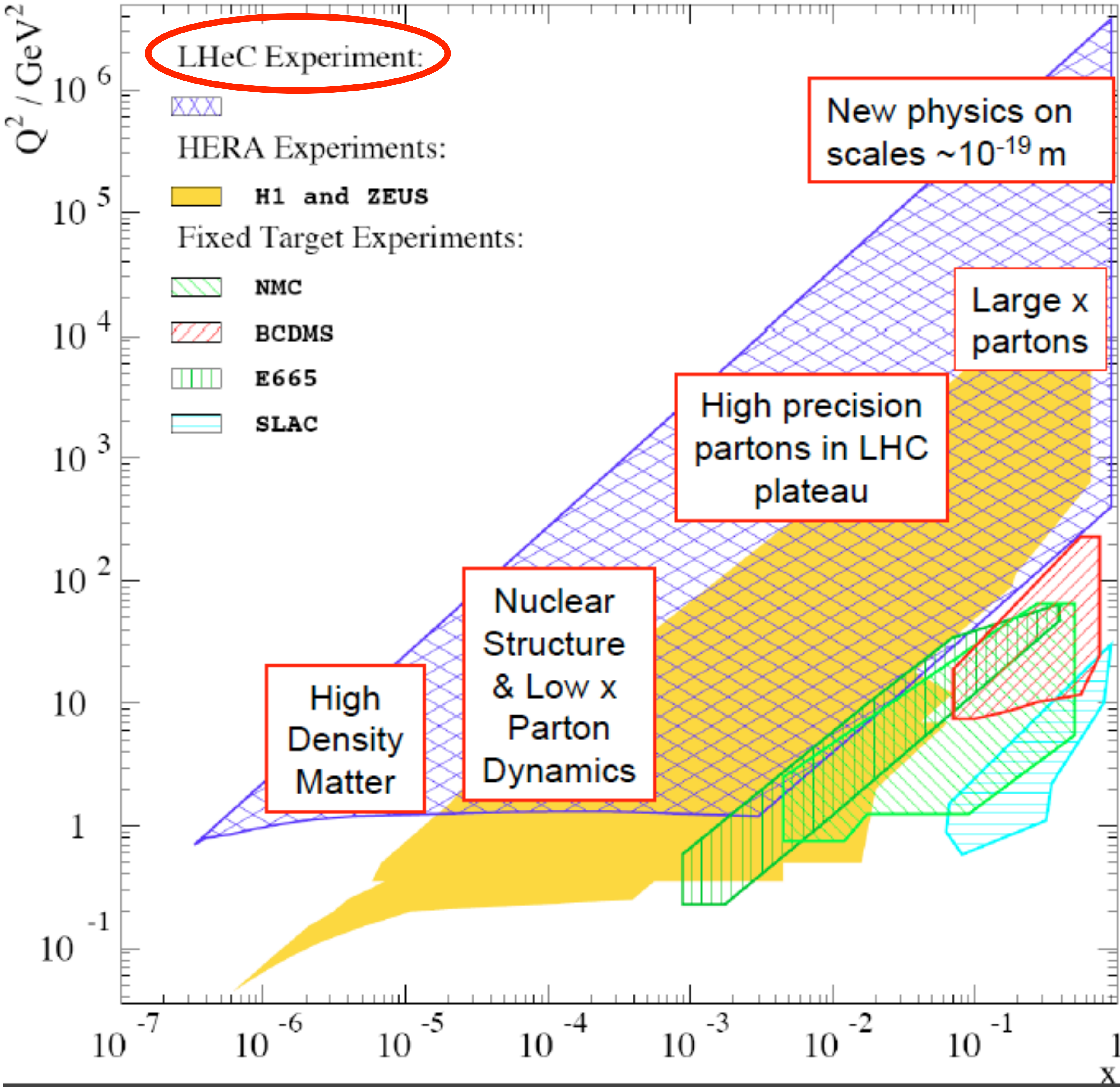
EIC and LHeC are complementary proposals

EIC: Focus on nuclei. Measurement of the nuclear pdfs. Polarized option.

LHeC: High energy. Extended kinematics. Nuclear option also possible.

# Kinematics & Motivation (140 GeV x 7 TeV)



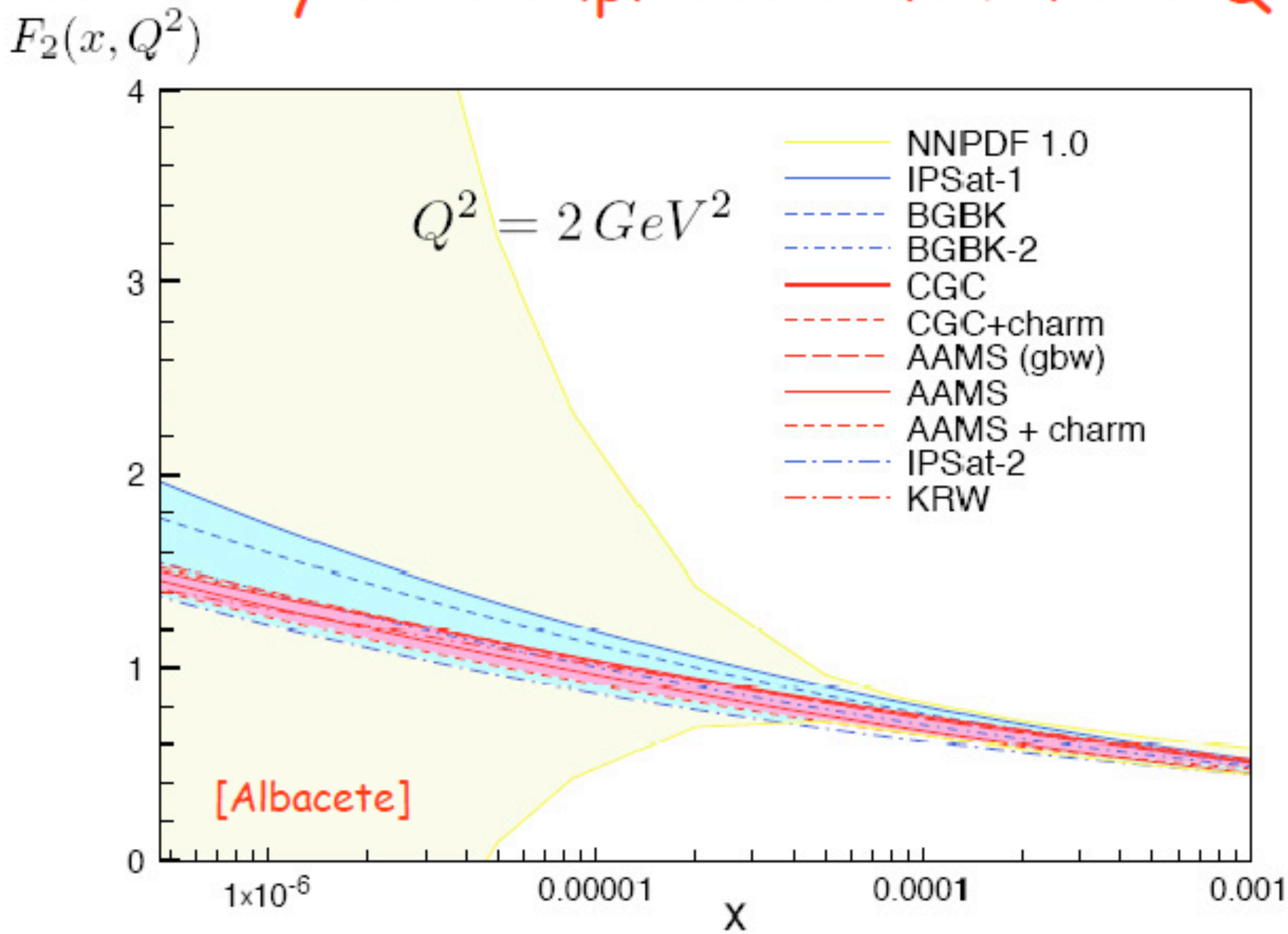

$\sqrt{s} = 2$ TeV

- High mass ($M_{eq}$, $Q^2$) frontier
- EW & Higgs
- $Q^2$ lever-arm at moderate & high x → PDFs
- Low x and eA Frontier → novel QCD …

$x \geq 5.10^{-7}$ at $Q^2 \leq 1$ GeV$^2$

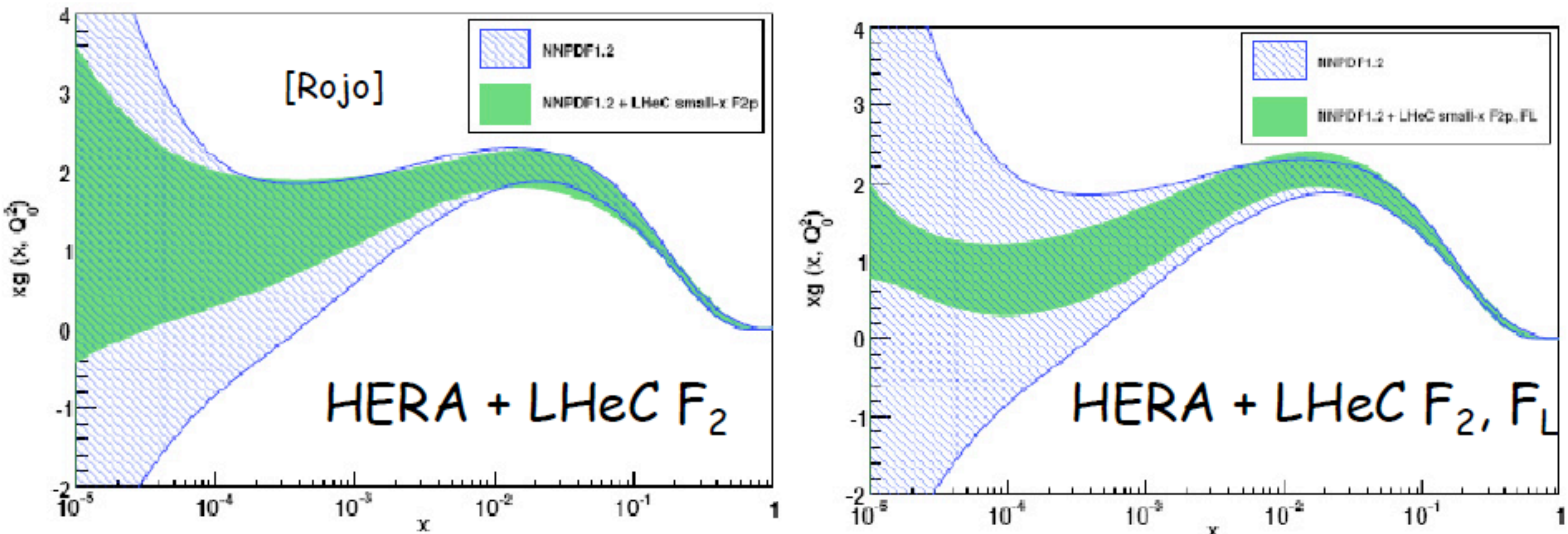
# Another look at Extrapolations of $F_2$

NNPDF parameter-free NLO DGLAP QCD fit …
uncertainty band explodes at low x and $Q^2$




Very wide range of possibilities allowed by pQCD …
… whilst retaining a good fit to to HERA data

# Constraining the Gluon with LHeC $F_2$ and $F_L$




$(Q^2 = 2\ \text{GeV}^2)$

Including LHeC data in NNPDF DGLAP fit approach ...

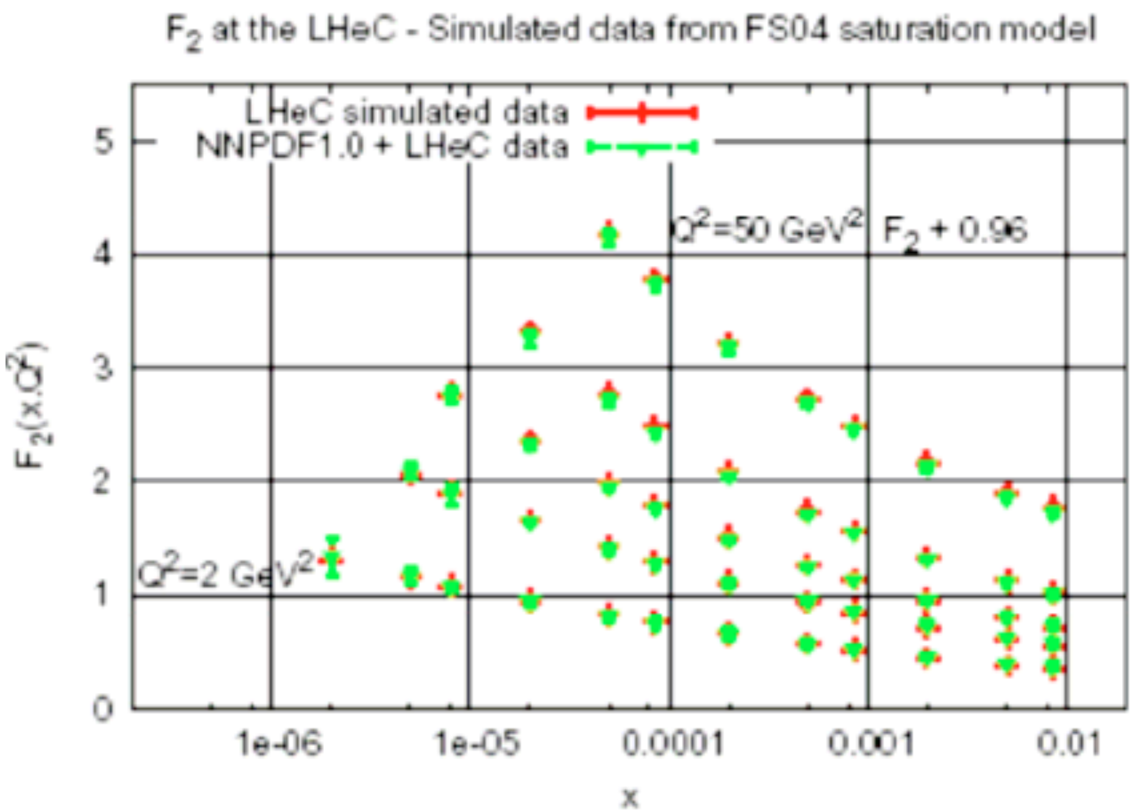
... sizeable improvement in error on low x gluon when both LHeC $F_2$ & $F_L$ data are included.

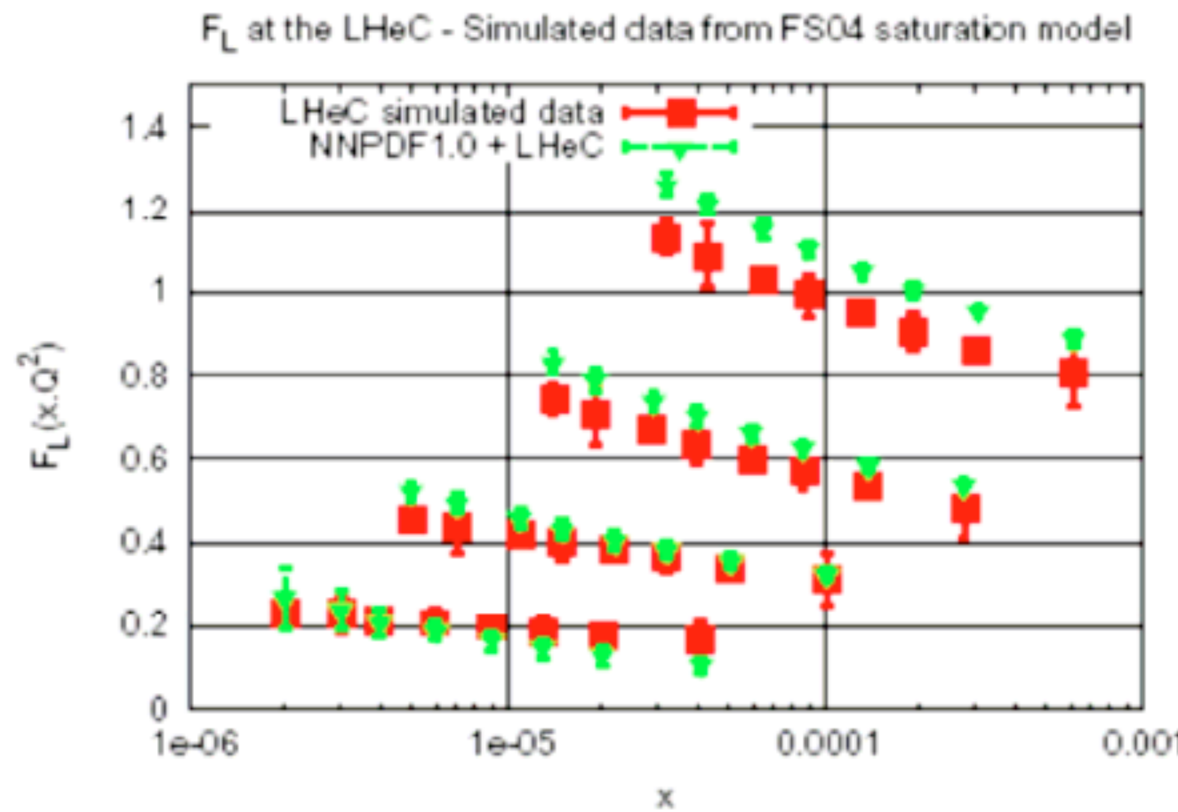
... but would DGLAP fits fail if non-linear effects present?

# Can Parton Saturation be Established @ LHeC?

Simulated LHeC $F_2$ and $F_L$ data based on a dipole model containing low x saturation (FS04-sat)...

... NNPDF (also HERA framework) DGLAP QCD fits cannot accommodate saturation effects if $F_2$ and $F_L$ both fitted




[Rojo]

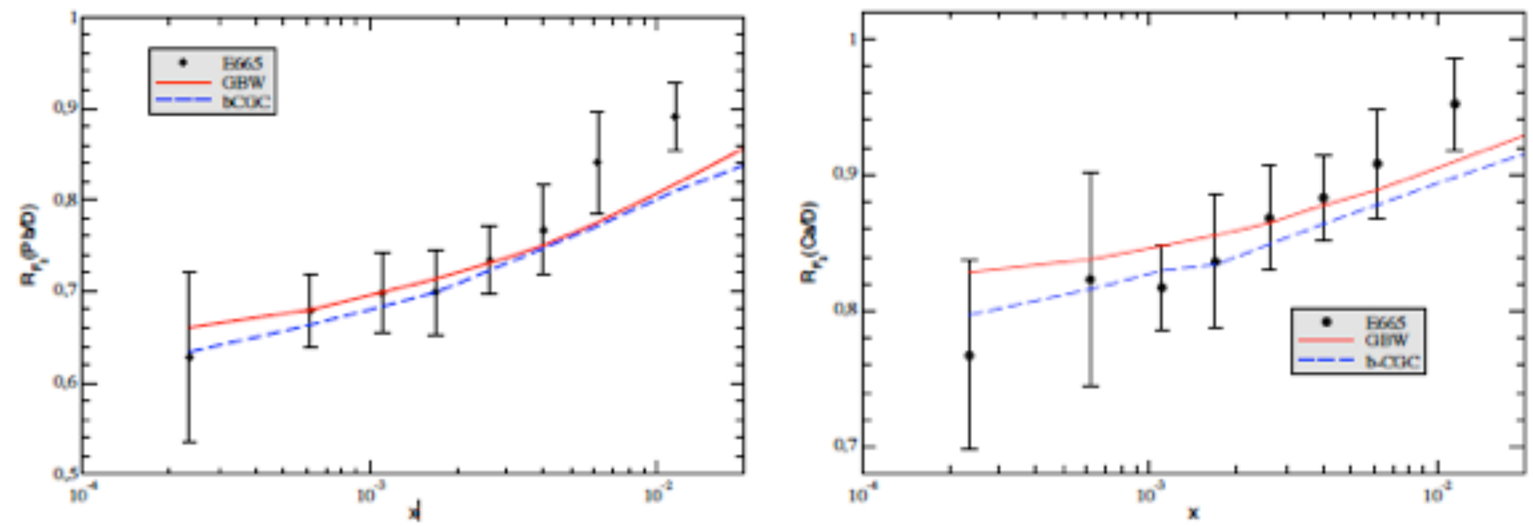
... even with LHeC low x region, multiple ep (& eA) observables will be required for a clear picture of non-linear dynamics.

# Inclusive ratios: ep/eA

Ratio $R_{F_2} \equiv 2F_2^A/AF_2^D$ for $A = Pb$ and $A = Ca$

Data from E665 collaboration

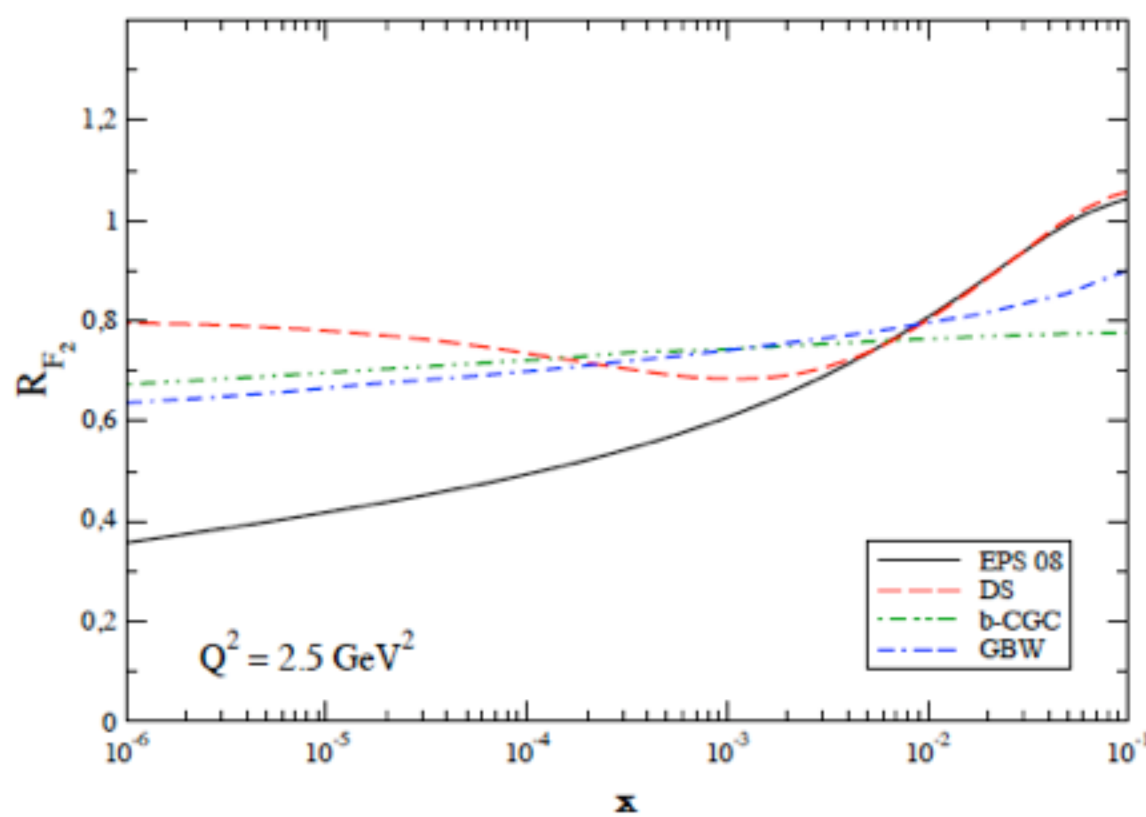
What we know now




*Cazaroto,Carvalho, Goncalves, Navarra*

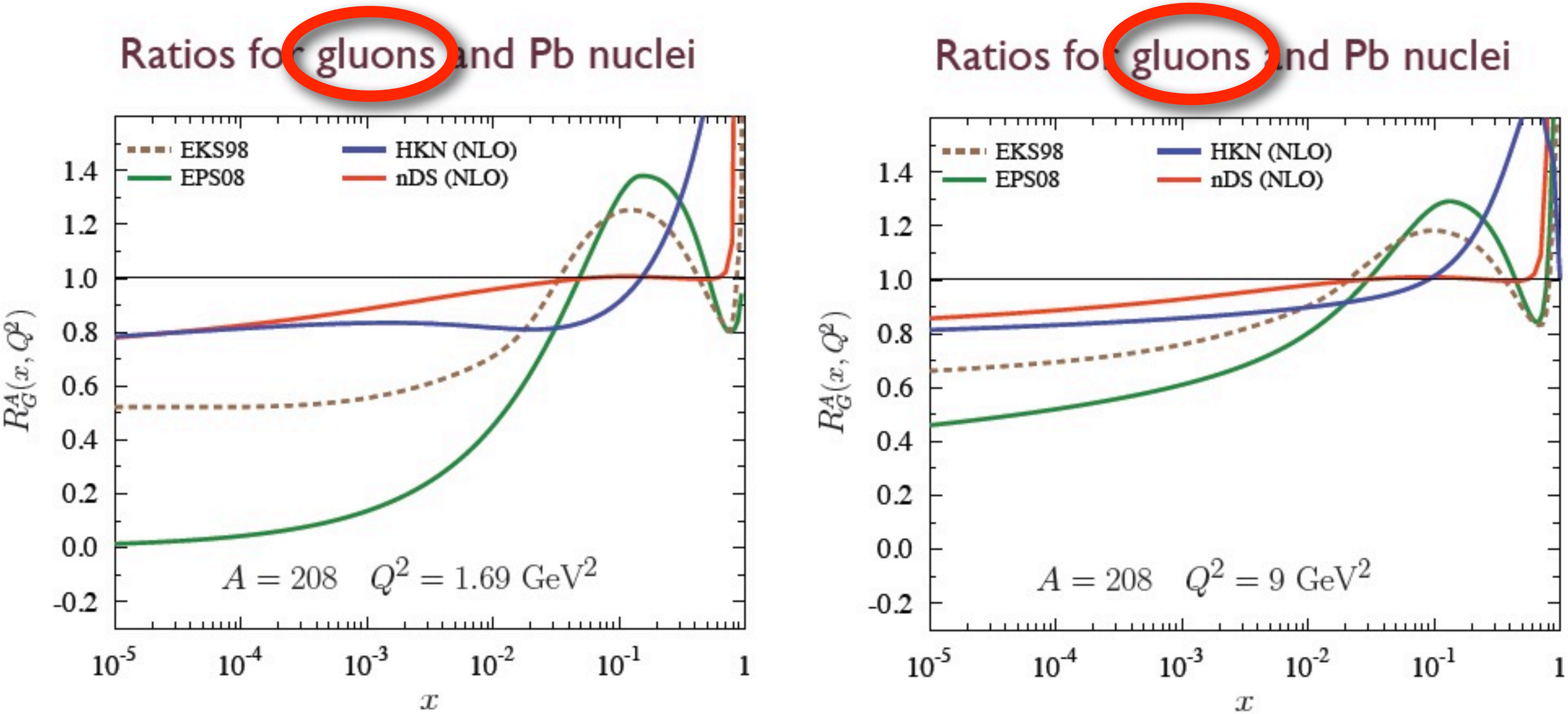
Extrapolation to lower x

A=Pb



# Inclusive ratios: ep/eA

Preliminary calculations of the ratios of gluon densities from N.Armesto et al. Huge difference between models at low x




Models tell us that the ratio is not larger than 1 for small x but can be anywhere between 0 and 1...

Completely new information could be gathered both from EIC and LHeC with nuclei

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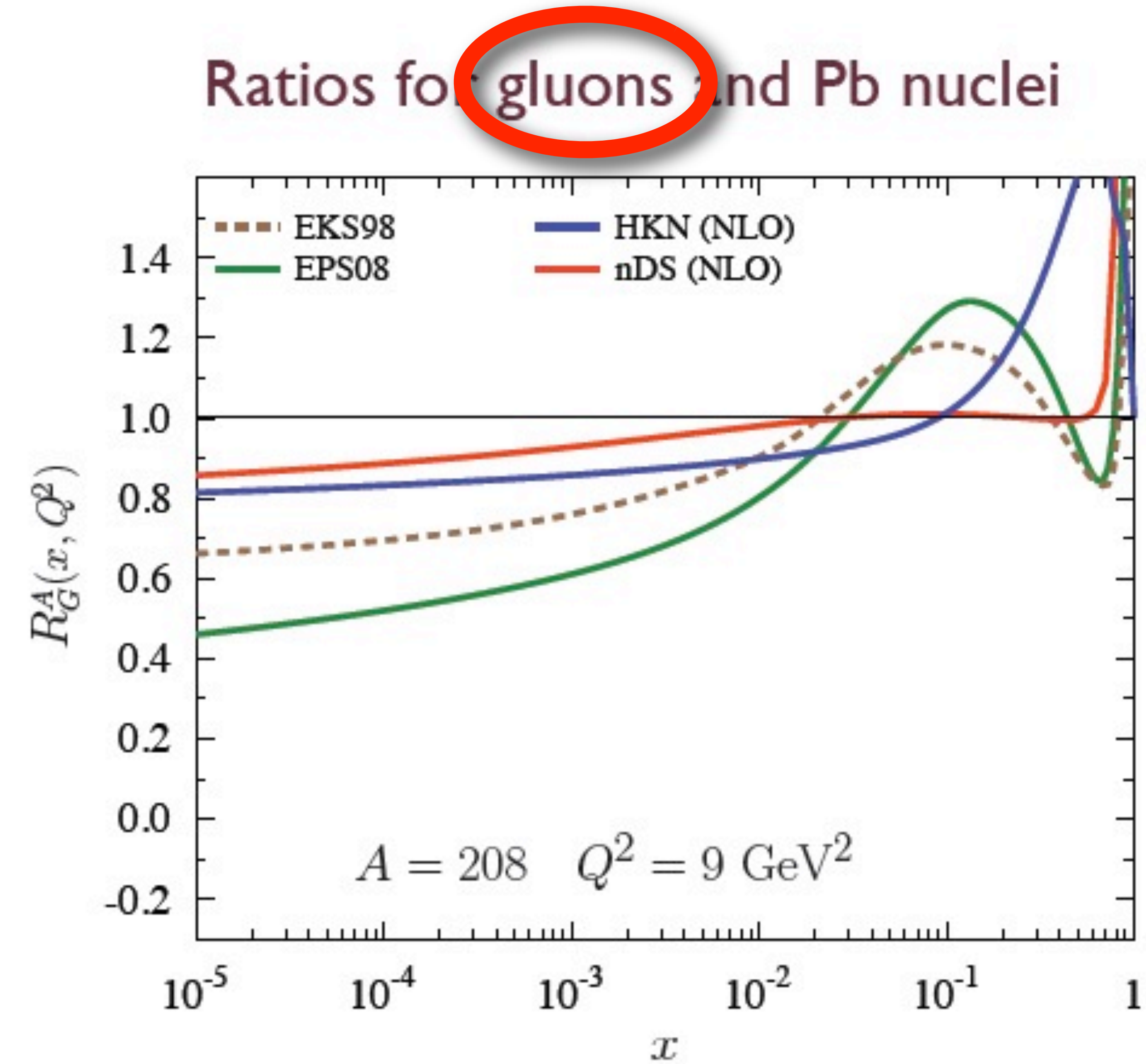


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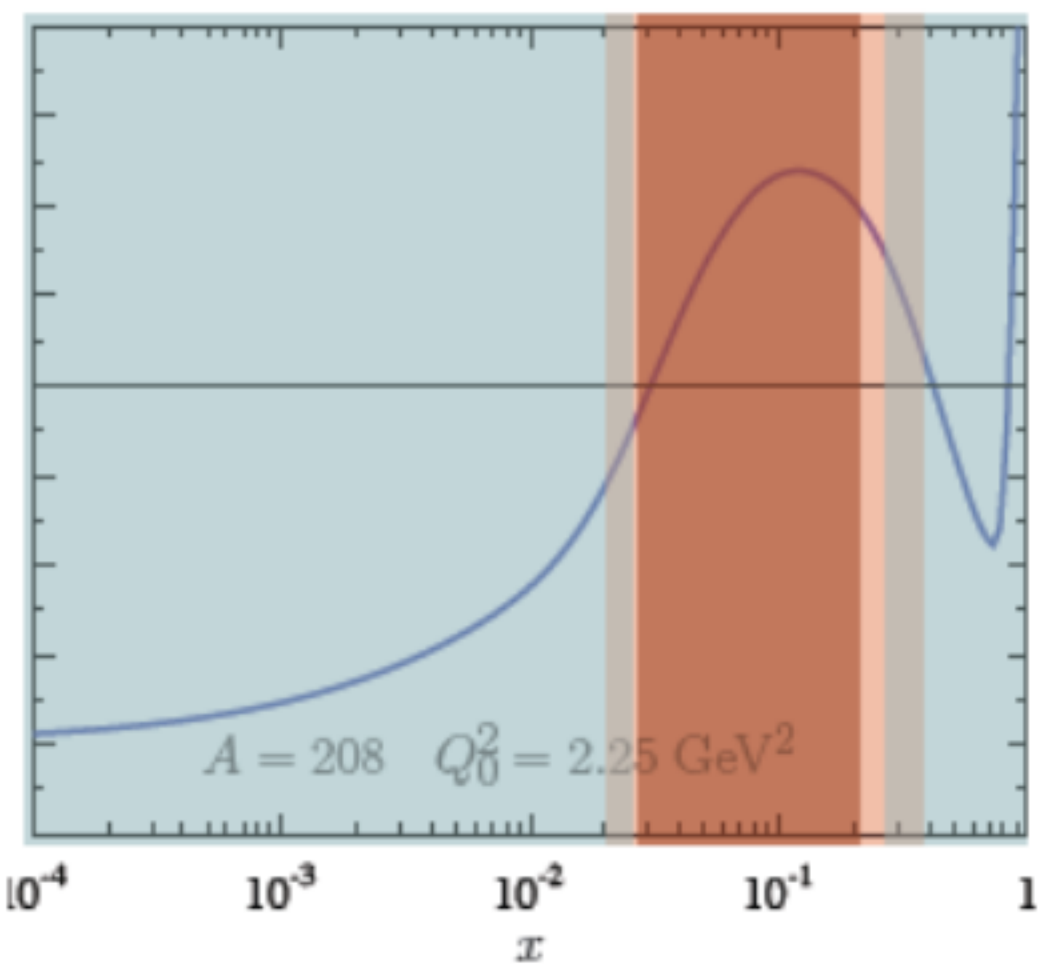


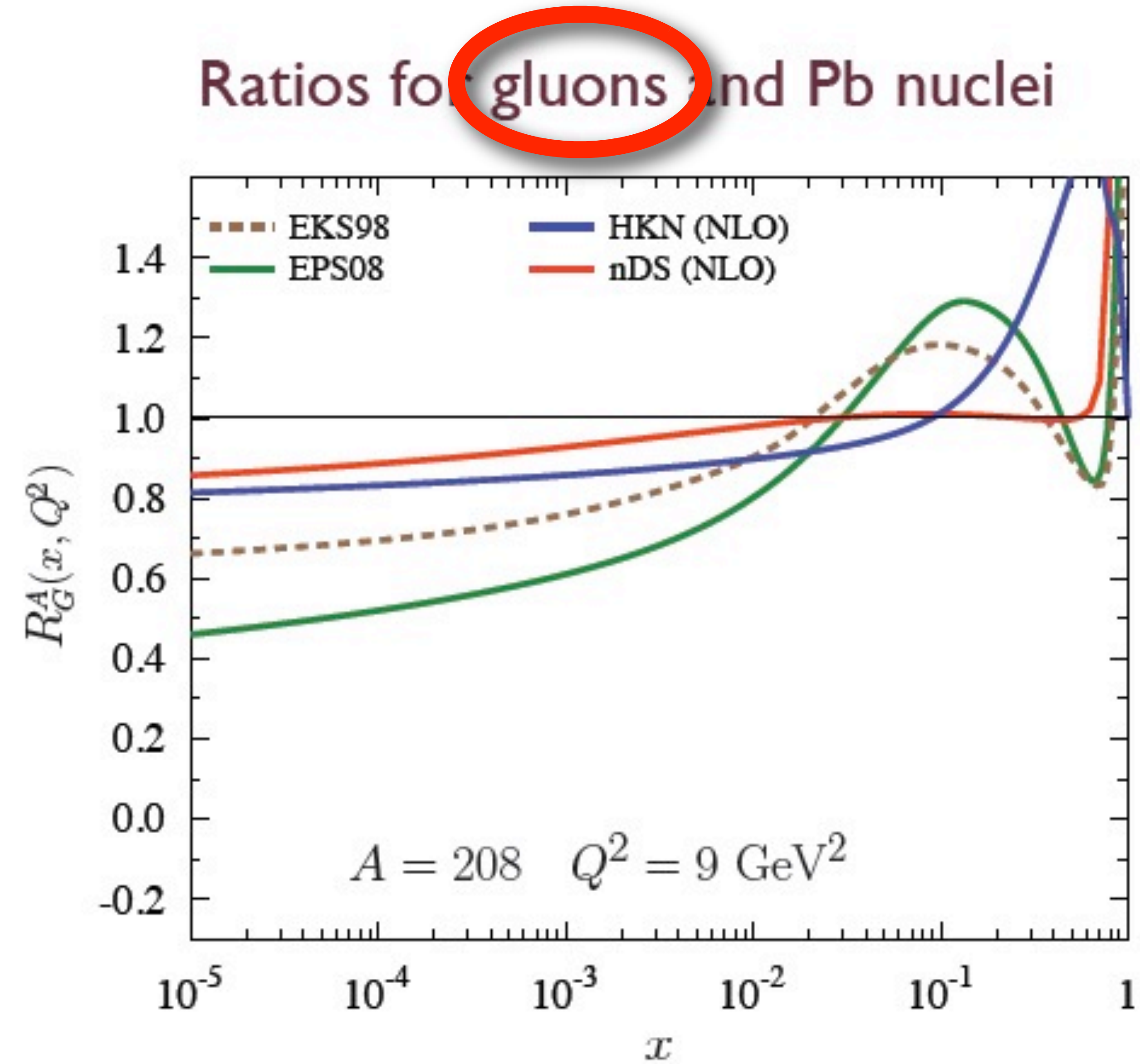


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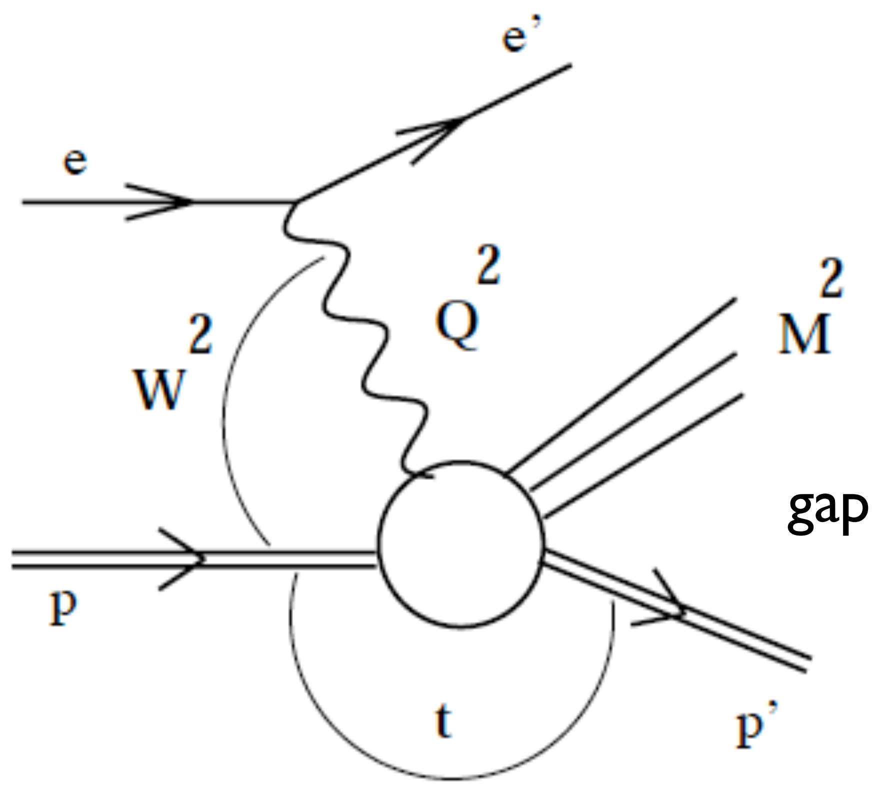
# Diffraction in ep and eA

# Diffraction




$$\boxed{e + p \rightarrow e' + p' + X}$$

Proton stays intact and separated by a rapidity gap

$M^2$ diffractive mass

$t = (p - p')^2$ momentum transfer

$\Delta\eta = \ln 1/x_{I\!P}$ Rapidity gap

$$x_{I\!P} = \frac{Q^2 + M^2 - t}{Q^2 + W^2}$$ momentum fraction of the Pomeron with respect to the hadron

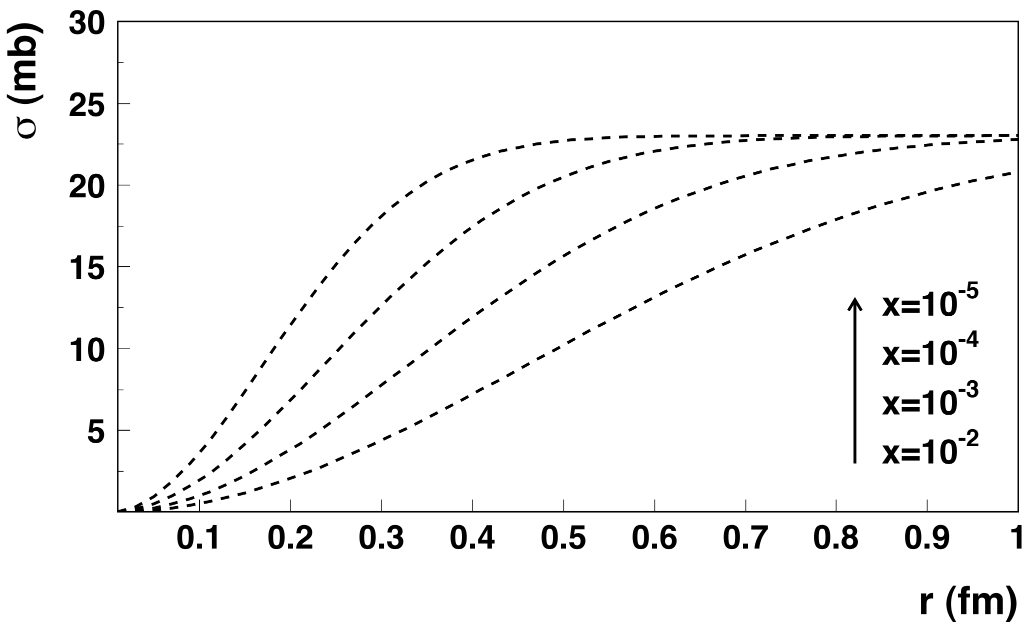
$$\beta = \frac{Q^2}{Q^2 + M^2 - t}$$ momentum fraction of the struck parton with respect to the Pomeron

$$x = x_{I\!P}\,\beta$$ Bjorken x

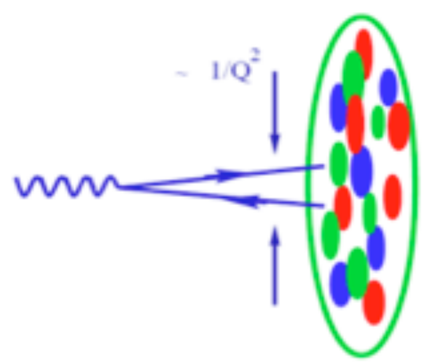
# Diffraction and saturation

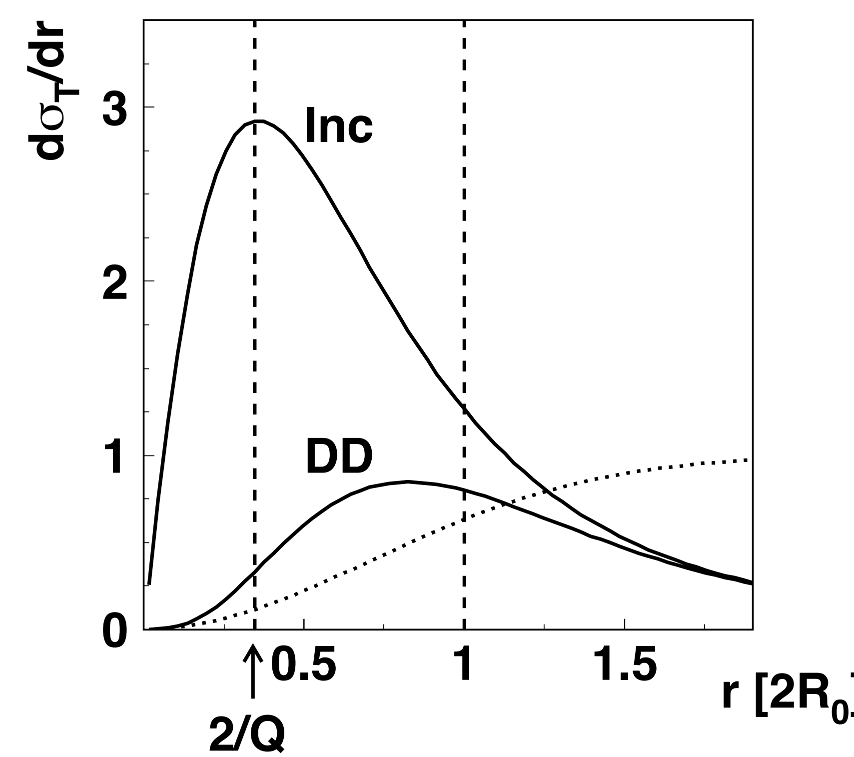
*Golec-Biernat, Wuesthoff*

overlap function in the dipole model




dipole cross section




$$\sigma_T \sim \underbrace{\frac{\sigma_0}{Q^2R_0^2}}_{r<2/Q} + \underbrace{\frac{\sigma_0}{Q^2R_0^2}\log(Q^2R_0^2)}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0}{Q^2R_0^2}}_{r>2R_0}$$

$$\sigma_T^D \sim \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r<2/Q} + \underbrace{\frac{\sigma_0^2}{Q^2R_0^2}}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0^2}{Q^2R_0^2}}_{r>2R_0}$$

$$R_0 = \frac{1}{Q_s}$$

$$\sigma_L^D \sim \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r<2/Q} + \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}\log(Q^2R_0^2)}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r>2r_0}.$$

contribution of different dipole sizes

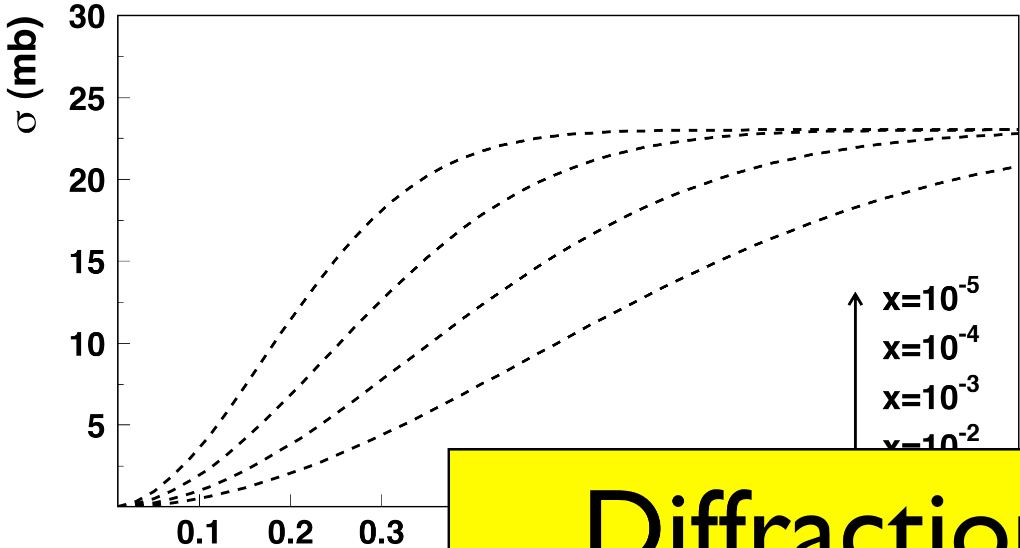
Inclusive: dominated by relatively hard component

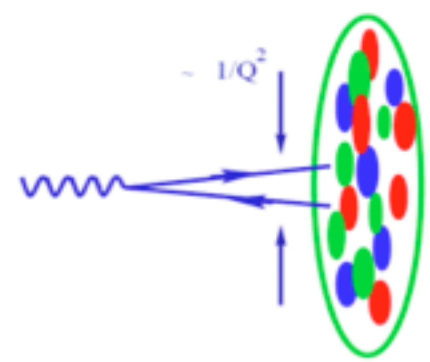
Diffractive: dominated by the semi-hard momenta

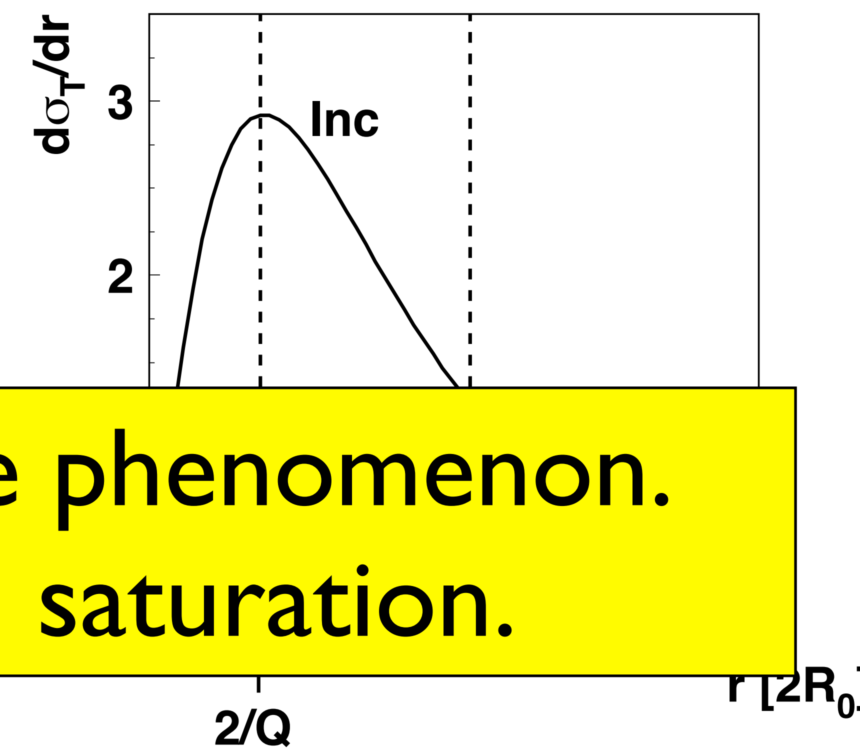
# Diffraction and saturation

*Golec-Biernat, Wuesthoff*

overlap function in the dipole model






dipole cross

**Diffraction is a collective phenomenon.**
**Explore relation with saturation.**

$$\sigma_T \sim \underbrace{\frac{\sigma_0}{Q^2R_0^2}}_{r<2/Q} + \underbrace{\frac{\sigma_0}{Q^2R_0^2}\log(Q^2R_0^2)}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0}{Q^2R_0^2}}_{r>2R_0}$$

$$\sigma_T^D \sim \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r<2/Q} + \underbrace{\frac{\sigma_0^2}{Q^2R_0^2}}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0^2}{Q^2R_0^2}}_{r>2R_0} \qquad R_0 = \frac{1}{Q_s}$$

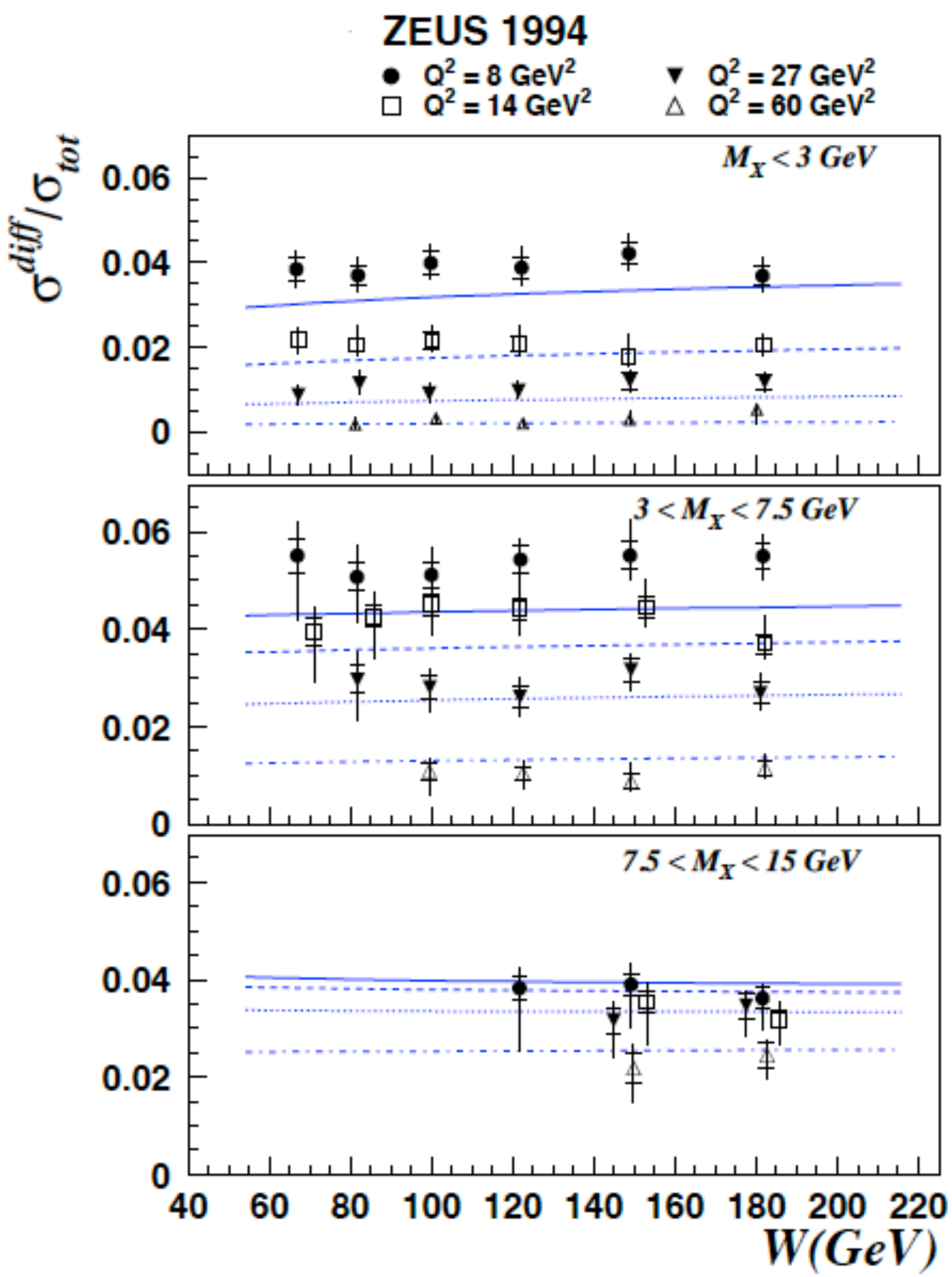
$$\sigma_L^D \sim \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r<2/Q} + \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}\log(Q^2R_0^2)}_{2/Q<r<2R_0} + \underbrace{\frac{\sigma_0^2}{Q^4R_0^4}}_{r>2r_0}.$$

contribution of different dipole sizes

Inclusive: dominated by relatively hard component

Diffractive: dominated by the semi-hard momenta

# Diffractive to inclusive ratio in ep



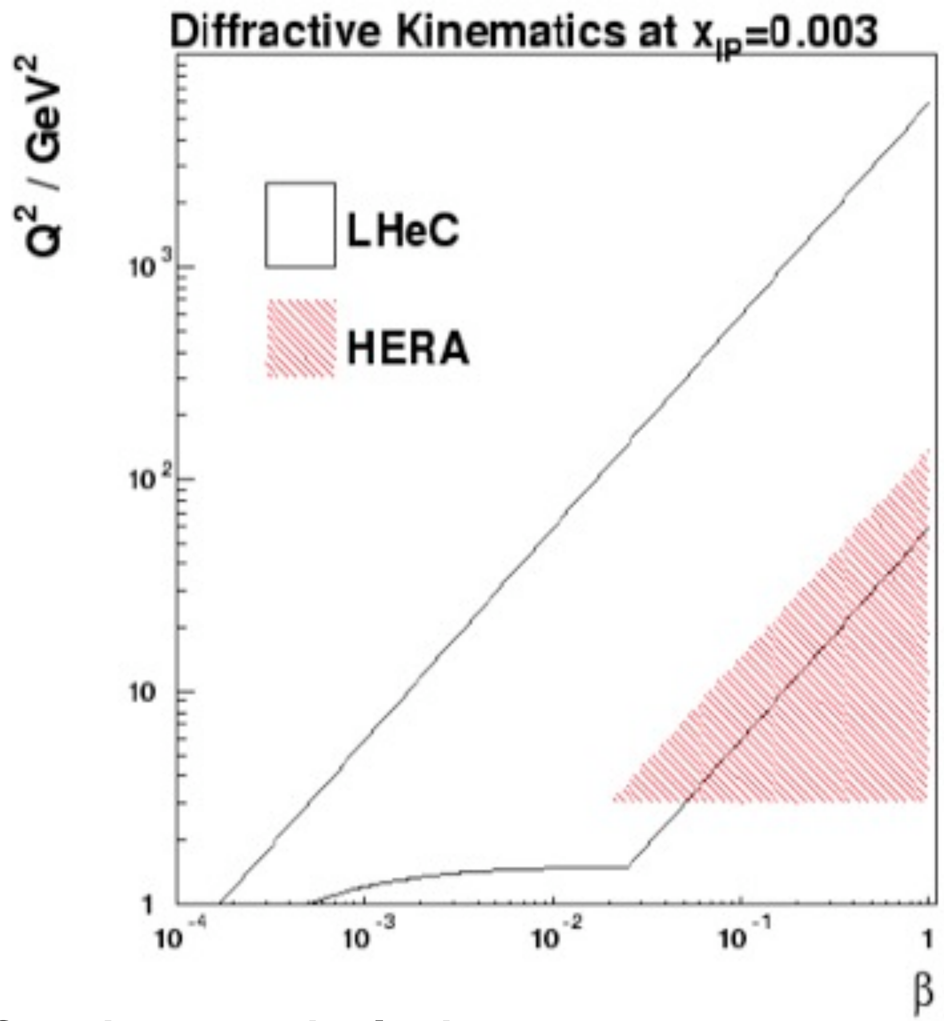

*Golec-Biernat, Wuesthoff*

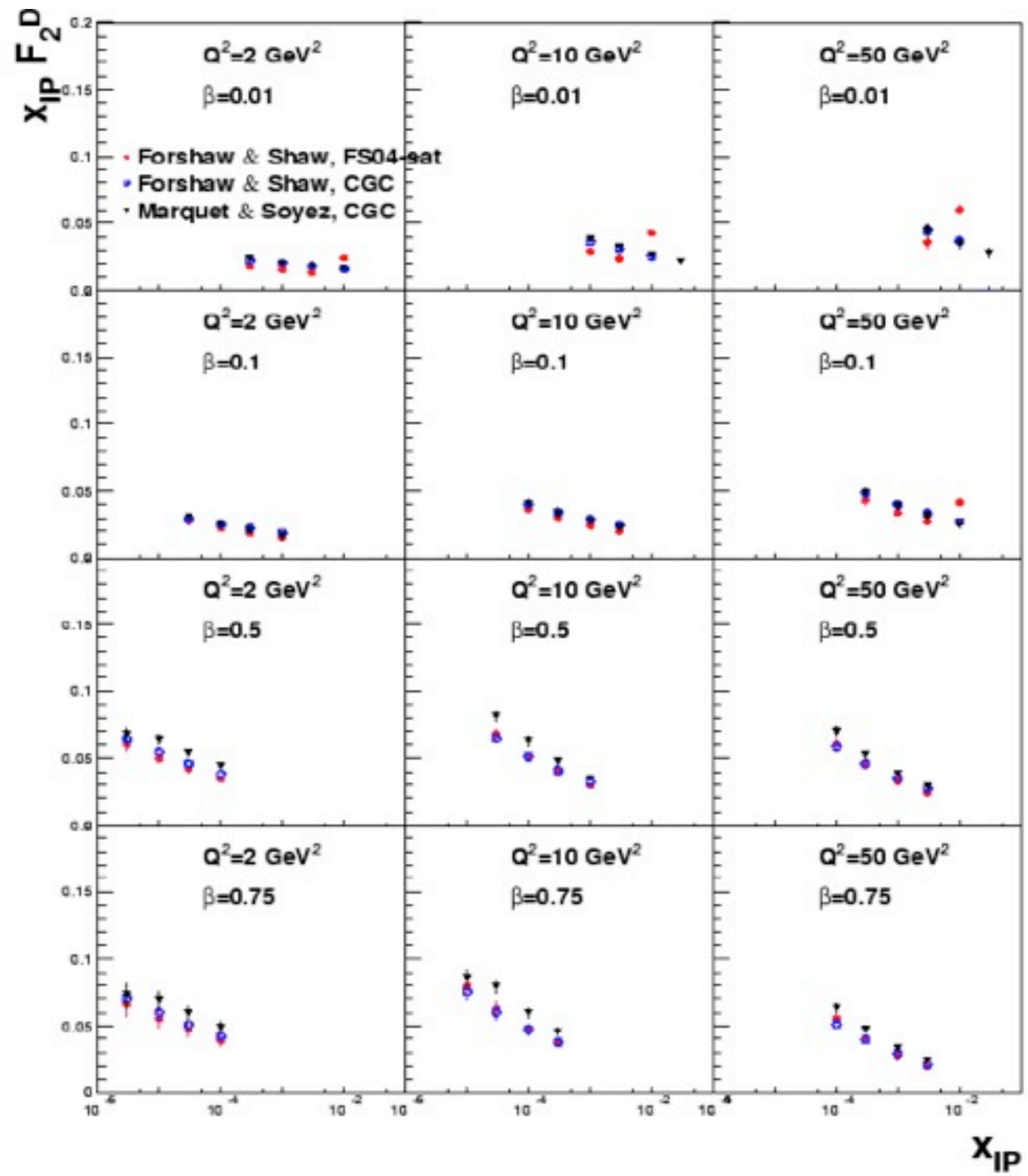
Constant ratio naturally explained in the saturation model.

Is it the same ratio and still constant at higher energy?

What happens in nuclei?

# Diffraction at LHeC: new possibilities



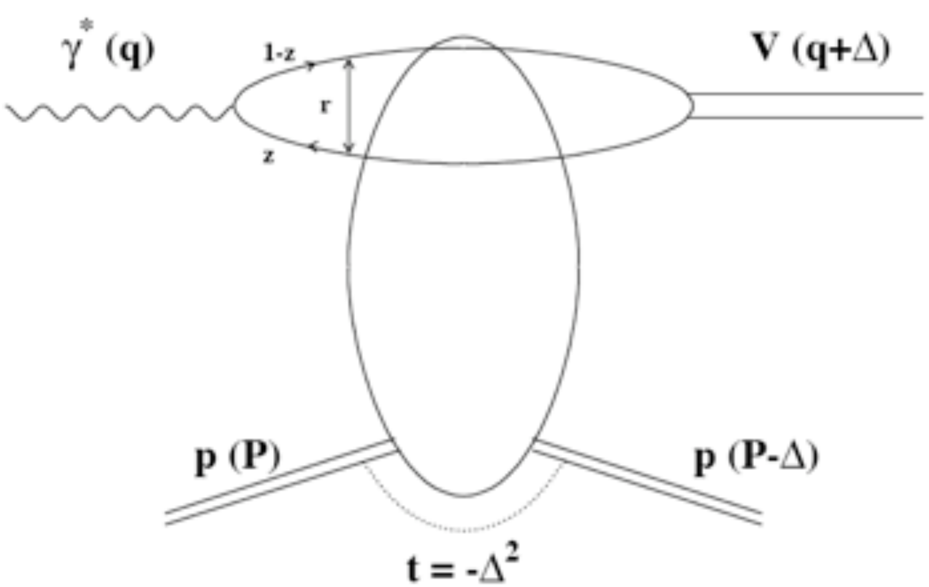




- Studies with 1 degree acceptance,
- Diffractive-PDFs
- Factorization in much bigger range
- Diffractive masses $M_X \sim 100 \mathrm{GeV}$ with $x_{I\!P} = 0.01$
- X can include W,Z,b

*Forshaw, Marquet, Newman*

# Exclusive diffraction of VM

- Exclusive diffractive production of VM is an excellent process for extracting the dipole amplitude
- Suitable process for estimating the 'blackness' of the interaction.
- t-dependence provides an information about the impact parameter profile of the amplitude.




Differential cross section for exclusive VM production

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}|\mathcal{A}_{\rm el}(x,\Delta,Q)|^2$$

Amplitude for elastic scattering

$$\mathcal{A}_{\rm el}(x,\Delta,Q) = \sum_{h,\bar{h}} \int d^2\mathbf{r}\, dz\, \psi^{h,\bar{h}*}_{\gamma^*}(z,\mathbf{r};Q)\, A^{q\bar{q}-p}_{\rm el}(x,\mathbf{r},\Delta)\, \psi^{h,\bar{h}}_{V}(z,\mathbf{r})$$

Elementary amplitude for elastic scattering

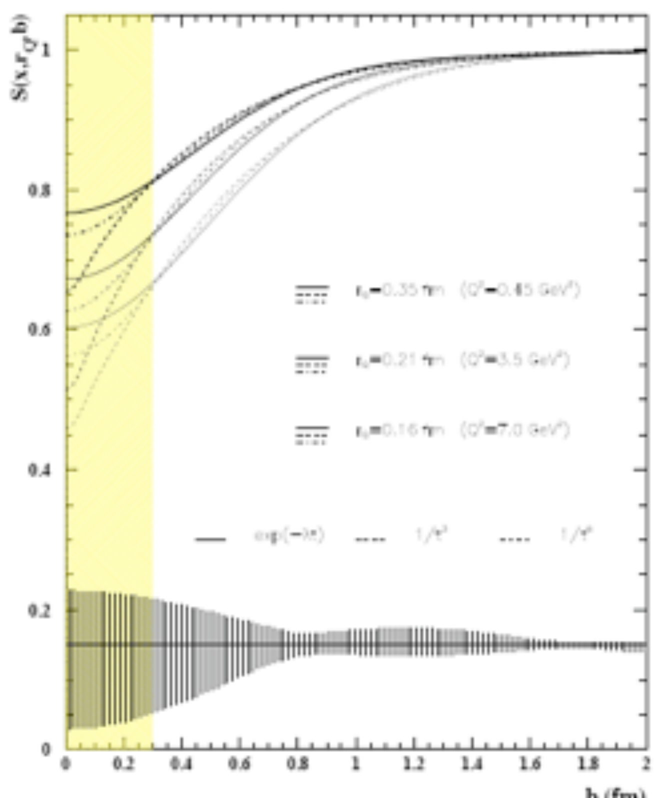
$$A^{q\bar{q}-p}_{\rm el}(x,\mathbf{r},\Delta) = \int d^2\mathbf{b}\, \tilde{A}^{q\bar{q}-p}_{\rm el}(x,\mathbf{r},\mathbf{b}) e^{i\mathbf{b}\Delta} = 2\int d^2\mathbf{b}\, [1 - S(x,\mathbf{r},\mathbf{b})] e^{i\mathbf{b}\Delta}$$

Optical theorem

$$\sigma^{q\bar{q}-p}_{\rm tot}(x,\mathbf{r}) = \mathcal{I}m\, i A^{q\bar{q}-p}_{\rm el}(x,\mathbf{r},\Delta=0)$$

# Impact parameter profile

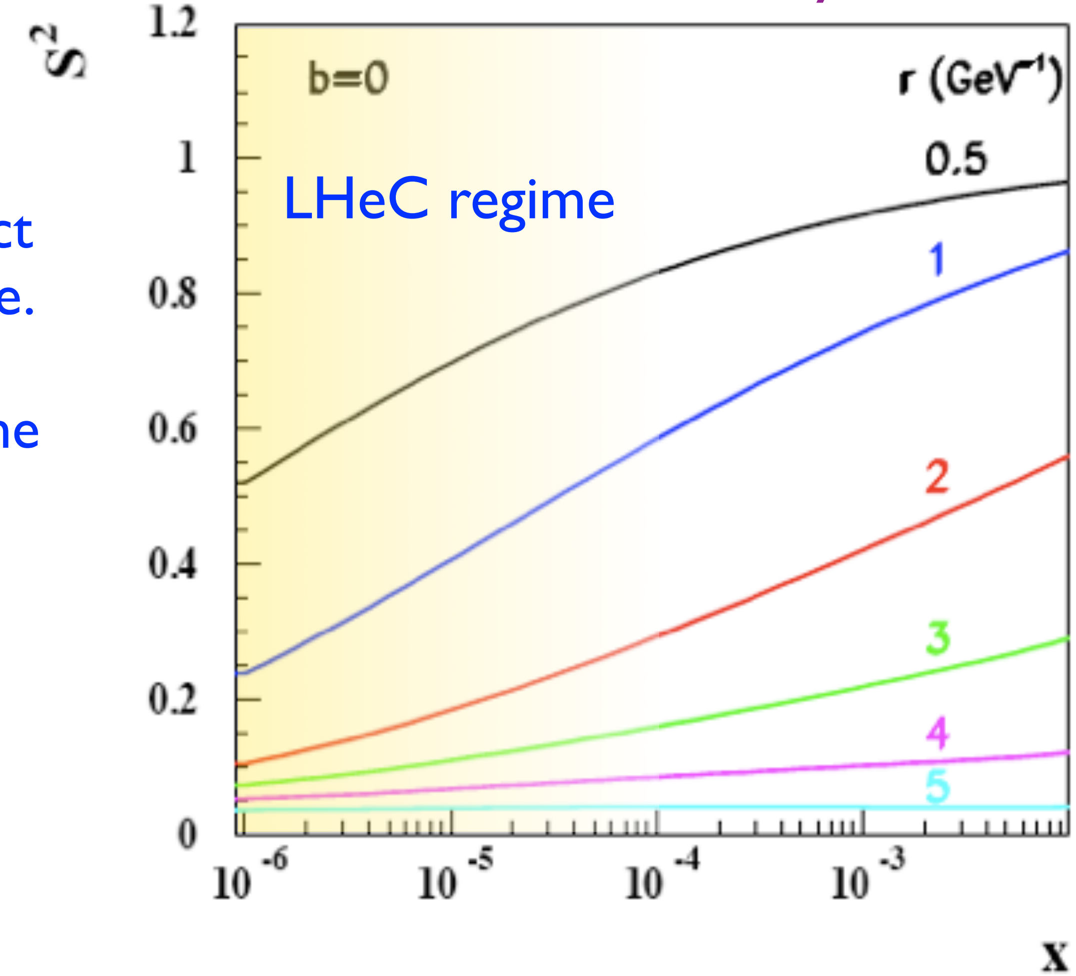
*Munier, Stasto, Mueller*




Profile extracted from the HERA data

t-dependence vs impact parameter dependence. What is the characteristic size of the proton in strong interactions?

*Kowalski, Teaney*




Extrapolations of the S matrix towards lower values of x

$1 - S^2$ probability that a dipole passing the proton will induce an inelastic reaction at the given impact parameter

Models indicate significant 'blackness' for central impact parameter

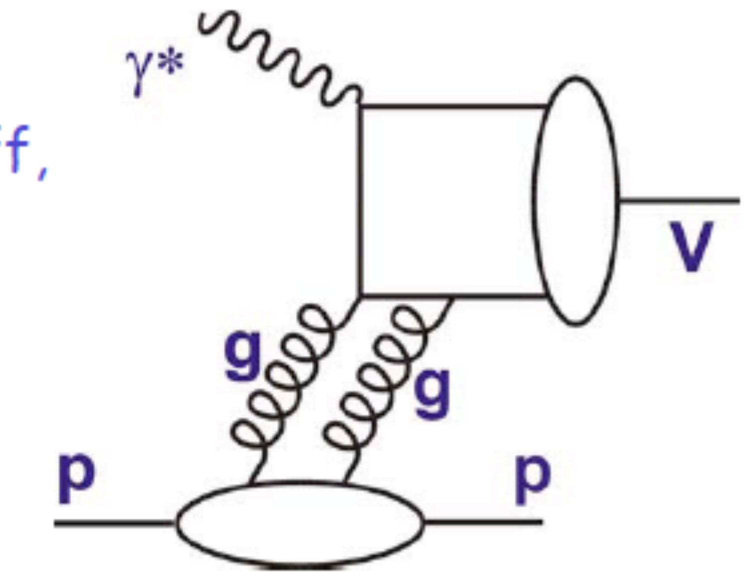
$Q^2 \sim 5\ \mathrm{GeV}^2$ $\qquad$ $x = 10^{-5} - 10^{-6}$

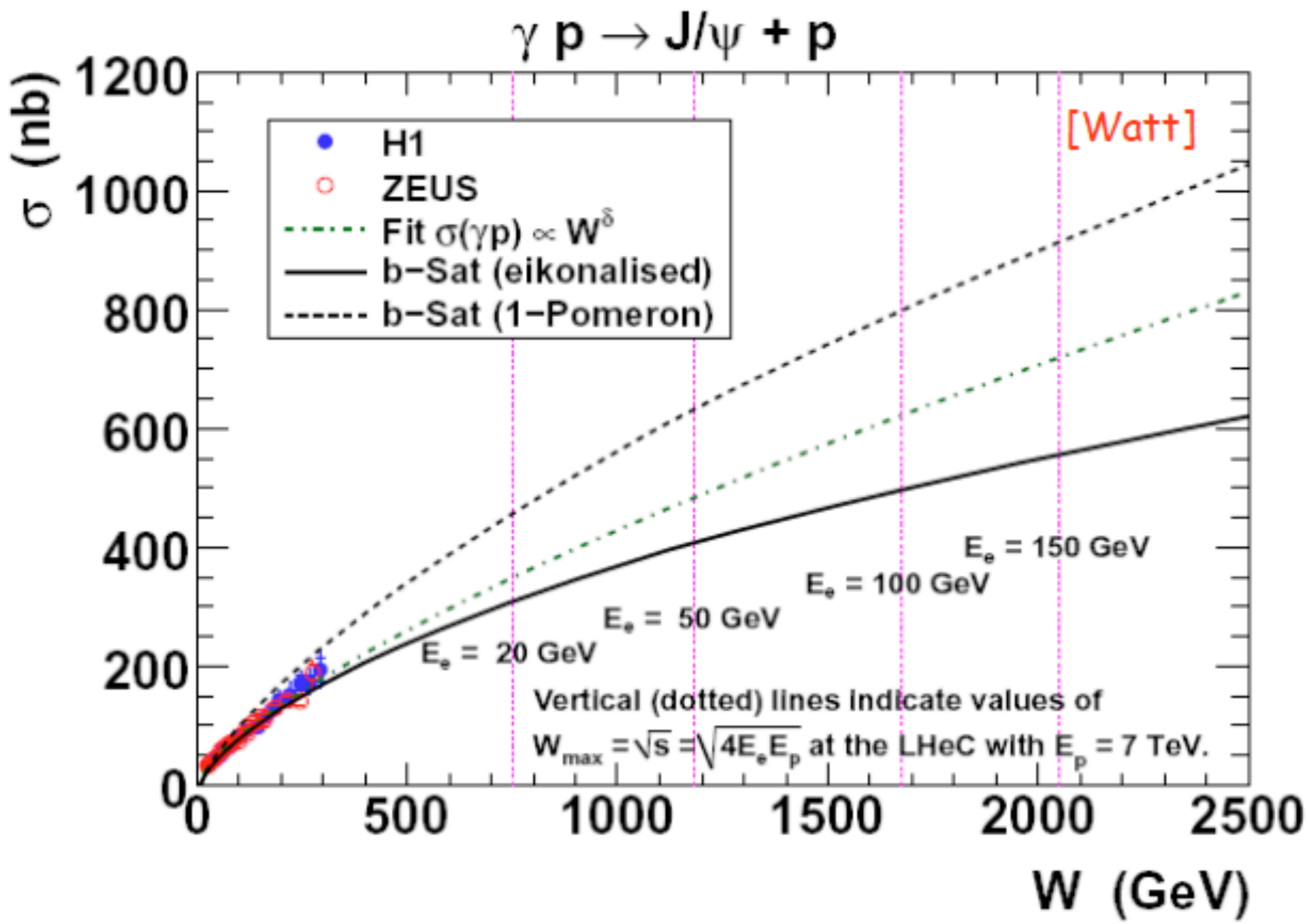
# e.g. J/ψ Photoproduction

e.g. "b-Sat" Dipole model [Golec-Biernat, Wuesthoff, Bartels, Teaney, Kowalski, Motyka, Watt] ...

"eikonalised": with impact-parameter dependent saturation

"1 Pomeron": non-saturating

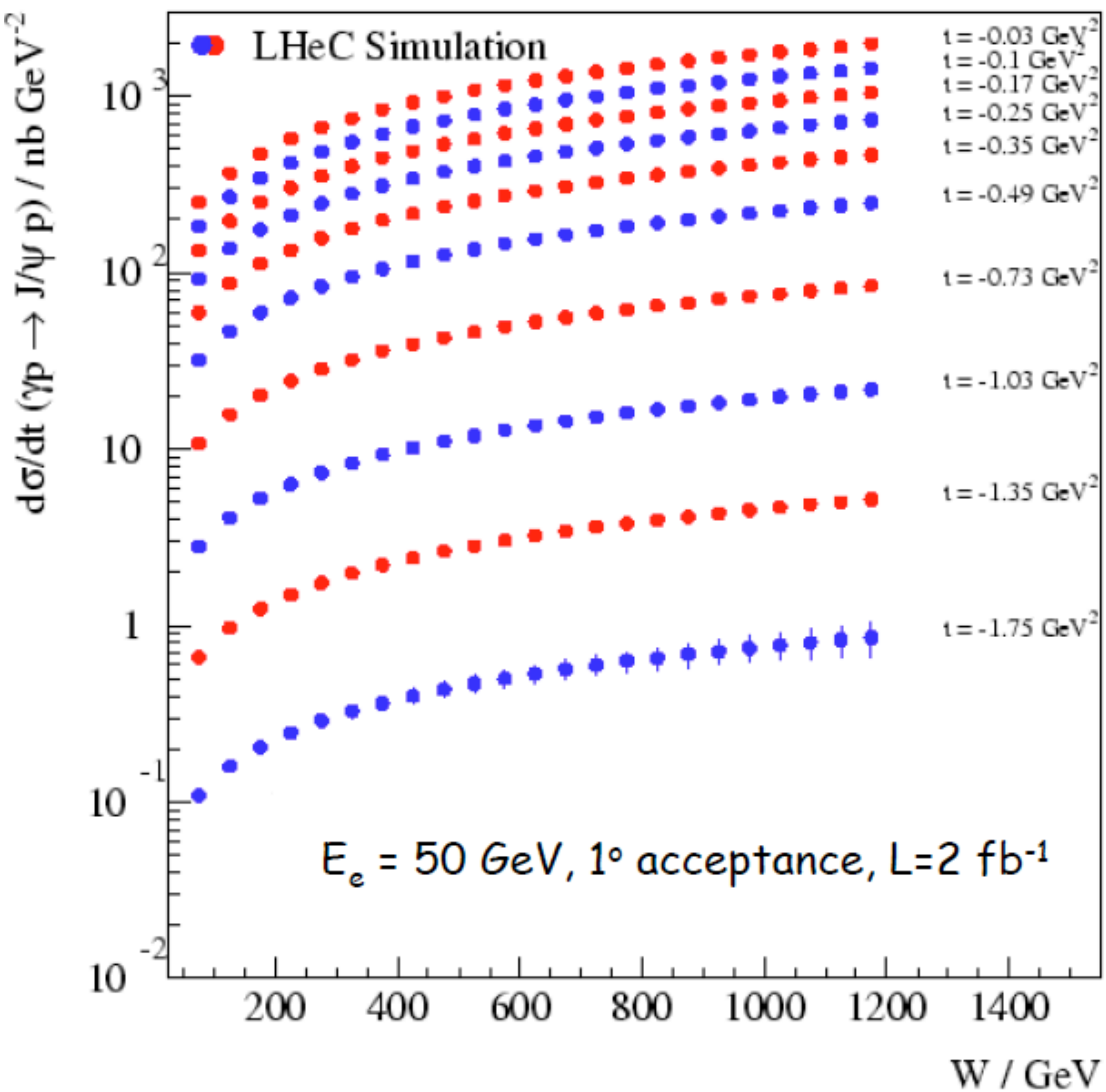



Significant non-linear effects expected even for t-integrated cross section in LHeC kinematic range.

f x

# Elastic J/ψ Production more Differentially




J/ψ photoproduction double differentially in W and t …

Inclusive cross sec probes to $x_g \sim 6.10^{-6}$

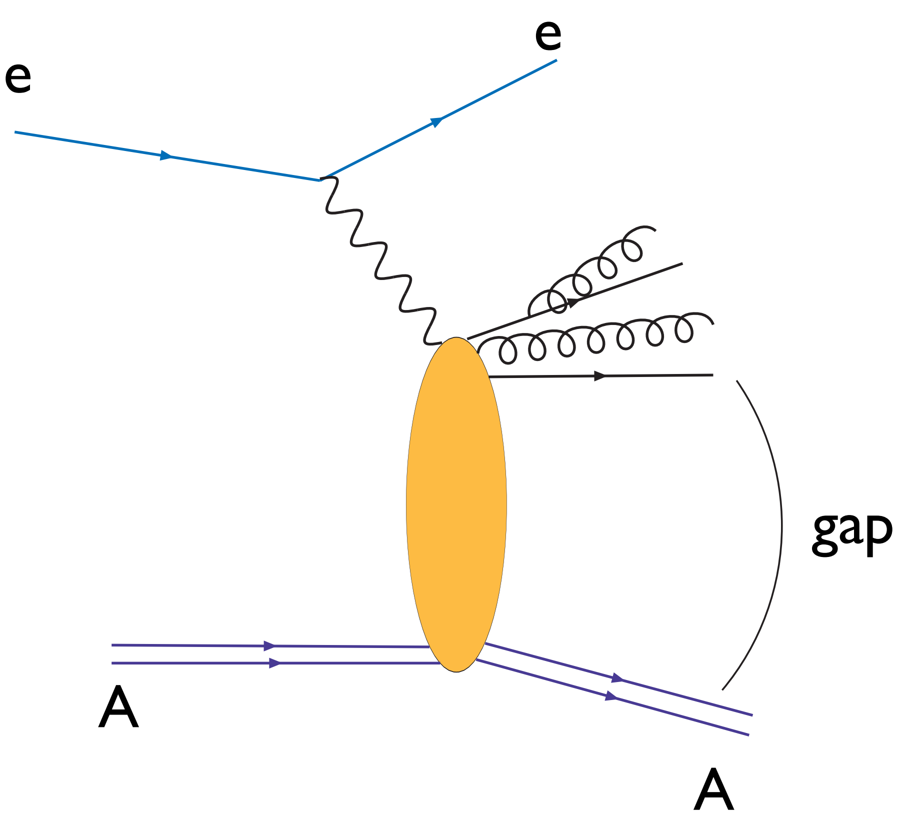
$Q^2_s \sim 3$ GeV$^2 \sim m_\psi^2/4$

Precise t dependence will be crucial to study sat$^n$ effects!

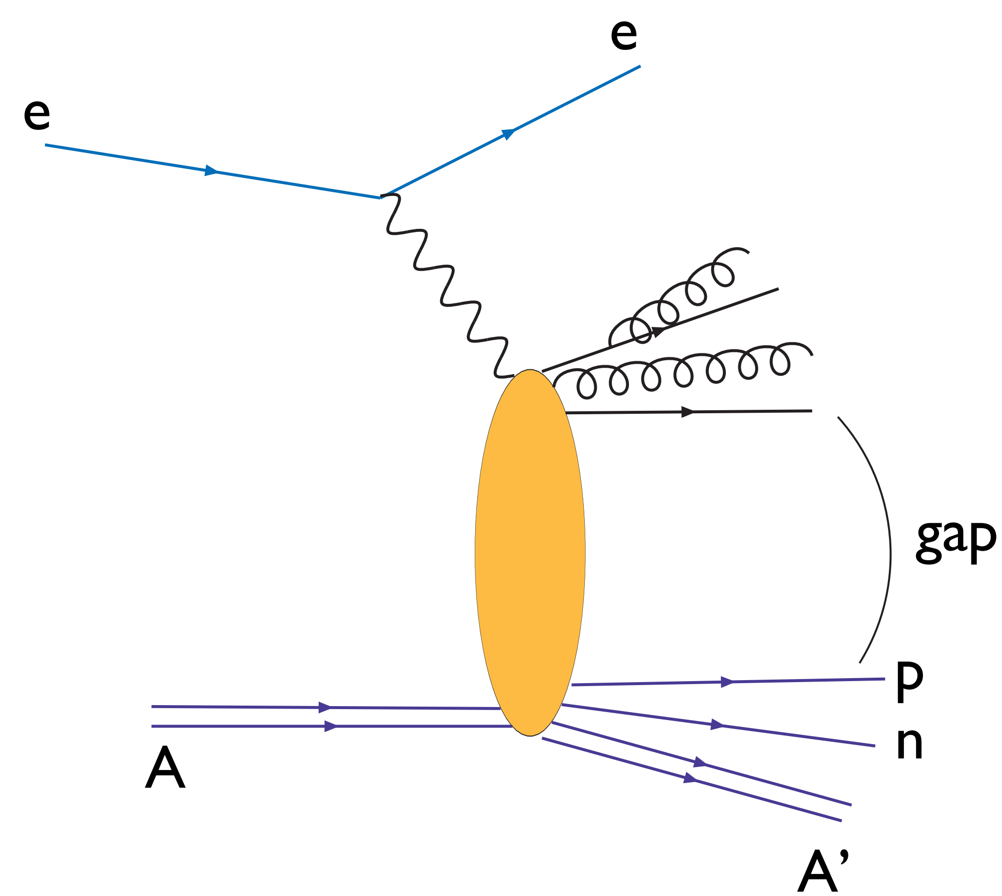
Also possible in several $Q^2$ bins

# Diffraction in eA

Two possibilities for the diffractive events in nuclei:

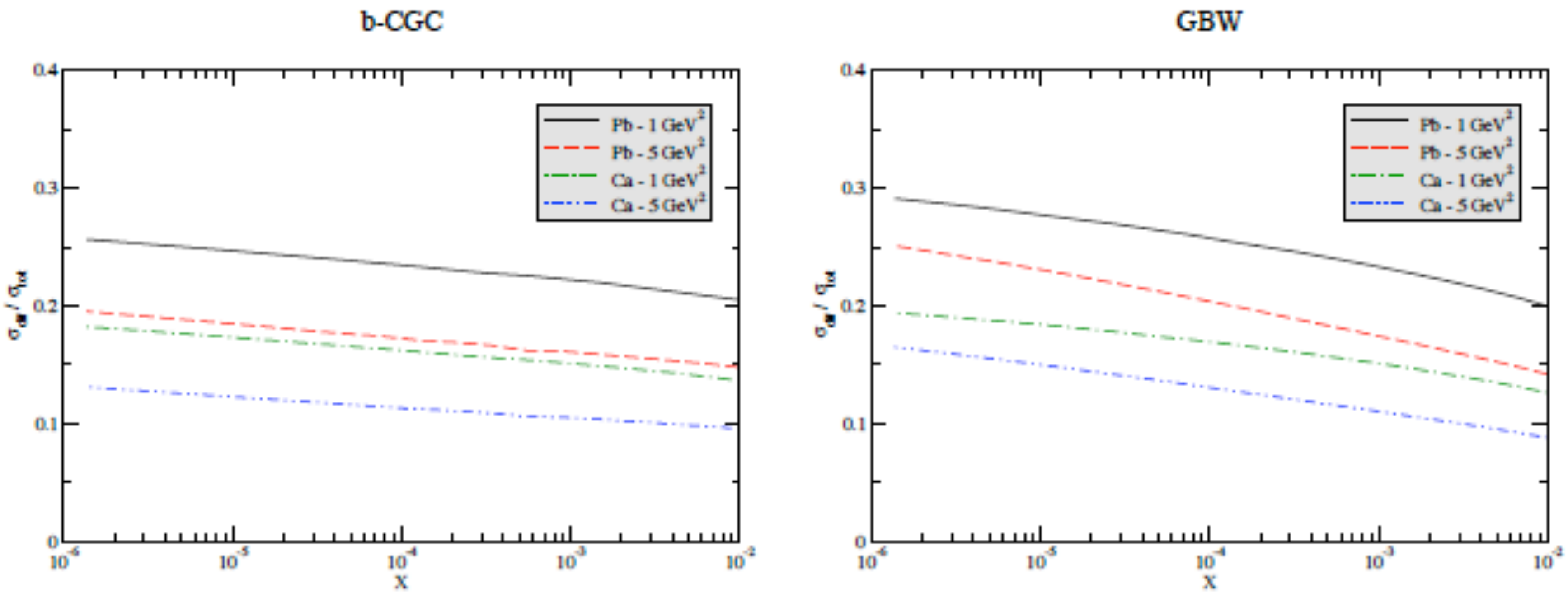



Coherent
No-breakup



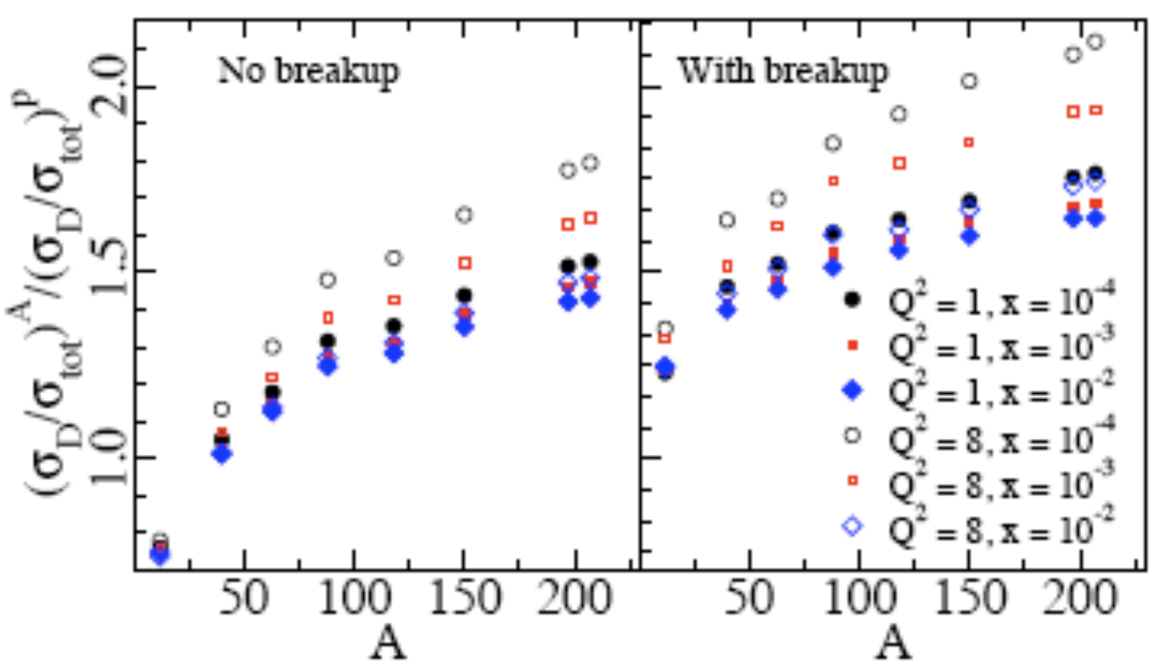

Incoherent
With breakup into nucleons
The gap is still there

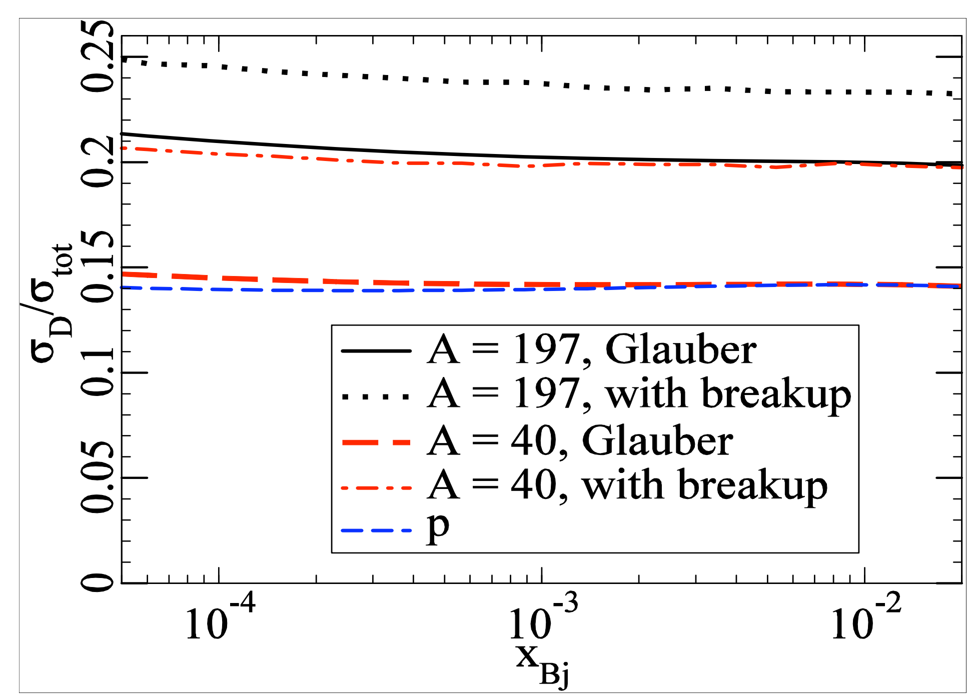
# Diffractive to inclusive ratio in eA




*Cazaroto, Carvalho, Goncalves, Navarra*

Predictions give
20%-40% for $\sigma_{\rm diff}/\sigma_{\rm tot}$
in the regime down
to $10^{-6}$




*Kowalski, Lappi, Venugopalan*

# Summary

- What have we learned from DIS at HERA:
    - fast growth of structure functions at small x
    - large gluon density
    - large number of diffractive events
- New ep/eA collider needed to:
    - explore new kinematic regime at yet smaller values of x
    - pin down the position of the saturation scale, establish the transition region between dilute and dense regime
    - measure the initial state for AA collisions, parton densities in nuclei
    - measure the transverse shape of the nucleus
    - impact of high densities on spin structure