# Deep Inelastic Scattering studies with the EIC

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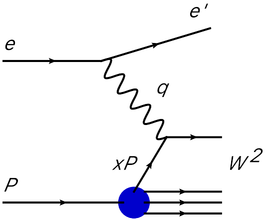
# Plan

- Basic idea and experimental results
- Electron Ion Collider
- Nuclear structure from EIC studies
- Nucleon/nucleus tomography
- Spin structure studies
- Parton saturation and diffractive processes

Electron Ion Collider: The Next QCD Frontier - Second Edition
(arXiv:1212.1701v3 30 Nov 2014)

# Basic idea of DIS

- DIS to study quark-gluon structure of hadrons with electroweak probes.




- Virtuality of the probe $(\gamma, Z^0, W^\pm)$

$$Q^2 = -q^2 = -(k_e - k_e')^2 > 0$$

- Bjorken variable

$$x = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{Q^2 + W^2}$$

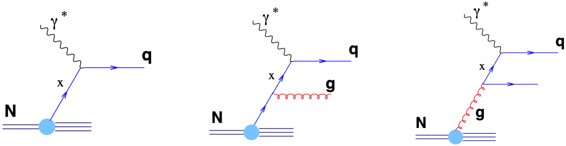
- Parton model interpretation - DIS on a parton with proton momentum fraction $x$.
- Inclusive cross section for $ep \to e'X$ in which $(E_e', \theta_e') \leftrightarrow (x, Q^2)$

$$\frac{d\sigma}{dxdQ^2} = \frac{2\pi\alpha_{\rm em}^2}{xQ^4} Y_+ \left( F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)\right)$$

where $x, y \in [0,1]$ and $Y_+ = 1 + (1-y)^2$

# Structure functions $F_2$ and $F_L$

- QCD improved parton model - partons are quarks, antiquarks and gluons




- Scale dependent parton distribution functions (PDFs):

$$q_f(x, Q^2), \qquad \bar{q}_f(x, Q^2), \qquad G(x, Q^2)$$

- Structure function in the leading approximation

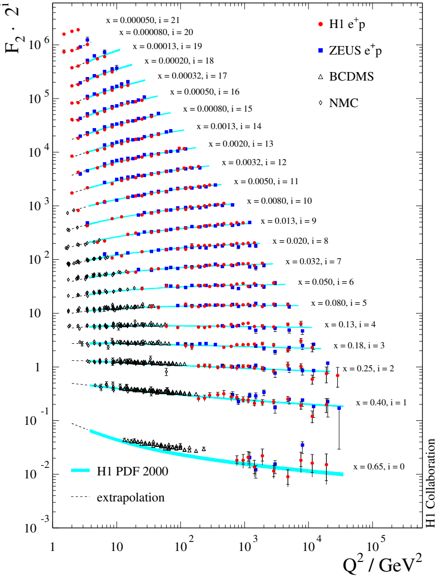
$$F_2(x, Q^2) = \sum_f e_f^2\, x \left[ q_f(x, Q^2) + \bar{q}_f(x, Q^2) \right], \qquad F_L = 0 + \alpha_s(Q^2)(\ldots)$$

- Bjorken scaling in the limit $x = const$ and $Q^2 \to \infty$

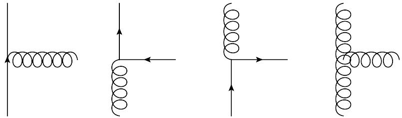
$$F_{2,L} = F_{2,L}(x, \ln Q^2)$$

- Logarithmic Bjorken scaling violation from $Q^2$-dependence of PDFs!

# Bjorken scaling and its logarithmic violation



- Summation of infitnie number of splittings below gives evolution equations



$P_{qq}$ $P_{qG}$ $P_{Gq}$ $P_{GG}$

- DGLAP evolution equations (Dokshitzer, Gribov, Lipatov, Altarelli, Parisi, 1972-77)

$$\frac{\partial q_f(x,Q^2)}{\partial(\ln Q^2)} = P_{qq}\otimes q_f + P_{qG}\otimes G$$

$$\frac{\partial \bar{q}_f(x,Q^2)}{\partial(\ln Q^2)} = P_{qq}\otimes \bar{q}_f + P_{qG}\otimes G$$

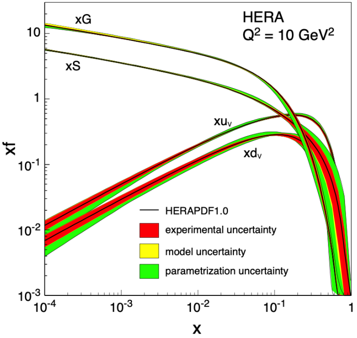
$$\frac{\partial G(x,Q^2)}{\partial(\ln Q^2)} = P_{Gq}\otimes \sum_f (q_f+\bar{q}_f) + P_{GG}\otimes G$$

- Initial conditions at $Q_0^2 \simeq 1~\mathrm{GeV}^2$ :

$$q_f(x,Q_0^2), \qquad \bar{q}_f(x,Q_0^2), \qquad G(x,Q_0^2)$$

- Global fits of PDFs to hard scattering data

# Parton distributions from global fits




- Valence quark distributions

$$u_v = u - \bar{u}\,, \qquad d_v = d - \bar{d}$$

- Sea quark distribution

$$S = 2\,(\bar{u} + \bar{d} + \bar{s} + \ldots)$$

- Gluons and sea dominate at small $x$

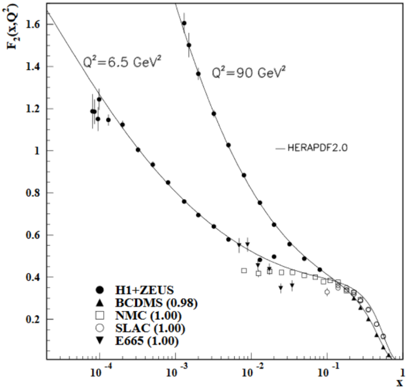
- Momentum sum rule

$$\underbrace{\int_0^1 dx\, x\, G(x,Q^2)}_{\approx\, 0.5} + \sum_f \int_0^1 dx\, x \left[q_f(x,Q^2) + \bar{q}_f(x,Q^2)\right] = 1$$

- Gluons carry half of proton's momentum.

# $F_2$ as a function of $x$

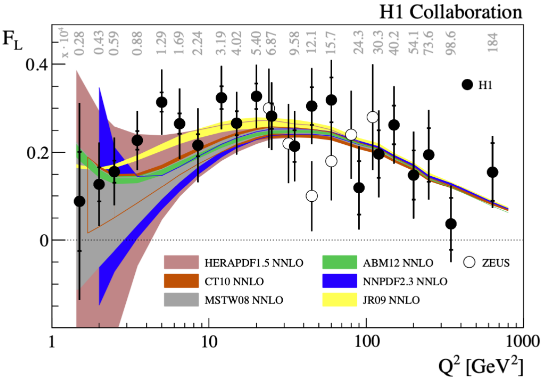
$$F_2(x,Q^2) = x\left\{\frac{4}{9}u_v + \frac{1}{9}d_v + \frac{2}{3}S\right\}$$



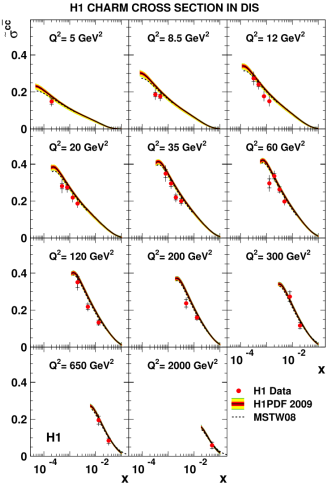

- Sea quark distribution seen for $x \to 0$
- Strong dependence on $Q^2$ at small $x$ driven by the gluon distribution

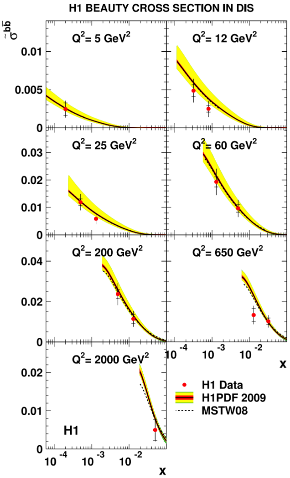
- NLO QCD formula

$$F_L(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left[ C_L^q\left(\frac{x}{z}\right) F_2^{LO}(z, Q^2) + C_L^g\left(\frac{x}{z}\right) zG(z, Q^2) \right]$$




- Strong sensitivity to gluon distributions for small $x$

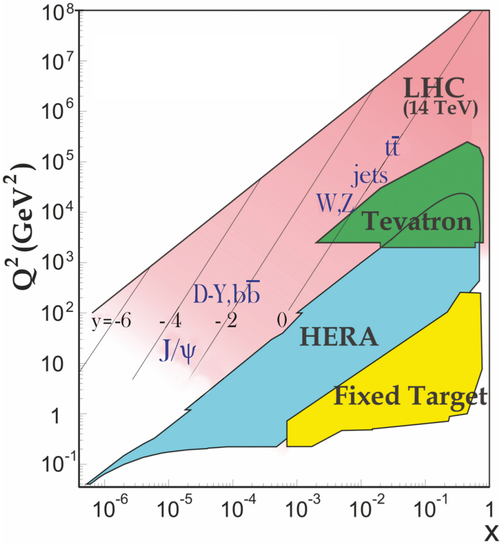



- Charm contribution up to $25 - 30\%$ for small $x$ and large $Q^2$
- $c$ and $b$ quarks generated radiatively: $\gamma^* g \to c\bar{c},\ b\bar{b}$
- Intrisic charm and beauty?

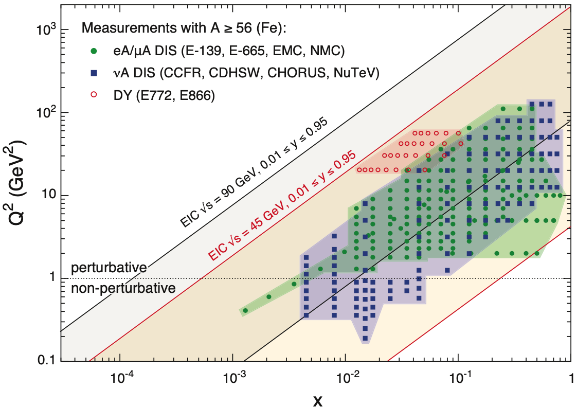
# Kinematic plane

(PDG Book)



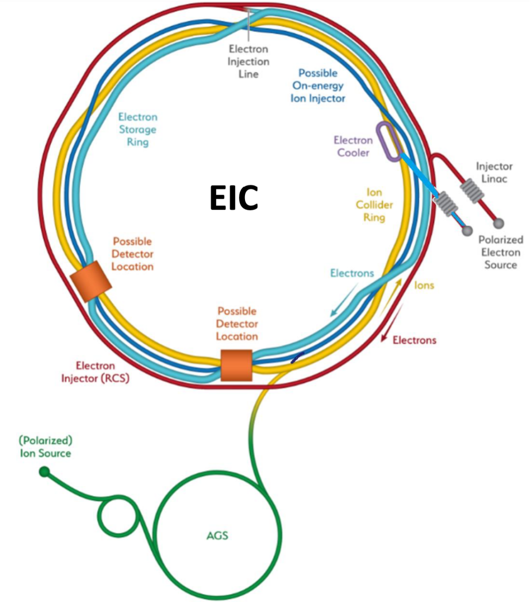

$xyS = Q^2$

# Electron Ion Collider at BNL



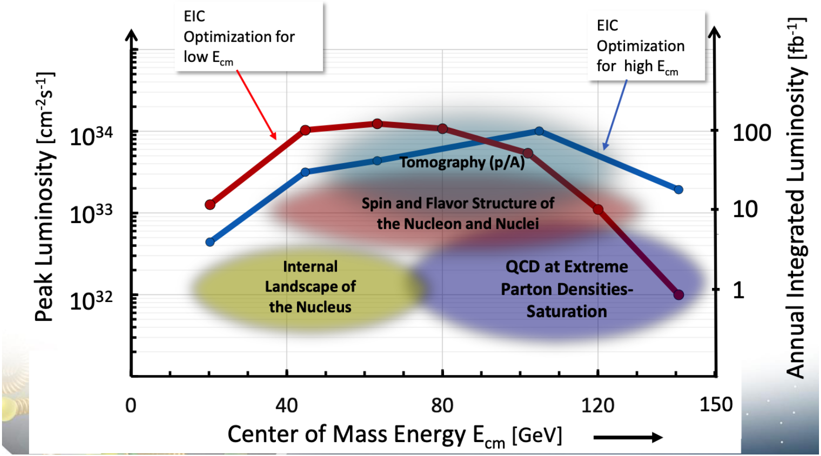

- EIC $\sqrt{S} = 20 - 140\,\mathrm{GeV}$ is smaller than HERA $\sqrt{S} = 318\,\mathrm{GeV}$
- Nuclear beams from $p$ to Uranium - QCD structure of nuclei
- Polarized electron and hadron beams $> 70\%$ - spin physics program
- Maximum Luminosity $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

# EIC Design

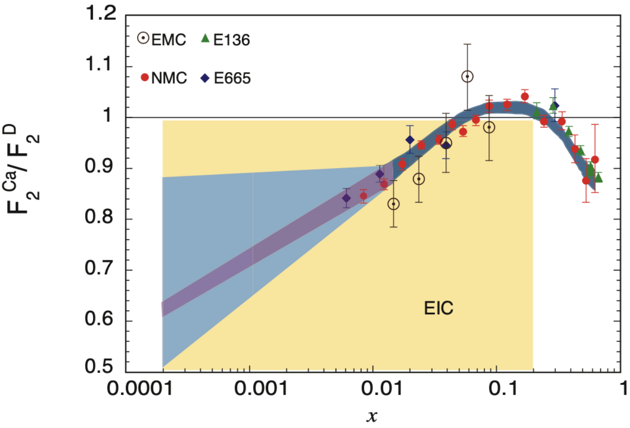


Electron
Injection
Line
Possible
On-energy
Ion Injector
Electron
Storage
Ring
Electron
Cooler
Injector
Linac
EIC
Ion
Collider
Ring
Polarized
Electron
Source
Possible
Detector
Location
Electrons
Ions
Possible
Detector
Location
Electrons
Electron
Injector (RCS)
(Polarized)
Ion Source
AGS

## Luminosity versus $E_{CM}$ center of mass energy



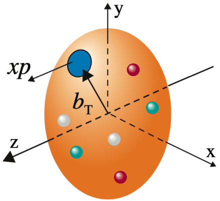
# EMC effect




- Quark and gluon distributions in bound nucleon - nuclear PDFs
- QCD structure of nuclei is directly probed.
- In heavy ion collisions, it is probed through initial state formed in the collision.

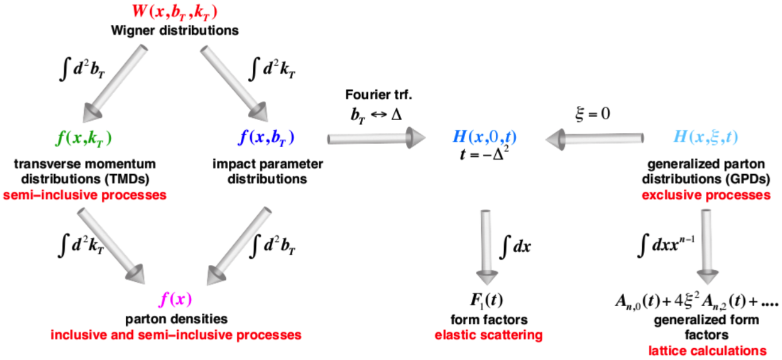
# Nucleon/nucleus tomography

- PDFs: 1-dimensional parton structure in longitudinal momenta - $q(x), \bar{q}(x), G(x)$
- Multidimensional structure - Wigner function $W(x, k_T, b_T)$




- Information on transverse momentum $k_T$ and transverse spatial $b_T$ distributions
- Information about spin structure

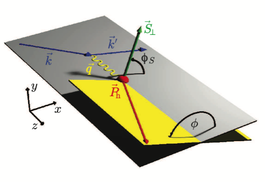
# EIC perspective




- $k_T$-dependence through TMDs: $f(x,k_T) = \langle\, p \,|\, Partonic\ \ Operators \,|\, p \,\rangle$
- $b_T$-dependence through GDPs: $H(x,\xi,t=-\Delta^2) = \langle\, p \,|\, Partonic\ \ Operators \,|\, p' \,\rangle$
- Spins of partons and target come into play

# How to study these distributions?

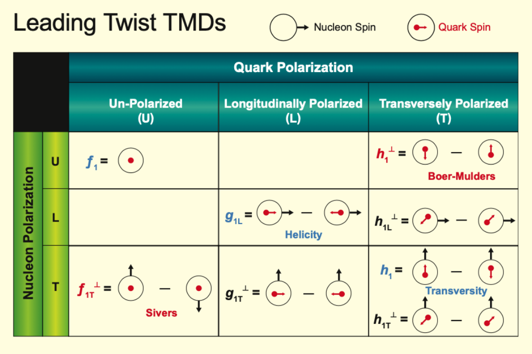
- Semi-inclusive DIS (SIDIS): $e + N(\vec{S}) \to e' + h(\vec{P}) + X$




- Probes 8 polarized and upolarized quark TMDs
- Access to gluon TMDs through

$$h = D\bar{D}$$

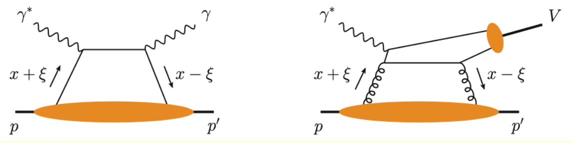
- TMDs - correlate intrinsic $k_T$ of partons with their spin $\vec{s}$ and target spin $\vec{S}$



# How to study these distributions?

- Deeply virtual Compton scattering (DVCS) and exclusive vector meson production:

$$e + N \to e' + \gamma/V + N'$$



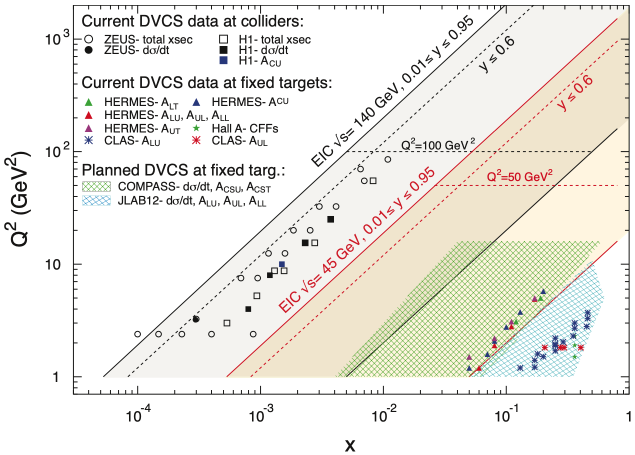

- Probe GPDs: $H^q(x, \xi, t)$ and $E^q(x, \xi, t)$

- Give total angular momentum of nucleon carried by quarks

$$J^q = \frac{1}{2} \int dx\, x\, [H^q(x, \xi, 0) + E^q(x, \xi, 0)]$$

- Spin-orbit correlations of quarks and gluons in nucleon

# DVCS studies at EIC




- Bridging the gap. More precison data.

# Spin physics program

- Longitudinal spin of the nucleon - Jaffe-Manohar sum rule:

$$\frac{1}{2} = S_q + L_q + S_G + L_G$$

- Polarized parton distributions: $\Delta f(x, Q^2) = f^+(x, Q^2) - f^-(x, Q^2)$

$$S_q = \frac{1}{2} \int_0^1 dx \left[\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \ldots\right] , \qquad S_G = \int_0^1 dx \, \Delta G$$

- $g_1(x, Q^2)$ structure function:

$$\frac{1}{2} \left[ \frac{d\sigma^{\leftrightarrows}}{dx dQ^2} - \frac{d\sigma^{\rightrightarrows}}{dx dQ^2} \right] \simeq \frac{4\pi\alpha_{\rm em}^2}{Q^4} y(2-y) \, g_1(x, Q^2)$$

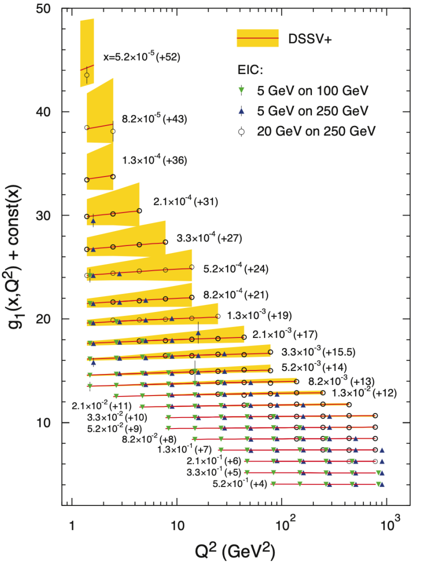
- Parton model relation:

$$g_1(x, Q^2) = \frac{1}{2} \sum_f e_f^2 \left[ \Delta q_f(x, Q^2) + \Delta \bar{q}_f(x, Q^2) - \frac{\alpha_s}{2\pi} \Delta G(x, Q^2) \right]$$

- Sum rule:

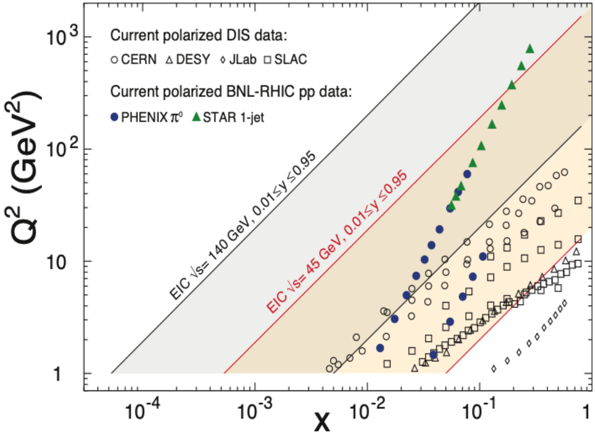
$$\int_0^1 dx \, g_1(x, Q^2) = S_q - \frac{\alpha_s}{4\pi} S_G$$

# Simulated $g_1$ at EIC energies



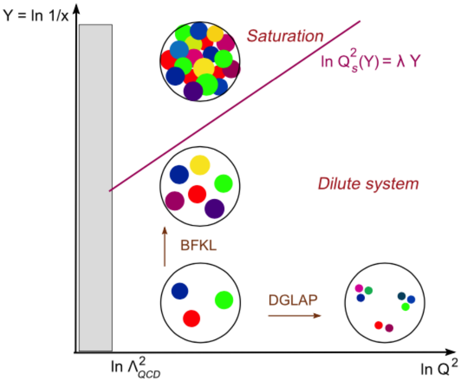

- Scaling violation due to polarized gluon distribution $\Delta G(x, Q^2)$

# Spin physics studies at EIC




- EIC will open new opportunities for spin physics studies

# Parton saturation physics program



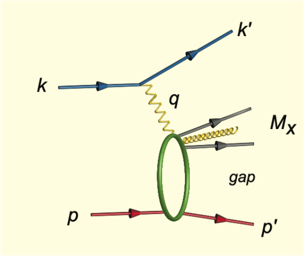

- Parton saturation effects due to dense partonic systems (new regieme of QCD)

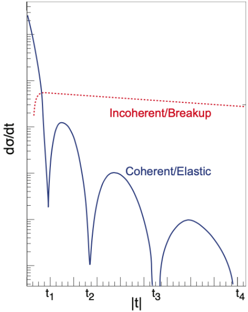
$$Q_s^2(x,A) = Q_0^2 \left(\frac{A}{x}\right)^{1/3} > 1\ GeV^2$$

- Impact on structure functions at low $x$. Diffractive processes at low $x$

# Diffractive DIS at EIC

- Diffractive processes: $25 - 30\%$ events in $eA$ - forward physics



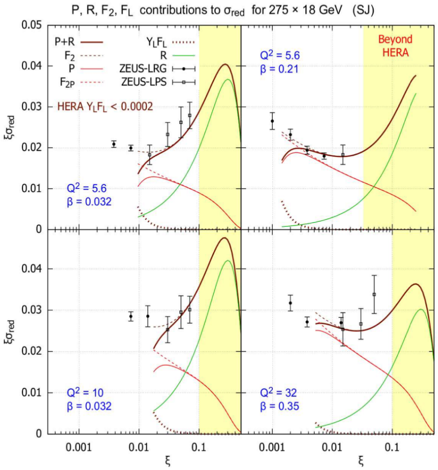




- Saturation effects in green interaction, responsible for rapidity gap
- Coherent and incoherent VM production - nucleus stays intact or breaks up
- Onset of the black disc limit?

$$\frac{(\sigma_{\rm el} + \sigma_{\rm diff})}{\sigma_{\rm tot}} = \frac{1}{2}$$

Wojtek Słomiński 2020

## Pomeron, Reggeon, $F_2$, $F_L$ components of $\sigma_{red}$




$$\xi \sigma_{\text{red}}^{D(3)} \sim \xi^{-0.2} \sigma_P + \xi^{0.6} \sigma_R$$

- ❑ Pomeron dominates at low $\xi$, particularly at high $\beta$
  - ❑ very interesting region for the Pomeron measurement
- ❑ $\mathbb{R}$ contribution grows with $\xi$
  - ❑ High $\xi$ required for the determination of subleading “Reggeon” term

$$\sigma_{\text{red}} = F_2 - \frac{y^2}{1 + (1-y)^2} F_L$$

- ❑ Significant $F_L$ component, ~30 times higher than at HERA
  - ❑ However, some intermediate beam energy settings needed for $F_L$ measurements

# Summary

- EIC opens new opportunities to study partonic structure of nucleons and nuclei:
- Nuclear PDFS
- Nucleon/nucleus tomography
- Spin physics
- Parton saturation studies