Diffraction in hadronic collisions

With focus on the ep/eA at EIC

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Outline

Lecture 1: introduction, diffraction in QCD, HERA measurements

Lecture 2: prospects at EIC: proton tagging capabilities, reduced cross section and DPDFs, longitudinal structure function, elastic vector meson production

Focus will be on ep/eA. Not pp.

EIC White paper 1212.1701

EIC Yellow Report, 2103.05419

Armesto, Newman, Słomiński, Staśto 1901.09076, 2112.06839

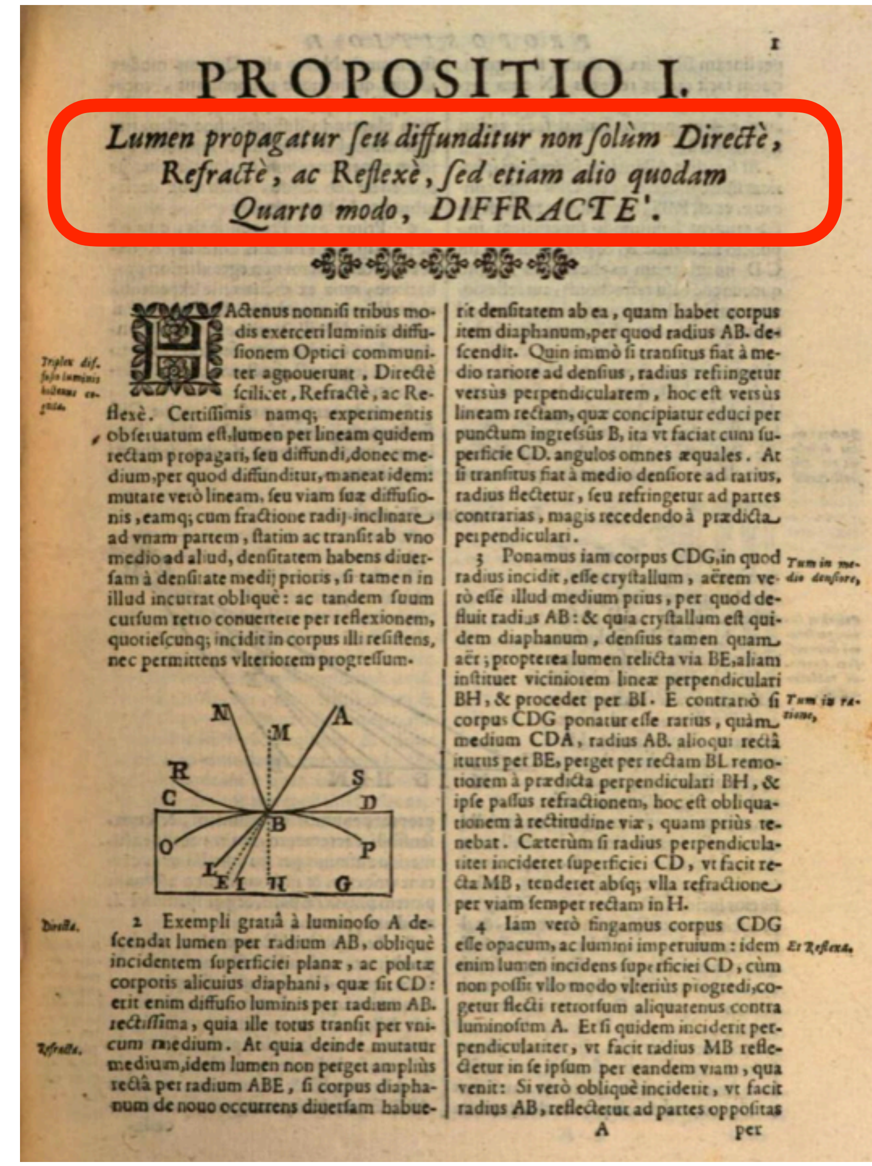
Frankfurt, Guzey, Staśto, Strikman 2203.12289

Diffraction in optics

Francesco Maria Grimaldi
1618-1663

Jesuit priest from Bologna

PHYSICO-MATHESIS
DE LVMINE,
COLORIBVS, ET IRIDE,
ALIISQVE ADNEXIS
LIBRI DVO,
In quorum Primo afferuntur Noua Experimenta, & Rationes ab iis deductæ pro Substantialitate Luminis.
In Secundo autem dissoluuntur Argumenta in Primo adducta, & probabiliter sustineri posse docetur Sententia Peripatetica de Accidentalitate Luminis.
QVA OCCASIONE
...
AVCTORE
P. FRANCISCO MARIA GRIMALDO
SOCIETATIS IESV.
OPVS POSTHVMVM.
BONONIÆ, M.DC.LXV.
Ex Typographia Hæredis Victorij Benatij. Superiorum permissu.



PROPOSITIO I.

Lumen propagatur seu diffunditur non solùm Directè, Refractè, ac Reflexè, sed etiam alio quodam Quarto modo, DIFFRACTE'.

Triplex diffusio luminis hactenus cognita. HActenus nonnisi tribus modis exerceri luminis diffusionem Optici communiter agnouerunt, Directè scilicet, Refractè, ac Reflexè. Certissimis namq; experimentis obseruatum est, lumen per lineam quidem rectam propagari, seu diffundi, donec medium, per quod diffunditur, maneat idem: mutare verò lineam, seu viam suæ diffusionis, eamq; cum fractione radij inclinare ad vnam partem, statim ac transit ab vno medio ad aliud, densitatem habens diuersam à densitate medij prioris, si tamen in illud incurrat obliquè: ac tandem suum cursum retro conuertere per reflexionem, quotiescunq; incidit in corpus illi resistens, nec permittens vlteriorem progressum.

Directè. 2 Exempli gratiâ à luminoso A descendat lumen per radium AB, obliquè incidentem superficiei planæ, ac politæ corporis alicuius diaphani, quæ sit CD: erit enim diffusio luminis per radium AB. rectissima, quia ille totus transit per vnicum medium. *Refractè.* At quia deinde mutatur medium, idem lumen non perget ampliùs rectâ per radium ABE, si corpus diaphanum de nouo occurrens diuersam habuerit densitatem ab ea, quam habet corpus item diaphanum, per quod radius AB. descendit. Quin immò si transitus fiat à medio rariore ad densius, radius refringetur versùs perpendicularem, hoc est versùs lineam rectam, quæ concipiatur educi per punctum ingressûs B, ita vt faciat cum superficie CD. angulos omnes æquales. At si transitus fiat à medio densiore ad rarius, radius flectetur, seu refringetur ad partes contrarias, magis recedendo à prædicta perpendiculari.

3 Ponamus iam corpus CDG, in quod radius incidit, esse crystallum, aërem verò esse illud medium prius, per quod defluit radius AB: & quia crystallum est quidem diaphanum, densius tamen quam aër; propterea lumen relicta via BE, aliam instituet viciniorem lineæ perpendiculari BH, & procedet per BI. *Tum in medio densiore,* E contrariò si corpus CDG ponatur esse rarius, quàm medium CDA, radius AB. alioqui rectâ iturus per BE, perget per rectam BL remotiorem à prædicta perpendiculari BH, & ipse passus refractionem, hoc est obliquationem à rectitudine viæ, quam priùs tenebat. *Tum in ratione,* Cæterùm si radius perpendiculariter incideret superficiei CD, vt facit recta MB, tenderet absq; vlla refractione per viam semper rectam in H.

4 Iam verò fingamus corpus CDG esse opacum, ac lumini imperuium: idem enim lumen incidens superficiei CD, cùm non possit vllo modo vlteriùs progredi, cogetur flecti retrorsum aliquatenus contra luminosum A. *Et Reflexè.* Et si quidem inciderit perpendiculariter, vt facit radius MB reflectetur in se ipsum per eandem viam, qua venit: Si verò obliquè inciderit, vt facit radius AB, reflectetur ad partes oppositas

A per

'Light propagates and diffuses not only directly, refractively and reflectively, but also, somehow, in a fourth manner, that is DIFFRACTIVELY.'

Theory of diffraction

Christiaan Huygens
1629-1695

Augustin Fresnel
1788-1827

Gustav Kirchhoff
1824-1887

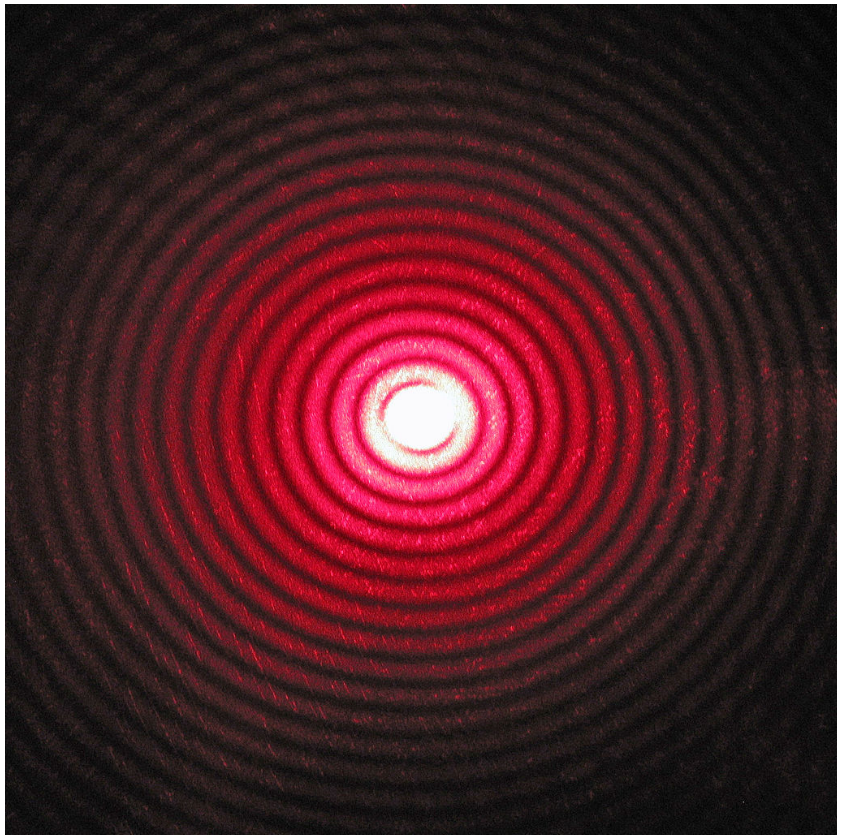
Geometrical optics: applicable in the limit when the wavelength is infinitely small

Diffraction phenomena: deviation from geometrical optics due to finite wavelength

Diffraction

Diffraction : occurs when a wave (for example light) encounters an obstacle or an opening. Most pronounced when the dimensions of obstacle/opening are comparable to wavelength

Laser light passing through a circular aperture



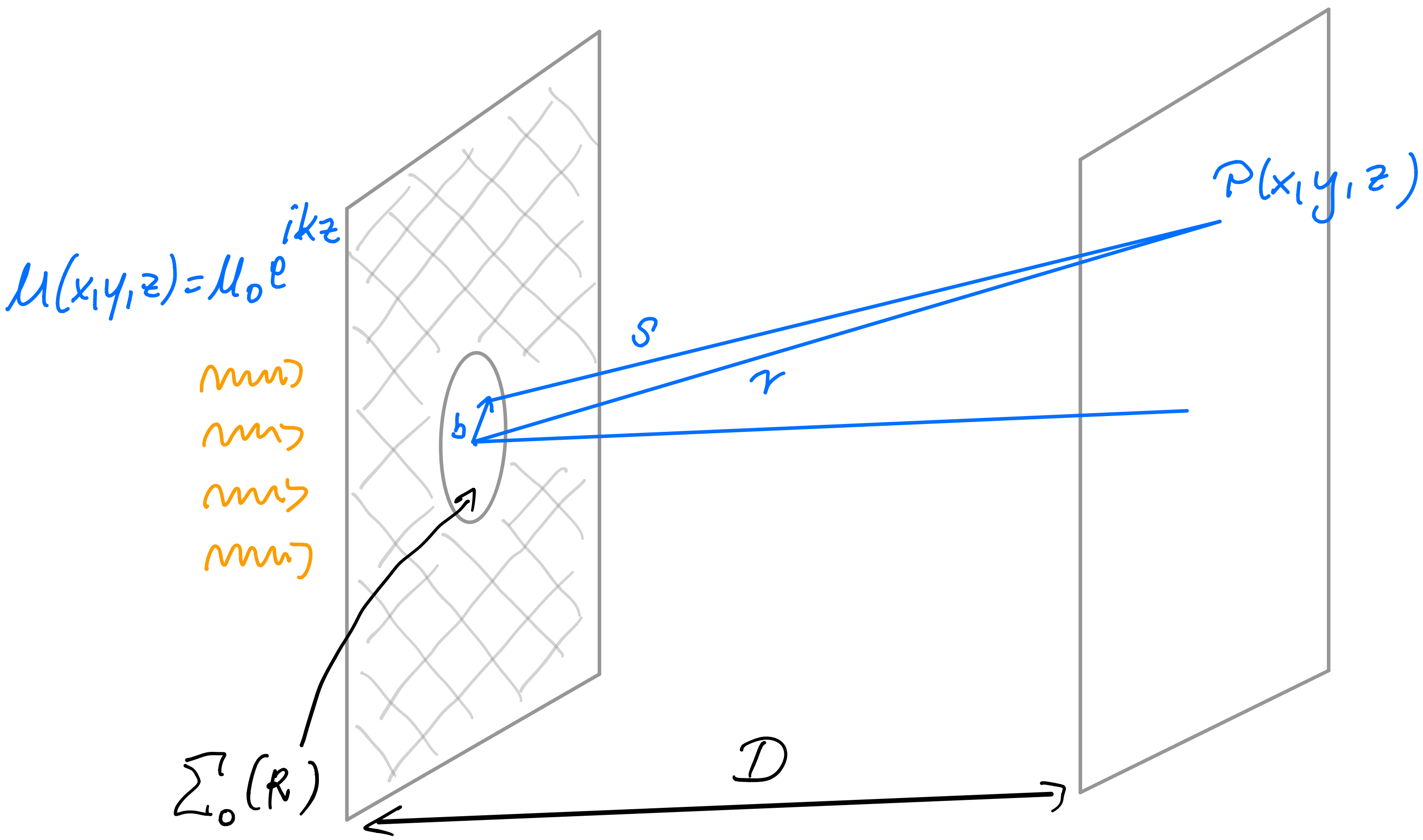
Source: Wikipedia
Author: Wisky

Water waves passing through small entrance

Source: Wikipedia
Author: Verbcatcher

In quantum theory: hadronic and nuclear **diffractive** scattering

Kirchhoff theory



$$P \equiv (x, y, z)$$

$$k = 2\pi/\lambda$$

Wave number

U Amplitude

$$\phi(x,y,z,t) = U(x,y,z)e^{-i\omega t}$$

$$(\nabla^2 + k^2)U = 0$$

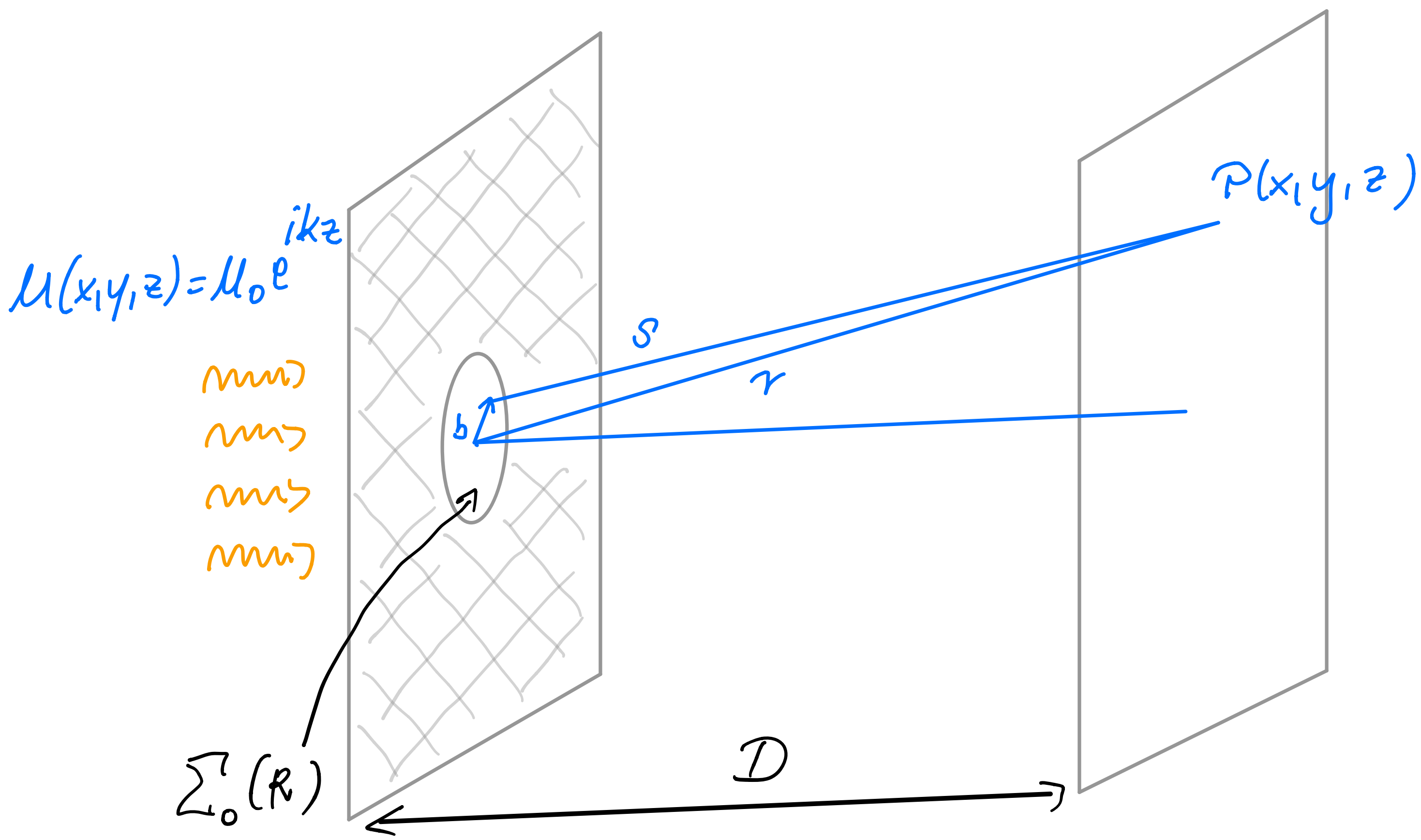
Helmholtz equation

Short wave length limit (kR>1)

$$U(x,y,z) = -\frac{ik}{2\pi} U_0 \int_{\Sigma_0} d^2\mathbf{b} \frac{e^{iks}}{s}$$

Fresnel-Kirchhoff integral

Kirchhoff theory



Geometrical optics: $kR^2/D \gg 1$

Fresnel diffraction: $kR^2/D \approx 1$ Near field

Fraunhofer diffraction: $kR^2/D \ll 1$ Far field

Relevant for hadronic physics

Fraunhofer diffraction

For the hole in the screen:

$$U(x,y,z) = -\frac{ik}{2\pi} U_0 \frac{e^{ikr}}{r} \int d^2\mathbf{b}\, \Gamma(\mathbf{b})\, e^{-i\mathbf{q}\mathbf{b}}$$

$\mathbf{q} \approx \mathbf{k}' - \mathbf{k}$ Momentum transfer (2 dimensional vector)

$\mathbf{k}$ Incoming wave vector

$\mathbf{k}'$ Outgoing wave vector

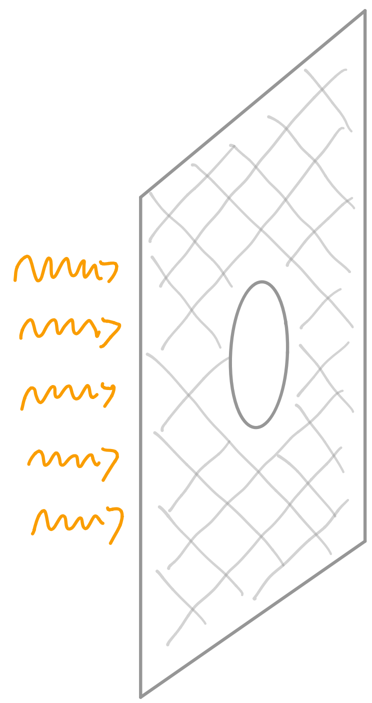
$\Gamma(\mathbf{b})$ Profile function

For the hole:

$$\Gamma(\mathbf{b}) = \begin{cases} 1, & \text{on } \Sigma_0 \\ 0, & \text{outside } \Sigma_0 \end{cases}$$

Diffraction off an obstacle

Babinet's principle:



S1 Screen with a hole

S2 Obstacle with the same size and shape as a hole

Waves diffracted by a hole S1 and obstacle S2 must combine to reconstruct the incident wave front.

Diffraction patterns away from incident direction are the same for screen with hole and complementary obstacle.

Diffraction off an obstacle

$$U(x,y,z) = U_{\text{inc}} + U_{\text{scat}}$$

$$U(x,y,z) = U_0 (e^{ikz} + f(\mathbf{q}) \frac{e^{ikr}}{r})$$

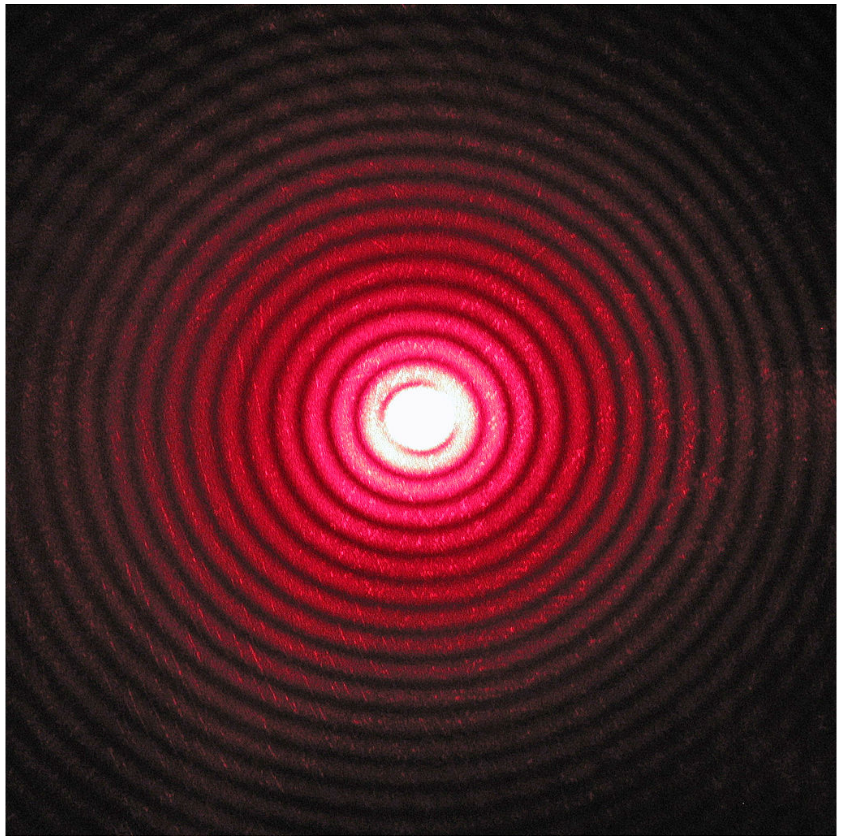
Scattering amplitude

$$f(\mathbf{q}) = \frac{ik}{2\pi} \int d^2\mathbf{b}\, \Gamma(\mathbf{b})\, \mathbf{e}^{-\mathbf{iq}\cdot\mathbf{b}}$$

$$\Gamma(\mathbf{b}) = \frac{1}{2\pi i k} \int d^2\mathbf{b}\, f(\mathbf{q})\, e^{i\mathbf{q}\cdot\mathbf{b}}$$

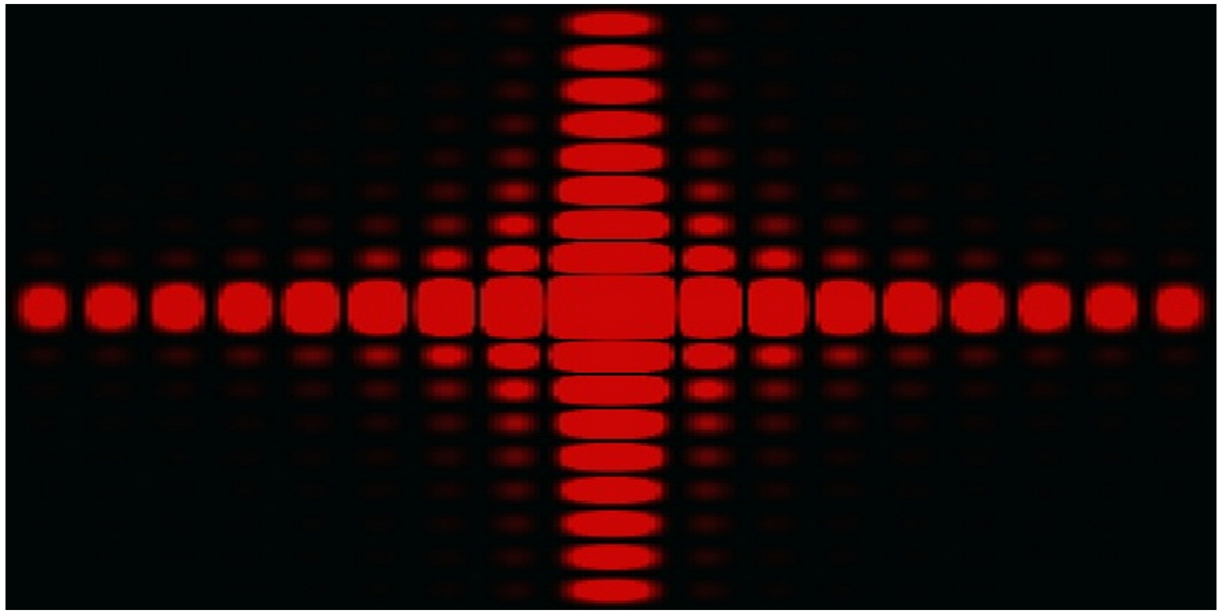
Scattering amplitude is Fourier transform of the profile function.
Profile function is inverse Fourier transform of the scattering amplitude.

Diffraction patterns



Source: Wikipedia
Author: Wisky

Circular aperture



Source: Wikipedia
Author: Epzcaw

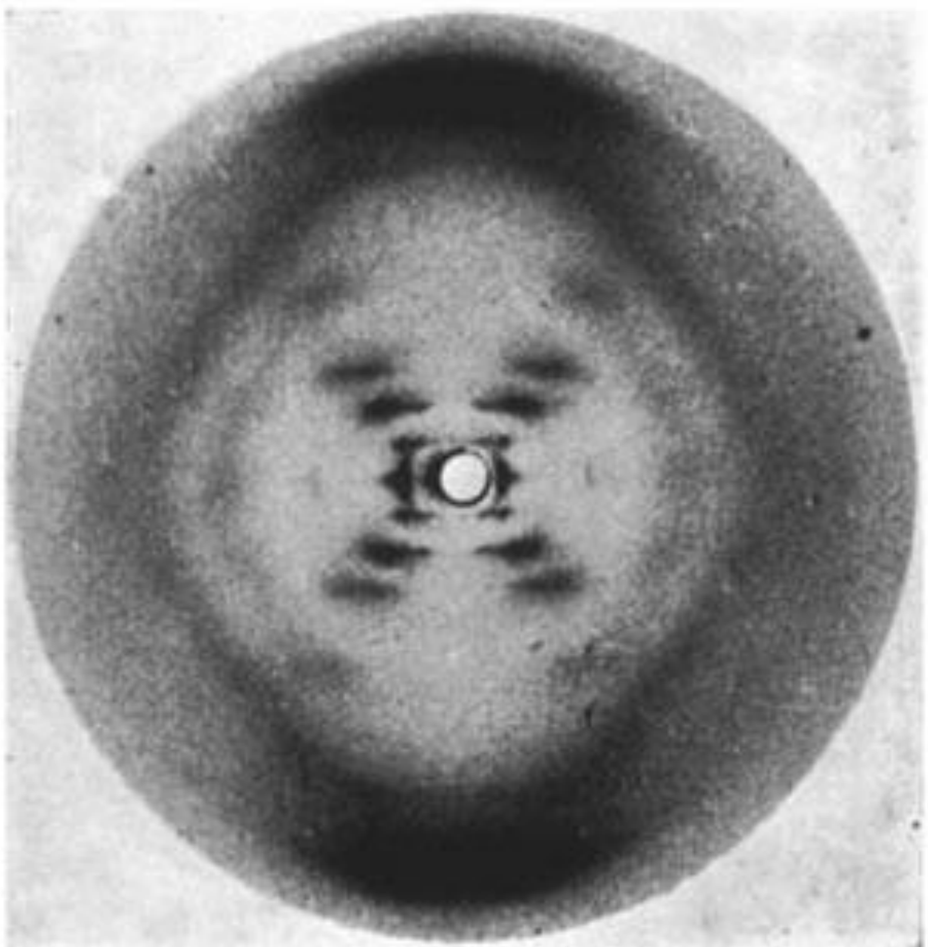
Rectangular aperture

The diffraction pattern (far away from obstacle) is a Fourier transform of the apertured field.

Diffraction pattern

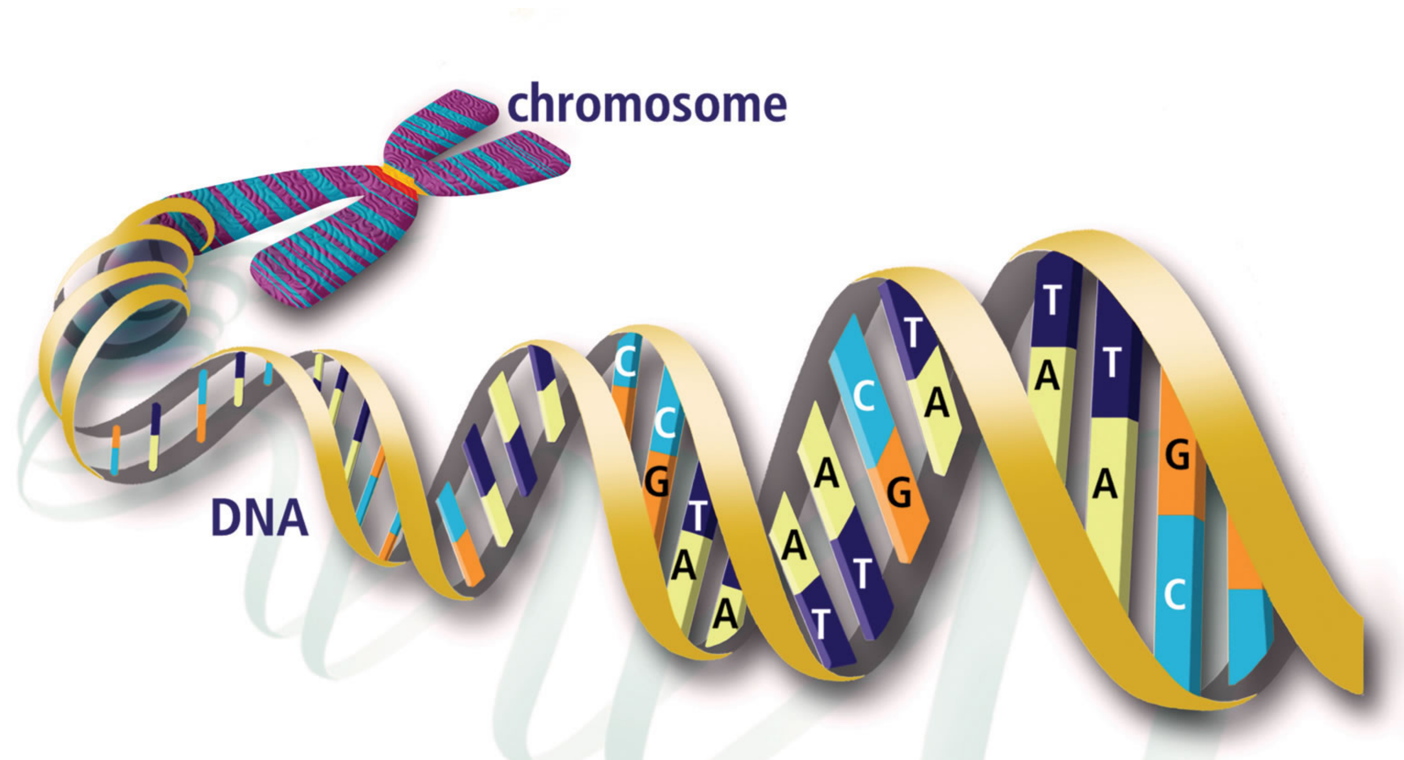
Photo 51

Gosling-Franklin



Source: Wikipedia

Watson-Crick



Source: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science

Diffraction can provide very detailed information about the structure of an object.

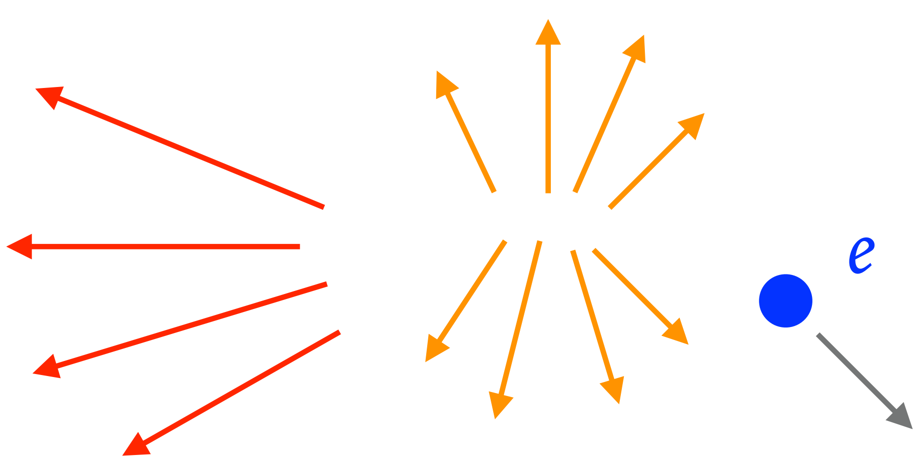
The object cannot be destroyed in this process.

Diffraction in hadronic / nuclear physics

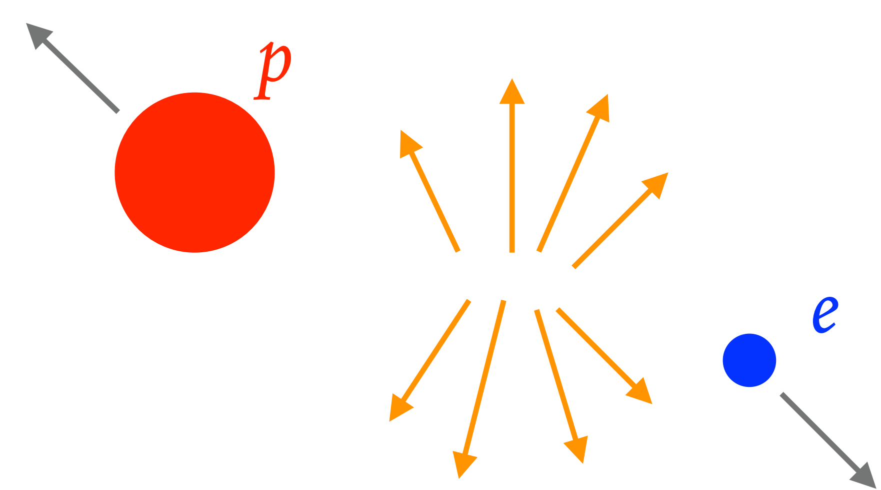
In quantum physics: propagation and interaction of particles as an absorption of the various components of their wavefunction

Electron - hadron(nucleus) scattering (like at EIC)

10% processes at HERA were diffractive



Proton is fragmented (inelastic process)



Target (proton) is intact
Activity in central region

Scattering at ep collider HERA

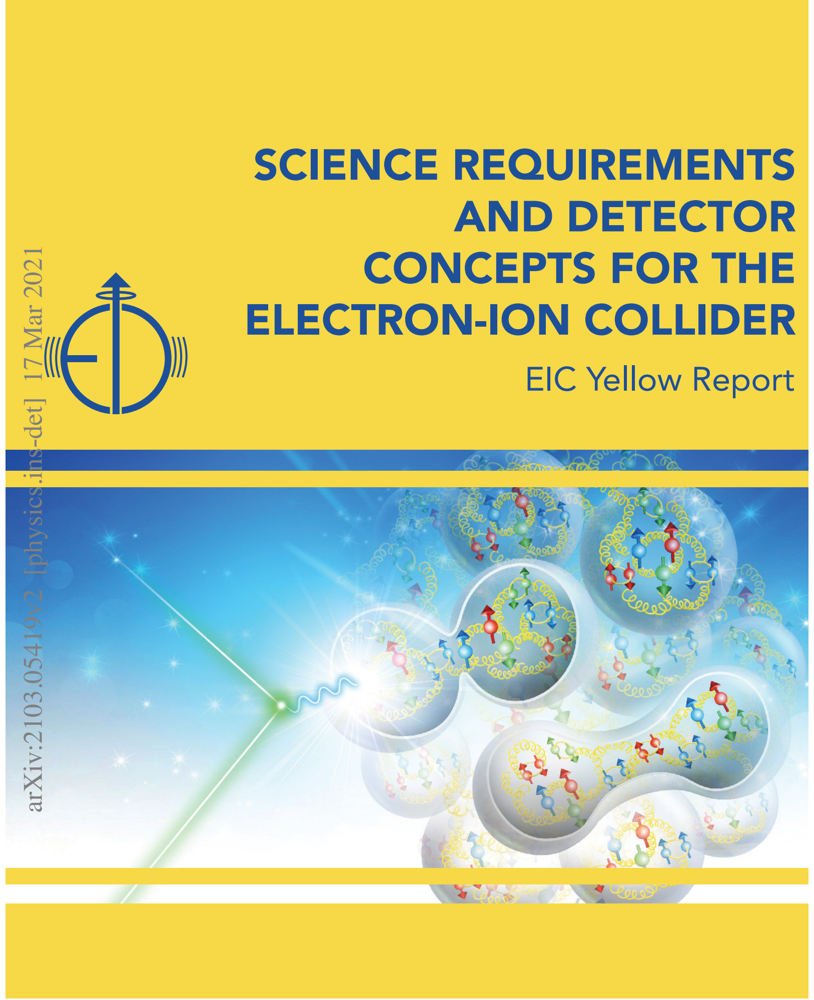
HERA: (1992-2007)
27.5 GeV electrons/positrons
820/920 GeV protons
318 GeV CoM energy
Lumi: 10^{31} cm^{-2} s^{-1}
Electrons, positrons and protons

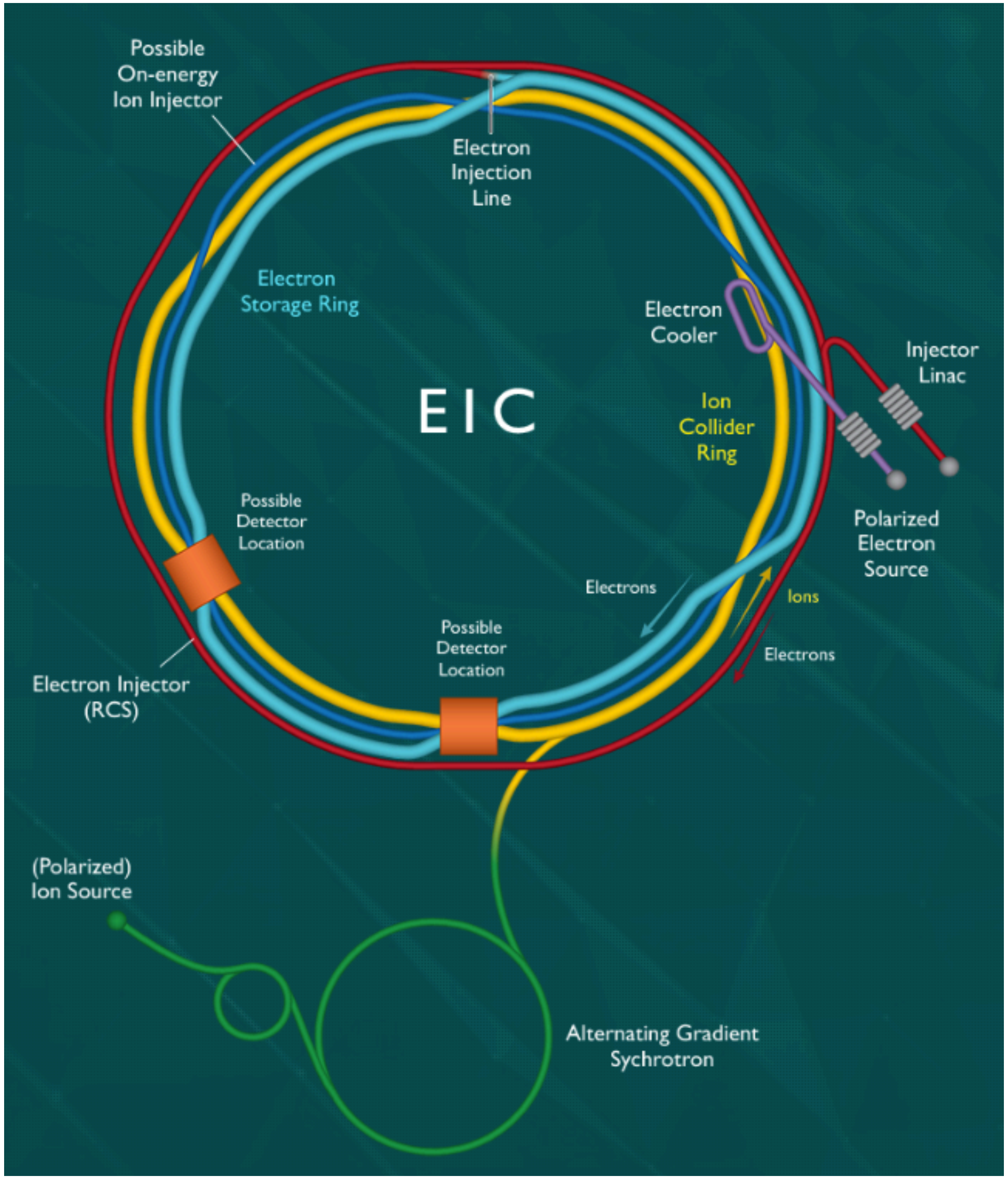
Physics:
Structure functions
Parton density functions
Established growth of gluon with decreasing Bjorken x
Measurement of coupling constant
Diffraction
Jets, heavy quarks
BSM searches

Low luminosity/limited statistics, no nuclei, no polarized beams

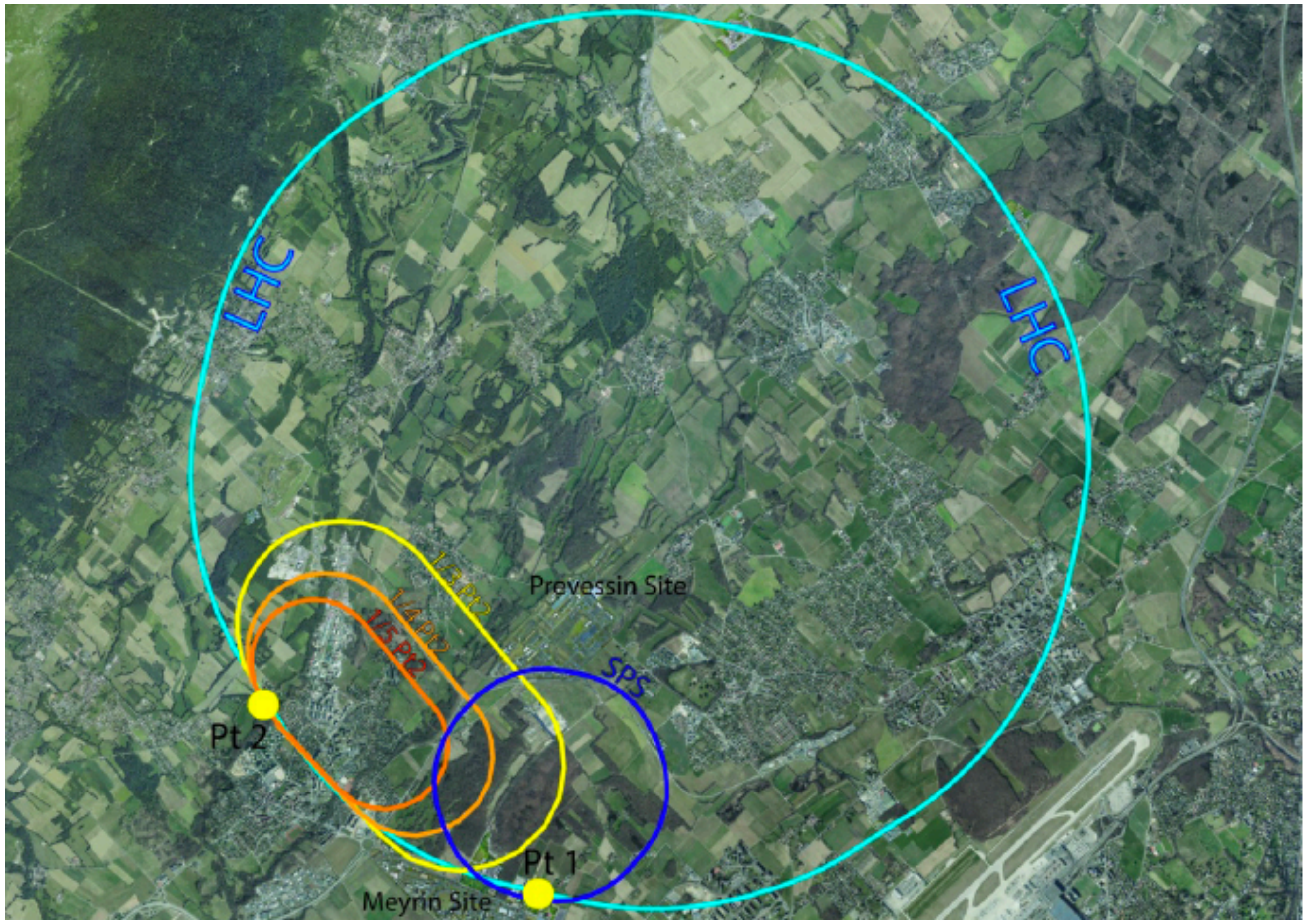
Future DIS machines EIC

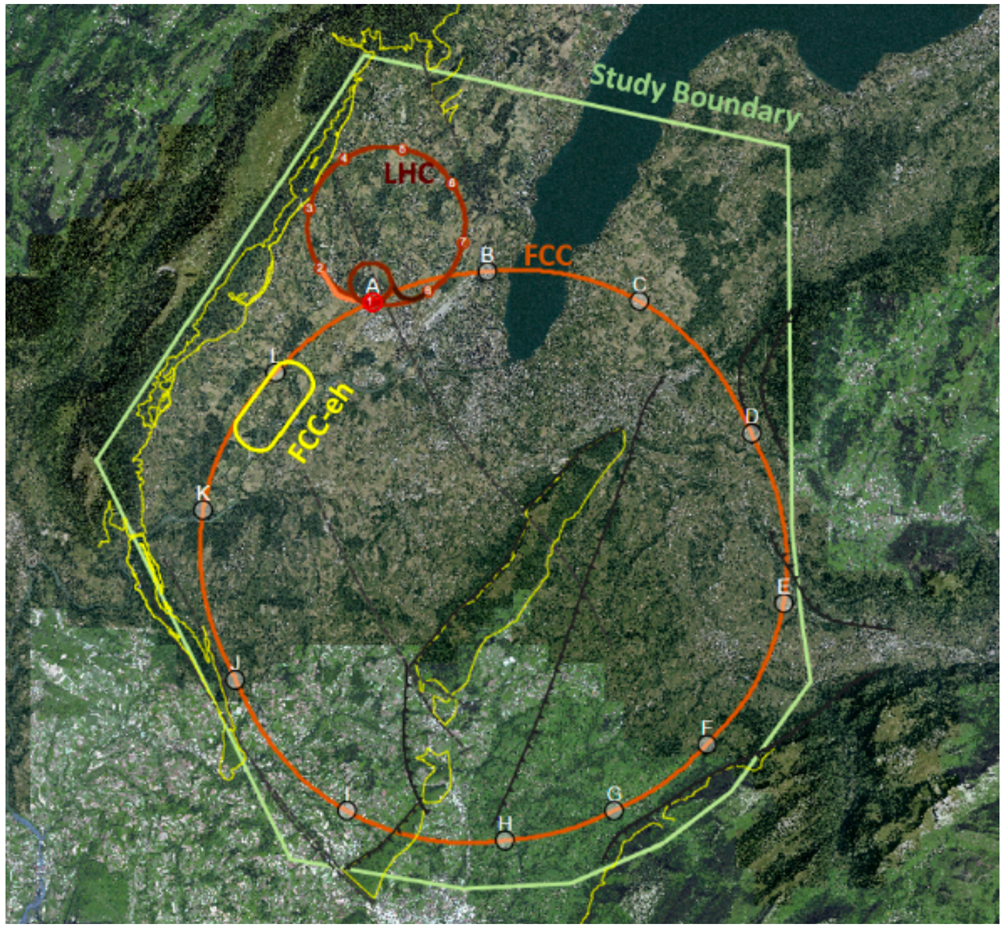
EIC: 5-20 GeV electrons
20-140 GeV CoM energy
Lumi: 10^{34} cm^{-2} s^{-1}
Polarized e,p,d,^{3}He
Wide range of nuclei





Future DIS machines LHeC, FCC-eh at CERN



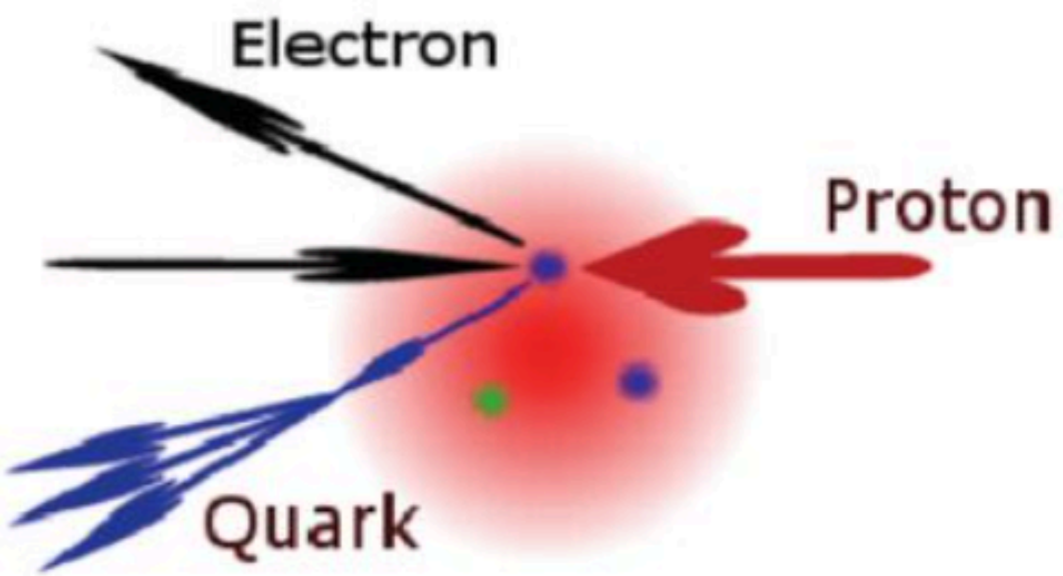


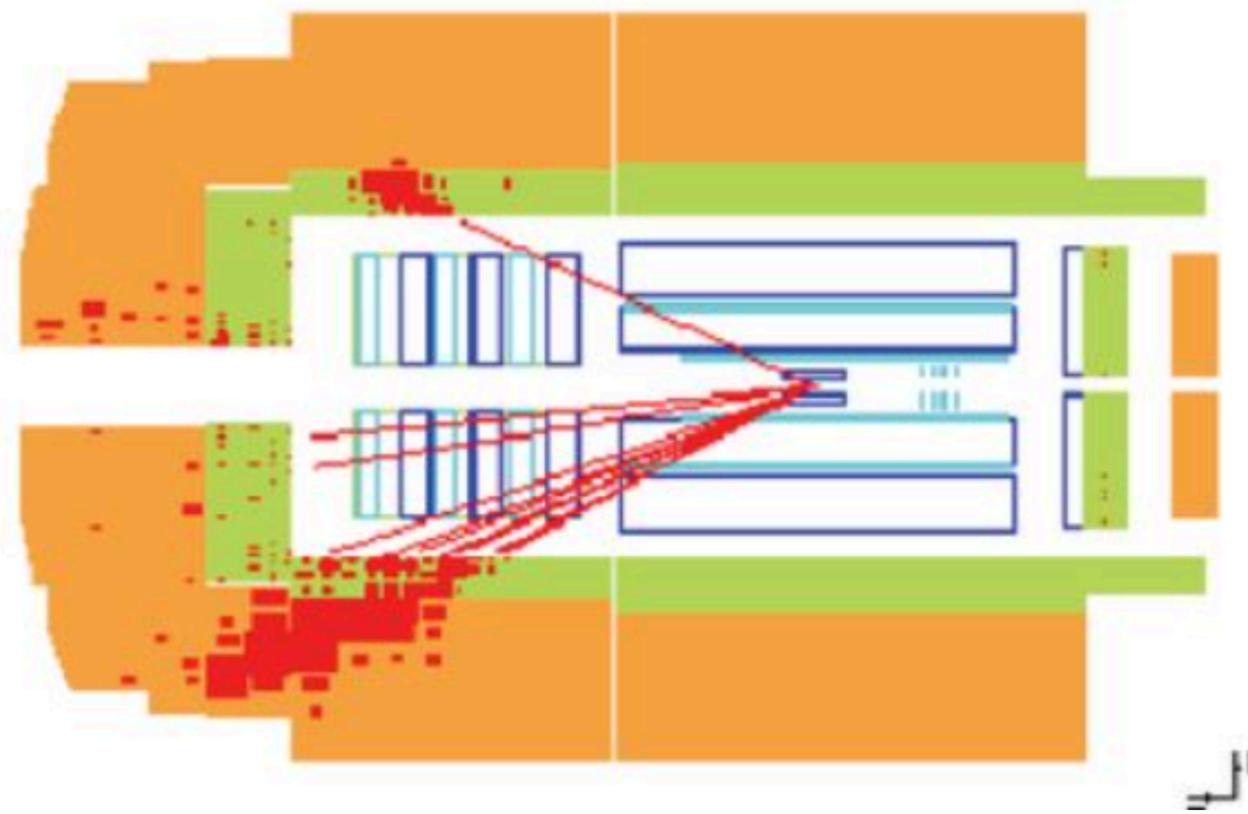
LHeC: 60(50) GeV electrons x LHC protons and ions
1.3 TeV CoM energy for ep
812 GeV CoM for ePb
Lumi: 10^{34} cm^{-2} s^{-1}
Simultaneous running with ATLAS and CMS in HL-LHC period

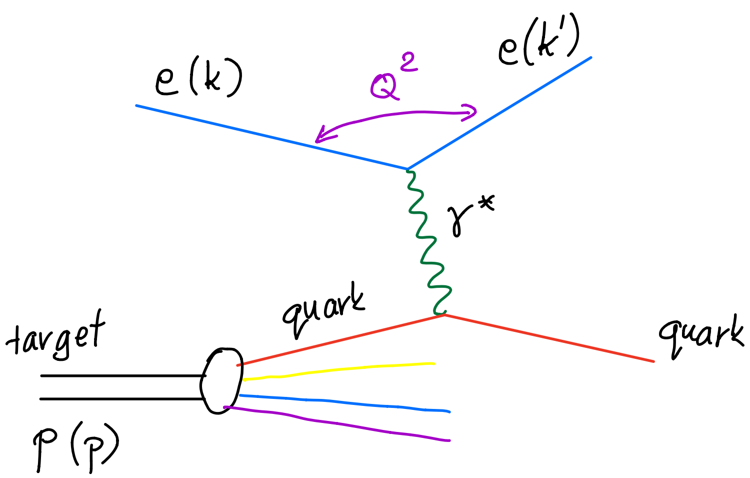
FCC-ep: 60(50) GeV electrons x 50 TeV protons from FCC, lead beams 19.7 TeV/per nucleon
3.5 TeV CoM energy for ep
2.2 TeV CoM for ePb
Lumi: 10^{34} cm^{-2} s^{-1}

Scattering at ep collider HERA

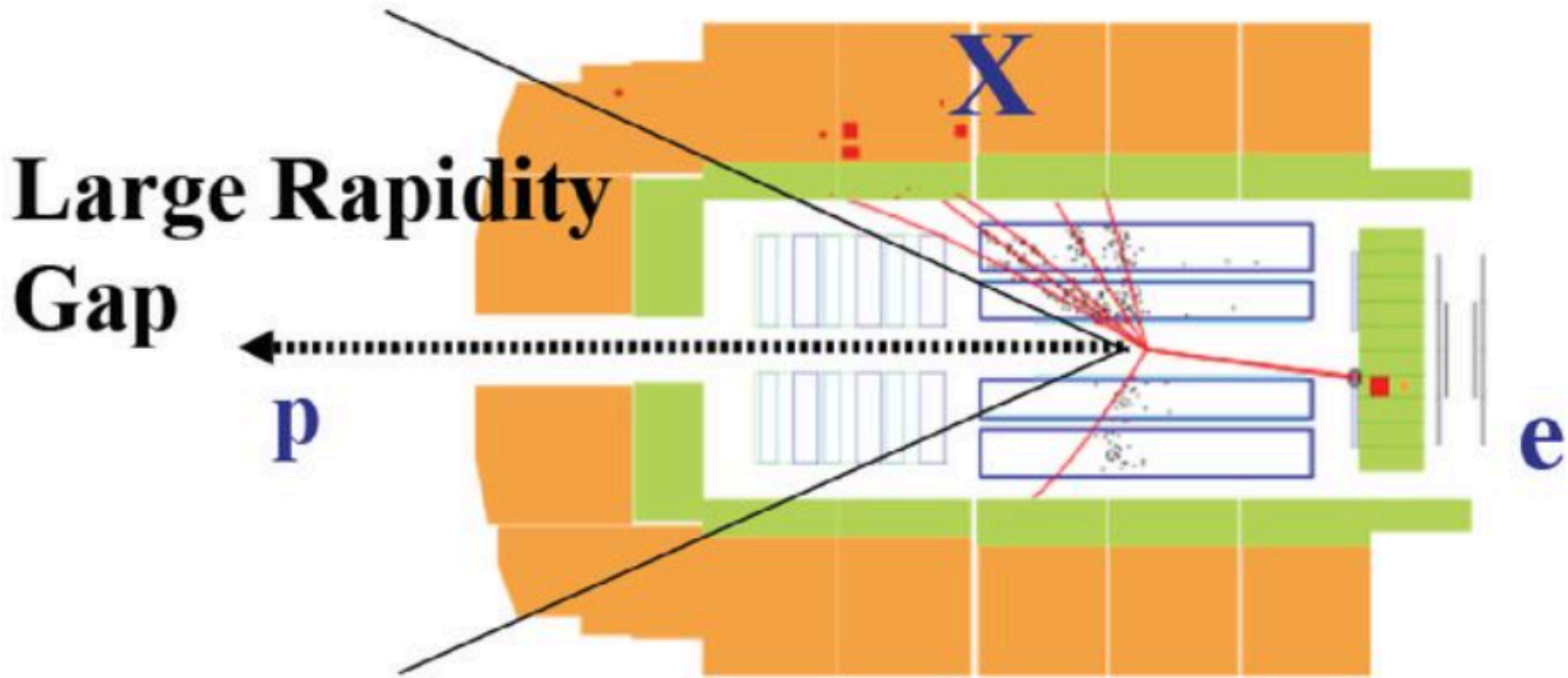
Non-diffractive DIS event







Diffraction at HERA



10% events at HERA were of diffractive type

Large portion of the detector void of any particle activity: rapidity gap

Proton stays intact despite undergoing violent collision with a 50 TeV electron (in its rest frame)

Rapidity: recap

$$p^\mu = (E, \vec{p}_T, p_z) \qquad y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \qquad \frac{E}{p_z} = \tanh y$$

Under boosts in z direction rapidity transforms additively

$$\begin{pmatrix} p_z \\ E \end{pmatrix} = \begin{pmatrix} \cosh\phi & \sinh\phi \\ \sinh\phi & \cosh\phi \end{pmatrix} \begin{pmatrix} p'_z \\ E' \end{pmatrix}$$

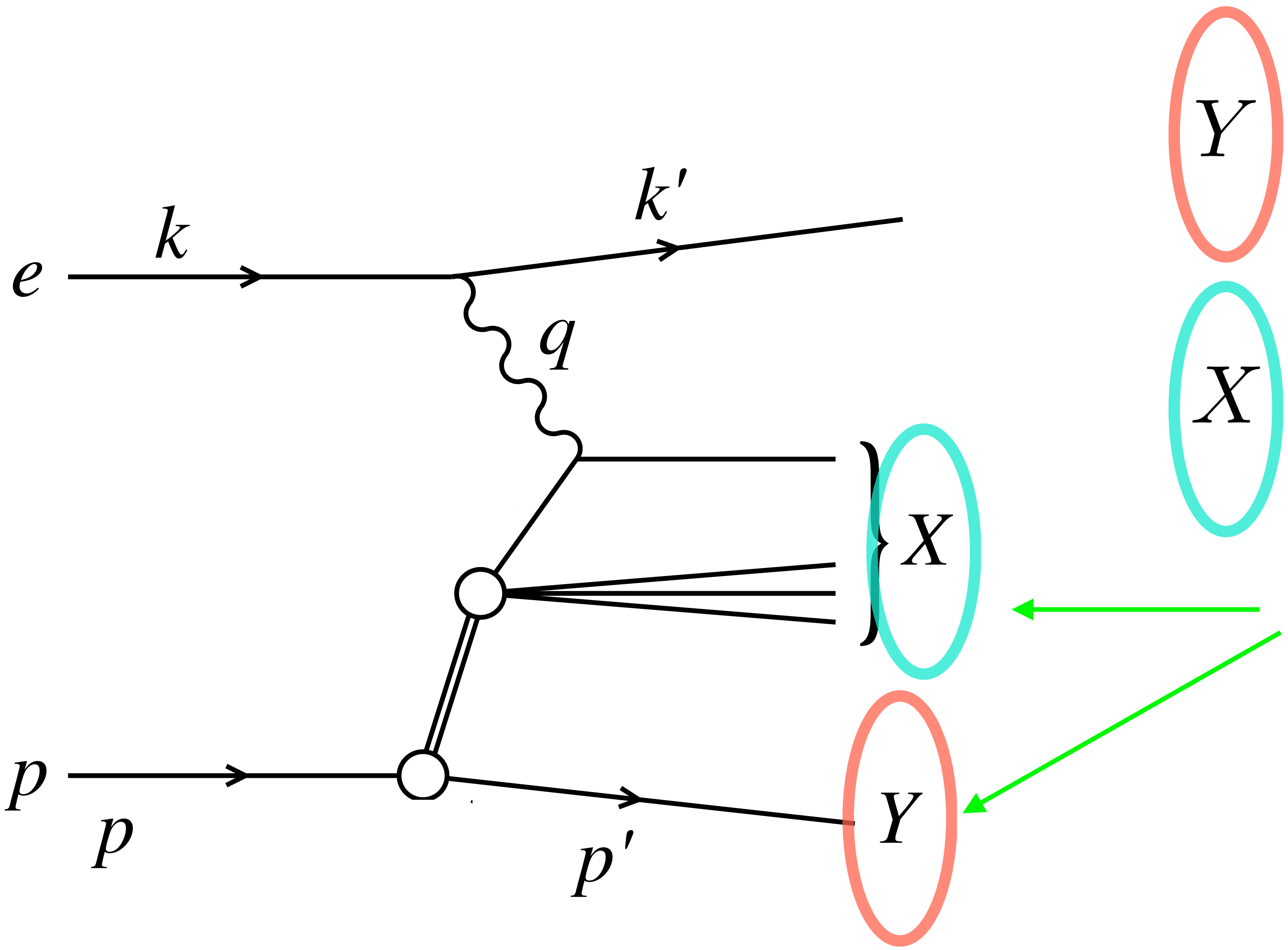
Then $y = y' + \phi$

Pseudorapidity $\eta = -\ln\tan\frac{\theta}{2}$

Angle between 3-momentum and z-axis

When $m \ll |\vec{p}_T|$ then $y \to \eta$

Diffraction in electron - proton(nucleus)



Final state: elastically scattered proton, or the system with the same quantum numbers

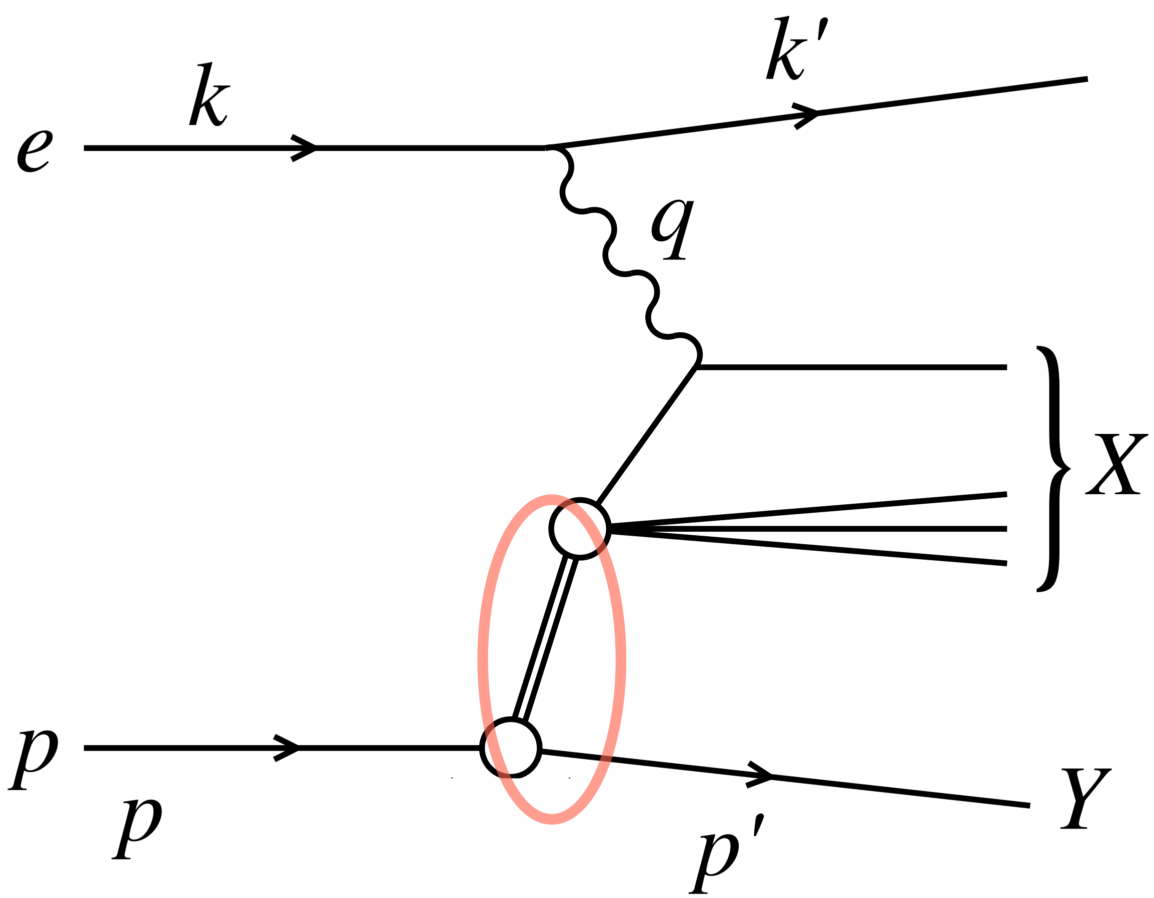
Diffractive system with mass M_x

Rapidity gap

In order for the rapidity gap to exist it needs to be mediated by the colorless exchange

Diffraction: a reaction characterized by a rapidity gap in the final state

Diffraction and the Pomeron



Diffraction: a reaction characterized by a large rapidity gap in the final state

In order for the rapidity gap to exist it needs to be mediated by the **colorless diffractive exchange**

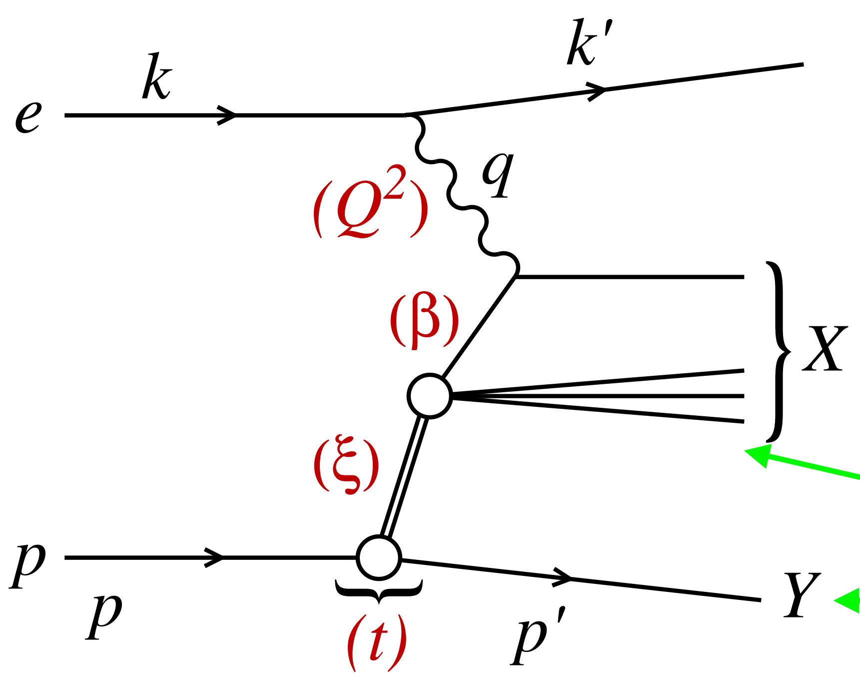
But what is this **diffractive exchange** ?

Usually referred to as the **Pomeron**.
Quantum numbers of the vacuum

Modeled as a composite system of gluons and/or quarks.

Studying diffractive processes can shed light onto properties of this intriguing object.

Diffractive kinematics in DIS



Standard DIS variables:

electron-proton cms energy squared:

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

photon-proton cms energy squared:

$$W^2 = (q+p)^2$$

inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Bjorken x

$$x = \frac{-q^2}{2p \cdot q}$$

(minus) photon virtuality

$$Q^2 = -q^2$$

Target is scattered elastically: elastic scattering

It can also dissociate into a state Y with the same quantum numbers, but still separated from the rest of particles

Diffractive DIS variables:

$$x = \xi \beta$$

$$\xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron w.r.t hadron

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

momentum fraction of parton w.r.t Pomeron

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

4-momentum transfer squared

Reduced cross section, structure functions

Recall the reduced cross section in inclusive DIS:

$$\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi\alpha_{\rm em}^2}{xQ^4} Y_+ \, \sigma_{\rm r}(x,Q^2)$$

Dimensions:

$$Y_+ = 1 + (1-y)^2$$

$\sigma_{\rm r}$ Dimensionless

Reduced cross section depends on two structure functions:

$$\sigma_{\rm r}(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

$$F_T = F_2 - F_L$$ transverse structure function

$$F_L$$ longitudinal structure function

Diffractive cross section, structure functions

Diffractive cross section depends on 4 variables (ξ,β,Q^2,t):

$$\frac{d^4\sigma^D}{d\xi d\beta dQ^2 dt} = \frac{2\pi\alpha_{\rm em}^2}{\beta Q^4} Y_+ \, \sigma_{\rm r}^{\rm D(4)}(\xi,\beta,Q^2,t)$$

$$Y_+ = 1 + (1-y)^2$$

Reduced cross section depends on two structure functions:

$$\sigma_{\rm r}^{\rm D(4)}(\xi,\beta,Q^2,t) = F_2^{\rm D(4)}(\xi,\beta,Q^2,t) - \frac{y^2}{Y_+} F_L^{\rm D(4)}(\xi,\beta,Q^2,t)$$

Upon integration over t:

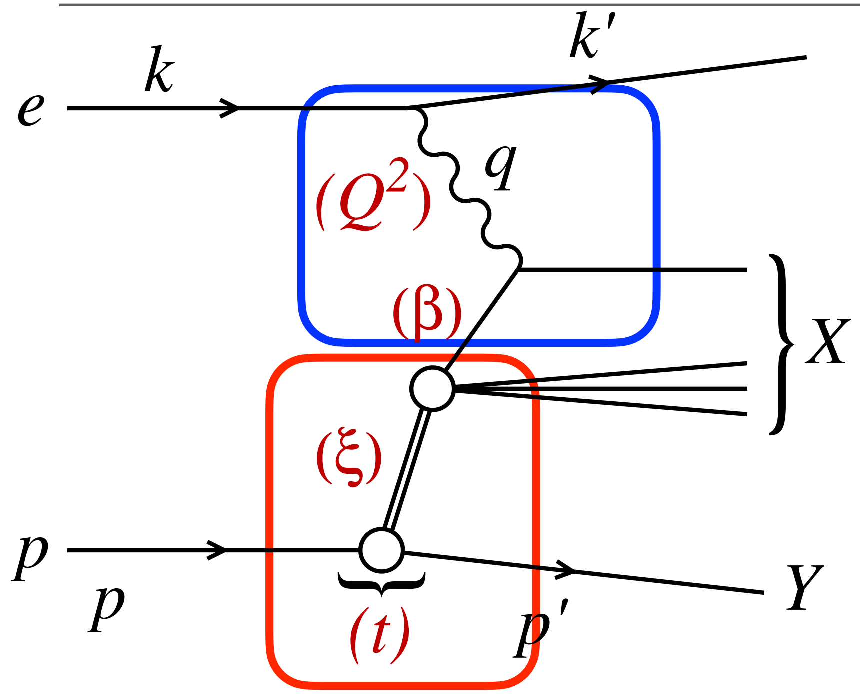
$$F_{2,L}^{\rm D(3)}(\xi,\beta,Q^2) = \int_{-\infty}^{0} dt \, F_{2,L}^{\rm D(4)}(\xi,\beta,Q^2,t)$$

Dimensions:

$[\sigma_{\rm r}^{\rm D(4)}] = {\rm GeV}^{-2}$

$\sigma_{\rm r}^{\rm D(3)}$ Dimensionless

Collinear factorization for diffraction



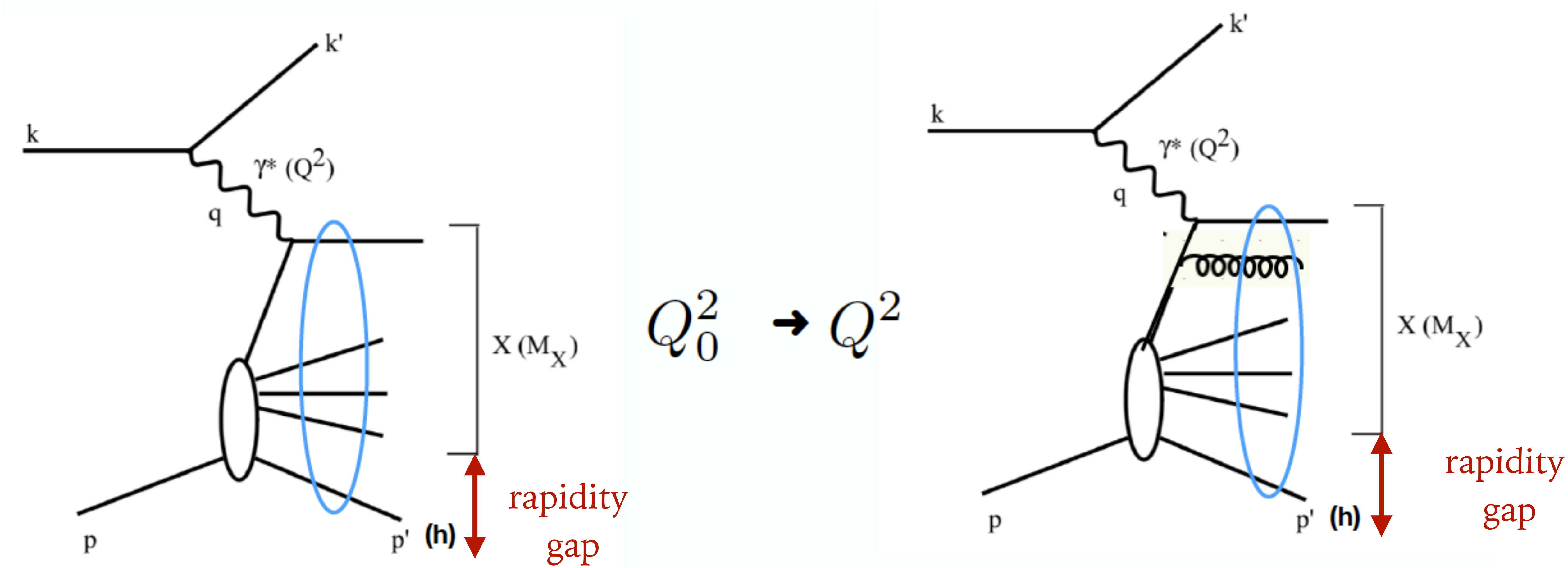
Collins

Collinear factorization in diffractive DIS

$$F_{2/L}^{D(4)}(\beta,\xi,Q^2,t) \;=\; \sum_i \int_\beta^1 \frac{dz}{z}\, C_{2/L,i}\left(\frac{\beta}{z},Q^2\right)\, f_i^{\mathrm{D}}(z,\xi,Q^2,t)$$

- Diffractive cross section can be factorized into the convolution of the perturbatively calculable partonic cross sections and diffractive parton distributions (DPDFs).
- Partonic cross sections are the same as for the inclusive DIS.
- The DPDFs represent (at least in LO) the probability distributions for partons i in the proton under the constraint that the proton is scattered into the system Y with a specified 4-momentum.
- Factorization should be valid for sufficiently(?) large Q^2 (and fixed t and ξ).

Factorization for diffraction

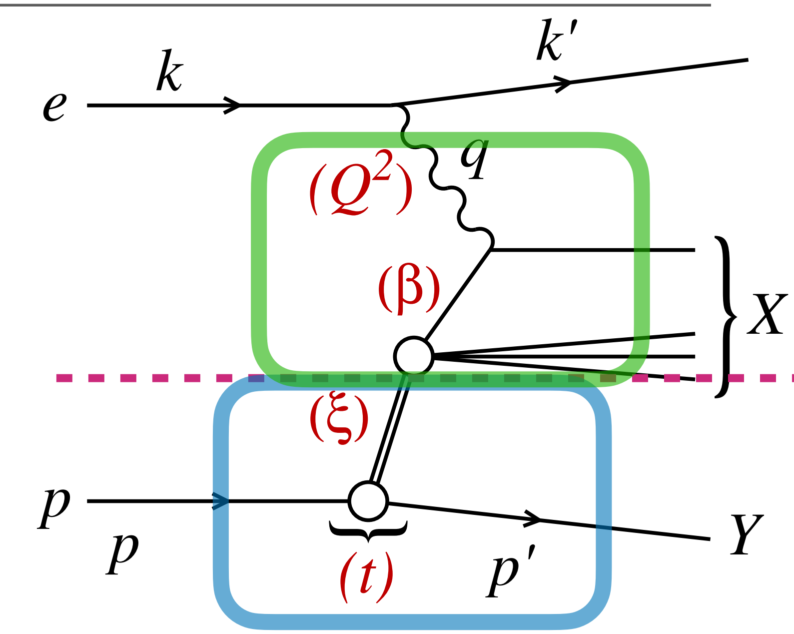


By changing the scale from Q_0^2 to Q^2 additional gluon is emitted in the diffractive system X
Soft gluons forming the system h are not able to resolve the qg system since it is localized at a distance smaller than $1/Q_0$

Model for diffractive structure functions

Regge factorization with Pomeron terms works for small $\xi<0.01$

At higher ξ additional exchanges `Reggeons' need to be included



$$f_i^{D(4)}(z,\xi,Q^2,t) = f^p_{I\!P}(\xi,t)\, f_i^{I\!P}(z,Q^2) + f^p_{I\!R}(\xi,t)\, f_i^{I\!R}(z,Q^2)$$

Pomeron *Reggeon*

Regge type flux:

$$f^p_{I\!P,I\!R}(\xi,t) = A_{I\!P,I\!R}\frac{e^{B_{I\!P,I\!R}t}}{\xi^{2\alpha_{I\!P,I\!R}(t)-1}}$$

Trajectory:

$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}\, t.$$

For t-integrated case

$$f_i^{D(3)}(z,\xi,Q^2) = \phi^p_{I\!P}(\xi)\, f_i^{I\!P}(z,Q^2) + \phi^p_{I\!R}(\xi)\, f_i^{I\!R}(z,Q^2)$$

Integrated flux:

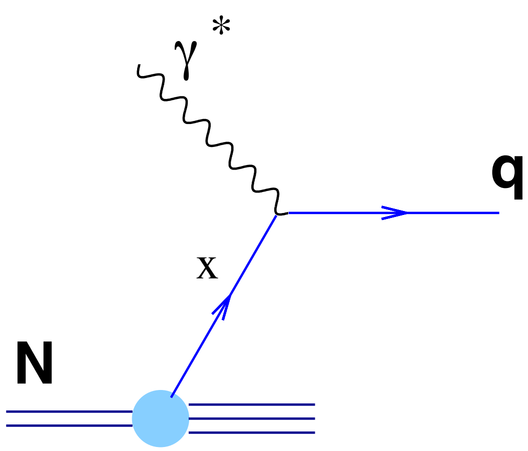
$$\phi^p_{I\!P,I\!R}(\xi) = \int dt\, f^p_{I\!P,I\!R}(\xi,t)$$

Pomeron PDFs obtained via NLO DGLAP evolution starting at initial scale $\mu_0^2=1.8\ \mathrm{GeV}^2$

$$z f_i(z,\mu_0^2) = A_i z^{B_i}(1-z)^{C_i} \qquad i=q,g$$

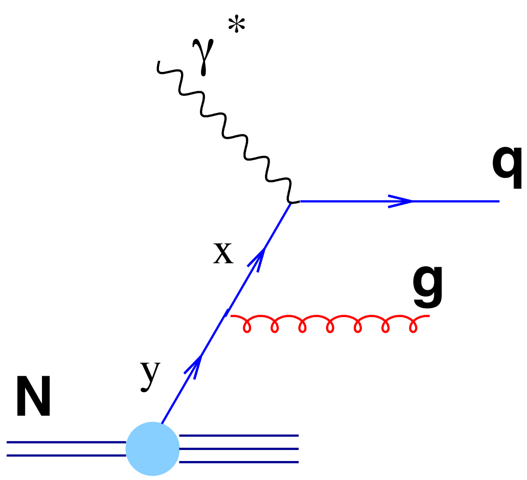
DGLAP evolution equations: recap

$t = \ln Q^2/Q_0^2$



$q(x,t)$

$t + \delta t$



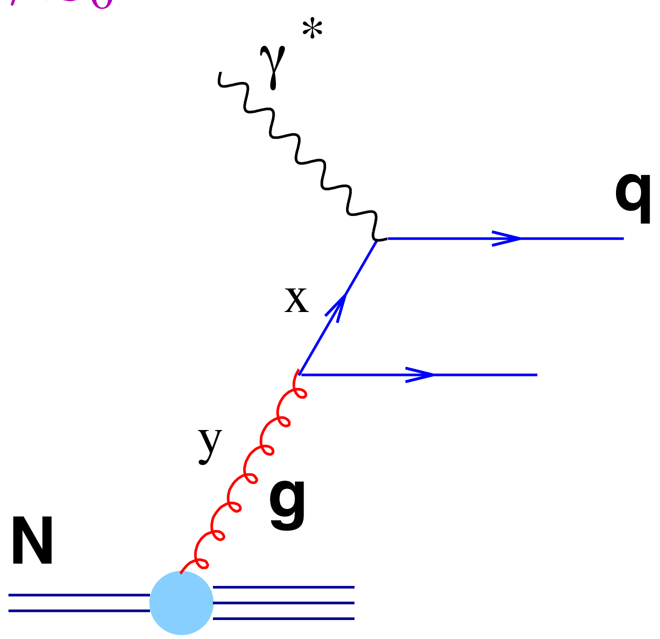
$q(x,t) + \delta q(x,t)$

quarks with fraction $x = \frac{Q^2}{s}$ of target momentum .

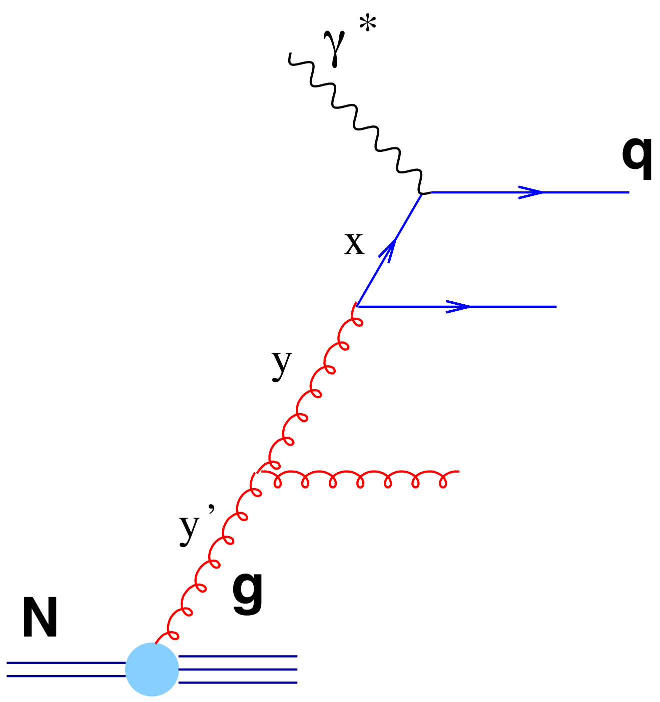
DGLAP evolution equations: recap

Apart from $q(x,t)$ one has to include $g(x,t)$

$t = \ln Q^2/Q_0^2$



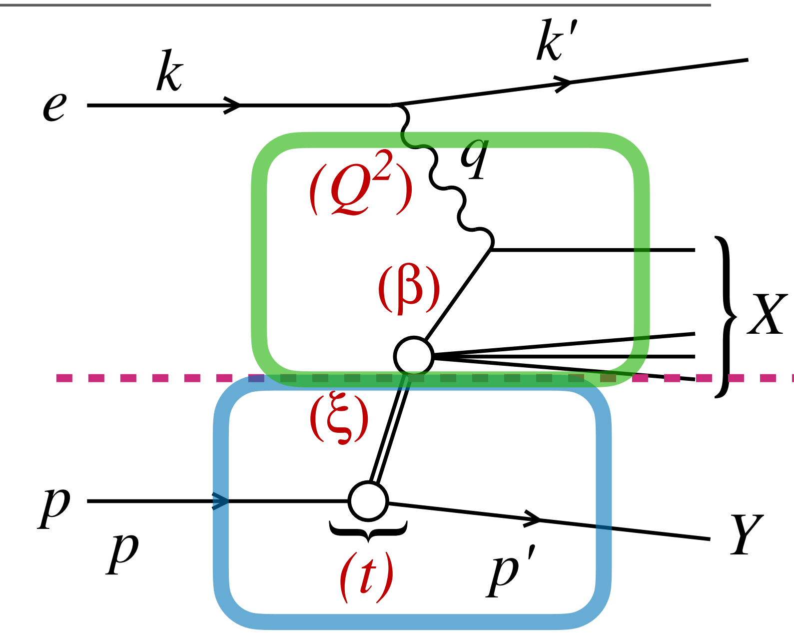
$t + \delta t$



Model for diffractive structure functions

Regge factorization with Pomeron terms works for small ξ<0.01

At higher ξ additional exchanges `Reggeons' need to be included



$$f_i^{\mathrm{D}(4)}(z,\xi,Q^2,t) = f^p_{I\!P}(\xi,t)\, f_i^{I\!P}(z,Q^2) + f^p_{I\!R}(\xi,t)\, f_i^{I\!R}(z,Q^2)$$

Pomeron *Reggeon*

Regge type flux:

$$f^p_{I\!P,I\!R}(\xi,t) = A_{I\!P,I\!R} \frac{e^{B_{I\!P,I\!R}t}}{\xi^{2\alpha_{I\!P,I\!R}(t)-1}}$$

Trajectory:

$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}\, t.$$

For t-integrated case

$$f_i^{\mathrm{D}(3)}(z,\xi,Q^2) = \phi^p_{I\!P}(\xi)\, f_i^{I\!P}(z,Q^2) + \phi^p_{I\!R}(\xi)\, f_i^{I\!R}(z,Q^2)$$

Integrated flux:

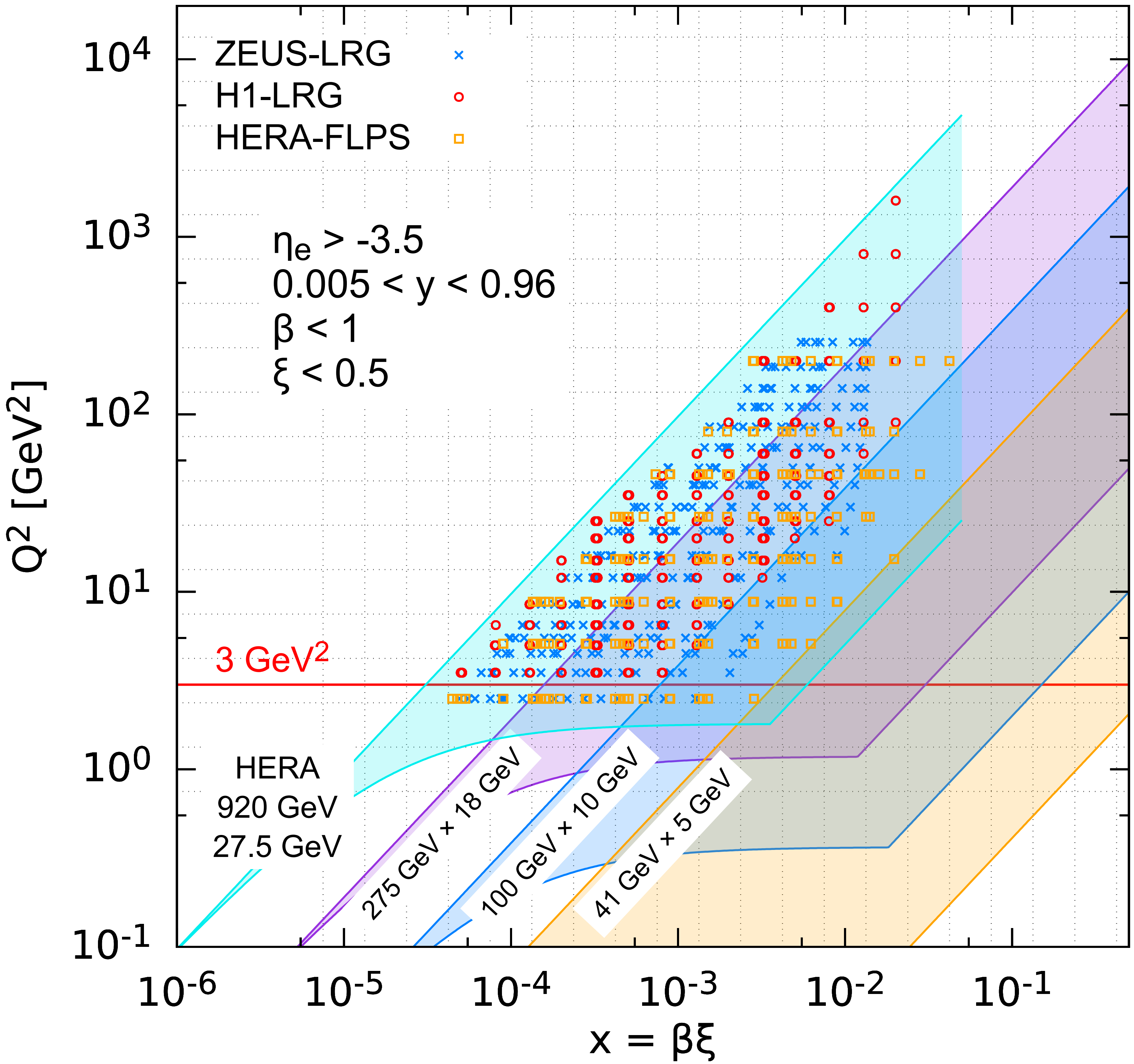
$$\phi^p_{I\!P,I\!R}(\xi) = \int dt\, f^p_{I\!P,I\!R}(\xi,t)$$

Pomeron PDFs obtained via NLO DGLAP evolution starting at initial scale $\mu_0^2 = 1.8\ \mathrm{GeV}^2$

$$z f_i(z,\mu_0^2) = A_i z^{B_i}(1-z)^{C_i} \qquad i=q,g$$

Phase space (x,Q^2) HERA–EIC

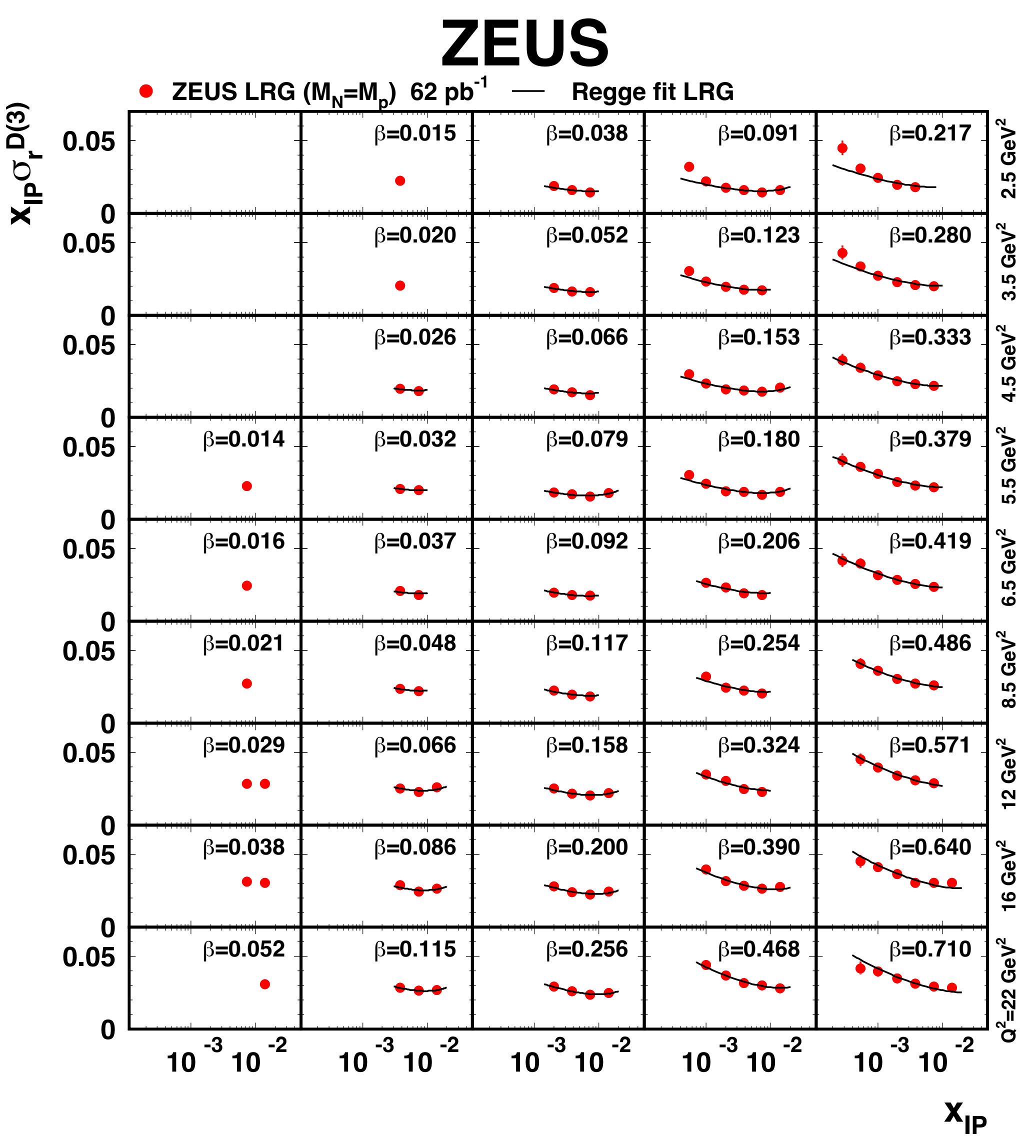
EIC 3 scenarios - HERA

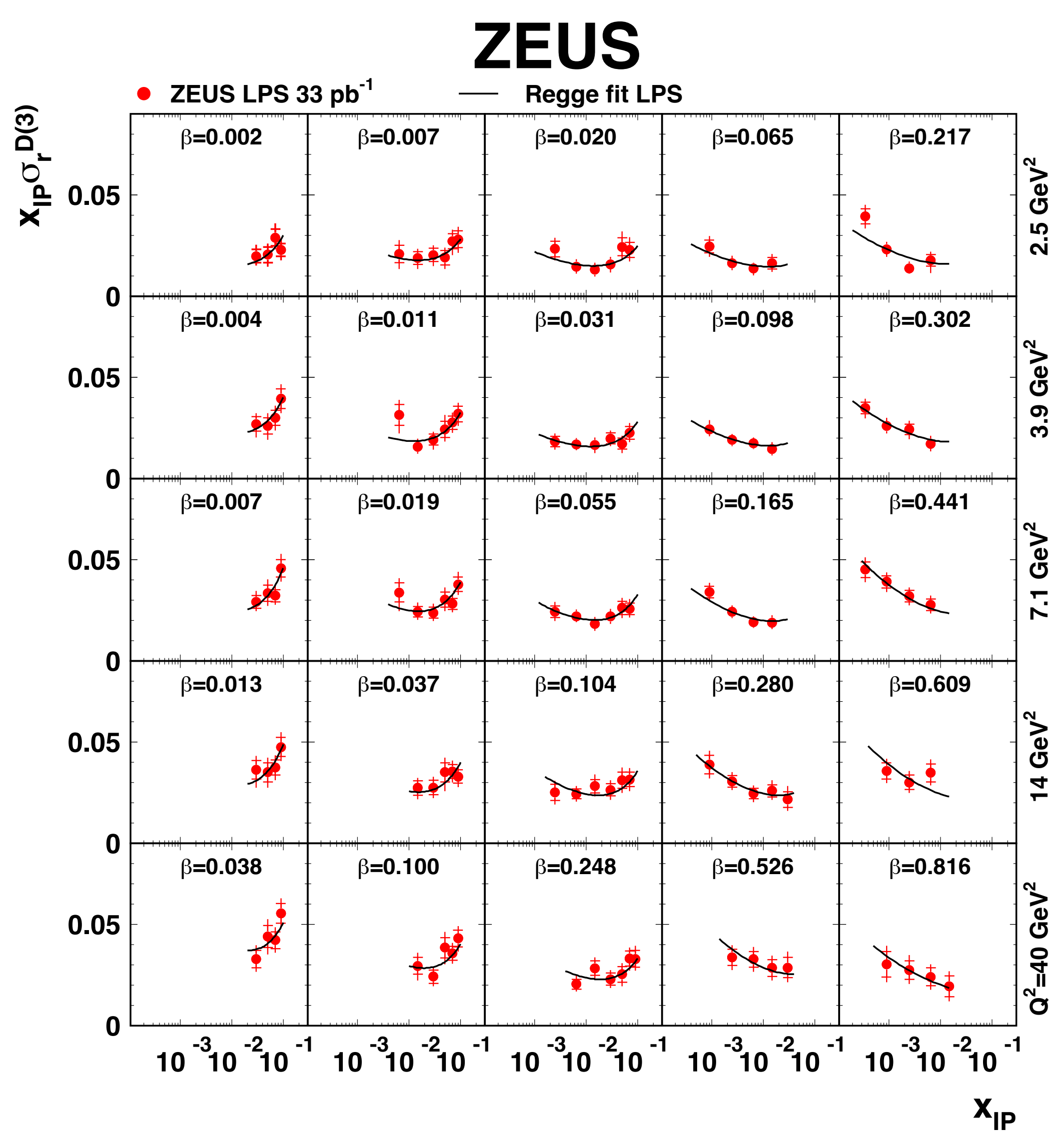


Measurement methods: LRG vs LP

Large Rapidity Gap method:
request a large rapidity gap (ex. ZEUS 2009 $\xi<0.02$)

Proton Tagging (Leading Proton) method:
detection of a leading proton (ex. Leading Proton Spectrometer in ZEUS, Forward Proton Spectrometer in H1, can go to higher $\xi<0.1$)

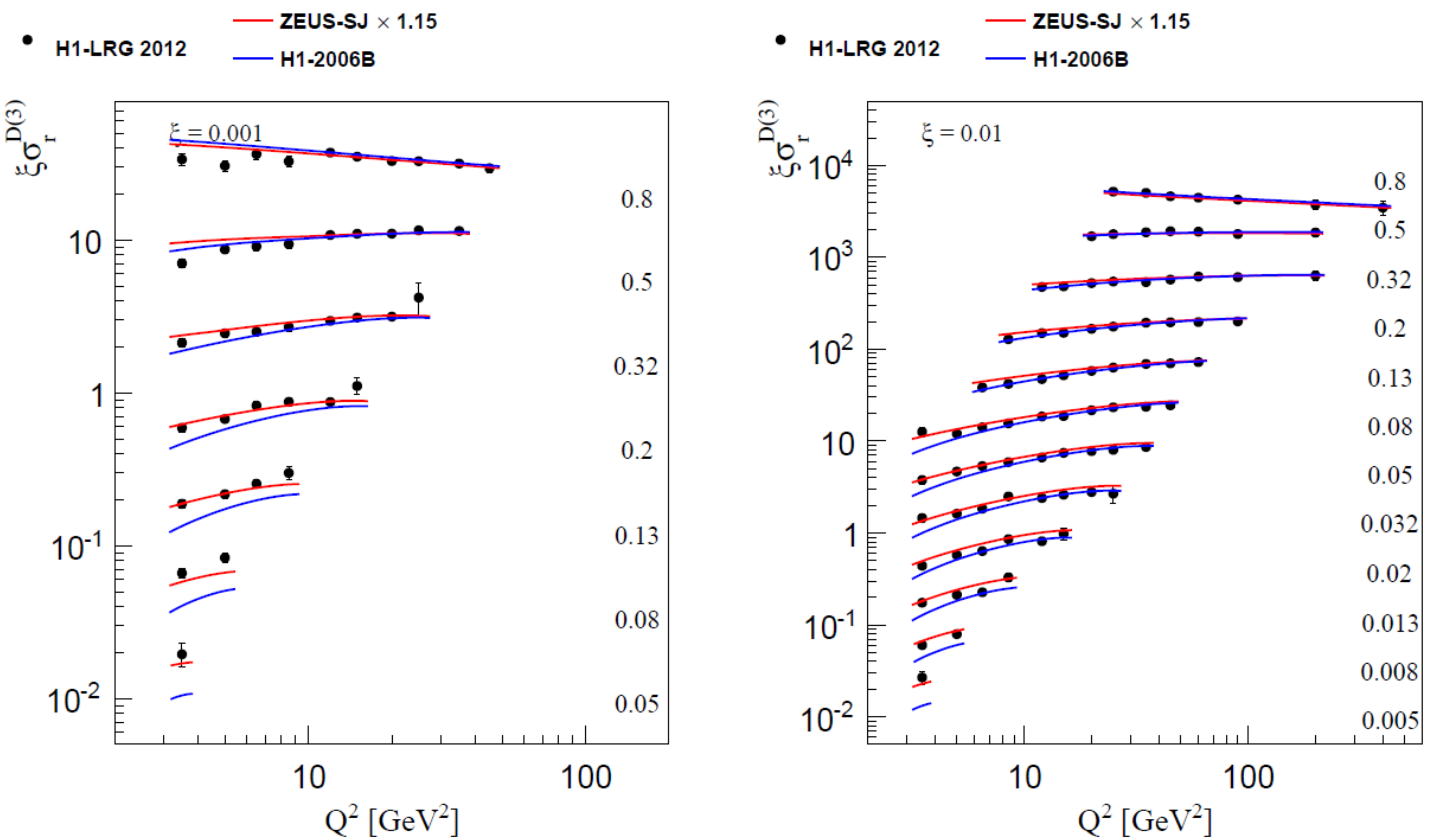




Diffractive fits

$\xi = x_{IP}$

Example of the DGLAP fit to the diffractive data



Comparison of H1-2006B and ZEUS-SJ fits to the H1-LRG 2012 data

ZEUS-SJ fit seems to better describe the data in the low β region

Fit examples to diffractive data at HERA

$$f_i^{D(4)}(z,\xi,Q^2,t) = f^p_{I\!P}(\xi,t)\, f_i^{I\!P}(z,Q^2) + f^p_{I\!R}(\xi,t)\, f_i^{I\!R}(z,Q^2)$$

$$f^p_{I\!P,I\!R}(\xi,t) = A_{I\!P,I\!R}\frac{e^{B_{I\!P,I\!R}t}}{\xi^{2\alpha_{I\!P,I\!R}(t)-1}}$$

$$z f_i(z,\mu_0^2) = A_i z^{B_i}(1-z)^{C_i}$$

i=q,g

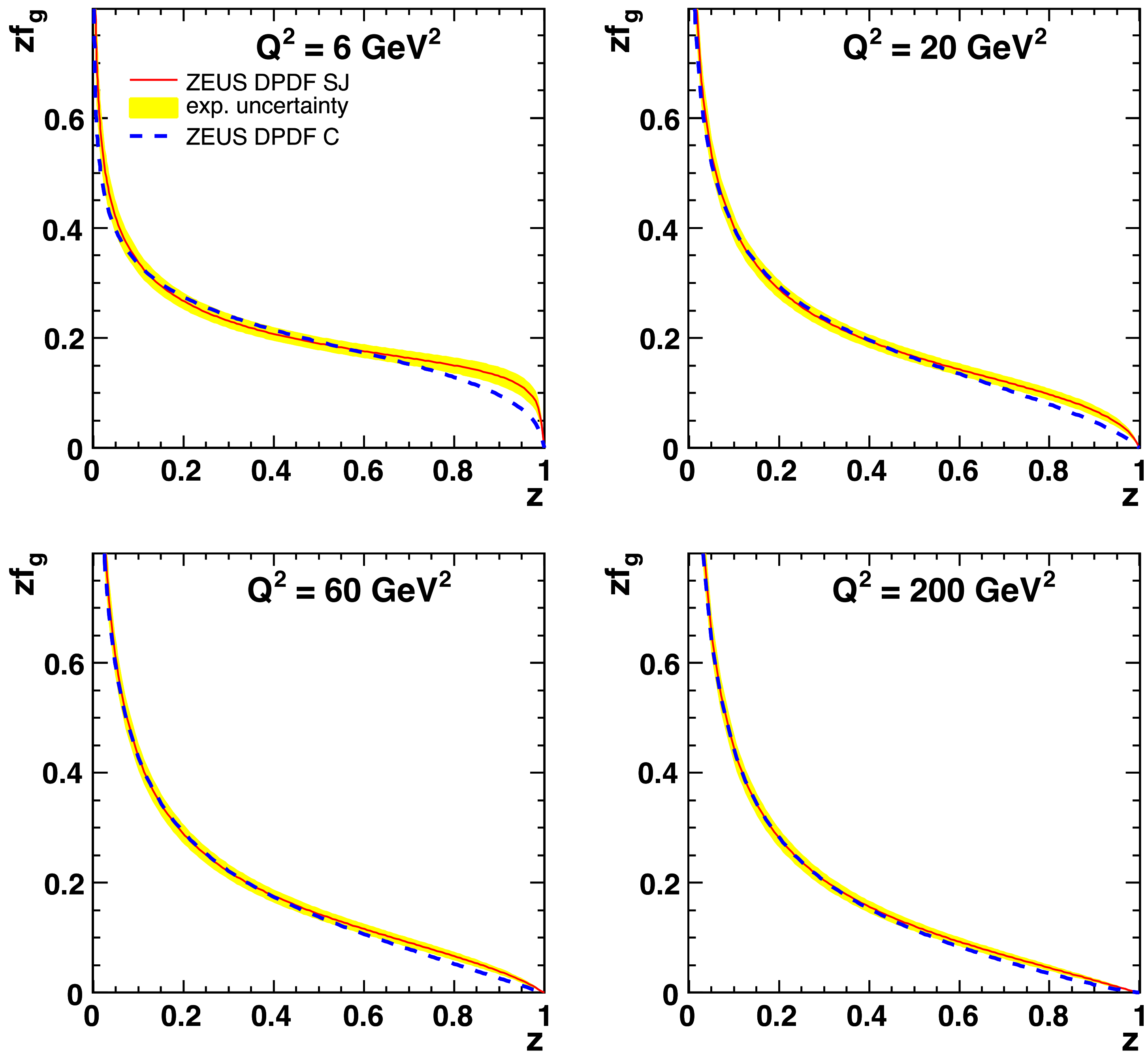
$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}\, t.$$

Parameter	ZEUS S	ZEUS C	ZEUS SJ	H1 A	H1 B
B_q	1.34 ±0.05	1.25 ± 0.03	1.23 ± 0.04	2.3± 0.36	1.5 ± 0.12
C_q	0.34 ± 0.043	0.358 ± 0.043	0.332 ± 0.049	0.57 ± 0.15	0.45 ± 0.09
B_g	-0.422 ± 0.066	**0**	-0.161 ± 0.051	**0**	**0**
C_g	-0.725 ± 0.082	**0**	-0.232 ± 0.058	-0.95 ± 0.20	**0**
$\alpha_{I\!P}(0)$	1.12 ± 0.02	1.11 ± 0.02	1.11 ± 0.02	1.118 ± 0.008	1.111 ± 0.007
$\alpha_{I\!R}(0)$	0.732 ± 0.031	0.668 ± 0.040	0.699 ± 0.043	**0.5**	**0.5**
$\alpha'_{I\!P}$	**0**	**0** GeV^{-2}	**0** GeV^{-2}	**0.06** GeV^{-2}	**0.06** GeV^{-2}
$\alpha'_{I\!R}$	**0.9** GeV^{-2}	**0.9** GeV^{-2}	**0.9** GeV^{-2}	**0.3** GeV^{-2}	**0.3** GeV^{-2}
$B_{I\!P}$	**7** GeV^{-2}	**7** GeV^{-2}	**7** GeV^{-2}	**5.5** GeV^{-2}	**5.5** GeV^{-2}
$B_{I\!R}$	**2** GeV^{-2}	**2** GeV^{-2}	**2** GeV^{-2}	**1.6** GeV^{-2}	**1.6** GeV^{-2}

Parameters in **bold font** were fixed in the fits

DPDFs: ZEUS fits

Gluon $f_i^D(x,Q^2,x_{IP},t) = f_{IP/p}(x_{IP},t)\, f_i(\beta = x/x_{IP}, Q^2)$



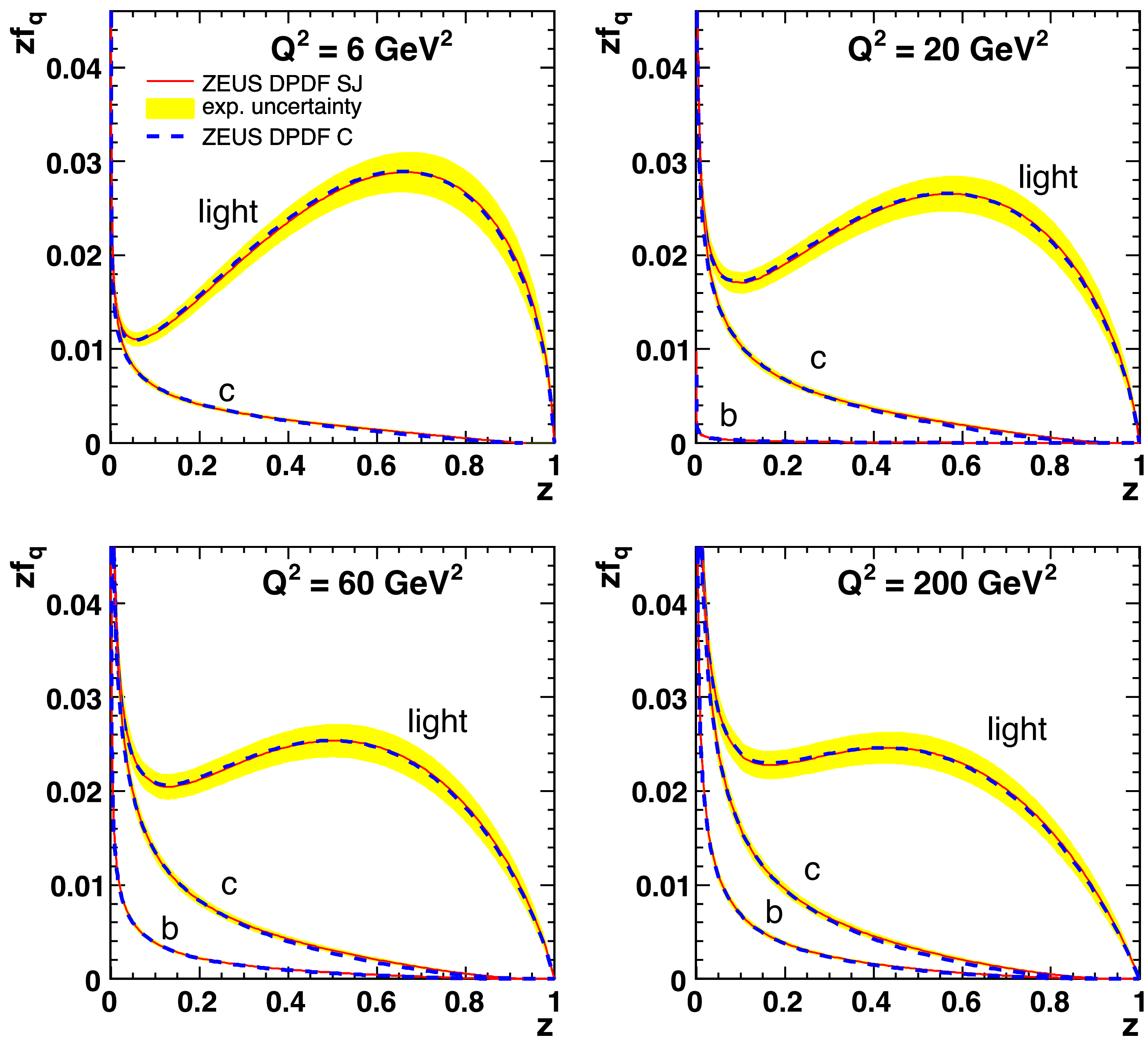
Inclusive data alone cannot fix the diffractive gluon distribution at large z.

Fit SJ includes diffractive dijets

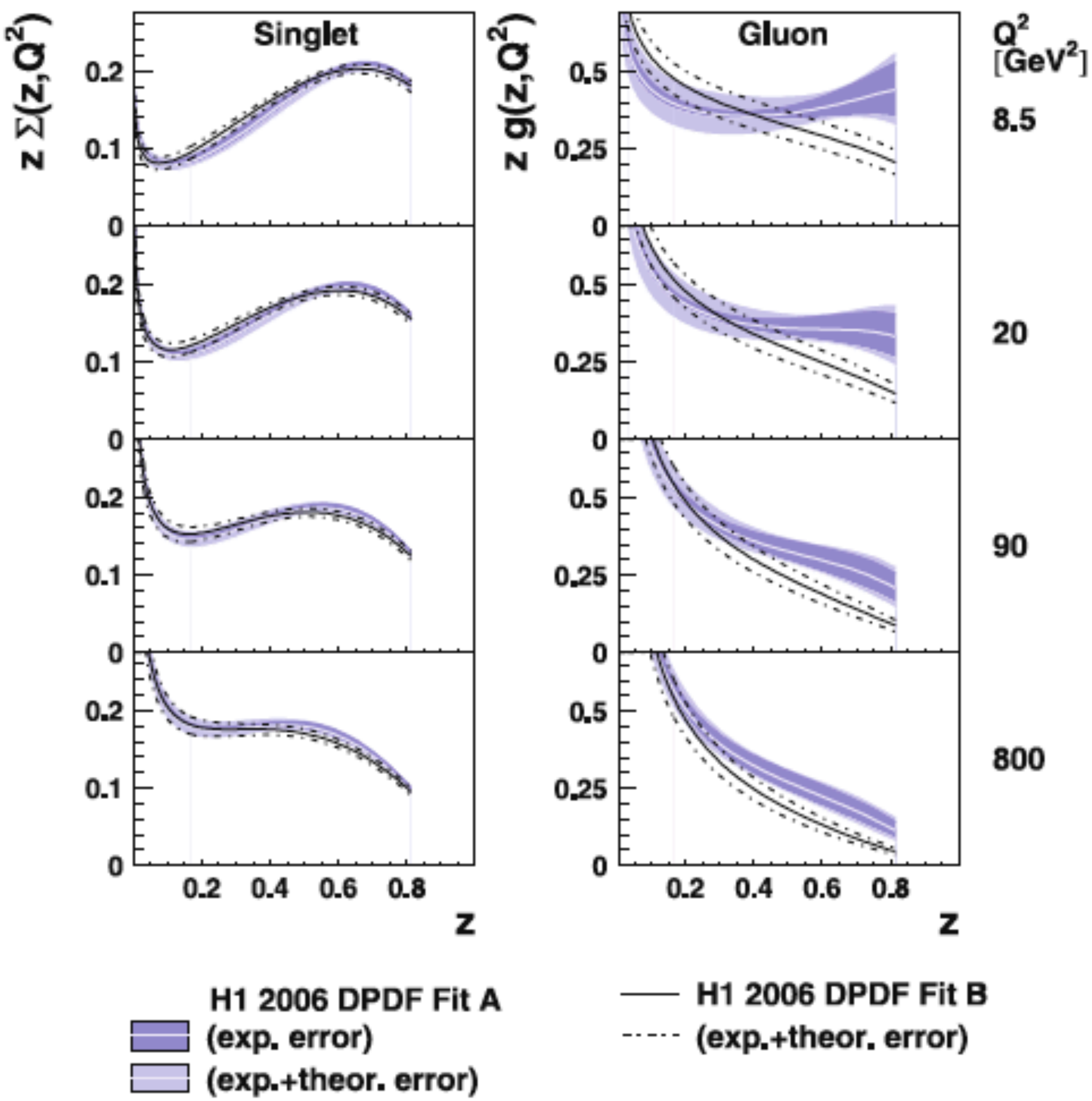
DPDFs: ZEUS fits

Quark

$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t)\, f_i(\beta = x/x_{IP}, Q^2)$$



DPDFs: H1 fits



DGLAP fits fail for low values of Q^2

H1: $Q^2 < 8.5$ GeV^2

ZEUS: $Q^2 < 5$ GeV^2

Higher twists / saturation … ?

Diffractive dijets in DIS

The factorization allows to use the diffractive parton distributions to predict other processes in diffraction with large scale present: universality

Examples include: diffractive dijets, diffractive charm production

Factorization formula for diffractive dijets:

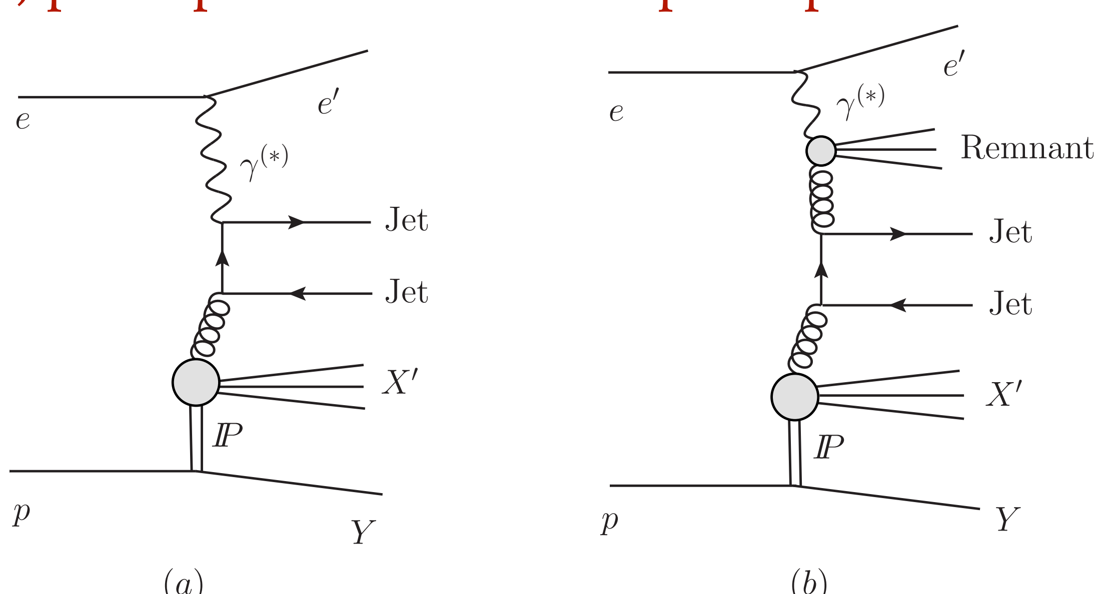
$$d\sigma(e+p \to e+2\text{jets}+X'+Y) = \sum_i \int dt \int d\xi \int dz \, d\hat{\sigma}(e+i \to e+2\text{jets}) f_i^{D(4)}(z,\xi,\mu^2,t)$$

μ^2 factorization scale

X' part of the diffractive syste that does not include the jets

DIS, photoproduction

photoproduction



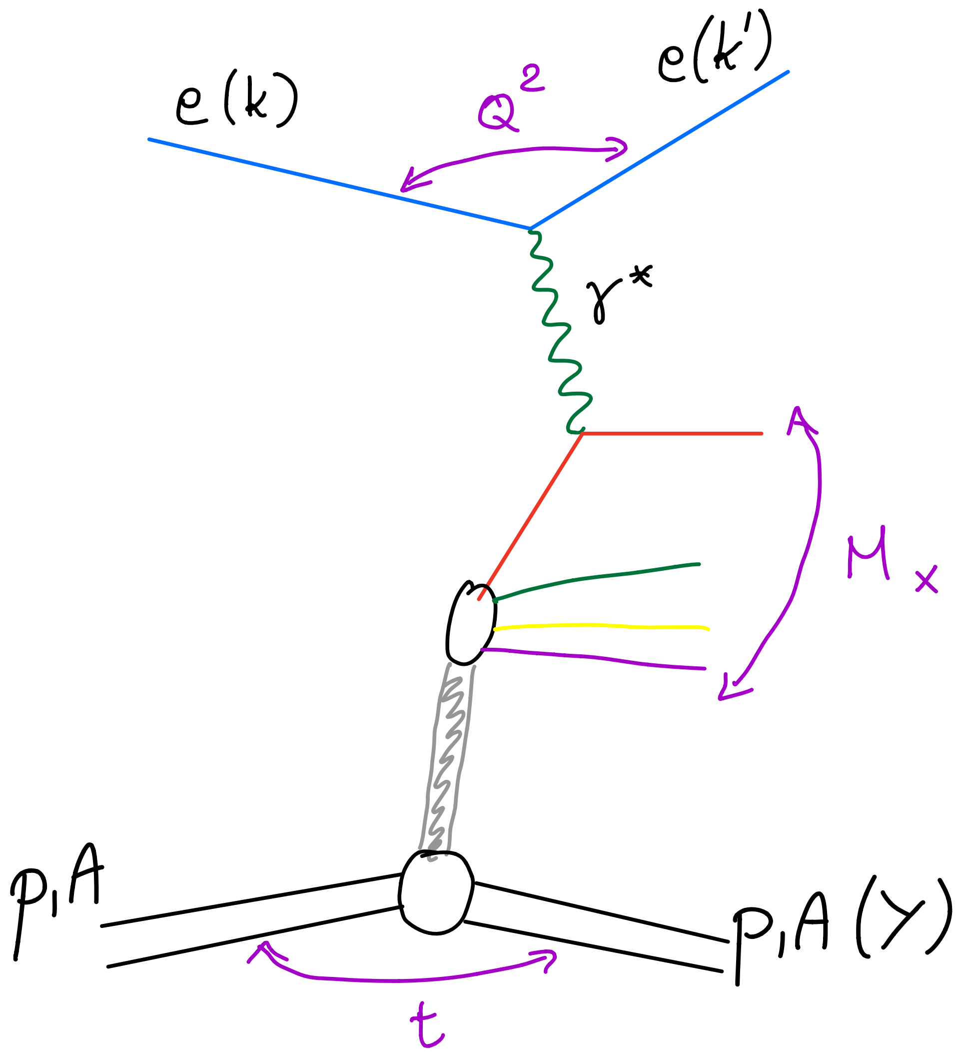
Direct

Resolved

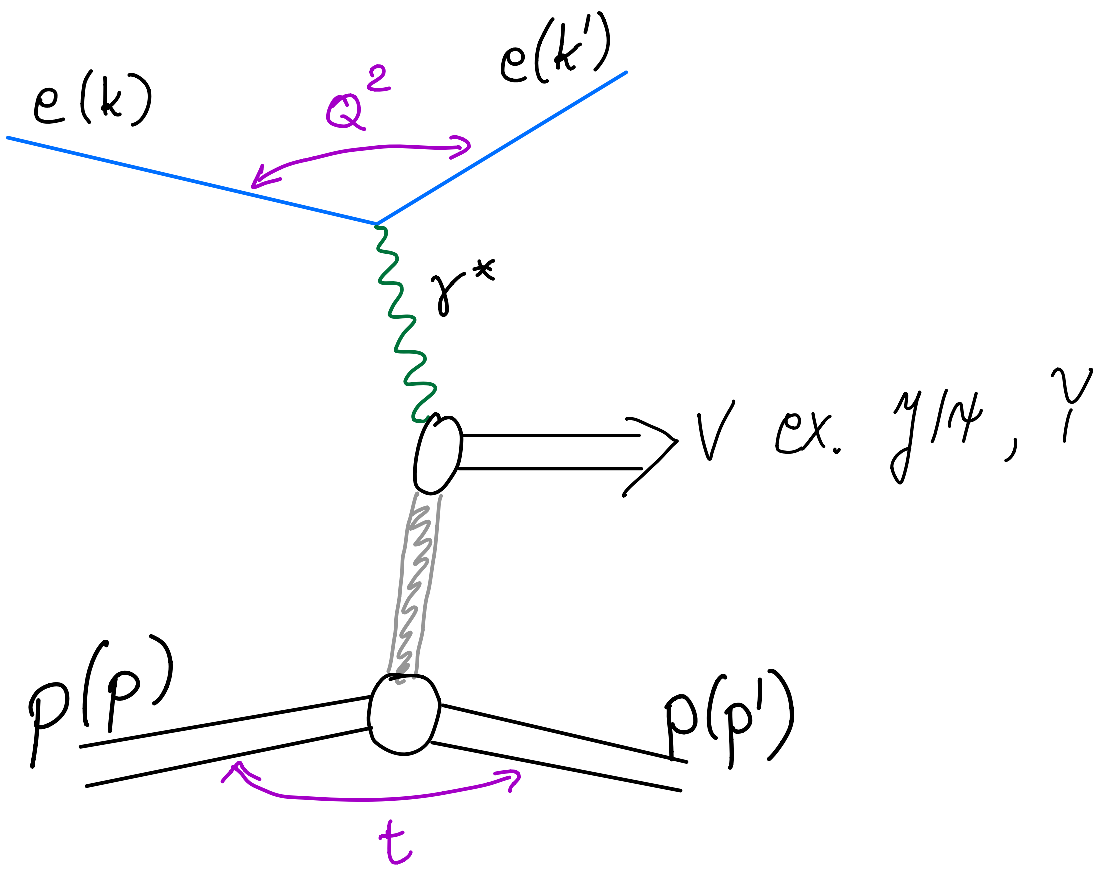
DIS diffractive dijets consistent with factorization. Used in ZEUS SJ fits for example.

Photoproduction diffractive dijets: ZEUS consistent with factorization within errors, H1 data lower than predictions

Diffractive elastic vector meson production



Final state contains only vector meson, scattered lepton and proton



J/ψ vector meson: charm -anti charm system $m = 3.09\ \mathrm{GeV}$

Upsilon vector meson: bottom - anti bottom system $m = 9.46\ \mathrm{GeV}$

Thank you!