# Experimental results on nucleon structure Lecture II

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# Outline


1. Course literature
2. Introduction
3. Nucleon elastic form factors
4. Parton structure of the nucleon
   - Feynman parton model
   - Partons vs quarks
   - Introducing gluons
   - Parton distribution functions
   - EMC effect
   - Fragmentation functions
   - Sum rules
5. "Forward physics"
   - Phenomena at low $x$
   - Diffraction

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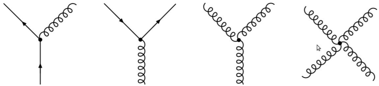
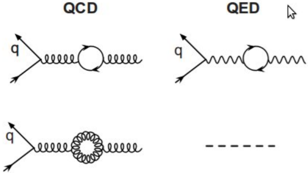
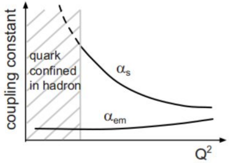
# Strong vs electromagnetic interactions

Basic strong interactions diagrams:






First order approximation:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - n_f) \cdot \ln \frac{Q^2}{\Lambda^2}}$$

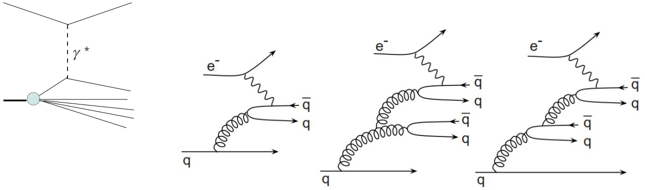
$n_f$ = number of quark types;
$\Lambda$ = (the only) free parameter of QCD,
$\Lambda \approx$ 250 MeV/$c$.

Perturbative approach to QCD valid only if:
$\alpha_s \ll 1$ i.e. $Q^2 \gg \Lambda^2 \approx$0.06 (GeV/$c$)$^2$.

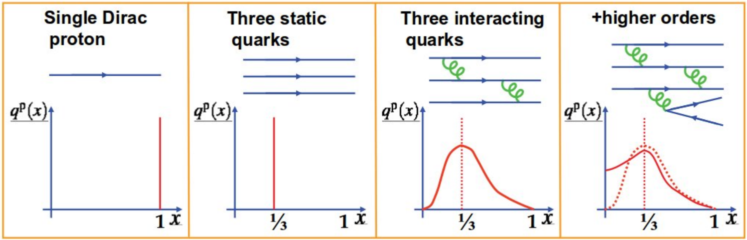
Figures from the book of B.Povh et al.

# Strong vs electomagnetic interactions in DIS

Quark-Parton Model (QPM) becomes complicated...

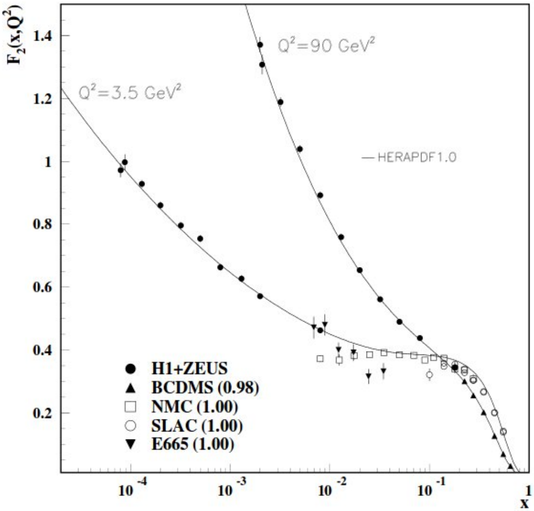



From the book of Povh et al.



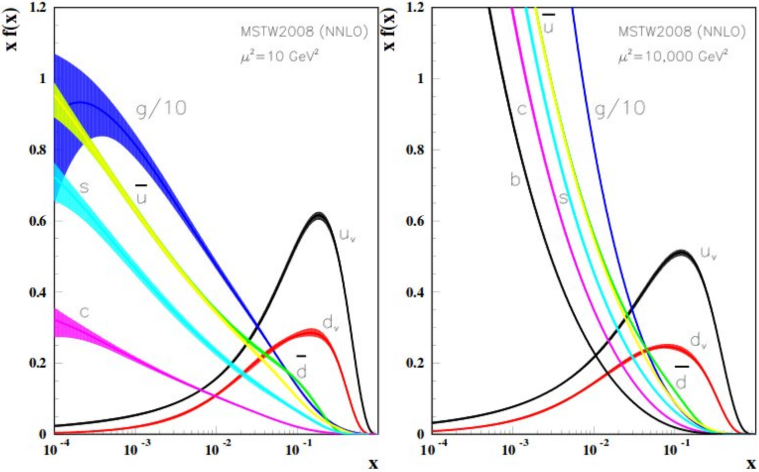

From M.A. Thomson, Michaelmas Term 2011

# Scaling violation



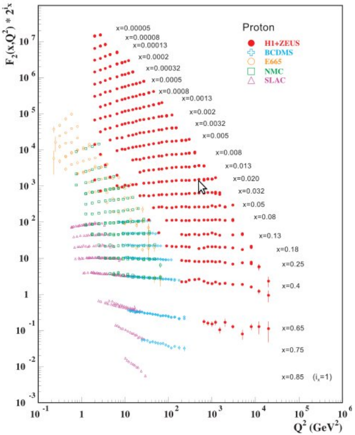

From Particle Data Tables, 2012

# Scaling violation,...cont'd

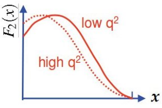


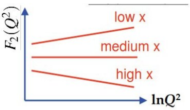

From Particle Data Tables, 2012

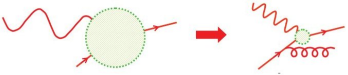
# Scaling violation,...cont'd




low $Q^2$ $\Longrightarrow$ high $Q^2$



QCD evolution equation (at lowest order):

$$\frac{dq(x,t)}{dt} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 dy \frac{q(y,t)}{y} \cdot P\left(\frac{x}{y}\right) \qquad (24)$$

$$t = \ln \frac{Q^2}{\Lambda^2}$$

QCD can predict the $Q^2$ dependence of $F_2(x, Q^2)$

From Particle Data Tables, 2012 and from M.A. Thomson, Michaelmas Term 2011

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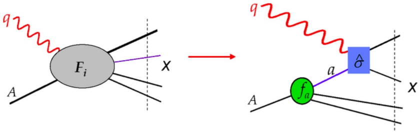
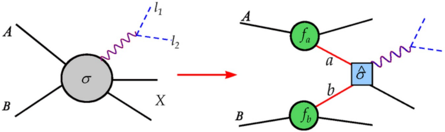
# Factorisation theorem




$$\lim_{Q^2\to\infty, x=\text{finite}} F_i(x,Q^2) = f_a \otimes \hat{\sigma}_i^a$$



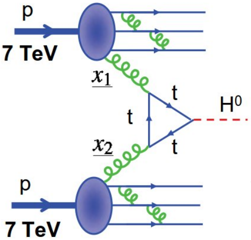

$$\sigma \sim f_a \otimes \hat{\sigma}^{ab} \otimes f_b$$

Figures from Scholarpedia

# Universality of parton distributions

PDFs are universal!

Example of the LHC Higgs particle production in a "gluon–gluon fusion":




$$\sigma(pp \to HX) \sim \int_0^1 \int_0^1 g(x_1) g(x_2) \sigma(gg \to H) dx_1 dx_2$$

Observe: uncertainty in $g(x)$ leads to 5% uncertainty in the cross section!

How do we get PDFs? Measure $F_2(x, Q_0^2)$ for "all" values of $x$ and assume a functional $x$ dependence. Fit its coefficients at any $Q^2$ from QCD predictions of the $Q^2$ dependence of $F_2$ ("QCD evolution).

From M.A. Thomson, Michaelmas Term 2011

# pdf determination "industry"

## Current status on PDFs

| | MSTW08 | CTEQ6.6/CT10 | NNPDF2.1/2.3 | HERAPDF1.0/1.5 | ABKM09/ABM11 | GJR08/JR09 |
|---|---|---|---|---|---|---|
| PDF order | LO, NLO, NNLO | LO, NLO, NNLO | LO, NLO, NNLO | NLO, NNLO | NLO, NNLO | NLO, NNLO |
| HERA DIS | ✔ (old) | ✔ (old/new) | ✔ (new) | ✔ (new/newest) | ✔ (new) | ✔ (new) |
| Fixed target DIS | ✔ | ✔ | ✔ | - | ✔ | ✔ |
| Fixed target DY | ✔ | ✔ | ✔ | - | ✔ | ✔ |
| Tevatron W, Z | ✔ | ✔ | some | - | some | some |
| Tevatron jets | ✔ | ✔ | ✔ | - | ✔ | ✔ |
| LHC | - | - | -/W,Z+jets | - | - | - |
| HF Scheme | RTGMVF | SACOT GMVFN | FONLL GMVFN | RT GMVFN | BMSN FFNS | FFNS |
| Alphas (NLO) | 0.120 | 0.118(f) | 0.119 | 0.1176(f) | 0.1179 | 0.1145 |
| Alphas (NNLO) | 0.1171 | 0.118(f) | 0.1174 | 0.1176(f) | 0.1135 | 0.1124 |

The analyses differ in many areas:

- different treatment of heavy quarks
- inclusion of various data sets and account for possible tensions
- different alphas assumption

HERAFitter is an Open Source QCD Platform which can be used fo r benchmarking and understanding such differences

Voica Radescu| DESY | Low x| HERAFitter 3

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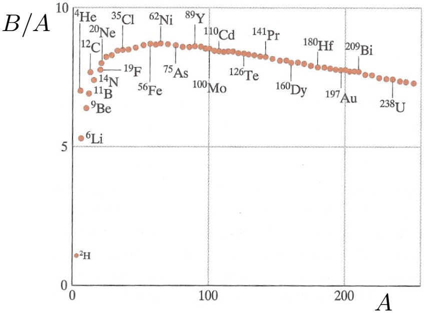
# Quarks in a nucleon (nucleus)

- Elastic ep maxima in Fig VII/4 smeared around $x = Q^2/2M\nu$ = 1 since nucleons are confined in a nucleus of radius $R_A \sim$ 1 fm. Thus a Fermi momentum:

$$p_F \sim \frac{\hbar}{R_A} \approx 0.2 \text{ GeV}/c$$

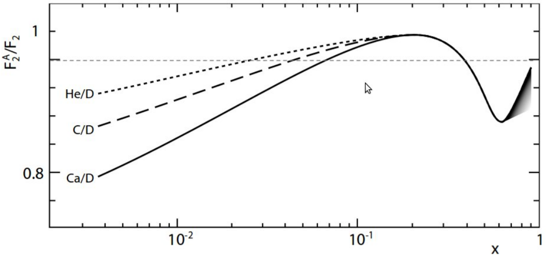
  which is a few % of a typical $\nu$.

- Remember also the nuclear binding energy, $B \sim$ 8 MeV/nucleon (can be neglected as compared with $\nu$).




$$B = \sum_{i=1}^{A} M_i\, c^2 - M_A\, c^2$$

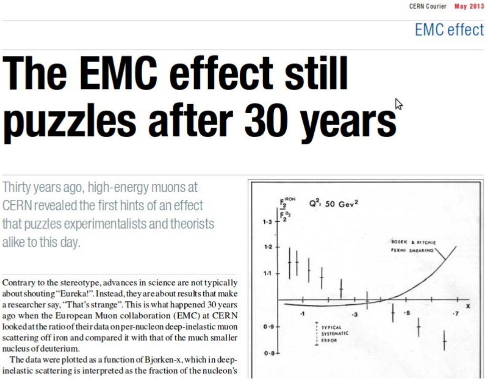
# Nuclear effects in parton distributions




- Here: $R \equiv \dfrac{F_2^A}{F_2} \equiv \dfrac{(F_2^A)/A}{(F_2^d)/2}$, i.e. nuclear structure functions “per nucleon”.
- For $x \lesssim$ 0.8, “the EMC effect” (a shift in the quark momentum distributions towards lower $x$ when nuclens are bound).
  Observe a nuclear “shadowing” for R $<$ 1, at lowest $x$
- At largest $x \Longrightarrow$ scaterring on a nucleon cluster?

From M.A. Thomson, Michaelmas Term 2011

# EMC effect in the CERN Courier, May 2013



CERN Courier May 2013

EMC effect

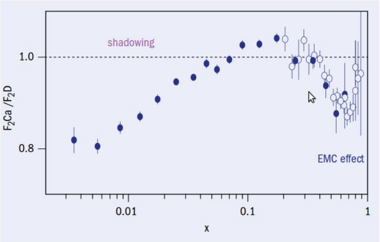
## The EMC effect still puzzles after 30 years

Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

Contrary to the stereotype, advances in science are not typically about shouting "Eureka!". Instead, they are about results that make a researcher say, "That's strange". This is what happened 30 years ago when the European Muon collaboration (EMC) at CERN looked at the ratio of their data on per-nucleon deep-inelastic muon scattering off iron and compared it with that of the much smaller nucleus of deuterium.

The data were plotted as a function of Bjorken-x, which in deep-inelastic scattering is interpreted as the fraction of the nucleon's






original EMC plot for $F_2^{\mathrm{Fe}}/F_2^{\mathrm{D}}$

NMC (filled symbols) and SLAC data for $F_2^{\mathrm{Ca}}/F_2^{\mathrm{D}}$

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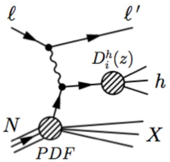
# Other universal functions: fragmentation functions, $D_q^h(z, Q^2)$

- Studied through measurements of charged (single-) hadron multiplicities.
  At LO:

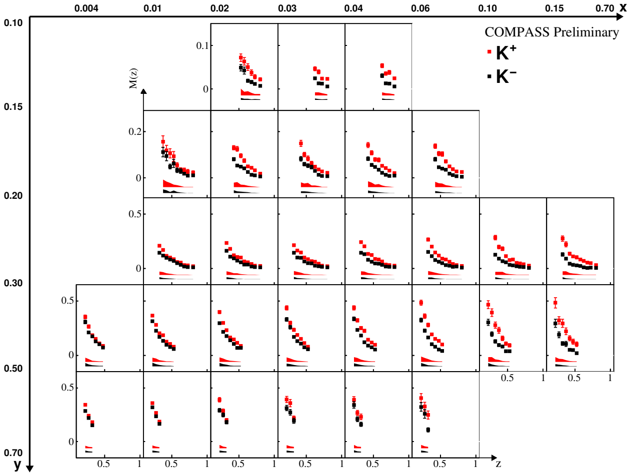
$$M^h(x,z) = \frac{\frac{d\sigma_{\mathrm{SIDIS}}}{dx\,dz}}{\frac{d\sigma_{\mathrm{DIS}}}{dx\,dz}} = \frac{\Sigma_q e_q^2 \left[q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right]}{\Sigma_q e_q^2 \left[q(x) + \bar{q}(x)\right]}$$

$$z = \frac{E_h}{\nu}$$




- High precision Single Inclusive $e^+e^-$ Annihilation data
  do not separate $q$ and $\bar{q}$ and only access charge sum of FF for a hadron h.
- Measurements at a fixed, large ($\sim M_Z$), scale, except BELLE ($Q^2$ ~10 GeV$^2$).
- Inclusive single hadron production by RHIC $\Longrightarrow$ improve constraints on gluon FF.
- Lepton–nucleon DIS: lower values and wide range of scales, sensitivity to parton flavour and hadron charge ($\Longrightarrow$ new data of HERMES, COMPASS).
- Global NLO analyses, e.g.: DSS, Phys. Rev. D **75** (2007) 114010.

# Charged (single-) hadron multiplicities; identified kaons




From N. Makke (COMPASS), DISXXI, 2013

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# Sum rules (examples)

- Hide a very important physics! Recall that for parton distributions (3 valence quarks):

$$\int_0^1 dx u_v(x,Q^2) \equiv \int_0^1 dx \left[u(x,Q^2) - \bar{u}(x,Q^2)\right] = 2$$

$$\int_0^1 dx d_v(x,Q^2) \equiv \int_0^1 dx \left[d(x,Q^2) - \bar{d}(x,Q^2)\right] = 1$$

$$\int_0^1 dx \left[s(x,Q^2) - \bar{s}(x,Q^2)\right] = 0$$

In this form they are subject to QCD corrections involving powers of $\alpha_s(Q^2)$ !

- Recall the quark momentum sum rule, Eq. (23), (gluon existence):

$$\frac{18}{5}\int F_2^{\mathrm{eN}}(x)dx = \int F_2^{\nu\mathrm{N}}(x)dx = \int \left[u(x) + \bar{u}(x) + d(x) + \bar{d}(x)\right] x dx \approx 0.5$$

- Gottfried sum rule (first checked by the NMC). From Eq. (21) we get:

$$\int_0^1 \left[F_2^{\mathrm{ep}}(x) - F_2^{\mathrm{en}}(x)\right]\frac{dx}{x} = \frac{1}{3} + \frac{2}{3}\int_0^1 \left[\bar{u}(x) - \bar{d}(x)\right] dx < \frac{1}{3} \qquad (25)$$

which means:
  - $q\bar{q}$ sea is not flavour symmetric
  - more $\bar{d}$ than $\bar{u}$ in the proton: $\int_0^1 \left[\bar{u}(x) - \bar{d}(x)\right] dx = -0.118 \pm 0.012$

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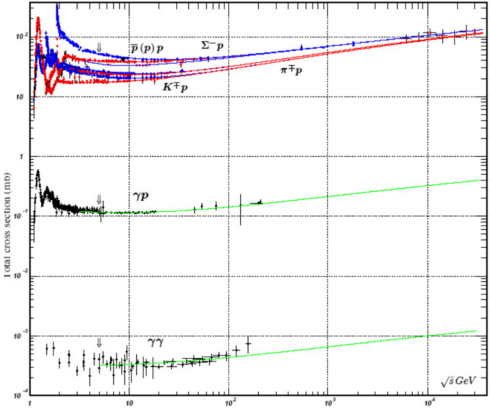
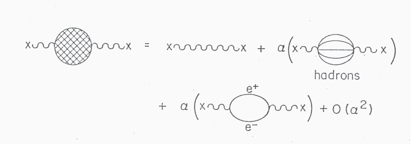
# Nucleon structure at low values of $x$; $\gamma^*$ behaviour

Experimental fact: photon interactions are often similar to those of a hadron

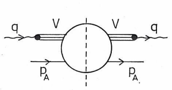



From Particle Data Tables, 2012

Contributions to the self-energy of a physical photon:




The hadron–type interaction:




$V$ has quantum numbers of the photon!

# Nucleon structure at low values of $x$, ...cont'd

Hadrons in the $\gamma$ fluctuation: either a pair of $q\bar{q}$ or a hadron of $J^P = 1^-$ (i.e. $\rho$, $\omega$, $\Phi$, $J/\Psi$,...). Observe that if $E_\gamma$ is much larger than mass of the fluctuation, $m$, then the hadronic fluctuation traverses

$$d(E_\gamma, Q^2) \sim \frac{2E_\gamma}{Q^2 + m^2} \approx 80 \;\; \text{fm!!!} \;\; (\text{for } Q^2 = 0, E_\gamma = 100\,\text{GeV}, m^2 = 0.5\,(\text{GeV}/c)^2). \tag{26}$$

But a highly virtual $\gamma^*$, $Q^2 \to \infty$, may have no time to develop a structure before the interaction:

$$d(E_\gamma, Q^2) \sim \frac{2E_\gamma}{Q^2 + m^2} \to \frac{2E_\gamma}{Q^2} \to 0 \tag{27}$$

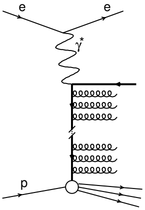
However the $\gamma^*$ structure is visible! Observe that

$$\frac{2E_\gamma}{Q^2} = \frac{1}{Mx} \tag{28}$$

and if $x \ll 1$ then $d(E_\gamma, Q^2)$ may be very high independently of $Q^2$
(e.g. @ x=0.001, $d \sim$ 200 fm! proton sea quarks outside proton ???)

# Nucleon structure at low values of $x$, ...cont'd

Low $x \equiv$ large parton densities, due to QCD processes, e.g.:

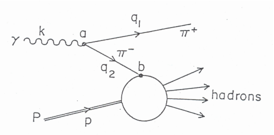



Who is probing whom?? (A. Levy)

Solution: cross section is Lorentz invariant
but time developement is not. (L. Frankfurt)

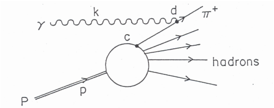
So $\gamma^*$ and proton are probing each other and we are measuring the interation as a whole. A consequence: @ low $x$, $F_2^P$ and $F_2^\gamma$ are related!

Two ways of $\gamma$ interactions (observe time ordering!)




dominant if $\nu \rightarrow \infty$ and target at rest

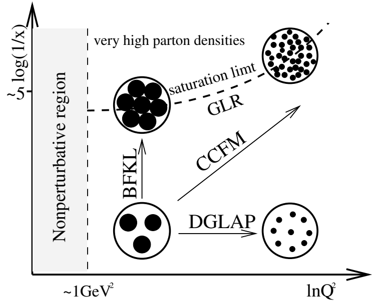
photon structure

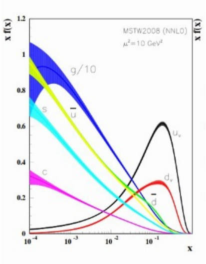



dominant in the $\infty$ target momentum system and finite $\nu$

proton structure (DIS)

# Physics domains: "Kwieciński plot"

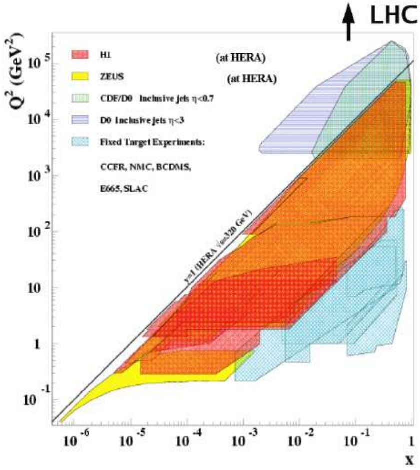


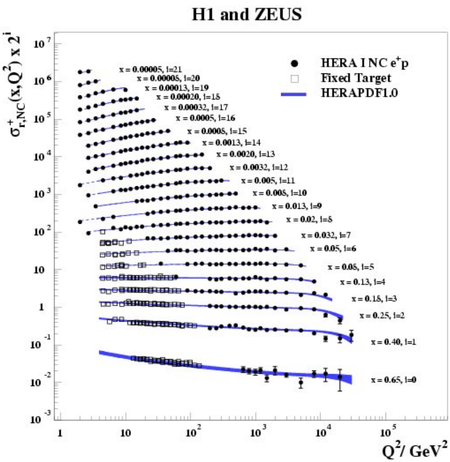




BFKL: $[\alpha_s \ln(1/x)]^n$
DGLAP: $[\alpha_s \ln(Q^2)]^n$

- At low $x$, energy in the $\gamma^*$p cms is large (large gluon cascades): $W^2_{\gamma^* p} = Q^2(1-x)/x$.
- Contributions from large $\alpha_s \ln \frac{1}{x}$ terms $\Rightarrow$ new evolution equations: BFKL, CCFM.
- At low $x$: strong increase of gluon density with decreasing $x$ (cf. HERA data) $\Rightarrow$ gluon recombination (saturation).
- At $Q^2 \ll Q^2_{sat}$ nonlinear effects of parton saturation must be considered.

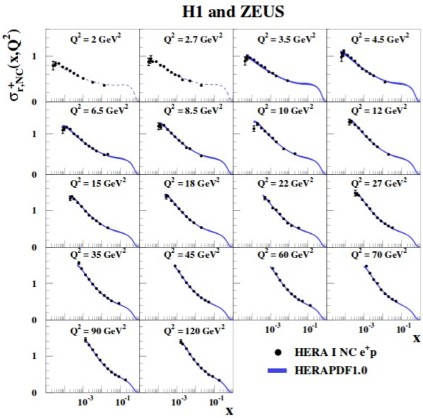
# HERA data at low $x$. Inclusive measurements

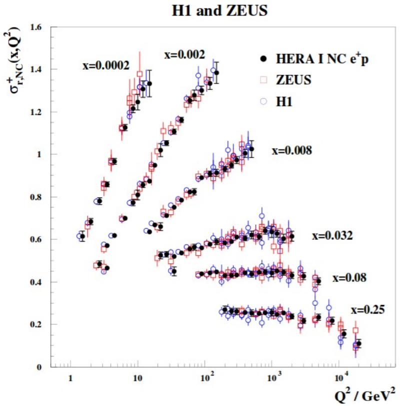



From arXiv: 0911.0884

# HERA data at low $x$. Inclusive measurements...cont'd

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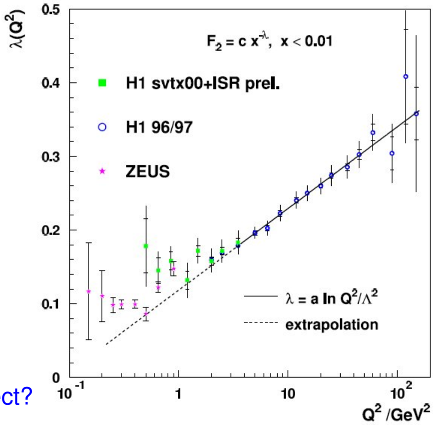
# HERA data at low $x$. Inclusive measurements...cont'd




What should we expect?

- From DGLAP (DLLA approximation): $xg(x)$ grows faster than any power of $\ln \frac{1}{x}$; partons do not necessarily overlap.
- From BFKL: $xg(x) \sim x^{-\lambda} \Rightarrow F_2 \sim x^{-\lambda}, \quad \lambda \approx 0.5$

Fig. from hep-ex/0211051

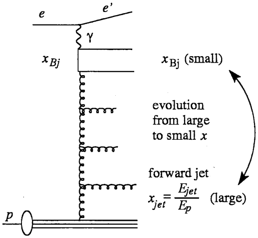
# HERA data at low $x$. Hadron final states

- At low $x$ parton probed by $\gamma^*$ comes from a cascade initiated by a parton of a large longitudinal momentum.
- No $k_t$ ordering of this cascade in BFKL
  $\Longrightarrow$ more hard gluons ($\rightarrow$ hadrons) in the forward and central region.
- Measured: transverse energy flow, $p_{\mathrm{T}}$ hadrons, forward hadrons and jets, multijets, azimuthal correlations between energetic jets,...
- Conclusions:

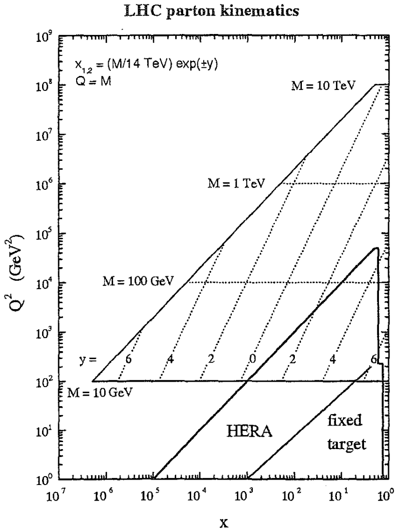
  NLO DGLAP + resolved photon describe data fairly well.

  BFKL effects not conclusive (too short cascade?)

Mueller's jet



# Low $x$ @ LHC



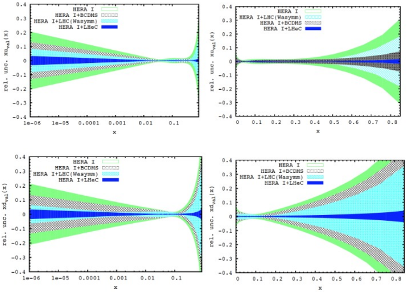

Expectations from the LHC

- Signatures for the BFKL evolution
- Parton saturation taming (espacially on nuclei)
- Colour Glass Condensates ?
- Meaning of geometric scaling...

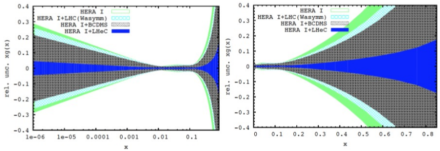
via observation of
jets, dijets, (semi-)inclusive reactions,...

# Low $x$ @ future e-p colliders (LHeC, EIC)

Example: $xq(x)$ at $Q^2$ = 1.9 GeV$^2$ at LHeC




valence quarks (u and d)




gluons

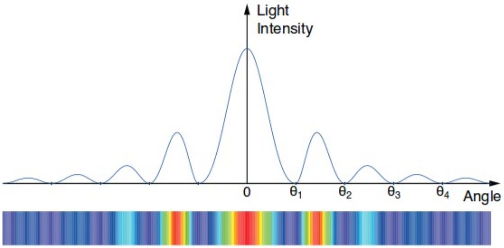
From LHeC CDR arXiv:1206.2913

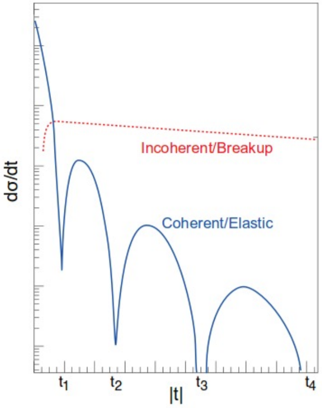
# Outline

1. Course literature
2. Introduction
3. Nucleon elastic form factors
4. Parton structure of the nucleon
   - Feynman parton model
   - Partons vs quarks
   - Introducing gluons
   - Parton distribution functions
   - EMC effect
   - Fragmentation functions
   - Sum rules
5. "Forward physics"
   - Phenomena at low $x$
   - Diffraction

# Diffraction in optics

Diffractive pattern of light on a circular disk and diffractive cross-section in HEP;
$\vartheta_i \sim 1/(kR), \quad |t| \approx k^2\vartheta^2$ ($k$ - wave number, $R$ - radius)




From EIC White Paper arXiv:1212.1701

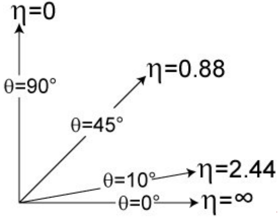
# Digression: rapidity, $y$

- Definition of rapidity, $y$:

$$y = \frac{1}{2}\ln\left(\frac{E + p_{\rm z}}{E - p_{\rm z}}\right)$$

(particle production is constant as a function of $y$).
- Under a boost in $z$ to a frame with velocity $\beta$, $y \to y - \tanh^{-1}\beta$...
- ...hence shape of rapidity, $\mathrm{d}N/\mathrm{d}y$ is invariant as are differences in rapidity $\Longrightarrow y$ is preferred over polar angle $\theta$ in hadron collider physics.
- "Forward" in a hadron–hadron collider experiment means close to the beam axis, i.e. high pseudorapidity, $|\eta|$, where

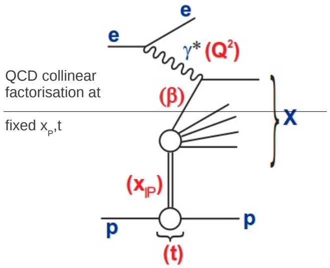
$$\eta = \frac{1}{2}\ln\left(\frac{|\vec{p}| + p_{\rm z}}{|\vec{p}| - p_{\rm z}}\right) = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$




- $\eta \Rightarrow y$ for $v \approx c$ or $m \approx 0$,
$\eta$ can be measured even if $m$ and $p$ unknown!

# Definition of diffraction in high energy physics

- No quantum number exchange in a process.
  Target (or both hadrons) emerges intact. "Pomeron, $\mathbb{P}$, exchange".
- Cross section not decreasing with energy.
- Secondary features: small $t$ and large $\Delta y$ (forward !) in final state hadrons.

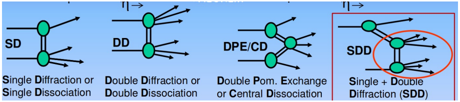



**reaction described by 4 variables:**
$Q^2, x, \beta = x/x_{\mathbb{P}}, t$

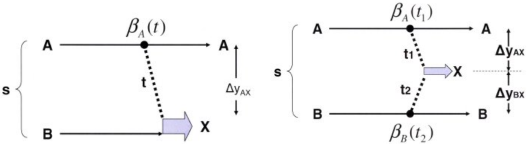
- Soft/hard diffraction $\Longrightarrow$ diffractive parton distributions! Universality?
  Rapidity gap survival probability for hadron–hadron.
- Diffractive PDF, $f_i^D = f_i^D(x, Q^2, x_{\mathbb{P}}, t)$.
  Within "vertex factorisation", $f_i^D(x, Q^2, x_{\mathbb{P}}, t) = f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) \cdot f_i(\beta = x/x_{\mathbb{P}}, Q^2)$

# Diffraction: brief experimental status

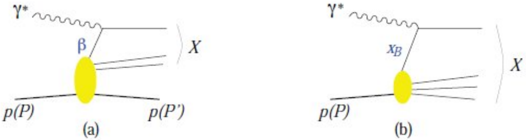
- Types of diffraction in high-energy physics:




- ISR @ CERN (pp, $\sqrt{s}$ = 23 – 63 GeV): $\sigma_{\rm el}$ had exponential slope and diffractive minimum; shrinkage; pomeron/double pomeron exchange.

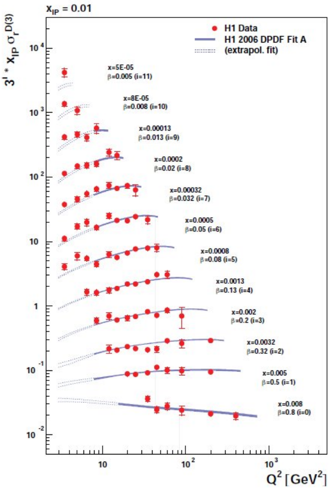


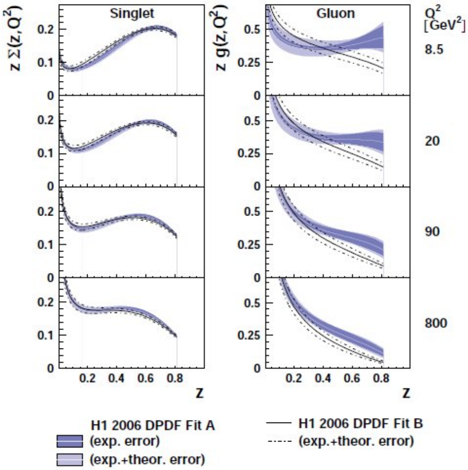

- Sp$\bar{\rm p}$S/UA8 @ CERN ($\sqrt{s}$ = 630 – 900 GeV): first observation of hard diffraction.
- HERA @ DESY (ep, $\sqrt{s}$ = 320 GeV): factorisation(s) holds; DPDFs.




From K. Goulianos, Low $x$ 2013 and arXiv:1006.1289

# Diffraction: brief experimental status,...cont’d

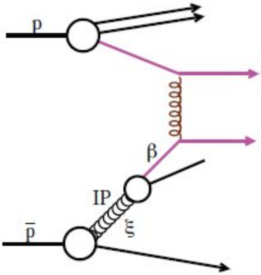


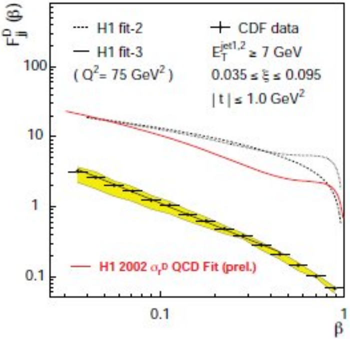




From hep-ex/0606004

# Diffraction: brief experimental status,...cont'd

- Tevatron @ FNAL ($p\bar{p}$, $\sqrt{s}$ = 550 – 1960 GeV): diffraction in hadron–hadron scatt. is more complicated; hard diffractive factorisation broken by multiple interactions.



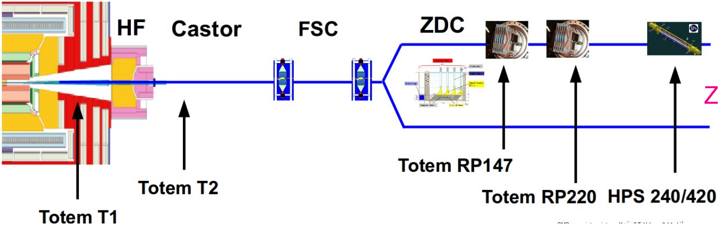




Gap survival problem??

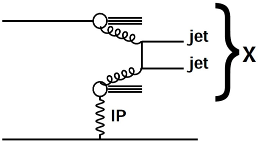
- LHC predictions (pp, $\sqrt{s}$ = 14 000 GeV): inclusive single diffraction and double pomeron exchange also with dijets, vector bosons, heavy quarks.

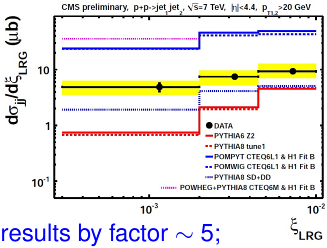
# Forward physics at LHC

- LHC “forward” arrangements (not to scale):




ZDC: $|\eta| \gtrsim 8$




- Diffractive MC models overestimate the results by factor $\sim 5$; gap survival probability ?

After G. Brona (2012) and CMS PAS FWD-10-004