# HERAでの PDF 測定
# つまりこれまでわかっていること:
# collinear PDFs, diffractive PDFs

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EICで展開する新たな原子核, 素粒子物理

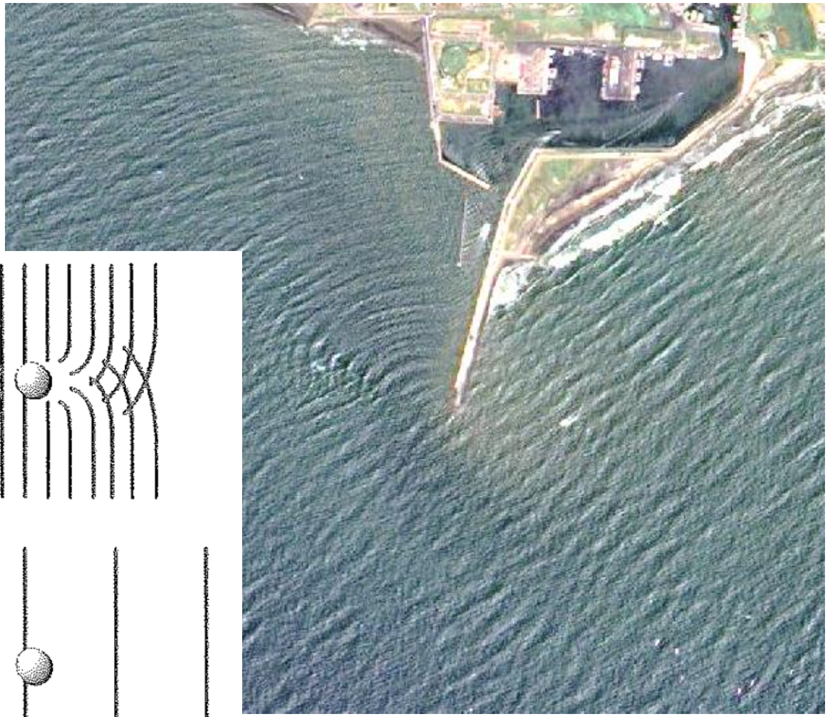
28 May 2024, Koshiba Hall, Univ of Tokyo

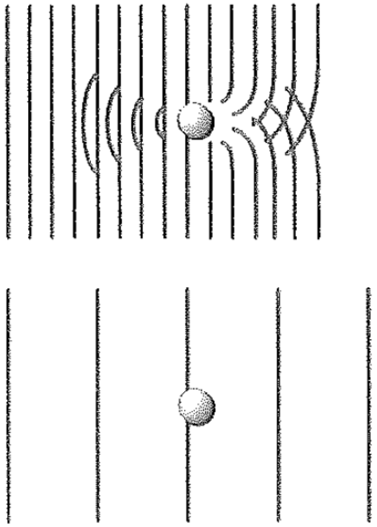
# 本日の内容

M1のみなさん向けから始めます

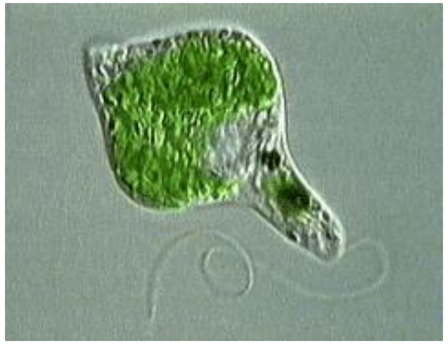
- Learning about the basics of DIS and parton densities of hadrons
  - Principle, kinematics, parton density
- Constraining gluon density through jet production
- DIS kinematics and detector requirement
- Diffractive scattering (時間があれば)

# 小さい構造を見るには
# 波長の短い波が必要



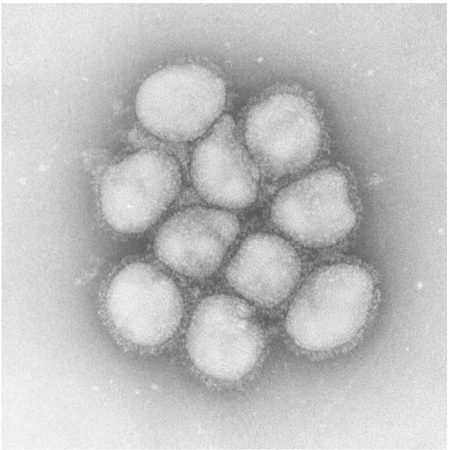


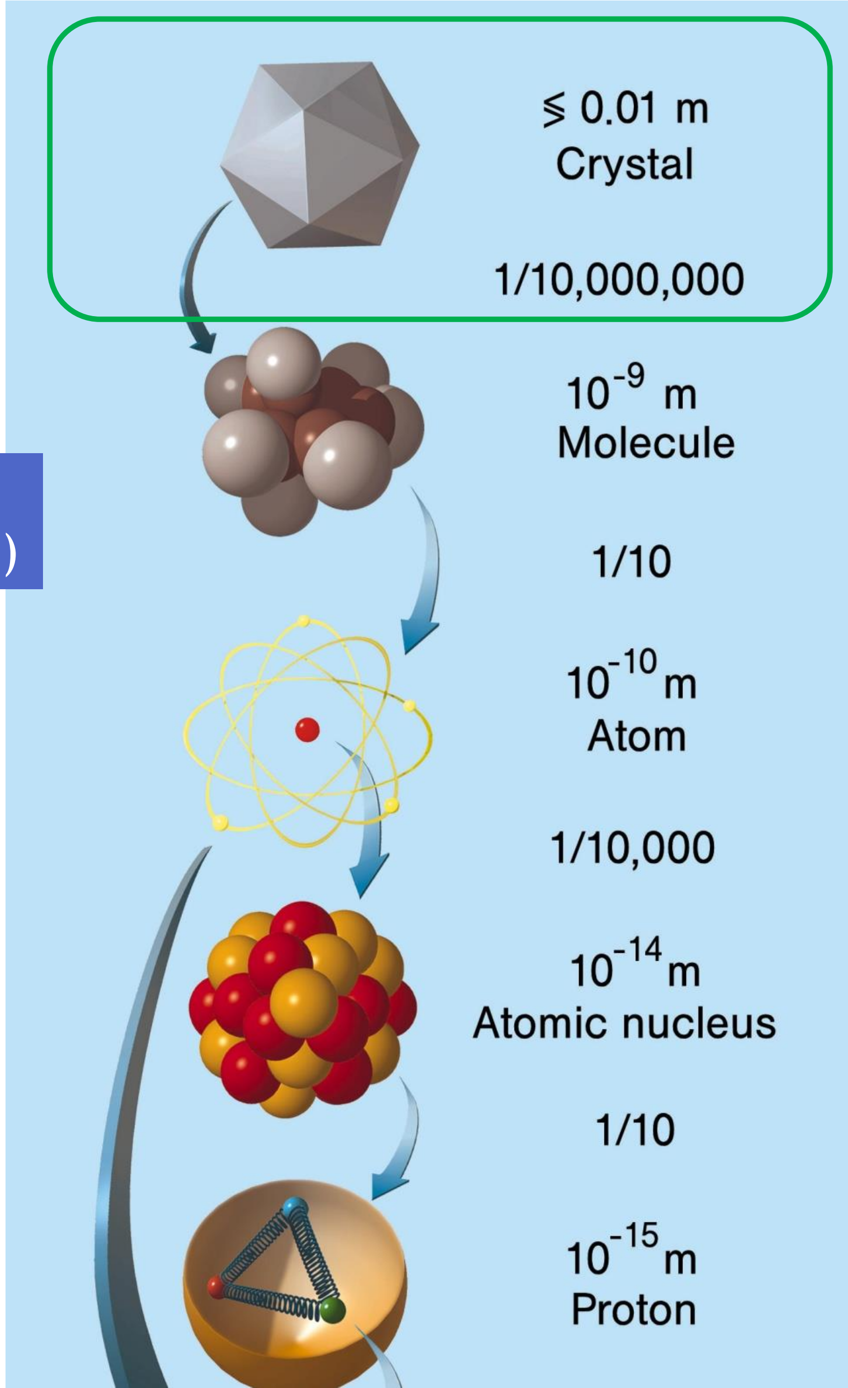
▲図 4−2　回　折



↑ Euglena
(optical microscope)

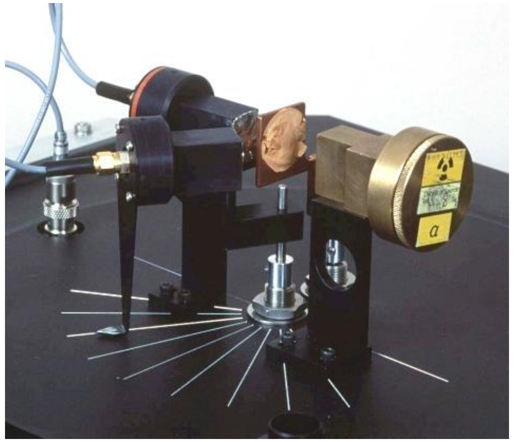
Virus
(electron
microscope)



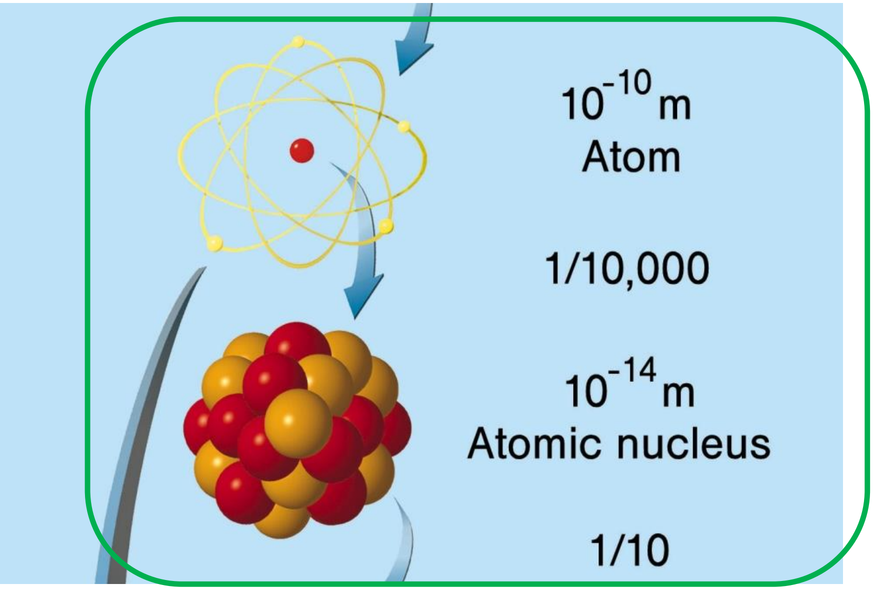


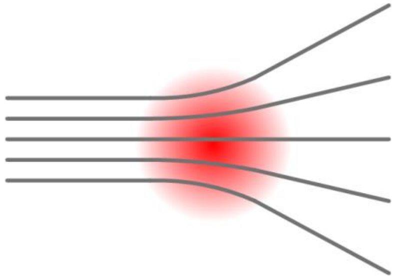
# 原子核の発見と
# 散乱実験の始まり

Rutherford experiment (1911) replica

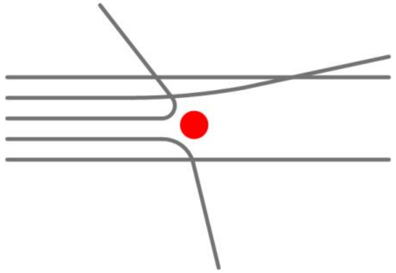


$\alpha$ 線を原子核に当て，
核分布から標的の大きさを求める



Large object:
May are scattered
but with small angles

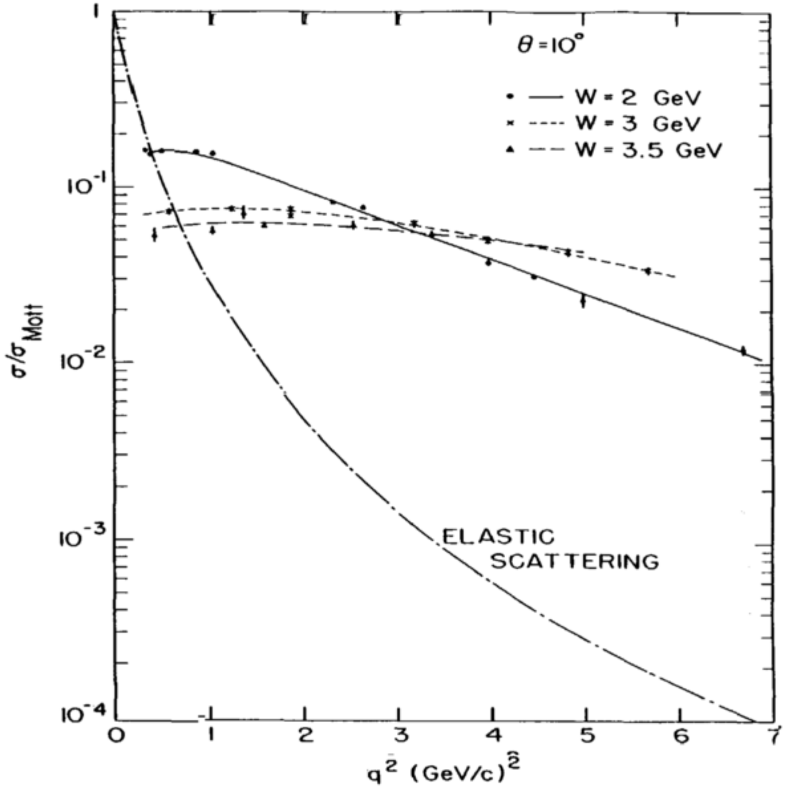


Small object:
mostly un-scattered,
but some with large angles

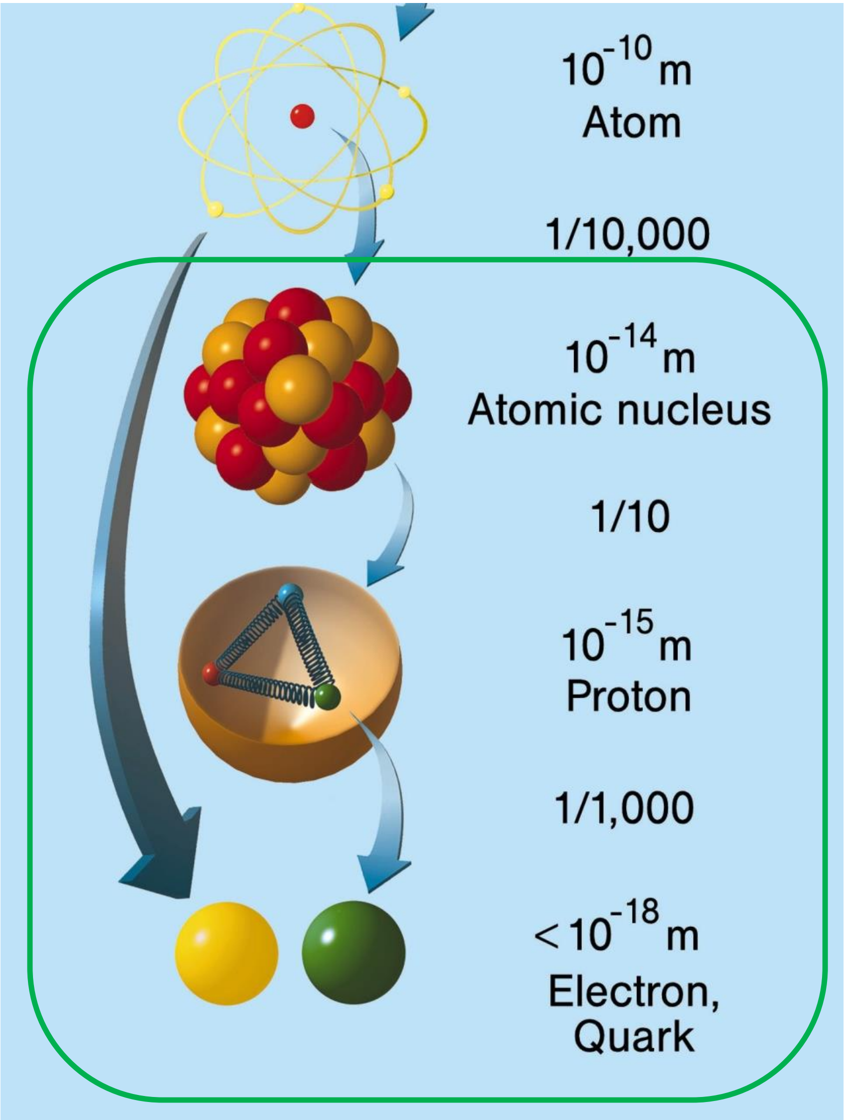
# The SLAC experiment and discovery of quarks

- $eN$ scattering has excess over elastic scattering in large angle, showing the same behavior as Mott scattering i.e. point-like particle
  - A nucleon consists of overlay of quarks

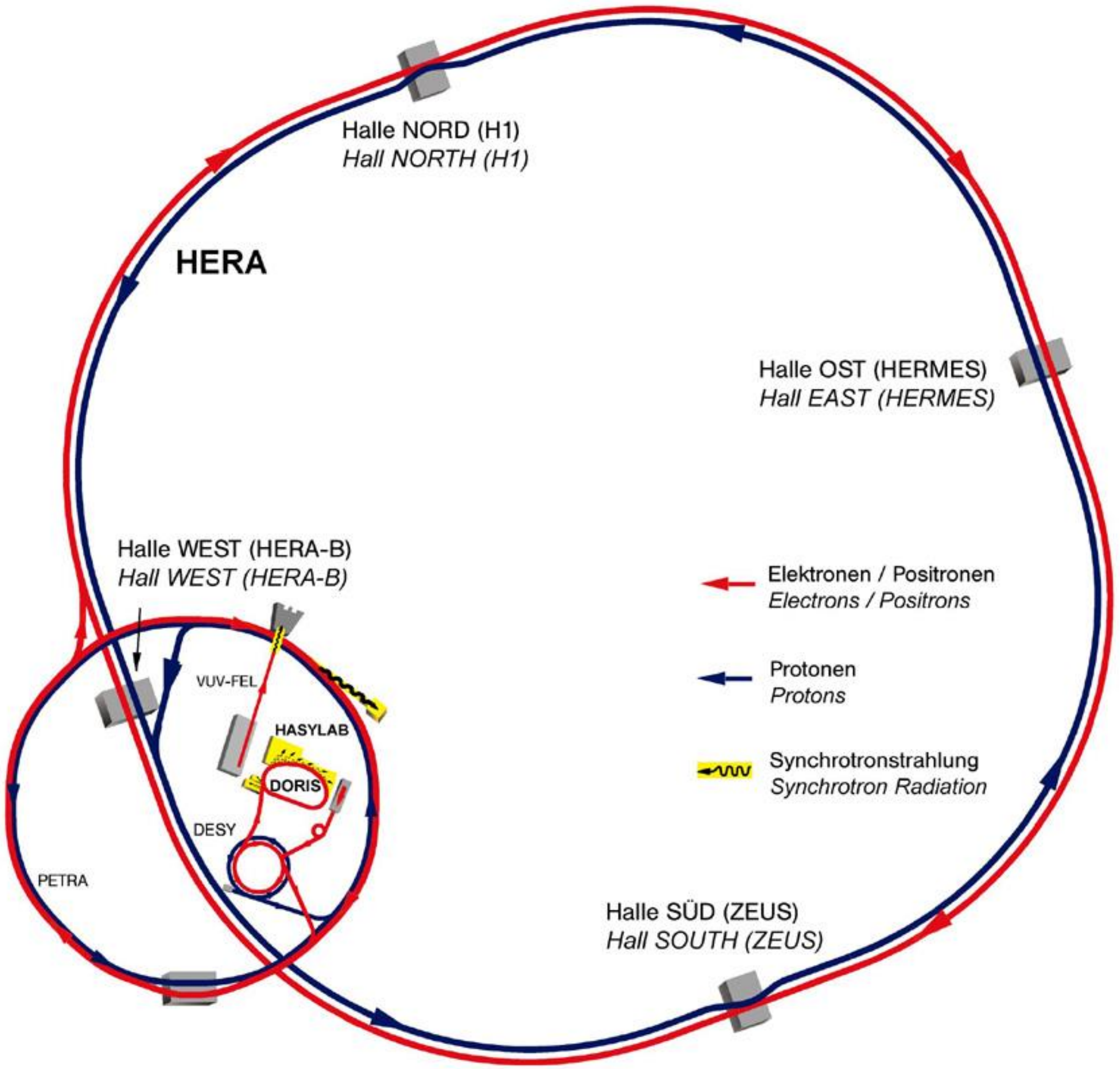
SLAC-MIT 1967
> 8 GeV electron beam




From: http://scholarpedia.org/article/Bjorken_scaling



# HERA: the only electron-proton collider (so far)



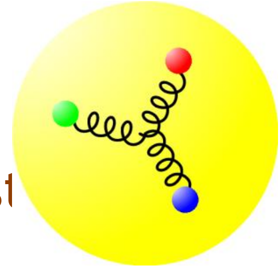

- Circumference: 6.3 km
  (similar size to the Tevatron at Fermilab)
- Proton beam: 920 GeV
- Electron/positron beam: 27.5 GeV

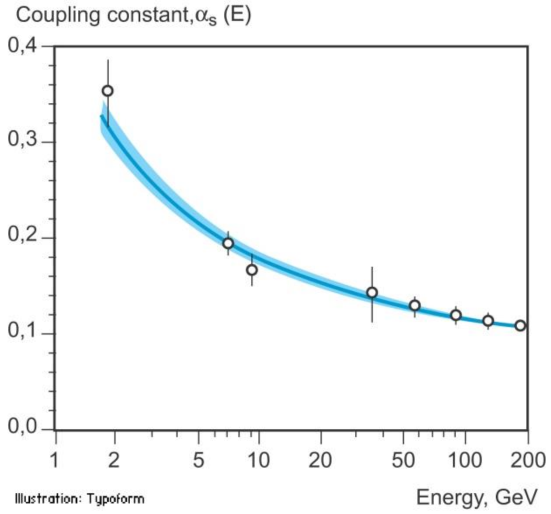
→ centre-of-mass energy $\sqrt{s} = 318\ \mathrm{GeV}$
  Resolve structure down to $10^{-18}$ m

- 220 bunch operation
  (96ns bunch spacing)
- Operated in 1992-2007

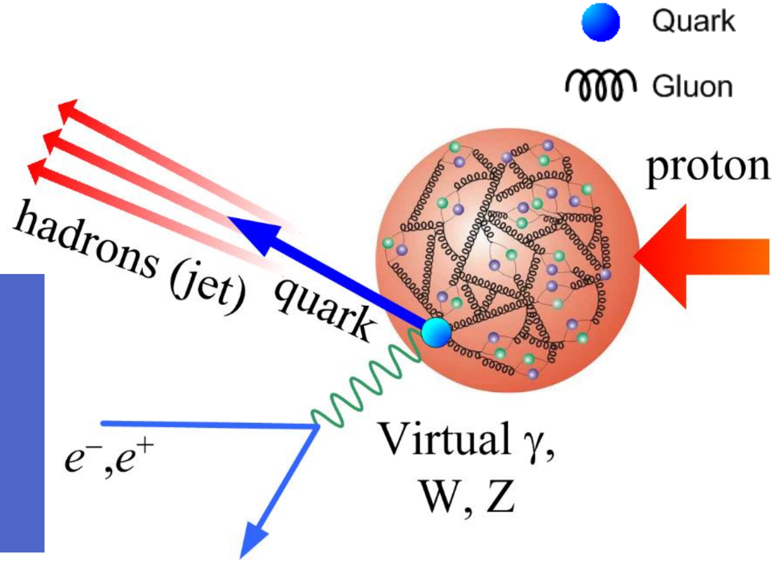
# Deep Inelastic Scattering

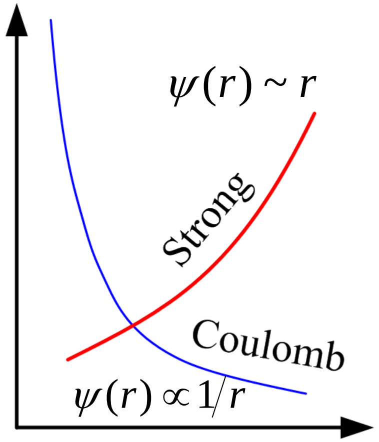
- Quarks are confined
  - A quark approaching the lower energy ($\Lambda_{QCD} \simeq 200$
    the strong coupling constant $\alpha_S$ larger
  - The knocked-out quark will be observed as bound st
- The quark state snapshot may be taken with photon with short wavelength
  - i.e. high-energy lepton-hadron collision

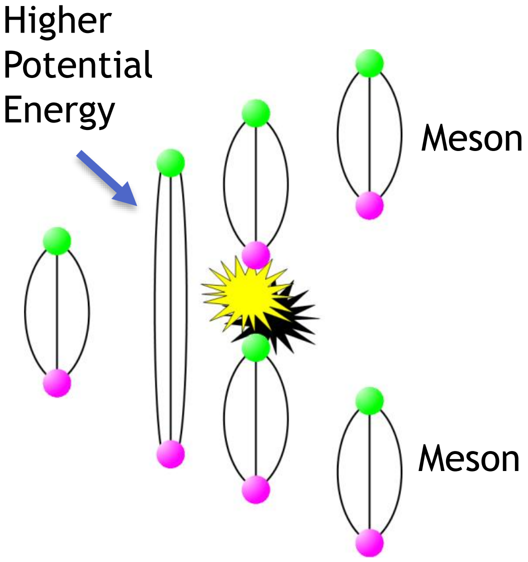




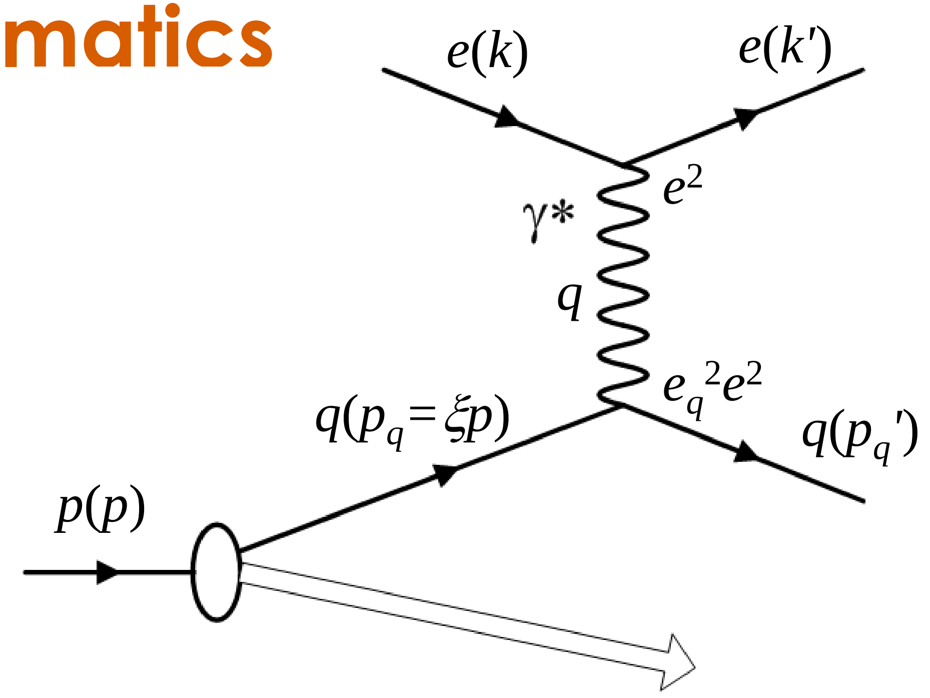

Hitting quarks by electron,
a point-like particle:
or more precisely,
a virtual photon
with short wave length



# DIS process and kinematics




## DIS variables:

$s = k \cdot p$ : CM energy squared

$q = k - k'$ : virtual photon 4-momentum

$Q^2 = -q^2 = -(k-k')^2$

: negative of the virtual photon 4-momentum squared, indicating the mass of the virtual photon

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

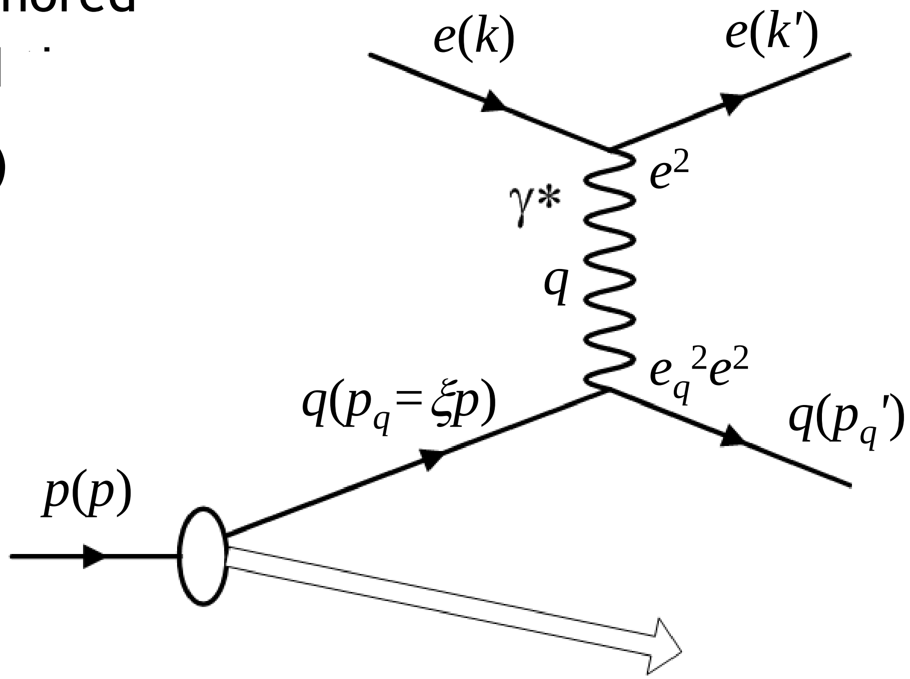
: related to the longitudinal momentum fraction of the quark coupled ($p_q$) to the virtual photon ($\xi$ in the left figure)

$y = \frac{p \cdot q}{p \cdot k}$ : related to the scattering angle & mom transfer

They satisfy $sxy = Q^2$ at high energy: massless limit

# The variable $x$

- $x = Q^2/2p \cdot q$ is defined only by beam parameters and variables determined from the scattered lepton
  - no need to measure hadronic final state in principle
- It is equal to $\xi = p_q/p$
  - Assuming that all initial & final particle masses are ignored
    - the centre-of-mass energy of the initial quark and virtual photon $\hat{s} = 2k \cdot p_q = 2\xi k \cdot q = \xi s = \xi \frac{Q^2}{xy}$ (1)
    - Assuming $m_q^2 = p_q^2 = p_q'^2 = 0$,
      $p_q'^2 = (p_q + q)^2 = q^2 + 2p_q \cdot q = -2xp \cdot q + 2\xi p \cdot q$
      $= 2p \cdot q(\xi - x) = 0$ (2)
  - This leads to: $\underline{x = \xi}$ (from (2))
    and $\hat{s} = \frac{Q^2}{y} = xs$ (from (1))



# The variable $y$

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

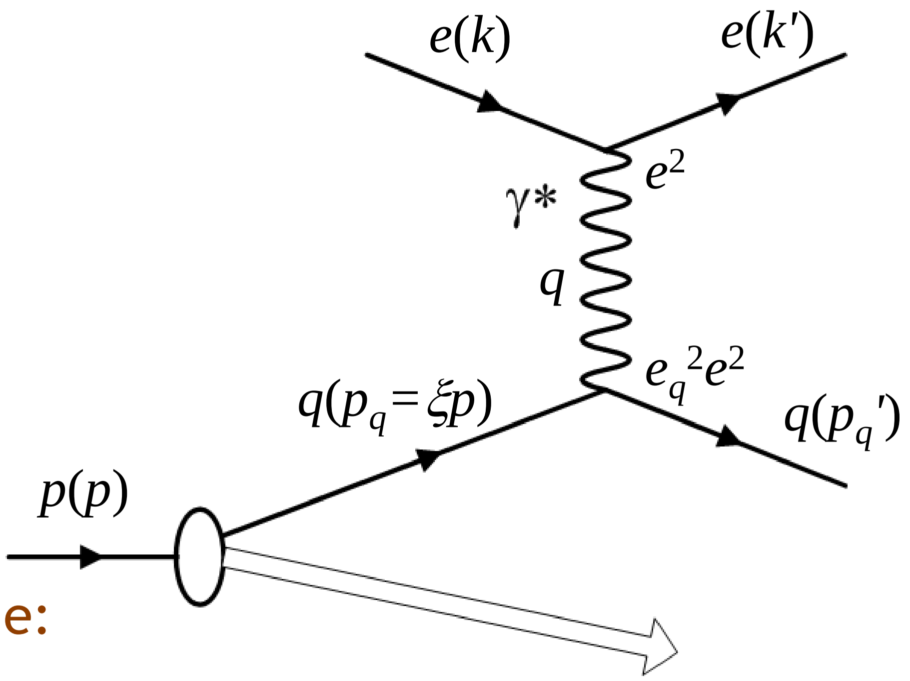
- it is the ratio of the photon momentum projected onto the proton direction, to the electron momentum projected onto the same direction

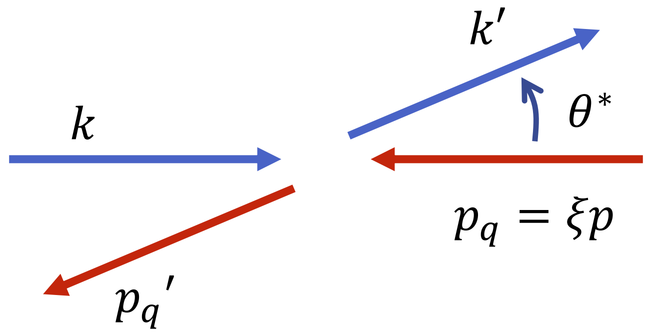
or: $1 - y = 1 - \frac{p \cdot q}{p \cdot k} = \frac{p \cdot k'}{p \cdot k} = \frac{p_q \cdot k'}{p_q \cdot k}$

- Let $\theta^*$ as the scattering angle in electron-quark CM frame: then $k'\left(k'_\perp, k'_\parallel, E\right) = (k' \sin\theta^*, k' \cos\theta^*, k')$
- In the CM frame, it satisfies $|k| = |k'|$, hence

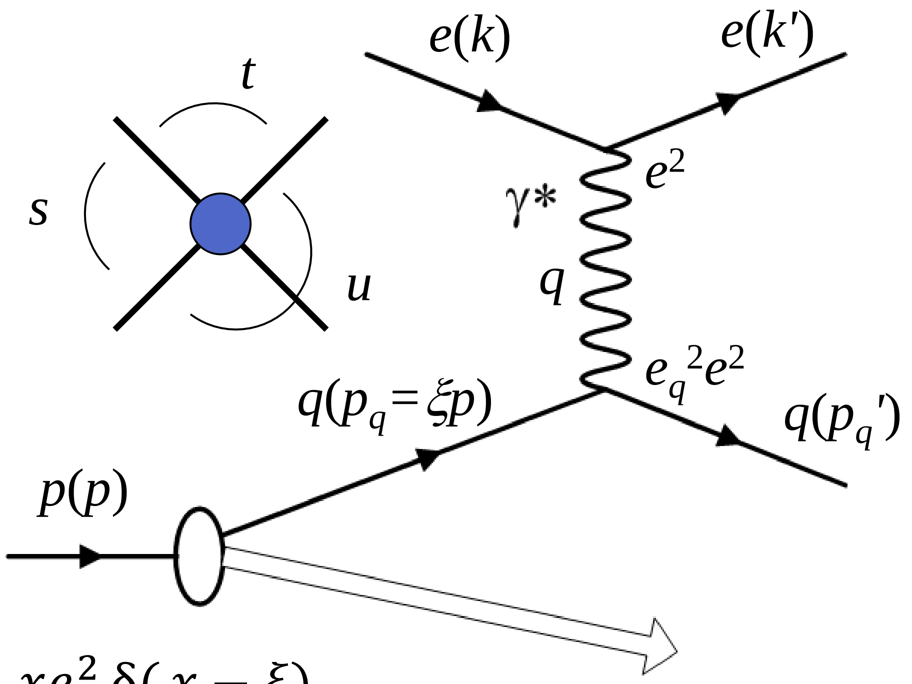
$$p_q \cdot k' = \left|p_q\right| |k'| (1 + \cos\theta^*) = \left|p_q\right| |k| (1 + \cos\theta^*)$$

- Since $p_q \cdot k = 2|p_q||k|$, it leads to $1 - y \simeq \frac{1}{2}(1 + \cos\theta^*)$ or $y = \frac{1}{2}(1 - \cos\theta^*) \simeq \sin^2\frac{\theta^*}{2}$ for small angle
- $y = 0$ : small scattering angle limit
  $y = 1$ : backscattering i.e. total momentum transfer to the hadronic system



# The structure function $F_2(x, Q^2)$



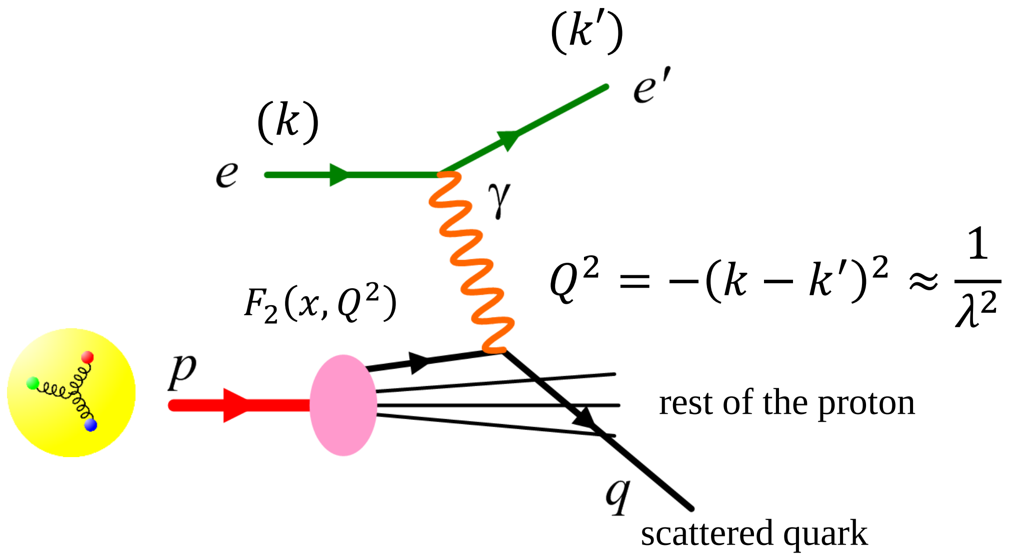

- Electron-quark scattering cross section in leading order perturbation theory:
  $\frac{d\hat{\sigma}}{d\hat{t}} = \frac{1}{16\pi\hat{s}} \cdot 2e_q^2 e^4 \cdot \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
  - $e_q$: fraction to the unit charge
  - Substituting, it gives: $\frac{d\hat{\sigma}}{dQ^2} = \frac{2\pi\alpha^2 e_q^2}{Q^4}[1+(1-y)^2]$
- defining a point-like quark structure function (SF) as: $\hat{F}_2(x) = xe_q^2\,\delta(x-\xi)$
  - The SF of a quark, integrating over $\delta$ function: $\frac{d^2\sigma}{dQ^2} = \int \frac{4\pi\alpha^2}{Q^4}[1+(1-y)^2]\frac{1}{2}e_q^2\delta(x-\xi)\,d\xi$
  
    or: $\frac{d^2\hat{\sigma}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}[1+(1-y)^2]\cdot\frac{1}{2}e_q^2\,\delta(x-\xi) = \frac{4\pi\alpha^2}{xQ^4}\left(1-y+\frac{y^2}{2}\right)\hat{F}_2$
- Now the contribution from all the quarks to sum up
  - Defining: $F_2(x) = \sum_{q,\bar{q}}\int_0^1 d\xi q(\xi)x\,e_q^2\,\delta(x-\xi) = \sum_{q,\bar{q}} e_q^2 xq(x)$
  - The cross section is given as: $\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)\right]$

Number density of quarks

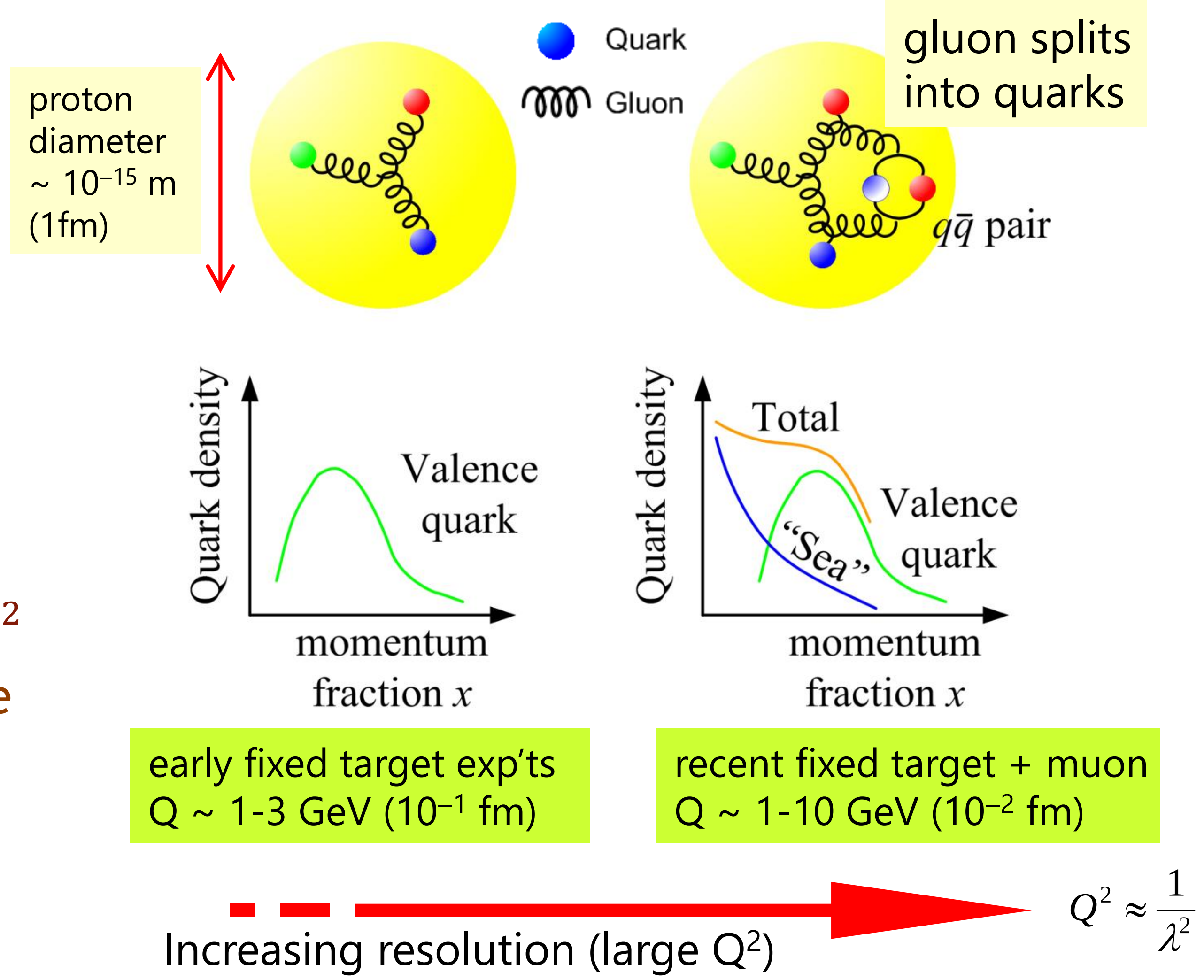
In principle, the point-like quark cross section does not depend on $Q^2$ apart from common kinematic factor
But the number of quark changes with $Q^2$: see next

# DIS measurements at HERA and extraction of Parton Density Functions (PDFs)

# DIS, and proton structure before HERA



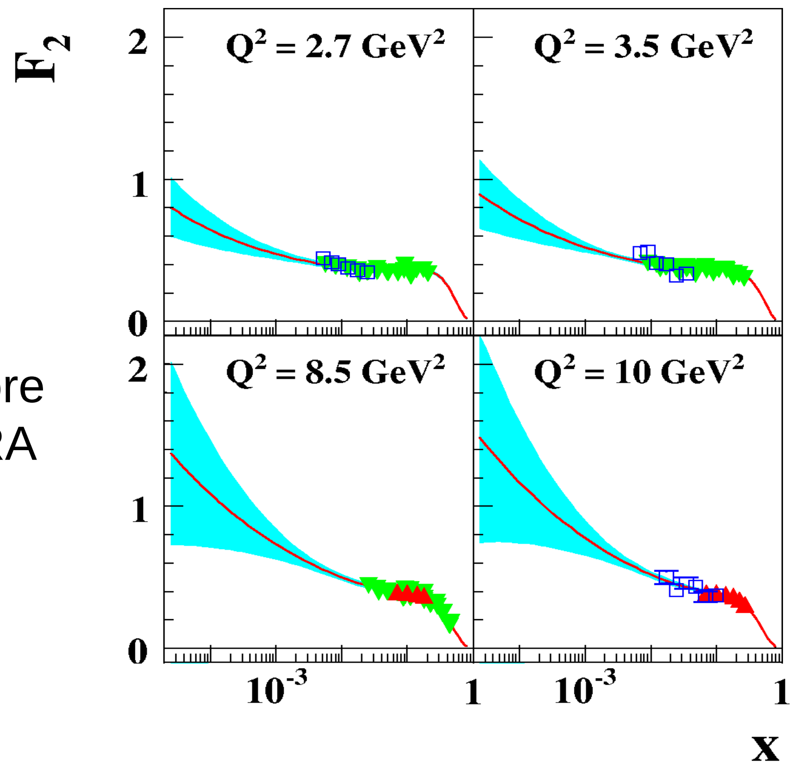

- The wavelength gets shorter with larger $Q^2$
  - Uncovering more microscopic structure
  - Start to see "sea quarks": a pair of $q\bar{q}$ from vacuum-polarised gluon

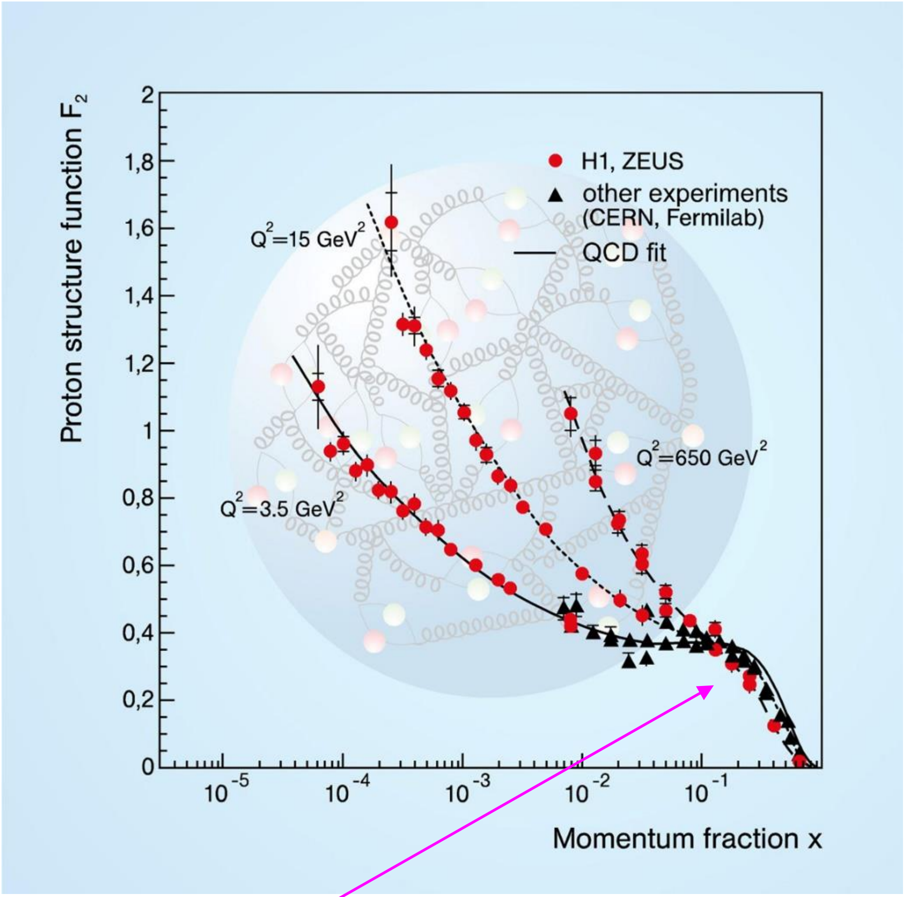


# HERA result

- HERA: higher energy scattering
  - low-$x$ partons are enough energetic to cause $e-q$ scattering to be observed in the detector
- Rapid increase in $F_2$ i.e. quark density observed

Before HERA



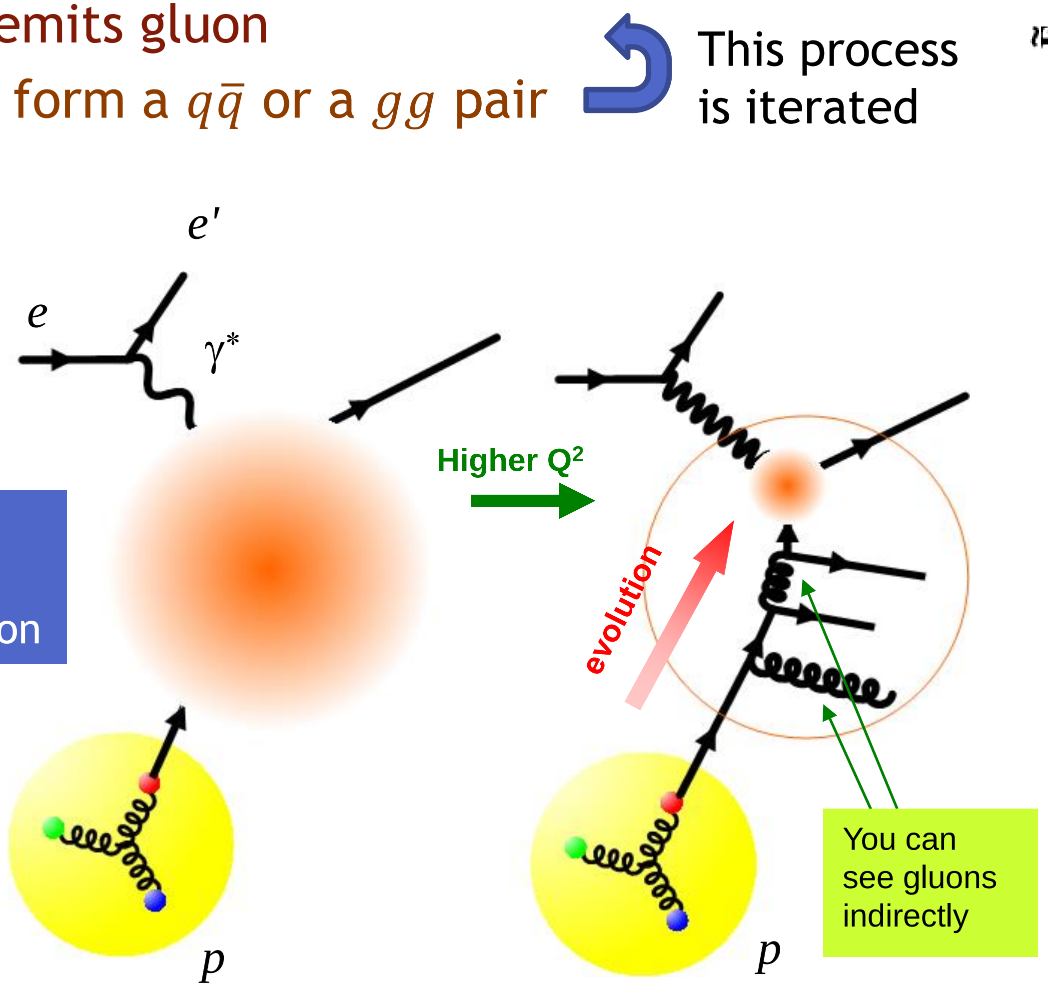

Quark density decreasing at high-$x$ with $Q^2$

Horizontal axis: momentum fraction to the proton: $x = \frac{Q^2}{2p\cdot q}$

# HERA result ($ep$ collider 27.5×920 GeV)

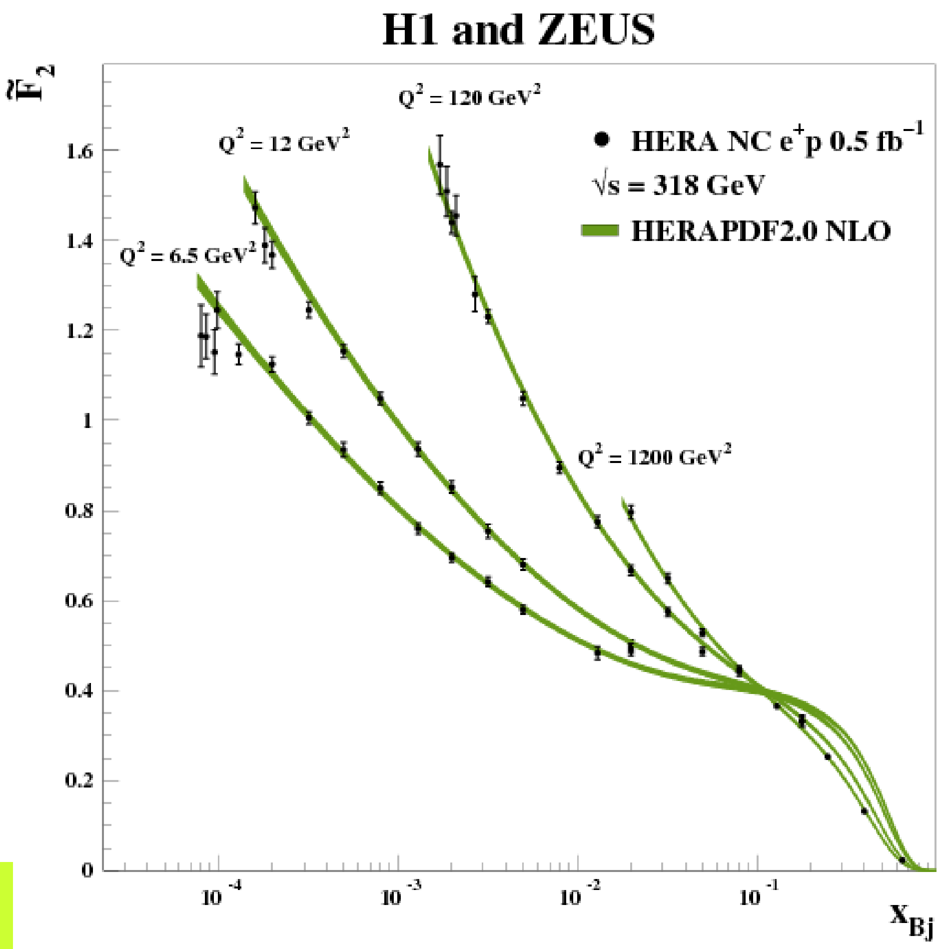
- Low-$x$ partons increases very rapidly
- quark or gluon emits gluon
  - Polarised to form a $q\bar{q}$ or a $gg$ pair

This process is iterated




Partons after branching is revealed by a short-wavelength photon

HERAPDF 2.0



# Extracting gluons

- The behavior of $F_2(x, Q^2)$ can be explained by the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) differential equation
  - The gluon PDF (parton distribution function) can be extracted by fitting the diff.eq.
  - Qualitatively: the slope in $F_2$ with $Q^2$ is given by the ratio of gluon and quark compoments: more gluons, steeper $Q^2$ dependence

$\hat{P}_{ba}(z)$: the probability that a fraction of $z$ is given to $b$ of $a$ for $a \to b(X)$

$$\hat{P}_{qq}(z) = C_F\left[\frac{1+z^2}{1-z}\right]: q \to q(g)$$

$$\hat{P}_{gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right]: q \to g(q)$$

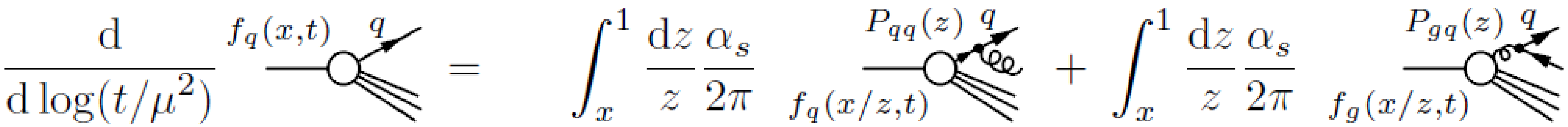
$$\hat{P}_{qg}(z) = T_R[z^2 + (1-z)^2]: g \to qq$$

$$\hat{P}_{gg}(z) = 2C_A\left[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z)\right]: g \to gg$$

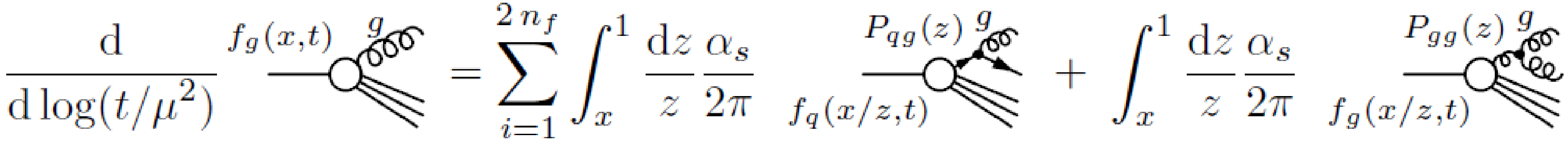
$$C_F = \frac{4}{3}, C_A = 3, T_R = \frac{1}{2}$$

Gluon radiates much stronger than quarks (large $C_A$)

$g \to qq$ has no divergence, others have infrared divergence @ z=1 or 0



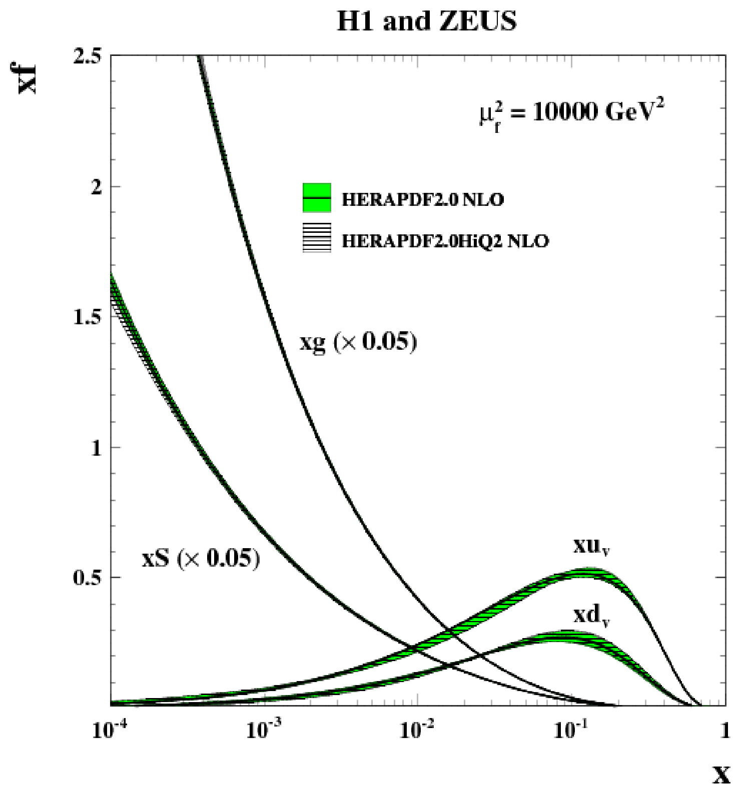
$$\frac{d}{d\log(t/\mu^2)} f_q(x,t) = \int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi} P_{qq}(z) f_q(x/z,t) + \int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi} P_{gq}(z) f_g(x/z,t)$$

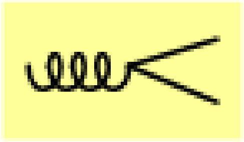


$$\frac{d}{d\log(t/\mu^2)} f_g(x,t) = \sum_{i=1}^{2n_f}\int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi} P_{qg}(z) f_q(x/z,t) + \int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi} P_{gg}(z) f_g(x/z,t)$$

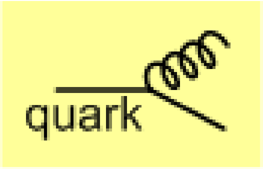
# Extracting gluons (cont'd)

- The data is very well explained by the DGLAP equation
  - Gluon density was determined from the DIS data very precisely
- The triumph of the perturbative QCD!

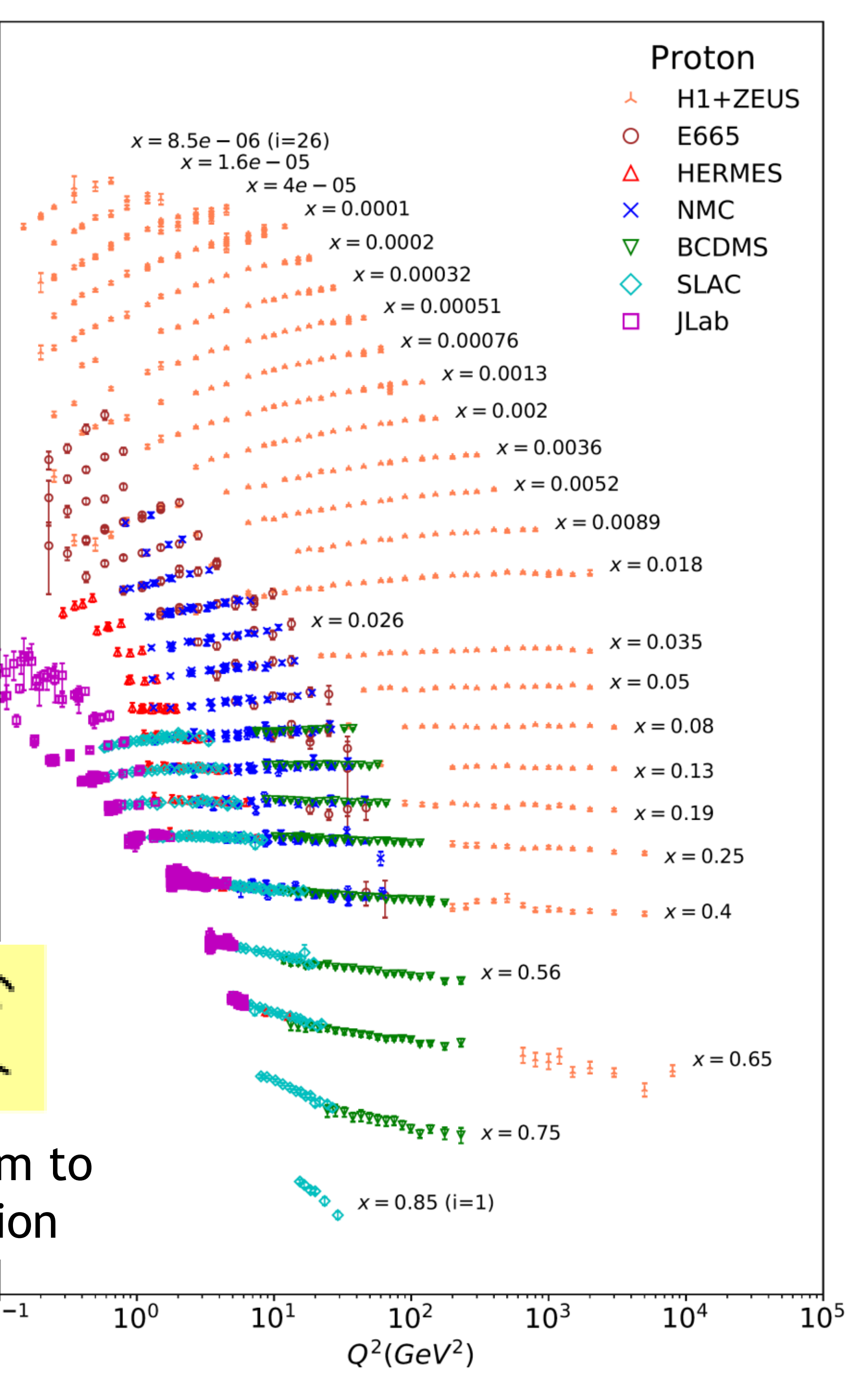


small $x$:
gluons drive quarks




large $x$:
quarks give momentum to gluons through radiation



# The fit parameters

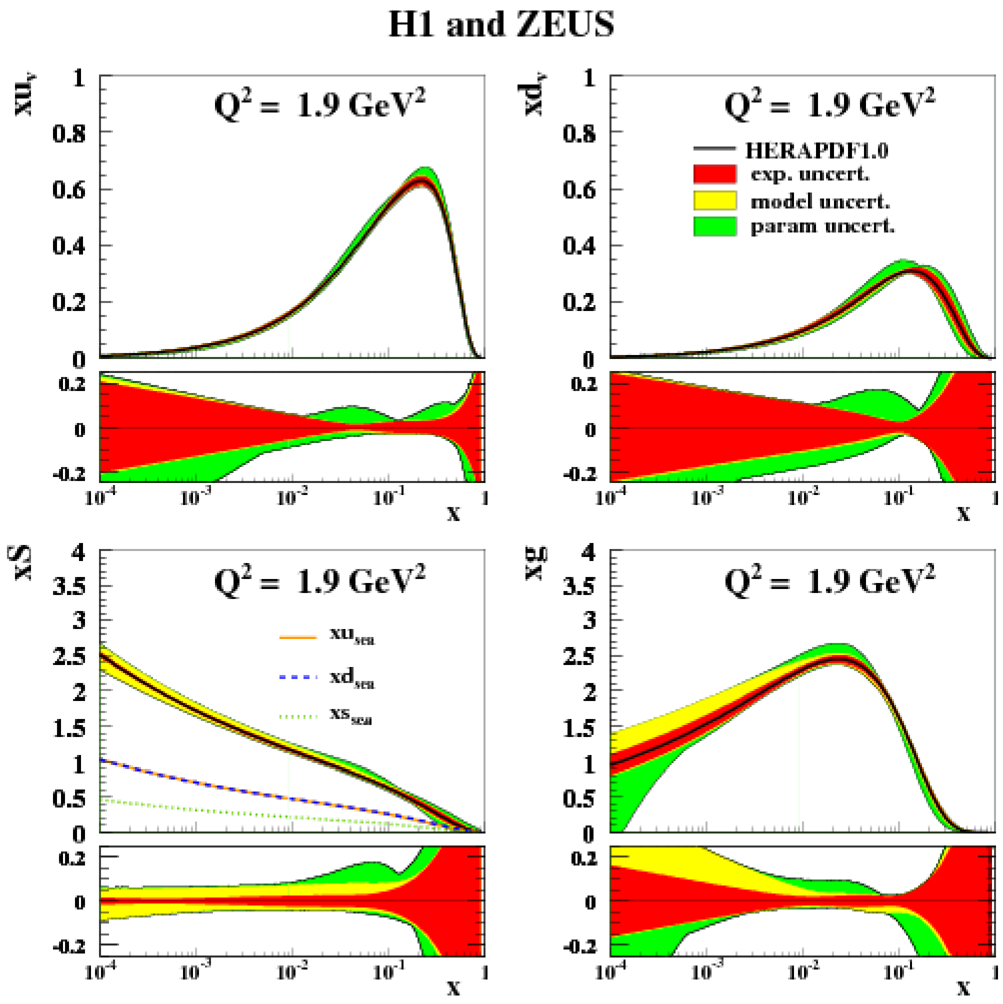
- Only the parton densities at the starting scale $Q^2 = Q^2_{min}$ are assumed
  - 3.5 $\mathrm{GeV}^2$ for the HERAPDF2.0
  - No explicit parameters on higher $Q^2$ data: it evolves in $Q^2$ with the slope determined at the parton distributions at $Q^2 = Q^2_{min}$ !
  - Steeper slope with more gluons at $Q^2 = Q^2_{min}$
- Parton density parameterization at $Q^2 = Q^2_{min}$:

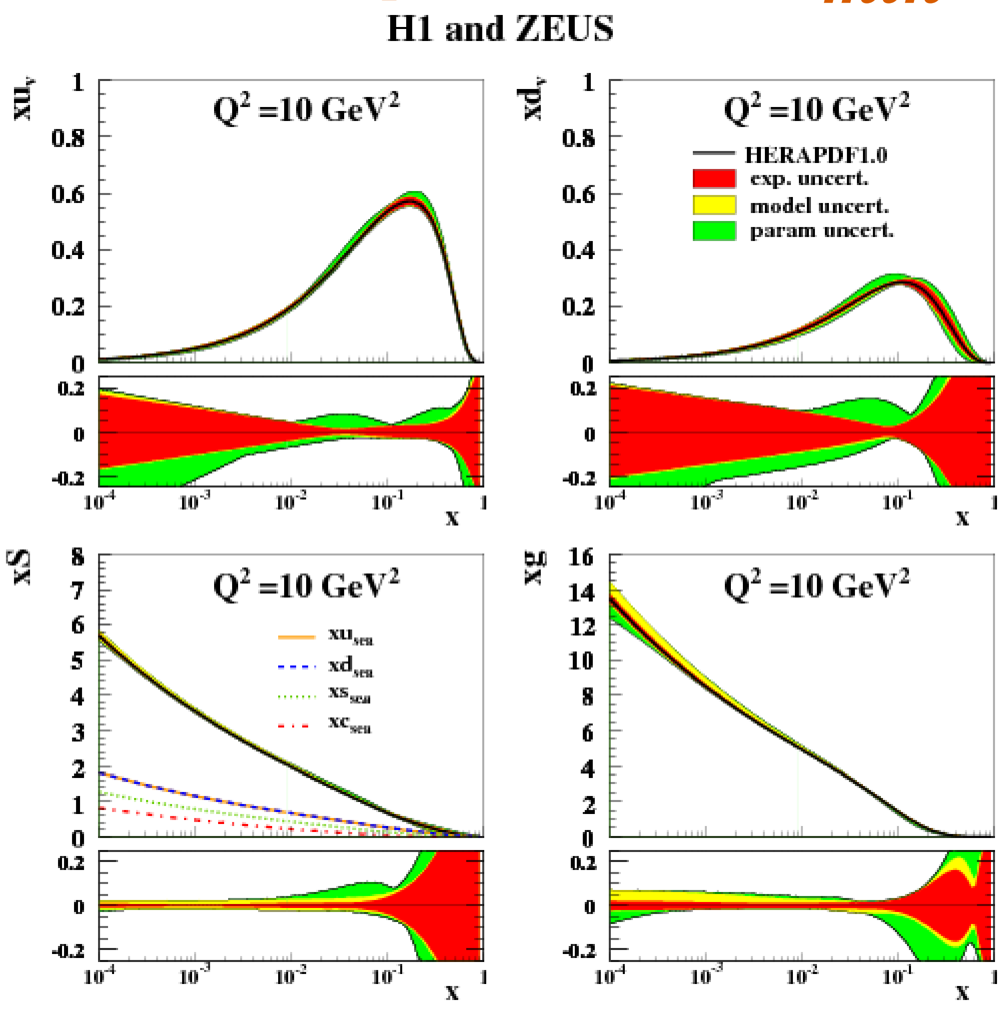
  $$xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2)$$
- Gluon term:

  $$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g}$$
  - Allowing gluon density to be more flexible at very low x values

| Variation | Standard value | Lower limit | Upper limit |
|---|---|---|---|
| $Q$min2 (GeV2) | 3.5 | 2.5 | 5.0 |
| $Q$min2 (GeV2) HiQ2 | 10.0 | 7.5 | 12.5 |
| $Mc$ (NLO) (GeV) | 1.47 | 1.41 | 1.53 |
| $Mc$ (NNLO) (GeV) | 1.43 | 1.37 | 1.49 |
| $Mb$ (GeV) | 4.5 | 4.25 | 4.75 |
| $fs$ | 0.4 | 0.3 | 0.5 |
| $\alpha s(MZ2)$ | 0.118 | – | – |
| $\mu f0$ (GeV) | 1.9 | 1.6 | 2.2 |

# Example of evolution (HERAPDF 1.0) around $Q^2_{min}$



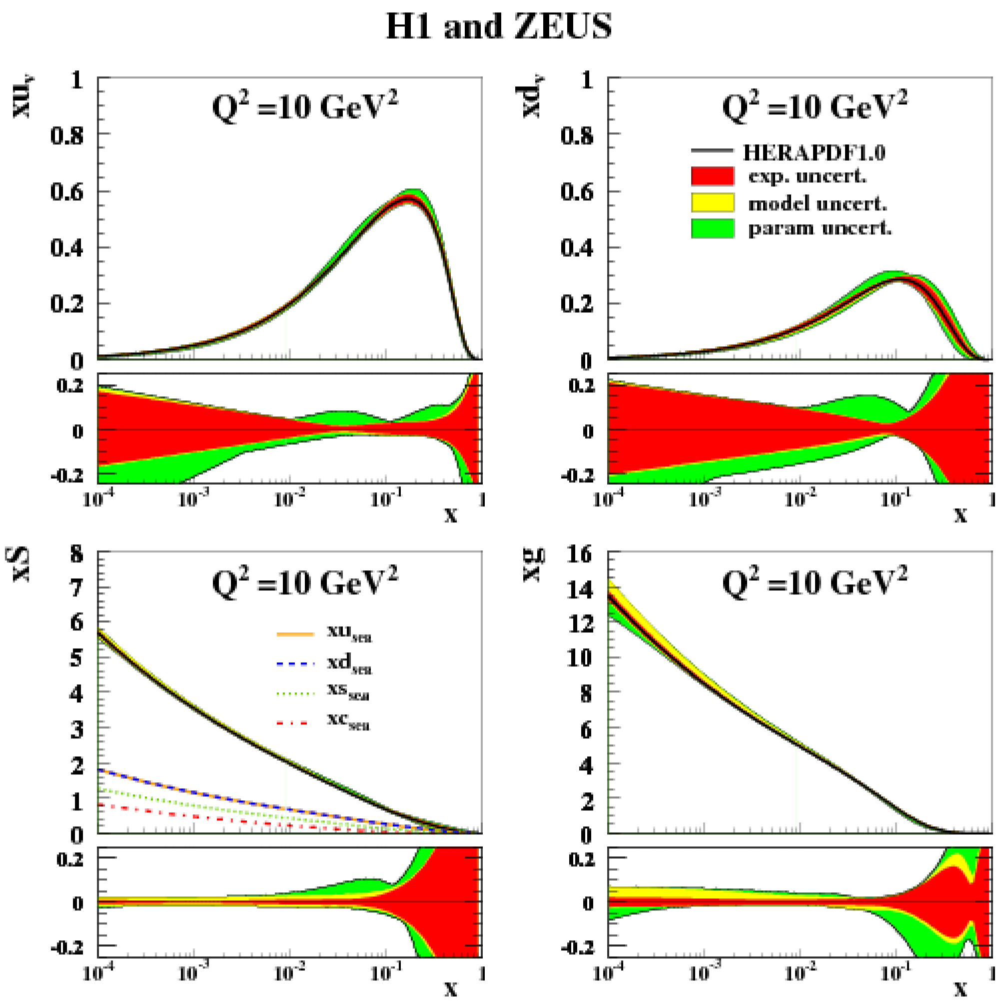



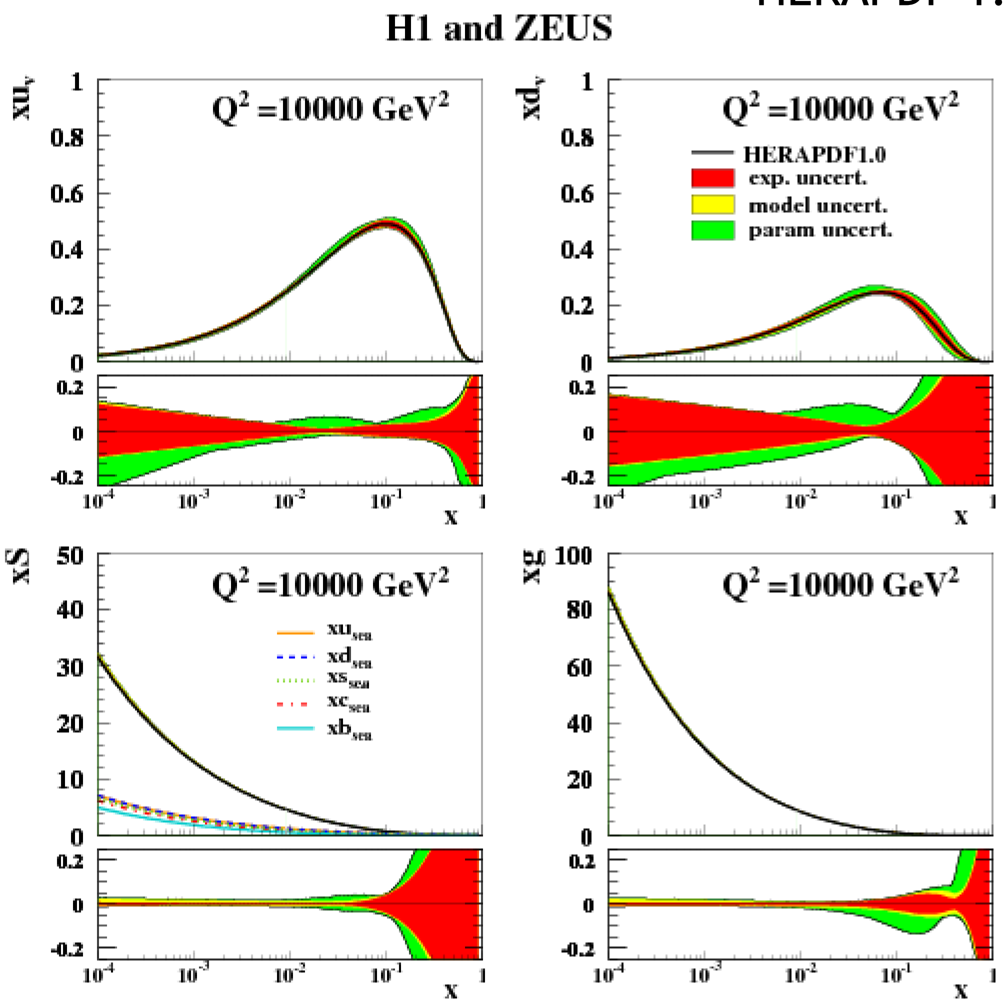

HERAPDF 1.0

- Gluon changes the shape drastically from $Q^2 = 1.9\ \mathrm{GeV}^2$ to $10\ \mathrm{GeV}^2$ as a consequence of radiation, described by the DGLAP equation

# Evolution towards higher $Q^2$

HERAPDF 1.0

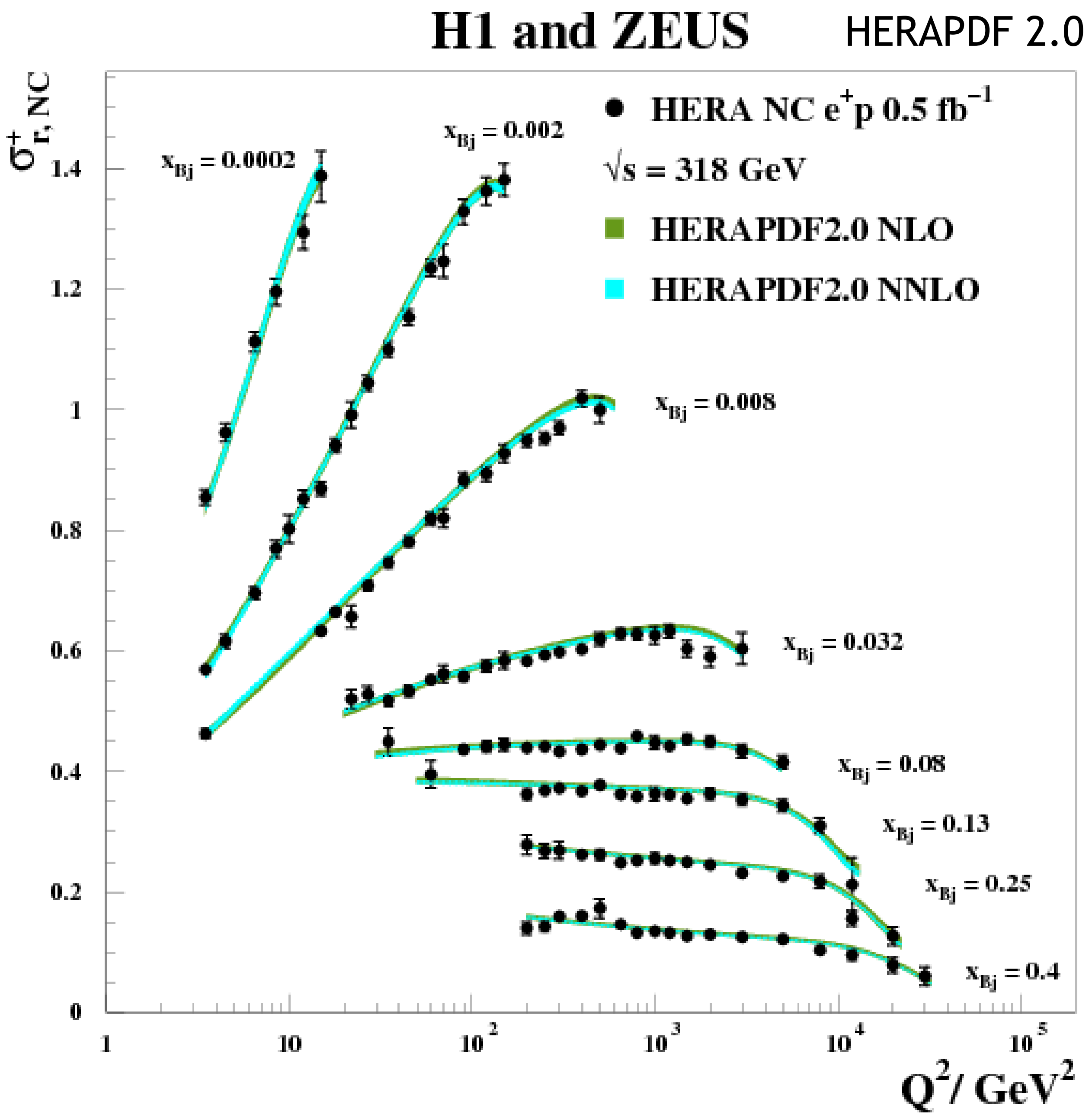


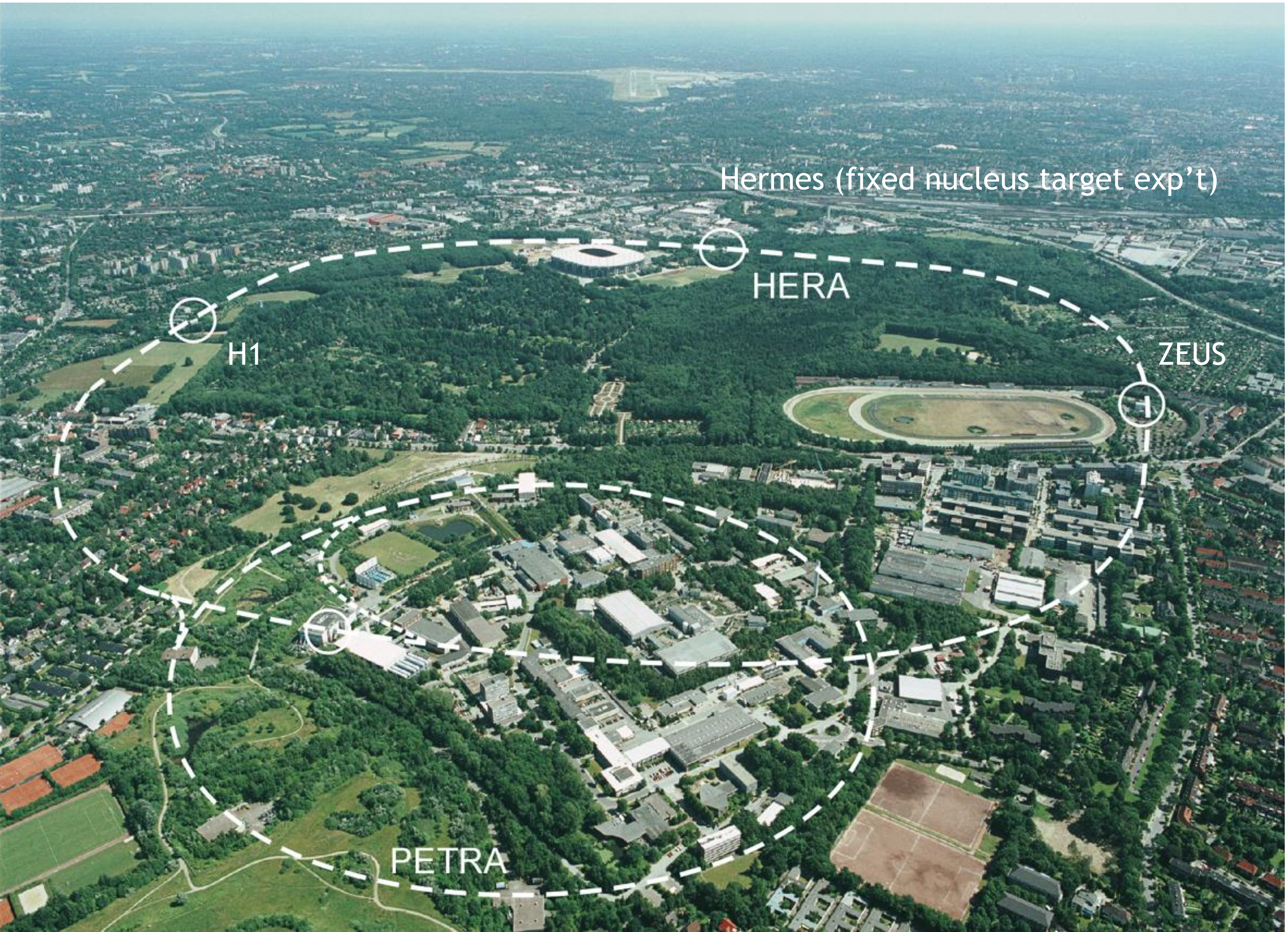

- Look at the vertical scales!
  Valences decreased a bit while sea is x6, gluon is x7 at $x = 10^{-4}$

# Evolution towards high $Q^2$

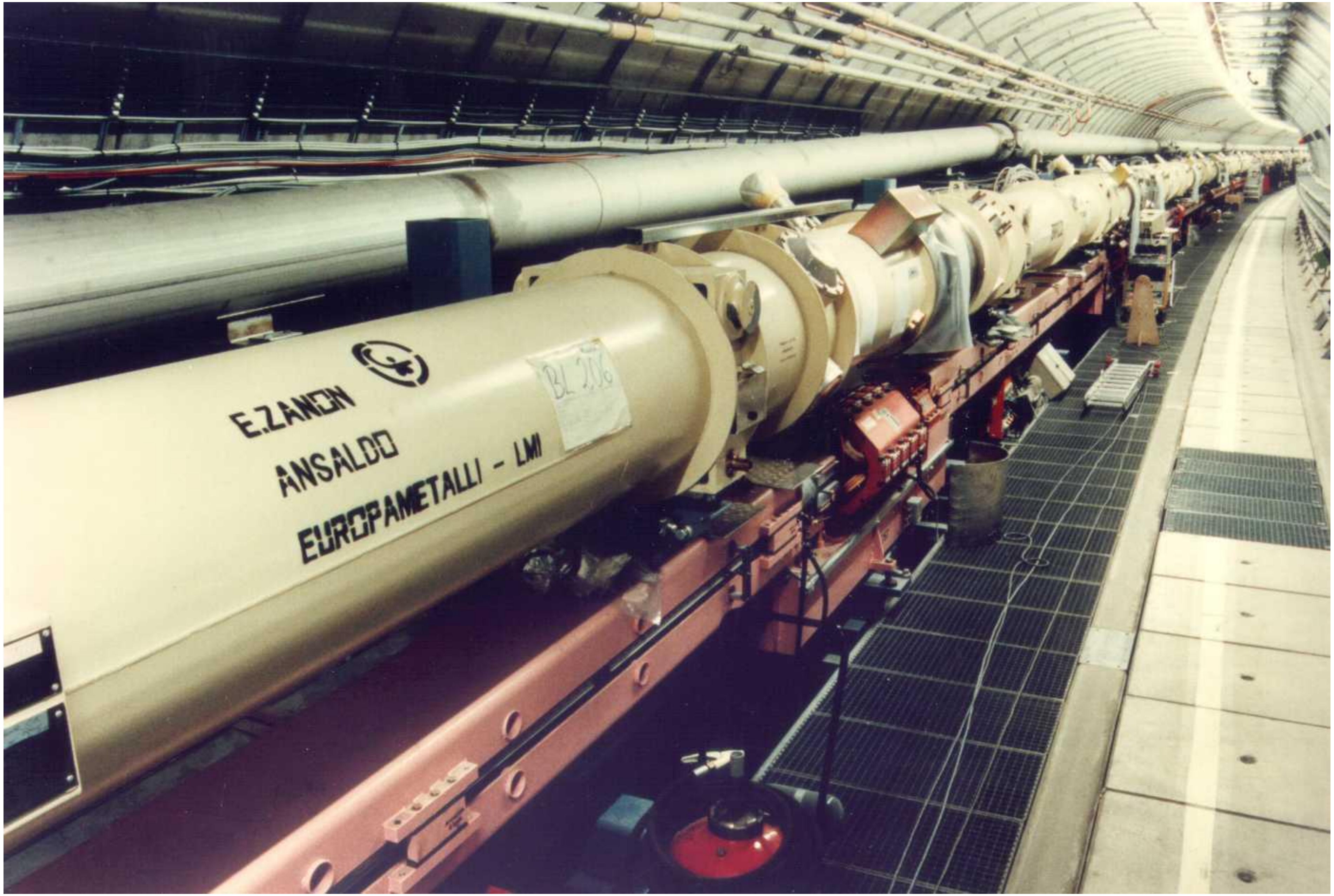
- Logarithmic increase/decrease of partons apparent
  - High-x: decreasing
  - Balanced around 0.1
  - Very rapid increase at very low x



# High-$Q^2$ charged current and neutral current cross sections




# DESY and HERA in the west of Hamburg, Germany

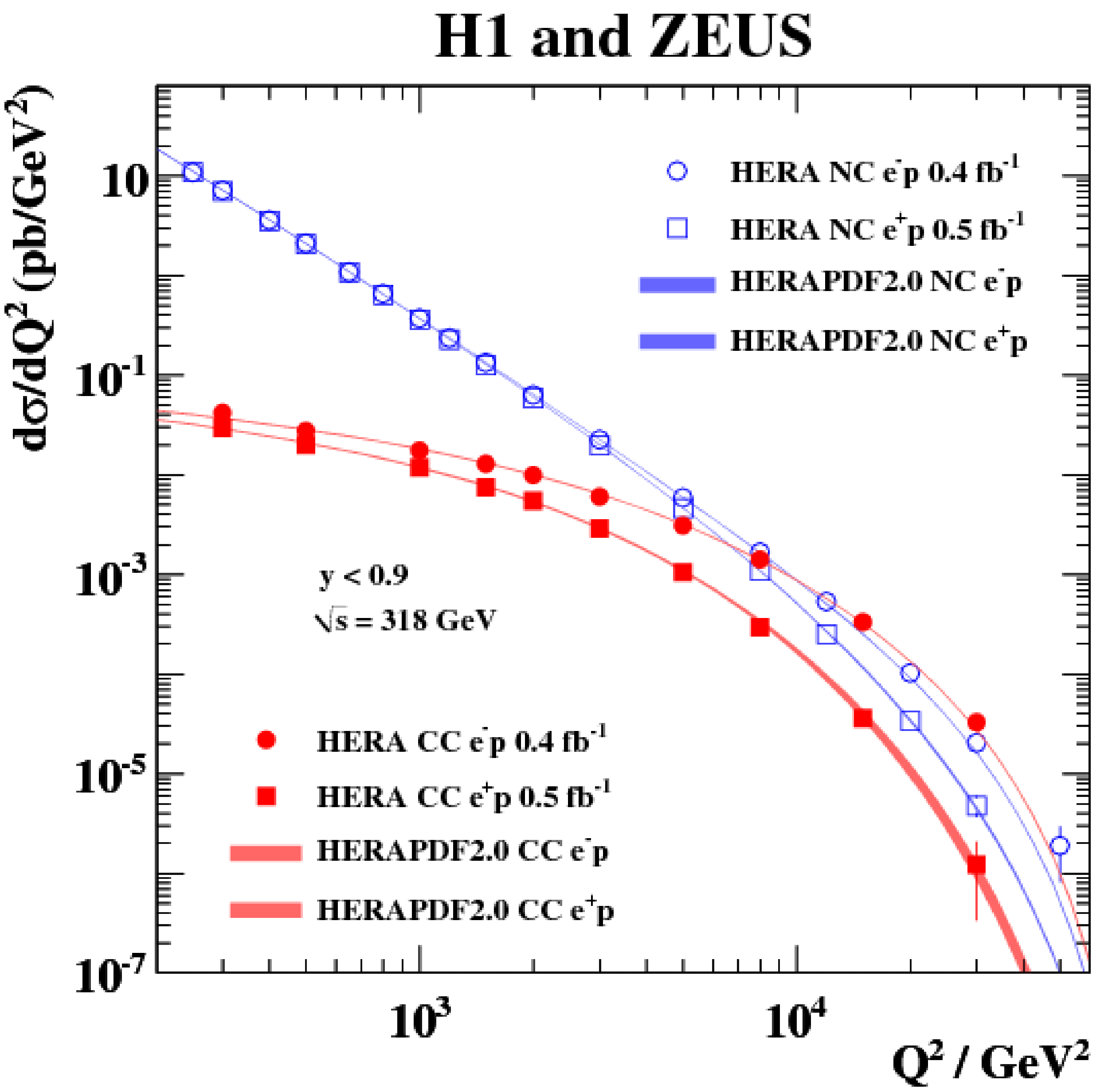



# HERA tunnel

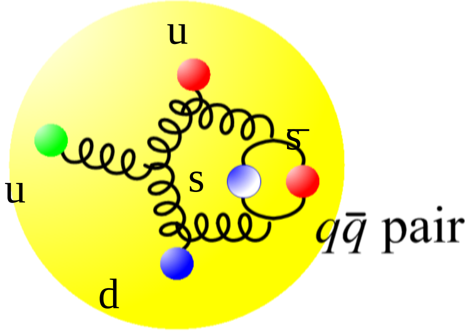
2-story ring
Upper: proton,
lower: electron

# NC/CC cross sections at high-$Q^2$

- "Direct" confirmation of the electroweak unification
- CC cross sections is larger than NC cross sections for $Q^2 \gg M_W^2$

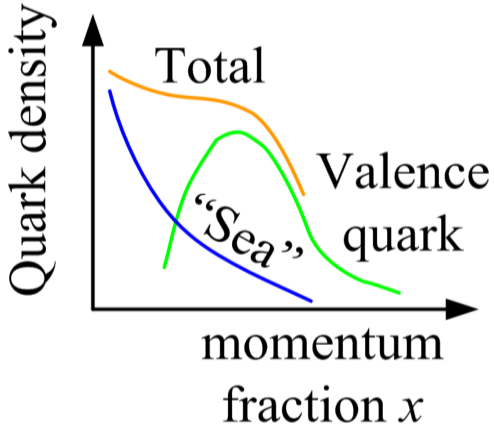


# Disentangling quark flavours



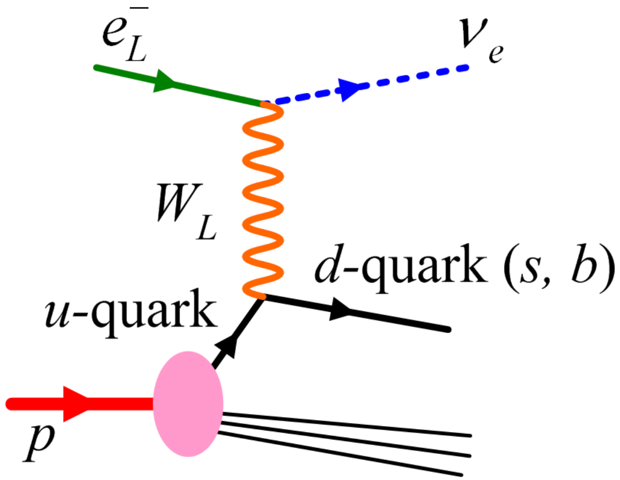

- Valence quarks: carrying the quantum number of the proton
  - Fermion → 3 quarks
  - Charge +1 (Isospin +½) → (uud)
- Sea quarks: assuming

$$u = \bar{u} = d = \bar{d}, s = \bar{s}$$



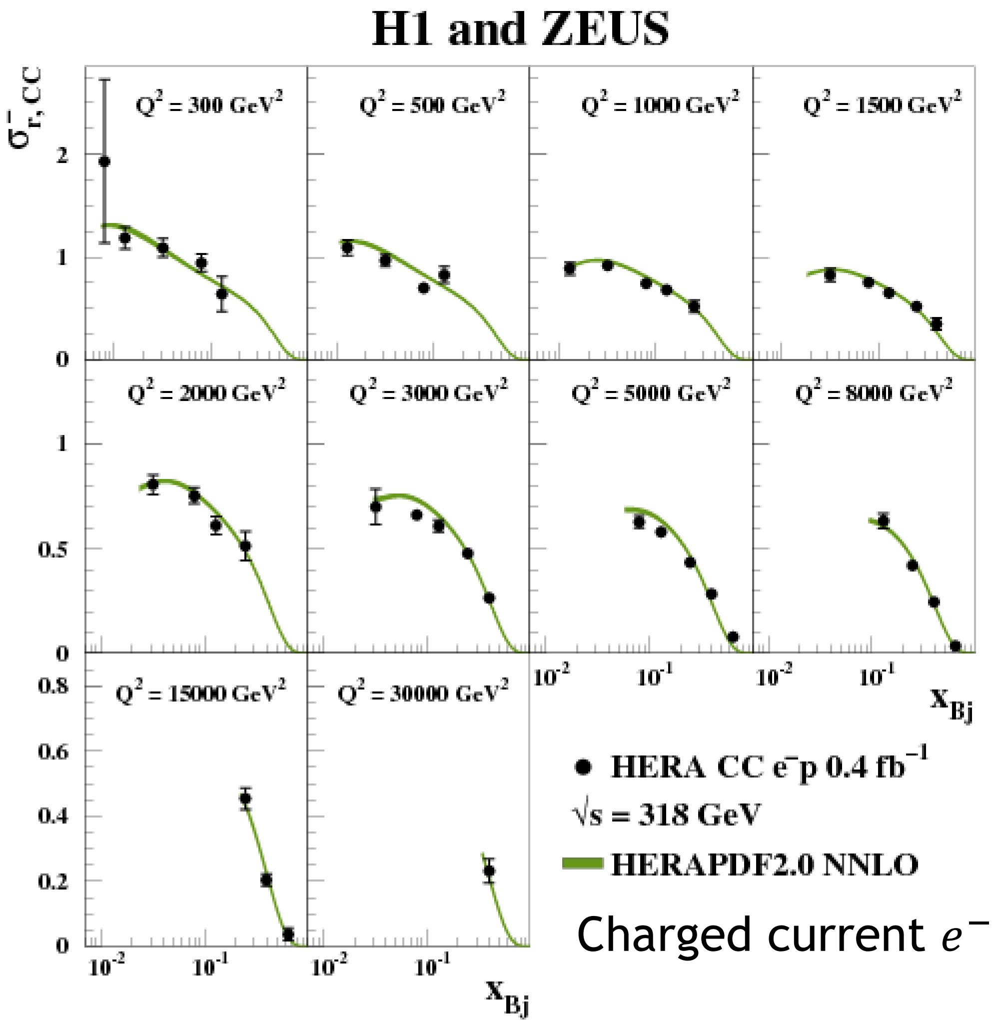

- Flavour decomposition by charged current (CC)
  - up-type quarks with $e^-$
  - down-type quarks with $e^+$
  - different scattering angle distribution for $q$ and $\bar{q}$
- NC has also different coupling
  - Sensitivity to valence e.g. $u_v = u - \bar{u}$

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad e^- \uparrow \quad \downarrow e^+$$

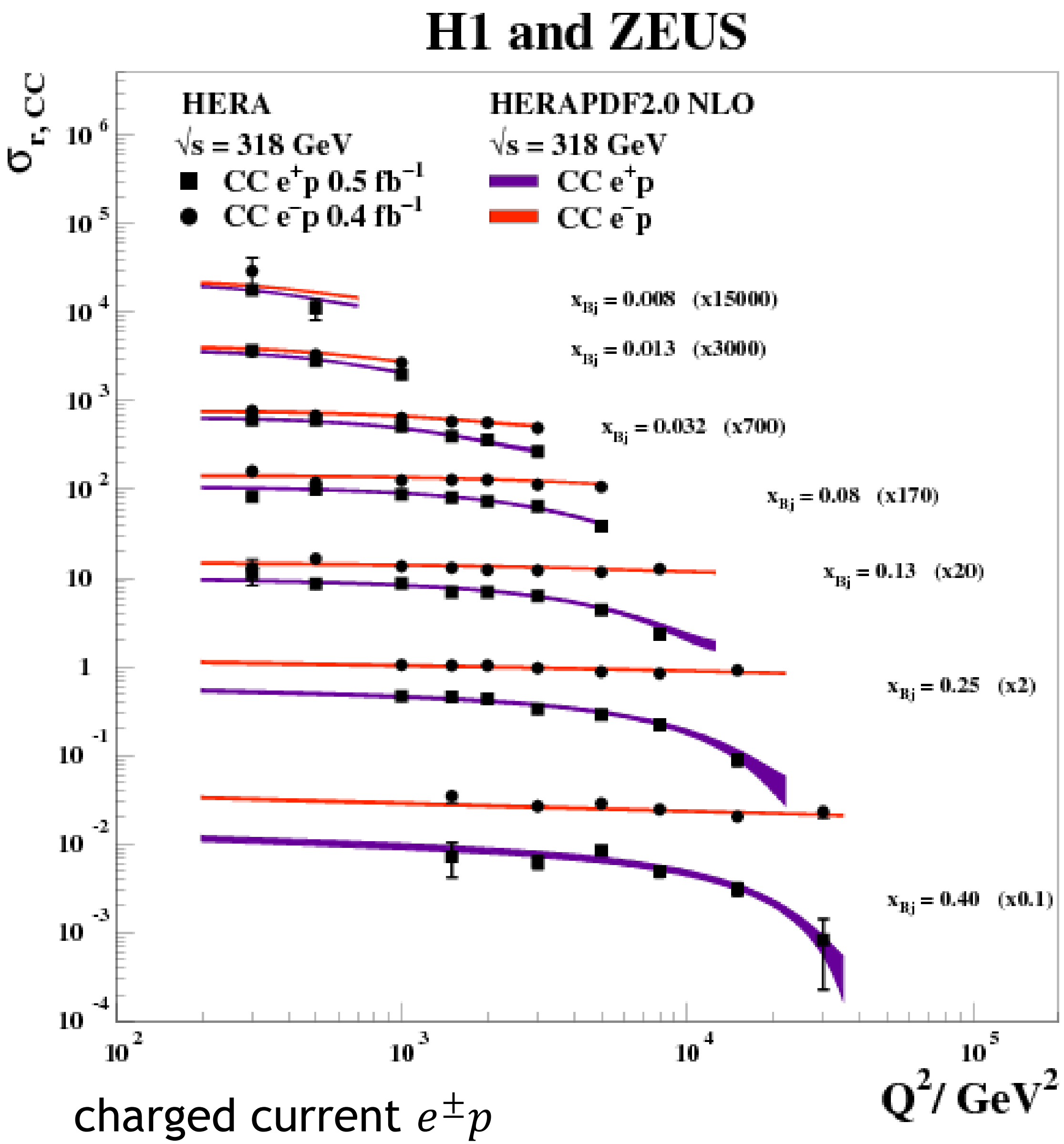


# CC data and high-x pdfs

- CC: more $e^{-}p$ than $e^{+}p$ : more up-type quarks



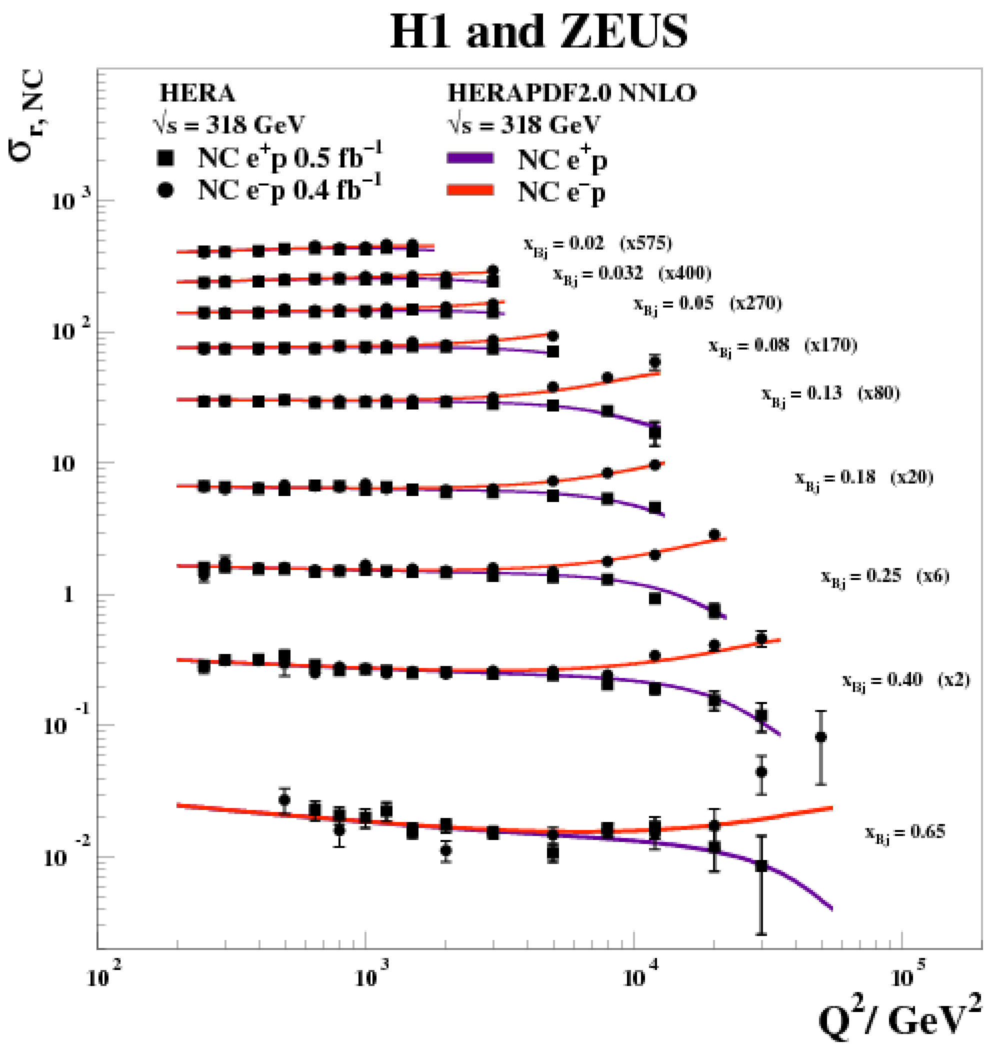

Charged current $e^{-}p$

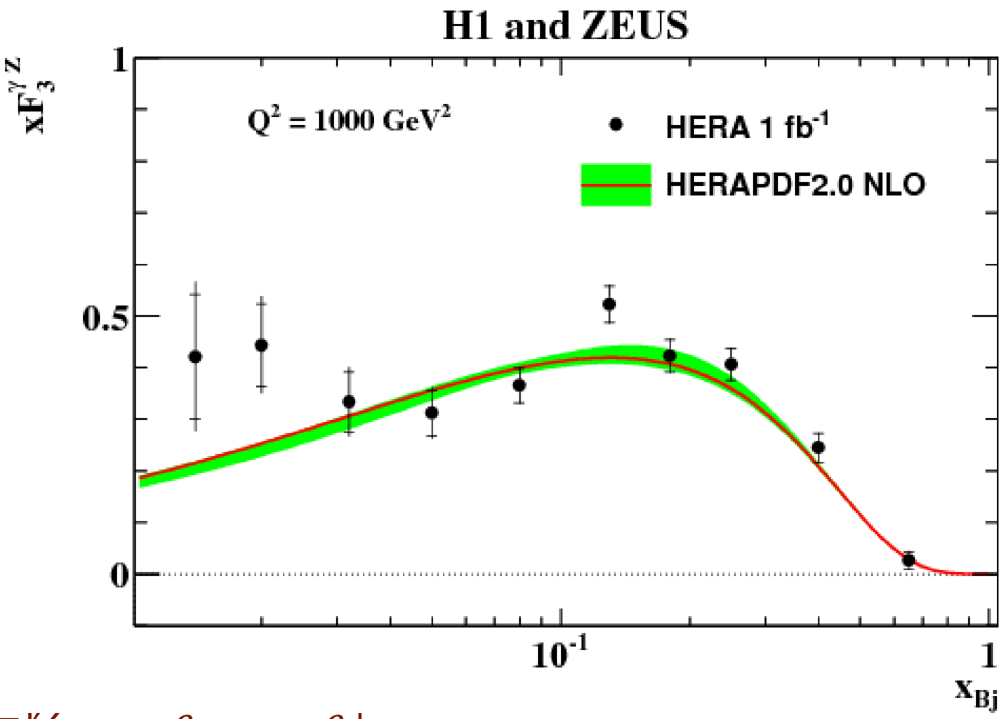



charged current $e^{\pm}p$

Give constraint also to valence quarks

# NC data and valence quark shape



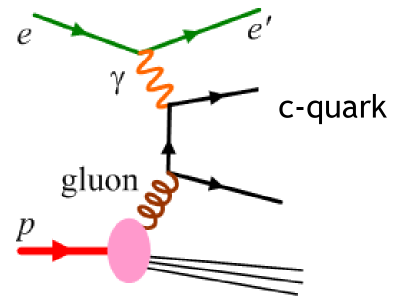




$xF_3^{\gamma Z} \propto \sigma_r^{e-} - \sigma_r^{e+}$

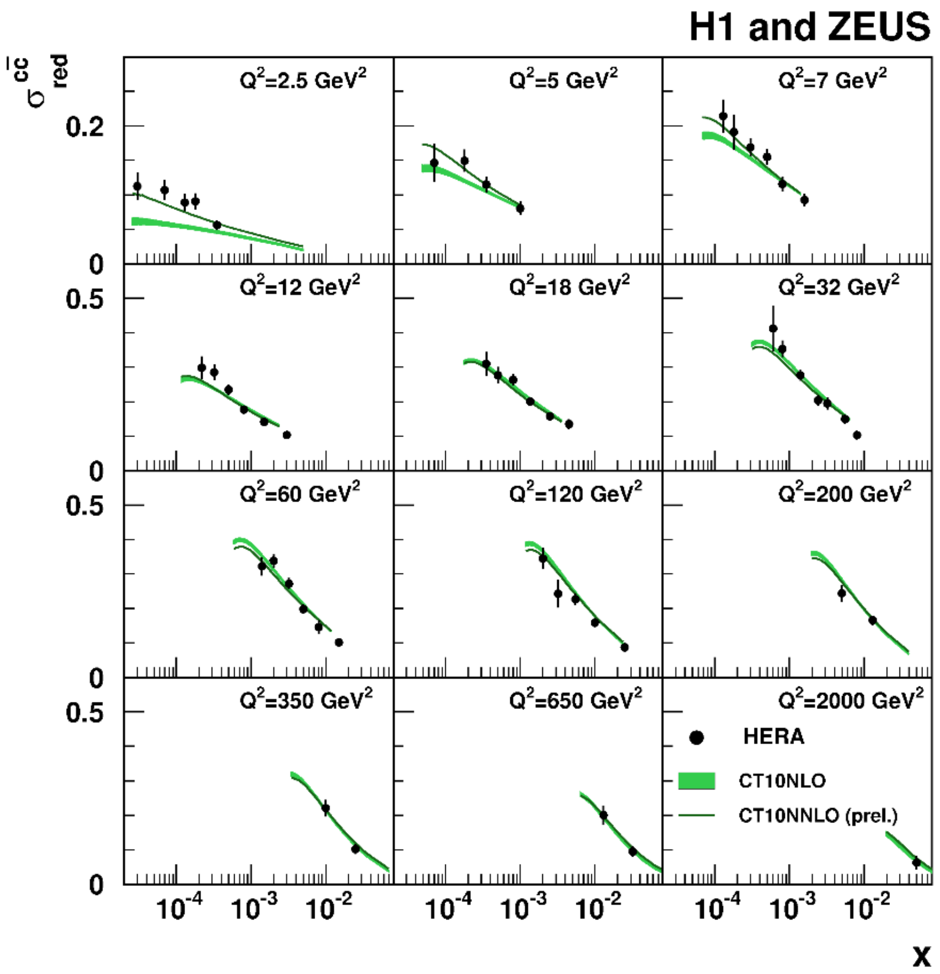
$xF_3^{\gamma Z} \approx \frac{x}{3}(2u_v + d_v)$

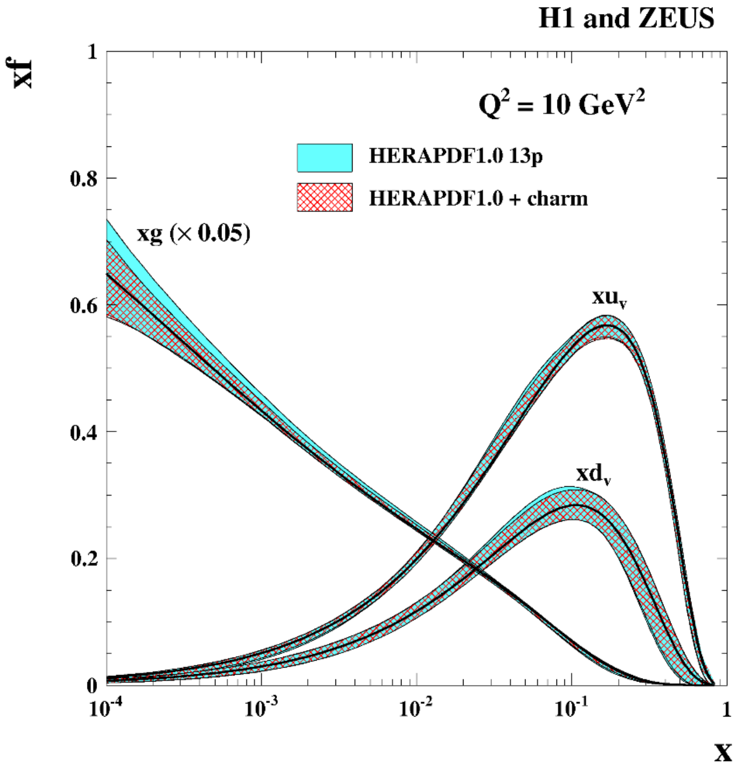
- Sensitive to the valence quark shape confirming that the parameterisation works also at high $Q^2$

# extracting gluons using DIS final states




- Using jets and charm/bottom final state
  - Heavy flavour pair: mostly gluon-induced process

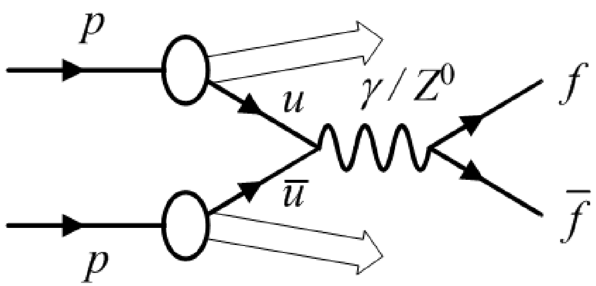


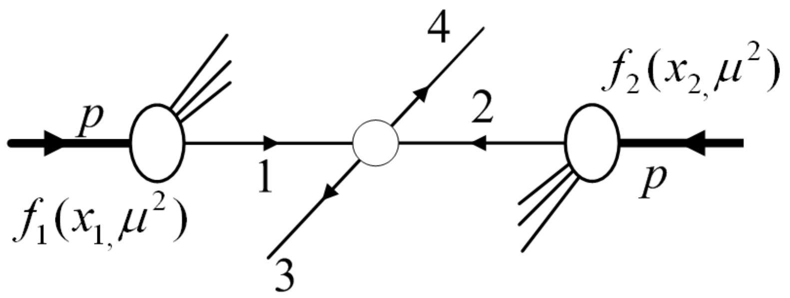




Gluons are better constrained at middle x ($10^{-3} < x < 10^{-1.5}$)

# Further constraining $q/g$ with hadron collisions

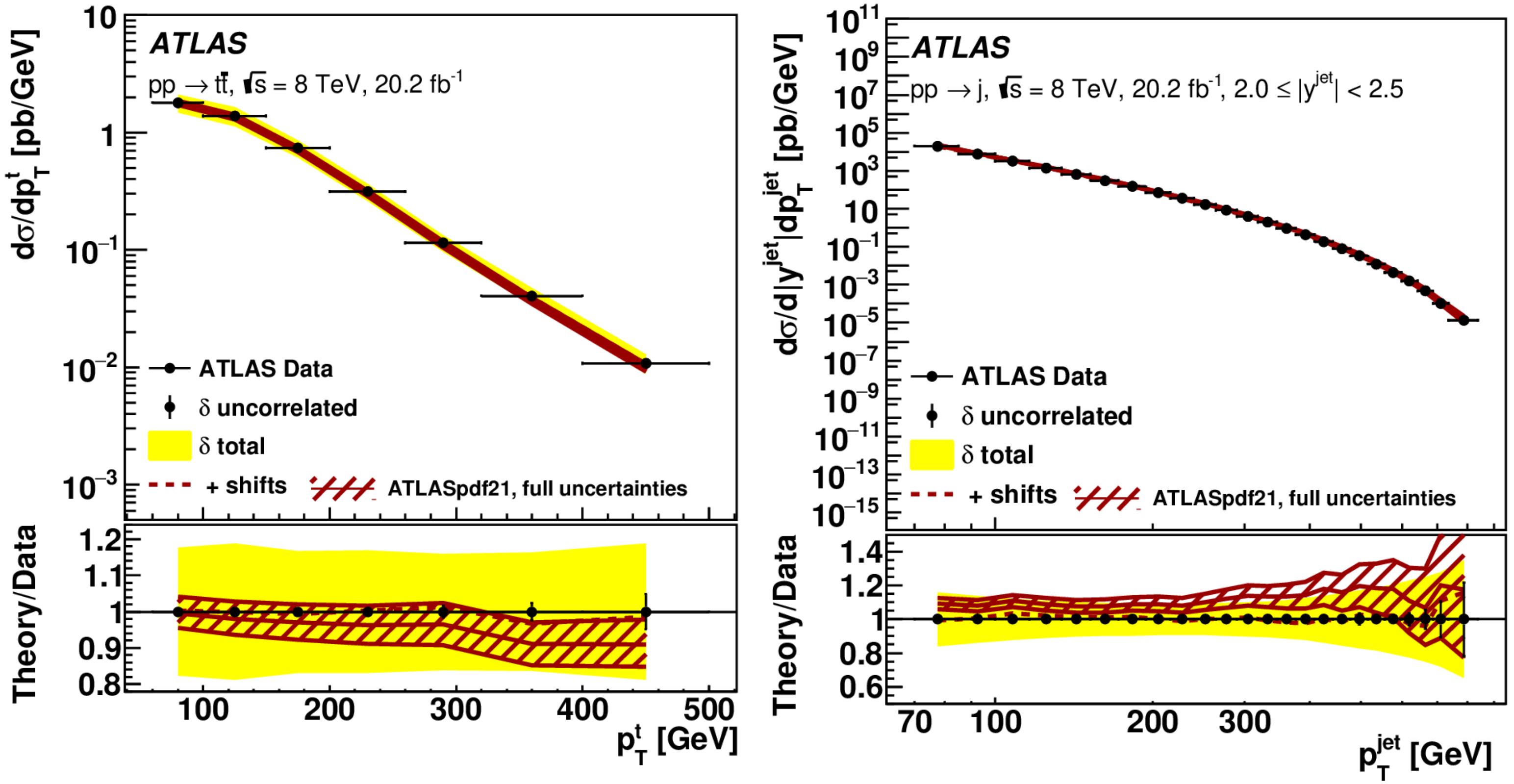
- Quark PDF: single vector-boson production
  - $W^+/W^- \to \ell\nu$ production: for flavours
  - Drell-Yan process $(\gamma/Z^0)$for completely reconstruct $x_1$ and $x_2$
- Gluon PDF: jet production, top-pair production



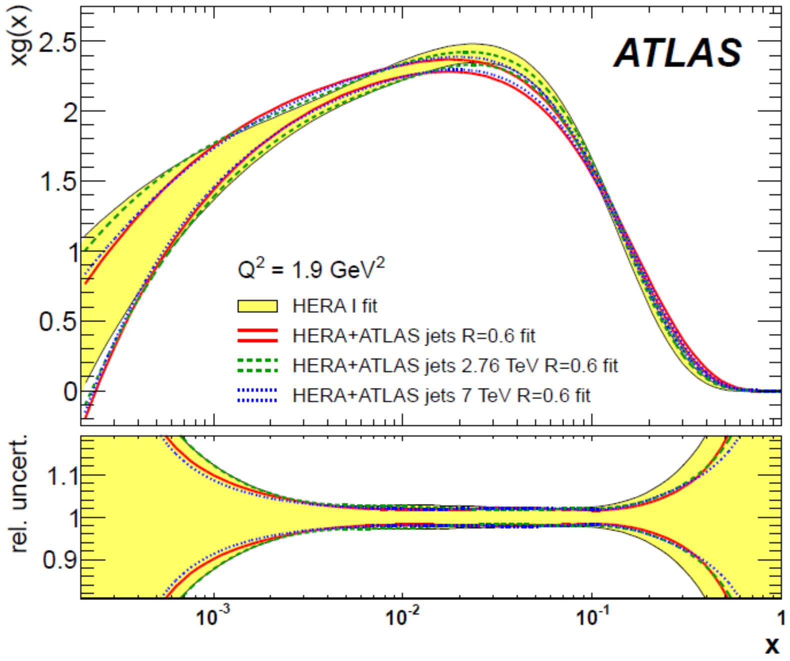




$\sigma \propto (\mathrm{PDF})_1 \otimes (\mathrm{PDF})_2 \otimes \big(P(12 \to 34)\big)$
$\otimes$ (3, 4 decaying to a particular final state)

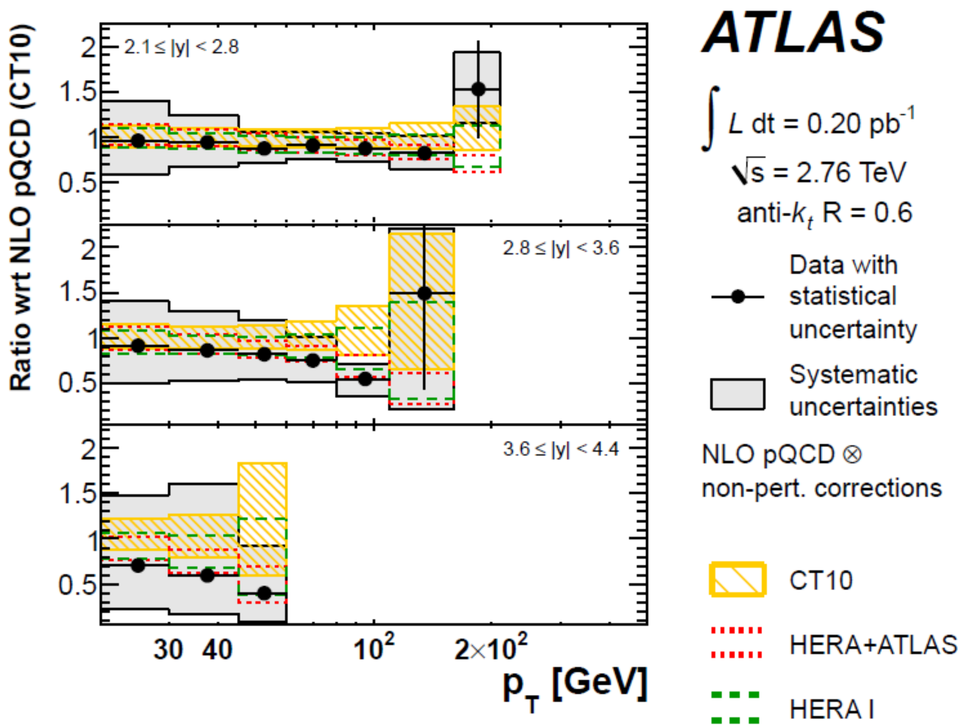
$$\sigma \propto \sum_{q,g} f_1(x_1,p_T) f_2(x_2,p_T) \sigma_{12\to34}(p_T) p(34 \to FS)$$



# Combined HERA+LHC fit using 2.76 TeV data

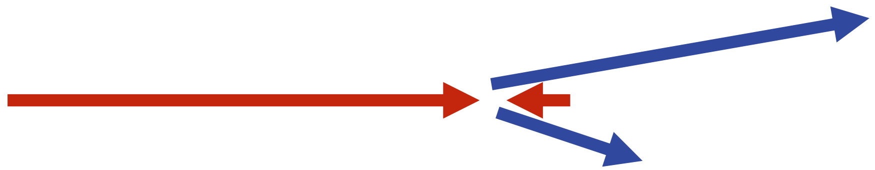



reducing mid – high-$x$ gluons
also reducing low-$x$ gluons




Improved description
on very forward jets

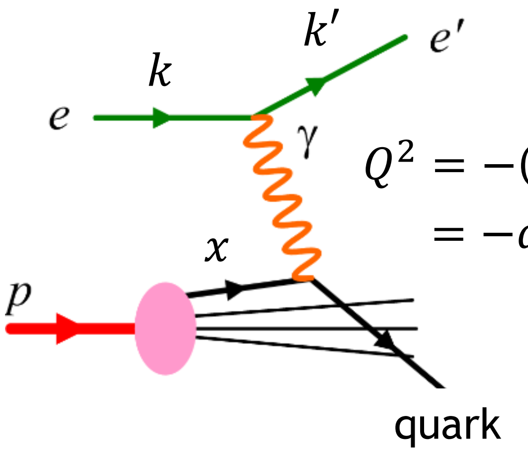
Forward jet: constraint
in large-$x$ regime



More comprehensive review on Wednesday keynote talks

# DIS kinematics and detector

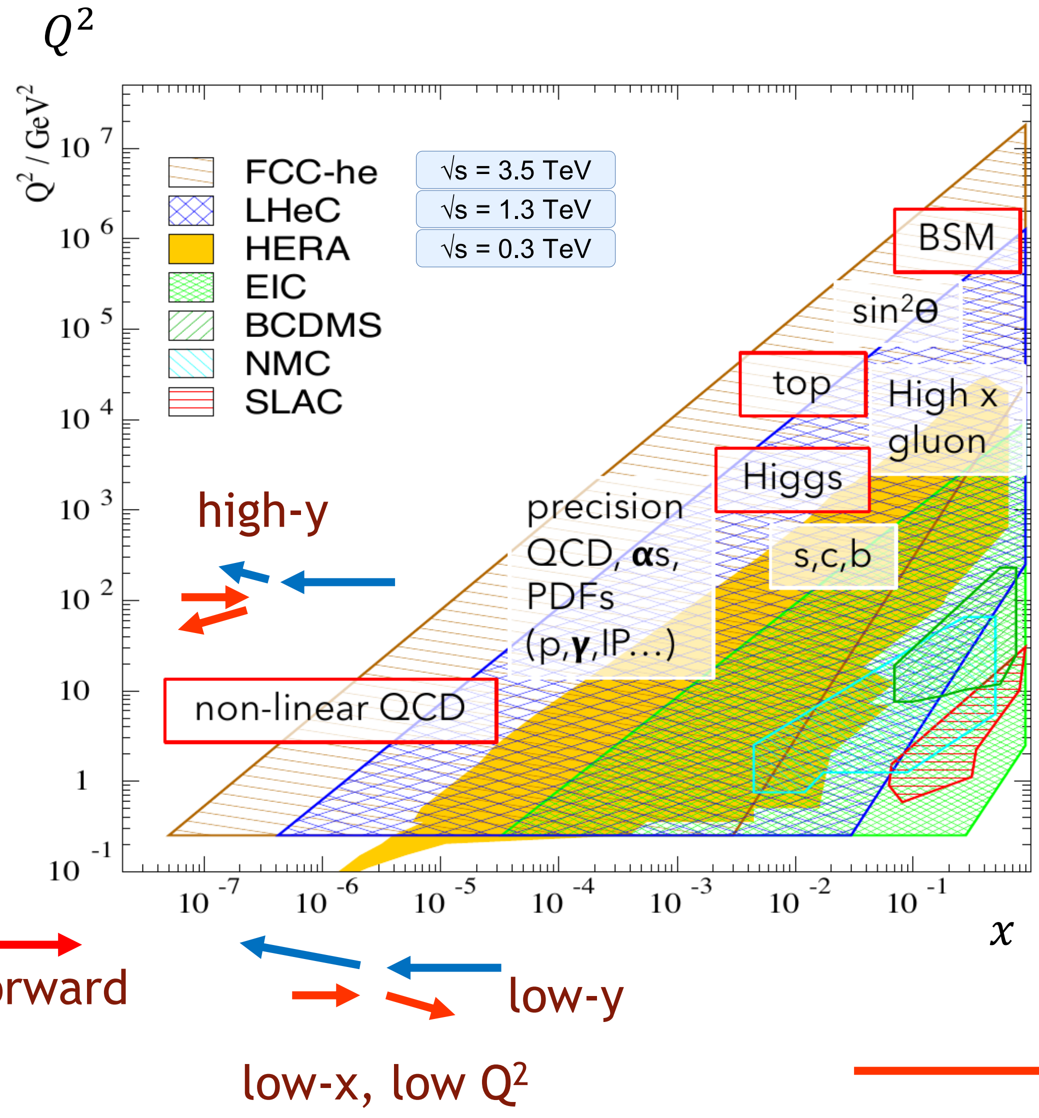
# DIS kinematic plane and event topology



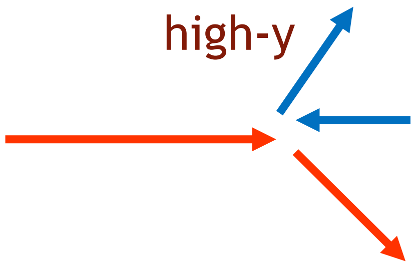

$$Q^2 = -(k - k')^2 = -q^2$$

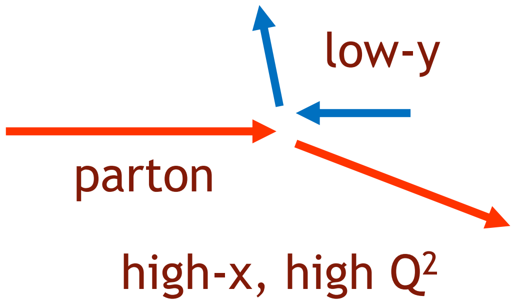
$$x = \frac{Q^2}{p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

$$sxy = Q^2$$

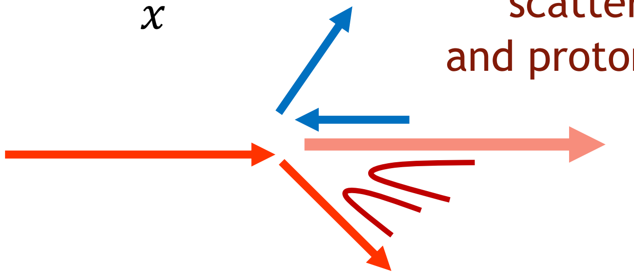







QCD radiation between scattered parton and proton remnant

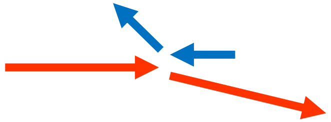


# Processes & Challenges (1): Neutral Current (NC) $ep \to eX$

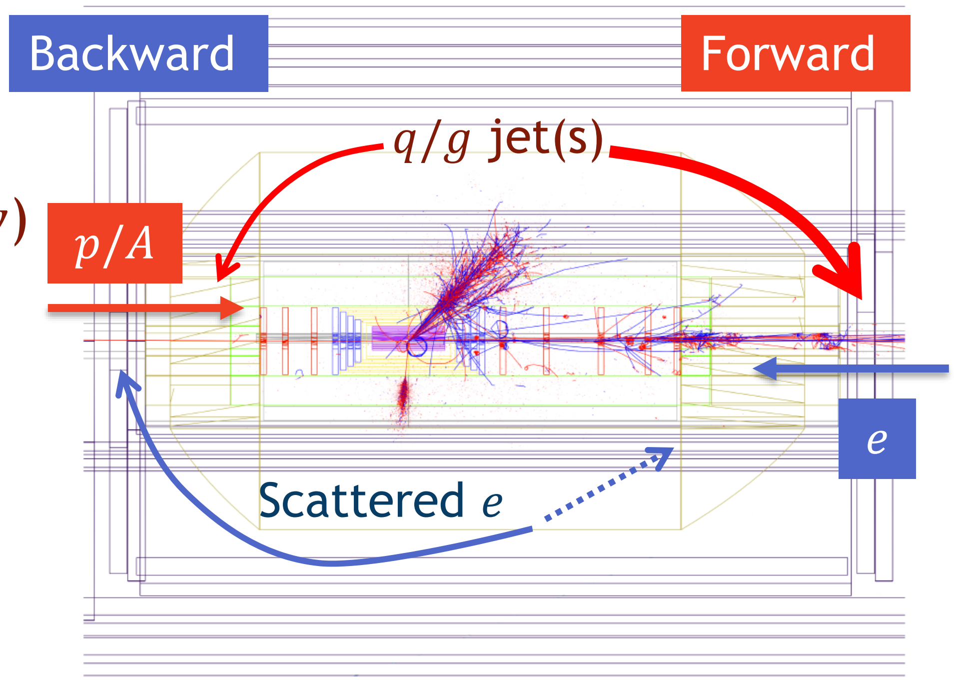
low-$x$ / low-$Q^2$ events

- Scattered electron $(e)$ towards small angle (< 179° )
- Hadrons $(X)$ go to forward (low-$y$) OR backward (high-$y$)
- High-y = small energy $e$ to be distinguished with $\pi^{\pm}/\pi^{0}$ **from photoproduction events $\gamma p \to X$**
- $b/c$ tagging for decomposing pdf beyond $\eta = 3$

high-$x$ / high-$Q^2$ events

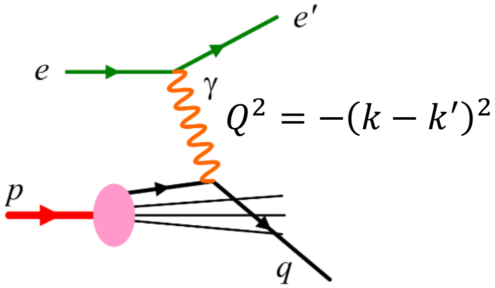


- electrons almost everywhere
- very high-energy jets ($O(\mathrm{TeV})$) also everywhere, especially in forward




An NC (leptoquark) event at LHeC

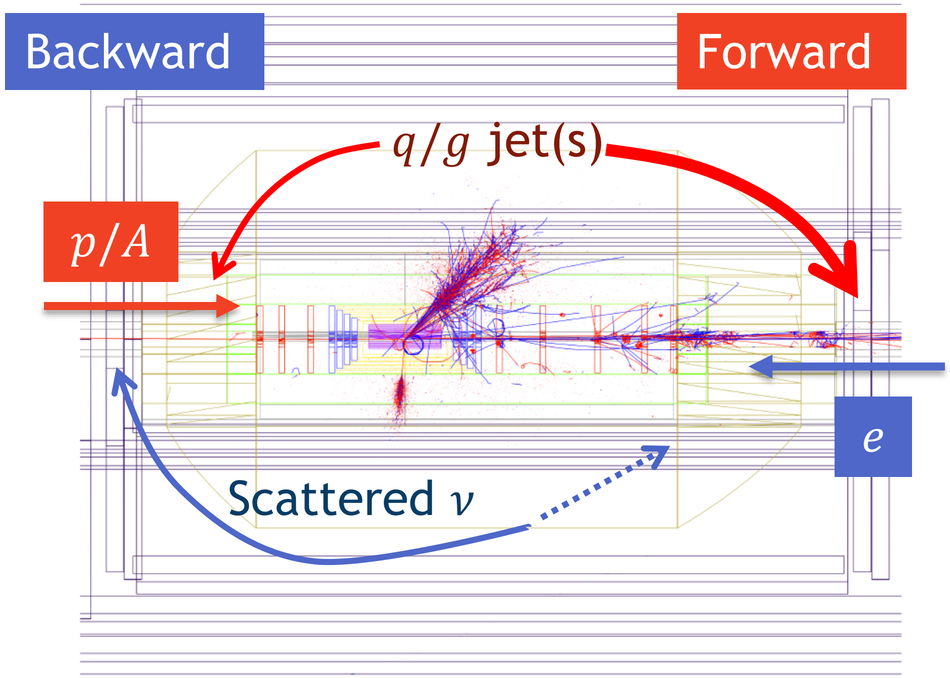
- Hermetic and thick EM and Hadron calorimetry
  - Fine granularity for $e/\pi$ separation (esp. backward)
- Fine-pitch tracking for vertexing
  - for heavy-flavour tagging (esp. forward)



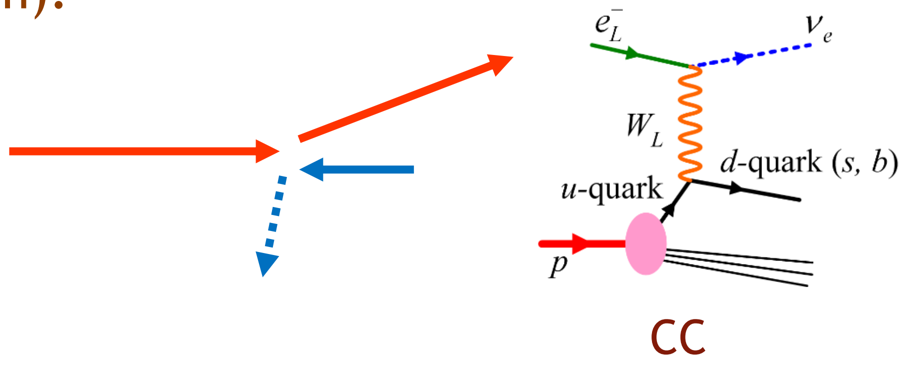

NC

# Processes & Challenges (2): Charged Current (CC) $ep \to \nu X$

- A jet like high-$x$ / high-$Q^2$ NC, but w/o scattered $e$
  - Kinematics should be reconstructed only from the hadronic system angle and missing $p_T$
- This also helps for:
  - QCD studies with jets
    - including photoproduction ($e \to e'\gamma,\ \gamma p \to X$)
  - detector cross-calibration using NC DIS:
    - two energies and angles ($e$ and hadronic system): over-constrained



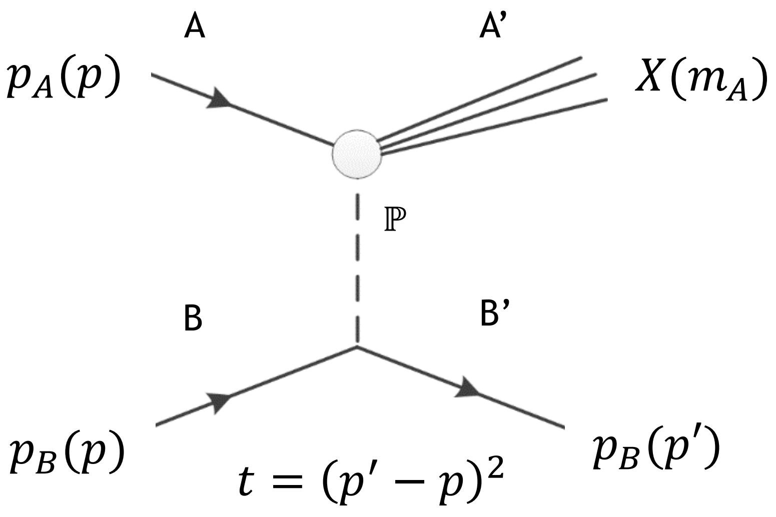

- Hermeticity (esp. forward)
- good HadCal resolution ($e/h$ etc.)
  - tracking should help (particle flow algorithm)

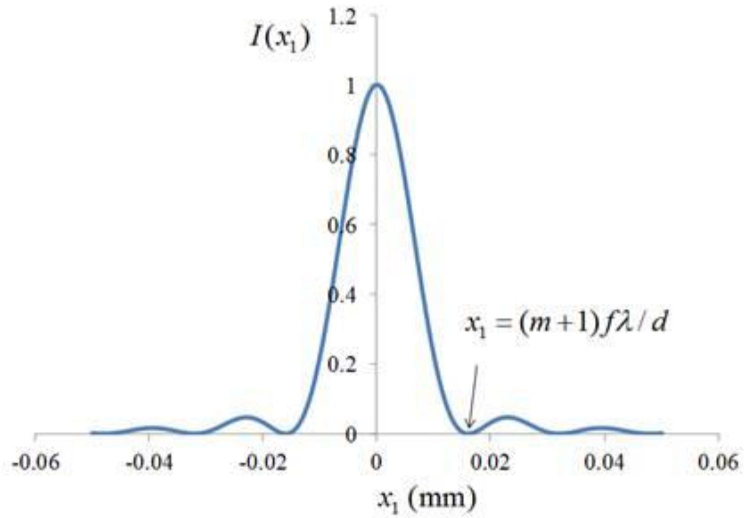


# Diffractive processes at HERA

# Diffractive scattering

- Consider hadron-hadron collisions e.g. $pp$ here (simpler)
- The most quiet: elastic scattering
  - No colour exchange between two proton A, B
- Slightly deeper:
  The system A may dissociate to multi-hadron state A', or B to B' (dissociation)
  - The masses $m_{A'}$, $m_{B'}$ are typically small
- These phenomena look similar to optical diffraction
  - No quantum number exchanged,
    while the spatial distribution is changed
- In this reaction, the exchanged particle carries force, but not quantum numbers, including colours
  - The exchanged particle is due to "Pomeron" in high energy regime

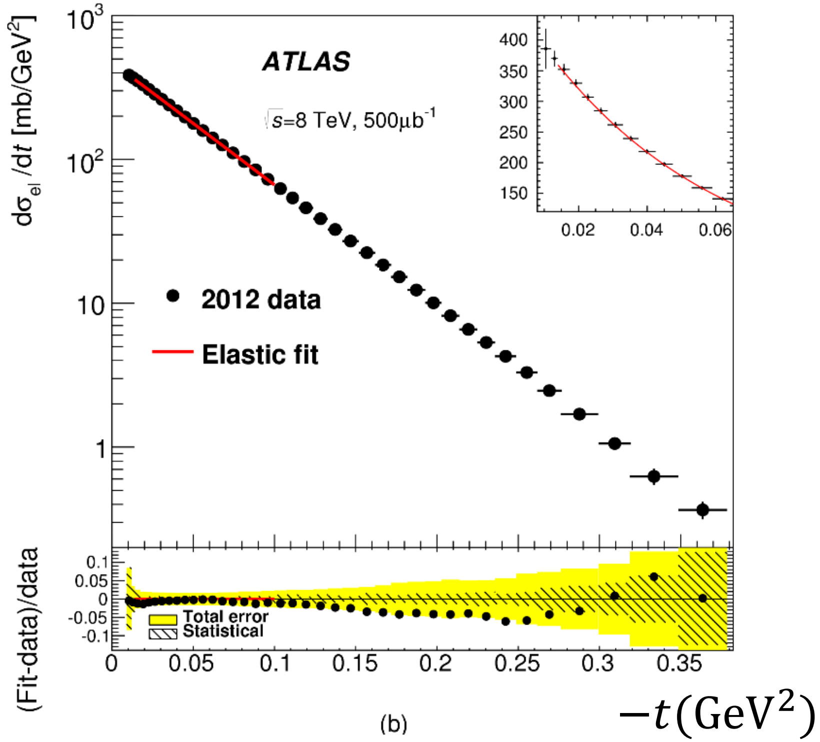


TOTEM collaboration, EPL 101 (2013) 21002

# Scattering angle of elastic/diffractive proton at the LHC ($pp$ collisions)

- You see diffractive peak and dip
- Approximately exponential until the first dip



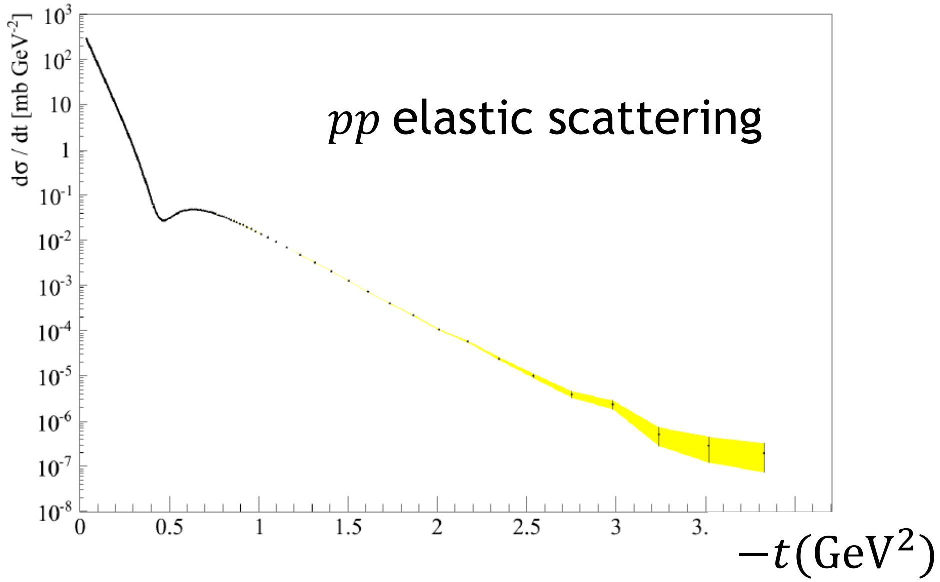




**Fig. 8:** (color) Differential elastic cross-section $d\sigma/dt$ at $\sqrt{s} = 13$ TeV. The statistical and $|t|$-dependent correlated systematic uncertainty envelope is shown as a yellow band.

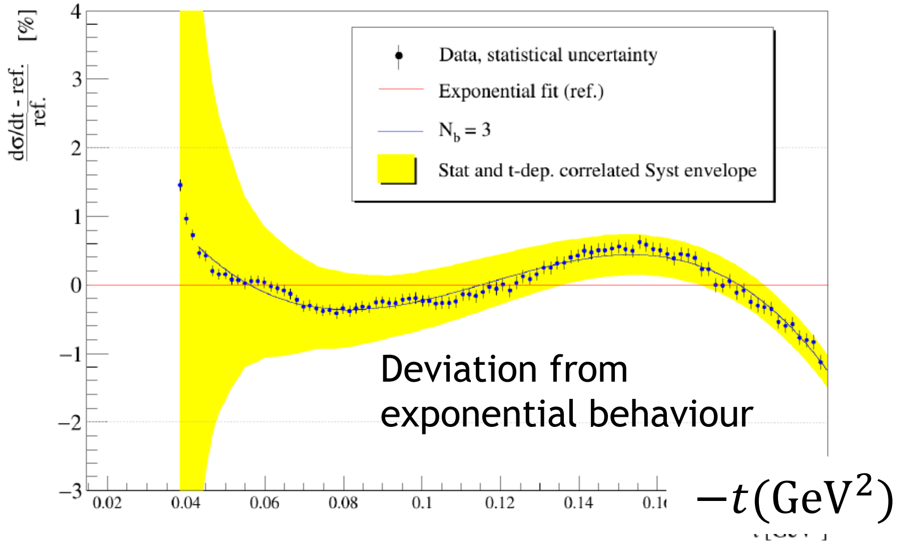


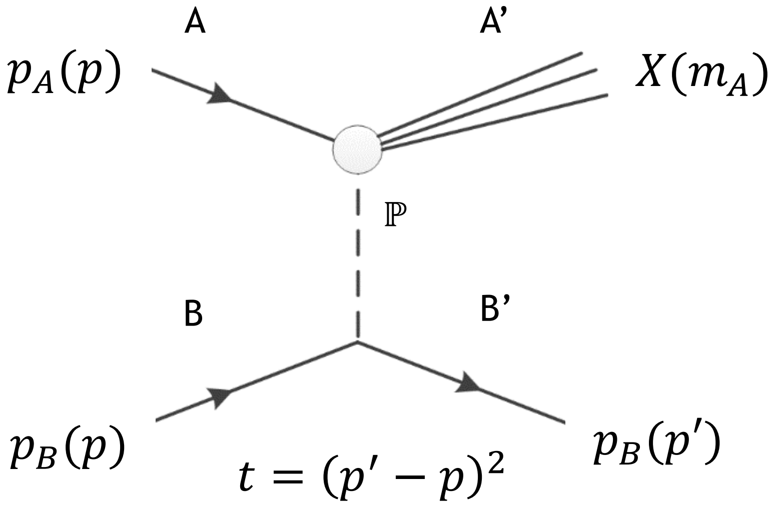

**Fig. 10:** The non-exponential part of the data. The statistical and $|t|$-dependent correlated systematic uncertainty envelope is shown as a yellow band, while the data points show the statistical uncertainty.

# What is Pomeron, guys?

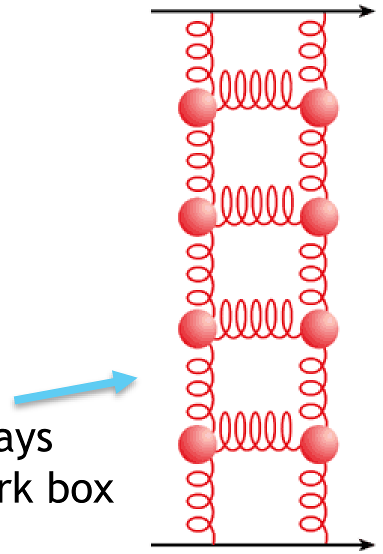
- It is a light meson-like object
  - but we know that the lightest mesons are not Pomeron

- Most likely: it is a “dressed” gluon
  - Lowest colourless gluonic object: 2-gluon state
  - Strongly interacting $\rightarrow$ becoming a gluon ladder i.e. not 100% gluonic object

- Questions:
  - Is that a particle, or just an intermediate state?
  - Partonic contents of the object?




From CERN courier



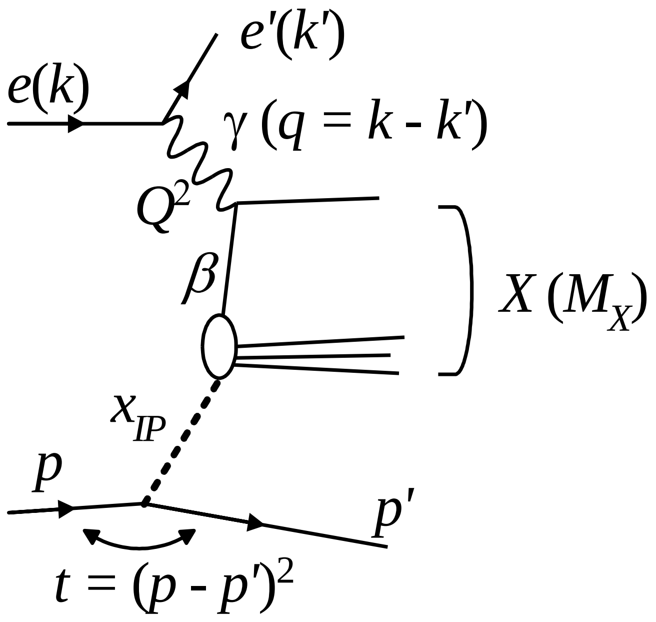
You can always insert a quark box

# Diffractive DIS (DDIS)

- $Q^2$ provides a hard scale
  - probing partonic structure
- Main task: $F_2^{D(3)}(\beta, Q^2, x_{\mathbf{P}})$
  - Structure function for diffractive processes integrating over $t$

$$\int dt \frac{d^4\sigma^{ep}_{diff}}{d\beta dQ^2 dx_{\mathbf{P}} dt} \cong \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y - \frac{y^2}{2}\right) F_2^{D(3)}(\beta, Q^2, x_{\mathbf{P}})$$

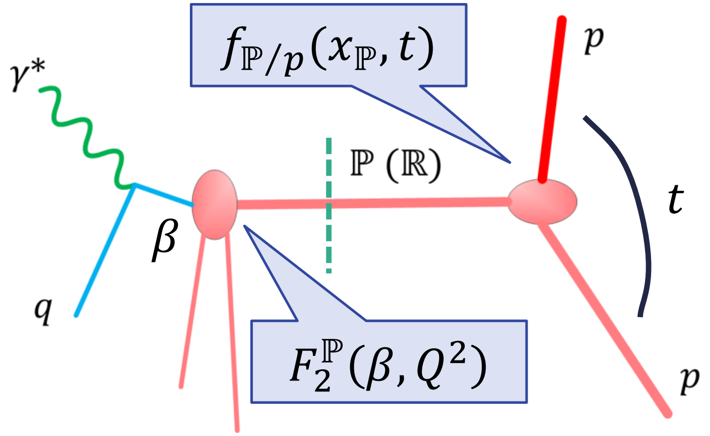
  - Sensitive to quarks
- Gluons are "measured" by
  - Jet and HQ production
  - Scaling violation of DDIS using DGLAP eq.



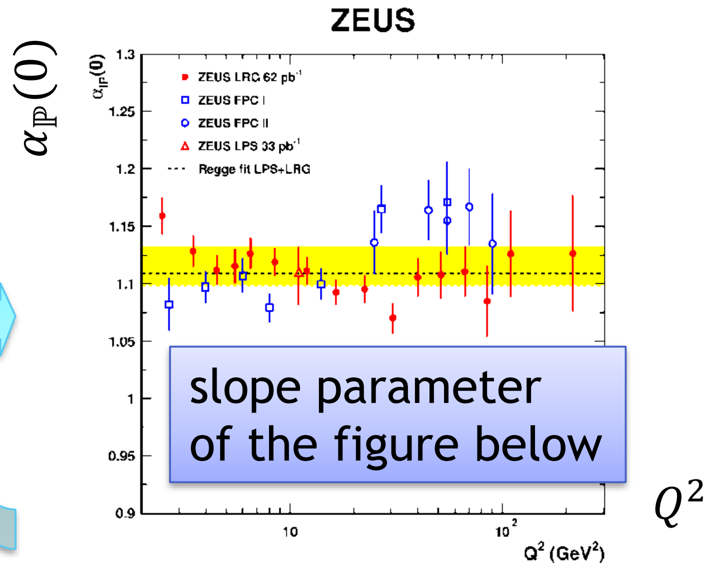

β: long. momentum fraction of the parton in the exchange

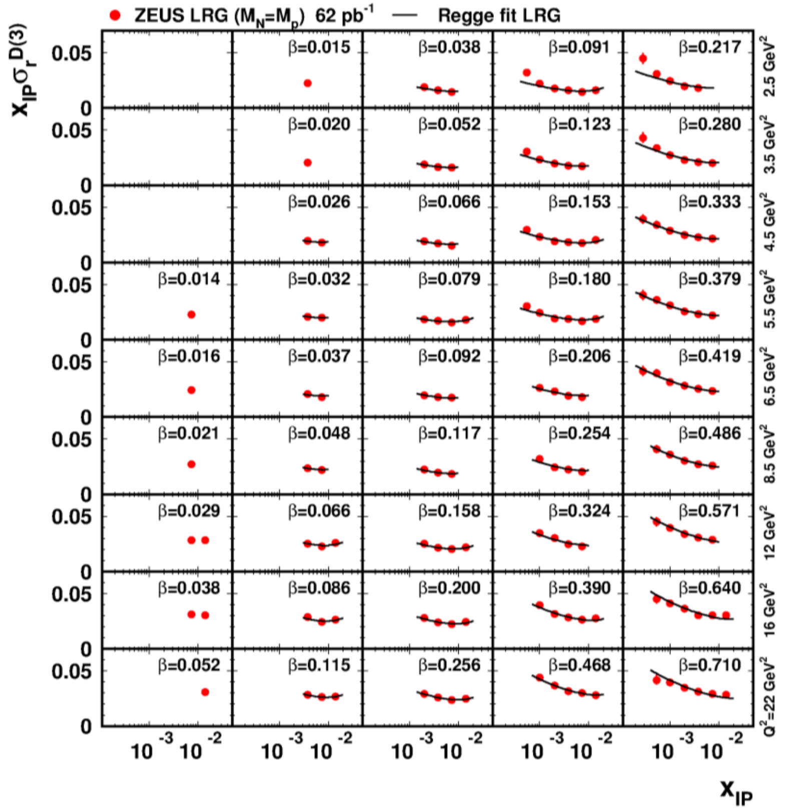
$x_{\mathbf{P}}$ : long. momentum fraction of the exchange in the proton

# Is Pomeron a "particle" ?



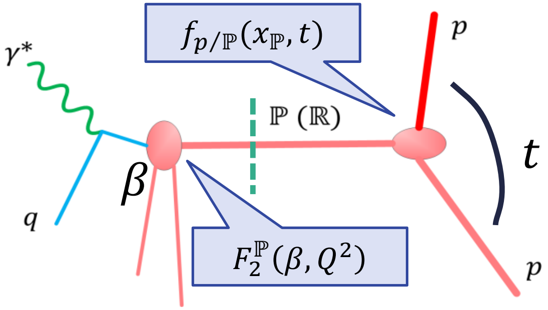

Fit by $\frac{1}{x_P^{2\overline{\alpha_P}-1}}$



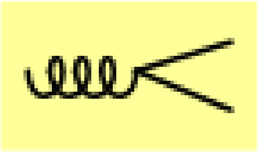

- If the cross section is factorised into two part, the Pomeron can be regarded as a particle
  - Pomeron flux $f_{p/\mathbb{P}}(x_{\mathbb{P}}, t)$; and
  - Pomeron structure function $F_2^{\mathbb{P}}(\beta, Q^2)$
- This hypothesis holds quite well: cross section shapes in $x_P$ are independent of $\beta$ and $Q^2$
  - If a Pomeron is 2-glu, it should depend on $x = \beta \cdot x_{\mathbb{P}}$ $\rightarrow x_{\mathbb{P}}$ rises steeper with $Q^2$ reflecting the gluon density in the proton

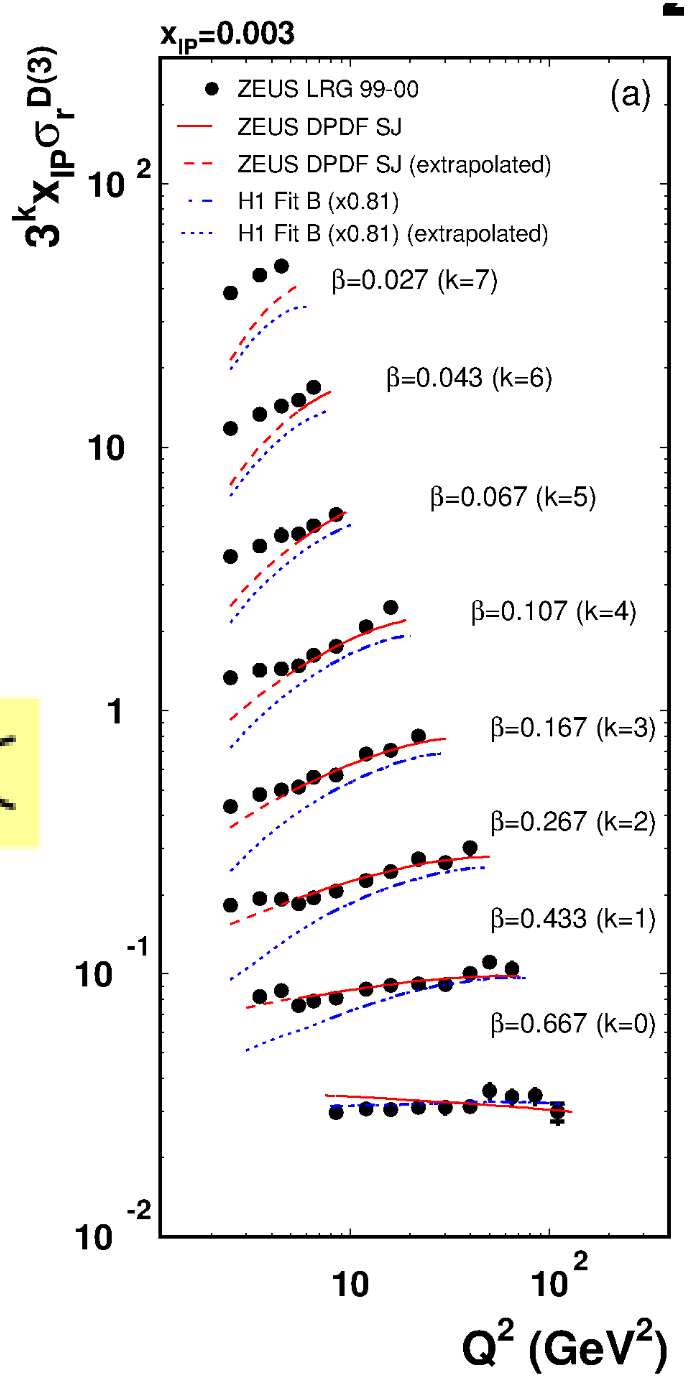
# Scaling violation analysis for $g(\beta, Q^2)$ in DPDF




$\beta = x/x_{\mathbb{P}}$

- The scaling-violation slopes are positive for most of the $\beta$ range
  - Quarks are dynamically generated from gluons
  - **The diffractive exchange is gluon-rich: in accord to naïve 2-gluon picture**

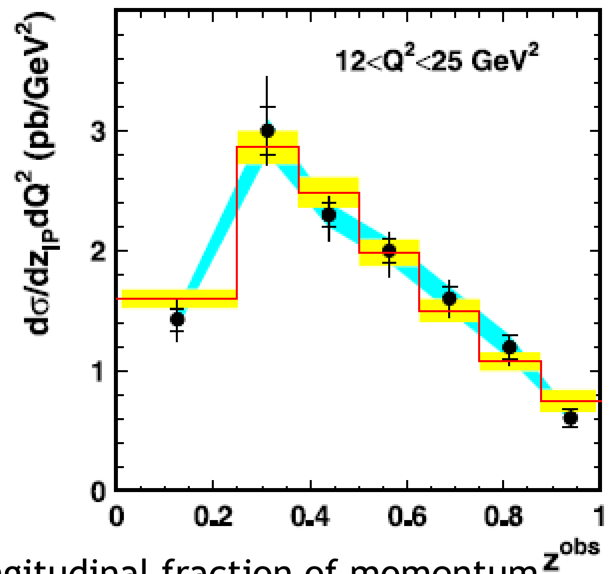




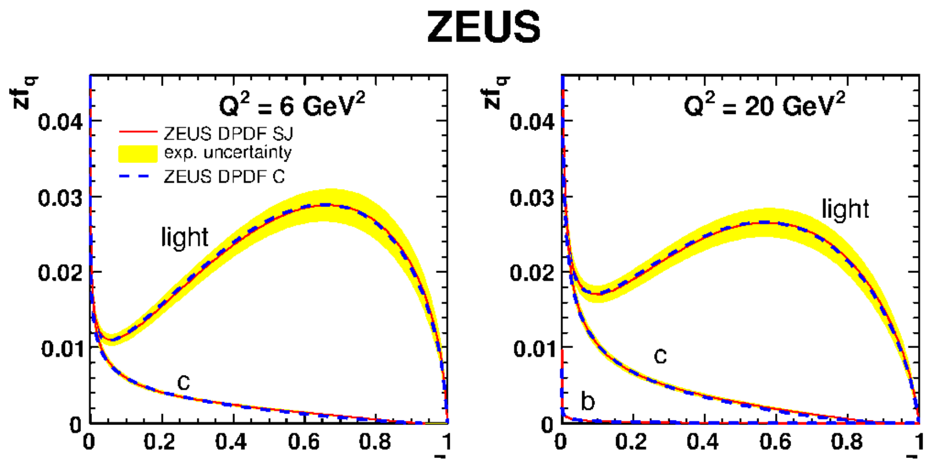
# Extracted diffractive parton densities

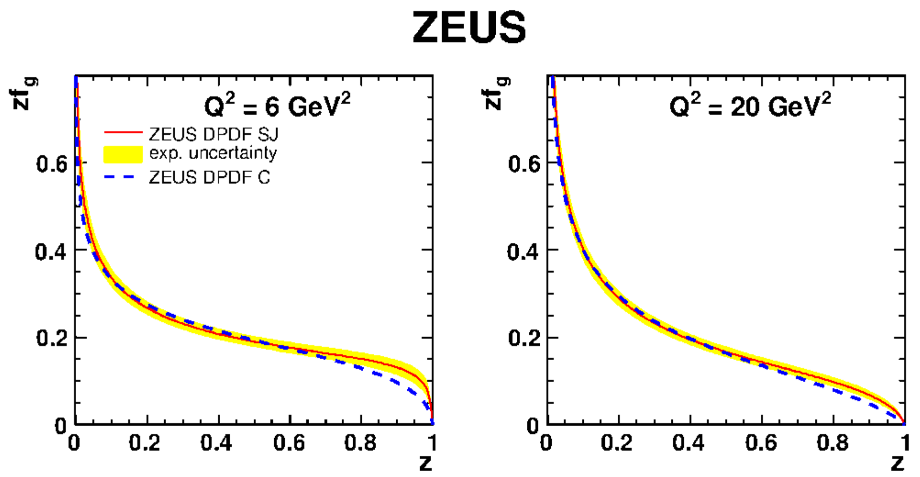
- Gluons: stronger information from jets and charm
- 63% are gluon at $Q^2 = 10\ \mathrm{GeV}$

ZEUS dijet cross section and DPDF SJ




Longitudinal fraction of momentum carreid by the dijet system, wrt Pomeron



# Summary

- DIS provides super microscope for hadrons
- The $F_2(x, Q^2; other\ variables)$ is well-defined physical observable
  - from which we extract quarks and gluons
  - … and their spin dependence (not covered today)
- Jets, heavy flavour and photon production constrains gluons

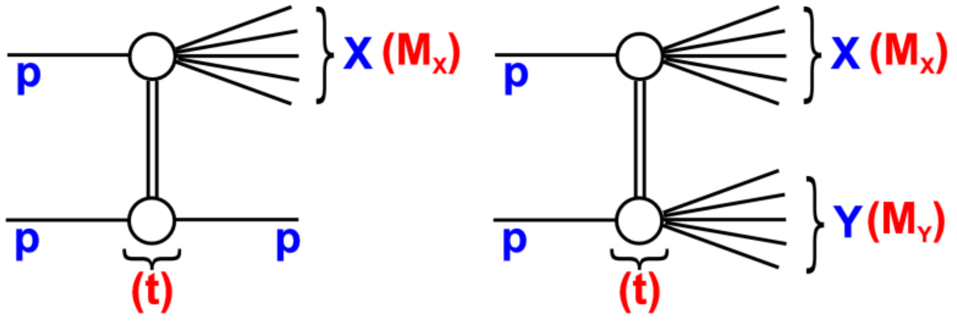
- Diffraction will play important role to understand the hadron structure further, in particular at the EIC

# BACKUP

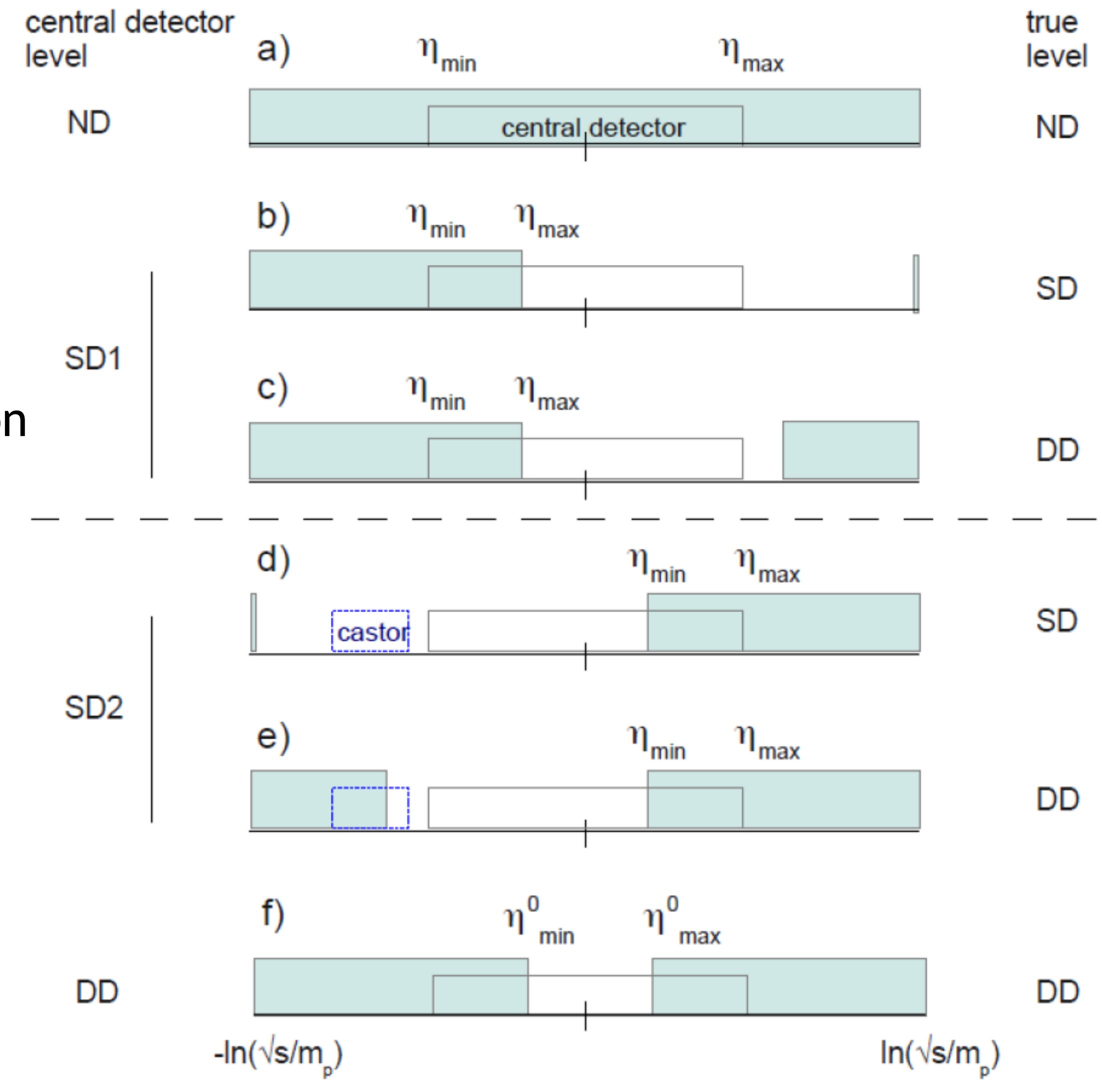
# Signal of diffraction in $pp$ collisions

- Observation of collimated hadrons (or a proton), system A' and B', in very forward direction
- Large Rapidity Gap (LRG) between the system A' and B'
  - rapidity $y = \ln\sqrt{\frac{E+P_Z}{E-P_Z}} = \ln\frac{E+P_Z}{m_T}$, $z$ axis in beam direction

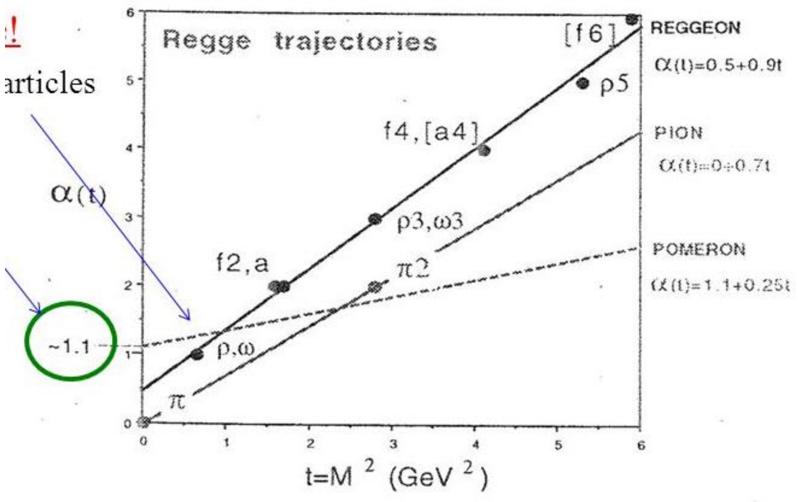
    $m_T^2 = p_x^2 + p_y^2 + m^2 = p_T^2 + m^2$
  - $y = \eta = -\ln\left(\tan\frac{\theta}{2}\right)$ (pseudorapidity) if $m \to$




Single diffraction Double diffraction



# The Pomeron




- Postulated by Pomeranchuk (PL)
- An imaginary composite particle to explain the cross section behaviour in (CM) energy and in $t$
  - Cross section by Regge theory
    $\frac{d\sigma_{el}}{dt} \sim \frac{1}{s^2}\,|A|^2 \sim \left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$
    : $t \sim -p_T^2(recoil\ proton)$ for elastic
    $\alpha(t)$: Regge trajectory
  - Total cross section from optical theorem
    $$\sigma_{tot}^2 \simeq 16\pi \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} \rightarrow \sigma_{tot}(s) = \sigma_0 \left(\frac{s}{s_0}\right)^{\alpha_0-1}$$
  - $\alpha(t) = \alpha_0 - \alpha' t = 1 + \epsilon - \alpha' t$ : “Pomeron trajectory”
    Linear approximation $\alpha_0 : \sim 1.08,\ \alpha' \sim 0.25\ \mathrm{GeV}^{-2}$
- We say: “the cross section behaviour is described by Pomeron exchange (or by Pomeron trajectory)”