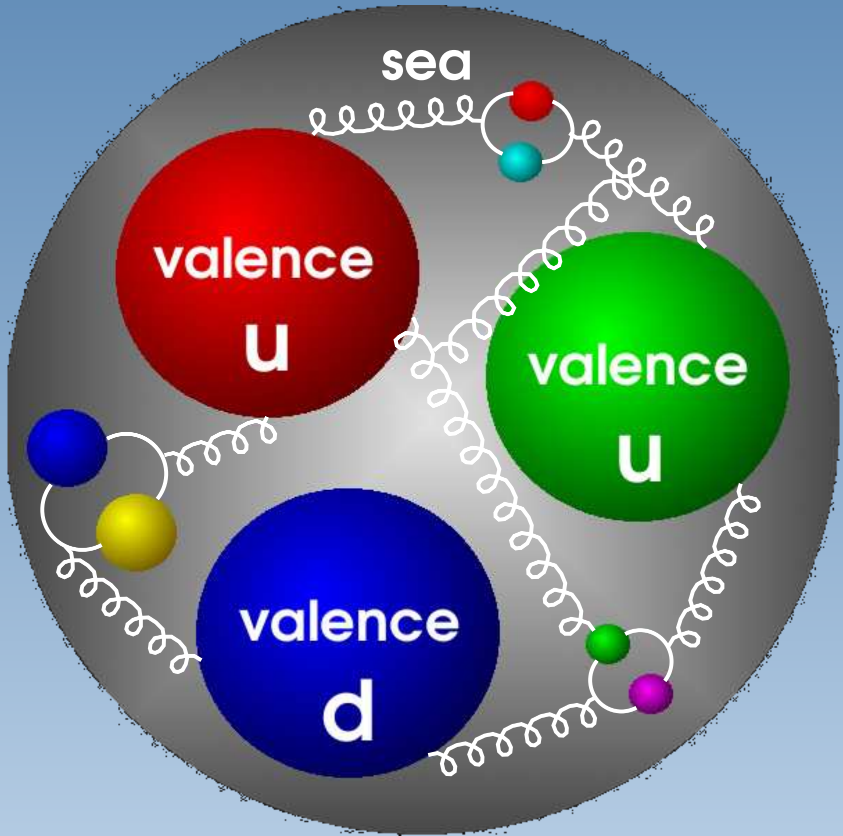
Proton Structure and Low X Physics

Outline

- Introduction
- Parton distributions
- Evolution at low x
- Non-linear dynamics



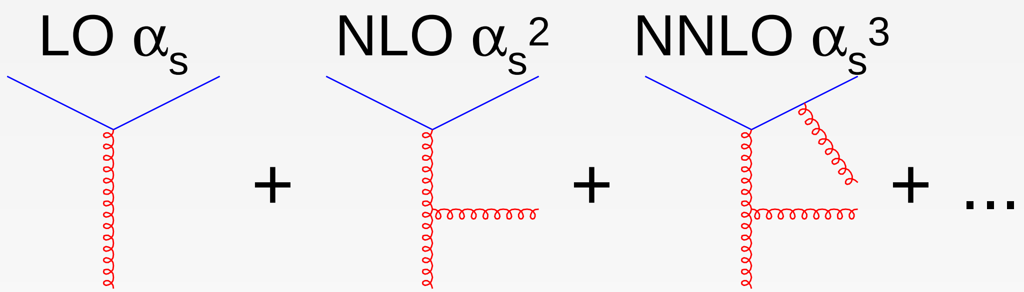
Victor Lendermann
Universität Heidelberg

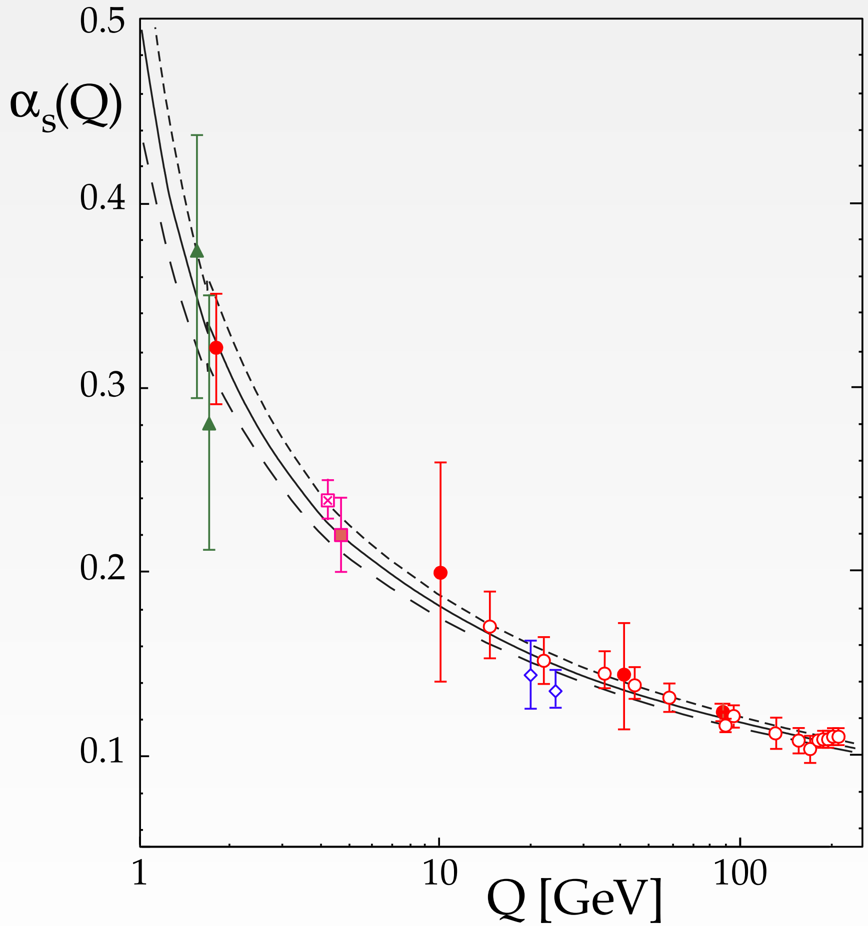
DPG-Frühjahrstagung
Heidelberg, 9.03.2007

QCD and Hadron Scattering

QCD: perturbative or non-perturbative? That is the question.

- pQCD calculates interactions of quarks and gluons using pert. expansion in α_s





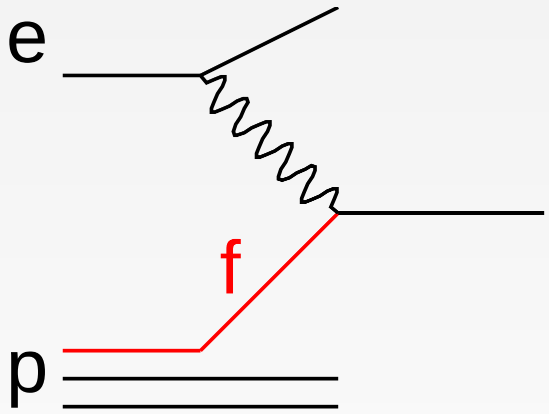
- Actually, hadrons are in initial and final state due to confinement

- The limit for pQCD is where α_s is large

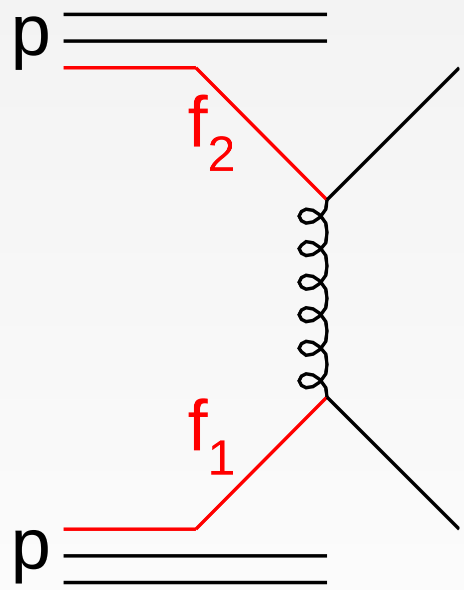
Factorisation Theorem

Non-perturbative input is given by universal parton distributions (PDF)

$$\sigma_{ep} = \sum_i f_i \otimes \hat{\sigma}_i$$



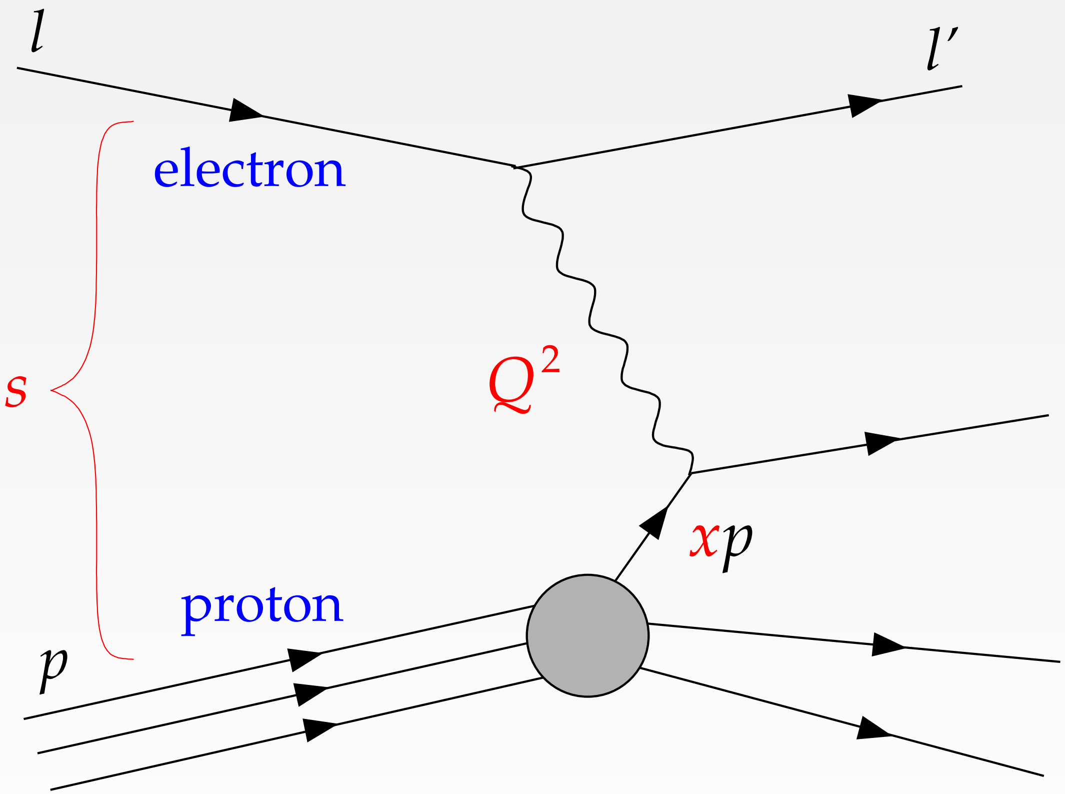
$$\sigma_{pp} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij}$$



PDFs must be determined experimentally
and can be used for other scattering processes

Inclusive Deep Inelastic ep Scattering

DIS – best method to determine the proton structure with highest precision



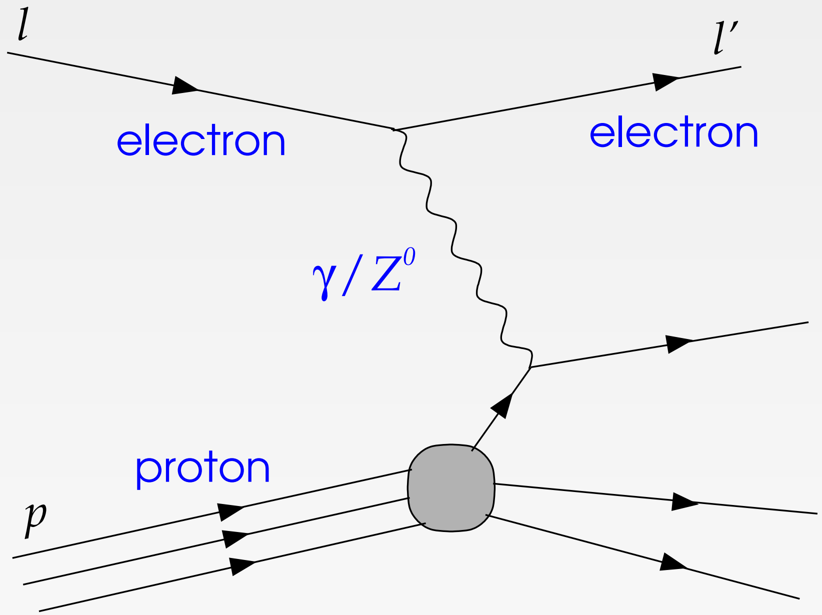
boson virtuality Q^2
= resolution scale

fractional momentum x
of struck quark

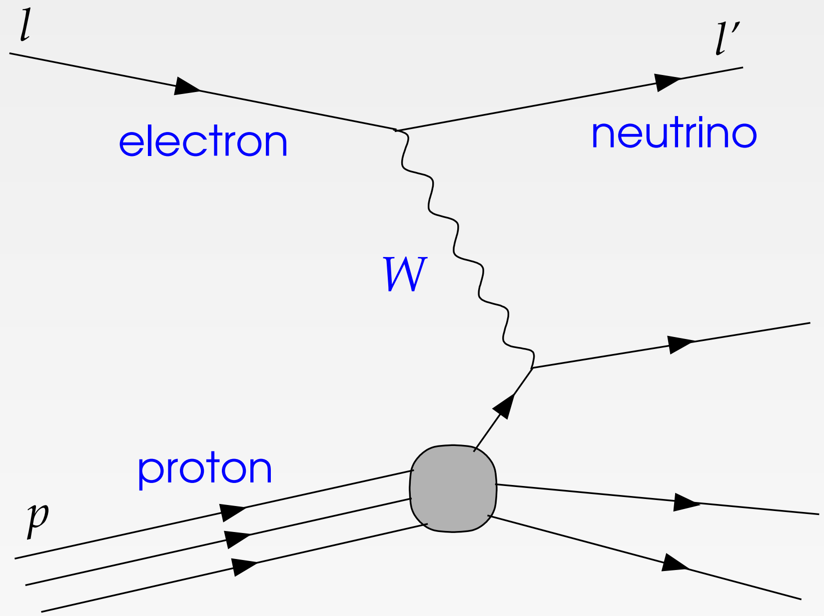
determine PDFs: $q_i(x, Q^2)$, $g(x, Q^2)$

Determination of Quark Distributions

Neutral Current



Charge Current



Cross sections: $\sigma^{NC}_{e^+p}, \sigma^{NC}_{e^-p}, \sigma^{CC}_{e^+p}, \sigma^{CC}_{e^-p}$
have different sensitivity to different quark flavours

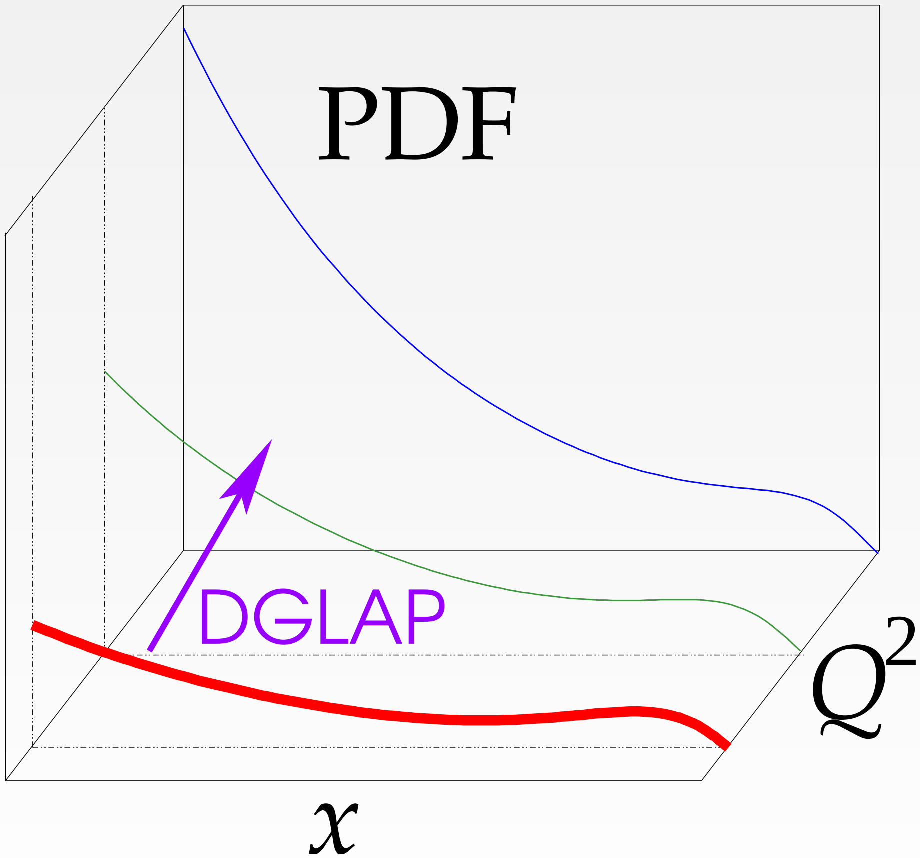
Almost full flavour decomposition is possible with HERA only

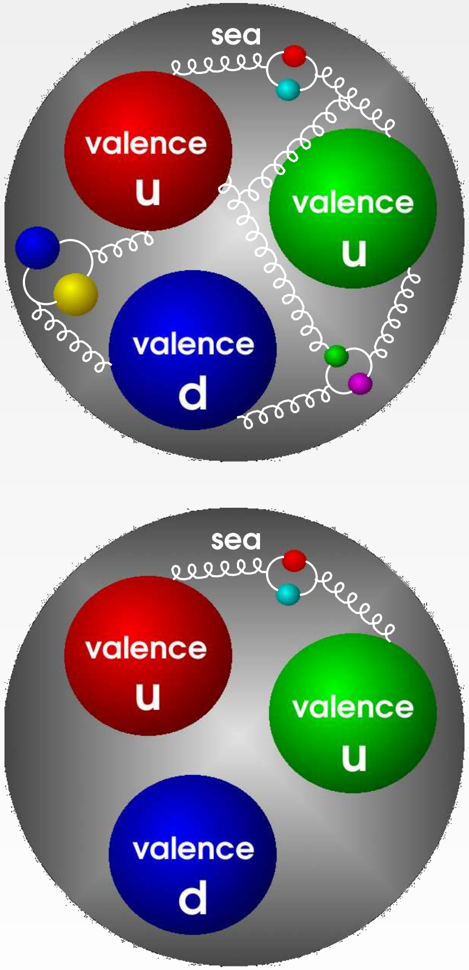
Highest precision by combining with fixed target DIS, Drell-Yan, . . .

DGLAP Evolution of PDFs

PDFs – intrinsically non-perturbative but evolve perturbatively in Q^2

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi (DGLAP)





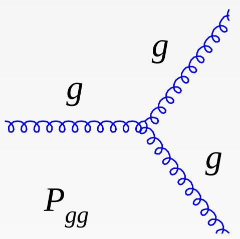
Only need start-up distributions $q(x)$, $g(x)$ at starting scale Q_0^2

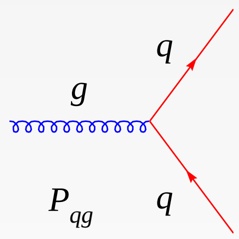
Inclusive DIS Data

$$F_2^{em} = x \sum e_q^2 (q + \bar{q})$$

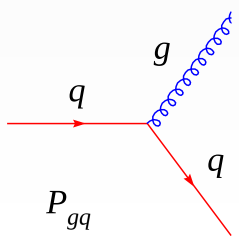
- 5 orders of magnitude in x and Q^2
  Only HERA covers low x domain

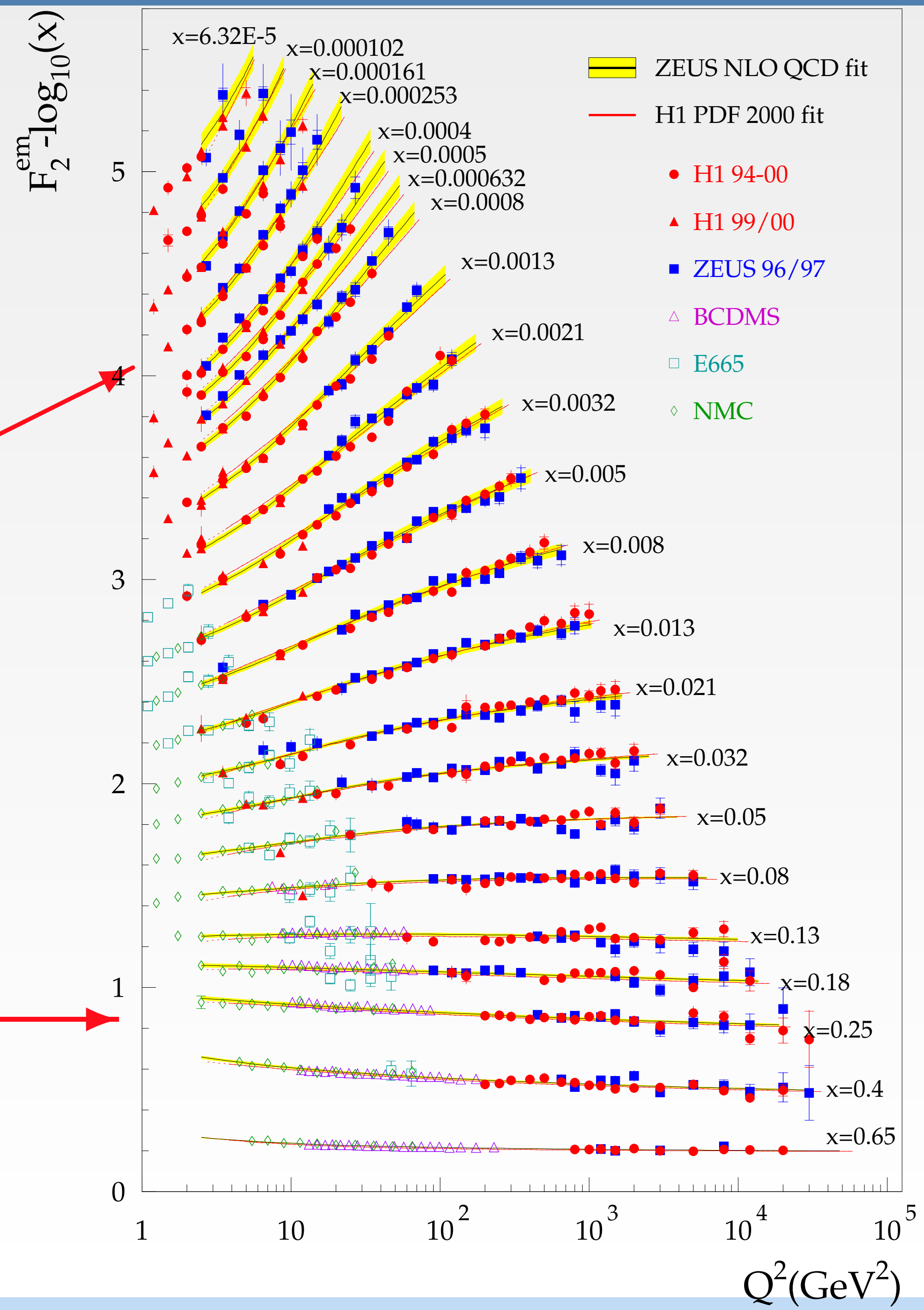
- At low x: rising F_2
  gluons → sea quarks dominate





- At high x: falling F_2
  valence quarks dominate



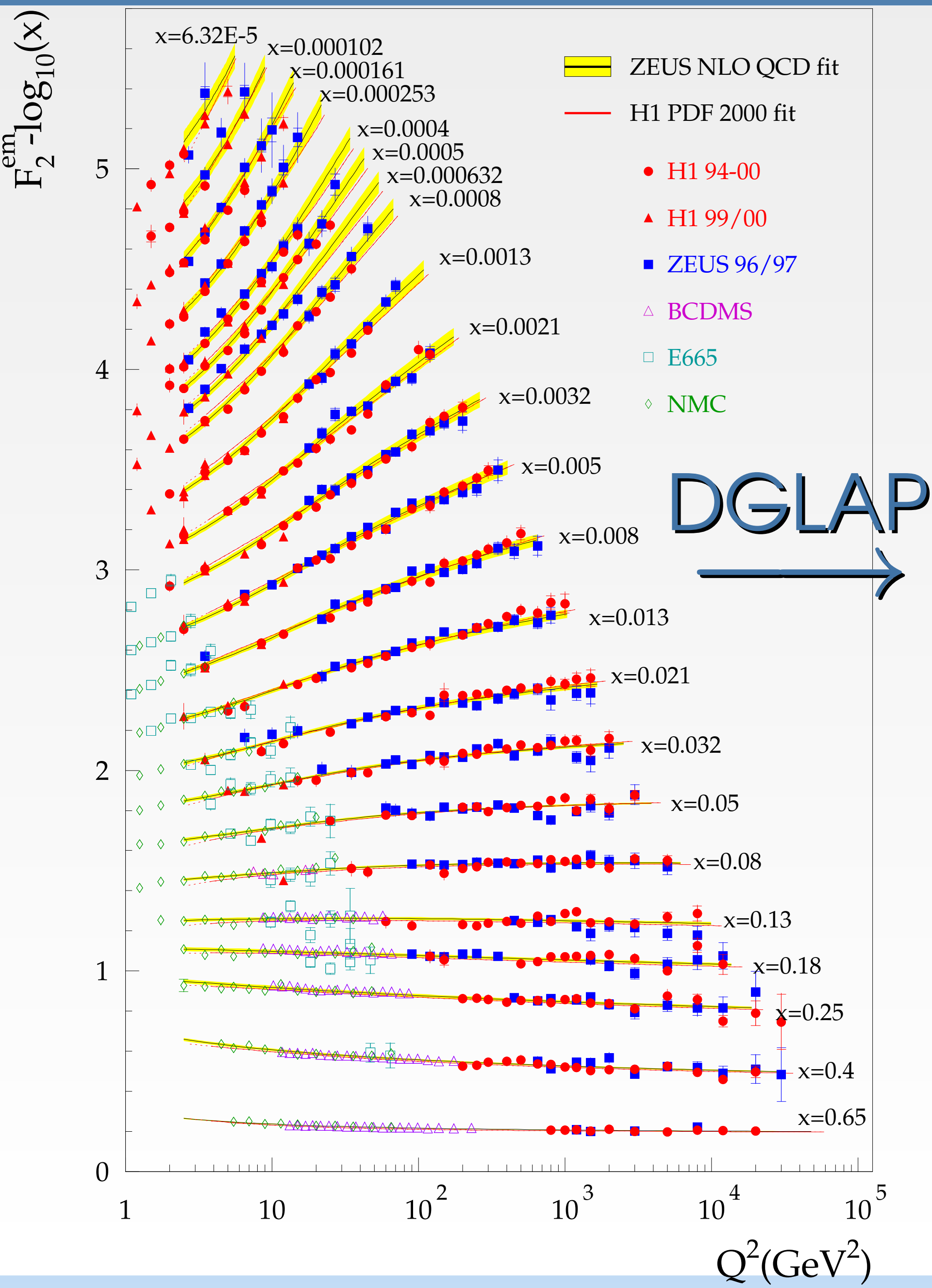


Inclusive DIS Data

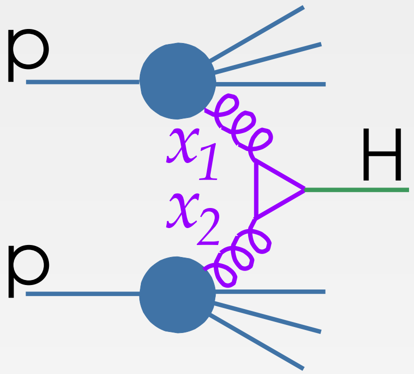
$$F_2^{em} = x \sum e_q^2 (q + \bar{q})$$

- 5 orders of magnitude in x and Q^2
  NLO DGLAP fits well describe inclusive data
  NLO $= \mathcal{O}(\alpha_s^2)$, first NNLO $\mathcal{O}(\alpha_s^3)$ fits available
- Data precision $2 - 3\%$ in bulk region
  $1 - 2\%$ seem feasible
- High Q^2 dominated by stat. errors
  Factor 2 reduction is aimed at with HERA II

So what is needed by LHC?



PDFs for LHC

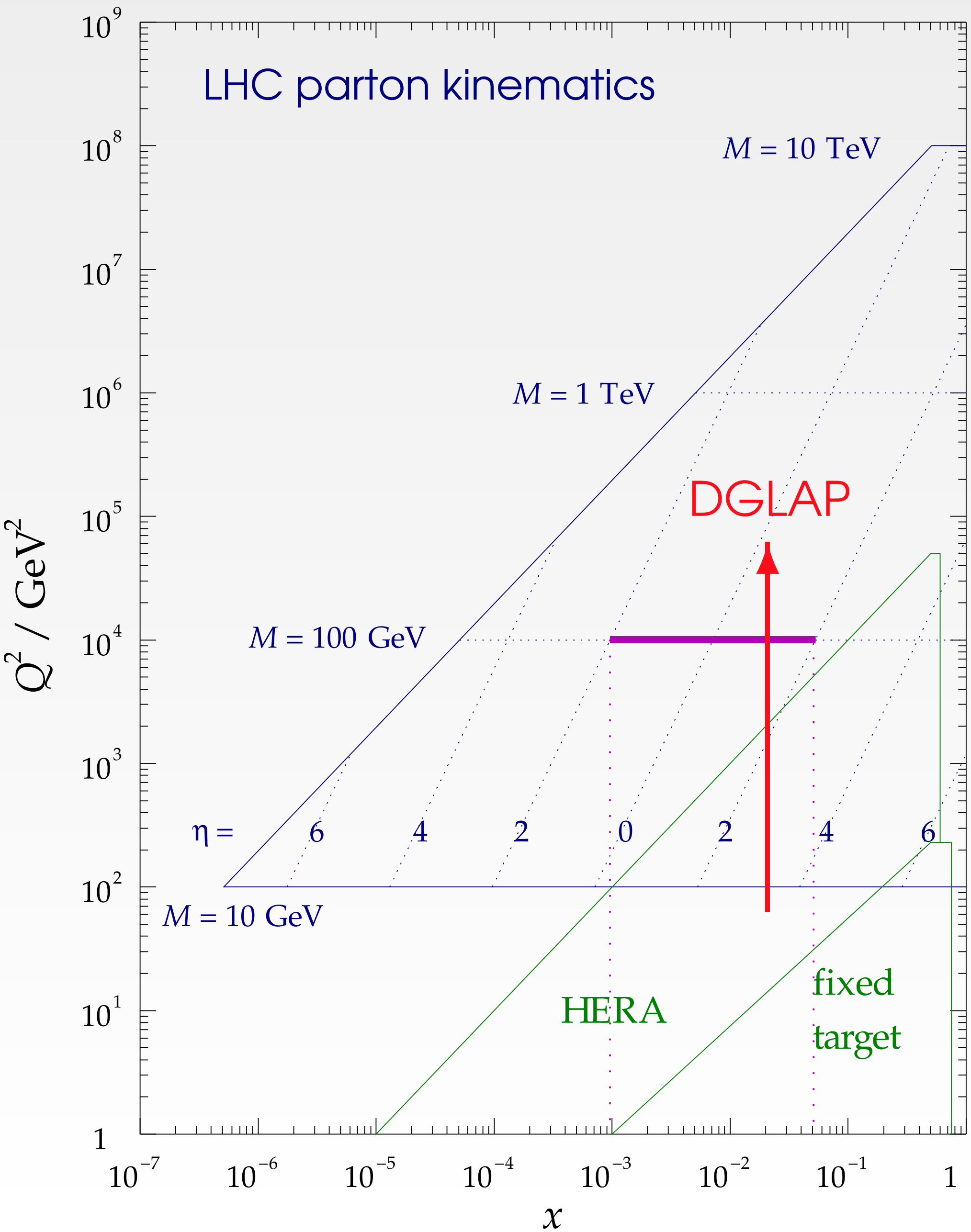


$$x_{1,2} = \frac{M}{\sqrt{S}} \exp\left(\pm \text{rapidity}\right)$$

Precise quark and gluon densities are required in the whole x range

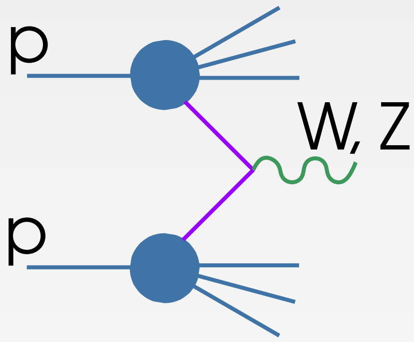
Solution:

Evolve from HERA Q^2 to LHC scales M^2



Luminosity Measurement at LHC with W, Z

$\sigma = \frac{N}{L} \quad \Longrightarrow$ Use reference 'standard candle' process to measure lumi: $L = \frac{N_{\text{ref}}}{\sigma_{\text{ref}}}$



W and Z production is well suited

- High rate: few Hz at low lumi → small stat. errors
- Well measurable: $1-2\%$ syst. error for Z
- Well-known parton x-section: 1% at NNLO

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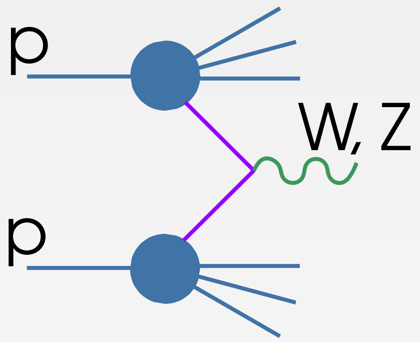

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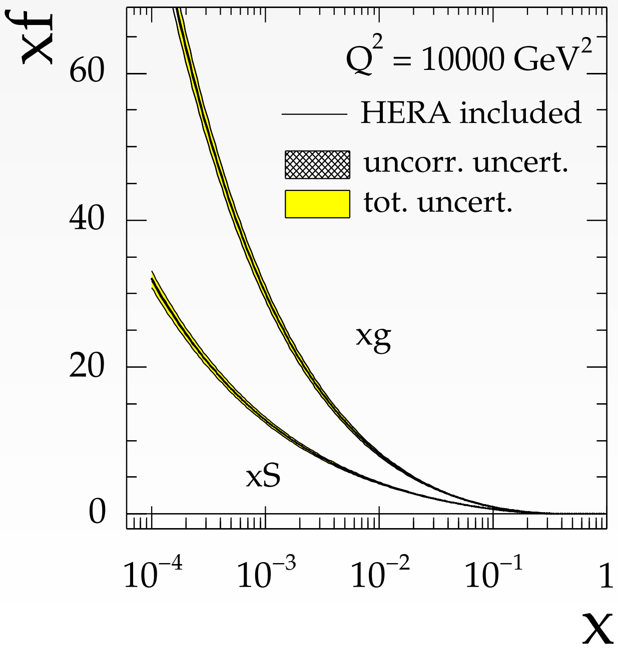
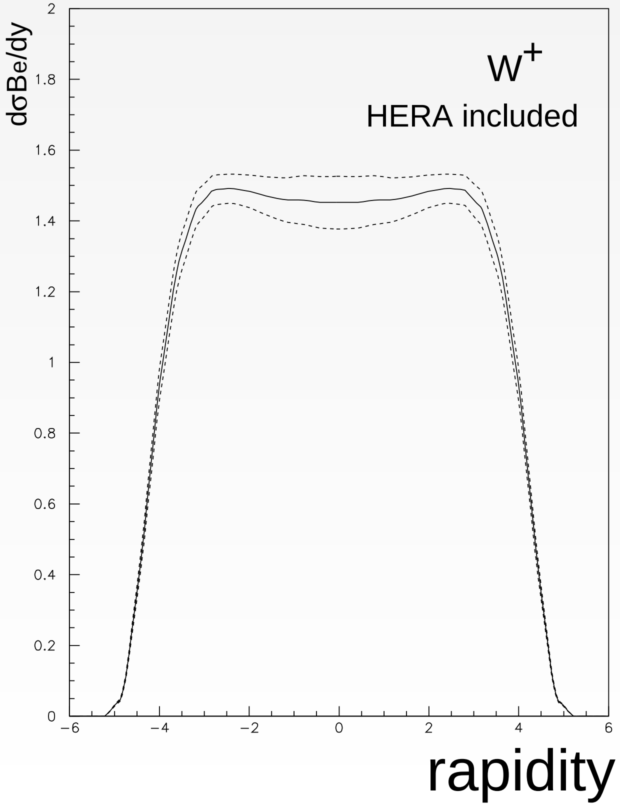
Crucial issue – knowledge of PDFs:

$\sim 4\%$ for total σ, $\sim 8\%$ for central rap.





Tricoli, Cooper-Sarkar, Gwenlan

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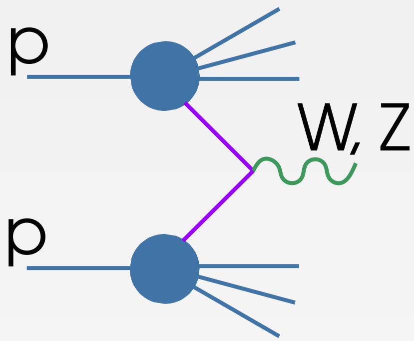

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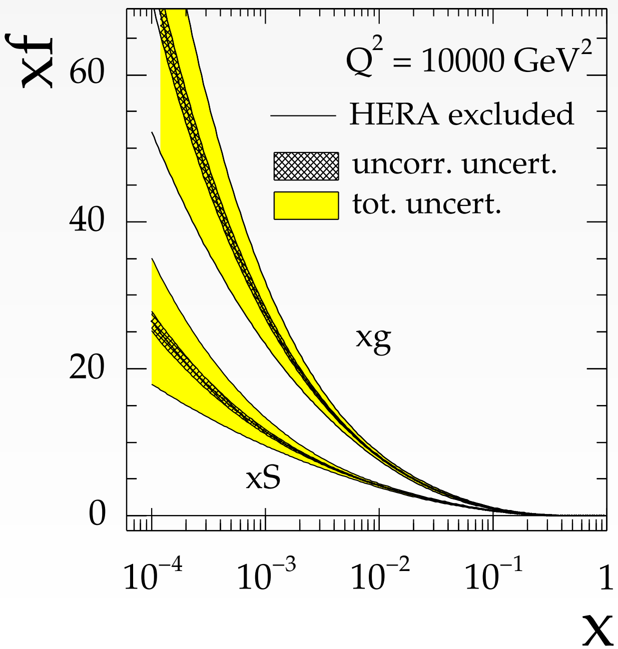
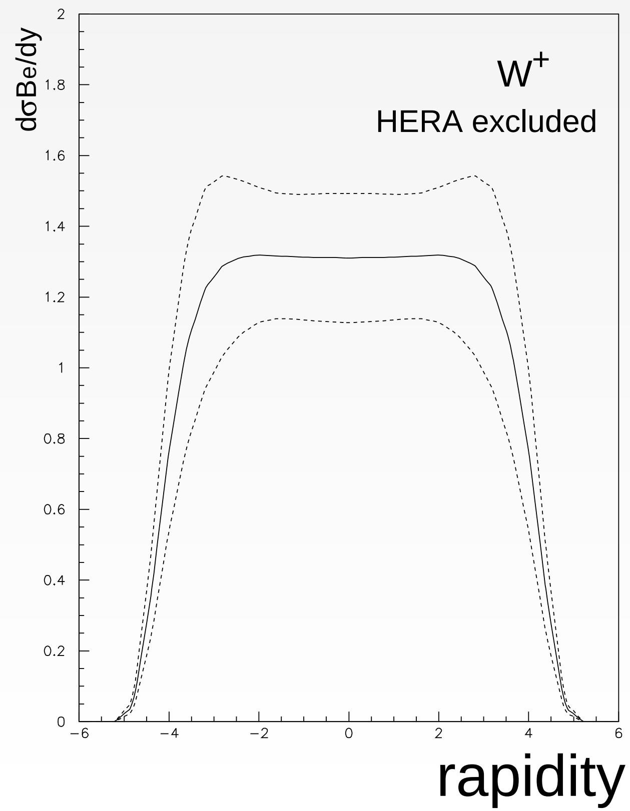
Crucial issue – knowledge of PDFs:
Error would be $\sim 15\%$ without HERA





Tricoli, Cooper-Sarkar, Gwenlan

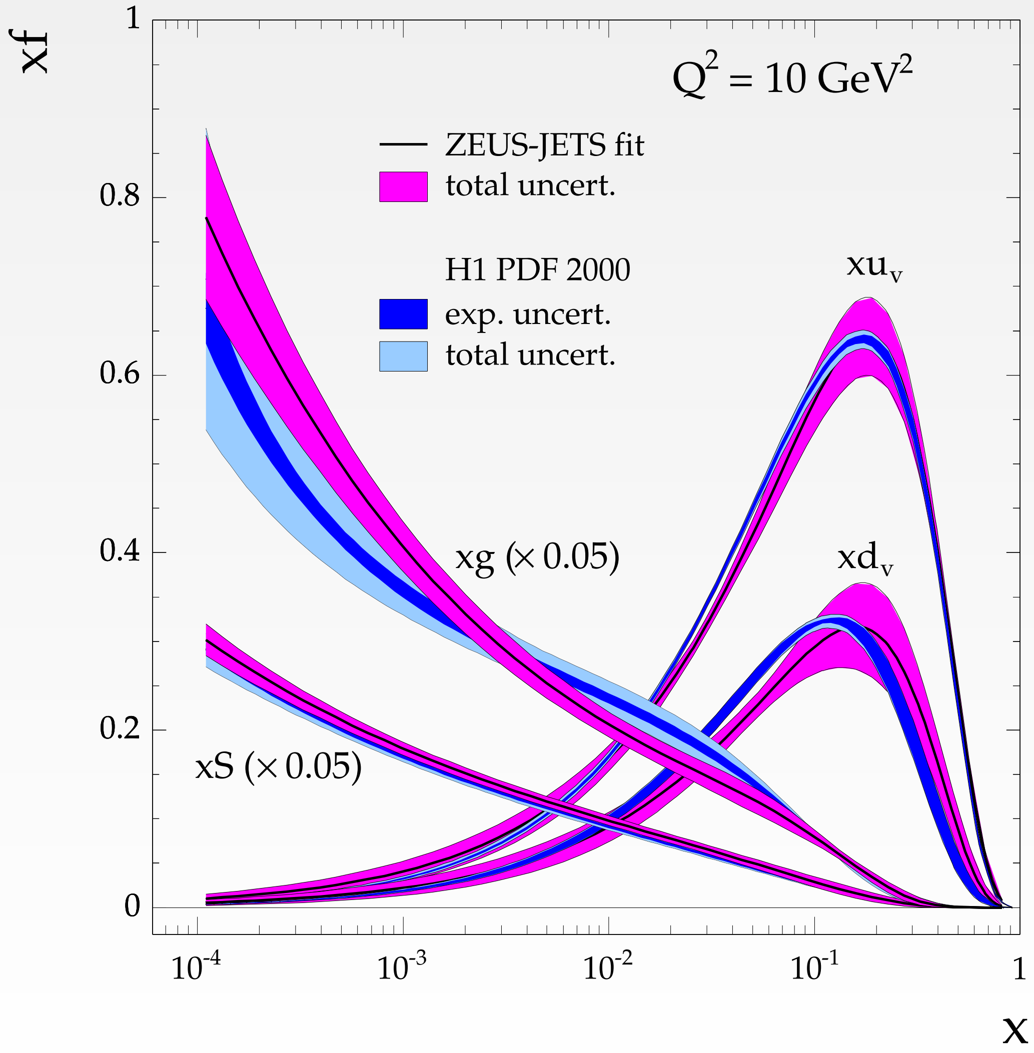
Questions

- How good is our knowledge of PDFs?
- Is DGLAP sufficient to extrapolate PDFs to LHC scales?
- Are non-linear QCD effects relevant?

Let´s look...

PDF Extraction

Typical uncertainties: u **density** 2 – 5% , d **density** 5 – 8% , **gluon density** 10 – . . . %



Example

H1/ZEUS mostly agree but

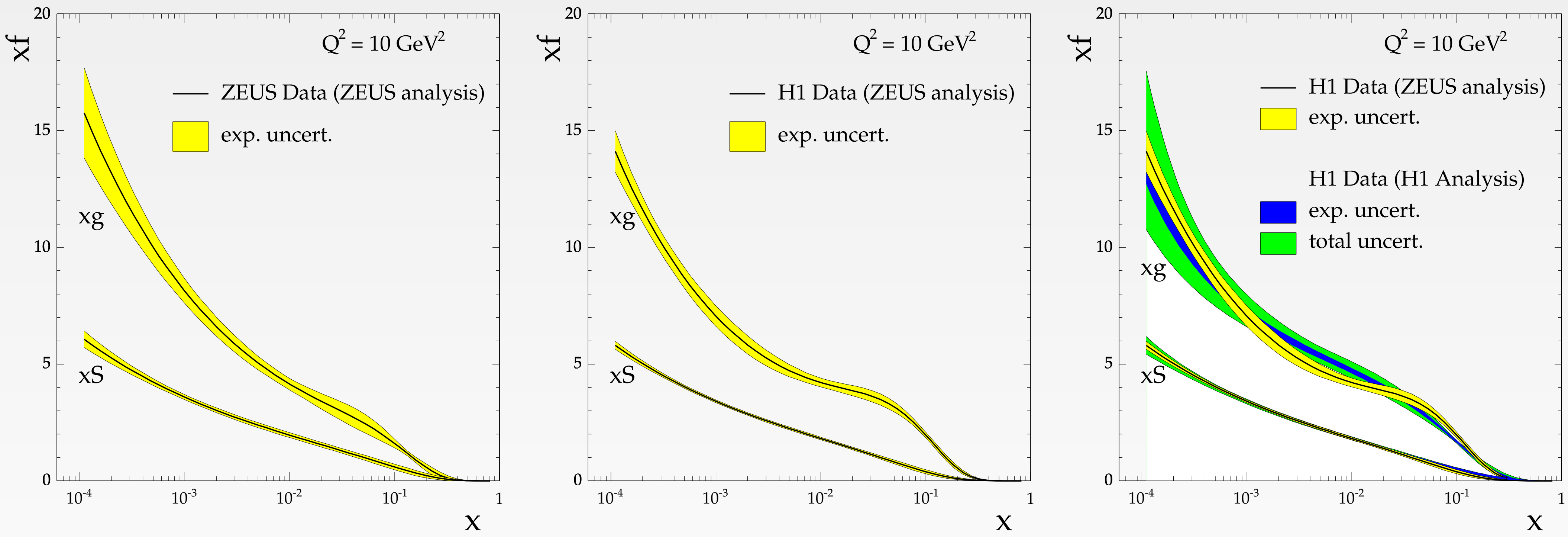
Differences

- Choice of data sets
- Treatment of systematic errors
- PDFs to extract
- Form of x distribution
- Number of parameters
- Constraints on parameters
- . . .

Many effects understood!

Differences between H1 and ZEUS

Cooper-Sarkar and Gwenlan, HERA-LHC Workshop



Different data, same analysis

Same data, different analysis

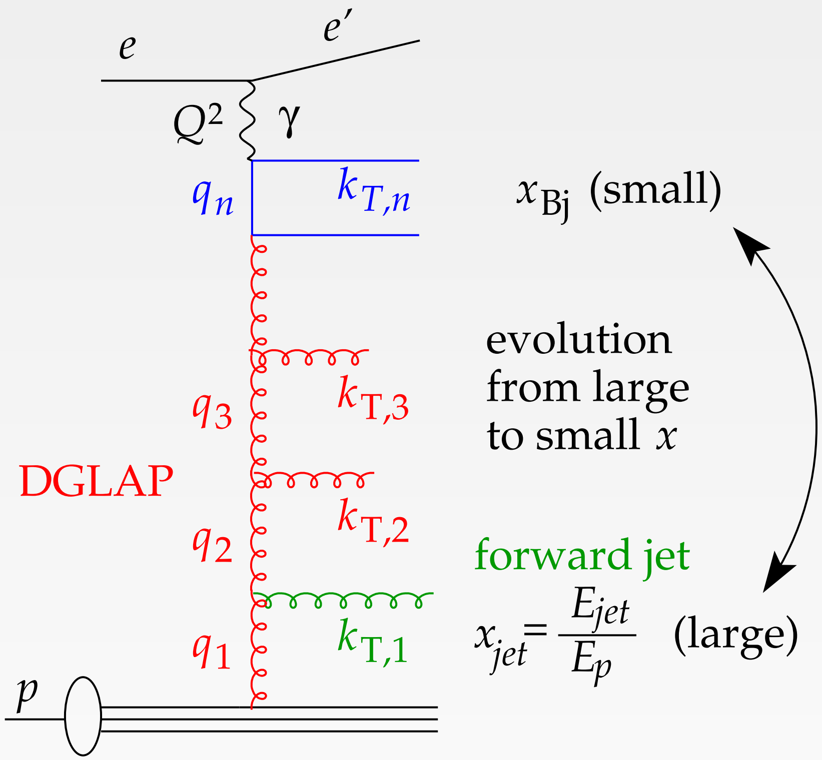
Differences already in the data

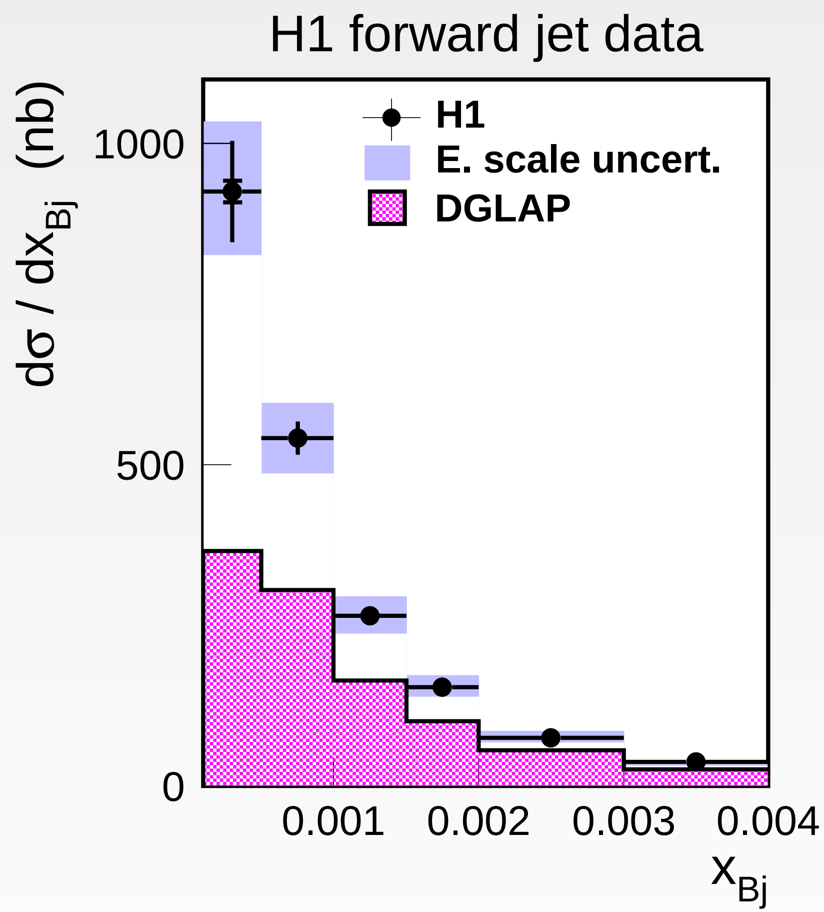
H1 and ZEUS intend to produce common data sets

Next Question

- How good is our knowledge of PDFs?
- Is DGLAP sufficient to extrapolate PDFs to LHC scales?
- Are non-linear QCD effects relevant?

Forward Jets at Low X

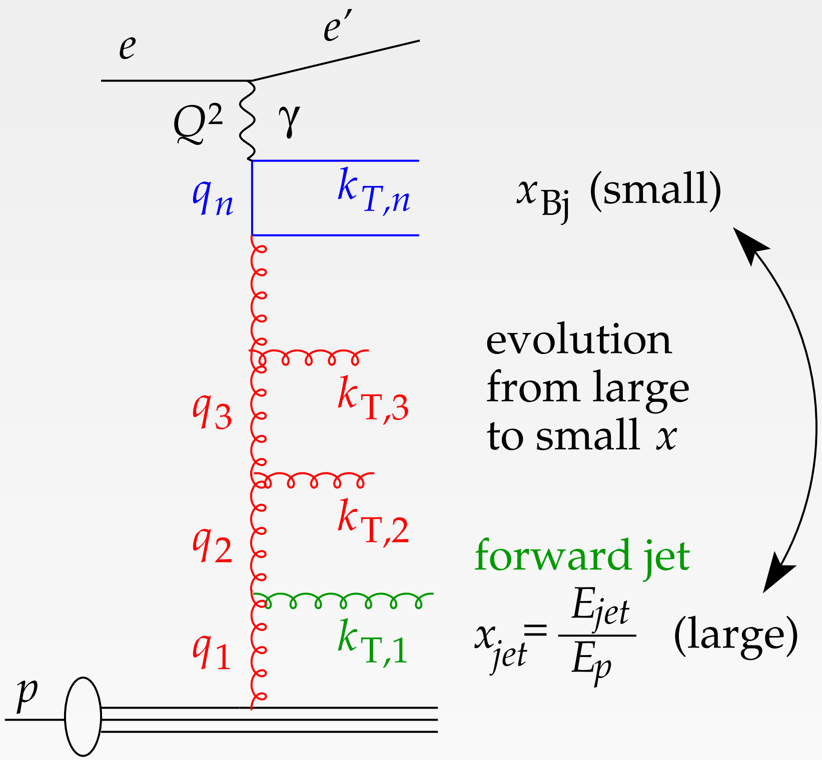


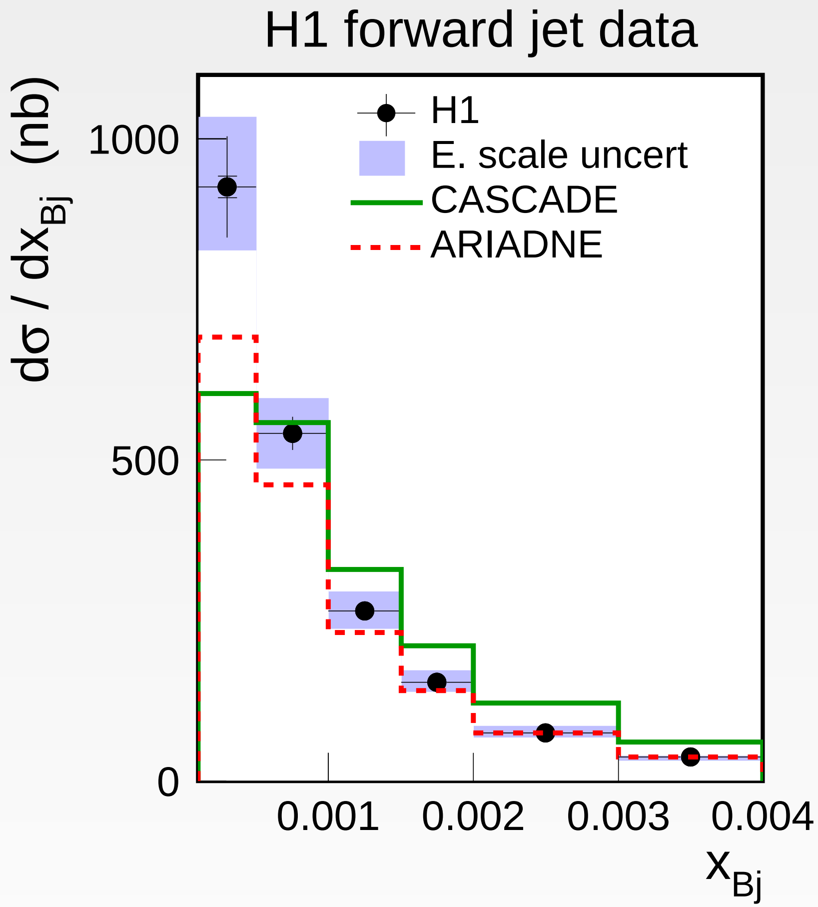


- If using DGLAP for parton shower $\Rightarrow$ k_T ordering

  $q_1^2 \ll q_2^2 \cdots \ll q_n^2 \ll Q^2 \quad \Rightarrow \quad k_{T,1} \ll k_{T,2} \cdots \ll k_{T,n}$

Forward Jets at Low X





- Parton shower schemes with different ordering
  - CCFM (MC Cascade)
  - CDM (MC Ariadne)

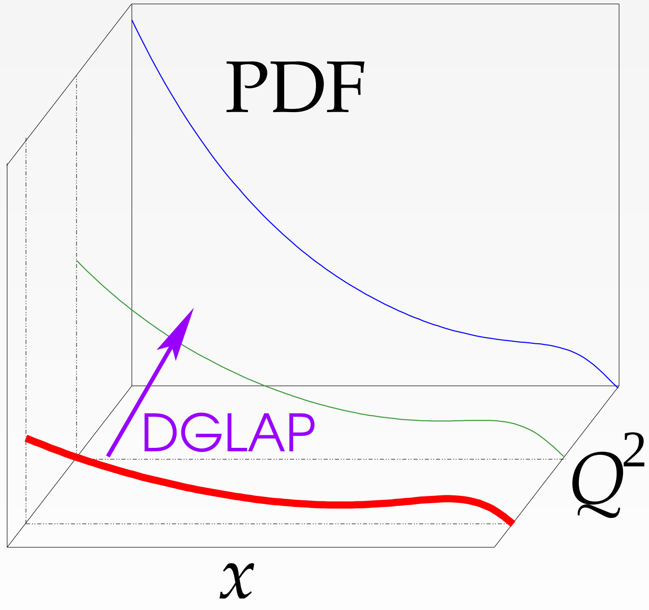
work better than DGLAP at low x

Resummation at Low X

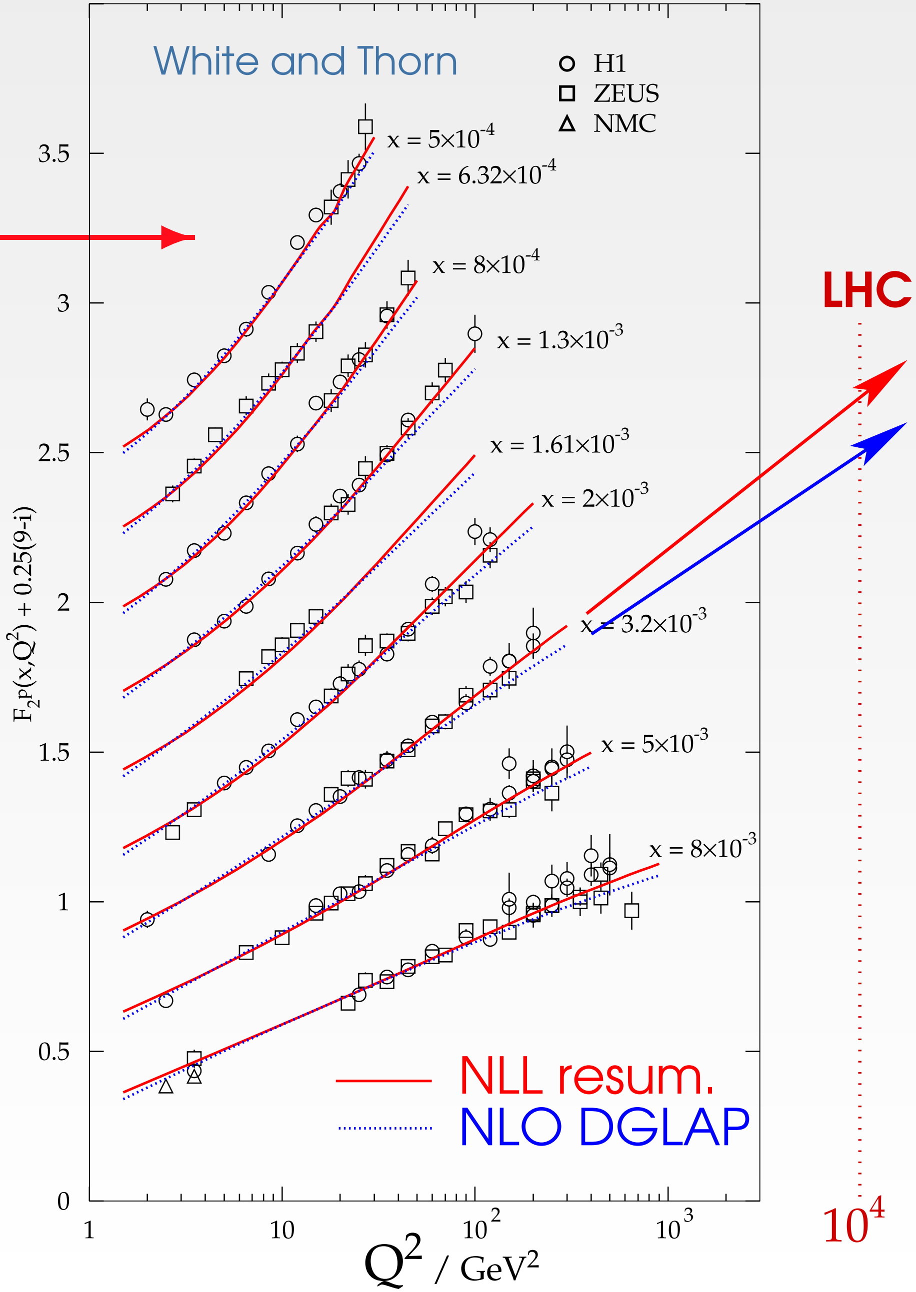
- Missing terms? $\left[\alpha_s \ln \frac{1}{x}\right]^k$

  Attempt to add these to evol. eqs

- Difficult to see in inclusive fits due to free choice of $q(x)$, $g(x)$ at Q_0^2



Critical corner – low x, low Q^2



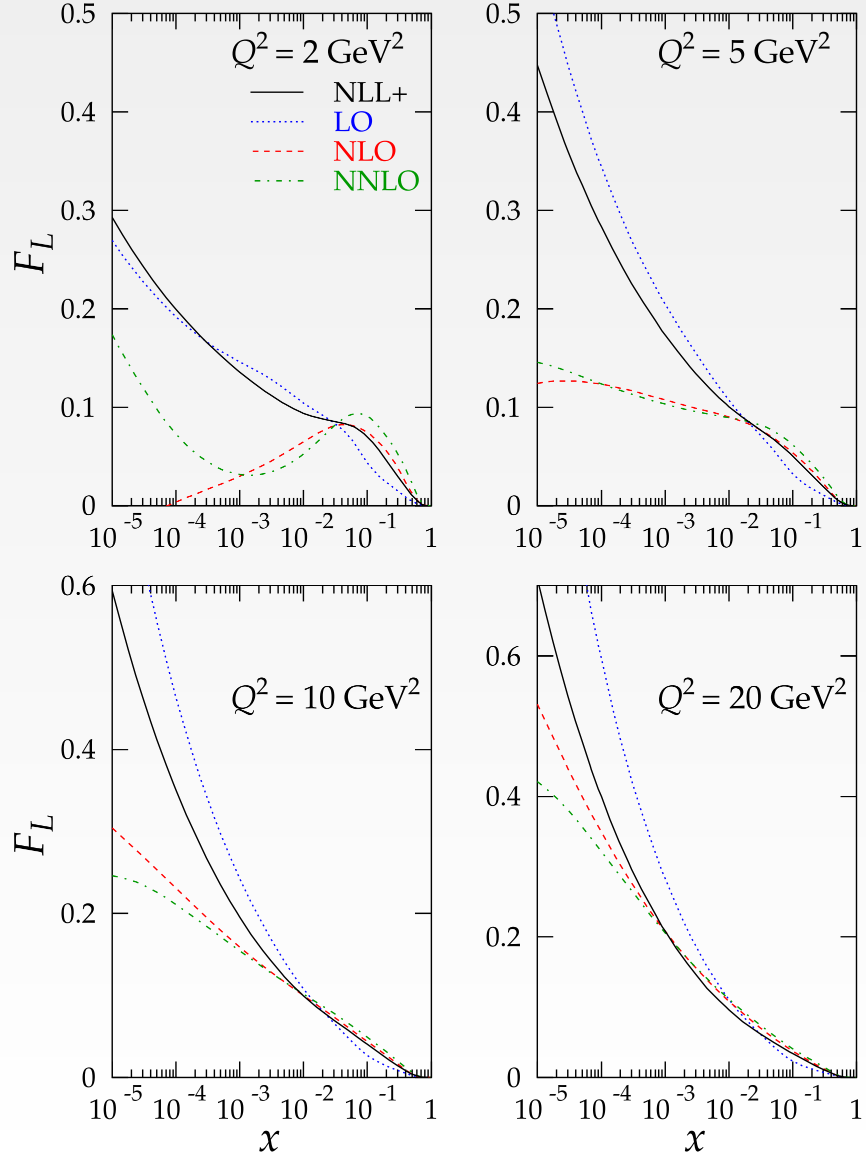
Longitudinal Structure Function F_L

$F_L(x, Q^2)$ – longitudinally polarised photons

- $F_L = 0$ in Quark Parton Model
- Sensitive to QCD higher orders (gluon emission)

  $F_L \sim \alpha_s x g$ — constrains gluon density

White and Thorne



Calculations

- Large spread of calculations for gluon and F_L
- Critical corner – low Q^2 and low x
- Can be used to test resummation approaches

Future Low Energy Run

Cross section:

$$\sigma(x,Q^2) \propto F_2(x,Q^2) - \frac{Q^4}{s^2 x^2 \ldots} F_L(x,Q^2)$$

Measure σ at the same x, Q^2 for different s

H1 Simulation

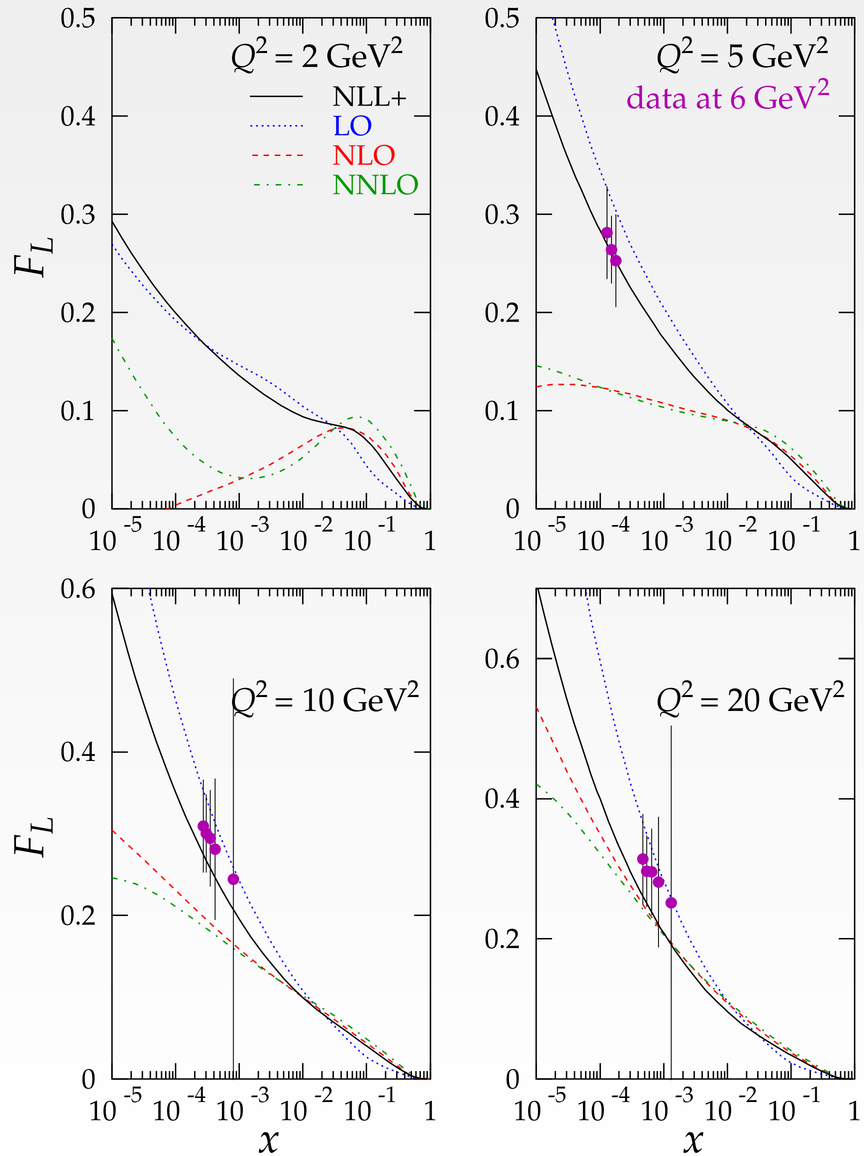
$30\,\mathrm{pb}^{-1}$ at $E_p = 920\,\mathrm{GeV}$

$10\,\mathrm{pb}^{-1}$ at $E_p = 460\,\mathrm{GeV}$

Can differentiate between calculations

Decision taken. Run in preparation

White and Thorne



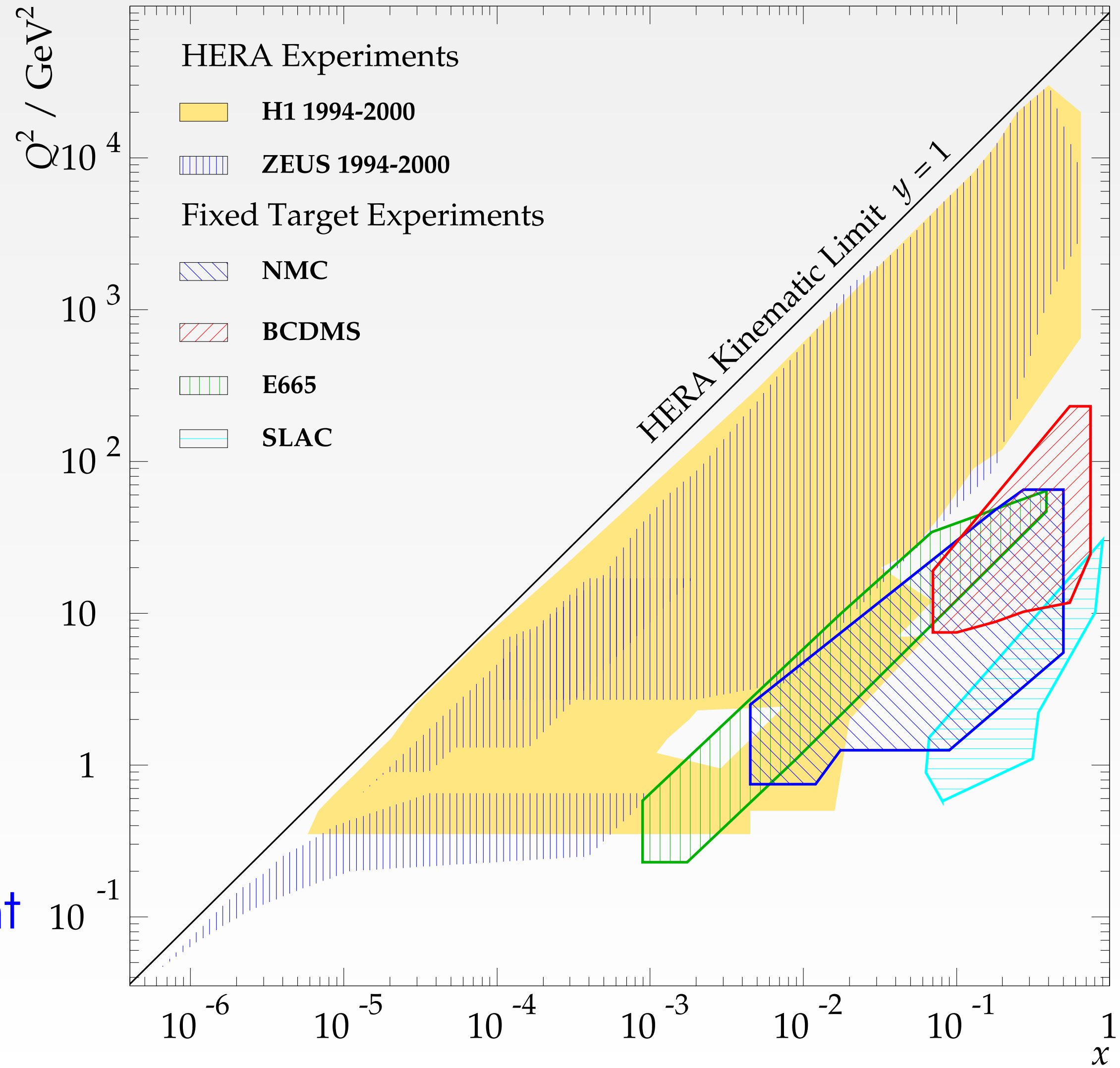
Last Question

- How good is our knowledge of PDFs?
- Is DGLAP sufficient to extrapolate PDFs to LHC scales?
- Are non-linear QCD effects relevant?

Going to High Parton Densities (Lowest X)

Non-linear QCD dynamics = multi-gluon exchange

Gluon density rises steeply towards low x

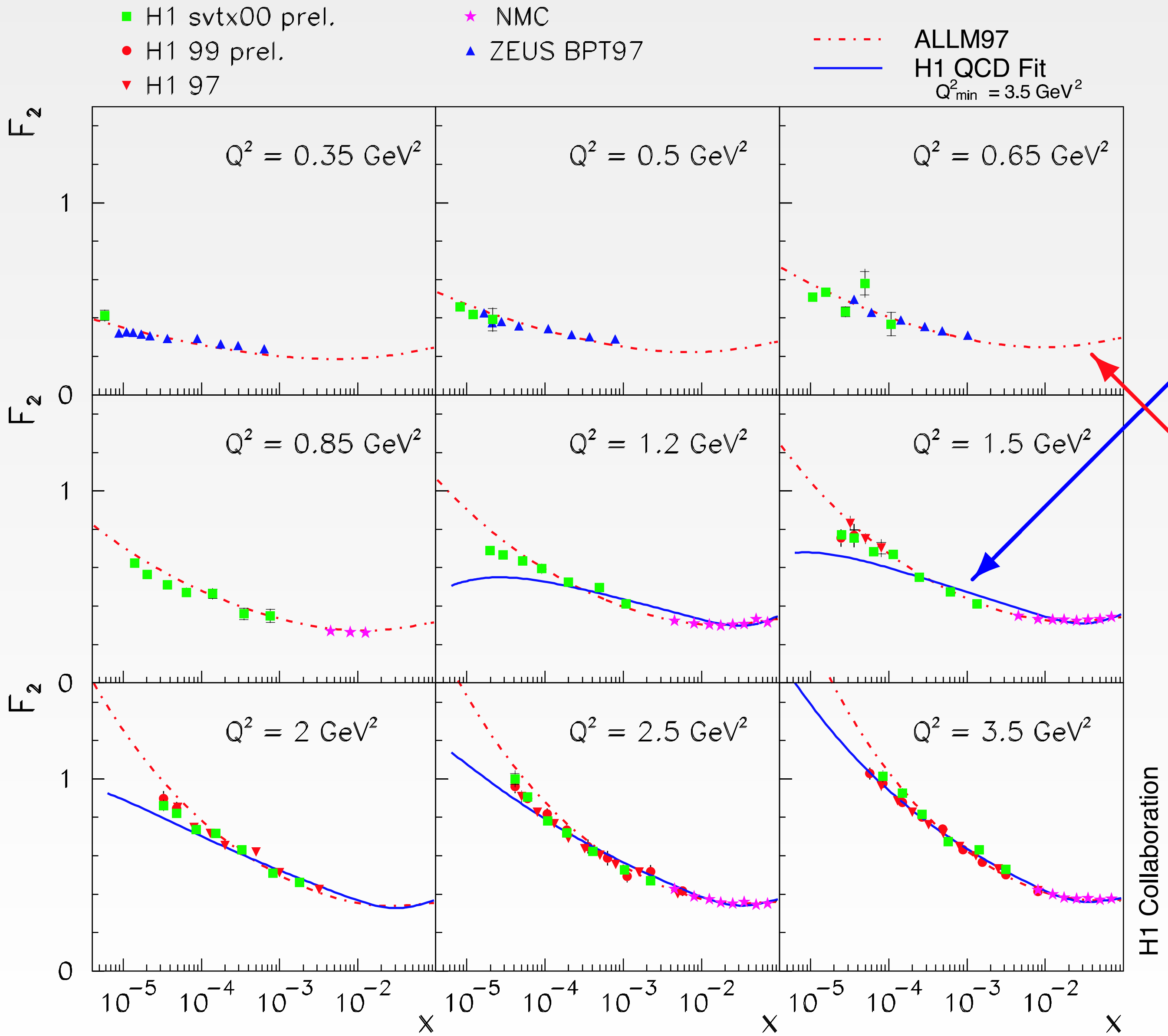


Lowest $x \Longrightarrow$ Lowest Q^2

$\alpha_s(Q^2)$ becomes large $\Longrightarrow$ confinement

quarks are no more free

Data in Transition Region



- At $Q^2 \lesssim 2\,\mathrm{GeV}^2$ pQCD fits fail
- Only phenomenological models describe data
- Rise of F_2 at $x < 10^{-2}$ is well described by

$$F_2 \propto x^{-\lambda(Q^2)}$$

as in pQCD region

Extraction of $\lambda(Q^2)$

$$F_2 = c(Q^2) \cdot x^{-\lambda(Q^2)}$$

- At $Q^2 \gtrsim 2\,\mathrm{GeV}^2$:

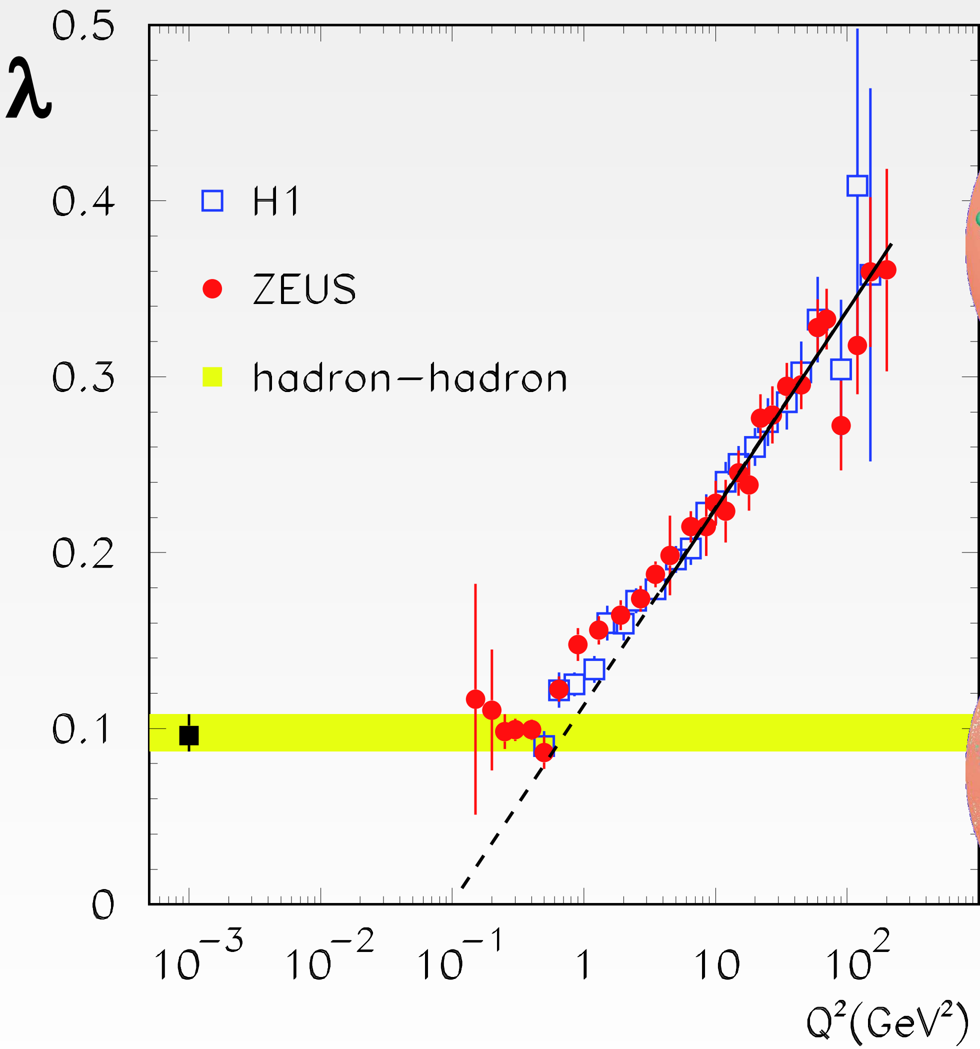
  $\lambda \sim \ln Q^2$

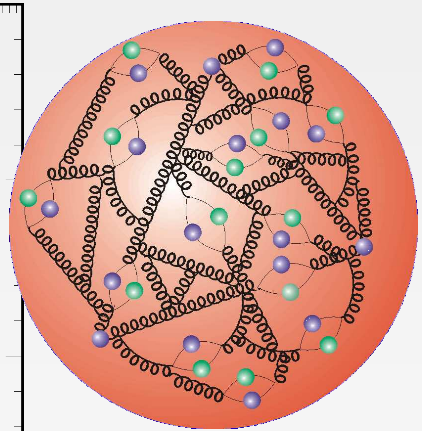
  Partonic degrees of freedom

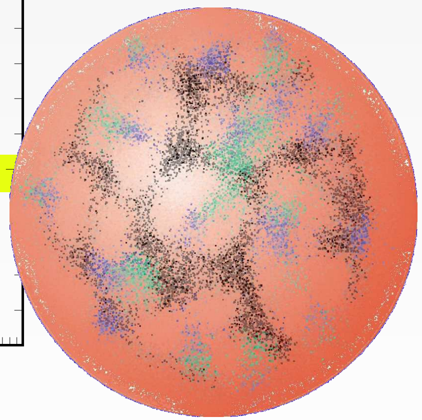
- At $Q^2 \lesssim 2\,\mathrm{GeV}^2$:

  Transition to hadronic d.o.f.

  $Q^2 \to 0$: $\lambda \to 0.08$ (Regge model)







Extraction of $\lambda(Q^2)$

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  Transition to hadronic d.o.f.

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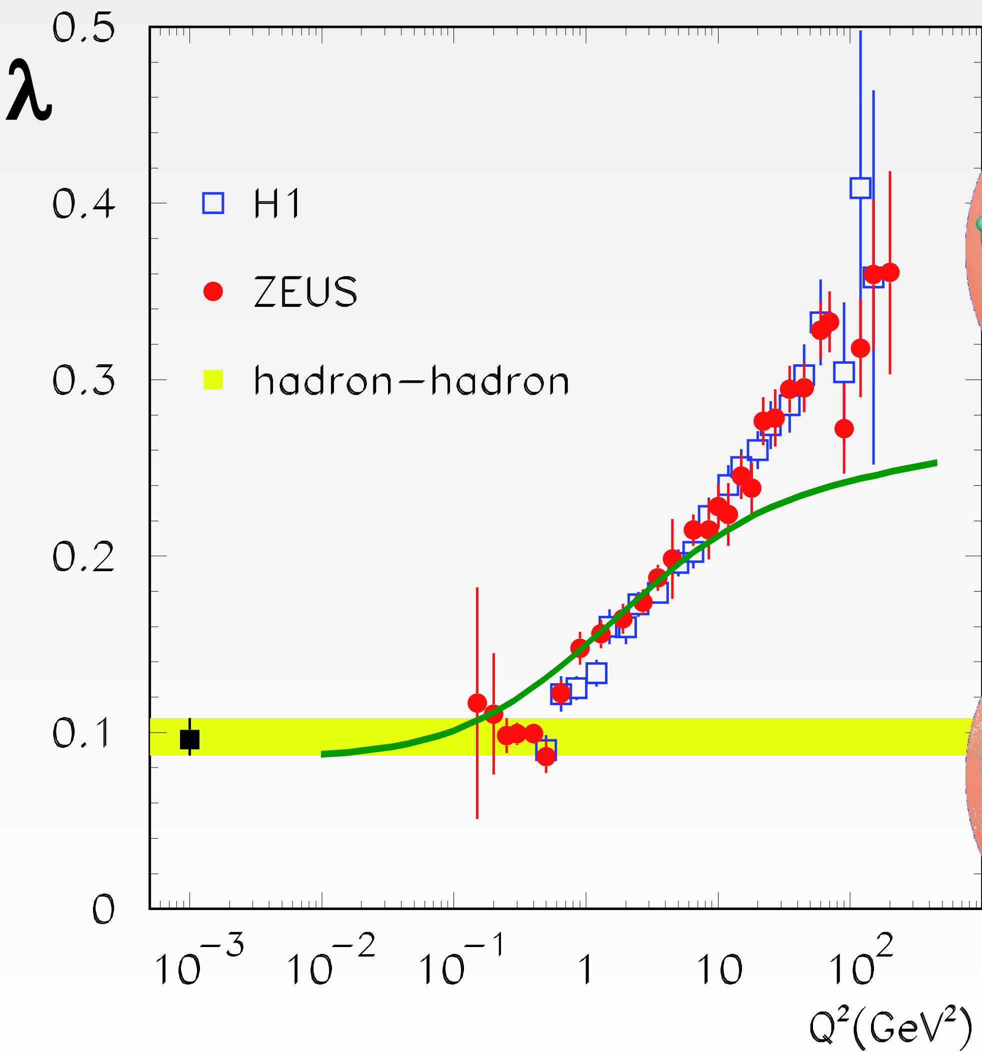
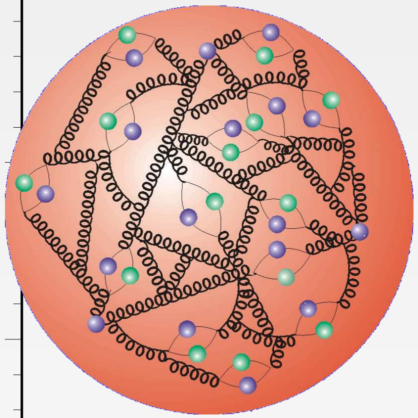
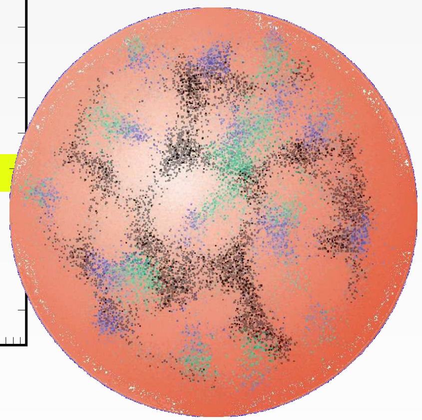
- Example dipole model



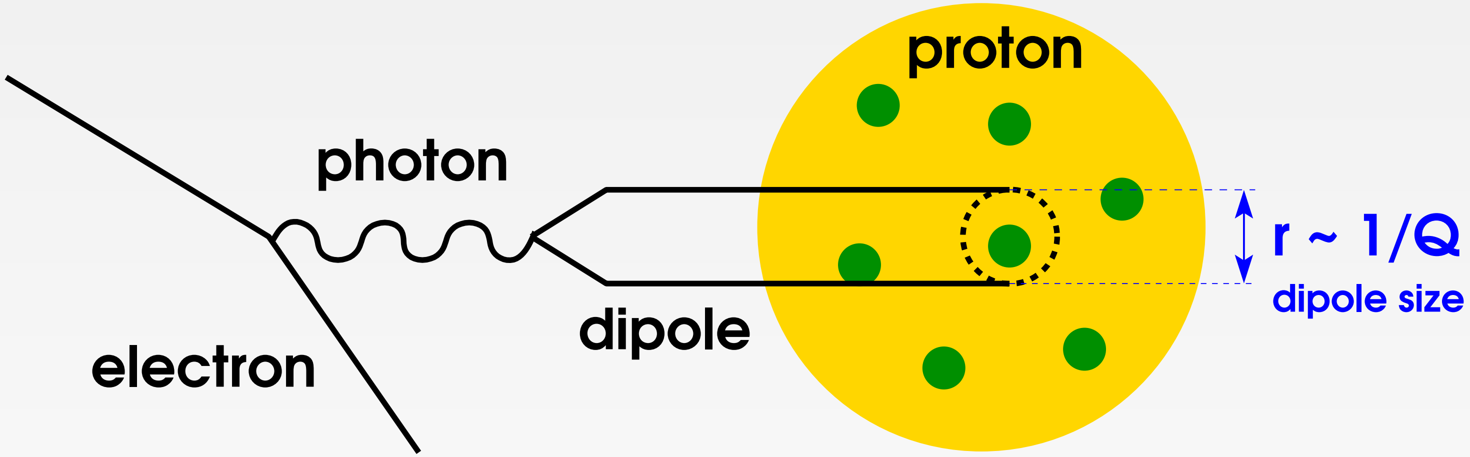




Dipole Models

Use colour $q\bar{q}$ dipoles as degrees of freedom

Proton rest frame: Photon fluctuates in $q\bar{q}$ pair which interacts with proton



$$\sigma_{T,L}^{\gamma^* p} = \int d^2 r \ \ldots \ |\psi_{T,L}(r, \ldots)|^2 \ \hat{\sigma}(r, \ldots)$$

photon wave function

(calculable)

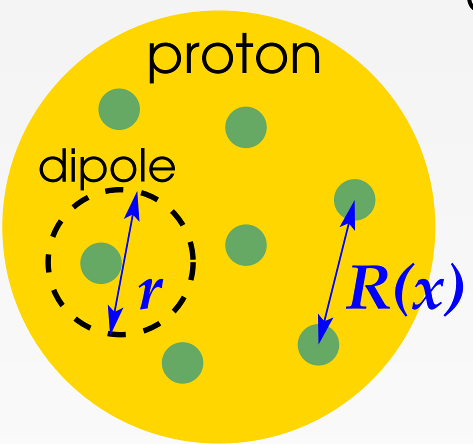
dipole x-section

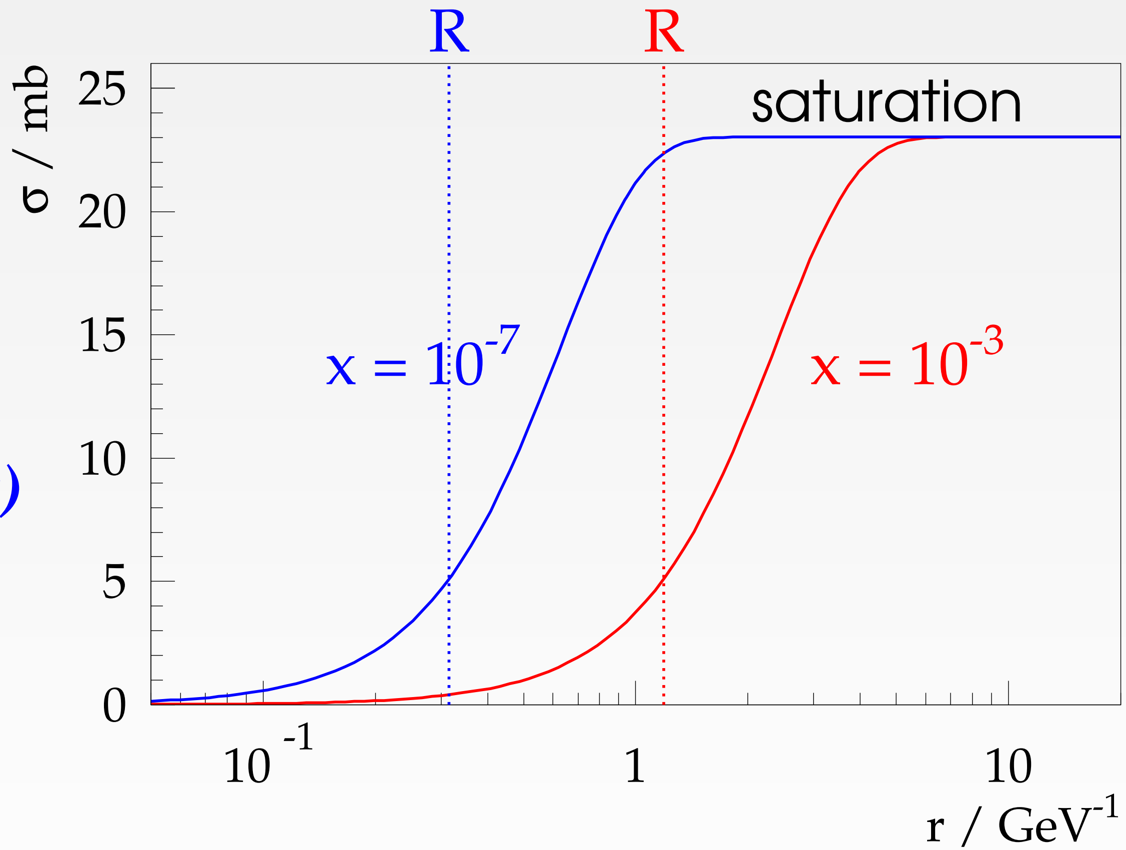
transverse gluon distribution

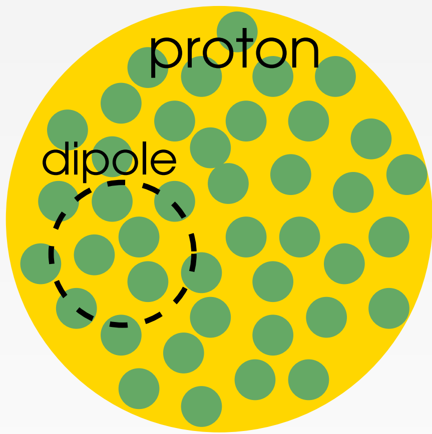
Dipole Saturation Model

Photon fluctuates in $q\bar{q}$ pair which interacts with proton — Golec-Biernat, Wüsthoff

Dipole–proton cross section:



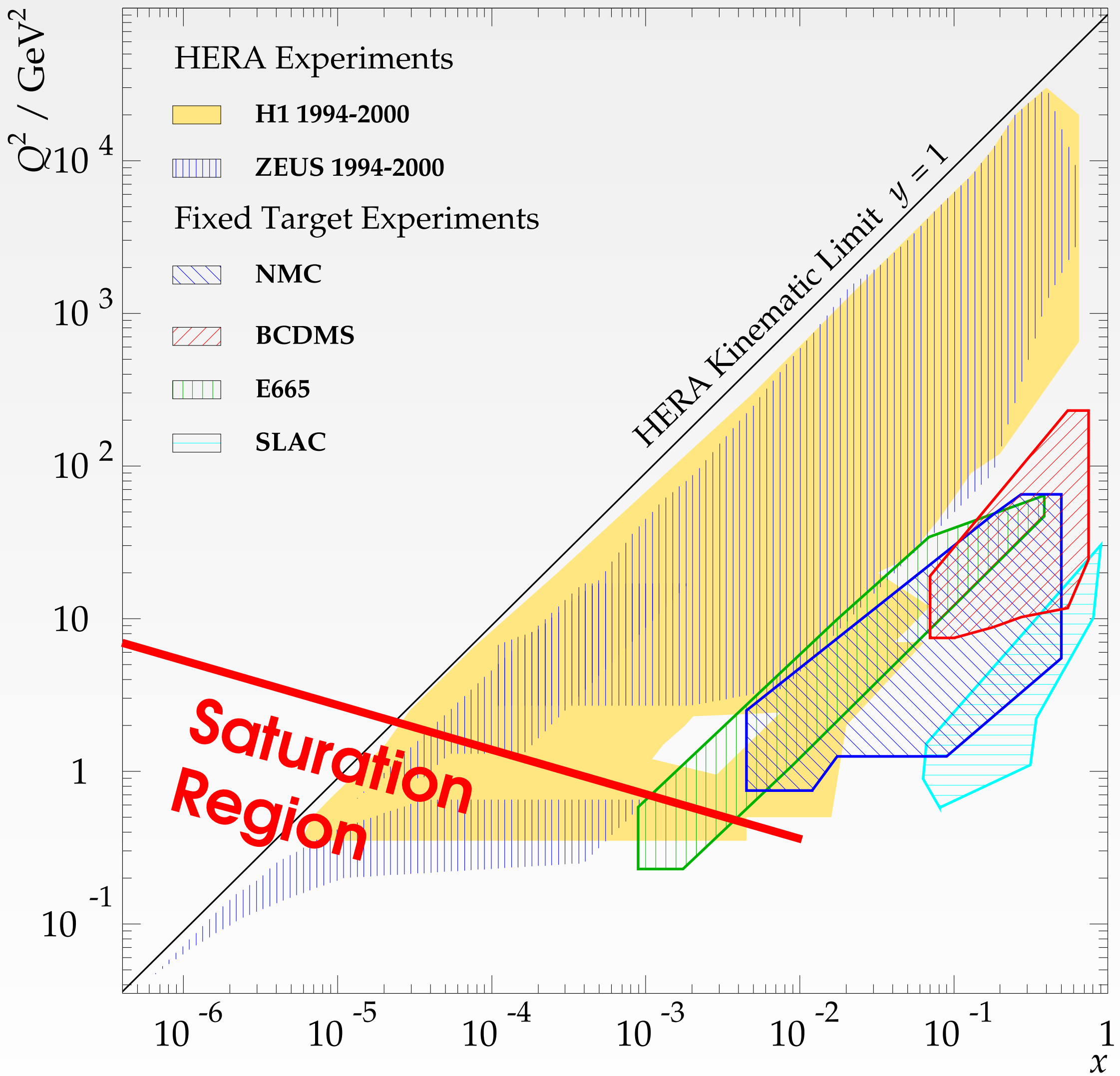




At small r: $\hat{\sigma} \sim \frac{r^2}{R(x)^2}$

At large r: non-linear interactions $\rightarrow$ **saturation**

Saturation Region in Dipole Model

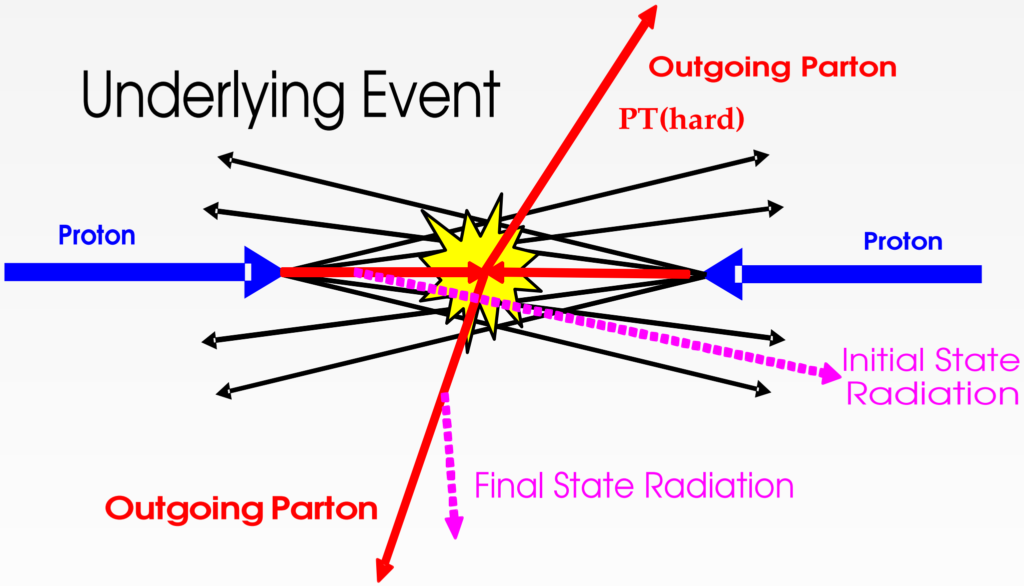


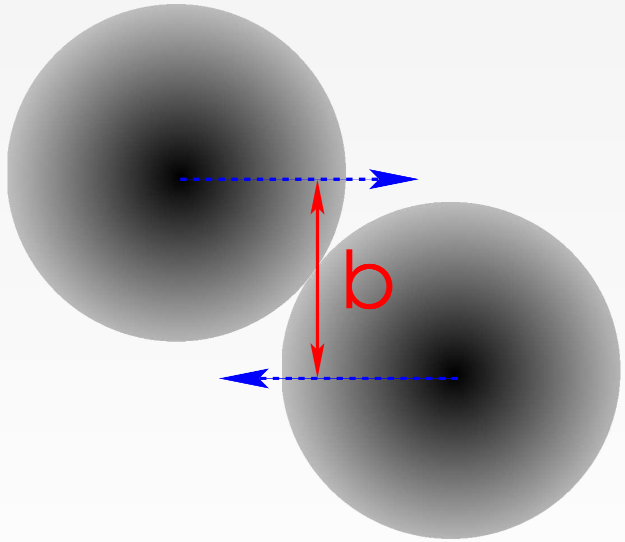
- For $Q^2 \lesssim 1 - 2\,\text{GeV}^2$ saturation model describes transition to soft interactions with only 3 parameters
- For pQCD Q^2 scales saturation region is beyond HERA reach
- Still, non-linear effects can affect pQCD evolution at low x and Q^2

Dipole Models

- Dipole models describe very successfully inclusive diffraction and exclusive channels (light VM, J/ψ, DVCS)

- They can be used to describe diffraction at pp and multiple interactions (underlying event, minijets . . .)





Summary

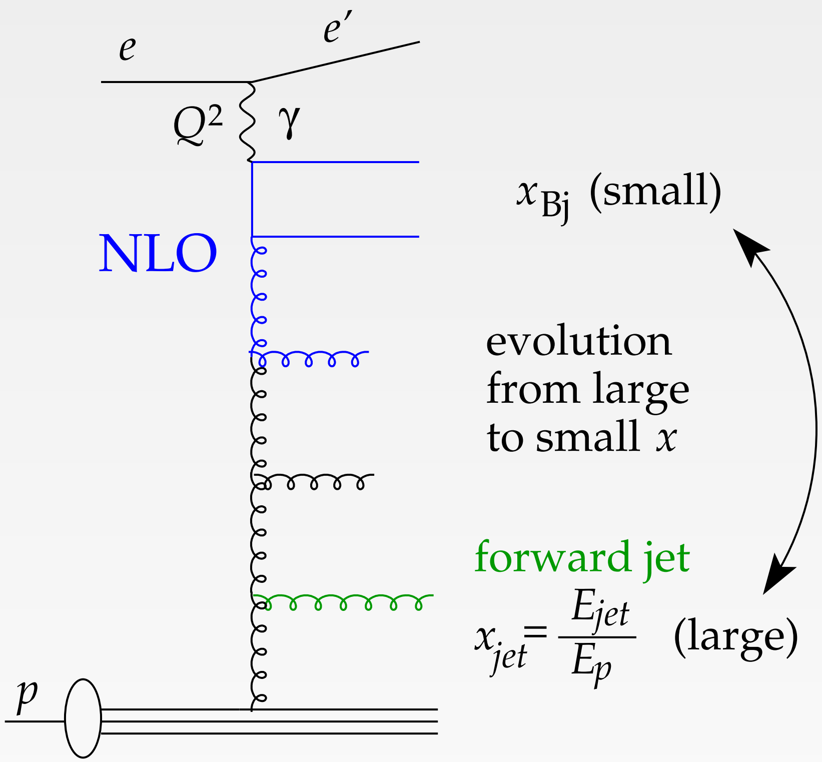
- The quest for precision and deeper undestanding continues
  Experiments $\longrightarrow$ statistics, combined data, $F_L, \ldots$
  Theory $\longrightarrow$ NNLO, resummation, non-linear effects ...

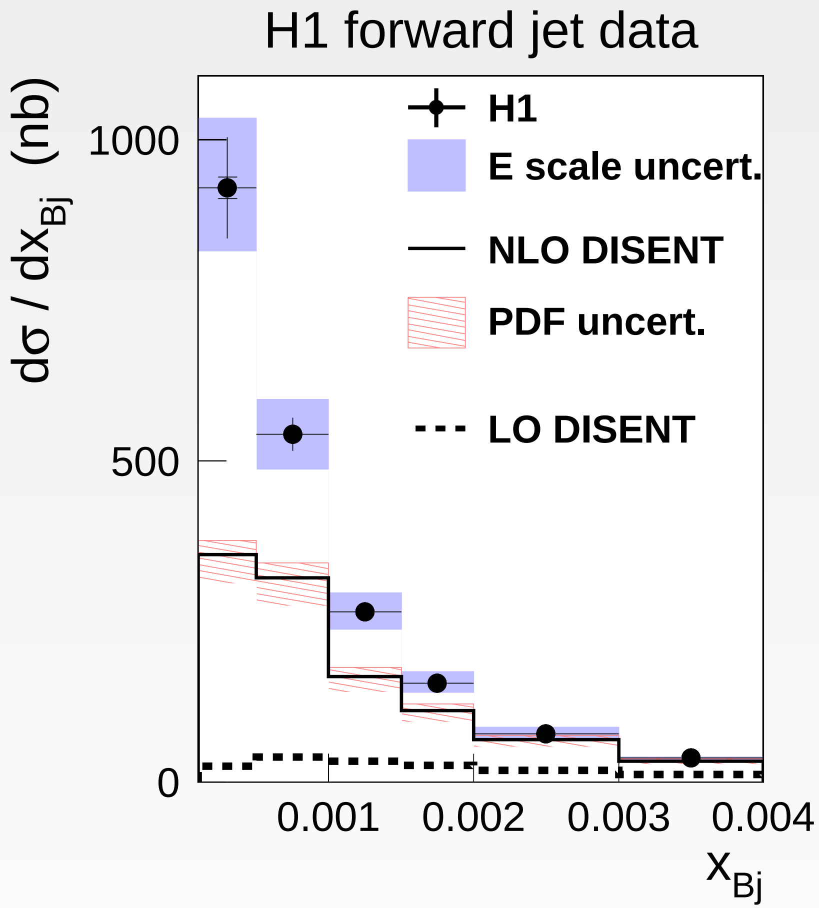
- DGLAP limitations are clearly visible in semi-inclusive measurements
  $\longrightarrow$ Alternative parton cascade models

- Models for non-linear dynamics are further developed
  $\longrightarrow$ Transverse picture of the proton
  $\longrightarrow$ Understanding of soft hadron interactions
  $\longrightarrow$ Diffraction, Multiple Interactions

Additional Information

Forward Jets at Low X

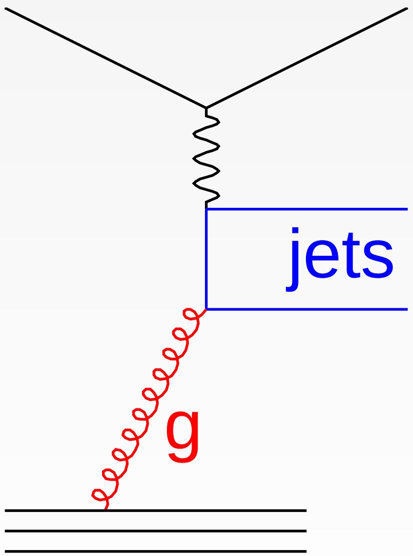


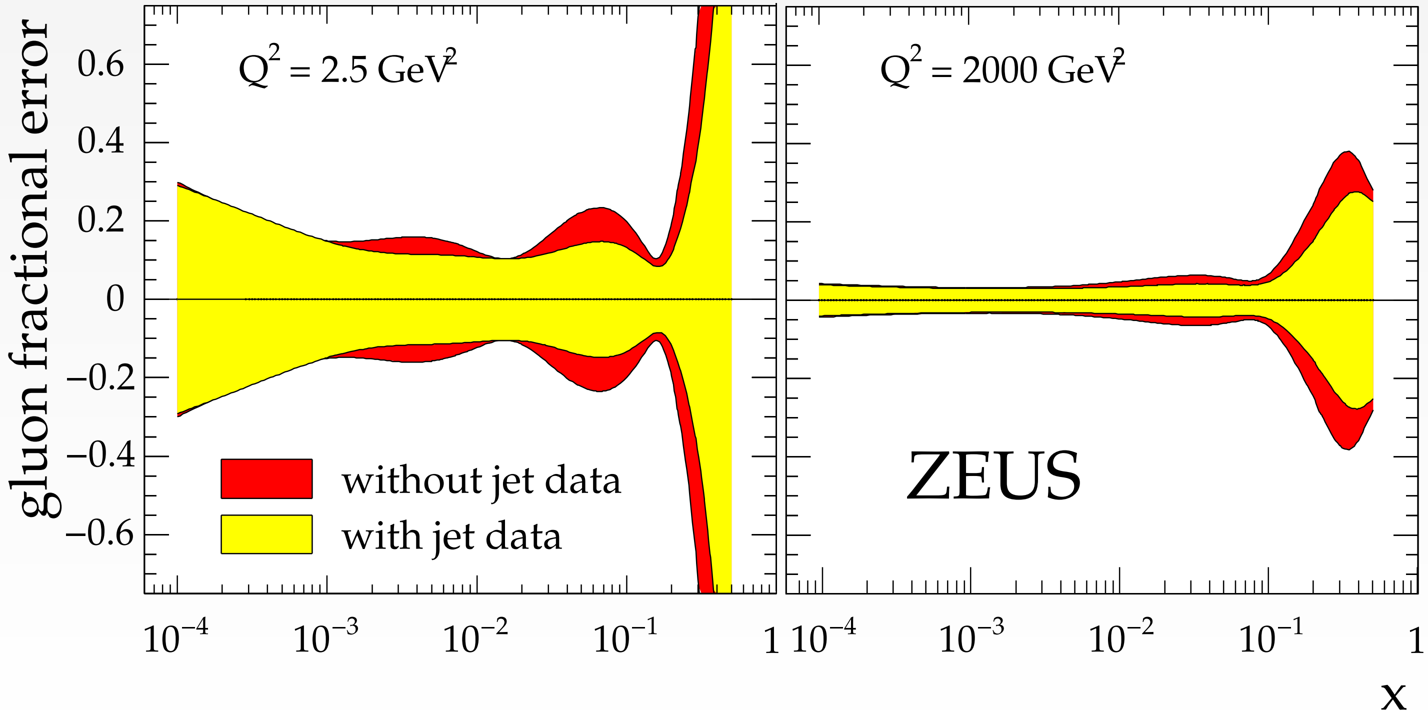


- Low x – long parton chain
- Look at forward jet – start of the chain
- NLO is not sufficient

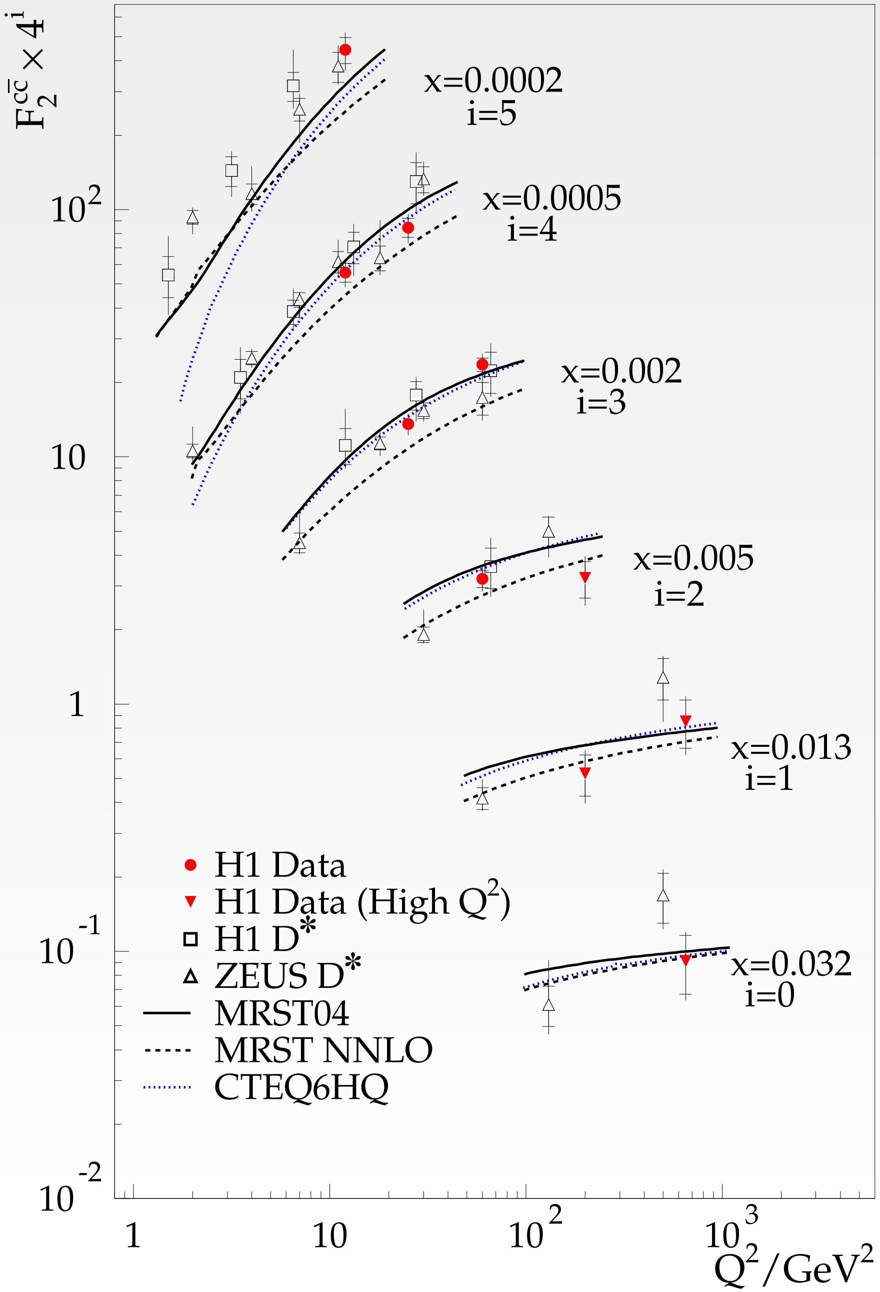
Including Jet Measurements in PDF Fits

- HERA data are stat. limited at high x (high Q^2)
- Theor. group include TeVatron jet data
  Large systematics due to jet energy scale
- ZEUS included its jet data in PDF fits
  $\Longrightarrow$ Improved gluon at medium–high x

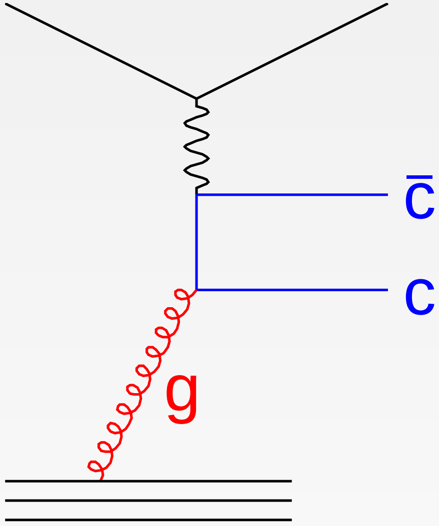




Heavy Flavour Measurements



- Inclusive c and b based on long lifetime
- Inclusive D^* production



Possible impact on PDFs

- Sea decomposition
  ($F_2^{c\bar{c}}$ already used by some theor. fit groups)
- Improve gluon distribution?

Large statistics is expected at HERA II

Indirect Extraction of F_L

- NC ep cross section

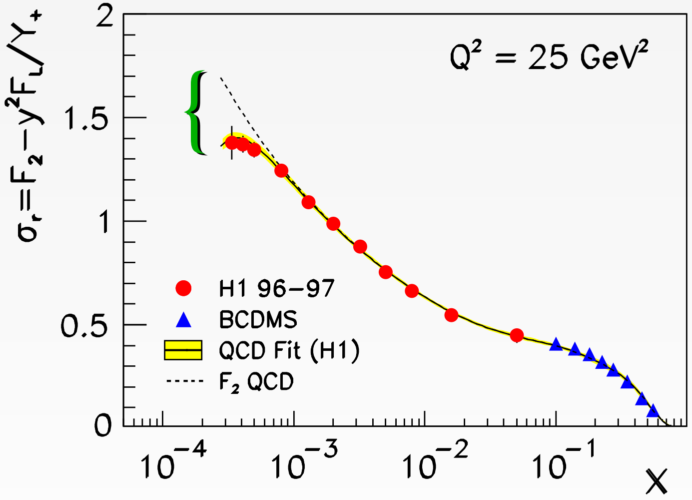
Inelasticity $y = Q^2/(xs)$

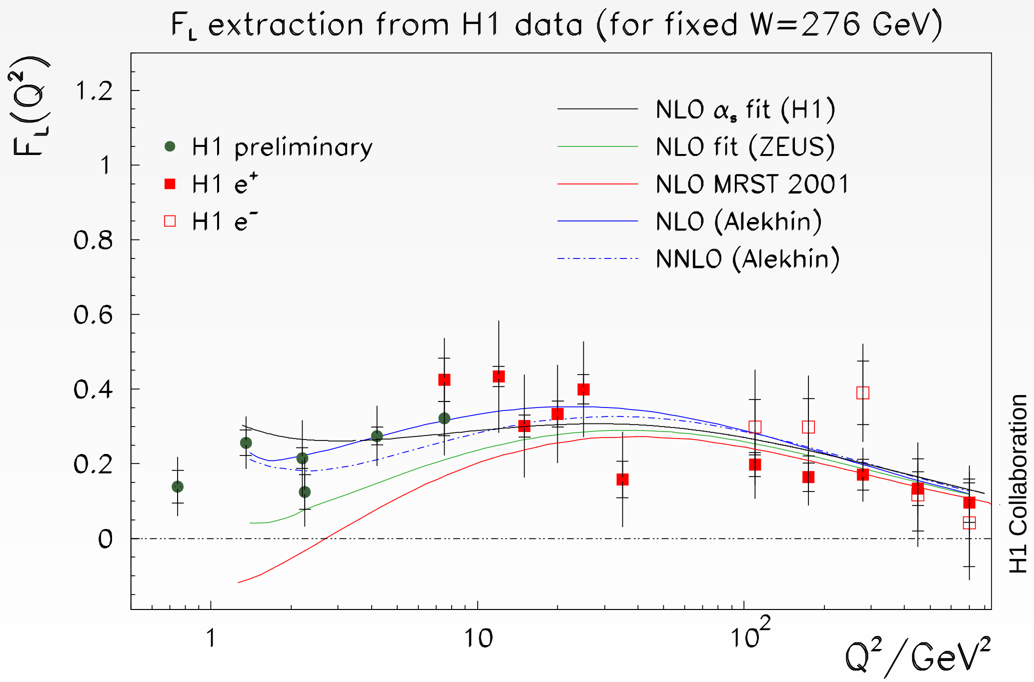
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} Y_+ \left\{ F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \right\}$$

$$Y_\pm = 1 \pm (1-y)^2$$

F_L contribution is significant only at high y = at low x

- Reduced cross section $\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$

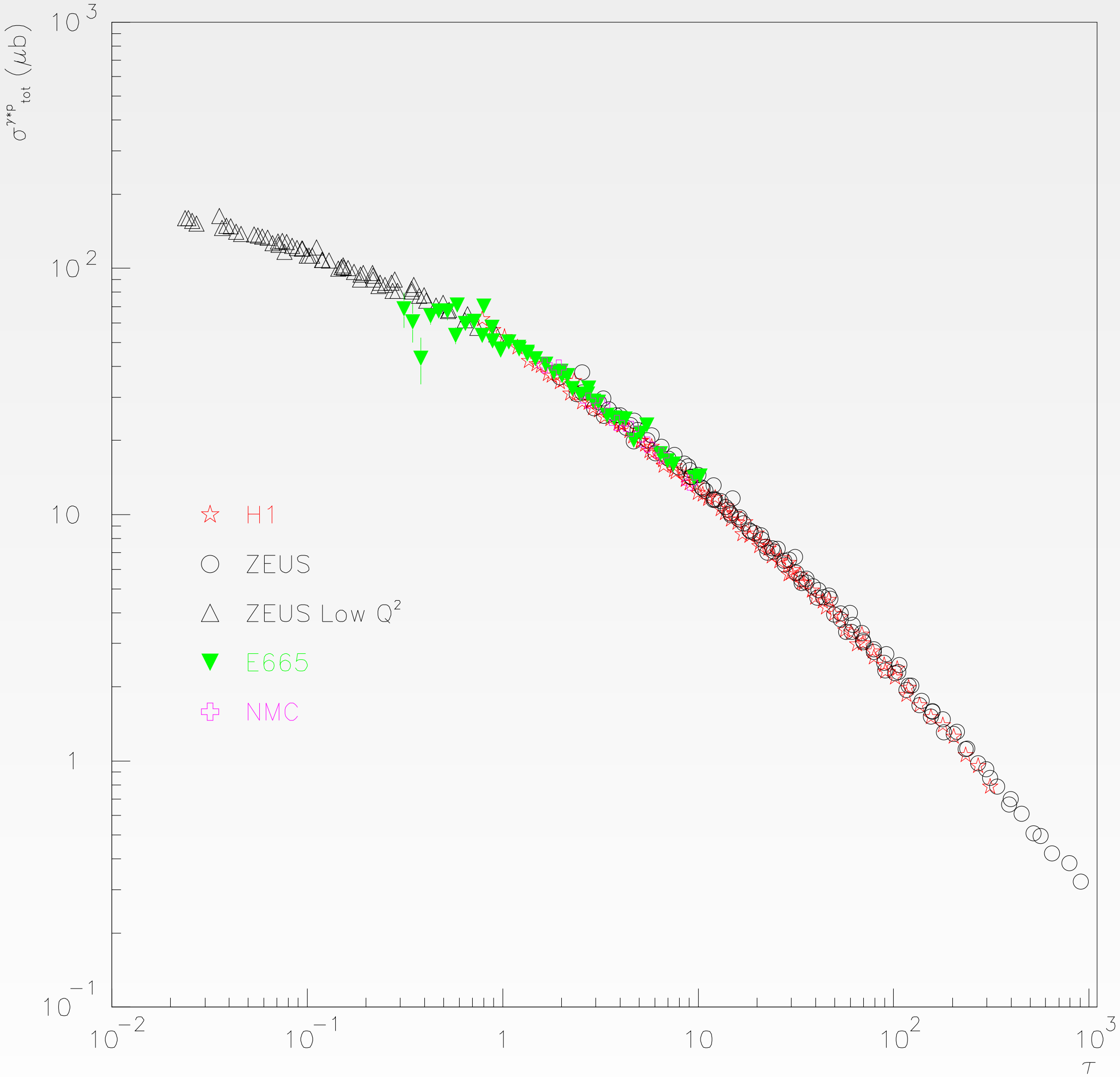




Drawbacks

- No x-dependence
- F_2-model dependent (esp. at low Q^2)

Geometric Scaling at $x < 10^{-2}$

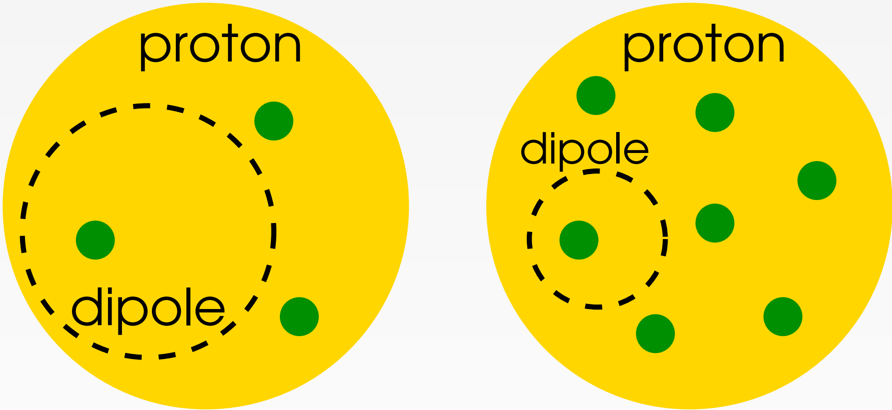


Stasto, Golec-Biernat, Kwieciński
updated plot by Marquet, Schoeffel

$$\tau = Q^2 R_0^2(x) \sim \frac{R_0^2(x)}{r^2}$$

$\sigma_{\gamma^* p}$ is function of only one variable τ:

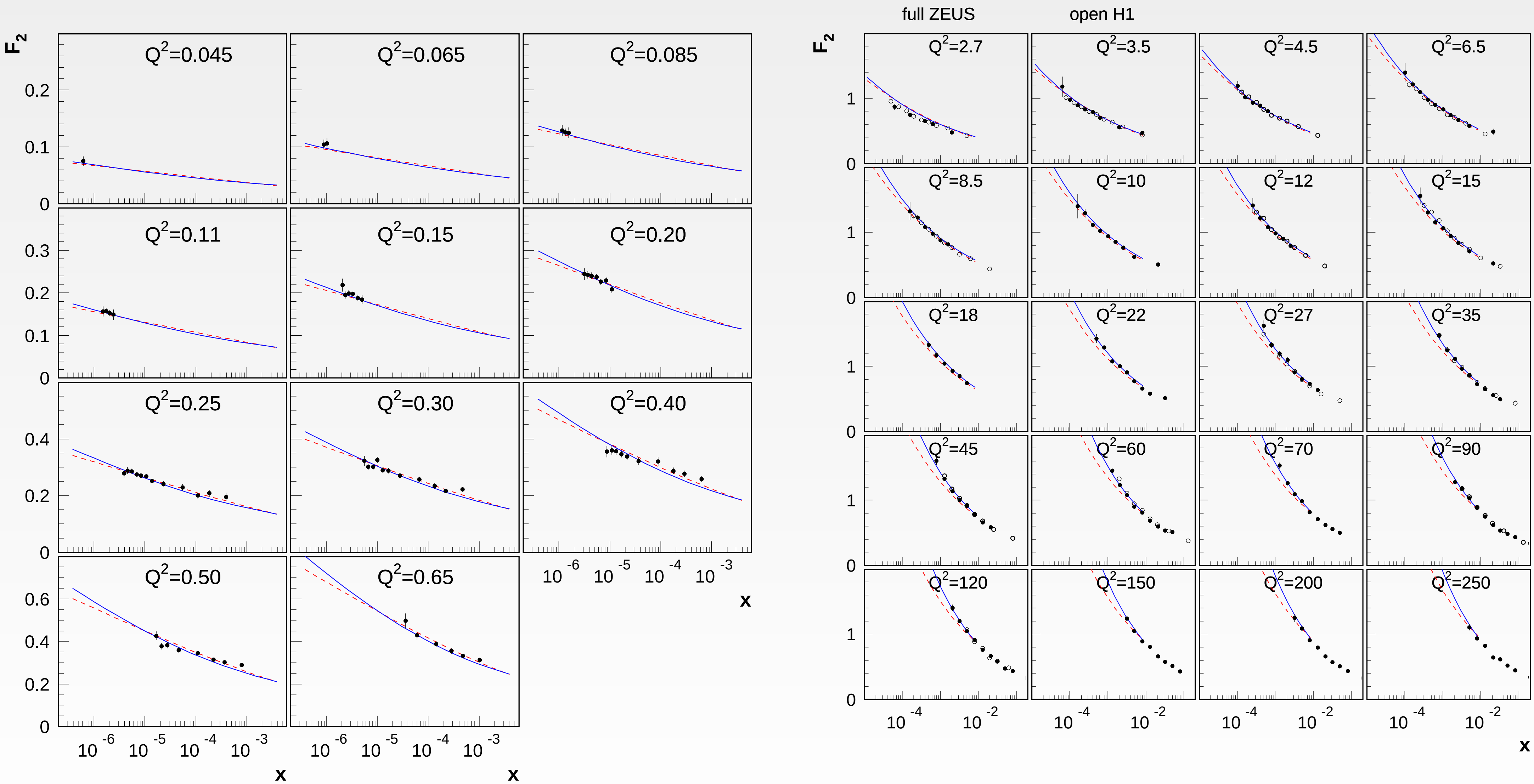
Data manifest existence
of saturation scale
as used in dipole model



At high τ: $\sigma \sim 1/\tau$

At lower τ: saturation?

F_2 Description by Saturation Model



Bartels, Golec-Biernat, Kowalski

GBW (+ DGLAP evolution in pQCD region)