Proton Structure from HERA

Kunihiro Nagano (KEK, Japan)

On behalf of the H1 and ZEUS collaborations

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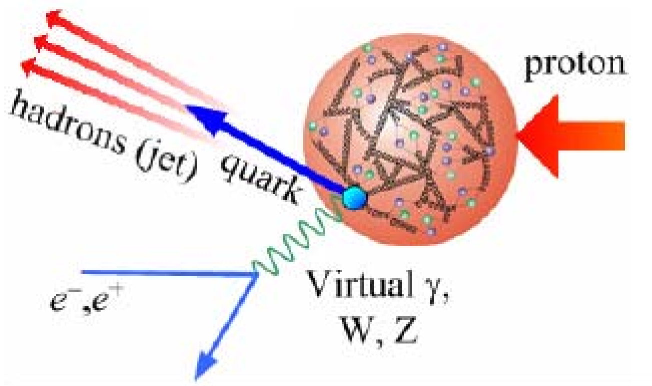
Contents

- NLO QCD analysis on SFs and Jets
- F_L
- Heavy-quark SFs
- High-x
- Low-Q^2 transition

Deep Inelastic Scattering

DIS is a straightforward tool to probe p structure

- Virtuality: $Q^2 = -(k - k')^2$
  ➔ Spatial resolution of probe $\lambda \sim 1/\sqrt{Q^2}$
- Bjorken scaling variable: $x = Q^2 / 2pq$
  ➔ Momentum fraction of struck parton



Experiment measures Cross-sections: ➔ Structure Functions (SFs)

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} \times \{y^2 (F_2 - F_L)/x + 2(1-y) F_2/x\}$$

Measure in terms of:
- **Mom.frac. of q**
- **Spatial resolution**

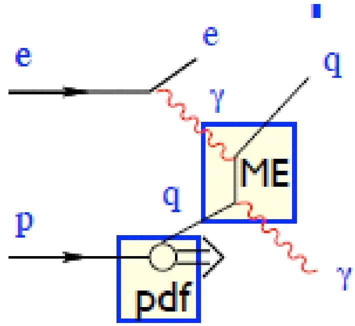
If proton is point like → $\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} \times \{y^2 + 2(1-y)\}$

► SFs parameterize target structure, i.e how far from point-like

※ Why two structures?
→ As seen differently from the two status of the probe γ^* (L, T)

SFs and PDFs

Theory interprets : SFs = Couplings × Parton Distribution Functions (PDFs)



- QCD factorization in matrix elements and PDFs
  PDF=represents probability that a quark carries
  momentum fraction between x and dx.
- pQCD:

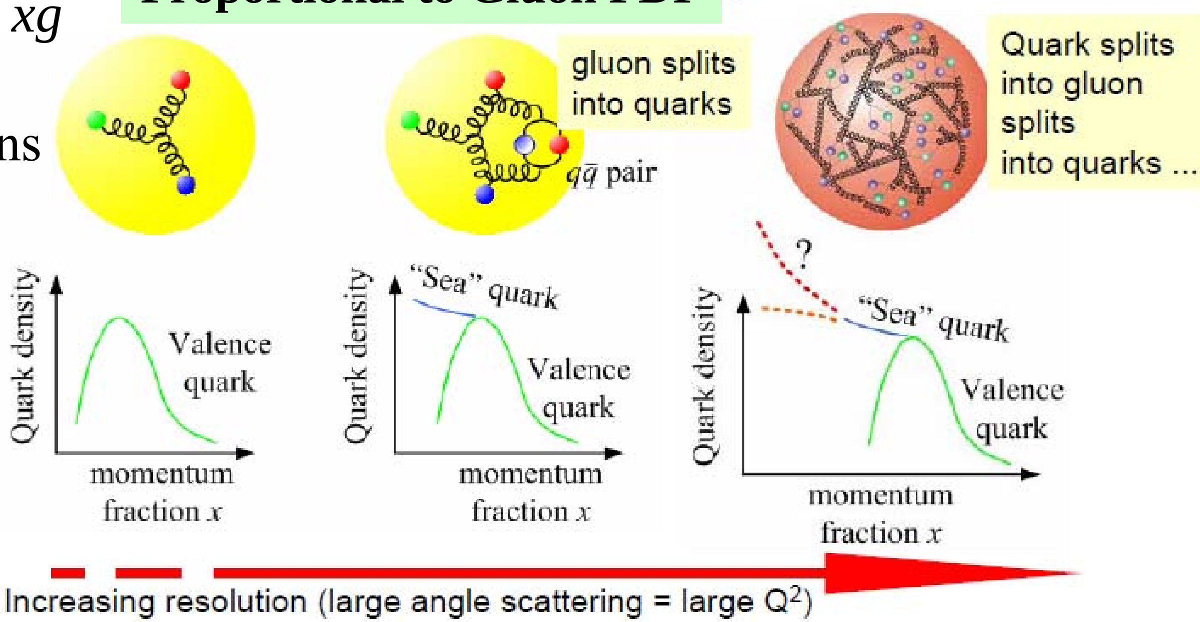
Sum of Quark PDFs

Spin-1/2 → $$F_2 = \frac{Q^2}{4\pi\alpha^2}(\sigma_L + \sigma_R) = x\Sigma e_q{}^2 (q + \bar{q})$$

Proportional to Gluon PDF

Spin-1 → $$F_L = \frac{Q^2}{4\pi\alpha^2}\sigma_L \propto xg$$

F_2 is dominant in cross sections
(F_L/F_2~0.2 only at high y)



<u>At: > LO</u>

PDF is not that static
→ "evolution" as Q^2 grows.
Structure depends on
resolution to see it.
→ FL is not zero.

Determination of PDFs

- pQCD cannot predict x-dependence of PDFs a priori
- But, once the input x-dependence at a certain Q^2_0 is given, DGLAP evolution describes Q^2 dependence of $q(x,Q^2)$

$$\frac{\partial}{\partial \ln Q^2}\begin{pmatrix}\Sigma \\ xg\end{pmatrix} = \alpha_s \begin{pmatrix}P_{QQ} & P_{gQ} \\ P_{gQ} & P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Sigma \\ xg\end{pmatrix}$$

$$\frac{\partial}{\partial \ln Q^2} q_{NS} = \sigma_s P_{QQ} \otimes q_{NS}$$

➔ Initial PDFs at Q^2_0 are determined by a global fit to various experimental data.

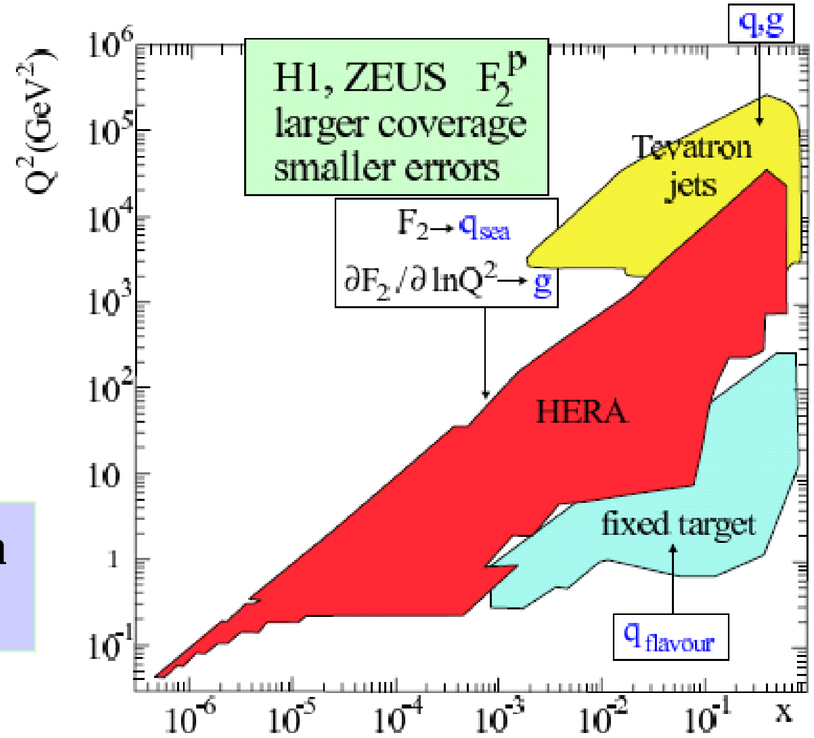
※ PDF are not observable (but F_2 are)
→ Universality should be checked in various processes

► HERA plays significant role, in particular:
-- Gluon
-- Sea quarks

At $x=10^{-4}$ to 10^{-1}
(LHC main kinematic region)

New data

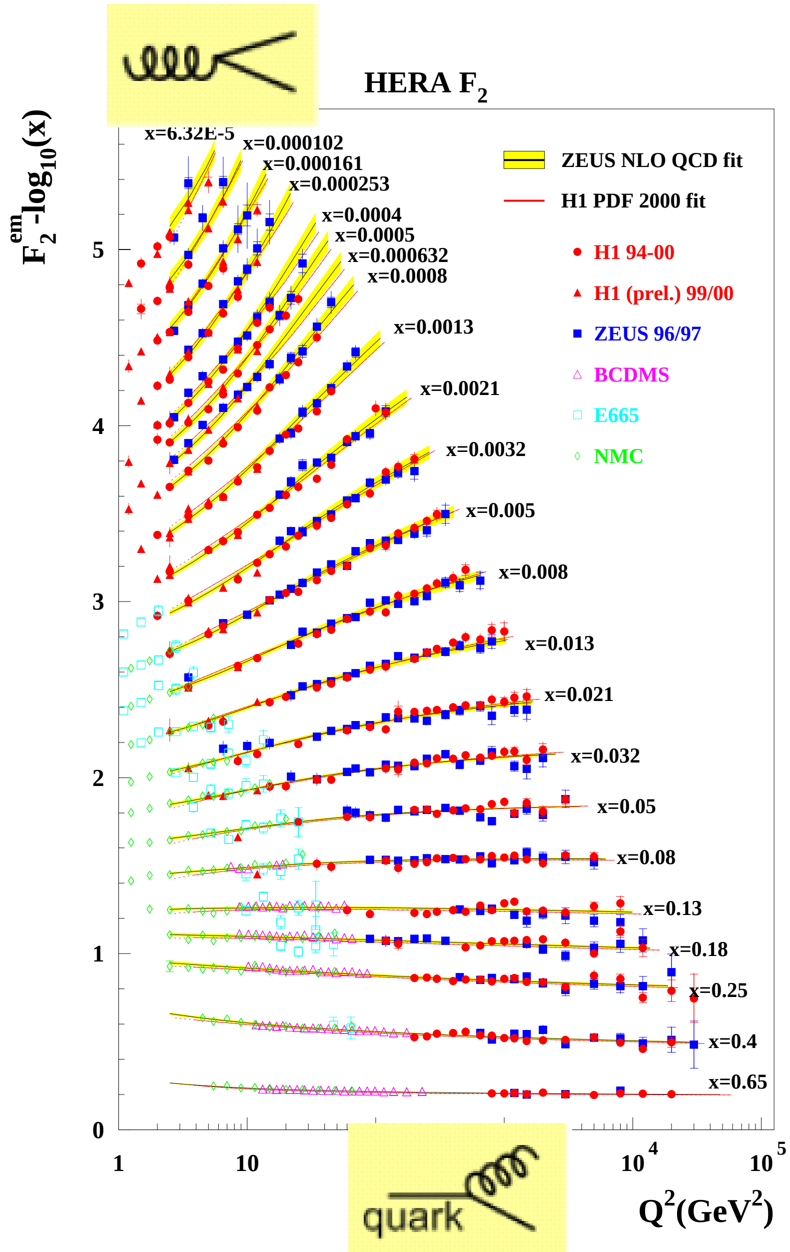
D0, CDF (jets)
η bins, stat + syst. correlations

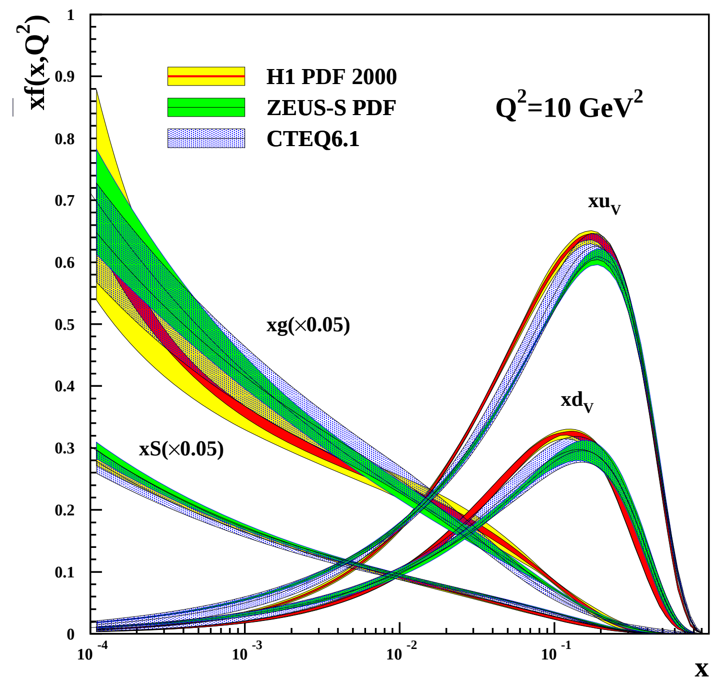


CCFR/NuTeV
(i) F_2, xF_3
(ii) $\mu^+\mu^- \rightarrow s, \bar{s}$

E866 D-Y $\rightarrow \bar{u}, \bar{d}$

HERA Legacy





Triumph of pQCD !

► NLO pQCD describes F_2 over:

-- 4 orders in Q^2

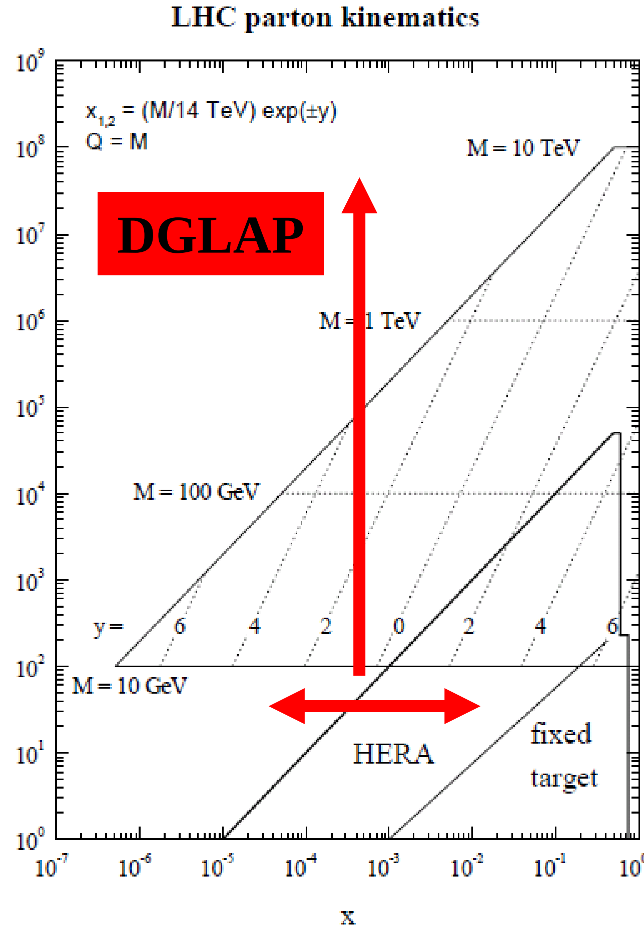
-- 3 orders in x

► Scaling violation excellently described

➔ DIS-invisible gluon could be determined so precisely from this scaling violations:

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s xg$$

PDFs : Remaining issues



Are we done? ➔ No!

① **Direct determination of gluon**

② **Flavor decomposition of quark PDFs**

Notice: with the inclusive F_2 (most precise)

→ Direct knowledge is:

-- Sum of (quark + antiquarks)

→ Gluon is indirectly from F_2's slope

③ **High Q^2 : ➔ DGLAP validity**

➔ xF3= Σ (q-qbar) , valence quarks, arising from Z exchange effects

→ See J. List's talk

④ **High x : ➔ NP with large mass at LHC, Tevatron**

➔ d/u at x=1 ?

⑤ **Low-Q^2 transition : ➔ from pQCD to Hadron picture**

⑥ **Very low-x : ➔ ln(1/x) resummation (not discussed in this talk)**

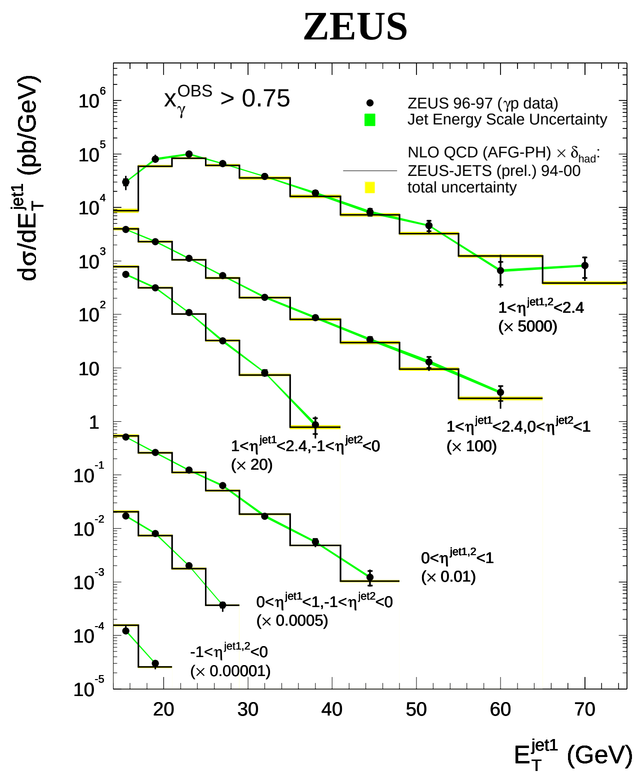
► New ideas, measurements, techniques, analyses are coming up

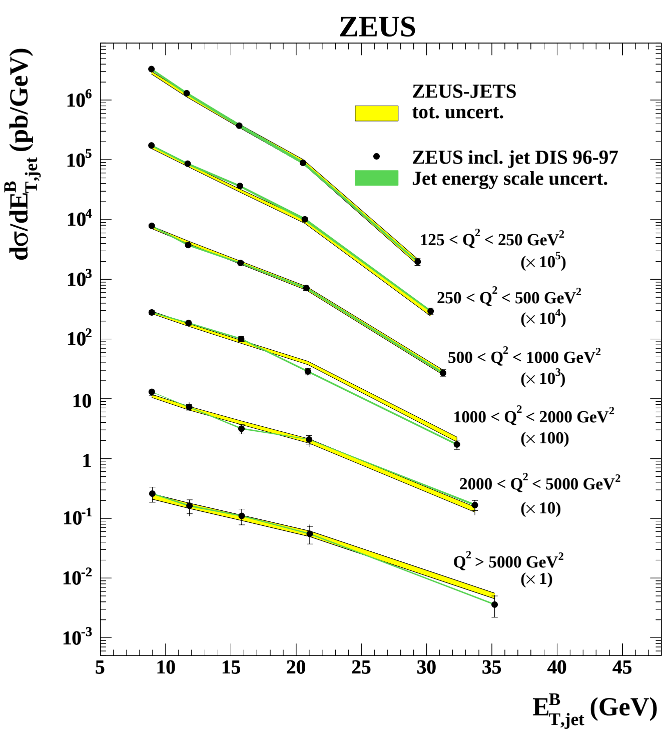
➔ as you'll see in the following slides!

① **Direct determination of gluon**
-- Jet @ Hera
-- FL

NLO QCD fit including Jets

Photoproduction (Q^2=0) dijets gives direct access to gluon and α_s ➔





🡐 DIS Inclusive jet gives general sensitivity to gluon and α_s

※ A first ambitious fit to use HERA data only but HERA SFs + HERA Jets

① **Direct determination of gluon**
-- Jet @ Hera
-- FL

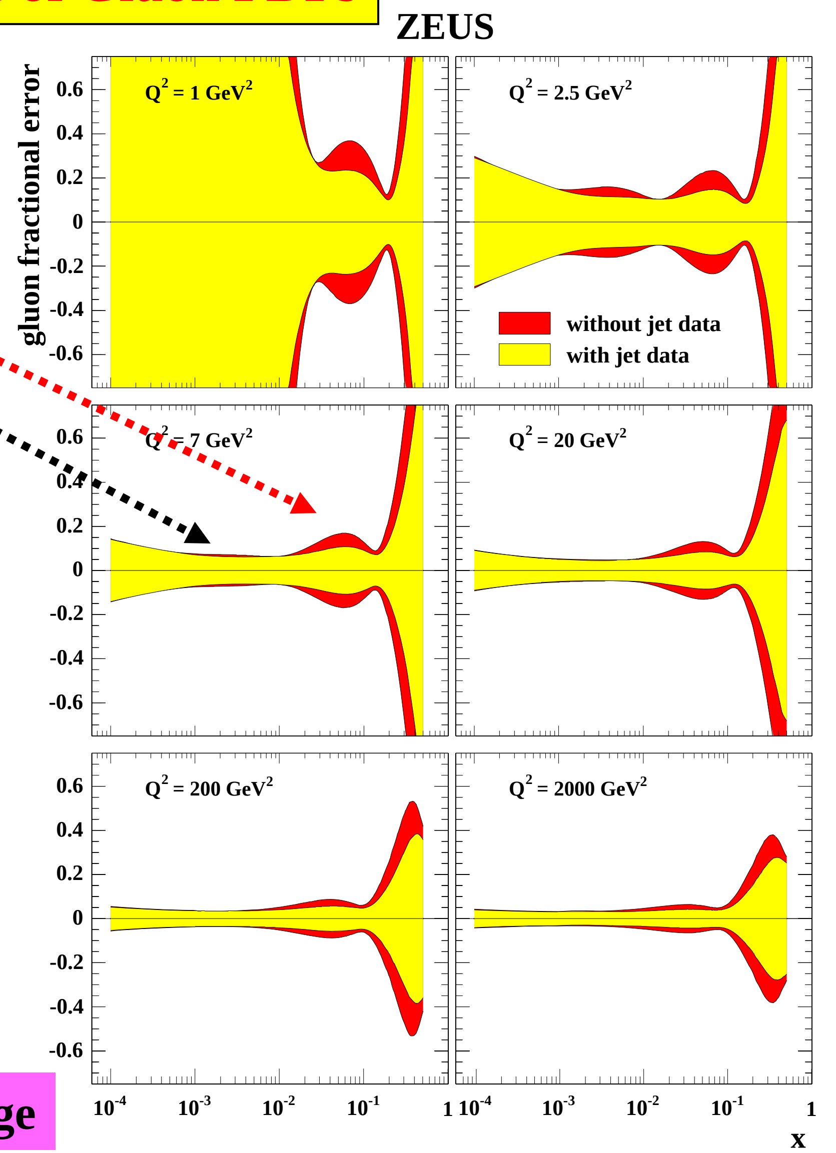
▶ Gluon determination improved at Medium-x: 0.01-0.3 owing to Jets

W/O Jets

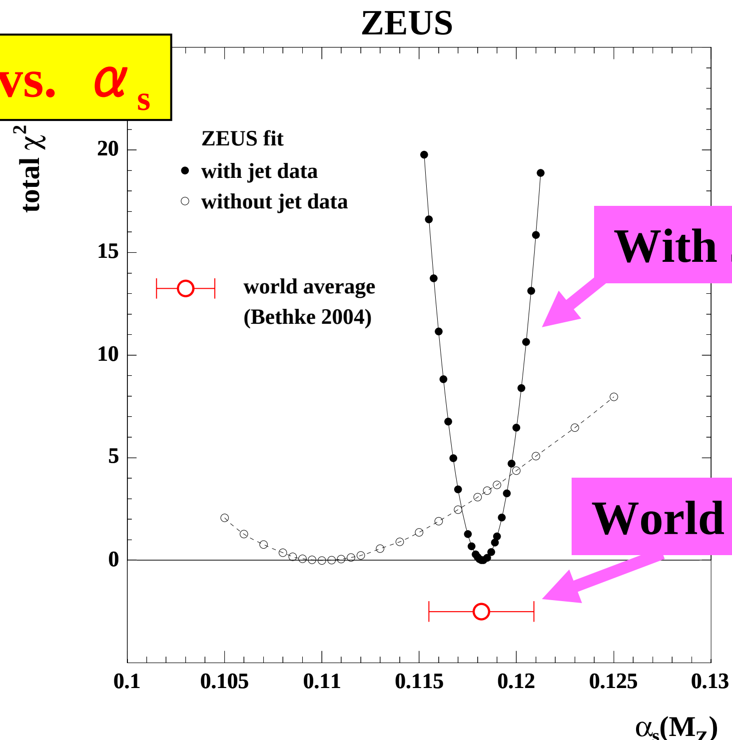
With Jets

▶ Also, jet helps to constrain α_s :
➔ alpha_s was determined precisely compatible as the world average!

Errors of Gluon PDFs



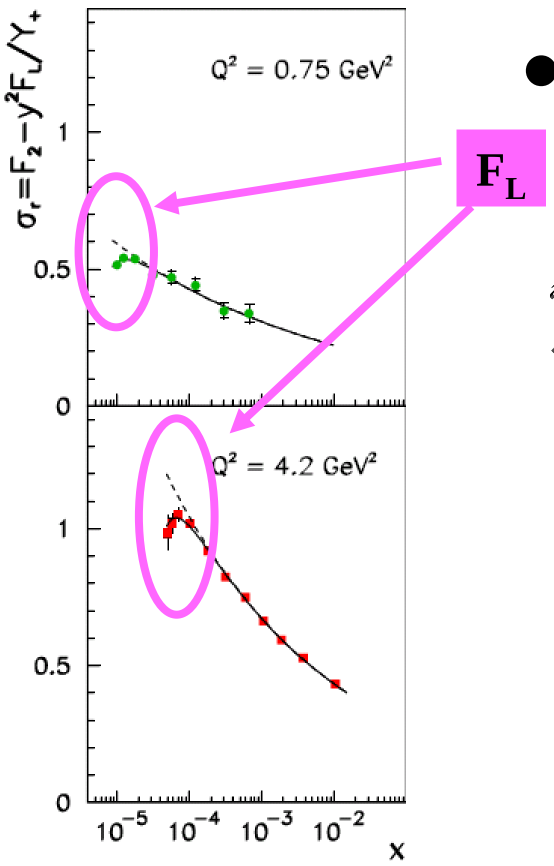
χ^2 vs. α_s



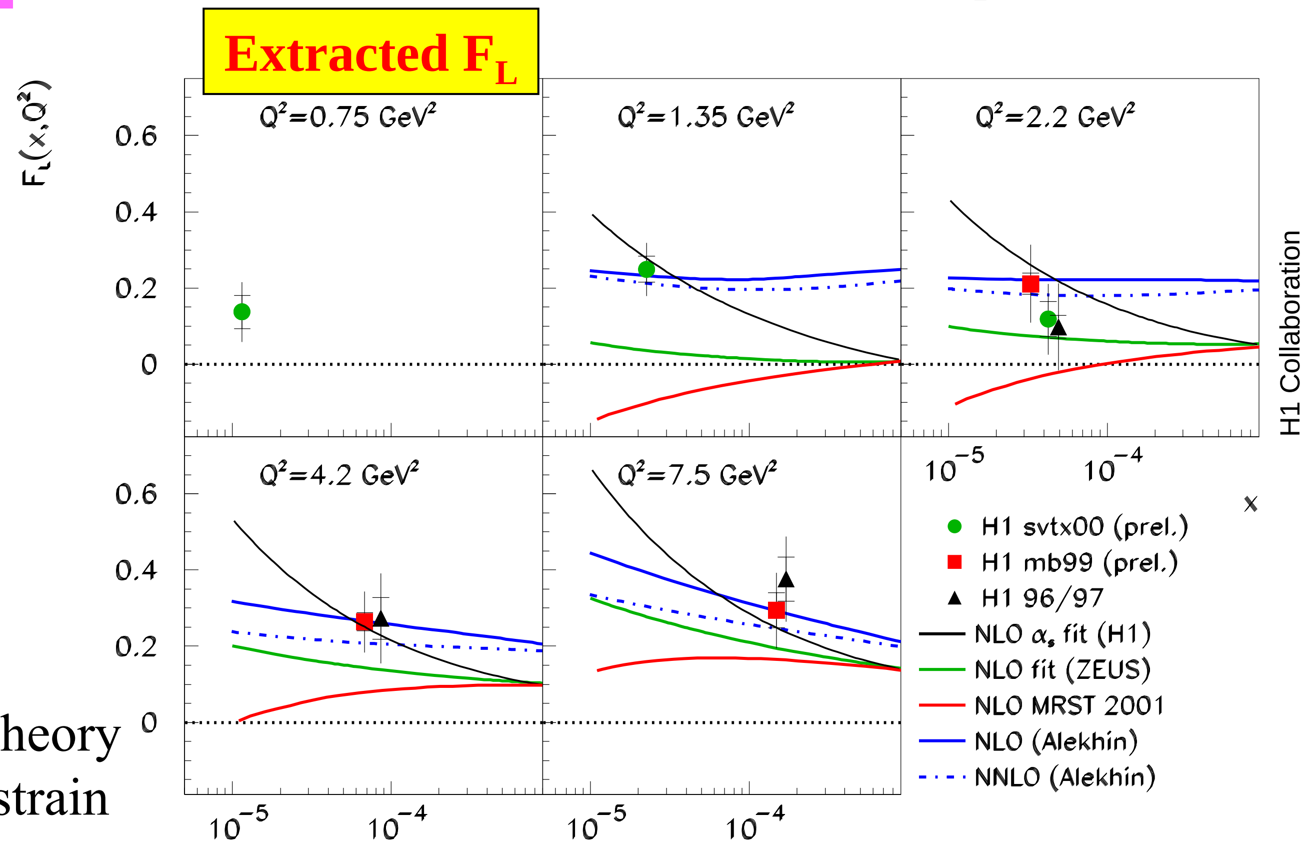
① **Direct determination of gluon**
-- Jet @ Hera
-- FL

F_L

$$F_L = \frac{Q^2}{4\pi\alpha^2}\sigma_L \propto xg$$



- "Shape Method" : Fit cross sections with: $\sigma = F_2 - \frac{F_L}{Y_+}$
  → λ is extrapolation from low-y $F_2 = x^{-\lambda}$



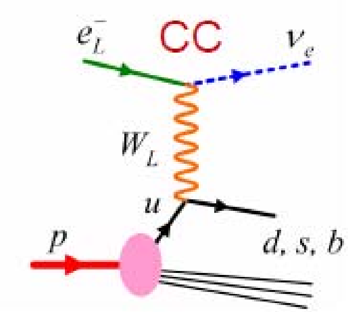
► Large uncertainty in theory
➔ Data will help to constrain

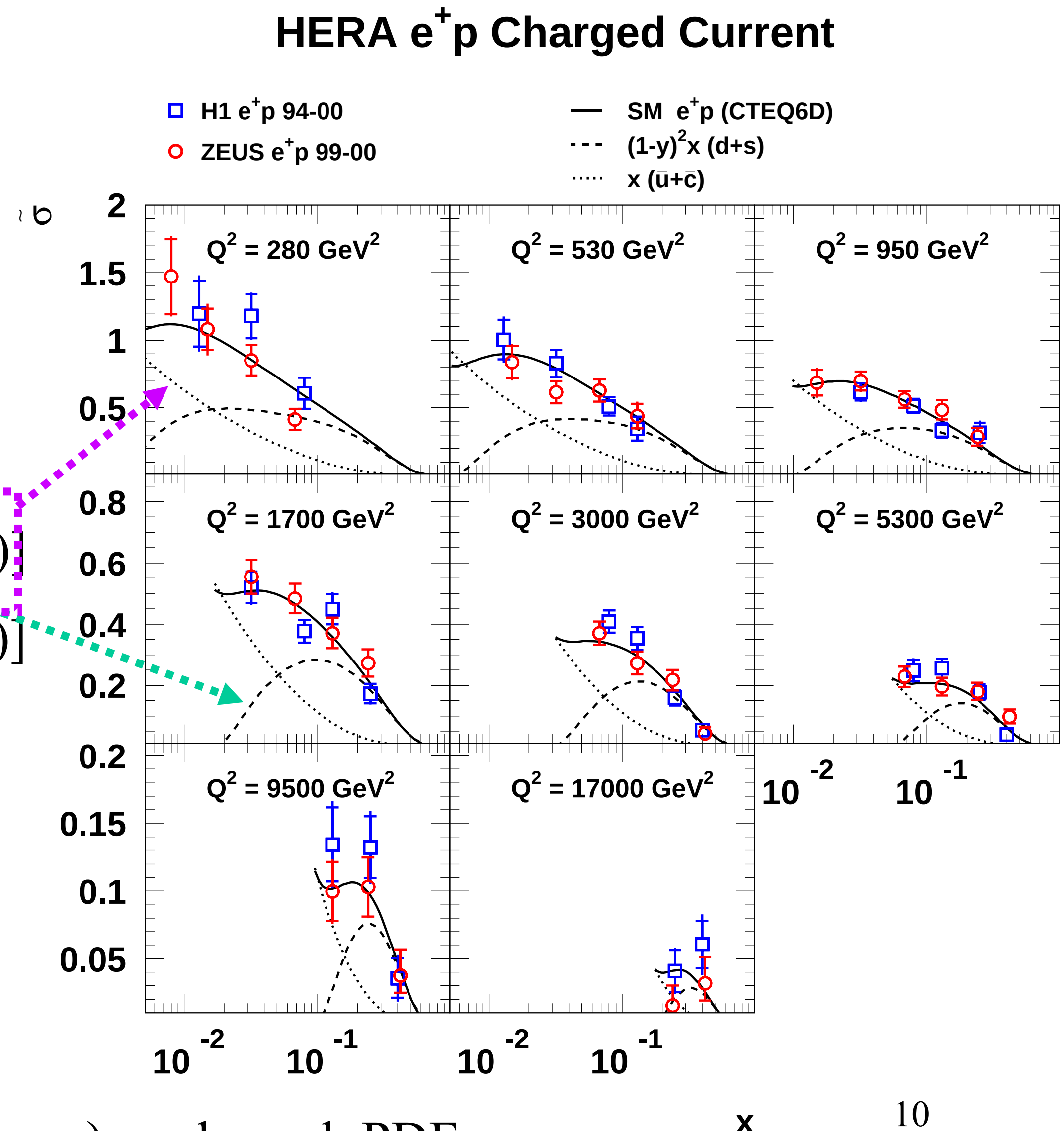
※ This is not a model-independent extraction

② Flavor decomposition
-- CC
-- Heavy flavor SF

CC DIS : Flavor sensitivity

Probe with W-boson





- Flavor selecting nature of CC

$$\sigma_{CC}(e^+p) \propto x[(1-y^2)(d+s) + (\bar{u}+\bar{c})]$$

$$\sigma_{CC}(e^-p) \propto x[(u+c) + (1-y^2)(\bar{d}+\bar{s})]$$

- In particular, d-quark PDFs:
  - -- F_2(NC) ~ 4u + d
  - -- u ~ 2d
  - ➔ Has been less determined
  - (ν N gives best sensitivity)

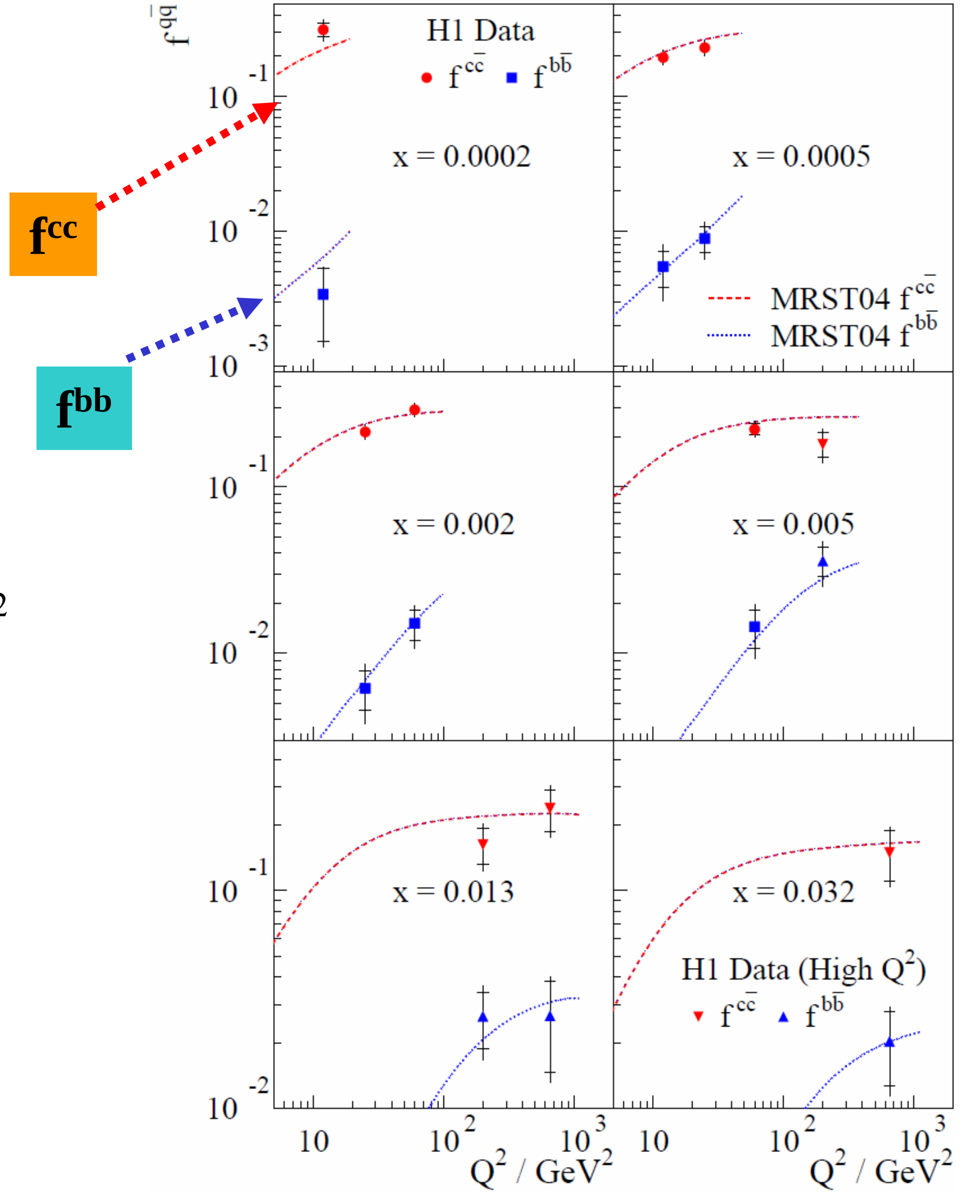
▶ HERA CC will give cleanest determination (w/o heavy-target coor.) on d-quark PDFs

② **Flavor decomposition**
-- CC
-- Heavy flavor SF

F_2^{cc}, F_2^{bb}

Fraction of cc(bb) to total σ

- **D*→ K π π**
- **Displaced vertex by signed impact parameter ← New!**



▶ First measurement of F_2^{bb} !
▶ F_2^{cc}: D* and impact parameter analyses agree
▶ c and b fractions increase with Q^2
-- c fraction up to ~ 30%
-- b fraction up to ~ 3%

※ Big prospect at HERA-II
→ See B.Kahle's talk.

④ High-x

New technique to access high-x

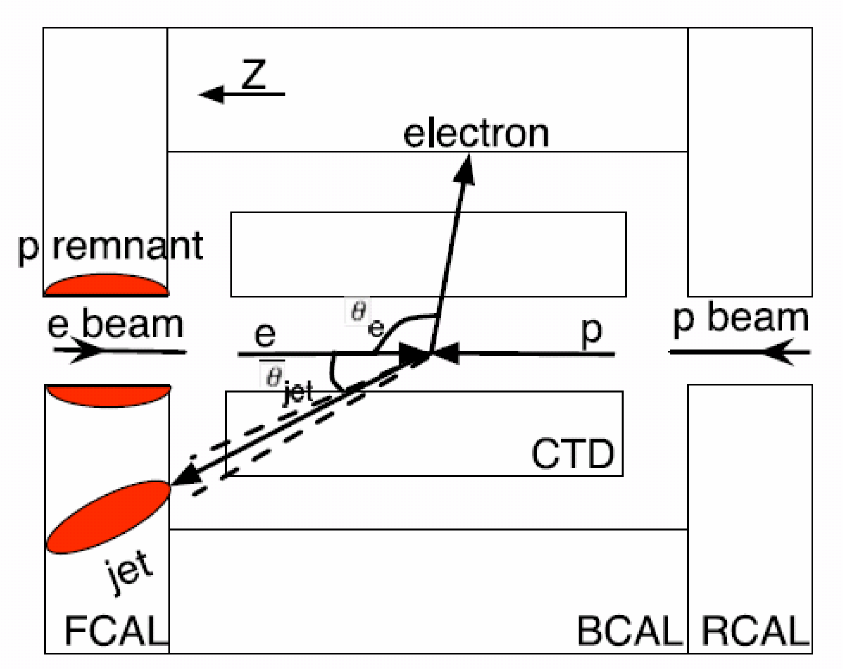
Experimentally difficult as recoiled quark goes close to the beam pipe

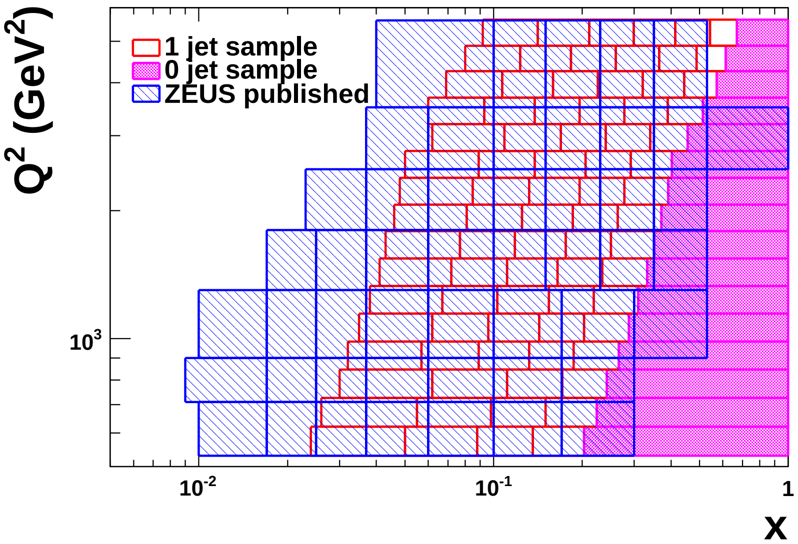
- Events can be tagged by e
- If we do not see any jet at

  -- $\eta_{jet} > 0.12$ (Et > 12 GeV)

  → Collect such events in a single bin, $x > x_{Edge}$

  → Measure integrated cross section in the bin, x > xEdge





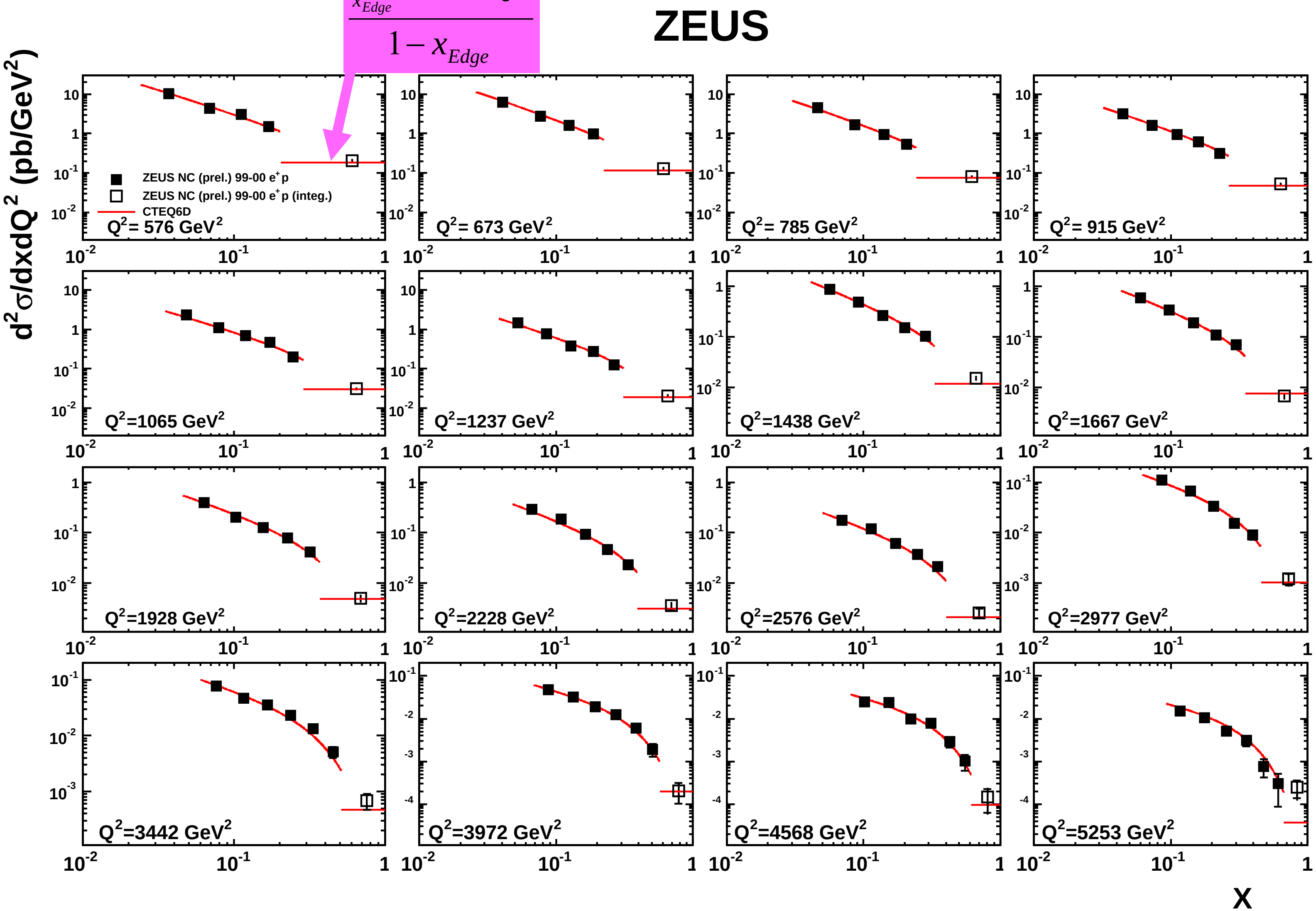
- For events with jets:

  → use jet for reconstructing x

← Finer bins as resolution improved

④ High-x

$$\frac{\int_{x_{Edge}}^{1} dx \frac{d^2\sigma}{dxdQ^2}}{1 - x_{Edge}}$$



► Generally in good agreement, data tends to be slightly higher at the highest-x

⑤ Low Q^2 transition

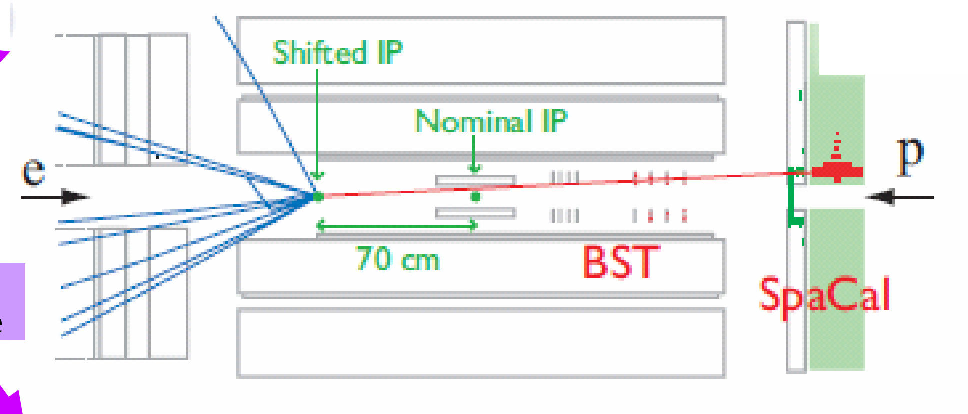
Techniques to access low Q^2

Shifted-vertex runs

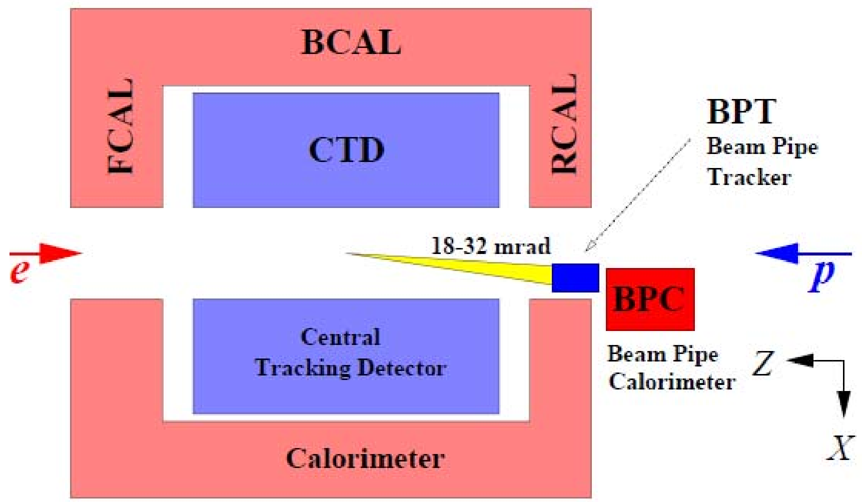
$$Q^2 = 2E_e E_e'(1+\cos\theta_e)$$

Lower initial energy

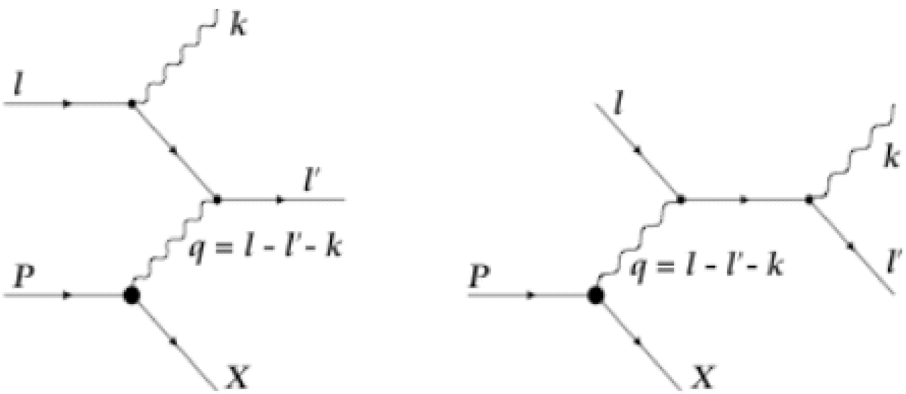
larger θ_e



Special device (beam-pipe CAL)



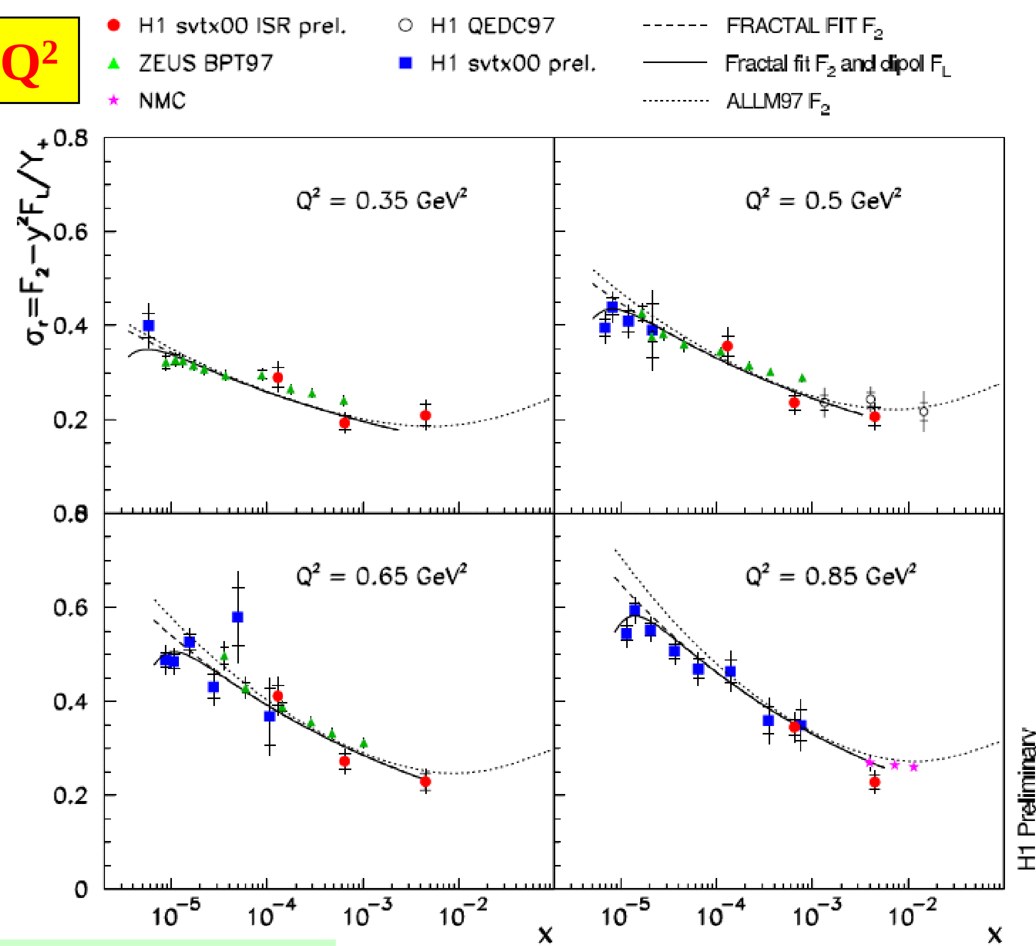
QED compton,
Initial state radiated (ISR) events



⑤ Low Q^2 transition

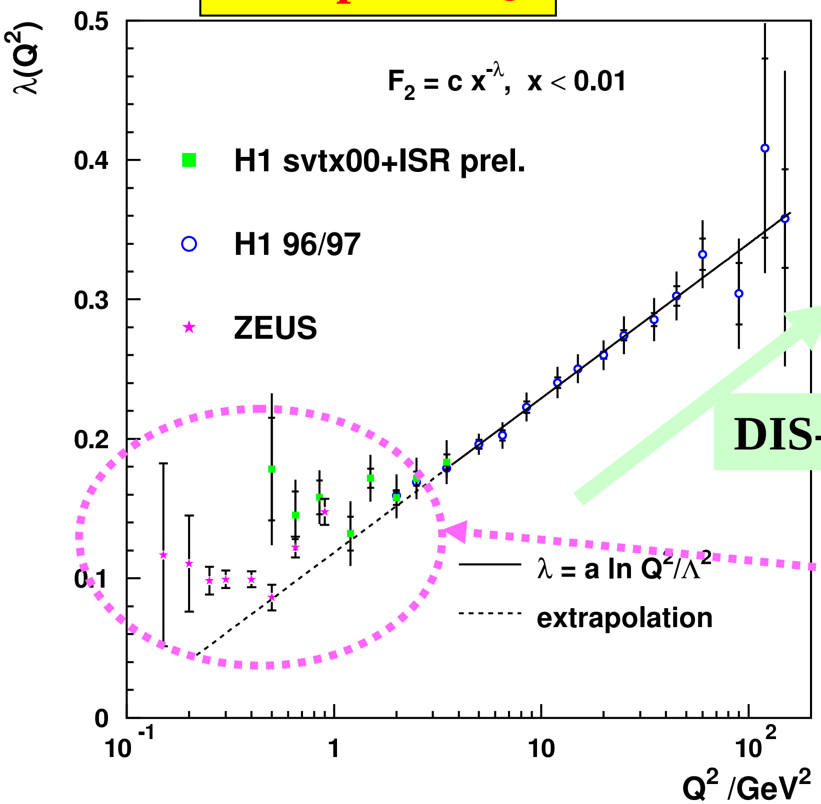
- F_2 by Shifted-vertex + ISR ➔

F_2 @ low Q^2



- “Slope” of F_2 rise:
  -- $F2 = c\ x^{-\lambda}$

λ slope vs. Q^2



DIS-like strong rise

Hadron-like

Summary

● **HERA has provided most precise inclusive structure function measurements, which brought significant improvements to our knowledge on proton structure**

● **For further more comprehensive and complete understanding of the pQCD and proton structure, new analyses with new techniques, ideas, and large amount of luminosity @ HERA-II are on-going.**

-- ~200 pb^{-1} already collected @ HERA-II

-- Possibility to have dedicated low energy runs for F_L

➔ **Understanding the whole proton structure is a real big project, we have just marked the first step.**

➔ **Stay tuned on the HERA, "super microscope"!**