# Soft Interactions

**ICHEP 2000, Osaka**

*Peter Schleper*

*DESY*

- **Photon Structure**
- **low-x Physics**
- **Diffraction**
- **Spin Structure**

**QCD is right:** (previous talk)

$\ell p$: partons, scaling (violations)

$e^+e^-$: gluons, $\alpha_s$, ...

$p\bar{p}$: small distance QCD

$\longrightarrow$ **QCD is predictive for hard interactions**

**QCD is difficult:**

$\Lambda_{QCD} \gtrsim m_{u,d,s}$, gluon self-coupling

$\longrightarrow \alpha_s$ large

low scales: pertubative QCD not applicable:

hardly any predictive power for:

- confinement, hadron structure, photon structure
- fragmentation
- total hadron-hadron cross sections, elastic scattering

## Important theoretical progress:

- **new factorisation theorems:**
  - **unintegrated parton densities**
  - **new QCD dynamics**
- **skewed parton densities**
- **proof of factorisation in diffraction**

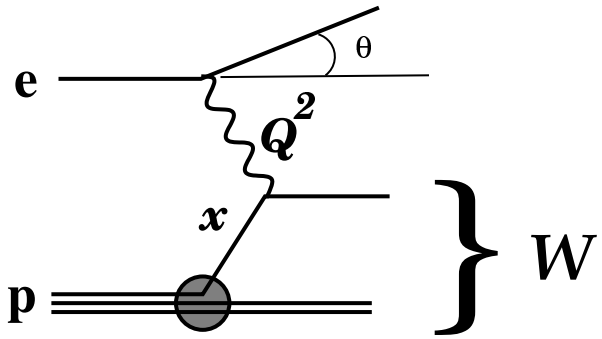
## Experimental progress:

- **high gluon density $\leftarrow$ low-x proton**
  **(HERA $\rightarrow$ LHC)**
- **hard $\rightarrow$ soft transition: photon structure**
  **(LEP,HERA)**
- ***hard* diffraction** **(Tevatron, HERA)**
  **hard scale processes for confinement**

*colliders dominate field of soft processes*

## Major field of activity in QCD:

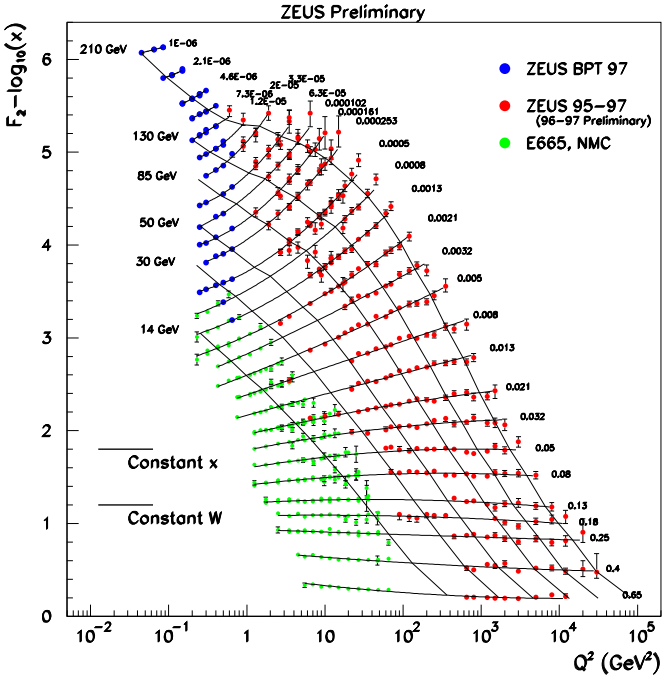
# Example: $\gamma^* p \to X$




$Q^2$ = $\gamma$ -virtuality

$x$ = $E_{\text{parton}} / E_p$

$W$ = $E^{\gamma-p}_{cms}$

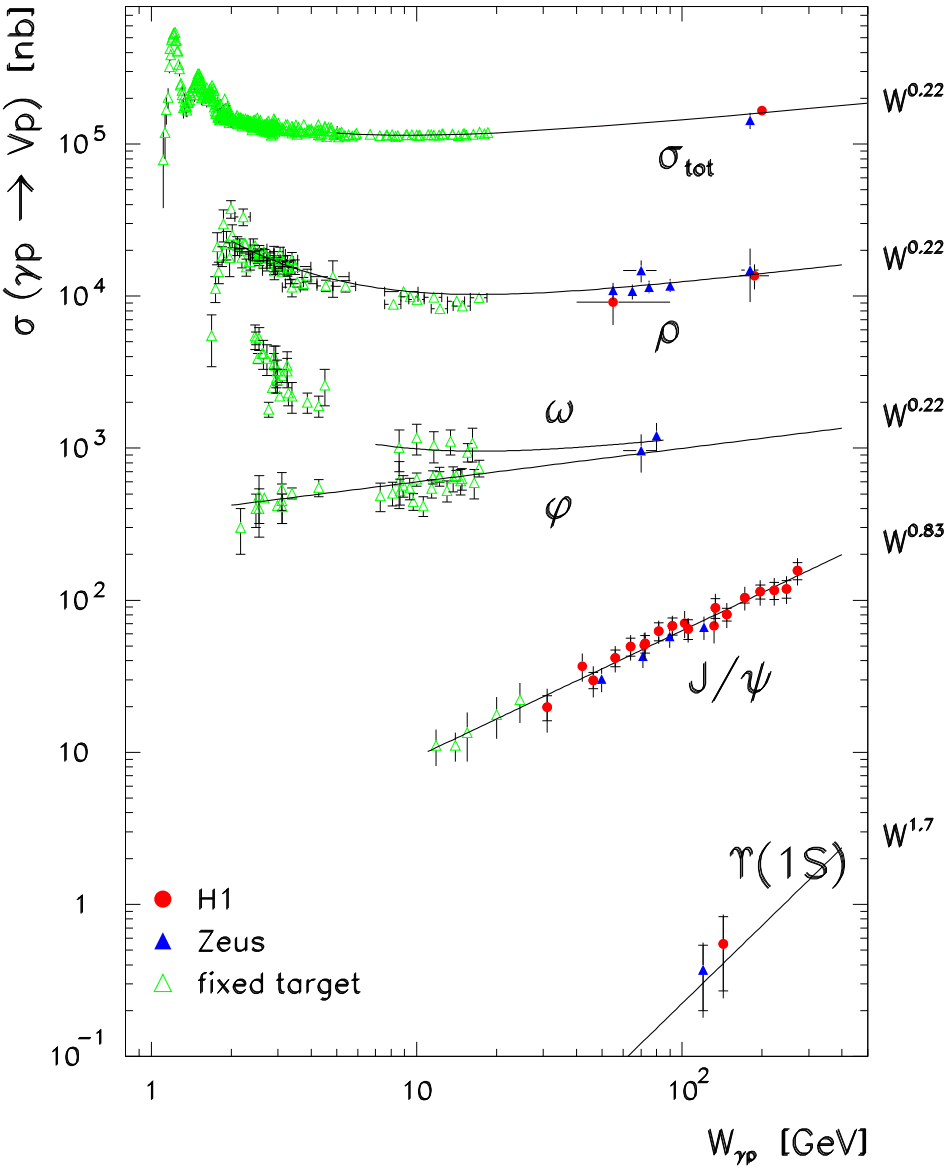



higher energy $W \leftrightarrow$ smaller $x$ needed for same $Q^2$

$$W^2 \approx Q^2 / x \qquad \text{(at small x)}$$

- small-$x$ = high-energy limit of QCD
- QCD as prototype for any strong interacting theory of general interest

# Example: Vectormesons at HERA



# Factorisation in QCD

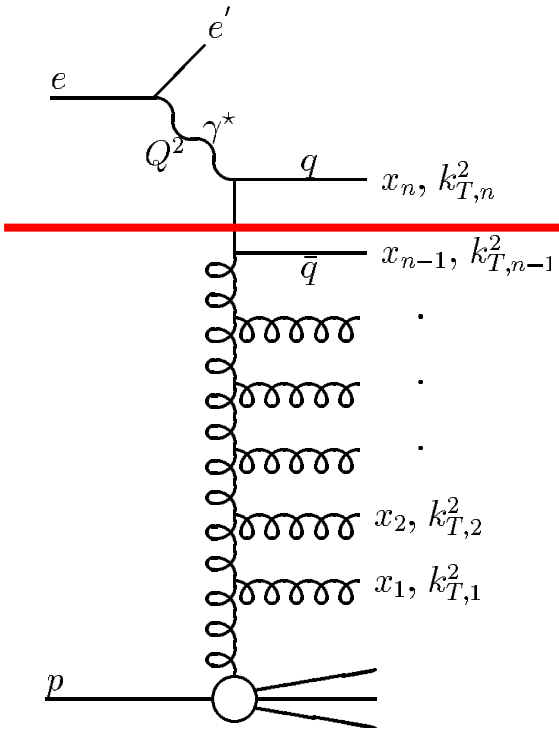
## 1) Altarelli-Paresi approximation (DGLAP)

**Assume: strong $k_T$ ordering:**

$$Q^2 >> k_{T,i} >> k_{T,i-1} \cdots$$

**$\rightarrow$ factorisation of hard and soft component:**

$$\sigma = \sum \hat{\sigma} \times f_q$$




$\hat{\sigma}$

$f_q(x, Q^2)$

**collinear sum:**

$\sum \ln Q^2$

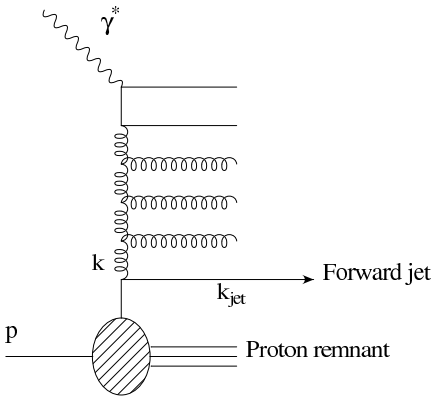
- **DGLAP basis for 'standard' QCD ($\alpha_s$, ...)**
- **DGLAP must fail when:**
  - **$Q^2$ too small (how small ?)**
  - **$x$ too small (phasespace!)**

    **(long parton ladder$\rightarrow$no $k_T$ ordering)**

# Factorisation in QCD

**e.g.: forward jets:**

**no clear ordering of $Q^2$ and $k_T^2$**




**Better: angular ordering**

*Unintegrated Parton Distributions:*

$f(x, k_T^2, Q^2)$

| | DGLAP | BFKL | CCFM |
|---|---|---|---|
| ordering | $k_T$ | $x$ | angle |
| | | | small $x$: NO $k_T$ |
| | | | large $x$: $\approx k_T$ |
| pdf | $f(x, Q^2)$ | $f(x, k_T^2)$ | $f(x, k_T^2, Q^2)$ |
| $\sum$ | $\ln Q^2$ | $\ln 1/x$ | $\ln Q^2, \ln 1/x$ |
| valid | $Q^2$ large | $k_T^2 \approx Q^2$ | |
| | $x$ not small | $x$ small | $x$ small |
| | $k_T >> Q^2$ | | (only $P_{gg}$) |
| | $k_T << Q^2$ | | |

# Outline of the Talk

- **Proton structure at low $Q^2$ and low-$x$**

  **gluon at low-$x$: HERA $\rightarrow$ LHC**

  **transition $Q^2 \rightarrow 0$**

- **Photon structure**

  **$F_2$, heavy flavour from LEP**

  **jets and gluon content from HERA**

- **QCD dynamics:**

  **virtual resolved photon**

  **jets, charm, HERA,TEVATRON**

  **$\gamma^*\gamma^*$ from LEP**

- **Diffraction**

  **jets, vectormesons**

  **HERA –TEVATRON**

- **Spin**

  **Transversity (short)**

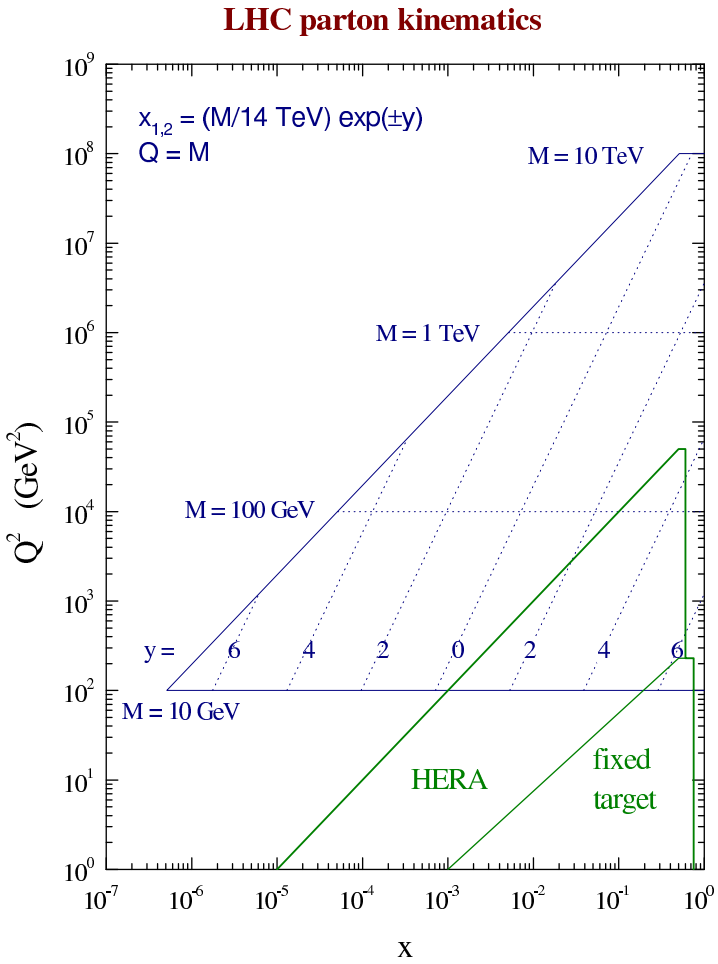
*emphasis on QCD interpretation of the data*

*very little on phenomenology*

# Proton Structure at low-$x$

**Motivation: 1) QCD dynamics (see above)**

**2) Parton densities**




**showcase:**

**Higgs at LHC**

$M_{\mathrm{H}} > 108$ GeV

**requires gluon density at and below**

$x = 10^{-4}$

**only process: Deep inelastic scattering at**

**HERA:** $x \lesssim 10^{-4}$ **implies** $Q^2 \lesssim$ **1GeV**

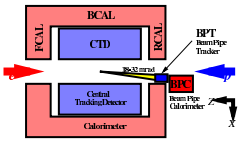
# Proton Structure at low-$x$

**New data sets with upgraded detectors:**

**H1:** silicon tr. + spaghetti calor.

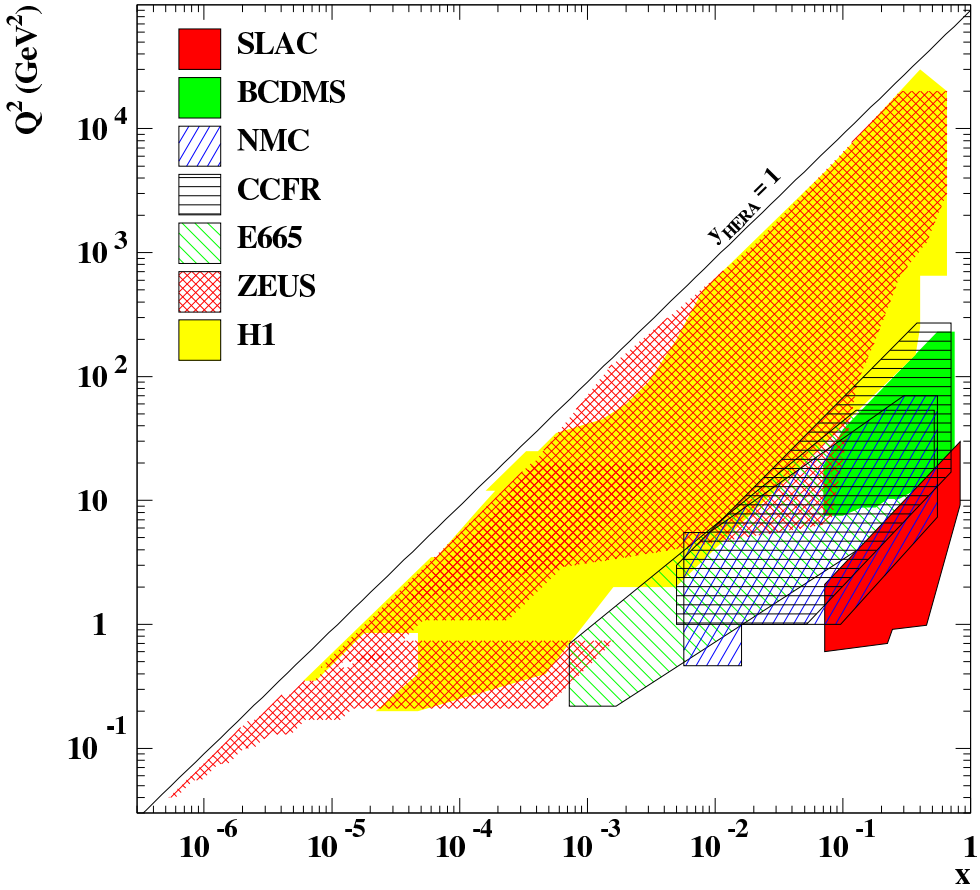
$$Q^2 > 1.5\text{GeV}$$

**ZEUS:** silicon tr. + calor. close to beam




$$0.6 > Q^2 > 0.045\text{GeV}$$

## HERA data on Proton Structure



# Proton Structure at low-$x$

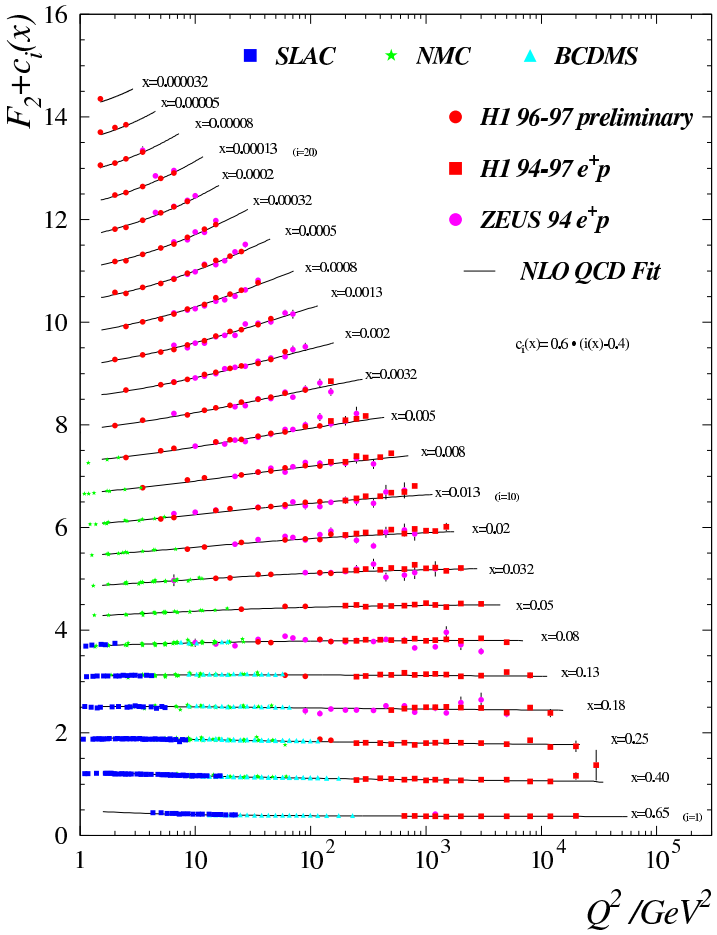
$ep \to eX$ at low $Q^2$:

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ \cdot F_2 - y^2 F_L\right]$$

with $Q^2 = xys, Y_+ = 1 + (1-y)^2$

to first approx: $F_2(x,Q^2) = \sum_{q\bar{q}} e_q^2 f_q(x,Q^2)$

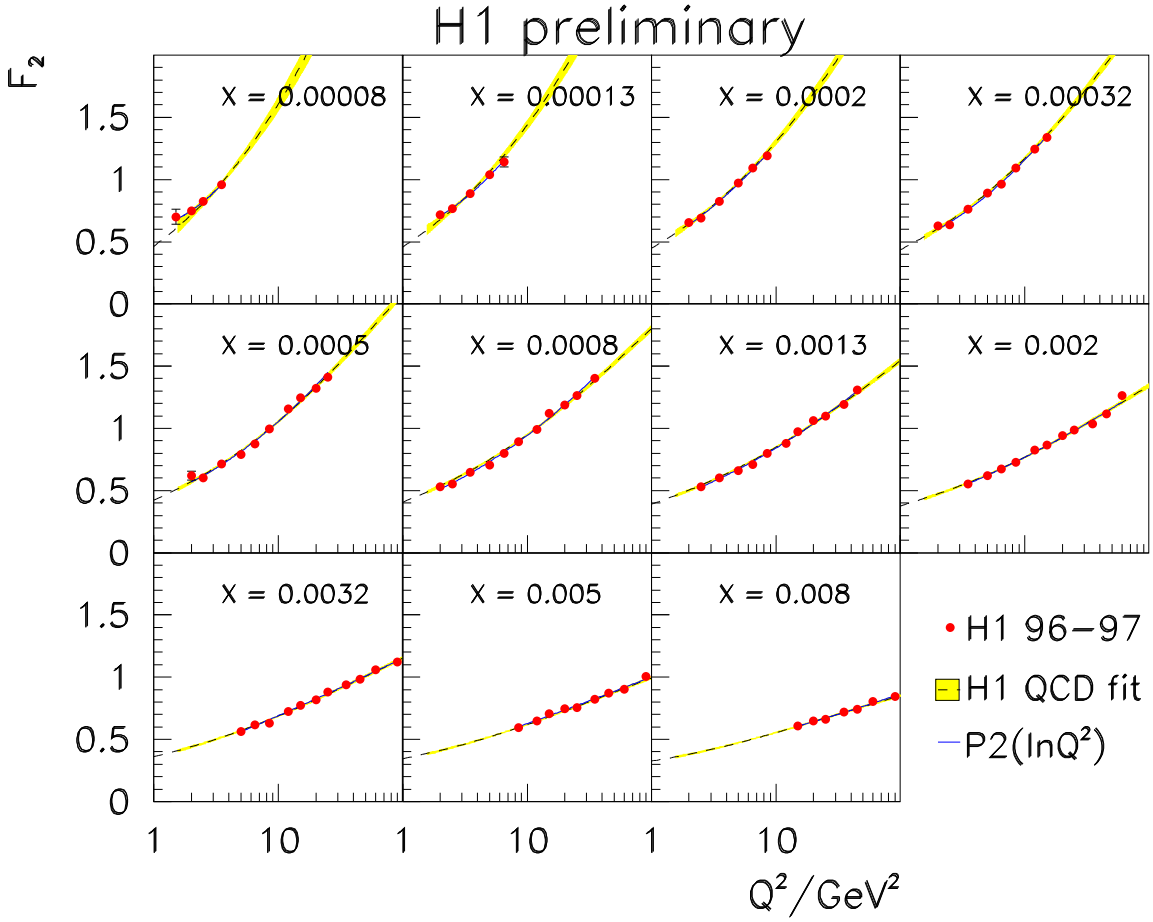
and $F_L(x,Q^2)$ contribution is typically small.




New quality step: 1% stat., 2-3 % syst. errors

# H1 analysis of Gluon density at low-$x$

- Very detailed NLO QCD fit (DGLAP)
- only H1 data, no corrections for fixed target data needed



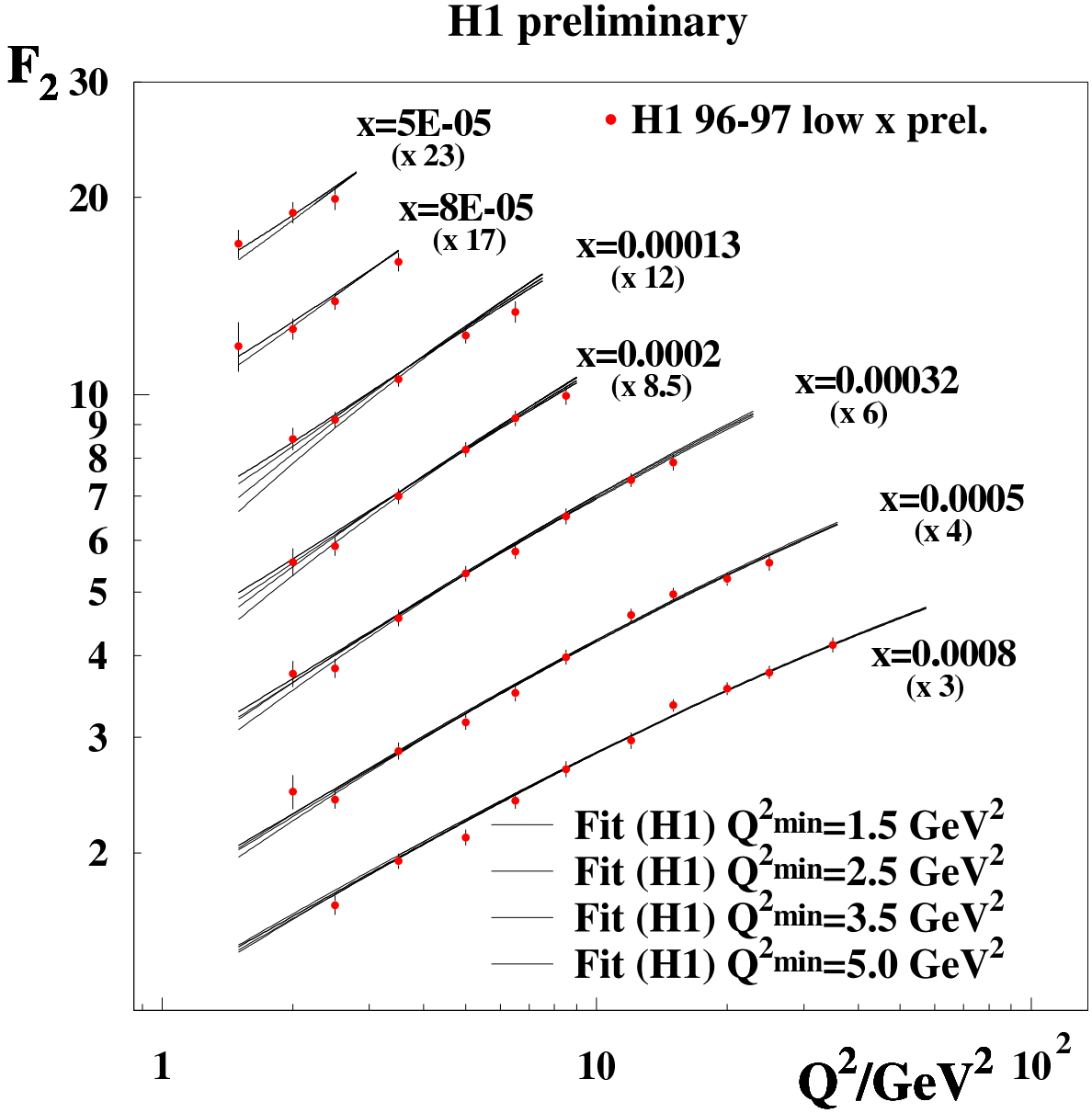

$F_2$ rises with $Q^2$: $g \rightarrow gg, q\bar{q}$ splitting

slope $dF_2/d\ln Q^2|_x \approx \alpha_s xg$ ← gluon

# H1 analysis of low-$x$ Gluon density

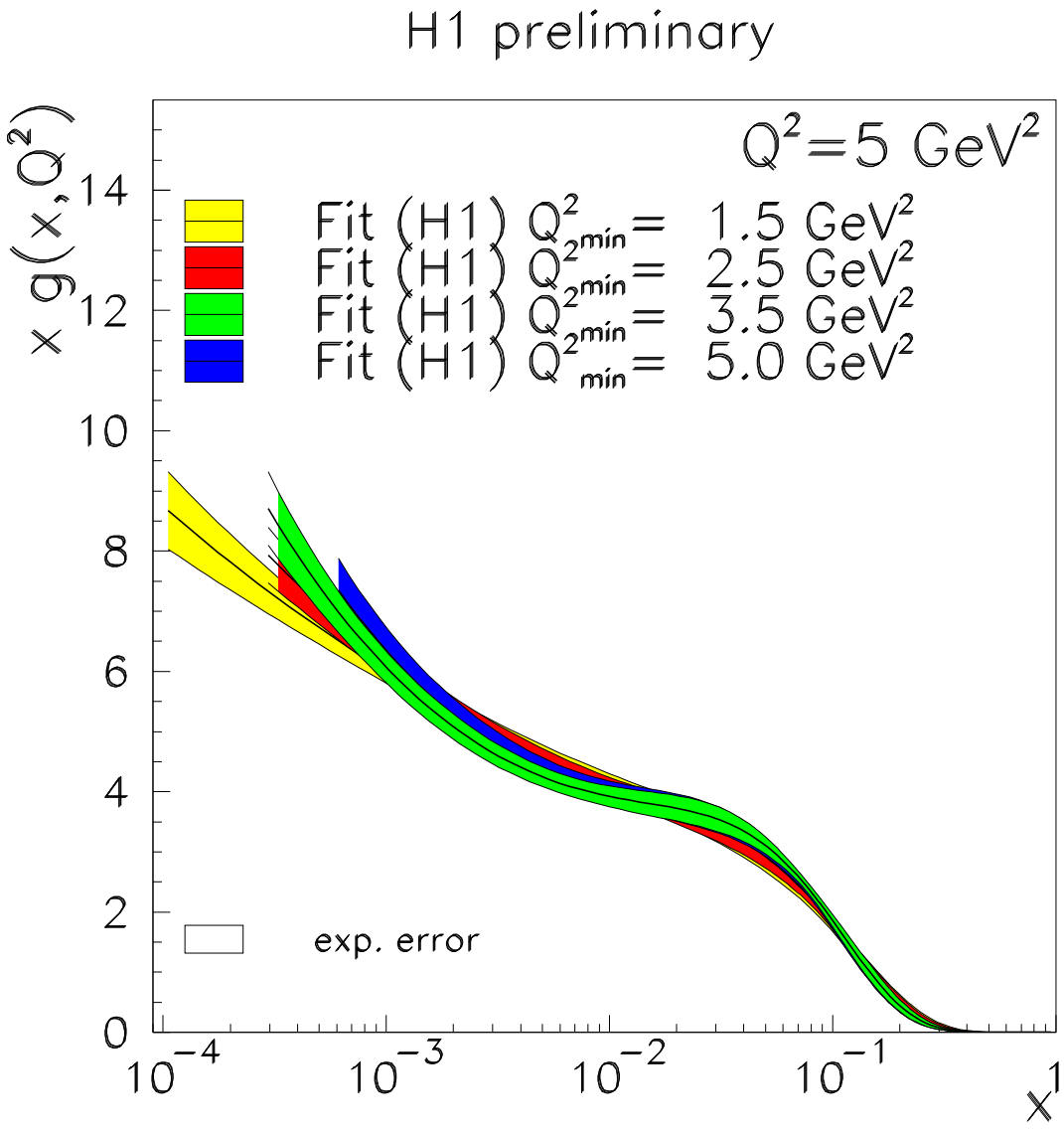
fit error dominated by $Q^2_{min}$ cut on data !

How low in $Q^2$ does NLO DGLAP work ?



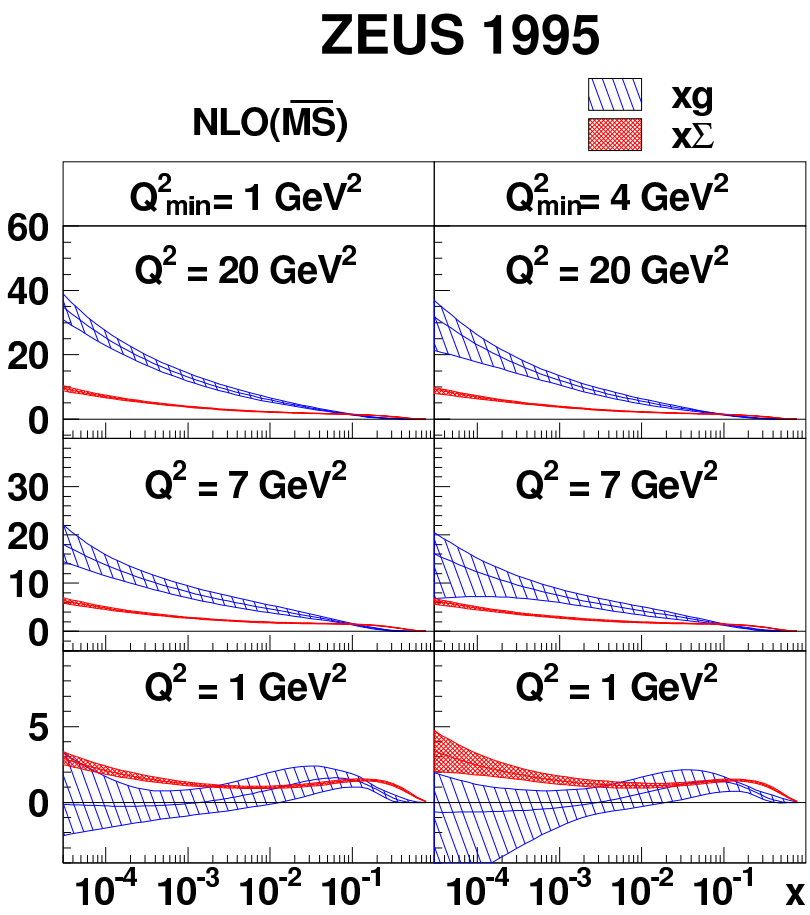

QCD fit works down to $Q^2_{min} = 1.5$ GeV$^2$

# H1 analysis of low-$x$ Gluon density




- $10^{-1} > x > 10^{-3}$: gluons contrained from H1 data alone to $\sim$ 15% precision
- $10^{-3} > x > 10^{-4}$: QCD fits works, but solution for $xg(x, Q^2)$ more uncertain

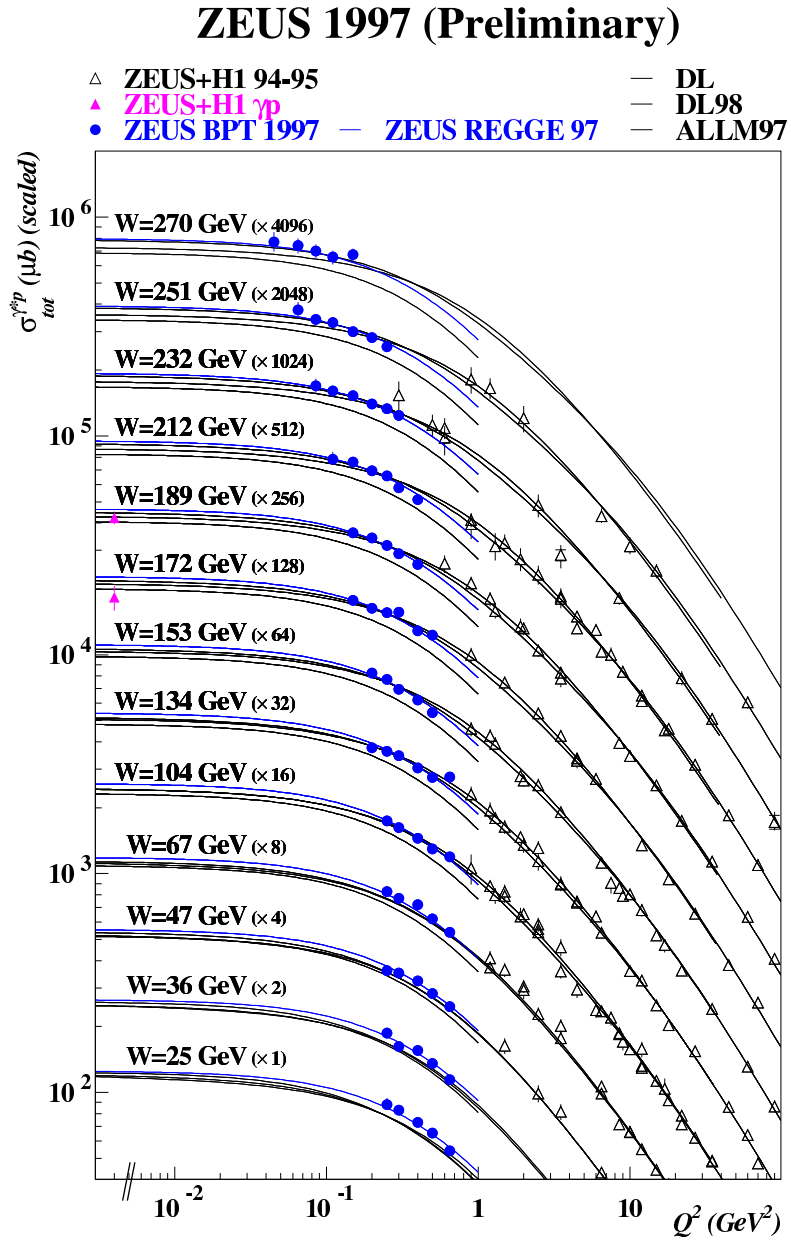
# Gluon density for $Q^2 \rightarrow 1\text{GeV}^2$




- $xg(x, Q^2)$ becomes 'valence like'
  (drops much faster than quark density)
- physics or artefact of the fits ?
- NNLO estimates show very large corrections to $xg(x, Q^2)$, much less for observable cross sections.

# Transition to Photoproduction
# $Q^2 \to 0$

## ZEUS beam-pipe calorimeter/tracker data

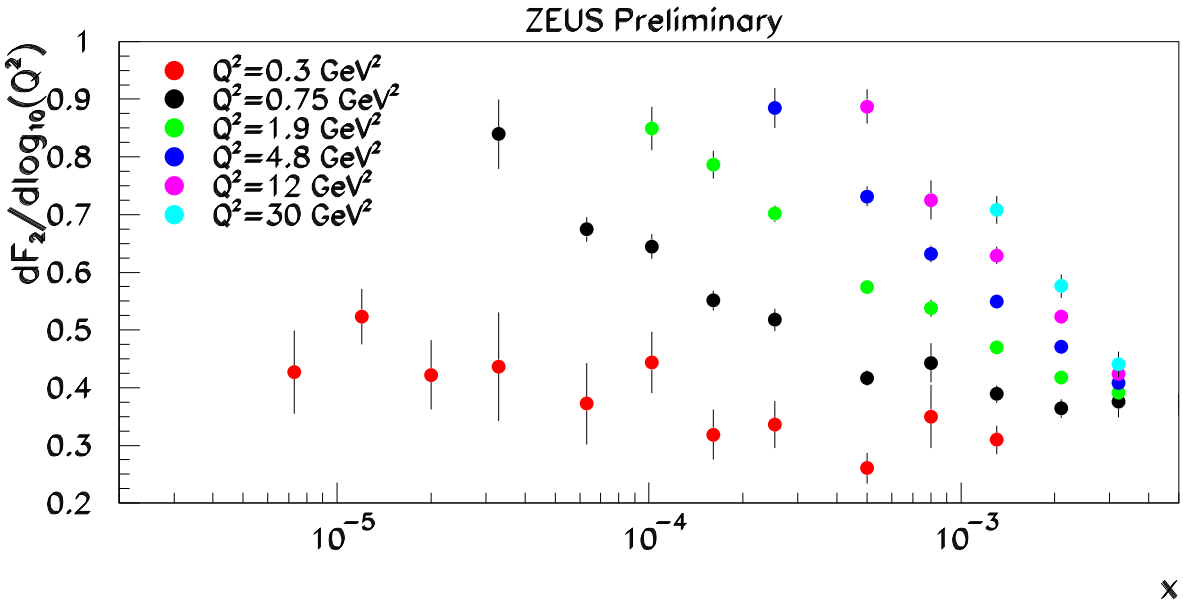



extremely low x: $10^{-6}$ for $Q^2 = 0.045\text{GeV}^2$

soft: $\sigma$ independent of $Q^2$ as $Q^2 \to 0$

# Transition to Photoproduction
# $Q^2 \to 0$

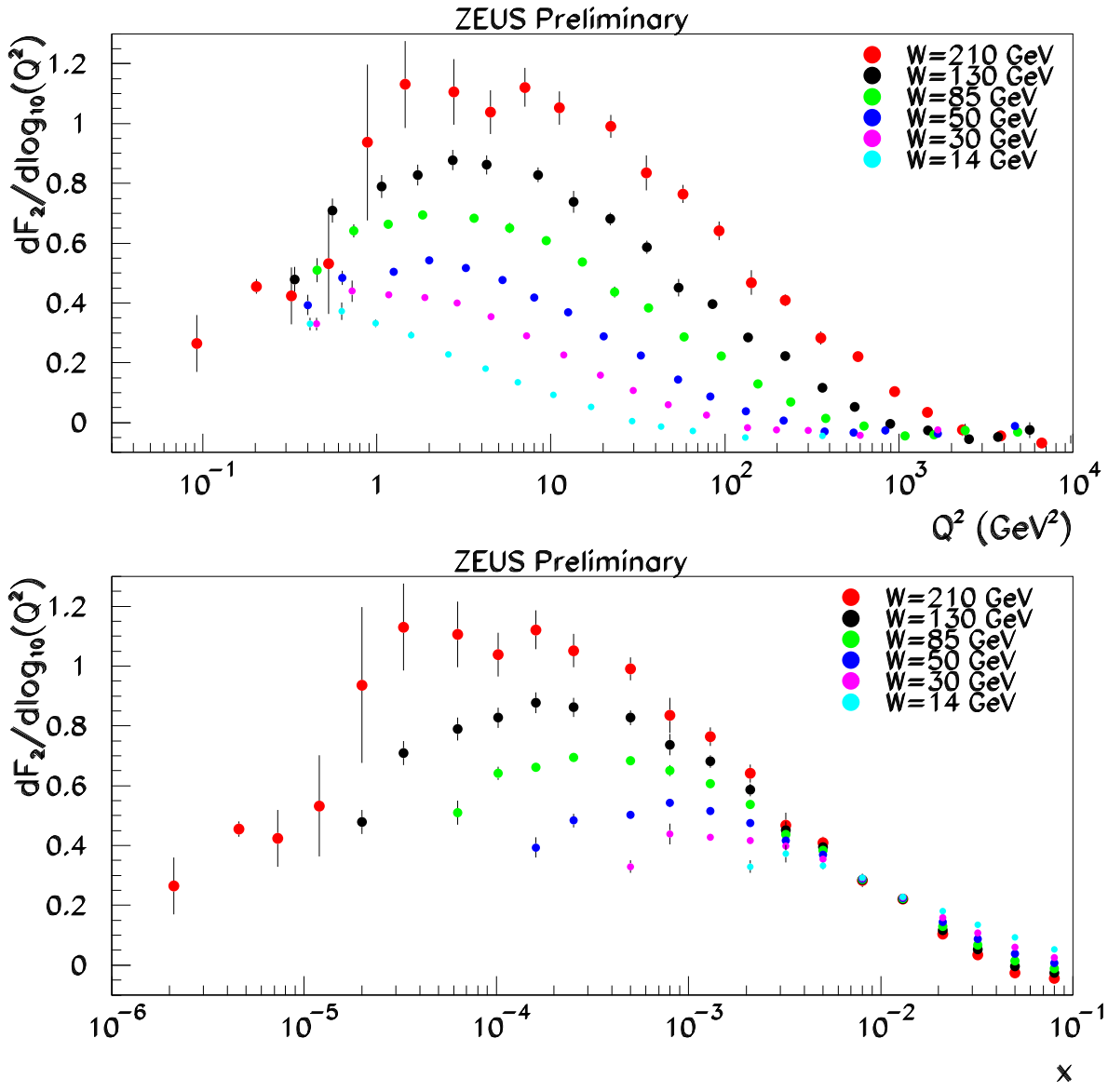
**expectation: slope $dF_2/d\ln Q^2|_x$ becomes smaller for small $Q^2$**




- **observation of transition to photoproduction at / below 1GeV$^2$**
- **no change of x-dependence at any fixed $Q^2$**
- **Saturation of gluon density ?**
  **$Q^2 > 1$GeV$^2$: not observed**
  **$Q^2 < 1$GeV$^2$: difficult (if possible at all) to disentangle low-x from low $Q^2$ effects.**

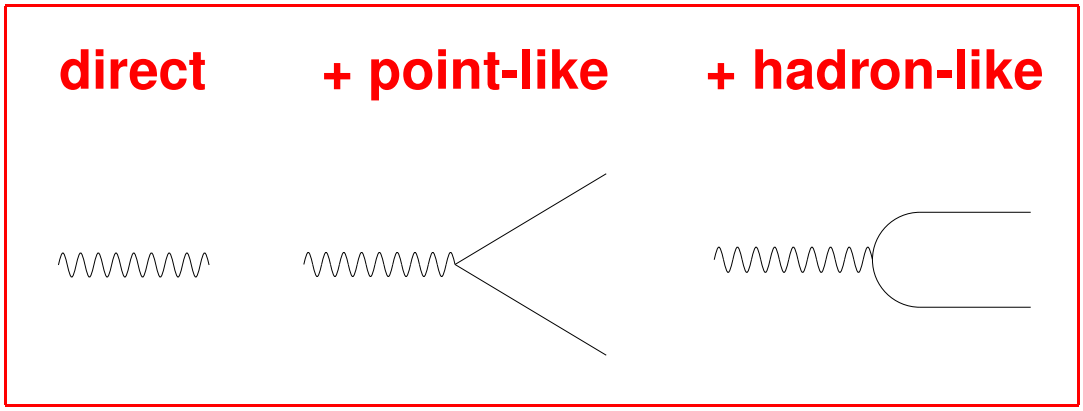
# Transition to Photoproduction

$$Q^2 \to 0$$



# Photon Structure

Quantum fluctuations of real $\gamma$ into $q\bar{q}$




- direct and point-like part predicted
- hadron-like part needs to be measured

**LEP:** $ee \rightarrow e^+e^-\gamma^*\gamma \rightarrow eeX$

$\gamma^*$ measured via electron: $Q^2$

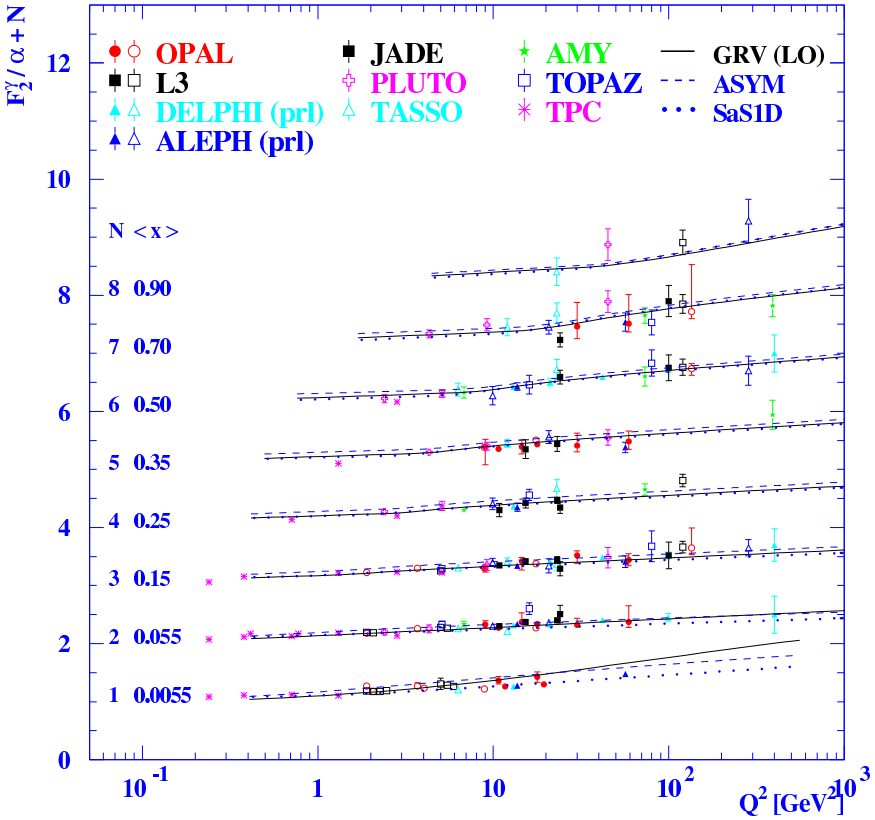
hadrons (X) used to obtain $x_\gamma$

- Previously: large uncertainties due to insufficient simulations
- Now: Major improvements: event generators, 2-dim unfolding in $x_\gamma$ and 2nd variable, detector response for hadrons close to beam, kinematic constraints $\rightarrow$ major improvement in systematics, better consistency between experiments

# Photon Structure from LEP

## Expectations for $F_2^\gamma$:

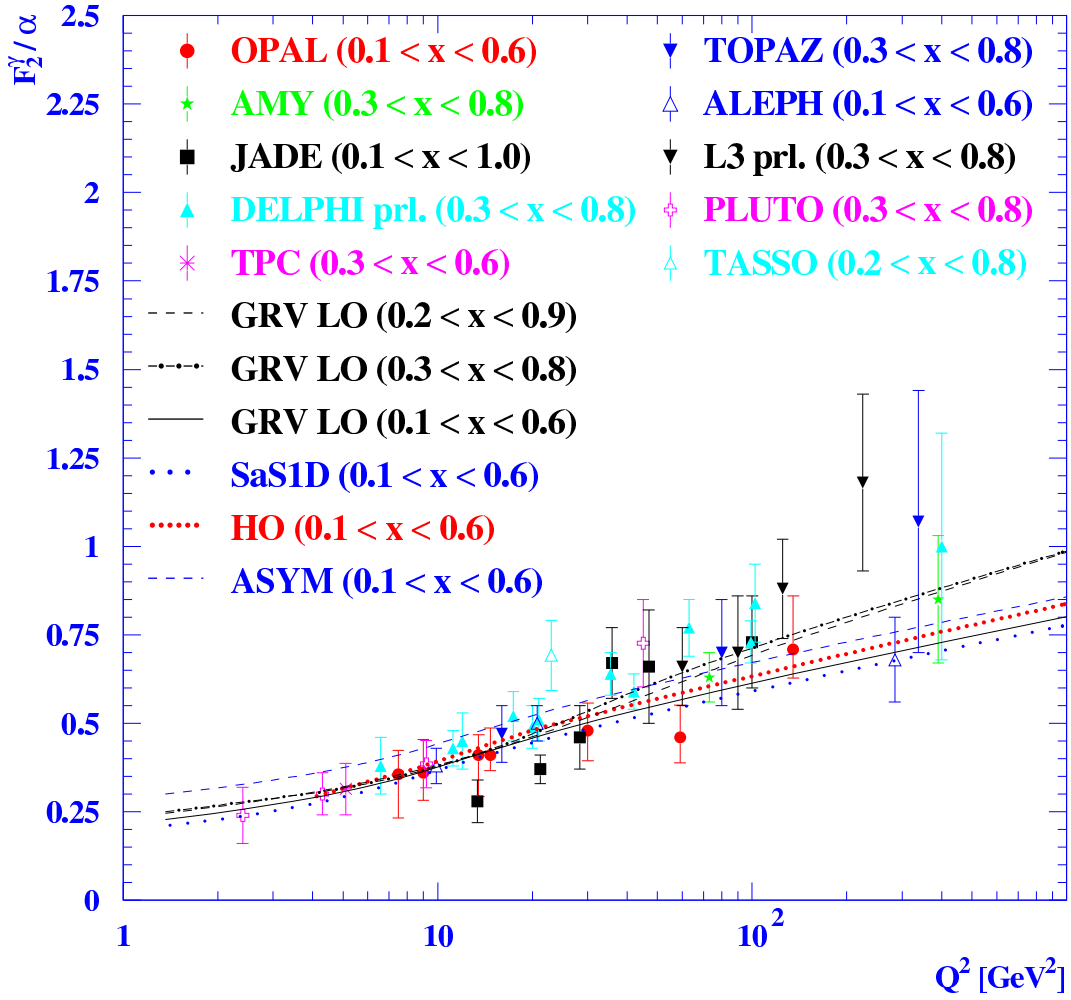
- rise for all $x_\gamma$ with $Q^2$ due to $\gamma \rightarrow q\bar{q}$
- dominant point-like part at high $x_\gamma$
- exceed point-like component at small $x_\gamma$
- rise at very small $x_\gamma$ due to gluons (hadronic component like proton)




- LEP2: extanded kinematic coverage
- consistent results between experiments

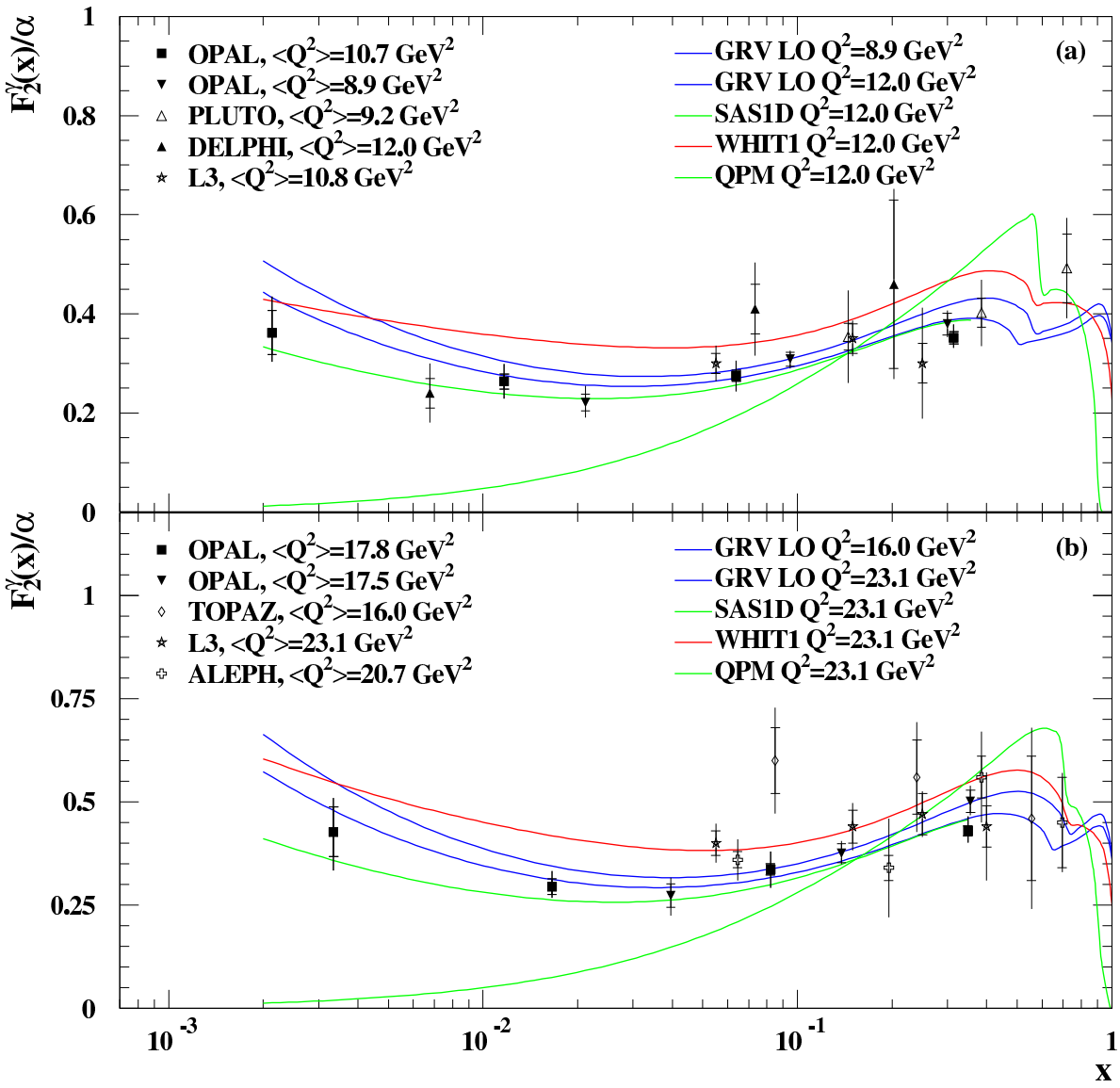
# Photon Structure from LEP

## large $x_\gamma$



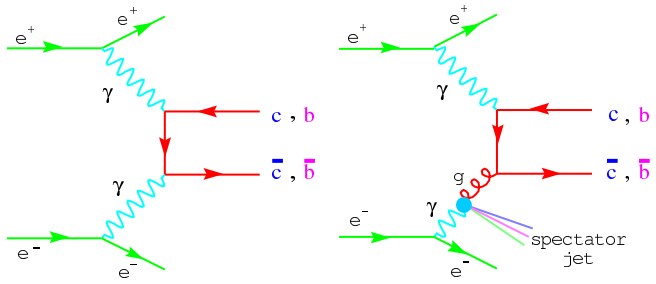

## clear rise of $F_2^\gamma$ with $Q^2$ also at high $x \longrightarrow$ point-like component

# Photon Structure from LEP



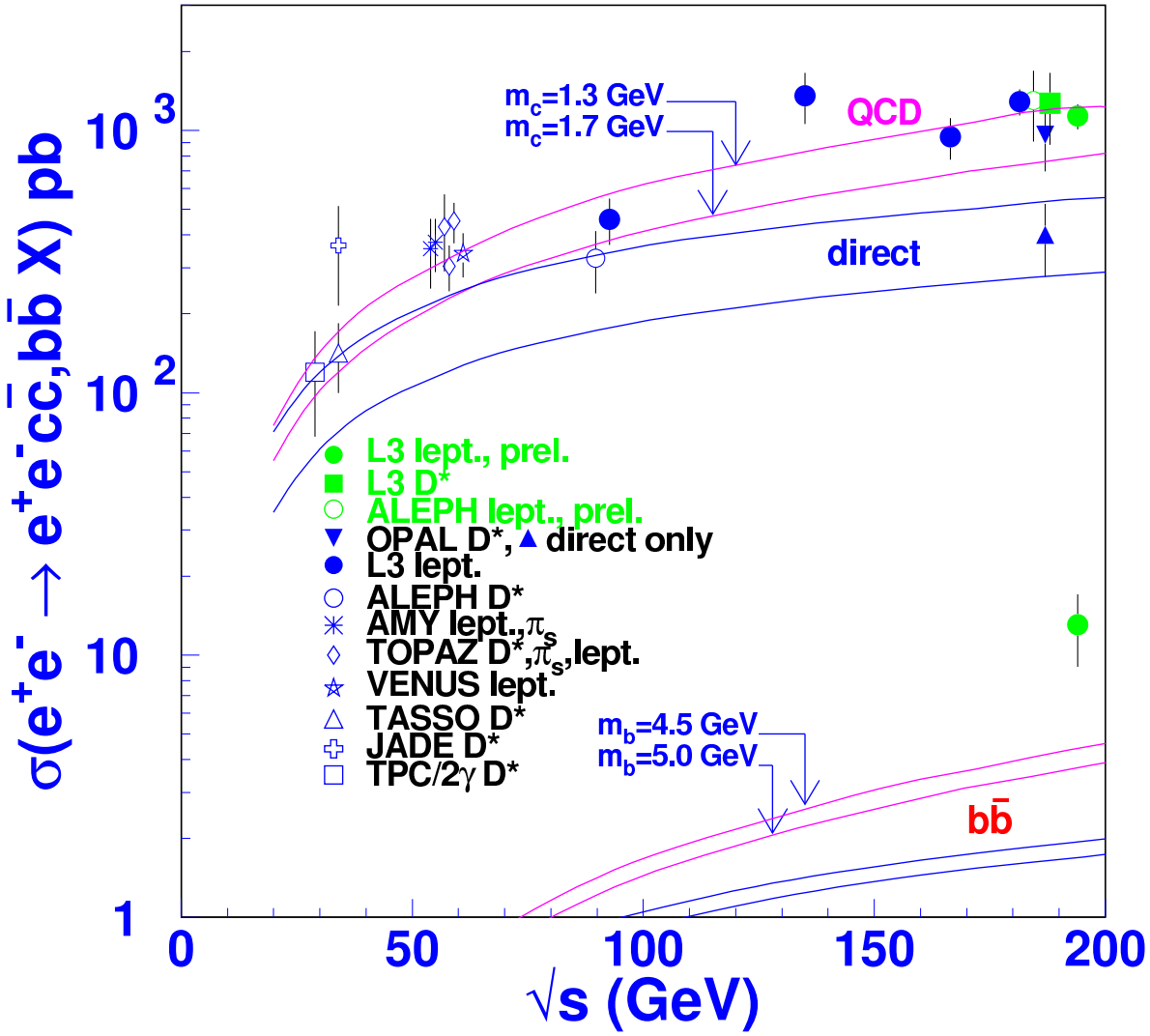

- hadronic component seen, but not yet rise of $F_2^\gamma$ at very low $x$.
- data consistent with e.g. GRV(LO)

# Heavy Flavour in $\gamma^*\gamma$ coll. from LEP



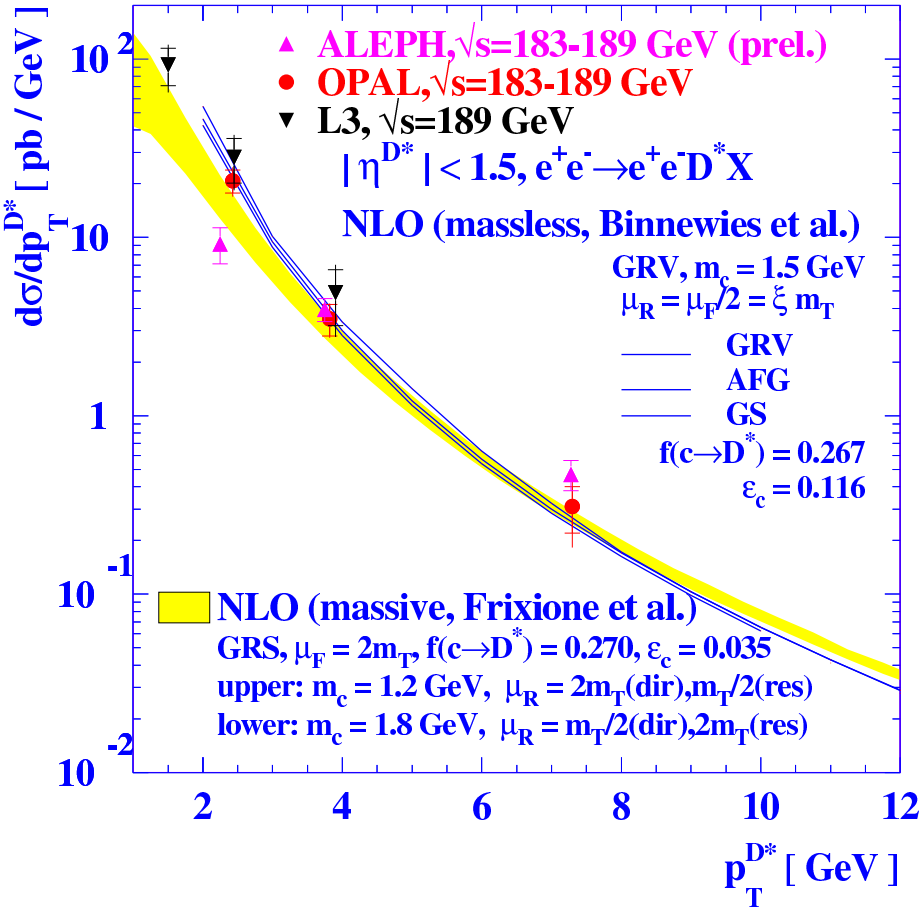

direct handle on gluon content for $x_\gamma \gtrsim 0.1$ !

**direct : Resolved = 1 : 1**



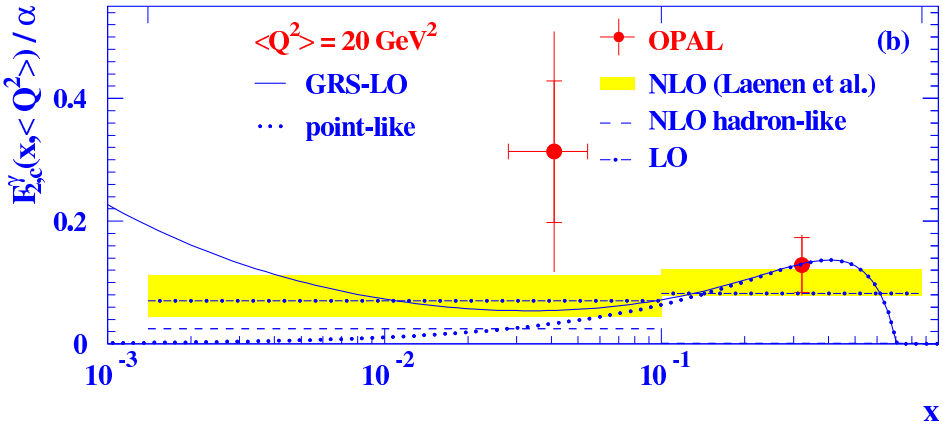

**nice agreement for charm, bottom too high ?**

# $F_2^{charm}$ in $\gamma^*\gamma$ coll. from LEP




good agreement with GRV (NLO)

first $F_2^{charm}$ !



# Photon Structure from HERA

Use dijet events to probe $\gamma$ structure

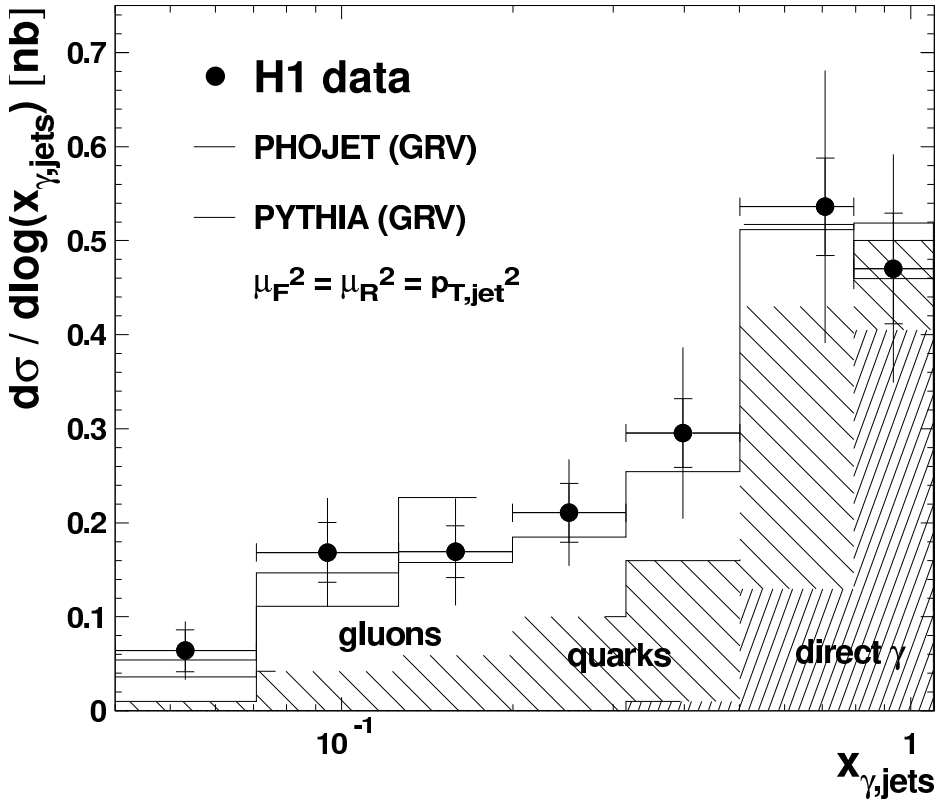
- low $x_\gamma \rightarrow$ low $E_{T,j} \leftarrow$ underl. event
- high $x_\gamma \rightarrow$ high $E_{T,j} \leftarrow$ cleaner

  see talk by R. Nania

Here: H1 analysis at $E_{T,j} > 6$GeV

$\rightarrow$ low $x$ to see rise of parton density

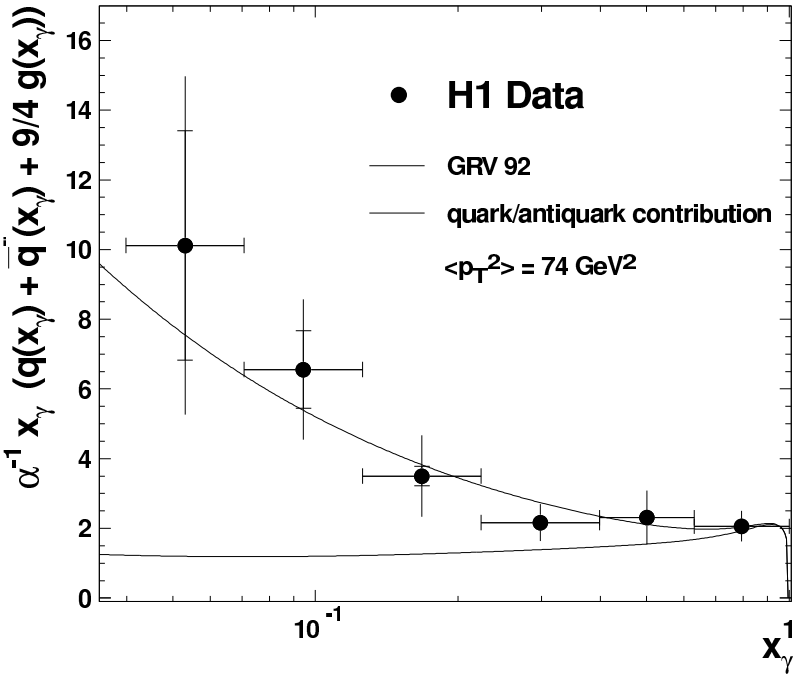
after subtraction of underlying event:



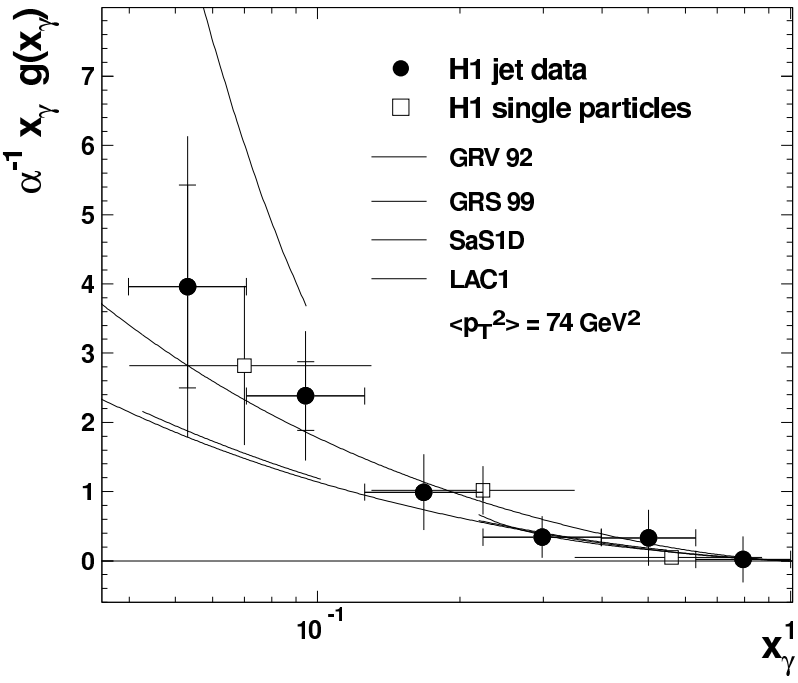

large sensitivity to gluons at small $x$

# H1 low-$x$ Photon Structure analysis

effective parton density



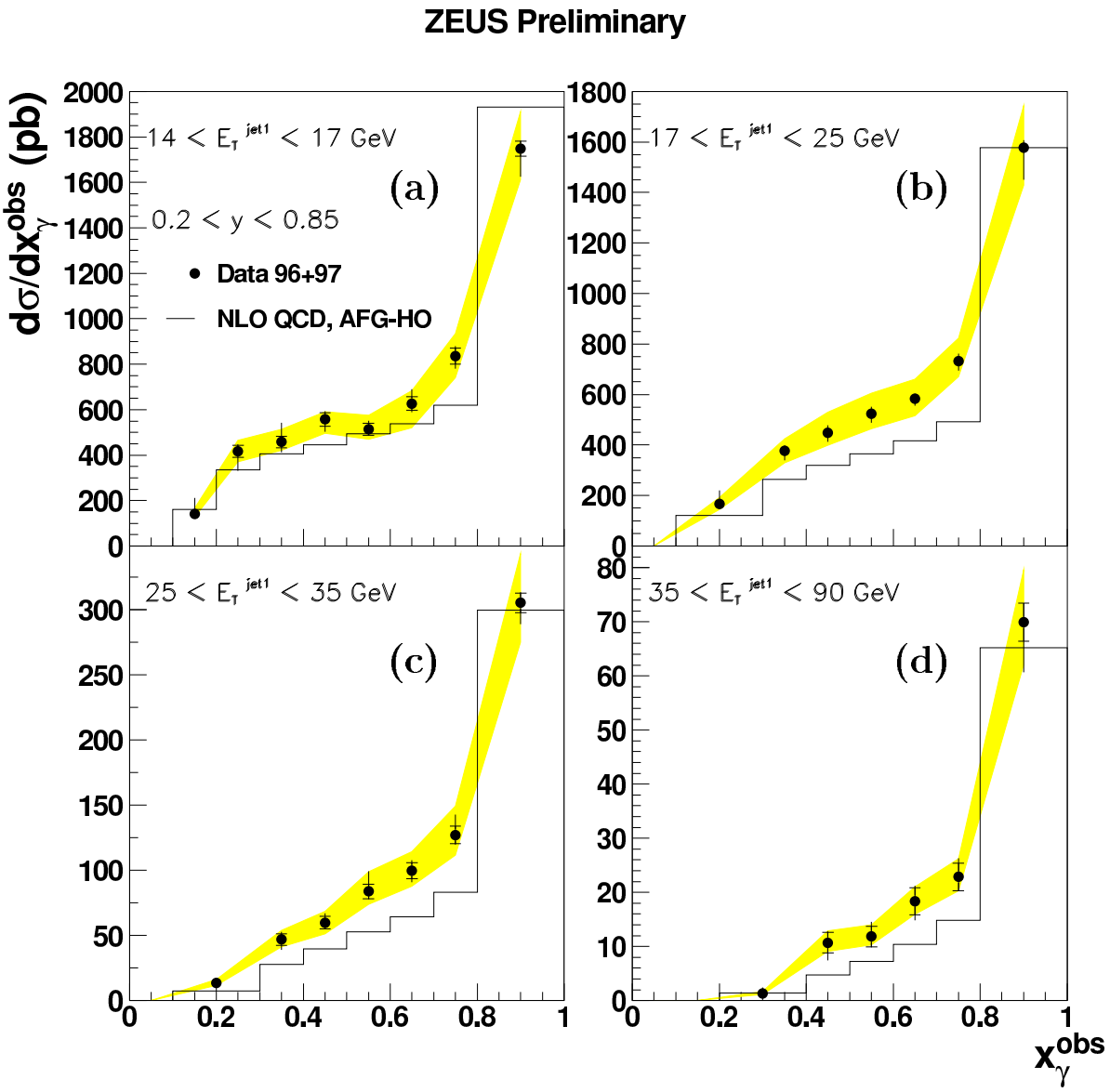

gluon density (quarks subtracted)




**Clear proton-like rise of gluon density visible.**

**Hadronic structure ! Limited by knowledge of underlying event.**

# Jets in $\gamma - p$ from HERA




**significant lower than standard parton density at**

**largest $E_T$ and $0.3 < x_\gamma < 0.8$**

# Conclusion on Photon Structure

New and very decisive datasets available NOW for a big step in the determination and QCD interpretation of the photon structure.

- LEP
  - $F_2^\gamma$ for quarks, charm + jets for gluons
- HERA
  - jets at high/low $E_T$ and $x_\gamma$ (q+g)

Note:

| | | | |
|---|---|---|---|
| $x_\gamma \lesssim 0.2$ | $F_2^\gamma$ | q | $\approx$ GRV |
| | HERA jets | q + g | $\approx$ GRV |
| $x_\gamma \gtrsim 0.2$ | HERA / LEP jets | q + g | $>$ GRV |
| | $F_2^\gamma$ | q | $\approx$ GRV |
| | $F_2^{charm}$ | g | $\approx$ GRV |

Is this consistent ? Calls for an

OVERALL NLO QCD fit to all data.

# QCD dynamics at low-$x$

- Unintergrated Parton Densities
- BFKL, CCFM

theoretical predictions not always a story of success:

- incomplete, predictions in LO failed, NLO corrections huge, range of application limited, signatures not as striking as thought, difficult !

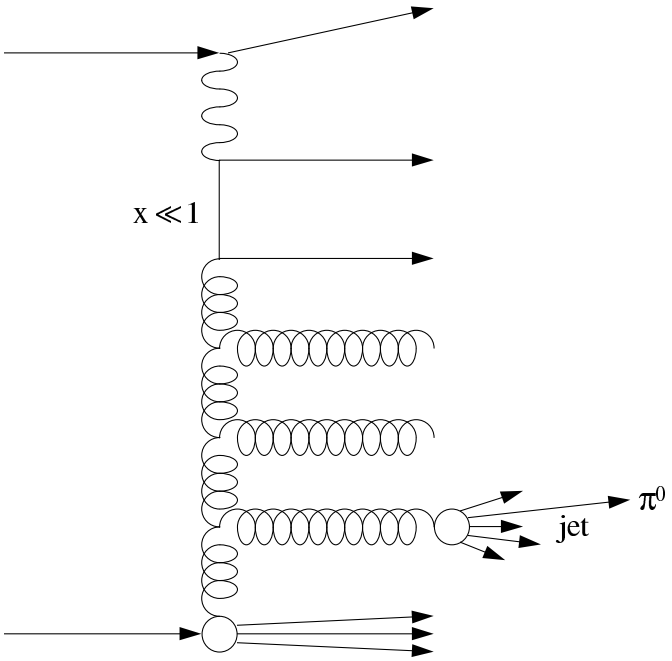
recent progress:

- BFKL: NLO corrections much reduced (kinematic constraints)
- CCFM: full $P_{gg}$ splitting function, first calculations appeared, event generators

Here: new experimental results:

- F2, forward jets, charm production, jets in diffraction, $\gamma^*\gamma^*$ from LEP

# QCD dynamics: Forward Jets



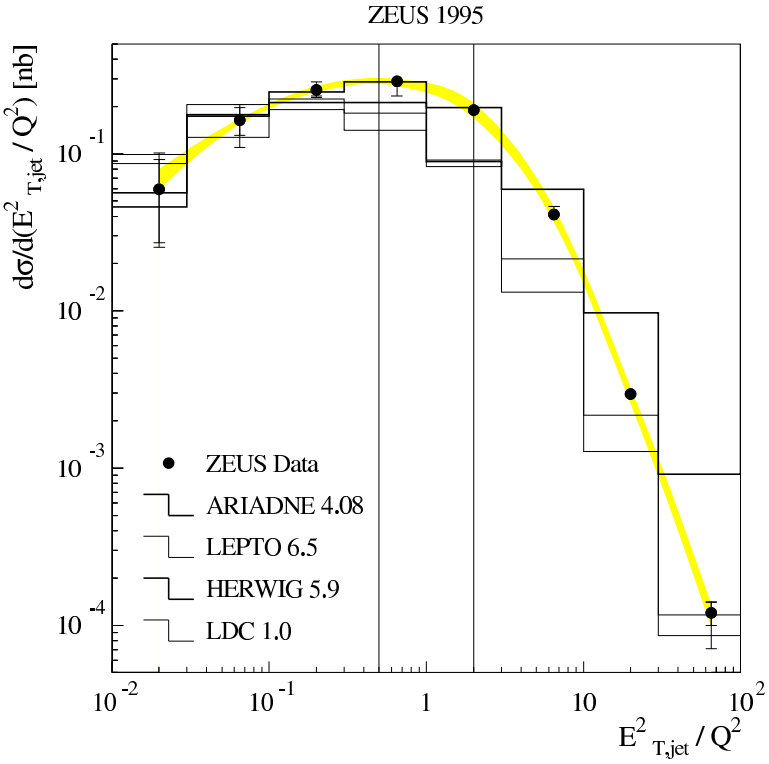

**select:**

- **small-$x$**
- **forward jet ($\pi^0$)**
- **$Q^2 \approx E^2_{T,jet}$**

**no $k_T$ order**

- **no large scale difference: DGLAP should fail**
- **BFKL CCFM test case**
- **approximation to non $k_T$ ordering:**
  **resolved virtual $\gamma$**
  **assume virtual photon has structure which is probed by largest scale $E^2_{T,jet}$:**
  **2 DGLAP evolution chains.**

# QCD dynamics: Forward Jets



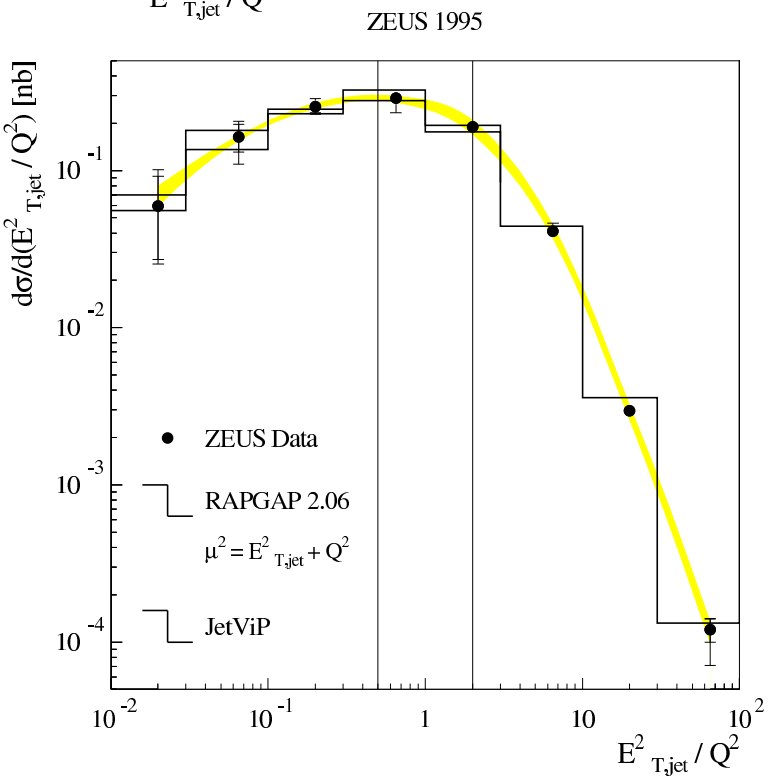

**DGLAP:**

**fails for**

$$Q^2 \lesssim E^2_{T,jet}$$

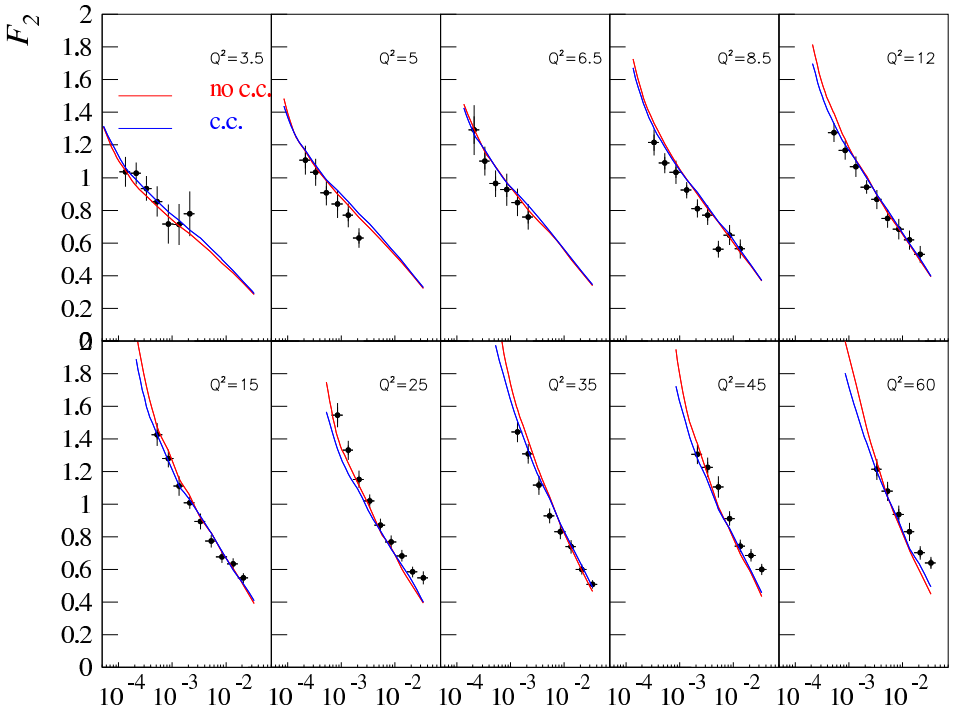
**resolved virtual $\gamma$ works:**

**sign for non-$k_T$ order**

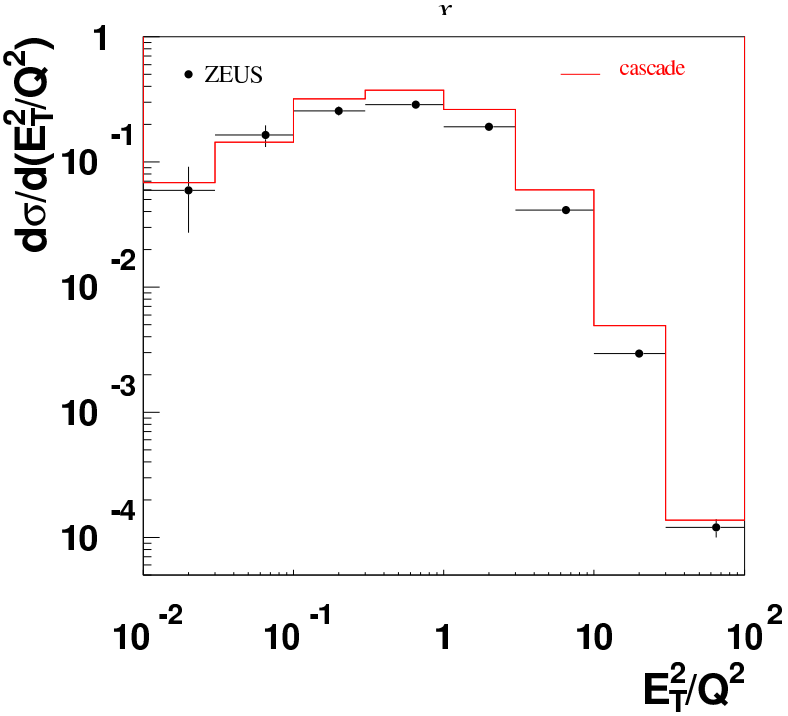


# QCD dynamics: Forward Jets with CCFM

## unintegrated parton density from fit to $F_2$

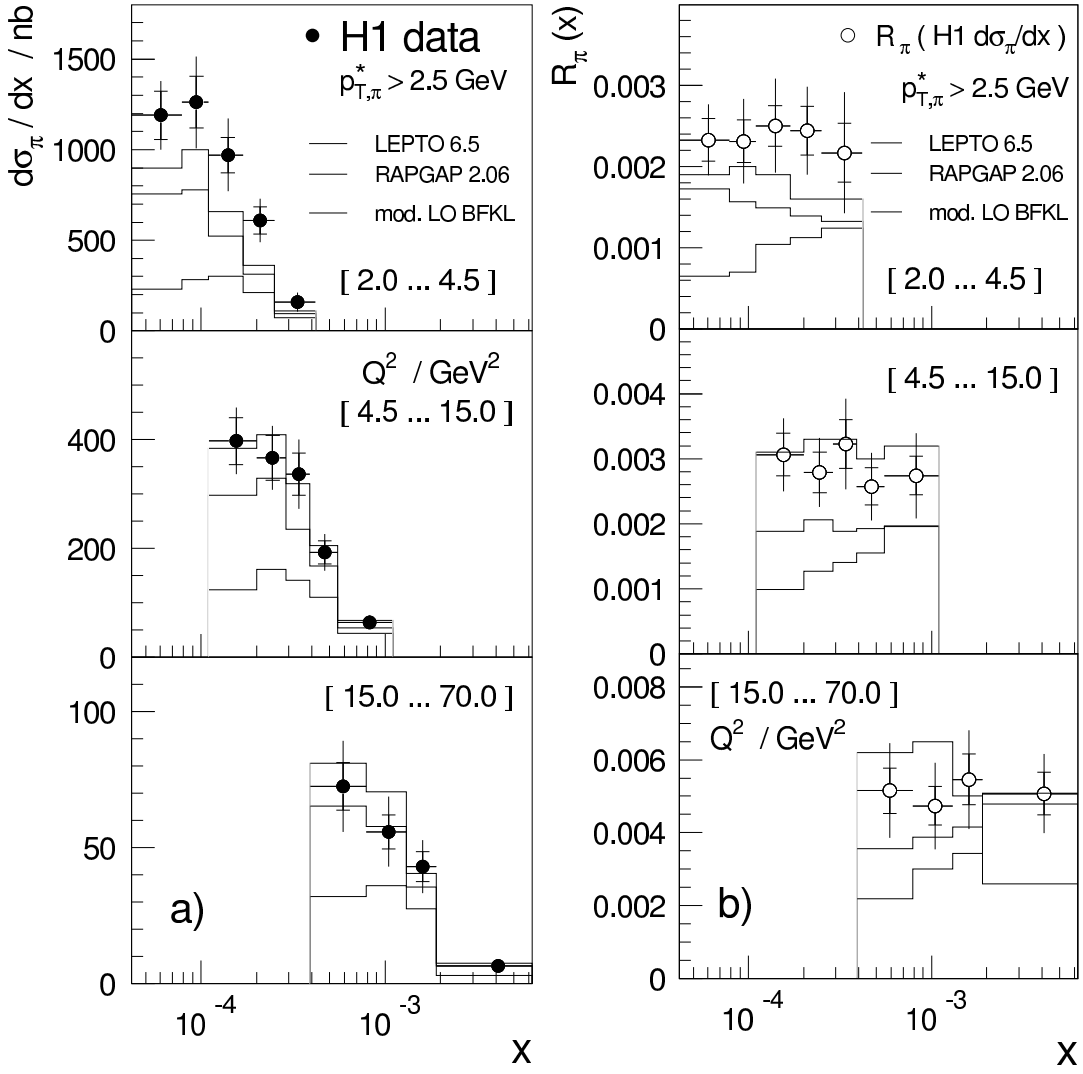



use CCFM evolution to describe jets



# QCD dynamics: Forward $\pi^0$

## high $E_T$ $\pi^0$ in very forward direction

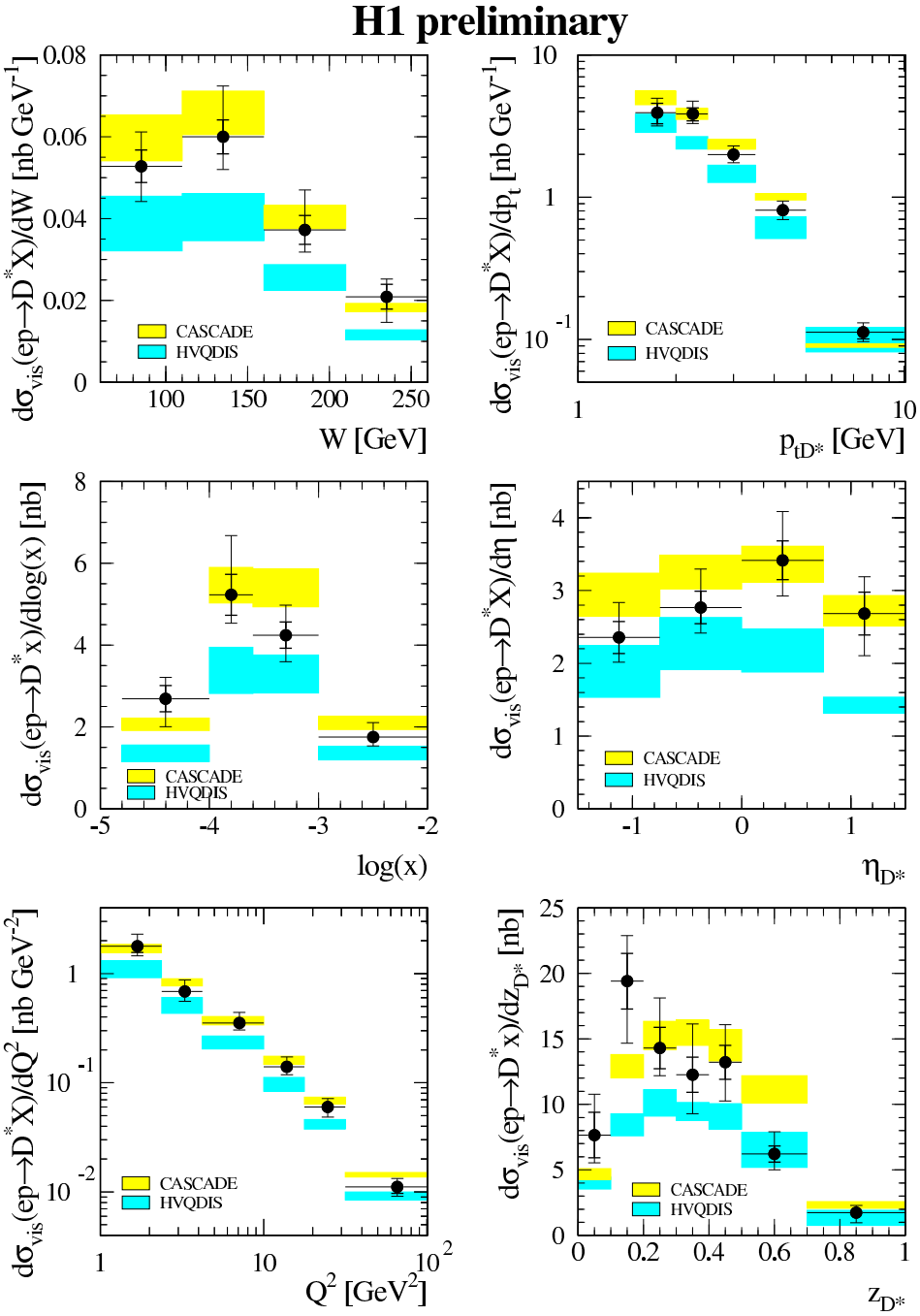



## only hint on dynamics beyond

## 'resolved virtual photon'

# QCD dynamics: Charm with CCFM

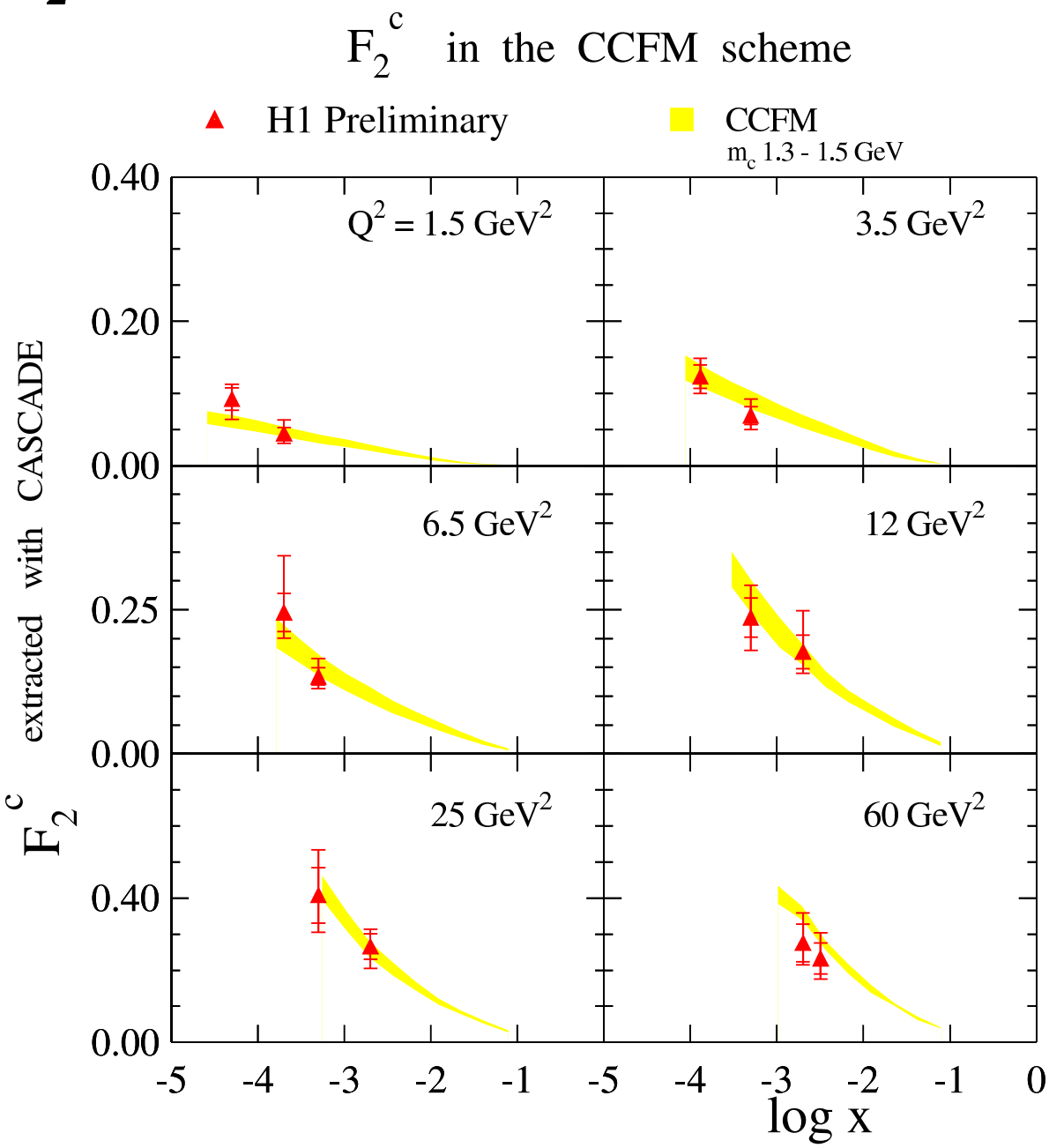
## $\gamma^* g \rightarrow c\bar{c}$: charm mass is 2nd hard scale




## CCFM slightly better than DGLAP

# QCD dynamics: Charm with CCFM

$F_2^{charm}$



# Conclusion on QCD dynamics

- need contributions beyond $k_T$- ordered chains (DGLAP)
- resolved $\gamma^*$ works astonishing well
- BFKL: week evidence only, NLO corrections huge ($\gamma^*\gamma^*$)
- unintegrated parton densities and CCFM: very promising first results (also for heavy flavour prod. at Tevatron)
- needs completion of CCFM formalism to do rigorous tests
- and event generators
- or NNLO DGLAP ..?

# Diffraction

elastic scattering: large part of total $\sigma^{tot}_{p\bar{p}}$

**QCD:** scattering via quark/gluon exchange

$\longrightarrow$ colour exchange $\longrightarrow$ **confinement** $\longrightarrow$

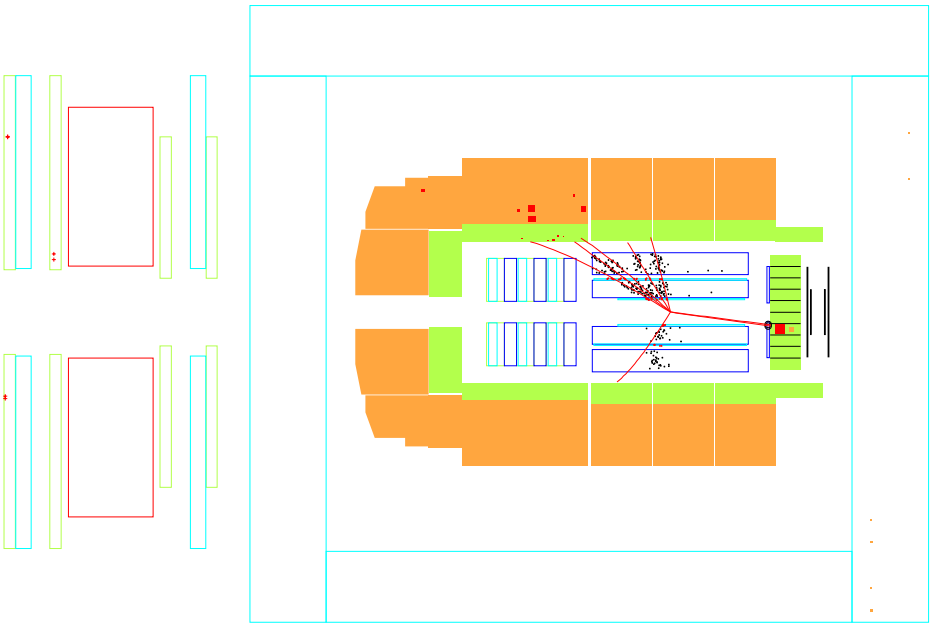
proton fragments

**What happens in elastic scattering ?**

- soft peripheral scattering: $\longleftarrow$ difficult
- **hard diffractive scattering:**
  - jet production with elastic scattered $p$
  - $\gamma^* p \rightarrow X p$

    $\gamma^*$ hits parton but $p$ survives

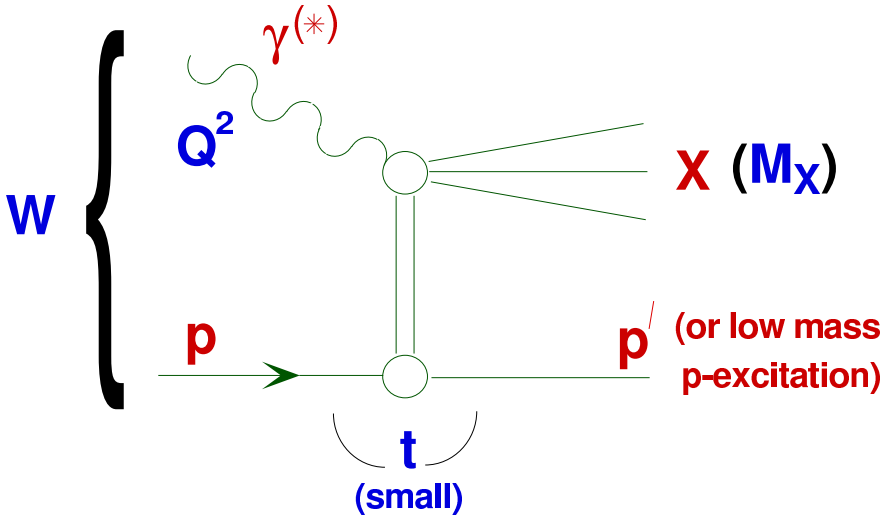
no proton frag-ments



**not rare: 10% of all events at HERA**

# Diffraction

**Aim: Identify the partonic colour-singlett system exchanged between $p$ and hard process.**




**Structure functions at HERA and Tevatron:**

**Factorisation: proof by J.Collins also for diffractive *lepton*-$p$ scattering.**

**Puts hard diffraction onto solid theoretical ground in QCD.**

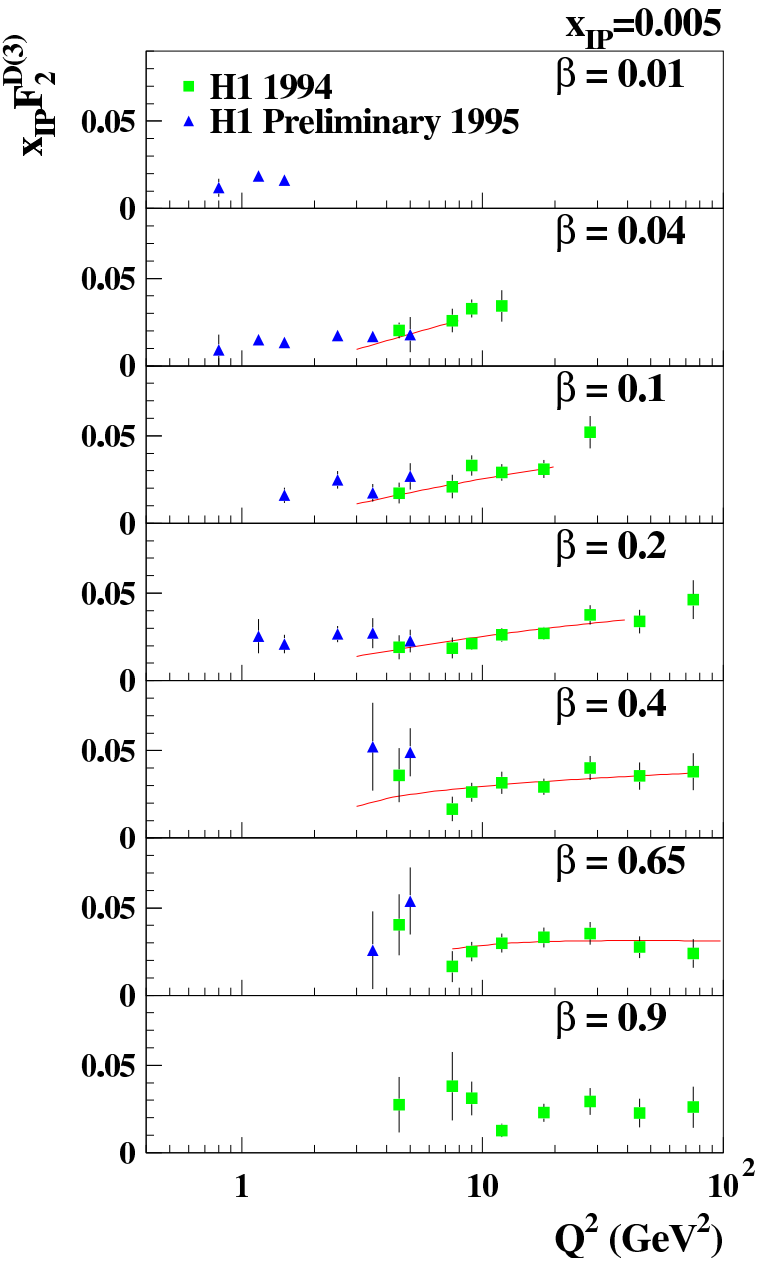
$$F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

$x_{I\!P}$ **momentum fraction of colour singlett in** $p$

$\beta = x/x_{I\!P}$ **momentum fraction of parton in colour singlett,** $t^2 = (p - p')^2$

# Diffractive parton density

integrated in $t$: $F_2^{D(3)}(\beta, Q^2, x_{I\!P}, )$




$F_2^{D(3)}$ increases with $Q^2$:

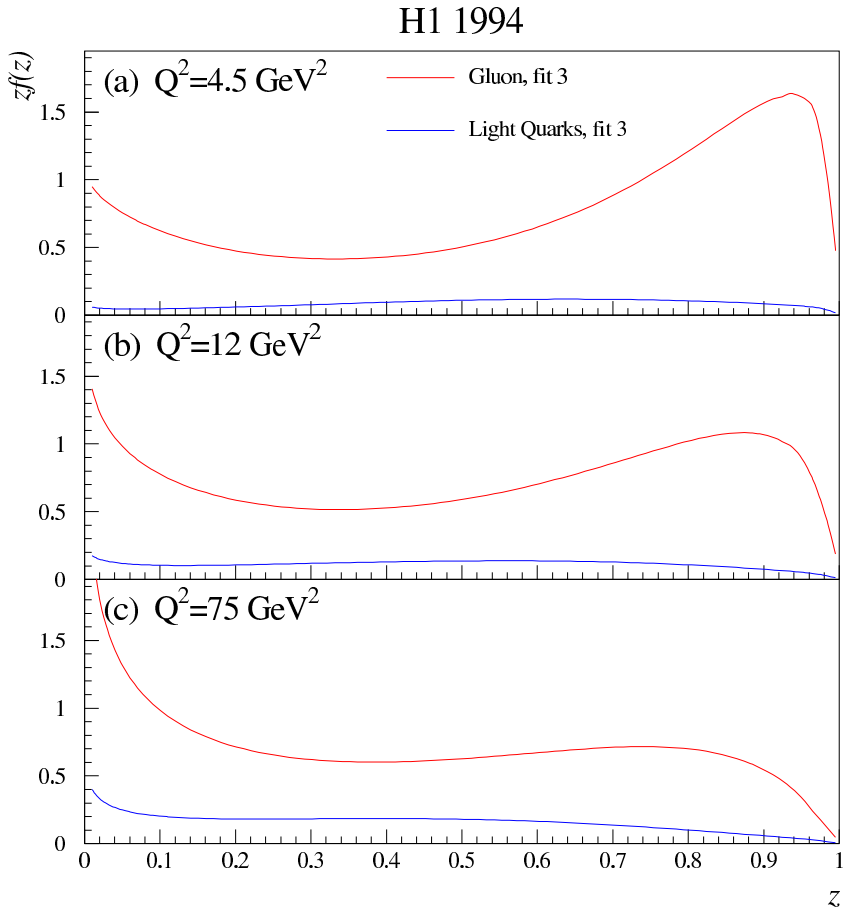
positive scaling violations:

gluons dominate (see proton at small $x$)

# Diffractive parton density

## QCD analysis

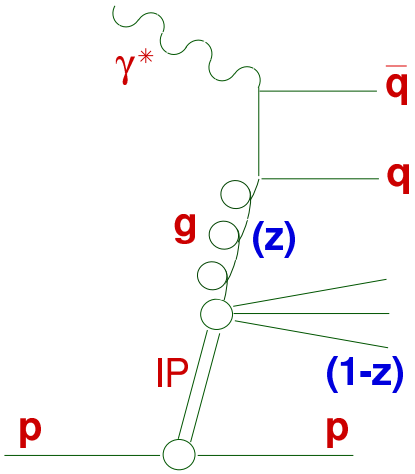
- approx. Reggee factorisation:
  $F_2^{D(3)}(\beta, Q^2, x_{I\!P}, ) = f(x_{I\!P}) \times f(\beta, Q^2)$
- gluon density flat in $\beta$, with large uncertainties




## Needs independent cross check in another process

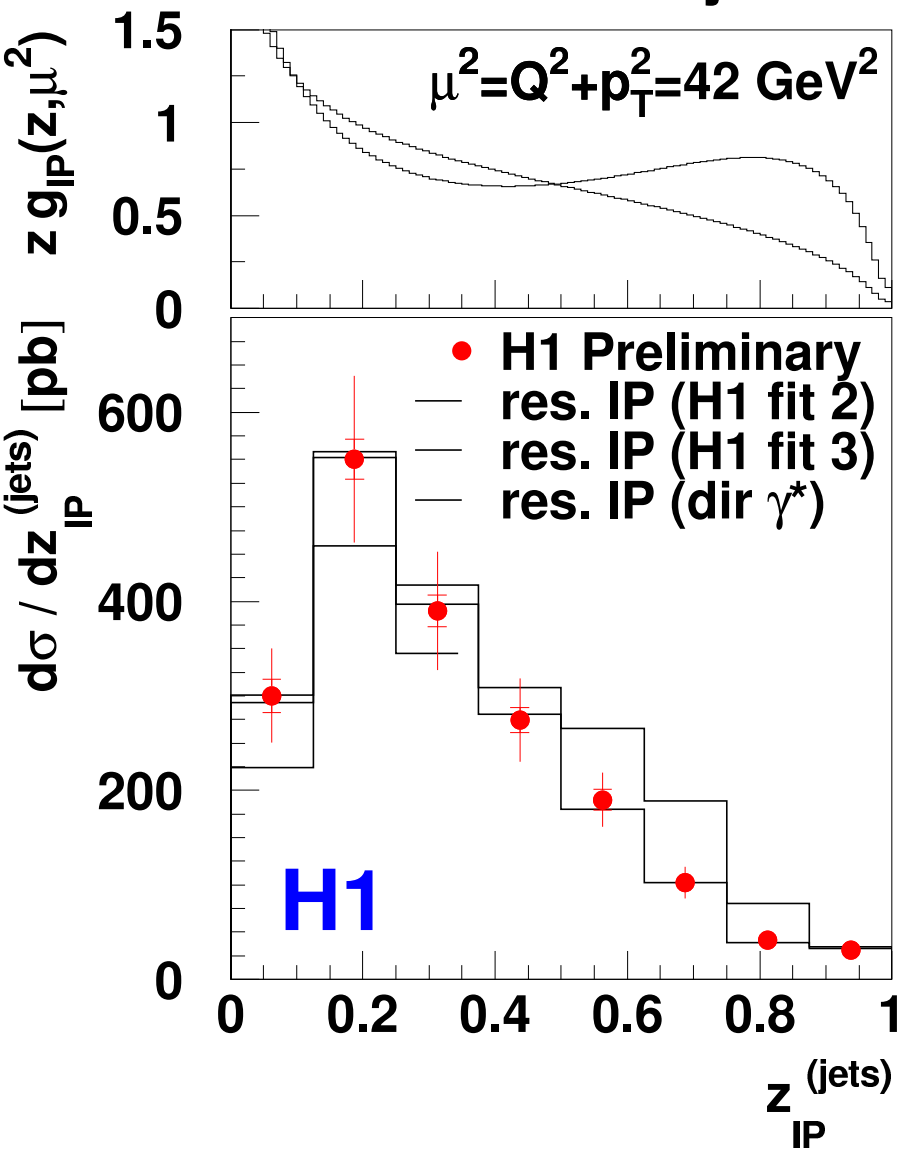
# Jet production in Diffraction

**New dataset**

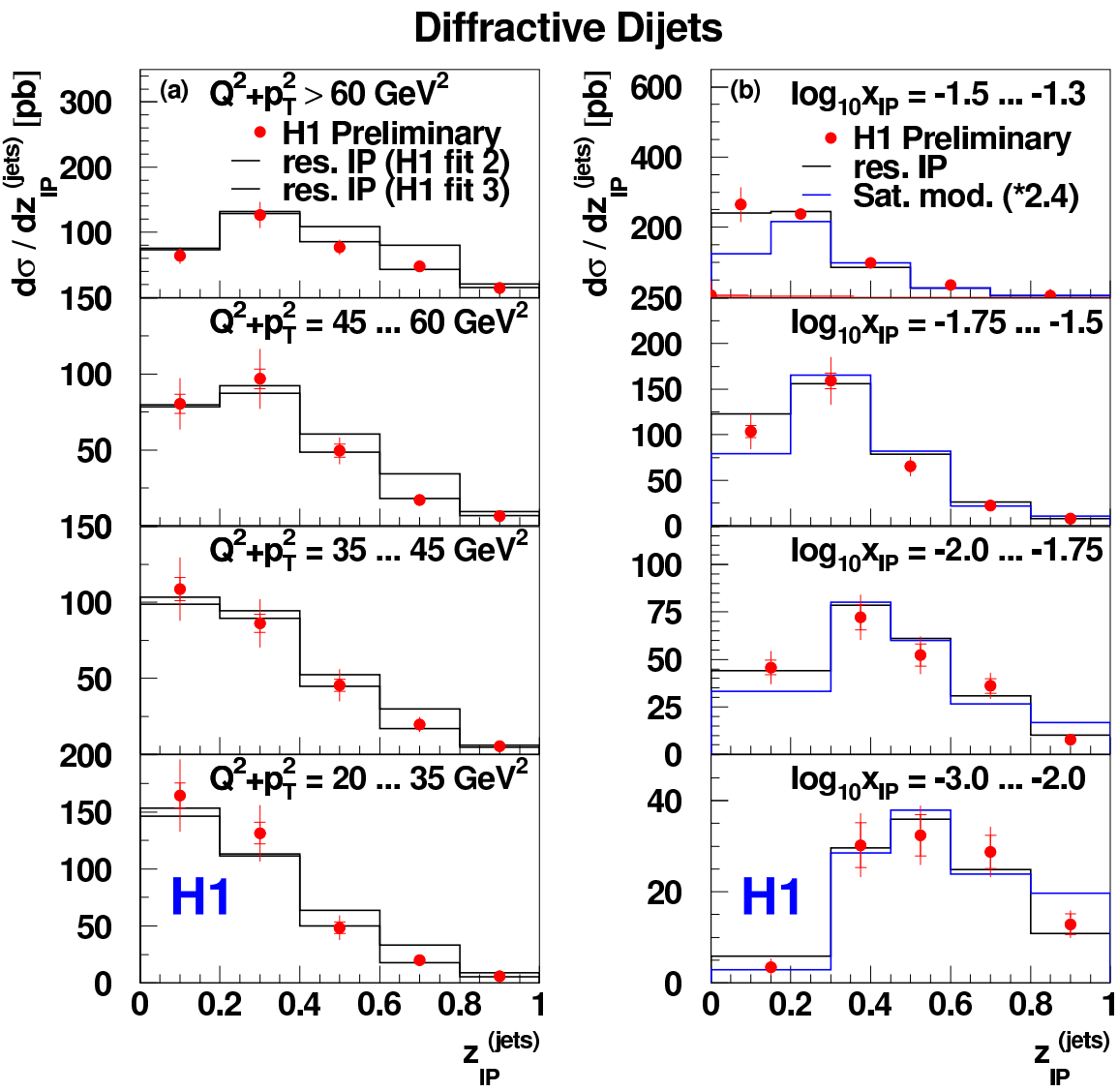



**directly sensitive to gluons**

## Diffractive Dijets



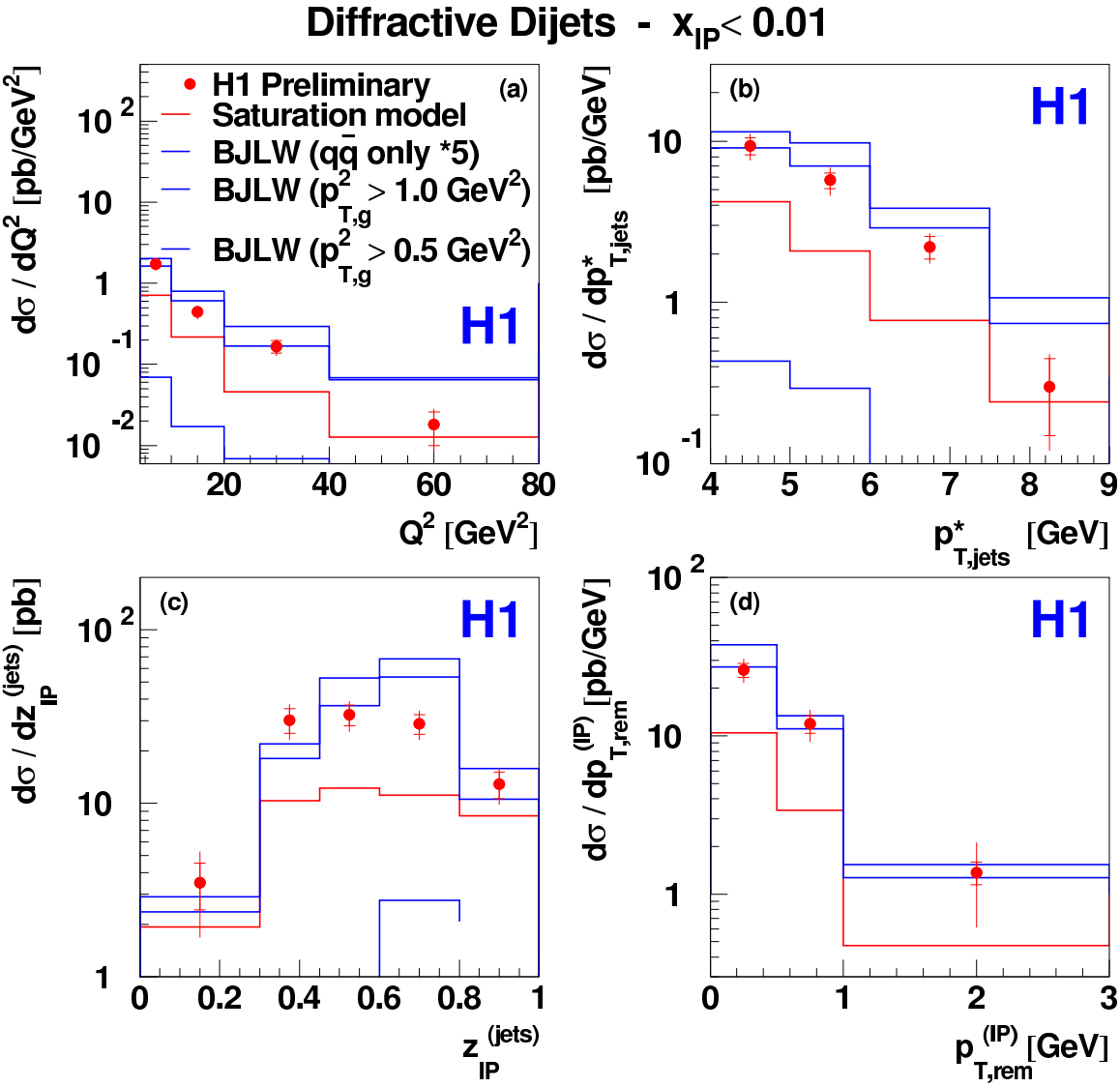
# Jet production in Diffraction




fully consistent picture from $F_2^{D(3)}$ and jets in either $Q^2$, $x_{I\!P}$ or $z$

# Jet production in Diffraction

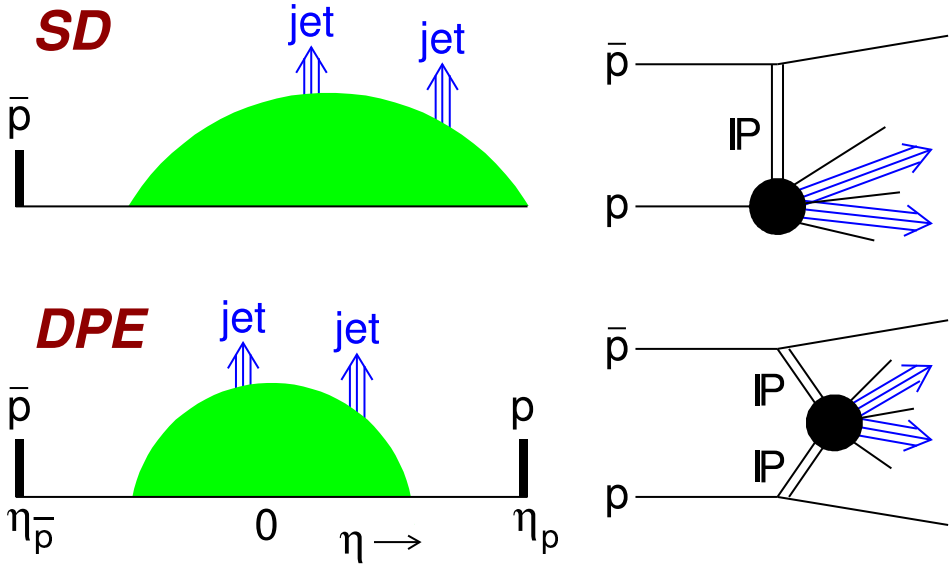
## Comparison with QCD calculation for 2-gluon exchange $\sigma \sim |g(z, Q^2)|^2$




**Note: reasonable agreement, considerable energy not contributing to hard process: remnant of colour singlet at low $P_T$**

# Diffraction at Tevatron

**use: (tagged proton or rapidity gap) + jets**




**Ratios:**

- **single diff. / non-diff. =** $R_{ND}^{SD}$
- **double diff. / single diff. =** $R_{SD}^{DD}$

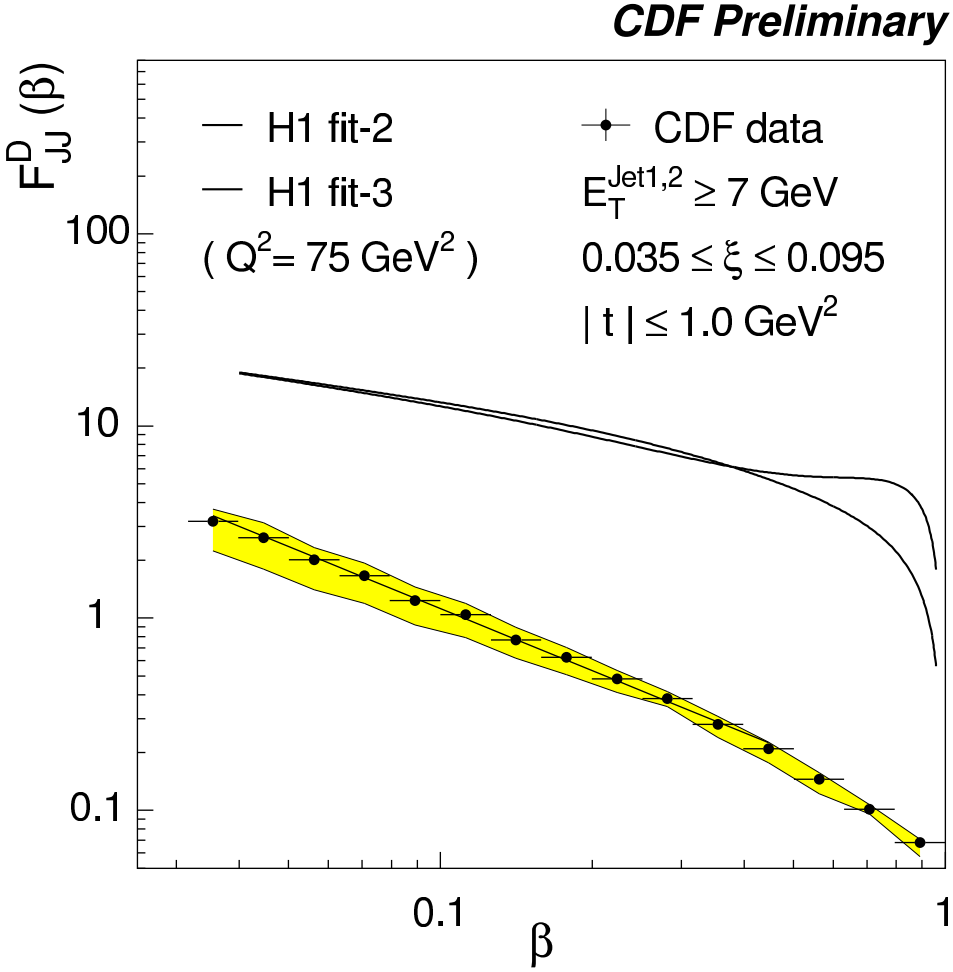
**structure function:**

$$F_{jj}^{D} = R_{ND}^{SD} \times F_{jj}$$

$$\sim x(g + 4/9[q + \bar{q}])$$

# Diffraction at Tevatron

**compare with HERA predictions**




**difference factor 20, no agreement in shape**

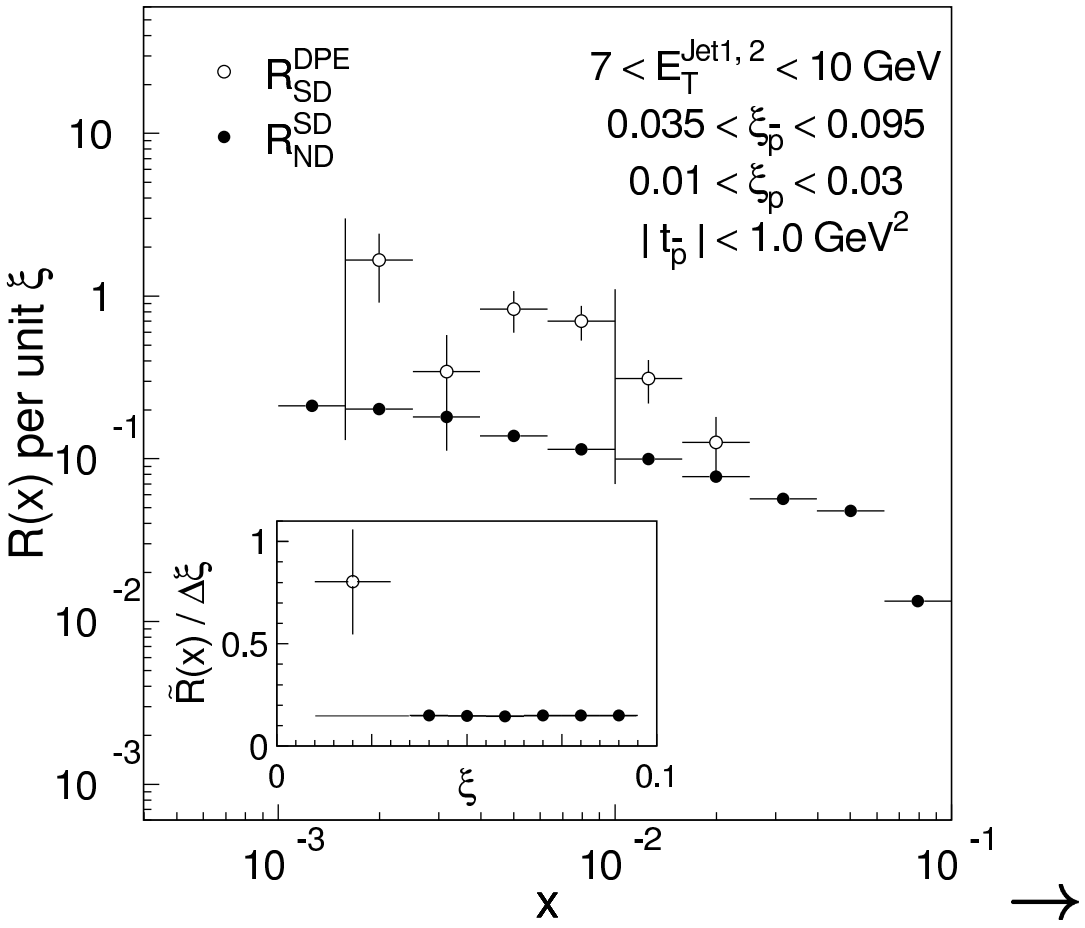
**$\longrightarrow$ Breakdown of factorisation**

**Note: factorisation proof does not hold for $p\bar{p}$, only for $ep$.**

# Diffraction at Tevatron

**compare $R_{SD}^{DD}$ with $R_{ND}^{SD}$**

**factorisation test within Tevatron**

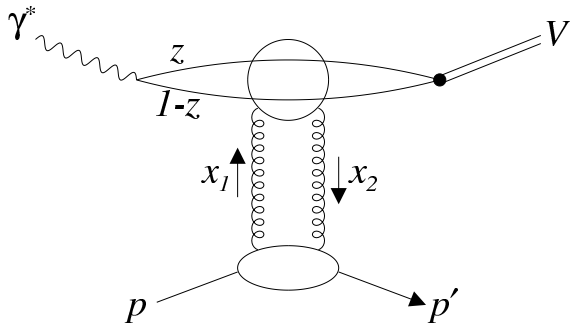



**Breakdown of factorisation**

$$R_{SD}^{DD} = 0.80 \pm 0.26$$

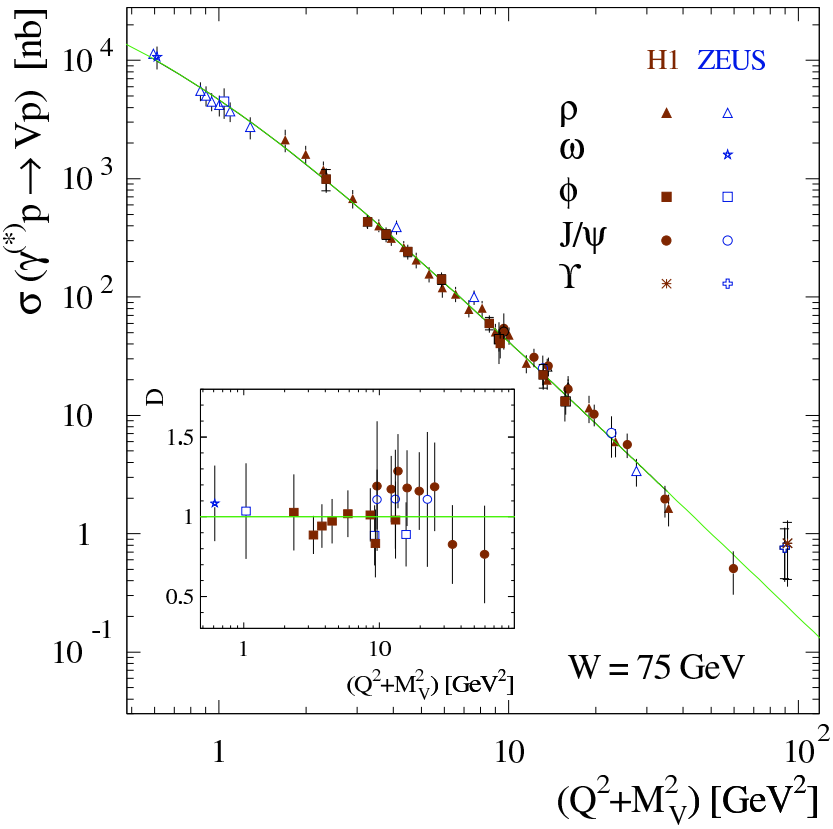
$$R_{ND}^{SD} = 0.15 \pm 0.02$$ **factor 5**

# Vectormeson production at HERA

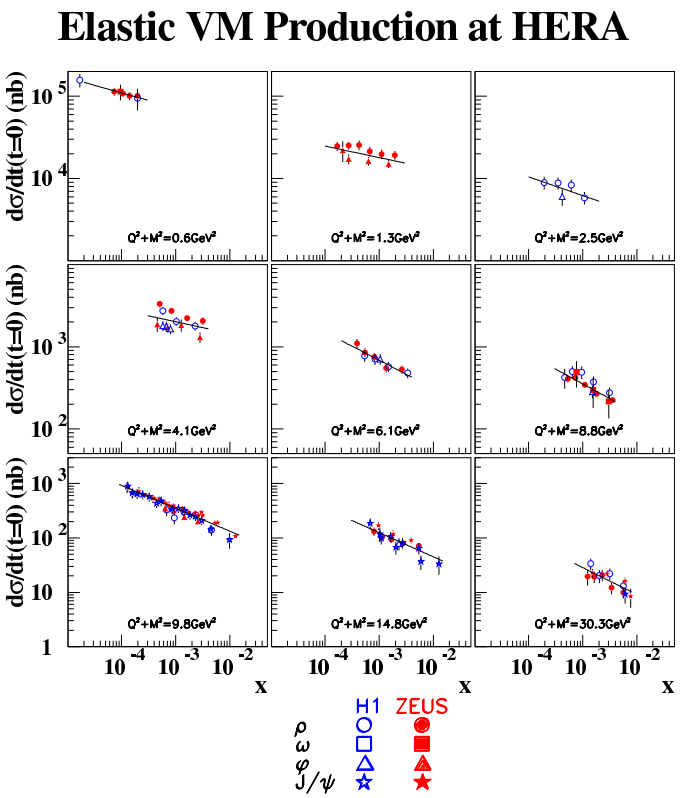


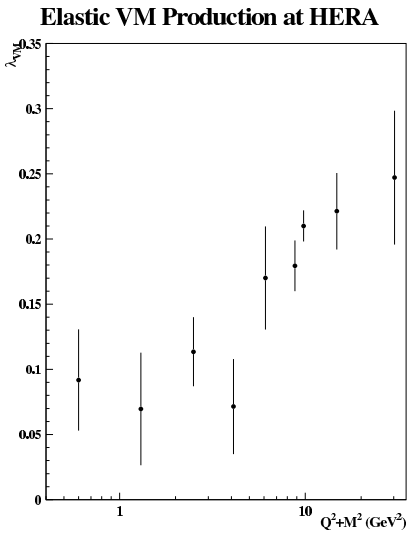

- $\gamma \rightarrow q\bar{q}$
- $q\bar{q}(g)$ **interacts with colour singlett**
- **formation of meson**

**Hard scales:** $Q^2$, $M_V$ **or** $t$



# Vectormeson production at HERA



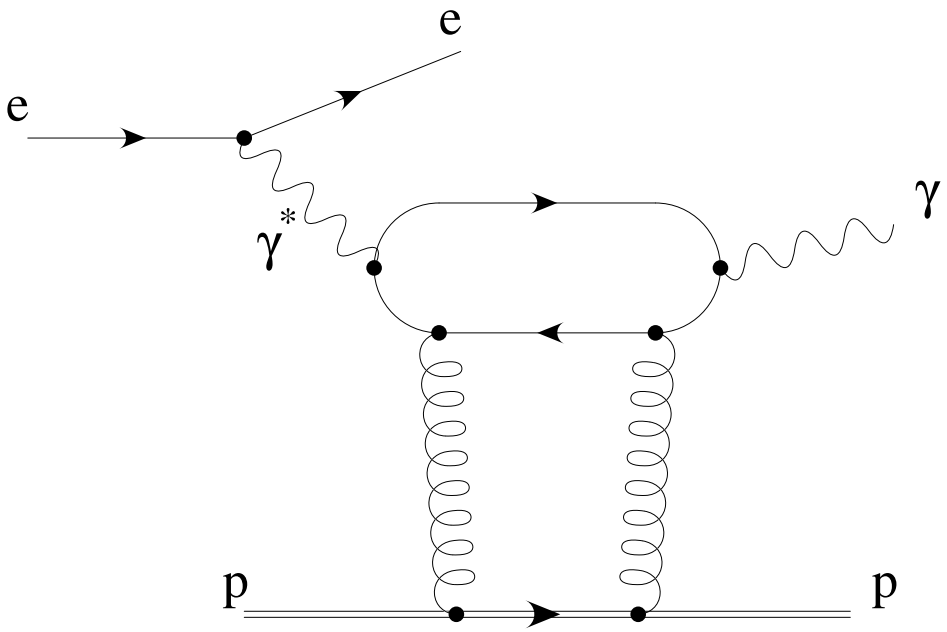

**soft process:**

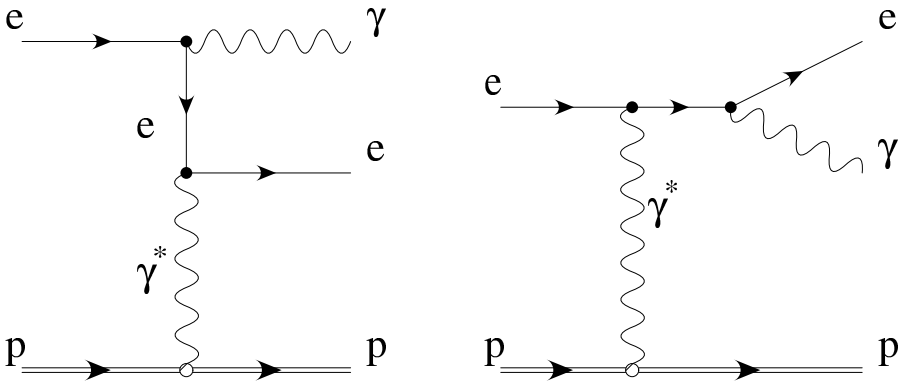
$$\lambda = 0.08$$

**clear transition between soft and hard**

**nice confirmation of pQCD scale**

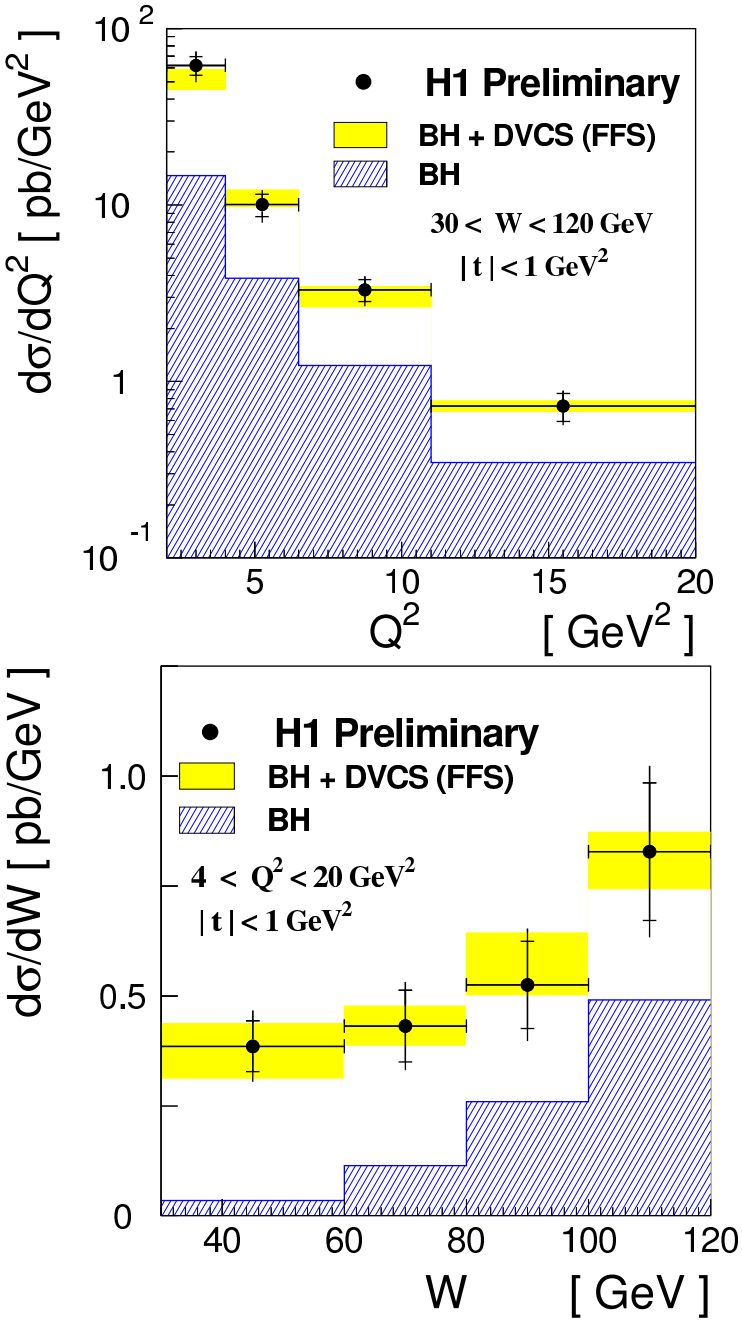
# Deeply Virtual Compton Scattering




**Interference yields access to skewed Parton Distributions** $f(x_1, x_2, Q^2)$

# Deeply Virtual Compton Scattering




**pQCD: predictd cross section nicely confirmed.**

**Needs major step in luminosity !**

# Conclusion

- **Proton structure at low $Q^2$ and low-$x$**

  significant step in precision, but gluon not yet well constrained at low-$x$ ($\sim 10^{-4}$). Nedds NNLO, and independant check: $F_L$, $F_2^{charm}$

- **Photon structure**

  much improved data: inflation of QCD fits ?!

- **QCD dynamics:**

  very promising progress in numerical predictions, theory still incomplete,

  unintegrated parton densities universal clue to many problems would be a major step !

- **Diffraction**

  pQCD successfully applied, statistics !

  factorisation theorem: HERA – TEVATRON ?

- **Spin**

  new observables: new clues for spin