Soft Interactions

ICHEP 2000, Osaka

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DESY

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

QCD is right: (previous talk)

ℓp: partons, scaling (violations)

e^+e^-: gluons, α_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**

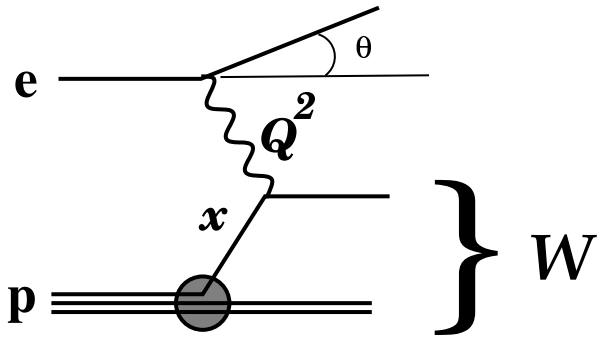
Experimental progress:

- **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:

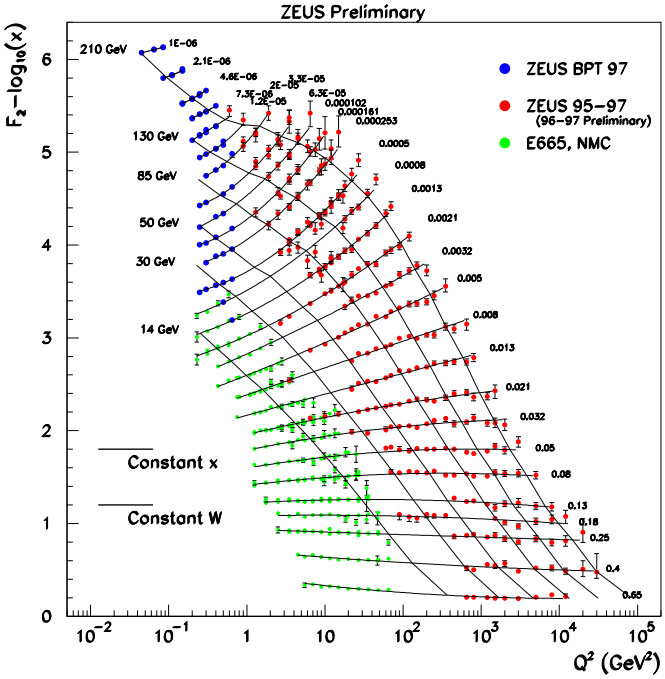
Example: $\gamma^* p \to X$



Q^2 = γ -virtuality

x = E_{parton} / E_p

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

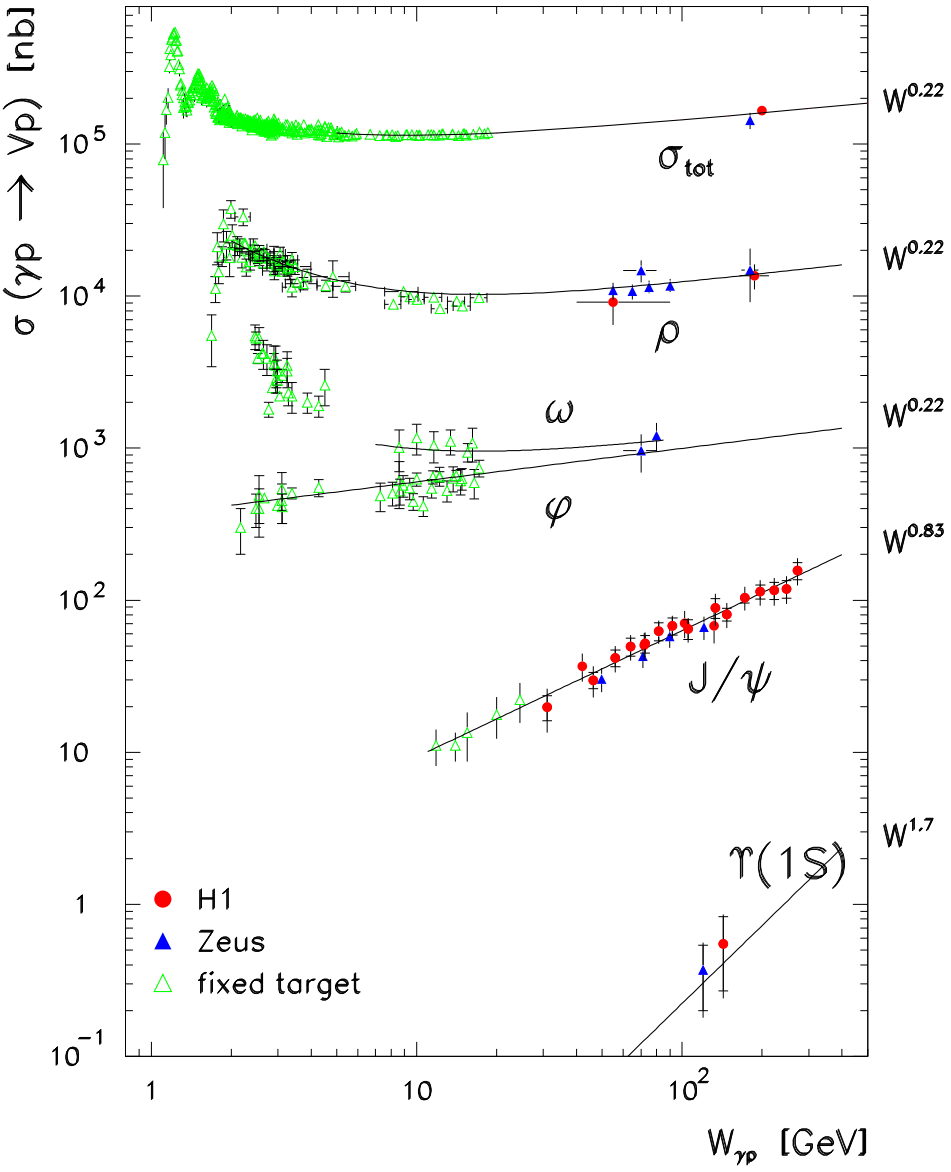


higher energy $W \leftrightarrow$ smaller x needed for same Q^2

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

- 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

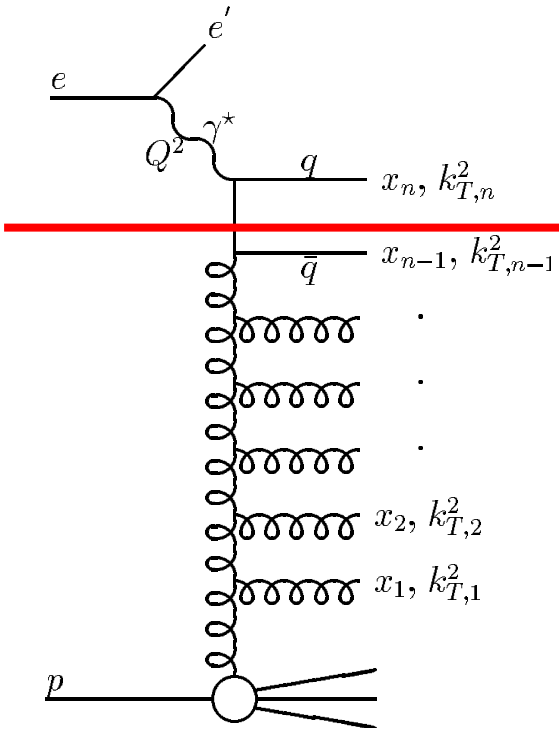
1) Altarelli-Paresi approximation (DGLAP)

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:

$\sum \ln Q^2$

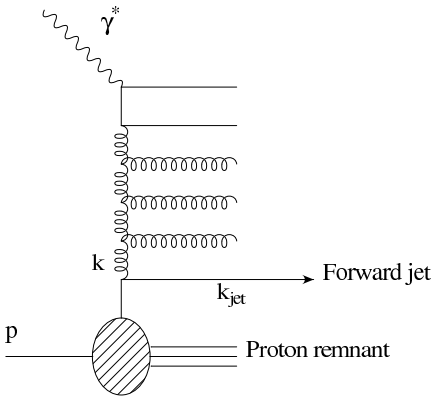
- **DGLAP basis for 'standard' QCD (α_s, ...)**
- **DGLAP must fail when:**
  - **Q^2 too small (how small ?)**
  - **x too small (phasespace!)**

    (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)

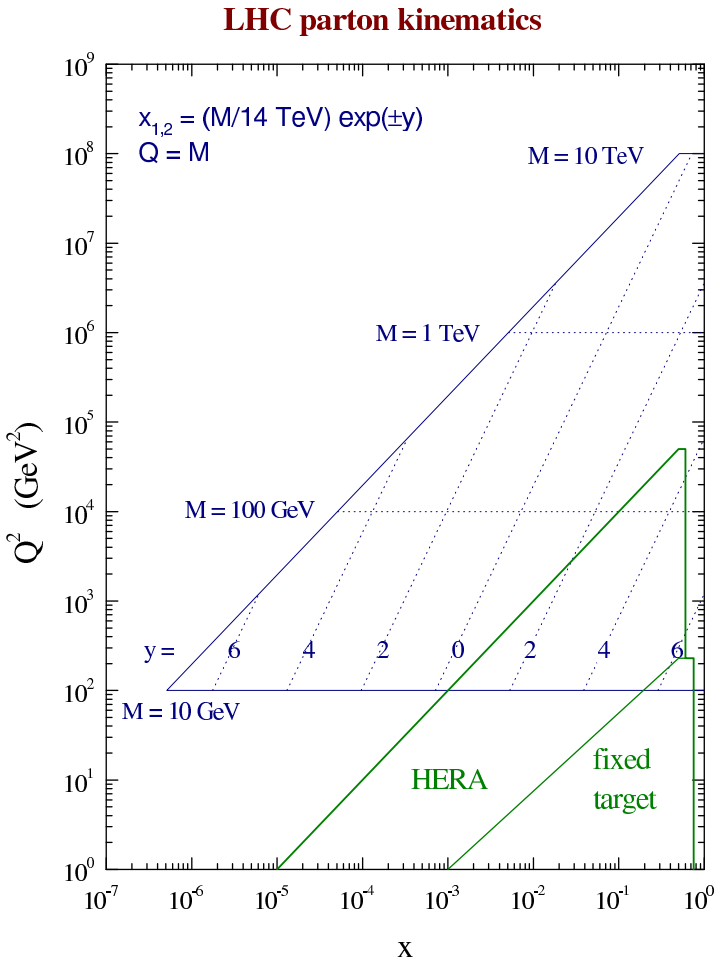
emphasis on QCD interpretation of the data

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**

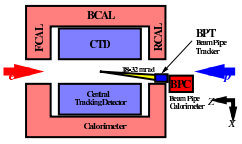
Proton Structure at low-x

New data sets with upgraded detectors:

H1: silicon tr. + spaghetti calor.

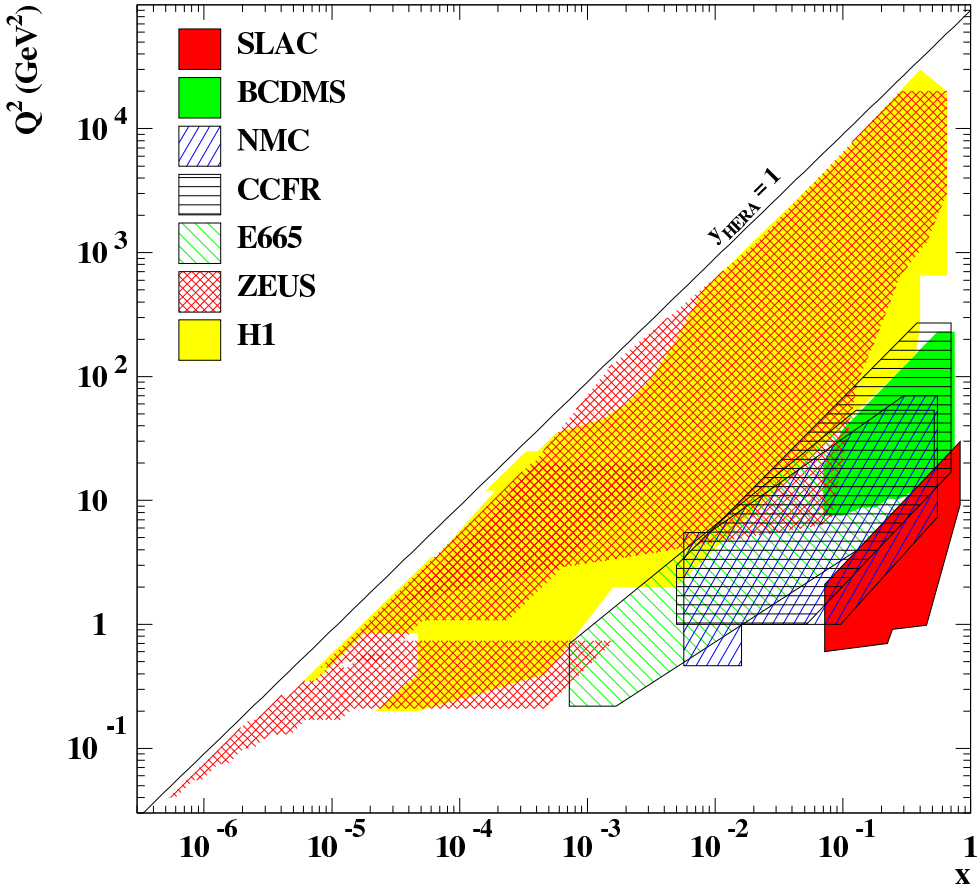
$$Q^2 > 1.5\text{GeV}$$

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

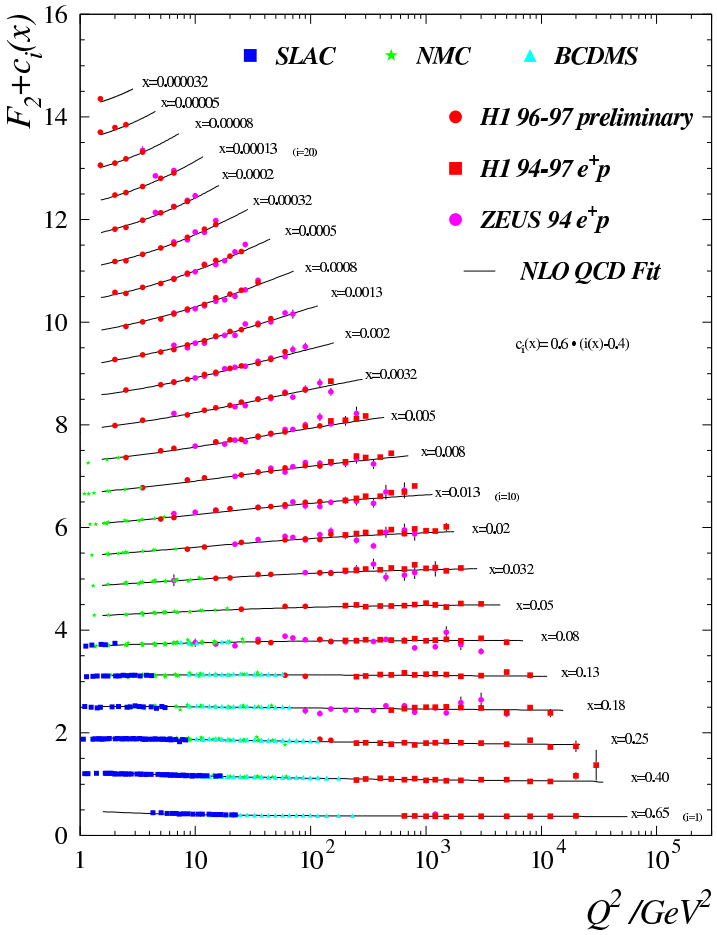
$ep \to eX$ at low Q^2:

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

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

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

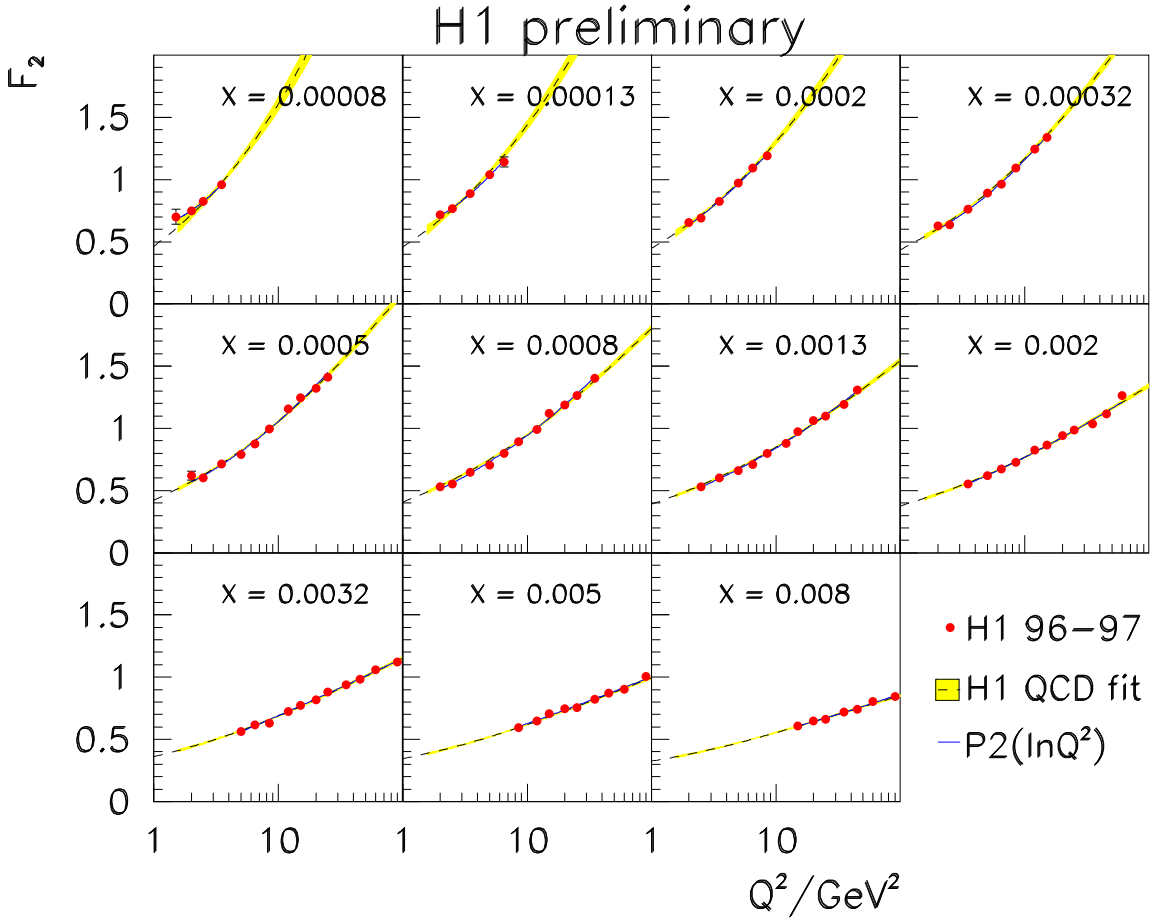
and $F_L(x,Q^2)$ contribution is typically small.



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



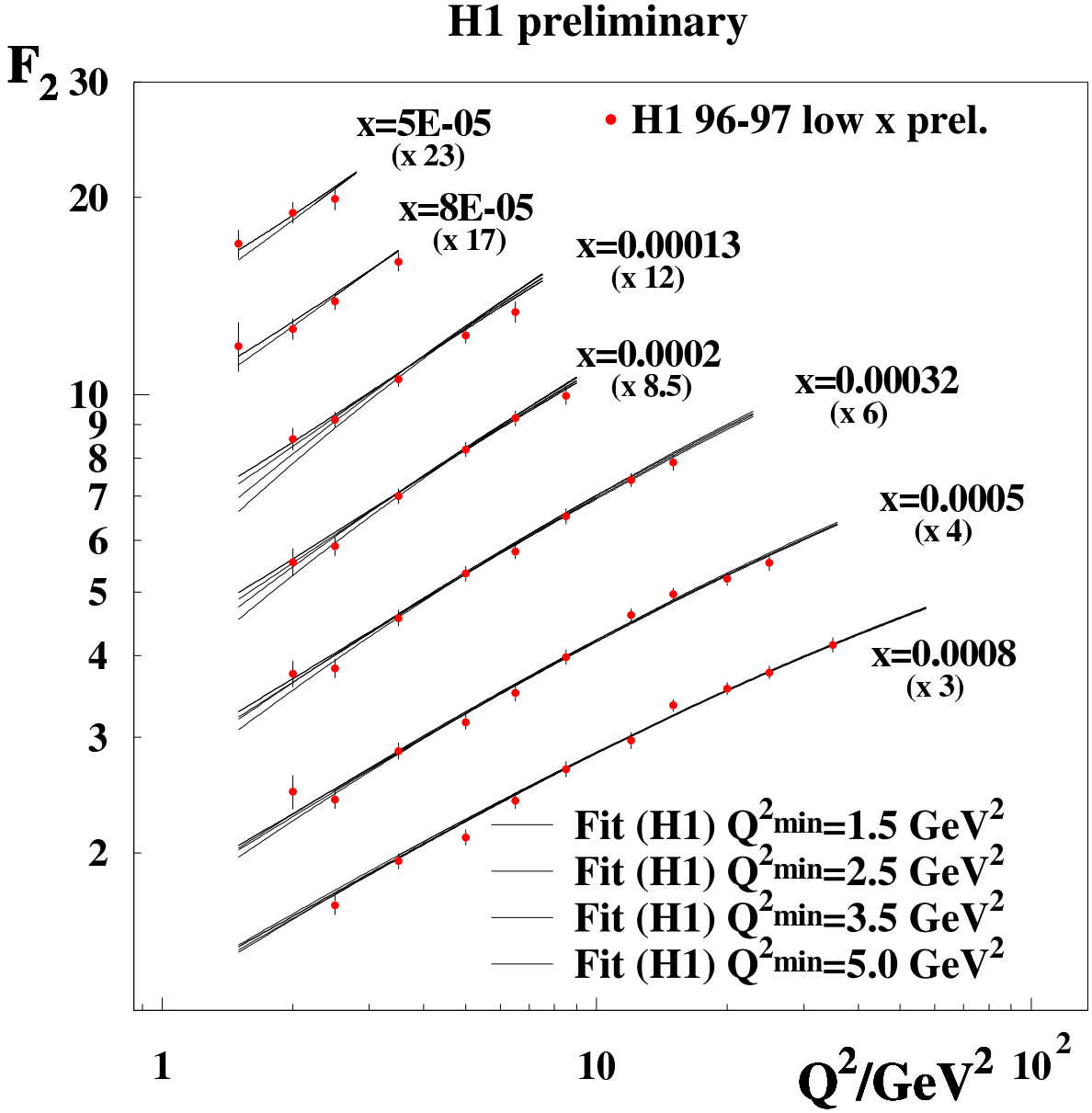
F_2 rises with Q^2: $g \rightarrow gg, q\bar{q}$ splitting

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

H1 analysis of low-x Gluon density

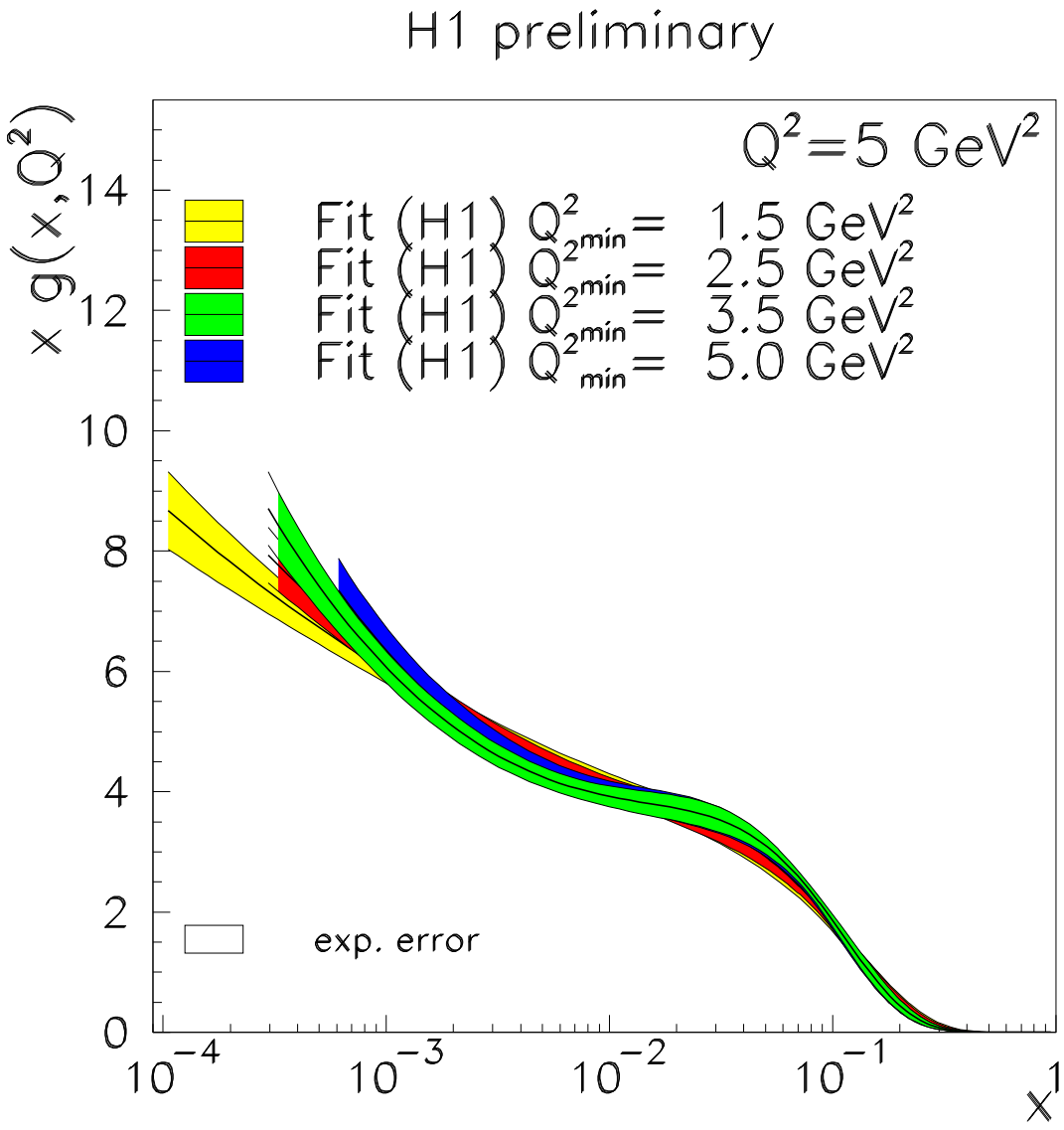
fit error dominated by Q^2_{min} cut on data !

How low in Q^2 does NLO DGLAP work ?



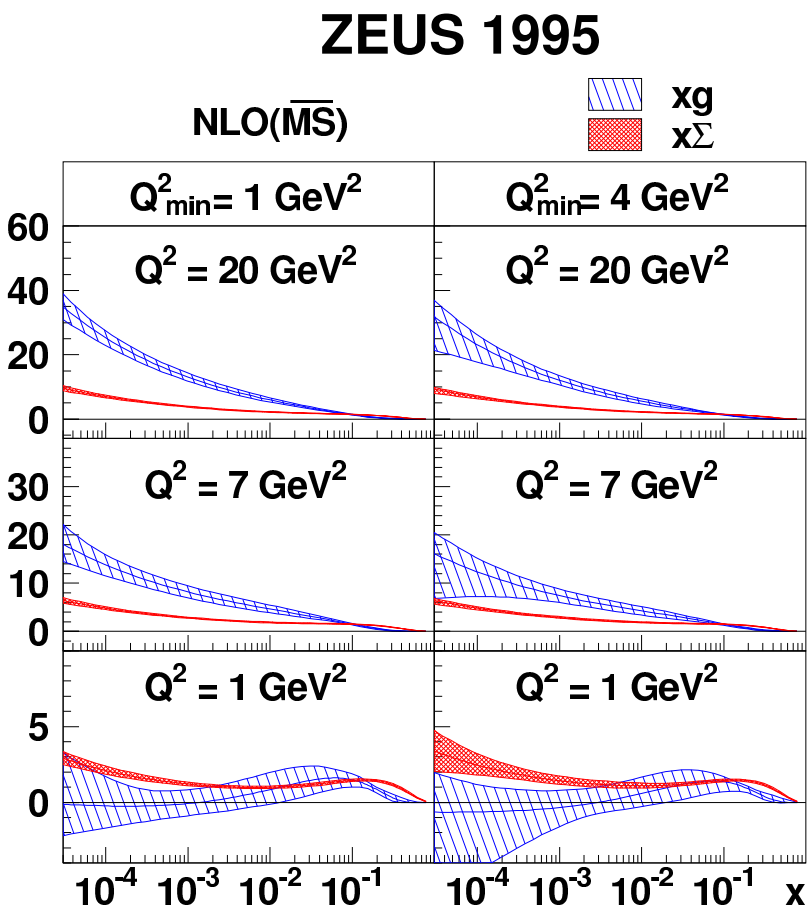
QCD fit works down to $Q^2_{min} = 1.5$ GeV^2

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

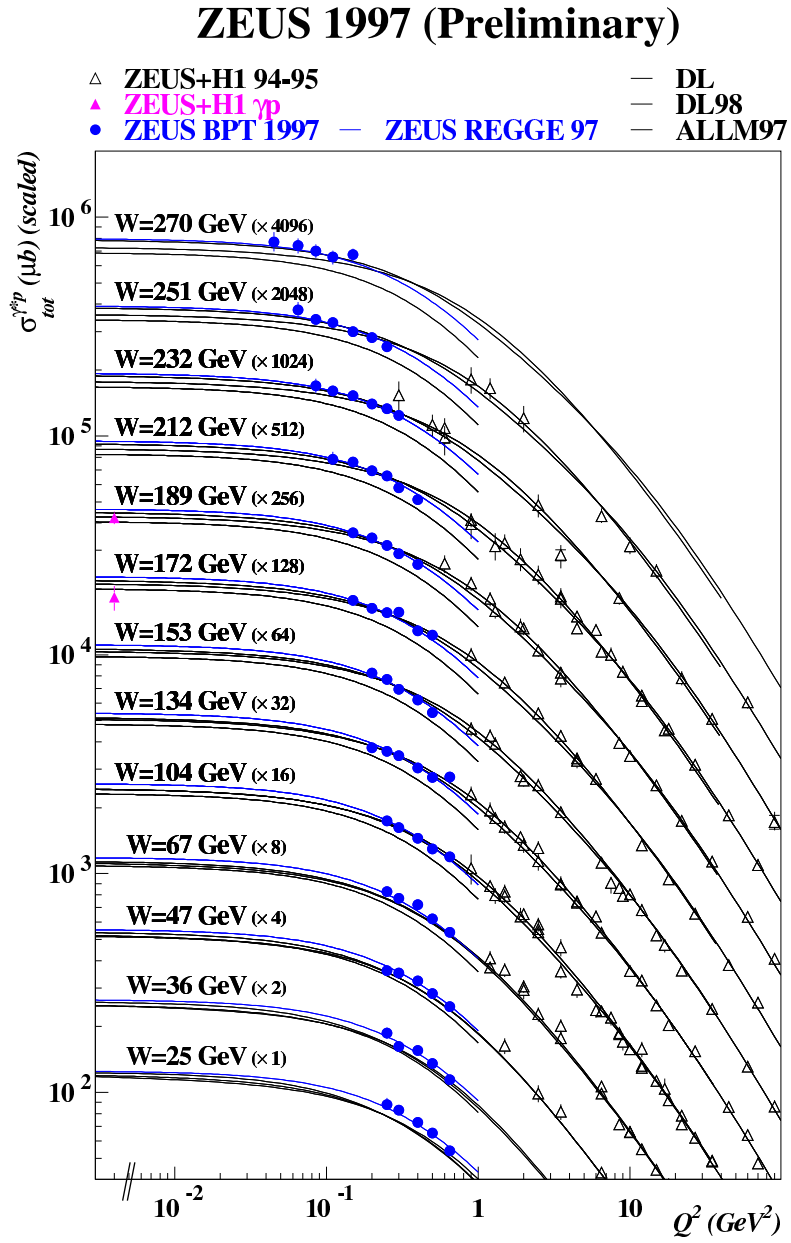
Gluon density for $Q^2 \rightarrow 1\text{GeV}^2$



- $xg(x, Q^2)$ 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

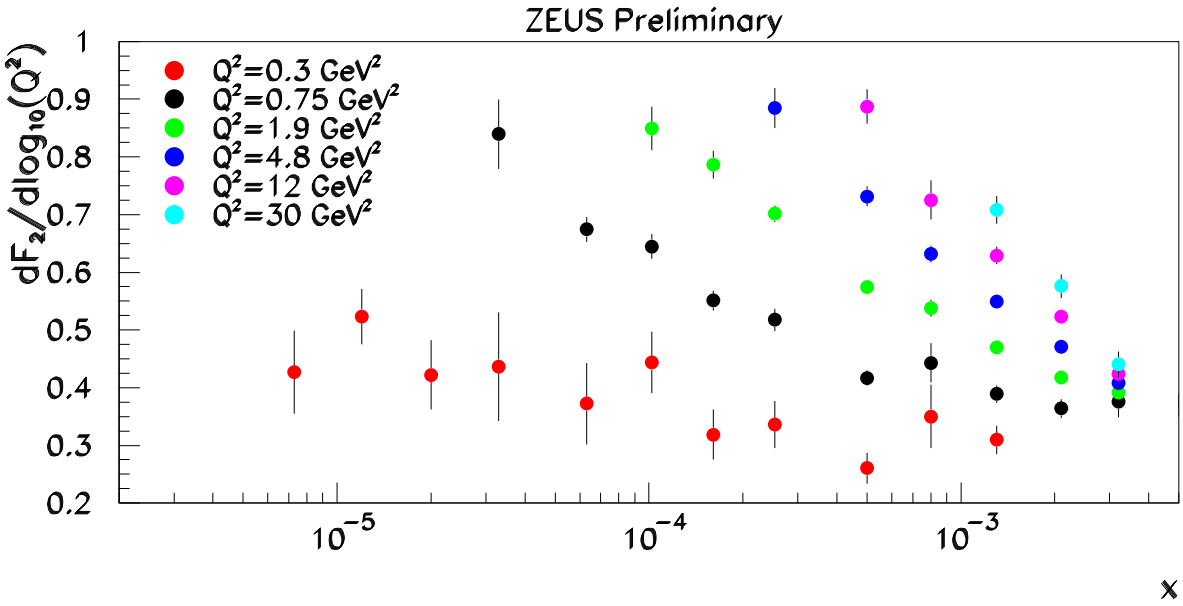


extremely low x: 10^{-6} for $Q^2 = 0.045\text{GeV}^2$

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

Transition to Photoproduction
$Q^2 \to 0$

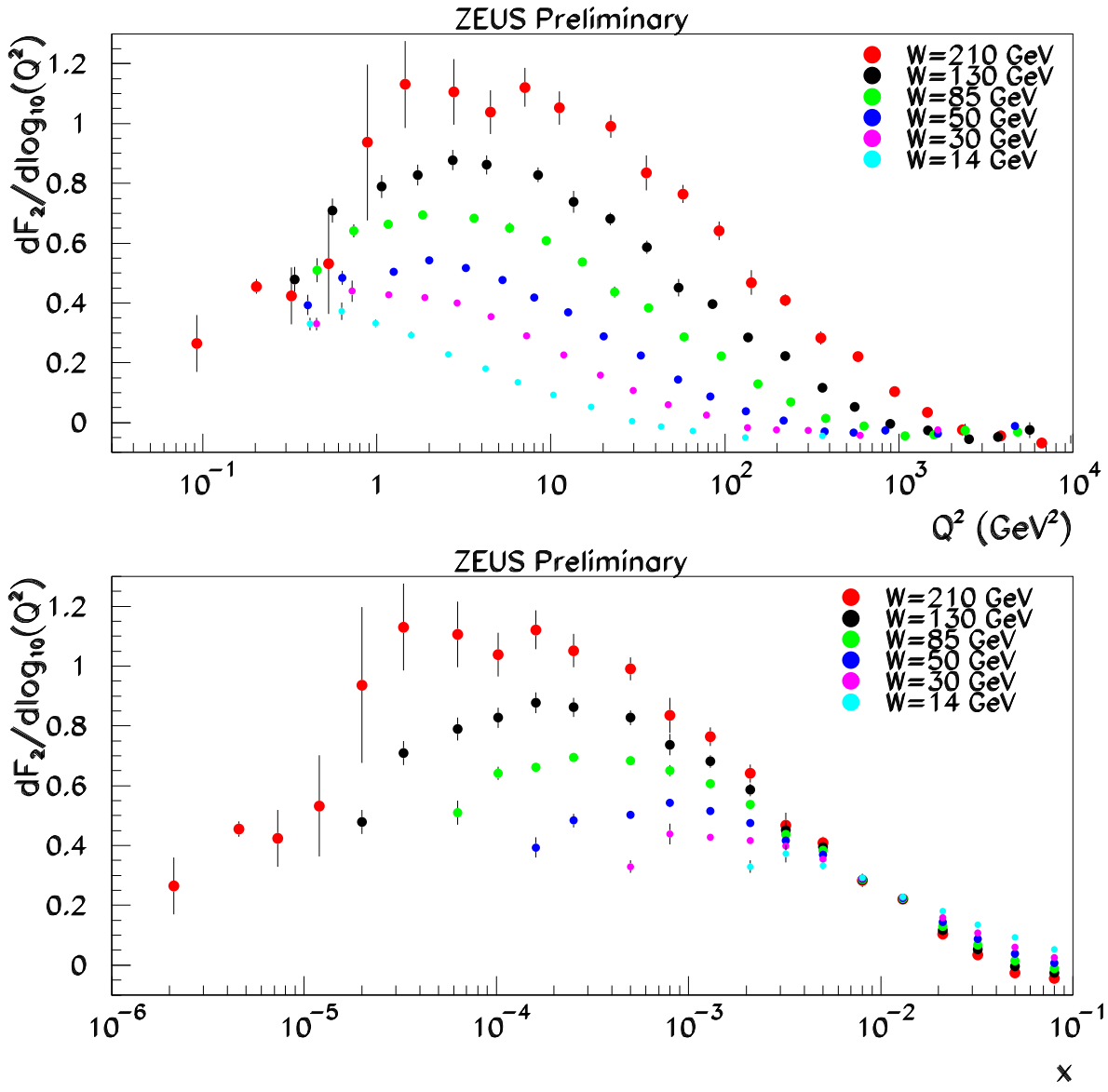
expectation: slope $dF_2/d\ln Q^2|_x$ becomes smaller for small Q^2



- **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.

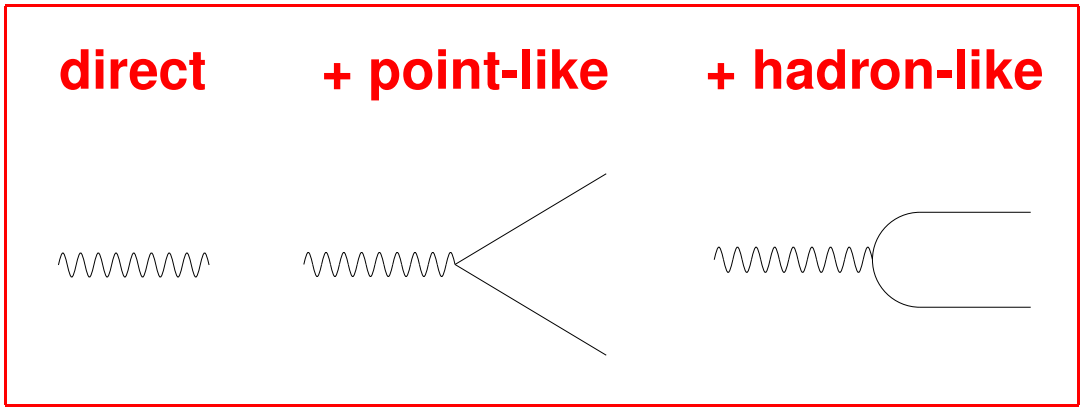
Transition to Photoproduction

$$Q^2 \to 0$$



Photon Structure

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



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

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

γ^* measured via electron: Q^2

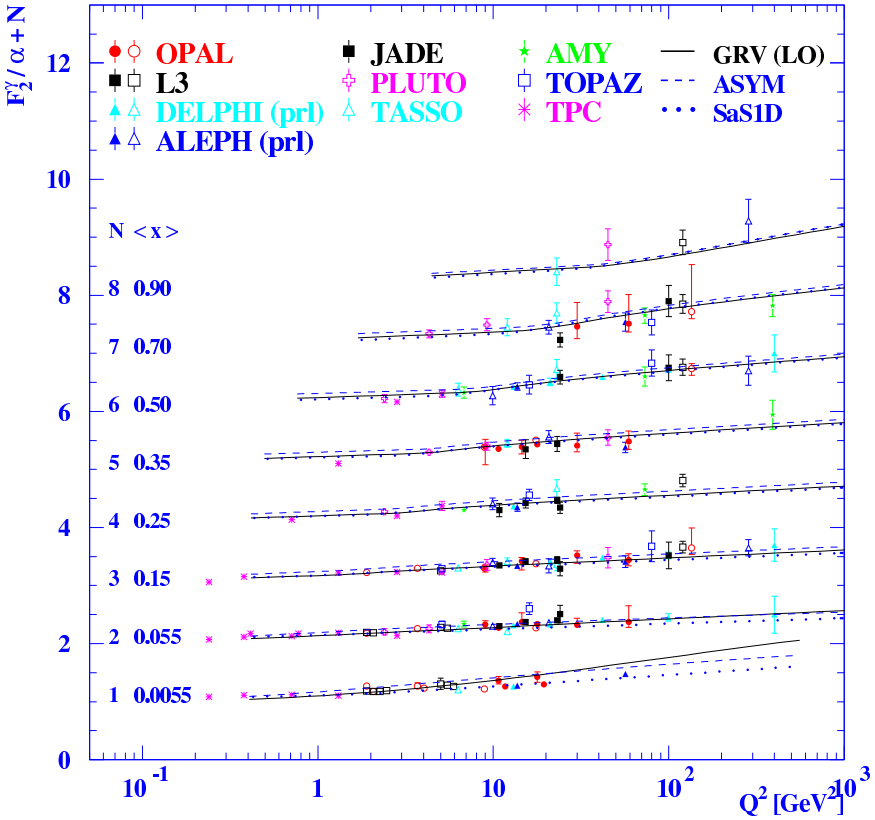
hadrons (X) used to obtain x_γ

- Previously: large uncertainties due to insufficient simulations
- Now: Major improvements: event generators, 2-dim unfolding in x_γ 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^γ:

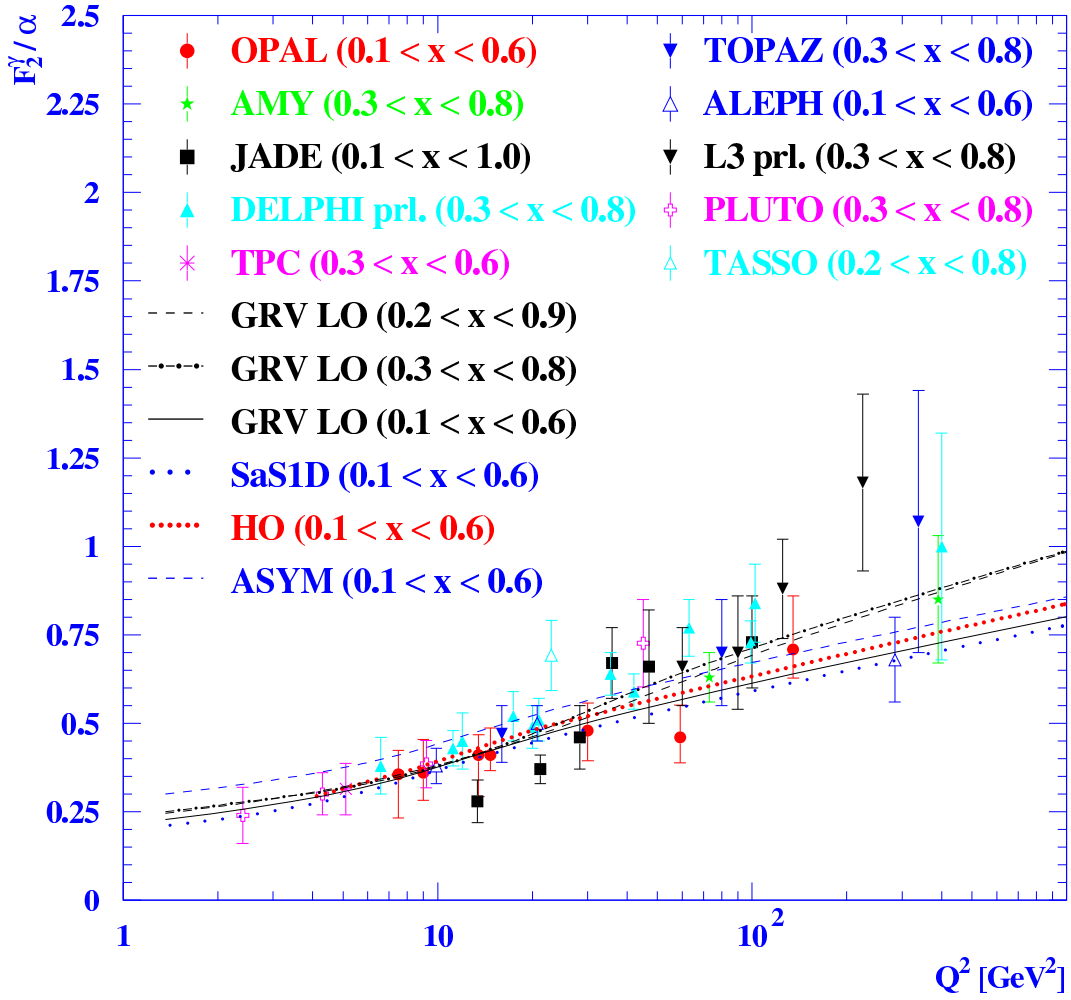
- rise for all x_γ with Q^2 due to $\gamma \rightarrow q\bar{q}$
- dominant point-like part at high x_γ
- exceed point-like component at small x_γ
- rise at very small x_γ due to gluons (hadronic component like proton)



- LEP2: extanded kinematic coverage
- consistent results between experiments

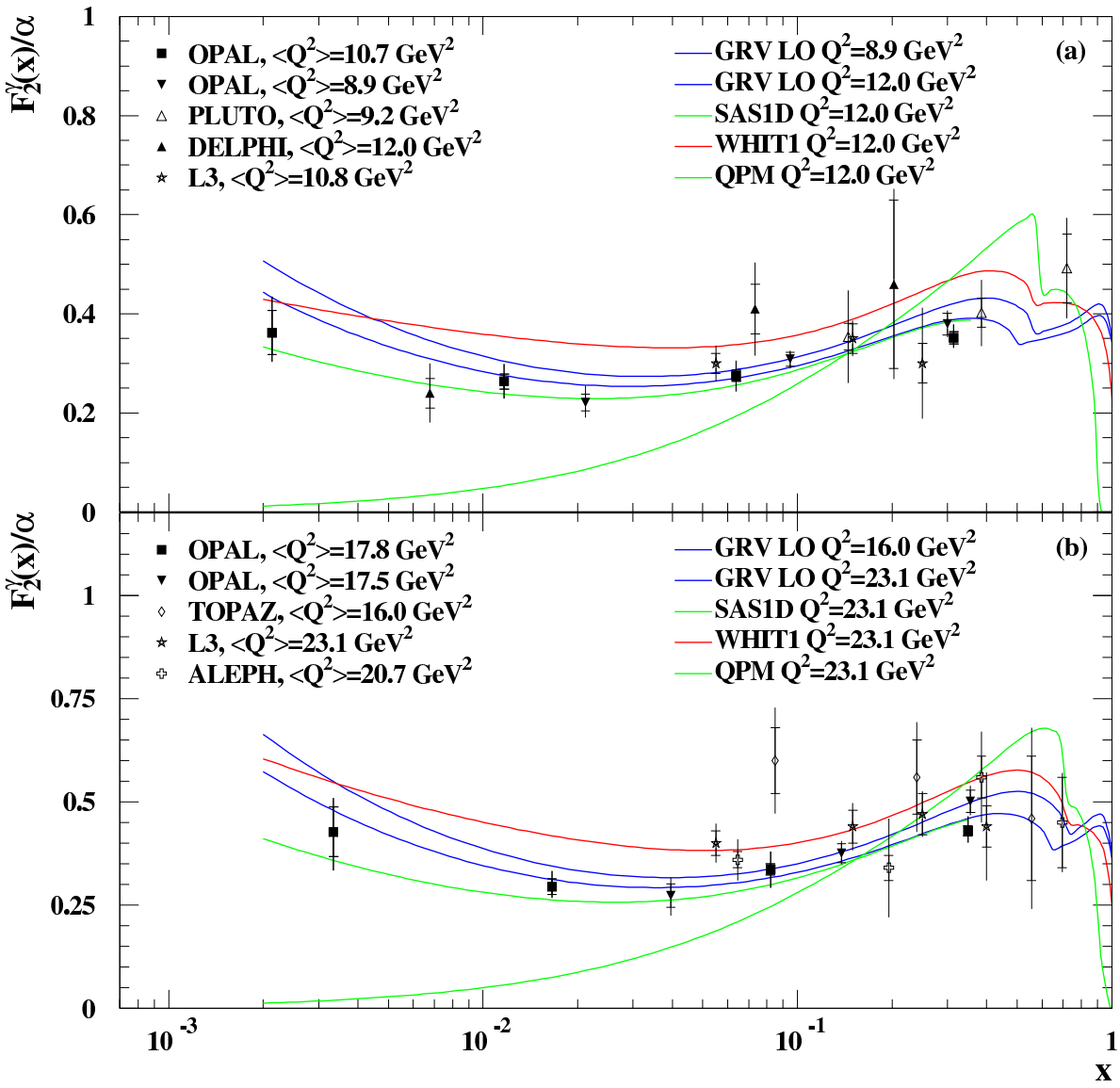
Photon Structure from LEP

large x_γ



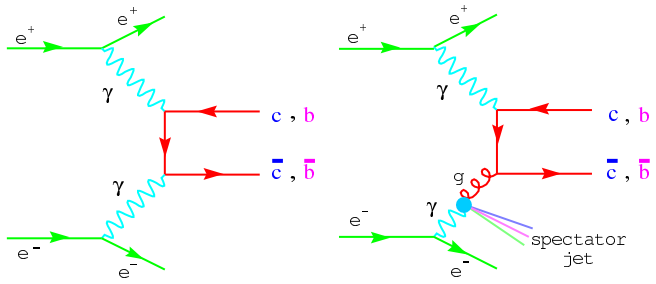
clear rise of F_2^γ with Q^2 also at high $x \longrightarrow$ point-like component

Photon Structure from LEP



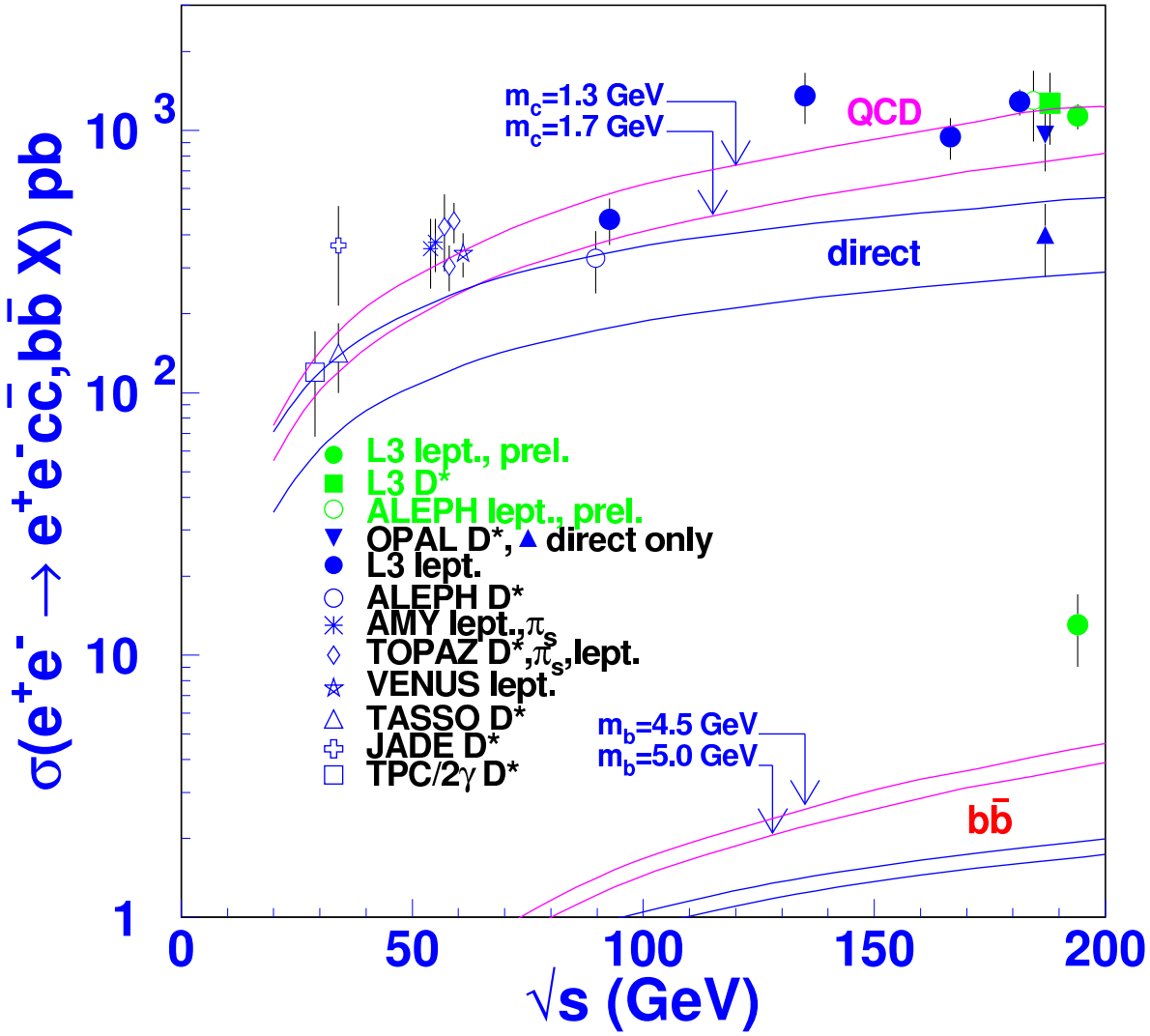
- hadronic component seen, but not yet rise of F_2^γ at very low x.
- data consistent with e.g. GRV(LO)

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



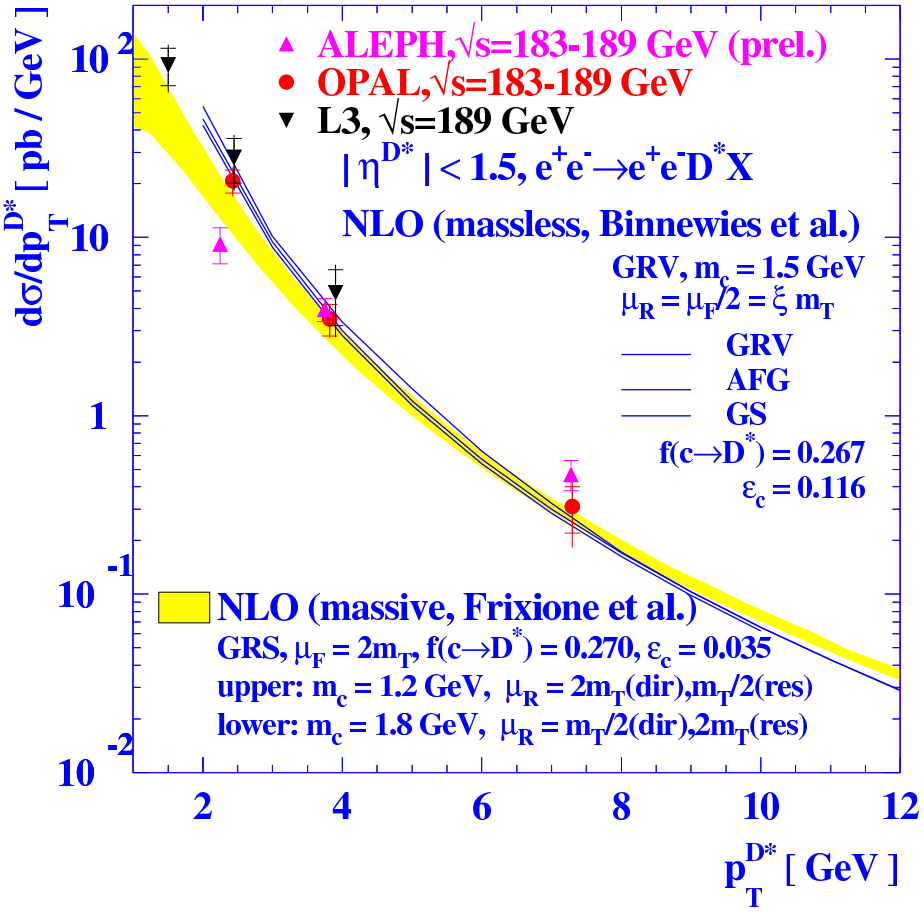
direct handle on gluon content for $x_\gamma \gtrsim 0.1$!

direct : Resolved = 1 : 1



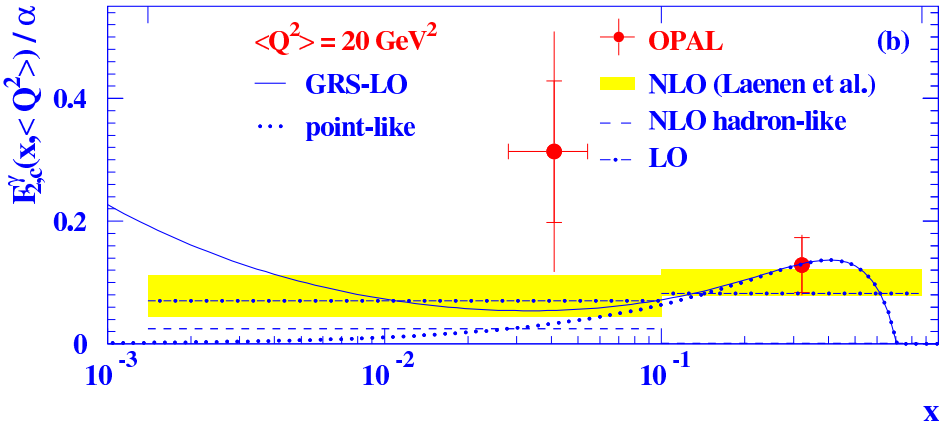
nice agreement for charm, bottom too high ?

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 γ structure

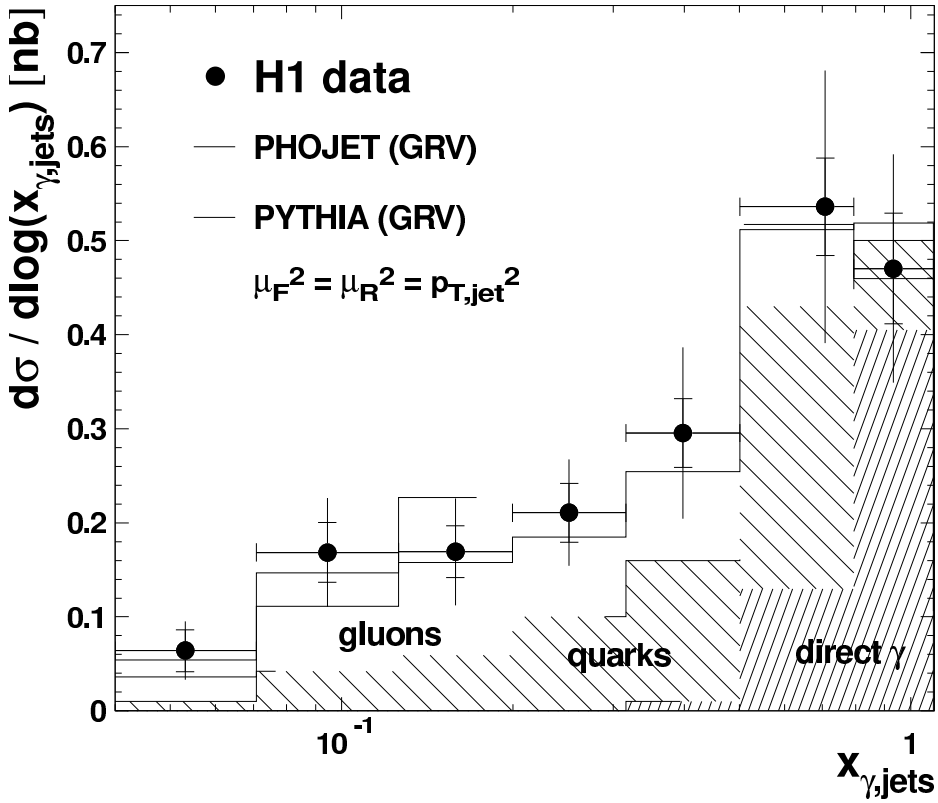
- low $x_\gamma \rightarrow$ low $E_{T,j} \leftarrow$ underl. event
- high $x_\gamma \rightarrow$ high $E_{T,j} \leftarrow$ cleaner

  see talk by R. Nania

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

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

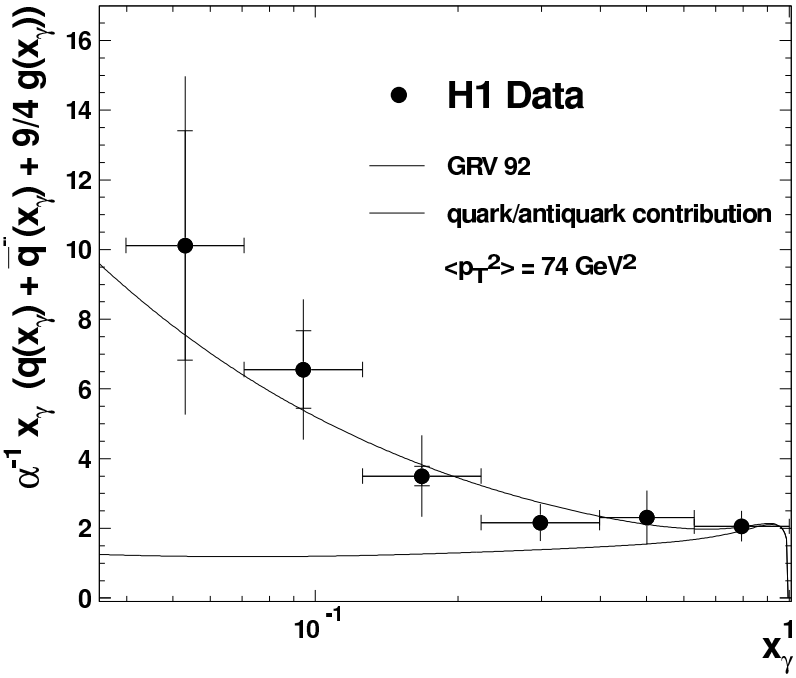
after subtraction of underlying event:



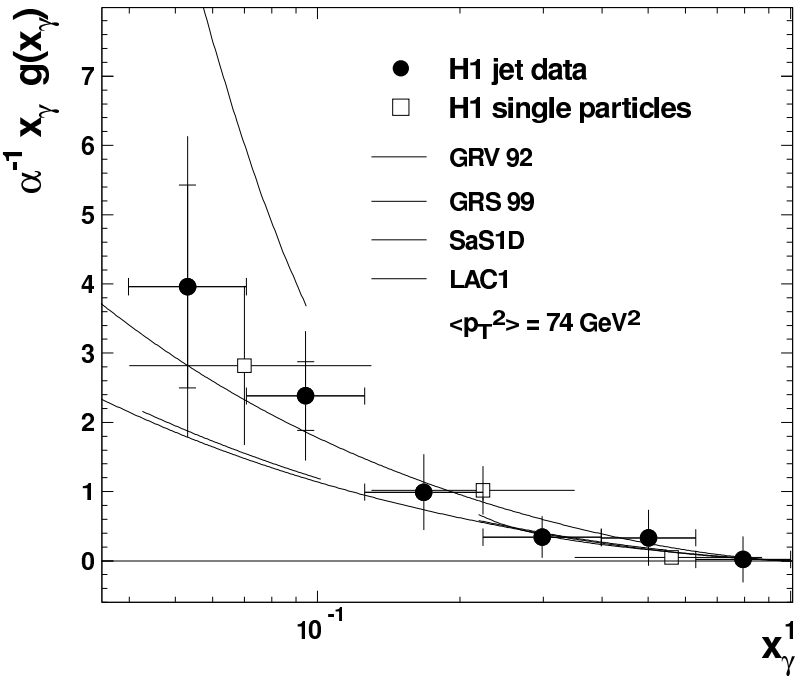
large sensitivity to gluons at small x

H1 low-x Photon Structure analysis

effective parton density



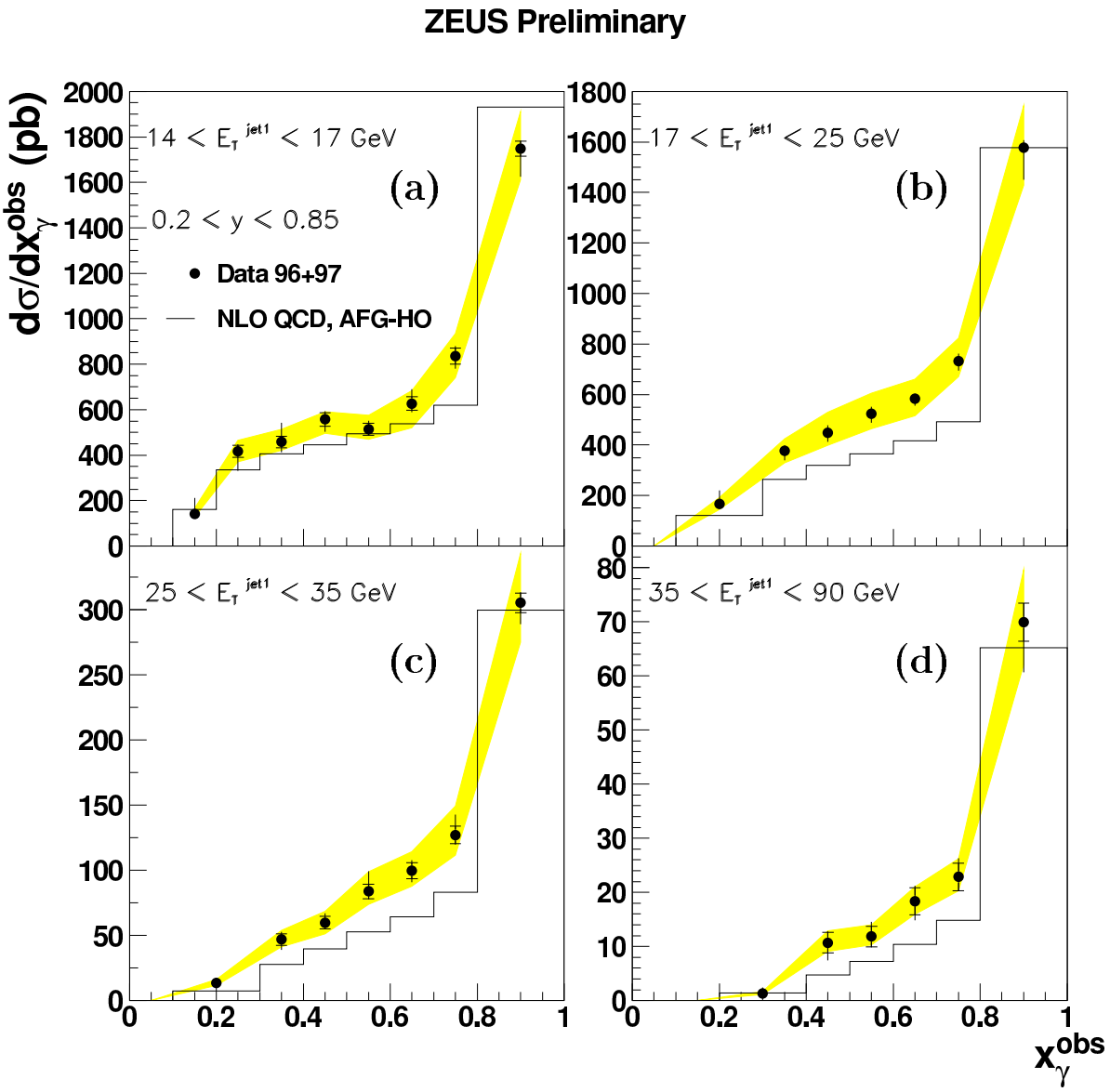
gluon density (quarks subtracted)



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^γ for quarks, charm + jets for gluons
- HERA
  - jets at high/low E_T and x_γ (q+g)

Note:

$x_\gamma \lesssim 0.2$	F_2^γ	q	$\approx$ GRV
	HERA jets	q + g	$\approx$ GRV
$x_\gamma \gtrsim 0.2$	HERA / LEP jets	q + g	$>$ GRV
	F_2^γ	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 !

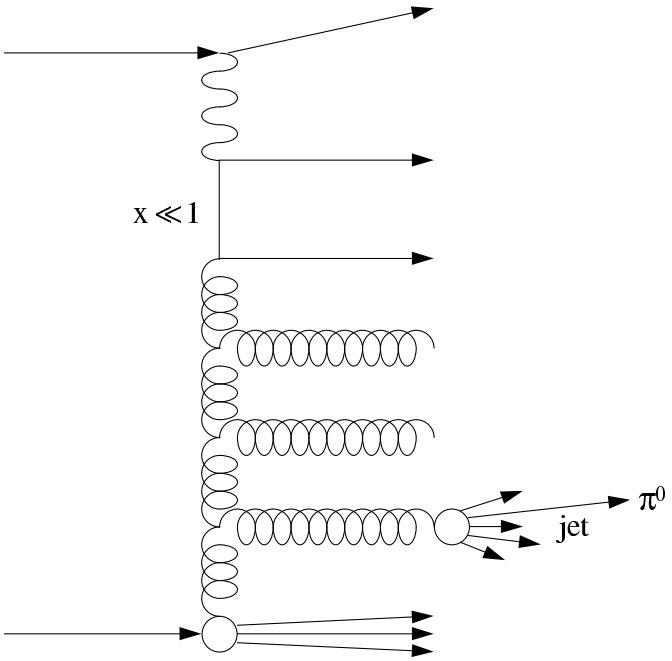
recent progress:

- 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



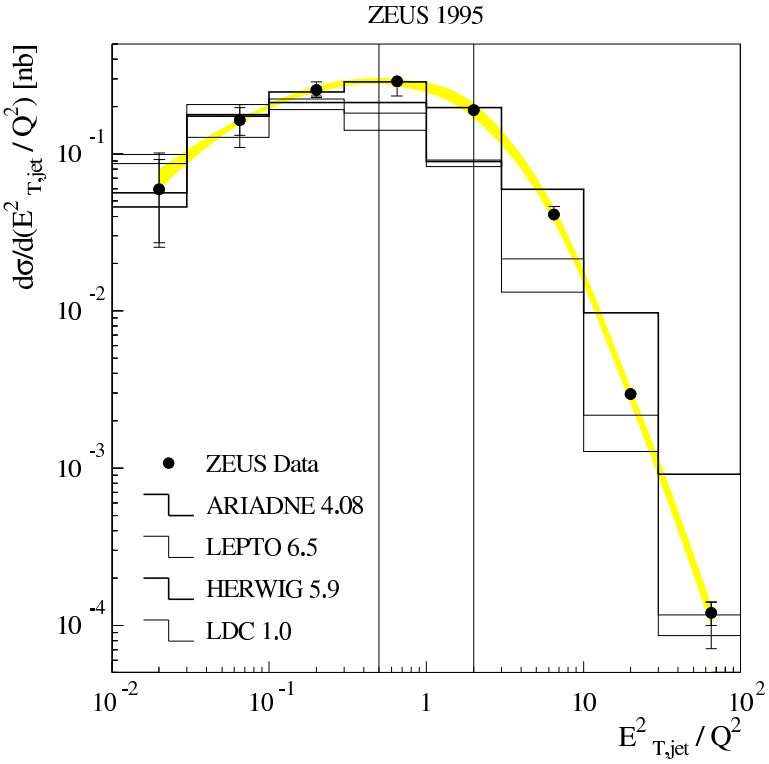
select:

- **small-x**
- **forward jet (π^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 γ
  assume virtual photon has structure which is probed by largest scale $E^2_{T,jet}$:
  2 DGLAP evolution chains.

QCD dynamics: Forward Jets



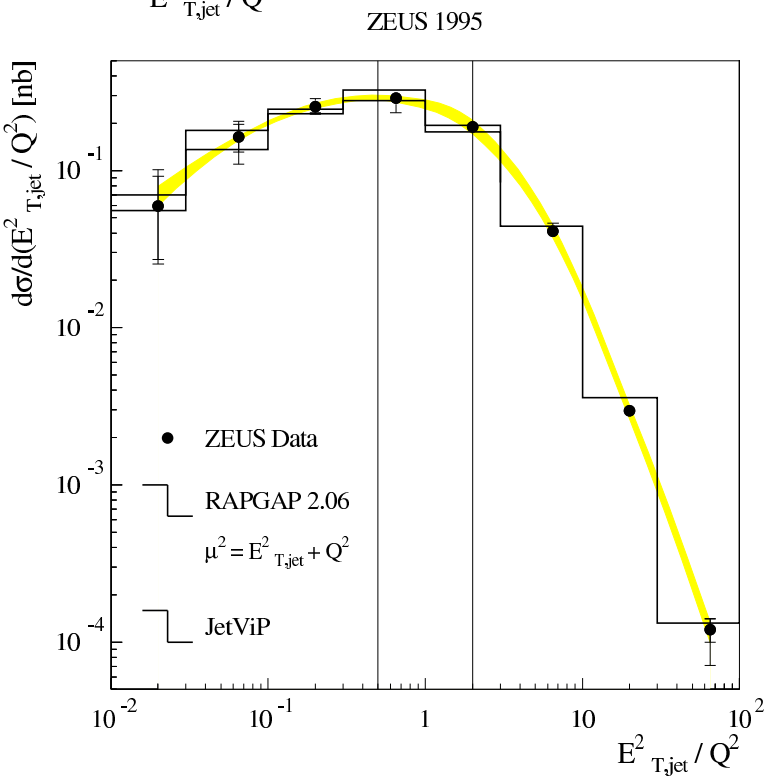
DGLAP:

fails for

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

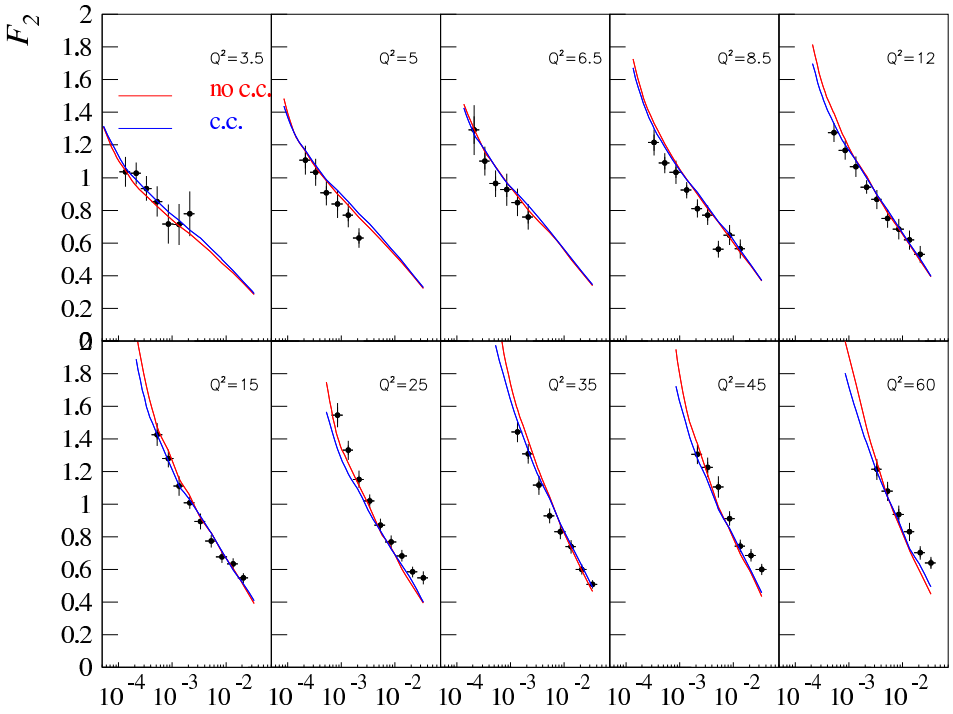
resolved virtual γ works:

sign for non-k_T order

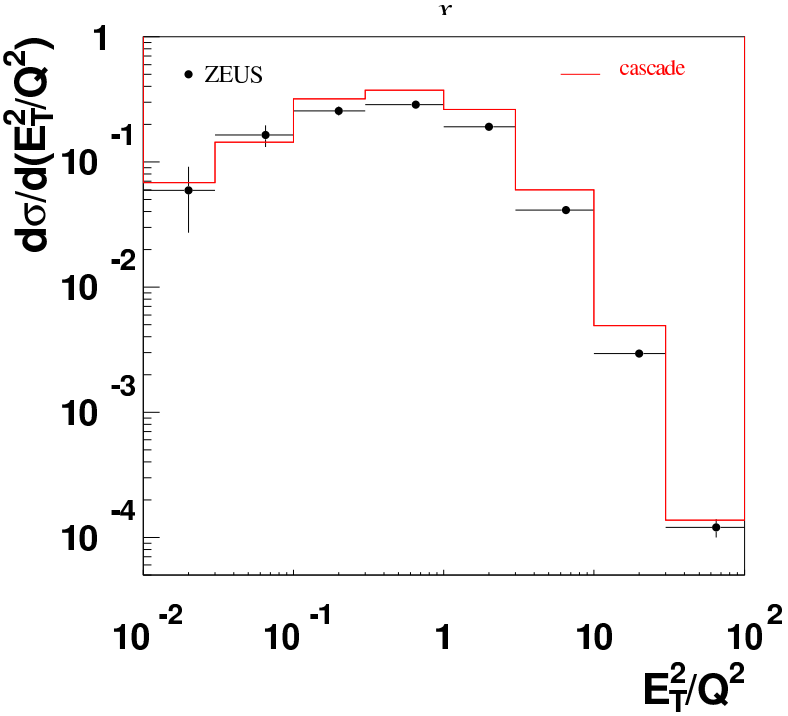


QCD dynamics: Forward Jets with CCFM

unintegrated parton density from fit to F_2

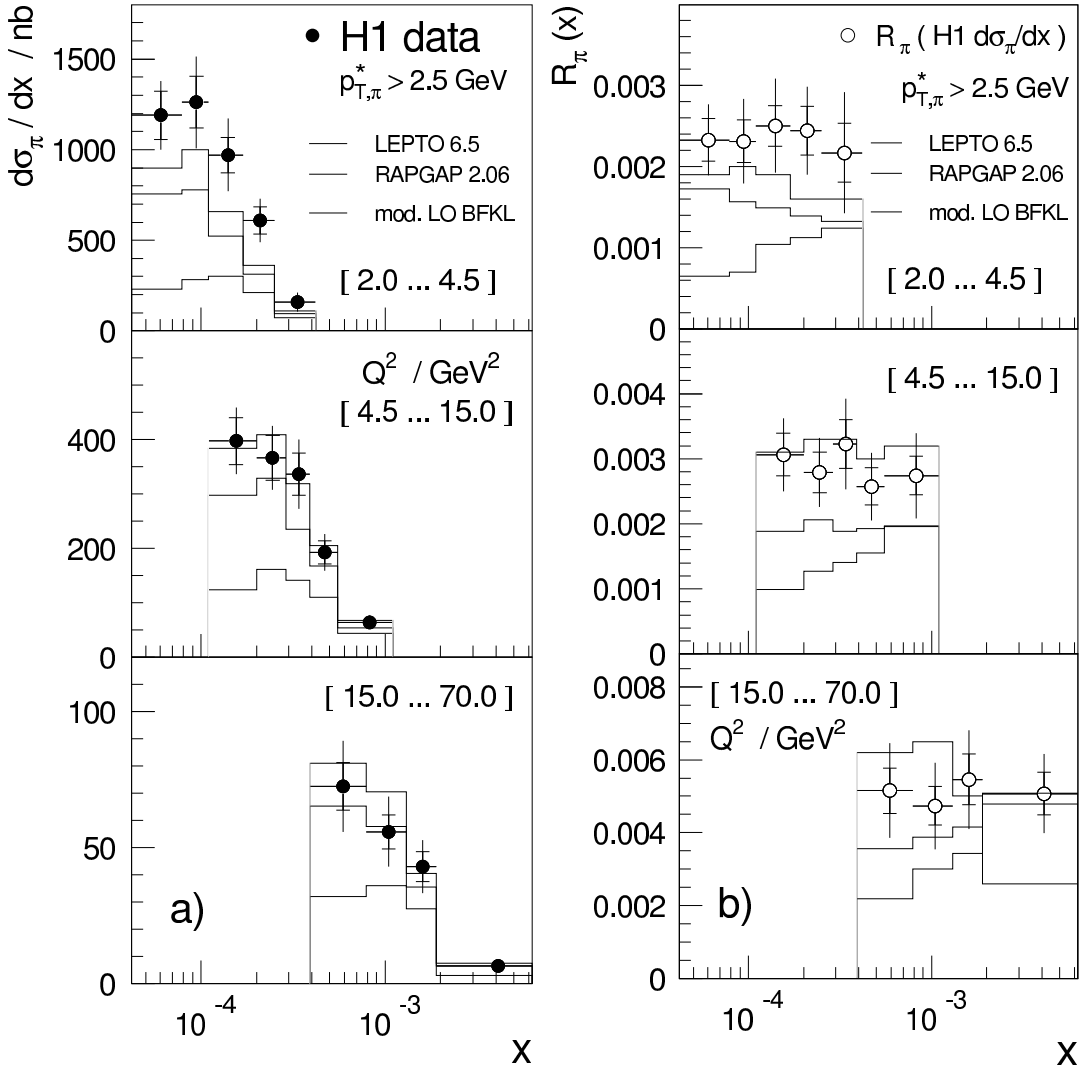


use CCFM evolution to describe jets



QCD dynamics: Forward π^0

high E_T π^0 in very forward direction

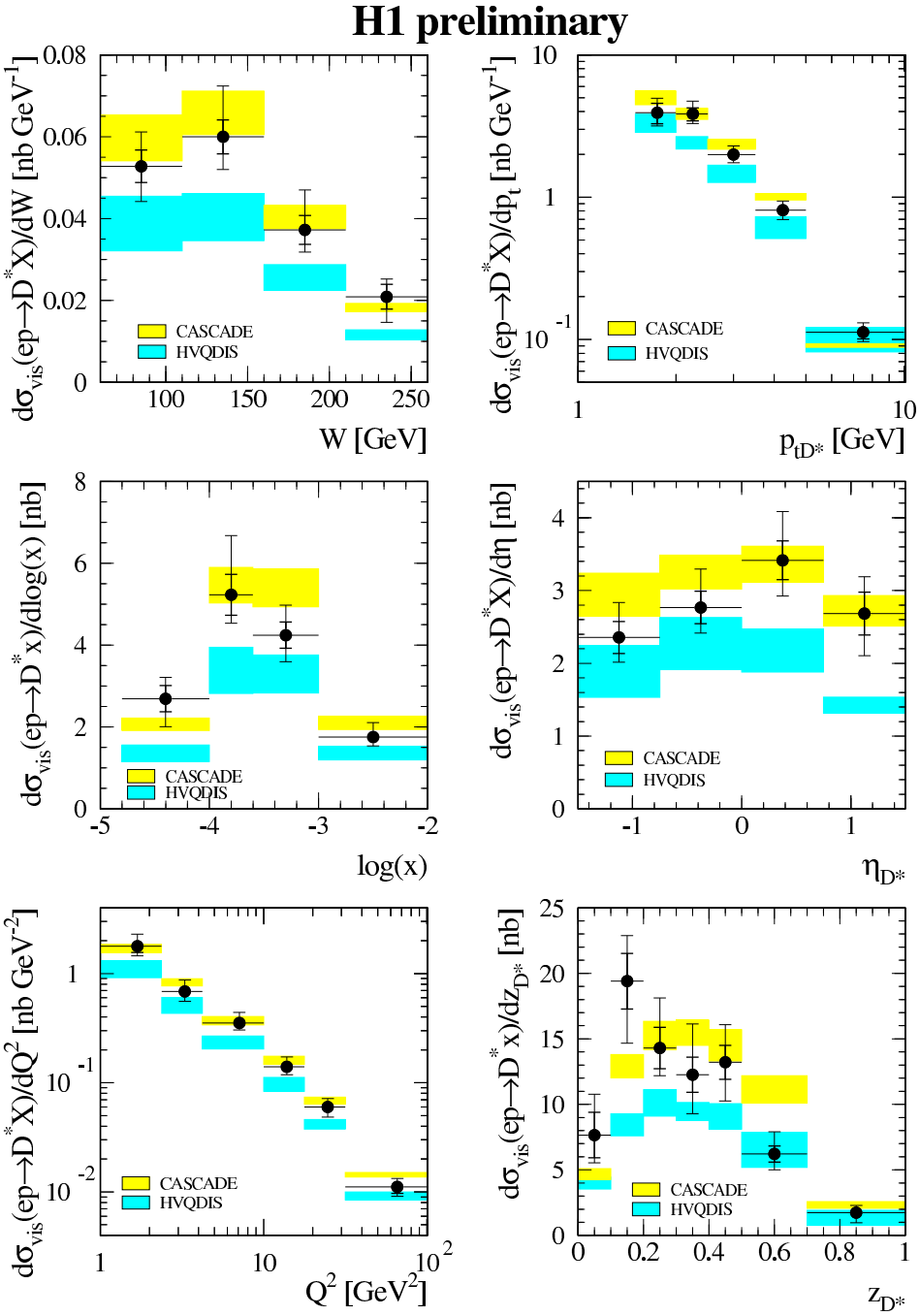


only hint on dynamics beyond

'resolved virtual photon'

QCD dynamics: Charm with CCFM

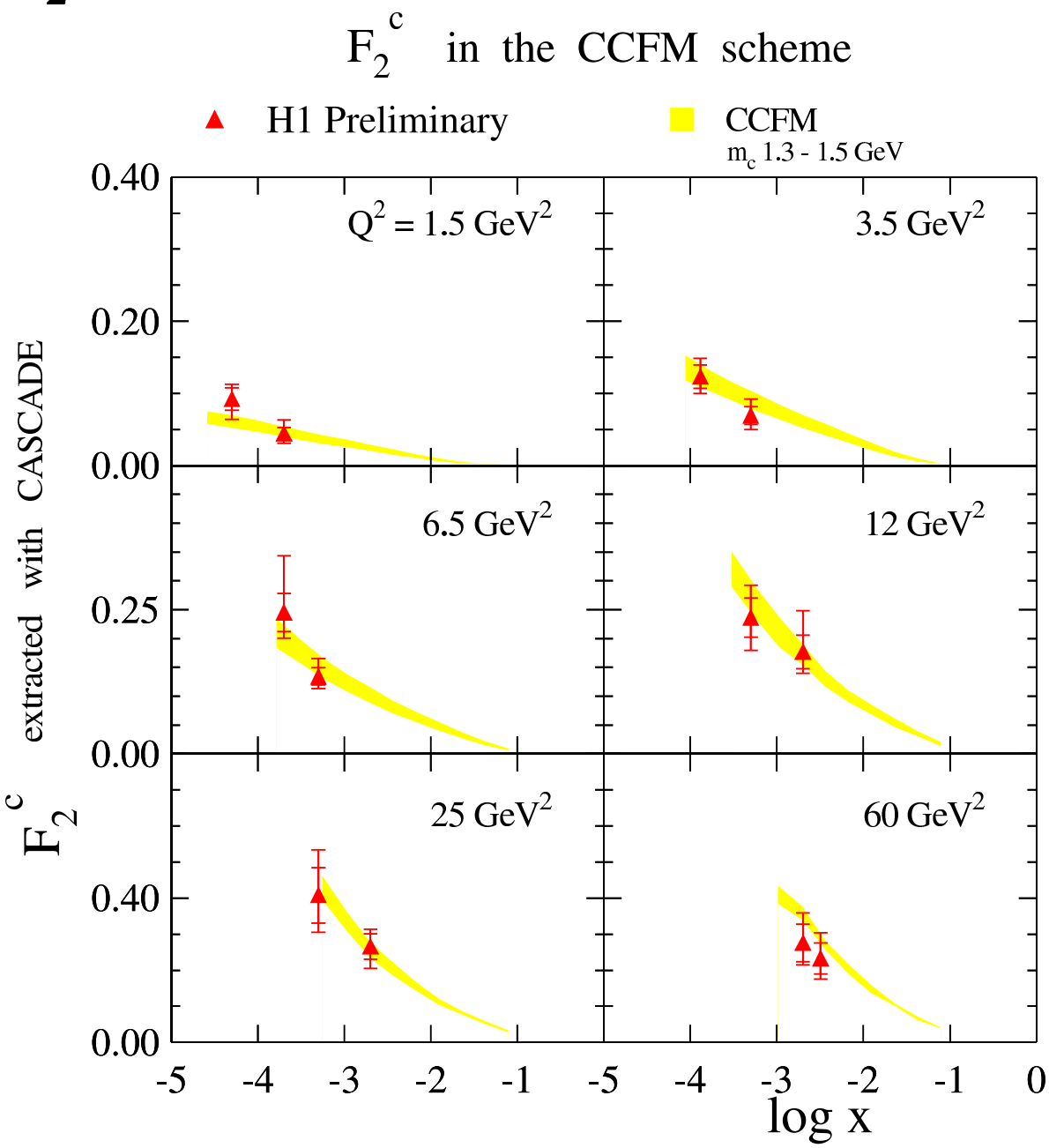
$\gamma^* g \rightarrow c\bar{c}$: charm mass is 2nd hard scale



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 γ^* 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** $\longrightarrow$

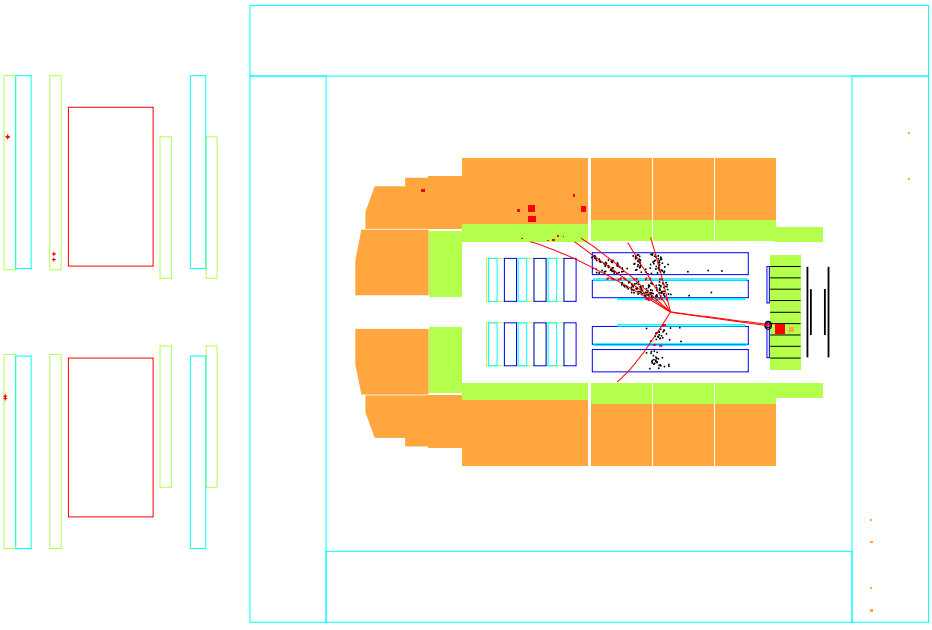
proton fragments

What happens in elastic scattering ?

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

    γ^* hits parton but p survives

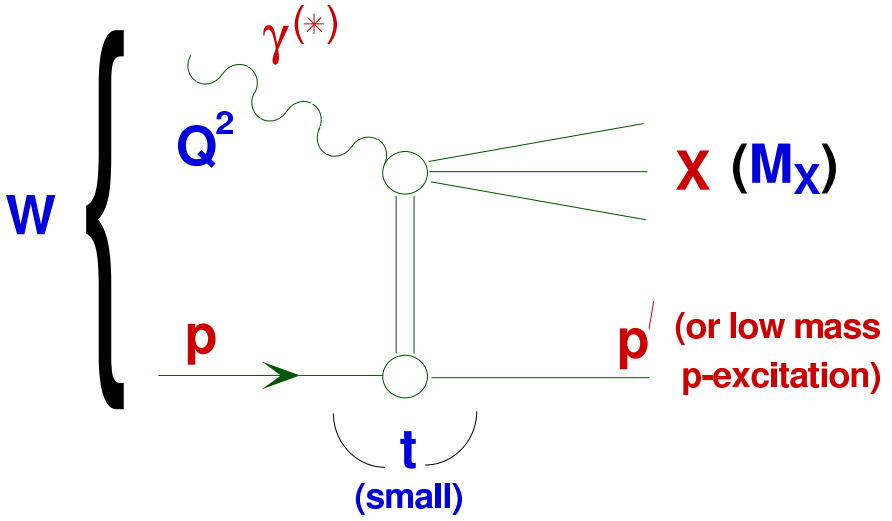
no proton frag-ments



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.

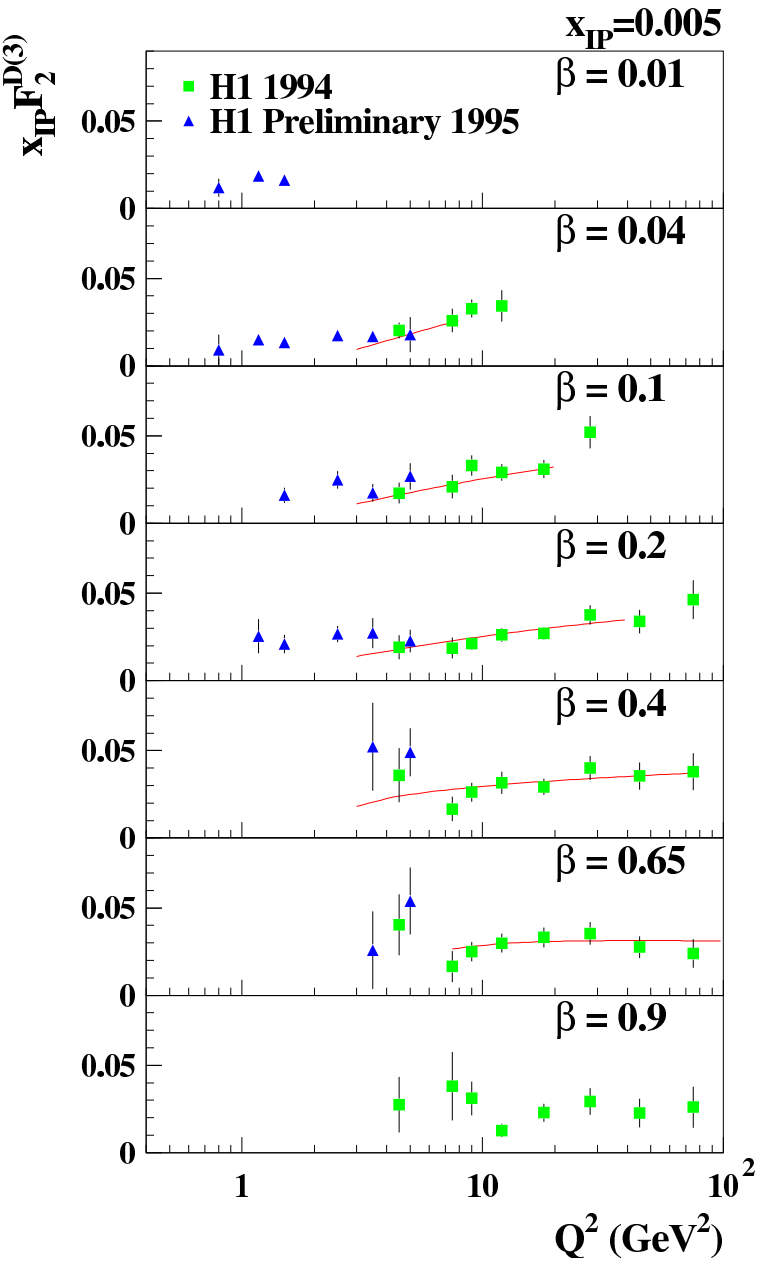
$$F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

$x_{I\!P}$ **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:

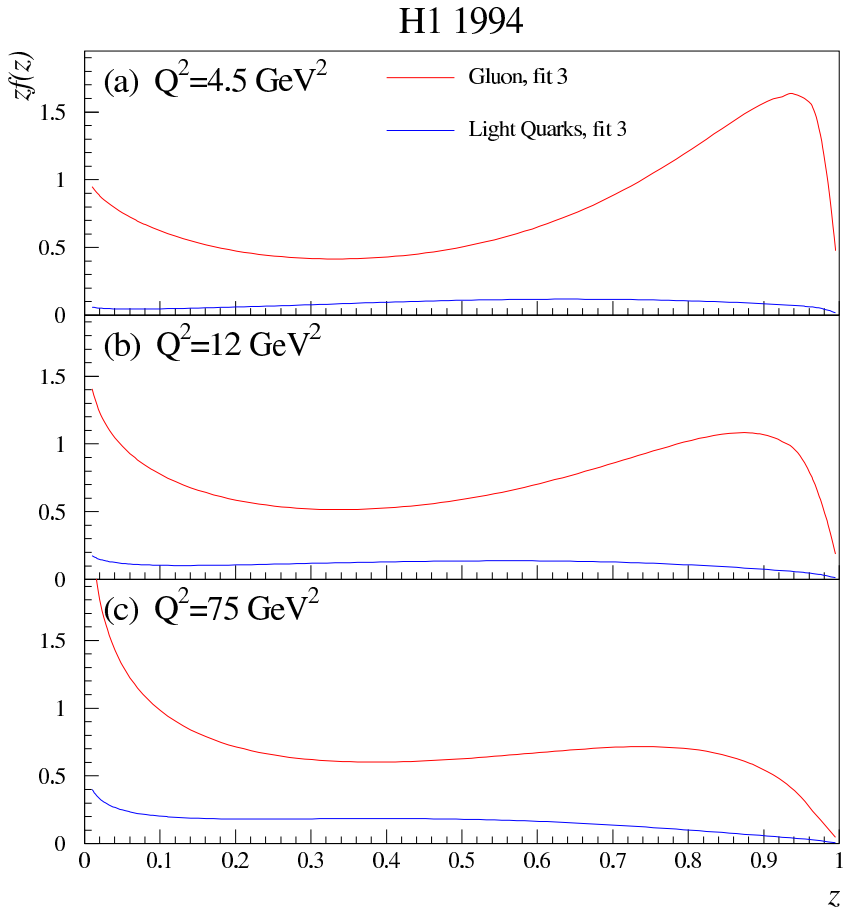
positive scaling violations:

gluons dominate (see proton at small x)

Diffractive parton density

QCD analysis

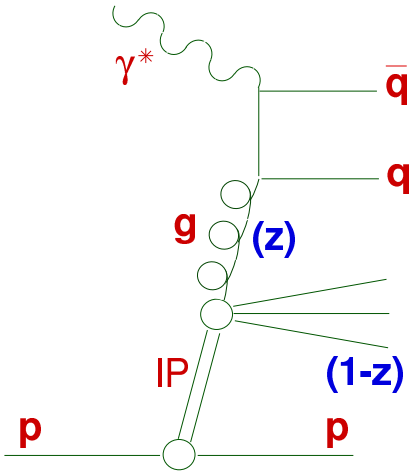
- approx. Reggee factorisation:
  $F_2^{D(3)}(\beta, Q^2, x_{I\!P},) = f(x_{I\!P}) \times f(\beta, Q^2)$
- gluon density flat in β, with large uncertainties



Needs independent cross check in another process

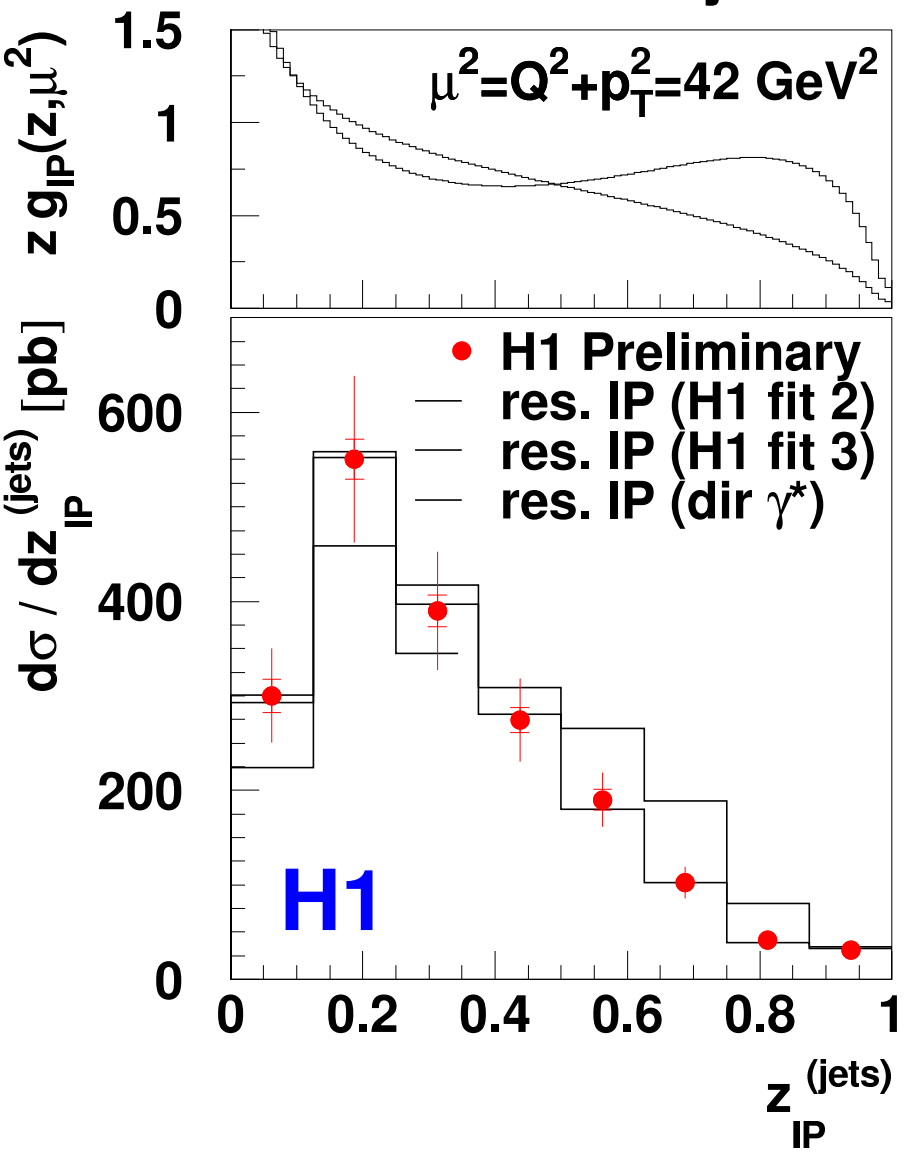
Jet production in Diffraction

New dataset

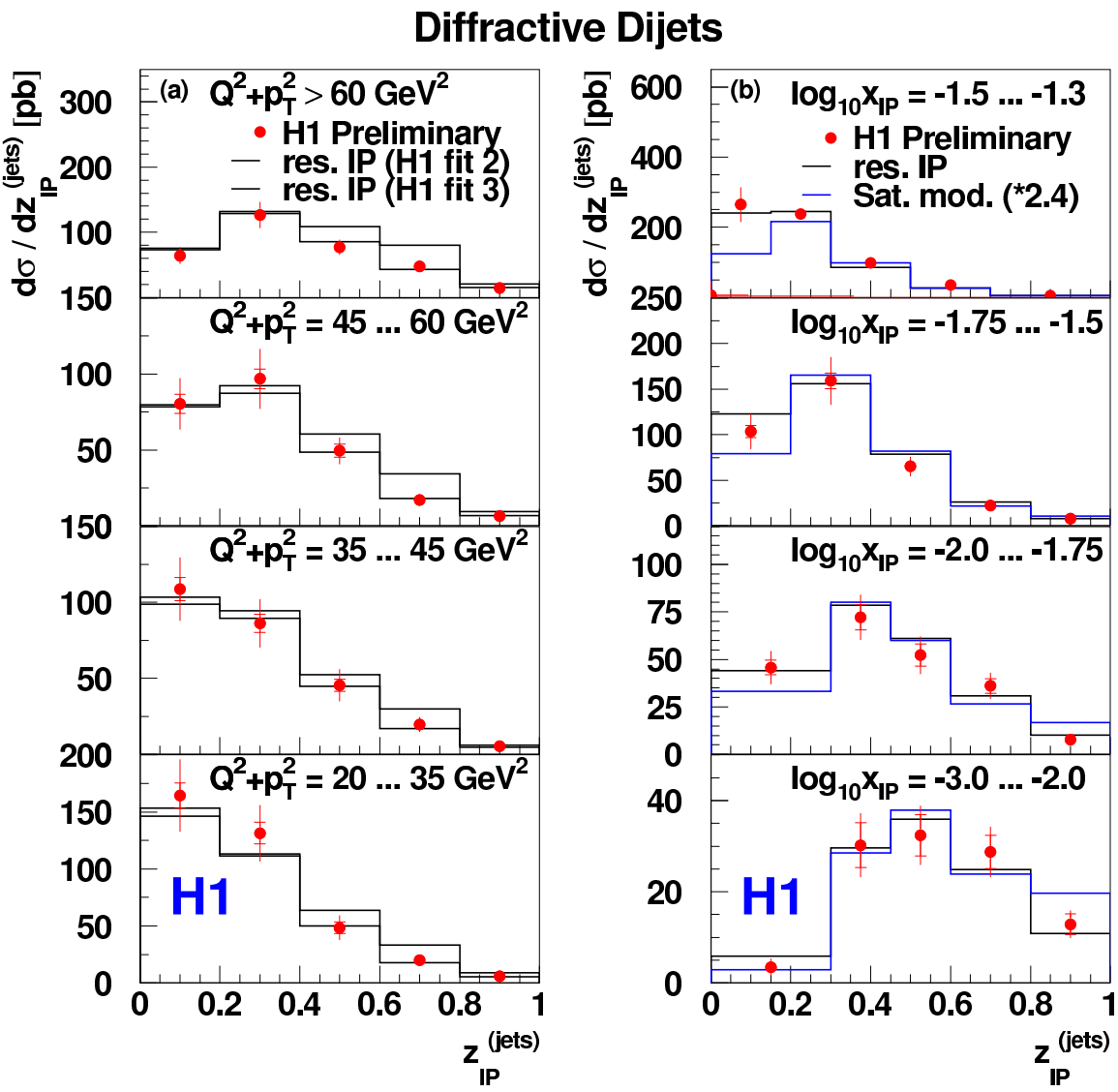


directly sensitive to gluons

Diffractive Dijets



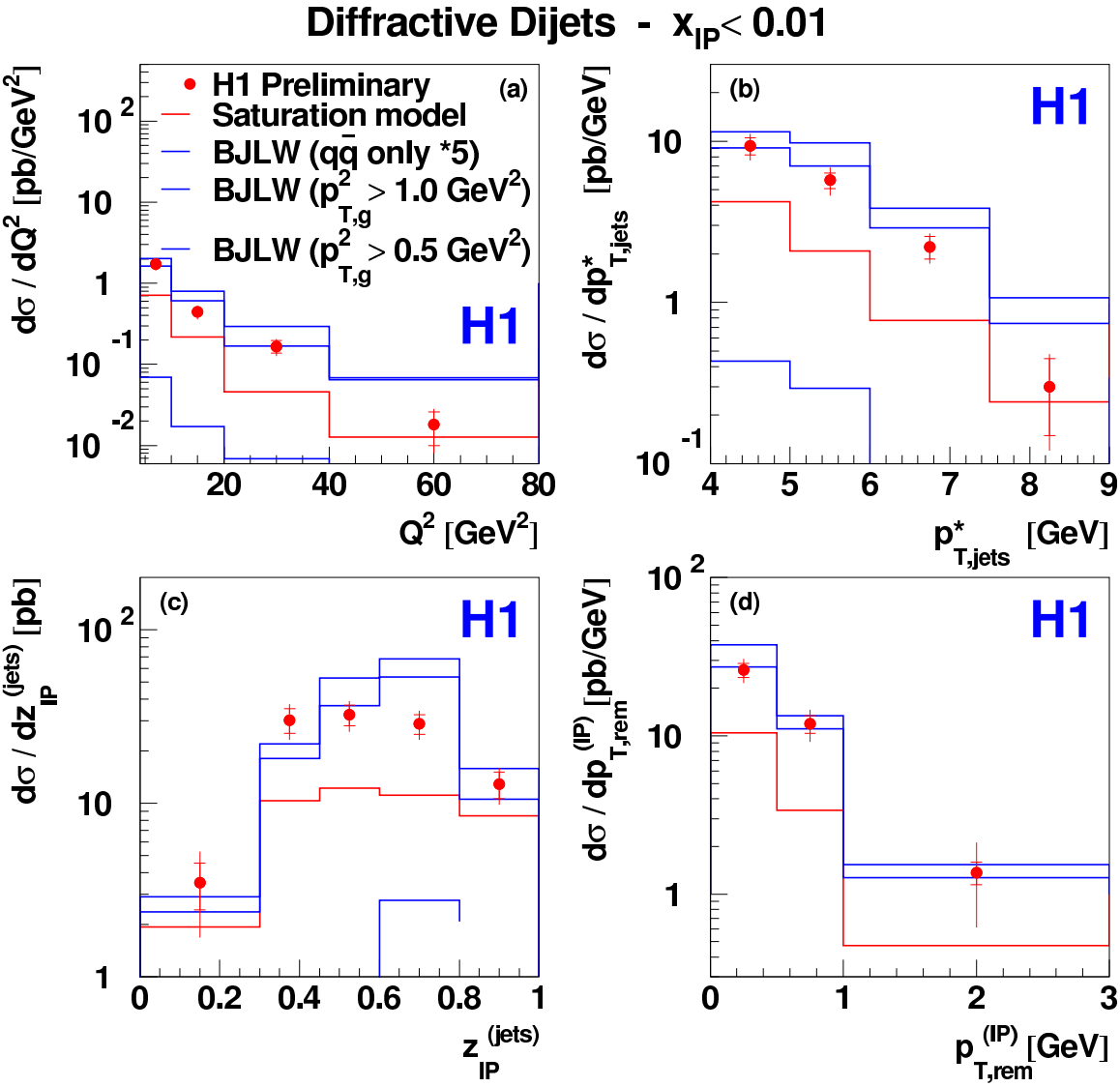
Jet production in Diffraction



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

Jet production in Diffraction

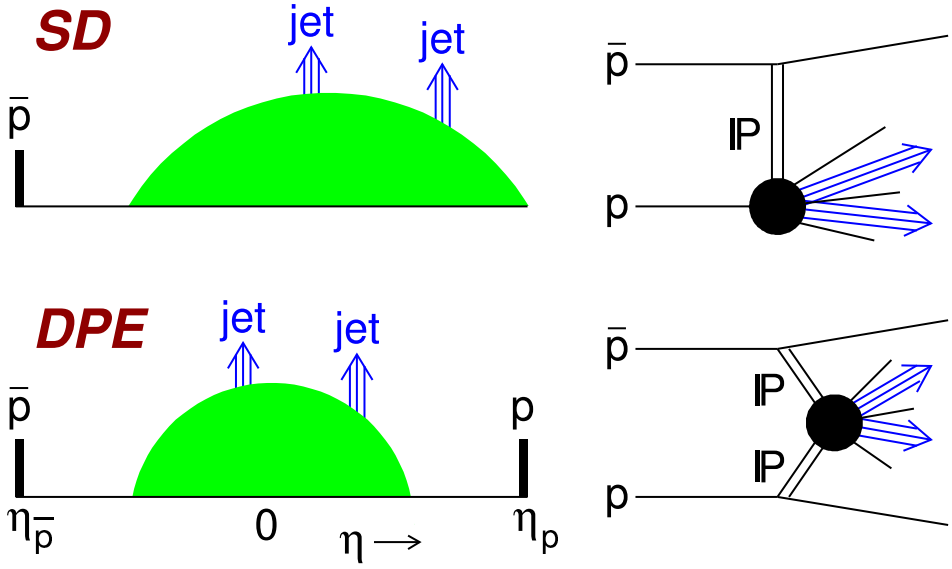
Comparison with QCD calculation for 2-gluon exchange $\sigma \sim |g(z, Q^2)|^2$



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}

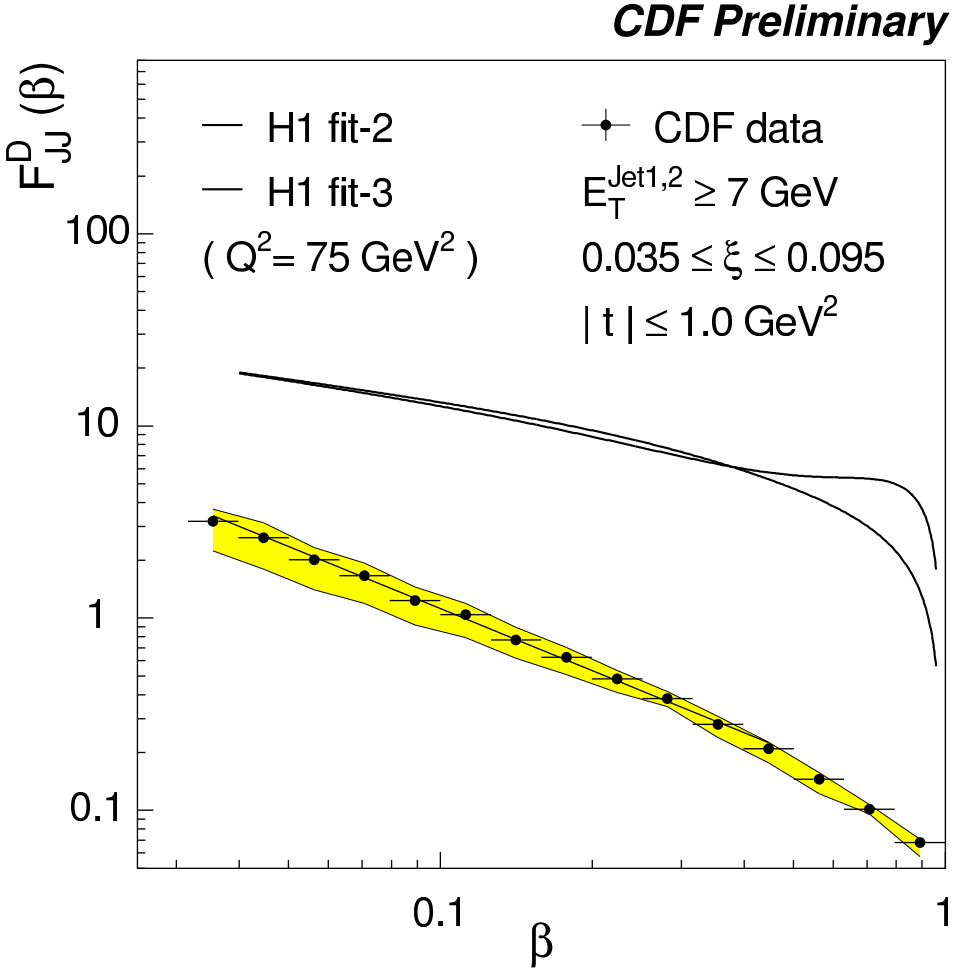
structure function:

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

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

Diffraction at Tevatron

compare with HERA predictions



difference factor 20, no agreement in shape

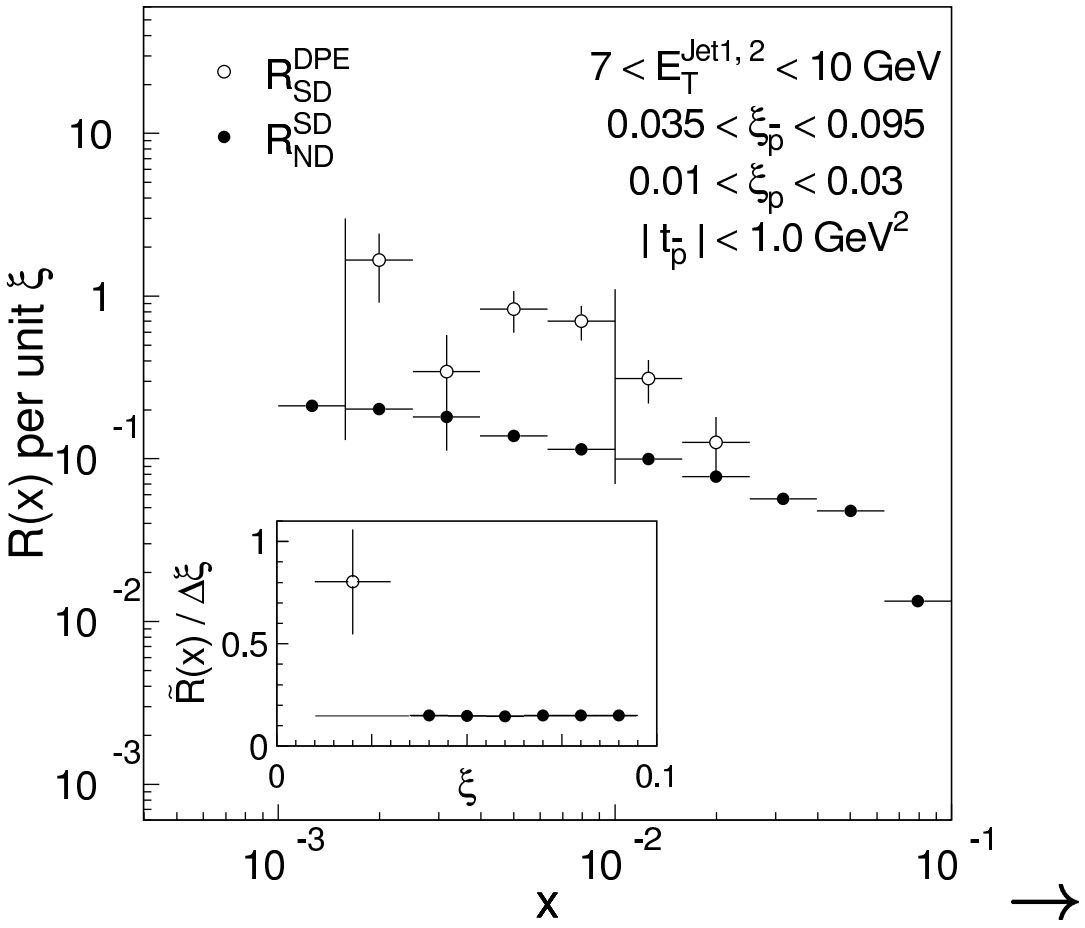
$\longrightarrow$ Breakdown of factorisation

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

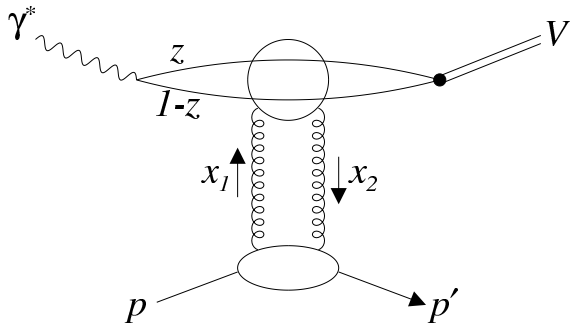


Breakdown of factorisation

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

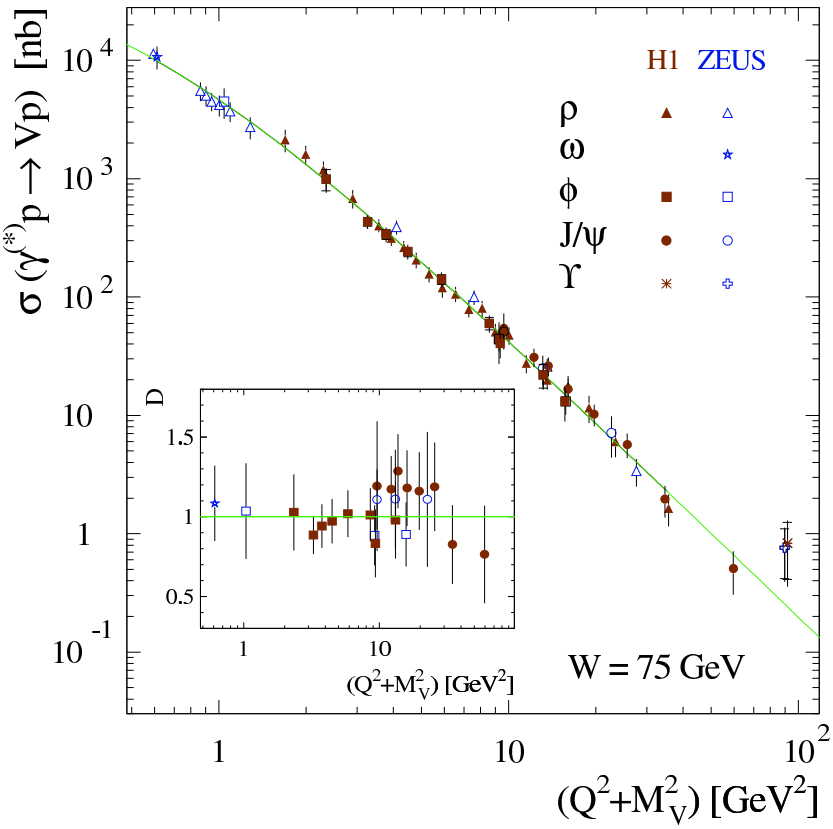
$$R_{ND}^{SD} = 0.15 \pm 0.02$$ **factor 5**

Vectormeson production at HERA

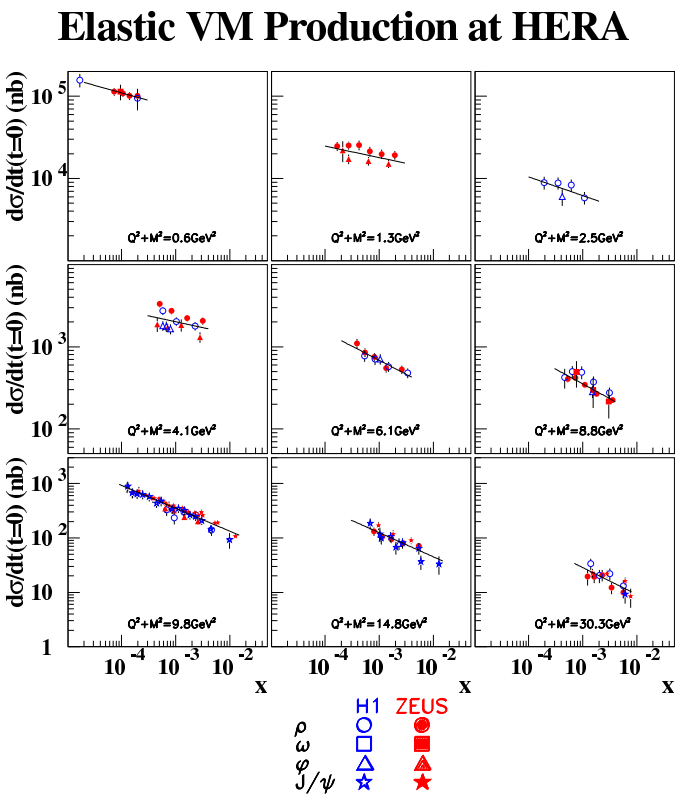


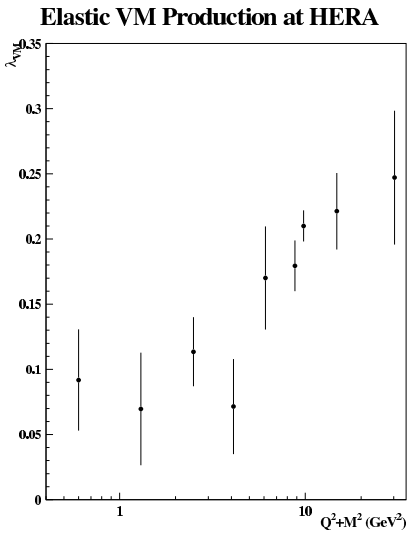
- $\gamma \rightarrow q\bar{q}$
- $q\bar{q}(g)$ **interacts with colour singlett**
- **formation of meson**

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



Vectormeson production at HERA





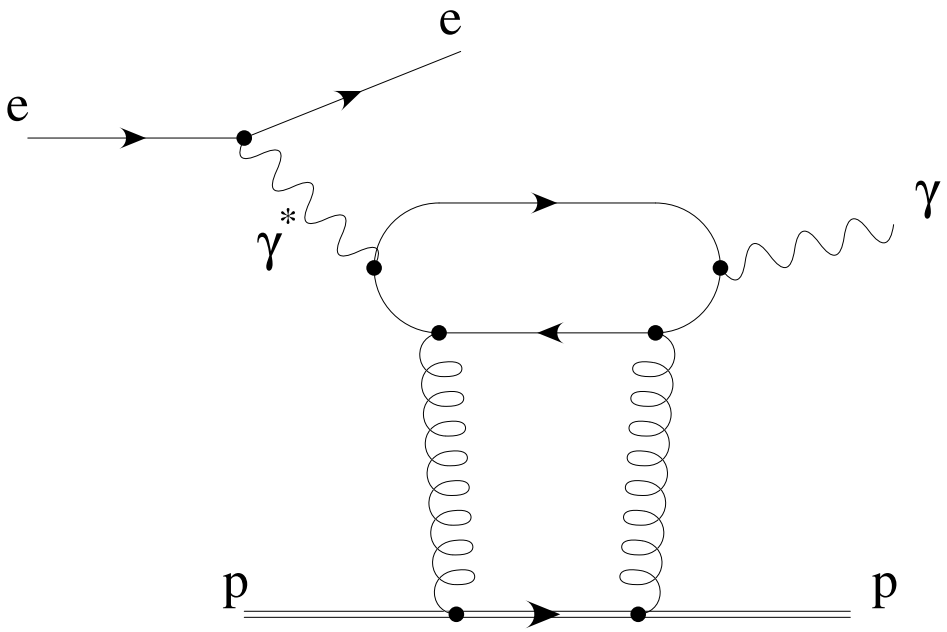
soft process:

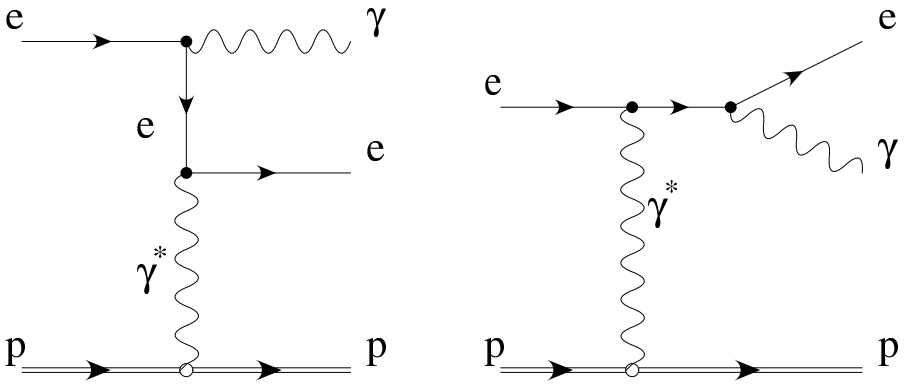
$$\lambda = 0.08$$

clear transition between soft and hard

nice confirmation of pQCD scale

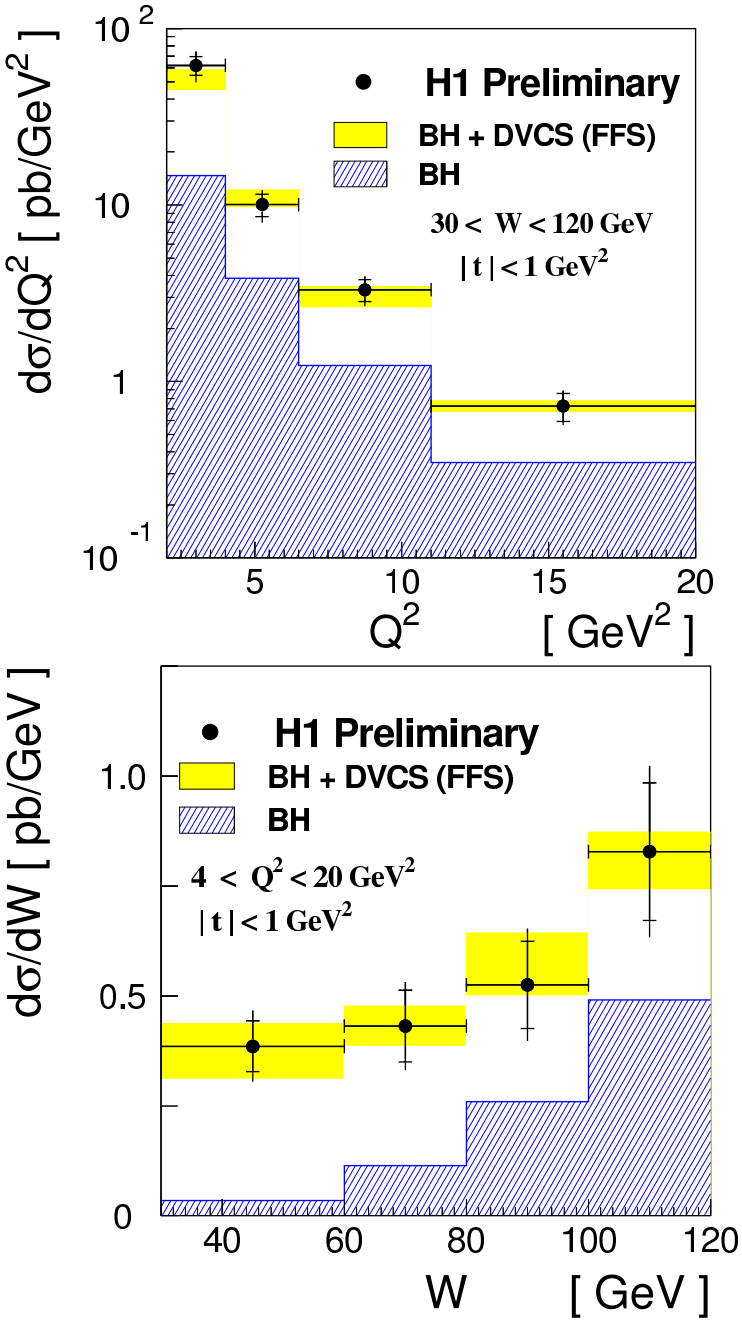
Deeply Virtual Compton Scattering





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