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

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

QCD is difficult:

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

$\rightarrow \alpha_s$ 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

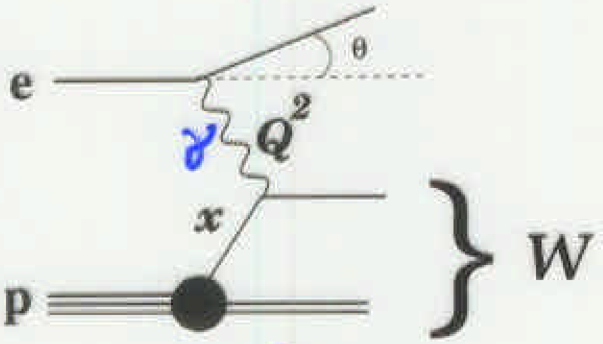
  (LEP,HERA)
- *hard* diffraction (Tevatron, HERA)

  hard scale processes for confinement

colliders dominate field of soft processes

Major field of activity in QCD:

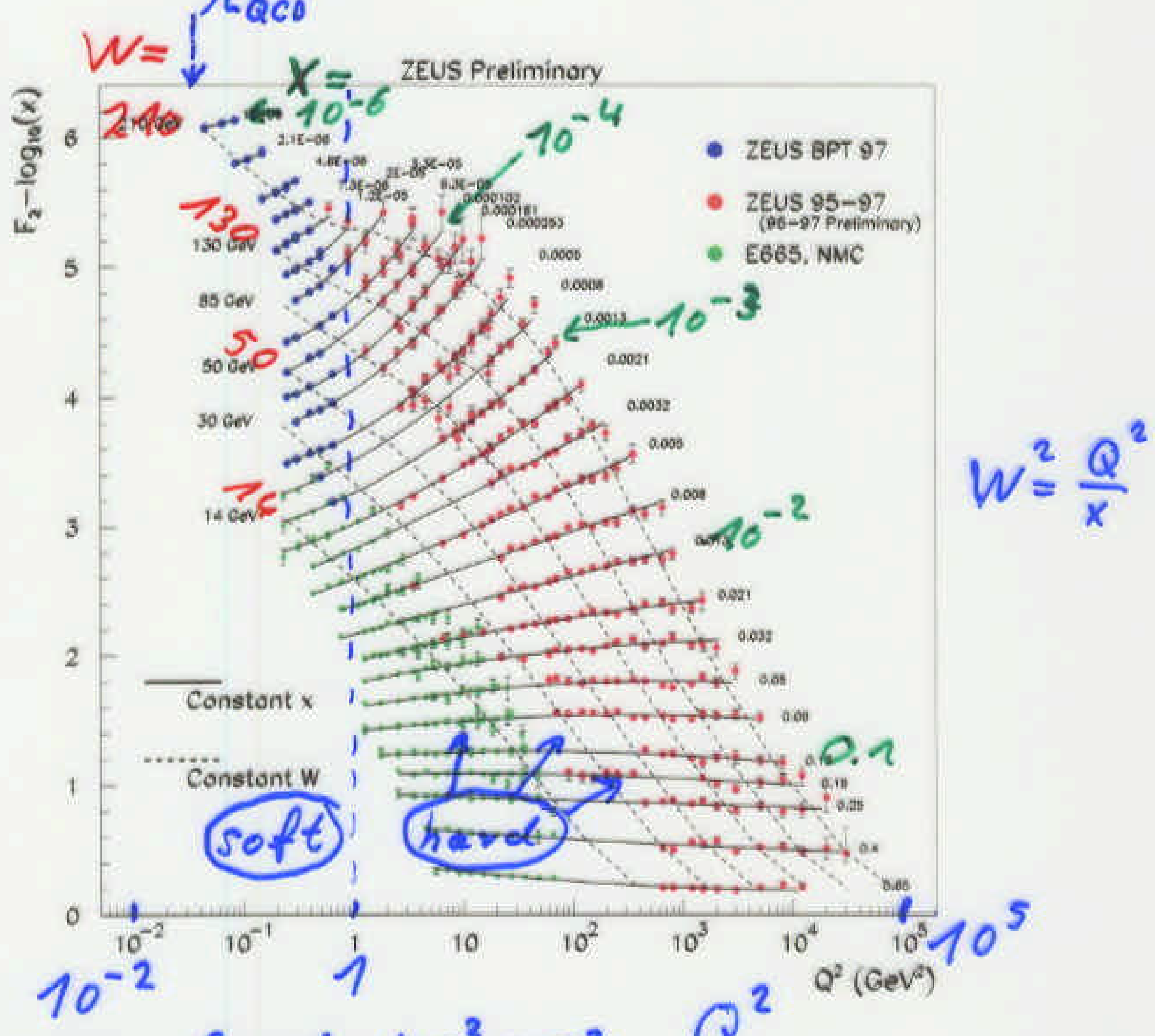
Example: $\gamma^* p \rightarrow X$



Q^2 = γ -virtuality

x = E_{parton} / E_p

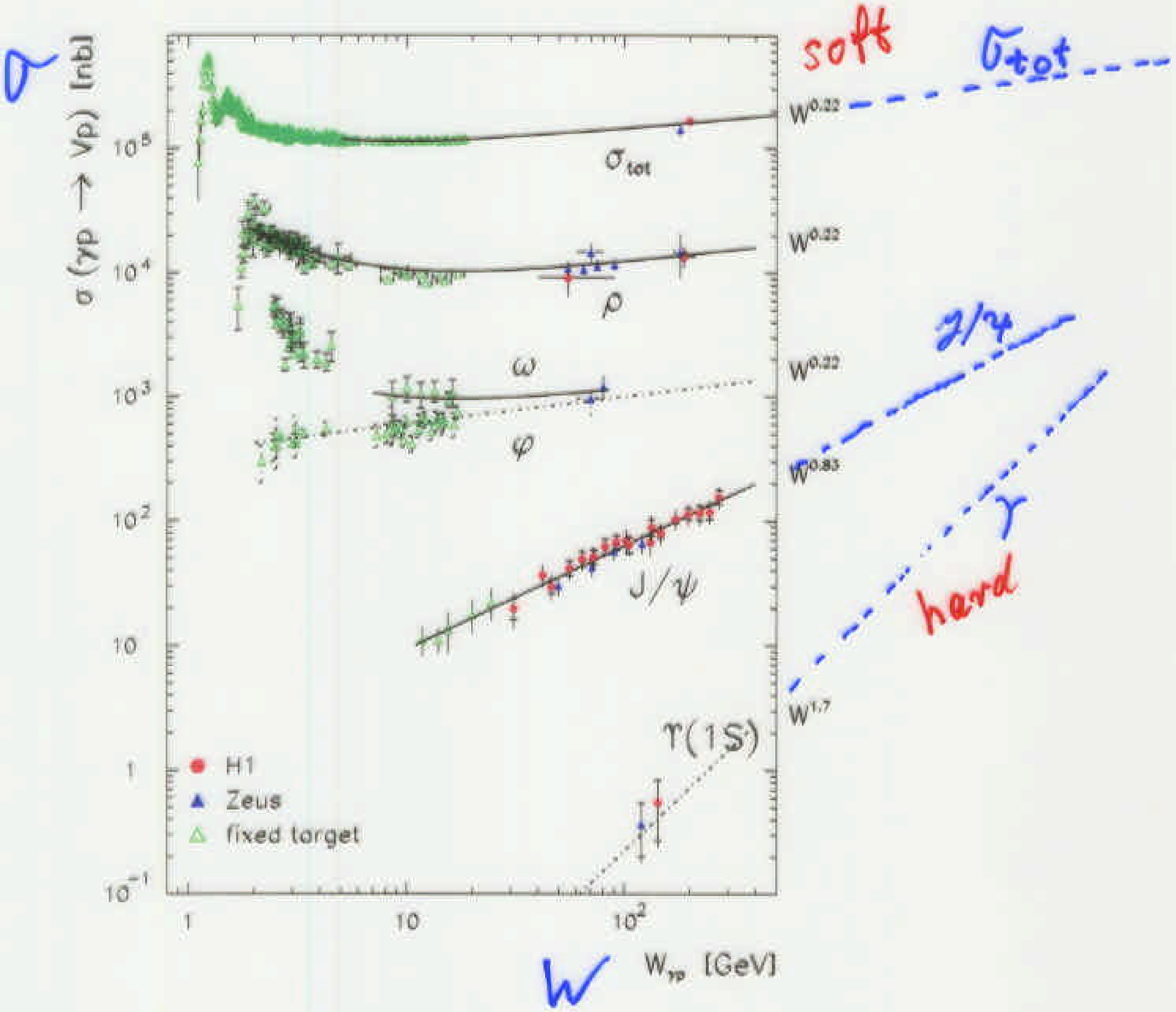
W = $E_{cms}^{\gamma-p}$



high energy limit: $W^2 \gg Q^2$

W high energy $\leftrightarrow$ small x for same Q^2

Example: Vectormesons at HERA



Factorisation in QCD

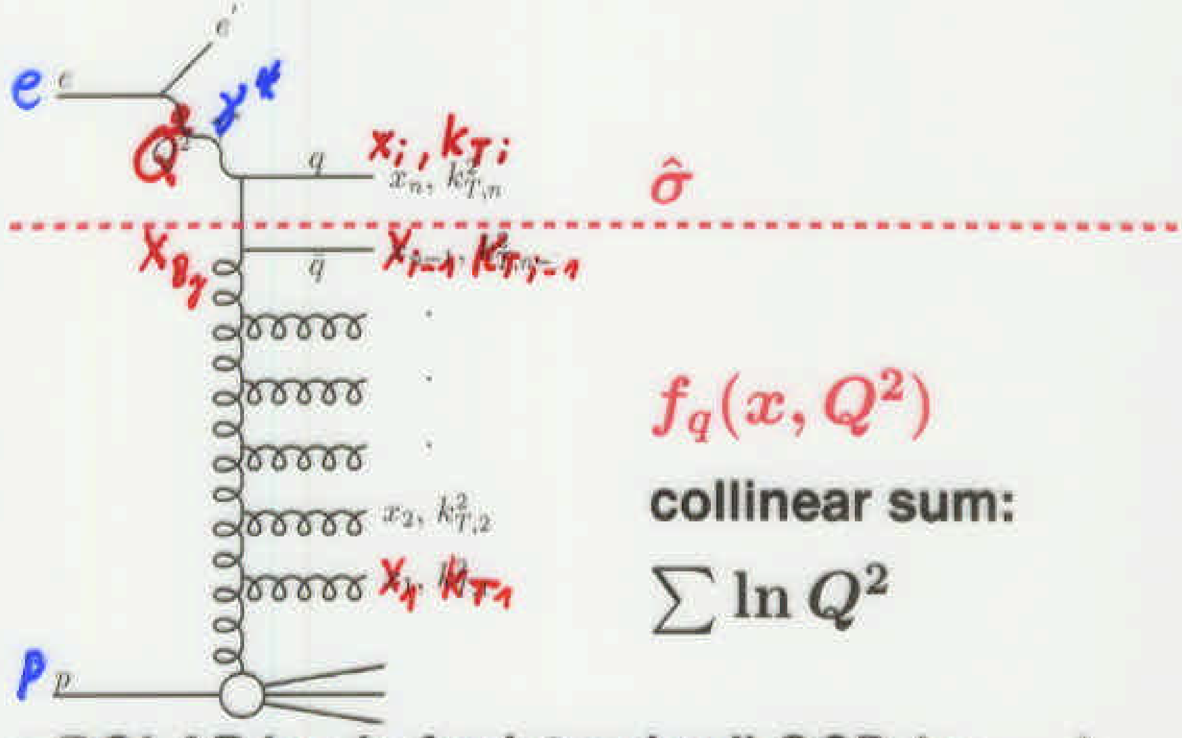
1) Altarelli-Paresi approximation (DGLAP)

Assume: strong k_T ordering:

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

$\rightarrow$ factorisation of hard and soft component:

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



$f_q(x, Q^2)$

collinear sum:

$\sum \ln Q^2$

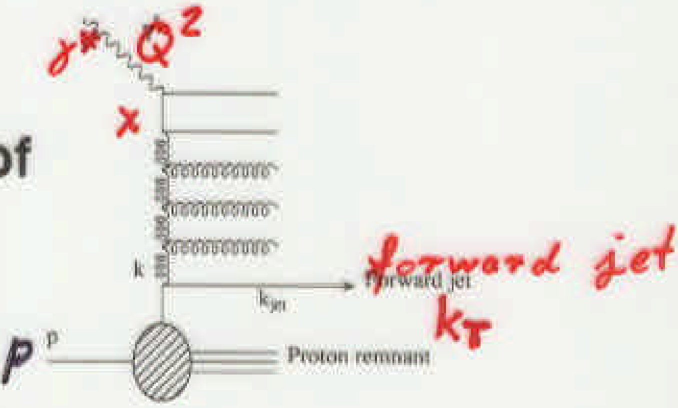
- DGLAP basis for 'standard' QCD (α_s, ...)
- DGLAP must fail when:
  - Q^2 too small (how small ?)
  - x too small (phasespace!)

    (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 x not small $k_T >> Q^2$ $k_T << Q^2$	$k_T^2 \approx Q^2$ x small	x small (only P_{gg})

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)

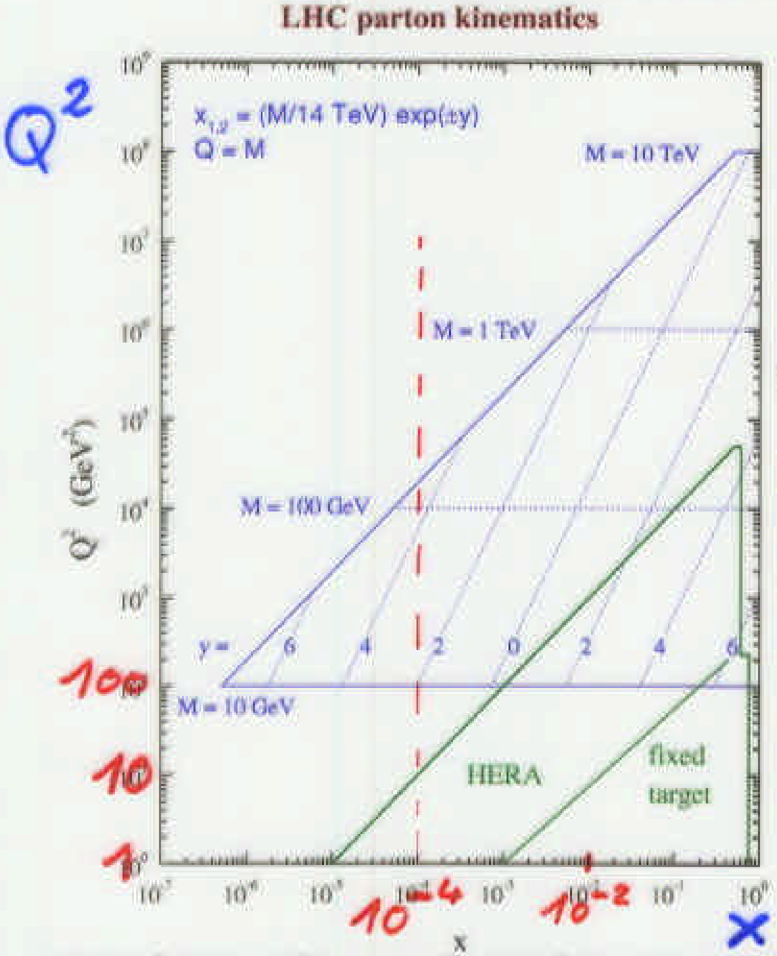
emphasis on QCD interpretation of the data

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

$x = 10^{-2}$

only process: Deep inelastic scattering at

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

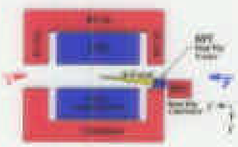
Proton Structure at low-x

New data sets with upgraded detectors:

H1: silicon tr. + spaghetti calor.

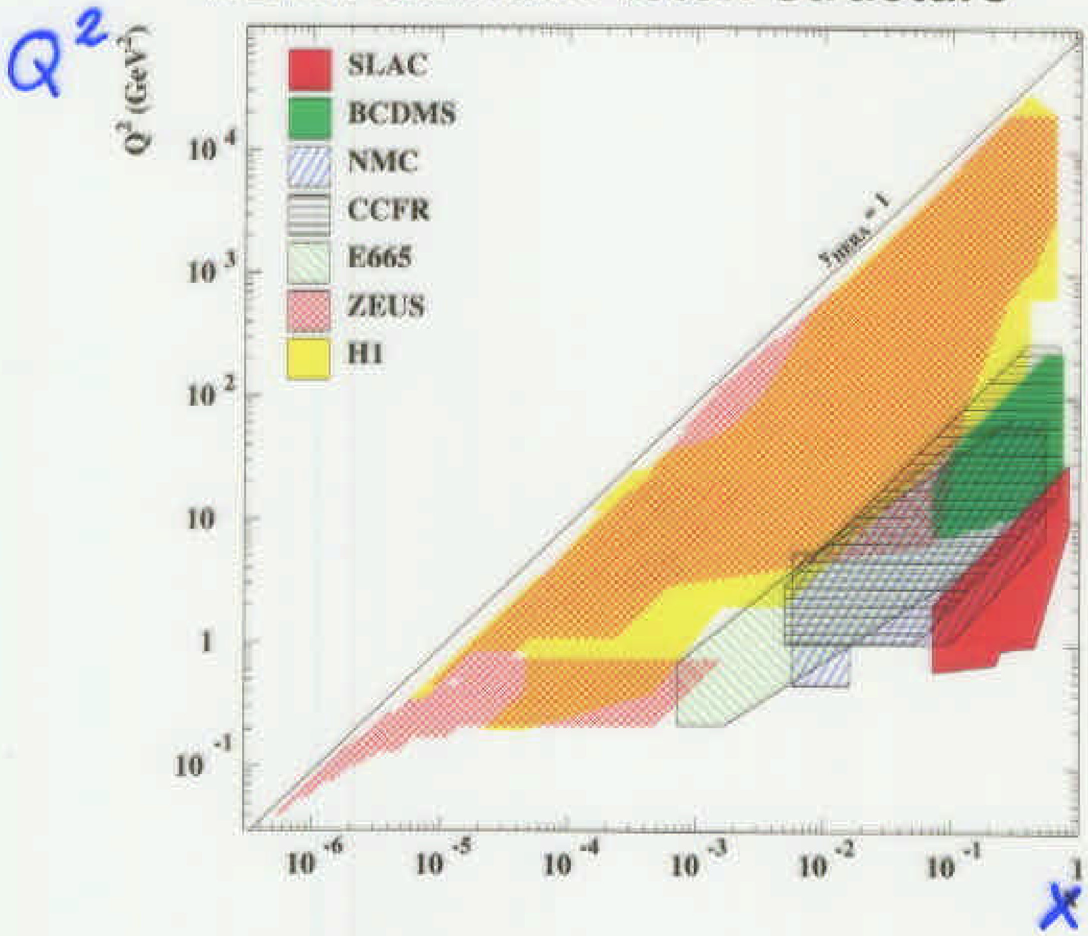
$Q^2 > 1.5$GeV

ZEUS: silicon tr. + calor. close to beam



$0.6 > Q^2 > 0.045$GeV

HERA data on Proton Structure



Proton Structure at low-x

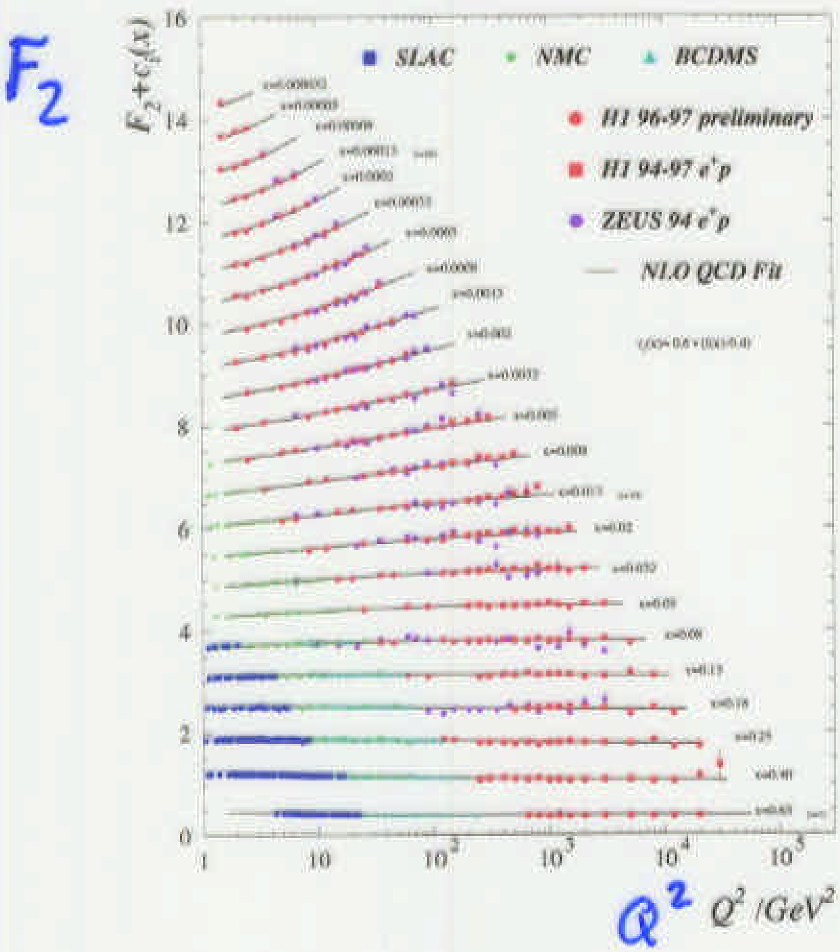
$ep \rightarrow eX$ at low Q^2:

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

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

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

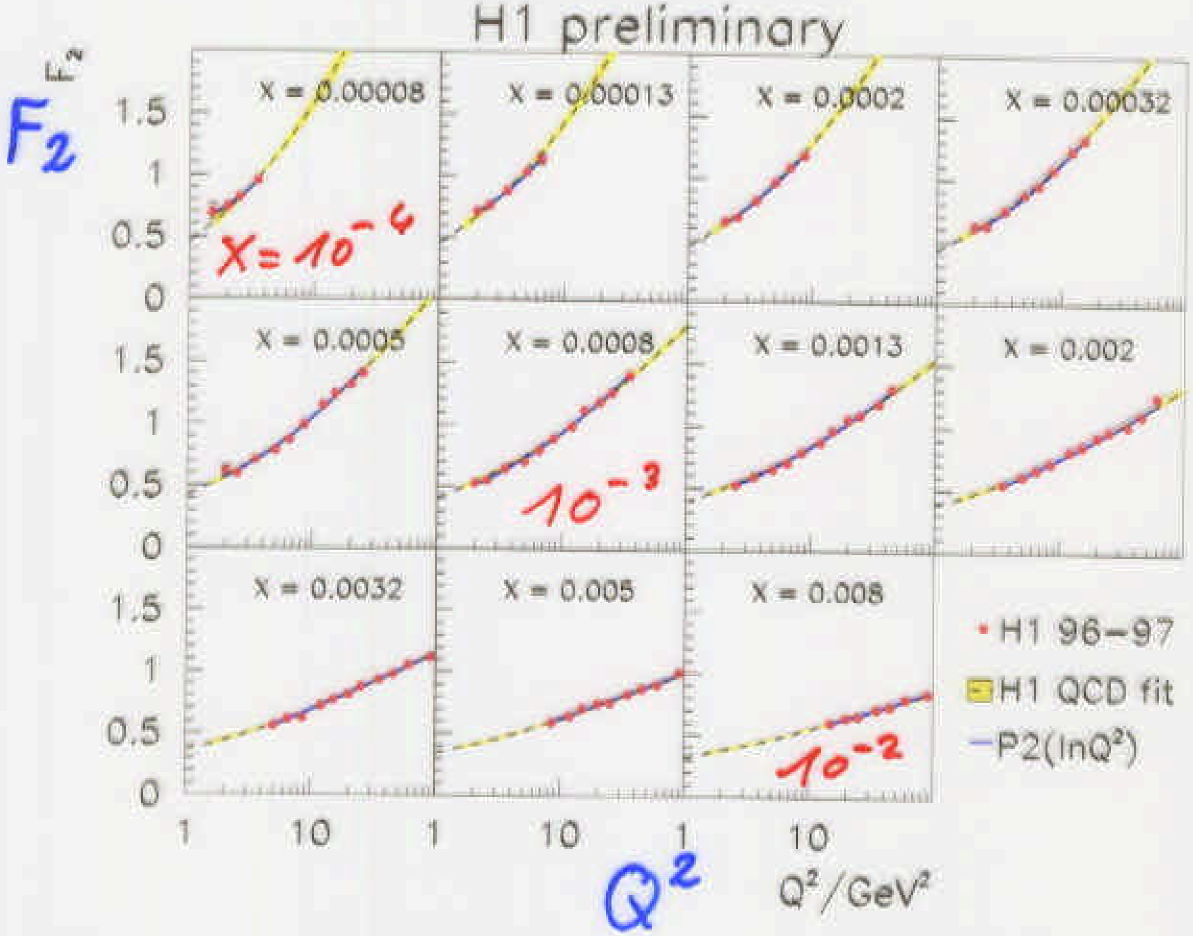
and $F_L\left(x, Q^2\right)$ contribution is typically small.



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

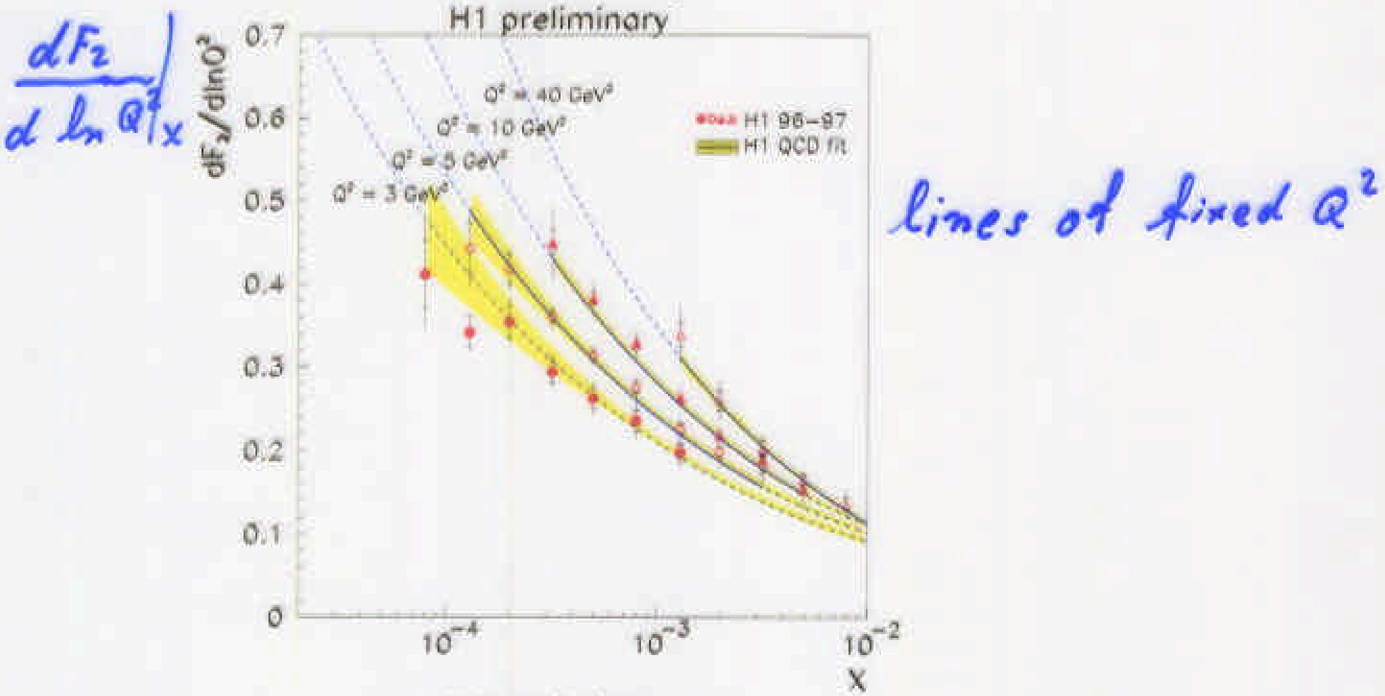


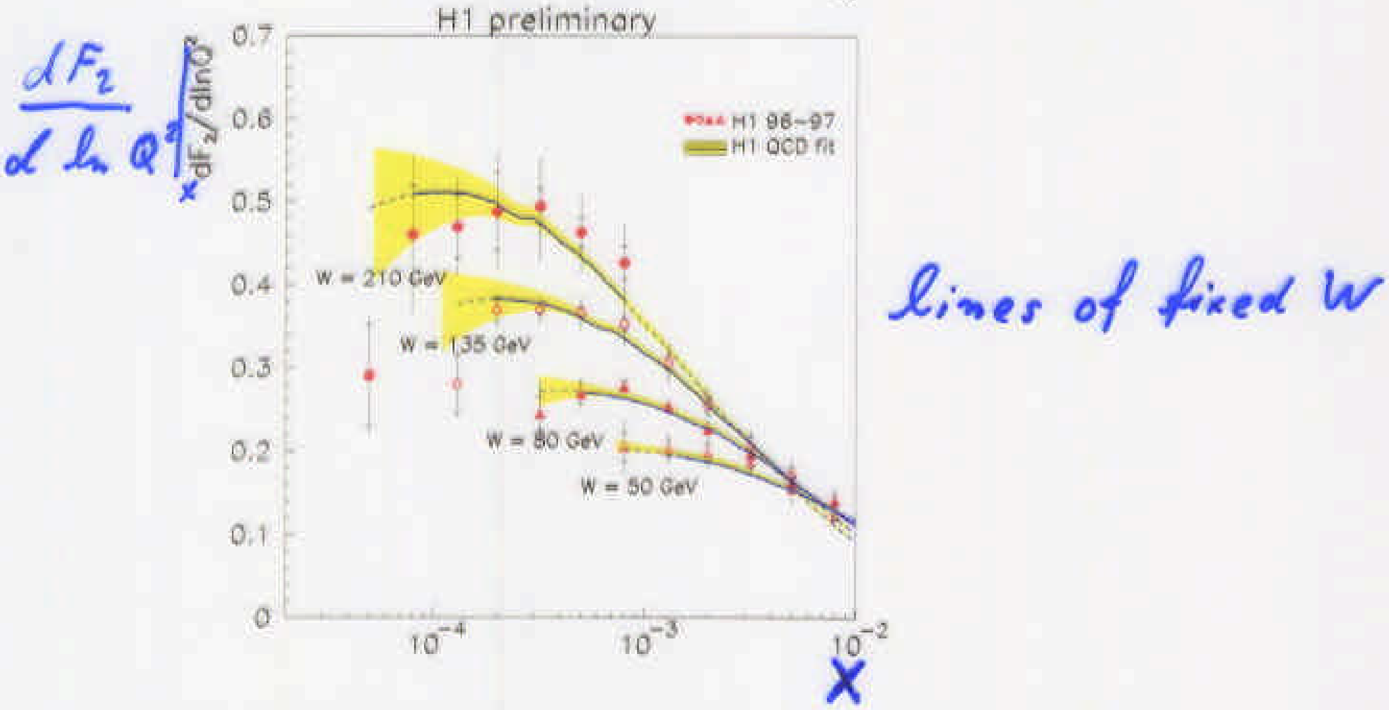
F_2 rises with Q^2: $g \to gg, q\bar{q}$ splitting

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

Slopes of F2

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

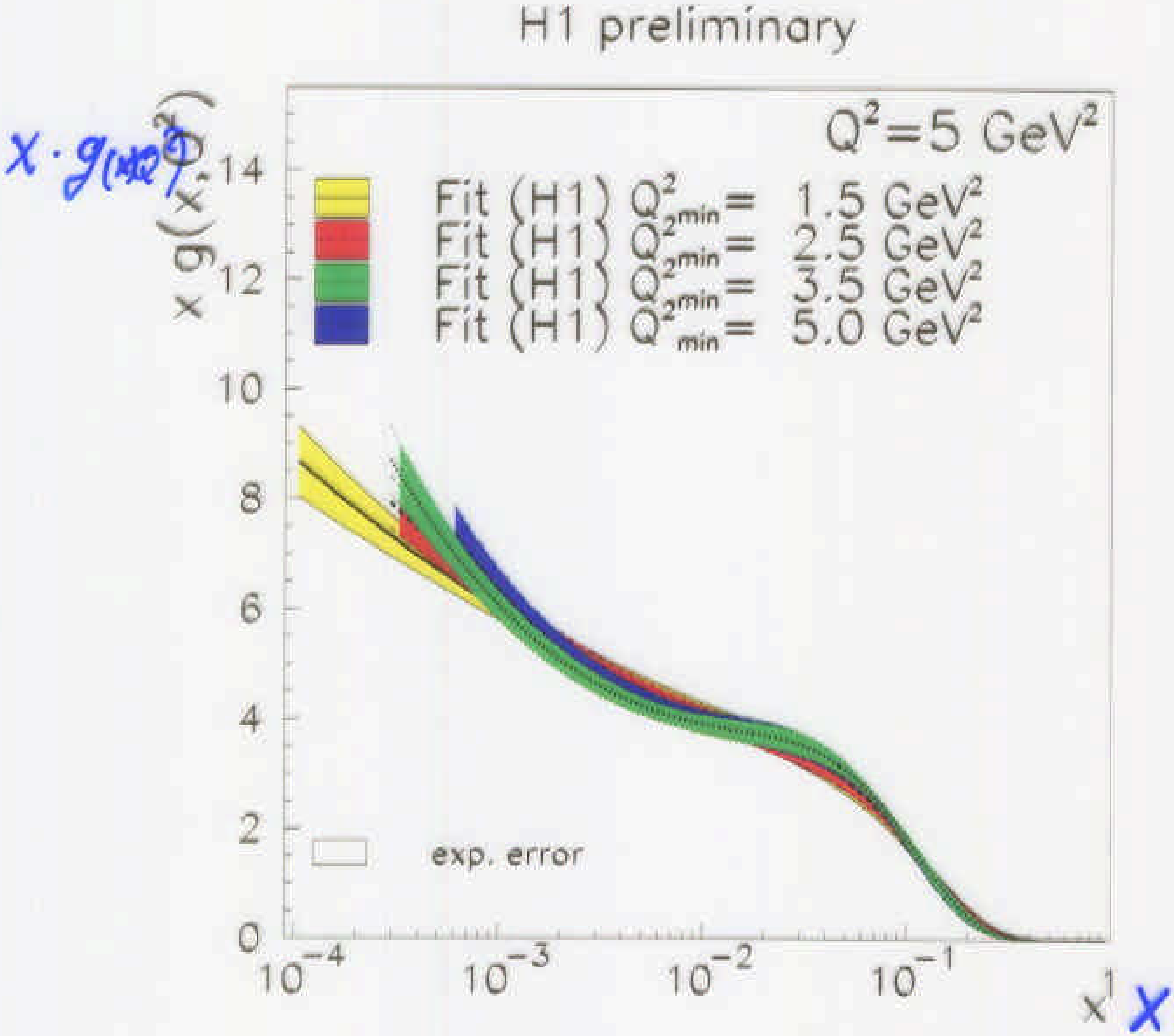




QCD fit works down to $Q^2 \approx 1$GeV^2.

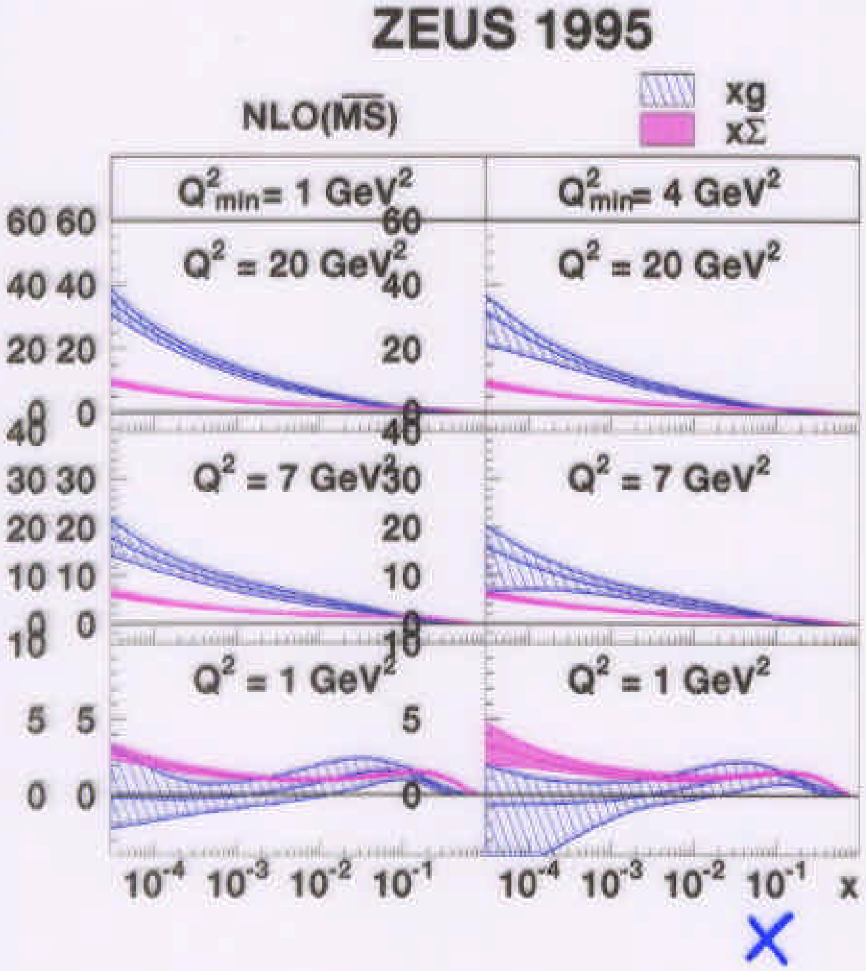
Fit result dependence on Q^2_{min}

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**

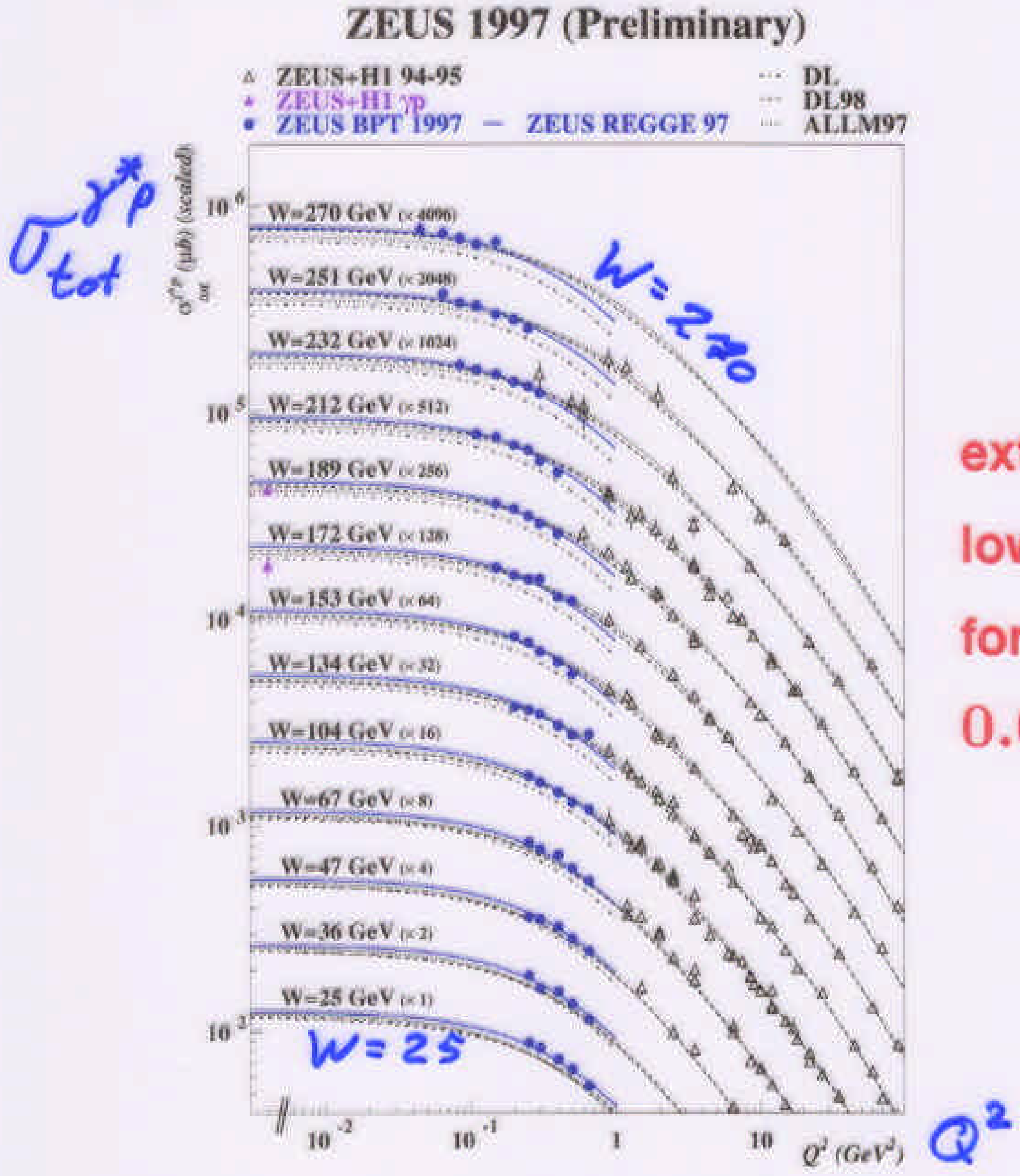
Gluon density for $Q^2 \to 1\text{GeV}^2$



- $xg(x, Q^2)$ 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

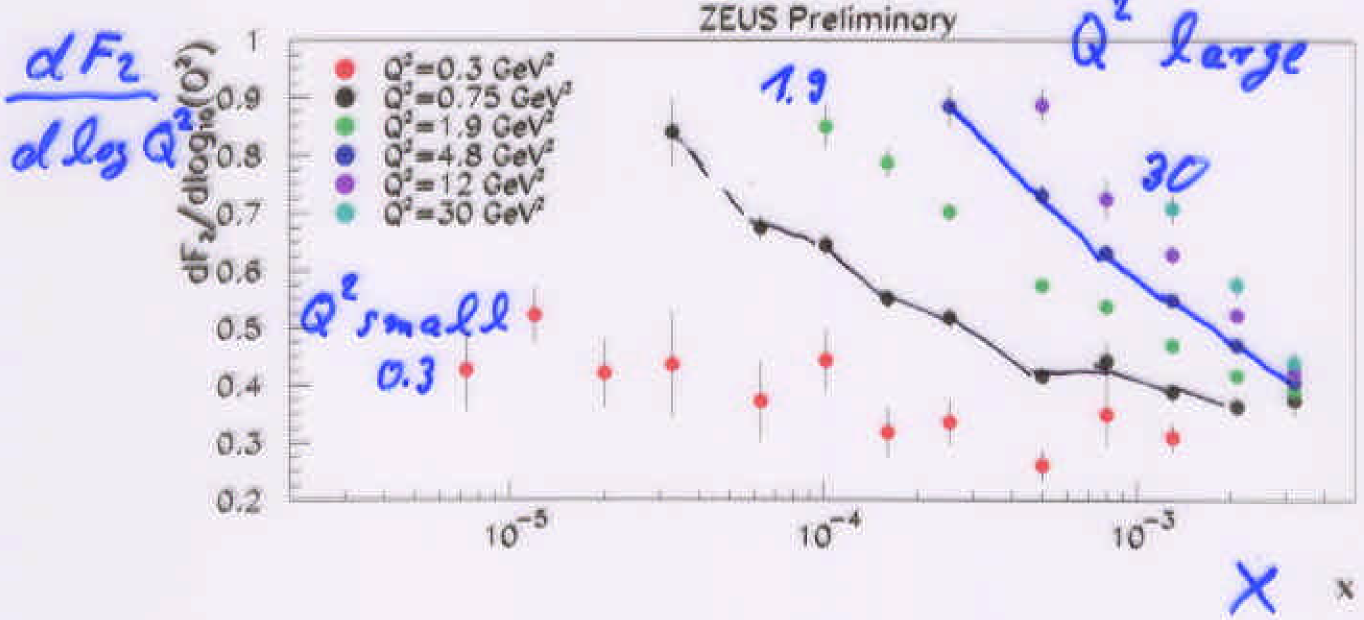


extremely low x: 10^{-6} for $Q^2 = 0.045\text{GeV}^2$

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

Transition to Photoproduction
$Q^2 \to 0$

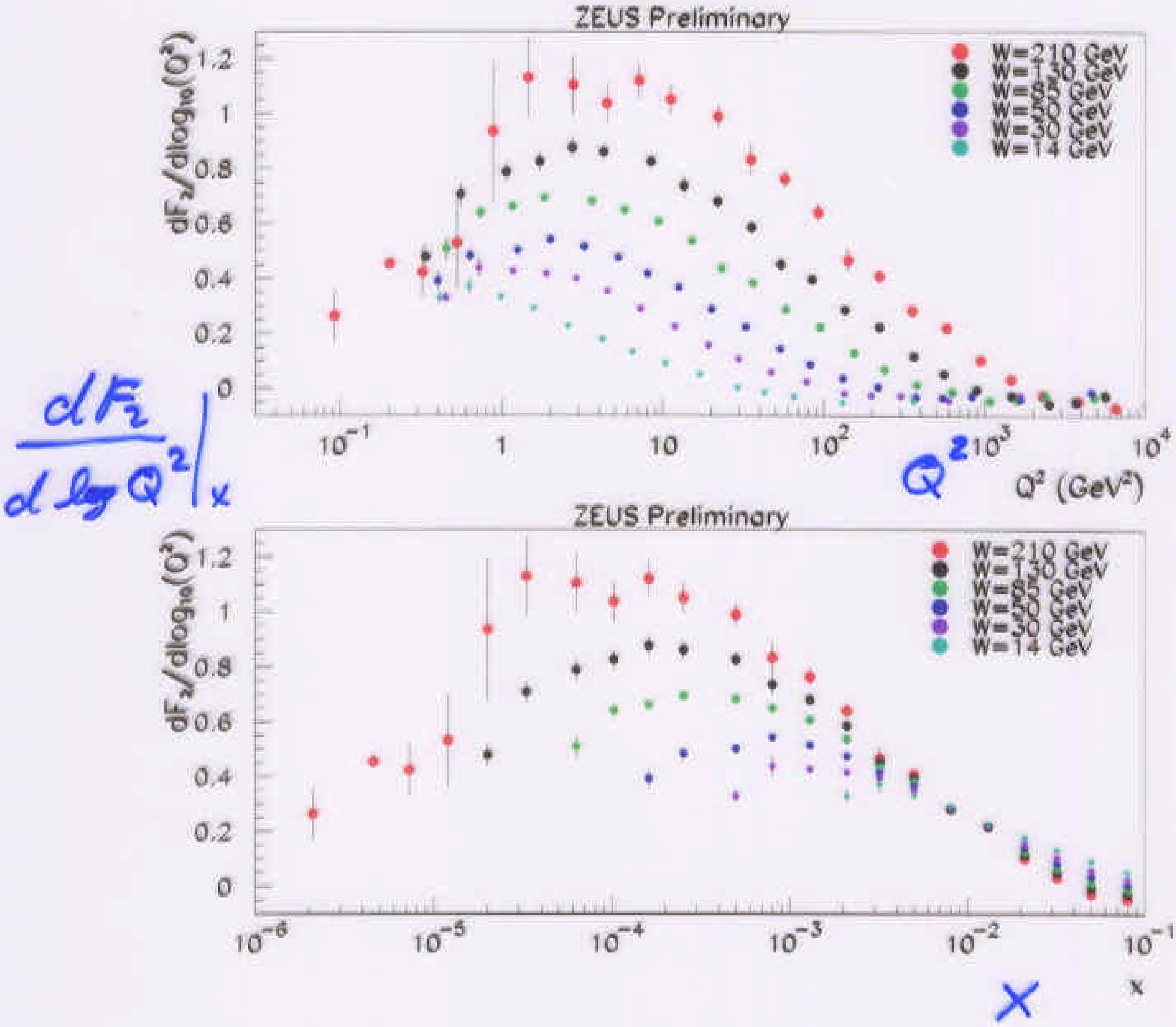
expectation: slope $dF_2/d\ln Q^2|_x$ becomes smaller for small Q^2



- 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

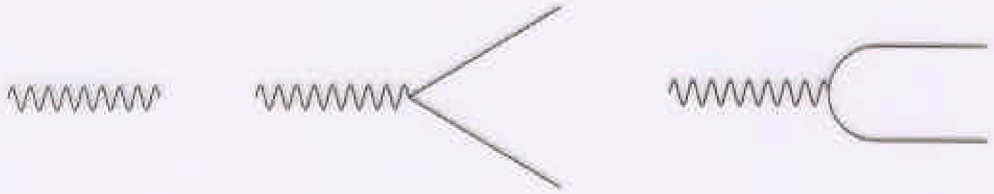
$$Q^2 \to 0$$



Photon Structure

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

direct + point-like + hadron-like



- 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

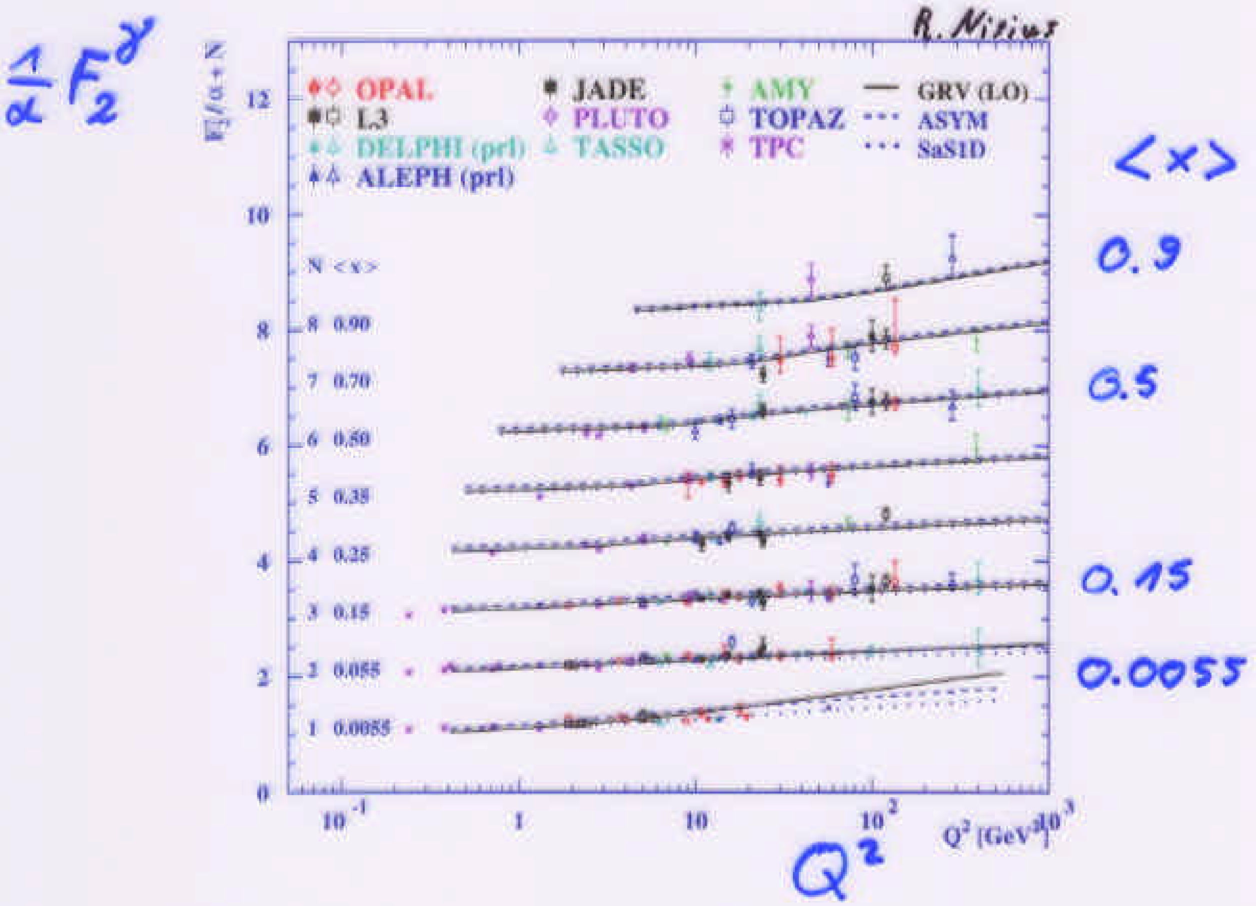
hadrons (X) used to obtain x_γ

- 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:

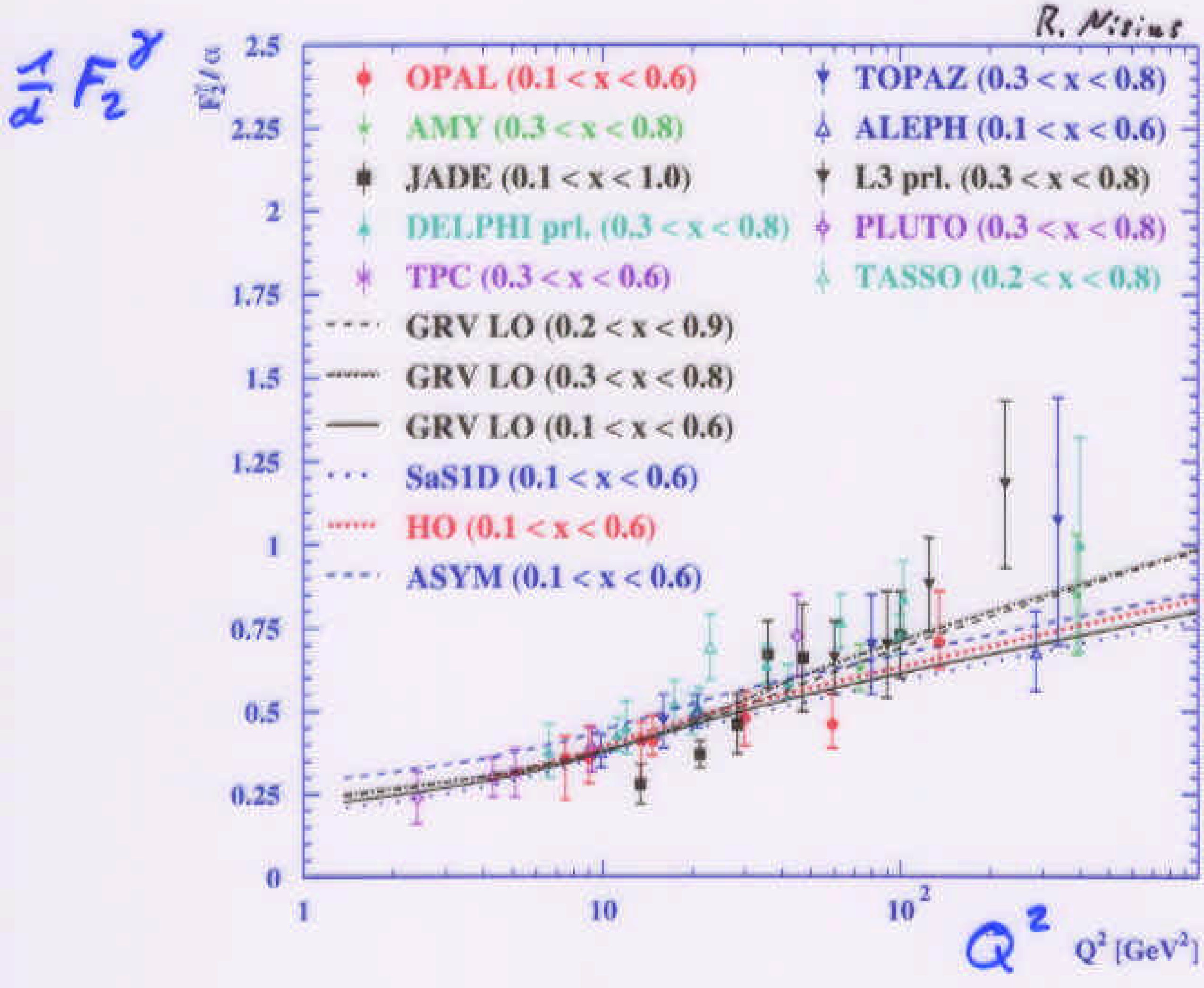
- rise for all x_γ with Q^2 due to $\gamma \rightarrow q\bar{q}$
- dominant point-like part at high x_γ
- exceed point-like component at small x_γ
- rise at very small x_γ due to gluons (hadronic component like proton)



- LEP2: extanded kinematic coverage
- consistent results between experiments

Photon Structure from LEP

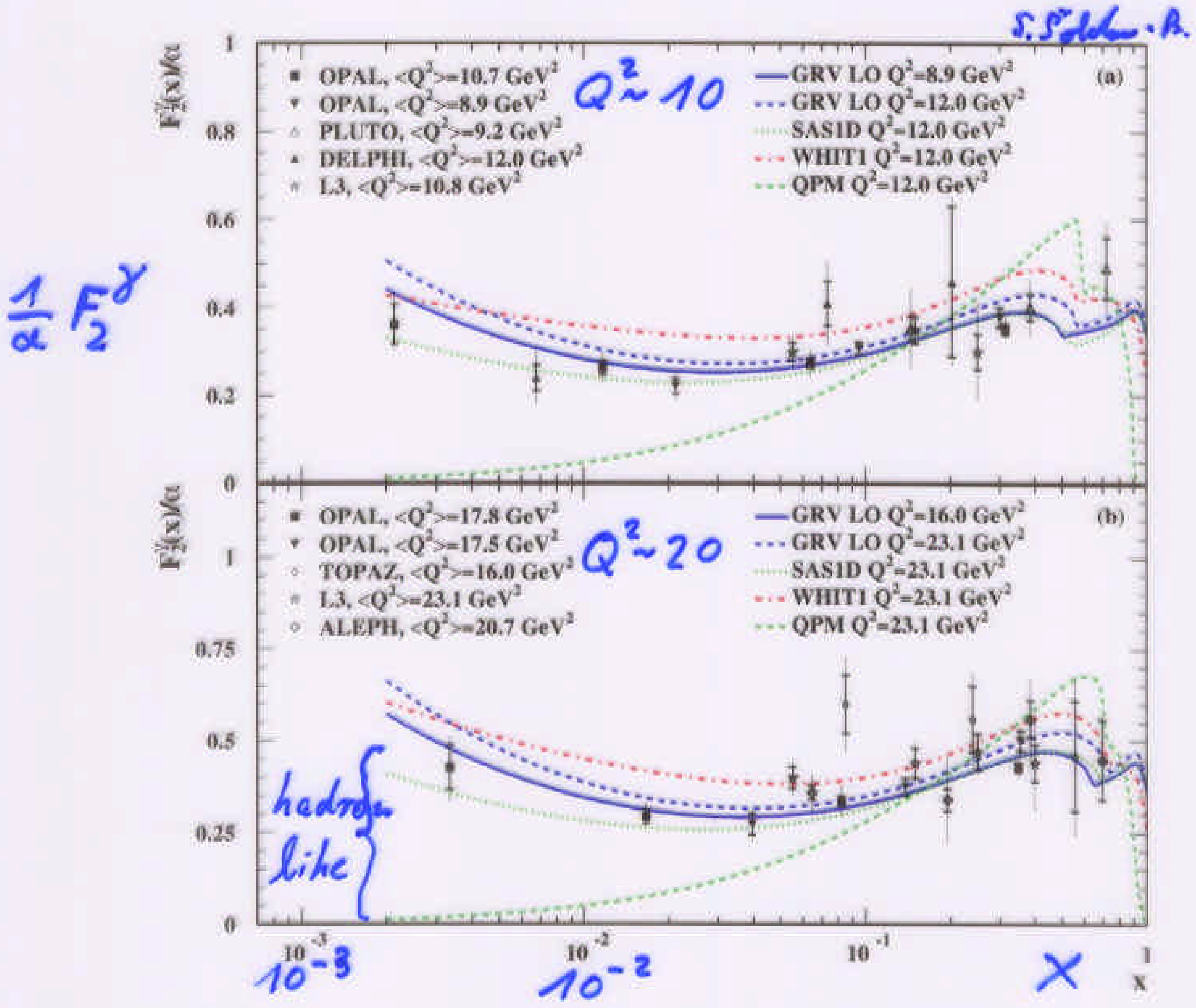
large x_γ



clear rise of F_2^γ with Q^2 also at high $x \rightarrow$

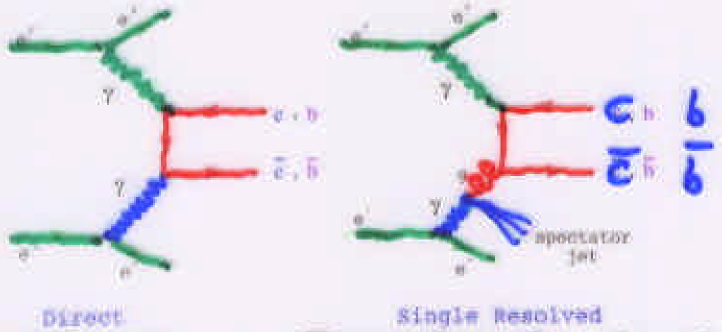
point-like component

Photon Structure from LEP



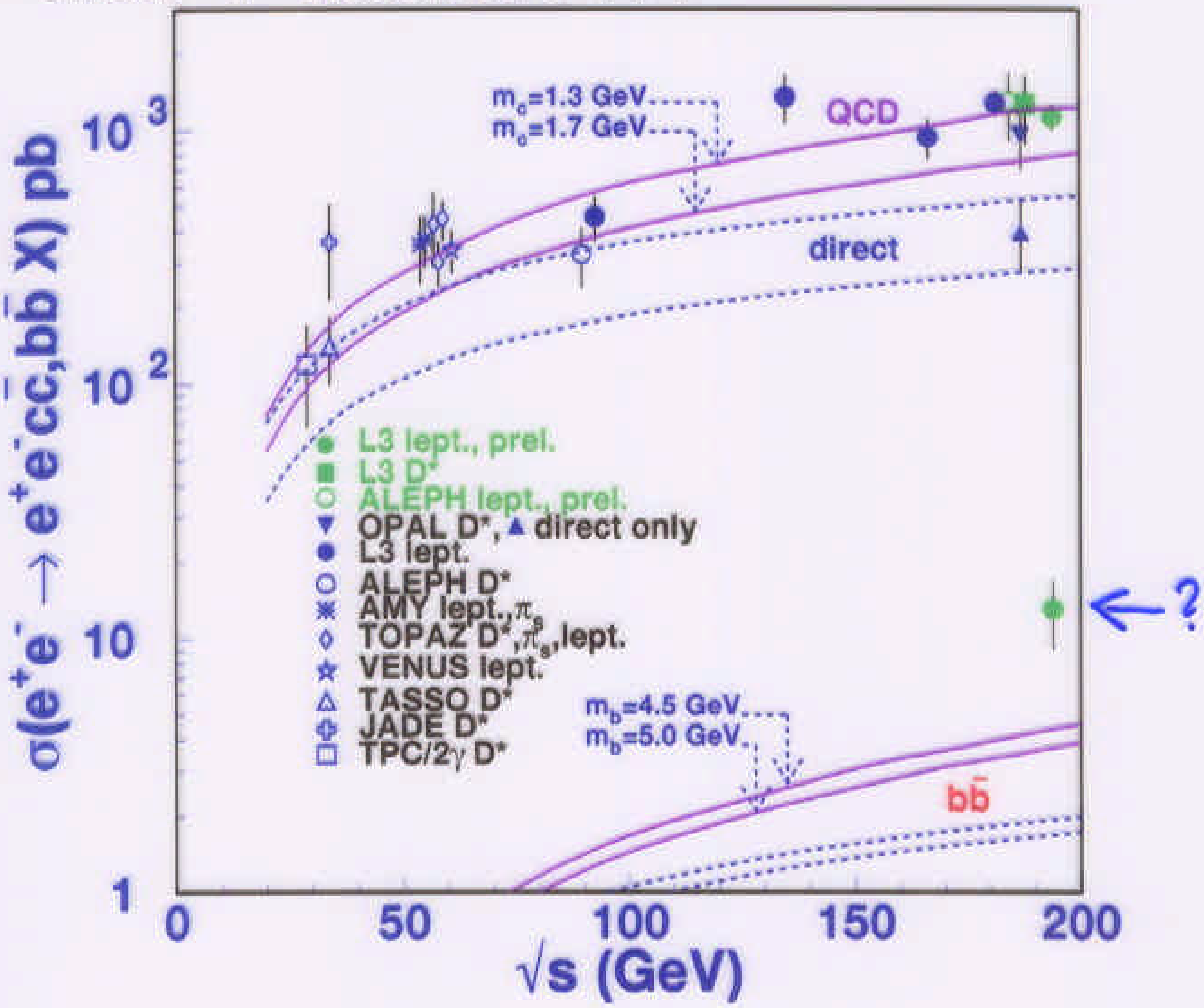
- hadronic component seen, but not yet rise of F_2^γ at very low x.
- data consistent with e.g. GRV(LO)

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



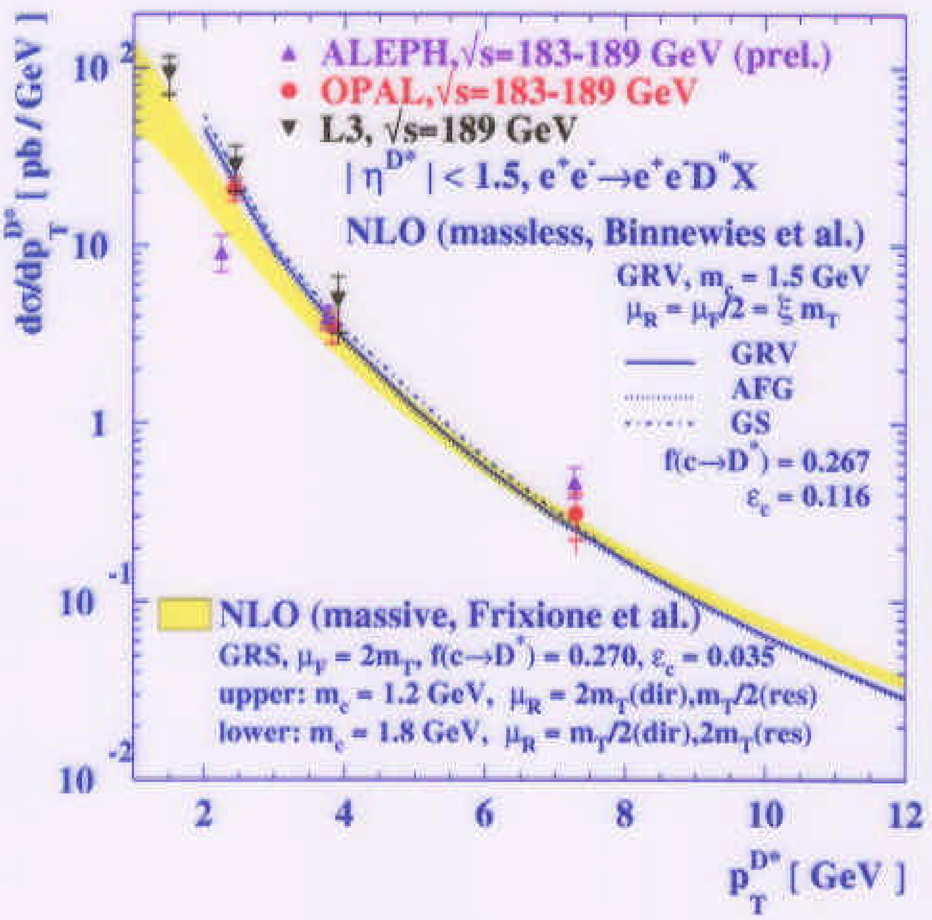
direct handle on gluon content for $x_\gamma \gtrsim 0.1$!

direct : Resolved = 1 : 1



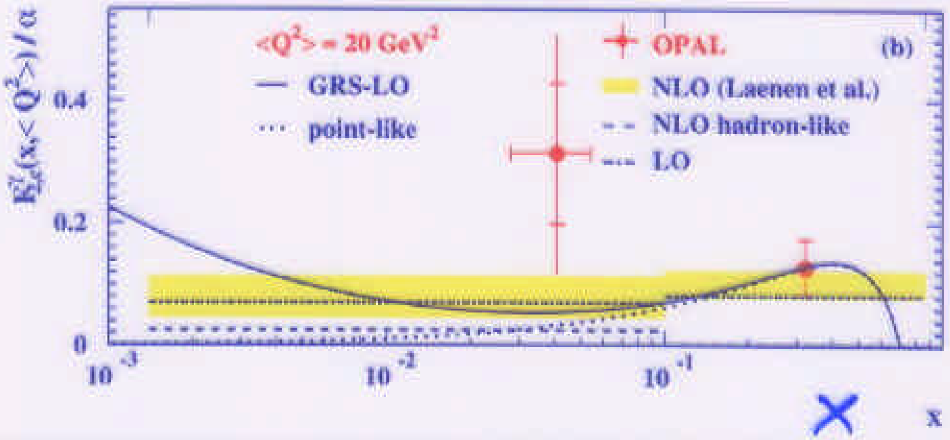
nice agreement for charm, bottom too high ?

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

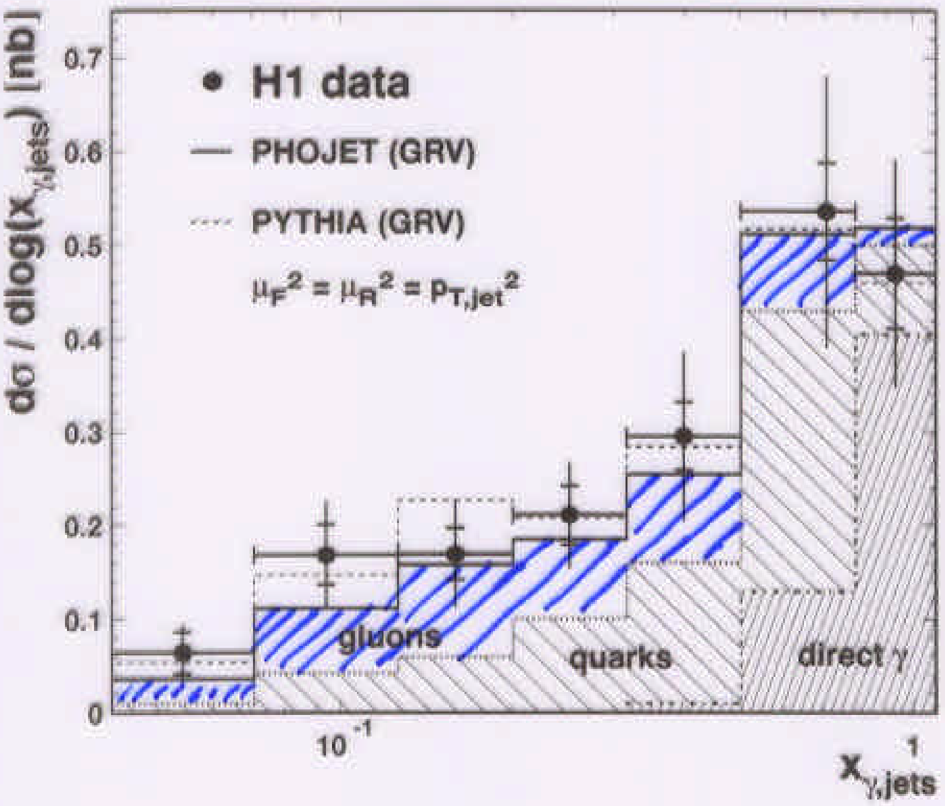
- low $x_\gamma \rightarrow$ low $E_{T,j} \leftarrow$ underl. event
- high $x_\gamma \rightarrow$ high $E_{T,j} \leftarrow$ cleaner

  see talk by R. Nania

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

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

after subtraction of underlying event:

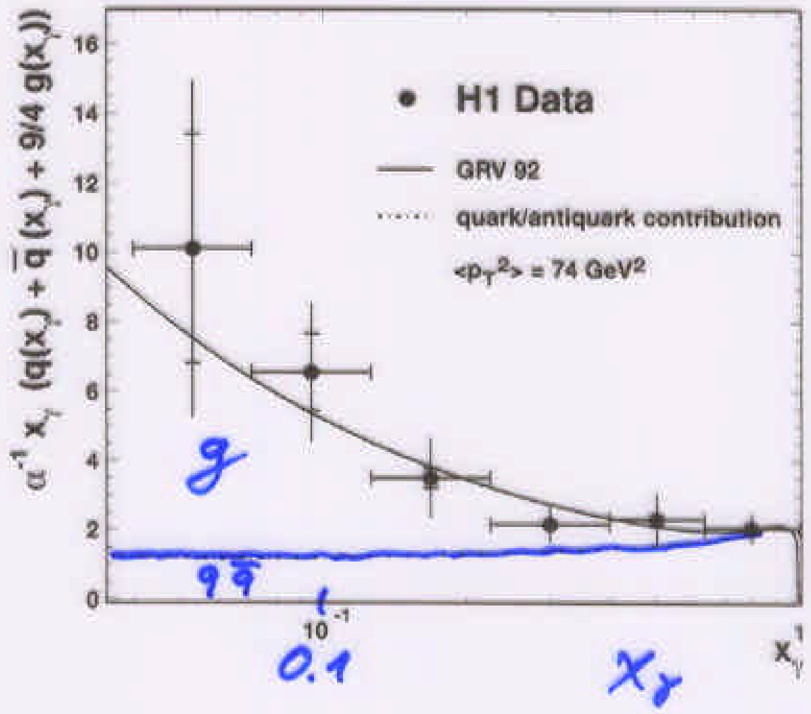


large sensitivity to gluons at small x

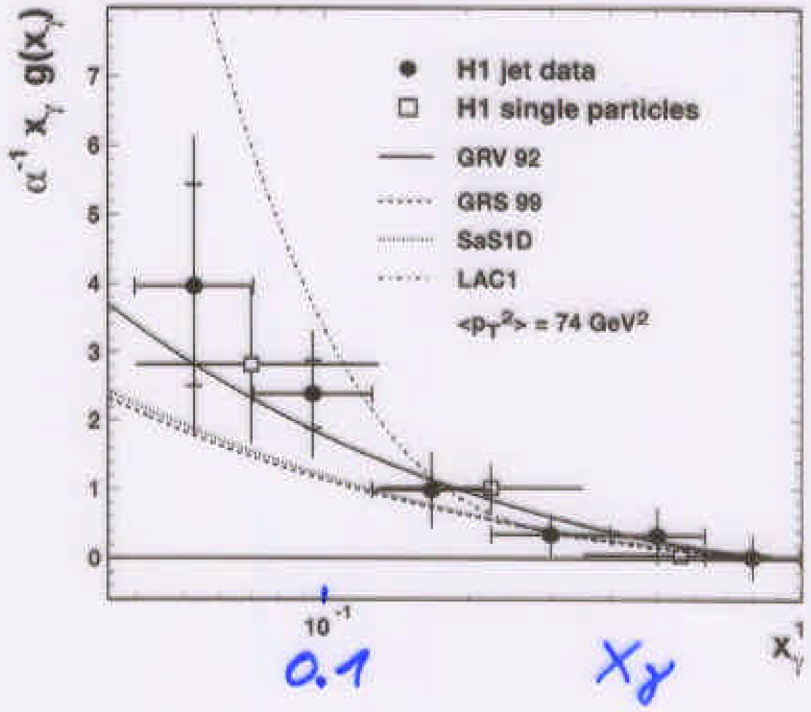
H1 low-x Photon Structure analysis

effective parton density

(q + g)



gluon density (quarks subtracted)



Clear proton-like rise of gluon density visible. Hadronic structure ! Limited by knowledge of underlying event.

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.

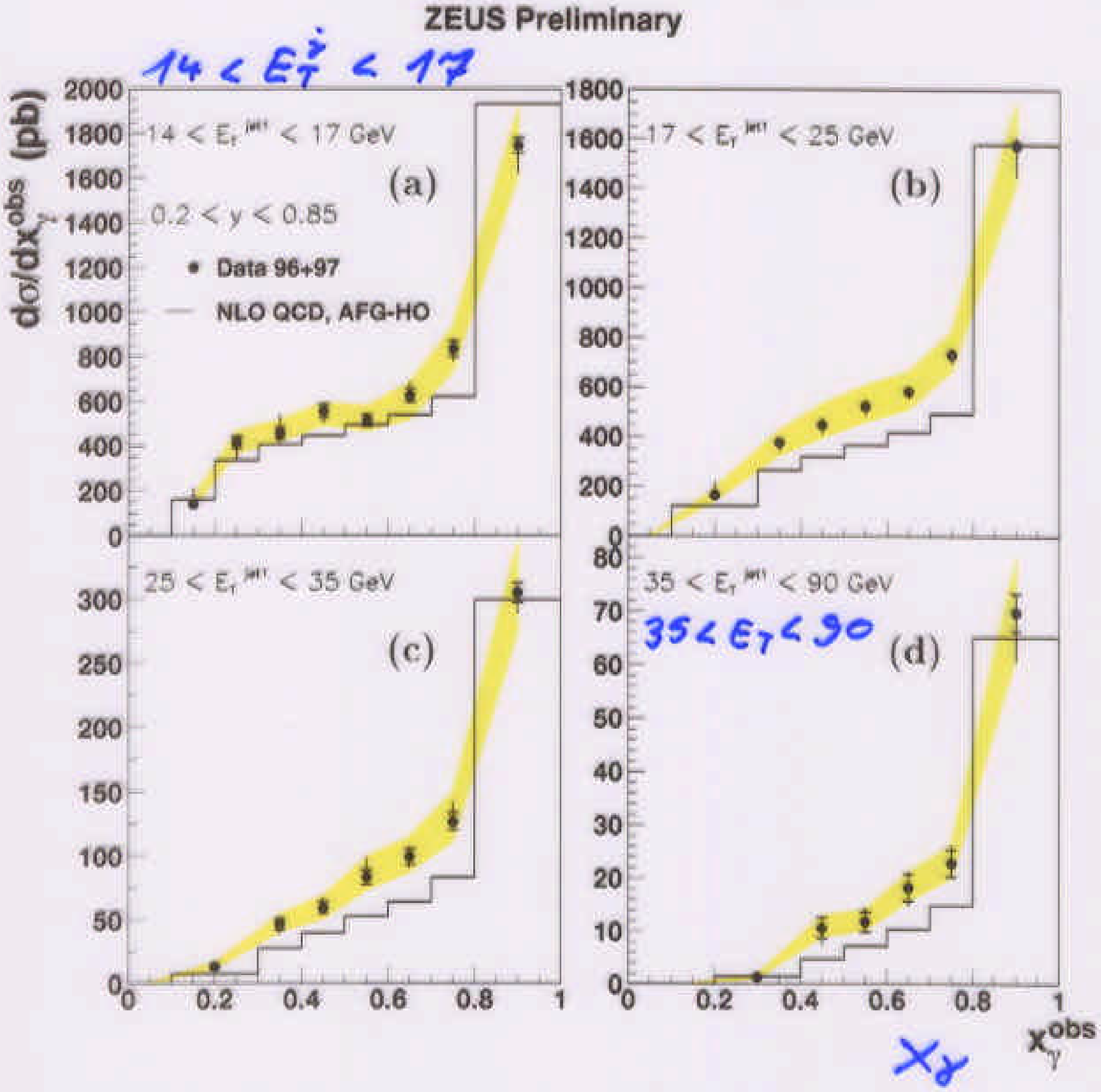
- LEP
  - F_2^γ for quarks, charm + jets for gluons
- HERA
  - jets at high/low E_T and x_γ (q+g)

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.

Jets in $\gamma - p$ from HERA



significant lower than standard parton density at largest E_T and $0.3 < x_\gamma < 0.8$

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 !

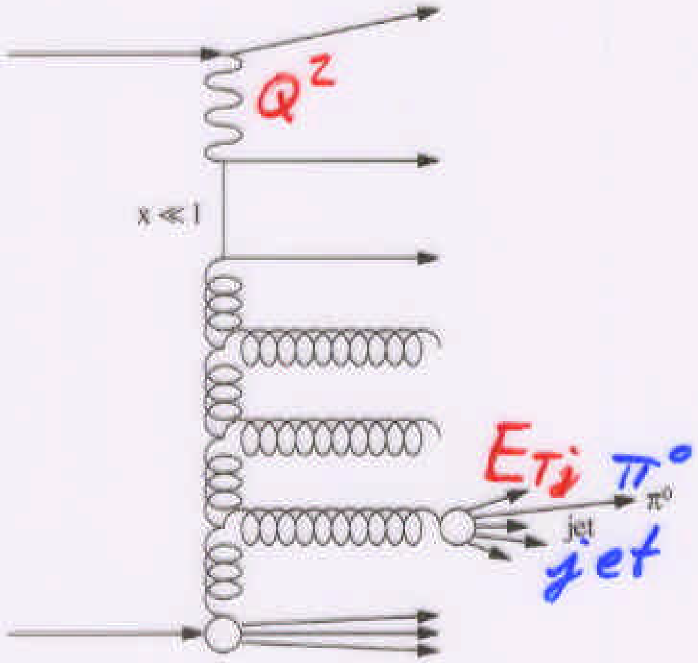
recent progress:

- 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



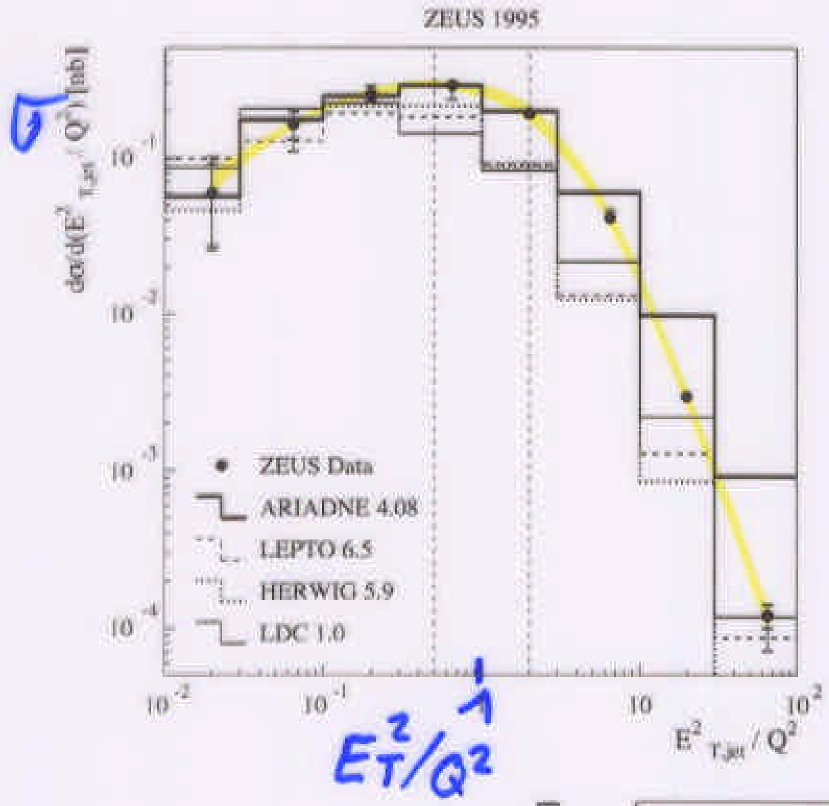
select:

- 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.

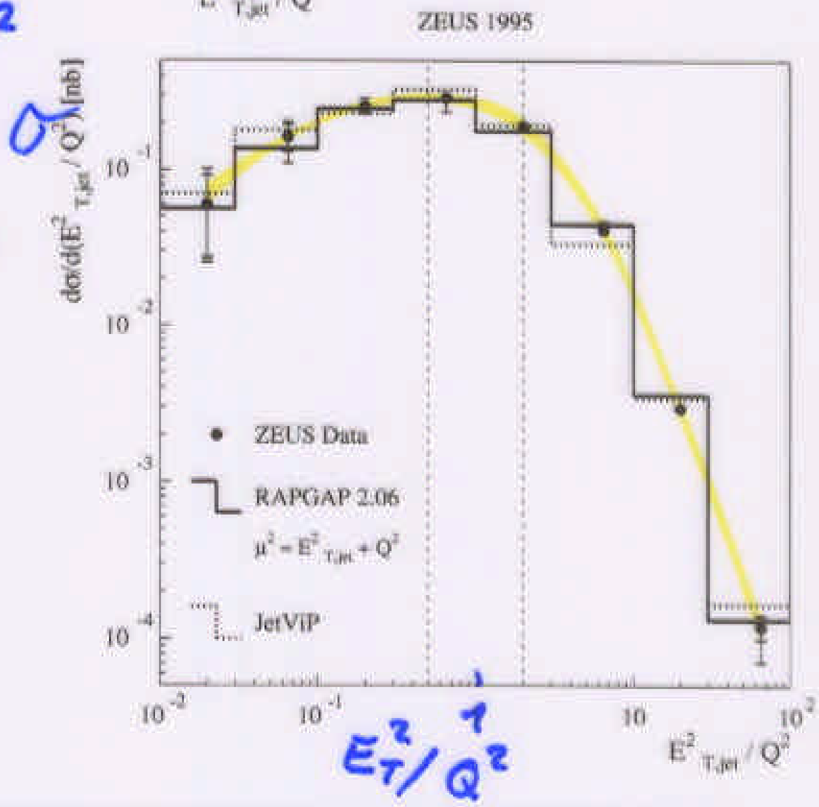
QCD dynamics: Forward Jets



DGLAP:

fails for

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



resolved virtual

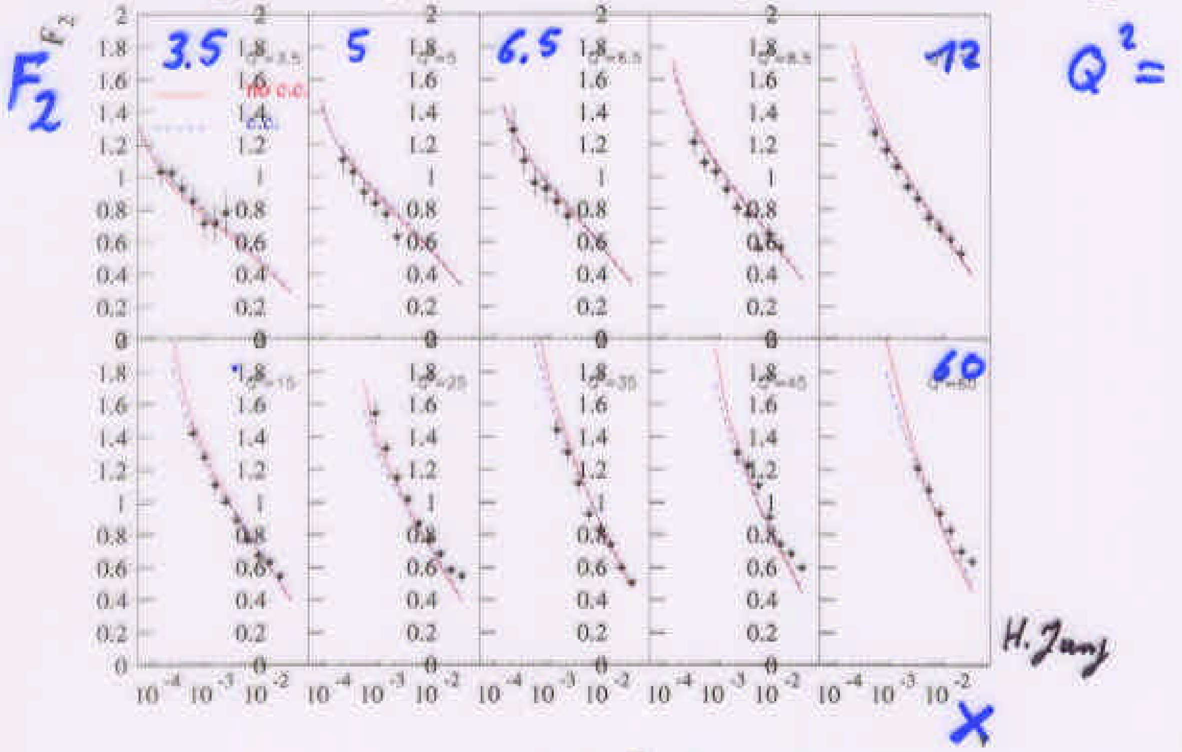
γ works:

sign for

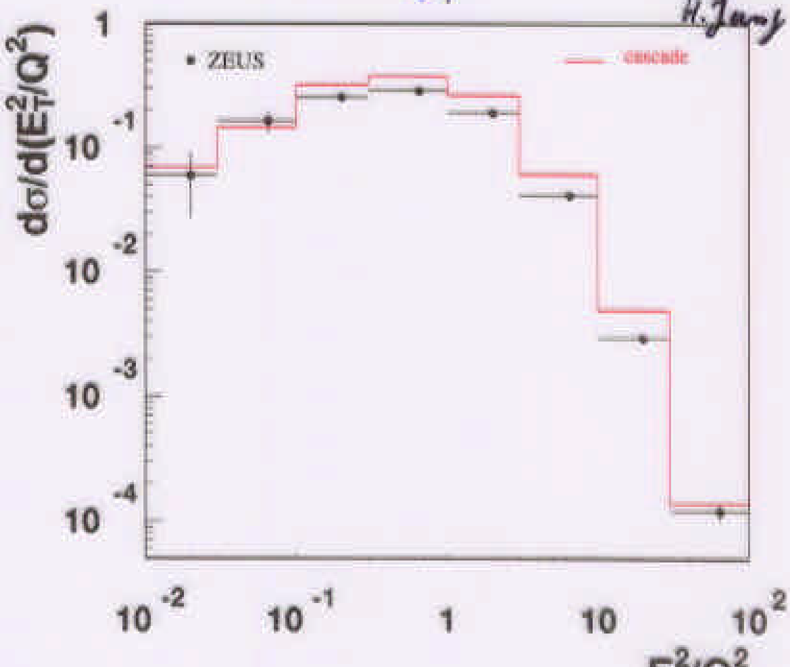
non-k_T order

QCD dynamics: Forward Jets with CCFM

unintegrated parton density from fit to F_2

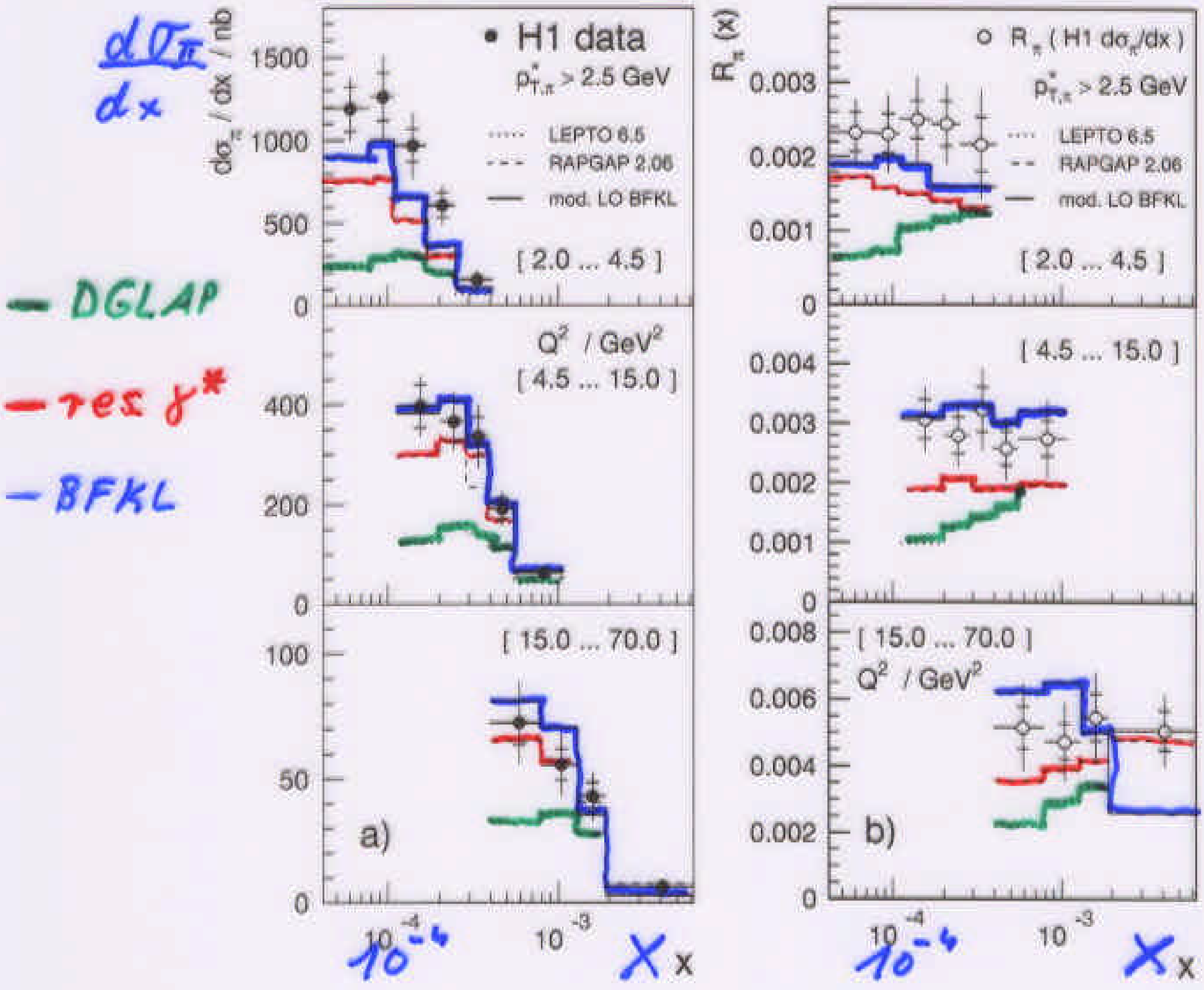


use CCFM evolution to describe jets



QCD dynamics: Forward π^0

high E_T π^0 in very forward direction

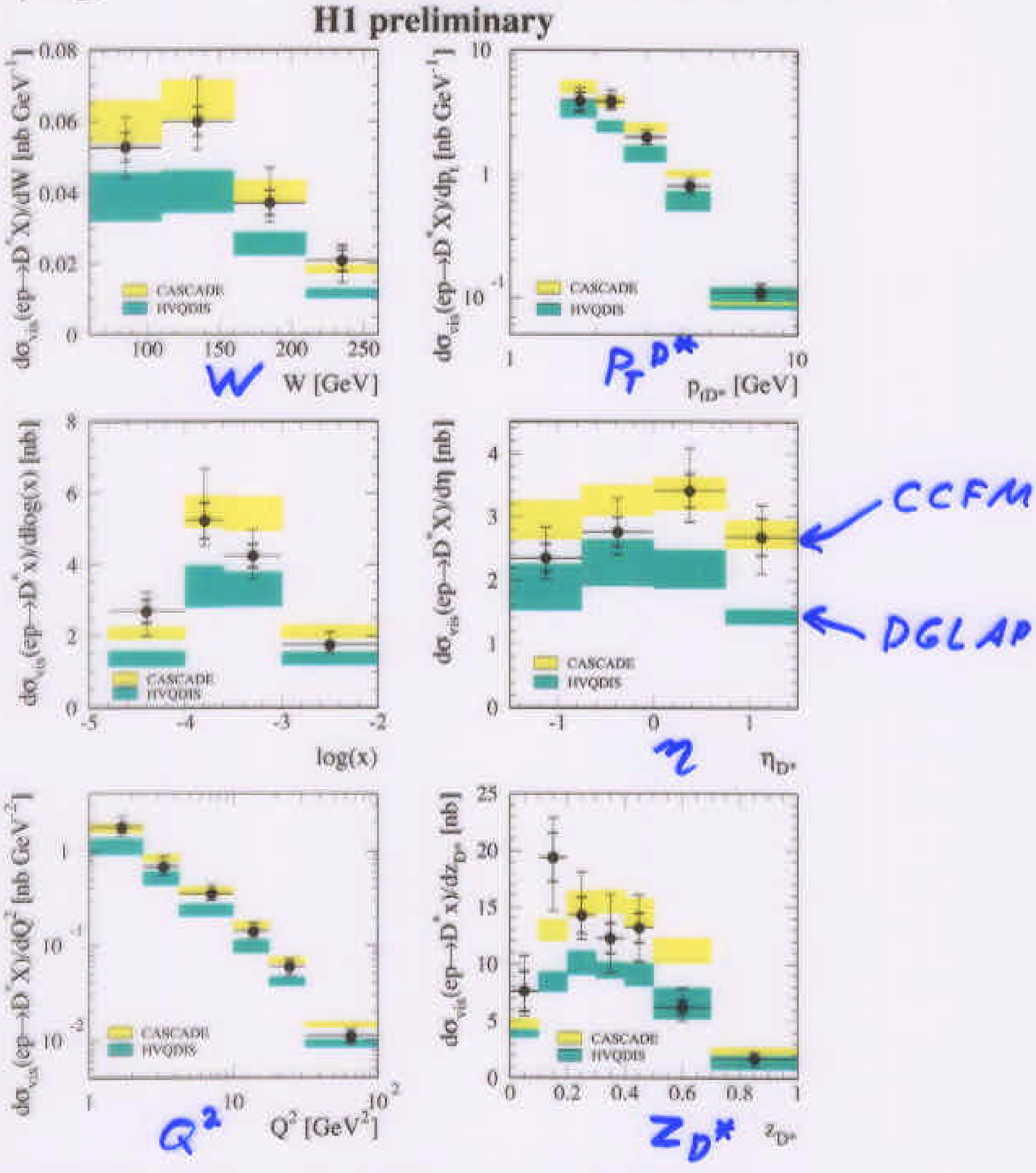


only hint on dynamics beyond

'resolved virtual photon'

QCD dynamics: Charm with CCFM

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

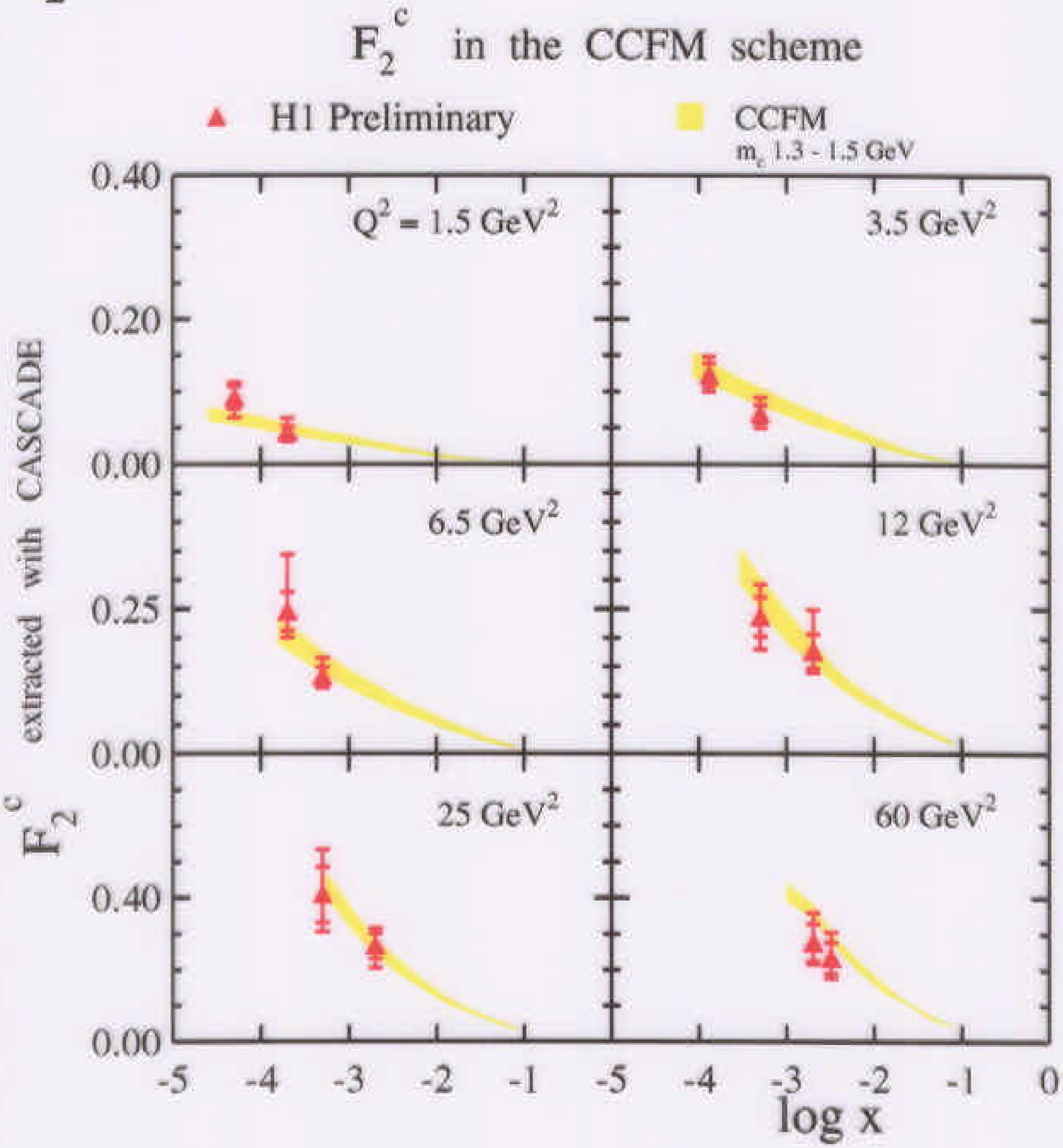


CCFM slightly better than DGLAP

also: J/ψ at Tevatron

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 $\sigma_{p\bar{p}}^{tot}$

QCD: scattering via quark/gluon exchange

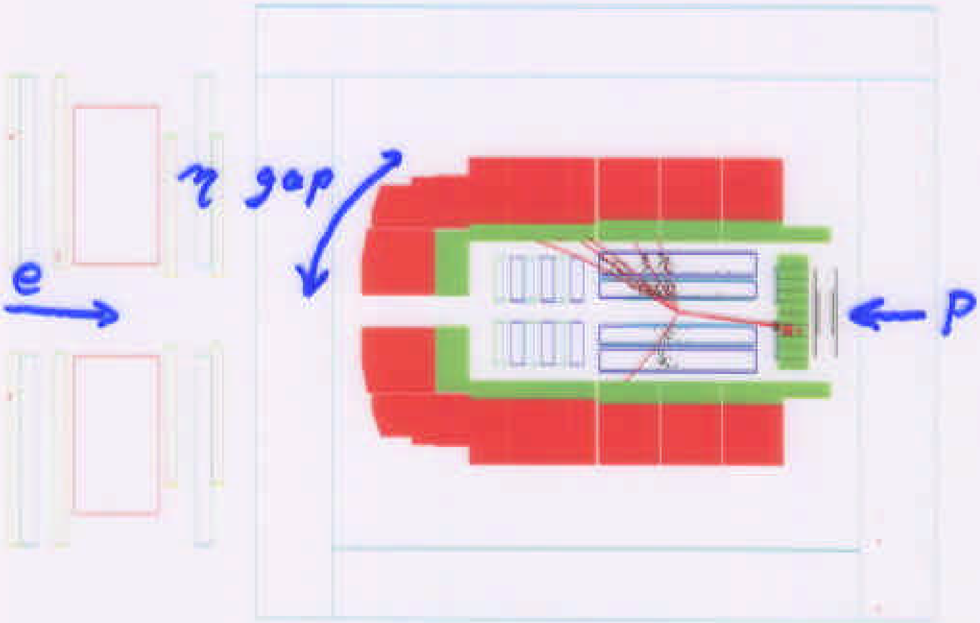
$\rightarrow$ colour exchange $\rightarrow$ confinement$\rightarrow$ proton fragments

What happens in elastic scattering ?

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

    γ^* hits parton but p survives

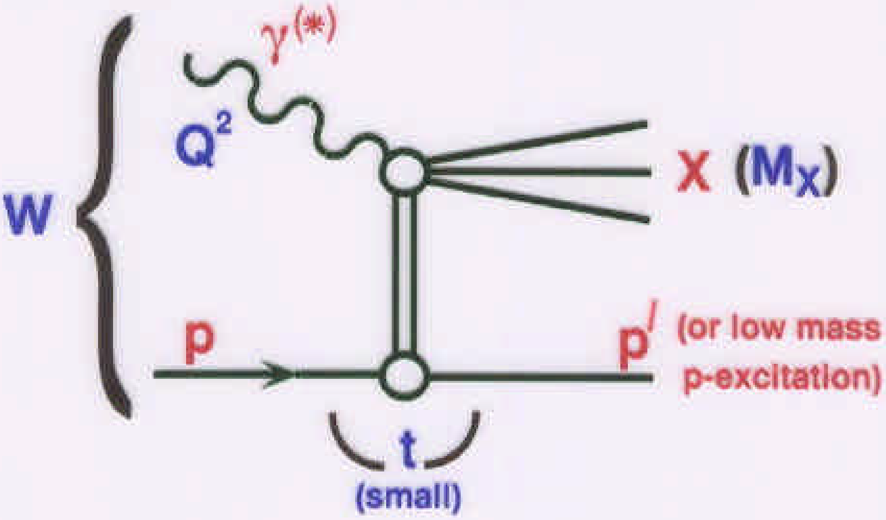
no proton frag- ments



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.

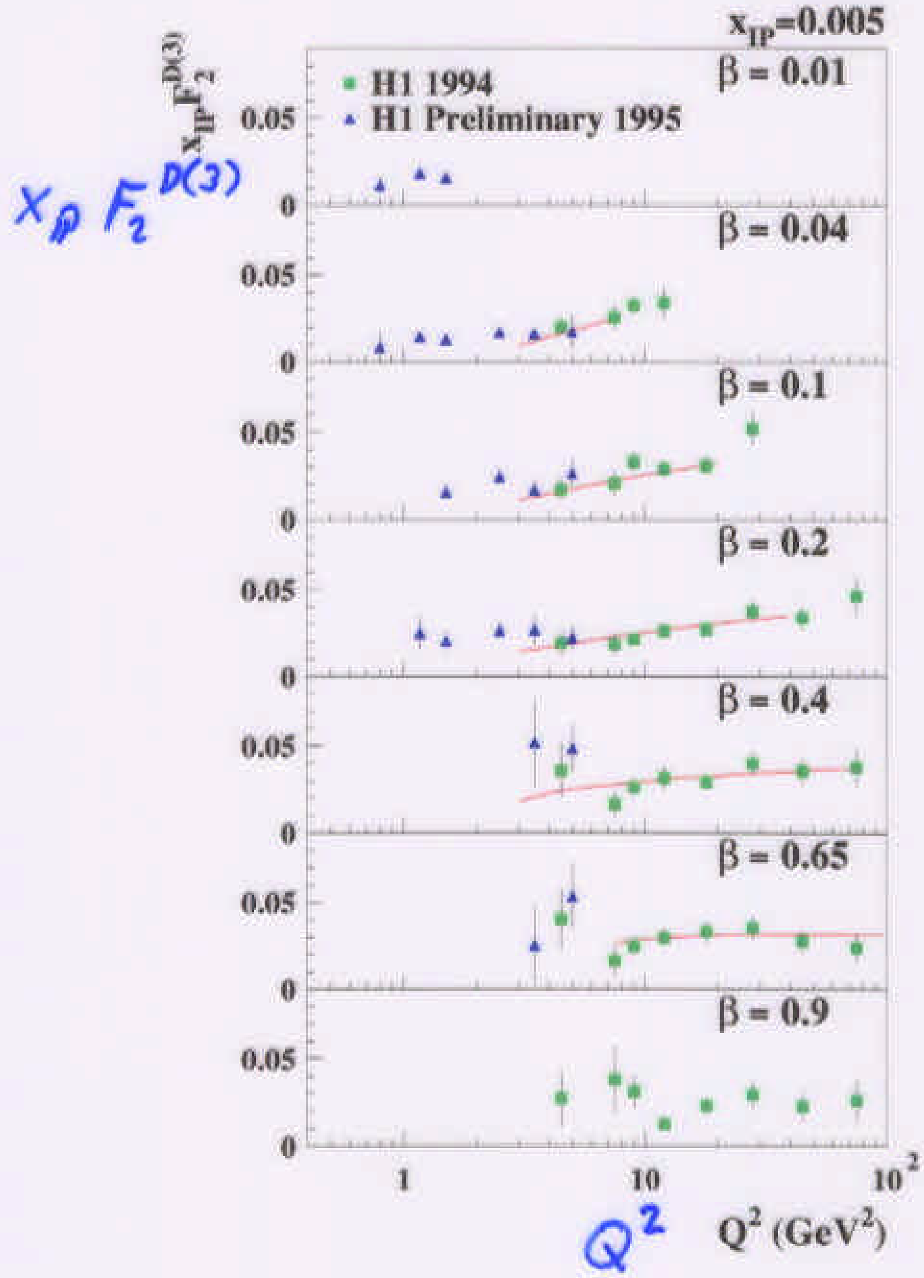
$$F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t)$$

$x_{I\!P}$ 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:

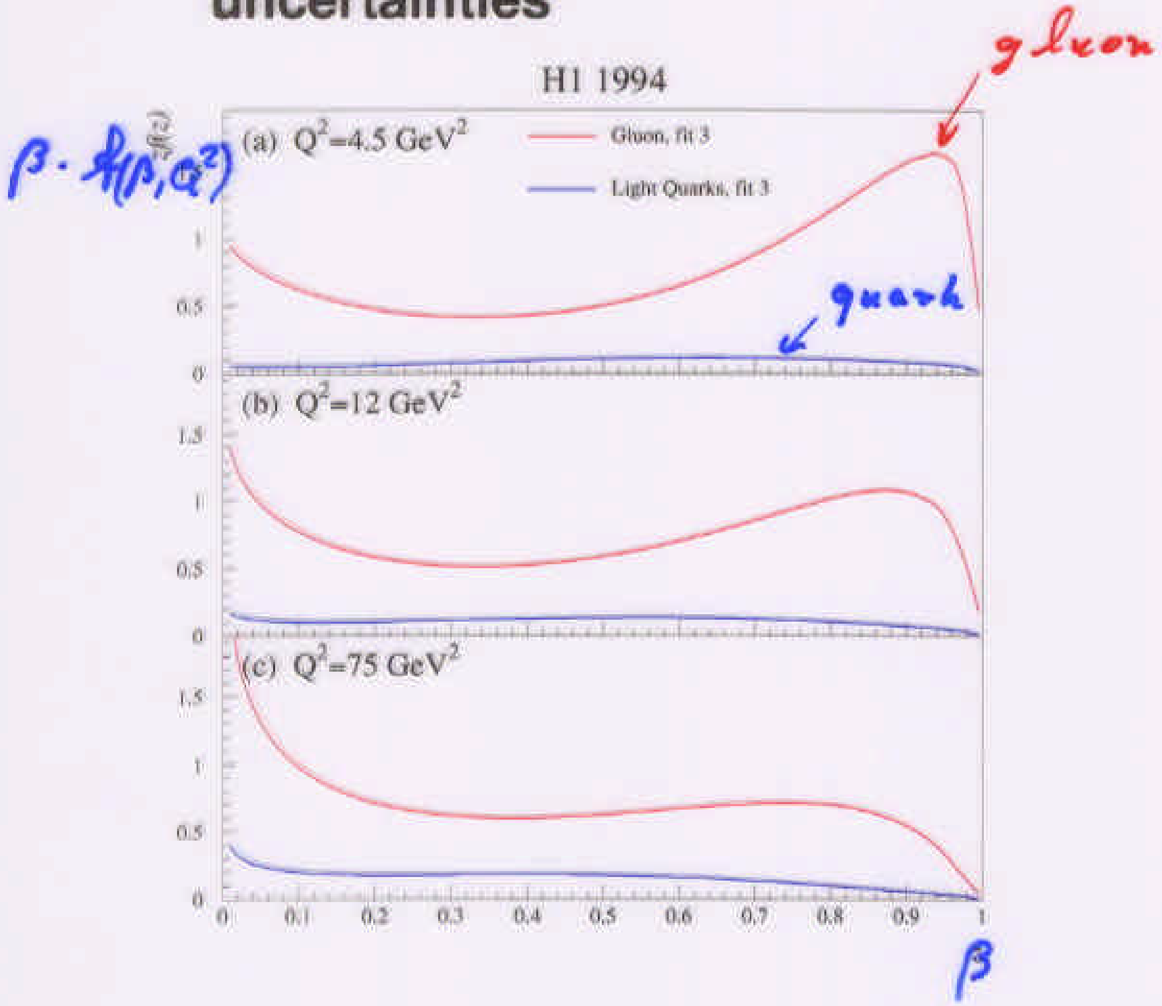
positive scaling violations:

gluons dominate (see proton at small x)

Diffractive parton density

QCD analysis

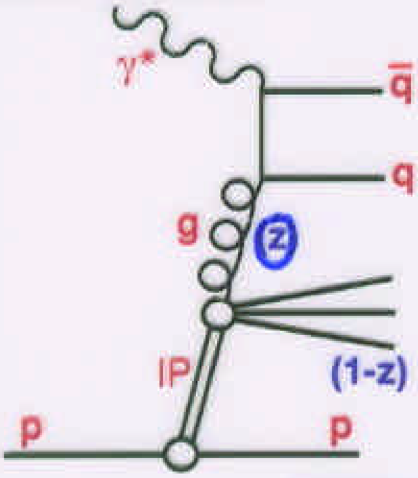
- **approx. Reggee factorisation:**
  $F_2^{D(3)}(\beta, Q^2, x_{I\!P},) =$
  $f(x_{I\!P}) \times f(\beta, Q^2)$
- **gluon density flat in β, with large uncertainties**



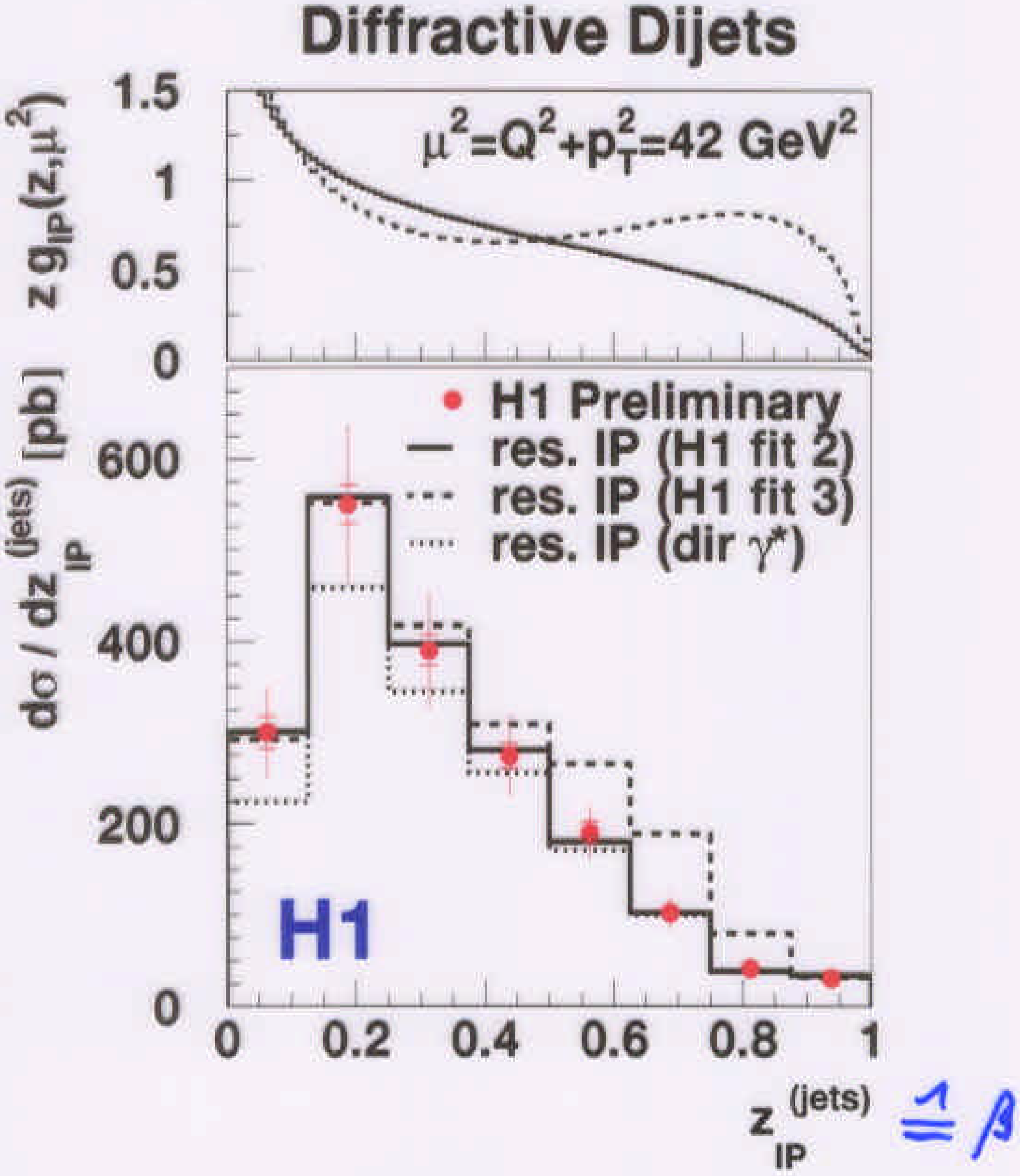
Needs independent cross check in another process

Jet production in Diffraction

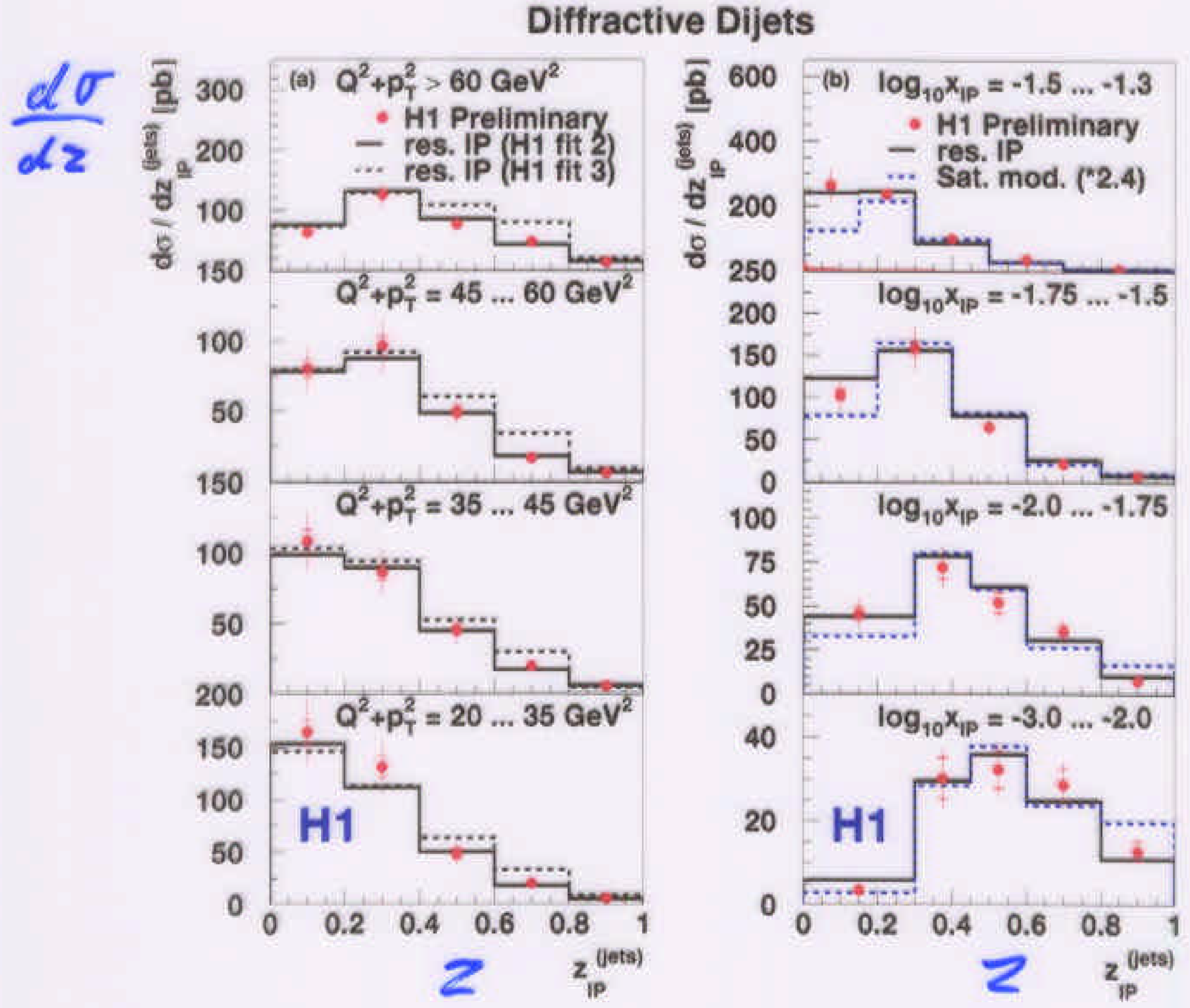
New dataset



directly sensitive to gluons



Jet production in Diffraction

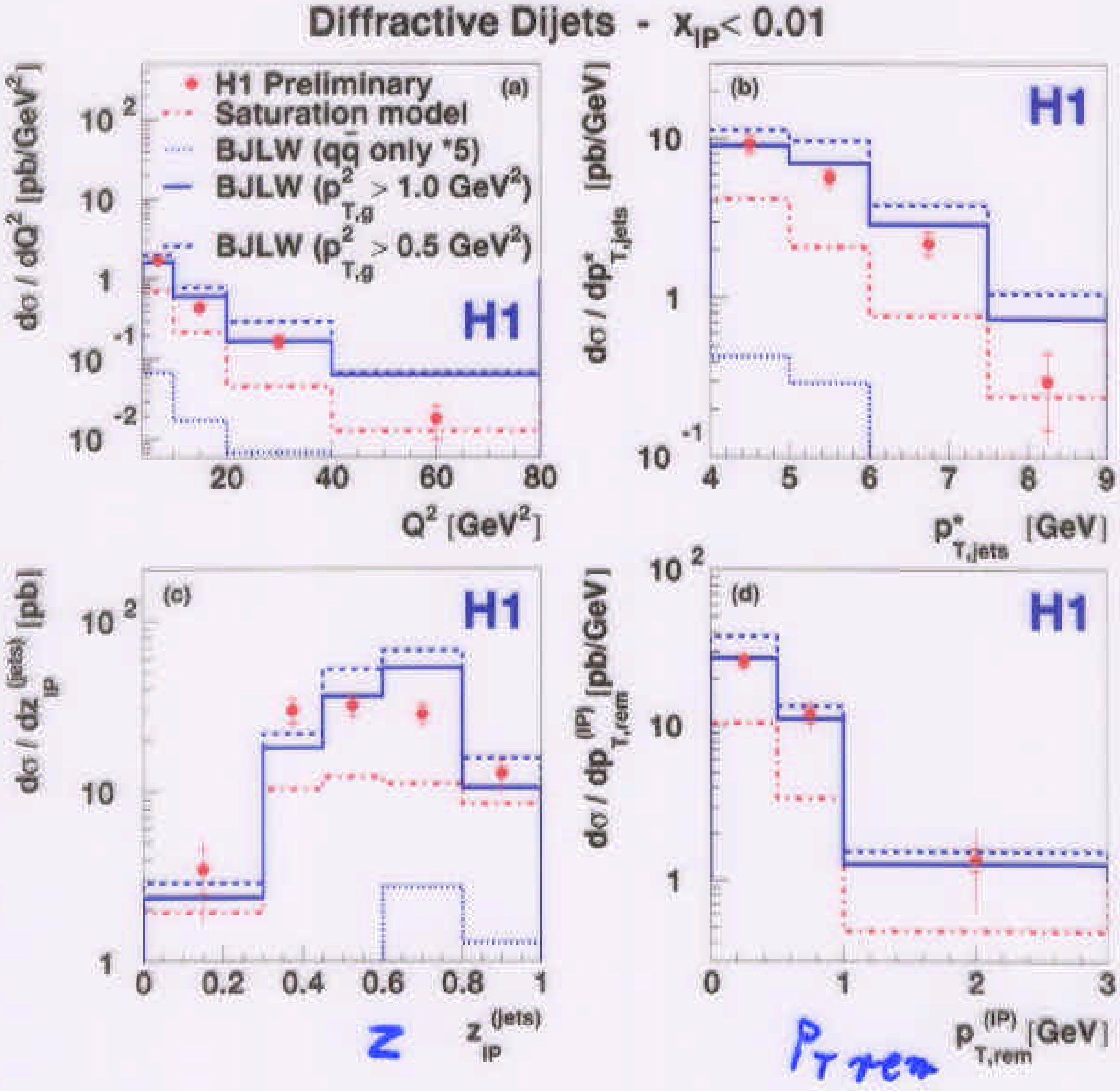


fully consistent picture from $F_2^{D(3)}$ and jets

in either Q^2, $x_{I\!P}$ or z

Jet production in Diffraction

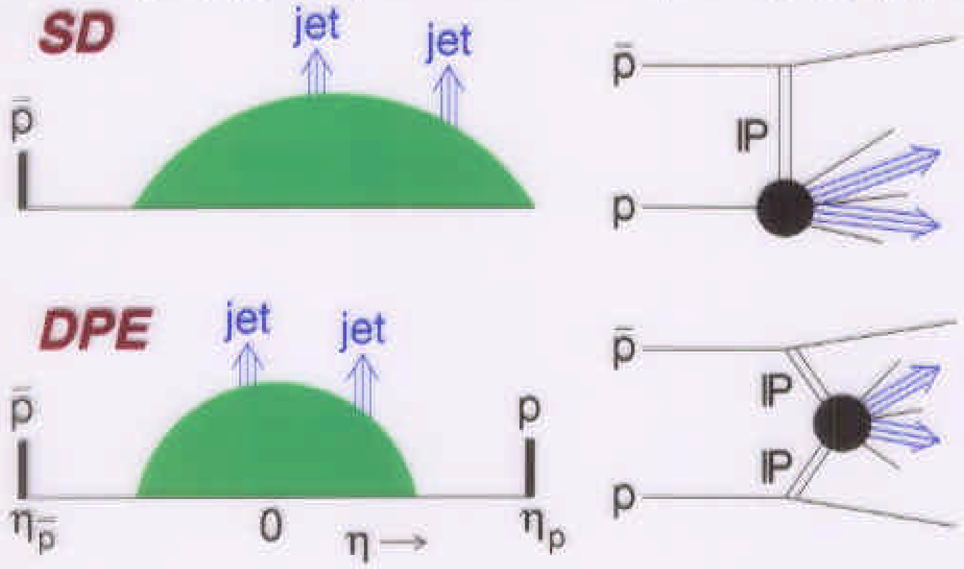
Comparison with QCD calculation for 2-gluon exchange $\sigma \sim |g(z, Q^2)|^2$



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^{SD}_{ND}**
- **double diff. / single diff. = R^{DD}_{SD}**

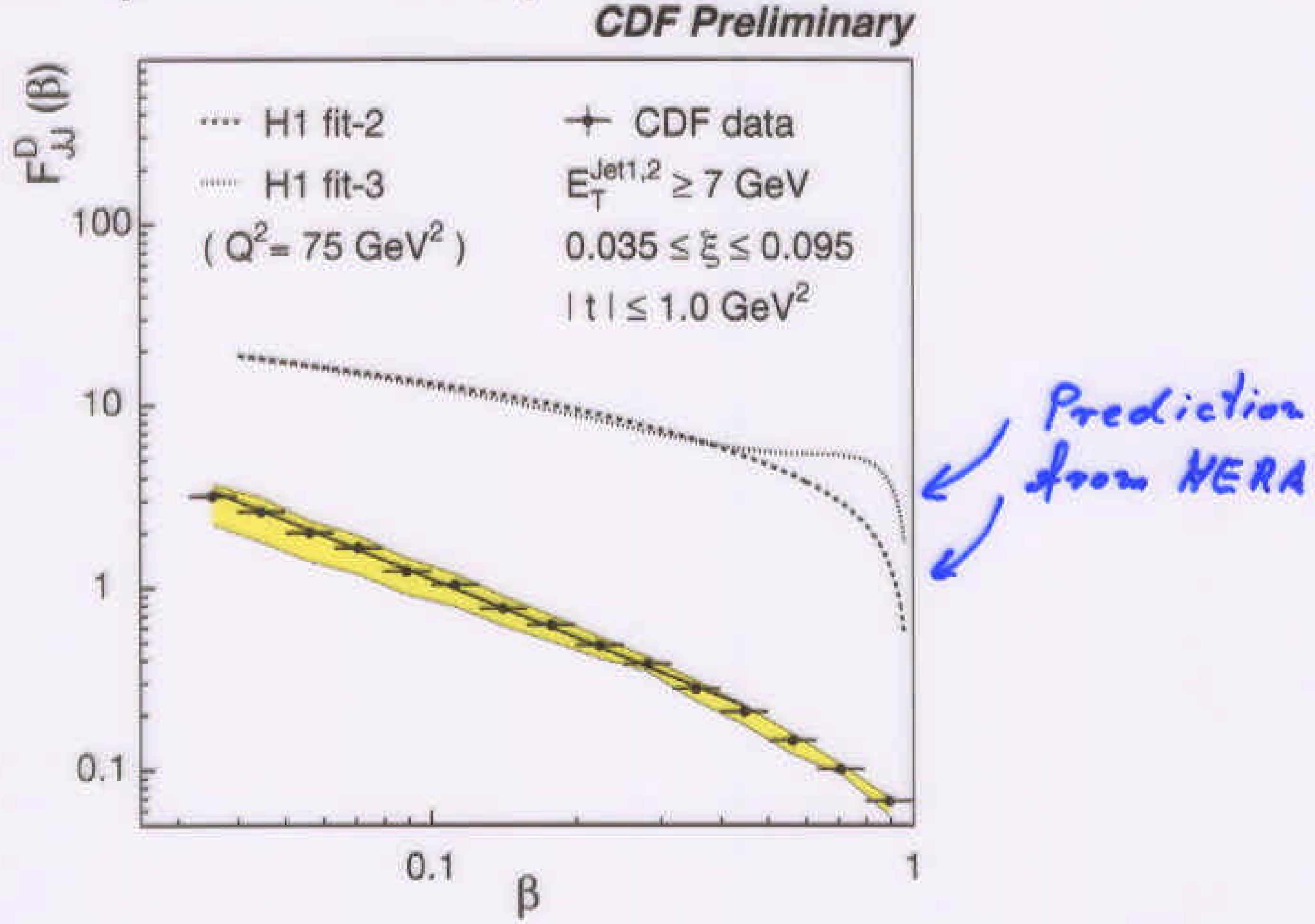
structure function:

$$F^D_{jj} = R^{SD}_{ND} \times F_{jj}$$

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

Diffraction at Tevatron

compare with HERA predictions



difference factor 20, no agreement in shape !

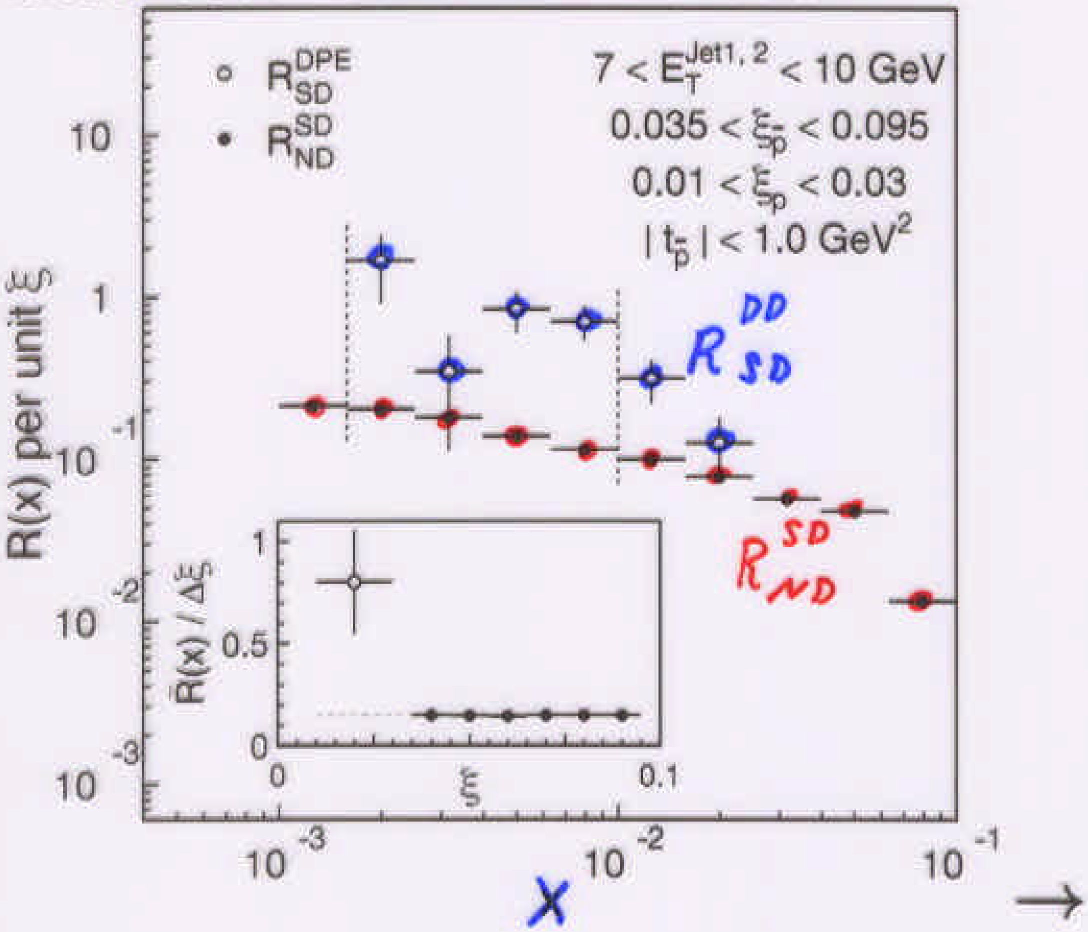
→ Breakdown of factorisation

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

Diffraction at Tevatron

compare R^{DD}_{SD} with R^{SD}_{ND}

factorisation test within Tevatron



Breakdown of factorisation

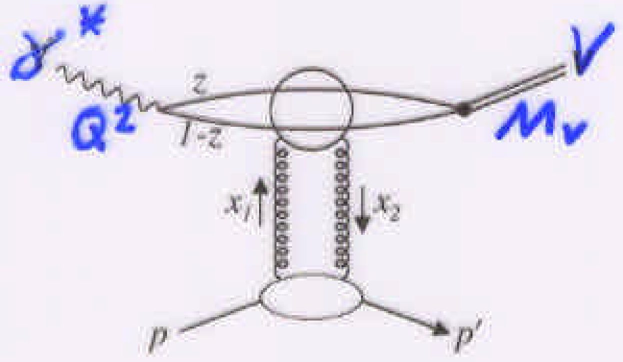
$$R^{DD}_{SD} = 0.80 \pm 0.26$$

$$R^{SD}_{ND} = 0.15 \pm 0.02 \qquad \text{factor 5}$$

similar factors for W, b

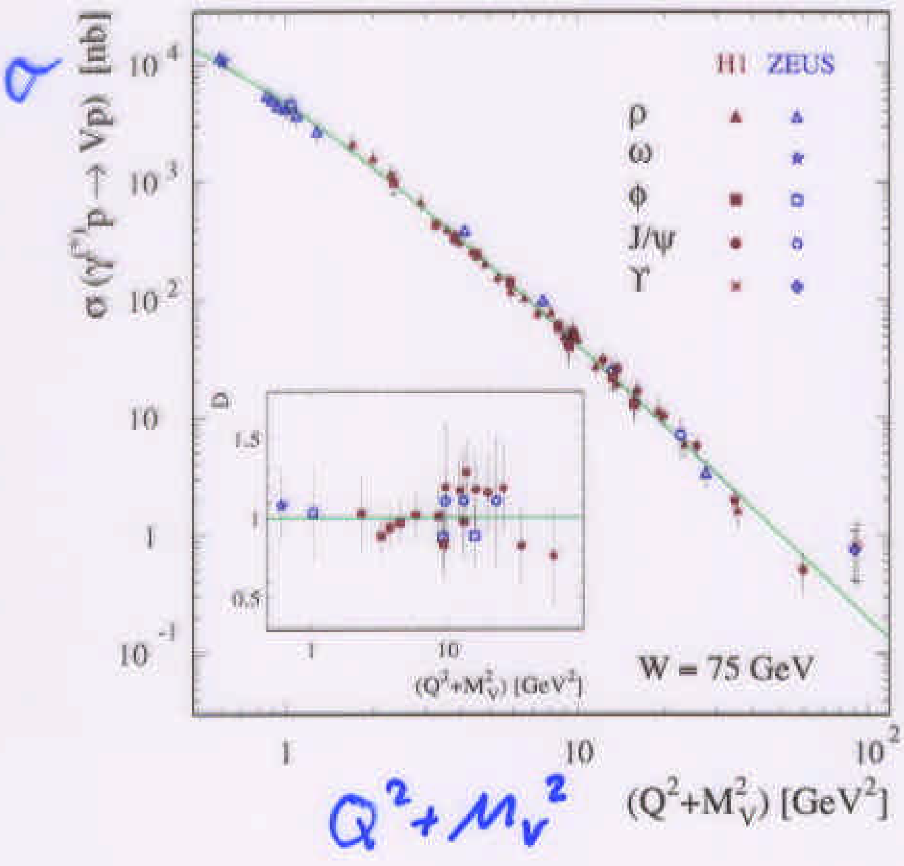
remnant – proton scattering : soft

Vectormeson production at HERA

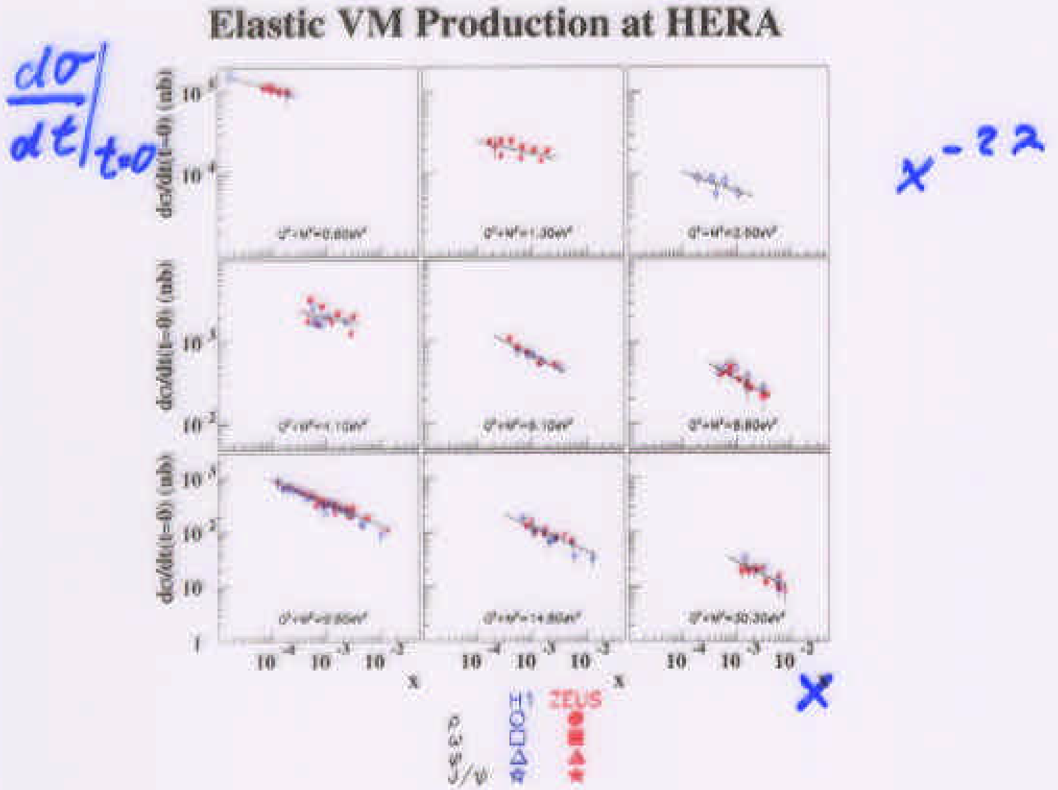


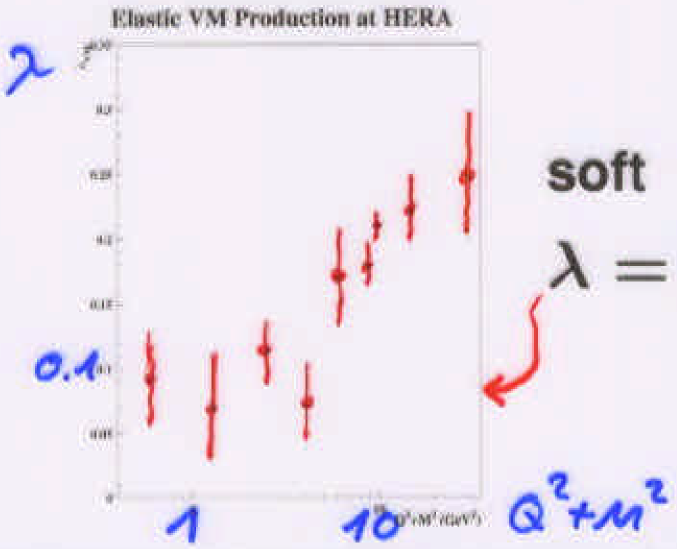
- $\gamma \rightarrow q\bar{q}$
- $q\bar{q}(g)$ interacts with colour singlett
- formation of meson

Hard scales: Q^2, M_V or t



Vectormeson production at HERA





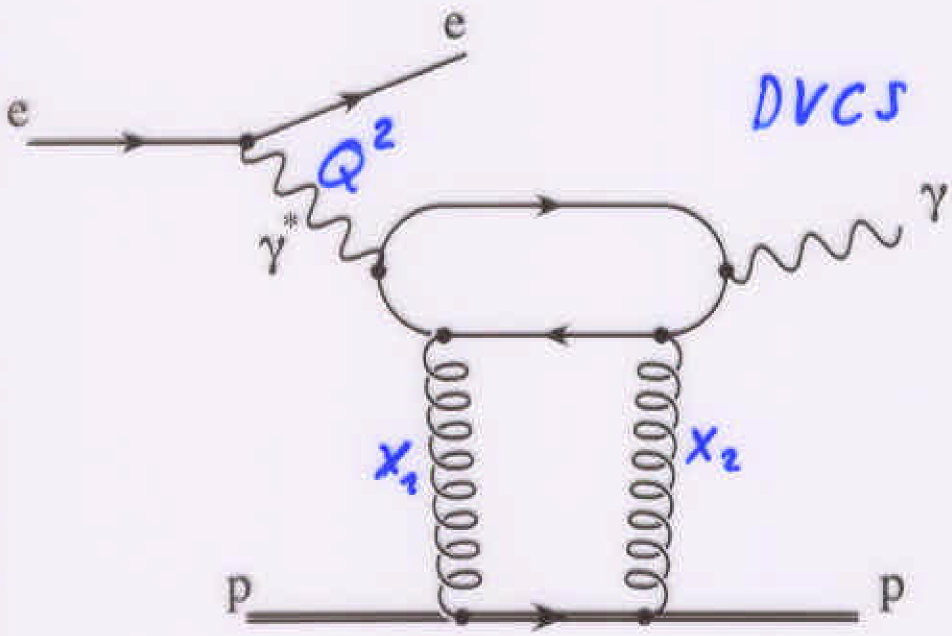
soft process:

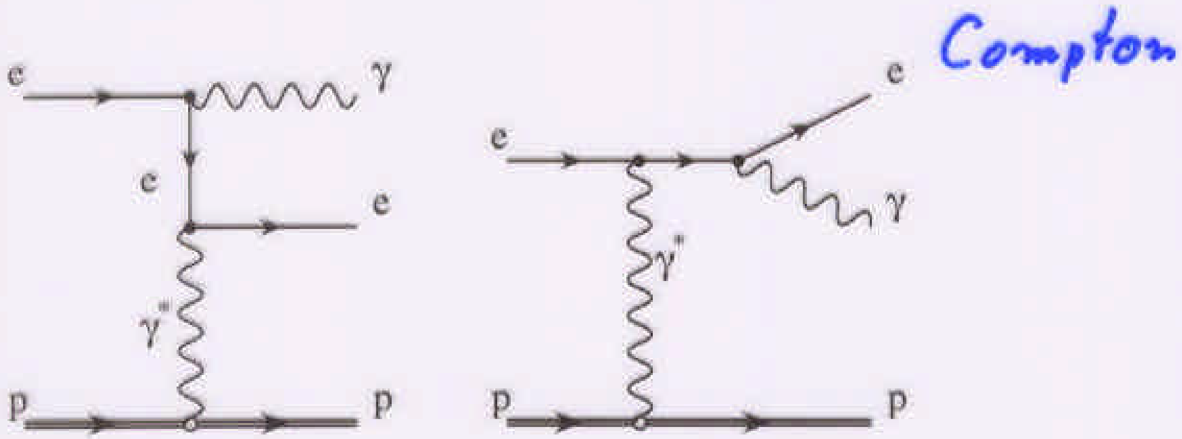
$\lambda = 0.08$

clear transition between soft and hard

nice confirmation of pQCD scale

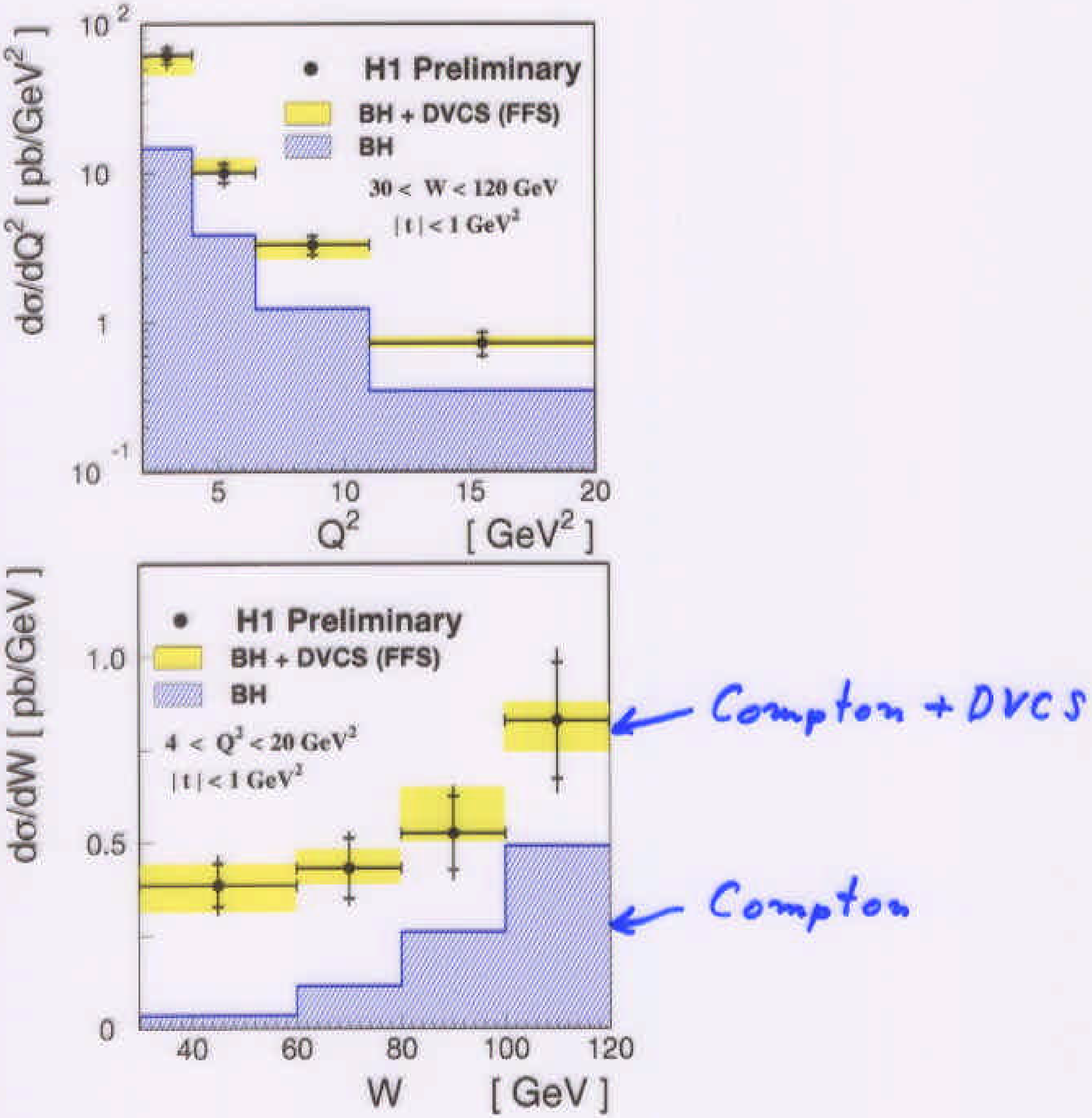
Deeply Virtual Compton Scattering





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

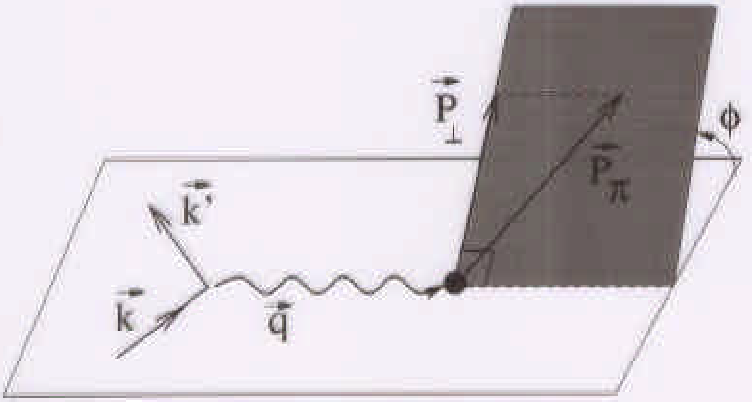
Deeply Virtual Compton Scattering



pQCD: predictd cross section nicely confirmed.

Needs major step in luminosity !

Transversity from HERMES



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