31st International Conference on High Energy Physics

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QCD at high energy (*experiments*)

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Mission statement

- **QCD: Theory of quarks and gluons**
- **Ambition: develop complete and quantitative understanding of QCD in *all* kinematic regions**
  - **Precise measurement of α_S and colour factors**
  - **Proton structure and pQCD: Structure functions, evolution; gluons → Pomeron transition**
  - **Compile extensive 'library' of precise measurements to compare with predictions and catalyze theoretical developments**

Plan of the talk:

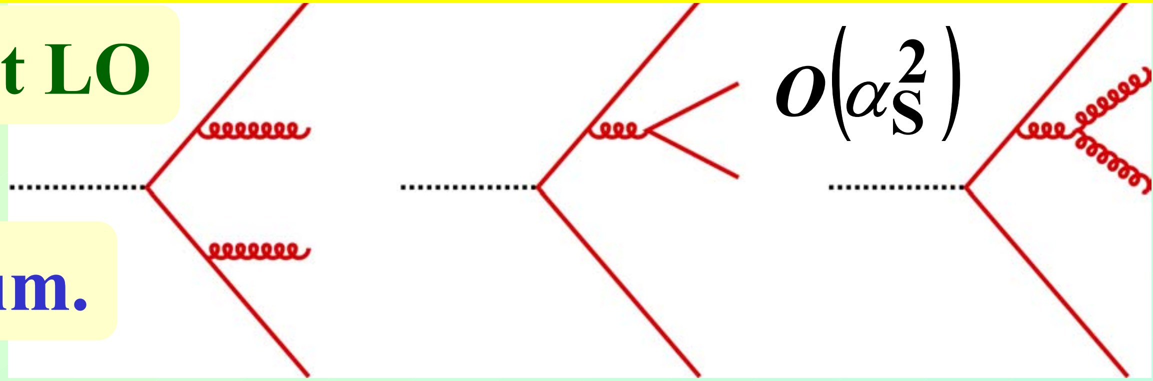
- Measurement of α_S and colour factors
- Proton and photon structure
- Diffraction
- Dijets in photoproduction

Apology:

Short talk covering broad, vibrant field: I apologise for not being able to show all important results.

α_S from 4-jet rate in e^+e^-

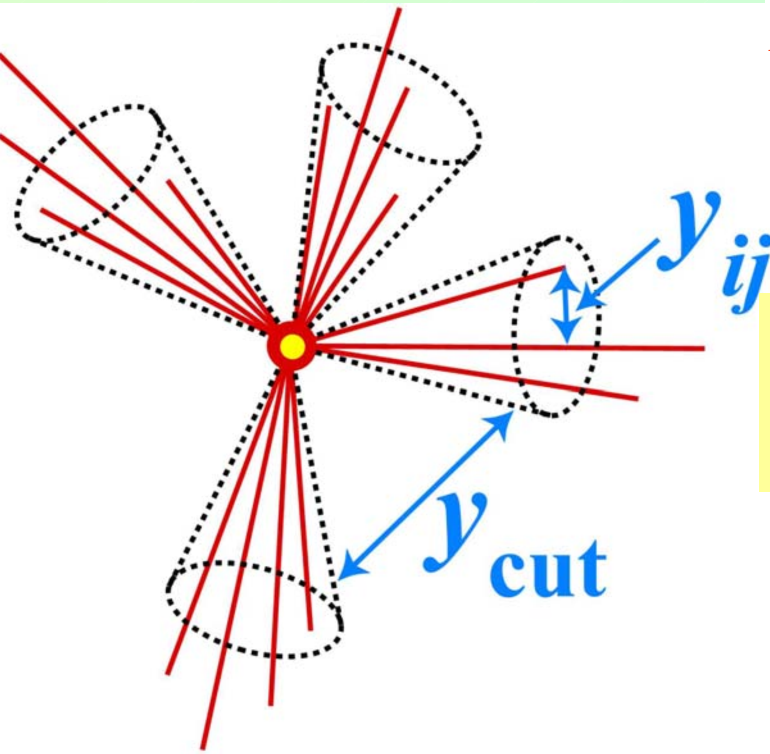
High sensitivity to α_S at LO



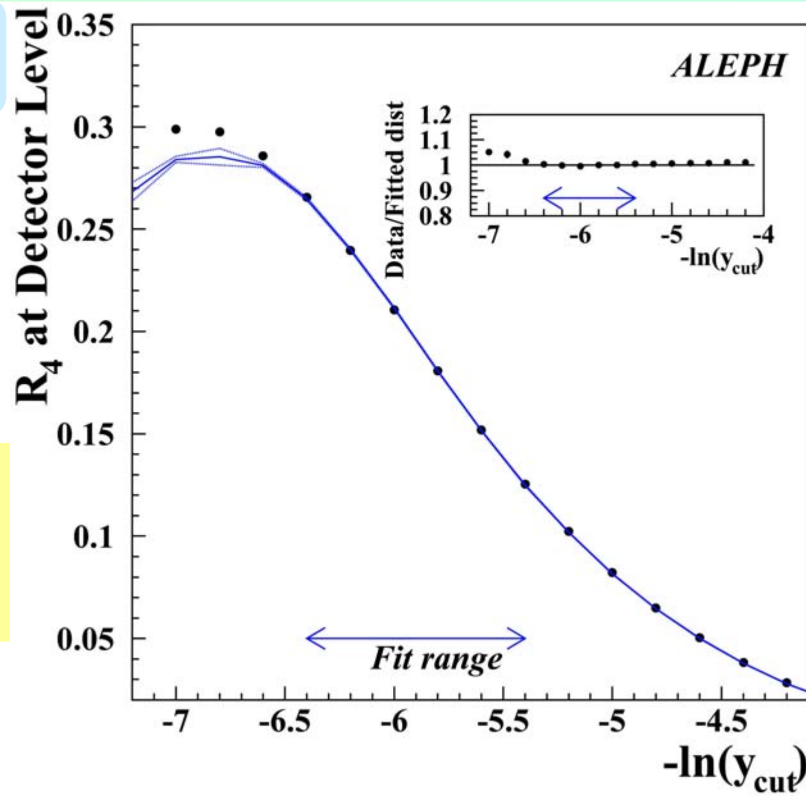
$O(\alpha_S^3)$ and NLL resum.

4-jet rate:

$$R_4 = \frac{\sigma_4(y_{cut})}{\sigma_{Tot}}$$

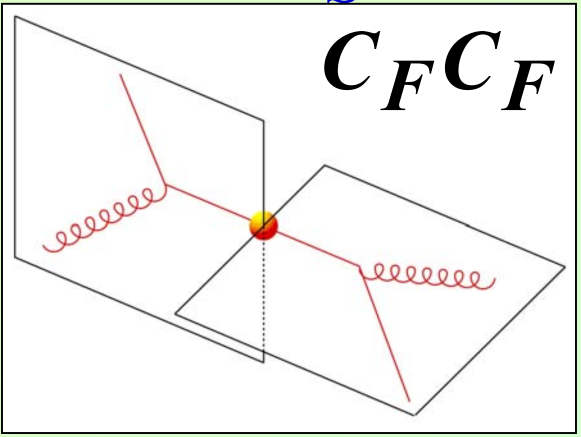


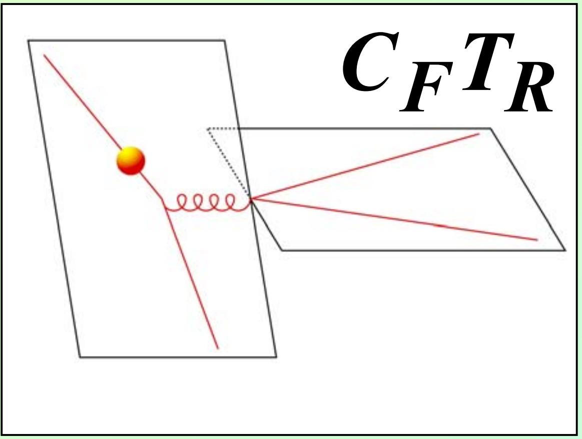
Precision!
~1%

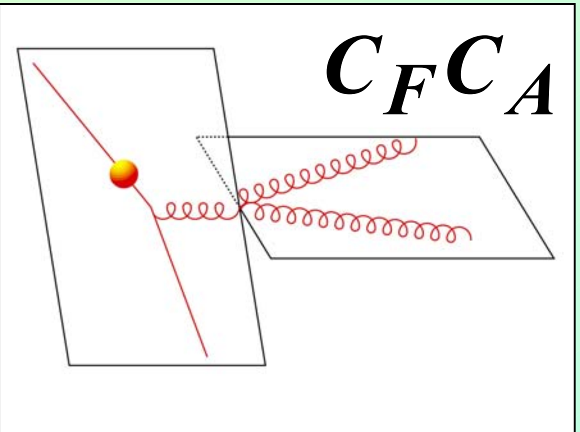


$$\alpha_S = 0.1170 \pm 0.0001 \pm 0.0013$$

α_S and colour factors from e^+e^-

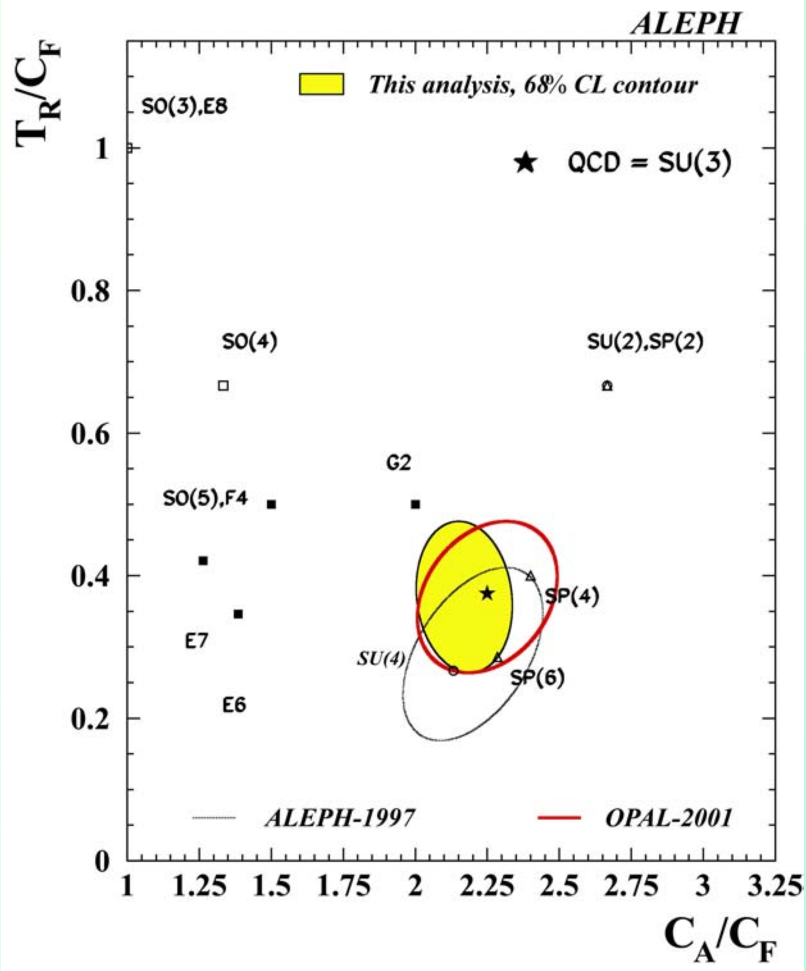






Angular correlations sensitive to colour factors

Simultaneous fit to 4 angles and R_4



ALEPH

$\alpha_S = 0.119 \pm 0.006 \pm 0.026$

$C_A = 2.93 \pm 0.14 \pm 0.58$

$C_F = 1.35 \pm 0.07 \pm 0.26$

OPAL

$\alpha_S = 0.120 \pm 0.011 \pm 0.020$

$C_A = 3.02 \pm 0.25 \pm 0.49$

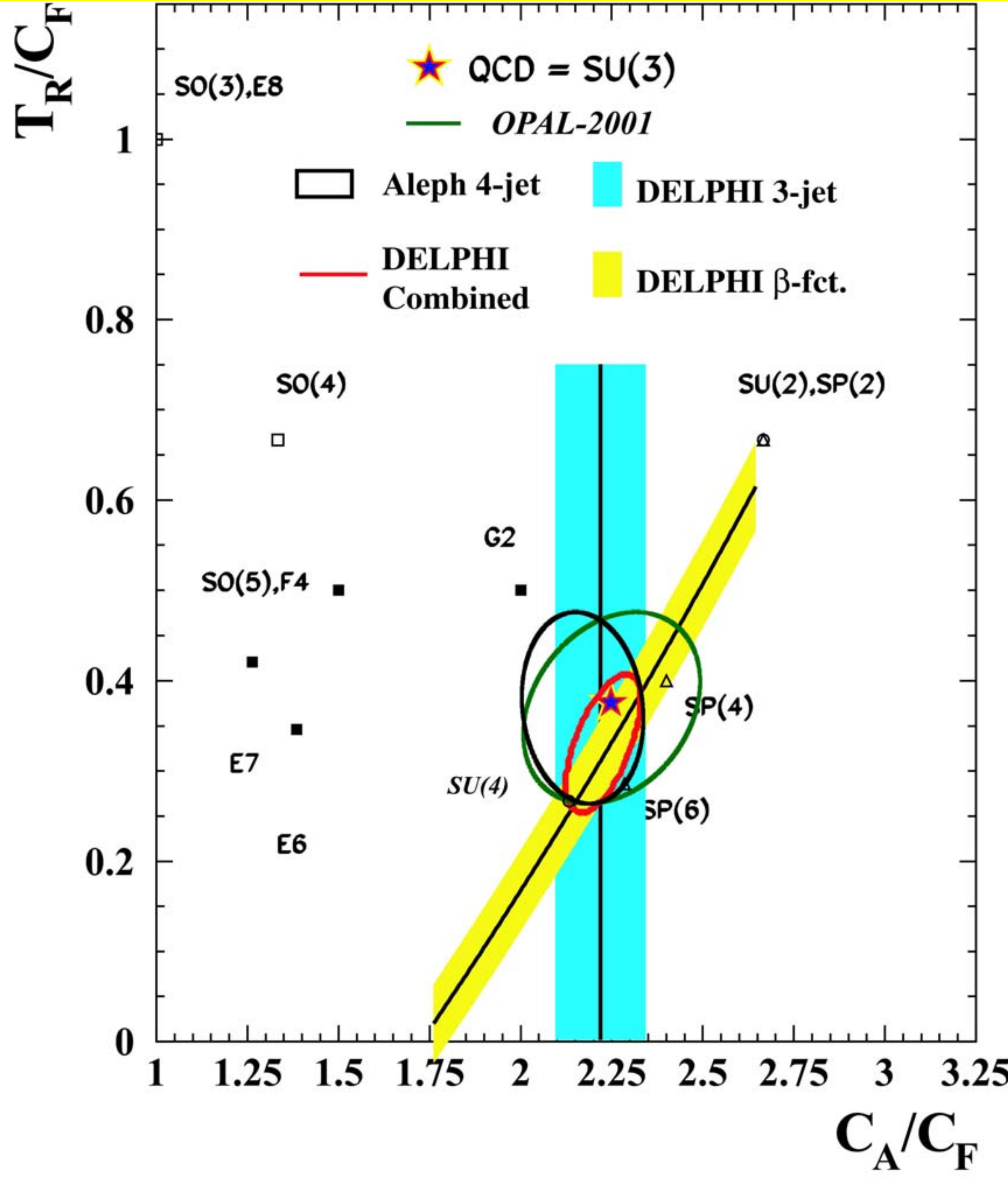
$C_F = 1.35 \pm 0.13 \pm 0.22$

α_S and colour factors from e^+e^-

Additional constraints:

- **Ratio of multiplicity in gluon and quark jets (DELPHI)**
- **β-function determined in RGI analysis (DELPHI)**

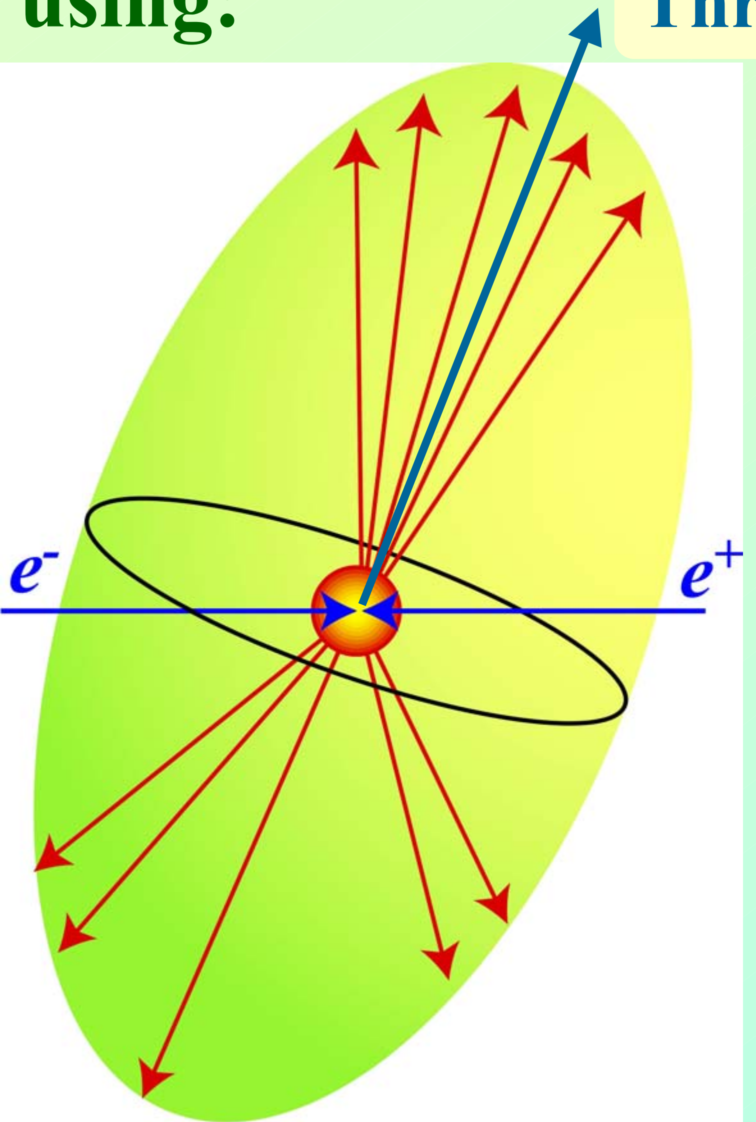
Note: DELPHI R_4 constraint is included in 'DELPHI combined'. Not shown for clarity.



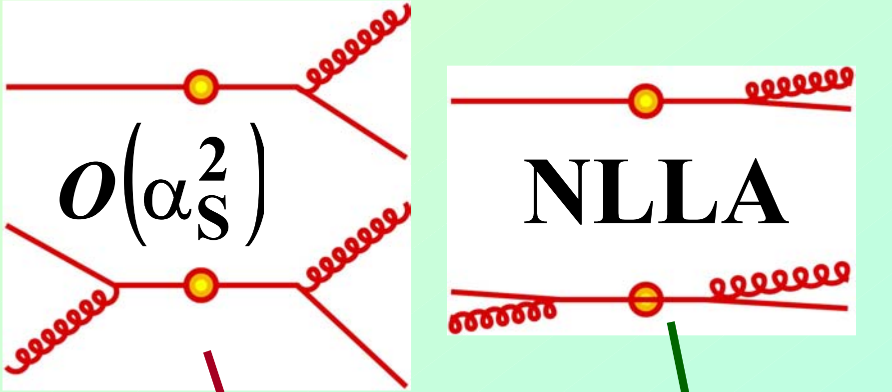
α_S from event shapes in e^+e^-

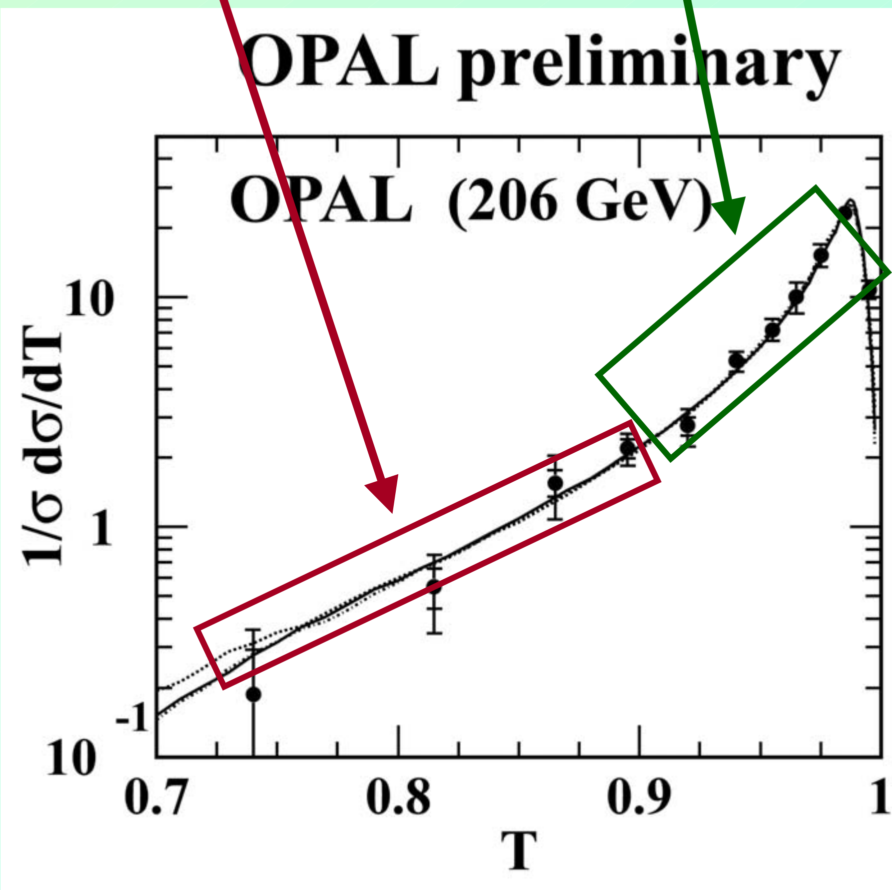
Characterise event shape using:

Thrust - T



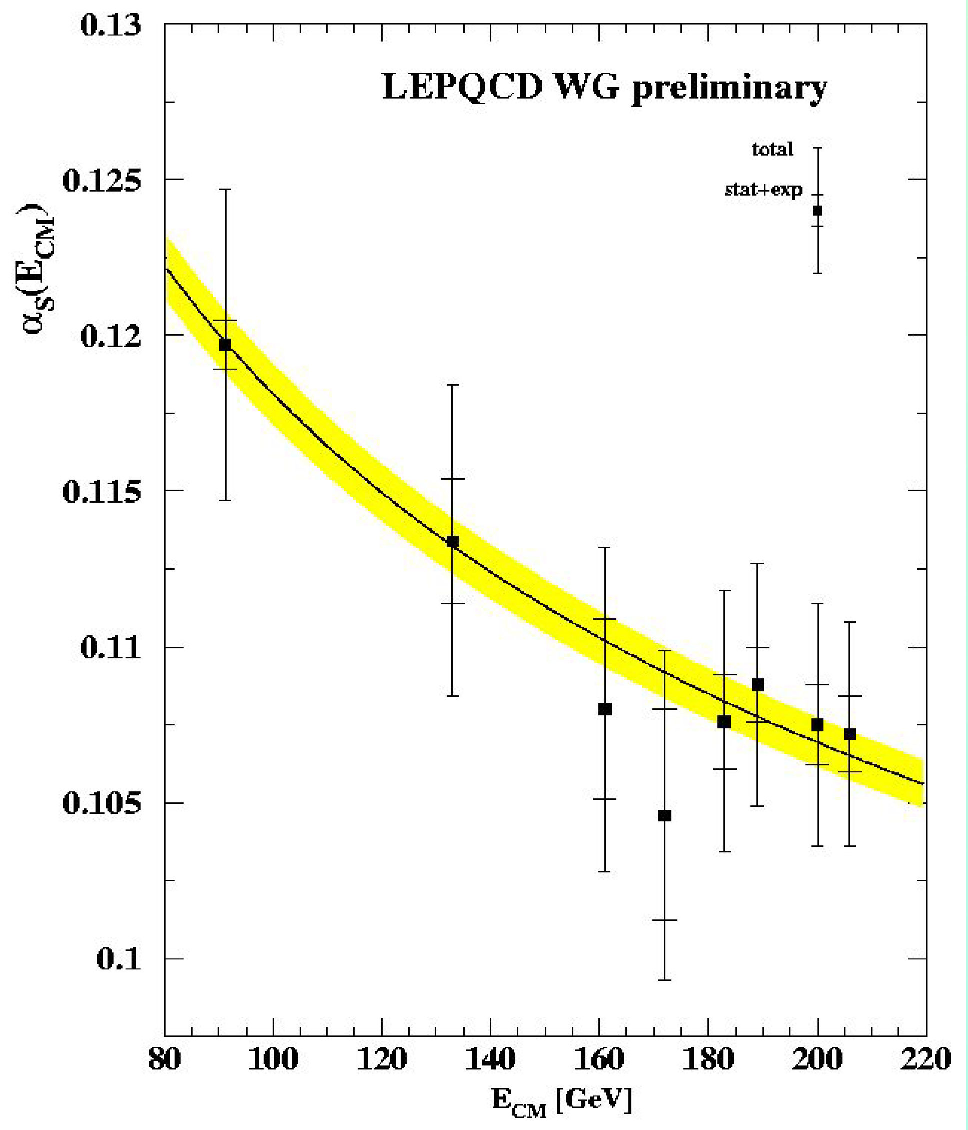
and
M_H
B_T
B_W
C
y_{23}





α_S from event shapes in e^+e^-

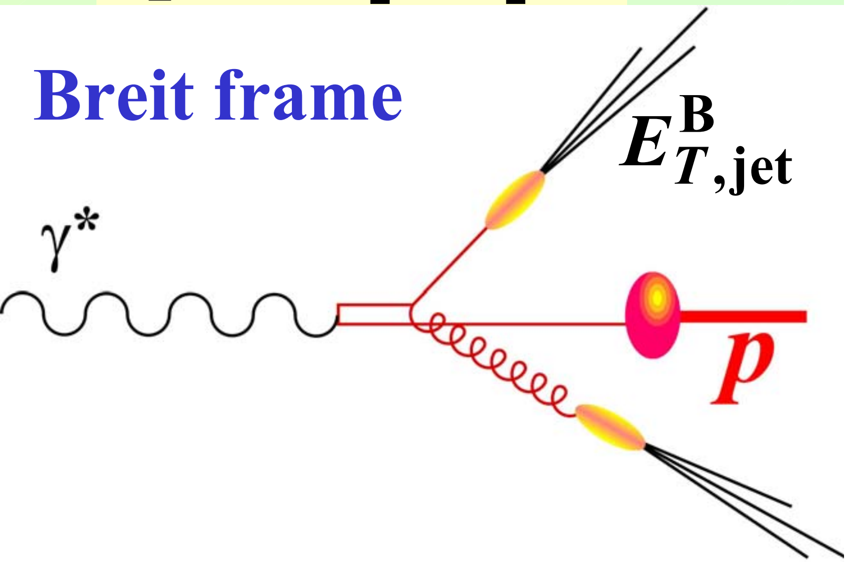
prelim	all LEP	LEP I	LEP II
$\alpha_s(M_Z)$	0.1198	0.1197	0.1197
Δ stat	0.0002	0.0002	0.0006
Δ exp	0.0009	0.0008	0.0010
Δ had	0.0008	0.0010	0.0007
Δ theo	0.0045	0.0048	0.0045
Δ tot	0.0047	0.0050	0.0047



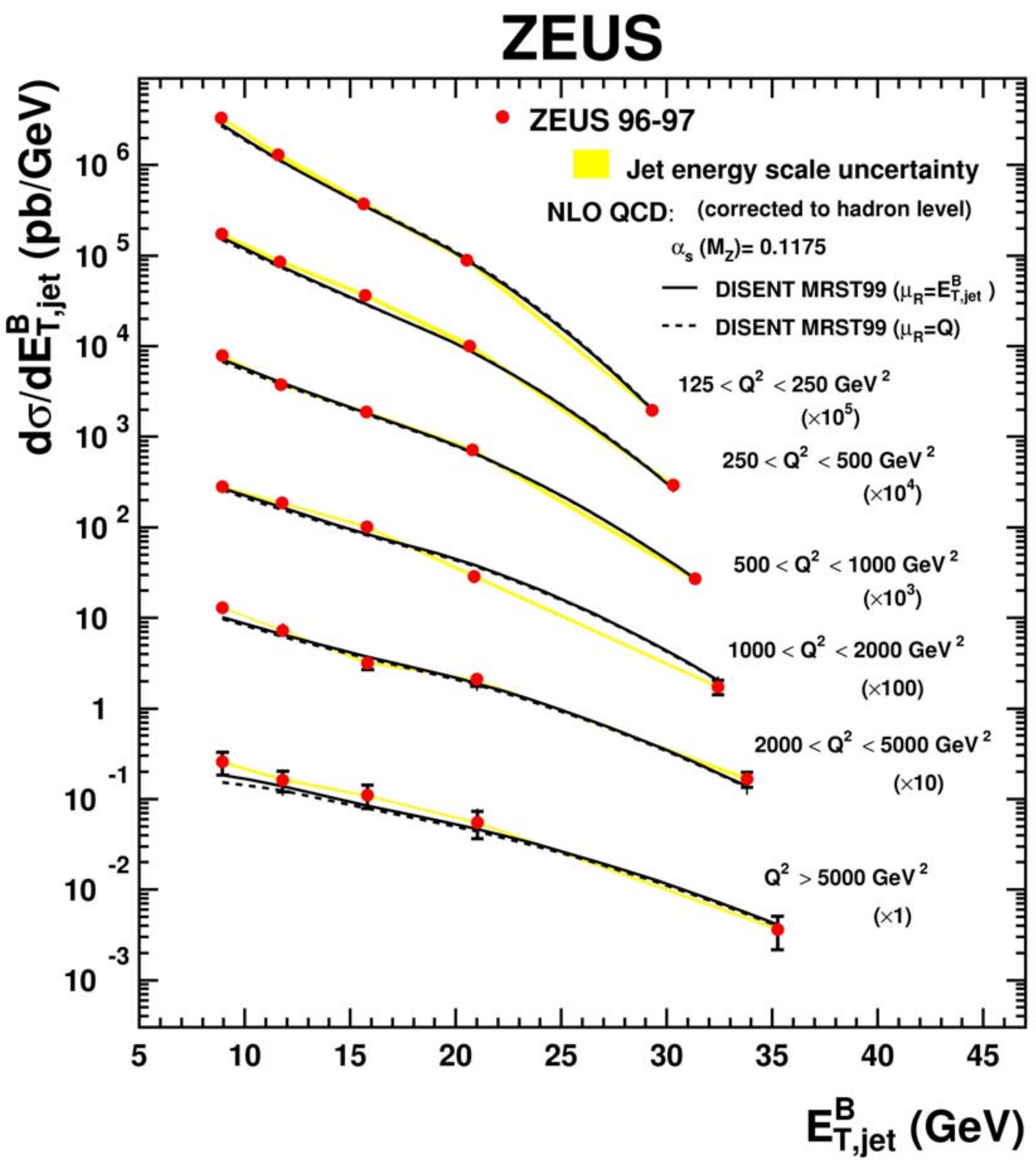
$$\alpha_S(M_Z) = 0.1198 \pm 0.0047 \text{ (LEP combined)}$$

α_S from inclusive jet production in *ep*

$$ep \rightarrow e[\text{Jet}]X$$

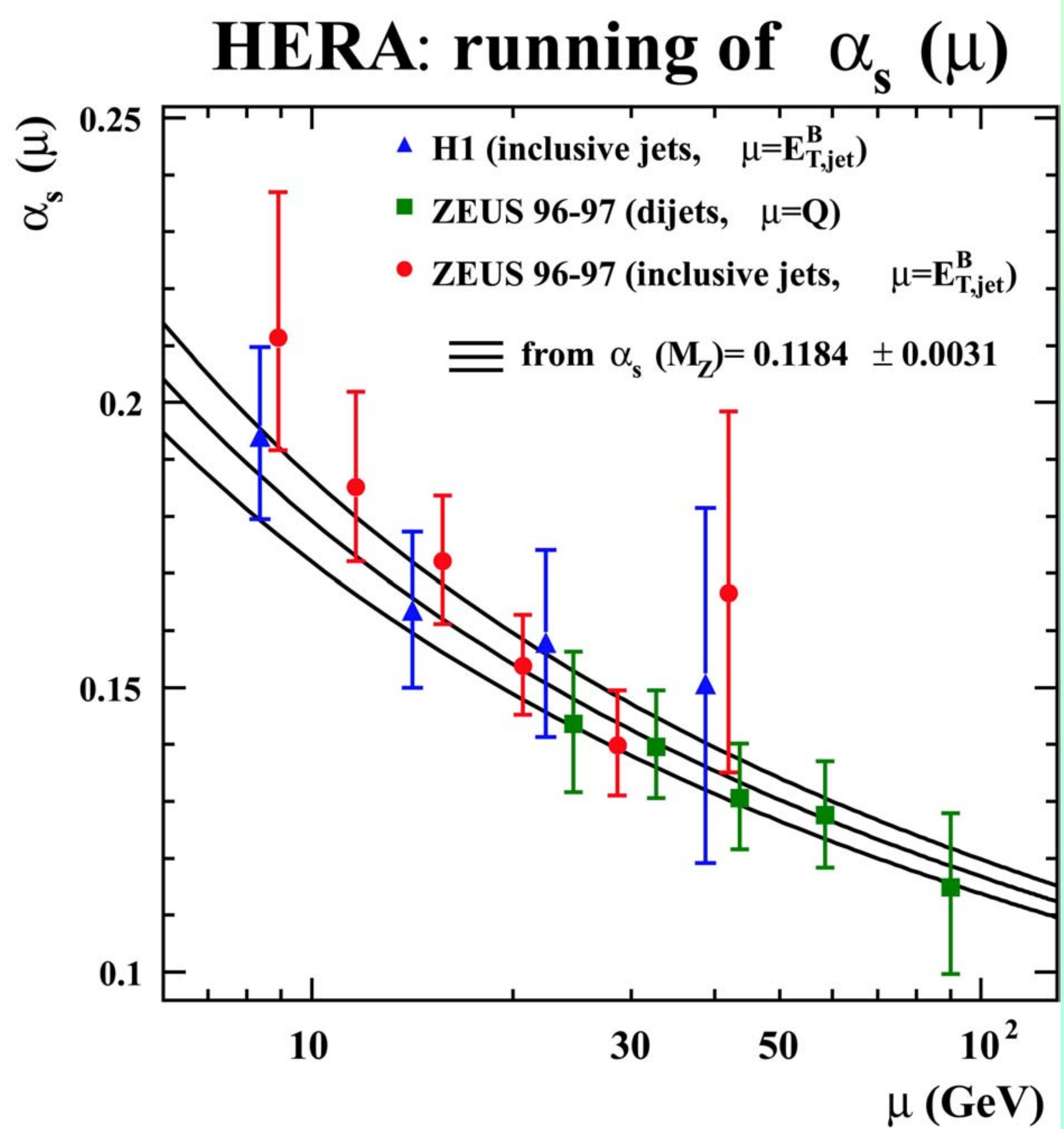


- NLO ($O(\alpha_S^2)$) gives reasonable description over wide range of Q^2 and $E^{B}_{T,\text{jet}}$
- Fit to extract α_S



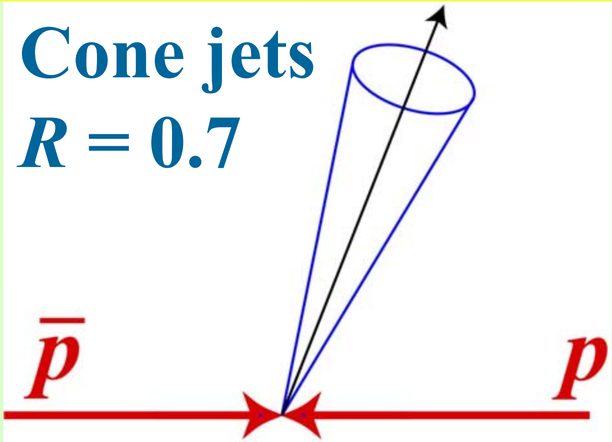
$$\alpha_S(M_Z) = 0.1212 \pm 0.0017(\text{stat.})^{+0.0023}_{-0.0031}(\text{sys.})^{+0.0028}_{-0.0027}(\text{th.})$$

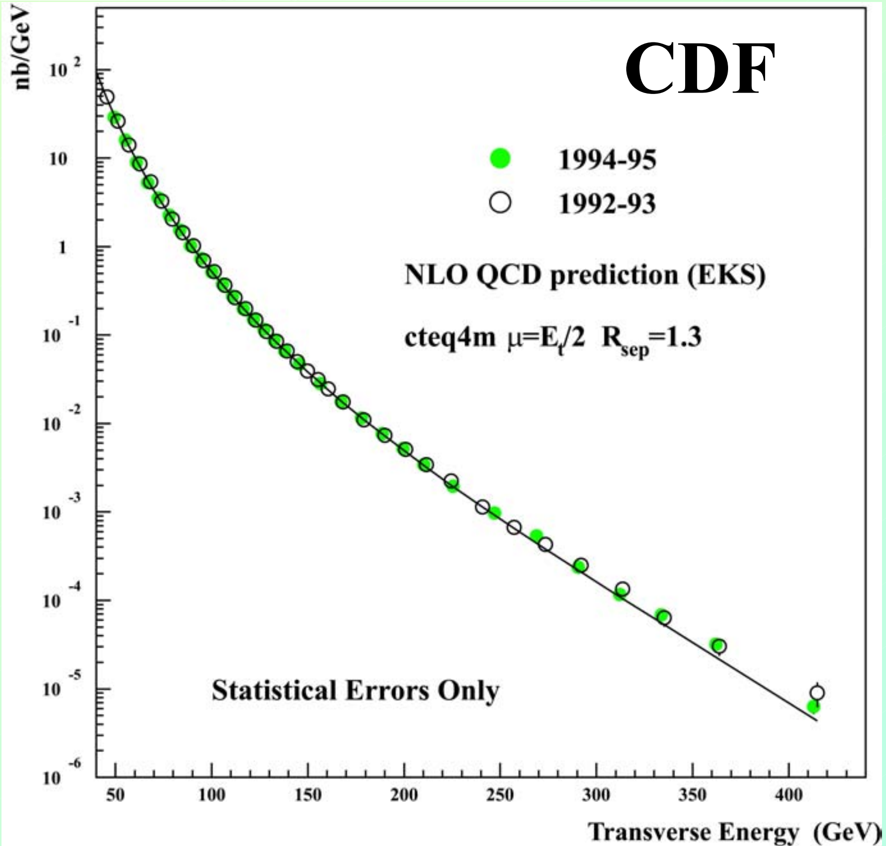
α_S from jet rates in *ep*

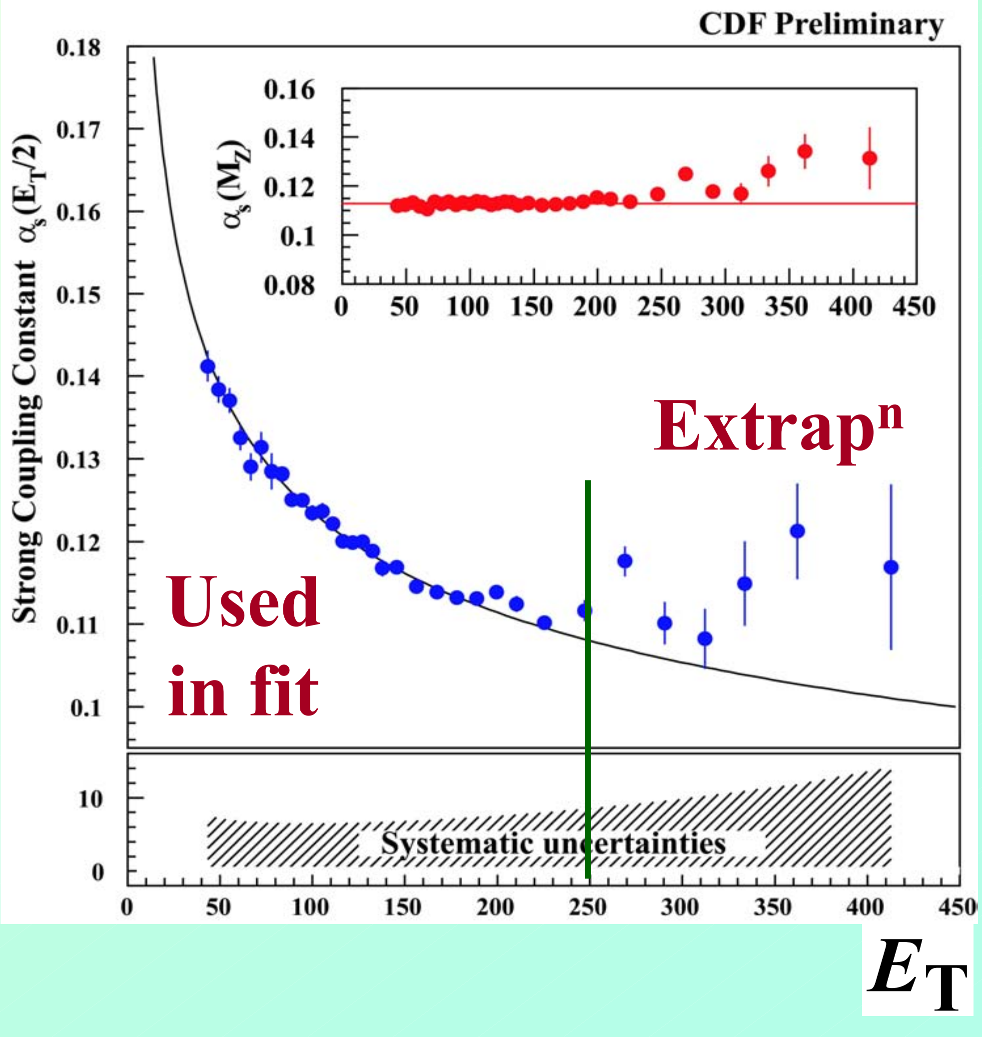


α_S from jet rates in $p\bar{p}$

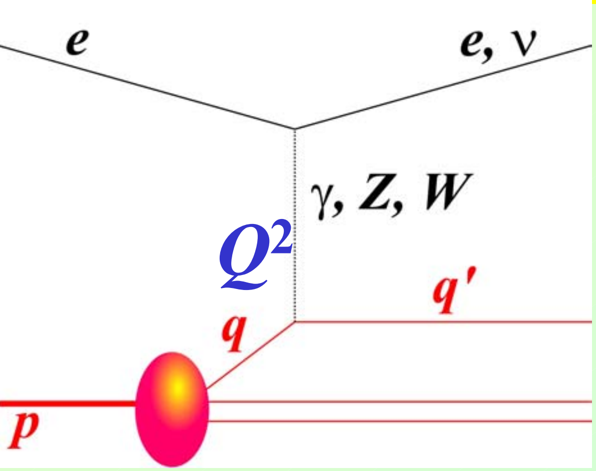
$$\frac{d\sigma}{dE_T} = \alpha_S^2 \times F_{LO} + \alpha_S^3 \times F_{NLO}$$

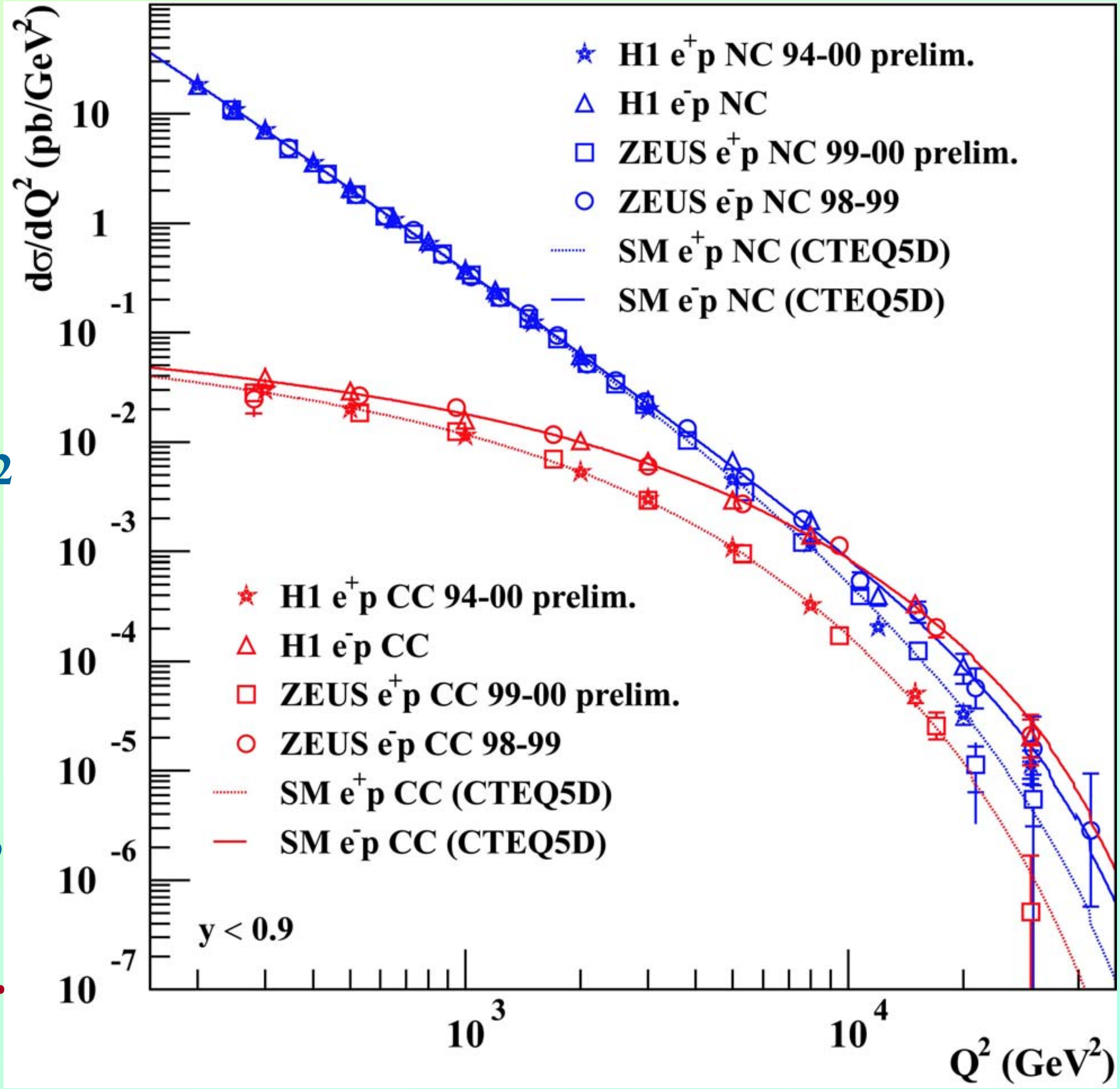






Deep inelastic scattering @ high Q^2

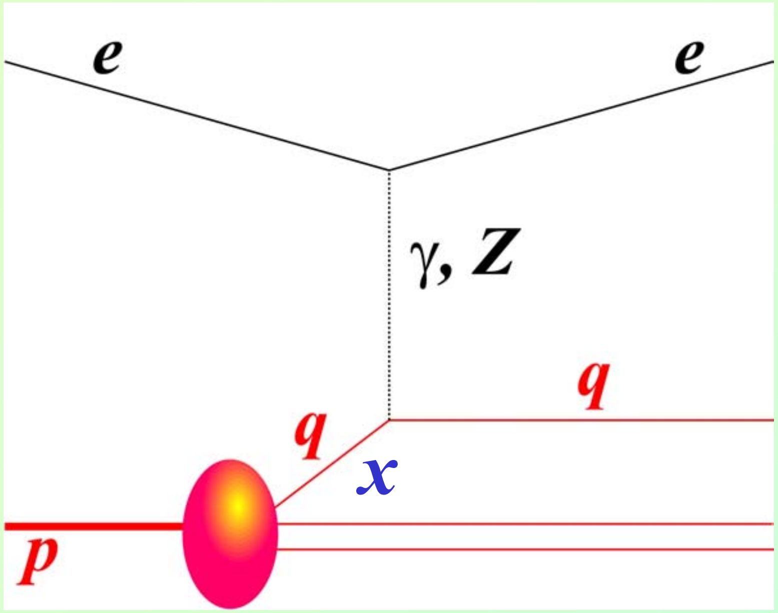


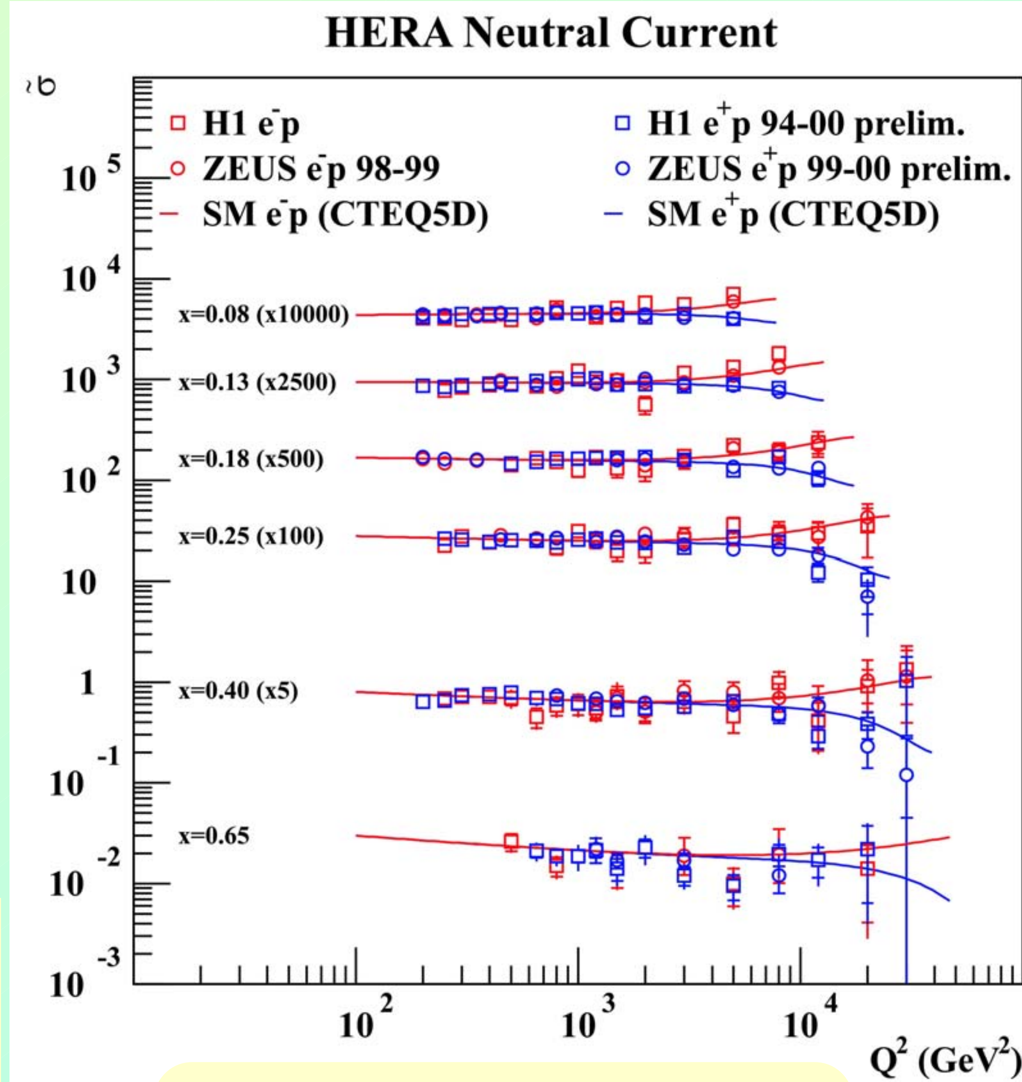


- NC~CC at high Q^2 – EW unification
- SM (⇒ QCD & EW) describes data over 6 orders of magnitude - long lever-arm for QCD studies

DIS at high Q^2

Neutral current





γZ interference for:

$e^- p$ constructive

$e^+ p$ destructive

$$\tilde{\sigma}^{NC}_{e^\pm p} = \left[\frac{2\pi\alpha^2}{Q^4 x}\right]^{-1} \frac{1}{Y_+} \frac{d^2\sigma^{e^\pm p}_{NC}}{dx dQ^2}$$

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

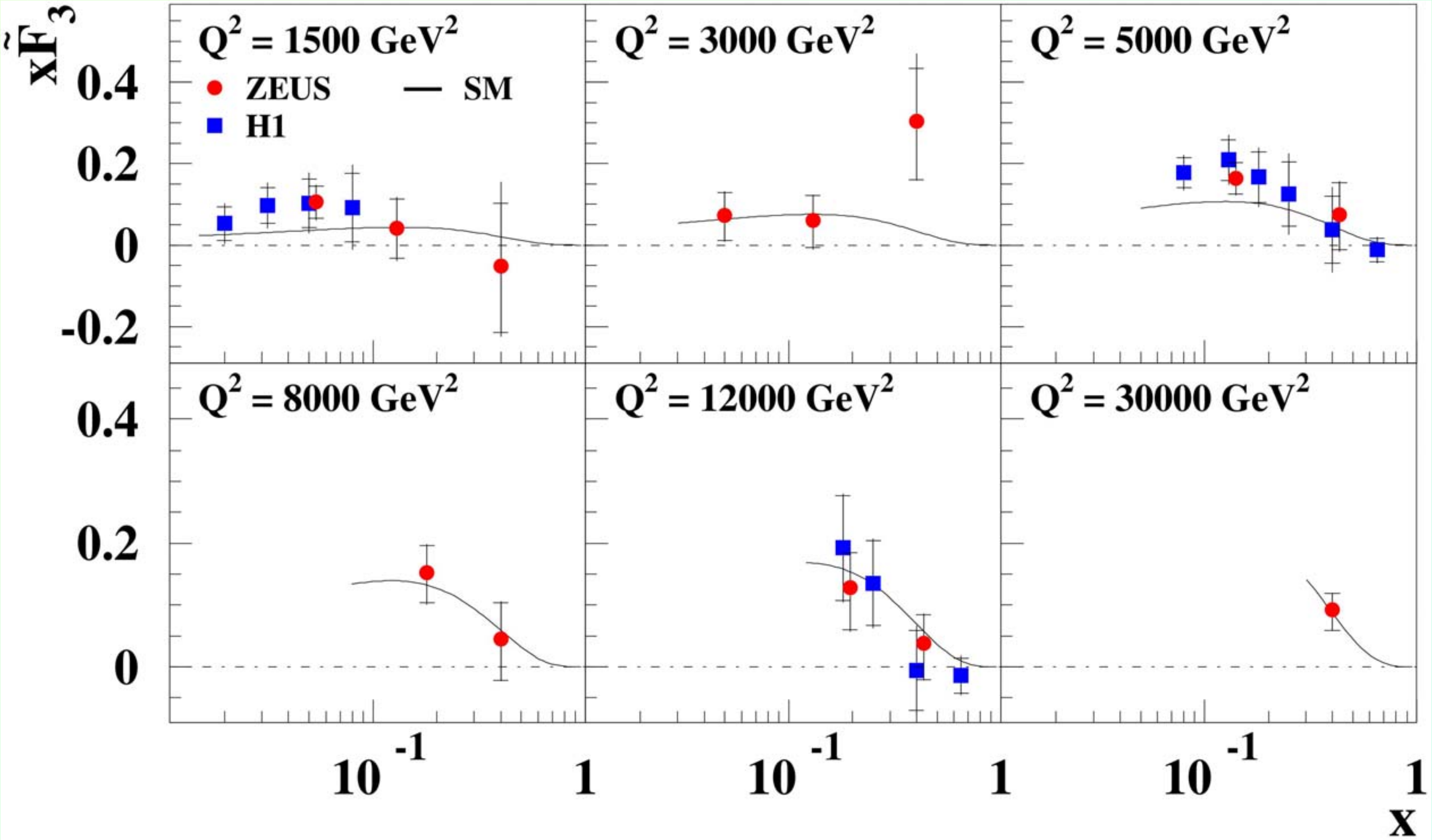
$e^- p$ > $e^+ p$ at high Q^2:

γZ-interference

Proton structure $xF_3^{NC} = x\sum B_q(q(x)-\bar{q}(x))$ DIS

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left[Y_+F_2^{NC} \mp Y_- xF_3^{NC} - y^2 F_L^{NC}\right]$$

$$xF_3 \approx \tilde{\sigma}_{e^-p}^{NC} - \tilde{\sigma}_{e^+p}^{NC}$$



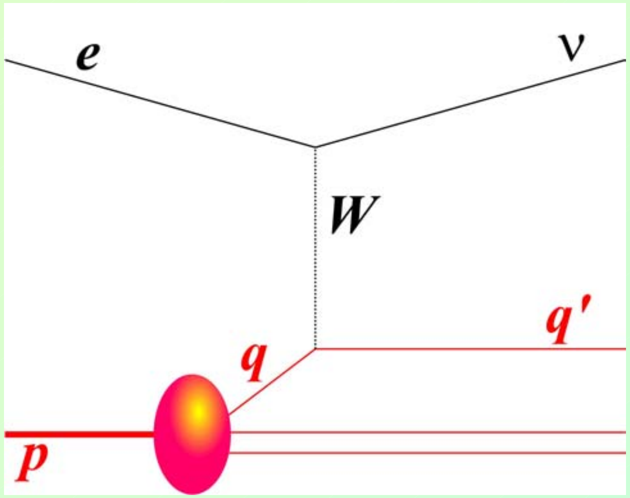
- **Measurement of valence quarks at high Q^2**
- **Needs HERA-II**

Proton structure

Charged current

DIS

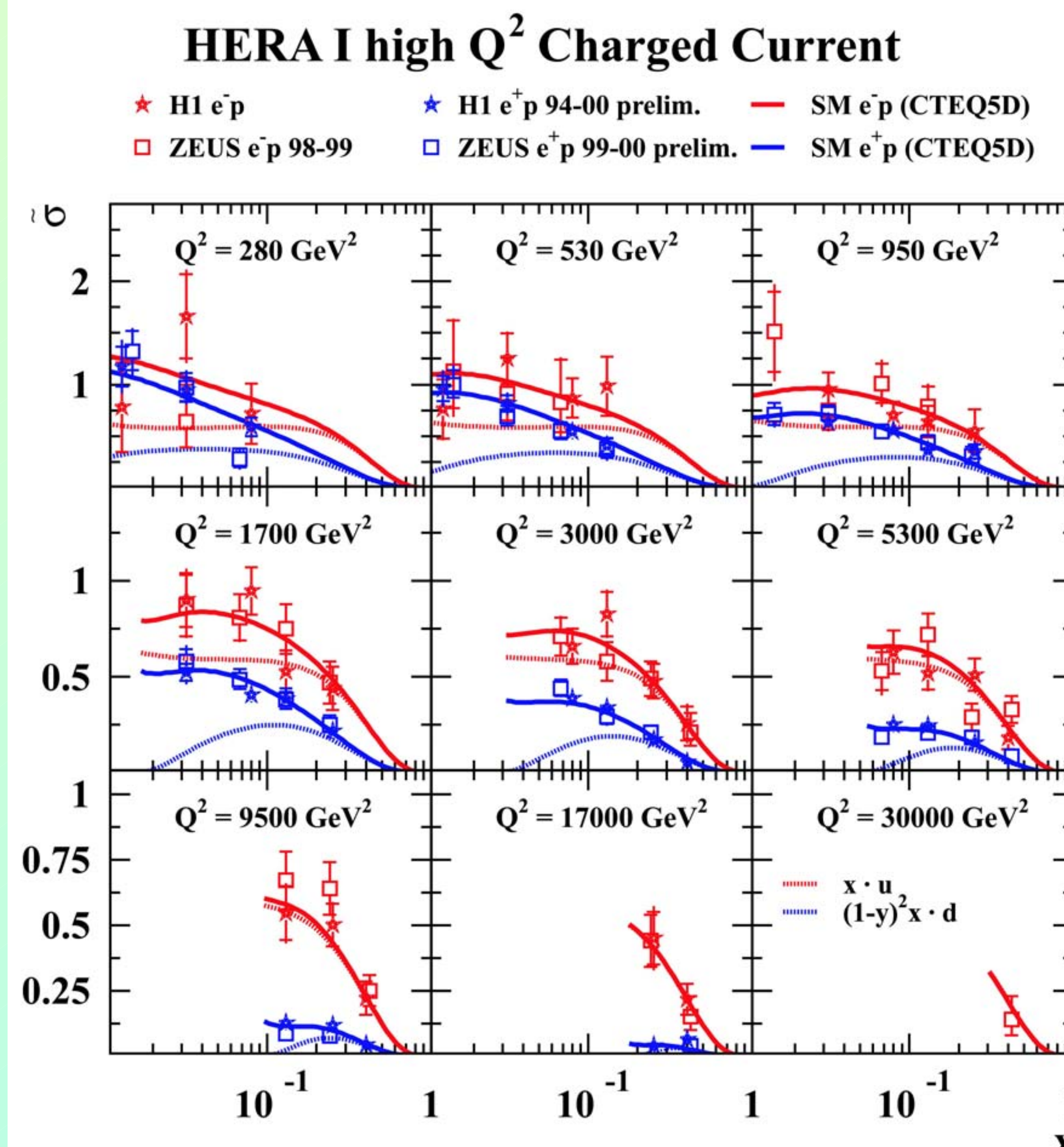
$$\tilde{\sigma}^{e^\pm p}_{CC} = \left\{ \frac{G_\mu^2}{2\pi x} \left[\frac{M_W^2}{Q^2 + M_W^2} \right]^2 \right\}^{-1} \frac{d^2\sigma^{e^\pm p}_{CC}}{dx dQ^2}$$



$$\tilde{\sigma}^{e^- P}_{CC} = x\left(u + c + (1-y)^2(\bar{d} + \bar{s})\right)$$

$$\tilde{\sigma}^{e^+ P}_{CC} = x\left(\bar{u} + \bar{c} + (1-y)^2(d + s)\right)$$

Towards flavour decomposition:



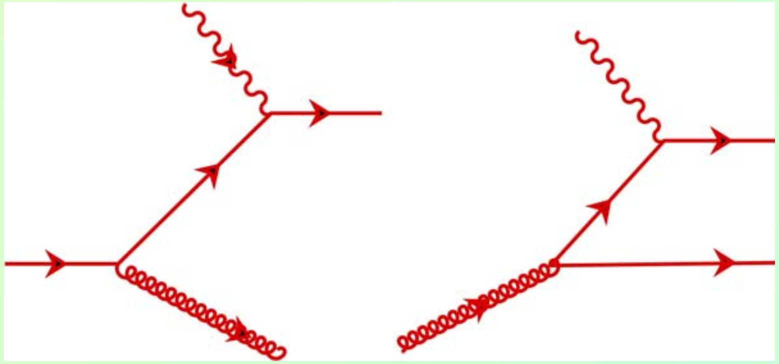
Sensitivity at high x:

$e^- p \rightarrow u$-quark

$e^+ p \rightarrow d$-quark

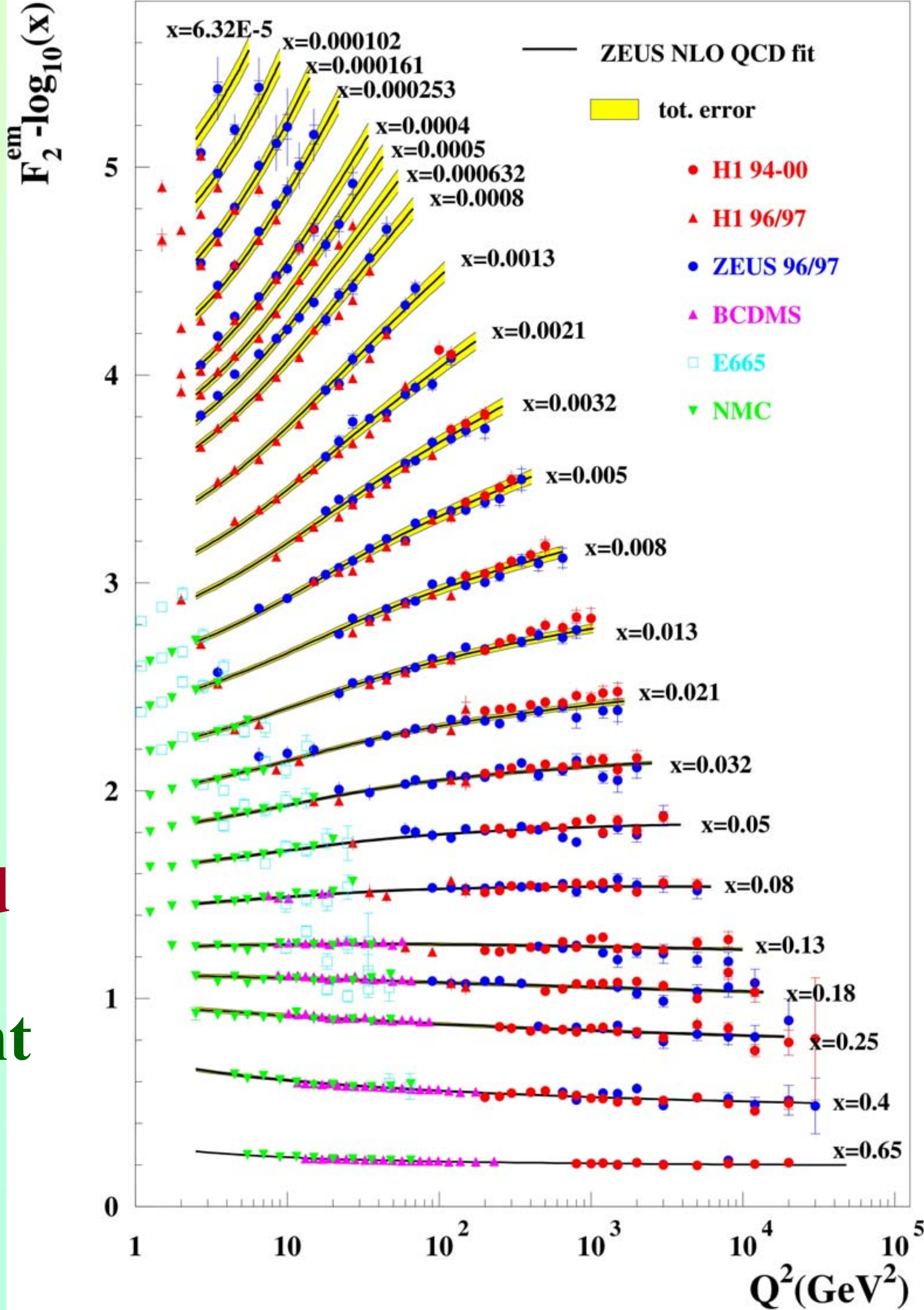
QCD anal. of Sfns

- Data well described by NLO QCD: DGLAP evolution:

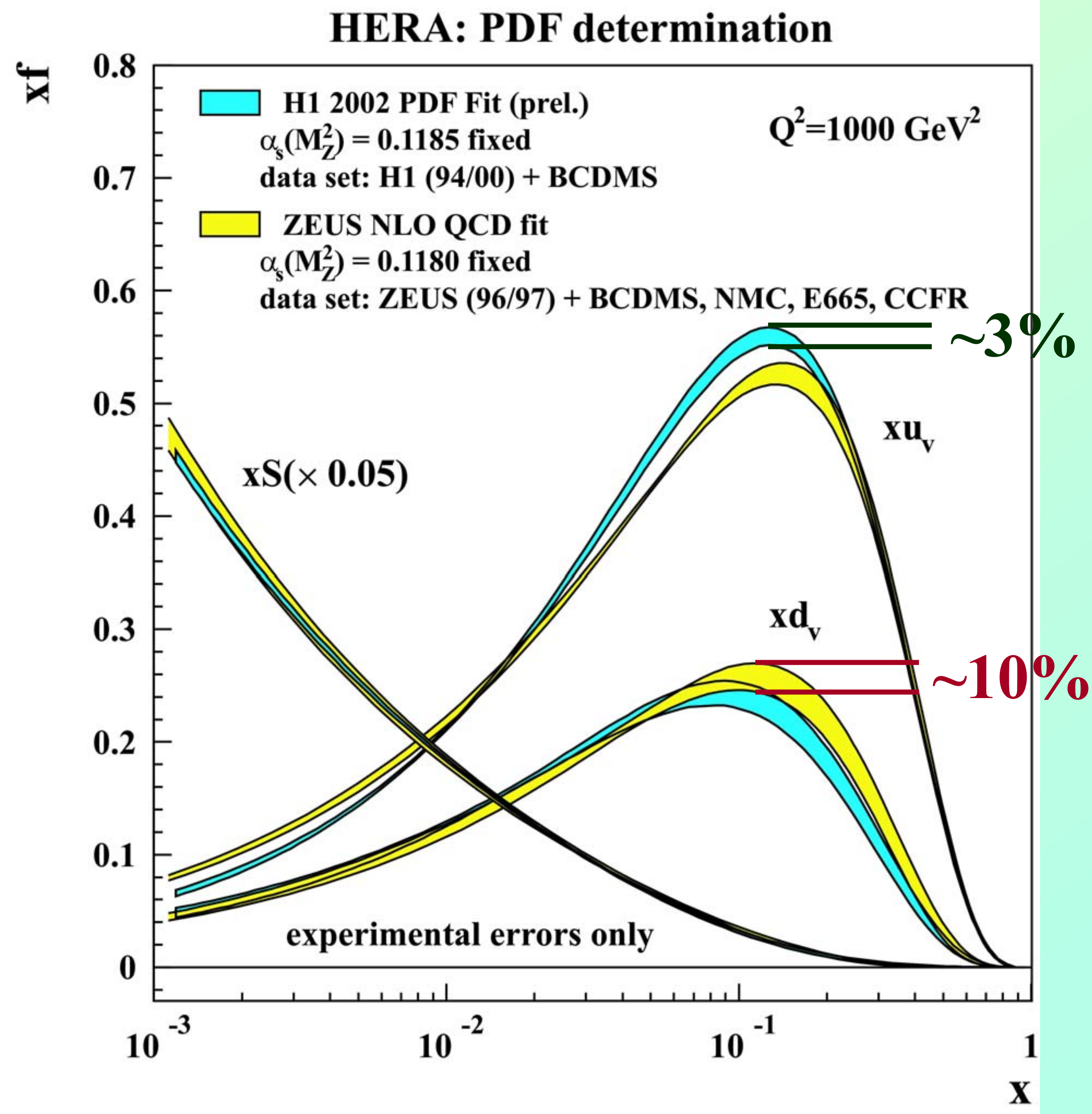


$$\frac{dF_2^{em}}{d\ln Q^2} = \frac{\alpha_S}{2\pi}\left\{\left[P_{qq}\otimes F_2^{em}\right]+\left[P_{qG}\otimes xG\right]\right\}$$

- Fit to determine PDFs and α_S:
  Emphasis on full treatment of errors:
  - Correlated exp. Errors
  - Theory/param. errors



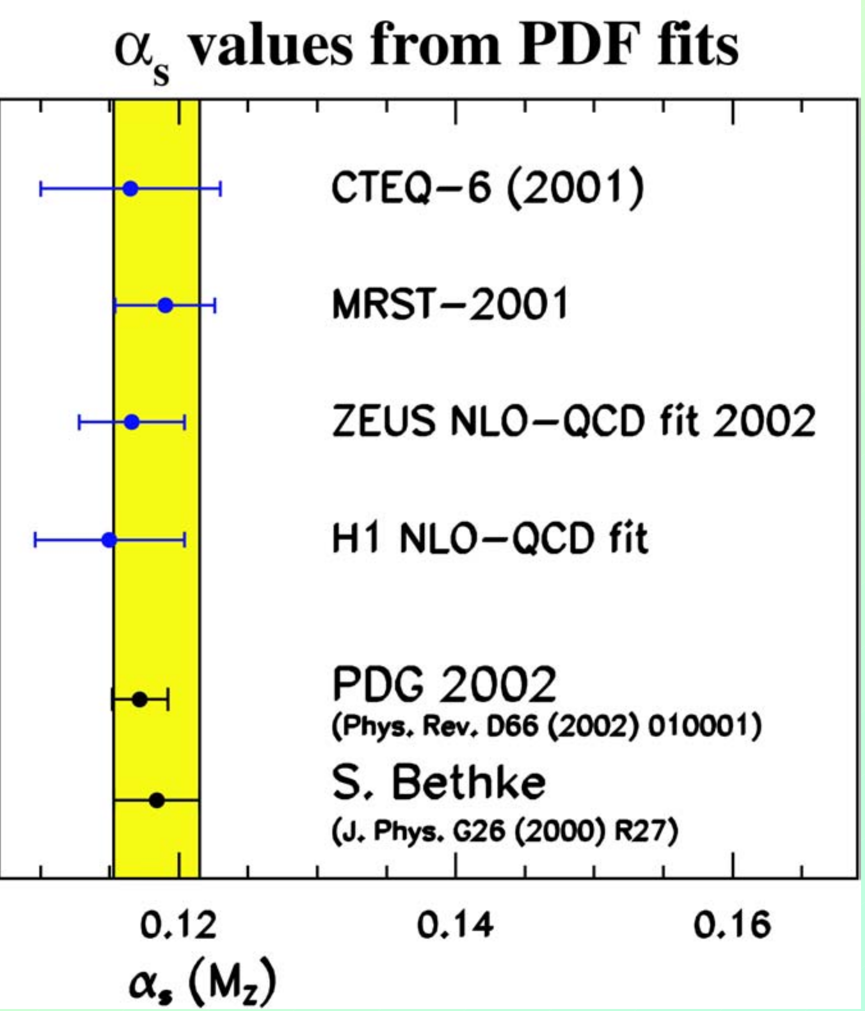
PDFs from NLO QCD analysis of S.Fns

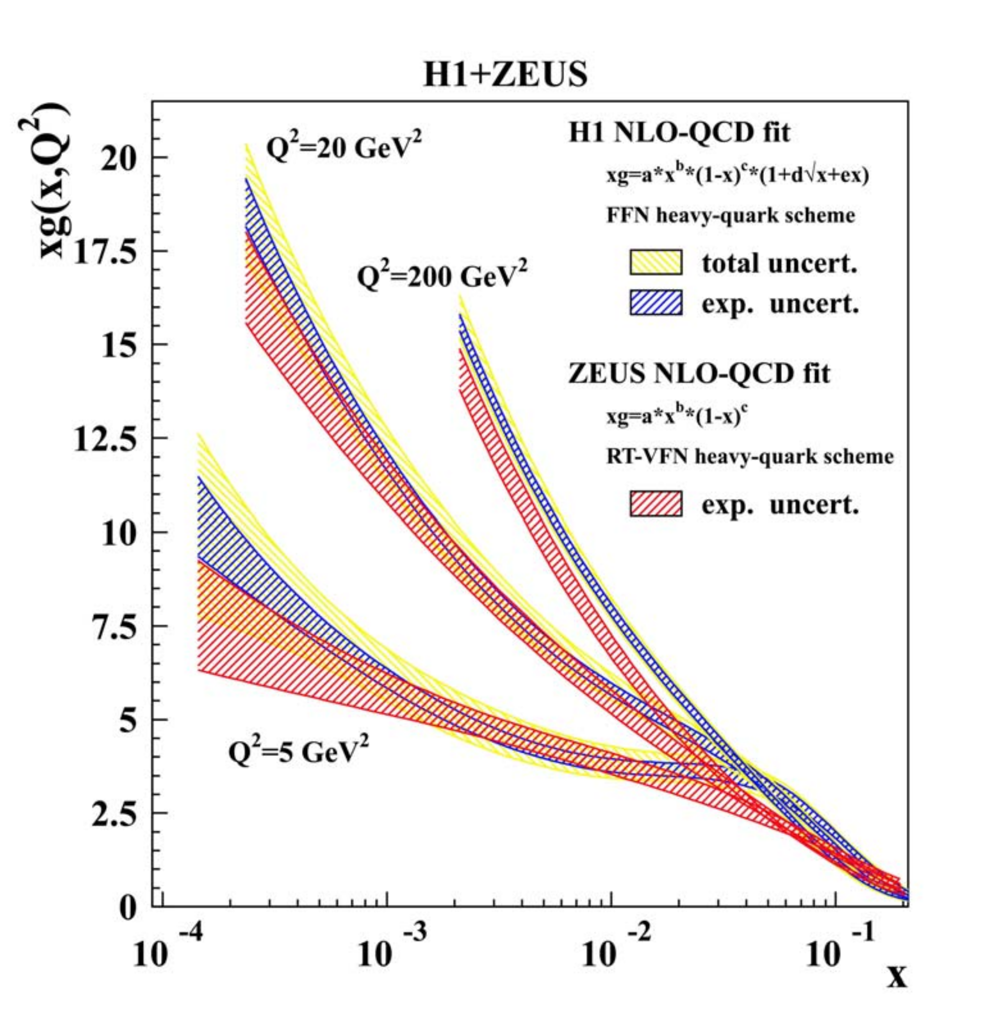


α_S and gluon from PDF fits

- α_S determined in PDF fits is correlated with gluon density

$$\frac{dF_2}{d\ln Q^2} \propto \alpha_S \otimes xG$$



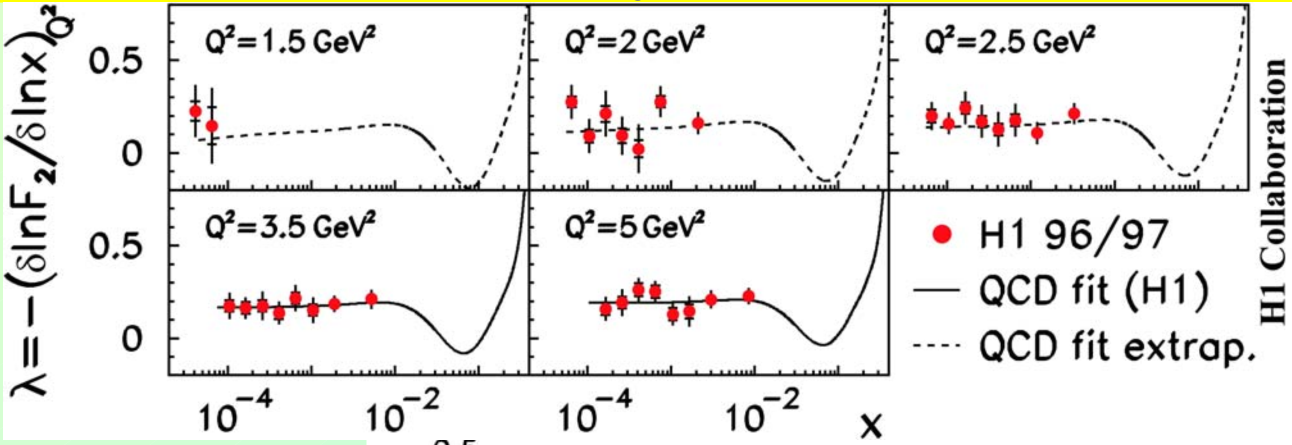


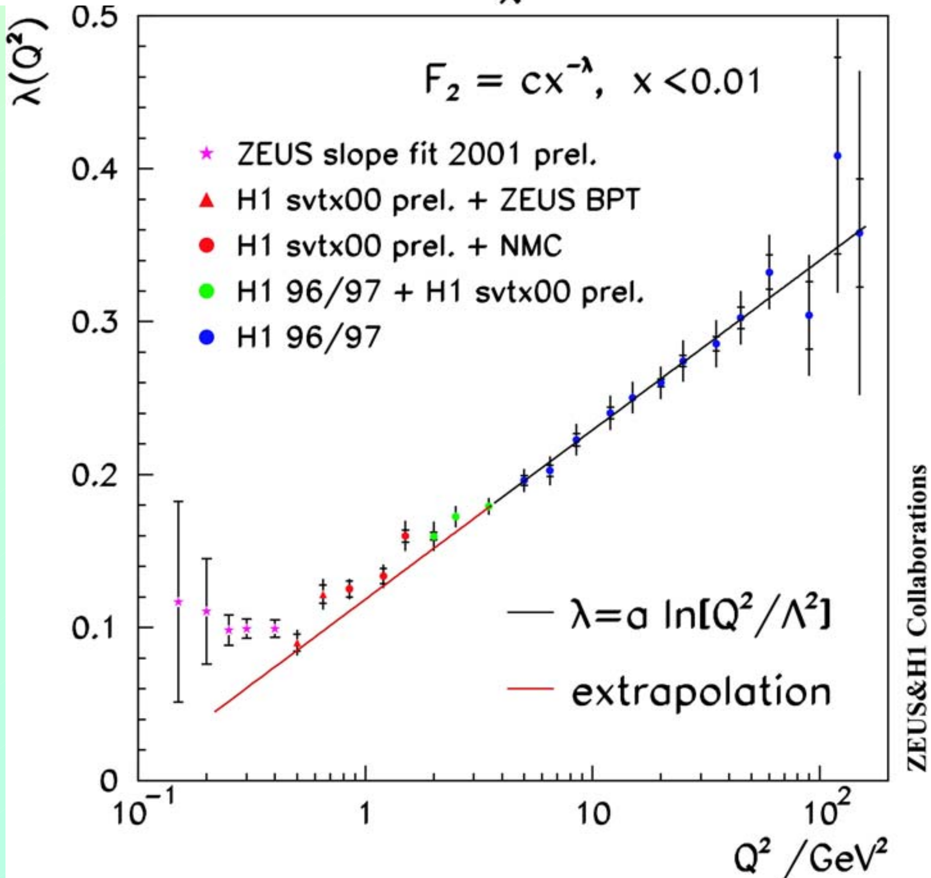
Search for limit of validity of DGLAP

- **Parameterise F_2:**

$$F_2 \cong cx^{-\lambda}$$

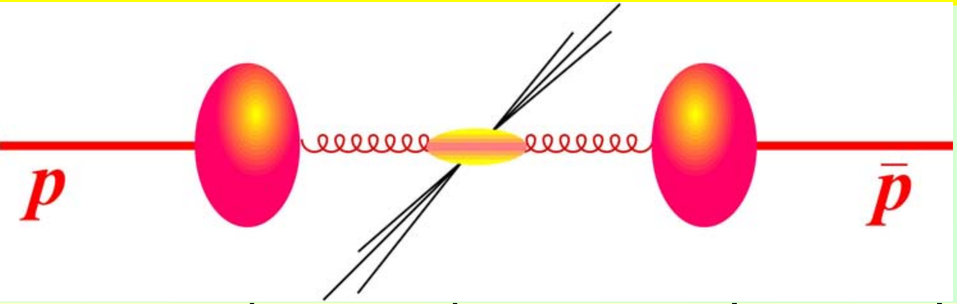
- **Fit for λ at fixed Q^2**





- **Change in dependence of λ on Q^2 for $Q^2 \sim 1$ GeV² …**
- **But at fixed Q^2, λ shows no dependence on x**

Inclusive jet cross section in $p\bar{p}$



$$\Delta\sigma \propto f_p(x_p, Q_p) \otimes \hat{\sigma} \otimes f_{\bar{p}}(x_{\bar{p}}, Q_{\bar{p}})$$

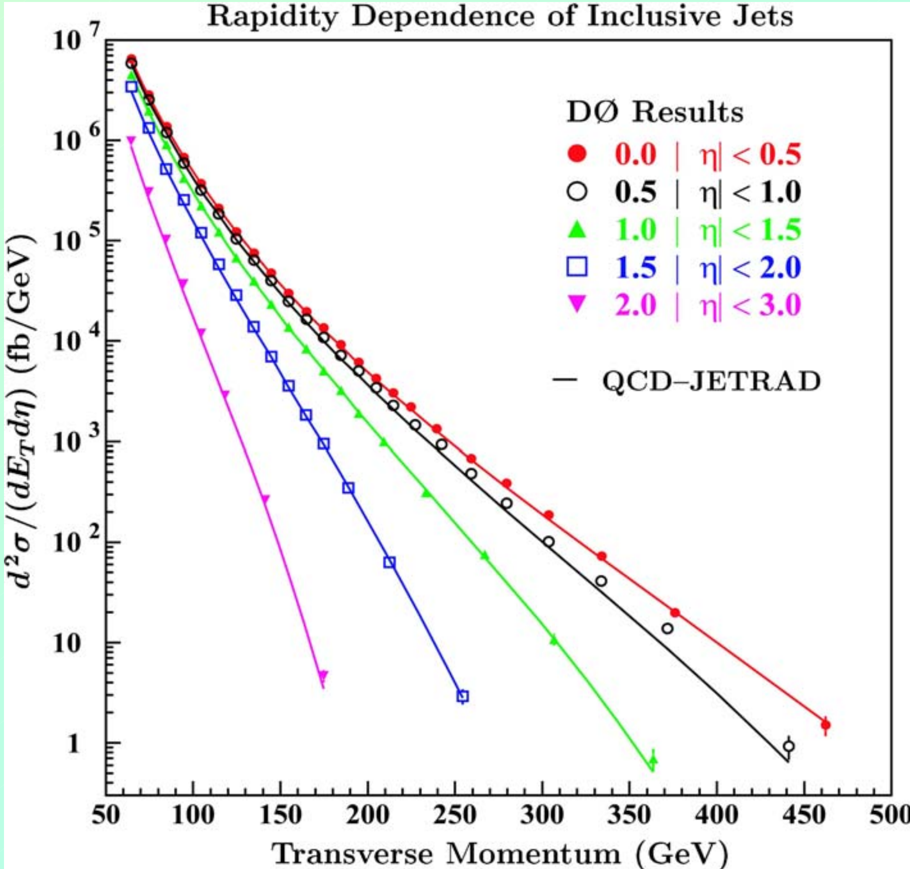
Tevatron jets:

- **QCD at very high scales**
- **Partons at high x and very high Q^2**

- **D0: inclusive jet cross section as a function of pseudorapidity**

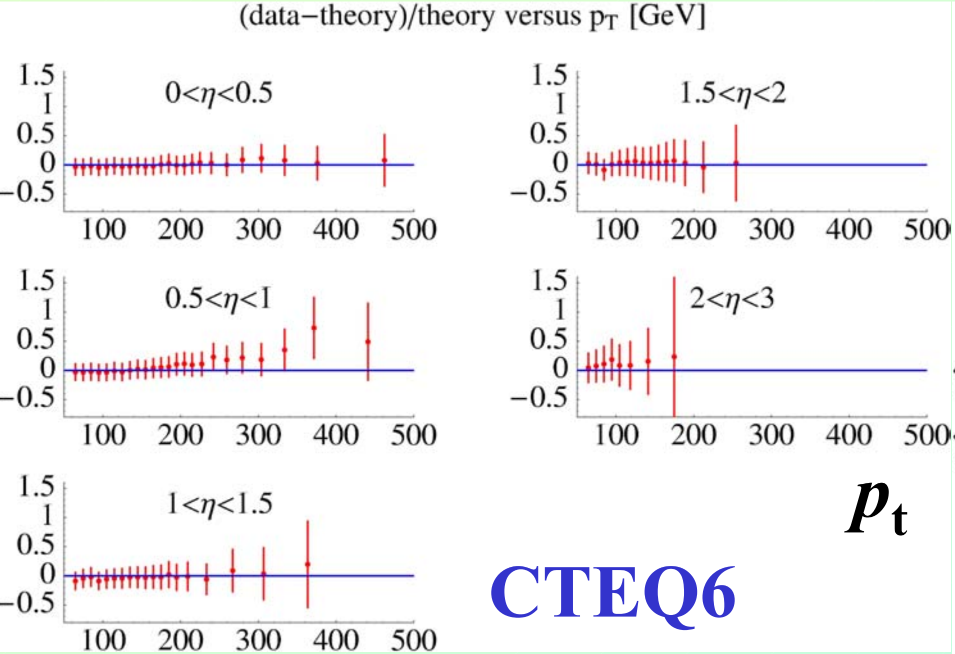
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

- **NLO QCD gives good description of E_T and η dependence**



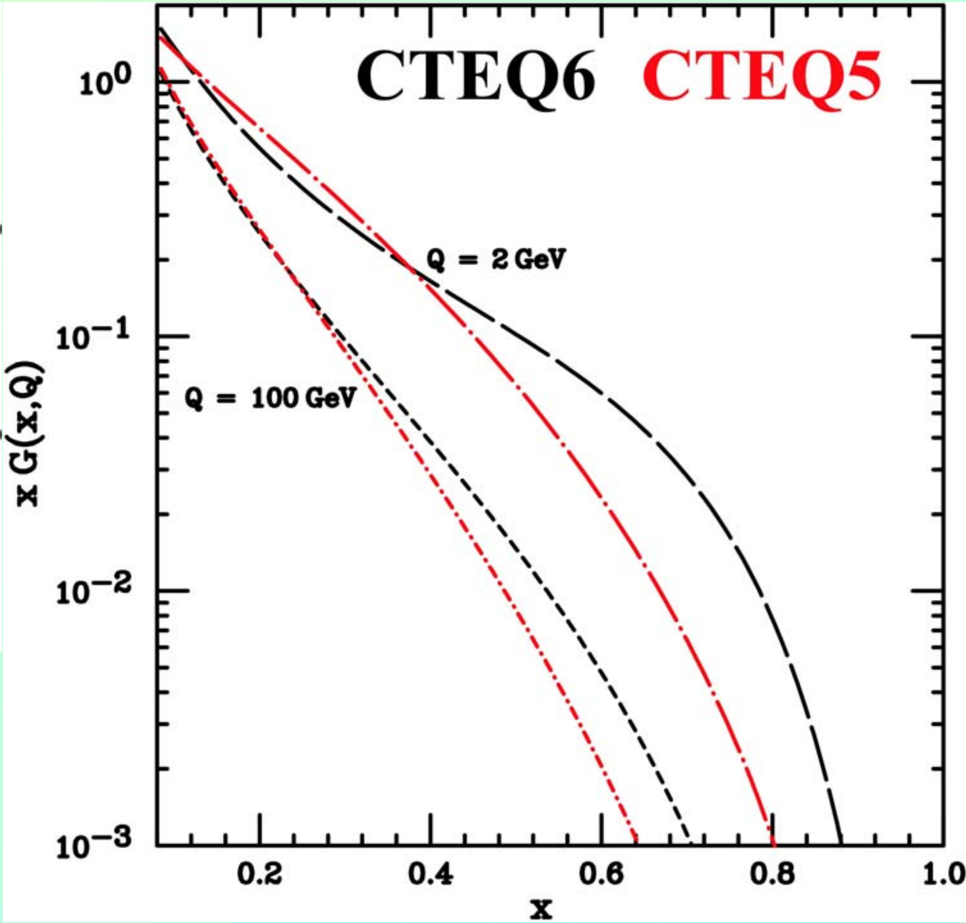
Inclusive jets in $p\bar{p}$

- **CTEQ/MRST groups: inclusion of D0 data in global fit to determine parton distributions**



p_t

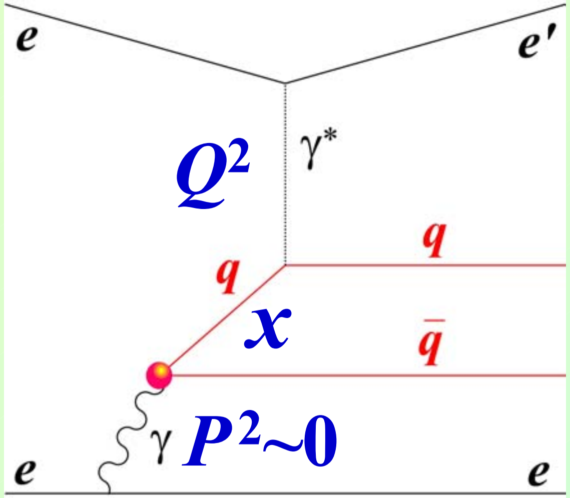
CTEQ6



- **Good description over full p_t and η range**

- **Main difference in new fits is enhanced gluon at high *x***

Photon structure

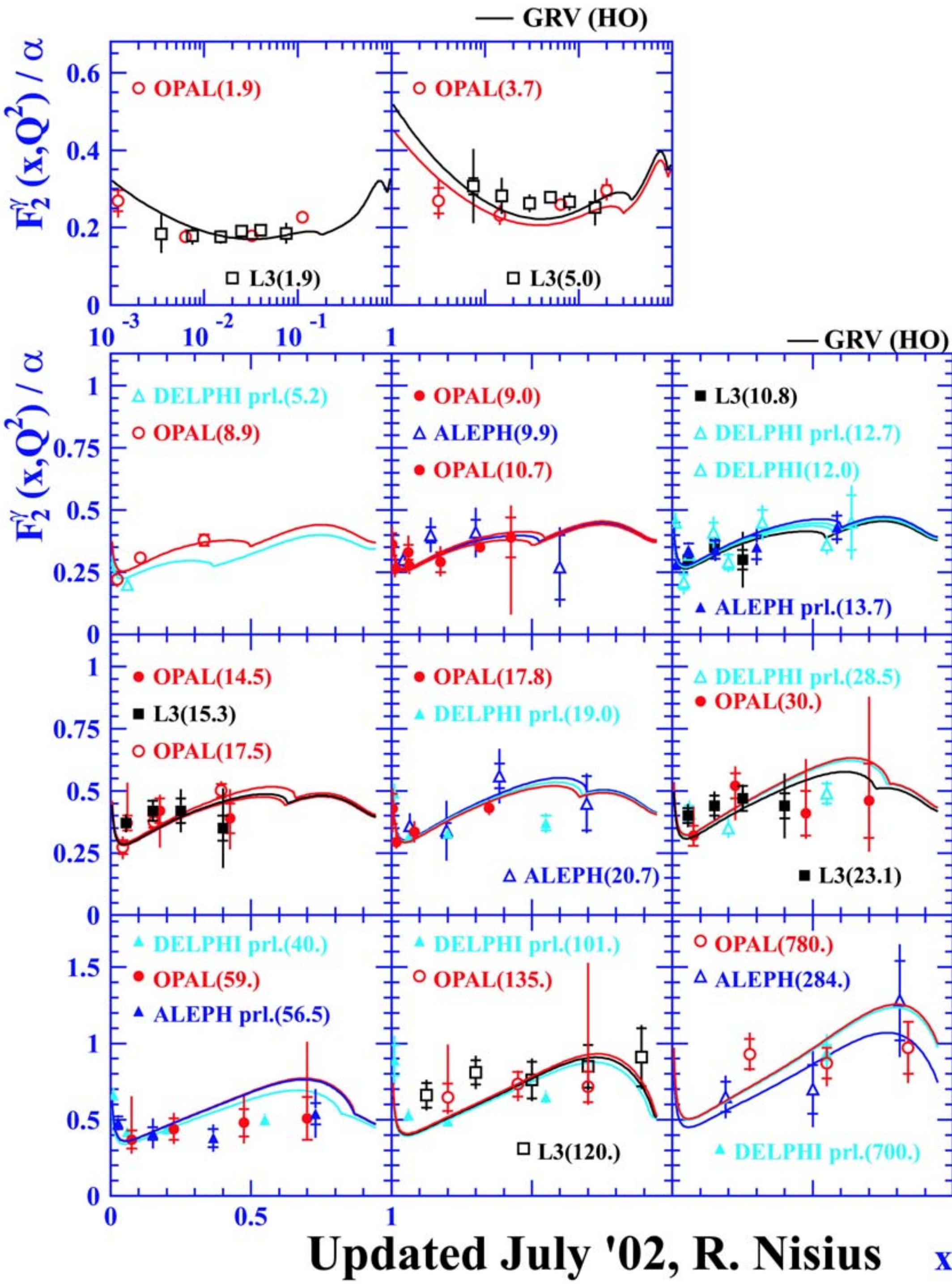


- **QCD evaluated with NLO PDFs (GRV-HO) describe data at ~20% level**
- **Fit to F_2^γ for α_S:**

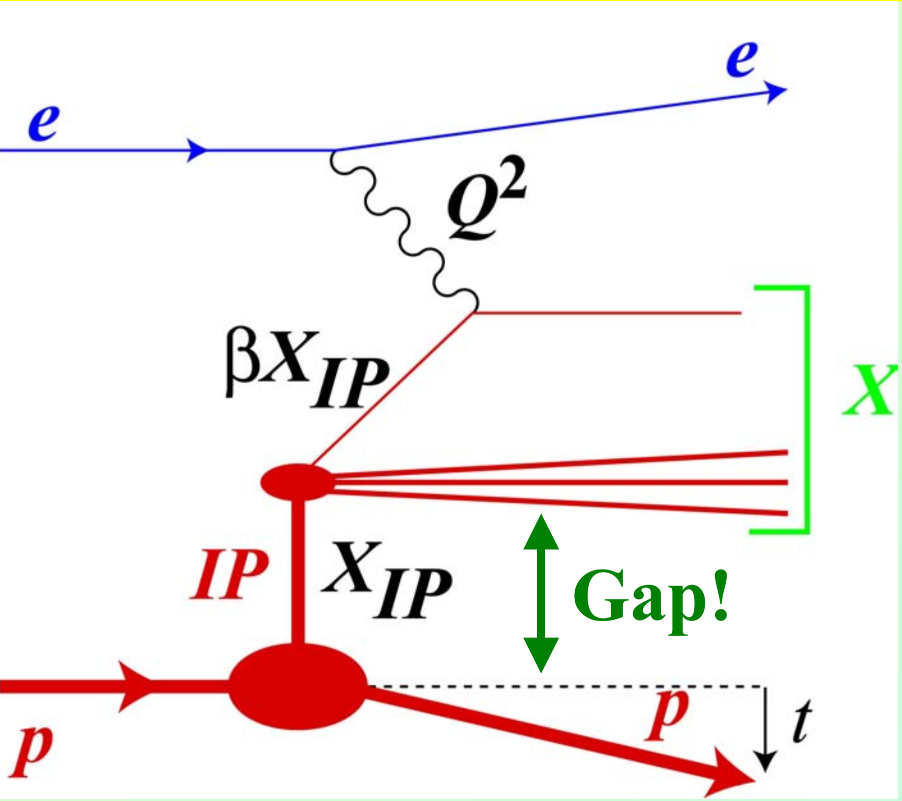
$$\alpha_S = 0.1198 \pm 0.0054$$

[Albino et al.]

PDF (*g*) uncertainty?



Diffraction in *ep* DIS

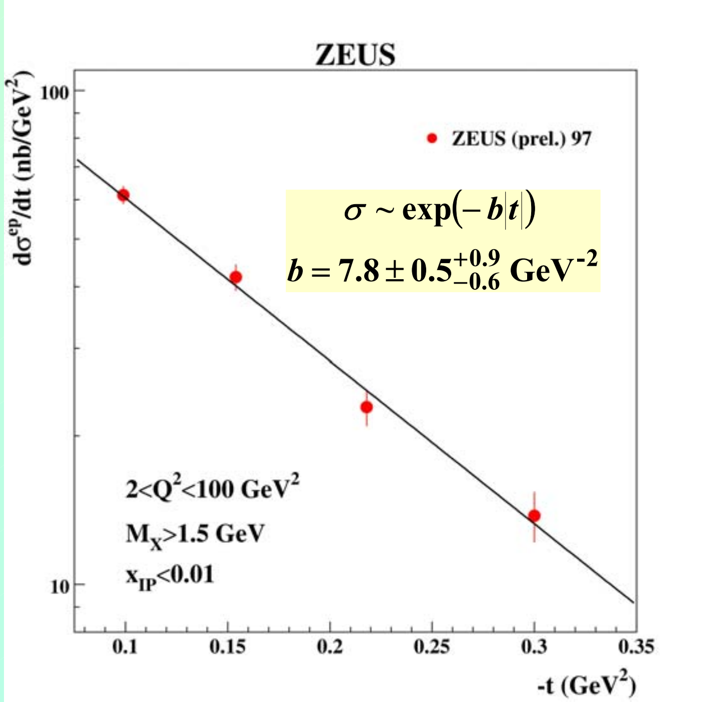


$$\frac{d^4\sigma}{d\beta dQ^2 dx_{IP} dt} \approx \frac{2\pi\alpha^2}{\beta Q^4} Y_+ F_2^{D(4)}$$

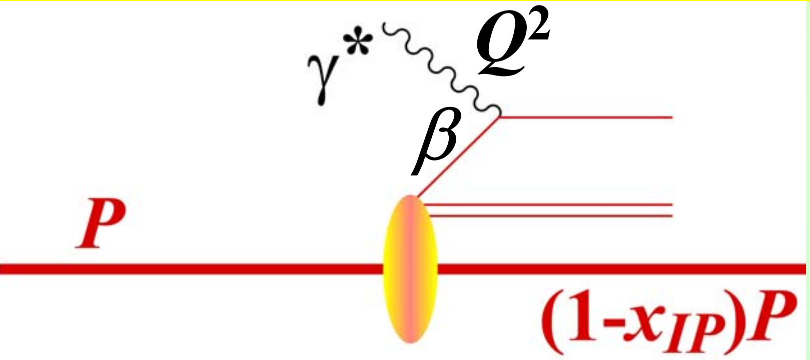
$$F_2^{D(4)}\left(\beta, Q^2, x_{IP}, t\right)$$

Two techniques:

- **Exploit absence of hadronic energy flow in forward direction – ‘rapidity-gap’ selection.**
- **Tag scattered proton to determine *t* dependence:**



Inclusive diffraction: interpretation



Factorisation (Collins)

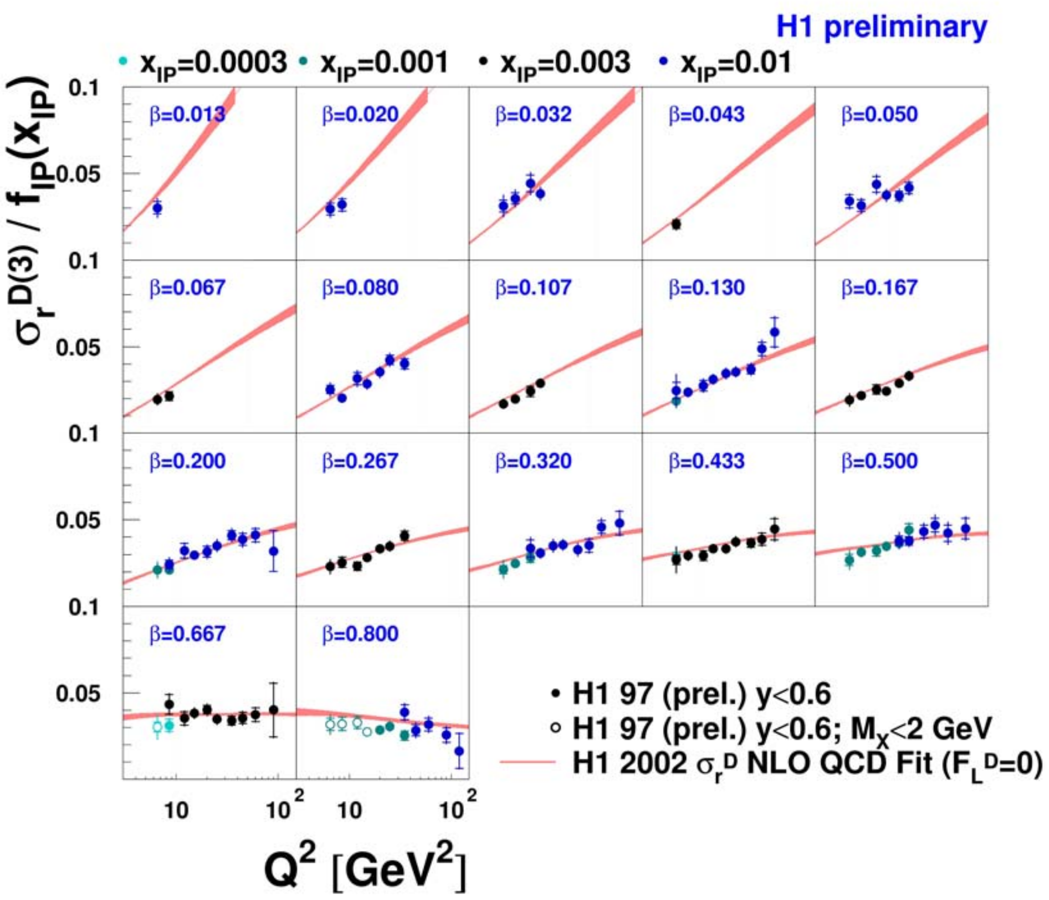
$$\sigma_i\left(x_{IP},t;\beta,Q^2\right)\sim q_i^{\text{Diff}}\left(x_{IP},t;\beta,Q^2\right)\otimes\hat{\sigma}_{\gamma^* q_i}\left(\beta,Q^2\right)$$

Data consistent with 'Regge' factorisation:

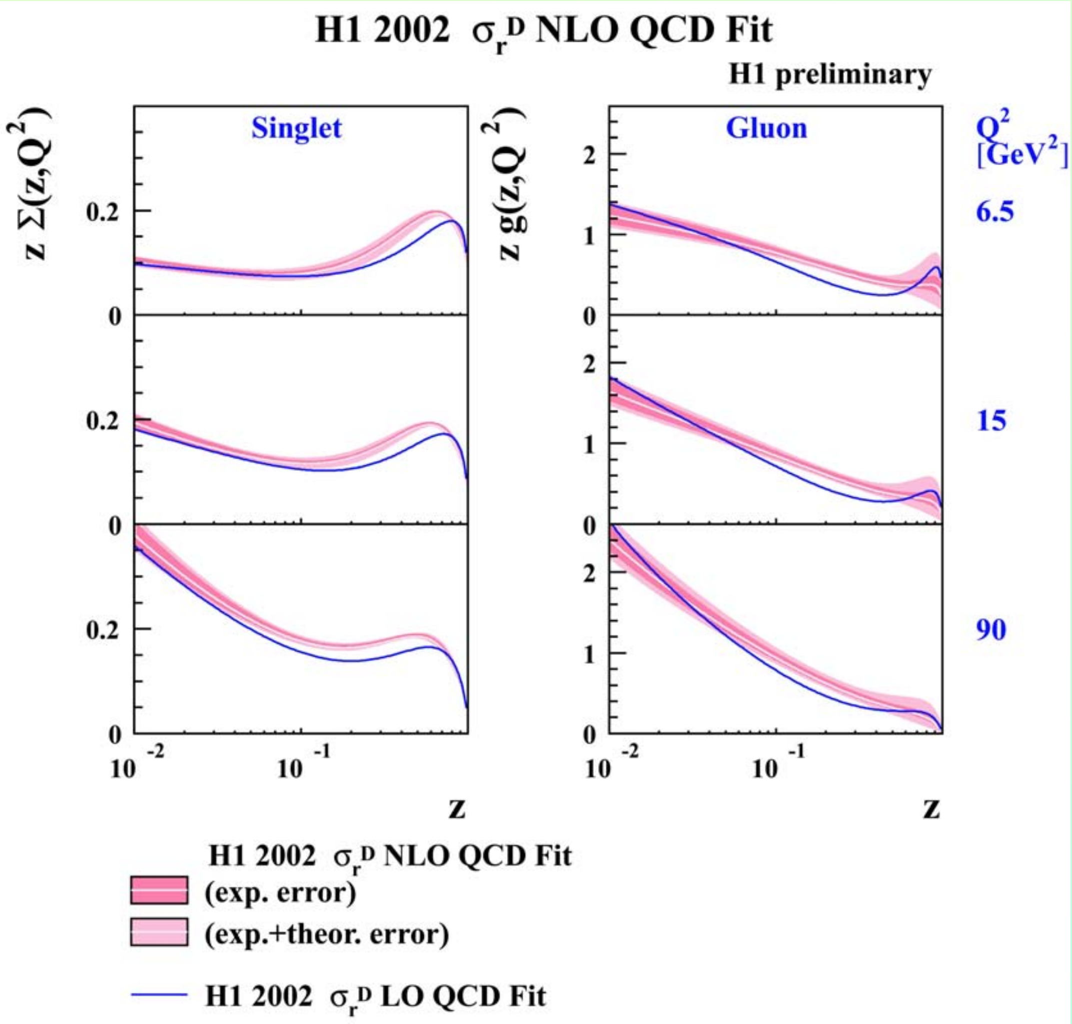
$$\sigma_r^{D(3)}\sim f_{IP/p}(x_{IP},t)\bullet F_2^{IP}\left(\beta,Q^2\right)$$

$$f_{IP/p}(x_{IP},t)=\frac{\exp(-b|t|)}{x_{IP}^{2\alpha(t)-1}}$$

- Good description of data
- Positive scaling violations (β < 0.6) → *diffractive* PDFs are gluon dominated



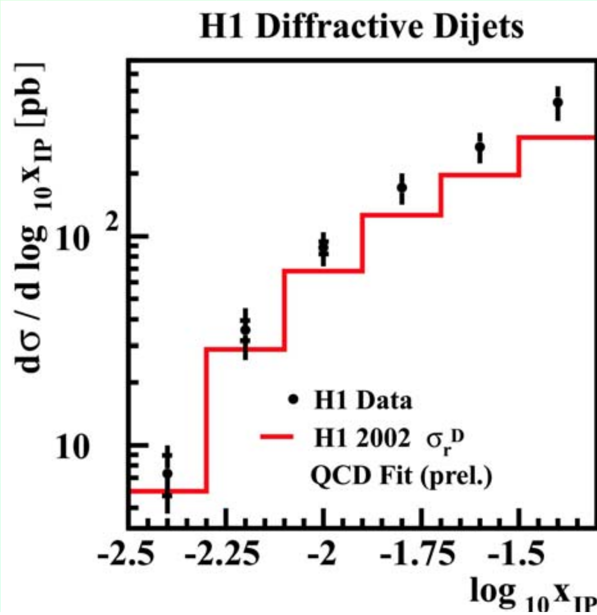
Diffractive parton densities



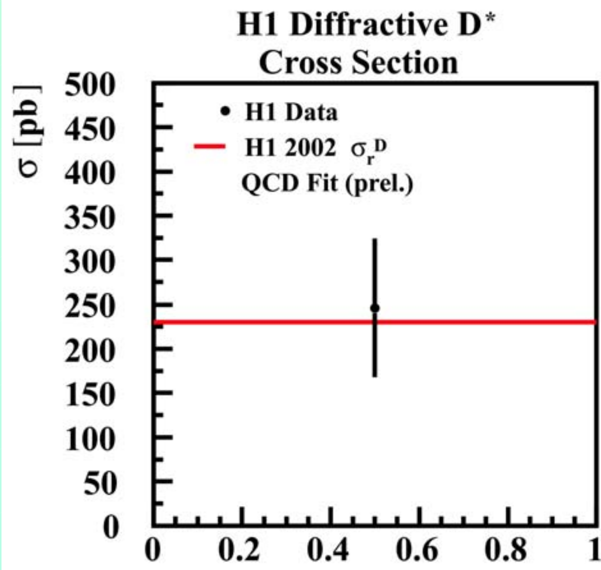
First set of diffractive PDFs!

Predictive?

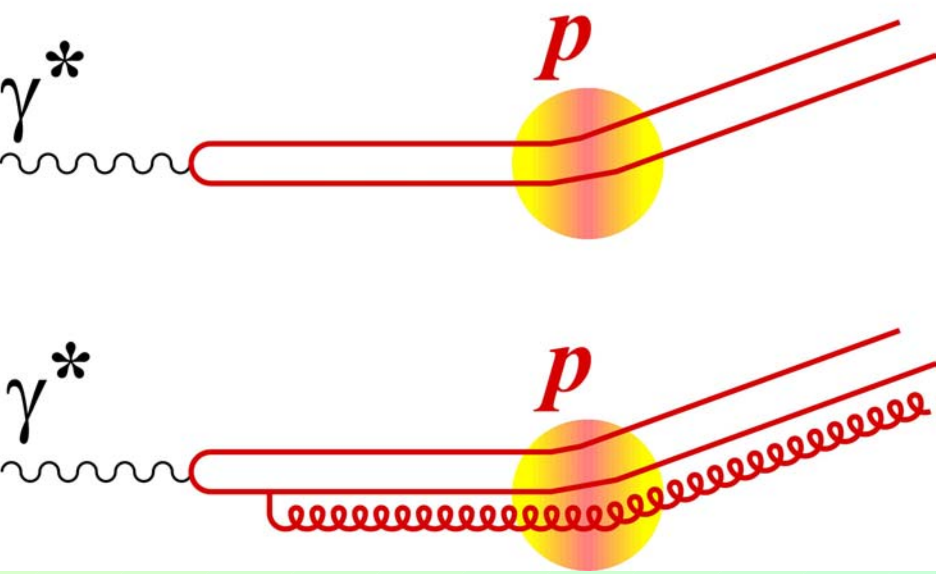
Diff. dijets

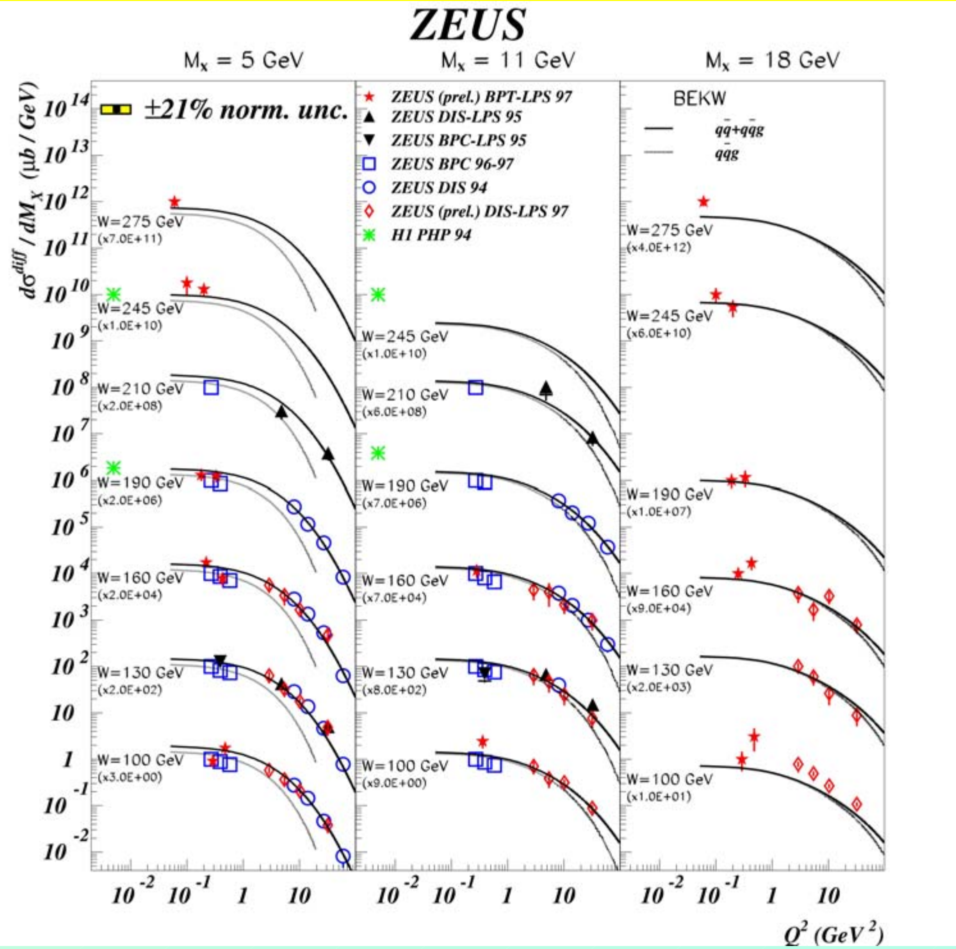


Diff. D^*



Inclusive diffraction: transition to low Q^2



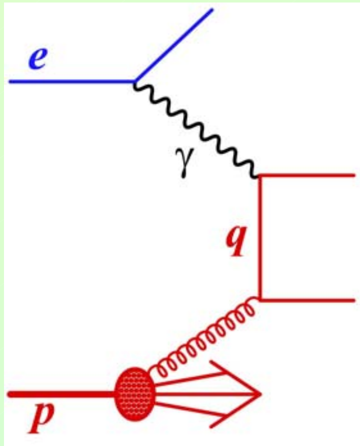


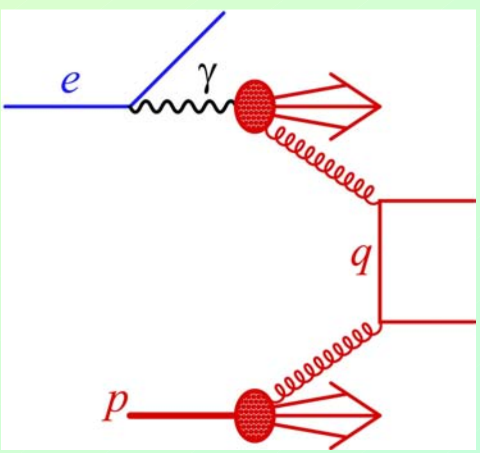
- Virtual photon fluctuates into a $q\bar{q}$ (or $q\bar{q}g$) state
- $q\bar{q}$ (or $q\bar{q}g$) dipole scatters elastically from proton
- Xsect. plateaus when dipole size ~ proton size
- Model gives reasonable description of data
- $q\bar{q}g$ contribution dominates

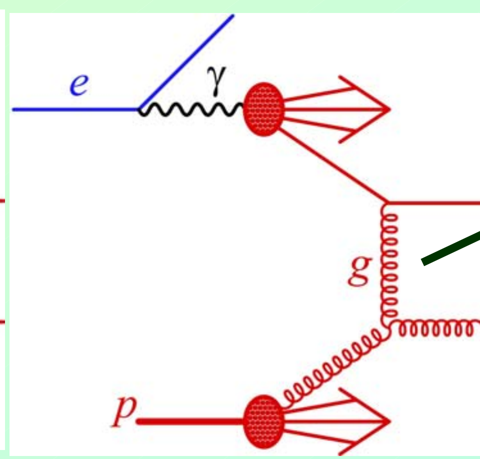
Dijet production in photoproduction

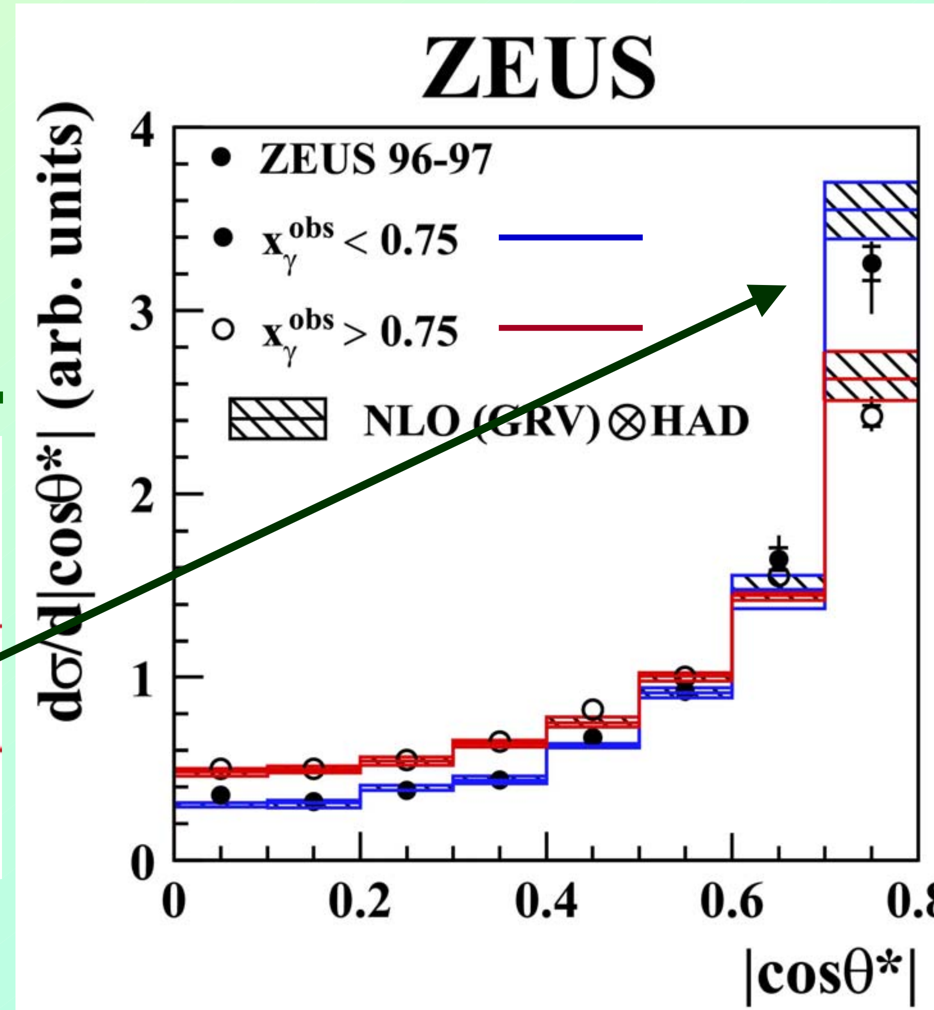
Direct: high x_γ^{obs}

$$x_\gamma^{obs} = \frac{E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}}{2yE_e}$$





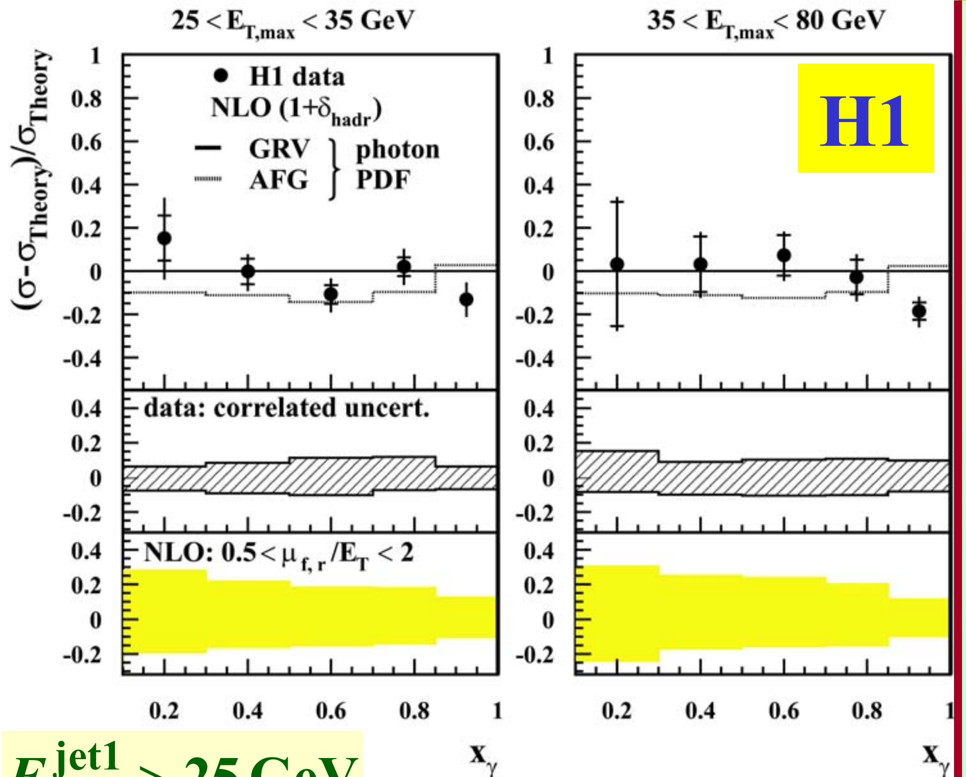




Resolved: low x_γ^{obs}

Dijet production in γp

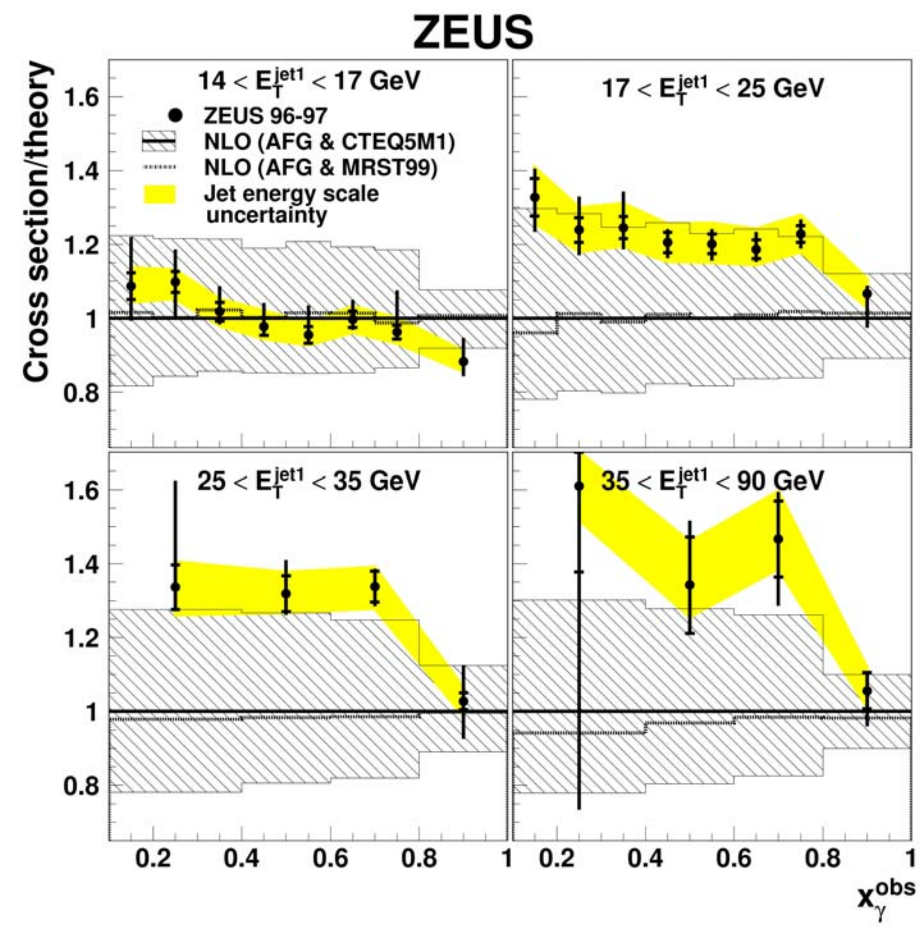
Sensitivity to γ-PDFs?



$E_T^{\text{jet1}} > 25\,\text{GeV}$

$E_T^{\text{jet2}} > 15\,\text{GeV}$

$-0.5 < \eta^{\text{jet1,2}} < 2.5$

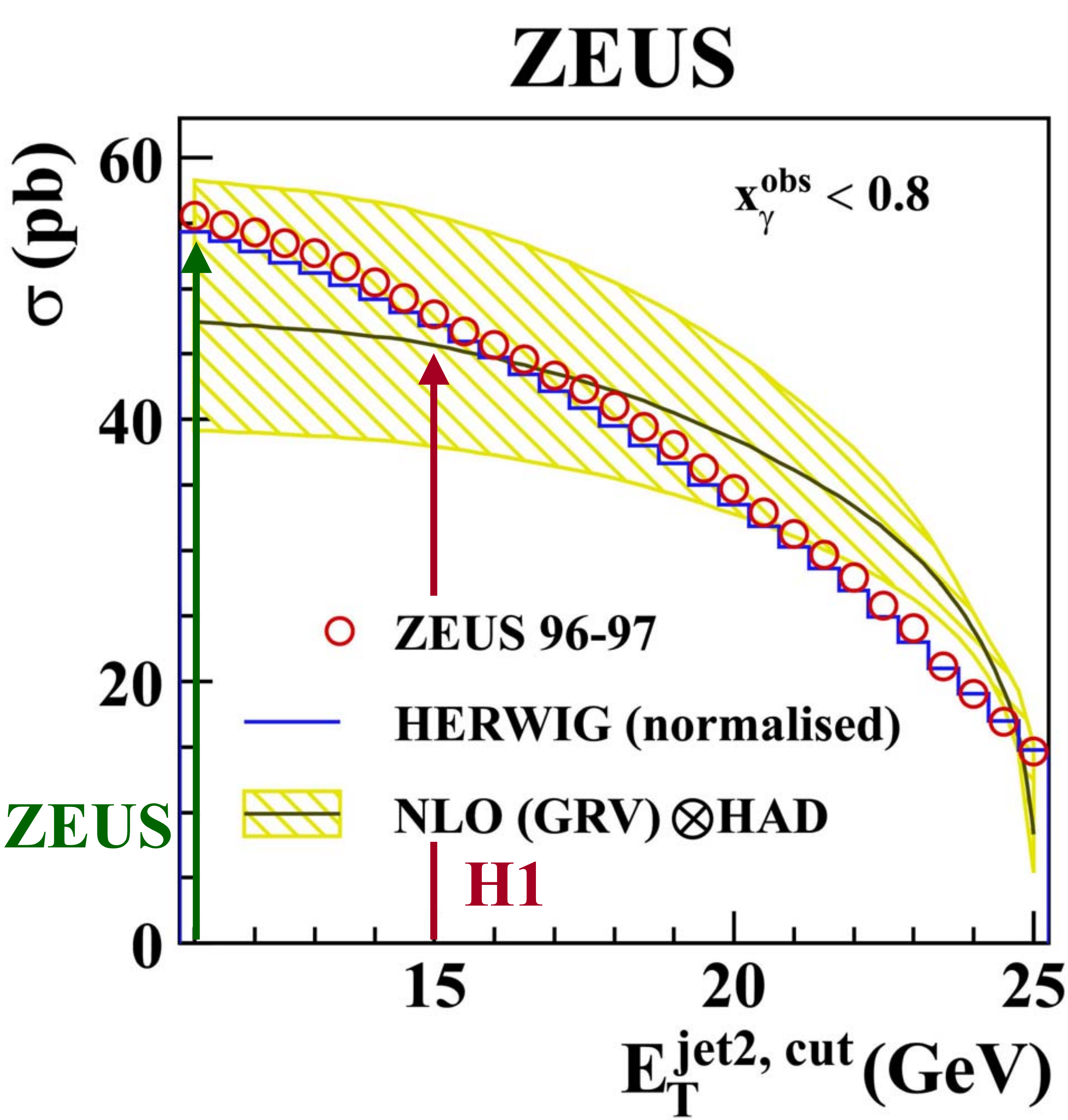


$E_T^{\text{jet1}} > 14\,\text{GeV}$ $E_T^{\text{jet2}} > 11\,\text{GeV}$ $-1 < \eta^{\text{jet1,2}} < 2.4$

- Data described by NLO QCD for $x_\gamma < 0.8$ in both $E_{T,\max}$ bins
- ZEUS data falls more slowly with E_T^{jet1} than NLO QCD

Dijet production in γp

Sensitivity to jet cuts

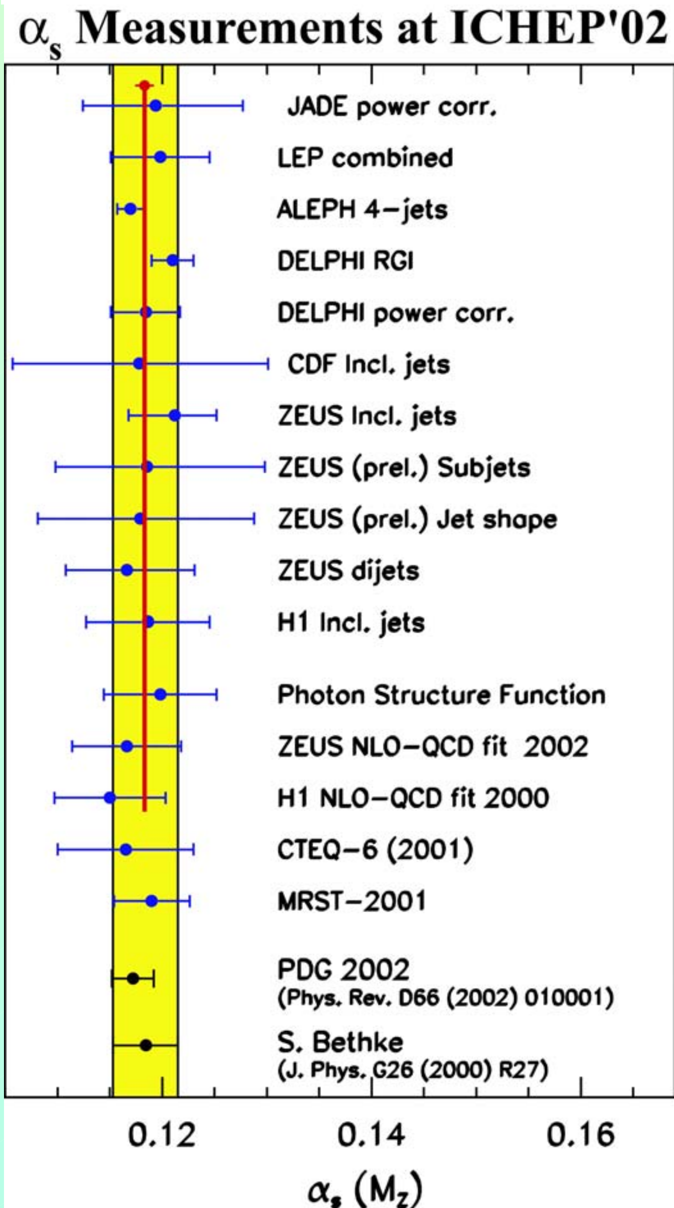


- Dijet cross section: resolved enriched versus $E_T^{jet2,cut}$
- LL MC (HERWIG) describes *SHAPE*
- NLO calculation gives reasonable normalisation, but *SHAPE* requires NNLO

Conclusions

- New and updated meas. of $\alpha_S \rightarrow$ 1-5%. Many techniques.
- Fundamentals of QCD 'check out': $\alpha_S(Q^2)$, colour factors.
- NLO QCD analyses have determined PDFs with precision. Data and theory (nearly) ready for NNLO
- Low Q^2, low x inclusive DIS and diffraction – fertile fields. New data, many new ideas.

$$\overline{\alpha}_S = 0.1183 \pm 0.0009$$



Conclusions

- **Jet and heavy flavour production:**

  NLO gives good *qualitative* description, require expt[l] and theor[l] progress to extract *quantitative* information

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- **Eagerly awaiting *large* data sets from HERA, TeVatron**
- **Now, more than ever, require diverse programme of measurement *and* interpretation**

In partnership we (theorists, phenomenologists and experimentalists) can achieve our ambition!

Many thanks to all who helped me prepare this talk. Especially, K. Nagano, O. Gonzalez, A. Tapper and E. Laenen.