Hard QCD and Structure Functions

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EPS HEP 2001

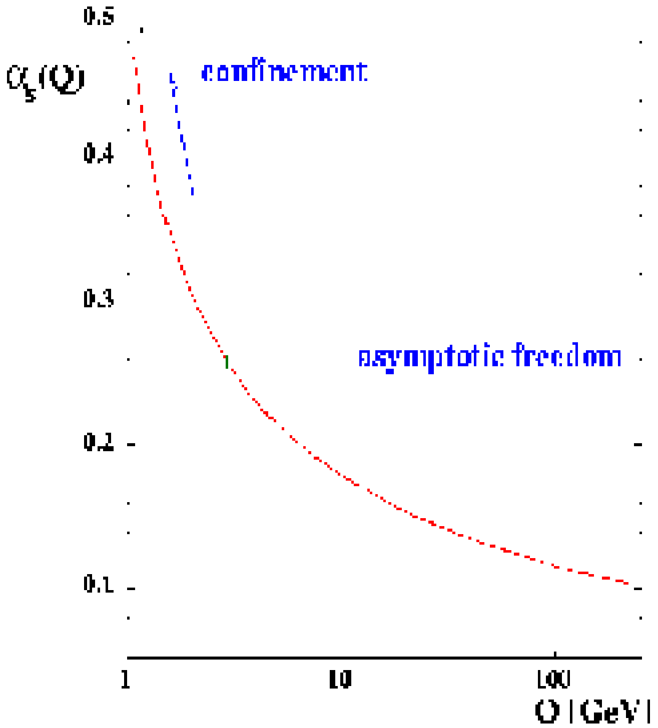
QCD is a simple and elegant theory... of quarks and gluons

But we live in a world of hadrons

Asymptotic freedom allows us to calculate hard processes, but we always have hadrons in the end.

α_s is still large: HO are important

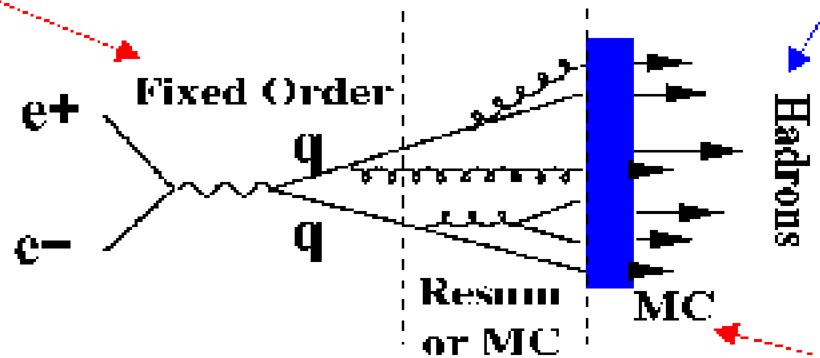
These considerations can make pQCD studies rather complicated.



QCD at e+e−:

Find an infrared safe observable:
total e+e− hadronic cross−section, event shapes, jets(kt type), etc.

Calculation typically to NLO in exist for "safe" observables. (sometime to NNLO or beyond..)



Hadronization Models and Monte Carlos: "Only models" hopefully small effect.

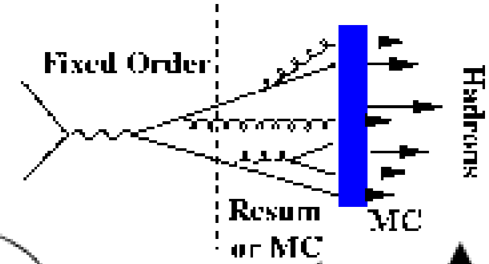
Resummations: for some observable R which is becoming small

$$\alpha_s^n (\ln 1/R)^{n+1-l}, (n = 1..\infty)$$

LL (*l=0*) , NLL(*l=1*) ...

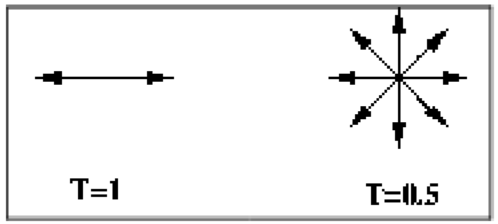
Monte Carlo implementations of HO
Parton Showers(Pythia, Herwig...)
Color Dipoles(Ariadne..)

QCD at e+e−:



EVENT SHAPES:

e.g. Thrust, T means and differ.



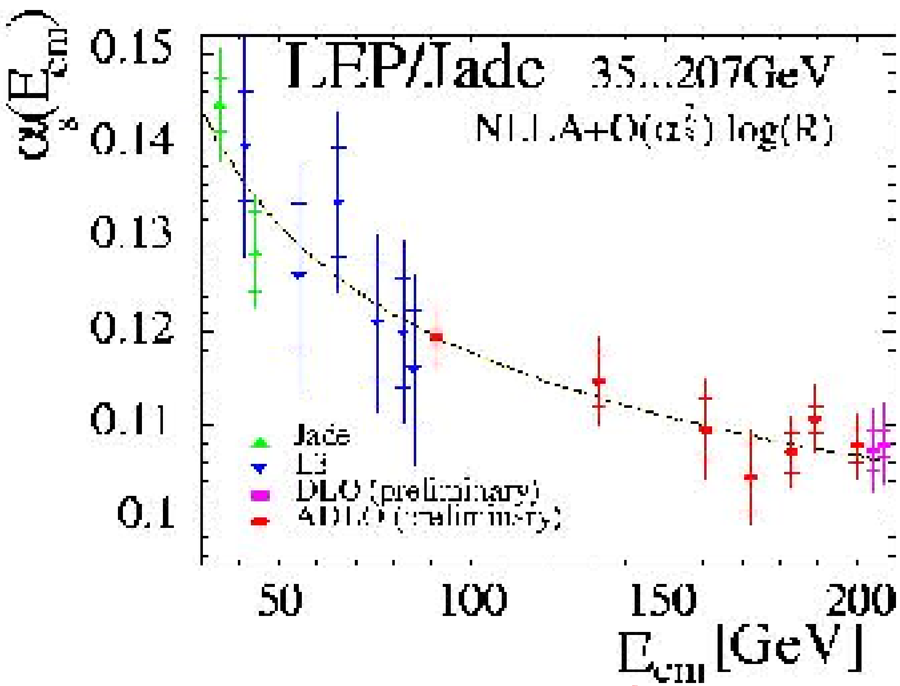
Large–ish corrections: 1/Q

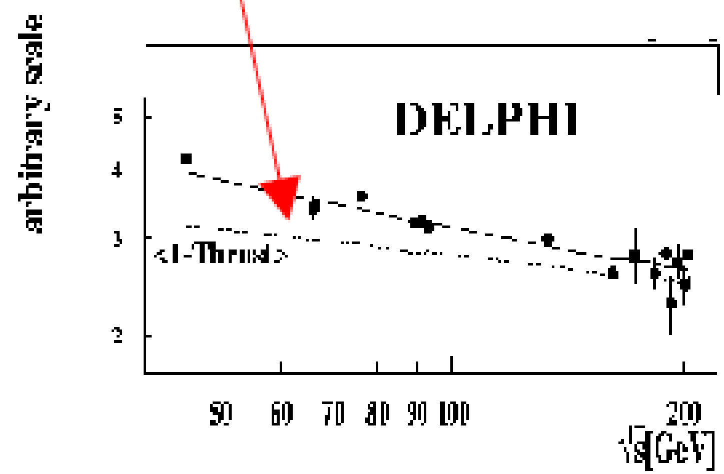
theo. cal here

(use many diff variable and fit for α_s)

MC cor.

measure here

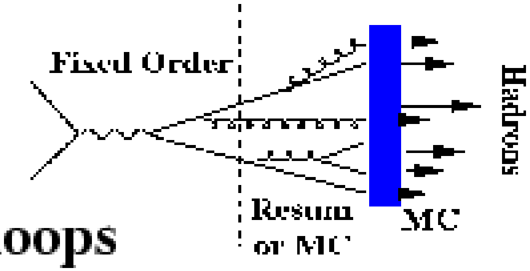




Measurements to highest LEP Energies. Running of α_s.

$\alpha_S(M_Z)=0.1195\pm0.0007\pm0.0048$

QCD at e+e−:



Running b quark mass: dependence known to 4 loops

Determined from :

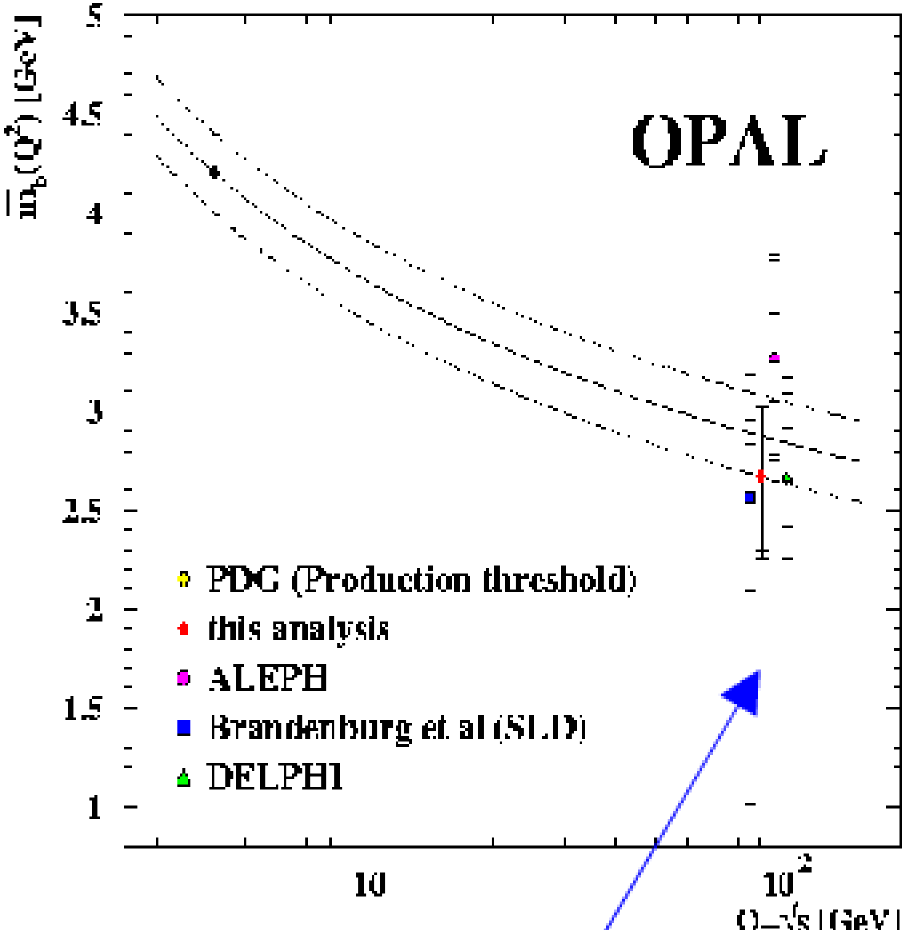
$$B_3 = \frac{b\bar{b} \rightarrow 3 \text{ jets}}{q\bar{q}(udsc) \rightarrow 3 \text{ jets}}$$

$$= a_0 + a_1 \, m_b^2$$

at the Z mass

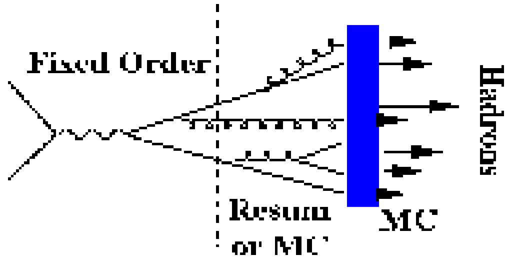
New measurement from OPAL

Running mass established with 3.9 sigma (from OPAL)

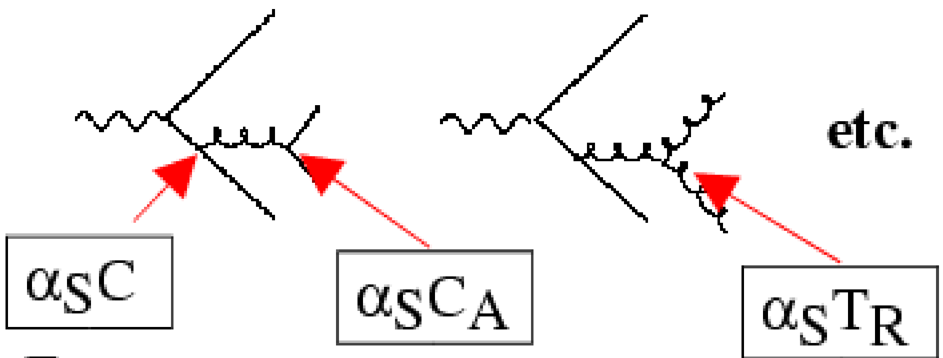


measurements separated for display

QCD at e+e−:

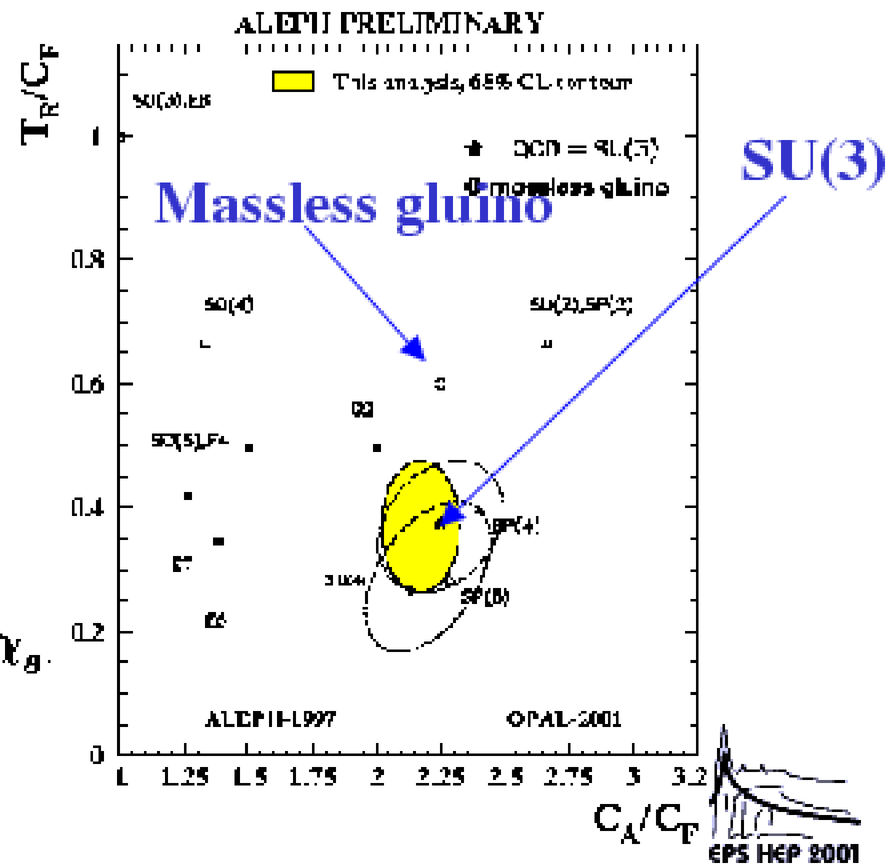


QCD color factors and α_s from 4−jets at LEP



Expect sensitivity in angular correlation of jets.

–Use several angular correlations and jet rates for fit using α_s^3 predictions.



New results from OPAL and ALEPH

Simultaneous fit of color factors and α_s.

15% determination

Summary QCD at e+e–

All LEP experiments have updated their measurements to the highest LEP II energies.

Several analyses that cover a very wide energy range , ~20 – 200 GeV, convincingly demonstrates running of α_s.

Event shapes, Jet rates(not shown here)

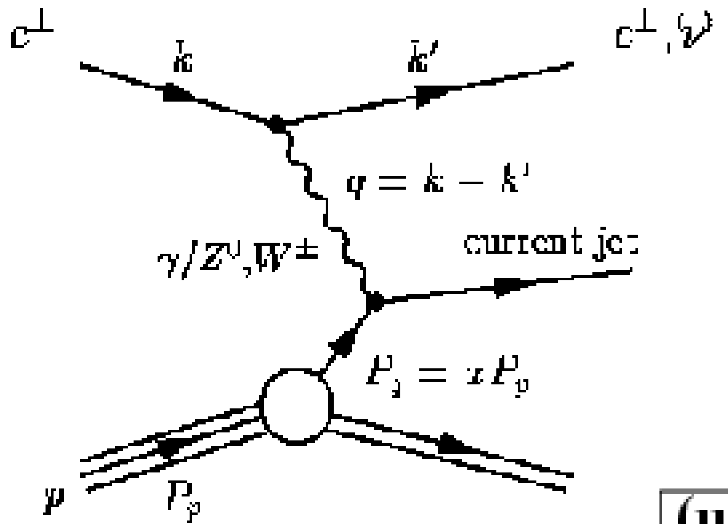
Error on α_s determination is typically 3–5 %.

All obtain consistent values.

Running of b mass is also seen. Basic check of QCD symmetry groups also give consistent answers.

Structure function and parton distributions:

Deep inelastic scattering



$Q^2 = -q^2$ Virtuality ("size" of probe)

x Mom. fraction of the struck parton.

Factorization: $\sigma_{DIS} \sim f_p(x) \otimes \hat{\sigma}$

(univeral) parton densities

PQCD cross–sec.

DGLAP evolution equations:

$$\frac{\partial f_p}{\partial \ln Q^2} \sim f_p \otimes P$$

***P*'s are splitting functions:**

Str. fcn. and parton dist.:

Neutral Current (γ, Z exchange) interaction

$$\frac{d\sigma^2_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+ F_2 - y^2 F_L \mp Y_- xF_3\right)$$

New HERA (H1 and ZEUS) measurements have ca. 3% precision.

$y = Q^2/xs$, the inelasticity parameter, $Y_\pm = (1 \pm (1-y)^2)$

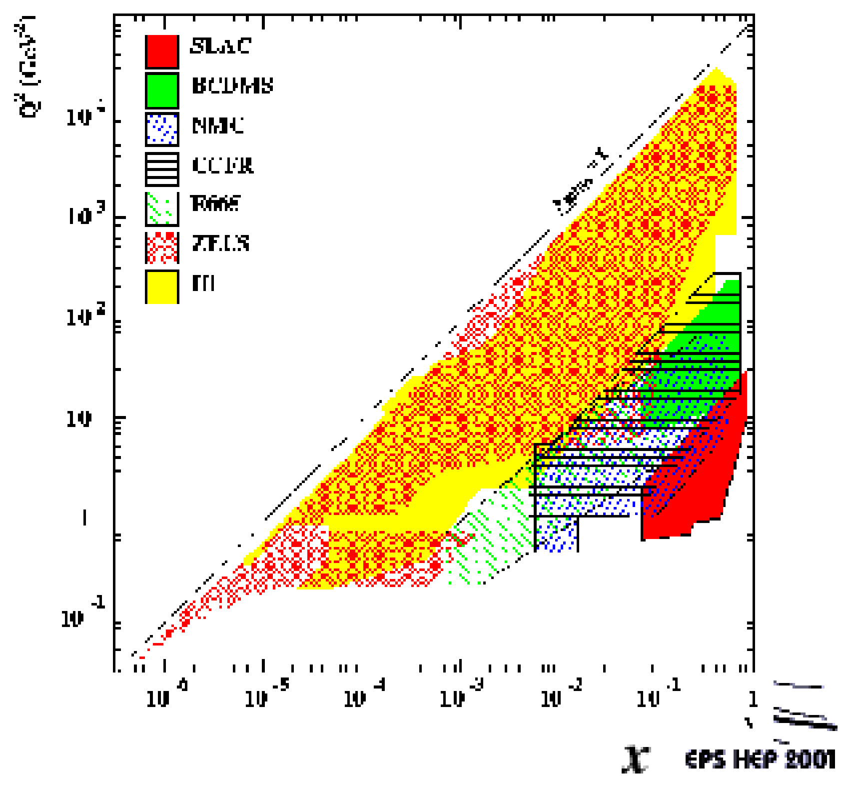
F_2, F_L, and xF_3 are structure functions of the proton.

- F_L: longitudinal component, damped by y^2.
- xF_3: Small at $Q^2 \ll M_Z^2$.

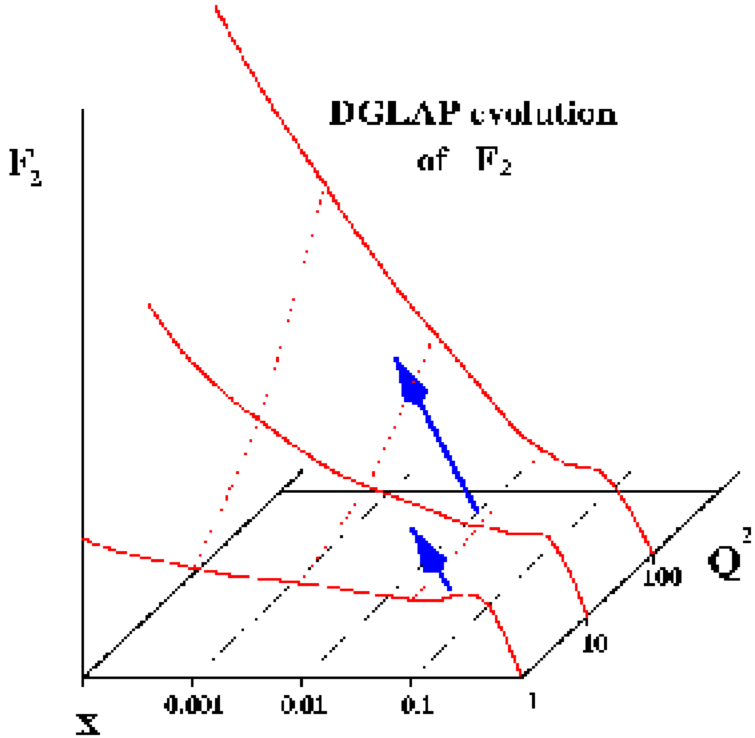
And (LO (in DIS scheme))

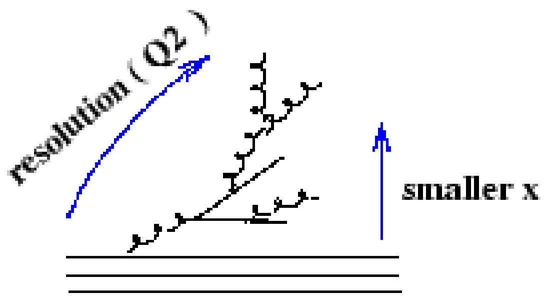
$F_2(x, Q^2) = x\sum_q e_q^2(q(x, Q^2) + \bar{q}(x, Q^2))$

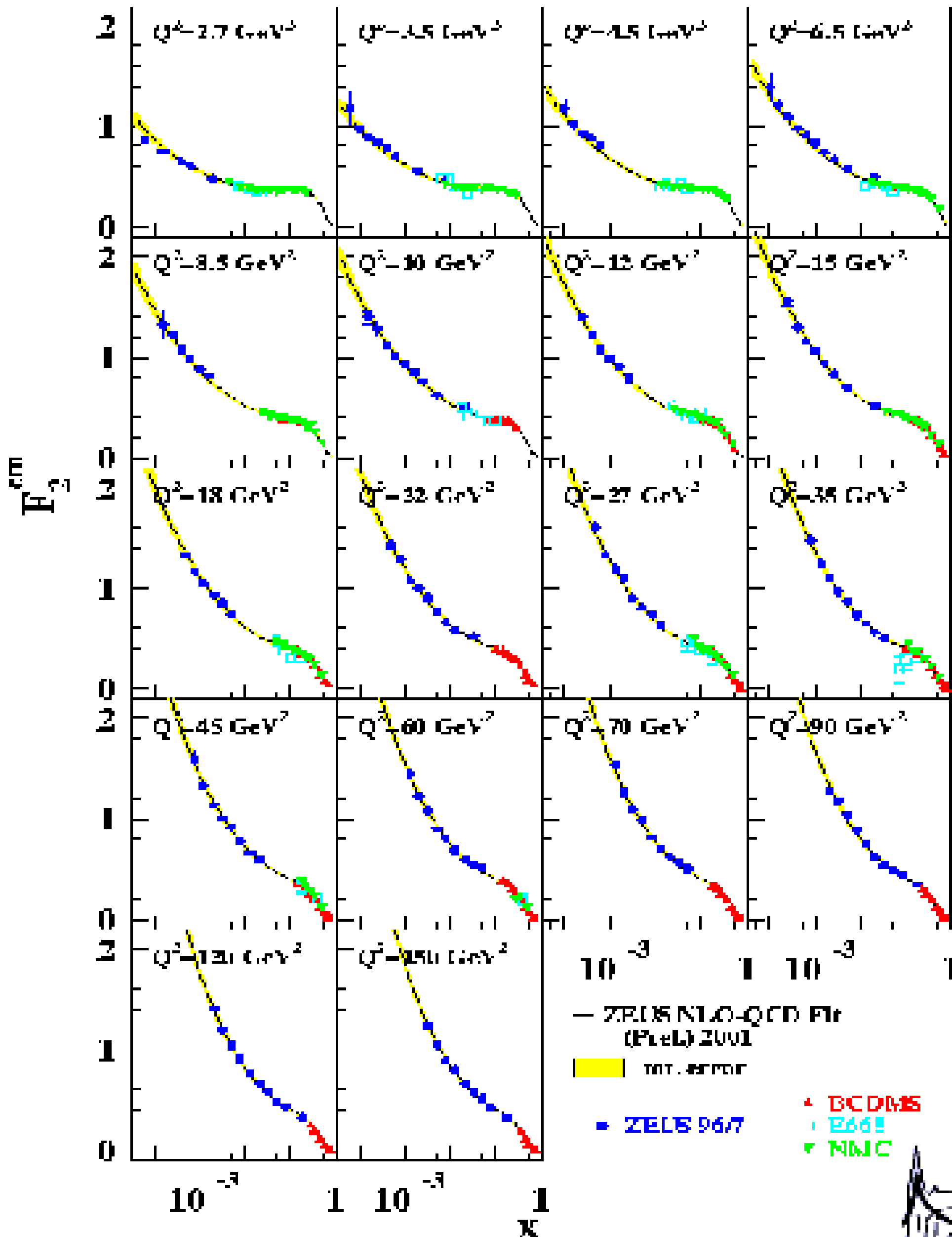
where q, $\bar{q}$ are quark, antiquark densities in the proton.



Str. fcn. and parton dist.:

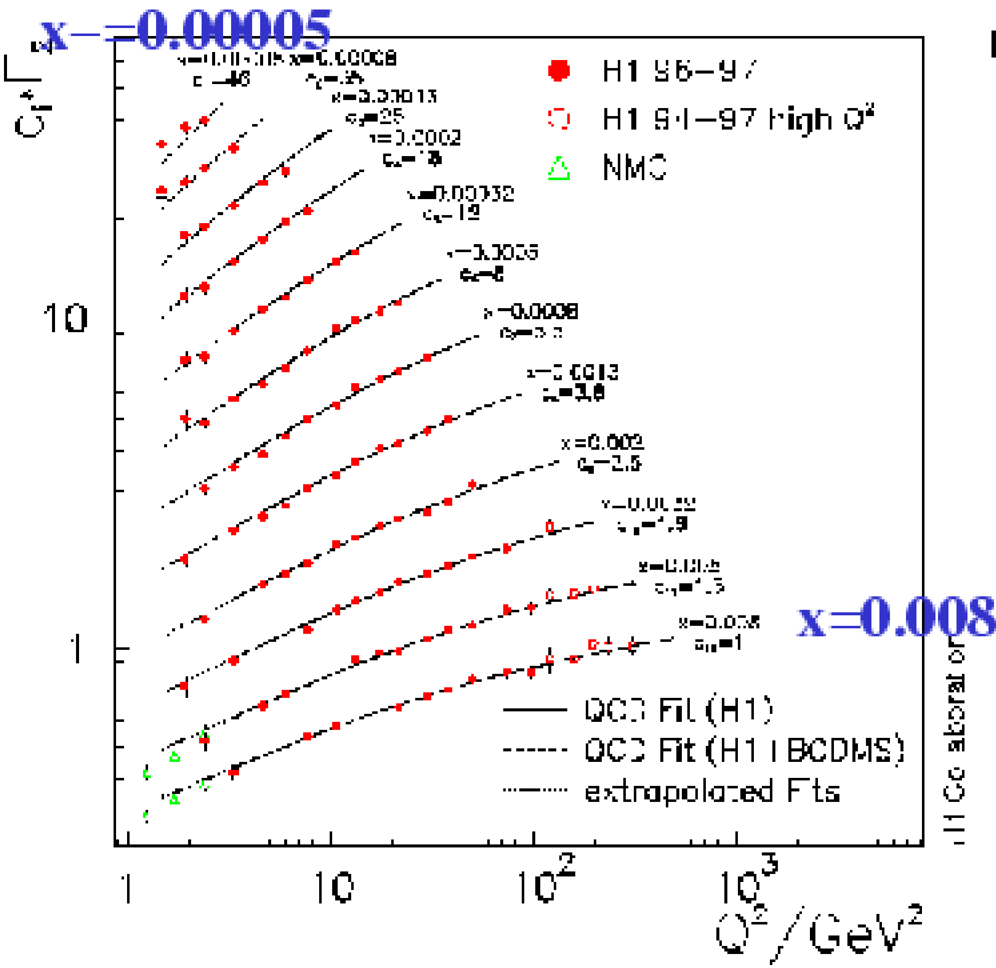


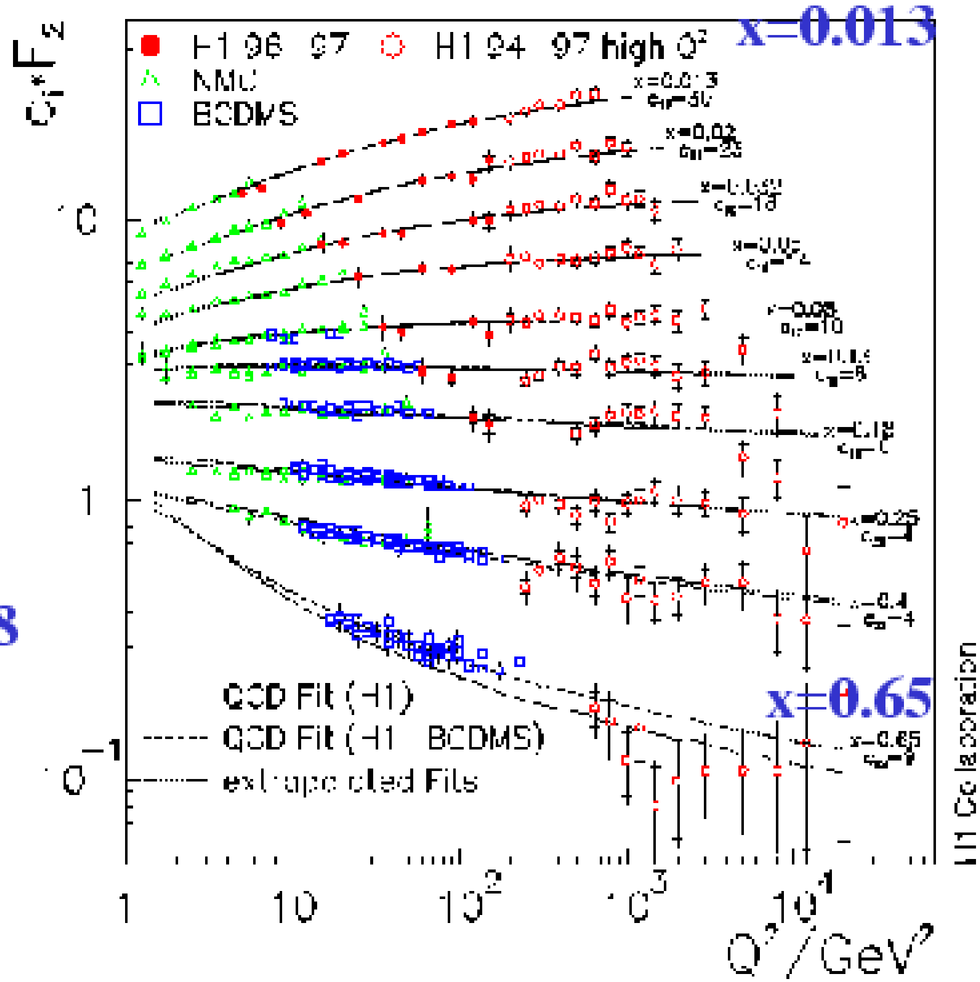




Incr. Q^2

Str. fcn. and parton dist.:





To LO: $\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g$

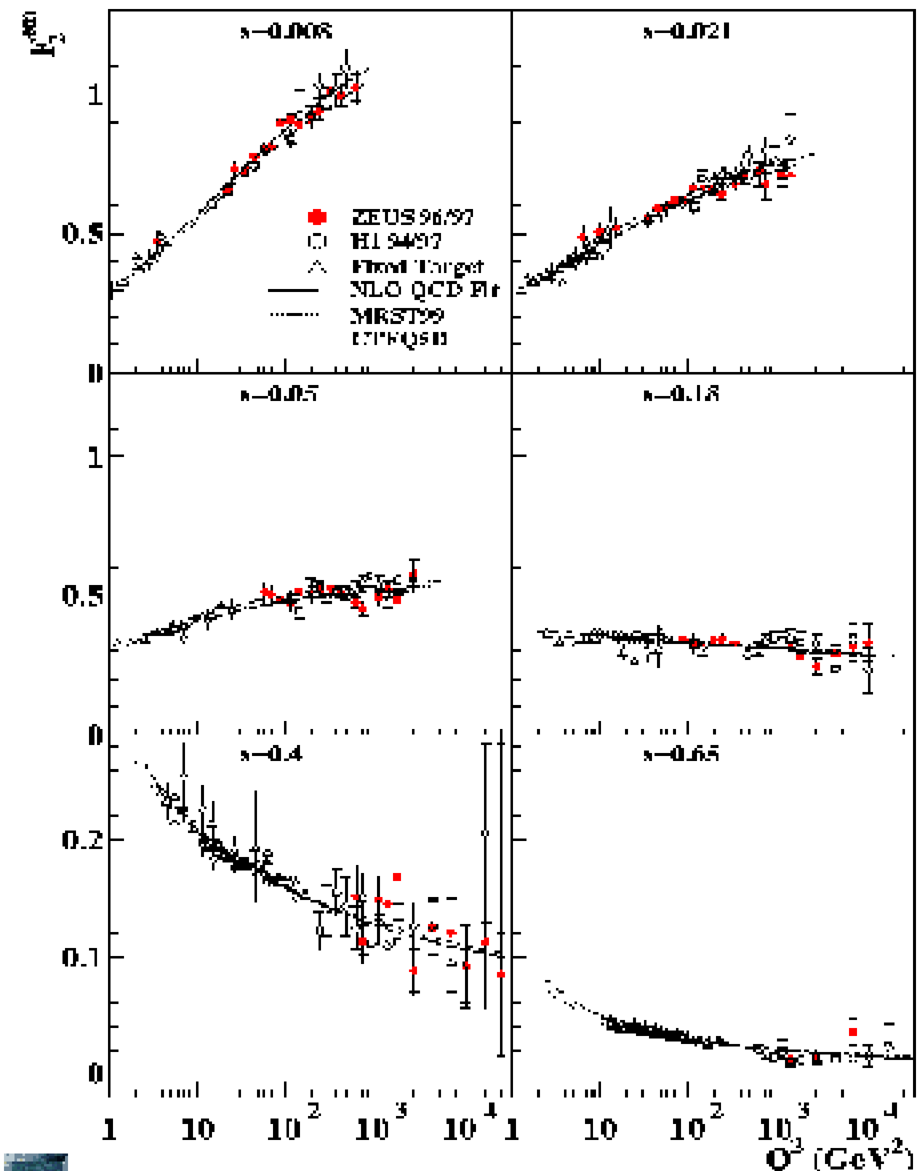
NLO DGLAP fit with q/g paramerized

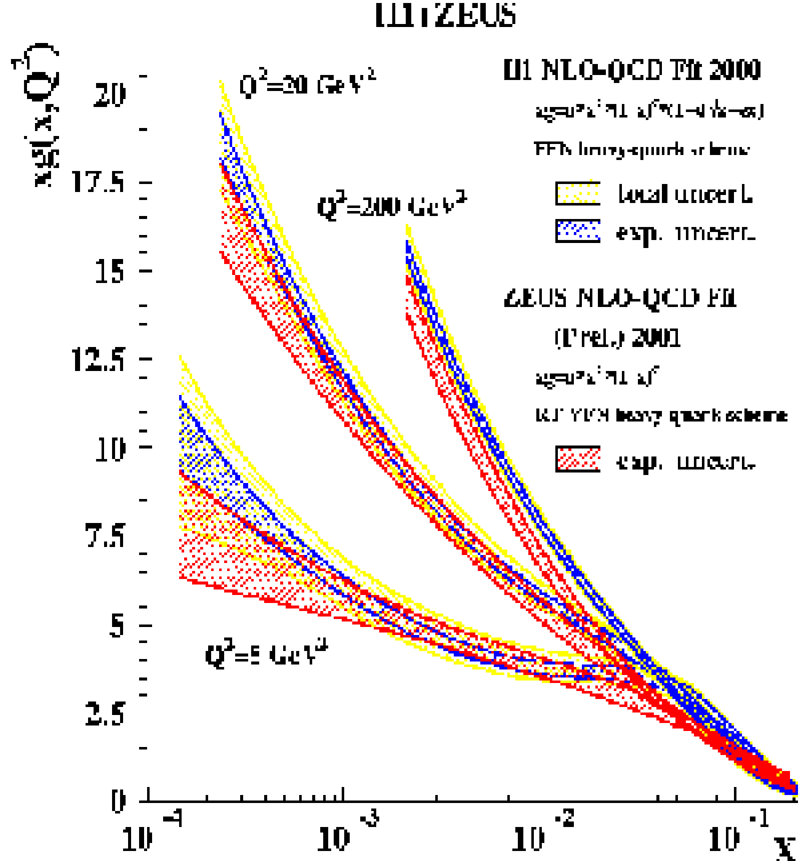
$$xq(x) = ax^b(1-x)^c[1 + d\sqrt{x} + ex]$$

Str. fcn. and parton dist.:

GLUONS

Good agreement H1 and ZEUS





H1

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(exp)^{+0.0009}_{-0.0005}(model)$$
$$\pm 0.005(\text{theory})$$

ZEUS (prel.)

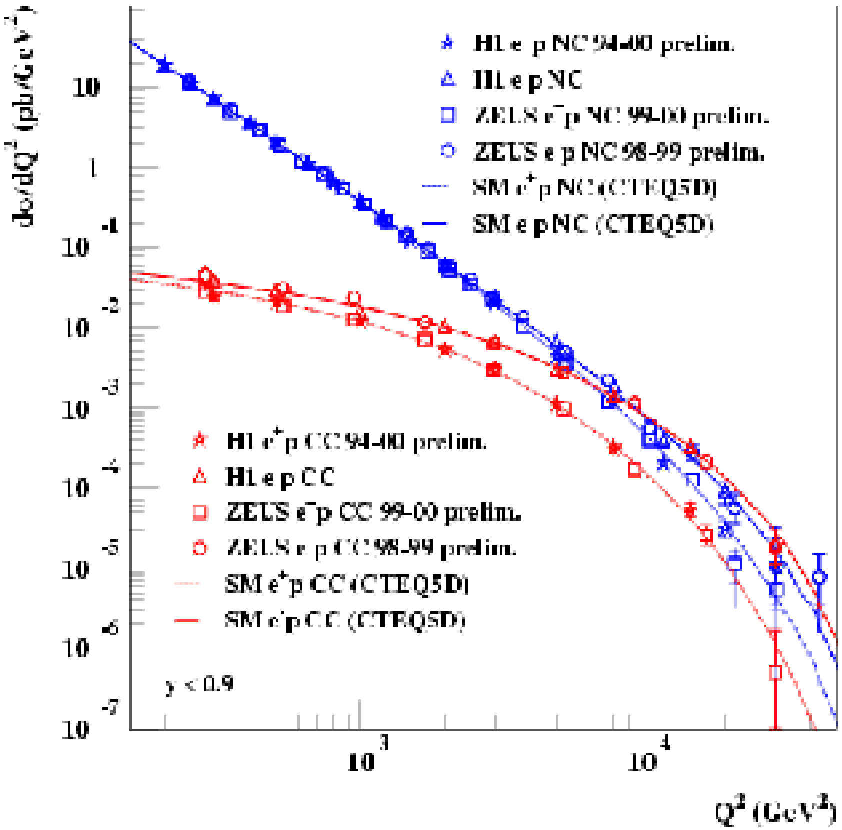
$$\alpha_s(M_Z^2) = 0.117 \pm 0.001(stat + uncorr) \pm 0.005(corr)$$

theory error to be evaluated

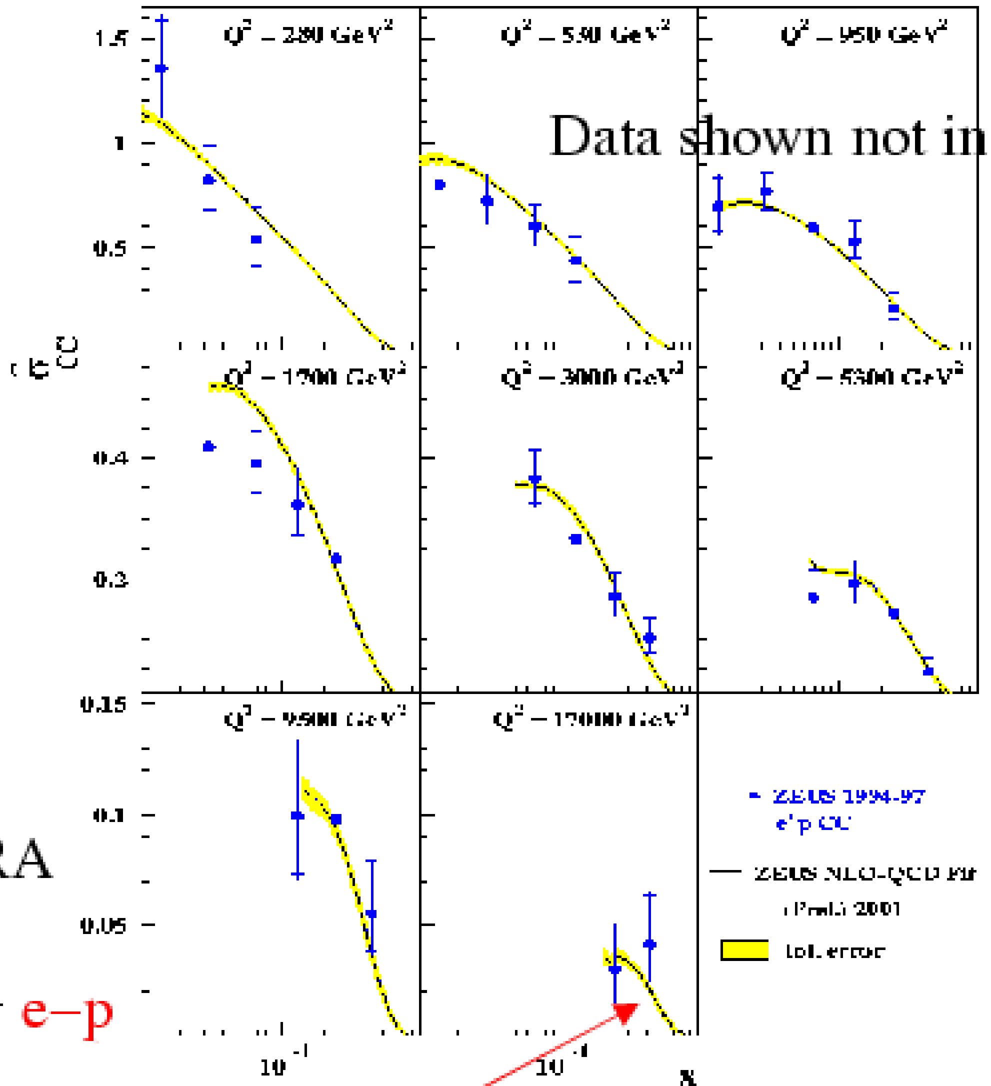
Str. fcn. and parton dist.:

Charged Current cross–section

$$\sigma_{cc}(e^-p) \sim G_F^2\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[(1-y)^2(d+s)+(\bar{u}+\bar{c})\right]$$



Measurements of NC and CC at HERA



Results ca. 100 pb^{-1} e+p **and** 15 pb^{-1} e−p

HERA upgrade will bring x10 data by 2005–6.

Precision of DGLAP fit from Fixed Target exp.results

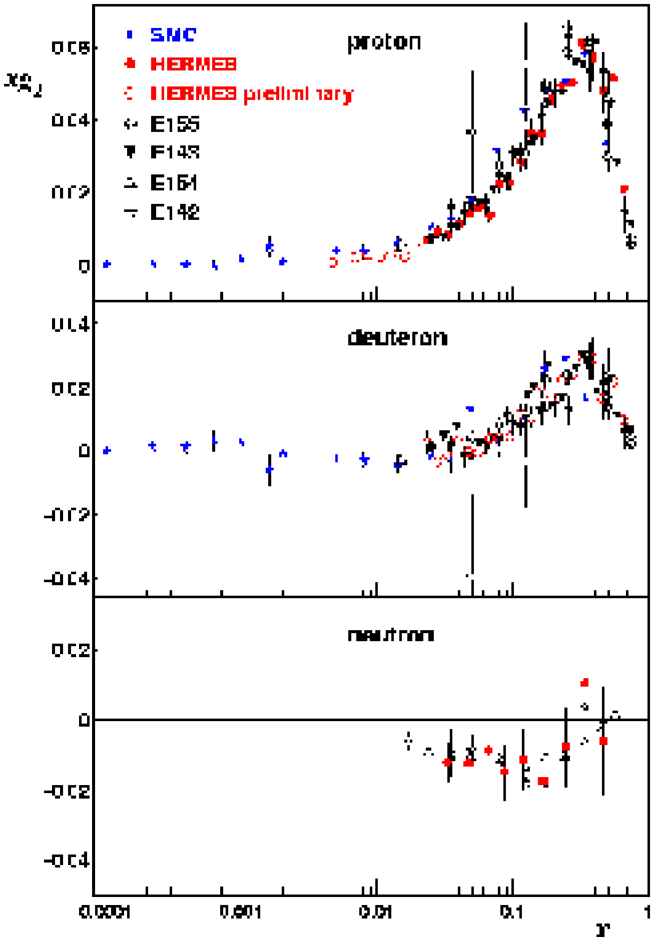
Str. fcn. and parton dist.:

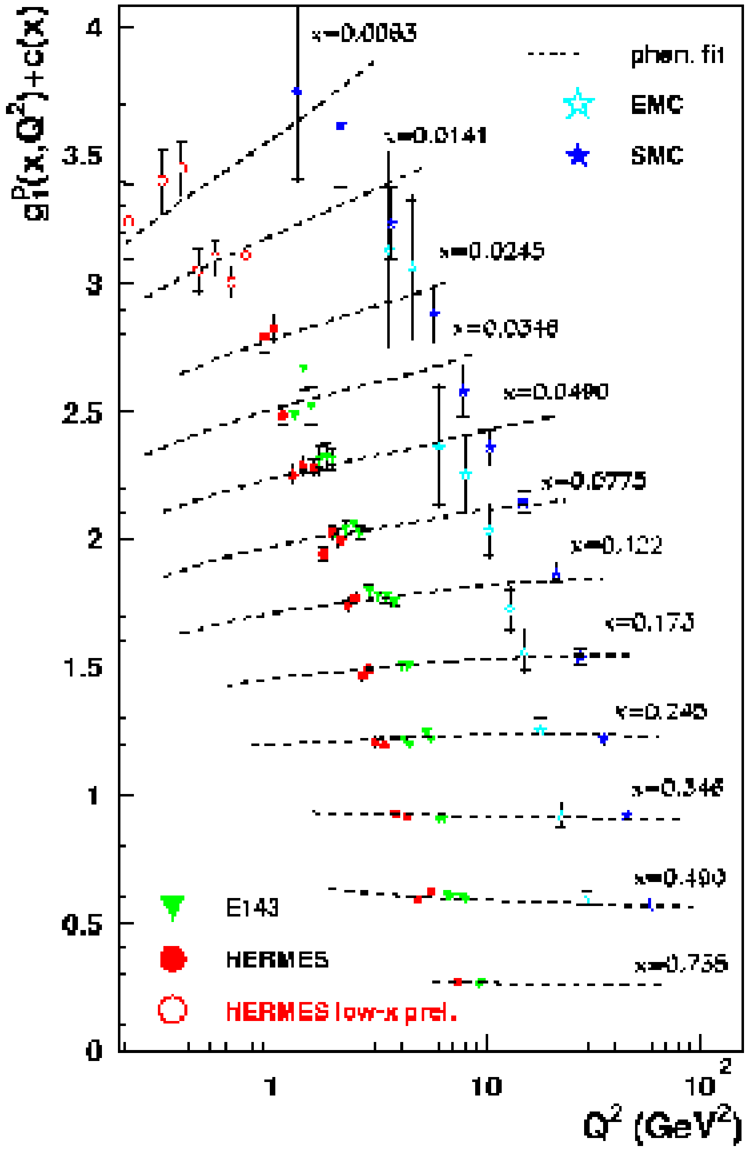
Proton spin structure

Asymmetry in pol. *lN* scattering

$$g_1(x) = \frac{1}{2}\sum_{i=1}^{n_f} e_i^2 \left[\Delta q_i(x) + \Delta \bar{q}_i(x)\right]$$

$$\Delta q_i(x) \;=\; \left(q_i^+(x) - q_i^-(x)\right),$$





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$ ← "spin puzzle"

Str. fcn. and parton dist.:

Bluemlein & Boettcher
NLO DGLAP fit

Flavor sym. assumed

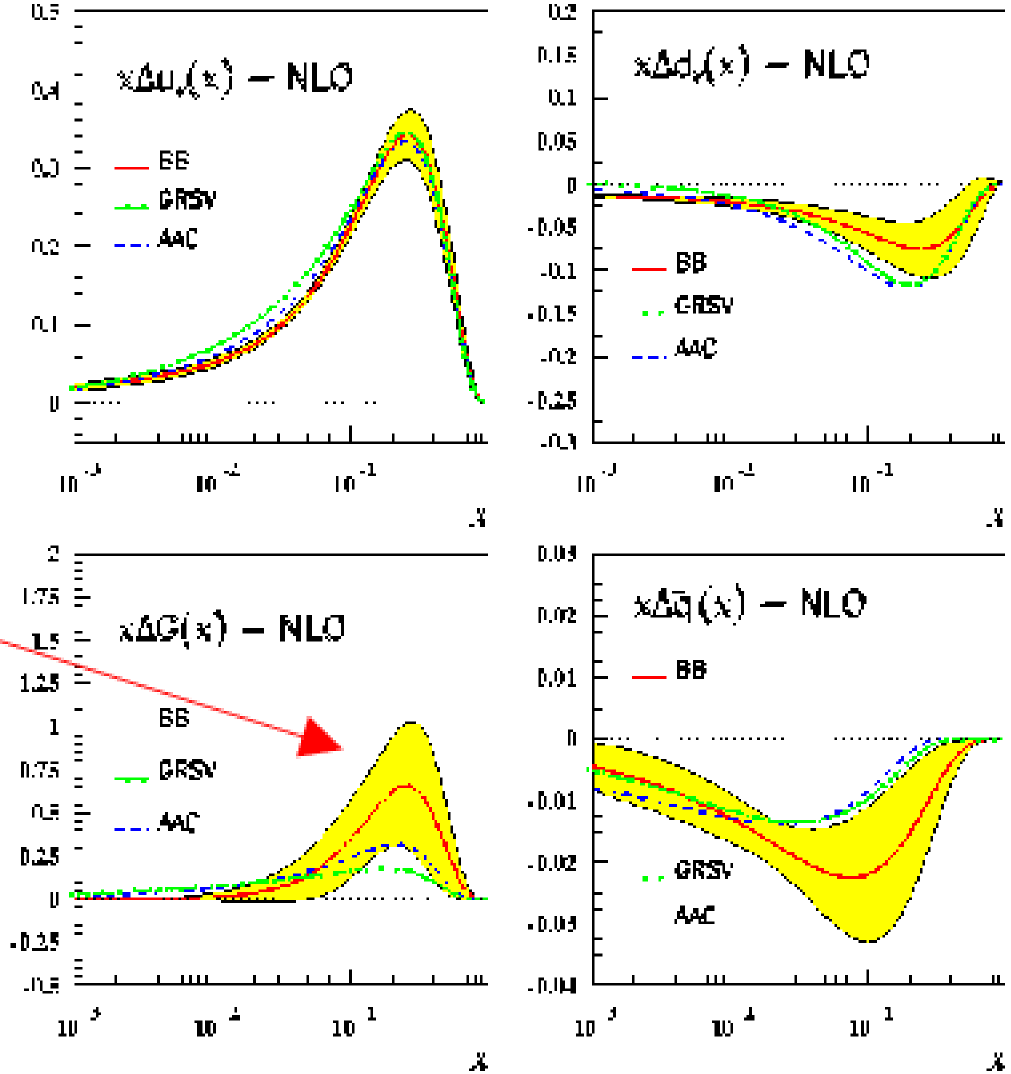
Full propagation of correlated errors

Spin carried by gluon

Proposed factorization scheme independent analysis

	(fit)	(fac)	(ren)
$\alpha_s(M_Z^2) = 0.114$	$+0.005$	-0.004	-0.007
	-0.006	-0.004	-0.005

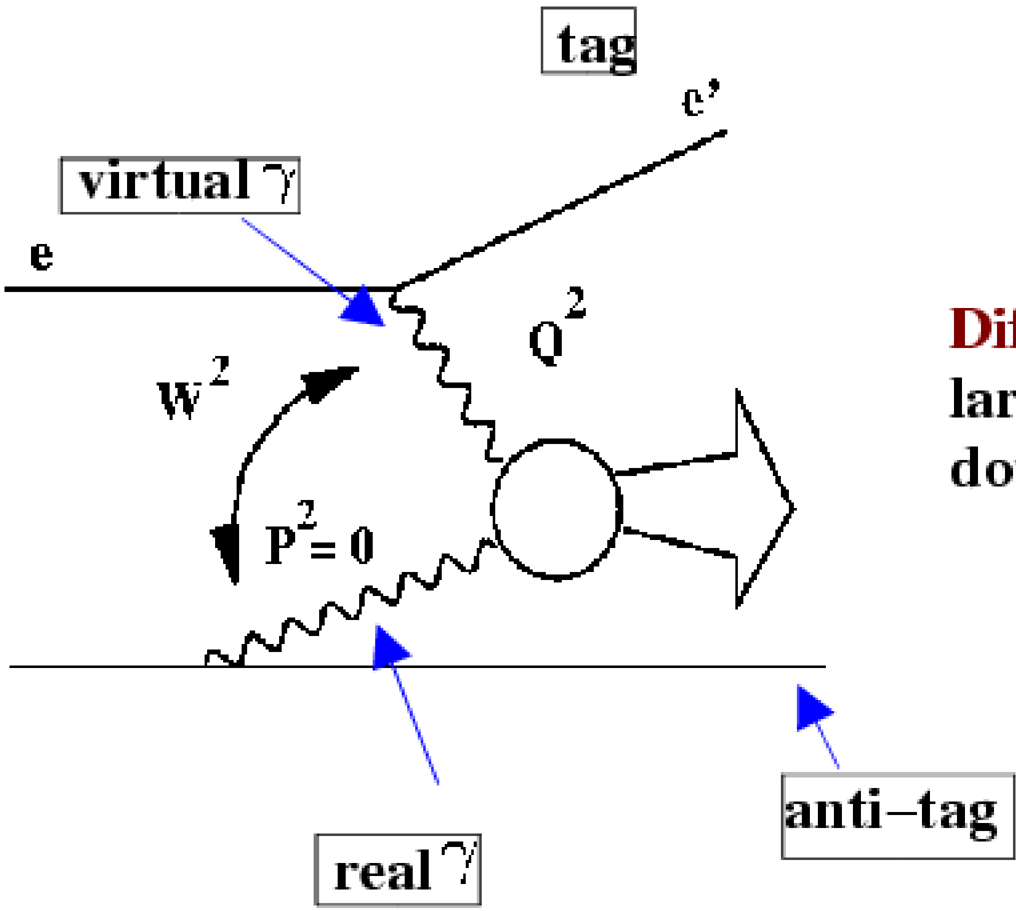
$Q_0^2 - 4.0\, GeV^2$



Results also from Sidrov et al.

Str. fcn. and parton dist.:

Deep Inelastic Scattering on a photon

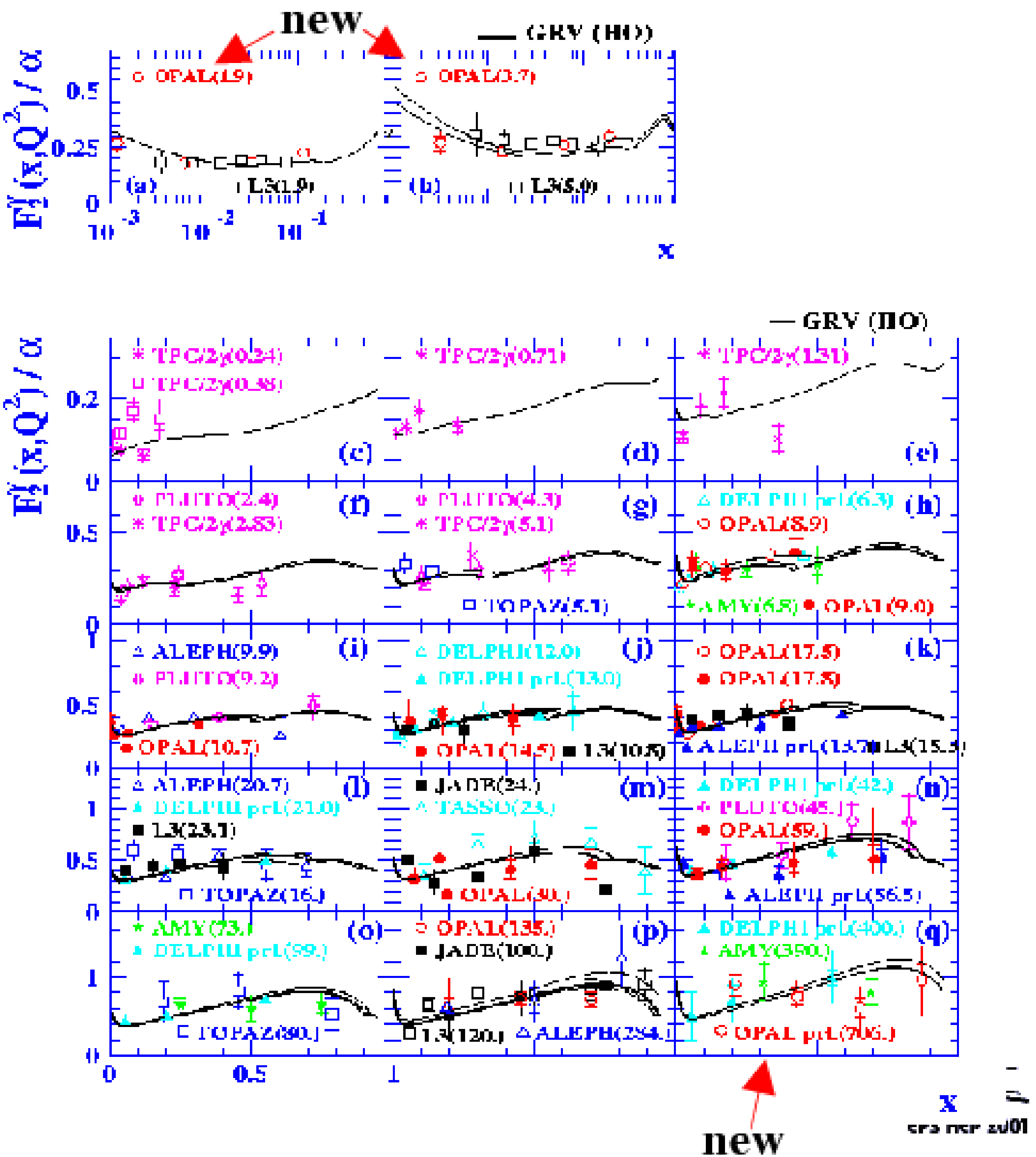


Difficult measurement:
large part of final state escapes down beampipe

World DATA on Photon F2

New results at low−x and high Q^2 from OPAL

Hadronic component of photon needed. Rising at low−x?



Summary: Structure functions and parton distributions

HERA data spanning 6 orders of magnitude in x and Q^2
Precision ~ 3% in large kinematic range.

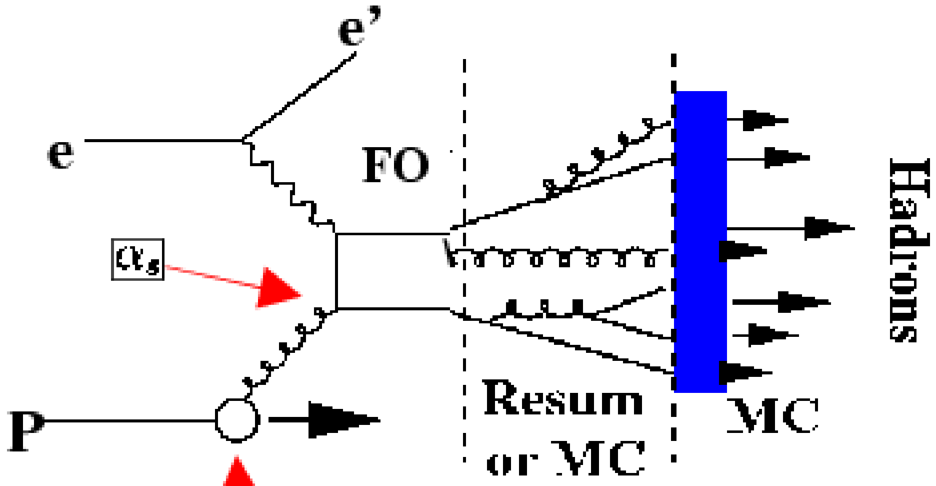
Precise determination of gluon at low *x* and determination of α_s to ~4% from scaling violations. Unc. is dominated by theory.

Efforts to produce proton pdf's with errors and correlations (not shown) also for polarized str. fcns.

Nearly all calculations needed for NNLO DGLAP analysis is ready. (S. Moch talk ––not shown here)
Will reduce theory errors!

Some additions to the photon structure data from LEP

QCD with initial hadrons: Combine the previous 2 types!



Look for jets (for example)

charm, pions, etc.

Proton structure (pdf)

Take from other processes (e.g. inclusive DIS) and evolve.

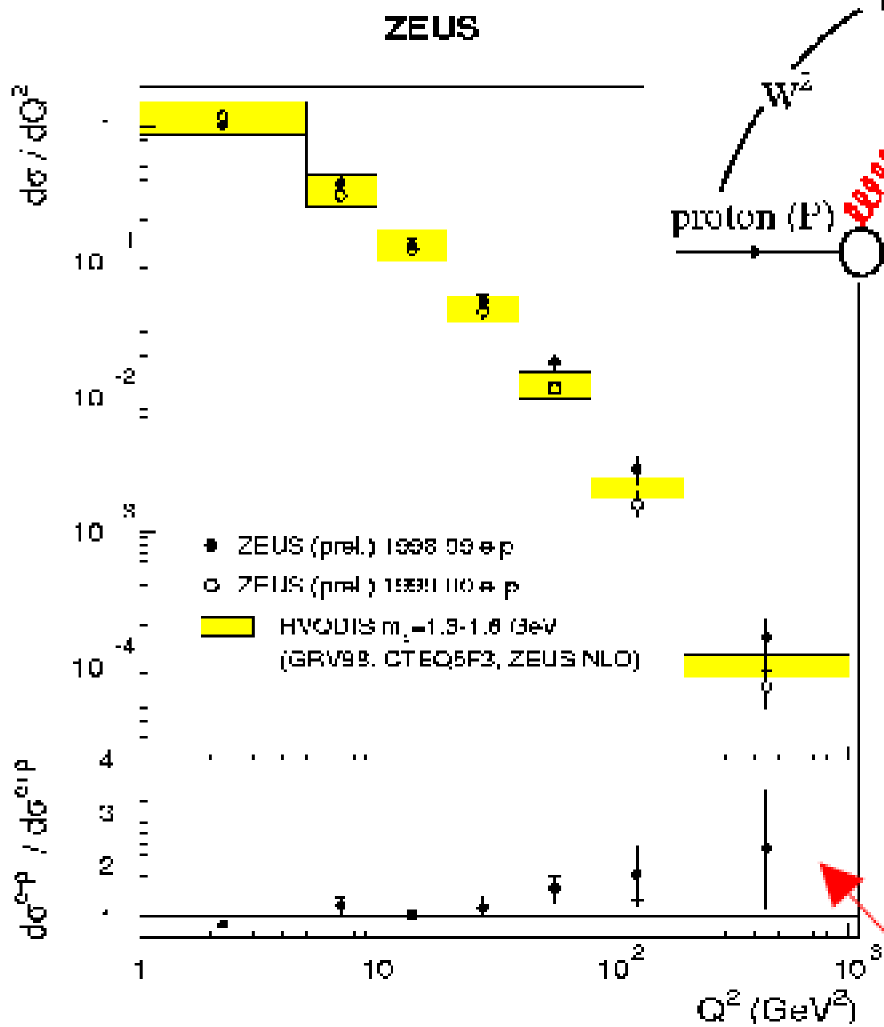
..or determine in analysis.

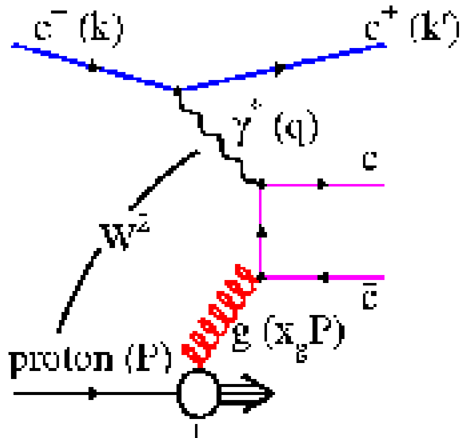
Depending on which is known better

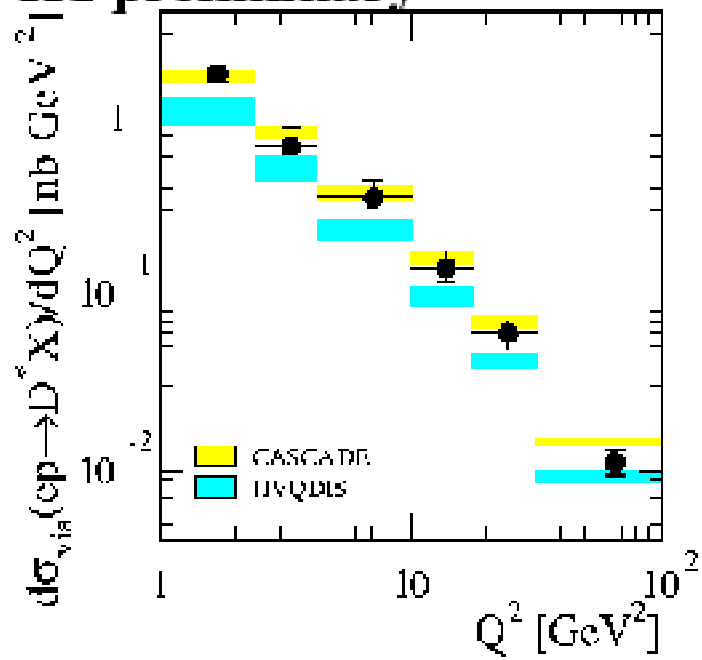
- Determine PDF
- Determine α_s
- ...

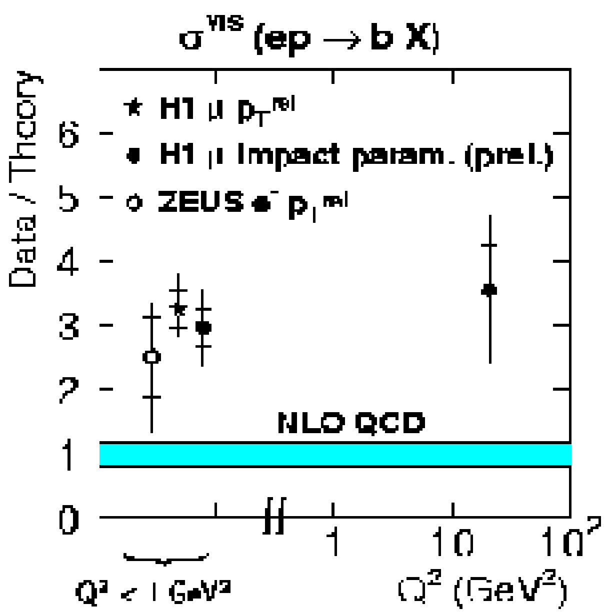
QCD, initial hadrons:

DIS Charm and Beauty







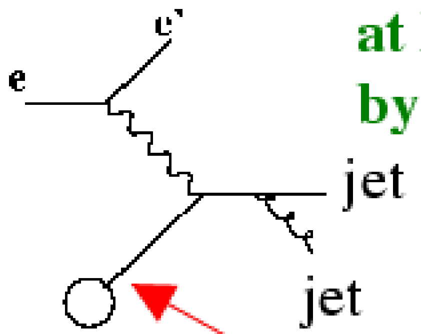


3 sigma effect

Beauty 2 sigma high

QCD, initial hadrons: DIS jet studies at HERA

At high Q^2, dijet production at HERA is dominated by QCDC.



Quark dist. well known at high x

Determine α_s.

H1 (inclusive jets):

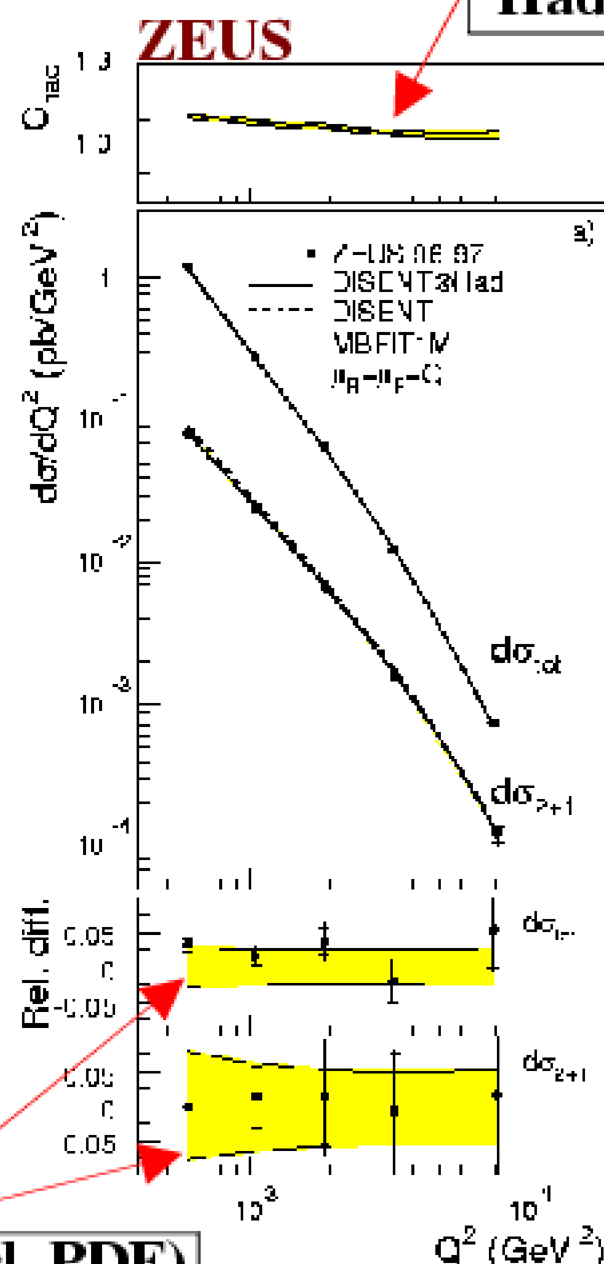
$$\alpha_s(M_z) = 0.1186 \pm 0.0030(exp) \pm^{0.0039}_{0.0015}(th.) \pm^{0.0033}_{0.0033}(pdf)$$

ZEUS (2jet/total ratio):

$$\alpha_s(M_z) = 0.1166 \pm 0.0019(stat) \pm^{0.0024}_{0.0033}(exp) \pm^{0.0057}_{0.0044}(th, pdf)$$

Theoretical unc. begins to dominate

Had.Cor.

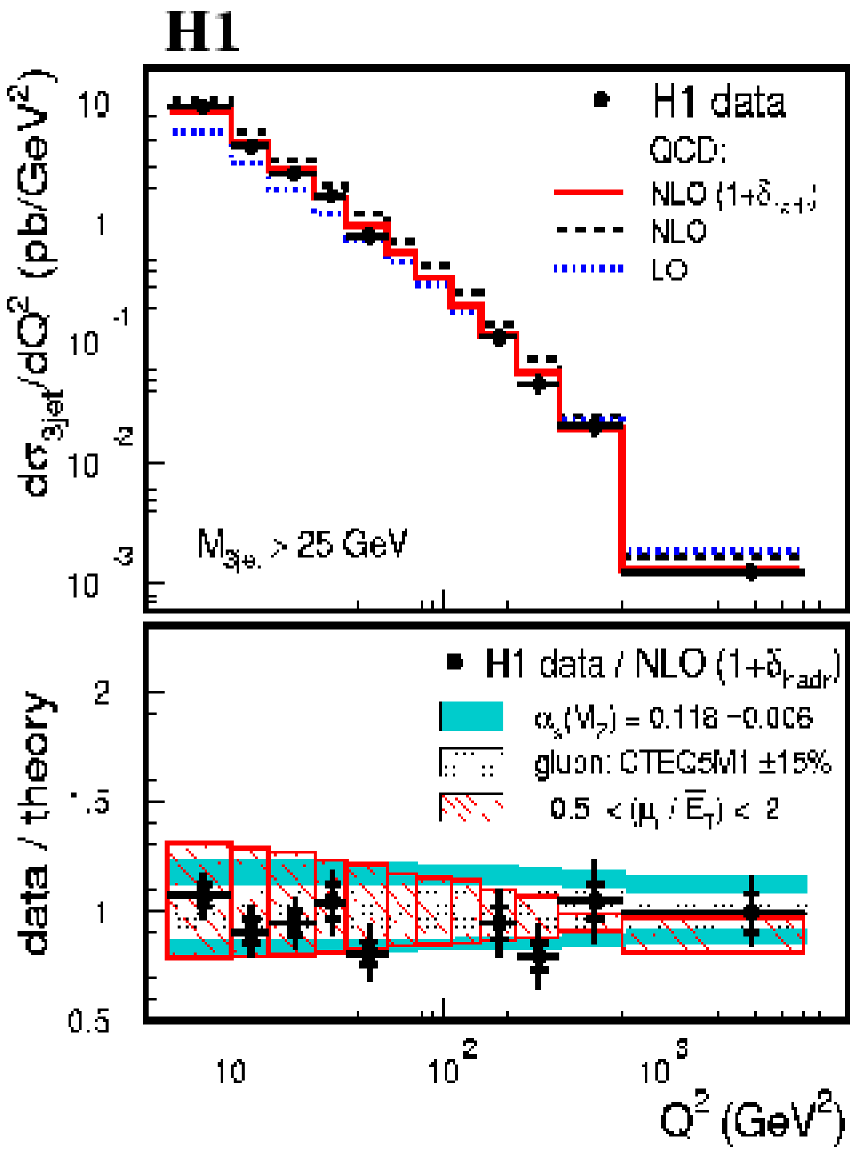


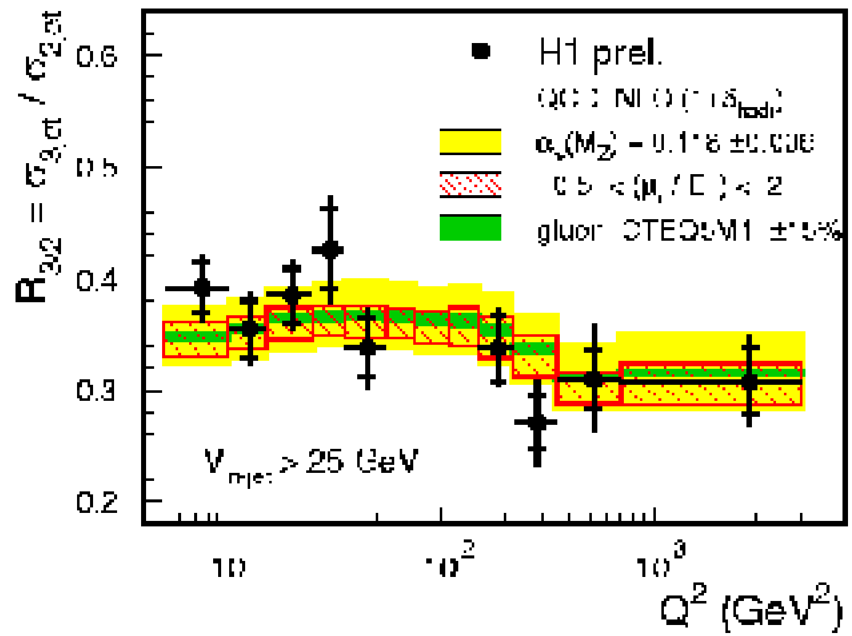
Theo. unc. (incl. PDF)

EPS HEP 2001

QCD, initial hadrons:

3–jets in DIS at HERA



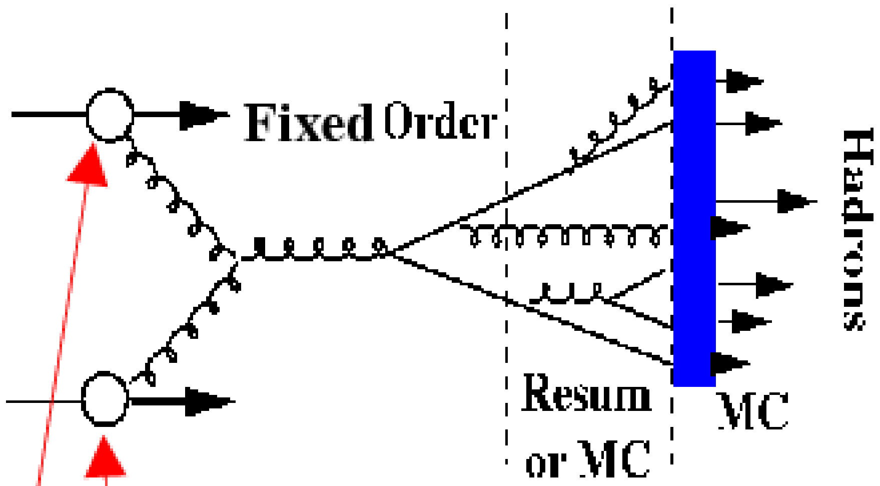


Recent NLO calculations
(Nagy and Trocsanyi)

Small theoretical unc. over wide Q^2 range. Maybe very sensitive test (with more data).

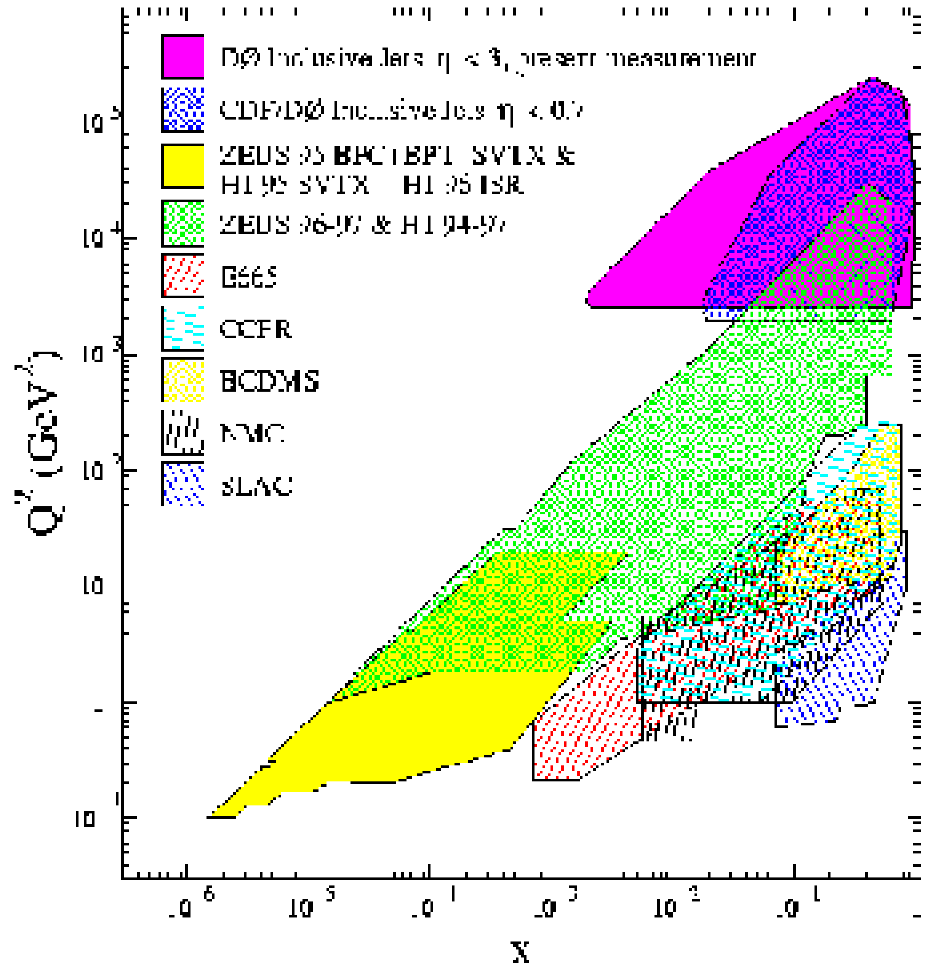
QCD, initial hadrons:

Tevatron jets



p(anti–p) PDF's

Q^2 upto 10^5 GeV

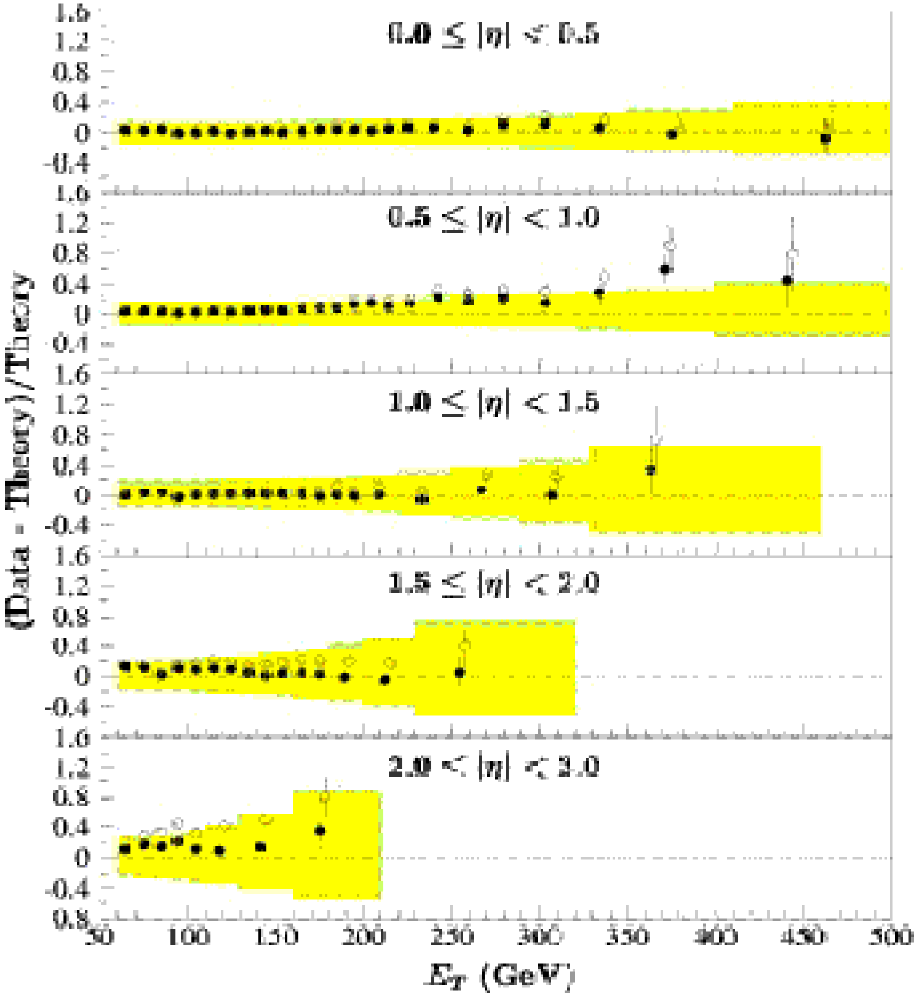


Early reports of high Et excess absorbed in high x gluons.

"CTEQ4HJ"

QCD, initial hadrons:

D0



Closed: CTEQ4HJ Open: CTEQ4M

Extend meas.
to higher rapidity

$$x_{12} = \frac{E_T}{\sqrt{s}}(e^{\pm\eta_1} + e^{\pm\eta_2})$$

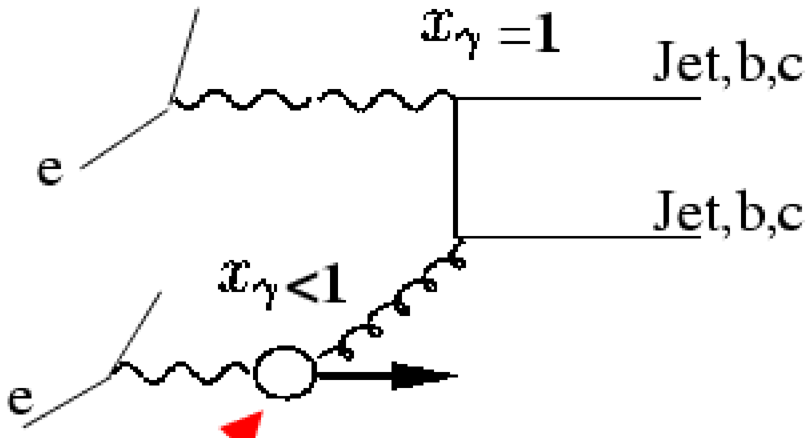
$$\eta = -\ln(\tan(\theta/2))$$

PDF	$\chi 2$	$\chi 2$/dof	Prob
CTEQ3M	121.56	1.35	0.01
CTEQ4M	92.46	1.03	0.41
CTEQ4HJ	59.38	0.66	0.99
MRST	113.78	1.26	0.05
MRSTgD	155.52	1.73	<0.01
MRSTgU	85.09	0.95	0.63

Consistent with several parton sets. Favors CTEQ4HJ

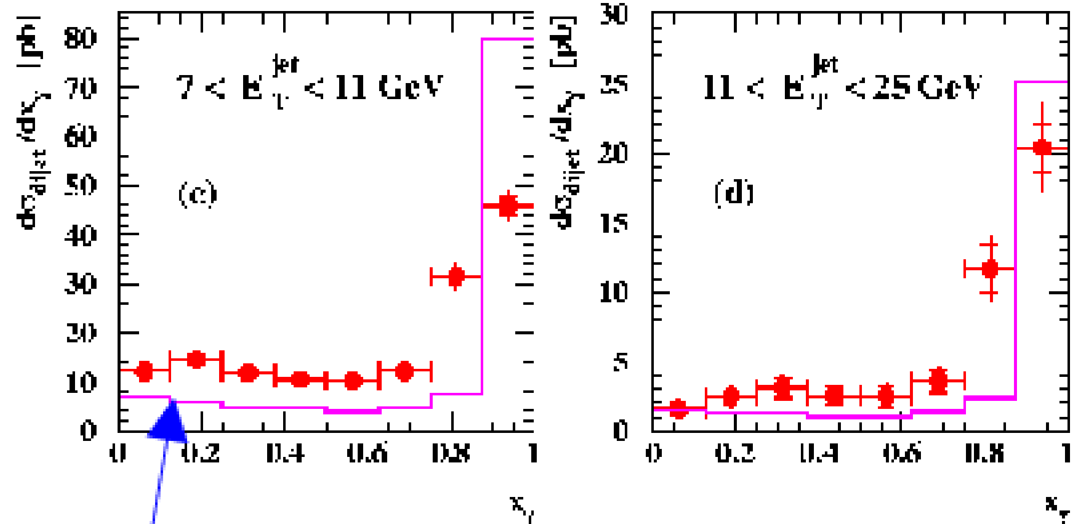
Note: there is a CDF dijet differ. cross–section analysis that finds no current PDF give a good fit hep/ex–0012013

QCD, initial hadrons:



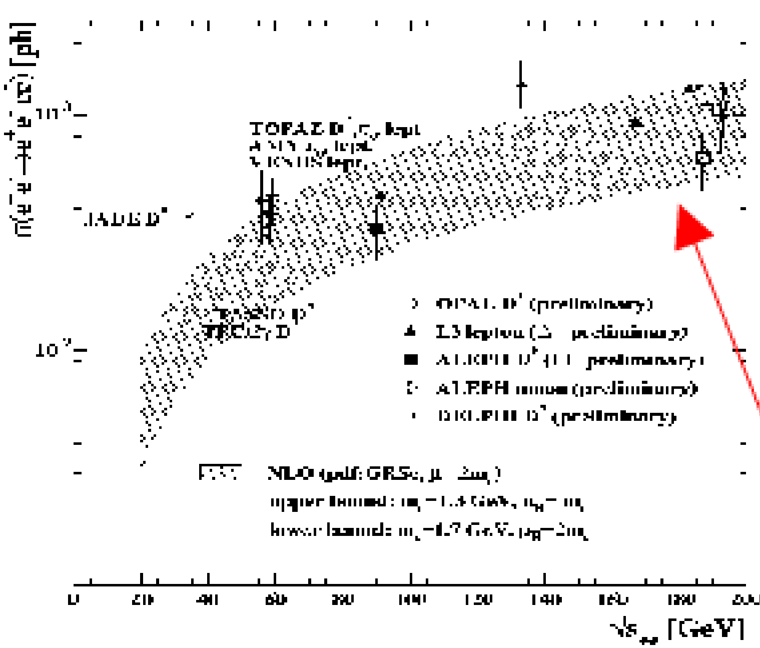
Photon structure (pdf)

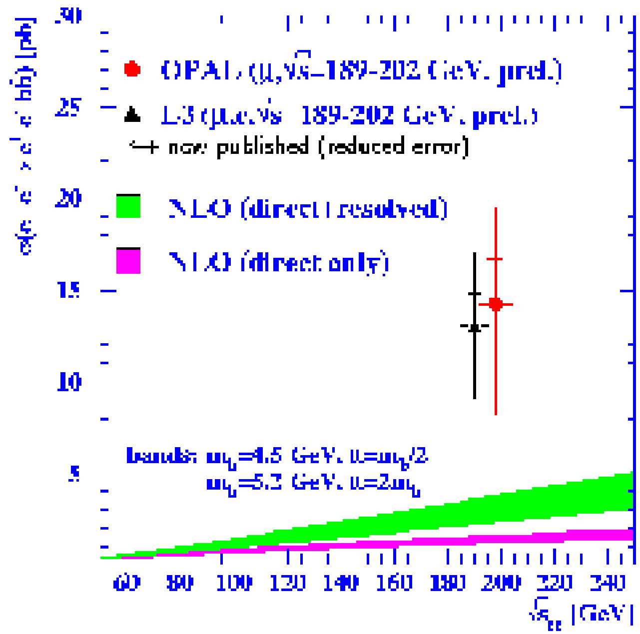
OPAL preliminary



NLO (no hadr.)

Deficit of resolved?





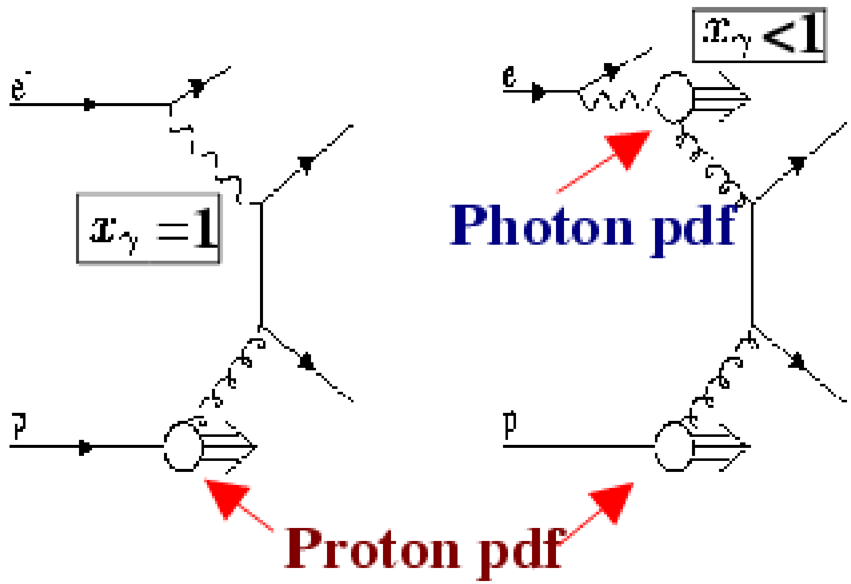
Beauty not described!

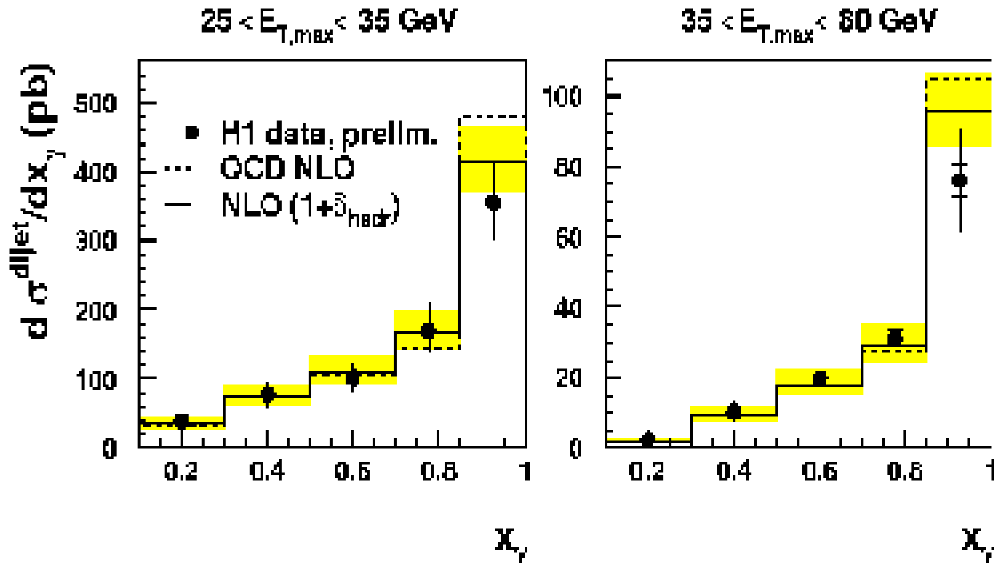
charm production described

EPS HEP 2001

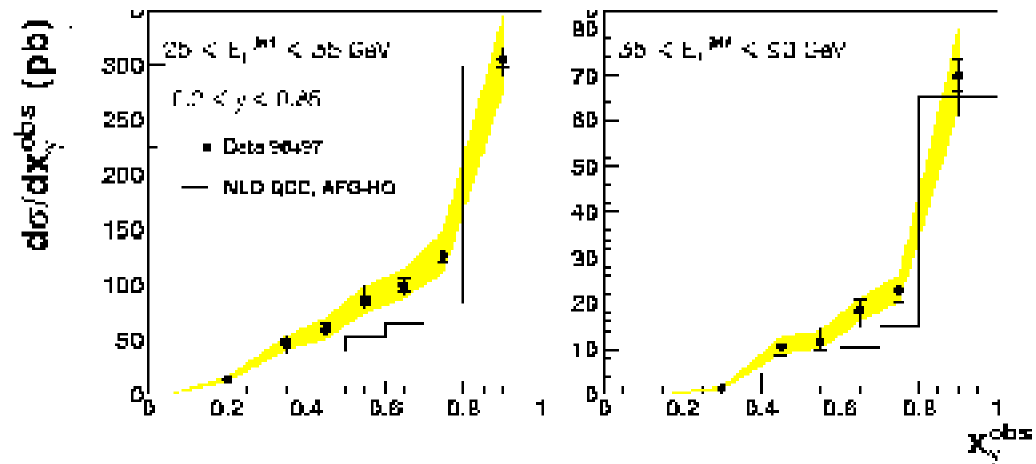
QCD, initial hadrons:

Photoproduction dijets at HERA





ZEUS preliminary



Proton pdf is relatively well–known.

Test photon pdf at $x_\gamma < 1$.

Awaiting detailed comparison **H1** and ZEUS..

Summary: QCD with hadrons in the initial state

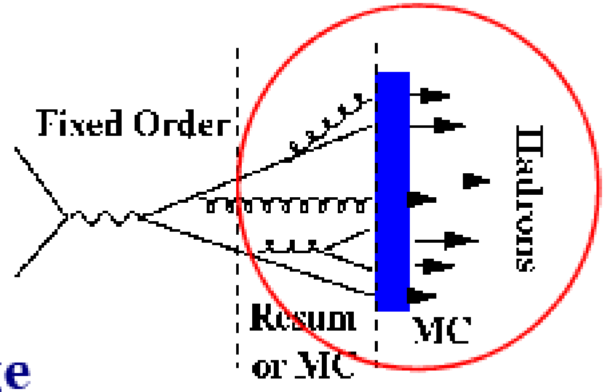
Jet measurements at HERA achieving ~4% uncertainty on α_s. Uncertainties are dominated by theory.

Tevatron jets consistent with current PDF's? Some apparent contradictions. Ununderstood effects?

Are NLO and photon pdf's describing the data? OPAL, ZEUS says no, H1 yes.

Beauty cross sections are (still) too high. (only partially shown here)
Discussion from Frixione (maybe frag not understood?)

Fragmentation:



Look more closely here

D0 quark/gluon jet study

–higher gluon color charge

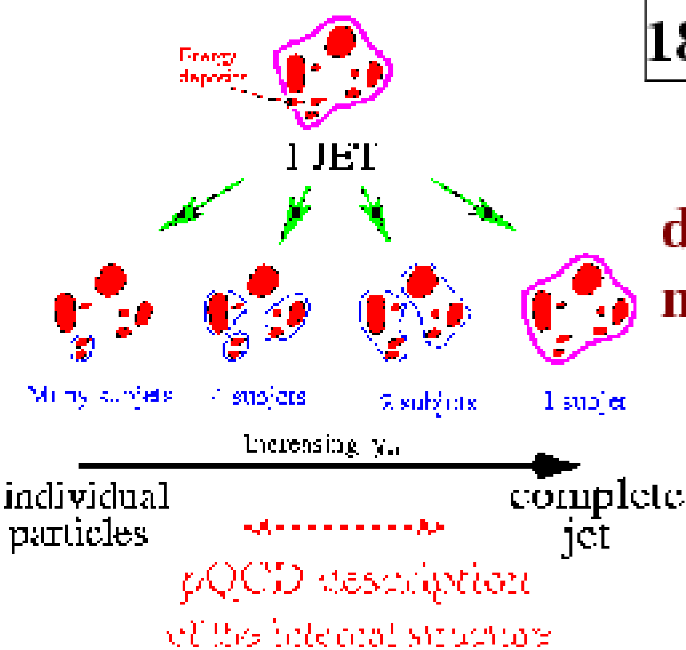
→ more subjets than quarks

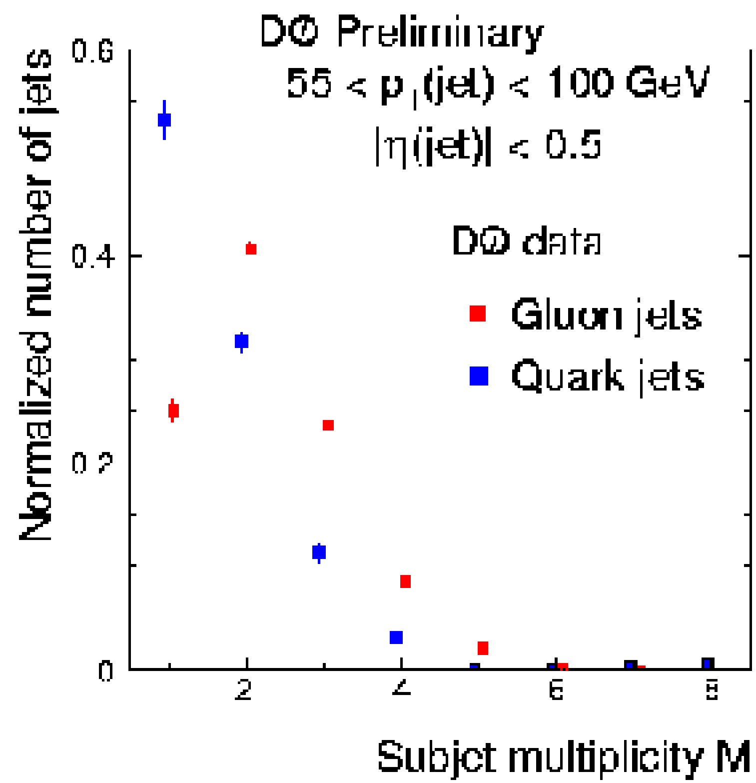
Modelled in parton showers

Herwig based extraction of q/g subjet distributions

630 and
1800 GeV runs

different q/g
mixture

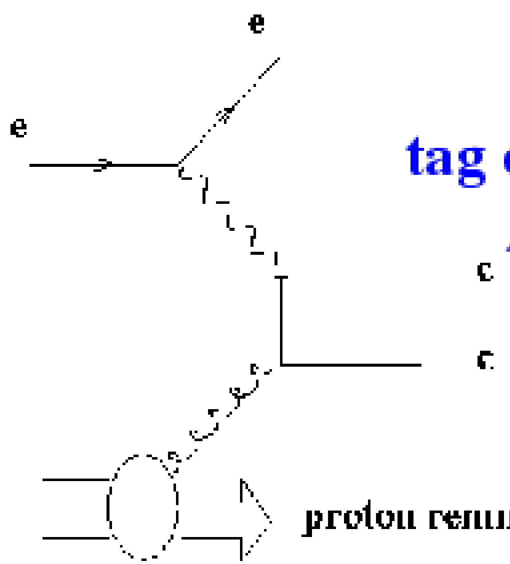




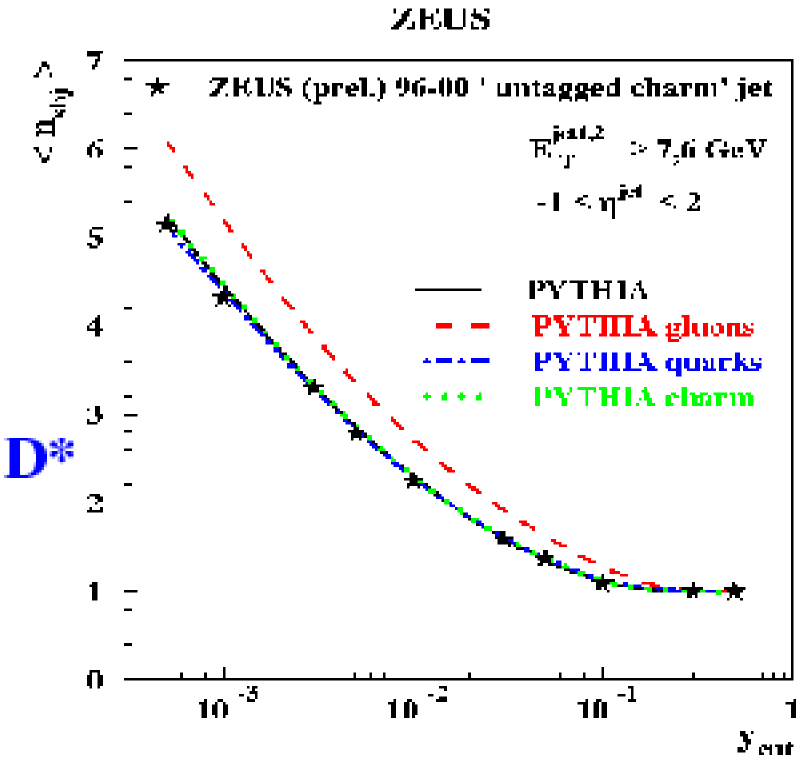
$y_{cut} = 0.001$

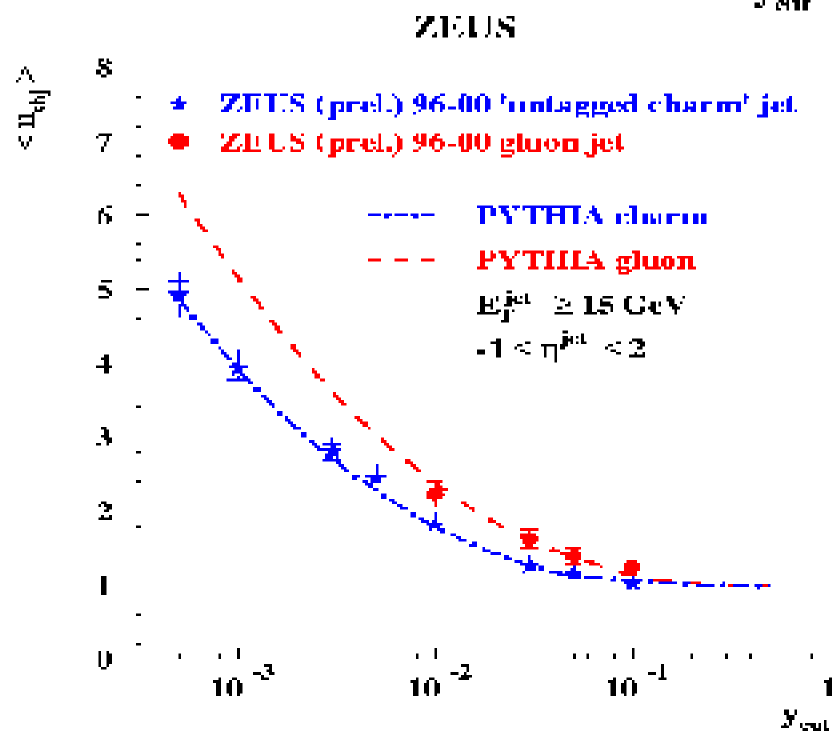
Fragmentation:

HERA quark/gluon shape



tag charm with D*





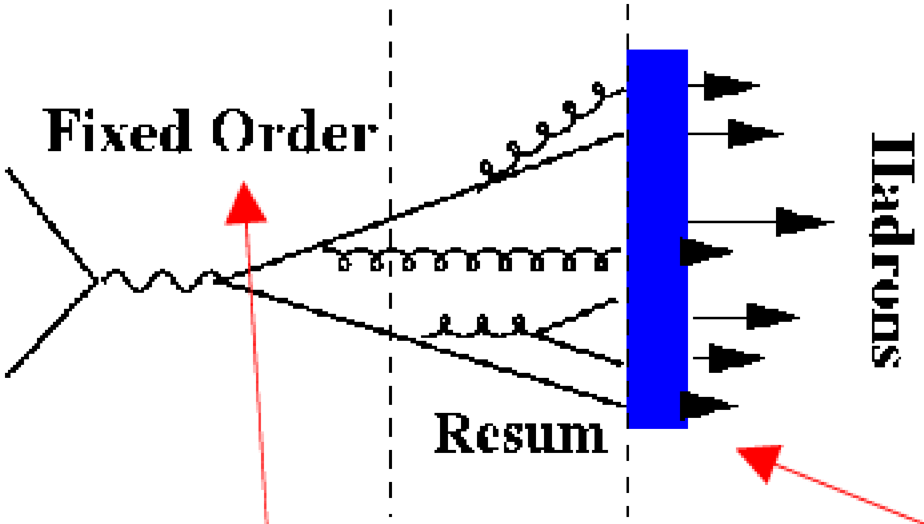
Study the "other jet" and compare to quark jets in MC.

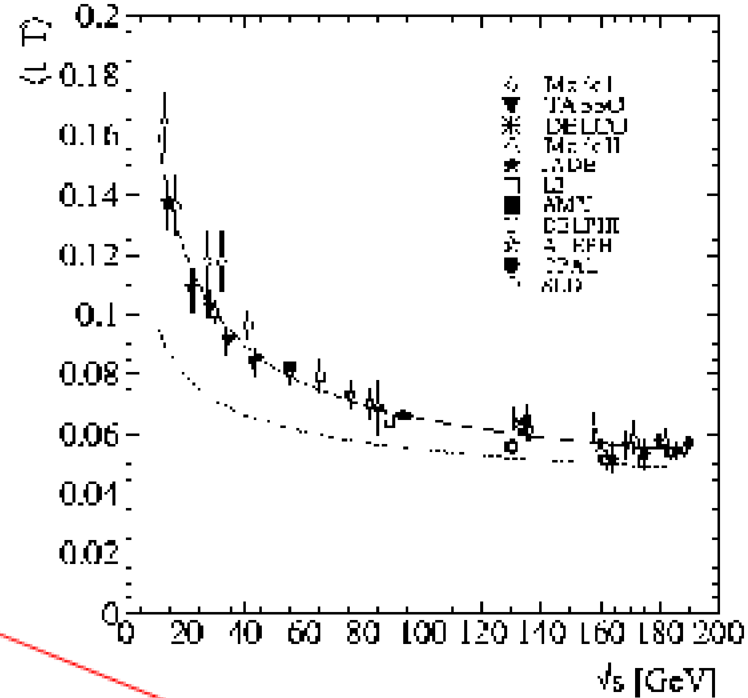
Pythia gives good description

Extract gluon jet shape using MC prediction of q/g ratio

EPS HEP 2001

Power corrections and event shapes:





Divergences HERE are related to non−pert. effects HERE

Get the form of the correction but not magnitude

Renormalons

Structure Functions: $1/Q^2$ corrections

identify with higher twist (OPE)

Event Shapes: 1/Q corrections

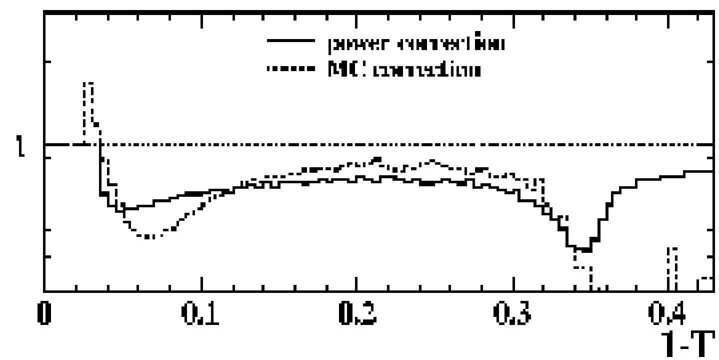
Power corrections:

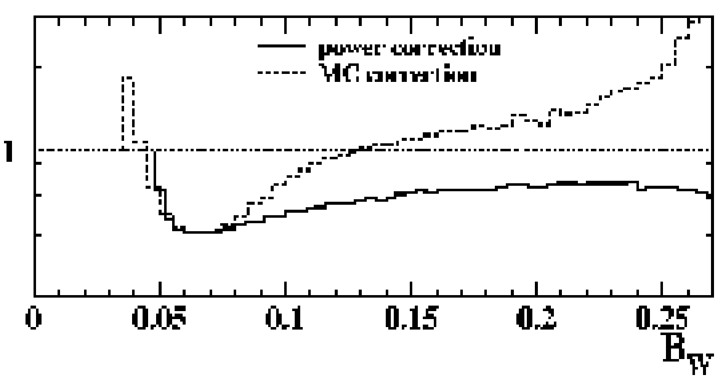
e+e– Event Shape+Power Cor.

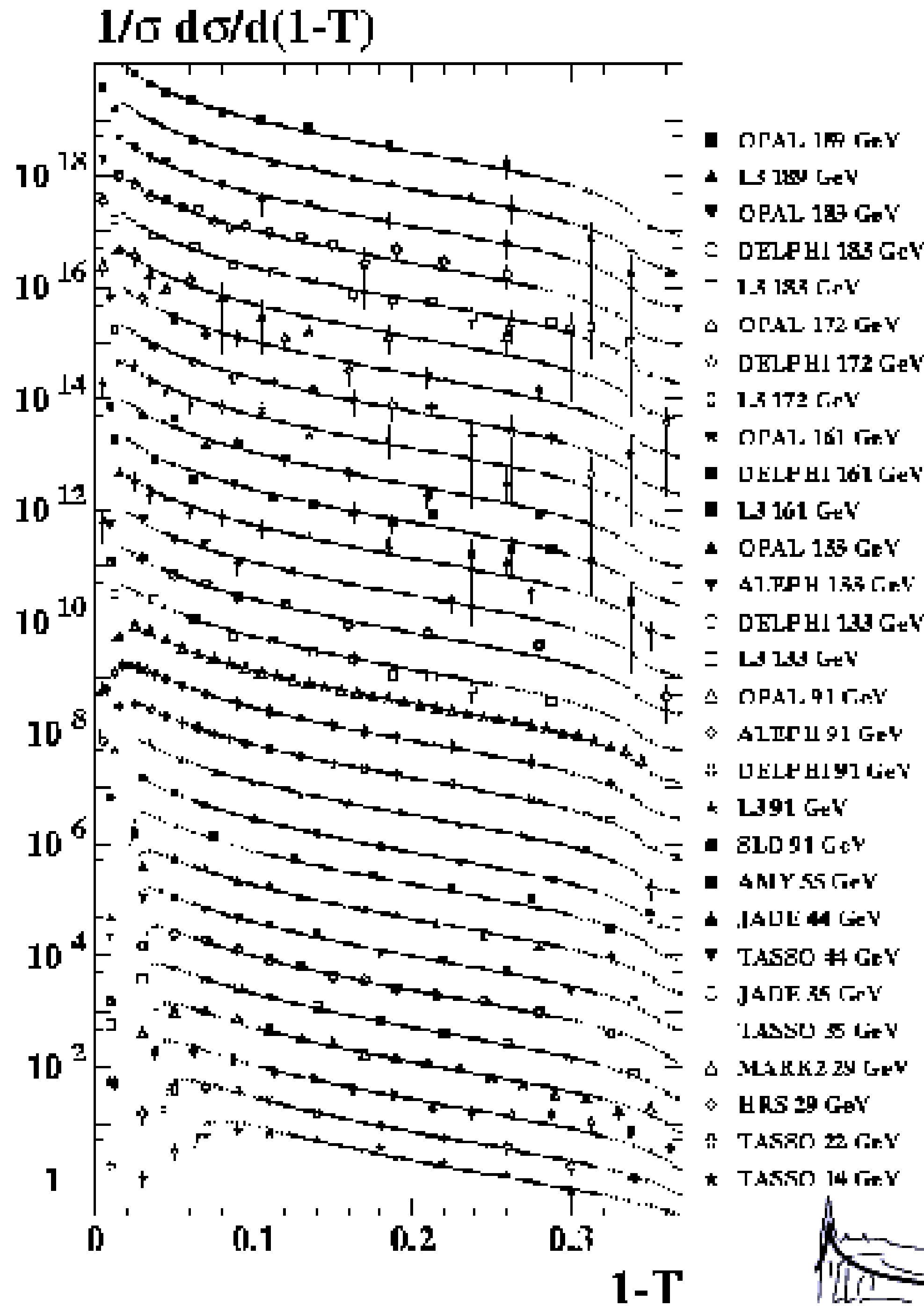
Movilla Fernandez, et al.

14 to 189 GeV data

Corrections at 35 GeV



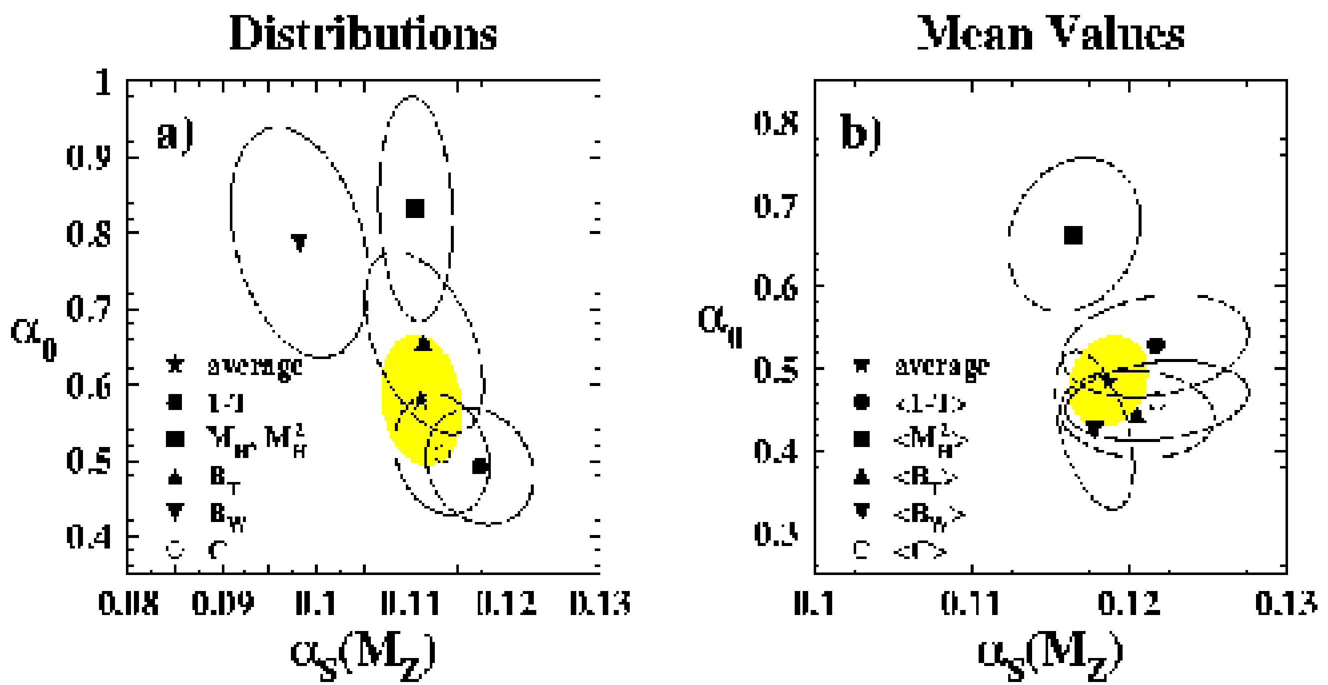




EPS HEP 2001

Power corrections:

Movilla Fernandez et. al.



Dokshitzer–Webber type analysis: Universal effective parameter α_0

Combining means and distribution gives:

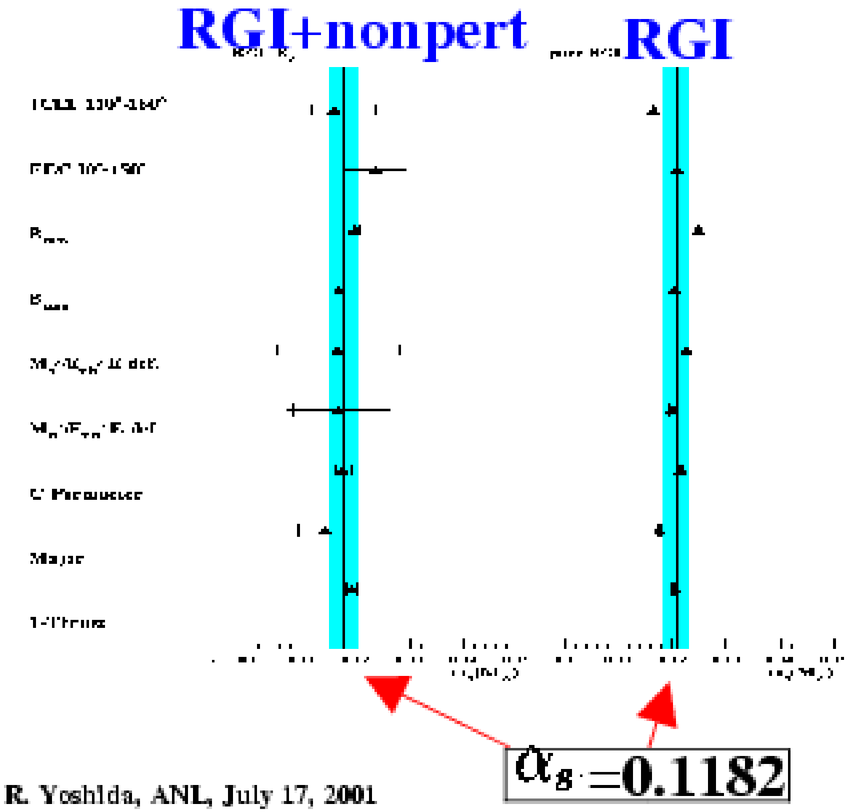
$$\alpha_S(M_{Z^0}) = 0.1171^{+0.0032}_{-0.0020} \quad \text{and} \quad \alpha_0(2\ \text{GeV}) = 0.513^{+0.066}_{-0.045}$$

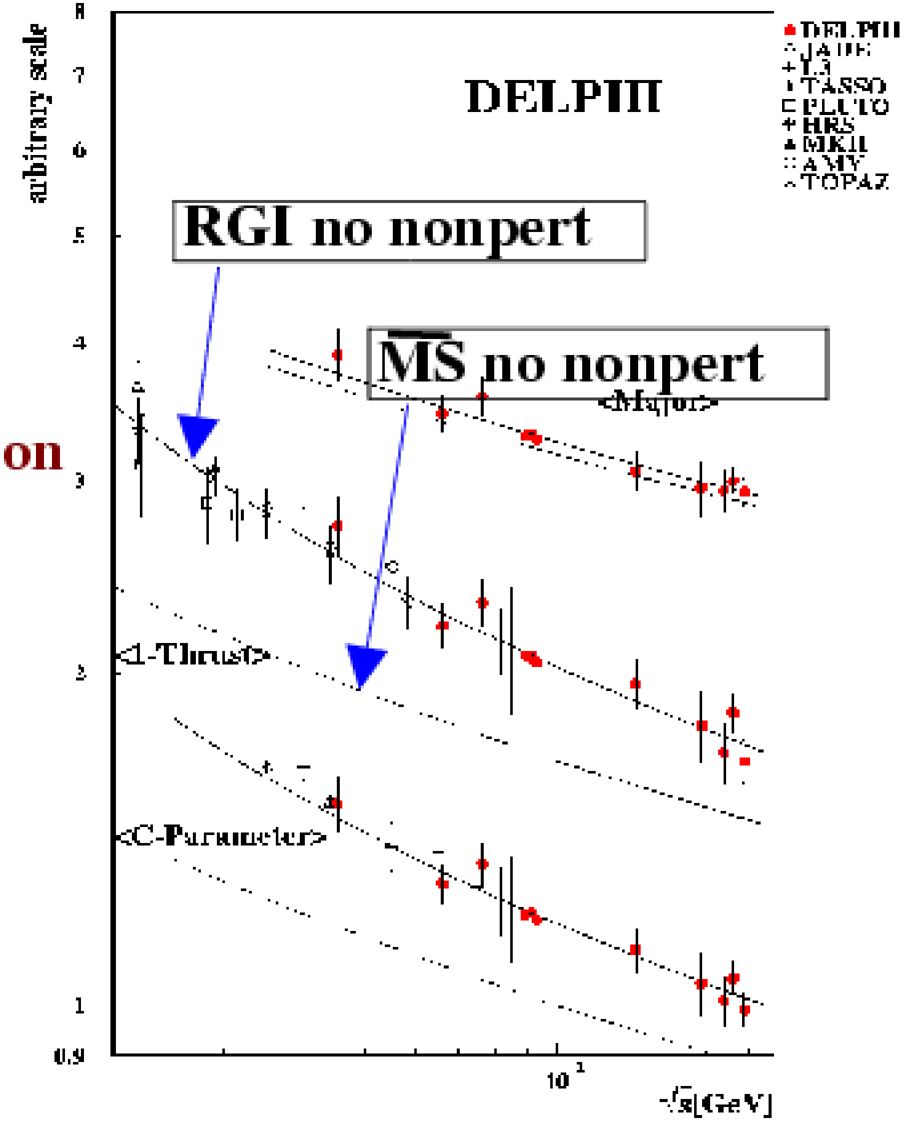
QCD studies type V:

DELPHI:

Renormalization Group Independent (RGI) analysis

Related to PMS, ECH type renormalization scale optimization





Thoretically justified procedure?

Summary Power corrections and event shapes

Many analyses for e+e–, spanning large energy range. Gives consistent answers. Are the D–W type ansatz correct? Uncertainty in α_s at 2.5% is among the smallest

Many more analyses than was shown here. Also using these techniques to measure color factors (Kluth et al)

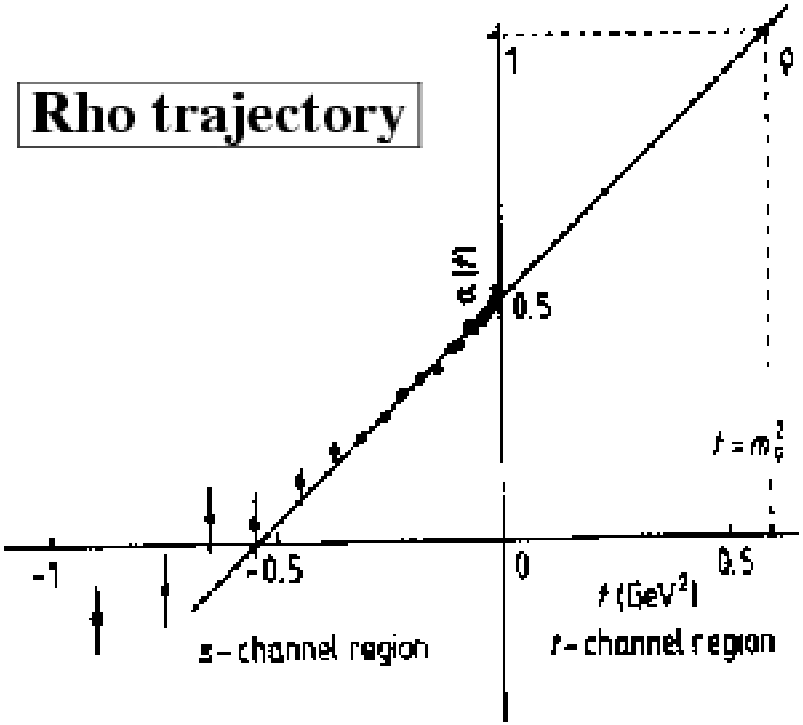
RGI analysis "gets rid" of power corrections.

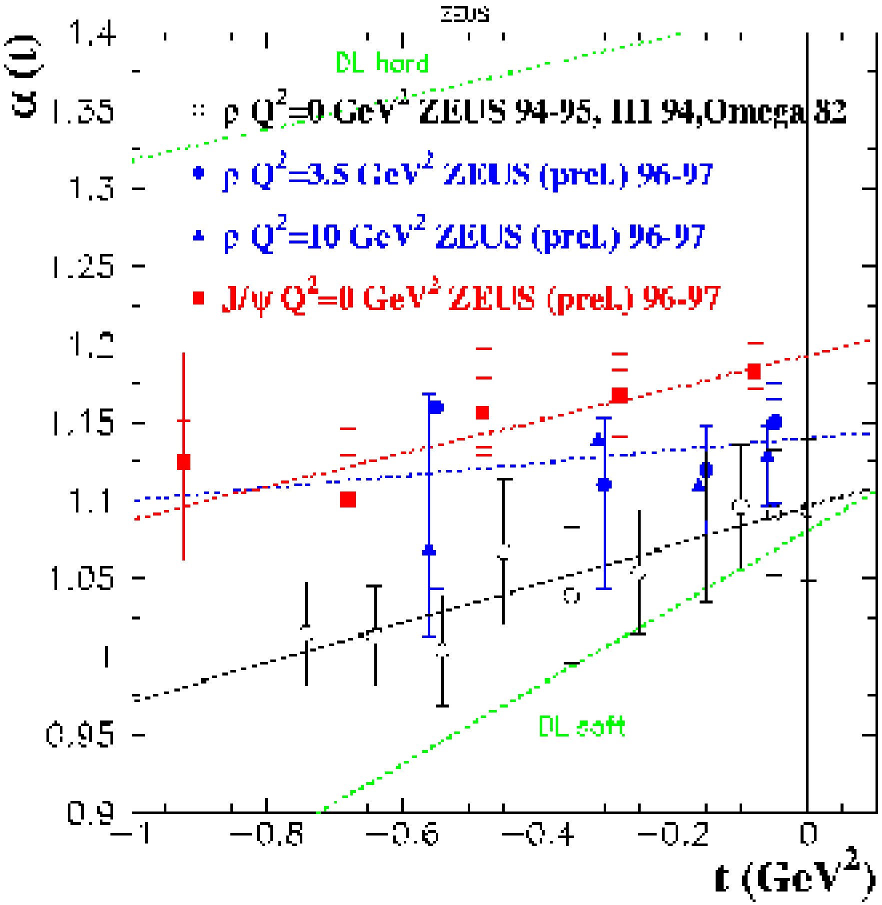
Connection with soft QCD:

Pomeron controls the rise of hadronic cross–sections?

Triumph of Regge theory (50's, 60's)

Pomeron trajectory(ies)?

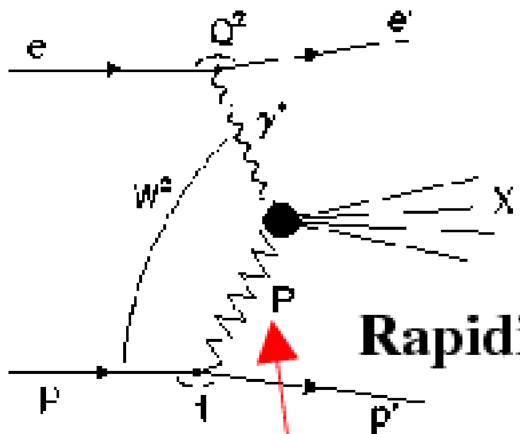




No universal Pomeron trajectory

Connection with soft QCD:

DIS diffraction at HERA



Rapidity gap

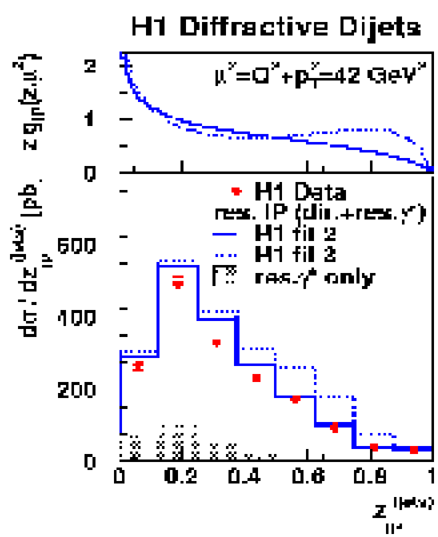
What is this object?

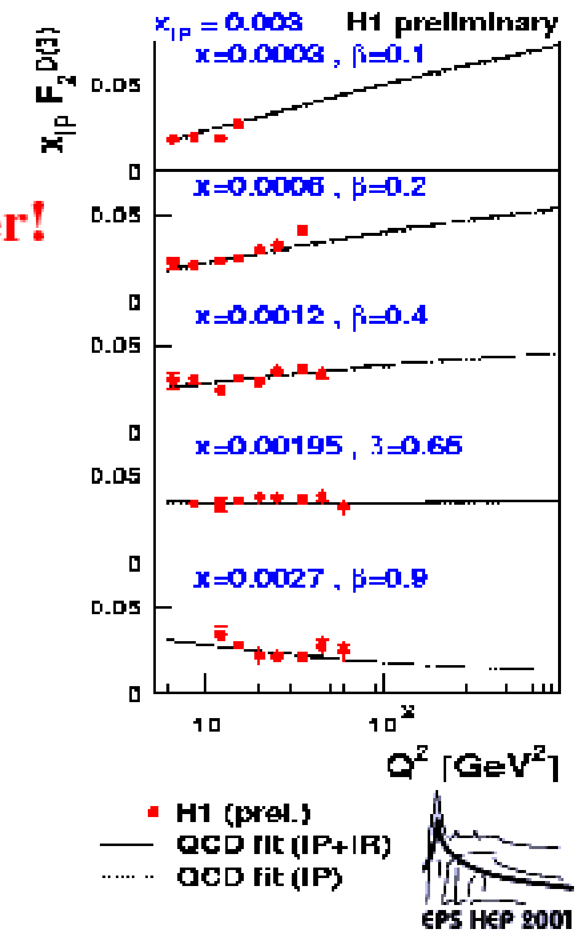
The flux factor must be telling us about gluon correlation in the proton!

⇒ Can do a GLAP analysis of $F_2^{\mathbb{P}}$, the Pomeron structure function.

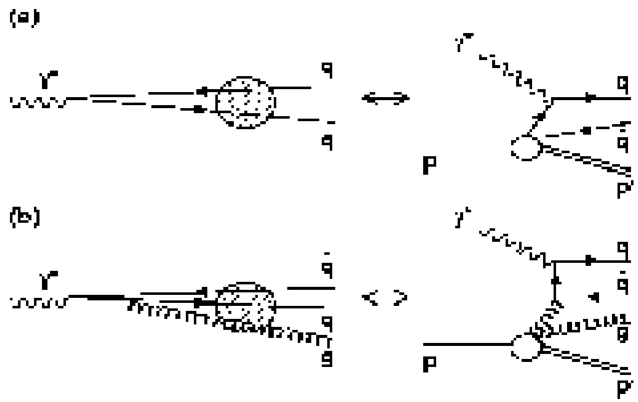
$f(x_{\mathbb{P}}, t) \approx 1/x_{\mathbb{P}}$, the Pomeron flux factor.

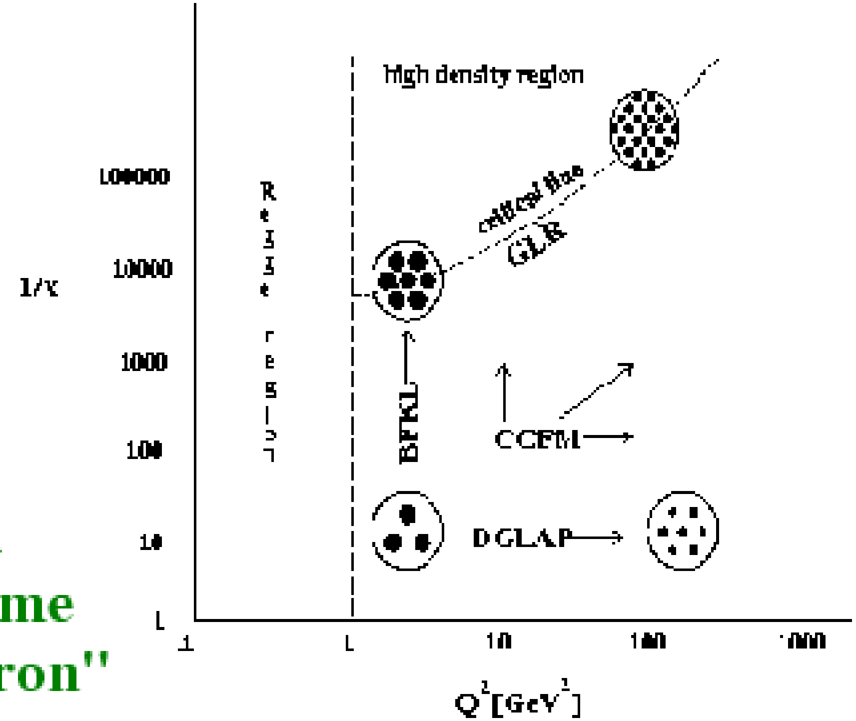
Predictive power!

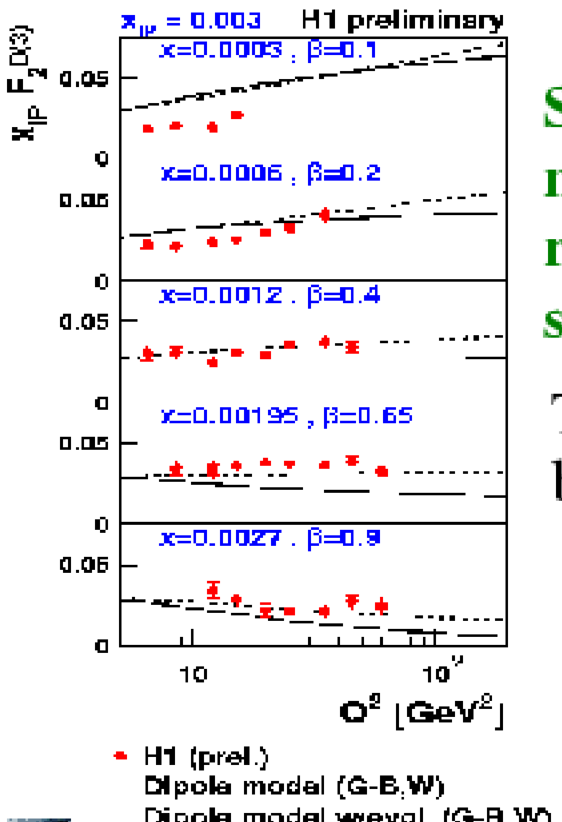




Connection with soft QCD:







Simple geometrical model in dipole frame reproduces "Pomeron" structure qualitatively

The simple model implies dynamics beyond DGLAP

Are we approaching the high density region in HERA?

Where are the signs of BFKL?

Conclusions:

QCD is (still) a vibrant and exciting field.

There are now very many *precision* tests of QCD

–As a benchmark..think of the number of 3–5% measurements of α_s presented here.

Still, QCD is a complex topic. In many analyses, need to look at the "fine print". Not just a matter of who's quoting the smallest errors!

While on the whole, there's an impressively consistent picture, there are many questions in detail.

2 years ago, the reviewer remarked on need for improvements in theory.–––this is beginning to appear now.

Some of the most intriguing results are coming out of studies of soft–hard QCD boundaries. From understanding pQCD to understanding Hadrons!

And finally....

Apologies and Acknowledgements

I have had to leave out very many important results. There were over 200 abstracts/papers. (The subjects of this talk were covered in 3 talks at Tampere).

Thanks to many people for helping me to prepare this talk:
In no particular order: M. Dasgupta, G Iacobucci, J Whitmore, P Schleper, I Bertram, D Elvira, F Chlebana, J Vossebeld, M Wing, S Soldner–Rembold, A Doyle, R Nisius, M Vincter M Arneodo, B Foster and many others..

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