Physics at the Highest Q^2 and P_T^2

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OUTLINE:

- **Introduction: uncertainties**
- **High P_T jets in photoproduction**
- **High P_T jets in DIS**
- **Inclusive high-Q^2 DIS cross sections at HERA**
- **High P_T jets at the Tevatron**
- **Anomalies at HERA and the Tevatron**
- **Conclusion**

I. Introduction

We want to be at highest Q^2 and P_T^2 where we can:

- Look for new Physics,
- Do precision tests of QCD and EW; determine parameters

undisturbed by unpleasant non-perturbative phenomena.

..in principle, undisturbed by...

I attempt here to assess where we are in each of the "Highest Q^2 and P_T^2" topic I have picked, and where we might go next in our investigations

First we have to know our uncertainties...

Uncertainties

We need to consider:

• Experimental uncertainties: statistical and systematic uncertainties of the measurement.

and

• "Theoretical" uncertainties:
So what does our understanding of the SM look like (schematically)?:

Factorization:

$$\sigma = f_1 \otimes f_2 \otimes \hat{\sigma}$$

where: f_1 and f_2 are pdf's of the two colliding particles (can be something simple, like a virtual photon).

$\hat{\sigma}$ = hard SM cross section

which contains QCD to NLO, typically (and EW).

The pdf's obey DGLAP equations:

$$\frac{df}{d\mu_f} = f \otimes P$$

Where μ_f is the factorization scale and P is the splitting function

pQCD uncertainties (i.e. factorization scale and renormalization scale uncertainties) enter in $\hat{\sigma}$ explicitely, and in f implicitely, through the DGLAP fit to σ_{data}.

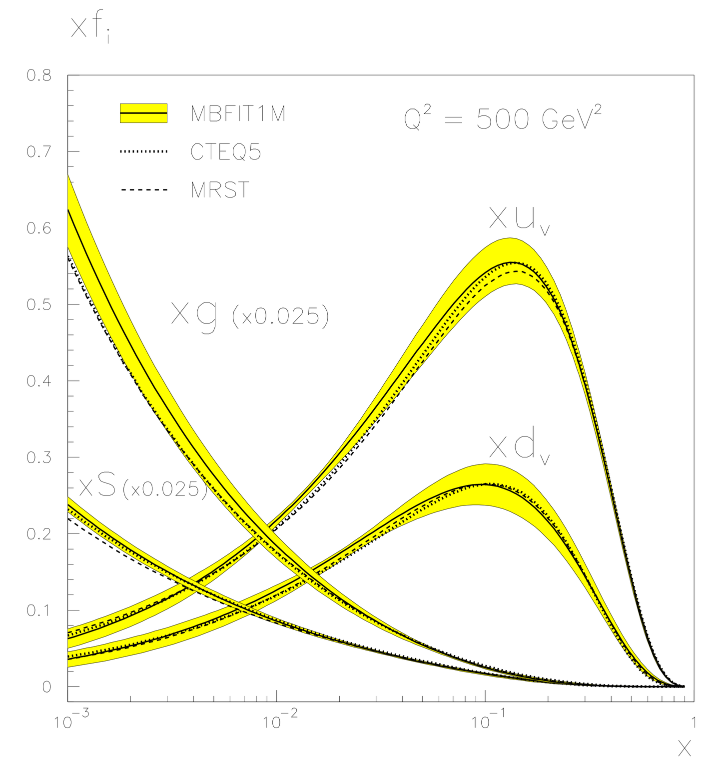
non-pQCD uncertainties, as well as measurement uncertainties of σ_{data} enter in f through the DGLAP fit

- Nuclear corrections
- Intrinsic Kt
- Higher twist
- Target mass
- etc. etc.

These uncertainties end up in the prediction of σ and may propagate up to our "Highest Q^2 and P_T^2"!

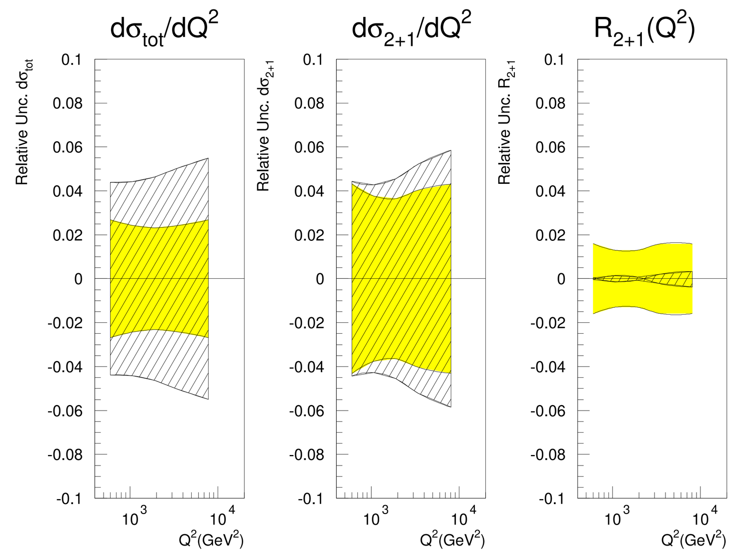
Uncertainties of the (proton) pdf

Recently M. Botje released a first (as far as I know) set of pdf's containing a full covariance matrix.



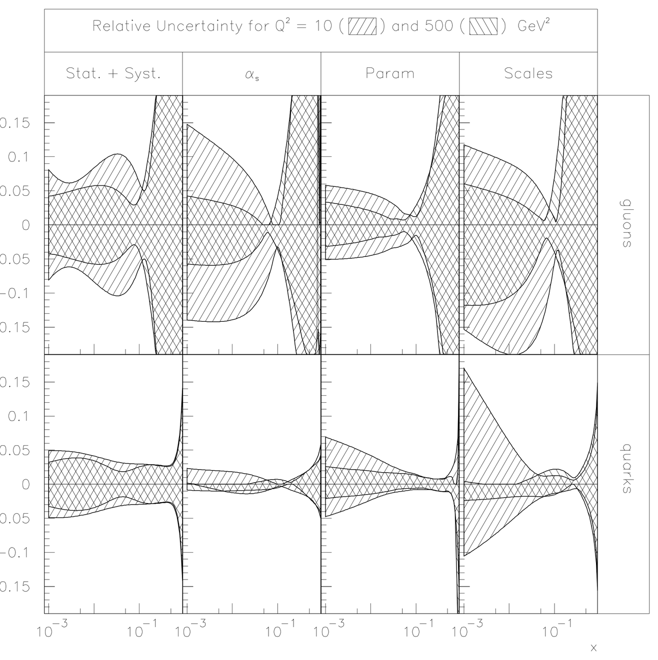
Not only error bands but correlations!

Relative errors due to the proton pdf in σ predictions for inclusive DIS, DIS dijets, and the ratio.



Errors are unreliable if correlations are not taken into account!

Tools to look at error components are provided



- Stat. + Syst.: Experimental uncertainties
- α_s: Varied by $\pm$0.005
- Param: Different choices in fitting. e.g. Bodek-Yang form for valence d.
- Scale: changes of renorm. and factor. scales.

PDF's cont..

MB fits: First serious attempt to quantify the errors in the proton pdf.

One may argue about particular choices in his fits, but we need this kind of pdf's more and more!

- Some final points
  - Photon pdf's are very badly constrained so far.
  - There are two basic strategies in QCD comparisons:

$$\sigma = f_1 \otimes f_2 \otimes \hat{\sigma}$$

    - Measure σ_{data} and compare with σ derived with f derived from other processes or data sets.
    - Use the measured σ_{data} to extract parameters such as α_s and f. Check for consistencies with other processes or data sets.

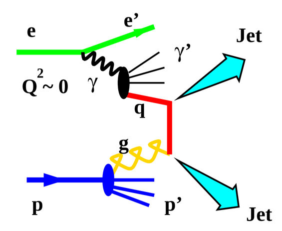
What is appropriate depends on what is uncertain by how much.

Now let's consider the following subjects...

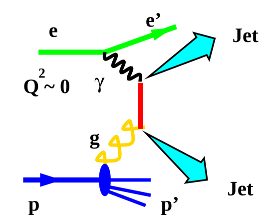
- High P_T jets in photoproduction
- High P_T jets in DIS
- Inclusive high-Q^2 DIS cross sections at HERA
- High P_T jets at the Tevatron
- Anomalies at HERA and the Tevatron

II. High P$_T$ jets in Photoproduction

To LO:



RESOLVED



DIRECT

$$\sigma = f_\gamma \otimes f_{proton} \otimes \hat{\sigma}$$

f_γ: Not well-known.

f_{proton}: Reasonably well-known.

$\hat{\sigma}$: QCD dijet cross section at NLO. Is it a good description?

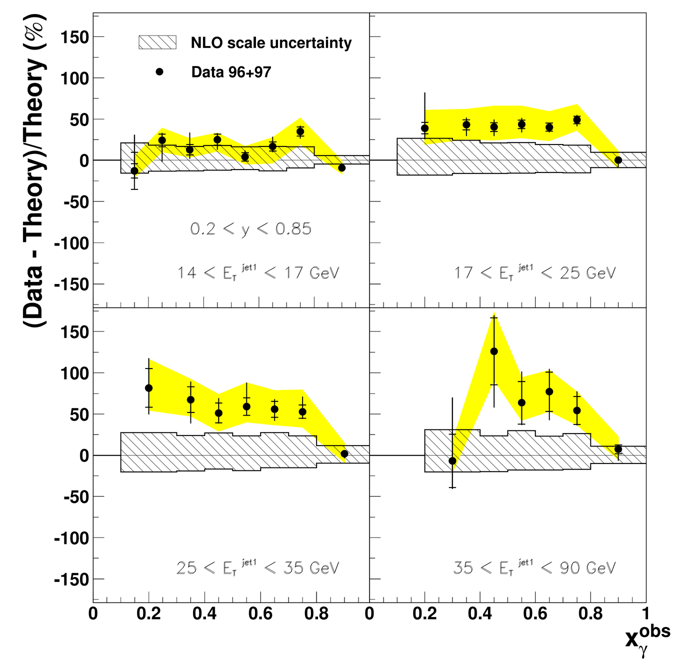
How do we disentangle $\hat{\sigma}$ from f_γ?

Several ways to isolate $\hat{\sigma}$:

- x_γ, the fraction of the photon momentum in the hard interaction is close to an observable x_γ^{obs}.
- The dijet angular distributions should follow the QCD NLO expectation

Photoproduction Dijet Cross-section in x_γ^{obs}

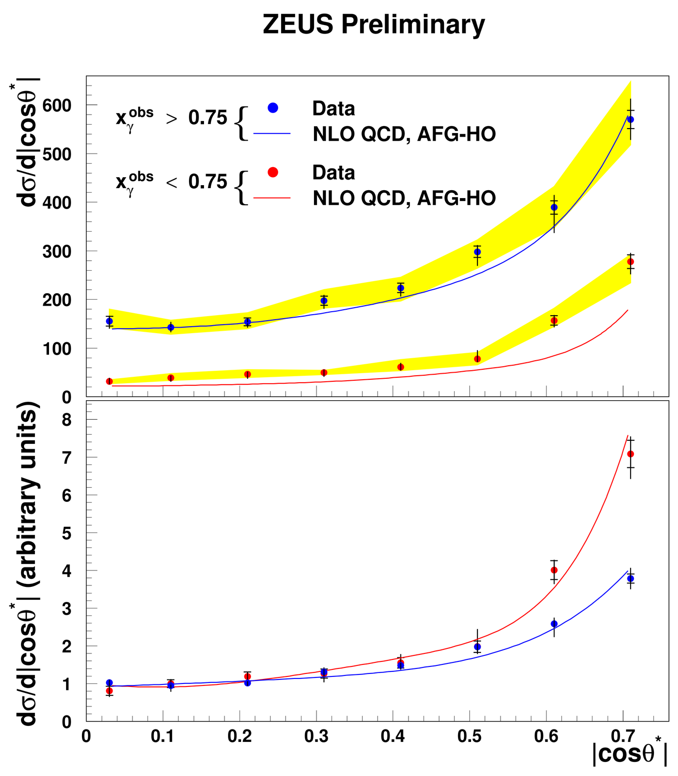
ZEUS Preliminary



⇒ Measurement errors now smaller than scale uncertainties.

⇒ Agreement at high x_γ^{obs}.

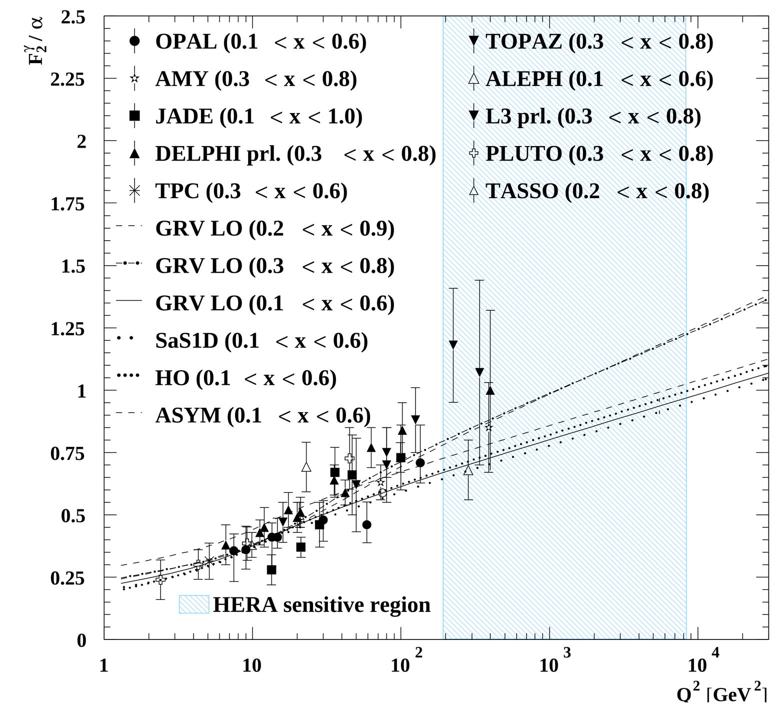
Photoproduction Dijet Angular Distributions



⇒ Shape well described by NLOQCD

⇒ Agreement in magnitude at high x_γ^{obs}.

Photon structure functions are unconstrained in the HERA region



Jets in photoproduction, cont..

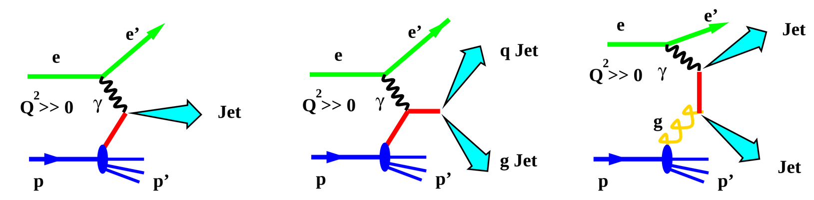
- There is a disagreement between σ predicted and measured which is bigger than the uncertainties of the measurement and the uncertainties of $\hat{\sigma}$

- The QCD NLO description seems adequate in regions where we expect the photon pdf to play a diminished role.

- The next logical step is to try to fit for the the NLO photon pdf and check for global consistency.

- The outcome of this process will determine the next steps in this area.
- Leading Order studies with its large accompanying scale uncertainties are of limited use.

III. Jets in DIS



LO QCD-COMPTON BGF

$\sigma = f_{proton} \otimes \hat{\sigma}$ (one f is a virtual photon)

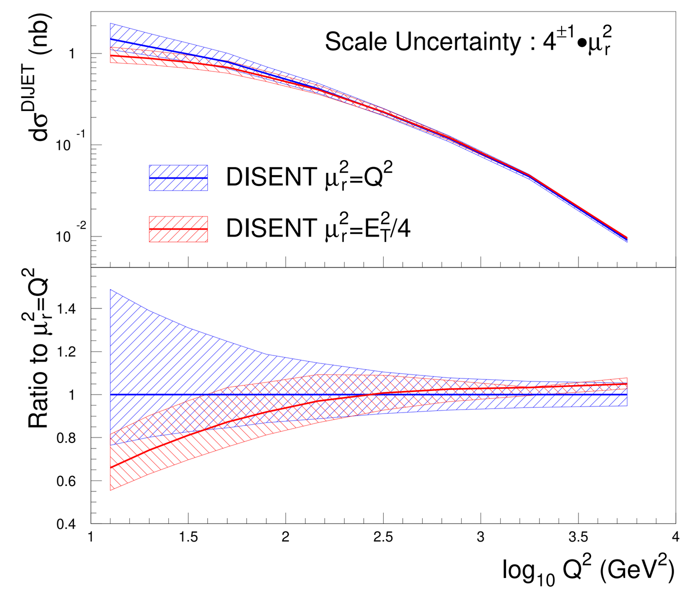
- At high Q^2 where QCDC dominates, we hope to measure α_s.

- At low Q^2 where BGF dominates, we hope to measure the gluon in the proton.

How well do we understand $\hat{\sigma}$ here?

Dijet production in DIS has two possible scales: Q and $E_T/2$

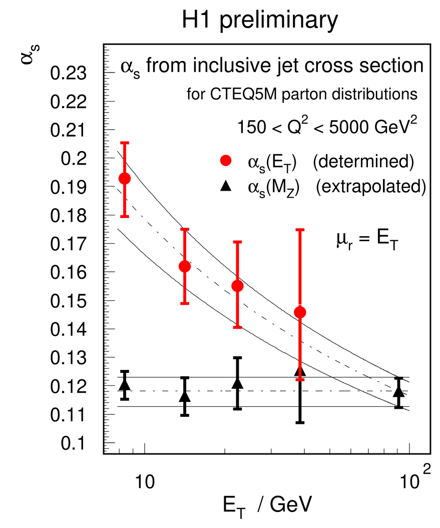
DIS dijet cross-section as calculated by the program DISENT. ($E_{T1} > 5$ GeV, $E_{T2} > 8$ GeV)

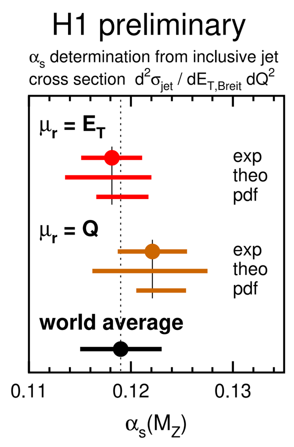


At the highest Q^2, the scale differences seem to disappear. The uncertainties also shrink to a manageable size.

1 1.5 2 2.5 3 3.5 4

H1 extraction of α_s from inclusive jet cross section



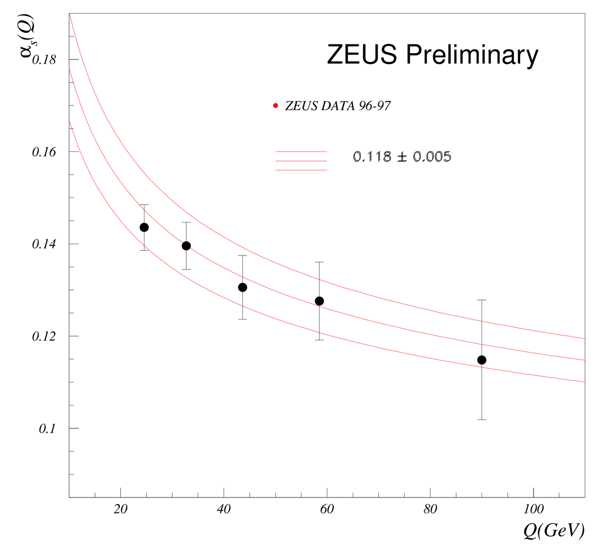


Preliminary:

E_T: $\alpha_s(M_Z)$ = 0.118$\pm$0.003(exp)$^{+0.004}_{-0.005}$(th)$^{+0.004}_{-0.002}$(pdf)

Q^2: $\alpha_s(M_Z)$ = 0.122$\pm$0.003(exp)$^{+0.005}_{-0.006}$(th)$^{+0.003}_{-0.002}$(pdf)

ZEUS extraction of α_s from dijet rates

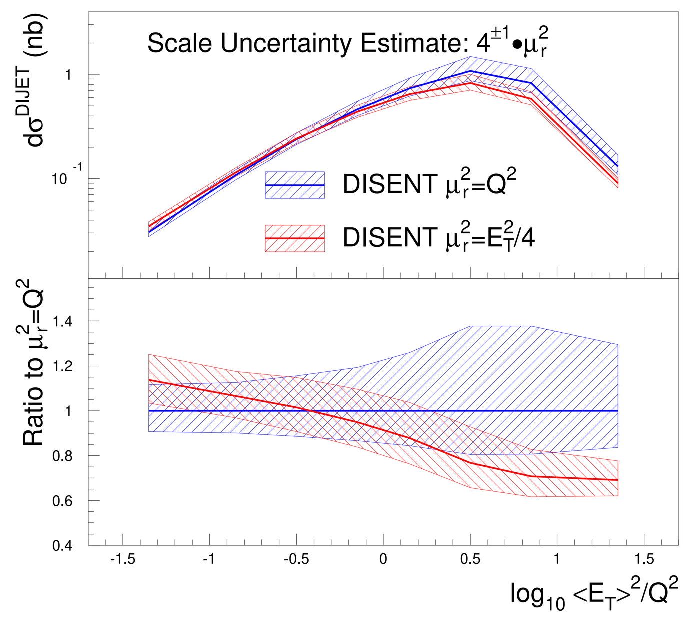


Preliminary:

$\alpha_s(M_Z)$=0.1166$\pm^{+0.0047}_{-0.0040}$(exp)$^{+0.0050}_{-0.0042}$(th)$^{+0.0012}_{-0.0011}$(pdf)

- PDF errors are calculated using the full error correlations.
- α_s is treated consistently in both $\hat{\sigma}$ and f. $\Rightarrow$ No “input dependence” on α_s.

Low Q2 jets:



$$\sigma = f_{proton} \otimes \hat{\sigma}$$

Q^2 scale is “preferred” (i.e. gives better agreement with data) than E$_T$/2 even in the region of E$_T$ $>$ Q^2.

Given the huge scale uncertainties, premature to try to extract f_{proton}, or use in a global fit. Needs better theoretical understanding.

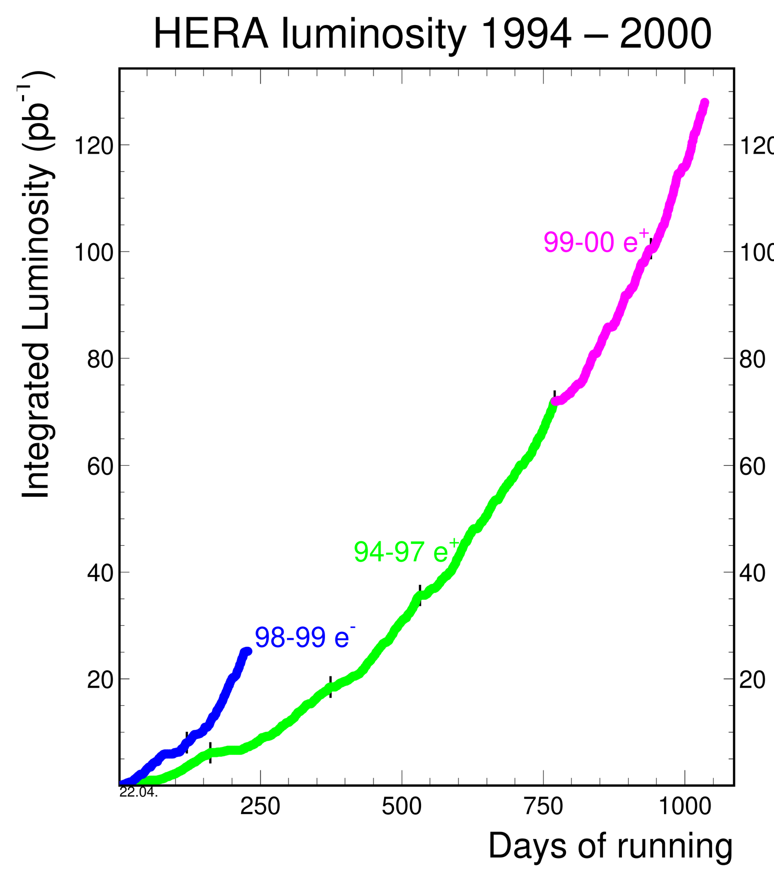
-1.5 -1 -0.5 0 0.5 1 1.5

Jets in DIS cont.

- At high Q^2:
  - Uncertainties from PDF's are small. (Reliable estimates of uncertainties are important!)
  - Uncertainties of $\hat{\sigma}$ seem to be under control.
  - They are, however, the largest uncertainty at ca. 5 %!

- At low Q^2:
  - Uncertainties of $\hat{\sigma}$ do not seem to be under control.
  - They must understood before we can meaningfully extract f (in this case the gluon distribution.

IV. High-Q^2 DIS Cross Sections



In a sloppy but (I hope) obvious notation...

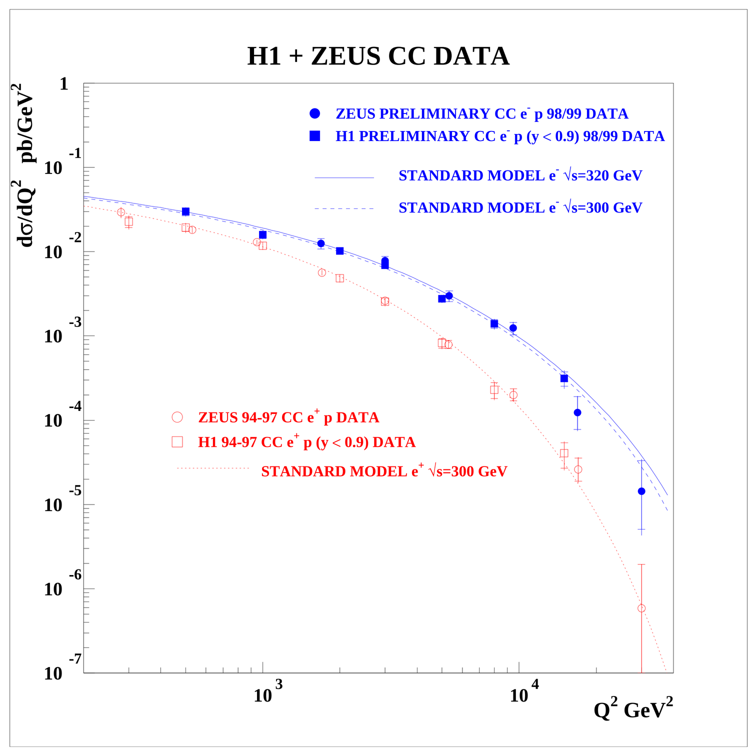
$$\sigma^+_{cc} \sim G_F^2(\frac{M_W^2}{M_W^2+Q^2})^2[(1-y)^2(d+s)+(\bar{u}+\bar{c})]$$

$$\sigma^-_{cc} \sim G_F^2(\frac{M_W^2}{M_W^2+Q^2})^2[(1-y)^2(\bar{d}+\bar{s})+(u+c)]$$

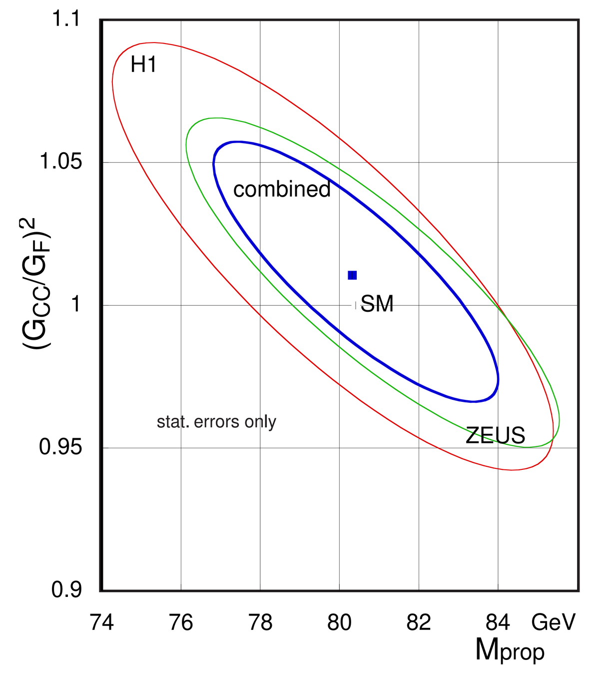
$$\sigma^\pm_{nc} \sim \frac{\alpha^2}{Q^4}[Y_+\sum e_q^2(q+\bar{q}) \mp Y_-\sum B(Q^2)(q-\bar{q})]$$

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

Richness of information in this data!



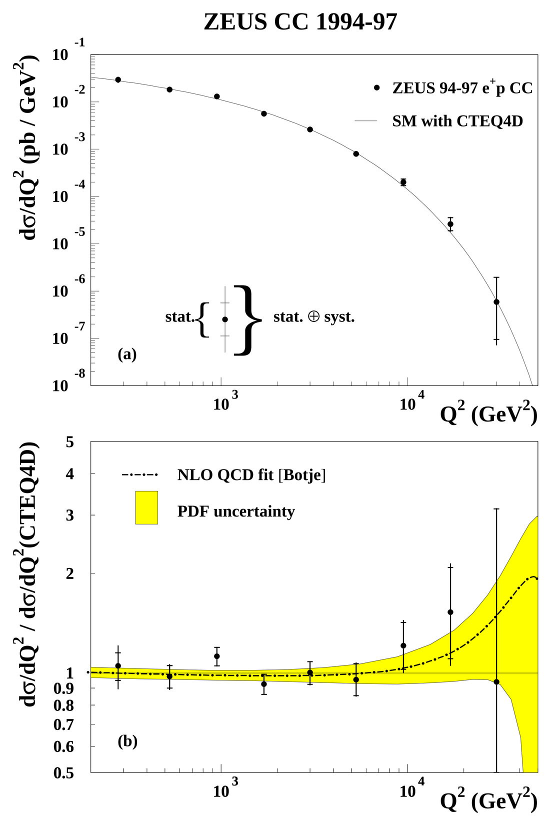
If you know the PDF's then you can extract M_{prop} (= M_W ?) and G_F from the shape.



Fix G_F to the PDG value:

H1: M_W=80.9±3.3(stat)±1.7(sys)±3.7(pdf) GeV

ZEUS: M_W=$81.4^{+2.7}_{-2.6}$(stat)±2.0(sys)$^{+3.3}_{-3.0}$(pdf) GeV

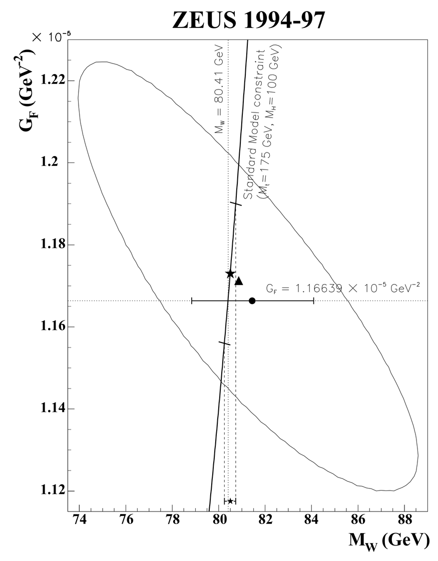


Normalization of the CC cross section is fixed by PDF's and G_F.

The Standard Model tells us that:

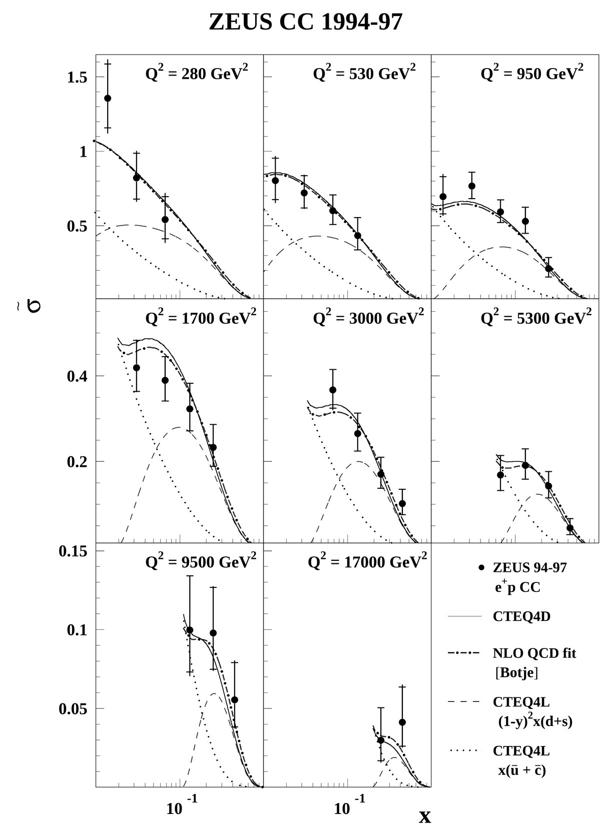
$$G_F \sim M_W^{-2} \Rightarrow \sigma_{cc} \sim M_W^{-4} f$$

Combining the normalization with shape gives a strong constraint:



With the SM constraint ZEUS obtains:
M_W=80.50$^{+0.24}_{-0.25}$(st)$^{+0.13}_{-0.16}$(sy)$\pm$0.31(pdf)$^{+0.03}_{-0.06}$(tHZ) GeV
(More a test of QCD!)

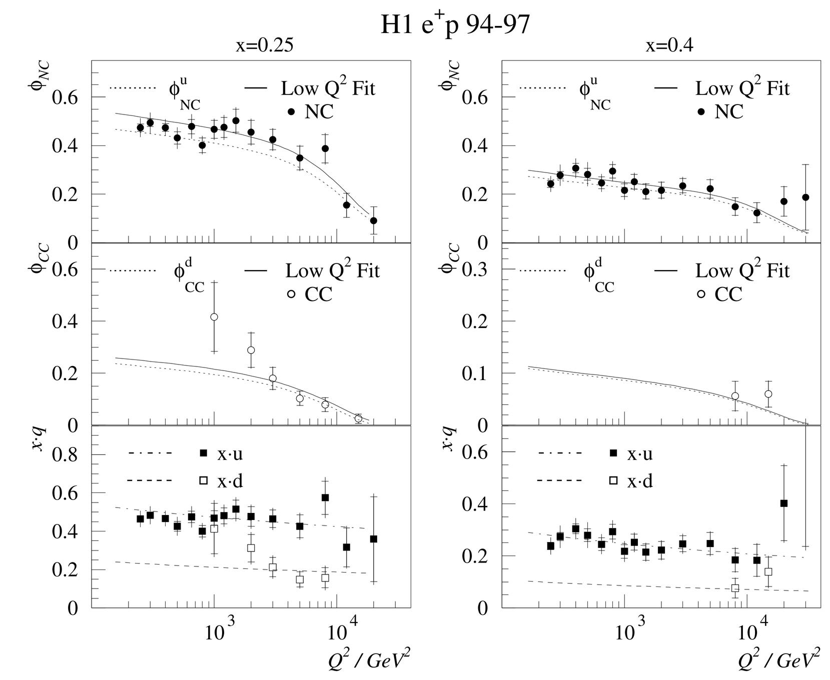
Now think about testing PDF's:



σ^+_{cc} is mostly d at high x.

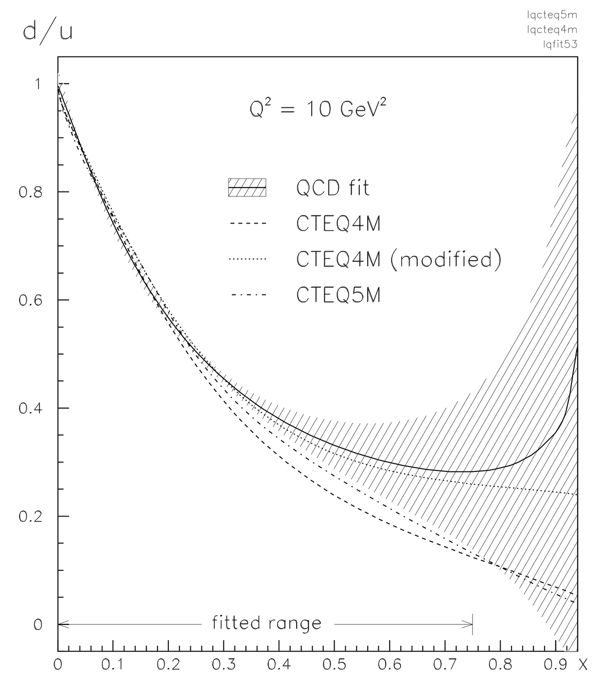
σ^{+}_{nc} is mostly u at high x.

So can get u and d with minimum corrections from the QCD fits.



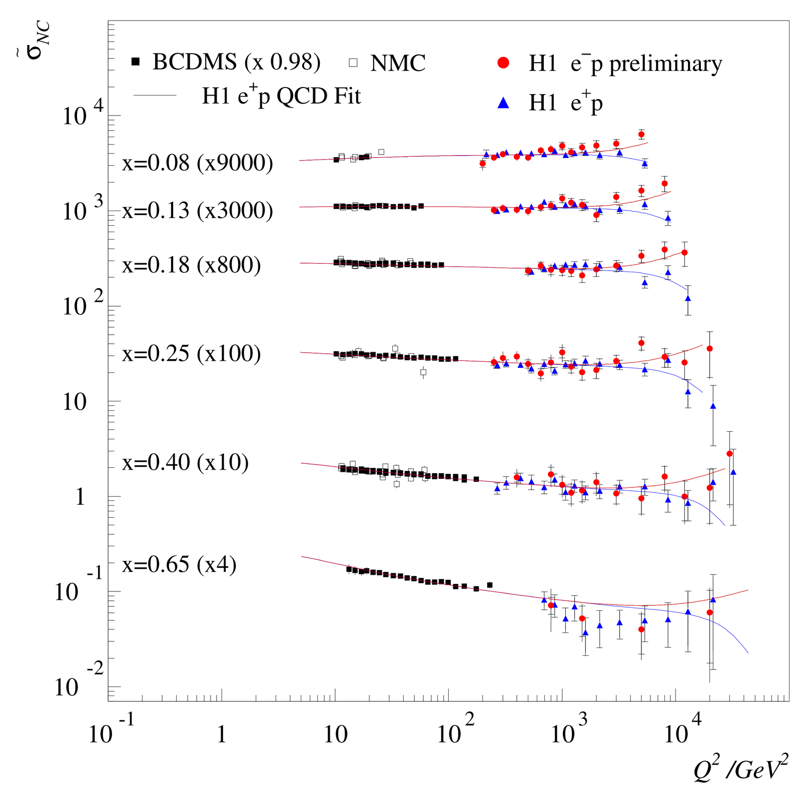
Recall d/u at large x is basically unconstrained.

d to u ratio from MBFIT



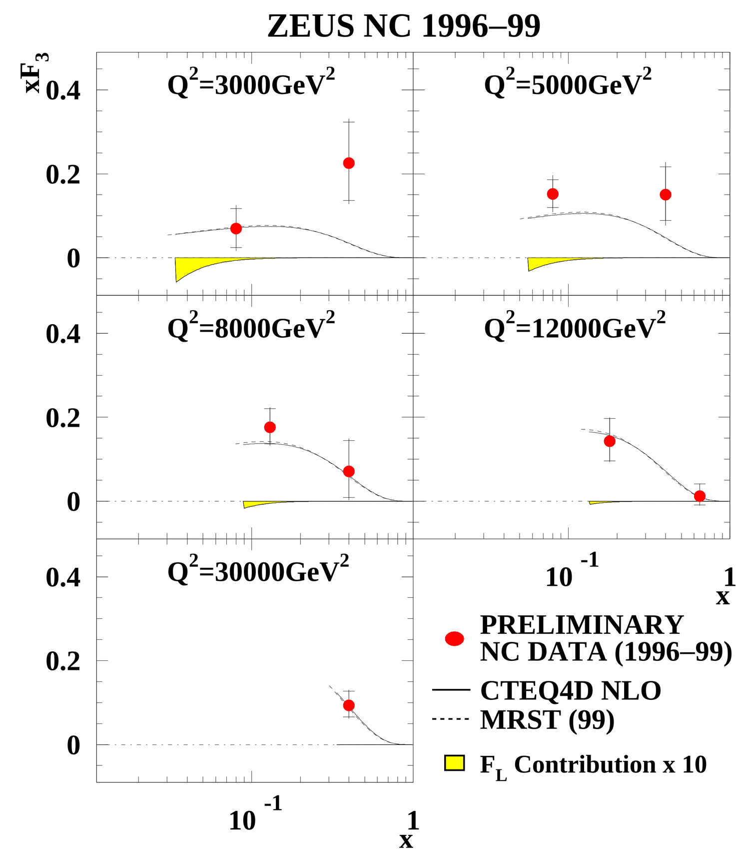
HERA might be in a position to say something about nuclear corrections to SLAC deuteron data!

NC cross-section e+p and e-p



The difference is xF_3.

0.4
0.2
0
0.4
0.2
0



Remember the first F_2 from HERA in 93?

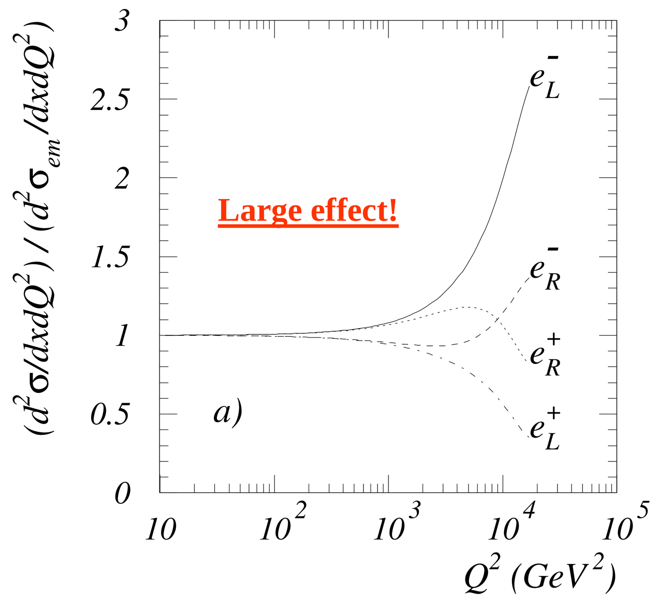
10^{-1} 1 10^{-1} 1

10^{-1} 1

High Q^2 DIS Cross Sections

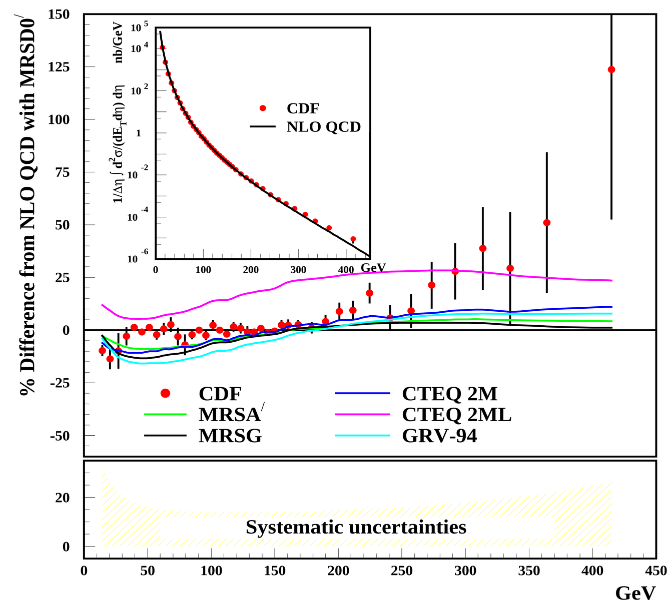
- Still statistically limited..
- Think about 10 times more data...
- And polarization!

- Neutral Current:



⇒ More about HERA's future in K. Long's talk (WG3).

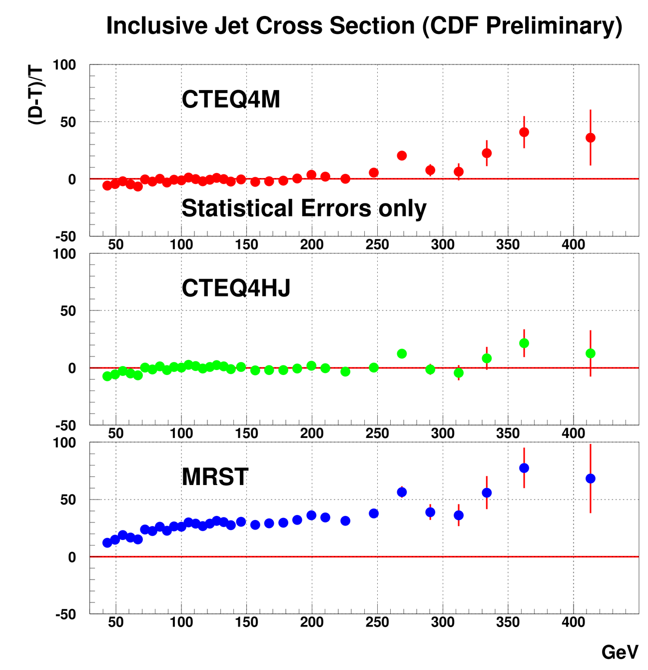
V. High P$_T$ jets at the Tevatron



$$\sigma = f_{\bar{p}} \otimes f_p \otimes \hat{\sigma}$$

- f's are mostly gluons.
- How well is f known?
- How well is $\hat{\sigma}$ known?

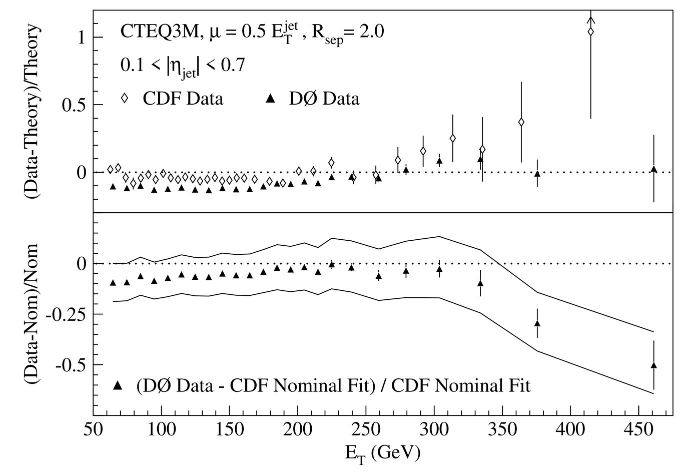
Different PDF's



- Gluons are not well constrained. (See MB fit from before)
- There is an additional 15-20 % experimental systematic errors.

⇒ Agreement with D0?

...is ok...



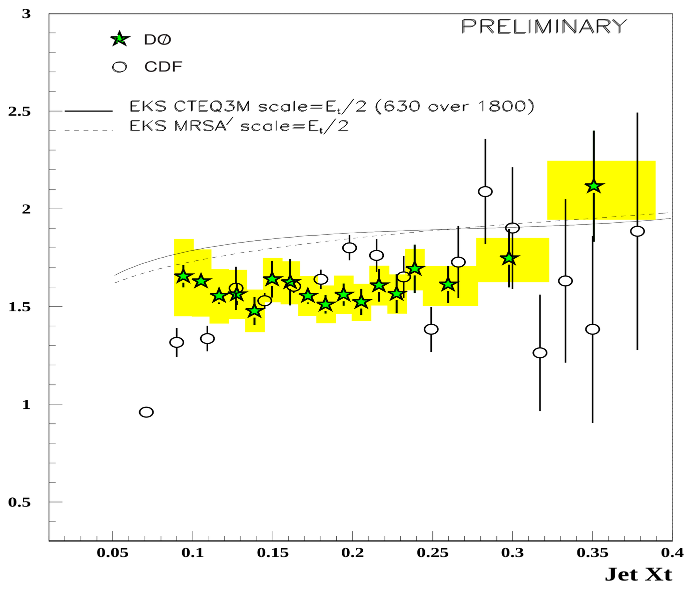
• The experiments are compatible after taking the correlated systematic errors into account.

⇒ Needs reduced uncertainties to compare meaningfully with predictions.

Ratio of Jet cross sections at different $\sqrt{s}$

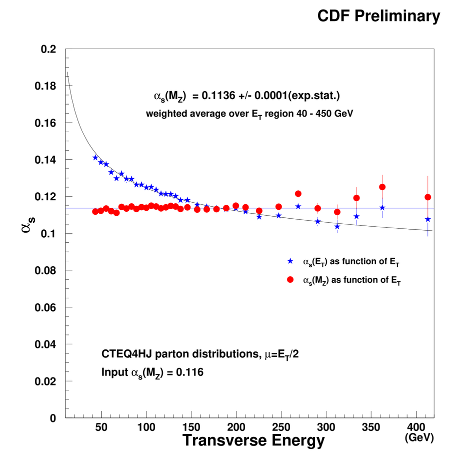
- D0 and CDF preliminary measurements of ratio of cross sections 0.63/1.8 TeV.

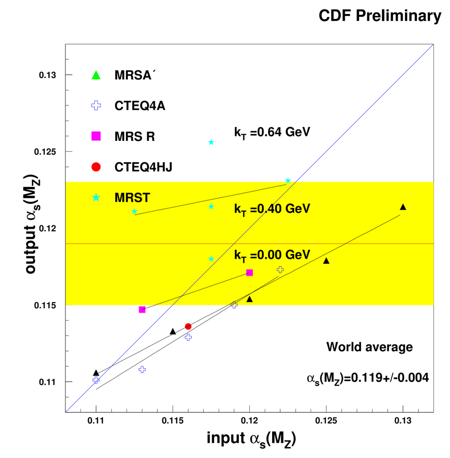
Ratio of Scaled Cross-Sections: CDF and DZero



- Measurement errors are much reduced.
- PDF errors are reduced?
- Agreement between experiments?
- Not consistent with NLO QCD theory.

Measuring α_s from the Jet cross section?





High P_T jets at the Tevatron cont.

- The gluons (f) are not well constrained in the predictions.

- Measurement errors are still large.

- Difficult to disentangle the uncertainties of f form the uncertainties of $\hat{\sigma}$.

- Indications of problems in $\hat{\sigma}$ in the cross section ratio 0.63/1.8 TeV.

- Too early to try to extract QCD parameters...

V. Anomalies at HERA and the Tevatron

Anomaly: departure from the expected!

- High E_T jet cross section at the Tevatron.

- High $Q2$, high x, high y (leptoquark) anomaly at HERA.

- High $Q2$, low y anomaly seen at ZEUS.

- Isolated lepton+Missing P_T anomaly seen at H1.

Try to answer the following questions:

- How far does it depart from the expected?
- Are there something we can do except to wait for more luminosity?
- Are the two experiments consistent?

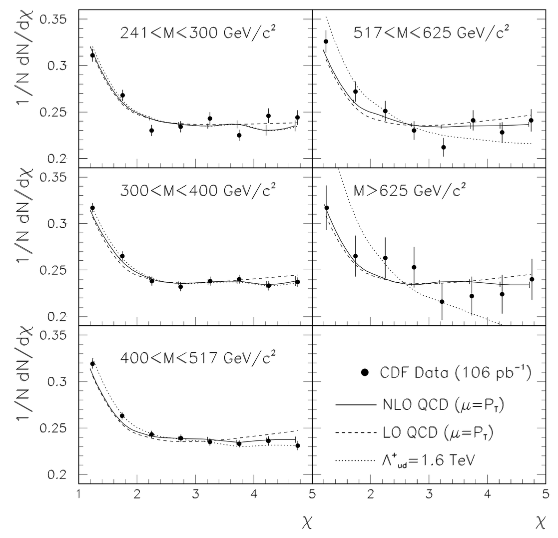
(and mostly fail..)

• High E_T jet cross section at the Tevatron.

This one, as we discussed earlier, no longer qualify as an anomaly:

CDF and D0 looked in several different variables to see if there are departures from expectation.

One example: Dijet angular distribution.

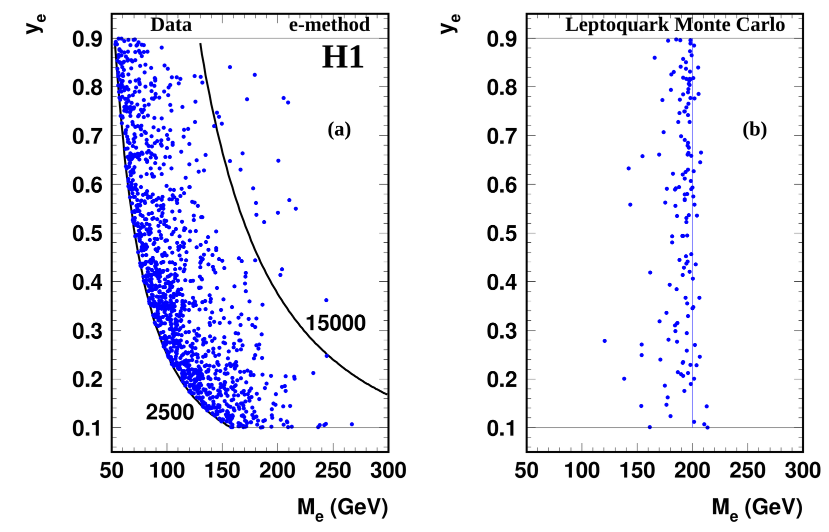


$\chi = (1 + |\cos\theta^*|)/(1 - |\cos\theta^*|)$

No departure from QCD expectation seen to the highest mass.

- High Q2, high x, high y (leptoquark) anomaly at HERA.

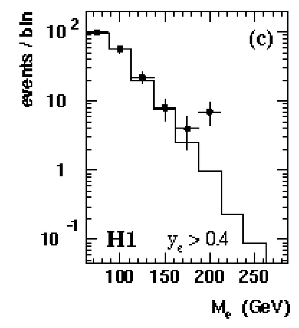
H1 1994-1997

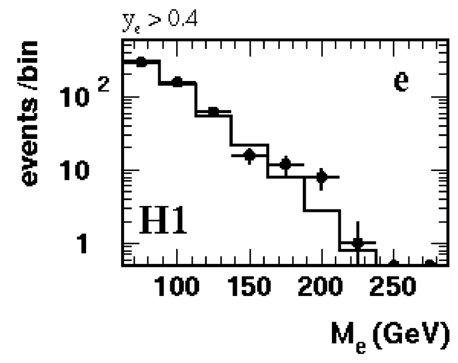


$M = \sqrt{sx}$

(Scalar) Leptoquarks (in S-channel) at mass M is flat in y.

H1 1994-1996 (14 pb^{-1}) H1 1994-1997 (37 pb^{-1})





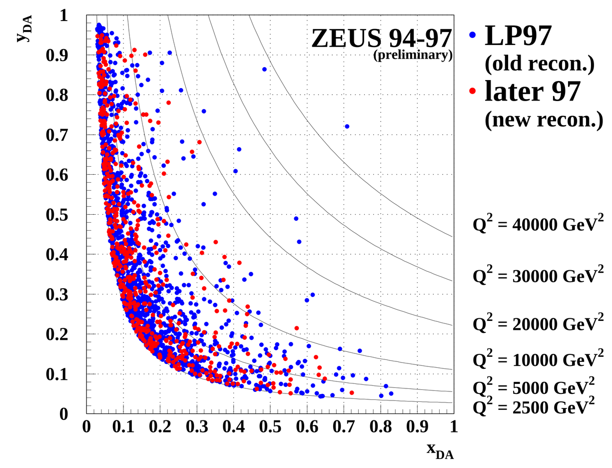
$y_e > 0.4$ and $M_e > 180$ GeV:

1994-1996: 2.21 expected 7 observed

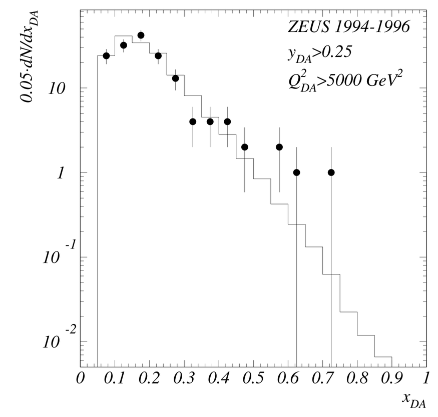
1997: 3.27 expected 4 observed

Total: 5.46 expected 11 observed.

Expectations have $\sim$ 15% errors.

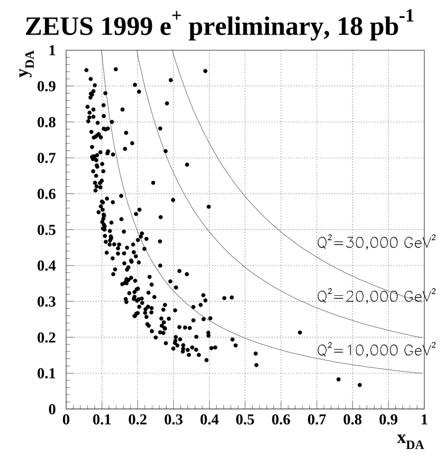


1994-1996 ONLY

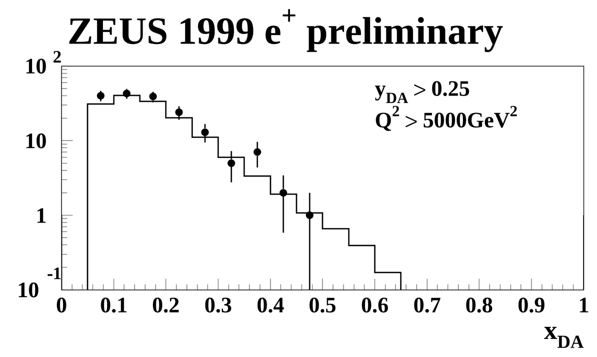


$M_{da} = \sqrt{s x_{da}}$

$x_{da} = 0.55 \rightarrow$
$M_{da} = 223$ GeV



$M_{da} = \sqrt{s x_{da}}$ $\quad x_{da} = 0.5 \rightarrow M_{da} = 223$ GeV



ZEUS summary

$y_{da} > 0.25$ and $x_{da} > 0.55 \rightarrow M_{da} > 223$ GeV:

1994-1996: 0.9 expected 4 found

1994-1997: approx.2.16 expected 5 found

unofficial expectations–scaled with luminosity

1999 (920 GeV proton): 1.4 expected 0 found. (for $M_{da} > 223$ GeV)

Total: approx. 3.56 expected 5 found.

The agreement is good.

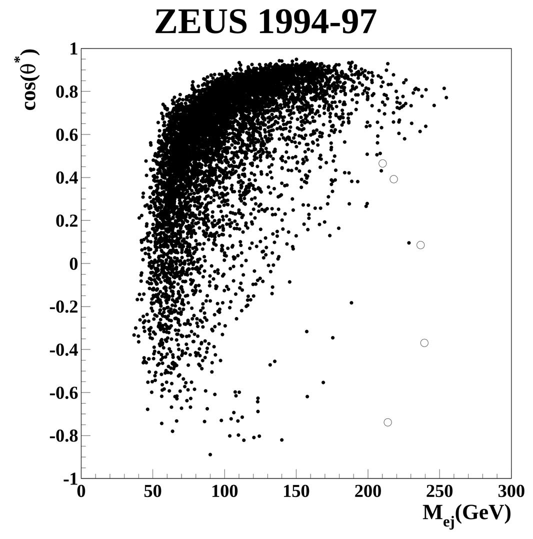
Combined (somehow) with the H1 results, the excess is a 2–2.5 sigma effect.

..at least in this simplistic way

- High Q2, low y anomaly seen at ZEUS.

ZEUS has done a general search for e-jet resonances.

No assumptions are made about its origin.

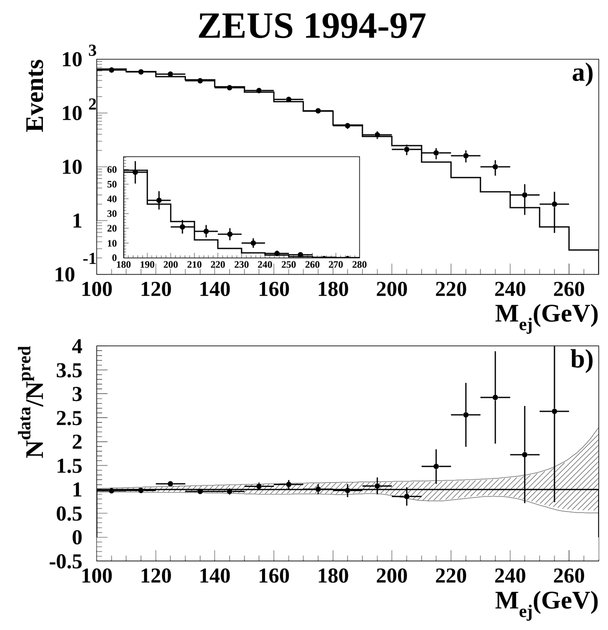


$\cos\theta^* = 1 - 2y \quad y = 0.25 \rightarrow \cos\theta^* = 0.5$

$\cos\theta^* = 0.8, M_{ejet} = 220$ GeV $\rightarrow Q^2 \approx 4800$ GeV^2

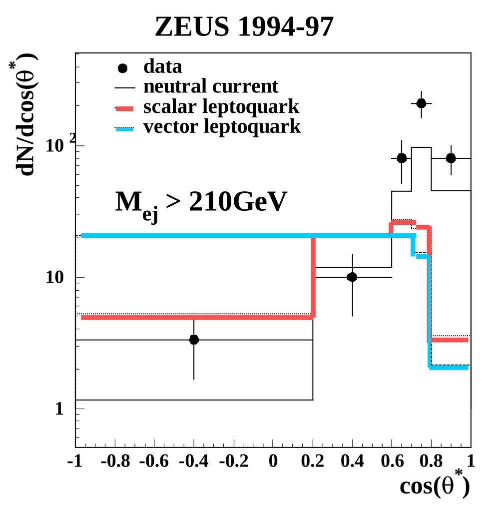
For $\cos\theta^* < 0.5$ and $M_{ej} > 200$ GeV

Expect 5 events and 7 events found.



For $M_{ej} > 210$ GeV:
24.7±5.6 events expected, 49 events found.

⇒ Look more closely at the angular distribution.



Events have the characteristics of NC

- Generate many MC experiments in which the jet and electron energies are varied within their uncertainties. (2% and 1%)
- Window of 3 times the M_{ej} resolution moved over the range.

$\Rightarrow$ 5% of the experiments observe a similar or larger excess somewhere in the mass range

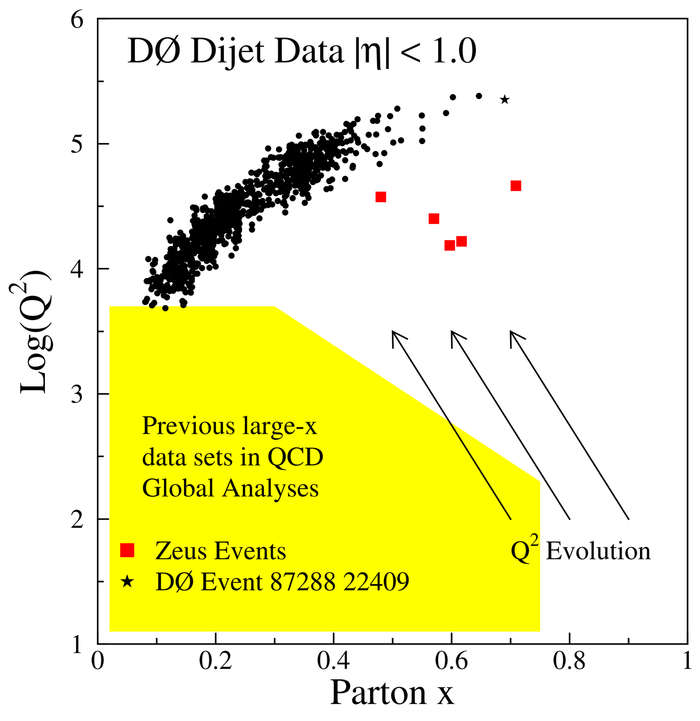
Not statistically compelling

Further questions..

What about H1?

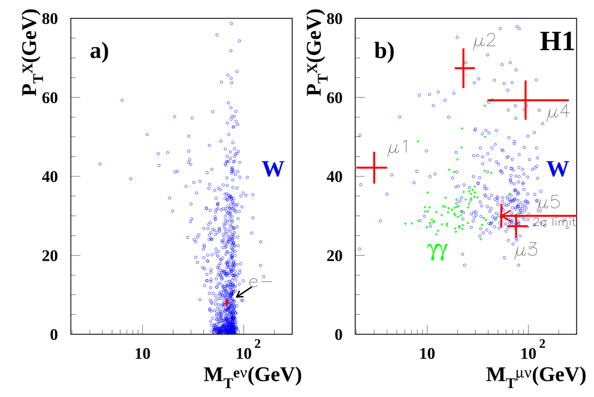
Why are all these effects sitting arond 200 GeV??

Can it be some kind of PDF effect?



- **Isolated lepton+Missing P_T anomaly seen at H1.**

H1 1994-1997



In 36.5 pb^{-1} of data, H1 has found: 5 events (0.8 expected) with:

- Isolated μ with high P_T (2 +, 2 -, 1 unknown).
- Large missing P_T
- High hadronic P_T

1 electron (remember it's e+p) is found when 2.4 (electron or positron) are expected.

The SM processes expected are mainly:

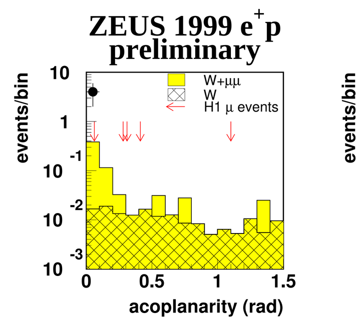
- W production
- muon channel: Dimuon photoproduction, where you miss one muon
- electron channel: Neutral Current events

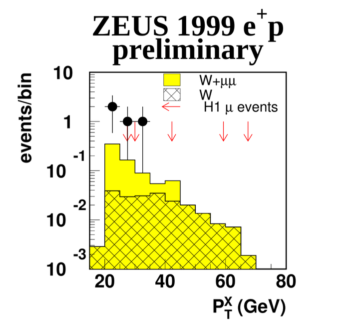
ZEUS does not see an excess

Isolated Leptons

HERA MODE YEAR	e^+p (300 GEV) 94-97	e^-p (320 GEV) 98/99	e^+p (320 GEV) 99
H1 LUMI	**37** PB^{-1}	**14** PB^{-1}	
EVENTS	OBSERVED (EXPECTED)	OBSERVED (EXPECTED)	
H1 e	**1** (2.4 ± 0.5)	**0** (0.37 ± 0.07)	
H1 μ	**5** (0.8 ± 02)	**0** (0.14 ± 0.04)	
ZEUS LUMI	**48** PB^{-1}	**16** PB^{-1}	**18** PB^{-1}
EVENTS	OBSERVED (EXPECTED)	OBSERVED (EXPECTED)	OBSERVED (EXPECTED)
ZEUS e	**3** (3.5 ± 0.7)	**2** (0.8 ± 0.4)	**2** (1.8 ± 0.4)
ZEUS μ	**0** (2.0 ± 0.4)	**0** (0.8 ± 0.1)	**4** (0.9 ± 0.1)

H1, ZEUS PRELIMINARY





IN TOTAL ZEUS OBSERVES (PRELIMINARY):

$\boxed{e\text{: } 7 \text{ (EXP. } 6.1 \pm 0.9) \quad \mu\text{: } 4 \text{ (EXP. } 3.7 \pm 0.4)}$

RATE AGREES WITH SM, μ-KINEMATICS STILL UNDER STUDY

There is an update from H1 at this conference. ⇒ N. Malden (WG3)

Before we go on to compare ZEUS and H1 results (available to me), some observations looking at H1 events alone.

- The significant excess is in the H1 μ channel in positron runs.
- Assume the whatsit-cross-section is 4 events/37 pb^{-1}. Then if it's the same in electron runs, then you expect 1.5 events.
- Then we can't rule out that the effect is only in positrons runs. 1.5 expected and 0 observed is rather likely.

Nevertheless now I make a comparison assuming the effect is only in the μ channel in positron runs. (This will become obsolete soon..I guess!)

Taking the μ events only in positron runs:

H1: 5 events found expecting 0.8 in 37 pb^{-1}.
ZEUS: 4 events found expecting 2.9 in 66 pb^{-1}.

Are these numbers “compatible”? (the usual question!)

- ZEUS data is compatible with SM
- H1 data is rather unlikely to be produced by SM

But that is not the question.

Are the two data so incompatible that there is no possible underlying distribution that could produce both results?
The answer: it’s easy to construct such a distribution by taking the average of the two data sets.

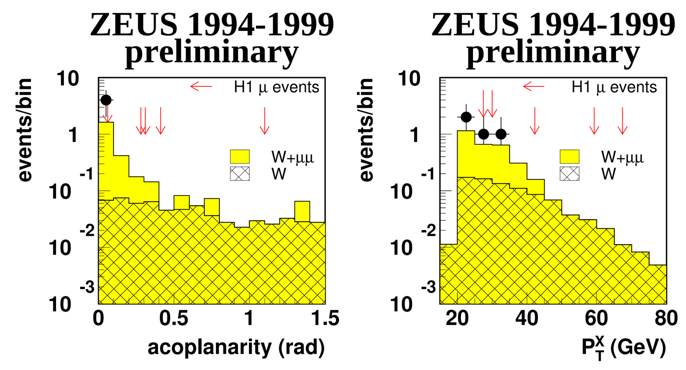
Think about a whatsit-cross-section of 2 events/37 pb^{-1}.

“Prediction” for H1 2.8 where 5 events found
“Prediction” for ZEUS 6.5 where 4 events found.

Let’s try to compare the events in a little more detail..

First attempts at comparing H1 and ZEUS..

Muon Events



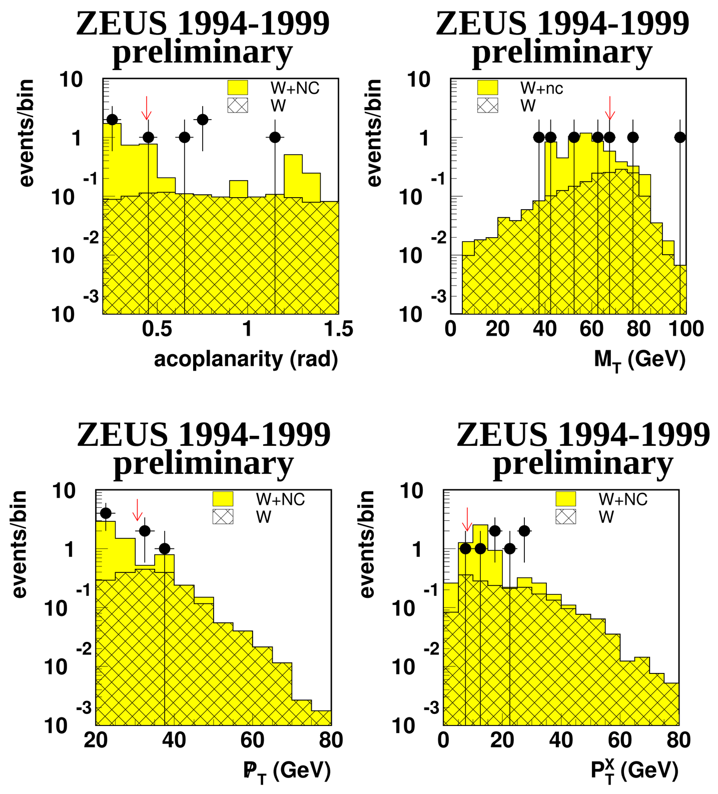
NOTE: Backgrounds drawn is for the ZEUS analysis.

ZEUS event shapes are compatible with the SM shapes. H1 events seems to be flatter in acoplanarity and P_T^X than SM (according to the ZEUS analysis..).

Need a real comparison.

⇒ Same for electrons..

Electron Events



NOTE: Backgrounds drawn is for the ZEUS analysis.

Anomalies at HERA and the Tevatron cont.

• The predictions of σ for the Tevatron jets are too uncertain to claim an observation of an anomaly.
Dijet mass, angular distribution show no sign of deviation from NLO QCD.

• There is a factor of 2 (but 2-2.5 sigma) excess of data at HERA at the highest Q^2, and high x. ("Leptoquarks")

We need more data!

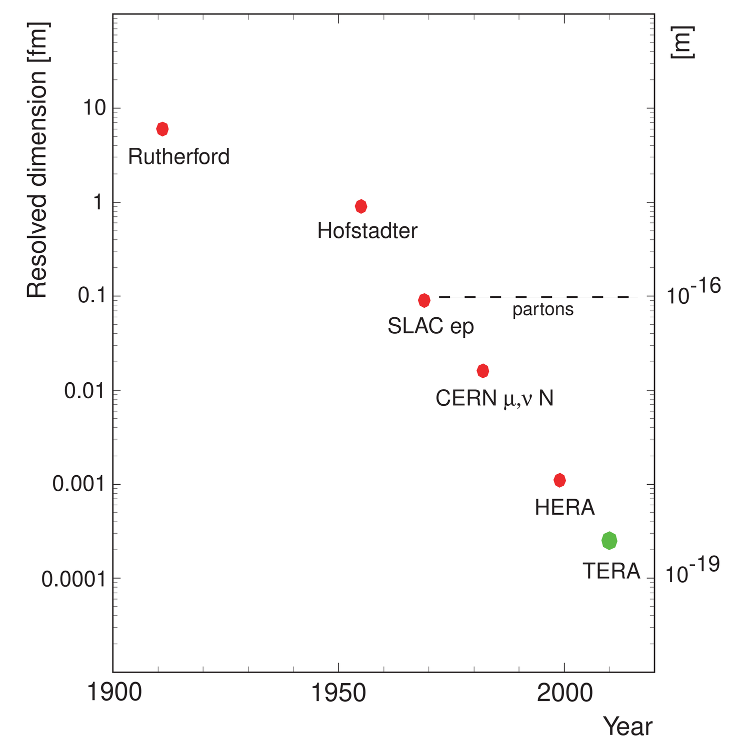
• There is an excess of events in the ZEUS data (1994-1997) at low y and high x. Tantalizingly, it sits around the same mass as the "leptoquark" anomaly.
Angular distribution of the excess is compatible with SM.
Statistically not compelling.

New data (1999-2000) at higher proton energies will help..

No comparison with H1 so far.

• There is an excess of high P_T isolated muons with large missing P_T in the H1 data (1994-1997). (Update at this conference!) Excess is not seen by ZEUS. Naively, likely hypotheses of underlying distributions to produce H1 and ZEUS data is not SM!

H1 and ZEUS needs to work together on this!



Conclusive proof that Rutherford was 30 years ahead of his time...

VII Conclusion

I have attempted here to assess where we are in each of the ”Highest Q^2 and P_T^2” topic I have picked, and where we might go next in our investigations

I did this by trying to find the “most uncertain thing” in each topic.

I’m sure many of you disagree with my statements!

I hope some of what I said can serve as a starting point in the discussions in this workshop.