Complementarity at HERA

Why H1 and ZEUS data combination worked so well

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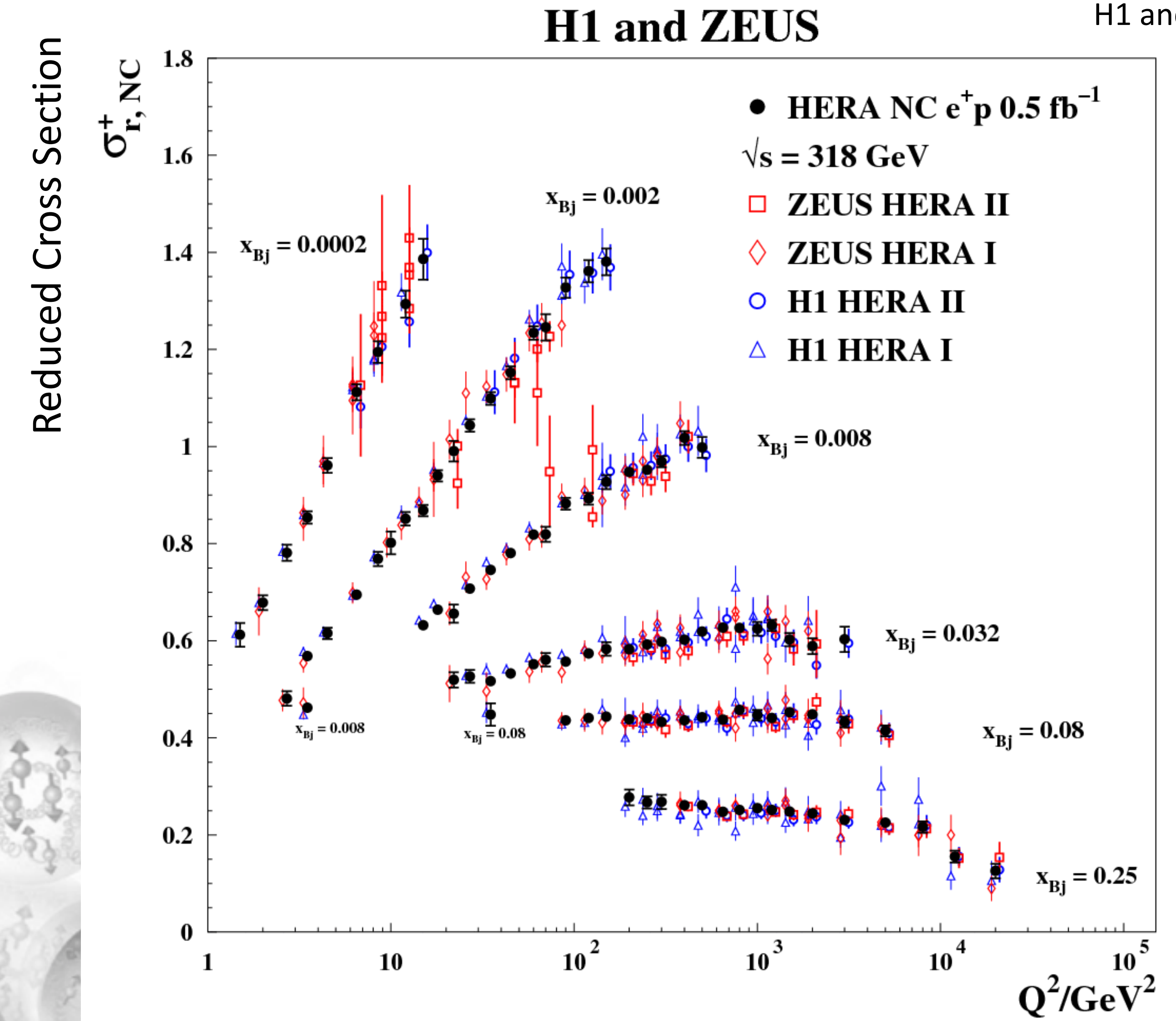
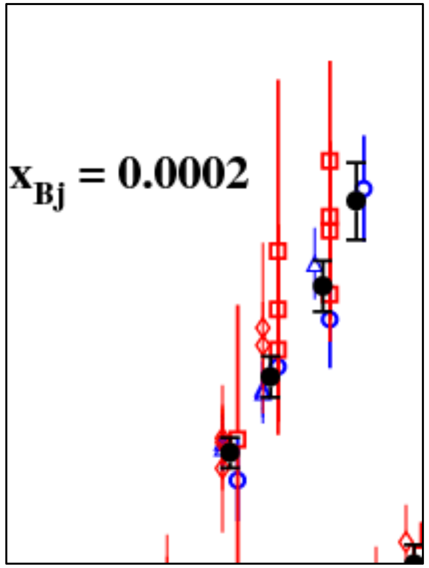
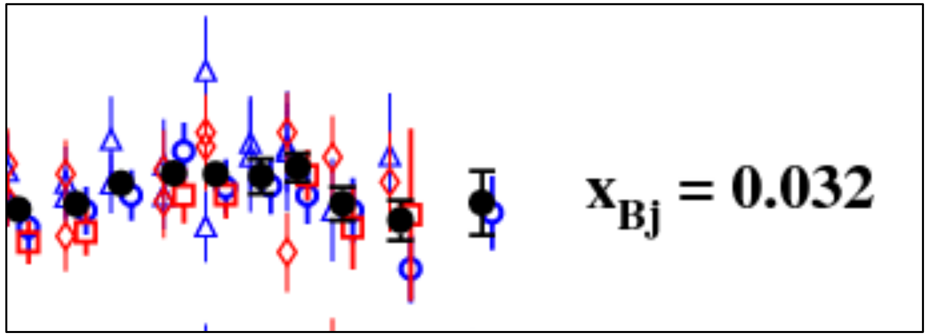
Neutral Current Cross Section (F_2), H1, ZEUS and combination.

H1 and ZEUS Collab., H. Abramowicz et al., Eur.Phys.J.C75 (2015) 12, 580

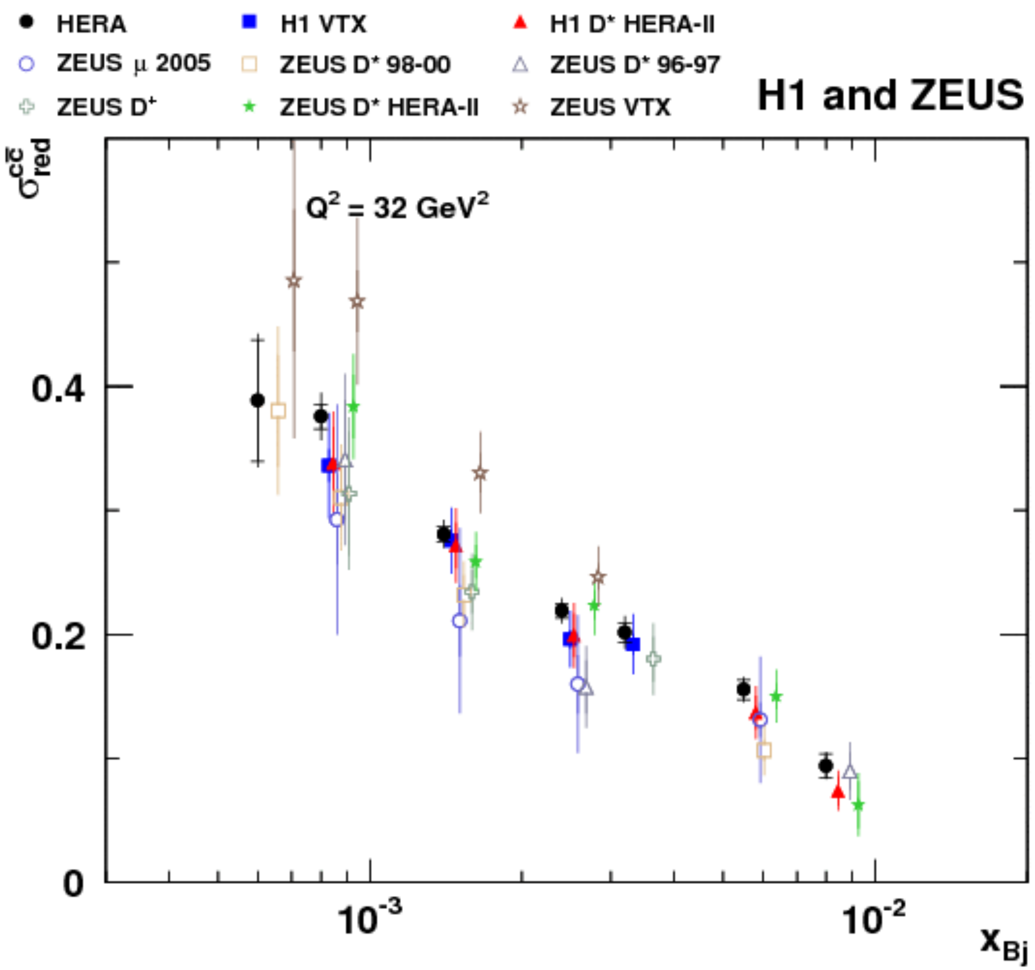


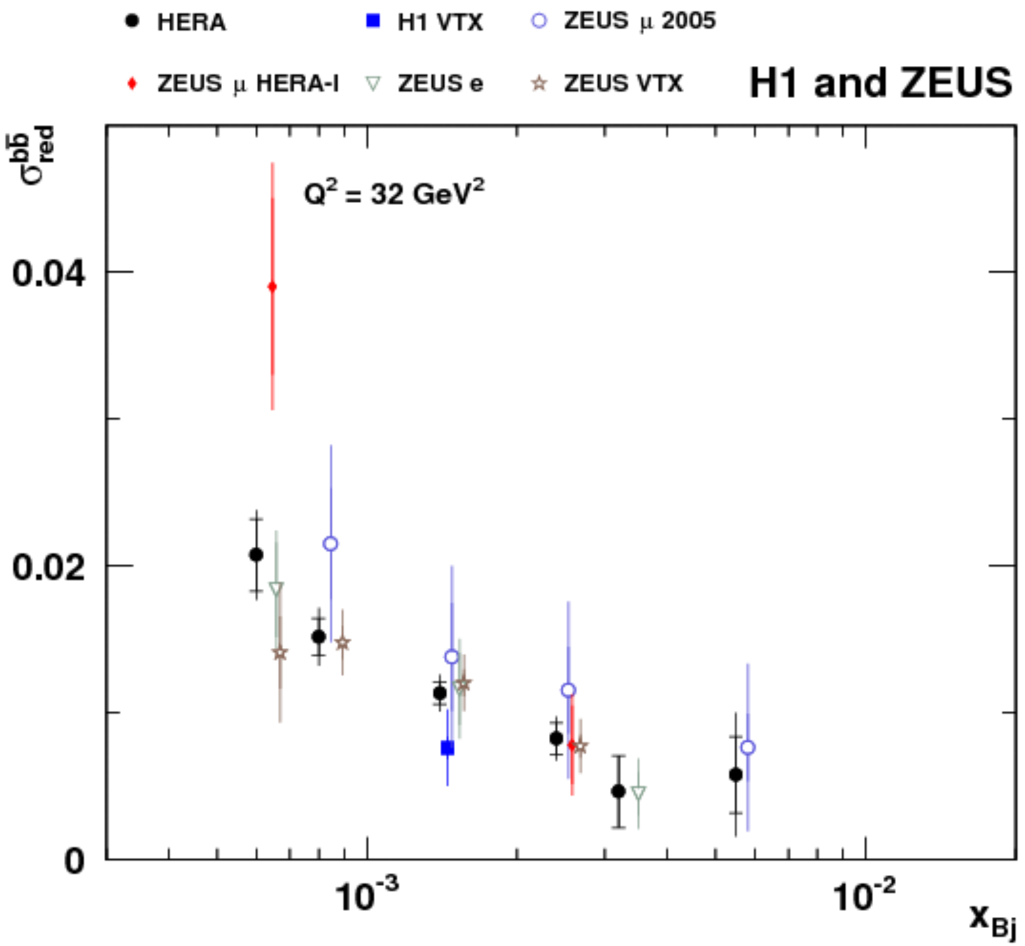




Neutral Current c and b Cross Sections, H1, ZEUS and Combined

H1 and ZEUS Collab., H. Abramowicz et al., Eur.Phys.J.C78 (2018), 473



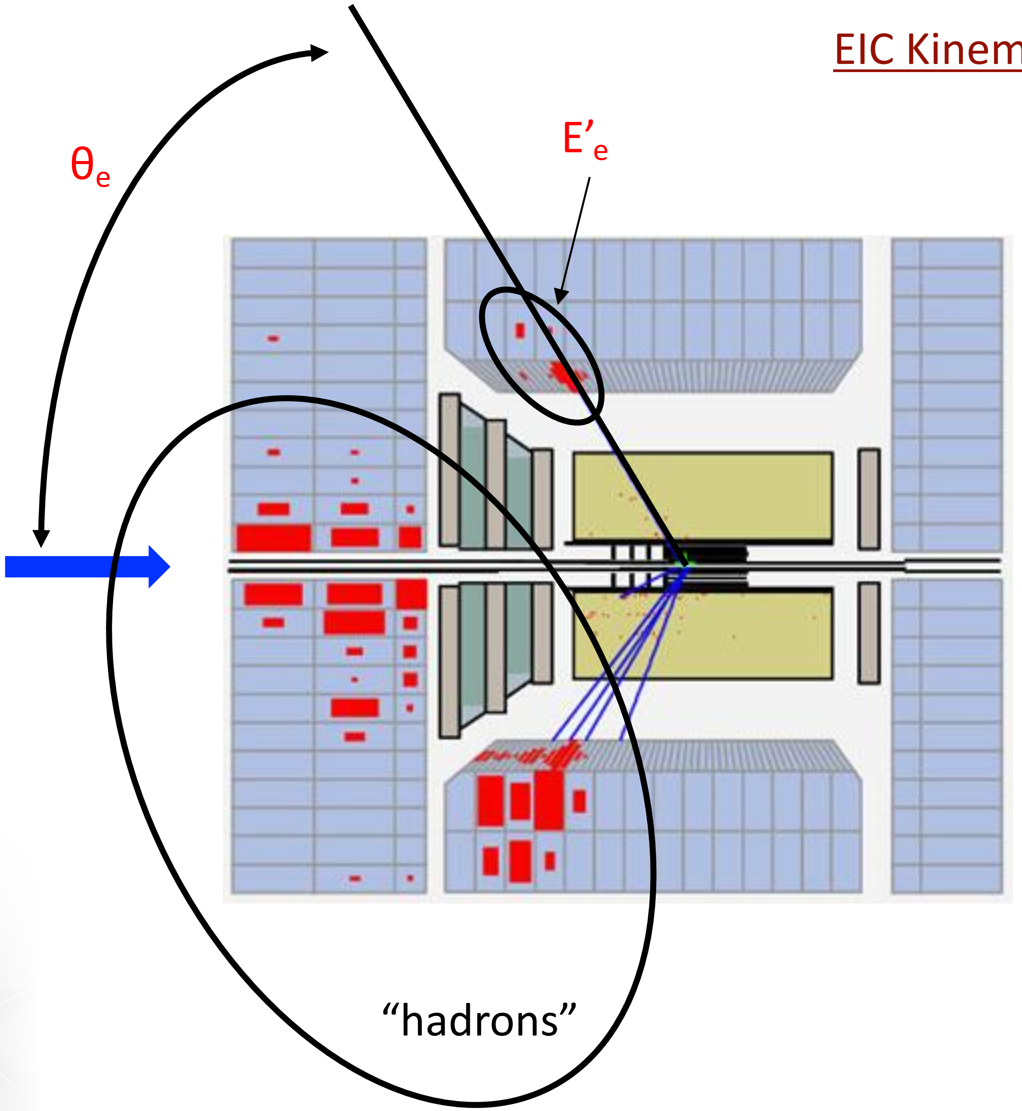


Systematic uncertainties are largely cancelling

So why does it work so well?

To understand this, we need to understand DIS kinematic reconstruction for colliders in general and conventions for HERA in particular.

EIC Kinematics for Fixed Target Physicists: E. Long



Electrons enter from the **left!!**   27.5 GeV

Z

Protons enter from the **right !!**   820 GeV

- Z and θ_e are defined in the opposite way from fixed target notation.
- "hadron" in this context means everything in the detector except the scattered electron.

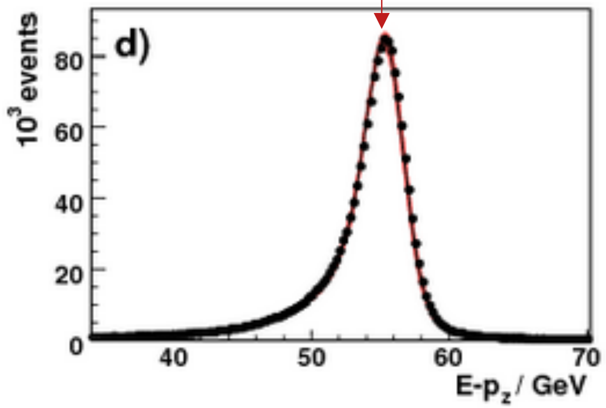
E-p_z

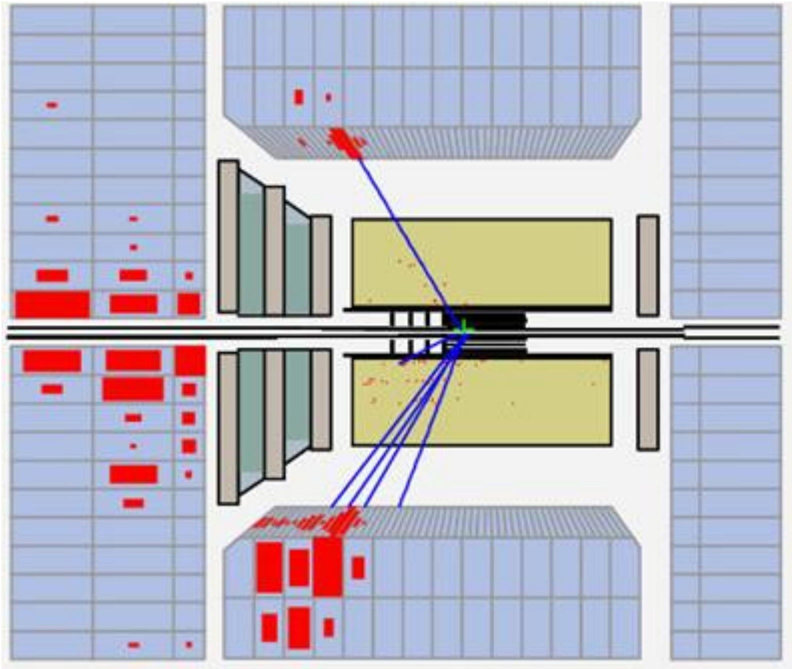
There is an important kinematical concept $\sum_n (E - pz)$ where n is over all particles: E-p_z for short.
The initial (before collision) E-p_z = 2E_e , because E_p=$p_{pz,}$ and E_e=-p_{ez} (remember the direction of Z!)

Remnants of the proton
escape down the beamhole

H1 detector

55 GeV



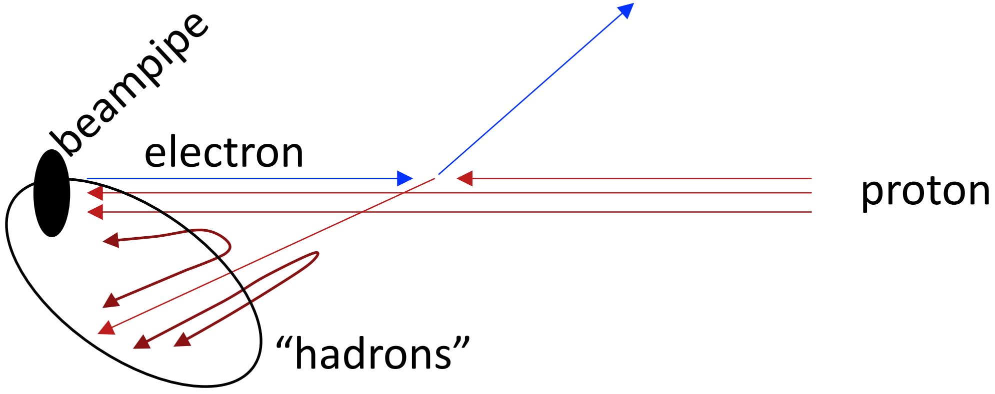


Z

I can evaluate E-p_z of an event by summing over all energy deposits in the detector.
Even though the detector is not completely hermetic, E-p_z=2E_e anyway as long as the electron didn't escape down the (right) beampipe!

Reconstructing x and Q^2

4 quantities are conveniently well-measured.
(because a lot of energy escapes down the beampipe in the positive Z direction.)



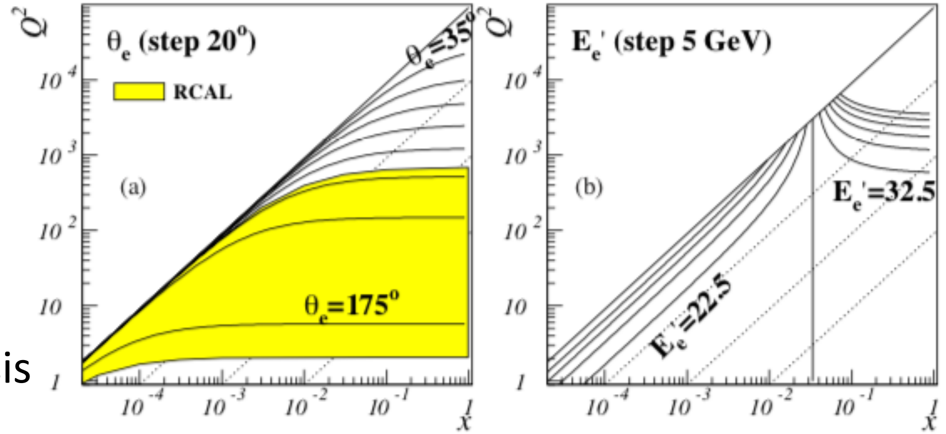
The scattered electron energy: E'_e
The scattered electron angle: θ_e
The transverse momentum of the "hadrons": p_{Thad}
"longitudinal momentum" of the "hadrons": $(E - pz)_{had}$
you can recast these as "angle" and "energy" of the quark

$E\text{-}p_z$ from last page without the contribution from the scattered electron.

x and Q^2 can be reconstructed using any 2 of these quantities (and the electron and proton beam energies)

So why do something other then use the electron energy and angle ?

N. Tuning thesis

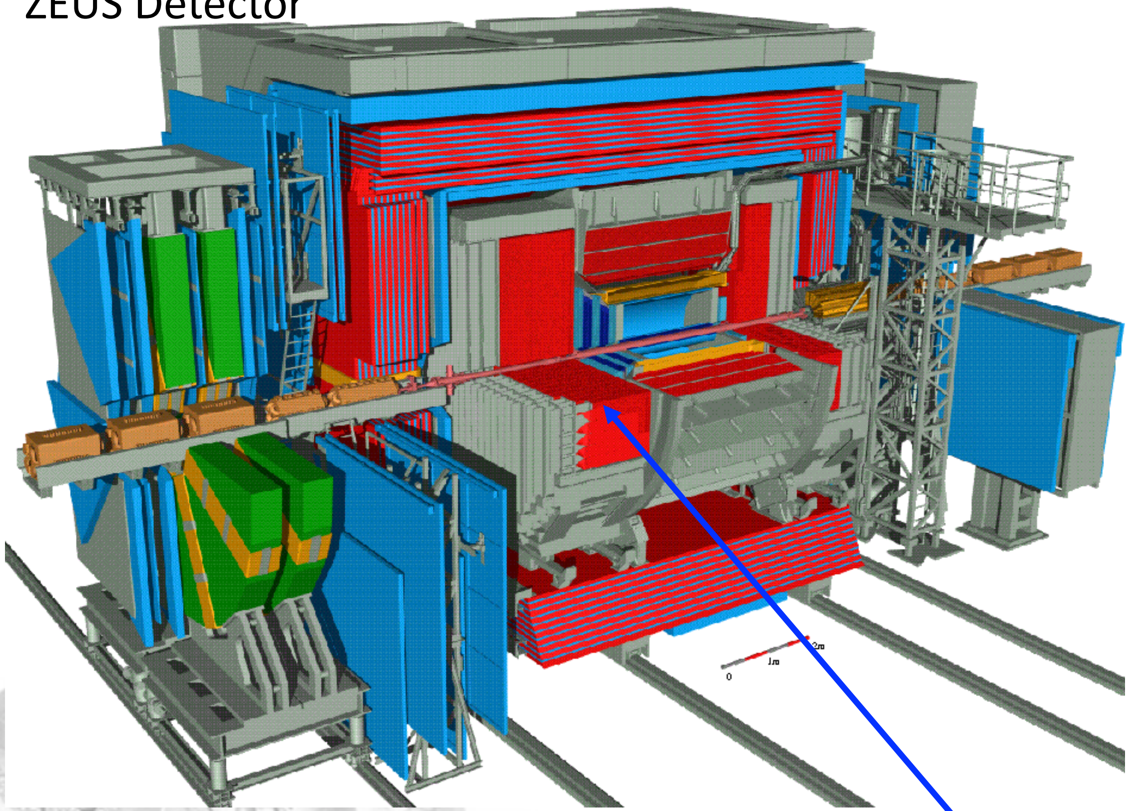


X not well measured by electron variables in large areas

Choosing how to reconstruct x and Q^2

Depends on the detector and its characteristics

ZEUS Detector

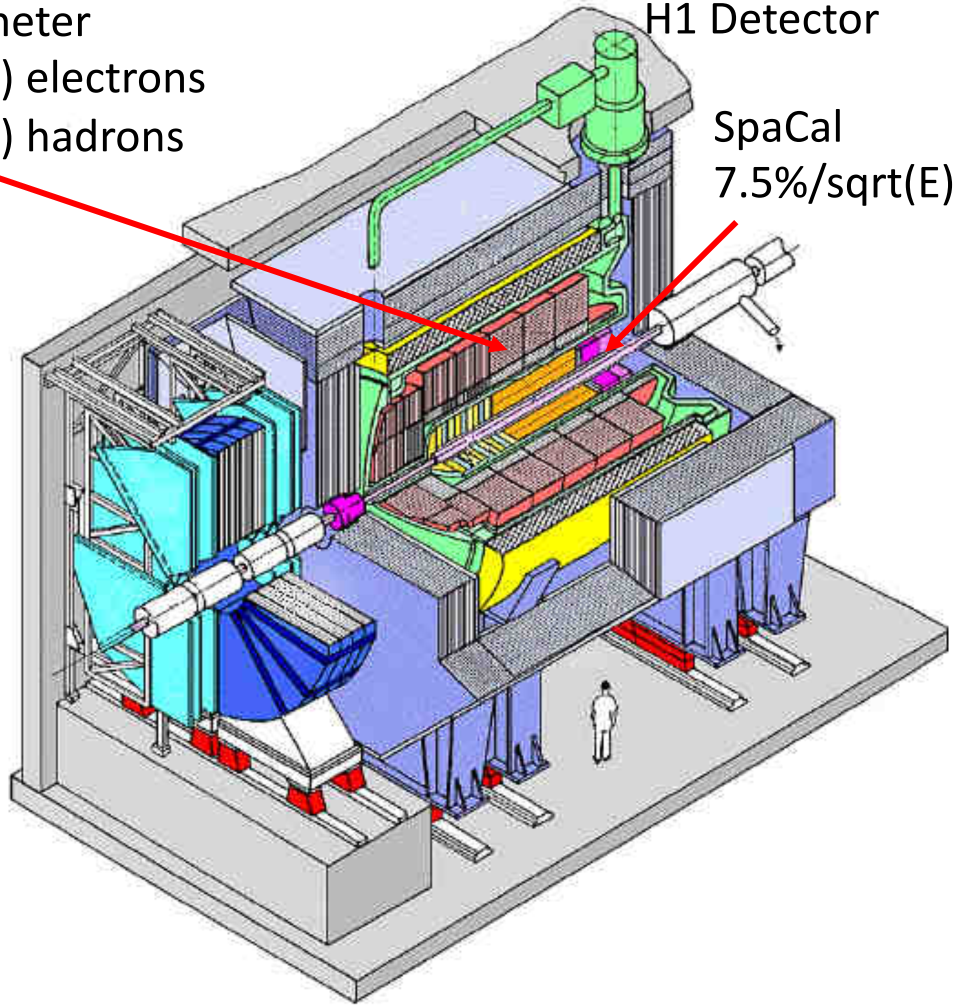


U-Scintillator Calorimeter
18%/sqrt(E) electrons
35%/sqrt(E) hadrons

LAr Calorimeter
12%/sqrt(E) electrons
50%/sqrt(E) hadrons

H1 Detector

SpaCal
7.5%/sqrt(E) electrons

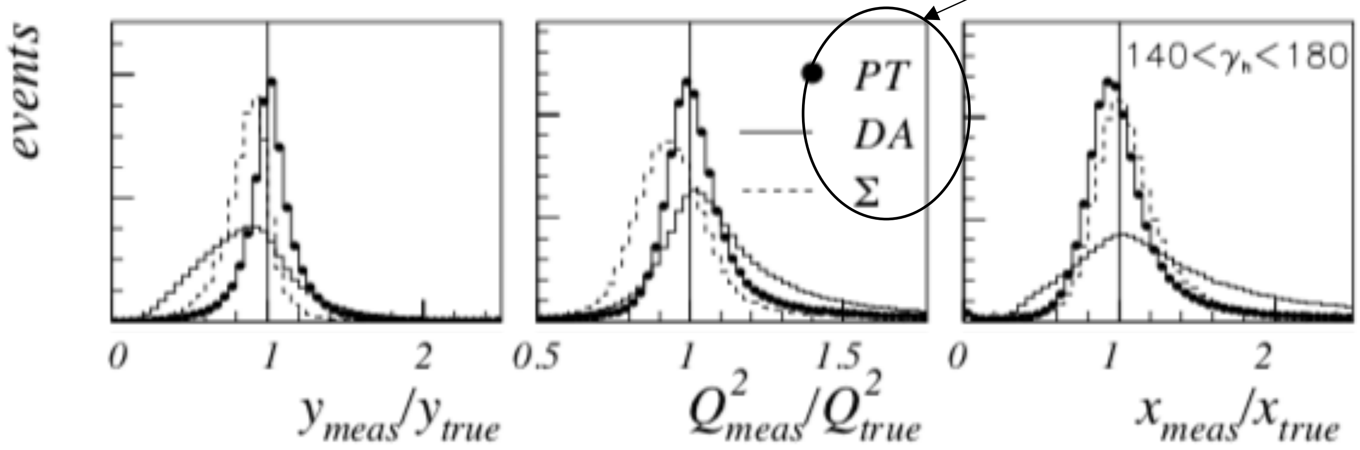


Many other differences: segmentation, tracking…

Optimizing reconstruction of x and Q^2 (and y)

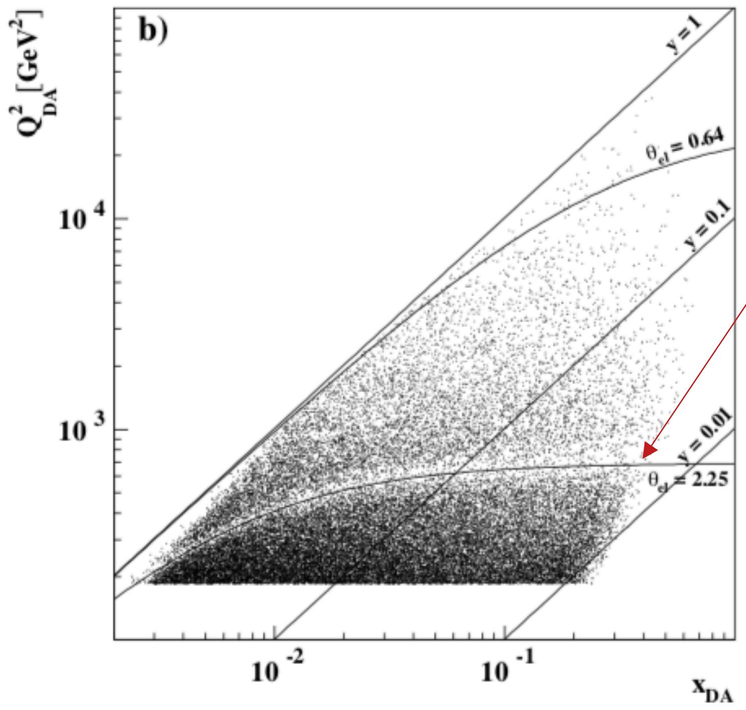
N. Tuning thesis (ZEUS)

Different ways of combining the 4 quantities; chose "PT" in this case.



H1 reached a different conclusion.
For them the Σ method worked best.

Alexander Kappes thesis (ZEUS)



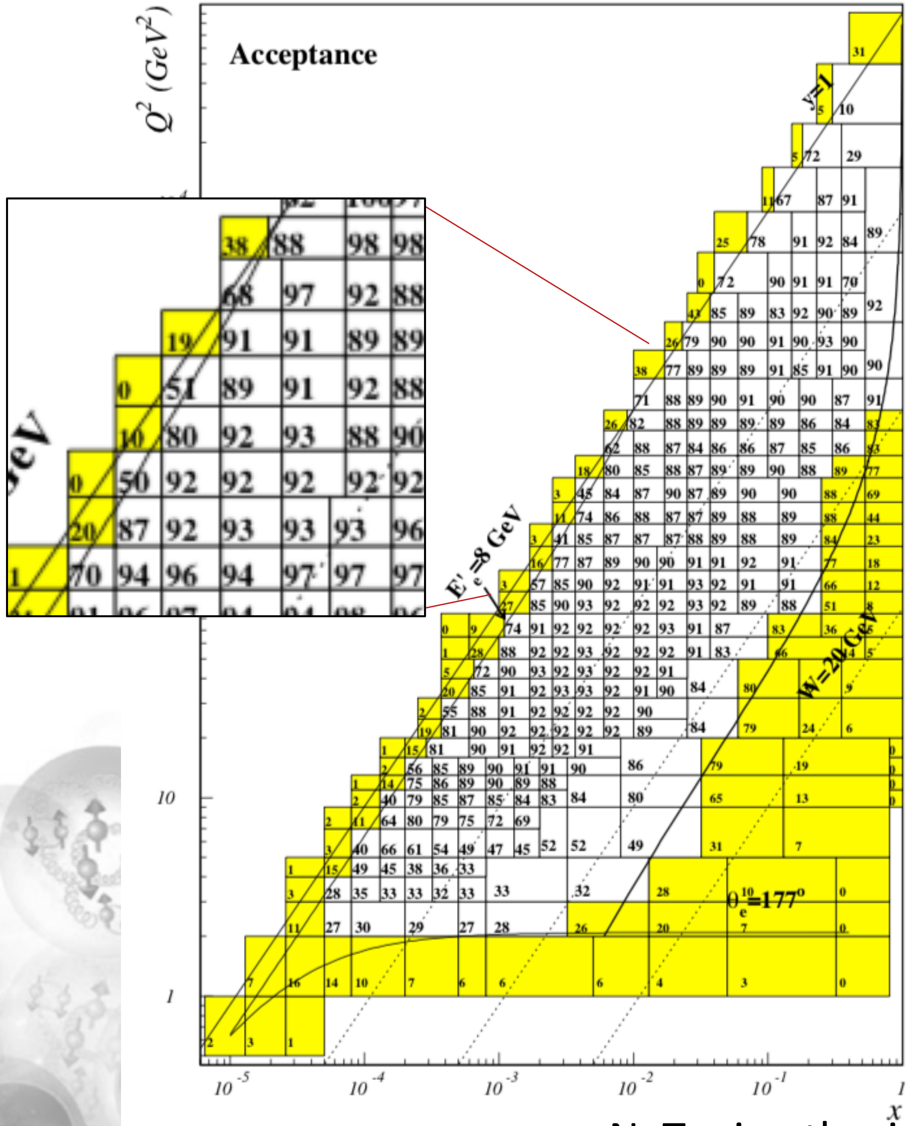
Crack between calorimeters

So what do we do now to get to cross-sections as function of x and Q^2?
First, reconstruct x and Q2 of each event →

Now decide on the binning

Binning and migration

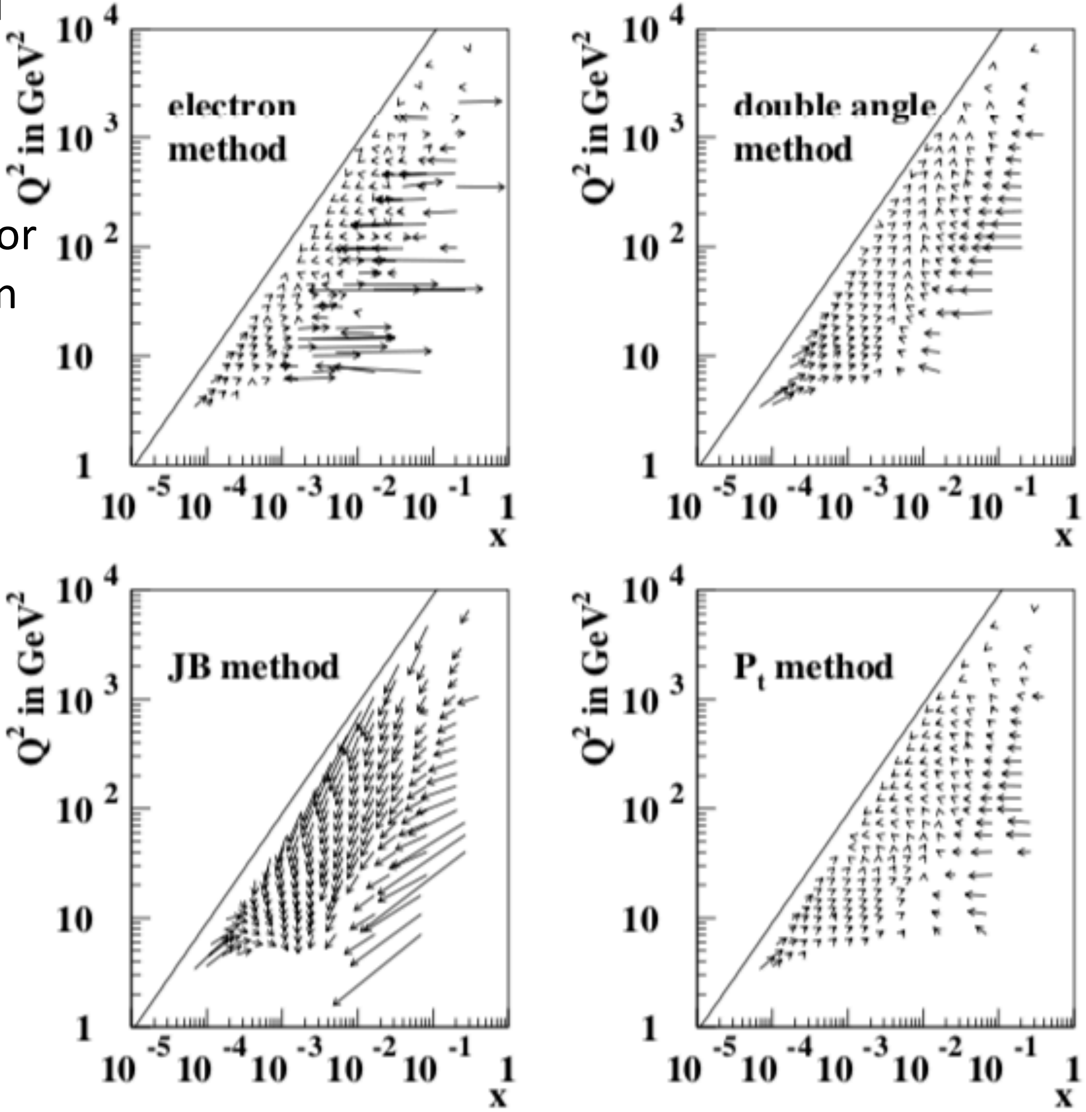
Acceptance is one of the criteria



N. Tuning thesis (ZEUS)

The reconstructed events will "migrate".
Migration will depend on detector and reconstruction method.

A. Quadt thesis (ZEUS) Migration



Cross Section (F_2) determination

In case of a perfect detector the cross section for a particular bin of x and Q^2 is:

$$\sigma_{\mathrm{meas}}(\Delta x, \Delta Q^2) = \frac{N_{data}}{\mathcal{L}}$$

Int. Luminosity

In reality, we need to take into account correction due to acceptance, migration, background…etc. so

$$\sigma_{\mathrm{meas}}(\Delta x, \Delta Q^2) = \frac{N_{data}}{\mathcal{L}} C(x, Q^2)$$

There are fancier ways of "unfolding" but the basic conclusion for our purposes will be the same

$C(x, Q^2)$ is the correction factor that takes into account all detector effects.

$C(x, Q^2)$ is affected by systematic uncertainties related to the detector

For example:

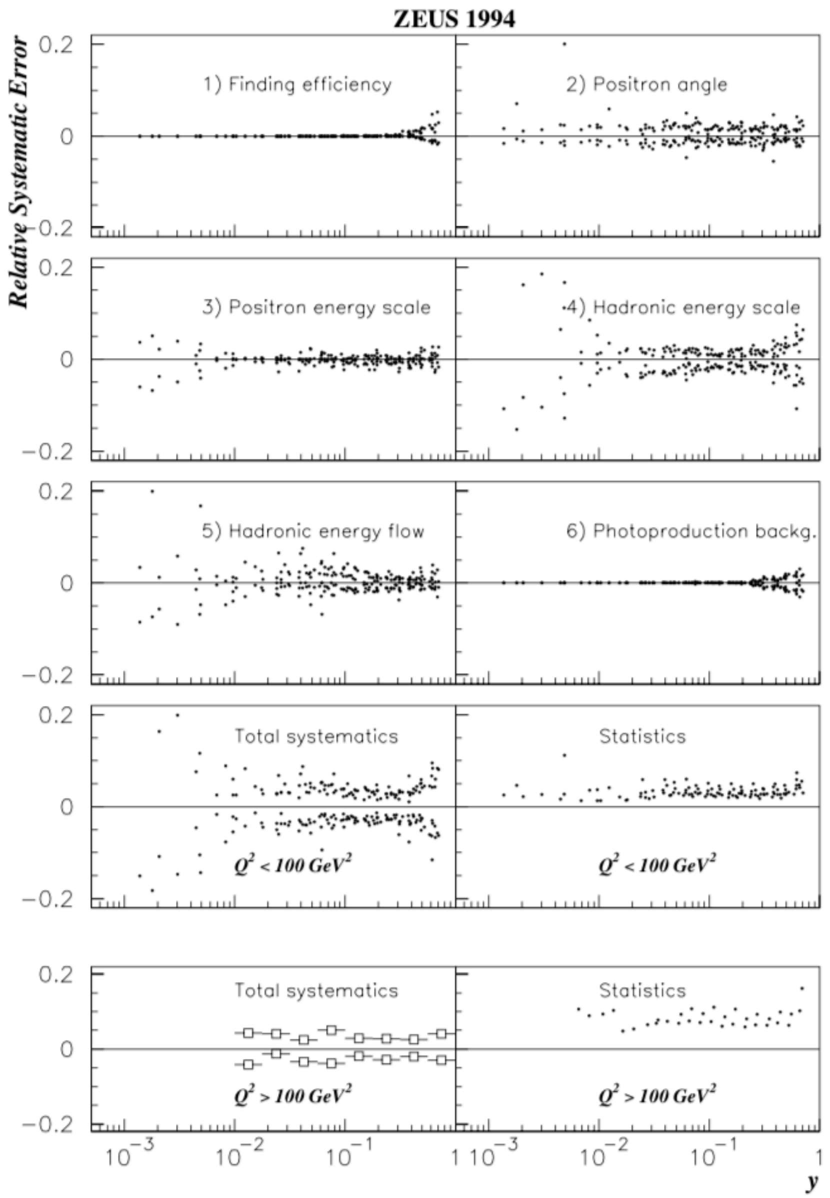
$$Q_e^2 = 2E_eE_e'(1+\cos\theta_e)$$

Angle mis-measurement will have a more complex effect

If this is mis-measured by n%, all Q^2 will be mis-measured by n%

Note: effects of mis-measurement (i.e. systematic errors) are completely correlated bin to bin

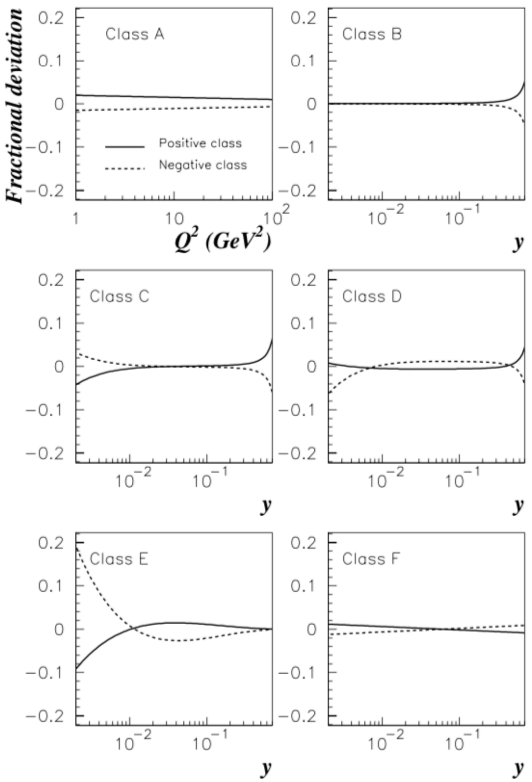
Correlation of Systematic Uncertainties



The systematic uncertainties are determined by changing something (e.g. calorimeter energy scale) within its uncertainties and determining the cross-section again.

The shape as a function of y (in this case), is determined by how the affected quantity (one of 4 from page 6) enters the reconstruction.

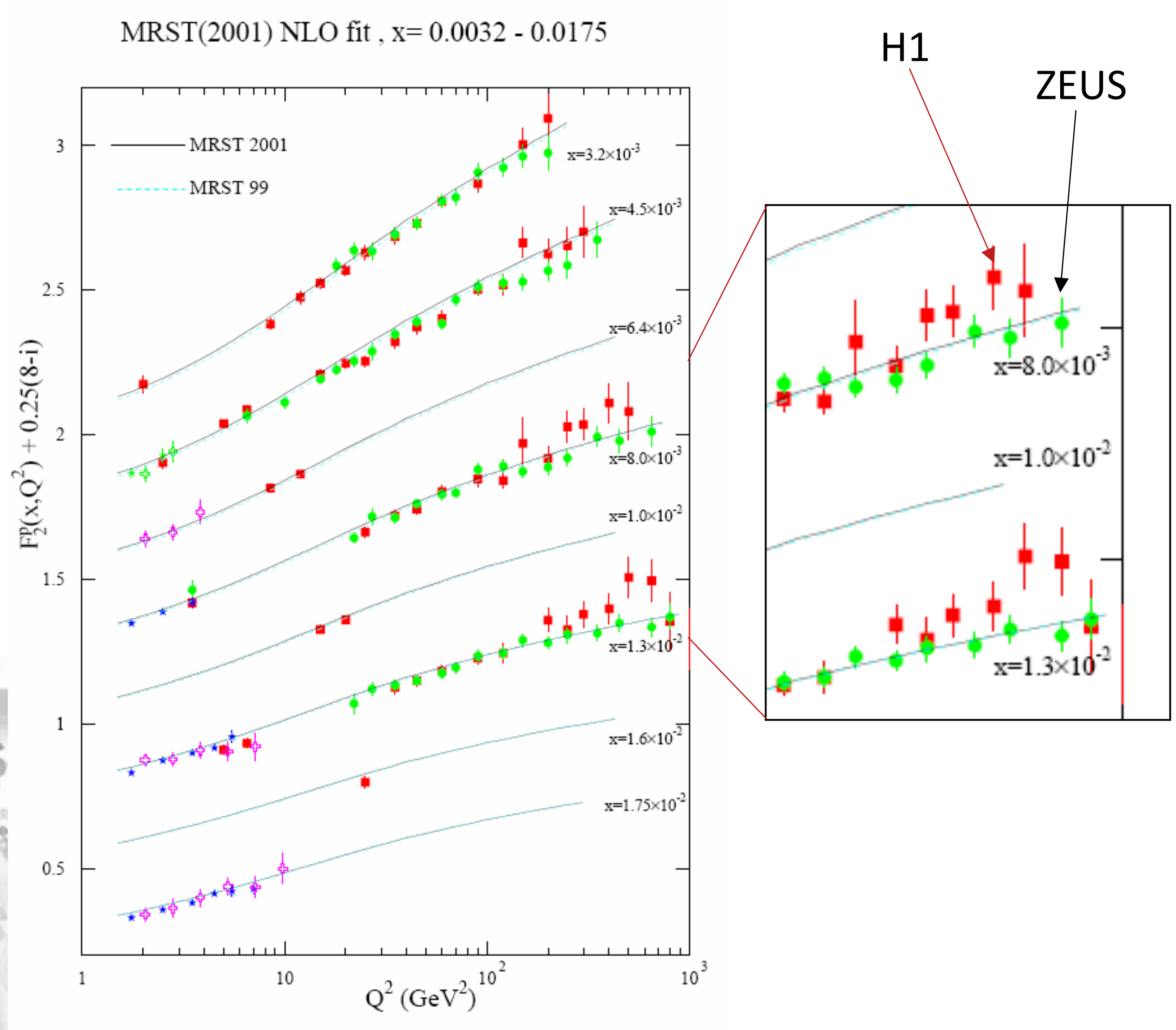
Different classed of uncertainties have different “shapes”



ZEUS Collaboration

Z. Phys. C 72 (1996) 399-424

Correlated systematic uncertainties.



Can lead to this kind of "difference" between H1 and ZEUS.

This is probably explainable by the central scale assumption on something (e.g. scattered electron energy) being off by a small percentage on one or both of the experiments.

So now let's think about how to combine the two data sets.

Construct a bin-by-bin Chi-square for the two experiments

H1 and ZEUS Collab., H. Abramowicz et al., Eur.Phys.J.C75 (2015) 12, 580

Constructed with only the assumption that the two experiments are measuring the same cross-section in each bin.
(This is unlike global fits where pQCD and other assumptions enter)

experiments

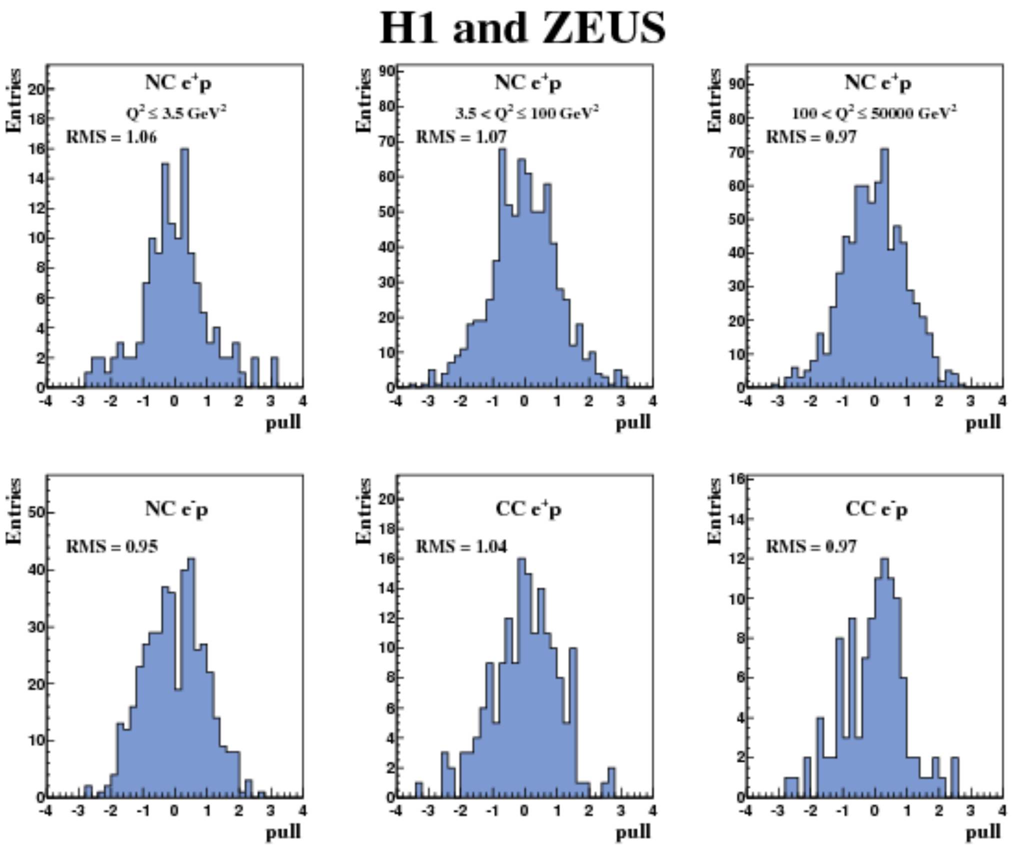
$$\chi^2_{\mathrm{tot}}(\boldsymbol{m},\boldsymbol{b}') = \chi^2_{\mathrm{min}} + \sum_{i=1}^{N_M} \frac{\left[m^i - \sum_j \gamma_j^{i,\mathrm{ave}} m^i b'_j - \mu^{i,\mathrm{ave}}\right]^2}{\delta^2_{i,\mathrm{ave,stat}}\,\mu^{i,\mathrm{ave}}\left(m^i - \sum_j \gamma_j^{i,\mathrm{ave}} m^i b'_j\right) + \left(\delta_{i,\mathrm{ave,uncor}}\, m^i\right)^2} + \sum_j (b'_j)^2$$

bins

Measured cross-section

Correlated systematics

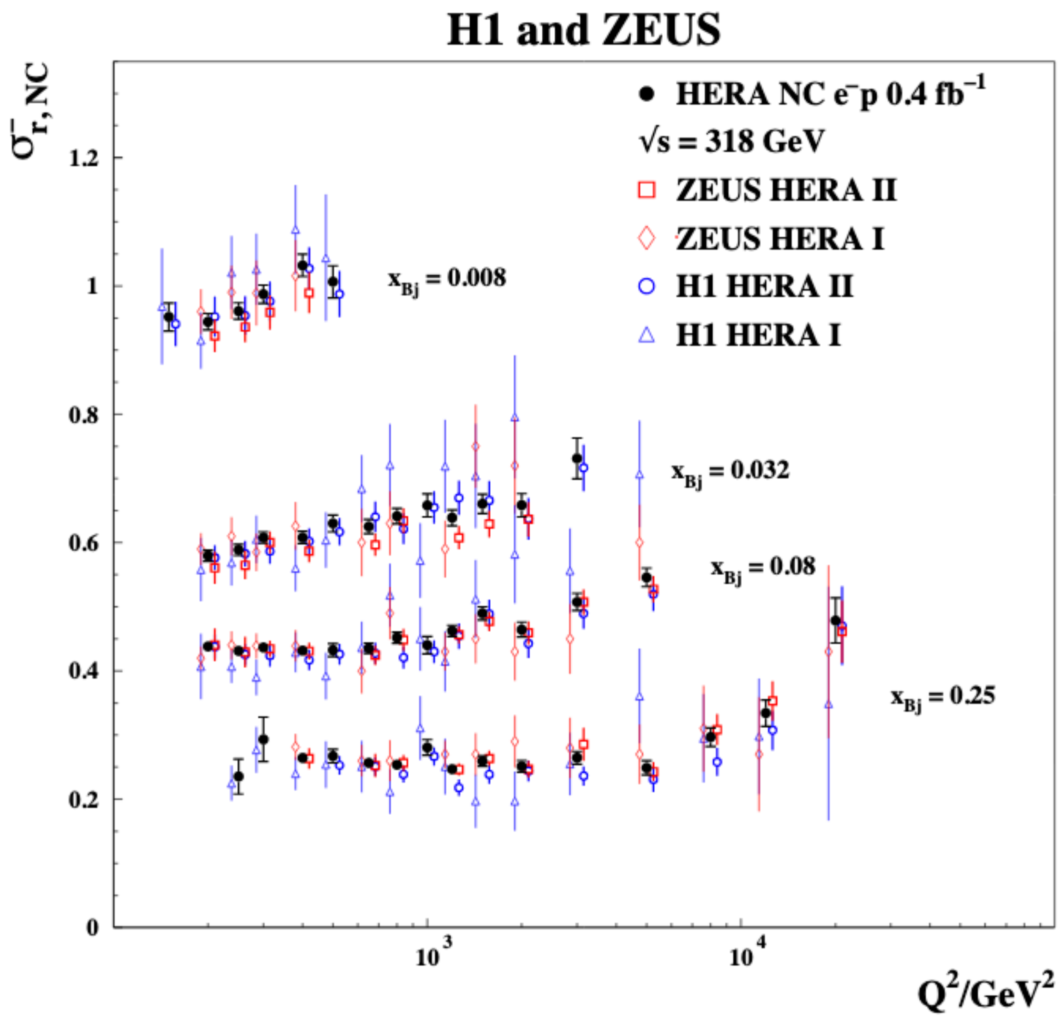
Fit for the systematics as well

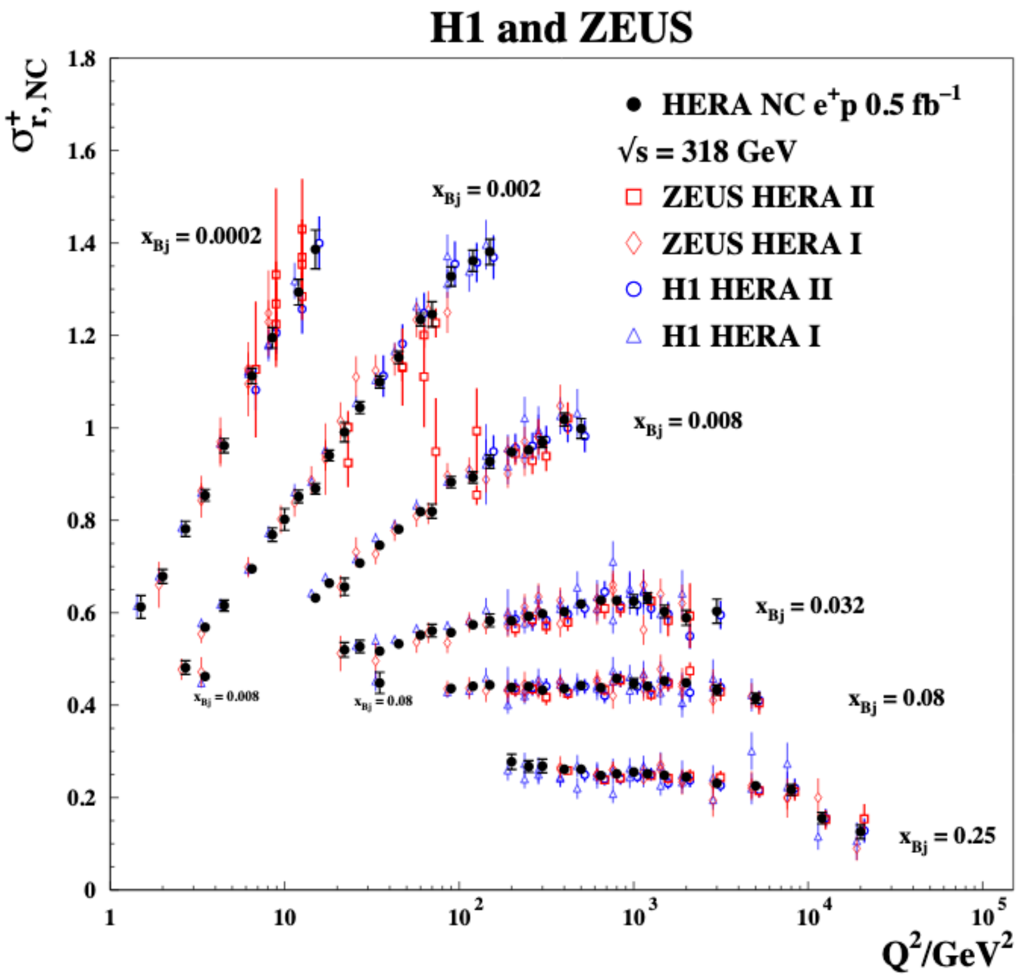


“pull distribution” $\frac{m-\mu}{\sigma}$

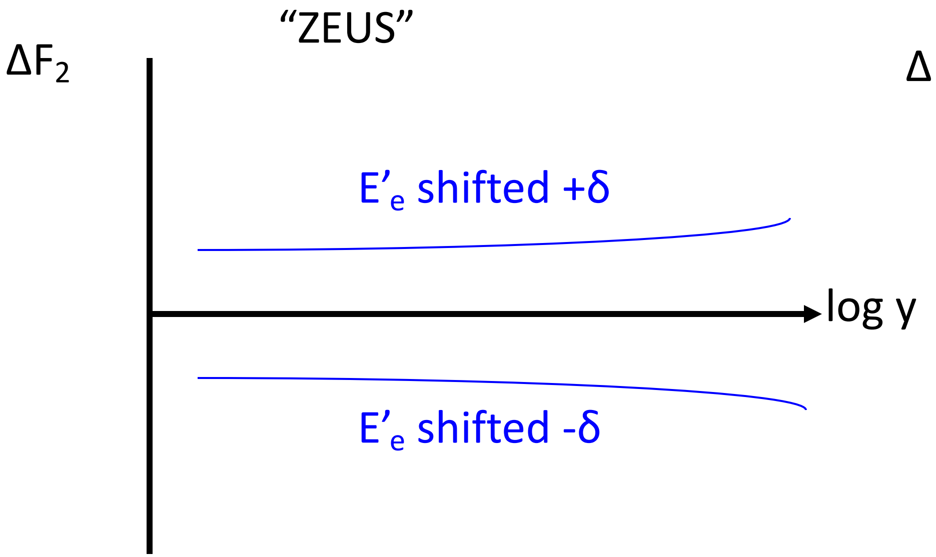
More examples of the combination results

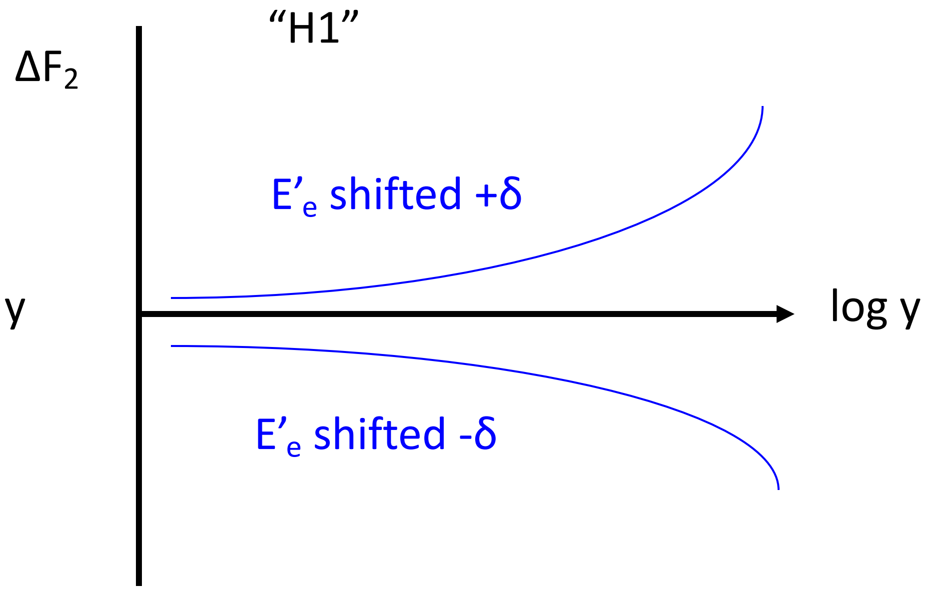
H1 and ZEUS Collab., H. Abramowicz et al., Eur.Phys.J.C75 (2015) 12, 580





What happens to systematic uncertainties.

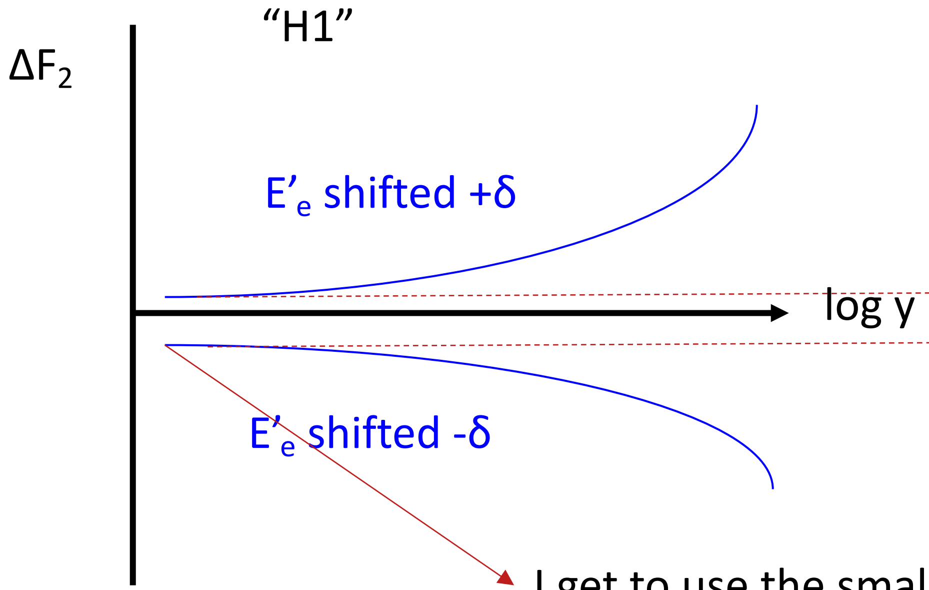


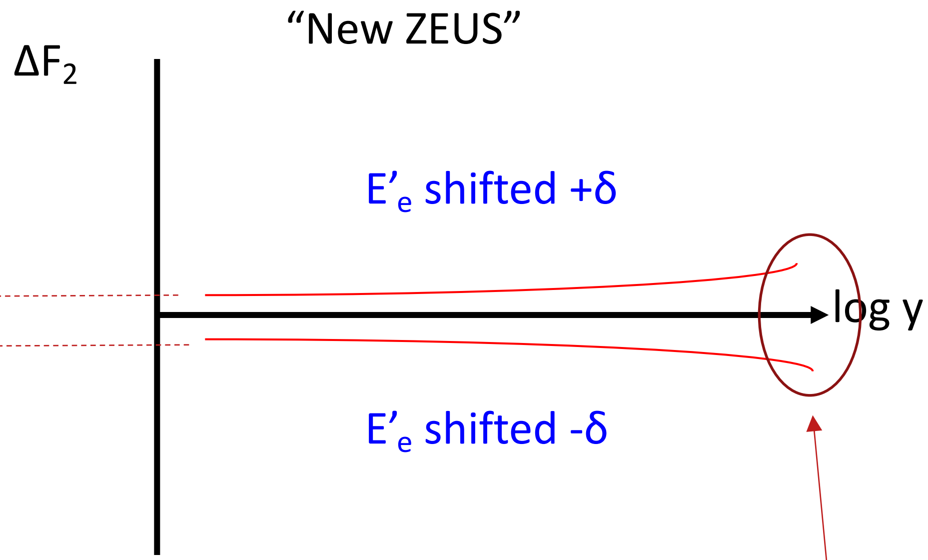


- ZEUS and H1 have similarly sized uncertainties.
- ZEUS and H1 have differently "shaped" uncertainty correlations—different detector and different reconstruction of kinematic quantities.
- ZEUS and H1 have different best measured regions.

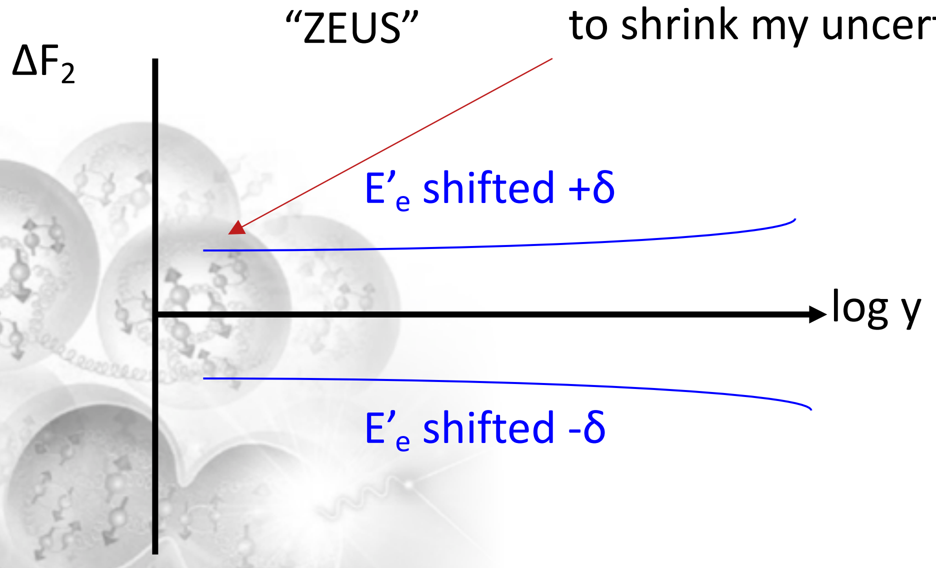
➔ You win big from the fit

Consider the case if there is no statistical uncertainty





I get to use the small uncertainty of “H1” at low y to shrink my uncertainty for ”ZEUS”



Now I can use the small uncertainty of “new ZEUS” to shrink the H1 errors to “nothing”

Of course in practice, the improvement is limited by statistical uncertainties, and our imperfect knowledge of the systematic correlations.

Designing Complementarity

- No one at HERA started by thinking about cancelling systematics between H1 and ZEUS.
- Maybe we should have, though…
- So what were the elements that made this work well?
  - H1 and ZEUS had opposite strength in calorimetry.
    - ZEUS: 18%/sqrt(E) electrons, 35%/sqrt(E) hadrons— ”4π” coverage
    - H1: [12%(barrel) to 7.5%(”rear”)]/sqrt(E) electrons, 50%(barrel)/sqrt(E) hadrons, no hadron calorimeter in “rear”.
  - What we were measuring (x and Q^2) were over-constrained (electron energy and angle, hadron energy and angle).
  - x and Q^2 could be measured over much of the kinematic plane using different methods that utilized different measurements.

So as a result ZEUS and H1 ended up deciding on reconstruction methods with the right characteristics for cancellation of systematics.

Conclusions

- To my knowledge, there has never been *a large scale attempt* to design collider detector(s) in such a way as to minimize systematics by trying to cancel them.
- Normally
  - Detector elements are individually studied for systematic uncertainties before the experiments.
  - After the experiment, during the analyses, we hunt for ways to control the systematics.
- There is no reason, that H1 and ZEUS detectors could not have been designed to cancel each others systematics.
  - This happened essentially by accident.
  - Could the cancellation been much better, if we had planned for it?
- I think it's time to start taking these things into account as we build new detector(s).