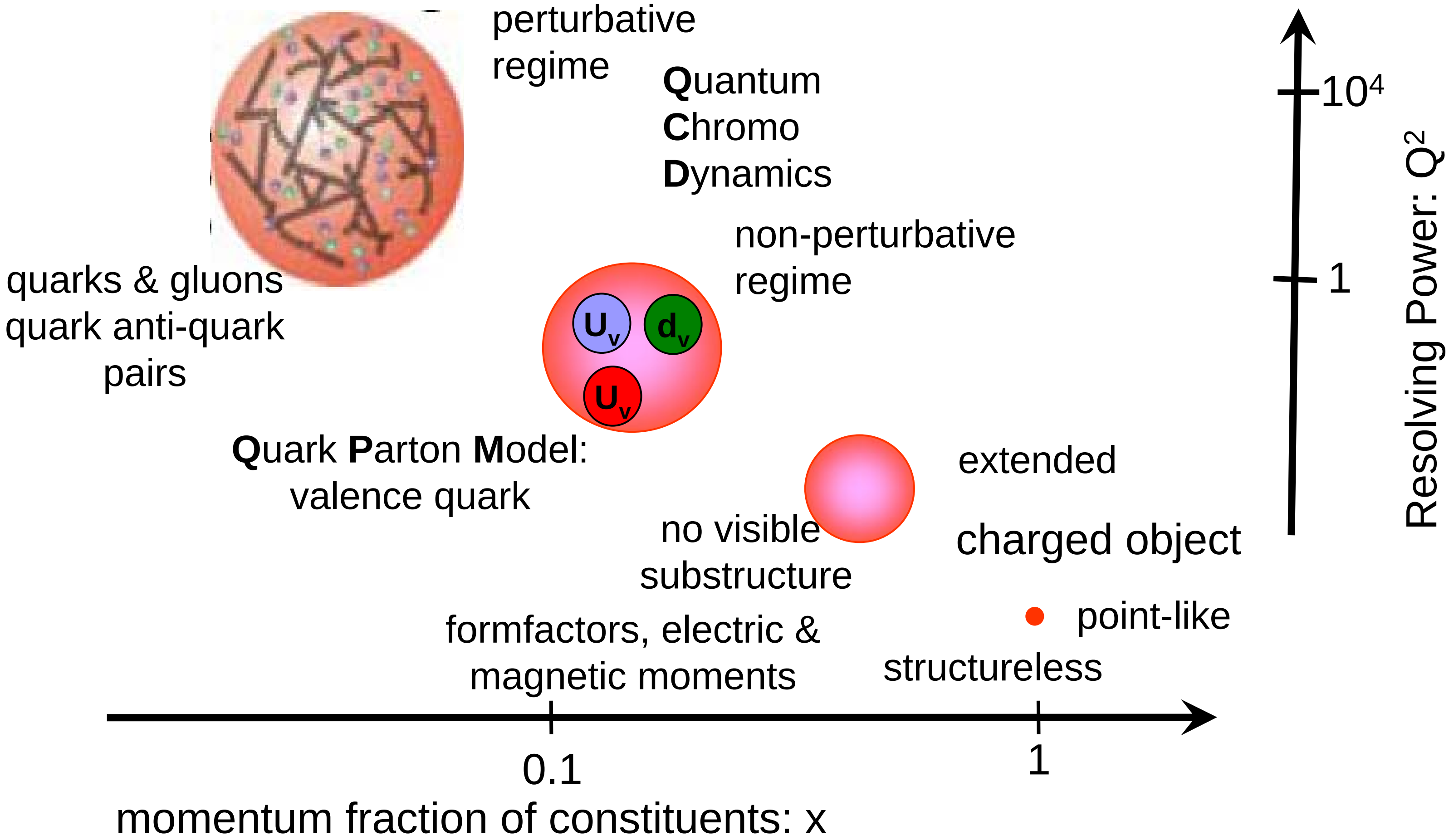
Proton Structure at Low x and Low Q^2 in Deep Inelastic Scattering at Hera

Burkard Reisert
for H1 and Zeus

- Deep Inelastic Scattering
- Hera, H1 & ZEUS
- Experimental Results
- Extraction of Parton Densities
- Hera Low Energy Run

Motivation: "Images" of the Proton



Low Q^2 : probing transition perturbative to non-perturbative QCD
Low x: probing quarks and gluons at high density

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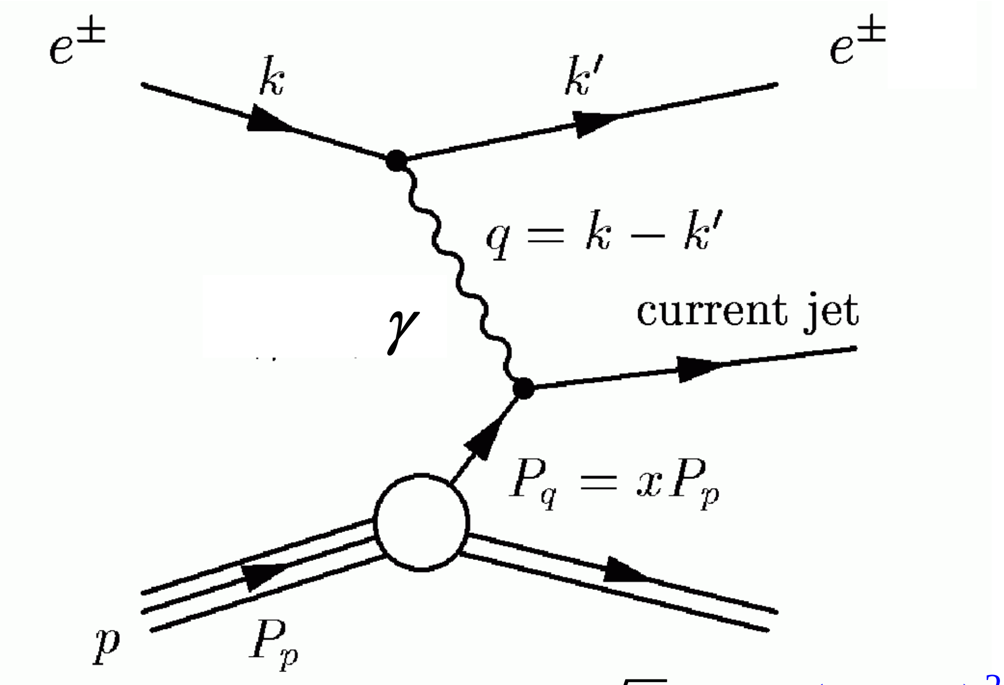
Deep Inelastic Scattering



Kinematic Variables

- **4-momentum transfer resolving power** $Q^2 = -q^2 = -(k-k')^2$
- **Bjørken scaling variable momentum fraction of struck parton** $x = \frac{Q^2}{2p\cdot q}$
- **Inelasticity:** $y = \frac{p\cdot q}{p\cdot k}$

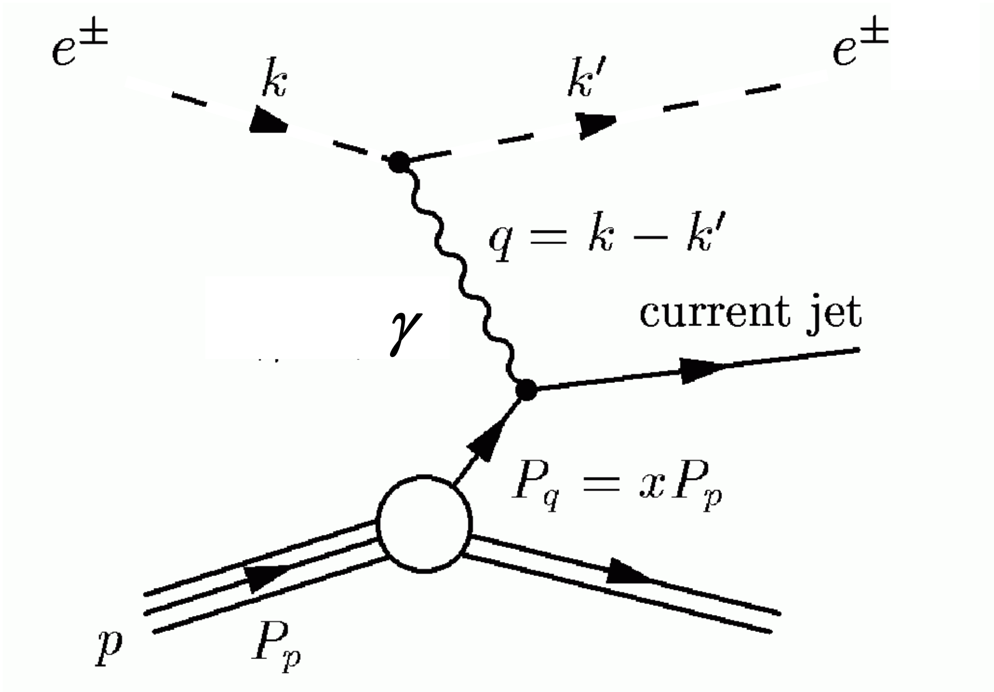
Center of mass energy $\sqrt{s}$: $s = (k+p)^2$ **relation for fixed s:** $Q^2 = sxy$

- **Neutral current DIS cross section expressed by structure functions:**

$$\frac{d^2\sigma^{e^\pm p\to e^\pm X}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{\left(1+(1-y)^2\right)}_{Y_\pm = 1\pm(1-y)^2}\cdot\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right)$$

$\tilde{\sigma}_r$: Reduced cross section

Photon Proton Scattering



- The same process may be interpreted as scattering of an virtual photon off an proton
- Photon Proton centre-of-mass energy:

$$W_{\gamma p}^2 \equiv -\left(P+q\right)^2 = ys - Q^2$$

γp Cross Sections:

$$\sigma_T^{\gamma p} = \frac{4\pi\alpha}{Q^2} 2xF_1$$

$$\sigma_L^{\gamma p} = \frac{4\pi\alpha}{Q^2}\left(F_2 - 2xF_1\right) = \frac{4\pi\alpha}{Q^2} F_l$$

Quark Parton Model (QPM)

$$F_1\left(x\right) = \frac{1}{2x}\sum\nolimits_q e_q^2 xq(x)$$

$$F_2\left(x\right) = \sum\nolimits_q e_q^2 xq(x)$$

$$F_L\left(x\right) = F_2 - 2xF_1 = 0$$

Callan Gross relation

Structure Functions

- **Proton Structure Function F_2**

$$F_2 = \sum_q A_q(Q^2)\left[xq + x\bar{q}\right], \quad \text{at low } Q^2\text{: } A_q(Q^2) = e_q^2$$

$$A_q(Q^2)\text{: Electro weak coefficient function}$$

- **Longitudinal Structure Function F_L**

  Quark Parton Model (spin ½ partons only): $F_L=0$

  QCD: (NLO)

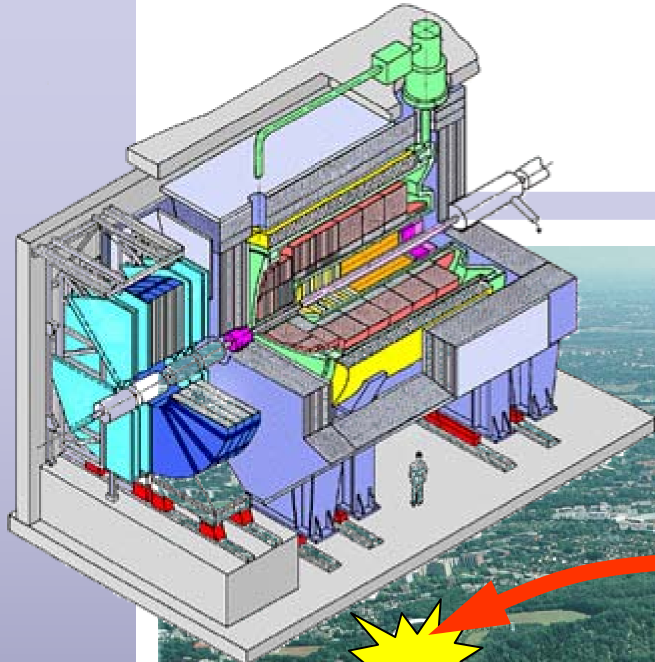
$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}\underbrace{\sum_q e_q^2\left(xq + x\bar{q}\right)}_{F_2} + 8\sum_q e_q^2\left(1-\tfrac{x}{z}\right) zg\right]$$

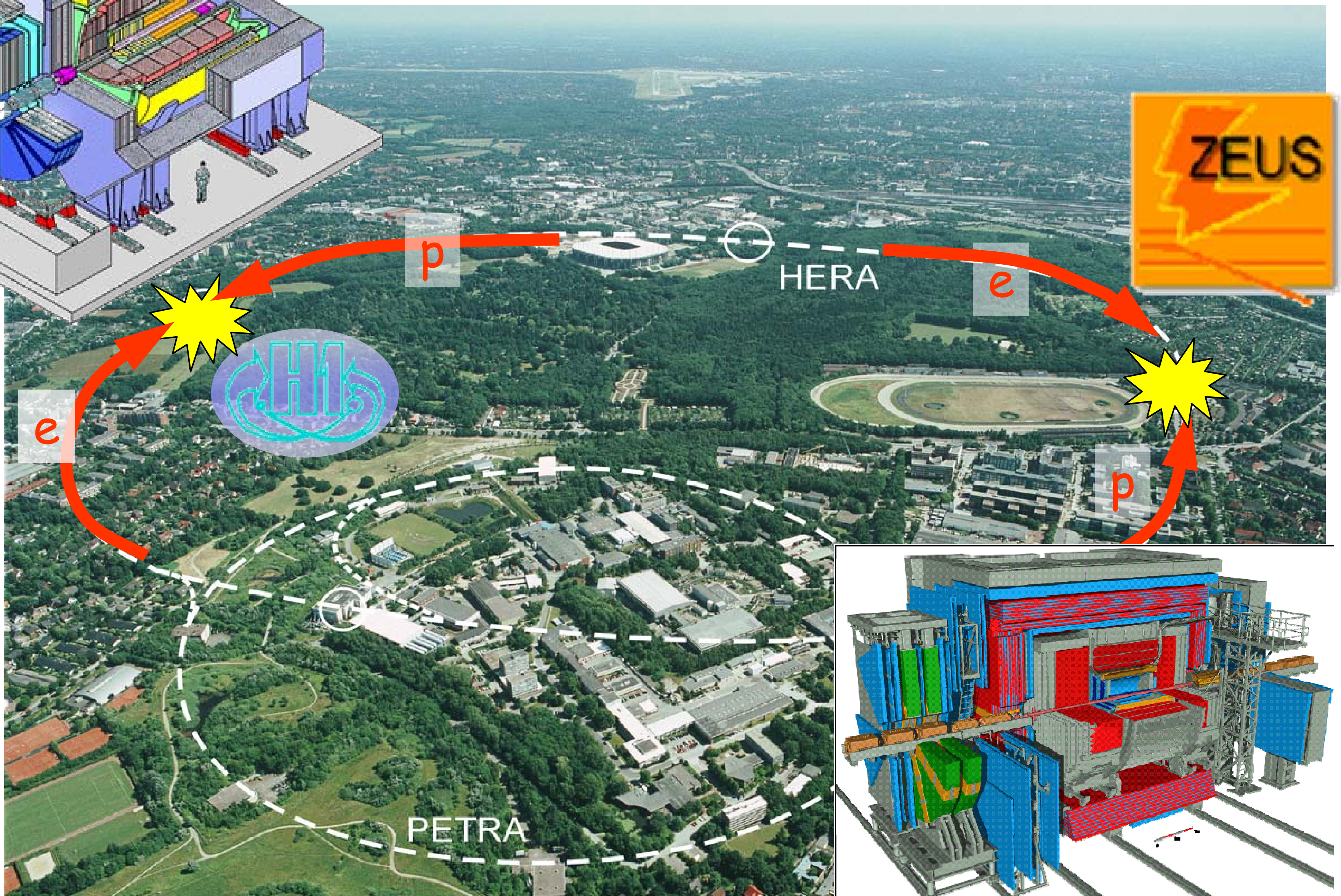
Direct sensitivity to gluon

- F2 is sensitive to quark densities,
  gluons are accessible only through scaling violations

- Sizable contribution of F_L only at high *y*

HERA Accelerator





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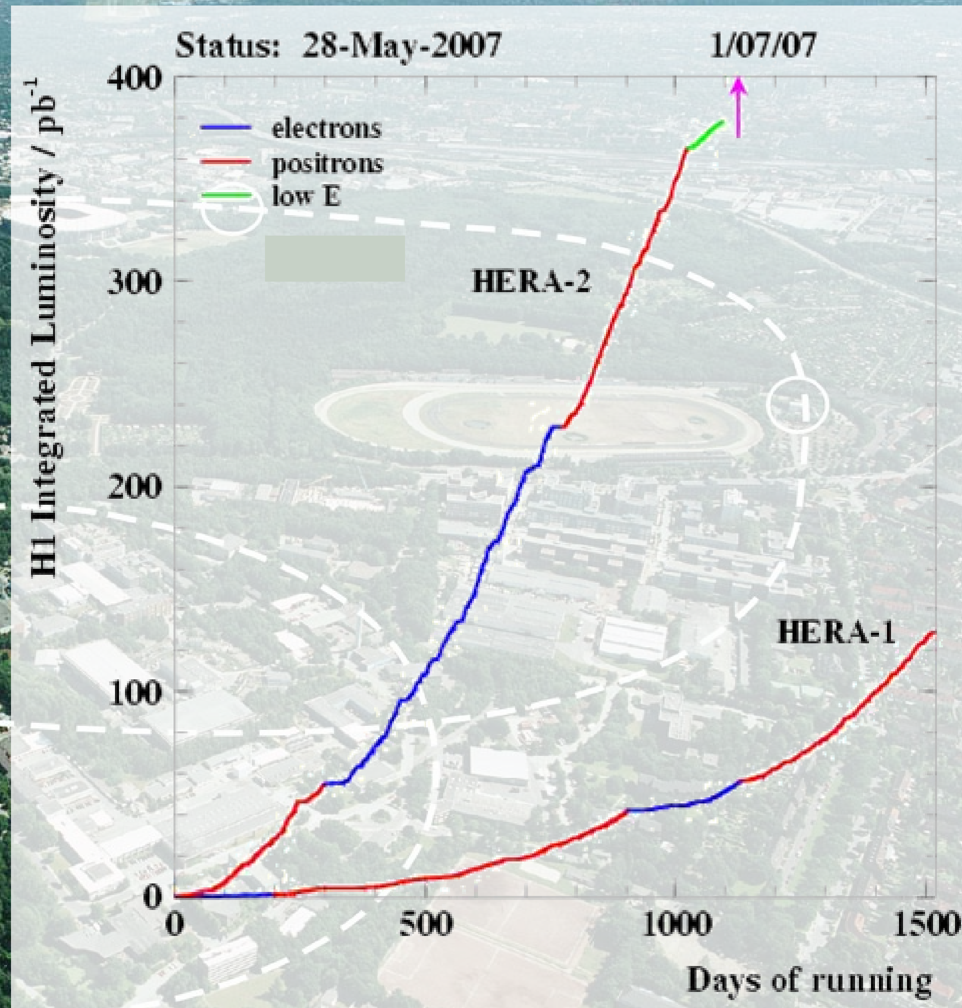
HERA Accelerator Performance

HERA High Energy Run

E_e=27.5GeV →← E_p =920GeV

Concluded March 21st

HERA-1 & HERA-2 combined integrated Luminosity L = 0.5 fb^{-1} per experiment



Special runs until July 2nd

HERA Low Energy Run

E_e=27.5GeV →← E_p=460 GeV

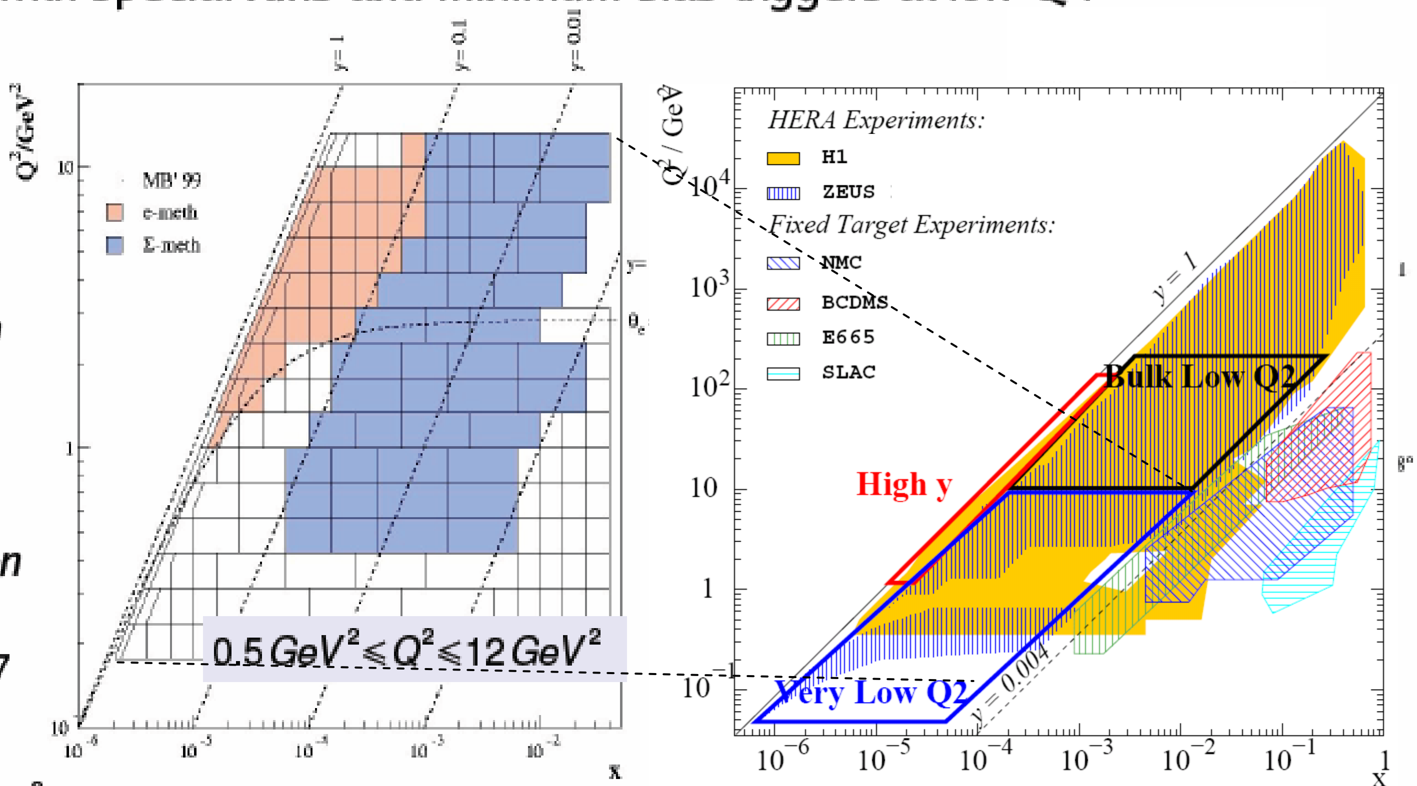
.. and ← E_p=575 GeV

H1 Low Q^2 Data Samples

Data sets taken with special runs and minimum bias triggers at low Q^2:

- MB'99
  $\mathscr{L}=2.1\ \text{pb}^{-1}$
  high y extension
- SVX'00
  $\mathscr{L}=504\ \text{nb}^{-1}$
  low Q^2 extension
- Published MB'97
  $\mathscr{L}=1.8\ \text{pb}^{-1}$

$1.5\,GeV^2 \leq Q^2 \leq 12\,GeV^2$



$\sqrt{s}=318\,GeV$ MB'99, SVX'00

$\sqrt{s}=300\,GeV$ MB'97

} to be combined

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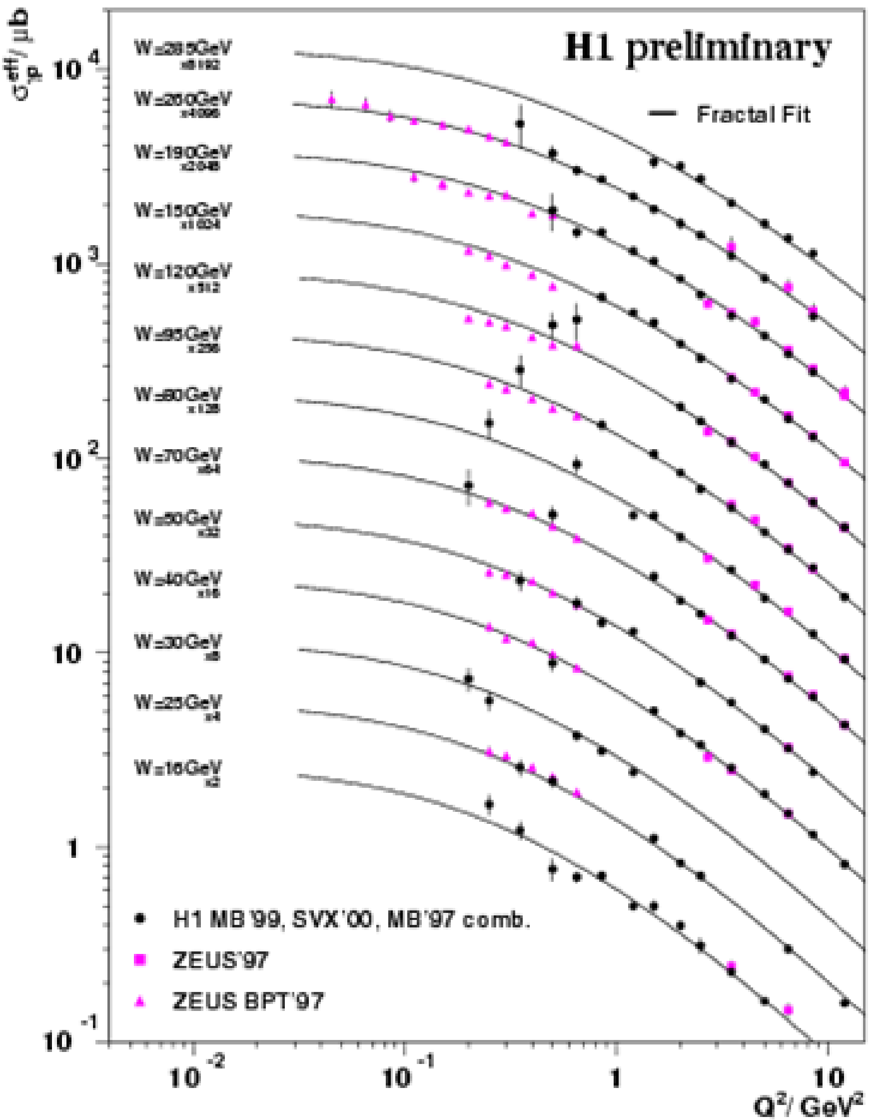
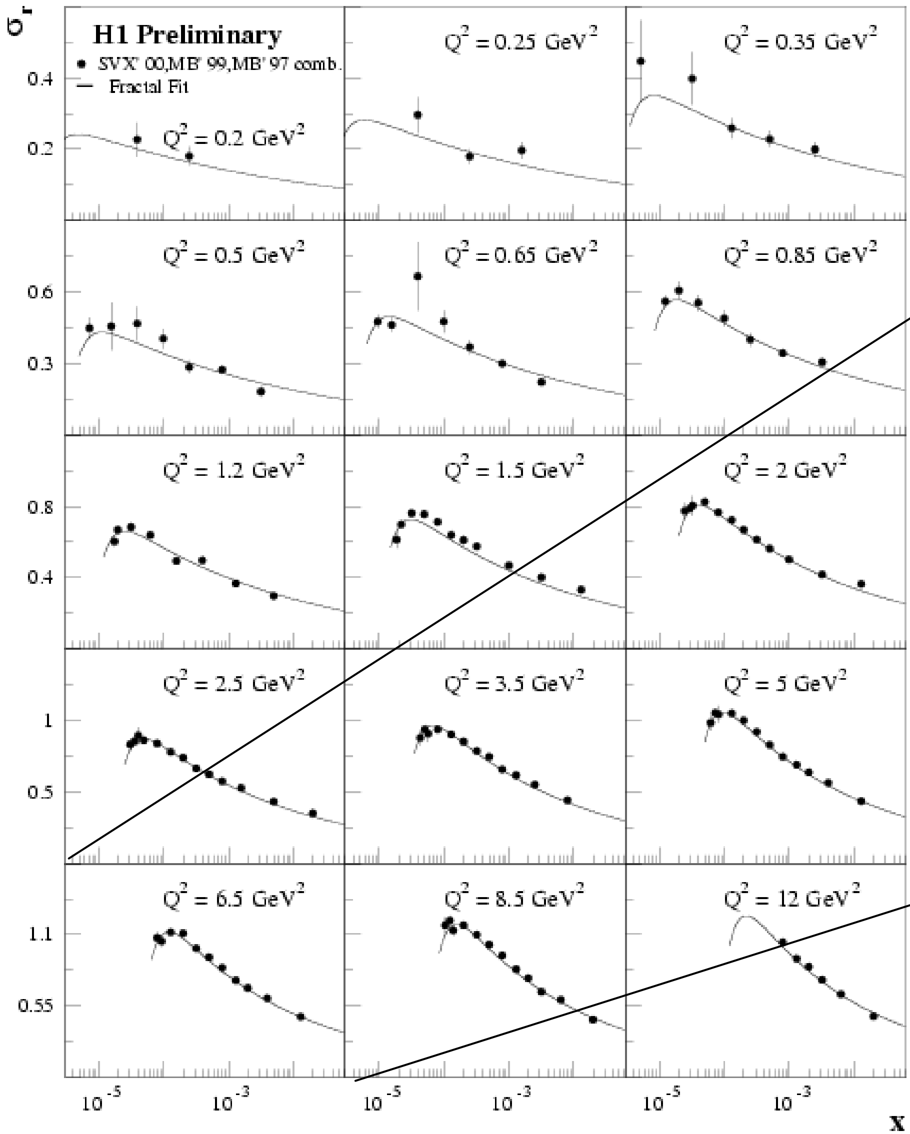
Cross Sections at Lowest Q^2

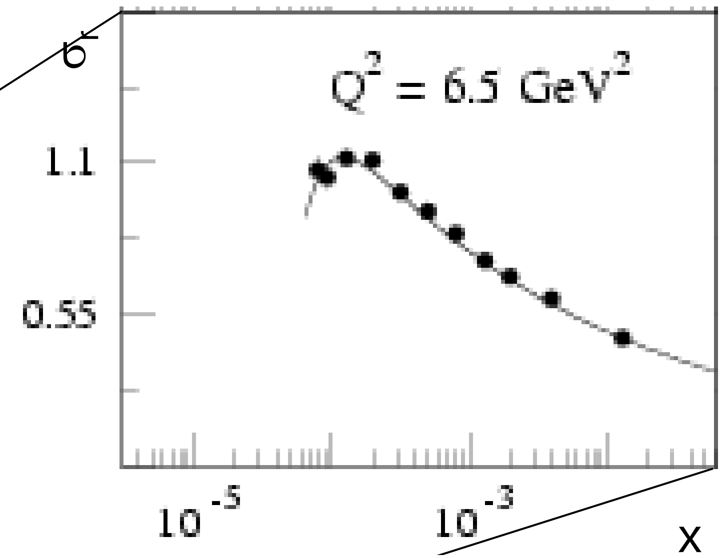


- Measurement presented as effective γ^*p cross section
- precision of combined measurements better than 2%
- Smooth transition from perturbative to non-perturbative regime at $Q^2 \sim 1GeV^2$

Cross Sections at Lowest Q^2



Same data presented as reduced ep cross section



Sensitivity to FL at High y (= low x)

$$\sigma_r = F_2 - \frac{y^2}{Y_+} F_L$$

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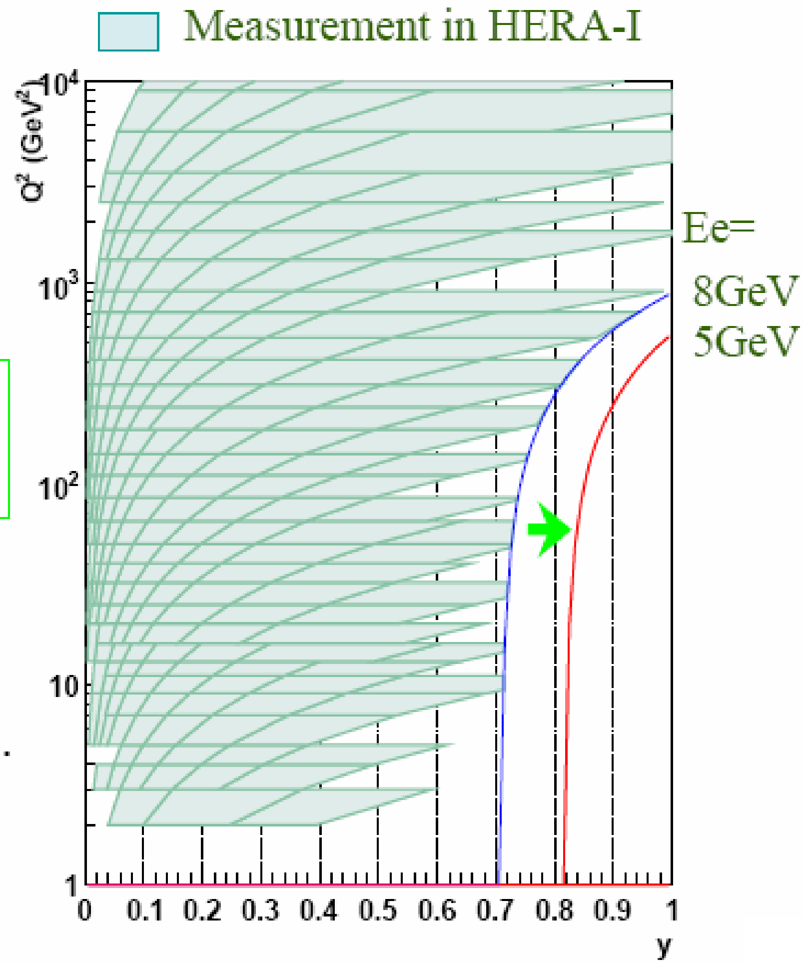
New Measurement at High *y*

ZEUS performed a new DIS measurement which is optimized for high-y.

- Previous measurement: 1996-97 data (HERA-I).
- New trigger was developed.
  → It allows to go to lower electron energy.
  8GeV → 5GeV

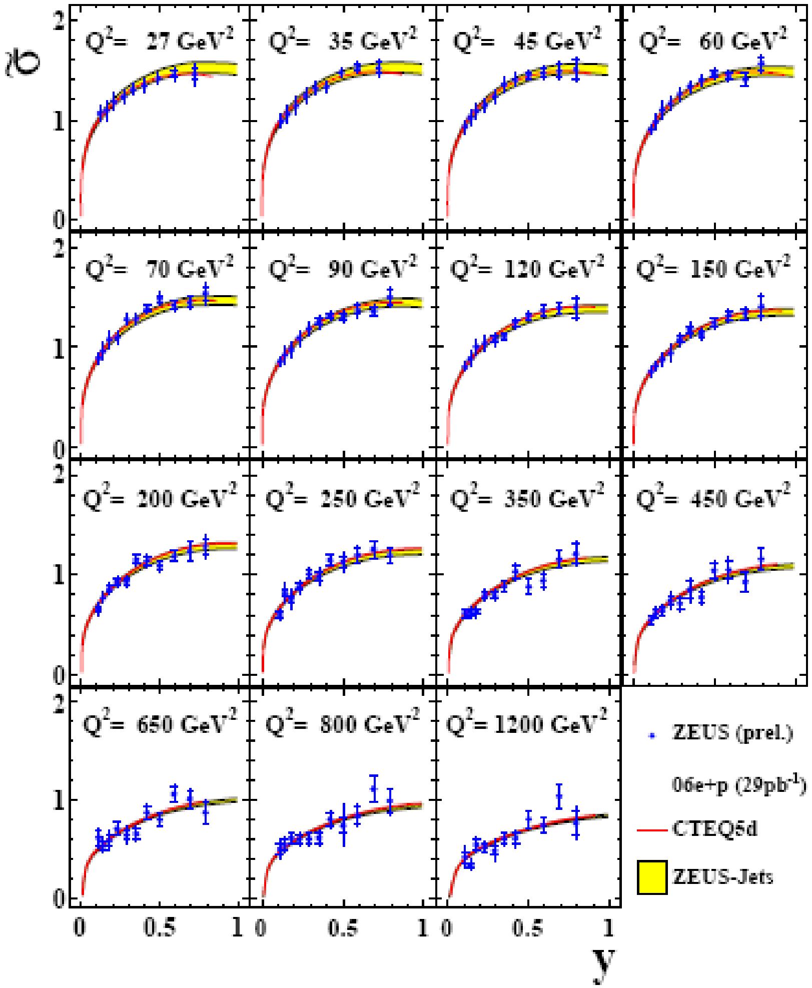
New kinematic region at high-y



- High-y = Low Ee;
  - Ee should be well understood.
  - Severe background contamination.

The same analysis method can be also used in F_L measurement.

Reduced Cross Section vs. y



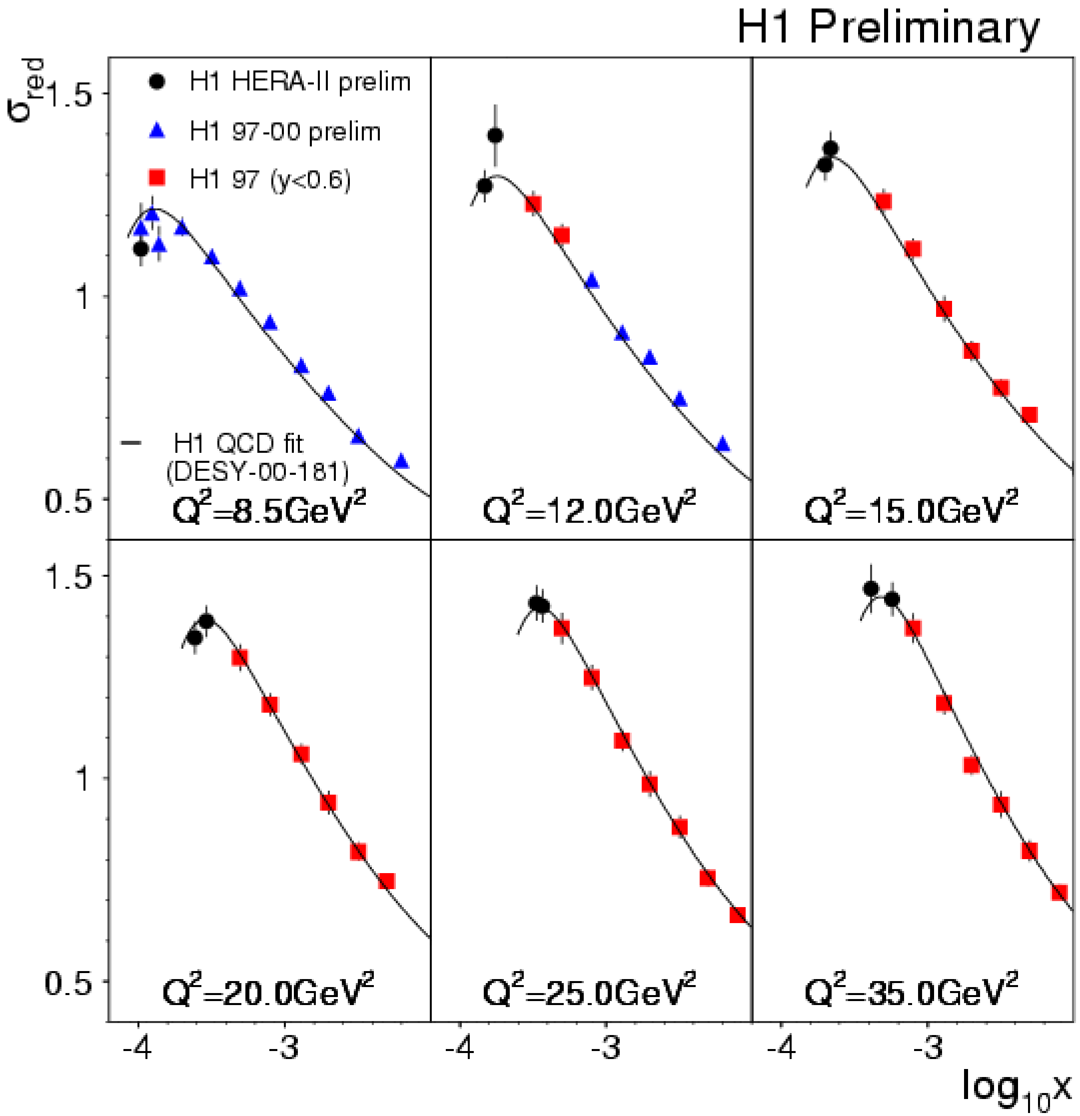
- Measured reduced cross sections are compared to SM predictions with
  - CTEQ5D
  - ZEUS-Jets PDF

  → They are well described by the predictions.

- Systematic checks

• Electron energy scale	2%
• PHP norm. factor	10%
• Electron finding inefficiency	10%
• E-pz threshold	2GeV

High y Results from H1



Precision improved by factor 2 w.r.t. previous publications

total error: 2-3%

Will be extended to lower and higher Q^2

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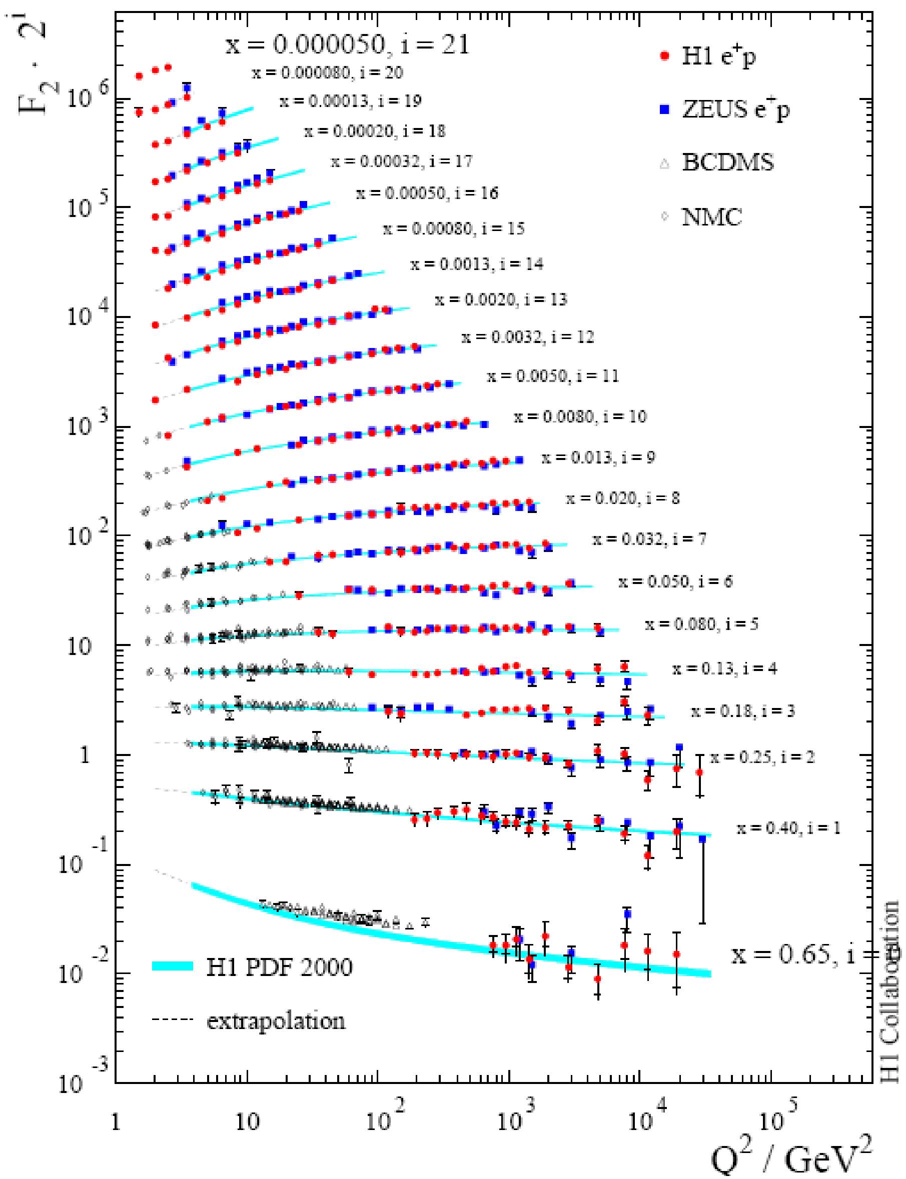
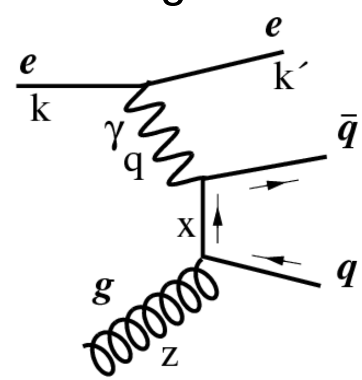
Structure Function F_2



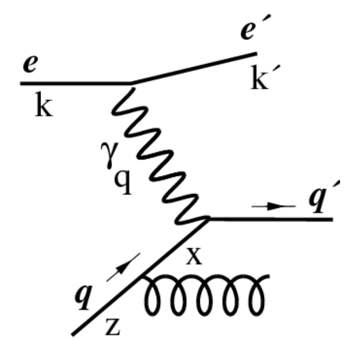
- H1 & Zeus extended fixed target kinematic regime in x and Q^2 by 2 Orders

- Scaling violations



rise at low x

drop at low x



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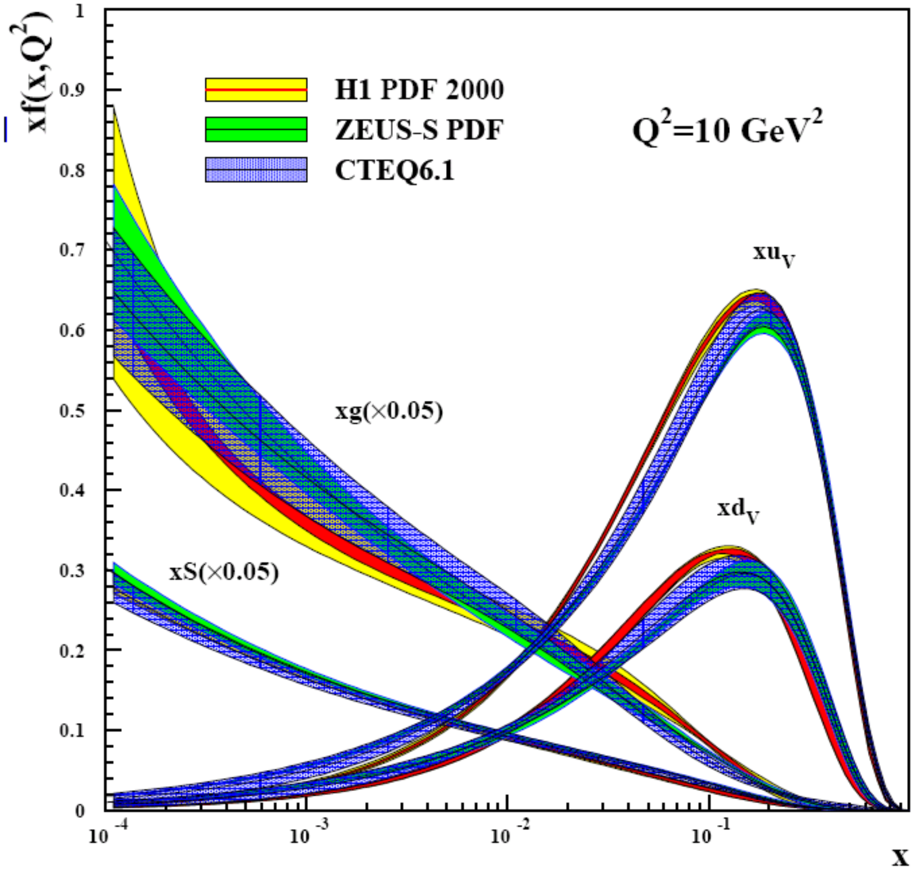
PDF results

Both Collaborations perform NLO QCD Fits to extract Parton Densities Functions from HERA data only

H1&Zeus: dedicated Fit exploiting inclusive cross sections
NC & CC, e^+p & e^-p,
Zeus includes Jet data

Despite many differences in details of the fits (e.g. data samples implementation of NLO scheme, parameterized PDFs, starting scale, etc…) resulting PDFs are in good agreement

Largest differences seen for gluon



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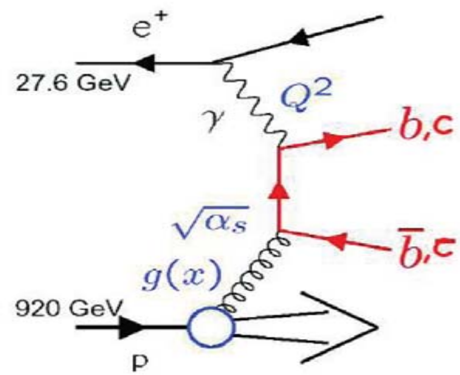
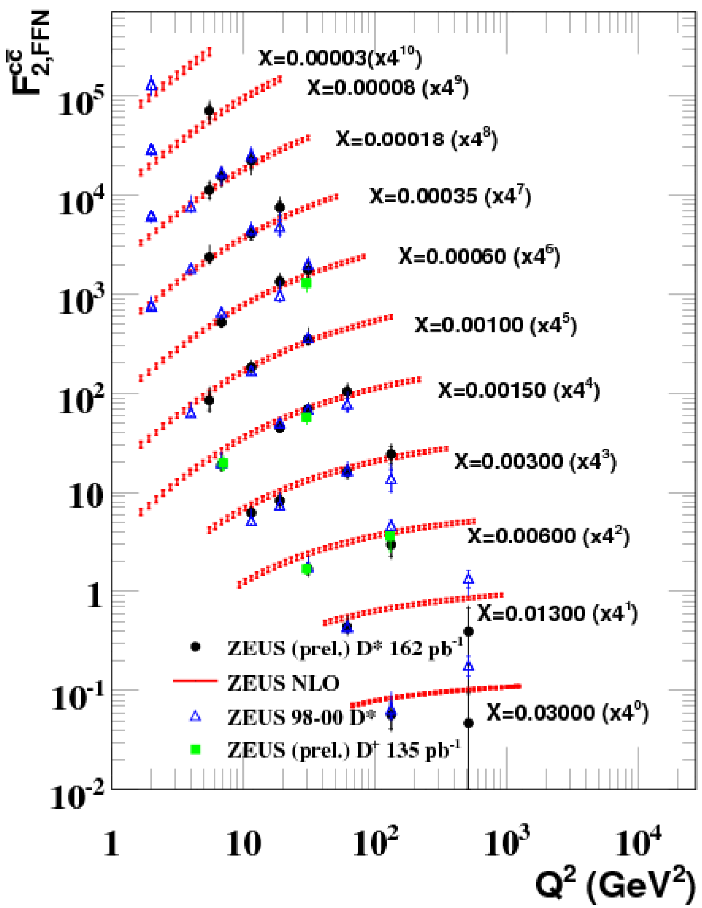
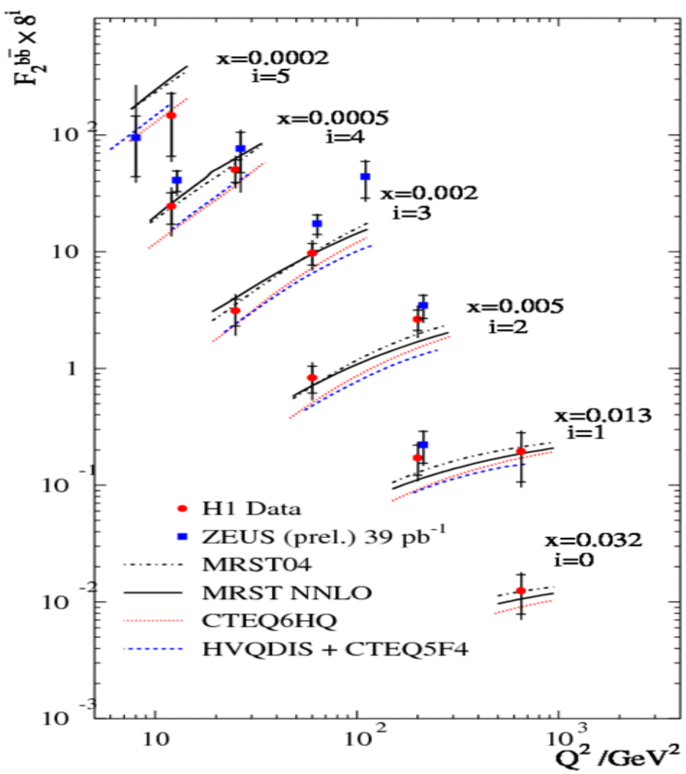
Charm & Beauty Structure

Charm and Beauty production in DIS is driven by gluons in the proton

Charm tag: reconstruct D mesons
Beauty tag: displaced vertex, soft μ







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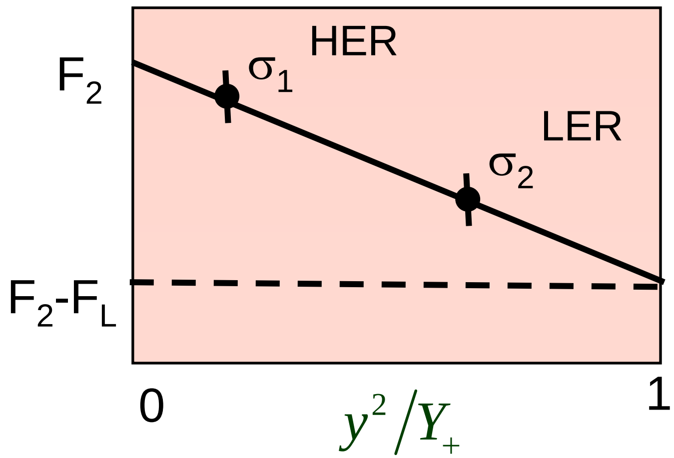
Direct measurement of F_L

- Measurement of F_L will give access to gluon: $F_L \propto \int_x^1 \frac{dz}{z^3}\left[\sum_q e_q^2 \left(1-\frac{x}{z}\right) zg\right]$
- Measure cross section $\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{Y_+} F_L\left(x,Q^2\right)$
at same *x* and Q2 but different y, i.e. different centre-of-mass energy



- Change proton beam energy to change cms energy
- Large level arm in y^2/Y_+
- measure at high *y* in LER

- measurement in is already extended to high y region
- Both detectors in good shape
- Need ~$10pb^{-1}$ for measurement

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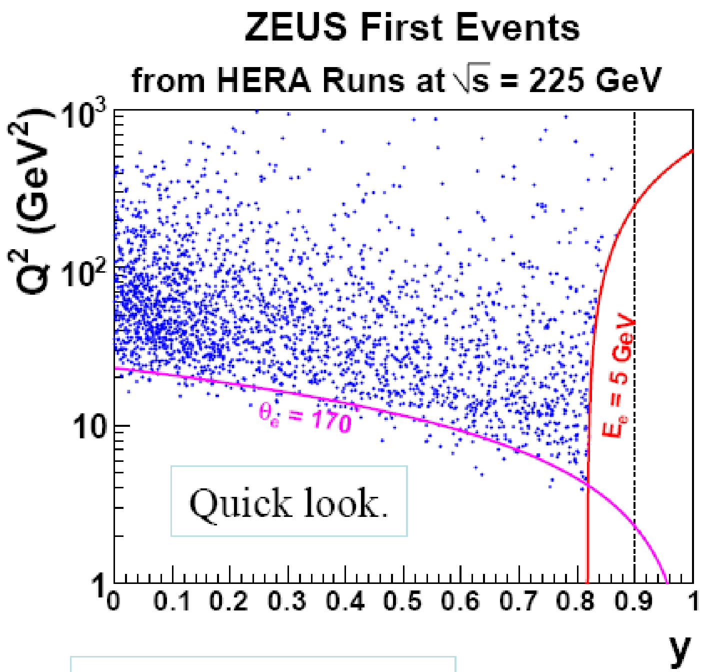
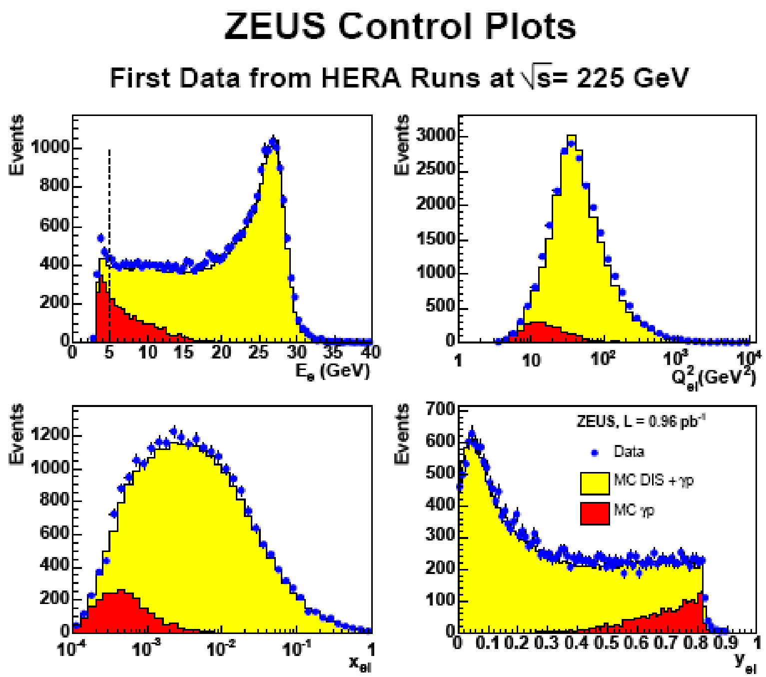
First Look at Low Energy Data

- Both experiments are collecting data with good efficiency
- Quick look at the first week of LER data taking (~1pb^{-1})
  → Good data quality



We will enlarge the measurement region.



- Performance of HERA exceeds expectations: Already more than 10pb-1 of good physics data recorded by each experiment
- Last month of HERA: record data at intermediate Energy $\sqrt{s}$ = 250 GeV

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Summary

- H1 performed final measurement of cross section at low Q2 for HERA-I, showing a smooth transition from perturbative to non-perturbative regime.
- H1 & Zeus explore the full kinematic regime accessible at HERA including high y region.
- Extraction of flavor separated PDFs by both experiments
- HERA Low Energy running will measure F_L giving access to gluon density
- Precise measurements of cross sections and structure functions are an integral part of the rich HERA legacy

Backup slide

Contents:

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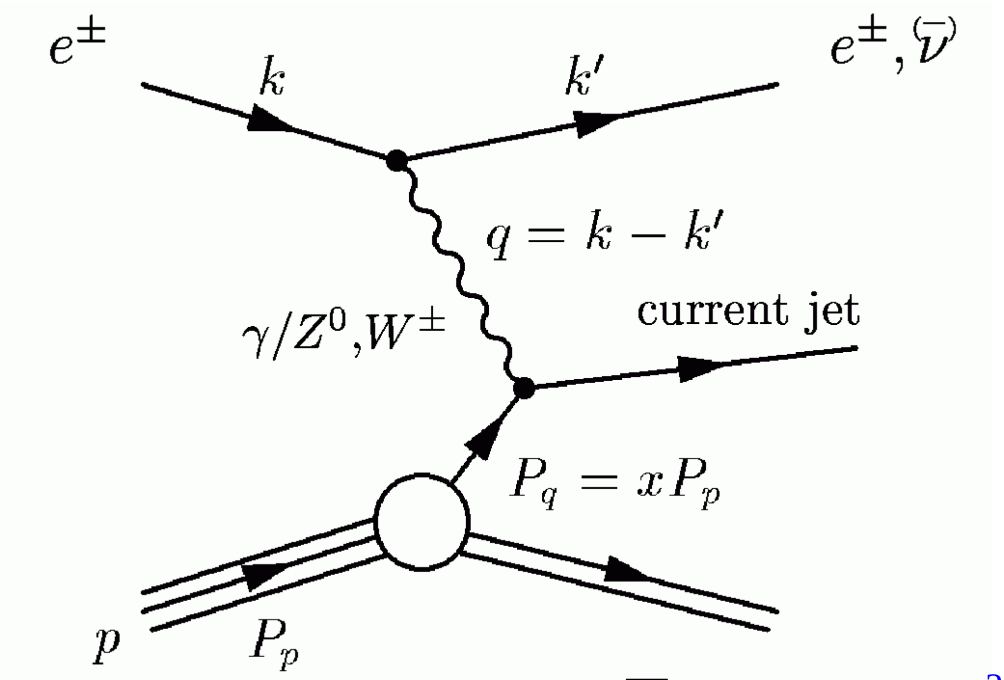
Deep Inelastic Scattering



Kinematic Variables

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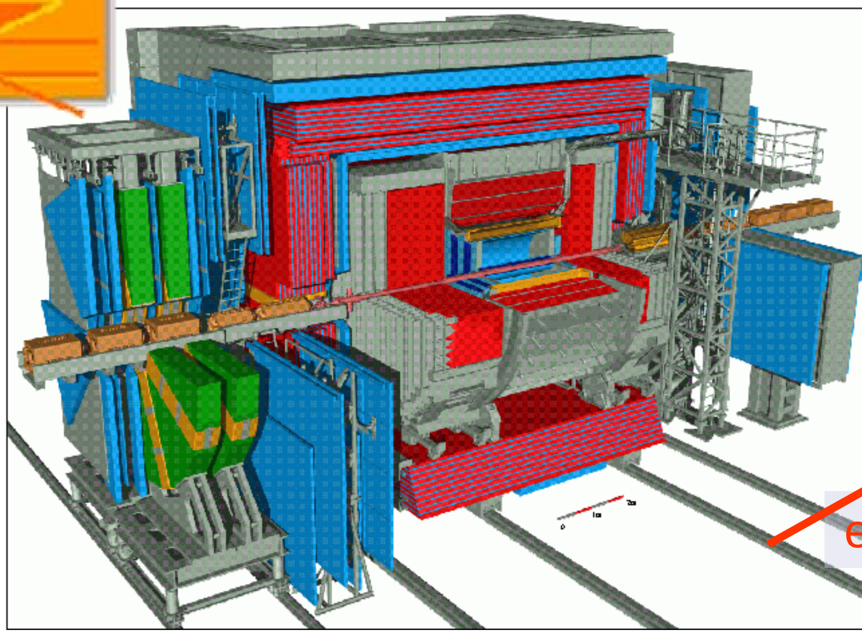
- **Neutral current DIS cross section expressed by structure functions:**

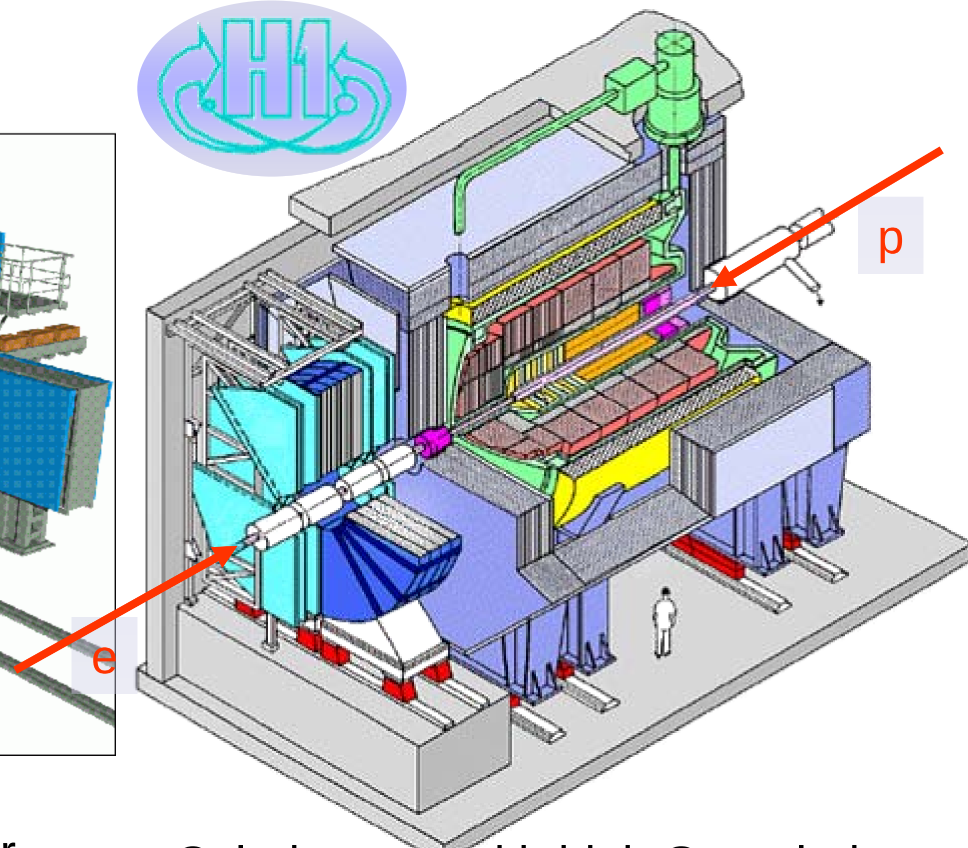
$$\frac{d^2\sigma^{e^{\pm}p \to e^{\pm}X}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \underbrace{\left(1+(1-y)^2\right)}_{Y_{\pm}=1\pm(1-y)^2} \cdot \left(F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \mp \frac{Y_-}{Y_+} xF_3(x,Q^2) \right)$$

High Q² only

$\tilde{\sigma}$: Reduced cross section

H1 & Zeus Experiments





Compensating Uranium Scintillator Calorimeter (~6000 cells)

$\Delta E_e/\mathrm{Sqrt}(E_e(\mathrm{GeV}) = 18\%$

$\Delta E_h/\mathrm{Sqrt}(E_h(\mathrm{GeV}) = 35\% \oplus 1\%$

$\delta\theta_e$ = 2mrad

Calorimeters with high Granularity (Liquid argon & Scint. fiber + lead Calorimeters: ~ 45000 cells)

$\Delta E_e/\mathrm{Sqrt}(E_e(\mathrm{GeV}) = 12\% \oplus 1\%$

$\Delta E_h/\mathrm{Sqrt}(E_h(\mathrm{GeV}) = 50\% \oplus 1\%$

$\delta\theta_e$ = 3mrad (cal) 2mrad (tracker)

Combination of Datasets

combination of data sets requires a proper handling of systematic & statistical errors.

Let Λ^i be a set of cross section measurement, then Λ^{Ave} is obtained:

$$\chi^2(\Lambda^{Ave},\alpha)=\sum_{k=1}^{exp}\sum_i^{bins}\frac{\left[\Lambda^{i,Ave}-\left(\Lambda_i^k+\sum_{j=1}^{syst}\frac{\partial\Lambda_i^k}{\partial\alpha_j^k}\alpha_j^k\right)\right]^2}{\sigma^2_{\Lambda_i^k}}+\sum_{k=1}^{exp}\sum_{j=1}^{syst}\frac{(\alpha_j^k)^2}{\sigma^2_{\alpha_j^k}}$$

- Input:

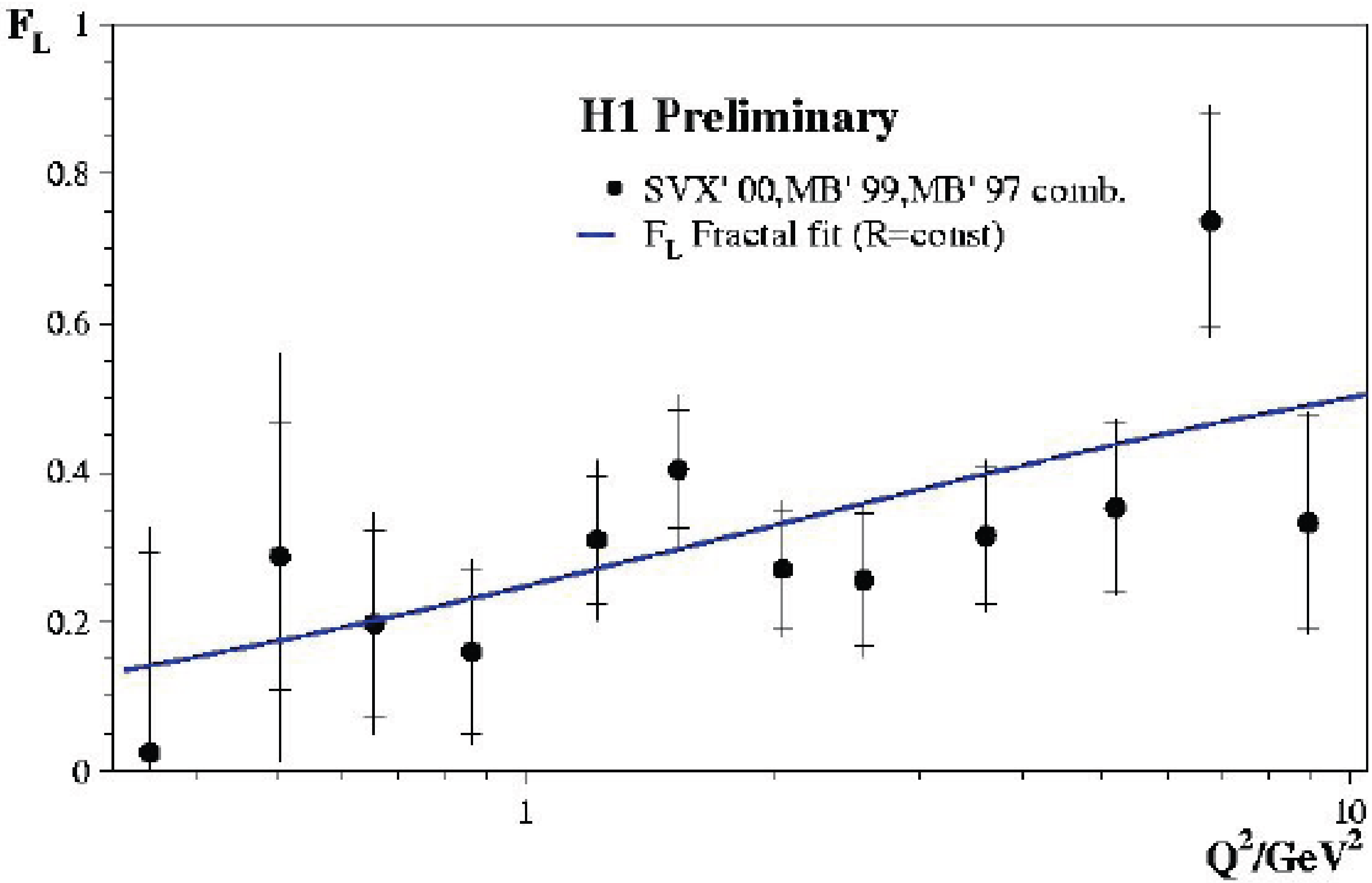
  $\Lambda^i, \frac{\partial\Lambda_i}{\partial\alpha_j}, \sigma^2_{\Lambda,i}, \sigma_{\alpha_j}$ uncertainty on the source

  sensitivity to correlated syst — stat+uncorr uncertainty

- Output:

  Λ^{Ave}, α_j shift on the uncertainty of the source

? Extraction of F_L



F_L extracted from λ fit

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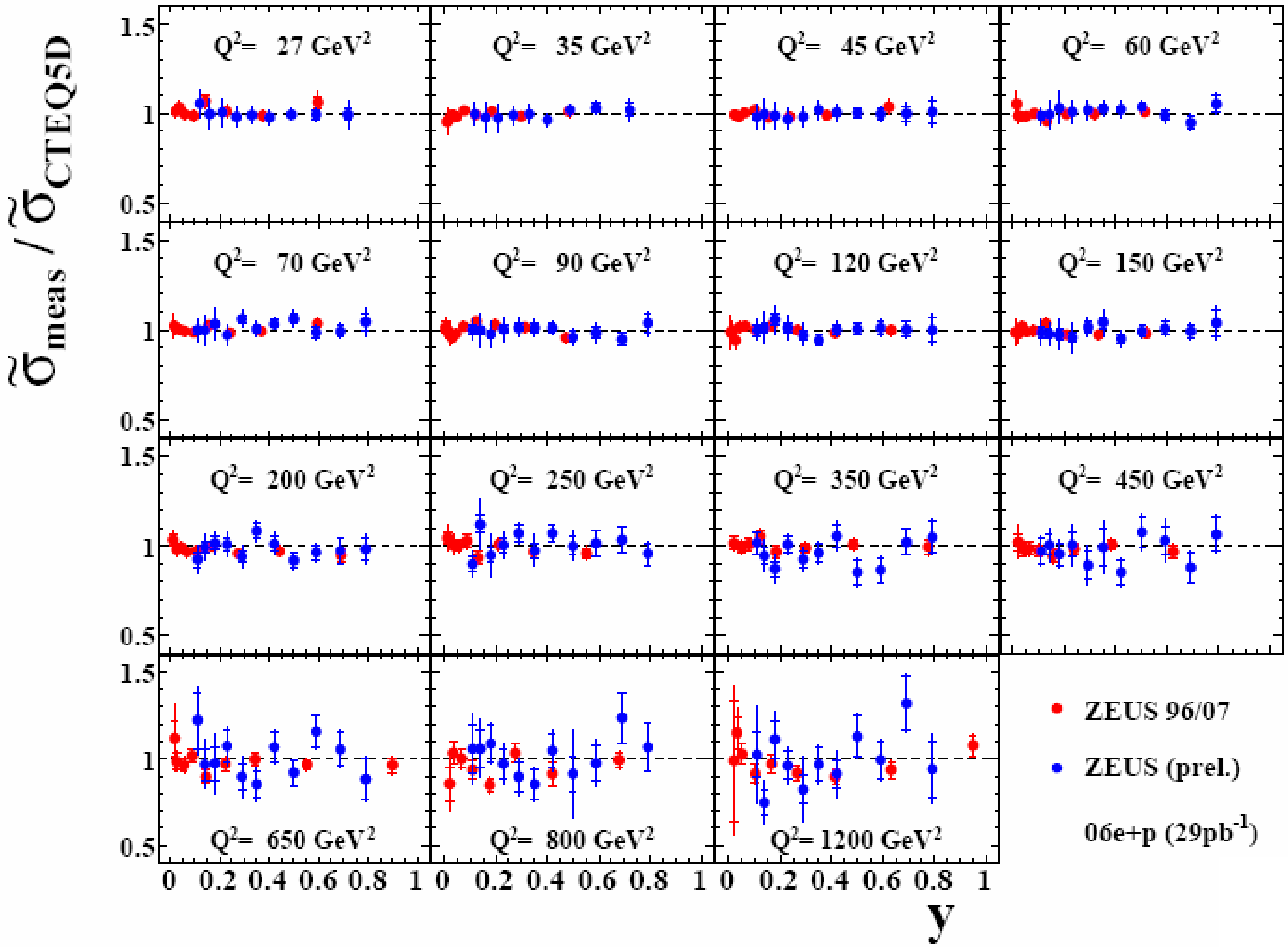
Comparison with HERA-I results



- Measurement is extended to high-y region especially at low Q^2 compared to HERA-I.

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Additional Material & Ideas for Improvements

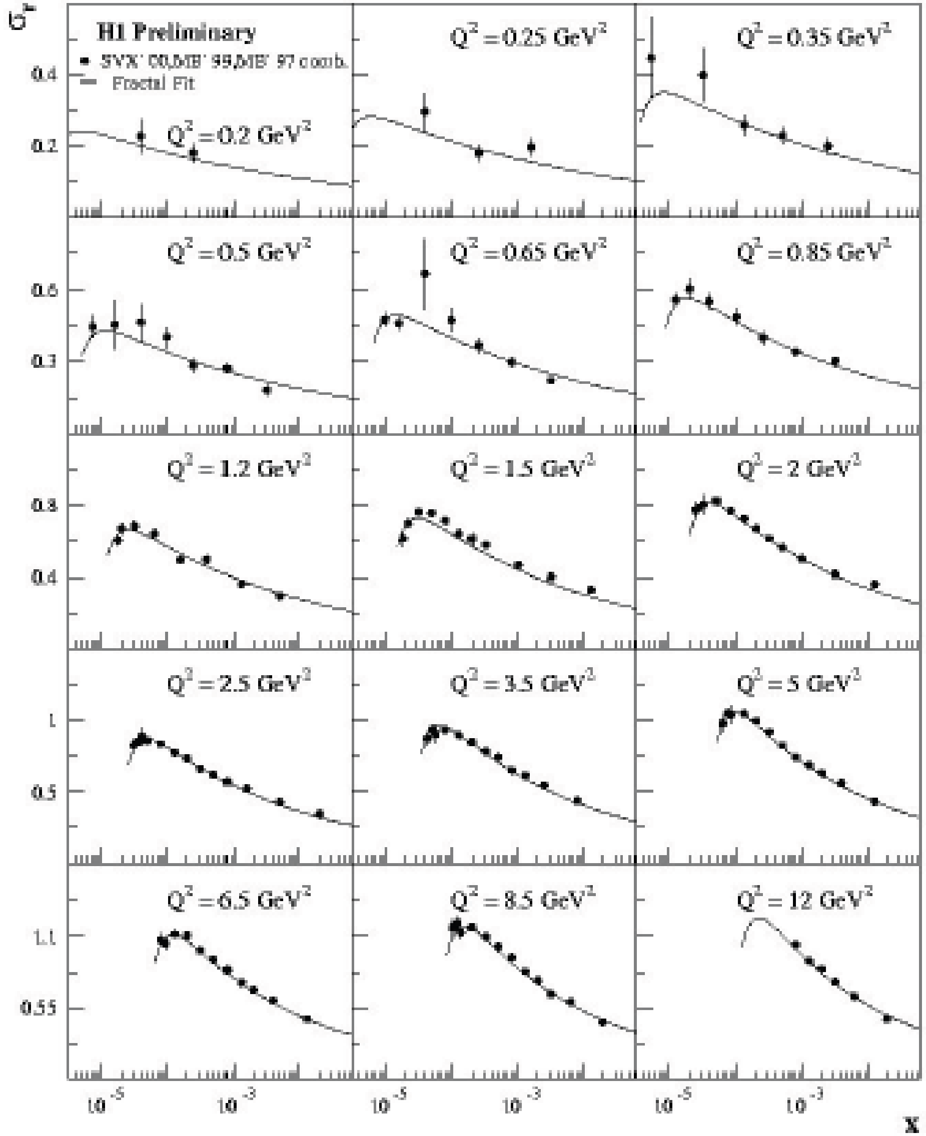
- Add F2 summary plot and slide of charged current results, before parton extraction
- I would like to include F2cc & F2bb if time allows.

? Candidates for being removed

To Do:

- Find figures of better quality for some plots

H1 Final Combination



- SVX'00, MB'99, MB'97 comb

$$1.7 < \delta_{tot} < 15\ \%$$

- Systematic shifts $\delta(\alpha_j)$ inside 1σ
- Cross section parametrization

$$F_2(x,Q^2) \longrightarrow \text{Fractal fit (4 param)}$$

$$F_L(x,Q^2) = F_2(x,Q^2)\frac{R}{1+R}$$

$$\chi^2/dof = 1.04$$

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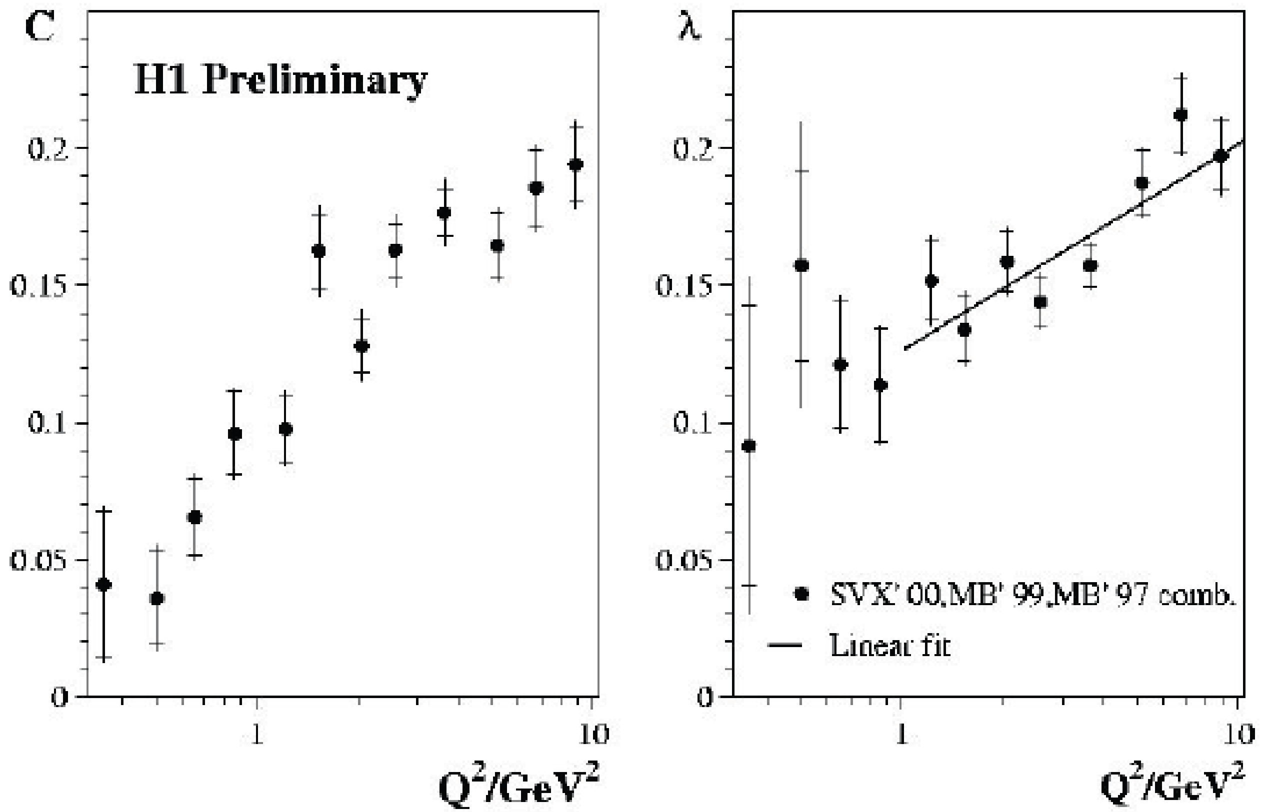
Rise of F_2

$$\sigma_r(Q^2,x) = c(Q^2)\,x^{-\lambda(Q^2)} - \frac{y^2}{(1+(1-y)^2)} F_L(x,Q^2)$$

$F_2 \sim x^{-\lambda}$

at low x (<0.01)



rise above 1 GeV² linear with ln Q²

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