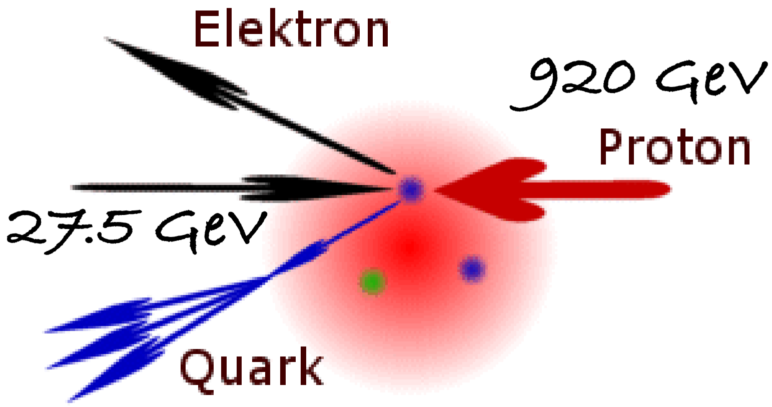
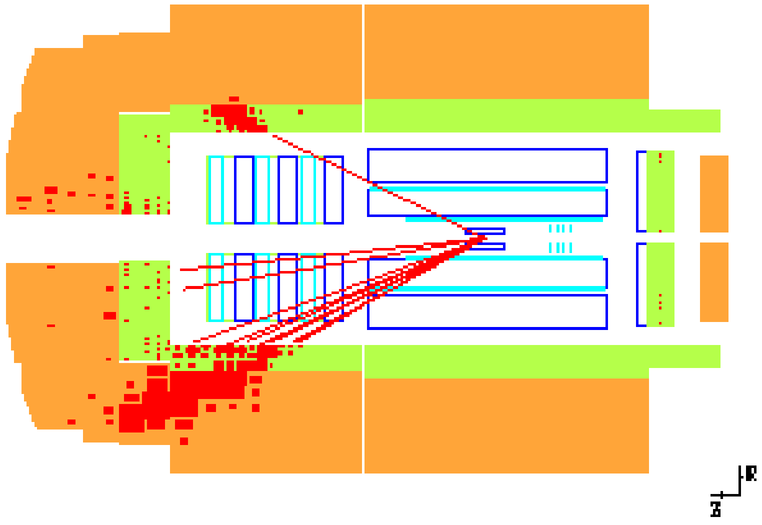
# ep-Scattering at large $Q^2$ and high Luminosity

E. Elsen (DESY/SLAC)

- QCD laboratory HERA
  - Site
  - Proton
  - eq-Scattering
- Electroweak Physics
- New Particle Searches
- Remaining Puzzles of HERA I
- Outlook



# HERA at DESY


## DESY site and Vicinity

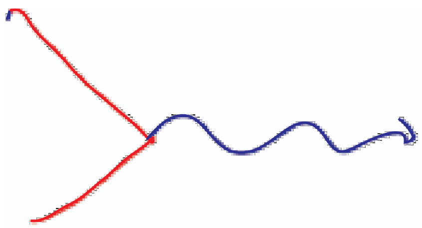
6.3 km HERA tunnel extends far into residential Hamburg.

Exptl. Halls are (typically) off site.

## HERA Tunnel

"Cold" proton ring on top of "warm" electron ring.

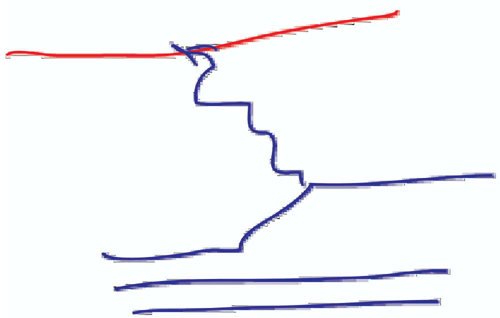
# Elementary Interactions



$e^+e^-$ LEP I

$SU(2)\times U(1)$

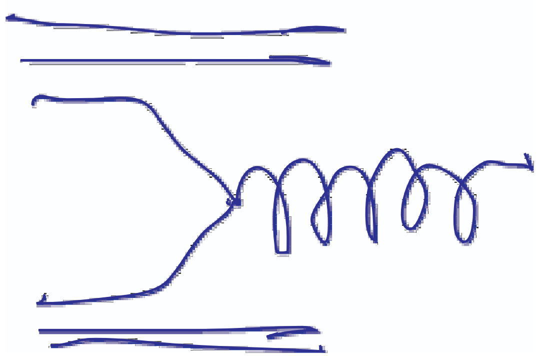
- pure elektroweak initial state



ep HERA

$SU(2)\times U(1)$

- electromagnetic coupling (probe) to the carriers of the strong interaction



pp Tevatron

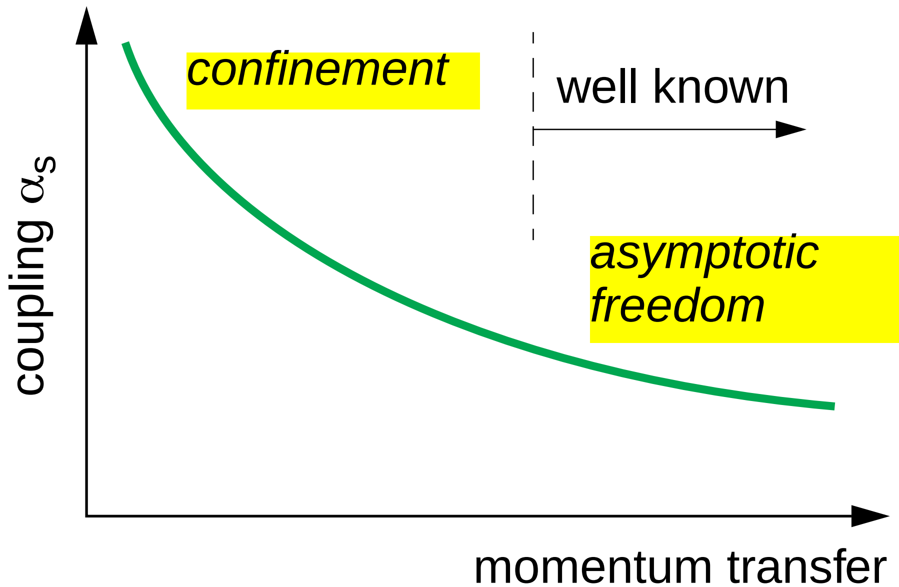
$SU(3)_c\times[SU(2)\times U(1)]$

- hadronic coupling, purely strong interaction

# Quantum Chromodynamics

- Quantum Chromodynamics
  Gauge theory of the strong interactions
- Coupling $\alpha_s$ varies with momentum transfer/distance
- in leading order (LO)

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln Q^2/\Lambda^2}$$




Validity of perturbation theory has been well confirmed for large momentum transfers over the past 20 years (few per cent accuracy).

Quarks, as asymptotically free objects are thus often treated as real "particles" manifesting themselves as jets of particles.

# Proton as a QCD-bound State

- Size:
  Quarks (3) confined to a region of 1 fm diameter
- Mass:
  938 MeV » $\Sigma m_q \approx 0$
- Momentum
  $\Sigma x_i \approx 1$, ~ proton momentum
- spin:
  1/2

not understood!

(Some partial success in specific systems)

## Methods of Investigation

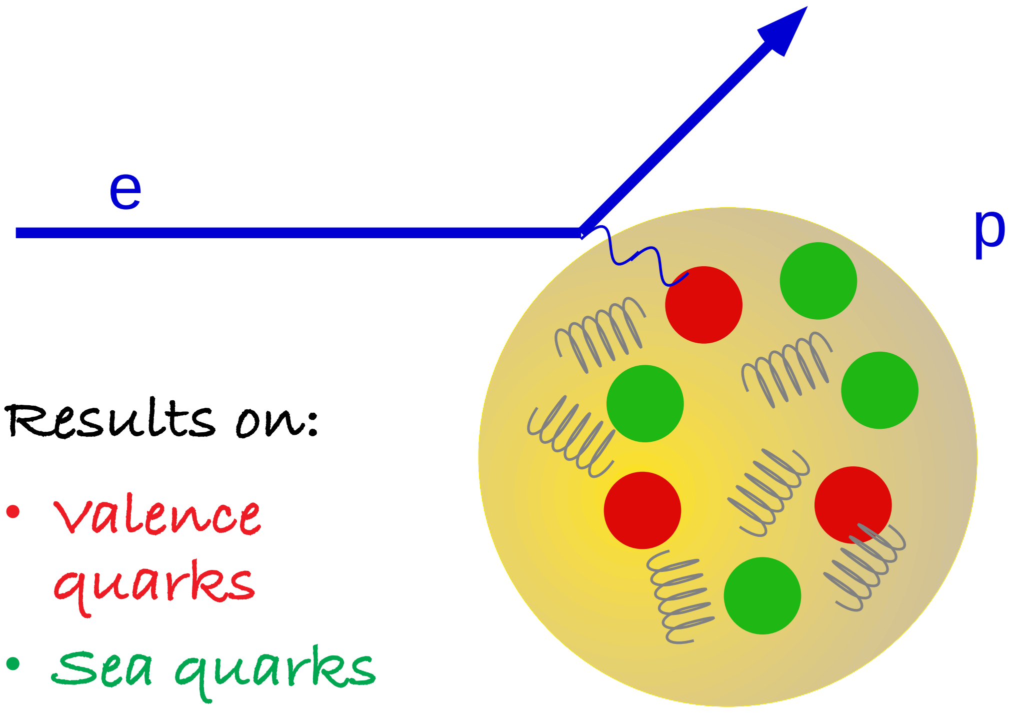
- Bound systems and their excitations
- lattice QCD
- Scattering experiments (preferentially with QCD-blind probe) to investigate structure

# Resolution of the Probe: $Q^2$

## Adjustable resolution at HERA

- $Q^2 \approx 1\ GeV^2$
  $<$ proton radius $r_p$
- $Q^2{}_{max} \approx s$
  $= 4E_eE_p \approx 100000\ GeV^2$
  corresponds to $\approx 1/1000\ r_p$

"Proton structure" may be explored over three orders of magnitude at HERA




Results on:

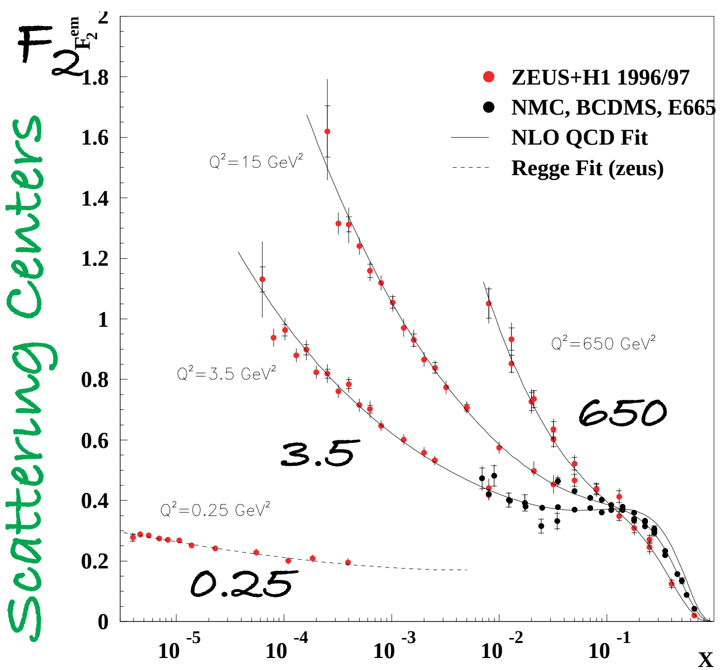
- valence quarks
- Sea quarks

i.e. scattering centres and

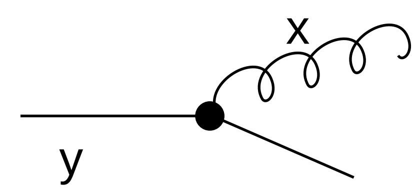
- gluons

# Strong Interaction - Perturbation Theory

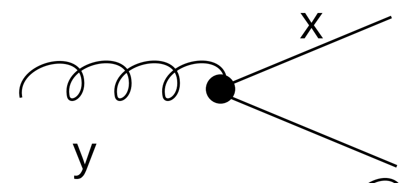
- Interaction between the constituents of the Proton
- Parton-Density distributions $q_i(x)$ are $Q^2$ dependent:



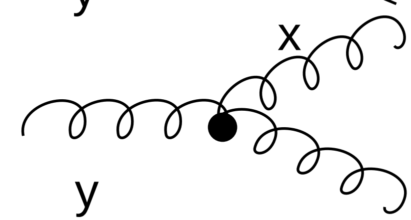

Bremsstrahlung




Pair creation

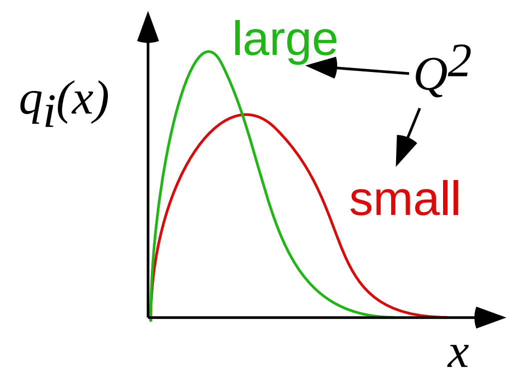



Gluon Self-Interaction



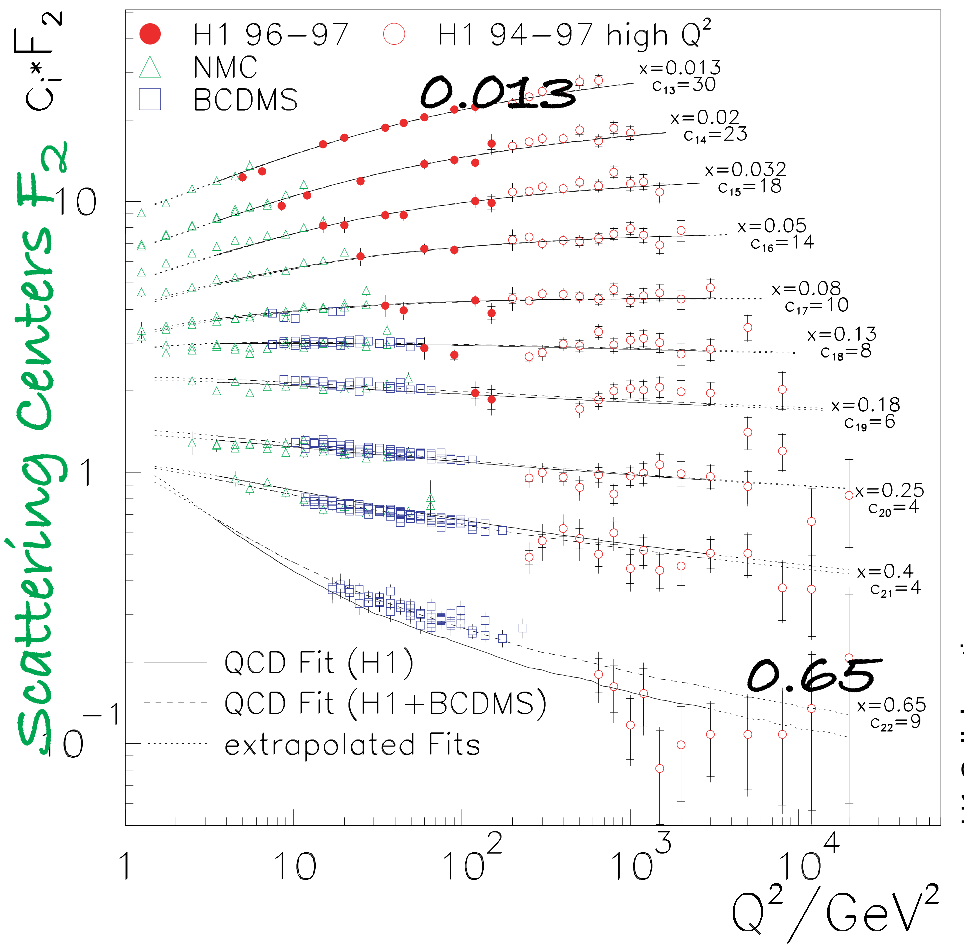

$$\frac{d}{d\log Q^2} q_i(x, Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left(q_i(y, Q^2)P_{qq}\left(\frac{x}{y}\right) + g_i(y, Q^2)P_{qg}\left(\frac{x}{y}\right)\right)$$

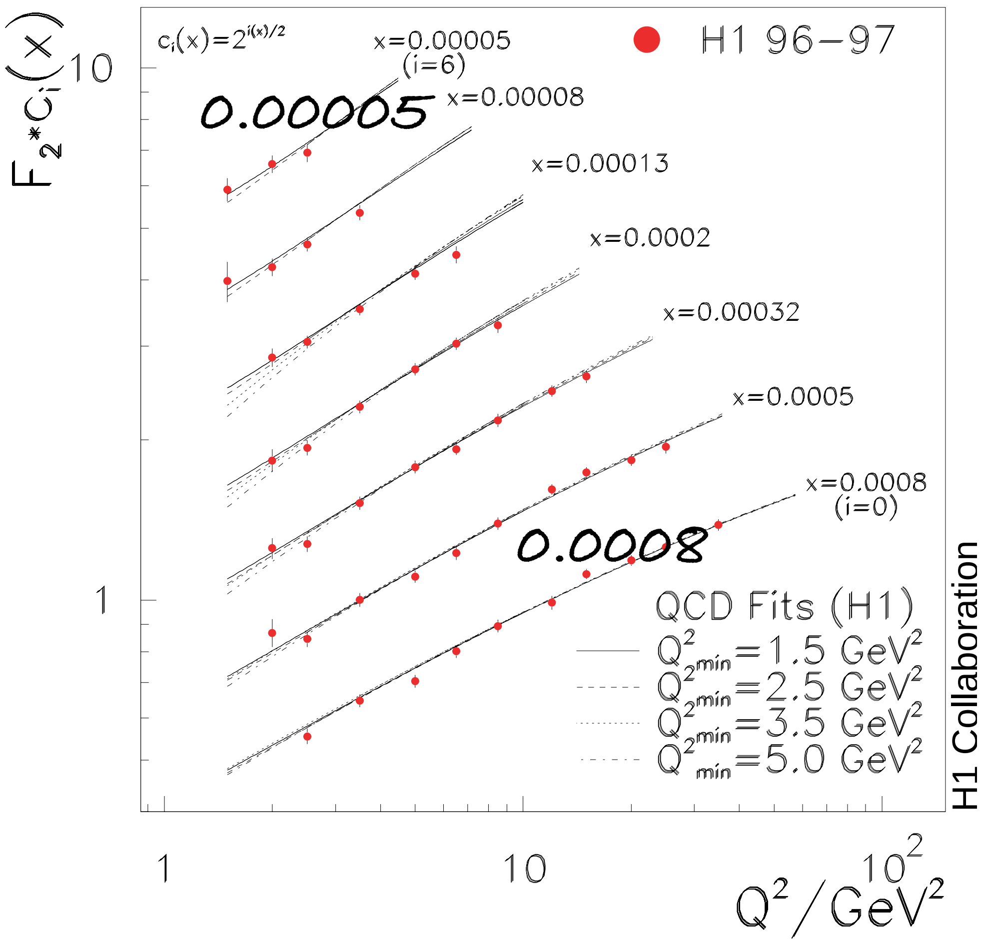
$q_i(x,Q^2)$ represent the density distributions of the scaled parton momenta.



# Scaling Violations

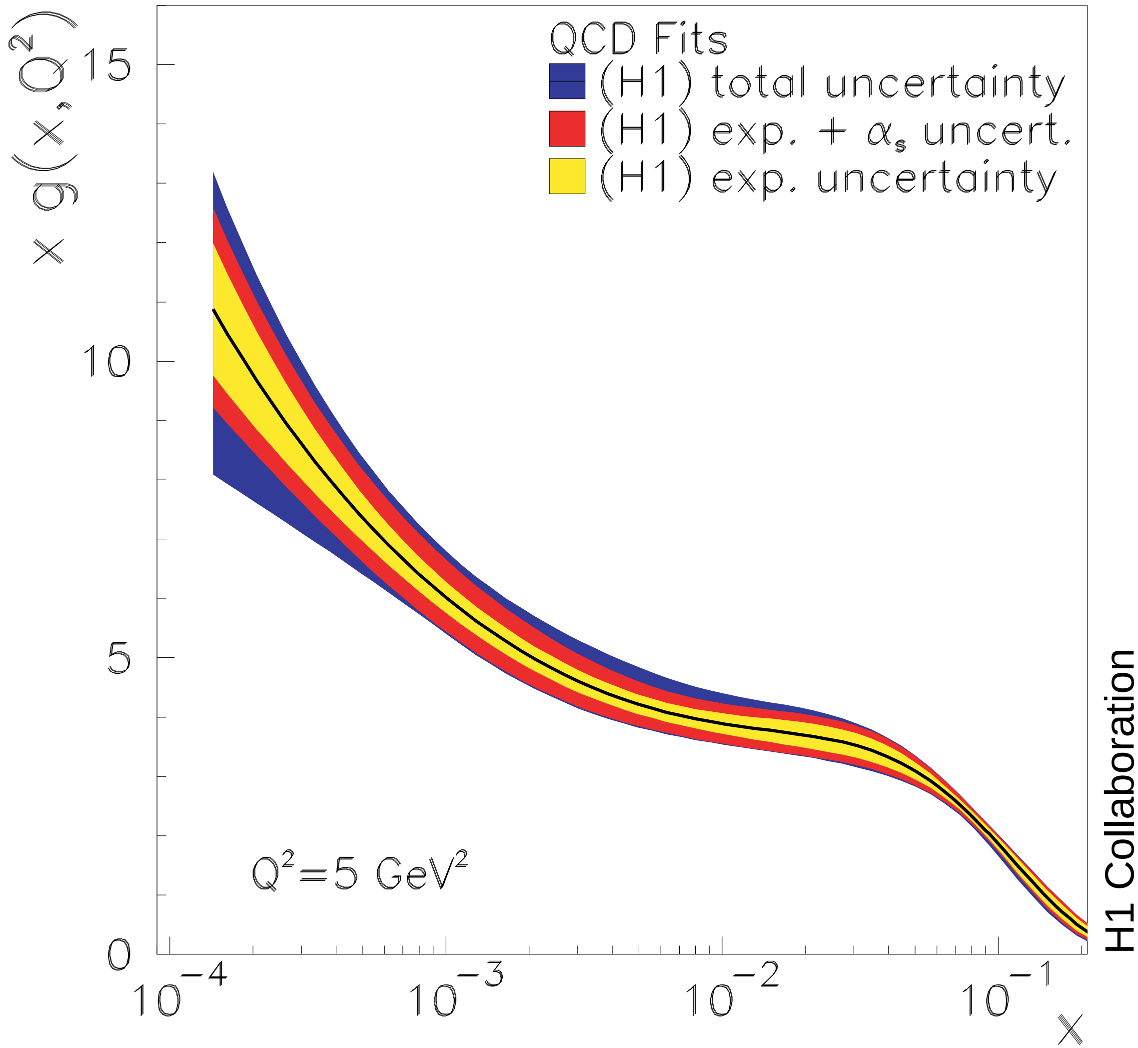
$$d\sigma/dxdQ^2 \sim 2\pi\alpha^2/(xQ^4) * F_2$$



# Gluon Distribution

$\alpha_s = 0.1150$
$\pm\ 0.0017$ (exp)
$+0.0009$
$-\ 0.0007$ (Model)
$\pm\ 0.0050$ (Scale)




- NNLO calculations start to be available
- theoretical residual uncertainty ~1%

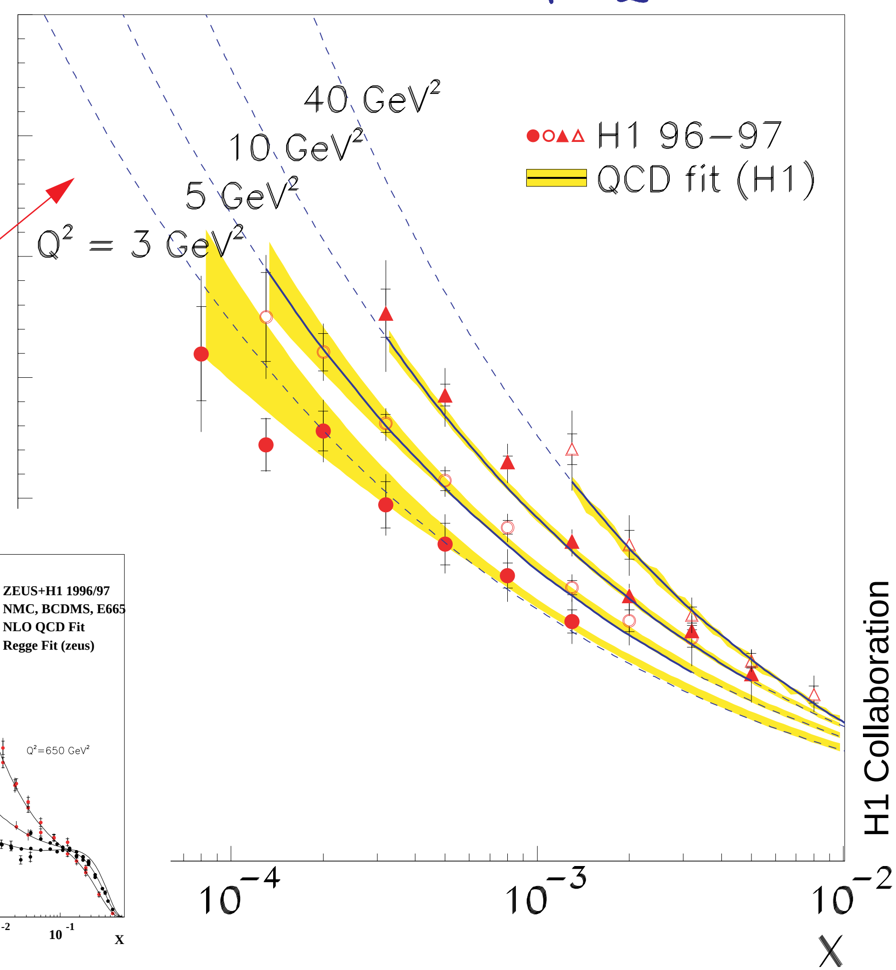
# Limits of Validity of Perturbative QCD Calculations

## Expansion in $Q^2$

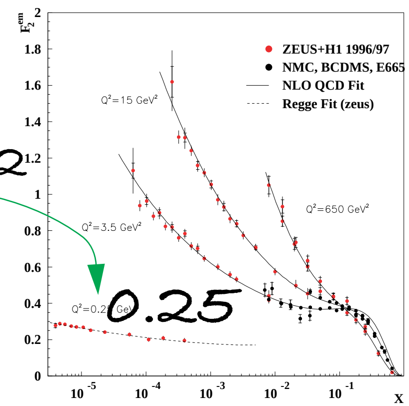
- Perturbation theory valid down to small $x$
- Rise at small $x$ is "unchanged"
- at smaller $Q^2$ the rise is moderated

Rise has to stop somewhere!

## Variation of $F_2$




$F_2$



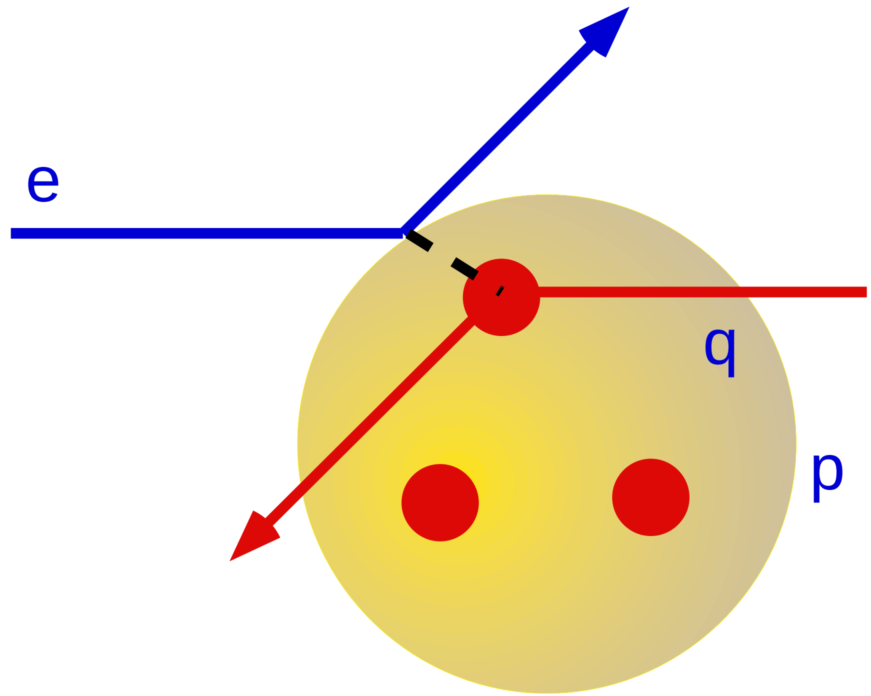

0.25

New quantum system?

# Electron Quark Scattering at large $Q^2$ or W

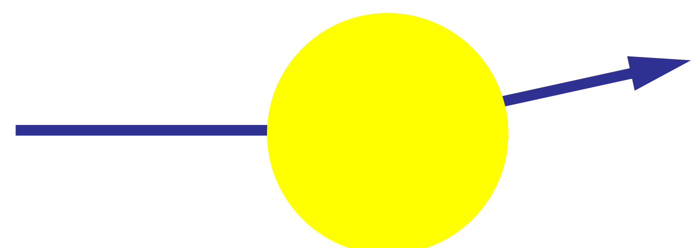
## Proton as a source of quarks

- Region of large x, preferentially valence quarks, i.e. u,d




## Proton as a target to create high mass systems

- Region of small x:
  $W^2 = Q^2/x*(1-x)$
  (W > 100 GeV easily attained)



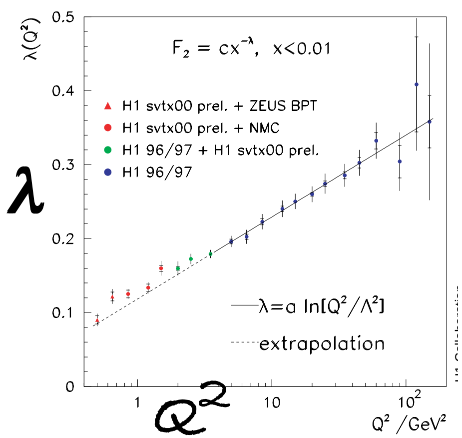
# Behavior at small x

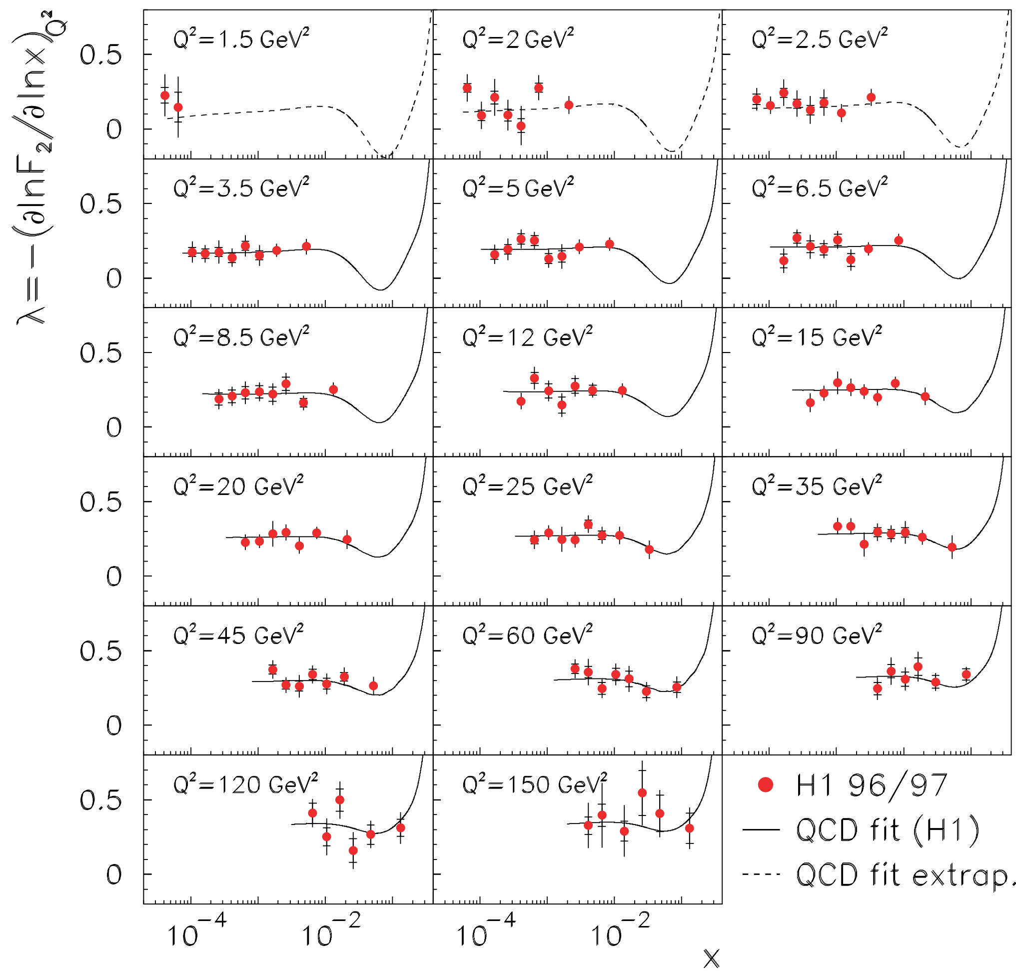
## Transition to high Energies

- $W^2 = Q^2/x*(1-x) \approx Q^2/x$
- for $x<0.01$ the variation of the structure functions seem to be independent of x
- $F_2 = c(Q^2) * x^{-\lambda}$

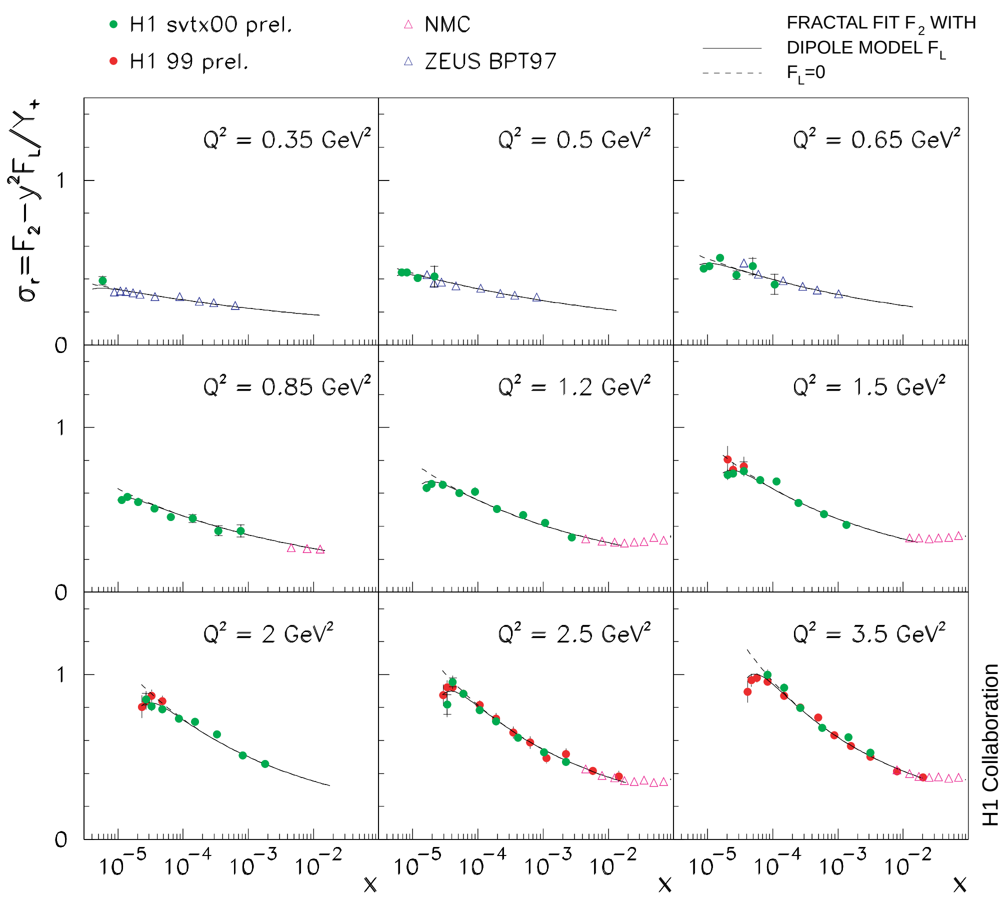
## Fractal structures in the Proton?

- $\lambda$ rises linearly with $Q^2$



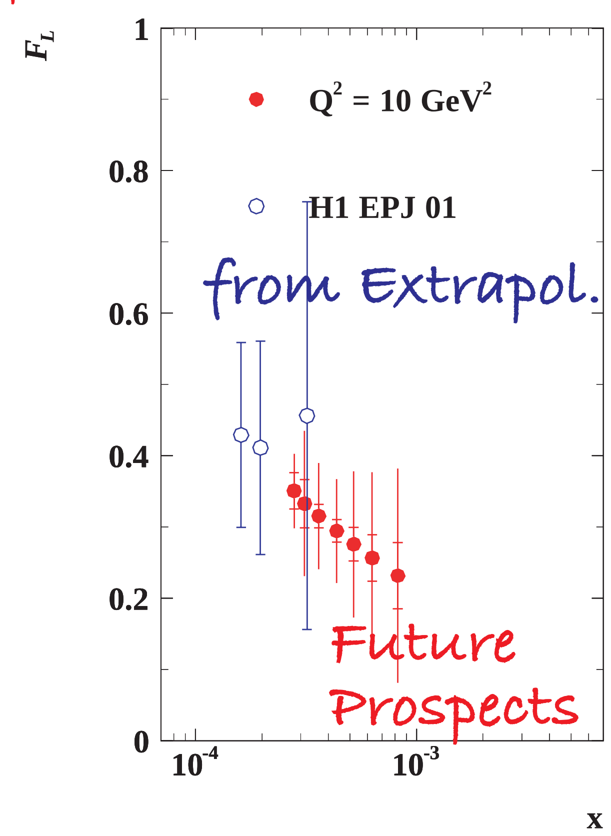



# Longitudinal Structure Function $F_L$



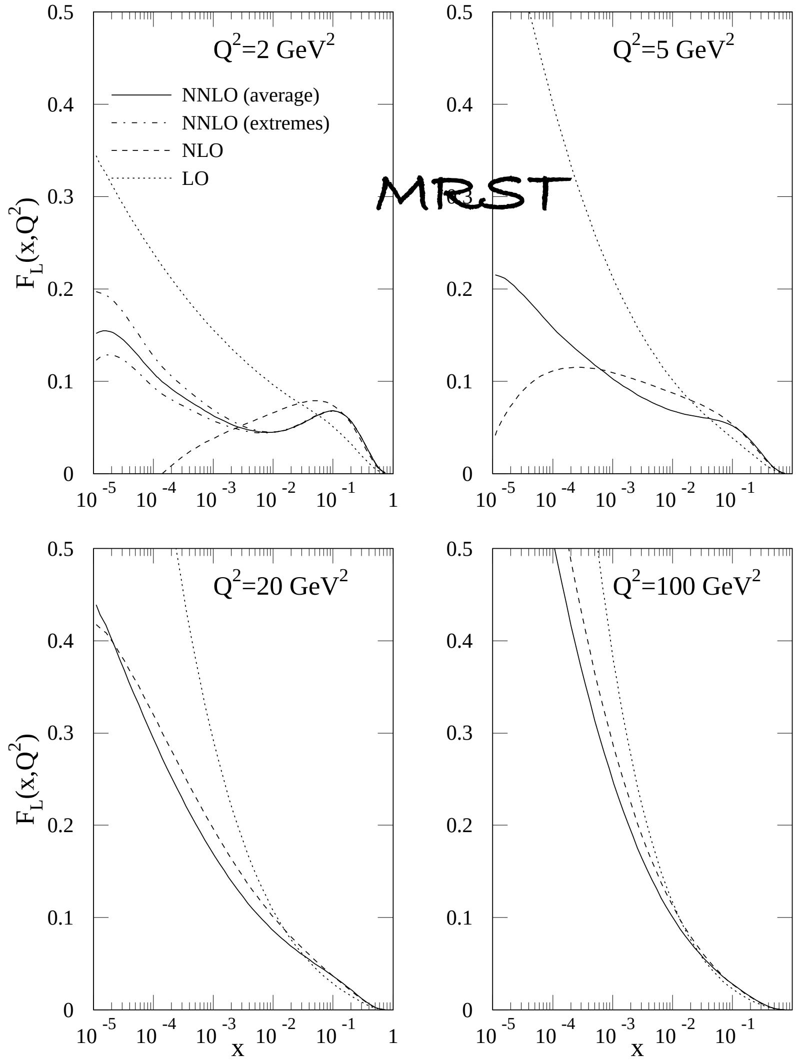

True measurement only from runs at different $E_{CM}$:

Example $E_p = 300, 350, 465$ GeV




$$\sigma_r \sim F_2 - y^2/(1+(1-y)^2) * F_L$$

# Theoretical Uncertainties of the Parton Densities

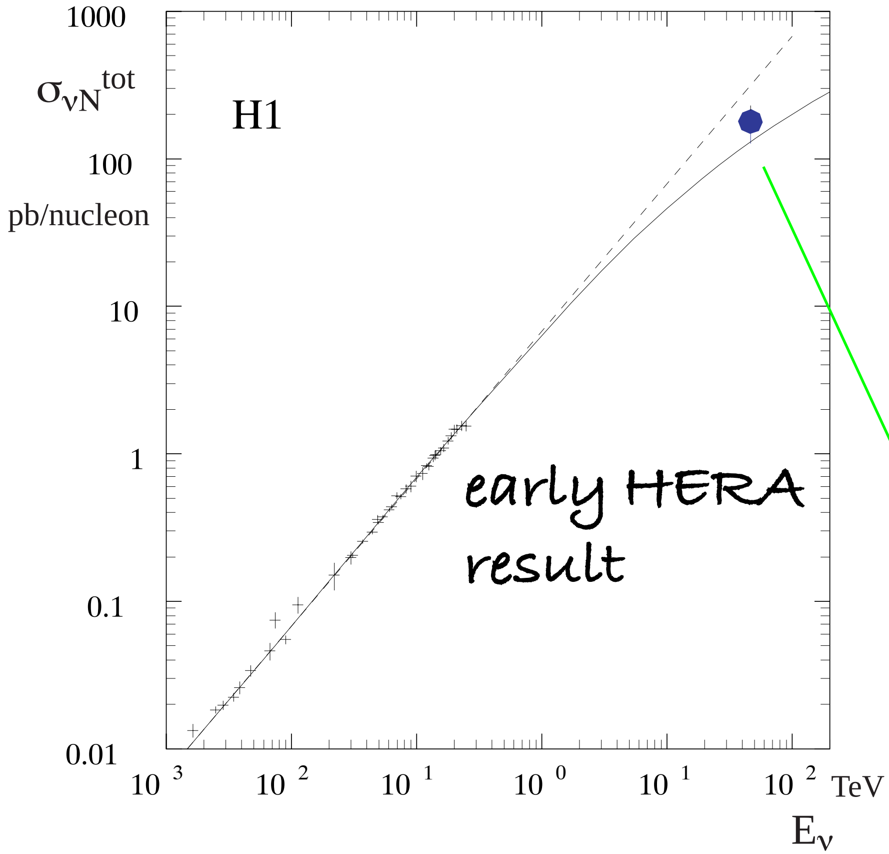



## Longitudinal Structure Functions:

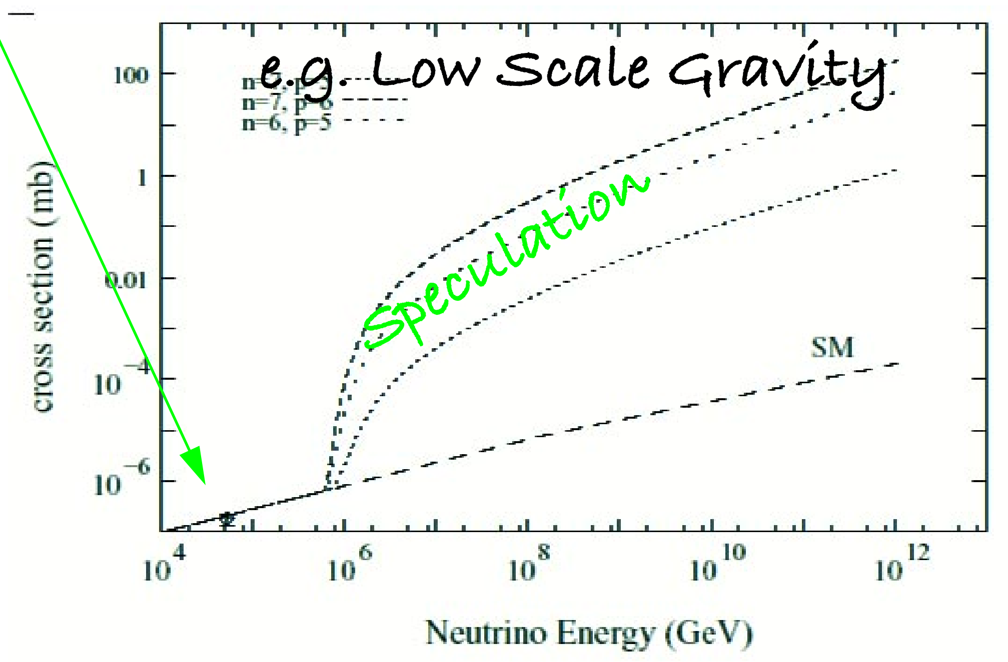
- large contributions of the next higher order
- uncertainties also in NNLO

Precision data on $F_L$ required to clarify issue.

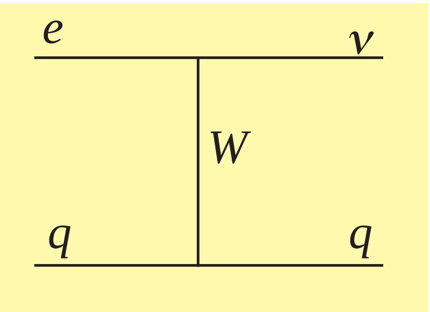
# ν-Nucleon Scattering Cross Section at high Energies



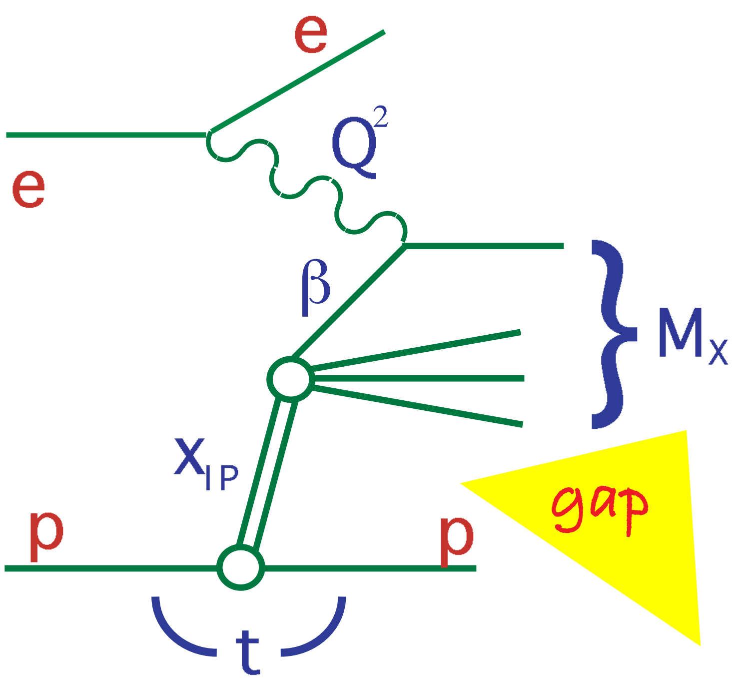

- large $E_\nu$ - even small x relevant
- reach of neutrinos from cosmic accelerators to initiate showers (cf. GZK limit for γ)?




derived from:



# Understanding Color Singlet Exchange in QCD




- Color-singlet exchange involving >1 Parton correlated parton density

## Generalized Parton Density

- $f_{i/p}(x_1, x_2, Q^2)$
- DVCS
- Vector meson-Production

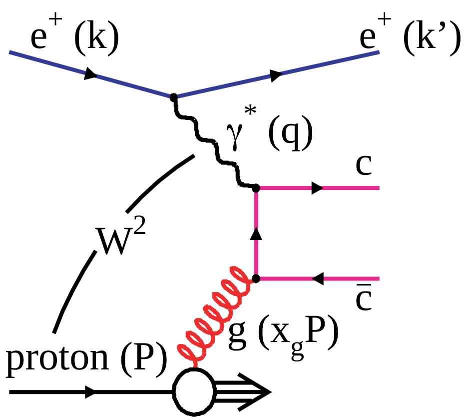
## Factorization

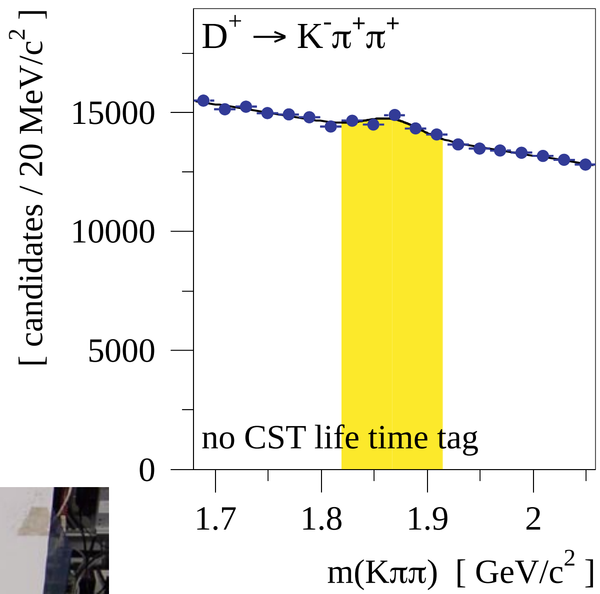
- σ~Flux * elem. X-section proven in hard diffraction (for fixed x,t)

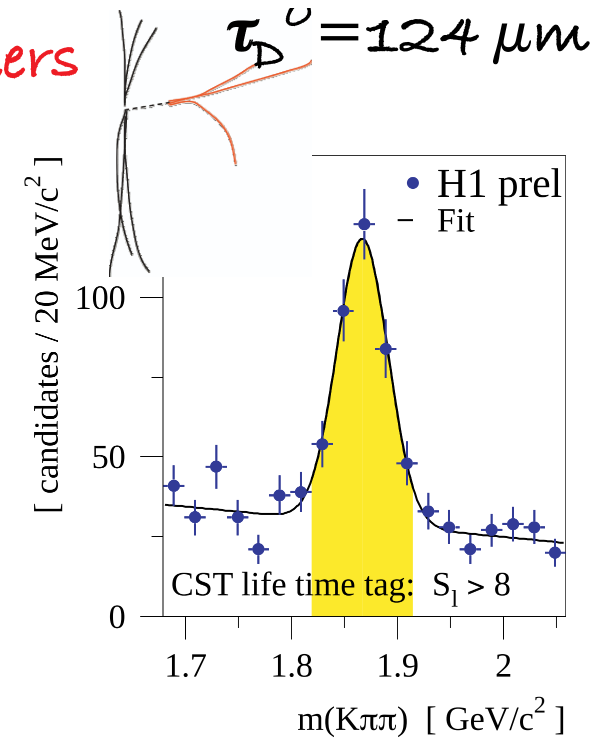
→ QCD interpretation of diffraction (see talk by D.Wegener)

# Charm in DIS

Application of the Si-Trackers



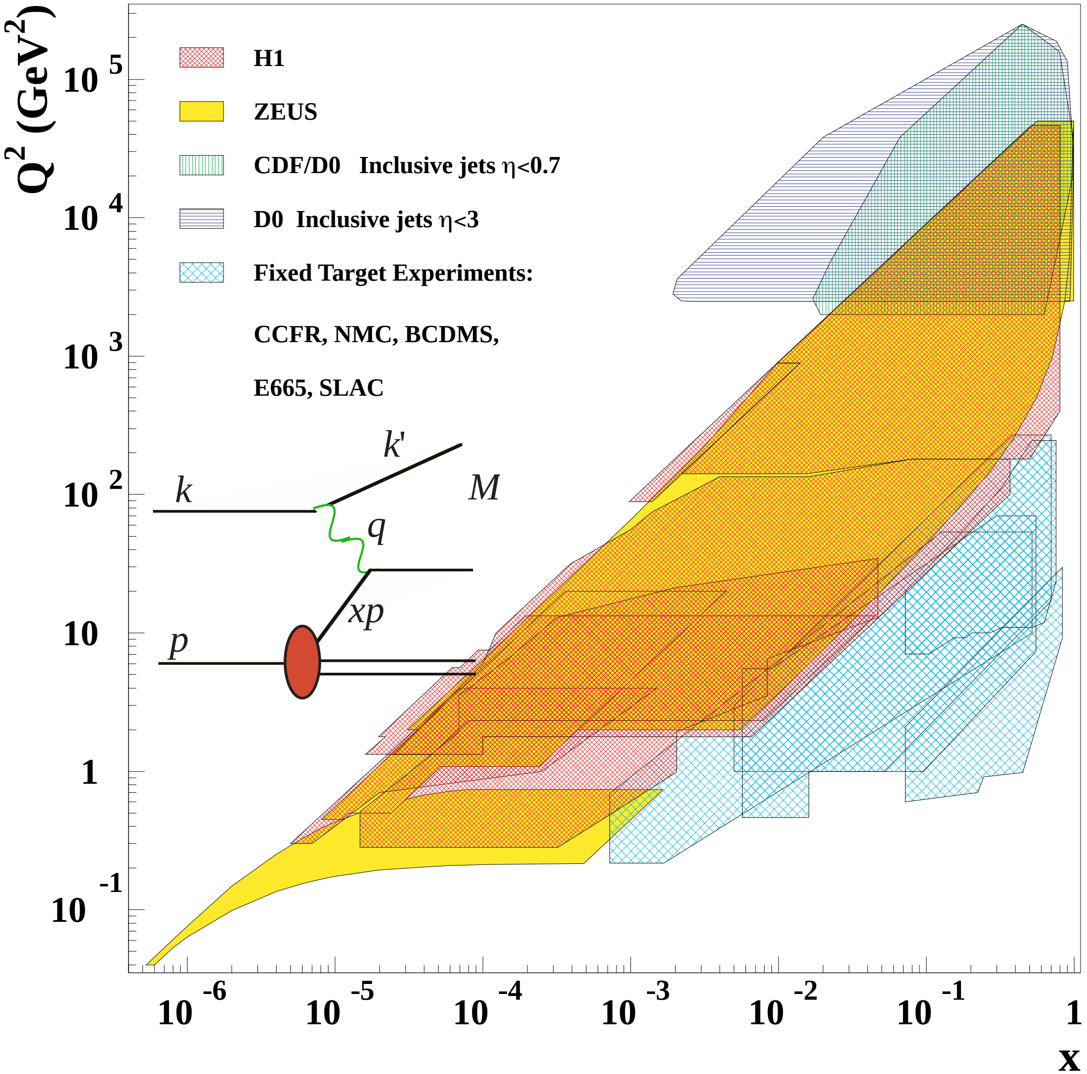

Vertex Detector as a tools to reconstruct heavy quarks.

# "Strong Tasks" for HERA II

## Domains

- Region of large $Q^2$:
  $\alpha_s$, parton densities
- small x:
  high Parton densities
  New quantum system?
- small $Q^2$:
  Confinement-region
- large CMS Energy:
  EW-Tests and
  "Beyond the SM"

→ QCD Experiments under well defined conditions

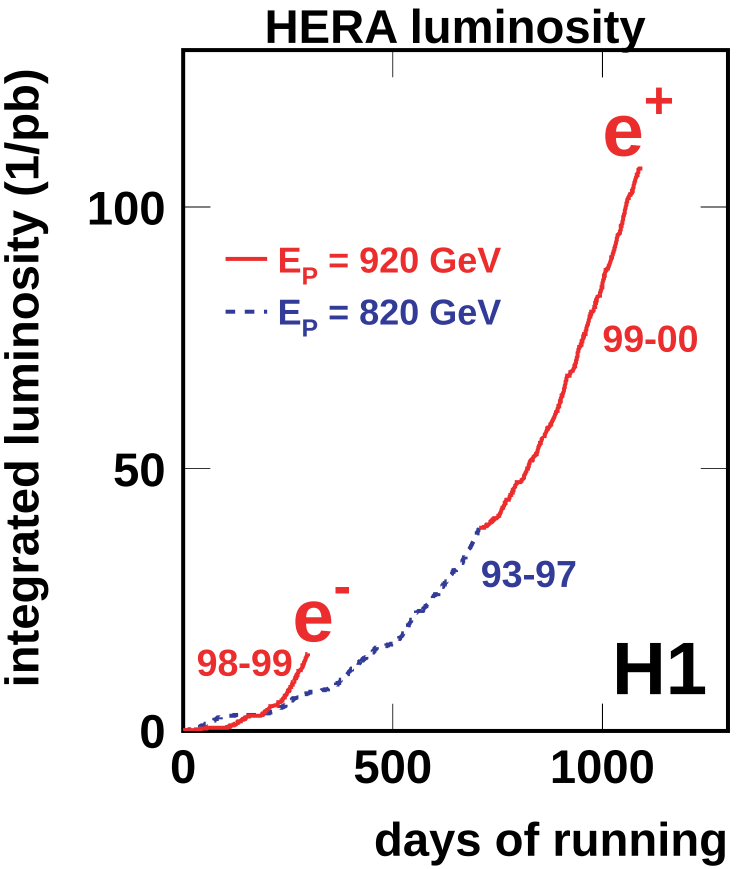


# Integrated Luminosity HERA I

## Events recorded

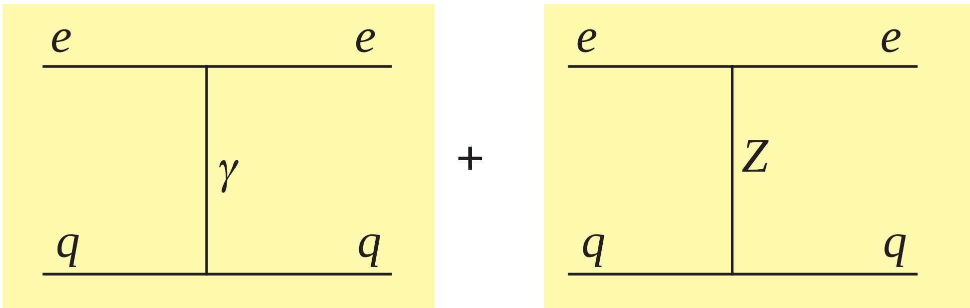
- $> 100\ pb^{-1}$ of $e^+p$-data available (more than half of that taken in 2000)
- $> 15\ pb^{-1}$ of $e^-p$-data available
- lots of data with high quality, which have not yet been examined in detail

→ Many opportunities for theses available.



# Elektroweak Processes at HERA

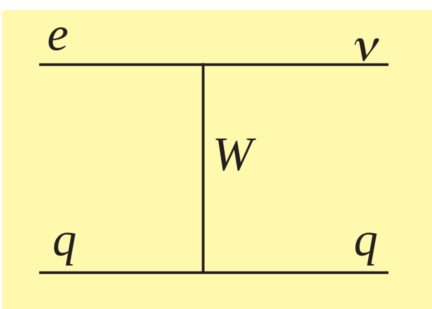
## Neutral Current (NC)




$$\frac{d^2}{dxdQ^2}\sigma(e^{\pm}p) = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2(x,Q^2) \mp Y_-xF_3(x,Q^2)\right]$$

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

## Charged Current (CC)




purely electroweak interaction

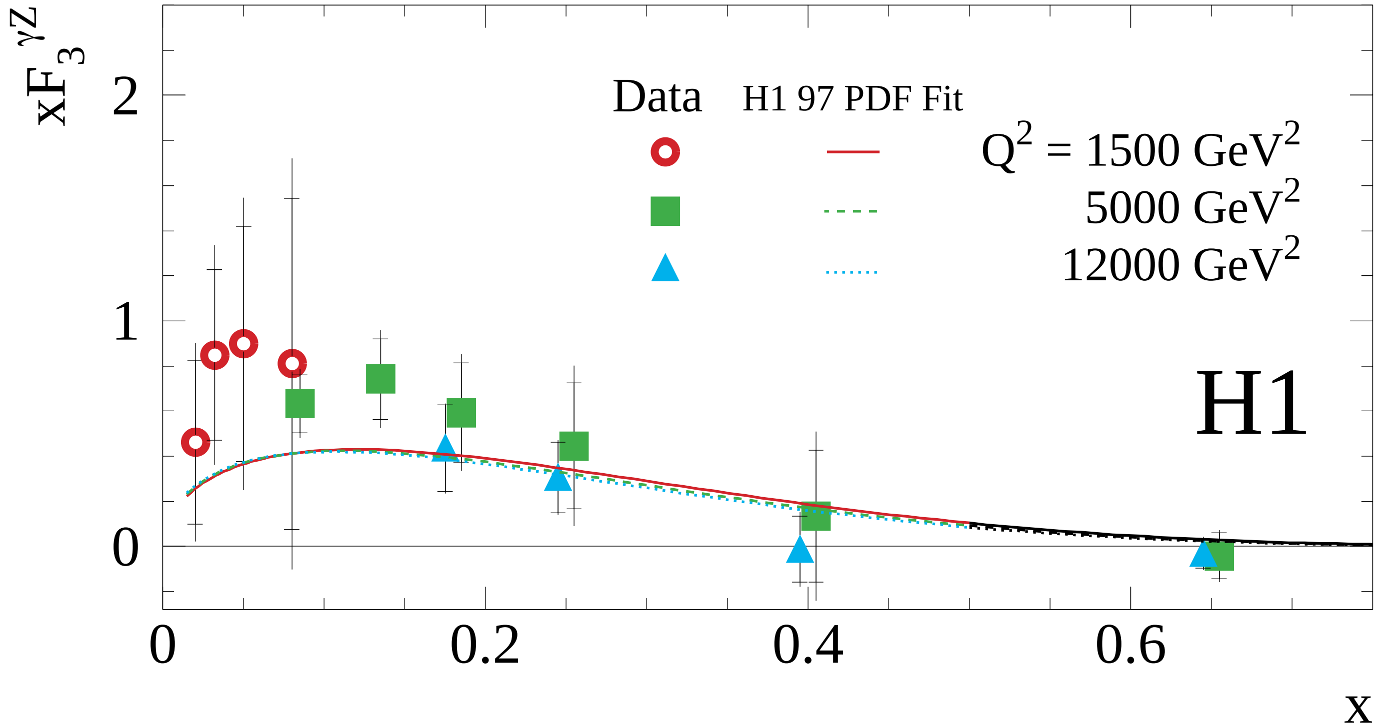
*characterized as*

- $1/Q^4$ dominates
- Z-contribution with $1/(1+(M_Z/Q)^2)$ and $1/(1+(M_Z/Q)^2)^2$ dampened
- $xF_3$, $\gamma Z$-Interference, charge sensitive and partially parity violating
- W-Propagator $1/(1+(M_W/Q)^2)^2$

# $xF_3$

## Interference

- $xF3 \sim q(x) - \bar{q}(x)$
- valence quark distribution
- Accuracy of measurement limited by available $e^-p$ data.

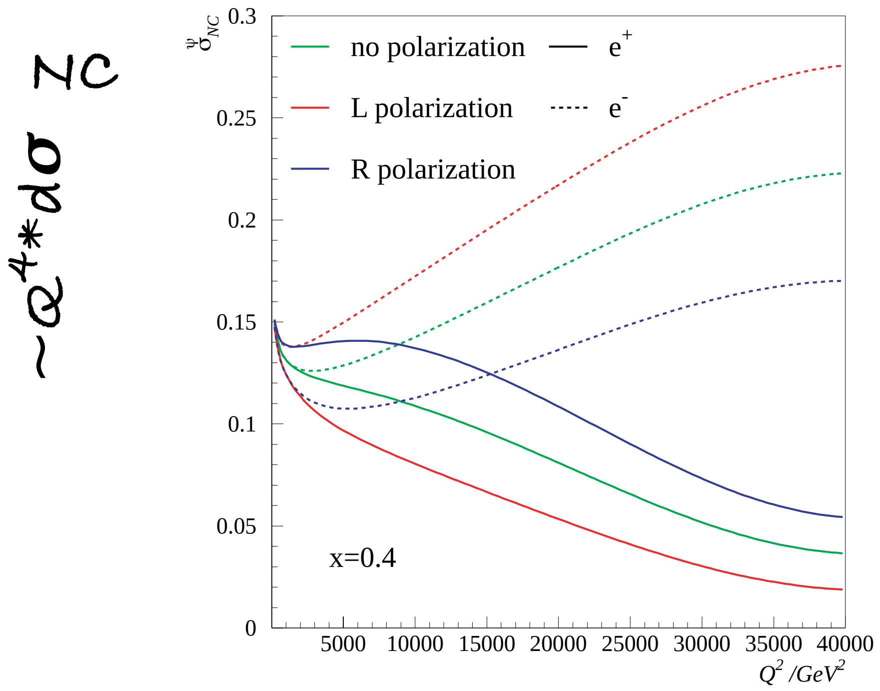



- Sum rules (analogous to νN Scattering), e.g. quark counting sum rules for $xF_3$ Integrals

# Expectation for Parity Violation with Polarized Beams

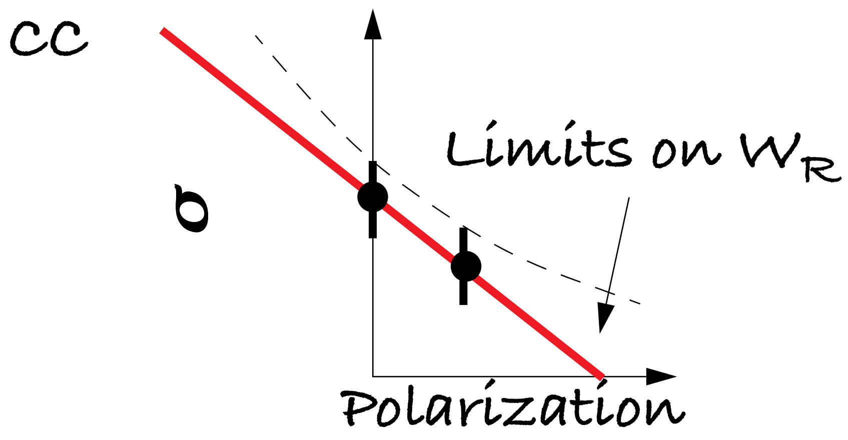
## Neutral Current

- axial and vector couplings only from pure Z-term:
- kinematical suppressed, relevant only for $Q^2 > 10000\ GeV^2$




## Charged Current

- $\sigma_{pol} = \sigma_{unpol} * (1+P)$ since $\sigma(e_L^+ p) = 0$
- "Textbook Experiment" feasible with a few 10 $pb^{-1}$



# Axial- und Vector Couplings for Light Quarks

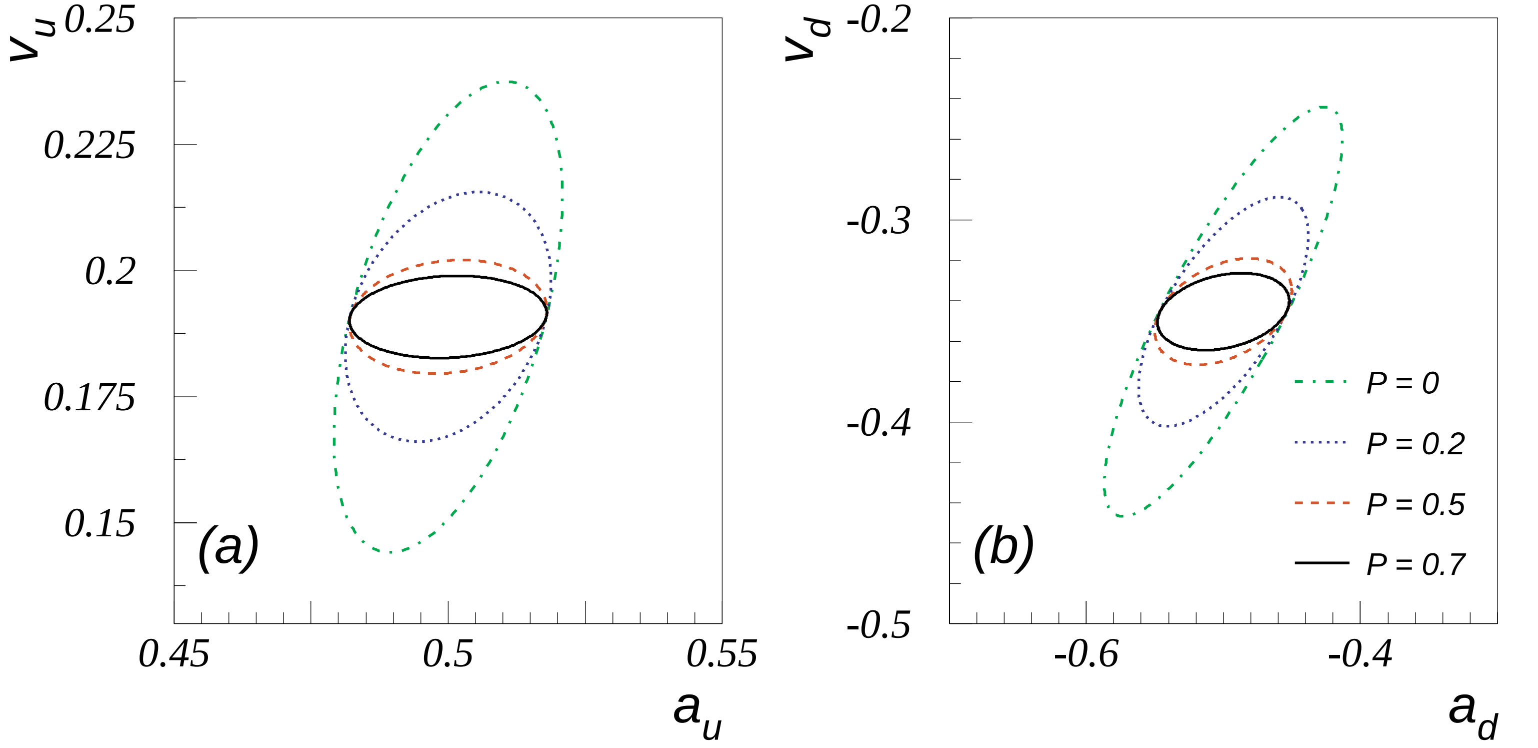
from LEP

- b and c couplings well-known

HERA

- u and d couplings from the analysis of NC/CC, $e^{\pm}$ and Polarization

Case Study




achievable precision comparable to that of Heavy Quarks at LEP

# Sensitivity to Elektroweak Parameters

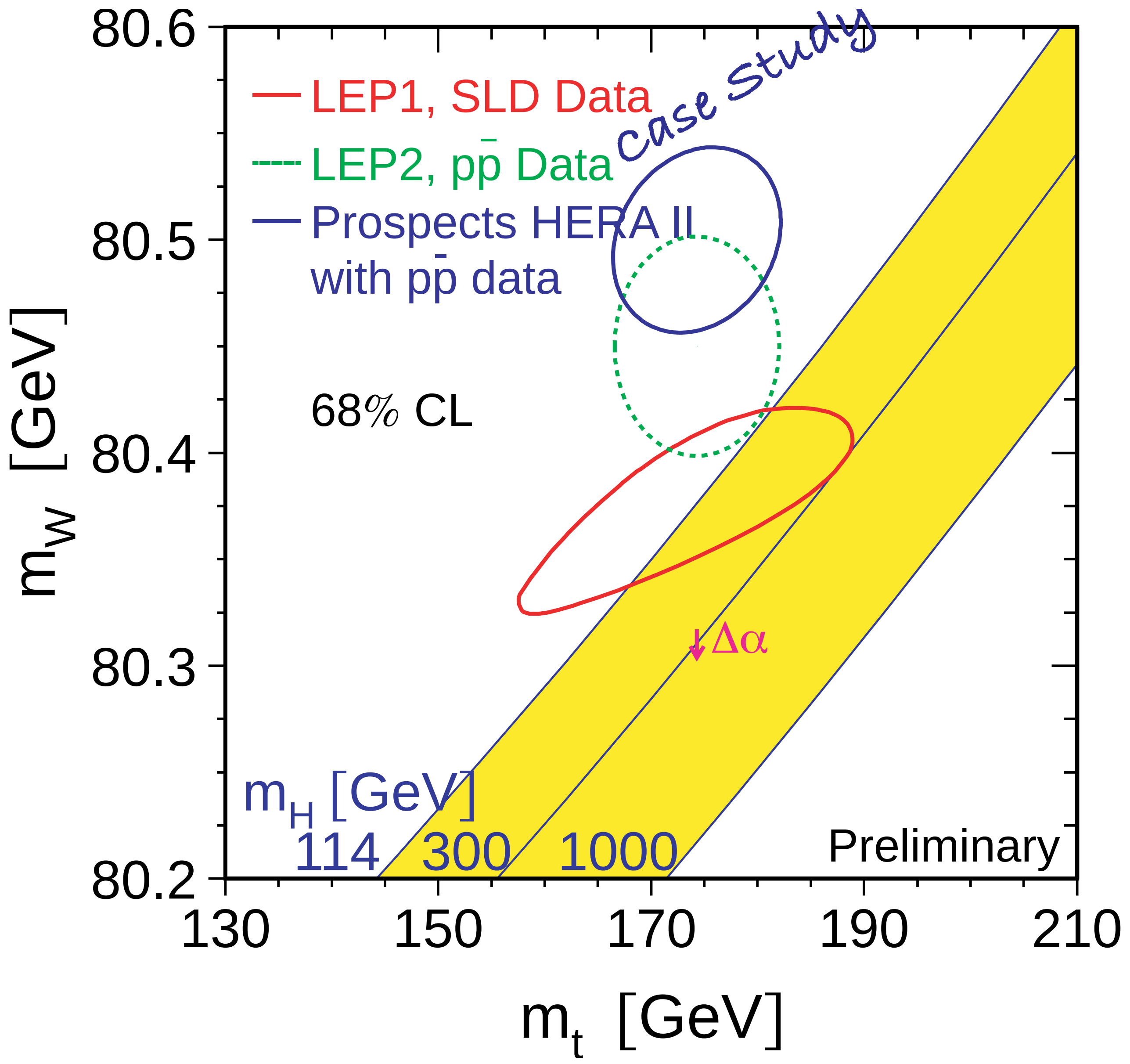
LEP

- $1/(s-M_Z{}^2)^2$ time-like

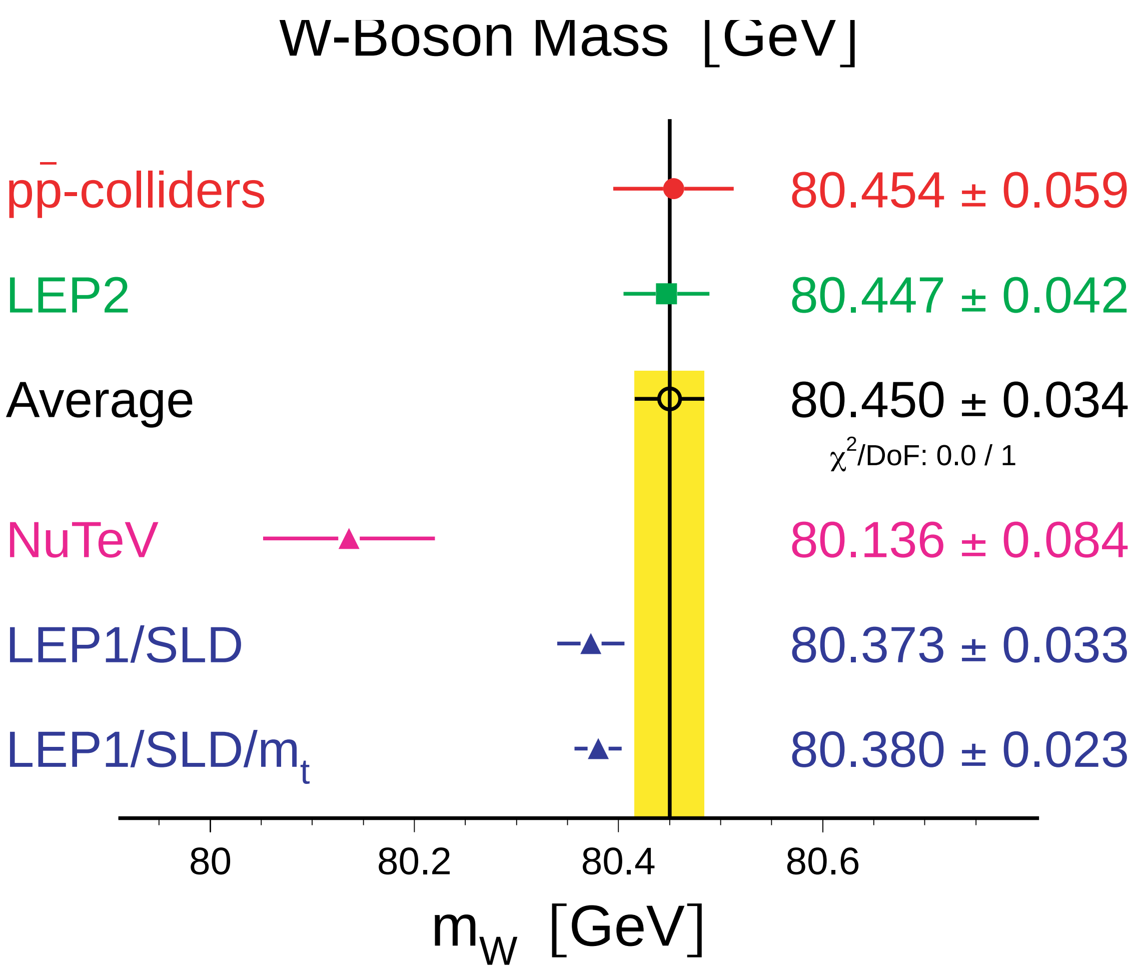
HERA

- $1/(Q^2+M_Z{}^2)^2$ space-like

HERA precision measurements are to provide consistency check with LEP (and Tevatron) results.



# Using $M_W$ to quantify Consistency




*direct measurements*

*indirect measurements*

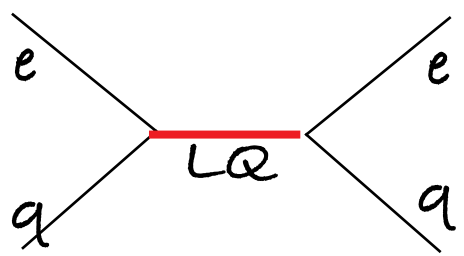
*→ with $m_{top}$ constraint*

*HERA to corroborate or refute consistency!*

# Leptoquarks

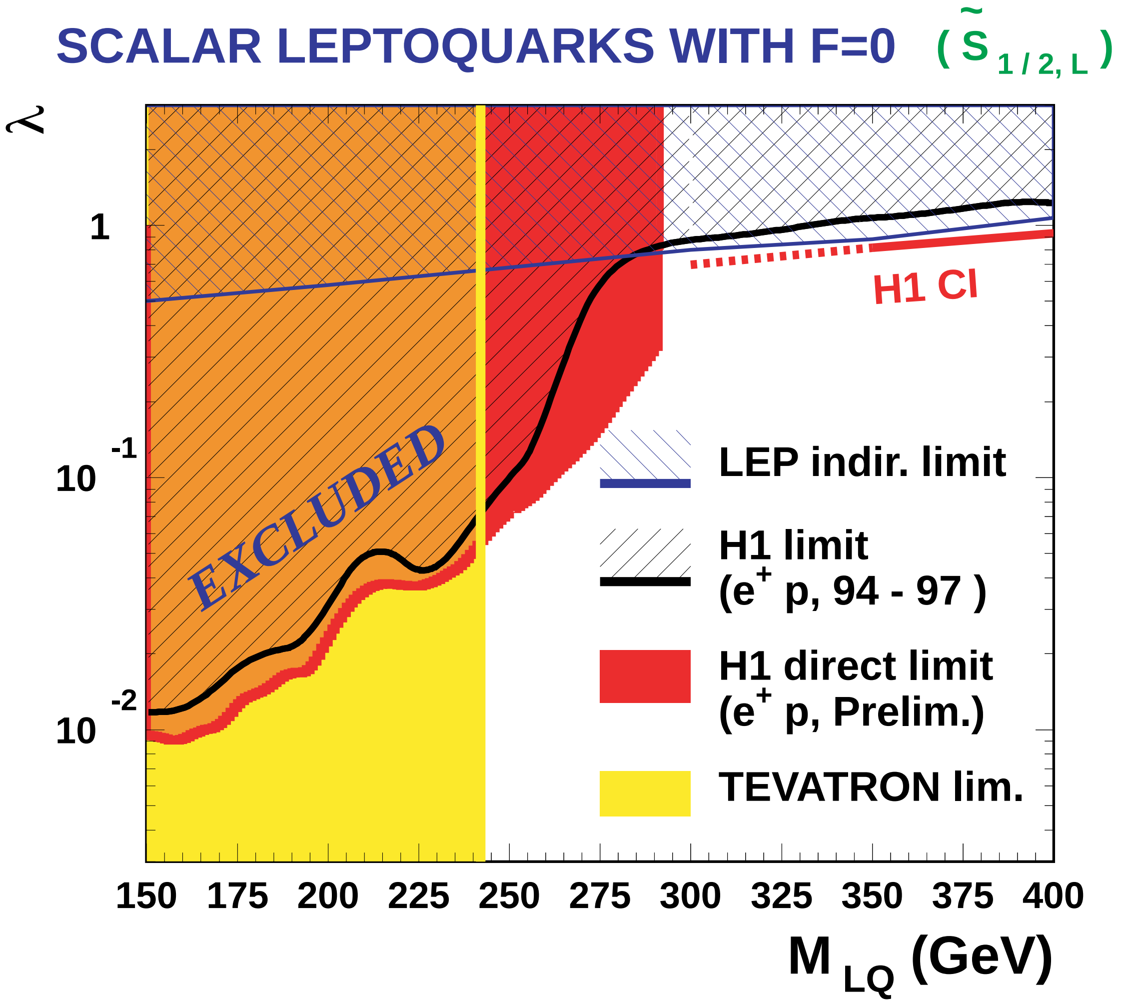
## HERA

- LQ directly produced in electron-quark fusion, coupling $\lambda$.




## Tevatron

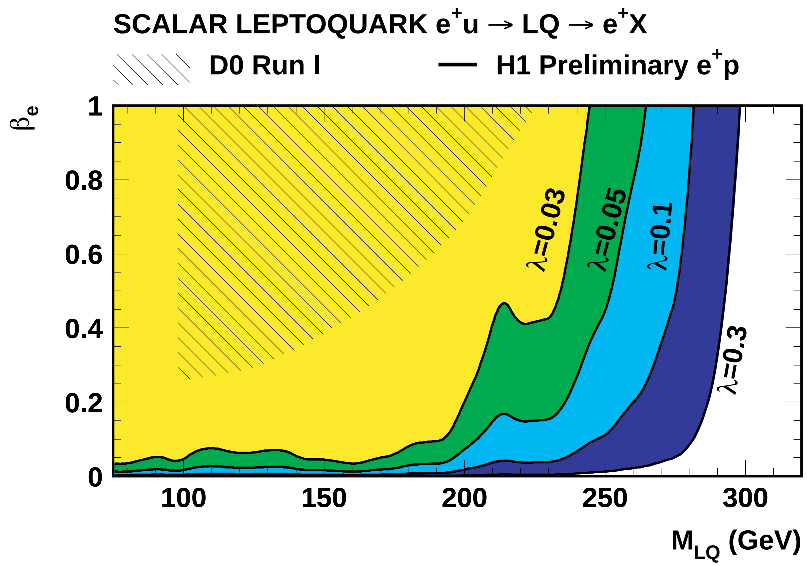
- pair creation, independent of coupling strength



# LQ Branching Ratios

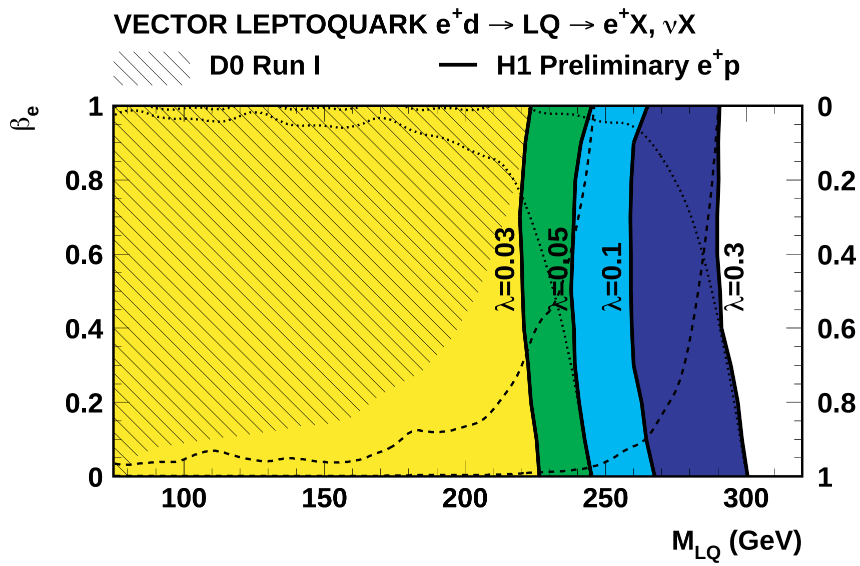
## Scalar LQ

- $eu \rightarrow LQ$

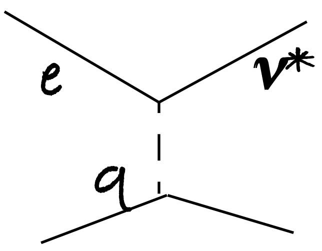


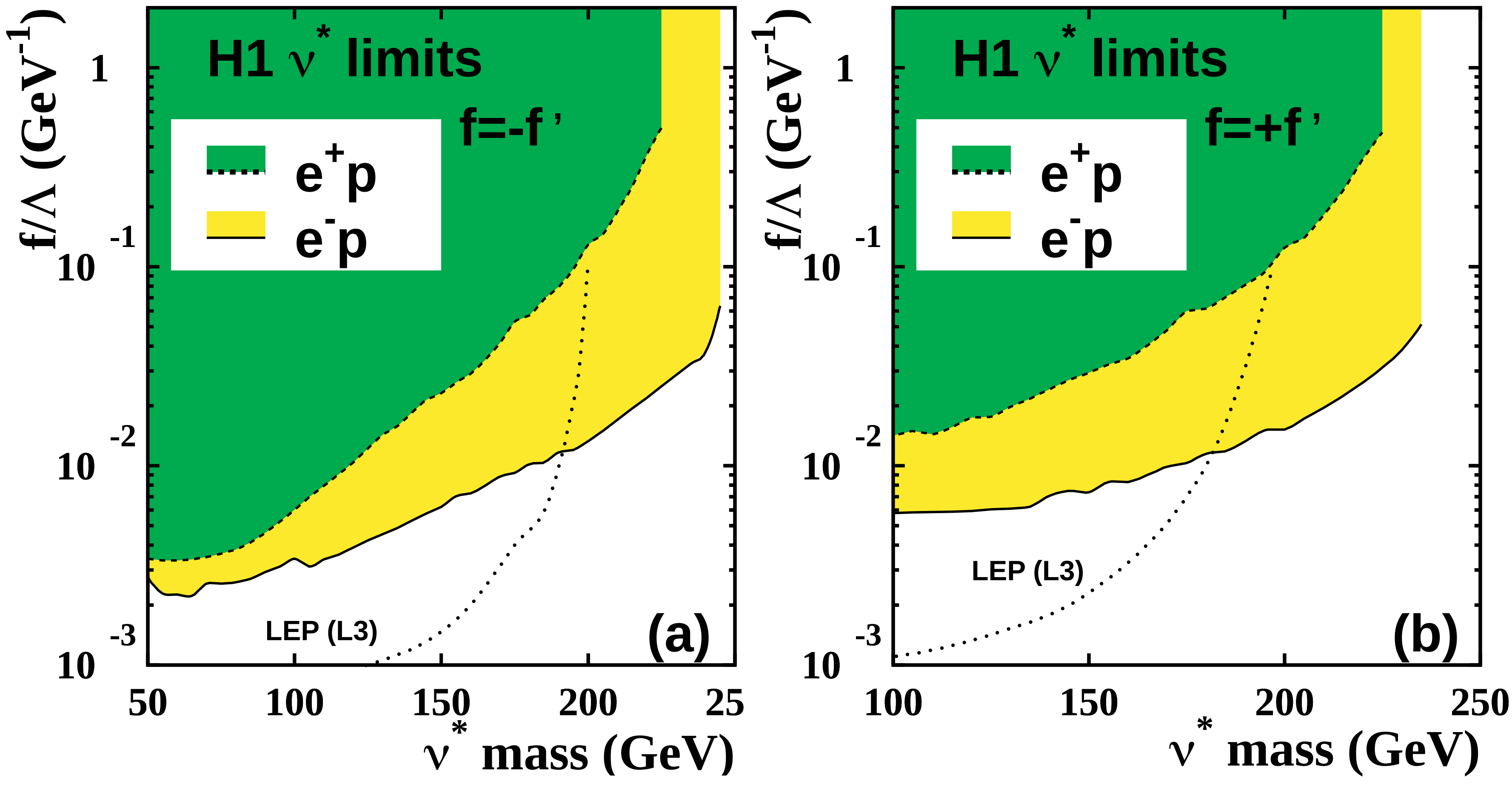

## Vector LQ

- $ed \rightarrow LQ \rightarrow eX, \nu X$
- Neutrino channel complements electron channel



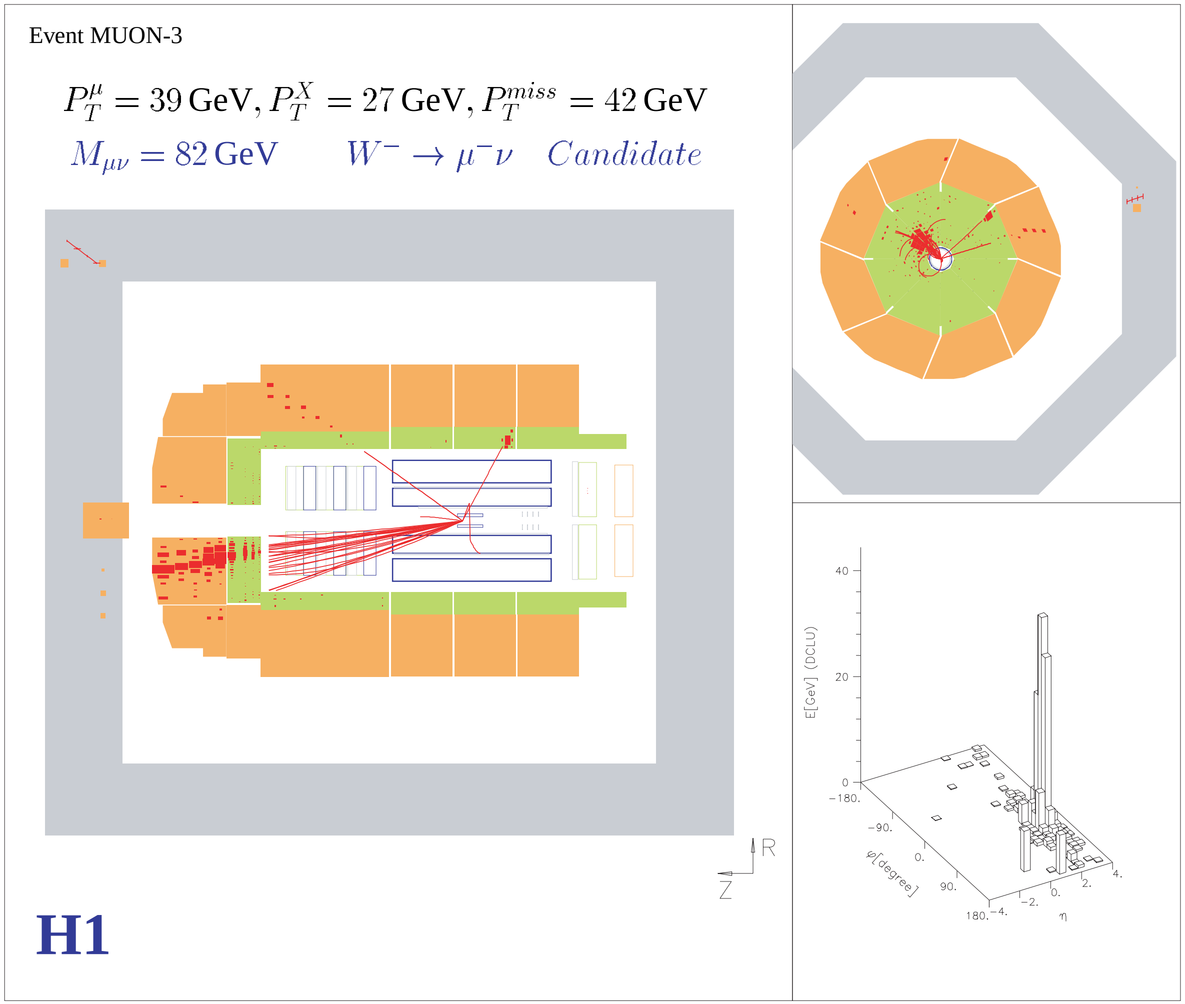
# Excited Leptons



# Remaining Puzzles from HERA I

$$e^+p \rightarrow e^+\mu^-X$$




Events with

- large missing transverse momentum $p_T^X$
- isolated leptons at large $p_T$

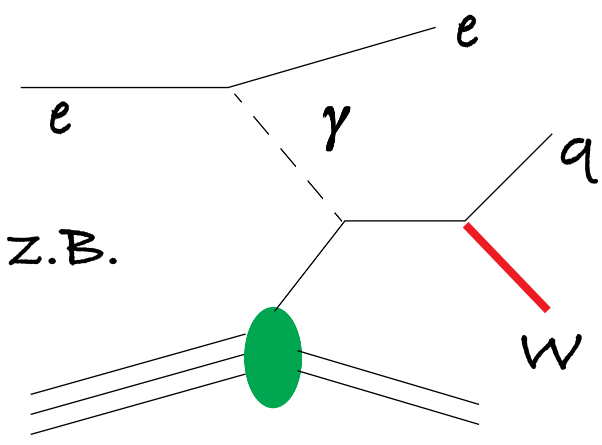
Explained in Standard-Model as

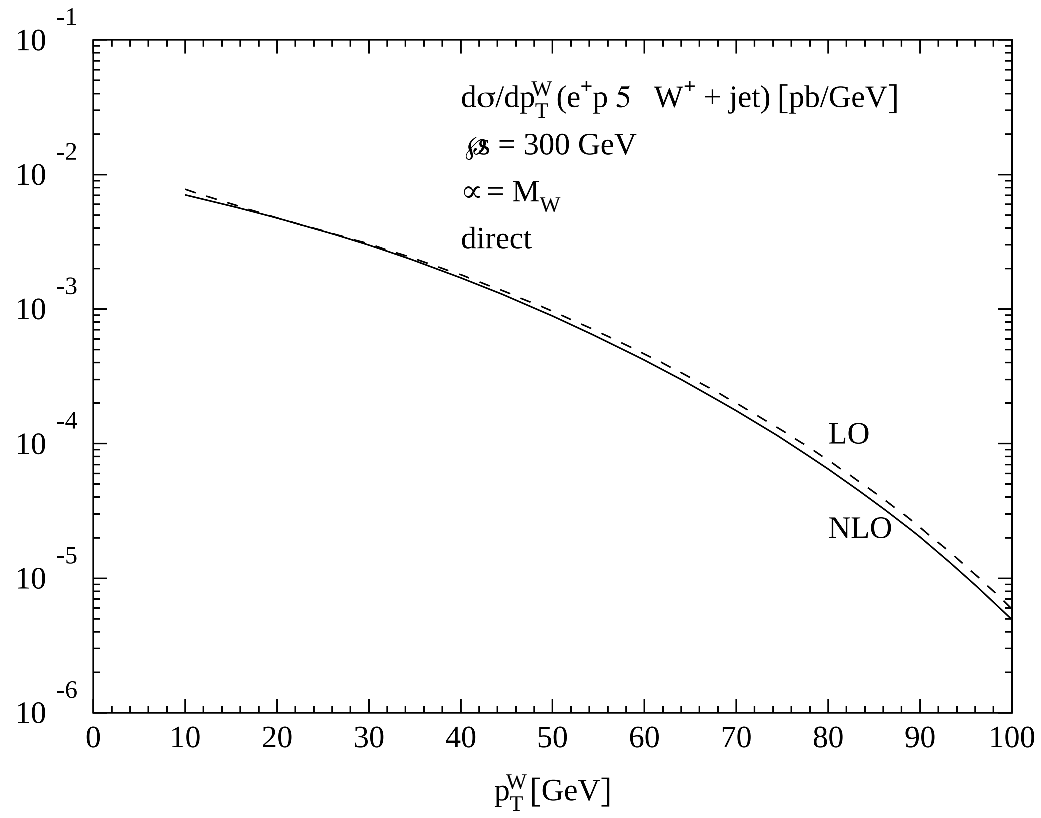
- W-Production

but rate!

# W-Production - Theory

## Production process



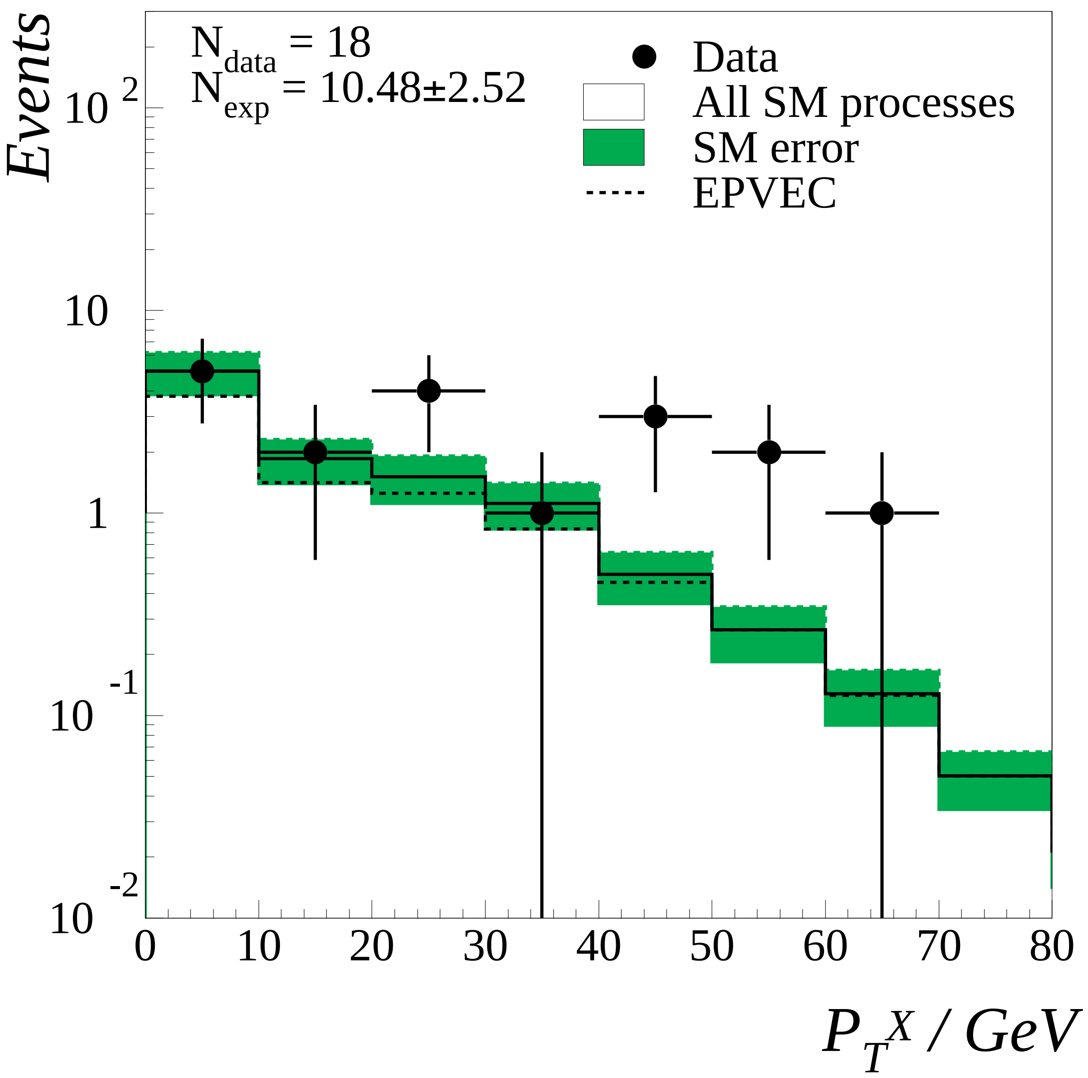

New calculations in NLO for the dominant contribution in γp result in small corrections to the LO result

Calculations reliable

# Isolated LeptonS at large $p_T^X$

## H1

| Electron & Muon | Daten | SM | W-Produktion |
|---|---|---|---|
| $P_T^X$>0 GeV | 18 | 10.48±2.52 | 8.19±2.46 |
| $P_T^X$>12 GeV | 13 | 5.14±1.31 | 4.22±1.27 |
| $P_T^X$>25 GeV | 10 | 2.82±0.73 | 2.34±0.73 |
| $P_T^X$>40 GeV | 6 | 0.99±0.28 | 0.93±0.28 |




## ZEUS

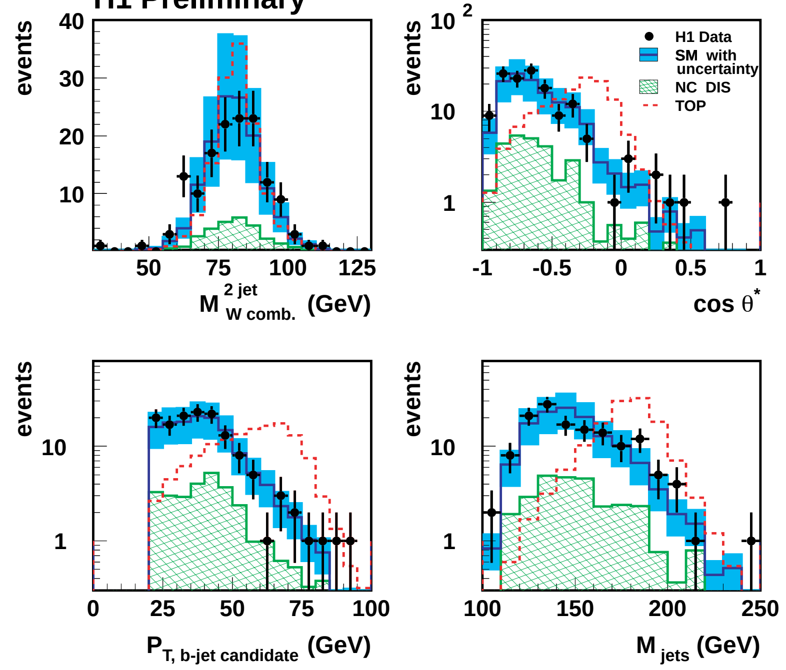
- Observation agrees with expectations (expectation similar to H1)

Explanation?

# Single Top-Production

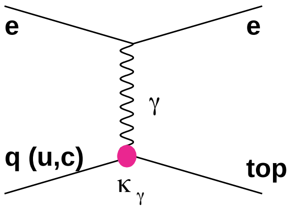
## Hadronic Channel

- 3 jets with $P_T > 40, 25, 20$ GeV

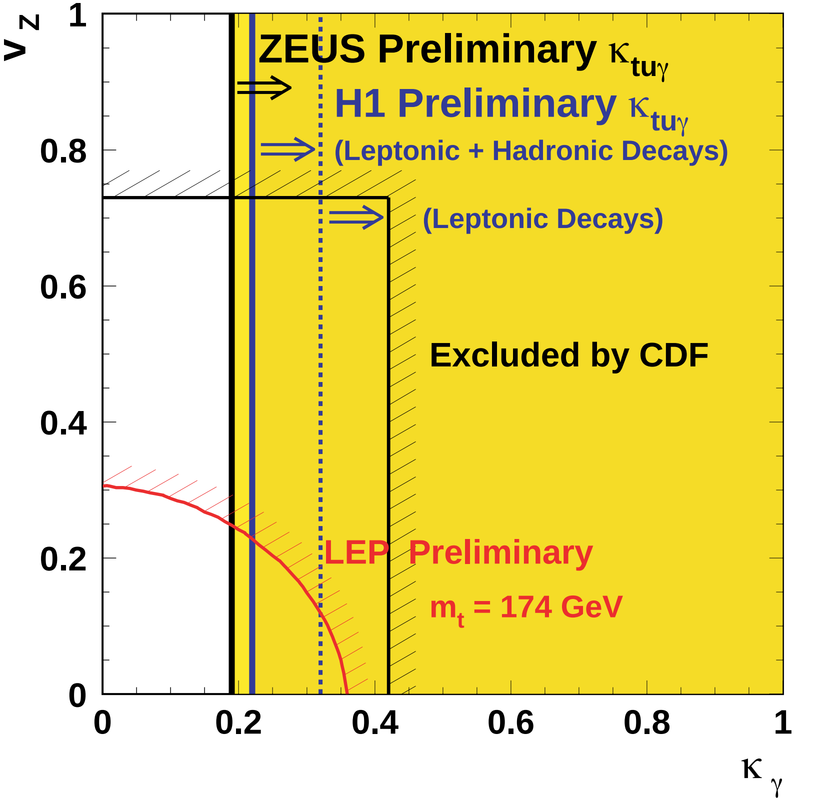



14 Events seen,

19.6±7.8 expected

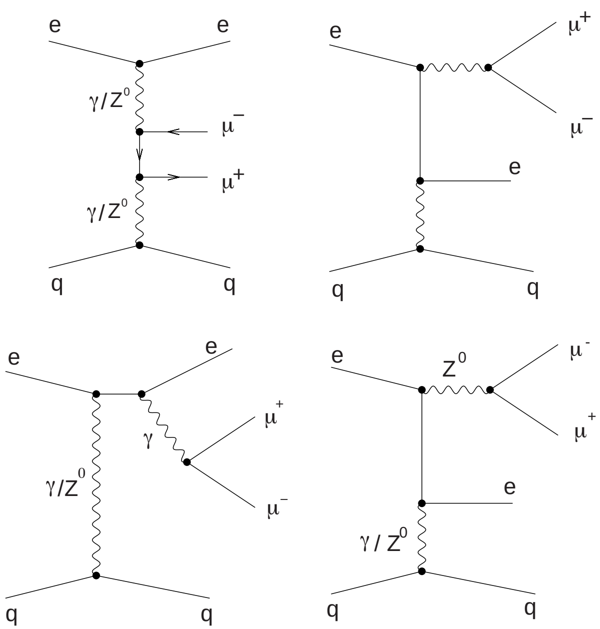



hadron. channel does not rule out top interpretation

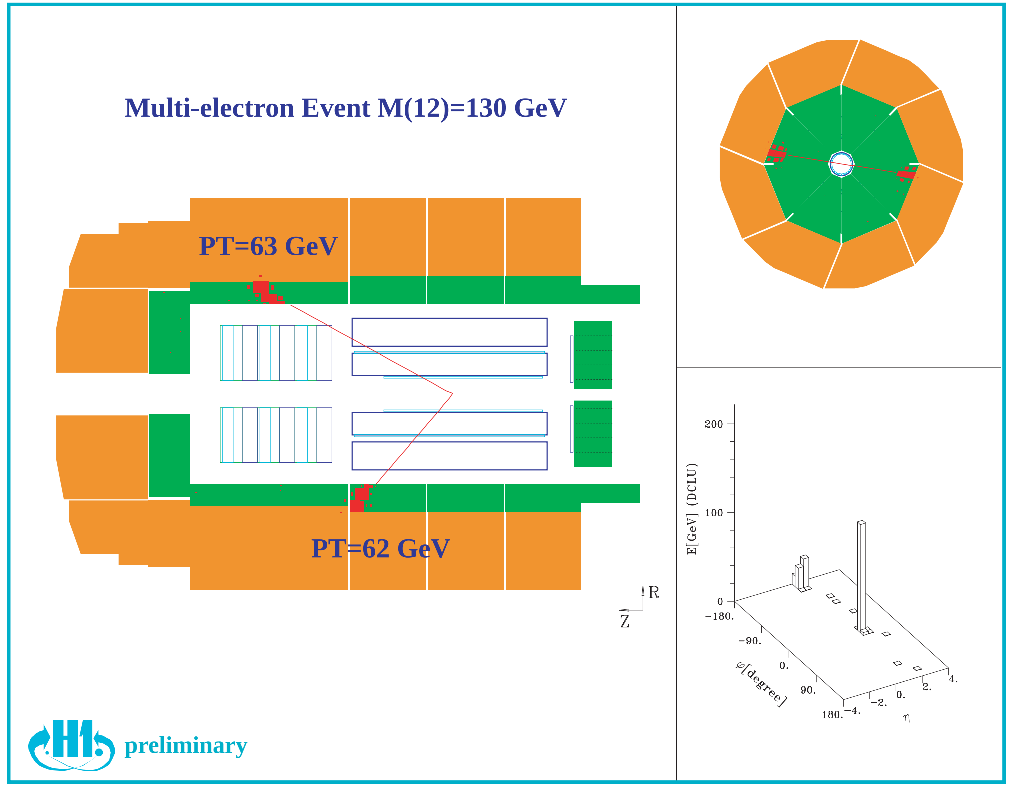


# Puzzle 2: Events with 2 Electrons

- 2 Electrons with $E_{1,2}>10$ GeV (5 GeV) and $20^0<\theta<150^0$
- a (possible) 3rd electron with $E_3>10$ GeV und $5^0<\theta<175^0$




Expectn: GRAPE (GRACE) for e and $\mu$

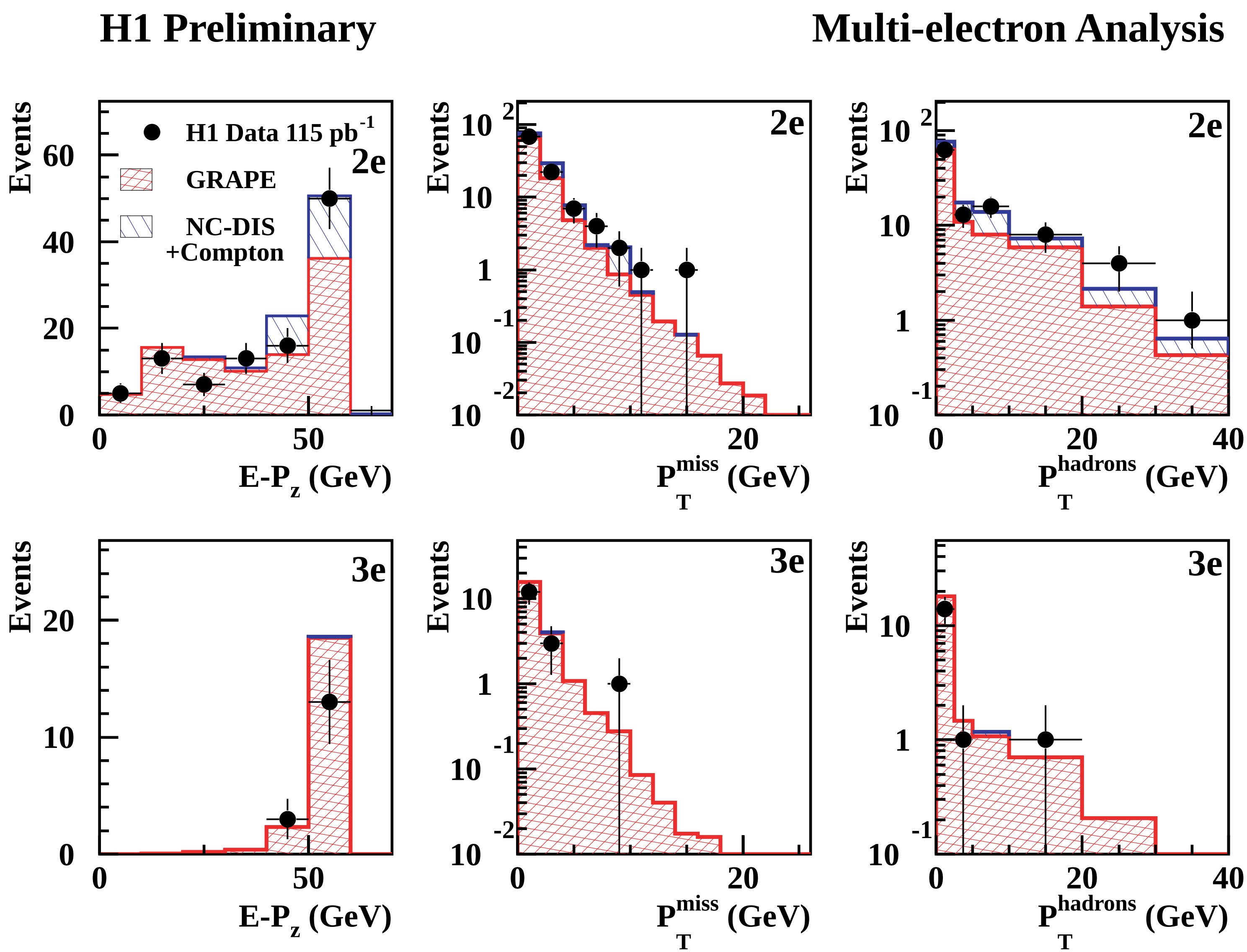



eq→eeeq   4 Fermion Final State

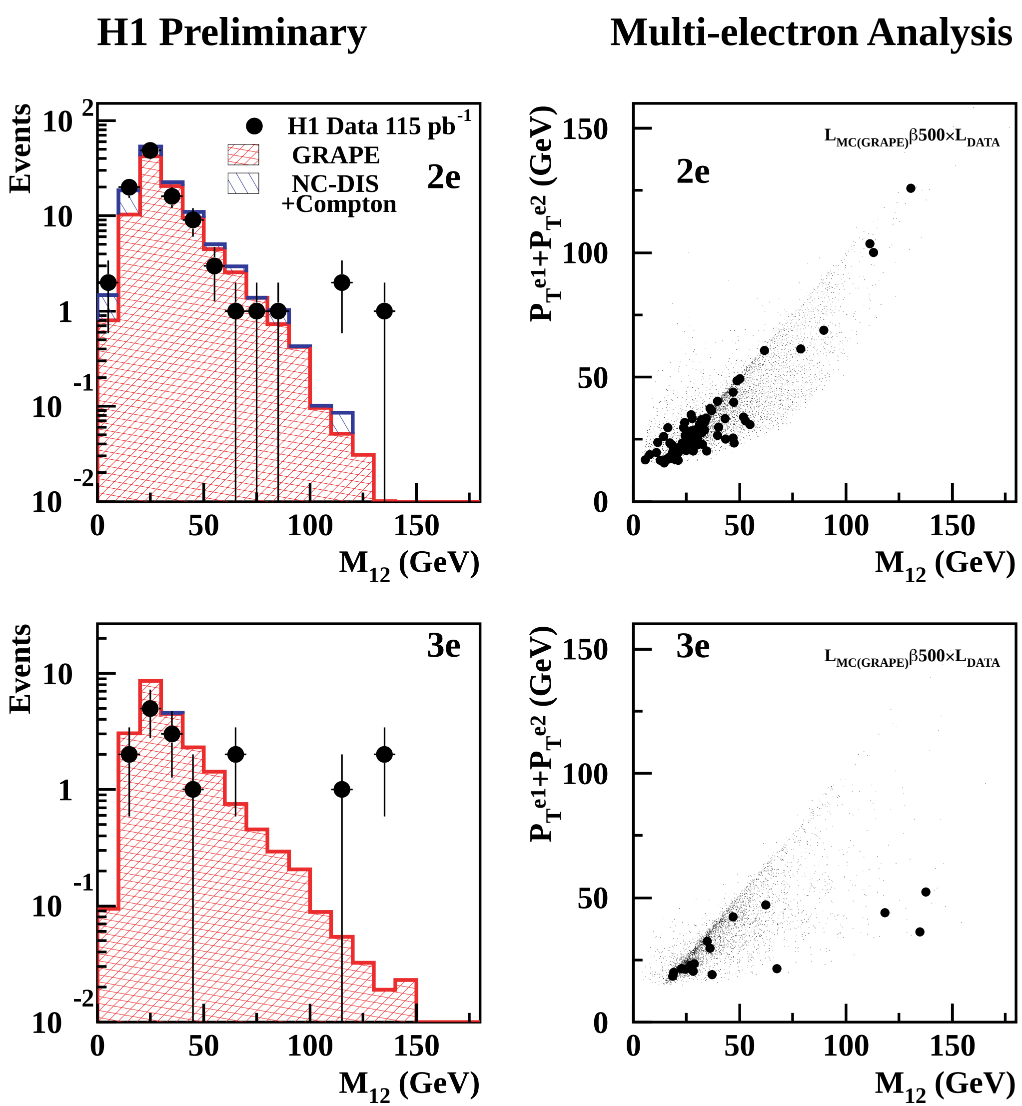
- EW Diagrams
- e-final state: Interference
- elastic + inelastic

# Expectation for Multi-Electron Production

Good overall description of the data



# Kinematical Distributions of the 2-Electron-Events




For $M_{12} > 100$ GeV

| | DATA | SM |
|---|---|---|
| 2e | 3 | $0.25 \pm 0.05$ |
| 3e | 3 | $0.23 \pm 0.04$ |

Excess for $M_{ee} > 100$ GeV

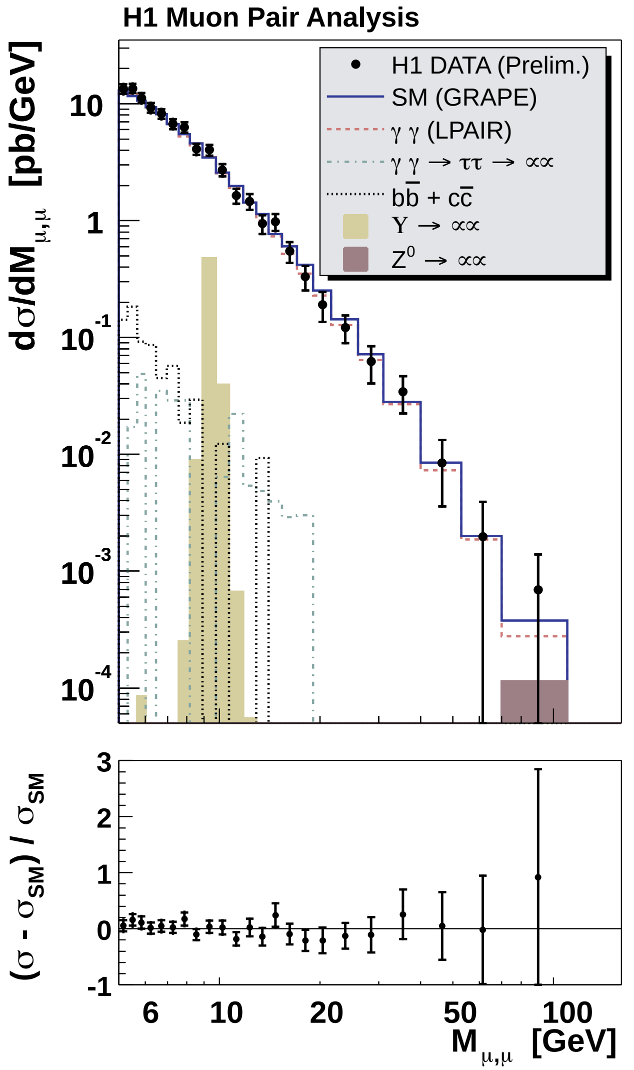
but:

2- and 3-electron-topology

more statistics!

→ HERA II

# 2 Muon Events




## Selection

- 2 muons with $20^0 < \theta < 160^0$
- good description by SM

## Comparison to the multi-electron-sample

- no excess!
- tests in the central angular range
- smaller acceptance and luminosity

→ not conclusive
(neither supporting nor refuting findings in electron channel)

# HERA II

## Goal

- 1 $fb^{-1}$ till end 2006
- Polarization (~55%)
- Runs with reduced Ep (e.g. 300, 365, 400 GeV) to measure $F_L$

## Method

- strong focussing of the beams at the Interaction Point

## Solution

- super conducting quadrupoles in the Experiment

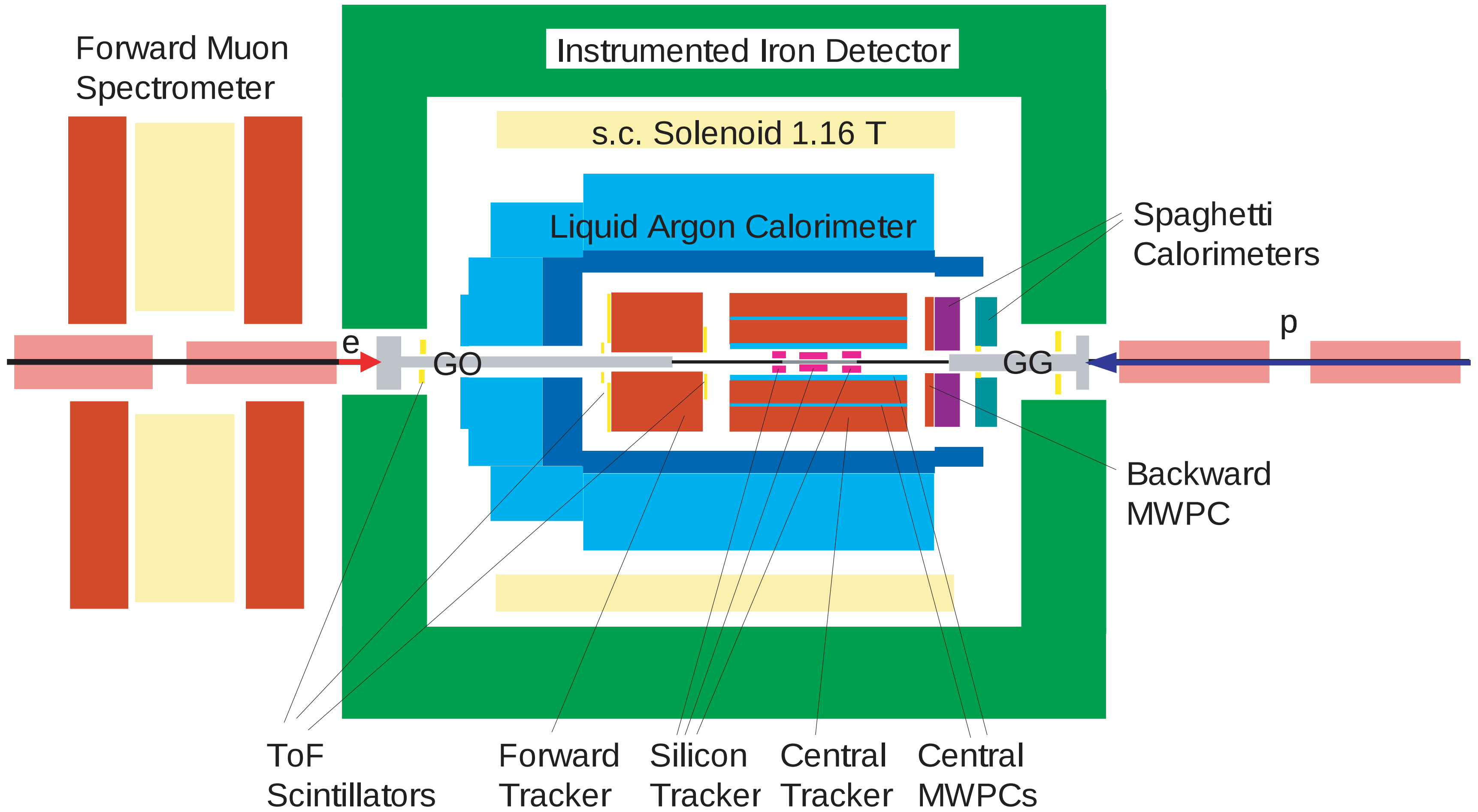
## Consequences

- Synchrotron radiation is generated in the IP-region
- no compensating magnets
- space restrictions

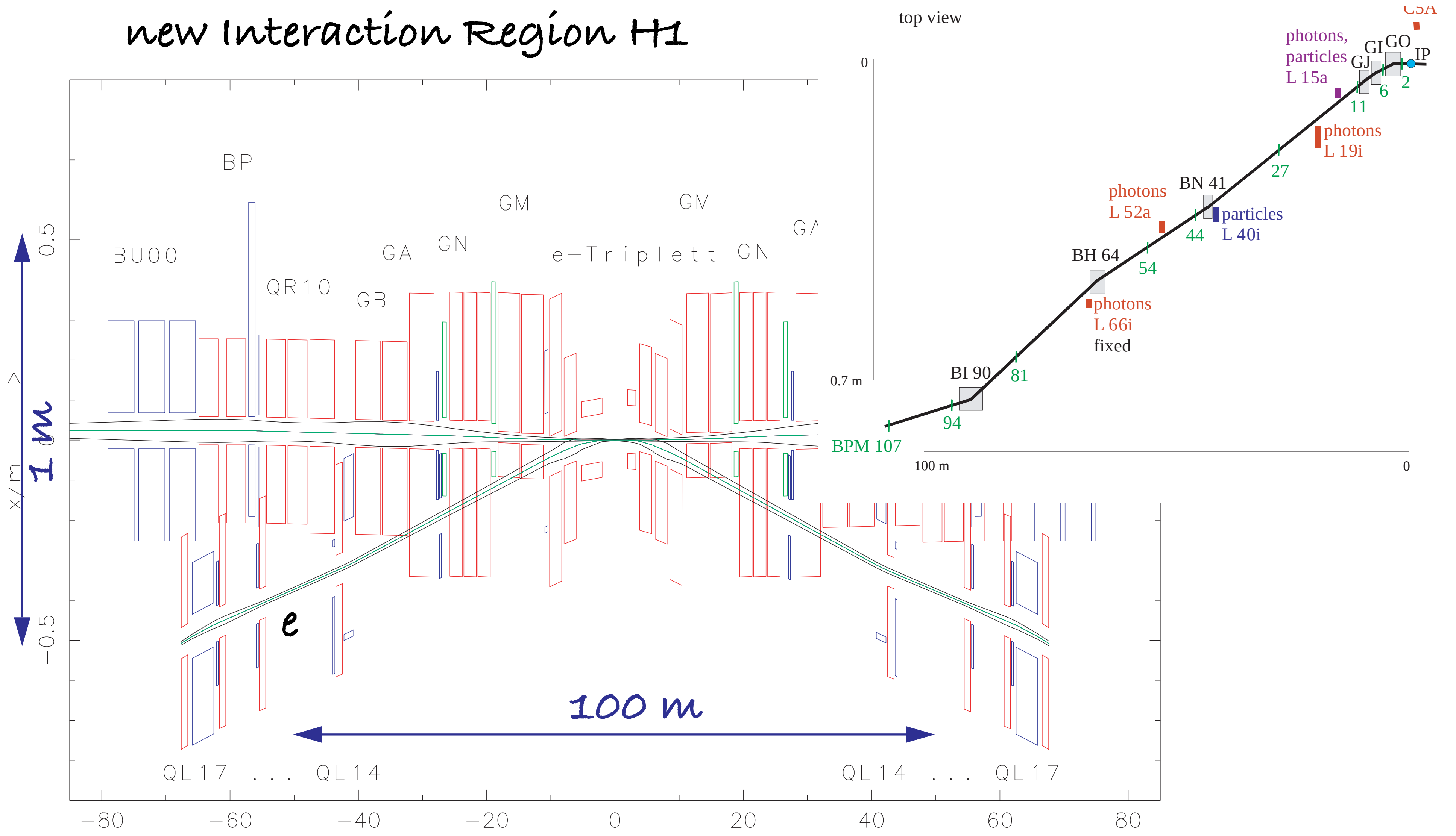
## Status

- spec. Luminosity has been achieved (design 1.8*...) $\sim 1.5 * 10^{30} cm^{-2} s^{-1} (mA)^{-2}$
- but...

# H1 Detector Upgrade



# Commissioning of HERA II



# HERA Startup

## Critical

- drift chamber currents

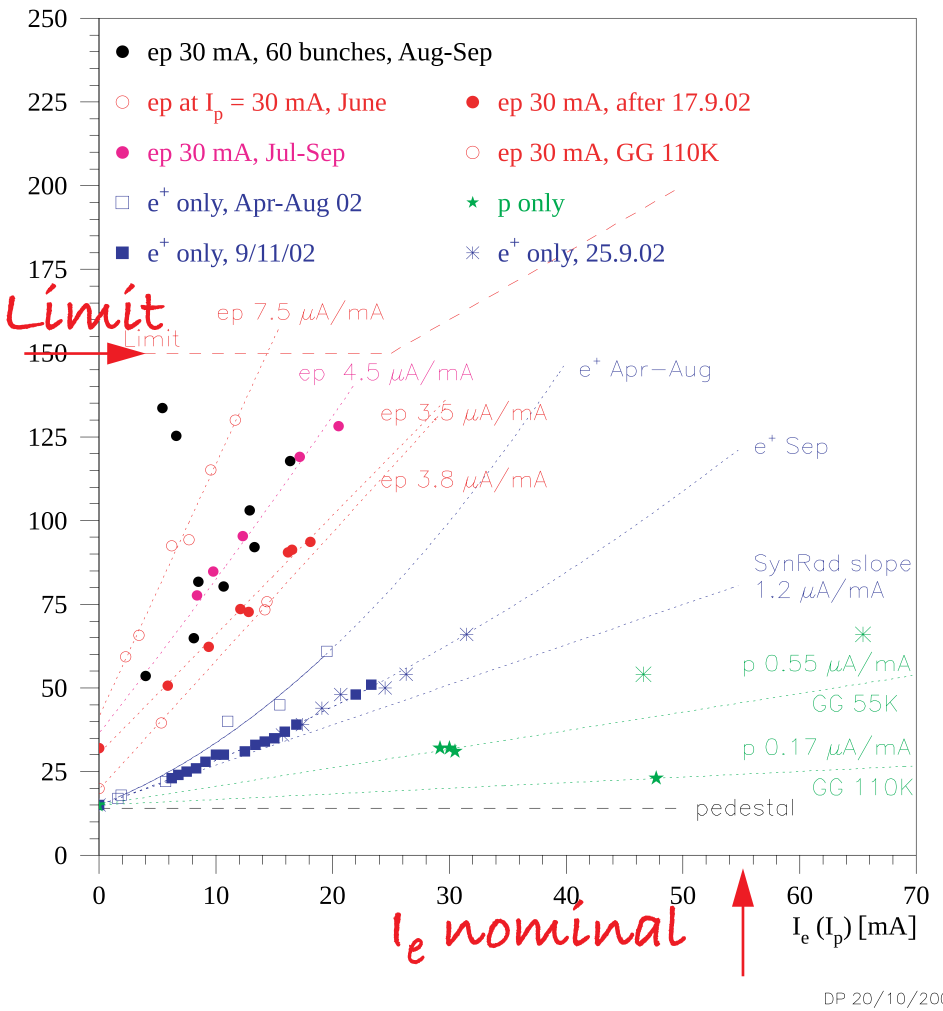
## Synchrotron Radiation

- careful beam steering
- coating of surfaces

## Vacuum

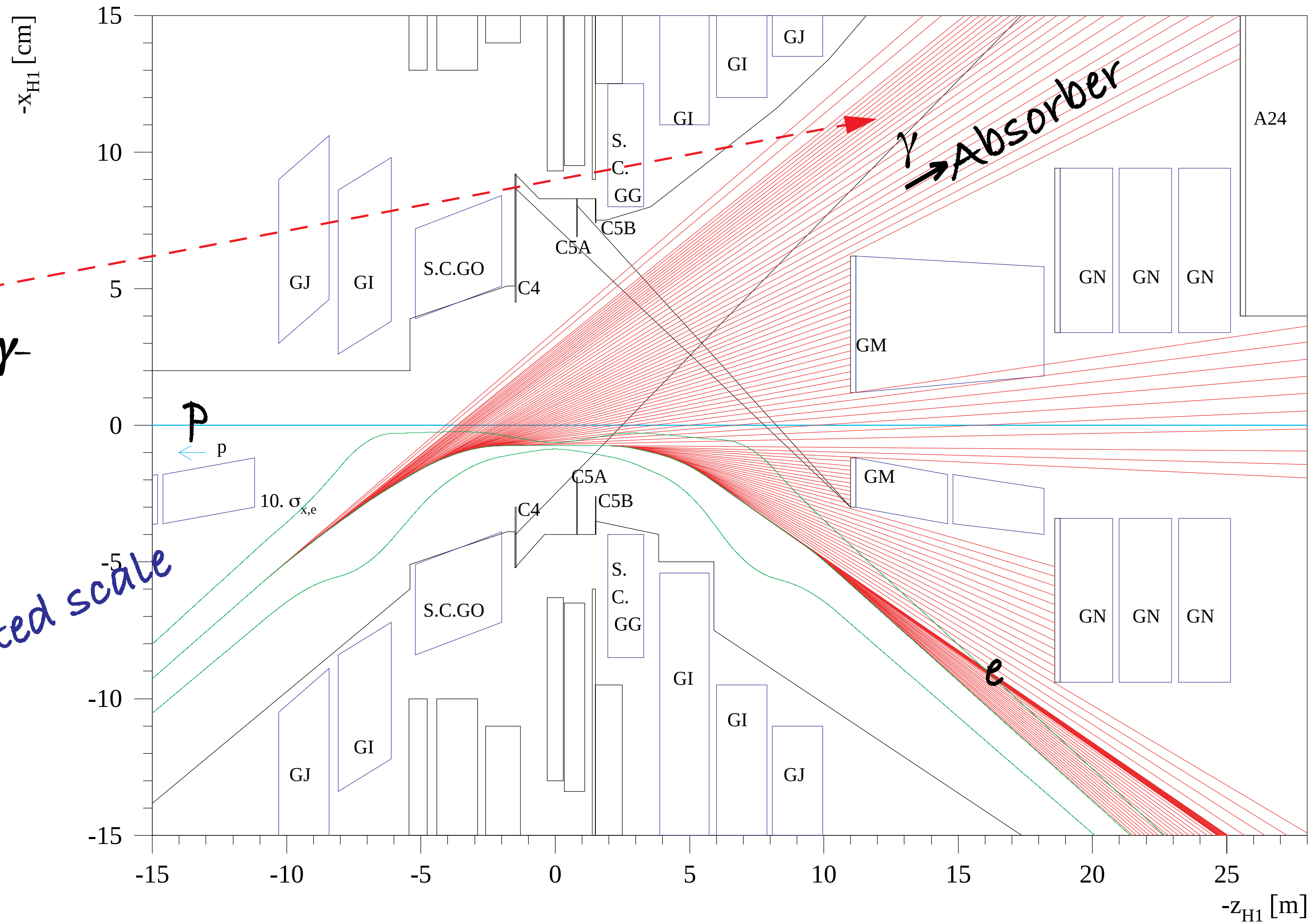
- cold/warm interface
- residual gas: $H_2O$, $CH_4$
- elastic scattering of 920 GeV protons on residual molecules

## Development of Chamber Current



# Synchrotron Radiation

3rd beam pipe to dispose of γ-radiation.




mind distorted scale

# Outlook for HERA II

## Combining

- direct observation
- precision physics (QCD & EW)

## Goals

**1fb-1**

- Search at small scales
- Electroweak Effects
- Solution to the remaining puzzles

"Tevatron aspect" of HERA

**Strong Interaction:**

- Parton structure ($F_2$, $F_L$, ...), charm, bottom, jets
- Diffraction
  inclusive and Final states:
  charm, (bottom), $\gamma$

"LEP aspect" of HERA