Physics and Physics prospects at HERA

58th Extended Scientific Council / 130th Scientific Council

21/22 June 2004

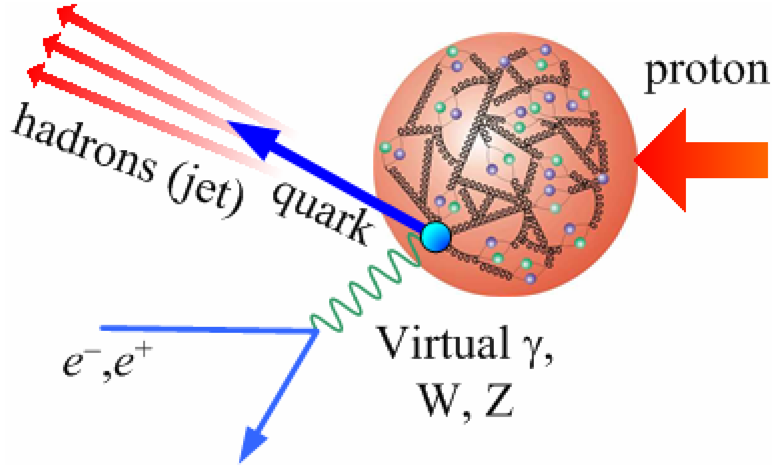
Yuji Yamazaki (KEK, ZEUS)

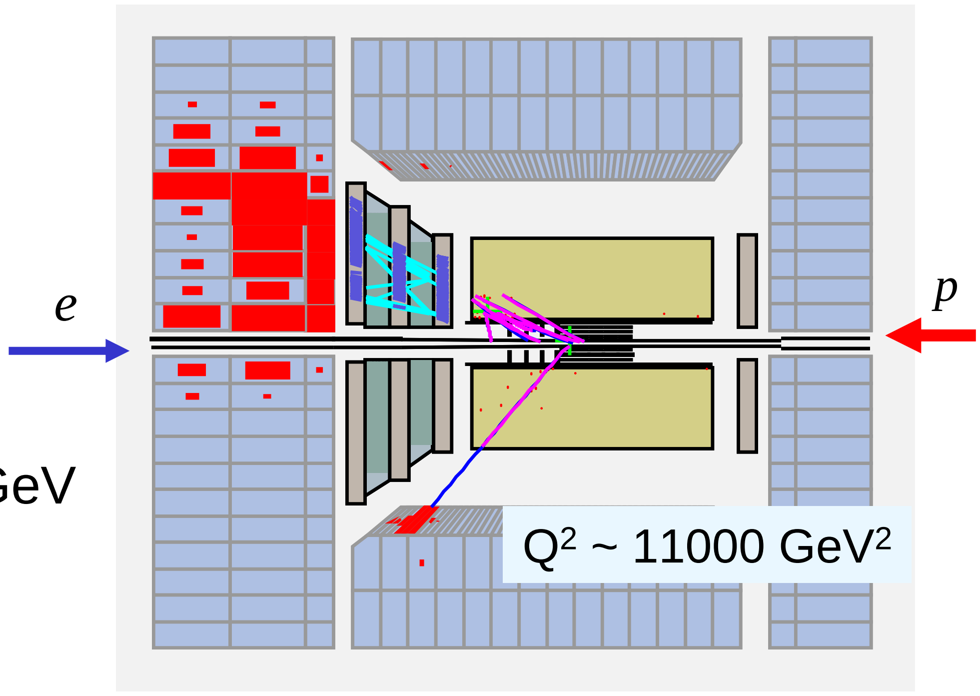
On behalf of

the H1, ZEUS, HERMES and HERA-B collaborations

The “Super Electron Microscope” HERA

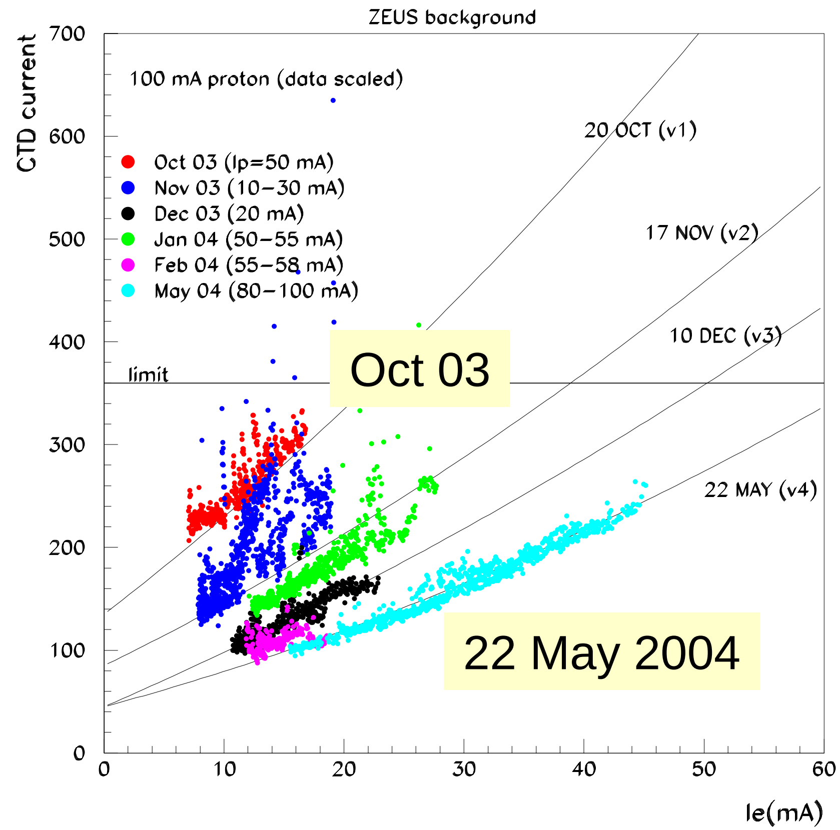
- Explore the structure of the nucleon by electron beam
  - Deep-inelastic scattering (DIS)
  - Scattering angle and energy of electron → momentum distribution of the quarks
- High energy = short wave length
  - Scattering angle ~ Q^2: mass of the exchanged particle
  - Centre-of-mass energy 314 GeV ≈ up to 10^{-18} m resolution



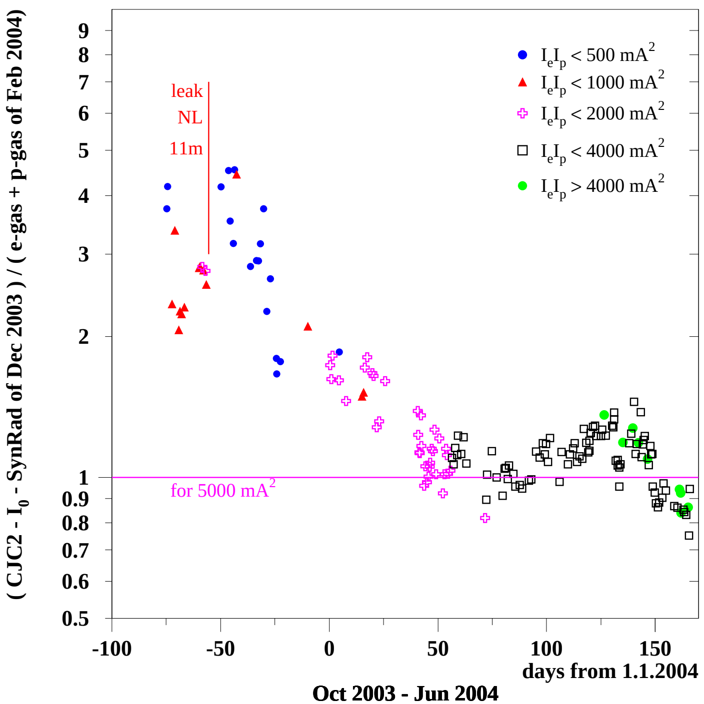


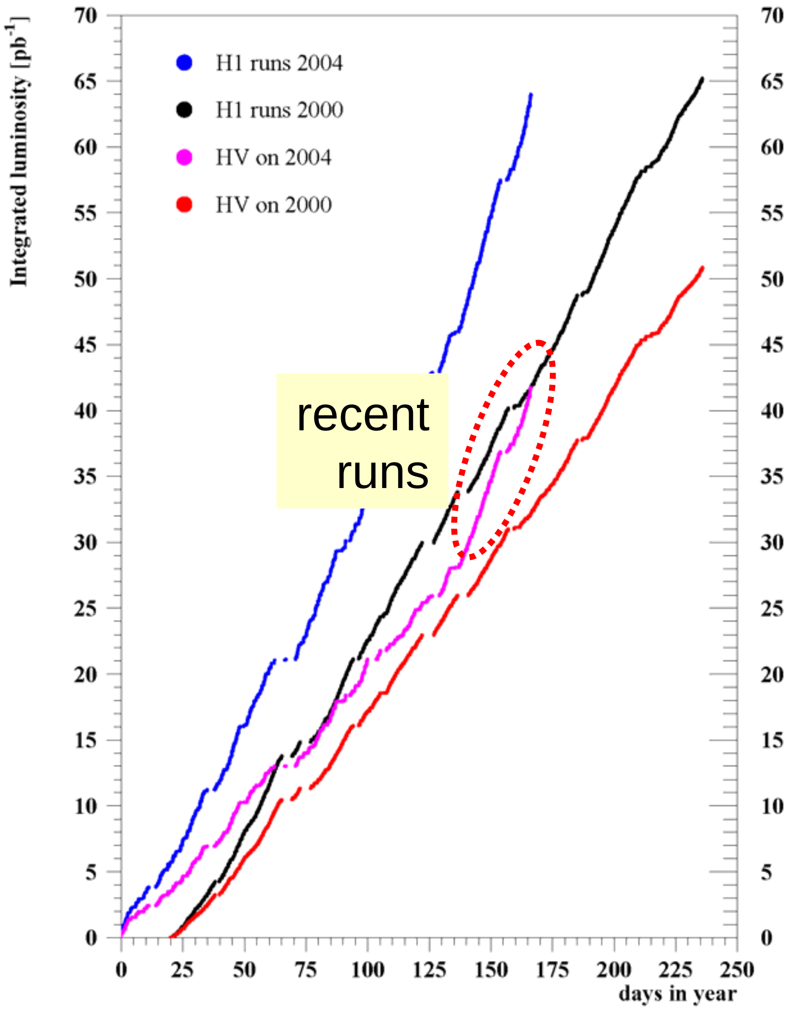
HERA-I and HERA-II running

- HERA-I: 1992-2000,
  Integrated Luminosity ~ 100pb^{-1}
- HERA-II: 2001-2007,
  Int. Lumi > 700 pb^{-1}, with lepton longitudinally polarised
- Startup problem as previously reported
  - Synchrotron radiation to detector
  - Proton-beam and residual beamgas collisions producing
    - Standing current in chambers
    - Load to trigger / DAQ
- All of them are solved !



HERA-II running

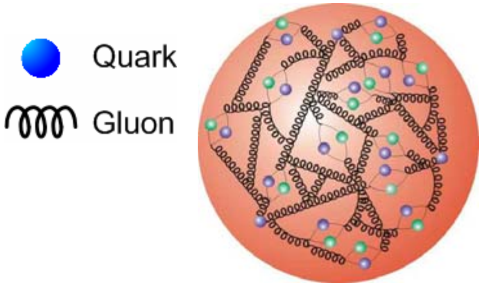




- H1 takes 42 pb^{-1} in 2004
  cf. HERA-I 2000: 51 pb^{-1} (8 months)
- ZEUS slightly behind, following up

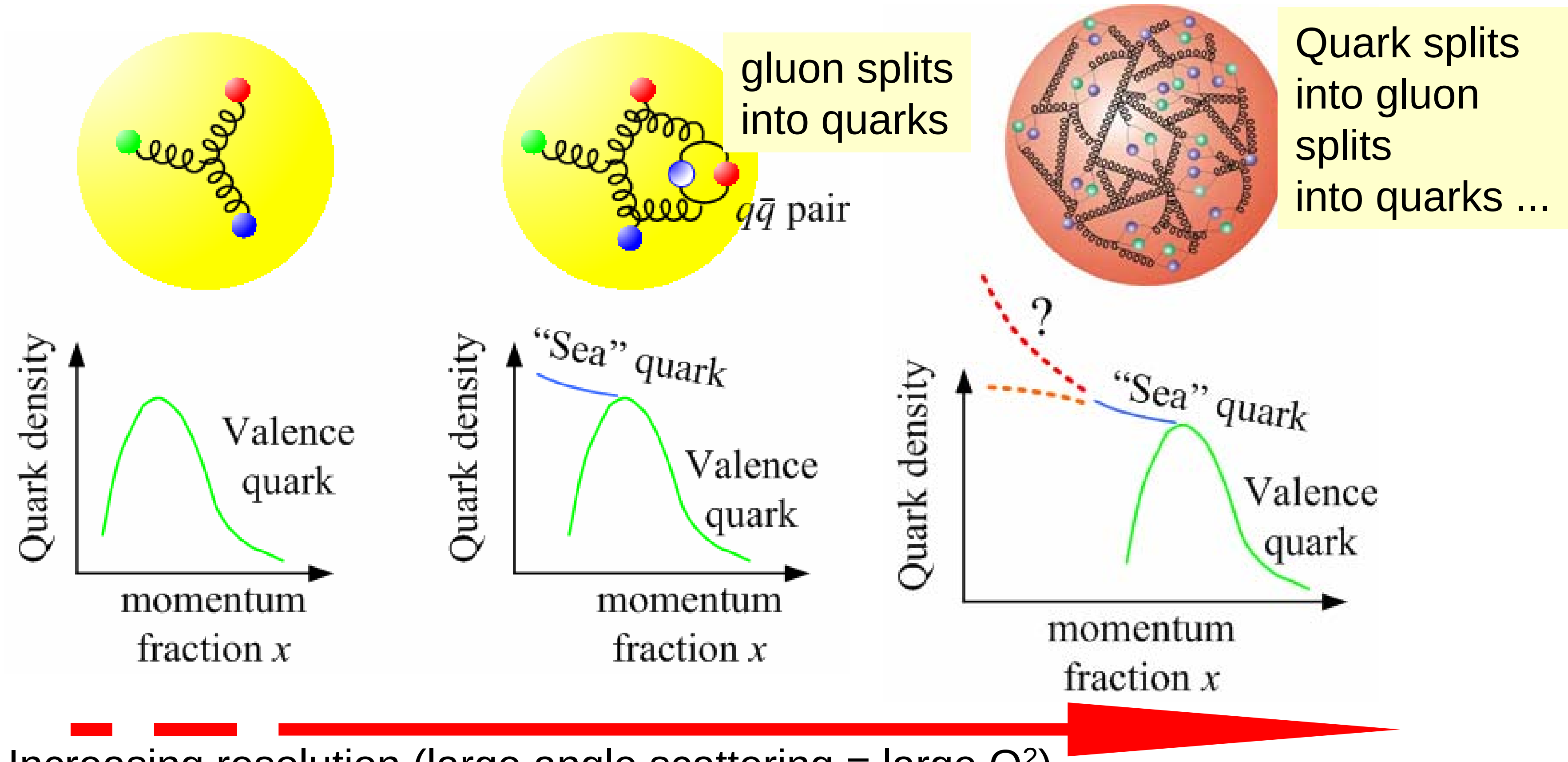
HERA II has begun

HERA physics: Questions to be answered



- Structure of the nucleons
  - How is it composed by quarks and gluons ? partons
  - Where the spin of the nucleon (½) come from ? **HERMES**
- The nature of the interactions
  - Strong interactions – quantum chromo-dynamics (QCD)
    - Force between quarks, mediated by gluons
  - Electroweak interactions
- The physics beyond standard model
  - Is the quark a fundamental particle ?
  - New interactions between leptons, quarks and gluons

Structure of the proton – simple view

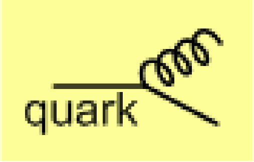


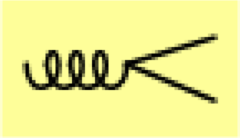
Increasing resolution (large angle scattering = large Q^2)

- More resolution: we see "small" partons
- How does the quarks behave at low-x ?

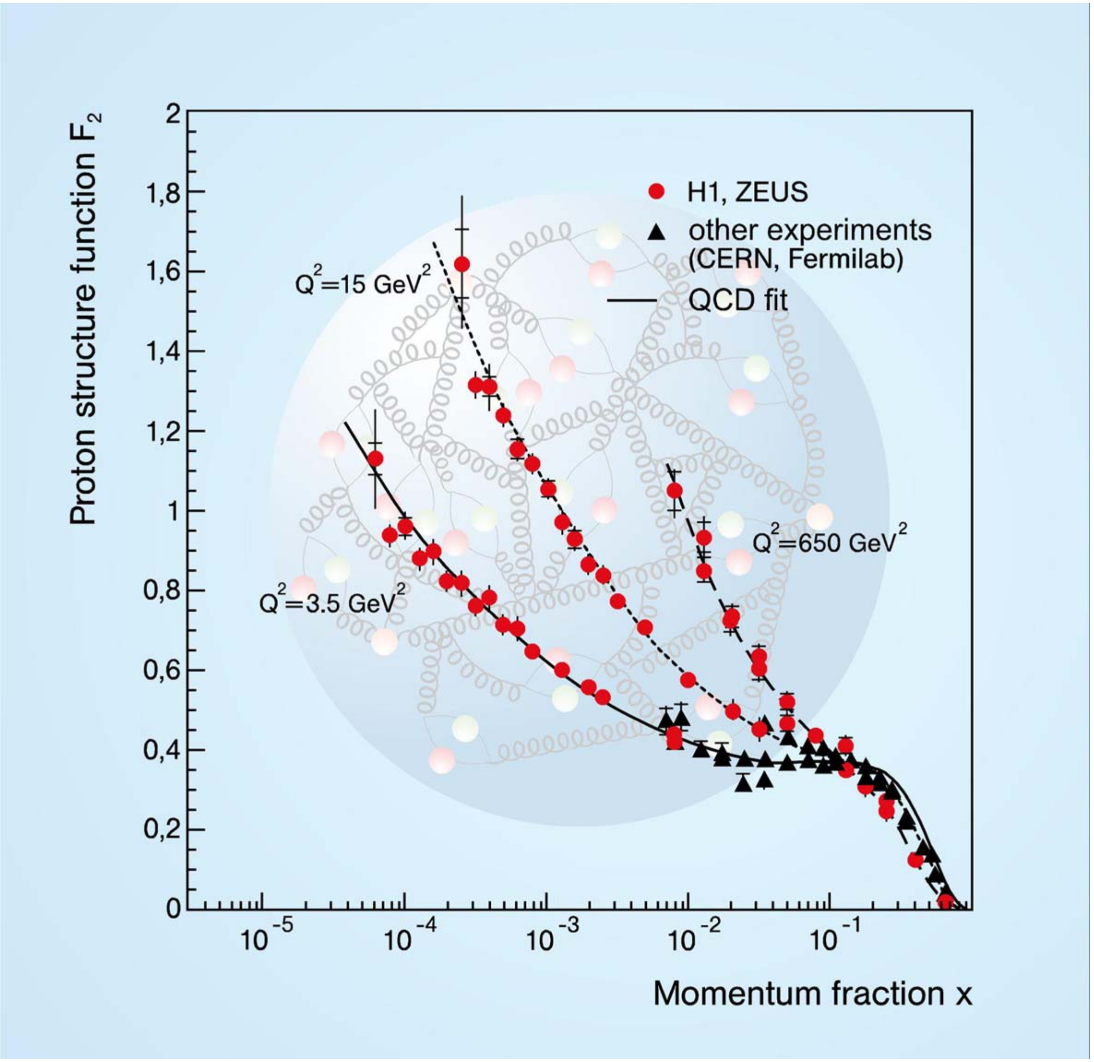
"Structure function" ∝ quark density

- Strong increase of sea quarks towards low x
  - $F_2(x) = e^2 x(\mathbf{q(x)}+\overline{\mathbf{q}}\mathbf{(x)})$
    quark density
- Density increase with Q^2
  - More partons by magnified view



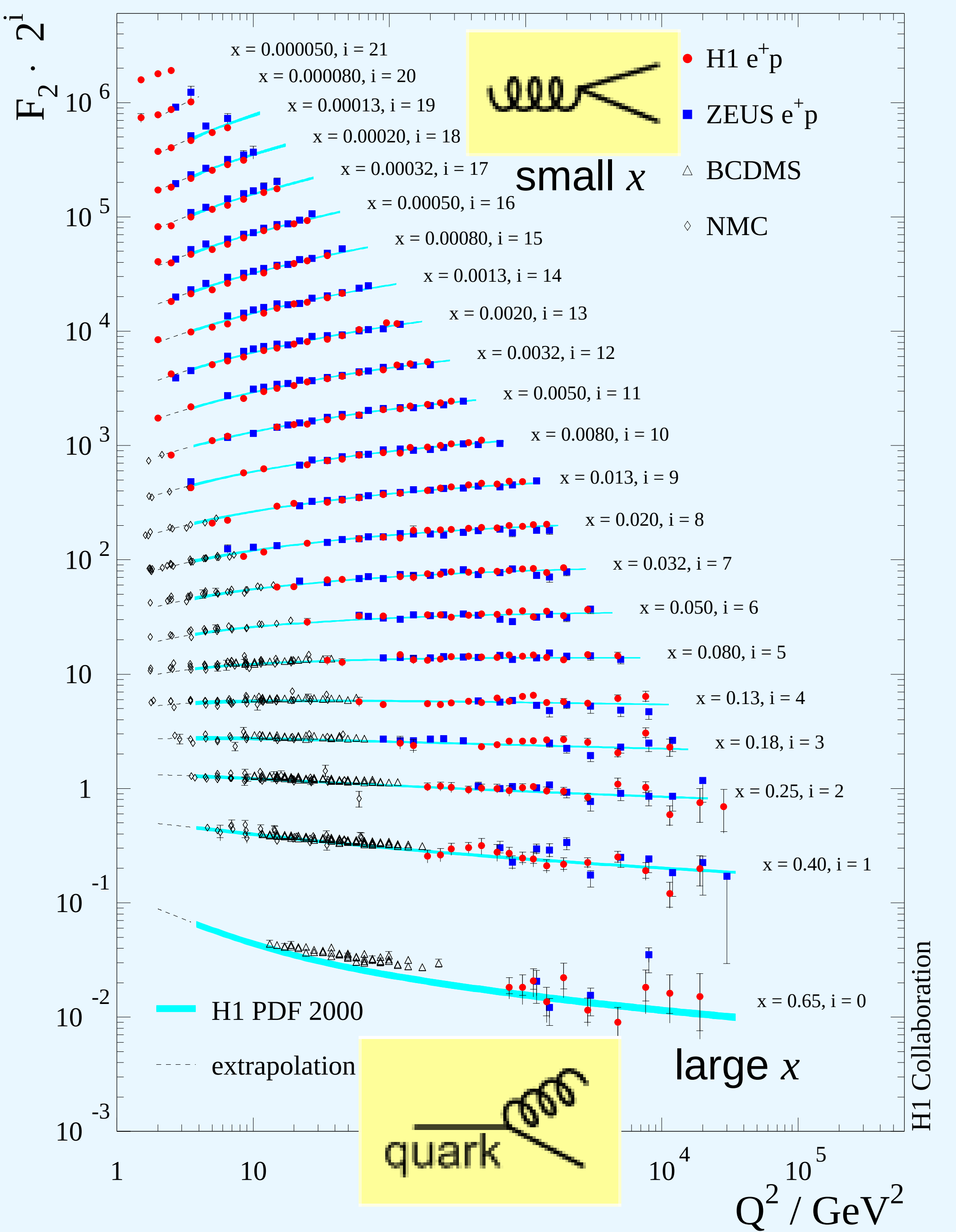


Dynamic creation of quarks at low-x



Evolution of the quark densities

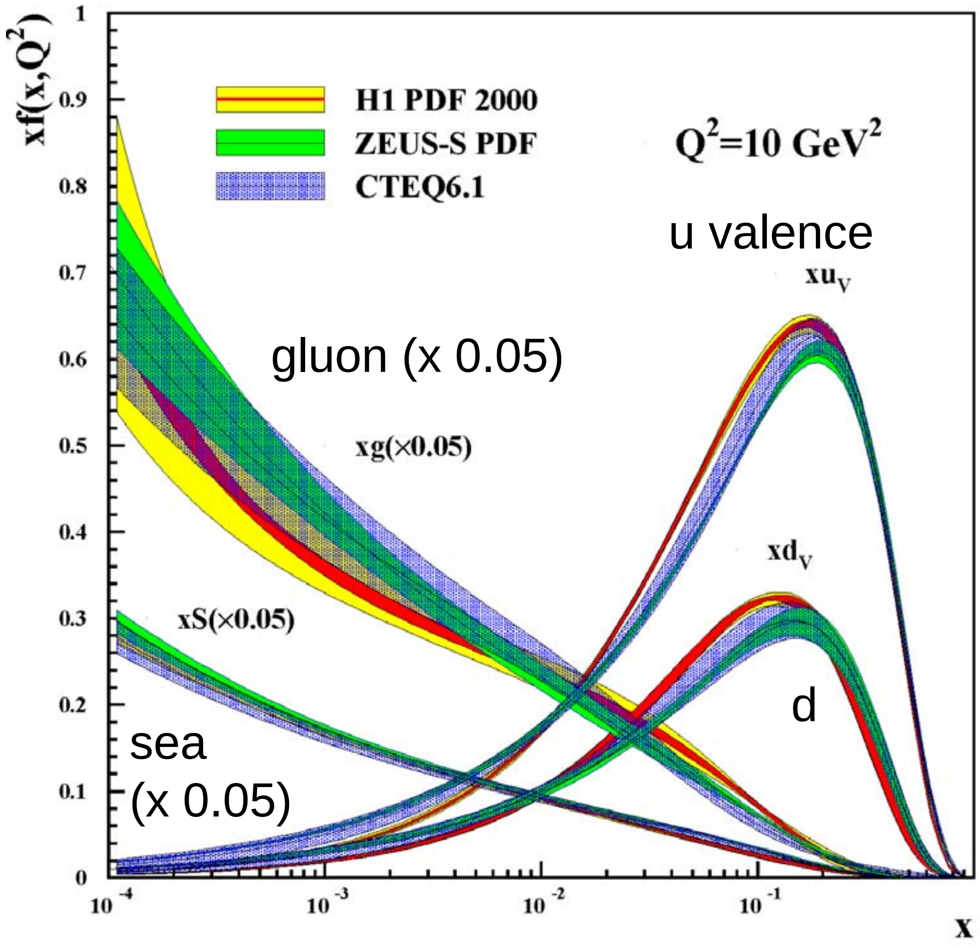
- Precise measurements in wide range of kinematics
  - except for high-*x*
- Scaling violation in Q^2 described well by "DGLAP" evolution equation (blue bands)
  - Dynamic production of quarks and **gluons** understood by perturbative QCD
  - Extraction of gluon density from F_2 data



Extraction of parton densities in the proton

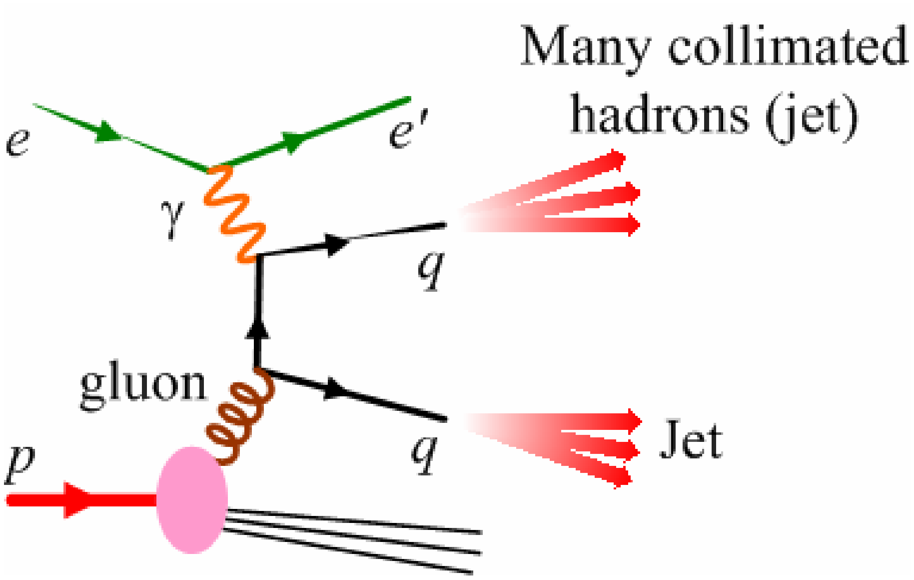
- Gluon density obtained from the QCD fit
- Precise determination of low-x parton densities
- **Gluon > quark at low-x**
- Still need precision:
  - High-x partons: constrained by fixed target data
  - Low-x: we can do better with more statistics

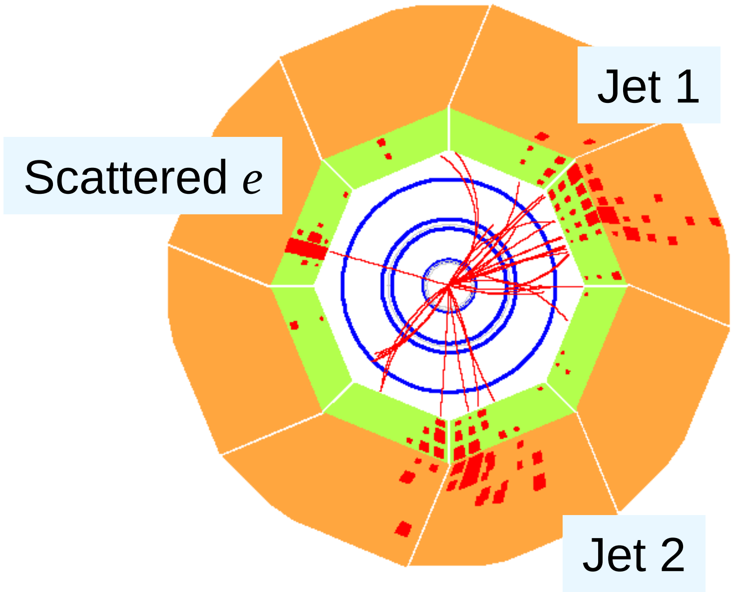
← homework for HERA-II



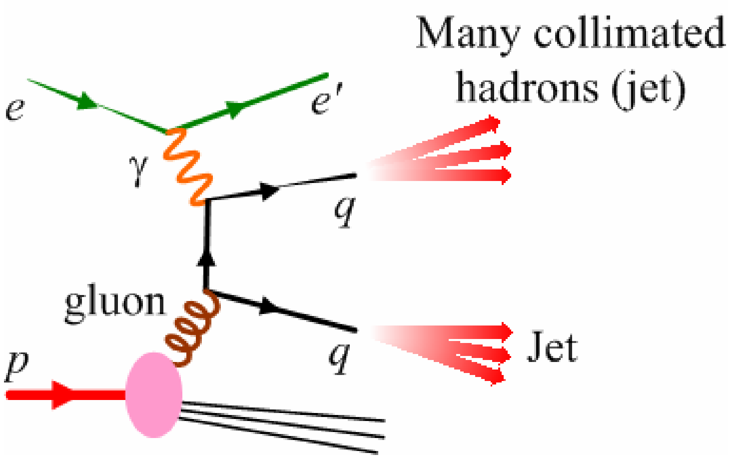
Probing gluons by hadronic final state

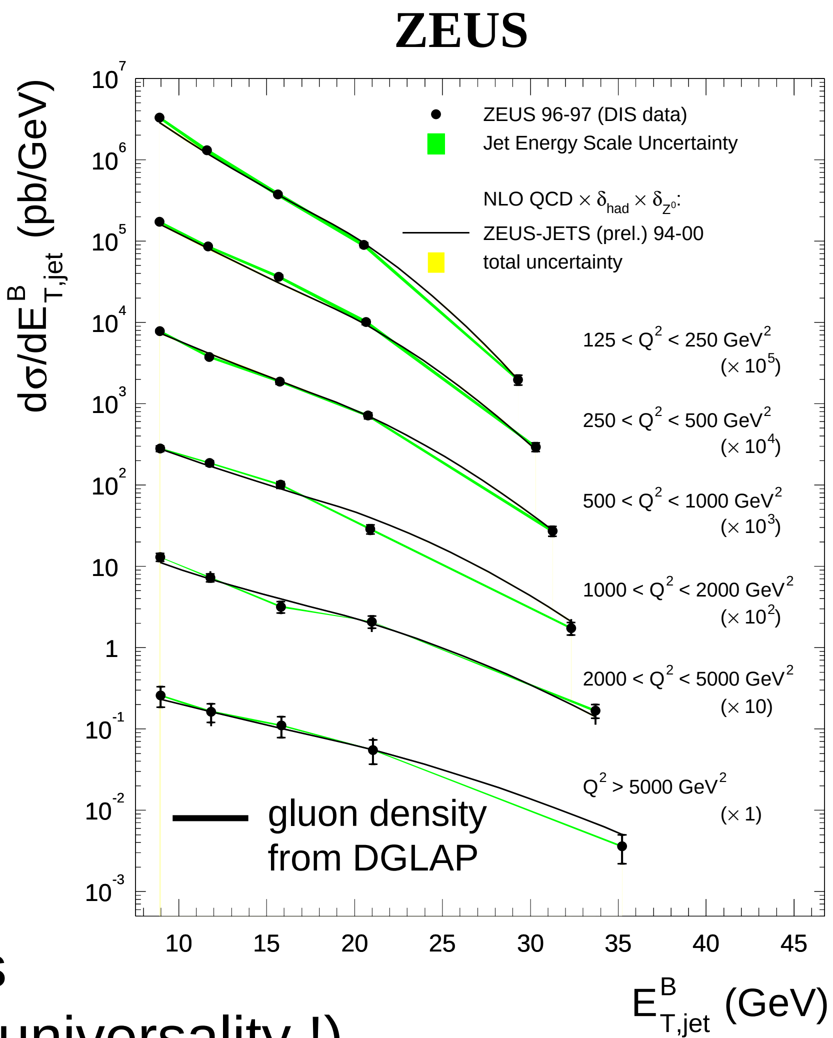
- Photon does not couple to gluons directly ...
  – hit a gluon by a quark instead
- At high energies, quark and gluon momentum can be reconstructed as jets





Gluon density from jets

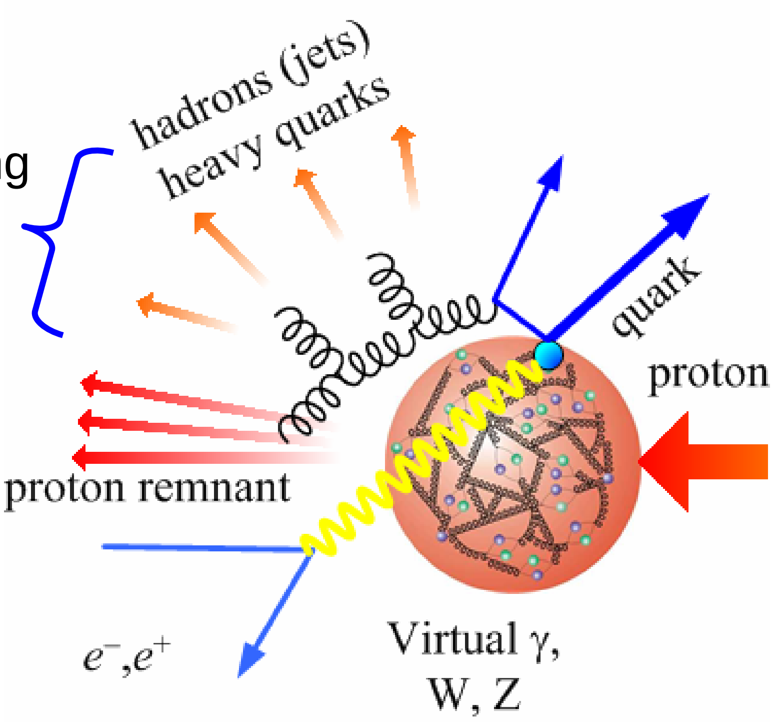


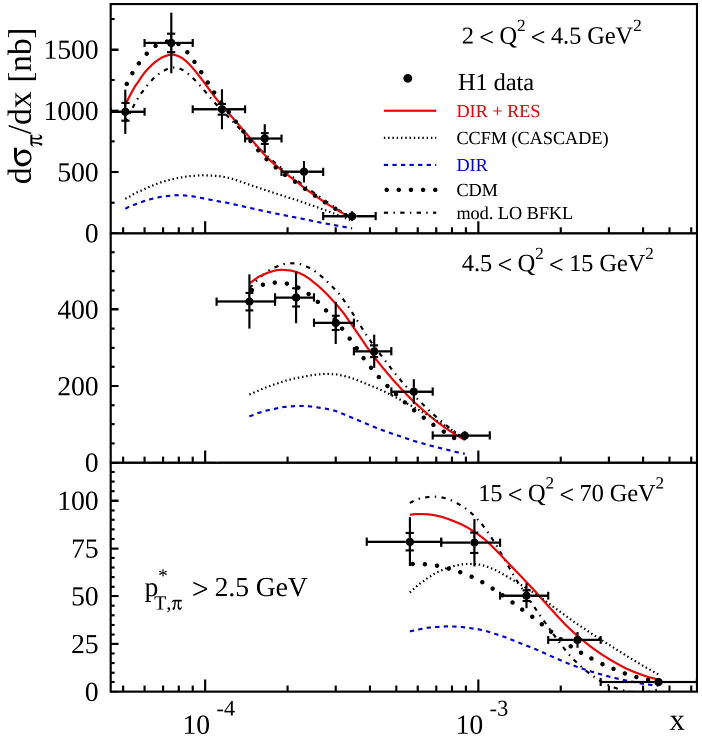


- Jet cross section well described
  → Gluon density from
  DGLAP is "confirmed"
- This means: we can predict cross section using the parton density (universality !) e.g. cross section for LHC
- Dynamically produced partons are quite well understood

Particle production near the proton

What is happening here ?

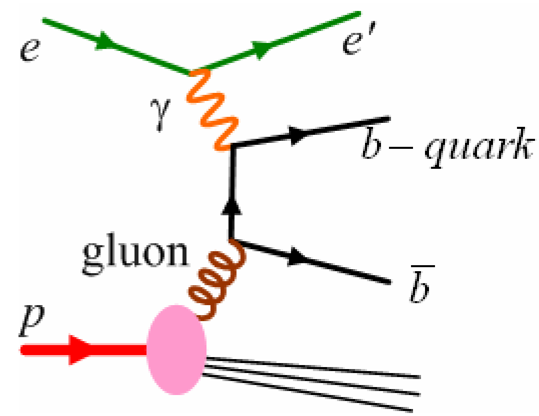


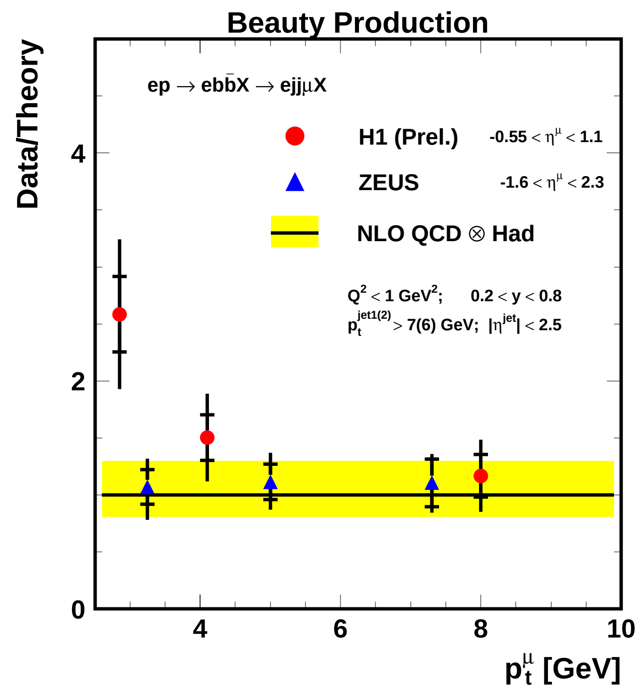


- Large number of particles produced between the struck quark and the proton remnant
- No unique method to describe “multi-body decay”
- Large excess over DGLAP framework
  - Many idea coming out for explaining the “ordering” of particles

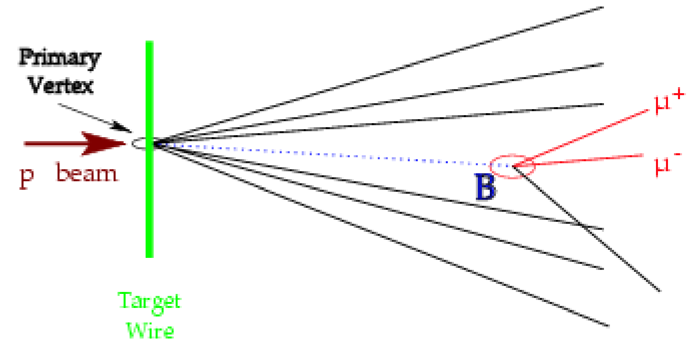
Gluon density and heavy flavour production

- Heavy flavour:
  only produced as a pair from a photon-gluon fusion
- Data tend to be above NLO at low p_T (transv. momentum)
- Important to understand the production mechanism
  - e.g. standard model background to Higgs at LHC
- Statistics limited
  Continue towards HERA-II

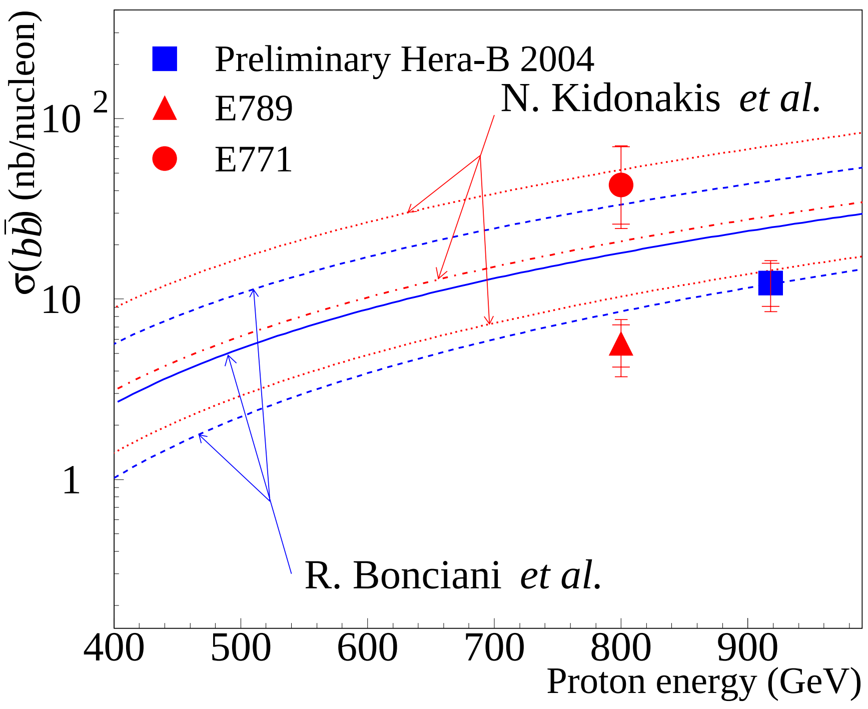




b-quark production at HERA-B

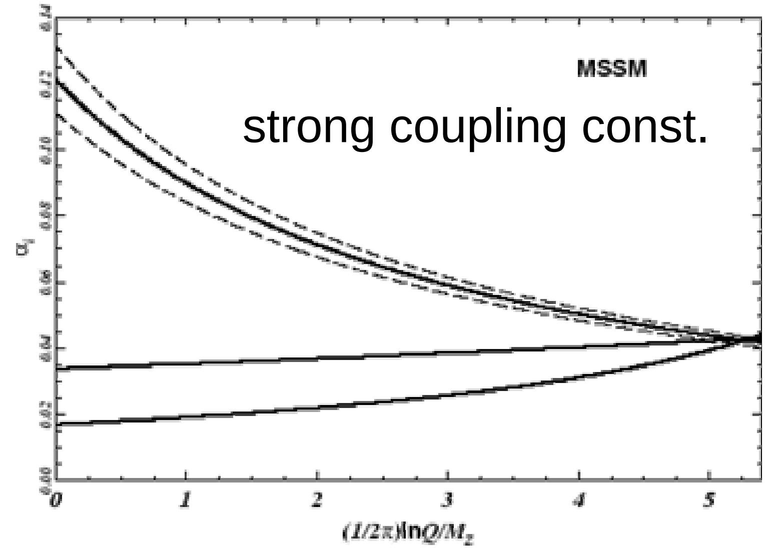


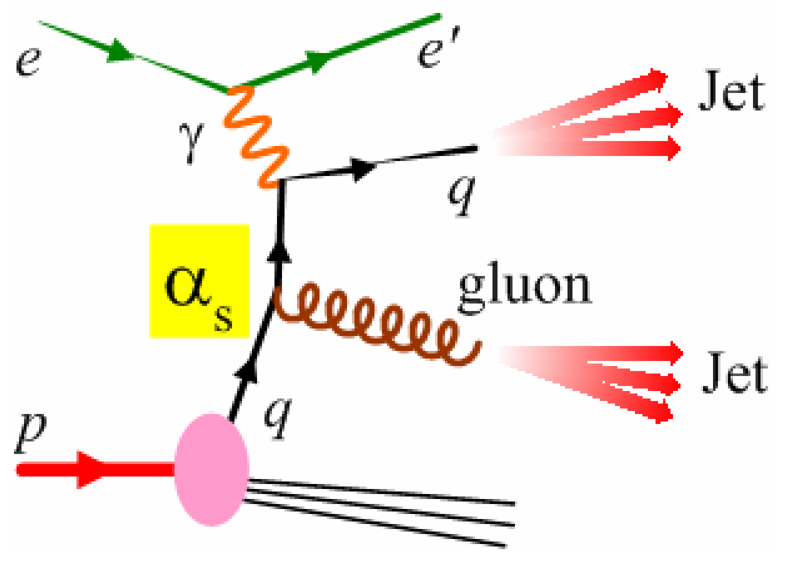
- Experiment: wire-target to the proton beam
- *b*-quark production cross section in *pp* collisions is also uncertain
  - Large difference in the past experiments
- Reducing uncertainty by new HERA-B data
- 5x data being analysed



Measuring strong coupling constant α_s

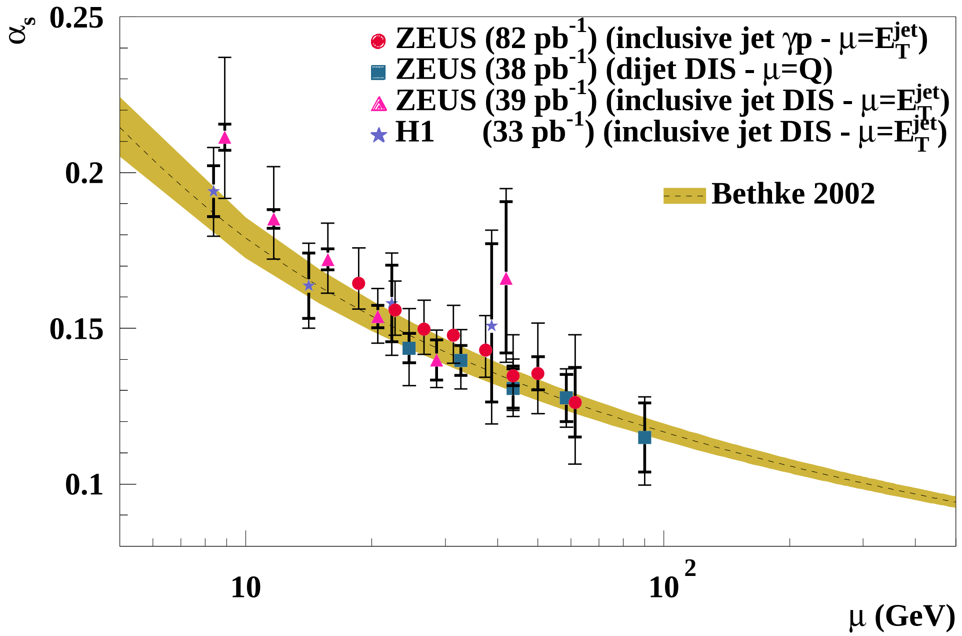
- Measurement of probability to radiate a parton
- But parton cannot be observed directly – worst precision among four forces
- 2-jet probability etc. sensitive to α_s

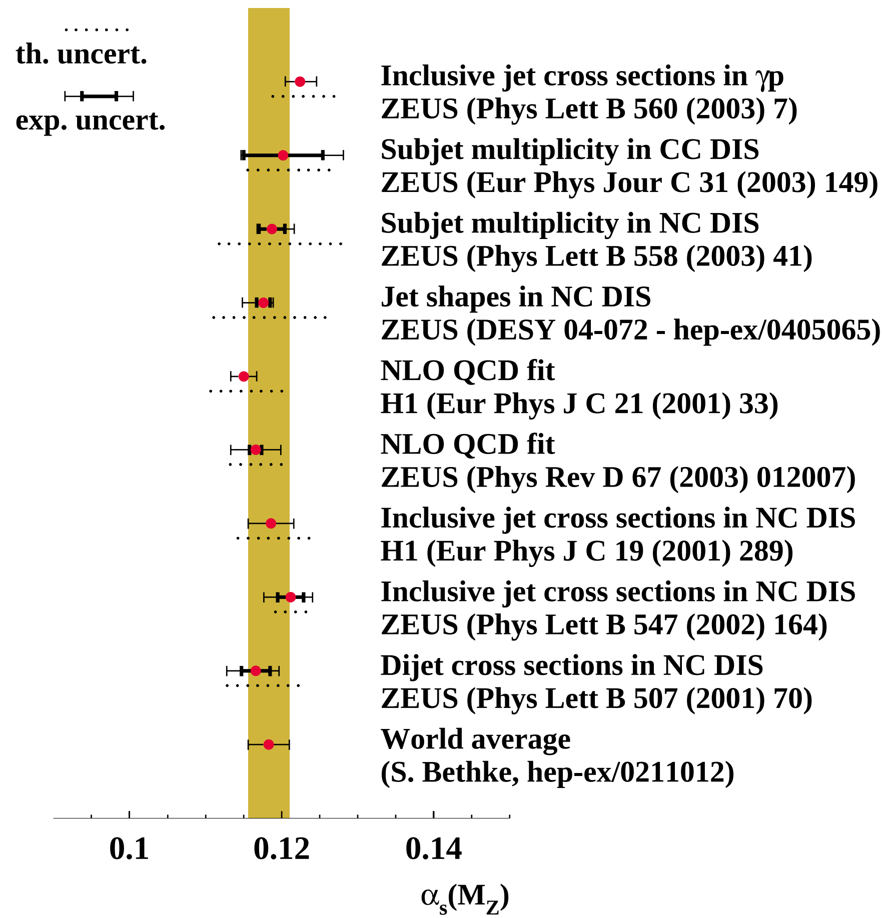




HERA measurements of α_s

- Running in single experiment
- Precision competitive, thanks to the high energy of HERA
  - Theoretical uncertainty from hadronisation is small



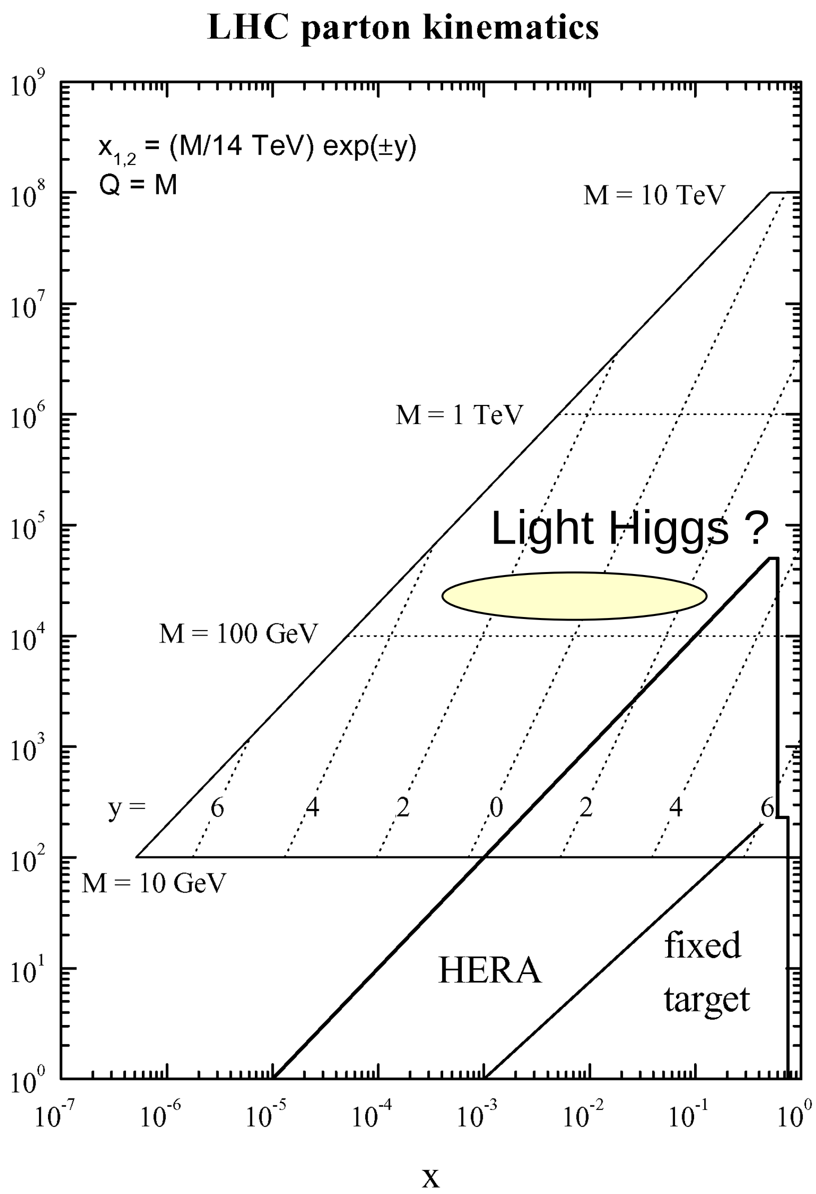


HERA-I study of proton structure and QCD (collider experiments)

- HERA-I study have unveiled:
  - The partonic structure of nucleons at low-x
    Rapid increase of quarks and gluons towards low-x
  - The QCD description of the hadronic final state
    - gluon density checked by jets
    - precise α_s determination
- Some subjects not completely understood :
  - Forward production, heavy flavour
    $\rightarrow$ **need more study with HERA-II**
- Most of the subjects at HERA cannot be covered here
  - e.g. diffraction (proton stays intact)

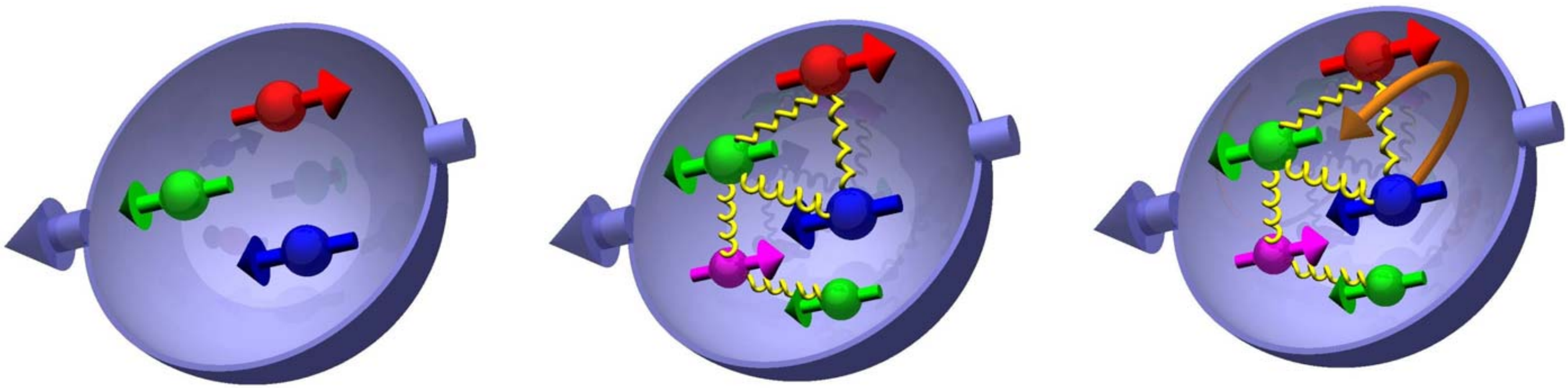
HERA-LHC workshop

- “Synergy” between running and future experiments
- Subjects:
  - Parton densities at LHC
  - Multi-jets, energy flow
  - Heavy quarks
  - Diffraction
  - Monte-Carlo simulation
- March 2004: 300 persons gathered
- Final report Jan 2005



Nucleon spin by HERMES – motivation

- Where the ½ spin of the nucleon comes from ?



Naive expectation:
u↑u↑d↓
but measurement :
only 12 % from
valence + sea quarks
(EMC, 1988)

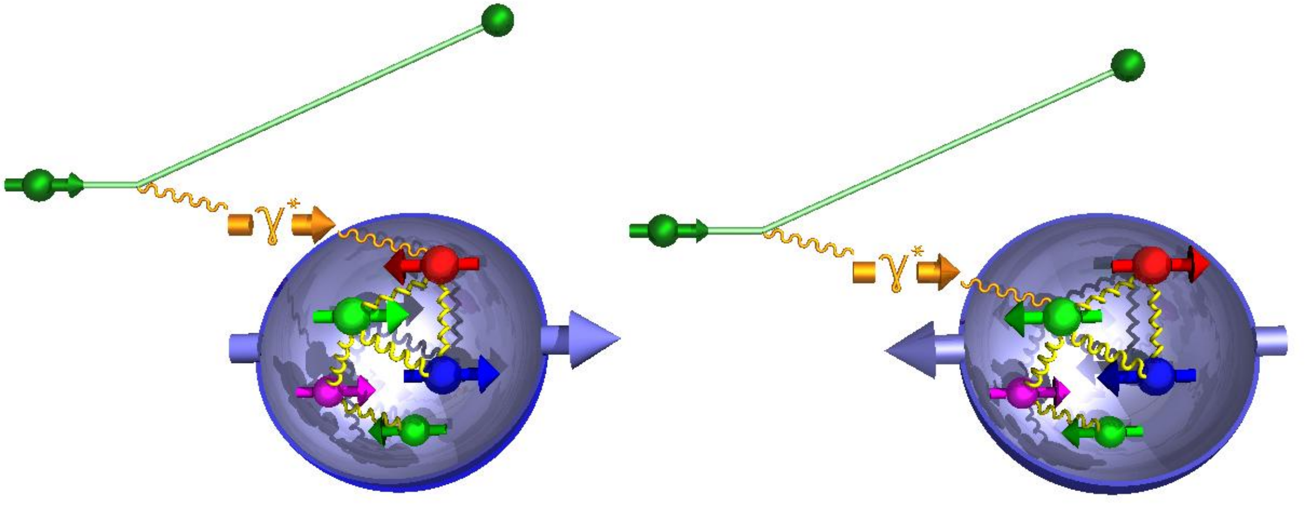
From gluon ?

From angular momentum of the quarks / gluons ?

$$\frac{1}{2} = \frac{1}{2}\left(\Delta\Sigma + \Delta G + L_q + L_g\right)$$

How to measure the proton spin contributions

- Longitudinally polarised nucleon (gas target) and electron beam
  - Observable: cross section asymmetry in spin parallel and anti-parallel

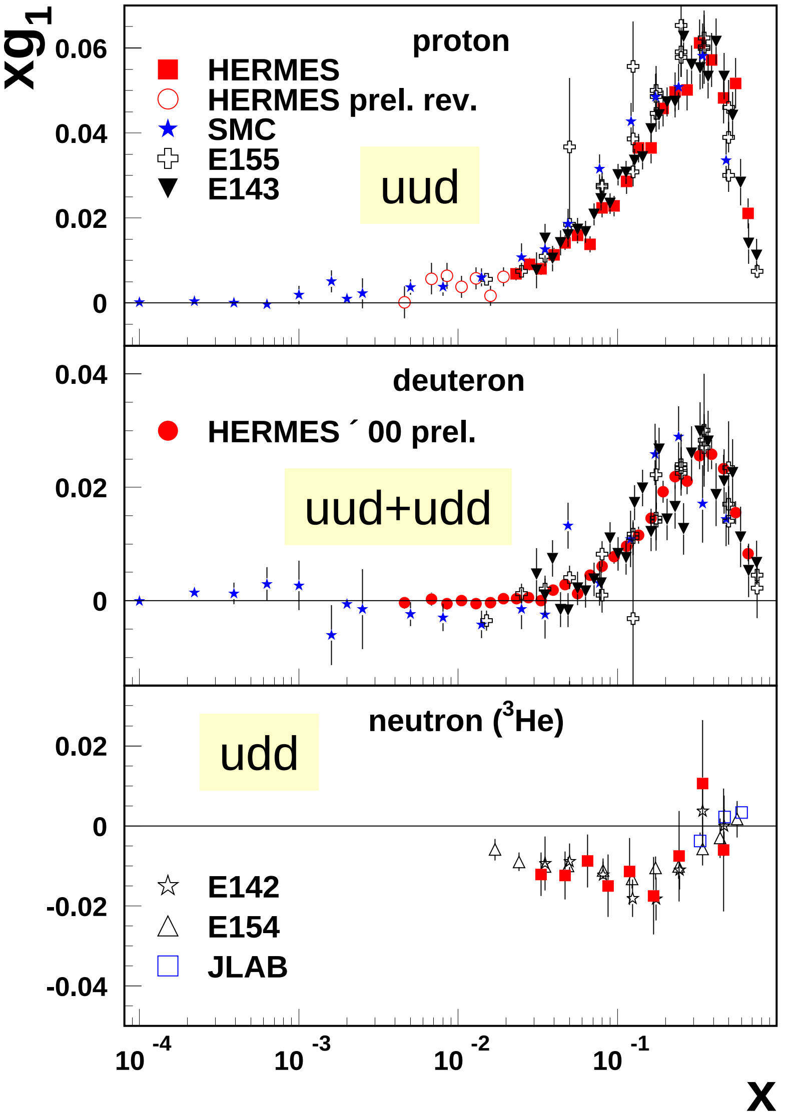


Photon can scatter with quarks
with spin anti-parallel – photon spin absorbed by quark spin flip

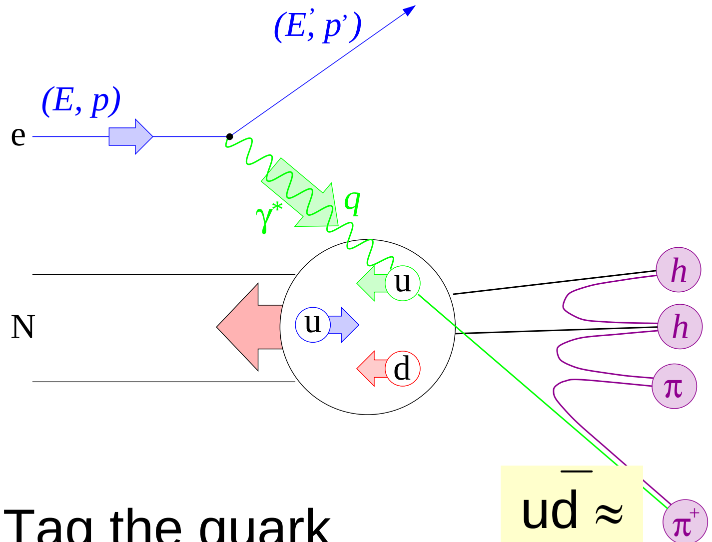
Quark spin from polarised structure function

$$F_1 \propto q\uparrow(x) + q\downarrow(x)$$
$$g_1 \propto q\uparrow(x) - q\downarrow(x)$$

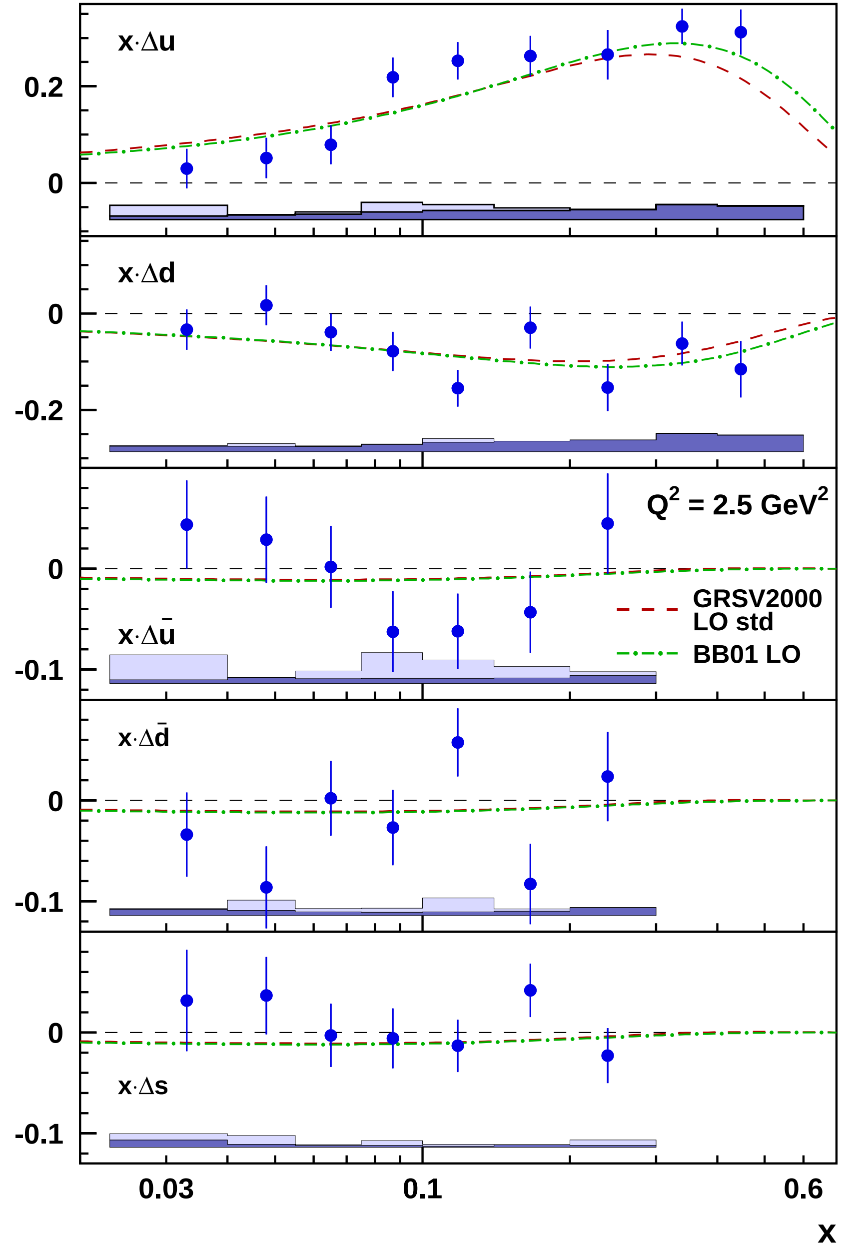
- g_1 – probability to find a quark with spin positive
- Precise measurement by HERMES
- Flavour decomposition from p, n and deuteron target
  - $u:\uparrow$, $d:\downarrow$ polarised
  - From strange quark, sea quark ?



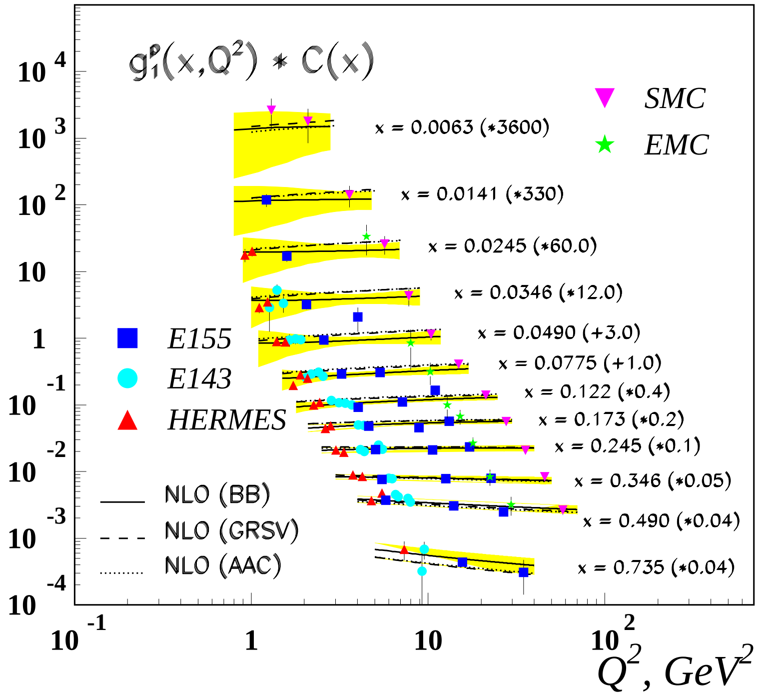
Flavour decomposition by semi-inclusive DIS

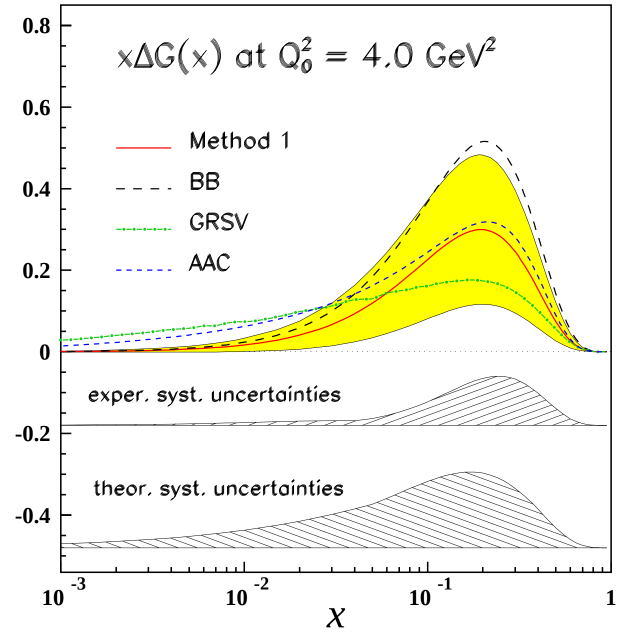


- Tag the quark flavour by fastest hadrons
- Sea quark spin is extracted without any assumption on the flavour symmetry
- Sea quark spin slightly negative
  Valence is ~30 %
  where is the spin ?



Extracted gluon polarisation from world data



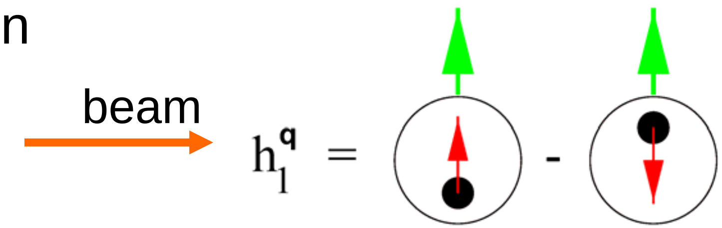


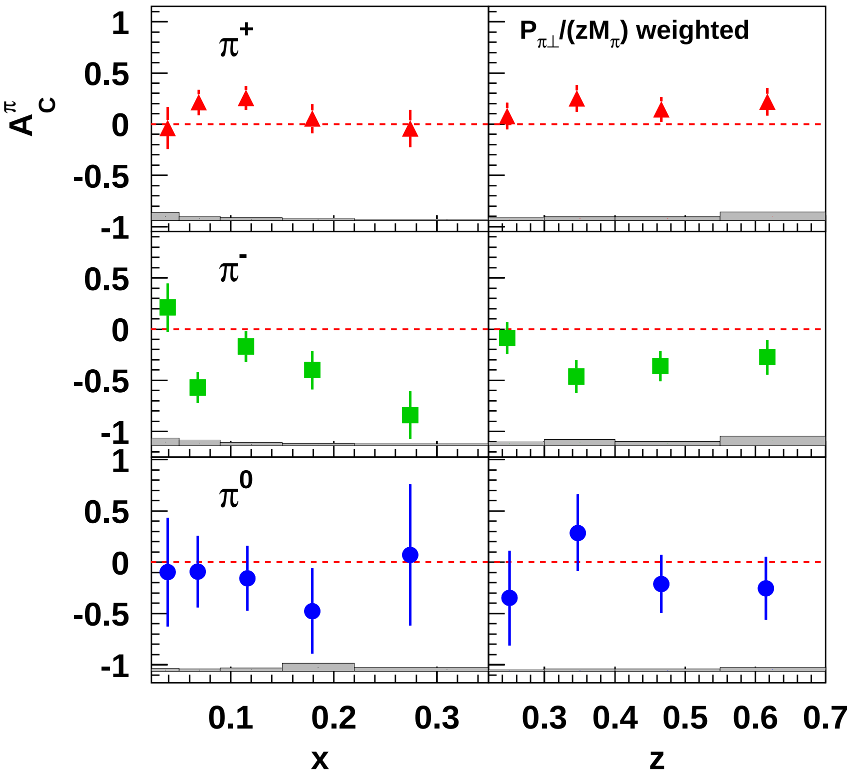
- Using spin-dependent QCD evolution of the parton densities
- Gluon, seems positive, but large uncertainty (small lever arm)
- Current decomposition: Valence+sea 21 ± 13 %, gluon 41 ± 27 %
  - Where is the rest ?

Now at HERMES: transversity $h_1(x)$

- Unmeasured polarised structure function – world premier
  - through azimuthal asymmetry of the produced hadrons: semi-inclusive DIS
- If quark is massless, $h_1 \sim g_1$
  - Quark mass effect to spin
  - Valence/sea separation:

    $$h_1 \sim x(\delta q - \delta\overline{q})$$
- Expect $|A^p_{\pi+}| \sim |A^p_{\pi-}|$ (both mainly from u)
- First result:
  - $A^p_{\pi-}$ largely negative: unexpected
  - Disfavoured fragmentation u-quark $\rightarrow \pi^-$?
- Run until summer 2005
  - Also addressing the angular momentum effect by measuring "Sivers" angle
  - then measuring DVCS





HERA-II physics : objectives

↓yearly

- Unique facility worldwide: ***ep* collision with $e^{\pm}$ polarisation**

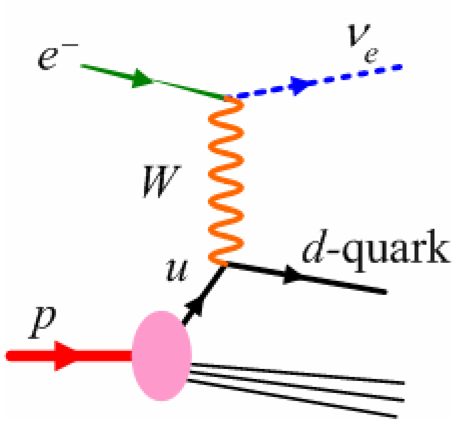
  monthly
- High luminosity for colliders
  - Nature of the valence quarks in the proton – density, flavour

    ← high-x, high-Q^2 cross sections are small
  - QCD study requiring large amount of data
    - *b*-quark production, jets at high-p_T
    - Diffraction with jets, heavy flavour
- Polarisation also for the collider exp't H1 and ZEUS
  - Electroweak interaction
  - Flavour decomposition of the quarks
- Searches: physics beyond standard model
- HERMES: deeply virtual Compton scattering (also H1/ZEUS)

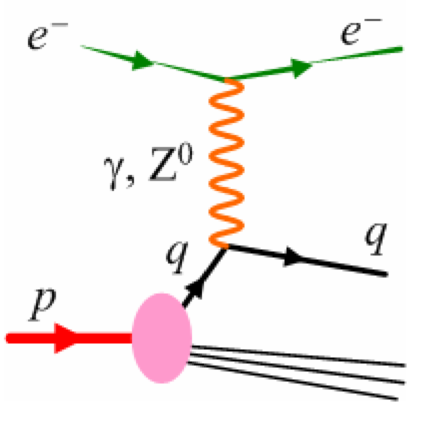
→ Next slides: Reviewing HERA-I status, prospect for HERA-II

Disentangling quark flavours by weak int'n

- Charged current (CC) – exchanging $W^{\pm}$
- Coupling to:
  - up-type quarks for e^- $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$
  - down-type quarks for e^+
  - spin polarisation: (1±Pz) dependence

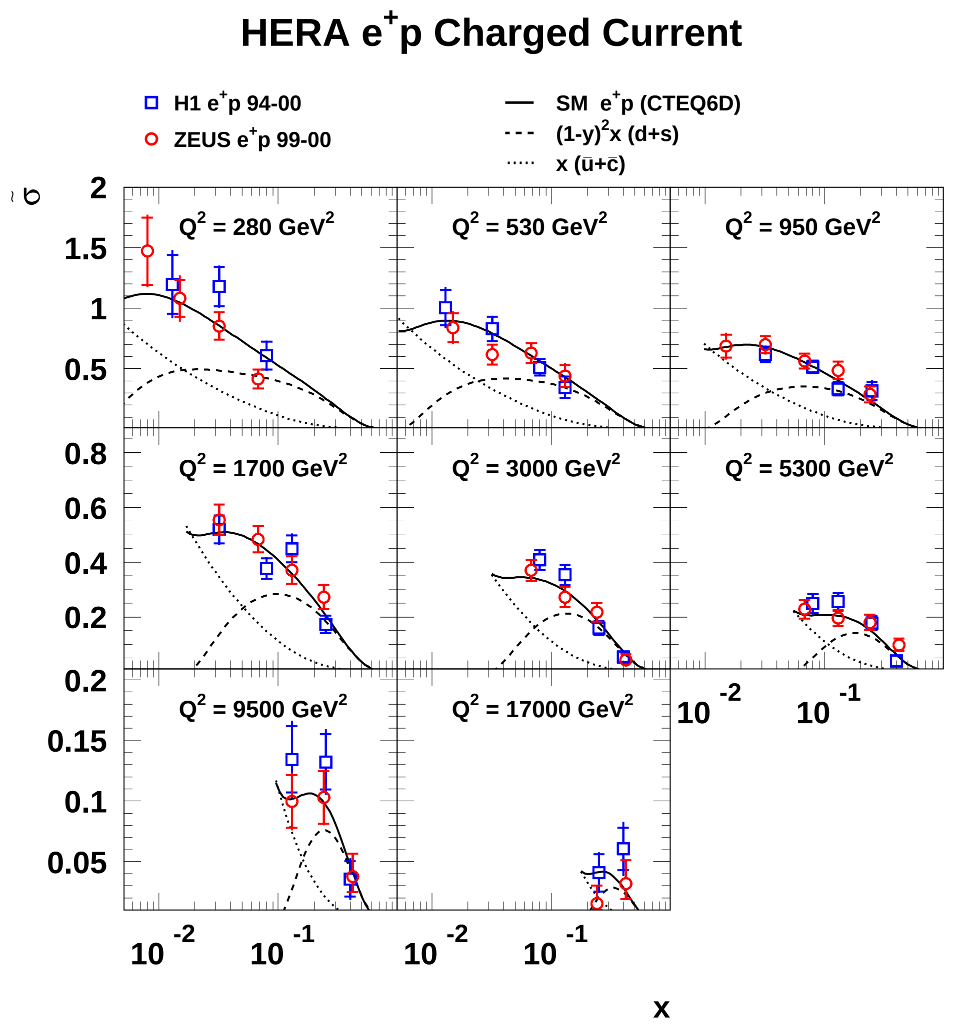


- High-Q^2 neutral current (NC) exchanging Z^0 ($Q^2 \approx M^2_{Z^0}$)
  - Cross section difference
    $$\sigma(e^-) - \sigma(e^+)$$
    is sensitive to $q - \bar{q}$
  - Spin polarisation gives similar effect



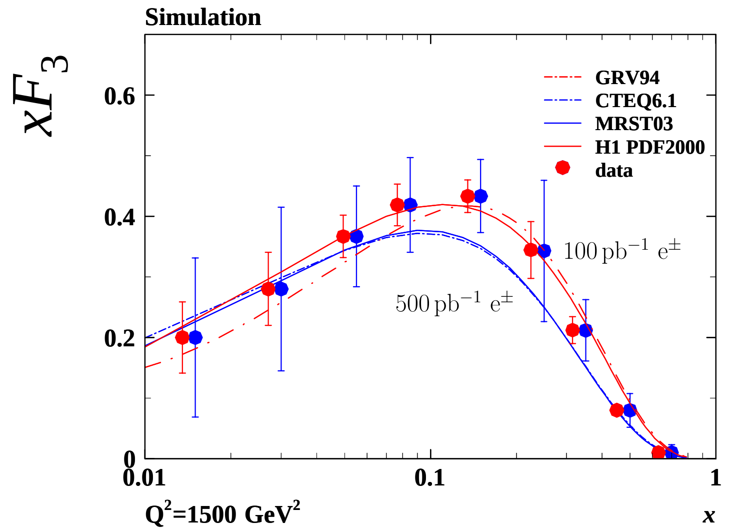
Charged current and parton densities

- Example : full HERA-I data(100pb^{-1}), e^+ beam
  - Different dependence in y decompose ($d+s$) and ($\bar{u}+\bar{c}$) $\rightarrow$ distinguishing flavour
  - Sensitive to d
- Precision limited by statistics
  - **Increasing statistics is main goal for HERA-II**

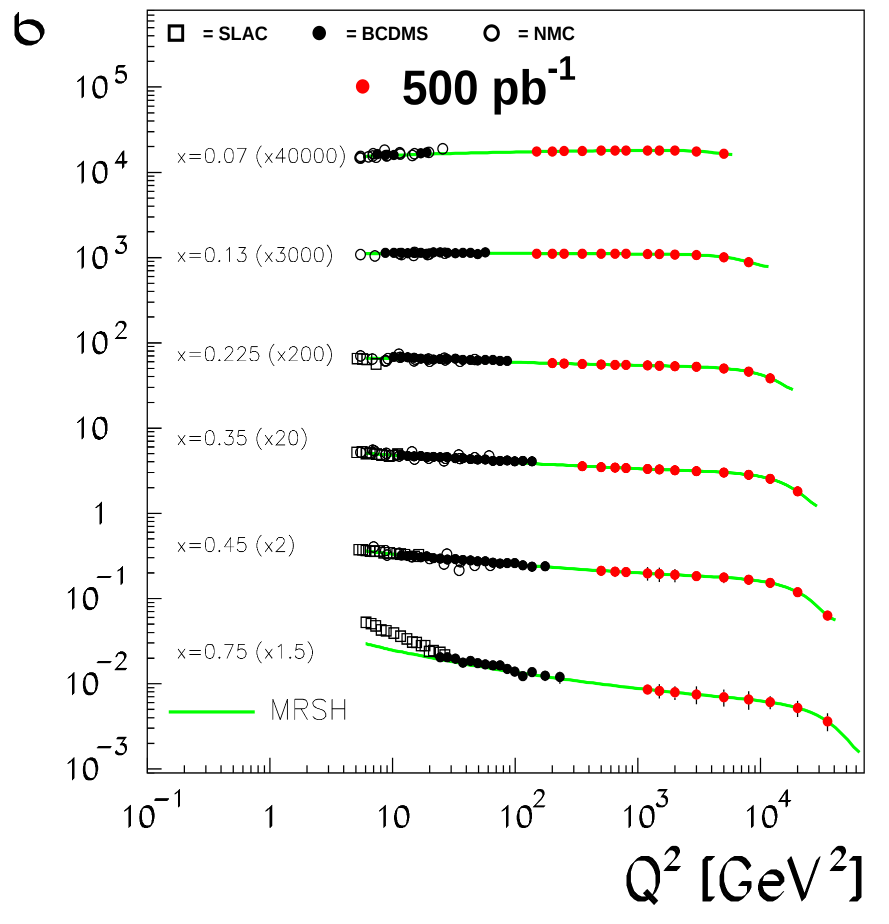


Precise measurement of the valence quark density at HERA-II

- Very high-x valence density is not well known
- $(d + u)$ valence quark by NC
- d valence by e^+ CC
- $xF_3 \propto \sigma(e^+) - \sigma(e^-) \propto q - \bar{q}$

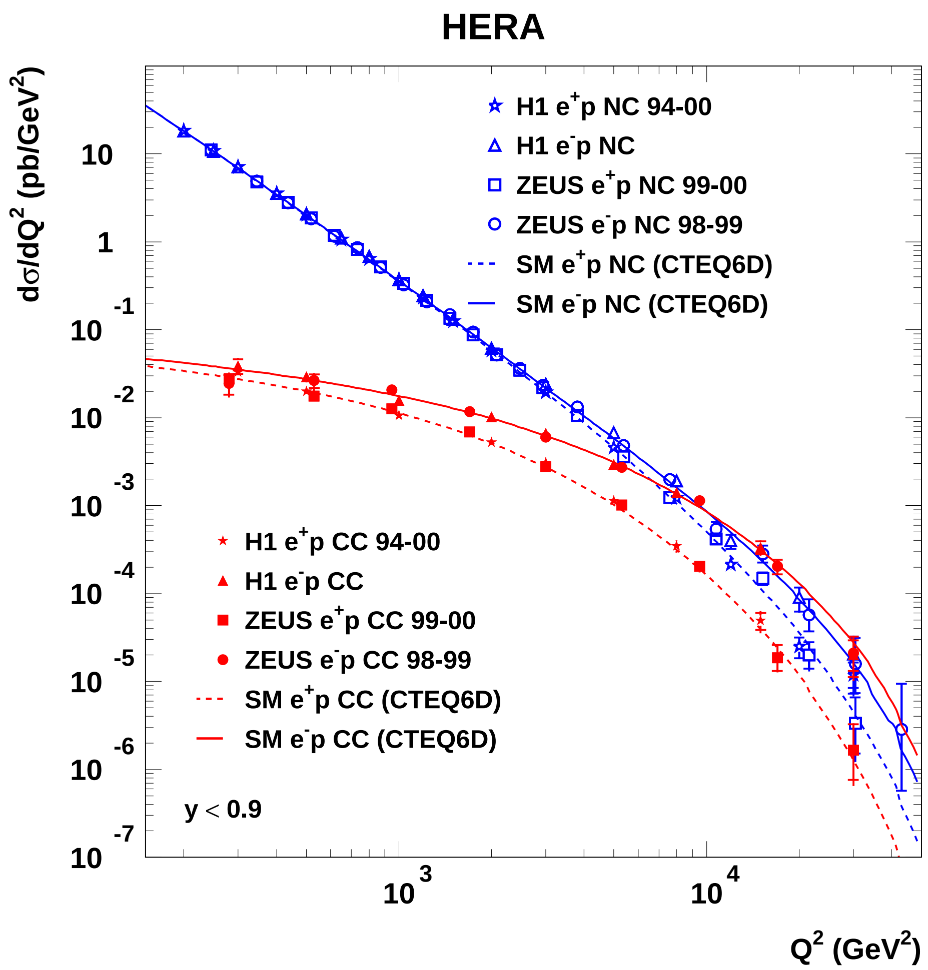


NC simulation for HERA-II

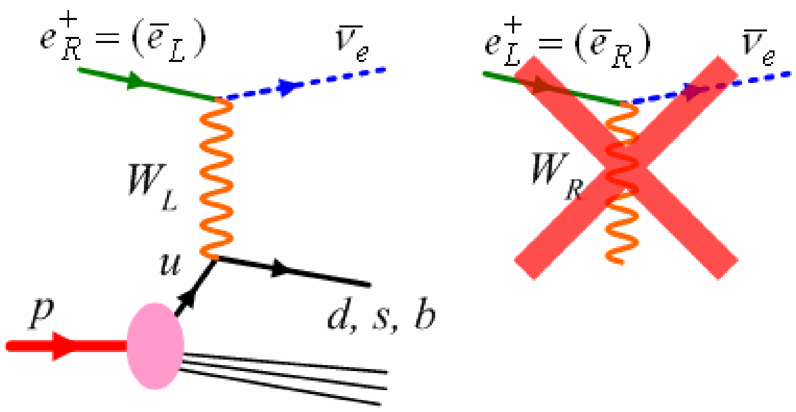


NC/CC cross section and electroweak unification

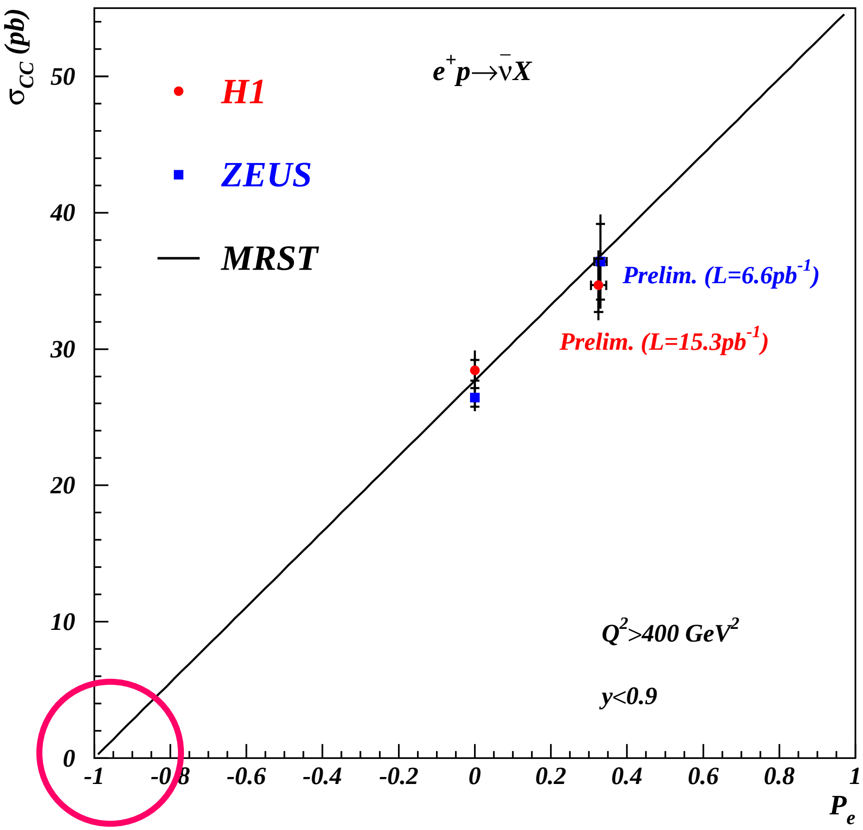
- Cross section of NC and CC becomes similar at $Q^2 \approx M_W{}^2, M_Z{}^2$
  - Manifestation of the electroweak unification
- Study at HERA-II – electroweak parameters in detail **with polarisation** e.g.
  - Electroweak coupling constants to u- and d-quarks (v_u, a_u) and (v_d, a_d)



Physics with polarised positron beam: charged current from HERA-II

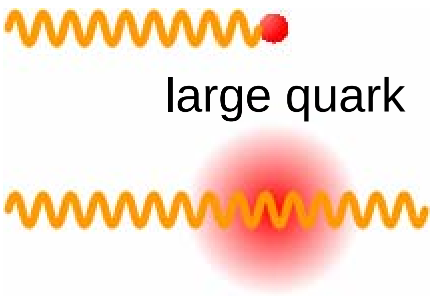


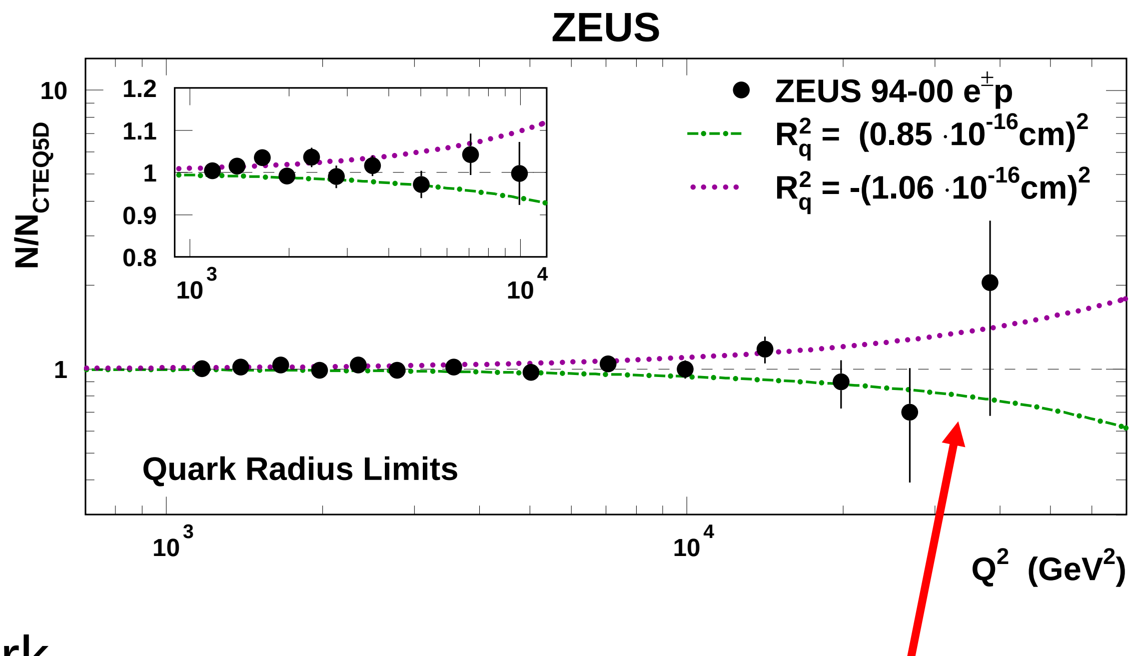
- First measurement of CC with polarisation
- If right-handed current exists, the cross section at 100 % RH polarisation is non-zero
- Consistent with no right-handed current so far



Data with opposite pol. being collected

Size of the quark

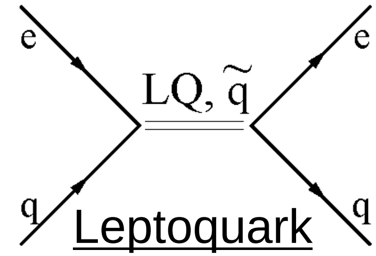




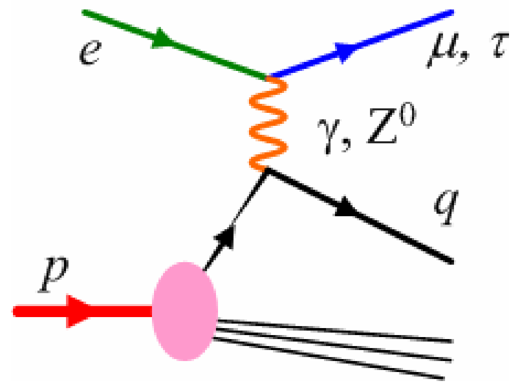
- Finite size of the quark
  → cross section becomes smaller at high-Q^2
  - Short wave cannot see a blur object
    quark becomes transparent
- Cross section agrees with SM: quark is point-like down to radius $R_q < 0.7\times10^{-18}$ m (< 1/1000 of proton – H1 and ZEUS)

Search for new particles and interactions

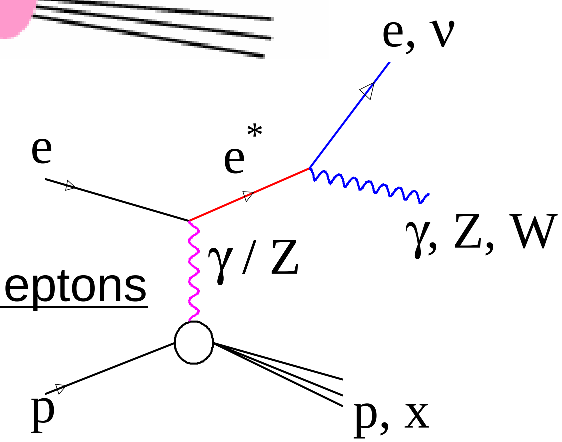
- Only Tevatron (2 TeV $p\bar{p}$) and HERA are the high-energy colliders in operation
- Giving world best limits on:
  - Leptoquark (next slide)
  - Flavour-changing neutral current
    - Lepton-flavour violation Observed in neutrino sector !
    - Quark flavour violation
    - Excited leptons e^*, ν^*
  - Super-symmetric particles
  - Extra-dimension etc.



Leptoquark

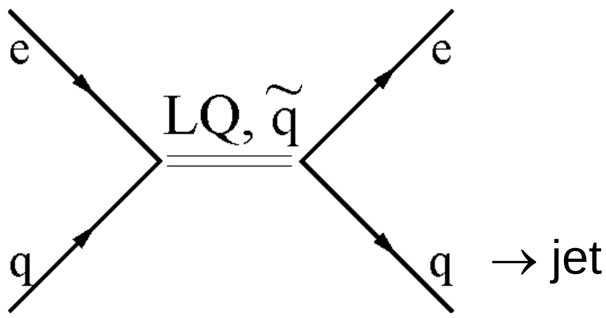


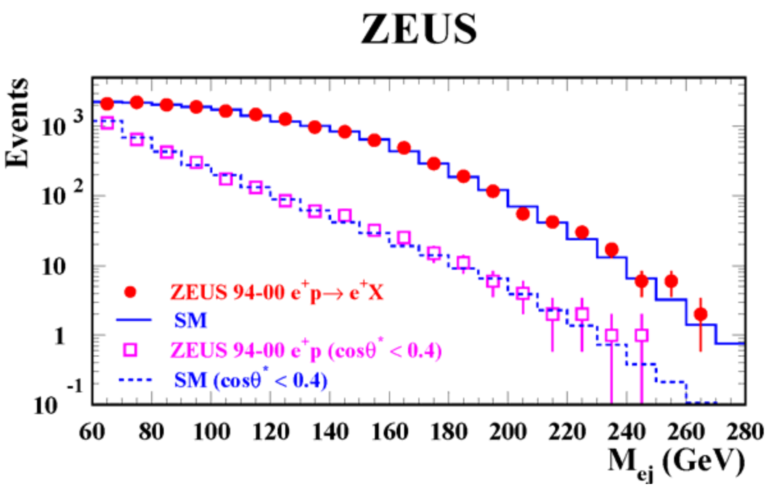
Lepton Flavor Violation



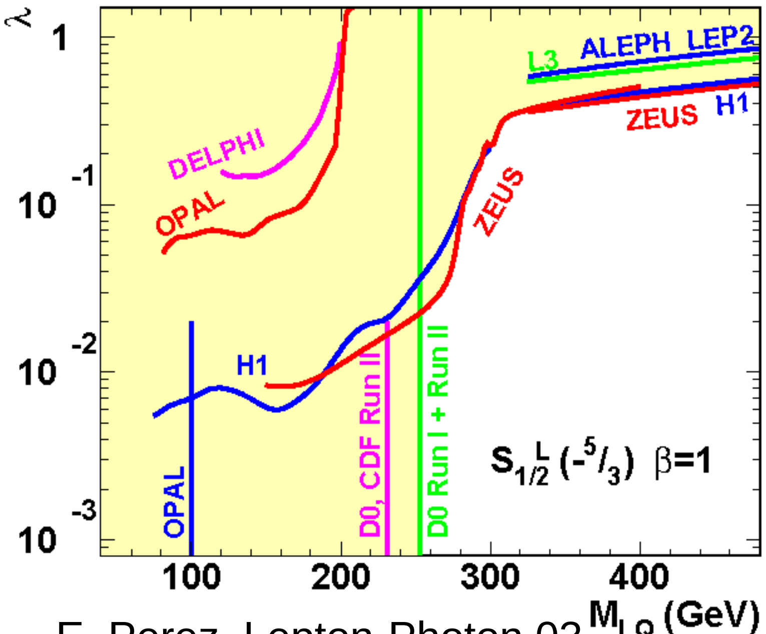
Excited leptons

Leptoquark: quark-lepton resonance



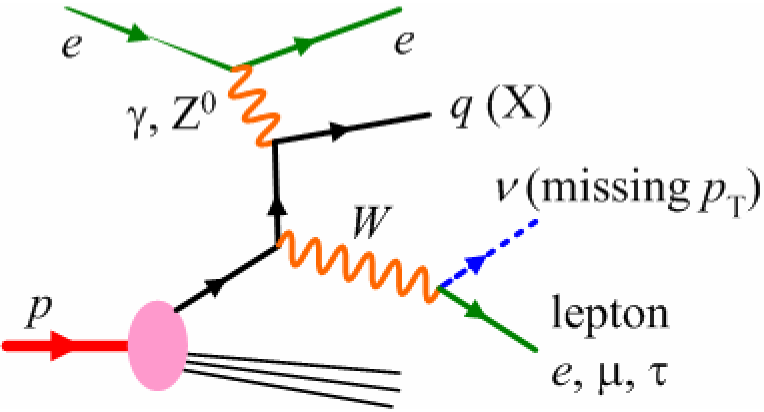


- Models from grand-unified theory, super-symmetry etc.
- Searching for a resonance in the eq = e+jet mass spectrum
- In large region of parameters HERA gives best limit
- Other region: complementary to Tevatron and LEP



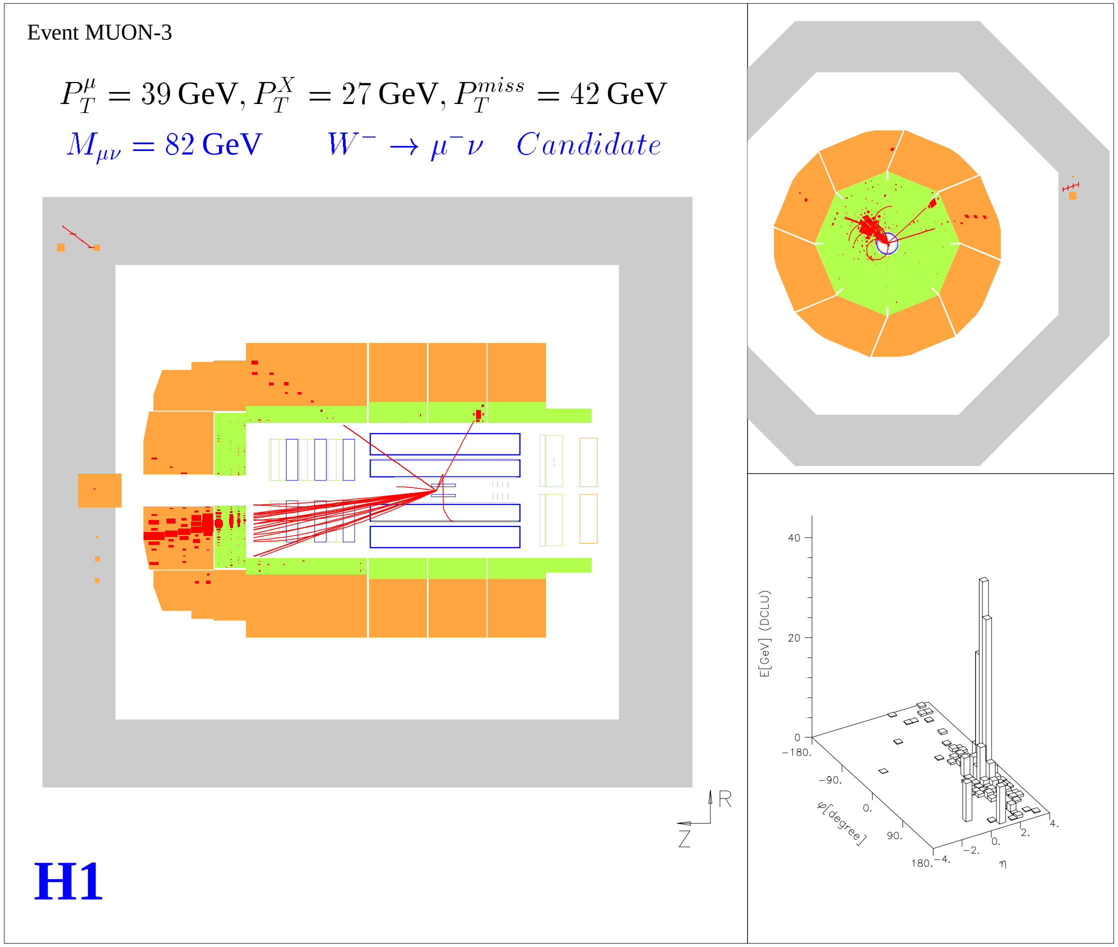
E. Perez, Lepton-Photon 03

High-p_T lepton + missing p_T excess ?

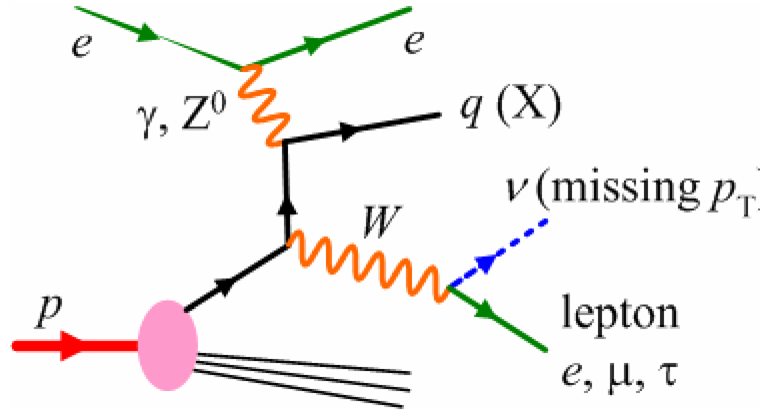


- SM: through W production
  - Not abundant at large p_T^X

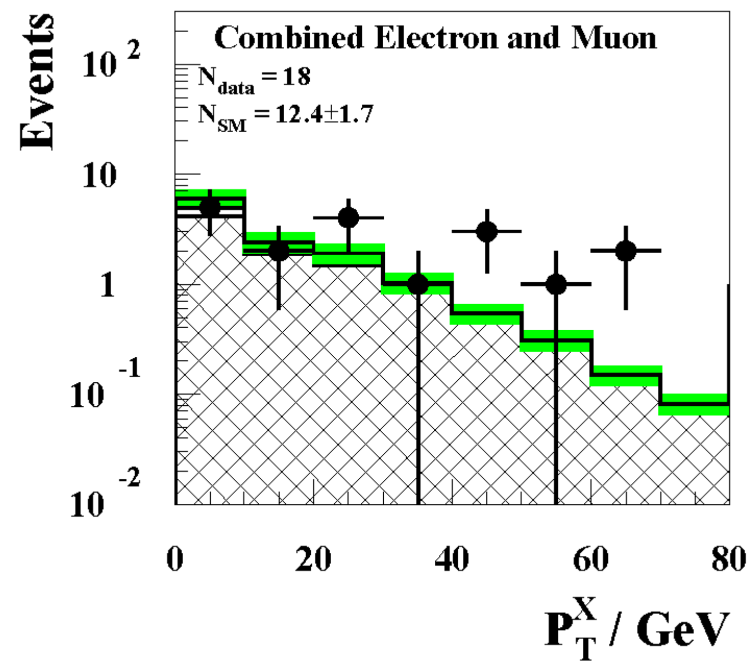
$$e^+p \rightarrow e^+\mu^- X$$



High-p_T lepton + missing p_T excess ?

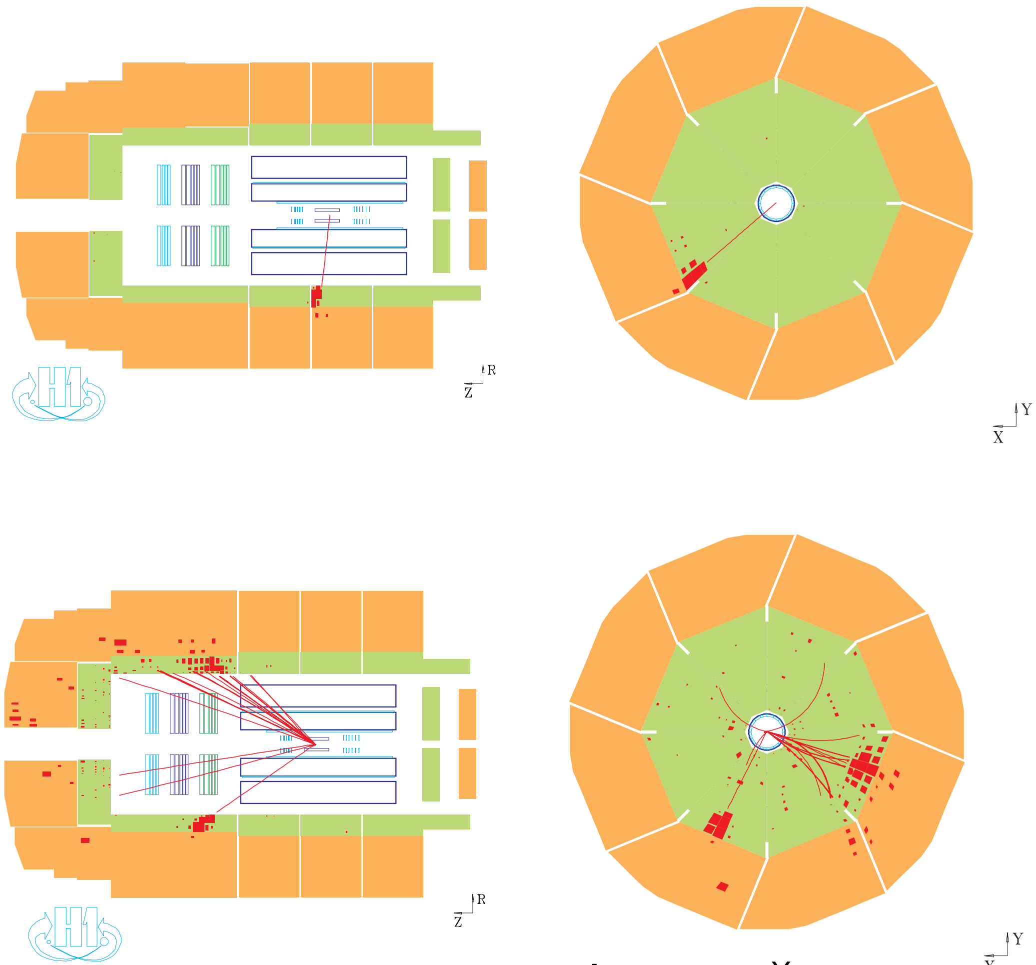


- SM: through W production
  - Not abundant at large p_T^X
  - 6 events observed/1.08 expected for e + μ decays **in H1**
  - No excess in e + μ decays in ZEUS
  - Less significant: 1 / 0.06 expected for τ channel in ZEUS
- New particle decaying to a neutral + lepton ??



High-p_T leptons in HERA-II

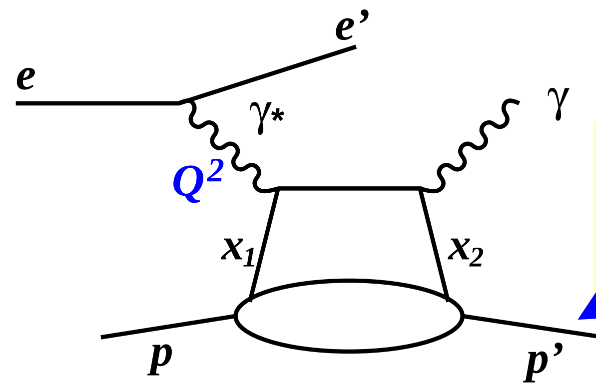
- H1 analysis on high-p_T leptons with HERA-II data
- For $p_T^X > 25$ GeV 2 events / 0.63 expected
  - agrees with the HERA-I yield
- More luminosity eagerly awaited



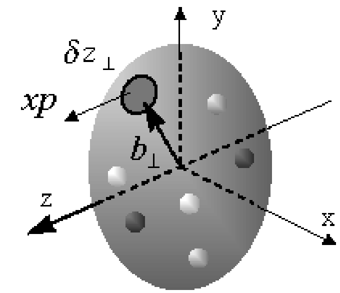
Large p_T^X events

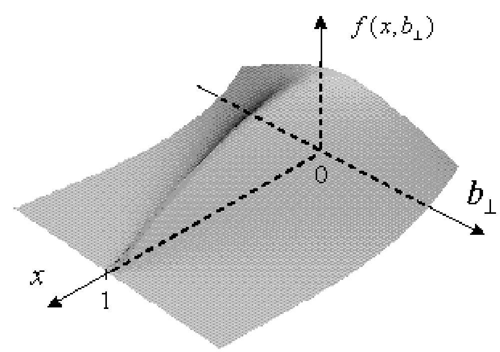
Deeply virtual Compton scattering (DVCS)

- Process to
  take out a quark with (x_1, k_{T1})
  then put back with (x_2, k_{T2})
  - Correlation of two partons in a nucleon
  - You can rotate a proton – sensitive to the angular momentum of the quark
- Amplitude through the interference with normal Compton events
  - Phase is also known – 3D reconstruction of proton structure
  - Changing interference pattern by e^+/e^- beam, L or R polarisation



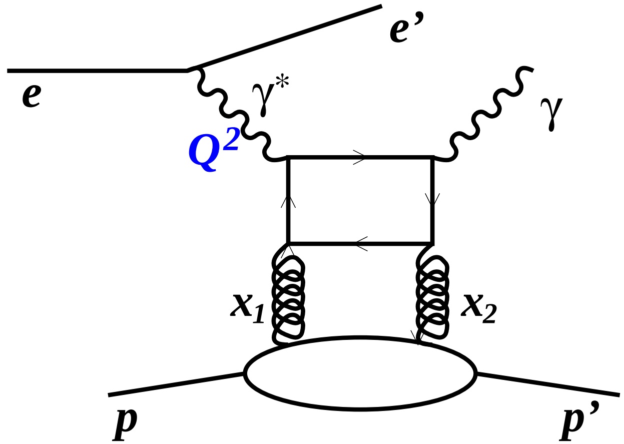
Tag scattered proton

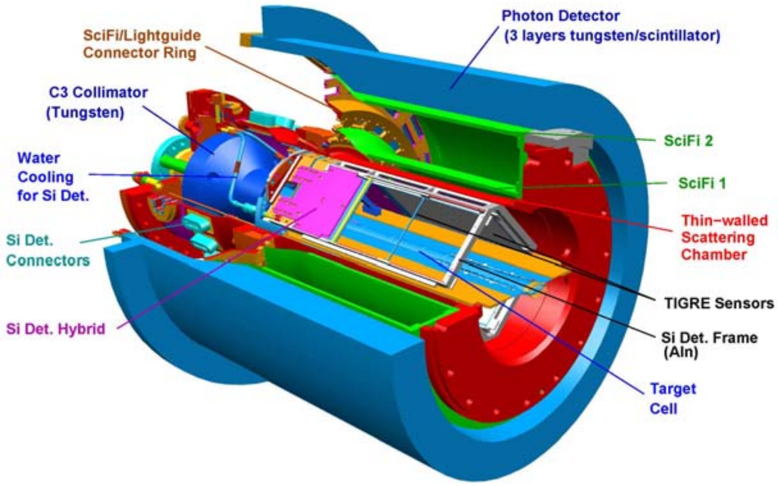




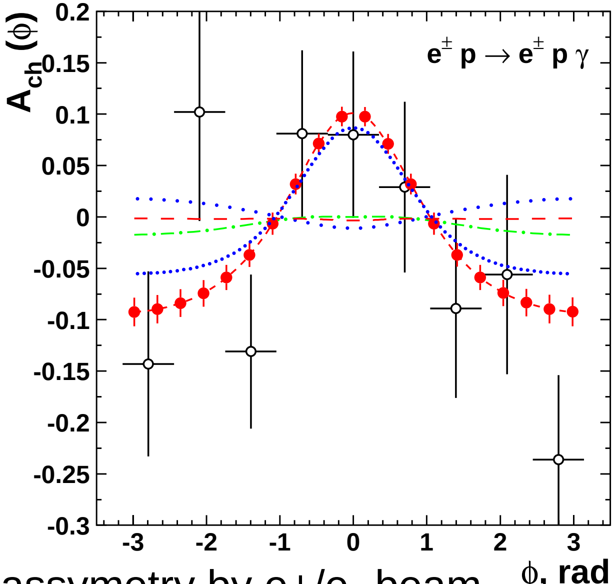
V. Belitsky, D. Müller, hep-ph/0206306

DVCS – measurement plan 2004~





- H1, ZEUS studies:
  low-x, gluon sector
- Reconstructing k_{T1} and k_{T2}:
  - Recoil proton angle+momentum measured by new recoil detector at HERMES
    (summer 2005)
  - H1 very forward proton detector
    (in operation from spring 2004)



ϕ assymetry by e+/e- beam

Summary

- HERA-I study being complete, understanding …
  - The partonic structure of nucleons at low-x
  - Nucleon spin carried by quarks
  - The QCD description of the hadronic final state
    – but some needs more data for better understanding
- HERA-II : unique machine world wide with $e^{\pm}$, pol'n
  - Proton structure at high-x, high-Q^2
  - Electroweak
  - and maybe surprise …
- The issue is the integrated luminosity for precision
  - We need planned increase of **order of magnitude** in luminosity w.r.t. HERA-I