
Physics and Physics prospects at HERA

58th Extended Scientific Council / 130th Scientific Council

21/22 June 2004

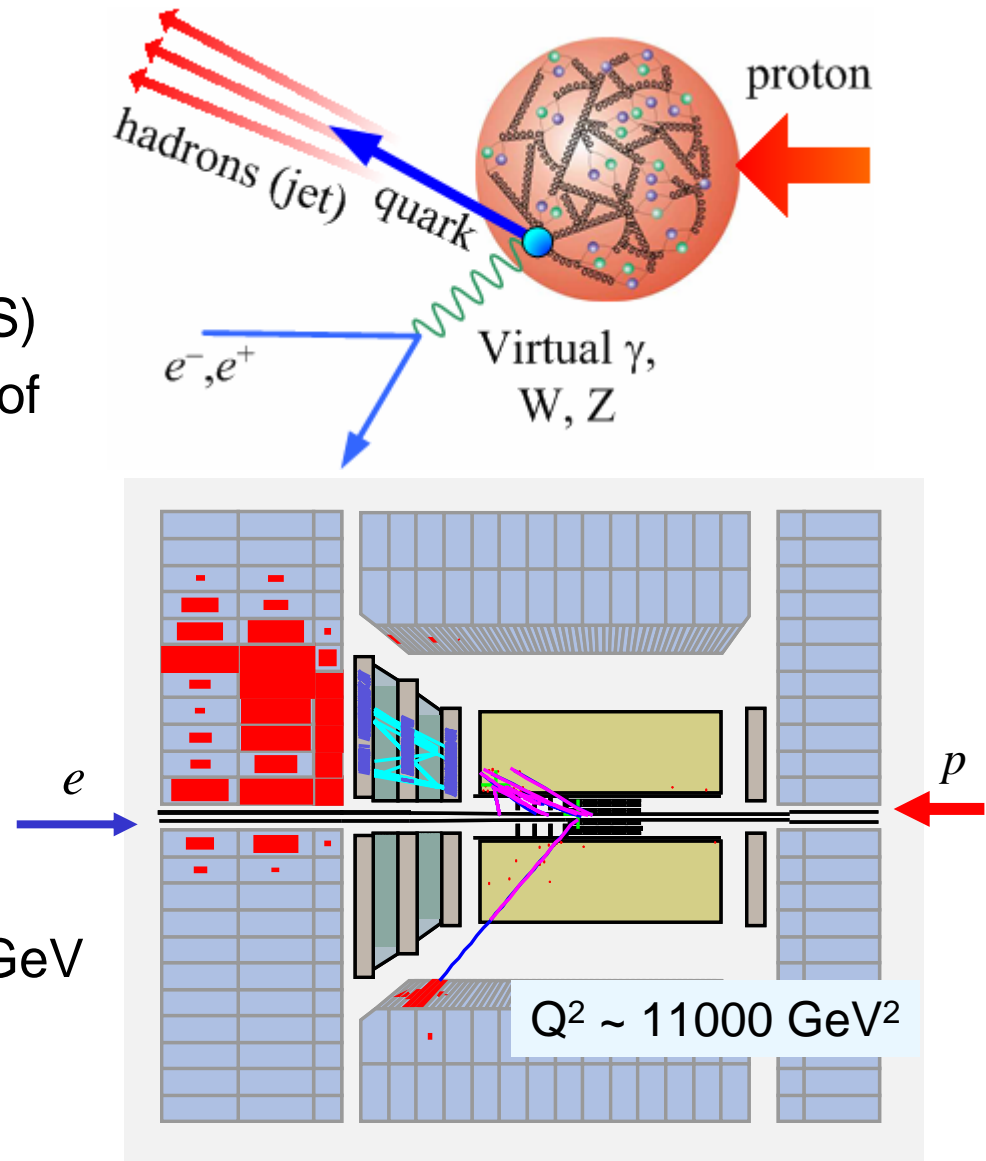
Yuji Yamazaki (KEK, ZEUS)

On behalf of

the H1, ZEUS, HERMES and HERA-B collaborations

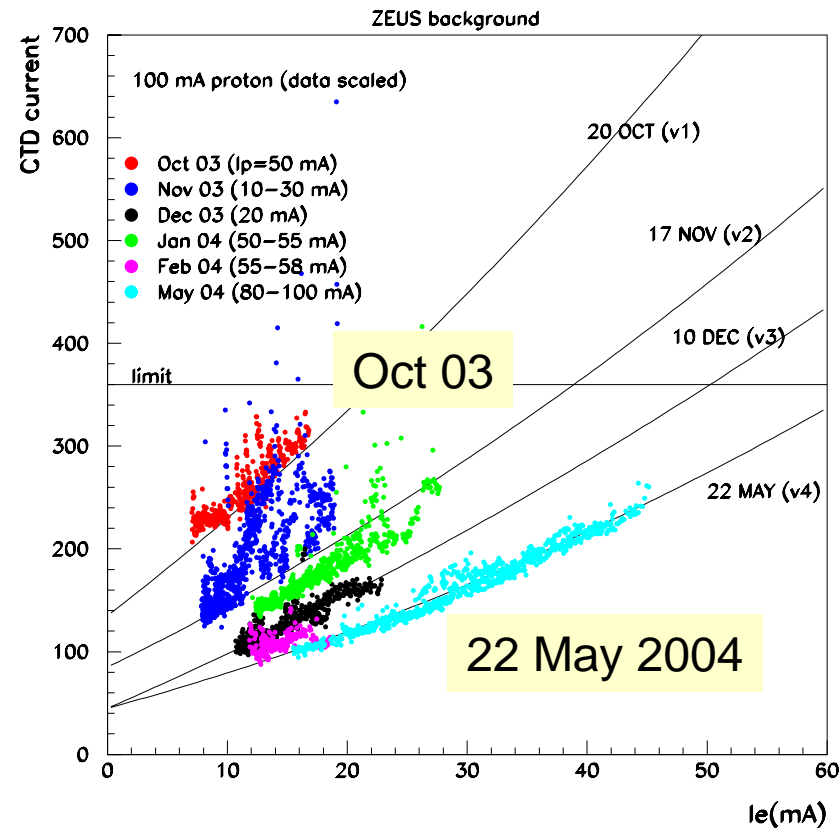
The “Super Electron Microscope” HERA

- 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 $\sim Q^2$: mass of the exchanged particle
 - Centre-of-mass energy 314 GeV \approx up to 10^{-18} m resolution

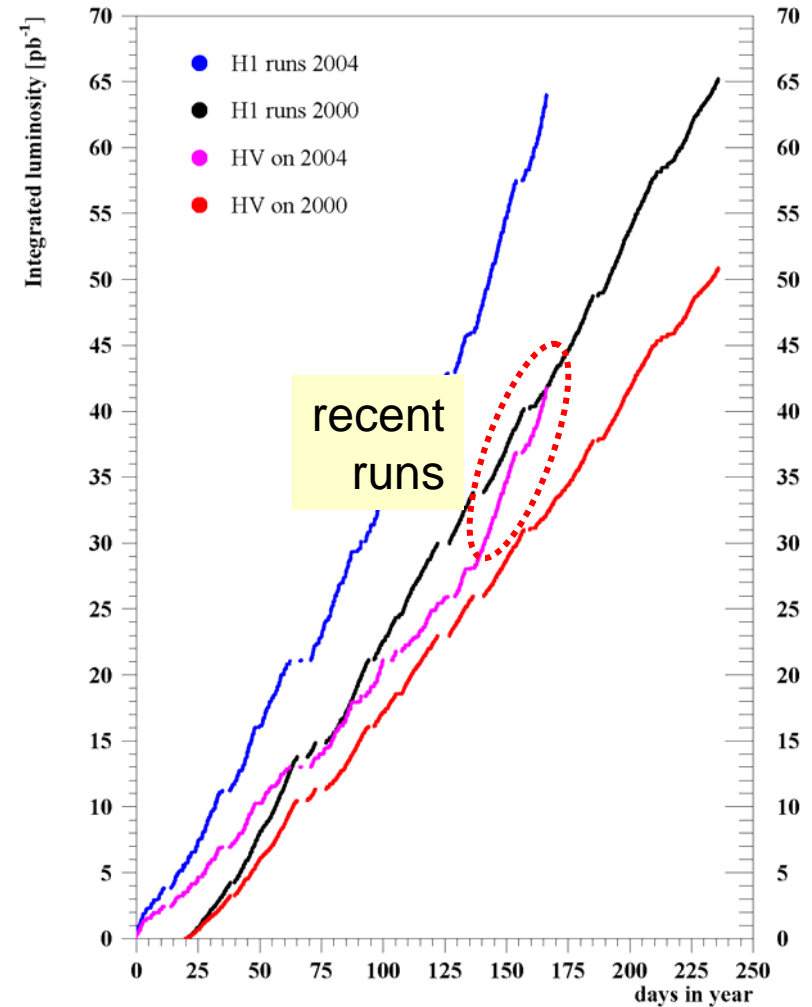
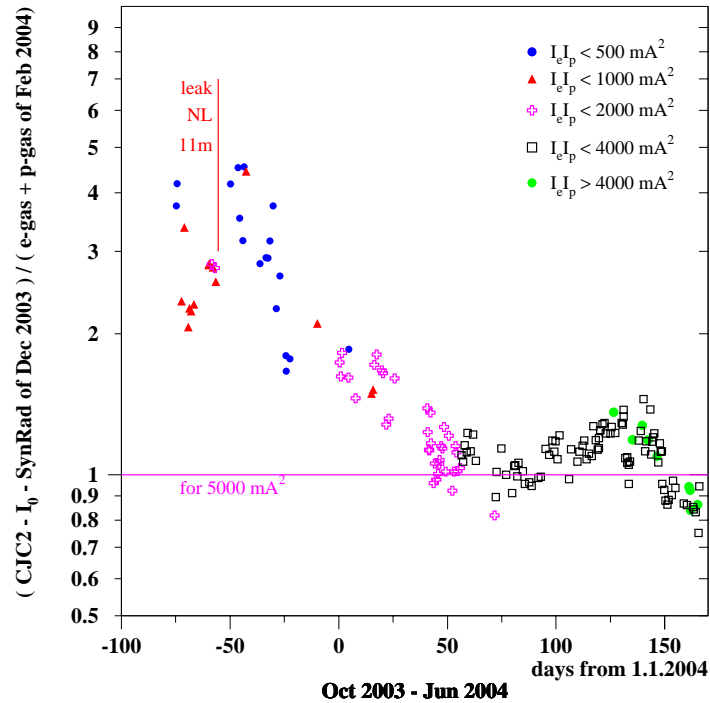


HERA-I and HERA-II running

- HERA-I: 1992-2000, Integrated Luminosity $\sim 100\text{pb}^{-1}$
- HERA-II: 2001-2007, Int. Lumi $> 700\text{pb}^{-1}$, 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 !



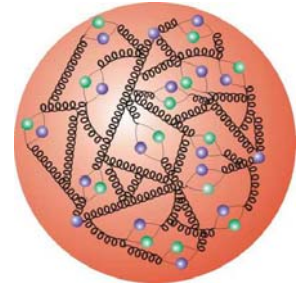
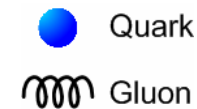
HERA-II running



- 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

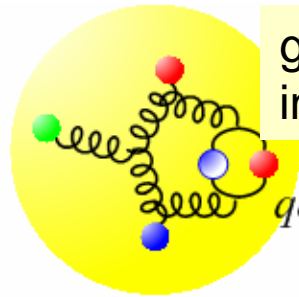
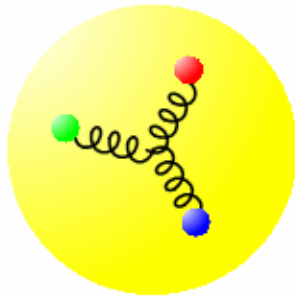


- Structure of the nucleons partons
 - How is it composed by quarks and gluons ?
 - Where the spin of the nucleon ($\frac{1}{2}$) come from ? **HERMES**

- 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

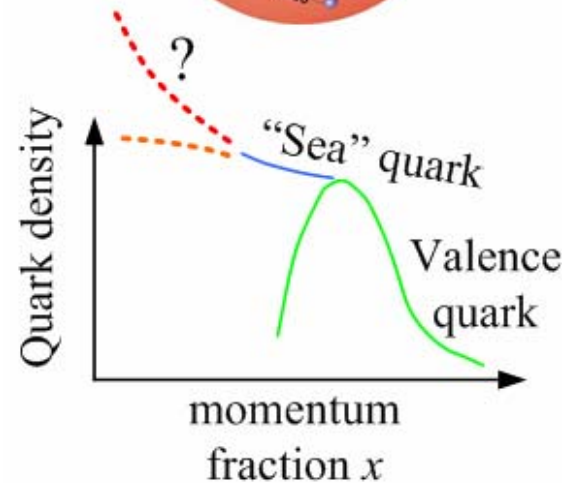
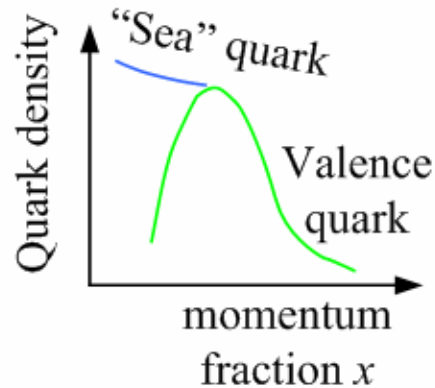
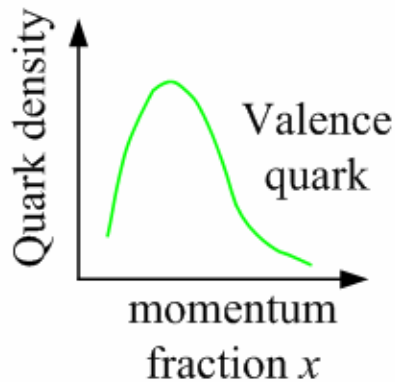


gluon splits
into quarks

$q\bar{q}$ pair



Quark splits
into gluon
splits
into quarks ...



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

- More resolution: we see “small” partons
- How do the quarks behave at low- x ?

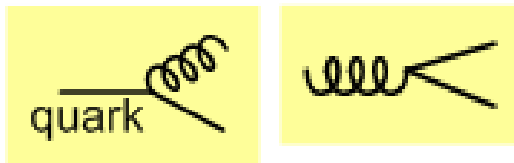
“Structure function” \propto quark density

- Strong increase of sea quarks towards low x

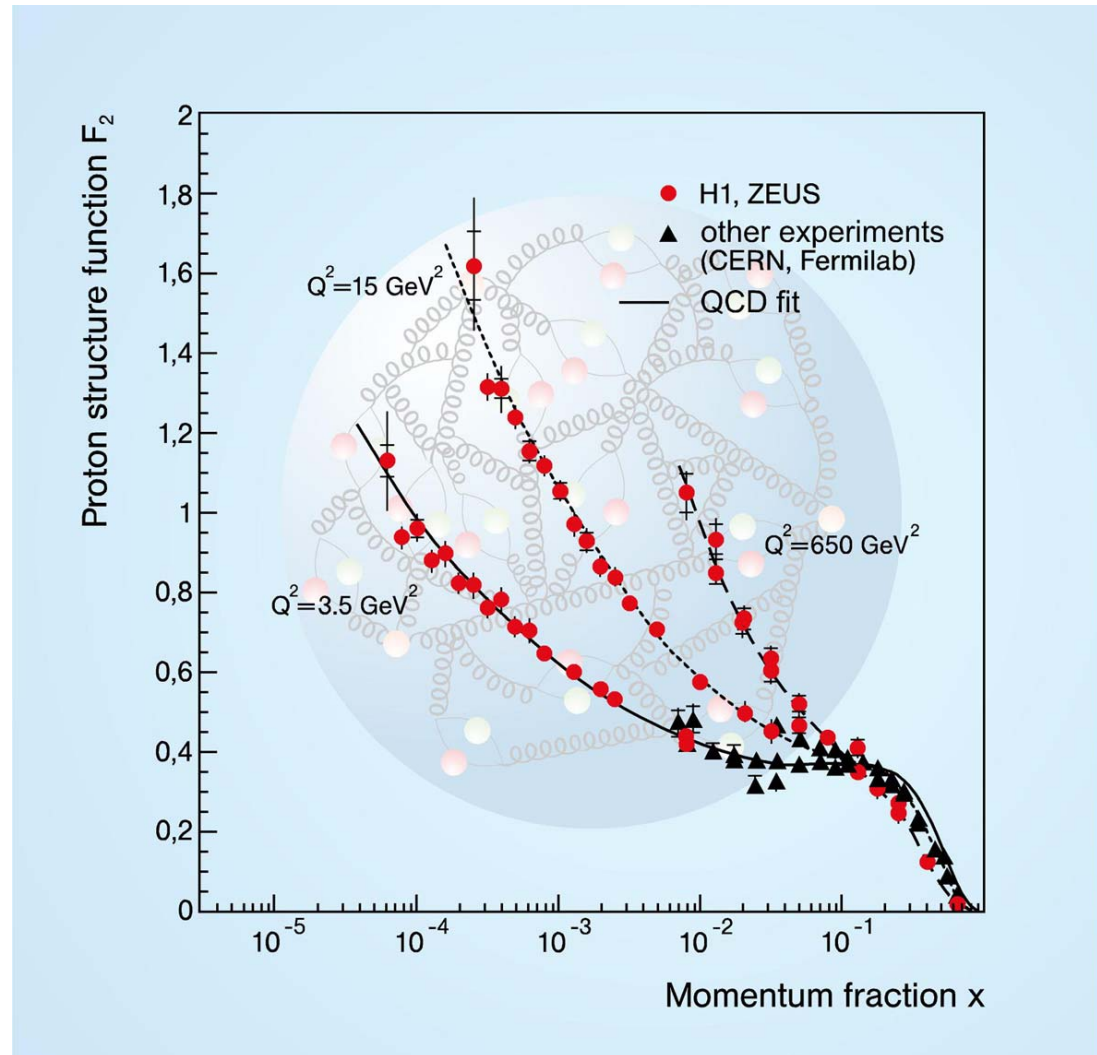
- $F_2(x) = e^2 x(q(x) + \bar{q}(x))$
quark density

- Density increase with Q^2

- More partons by magnified view

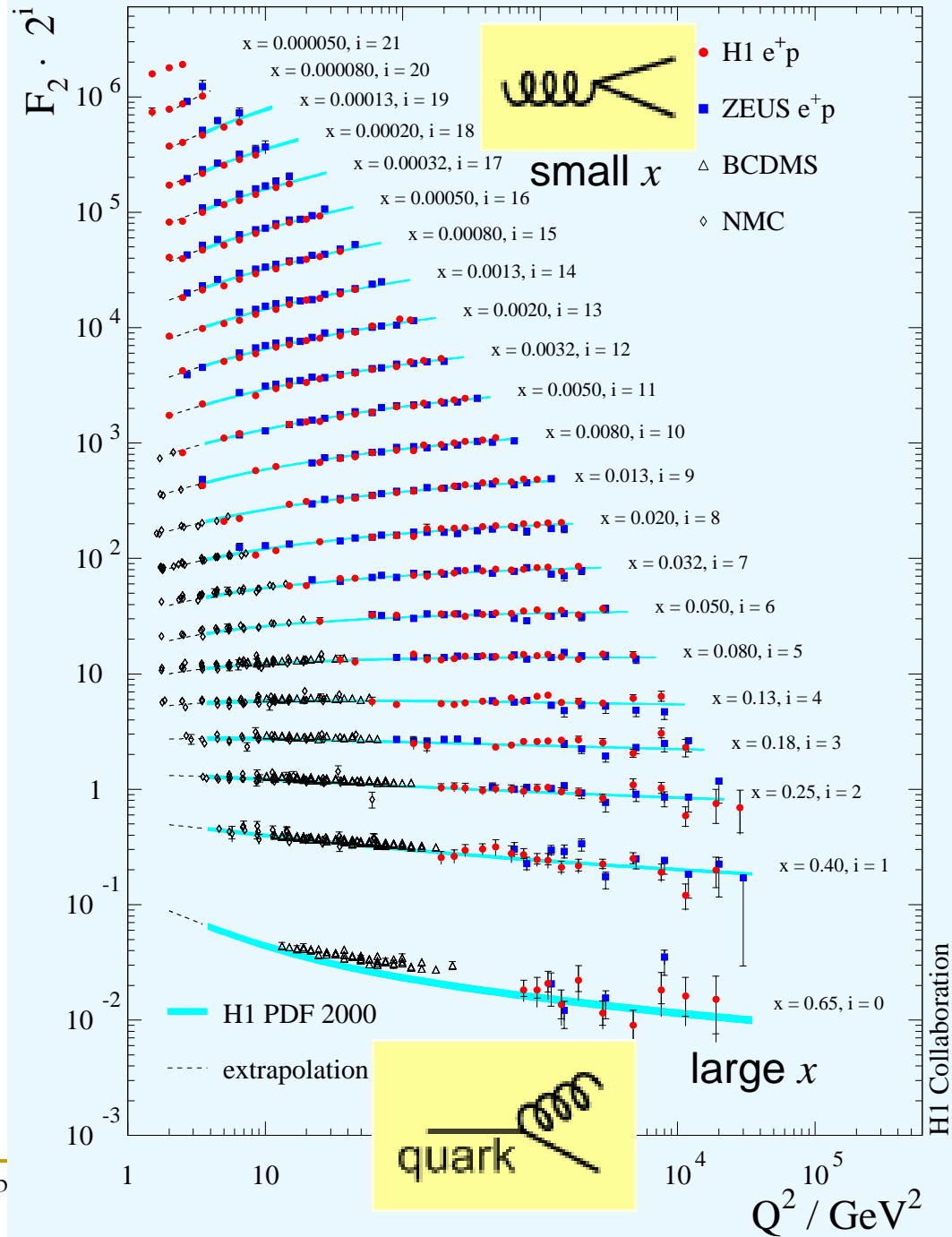


Dynamic creation of quarks at low- x



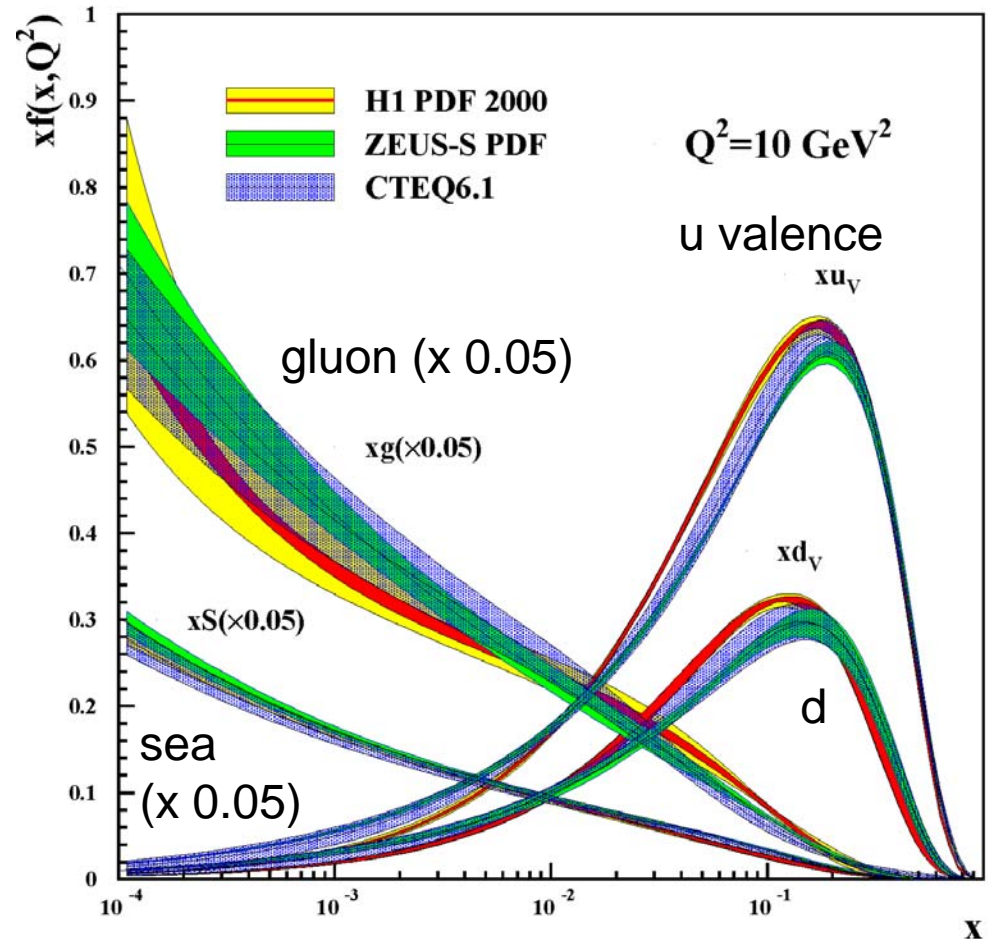
Evolution of the quark densities

- 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

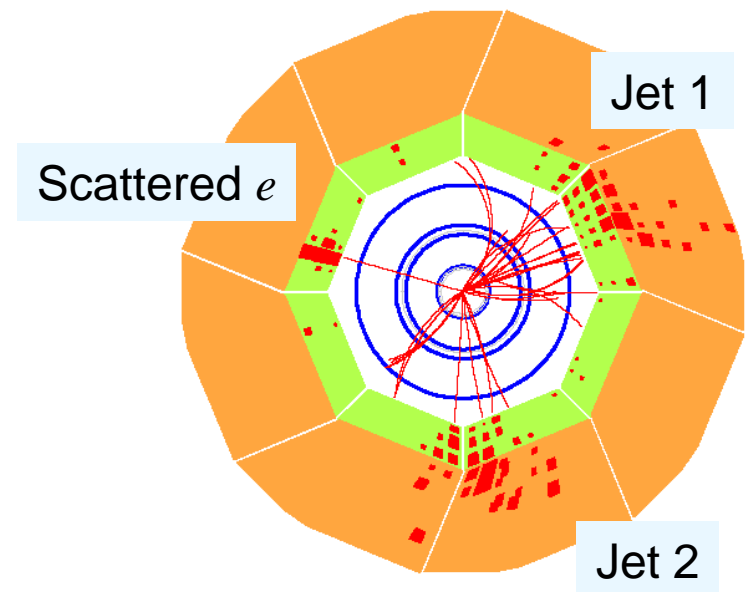
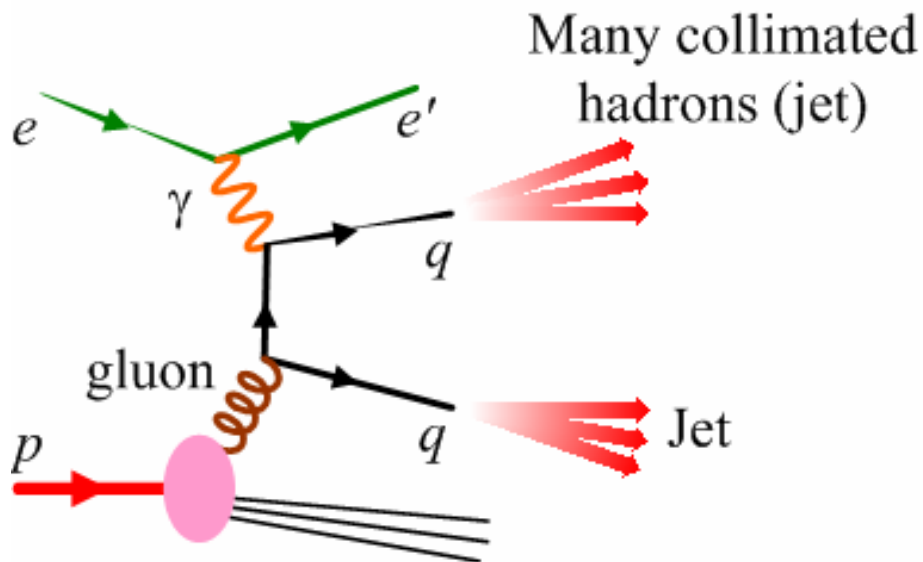
- Gluon density obtained from the QCD fit
- Precise determination of low- x parton densities
- **Gluon > quark at low- x**
- Still need precision:
 - High- x partons: constrained by fixed target data
 - Low- x : we can do better with more statistics



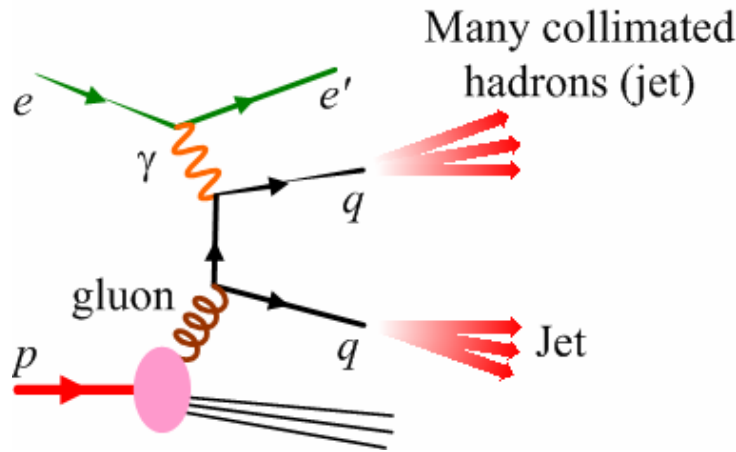
← homework for HERA-II

Probing gluons by hadronic final state

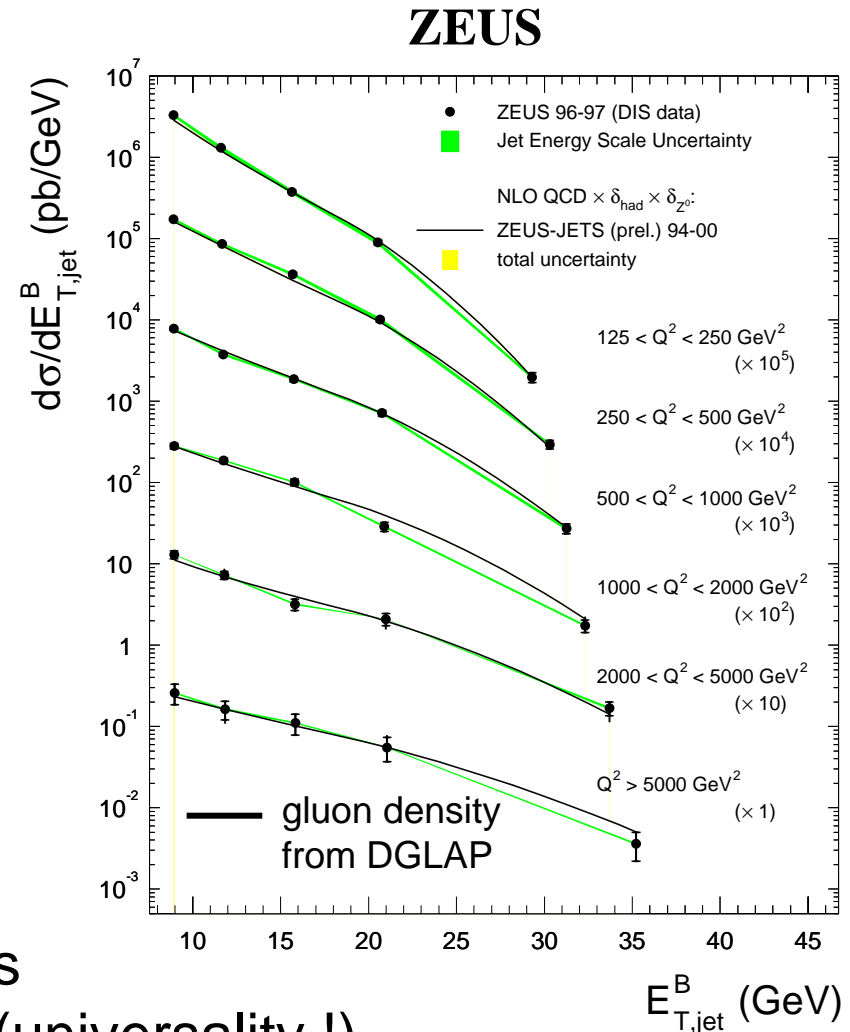
- Photon does not couple to gluons directly ...
 - hit a gluon by a quark instead
- At high energies, quark and gluon momentum can be reconstructed as jets



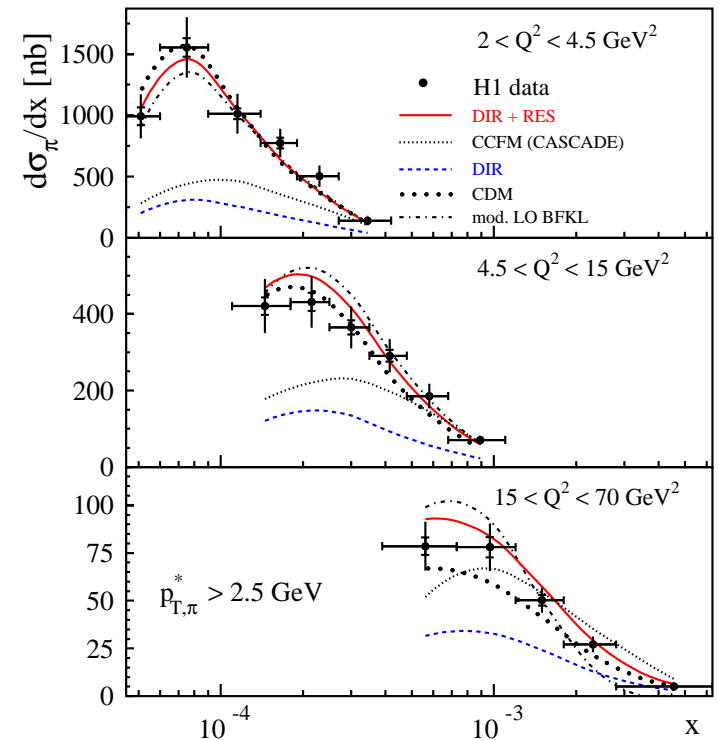
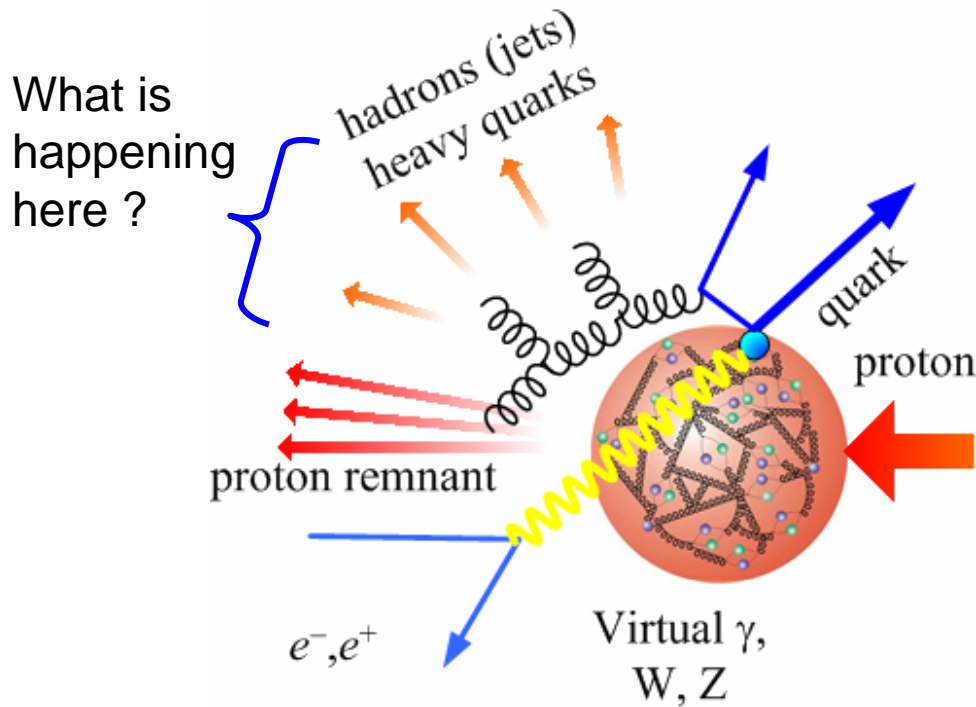
Gluon density from jets



- 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



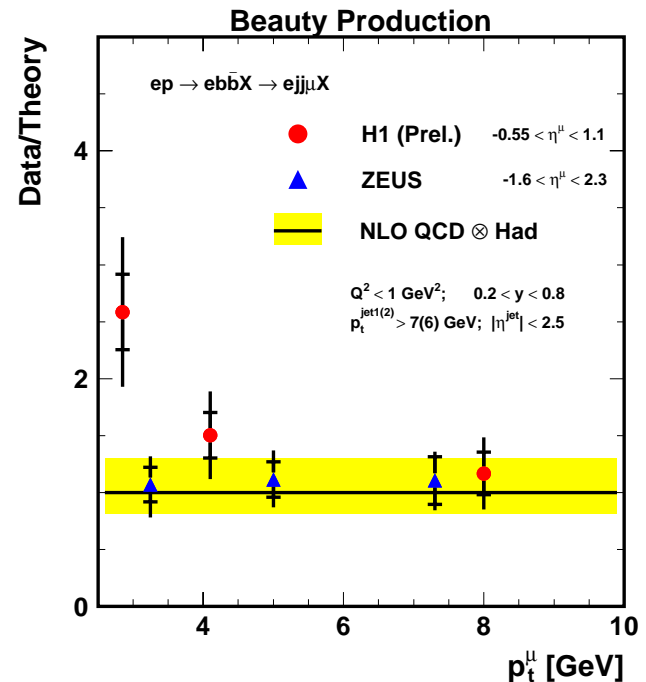
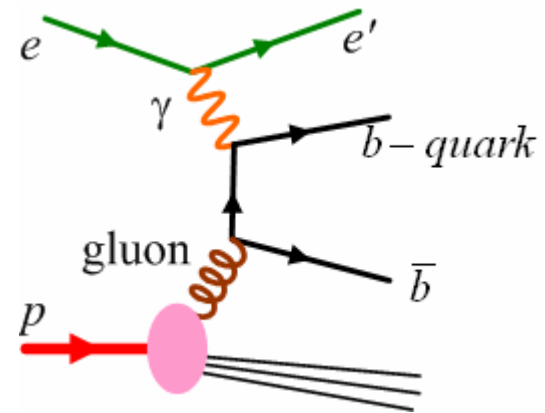
Particle production near the proton



- 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

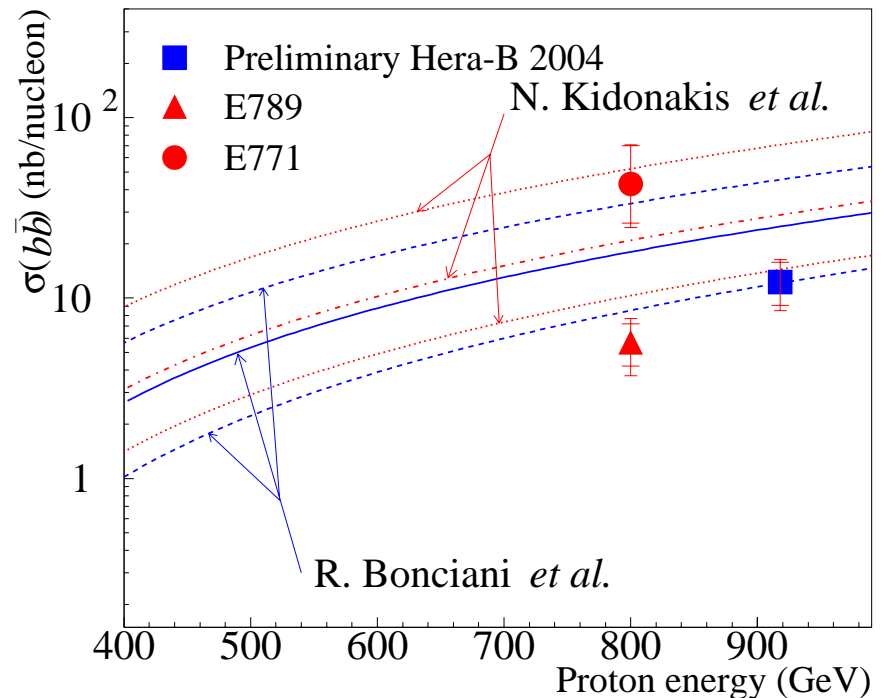
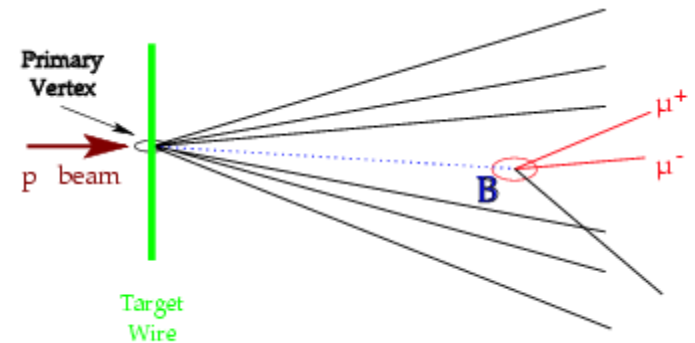
Gluon density and heavy flavour production

- 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**



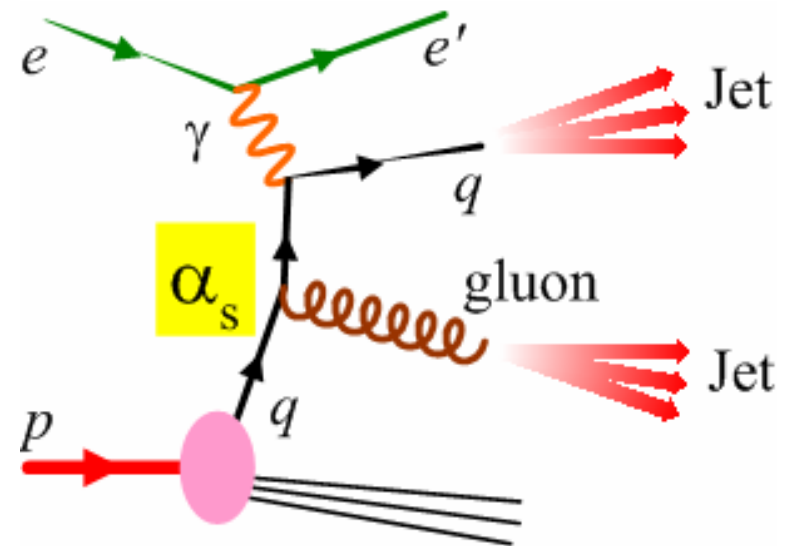
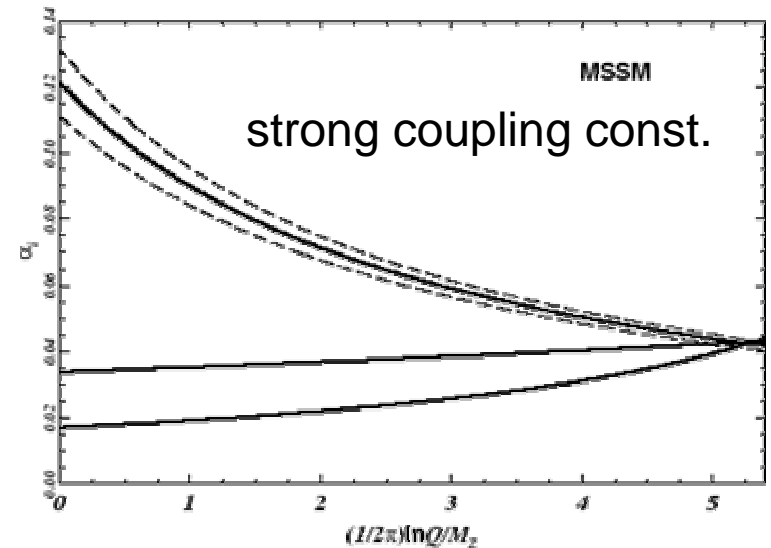
b -quark production at HERA-B

- 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



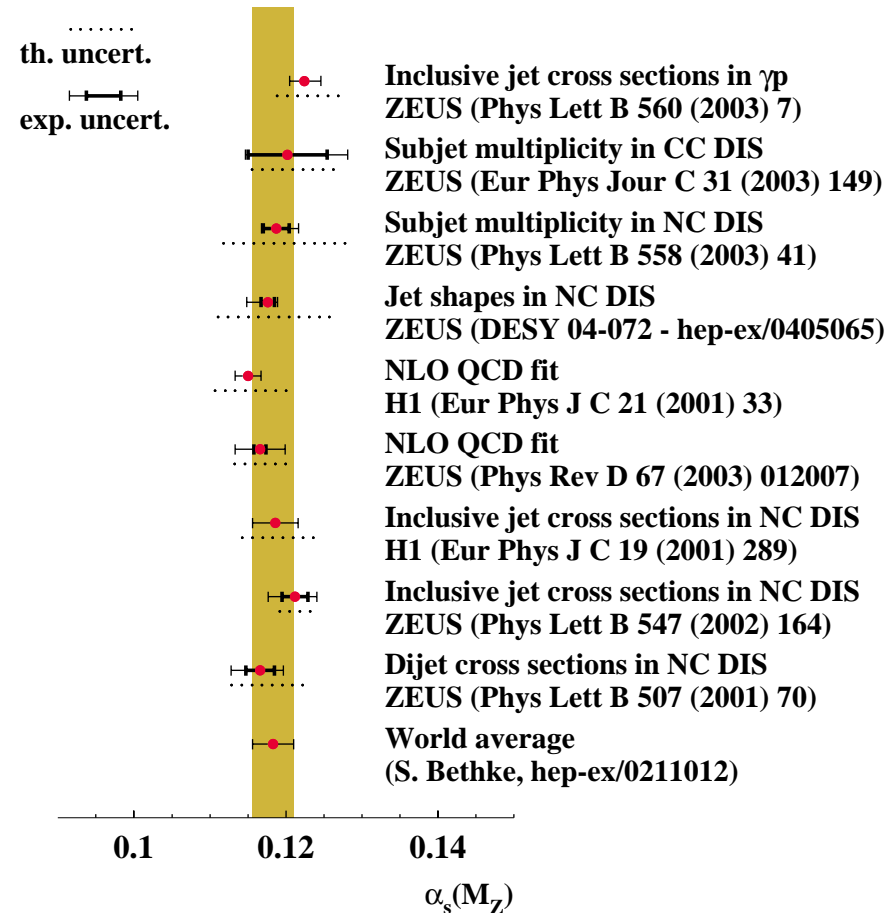
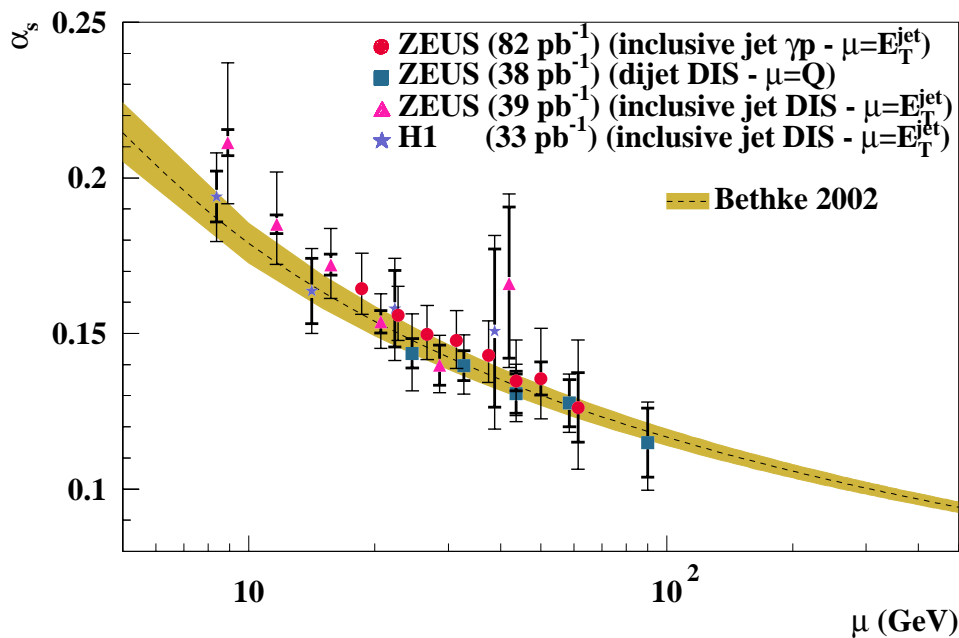
Measuring strong coupling constant α_s

- 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

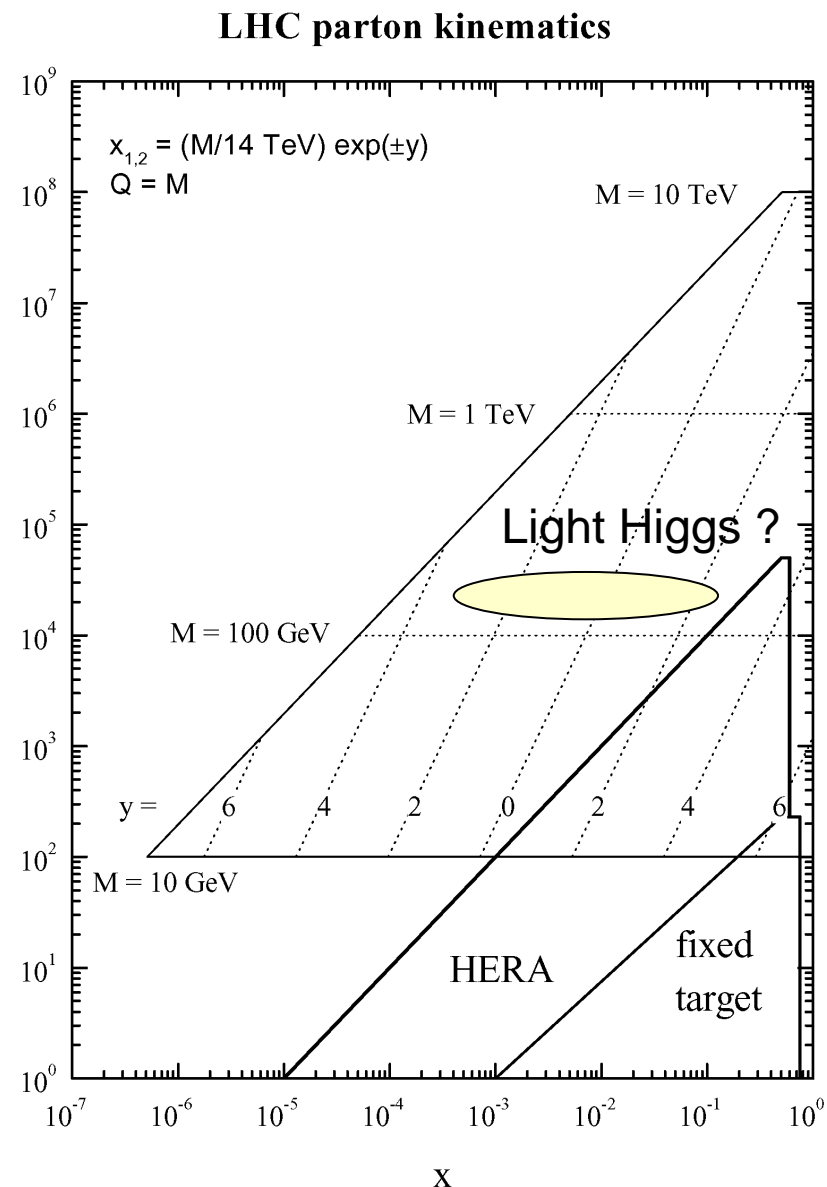


HERA-I study of proton structure and QCD (collider experiments)

- 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
→ **need more study with HERA-II**
- Most of the subjects at HERA cannot be covered here
 - e.g. diffraction (proton stays intact)

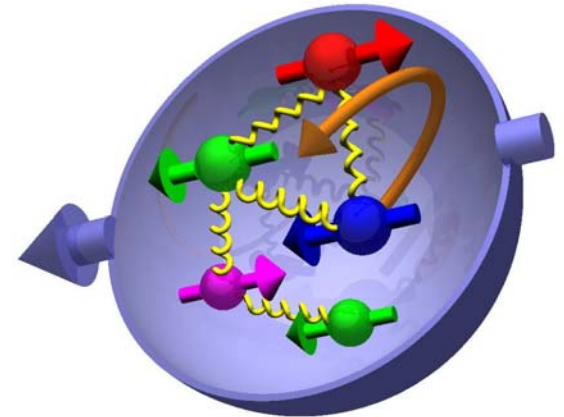
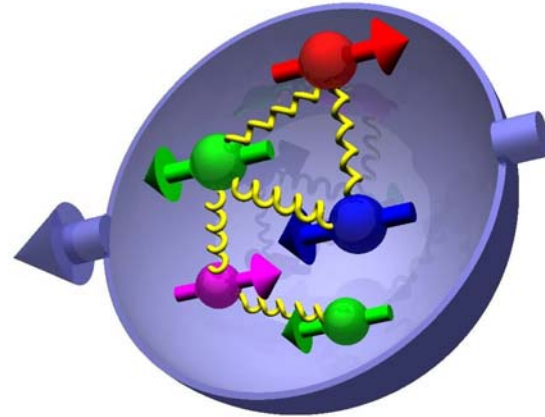
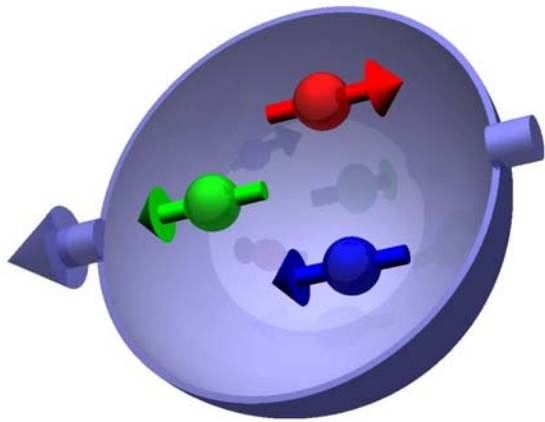
HERA-LHC workshop

- “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 $\frac{1}{2}$ spin of the nucleon comes from ?



Naive expectation:
 $u\uparrow u\uparrow d\downarrow$
 but measurement :
 only 12 % from
 valence + sea quarks
 (EMC, 1988)

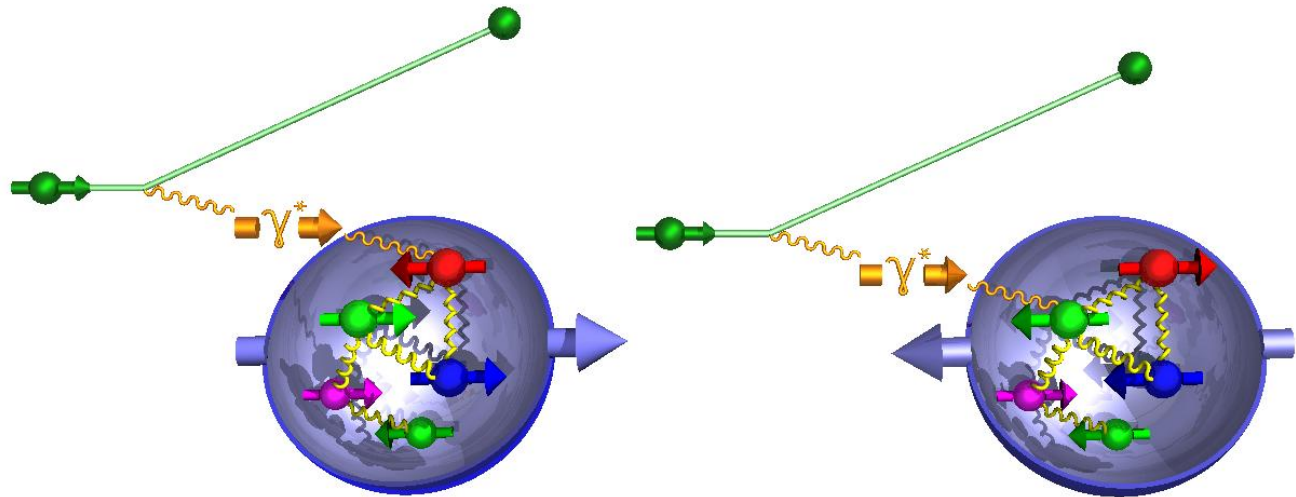
From gluon ?

From angular momentum
 of the quarks / gluons ?

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

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



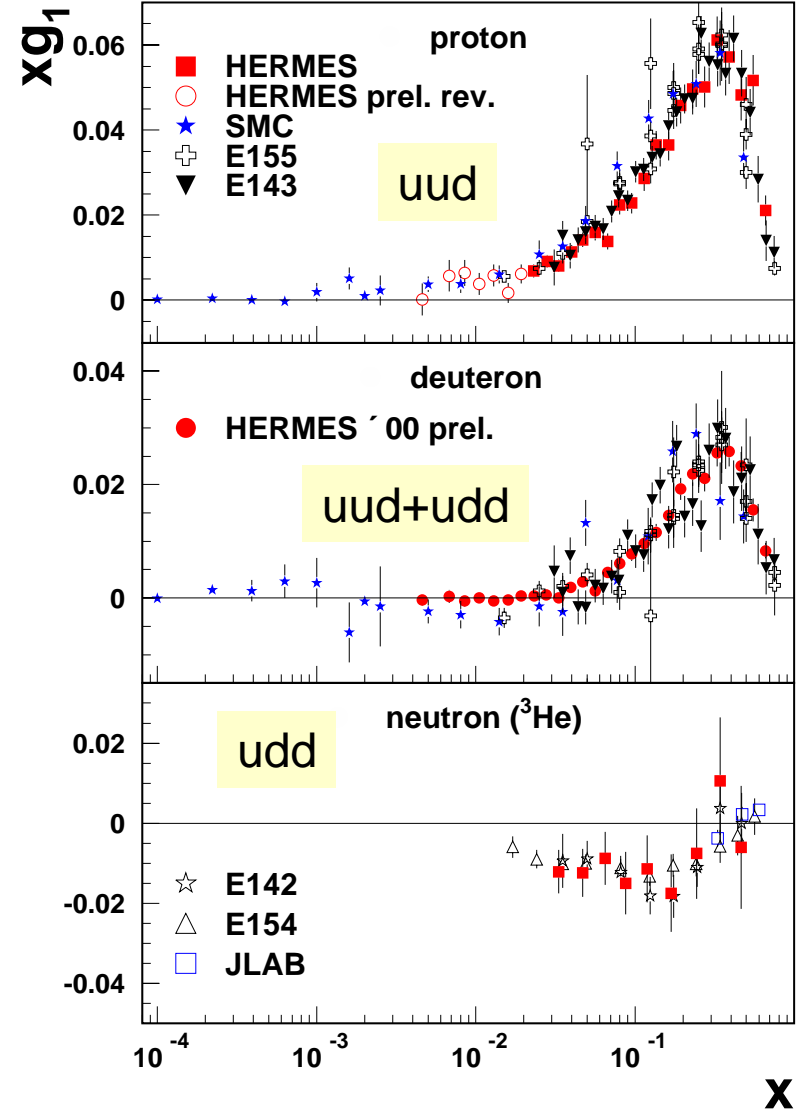
Photon can scatter with quarks
with spin anti-parallel – photon spin absorbed by quark spin flip

Quark spin from polarised structure function

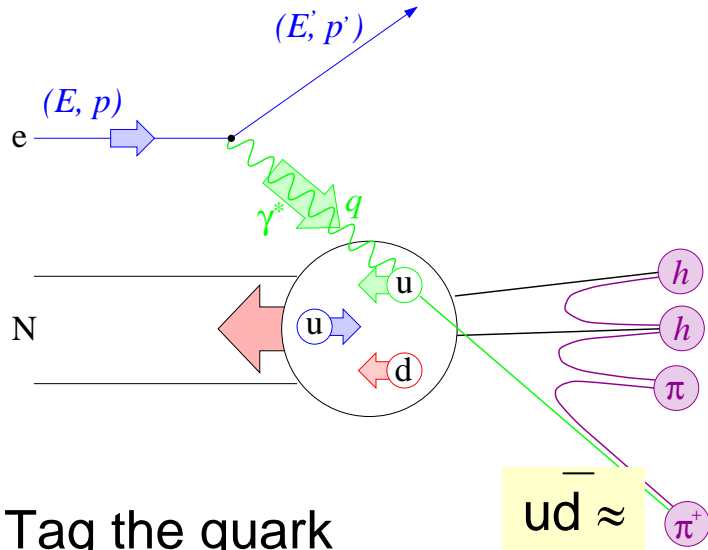
$$F_1 \propto q \uparrow(x) + q \downarrow(x)$$

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

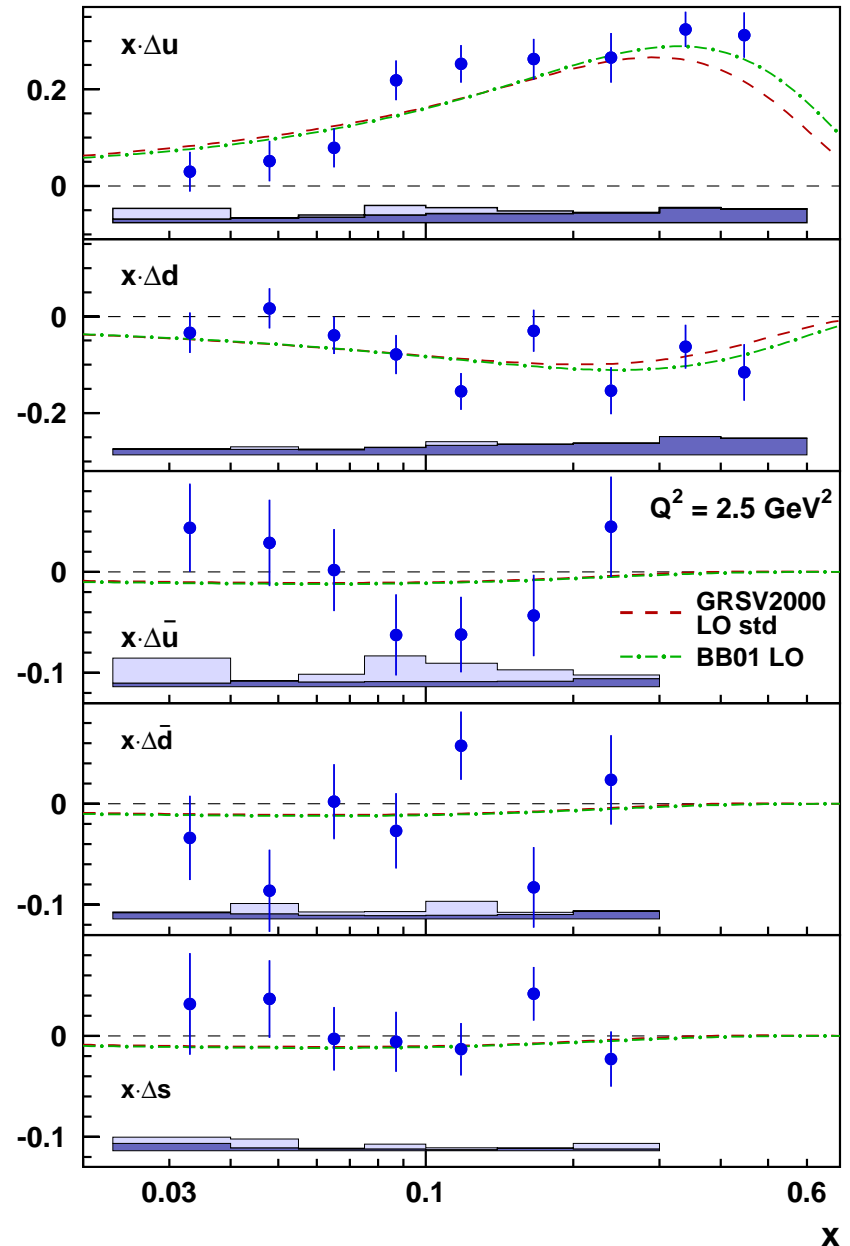
- g_1 – probability to find a quark with spin positive
- Precise measurement by HERMES
- Flavour decomposition from p , n and deuteron target
 - $u : \uparrow, d : \downarrow$ polarised
 - From strange quark, sea quark ?



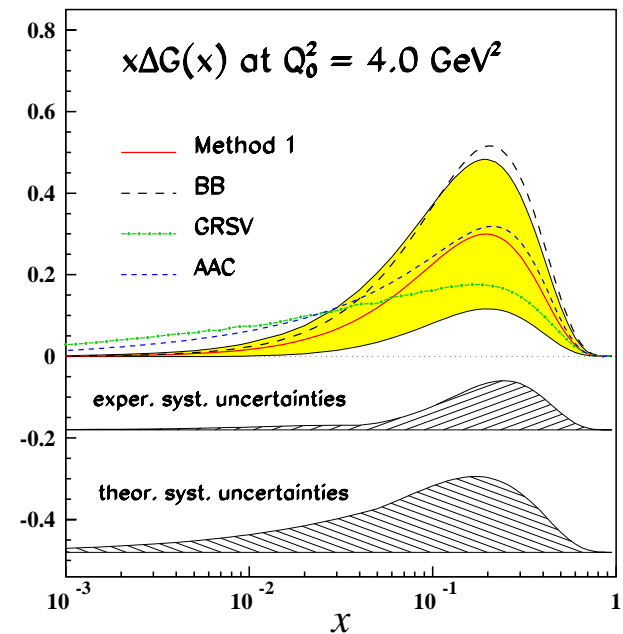
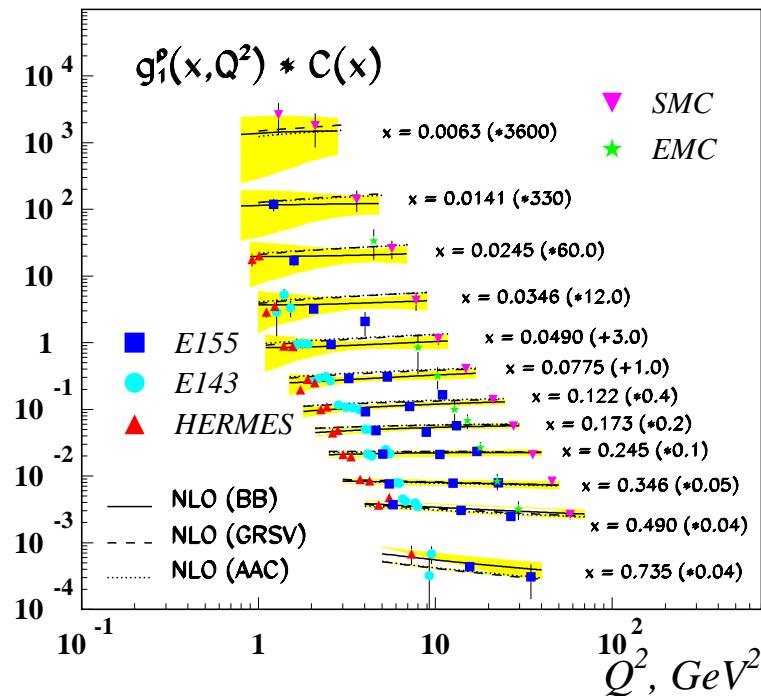
Flavour decomposition by semi-inclusive DIS



- 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 $\sim 30\%$
where is the spin ?



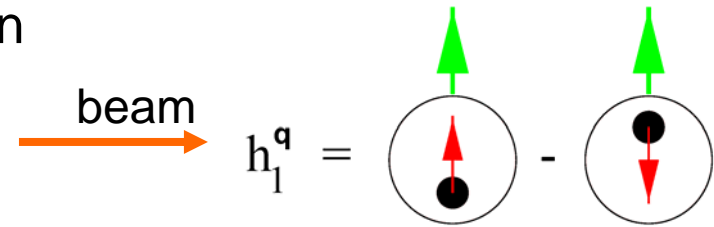
Extracted gluon polarisation from world data



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



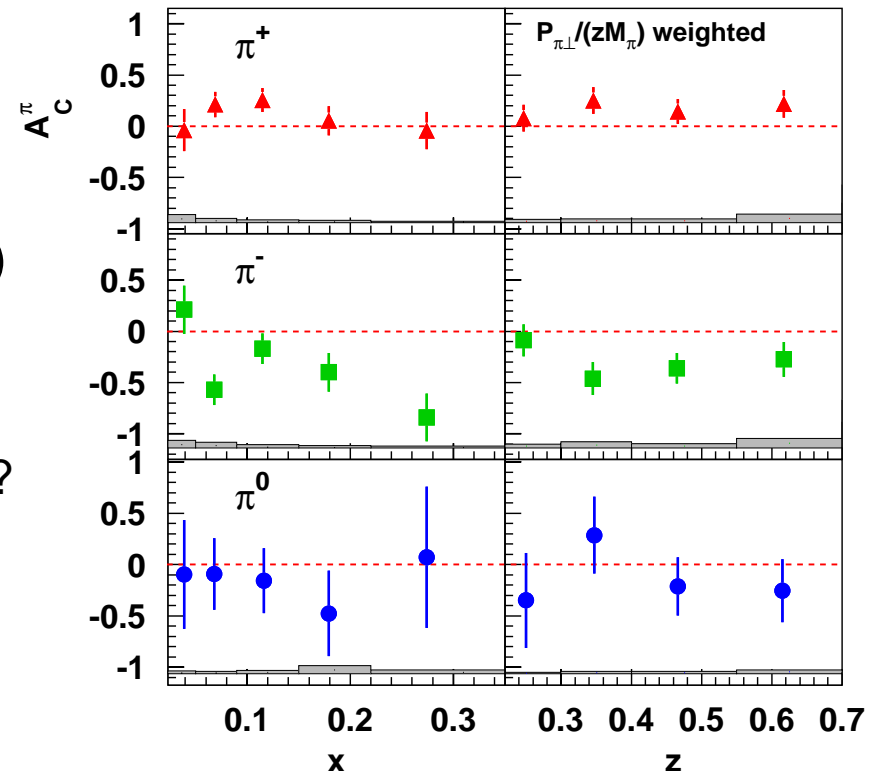
- If quark is massless, $h_1 \sim g_1$
 - Quark mass effect to spin
 - Valence/sea separation:
 $h_1 \sim x(\delta q - \delta \bar{q})$
- Expect $|A_{\pi^+}^P| \sim |A_{\pi^-}^P|$ (both mainly from u)

First result:

- $A_{\pi^-}^P$ 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



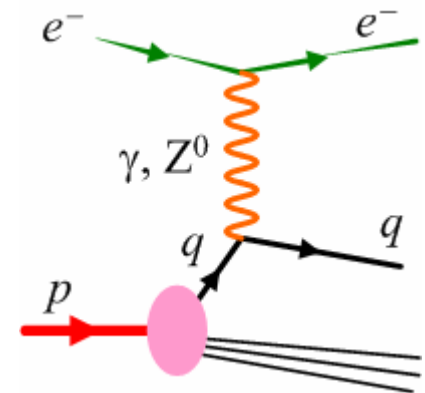
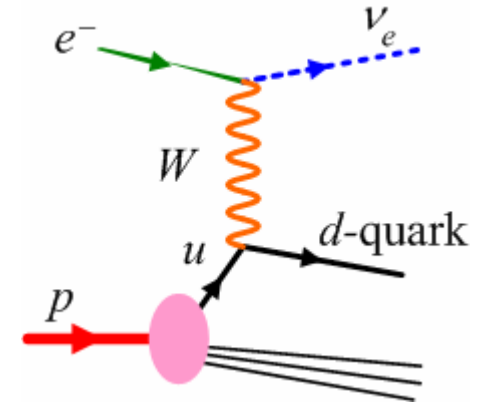
HERA-II physics : objectives

- Unique facility worldwide: *ep* collision with e^\pm polarisation
 - 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^- $\begin{pmatrix} u \\ c \\ t \end{pmatrix}$
 - down-type quarks for e^+ $\begin{pmatrix} d \\ s \\ b \end{pmatrix}$
 - spin polarisation: $(1 \pm P_z)$ dependence

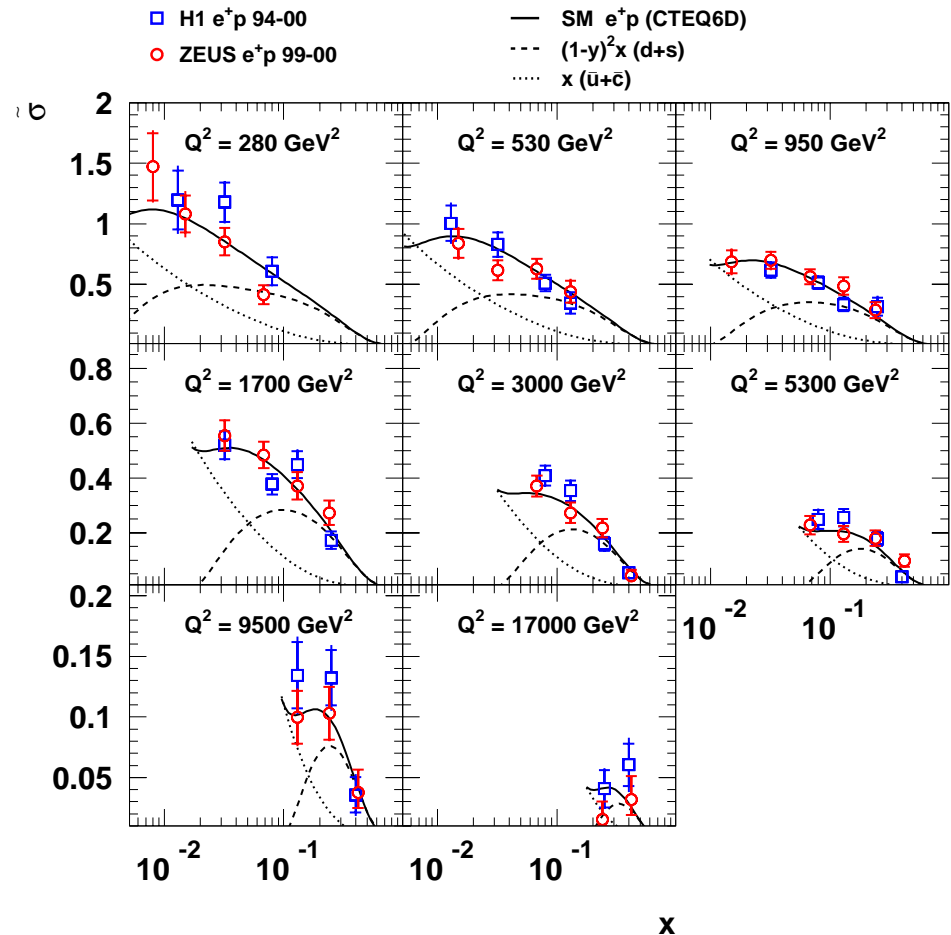
- High- Q^2 neutral current (NC) exchanging Z^0 ($Q^2 \approx M_{Z^0}^2$)
 - Cross section difference $\sigma(e^-) - \sigma(e^+)$ is sensitive to $q - \bar{q}$
 - Spin polarisation gives similar effect



Charged current and parton densities

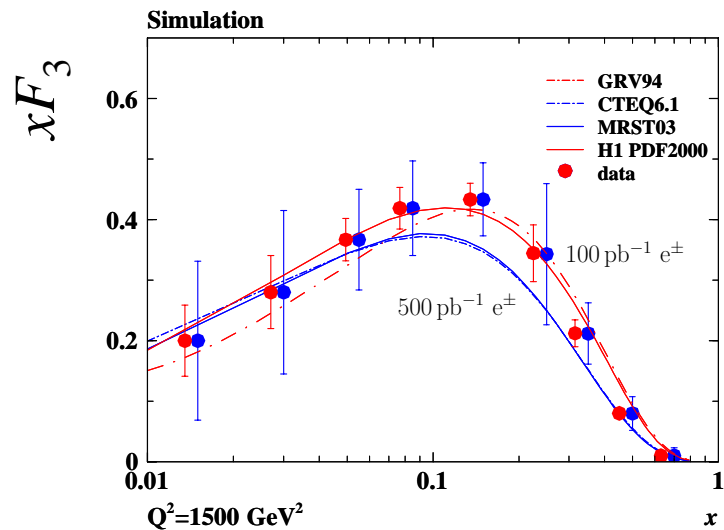
- Example : full HERA-I data(100pb⁻¹), e⁺ beam
 - Different dependence in y decompose ($d + s$) and ($\bar{u} + \bar{c}$)
→ distinguishing flavour
 - Sensitive to d
- Precision limited by statistics
 - **Increasing statistics is main goal for HERA-II**

HERA e⁺p Charged Current

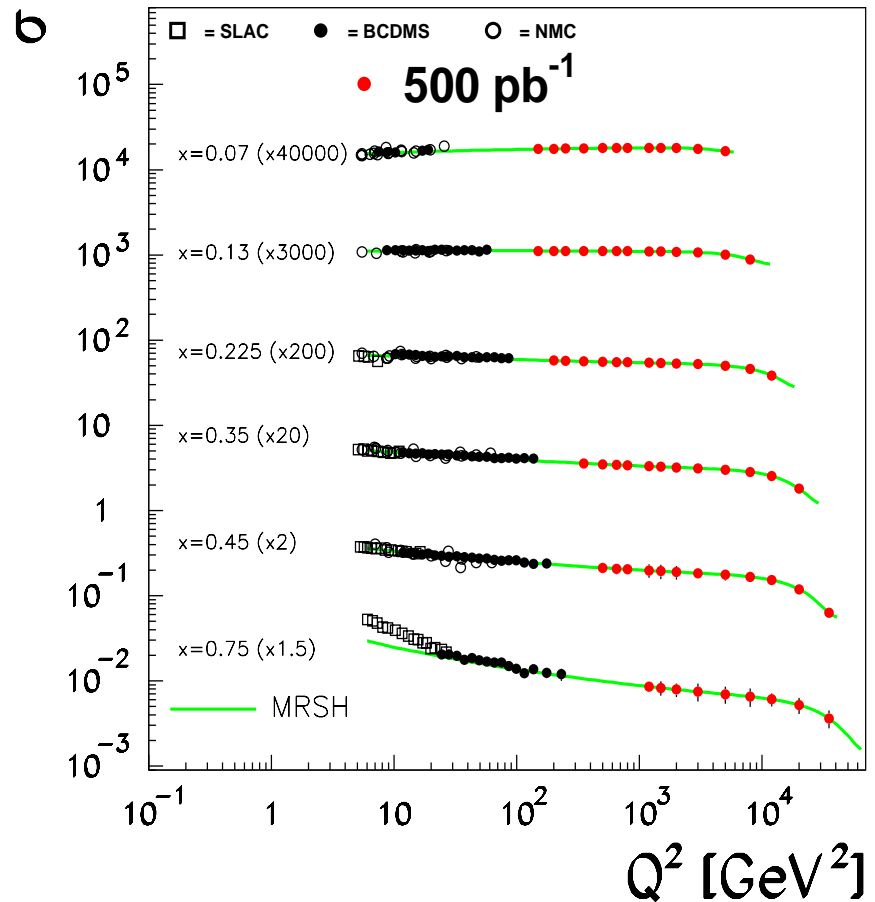


Precise measurement of the valence quark density at HERA-II

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

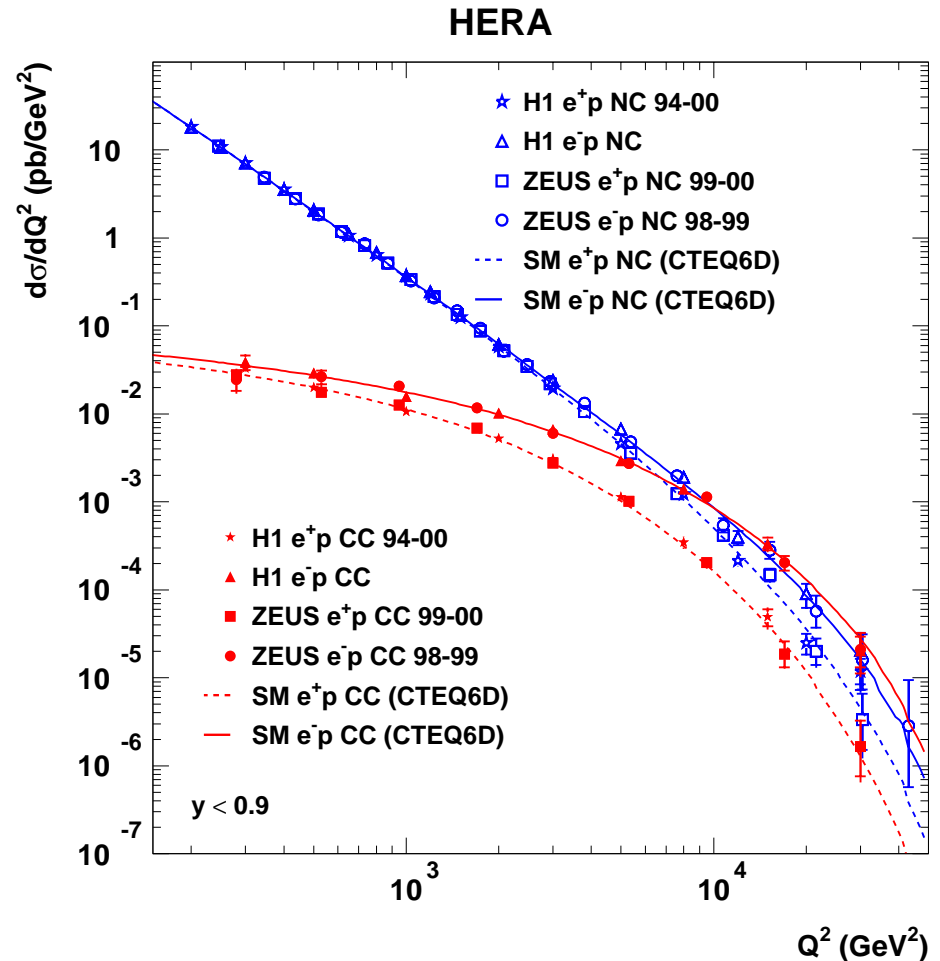


NC simulation for HERA-II

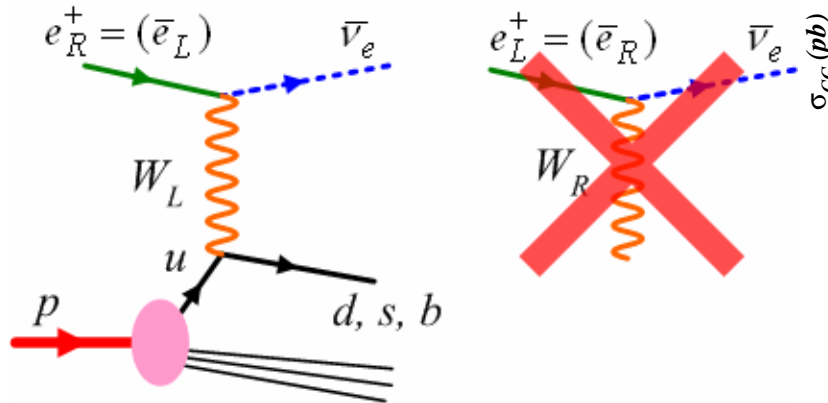


NC/CC cross section and electroweak unification

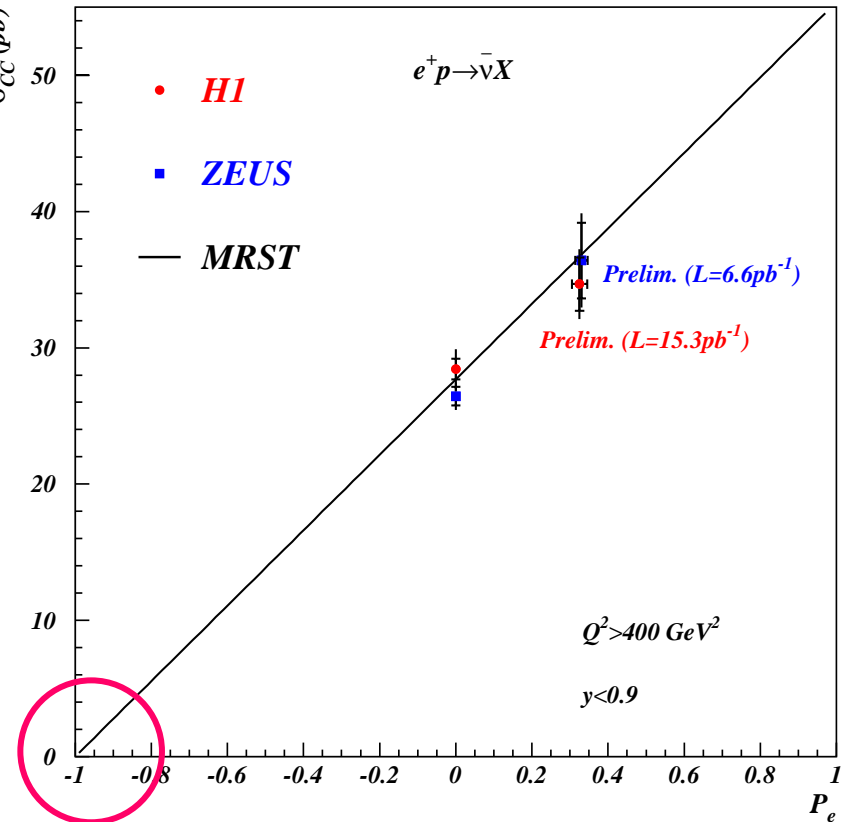
- Cross section of NC and CC becomes similar at $Q^2 \approx M_W^2, M_Z^2$
 - Manifestation of the electroweak unification
- Study at HERA-II – electroweak parameters in detail **with polarisation** e.g.
 - Electroweak coupling constants to u- and d-quarks (v_u, a_u) and (v_d, a_d)



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

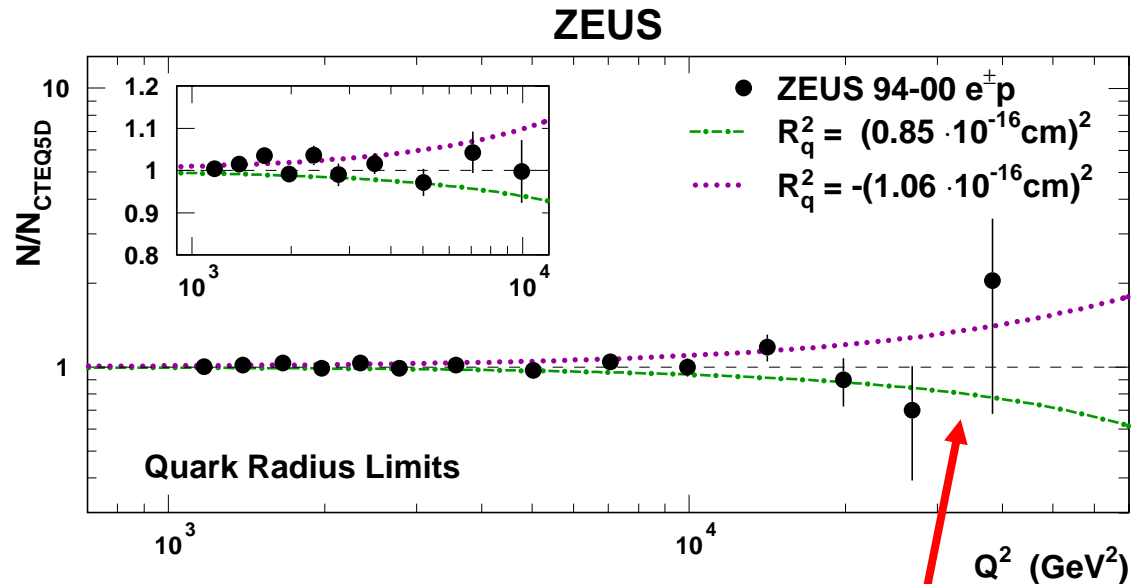
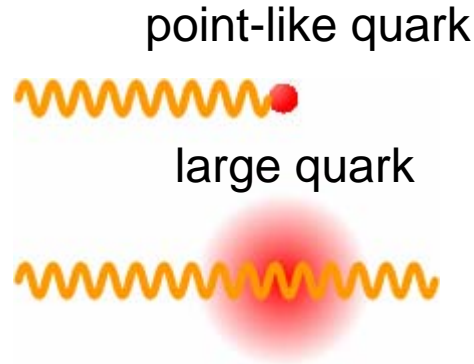


- First measurement of CC with polarisation
- If right-handed current exists, the cross section at 100 % RH polarisation is non-zero
- Consistent with no right-handed current so far



Data with opposite pol. being collected

Size of the quark

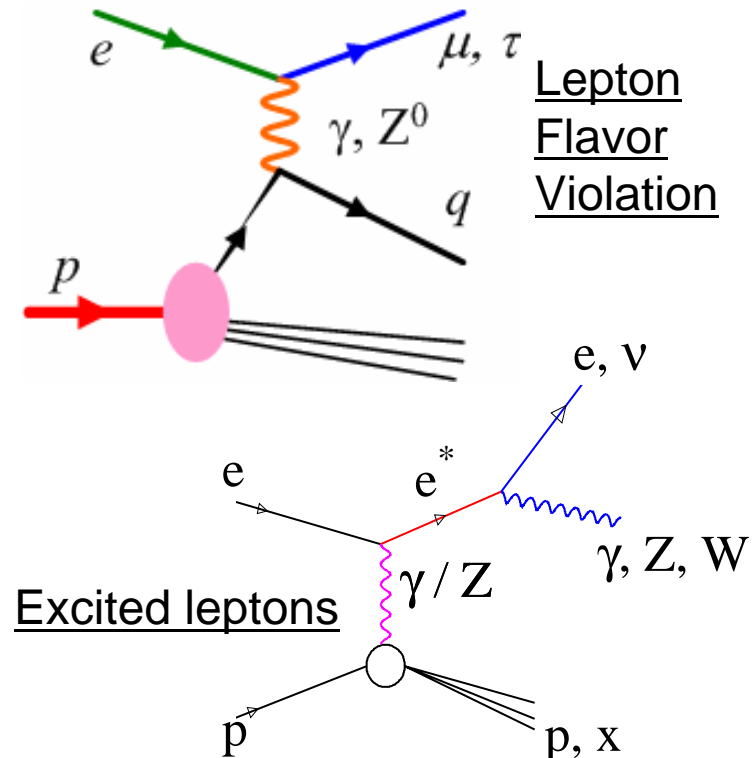
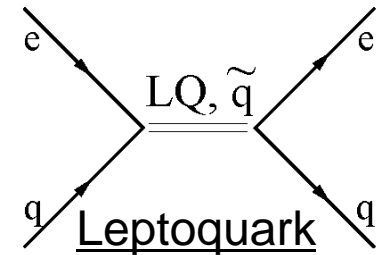


Expectation with finite quark size

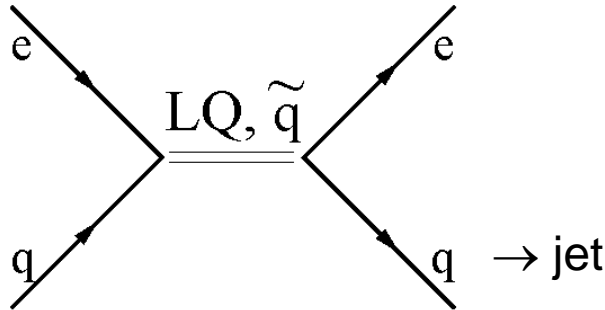
- Finite size of the quark
 - cross section becomes smaller at high- Q^2
 - Short wave cannot see a blur object
quark becomes transparent
- Cross section agrees with SM: quark is point-like down to radius $R_q < 0.7 \times 10^{-18} \text{ m}$ ($< 1/1000$ of proton – H1 and ZEUS)

Search for new particles and interactions

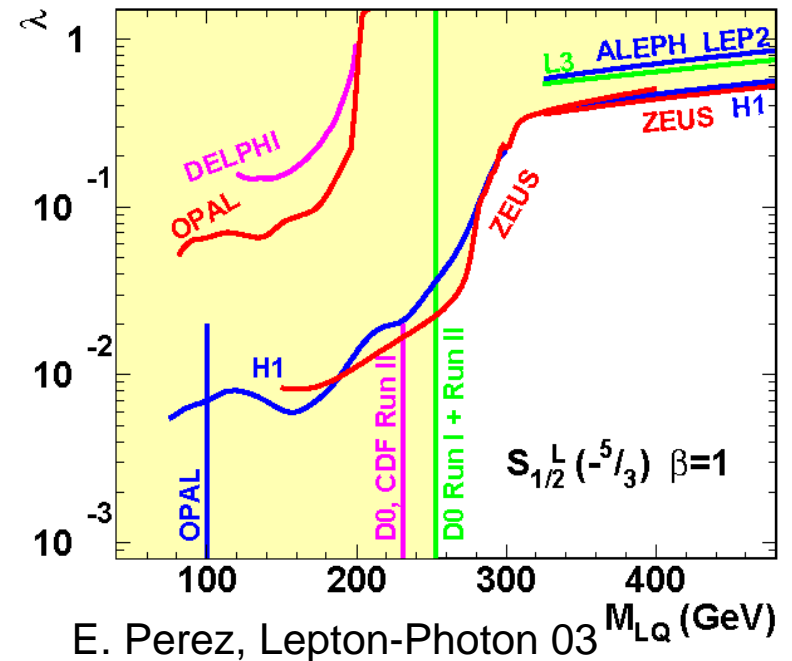
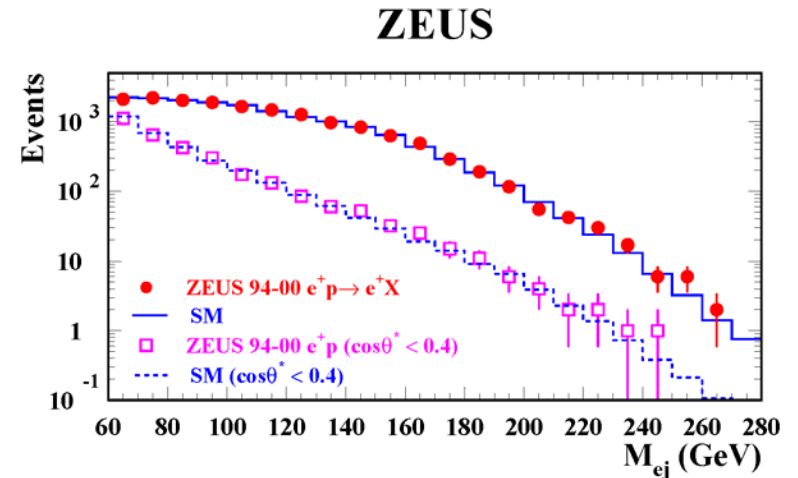
- Only Tevatron (2 TeV $p\bar{p}$) and HERA are the high-energy colliders in operation
- Giving world best limits on:
 - Leptoquark (next slide)
 - Flavour-changing neutral current
 - Lepton-flavour violation Observed in neutrino sector !
 - Quark flavour violation
 - Excited leptons e^* , ν^*
 - Super-symmetric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



Leptoquark: quark-lepton resonance

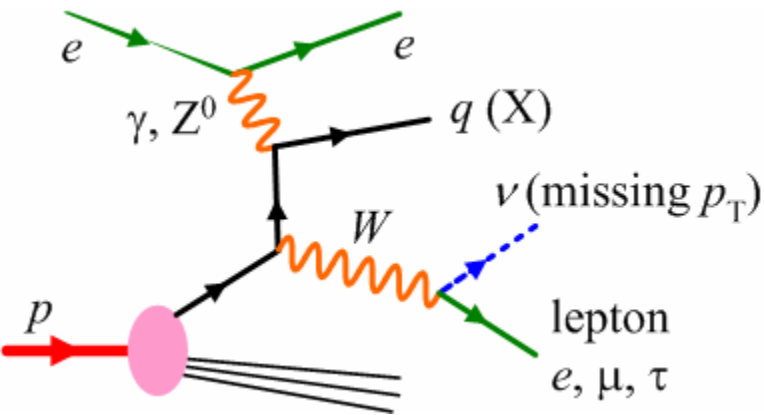


- Models from grand-unified theory, super-symmetry etc.
- Searching for a resonance in the $eq = e+\text{jet}$ mass spectrum
- In large region of parameters HERA gives best limit
- Other region: complementary to Tevatron and LEP



E. Perez, Lepton-Photon 03 M_{Lq} (GeV)

High- p_T lepton + missing p_T excess ?



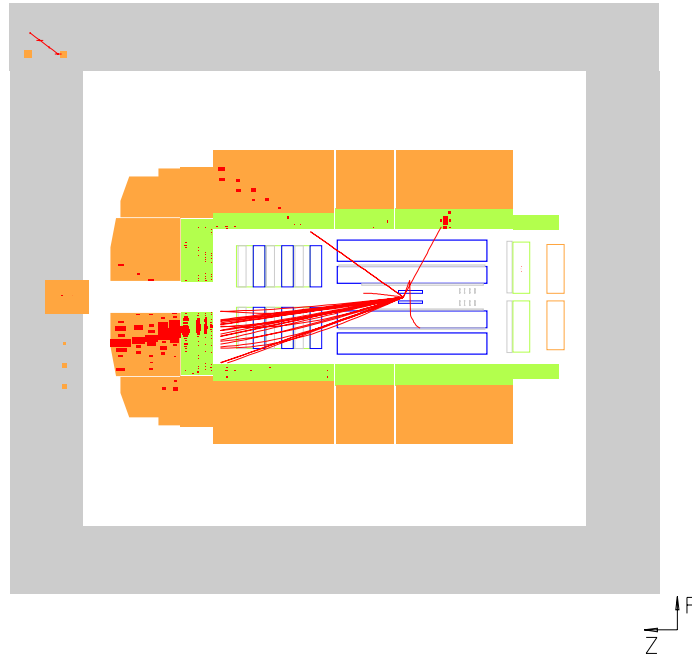
- SM: through W production
 - Not abundant at large p_T^X

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

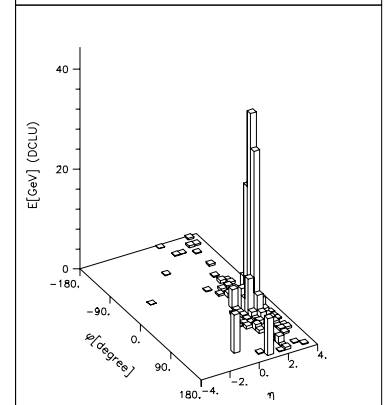
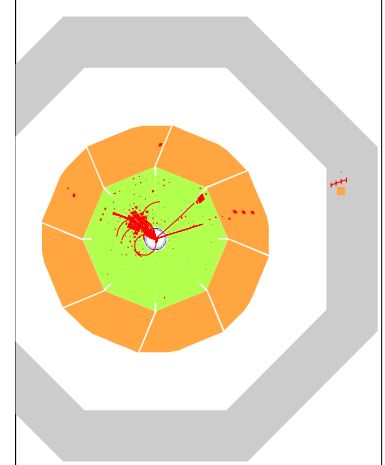
Event MUON-3

$$P_T^\mu = 39 \text{ GeV}, P_T^X = 27 \text{ GeV}, P_T^{\text{miss}} = 42 \text{ GeV}$$

$$M_{\mu\nu} = 82 \text{ GeV} \quad W^- \rightarrow \mu^- \nu \quad \text{Candidate}$$

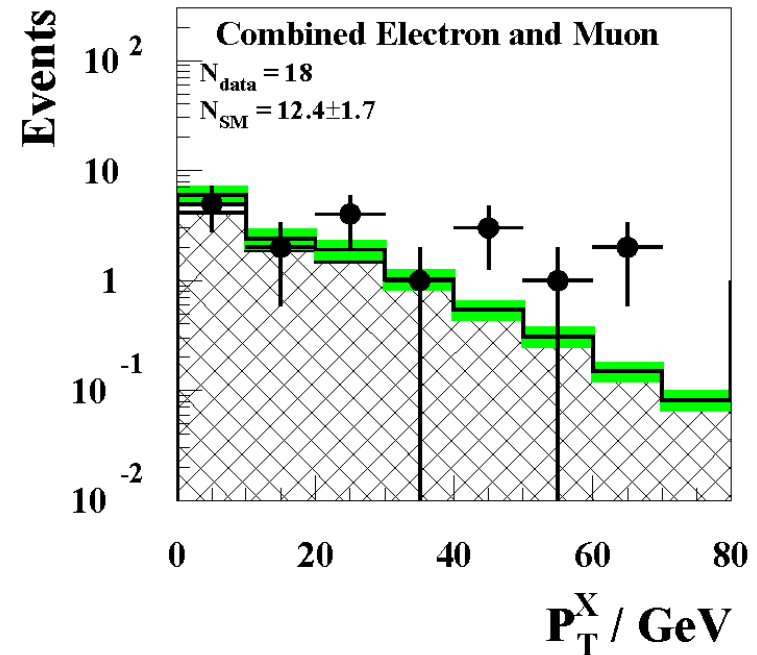
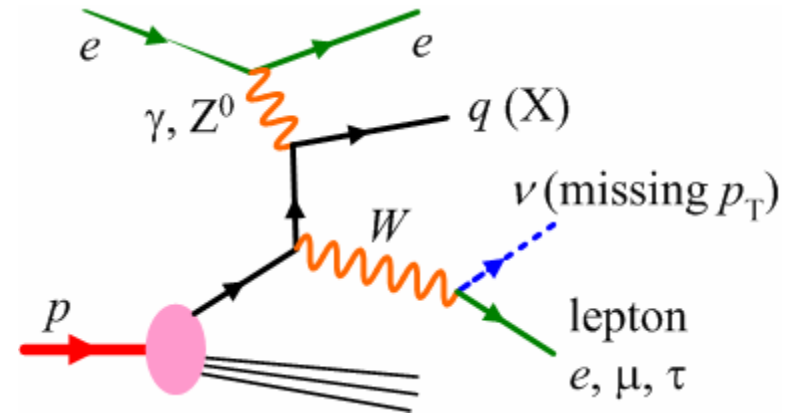


H1



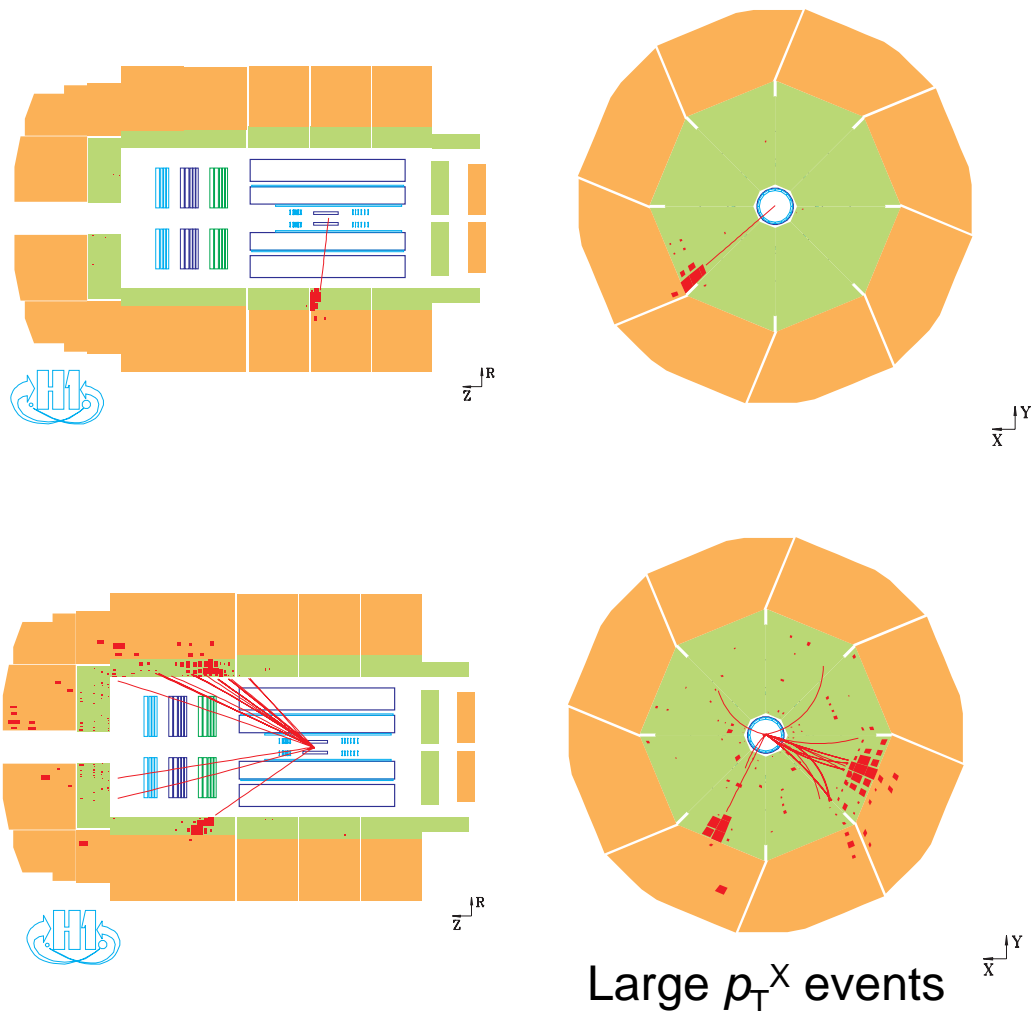
High- p_T lepton + missing p_T excess ?

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



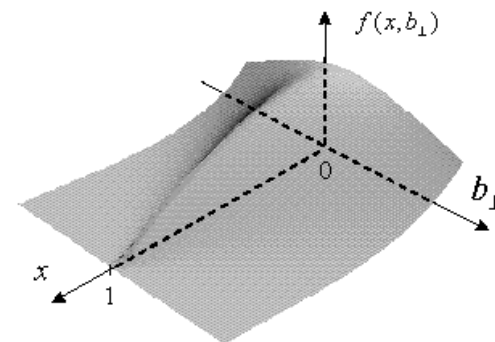
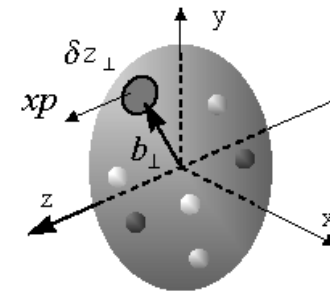
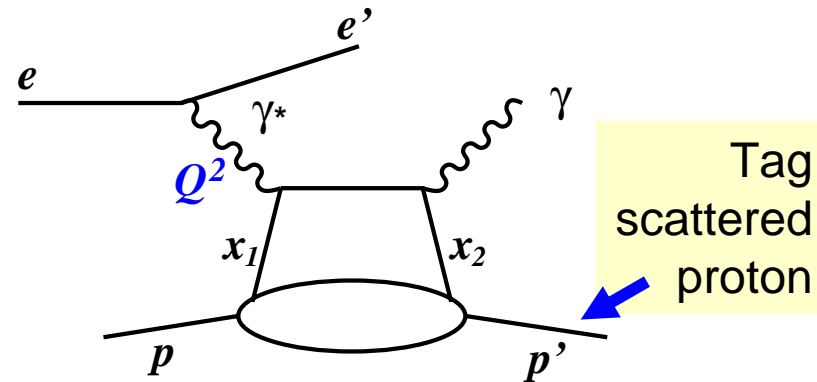
High- p_T leptons in HERA-II

- 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



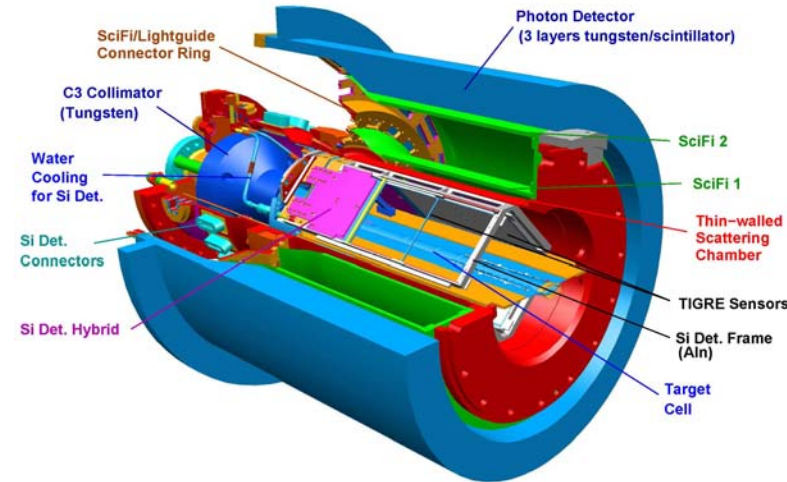
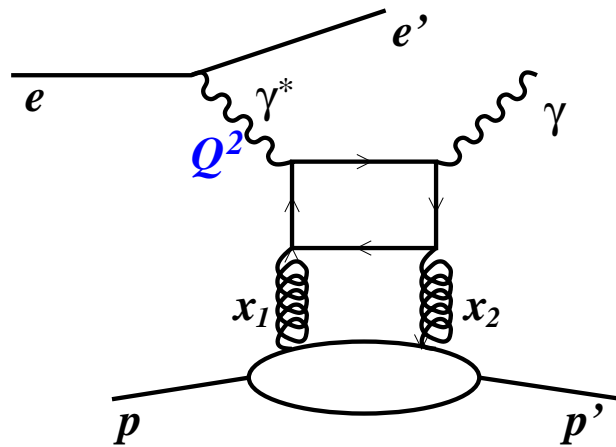
Deeply virtual Compton scattering (DVCS)

- 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

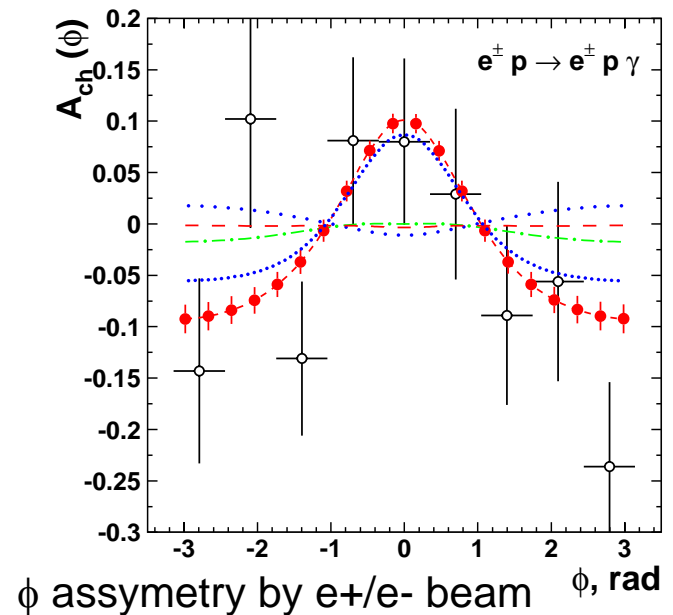


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D. Müller,
hep-ph/
0206306

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)



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**