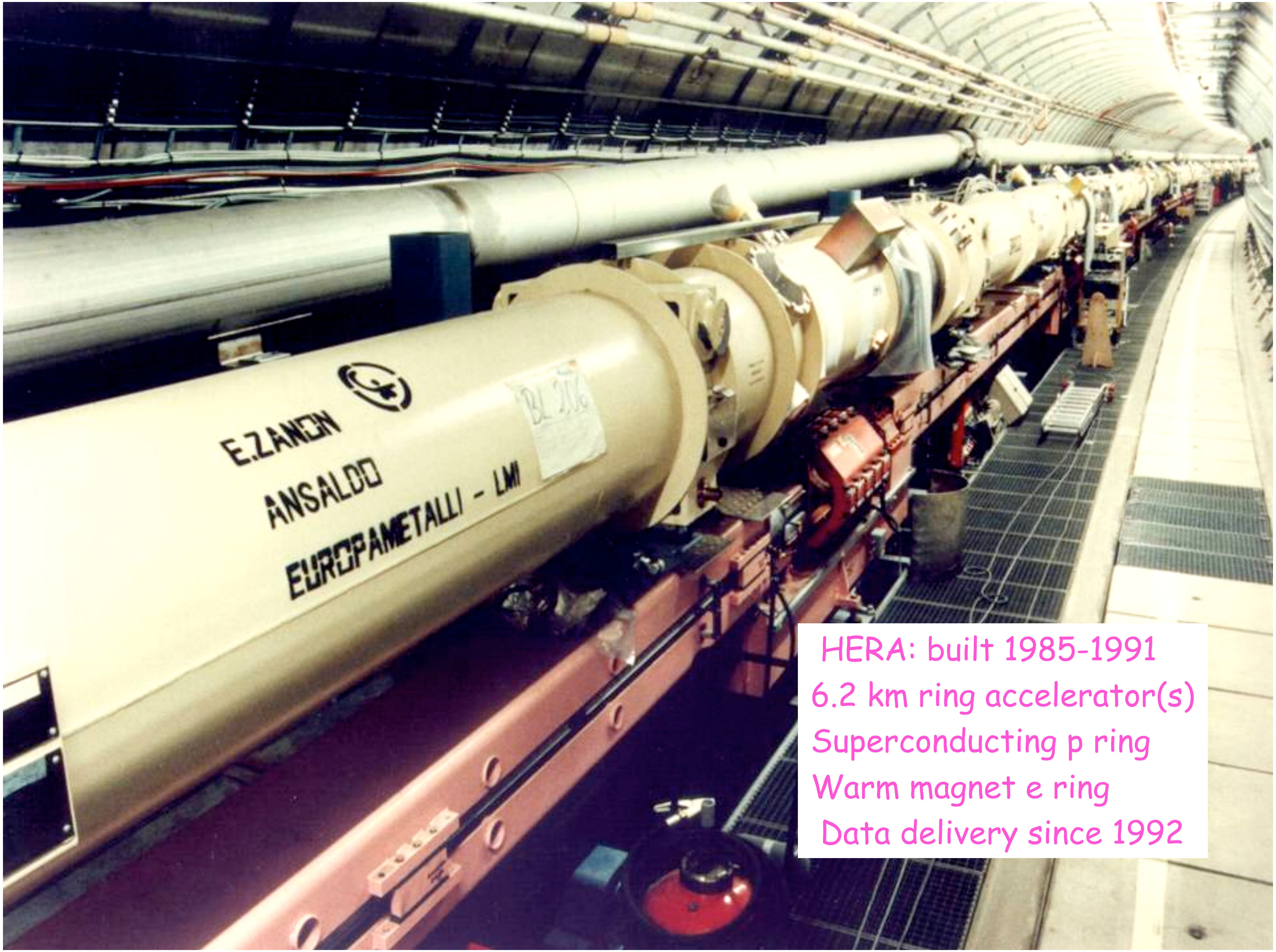
Deep Inelastic Scattering at HERA

Results and Outlook

HERA and LHC
Inclusive Scattering and pdf's
Final State Physics (c,b,jets)
Diffractive DIS
Electroweak Physics and Searches
LHeC

LHC days, Split, 3rd of October 2006

Max Klein (DESY) klein@ifh.de

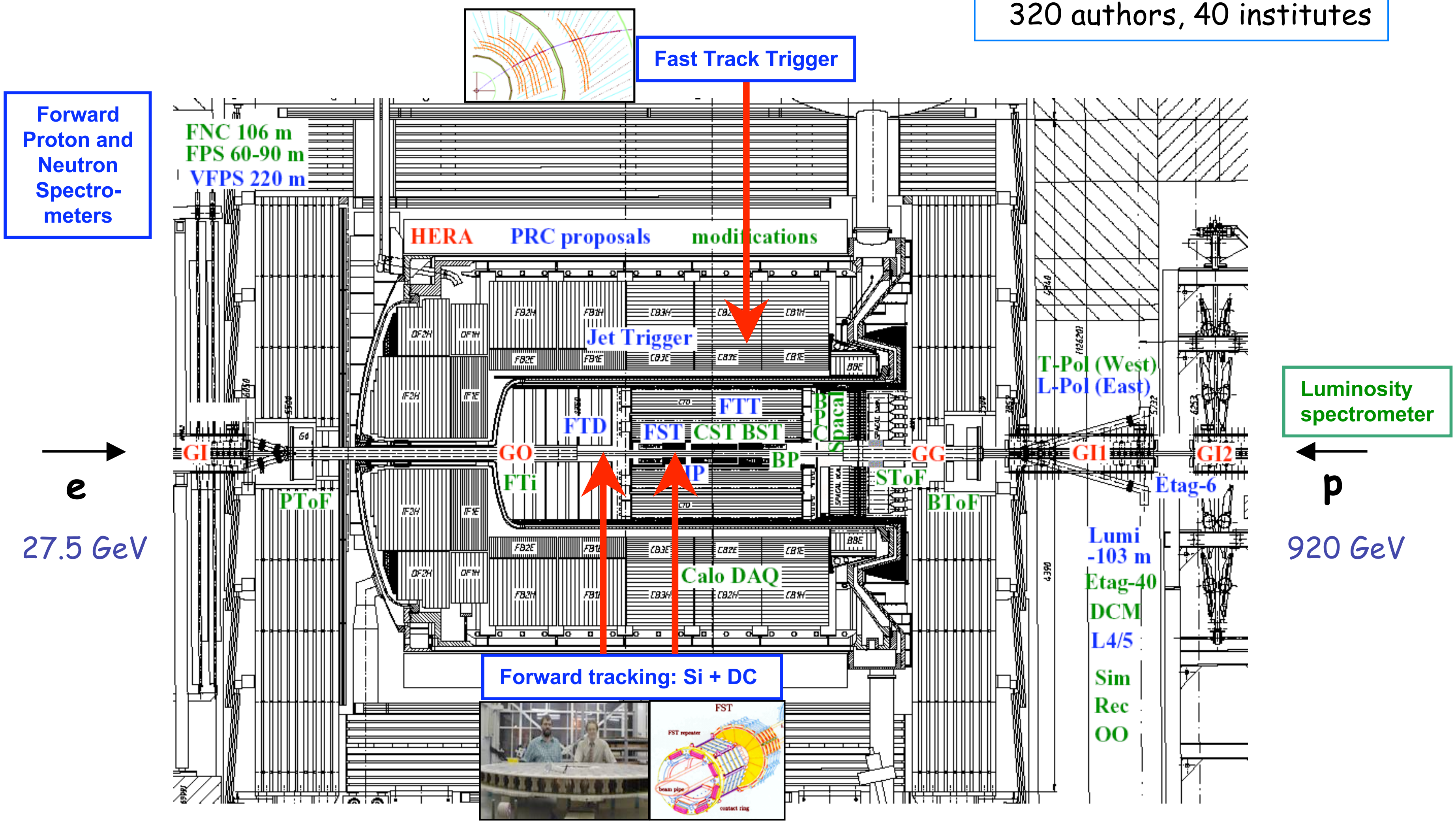


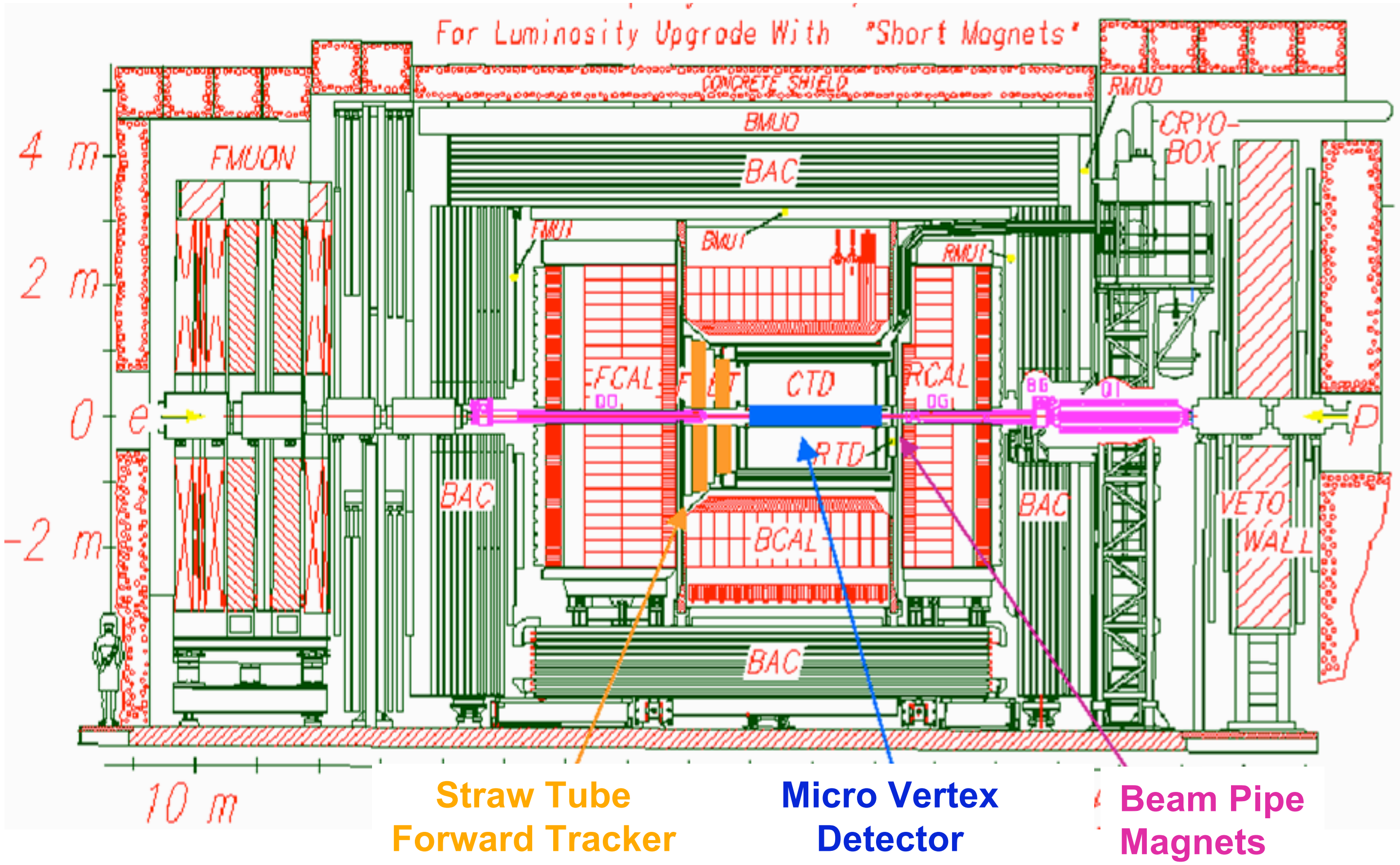
HERA: built 1985-1991
6.2 km ring accelerator(s)
Superconducting p ring
Warm magnet e ring
Data delivery since 1992

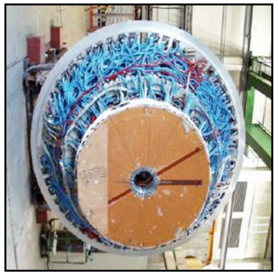
ep-collider expts H1, ZEUS @319GeV [and polarised target expt HERMES @7GeV]

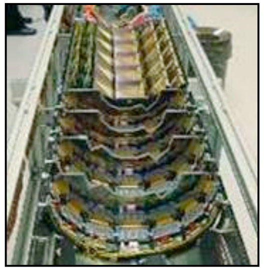
The H1 Detector

320 authors, 40 institutes









Luminosity spectrometer

350 authors
~35 institutes

The ZEUS Detector

Physics at HERA (the expected and the unexpected)

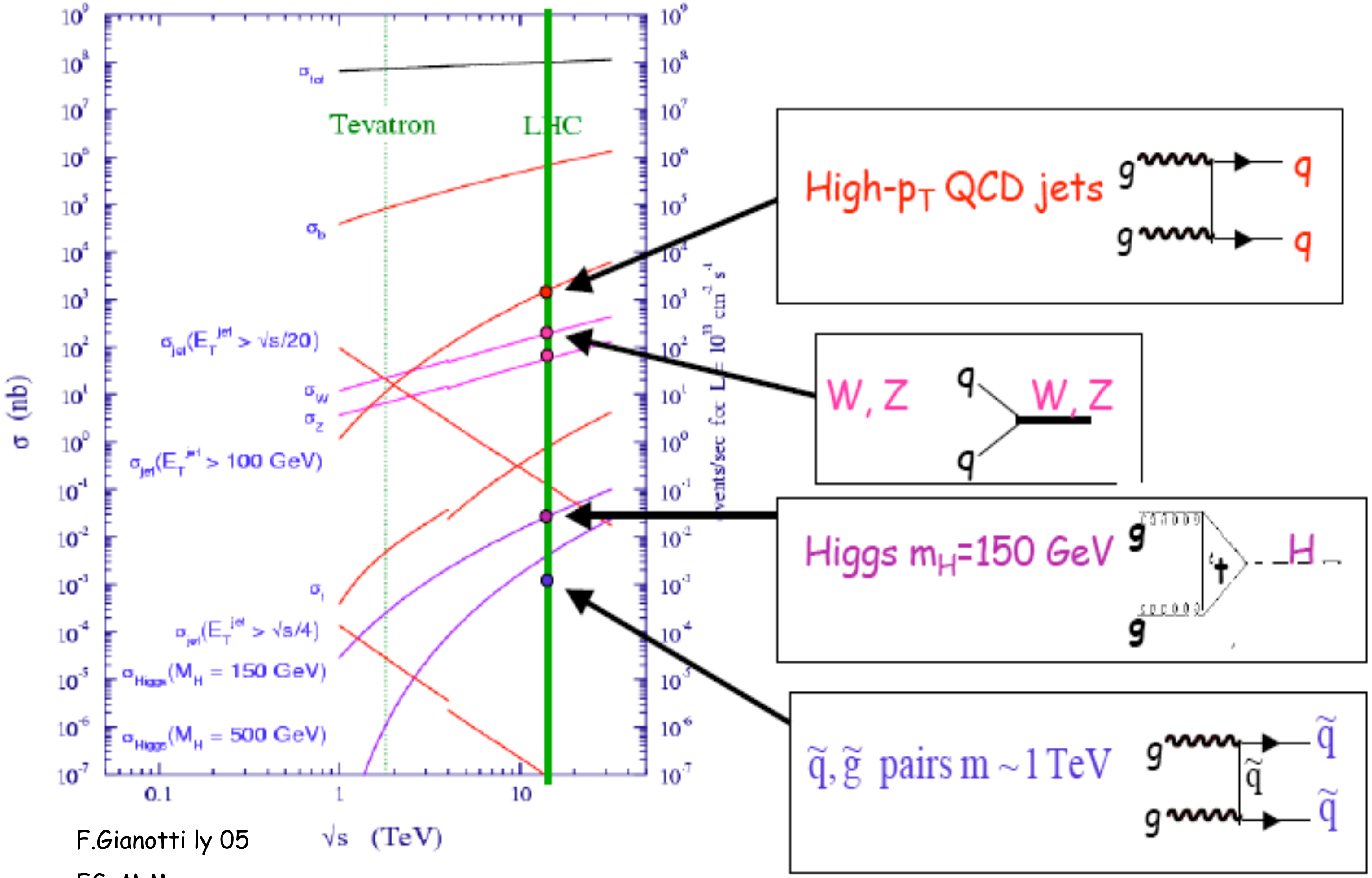
•classic DIS	• Inclusive ep measurements (NC, CC-inverse neutrino i.a.) -> pdf's, gluon,
•QCD	• Low x physics: small coupling and high density of partons -> "CGC, BFKL.."
	• Heavy flavour physics (c and b: production and fragmentation dynamics)
	• Final state physics (parton emission,,jets, γ structure, dijet correlations)
	• Diffraction [all related: e.g. "the structure of charm jets in diffraction"]
	• Parton amplitudes (DVCS)
	• Searches for exotic states (pentaquarks) and less? exotic ones (instantons)
•Searches	• Searches: substructure, leptoquarks, SUSY, isolated lepton events (15/5)
•elweak	• Electroweak physics (spacelike region)

for HERA physics see also:

- Talks at DIS05, Madison, DIS06, Tsukuba
- Ringberg Workshop (2003/05) Proceedings ed by G.Grindhammer, B.Kniehl, G.Kramer

LHC physics - The only place where success appears before work is a dictionary

G.Dissertori Lisbon05

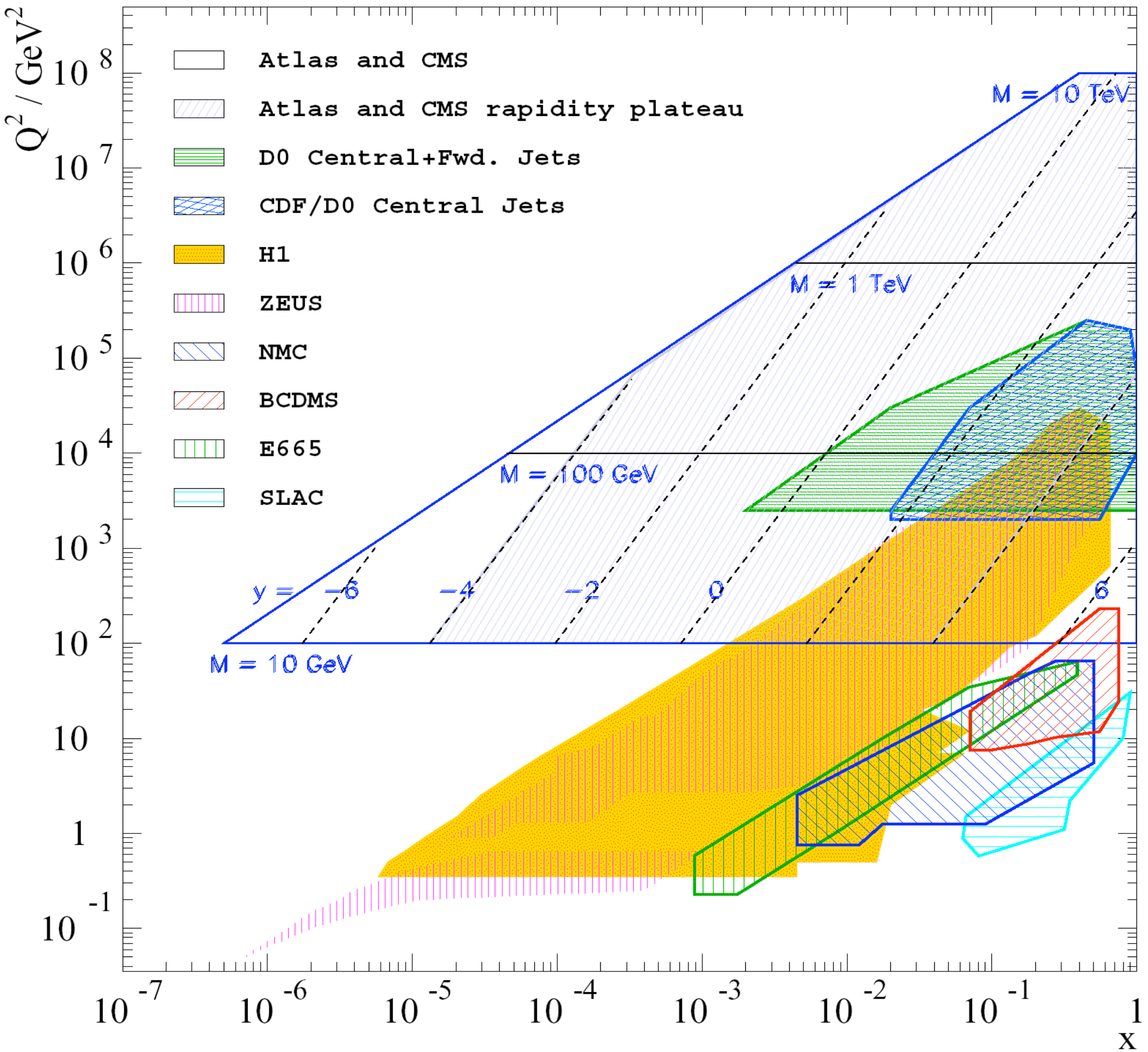


F.Gianotti ly 05

FG, M.Mangano

hep-ph/0504221

No discovery without understanding QCD. HERA 'delivers' partons and understanding of production mechanism



pp collider

e.g. W production

$Q^2=M^2$

$x=(M/\sqrt{s})\, e^{\pm y}$

HERA kinematics

$$E_e = 27.6 GeV, E_p = 920 GeV$$

$$\sqrt{s} = 2\sqrt{E_e E_p} = 319 GeV$$

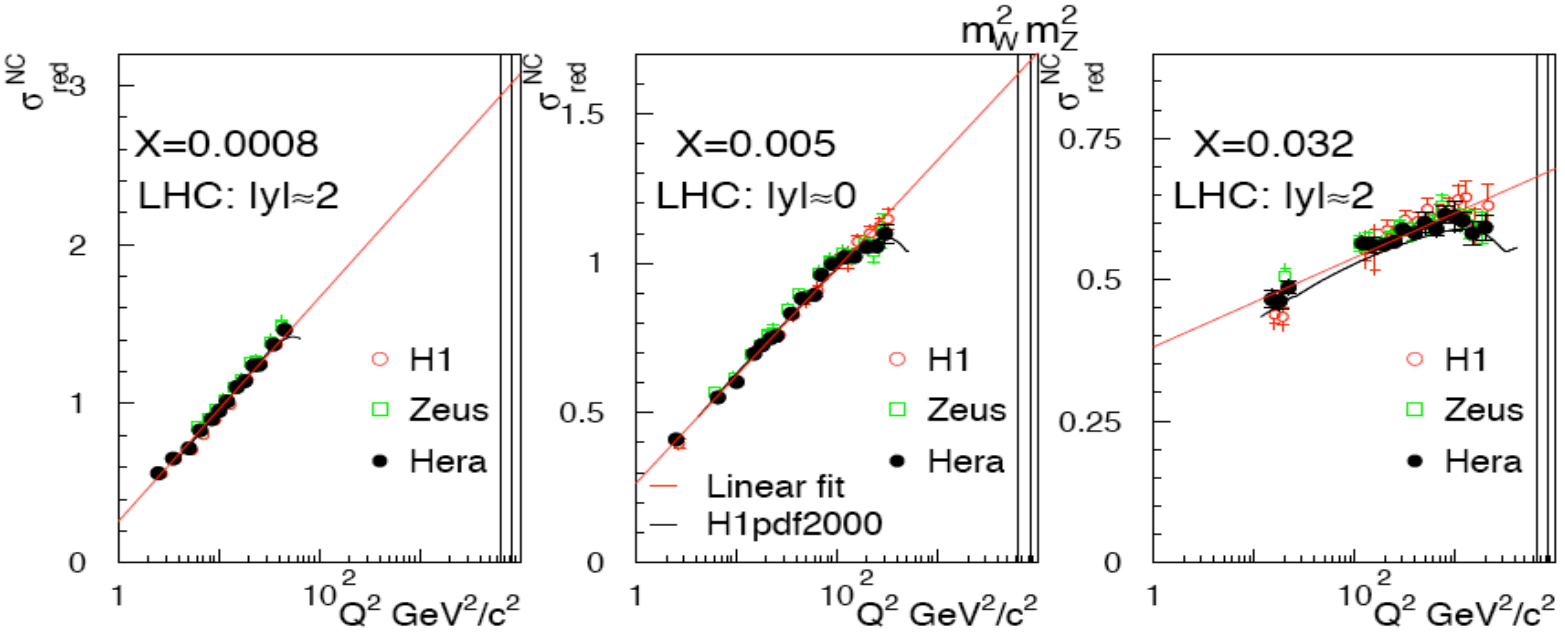
$$\Leftrightarrow E_e^{ft} = 54.1 TeV$$

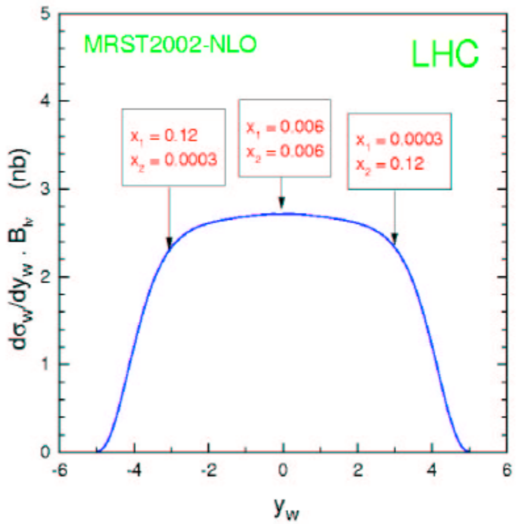
$$Q^2 = sxy - high$$

$$x = Q^2 / sy - low$$

Low x physics at HERA: "backward" at H1 and forward at LHC
Medium x: central at H1 and "rapidity plateau region at the LHC"

Extrapolation from HERA to the LHC

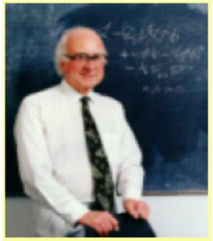


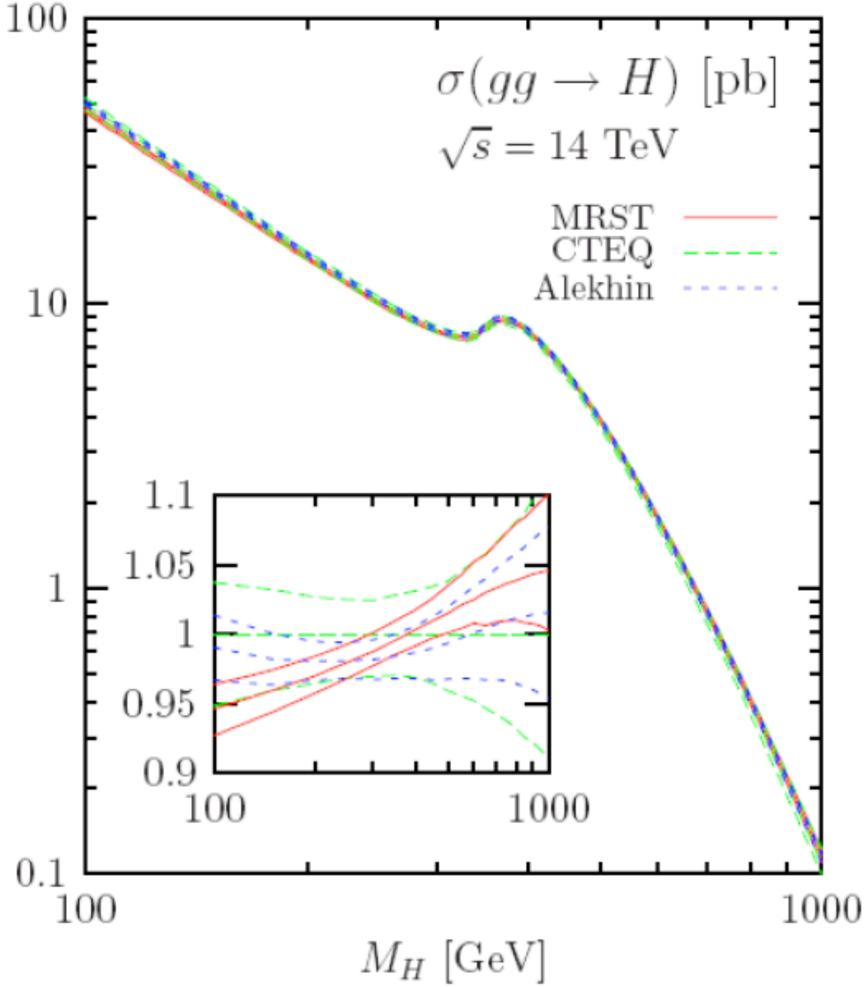


W,Z related to structure fcts (quarks)

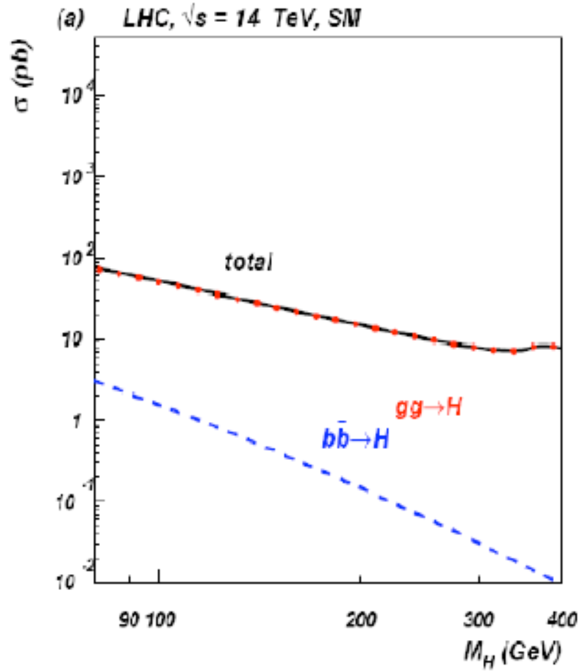
-QCD at low x
-extrapolation
-parton luminosity determination?

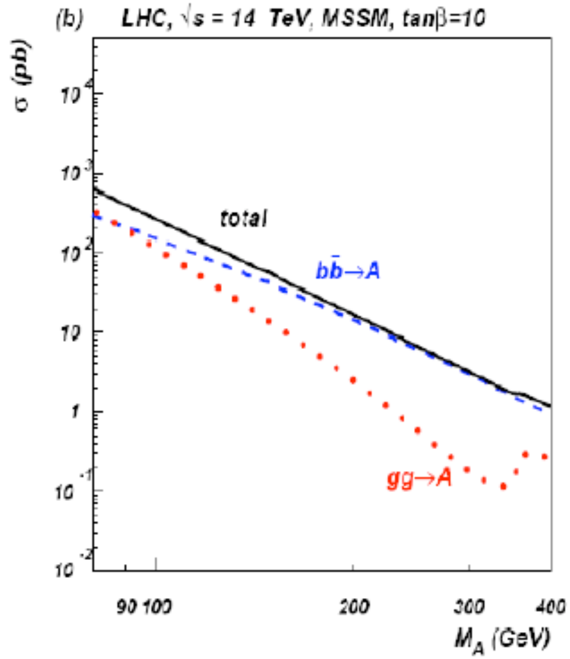
-calibration



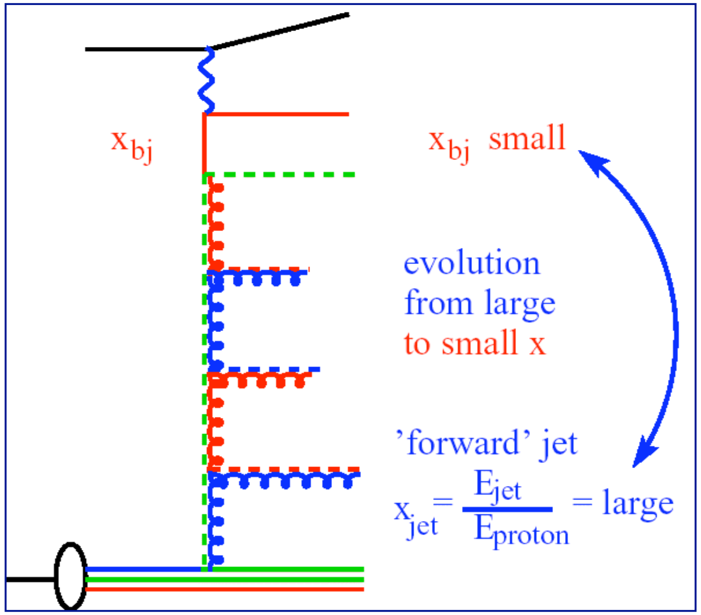


Higgs related to gluon, b quark

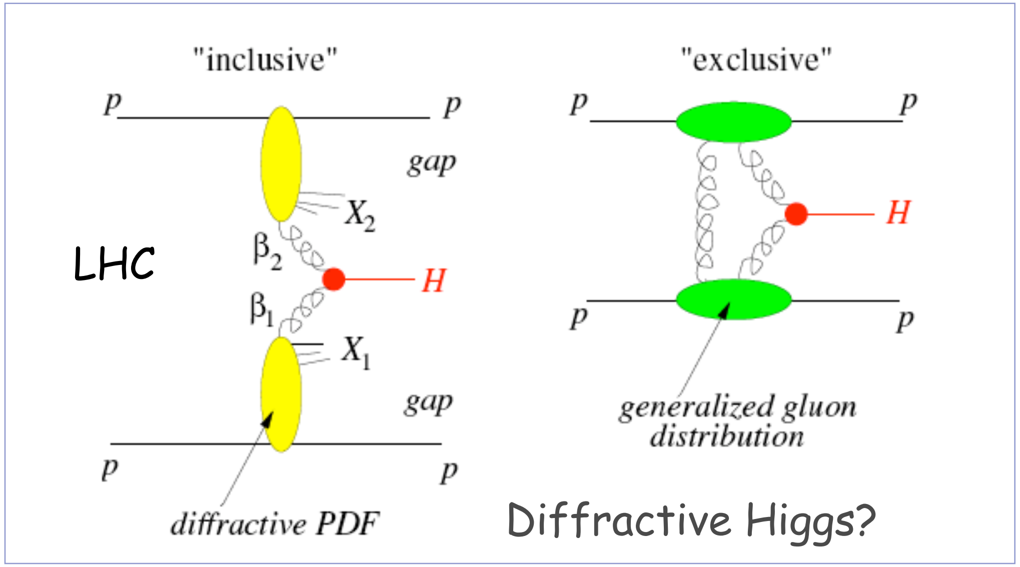


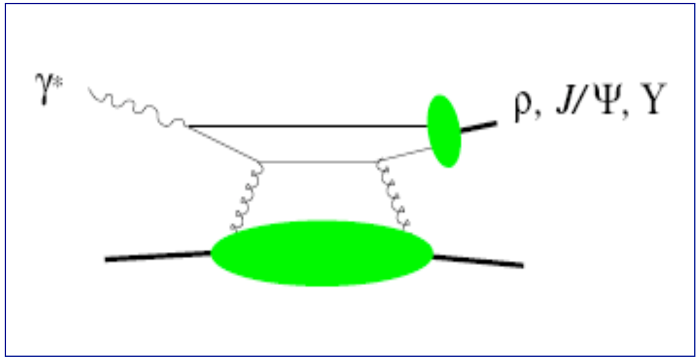


Low x Physics - Forward at the LHC - rich of unknowns and new developments

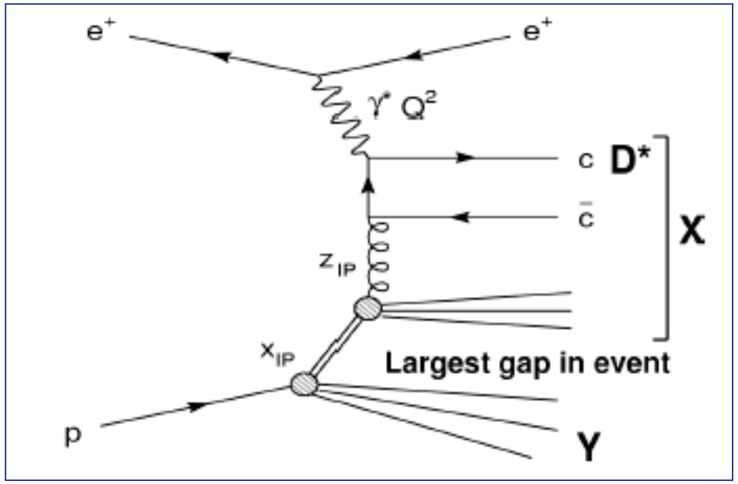


Parton radiation dynamics





Generalised Parton Distributions



Diffractive Factorisation? dpdf's?

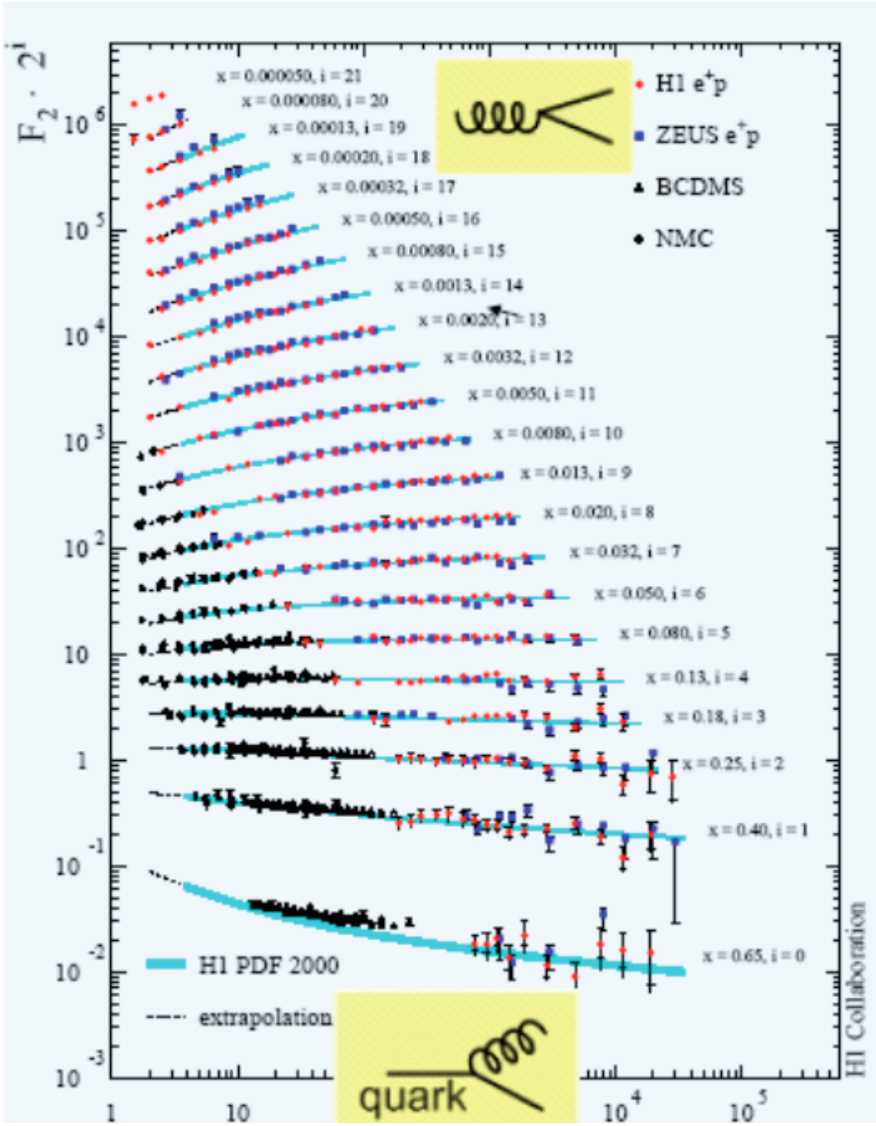
Results

HERA and LHC
Inclusive Scattering and pdf's
Final State Physics (c,b,jets)
Diffractive DIS
Electroweak Physics and Searches
LHeC

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)xg(x,Q^2)$$

resolve correlation of coupling and gluon by accessing wide range of x and Q2

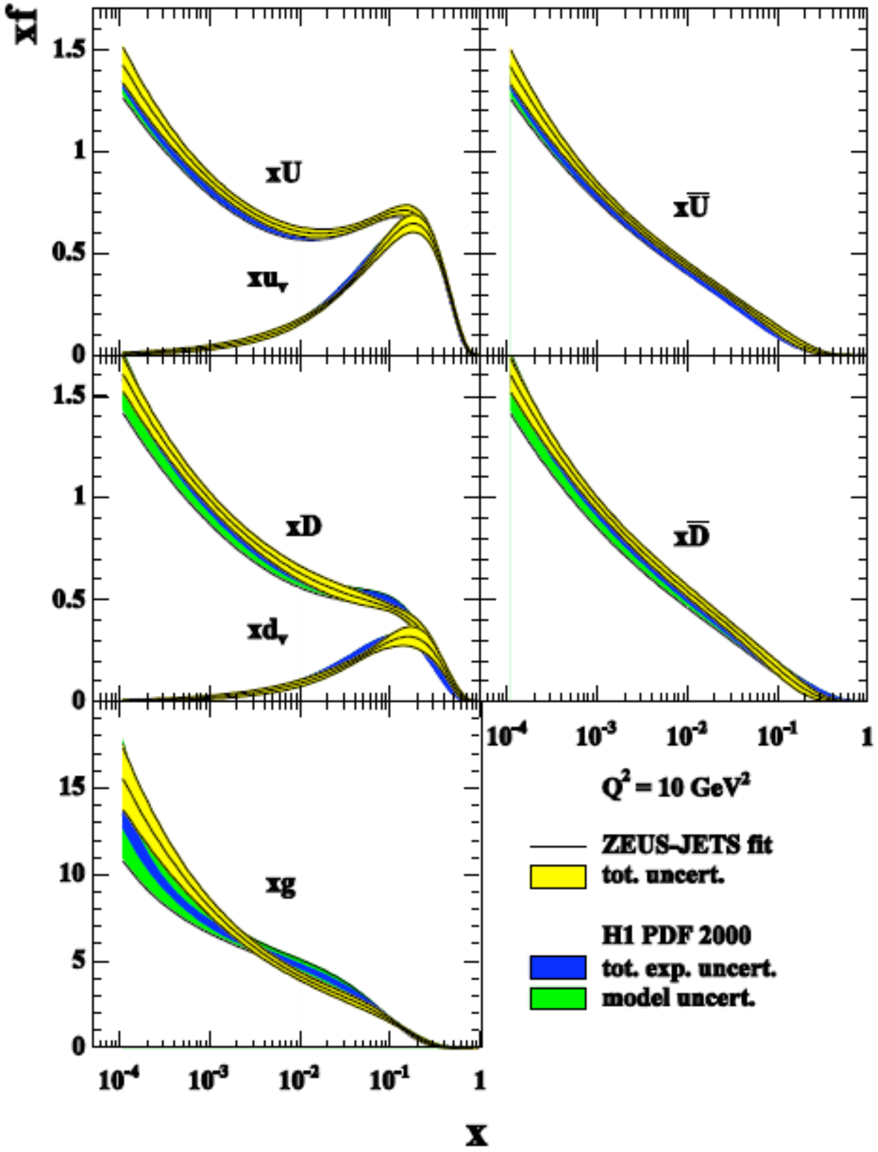
$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)q(x,Q^2)$$

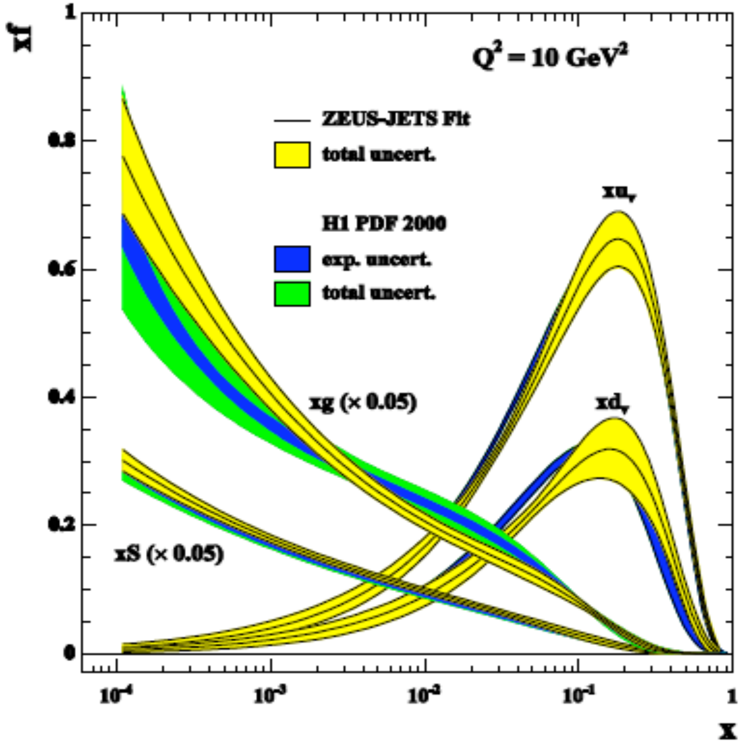


Q^2 /GeV^2

New data and analyses space ongoing! Calibration, lumi, detectors, H1/ZEUS, NNLO

Status of NLO pdf's from HERA





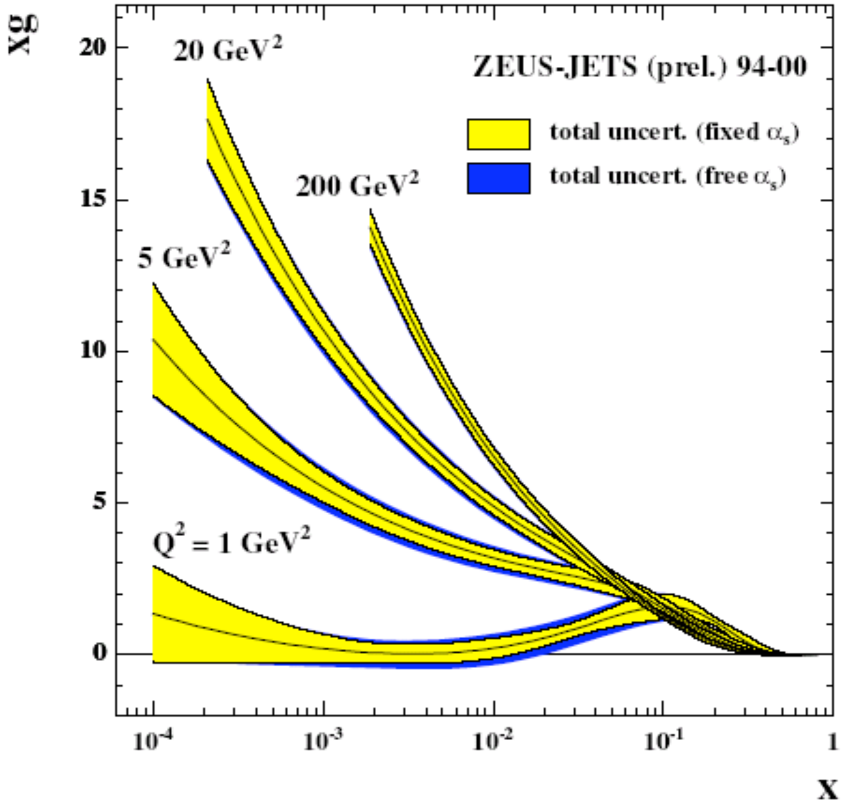
exp uncertainties of H1 pdfs based on HERA I data using Lagrange method for fit:

x	0.01	0.4	0.65
xU	1%	3%	7%
xD	2%	10%	30%

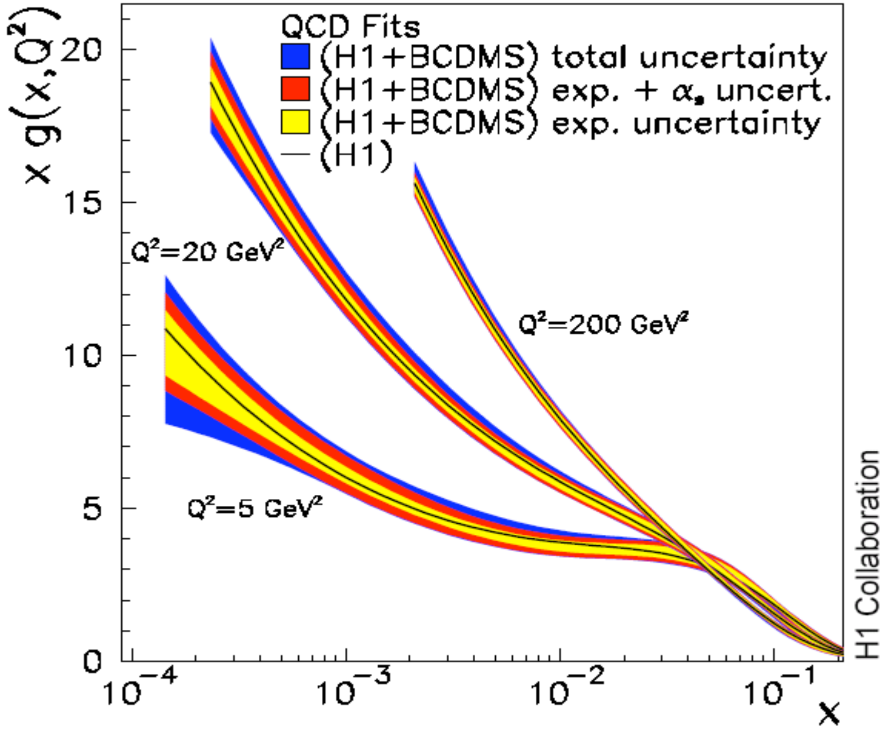
Some improvements with polarised data

The Gluon Distribution from HERA

ZEUS inclusive NC+CC & jets



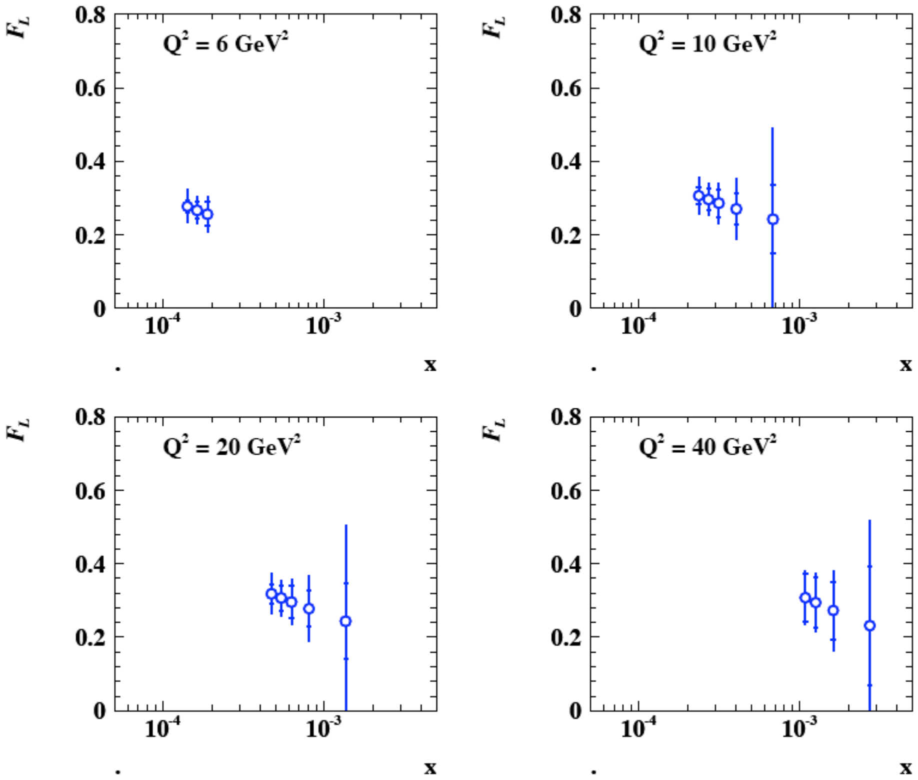
H1 inclusive NC+CC



$xg \leftrightarrow \alpha_s$

- **xg is NOT an observable. Low x theory requires nontrivial constraint: FL**
- at large x > 0.1, the gluon distribution is not well known.
- further improvement from higher precision, jets, charm and from long. structure fct.

F_L - simulation (H1) for two energies



H1 EoI subm.
to PRC
10/2005
H1-10/05-622

ZEUS LoI
subm March06

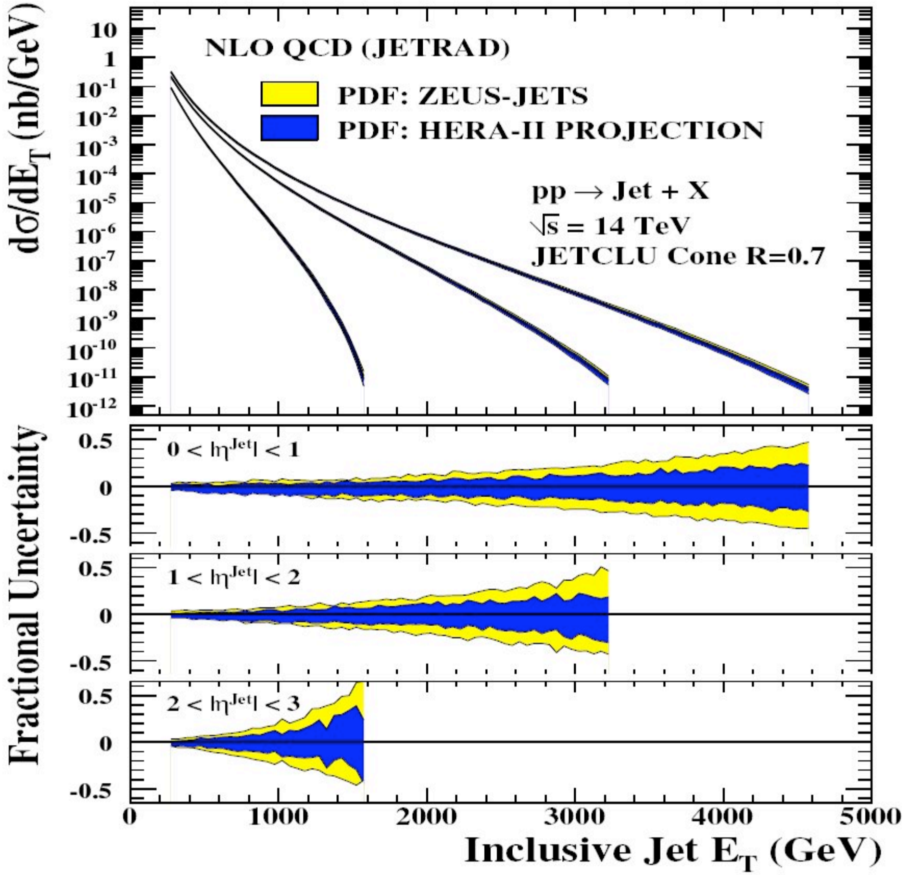
920 GeV
30 pb^{-1}

460 GeV
10 pb^{-1}

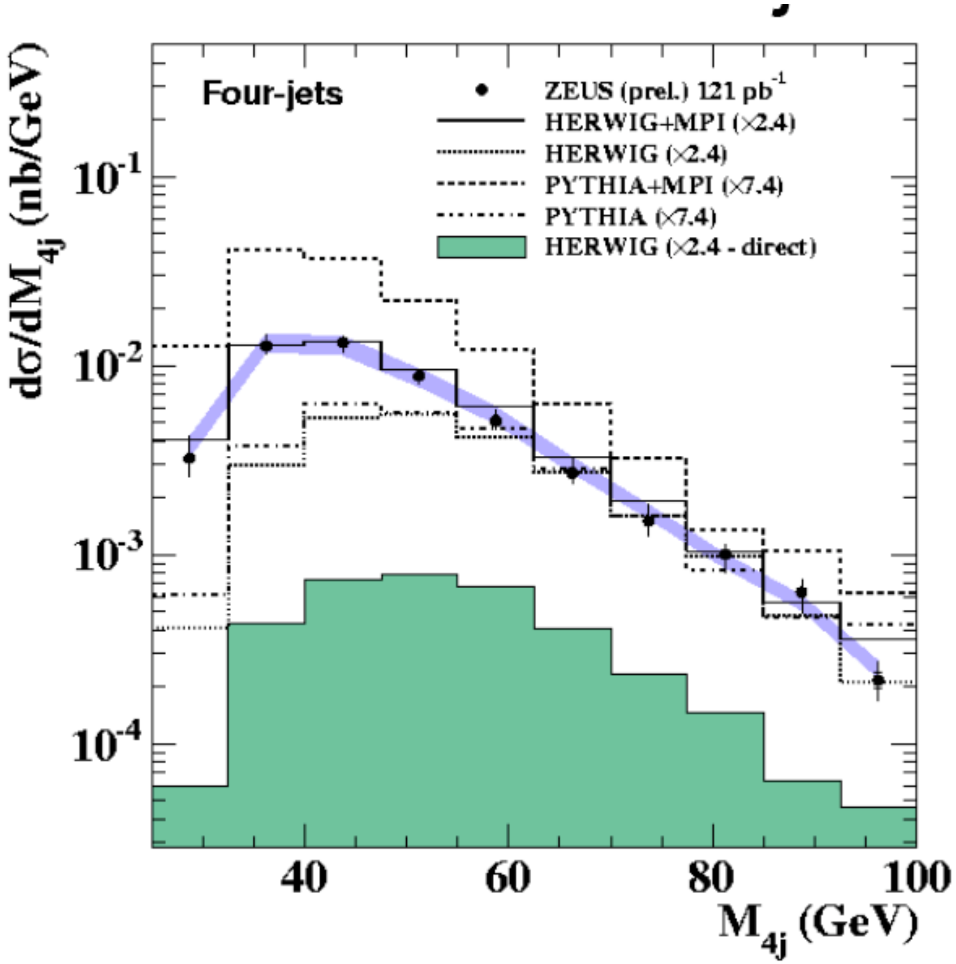
$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \cdot \left[\frac{16}{3} F_2 + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) z g \right]$$

Error between 0.05 and 0.1, statistical and systematics about matched,
At high y efficiency and yp background sources of uncertainty similar.
Prepare run of HERA for ZEUS and H1 at lowered Ep to measure FL, FLD.

Jets at HERA



Role of di-jets being studied in the determination of pdf's

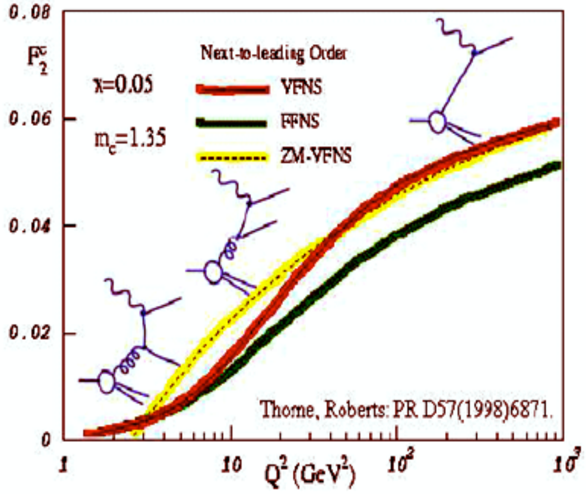


Role of multi-jets (+MI) being studied in the understanding of the final state.

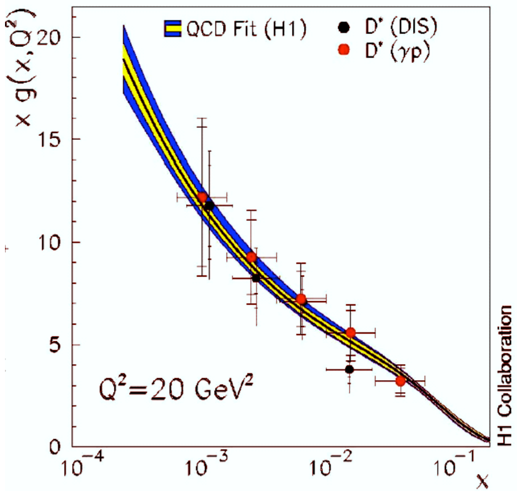
Investigation of multijets and fwd jets: non kt ordered emission at low x --> Low x parton dynamics vital for LHC.

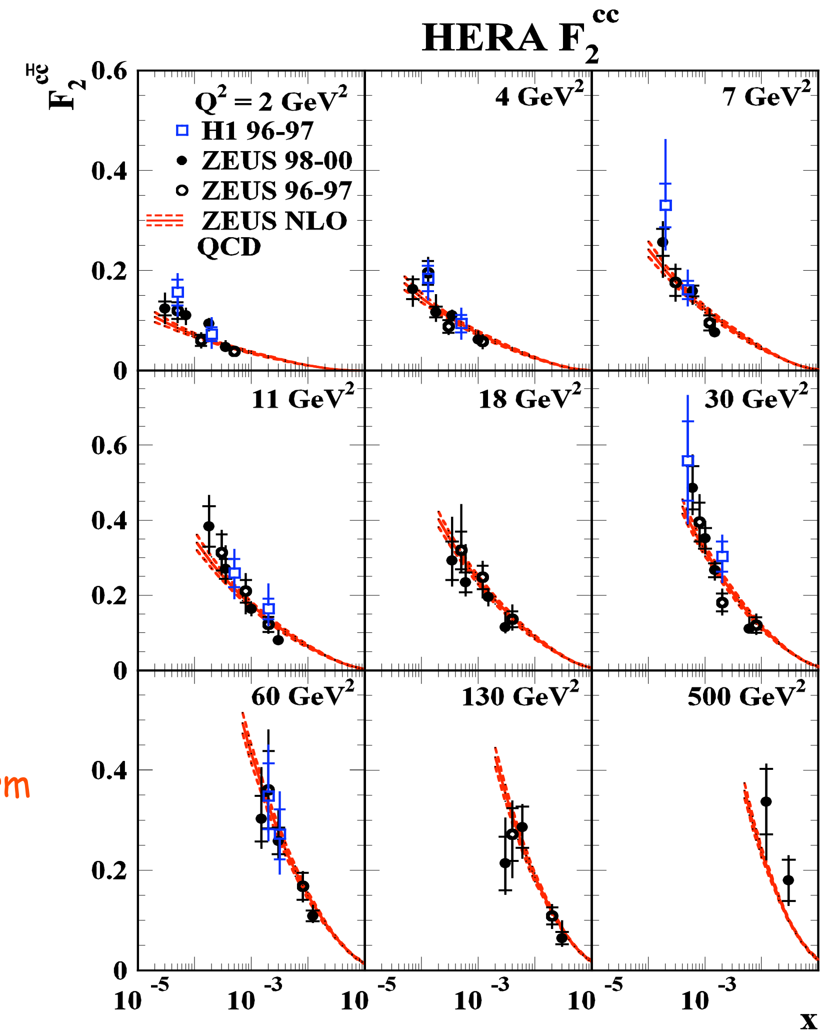
cf ICHEP06

theory of heavy flavour production



independent determination of xg from charm

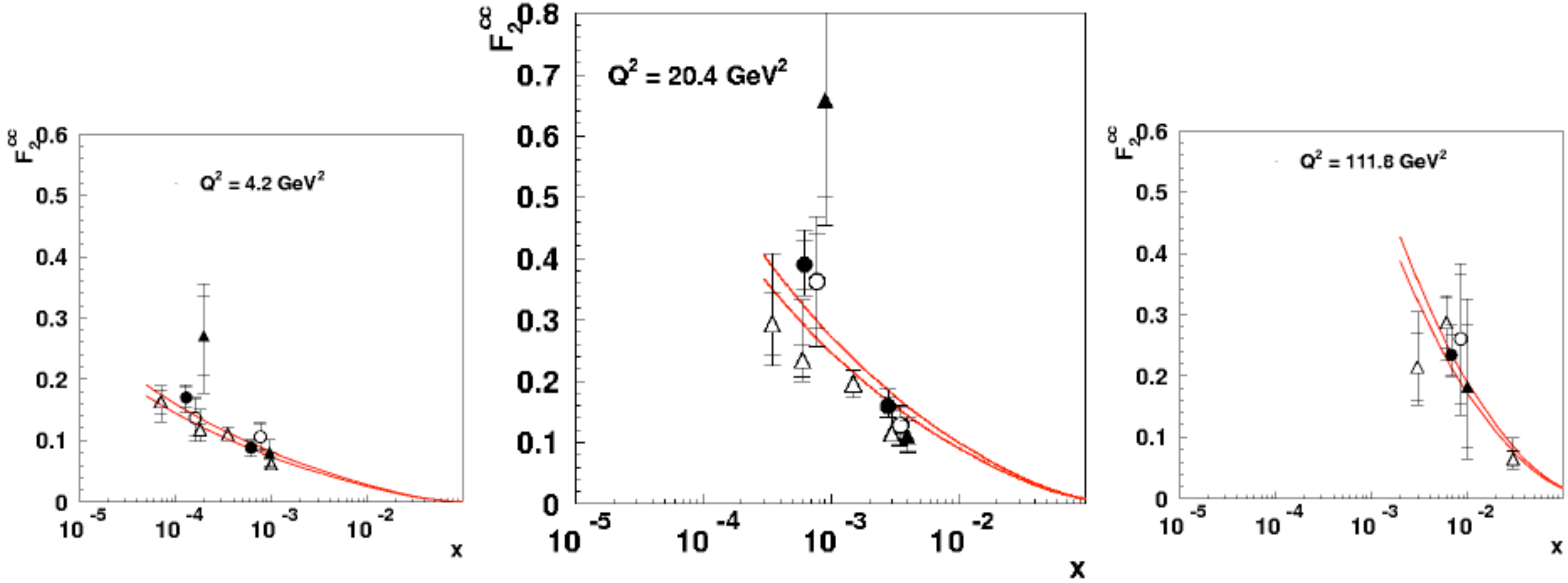




HERA II

- high statistics through luminosity upgrade
- and upgraded silicon detectors, more channels

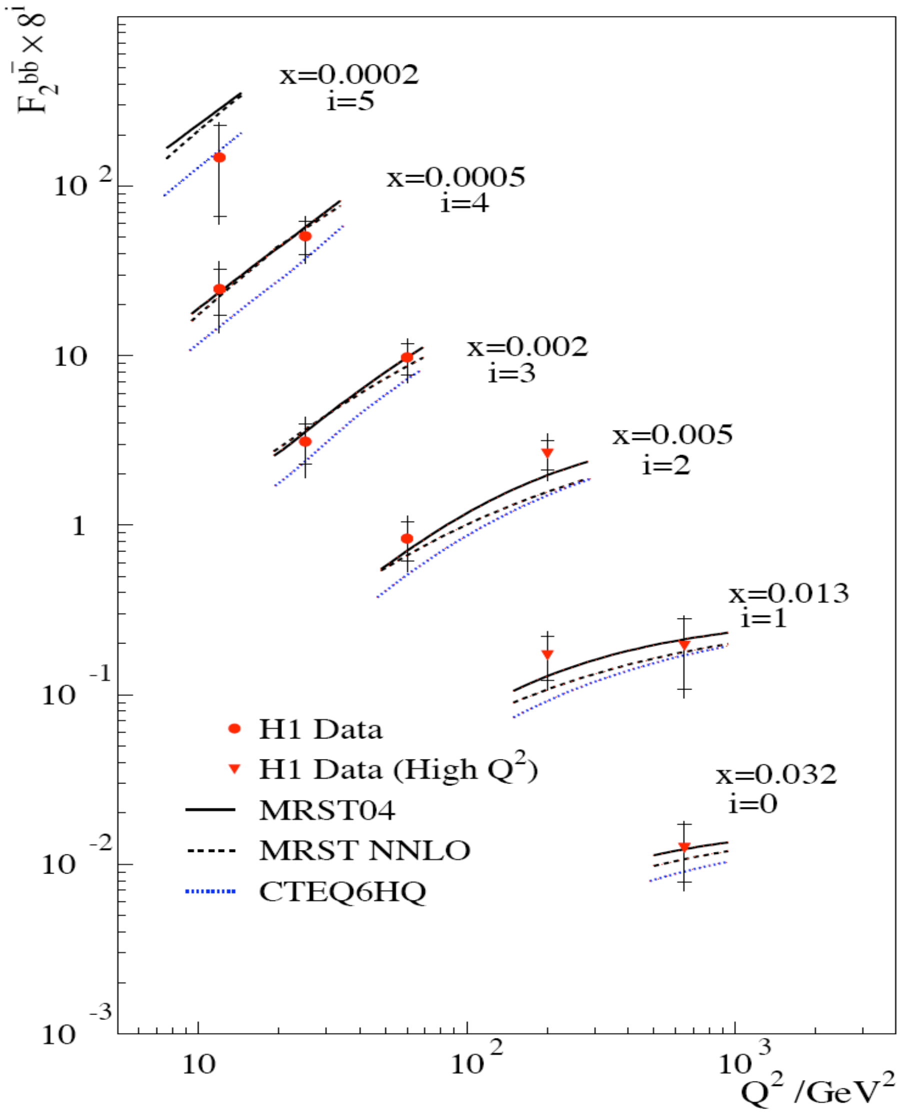
F_2^c from D^0, D_s, D^+



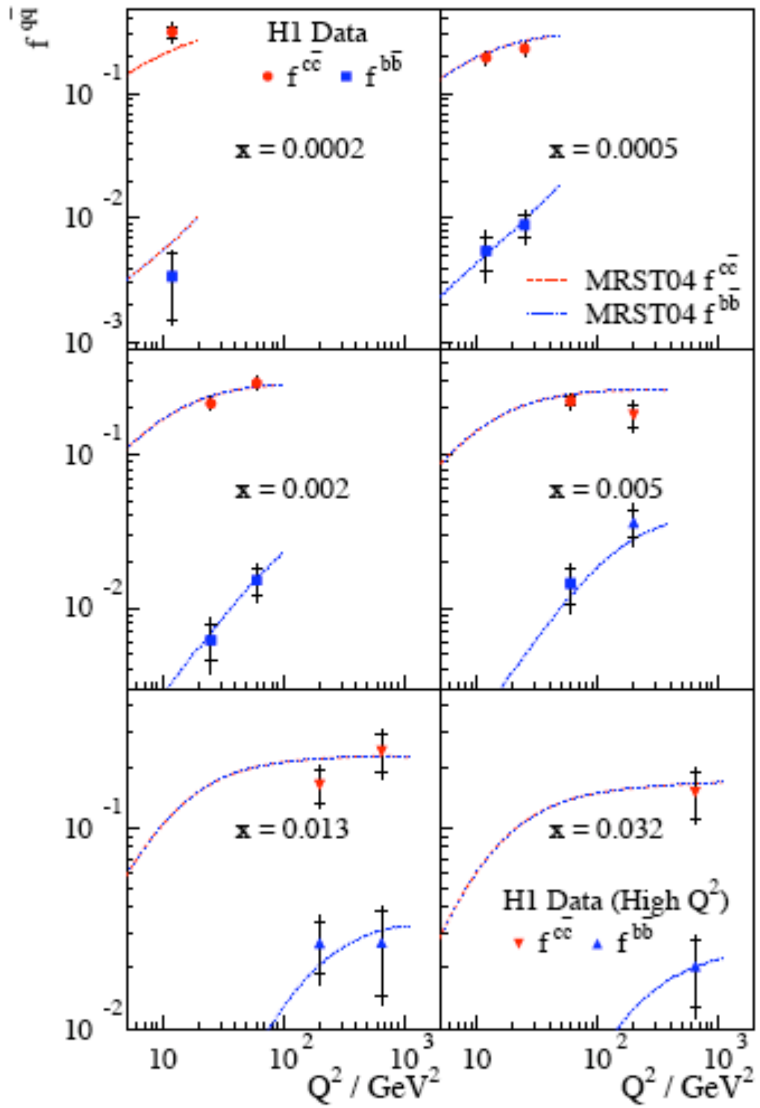
- ● ZEUS (prel.) 98-00 D^0
- ▲ ZEUS (prel.) 98-00 D_s
- ○ ZEUS (prel.) 99-00 D^+
- △ ZEUS 98-00 D^*
- — NLO QCD

- Good agreement with F_2^c from D^*.
- High statistics in direct D^0 channel.

Beauty Quark Density

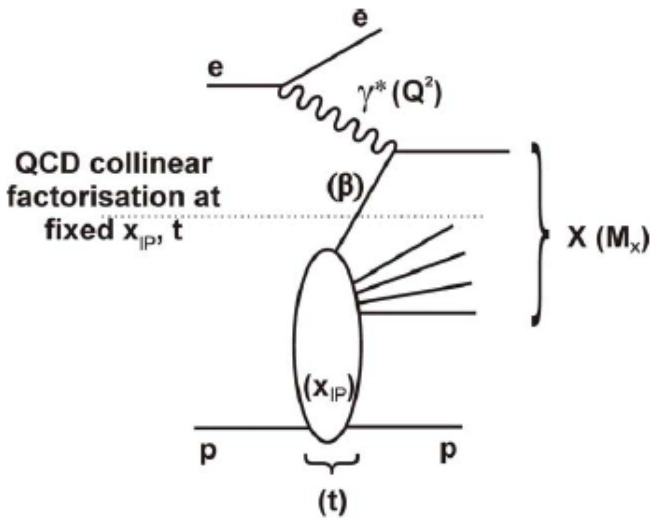


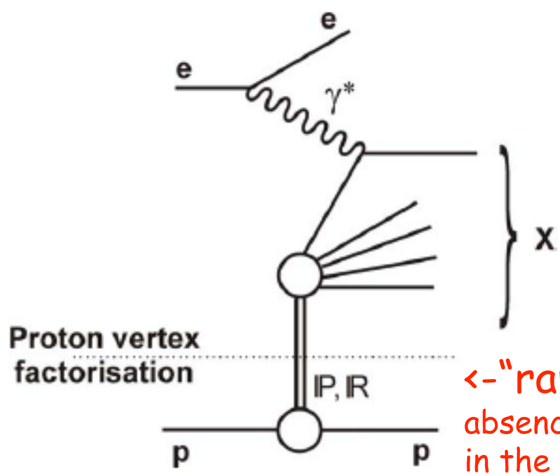
fractions of c and b



Deep Inelastic Diffractive ep Scattering

Huge amount of data obtained by the HERA collider experiments





<-“rapidity gap”
absence of fwd activity
in the main detector for
about 10% of DIS events

Diffractive, universal?
conditional q,g densities

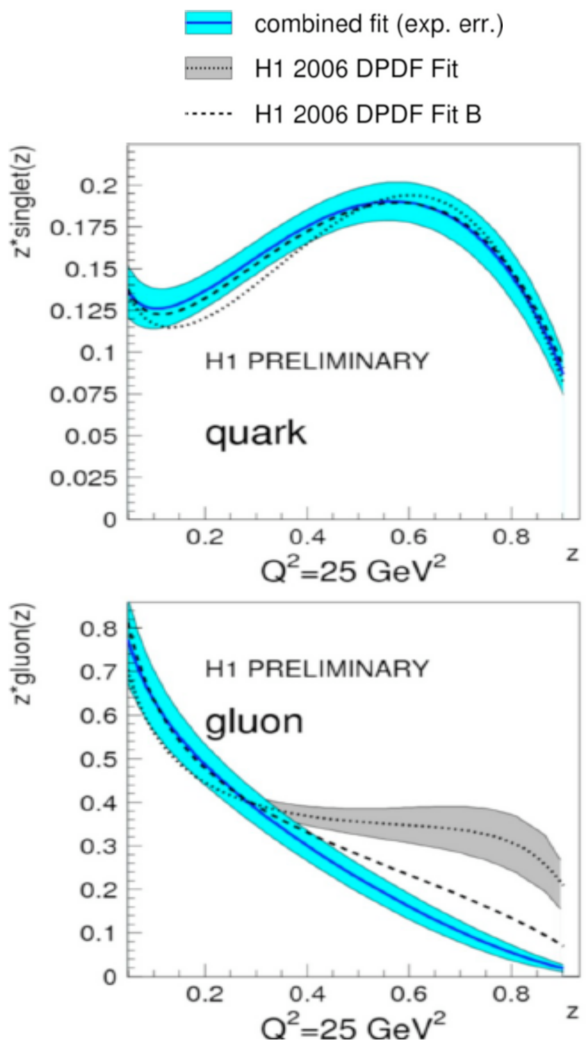
$$f_i^D(x, Q^2, x_{I\!P}, t) = f_{I\!P/p}(x_{I\!P}, t) \cdot f_i^{I\!P}(\beta = x / x_{I\!P}, Q^2)$$

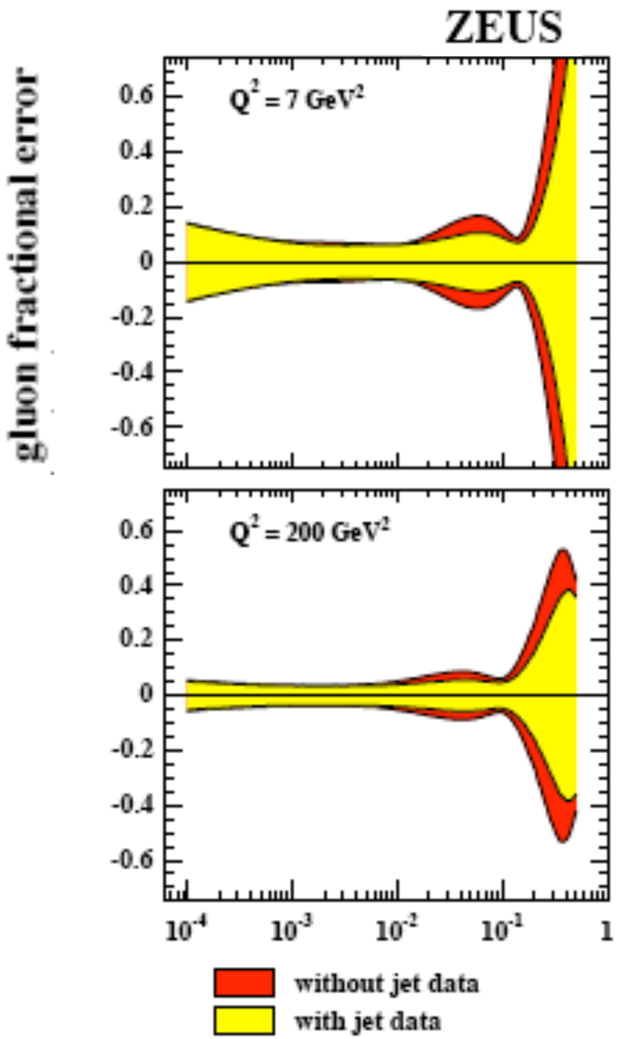
QCD

phenomenology

Tagged and rapidity gap data to check

Diffraction resembles inclusive DIS: jets improve gluon determination at large x

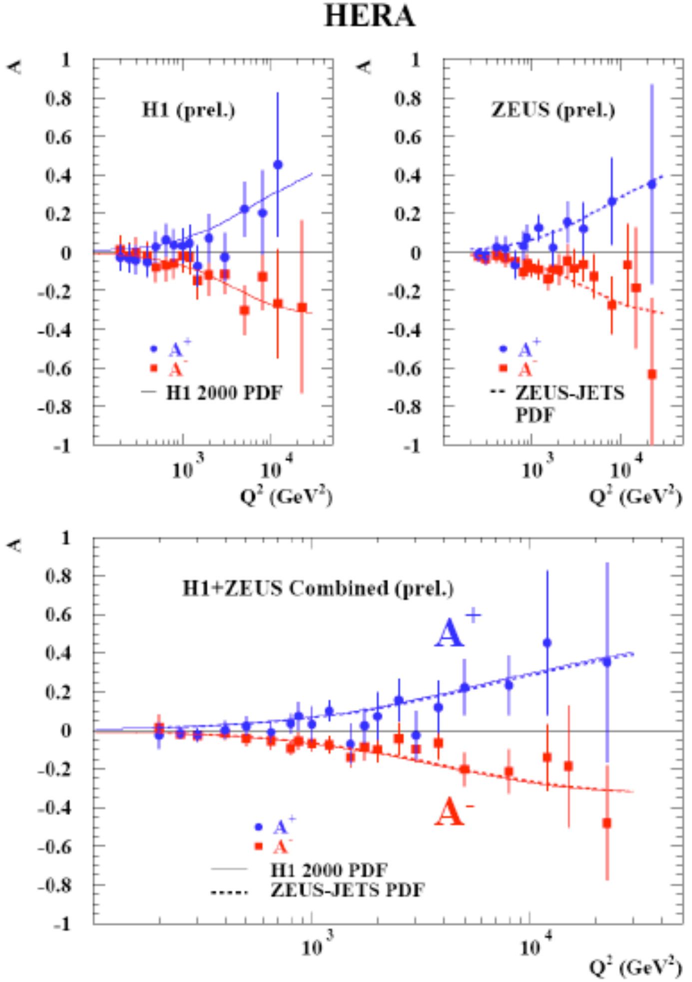




Diffractive gluon is lower
at large x than first thought
QCD factorisation in dDIS holds

Dijet data reduce xg uncertainty (?thy)
improve much the strong coupling det.

Parity Violation - Joint H1&ZEUS Results



Polarisation asymmetry (**H1, ZEUS, H1 & ZEUS**):

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}_{NC}(P_R) - \sigma^{\pm}_{NC}(P_L)}{\sigma^{\pm}_{NC}(P_R) + \sigma^{\pm}_{NC}(P_L)} \qquad \begin{array}{l} P_R > 0 \\ P_L < 0 \end{array}$$

→ a direct measure of parity violation in NC

$$A^{\pm} \simeq \mp \frac{a_e \kappa Q^2}{Q^2 + M_Z^2} \cdot \frac{F_2^{\gamma Z}}{F_2} = \pm \frac{\kappa Q^2}{Q^2 + M_Z^2} \cdot \frac{1 + d_v / u_v}{4 + d_v / u_v}$$

$\mathbf{A}^+$ and $\mathbf{A}^-$ are of opposite sign

$\delta\mathbf{A} = \mathbf{A}^+ - \mathbf{A}^- \approx 0$ at low Q^2 and significantly >0 at high Q^2

χ^2 for $\delta\mathbf{A}$ with respect to zero ($Q^2 > 5000$ GeV²):

χ^2 /dof = 4.0

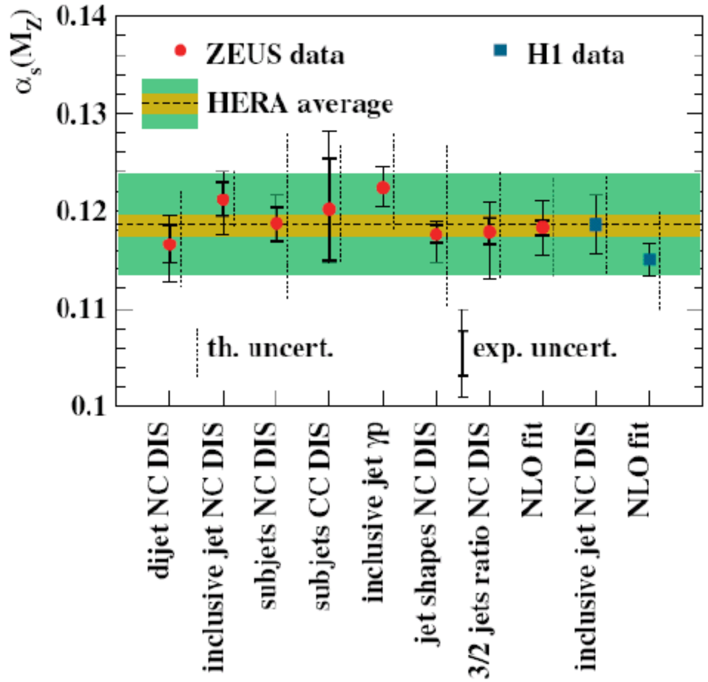
probability of $3.1\ 10^{-3}$ for $\delta\mathbf{A}$ to be zero

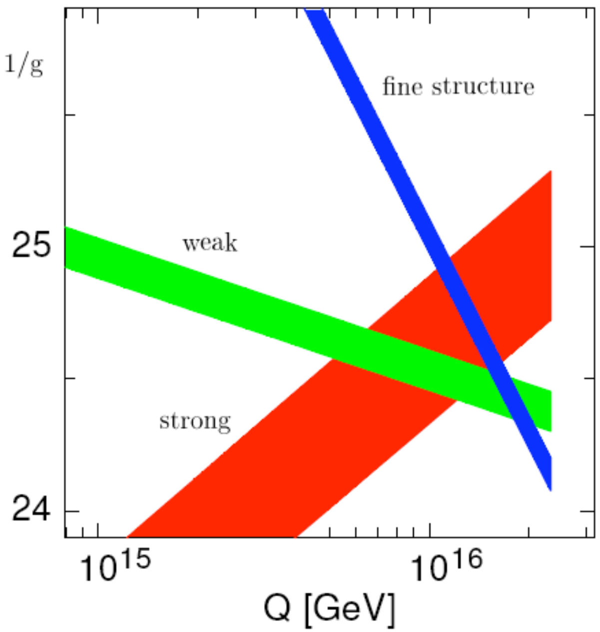
ICHEP06

Further electroweak results: light quark couplings, CC vs polarisation and propagator mass, xF_3

- 2006 α @ 10^{-9}
- 2006 G_F @ 10^{-5}
- 2006 G @ 0.02%
- 2006 α_s @ 1-2%
- LHeC ® α_s few/mil

$$HERA(prel.) - \alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\exp) \pm 0.005(thy)$$





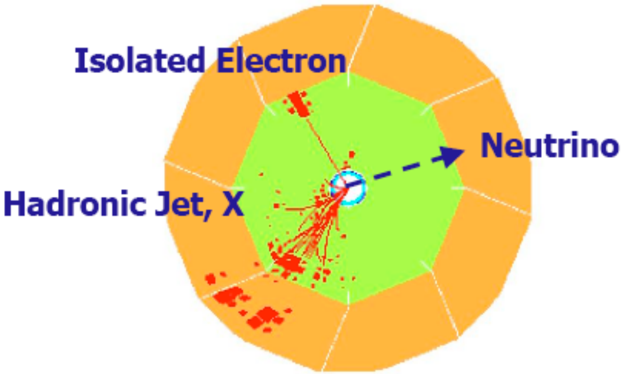
$$\alpha_s(M_Z^2) = 0.1209 \pm 0.0015(\exp) \pm^{0.0048}_{0.0049}(thy) - ZEUS$$
$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0016(\exp) \pm^{0.0058}_{0.0046}(thy) - H1$$

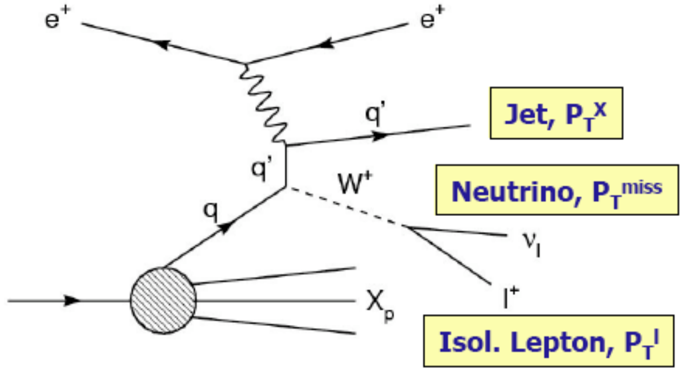
C. Glasman, hep-ex/0506035

Improved accuracy with more and more accurate data (statistics and systematics), inclusive and jets

Theory uncertainty: NNLO, $\mu/2$?

Discoveries? Isolated Leptons at HERA





$P_T^X > 25$ GeV	e channel obs. / exp. (signal)	μ channel obs. / exp. (signal)	e and μ channels obs. / exp. (signal)
H1 e^+p data 158 pb^{-1}	9 / 2.3 ± 0.4 (80%)	6 / 2.3 ± 0.4 (84%)	15 / 4.6 ± 0.8 (82%)
H1 e^-p data 121 pb^{-1}	2 / 2.4 ± 0.5 (62%)	0 / 2.0 ± 0.3 (76%)	2 / 4.4 ± 0.7 (68%)
H1 $e^\pm p$ data 279 pb^{-1}	11 / 4.7 ± 0.9 (69%)	6 / 4.3 ± 0.7 (78%)	17 / 9.0 ± 1.5 (73%)

[status of DIS06 - April 06]

98-05 e^-p (143 pb^{-1})	$3/2.86 \pm 0.46(53\%)$
99-04 e^+p (106 pb^{-1})	$1/1.50^{+0.12}_{-0.13}(78\%)$
98-05 $e^\pm p$ (249 pb^{-1})	$4/4.4 \pm 0.5(61\%)$

Expect to ~ double statistics by end of HERA running.

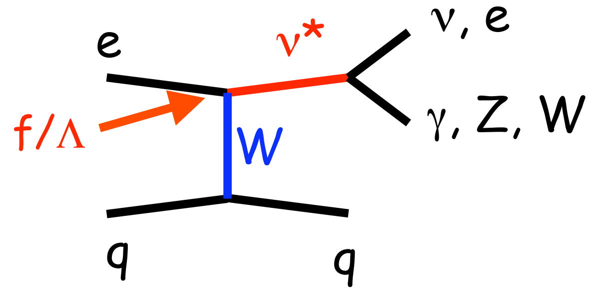
ZEUS full data on isolated electrons presented here.

Note HERA search results on SUSY, LQs,..

Jets in high Q^2 NC DIS: constraints on ν^*

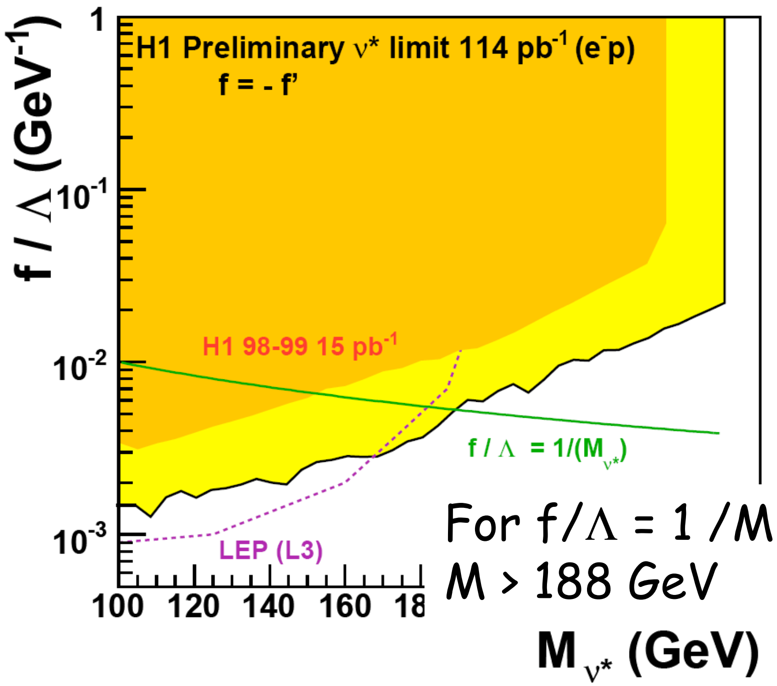
- Excited fermions: signature of a new scale of matter
- Can be singly produced in DIS
- Excited neutrinos would be produced much more copiously in $e^- p$ than in $e^+ p$

→ Analysis of 2005 e^- data (114 pb^{-1})



All decays analysed (with W/Z → jets)
For large $M(\nu^*)$: $\nu^* \to eW$ dominates

decay	$\nu\gamma$	νZ	eW
SM background	Radiative CC	CC multijets	NC multijets

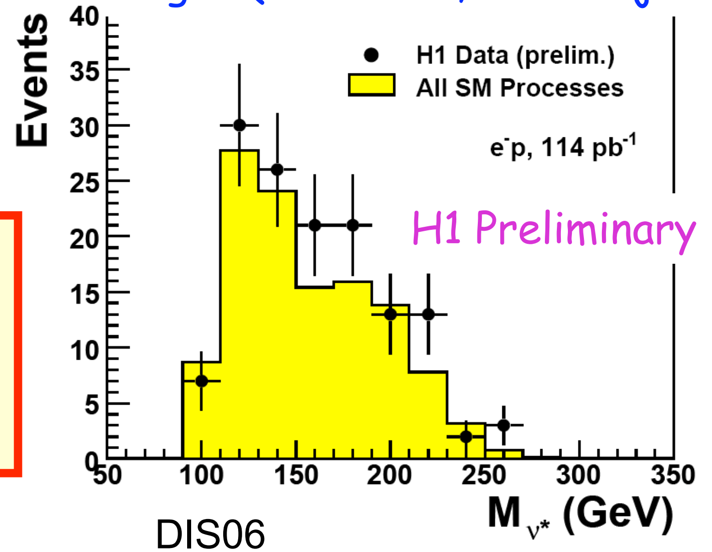


For f/Λ = 1 /M
M > 188 GeV

No resonance in any of the 3 channels

Most stringent constraints so far

High Q^2 NC DIS, several jets



DIS06

Future ep

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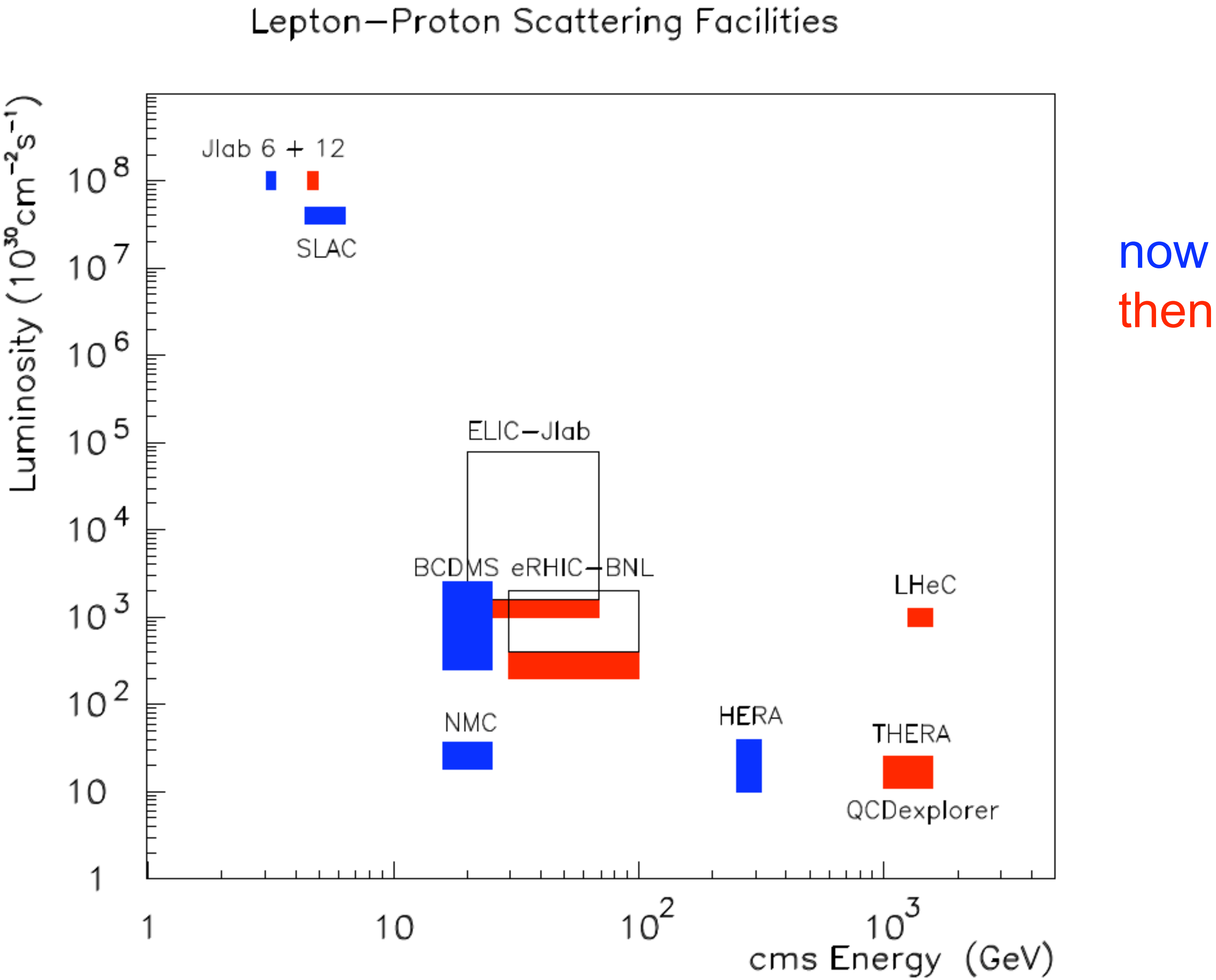
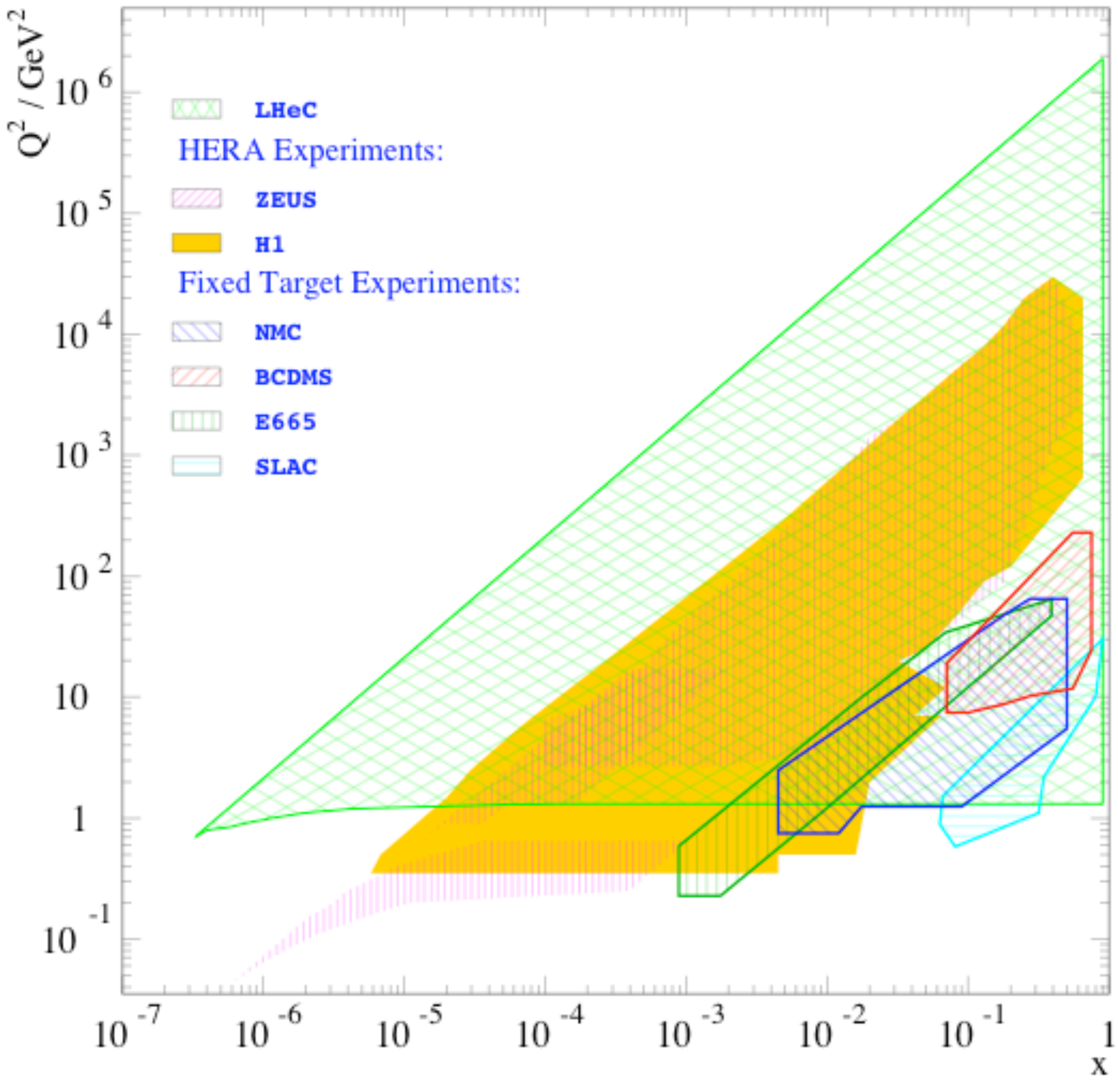


Lepton−Proton Scattering Facilities
Luminosity ($10^{30}cm^{-2}s^{-1}$)
cms Energy (GeV)
Jlab 6 + 12
SLAC
ELIC−Jlab
BCDMS
eRHIC−BNL
LHeC
NMC
HERA
THERA
QCDexplorer
now
then

Kinematics of the Large Hadron Electron Collider



$s = 4E_eE_p$

$LHeC: 70 \cdot 7000 \rightarrow 2 \cdot 10^6 GeV^2$

$HERA: 27.6 \cdot 920 \rightarrow 10^5 GeV^2$

$s = 2M_pE_l$

$BCDMS: 280 \rightarrow 500 GeV^2$

$SLAC: 20 \rightarrow 40 GeV^2$

$Q^2 = sxy$

$x = \frac{Q^2}{sy}$

$Bjorken - x \leq 1$

$inelasticity - y \leq 1$

$Q^2 \leq s$

hep-ex/0306016 → JINST

DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

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Abstract

The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and high energy, $\sqrt{s} = 1.4$ TeV, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (ep, eD and eA) scattering for momentum transfers Q^2 beyond $10^6\,\mathrm{GeV}^2$ and for Bjorken x down to the 10^{-6}. New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The precision possible with an electron-hadron experiment brings in addition crucial accuracy in the determination of hadron structure, as described in Quantum Chromodynamics, and of parton dynamics at the TeV energy scale. The LHeC thus complements the proton-proton and ion programmes, adds substantial new discovery potential to them, and is important for a full understanding of physics in the LHC energy range.

*Contributed to the Open Symposium on European Strategy for Particle Physics Research, LAL Orsay, France, January 30th to February 1st, 2006.

ep collider in the LHC tunnel

70 * 7000 GeV^2

further studies at forthcoming workshop

cost estimate and design study ready by about 2010

an attractive option for upgrading the LHC

physics

Search for and spectroscopy of new particles (eq states), new strong i.a. at TeV scale?

Exploration of high density QCD

High precision ep in LHC range

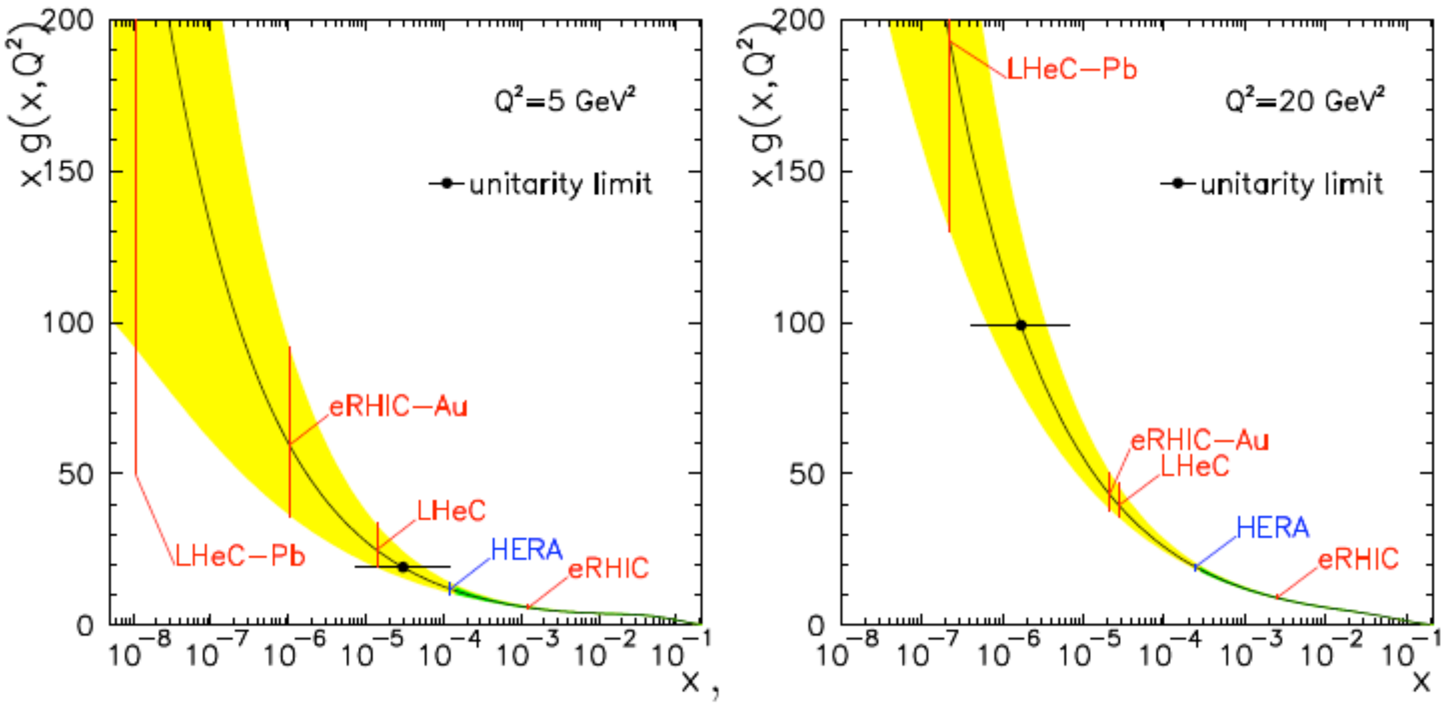
LHeC parameters

Table 3: *Main Parameters of the Lepton-Proton Collider*

Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	7.6	0.501
Vertical Beam Emittance	nm	3.8	0.501
Horizontal β-functions at IP	cm	12.7	180
Vertical β-function at the IP	cm	7.1	50
Energy loss per turn	GeV	0.707	$6 \cdot 10^{-6}$
Radiated Energy	MW	50	0.003
Bunch frequency / bunch spacing	MHz / ns	40 / 25	
Center of Mass Energy	GeV	1400	
Luminosity	$1.1 \cdot 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.04	

Compare with HERA: maximum reached was 0.05 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Estimated luminosities of linac-ring ep colliders below HERA

High density states



High density $\frac{g_A/\pi r_A^2}{g_p/\pi r_p^2} = A^{1/3}\frac{g_A}{Ag_p}$

Unitarity $xg(x,Q^2) \leq \frac{1}{\pi N_c \alpha_s(Q^2)} Q^2 R^2 \simeq \frac{Q^2}{\alpha_s}$

Striking effects predicted:
bj -> black disc limit $F_2 \to Q^2 \ln(1/x)$
~50% diffraction
colour opacity, change of $J/\Psi(A)$

Understanding the possible observation of QGP in AA with eA

Some Concluding Remarks:

With increasing luminosity, time and precision, HERA delivers increasingly important results. These require a few more years of dedicated analyses (also combining H1+ZEUS):

pQCD: pdf's in NNLO, c, b density, strong coupling, gluon (F_L run to come in 2007)
this provides deep understanding of p structure and of the QCD vacuum
extrapolation of W,Z cross sections to the LHC with high (which??) precision

From low x final state measurements strong hints for non ordered emission

QCD is being much developed further, e.g. unintegrated gluon distribution to account for kinematic kt dependence, QCD of hard diffraction, variable HQ schemes, parton amplitudes (DVCS) - where are instantons, odderons?

HERA becomes electroweak machine, searches are still puzzling (isolated leptons in e+)

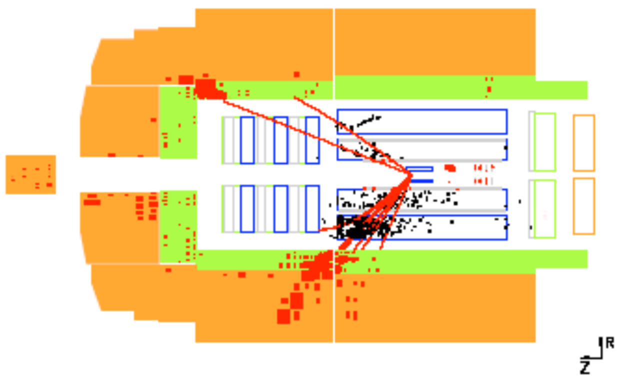
HERA closes mid07, BUT higher luminosity desirable for hix and scales, neutron structure?

DIS at Fermi scale has been much richer than thought and vital in complementing LEP and the TeVatron. It is important to investigate the possibilities to reach TeV scale with a future ep, eA collider. Highest luminosity may be achieved with a ring-ring solution (70 x 7000 GeV^2) as an upgrade to the LHC.

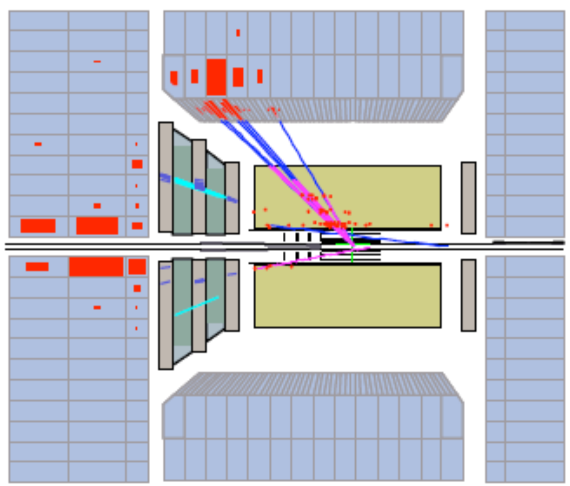
Workshops next year: HERA-LHC [CERN], DIS07[MPI], DIS@TeV[CERN]

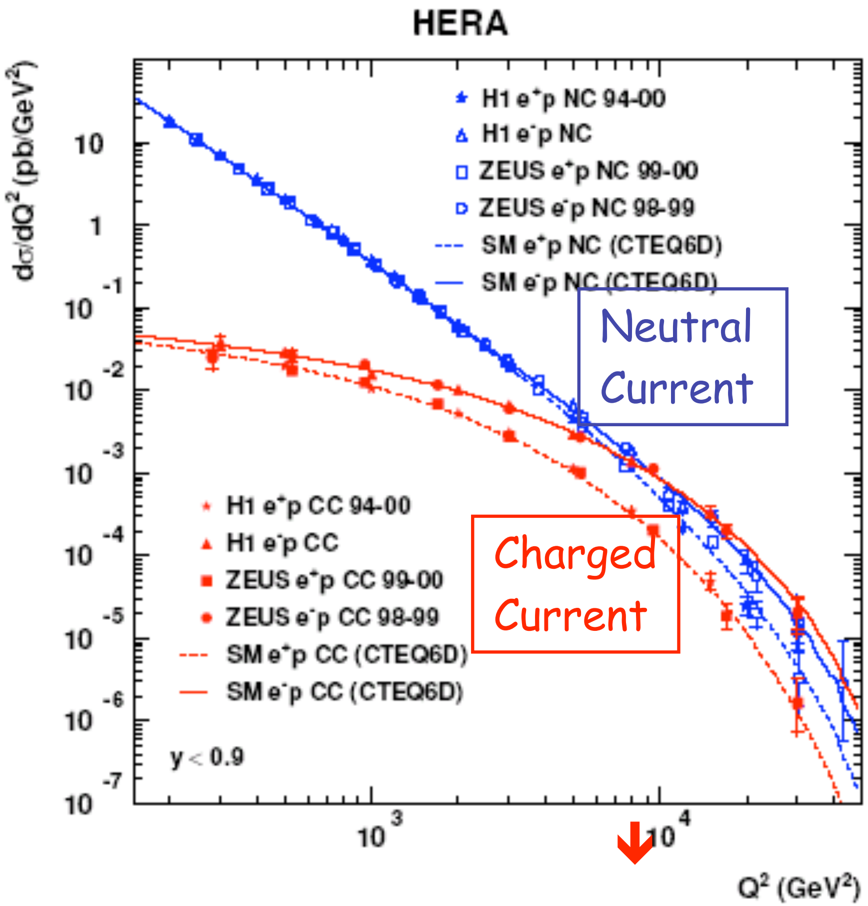
HERA was built mainly to study Rutherford backscattering and the unification of electromagnetic and weak interactions at high Q^2 but it turned out to be much richer. **Lets hope the LHC leads BSM**

Neutral current $e^+ p \rightarrow e^+ X$



Charged current $e^+ p \rightarrow \bar{\nu} X$





$$\sigma^{\pm}_{NC} \approx \sigma^{\pm}_{CC} \leftrightarrow Q^2 \approx M_Z^2 \approx 10^4\, GeV^2$$

--> the quark radius is below 1/1000 r_p $=10^{-18}$m

Thanks to the organizers

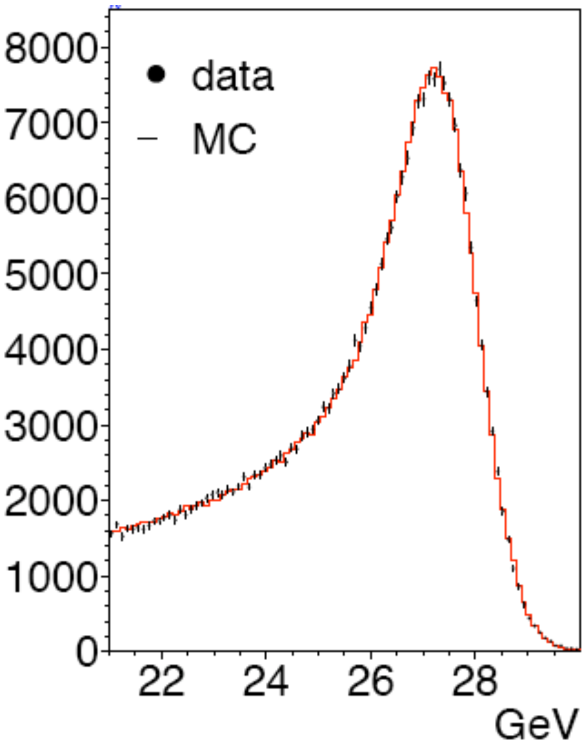
and to many colleagues
at HERA, in the experiments and theory.

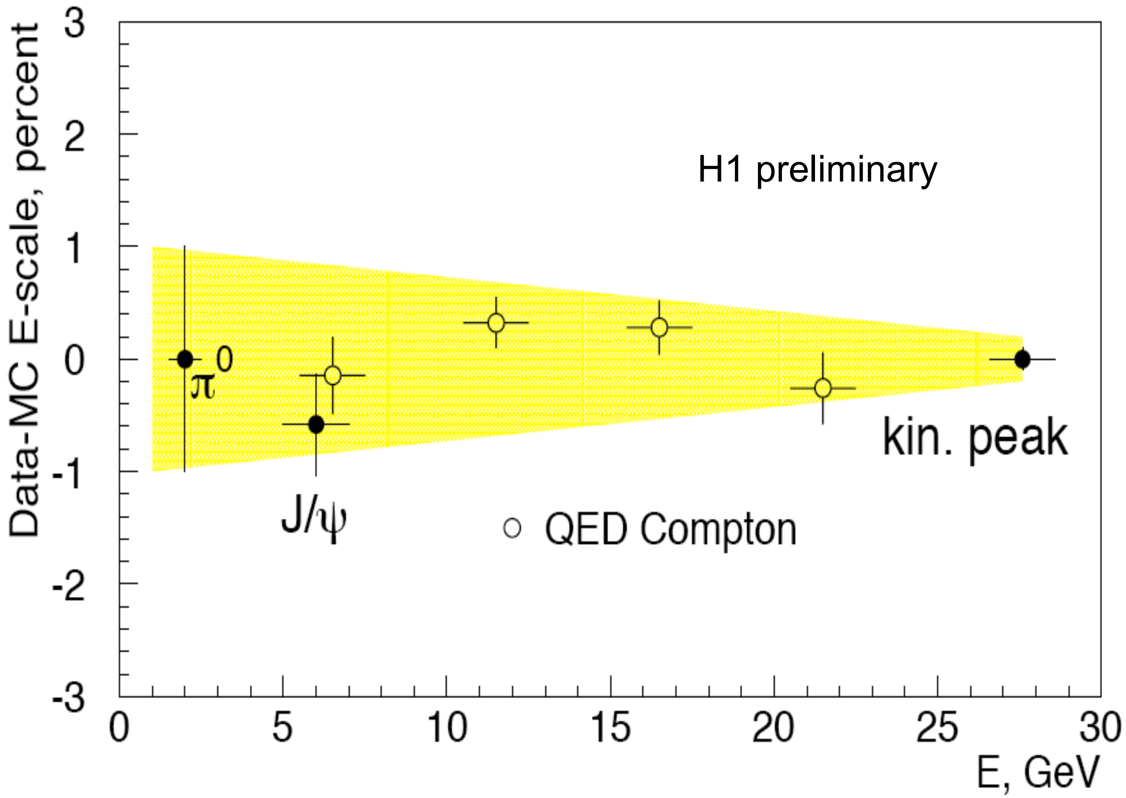
backup

Systematic uncertainties in FL measurement are most challenging

Important are
relative cross section accuracy to 1%
data/MC calibration [e.g. energy calibration in H1, see below]
control of hadronic background in electron ID (use E/p in upgraded Silicon detector BST)

HERA has to perform well, lumi reduced as E_p^{-2} -> run comes at the end of HERA





beauty density at the LHC

The bottom quark can enter, in the form of a PDF, a number of interesting processes:

Process	Interest	Accuracy	
single-top t-channel	SM, top EW couplings and polarization, V_{tb}. Anomalous couplings.	NLO	Standard processes
single-top + W		NLO	
Wbj	SM, bkg to single top	(NLO)	
gamma+b	SM, SUSY bkg, b-pdf	NLO	
Z+b		NLO	
inclusive h,A	SUSY discovery/ measurements at large tan(beta)	NNLO	Searches (discoveries?)
h,A+b		NLO	
H^+ + t	SUSY discovery, couplings	NLO	

b g --> t W (single-top + W)

A.Tonazzo Study in ATLAS. (Z+b)

F. Maltoni

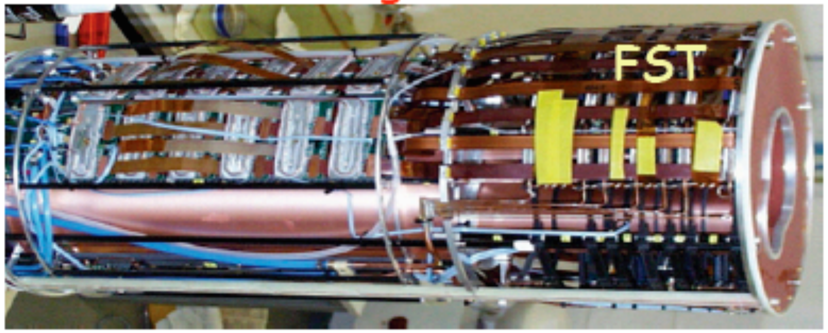
b is 5% of pp to Z

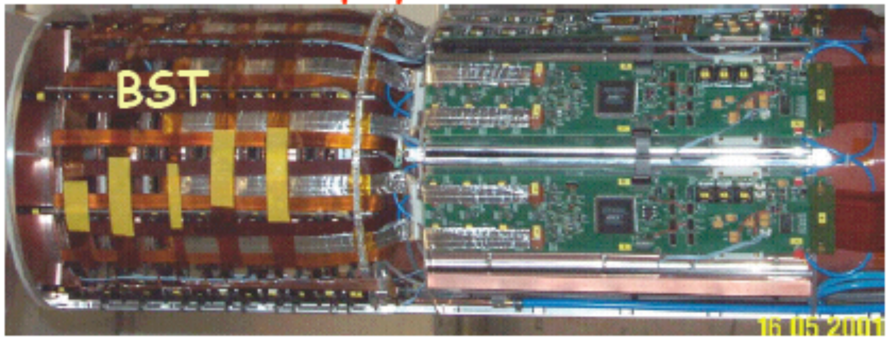
thus <20% accuracy required for 1% accurate cross section

M. Cacciari HERA LHC March 05

Note: HERA LHC Workshop ongoing

New tracking detectors of H1 and ZEUS for HF physics in HERA II



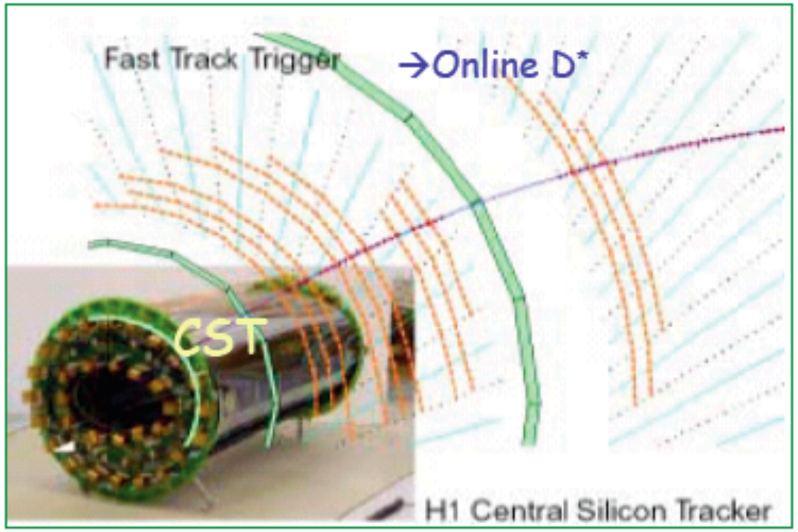


charm and beauty

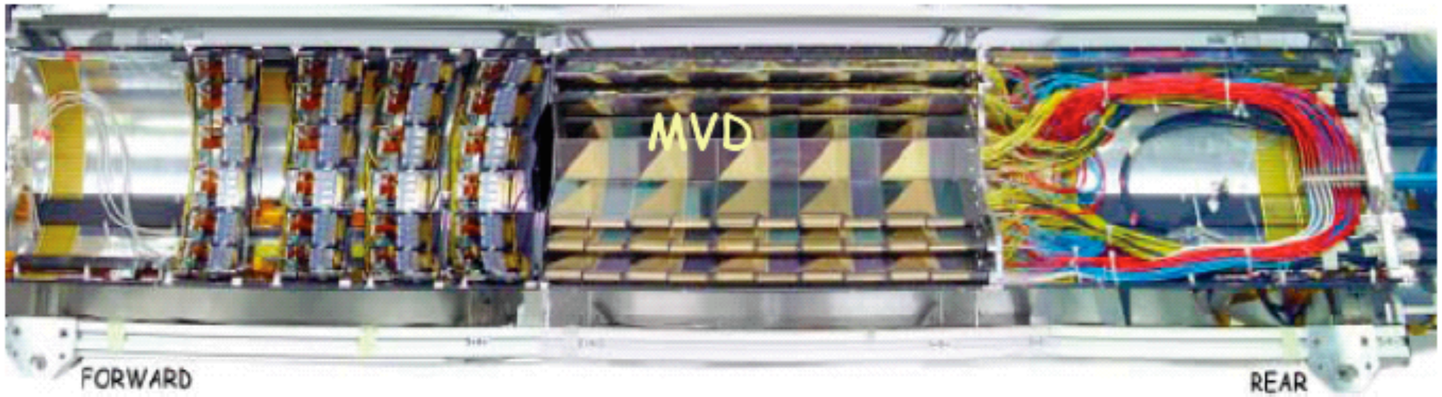
evt vtx (lo and hi y)

eID (DVCS, J/Ψ,
searches)

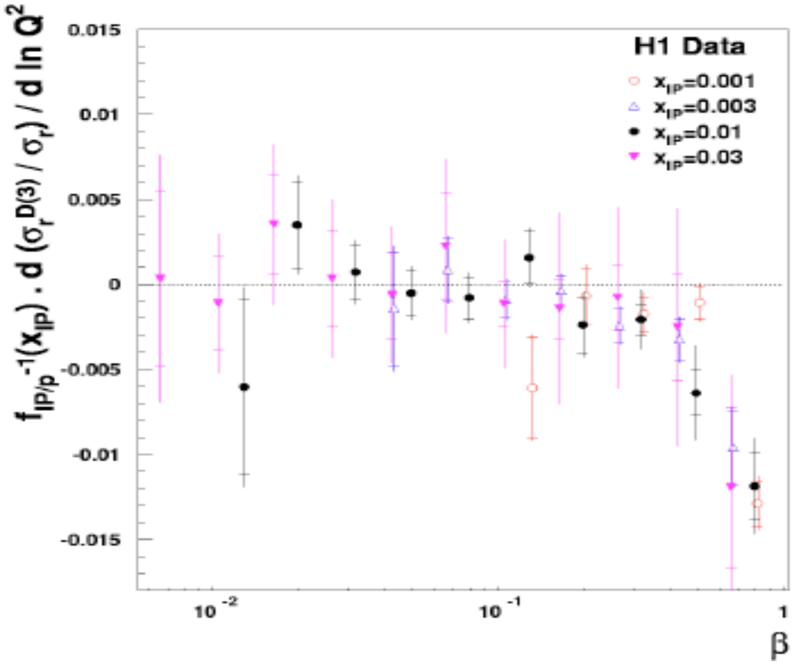
F_L

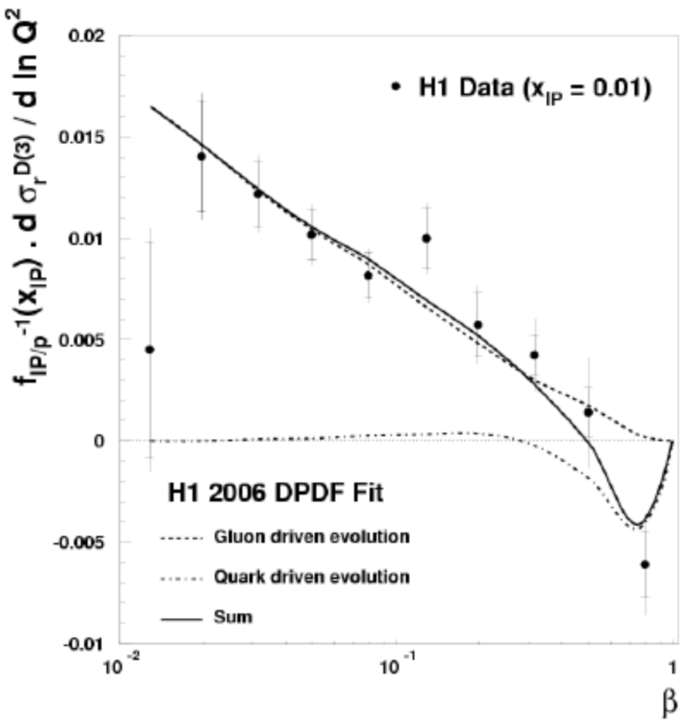


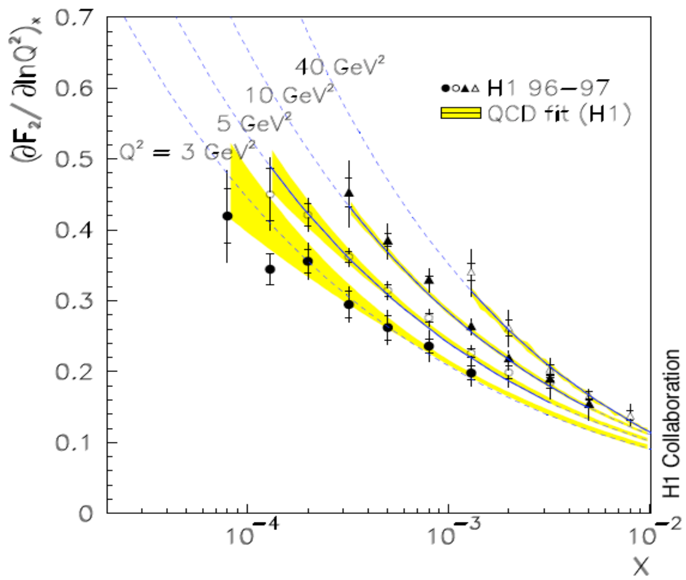
Huge investments for high lumi phase by H1 and ZEUS & fwd chambers



Diffraction resembles inclusive DIS: Gluon dominates low x dynamics







$$\text{If } \frac{d(\sigma_r^D/\sigma_r)}{d\ln Q^2} \sim 0 \text{ , then } \frac{1}{\sigma_r^D}\frac{d\sigma_r^D}{d\ln Q^2} \approx \frac{1}{\sigma_r}\frac{d\sigma_r}{d\ln Q^2}$$

3-Jets in low Q^2 DIS : QCD at low x

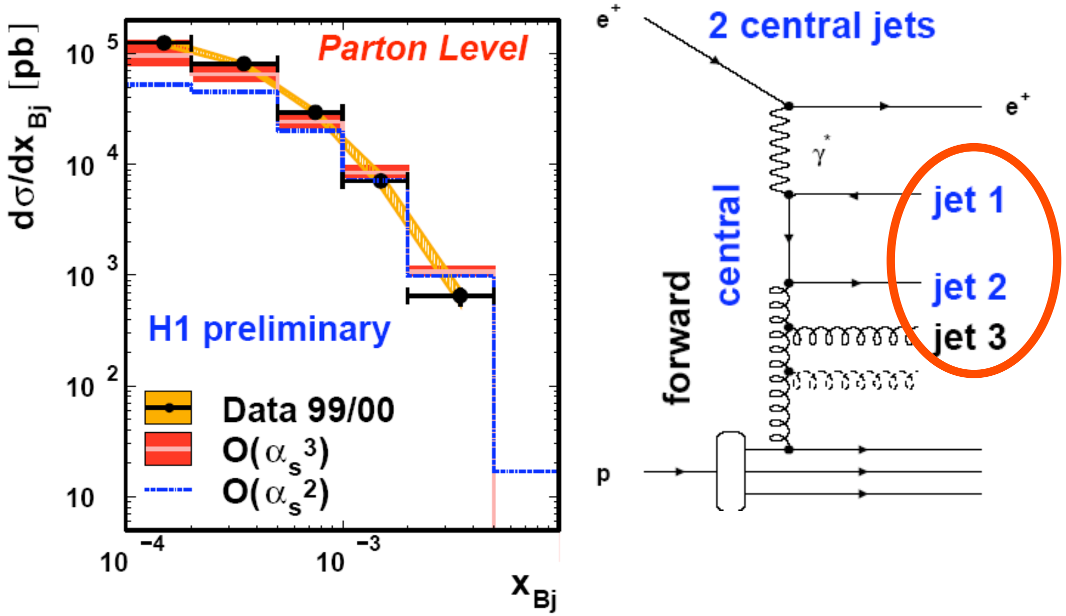
Comparison with NLO $O(\alpha_S{}^3)$):
NLO < data at lowest x, largest η

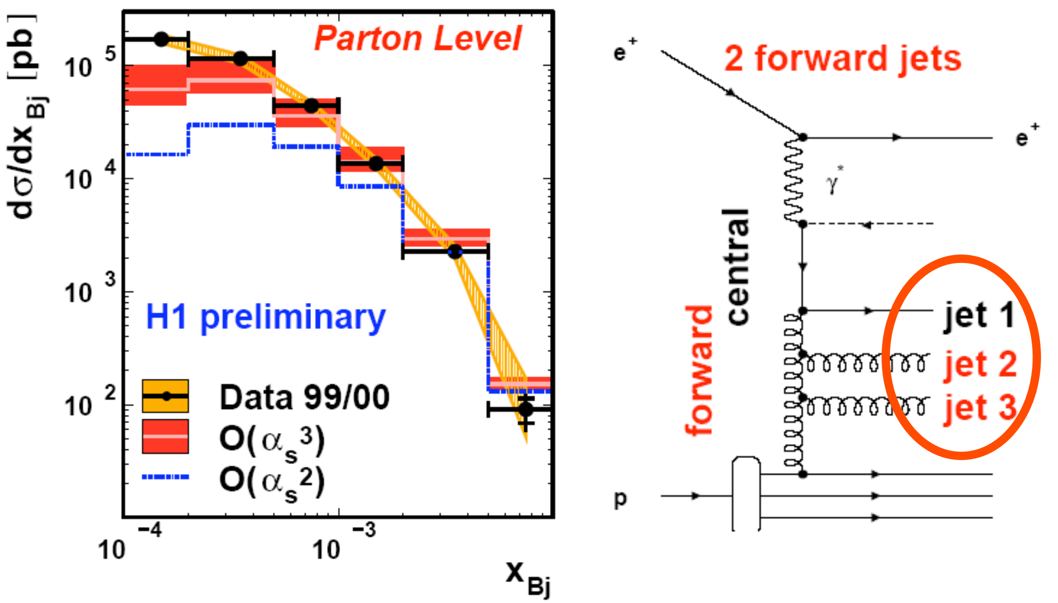
→ Look separately in 2 subsamples:
- 1 forward + 2 central jets
- 2 forward + 1 central jets

Discrepancy mainly in the "2 forward jets" sample.

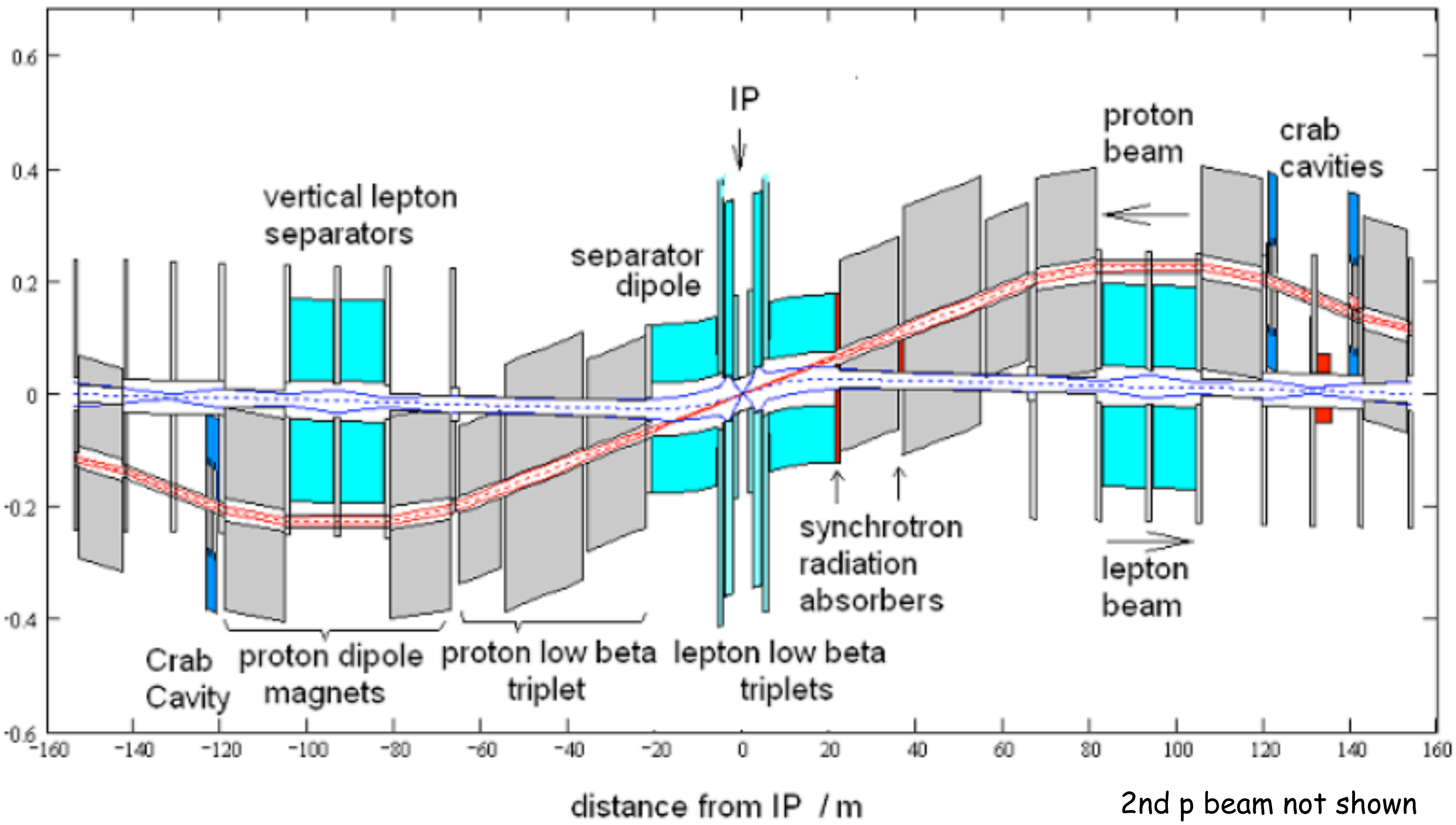
Huge improvement LO → NLO : $O(\alpha_S{}^3)$ includes the "first k_T-unordered" radiation

Strong hints that, in this region of phase space, the effect of k_T-unordered gluon radiations is important.





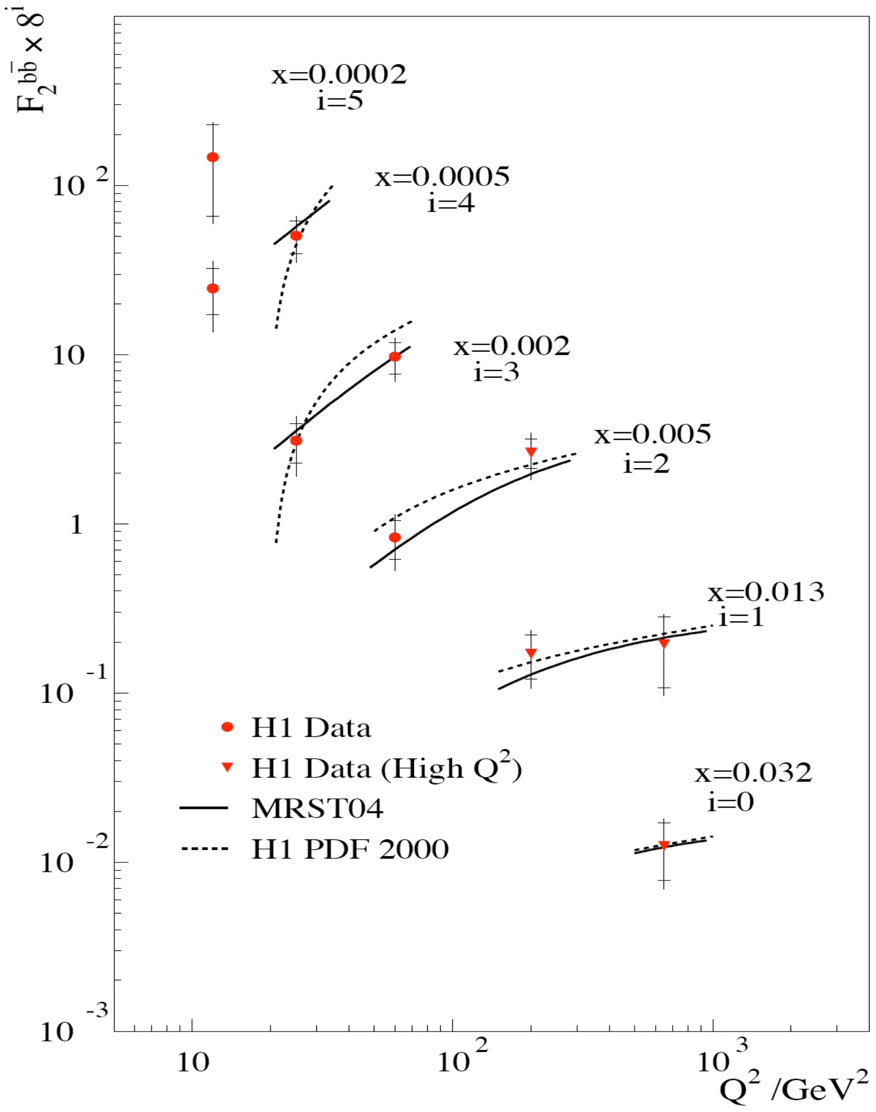
LHeC - top view of IR



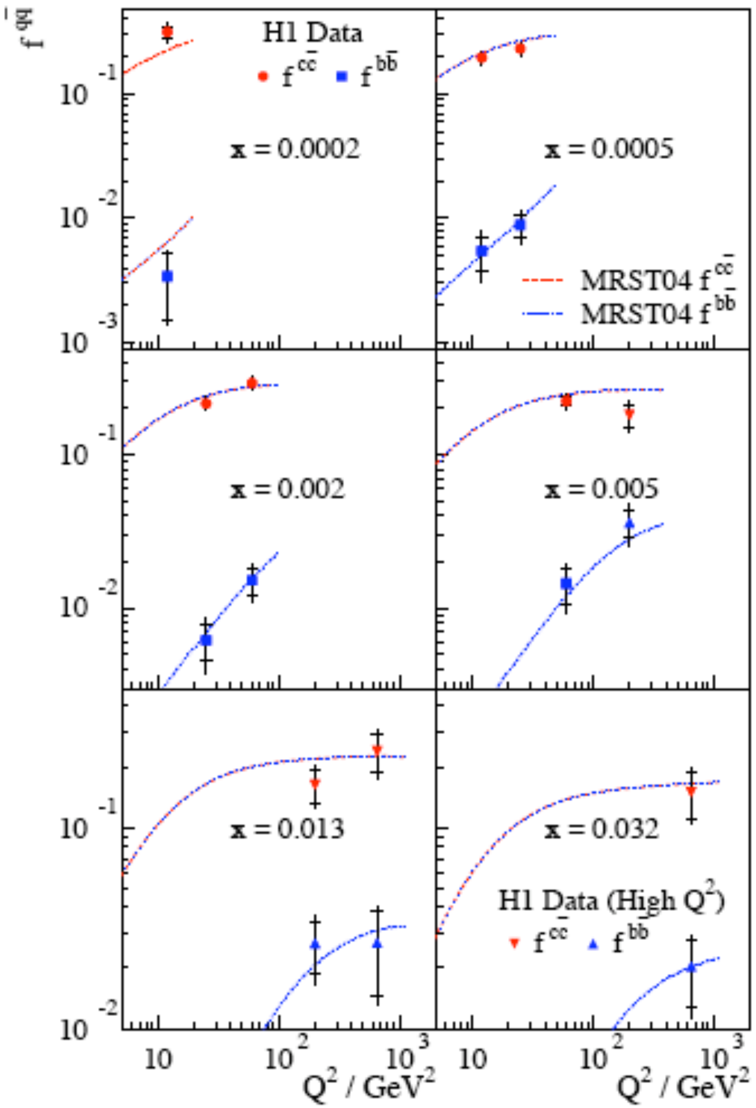
2nd p beam not shown

Design foresees to run in parallel with pp and e around ATLAS+CMS
Further, more detailed studies required but so far encouraging

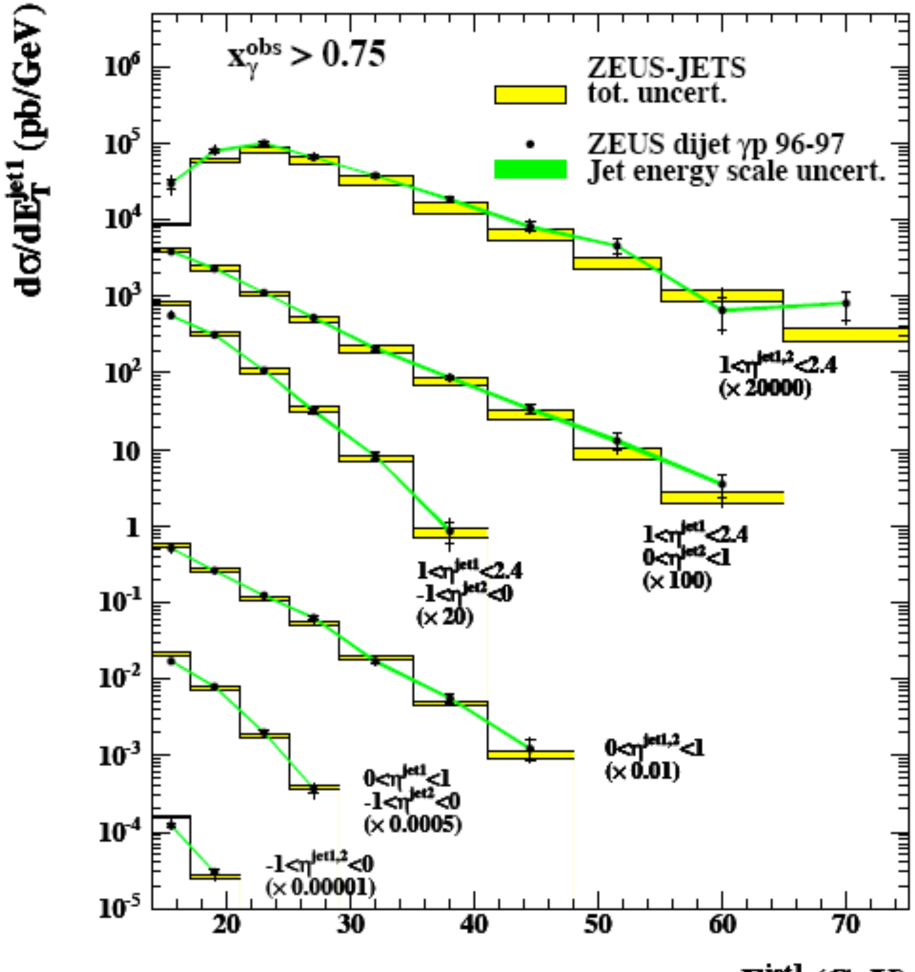
Beauty Quark Density



fractions of c and b



Dijets in direct photoproduction (Q^2~0)



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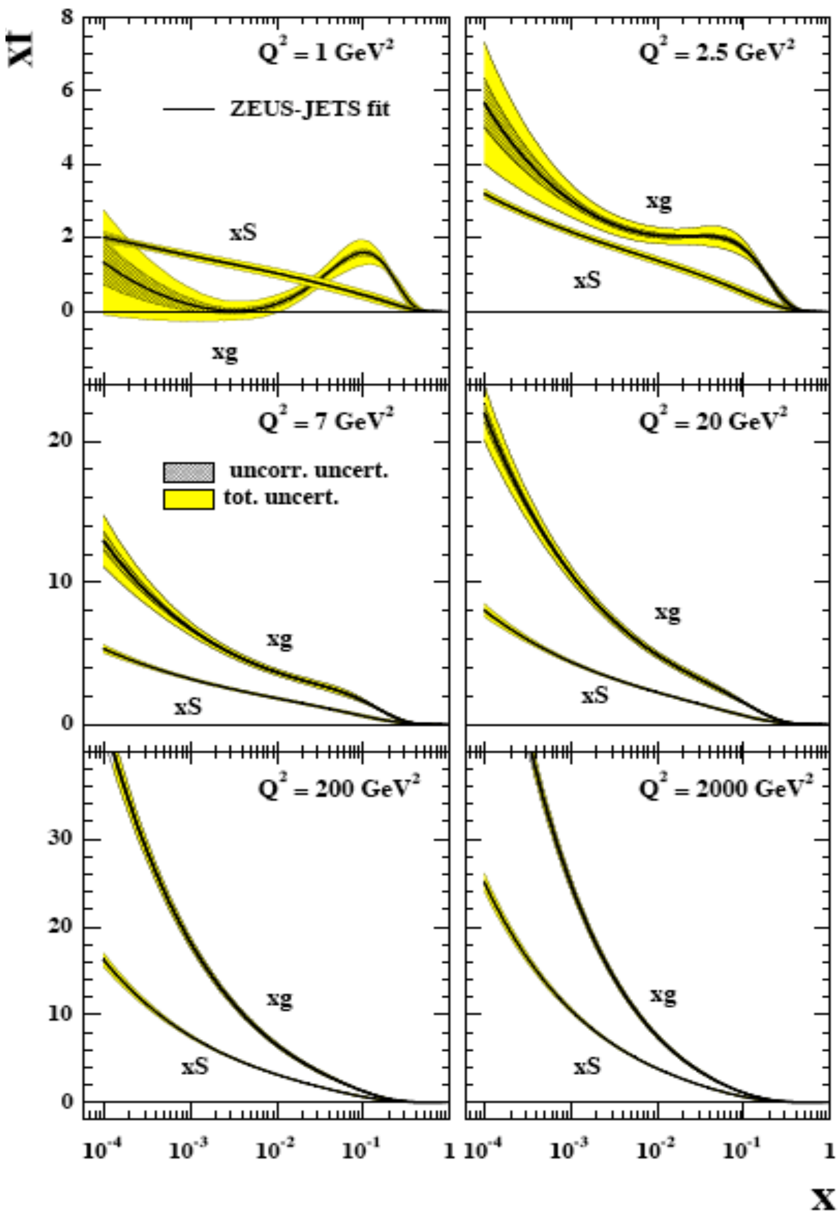
Sea and gluon dynamics



ZEUS fit NC, CC, and dijet HERA data jets improve much the α_s determination and somewhat the accuracy of xg at x ~ 0.05