Lepton-Hadron Colliders

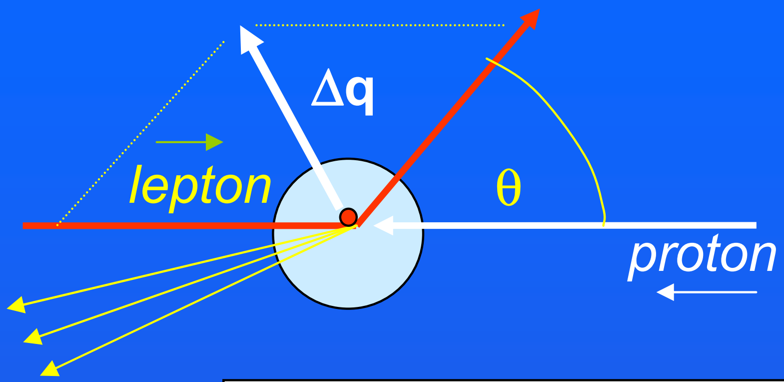
EPAC06, Edinburgh

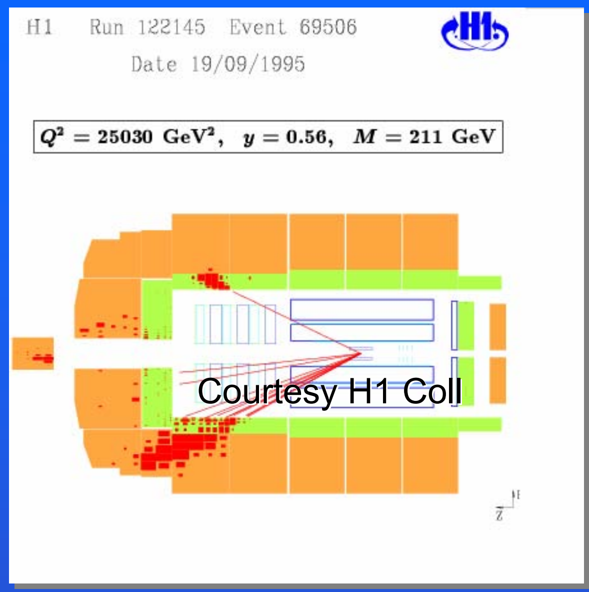
June 30, 2006

F. Willeke, DESY

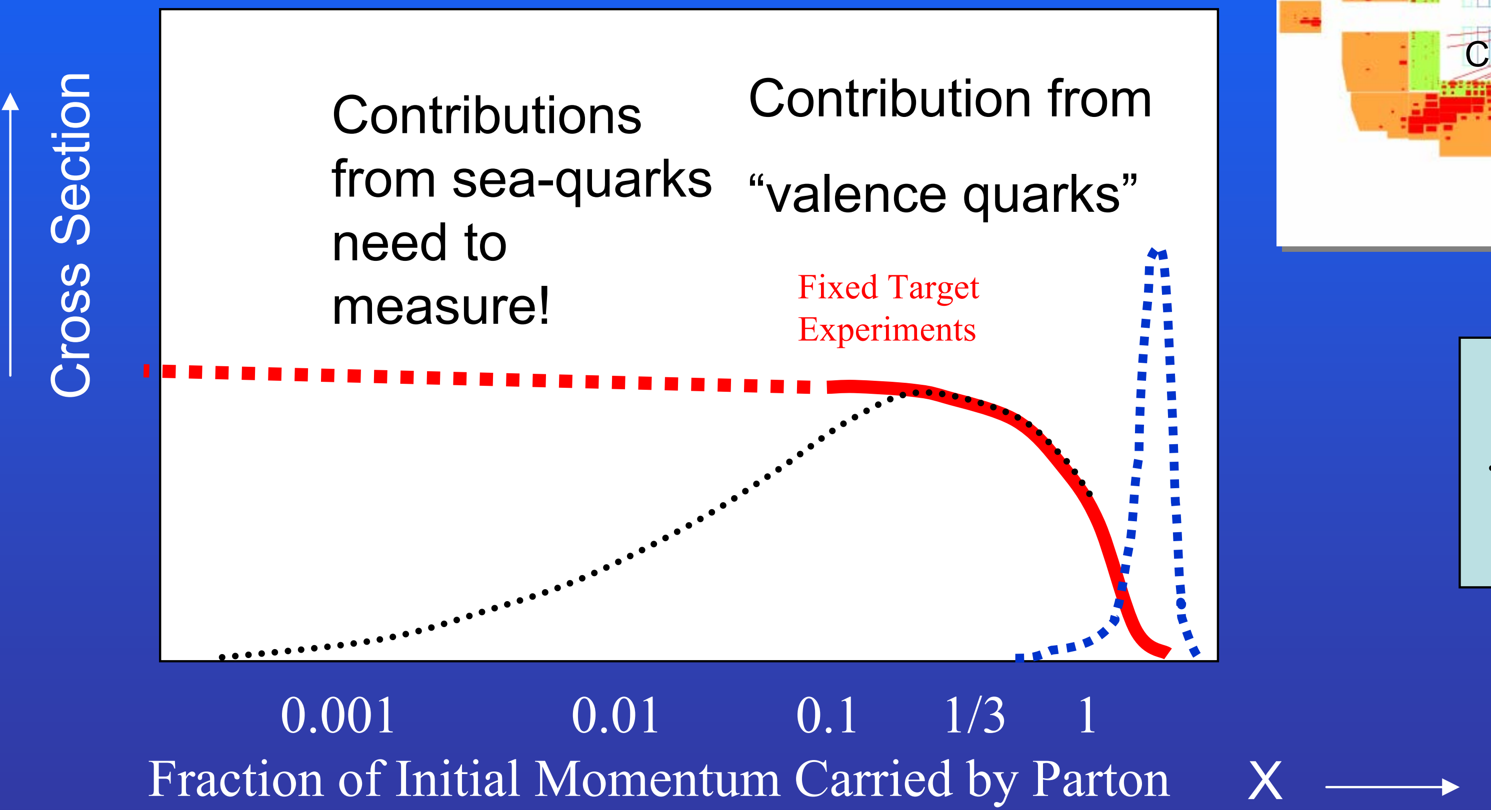
- Physics Motivation
- HERA Features, Status and Plans
- HERA Experience Relevant for LHC
- HERA Physics Results
- Future Lepton-Hadron Colliders

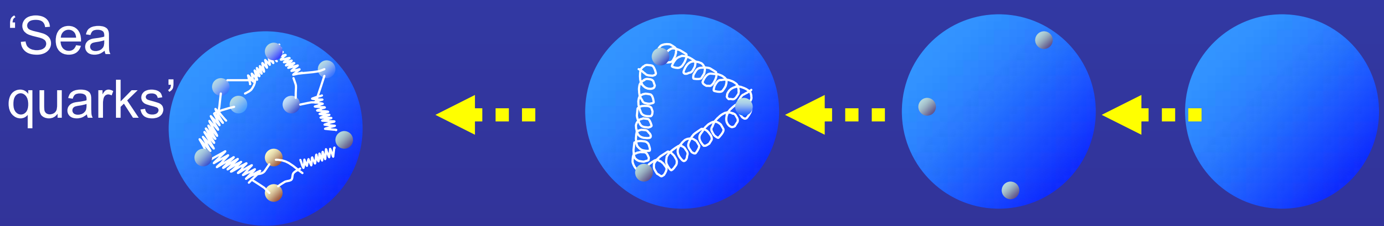
Structure of the Proton





$$x = \frac{Q^2}{2m_p \nu}$$





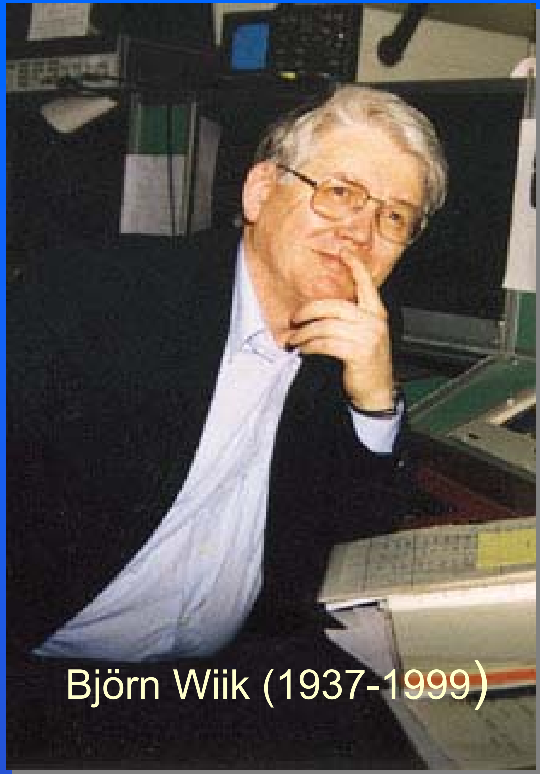
➔Build a Lepton-Proton Collider with 320 GeV center of mass Energy in international collaboration

HERA Double Ring Collider

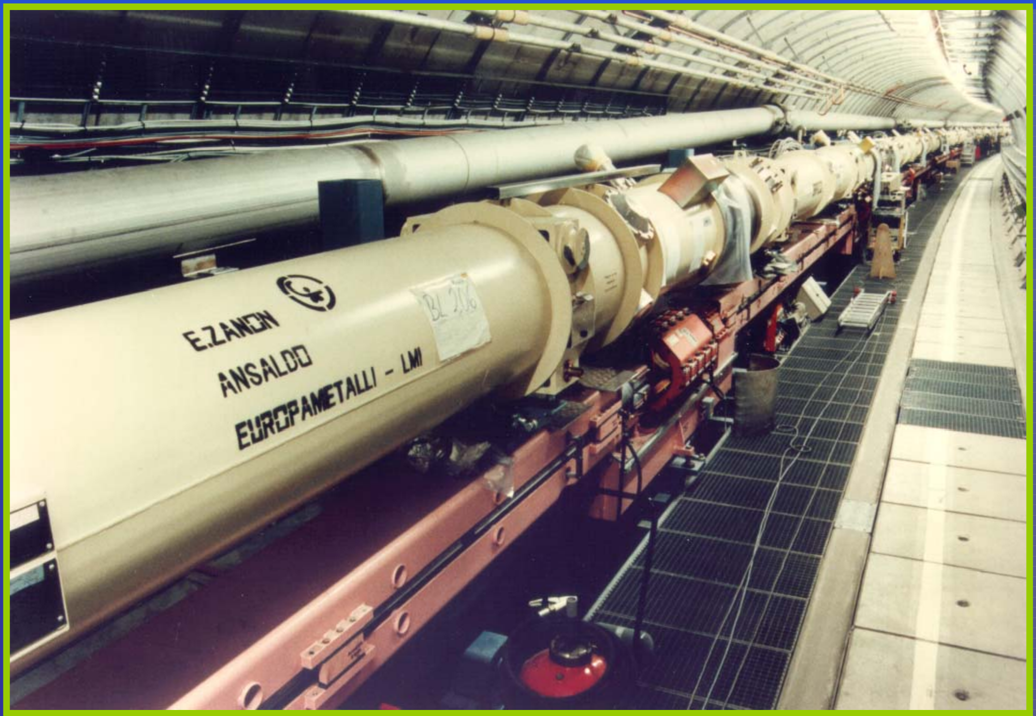
820 GeV Protons (actual **920 GeV**)

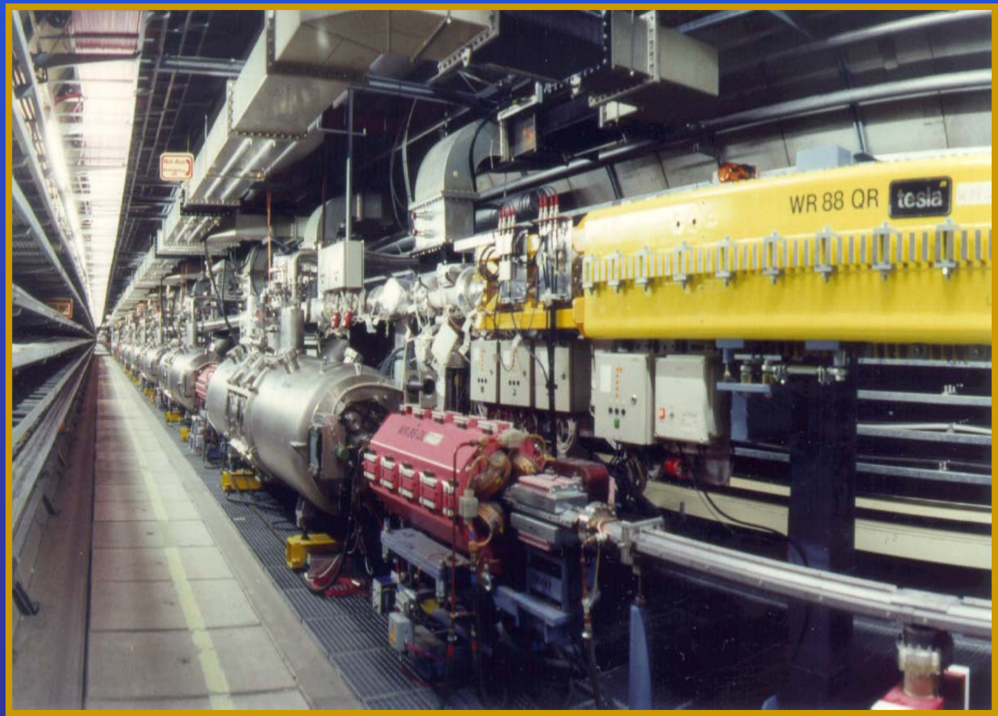
30 GeV Leptons e^+ or e^- (actual **27.5 GeV**)

Spatial resolution 10^{-18}m

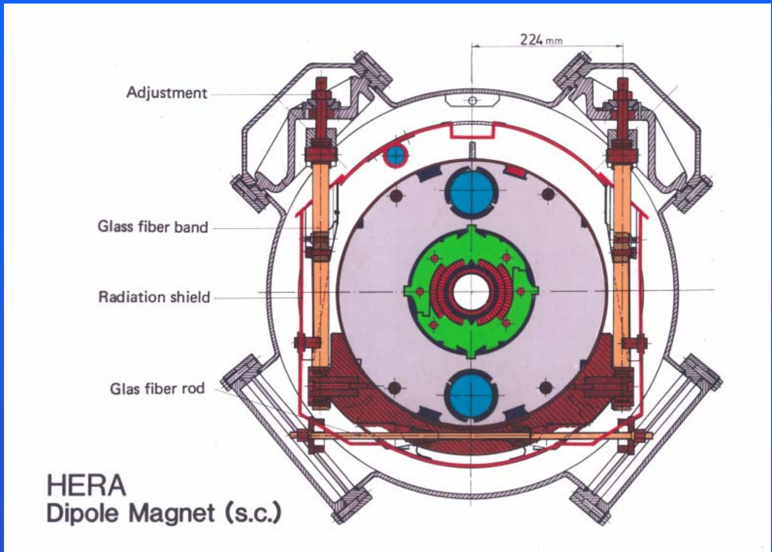


Björn Wiik (1937-1999)





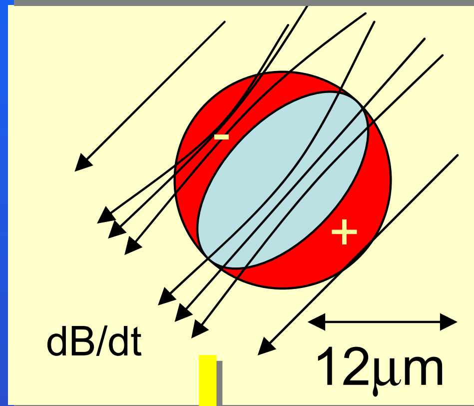
The technically most challenging component of HERA: the 400 superconducting 5.6T dipoles (@1TeV)



Rutherford type S.C. Cable 6kA, NbTi, Cu/NbTi=1.8

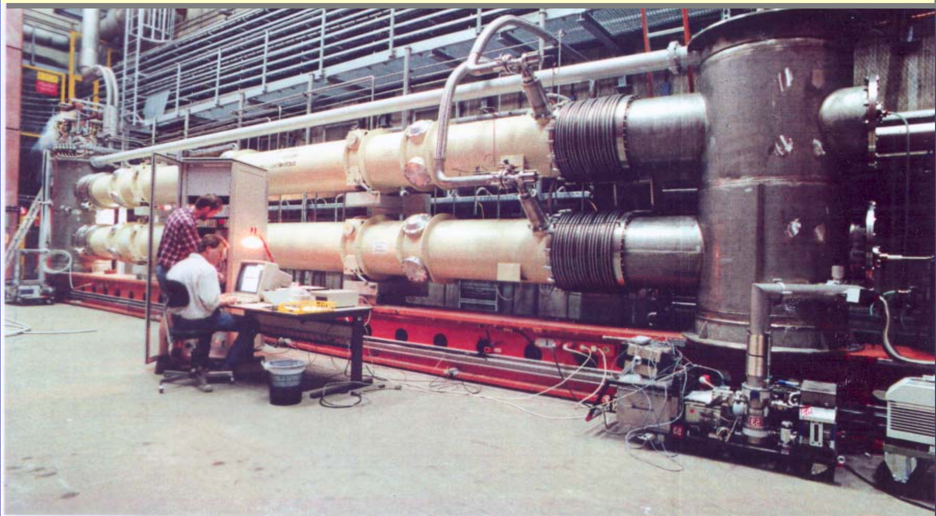
Induced persistent

eddy currents

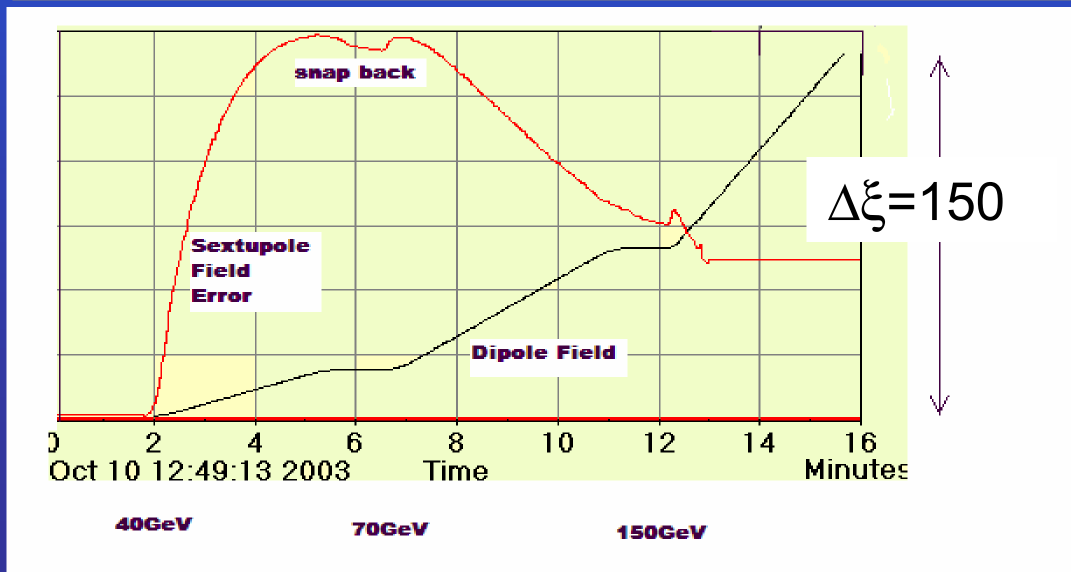


Beam Pipe wound 6-pole, 10-pole+12pole coils

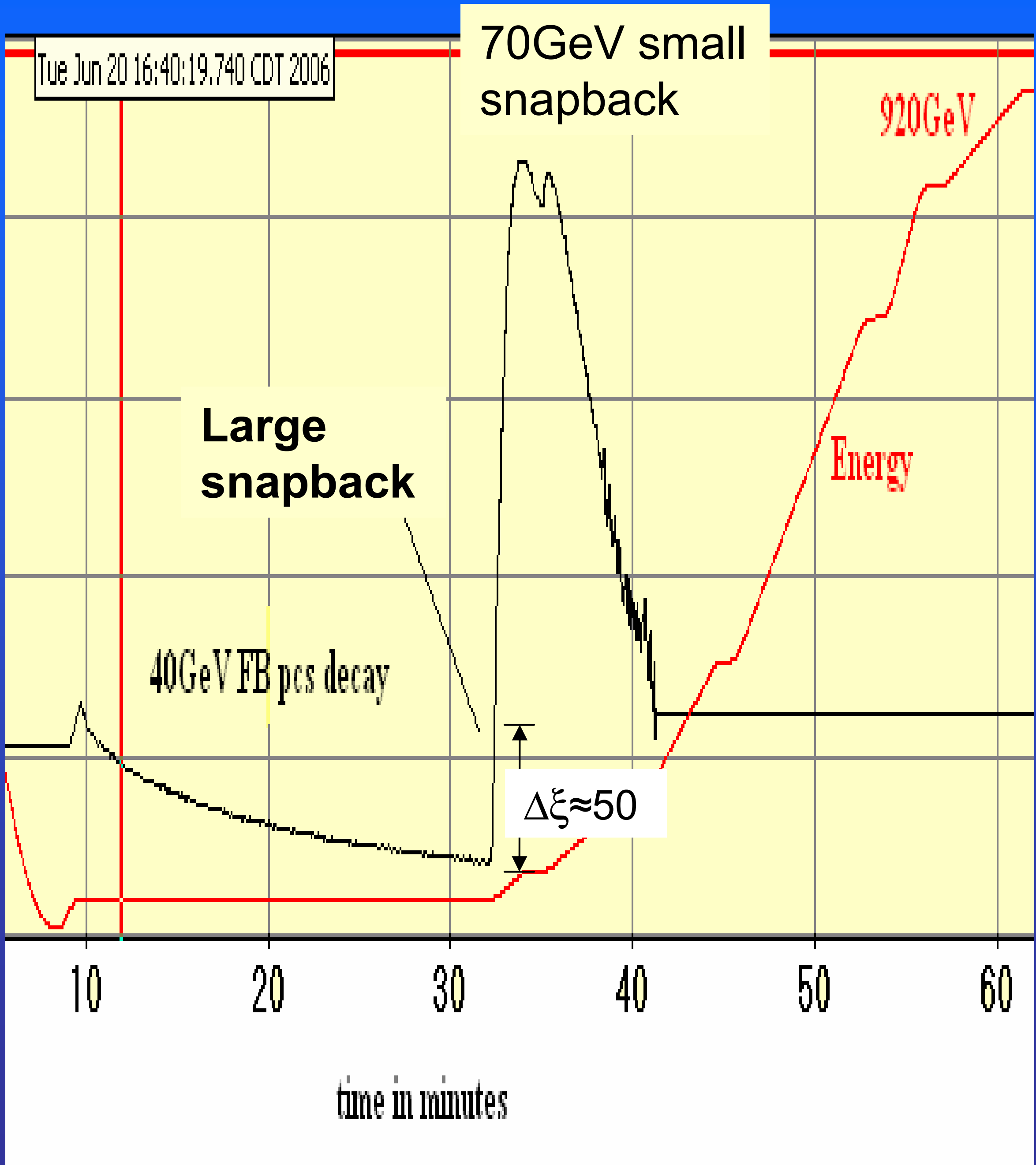
S.C. Reference Magnets



Persistent Current Sextupole Field Error



Persistent Current Sextupole during Acceleration



With Reference magnet
+ Ramp-tables ➔ Δξ=±5

ξ >5 bad lifetime ➔ beam loss
ξ≤0 head tail instability ➔ beam loss

fine tuning 'by hand'
feedback not helpful

Relevance for LHC: tolerance for beam loss much tighter

➔ NEED precise, non-destructive ξ measurements
+ low noise transverse dampers
+ good modeling of dynamic p.c.
(no reference magnets)

Summary of HERA Operational Experience

- Luminosity limited by RF power,
  and proton beam brightness
  - given by injectors
  - and beam-beam limit of lepton beam ($\Delta\nu_y \approx 0.1$)
- Matched electron and proton cross sections
- P-,e-Orbital Stability is of critical importance
- Effect of the large circumference in HERA e
  dispersion beats and large synchro-betatron resonances
- e-beam lifetime critical ➔ good vacuum conditions
  (dynamic arc+ RF section vacuum ≈1 ntorr)
- Vacuum conditions in the IR critical dynamic pressure of 0.1ntorr in IR required

Effect of Mechanical Vibrations

Sub micron vibrations ➔

orbit oscillations 100 µm ampl.

Beam moves away from collimator

Particles diffusing into the gap

Beam moves to the collimator

All diffused particles are lost

instantaneously

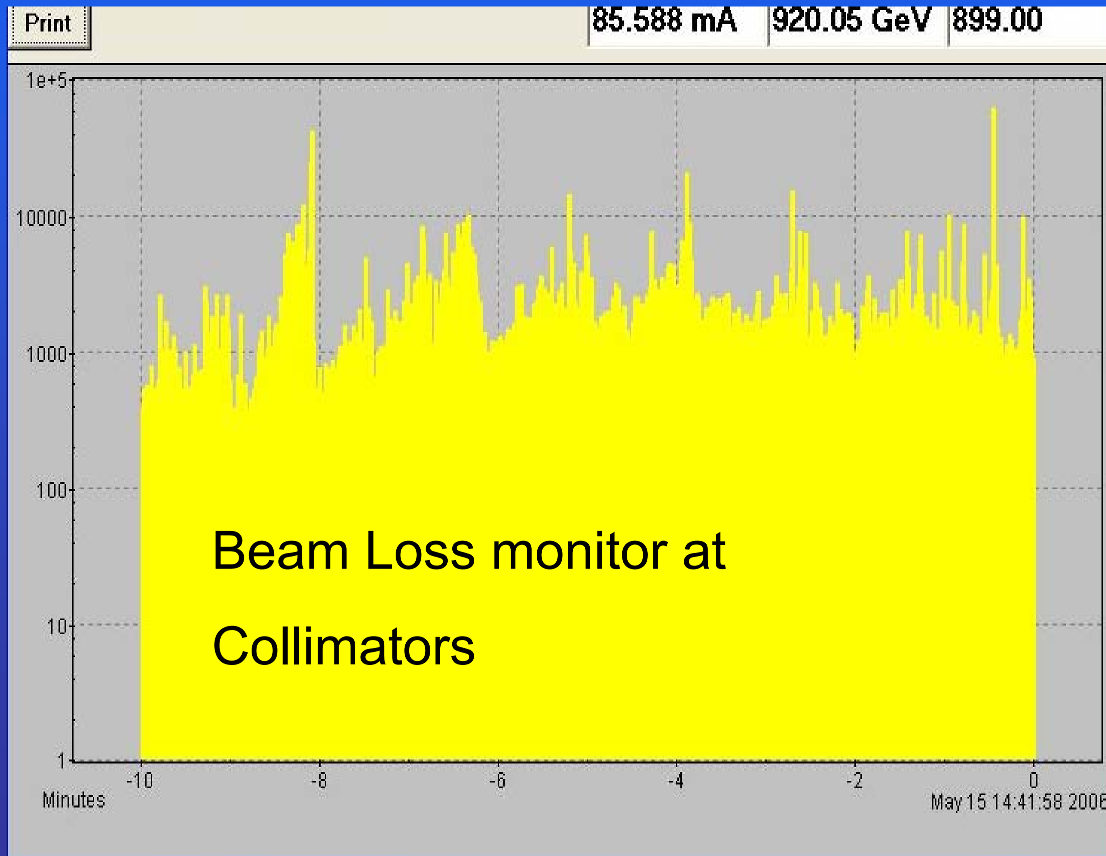
Due to 1% leakage of the collimator system

Sudden increase of detector backgrounds

➔ Poor HV-on efficiency

Effect of civil construction

for football World Championship 2006



IR Vacuum Issues and Backgrounds

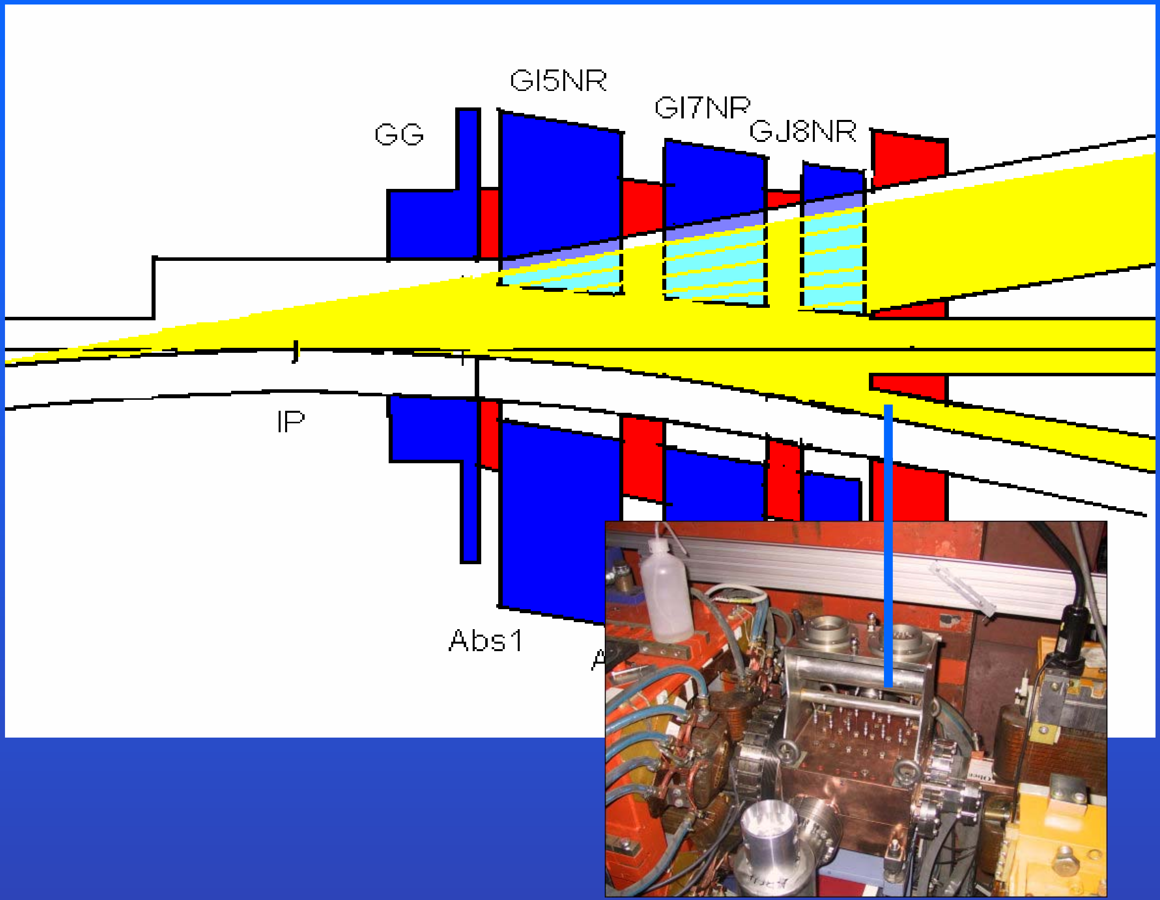
Particular ep Problem:

Synchrotron Radiation from lepton beam separation and corresponding gas desorption

+ proton gas scattering in the IR

Create a large issue

Need P=0.1ntorr dynamic pressure in an environment with 30kW of SR power



Problem solved by

- High pumping speed due to combination of **ion-sputter pumps**, **NEG-pumps**, **Ti-sublimation pumps** and **cryo-pumping** of cold beam pipe of the s.c. IR magnets.
- Fairly long vacuum conditioning with beam (20Ah, 3month)
- Regular (1/2week) warm-up with subsequent turbo-pumping (rinsing of the system?) and NEG regeneration

HERA Present Performance

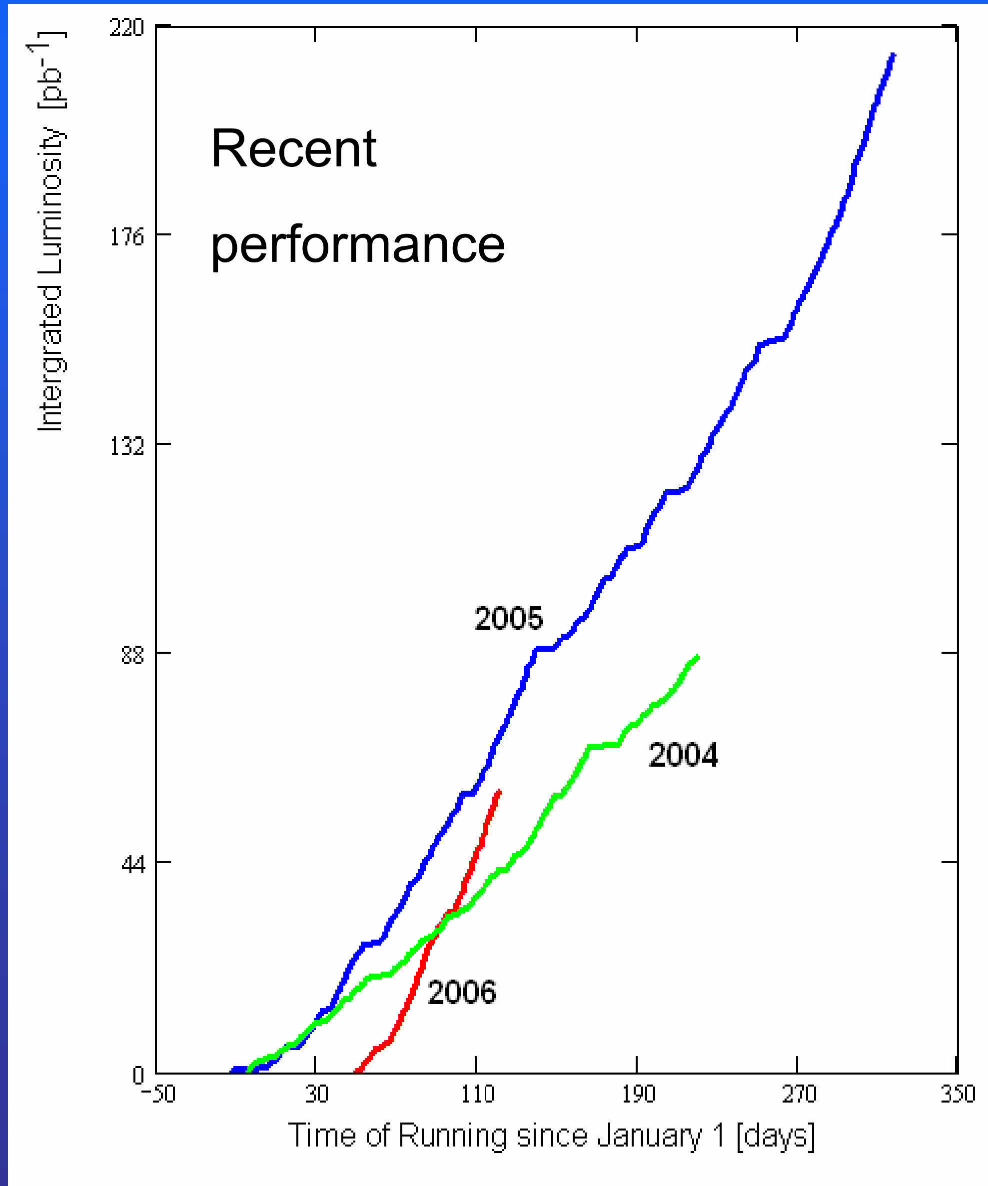
Peak Luminosity

$5.1\ 10^{31} cm^{-2} s^{-1}$

Luminosity production

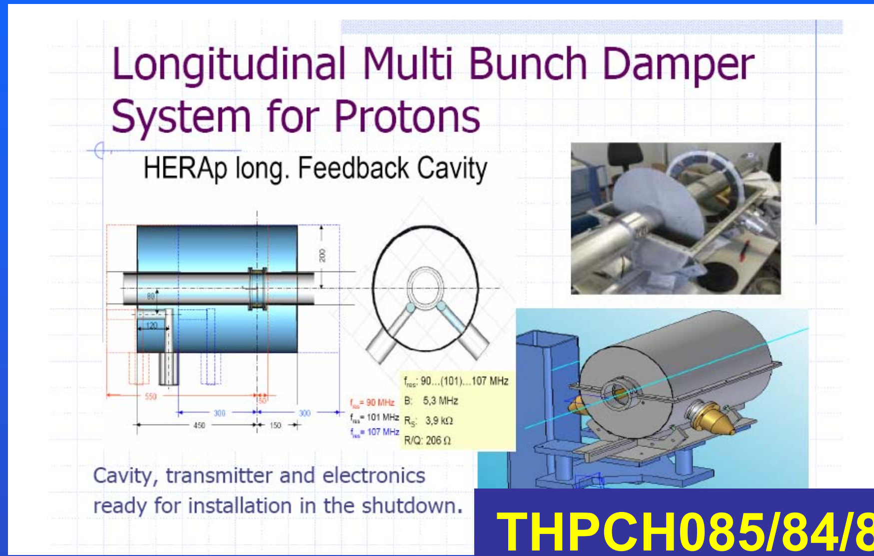
per day 1-2 pb^{-1}

There is potential to increase the luminosity by a factor of 1.4 with positrons



Improvements:
Damping of longitudinal instabilities

- Implementation of a longitudinal broad band damper system for protons to preserve the longitudinal emittance

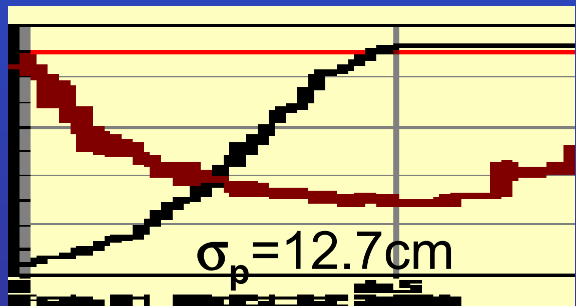


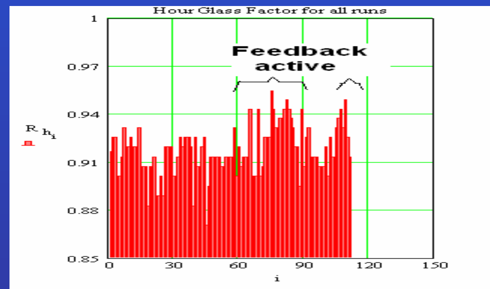
THPCH085/84/87

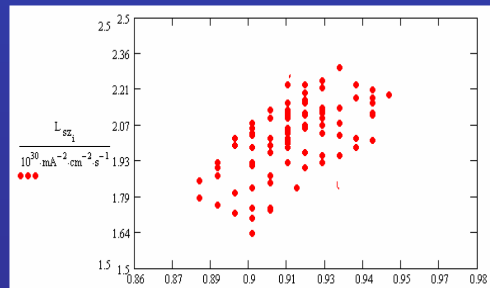
System commissioned, tuned up and tested during Start-up

➔ SUCCESS!

Feb 11-06



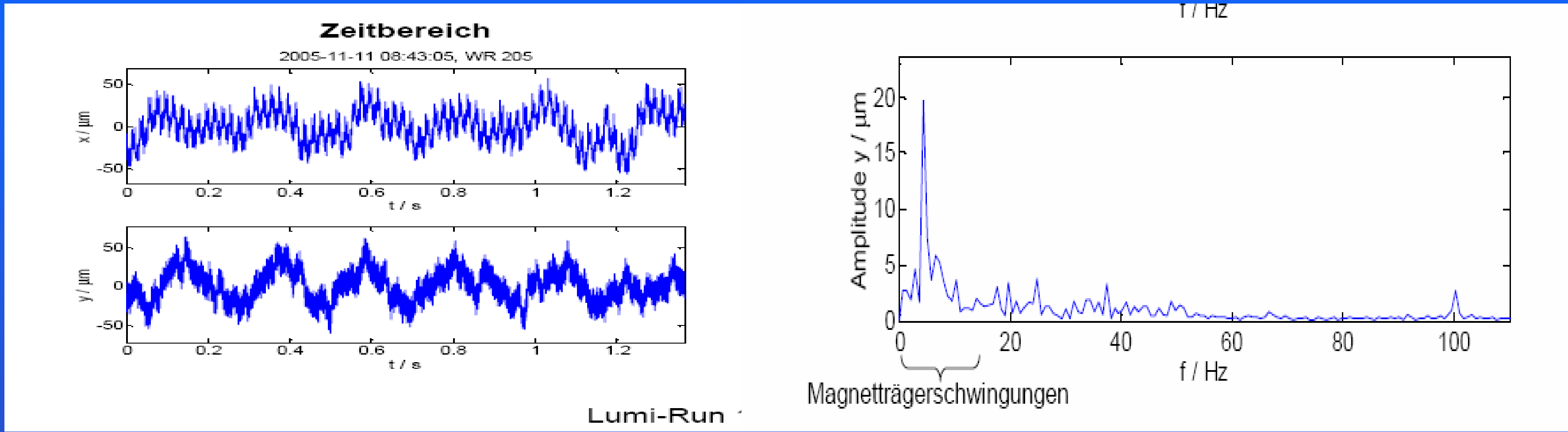




HERA p Acceleration without emittance blow-up

Need further studies to reduce emittance growth by RF noise and IBS

Improvements: Fast Orbit Feedback



aim for compensating orbit oscillations up 100Hz to the level of about 10mmBPM electronics existing , readout based on 10kHz Field bus

Prototype of air coil built and tested, production in progress

Programming DAQ & feedback algorithm availalble,

Ready for a test soon **THPCH086**

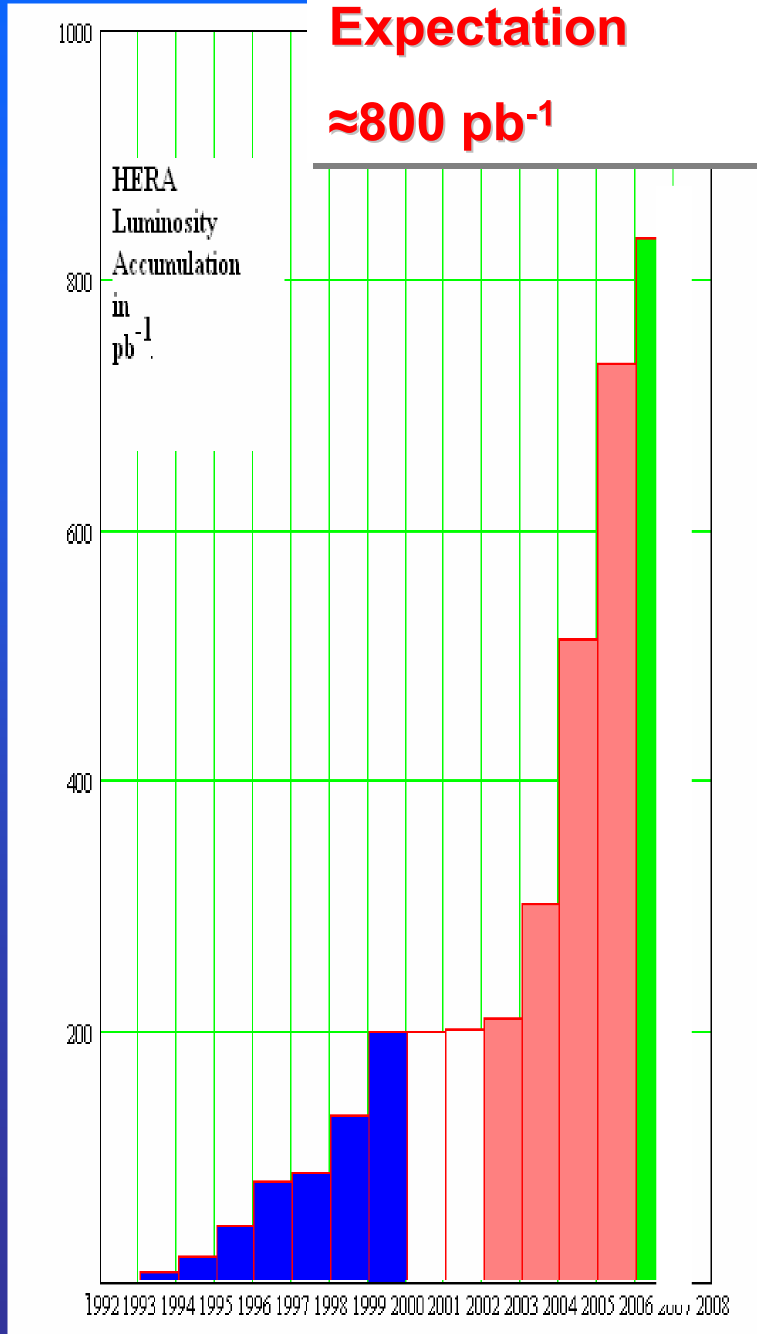
Proton Software Feedback eases operation and helps to keep the tunes in a window of $\Delta Q<0.002$ **THPCH083**

HERA PLANS

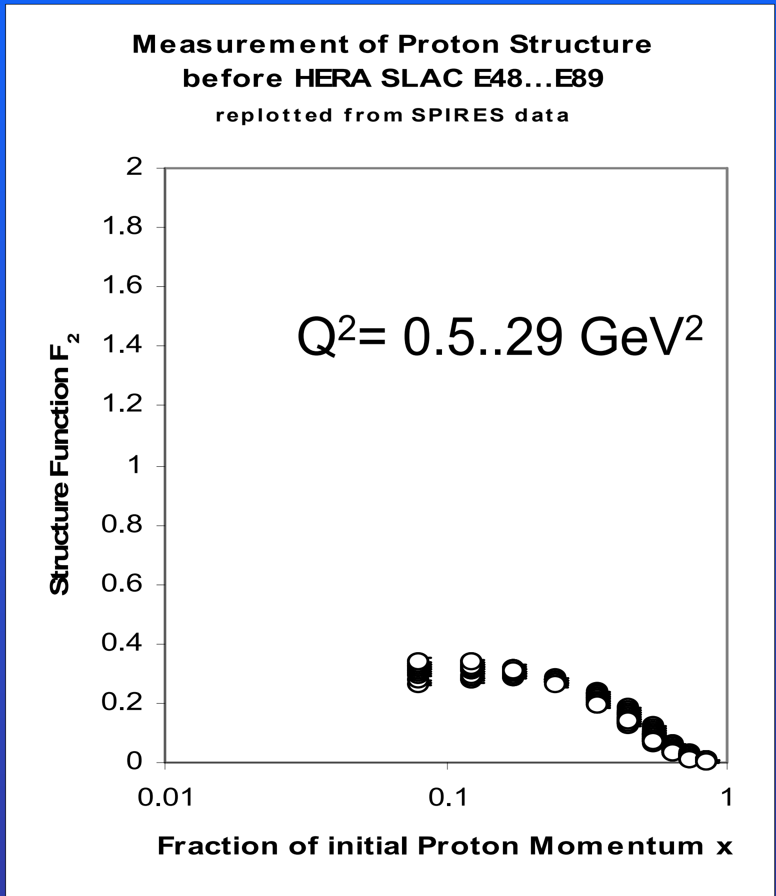
- Electron Proton Run Completed
- Switching from electron-proton running to positron-proton running during this week
- Positron Proton Running until end of June 2007
- In-between a run with reduced proton energy of 460GeV planned for measurement of F_L with $10pb^{-1}$
- Shutdown of HERA and termination of the HERA Physics program End of June 2007

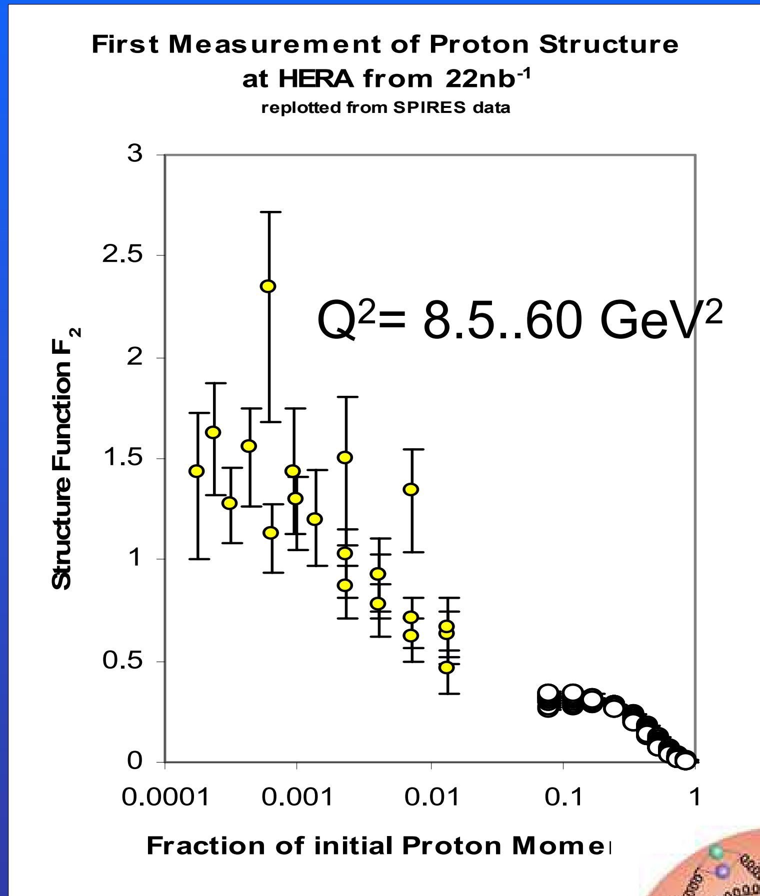
Total Luminosity Expectation

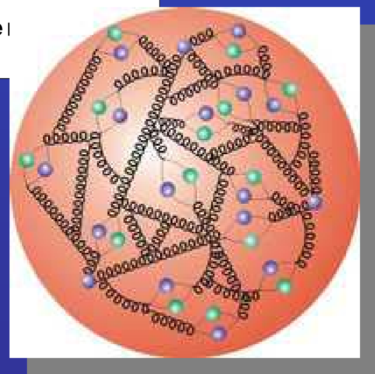
$\approx 800\ pb^{-1}$



1992: Spectacular Start-up of HERA Physics program (with 60nb^{-1})

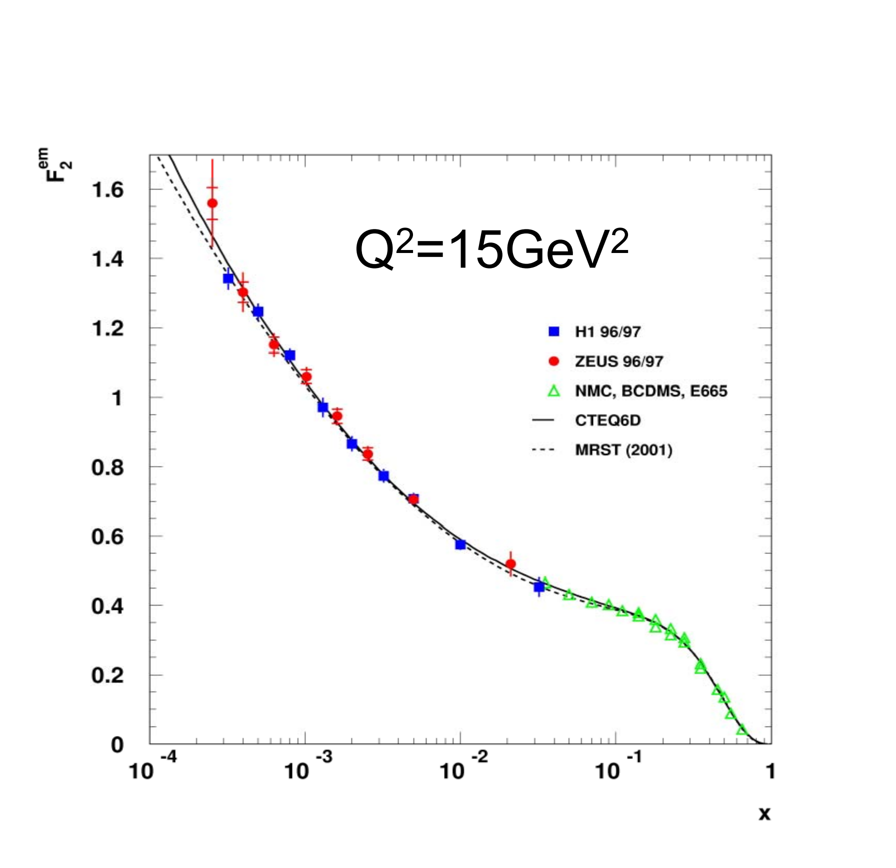




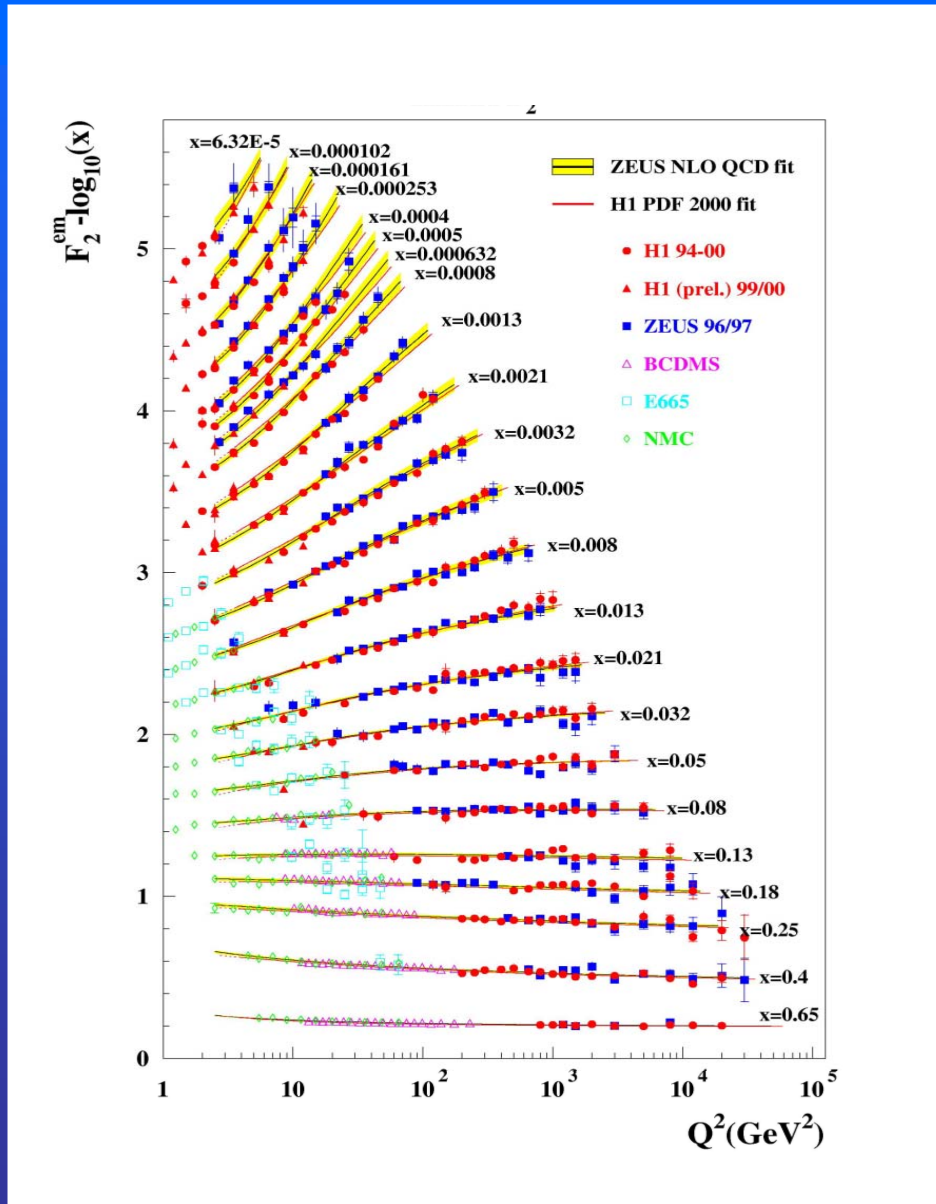


➔ Changed our understanding of the structure of the proton

Structure of the Proton as seen by HERA and previous deep inelastic scattering experiments (BCDMS; E665, NMC)



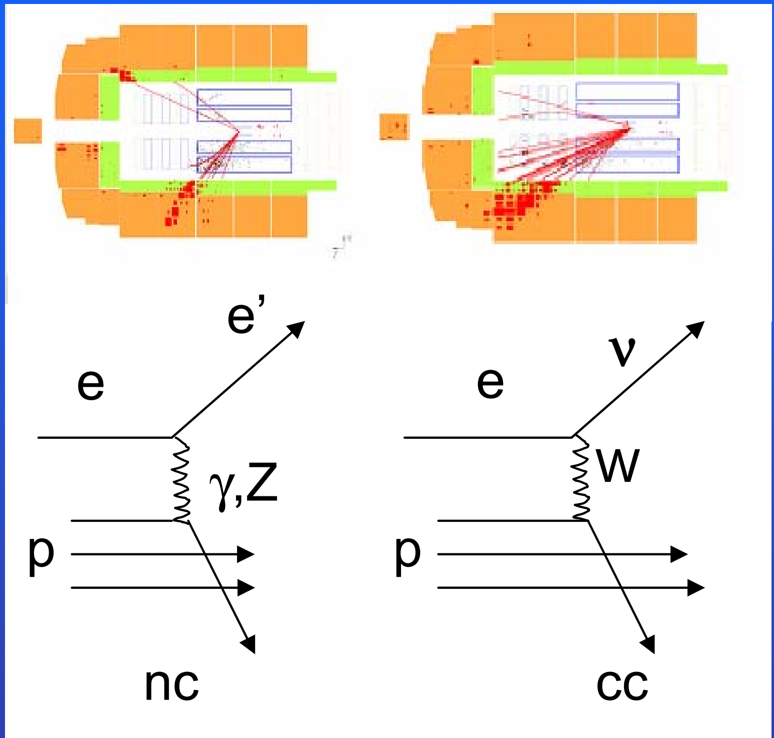
The more precisely one is looking into the proton, the richer the structure uncovered



Measurement on electromagnetic-weak unification from ZEUS and H1:

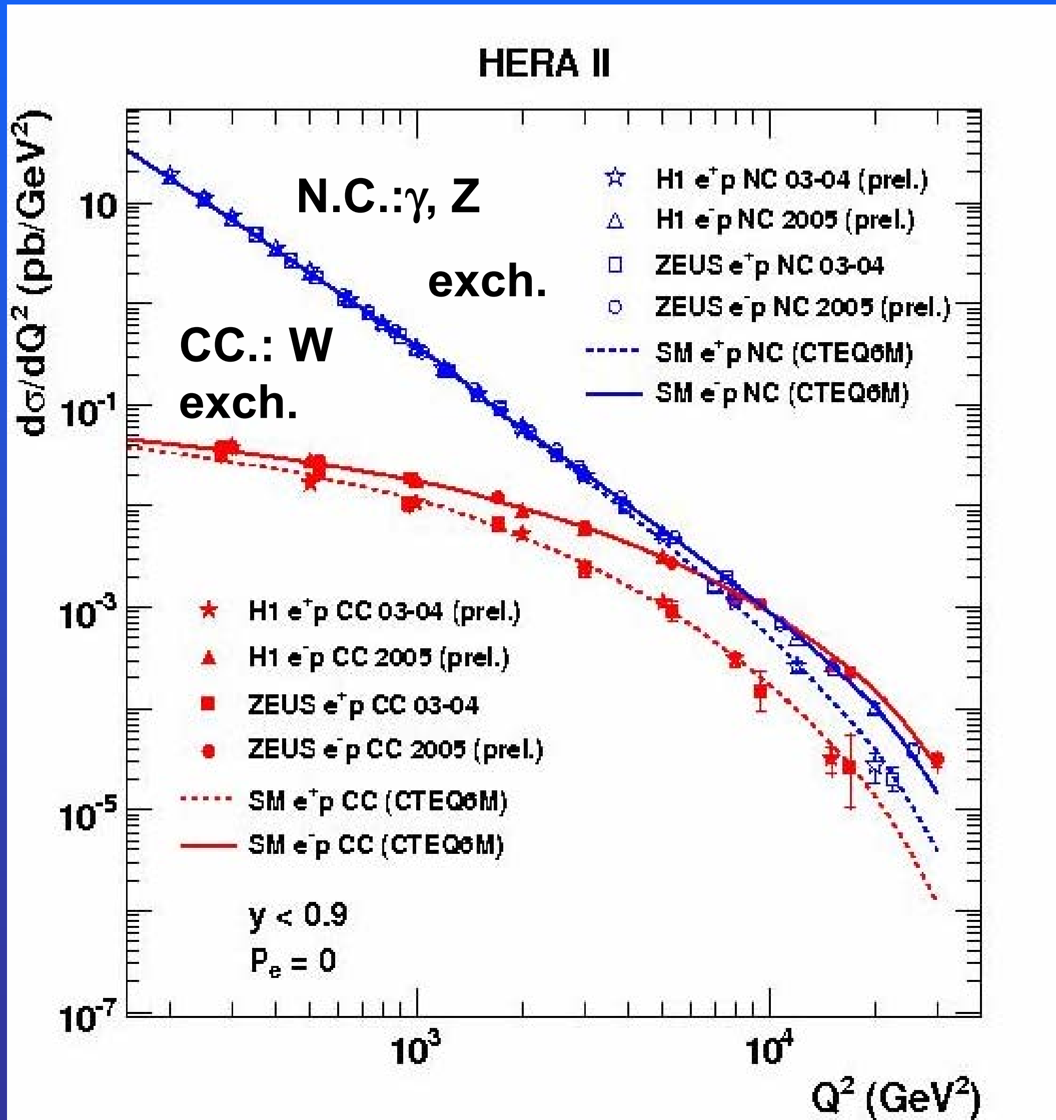
At low Q^2 weak interaction cross sections are suppressed by the W mass, but from high Q^2 data, where the influence of the W mass becomes smaller, it becomes apparent that the weak and electromagnetic coupling constants become very close

Difference between e- and e+ data sensitive to interference of γ and Z exchange

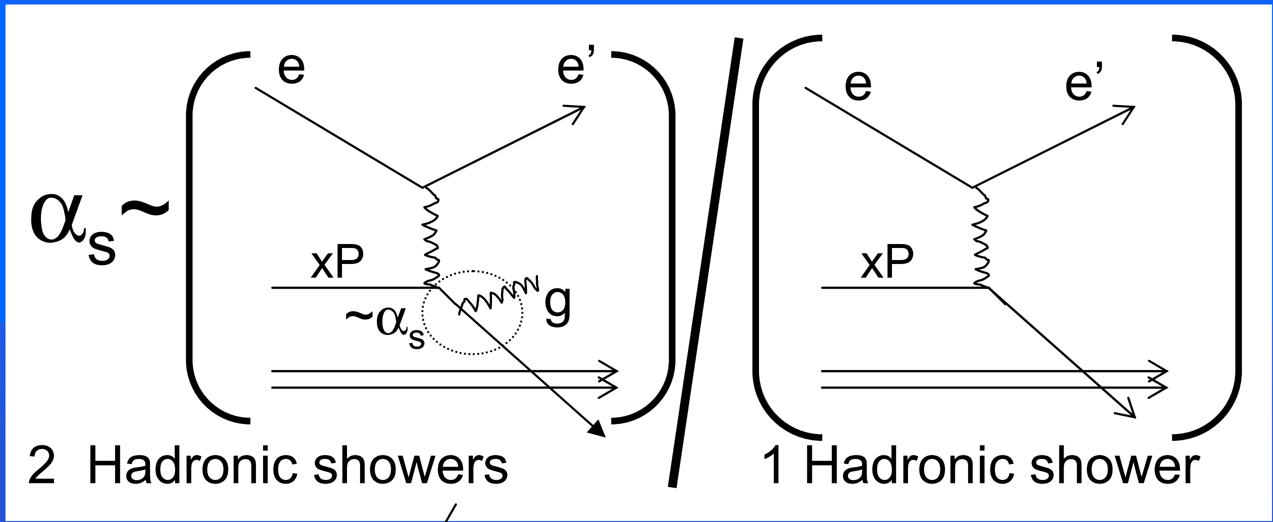


$$\frac{d\sigma_{nc}}{dQ^2} \propto \left[\frac{G_F M_Z^2}{(M_Z^2 + Q^2)} + \frac{\alpha}{Q^2} \right]^2 \cdot (F_2(Q^2, x) \ldots)$$

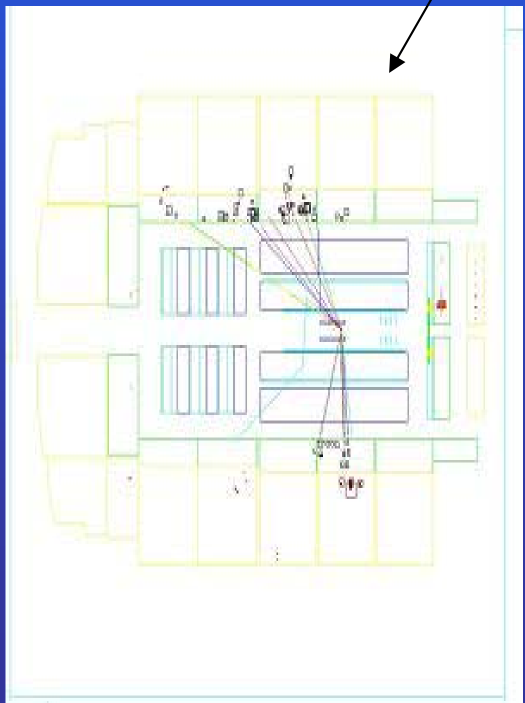
$$\frac{d\sigma_{cc}}{dQ^2} \propto \left[\frac{G_F M_W^2}{(M_W^2 + Q^2)} \right]^2 \cdot (F_2(Q^2, x) \ldots)$$

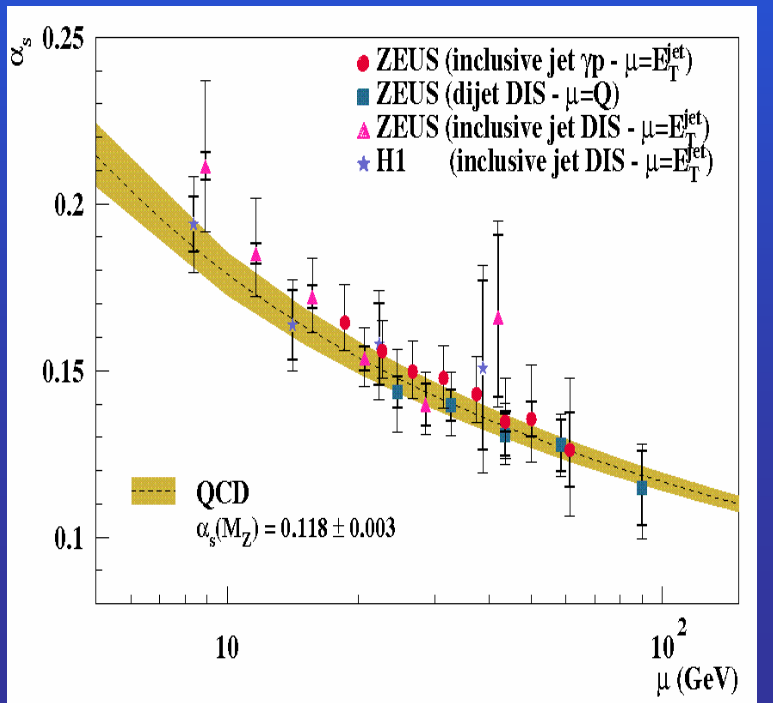


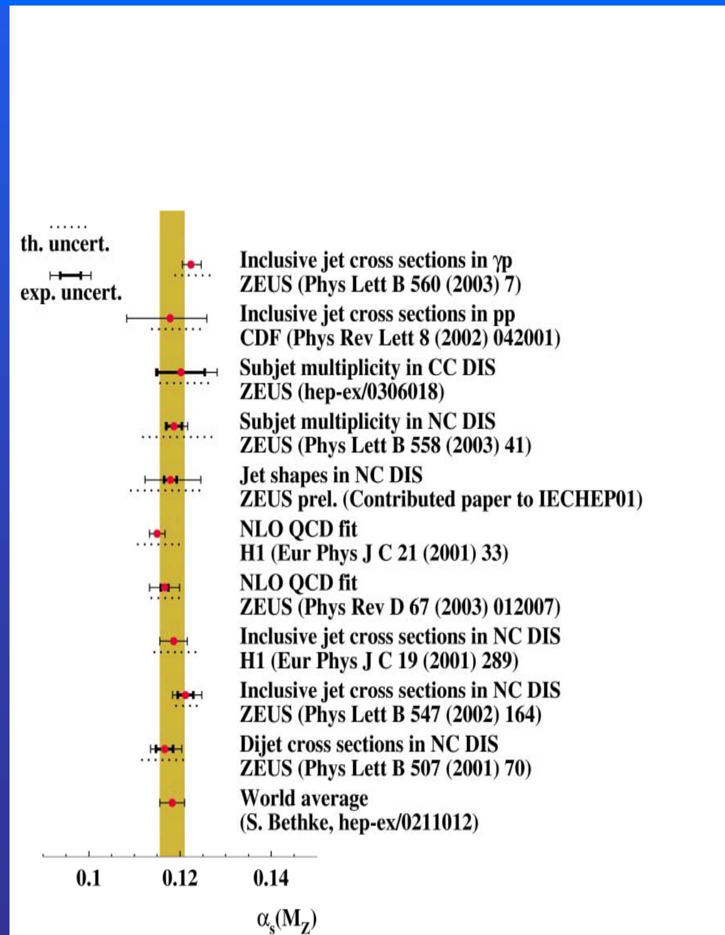
Obtaining more precise data on the coupling constant of the strong interaction α_s



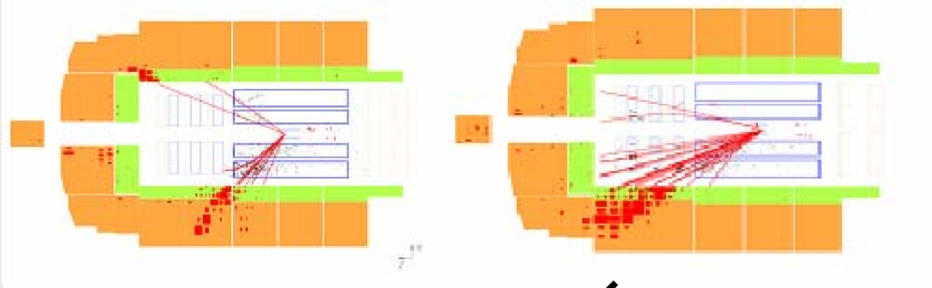
Comparison of existing measurement of α_s



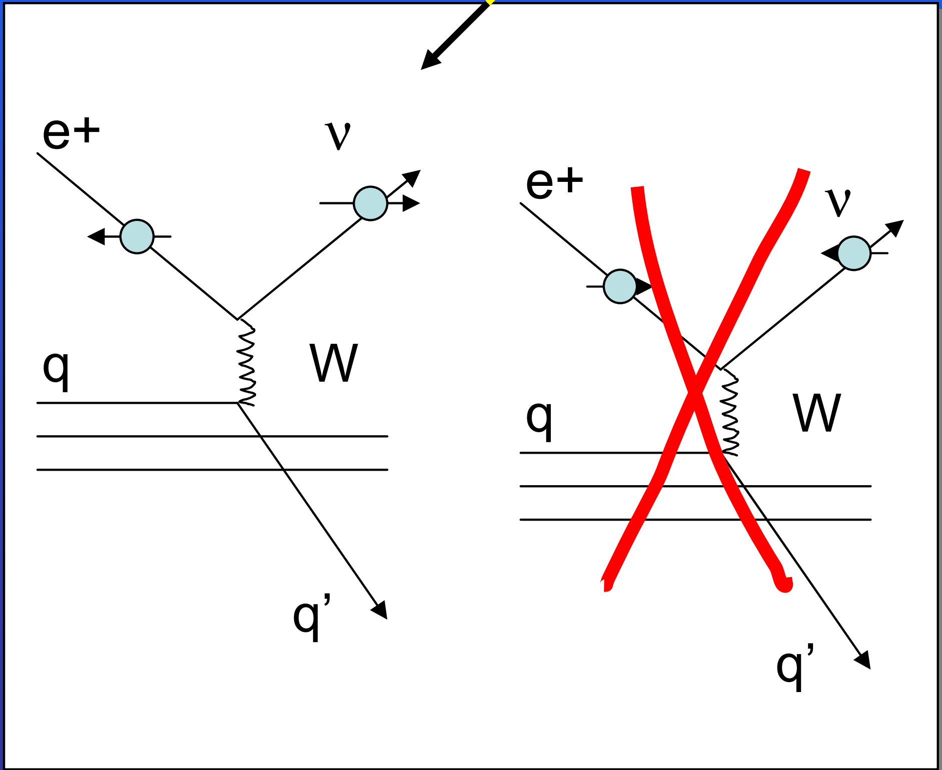


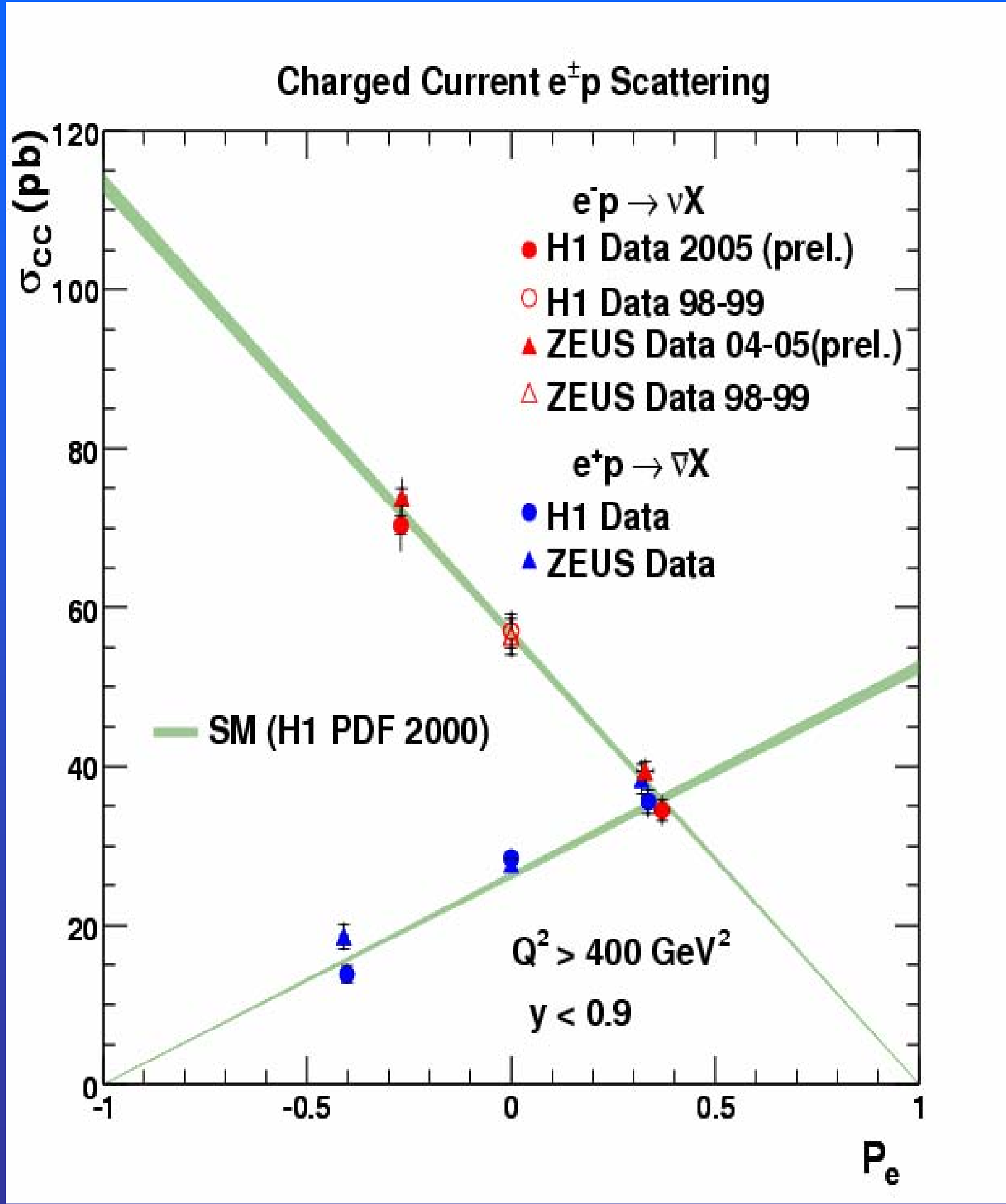


New HERA Physics Results 2004-2005



Courtesy H1 Collaboration





Future of DIS

- The end of HERA operation in July 2007 leaves the physics program unfinished.
- most desirable to obtain further knowledge of the evolution of gluons density towards lower x (saturation)
- investigation of the structure of the neutron
- The study of the gluon density of nuclei with high resolution ➔ extrapolation of quantum chromo dynamics from the perturbative into the non-perturbative domain.
- symmetry of hadrons and lepton species and the agreement of lepton and proton charge ➔ quark-lepton resonances➔ major step in understanding of matter
- HERA results raised a number of interesting questions which will be left unanswered due to limited kinematic range or limited statistics such as the isolated leptons and missing momentum, heavy quark content of the proton, CP, diffractive events which point to ‘colorless’ objects in the proton

Possible Facilities for Future DIS Physics

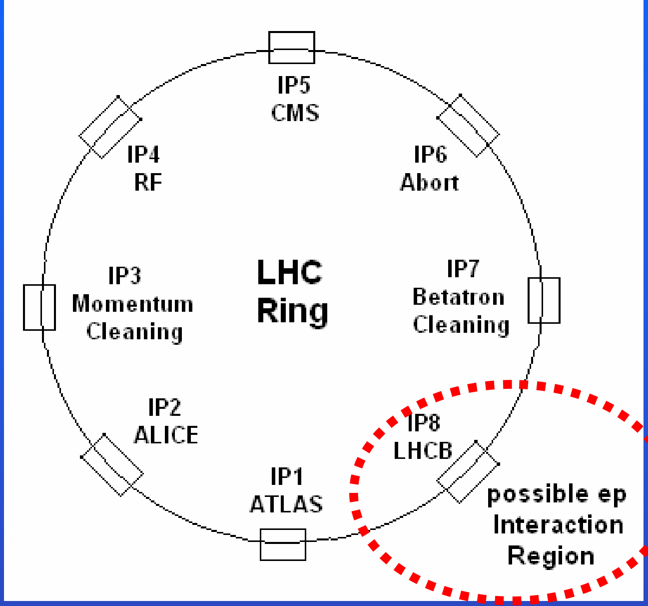
- HERA III LOI, continuation of the HERA physics with a new injector complex for eD scattering and an IR specialized for low x
- Ring-LINAC colliders with a high energy proton ring like HERA, TEVATRON of LHC and a linear collider

  ➔ ultimate extension of kinematics range but low luminosities around $10^{31}cm^{-2}s^{-1}$

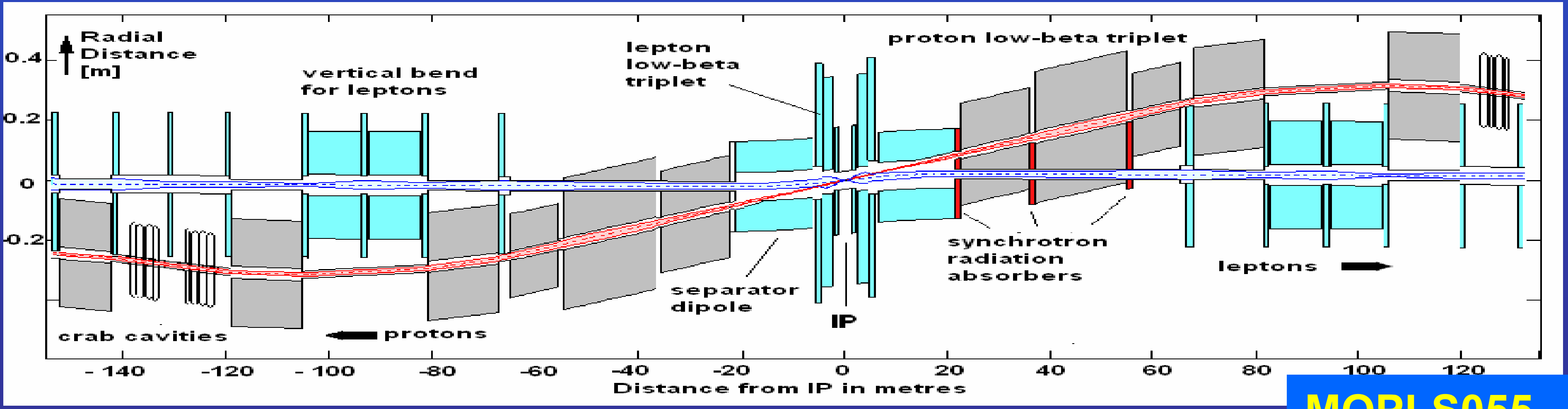
  Recent idea: collision of CLIC-like beams (short trains) with an LHC super-bunch
- Ring-Ring Collider: LHC proton beam colliding with a LEP-like lepton beam compromise between high center of mass and high luminosity, recent work based on LHC parameters and HERA experience $10^{33}cm^{-2}s^{-1}$ & E_{cm}=1.4TeV should be possible
- Lepton-Ion Colliders at low E_{cm} but large ep luminosity

LEHC

Lepton-Hadron Collider in LHC



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	



MOPLS055

Colliders with low E_{cm} but very large Luminosity

Instead of aiming for maximum kinematic reach, concepts are developed to achieve ep and eI collisions with a very high luminosity of up to

$L= 10^{35} cm^{-2} s^{-1}$.

physics program:

- precise measurement of the proton structure at low-x,
- the measurement of spin structure functions
- and the exploration of the high gluon density regime ("colour glass condensate").

Two facilities under consideration

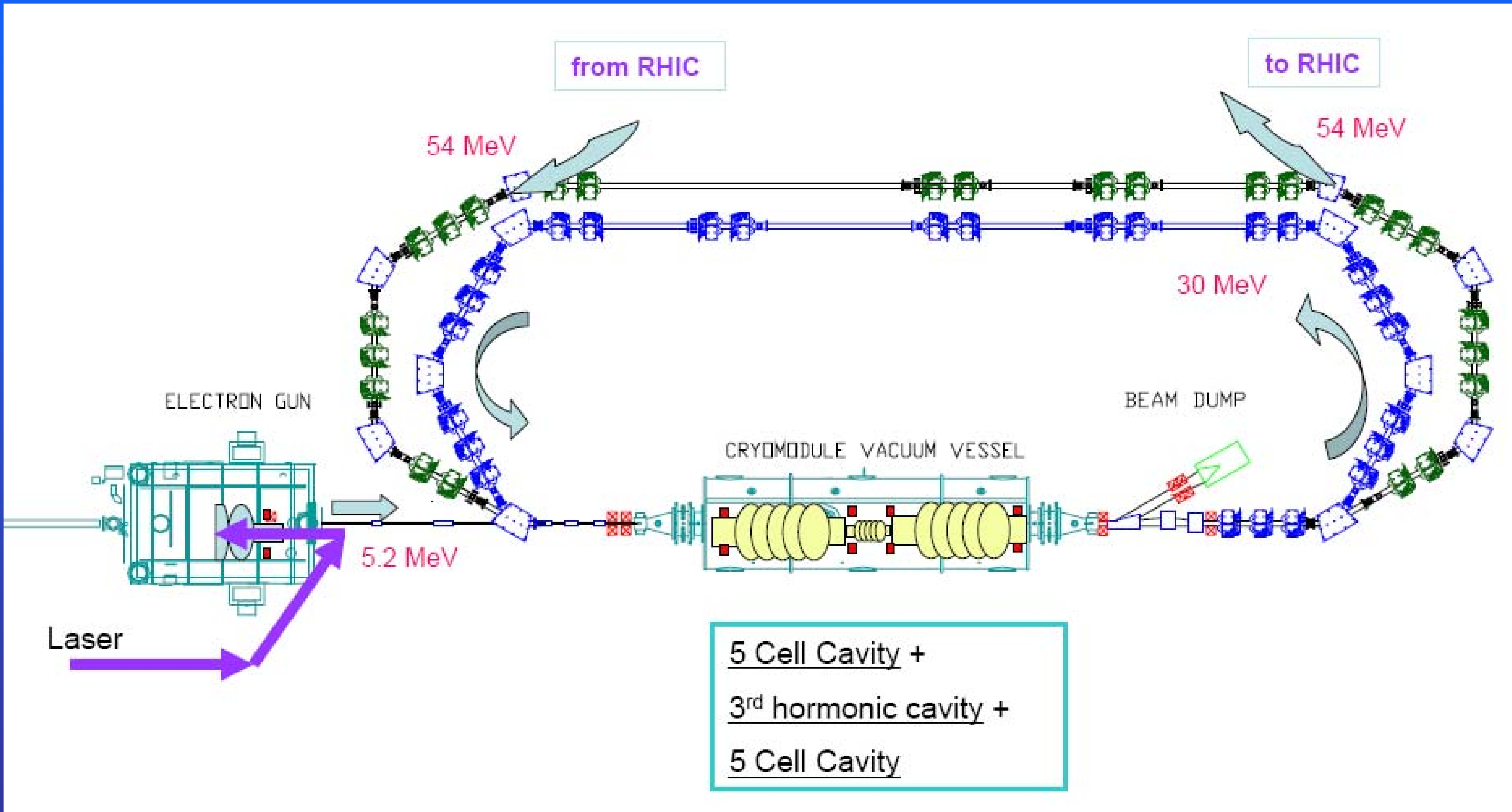
ERHIC @BNL and ELIC @TJNAF

High Luminosity, ERL based Lepton Hadron Colliders:

Common Design Challenges

- Need strong cooling of hadron beams to balance IBS to obtain short bunches and small transverse emittance
  - ERL based
    - bunched beam
      - high current (0.5A)
        - high energy @54MeV
- Low HOM SC RF Cavity design for Ampere CW beam currents
- High intensity polarized electron source

For bright RHIC hadron beams: Layout of a RHIC Electron Cooler



Superconducting Photo-cathod developement for high Energy Electron Cooling

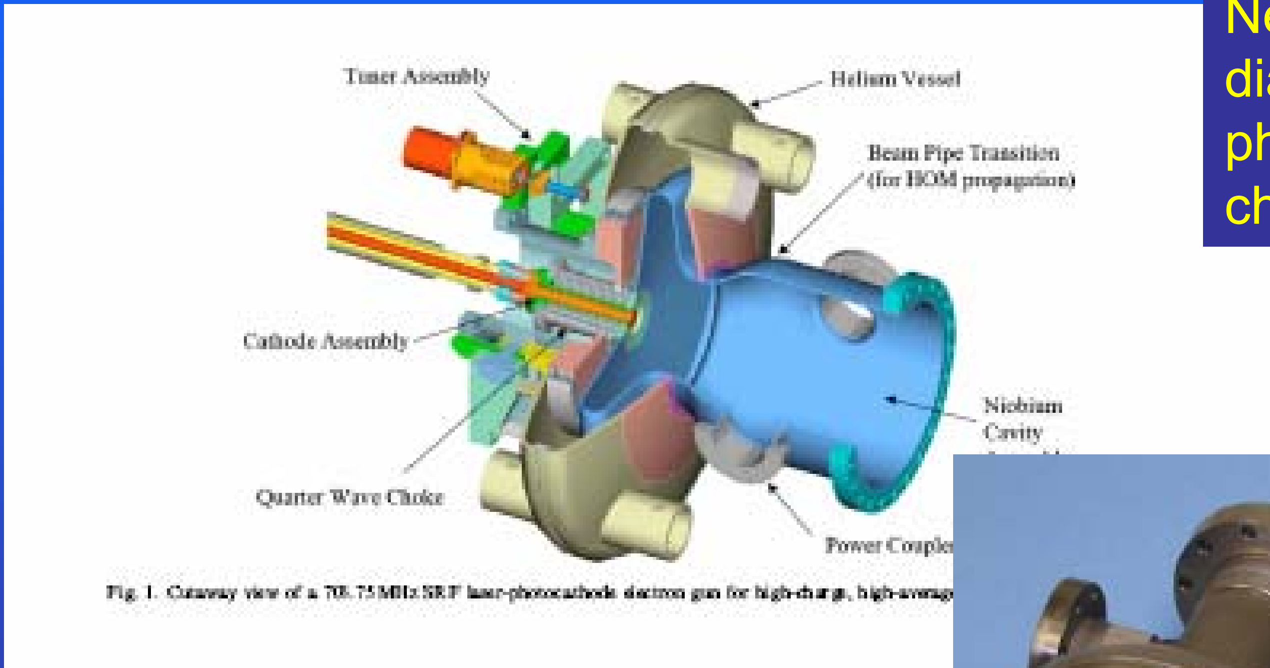
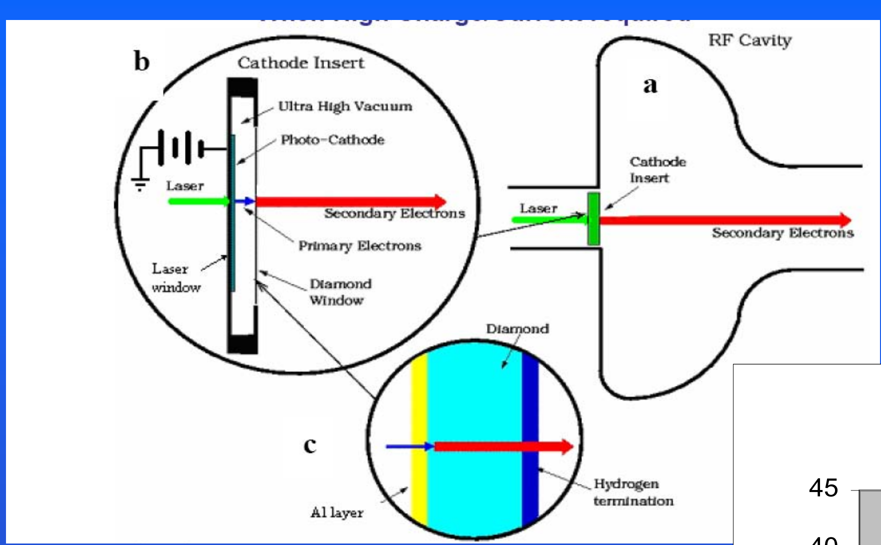
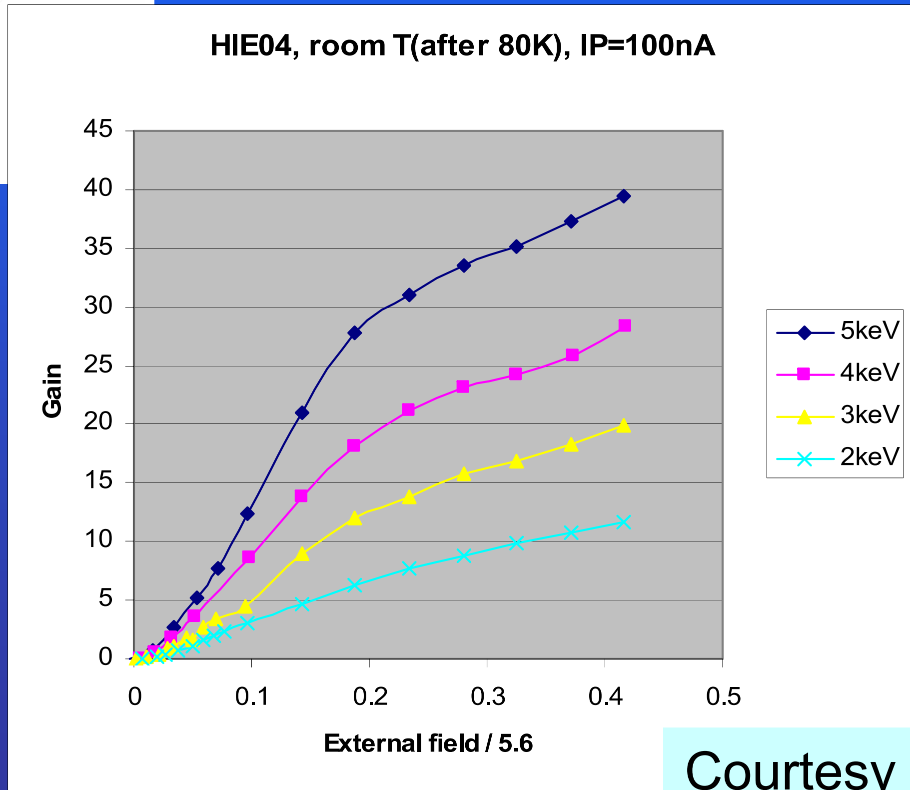


Fig. 1. Cutaway view of a 703.75 MHz SRF laser-photocathode electron gun for high-charge, high-average

New Concept of diamont coated photo-cathod for charge amplification

Recent Results on Photocathode with Diamont Charge Amplifier



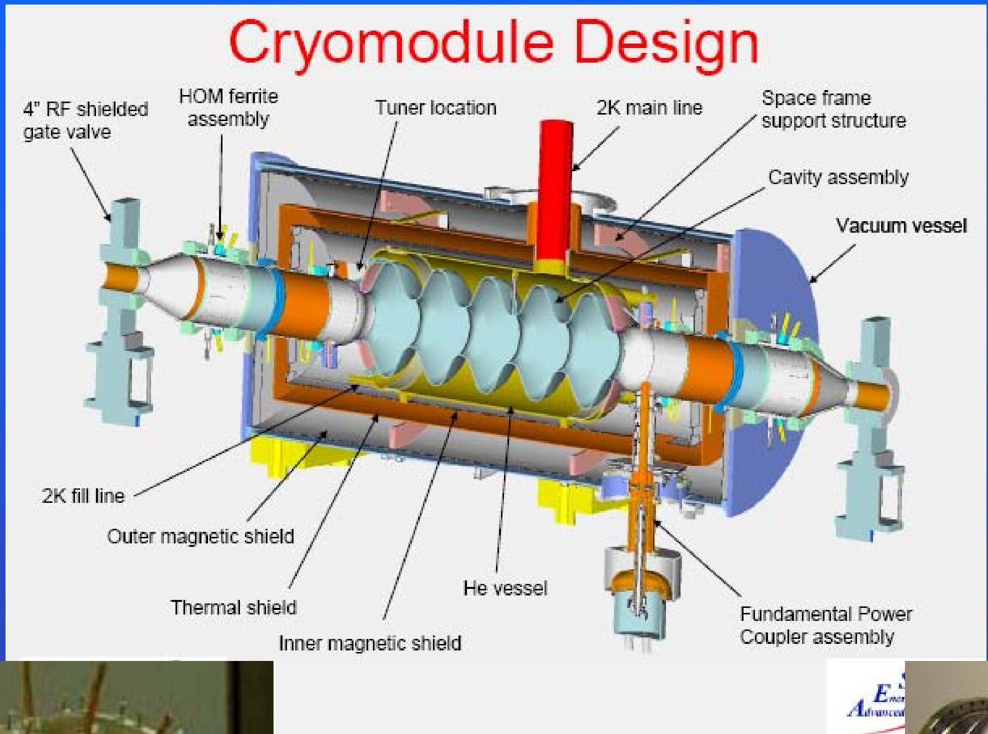


Gain (current measured after emission into vacuum divided by primary current) as function of the field in the diamond. A few primary electron energies are shown.

Courtesy Ilan Ben Zvi

Low- HOM S.C. 0.7GHz Cavities

for CW Beam Currents of 2 Amps



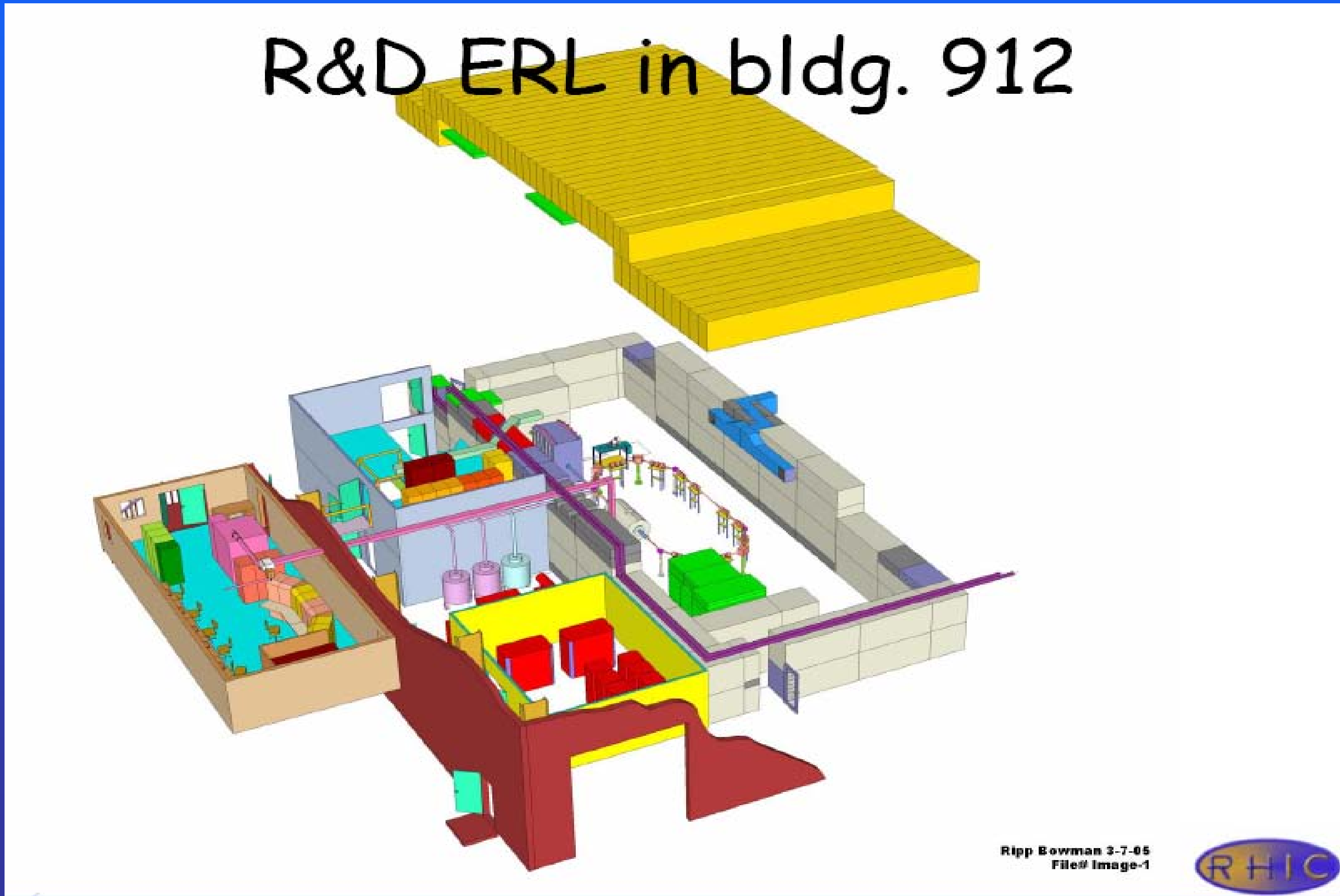
$E_{peak}/E_{av} \approx 2$

E_p/E_a	1.97
H_p/E_a	5.78 $[mT/MV/m]$

Cornell type-

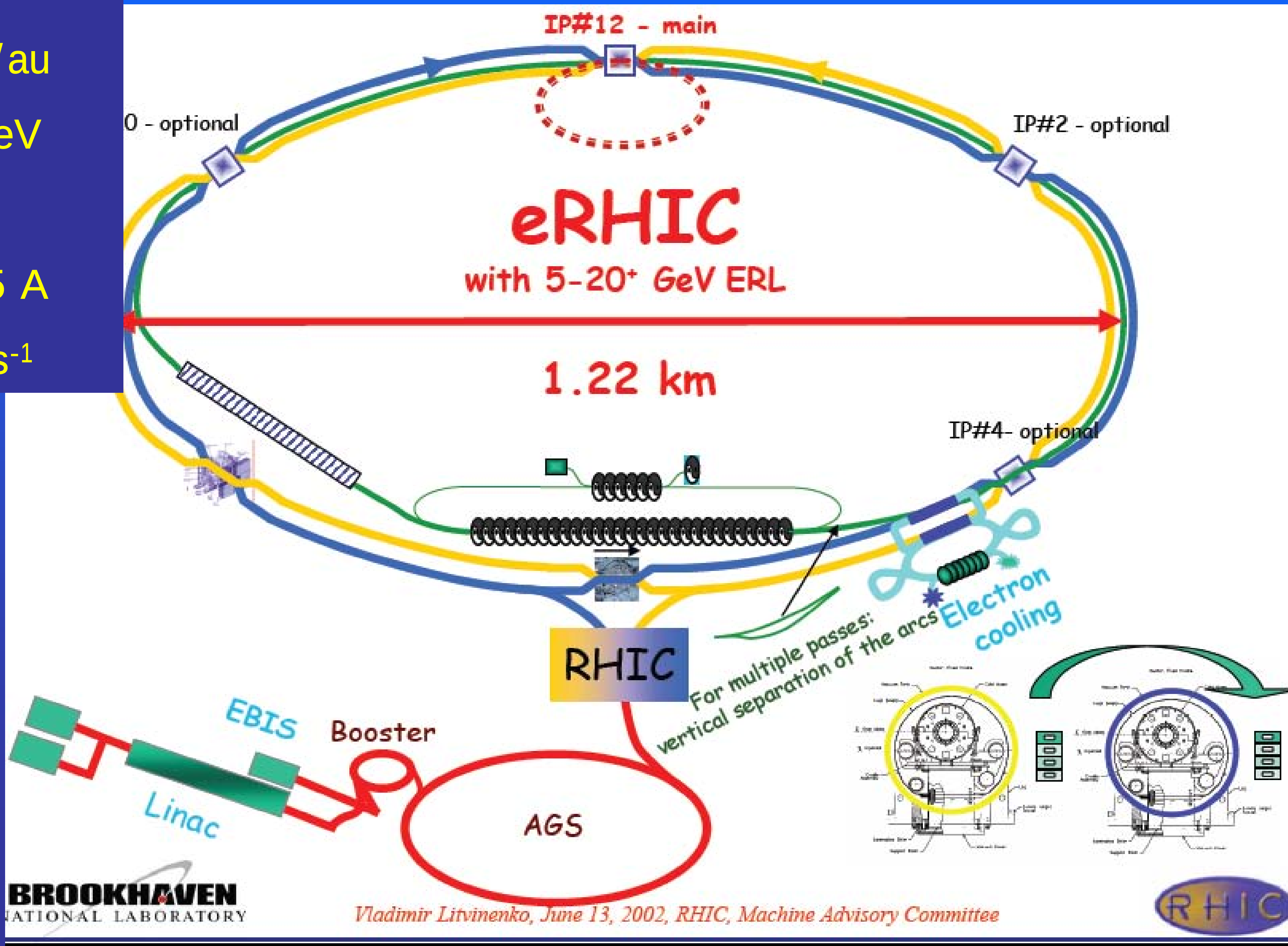
HOM Absorber

Electron Cooler R&D Facility under Construction at BNL



eRHIC: RHIC + 2 Pass ERL

- $E_p \leq 250GEV$
- $E_{au} \leq 100GeV/au$
- $E_e \leq 10(20)$ GeV
- $N_p = 2 \cdot 10^{11}$
- $I_e = (4x)\ 0.45$ A
- $L = 10^{34}\ cm^{-2}s^{-1}$



ELIC

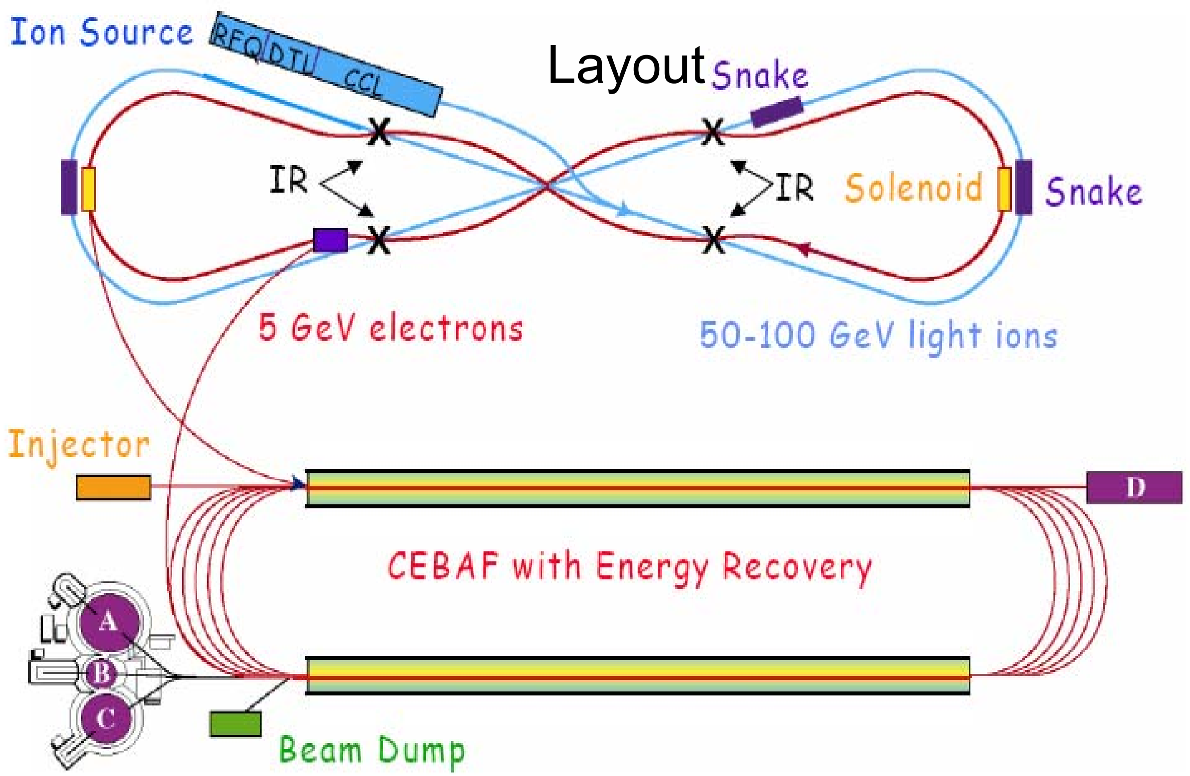


Figure 1: ELIC layout

$E_p \times E_e \leq 100GeV \times 5GeV$

I_e=2.5A

$N_p=10^{10}$, f_b=1.5GHz

$L_{goal}=10^{35}cm^{-2}s^{-1}$

Large crossing angle

& crab crossing

ERL + 100 turn circulator ring ⟶ low current, on energy injector + storage ring

Conclusions

- The successful HERA ep collider comes to an early conclusion with a large number of important physics results
- However the structure of hadronic matter is still far from being understood fully→ large interest to continue lepton hadron collisions at an extended kinematic range and with more luminosity
- Accelerator scientist have taken up the challenge to provide new lepton hadron collision facilities to satisfy the needs of the physics programme

Orbital Stability

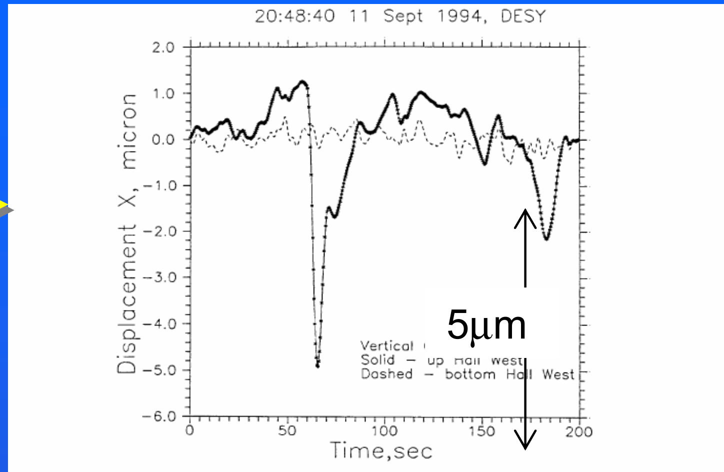
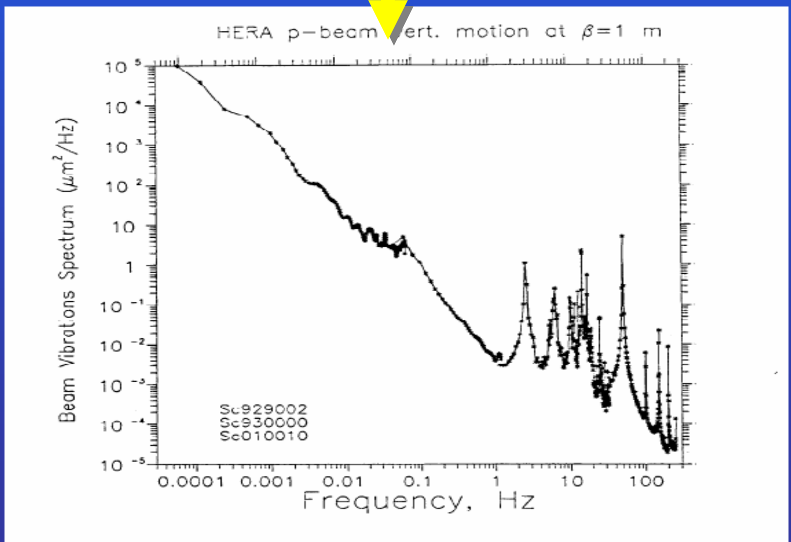


Figure 14:
a) Vertical ground motion about 0.6 km beneath flying airplane: solid line - on the surface. dashed line - on the bottom of HERA Hall West

Brinkmann et al '95

Street noise from a highway crossing HERA 60Hz, ~1 μm (occasional)



Brinkmann et al '95

More important: vibrations from pumps, turbulent cooling water, power supply ripple + NONLINEAR FIELD of e-Beam, coherent e-beam oscillations

➔Chaotic Proton Orbits➔ Diffusion, Halo, **BACKGROUNDS**

➔**Tune Modulation Feedback**

➔**Improved Power Supplies**

➔**Careful control of proton beam parameters**
$\Delta Q < 0.001$

RING-LINAC Colliders

Limited luminosity, (≈10^{31}cm^{-2}s^{-1})limited by beam power

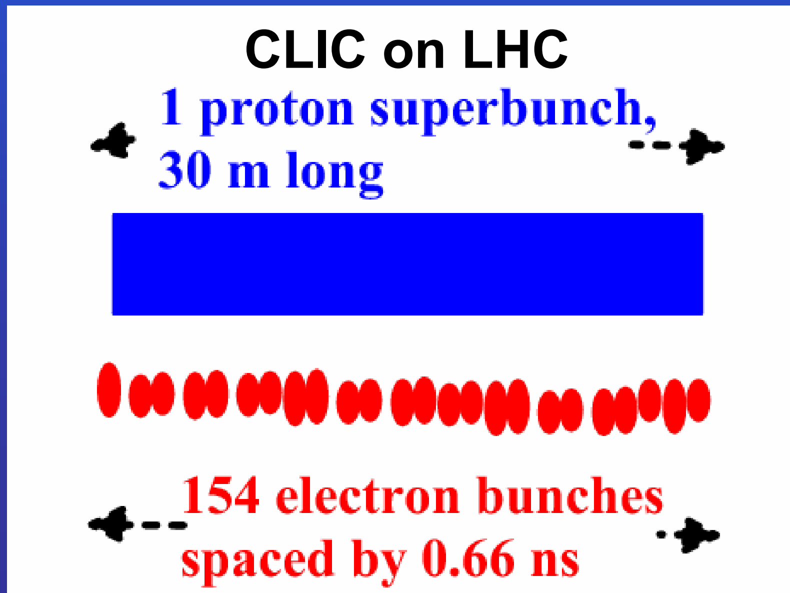
$$L = 4.8\times10^{30}\cdot cm^{-2}s^{-1}\frac{N_p}{10^{11}}\cdot\frac{10^{-6}m}{\varepsilon_p}\cdot\frac{\gamma_p}{1066}\cdot\frac{10cm}{\beta_p^*}\cdot\frac{P_e}{22.6MW}\cdot\frac{250GeV}{E_e}$$

but ultimate center of mass energy

ILC+LHC➔ E_{cm} up to 3.7 TeV (11 x HERA)

Fairly recent idea: collision of short CLIC bunch train with 30m long p super-bunch

(Schulte, Zimmerman, CERN @ EPAC04)



HERA Physics Results

Only a small fraction is shown here

Topics which should at least be mentioned:

- Existence of a large number of „diffractive events“ ➔ existence of a color less object inside the proton
- Heavy quark content of the proton

...

Non-collider results (HERMES)

Large contributions of the gluons to the proton spin, little contribution of the „sea-quarks“ to the proton spin, valence quark contribute with only 0.3

...

Operational Issues with P.C. Sextupoles

Sextupole Change during Ramp $\xi \approx 150$ or 30 units in b_3 (10^{-4} @r=25mm)

➔ beam-pipe wound sextupoles + reference magnets and on-line b_3 measurements with correction fed into corrector circuits

(precision of dynamic measurements ≈1 unit ($\xi \approx 6$))

+ Systematic corrections stored in ramp tables

➔ Corrected $\xi \approx 5$

➔ If $\xi > 5$ ➔ bad life time during snapback, 1-5% beam loss
If $\xi < 0$ ➔ multi mode head tail instability (enhanced by coupling) large beam loss and / or spoiled emittance

➔ Need ξ fine tuning by hand based on analysis of tune spectra

➔ Feedback controls instability by does not allow fine tuning
some emittance growth and L_{spec} reduction

Relevance for LHC: tolerance for beam loss much tighter

➔ **NEED precise, non-distructive ξ measurment**
+ low noise transverse dampers