2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

The Cockcroft Institute of Accelerator Science and Technology

UNIVERSITY OF LIVERPOOL

The LHeC :

Precision sub-attometric Science

John Dainton

Univ Liverpool and the Cockcroft Institute, UK

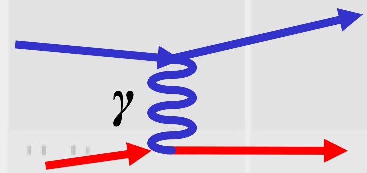
1. The Structure of Matter 2011
2. Beyond the Fermi scale: How?
3. Beyond the Fermi scale: What might be?
4. Status and Summary

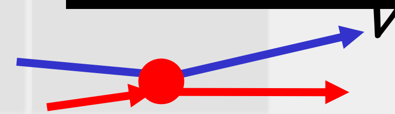
CERN ECFA NuPECC ICFA

2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

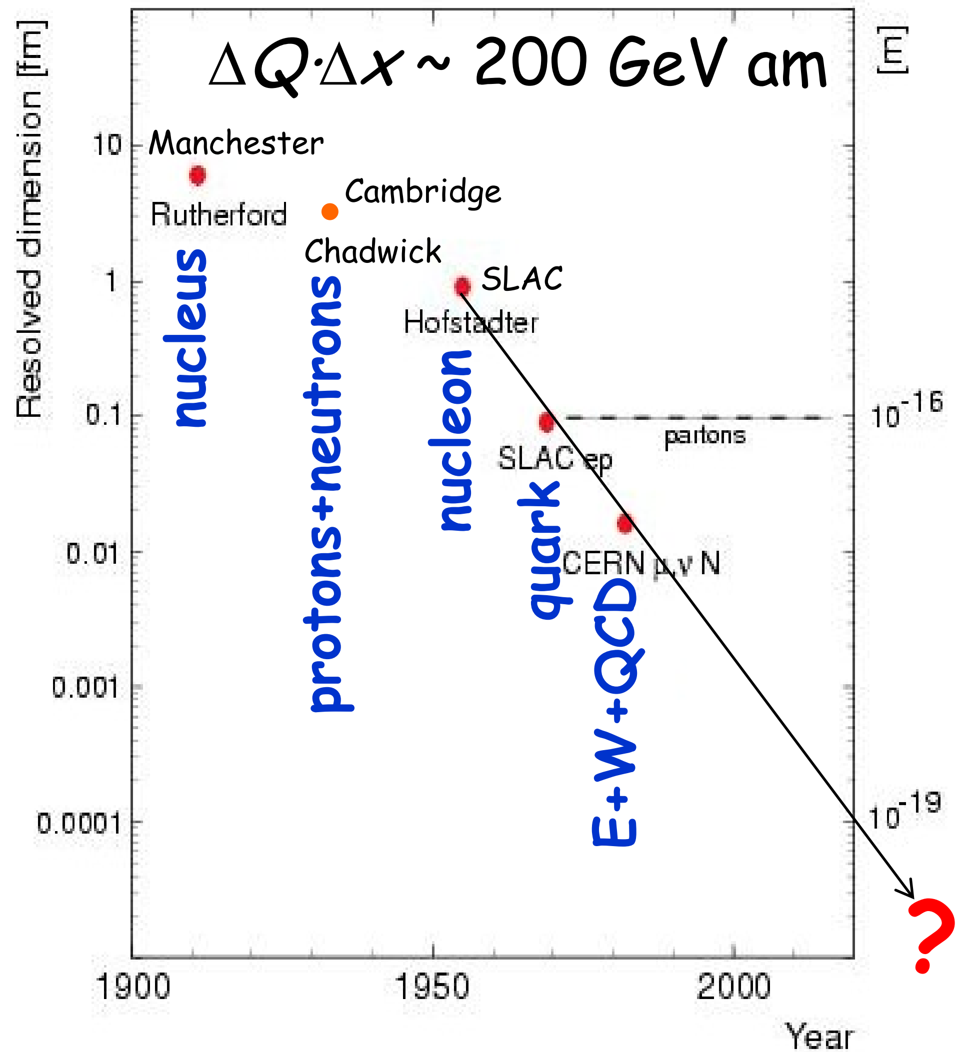
1.The Structure of Matter 2011

Matter @ Short-Distance





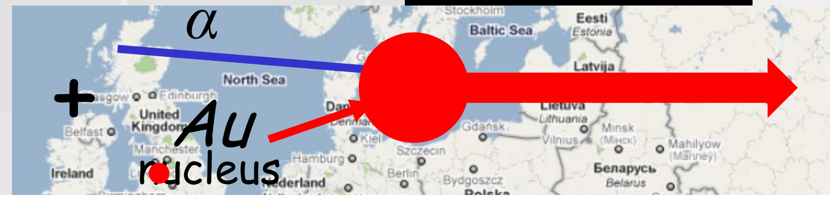
- Rutherford: Nobel
  - 1909 nucleus Megascale
- SLAC end station: Nobel
  - 1959 nucleus size
    nucleon size
    sub-nuclear scale
  - 1967 quarks Nobel
- CERN + Fermilab
  - fixed target
  - sub-fm ($Q \lesssim 20$ GeV)
  - 1972 EW Nobel
    1977 QCD Nobel
    Gigascale

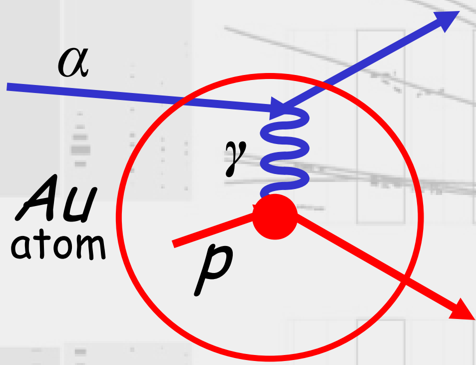


2nd Intl Conference on Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

Matter @ Short-Distance

- Rutherford: Megascale Nobel
  - 1909 nucleus





Philosophical Magazine, volume 21 (1911), pages 669-688

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* By Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a

J. Appl. Phys., Vol. 84, No. 4, 15 August 1998

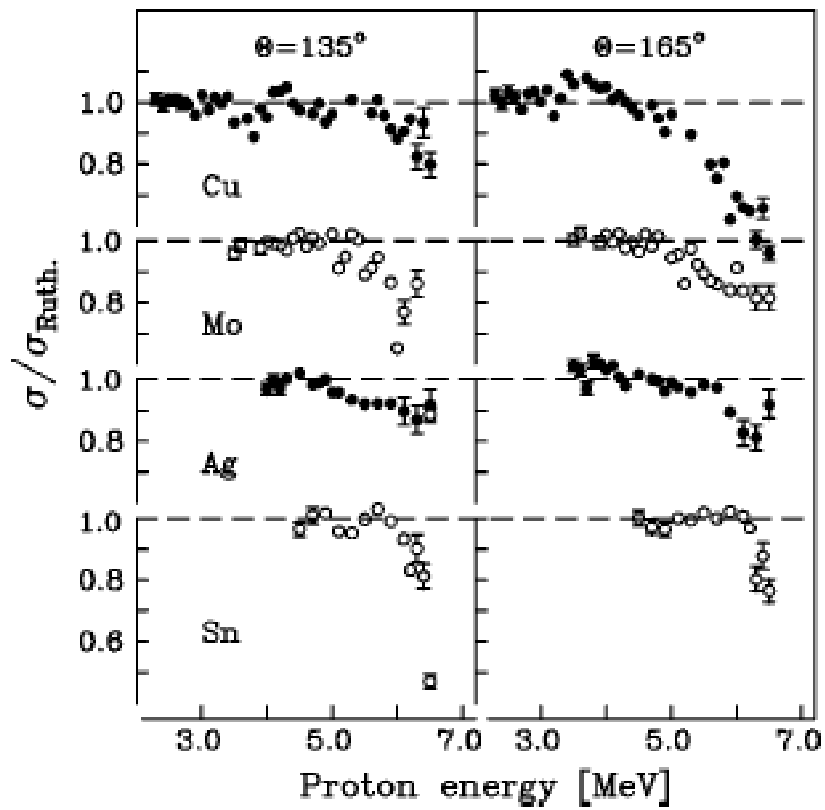
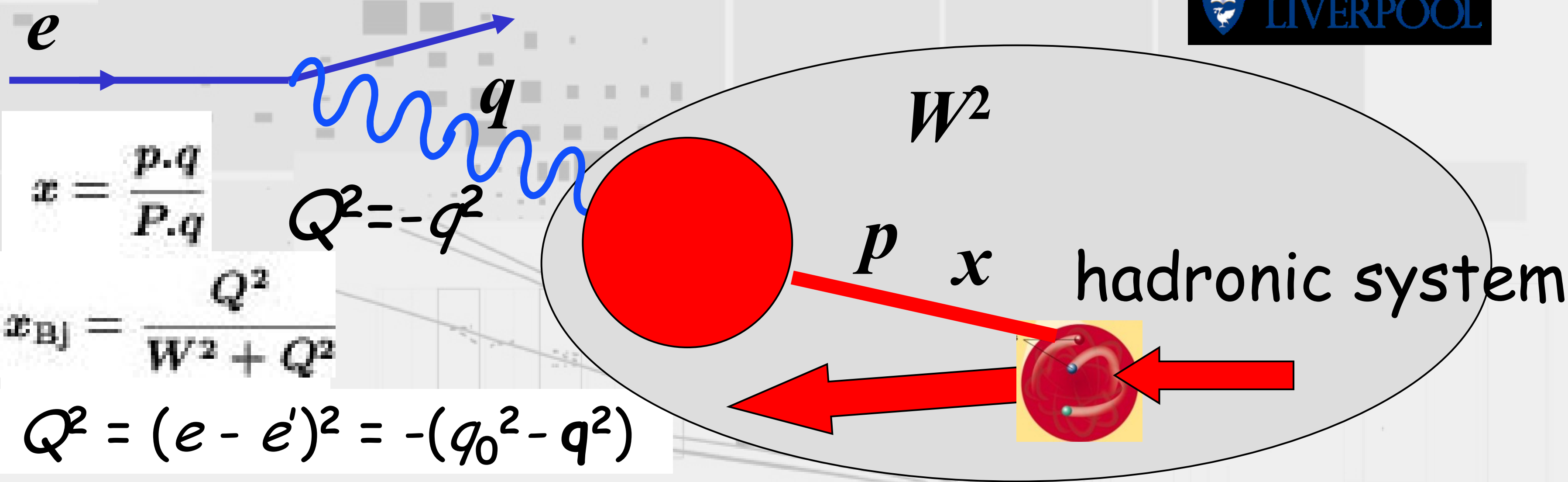


FIG. 1. Elastic scattering cross sections relative to Rutherford cross sections for proton scattering by copper, molybdenum, silver and tin at laboratory scattering angles of 135° and 165°. The uncertainties in the cross section values are indicated in some of the data points.

Kinematics now



$$x = \frac{p.q}{P.q}$$

$$Q^2 = -q^2$$

$$x_{\rm Bj} = \frac{Q^2}{W^2 + Q^2}$$

$$Q^2 = (e - e')^2 = -(q_0^2 - \mathbf{q}^2)$$

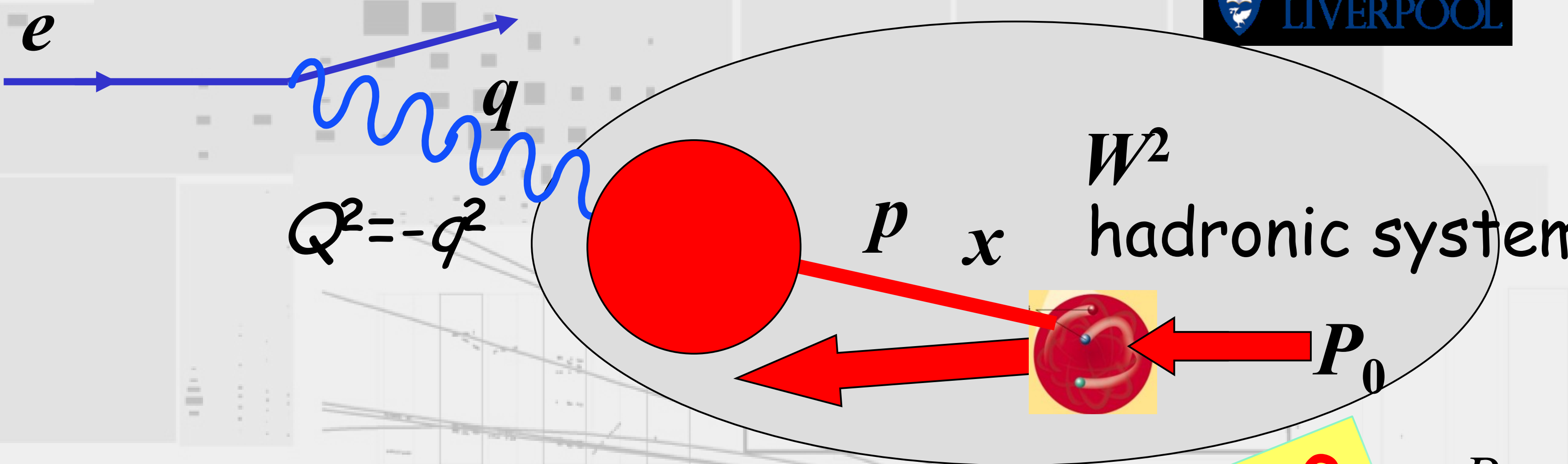
- $\mathbf{q}$ = 3-mom$^{\underline{m}}$ transfer in lepton-hadron interaction
  sensitive to spatial extent of interaction
  $-q_0$ = energy transfer from lepton in interaction
  phase space for dynamics in interaction (W)

↳ probe kinematics → extent+view of interaction

- x = "inelasticity" of struck piece of hadron

↳ target kinematics ↔ extent of interaction

Interaction Scale



- scale $\mathbf{q}\cdot\Delta\mathbf{r}$ ~ 200 GeV·am

$$q_T^2 + \frac{q_L^2}{\gamma^2} = -q^2(1 - \beta\frac{q_L}{xP} - \ldots q^2 \ldots$$

$$= \frac{P_0}{M}$$

- hadron ∞ mom ... q

"snapsh ... contracted target hadron

- had ...

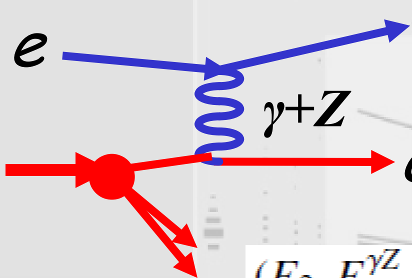
$$\mathbf{q}^2 = q_T^2 + q_L^2 = -q^2\left(1 - \frac{q^2}{4x^2M^2}\right)$$

Where to factorise target↔interaction?
no single solution (Gribov 1965)

magnification of interaction and structure as $x \rightarrow 0$

Hadronic Structure

- EW probe of hadronic structure …
  - neutral current



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

$$\sigma^\pm_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^\pm p}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2}\cdot\frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

$$\tilde{F}_2 = F_2 - \kappa_Z v_e \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2)\cdot F_2^Z ,$$

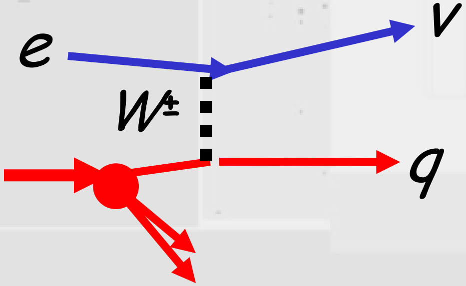
$$\tilde{F}_L = F_L - \kappa_Z v_e \cdot F_L^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2)\cdot F_L^Z ,$$

$$x\tilde{F}_3 = \kappa_Z a_e \cdot xF_3^{\gamma Z} - \kappa_Z^2 \cdot 2v_e a_e \cdot xF_3^Z .$$

$$(F_2, F_2^{\gamma Z}, F_2^Z) = [(e_u^2, 2e_u v_u, v_u^2 + a_u^2)(xU + x\bar{U}) + (e_d^2, 2e_d v_d, v_d^2 + a_d^2)(xD + x\bar{D})]$$

$$(xF_3^{\gamma Z}, xF_3^Z) = 2[(e_u a_u, v_u a_u)(xU - x\bar{U}) + (e_d a_d, v_d a_d)(xD - x\bar{D})] ,$$

  - charged current

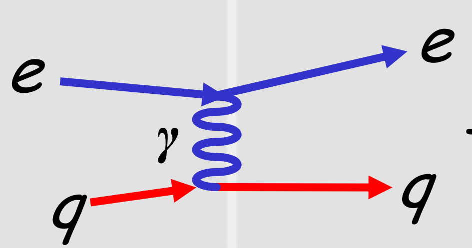


$$\sigma^\pm_{r,\mathrm{CC}} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma^{e^\pm p}_{\mathrm{CC}}}{\mathrm{d}x\mathrm{d}Q^2}$$

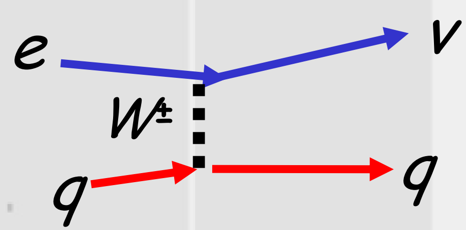
$$\sigma^\pm_{r,CC} = \frac{Y_+}{2}W_2^\pm \mp \frac{Y_-}{2}xW_3^\pm - \frac{y^2}{2}W_L^\pm$$

$$\sigma^+_{r,\mathrm{CC}} = x\overline{U} + (1-y)^2 xD , \qquad \sigma^-_{r,\mathrm{CC}} = xU + (1-y)^2 x\overline{D} .$$

- and beyond ?
  q structure ?



\+

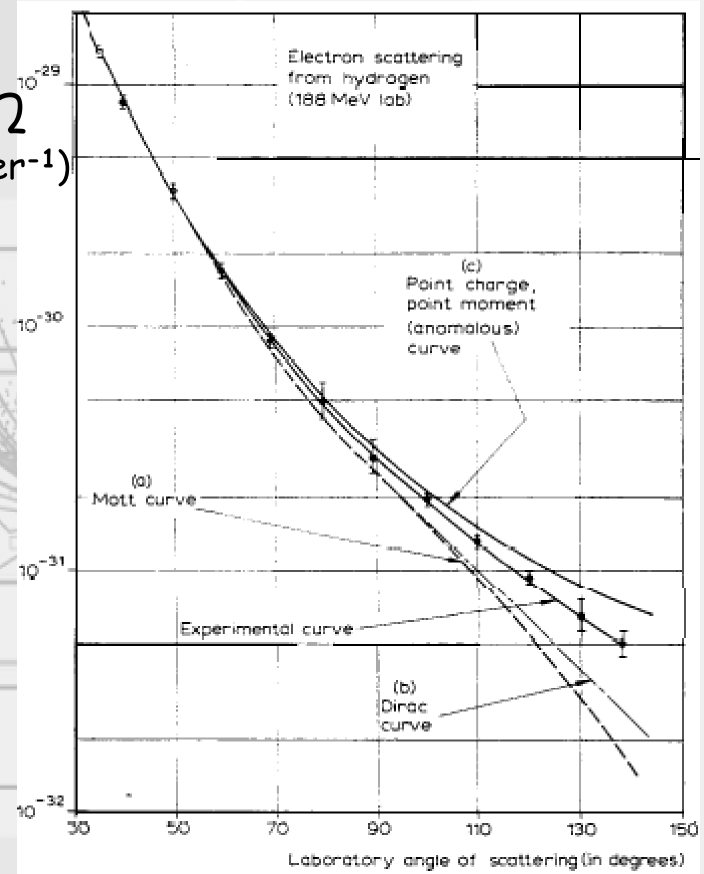


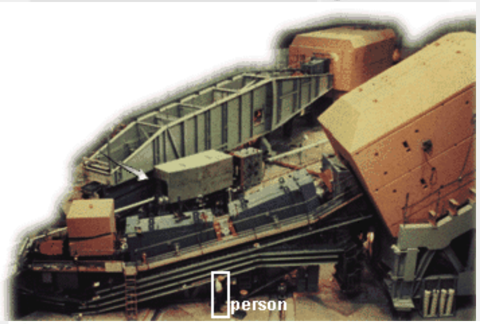
\+ ?

Matter @ Short-Distance

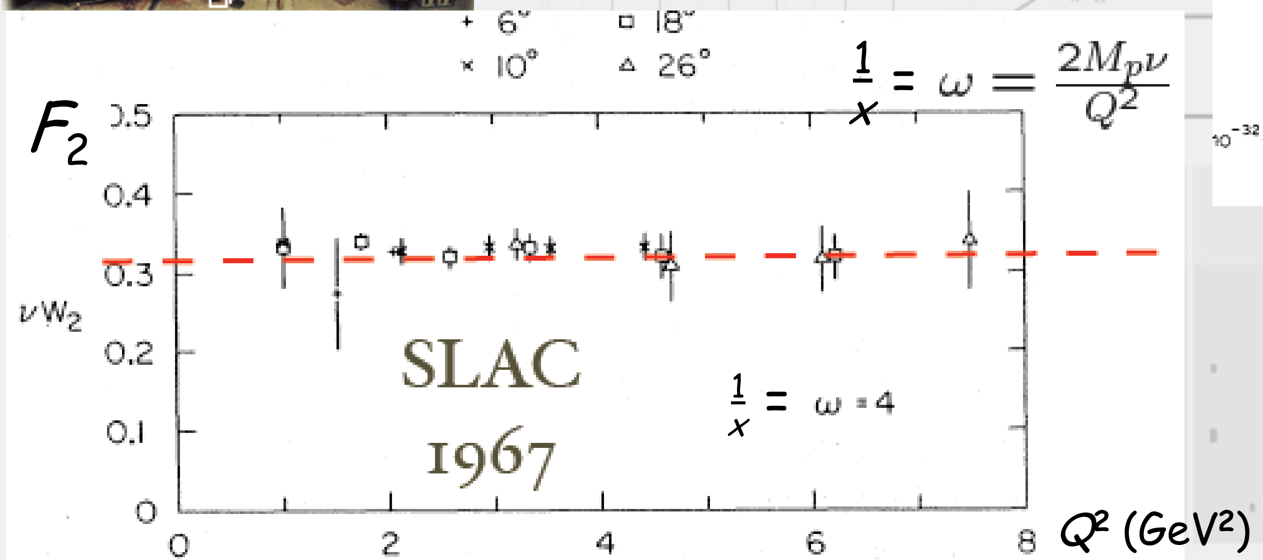
- SLAC end station: **sub-nuclear scale**
  - 1959 nucleus size
    nucleon size — Nobels Hofstädter
  - 1967 quarks — Friedman Kendall Taylor

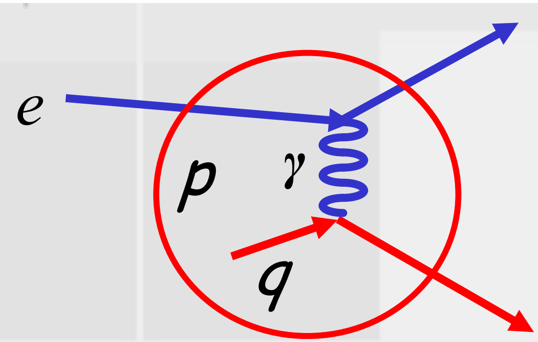
$d\sigma/d\Omega$ ($cm^2 ster^{-1}$)





Proposal:
"A general survey of the basic cross sections which will be useful for future proposals"

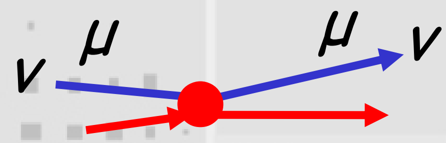




Matter @ Short-Distance

- CERN + Fermilab
  - fixed target
  - sub-fm ($Q \lesssim 20$ GeV)
  - 1972 weak NC

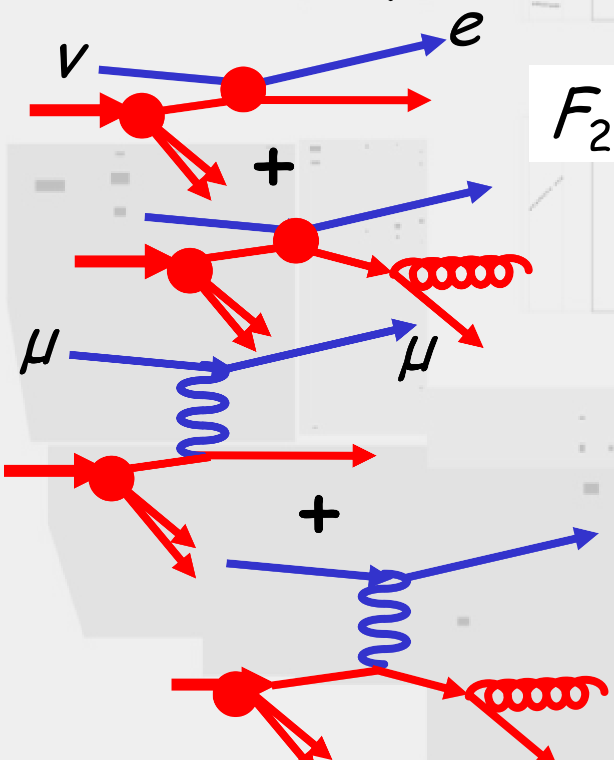
    1977 QCD

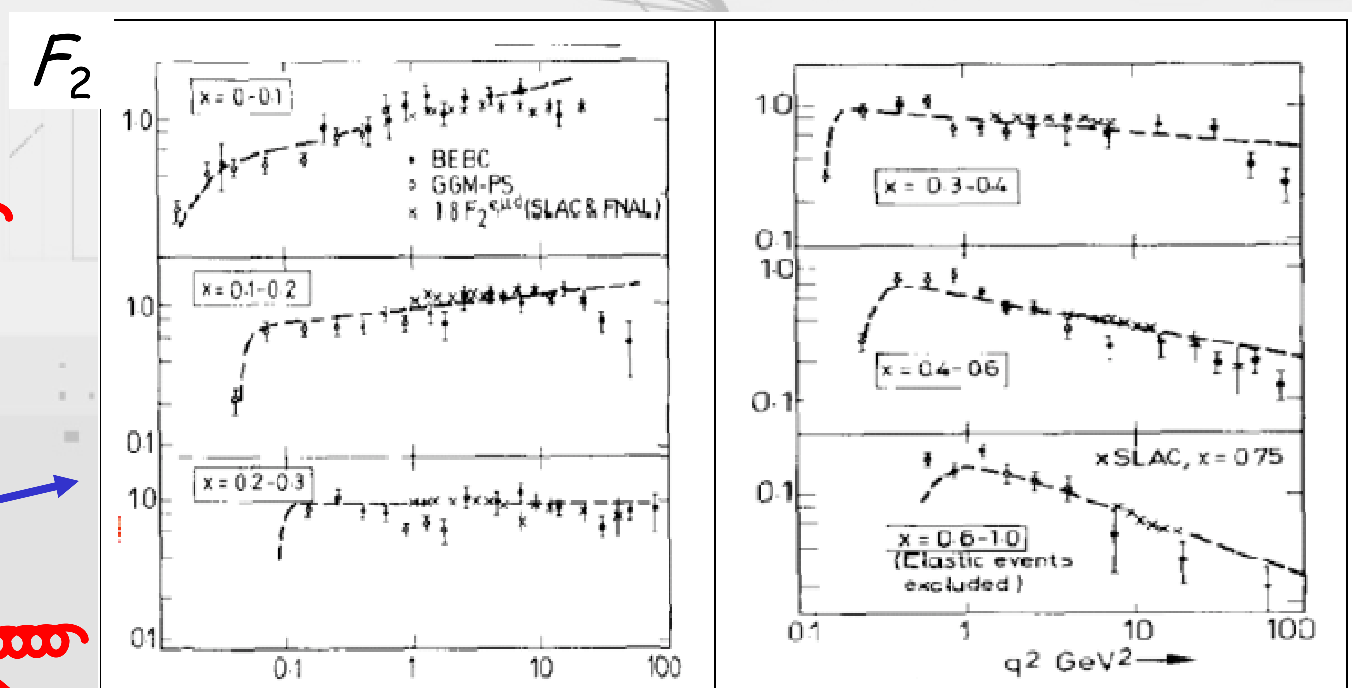


Gigascale

Nobel

Nobel





The Energy Frontier

The Cockcroft Institute of Accelerator Science and Technology
University of Liverpool

- 1968-1986

Gigascale

(charged and neutral lepton l)

pp
Drell Yan
charm
beauty
W,Z
jets

lp
quarks
neutral currents
U(1) e_R
asymptotic freedom

e^+e^-
charm
beauty
jets
3 colours
gluon

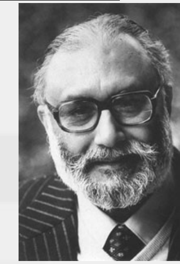
$SU(2)_L \otimes U(1)$

$SU(3)_C$

2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

Why Leptons ↔ Quarks ?

The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL



- beyond the gigascale to the Fermi scale: how are leptons and quarks related ?

THE UNCONFINED QUARKS AND GLUONS

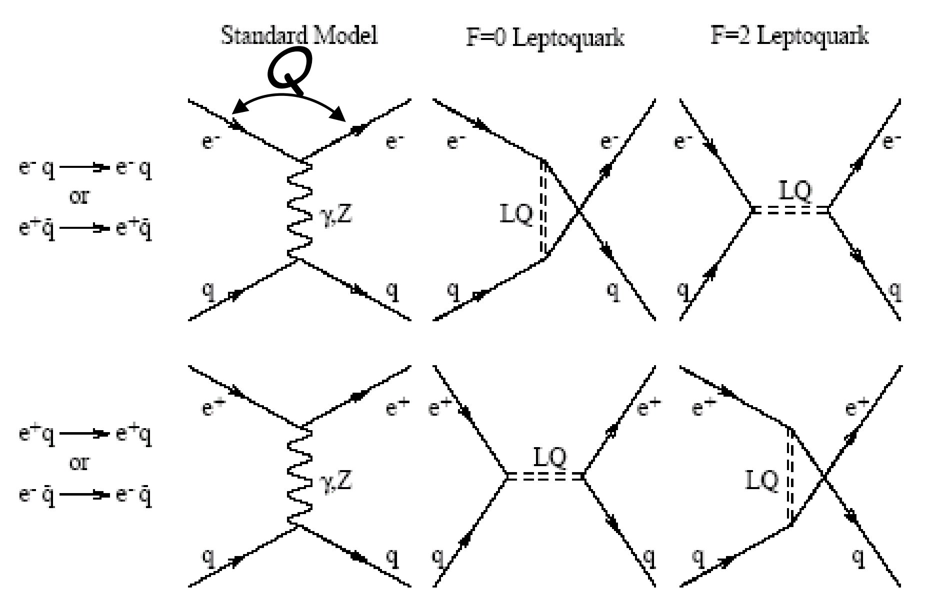
Abdus Salam

International Centre for Theoretical Physics, Trieste, Italy and Imperical College, London, England

1. Introduction

Leptons and hadrons share equally three of the basic forces of nature: electromagnetic, weak and gravitational. The only force which is supposed to distinguish between them is strong. Could it be that leptons share with hadrons this force also, and that there is just one form of matter, not two?

ICHEP76 Tblisi



- put them together at the highest energy in the finest detail $\Delta x \Delta Q \sim \hbar$

2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

A precision Fermiscale *ep* Collider HERA @ DESY

The Cockcroft Institute of Accelerator Science and Technology

UNIVERSITY OF LIVERPOOL

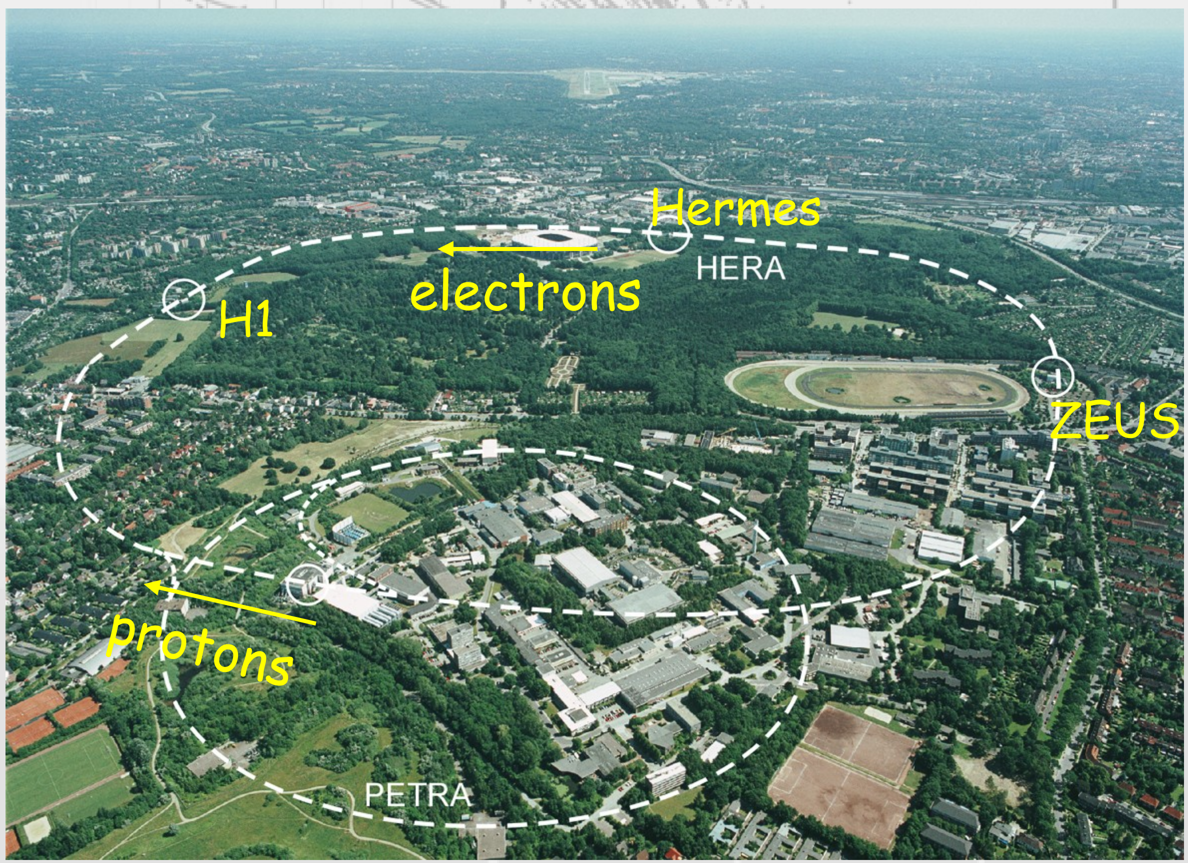
- challenge: different particle species *ep* in collision

27.6 GeV electrons + 920 GeV protons ← *uud* +sea

lepton

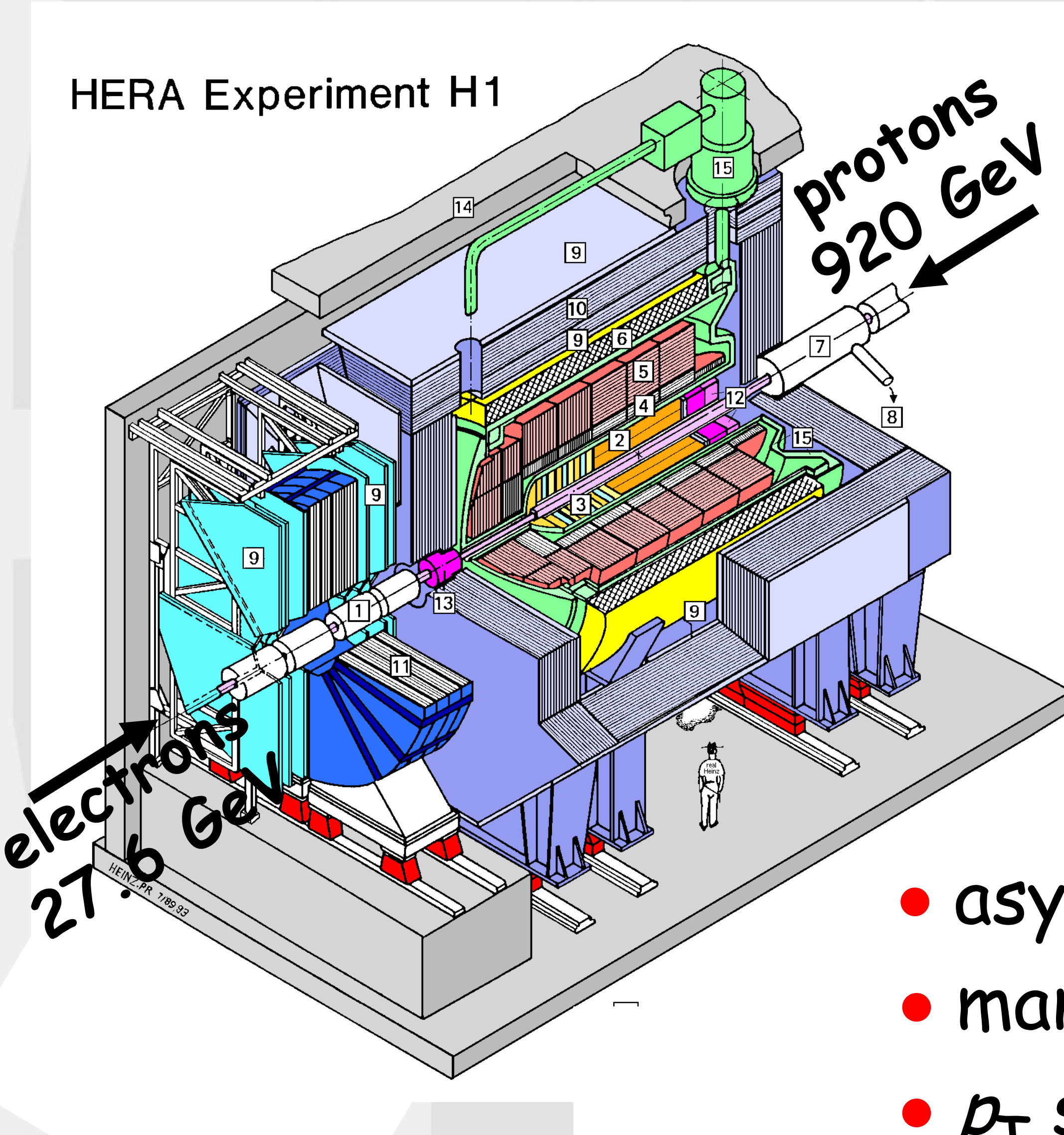
ep cm energy 314 GeV

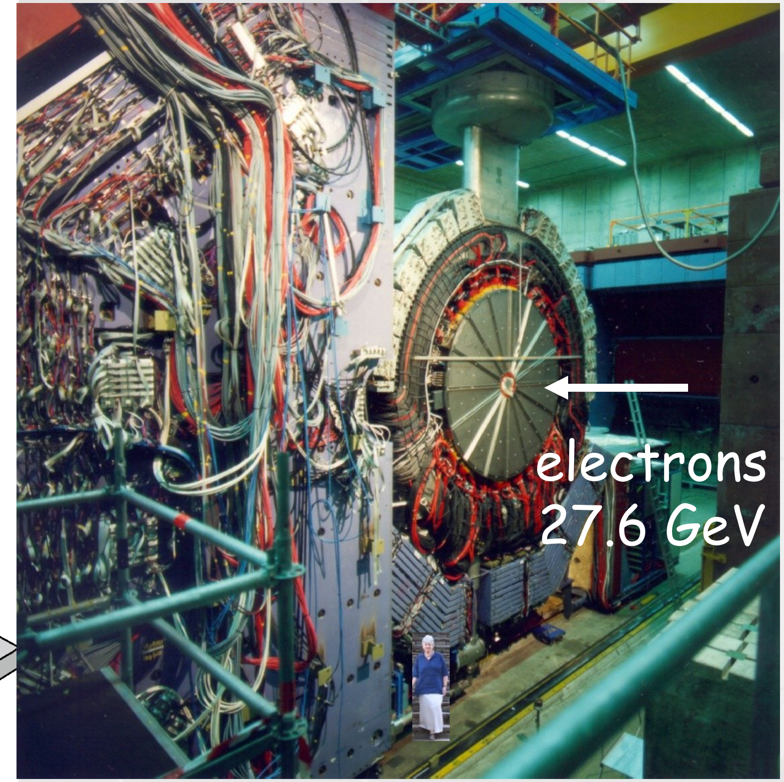
HERA
DESY
Hamburg



HERA
+
1992-2007
RIP

Fermiscale Experiment @ HERA

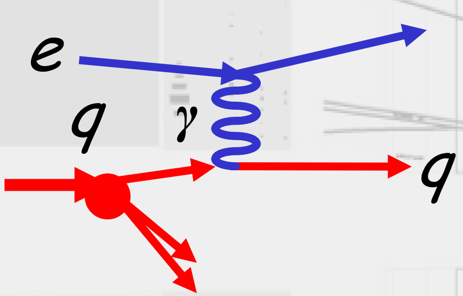




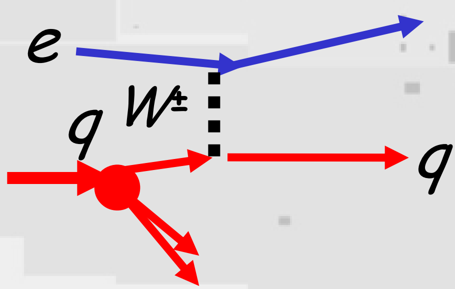
- asymmetric *e* and *p*
- many bunch Δt_{ep} = 75 ns
- p_T scale ~ 300 GeV (Fermi)

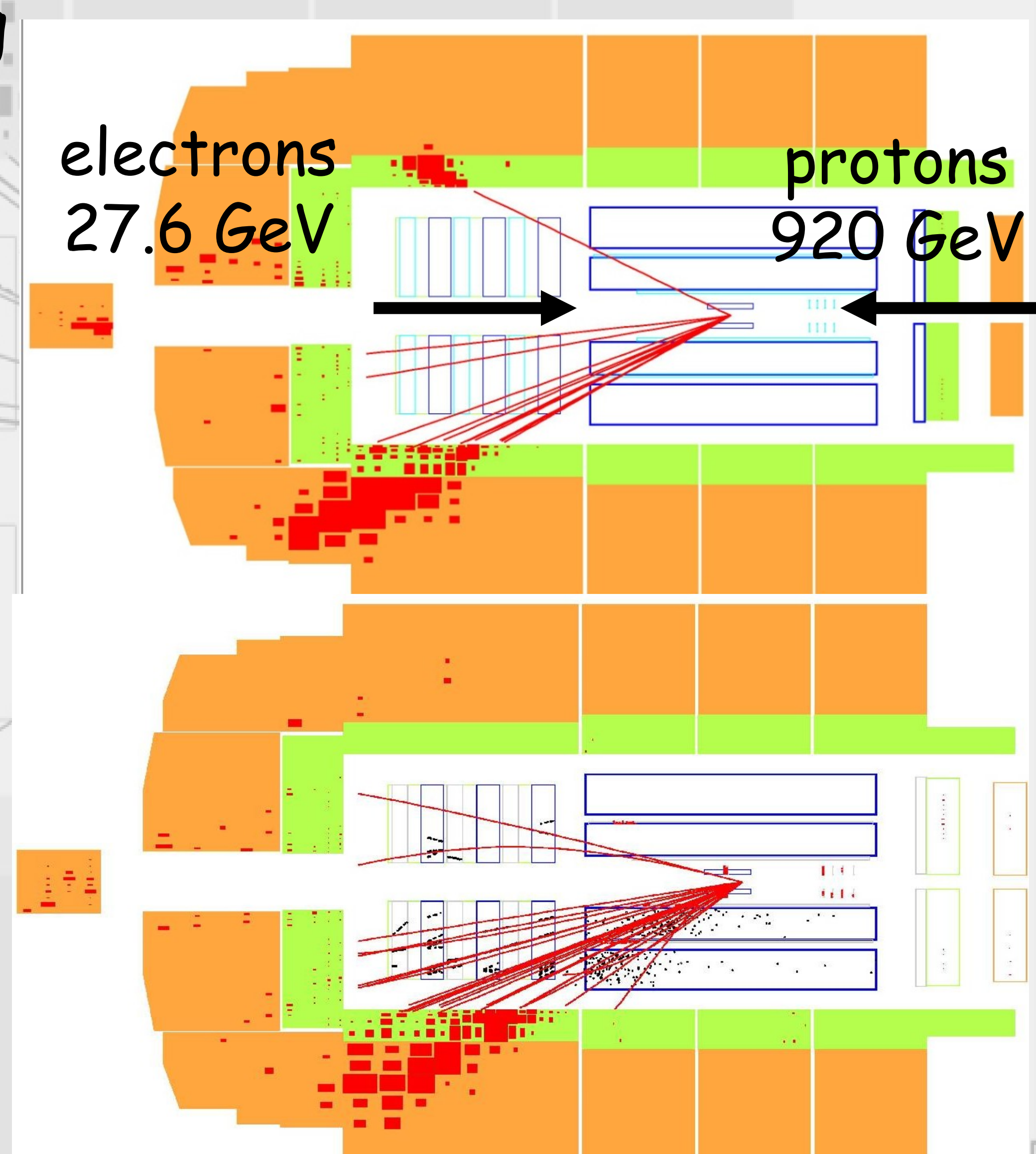
Matter @ Short-Distance

- Rutherford scattering at the Fermi scale
  - neutral current



  - charged current





eq @ Fermi scale

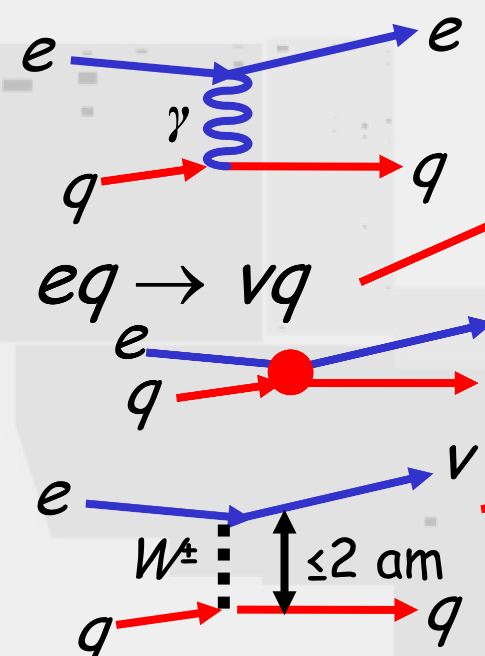
- resolving structure in $SU(2) \otimes U(1)$

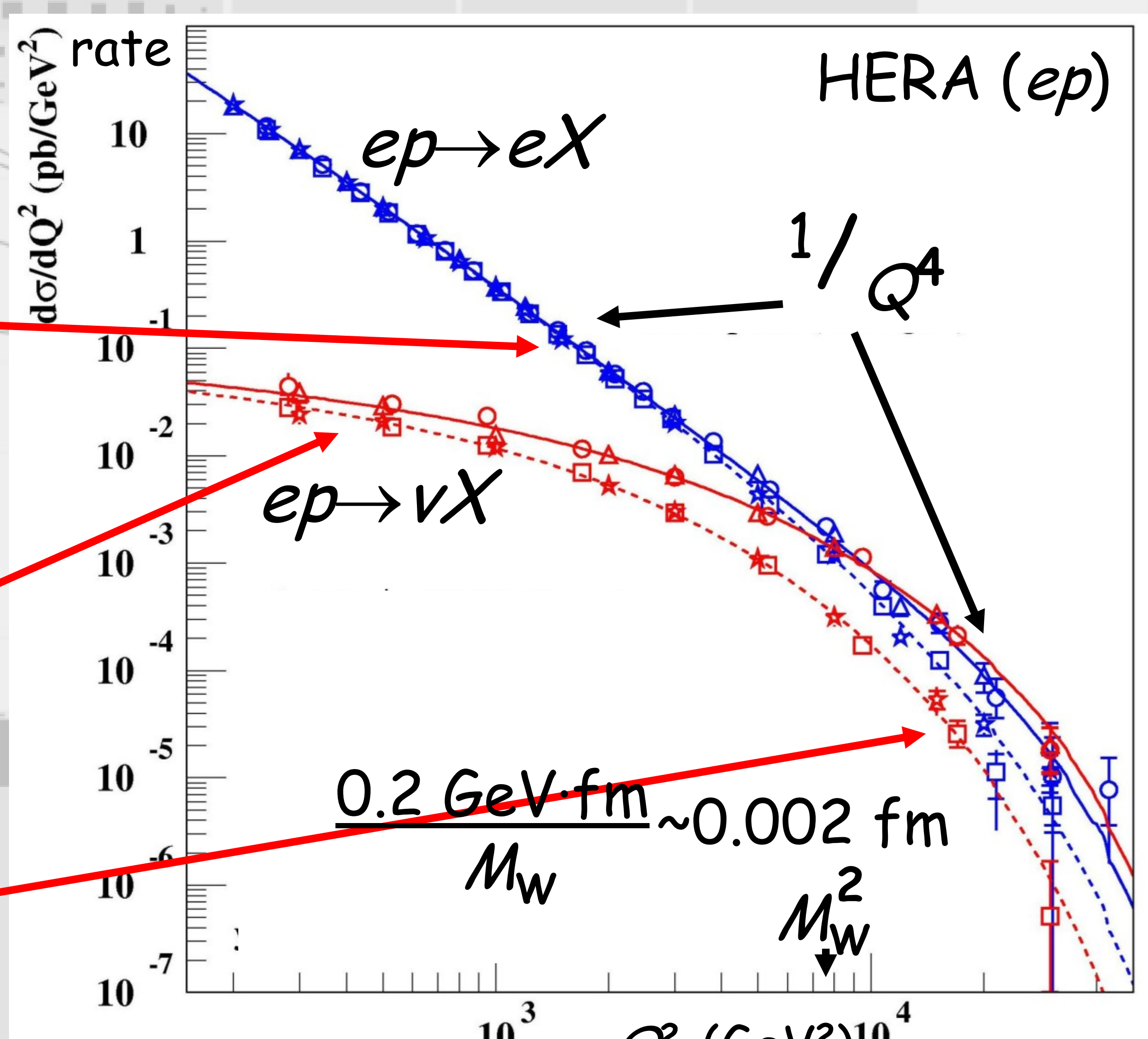
$$\Delta x \sim \frac{0.2\ \text{TeV·am}}{Q}$$

- Rutherford scattering

eq → *eq*

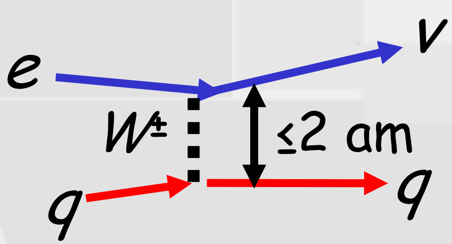
eq → *νq*

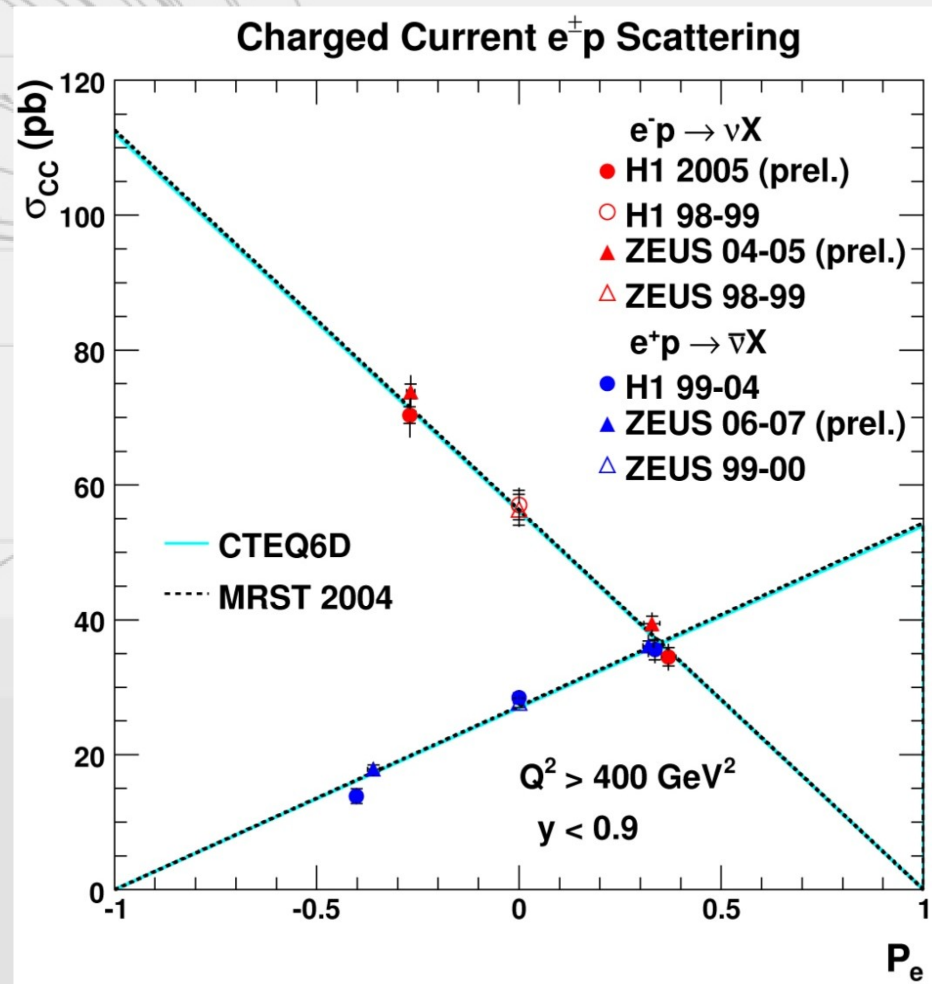




Electron-Quark Physics

- resolving chirality in $SU(2)_L \otimes U(1)_R$
  $O(m^2/s)$: fermion_L anti-fermion_R
- Rutherford scattering + SM helicity $eq \rightarrow \nu q$

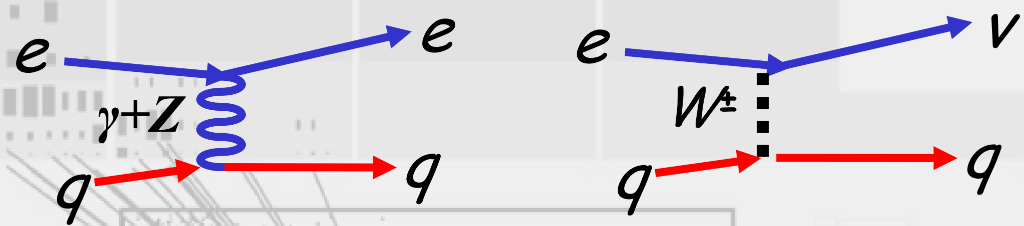


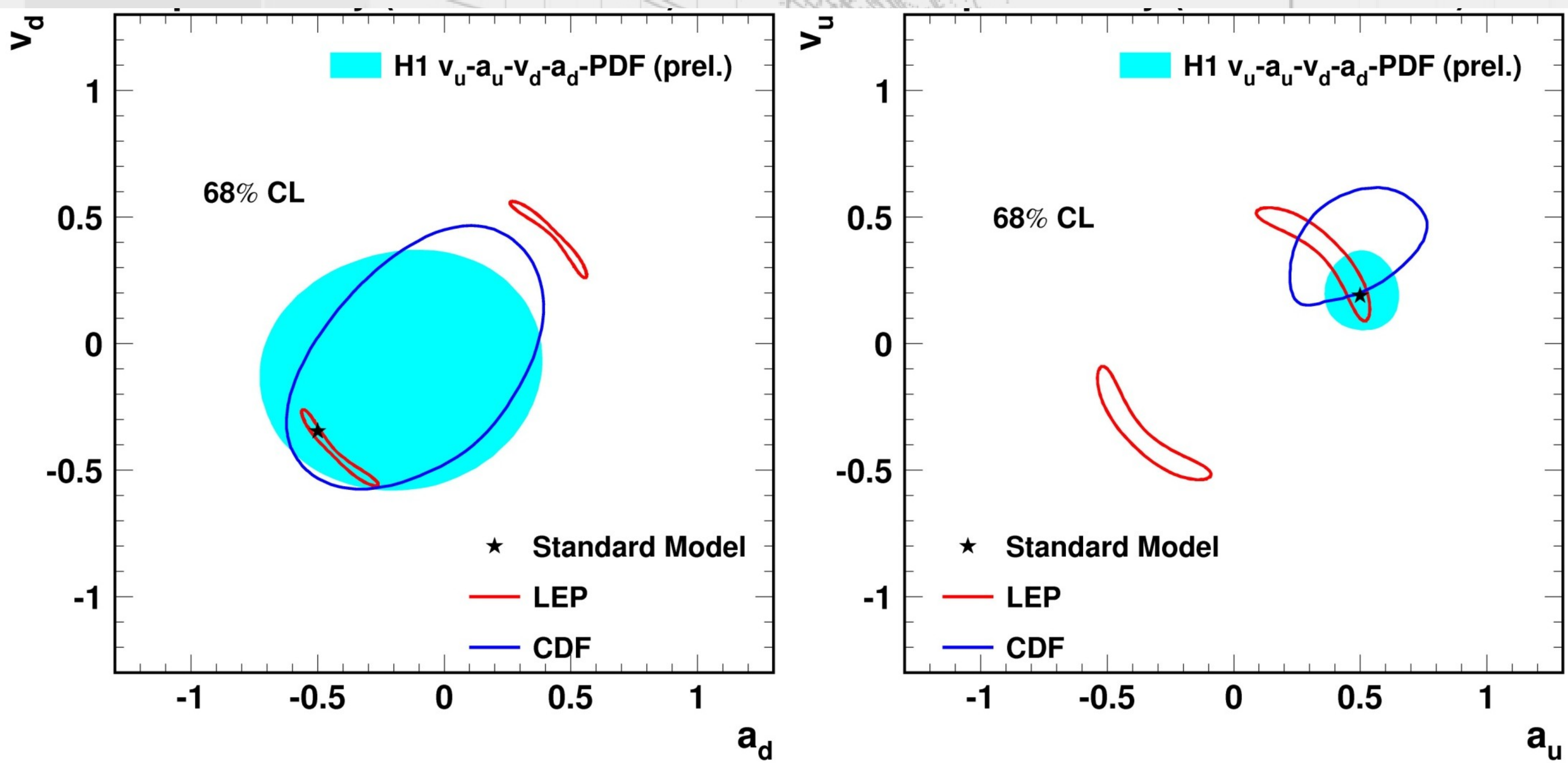


2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

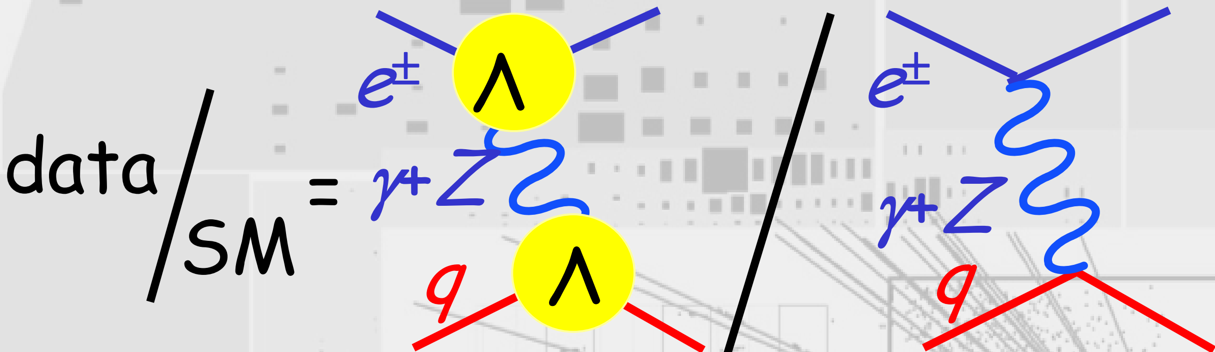
Electron-Quark Physics

- EW q couplings (in proton matter)

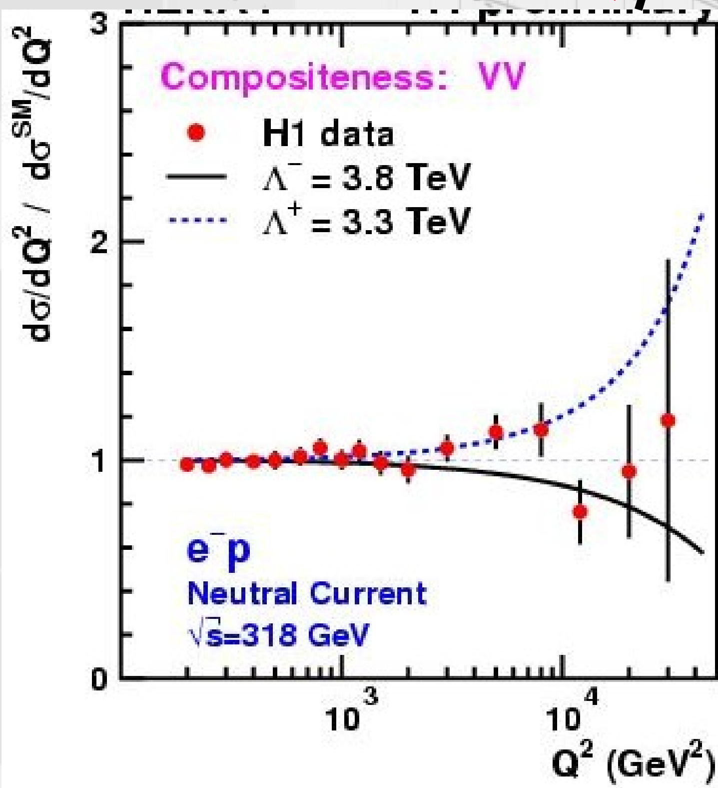


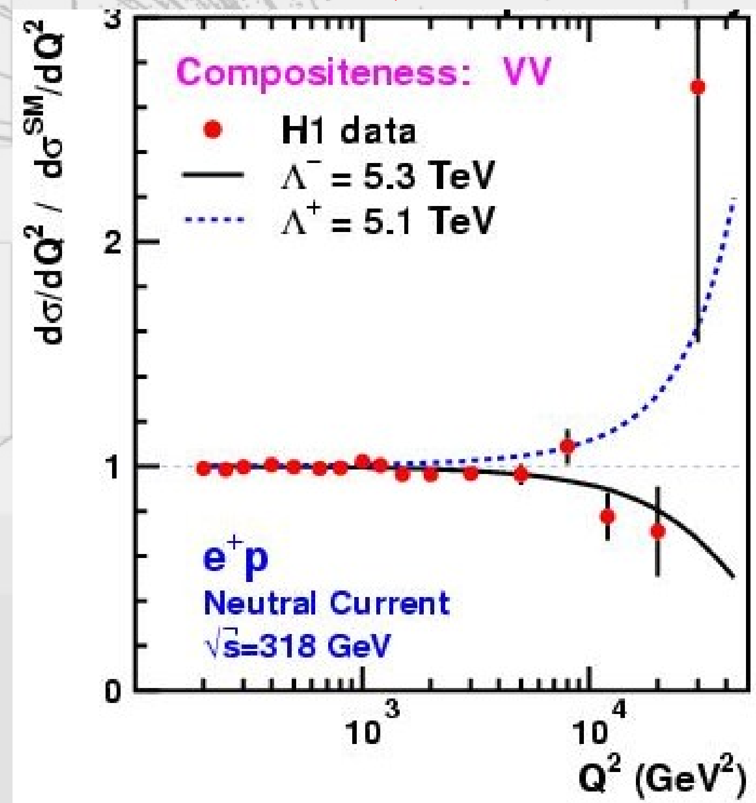


q @ Fermi scale ≥ 1 am



200 GeV·am
(lattice 200 am
@ 1%)

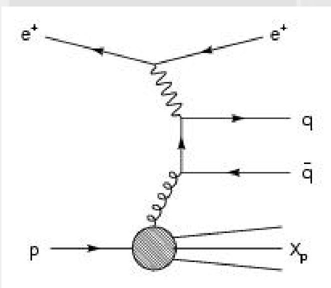


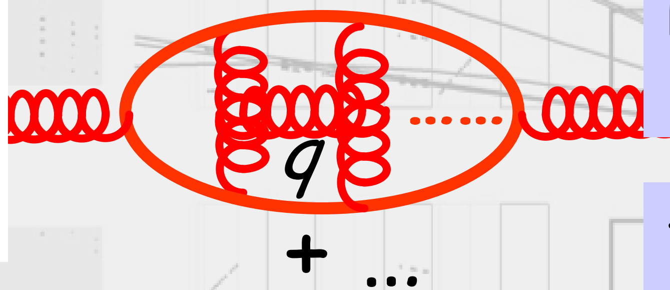


- point-like $Q^2 \leq 4 \times 10^4$ GeV^2 → M_{Planck} > 72 TeV

Nucleon Structure @ Fermi scale

- discovery: q in QCD OK @ Fermi scale
  - magnification at low-x
    QCD → q and g structure

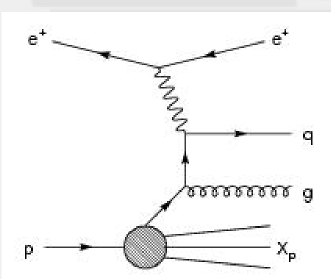


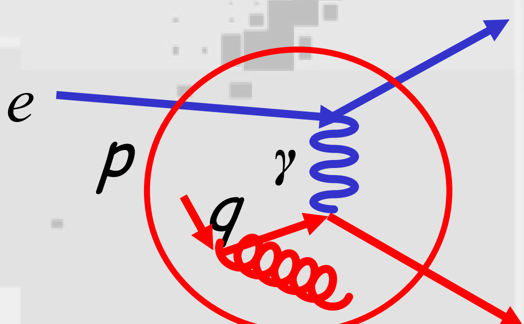


rise at low x

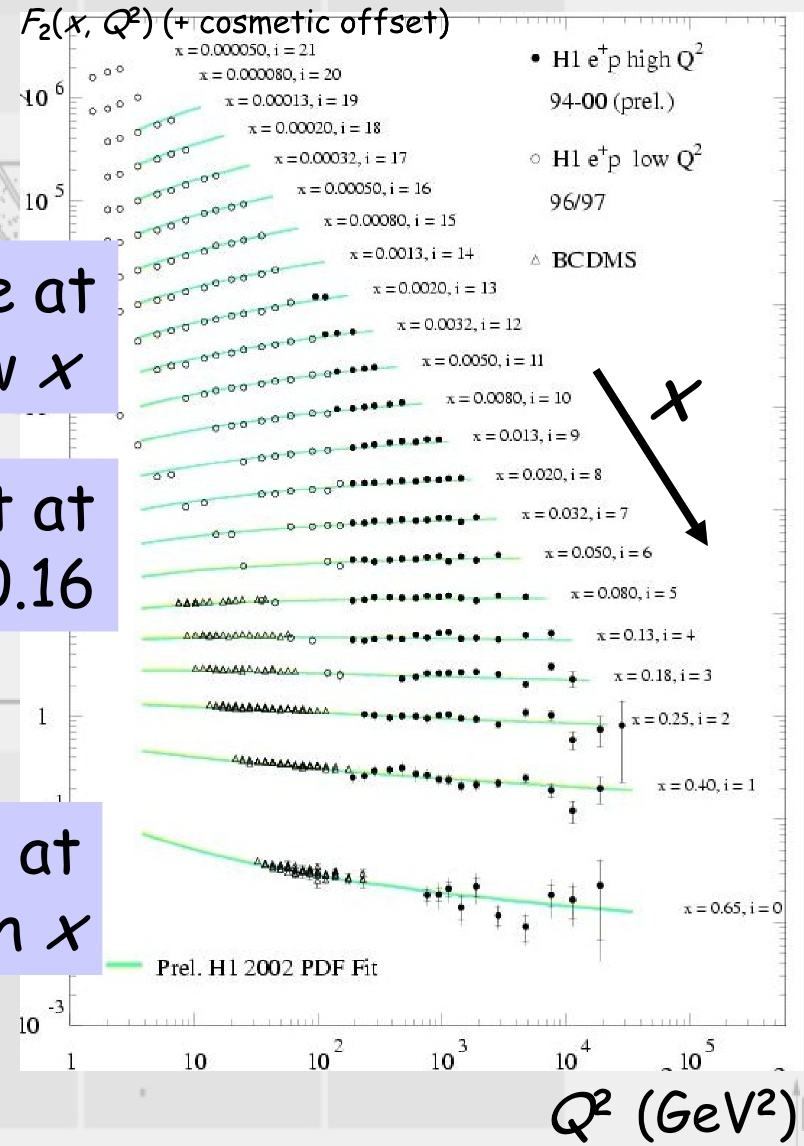
flat at x~0.16

  - precision q_T @ higher-x
    QCD in hadron structure



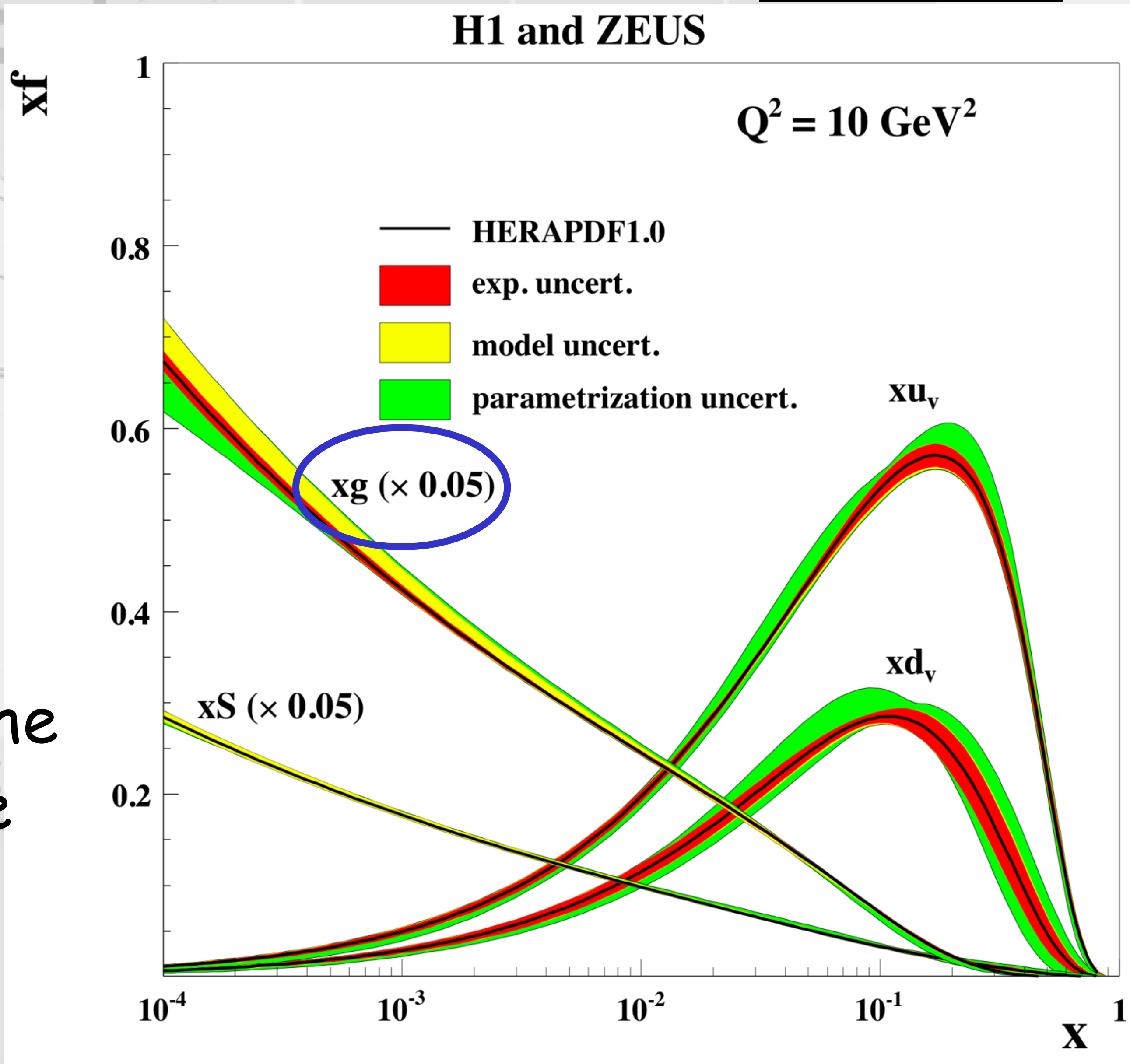


fall at high x



Nucleon Structure

- precision structure of the proton down to the Fermi scale > 1 am
- (almost) what interacts at the LHC Terascale
- what you are made of!

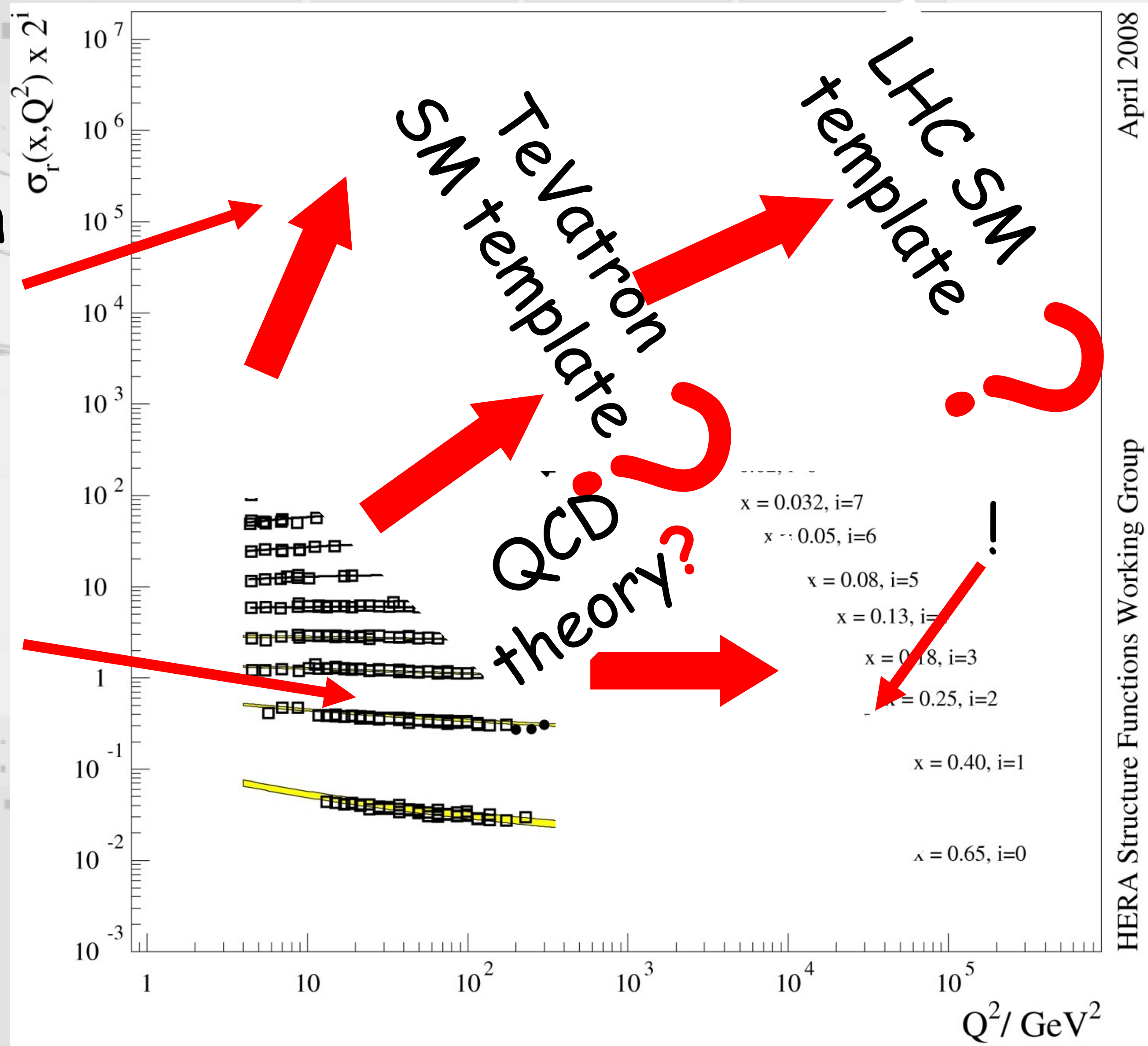


2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

No HERA, no Fermi scale ?

The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

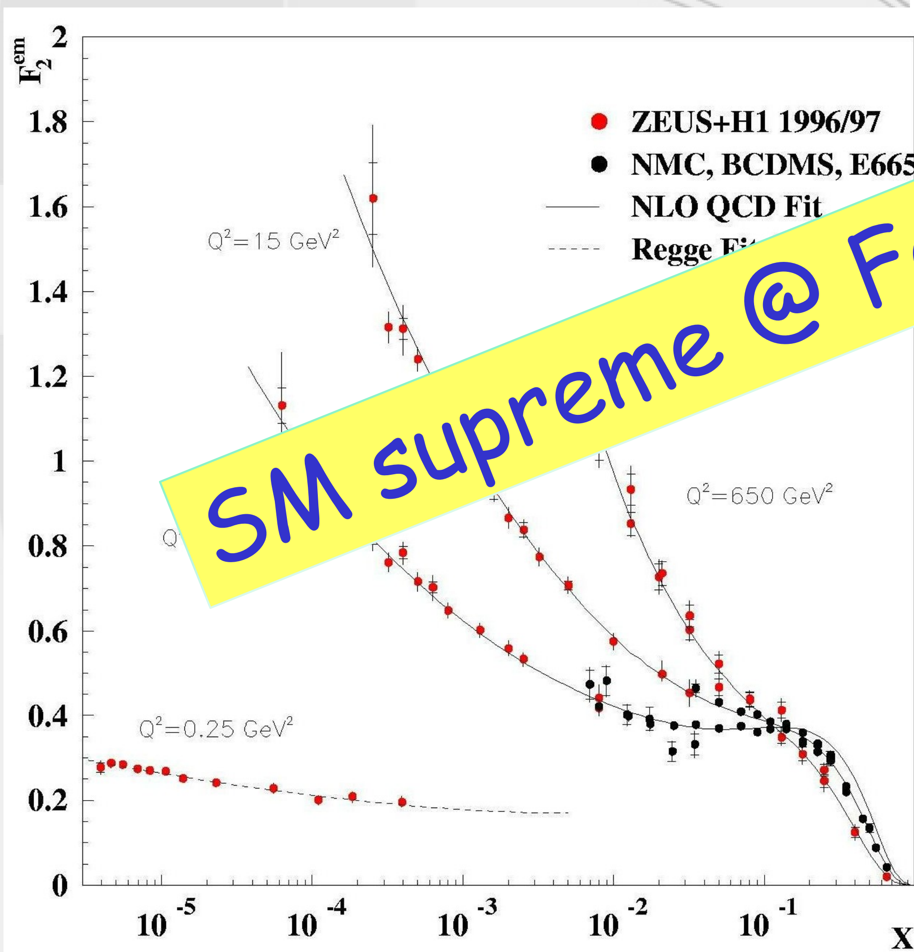
- flavour singlet field q_s evol$^{\underline{n}}$
  - resolving q_s in structure in QCD field
- valence q_v fixed flavour (u d) evolution
  - resolving q_v in p structure

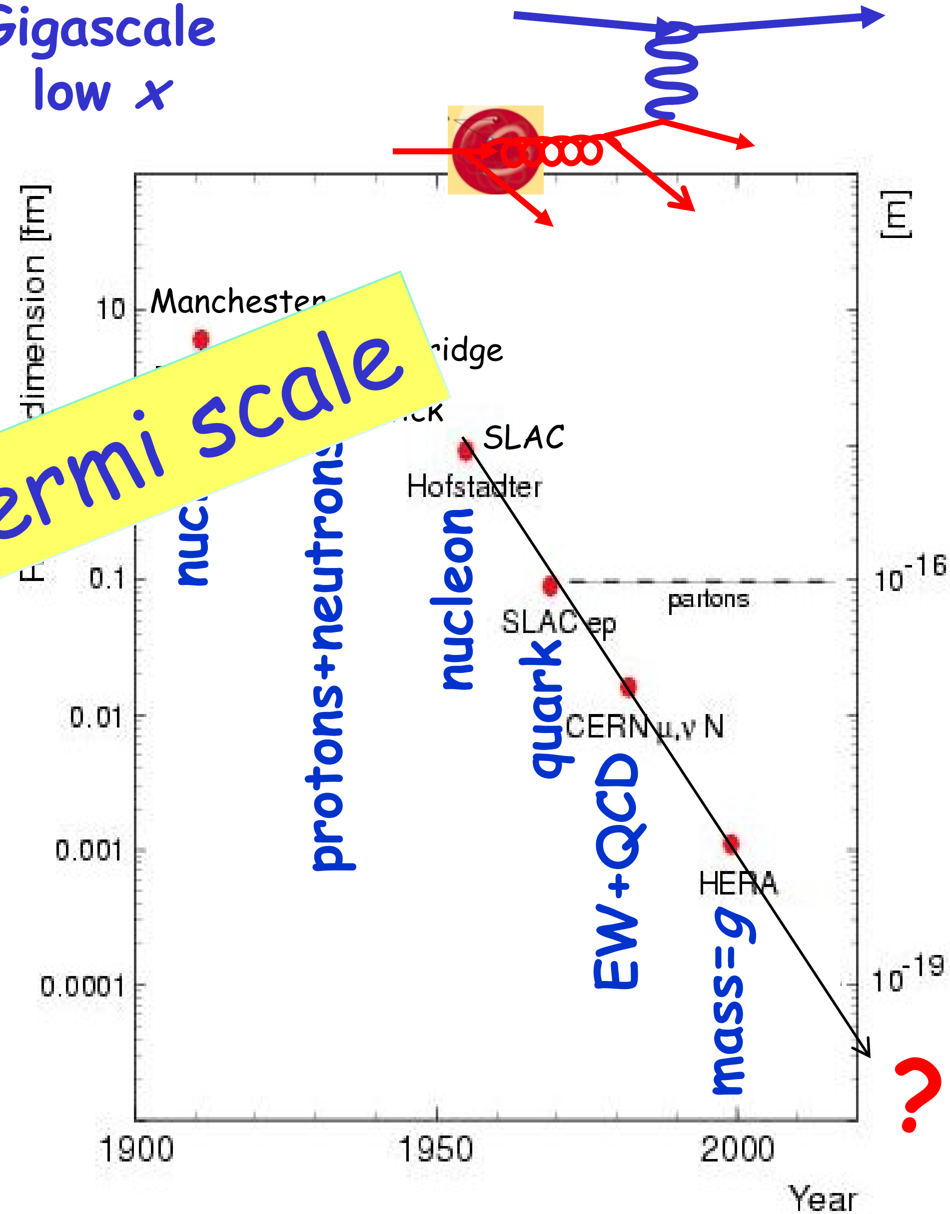


Matter @ Short-Distance

- discovery @ HERA:
  - 1992 origin of visible mass in the Universe

Gigascale
low x





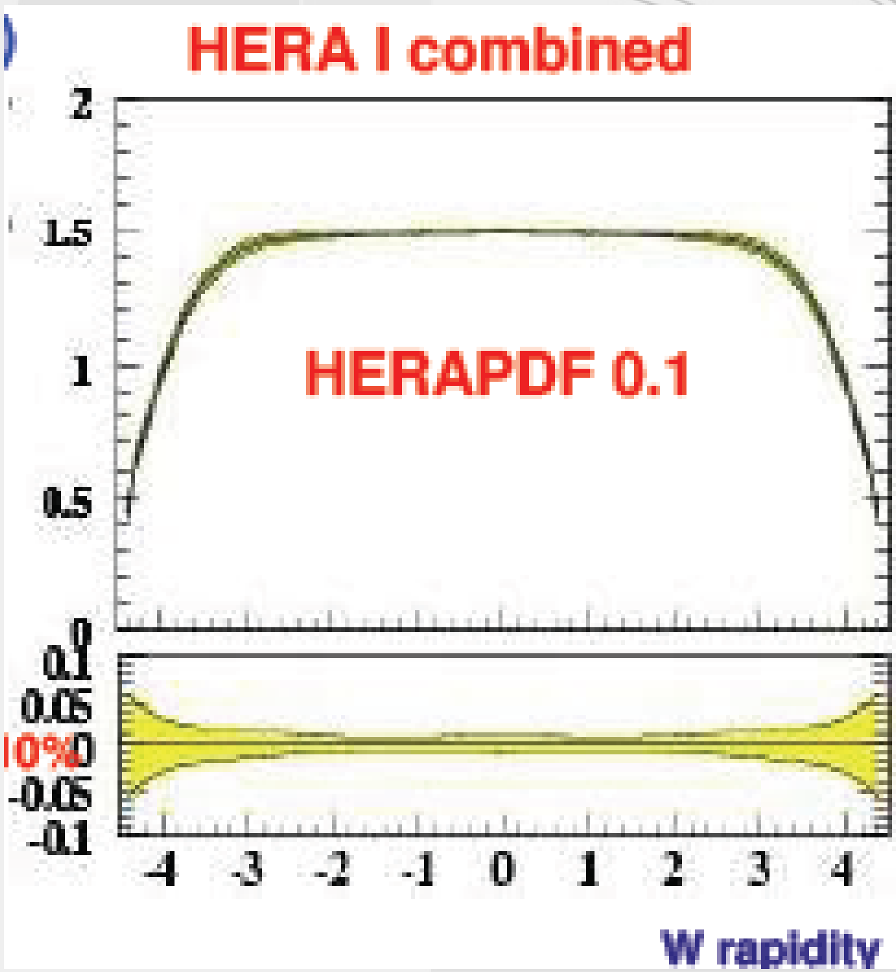
SM supreme @ Fermi scale

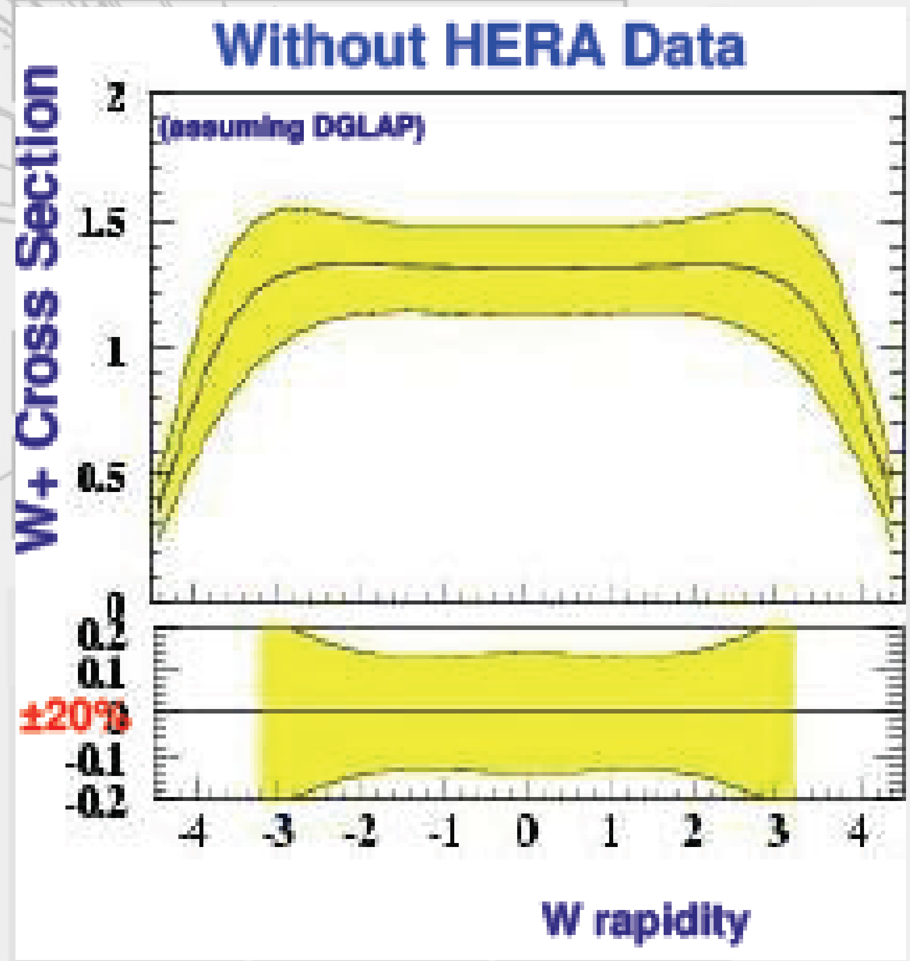
Critical Precision @ HERA

- precision (≲2%) measurements of proton structure
  + QCD evolution Fermi to Terascale

W production @ LHC

Diaconnu ICHEP08





The Energy Frontier

- 1986 - ≥2011
  Fermi scale

pp

b quark
t quark
M_W
(TeVatron)

lp
spacelike EW
quarks > 1 am
precision QCD
high density QCD
c,*b* in hadrons
(HERA)

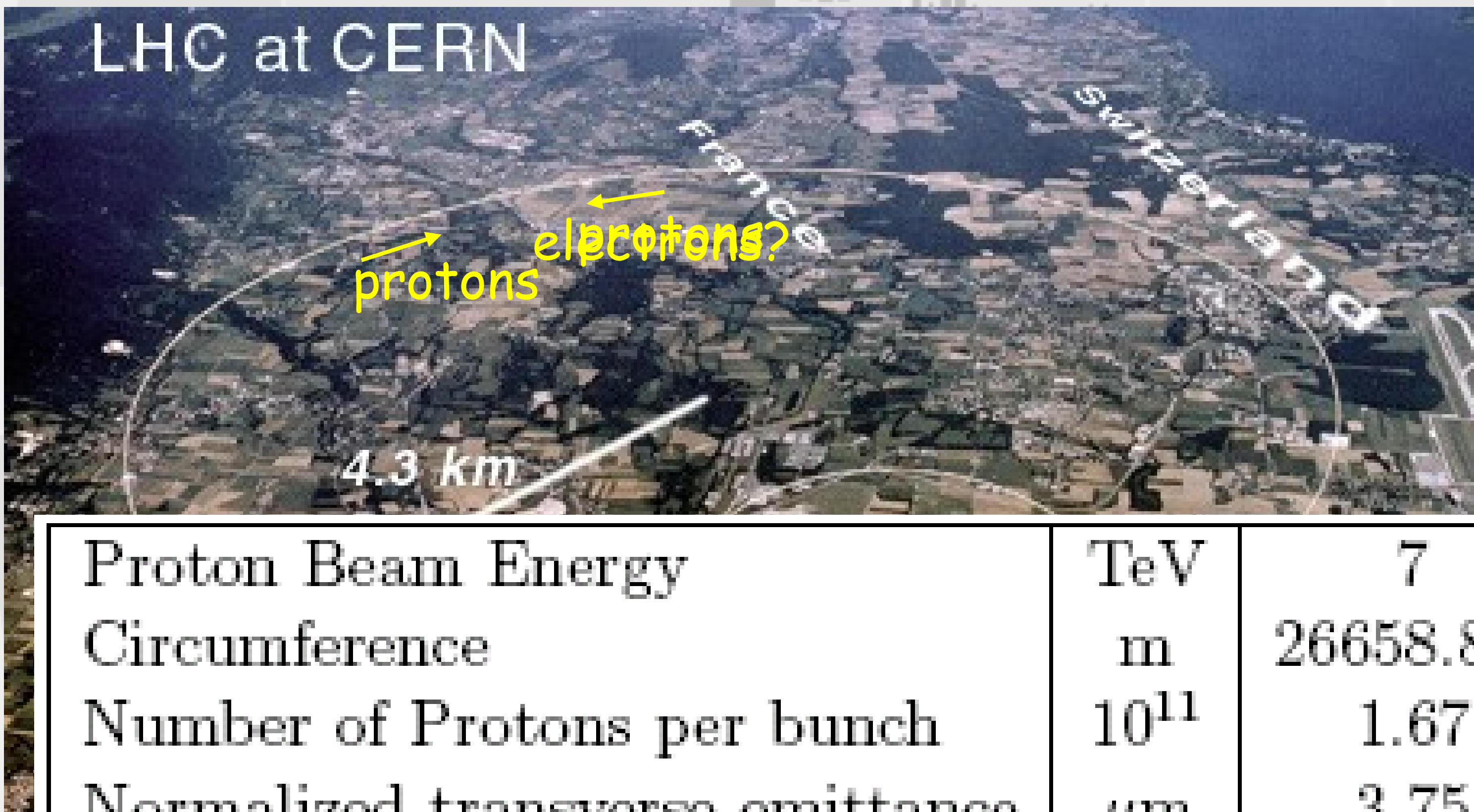
Standard
Model

e^+e^-
M_Z, $\sin^2\theta$, 3 ν
h.o. EW (*t*,*H*?)
(LEP/SLC)
CKM
(*B*-factory)

2.The Structure of Matter beyond the Fermi scale: How?

LHC hadrons … and leptons ?

- "standard" LHC protons … with electrons?



Proton Beam Energy	TeV	7
Circumference	m	26658.883
Number of Protons per bunch	10^{11}	1.67
Normalized transverse emittance	μm	3.75
Bunch length	cm	7.55
Bunch spacing	ns	25

N_p

ε_{pN}

LHeC: a future

- LHeC:
  - highest $\sqrt{s}$: Terascale
  - exceptional lumi
  - precision e-quark
    e-proton
    e-deuteron
    e-ion

beside ion-ion

European strategy 2006
JINST 1 (2006) P10001

DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

Abstract

The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\,\mathrm{cm^{-2}s^{-1}}$, and high energy, $\sqrt{s} =$ 1.4 TeV, such a collider can be built in which a 70 GeV electron (positron)

are sketched. With high luminosity, $10^{33}\,\mathrm{cm^{-2}s^{-1}}$, 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 pos-

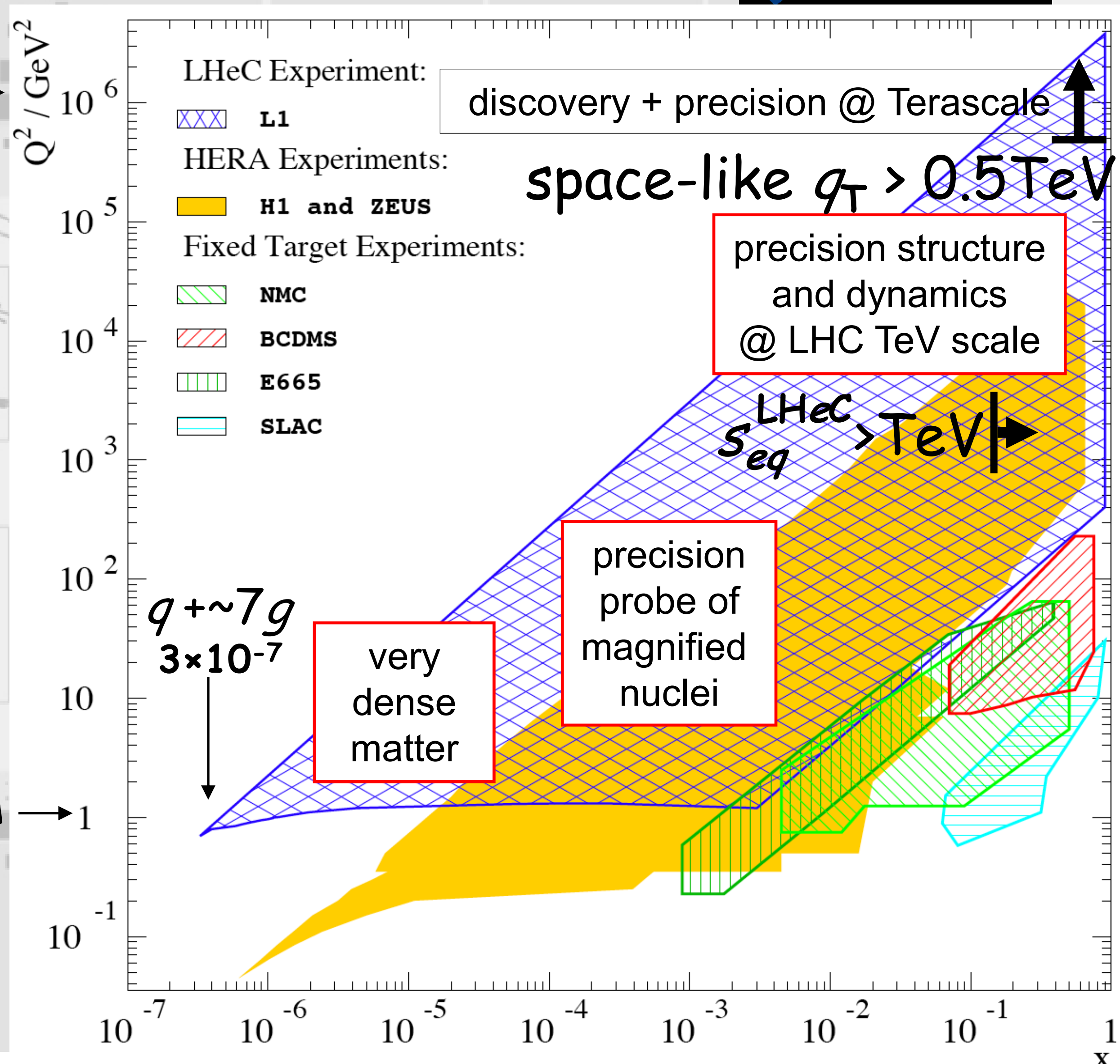
understanding of physics in the LHC energy range.

Matter @ Shorter-Distance: LHeC

0.2 am →

- Terascale
- 70 ⊗ 7000 GeV
  e ⊗ p or ion A
  - cm energy
  1400 GeV
- e-ring ⊗ LHC
- e-linac ⊗ LHC

0.2 fm →

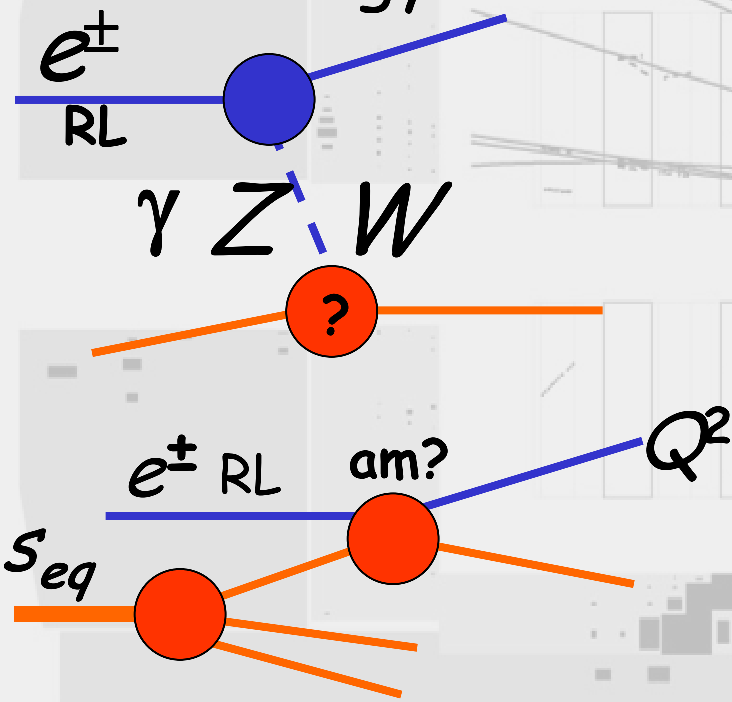


Q^2 > 10 GeV² low-x magnification > 120,000 1200 12

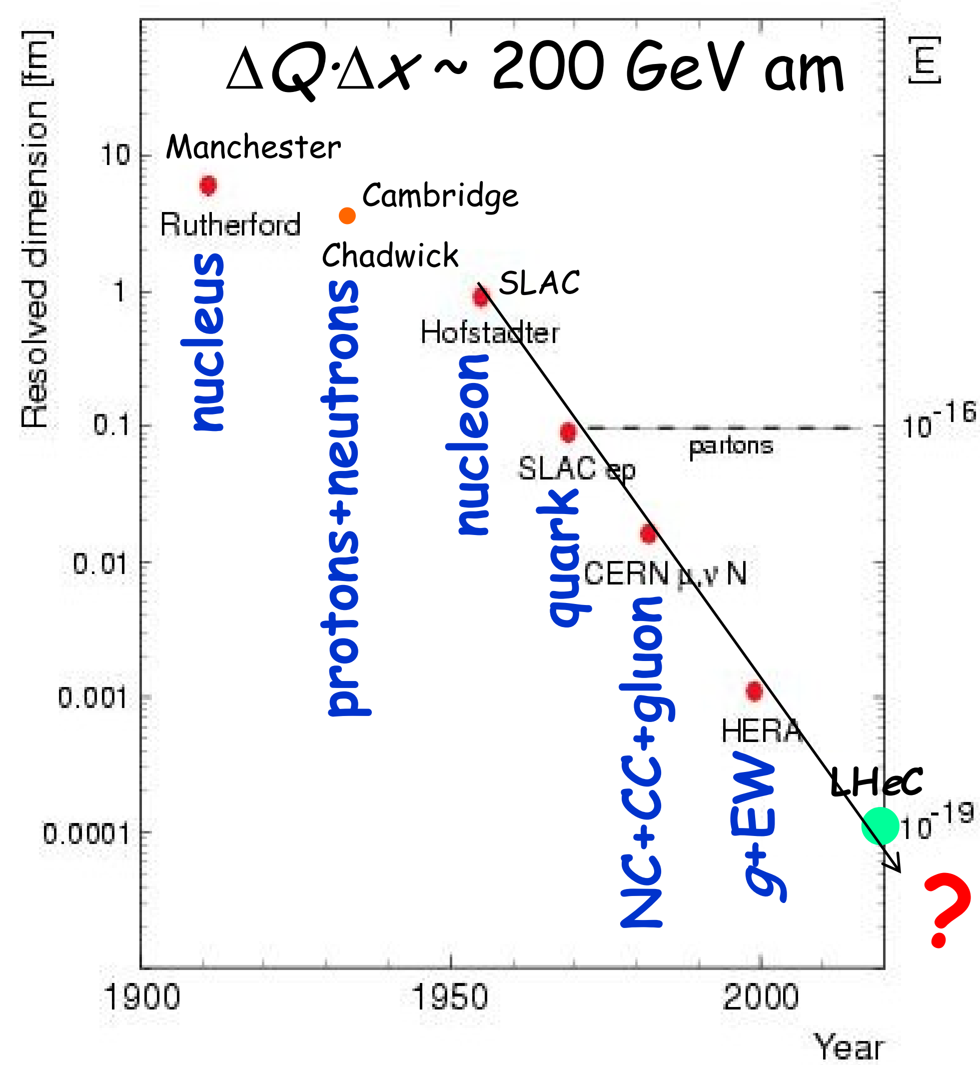
2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

Lepton+quark @ TeV

- unique chiral probe @ 0.1 am ?
- 70 $e^{\pm} \otimes p$ 7000 GeV
  cm energy 1400 GeV



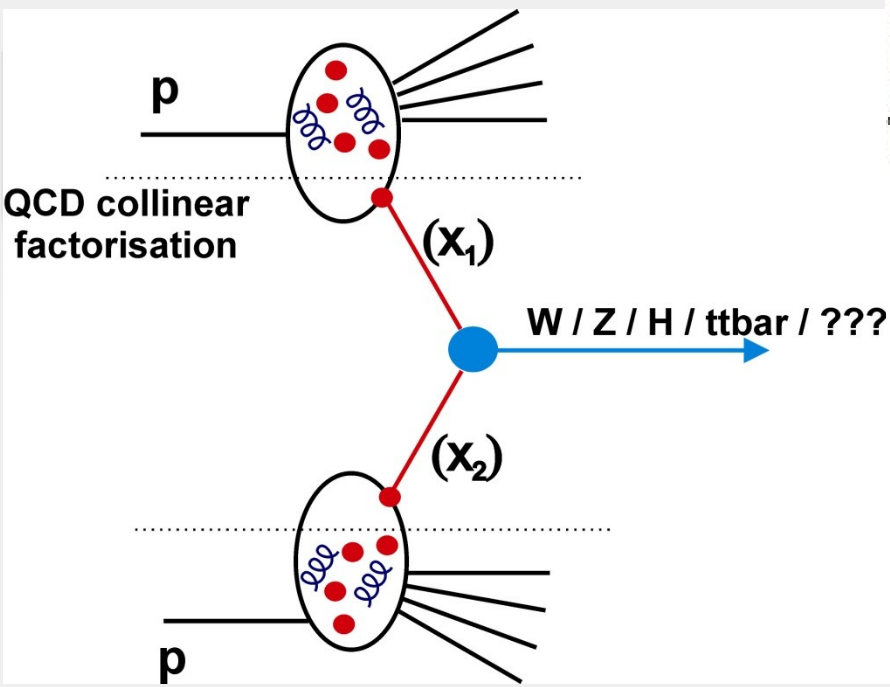
SM @ ~ 0.1 am ?

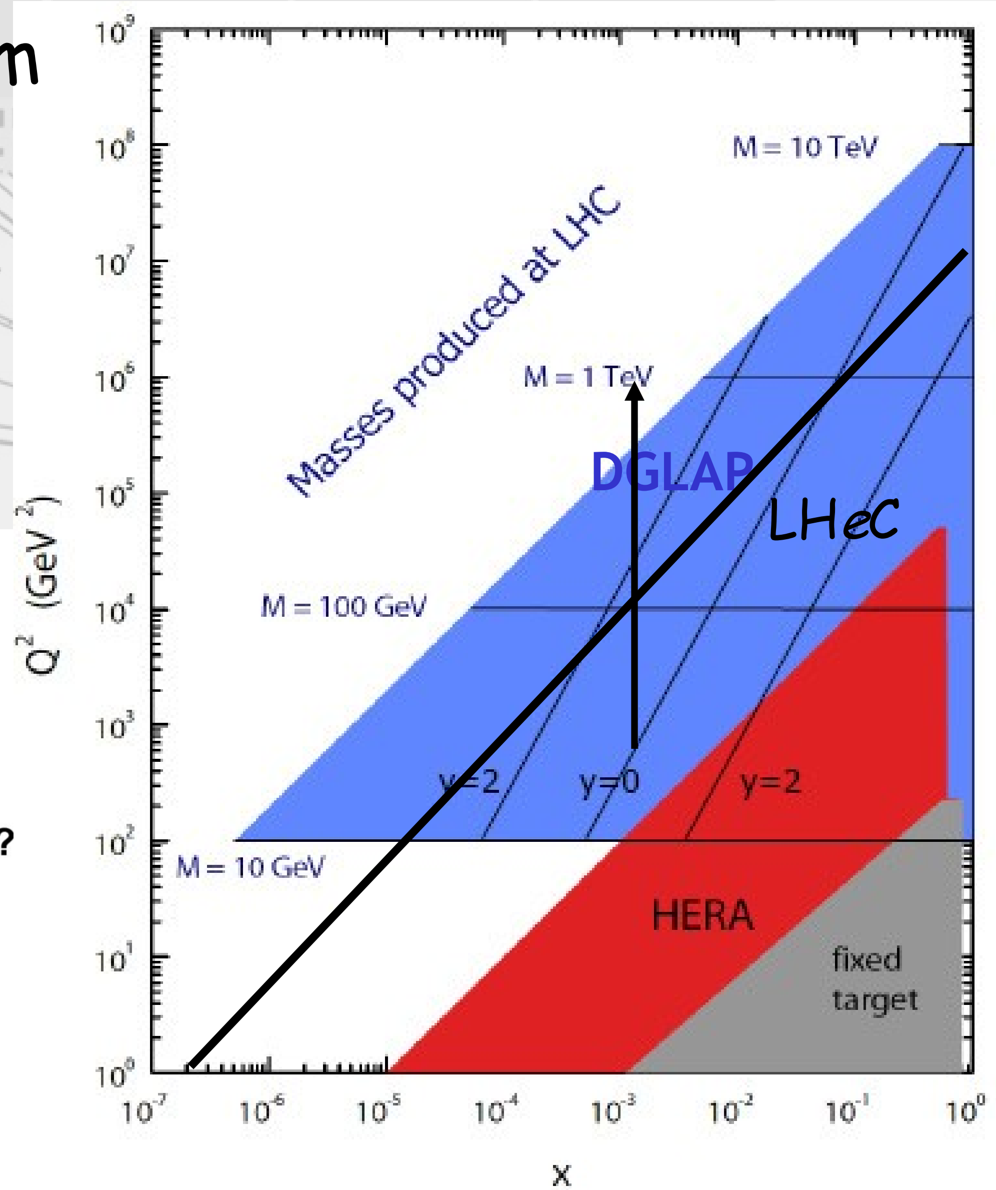


Quark+quark @ LHC

- *g* or *q* probe @ > 0.01 am
  - central dijets
  - DGLAP QCD required
  - soft colour?

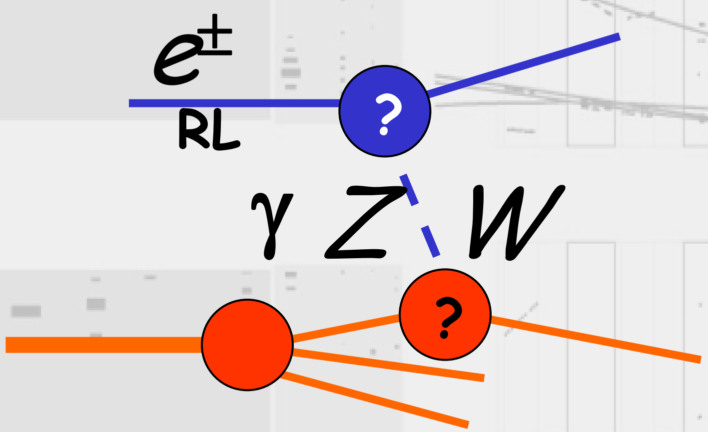
↳ precision ?





Lepton-Parton and Parton-Parton ?

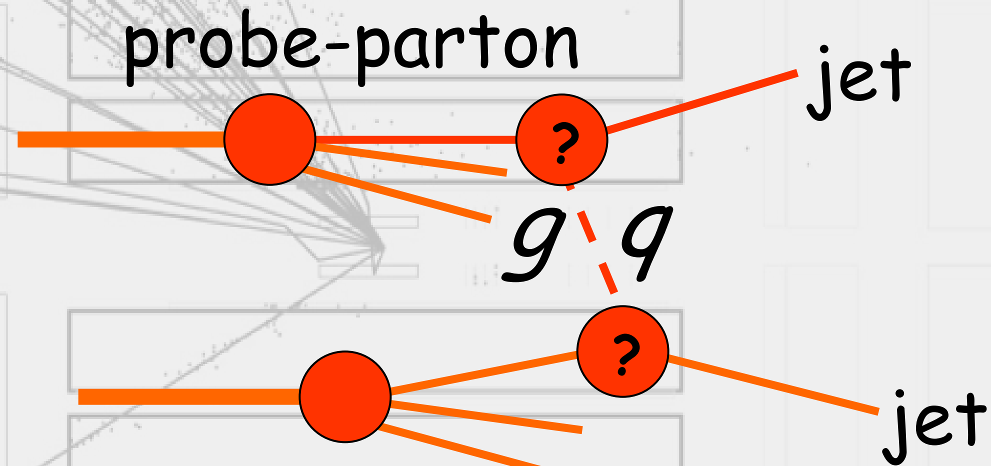
- $ep \rightarrow eX$



- LH*e*C energy scale: 70⊗7000 GeV

probe = $e^{\pm}$ (x = 1)

- $pp \rightarrow$ (jet+jet)X



- pp energy scale: 7000⊗7000 GeV

probe+p at LH*e*C scale

$x_{\mathrm{probe}/p}$ = 0.01

LHC probe parton

- probe-parton @ $x \leq 0.01$
  - $xq = xU + xD + x\bar{U} + x\bar{D}$

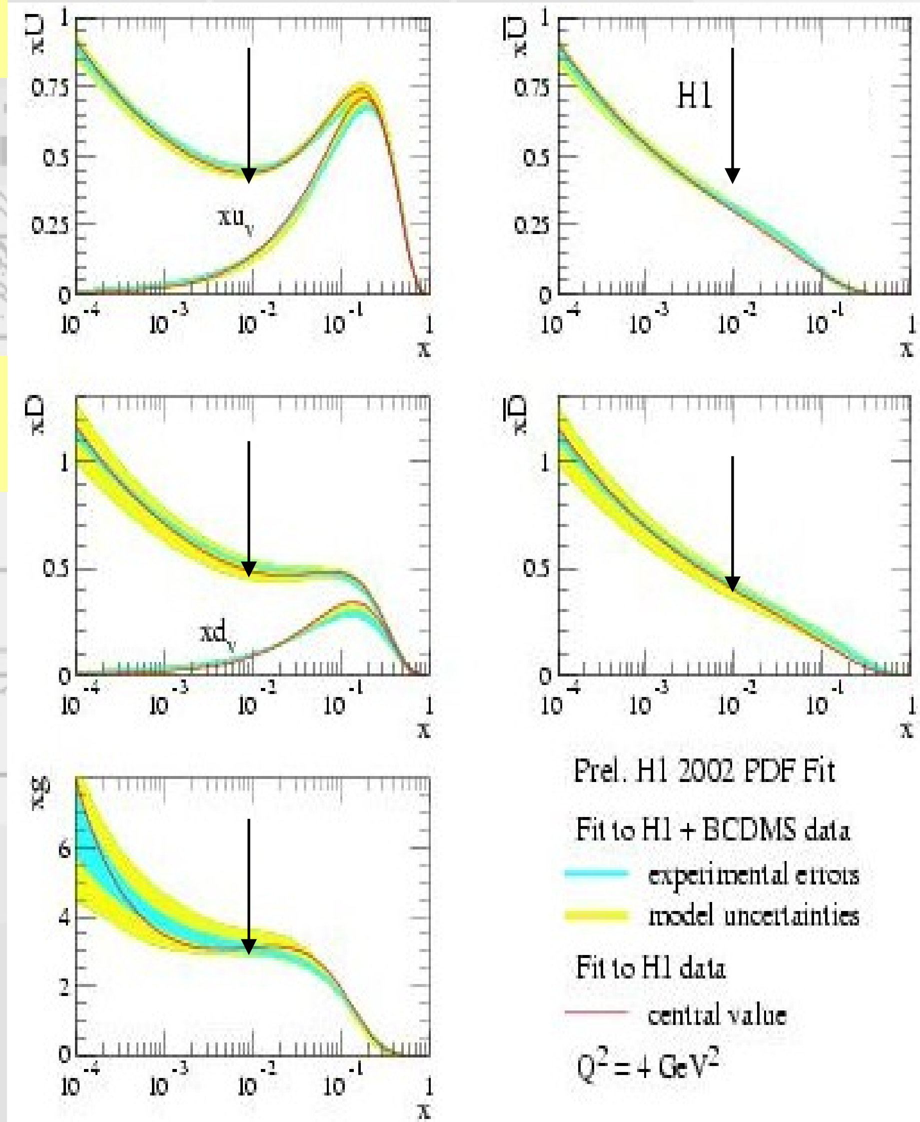
  $g:q \sim 2:1 \rightarrow$ mixed

- probe-parton @ $x \gg 0.01$

  $g:q \sim 1 \rightarrow$ all quark

↳ "mixed" LHC probe @ LH*e*C energy "mainly *q*" LHC probe @ LHC top energy

↳ LH*e*C only precise SM probe in critical domain



ep (with *pp*) @ LHC?

- ring-ring (RR)
  <100 MW wall plug
  "ultimate" LHC *p* beam
  60 GeV $e^{\pm}$ beam
  $\mathcal{L} = 2\ 10^{33}\ cm^{-2}s^{-1}$
  → O(100) fb^{-1}

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\,\mu m, \beta_{px(y)} = 1.8(0.5)\,m, \gamma = \frac{E_p}{M_p}$$

$$L = 8.2 \cdot 10^{32}\, cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{m}{\sqrt{\beta_{px}\beta_{py}}} \cdot \frac{I_e}{50\, mA}$$

$$I_e = 0.35\, mA \cdot P[MW] \cdot (100 / E_e[GeV])^4$$

- linac-ring (LR)
  pulsed, 60 GeV: $\mathcal{L}\sim 10^{32}$
  higher luminosity:
  energy recovery
  $P=P_0/(1-\eta)$
  $\beta^* = 0.1m$
  $\mathcal{L} = \ 10\ cm^2s^{-1}$
  → O(100) fb^{-1}

$$L = \frac{1}{4\pi} \cdot \frac{N_p}{\varepsilon_p} \cdot \frac{1}{\beta^*} \cdot \gamma \cdot \frac{I_e}{e}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\,\mu m, \beta^* = 0.2\,m, \gamma = 7000/0.94$$

$$L = 8 \cdot 10^{31}\, cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^*/m} \cdot \frac{I_e/mA}{1}$$

$$I_e = mA \frac{P/MW}{E_e/GeV}$$

synchronous *ep* and *pp*
~ 100 × $\mathcal{L}_{HERA}$

2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

The LHeC project

The Cockcroft Institute of Accelerator Science and Technology

UNIVERSITY OF LIVERPOOL

SLAC NATIONAL ACCELERATOR LABORATORY

NTNU Norwegian University of Science and Technology

CERN

The Cockcroft Institute of Accelerator Science and Technology

Jefferson Lab Thomas Jefferson National Accelerator Facility

clic

ANKARA ÜNİVERSİTESİ

ANKARA ÜNİVERSİTESİ 1946

NİĞDE ÜNİVERSİTESİ 1992

ULUDAĞ ÜNİVERSİTESİ 1975

TOBB ETU

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Legnaro

DESY

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

LAL Physique des accélérateurs

ECFA

UNIVERSITY OF LIVERPOOL

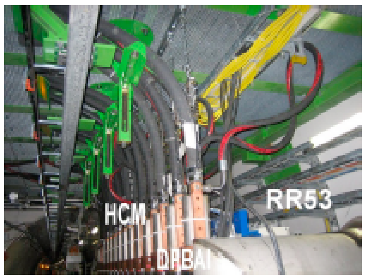
BROOKHAVEN NATIONAL LABORATORY

СИБИРСКОЕ ОТДЕЛЕНИЕ РАН
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И.Будкера
630090 Новосибирск

KEK

LHeC RR

- 10 GeV linac injection into 60 GeV R



Lattice Design dominated by geometry:

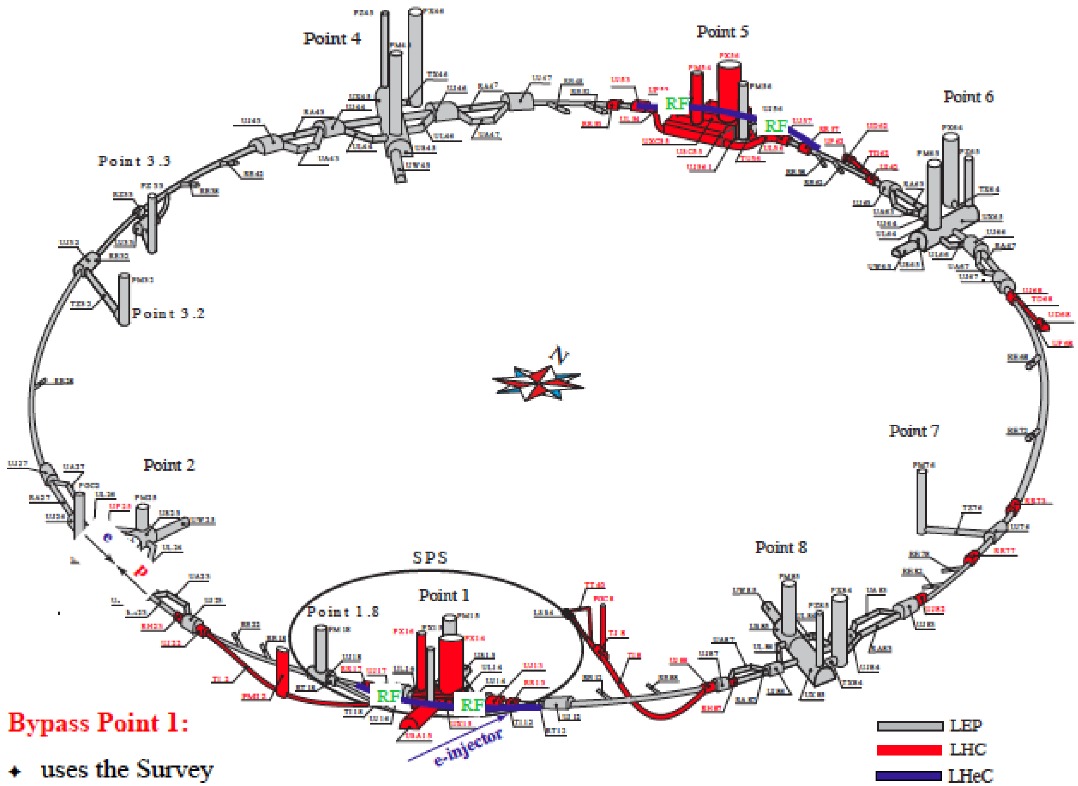
- forbidden space (usually DFBMs) induces an asymmetric lattice
- asymmetric lattice needs to be matched to the symmetric LHC lattice
- ➡ most choices for the LHeC lattice structure are made due to integration

Bypass Design:

- Bypasses increase the circumference of the ring
- ➡ Compensation of the increase in circumference by placing the electron ring 0.61 cm to the inside of the LHC (Idealized Ring)

Bypass Point 5:

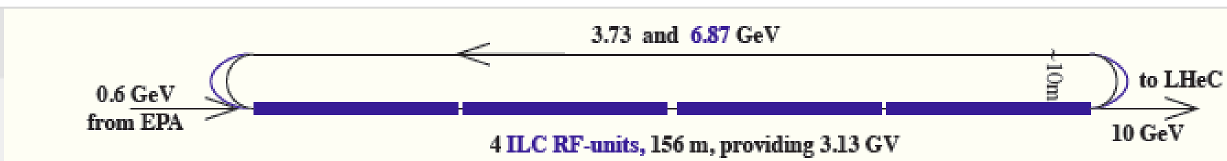
- adjustment of the circumference by varying the separation
- Δ=20.56 Meter



Bypass Point 1:

- uses the Survey Gallery
- Δ=16.25 Meter

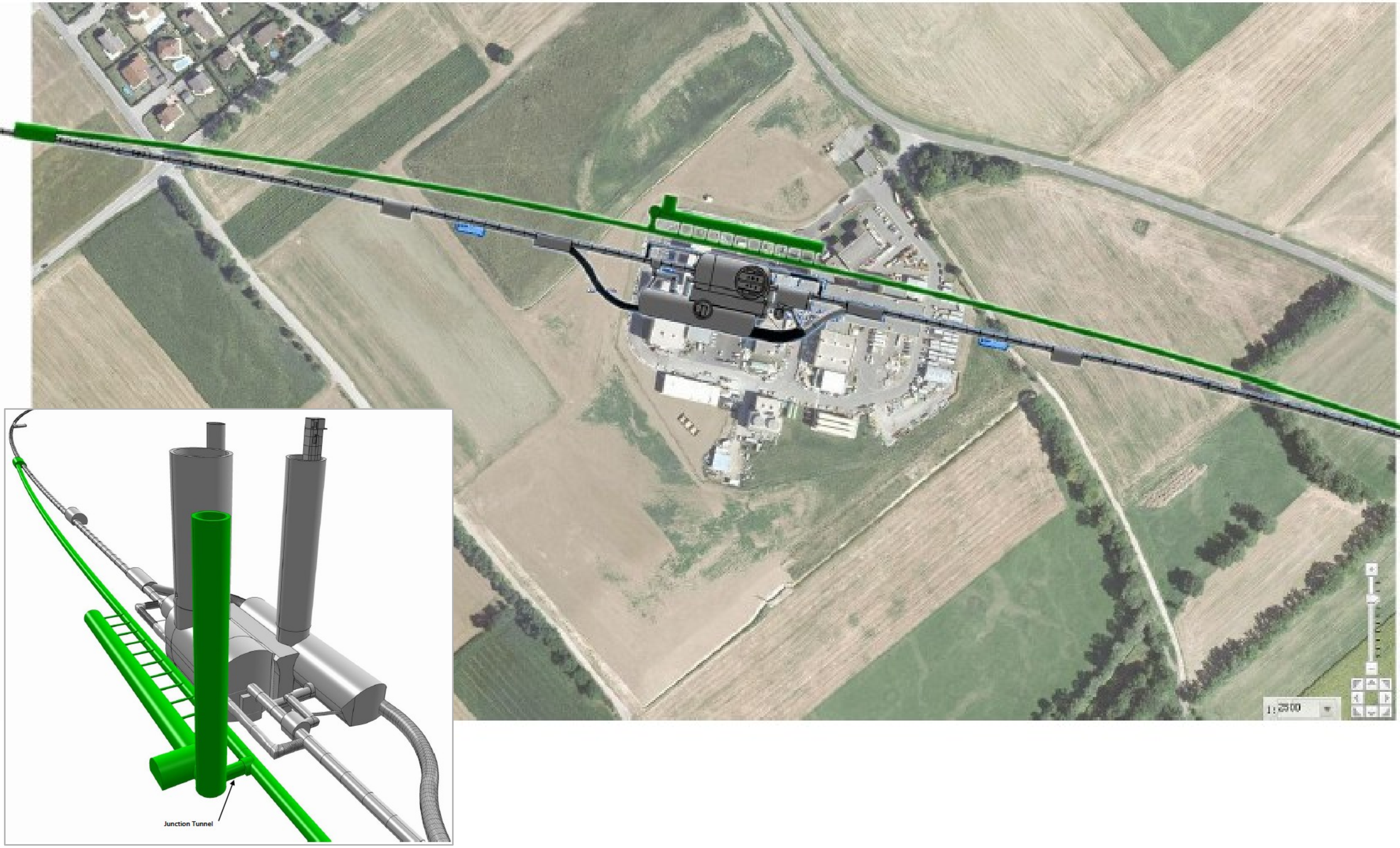
5min fill



LHeC RR

- $\mathcal{L}$ = 10^{33} $cm^{-2}s^{-1}$ (100×HERA) not difficult
- e^+ and e^-
- polarisation ~40%
- magnet concepts defined and non-controversial
- injector linac with ILC-like cavities < 25 MV/m
- interference with hadron rings
- by-passes (civil engineering) of CMS+ATLAS+…
- footprint within CERN territory
- cost coming (well within CERN pa budget)

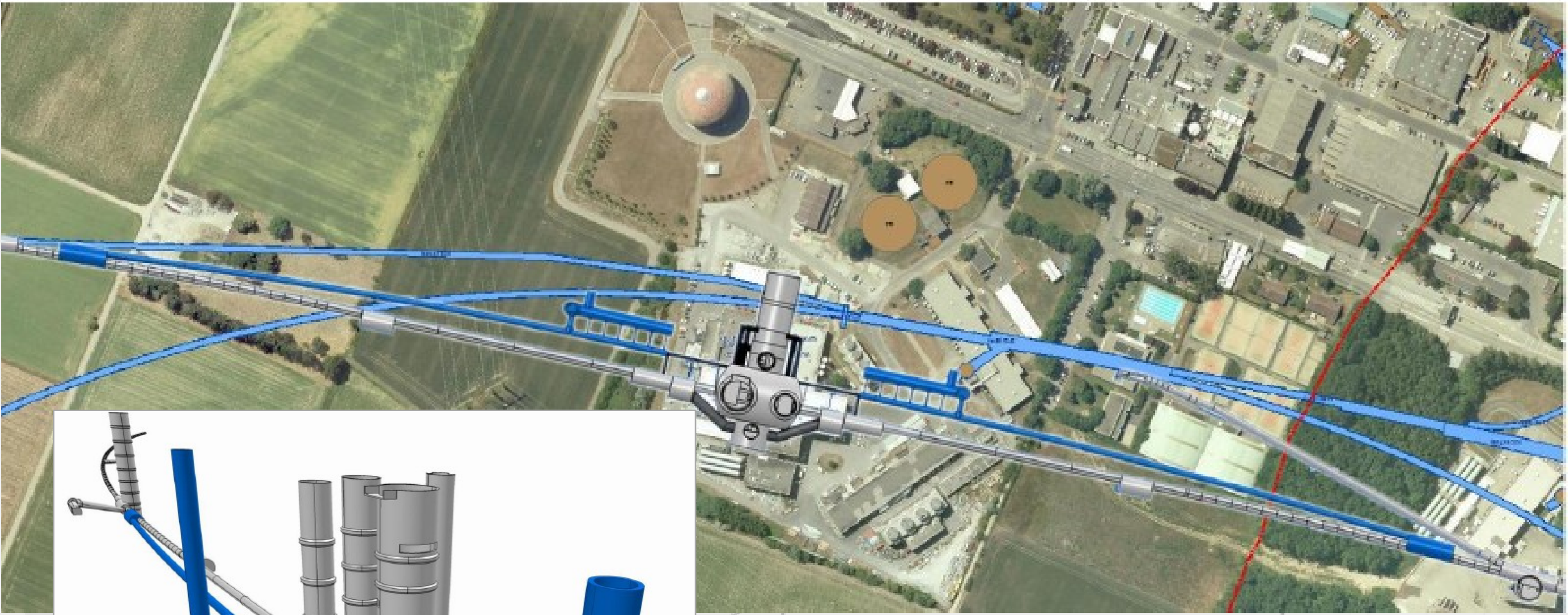
LHeC RR: CMS bypass

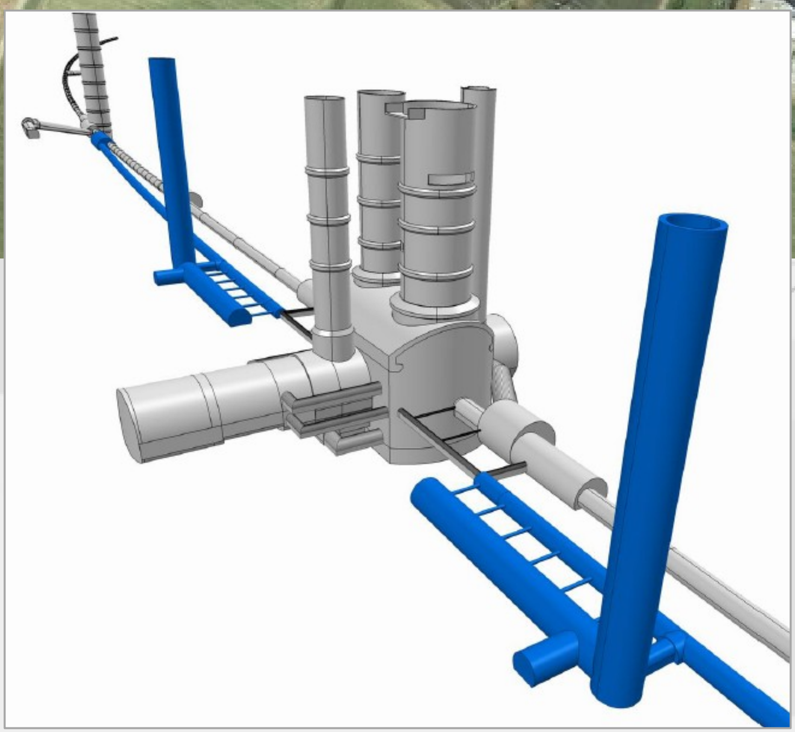


2nd Intl Conference on Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

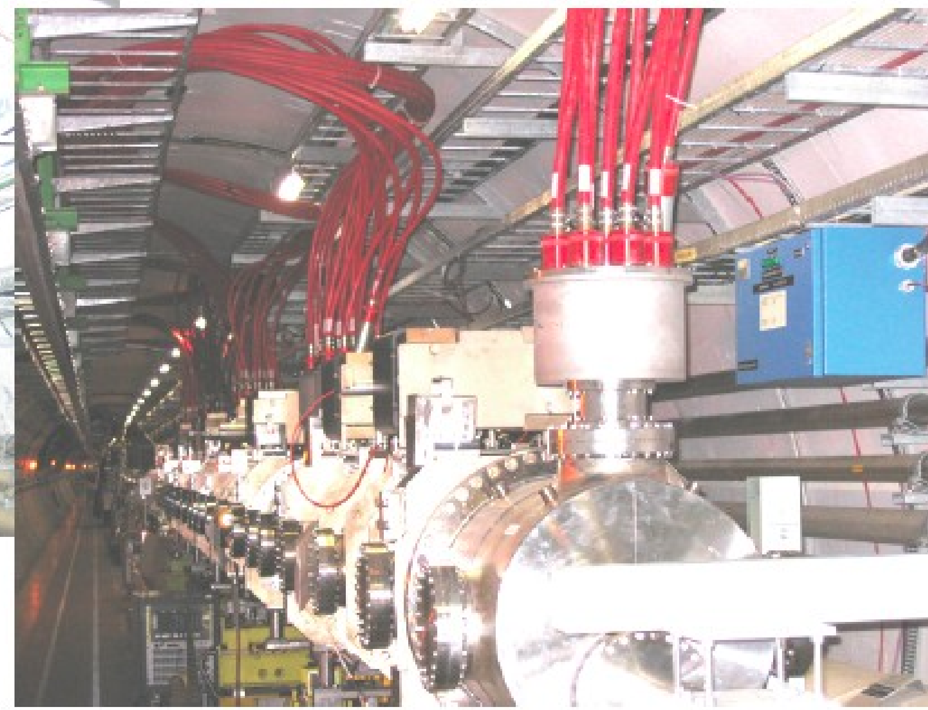
LHeC RR: ATLAS bypass

The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL





LH*e*C RR: *e* ring installation



- Installation of an e ring is challenging
- Modifications of the existing installations will be necessary
- No show stopper

- LHC interference, activation?

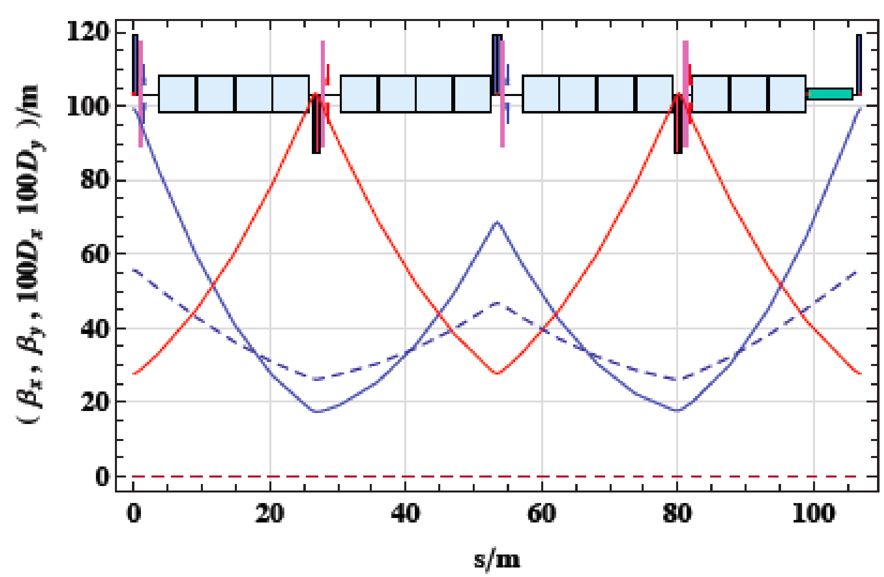
2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

LHeC RR: *e* ring optics

Beam Energy	60 GeV
Numb. of Part. per Bunch	2.0×10^{10}
Numb. of Bunches	2808
Circumference	26658.8832 m
Syn. Rad. Loss per Turn	437.2 MeV
Power	43.72 MW
Damping Partition $J_x/J_y/J_e$	1.5/1/1.5
Damping Time τ_x	0.016 s
Damping Time τ_y	0.025 s
Damping Time τ_e	0.016 s
Polarization Time	61.7 min
Coupling Constant κ	0.5
Horizontal Emittance (no coupling)	5.49 nm
Horizontal Emittance ($\kappa = 0.5$)	4.11 nm
Vertical Emittance ($\kappa = 0.5$)	2.06 nm
RF Voltage V_{RF}	720 MV
RF frequency f_{RF}	359.856 MHz
Bunch Length	6.05 mm
Max. Hor. Beta	141.26 m
Max. Ver. Beta	135.25 m

Table 8.4: Optics Parameters of one LHeC arc cell with a phase advance of 180°/120°.

23 arc cells, L_{Cell}=106.881 m



Half the LHC FODO size for emittance

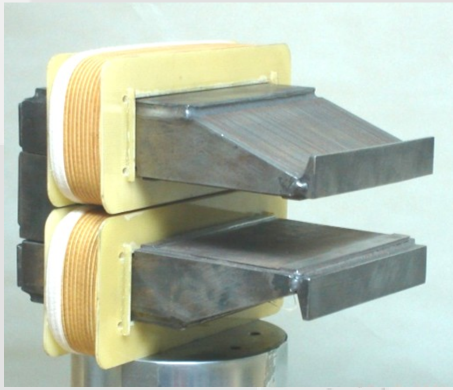
Asymmetric FODO cell to account for regular cryo jumpers of LHC

Put maximum number of dipole magnets to keep synchrotron radiation small

Also designed: dispersion suppressor (8 quads), by-pass optics, matched IR optics

2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

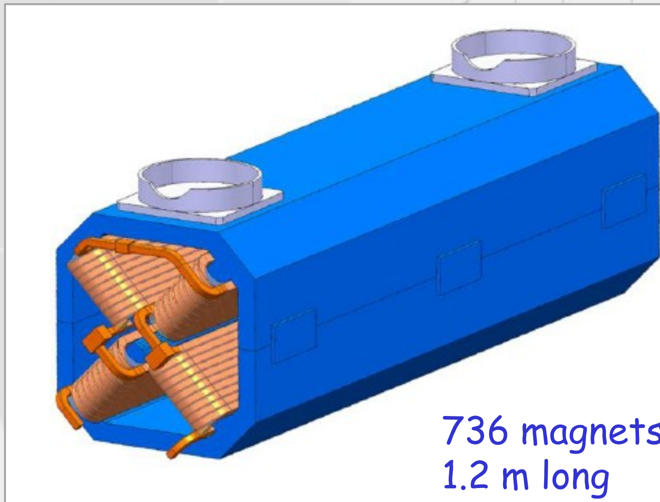
LHeC RR: dipoles + quads



BINP & CERN prototypes

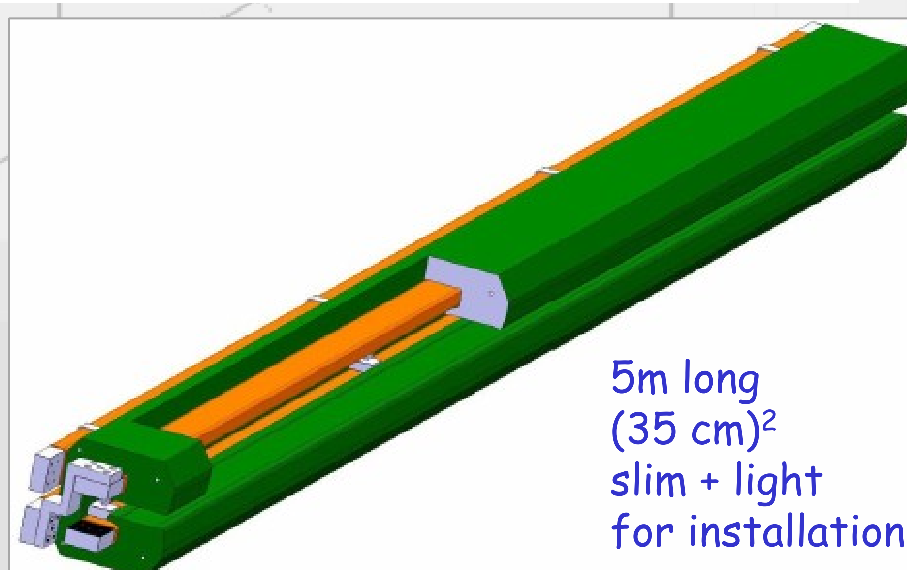
Parameter	Value	Units
Beam Energy	10-60	GeV
Magnetic Length	5.35	Meters
Magnetic Field	0.127-0.763	Tesla
Number of magnets	3080	
Vertical aperture	40	mm
Pole width	150	mm
Number of turns	2	
Current @ 0.763 T	1300	Ampere
Conductor material	copper	
Magnet inductance	0.15	milli-Henry
Magnet resistance	0.16	milli-Ohm
Power @ 60 GeV	270	Watt
Total power consumption @ 60 GeV	0.8	MW
Cooling	air or water	depends on tunnel ventilation

Table 3.2: Main parameters of bending magnets for the RR Option.



736 magnets
1.2 m long

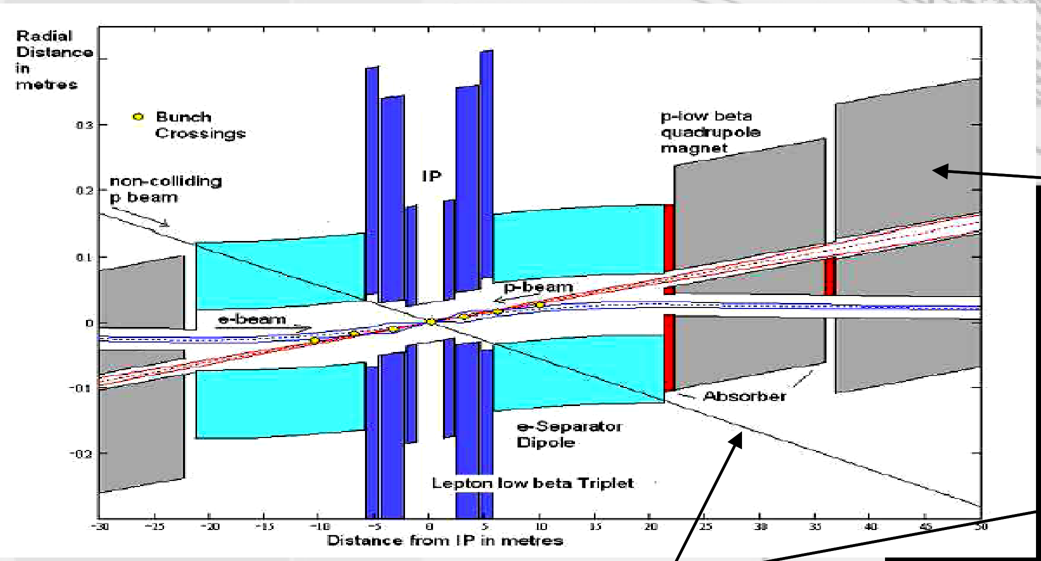
Arc quadrupole magnets for the RR Option

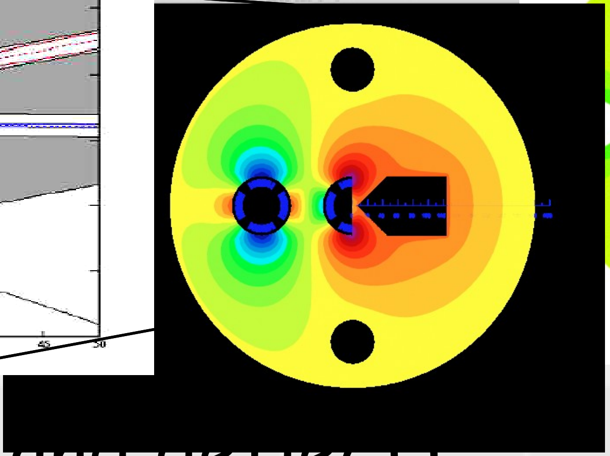


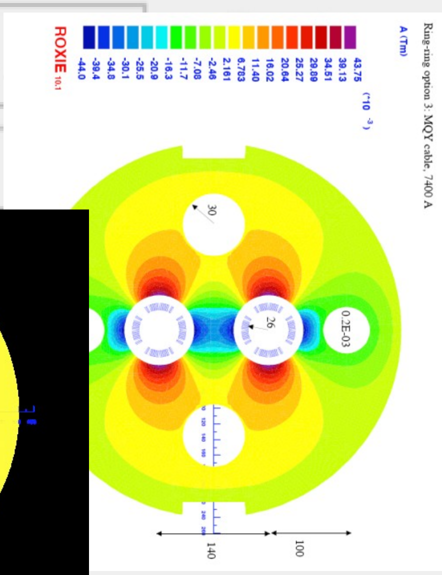
5m long
$(35\ \text{cm})^2$
slim + light
for installation

RR + LR interaction region

- RR ~1mrad (25ns) cross angle for no bunch x-talk
- LR – head-on collisions + dipole beam separation
- synchrotron radiation: shielding under control







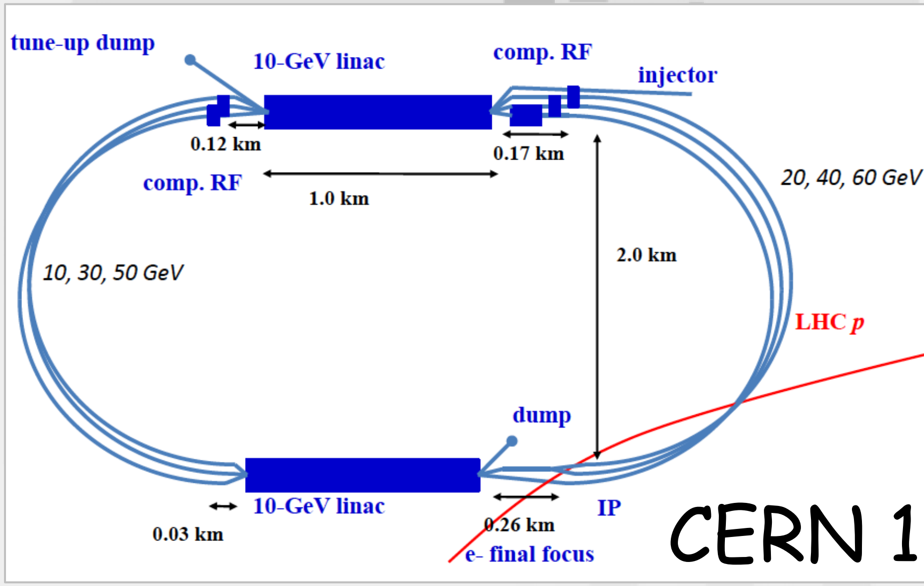
- 1st sc half quad (focus and deflect)
  separation 5cm, 127T/m, MQY cables, 4600 A

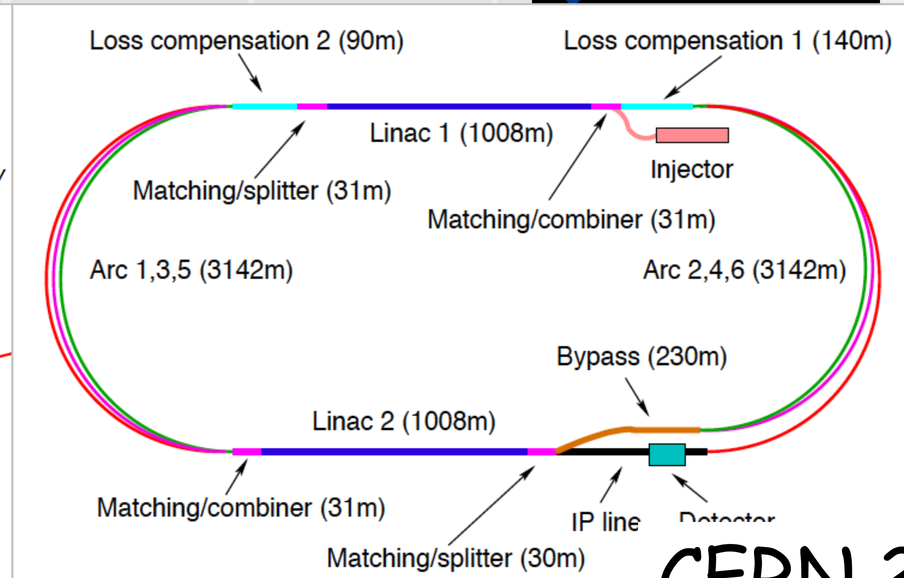
[July 2010]

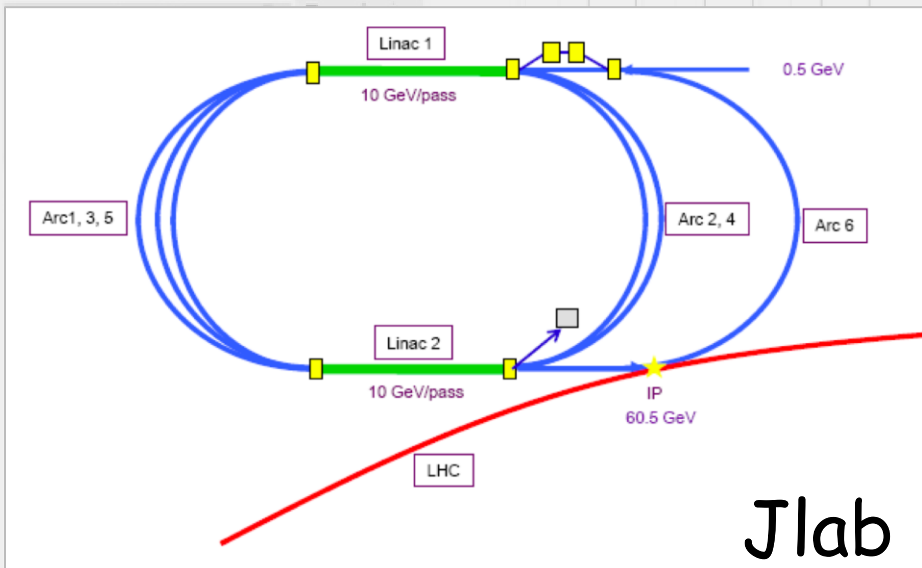
- 2nd quad: 3 beams in horizontal plane
  separation 8.5cm, MQY cables, 7600 A

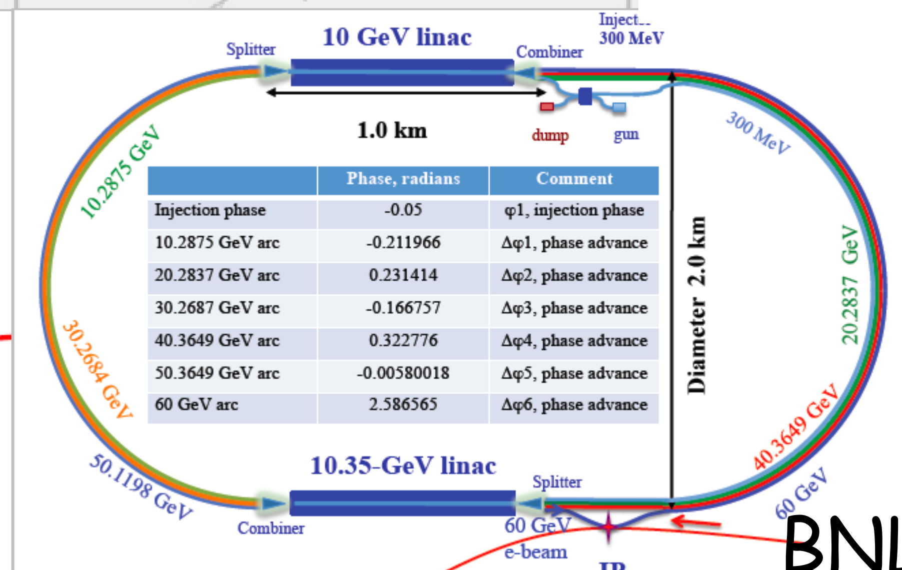
2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

LR: linac concepts









	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc	2.586565	Δφ6, phase advance

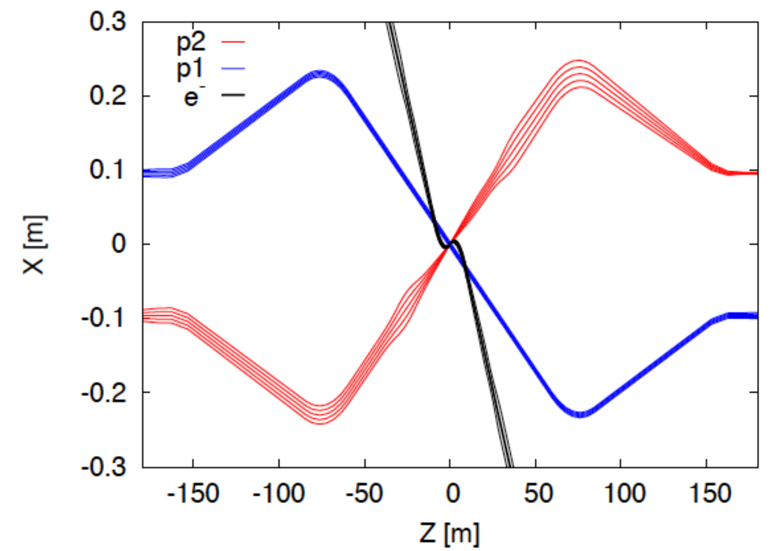
Two 10 GeV Linacs, 3 returns, ERL, 720 MHz cavities, rf, cryo, magnets, injectors, sources, dumps…

LHeC LR

- $L \sim 10^{33}\text{cm}^{-2}\text{s}^{-1}$ possible for e^-
- e^+ require energy recovery AND recycling, $L^+ < L^-$
- energy limited by SR in racetrack mode
- may be 2-beam recovery for high energy LINAC ?
- $e^{-(+)}$ polarisation 90(0)%
- cavities: synergy with SPL, ESS, XFEL, ILC
- cryo: fraction of LHC
- energy recovery (Cockcroft, Cornell, BINP, ..)
- small interference with LHC hadrons
- by-pass of LHeC IP
- extended dipole at ~1m radius in detector
- footprint beyond CERN territory (~9 km tunnel)
- cost coming (well within CERN pa budget)

LHeC LR: interaction region

- 3 beams, head-on collisions
- *p* and *e*



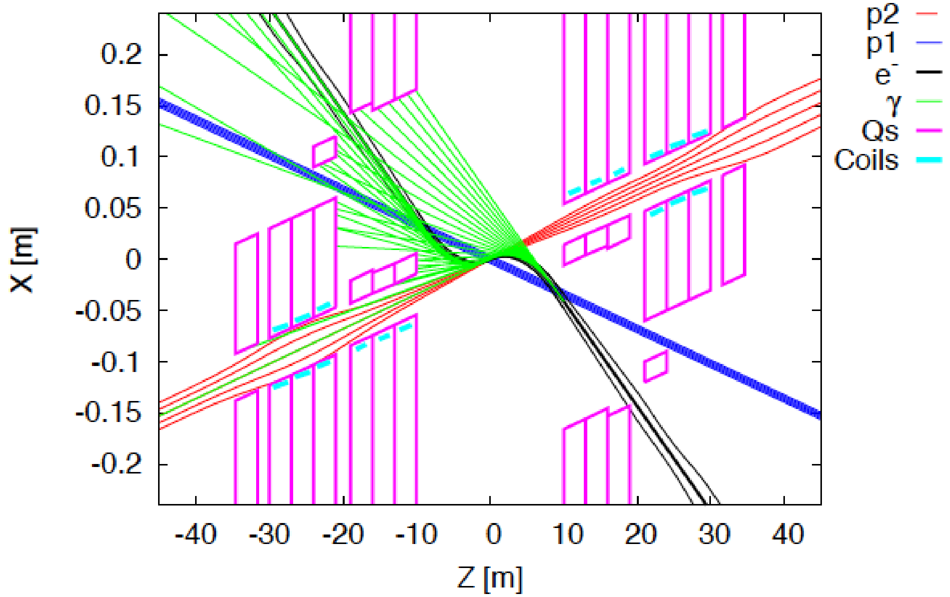


Figure 9.14: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with 5σ and 10σ envelopes are shown.

LHeC LR: Energy Recovery

- multibunch wakefields ✓
- emittance growth μm ✓
- 36σ separation at 3.5m ✓
- Q (between ILC/BNL) ✓
- layout tentative ✓

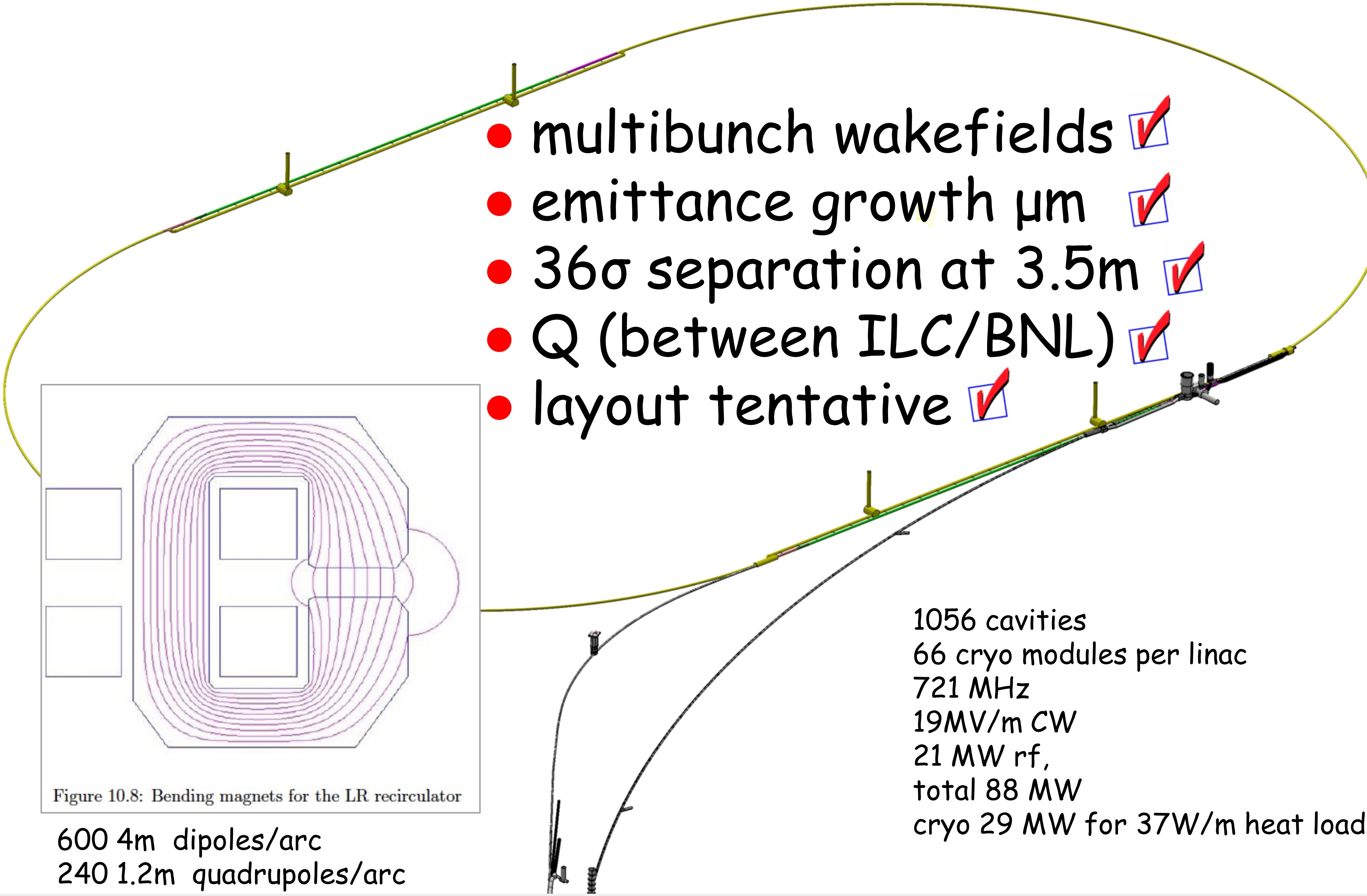


Figure 10.8: Bending magnets for the LR recirculator

600 4m dipoles/arc
240 1.2m quadrupoles/arc

1056 cavities
66 cryo modules per linac
721 MHz
19MV/m CW
21 MW rf,
total 88 MW
cryo 29 MW for 37W/m heat load

LHeC Design Parameters

electron beam	RR	LR	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

- "ultimate p beam"
- deuterons + Pb

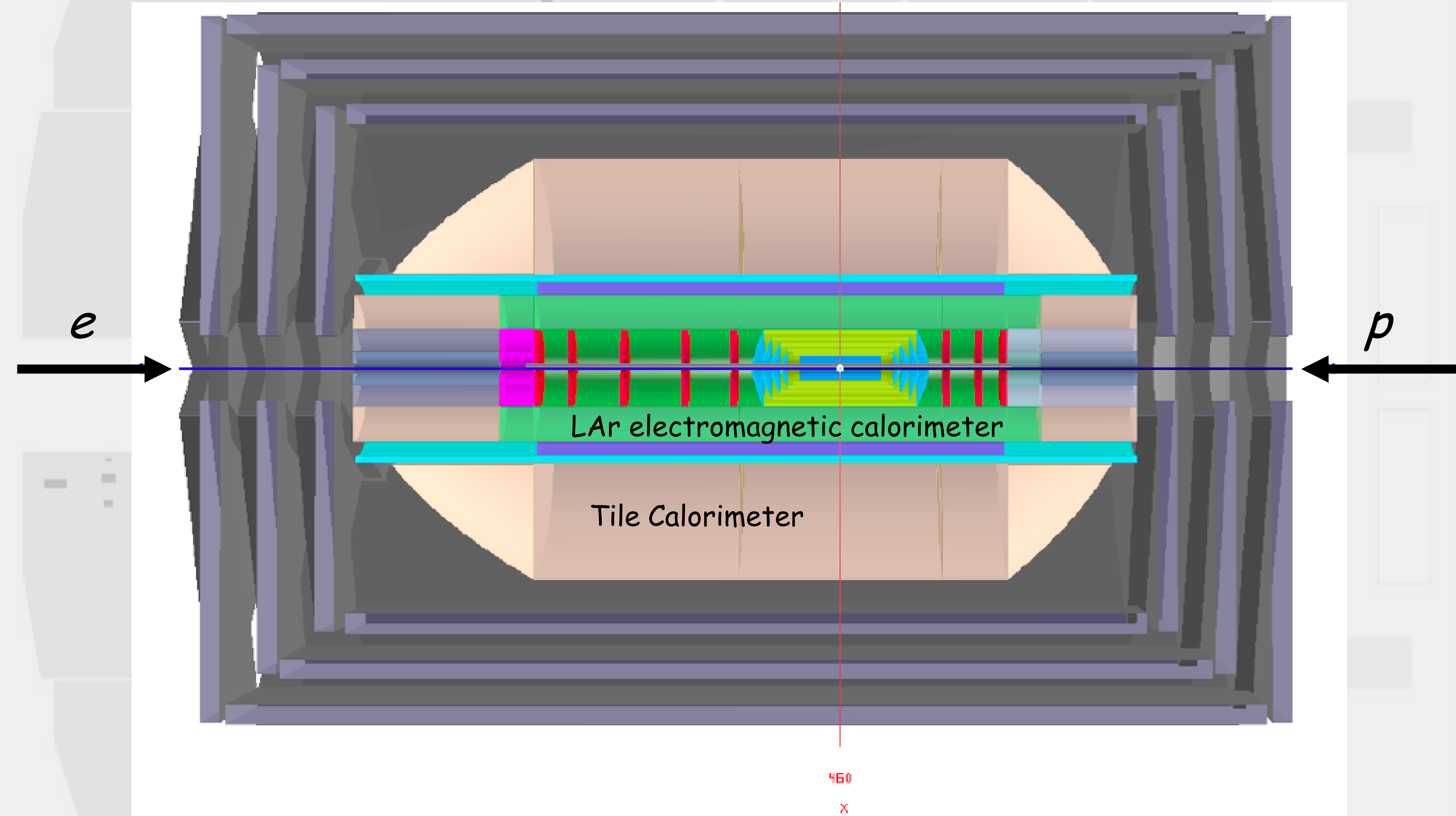
LHeC Experiment

	LHeC	H1	
• high *L* for large Q^2 and large *x*	10^{33}	1-5 10^{31}	
• largest possible acceptance	1-179°	7-177°	kinematic coverage
• precision tracking	0.1 mrad	0.2-1 mrad	modern Si
• precision electromagnetic calorimetry	0.1%	0.2-0.5%	kinematic reconstructi
• precision hadronic calorimetry	0.5%	1%	track+calo *e/h*
• accurate luminosity/polarisation	0.5%	1%	not straight-forward

2nd Intl Conference on Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

LHeC Experiment

The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

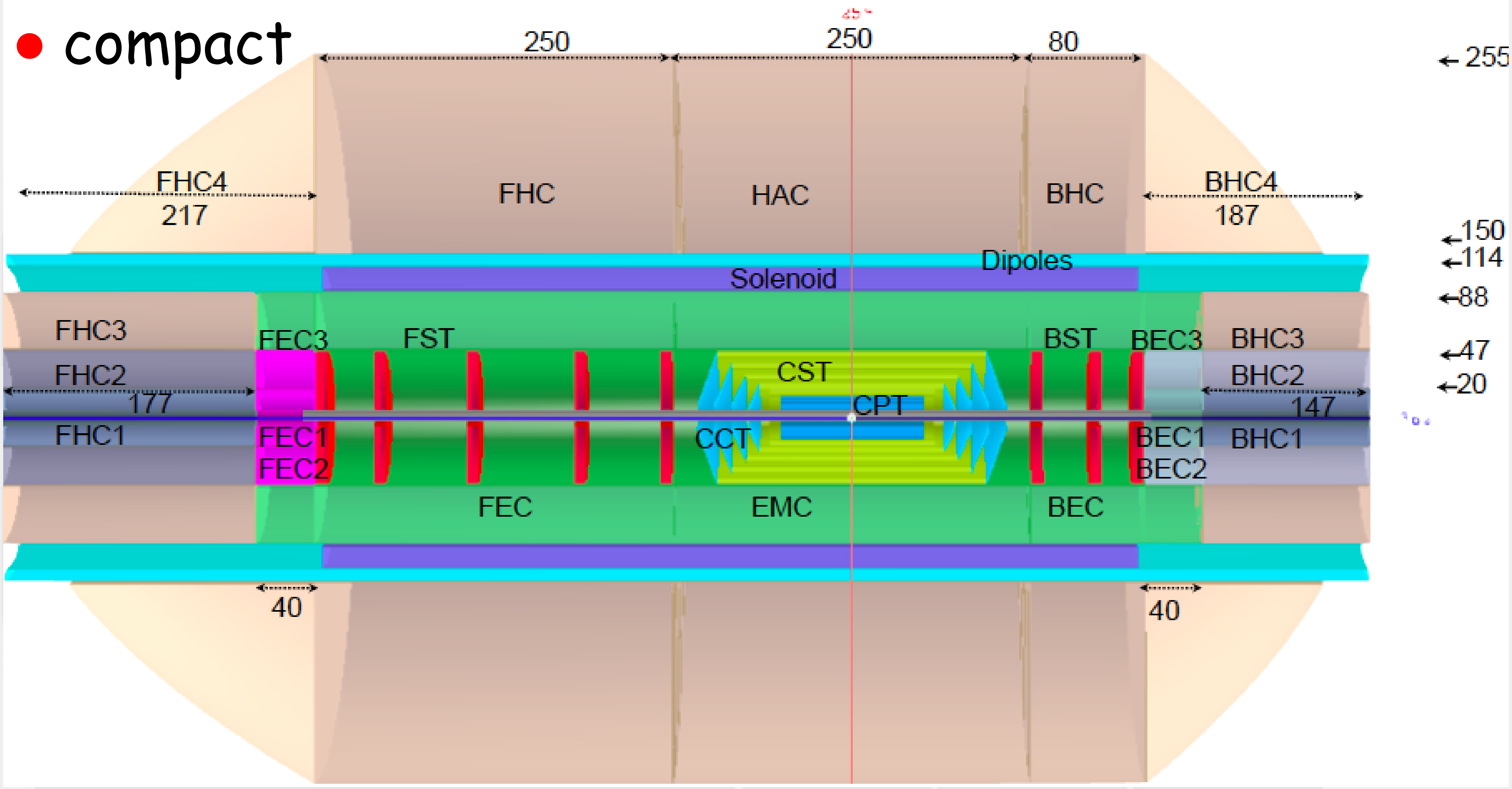


Fwd/Bwd asymmetry in energy deposited and thus in geometry and technology [W/Si vs Pb/Sc..]
Present dimensions: LxD =13x9m^2 [CMS 21 x 15m^2 , ATLAS 45 x 25 m^2]
Tentative 21.3.11 **Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)**

LHeC Experiment

The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

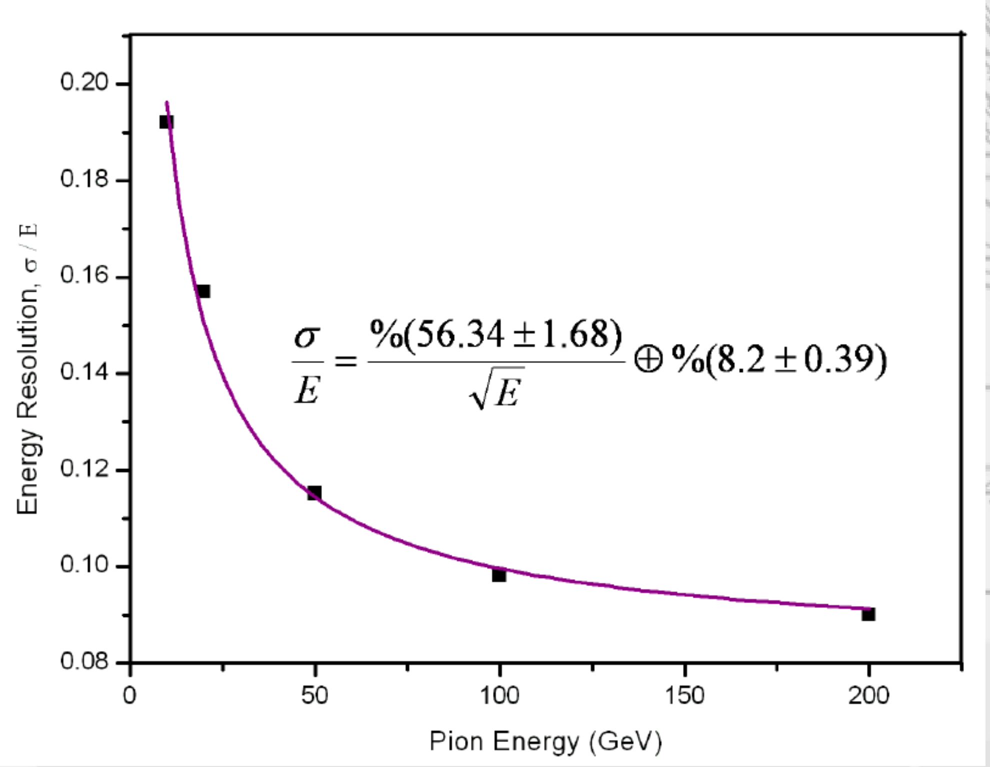
- compact



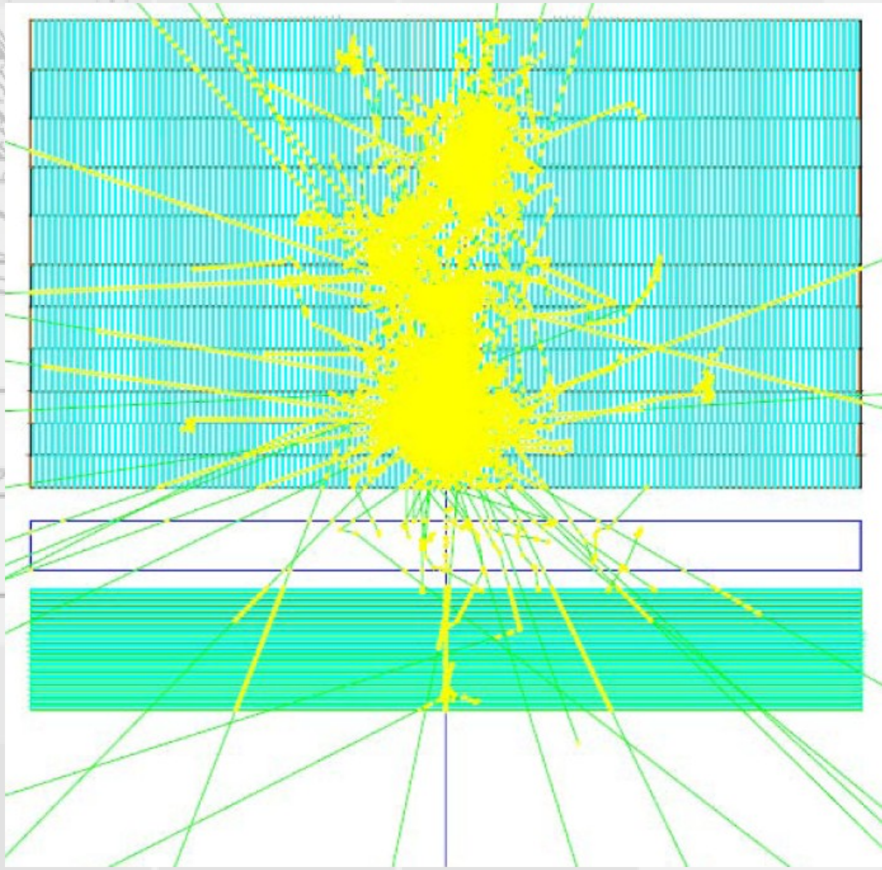
Fwd/Bwd asymmetry in energy deposited and thus in geometry and technology [W/Si vs Pb/Sc..]
Present dimensions: LxD =13x9m^2 [CMS 21 x 15m^2 , ATLAS 45 x 25 m^2]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

LHeC Experiment

- segmented calorimetry



A charged pion in the LHeC HCAL



Performance simulated for tile cal only

LHeC Experiment

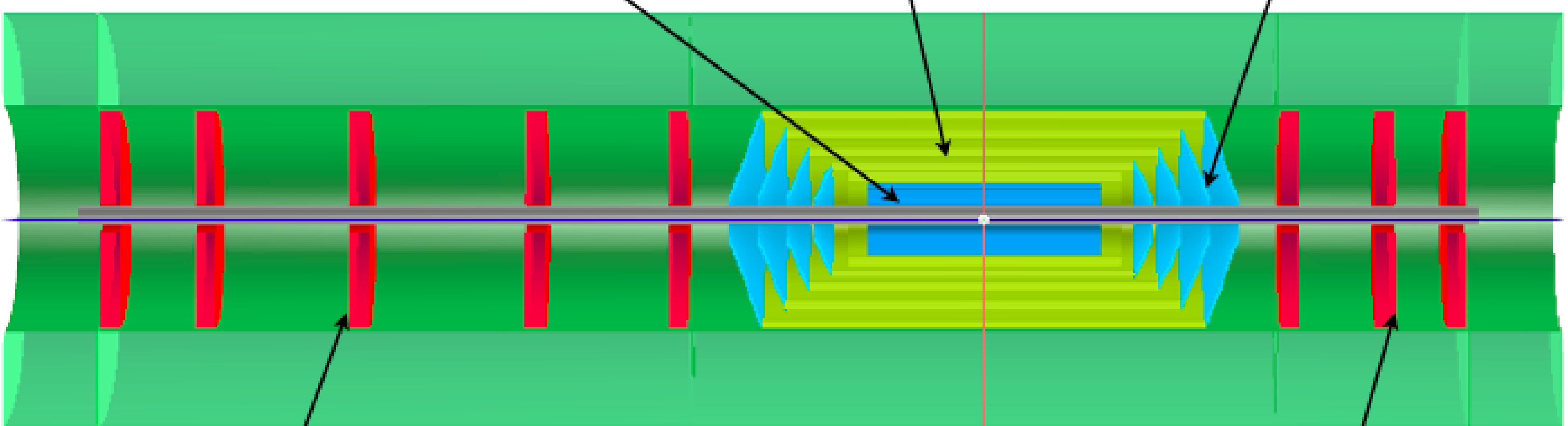
- foreseeable semiconductor development (LHC)

4 layer CPT:
min-inner-R = 3.0 cm
max-inner-R = 6.5 cm

ΔR = 12.3 cm

CST - ΔR 3.5cm each
1. layer: inner R = 16. 3 cm
2. layer: = 20.8 cm
3. layer: = 26.6 cm
4. layer: = 34.6 cm
5. layer: = 42.6 cm

4 CCT
min-inner-R = 3.0 cm, max-inner-R = 6.5 cm

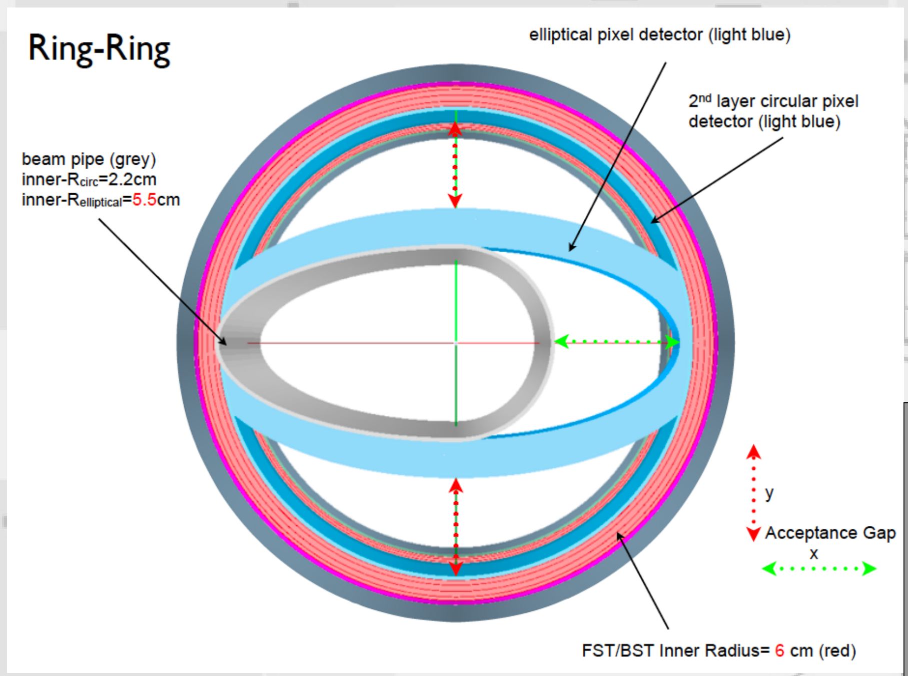


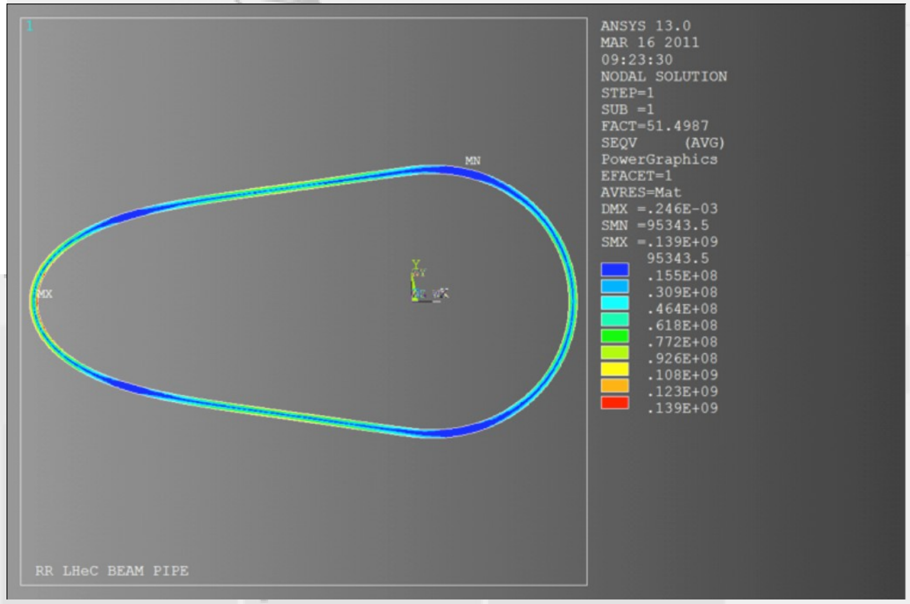
FST - ΔZ=8. cm
min-inner-R = 3.0 cm; max-inner-R= 6.5 cm
outer R = 46.1 cm
Planes 1 - 5:
$z_{5\text{-}1}$ = 370. / 350. / 320. / 230. / 140. cm

BST - ΔZ=8. cm
min-inner-R = 3.0 cm; max-inner-R= 6.5 cm
outer R = 46.1 cm
Planes 1 - 3:
$z_{1\text{-}3}$ = -140. / -170. / -200. cm

LHeC Experiment

- beam pipe





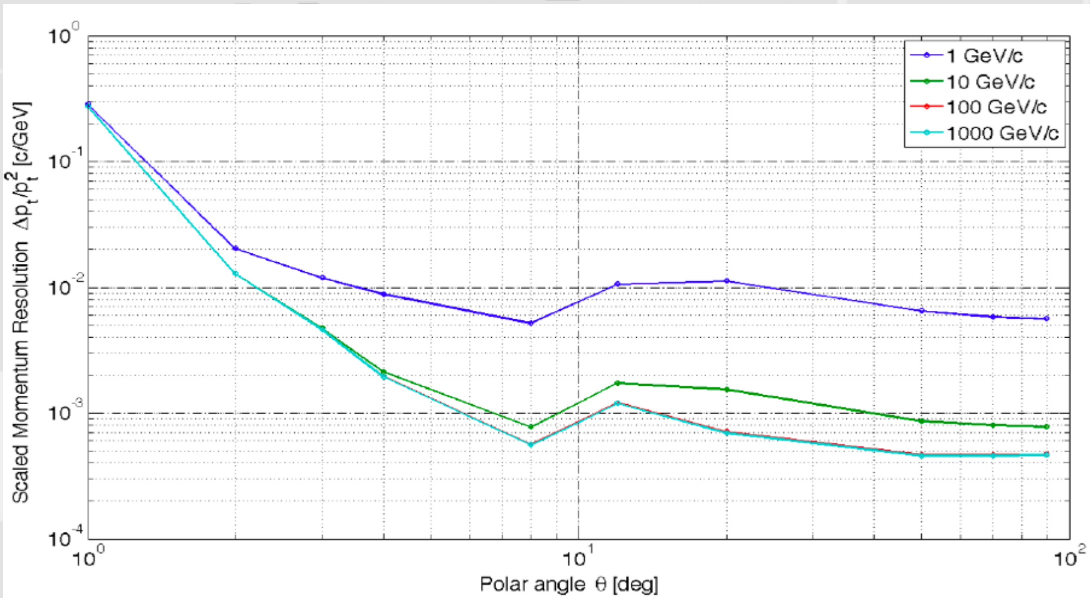
Beam pipe design – work in progress

LR more challenging than RR due to extended synchrotron radiation fan

R. Veness et al CERN

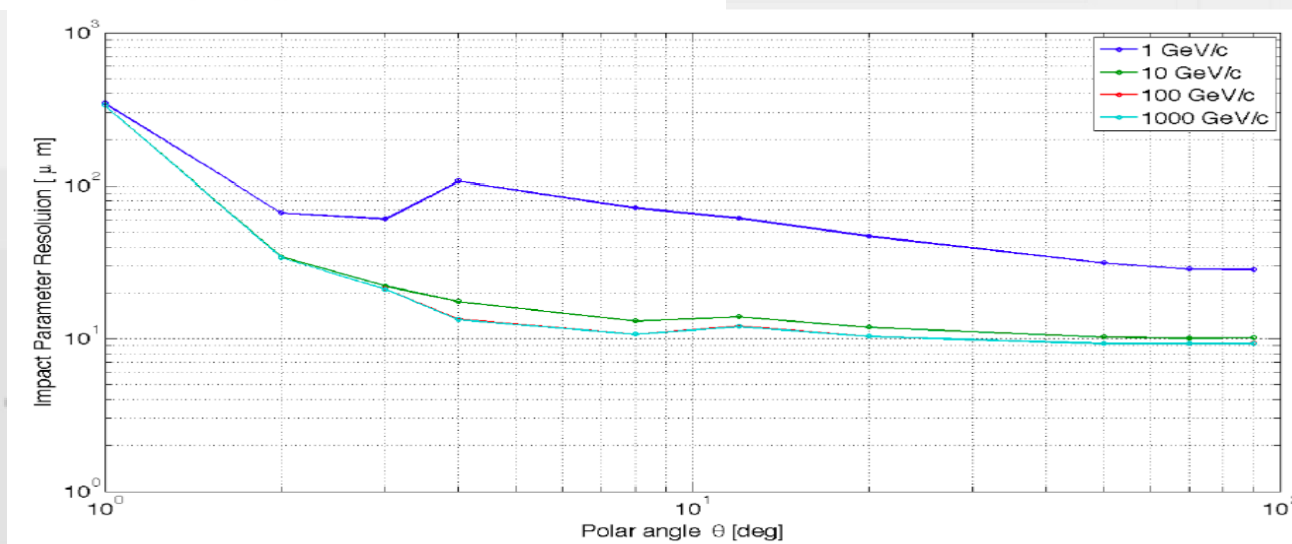
LHeC Experiment

- charged particle reconstruction



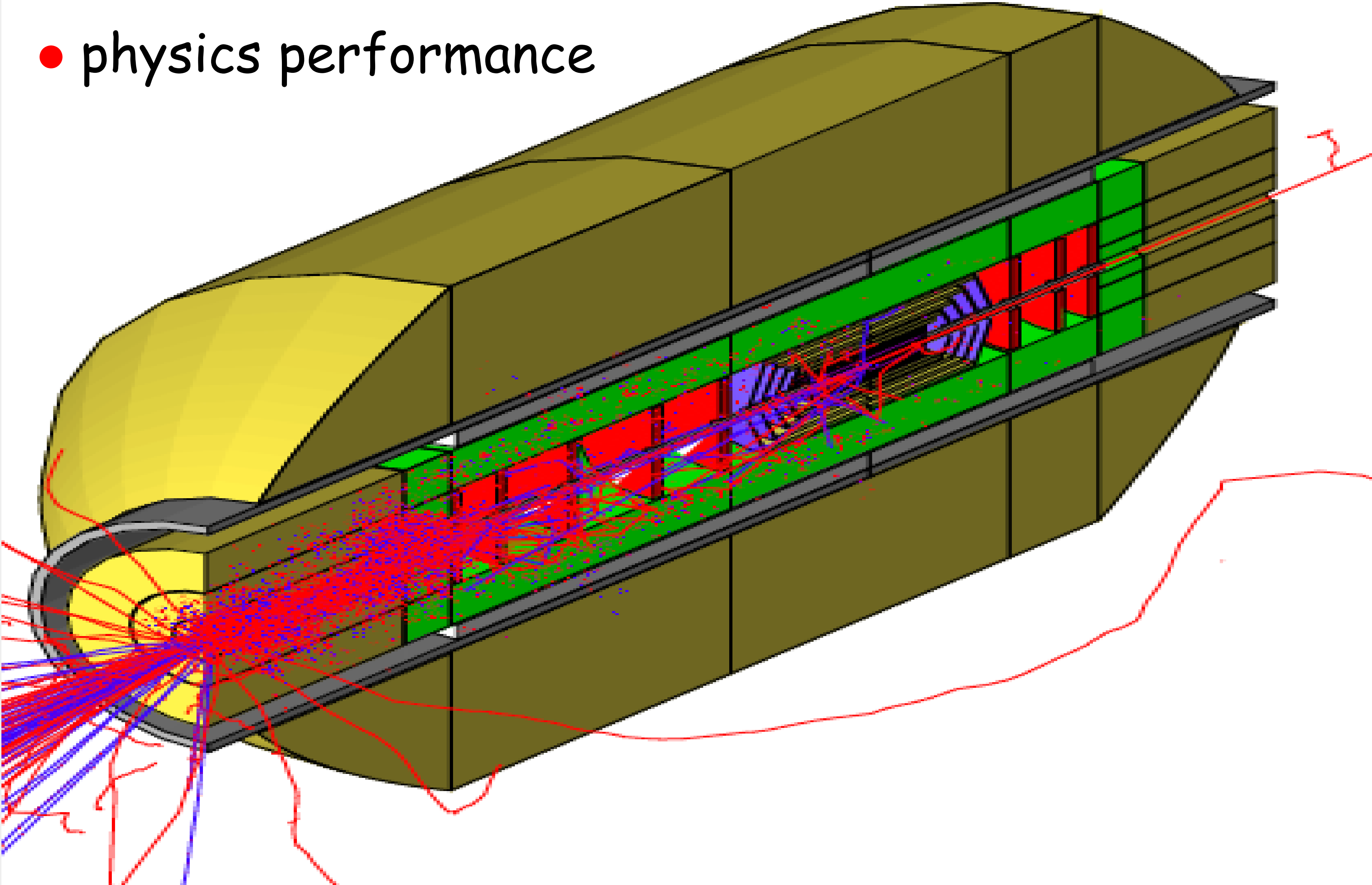
transverse momentum
$\Delta p_t/p_t^2 \rightarrow 6\ 10^{-4}\ GeV^{-1}$

transverse
impact parameter
→ 10µm



LHeC Experiment

- physics performance

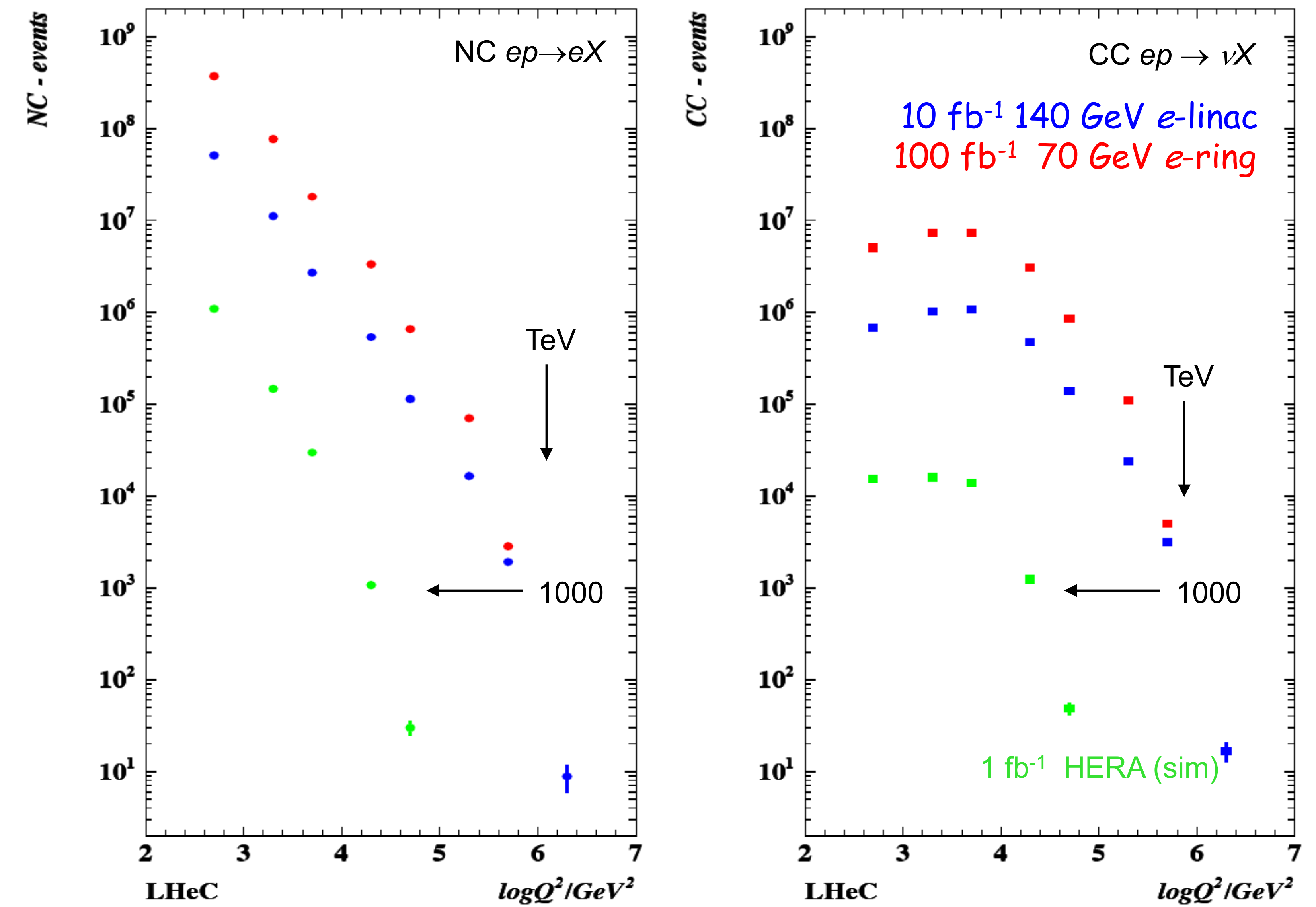


The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

3. The Structure of Matter beyond the Fermi scale: what might be?

Sensitivity

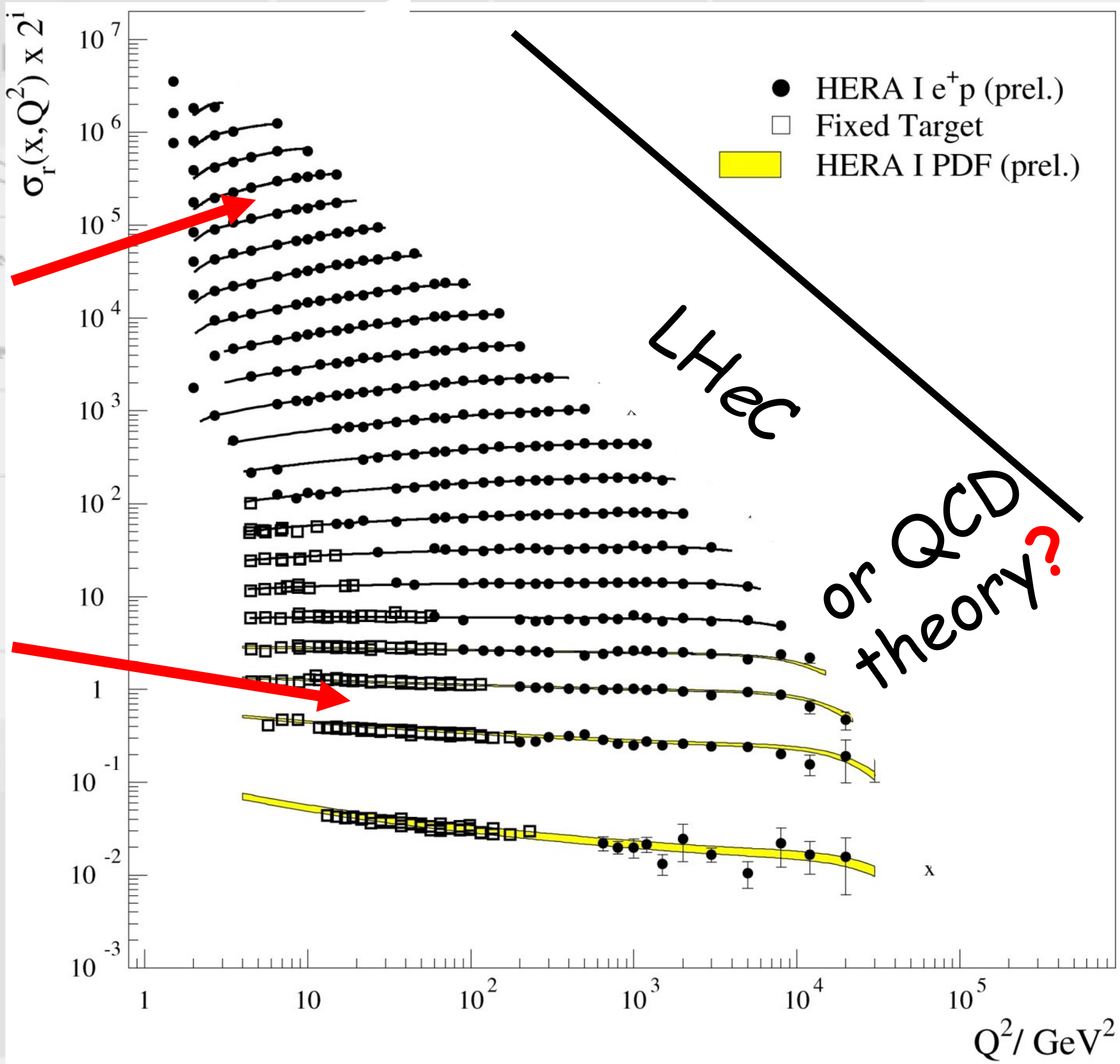
- rates: energy and lumi → TeV² reach in Q^2



No LHeC, no Terascale ?

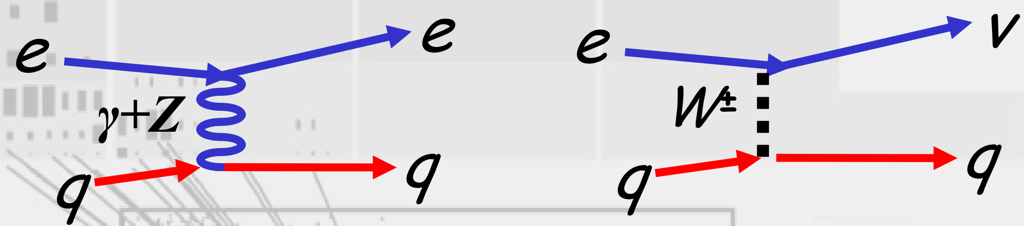
- flavour singlet field q_s evol$^{\underline{n}}$
  - resolving q_s in structure in QCD field

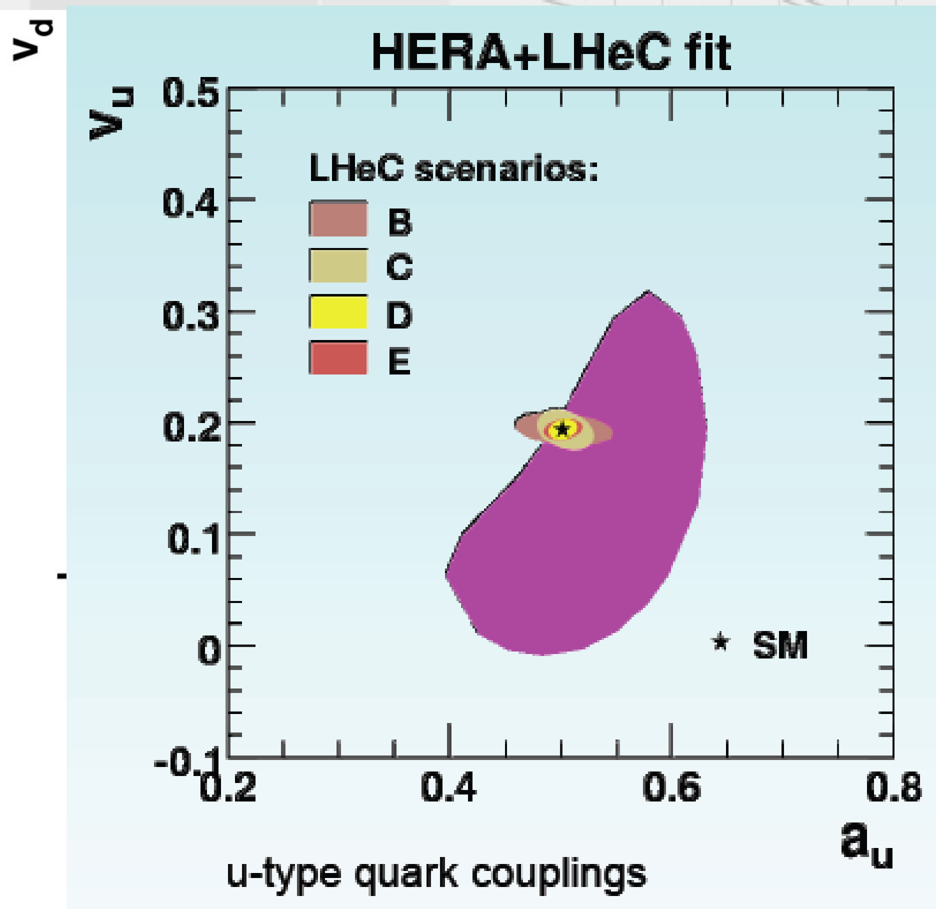
- valence q_v fixed flavour (u d) evolution
  - resolving q_v in p structure

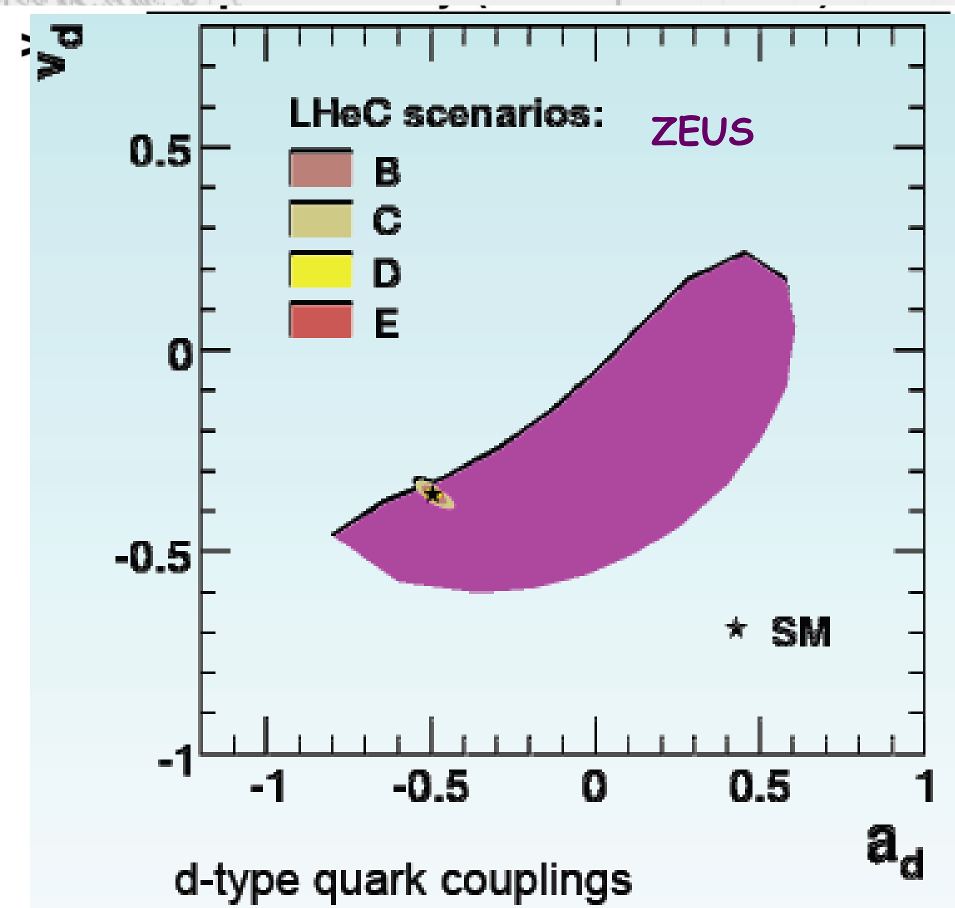


Electron-Quark Physics

- EW light q couplings (in proton matter)

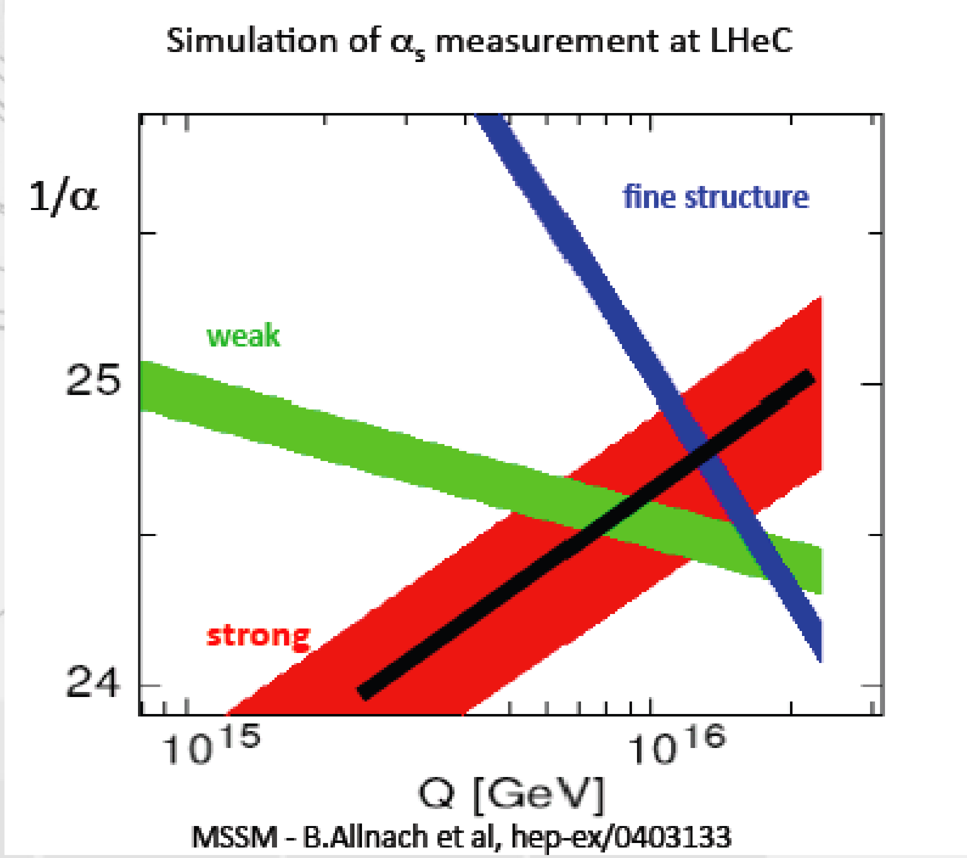






Probing Unification ?

- precision → QCD at highest energy
- short distance structure of SM+
  - 2007 α @ 10^{-3} ppm
  - 2007 G_F @ 10 ppm
  - 2007 G @ 0.1%
  - 2007 α_s @ 1-2%
  - LHeC + detector → α_s @ few ‰

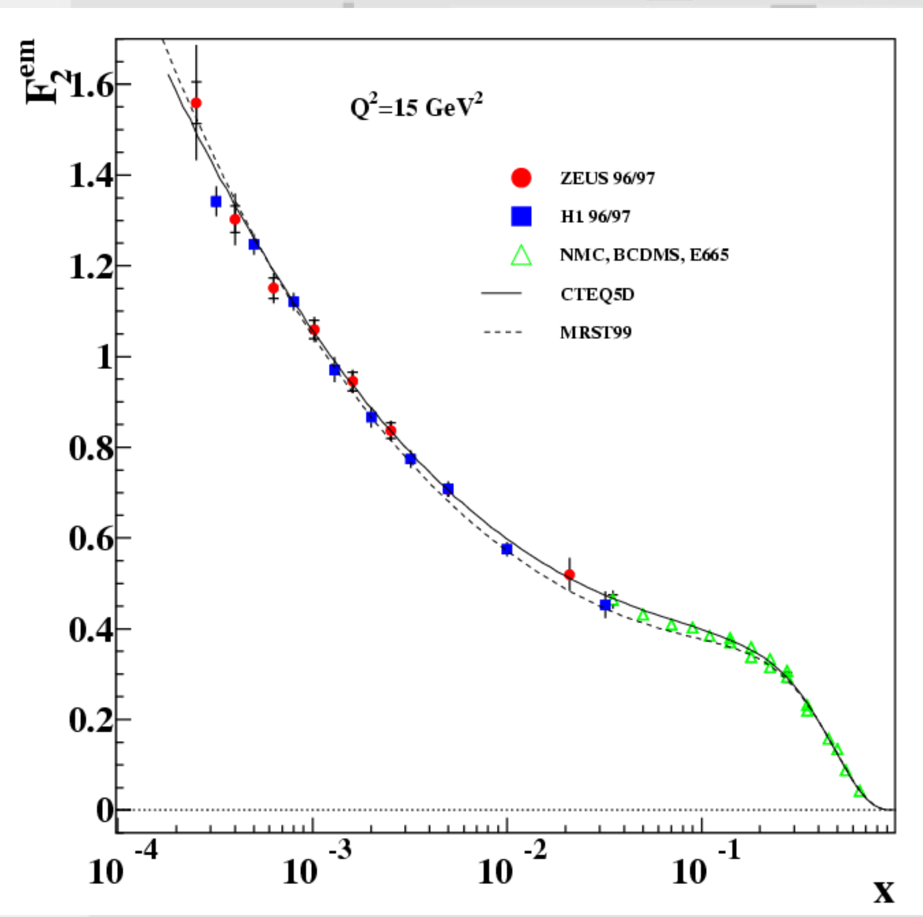


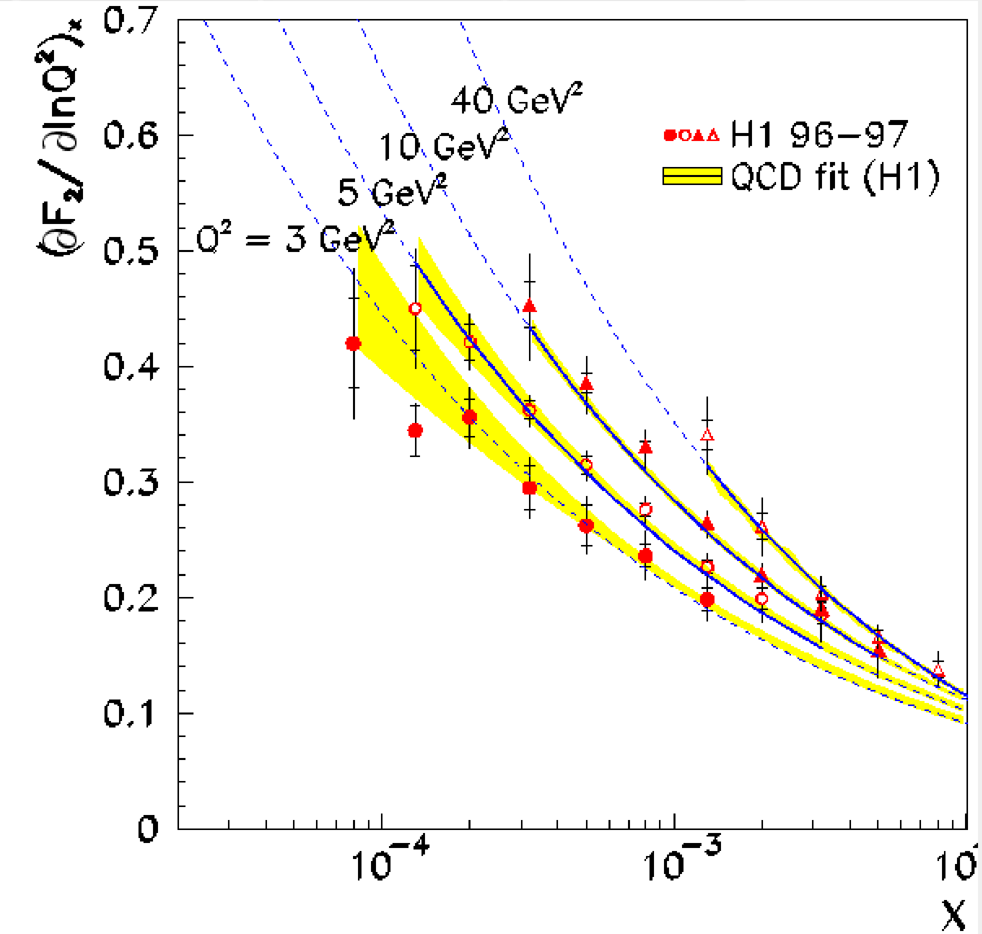
precision → extrapolation → discovery
probe new chromodynamic physics - beyond SM ?

2nd Intl Conference on Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

How heavy can you be?

- low-x magnifier: HERA: $x > 10^{-4}$ @ Q^2=10 GeV^2





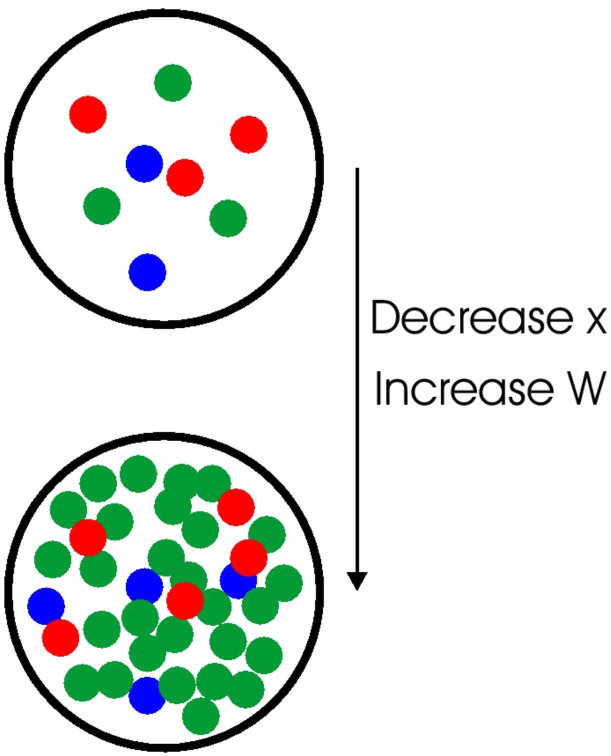
- relentless rise of quark (F_2) and gluon $\partial F_2 / \partial \ln Q^2$

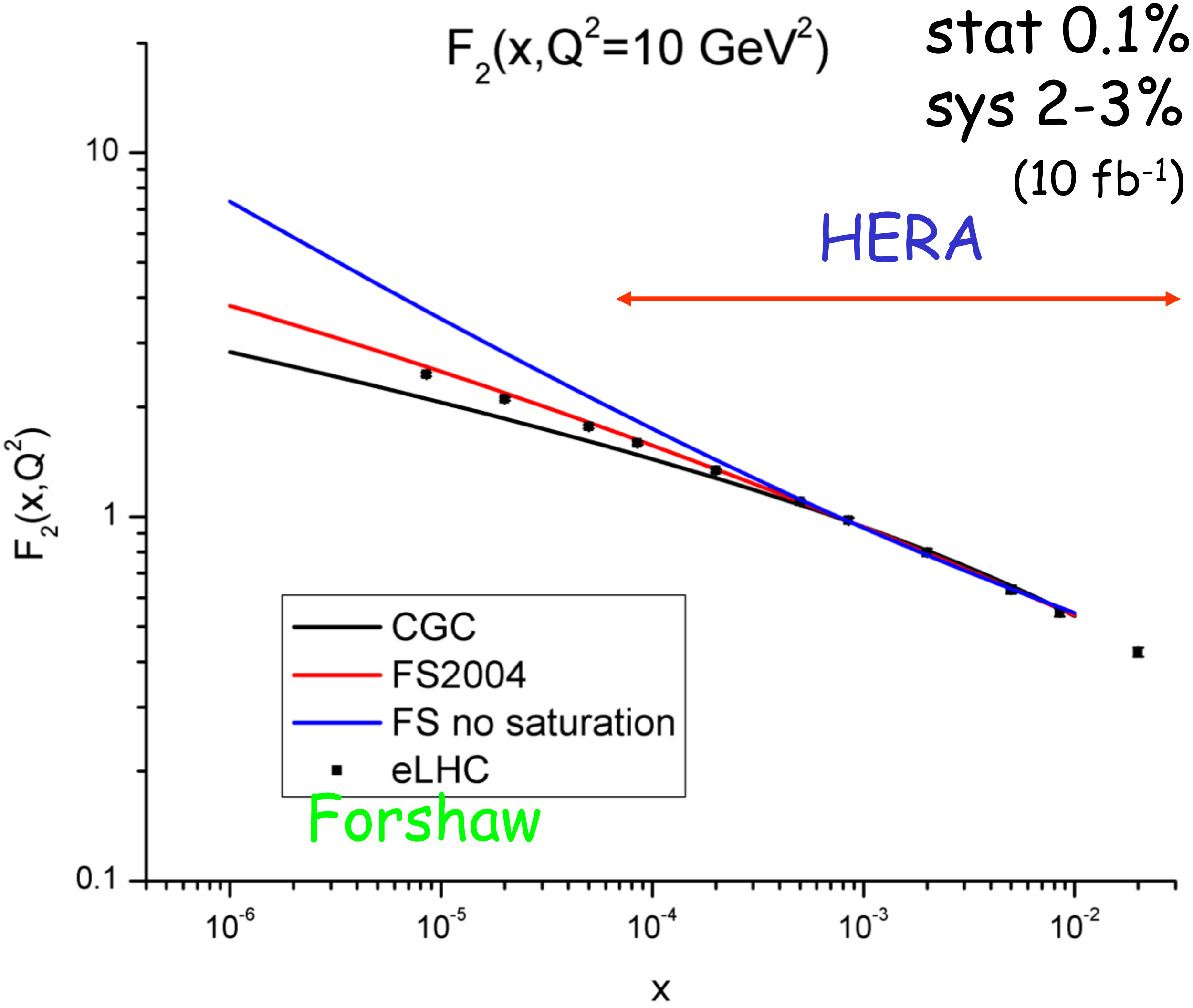
2nd Intl Conference on Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

How heavy can you be?

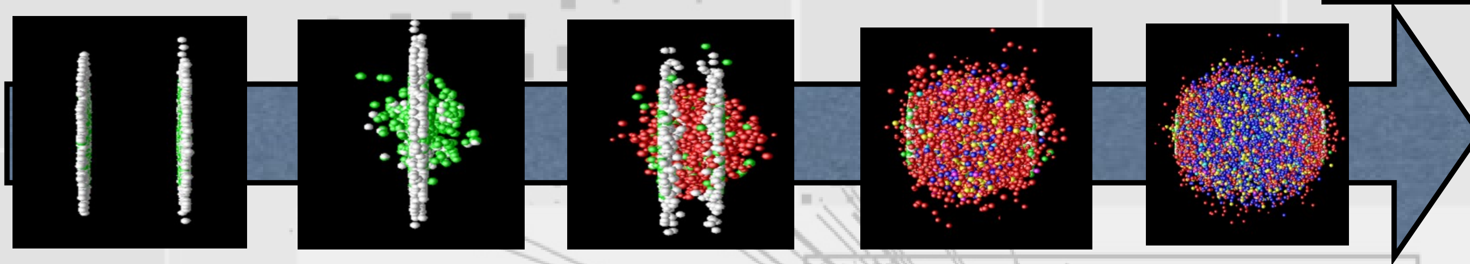
The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

- low-x magnifier: LHeC: $x > 4 \times 10^{-6}$ @ $Q^2 = 10$ GeV^2
- LHeC "nails"
  saturation
- unitarity



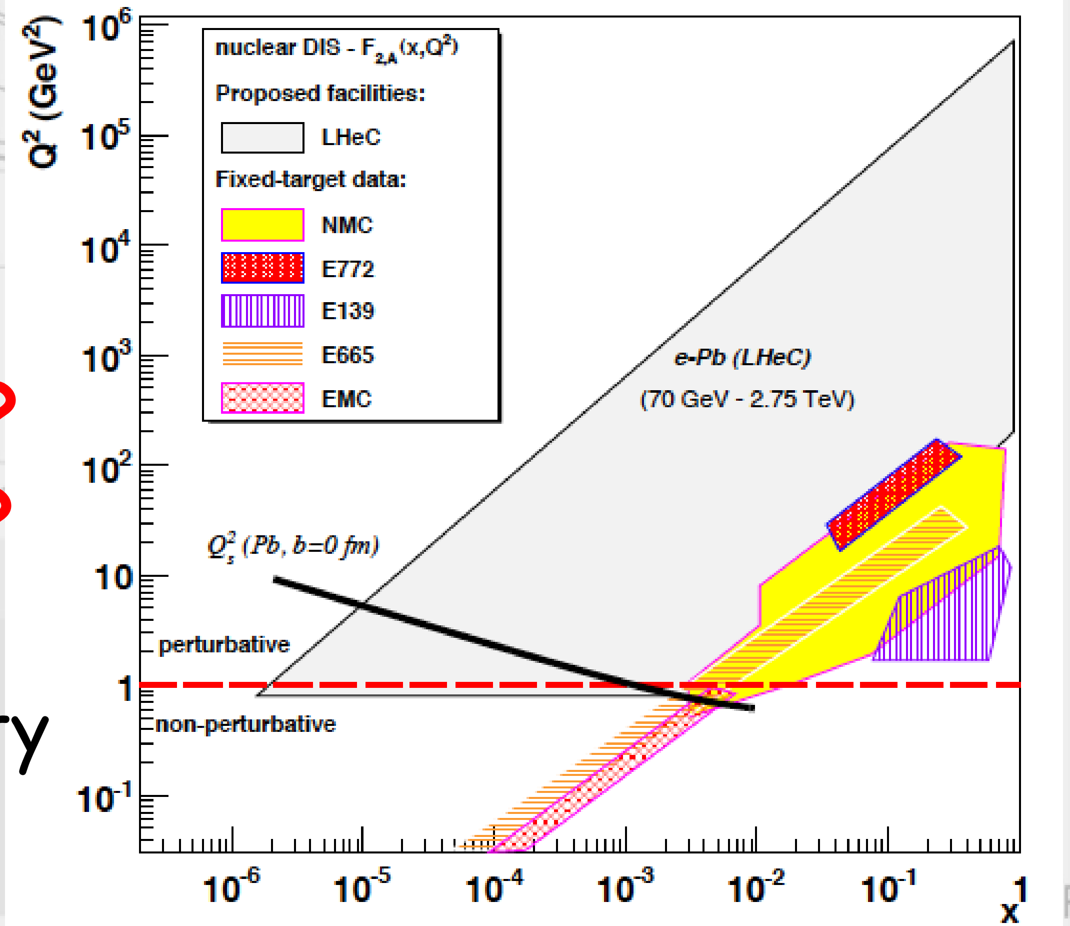


More on your mass!



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

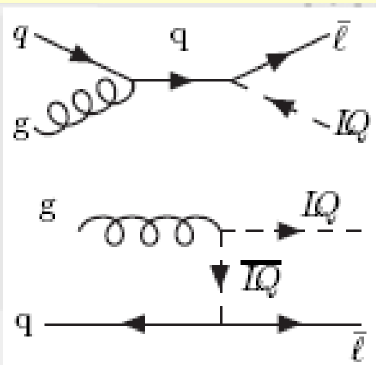
- low-x magnifier in nuclei
  - stacking up nucleons gluons behind gluons?
  - amplified saturation?
  - QCD phase equilibria
  - nuclear parton density (no HERA)



Beyond SM

LHC *Lq* physics +decay

fermion number



spin parity and chirality

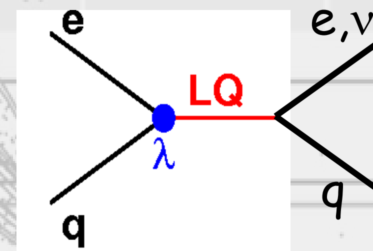
$gq \rightarrow Lq\,\bar{l}$

production mechanism ?

disentangle mass spectrum ?

signature jet + leptons

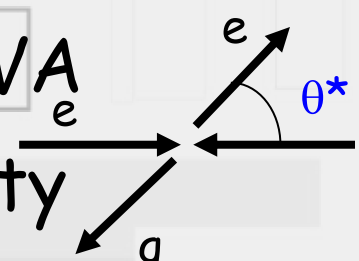
LH*e*C *Lq* formation+decay



e+ F=0
e- F=2

defined formation (e_{LR})
→ precision BRs (NC CC)

coherence → PWA



flavour sensitivity

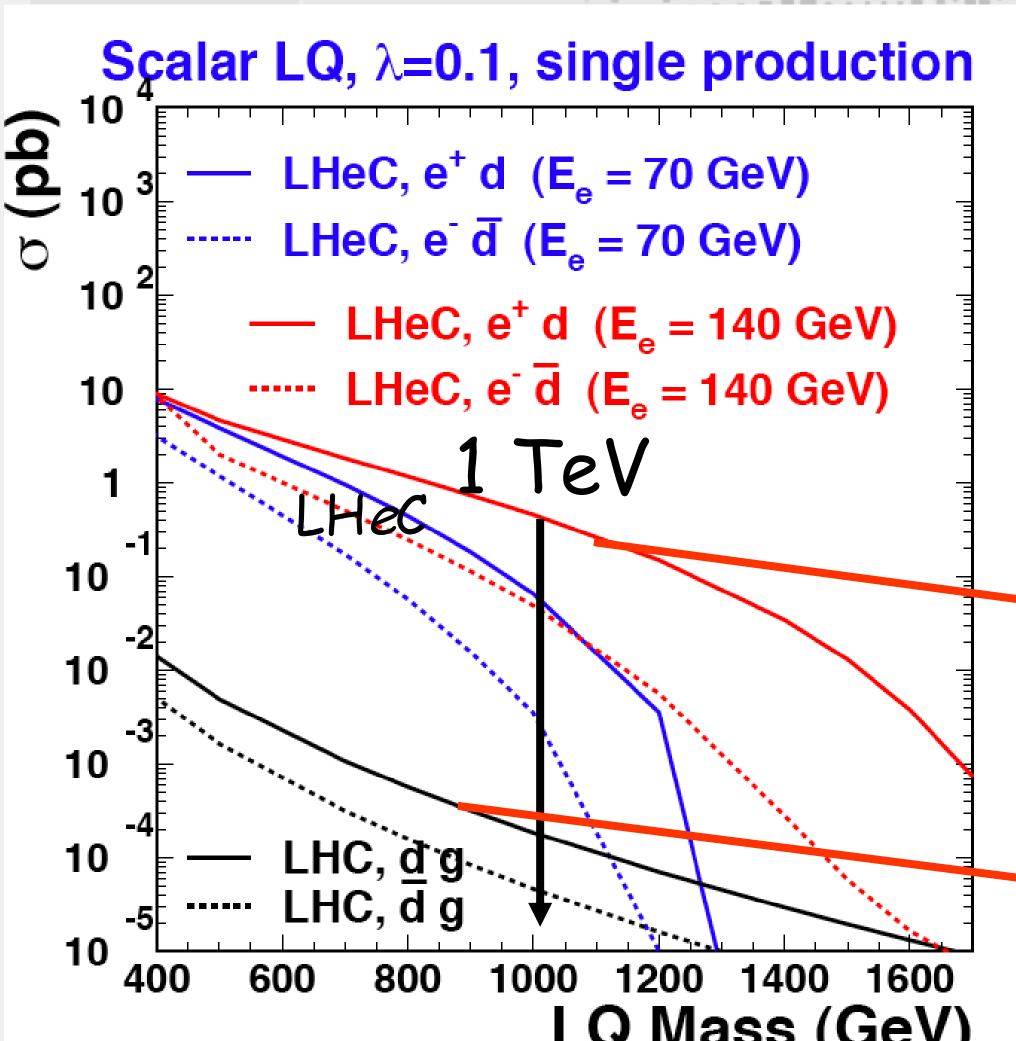
SM + signal + interference

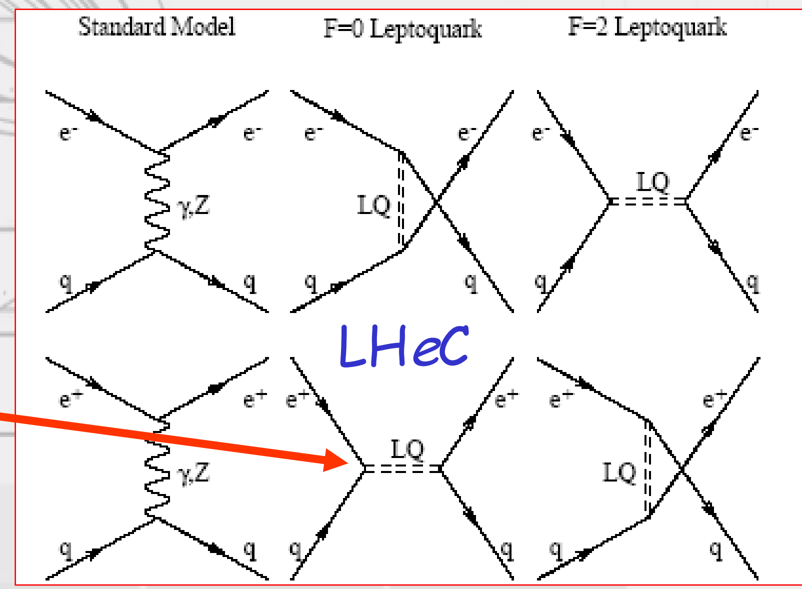
jet+lepton+p_T balance
jet +p_T imbalance

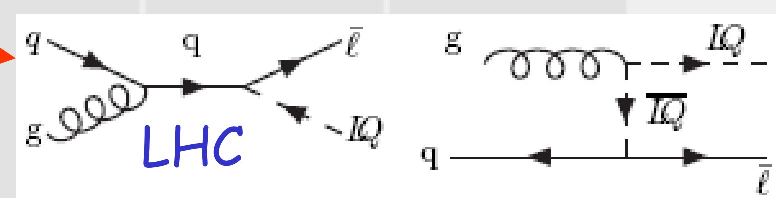
2nd Intl Conference on
Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

Lepton+quark @ Terascale

- new lepton+quark physics (*Lq*) + SM (precision)
  - resonance (incl. below threshold in *u*-channel)



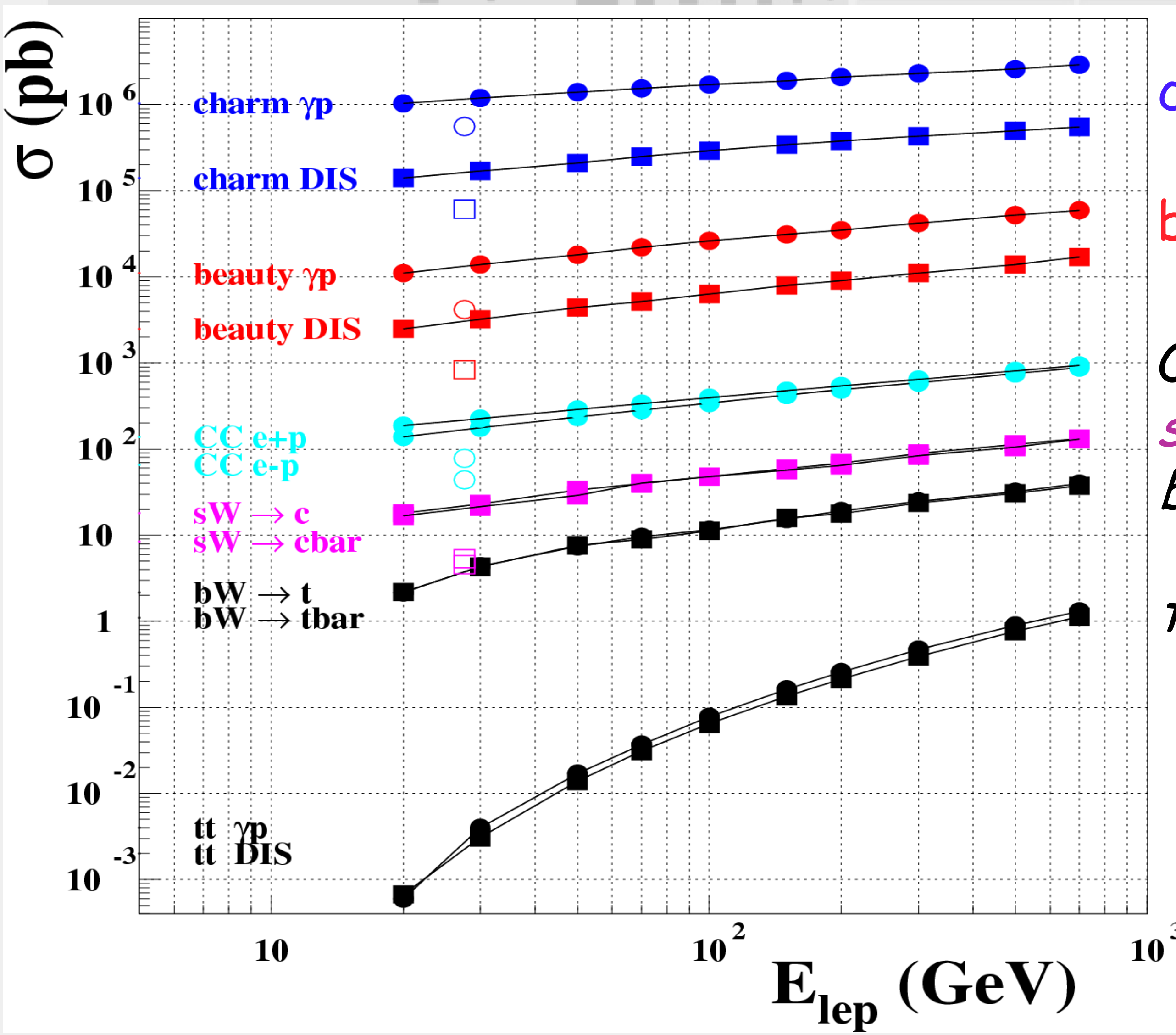




2nd Intl Conference on Particle Physics
Dogus Universit Turkey
June 20 to 25 2011

Heavy Quark @ Terascale

- HF-scale @Terascale



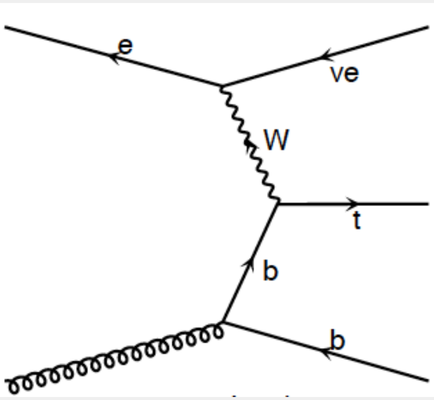
charm [10^{10} / 10 fb^{-1}]

beauty [10^{8} / 10 fb^{-1}]

CC [4.10^{5} / 10 fb^{-1}]

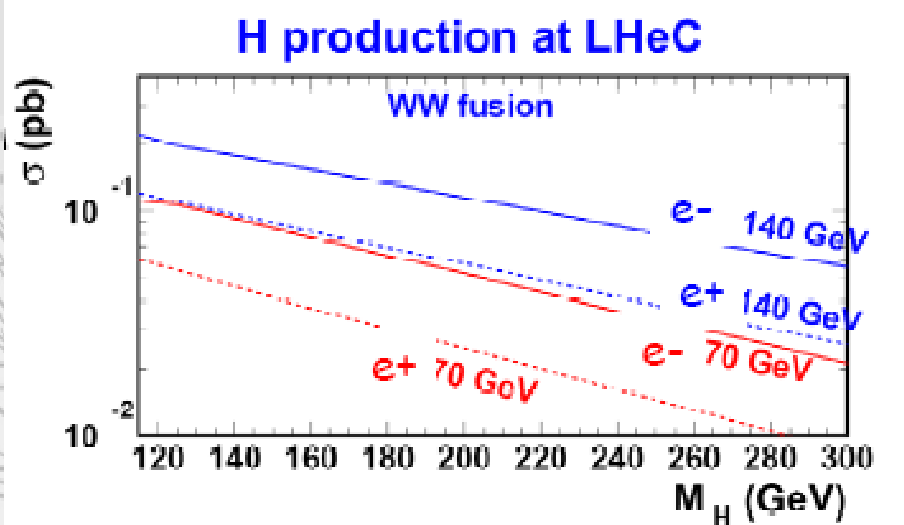
sW → c
bW → t [10^{5} / 10 fb^{-1}]

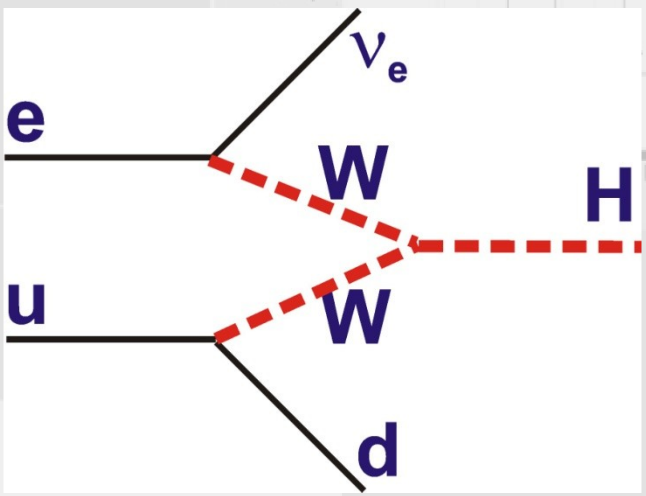
ttbar [10^{3} / 10 fb^{-1}]

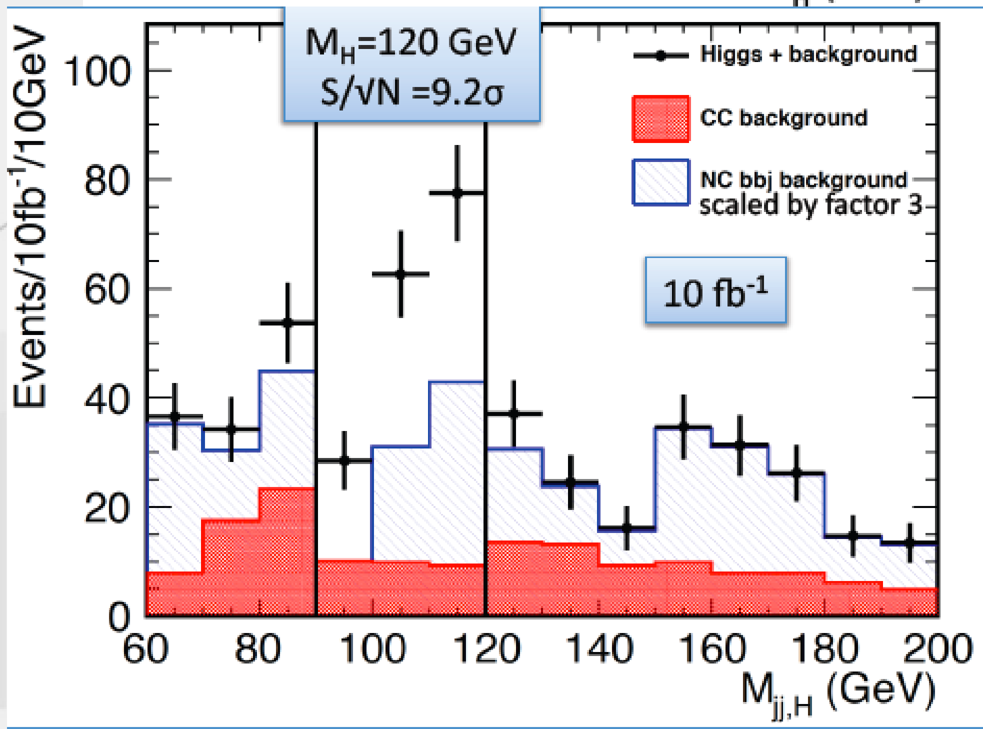


Higgs

- $H \to b$-jets + p_{Tmiss}
  - few x10^3/year before cuts
  - 2 b-tag
  - background: jets in NC top







The Energy Frontier

The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

- 2011-2033?
  Terascale

pp
TeV discovery ?
Higgs?
new particles?
new symmetries?
(LHC)

lp
TeVdiscovery
& precision ?
particles ?
symmetries ?
dense QCD
(LH*e*C)

Beyond
Standard
Model

new physics

e^+e^-
$t\bar{t}$
discovery &
precision ?
spectroscopy
Higgs ?
(ILC/CLIC)

The Matter Frontier

- 2011-2033: the mass we're made of ? chromodynamics?

ion = *A*

AA
QGP ?
QCD phase
equilibria?
nuclear dynamics?
nuclear formation
(LHC)

lA
QCD dof @
extremes
strong QCD ↔ 1_c
(LH*e*C)

matter creation
new physics

***e*⁺*e*⁻**
pQCD
(SuperKEKB
ILC/CLIC)

3. Status and Summary

LHeC

The Cockcroft Institute of Accelerator Science and Technology

University of Liverpool

- LHeC is the terascale lepton-quark machine
  - to date most pragmatic (and cost effective) means of getting a lepton into a TeV interaction
  - "upgrade of LHC" - simultaneous *pp ep* (*AA eA*)
  - exploits stupendous LHC hadron beams
  - challenges contemporary *e*-beam technology synergies (ERL, linac, low emittance rings)
  - no showstoppers so far
  - CERN ECFA and NuPECC support EIC/eRHIC collaboration
  - evaluation → CDR → ECFA, Europe strategy, CERN
  - TDR > 2011 → approval → physics ≥2020

↳ quarks and leptons; why and how ? When ?

LHeC Time-line

<table>
<tr><th>Year</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th></tr>
<tr><td></td><td colspan="3">Prototyping-testing</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="3">Production main components</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="6">Civil engineering</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Installation</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Operation</td></tr>
</table>

Variations on timeline:

- ➔ production of main components can overlap with civil engineering
- ➔ Installation can overlap with civil engineering
- ➔ Additional constraints from LHC operation not considered here
- ➔ in any variation, a start by 2020 requires launch of prototyping of key components by 2012

ECFA 11/2010: mandate to 2012

LHeC organisation

Scientific Advisory Committee

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell -chair (MPI Munich)
Swapan Chattopadhyay (Cockcroft)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (CERN)
Joel Feltesse (Saclay)
Lev Lipatov (St.Petersburg)
Roland Garoby (CERN)
Roland Horisberger (PSI)
Young-Kee Kim (Fermilab)
Aharon Levy (Tel Aviv)
Karlheinz Meier (Heidelberg)
Richard Milner (Bates)
Joachim Mnich (DESY)
Steven Myers, (CERN)
Tatsuya Nakada (Lausanne, ECFA)
Guenther Rosner (Glasgow, NuPECC)
Alexander Skrinsky (Novosibirsk)
Anthony Thomas (Jlab)
Steven Vigdor (BNL)
Frank Wilczek (MIT)
Ferdinand Willeke (BNL)

Steering Committee

Oliver Bruening (CERN)
John Dainton (Cockcroft) Inst
Albert DeRoeck (CERN)
Stefano Forte (Milano)
Max Klein - chair (Liverpool)
Paul Laycock (secretary) (L'pool)
Paul Newman (Birmingham)
Emmanuelle Perez (CERN)
Wesley Smith (Wisconsin)
Bernd Surrow (MIT)
Katsuo Tokushuku (KEK)
Urs Wiedemann (CERN)
Frank Zimmermann (CERN)

Working Group Convenors

Accelerator Design [RR and LR]
Oliver Bruening (CERN),
Max Klein (Liverpool)

Interaction Region and Fwd/Bwd
Bernhard Holzer (DESY),
Uwe Schneekloth (DESY),
Pierre van Mechelen (Antwerpen)

Detector Design
Peter Kostka (DESY),
Rainer Wallny (U Zurich),
Alessandro Polini (Bologna)

New Physics at Large Scales
George Azuelos (Montreal)
Emmanuelle Perez (CERN),
Georg Weiglein (Durham)

Precision QCD and Electroweak
Olaf Behnke (DESY),
Paolo Gambino (Torino),
Thomas Gehrmann (Zuerich)
Claire Gwenlan (Oxford)

Physics at High Parton Densities
Nestor Armesto (Santiago),
Brian Cole (Columbia),
Paul Newman (Birmingham),
Anna Stasto (MSU)

QCD/electroweak:
Guido Altarelli, Alan Martin, Vladimir Chekelyan

BSM:
Michelangelo Mangano, Gian Giudice, Cristinel Diaconu

eA/low x
Al Mueller, Raju Venugopalan, Michele Arneodo

Detector
Philipp Bloch, Roland Horisberger

Interaction Region Design
Daniel Pitzl, Mike Sullivan

Ring-Ring Design
Kurt Huebner, Sasha Skrinsky, Ferdinand Willeke

Linac-Ring Design
Reinhard Brinkmann, Andy Wolski, Kaoru Yokoya

Energy Recovery
Georg Hoffstatter, Ilan Ben Zvi

Magnets
Neil Marx, Martin Wilson

Installation and Infrastructure
Sylvain Weisz

http://www.ep.ph.bham.ac.uk/exp/LHeC/