Seminar: Jlab and BNL
August 2011

# 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

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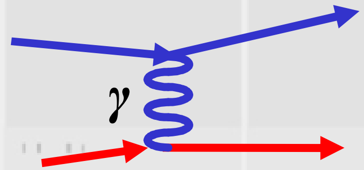
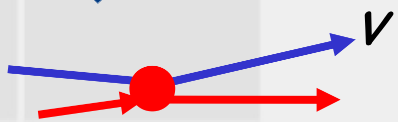
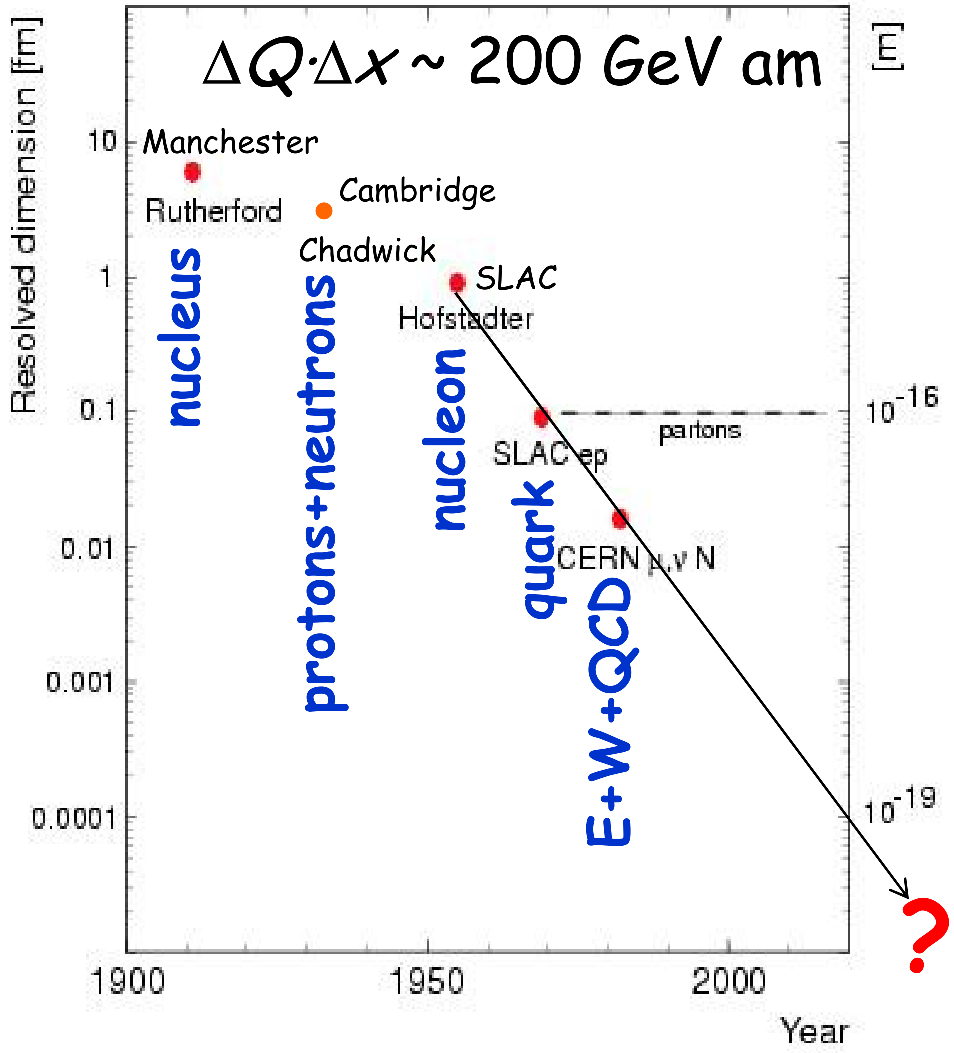
# 1.The Structure of Matter 2011

# 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



# Matter @ Short-Distance

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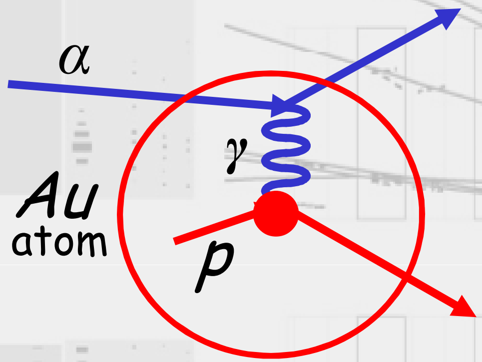
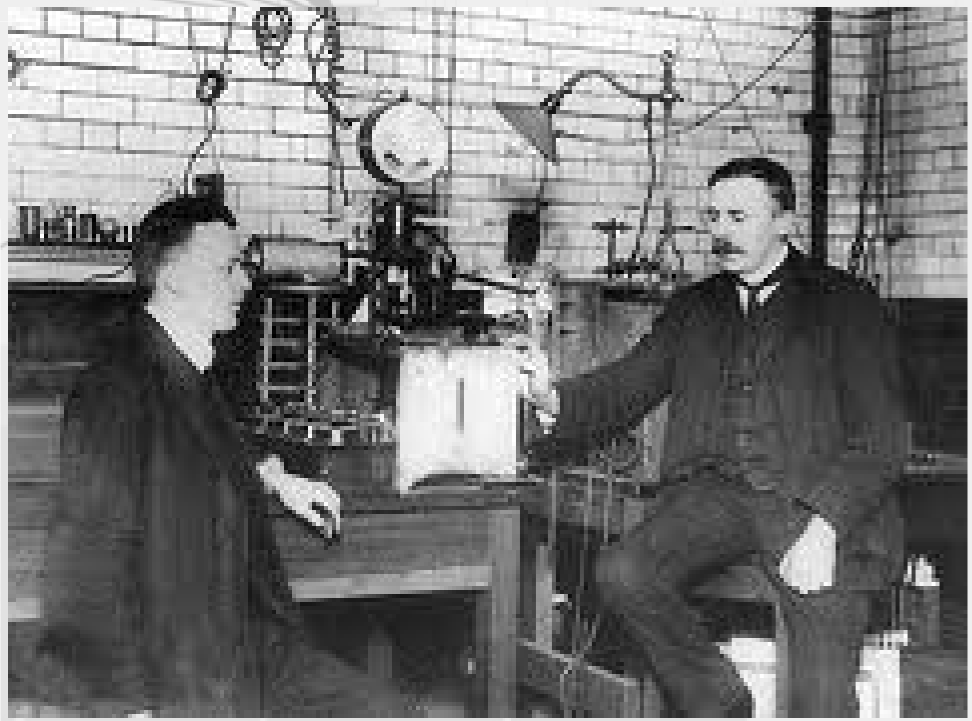
- Rutherford: Megascale Nobel
  - 1909 nucleus




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



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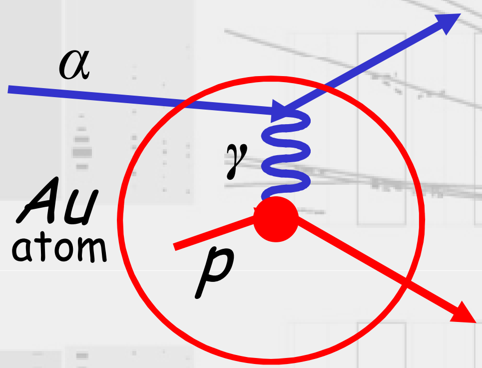
# Matter @ Short-Distance

- Rutherford: Megascale Nobel
  - 1909 nucleus

penetrating the nucleus

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

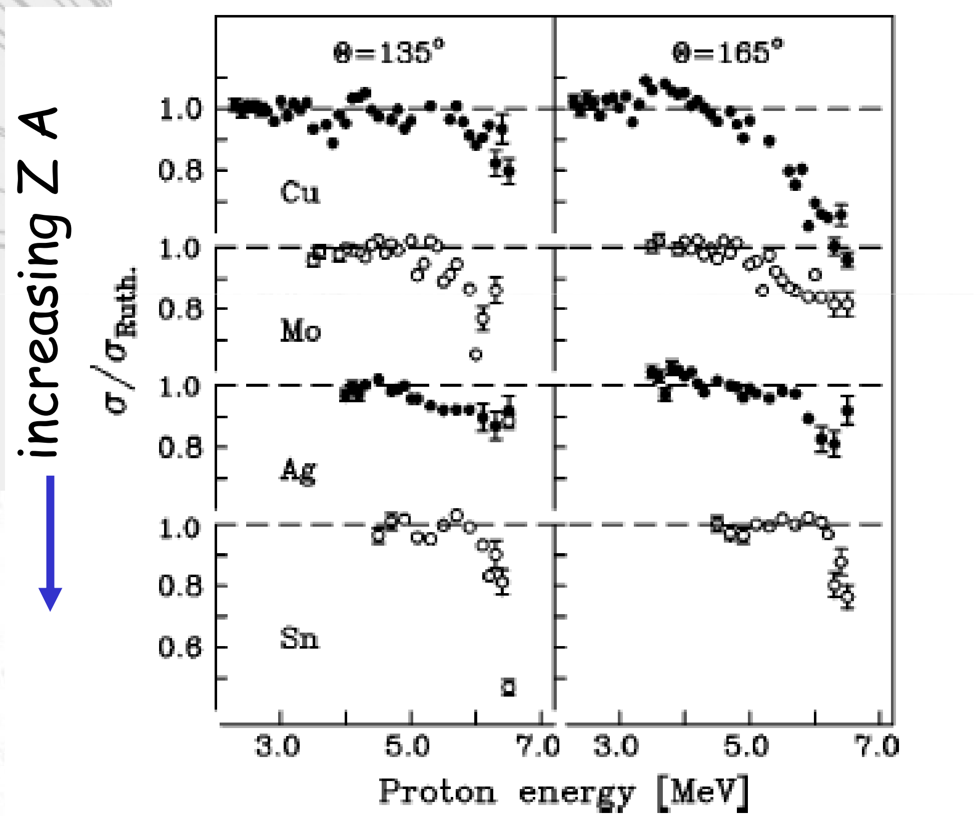


FIG. 1. Elastic scattering cross sections relative to Rutherford cross sections for proton scattering by copper, molybdenum, silver and tin at laboratory scattering angles of 135° and 165°. The uncertainties in the cross section values are indicated in some of the data points.

# Kinematics

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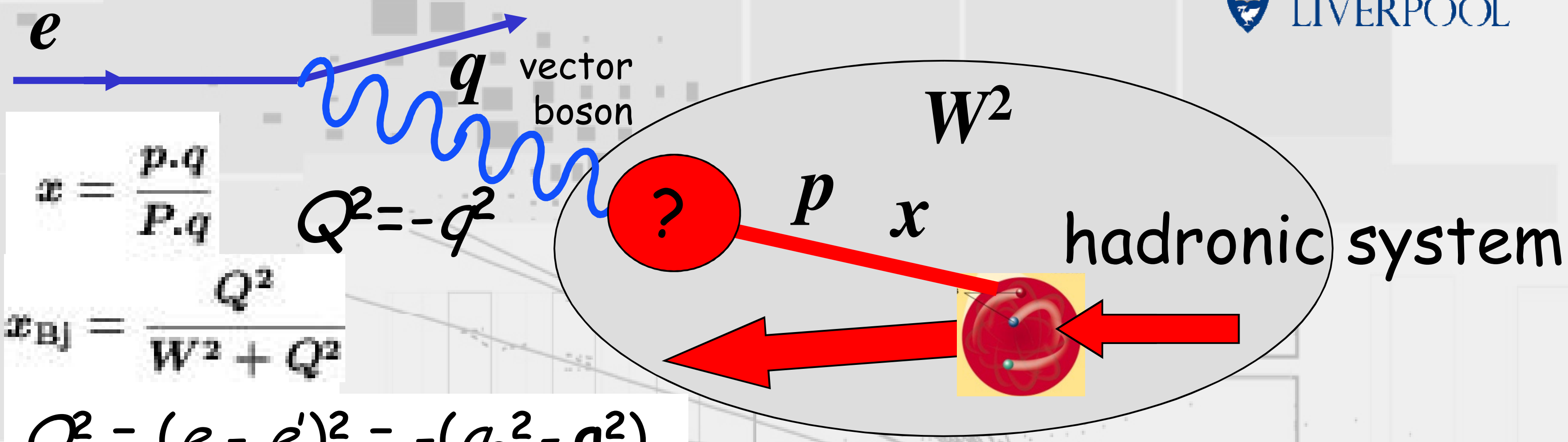



$$x = \frac{p.q}{P.q}$$

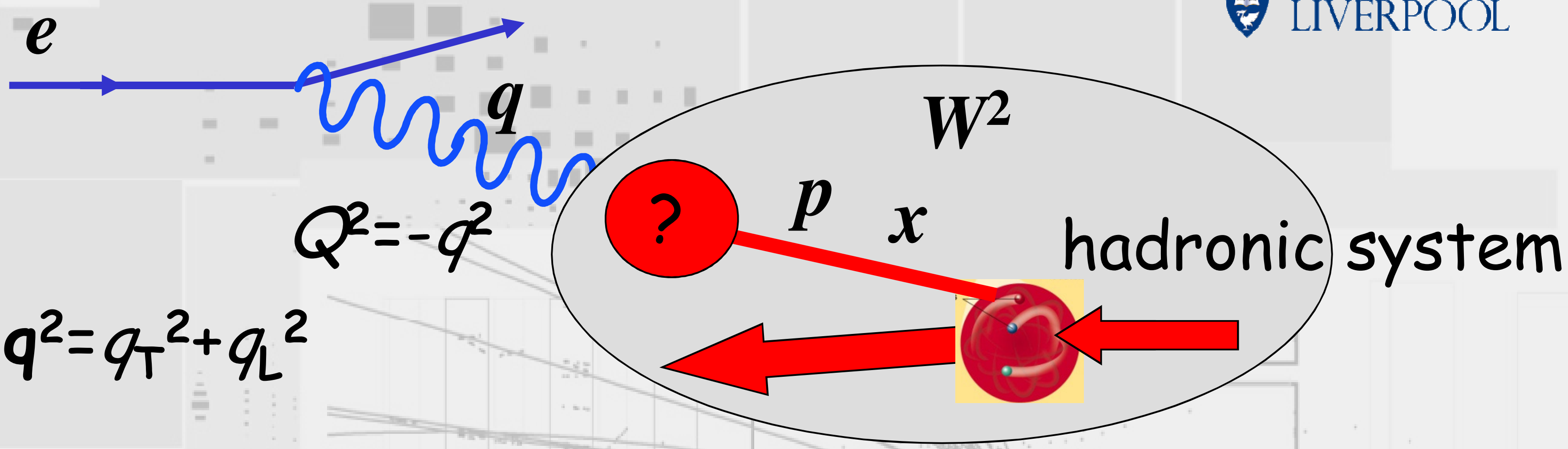
$$Q^2 = -q^2$$

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

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

- **q** = 3-mom$^{\underline{m}}$ transfer in lepton-hadron interaction
  → view of spatial extent of interaction+quanta
  $-q_0$ = energy transfer from lepton in interaction
  phase space for dynamics of interaction ($W$)
  ↳ probe kinematics → extent+view of interaction
- $x$ = "inelasticity": struck piece out of hadron
  ↳ target kinematics ↔ extent of interaction

# Interaction Scale




- scale **q**·Δ**r** ~ 200 GeV·am

$$\beta = \frac{P}{P_0} \qquad \gamma = \frac{P_0}{M}$$

$$q_T^2 + \frac{q_L^2}{\gamma^2} = -q^2\left(1 - \beta\frac{q_L}{xP_0} - \frac{q^2}{4x^2P_0^2}\right)$$

- hadron ∞ momentum: $q_T^2 = -q^2$

"EW snapshot" of Lorentz contracted target hadron

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

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

# Interaction Scale

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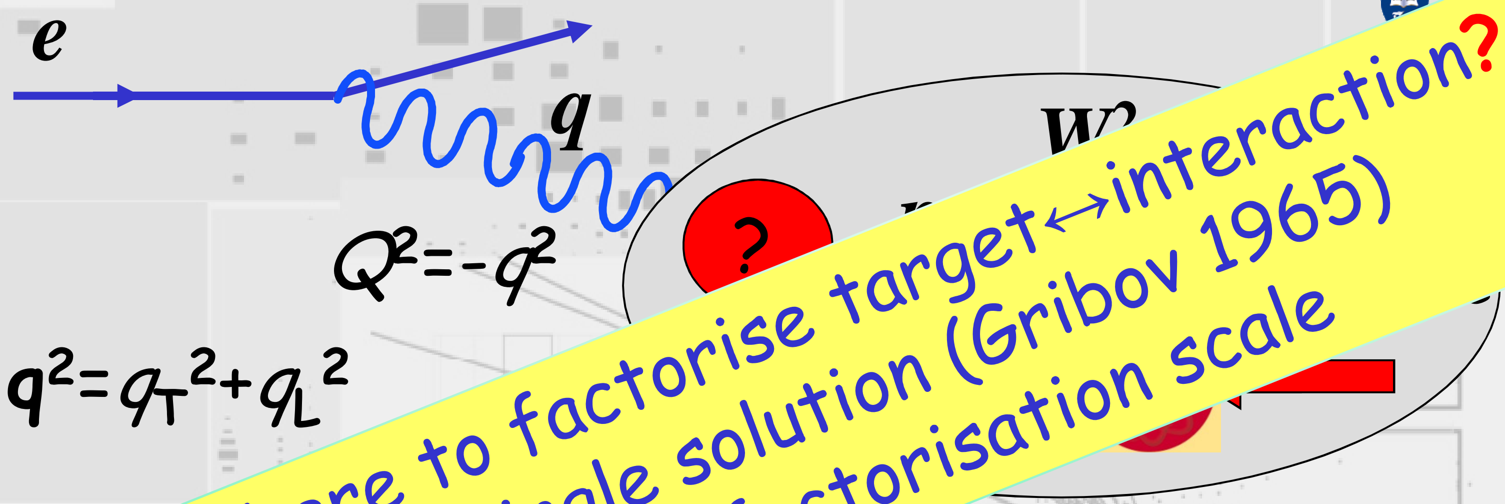



Where to factorise target↔interaction?
no single solution (Gribov 1965)
(QCD) factorisation scale

- scale ... um

$$q_{?}^{2} = \ldots -q^2\left(1-\beta\frac{q_L}{xP_0}-\frac{q^2}{4x^2P_0^2}\right)$$

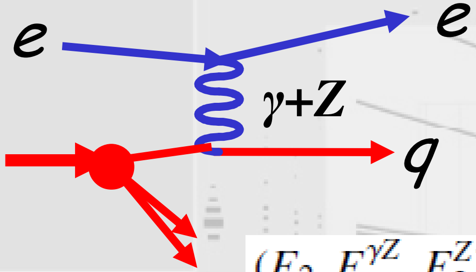
$$\beta=\frac{P}{P_0} \qquad \gamma=\frac{P_0}{M}$$

- hadron ∞ momentum: $q_T^2=-q^2$
  "EW snapshot" of Lorentz contracted target hadron
- hadron at rest: $\mathbf{q}^2=q_T^2+q_L^2=-q^2\left(1-\frac{q^2}{4x^2M^2}\right)$

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

# Hadronic Structure

- EW probe of hadronic structure …
  - neutral current




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

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

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

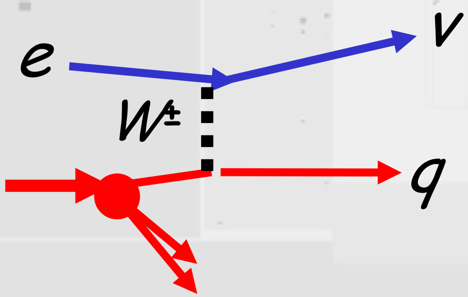
$$\tilde{F}_L = F_L - \kappa_Z v_e \cdot F_L^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2)\cdot F_L^Z ,$$

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

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

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

  - charged current

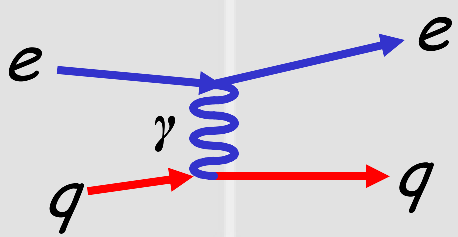



$$\sigma^{\pm}_{r,\mathrm{CC}} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma^{e^\pm p}_{\mathrm{CC}}}{\mathrm{d}x\mathrm{d}Q^2}$$

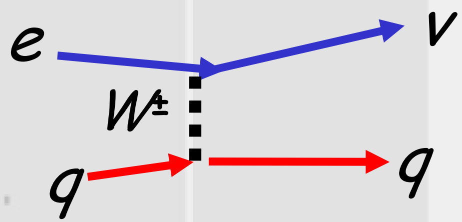
$$\sigma^{\pm}_{r,CC} = \frac{Y_+}{2}W_2^\pm \mp \frac{Y_-}{2}xW_3^\pm - \frac{y^2}{2}W_L^\pm$$

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

- and beyond ?
  q structure ?



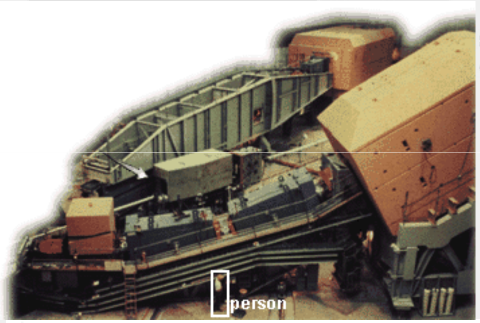

\+



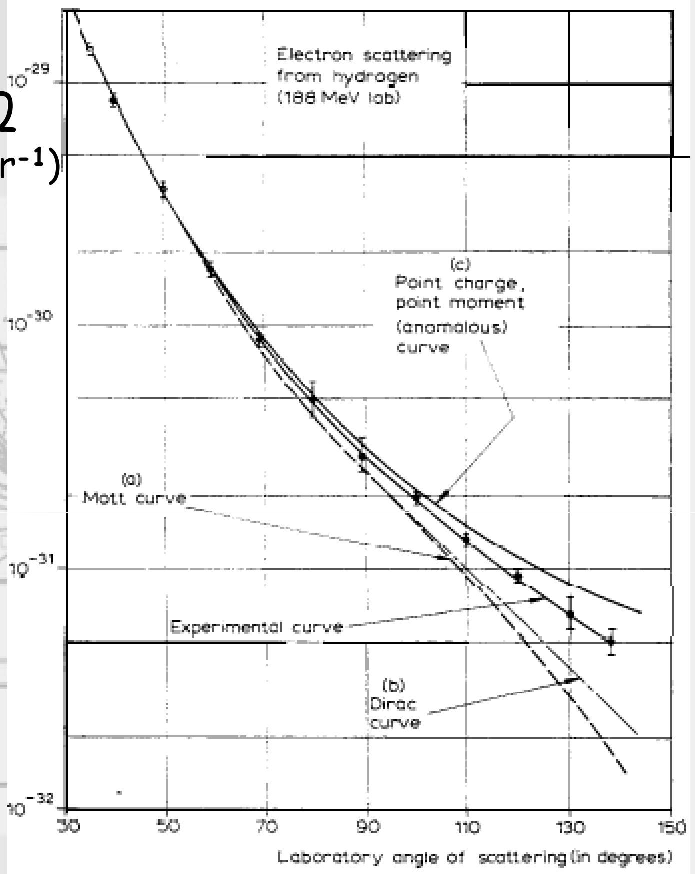

\+ ?

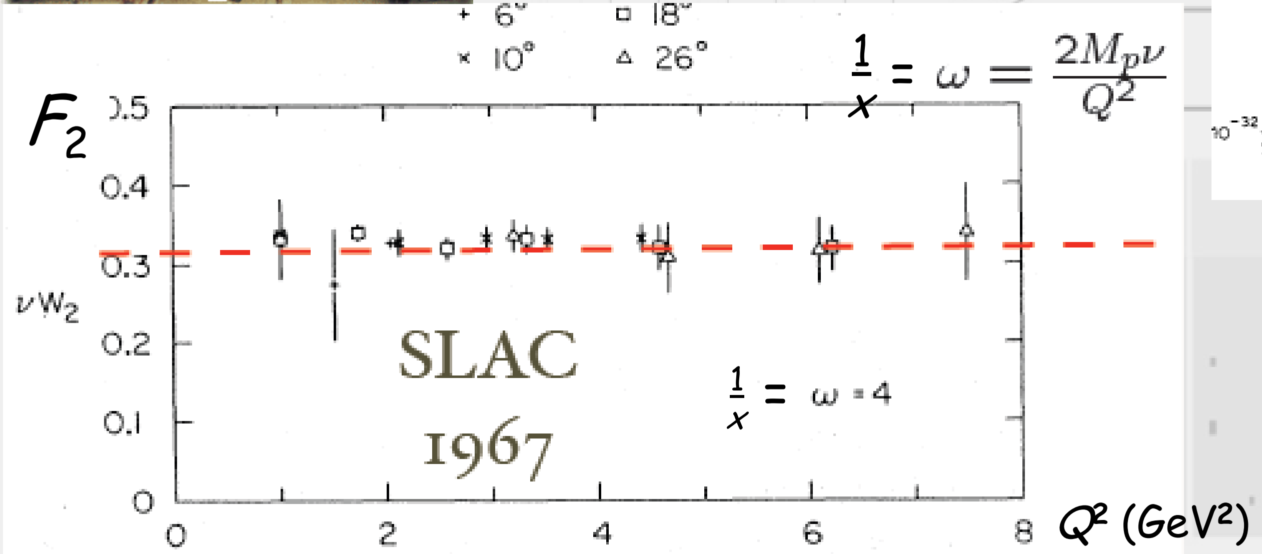
# Matter @ Short-Distance

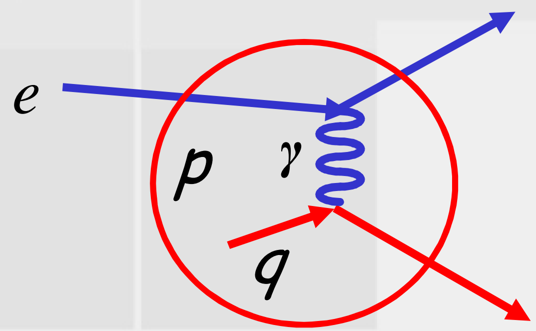
- SLAC end station: sub-nuclear scale
  - 1959 nucleus size
    nucleon size — Nobels Hofstädter
  - 1967 quarks — Friedman Kendall Taylor




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

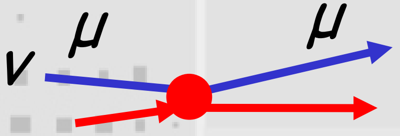


# Matter @ Short-Distance

- CERN + Fermilab
  - fixed target
  - sub-fm ($Q \lesssim 20$ GeV)
  - 1972 weak NC
  - 1977 QCD

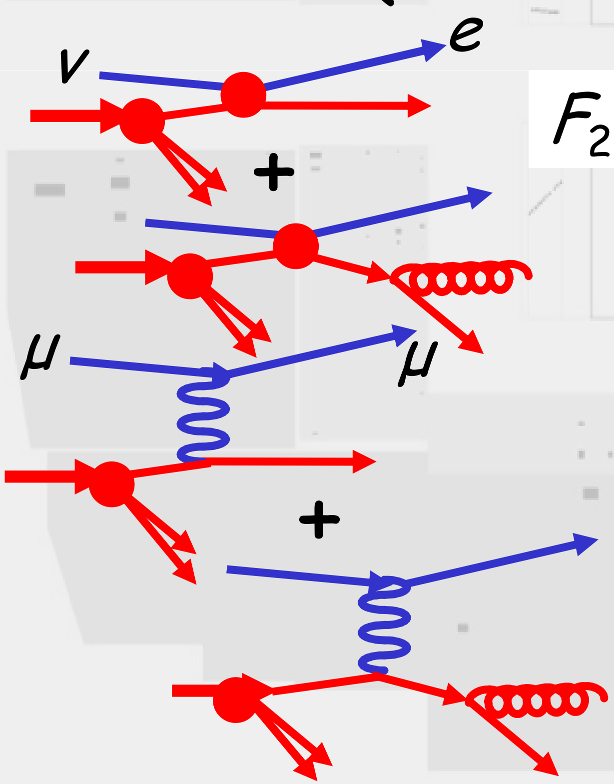


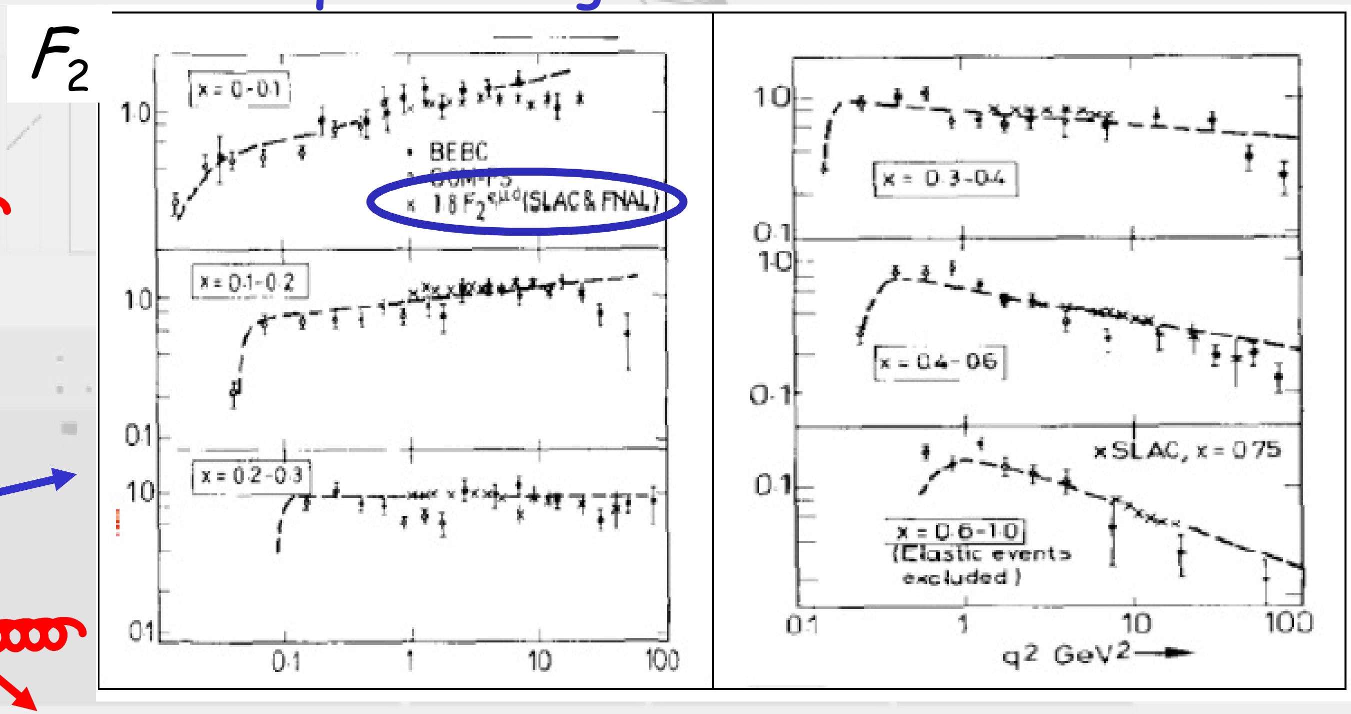

Gigascale

Nobel

Nobel

quark charge

# The Energy Frontier

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- 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

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

$SU(3)_C$

$e^+e^-$

charm
beauty
jets
3 colours
gluon

# Why Leptons ↔ Quarks ?

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

THE UNCONFINED QUARKS AND GLUONS

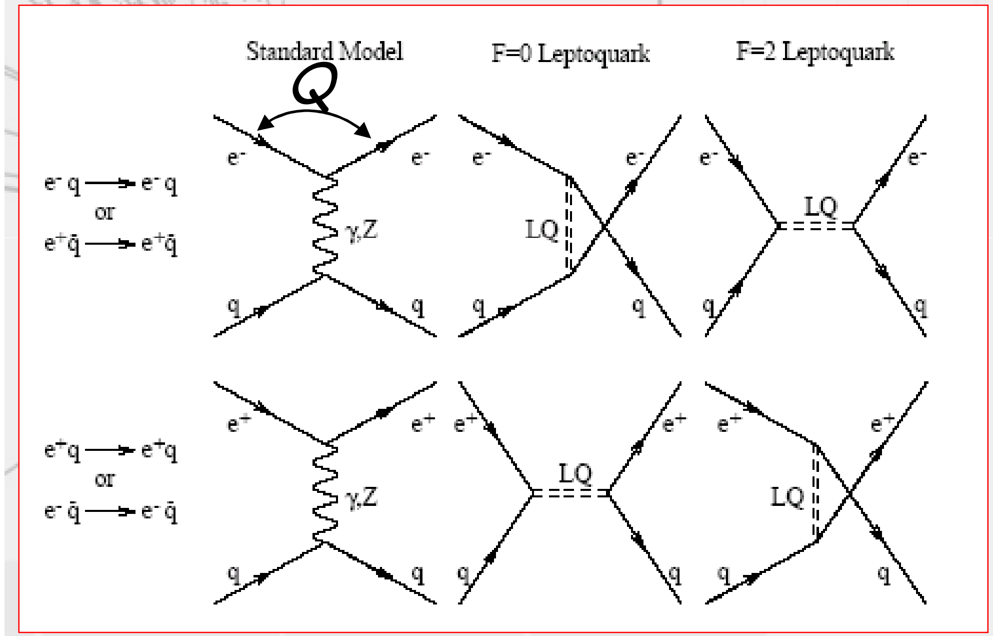
Abdus Salam

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 $\Delta x \Delta Q \sim \hbar$

# A precision Fermiscale *ep* Collider HERA @ DESY

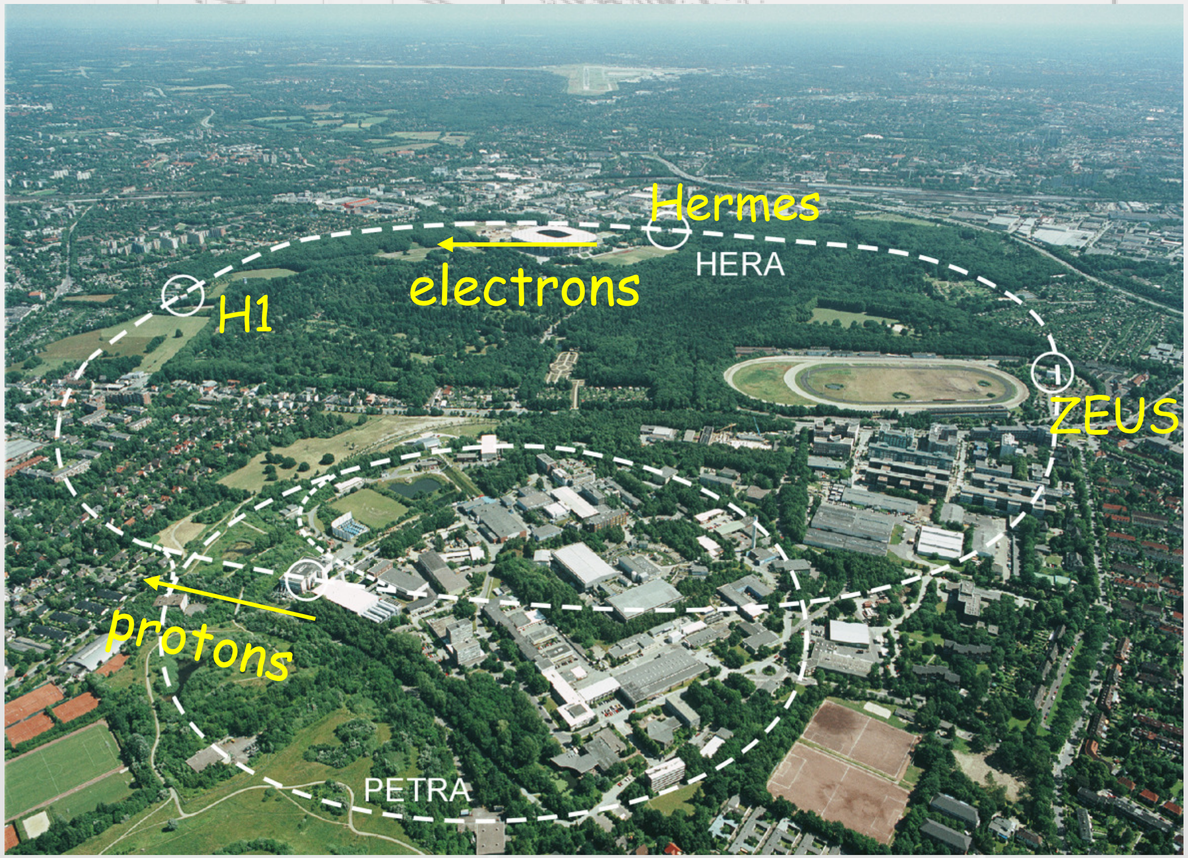
- challenge: different particle species *ep* in collision

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

lepton

*ep* cm energy 314 GeV

**HERA**
DESY
Hamburg




HERA
+
H1

1992-2007
RIP

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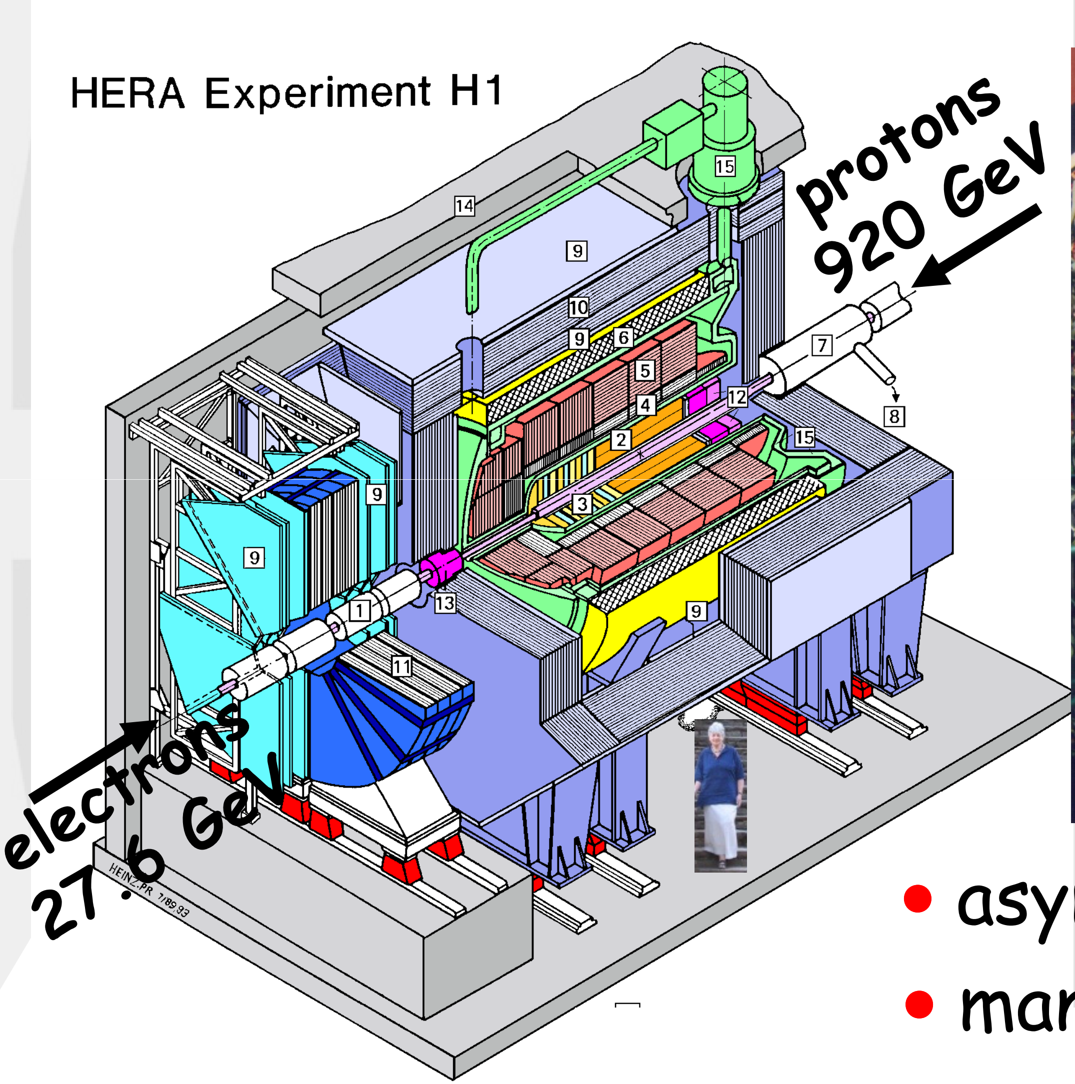
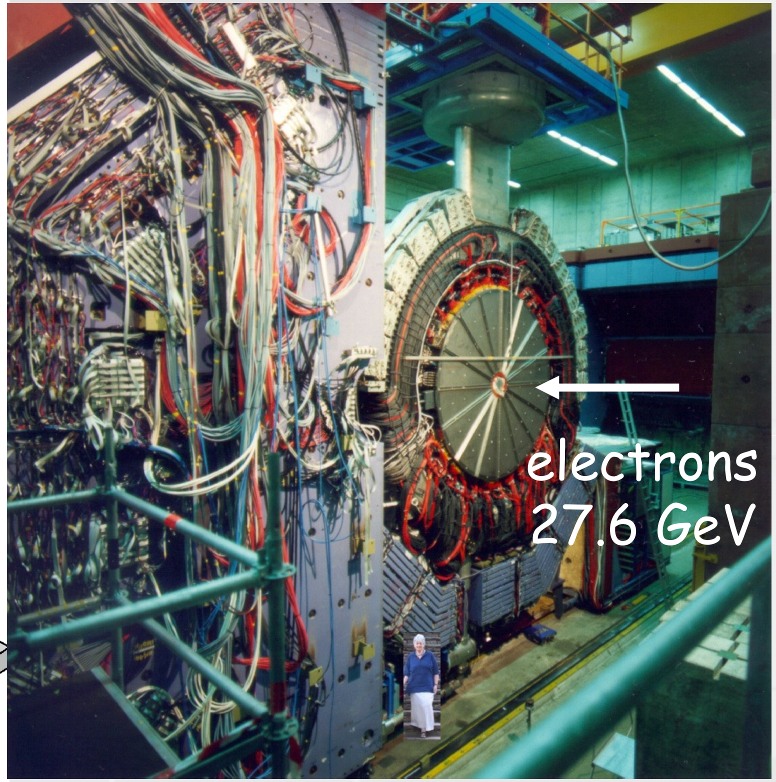
# Fermiscale Experiment @ HERA



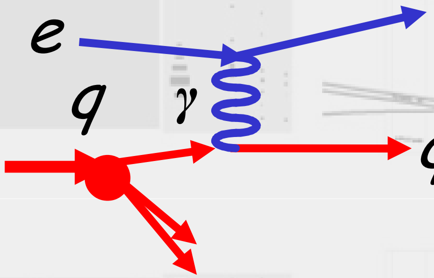




- asymmetric $e$ and $p$
- many bunch $\Delta t_{ep}$ = 75 ns
- $p_T$ scale ~ 300 GeV (Fermi)

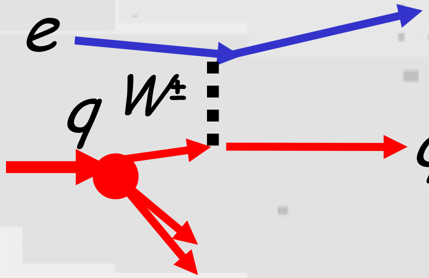
# Matter @ Short-Distance

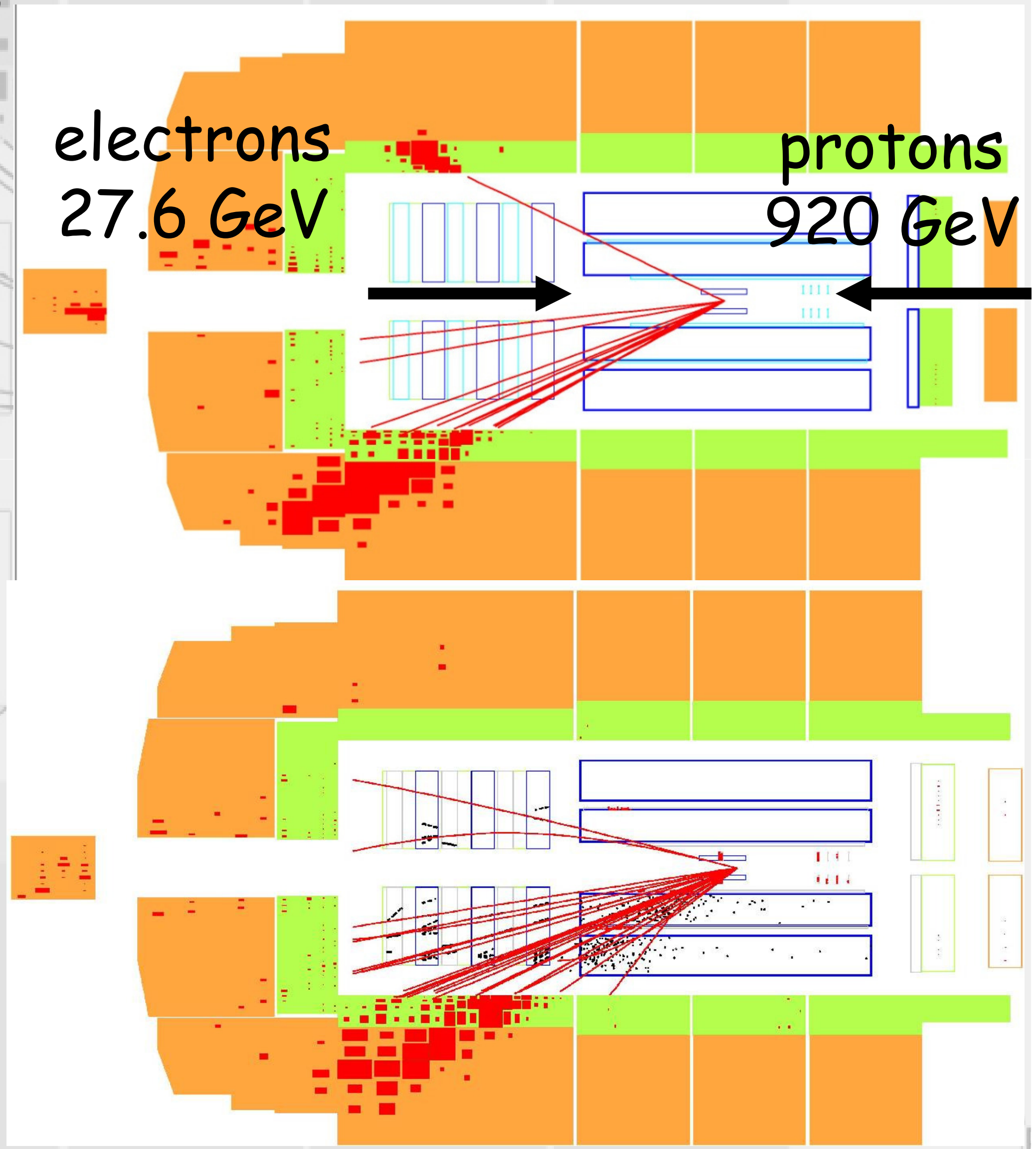


- Rutherford scattering at the Fermi scale
  - neutral current




  - charged current



# *eq* @ Fermi scale

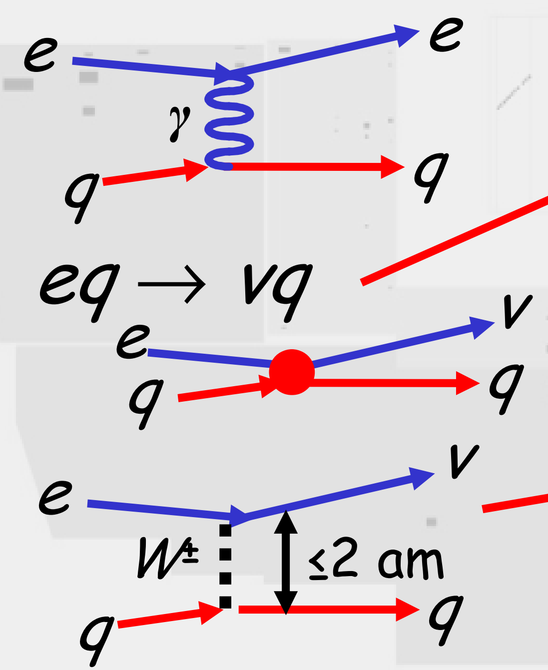
- resolving structure in SU(2) ⊗ U(1)

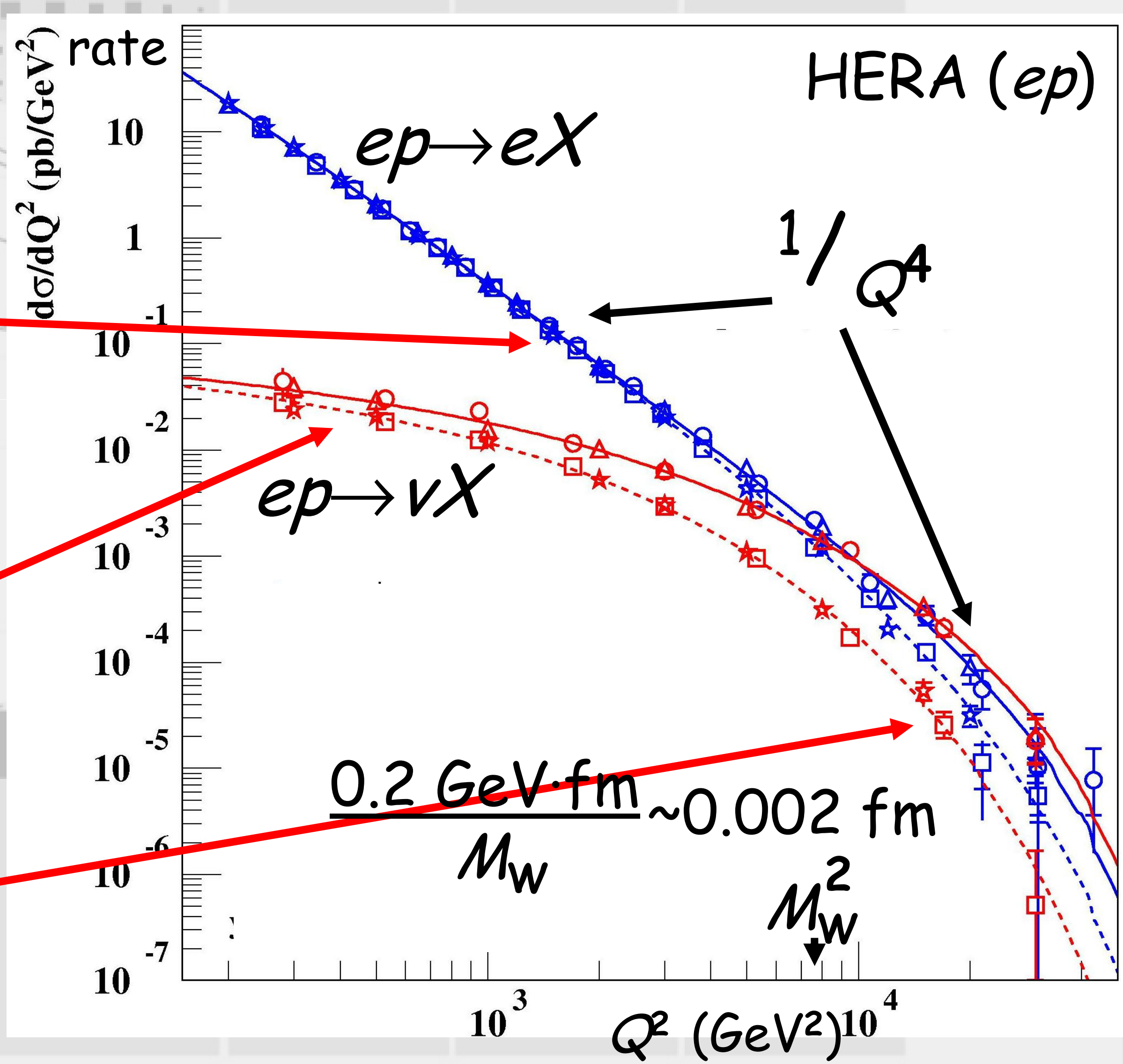
$$\Delta x \sim \frac{0.2\ \text{TeV}\cdot\text{am}}{Q}$$

- Rutherford scattering

$eq \rightarrow eq$

$eq \rightarrow \nu q$



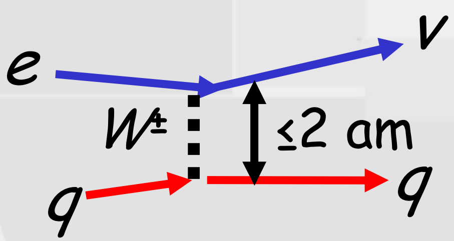



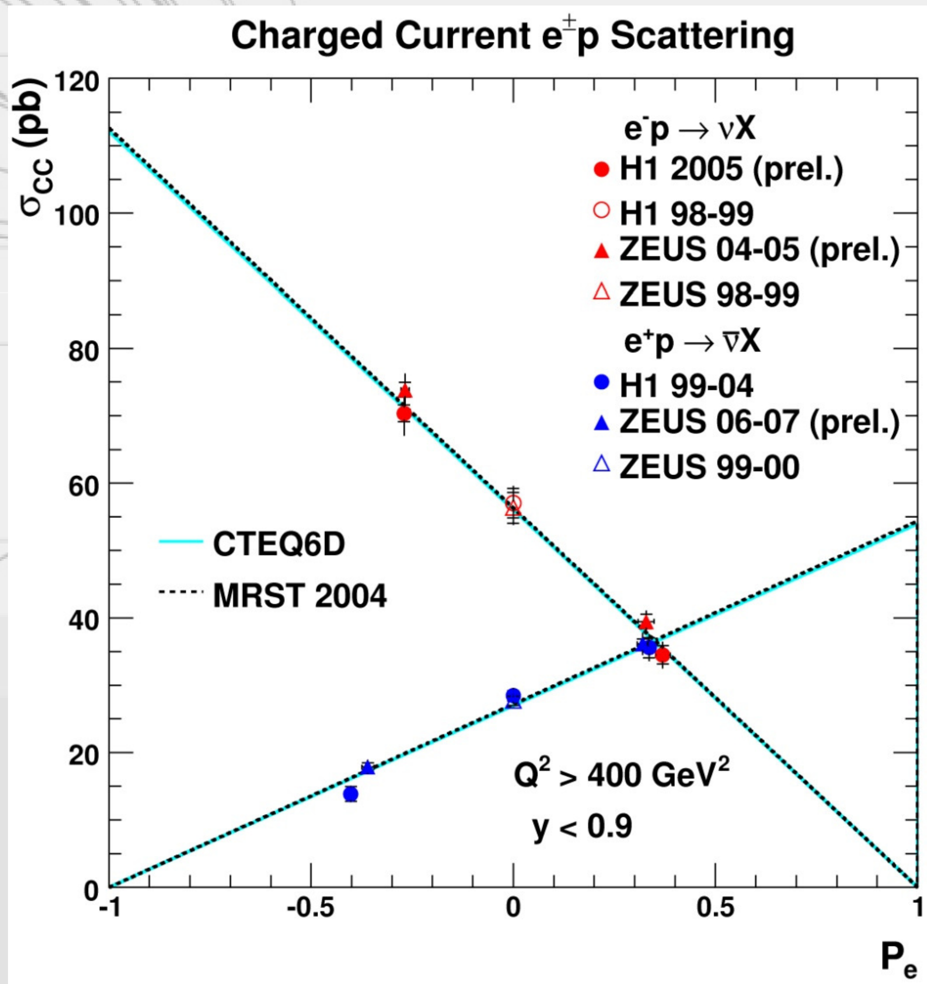

$$\frac{0.2\ \text{GeV}\cdot\text{fm}}{M_W} \sim 0.002\ \text{fm}$$

# Electron-Quark Physics

- resolving chirality in $SU(2)_L \otimes U(1)_R$
  $O(m^2/s)$: $\text{fermion}_L$ $\text{anti-fermion}_R$

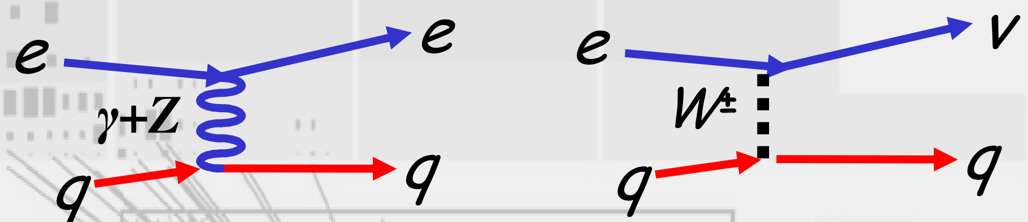
- Rutherford scattering
  + SM helicity
  $eq \to \nu q$

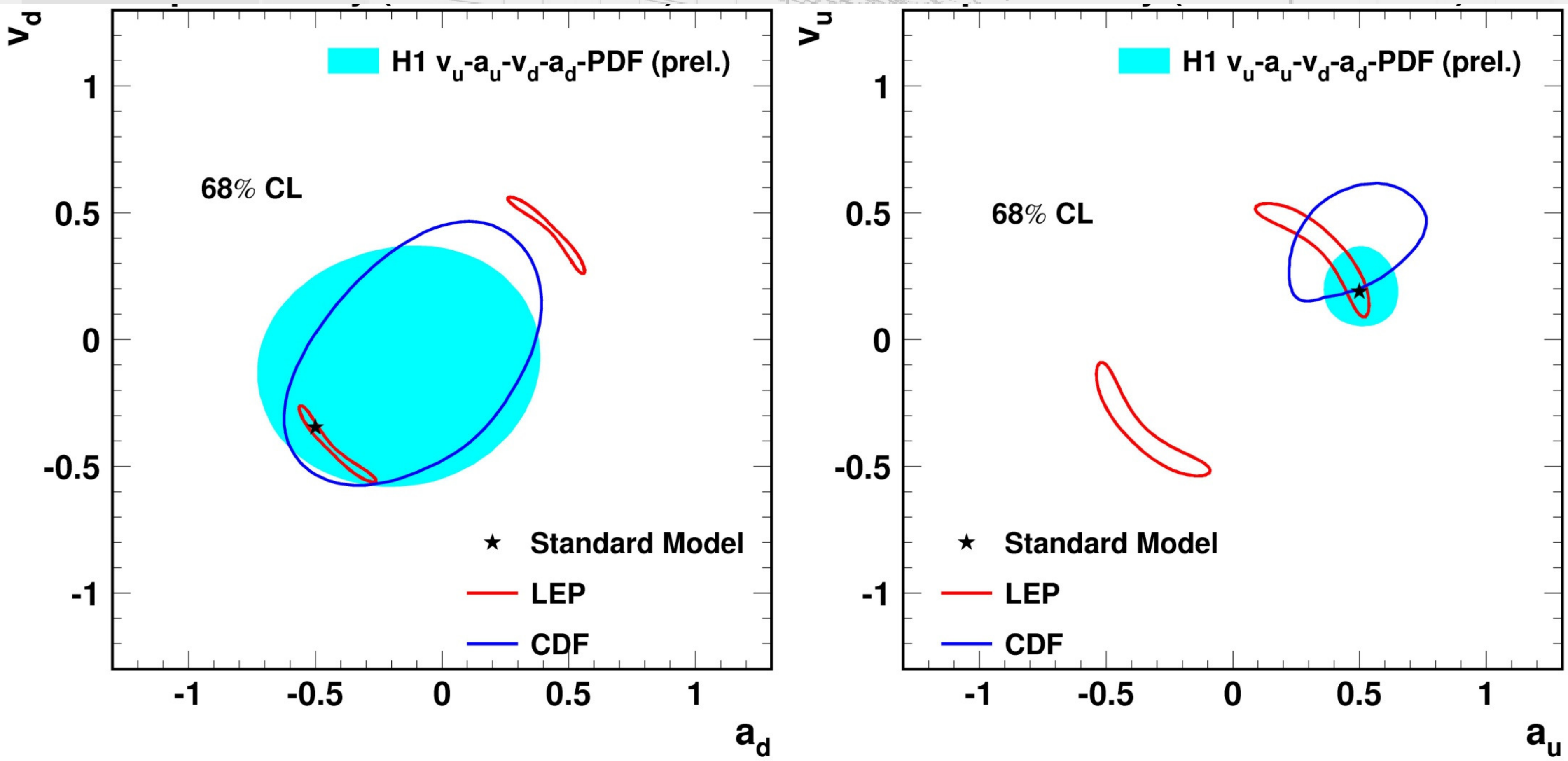


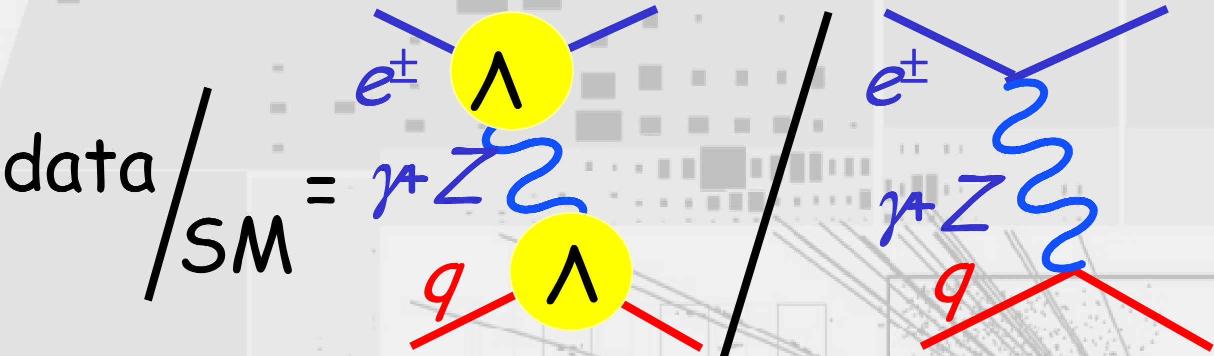
# Electron-Quark Physics

- EW $q$ couplings (in proton matter)

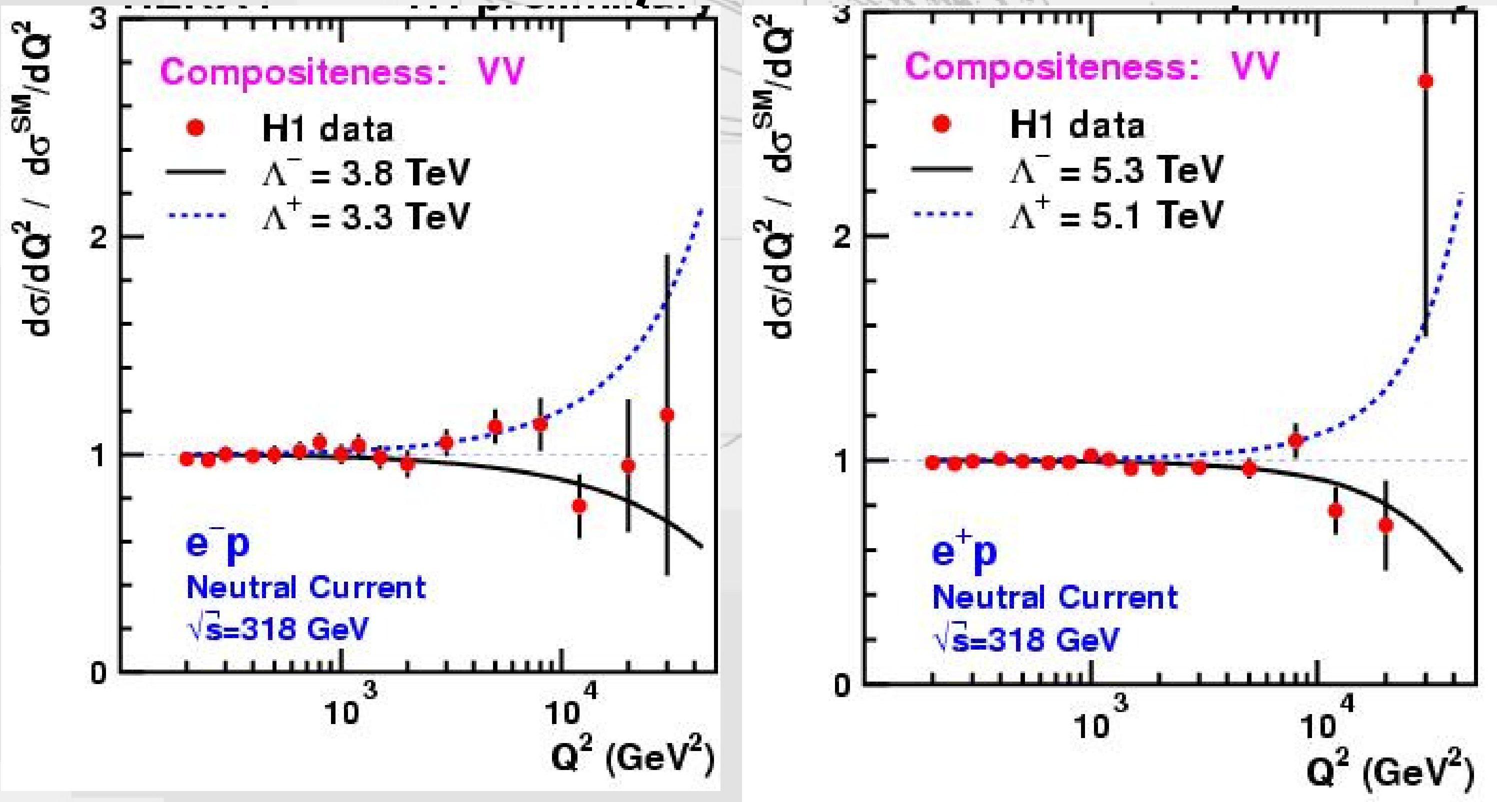


# $q$ @ Fermi scale ≥ 1 am



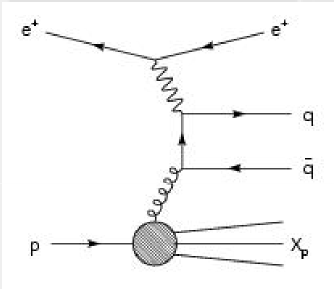

200 GeV·am
(lattice 200 am
@ 1%)

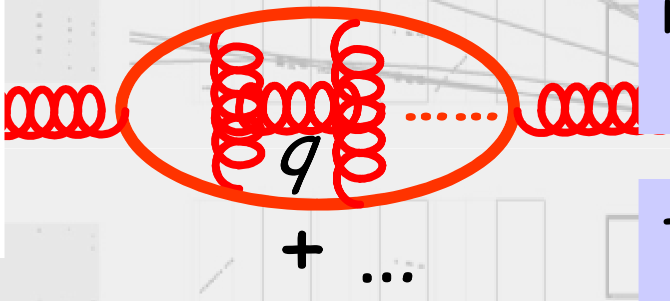



- point-like $Q^2 \leq 4\times10^4$ GeV$^2$ → $M_{Planck} > 72$ TeV

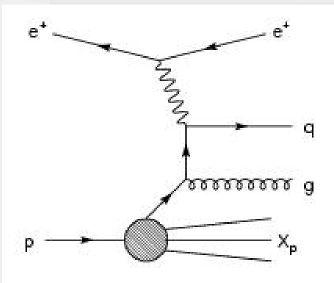
# Nucleon Structure @ Fermi scale

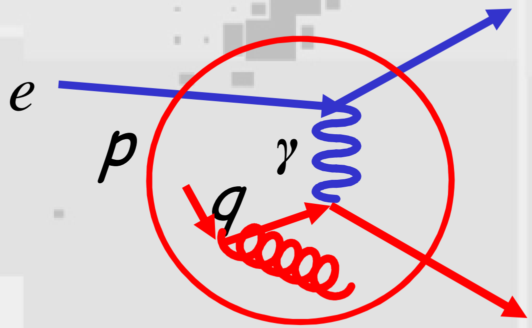
- discovery: *q* in QCD OK @ Fermi scale
  - magnification at low-*x*
    QCD → *q* and *g* structure

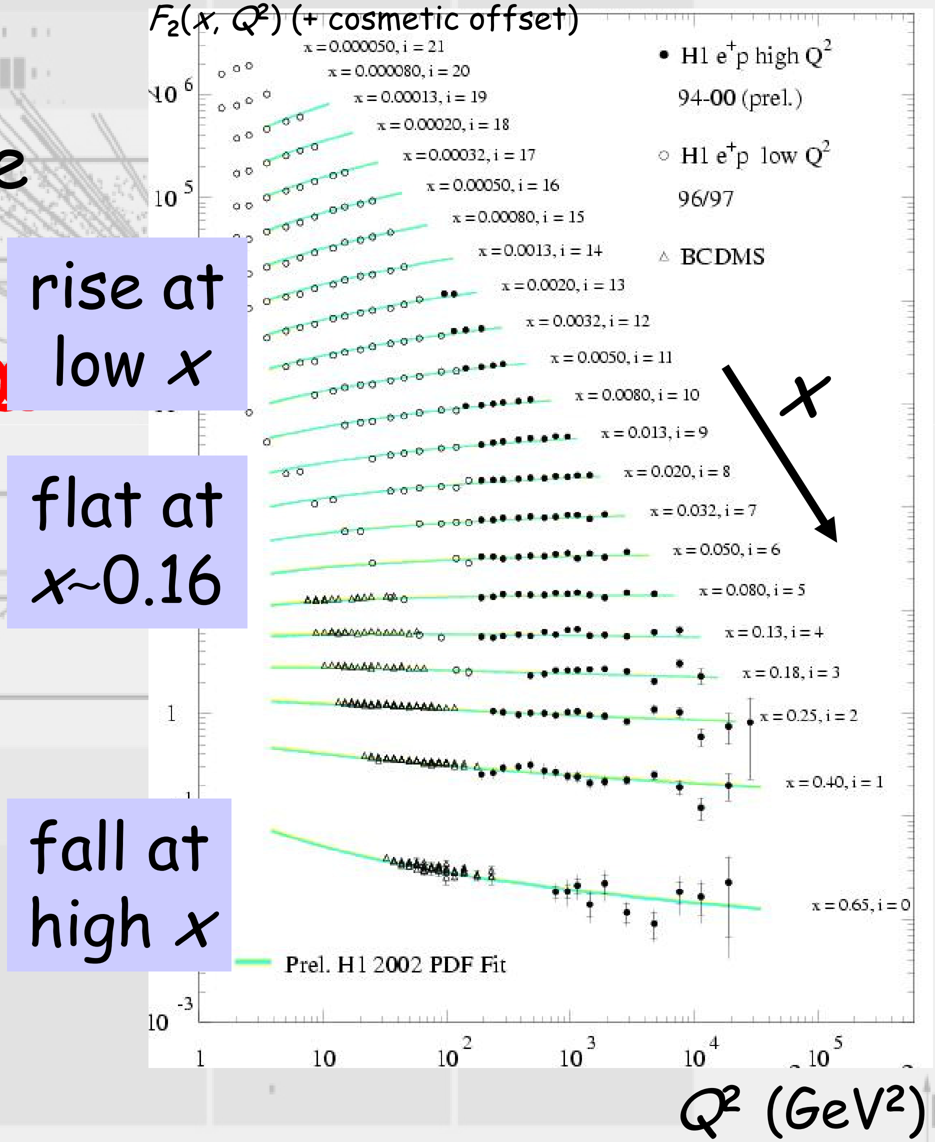



  - precision $q_T$ @ higher-*x*
    QCD in hadron structure

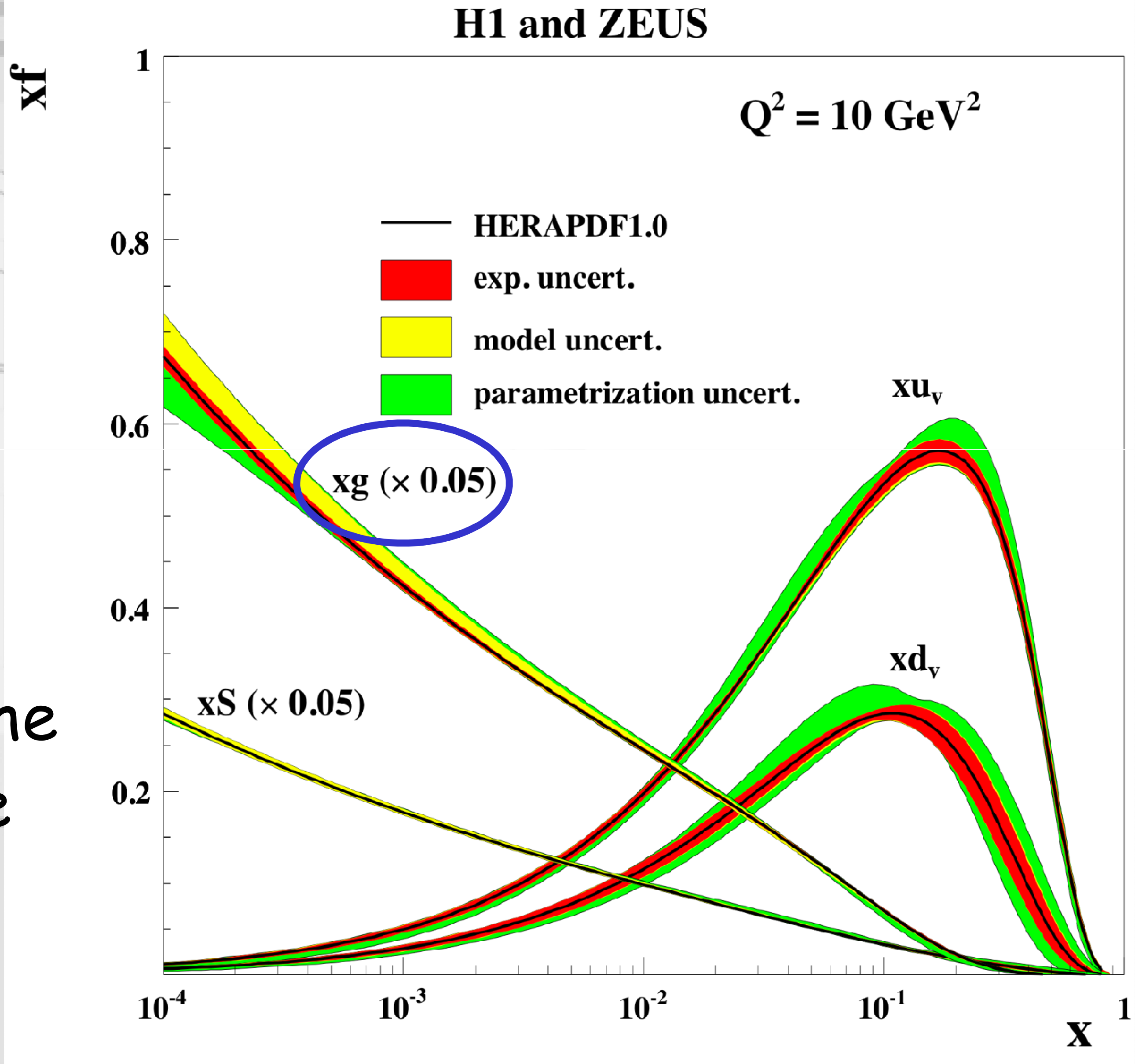


# Nucleon Structure

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



# No HERA, no Fermi scale ?

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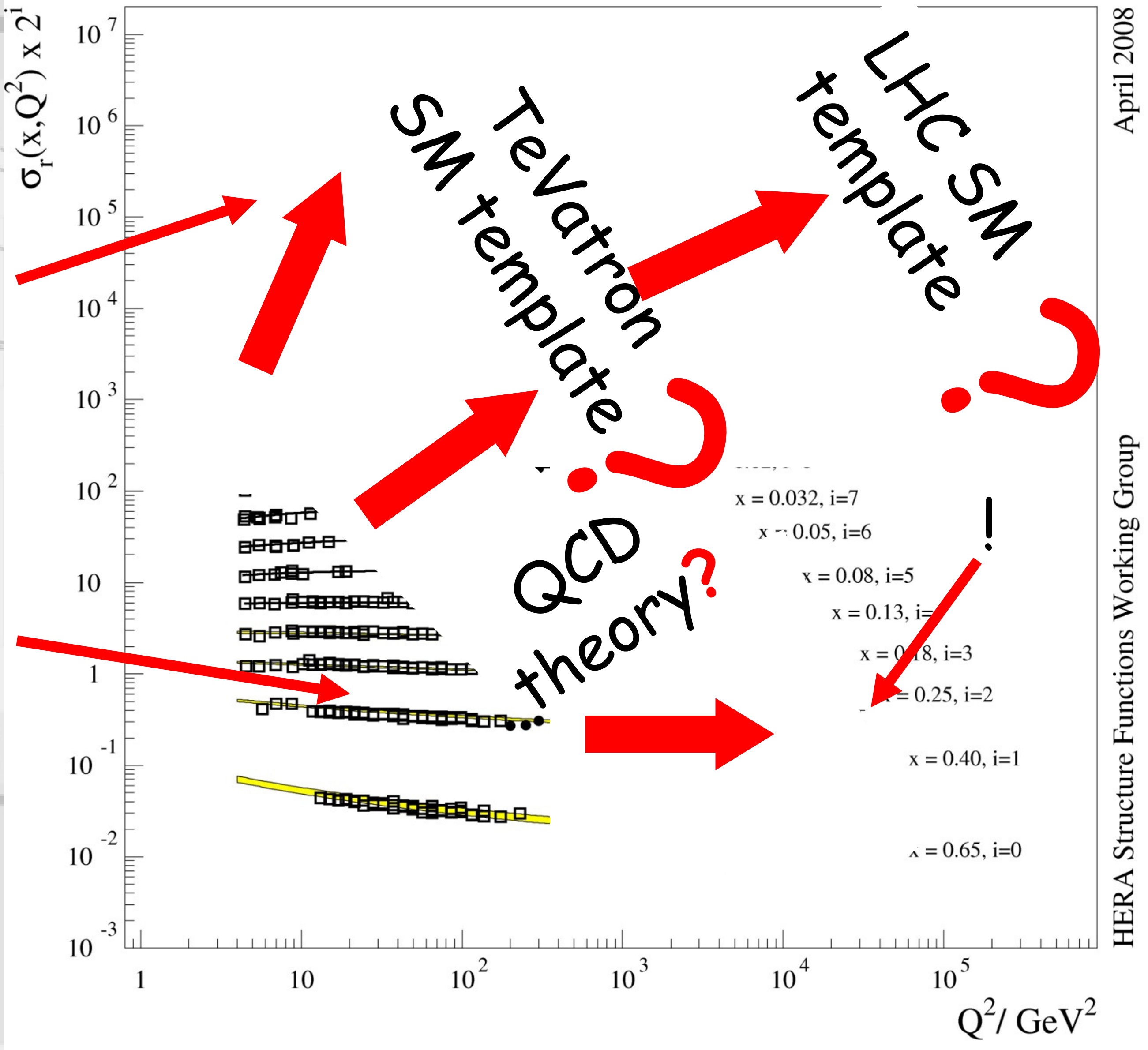
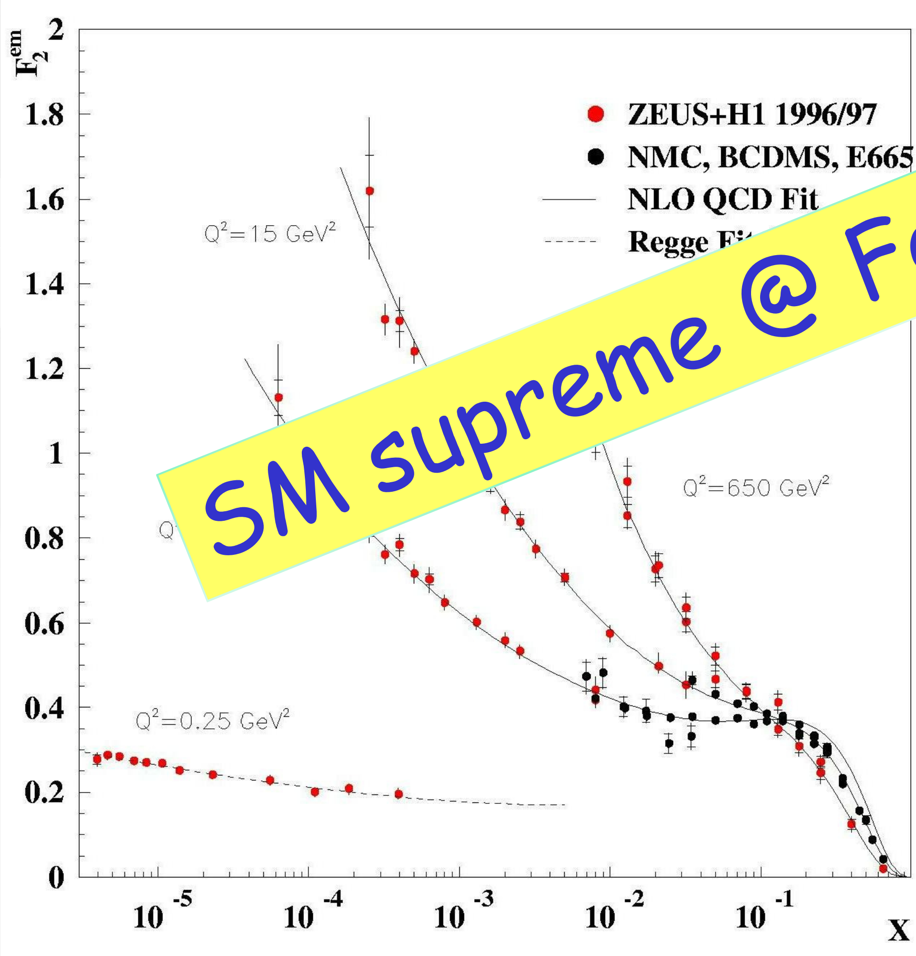
- flavour singlet field $q_s$ evol$^{\underline{n}}$
  - resolving $q_s$ in structure in QCD field
- valence $q_v$ fixed flavour ($u$ $d$) evolution
  - resolving $q_v$ in $p$ structure

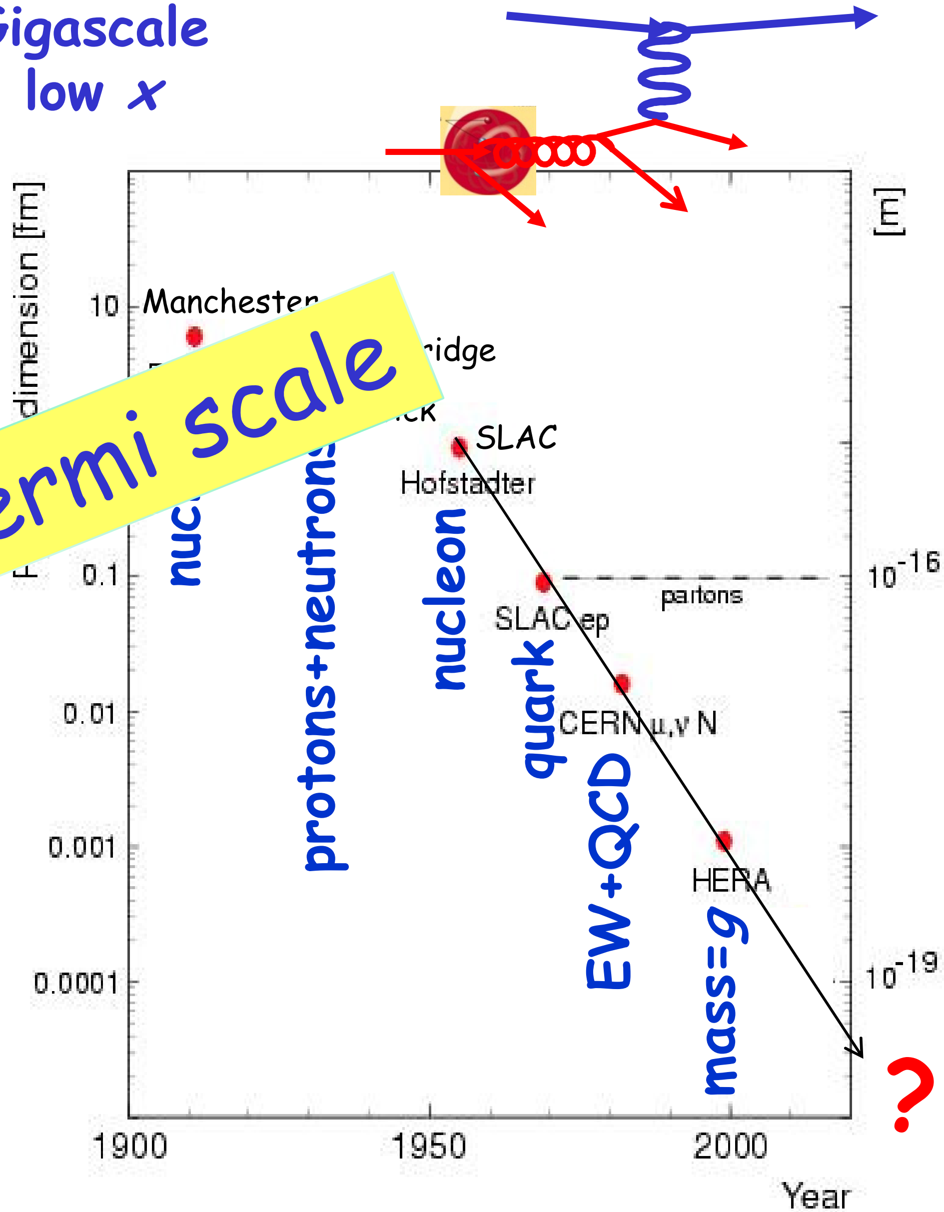


# Matter @ Short-Distance

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




SM supreme @ Fermi scale

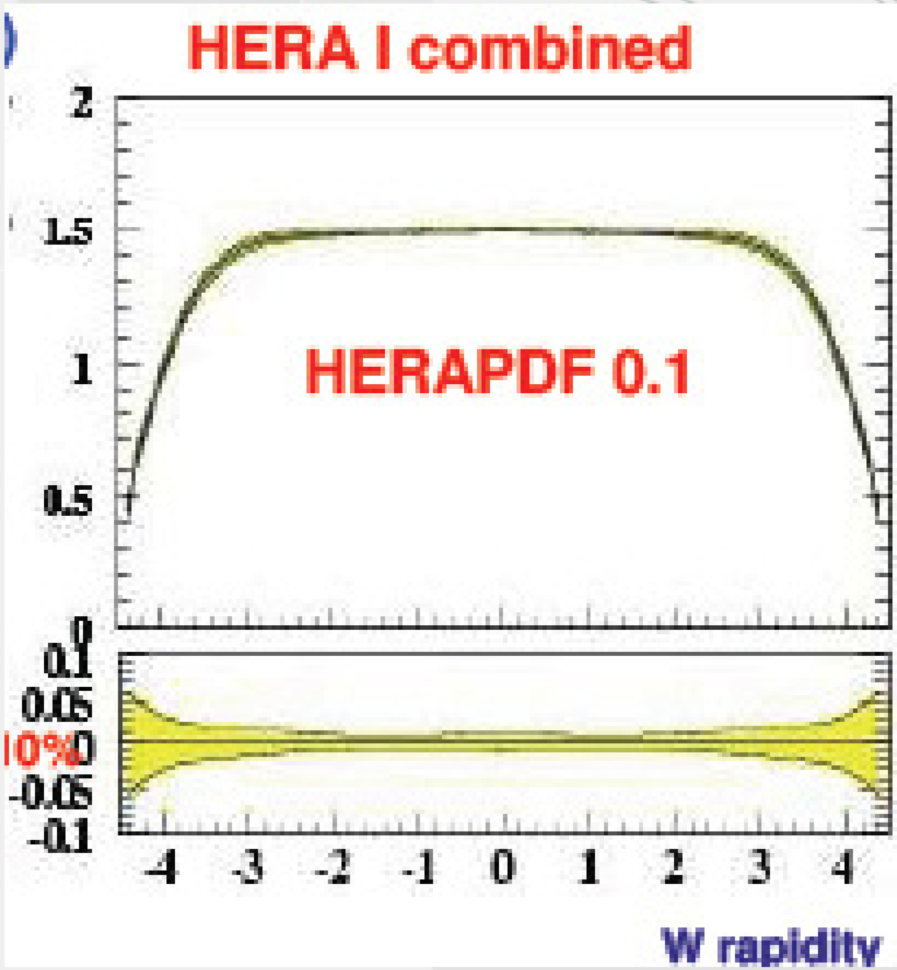


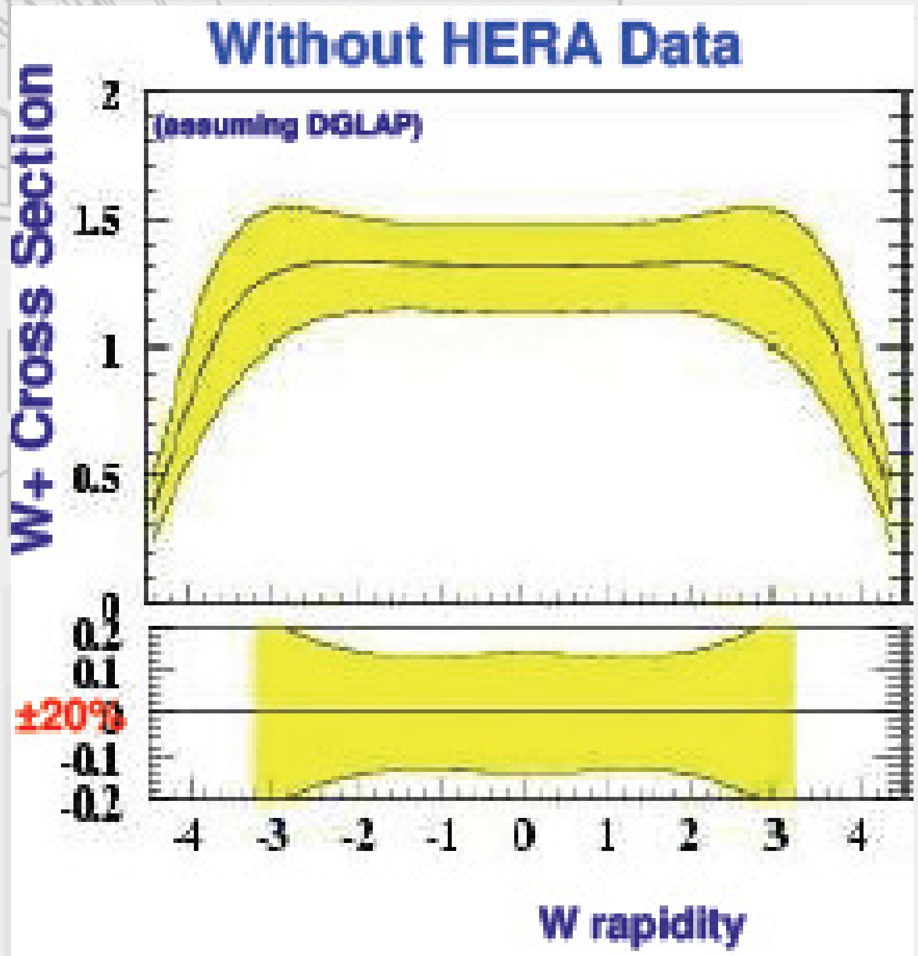
# Critical Precision @ HERA

- 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 $\nu$
h.o. EW (*t*,*H*?)
(LEP/SLC)
CKM
(*B*-factory)

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

# LHC hadrons…and leptons ?

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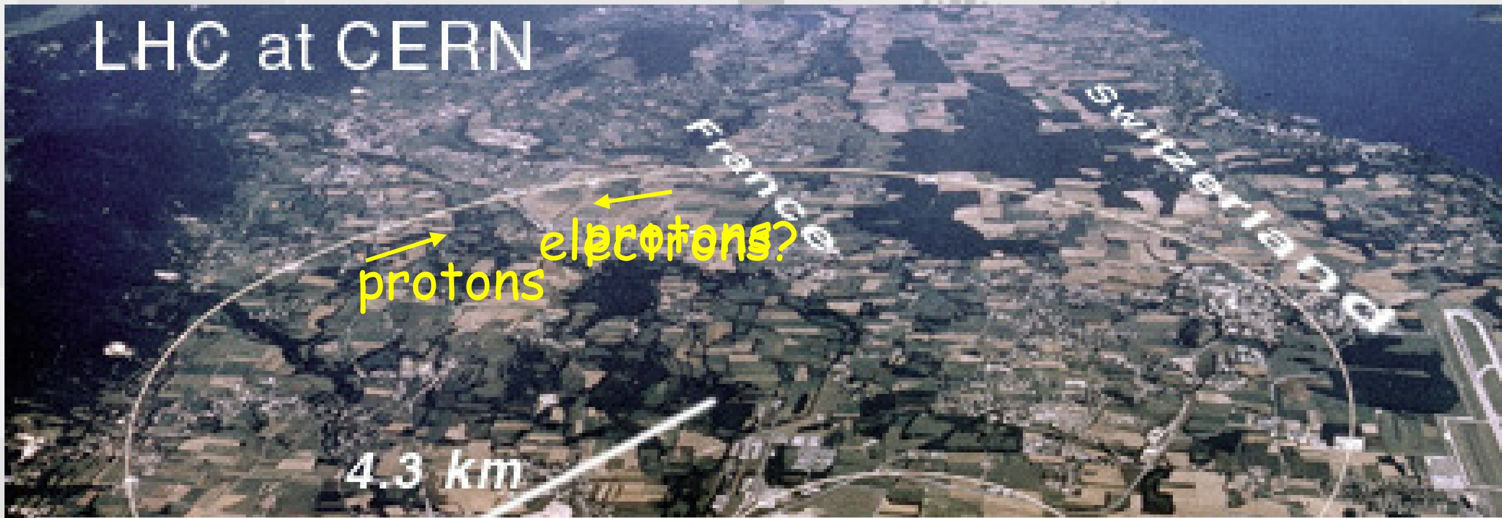
- "standard" LHC protons … with electrons?

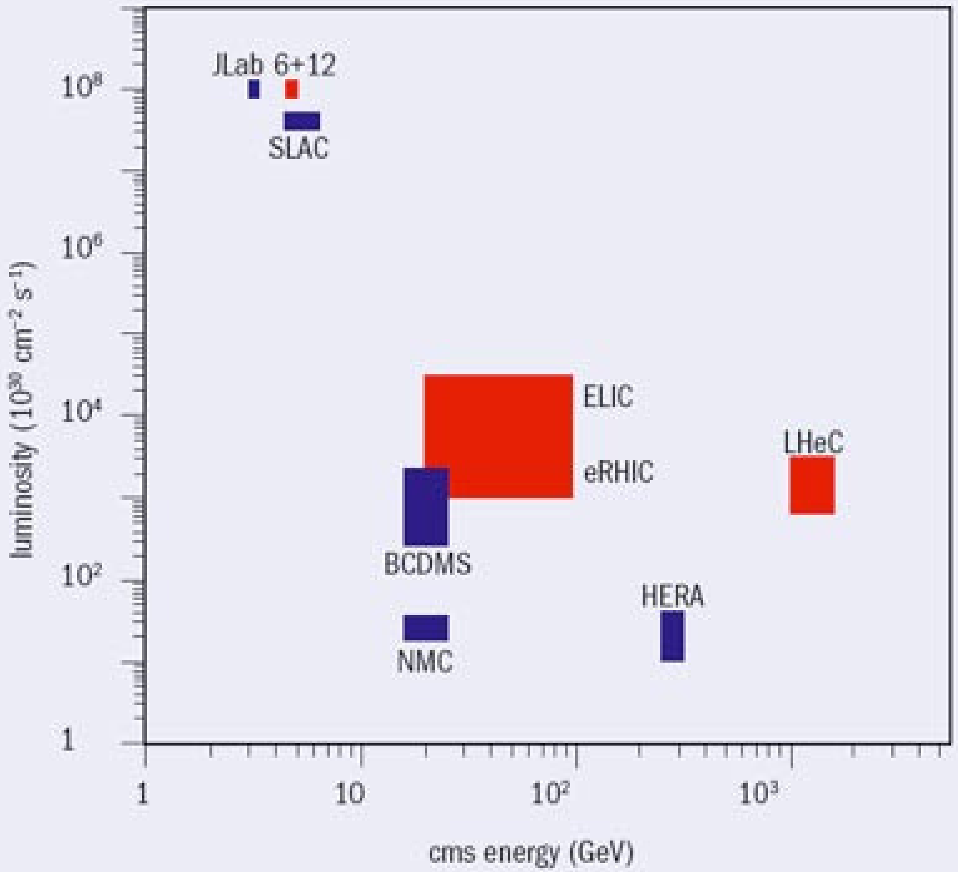



| | | | |
|---|---|---|---|
| Proton Beam Energy | TeV | 7 | |
| Circumference | m | 26658.883 | |
| Number of Protons per bunch | $10^{11}$ | 1.67 | $N_p$ |
| Normalized transverse emittance | $\mu$m | 3.75 | $\varepsilon_{pN}$ |
| Bunch length | cm | 7.55 | |
| Bunch spacing | ns | 25 | |

# LHeC: a future



- LHeC:
  - highest $\sqrt{s}$: Terascale
  - exceptional lumi
  - precision *e*-quark
    *e*-proton
    *e*-deuteron
    *e*-ion
  - "could be built now"
  - "could run now" @ LHC
    beside *pp*
    beside ion-ion



# LHeC: a future

- LHeC:
  - highest $\sqrt{s}$: Terascale
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    *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

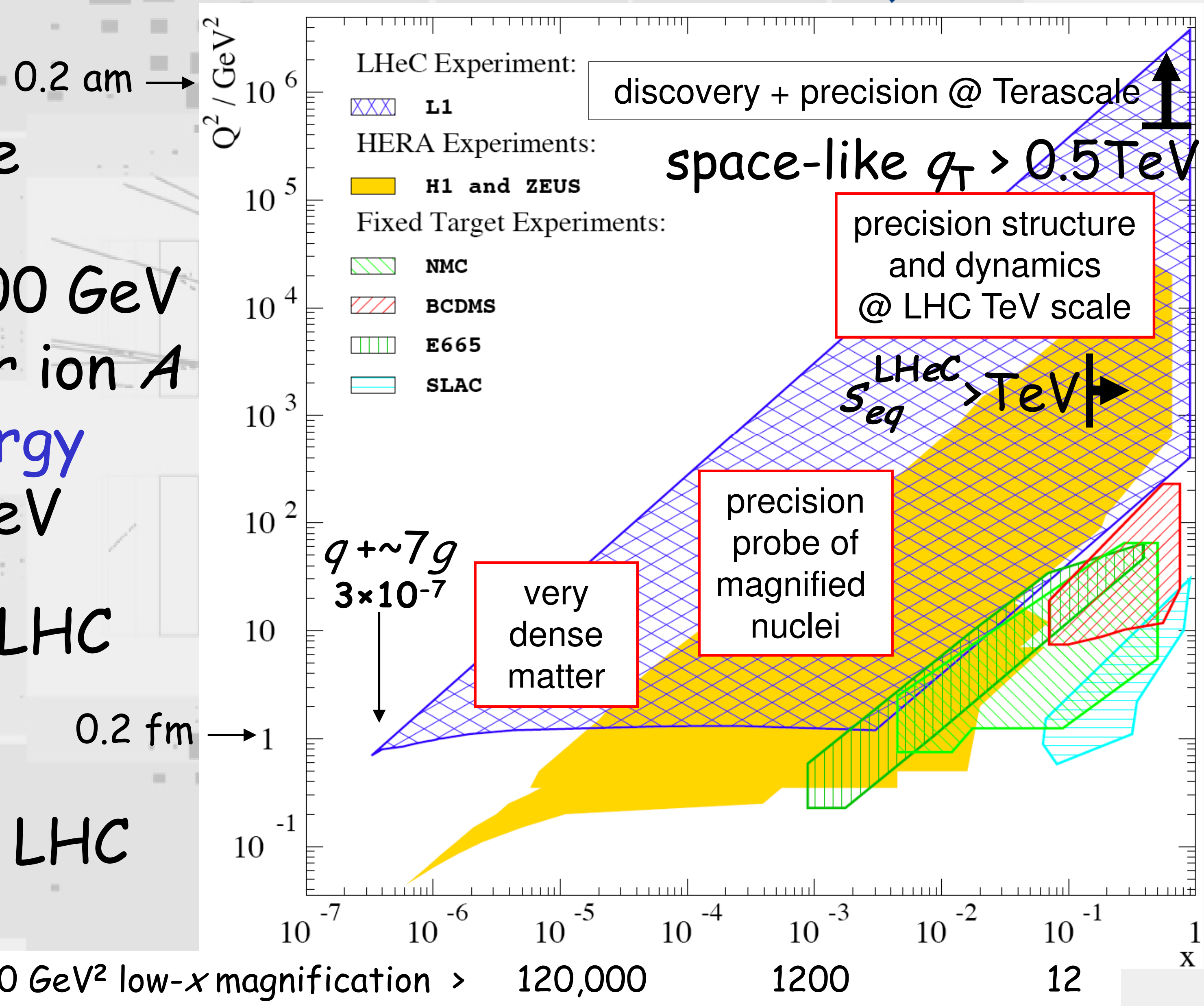
Abstract

The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}$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-

are sketched. With high luminosity, $10^{33}$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-

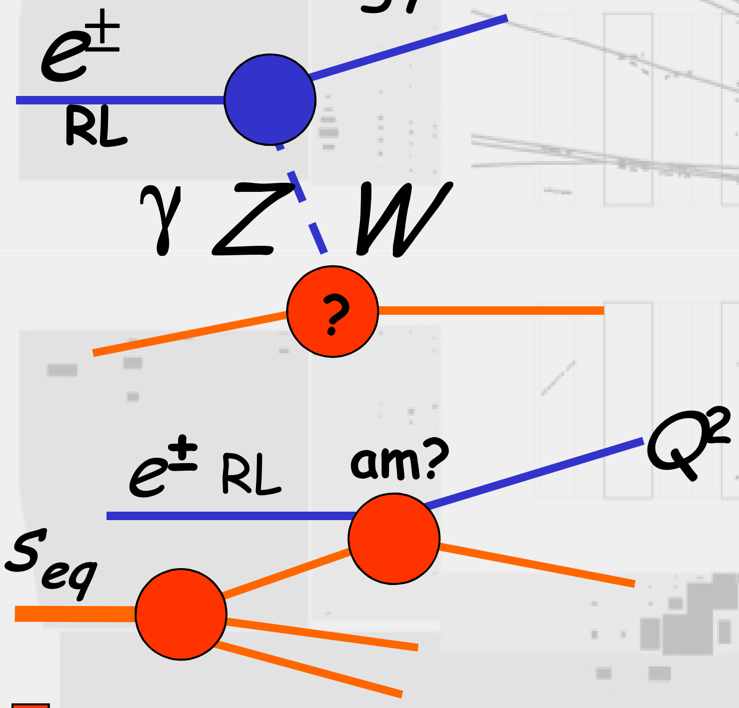
# Matter @ Shorter-Distance: LHeC

- Terascale
- 60 ⊗ 7000 GeV
  $e \otimes p$ or ion $A$
  - cm energy
  1300 GeV
- e-ring ⊗ LHC
- e-linac ⊗ LHC

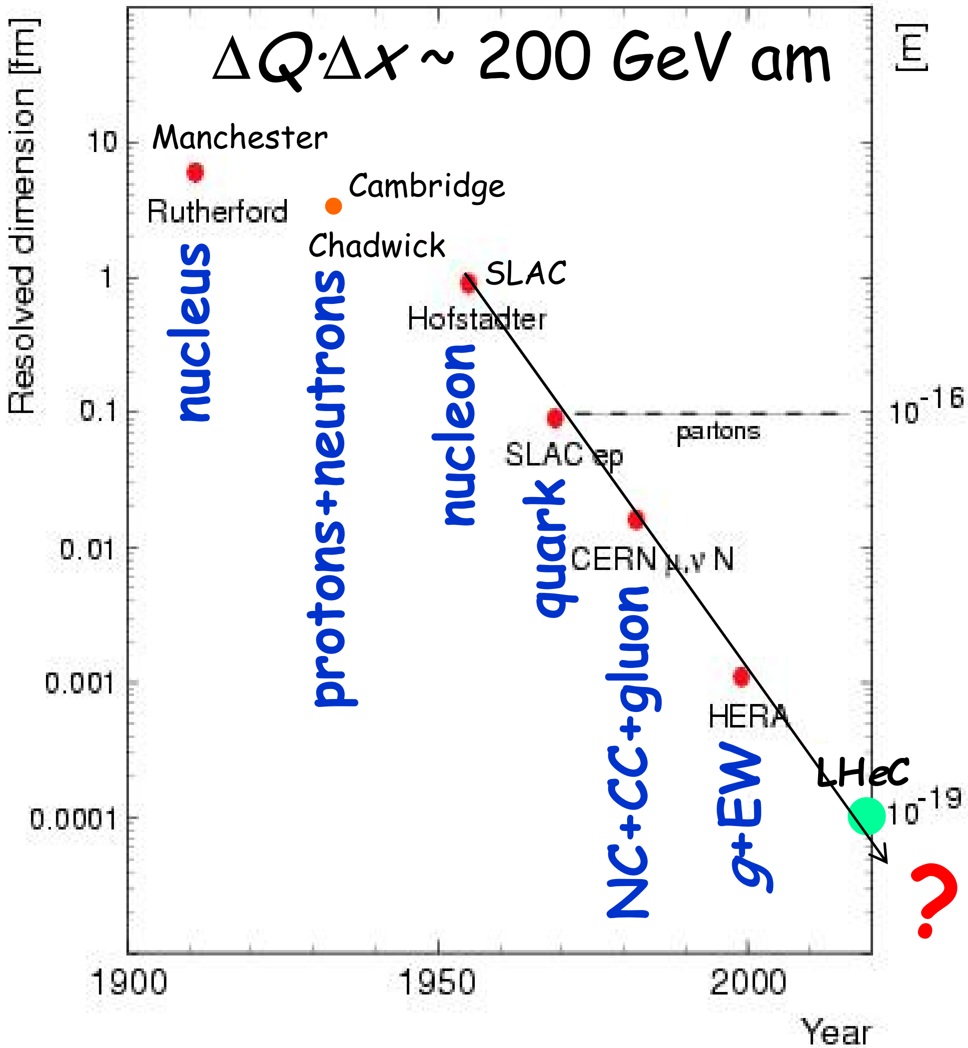


# Lepton+quark @ TeV

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

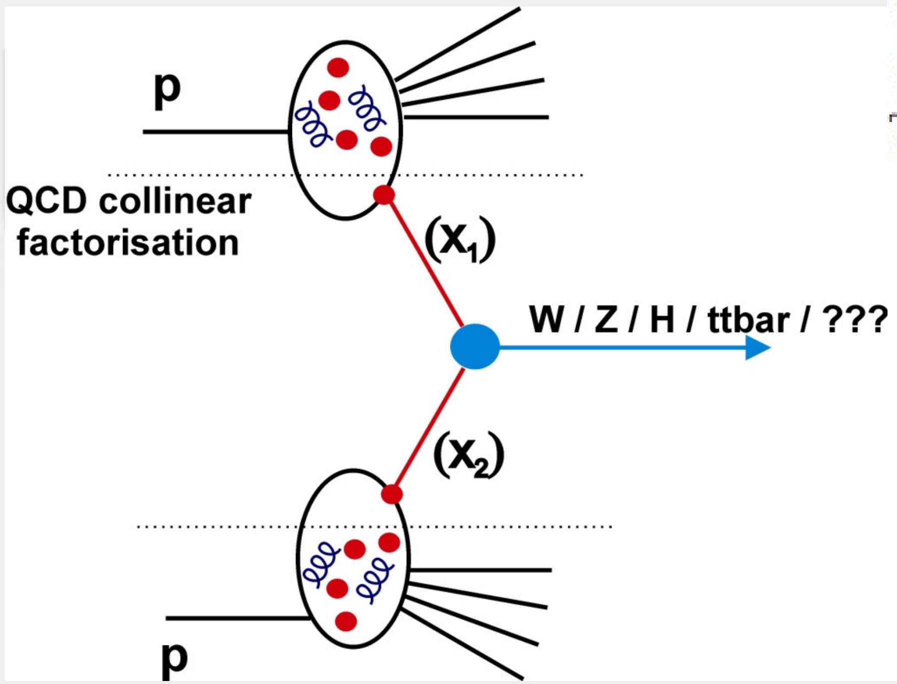


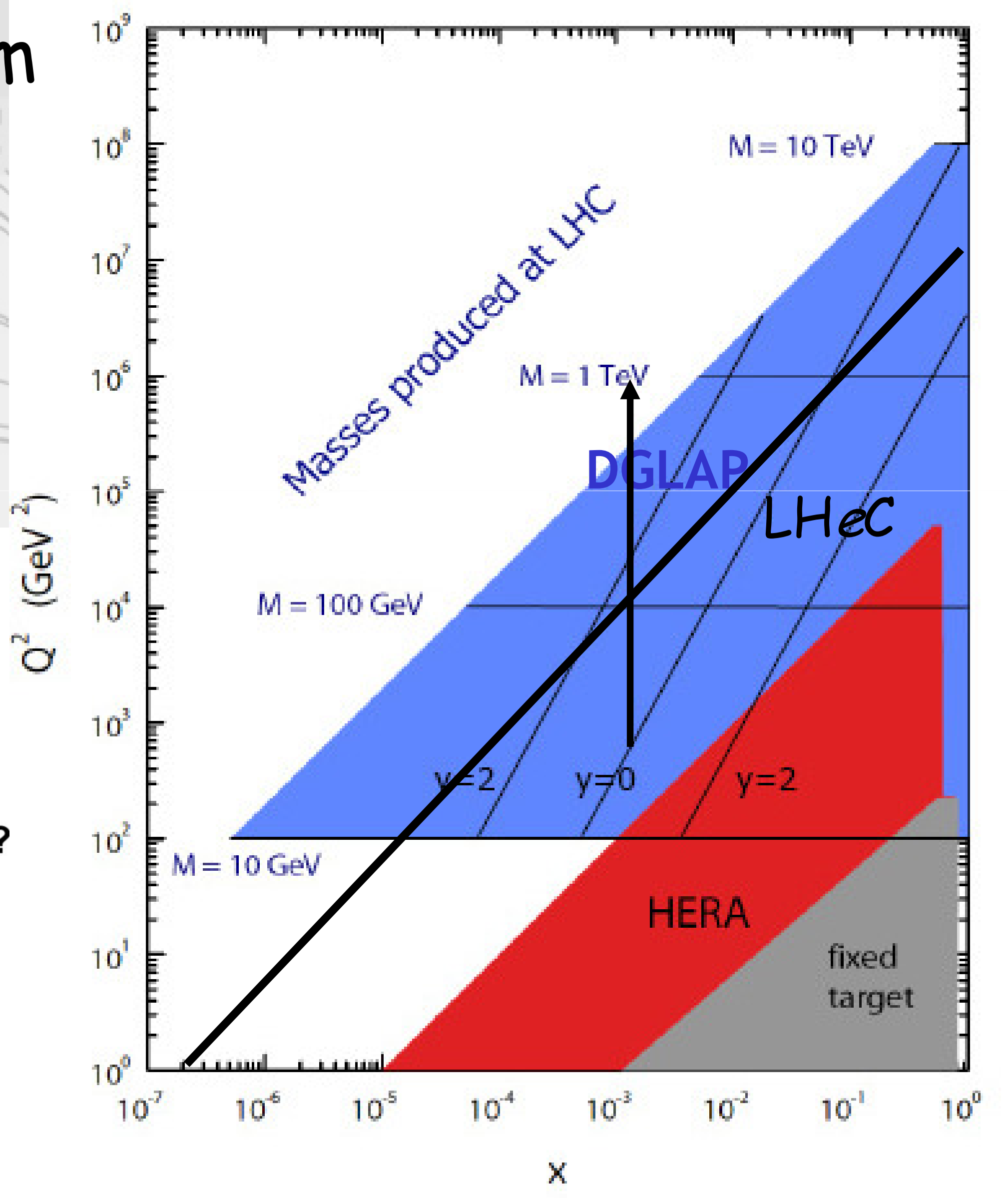

SM @ ~ 0.1 am ?



# Quark+quark @ LHC

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



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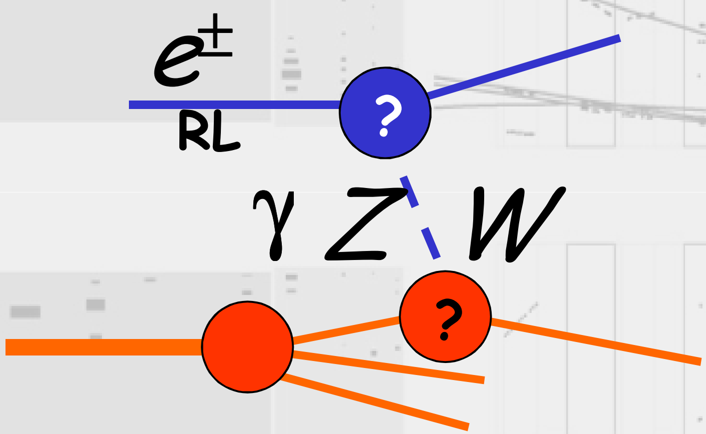
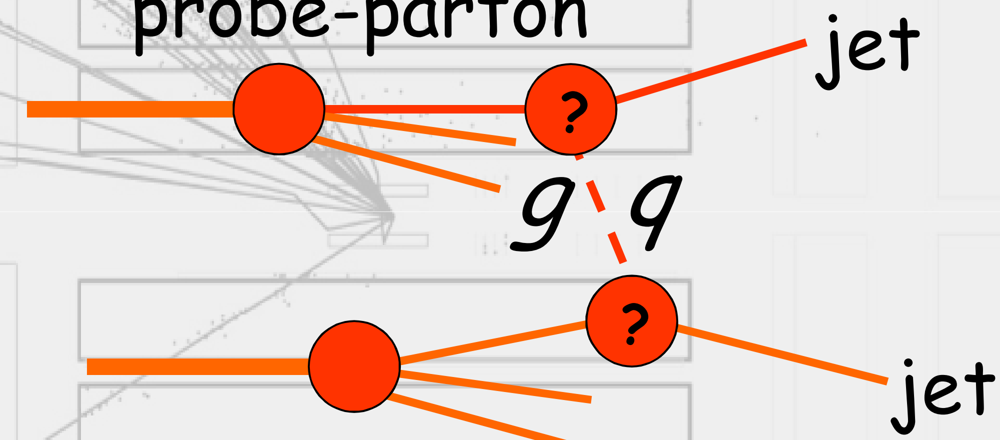
# Lepton-Parton and Parton-Parton ?

- $ep \to eX$
- $pp \to$ (jet+jet)$X$




- LH*e*C energy scale: 70⊗7000 GeV
- *pp* energy scale: 7000⊗7000 GeV

probe+*p* at LH*e*C scale

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

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

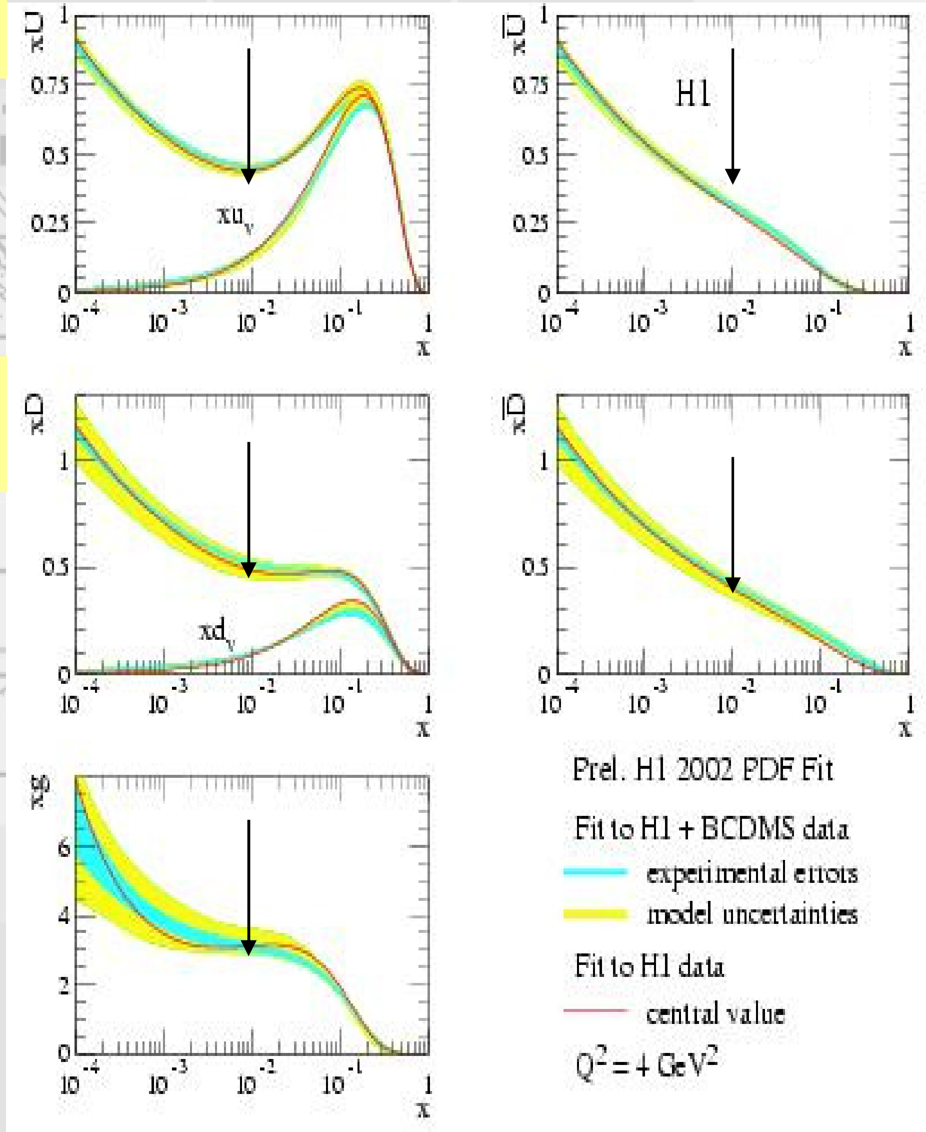
- probe-parton @ $x \gg 0.01$

  $g:q \sim 1 \longrightarrow$ 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



# The LHeC project

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UNIVERSITY OF LIVERPOOL

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

NTNU Norwegian University of Science and Technology

The Cockcroft Institute of Accelerator Science and Technology

Jefferson Lab Thomas Jefferson National Accelerator Facility

CLIC

ANKARA ÜNİVERSİTESİ

NİĞDE ÜNİVERSİTESİ 1992

ULUDAĞ ÜNİVERSİTESİ 1975

TOBB ETU

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Legnaro

DESY

LAL Physique des accélérateurs

ECFA

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

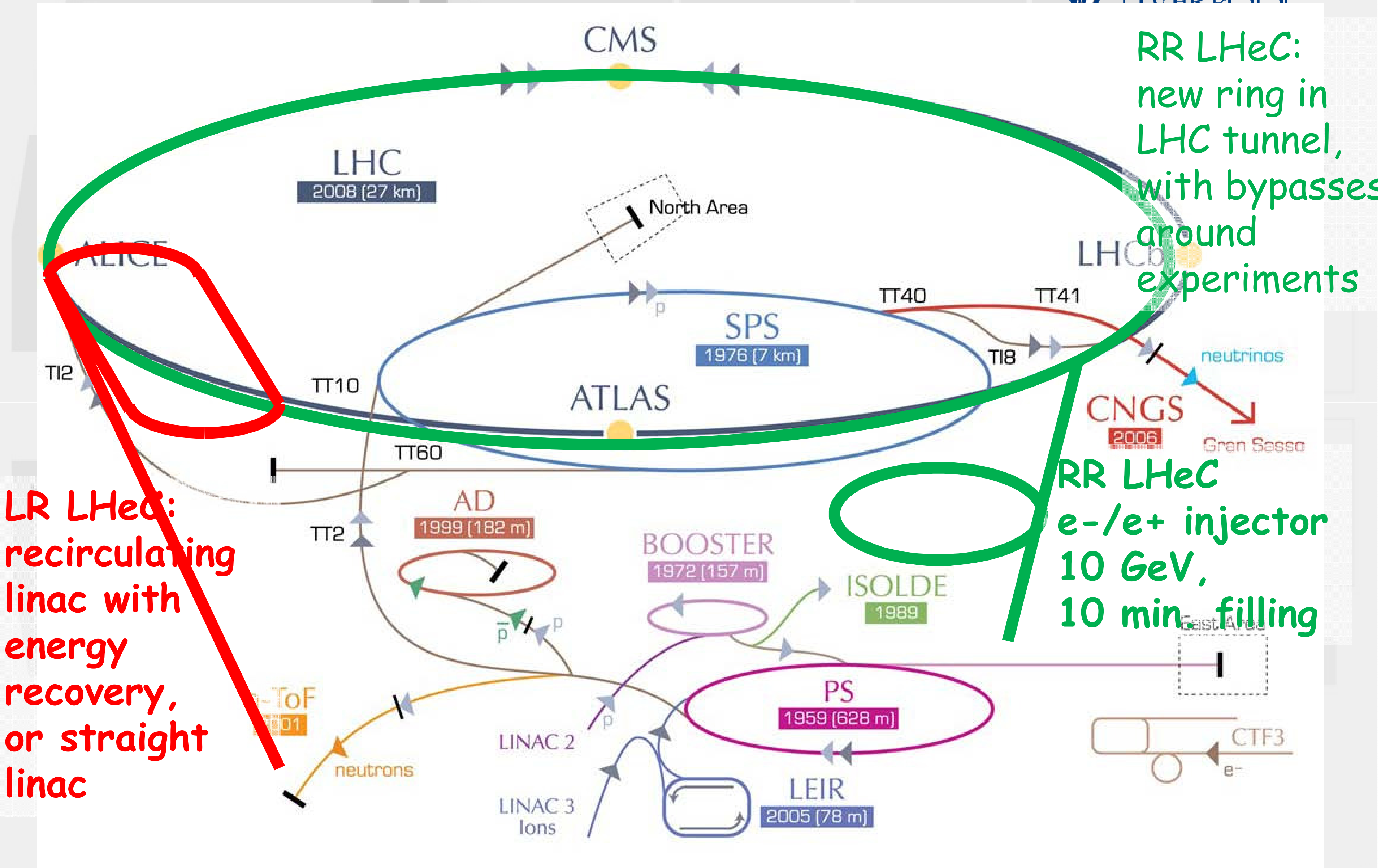
UNIVERSITY OF LIVERPOOL

BROOKHAVEN NATIONAL LABORATORY

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

KEK

# LHeC: RR and LR



# *ep* (with *pp*) @ LHC?

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

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

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

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

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

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

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

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

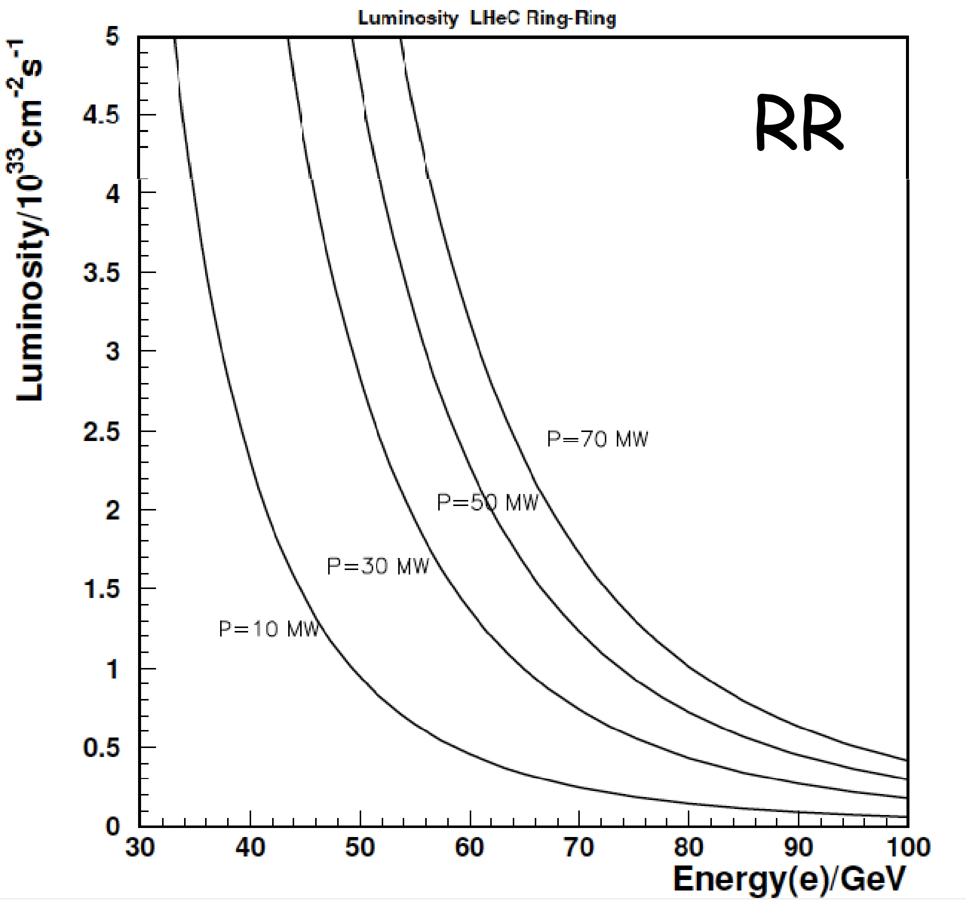
$$L = 8\cdot 10^{31} cm^{-2}s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^*/m} \cdot \frac{I_e/mA}{1}$$

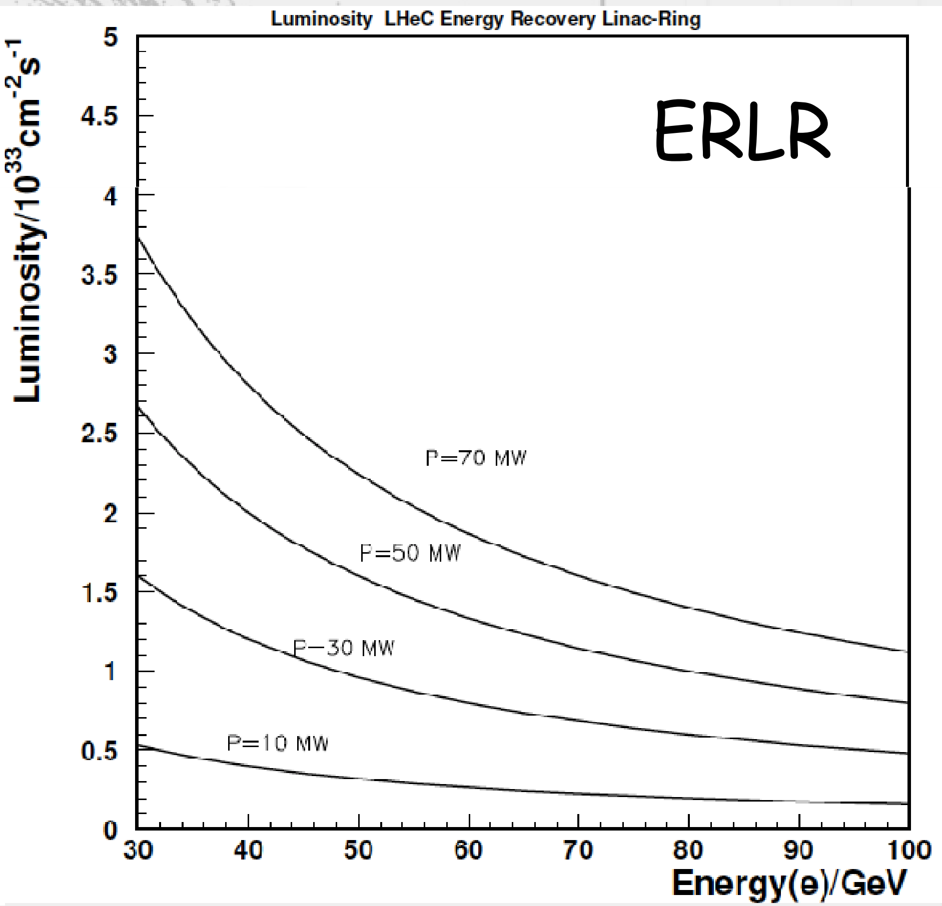
$$I_e = mA \frac{P/MW}{E_e/GeV}$$

synchronous *ep* and *pp*
~ 100 × $L_{HERA}$

# *ep* (with *pp*) @ LHC?

- wall-plug ?
  - from HEP to photon physics to HEP !



# LHeC RR

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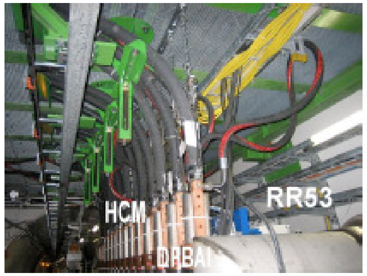
- 10 GeV linac injection into 60 GeV R




**Lattice Design dominated by geometry:**

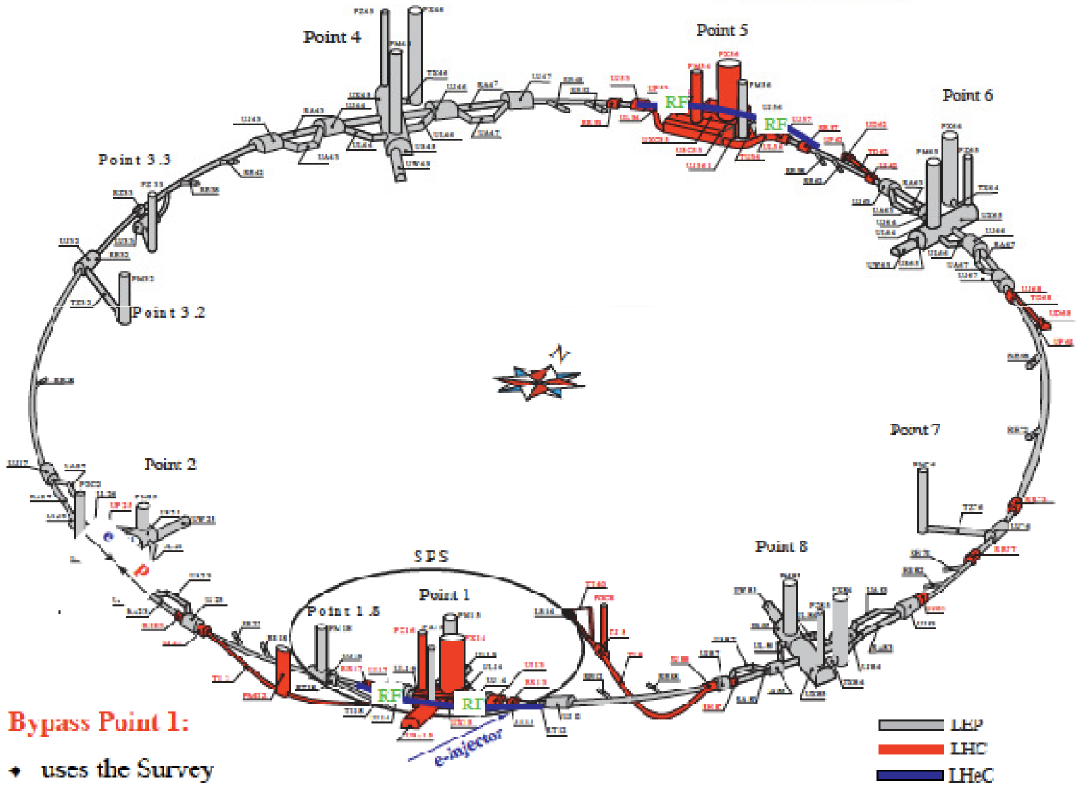
- forbidden space (usually DFBMs) induces an asymmetric lattice
- asymmetric lattice needs to be matched to the symmetric LHC lattice
- ➡ most choices for the LHeC lattice structure are made due to integration

**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:**

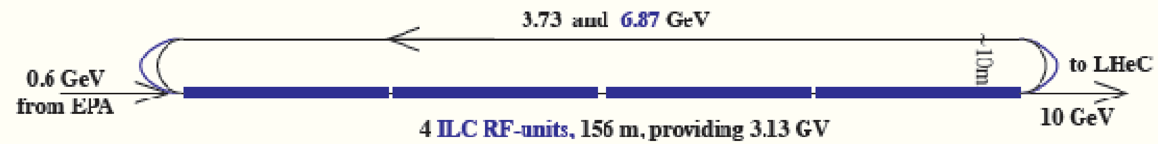
- adjustment of the circumference by varying the separation
- Δ=20.56 Meter




**Bypass Point 1:**

- uses the Survey Gallery
- Δ=16.25 Meter

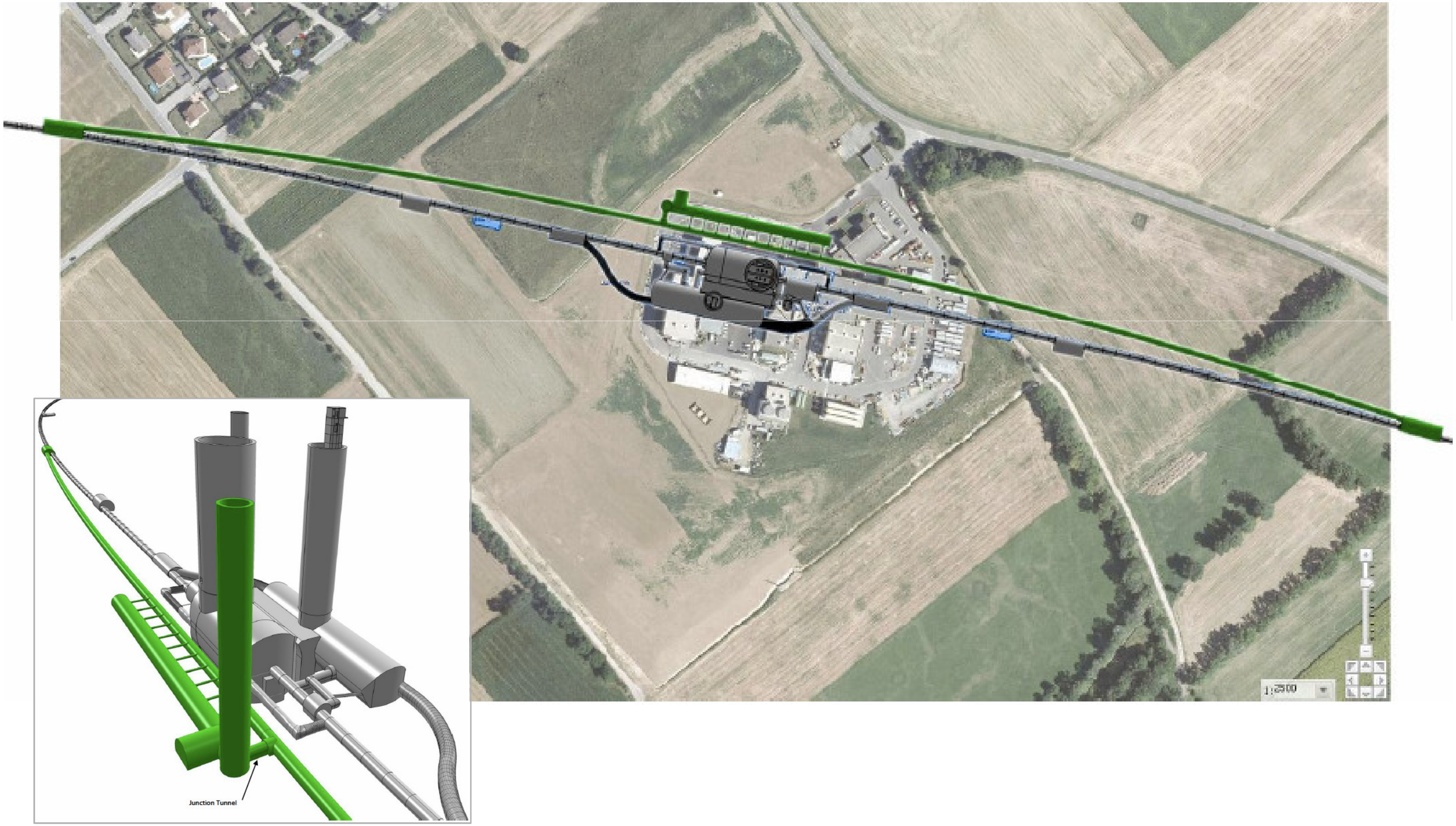
5min fill



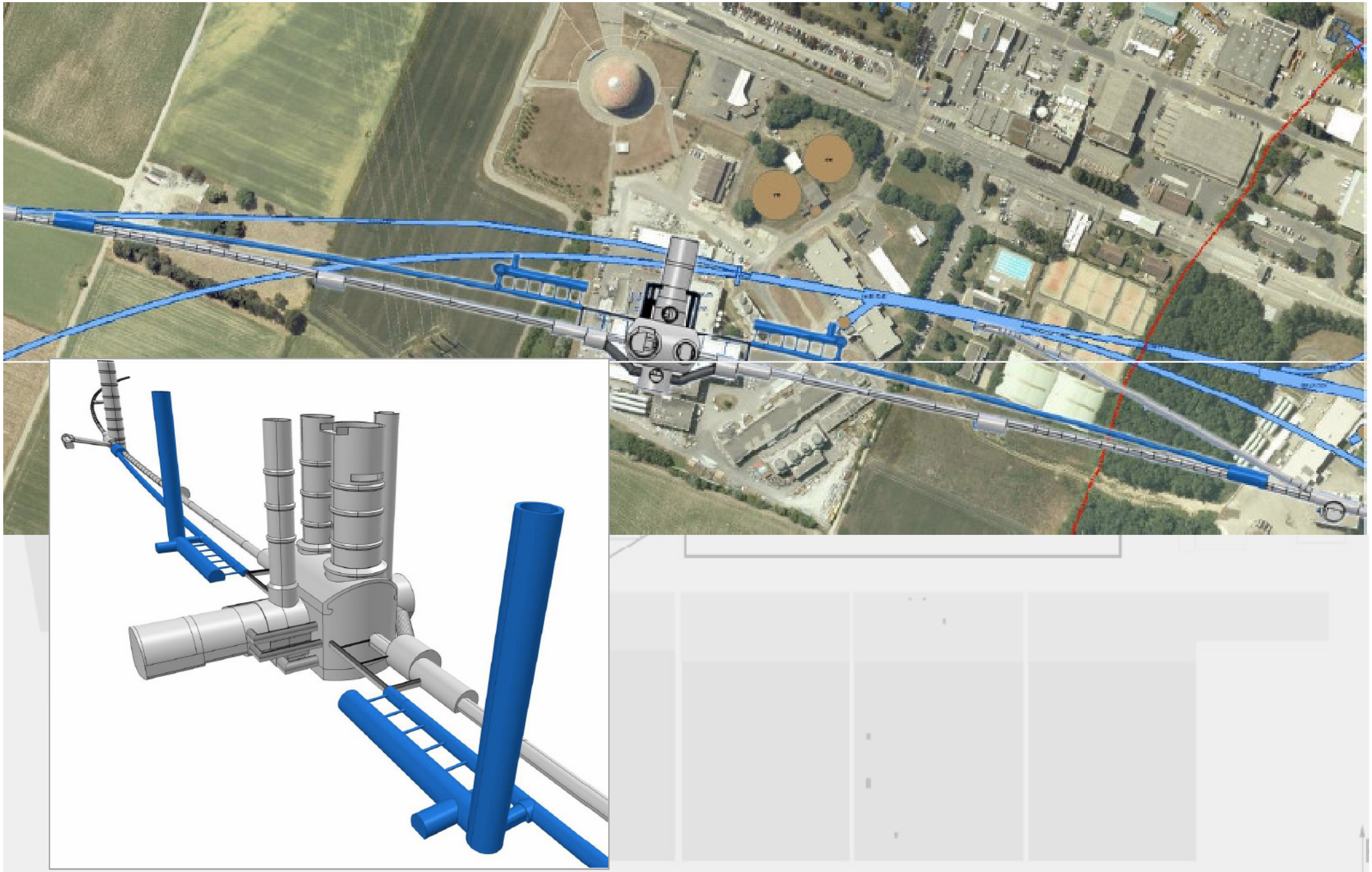
# LHeC RR

- $\mathcal{L} = 10^{33}$ 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



# LHeC RR: ATLAS bypass



# LHeC RR: *e* ring installation

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

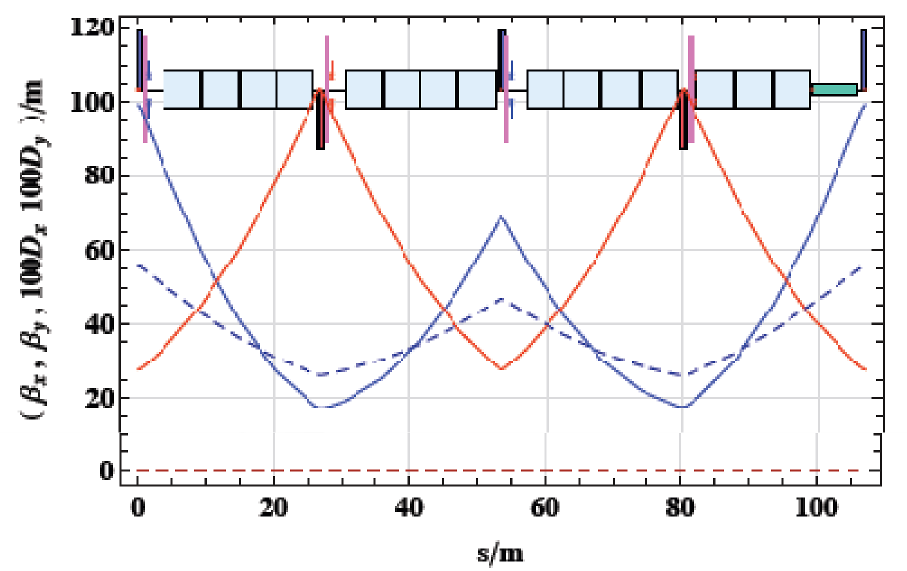
- LHC interference, activation?

# LHeC RR: e ring optics

| | |
|---|---|
| Beam Energy | 60 GeV |
| Numb. of Part. per Bunch | $2.0 \times 10^{10}$ |
| 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 $\tau_x$ | 0.016 s |
| Damping Time $\tau_y$ | 0.025 s |
| Damping Time $\tau_e$ | 0.016 s |
| Polarization Time | 61.7 min |
| Coupling Constant $\kappa$ | 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



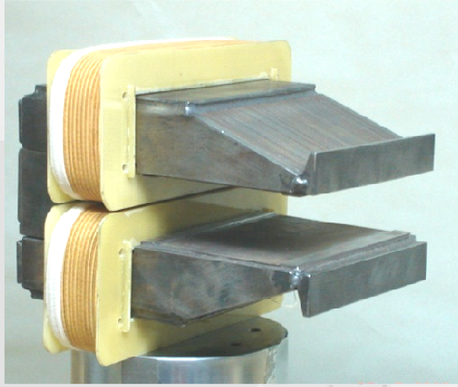

Half the LHC FODO size for emittance

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

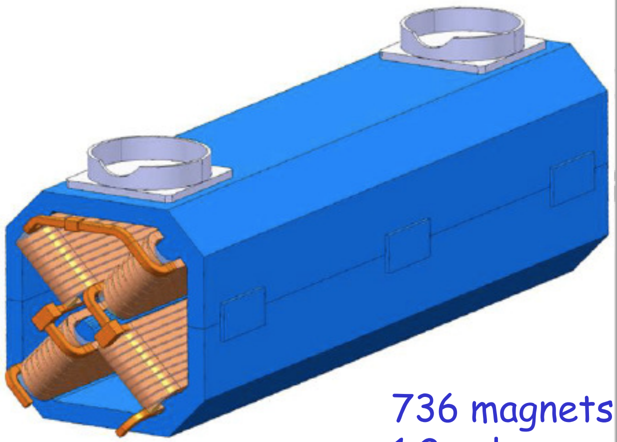
# LHeC RR: dipoles + quads



BINP &
CERN
prototypes

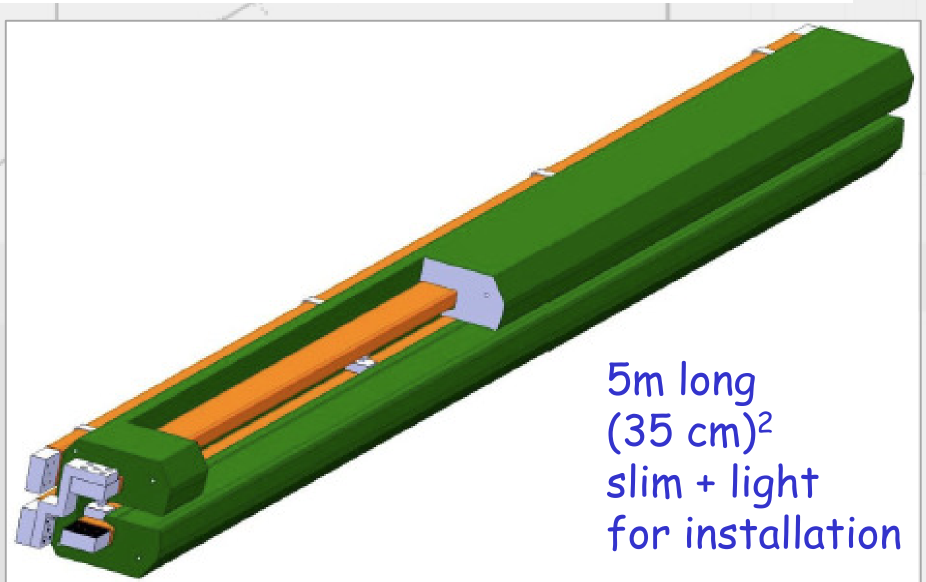
| Parameter | Value | Units |
|---|---|---|
| Beam Energy | 10-60 | GeV |
| Magnetic Length | 5.35 | Meters |
| Magnetic Field | 0.127-0.763 | Tesla |
| Number of magnets | 3080 | |
| Vertical aperture | 40 | mm |
| Pole width | 150 | mm |
| Number of turns | 2 | |
| Current @ 0.763 T | 1300 | Ampere |
| 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

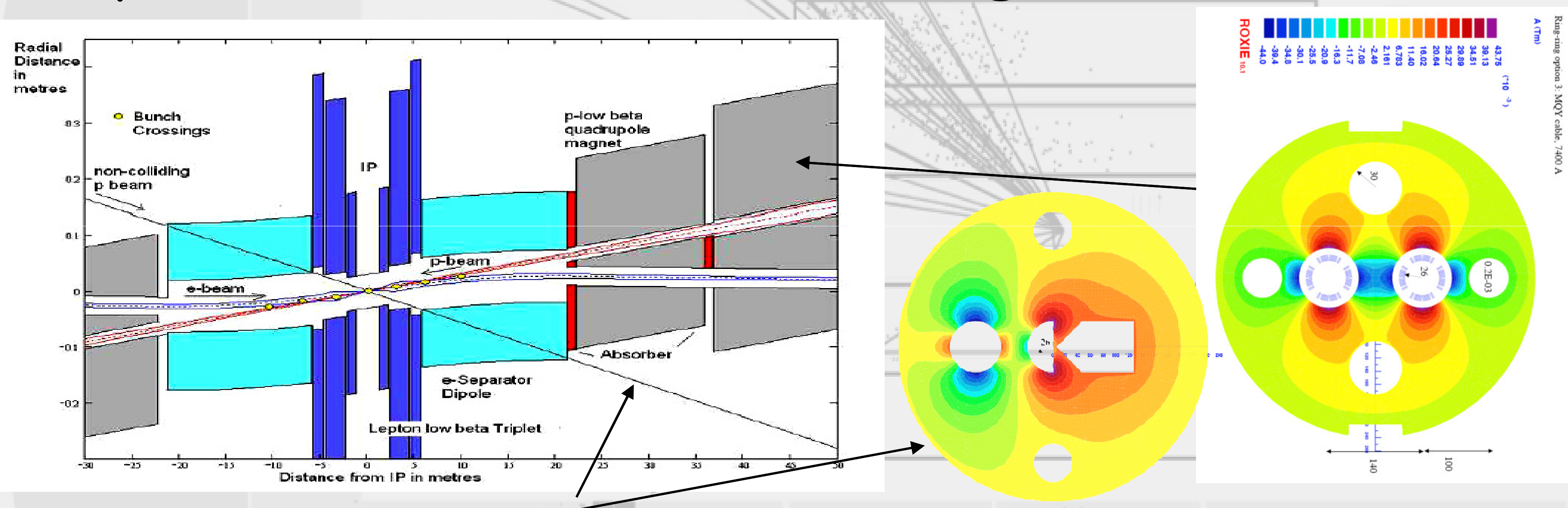
Arc quadrupole magnets for the RR Option



5m long
(35 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

# LR: linac concepts

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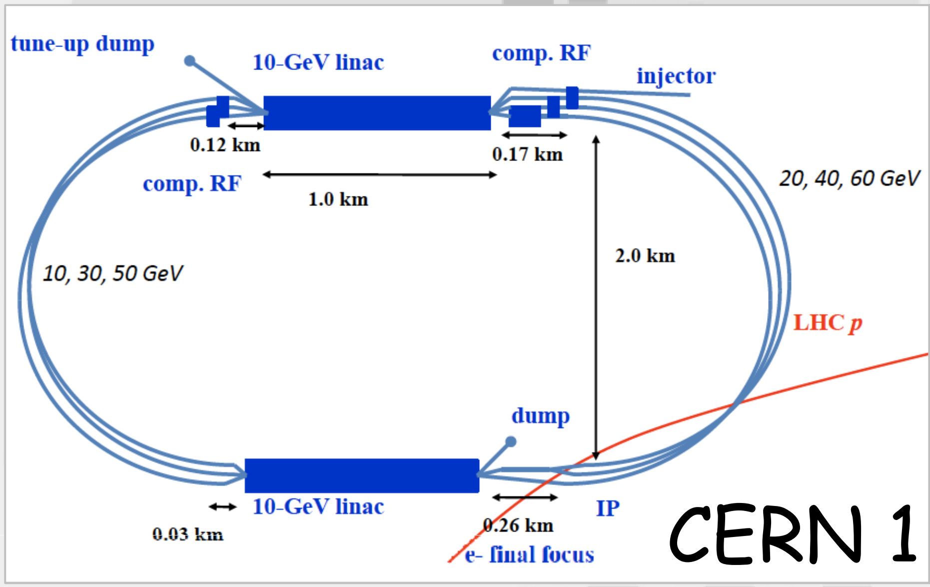
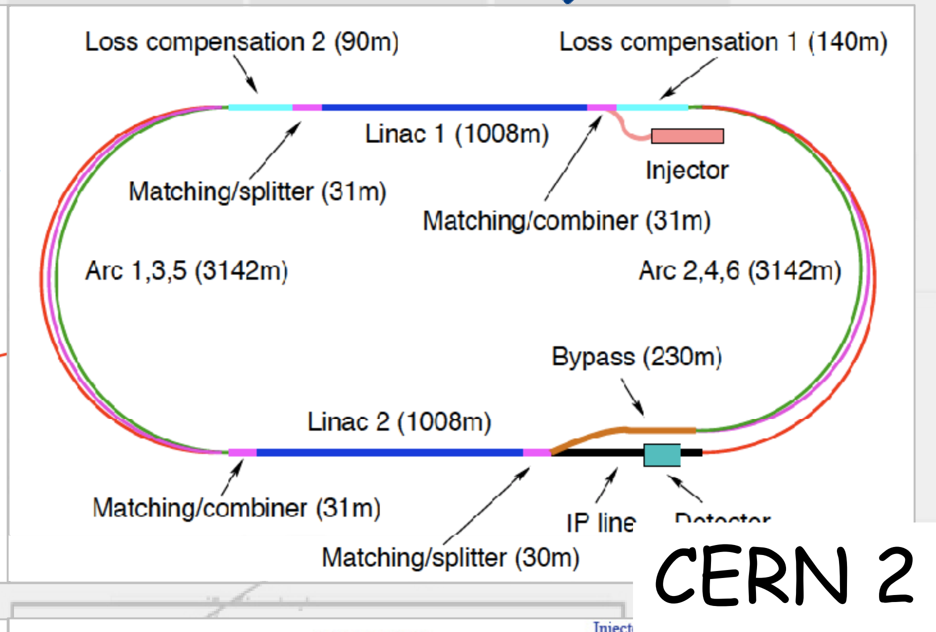
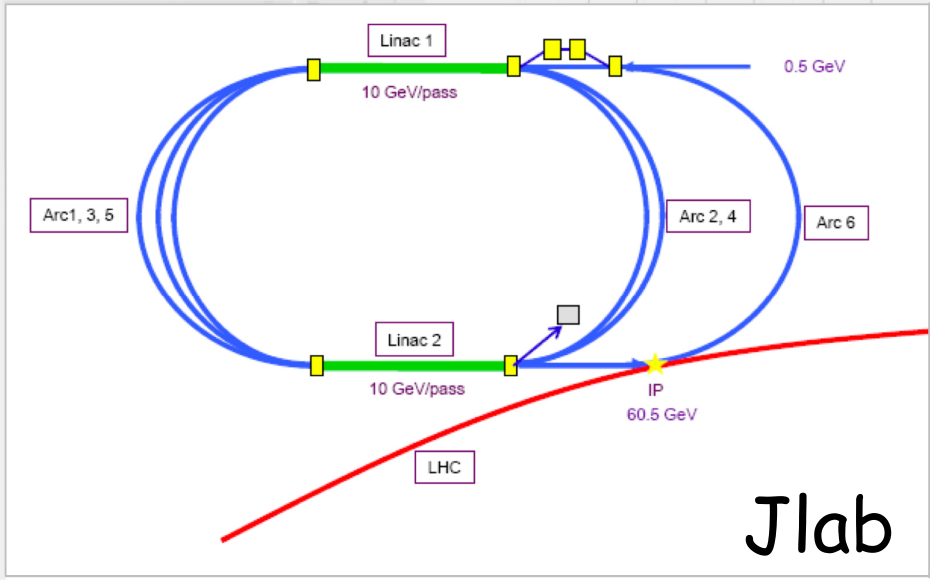
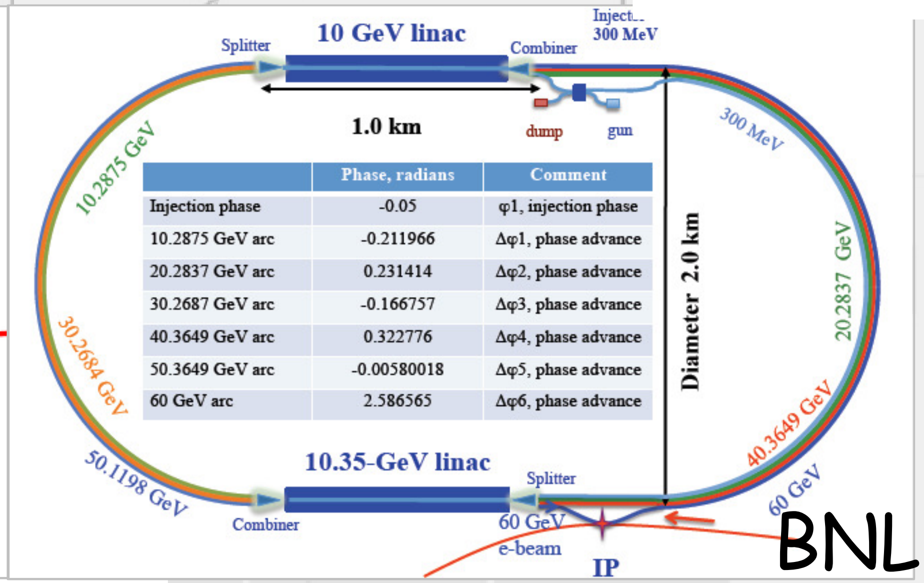



| | Phase, radians | Comment |
|---|---|---|
| Injection phase | -0.05 | φ1, injection phase |
| 10.2875 GeV arc | -0.211966 | Δφ1, phase advance |
| 20.2837 GeV arc | 0.231414 | Δφ2, phase advance |
| 30.2687 GeV arc | -0.166757 | Δφ3, phase advance |
| 40.3649 GeV arc | 0.322776 | Δφ4, phase advance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

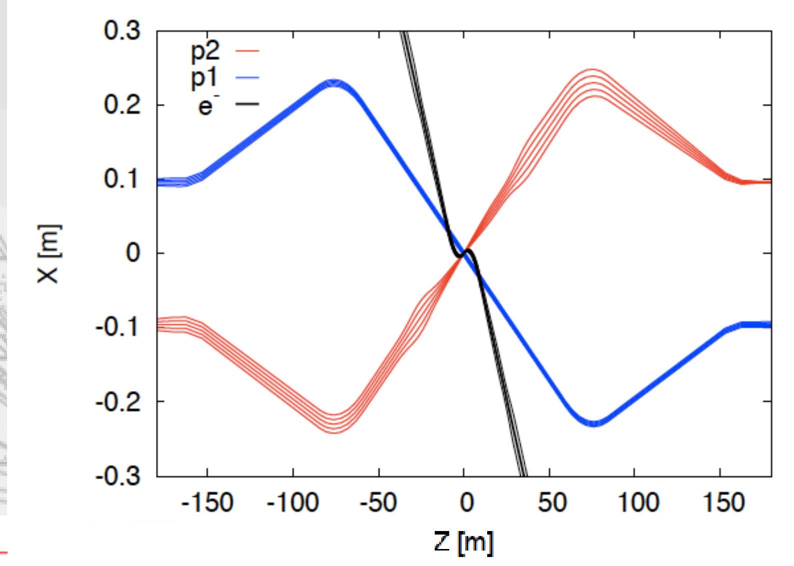
Two 10 GeV Linacs, 3 returns, ERL, 720 MHz cavities, rf, cryo, magnets, injectors, sources, dumps…

# LHeC LR

- $\mathcal{L} \sim 10^{33}cm^{-2}s^{-1}$ possible for $e^-$
- $e^+$ require energy recovery AND recycling, $\mathcal{L}^+ < \mathcal{L}^-$
- 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*



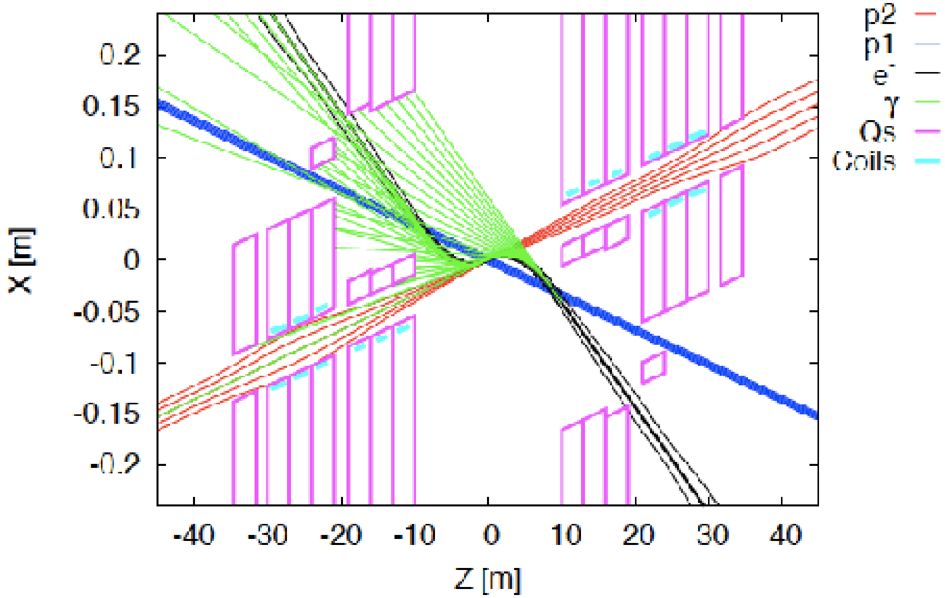




Figure 9.14: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with $5\sigma$ and $10\sigma$ envelopes are shown.

# LHeC LR: Energy Recovery

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

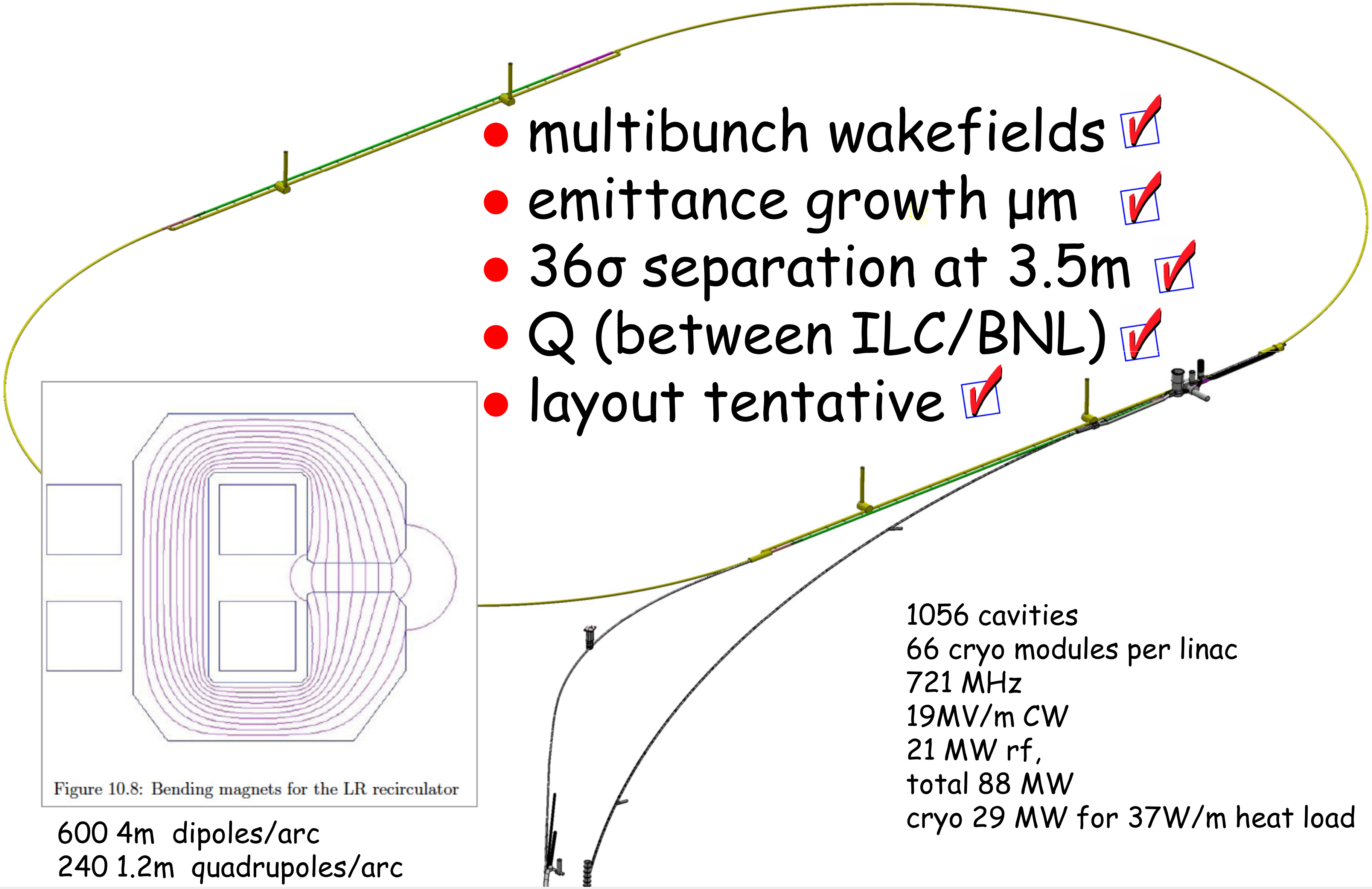


Figure 10.8: Bending magnets for the LR recirculator

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

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| 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 $\sigma_{x,y}$ [$\mu$m] | 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.$\gamma\varepsilon_{x,y}$ [$\mu$m] | 3.75 | 3.75 |
| spot size $\sigma_{x,y}$ [$\mu$m] | 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

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- high *L* for large $Q^2$ and large $x$

  $10^{33}$ — $1\text{-}5\ 10^{31}$

- largest possible acceptance — kinematic coverage

  1-179° — 7-177°

- precision tracking — modern Si

  0.1 mrad — 0.2-1 mrad

- precision electromagnetic calorimetry — kinematic reconstructi

  0.1% — 0.2-0.5%

- precision hadronic calorimetry — track+calo

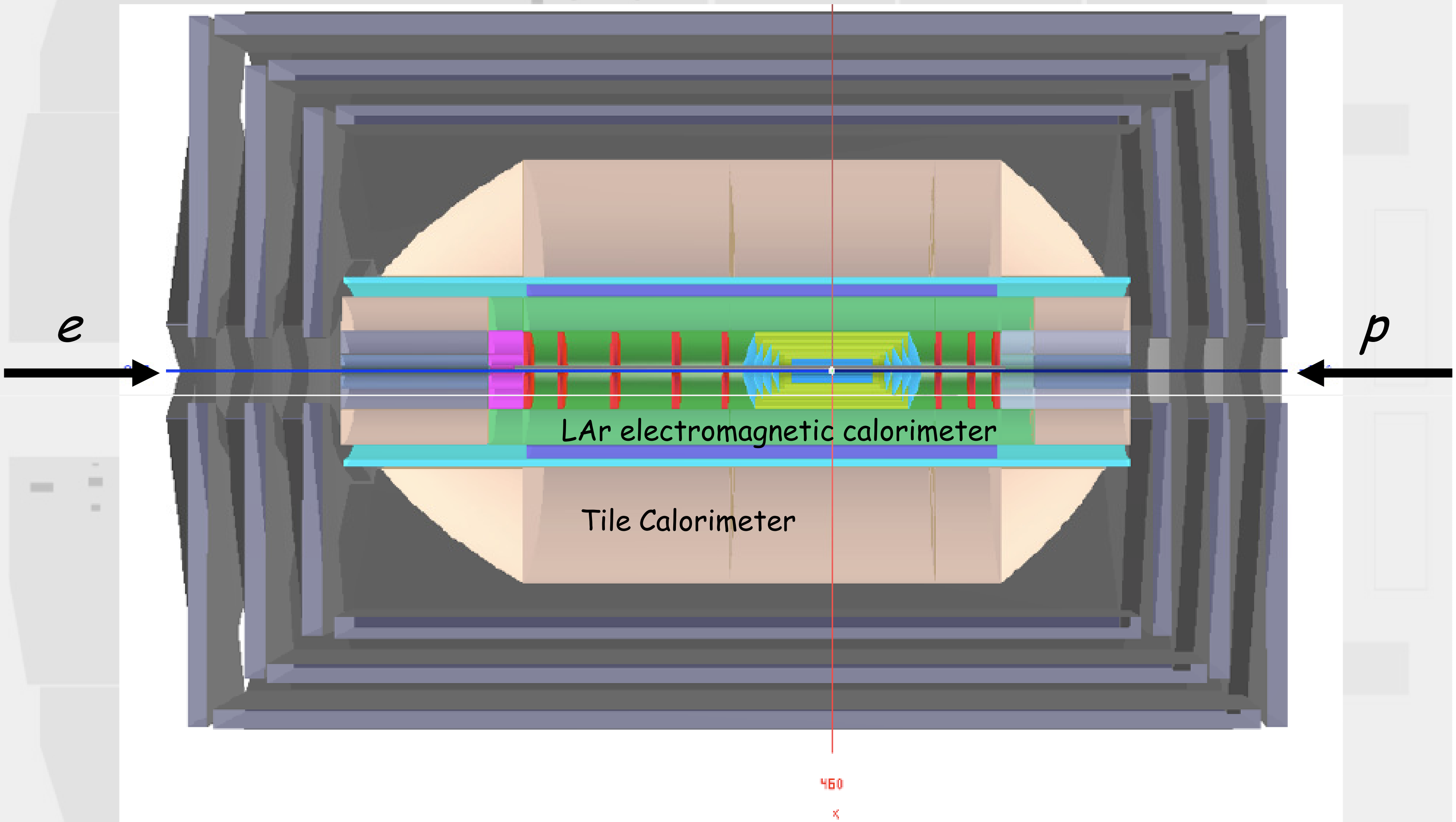
  0.5% — 1% — *e/h*

- accurate luminosity/polarisation — not straight-forward

  0.5% — 1%

LHeC — H1

# LHeC Experiment




**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

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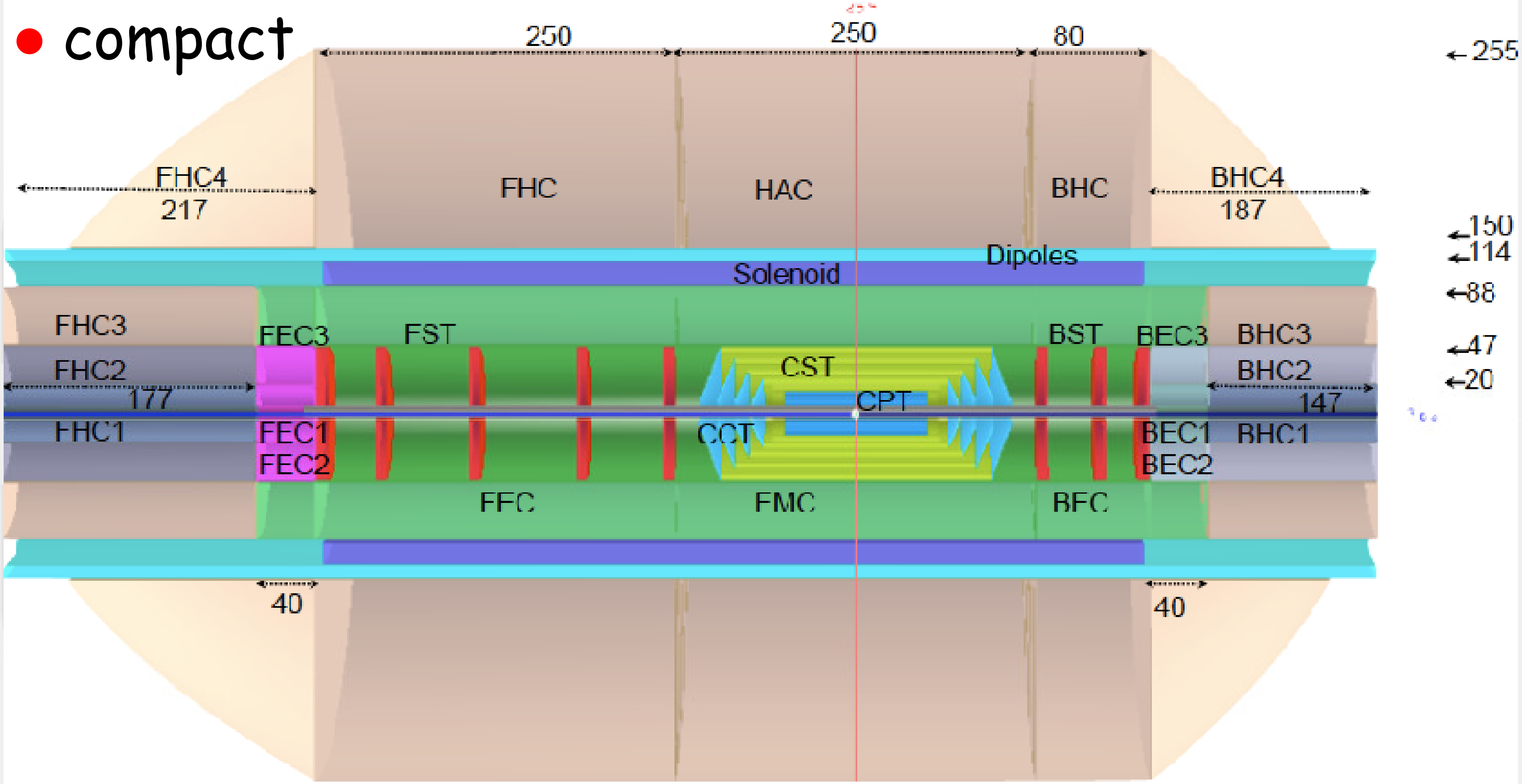
- compact

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**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

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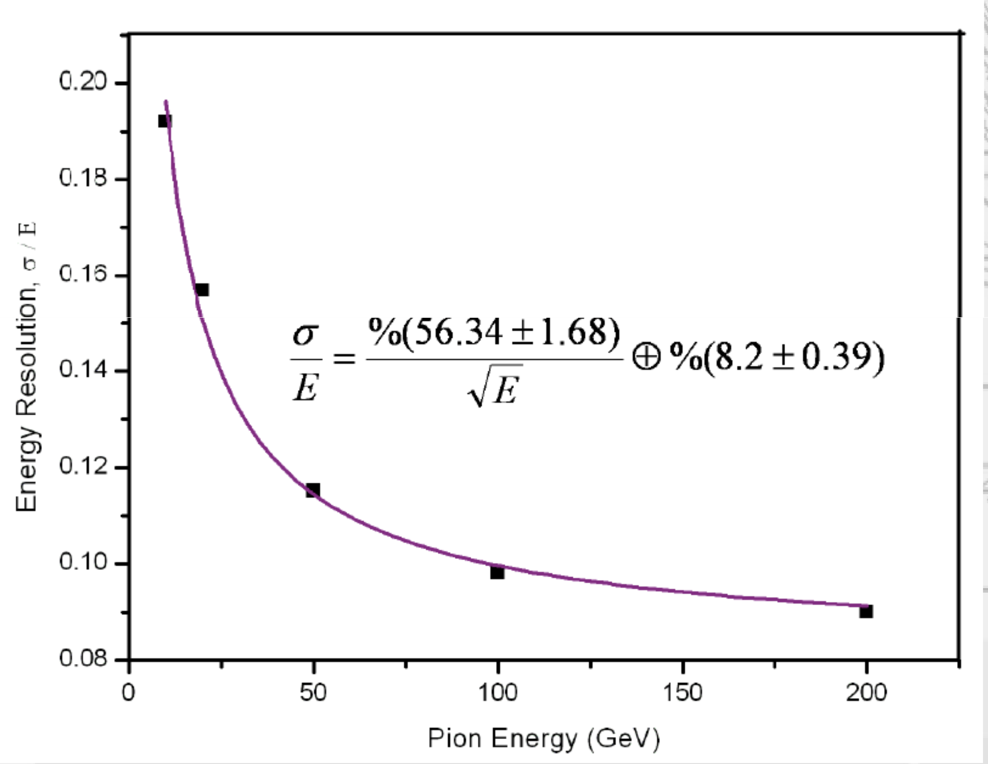
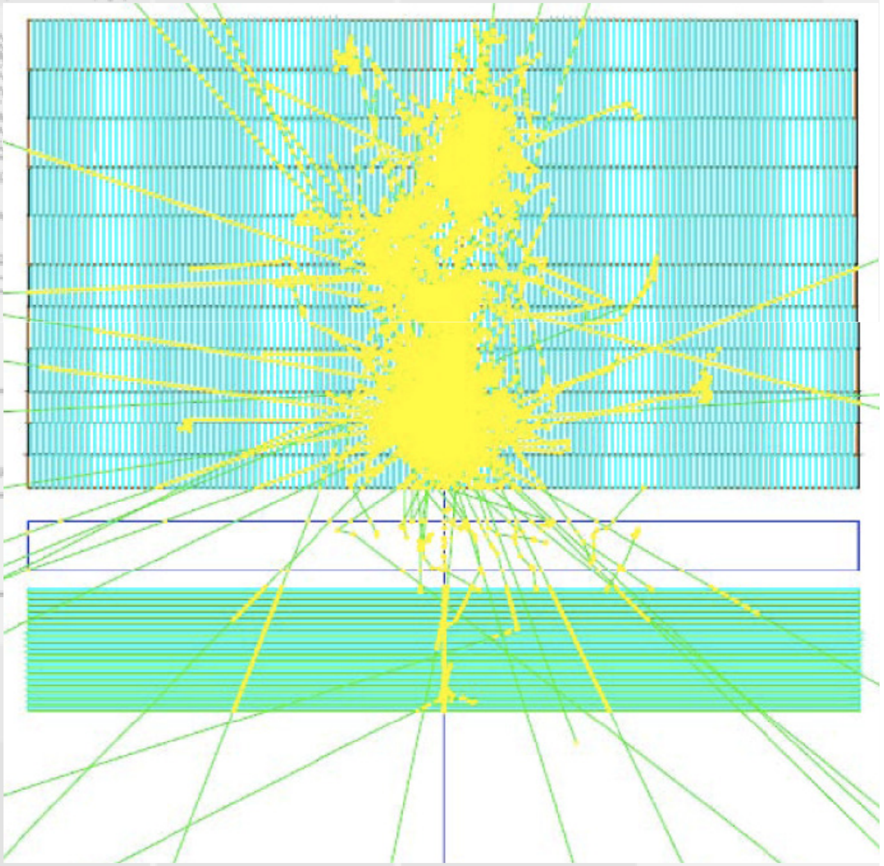
- segmented calorimetry




A charged pion in the LHeC HCAL

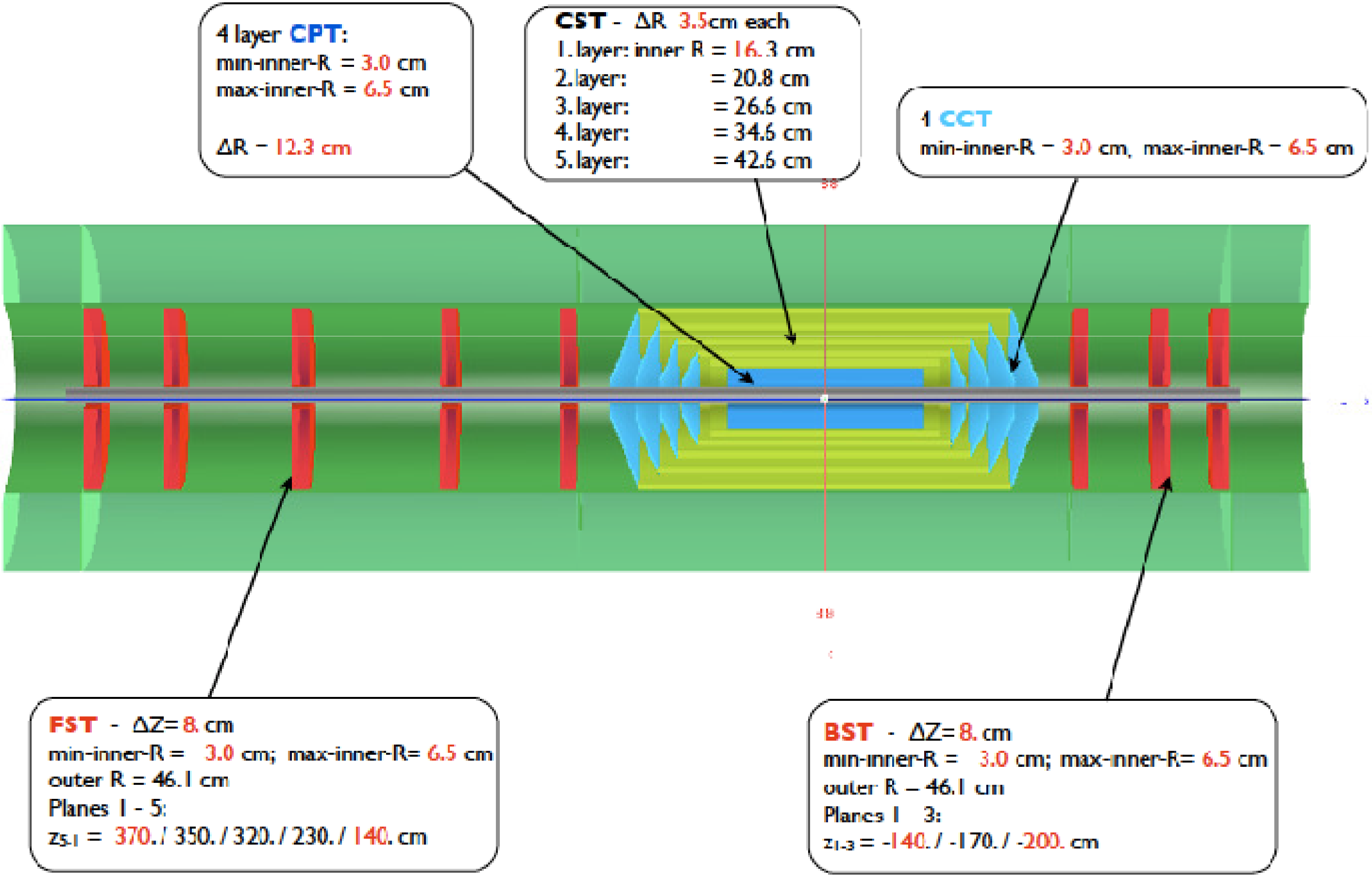


Performance simulated for tile cal only

# LHeC Experiment

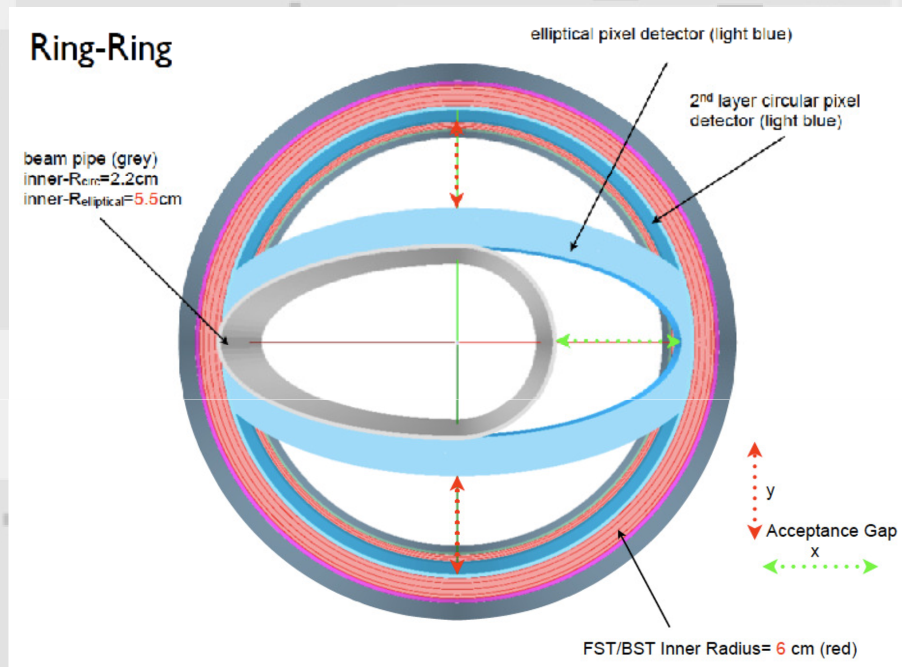


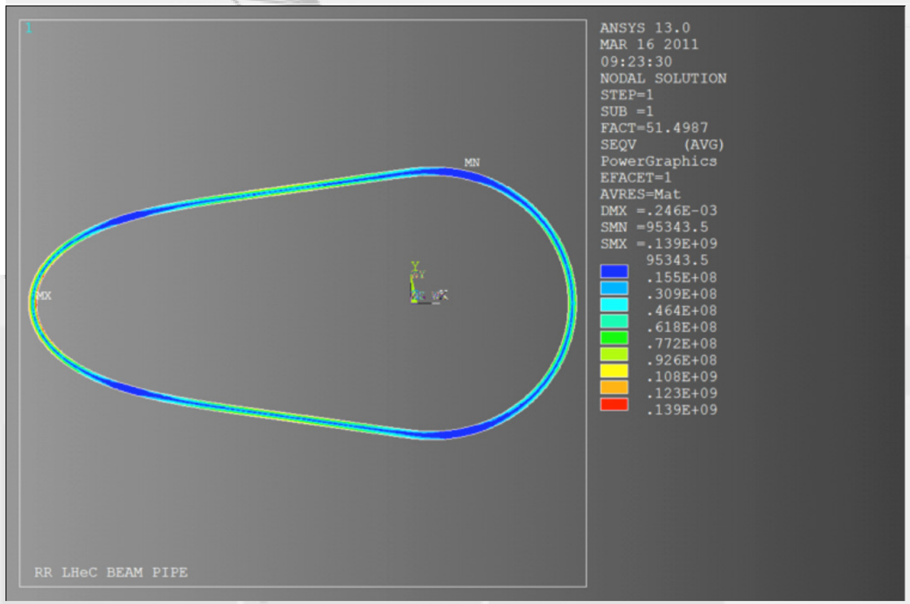
- foreseeable semiconductor development (LHC)



# LHeC Experiment

- beam pipe




Beam pipe design – work in progress

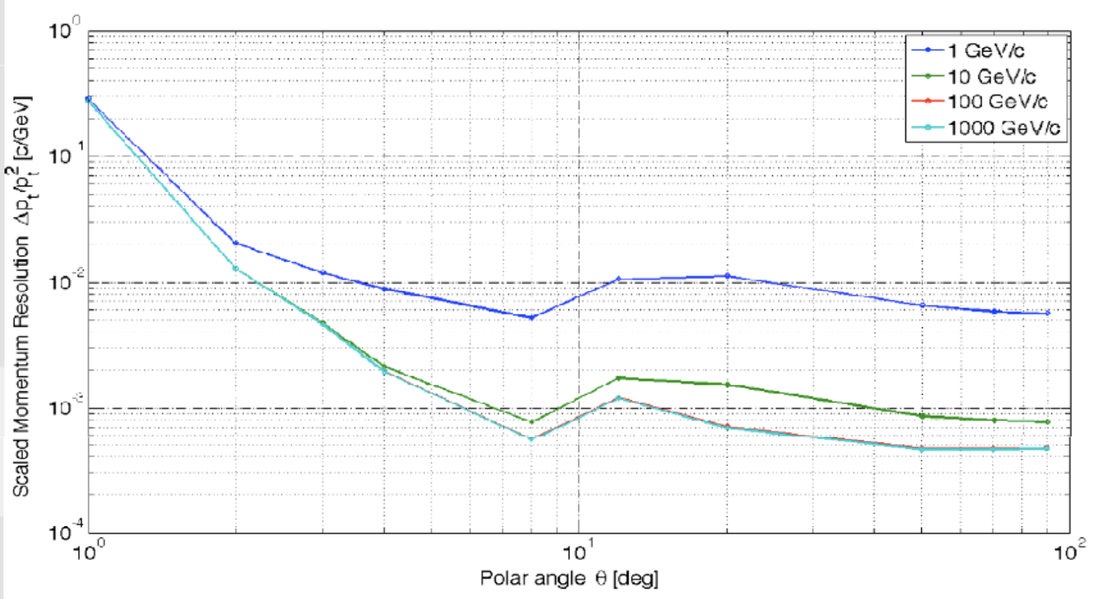
LR more challenging than RR due to extended synchrotron radiation fan

R. Veness et al CERN

Seminar: Jlab and BNL
August 2011

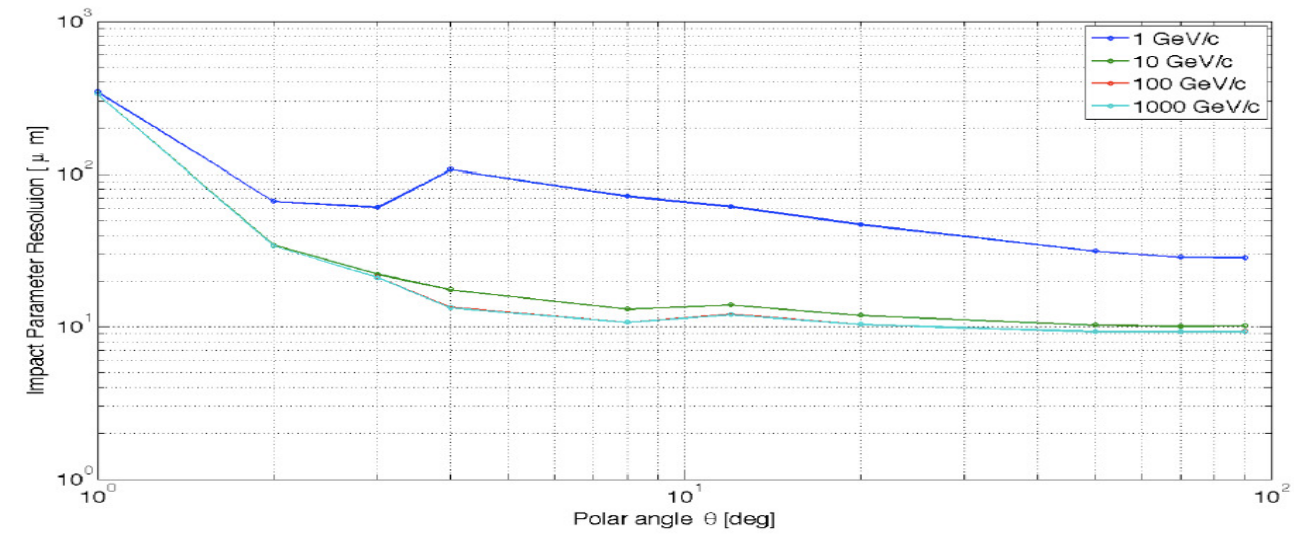
# LHeC Experiment

- charged particle reconstruction




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

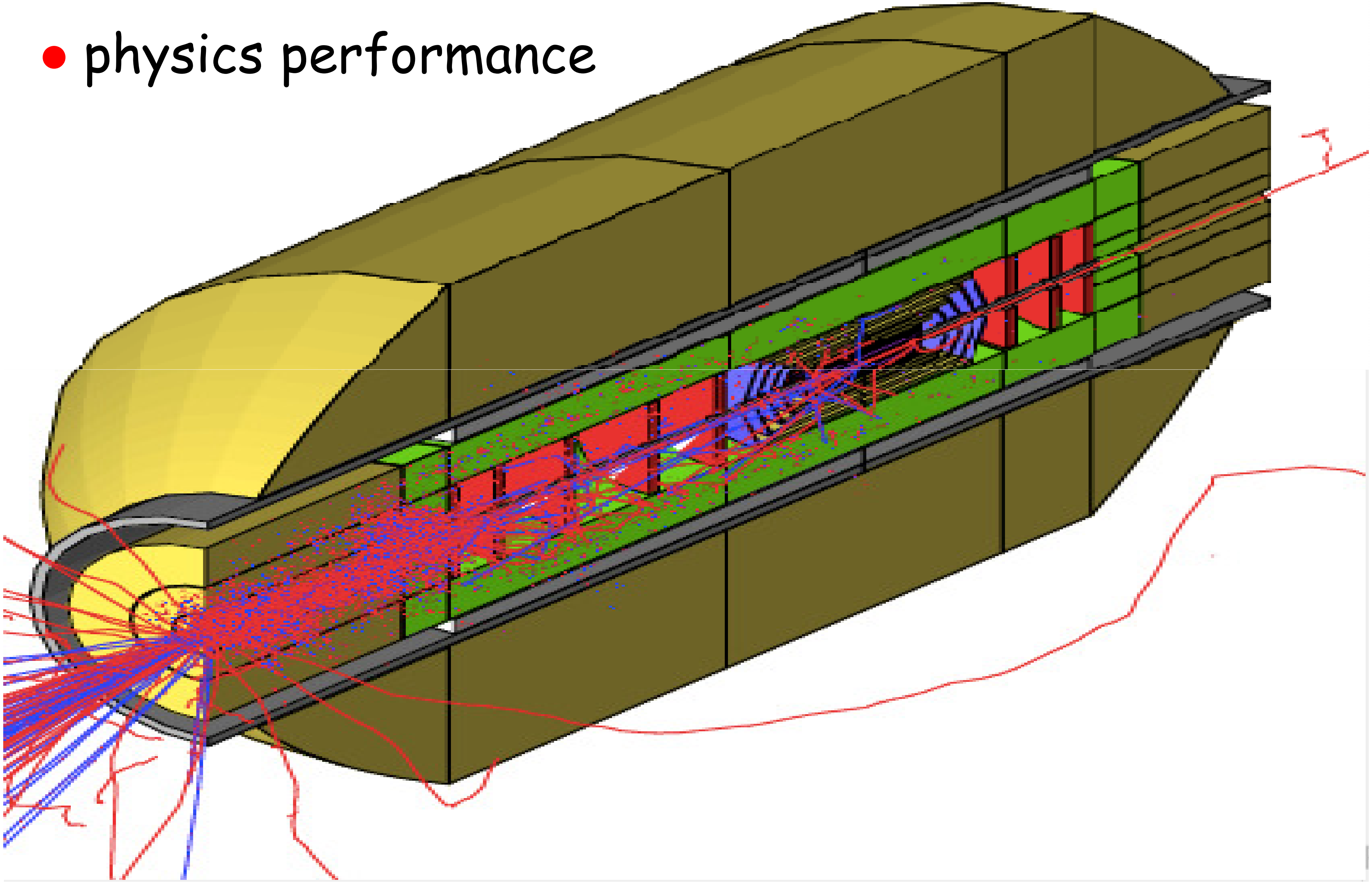
transverse
impact parameter
→ 10μm



# LHeC Experiment



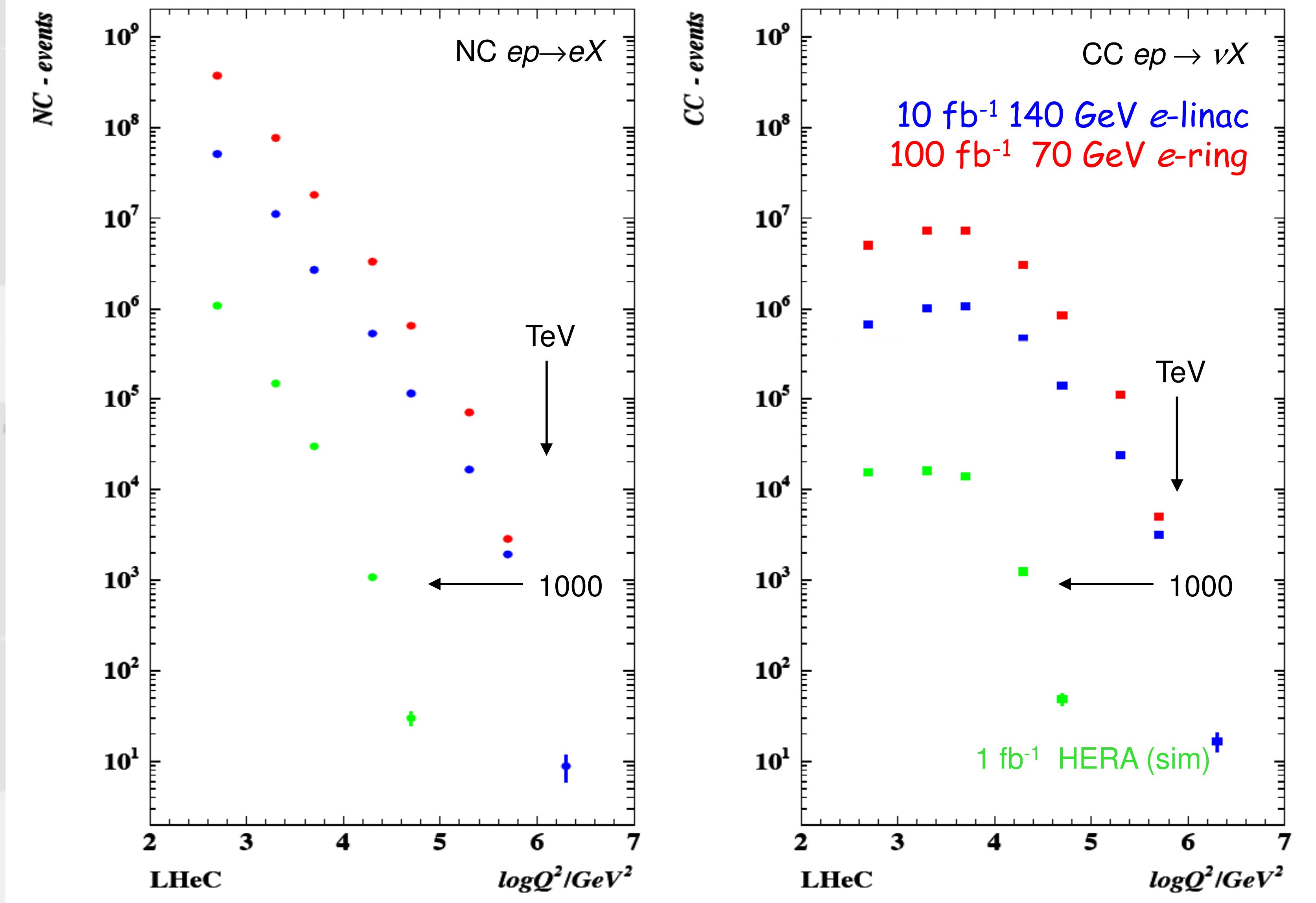
- physics performance



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

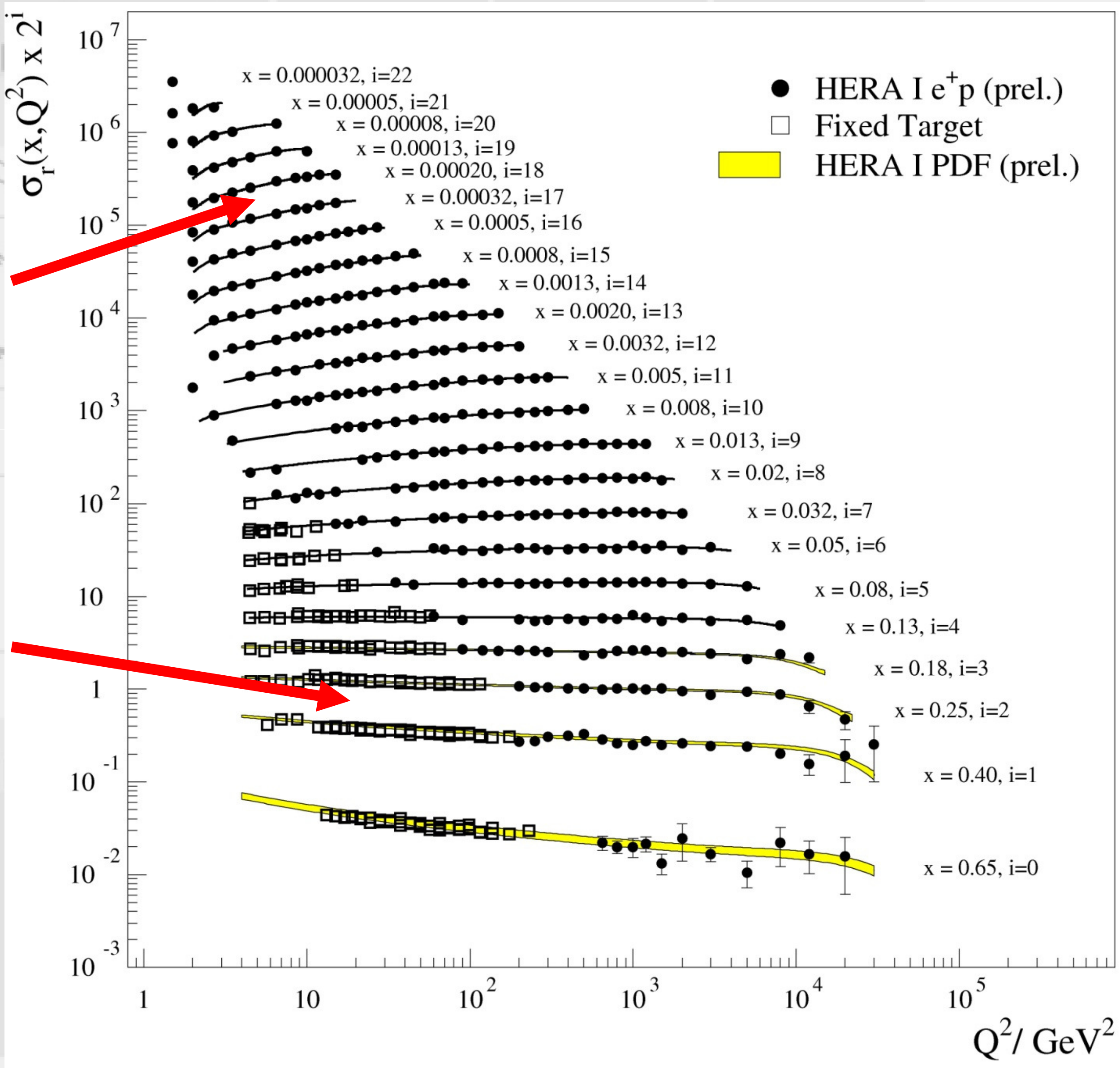
# Sensitivity

- 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



# No LHeC, no Terascale ?

- flavour singlet field $q_S$ evol$^{\underline{n}}$
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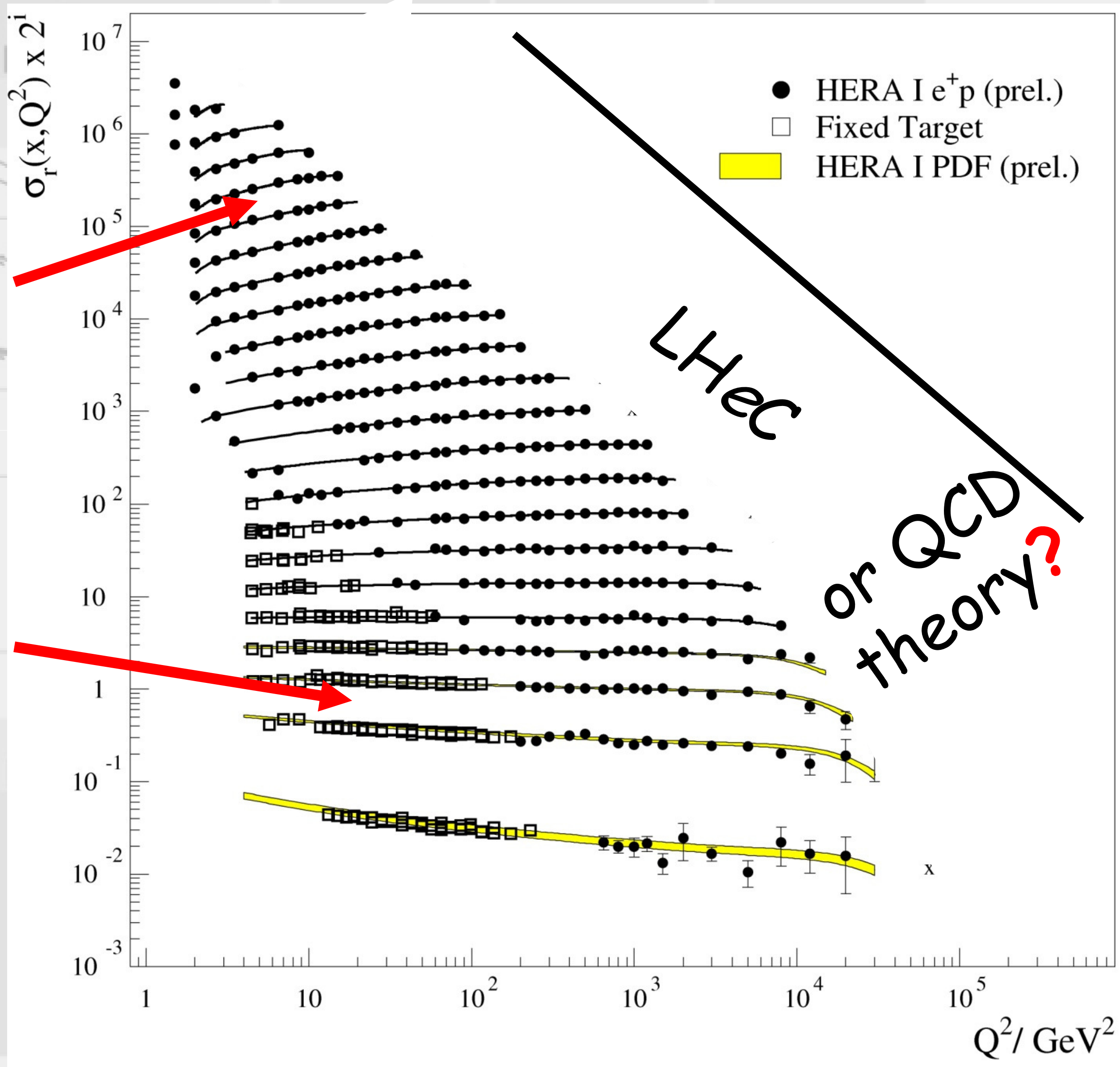
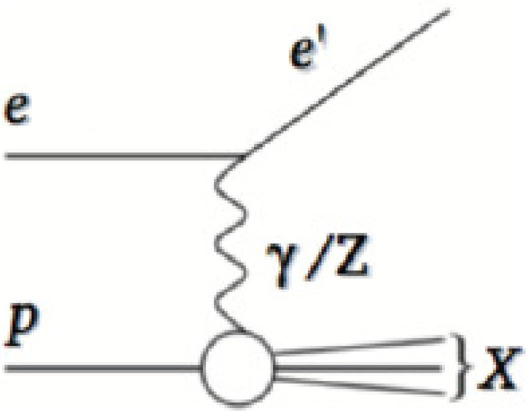
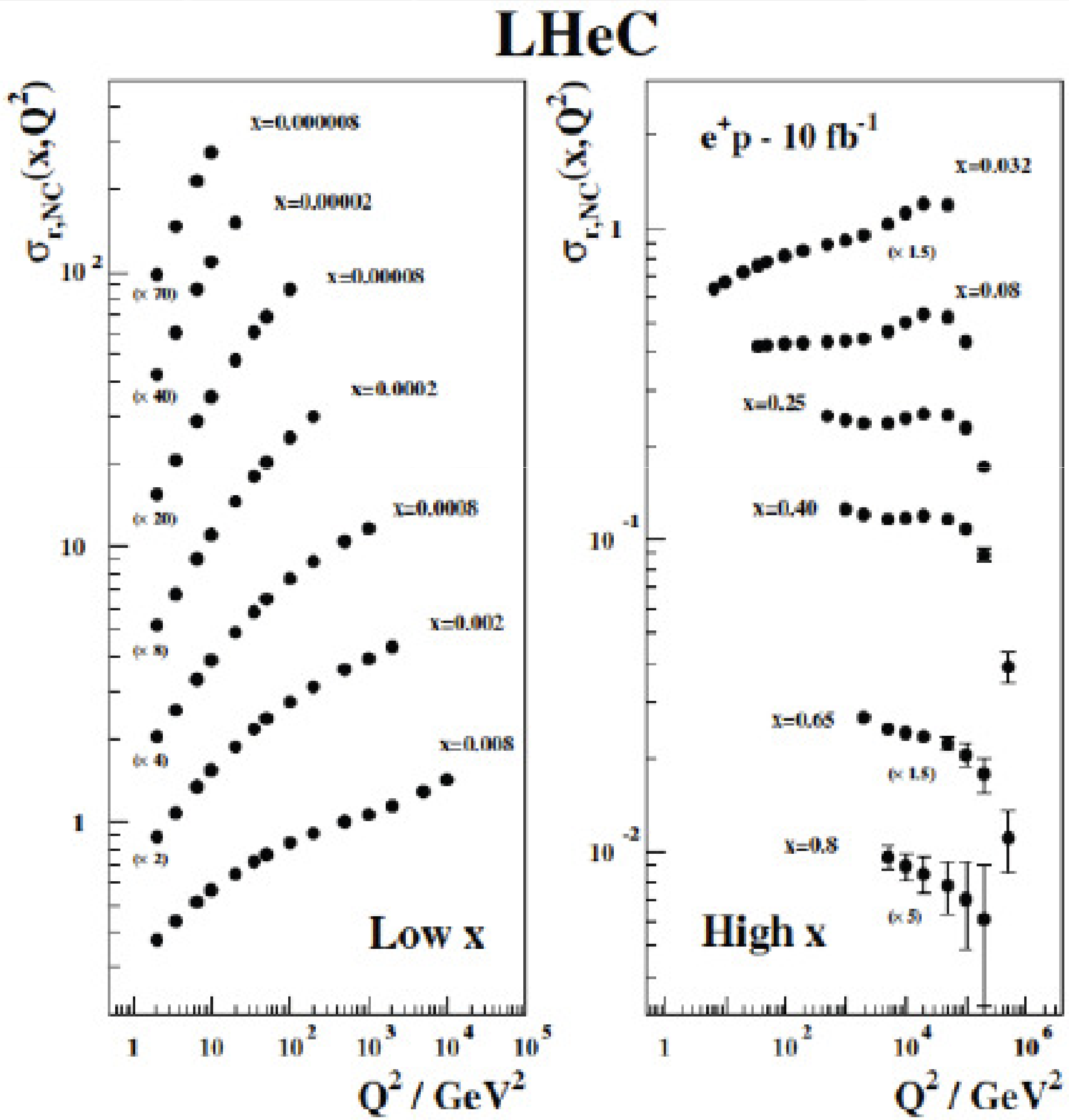


# The SM proton @ LHeC

NC : $e\,p \rightarrow e'\,X$

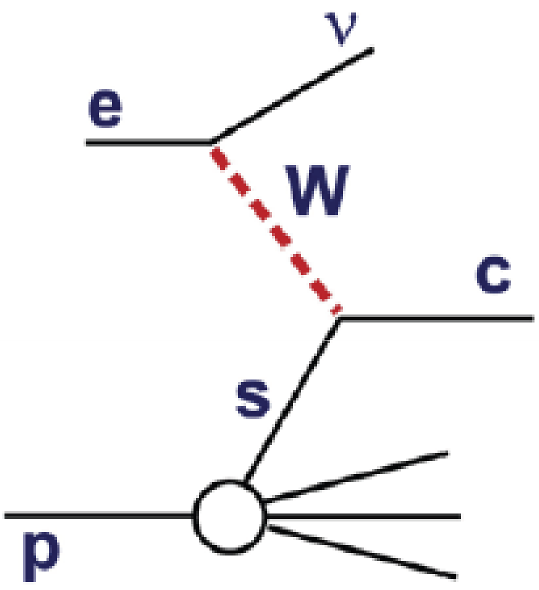


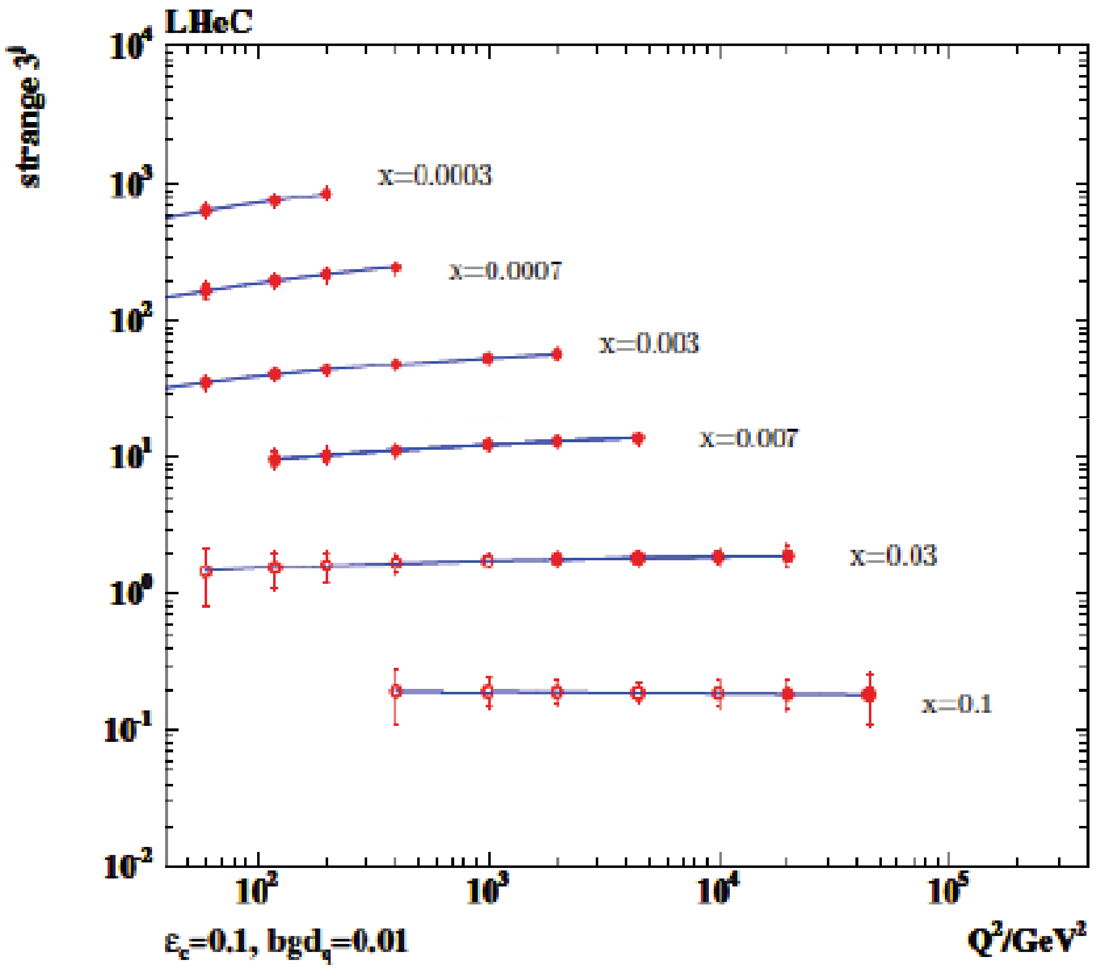




- no pile-up
  → clean unfolding

# Strangeness in the Proton






- strange and anti-strange with $e^+$ and $e^-$

# Charm in the Proton

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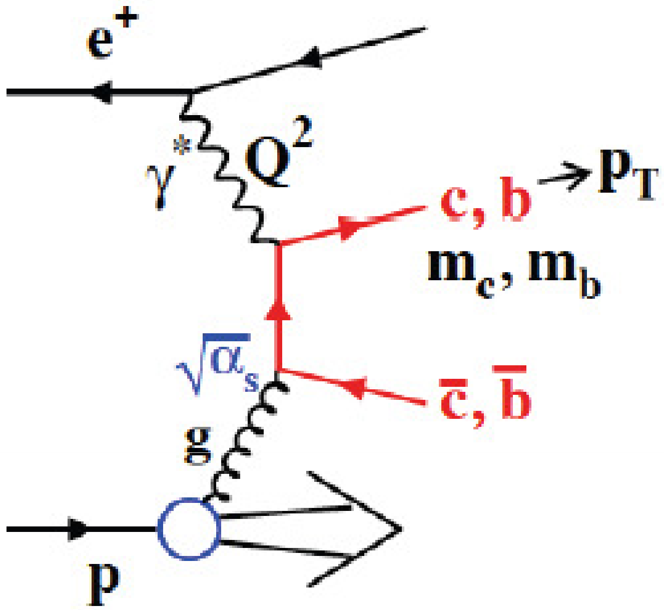
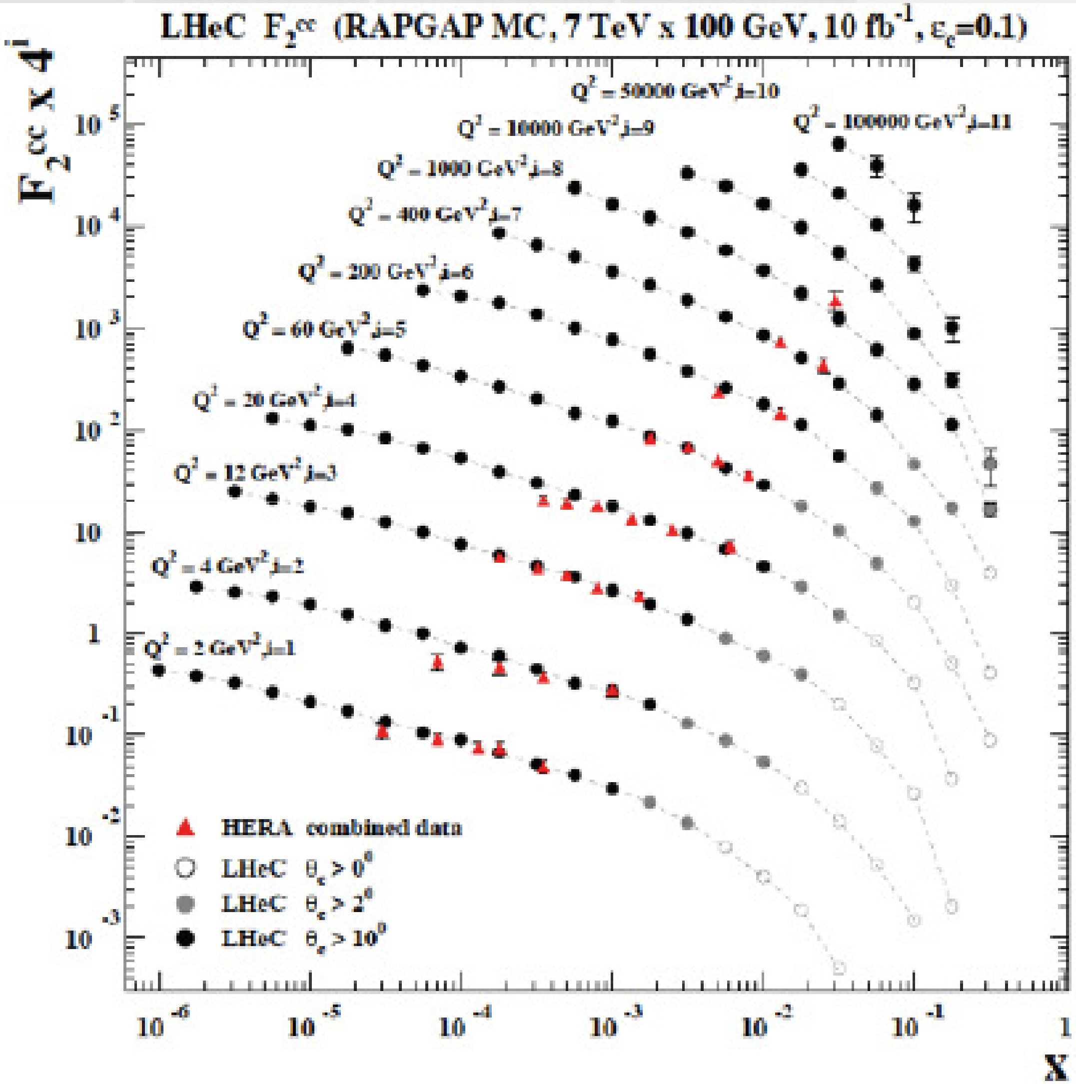
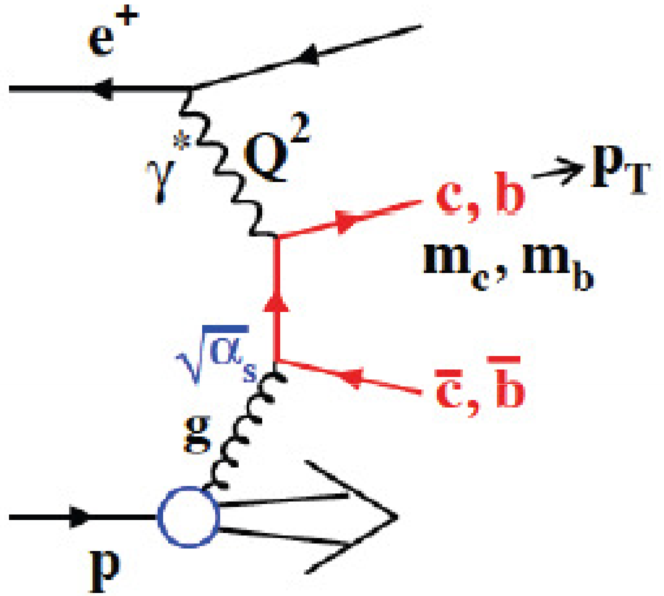
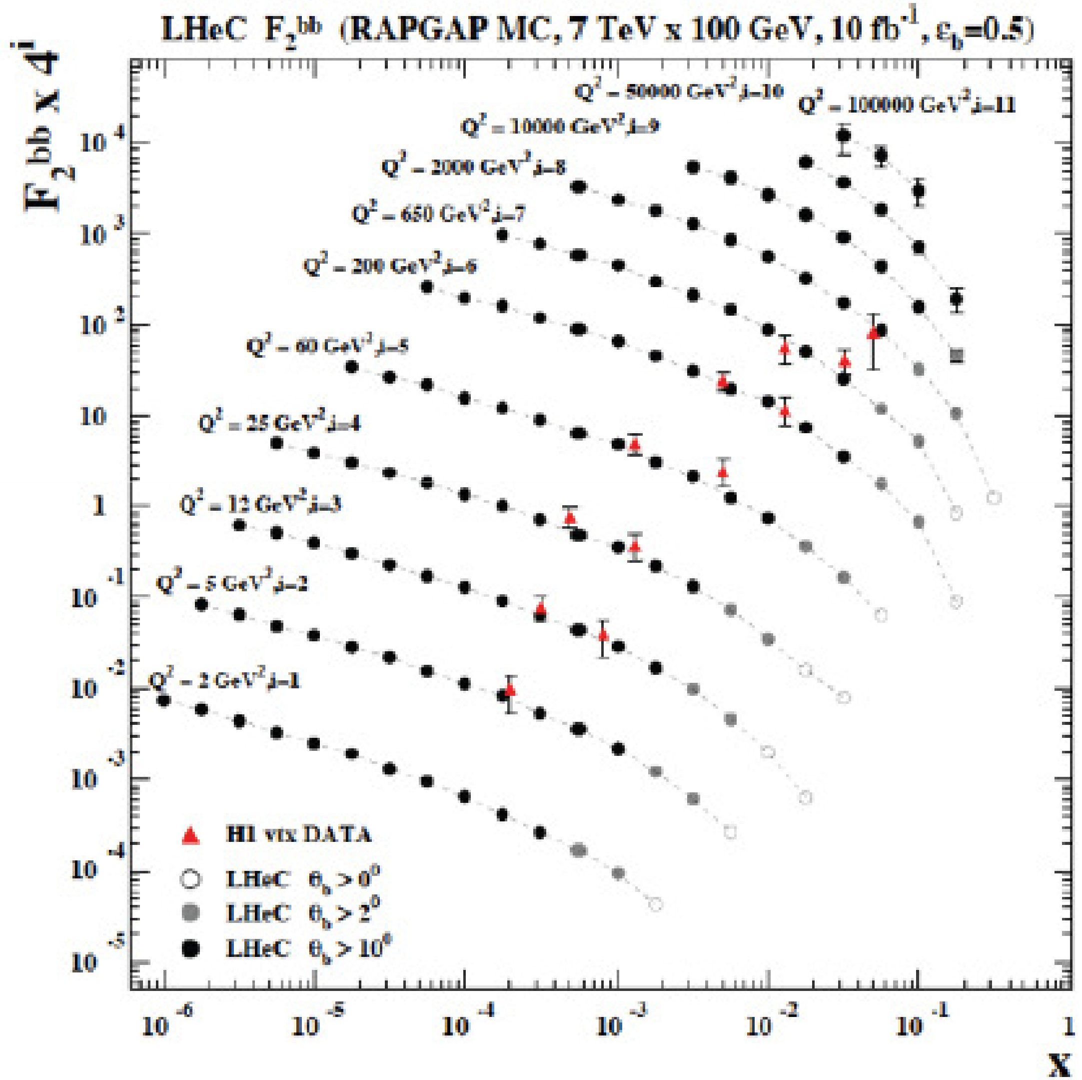



- including high $x$ cf HERA

# Beauty in the Proton

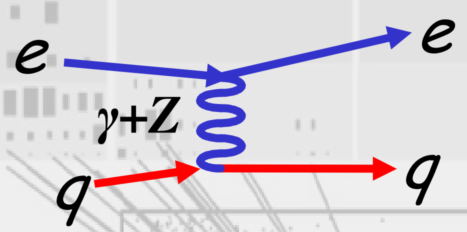


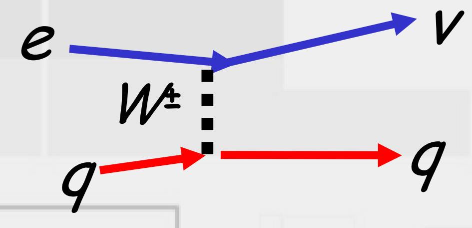



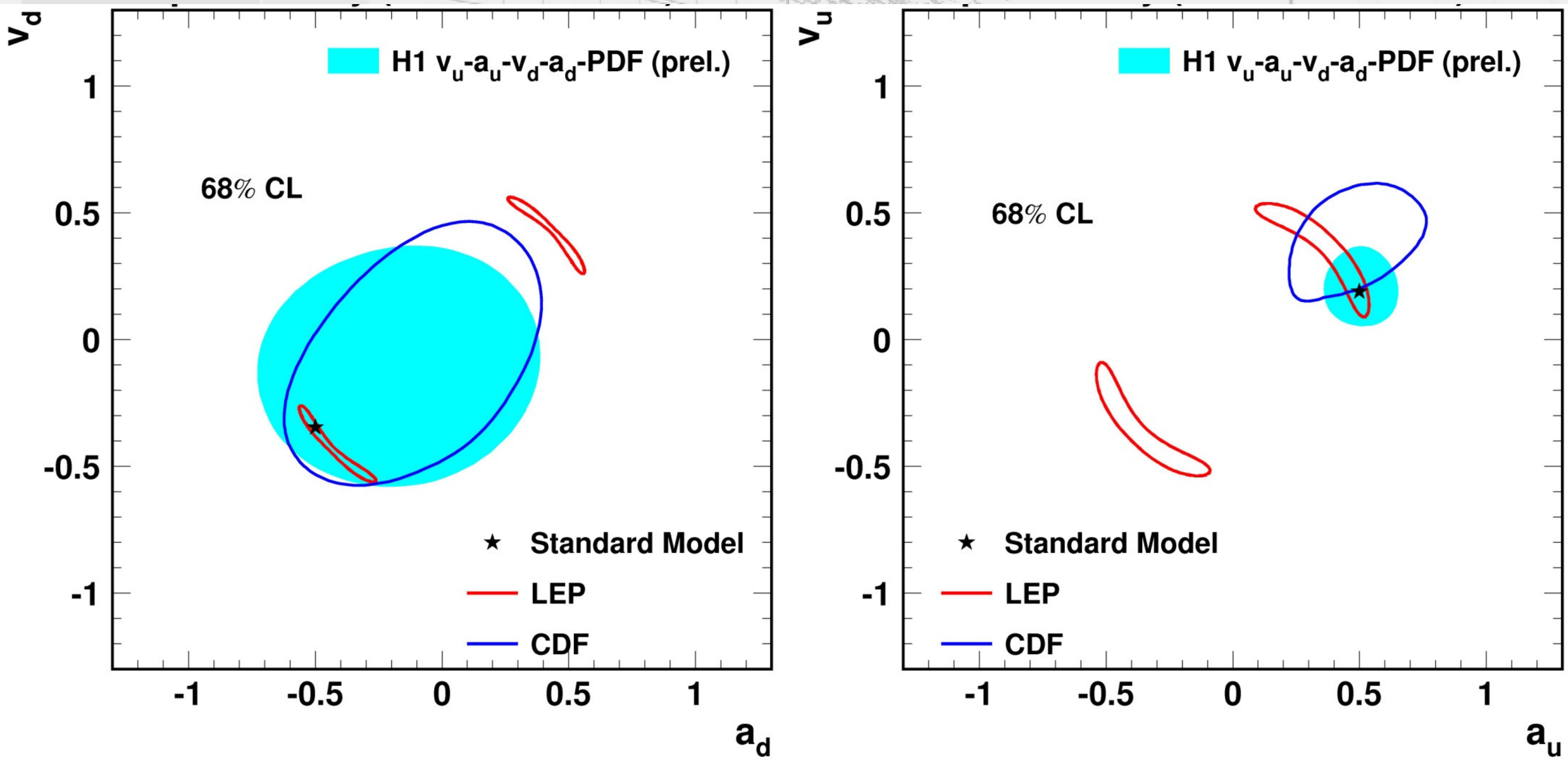

- precision → quark mass in QCD evolution

# Electron-Quark Physics

- EW light $q$ couplings (in proton matter)



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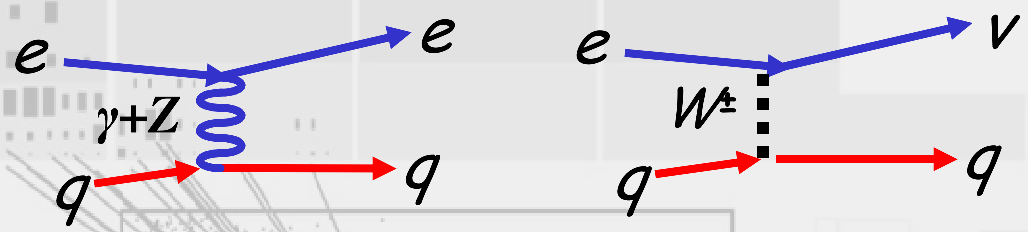


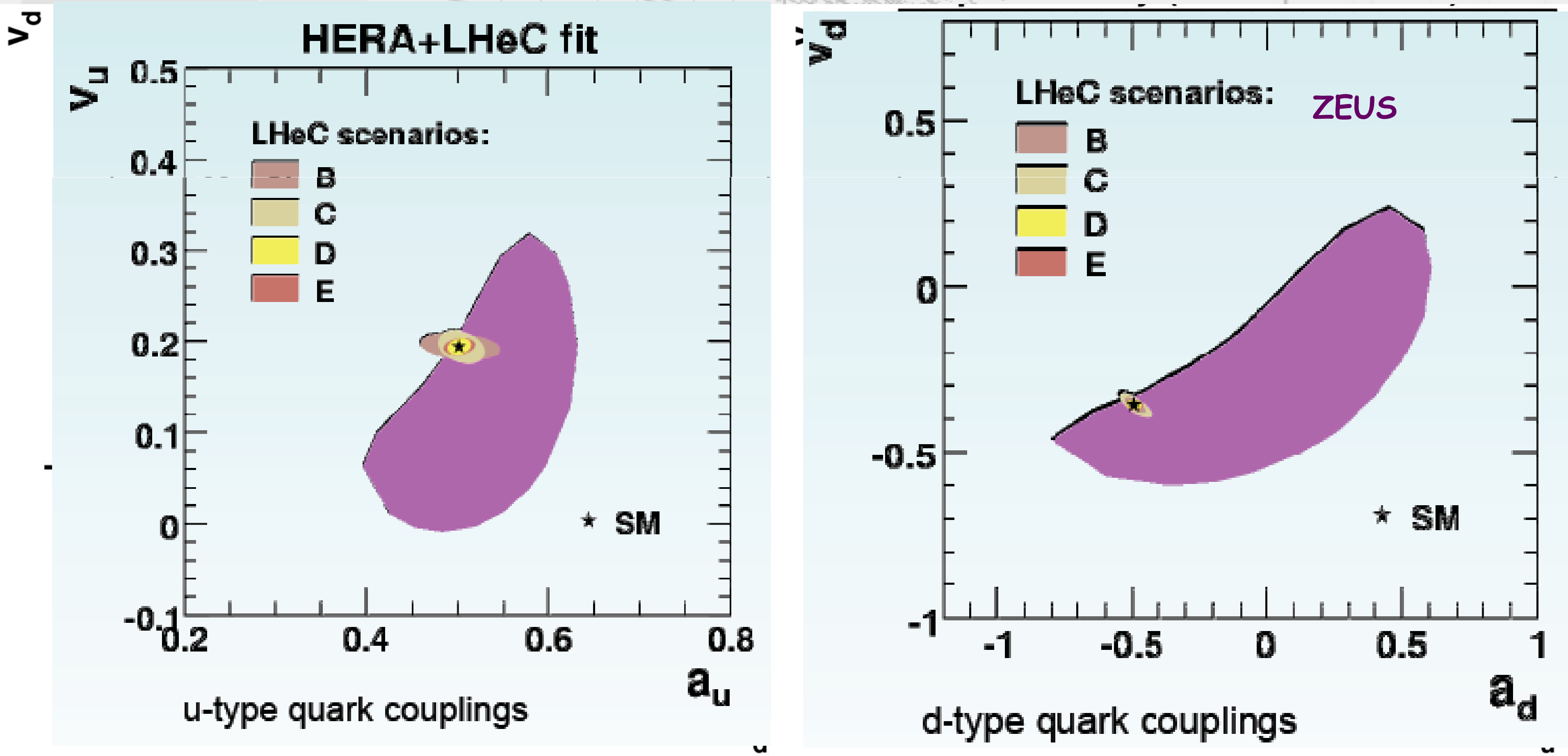

# Probing Unification ?

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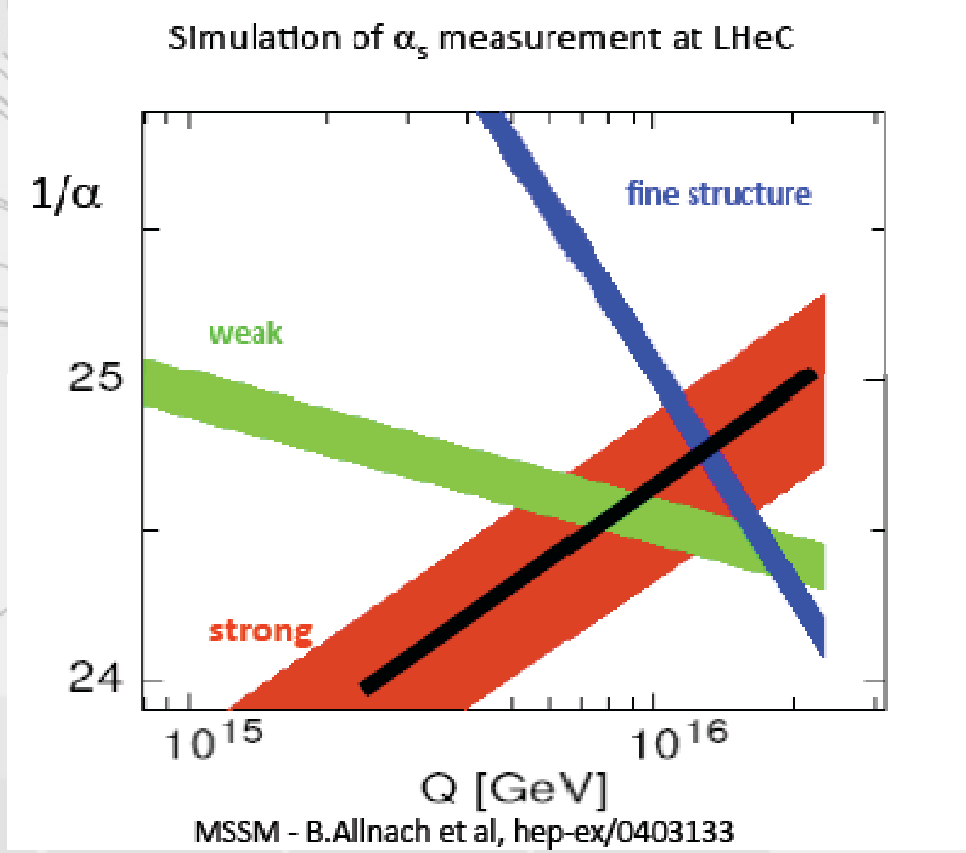
- precision → QCD at highest energy
- short distance structure of SM+
  - 2007 $\alpha$ @ $10^{-3}$ ppm
  - 2007 $G_F$ @ 10 ppm
  - 2007 $G$ @ 0.1%
  - 2007 $\alpha_s$ @ 1-2%
  - LHeC + detector → $\alpha_s$ @ few ‰




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

# How heavy can you be?

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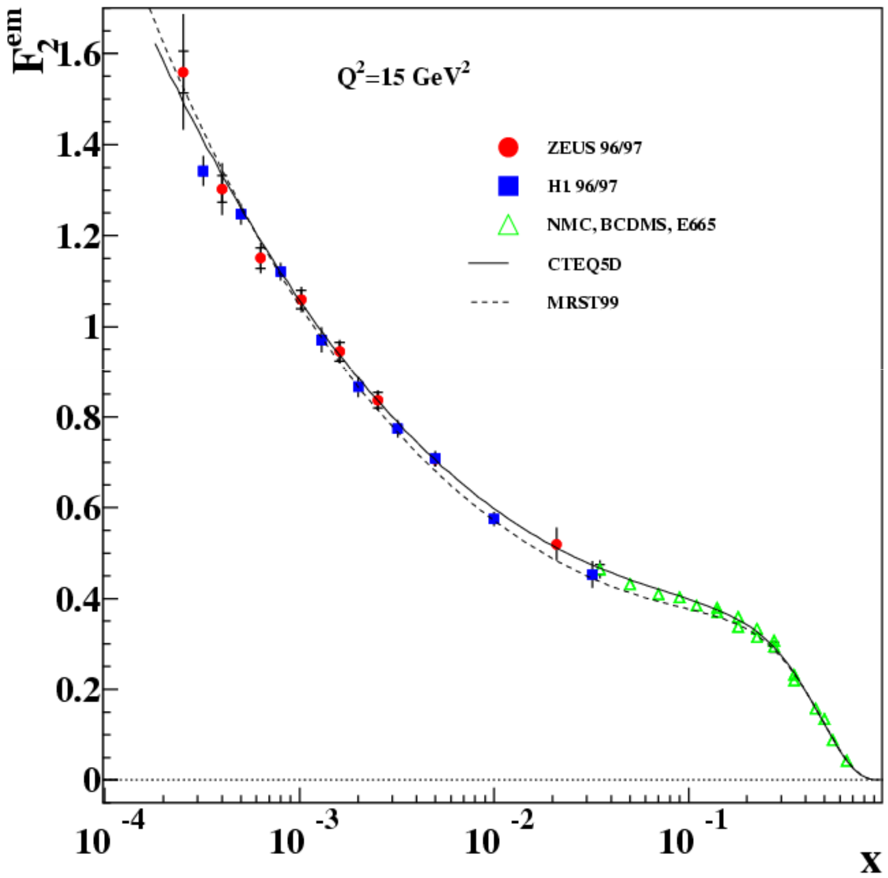
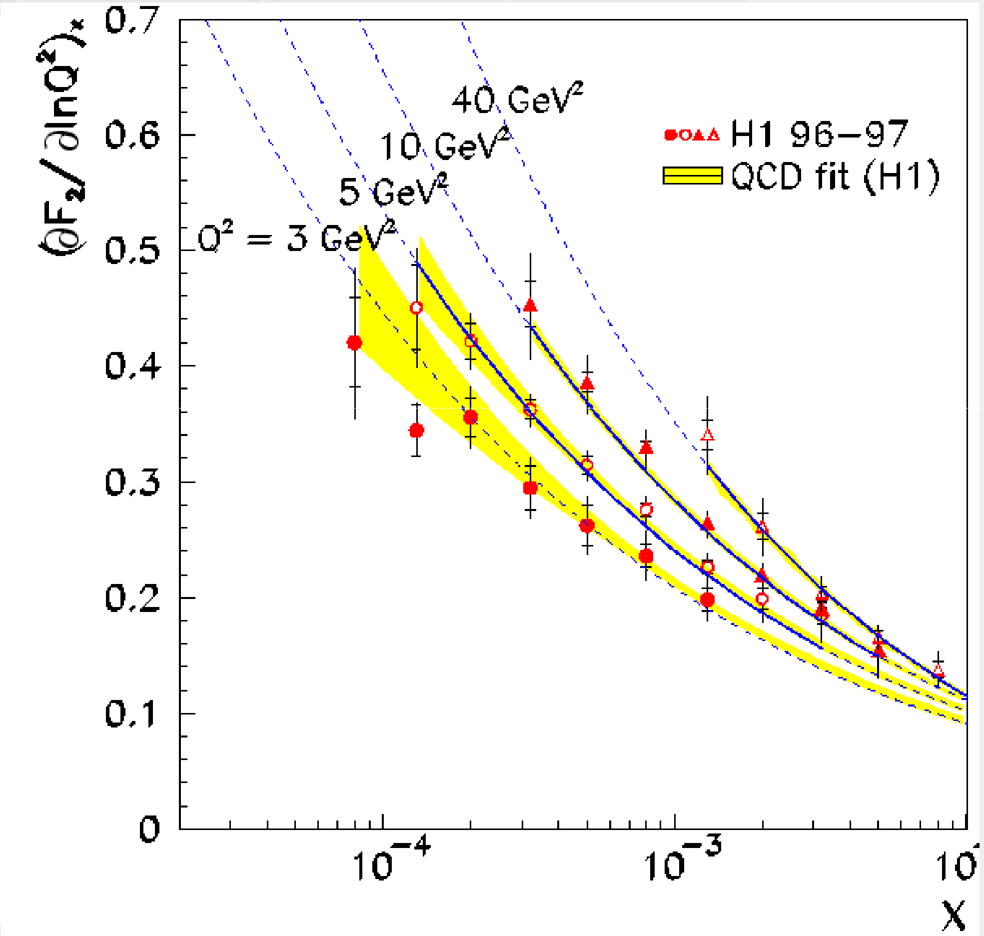
- low-$x$ magnifier: HERA: $x > 10^{-4}$ @ $Q^2$=10 GeV$^2$




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

# How heavy can you be?

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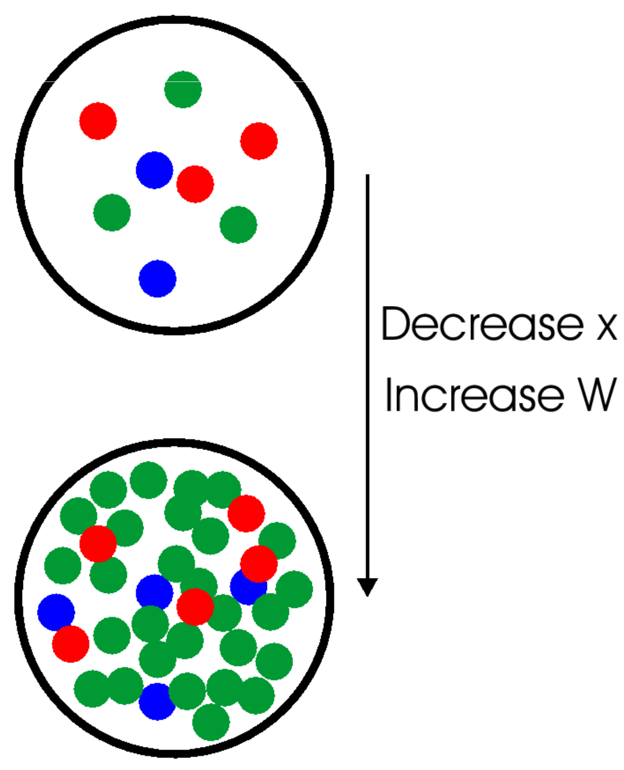
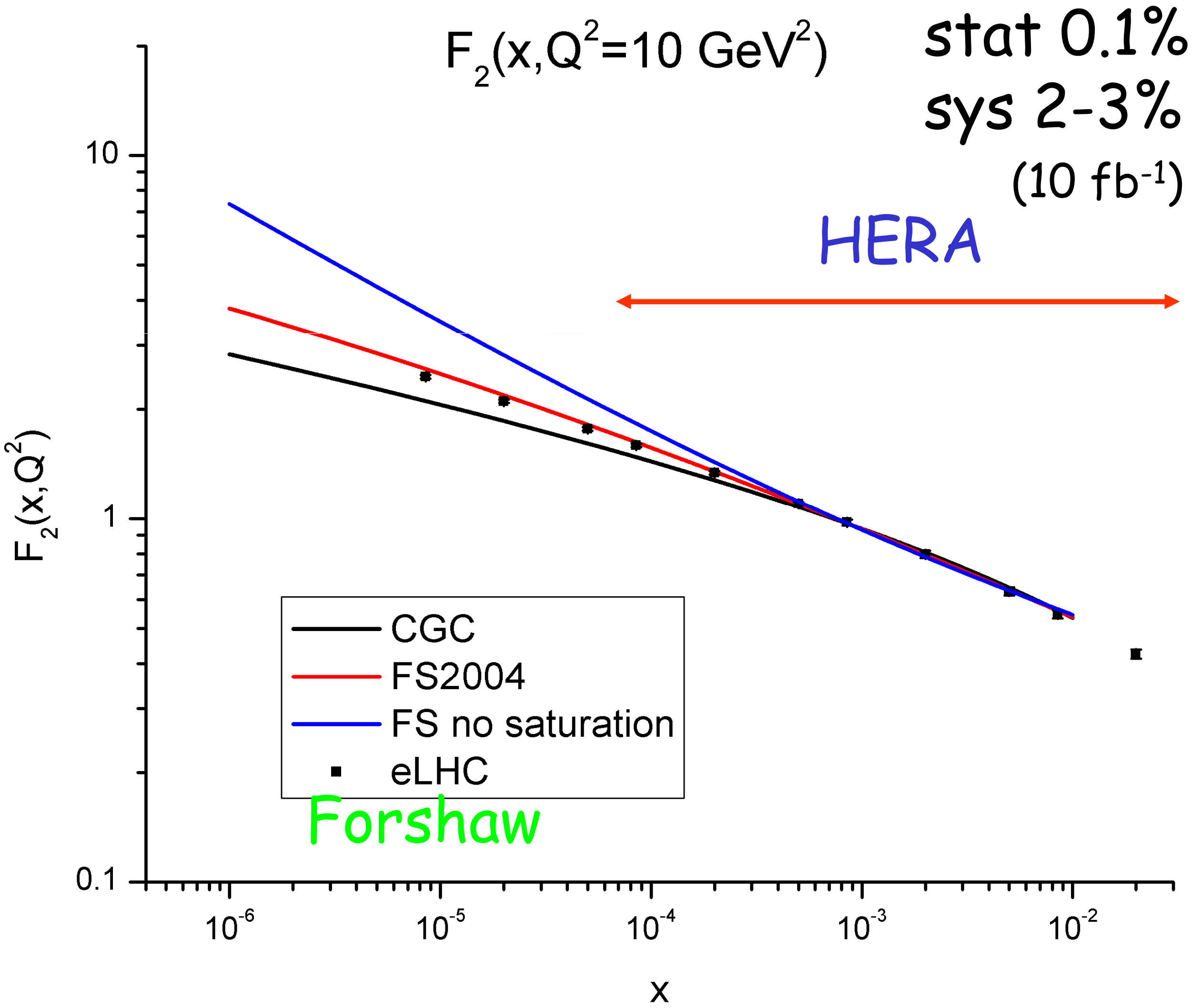
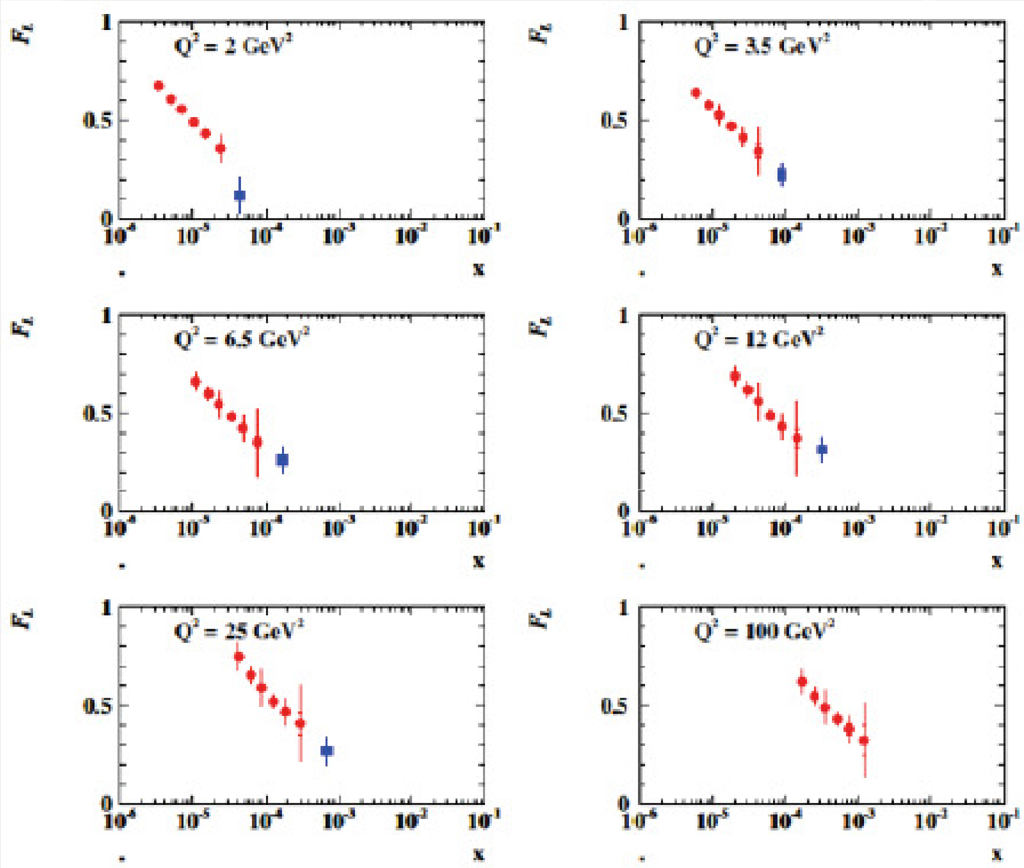
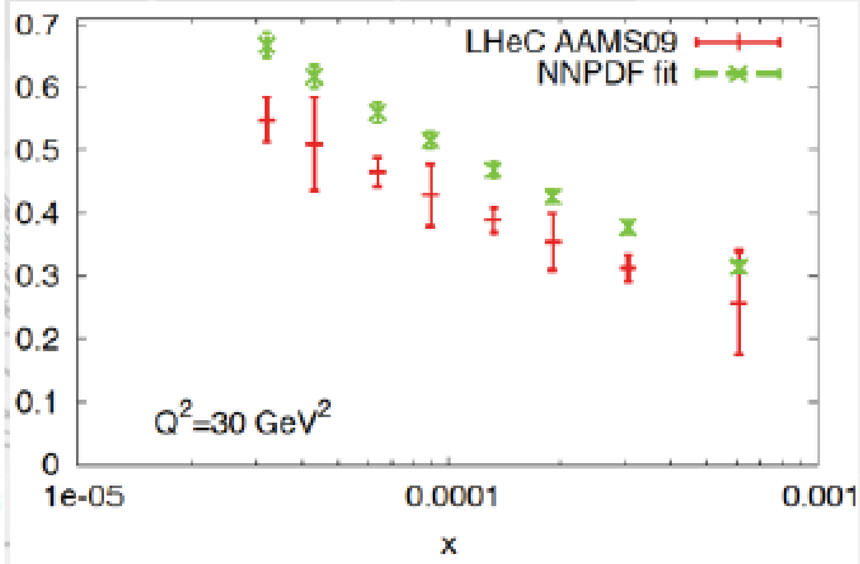
- low-$x$ magnifier: LHeC: $x > 4\times10^{-6}$ @ $Q^2=10$ GeV²
- LHeC "nails"
  saturation
- unitarity



# Unambiguous Saturation




- signature in experimental observable
  - DGLAP in $F_2 + F_L$

# More on your mass!

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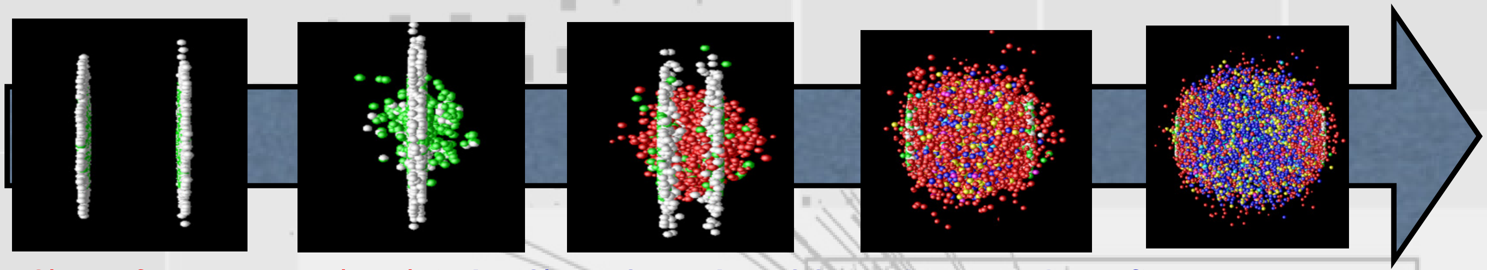
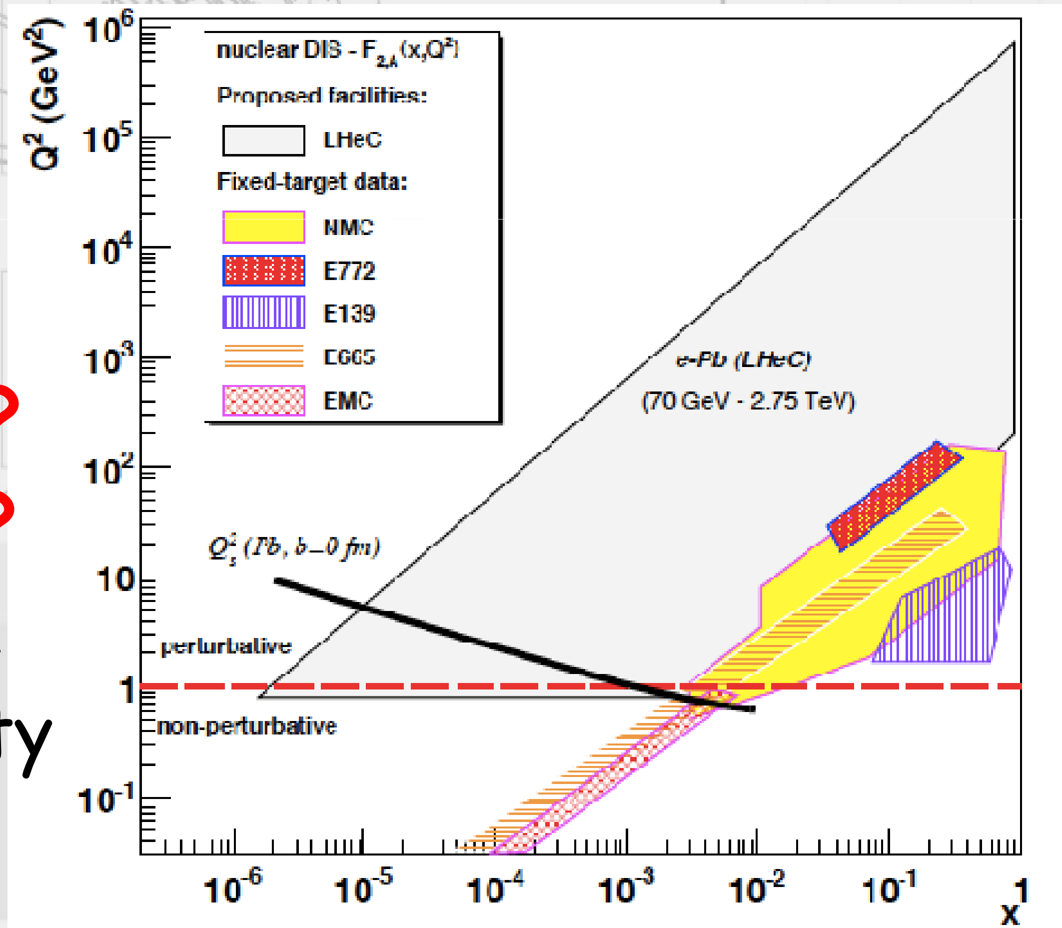


Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

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



# Beyond SM

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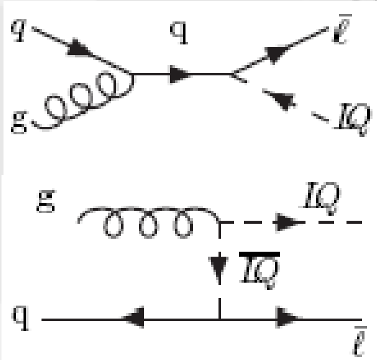
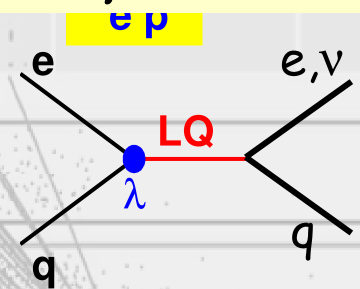
## LHC *Lq* physics +decay

## LHeC *Lq* formation+decay

**fermion number**




e+ F=0
e- F=2

**spin parity and chirality**

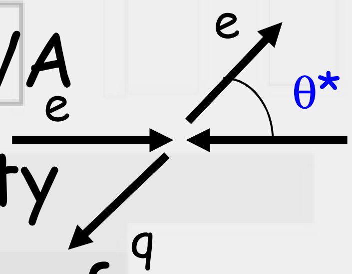
$gq \rightarrow Lq\,\bar{l}$

production mechanism ?

disentangle mass spectrum ?

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

coherence → PWA




flavour sensitivity

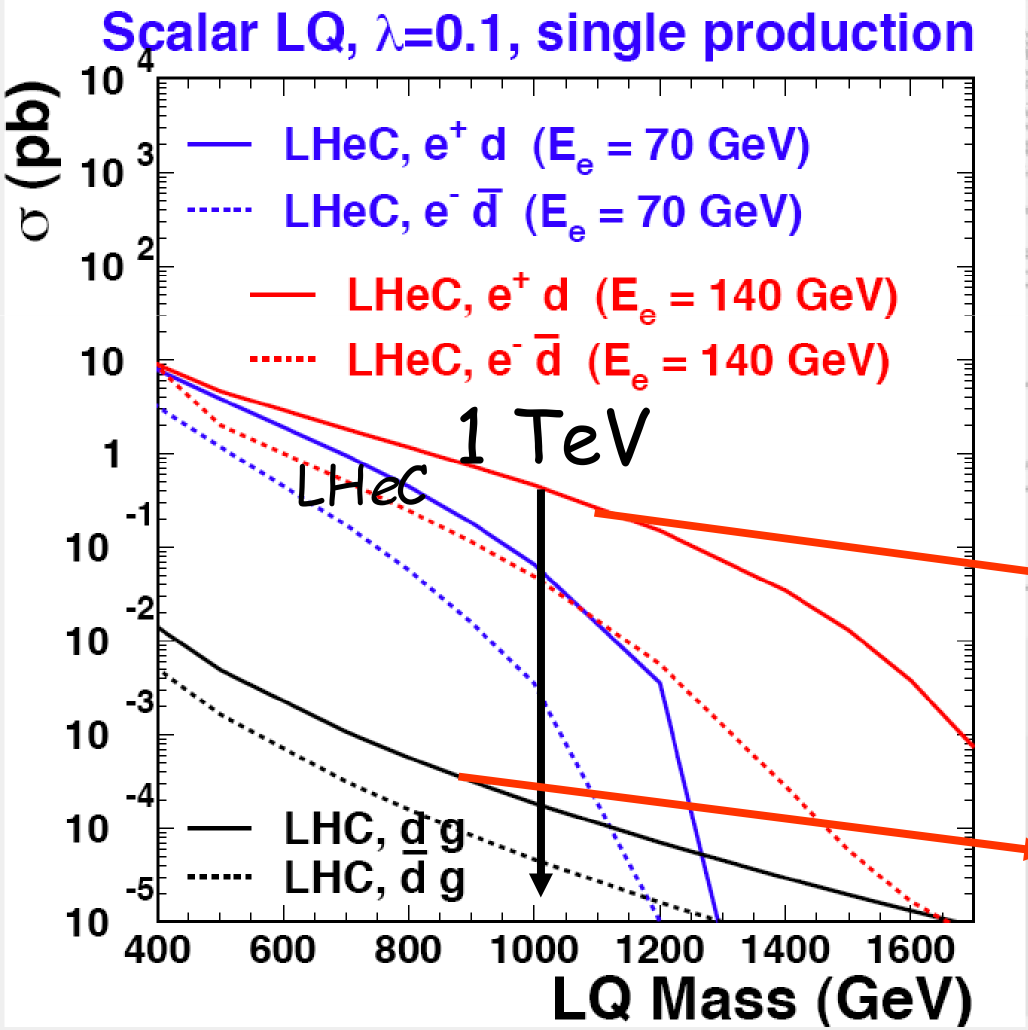
SM + signal + interference

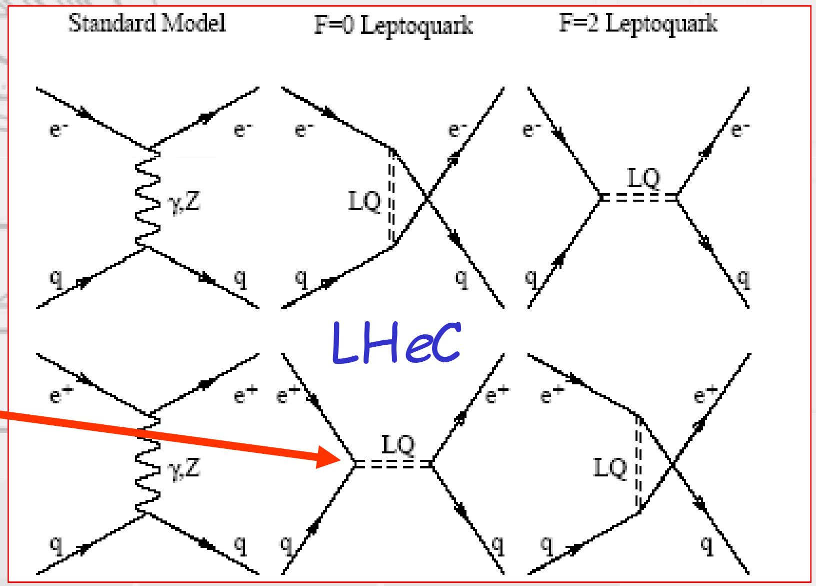
**signature** jet + leptons

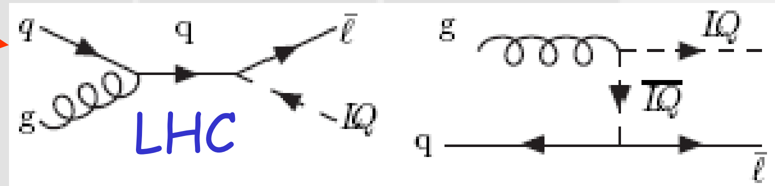
jet+lepton+$p_T$ balance
jet +$p_T$ imbalance

# Lepton+quark @ Terascale

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

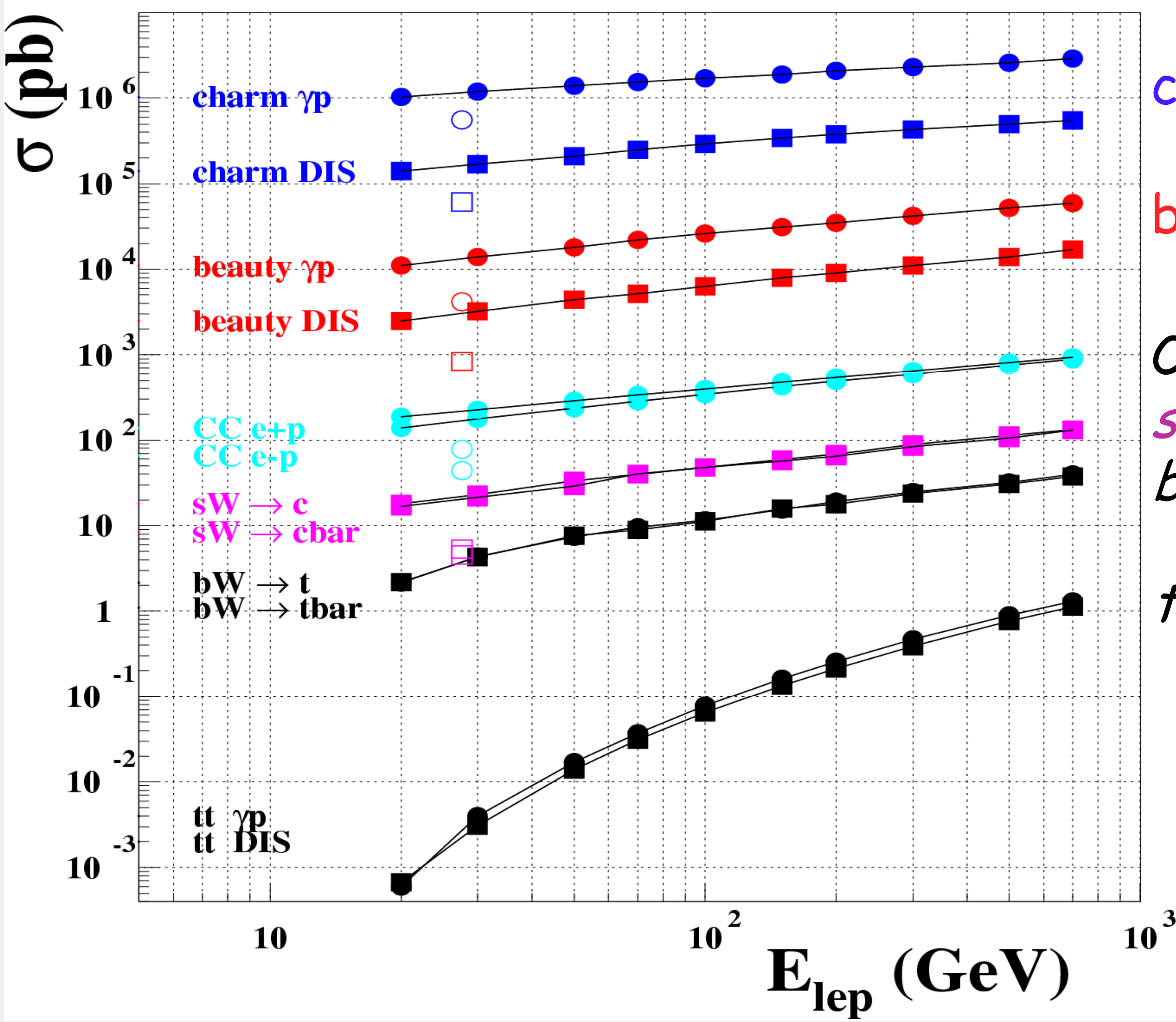


# Heavy Quark @ Terascale

- HF-scale @Terascale



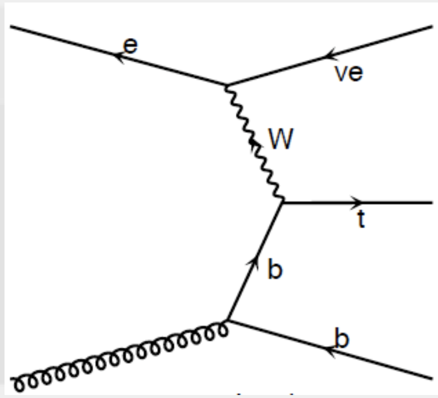

charm $[10^{10}$ / 10 $fb^{-1}]$

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

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

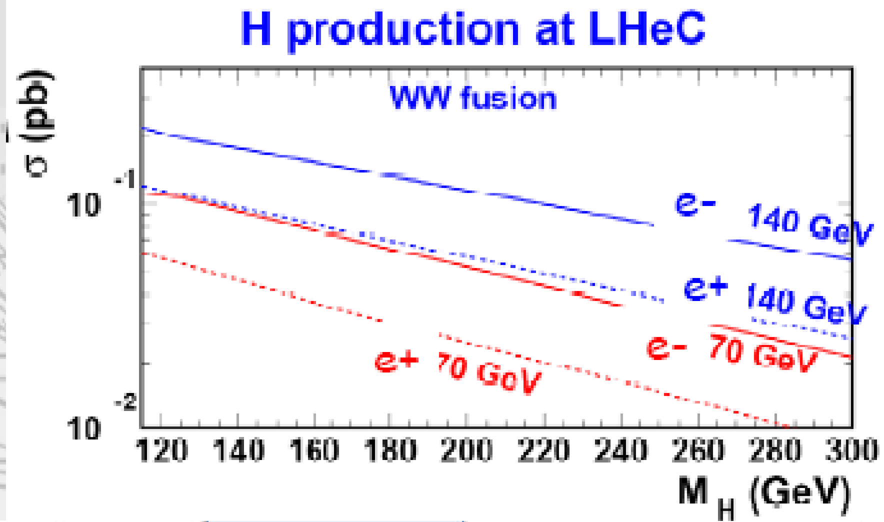
sW→ c
bW→ t $[10^5$ / 10 $fb^{-1}]$

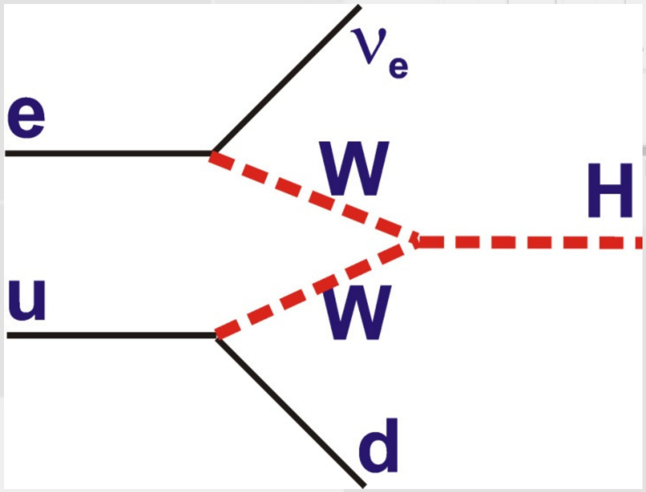
ttbar $[10^3$ / 10 $fb^{-1}]$

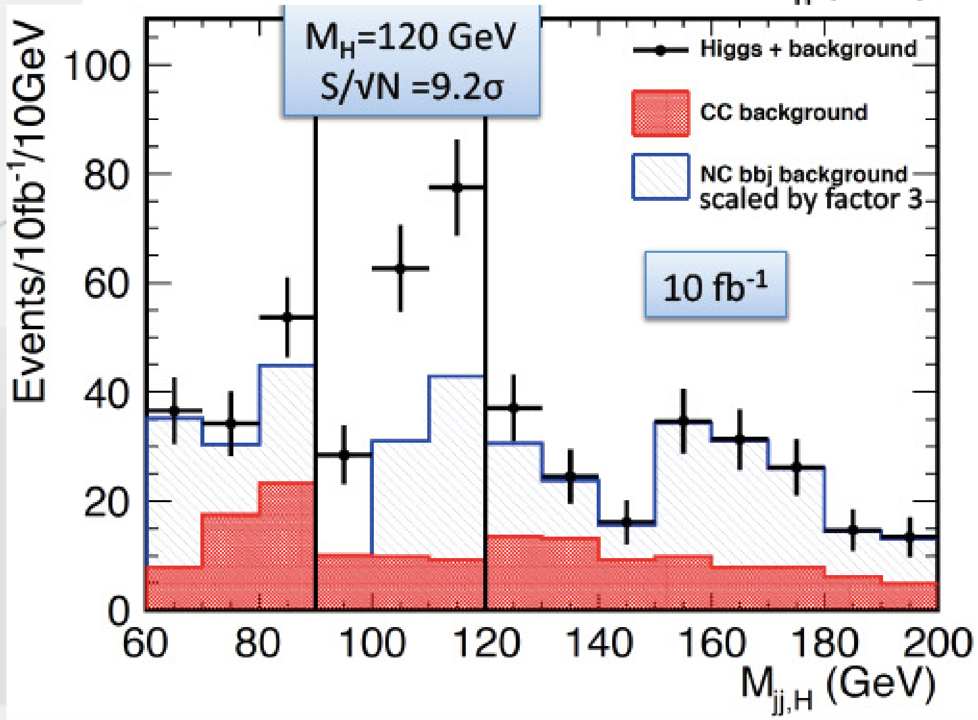


# Higgs

- $H \rightarrow b$-jets + $p_{Tmiss}$
  - few x10³/year before cuts
  - 2 $b$-tag
  - background: jets in NC top



# The Energy Frontier

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- 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

The Cockcroft Institute of Accelerator Science and Technology
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- 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

- LHeC is the terascale lepton-quark machine
  - to date only pragmatic (and cost effective) means of getting a lepton into a TeV interaction
  - unique new window on the proton … and ions
  - "upgrade of LHC" – simultaneous *pp ep* (*AA eA*)
  - exploits stupendous LHC hadron beams
  - challenges contemporary *e*-beam technology synergies (ERL, linac, low emittance rings)
  - 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

| Year | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Prototyping-testing | | | | | | | | | | |
| | | | | Production main components | | | | | | | |
| | | | Civil engineering | | | | | | | | |
| | | | | | | | | Installation | | | |
| | | | | | | | | | | Operation | |

## 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

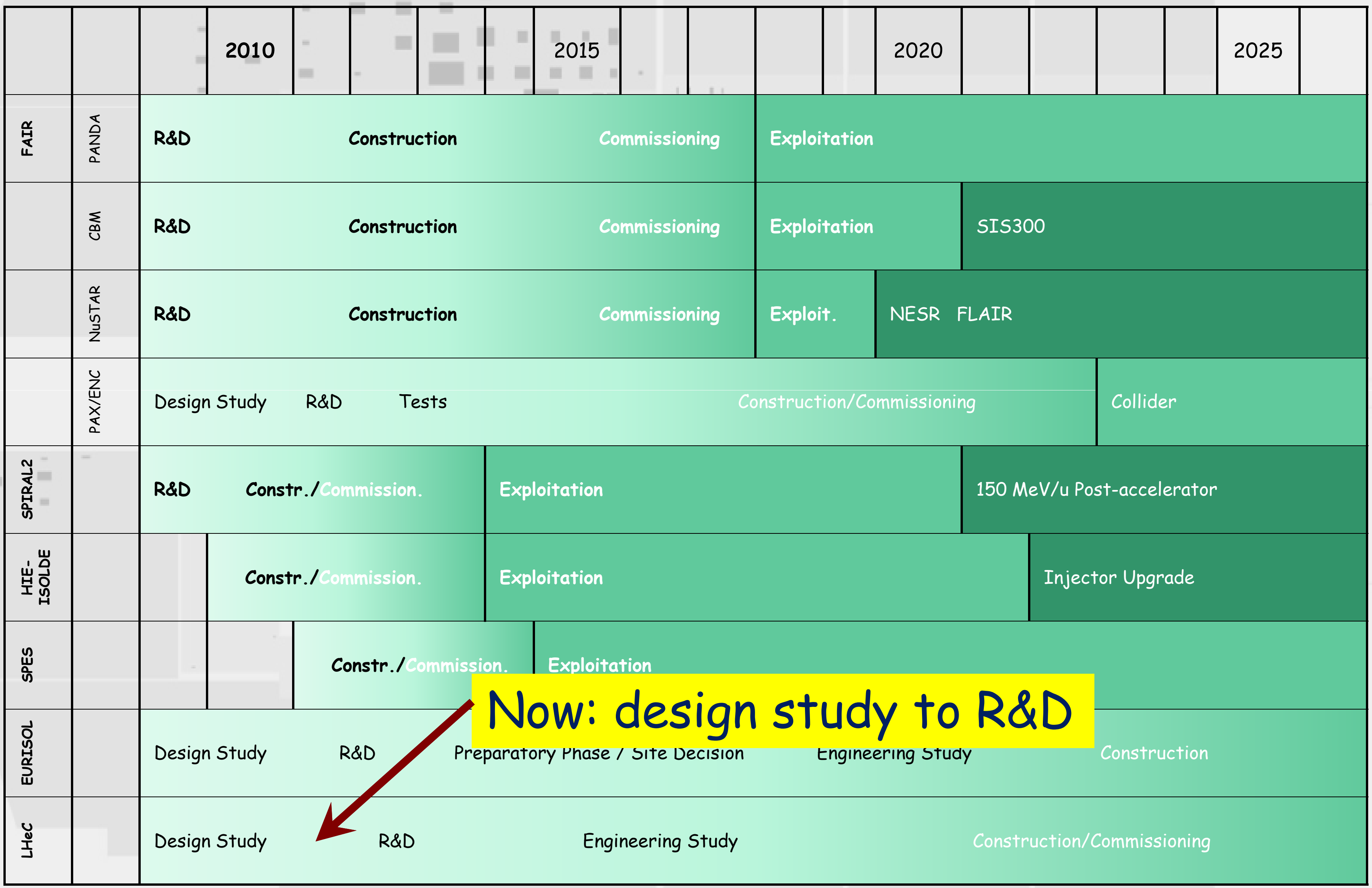
ECFA 11/2010: mandate to 2012

Seminar: Jlab and BNL
August 2011

# CERN Directorate @ EPS11

The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL

# NuPECC Long Range Facilities




G. Rosner, NuPECC Chair, Madrid 5/10 – published in December 2010

# CDR Status August 2011

DRAFT 0.95
July 29, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-001 GEN

## A Large Hadron Electron Collider at CERN

### Report on the Physics and Design Concepts for Machine and Detector

**LHeC Study Group**

THIS IS THE VERSION FOR THE AUTHORS TO CHECK PRIOR TO REFEREEING

# LHeC organisation

## Scientific Advisory Committee

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Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell -chair (MPI Munich)
Swapan Chattopadhyay (Cockcroft)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (CERN)
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Roland Horisberger (PSI)
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Stefano Forte (Milano)
Max Klein - chair (Liverpool)
Paul Laycock (secretary) (L'pool)
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**Accelerator Design [RR and LR]**
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**Interaction Region and Fwd/Bwd**
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Pierre van Mechelen (Antwerpen)
**Detector Design**
Peter Kostka (DESY),
Rainer Wallny (U Zurich),
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**New Physics at Large Scales**
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**Precision QCD and Electroweak**
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Claire Gwenlan (Oxford)
**Physics at High Parton Densities**
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Energy Recovery
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http://www.ep.ph.bham.ac.uk/exp/LHeC/