John Dainton
September
2007

CAS07
Cockcroft
Institute

Accelerator Physics

THE COCKCROFT INSTITUTE of
ACCELERATOR SCIENCE AND TECHNOLOGY

John Dainton
Cockcroft Institute and
University of Liverpool, GB

1. Welcome
2. Accelerator Physics History … and Pedigree
3. The Energy Frontier 2007
   - what and how we know
4. Detection – how and why?
5. How we learn with data
6. Discovery
7. Onwards
8. Conclusion

A personal perspective at the CERN Accelerator School 2007 at the Cockcroft Institute after 35 years as an experimentalist!

John Dainton
September
2007

THE COCKCROFT INSTITUTE *of*
ACCELERATOR SCIENCE AND TECHNOLOGY

http://www.cockcroft.ac.uk/

CAS07
Cockcroft
Institute

1. Welcome

LANCASTER UNIVERSITY

UNIVERSITY OF LIVERPOOL

The University of Manchester
MANCHESTER 1824

Northwest
REGIONAL DEVELOPMENT AGENCY

Science & Technology Facilities Council

John Dainton
September
2007

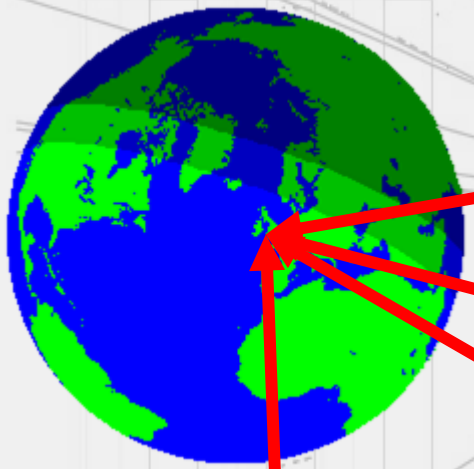
Science "Driver"

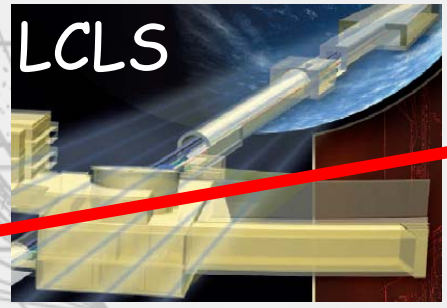
CAS07
Cockcroft
Institute

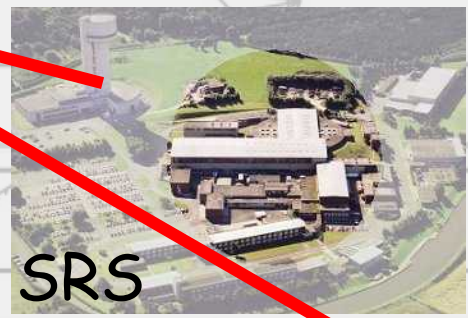
High Energy Physics

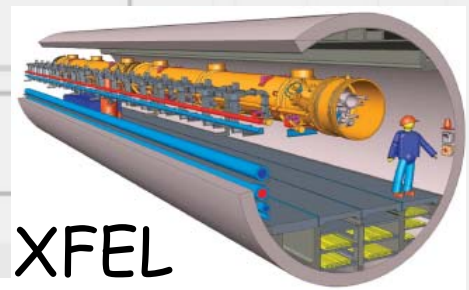
- global
- UK membership

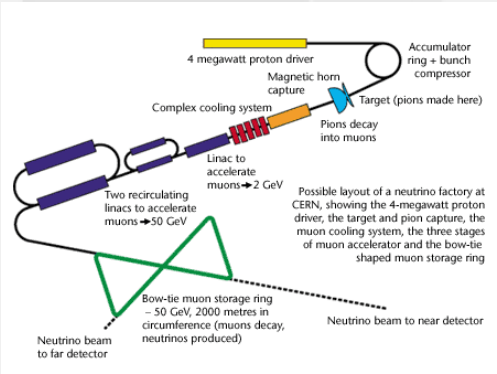
"light fantastic"



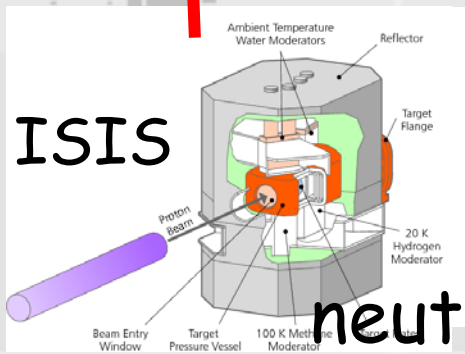








ν-Factory



ISIS

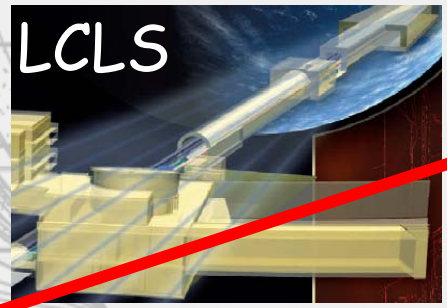
neutrons

R&D Challenge …

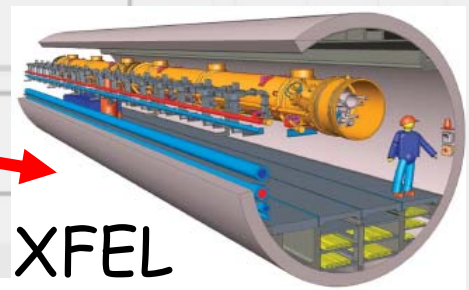
High Energy Physics

- global
- universal
  - MV/m
  - intensity
  - nm delivery

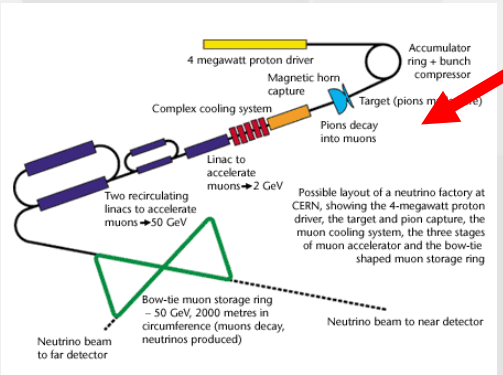
"light fantastic"



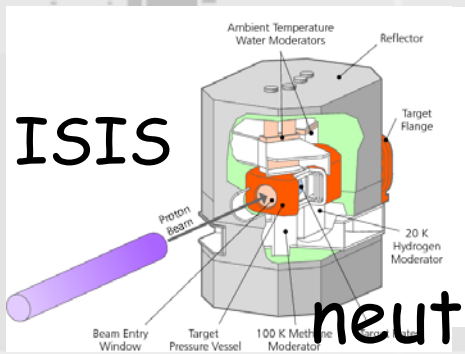
Cockcroft Institute



XFEL



ν-Factory



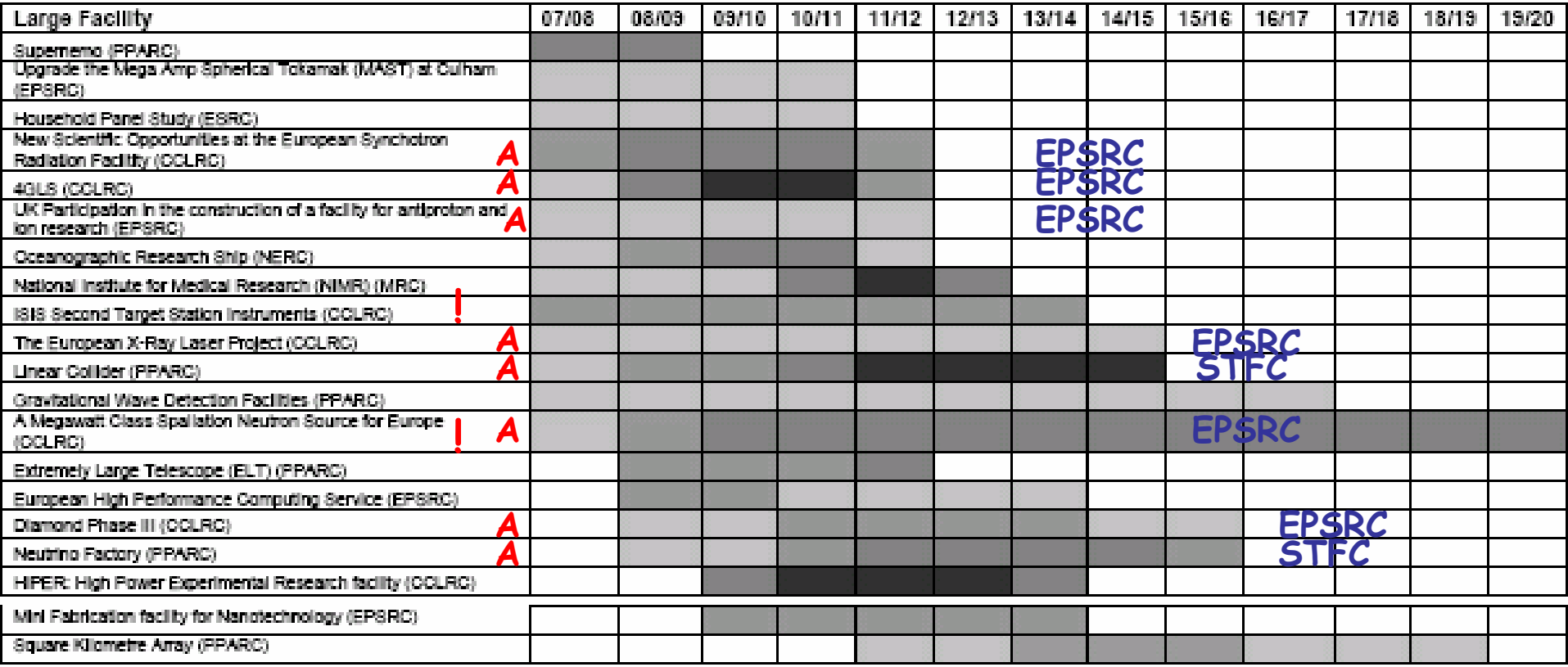
neutrons

John Dainton
September
2007

… for tomorrow's science

CAS07
Cockcroft
Institute

- RCUK prioritisation to come (SR07) ?



! SNS (1 MW) from 2007

! JPARC (1 MW) from 2009/10 ?

EPSRC science

STFC science

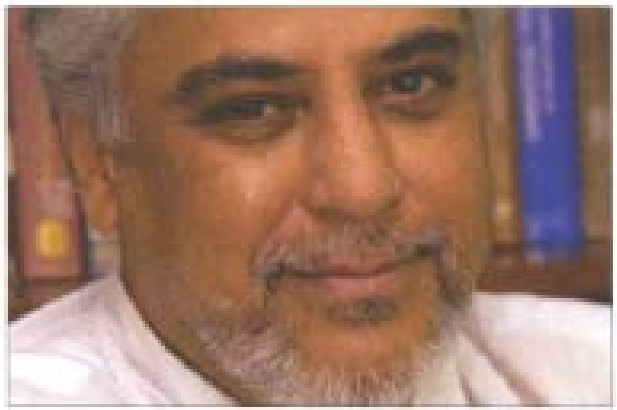
A accelerator science and technology

Director

- there are three C's in CoCkCroft !

. . .while Chattopadhyay moves to Crockcroft

Swapan Chattopadhyay, currently associate director of Jefferson Lab, is to become the inaugural director for the newly created Crockcroft Institute – one of the UK's two new centres for accelerator science and technology. In addition, the universities of Lancaster, Liverpool and Manchester have made him the first chair of Accelerator Physics in the UK. He will take up his new position in March.



These new appointments reflect Chattopadhyay's contributions to phase space cooling, innovative particle colliders, novel synchrotron-radiation production and ultra-short femtosecond X-ray sources. His achievements also include the development of postgraduate education in accelerator physics and engineering and a number of successful industrial collaborations with hi-tech commercial partners.

... but two R's ? !

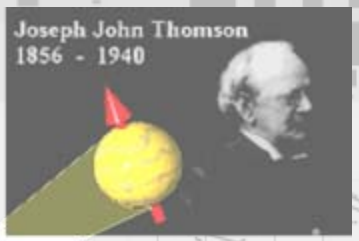
CERN Courier

2. History … and Pedigree

John Dainton
September
2007

CAS07
Cockcroft
Institute

Engauging Matter

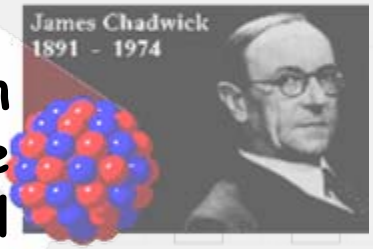


electron

Cambridge

nucleus

Manchester



neutron

Cambridge

Liverpool

SLAC
1969

quark

Pasadena

[click auf Bilder für Film]

Stanford

400BC

By convention there is colour,
by convention sweetness,
by convention bitterness,
but in reality
there are atoms, and space.

Democritus ~400BC

2007

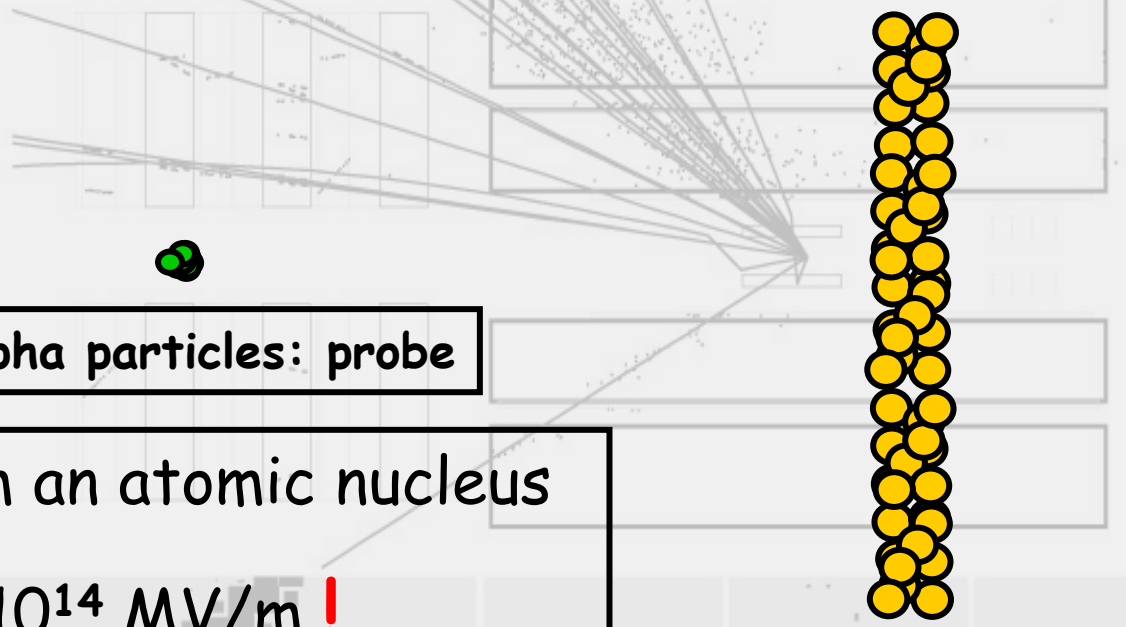
Standard Model of the Universe ? Fundamental particles of matter

The first Accelerator

- matter @ MeV scale: the discovery of the "point-like" atomic nucleus

Marsden and Rutherford, Manchester 1909

rare



Alpha particles: probe

MeV from an atomic nucleus

~ 10^{14} MV/m !

Ultra thin Gold foil: target

- **large** energy transfer Q
- **large** scattering angle

$\sigma \sim 1/Q^4$

Rutherford Scattering

Manchester: the discovery of the "point-like" Atomic Nucleus

"… something like that of a cat delivering a choice mouse to his mistress."

Ernest Marsden FRS
when a PhD student, describing his feelings reporting the discovery of the atomic nucleus to his supervisor Ernest Rutherford at Manchester University
(from Rutherford Memorial Lecture, Royal Society London, 1954)

"… quite the most memorable event that ever happened to me in my whole life."

Ernest Rutherford, 1909
then Professor of Physics at Manchester University

England: the birthplace of Experimental High Energy Physics

"It would be of great scientific interest if it were possible in scientific experiments to have a supply of electrons and atoms in general, of which the individual energy of motion is greater even than that of the alpha particle. This would open up an extraordinarily interesting field of investigation which could not fail to give us information of great value, **not only in the constitution and stability of atomic nuclei, but in many other directions.**"

Professor Sir Ernest Rutherford PRS
(formerly Professor of Physics at Manchester University
later Cavendish Professor of Physics at Cambridge University
and Lord Rutherford FRS)
at the Royal Society, London, 30th November 1927

"Information of great value"

- Why a positively charged, massive, nucleus and negatively charged, light, electron cloud ?
- Are nuclei and electrons fundamental ?
  If not, do they have substructure ?
- What new physics is beyond the Periodic Table ?
- Why are some atoms radioactive ?
- Are there new particles and forces at play in atoms ?

Cambridge: splitting the atom

- splitting the atom 14th April 1932
  the birth of the energy frontier
  - 800 KeV p + Li → He + He fundamental

John Cockcroft

b. Todmorden (Lancs and Yorks!)
ed. Manchester Univ (Maths)
Manchester College of Technology (Elec. Eng.)
Metropolitan-Vickers, Manchester
PhD then post-doc Cambridge Univ.

Ernest Walton

ed. TC Dublin, MSc hydrodynamics
PhD student, Cambridge Univ.

Li

Cambridge: splitting the atom … with NW England's industry

"The facts are that we looked first for gamma rays and not alpha particles, since at that time we had a fixed idea that gamma rays would be the most likely disintegration products."

Sir John Cockcroft FRS 1938

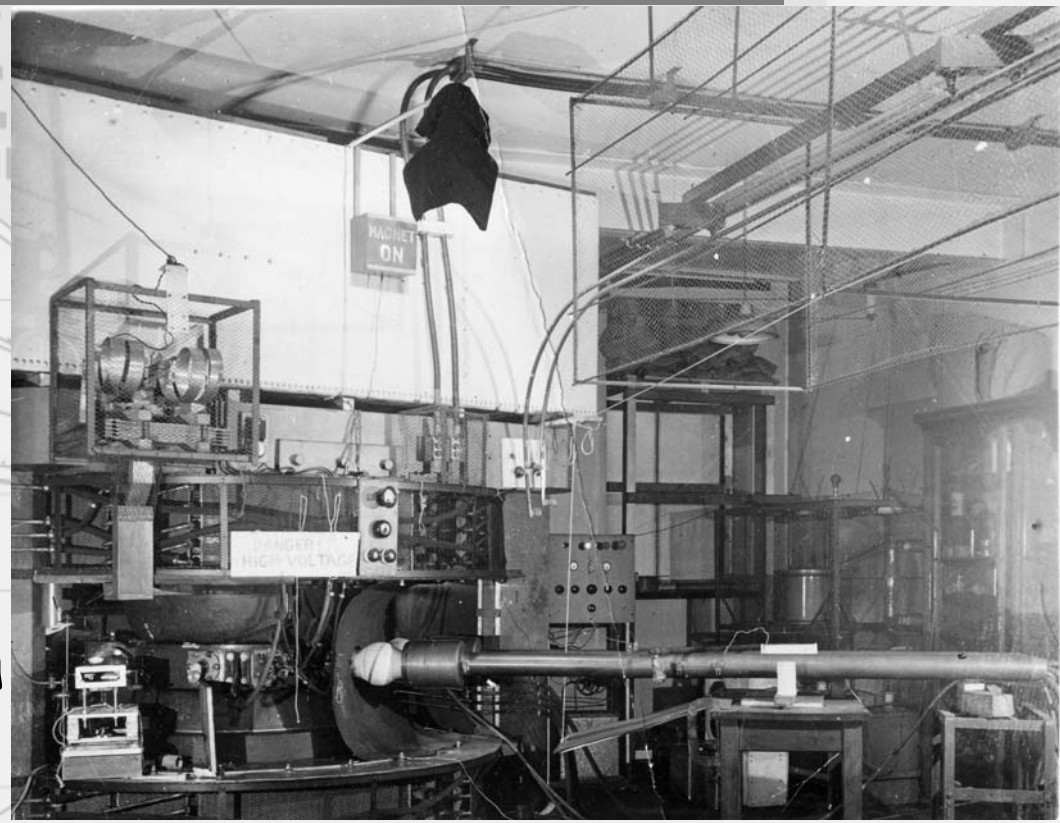
"… a singularly modest and self-effacing life."

C P Snow on John Cockcroft in "Physicists"

"… they were fortunate to have the support of Metropolitan Vickers: … the Manchester company."

B Cathcart in "The Fly in the Cathedral"

Synchronous Acceleration rget



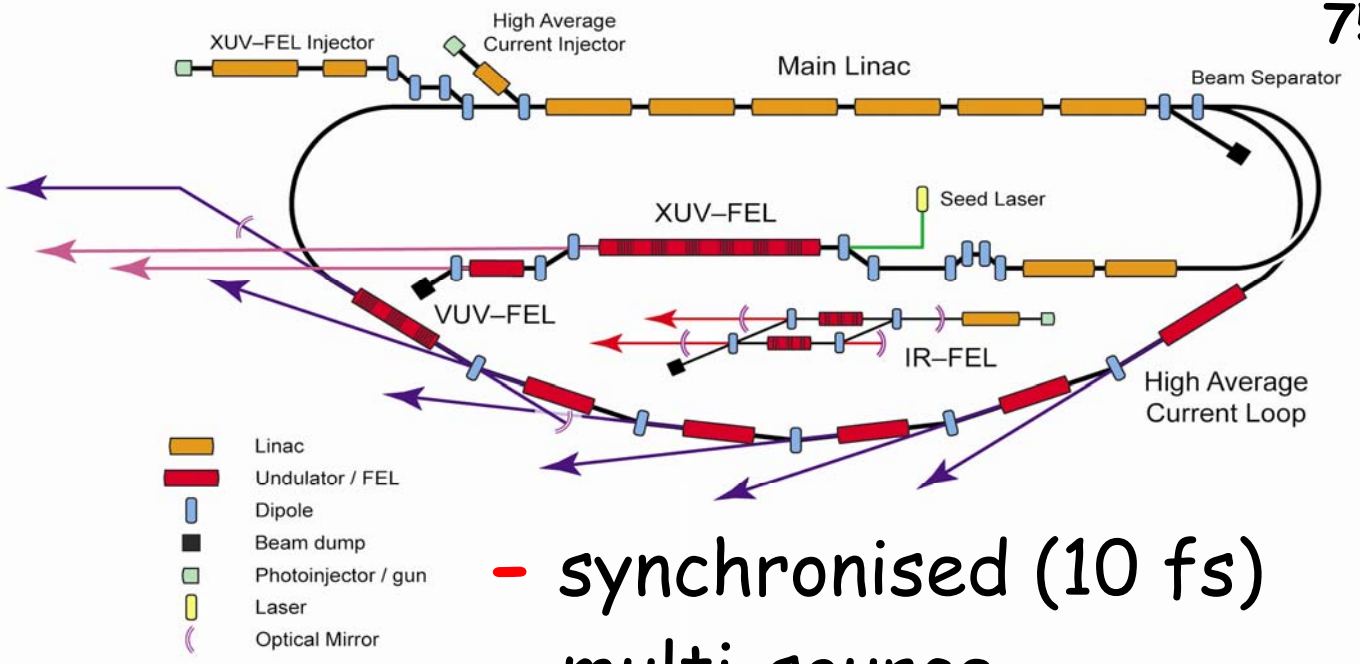
- NW England (again)
  James Chadwick era
- Liverpool cyclotron
  - first outside US?
  - cross sections for Manhattan
  - Liverpool Physics in Downing Street !

↳ Liverpool synchrocyclotron "Metro Vick"
- first extracted beam 1955 Crewe and Gregory

↳ NIMROD (p) and NINA (e) synchrotrons
CERN (p) PS, SPS, DESY, SLAC, BNL, Fermilab …

Next Generation Light: 4GLS energy storage ring

600 MeV, 100 mA
750-950 MeV, 1 kA



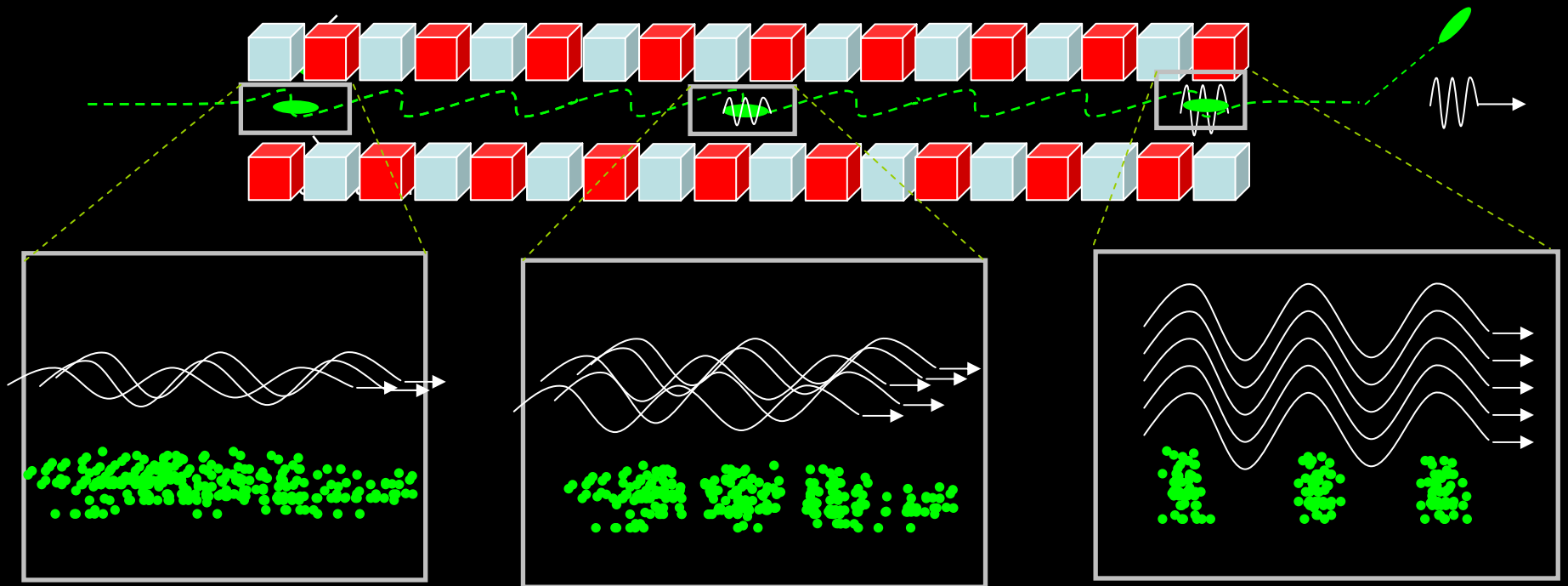
Scope under
(cost) review
Daresbury 2012?

- synchronised (10 fs)
- multi-source
- IDs
- FELs

- energy storage and manipulation ring

Next Generation Light: Free Electron Laser

- electrons bunched at photon wavelength
  - intense pulsed fs radiation



Random electron phase
incoherent emission

Electrons bunching:
coherence growing

Electrons bunched at radiation wavelength:
coherent emission and saturation

The Energy Frontier: Colliders

- 1970s: CERN

  Intersecting Storage Rings (ISR)

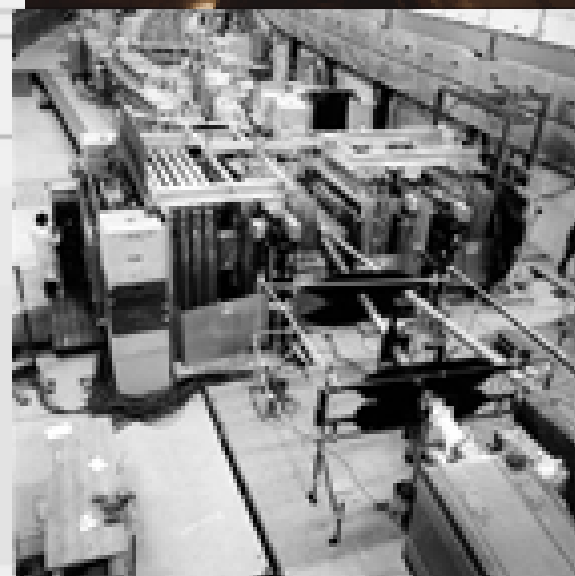
$$p_1 \longrightarrow s \longleftarrow p_2$$

$$s = (p_1 + p_2)^2 = m_1^2 + m_2^2 + 2p_1 \cdot p_2$$

$$\rightarrow 4P_1P_2$$

$$= (63\ \mathrm{GeV})^2$$

- efficient beam crossing

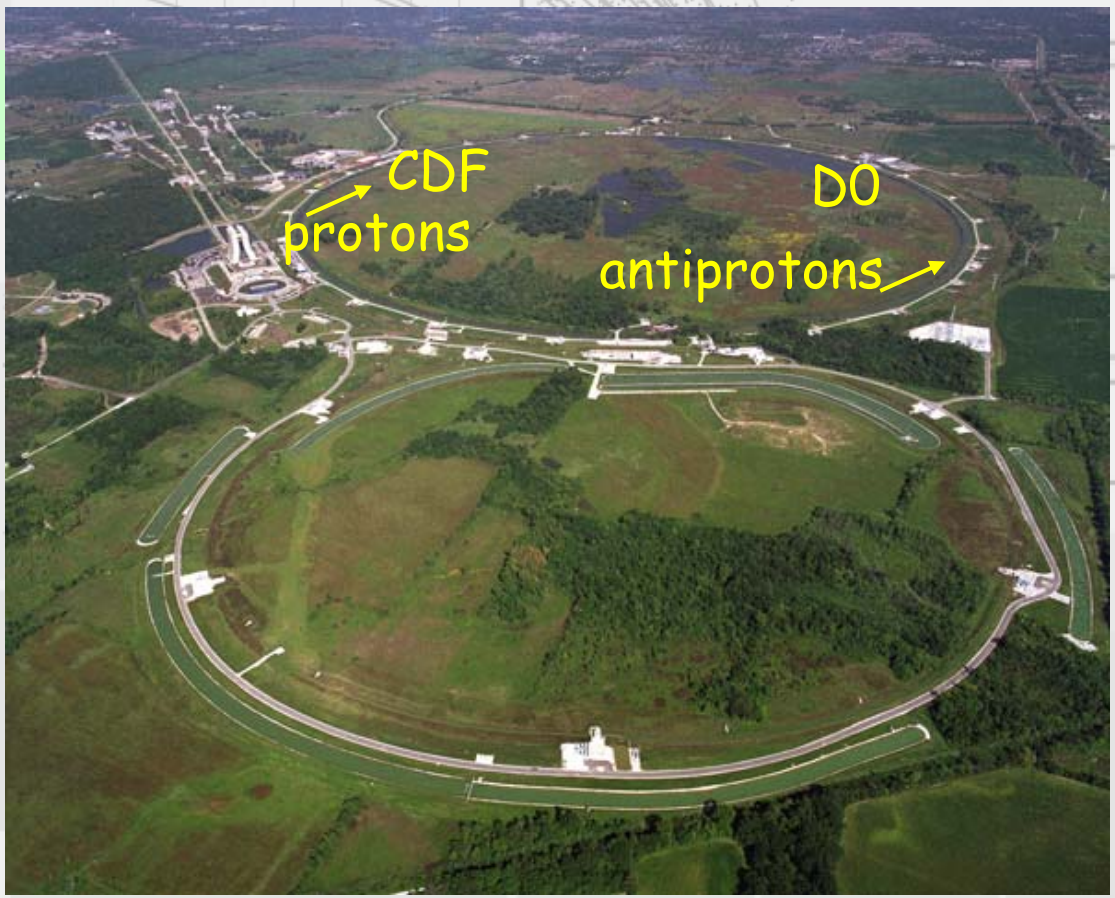


A "100 GeV" scale Collider
TeVatron @ Fermilab

- accelerate beams to "head-on" collision
  1 TeV antiprotons + 1 TeV protons

uud +sea

$\bar{u}\bar{u}\bar{d}$ +sea



TeVatron
Fermilab
Nr Chicago

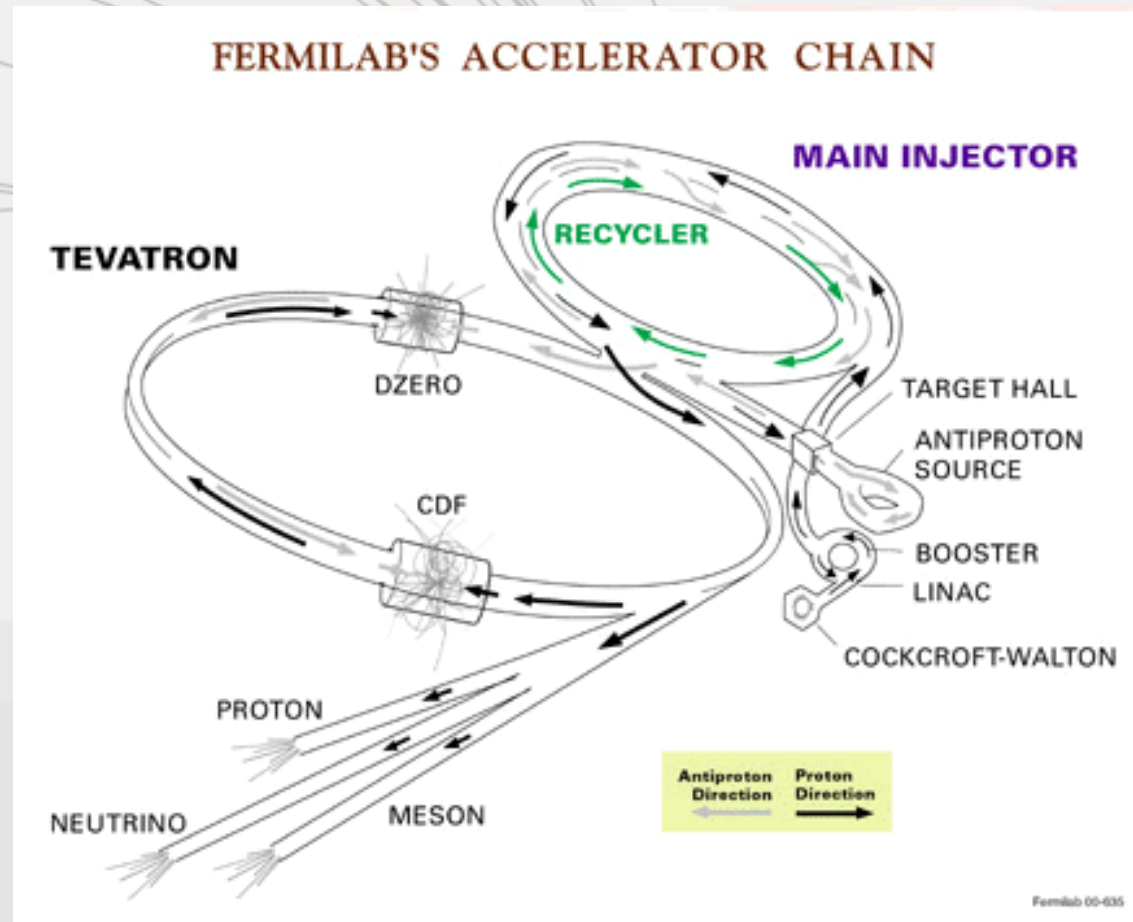
2 TeV cms

A "100 GeV" scale Collider
TeVatron @ Fermilab

- challenge: antiproton intensity

TeVatron
Fermilab
Nr Chicago

2 TeV cms



John Dainton
September
2007

A "100 GeV" scale precision Collider HERA @ DESY

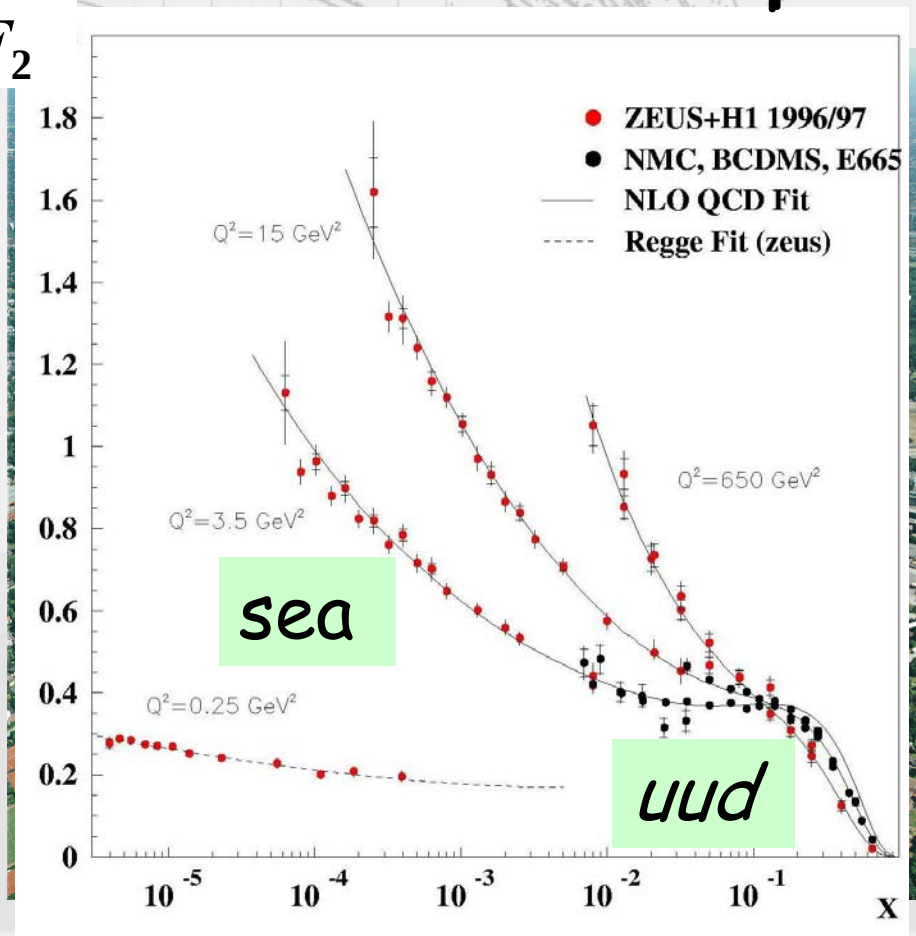
CAS07
Cockcroft
Institute

- ~~challenge: different "particle species"~~ accelerate beams to particle collision

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

lepton

F_2



HERA
DESY
Hamburg

0.32 TeV
cms

1992-2007
RIP

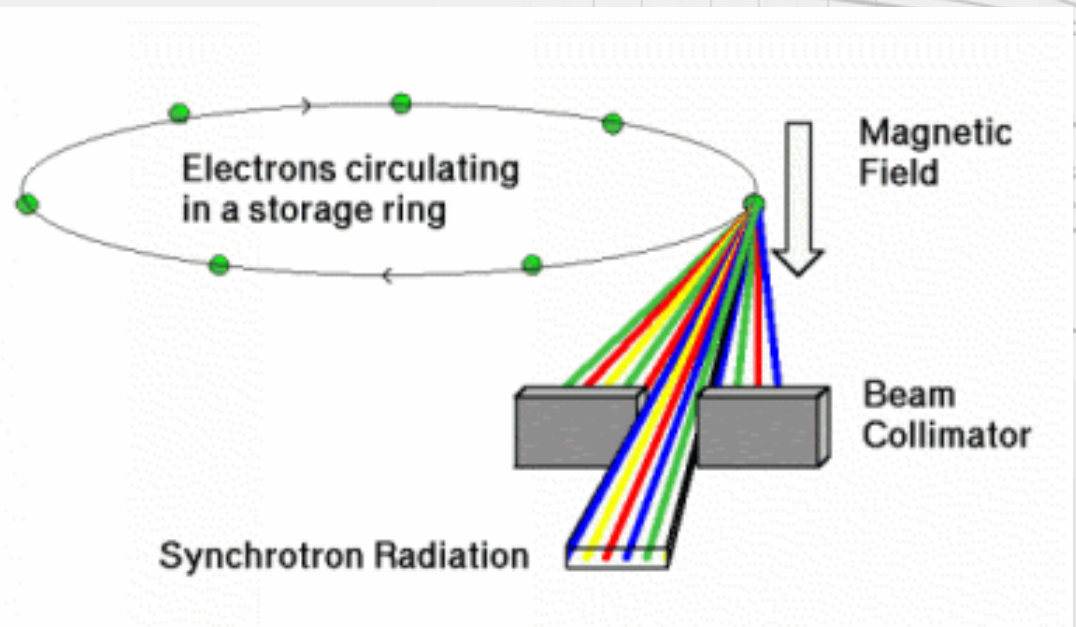
Synchrotron Radiation

- radiated power = $\frac{2Ke^2\gamma^4 c}{3r^2}$

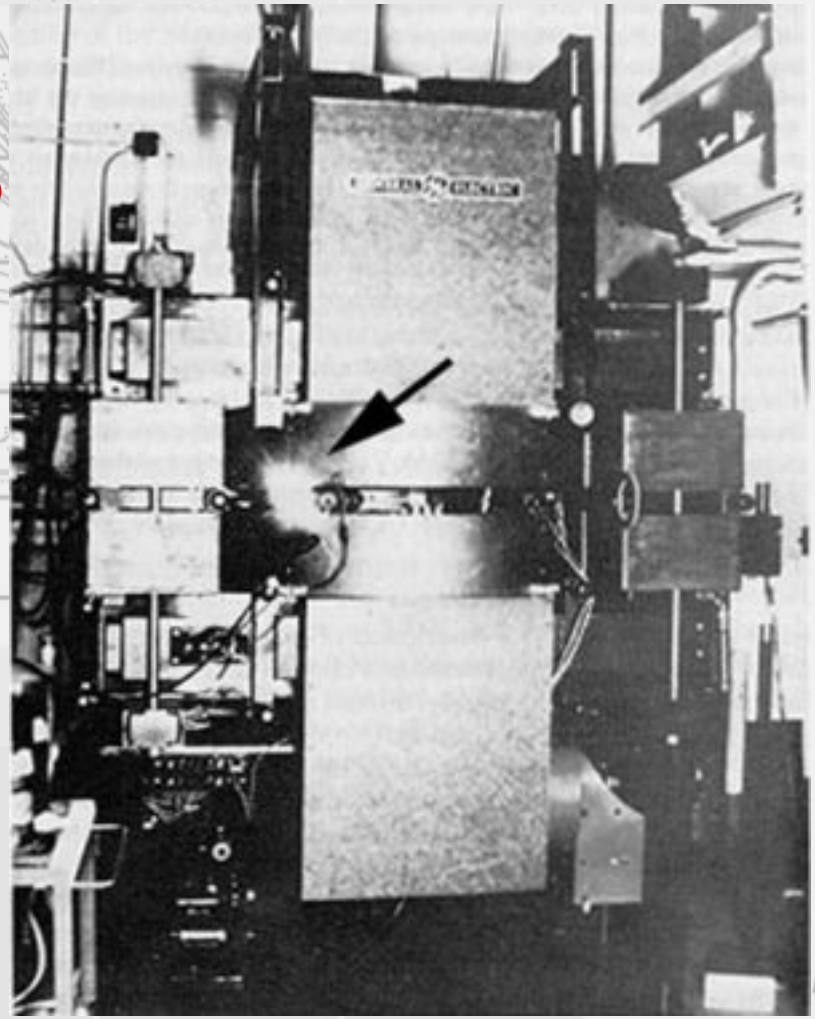
  3.5 GeV $e \cong$ 7 TeV p

  4 mT $e \cong$ 8 T LHC p

- dynamics including radiation?



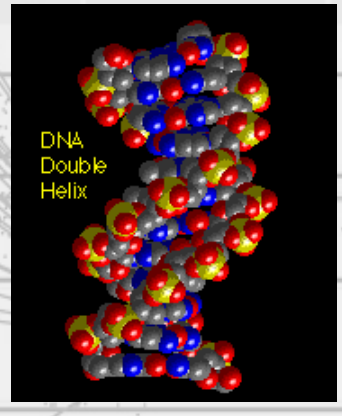
1946



- sub-atomic radiation

Spin off: tunable sub-atomic radiation

- accelerate electrons and "store"
  - ↳ synchrotron radiation
    IR visible UV *X*-ray
    - ↳ structure



"light source"

Rotating Spin

- stored e radiates

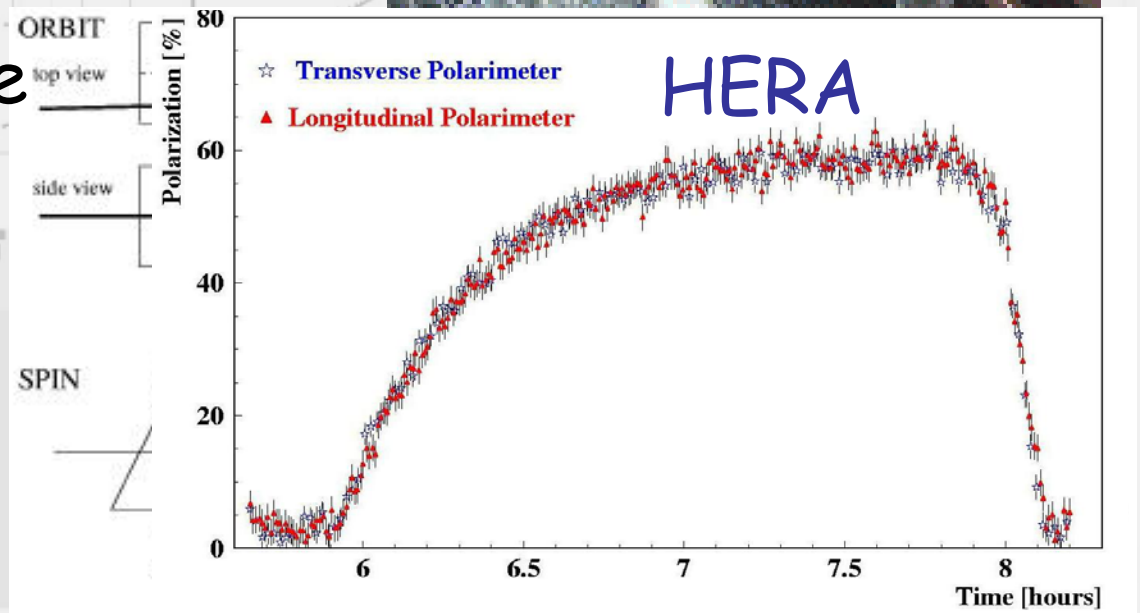
  $e \rightarrow e_T$

  transversely polarised e

  synchrotron radiation

- "spin-rotator"
  - subtle and precise precession

    $e_T \rightarrow e_{RL} \rightarrow e_T$
  - "Siberian snake" insertion device



John Dainton
September
2007

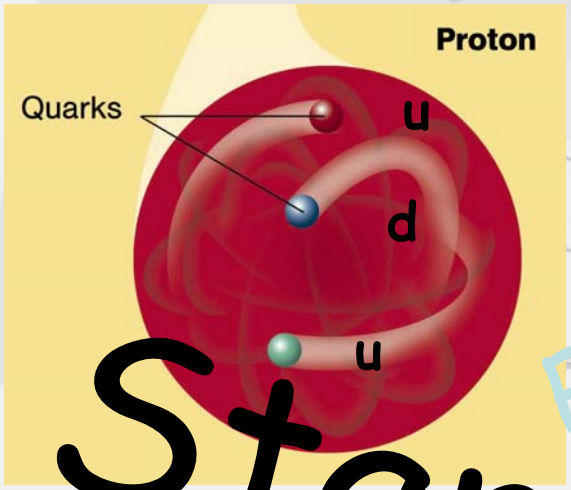
3. The Energy Frontier 2007 - what and how we know (and spin-off)

John Dainton
September
2007

Matter @ 100 GeV scale

CAS07
Cockcroft
Institute

0.2 TeV e^+e^- 0.3 TeV ep 2 TeV pp cms



proton is *uud*

mass is quarks + binding energy

small large

chromodynamics → weight!

$E=mc^2$

Standard Model

	100 MeV	1.5 GeV	charge	
	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} b \\ t \end{pmatrix}$	+ 2/3 / - 2/3
mass →				
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$	-1 / 0
	0.5 MeV	0.1 GeV	1.5 GeV	

quarks

leptons

gauge bosons

gluon

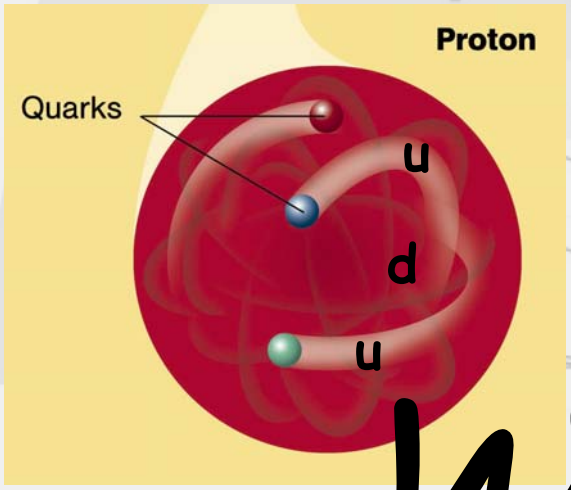
W^+ W^-

John Dainton
September
2007

Matter @ 100 GeV scale

CAS07
Cockcroft
Institute

0.2 TeV e^+e^- 0.3 TeV ep 2 TeV pp cms



Standard Model

a 20th century triumph
short-distance structure of matter

$(\hbar c = 200\ \text{MeV.fm})/175000 = 0.001\ \text{fm}$

Whither?

100 MeV 175 GeV charge

$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$ $+\frac{2}{3}$ $-\frac{1}{3}$ quarks L-handed

gauge bosons

gluon QCD

γ W Z QFD

mass →

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$

? eV 1.5 GeV

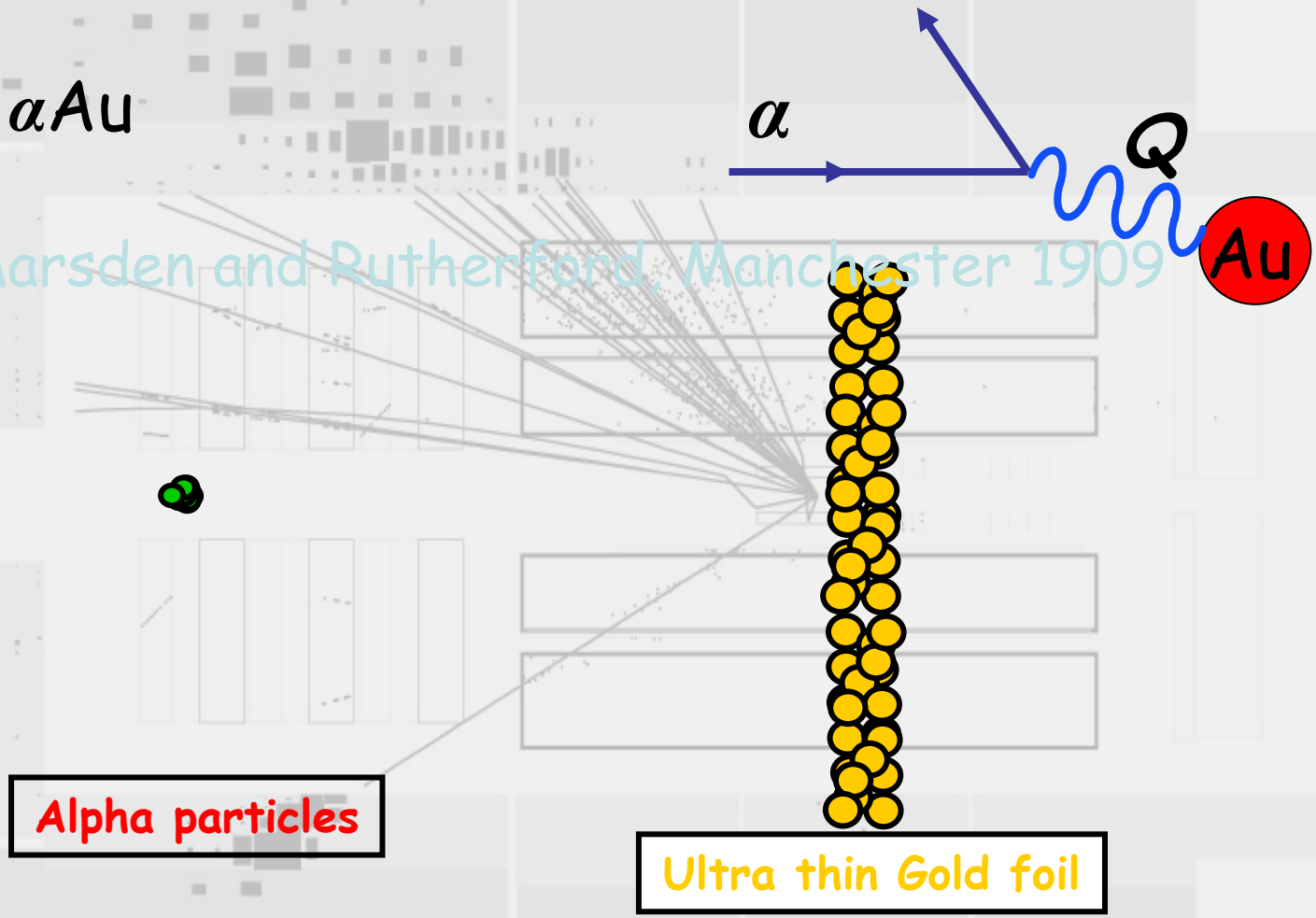
leptons
L-handed

Higgs?

gauge theory

Rutherford Scattering

- $\alpha Au \rightarrow \alpha Au$

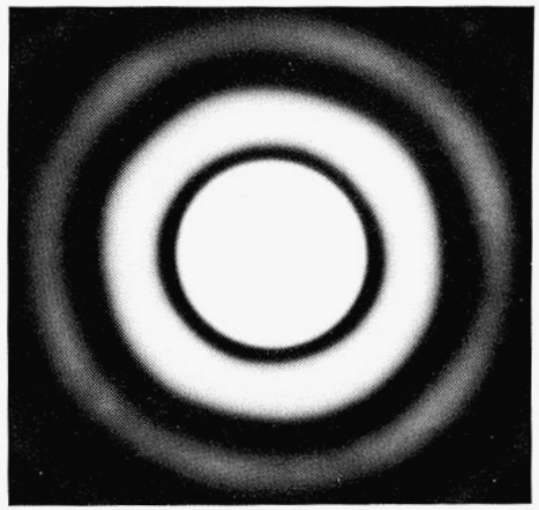


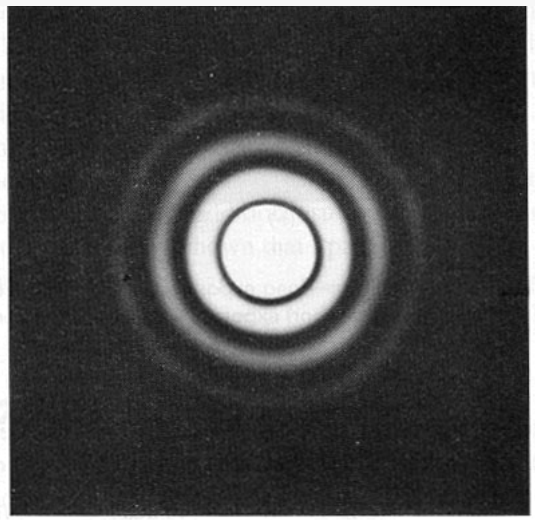
- **large** energy transfer Q
- **large** scattering angle

$$\sigma \sim 1/Q^4$$

(Photon) Diffraction

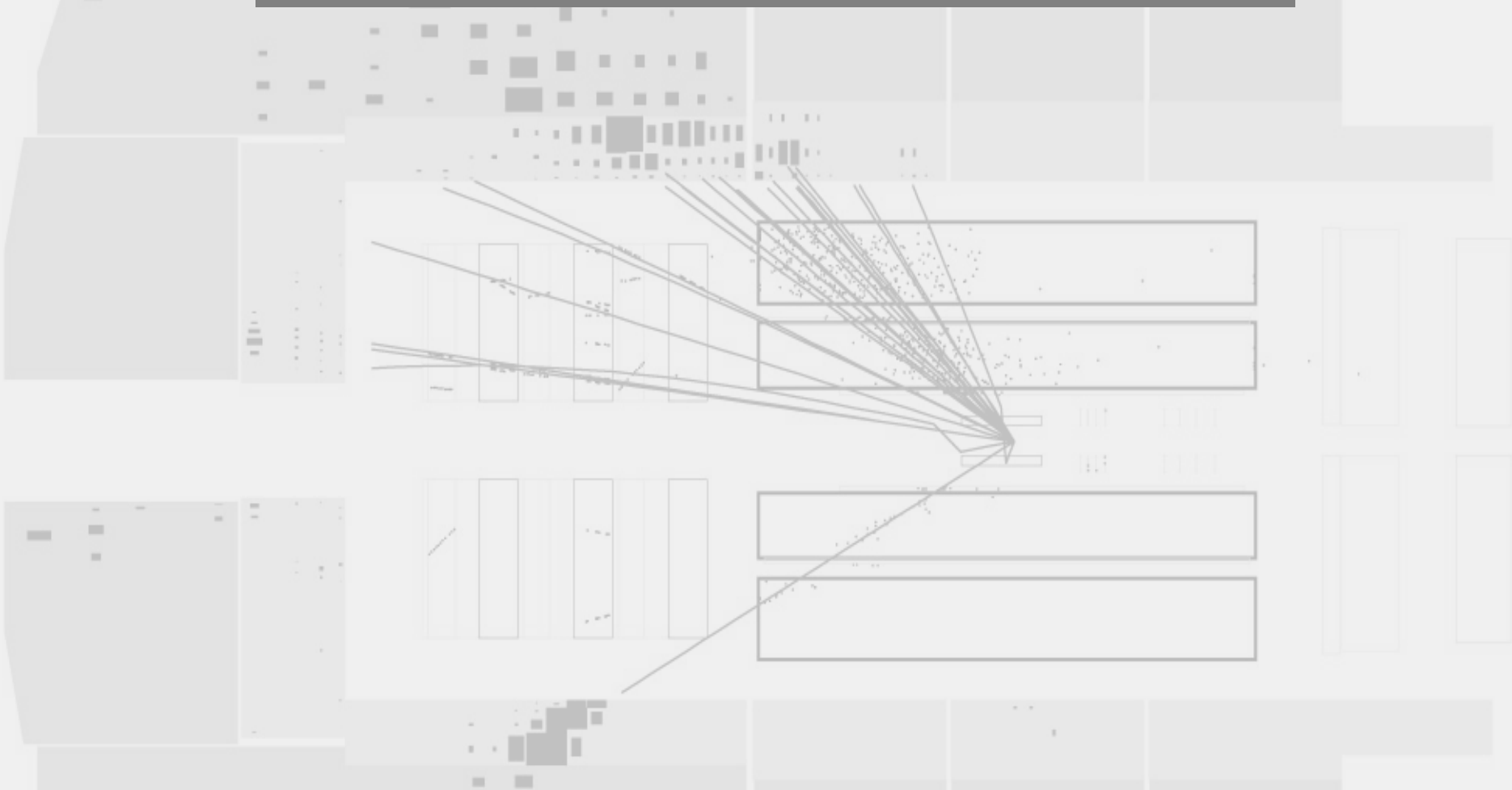
- light (photons) scattered by large disc
  - darker @ wider angle
  - less scattering @ large angle
  - larger target (less point-like)
    → less large angle scattering
- light (photons) scattered by small disc
  - brighter @ wider angle
  - more scattering @ large angle
  - smaller target (more point-like)
    → more large angle scattering





↳ large angle (large Q) scattering ← small target

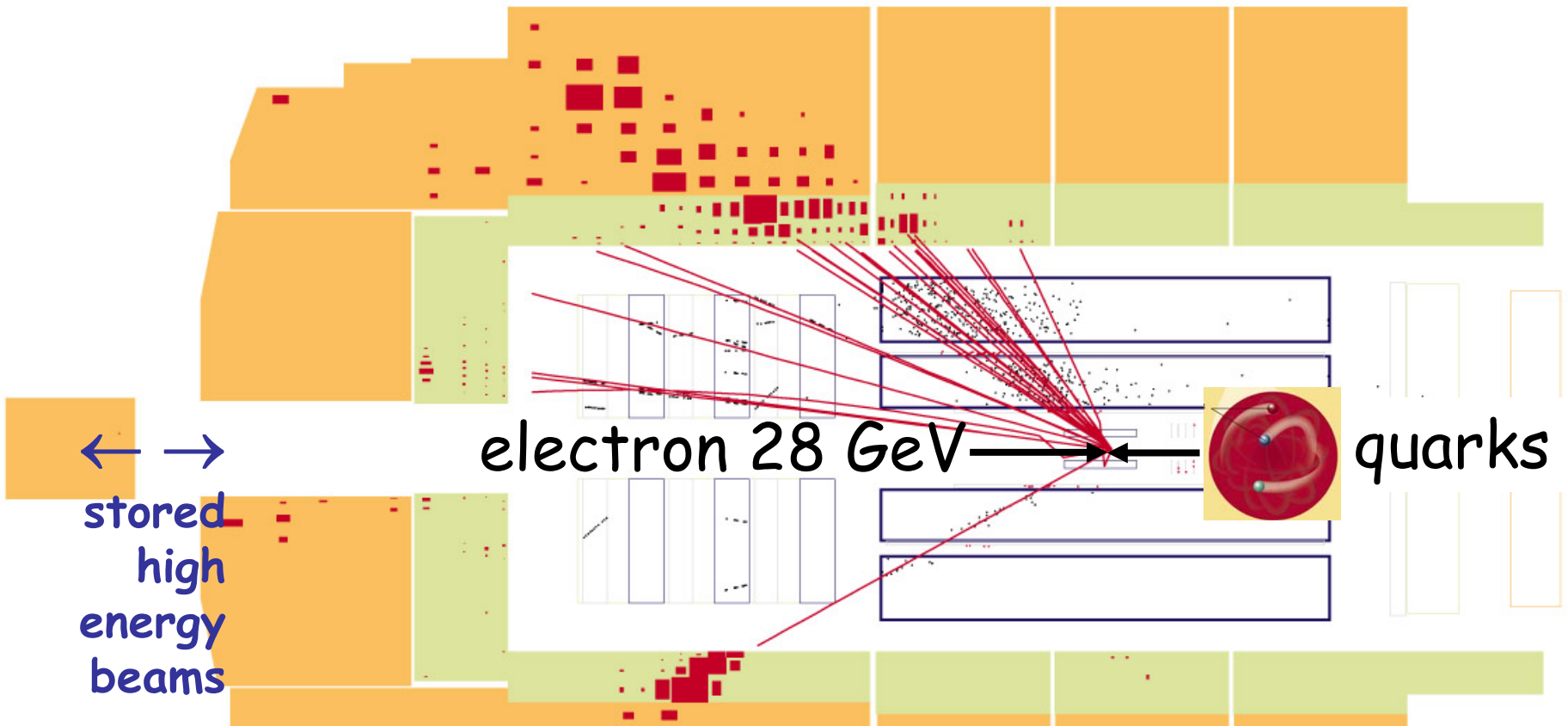
Rutherford Scattering



- **large** energy transfer Q
- **large** scattering angle

$$\sigma \sim 1/Q^4$$

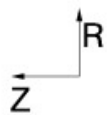
20th Rutherford Scattering



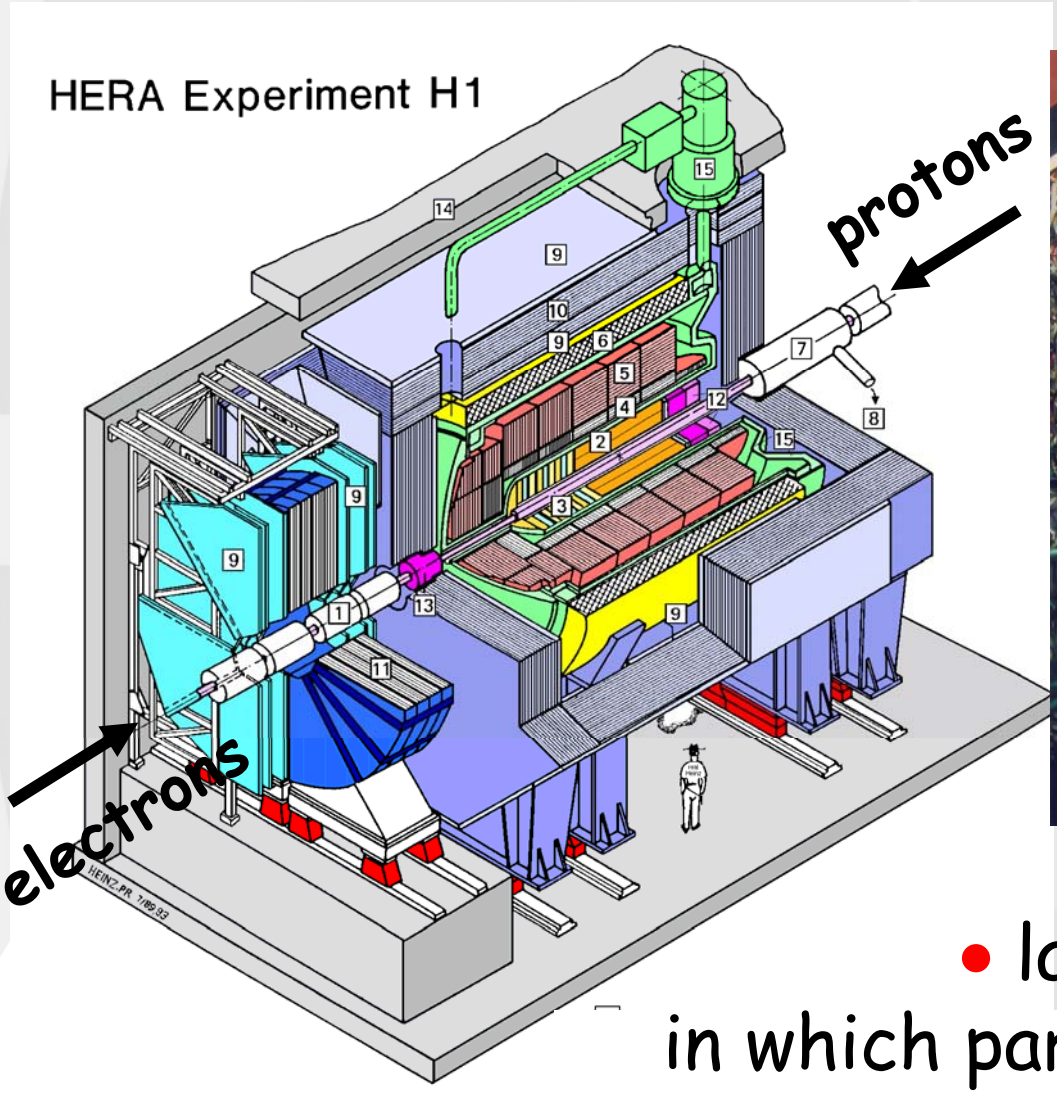
engauging leptons and quarks
at highest energy = shortest distance

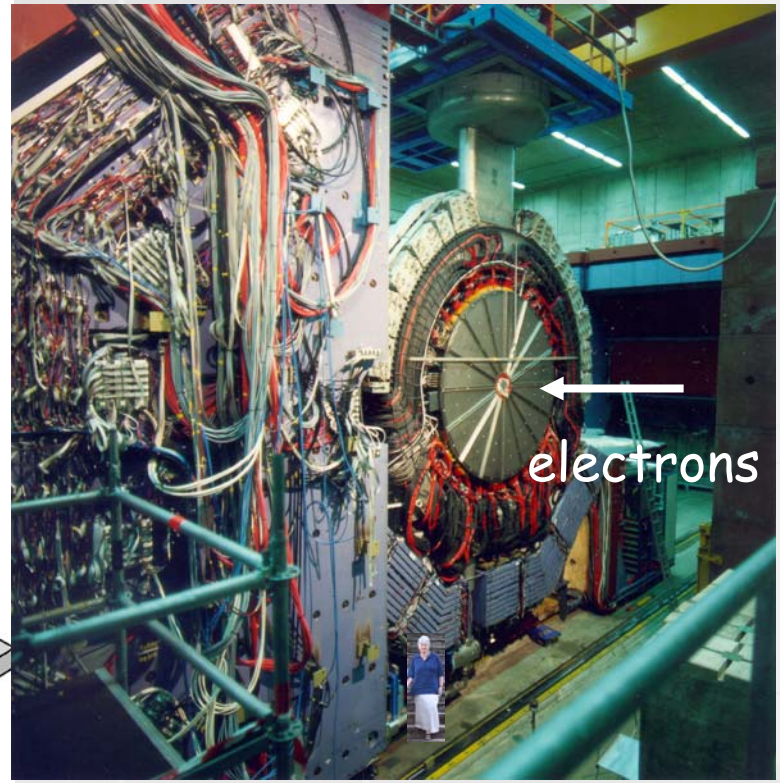
- large energy transfer Q
- large scattering angle

$\sigma \sim 1/Q^4$ new physics?



Detect collision fragments

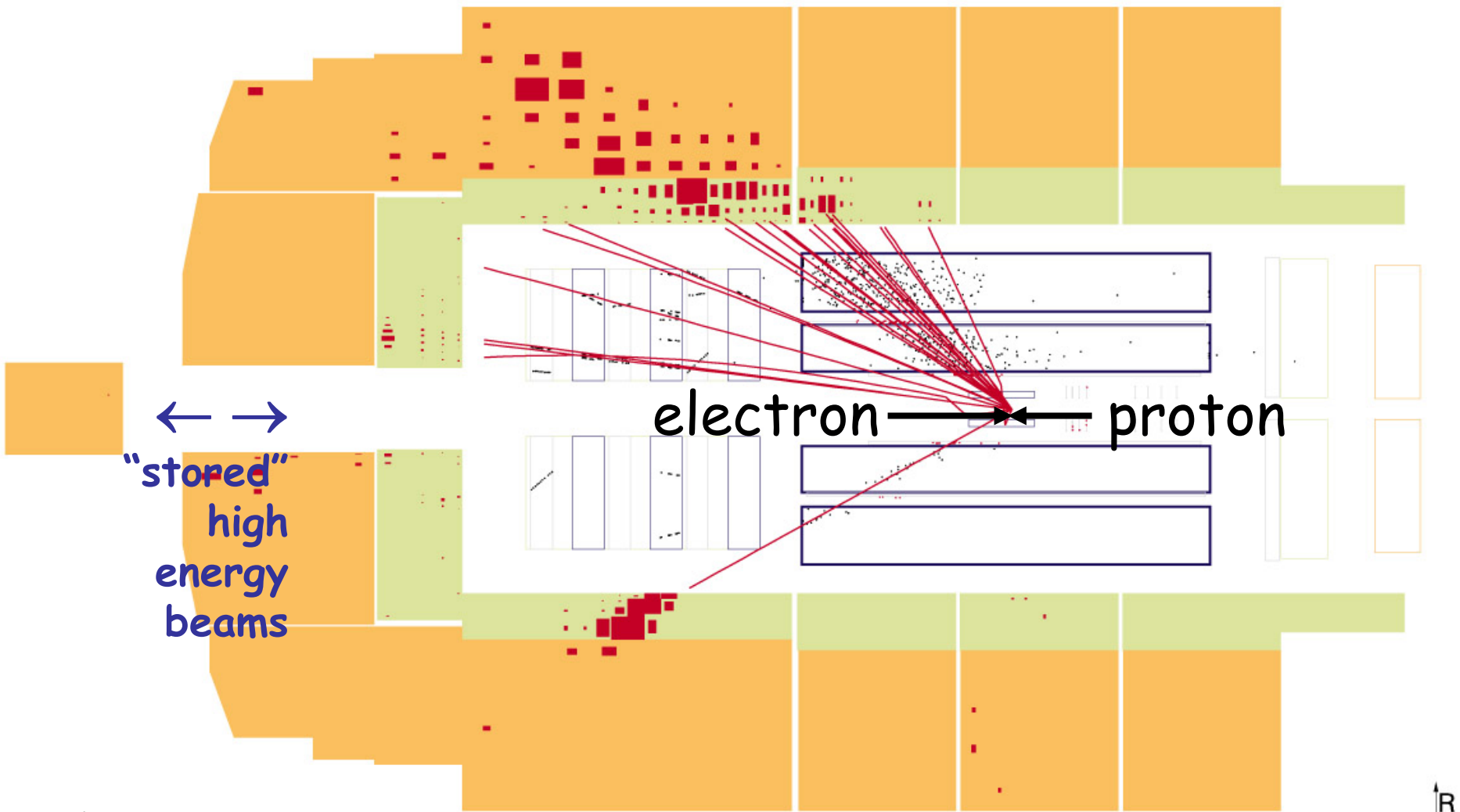




- large complex detectors

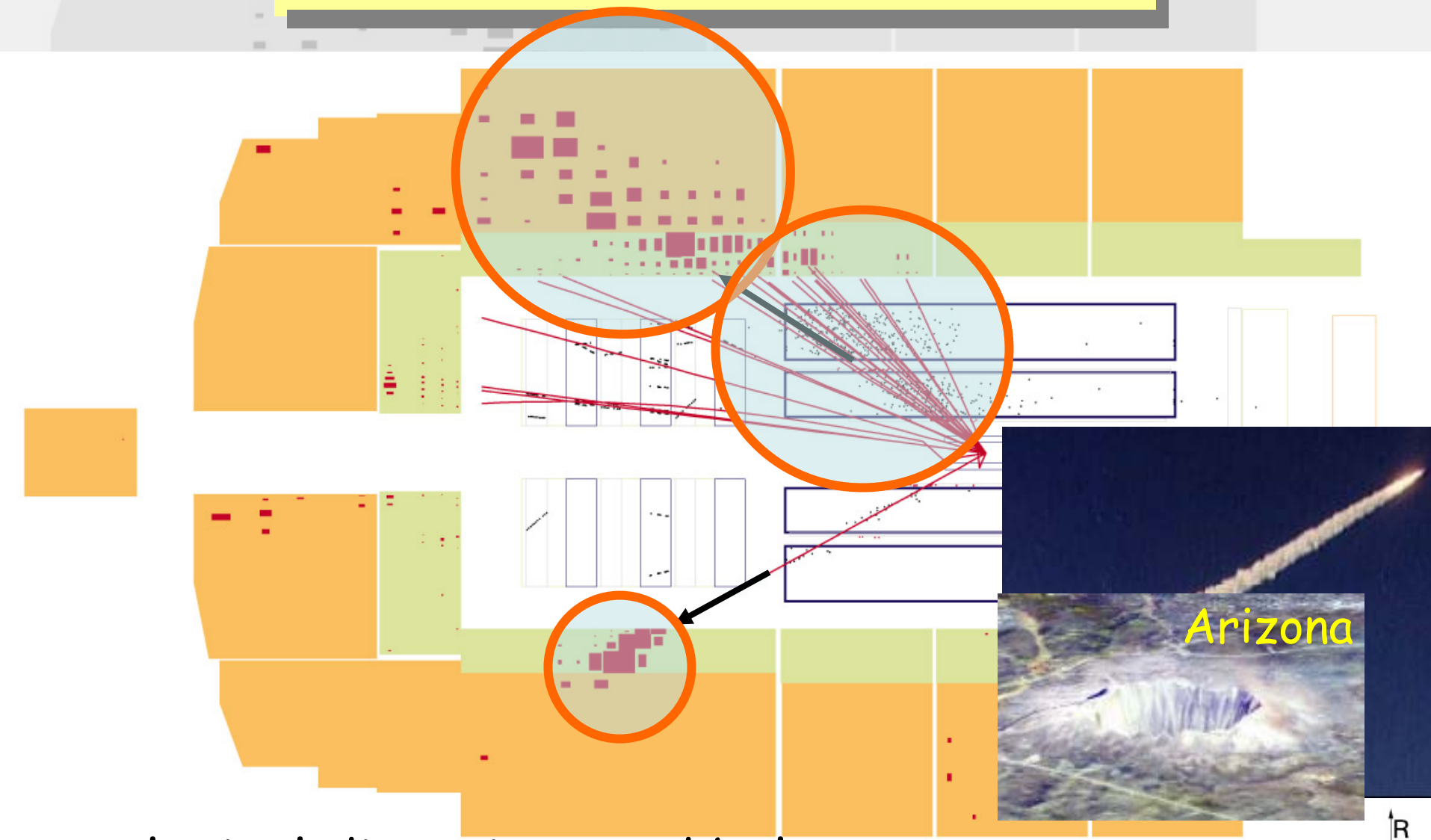
in which particles leave their mark

Electron and proton collide



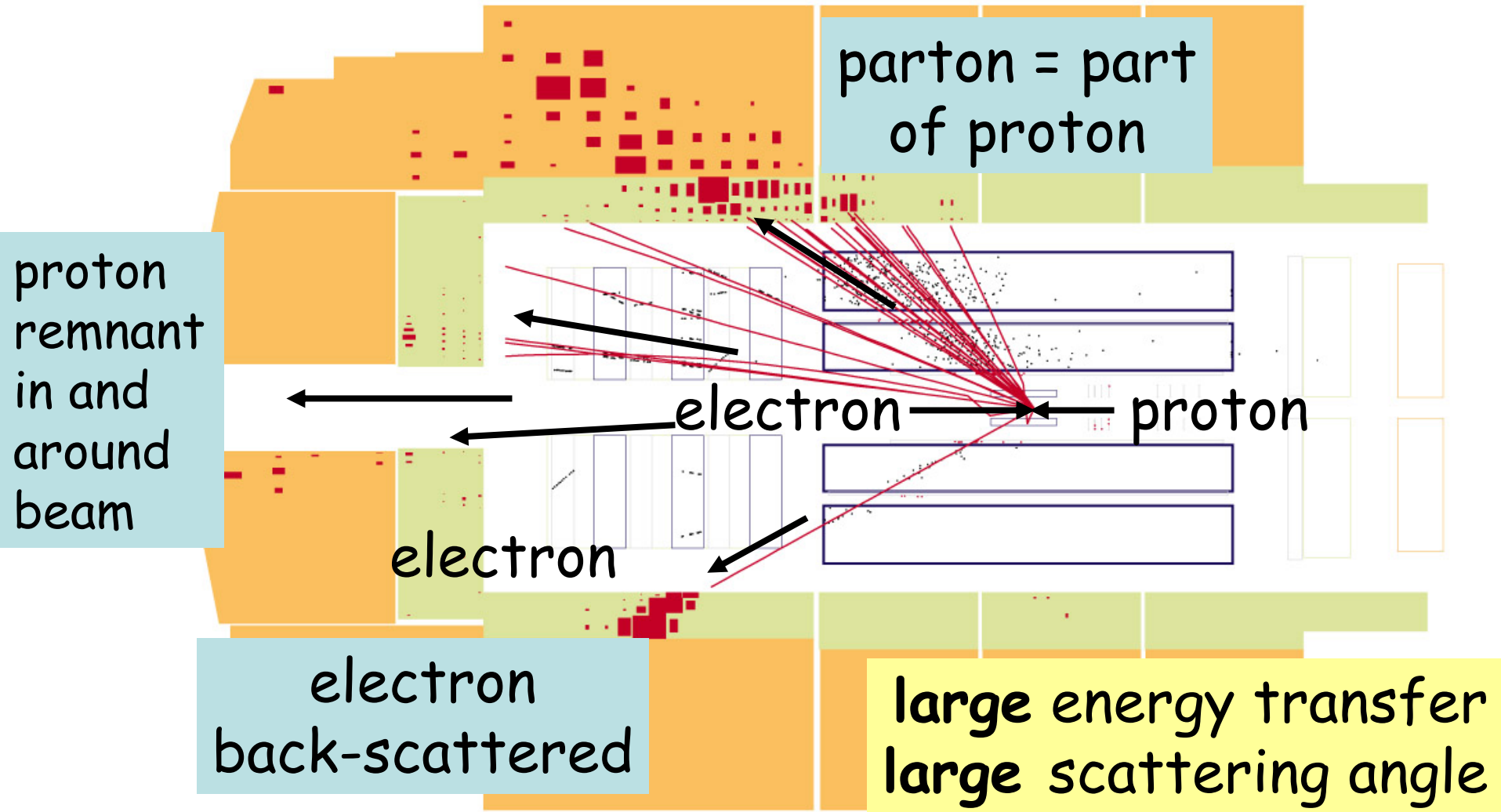
side-view

Detect Particles in Matter



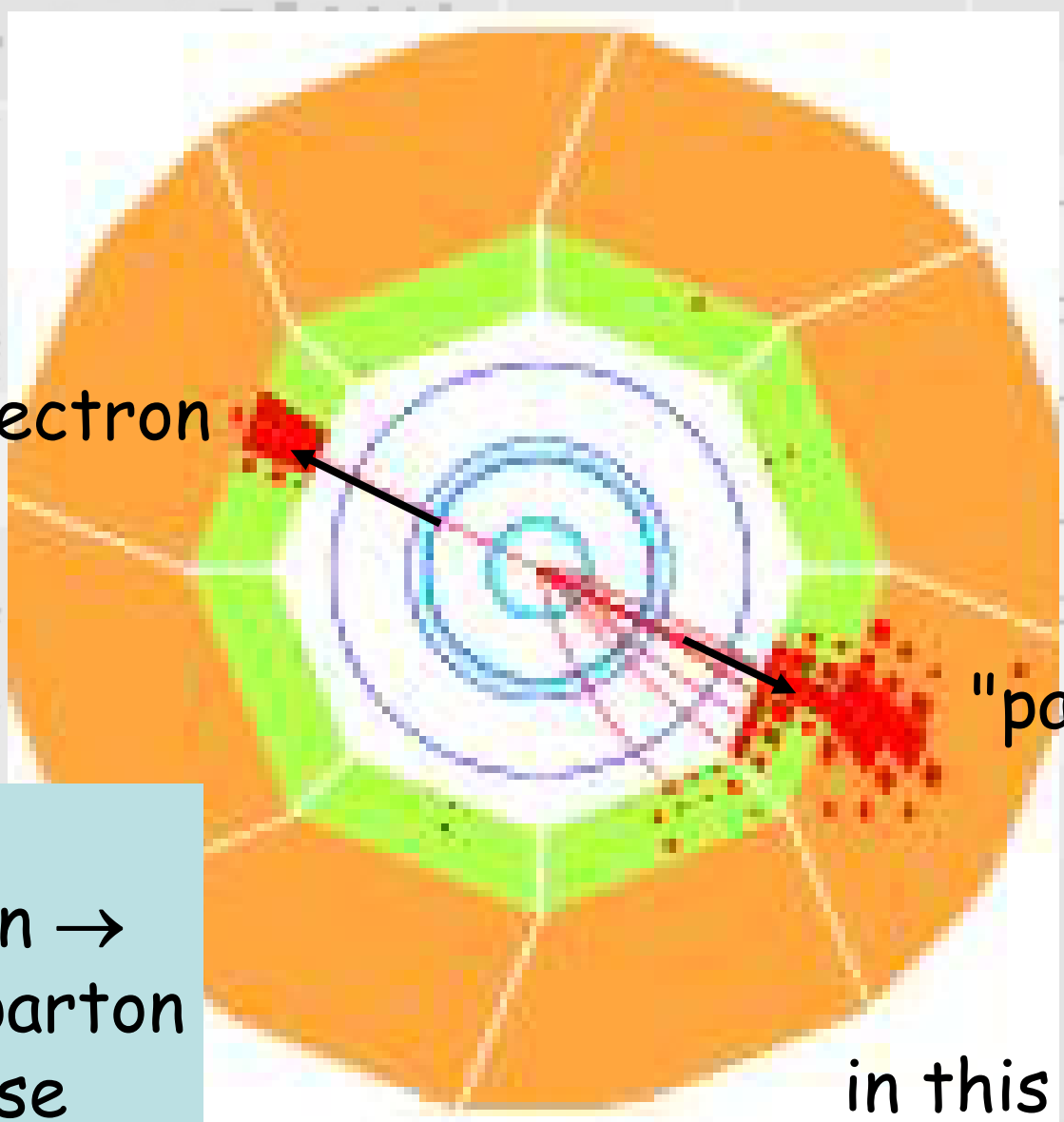
topological directions and balance

Electron recoils, proton shatters



large energy transfer
large scattering angle
small light quarks

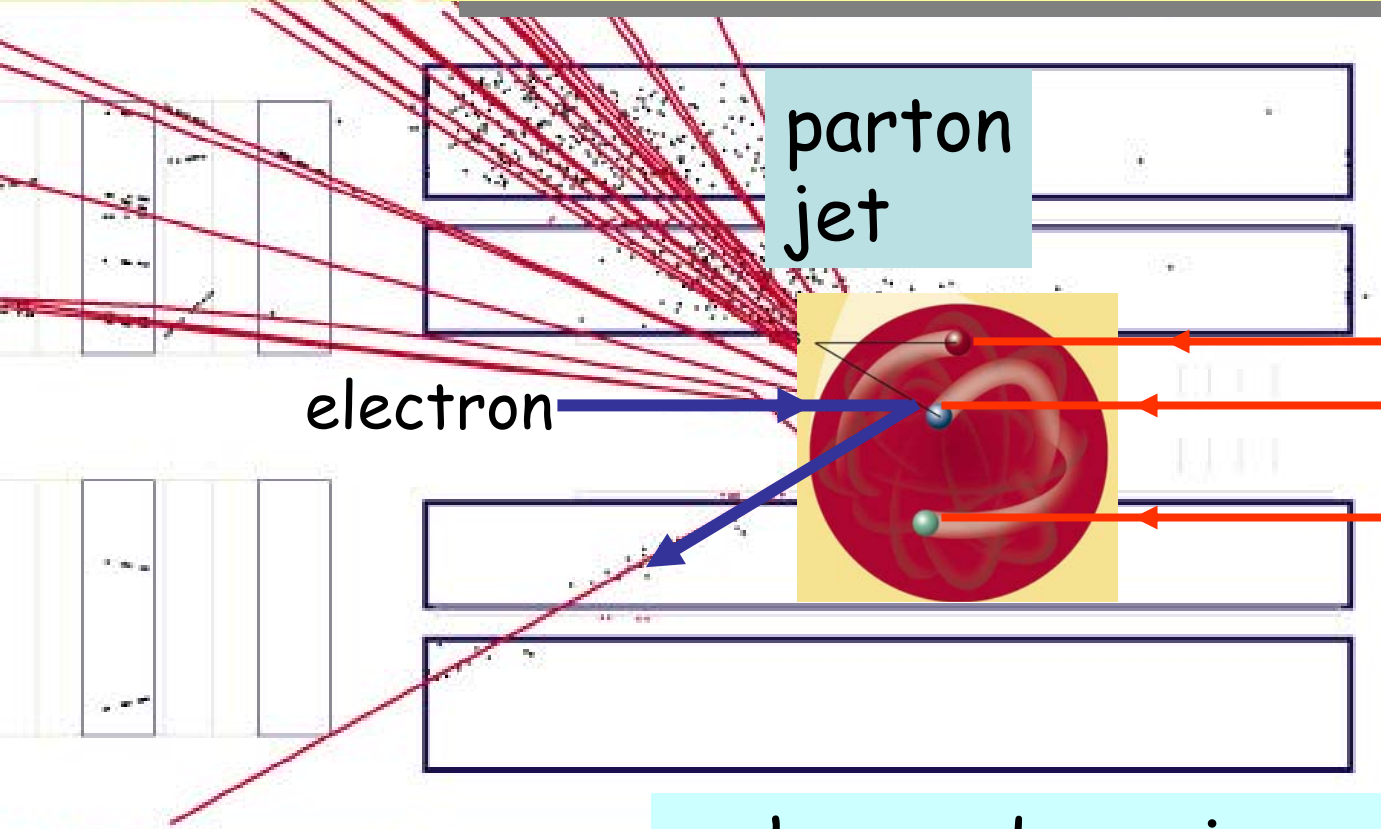
"Beam's eye view"



momentum conservation → electron + parton + nothing else

in this SM event!

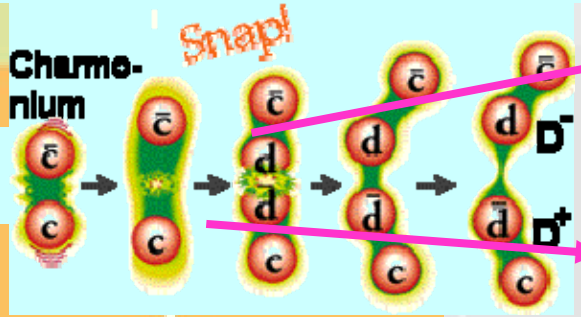
Quarks confined in proton



- chromodynamics confines quarks

scattered
electron

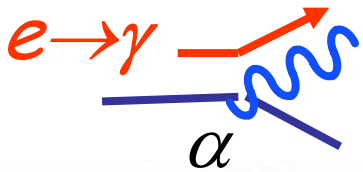
quark →

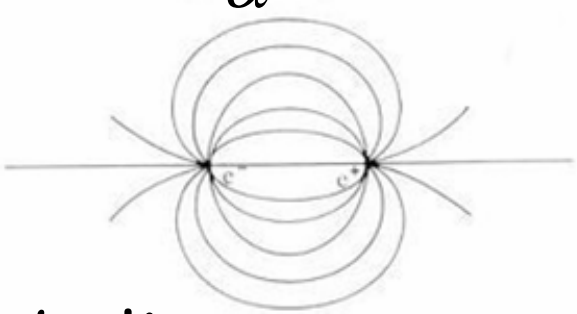


parton
jet

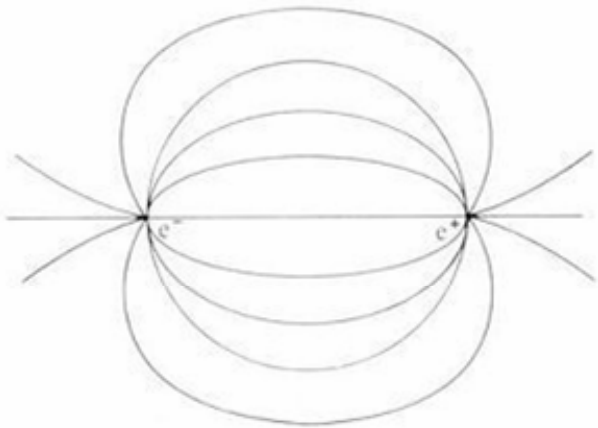
Colour Confinement

- electrodynamics



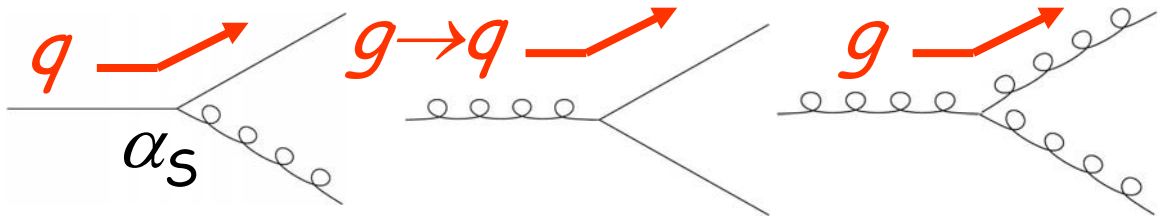


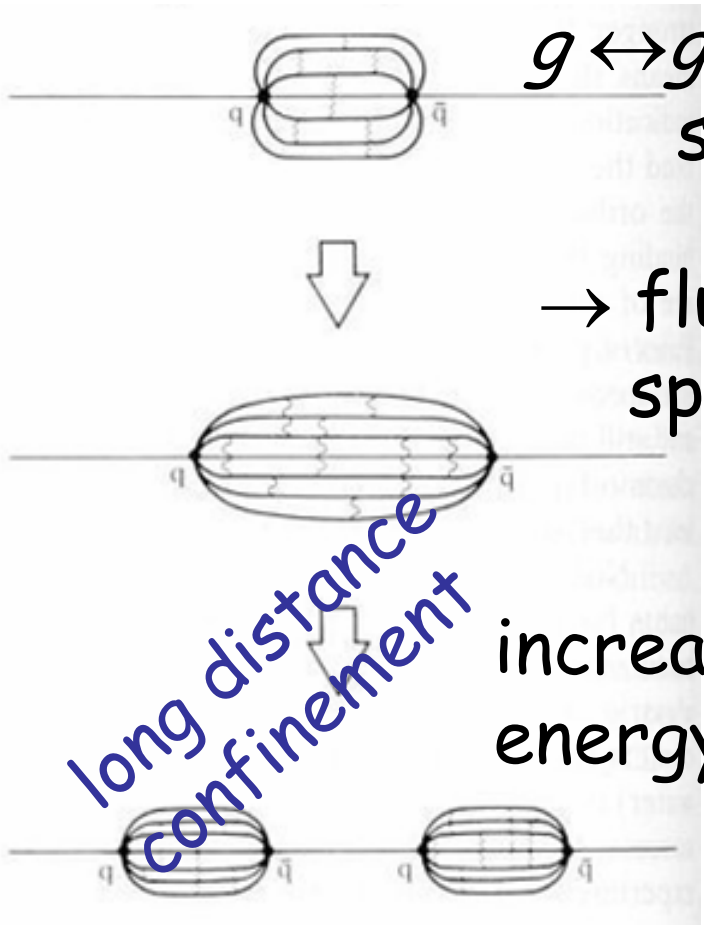
abelian



long distance freedom ($^1/_r$)

- chromodynamics





4. Detection – how and why?

High Energy Charged Particles and Matter

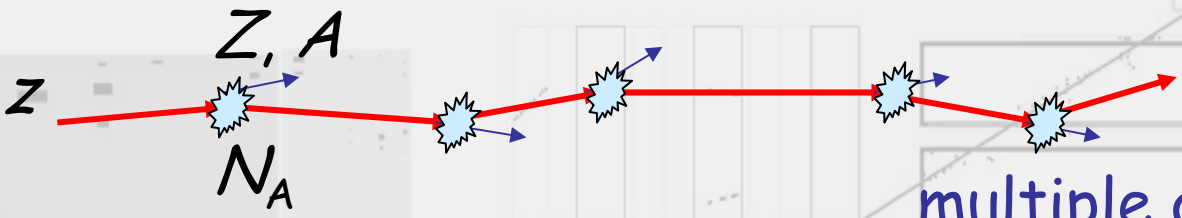
- particle with mass - ionisation energy loss

$$-\frac{dE}{dx} = Cz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}ln\left(\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right]$$

Bethe Bloch

$$T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

$$C = 4\pi N_A r_e^2 m_e c^2$$



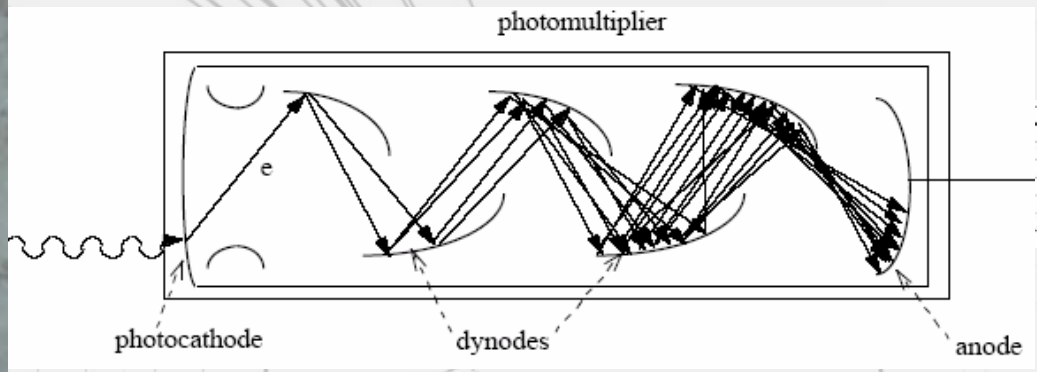
schematic
multiple atomic interactions

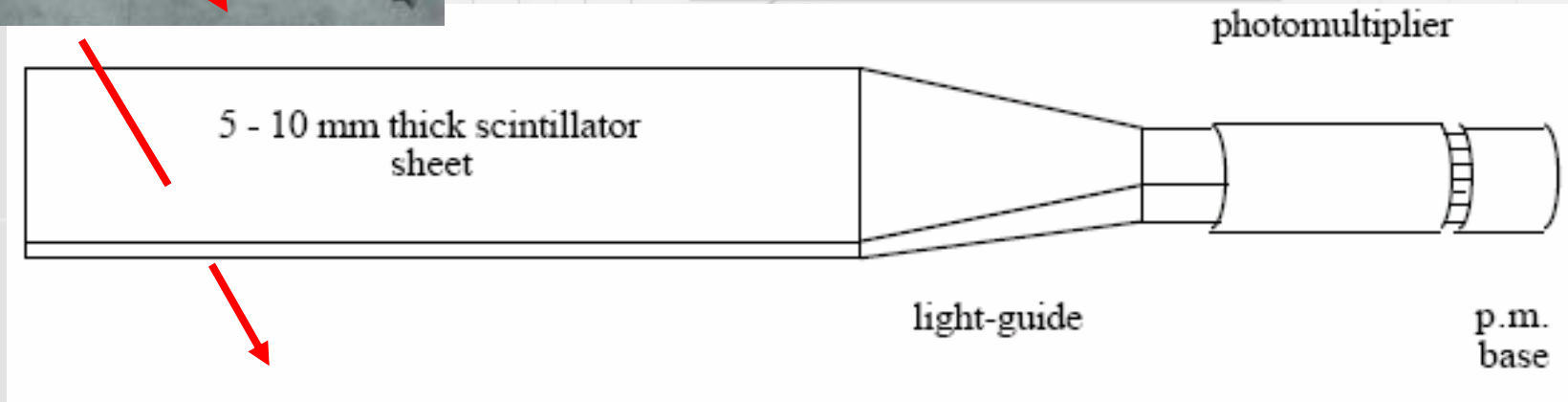
↳ ionisation charge: spatially distributed

↳ atomic de-excitation ➡ scintillation light

Scintillation Counter

- scintillation light → current

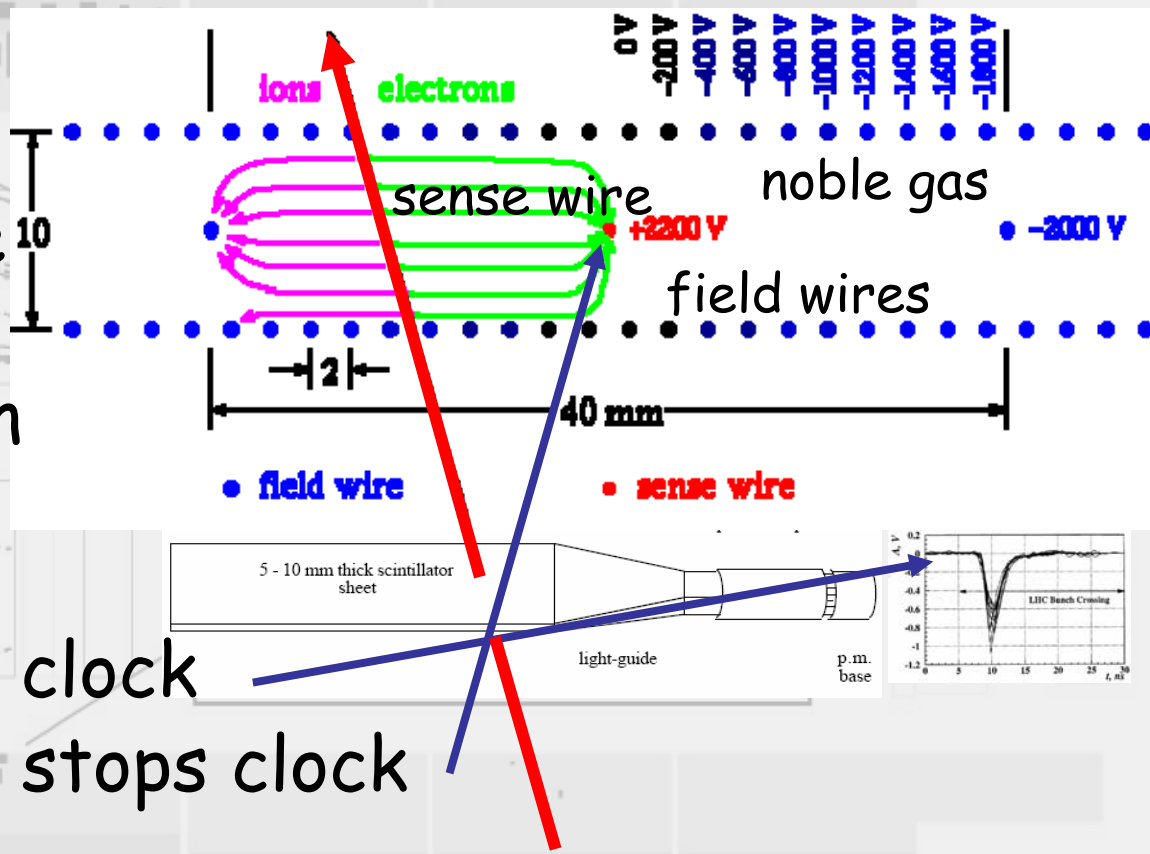




- very fast (0.1 ns), not localised → trigger

Ionisation Chamber

- ionisation charge drifts to sense wire
  → avalanches
  → self-amplification
  → current pulse



- trigger pulse starts clock
  sense current pulse stops clock

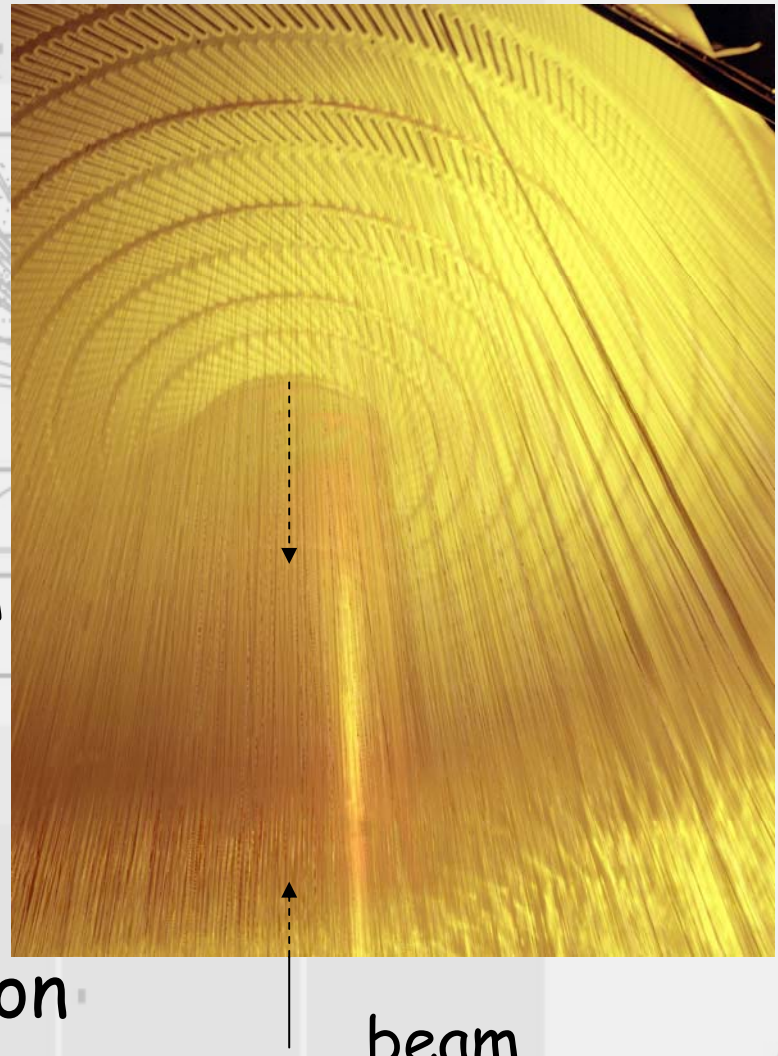
↳ drift chamber:
"slow" timed drift (μs), localised to wire
→ spatial precision 100 μm (diffusion in noble gas)

Drift Chamber Technology to limit

- many 1000s sense wires
  many many 1000s field wires
  many 1000s channels
  sophisticated data acquisition
  track/pattern recognition
  track fitting + reconstruction
  charge particle reconstruction
  + magnetic field

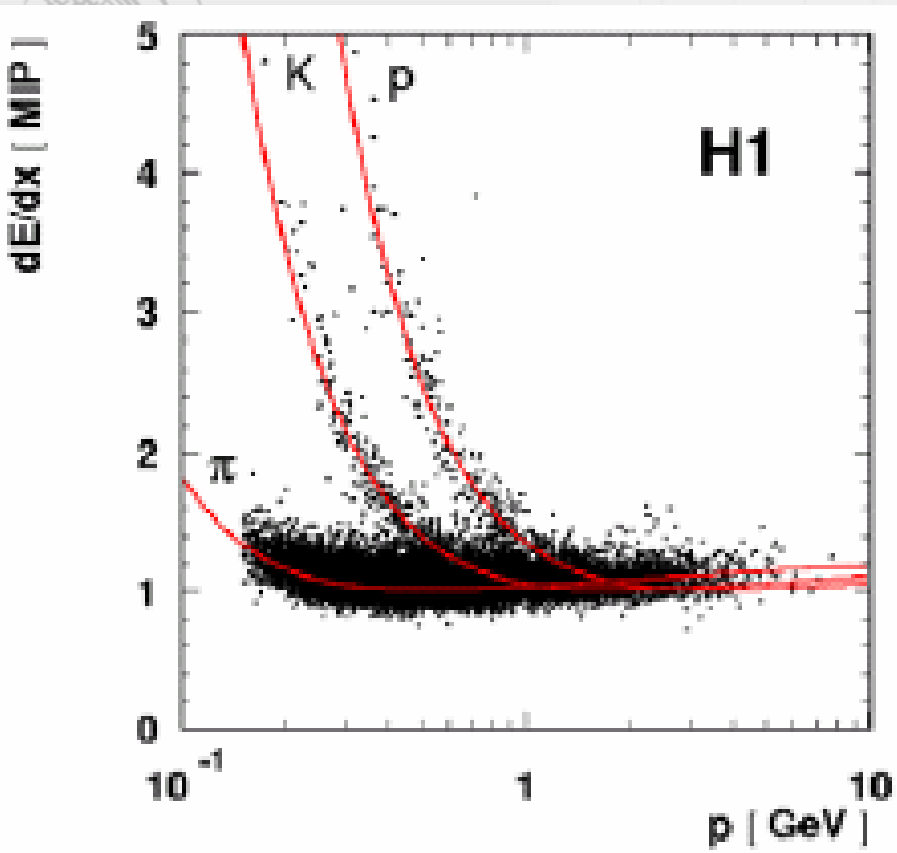
and

- many samples of track ionisation



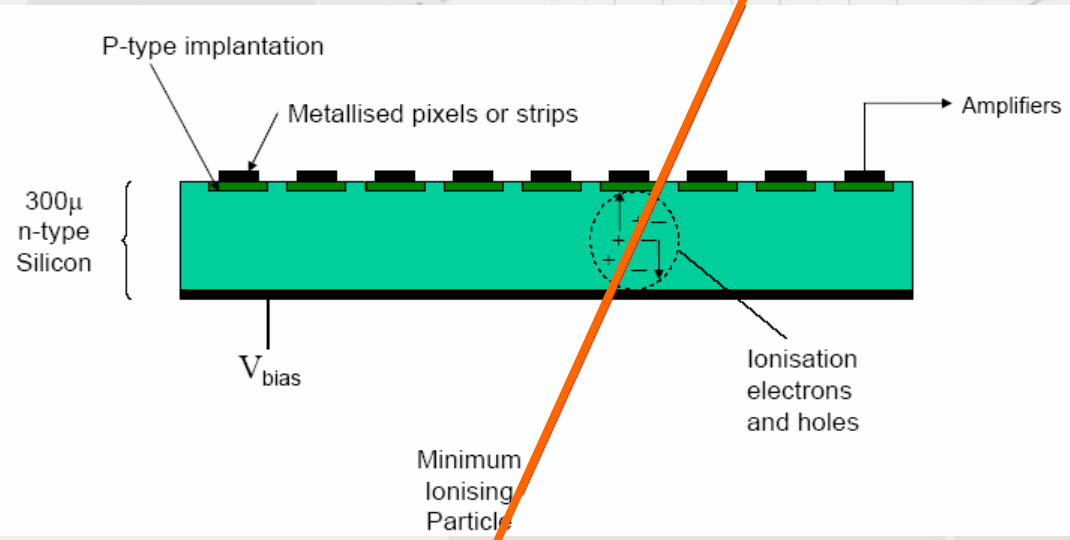
Track Ionisation

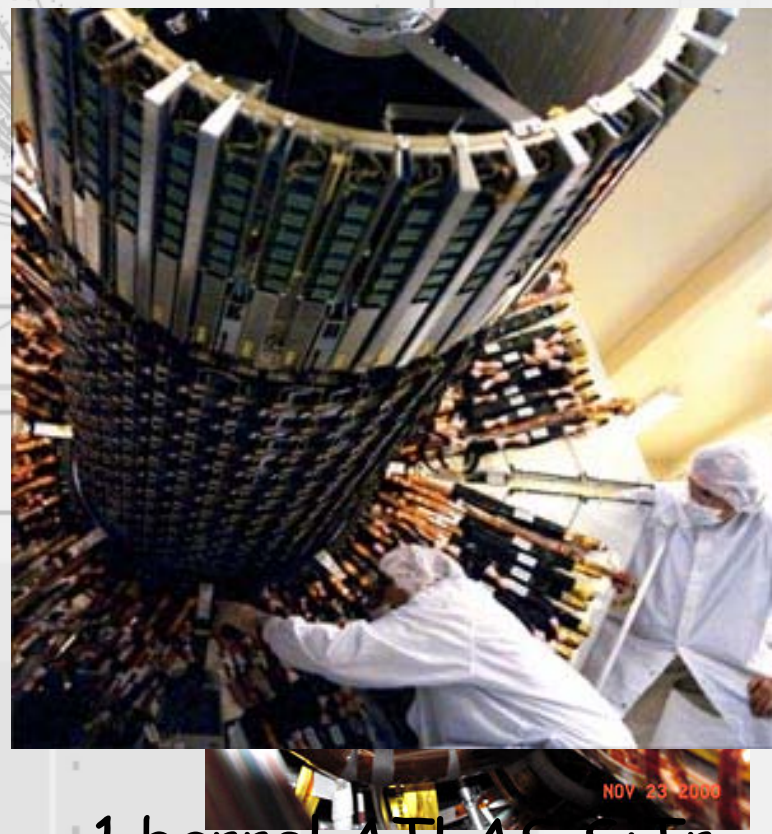
- many samples of track ionisation
  - precision points → precision trajectories
  - measurement of <ionisation>
- Bethe Bloch → particle identification
- the backbone of charged particle reconstruction



Precision μm Tracking

- Si semiconductor: smaller for same ionisation
  → point spatial precision: less diffusion ~20 μm
  → faster
- LEP/HERA vertex detectors
  all track detectors @ LHC

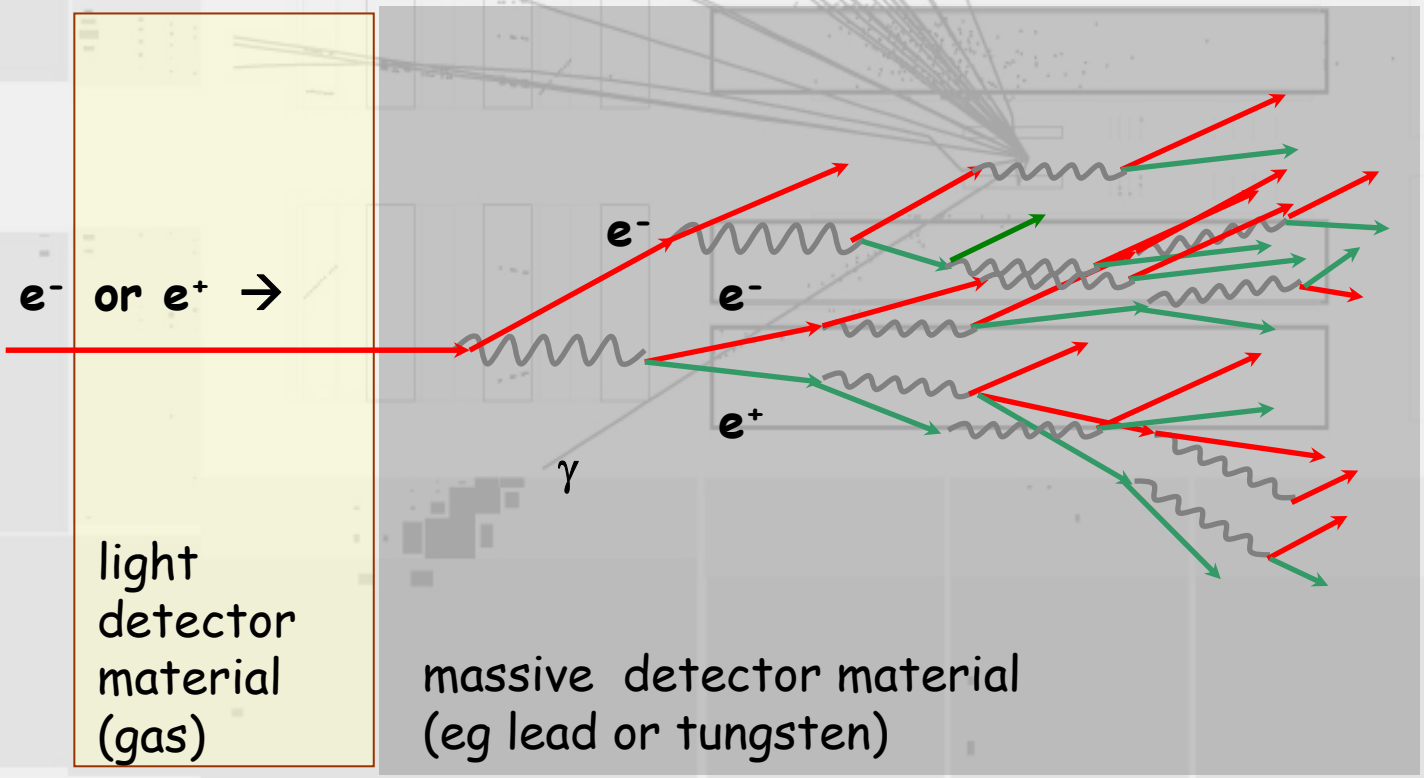




1 barrel ATLAS SiTr
layer00 CDF

High Energy Charged Particles and Matter

- low mass energetic particles: electrons + positrons
  Bremsstrahlung + pair production = EM showers

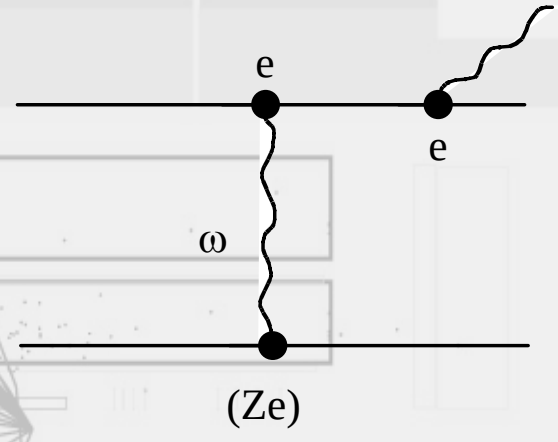


High Energy Charged Particles and Matter

- Bremsstrahlung cross section

$$\frac{\mathrm{d}\sigma(E,E')}{\mathrm{d}E'} = \frac{4}{E'} Z^2 \alpha r_e^2 \ln\frac{183}{Z^{\frac{1}{3}}} g(\frac{E'}{E})$$

$$g(w) = [1 + (1-w)^2 - \frac{2}{3}(1-w)] + \frac{1-w}{9\ln\frac{183}{Z^{\frac{1}{3}}}}$$



slight and negligible dependence on parent energy E

↳ energy loss traversing material thru radiation

$$\frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4N_0 Z^2 r_e^2}{137A}[\ln\frac{183}{Z^{\frac{1}{3}}} + \frac{1}{18}] \approx \frac{4N_0 Z^2 r_e^2}{137A}[\ln\frac{183}{Z^{\frac{1}{3}}}] = -\frac{1}{X_0}$$

$$\frac{E(x)}{E_{\mathrm{incident}}} = \exp -\frac{x}{X_0}$$

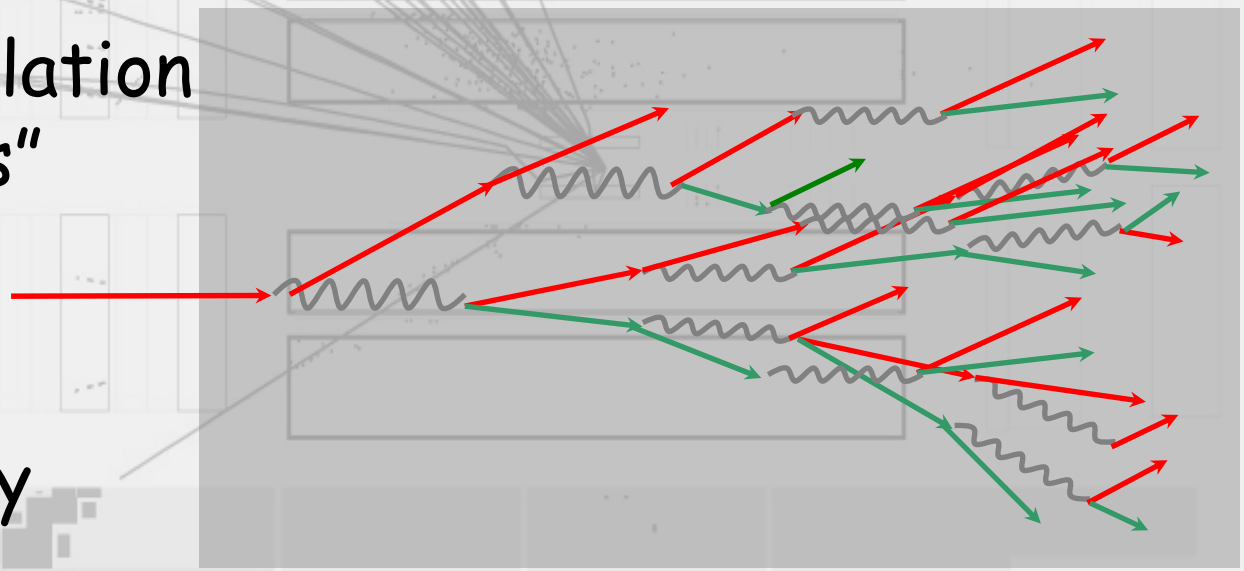
radiation length

EM Shower and Energy Measurement

- Bremsstrahlung + pair production = EM shower
- EM shower $E \rightarrow$ total $e^{\pm}$ charged particle length

ionisation/scintillation
energy loss "saps"
shower energy

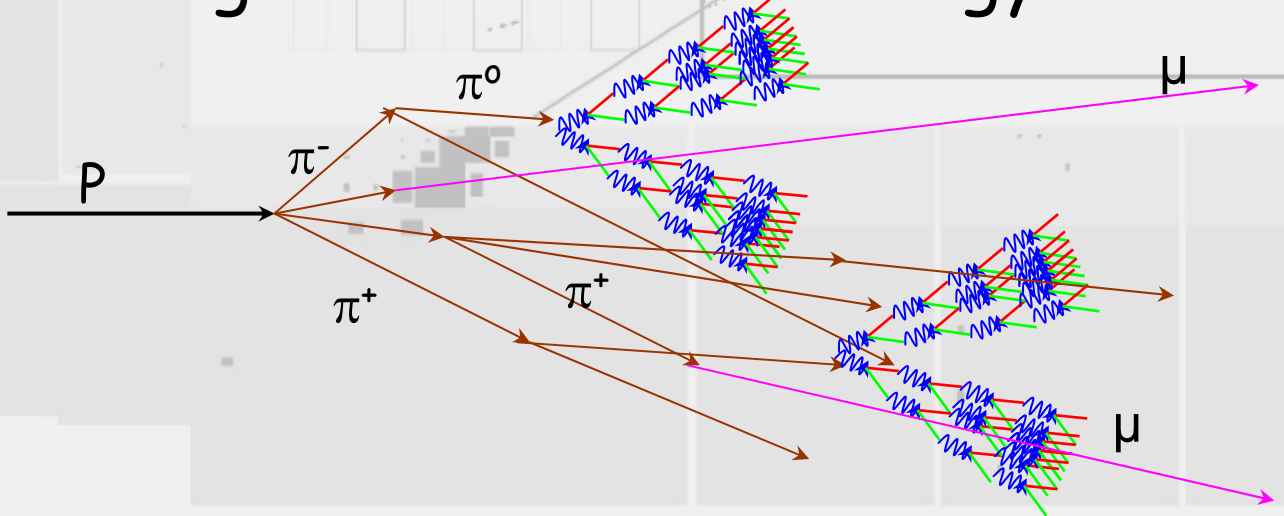
total $e^{\pm}$ length
$\propto$ incident energy



↳ ionisation/scintillation energy $\propto$ incident energy E
track length statistics $\rightarrow$ energy resolution $\propto \sqrt{E}$

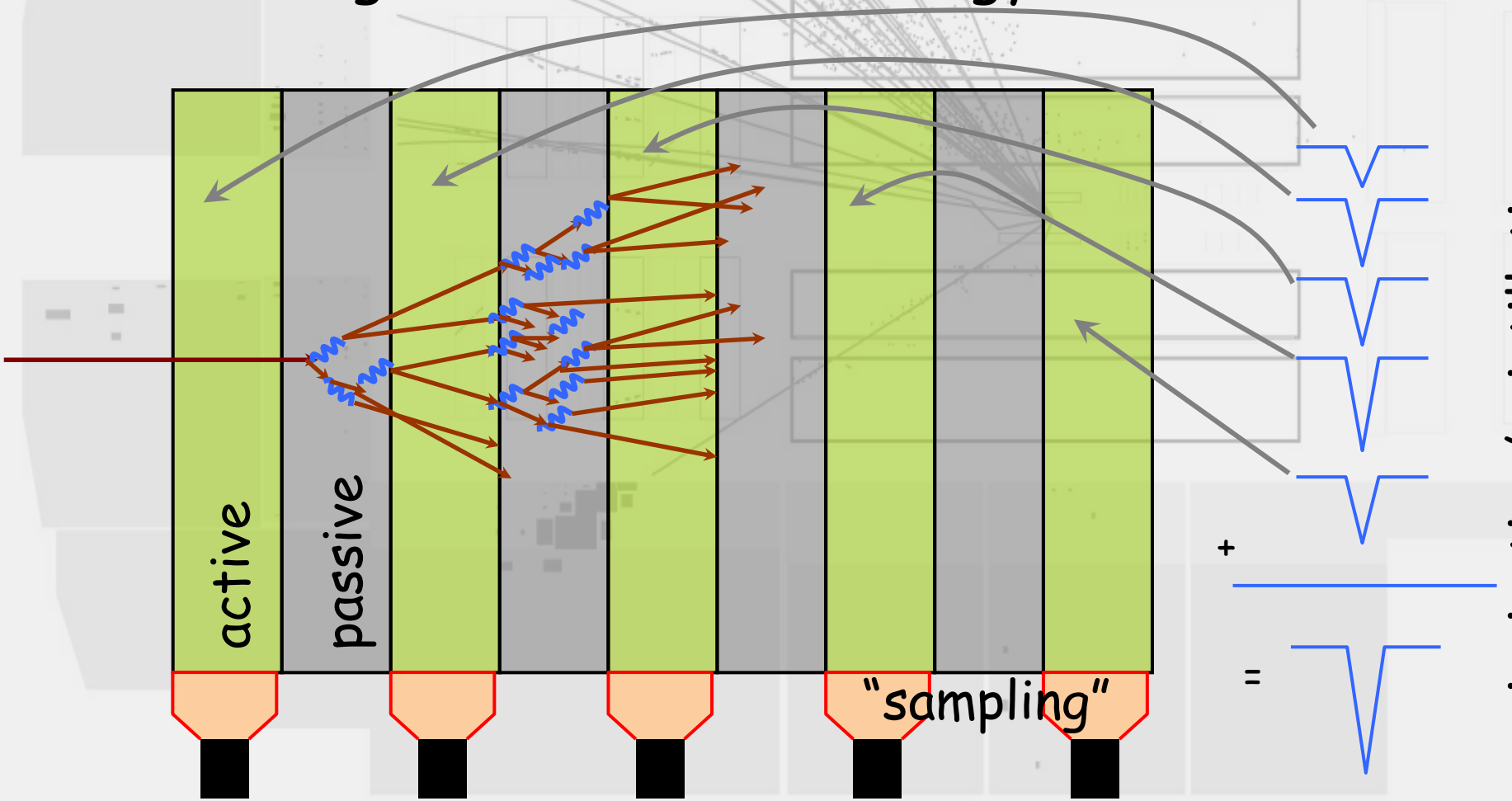
Hadronic Showers

- heavy energetic hadrons
  inelastic interaction + π^0 decay $\rightarrow$ shower
  - absorption length
    laterally broader than EM
    shower $E \rightarrow$ total charged particle length
    ionisation/scintillation energy $\propto$ incident energy E
    track length statistics $\rightarrow$ energy resolution $\propto \sqrt{E}$



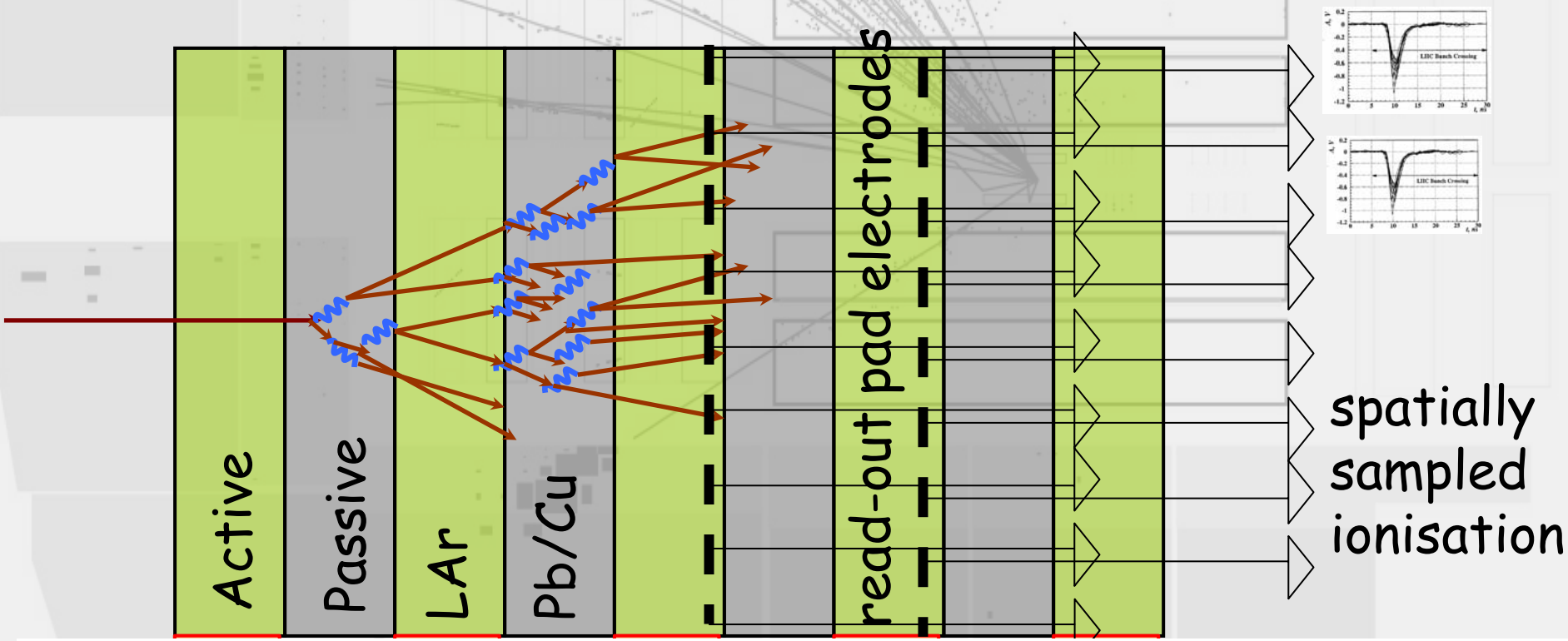
Calorimeter

- ionisation/scintillation energy $\propto$ incident energy E
  track length statistics $\rightarrow$ energy resolution $\propto \sqrt{E}$



Finely Segmented Calorimeter

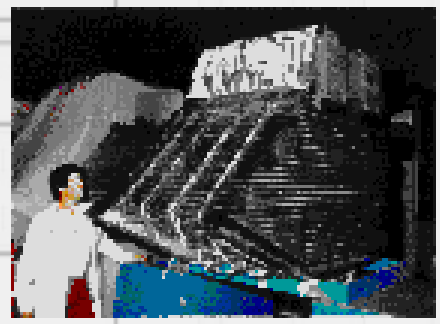
- ionisation/scintillation energy $\propto$ incident energy E
  track length statistics $\rightarrow$ energy resolution $\propto \sqrt{E}$



- longitudinal and lateral shower "sampling" $\rightarrow$ profile

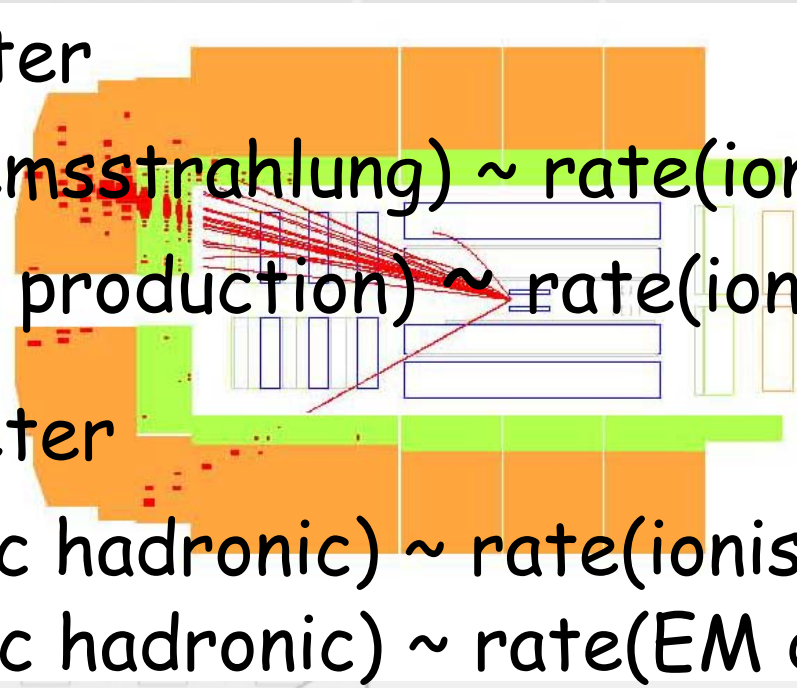
LAr Ionisation Calorimeter

- ionisation energy $\propto$ incident energy E
  track length statistics $\rightarrow$ energy resolution $\propto \sqrt{E}$
- LAr active medium: mobile ionisation
  "pad" electrodes $\rightarrow$ spatial sampling
  $\rightarrow$ spatial topology of shower EM/had
  many 1000s channels



- ionisation drift in liquid
  $\rightarrow$ slow
- cryostat
  LAr purity

Muon



- EM calorimeter

  rate(EM Bremsstrahlung) ~ rate(ionisation)

  rate(EM pair production) ~ rate(ionisation)

- Had calorimeter

  rate(inelastic hadronic) ~ rate(ionisation)

  rate(inelastic hadronic) ~ rate(EM decay$\rightarrow\gamma$)

- "calorimeter" with

  rate(EM) « rate(ionisation)

  rate(inelastic had) « rate(ionisation)

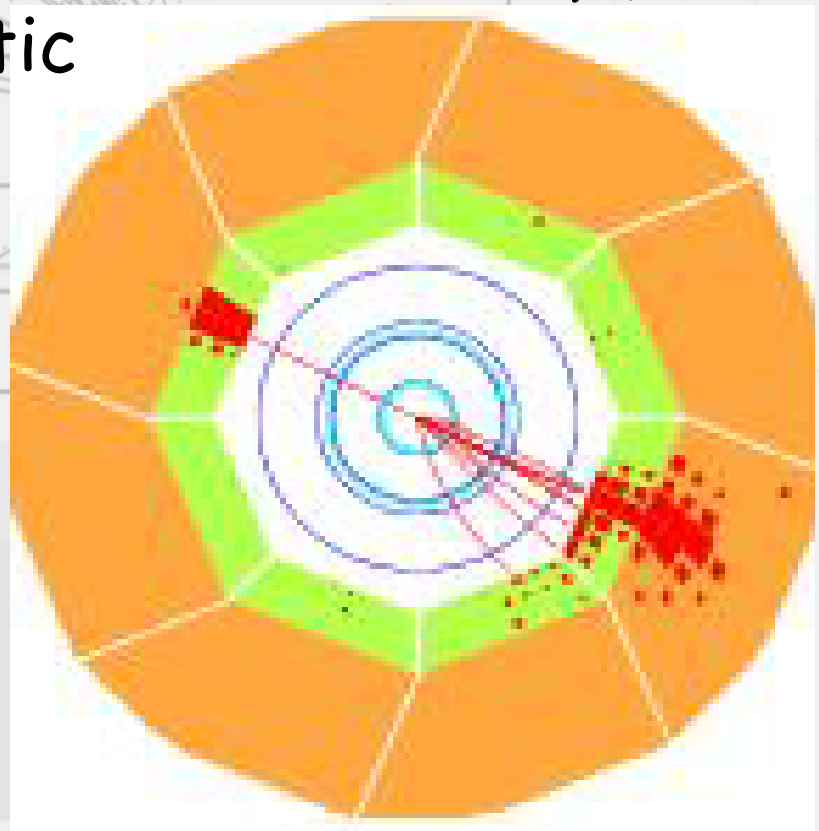
muon
√
rate(had)=0
penetrating
?

Experimentation

- hermeticity → design and build well
  - reliability
  - calibration
  - efficiency
- redundancy → inter- performance
  inter-calibration
  - reliability
  - calibration
  - efficiency
- precision → understand functionality
  monitor performance
  maintain best calibration
  - reliability
  - calibration
  - efficiency

Calibration

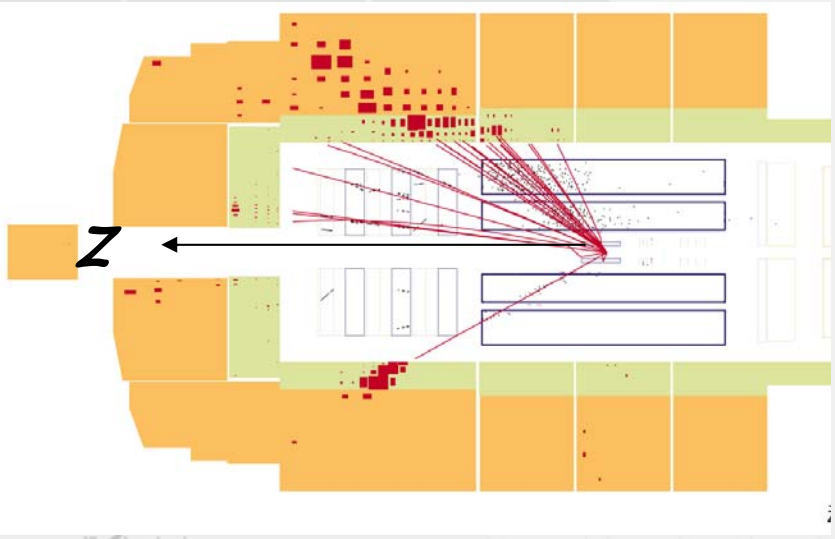
- energy scale
  - kinematics: total *ep* interaction energy
    transverse momentum $p_T = 0$
  - hadronic ↔ electromagnetic
    jet ↔ electron
  - hadronic ↔ hadronic
    jet ↔ jet
  - calorimetric ↔ tracks



- monitor throughout
  data-taking

Calibration

- energy scale
  - kinematics:
    total *ep* interaction energy
    longitudinal (*z*) $E - p_z$



$$E_{\text{beampipe}} + E_{\text{measured}} = E_e + E_p$$

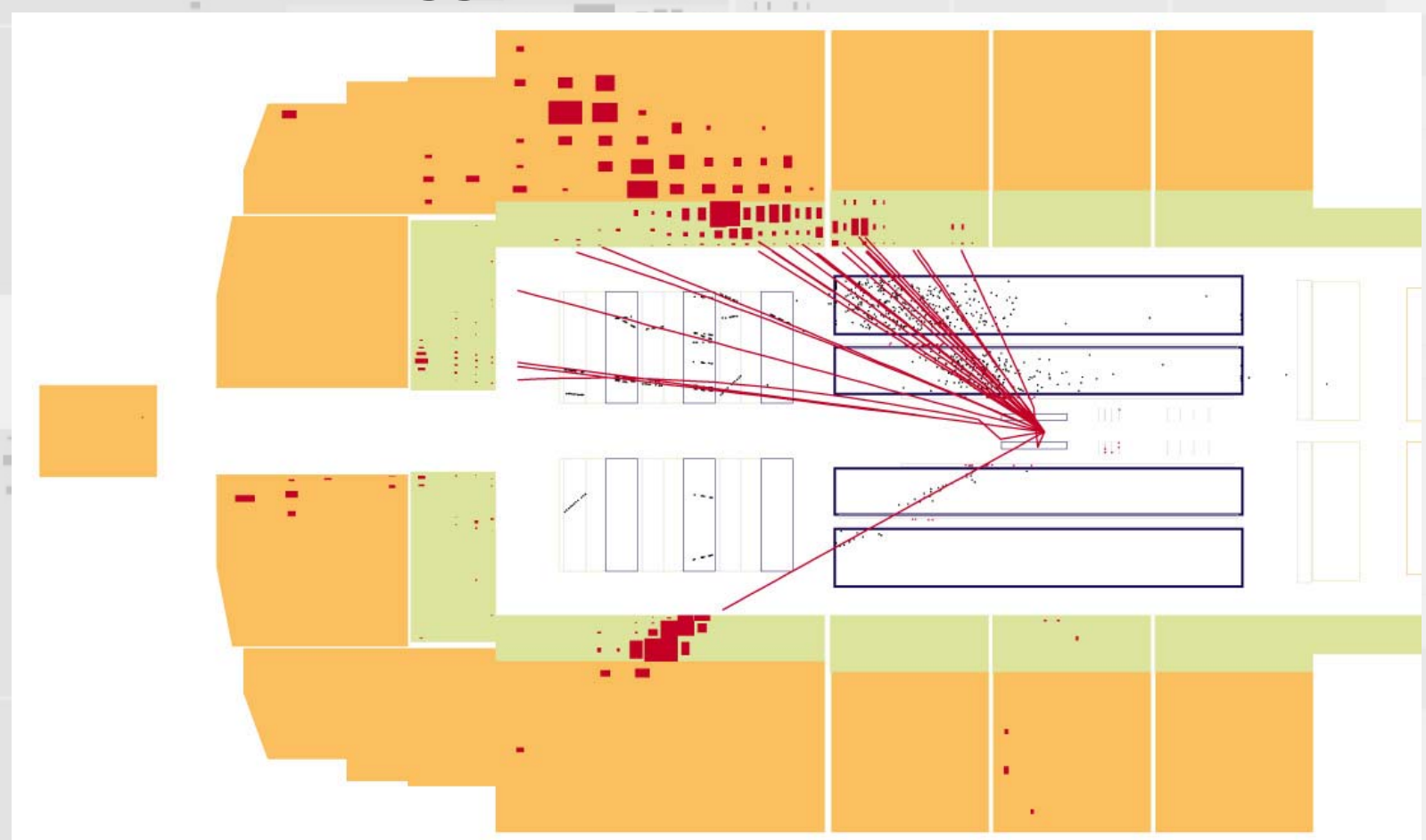
$$P_{\text{beampipe}} + P_{z\,\text{measured}} = -P_e + P_p$$

$$\cancel{(E-P)}_{\text{beampipe}} + (E-P_z)_{\text{measured}} = (E+P)_e + \cancel{(E-P)}_p$$

$$(E-P_z)_{\text{measured}} \approx 2E_e$$

An experimentalist's moment !

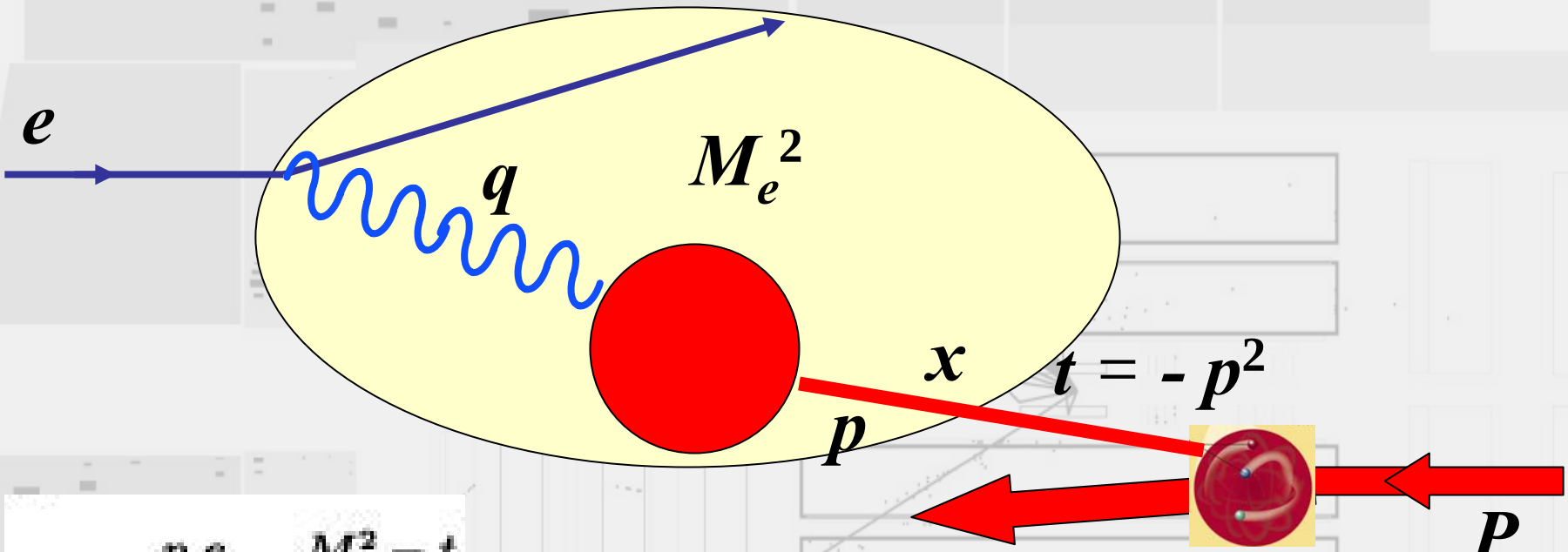
- the first trigger



- … just after the accelerator physicist asks !

5.How we learn with data?

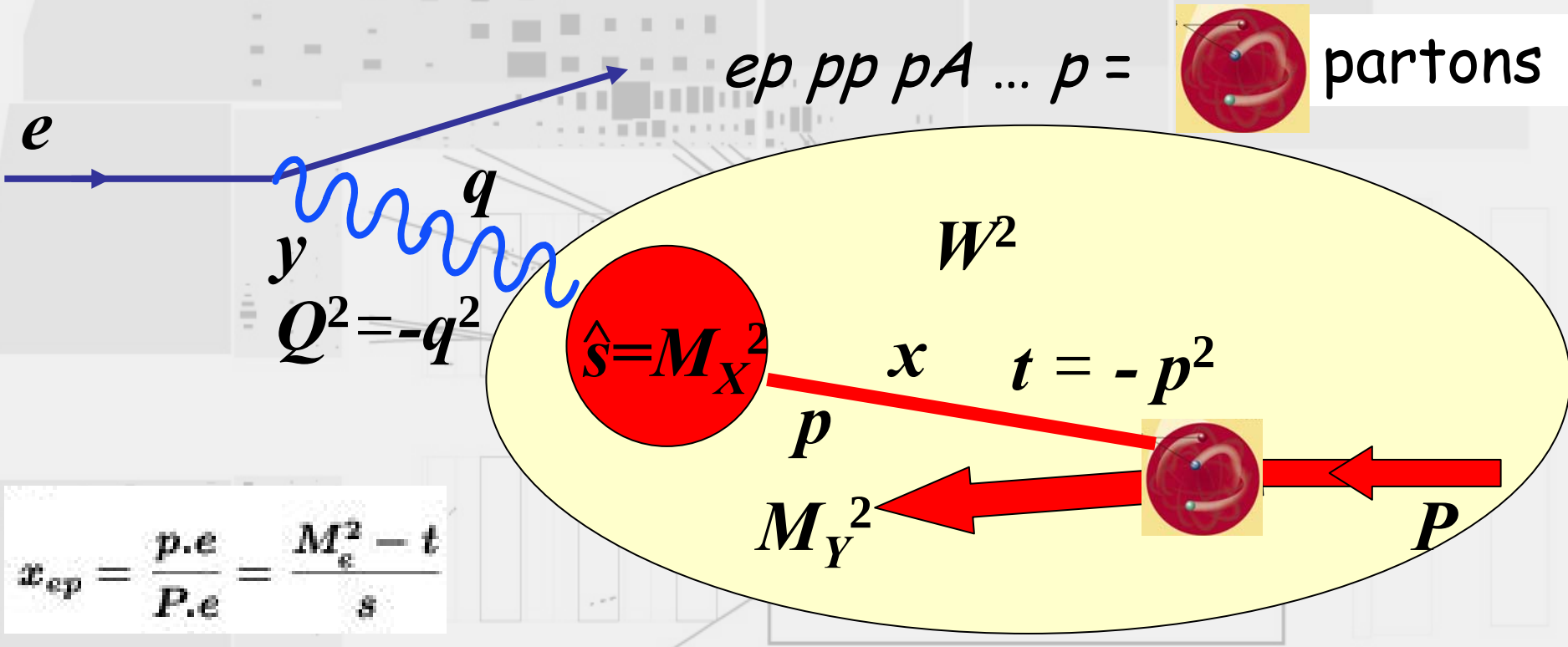
Kinematics



$$x_{ep} = \frac{p.e}{P.e} = \frac{M_e^2 - t}{s}$$

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

Kinematics



$$x_{ep} = \frac{p.e}{P.e} = \frac{M_e^2 - t}{s}$$

$$x = \frac{p.q}{P.q} = \frac{M_X^2 + Q^2 - t}{W^2 + Q^2}$$

$$x_{ep} \sim x \qquad \text{when } |P| \text{ is large}$$

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

quark $M_X = 0$

$$y = \frac{q.P}{e.P} = \frac{W^2 + Q^2}{s}$$

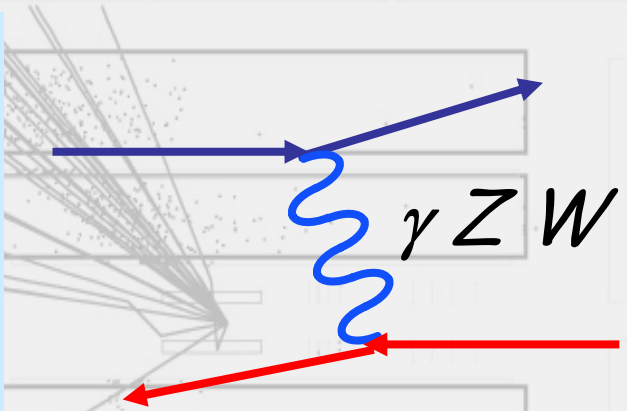
$$Q^2 = x_{Bj} y s$$

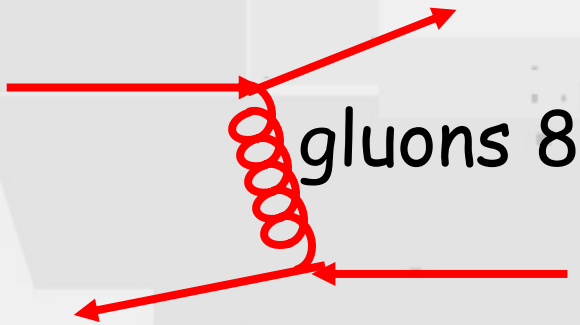
- x and $y \rightarrow$ daughter momentum/parent momentum

The Engauging Framework

- Standard Model (SM): (Dirac) leptons + quarks

Quantum Flavour Dynamics
QFD
gauge field quanta: $\gamma\, Z\, W$
$SU(2)_L$ weak isospin
non-abelian

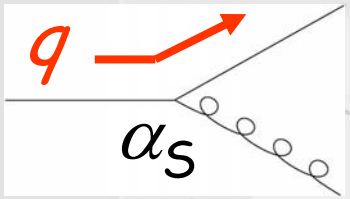


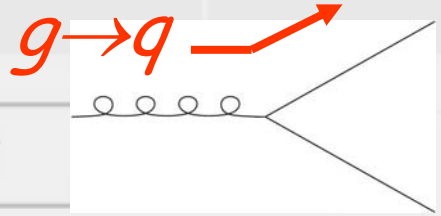


Quantum Chromo Dynamics
QCD
gauge field quanta: gluons 8_C
$SU(3)_{LR}$ colour C
non-abelian

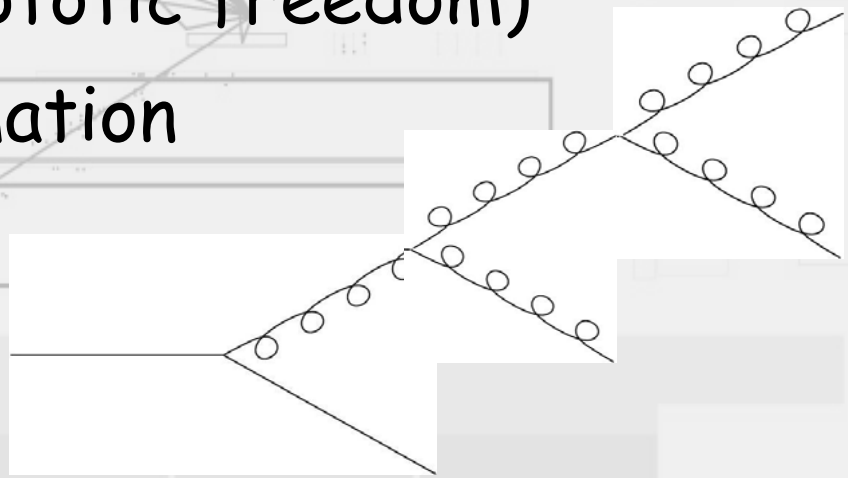
The Perturbative Framework: QCD

- chromodynamic splitting





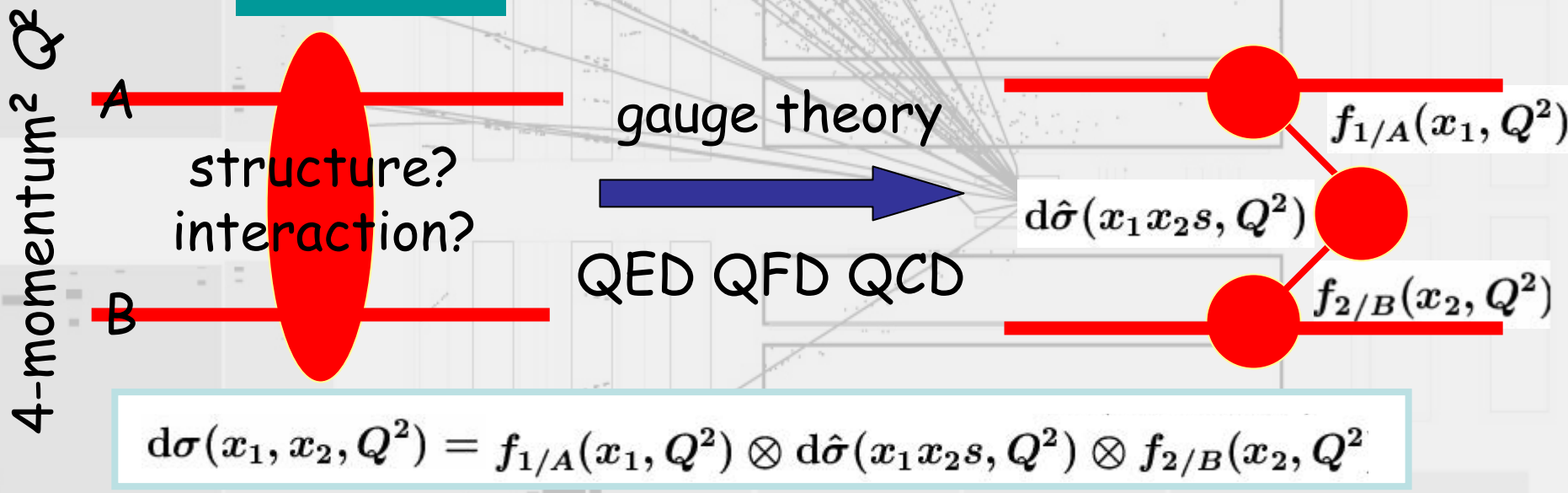
- order by diagram (asymptotic freedom)
  - exponentiation in summation
  - leading log ($\alpha_S \cdot \ln Q^2$)
  - next-to-leading log



- colour factors: $ggg = {}^{9}/_{4}\, qqg$
- low scale (large distance) α_S large !

QCD tool: Factorisation

- factorisation: hadronic salvation!
  - universal structure ↔ interaction ? Gribov



$$d\sigma(x_1, x_2, Q^2) = f_{1/A}(x_1, Q^2) \otimes d\hat{\sigma}(x_1 x_2 s, Q^2) \otimes f_{2/B}(x_2, Q^2$$

  - universal structure $f_{i/P}$ which evolves with Q^2
  - $f_{i/P}$ non-perturbative, presently incalculable
- experiment ↔ theory

The Perturbative Framework: QFD

- QFD vertices

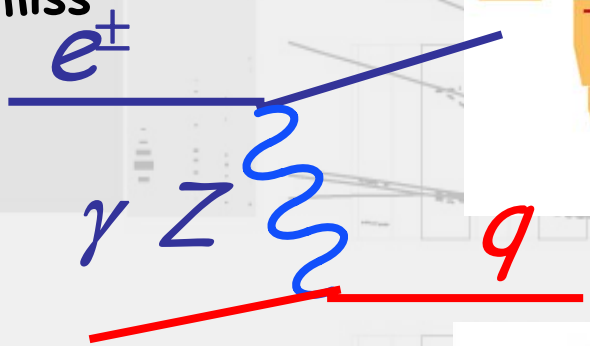
- order by diagram (α small)
  - precision perturbative convergence
  - precision experimental verification (LEP)
  - theory drives experiment

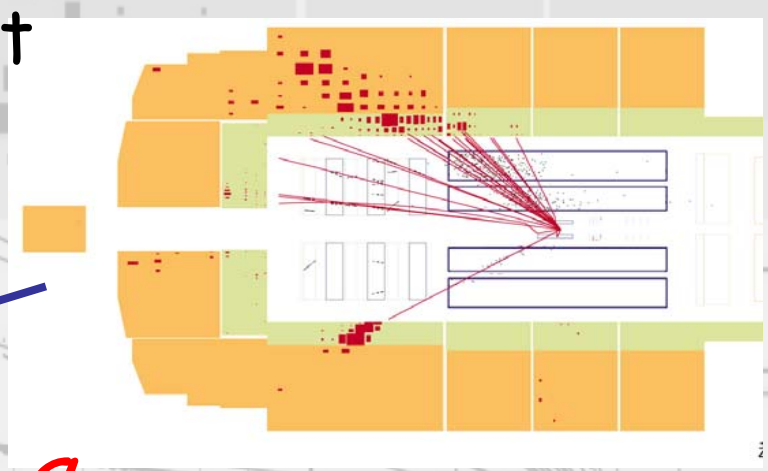
Selection: distinct Topologies

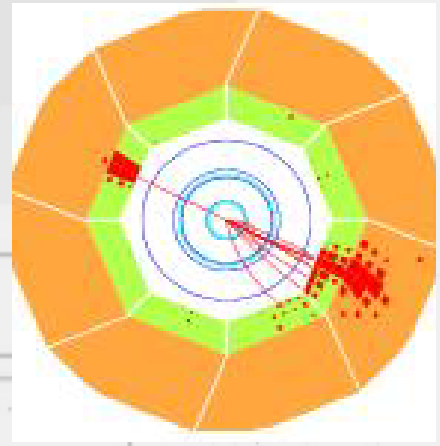
- Neutral Current

$ep \to eX$

~~p_{Tmiss}~~



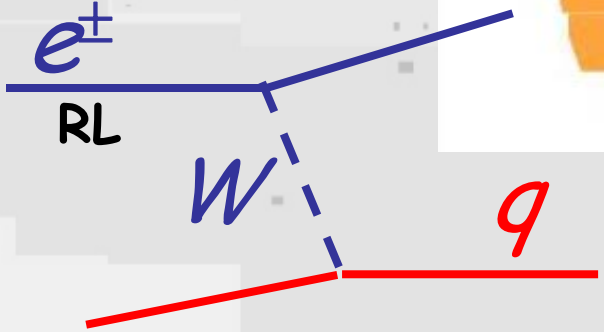


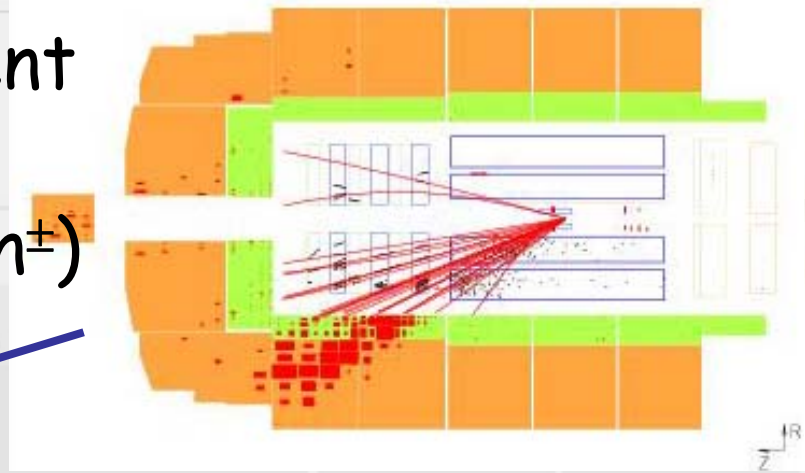


- Charged Current

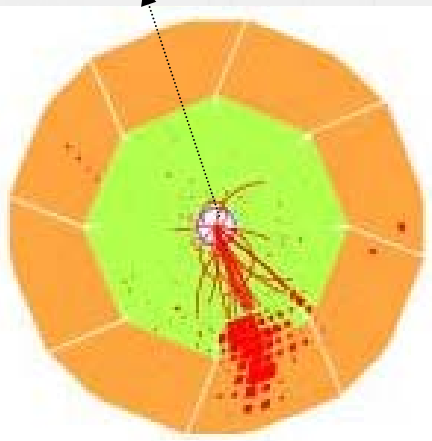
$ep \to \nu X$

p_{Tmiss} (no lepton$^{\pm}$)



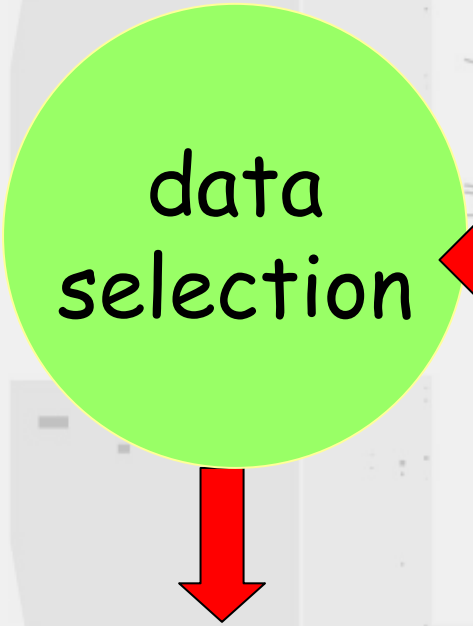


$p_{Tmiss} = \nu$



How we do learn with data

- build Standard Model template for experiment

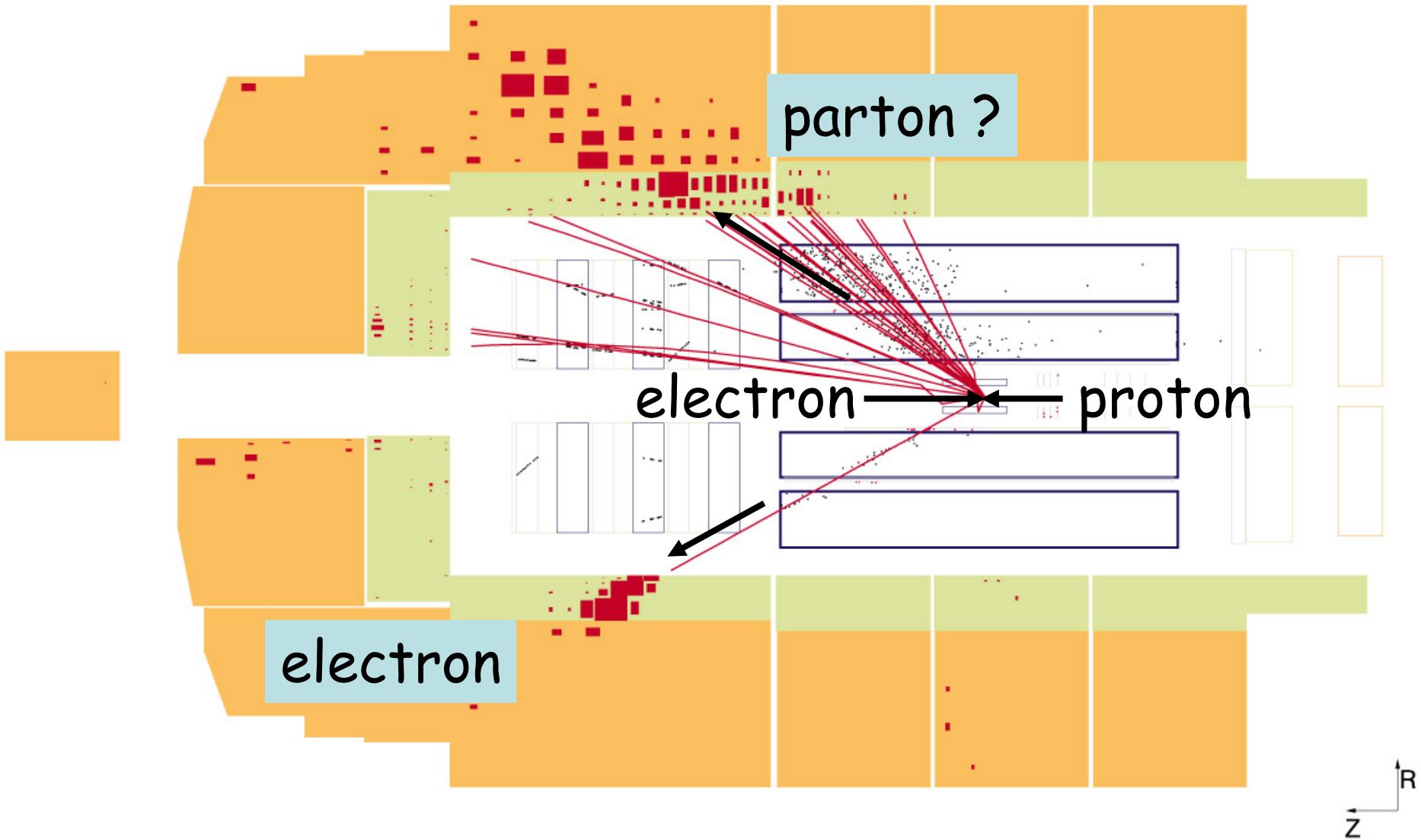


- QCD phenomenology
  hadron structure+dynamics
  hadronic synthesis
  pQCD evolution
- QFD dynamics
  u d s couplings
  space-like propagator

theorist
phenomenologist
Monte Carlo

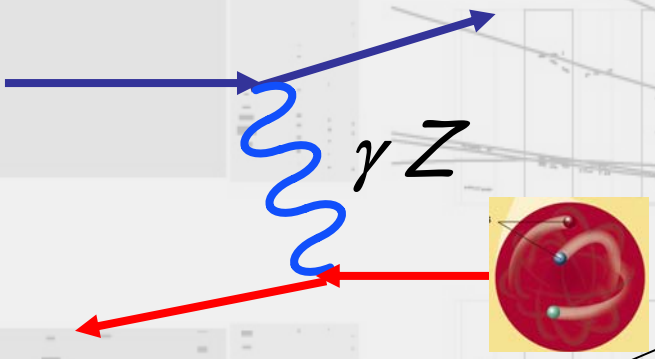
- identify anomalies
- *pp* (TeVatron) → quark/gluon+quark/gluon 10^{-18} m
- *ep* (HERA) → lepton+quark 10^{-18} m:

How do we know it's lepton+quark?

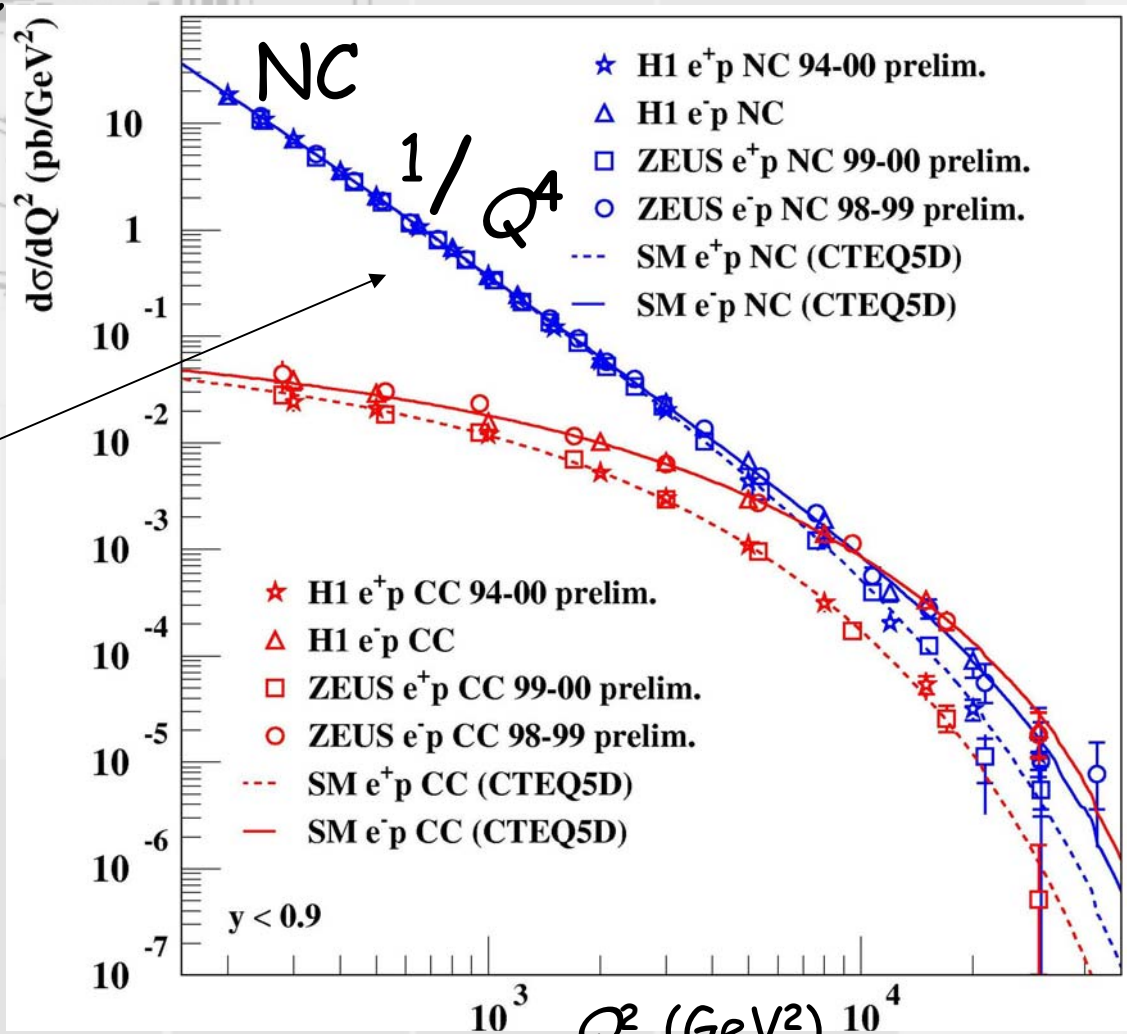


The Data speak: Dirac Quarks and Leptons

- angular dependence - Q^2 dependence
- inclusive NC $ep \rightarrow eX$



$\sigma \sim 1/Q^4$

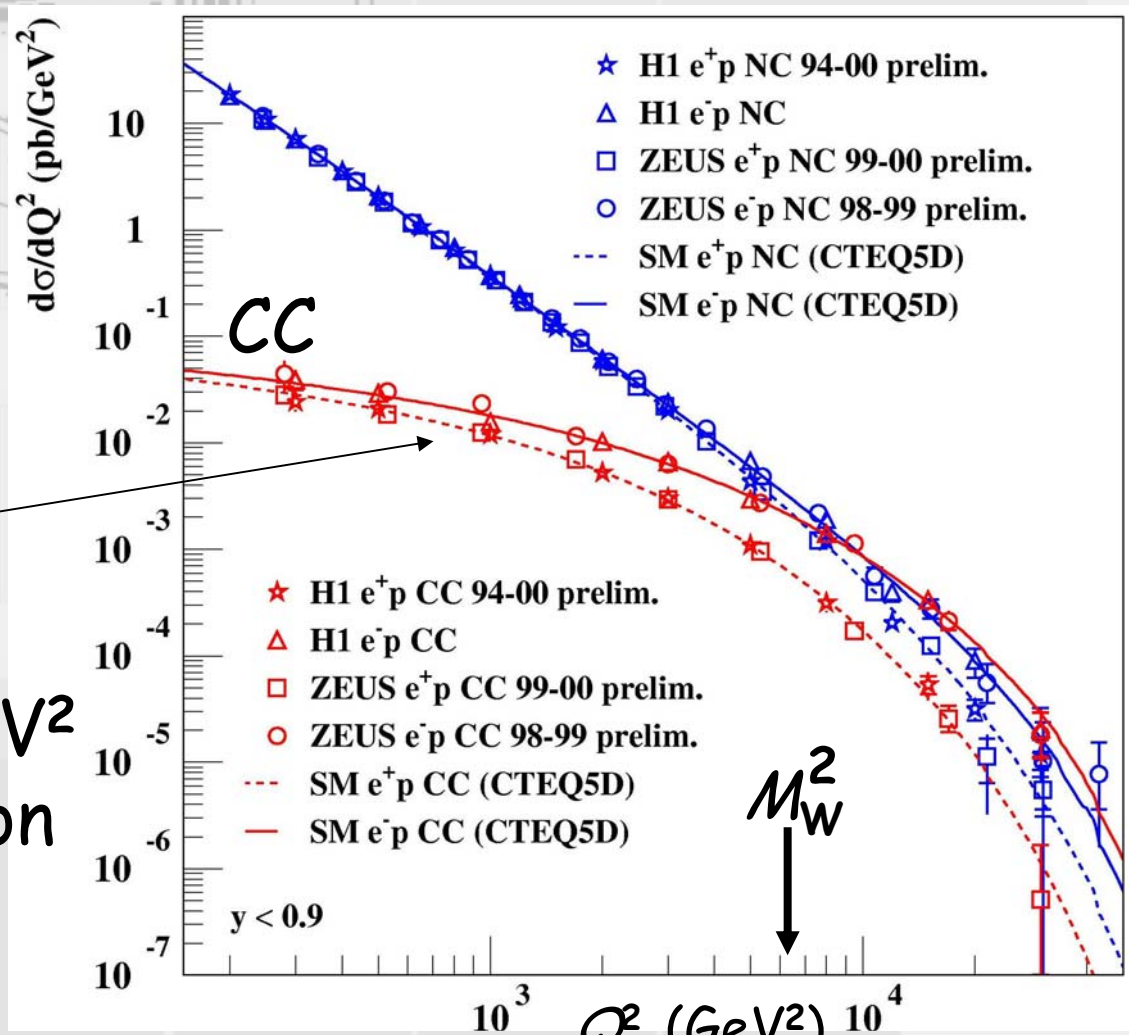


↳ Rutherford *eq*
= Dirac quarks
= SM

The Data speak: Dirac Quarks and Leptons

- angular dependence - Q^2 dependence
- inclusive CC $ep \rightarrow \nu X$

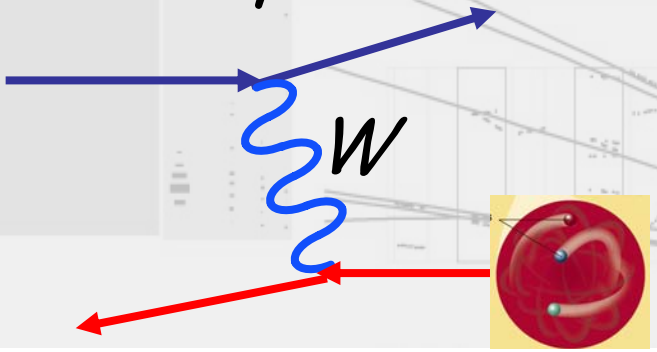
$$\sigma \sim 1/(Q^2+M_W^2)^2$$

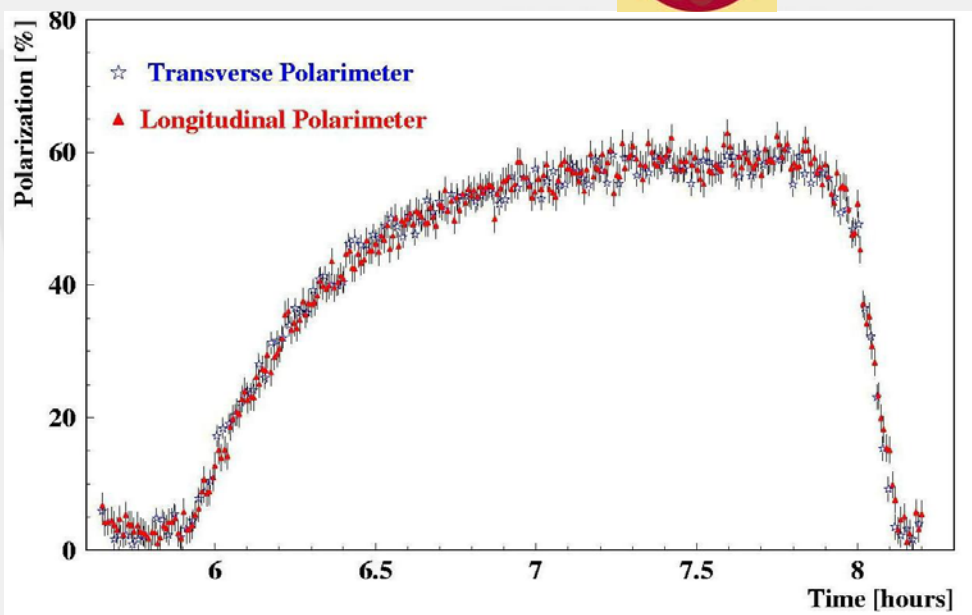


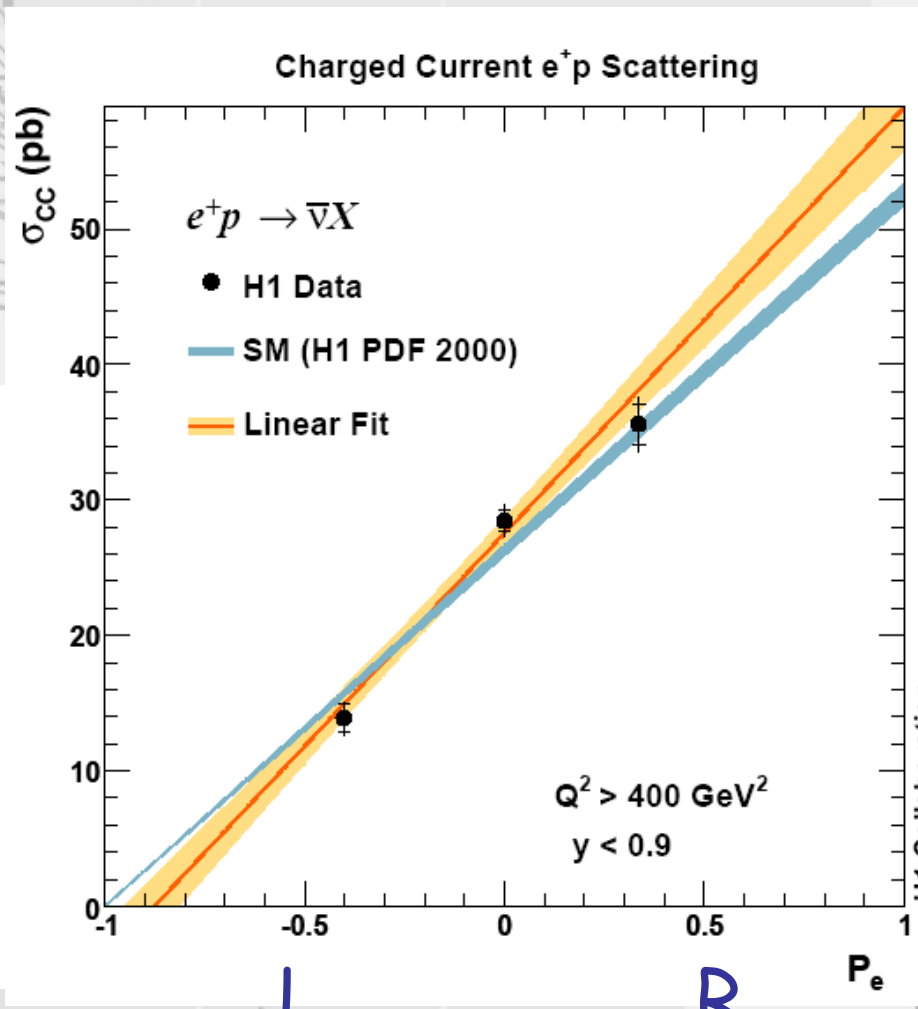
↳ "point-like" < 10^4 GeV^2
= Fermi β-interaction
Rutherford eq
> 10^4 GeV^2

SM Chirality

- CC e_{LR} probe: $u_q \gamma^\mu (v_q + a_q \gamma^5) u_q$ (R)L (anti)fermions ?
  - chirality @ 10^{-18} m

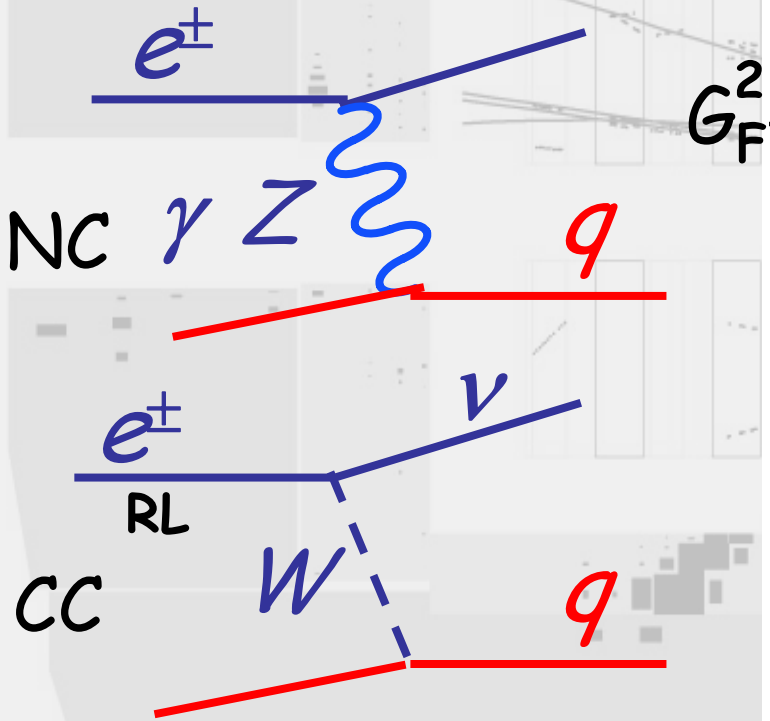


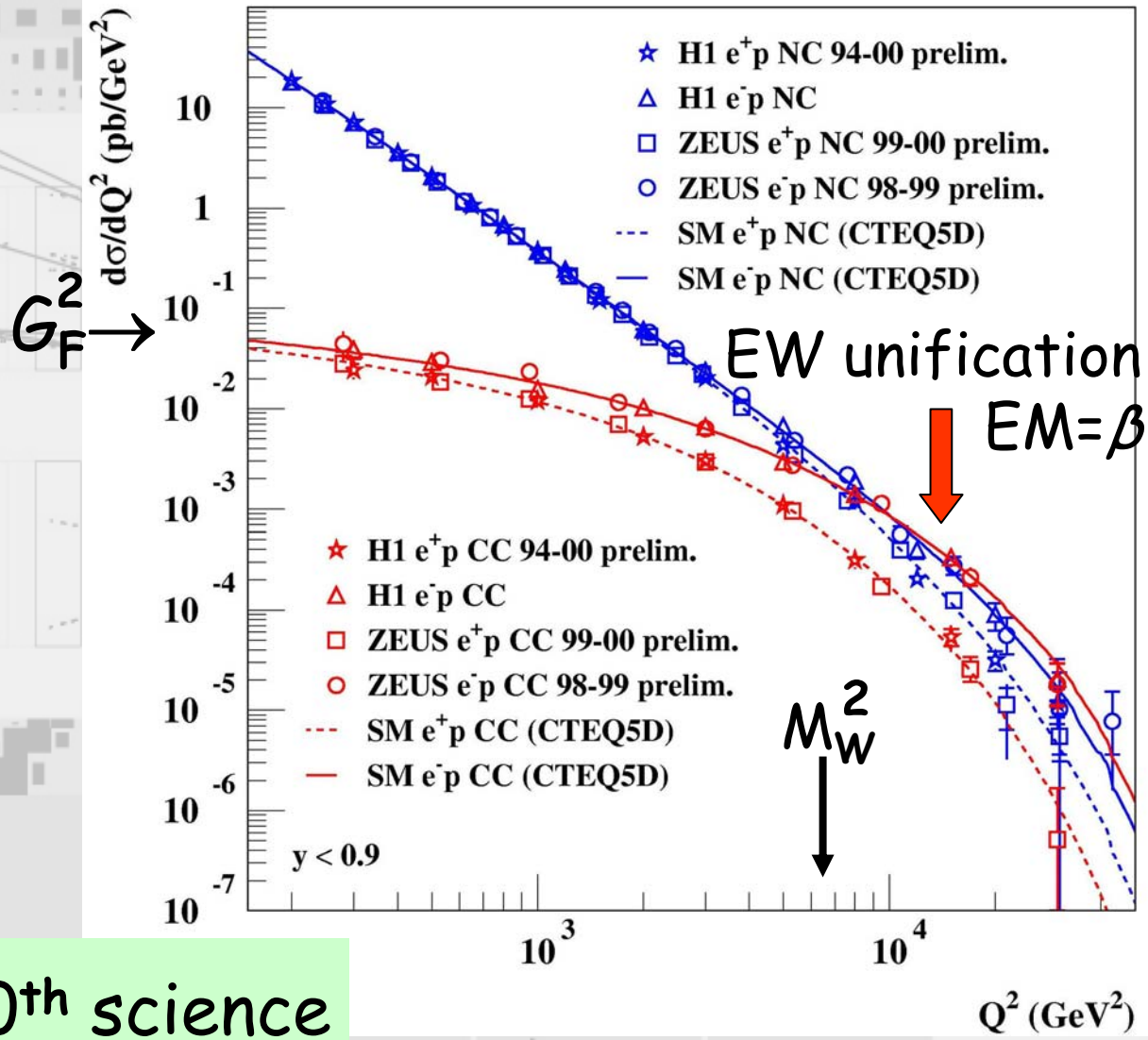




EW Unification

- EW unification @ IVB scale

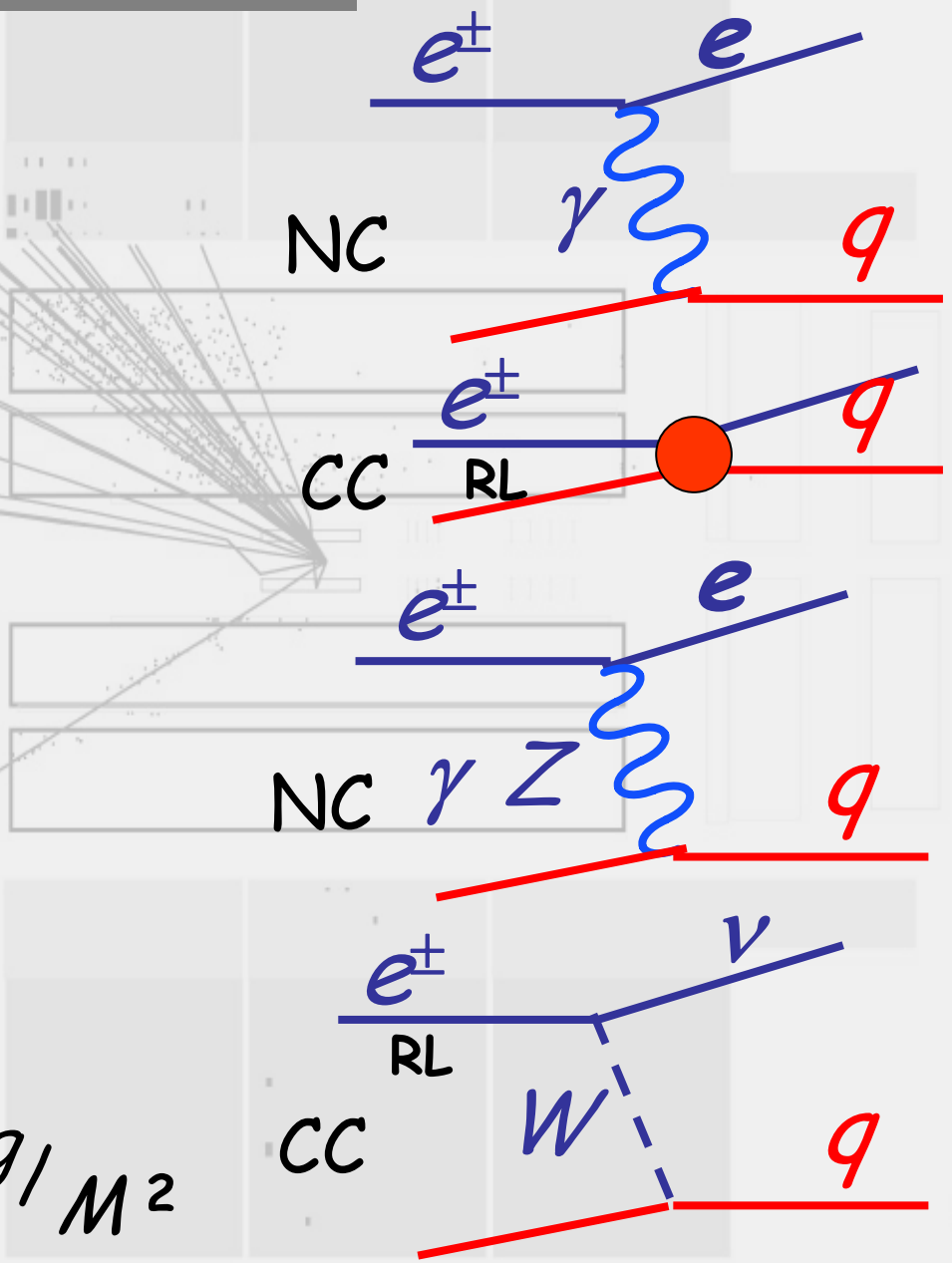




- a triumph of 20th science

EW Unification

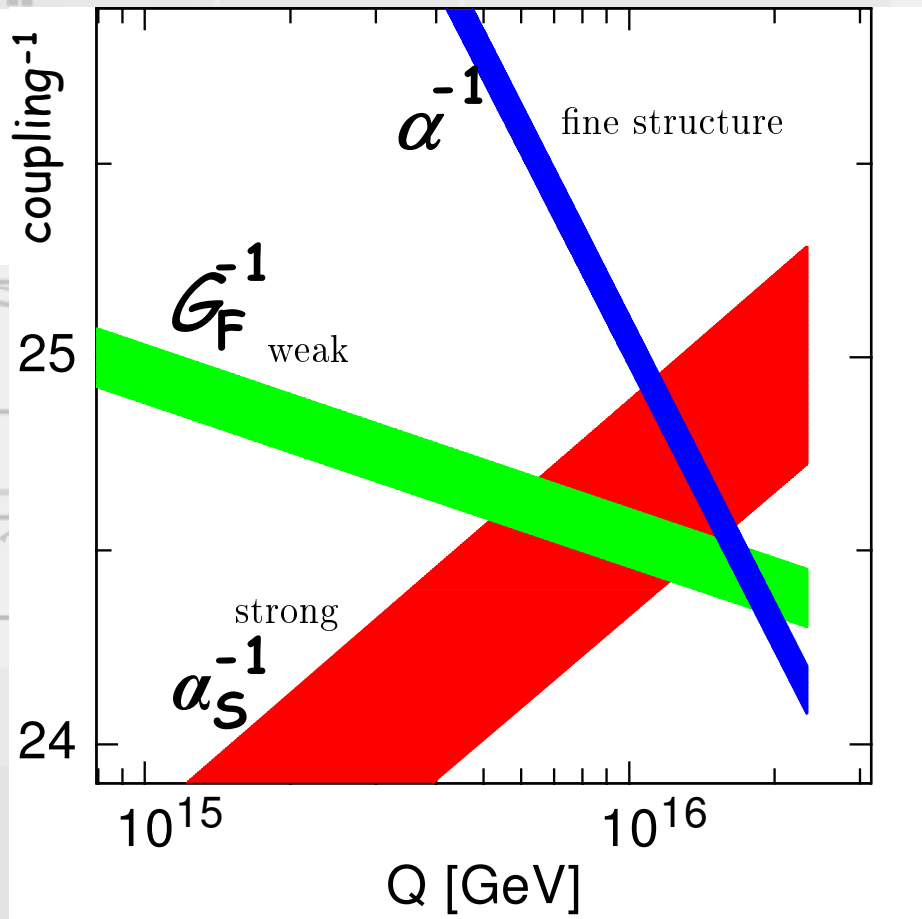
- QED @ few GeV
- β @ few GeV
  Fermi constant G_F
- EW unification @
  $M_W \sim M_Z \sim$ 100 GeV
  - EW=(QED+β)
  - EW gauge theory
  - new structure
  - new gauge bosons
  - Fermi constant $G_F = g/M^2$



Grand(er) Unification ?

- short distance structure of SM → new physics
  → unification: [(QED+β)+QCD] @ 10^{16} GeV
  - 2007 α @ 10^{-9}
  - 2007 G_F @ 10^{-5}
  - 2007 G @ 0.1%
  - 2007 α_s @ 1-2%
  - LHC + detector
    → α_s @ few ‰
    → new physics

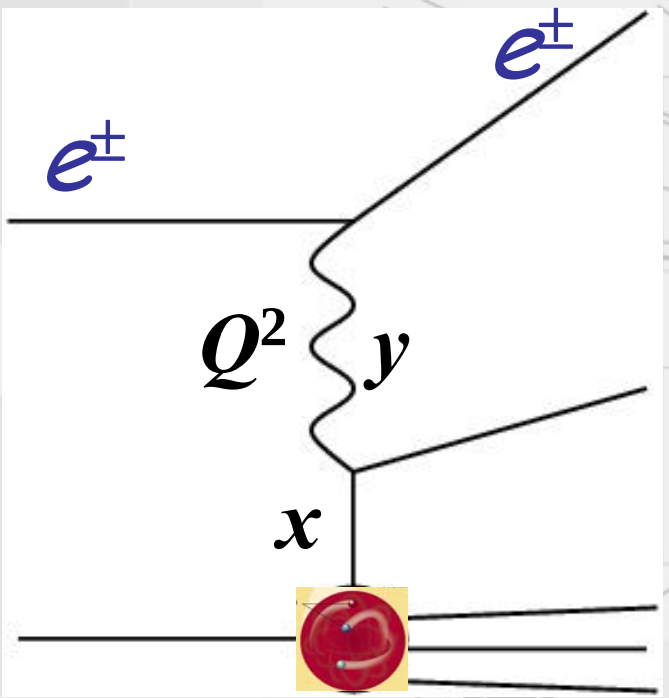
↳ precision + discovery beyond SM

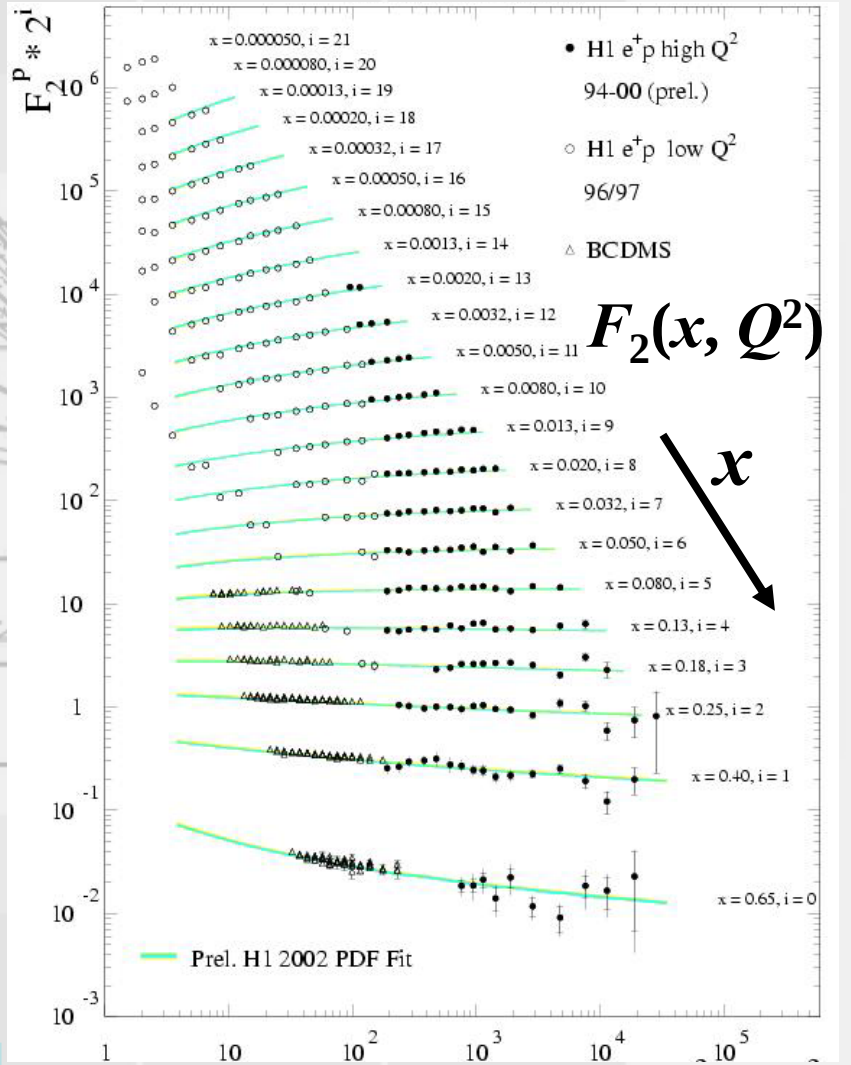


- {[(QED+β)+QCD]+gravity} @ 10^{19} GeV ?

Proton Synthesis

- proton = *uud* + "sea" + *g*



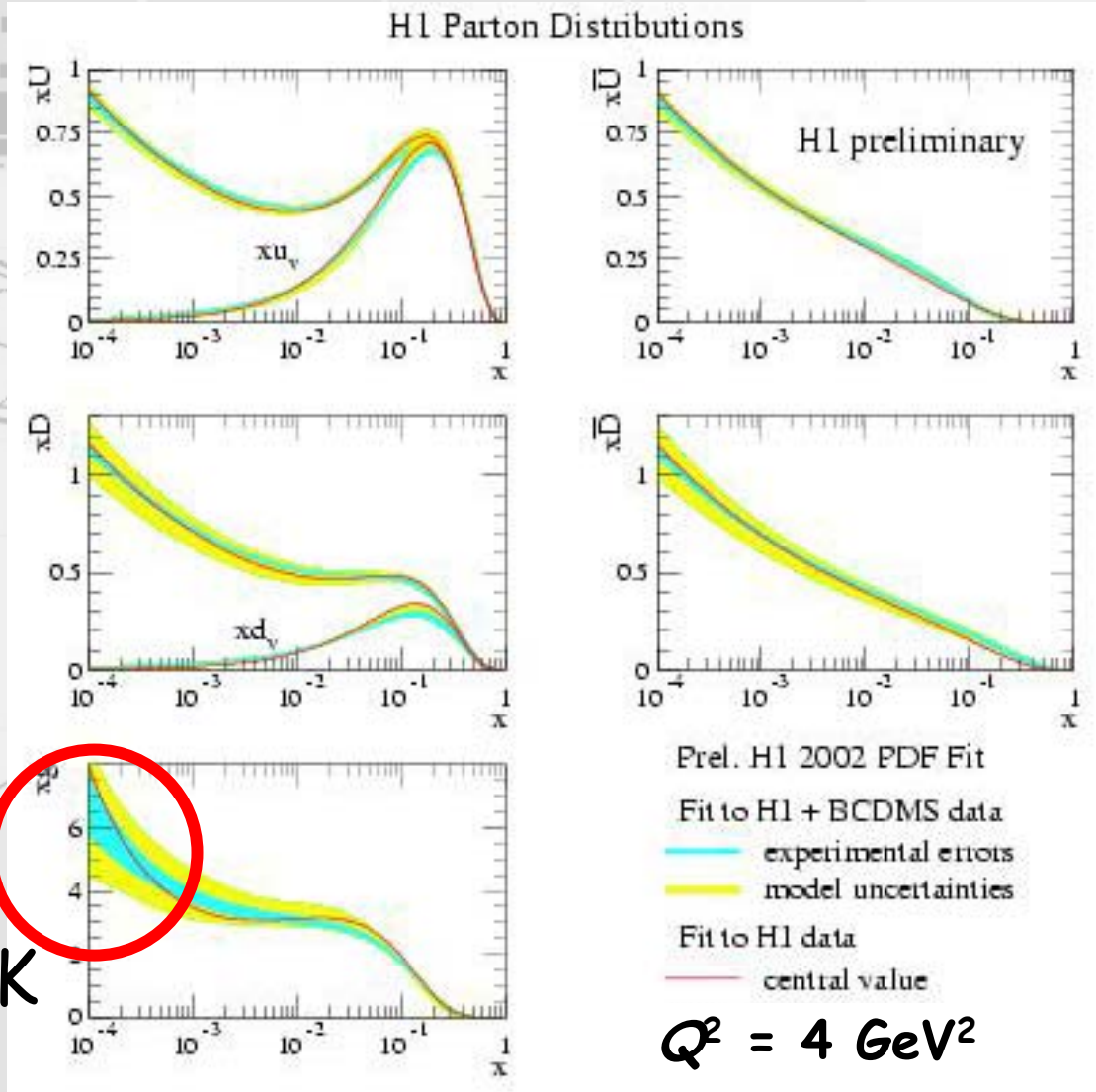


- DGLAP → excellent fit

$$\alpha_S(M_Z^2) = 0.1150 \pm 0.0017(\text{exp.})^{+0.0009}_{-0.0006}(\text{model})$$

Proton Synthesis

- pdf parametrisations
  - leading valence *uud*
  - large sea $q\,\bar{q}$
  - large g ($\frac{1}{2}$ mom^{m})
  - @ factorisation scale (here 4 GeV^2)
- NLO DGLAP *p*QCD OK

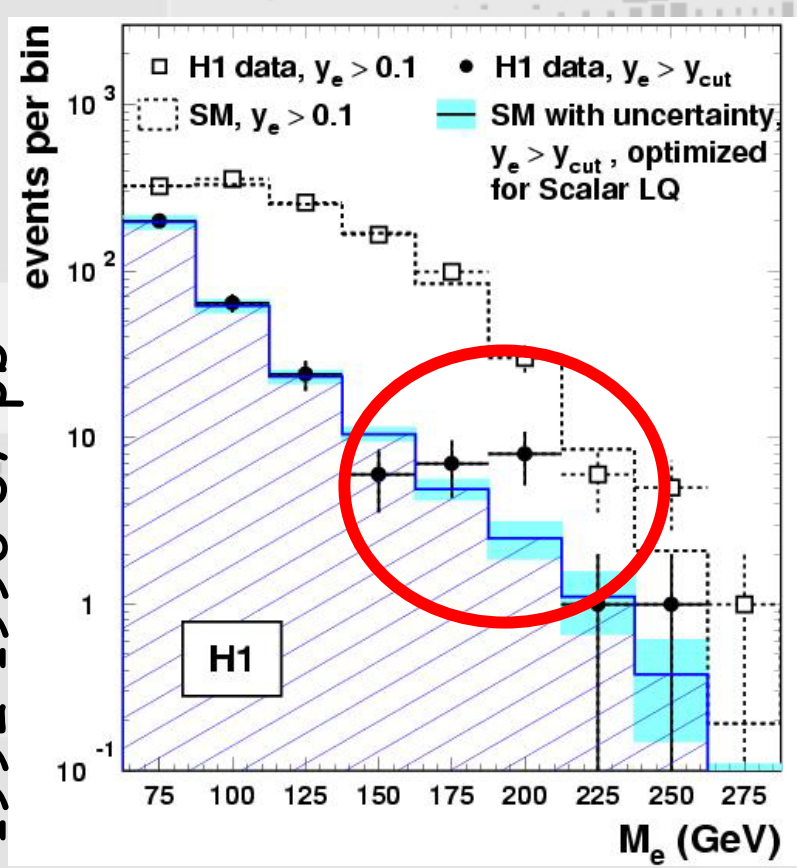


↳ matter is chromodynamic field energy = gluons

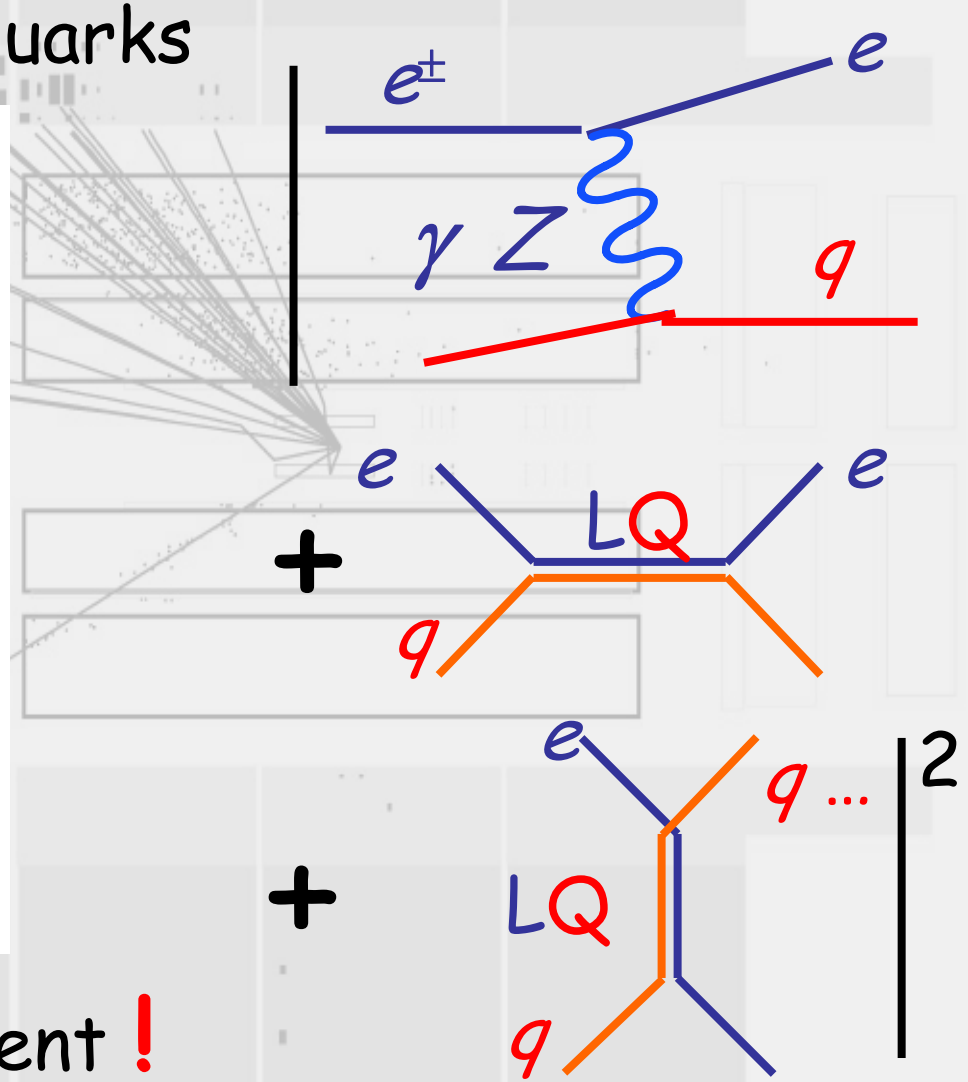
6. Discovery

1990s Example: Leptoquarks?

- new *eq* physics - leptoquarks



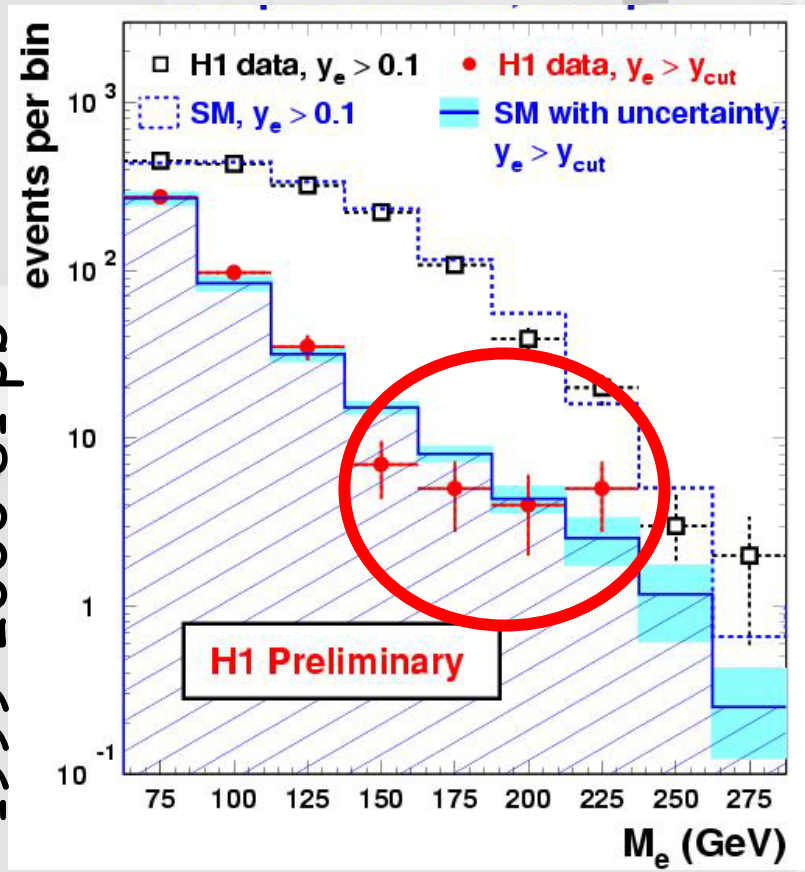
experiment #1
1992-1996 37 pb-1



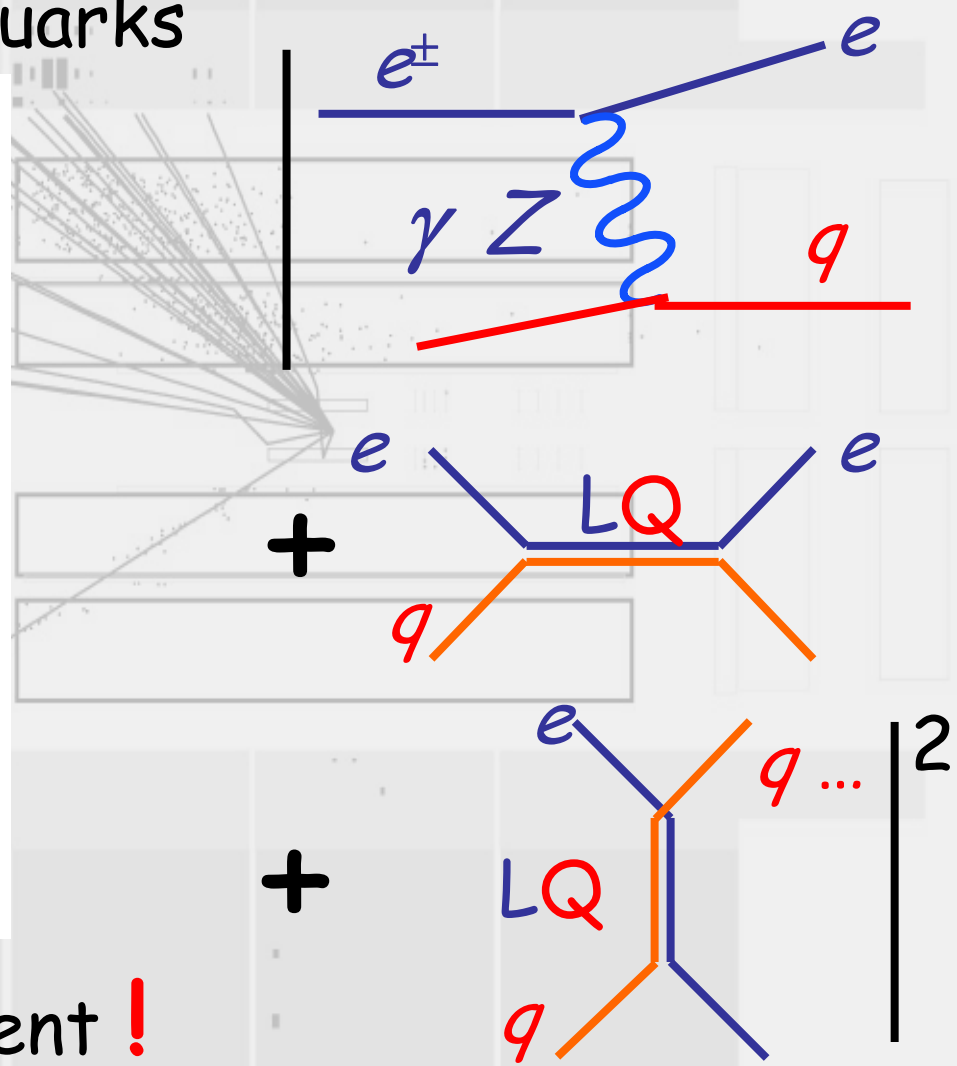
- SM theory ↔ experiment !

1990s Example: Leptoquarks?

- new *eq* physics - leptoquarks



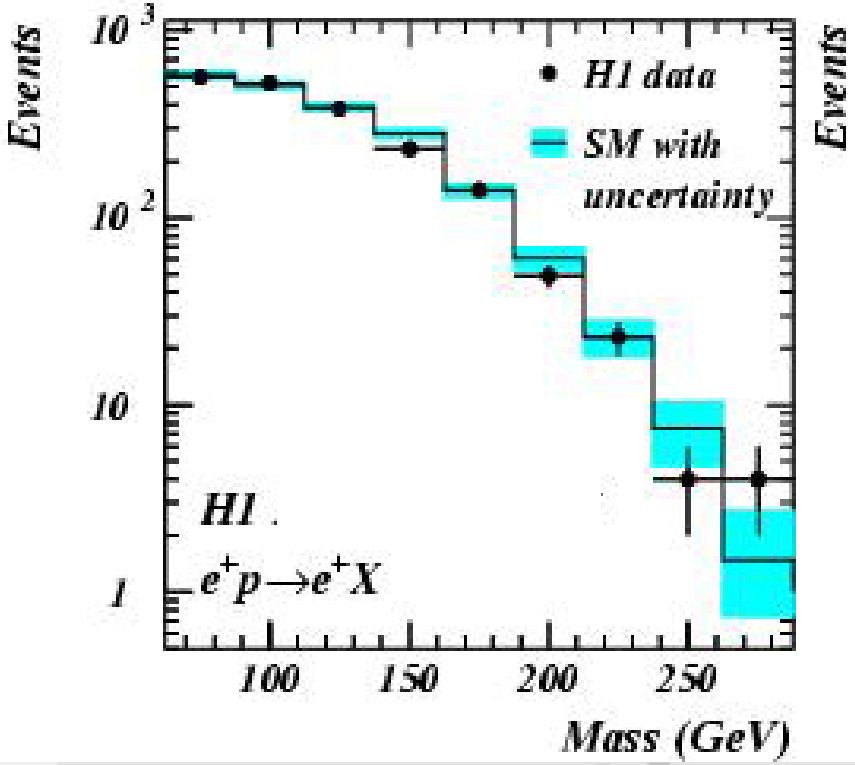
experiment #2
1999-2000 81 pb-1

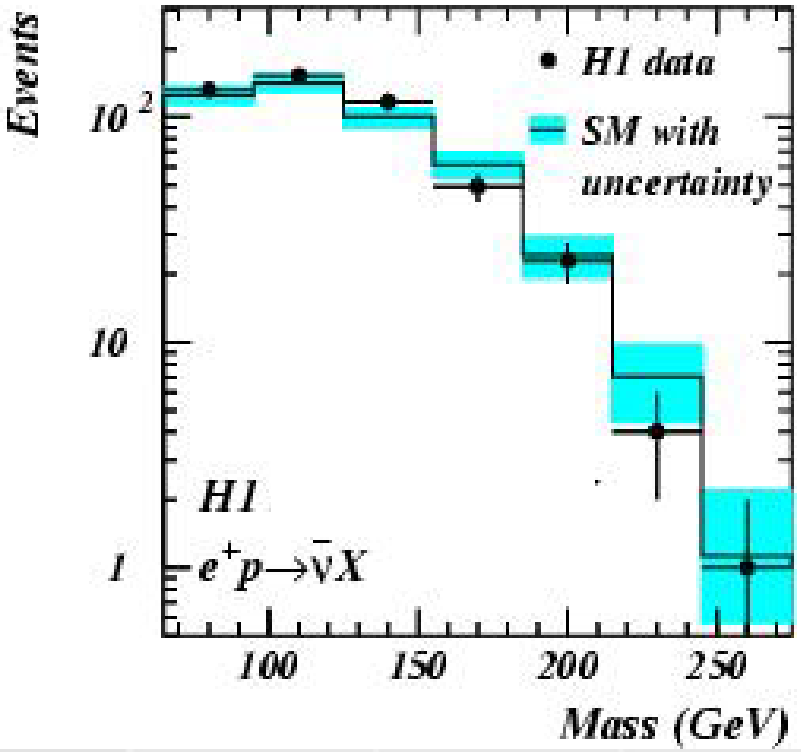


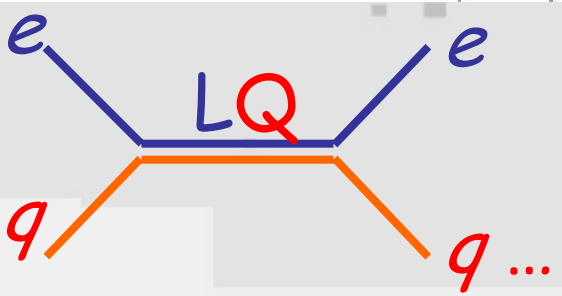
- SM theory ↔ experiment !

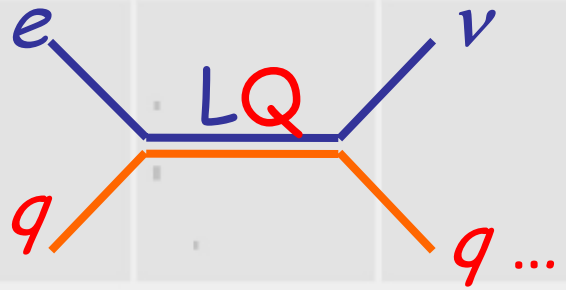
1990s Example: Leptoquarks?

- new *eq* physics – 1992-2000 120 pb^{-1}







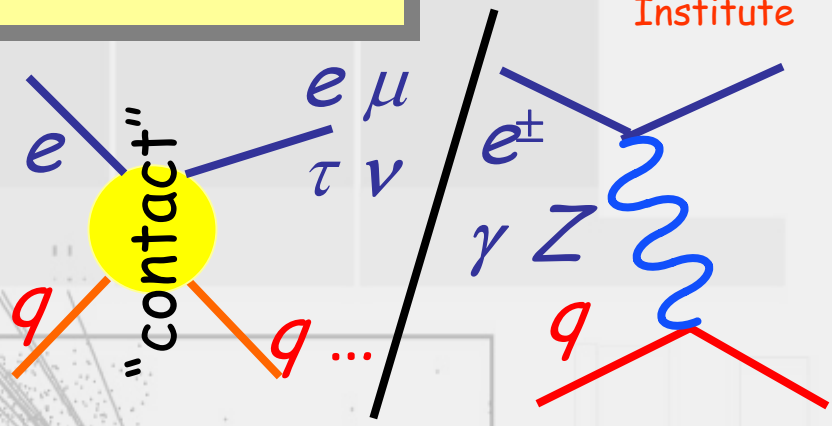


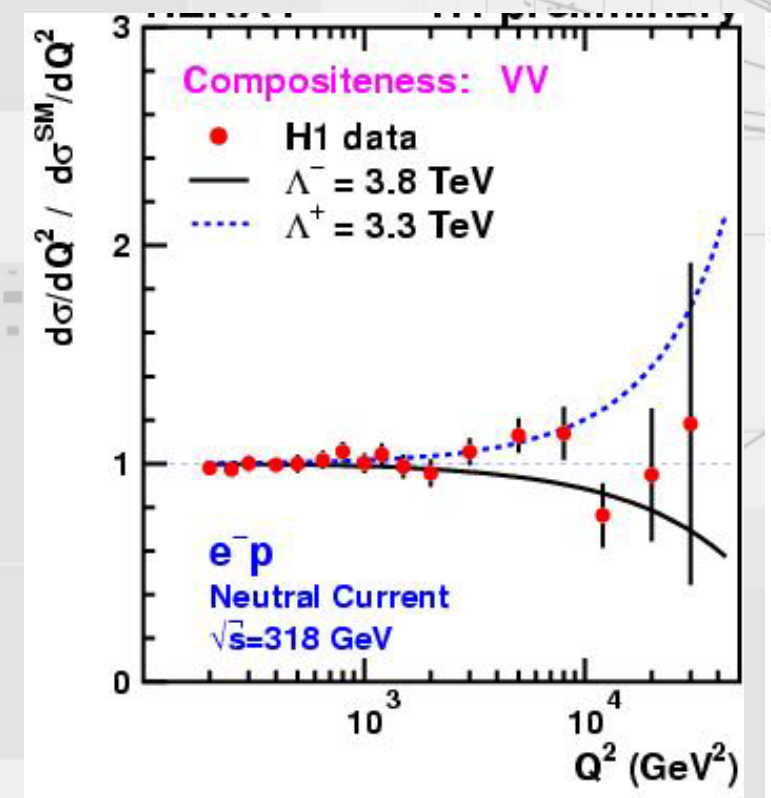
- SM theory ↔ experiment !

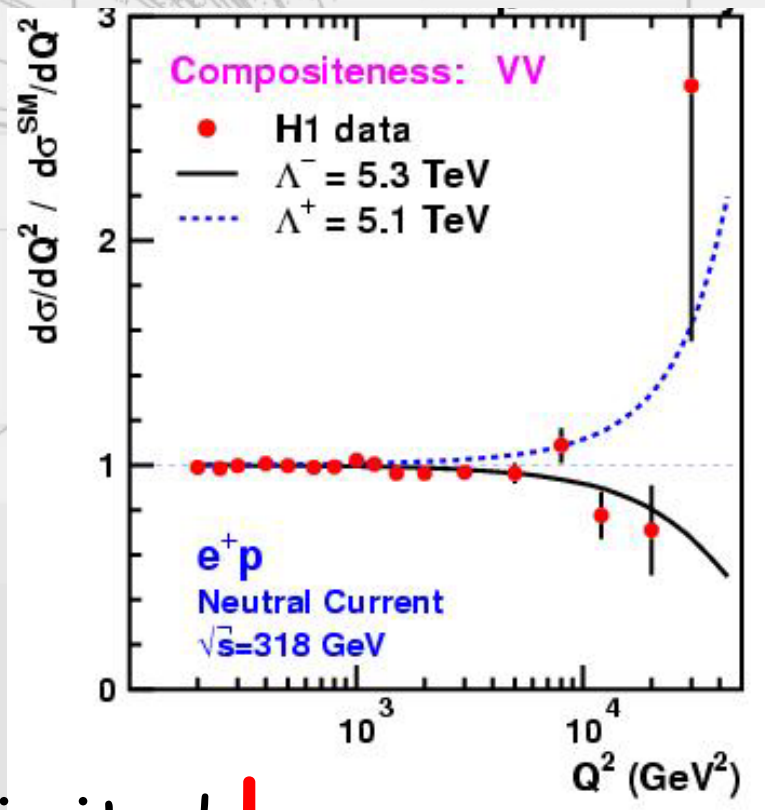
Contact Interactions ?

- large $Q \leftarrow$ small target
  Rutherford scattering

$$\frac{\text{data}}{\text{SM}} =$$







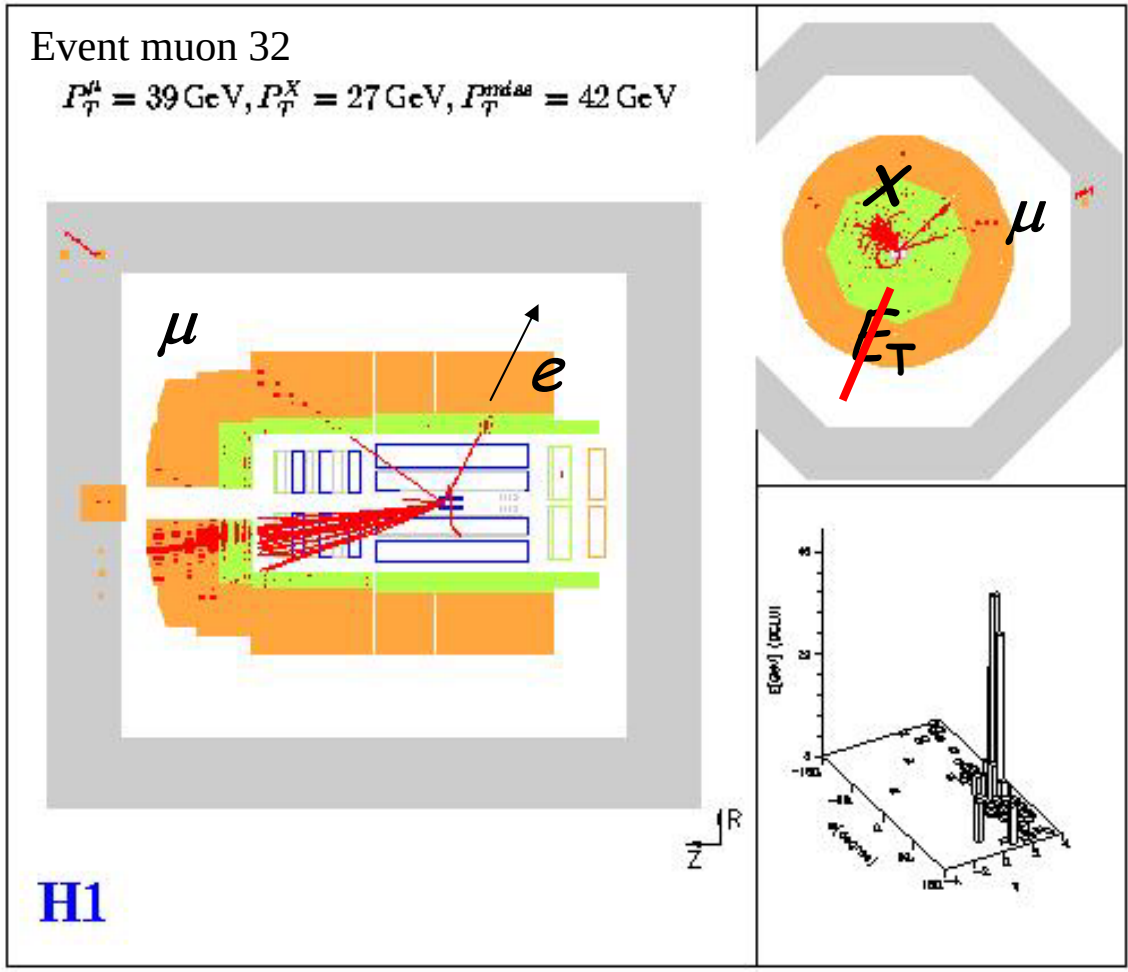
- theory driven – data limited !

Lepton Production

- high p_T leptons
  - striking signature

    $ep \rightarrow (e)\ \mu\ X\ \not{E}_T$
  - anomalous

    $ep \rightarrow (e)\ e\ X\ \not{E}_T$
  - $Q^2 \geq 0$
  - <1 event/7 pb^{-1}>



- signature of new physics

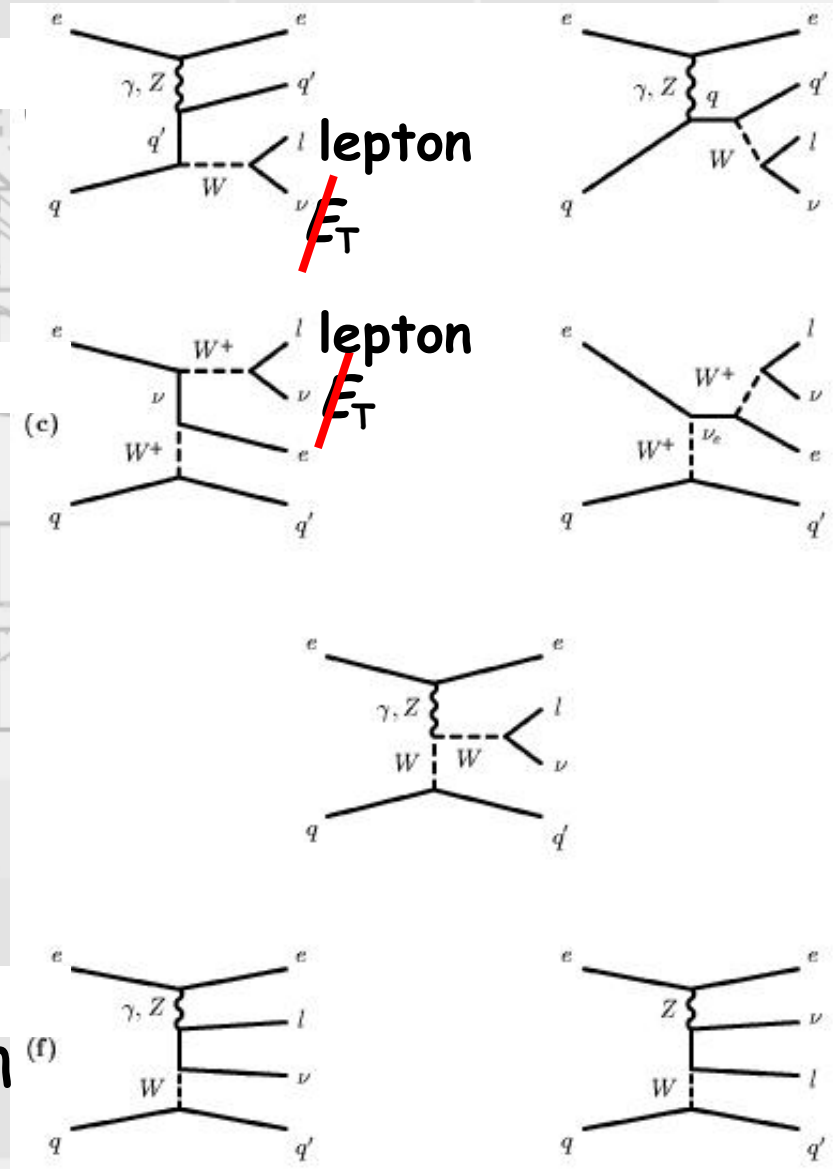
Lepton Production: SM

- high p_T leptons
  - striking signature

    $ep \rightarrow (e)\ \mu\ X\ \not{E}_T$
  - anomalous

    $ep \rightarrow (e)\ e\ X\ \not{E}_T$
  - $Q^2 \geq 0$
  - <1 event/7 pb^{-1}>

- SM W production
  NLO QCD/EW calculation

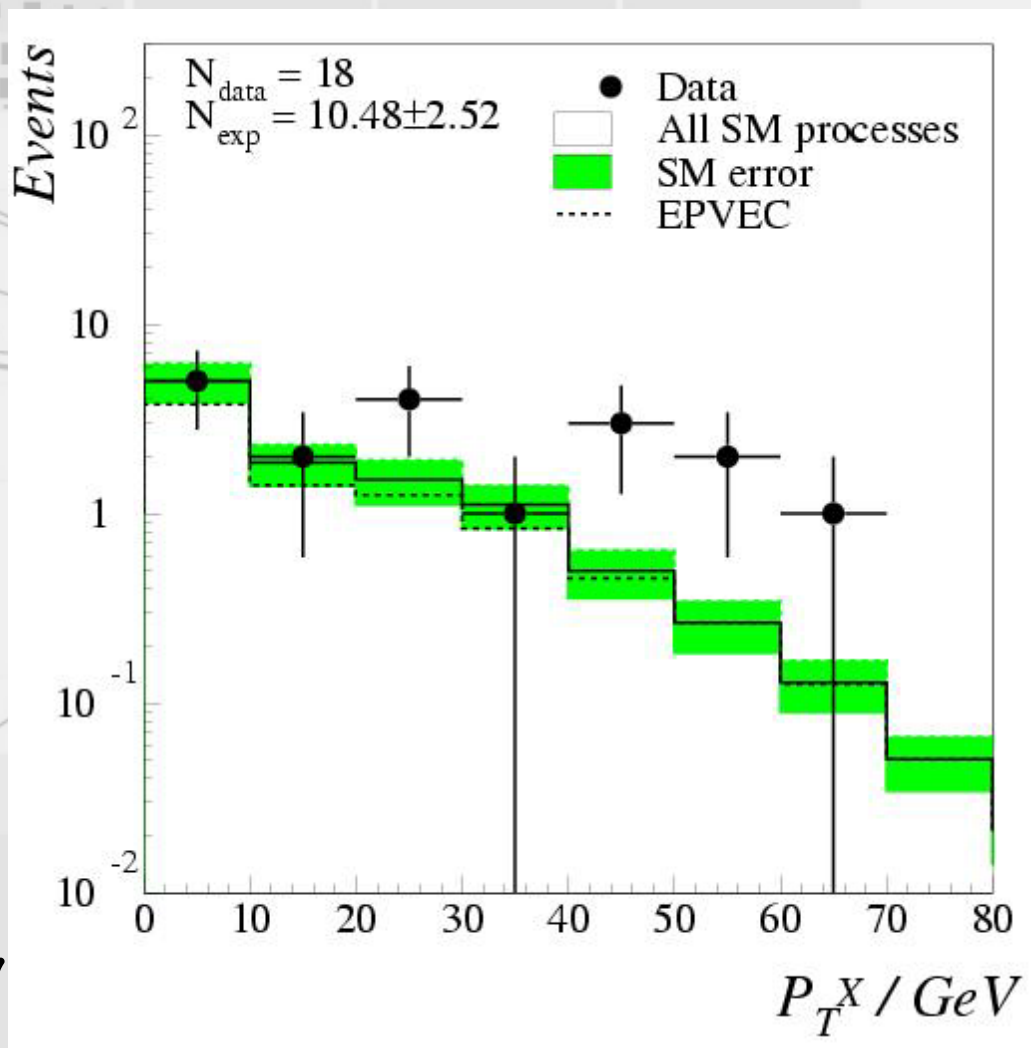


Lepton Production

- high p_T leptons
  - striking signature

    $ep \rightarrow (e)\ \mu\ X\ \not{E}_T$
  - anomalous

    $ep \rightarrow (e)\ e\ X\ \not{E}_T$
  - $Q^2 \geq 0$
  - <1 event/7 pb^{-1}>
- "excess" p_T > 25 GeV



Lepton Production

- high p_T leptons

$ep \rightarrow (e)\ e\ X\ \not{E}_T$

Electron	Data	SM expectation	W	Other SM processes
$P_T^X > 0$ GeV	10	7.92 ± 1.88	6.08 ± 1.83	1.83 ± 0.45
$P_T^X > 12$ GeV	5	2.57 ± 0.65	2.11 ± 0.63	0.46 ± 0.16
$P_T^X > 25$ GeV	4	1.29 ± 0.33	1.05 ± 0.32	0.24 ± 0.11
$P_T^X > 40$ GeV	2	0.41 ± 0.12	0.40 ± 0.12	0.01 ± 0.01

excess

$ep \rightarrow (e)\ \mu\ X\ \not{E}_T$

Muon	Data	SM expectation	W	Other SM processes
$P_T^X > 12$ GeV	8	2.56 ± 0.69	2.11 ± 0.63	0.46 ± 0.27
$P_T^X > 25$ GeV	6	1.54 ± 0.41	1.29 ± 0.39	0.25 ± 0.13
$P_T^X > 40$ GeV	4	0.58 ± 0.16	0.53 ± 0.16	0.05 ± 0.03

excess

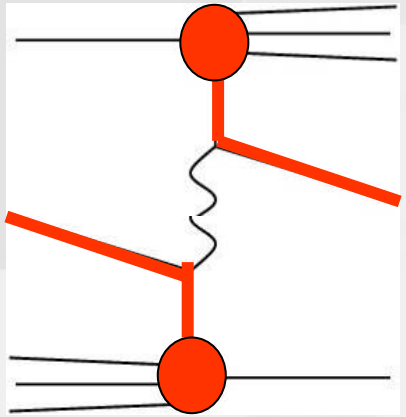
- SM theory $\leftrightarrow$ experiment !

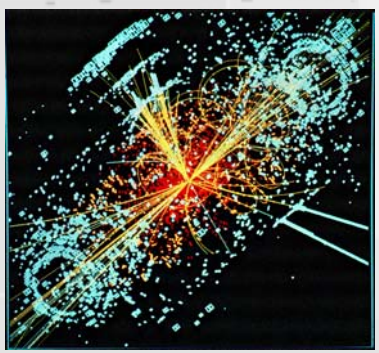
7. Onwards

Many ILC and CLIC slides courtesy J-P Delahaye (CERN)
Auger results courtesy Alan Watson (Leeds)
CERN Atlas website

The Higher Energy Frontier

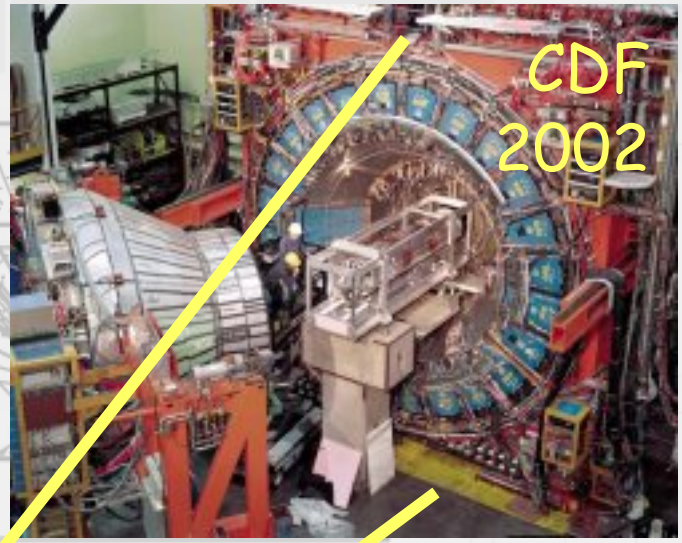
- high energy quarks and gluons

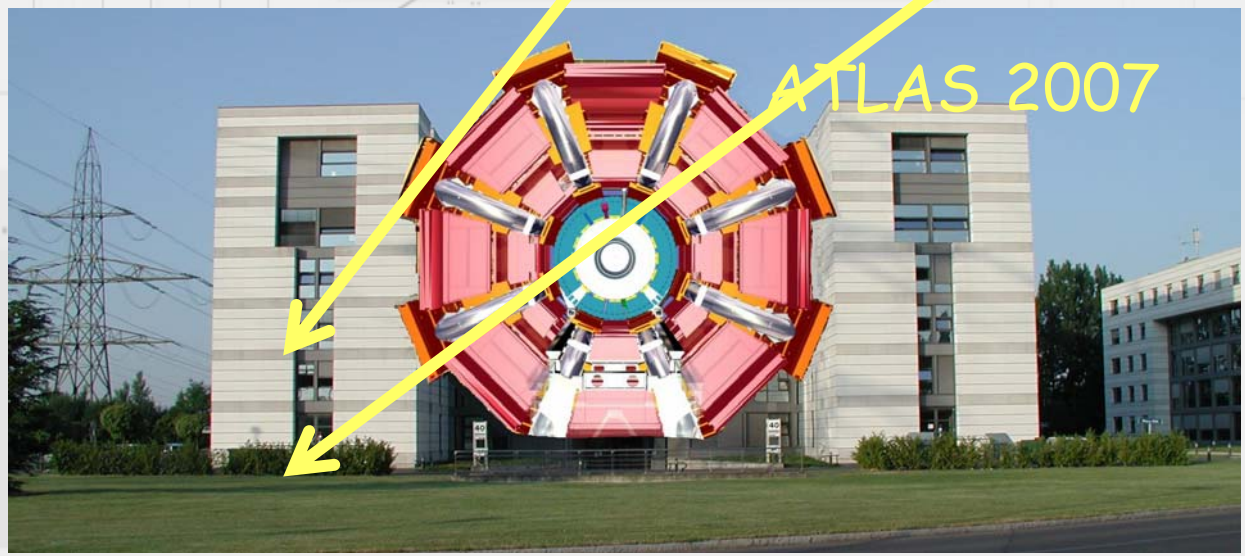




- ATLAS: LHC
  7+7 TeV *pp*
  CERN

- CDF: Tevatron
  1+1 TeV *pp*
  Fermilab USA

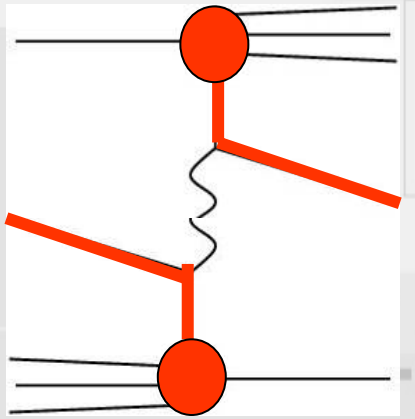


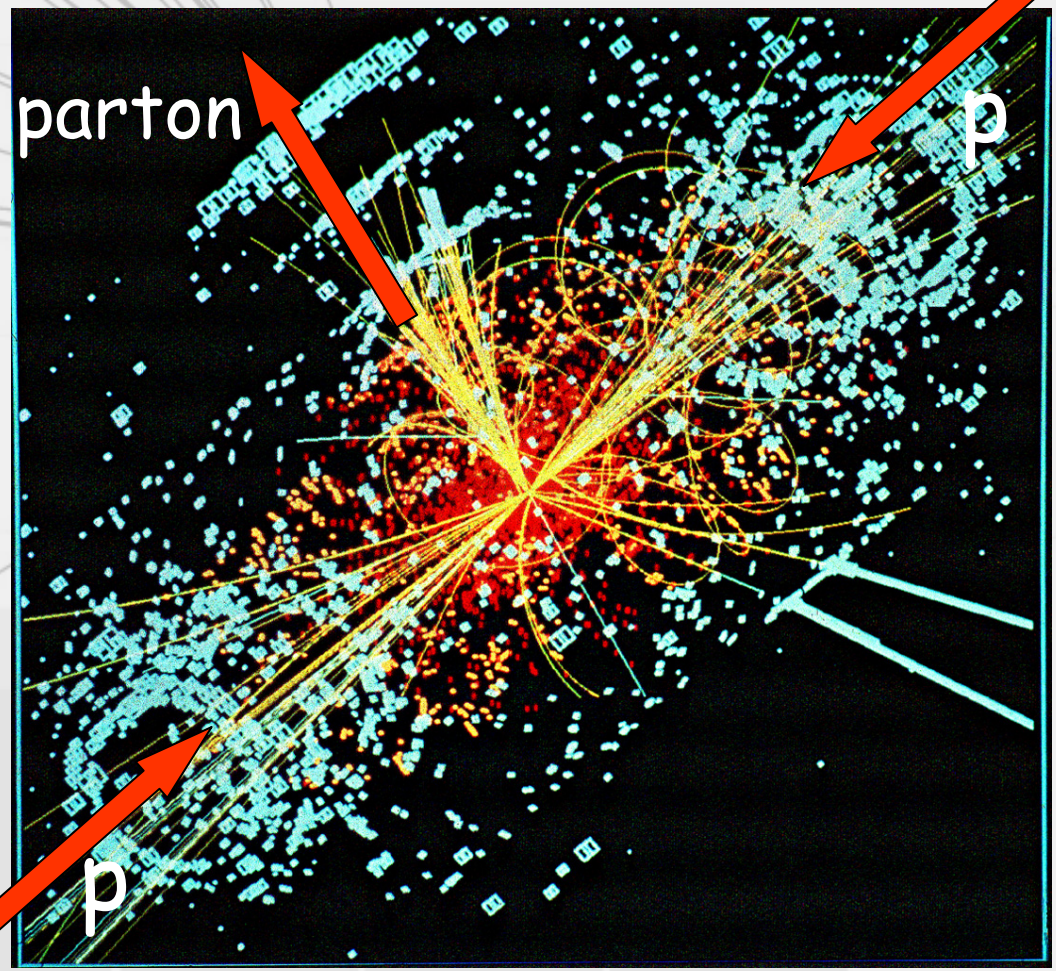


The Higher Energy Frontier: the next step

- putting 14 TeV energy and quarks together @ LHC
  - underlying partons at large momentum
  - TeV scale physics ? 2007 !

Rutherford Scattering par excellence!

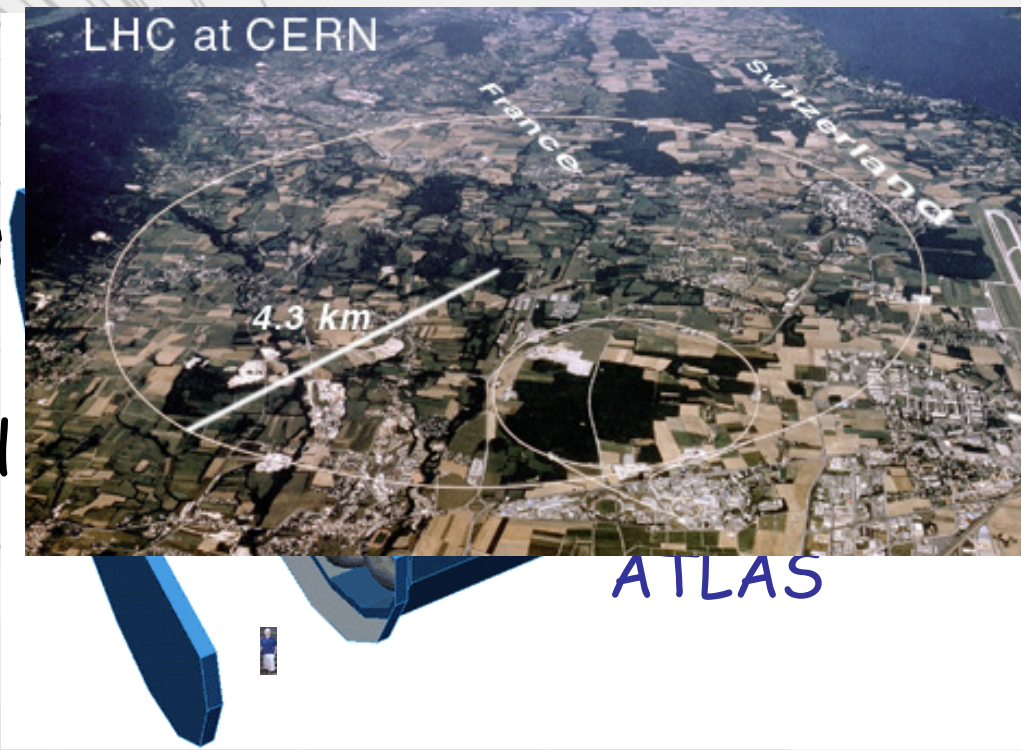




large energy transfer
large scattering angle

ATLAS and CMS @ LHC

- a new energy scale – a new scale of experiment
  - huge *pp* luminosity
  - rad-hard detectors
  - sophisticated triggers
  - huge data rate:
  - $^{1}/_{500,000}$ events wanted



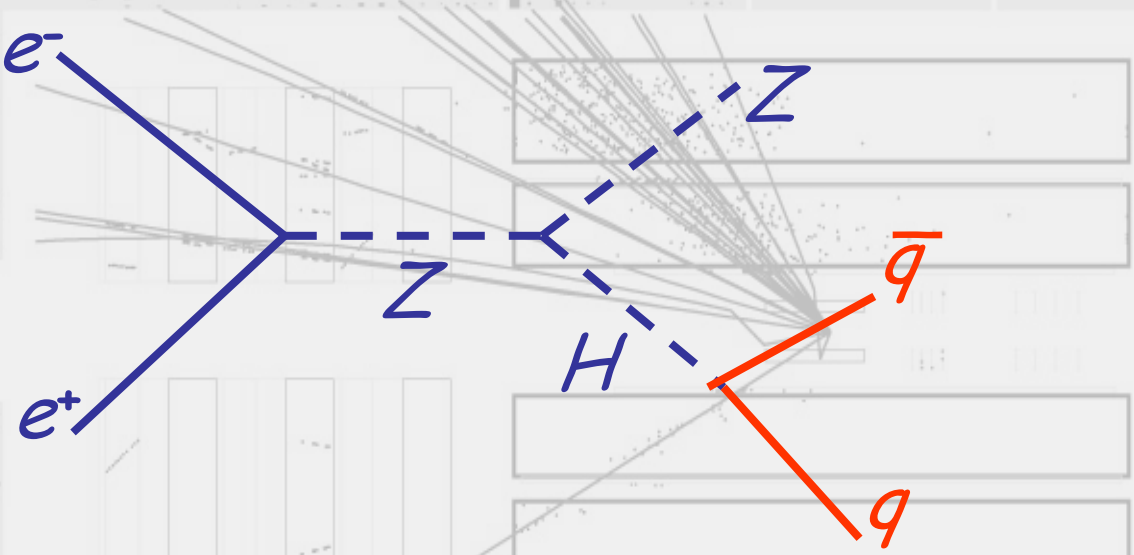
data ?

+

SM theory ↔ experiment ➡ discovery !

The Future Energy Frontier ?

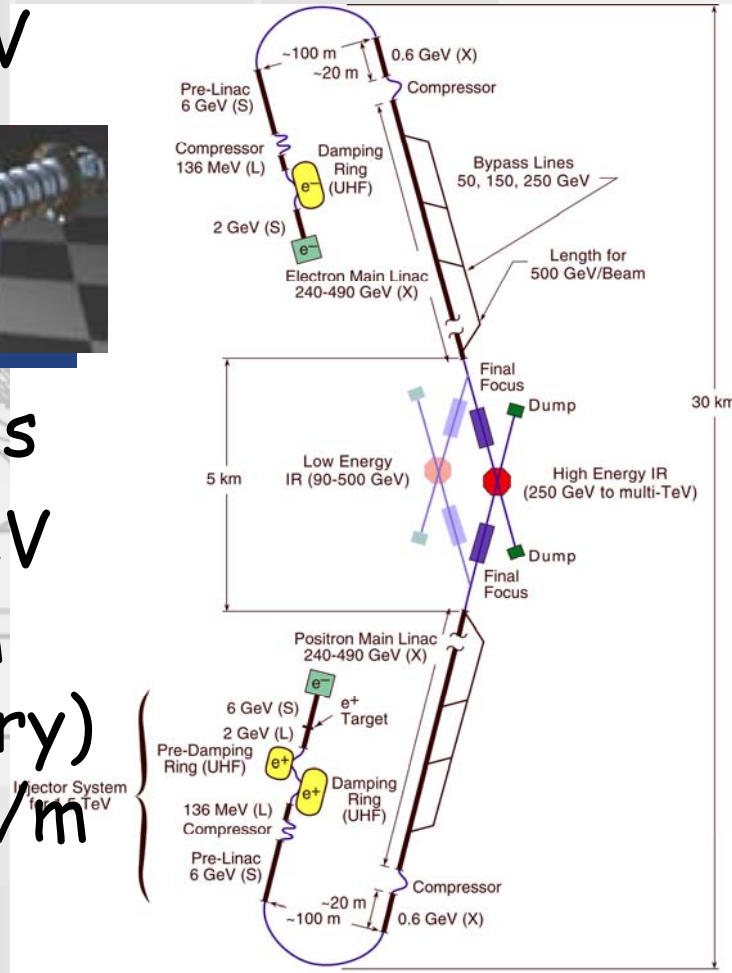
- exciting the vacuum @ TeV energy



- measuring the new physics
  - precision
  - chromodynamics from the vacuum
- TeV ?

The Future Energy Frontier ?

- energy frontier e^+e^- @ 500 GeV
  - energy + bend
    = radiation → ~~rings~~
  - e^+e^- linear acceleration
    → linear collider → single pass
  - challenging technology 500 GeV
    luminosity → sub-micron beam
    many sc cavities (world industry)
    all working flawlessly @ 31 MV/m
    → 250 GeV in 15 km !

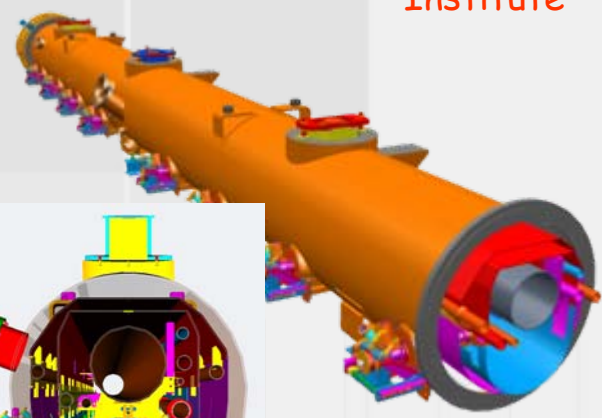


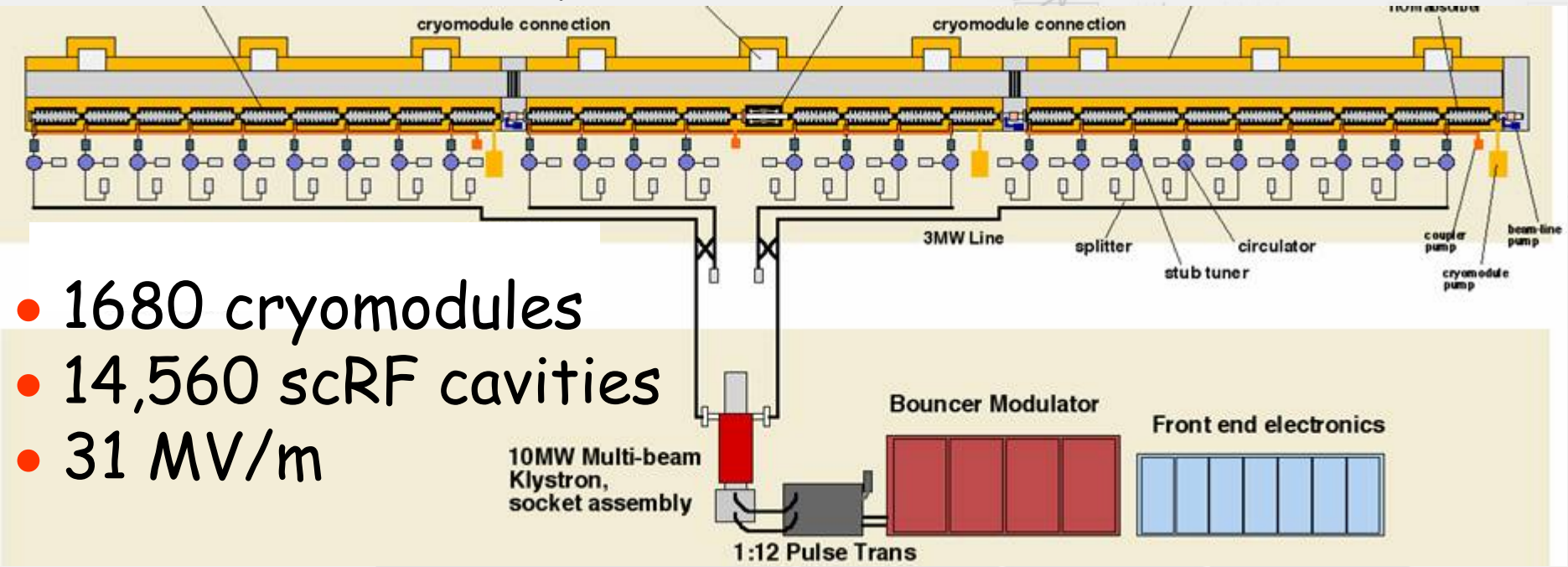
- Where? When? (from 2011?) With what? (>$7 bn)

John Dainton
September
2007

ILC RF

- 560 x RF unit:
  - 1 bouncer-type modulator
  - 1 multibeam klystron (10 MW, 1.6 ms)
  - 3 cryostats (9+8+9=26 cavities)
  - 1 central quadrupole





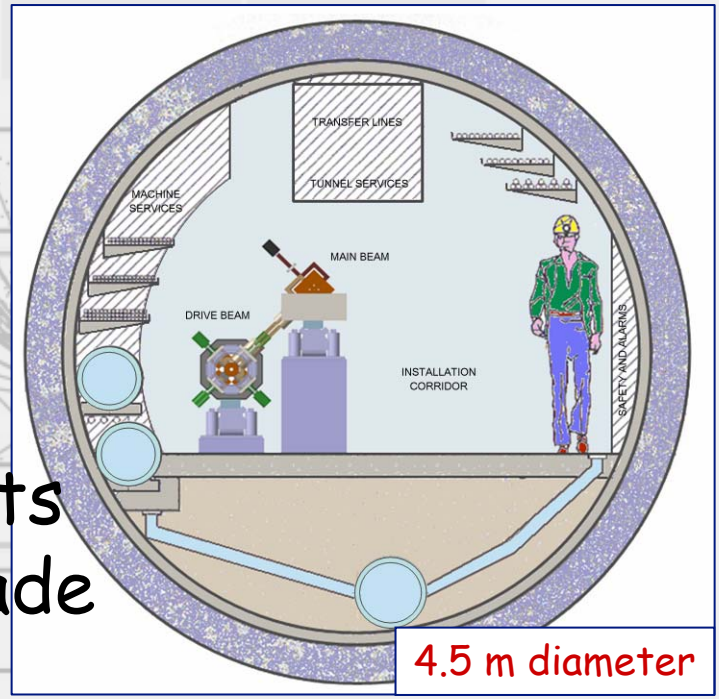
- 1680 cryomodules
- 14,560 scRF cavities
- 31 MV/m

CLIC – basic features

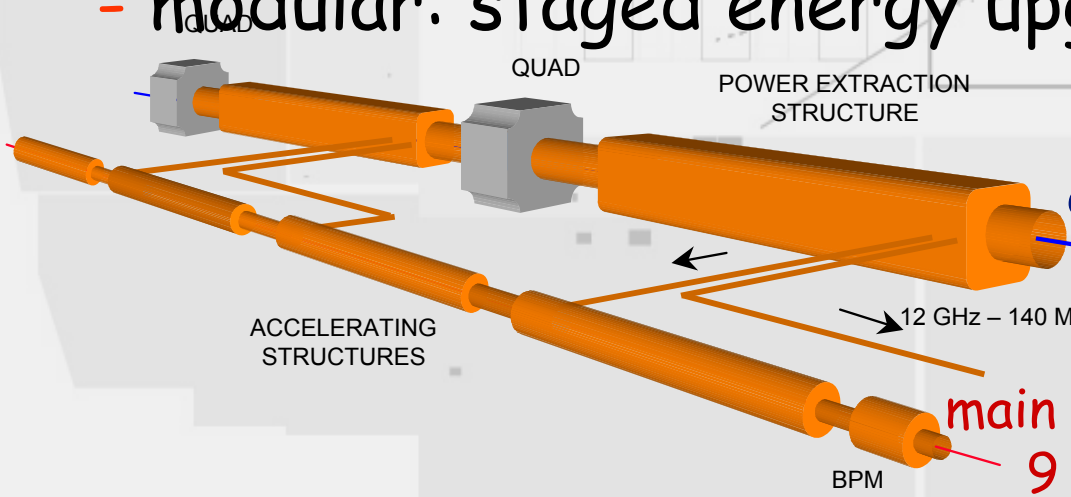
- high acceleration gradient: > 100 MV/m

"Compact Linear Collider"

- total length < 50 km @ 3 TeV
- normal conducting
- high frequency
  - novel 2-beam acceleration
  - simple tunnel: passive elements
  - modular: staged energy upgrade



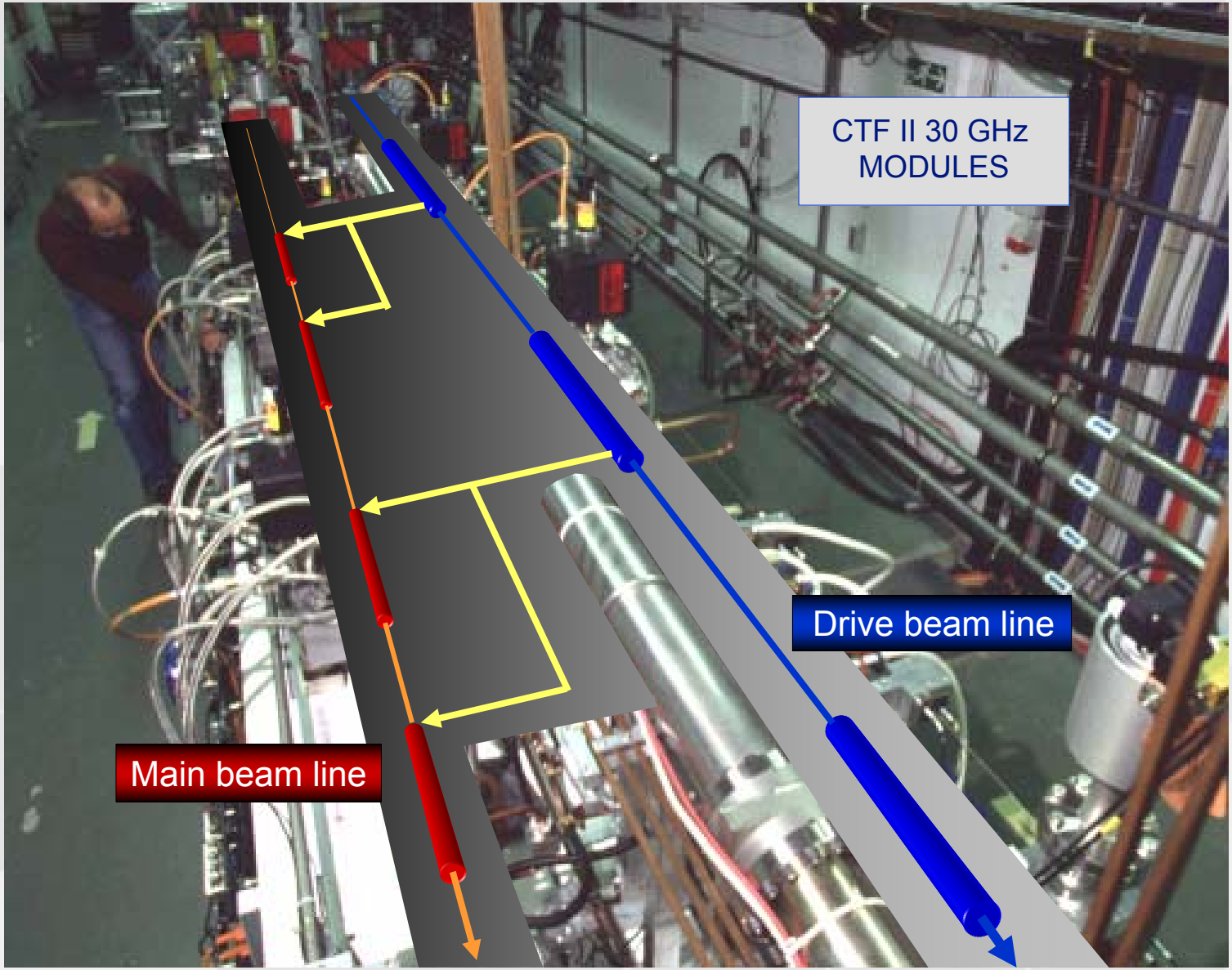
4.5 m diameter



drive beam - 95 A, 300 ns
2.4 GeV to 240 MeV

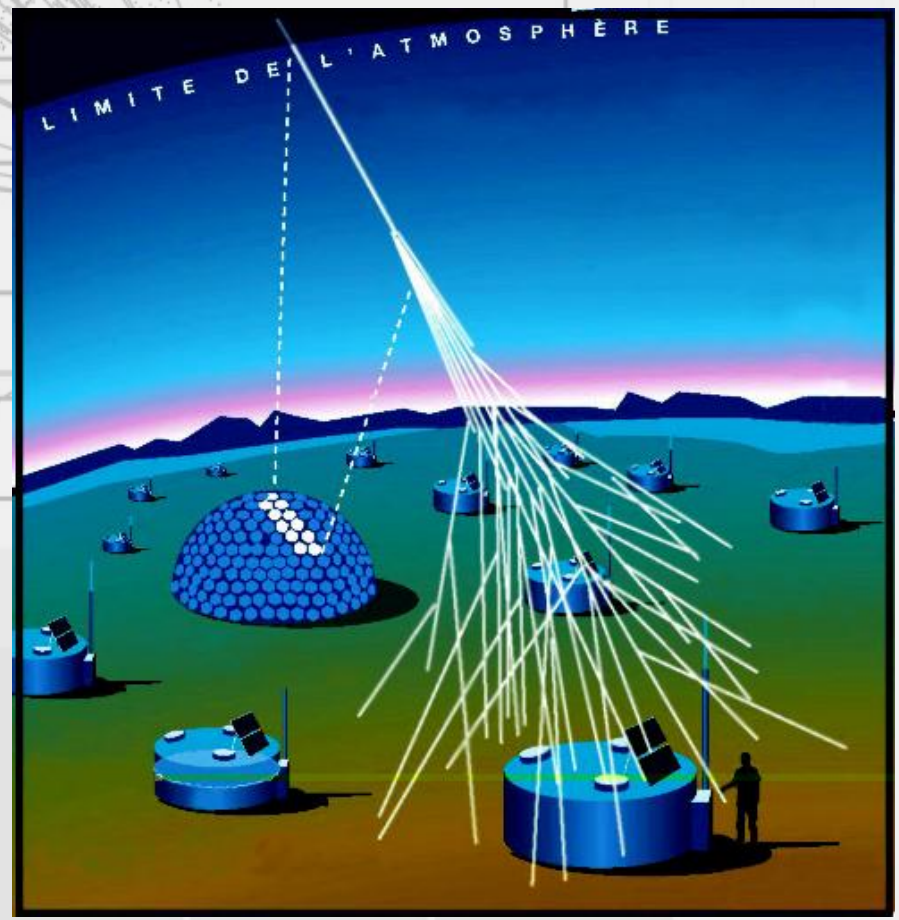
main beam: 1 A, 200 ns
9 GeV to 1.5 TeV

CLIC principle – CTF2



… and Onwards

- the cosmic accelerator to 10^{12} GeV (« 10^{19} GeV cm !)
- southern Pierre Auger Observatory
  - 1600 water Čerençov
  - fluorescence telescopes
  - radio detection
  - 3000 km²



- northern Utah ?

The Cosmic Accelerator

- the cosmic accelerator @ 10^{10} to 10^{12} GeV
  how to interpret ?

$dN/_{dE} \sim E^{-3}$ $E \ll 10^{10.6}$ GeV

$dN/_{dE} \not\sim E^{-n}$ $E > 10^{10.6}$ GeV
6σ

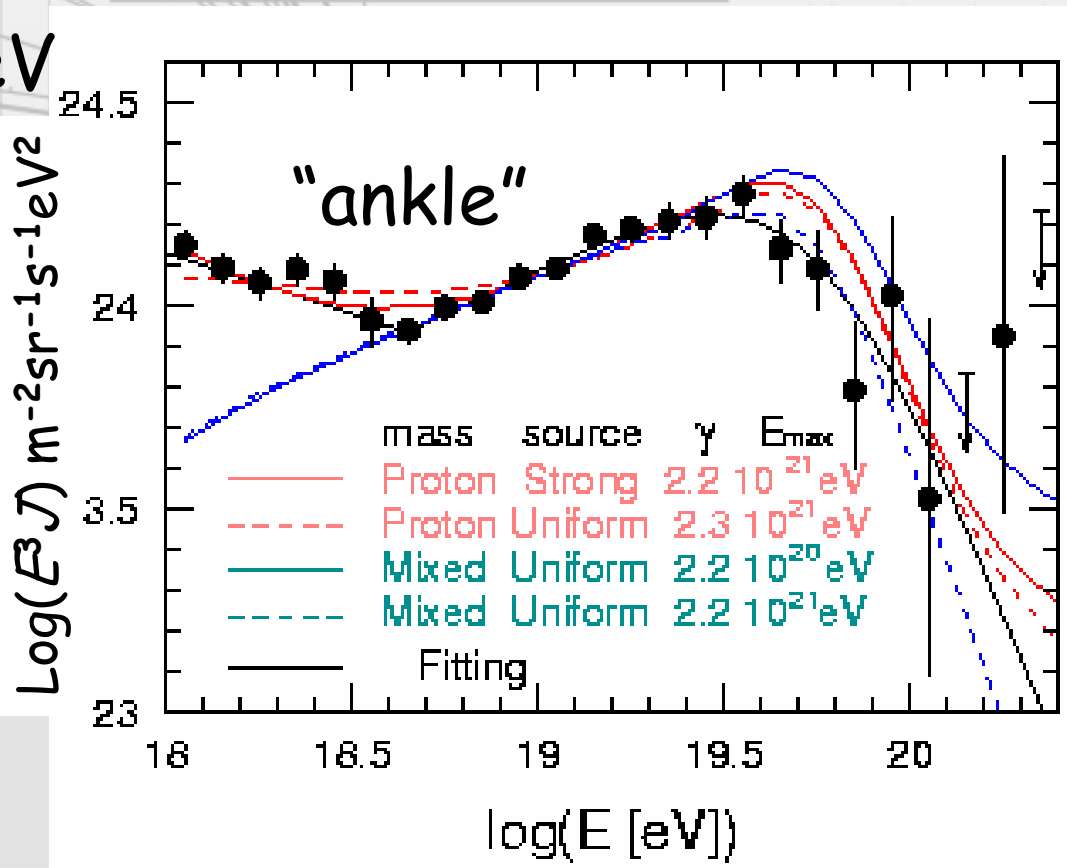
GZK steepening ?

$p\gamma \rightarrow \Delta \rightarrow p\pi$

↳ CMB @ 2.7 K
$h\nu$ = 0.23 meV

galactic source ?

galactic mechanism ?



8. Conclusion

With thanx to very many, too many to name!

Conclusion

- we are on the threshold of a revolution in physics: the LHC (TeV) energy scale
- theoretical expectations are high
- experimental hints are numerous
- experimental challenges are huge and varied
- any significant observation will be a discovery
- theory $\leftrightarrow$ experiment essential (and soon very hot!)
- technologies for further steps not yet established
- already a glint beyond TeV with cosmos

"Rutherford" 2007

"It would be of great scientific interest if it were possible in scientific experiments to have a supply of electrons and protons in general, of which the individual energy of motion is greater even than 7 TeV. This would open up an extraordinarily interesting field of investigation which could not fail to give us information of great value, not only in the constitution, evolution and stability of the Universe, but in many other directions."

with thanks, appreciation, and apologies, to Lord Rutherford PRS

"Information of great value" 2007

- Why three types of quarks and leptons of each charge ?
- Is there some pattern to their masses ?
- Are quarks and leptons fundamental ?
  If not, do they have substructure ?
- What is mass?
- Are there new particles and forces at higher-energy ?