Cashmore @ 70
Oxford
30 June 2015

Constituents, Currents, Colour … and Cashmore

John Dainton

University of Liverpool, UK

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Oxford
30 June 2015

Constituents @ Oxford 1970

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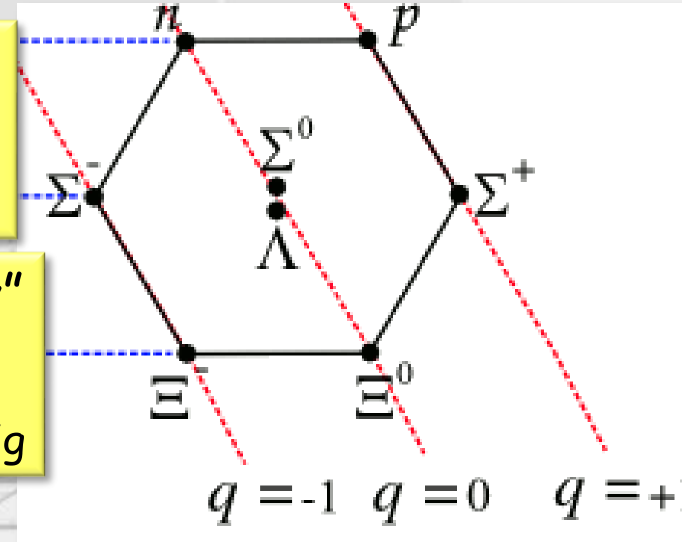
mass ? GeV

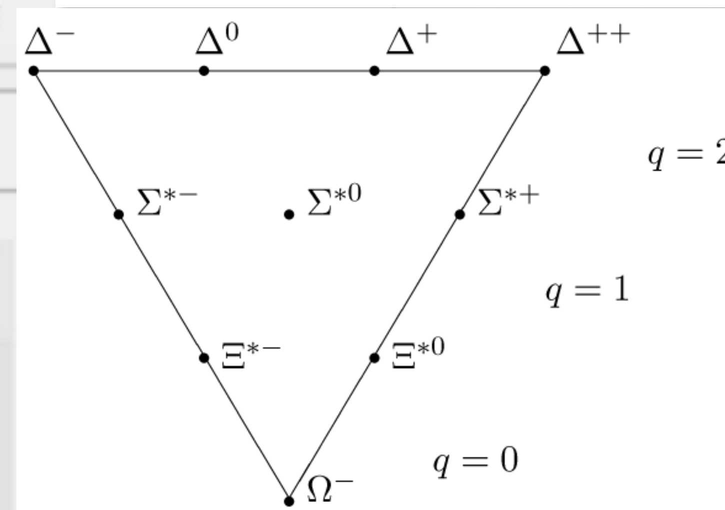
Dalitz

"Three quarks for Muster Mark!"
James Joyce "Finnegans Wake"

"The Eightfold Way"
$SU(3)_F$
M Gell Mann, G Zweig



mass ? GeV



- 3 quarks for a proton
  uud → 938 MeV = ?
  and resonances ?
- sub-femtoscopic matter
  = Dirac fermions ($uds + e\nu / \mu\nu$)?
- strong, EM, weak: Fermi+unitarity = *W*? Perkins "B" 1969

Constituents @ Oxford 1970

"… This allows one to set a lower limit $M_q > 5$ GeV on the quark mass."

"(The quark) model is non-relativistic. The quarks supposed extremely massive, and bound in a deep potential well W by the superstrong forces, so as to yield the physical masses $M_q = 2M_{u/d} + M_{d/u} - W$. … So the quarks are in non-relativistic motion."

Oxford 1970: setting the stage for the quark era

…erkins
Lectures on "Particle Ph… …al Honour Schools
Distributed n… …ar Physics B Oct-Dec 1968
and "Introduction t… …rgy Physics" (Addison Wesley 1972)
pp. 248 and 249

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Constituents: Cashmore's Shadow

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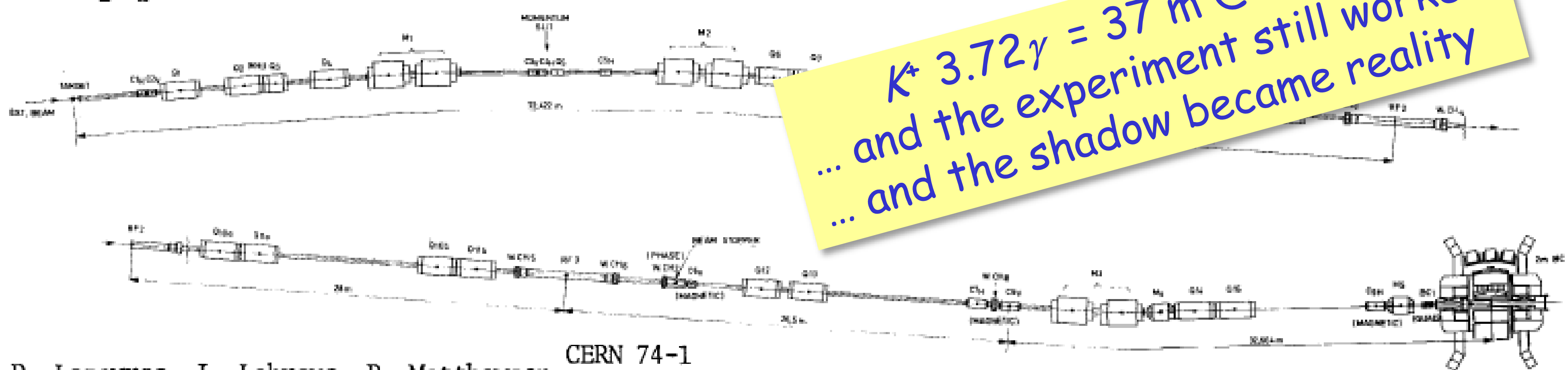
- 1969 strange resonances in Oxford
  - "Cashmore would have …" Bowler and he had!

The external proton beam line e6 transports the ejected protons onto an external target of the high energy radio-frequency (RF) separated U5 beam, which works in the momentum range of about 4 to 20 GeV/c.

The total length of the U5 beam from the target to the center of the bubble chamber is 181.6 m, of which some 148 m are inside vacuum beam pipe.



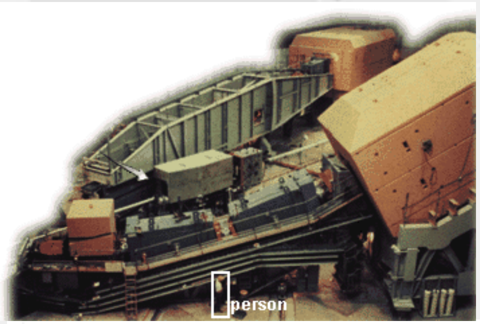
K^{+} 3.72γ = 37 m @ 5 GeV!
… and the experiment still worked
… and the shadow became reality

P. Lazeyras, I. Lehraus, R. Matthewson and W. Tejessy

CERN 74-1
Laboratory I
Track Chambers Division

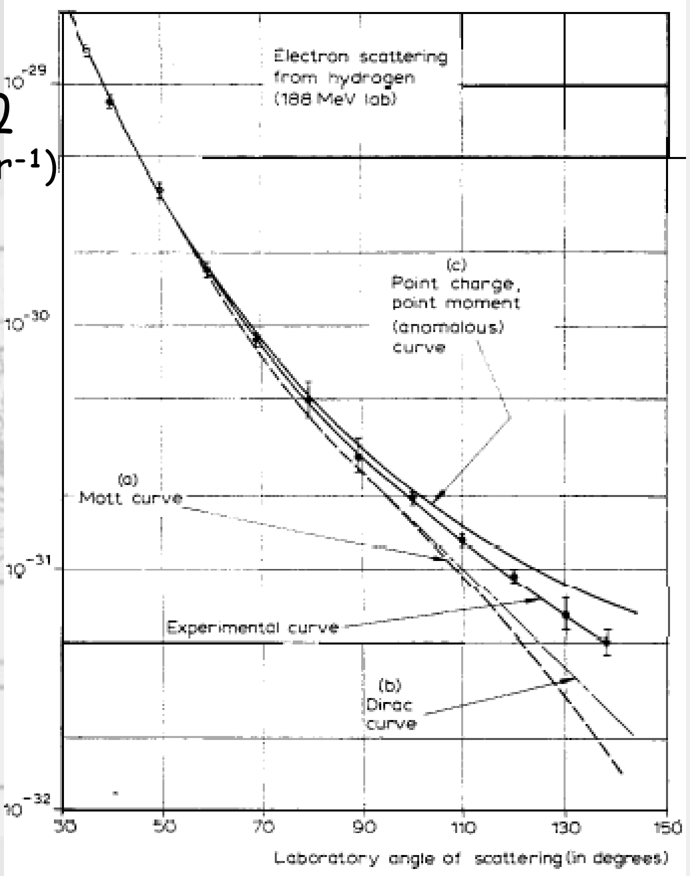
Constituents

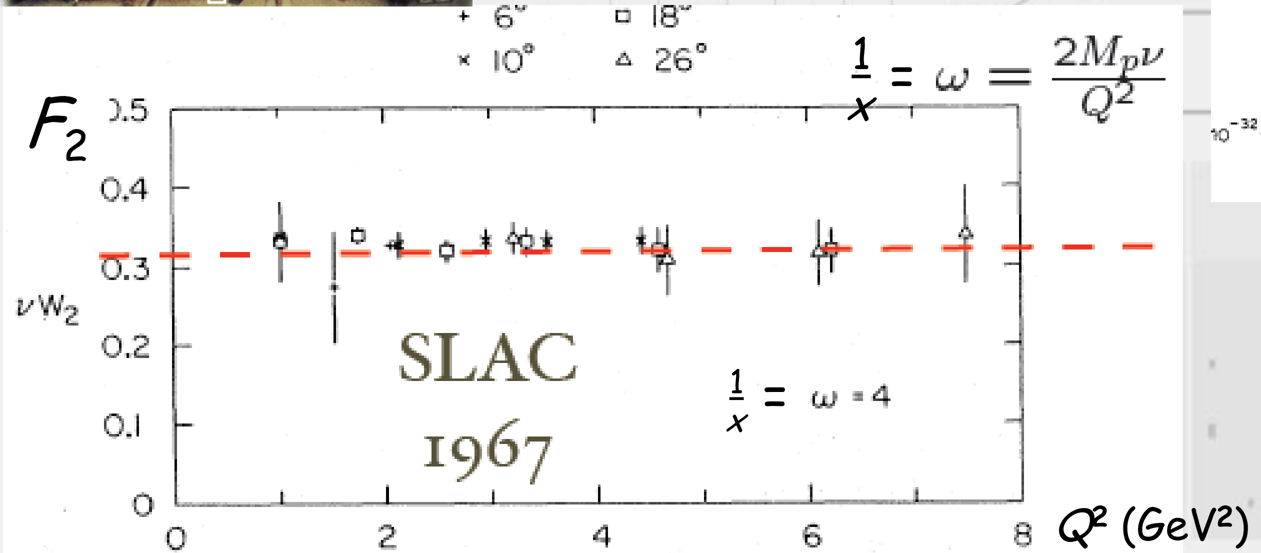
- SLAC end station:
  - 1959 nucleus size
    nucleon size Hofstädter
  - 1967 quarks Friedman Kendall Taylor

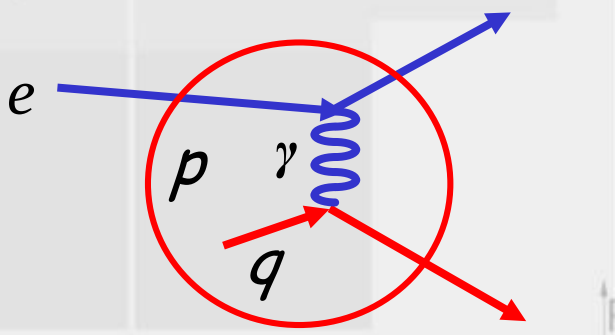


Proposal:
"A general survey of the basic cross sections which will be useful for future proposals"

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

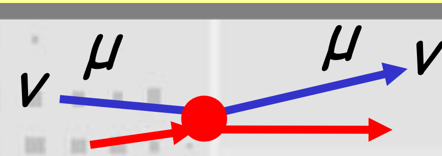




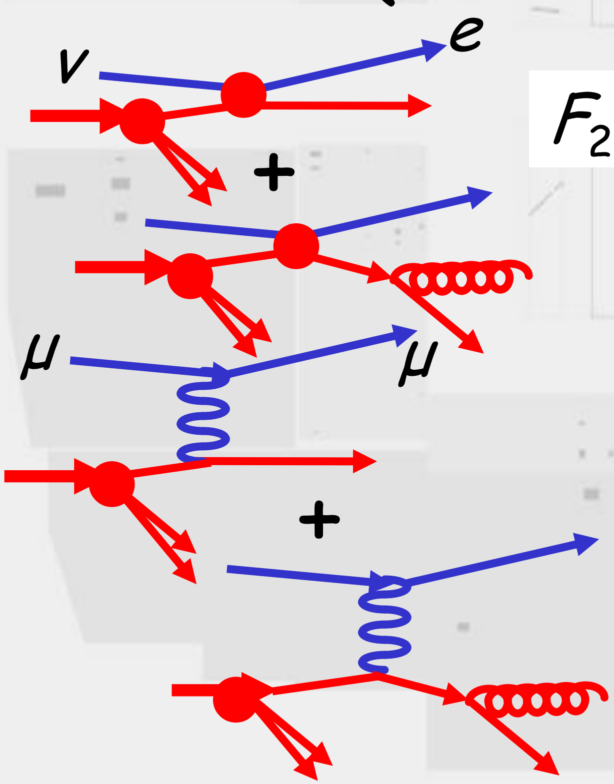


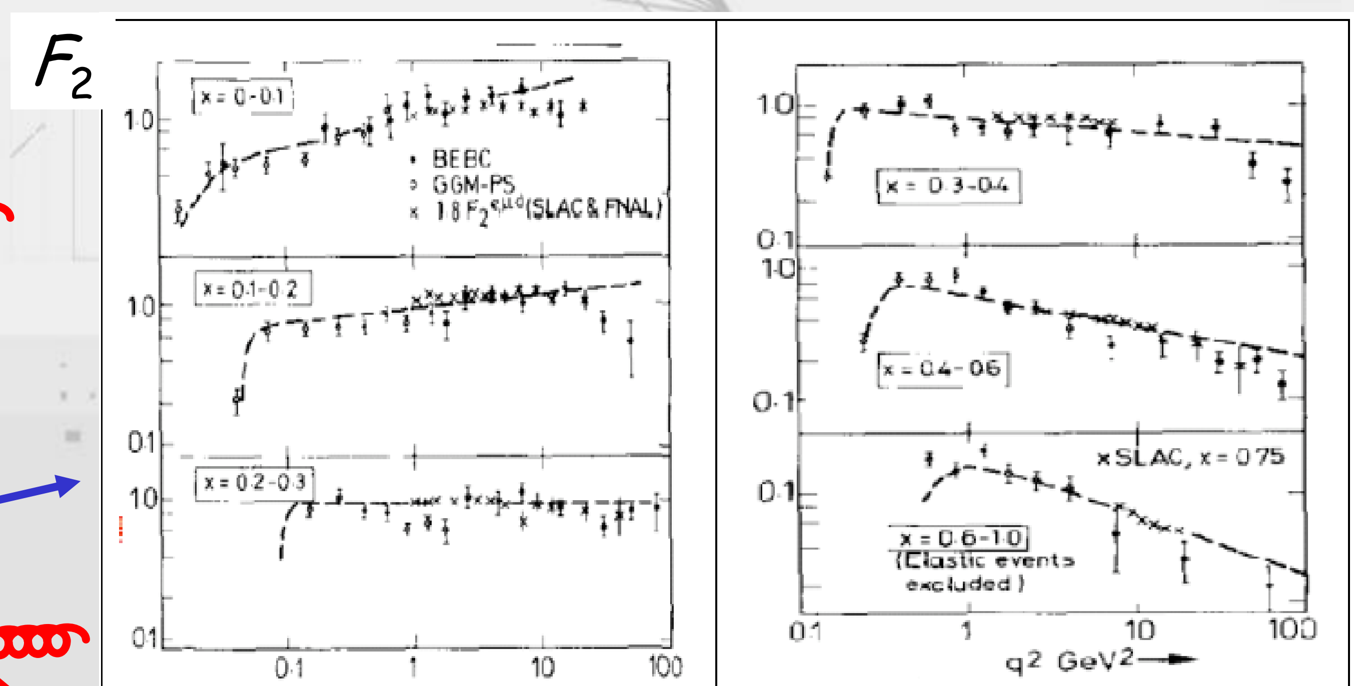
Constituents

- CERN + Fermilab
  - fixed target
  - sub-fm ($Q^2 \lesssim 20$ GeV)
  - 1972 weak NC
    1977 QCD



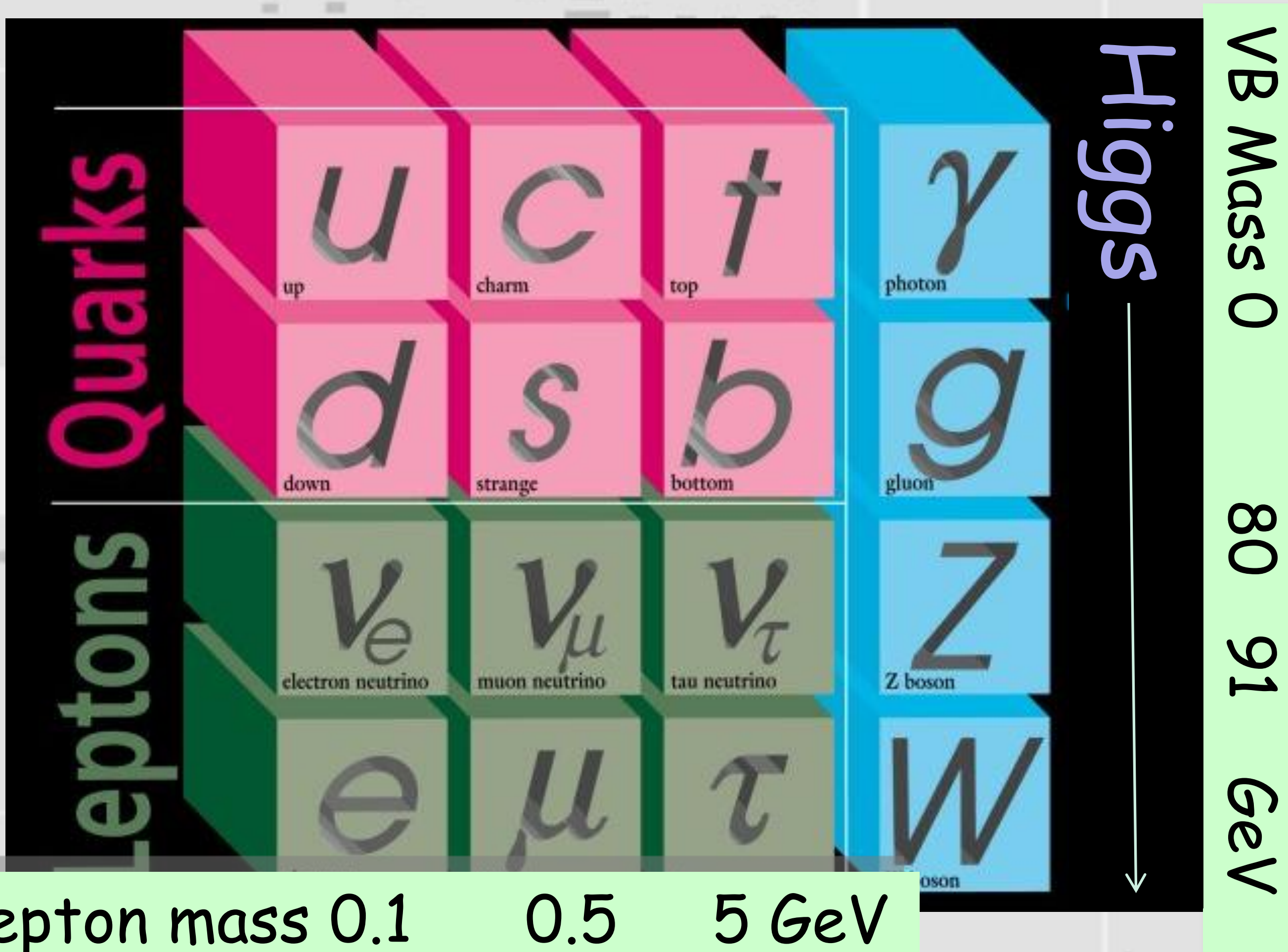
CERN (Perkins et al.)
Fermilab

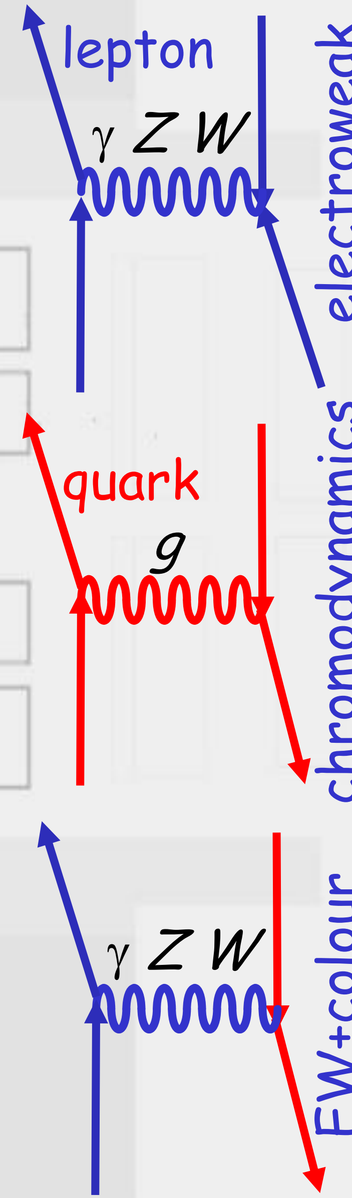




Constituents and Currents

- the Standard Model landscape





➥ matter = Dirac fermions
force = colour, charge, gauge bosons

Why Leptons and Quarks ?

- how are leptons and quarks related ? (1976)

THE UNCONFINED QUARKS AND GLUONS

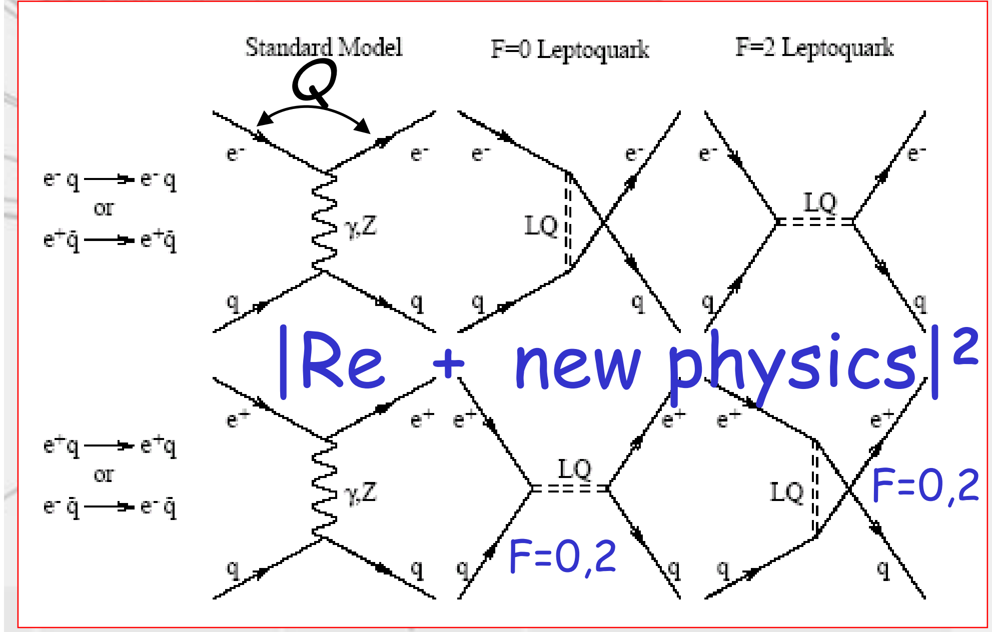
Abdus Salam

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 Tbilisi



- precision SM template for new physics

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Why Leptons and Quarks ?

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DEUTSCHES ELEKTRONEN—SYNCHROTRON DESY

NOTKESTR. 85 · 2000 HAMBURG 52 · TEL. 040 – 89 980 · TELEX 2 15 124 desy d · TELEGR.-ADR. DESY HAMBURG

DESY HERA 81/10
July 1981

HERA

A Proposal for a large Electron-Proton Colliding Beam Facility at DESY

CONTENT

Why Leptons and Quarks ?

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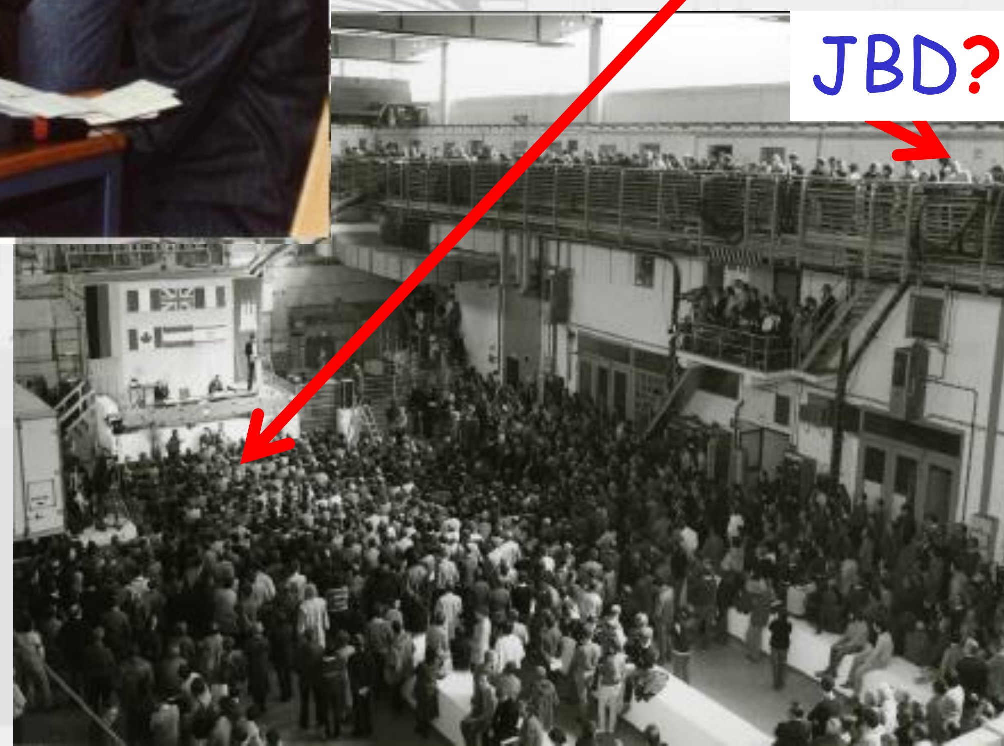
JBD?



Why Leptons ↔ Quarks ?

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EXOTIC PHENOMENA IN HIGH ENERGY ep COLLISIONS

R.J. CASHMORE[(a)], S. CHADHA[(b)], M. CRIBIER[(c)], D. CORDS[(d)], R. DEVENISH[(a)], B. LOHR[(d)], P. MATTIG[(d)], J. PROUDFOOT[(b)], R. RUCKL[(e)], H. RYKACZEWSKI[(f)], D.H. SAXON[(b)], D. SCHILLER[(g)], J. WHEATER[(a)] and C. YOUNGMAN[(a)]

[(a)] *Dept. of Nuclear Physics, Oxford University, England*
[(b)] *Rutherford Appleton Laboratory, Chilton, England*
[(c)] *CEN, Saclay, France*
[(d)] *DESY, Hamburg, West Germany*
[(e)] *M.P.I., Munich, West Germany*
[(f)] *M.I.T., Cambridge, U.S.A*
[(g)] *Dept. of Physics, Siegen University, West Germany*

Physics Reports **22** (1985) pp 275-386

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A precision Fermiscale *ep* Collider HERA @ DESY

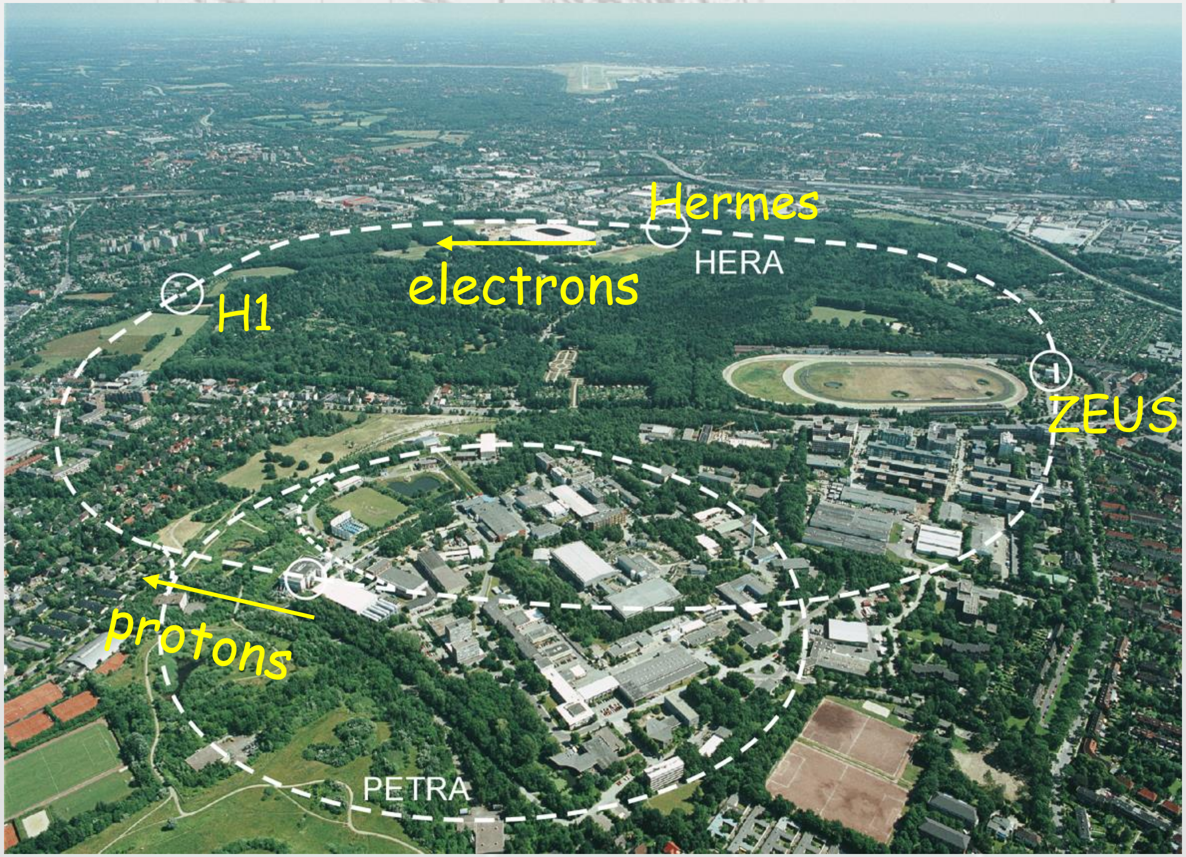
- challenge: different particle species *ep* in collision

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

lepton

ep cm energy 314 GeV

HERA
DESY
Hamburg



HERA
+
1992-2007
RIP

A Precision Fermiscale Experiment @ HERA

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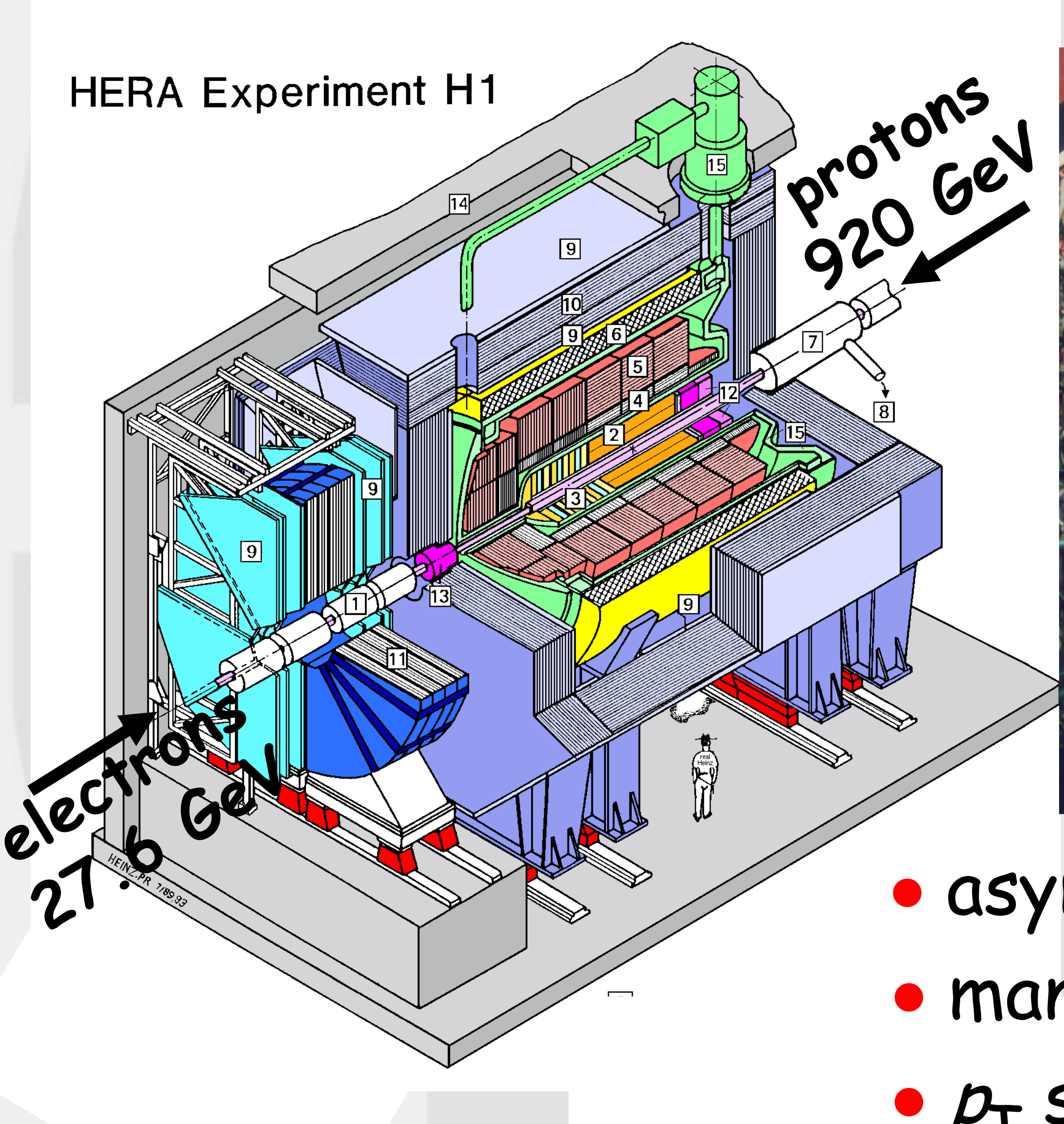
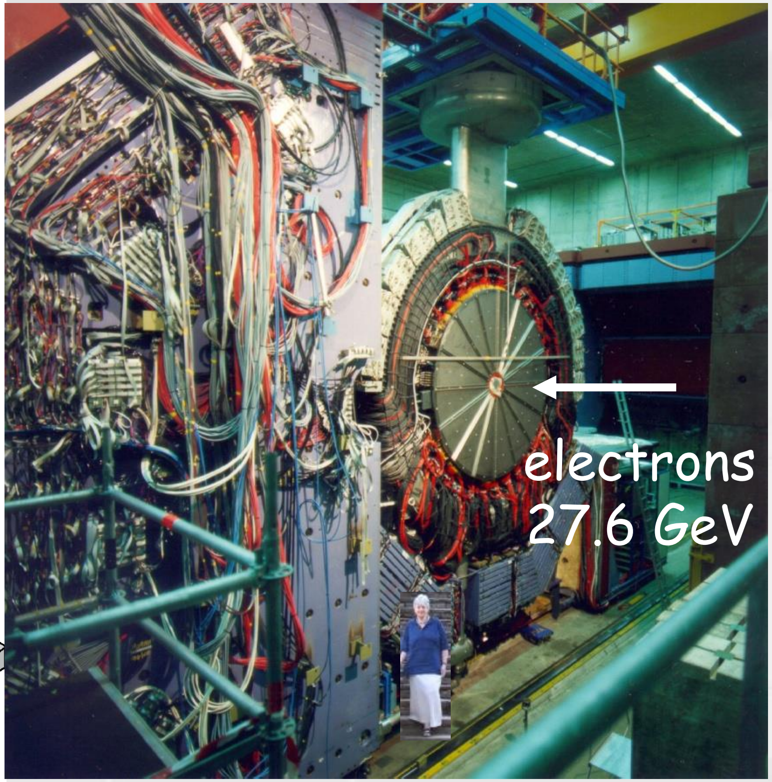
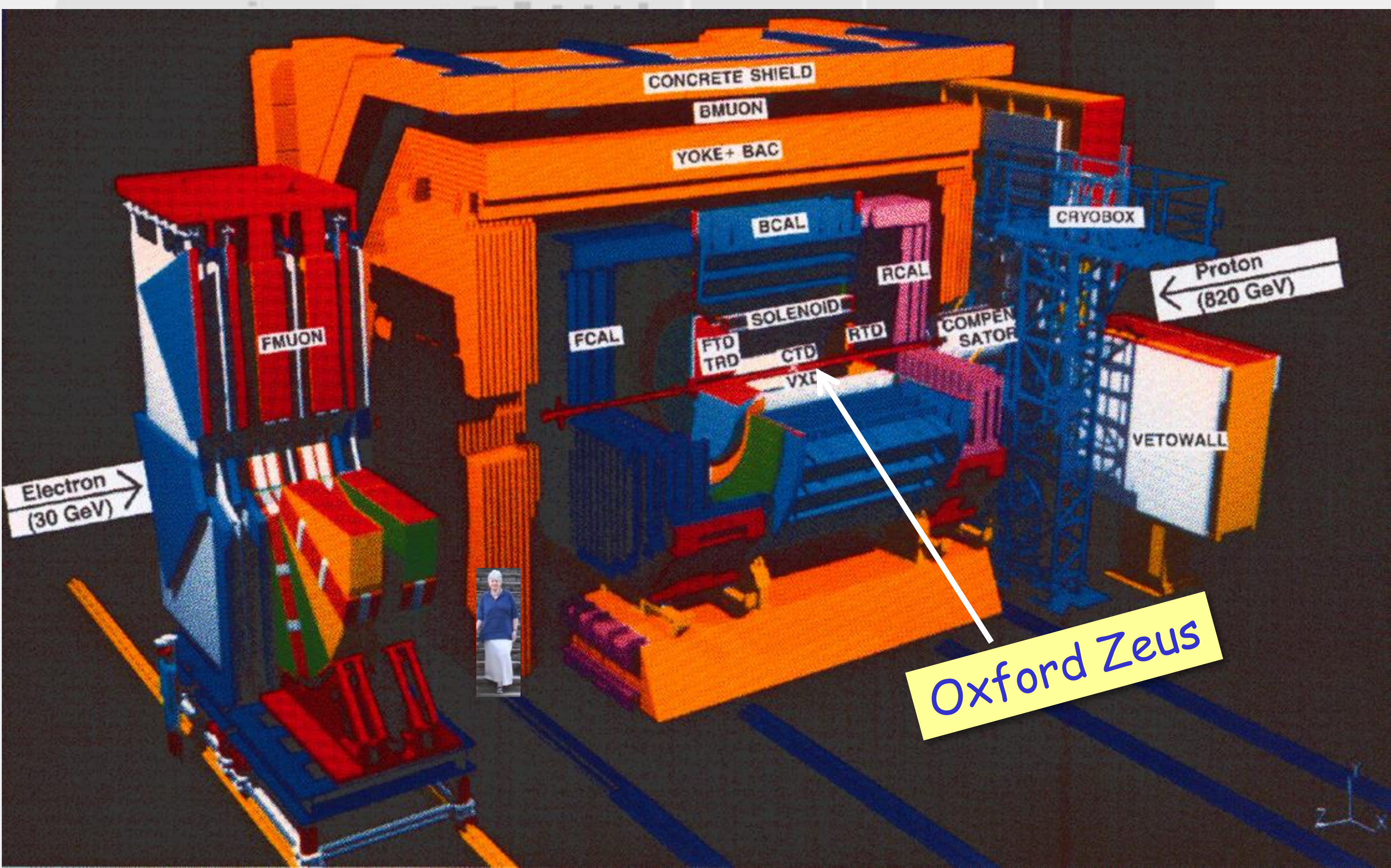




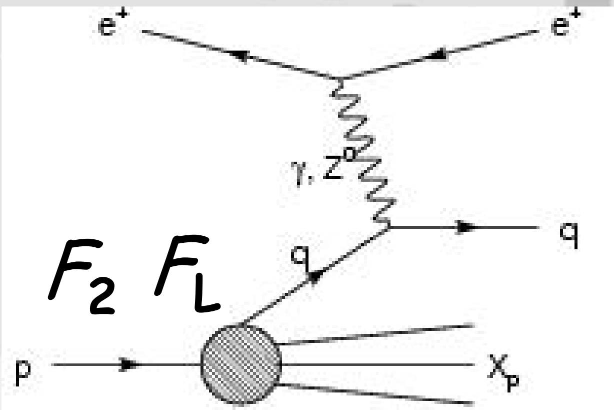
- asymmetric *e* and *p*
- many bunch Δt_{ep} = 75 ns
- p_T scale ~ 300 GeV (Fermi)

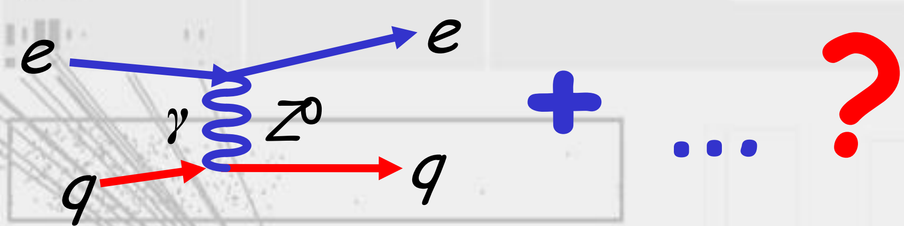
Another Precision Fermiscale Experiment @ HERA !

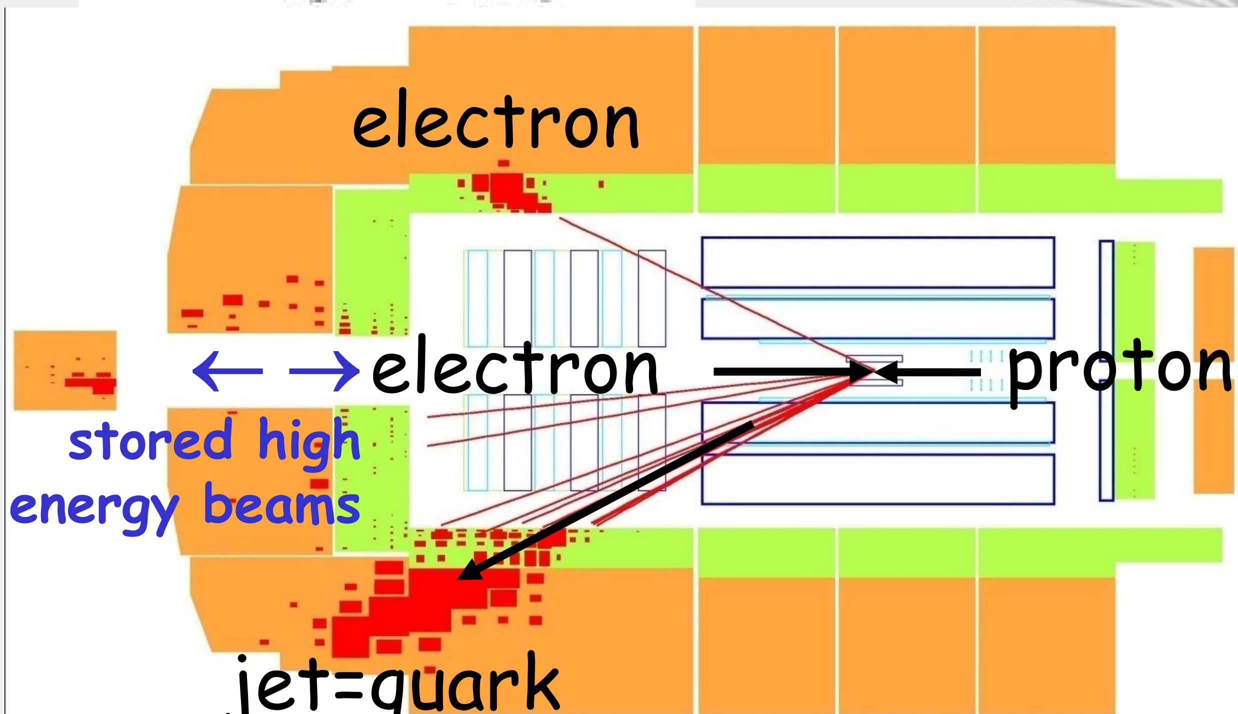


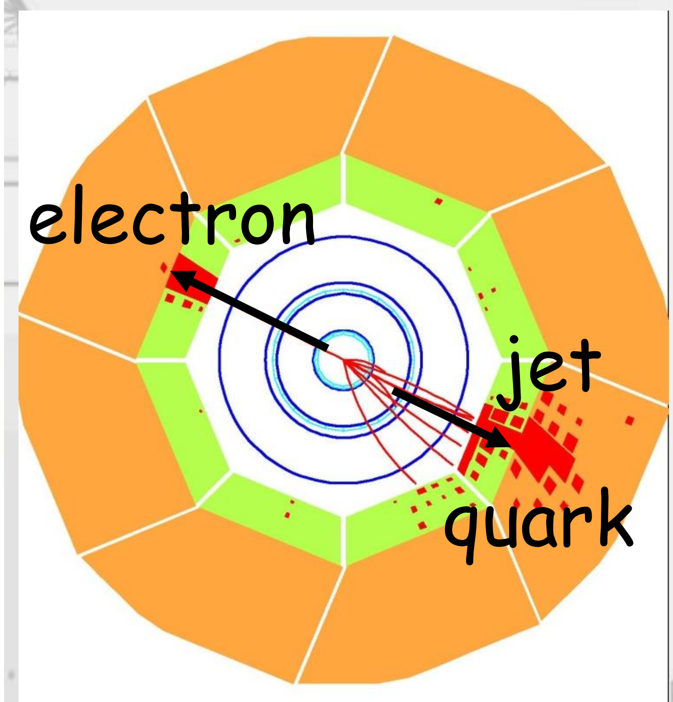
Constituents with Currents

- >1992: Rutherford scattering at the Fermi scale



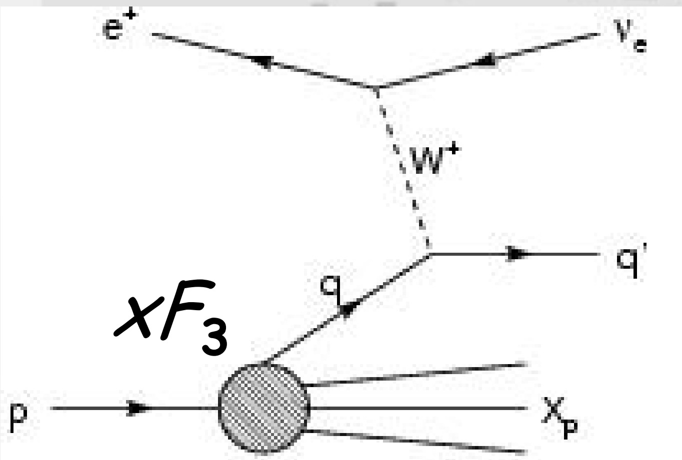


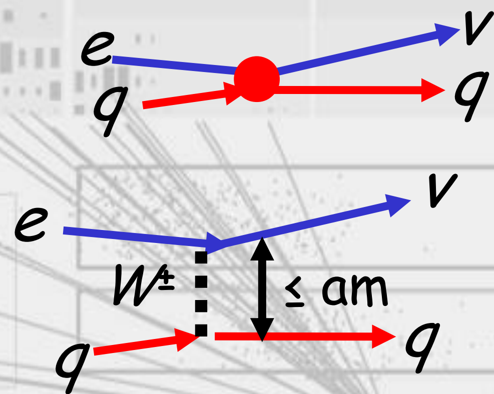




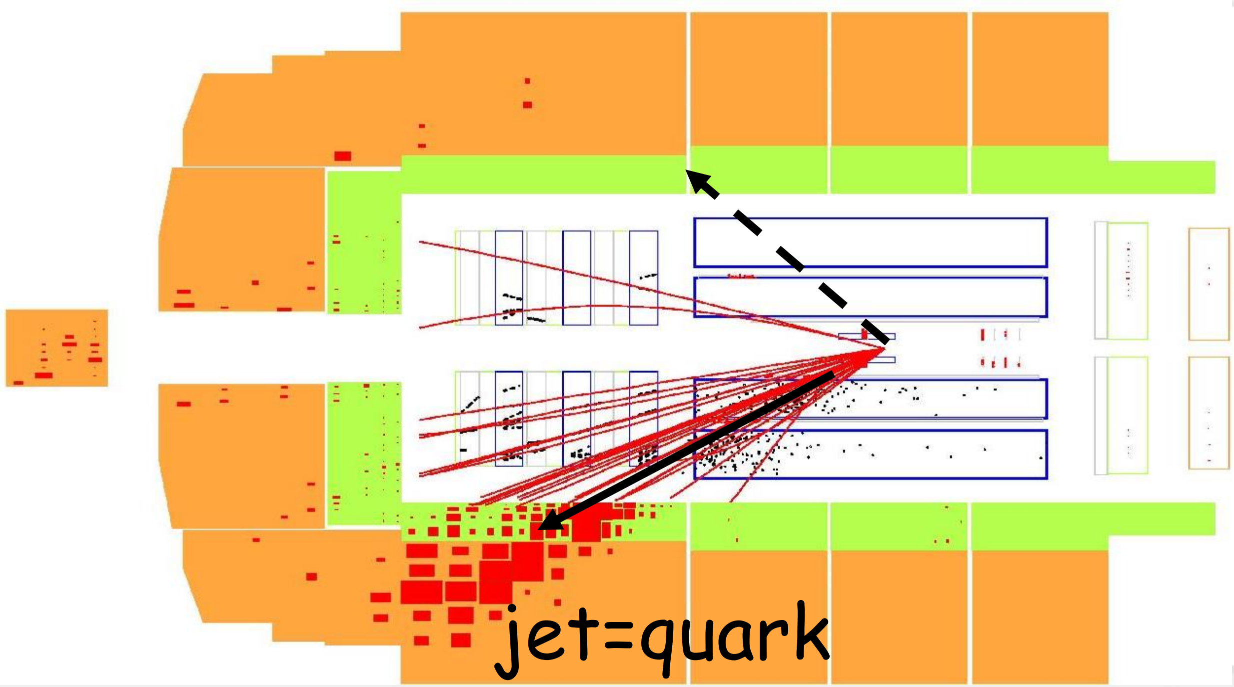
Constituents with Currents

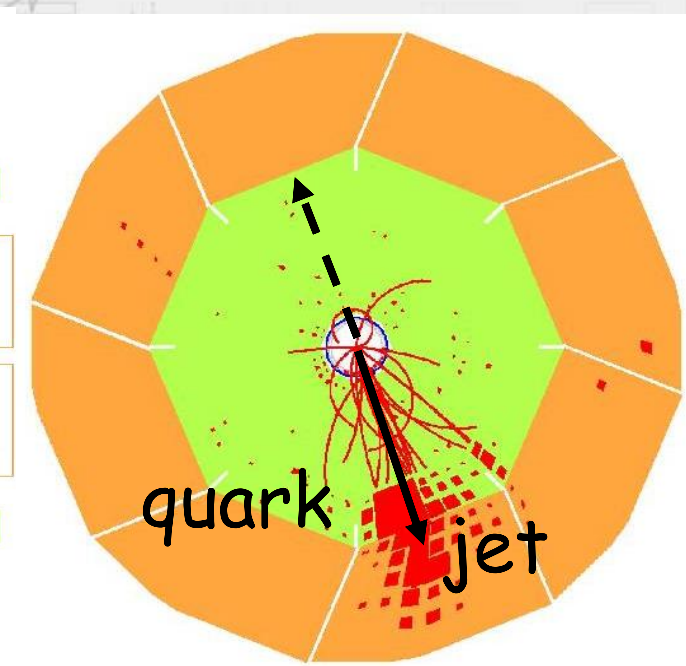
- >1992: inside Fermi's β-interaction





+ ... ?





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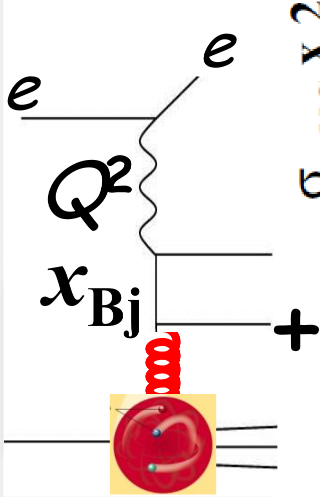
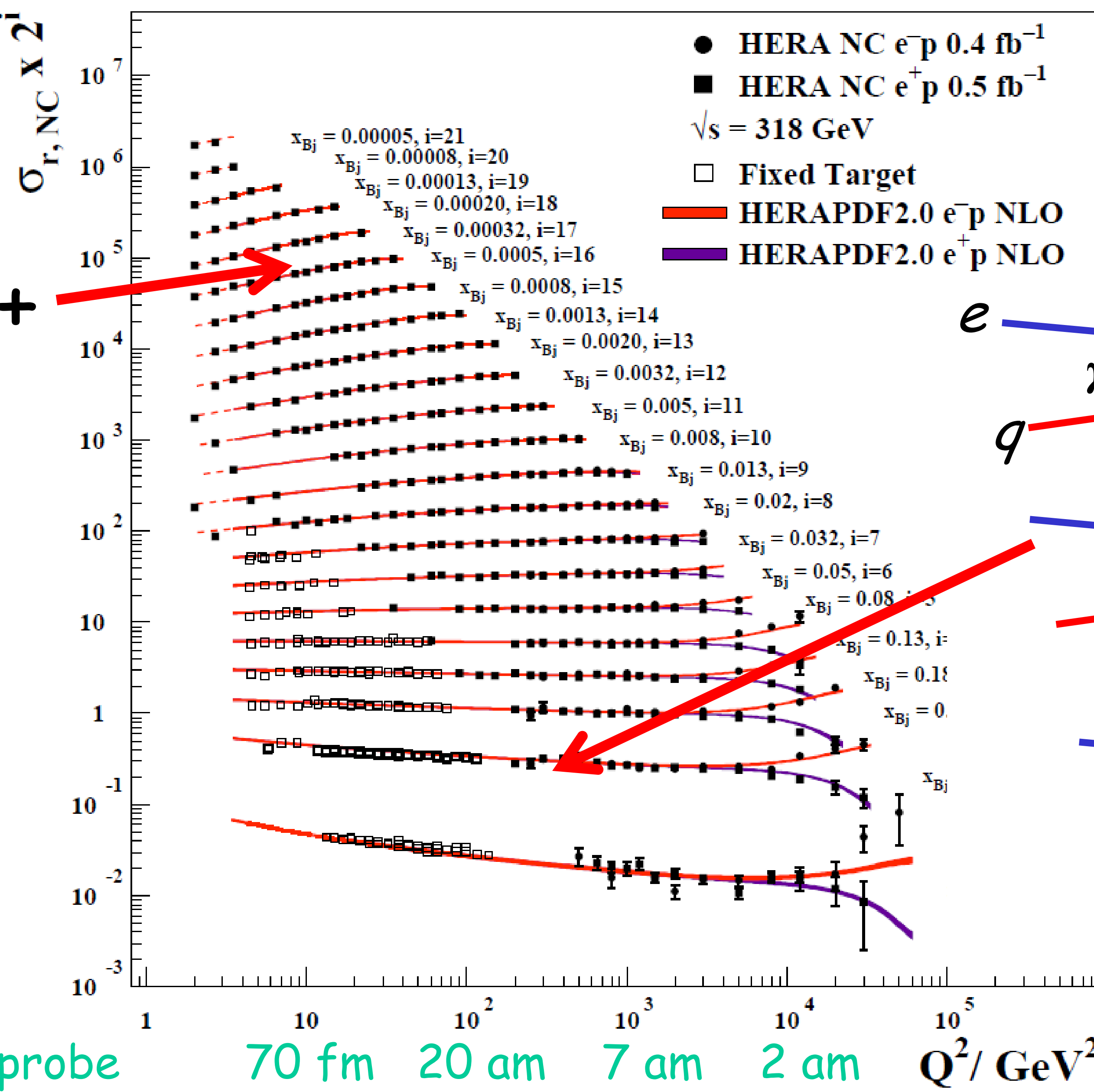
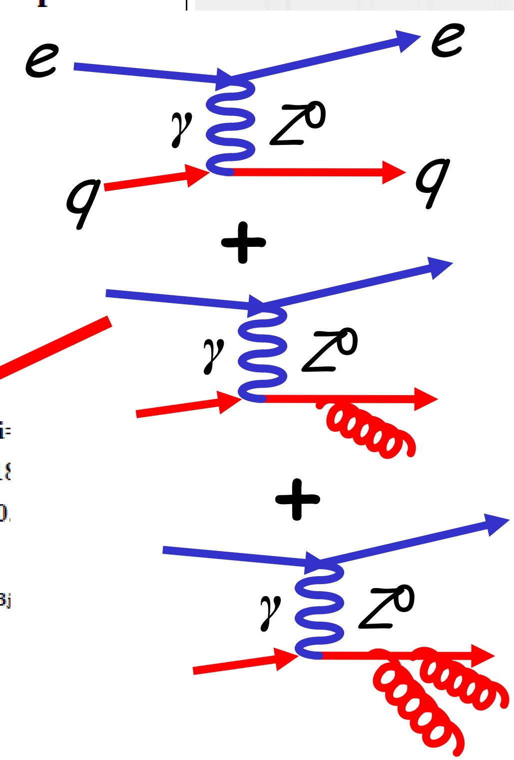
Constituents with Currents



colour
driven

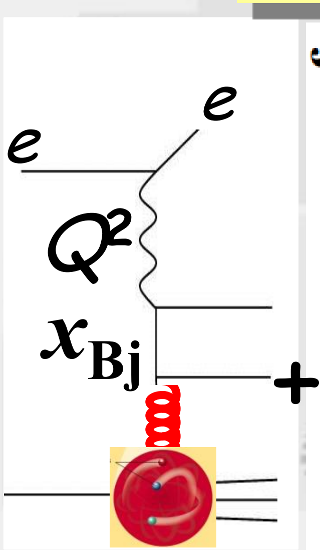




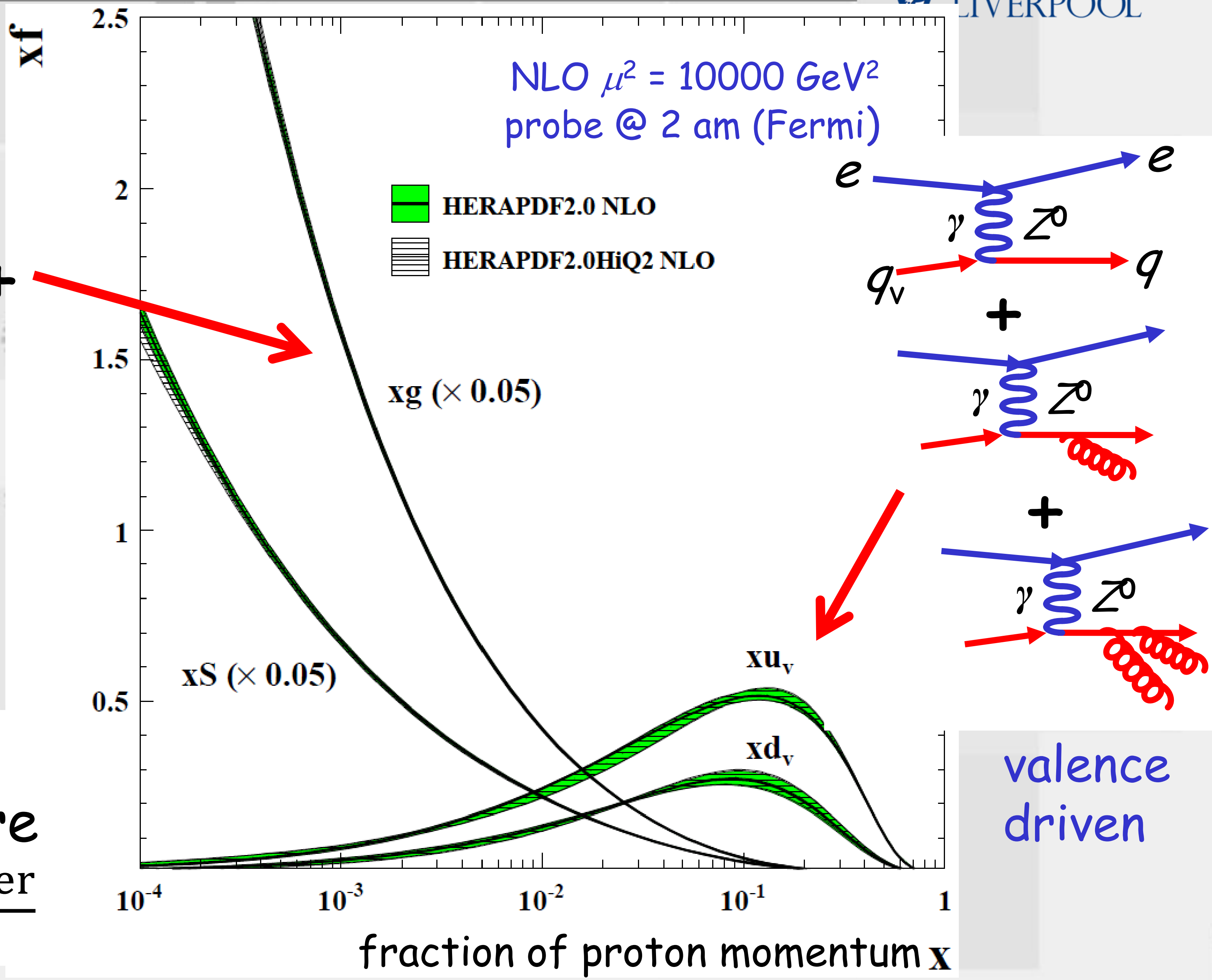
probe 70 fm 20 am 7 am 2 am

valence
driven

Constituents with Currents



colour driven



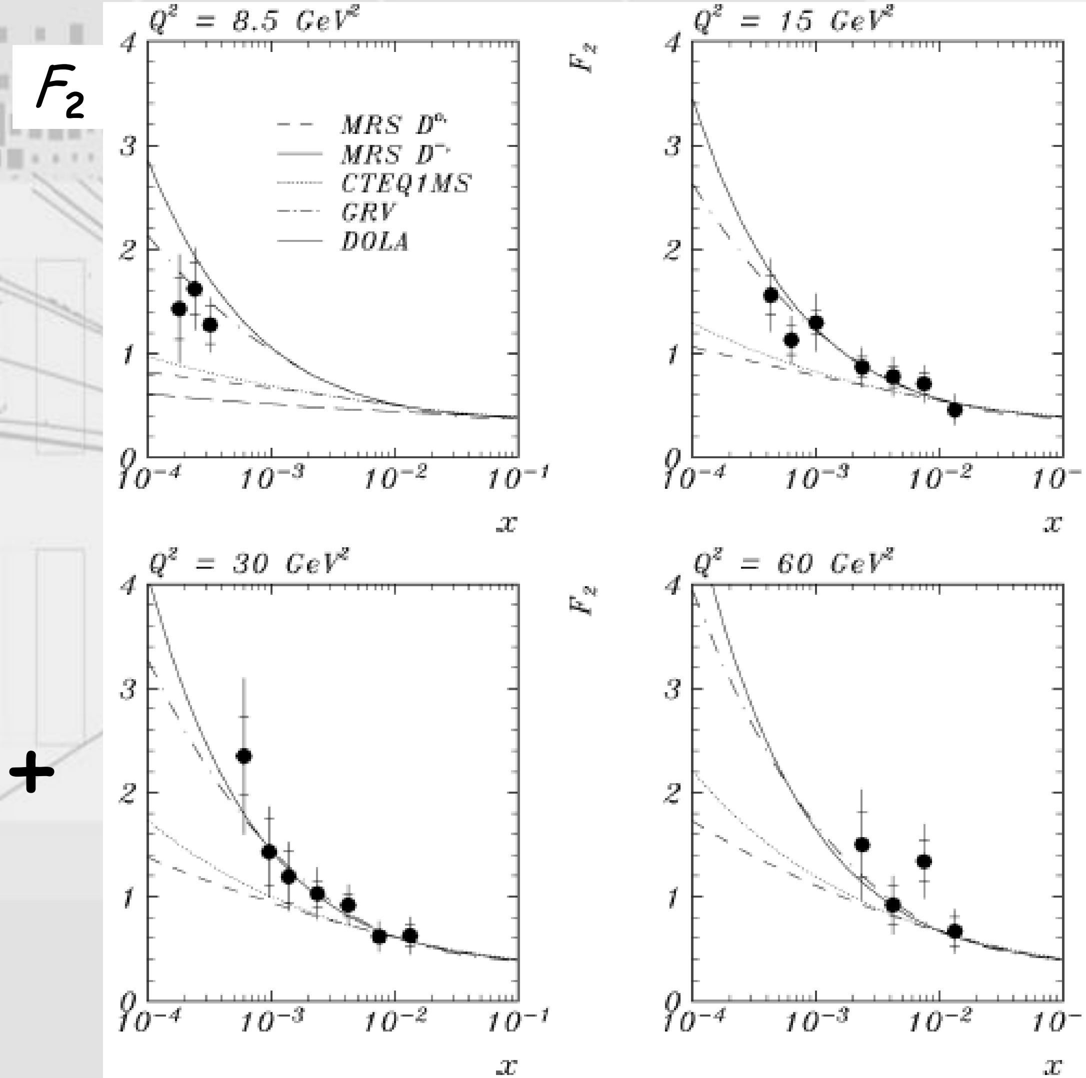
valence driven

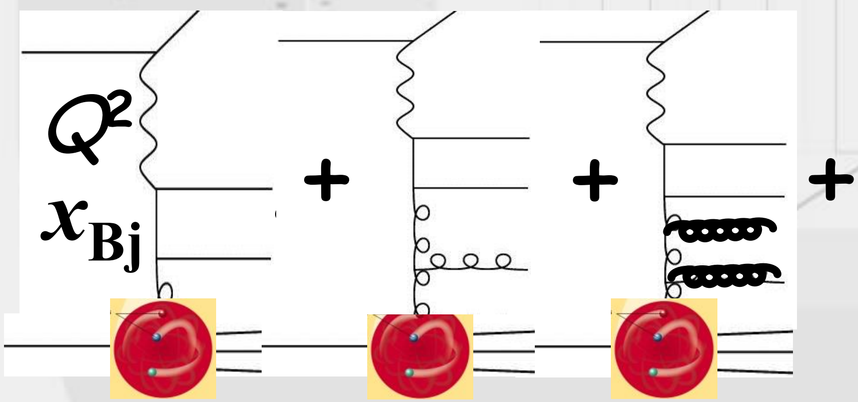
proton structure

$$@ \frac{\text{diameter}}{1000}$$

Colour and Constituents

- 1993: rise to low x of proton structure function F_2
  - the gauge field theory QCD **is** proton structure

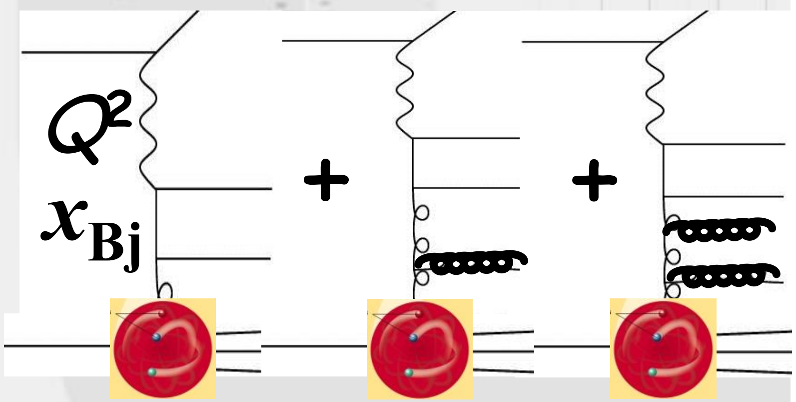


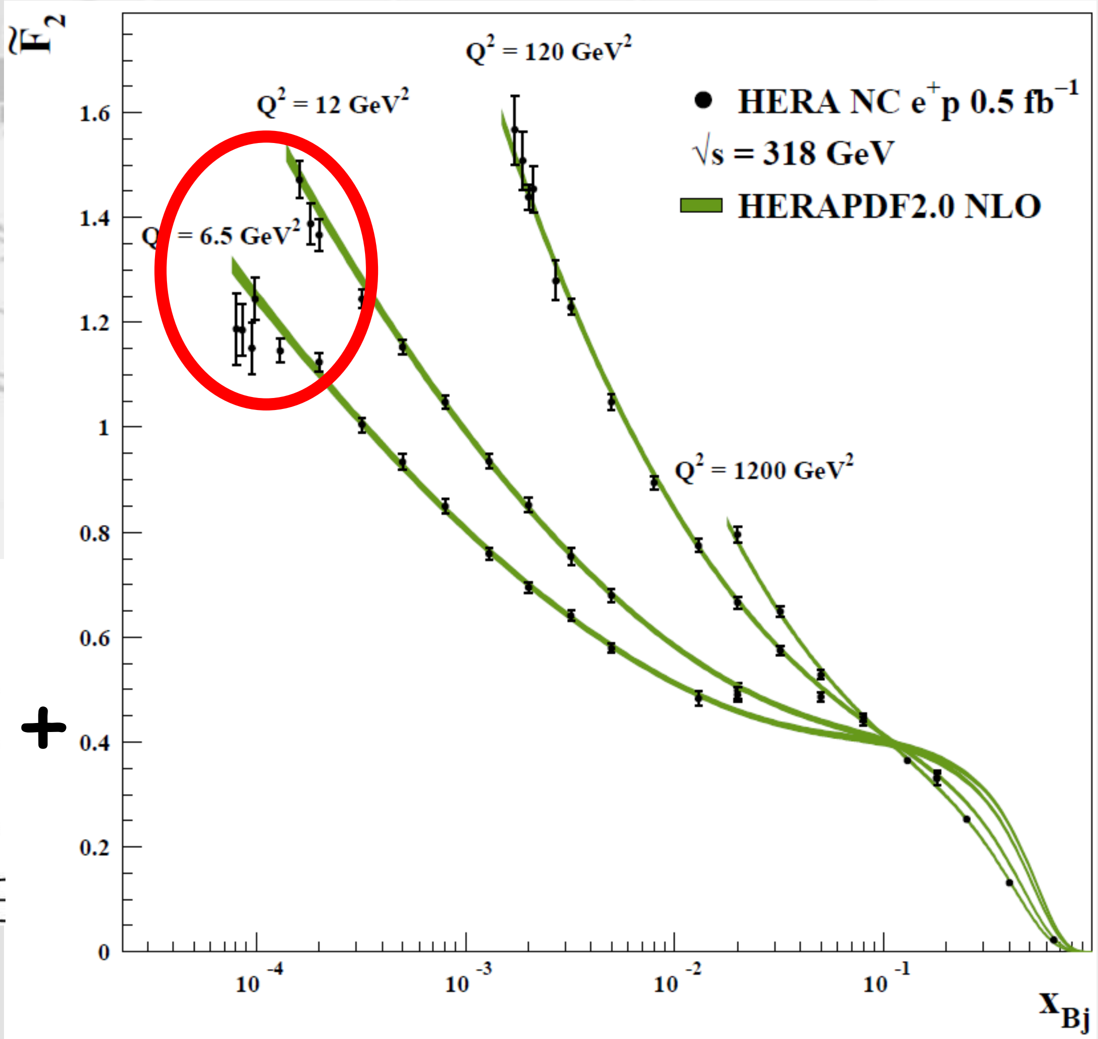


discovery: **we** are chromodynamic energy

Colour Conundrum

- 2015: rise to low x of proton structure function F_2
  - the gauge field theory QCD **is** proton structure

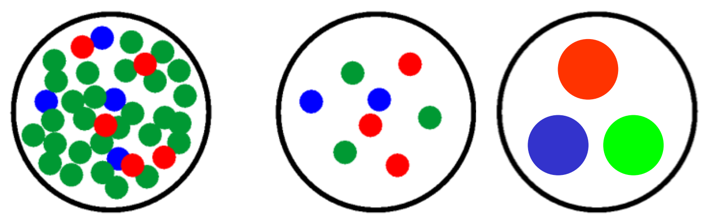




↳ discovery: but we don't understand how: $\ln\frac{1}{x}$?

Colour Conundrum

- F_2 @ low x
  - saturation in $F_2 \propto x^{-\lambda}$?

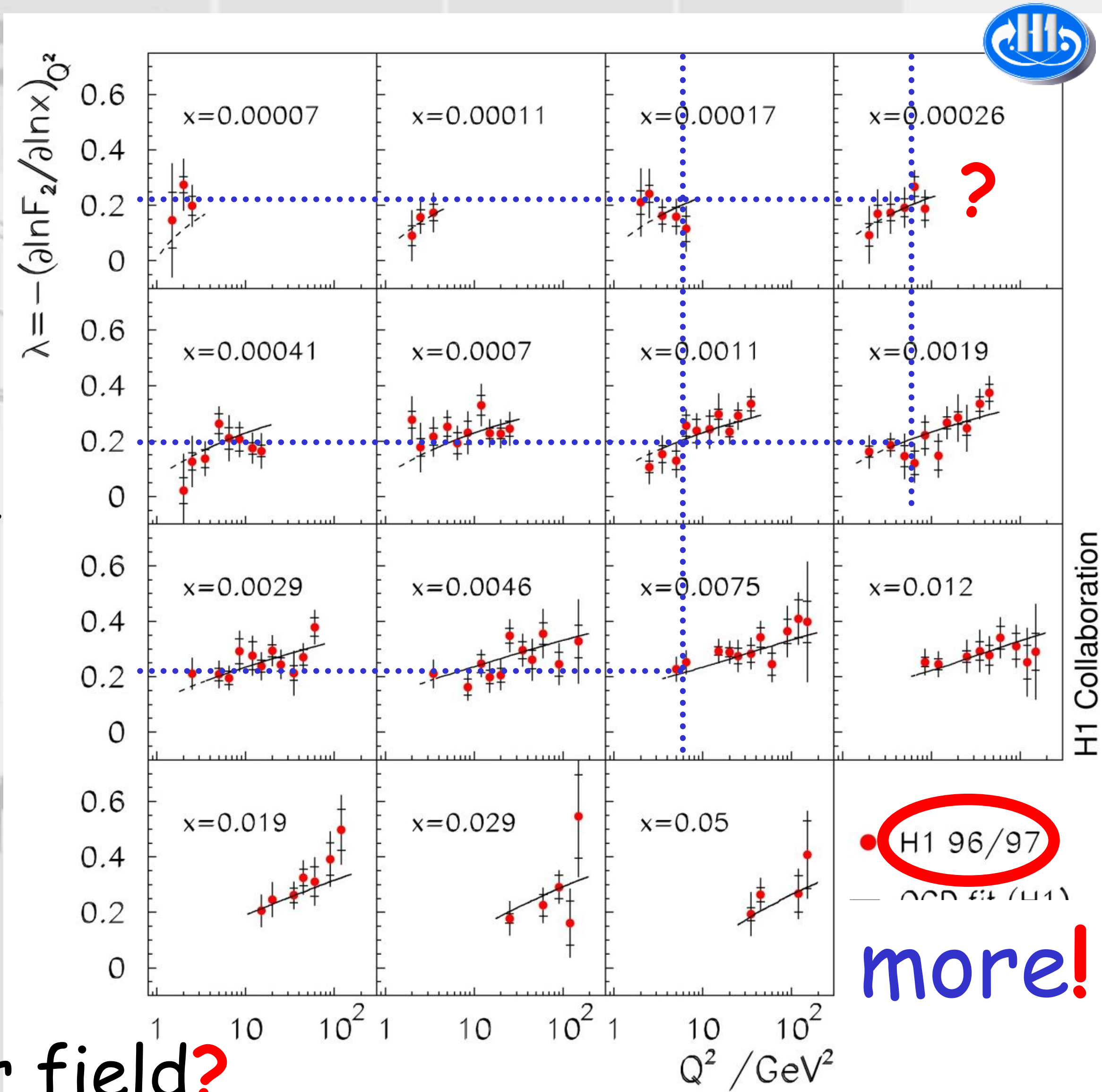


lower x higher x

$$\lambda = -(\partial \ln F_2/\partial \ln x)_{Q^2}$$

smaller λ larger ?

- experiment → observation in measurements?
- unitarity in colour field?



more!

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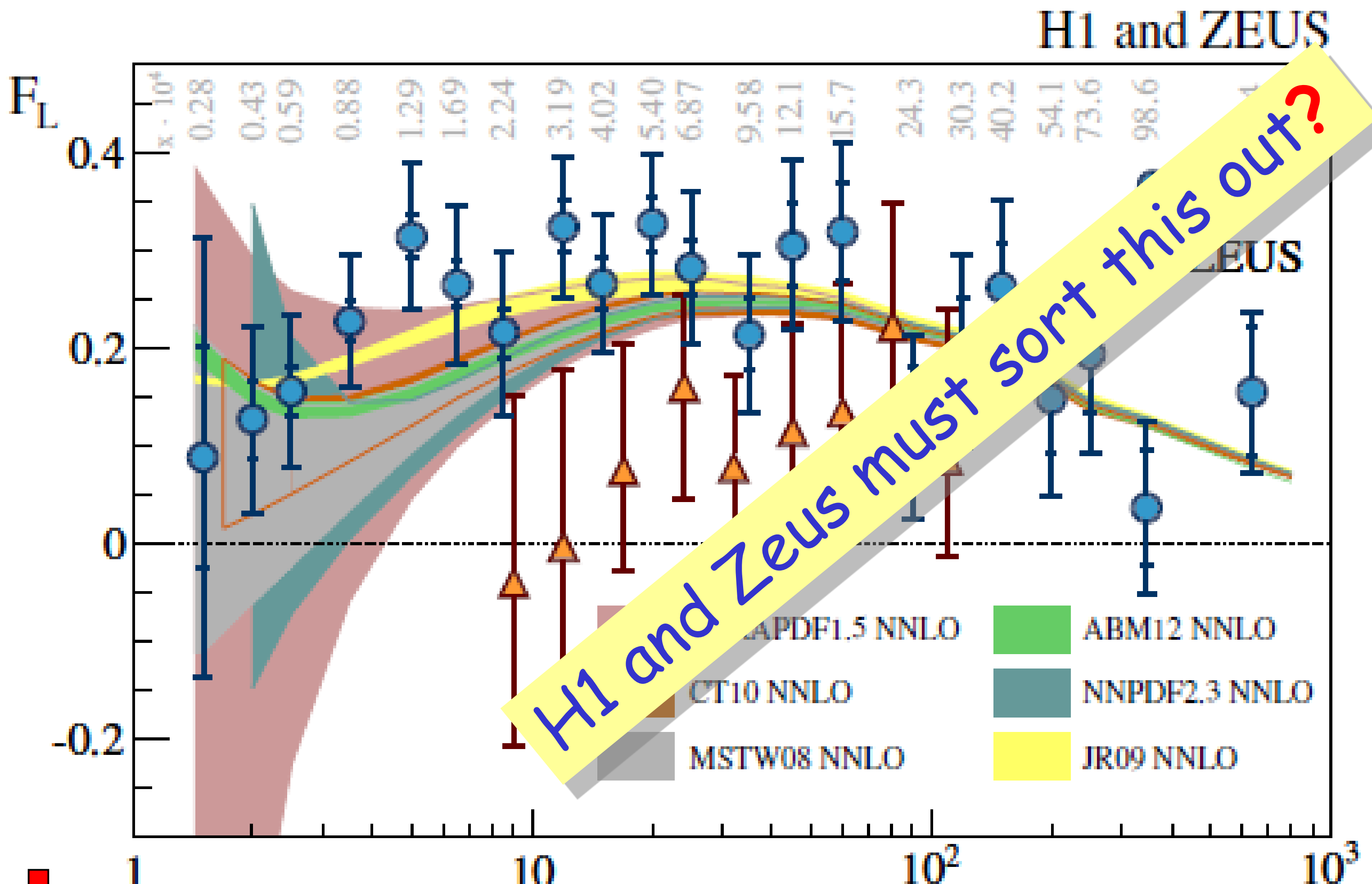
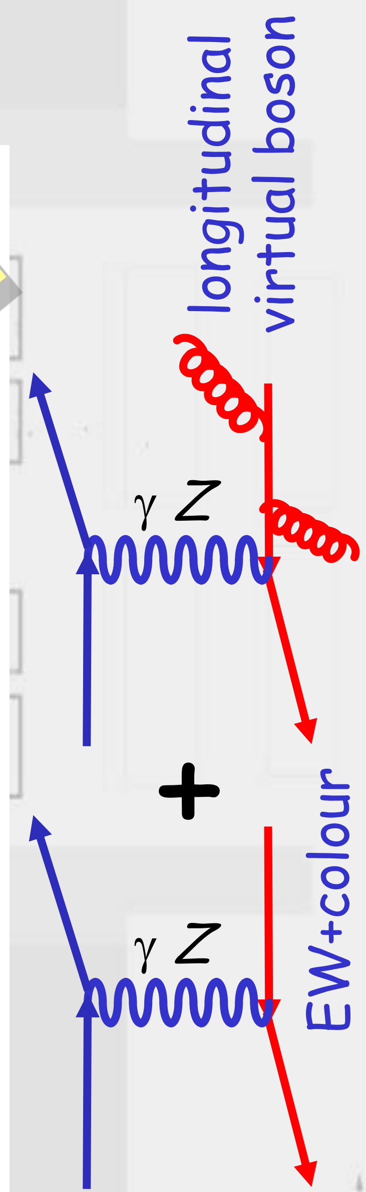
Colour Conundrum

- colour field structure of hadron F_L ?



H1 and Zeus must sort this out?



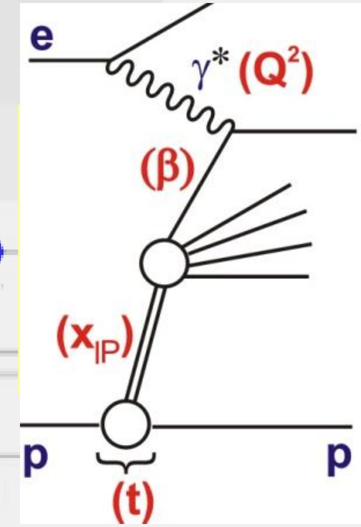
↳ Dirac fermions in colour ?

Colour Interaction Dynamics

- experiment $ep \to epXY$ with $Q^{-1} < 50$ am
  - p isolated in rapidity
  - forward hadrons $M_Y^2 < 2.5$ GeV² isolated in rapidity

  } gap ➡

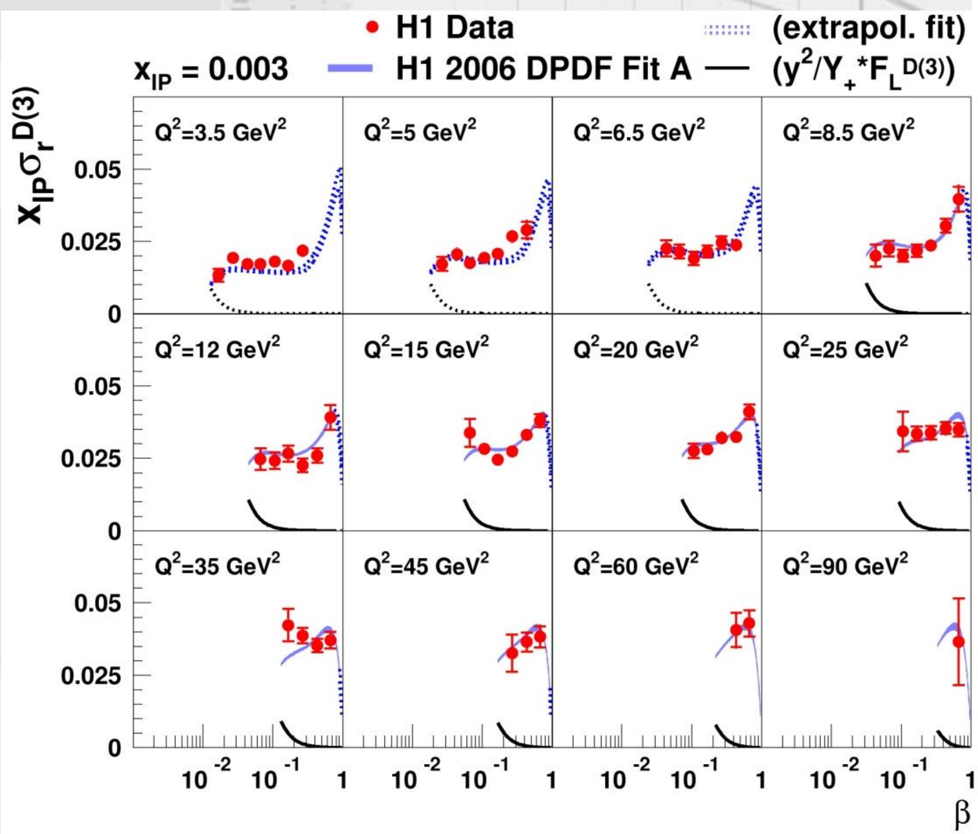
  ↳ probe hadronic interaction

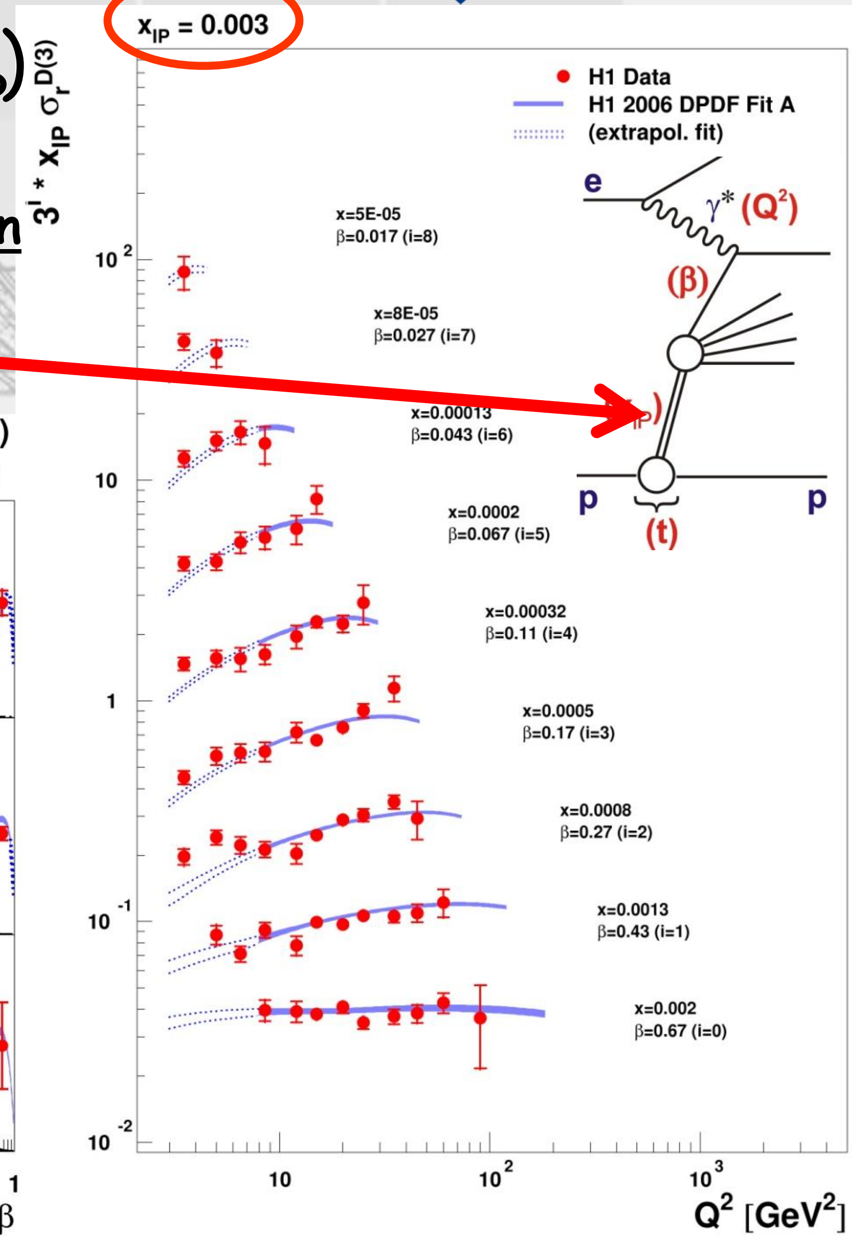


- unquestionably dramatic: void ← 920 GeV proton

Colour Interaction Dynamics

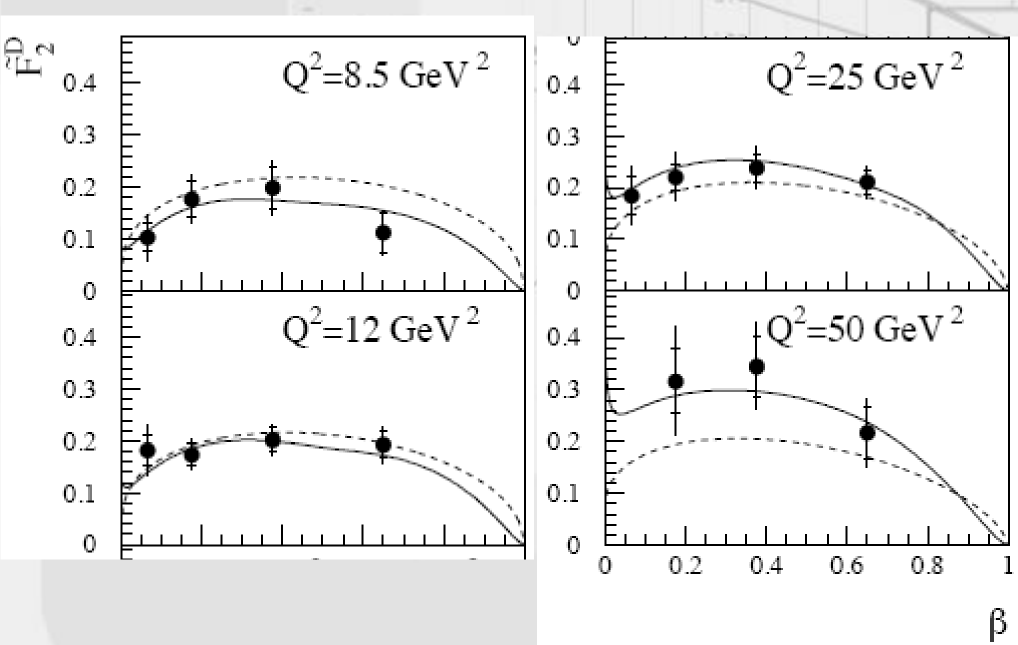
- x-section $x_{I\!P}\sigma_r \sim F_2^D(\beta, Q^2, x_{I\!P})$
  - scaling violations $\rightarrow$ flavour singlet q_s QCD evol$^{\underline{n}}$
  - β dep$^{\underline{c}}$ $\sim g \rightarrow q\bar{q}$

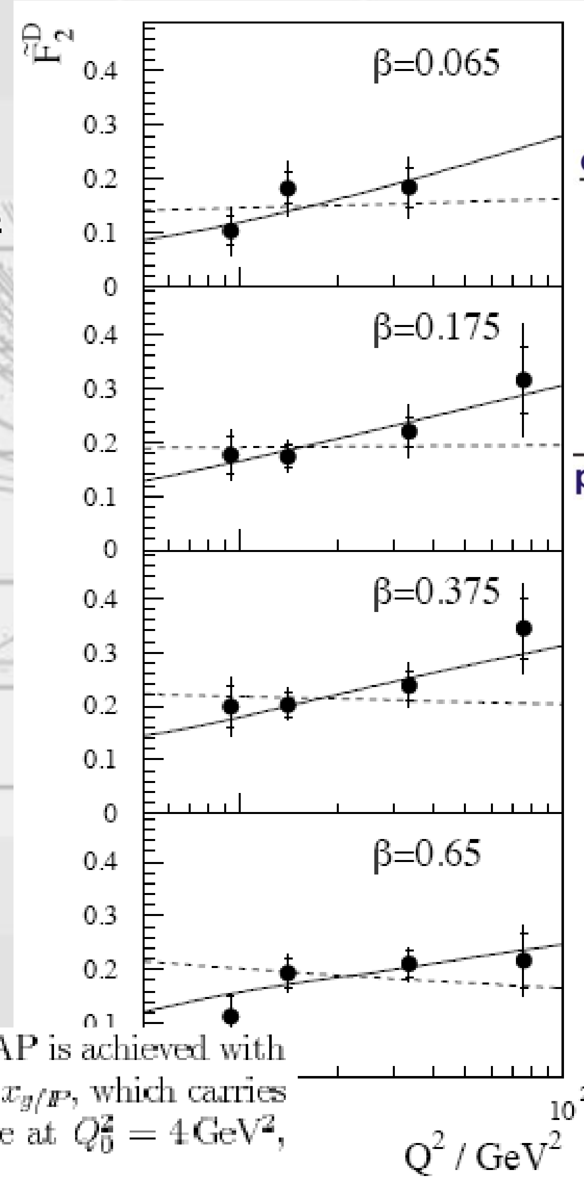


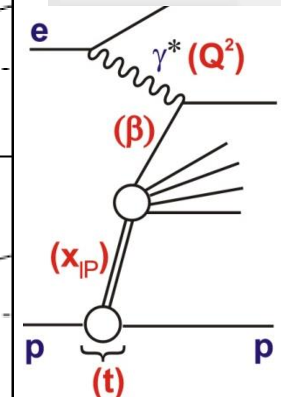


Colour Interaction Dynamics

- H1 F_2^D 1996 (Brussels)
  - scaling violations → flavour singlet q_s QCD evol$^{\underline{n}}$
  - β dep$^{\underline{c}}$ ~ $g \to q\bar{q}$



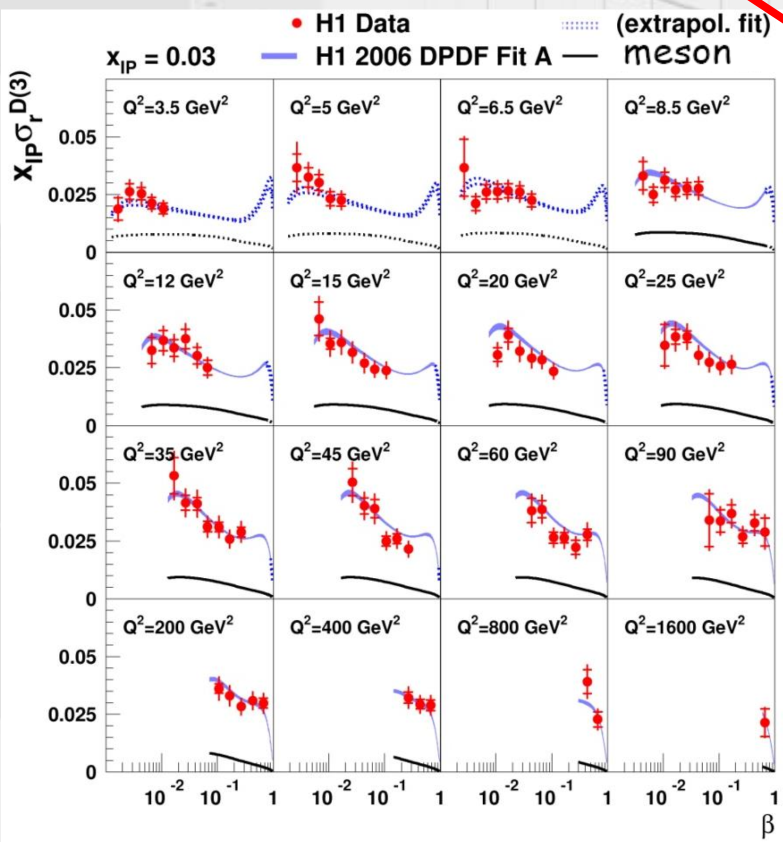


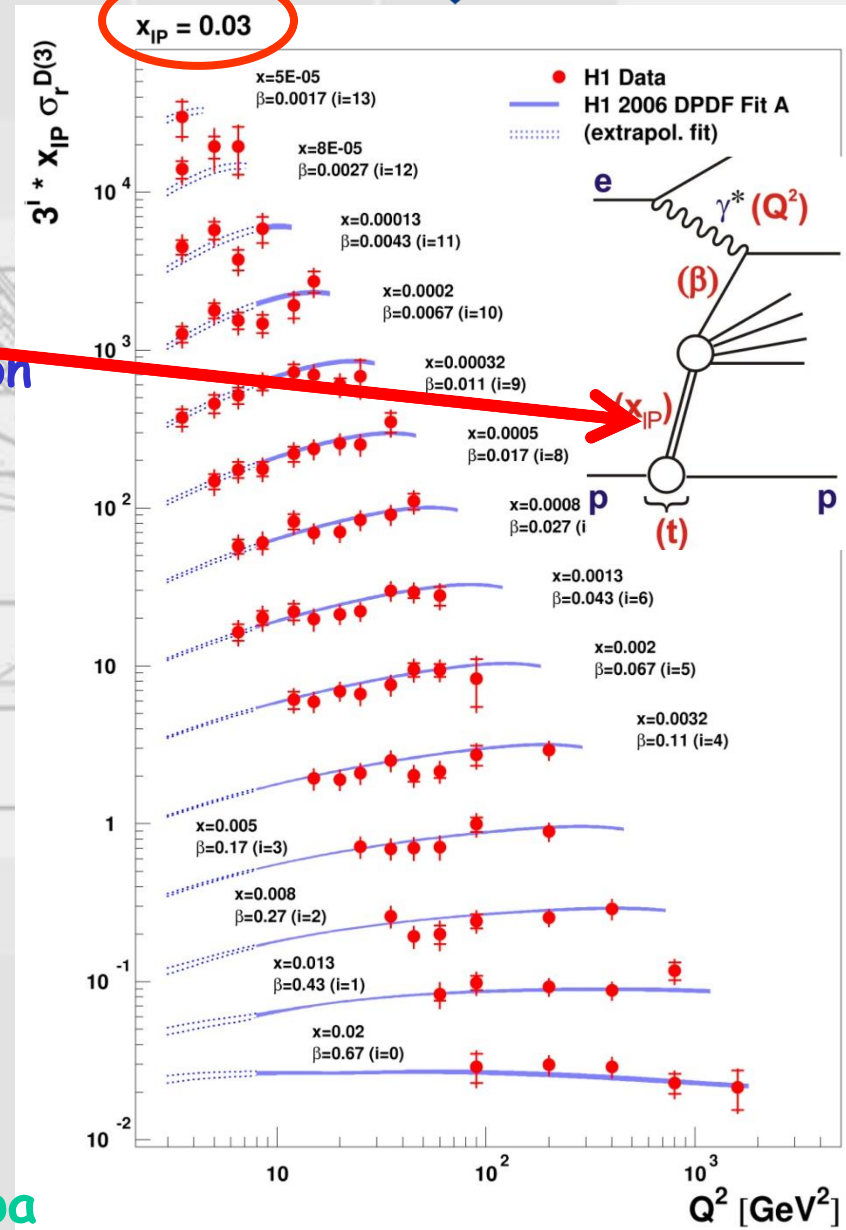


An excellent description of $\tilde{F}_2^D$ in the framework of LO DGLAP is achieved with a gluon density which predominates at larger fractional momenta $z = x_{g/\mathbb{P}}$, which carries approximately 80% to 90% of the momentum in diffractive exchange at $Q_0^2 = 4\,\mathrm{GeV}^2$, and which supports a leading gluon interpretation.

Colour Interaction Dynamics

- x-section $x_{\mathbb{P}}\sigma_r$ @ larger $x_{\mathbb{P}}$
  - scaling violations $\rightarrow$ flavour singlet q_S evol$^{\underline{n}}$
  - β dep$^{\underline{c}}$ ~ $1^c_{g\rightarrow q\bar{q}}$ + q_{meson}



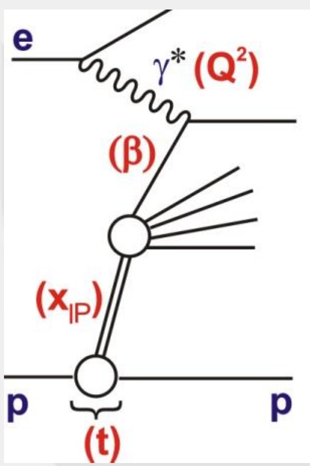


Ruspa

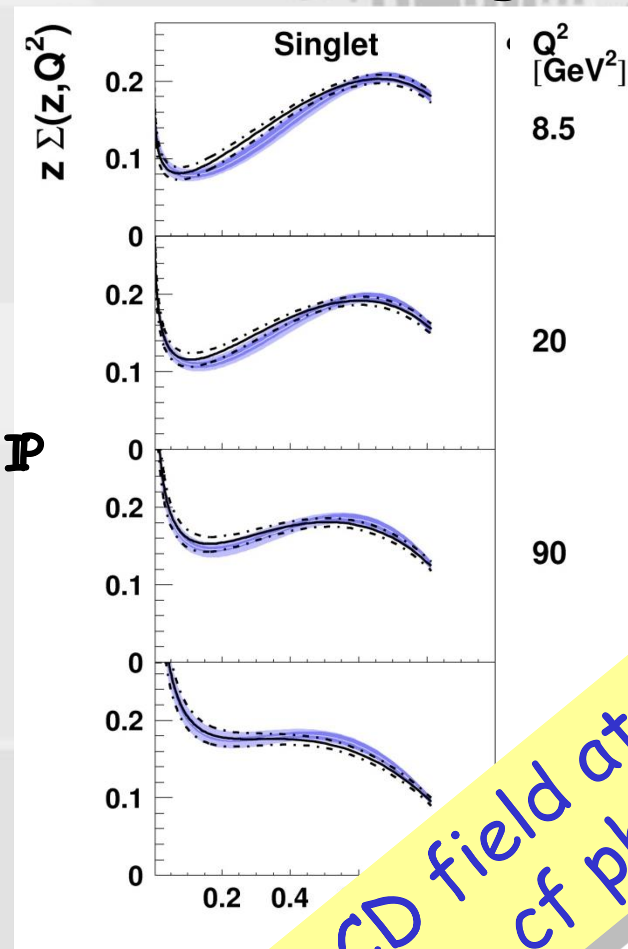
Colour Interaction Dynamics

- the colour dynamics of the nucleon interaction
  - NLO $\rightarrow$ 1^c colour singlet q interaction

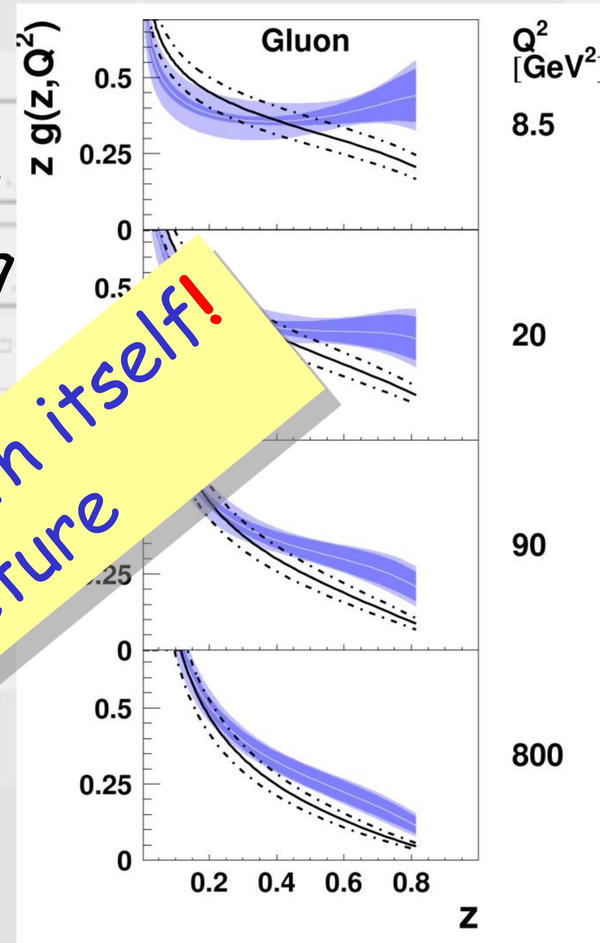
$g\rightarrow q\bar{q}$
$+\ g\rightarrow q\bar{q}g$
$+\ \ldots$



IP



g +
$g\rightarrow gg$+
$g\rightarrow ggg$
+…

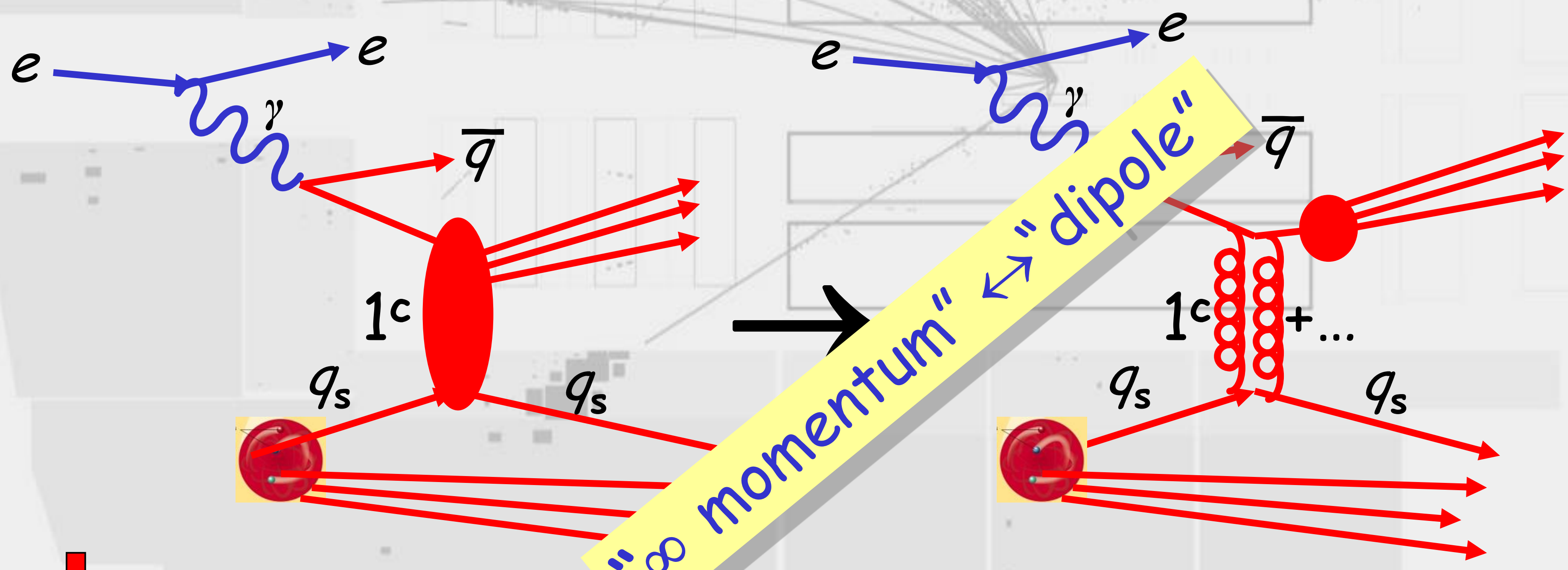


QCD field at work … with itself!
cf photon structure

↳ “hard” (~70%) … n $g\rightarrow gg$ and $g\rightarrow q\bar{q}$ splitting

Inelastic QCDiffraction

- inelastic (dissociative) quark diffraction
  $\rightarrow 1^c$ singlet q interaction ?
  - space-like photon "delivers asymptotically free quark" to short distance diffractive interaction



↳ colour singlet 1^c quark dynamics in QCD

Elastic Quark Scattering

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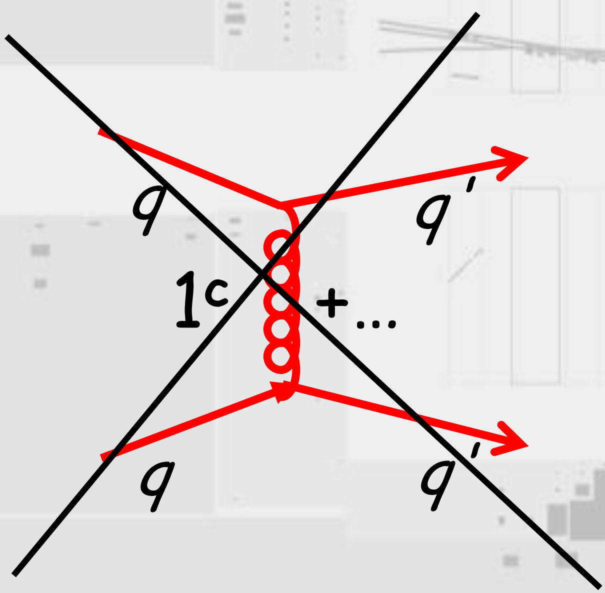
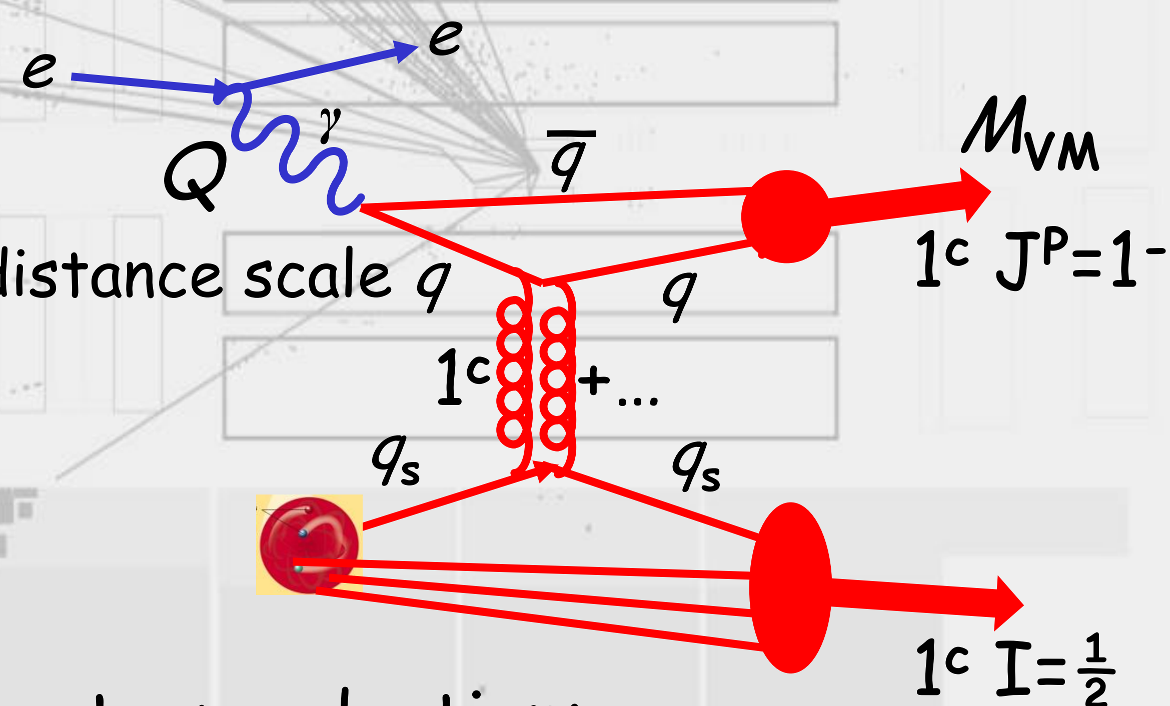
- elastic quark diffraction = scattering
  $\rightarrow$ 1^c singlet q interaction
  - space-like photon "delivers asymptotically free quark " to short distance elastic interaction





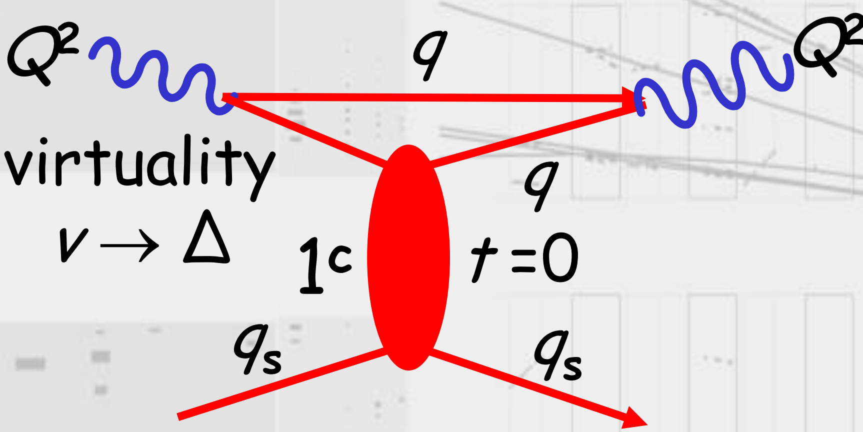
↳ exclusive VM electroproduction:
unique control of distance scale with Q and M_{VM}

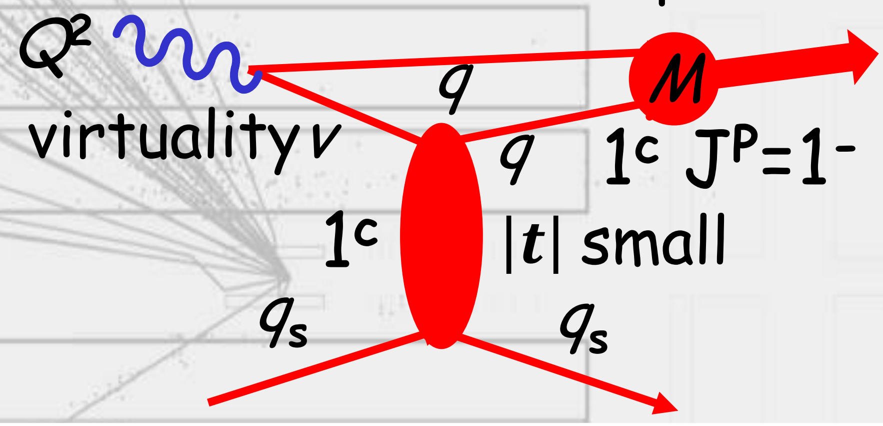
Elastic Quark Scattering

- kinematics and size Δ of elastic *q* scattering

total $\gamma^* p$ cross-section $\propto \mathrm{Im}\left[T_{\gamma^* p \to \gamma^* p}(Q^2, t=0)\right]$

elastic and dissociative vector-meson electropruction





$$-m_q^2 - Q^2 > v^2 > -m_q^2 - Q^2$$

quark mass m_q

$$v^2 \sim -\left(\frac{\hbar}{\Delta}\right)^2$$

$$-\frac{M^2+Q^2-t}{2}\left(1-\sqrt{1+4\frac{Q^2 t}{(M^2+Q^2-t)^2}}\cdot\sqrt{1-4\frac{m_q^2}{M^2}}\right)$$

$$\gtrsim v^2 - m_q^2 \gtrsim$$

$$-\frac{M^2+Q^2-t}{2}\left(1+\sqrt{1+4\frac{Q^2 t}{(M^2+Q^2-t)^2}}\cdot\sqrt{1-4\frac{m_q^2}{M^2}}\right)$$

$$F_2 \sim x_{\mathrm{Bj}}^{-\lambda(Q^2)} \to \mathrm{size}(Q^2) \propto \frac{\hbar}{v}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(W,t,Q^2) \xrightarrow[W^2 \gg Q^2]{} \propto (W^2)^{2\lambda(Q^2,t)}$$

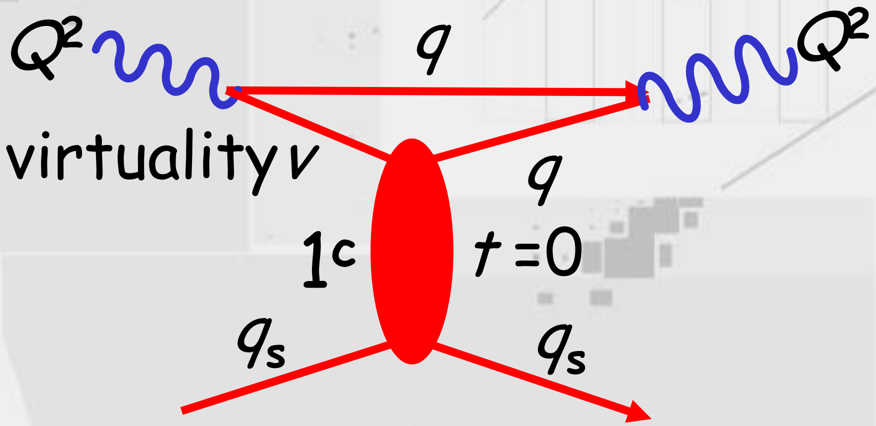
Elastic Quark Scattering

- kinematics and size Δ of elastic q scattering
  - total $\gamma^* p$ cross-section

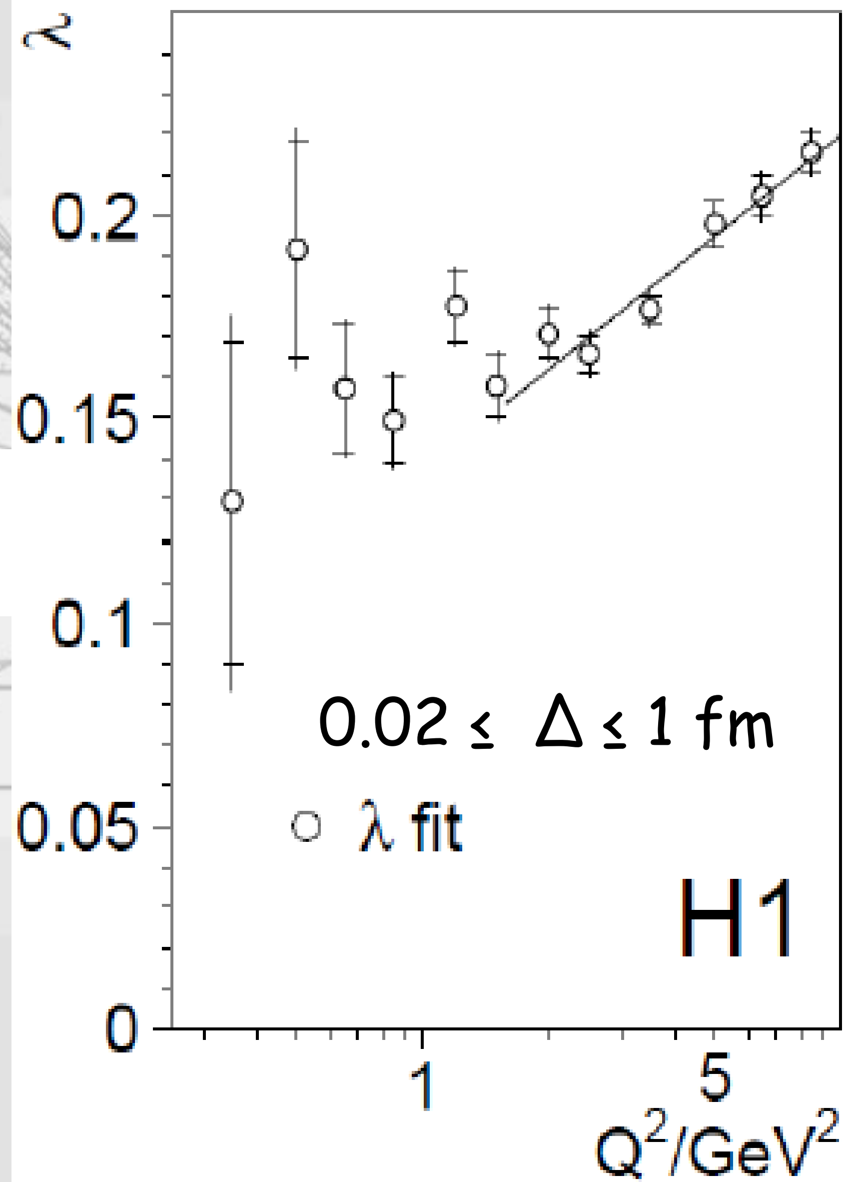
$$\propto \mathrm{Im}\left[T_{\gamma^* p \to \gamma^* p}(Q^2, t=0)\right]$$

$$\propto F_2(Q^2, x) \text{ @ low } x$$

$$F_2 \sim x_{\mathrm{Bj}}^{-\lambda(Q^2)} \rightarrow \mathrm{size}(Q^2) = \Delta(Q^2) \propto \frac{\hbar}{v}$$

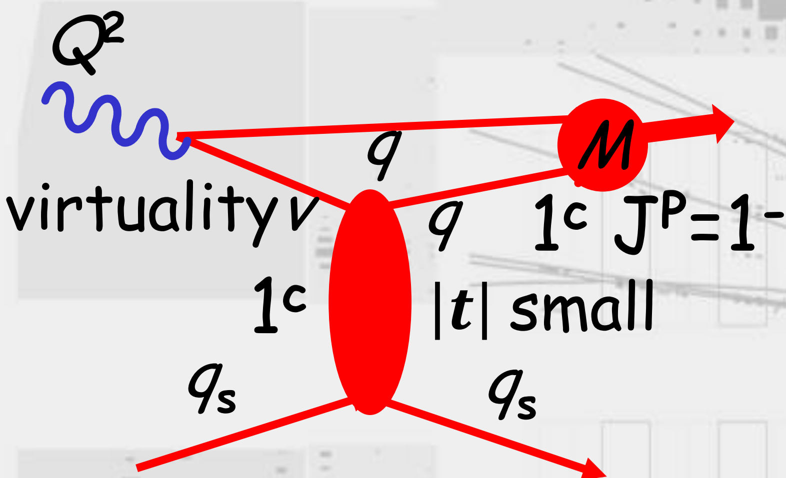


$$\lambda(\Delta) \sim 0.14 \pm 0.01 - \frac{0.15}{2.303} \ln \frac{\Delta\ \mathrm{fm}}{0.2}$$

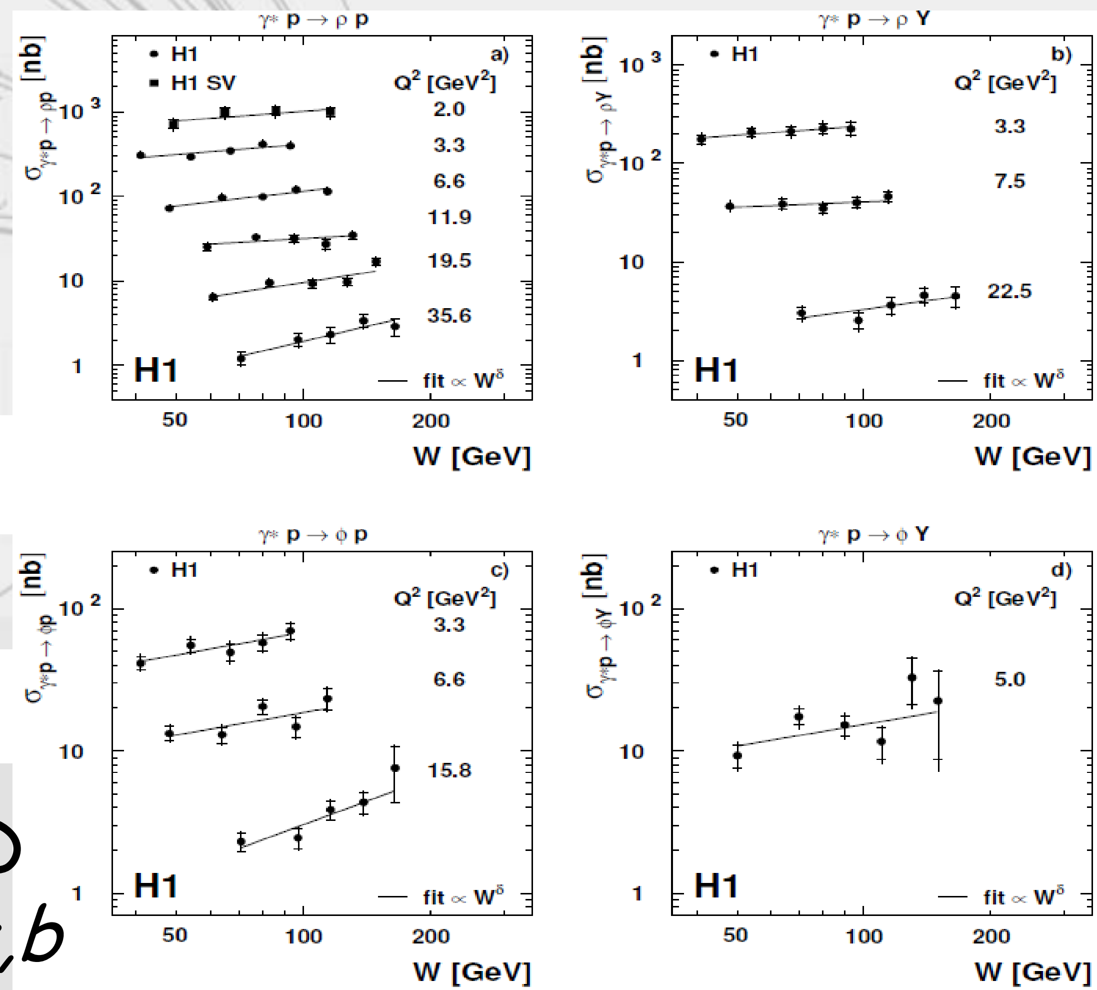


Elastic Quark Scattering

- kinematics and size Δ of elastic *q* scattering
  - elastic and dissociative VM electroproduction



$$\frac{d\sigma}{dt}(W,t,Q^2) \propto (W^2)^{2\lambda(Q^2,t)}$$



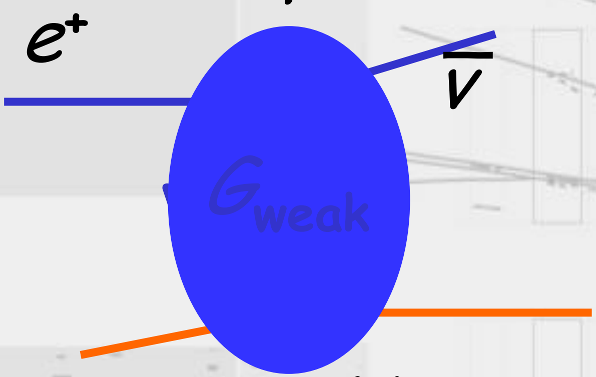
- consistency with

$$\lambda(\Delta) \sim 0.14 \pm 0.01 - \frac{0.15}{2.303} \ln \frac{\Delta\ \mathrm{fm}}{0.2}$$

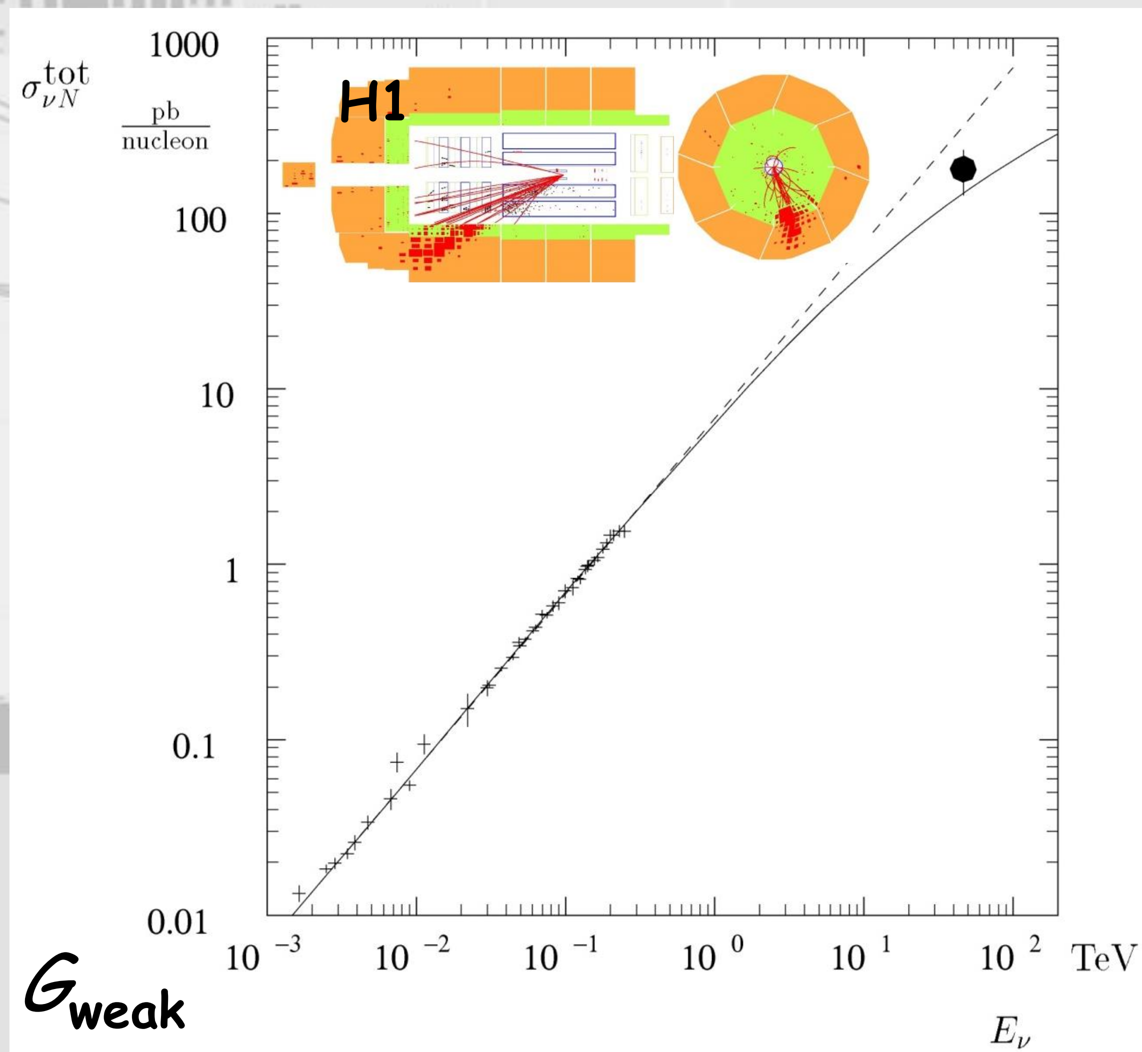
↳ 1^c colour singlet QCD
$qq \to qq$ for $q = u,d,s,c,b$

GSW Current

- 1993: hint of weak unitarity = GSW unification **?**
  - from $ep \rightarrow \bar{\nu}X$



to $\nu p \rightarrow eX$



  - IVB in CC
  - EW probe
  - structure of Fermi constant G_{weak}

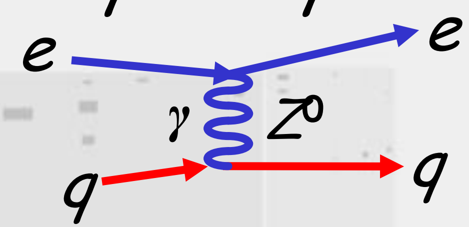
GSW Current

- now: resolved structure in GSW $SU(2)_L \otimes U(1)$

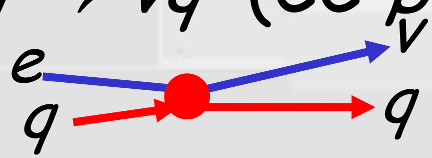
$$\Delta x \sim \frac{0.2\ \text{TeV}\cdot\text{am}}{Q}$$

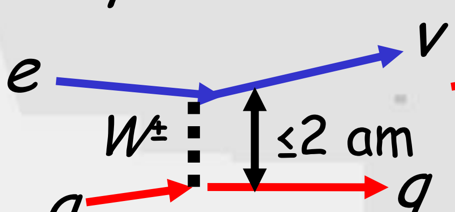
- Rutherford scattering

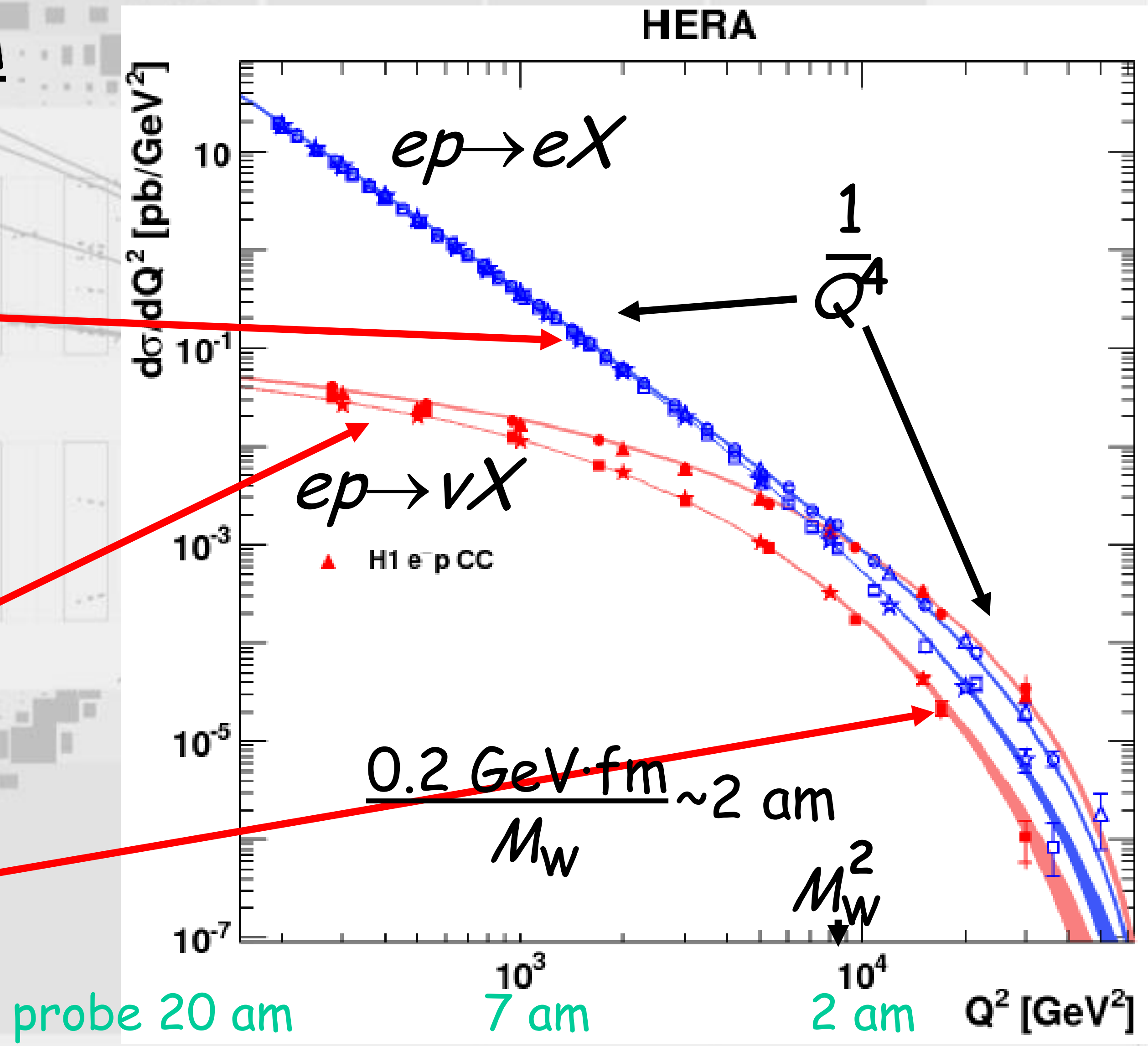
$eq \to eq$



$eq \to \nu q$ (CC β)





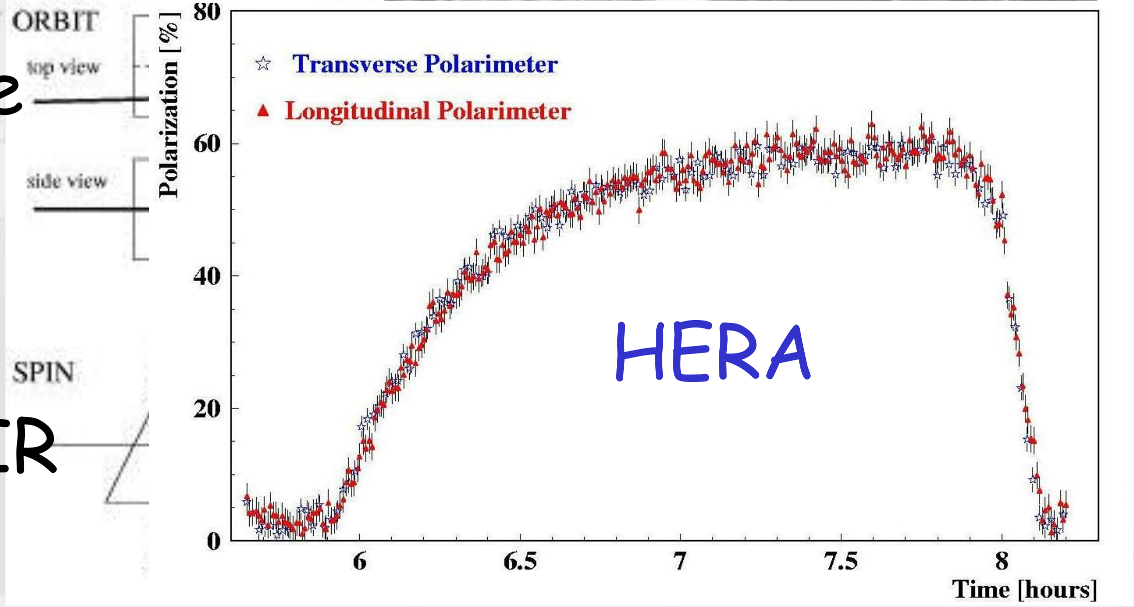


Rotating Spin

- stored e radiates
  $e \rightarrow e_T$ Sokolov-Ternov
  transversely polarised e
  synchrotron radiation

- "spin-rotator"
  - subtle and precise precession
  - "Siberian snake" insertion device

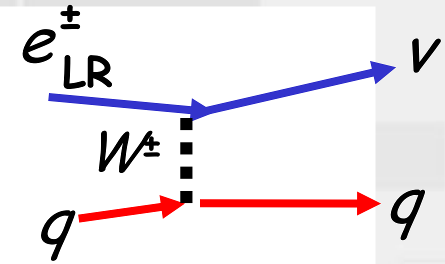
  $e_T \rightarrow e_{RL} \rightarrow e_T$ at IR

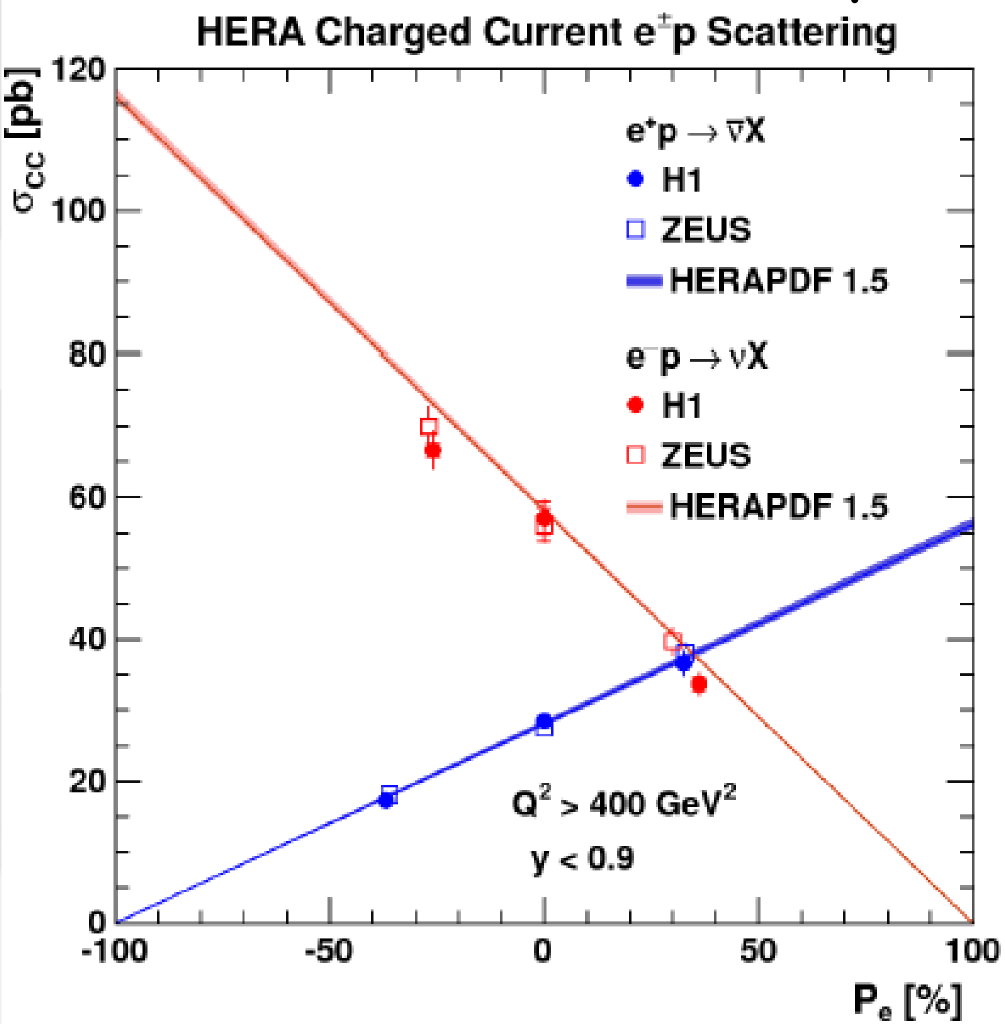


Barber, Steffen (DESY)

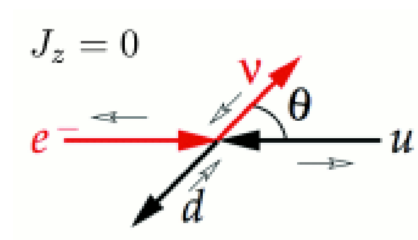
GSW Current

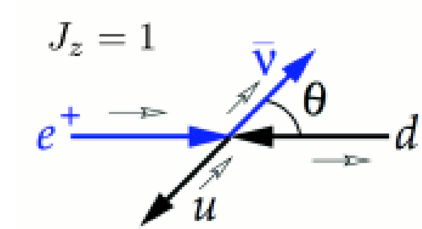
- quarks = L(R) Dirac (anti-)fermions
  L(R) (anti-)leptons





- Chiral structure of EW interactions probed
- No sign for right-handed currents



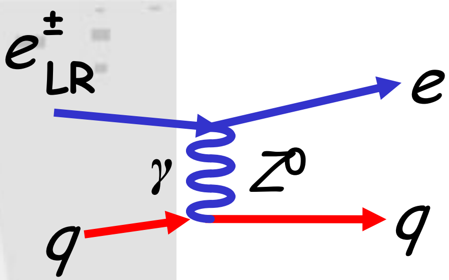


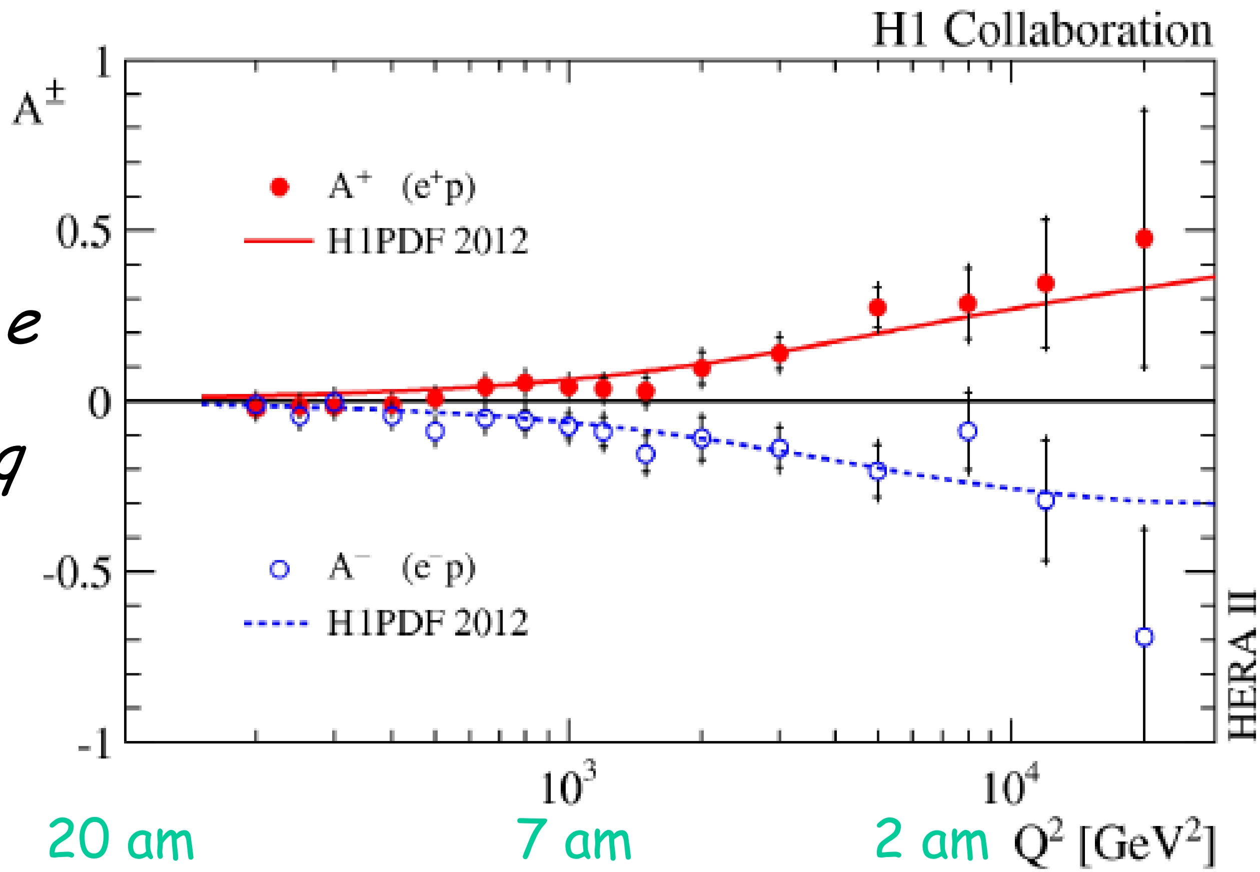
GSW Current

- polarisation asymmetry: $e^{\pm} \rightarrow$ NC parity violation

NC polarization asymmetry

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$



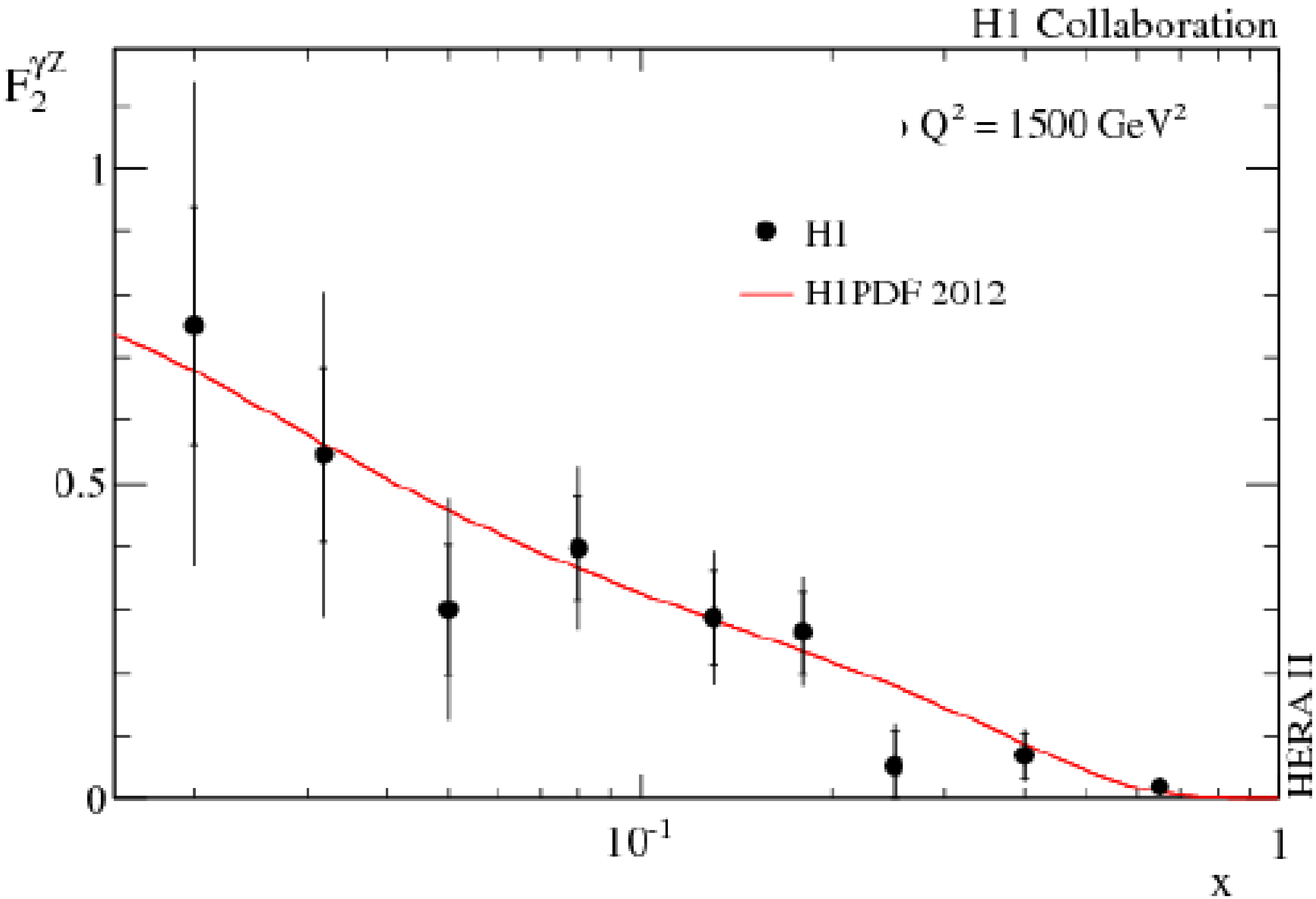


probe 20 am 7 am 2 am

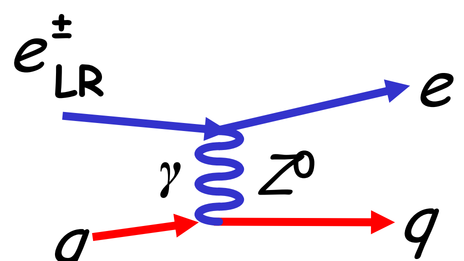
Anti-matter GSW Current

- in *ep* interaction chirality probes anti-matter in *p*

$$\frac{\sigma^{\pm}(P_L^{\pm})-\sigma^{\pm}(P_R^{\pm})}{P_L^{\pm}-P_R^{\pm}}=\frac{\kappa Q^2}{Q^2+M_Z^2}\left[\mp a_e F_2^{\gamma Z}+\frac{Y_-}{Y_+}v_e x F_3^{\gamma Z}-\frac{Y_-}{Y_+}\frac{\kappa Q^2}{Q^2+M_Z^2}(v_e^2+a_e^2)xF_3^Z\right]$$



$F_2^{\gamma Z} \sim$ q+qbar



Current Quark Couplings

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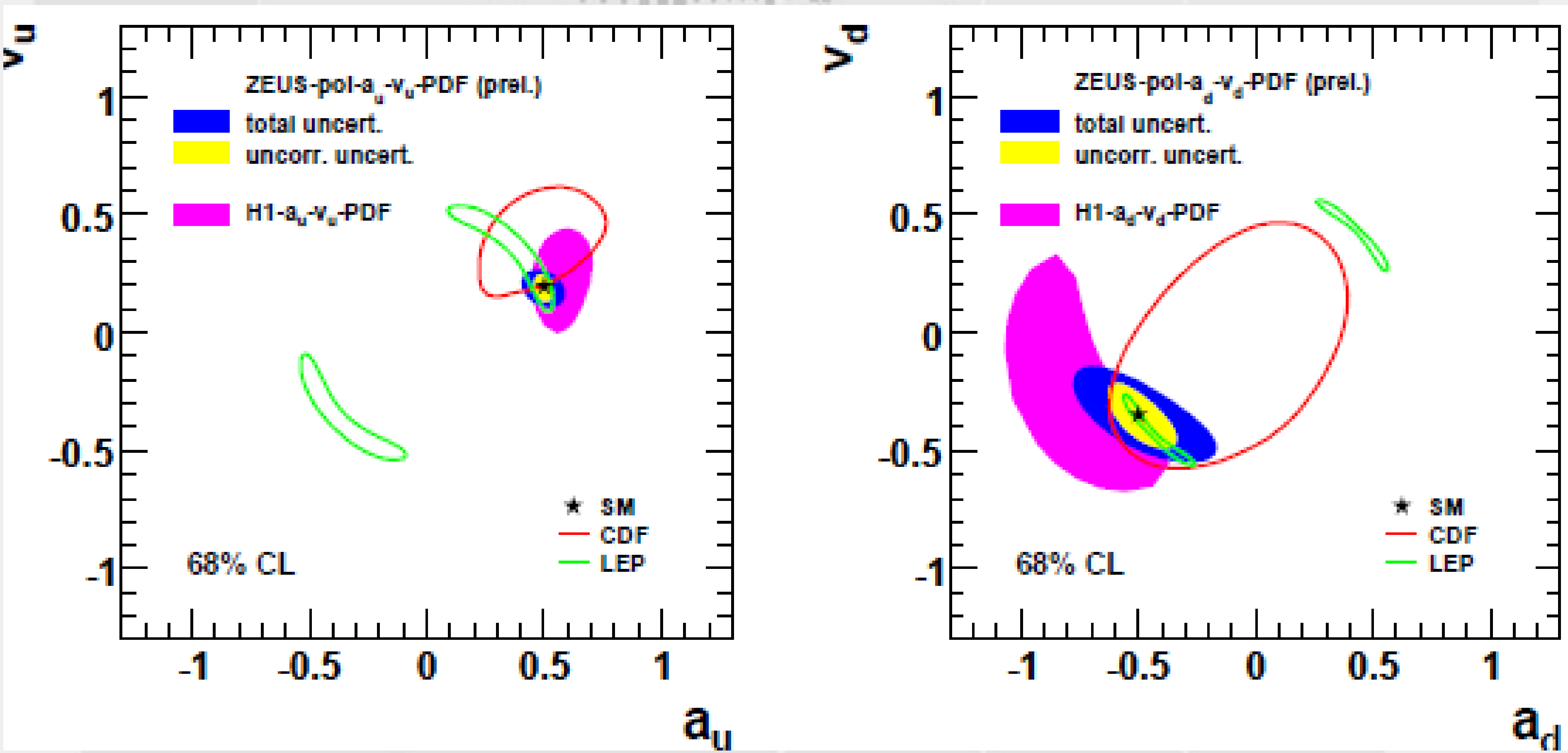
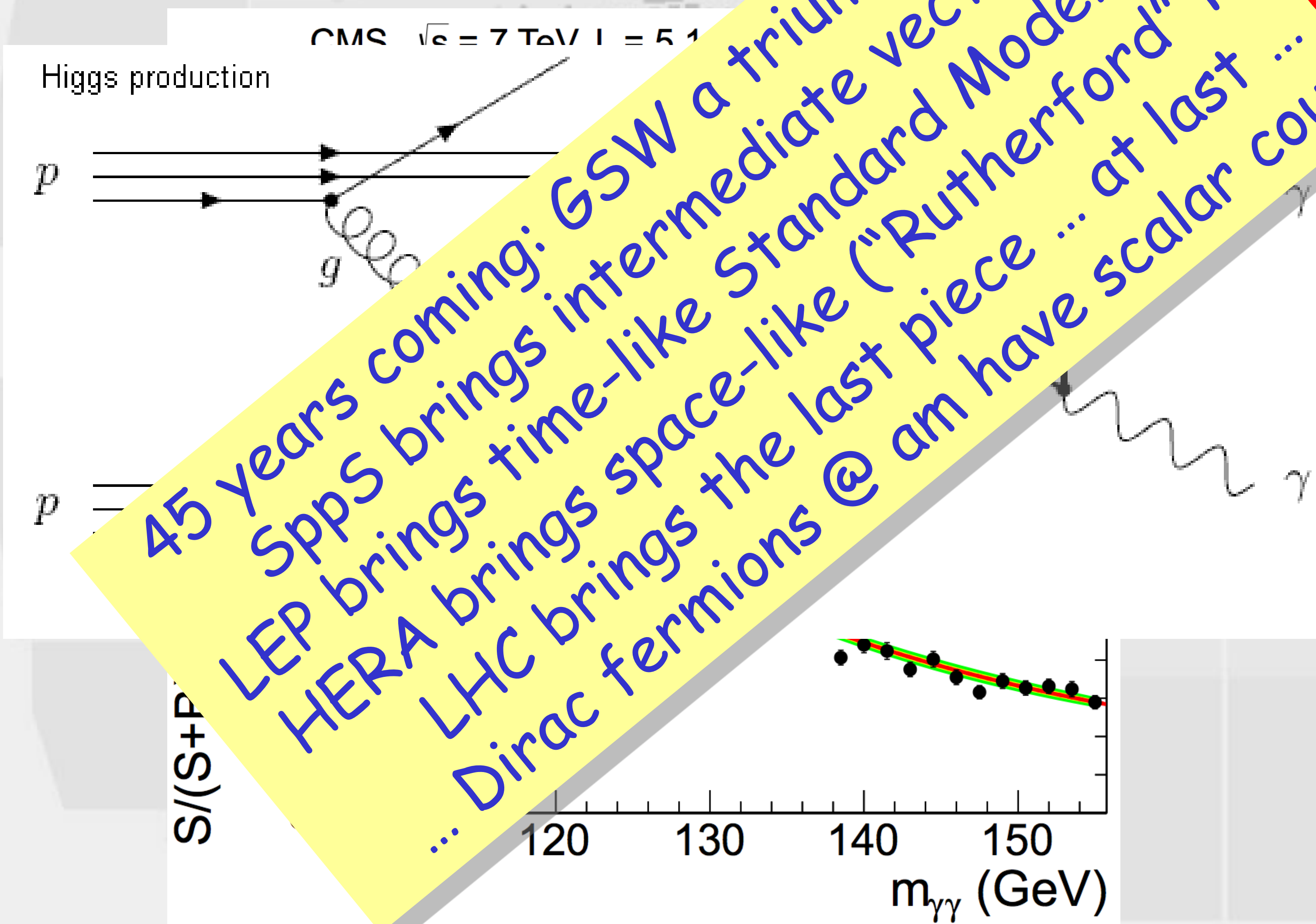
- V and A current quark couplings: *e* polarisation and $\gamma^* Z$ interference



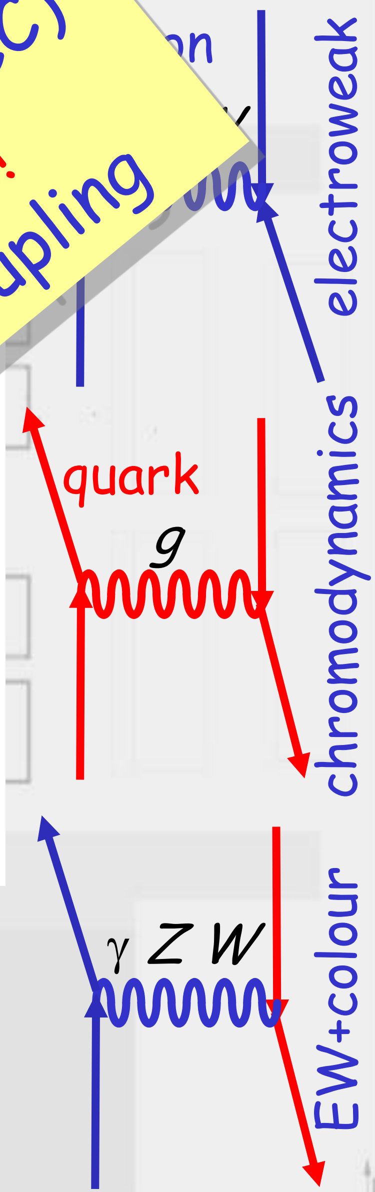
- space-like (HERA) and time-like (LEP+Tevatron)

GSW Bosons

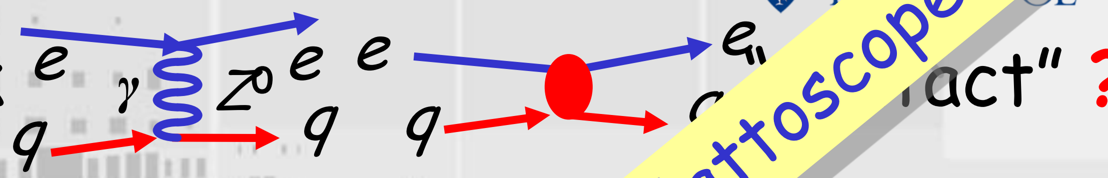
- Fermi scale complete: EW

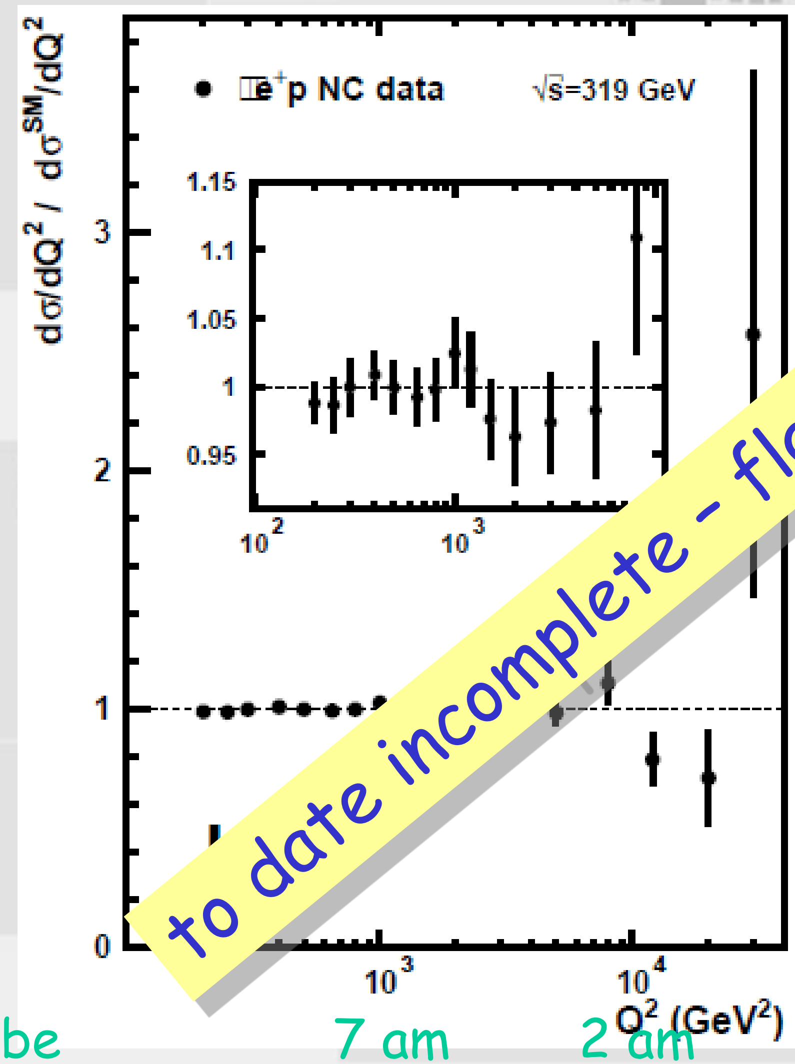


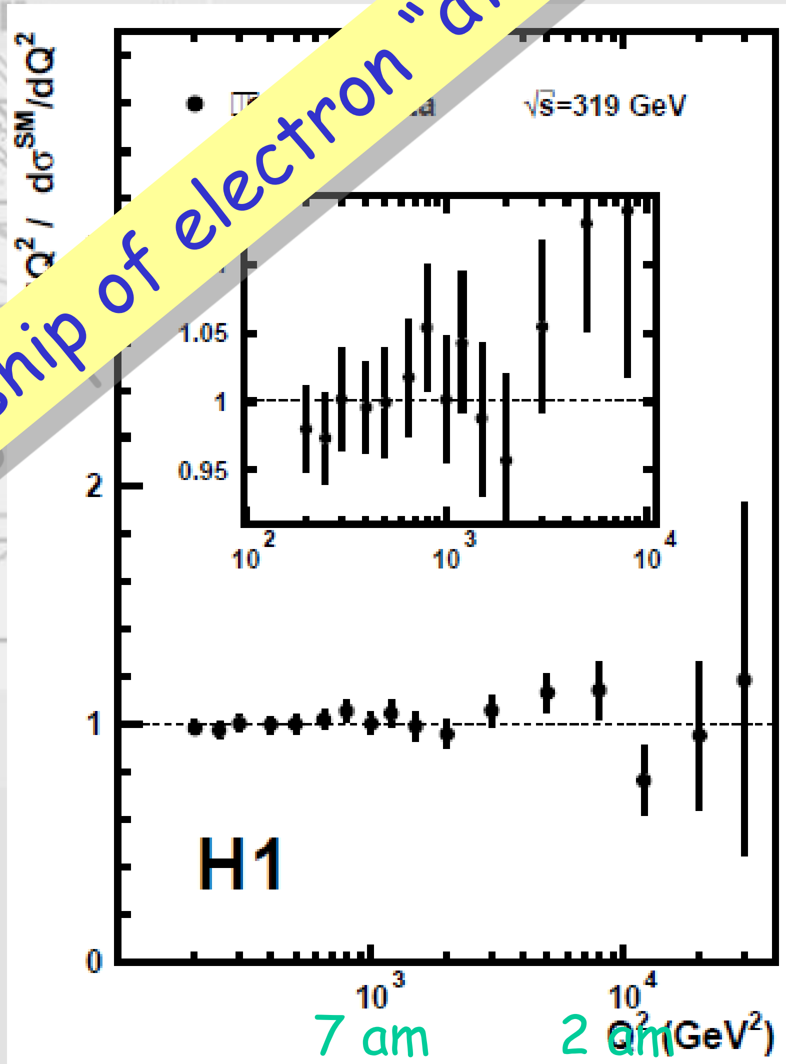
45 years coming: GSW a triumph of humanity
SppS brings intermediate vector bosons
LEP brings time-like Standard Model precision
HERA brings space-like ("Rutherford" NC CC)
LHC brings the last piece … at last … !
… Dirac fermions @ am have scalar coupling



New Constituents and Currents ?

- beyond Dirac quark




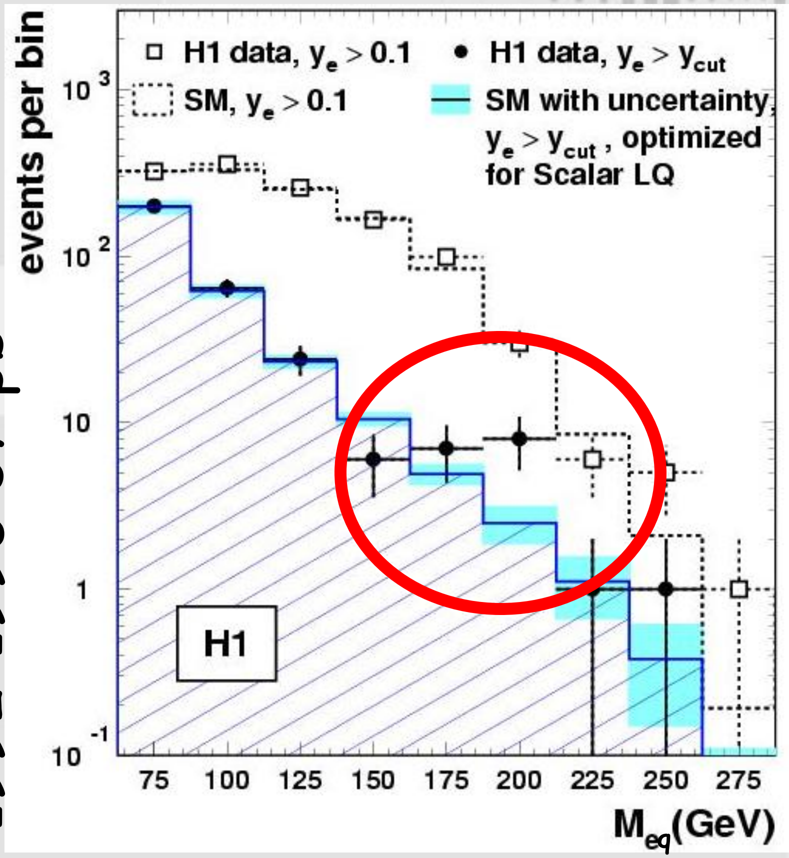


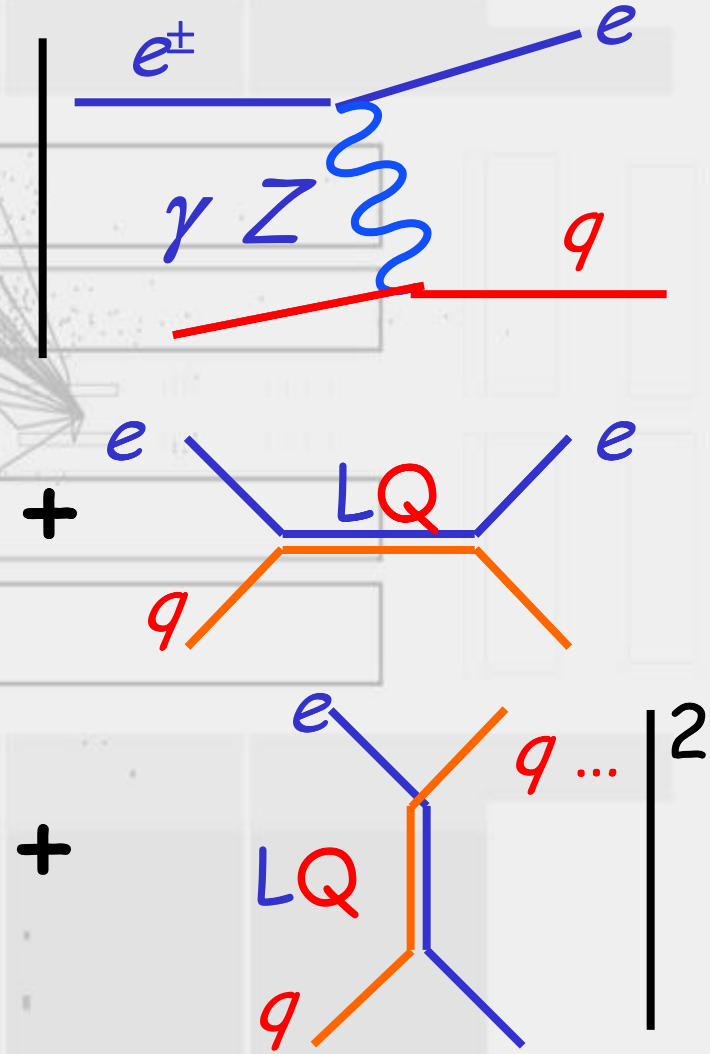
to date incomplete - flagship of electron " attoscope"

New Constituents and Currents ?

- new *eq* physics – "LQ"

experiment #1
1992-1996 37 pb-1





- SM template ↔ experiment !

New Constituents and Currents ?

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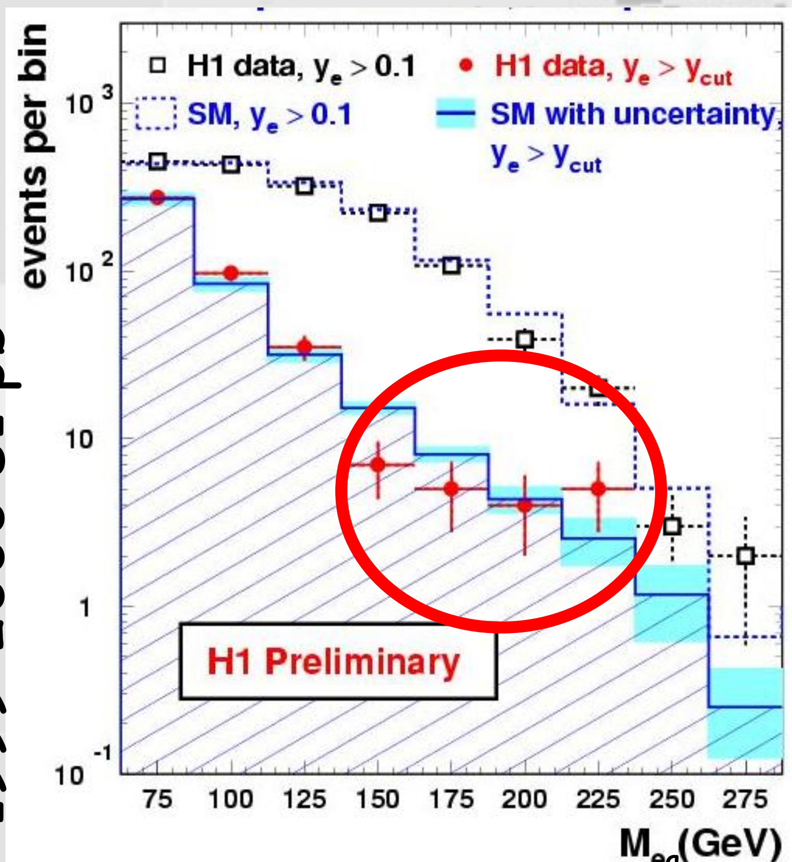
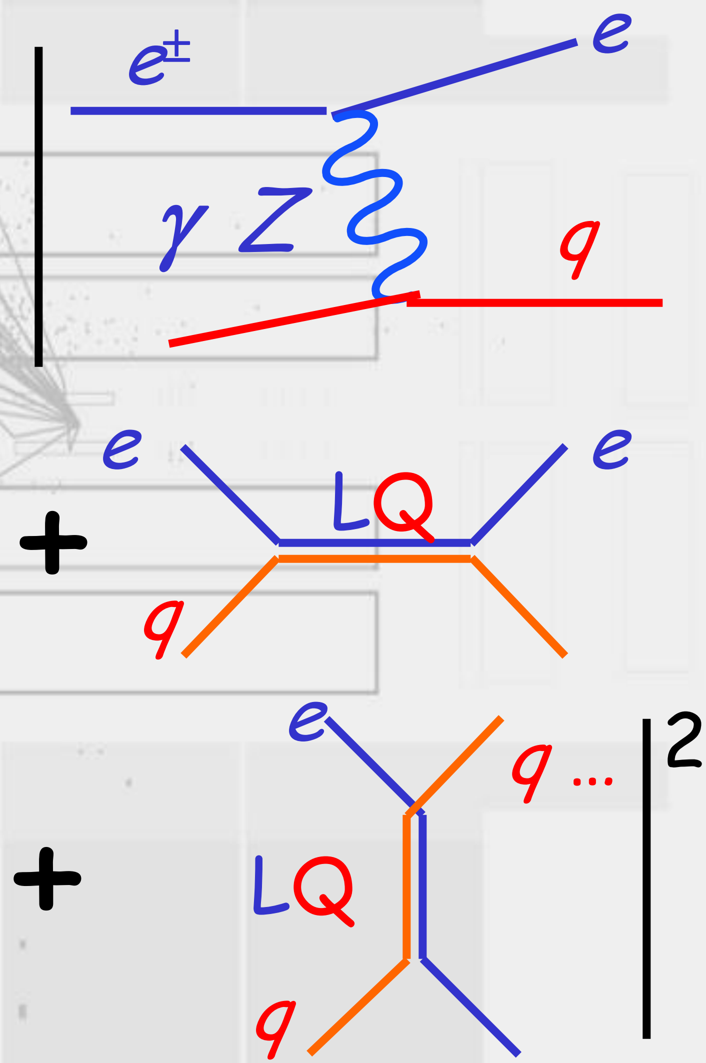
- new *eq* physics - leptoquarks

experiment #2
1999-2000 81 pb-1

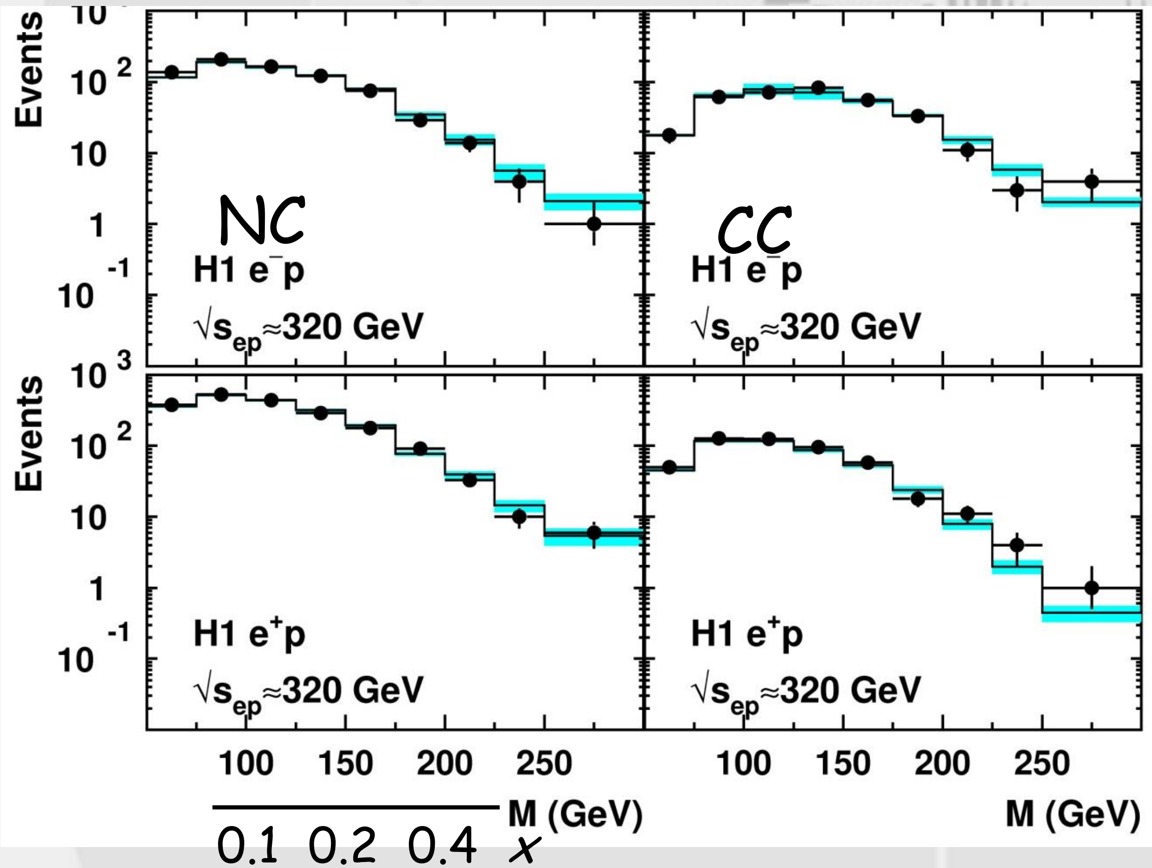


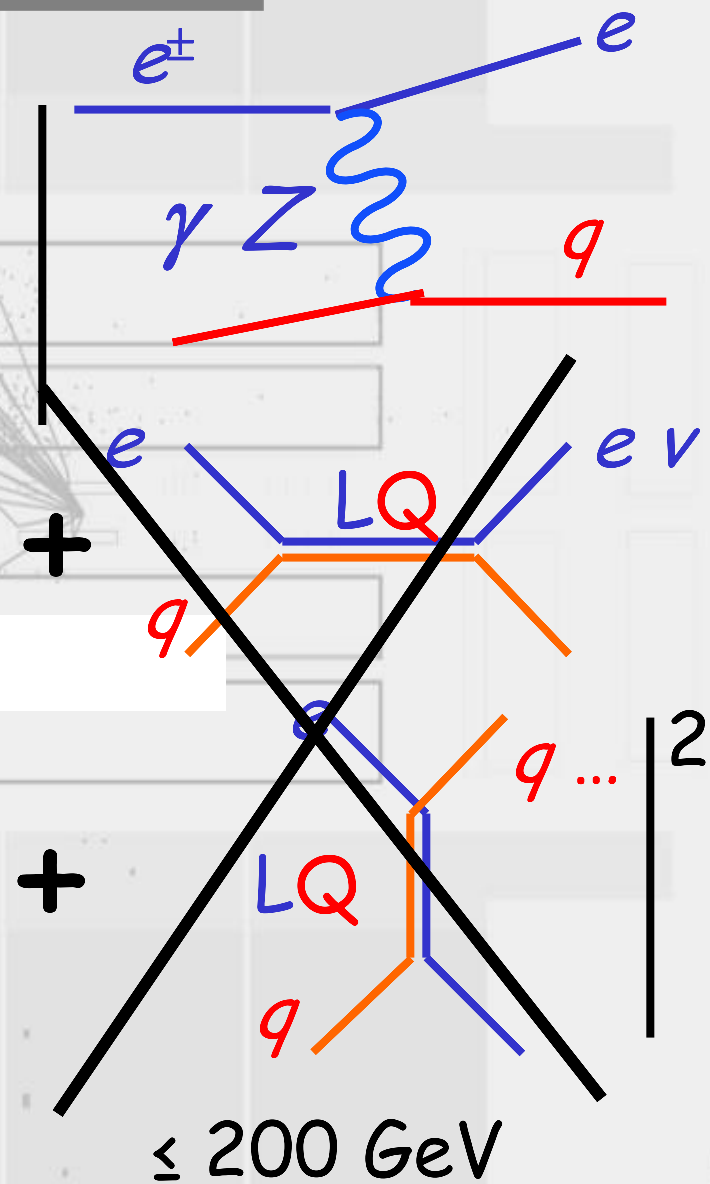


- SM template ↔ experiment !

New Constituents and Currents ?

- new *eq* physics – 1992-2007

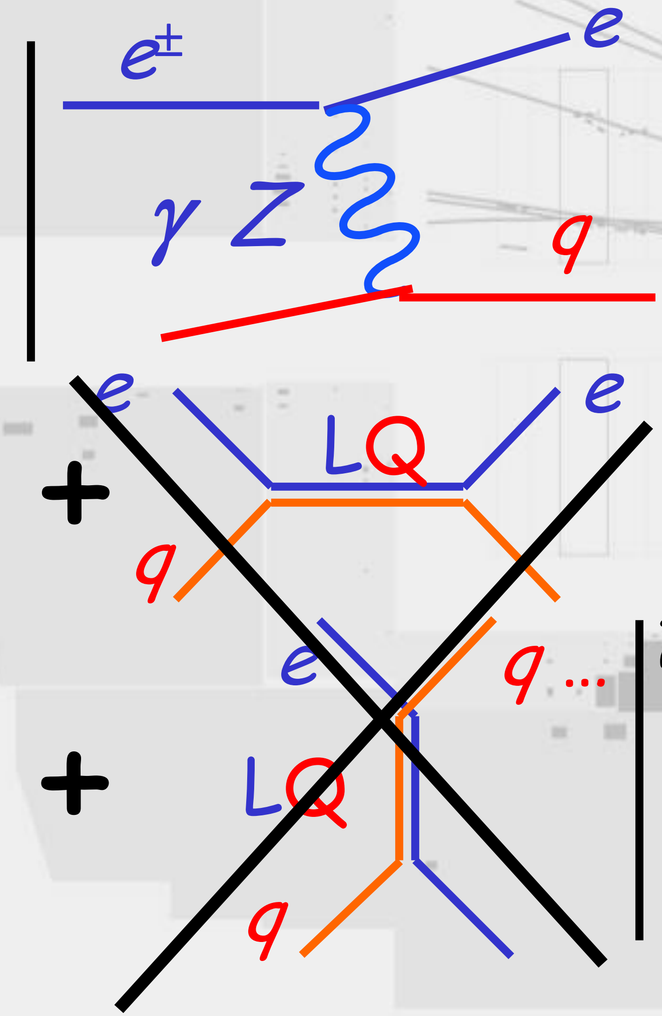


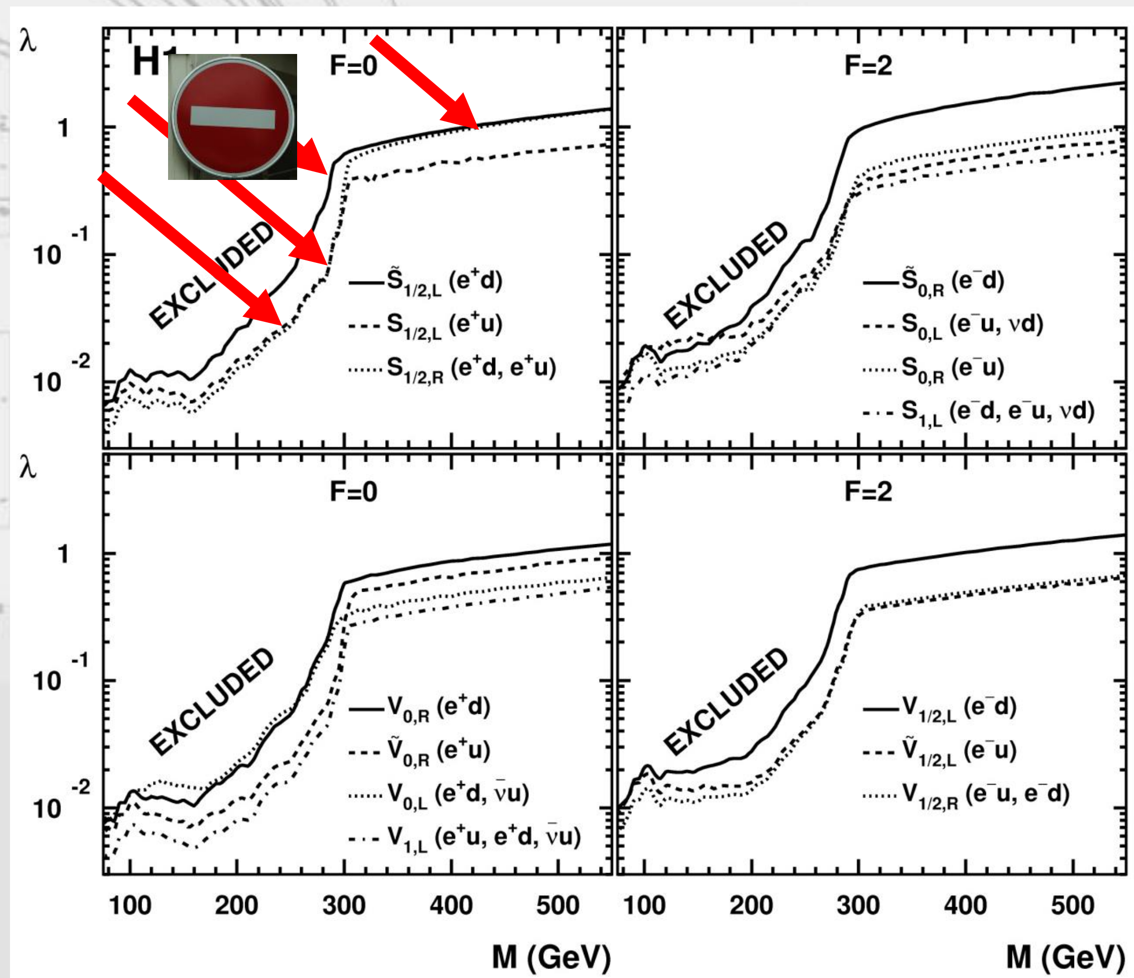


↳ discovery: SM @ Fermi scale !

New Constituents and Currents ?

- LQ ?
  - SM consistency → Dirac fermion + gauge coupling



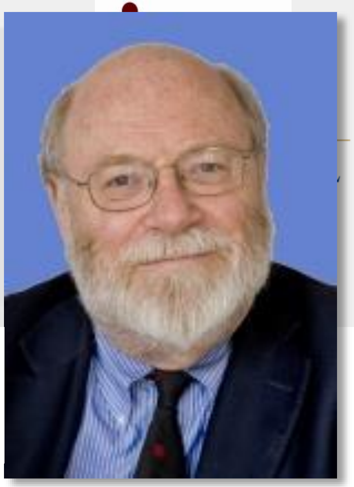


Electron-Quark Physics: the HERA Era

- HERA - leptons and quarks together @ 314 GeV
  - tells us that we are field energy
  - measures the quantum structure of hadron force
  - identifies colour-singlet colour physics
  - questions quarks as Dirac QCD fermions ?
  - says quarks are Dirac GSW SM fermions > 2 am
  - electron and positron are gauge fermions > 2 am
  - defines SM+QCD template(s) @ the Fermi scale
  - sets new $e^{\pm}q$ physics threshold

coupling $\lambda \geq {0.01 \atop 1}$ $\quad M_{eq} \geq {200 \atop 314}$ GeV

… and after the constituents, the currents, the colour, … now the Cashmore



A University

"There are few earthly things more beautiful than a university. It is a place where those who hate ignorance may strive to know, where those who perceive truth may strive to make others see; where seekers and learners alike, banded together in the search for knowledge, will honour thought in all its finer ways, will welcome thinkers in distress or in exile, will uphold ever the dignity of thought and learning, and will exact standards in these things.

Religions may split into sect or heresy; dynasties may perish or be supplanted, but for century after century the University will continue, and the stream of life will pass through it, and the thinker and the seeker will be bound together in the undying cause of bringing thought into the world…."

John Masefield 1878-1967
Poet Laureate 1947-1967

Happy 70th Birthday Roger and many many more happy returns … to physics too … for we will always need your wisdom and judgement