Humboldt @ Kitzbuehl
27 June to 1 July 2016

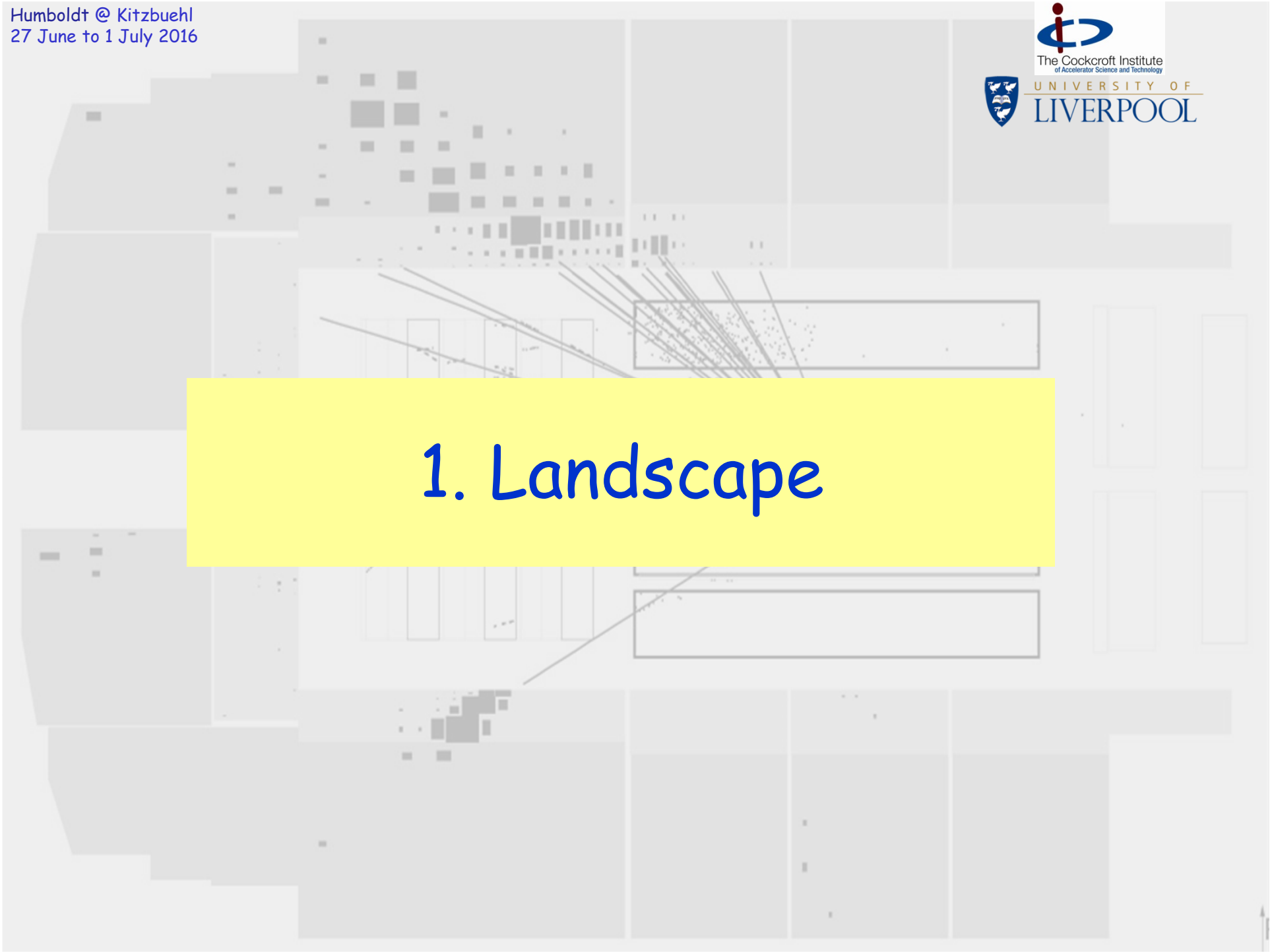
Constituents, Currents and Colour

John Dainton†

University of Liverpool, UK

1. Landscape
2. Landmarks
3. Outlook

† European Research Council Grant GA No. 268062 "UniversaLepto"



1. Landscape

Electron-Proton Physics

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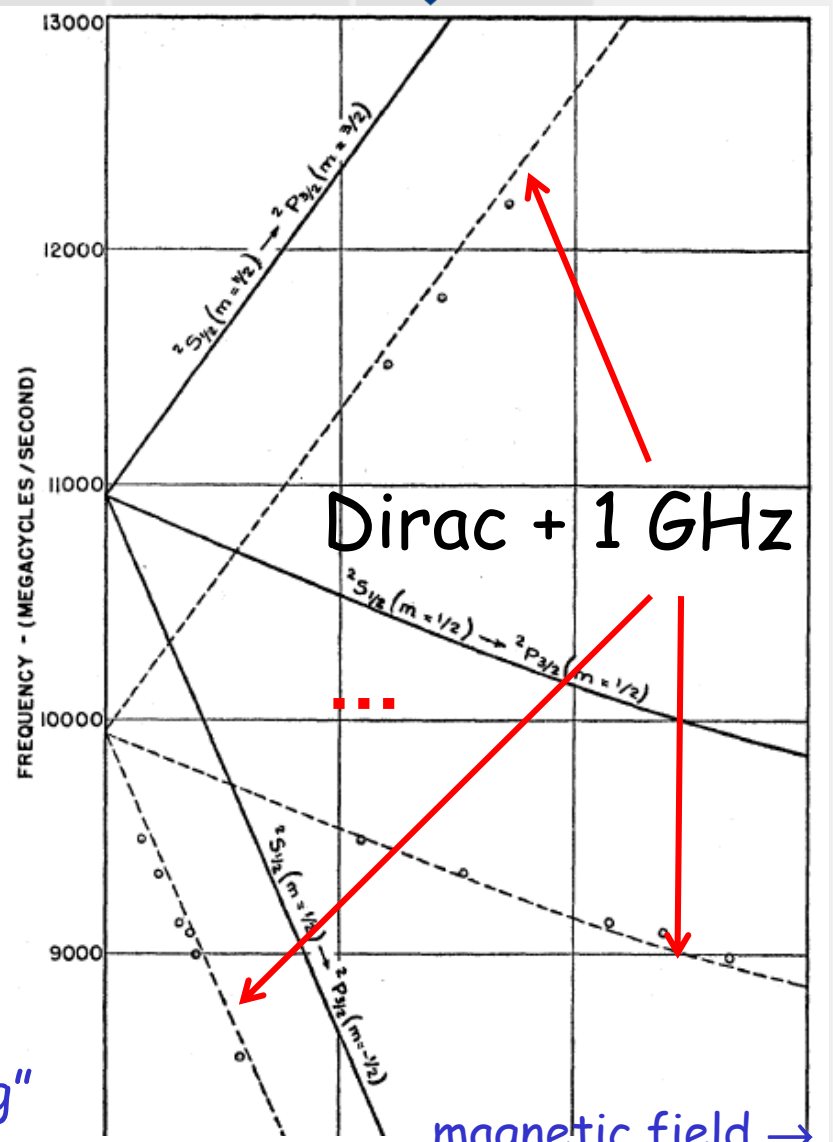
- Dirac 1928
  (n integer j $\frac{1}{2}$-integer)

$$E_{nj} = \frac{mc^2}{\sqrt{1+\left[\frac{1}{\hbar c}\left(\frac{Ze}{n-\left|j+\frac{1}{2}\right|}\right)^2+\sqrt{\left|j+\frac{1}{2}\right|^2-\frac{Z^2e^2}{\hbar c}}\right]^2}}$$

- Lamb-Retherford 1947
  - Dirac+3 ppm observed
  - 3 ppm = 1 GHz splitting

↳ relativity + electron + field quantisation → mode $E_\nu = \left(n+\frac{1}{2}\right)h\nu$

integer — "Zitterbewegung"



↳ relativity + electron + field + quantisation + space

Electron-Proton Physics

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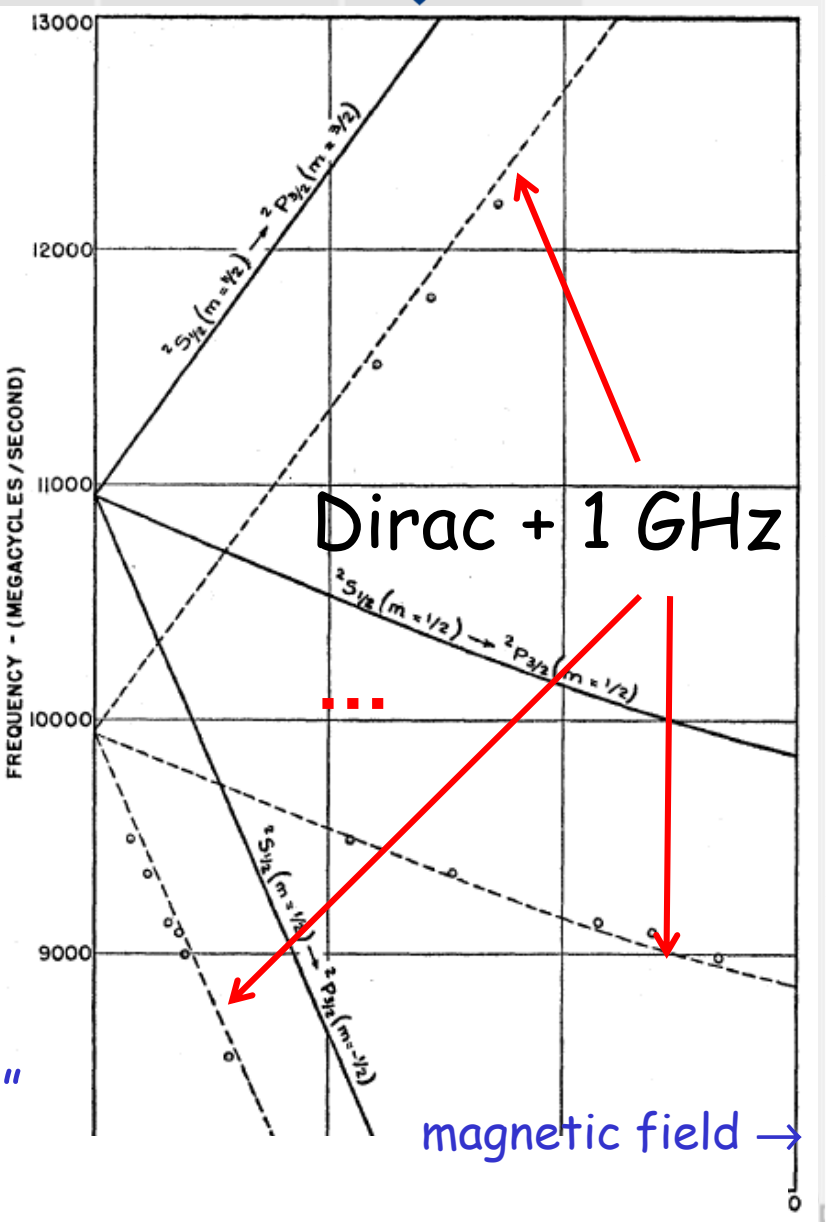
↳ relativistic quantum field



Constituents 1970 ?

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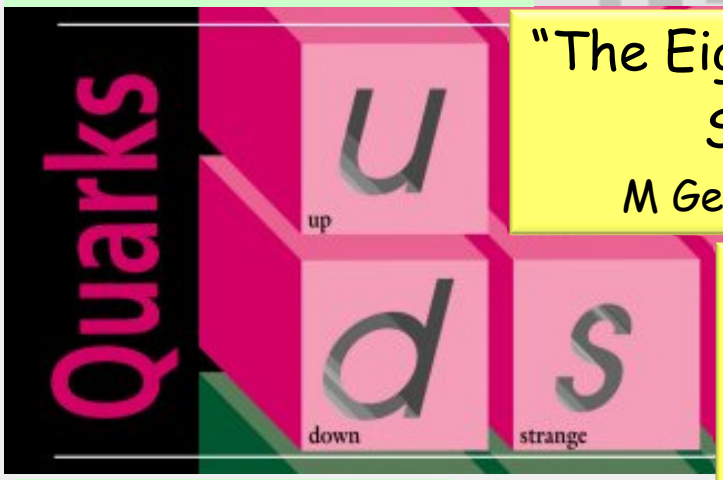
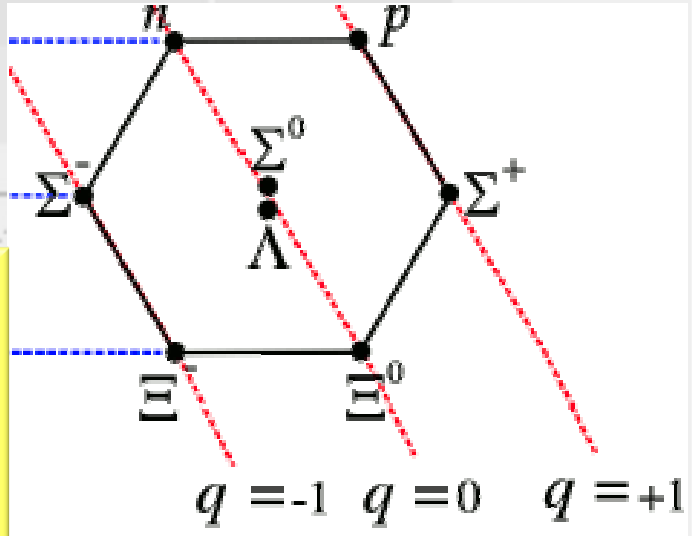
mass ? GeV

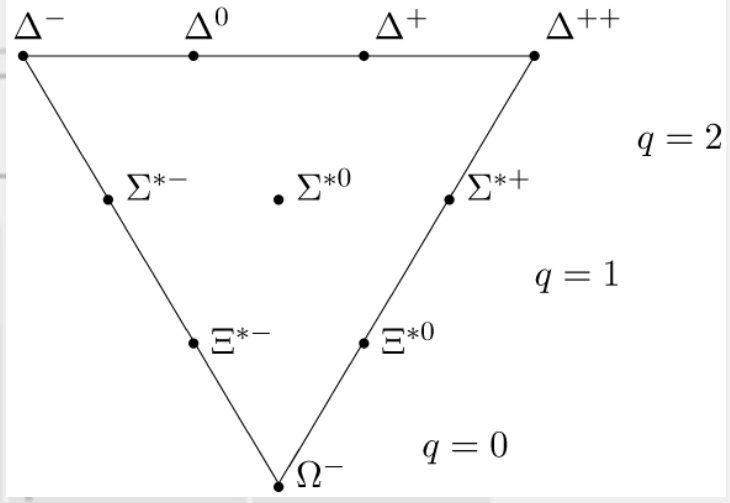


"The Eightfold Way"
$SU(3)_F$
M Gell Mann, G Zweig

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



mass ? GeV



- 3 quarks for a proton *uud* → 938 MeV = ? and resonances ?

constituent quarks

- sub-femtoscopic matter = Dirac fermions (*uds* ?+*ev*/*μν*)
- strong, EM, weak: Fermi+unitarity = *W*?

Constituents - quarks ?

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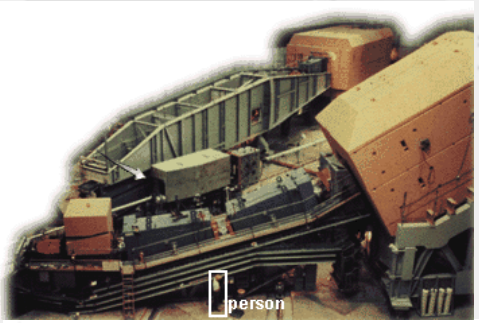
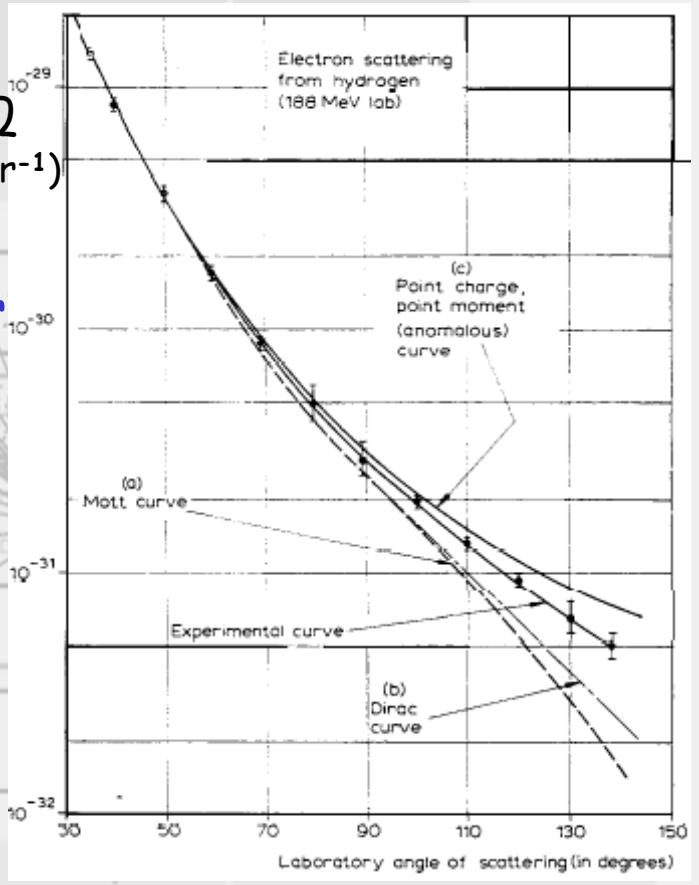
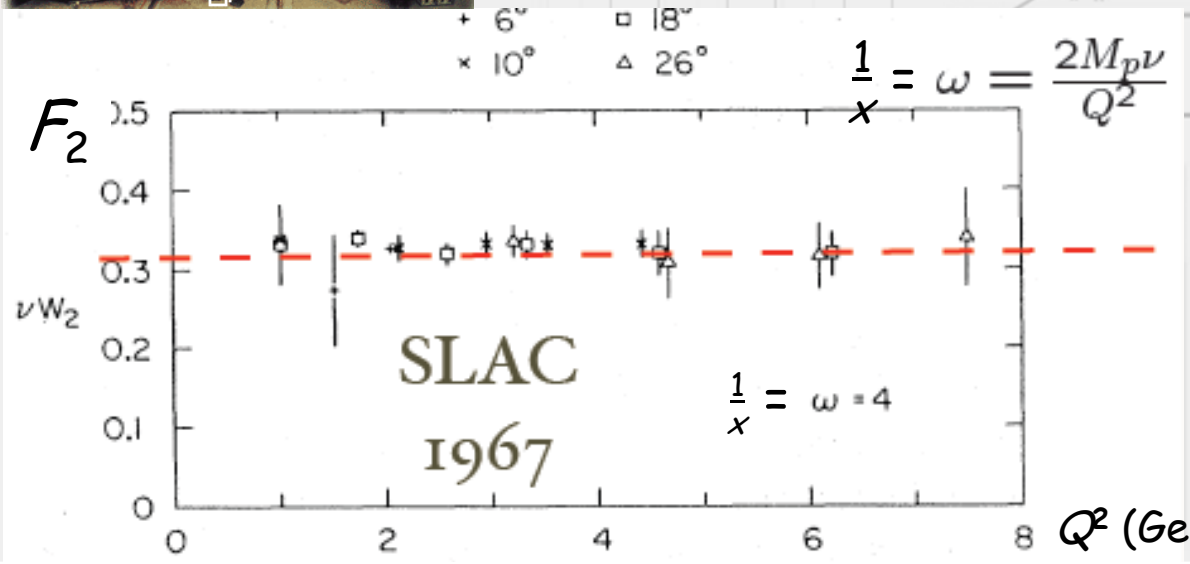
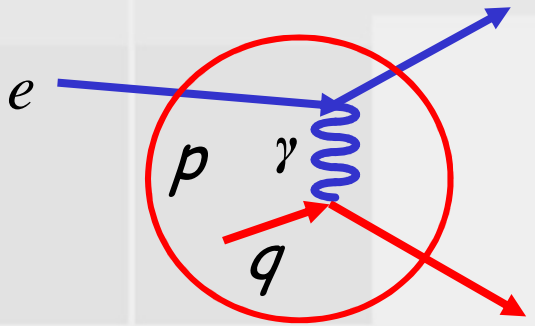
- SLAC end station:
  - 1959 nucleus size
    nucleon size — Hofstädter
  - 1967 partons — Friedman Kendall Taylor



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







Constituents - quarks

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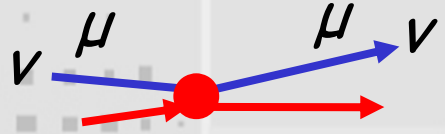
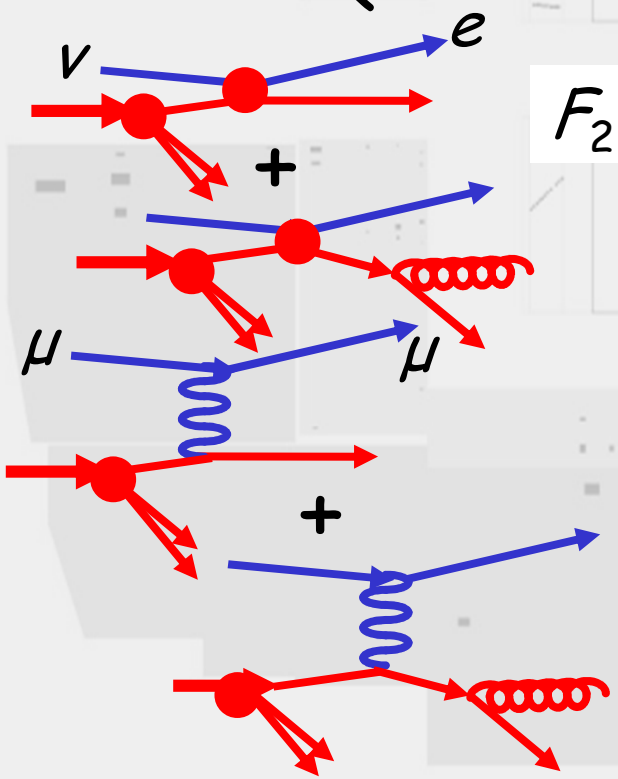
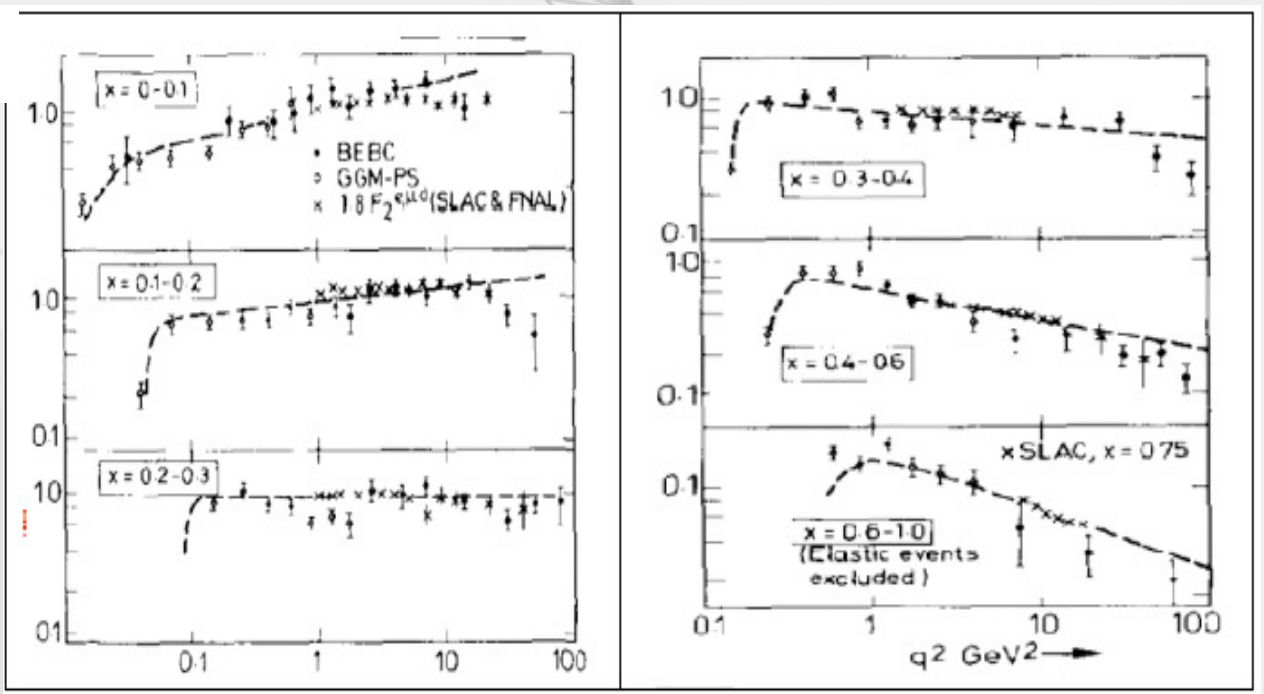
- CERN + Fermilab
  - fixed target νp
  - sub-fm ($Q^2 \leq 20$ GeV)
  - 1972 $\frac{\text{NC}}{\text{elm}}$ and $\frac{\text{CC}}{\text{elm}} \rightarrow$ quarks
    1977 QCD







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Quark Confinement and Jets

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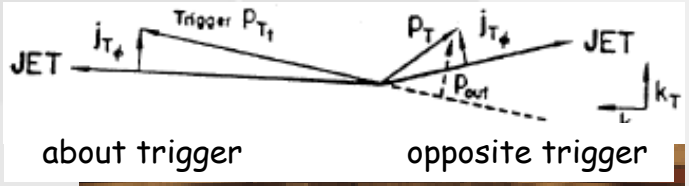
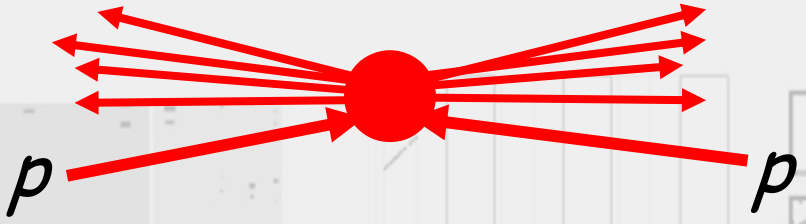
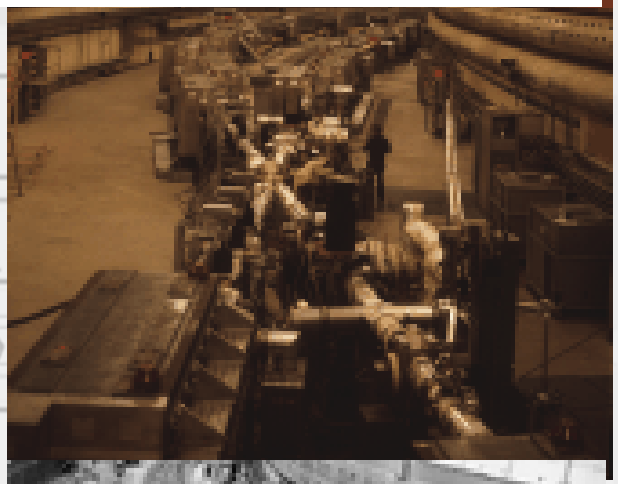


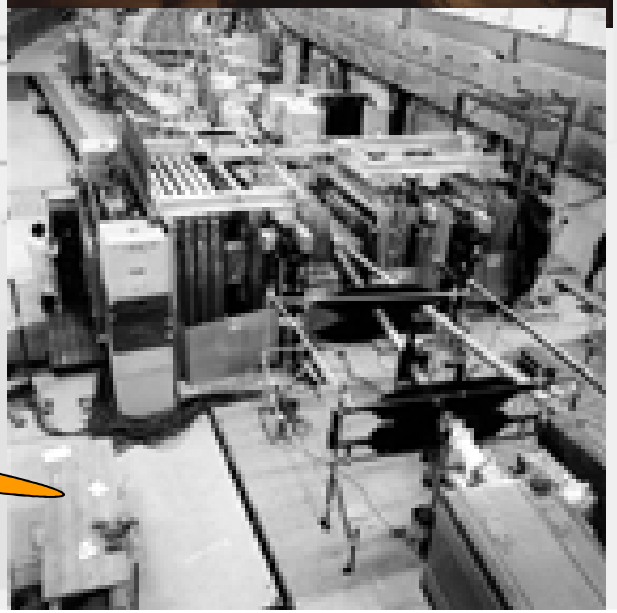
about trigger opposite trigger

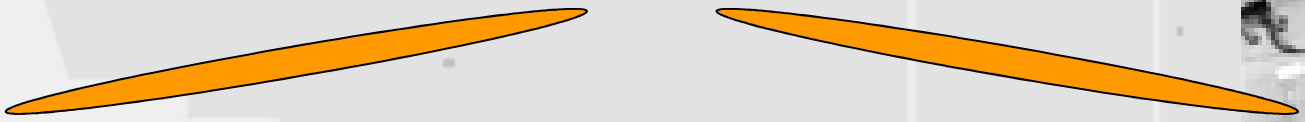
- first collider
  CERN ISR ≥ 1972
  - $pp \rightarrow X$



- efficient beam crossing







Quark Confinement and Jets

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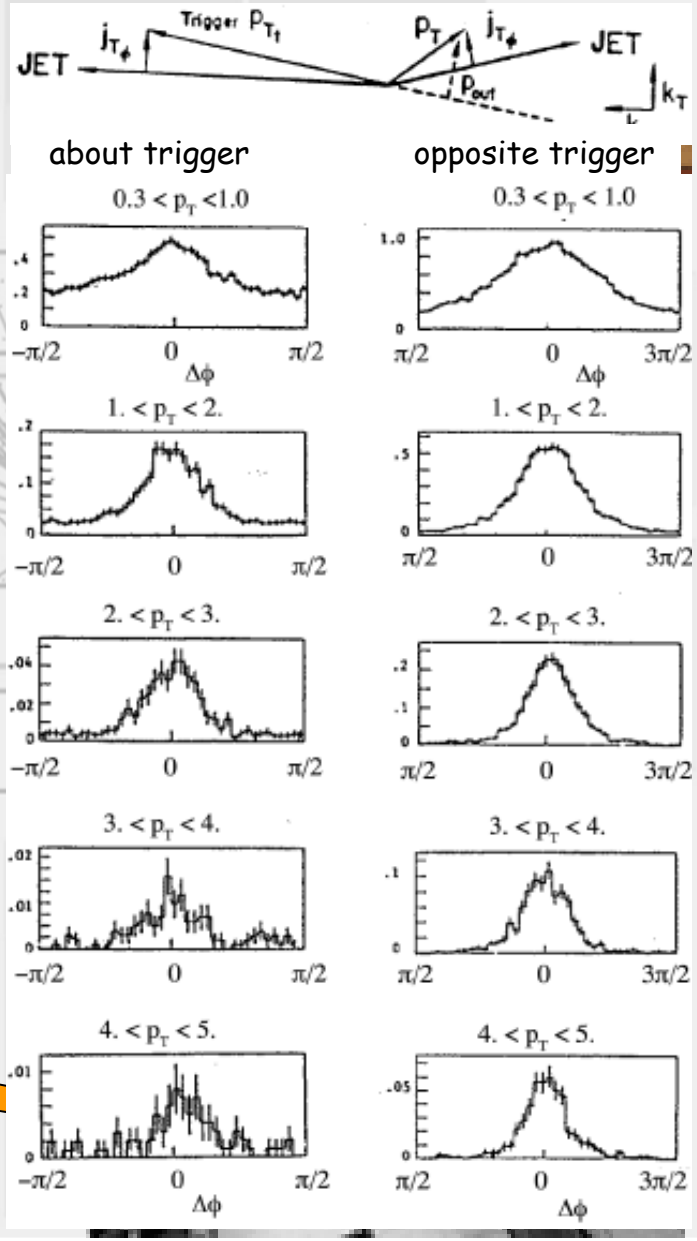
- first collider
  CERN ISR ≥ 1972
  - $pp \rightarrow X$
  - $pp \rightarrow$ trigger $\pi^0 + X$
    @ 63 GeV CM
  - co-planar
    opposite hemisphere
- efficient beam crossing
  "jets"
  - production $k_T \leftrightarrow$
    fragmentation p_T



Intermediate Vector Bosons

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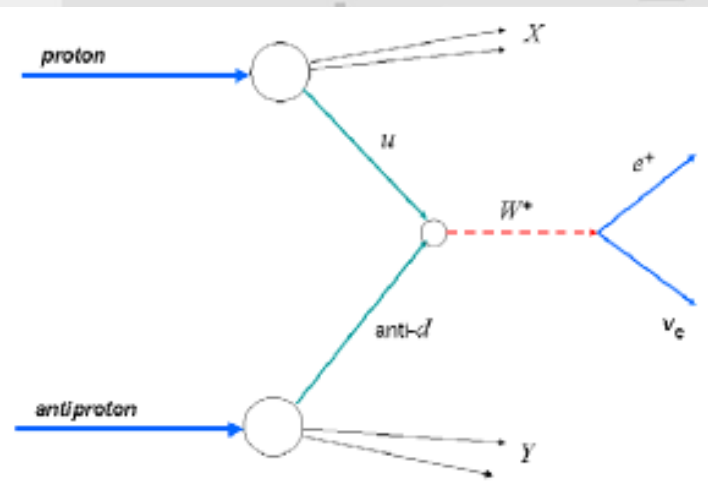
- $S\bar{p}pS$ @ CERN: E_T conserved

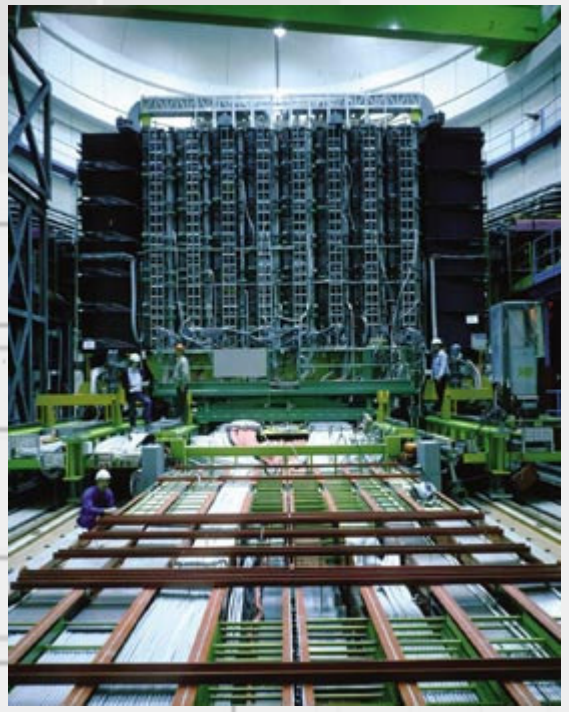
Nobel
Rubbia+van der Meer

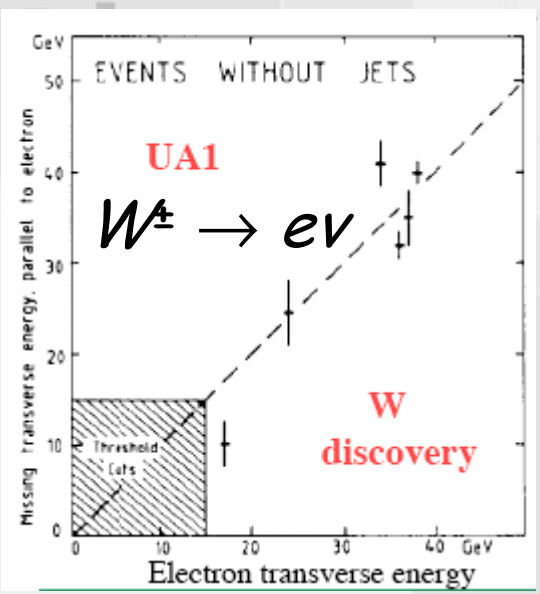


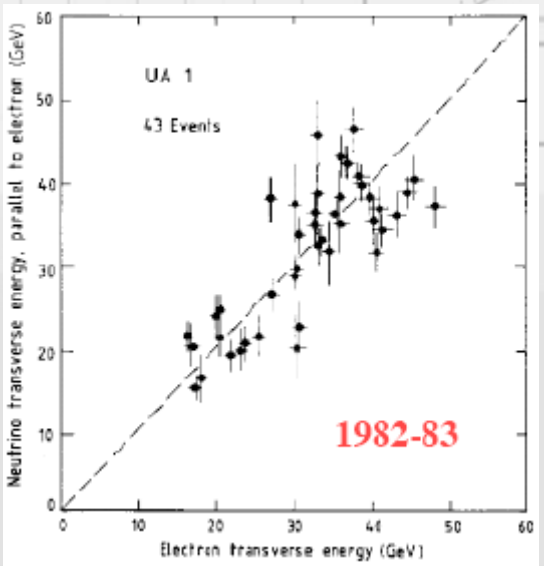
$pp \rightarrow X + Z^0 \rightarrow e^+e^-$

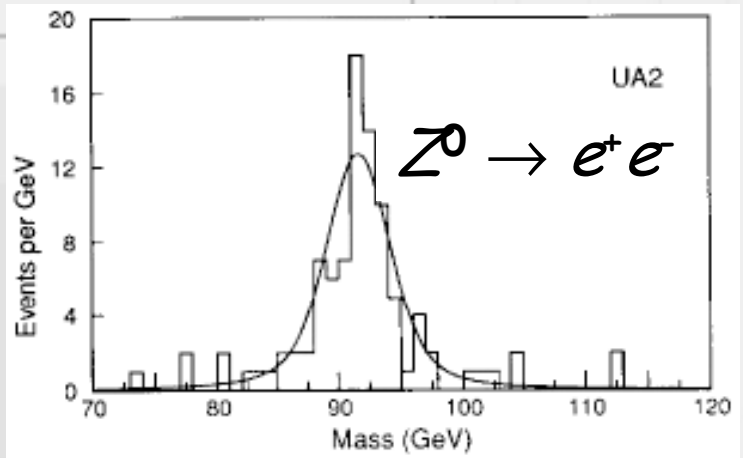
$\mu^+\mu^-$

$pp \rightarrow X + W^{\pm} \rightarrow \mu\nu$









Flavours

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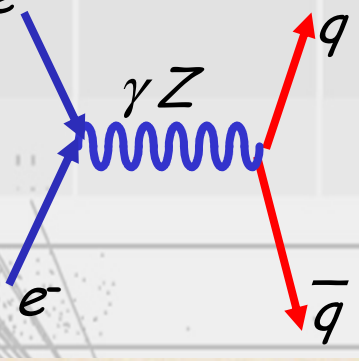
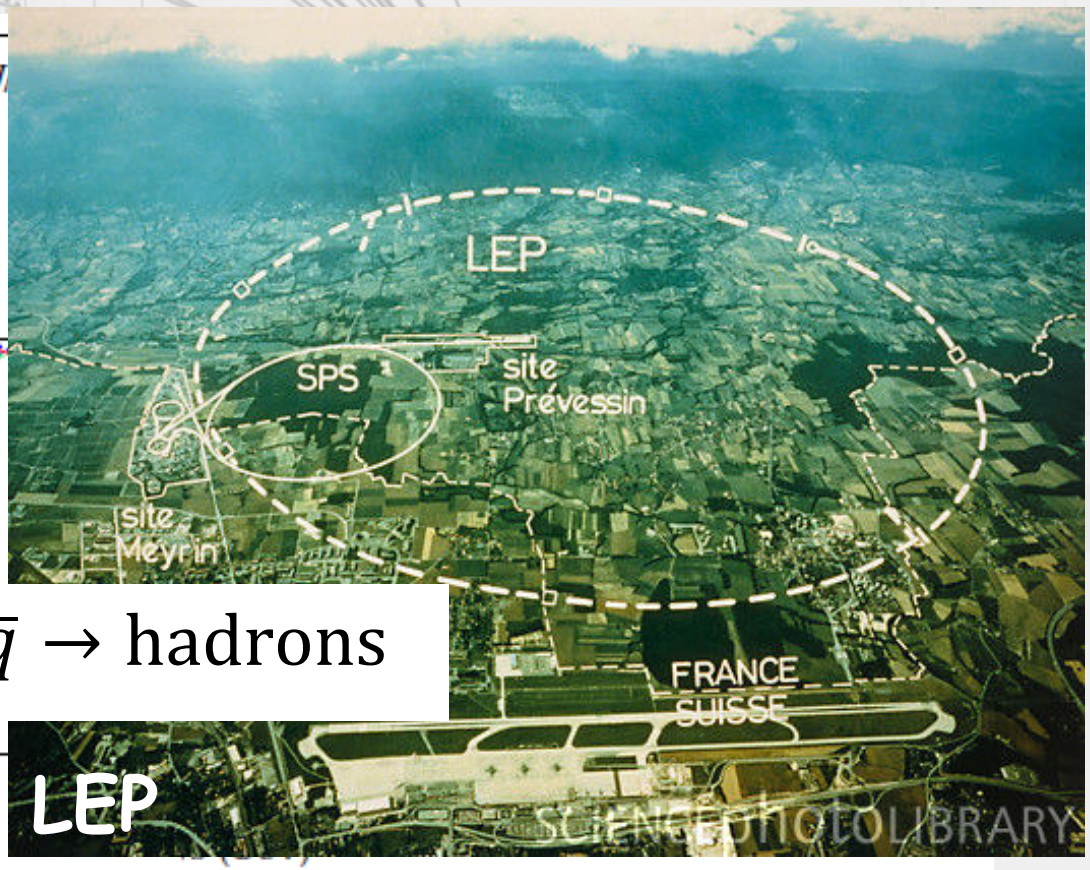
- e^+e^- annihilation $\rightarrow$ hadrons

$$q = \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$+g$ in $SU(3)_c$



Nobels
Richter+Ting
Perl



$$e^+e^- \rightarrow q\bar{q} \rightarrow \text{hadrons}$$

AdA

LEP

Experiment

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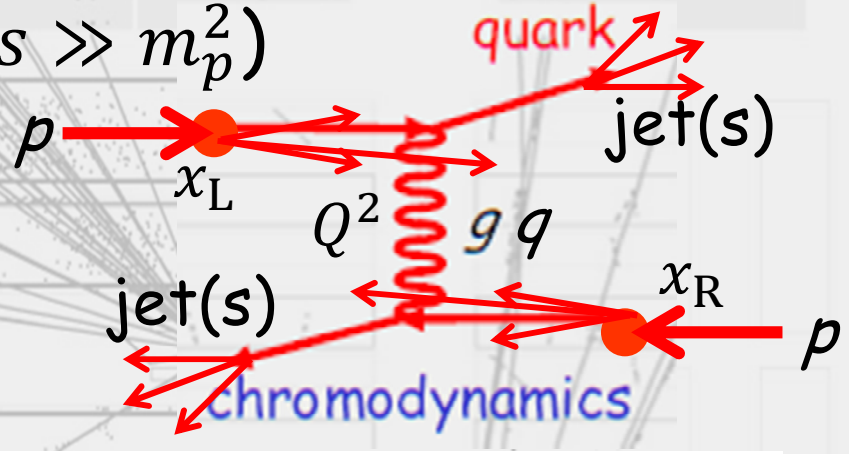
- high energy for precision "Rutherford" probe
  - deep ($Q^2 \gg m_p^2$) inelastic ($s \gg m_p^2$)
  - $pp \rightarrow \text{jet(s)}_1 + \text{jet(s)}_2 + X$
  - space-like factorisation



$$\mathbf{d}\sigma = \sum_{\text{parton}} f_{p\rightarrow\text{parton}}(x_L, Q^2) \otimes \quad \leftarrow \text{parton density f}^{\underline{n}}$$
$$\frac{\mathbf{d}\hat{\sigma}_{\text{parton+parton}}}{\mathbf{d}x_L \mathbf{d}x_R \mathbf{d}Q^2}(\hat{s} = x_L x_R s, Q^2)\mathbf{d}x_L \mathbf{d}x_R \mathbf{d}Q^2$$
$$\otimes \sum_{\text{parton}} f_{p\rightarrow\text{parton}}(x_R, Q^2) \ (\text{parton} = q, g)$$

- remnants in+out beam-pipe

$$x_{L,R} = \frac{\text{daughter}_\mu \cdot \text{reference}^\mu}{\text{parent}_\mu \cdot \text{reference}^\mu}$$

Experiment

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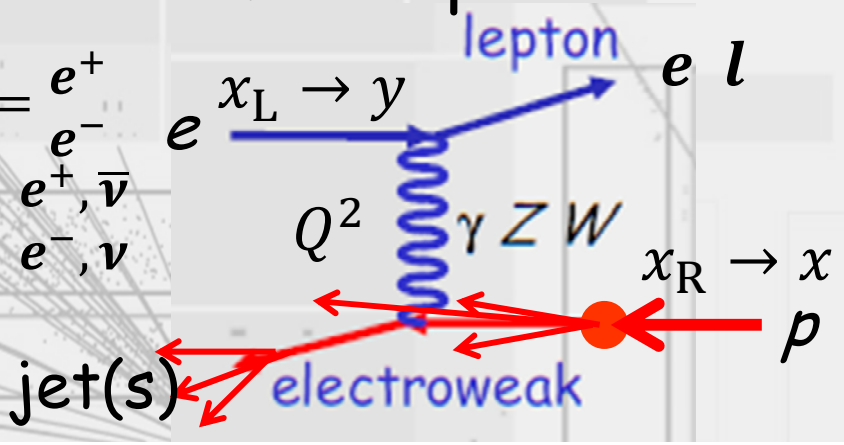

$$\sigma^{\pm}_{r\,\mathrm{NC}}(x, Q^2) = \frac{Q^4 x}{2\pi\alpha^2_{\mathrm{em}} Y_+} \frac{\mathrm{d}^2\sigma^{e^\pm p}_{r\,\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} = \widetilde{F}_2 - \frac{y^2}{Y_+}\widetilde{F}_L \mp \frac{Y_-}{Y_+} x\widetilde{F}_3$$

$$\sigma^{\pm}_{r\,\mathrm{CC}}(x, Q^2) = \frac{2\pi x}{G_F^2 Y_+} \left|\frac{M_W^2}{Q^2 + M_W^2}\right|^2 \frac{\mathrm{d}^2\sigma^{e^\pm p}_{r\,\mathrm{CC}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{Y_+}{2} W_2^{\pm} - \frac{y^2}{2} W_L^{-} \mp \frac{Y_-}{2} x W_3^{\pm}$$

Fermi constant G_F

Experiment

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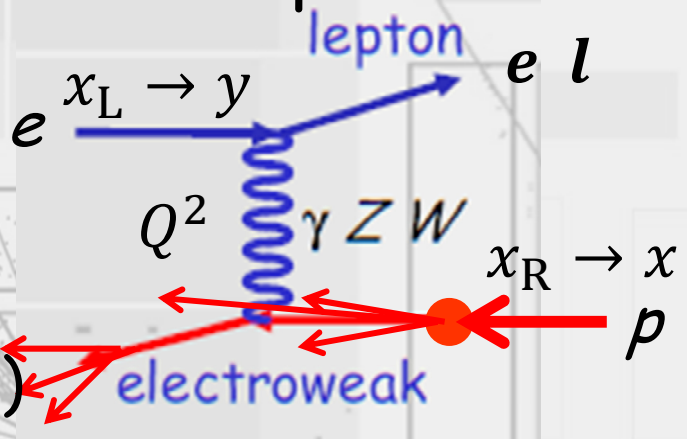
- high energy for precision "Rutherford" probe
  - deep ($Q^2 \gg m_p^2$)
    inelastic ($s \gg m_p^2$)
  - $ep \to e/\nu + \text{jet(s)} + X$
  - space-like factorisation

$$e = e^+, e^-$$
$$l = e^+, \bar{\nu}, e^-, \nu$$



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

$$\tilde{F}_2 = F_2 - \kappa_Z v_e F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_2^Z$$
$$\tilde{F}_L = F_L - \kappa_Z v_e F_L^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_L^Z$$
$$x\tilde{F}_3 = -\kappa_Z a_e F_3^{\gamma Z} + 2\kappa_Z^2 v_e a_e F_L^Z$$

$$\kappa_Z(Q^2) = \frac{1}{4 \sin^2\theta_W \cos^2\theta_W} \frac{Q^2}{Q^2 + M_Z^2}$$

$$y = \frac{\gamma \cdot p}{e \cdot p} \qquad x = \frac{Q^2}{\gamma \cdot p} \qquad Y_\pm = 1 \pm (1-y)^2$$

- precision
  - structure functions
- remnants in+out beam-pipe

$\tilde{F}_{2,L,3}$
$W^{\pm}_{2,L,3}$ ↔ parton density

A precision Fermiscale *ep* Collider HERA @ DESY

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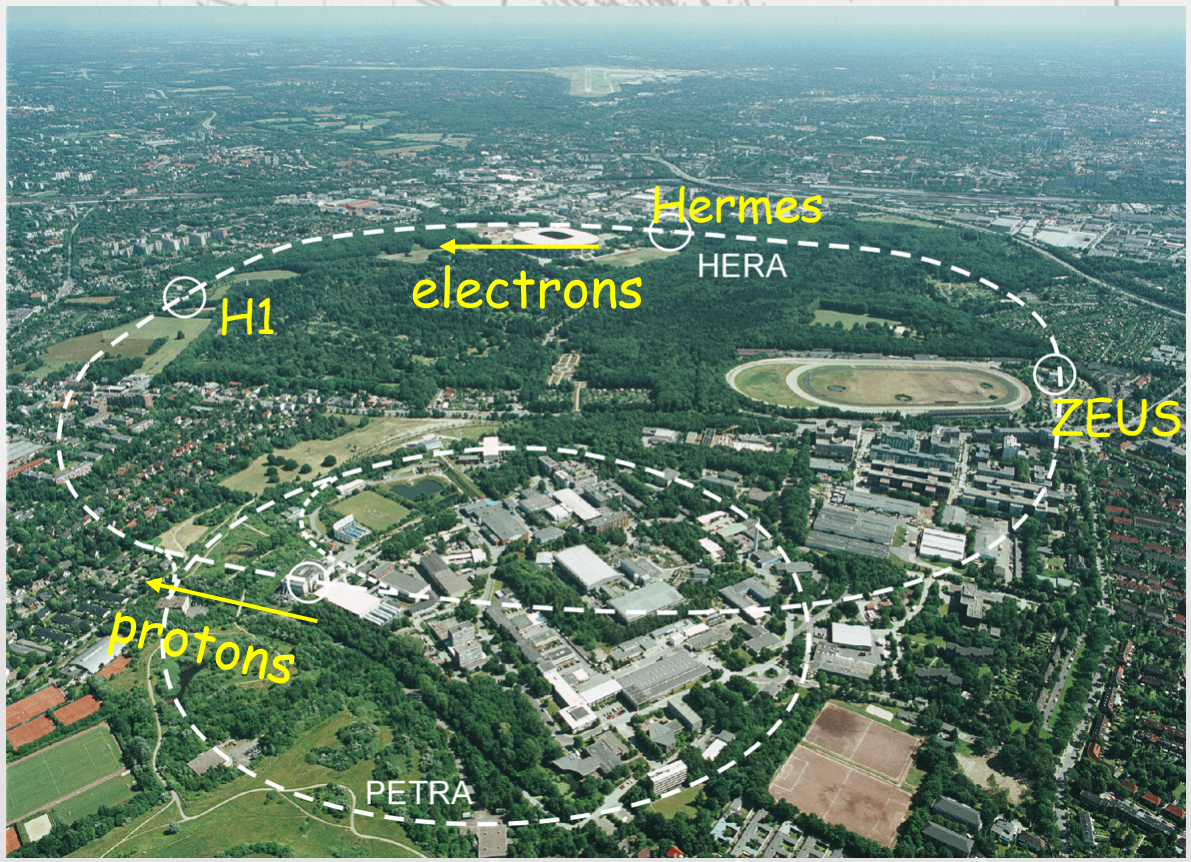
- challenge: different particle species *ep* in collision

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

ep cm energy 314 GeV

lepton

HERA
DESY
Hamburg



HERA
+
1992-2007
RIP

Rotating Spin

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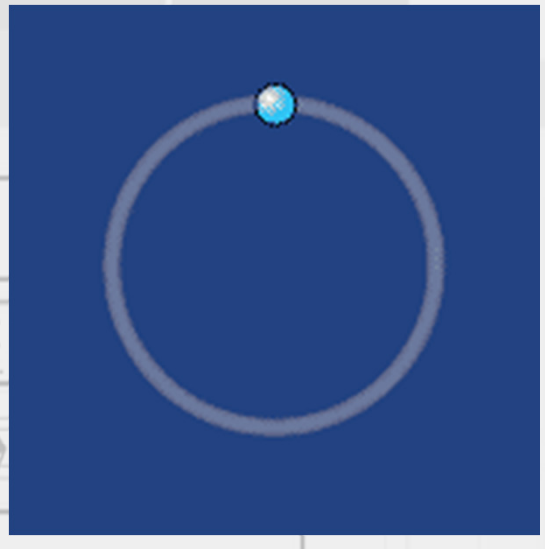
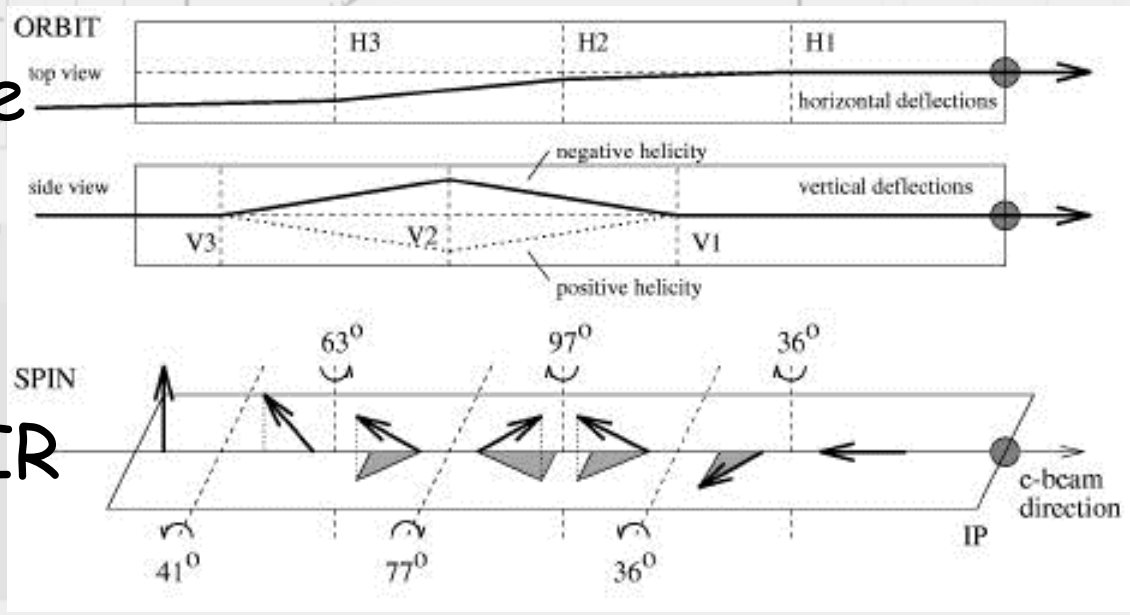
- stored e radiates
  $e \rightarrow e_T$ Sokolov-Ternov
  transversely polarised e
  synchrotron radiation



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

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



Barber, Steffen (DESY)

Rotating Spin

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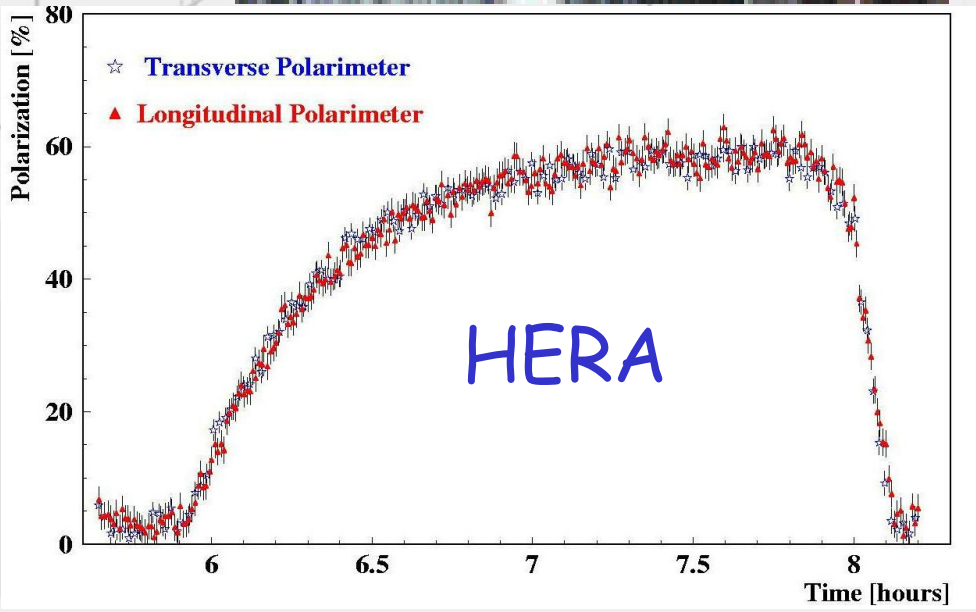

A Precision Fermiscale Experiment @ HERA

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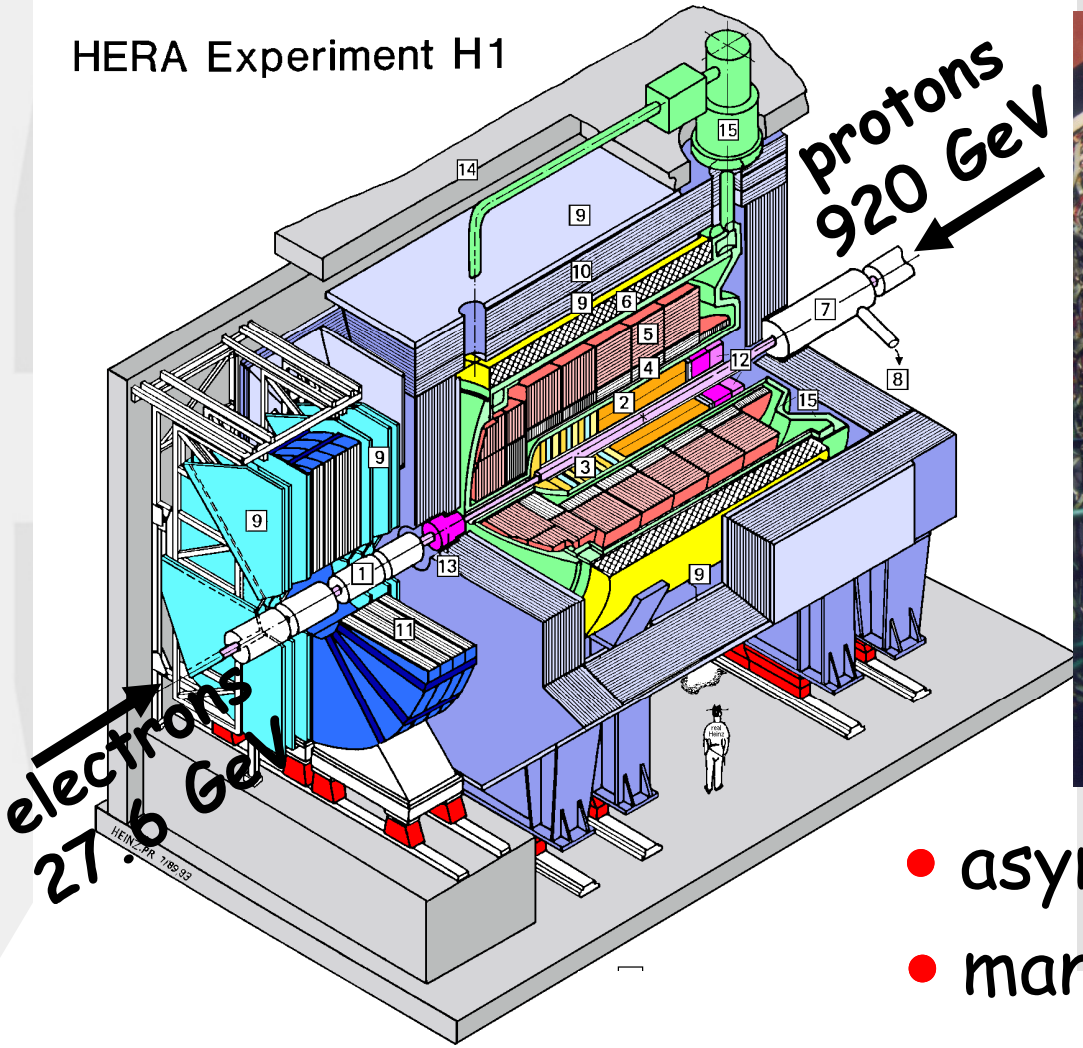

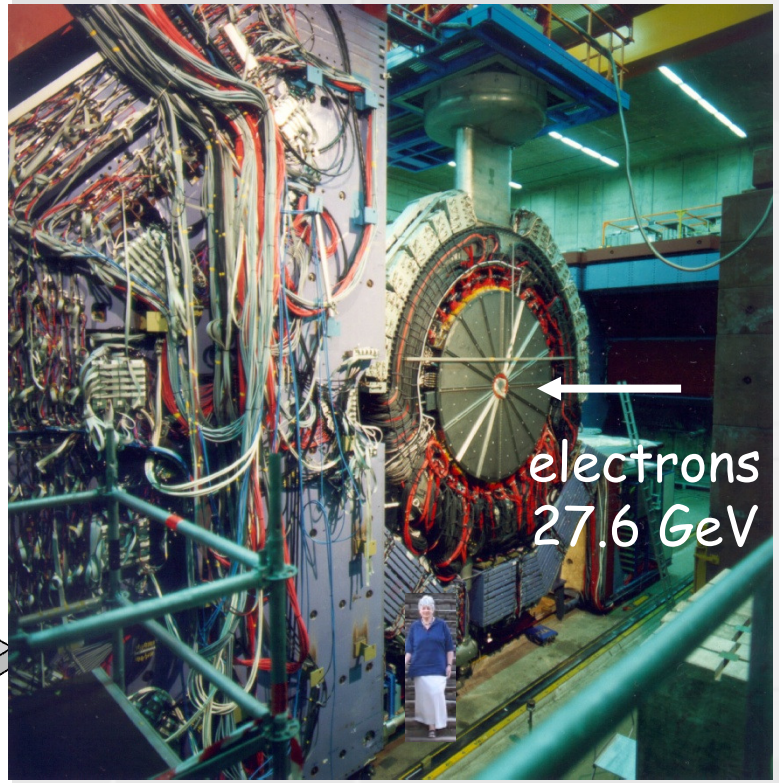

- asymmetric e and p
- many bunch Δt_{ep} = 75 ns
- p_T scale ~ 300 GeV (Fermi)

Constituents with Currents

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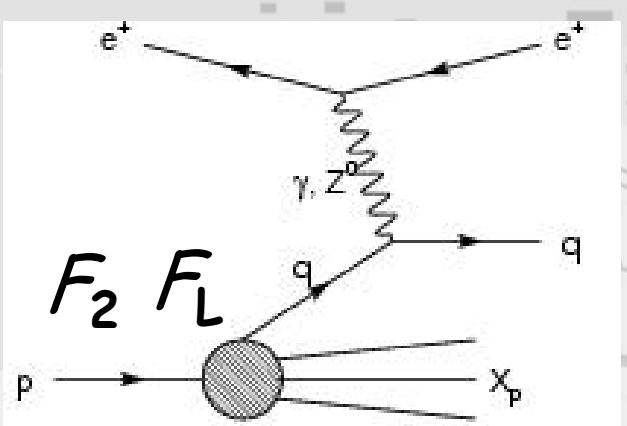
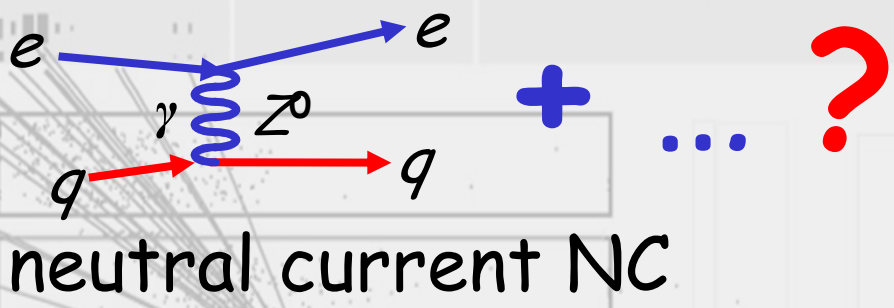
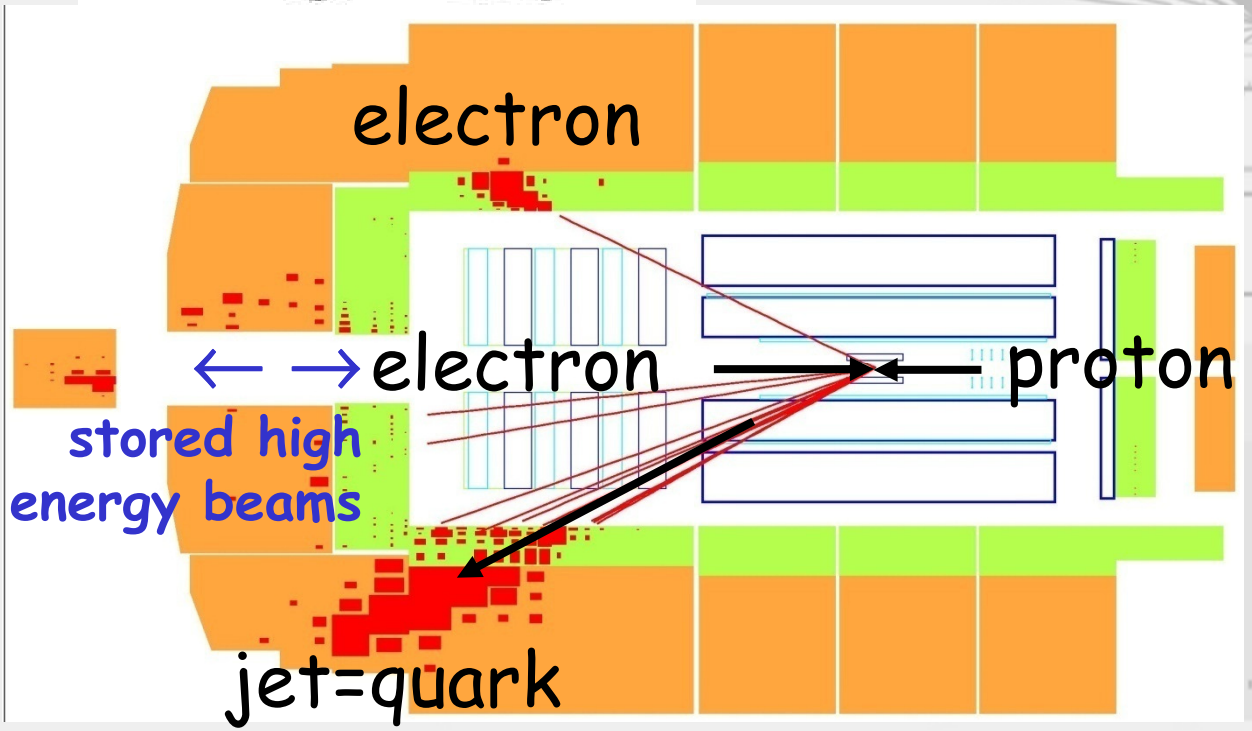
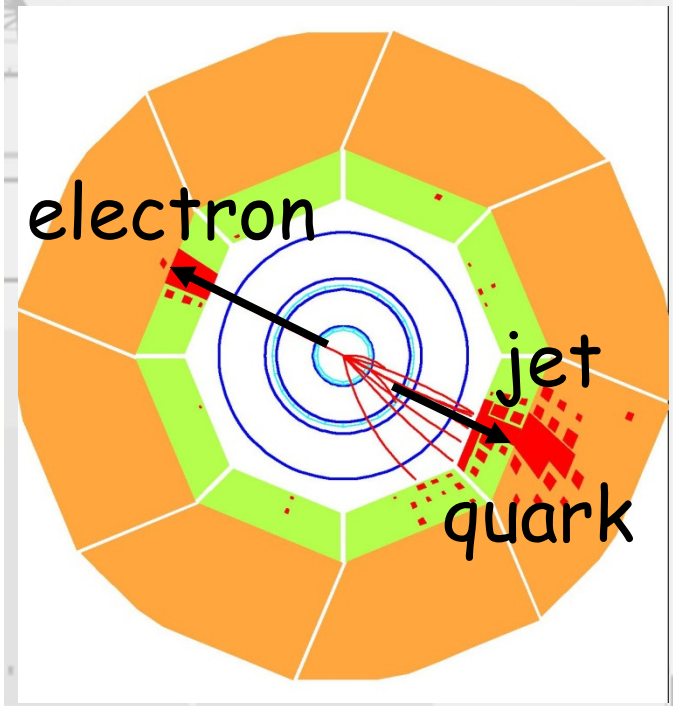
- >1992: Rutherford scattering at the Fermi scale









Constituents with Currents

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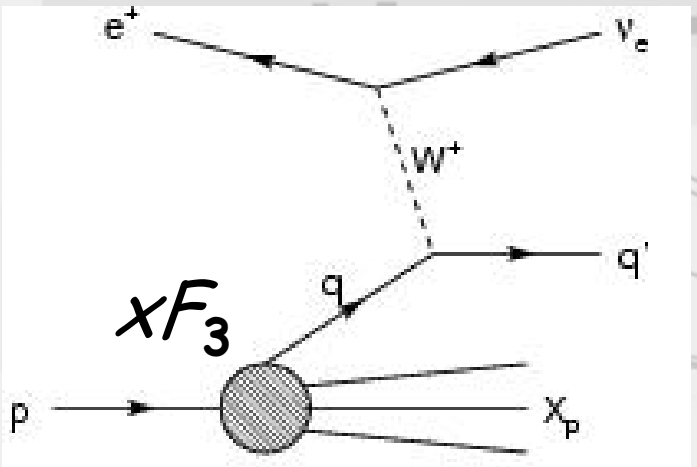
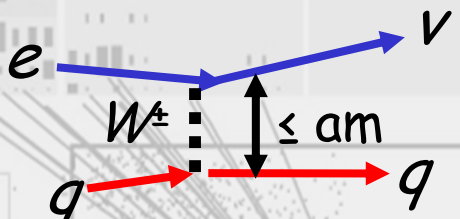
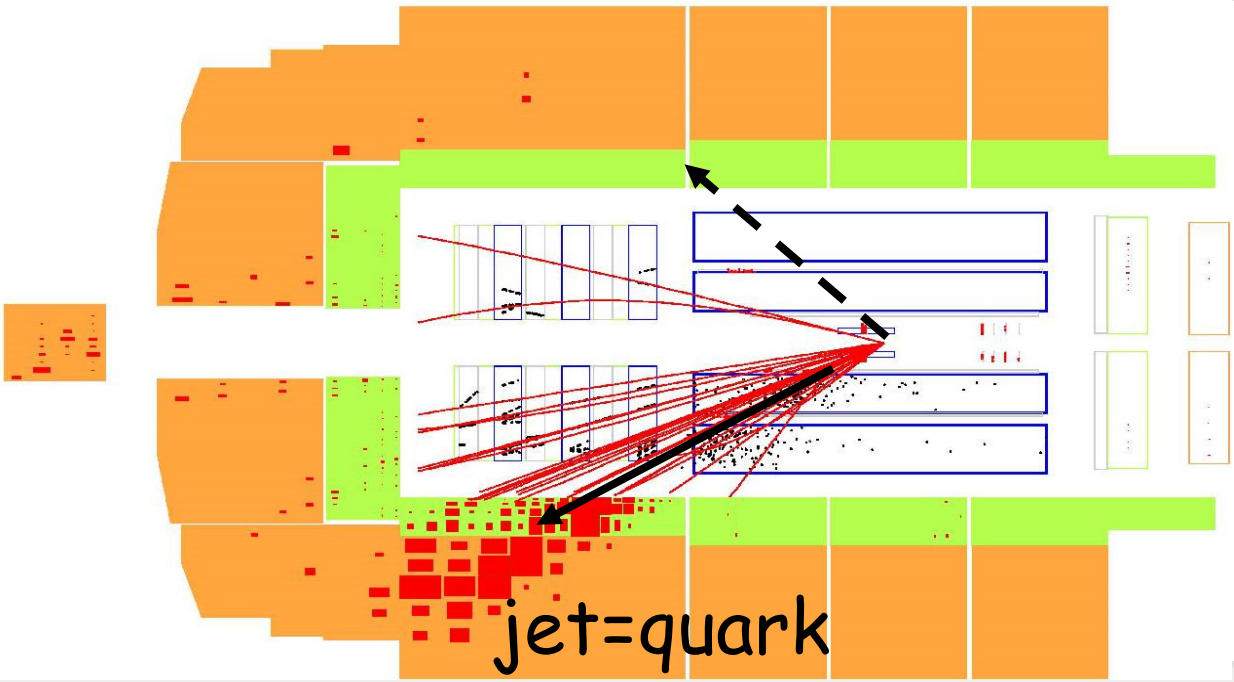
- >1992: inside Fermi's β-interaction

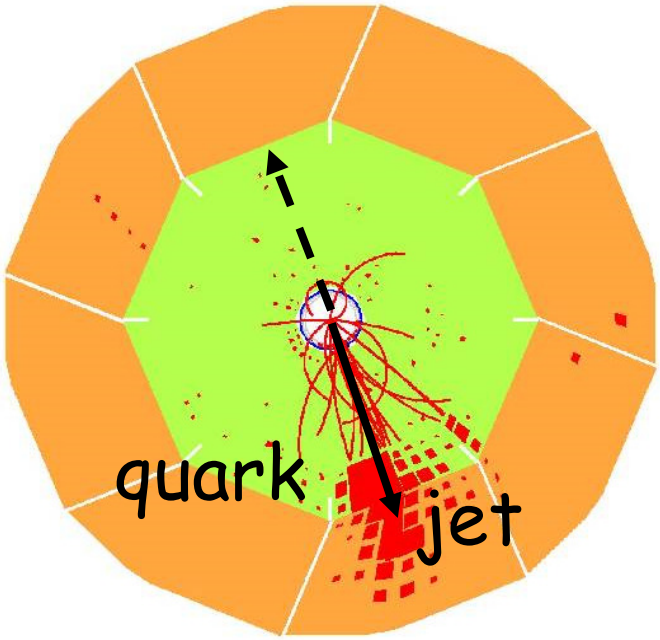




+ … ?

charged current CC





The LHC Triumph

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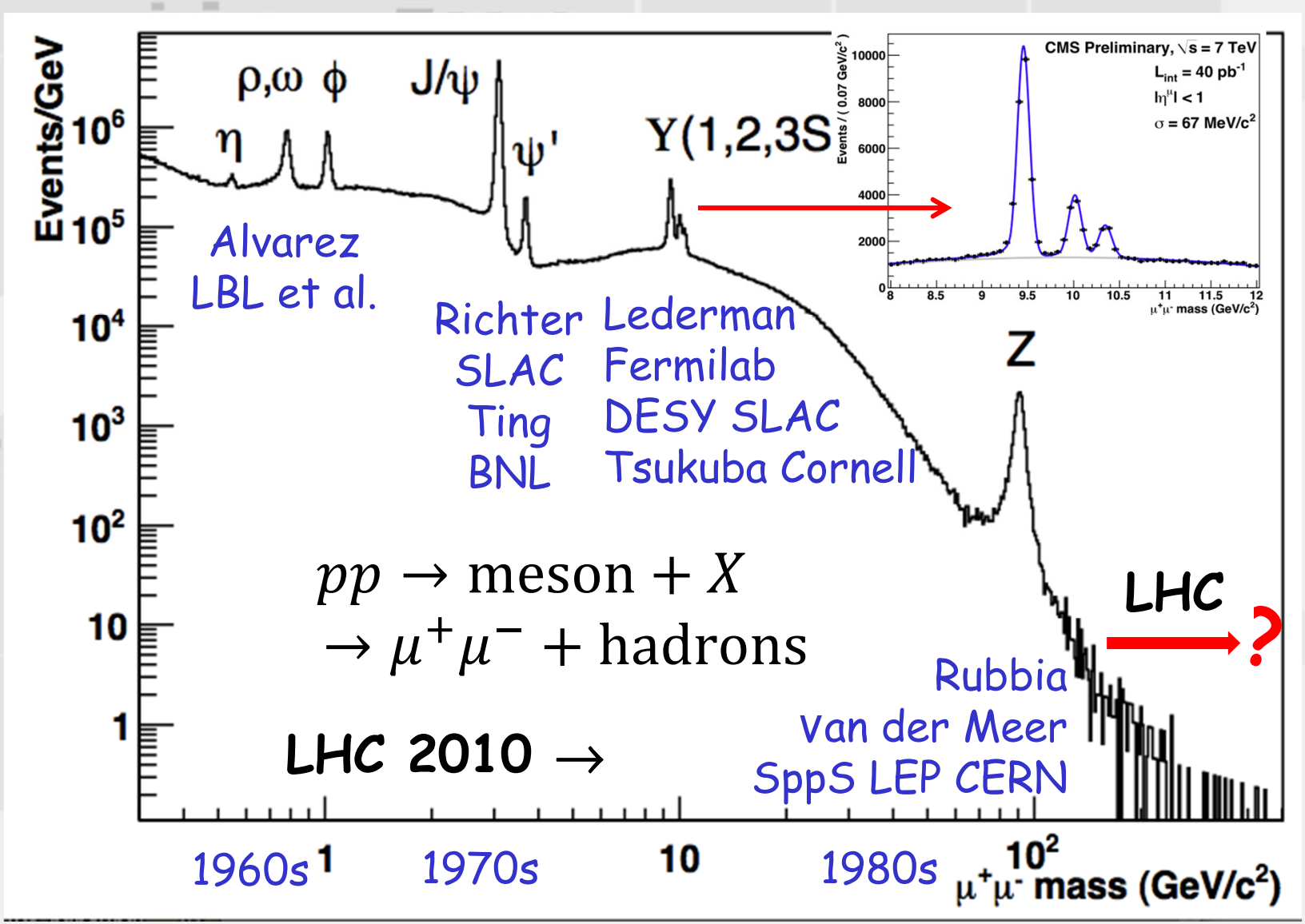
- 60 years of physics in 40 pb^{-1} at LHC 2010!



Fermi Scale complete

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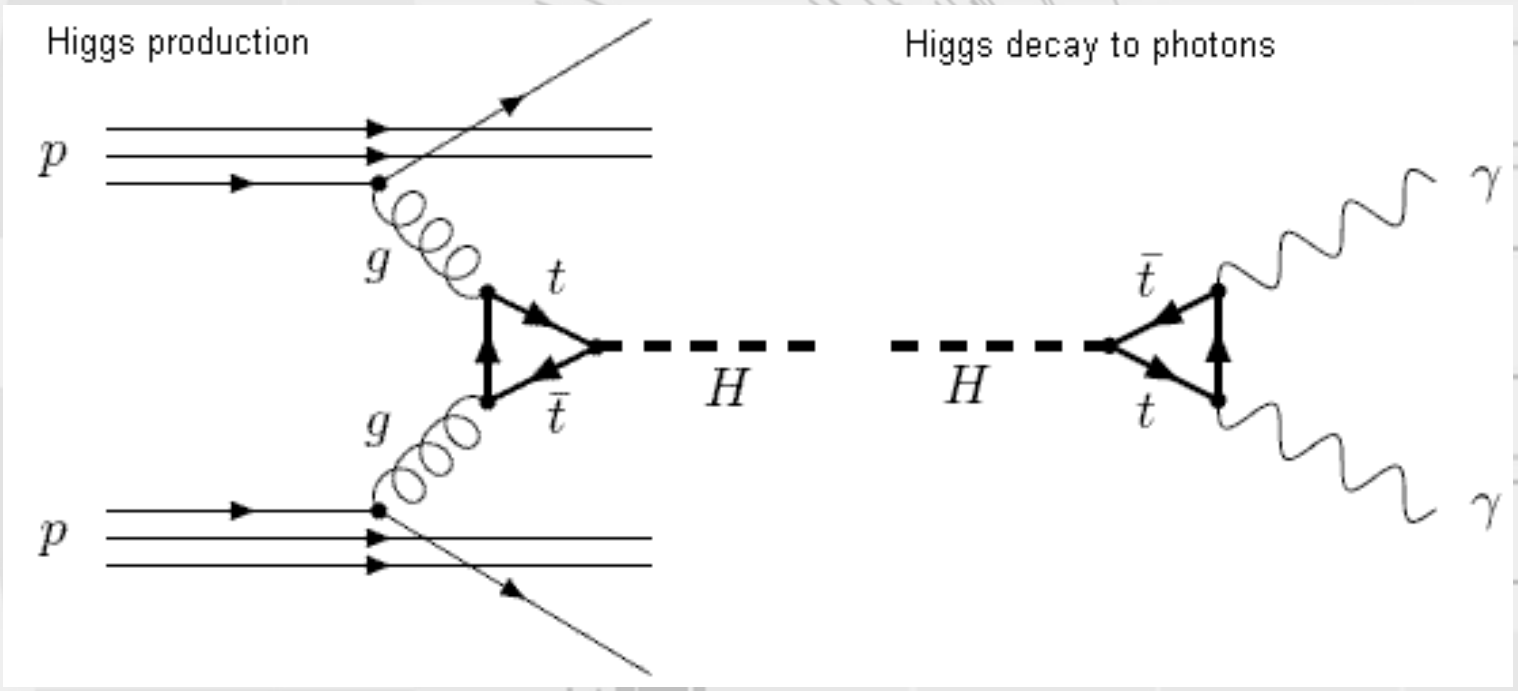
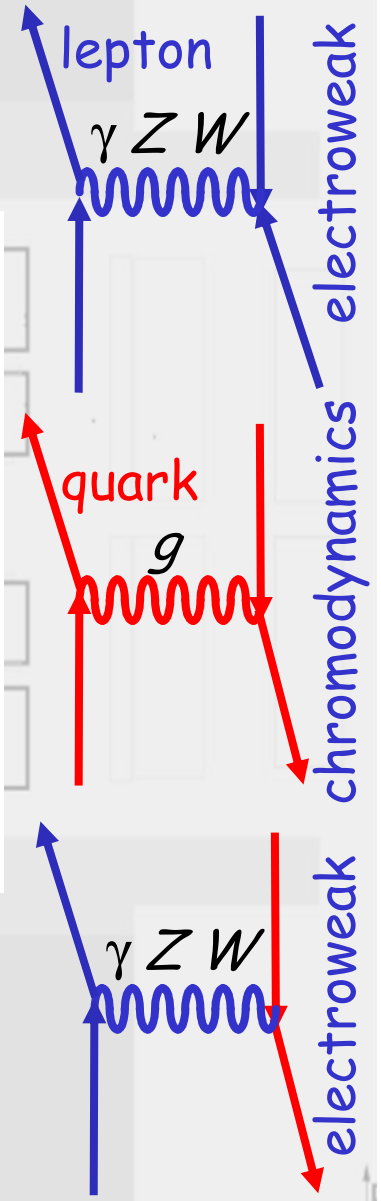
- EW unification @ Fermi scale
- $pp \to \gamma\gamma X$





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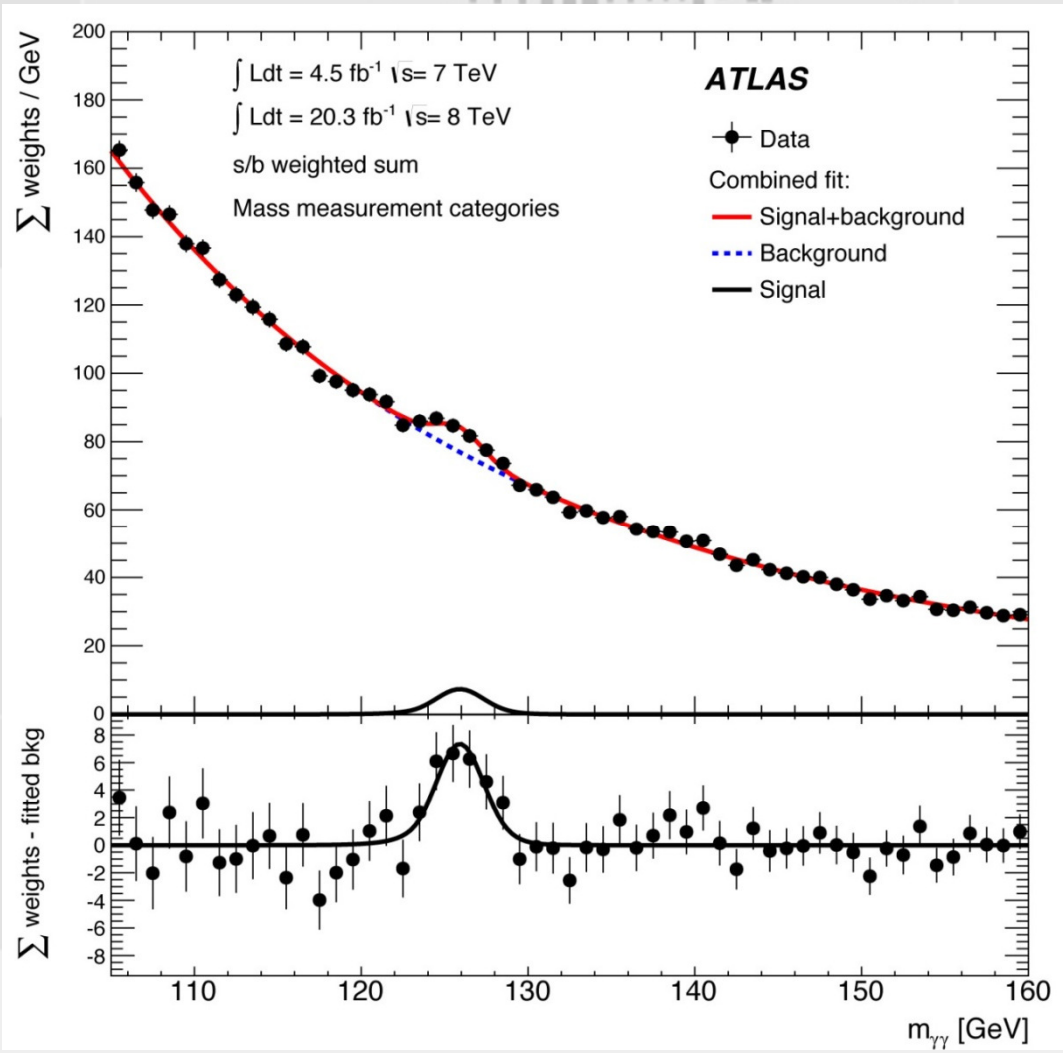

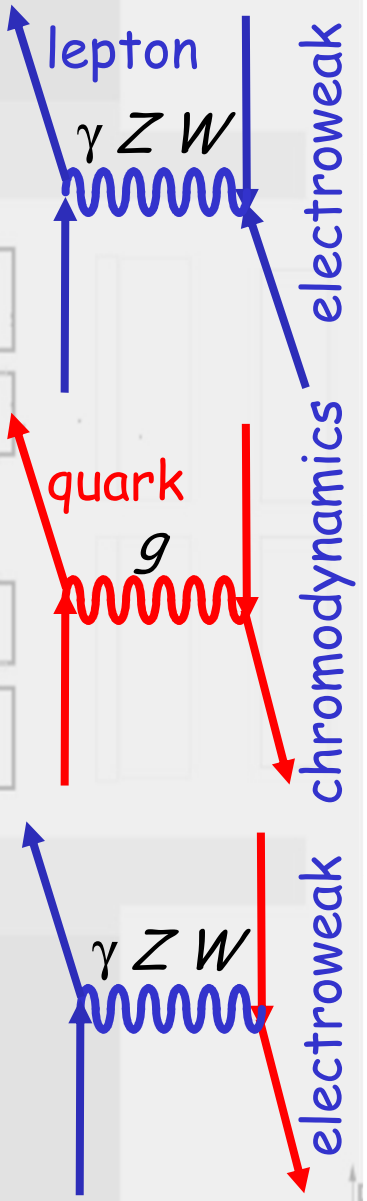

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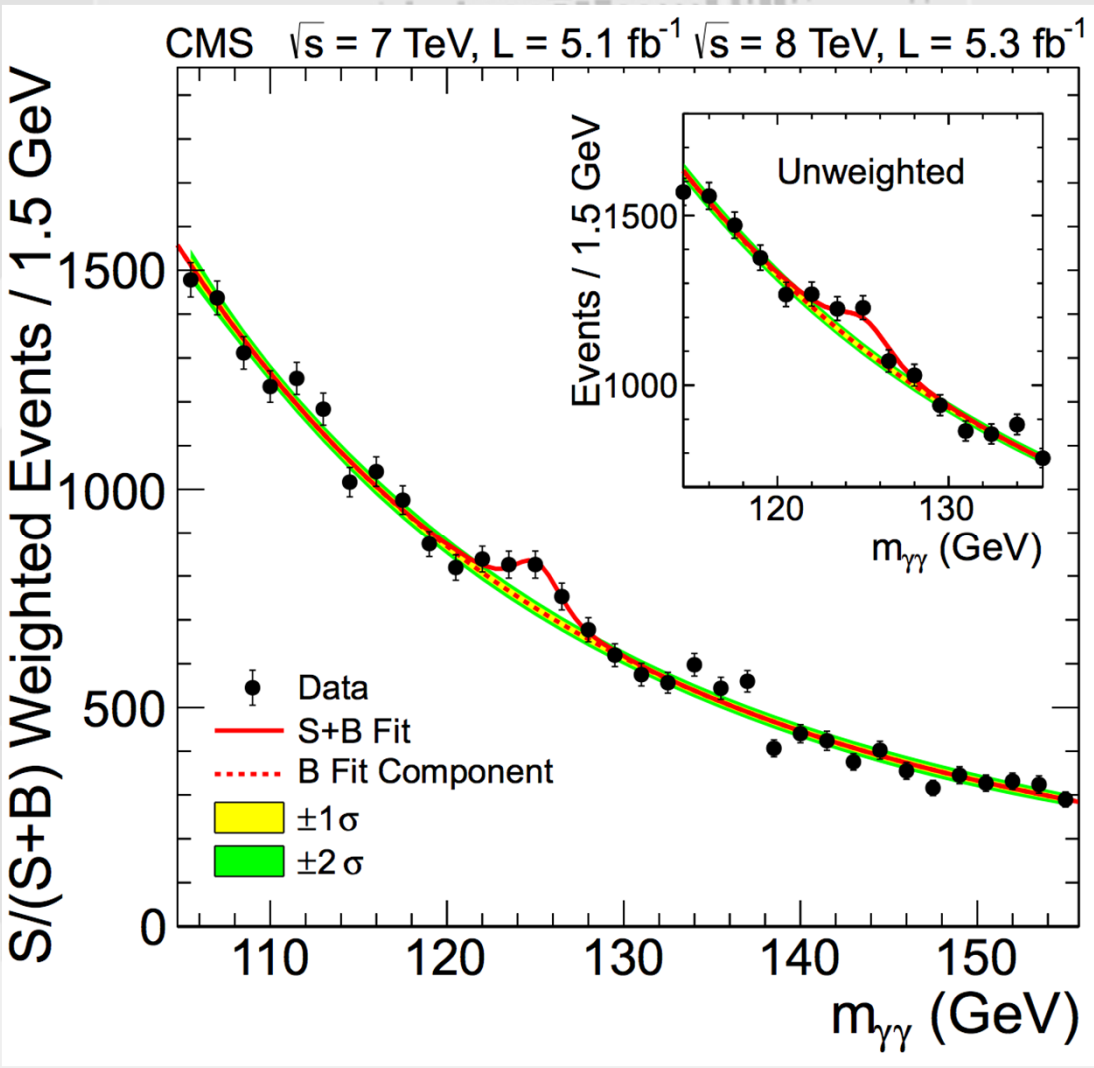

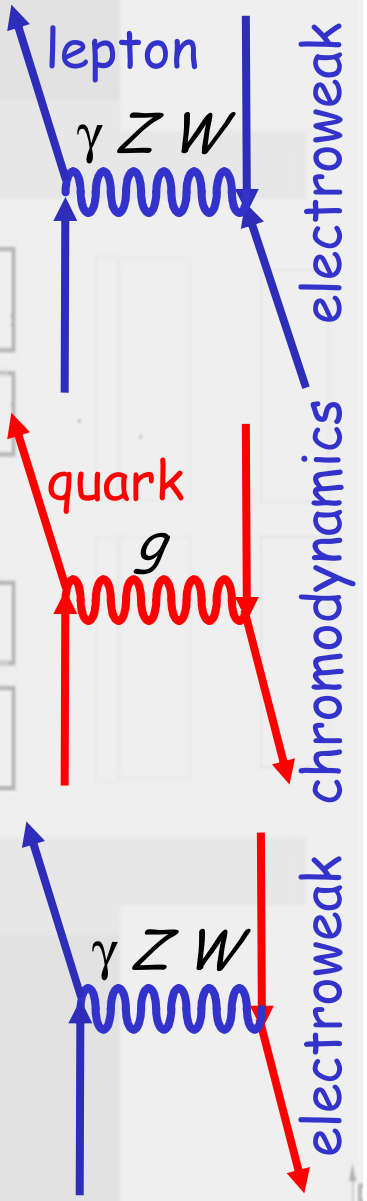

Constituents and Currents

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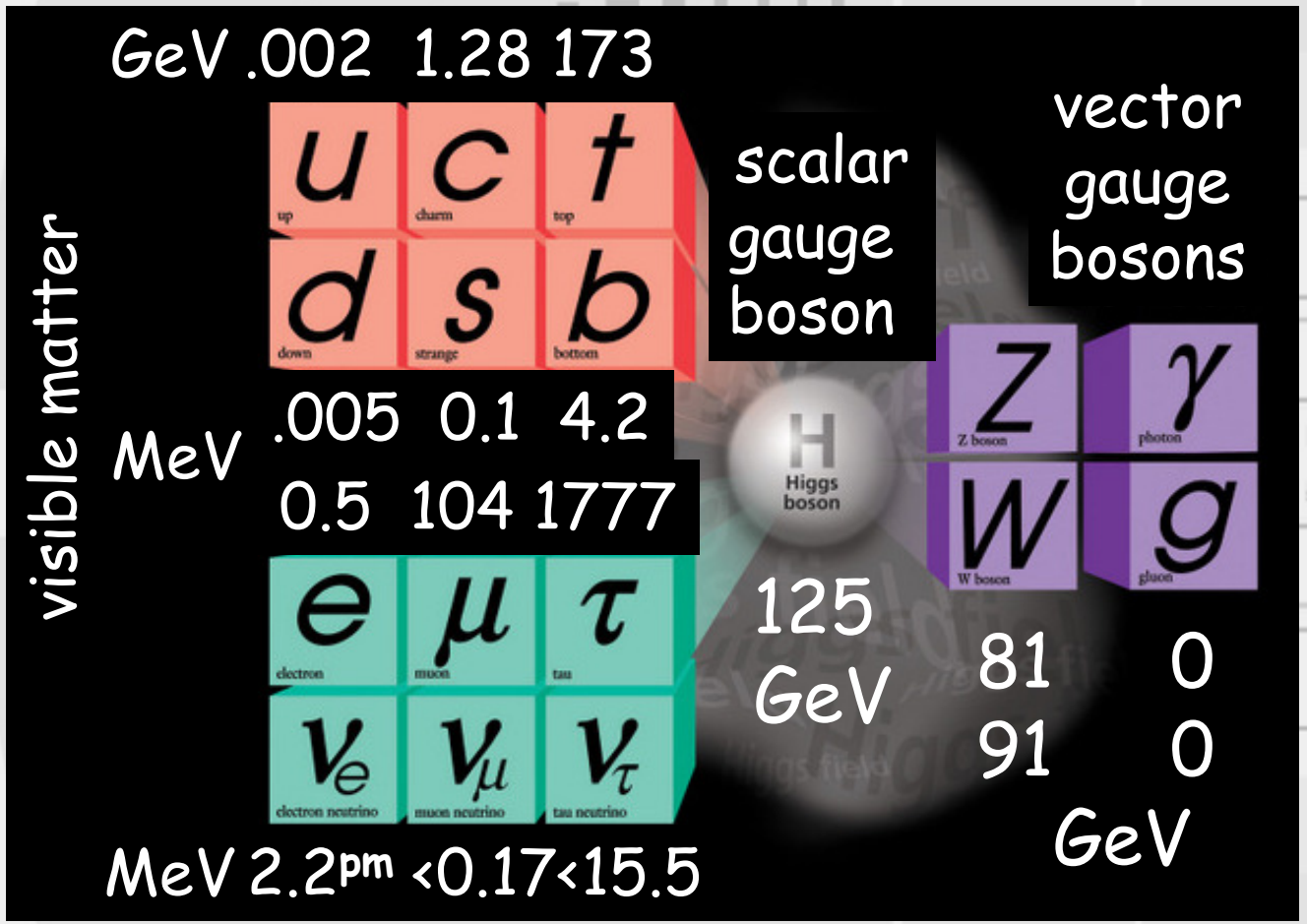
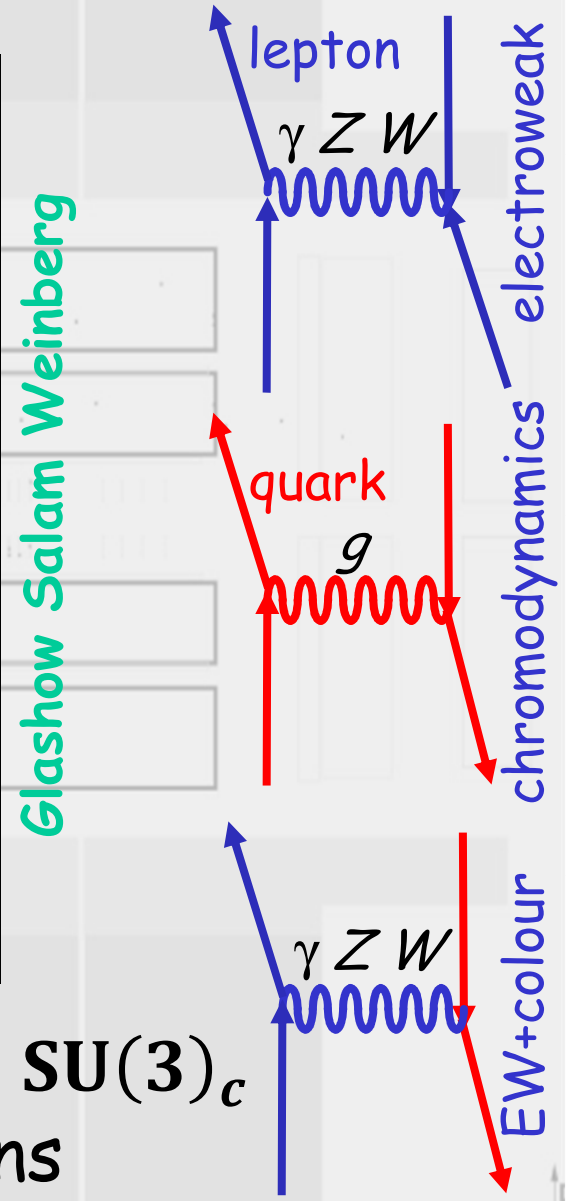
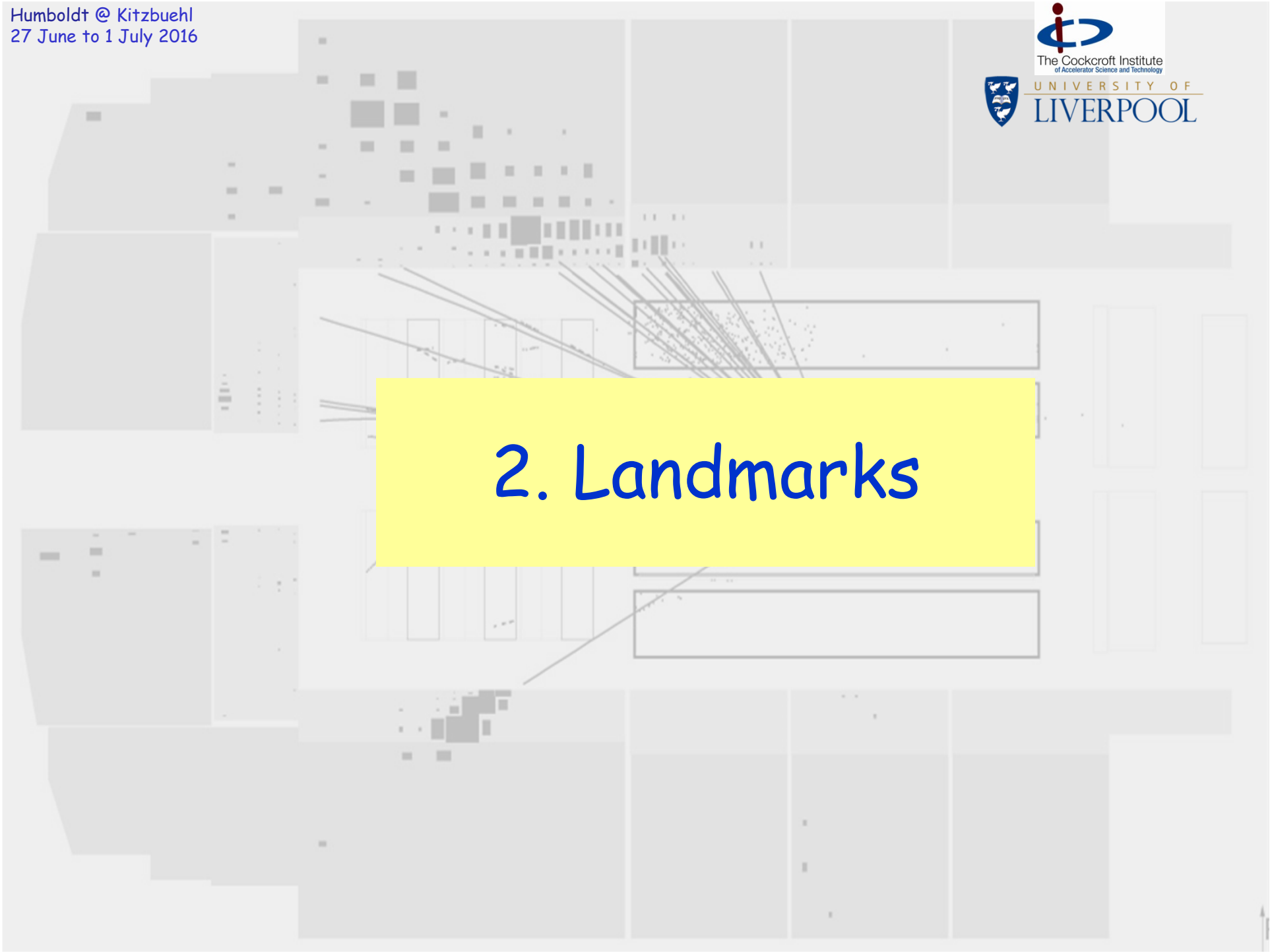
- the Standard Model landscape 2016





Dirac fermions in $\mathbf{SU(2)}_L \otimes \mathbf{U(1)} \otimes \mathbf{SU(3)}_c$
force = colour + GSW + gauge bosons



2. Landmarks

GSW Current

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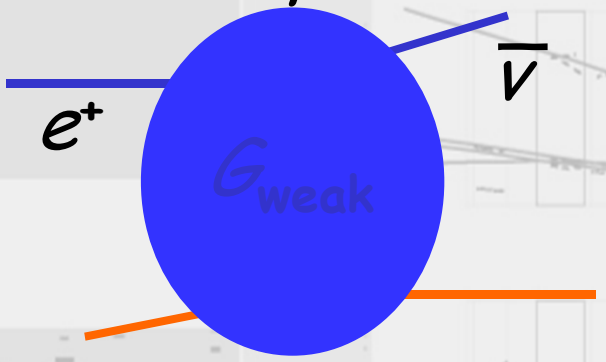
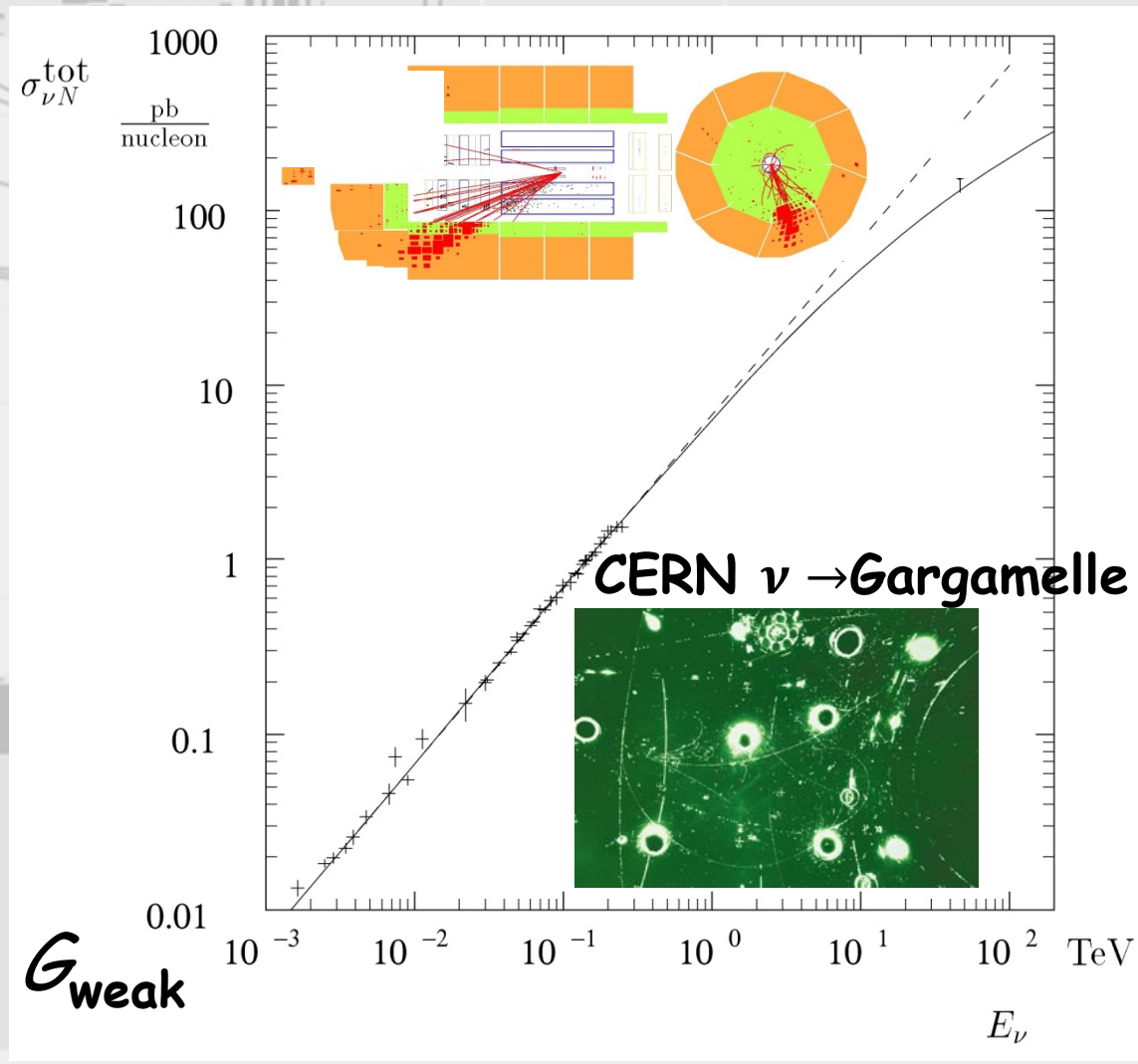
- then: point-like Fermi-β $\sigma_{tot}^{\nu N}(E_\nu) \propto E_\nu$
  1993: hint of weak unitarity = GSW unification ?

- from $ep \rightarrow \bar{\nu}X$



to $\nu p \rightarrow eX$

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



GSW Current

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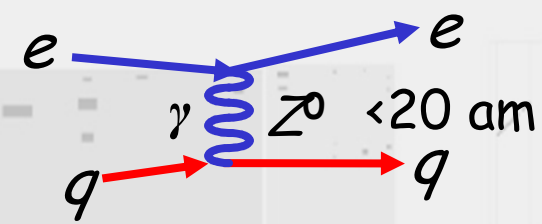
- now: resolved structure in GSW $SU(2)_L \otimes U(1)$ force

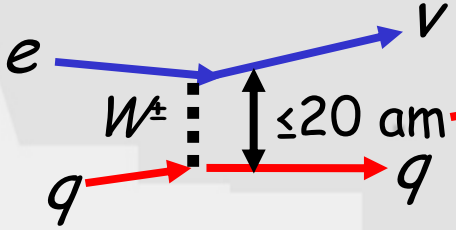
$$\text{resolution} \sim \frac{0.2\ \text{TeV}\cdot\text{am}}{Q}$$

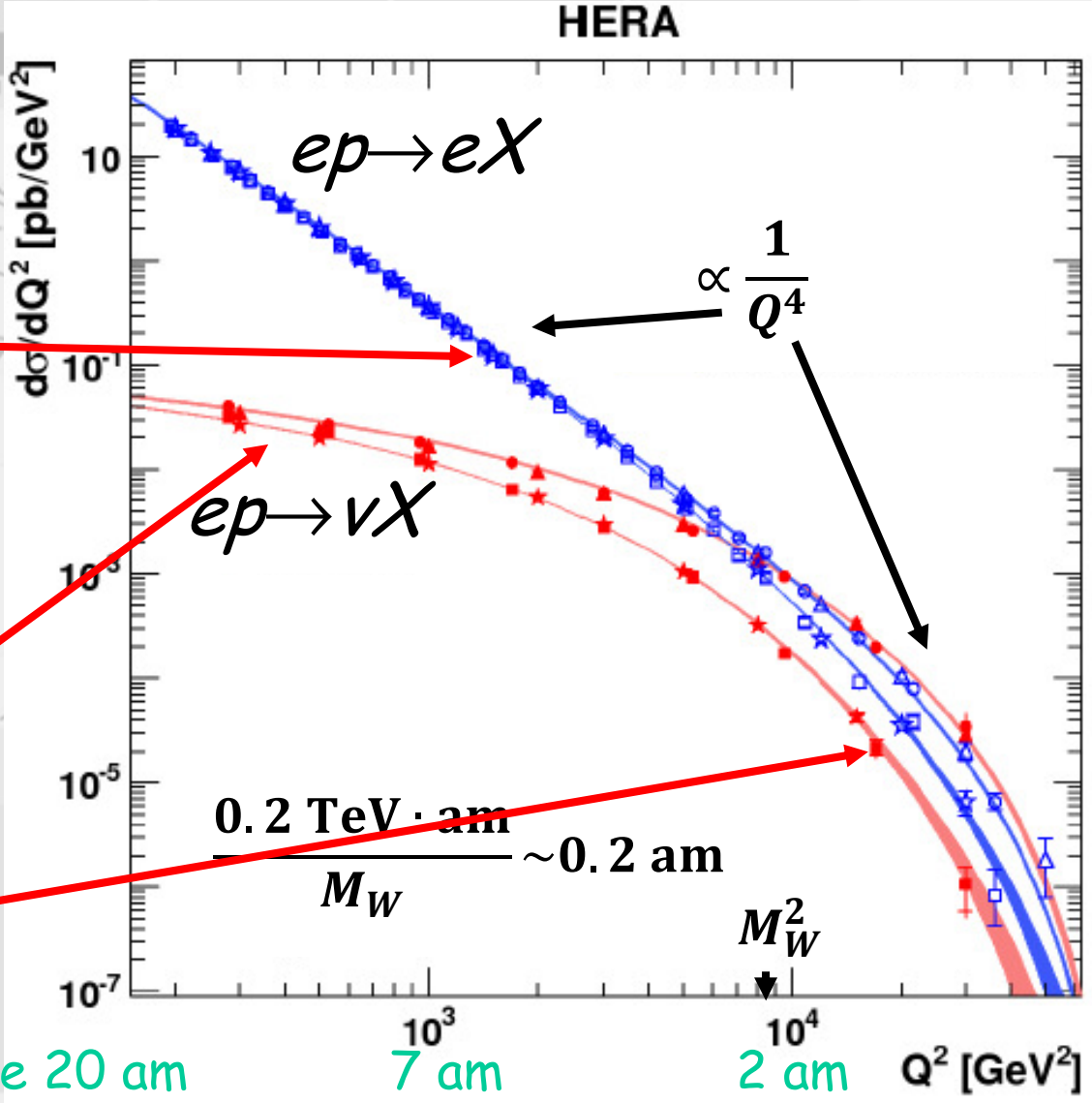
- Rutherford scattering

$eq \rightarrow eq$ NC



$eq \rightarrow \nu q$ CC





GSW Current Chirality

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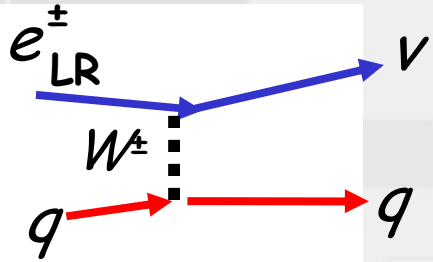
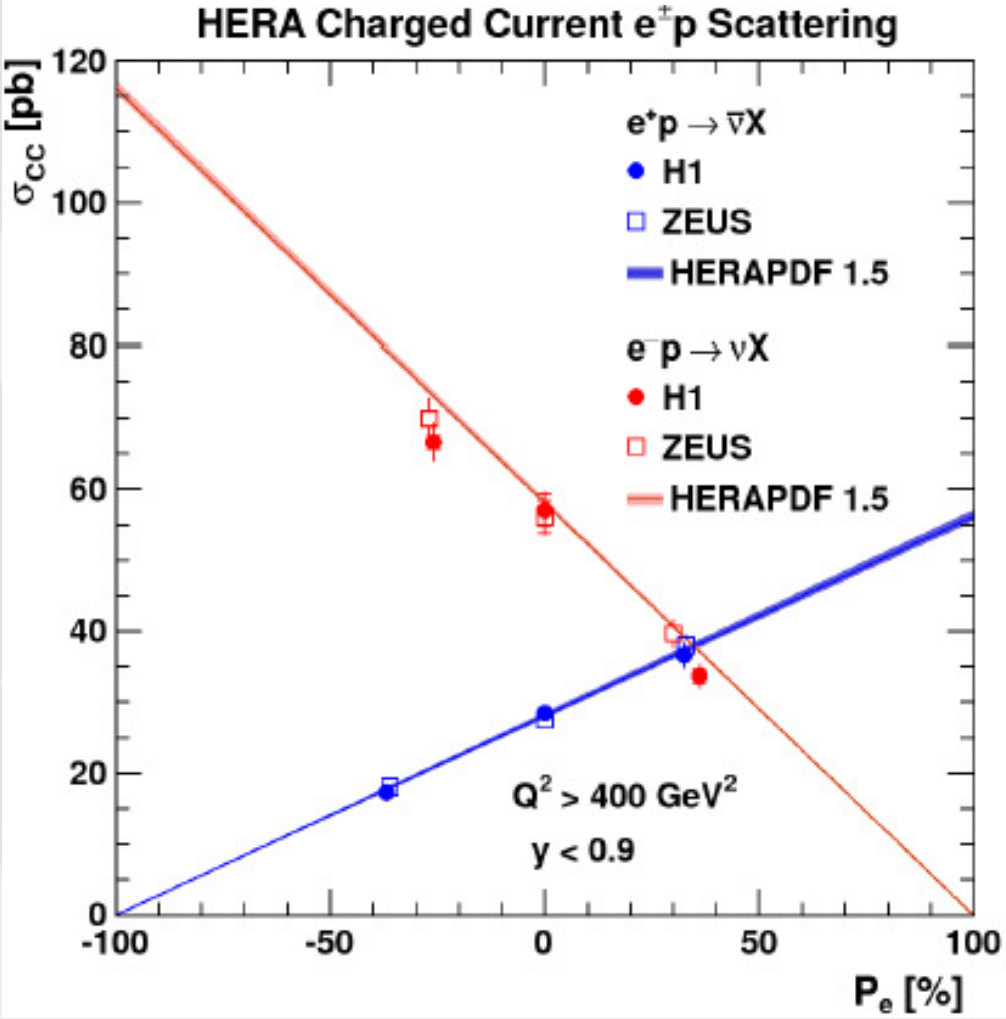
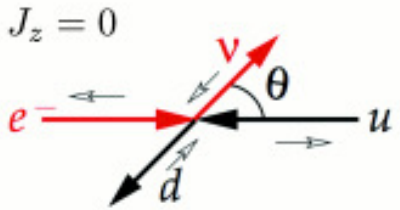
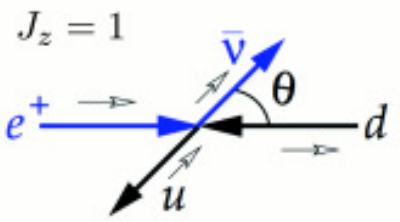
- quarks = L(R) Dirac (anti-)fermions
  L(R) (anti-)leptons





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





GSW Current

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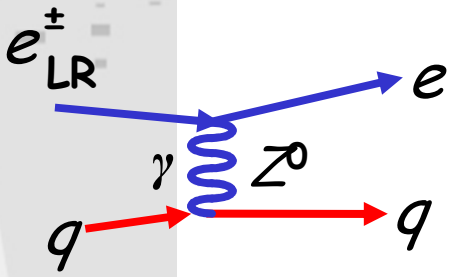
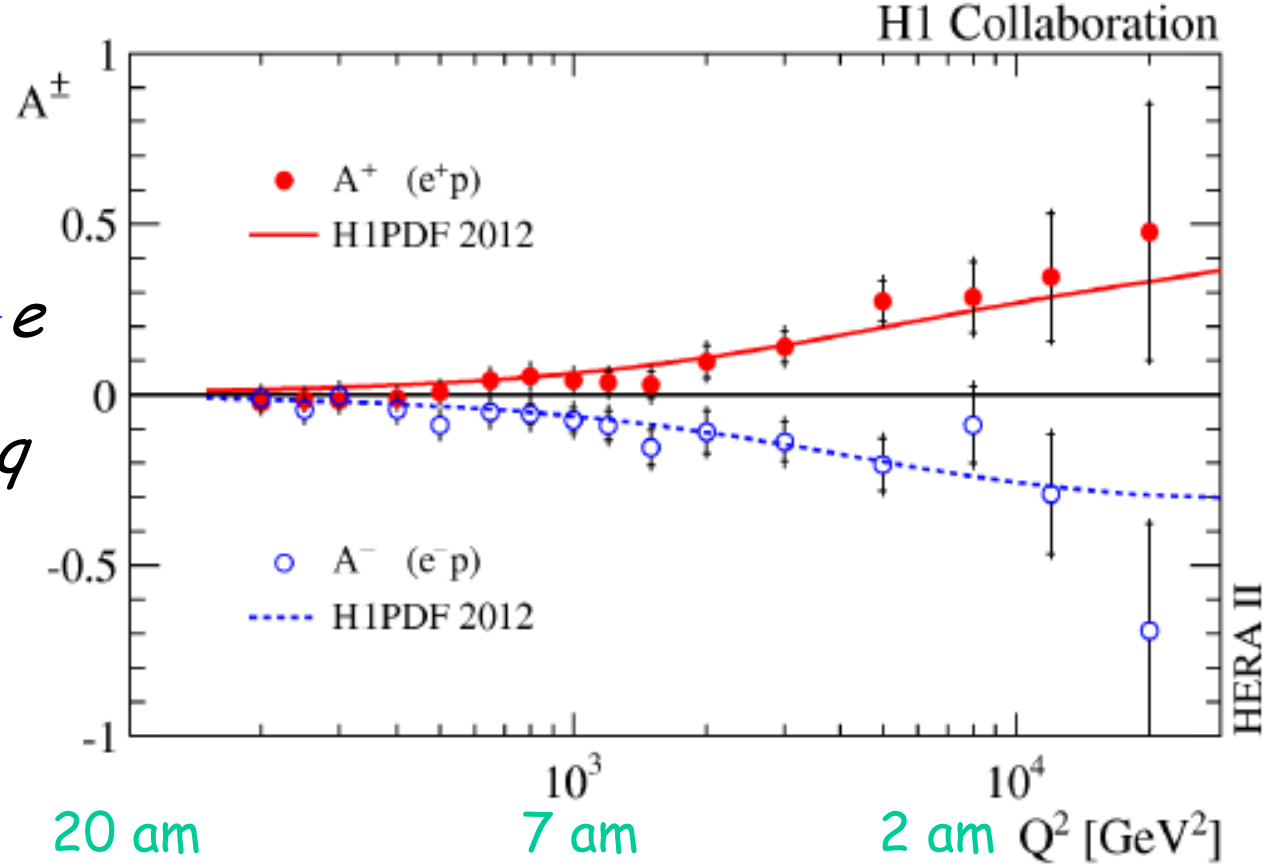
- polarisation asymmetry: $e^{\pm}q \rightarrow$ NC parity violation

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

Current Quark GSW Couplings

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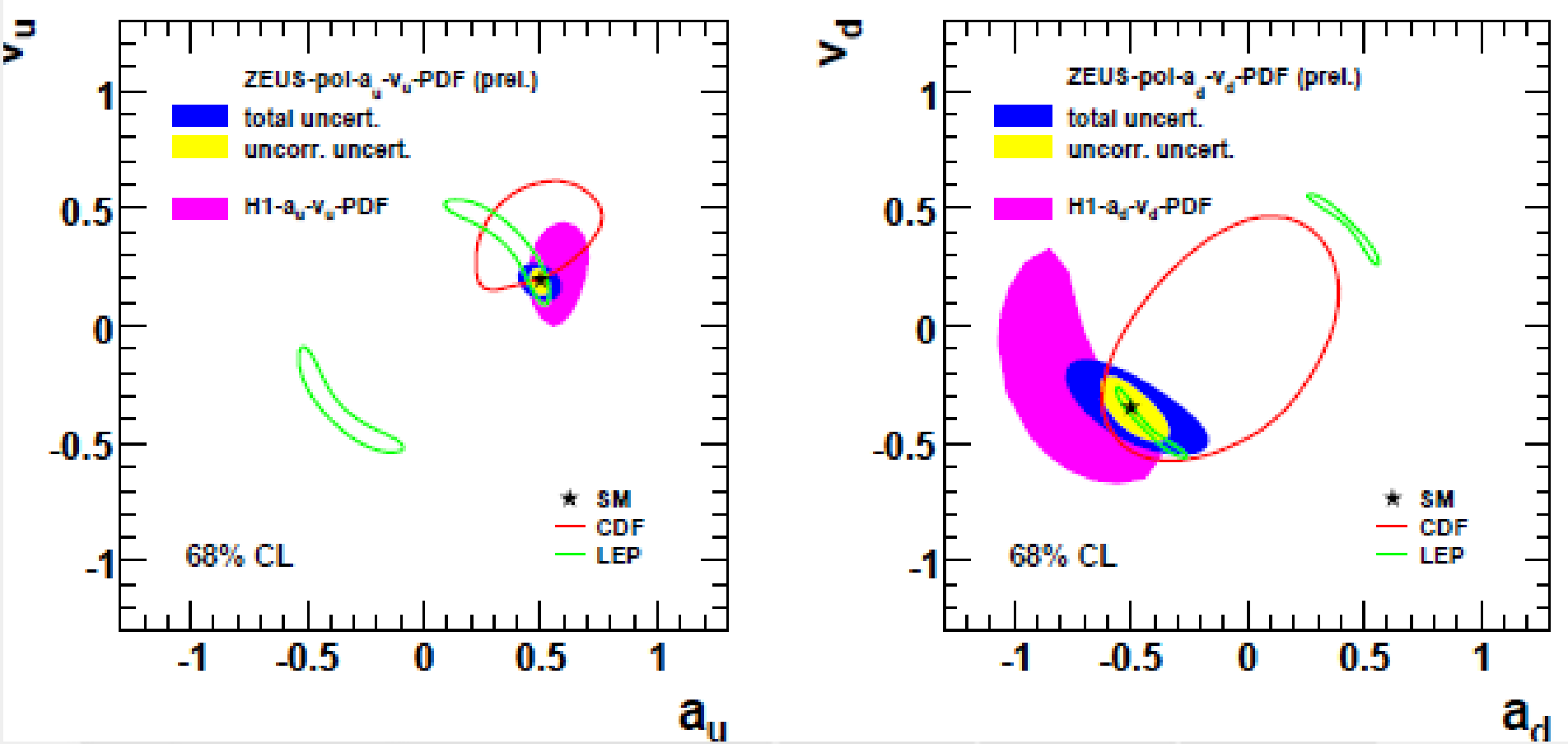
- V and A current quark couplings:
  e polarisation and $\gamma^* Z$ interference



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

Current Quark GSW Couplings

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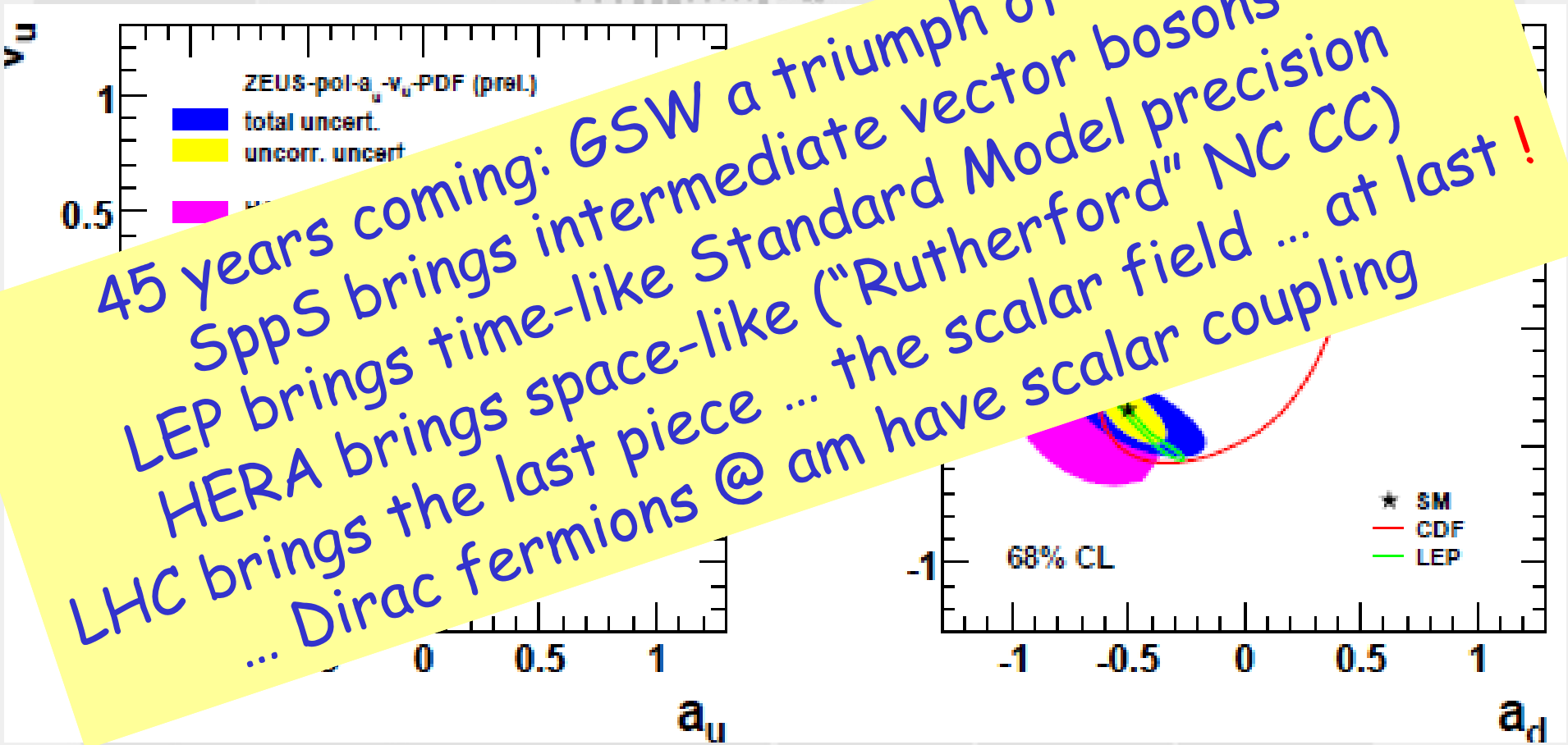
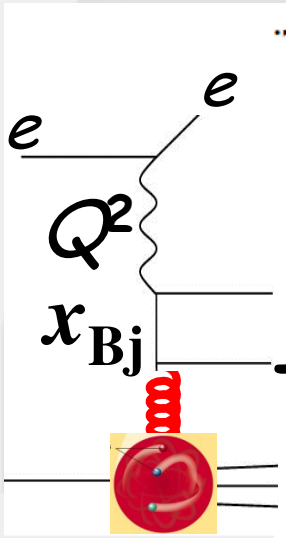


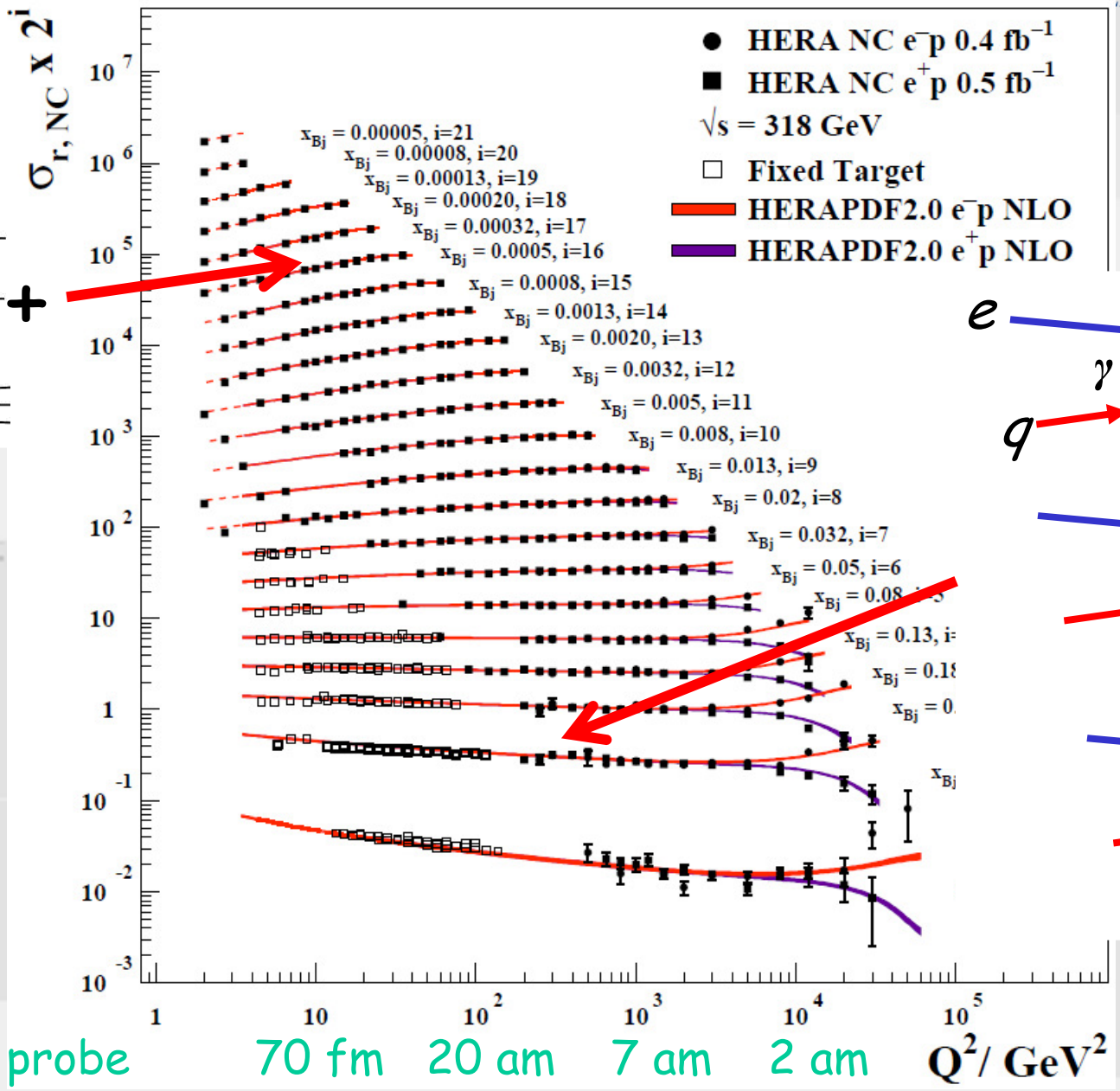
45 years coming: GSW a triumph of humanity
SppS brings intermediate vector bosons
LEP brings time-like Standard Model precision
HERA brings space-like ("Rutherford" NC CC)
LHC brings the last piece … the scalar field … at last !
… Dirac fermions @ am have scalar coupling

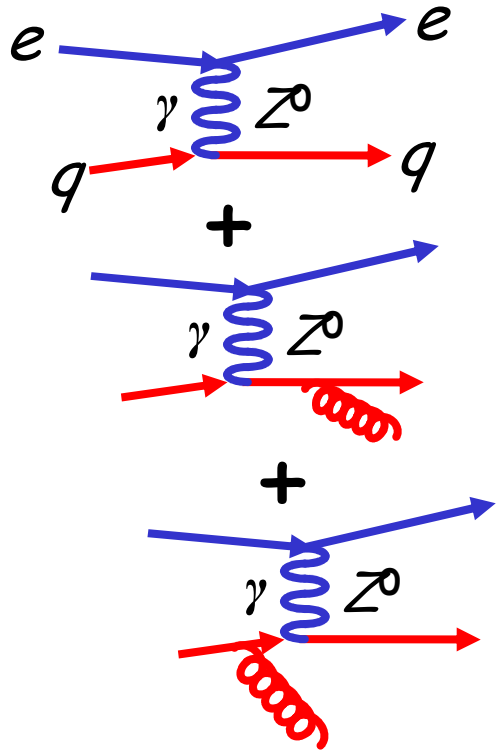
- space-like (HERA) and time-like (LEP+Tevatron)

Constituents with GSW Currents



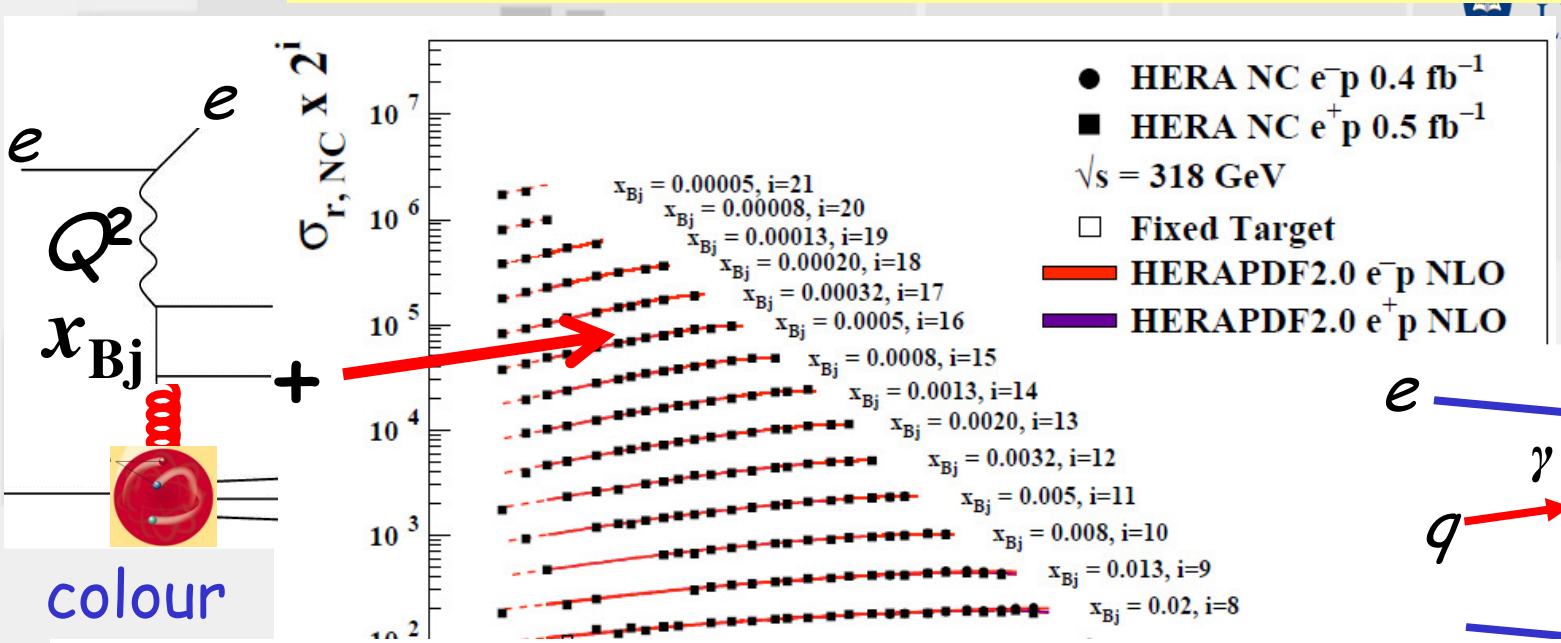
colour driven

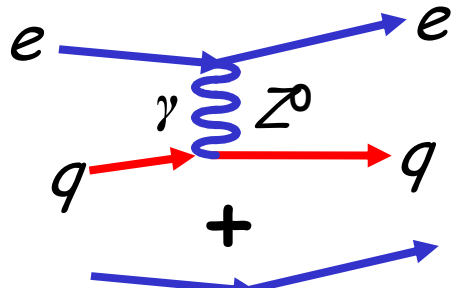




valence driven

Constituents with GSW Currents





$$\sigma_{r\mathrm{NC}}^{\pm}(x,Q^2) = \frac{Q^4 x}{2\pi\alpha_{\mathrm{em}}^2 Y_+}\frac{\mathrm{d}^2\sigma_{rNC}^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_{\mathrm{L}} \mp \frac{Y_-}{Y_+}x\tilde{F}_3$$

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

$$\tilde{F}_{\mathrm{L}} = F_{\mathrm{L}} - \kappa_Z v_e F_{\mathrm{L}}^{\gamma Z} + \kappa_Z^2(v_e^2+a_e^2)F_{\mathrm{L}}^Z$$

$$x\tilde{F}_3 = -\kappa_Z a_e F_3^{\gamma Z} + 2\kappa_Z^2 v_e a_e F_{\mathrm{L}}^Z$$

$$\kappa_Z(Q^2) = \frac{1}{4\sin^2\theta_W\cos^2\theta_W}\frac{Q^2}{Q^2+M_Z^2}$$

$$y = \frac{\gamma\cdot p}{e\cdot p} \qquad x = \frac{Q^2}{\gamma\cdot p}\,Y_{\pm} = 1 \pm (1-y)^2$$

$\tilde{F}_{2,\mathrm{L},3}$
$W_{2,\mathrm{L},3}^{\pm}$ ↔ parton density

Colour Driven

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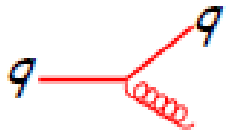
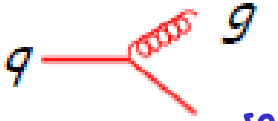
- precision $\sigma_r^{epNC}(x,Q^2)$: quarks in quantum field quarks and gluons in chromodynamics

splitting functions

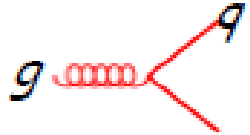
$$P_{qq} = \frac{4}{3}\left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\delta(1-x)\right] + o(\alpha_s) \rightarrow \frac{4}{3}\mathrm{d}x\frac{\mathrm{d}t}{t}$$



$$P_{gq} = \frac{4}{3}\frac{1+(1-x)^2}{x} + o(\alpha_s) \rightarrow \frac{4}{3}\frac{\mathrm{d}x}{x}\frac{\mathrm{d}t}{t}$$



$$P_{qg} = \frac{1}{2}\left[x^2+(1-x)^2\right] + o(\alpha_s) \rightarrow \frac{1}{2}\mathrm{d}x\frac{\mathrm{d}t}{t}$$



$$P_{gg} = 6\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] \cdot \rightarrow 6\frac{\mathrm{d}x}{x}\frac{\mathrm{d}t}{t}$$

$$+ \frac{33-2n_f}{6}\delta(1-x) + o(\alpha_s)$$

g→g dominates

$$x = \frac{parent_\mu \cdot reference^\mu}{daughter_\mu \cdot reference^\mu}$$

- parton densities $f_{p\rightarrow q,g}(x,Q^2) \propto \left(\ln Q^2 + \cdots\right)_x$

Valence Driven

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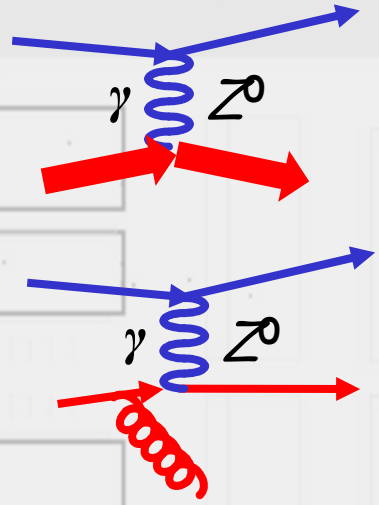
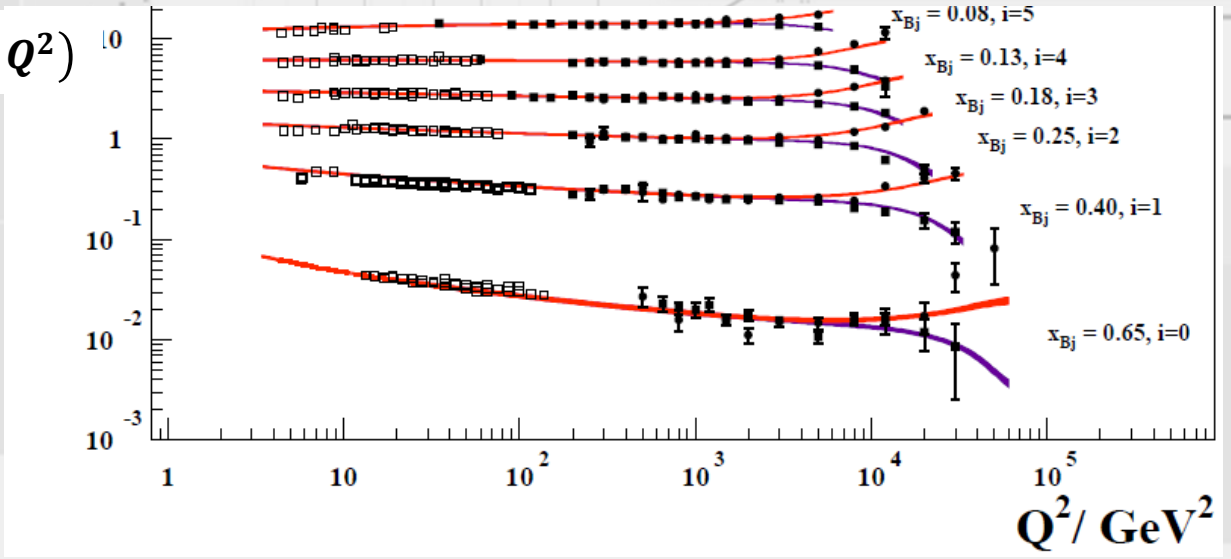
- precision $\sigma_r^{epNC}(x, Q^2)$ at larger x :

  low Q^2: valence q presence,
  but not structure, resolved

  larger Q^2:
  valence q "field structure" resolved,
  therefore "struck q" at lower x



$\sigma_r^{epNC}(x, Q^2)$



Constituents with Currents

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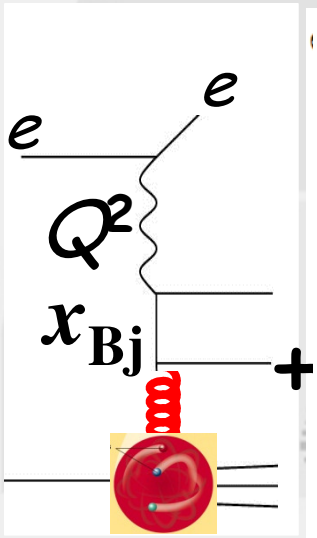
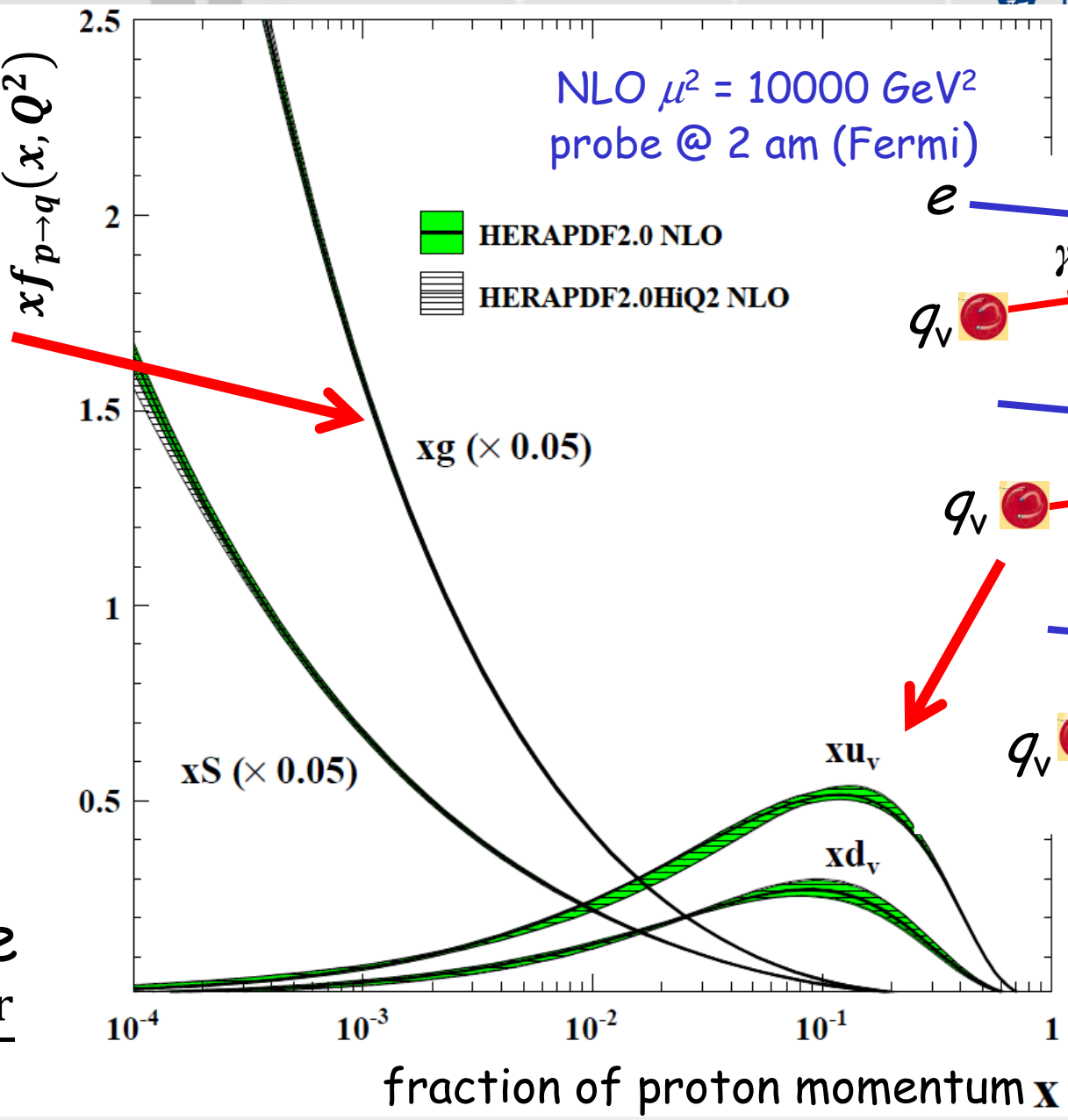
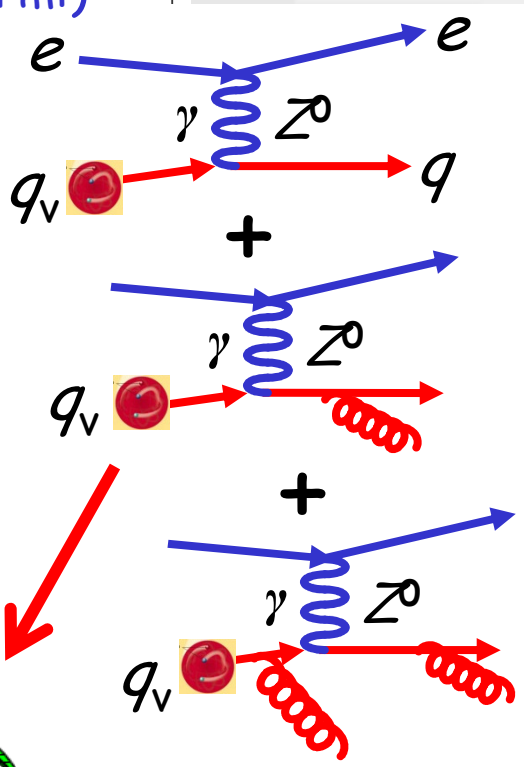


colour driven



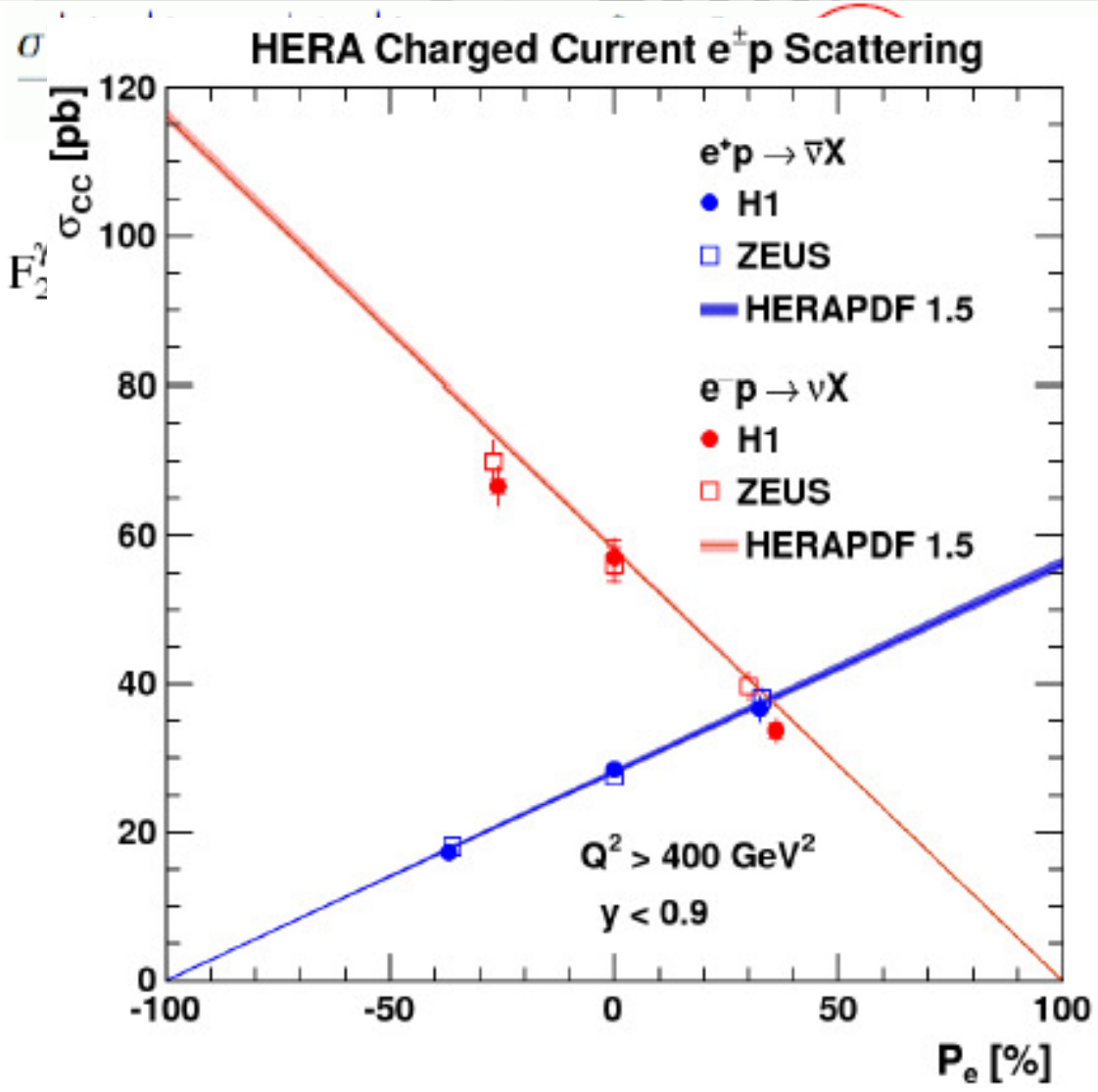


valence driven

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

GSW Current → Proton Anti-matter

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



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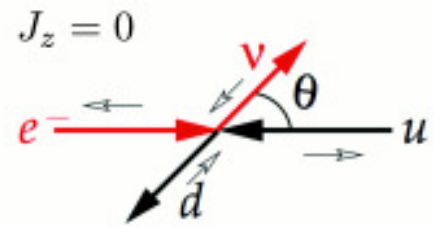

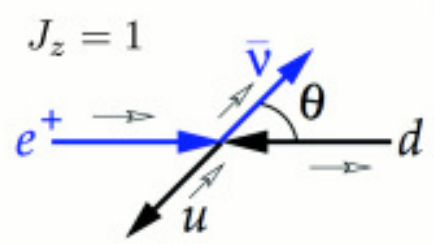

Colour Field Constituents

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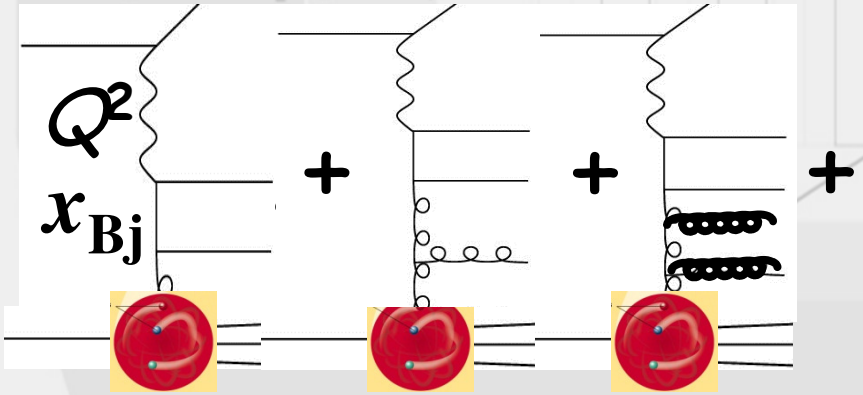
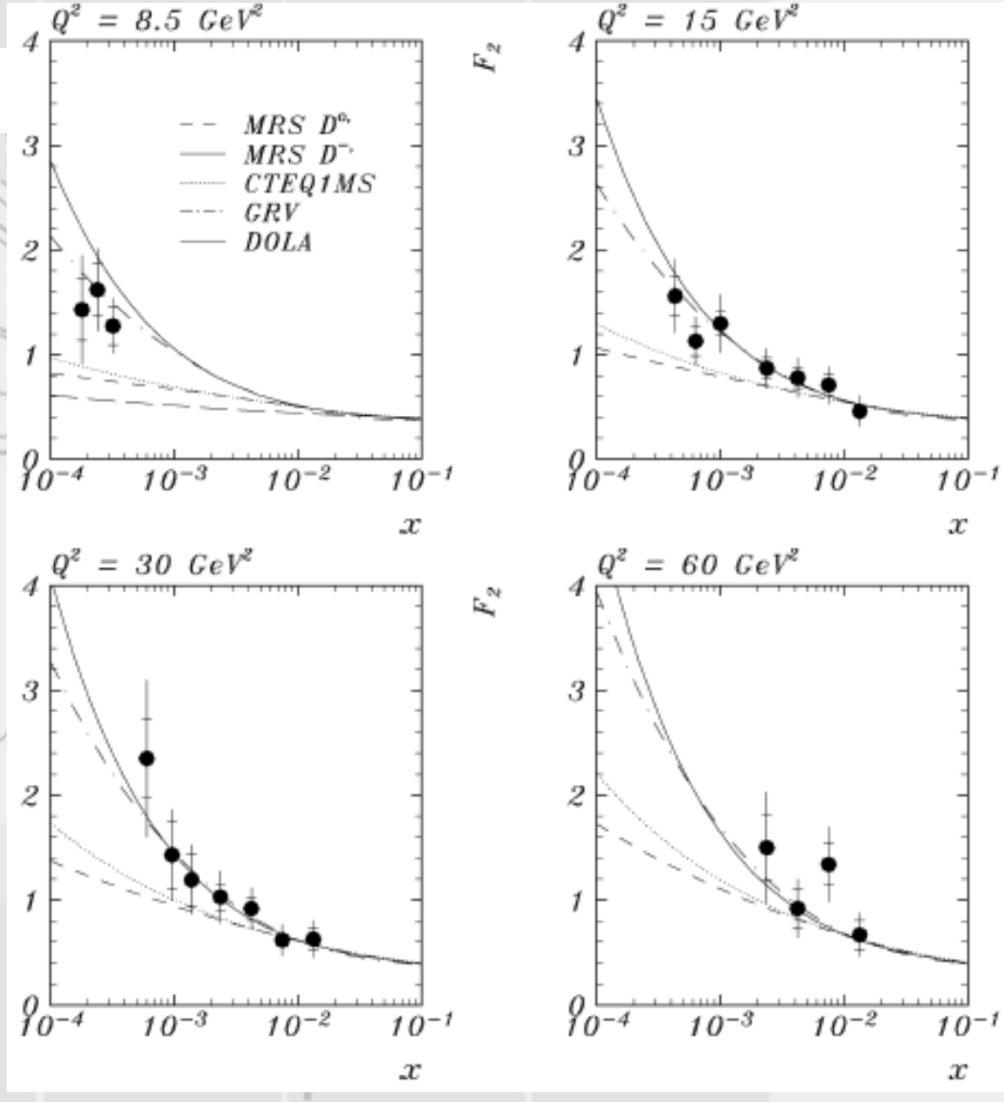
- 1993: rise to low x of proton structure function F_2
  - now: the gauge field theory QCD (gluons) **is** proton structure



F_2



↳ discovery: **we** are (>99%) chromodynamic energy

Colour Conundrum

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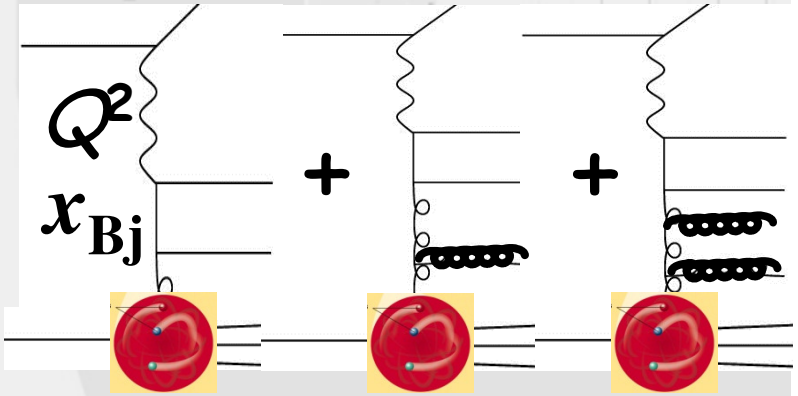
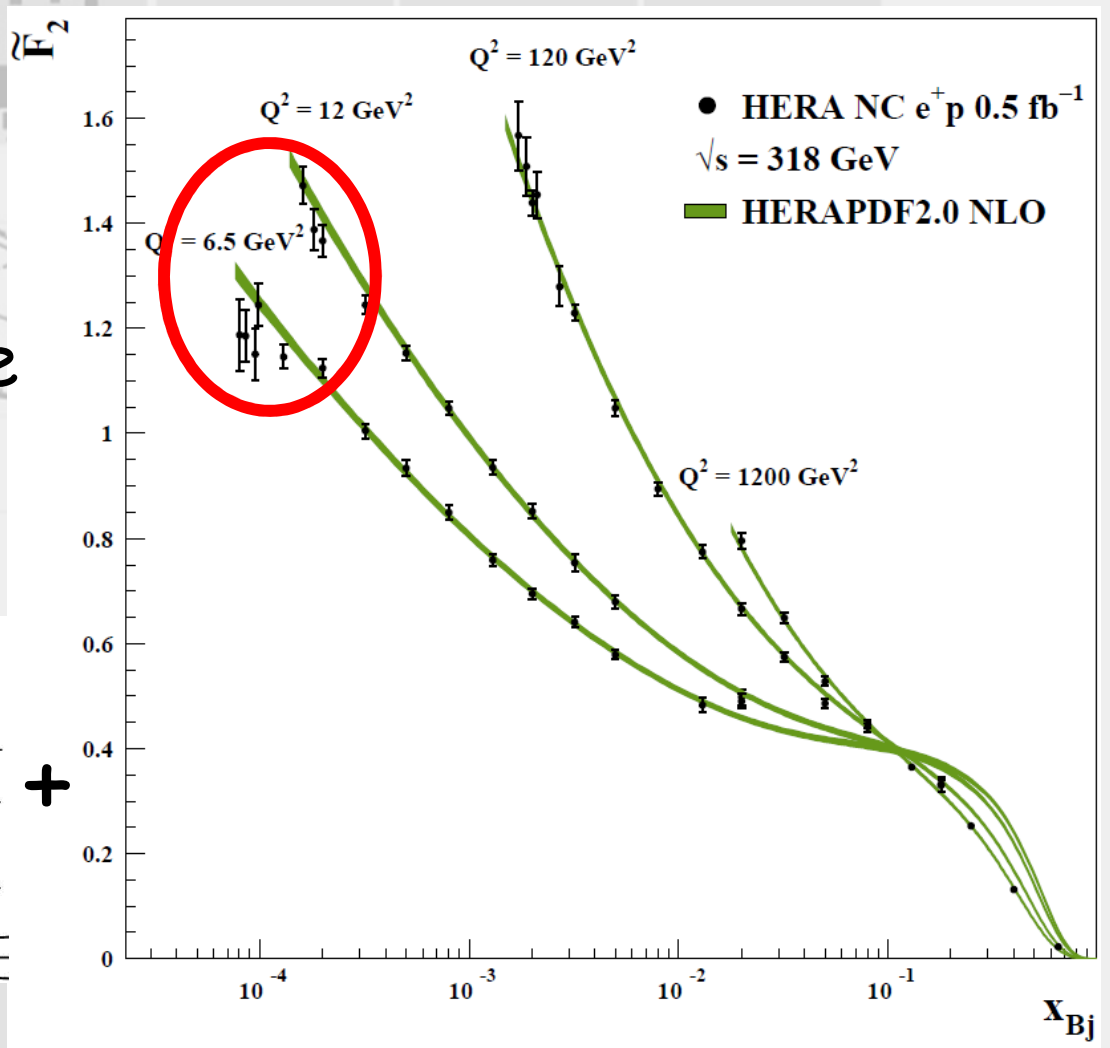
- relentless rise to low x of structure function F_2 ?
  - colour gauge field **is** proton structure
  - **we** are the colour gauge field





↳ discovery: $g \to gg \to ggg$ … but : $\ln\frac{1}{x}$?

Multi-gluons in F_2 at low-x

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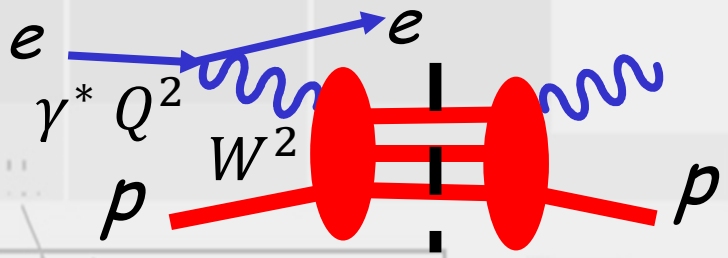
- data $ep \to eX$ and $\gamma^* p \to X$
  - total cross-section



$$\sigma_{\gamma^* p \to X}(Q^2, W^2) \xrightarrow[\text{large } W^2]{} \frac{4\pi^2 \alpha_{\text{em}}}{Q^2} F_2\left(Q^2, x_{\text{Bj}}\right)$$

$$\sigma_{\gamma^* p \to X}(Q^2, W^2) \xrightarrow[\text{low } x_{\text{Bj}}]{\text{optical theorem}} \frac{1}{W^2+Q^2} \operatorname{Im} A_{\gamma^* p \to \gamma^* p}(Q^2, W^2, t=0)$$

$$\propto \frac{1}{W^2+Q^2} (W^2+Q^2)^{1+\lambda(t=0)}$$

↳ proton structure function

Regge asymptotic ↔ Lipatov multi-gluons

$$F_2(Q^2, x)_{\text{low } x} \propto \left[\left(\frac{1}{x}\right)^{\lambda}\right]_{Q^2} \sim \left[\left(\frac{W^2}{Q^2}\right)^{\lambda} \propto \sigma_{\text{tot}}^{\gamma^* p}(\sim W^2)\right]_{Q^2} \qquad x = \frac{\boldsymbol{Q^2}}{\boldsymbol{\gamma \cdot p}} = \frac{Q^2}{W^2+Q^2}$$

↳ "Regge intercept" $1+\lambda$ from $[F_2(Q^2, x)]_{Q^2}$

Colour Conundrum

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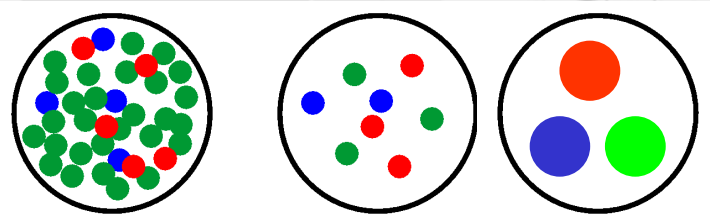
- F_2 @ low x
  - saturation in $F_2 \propto x^{-\lambda}$?

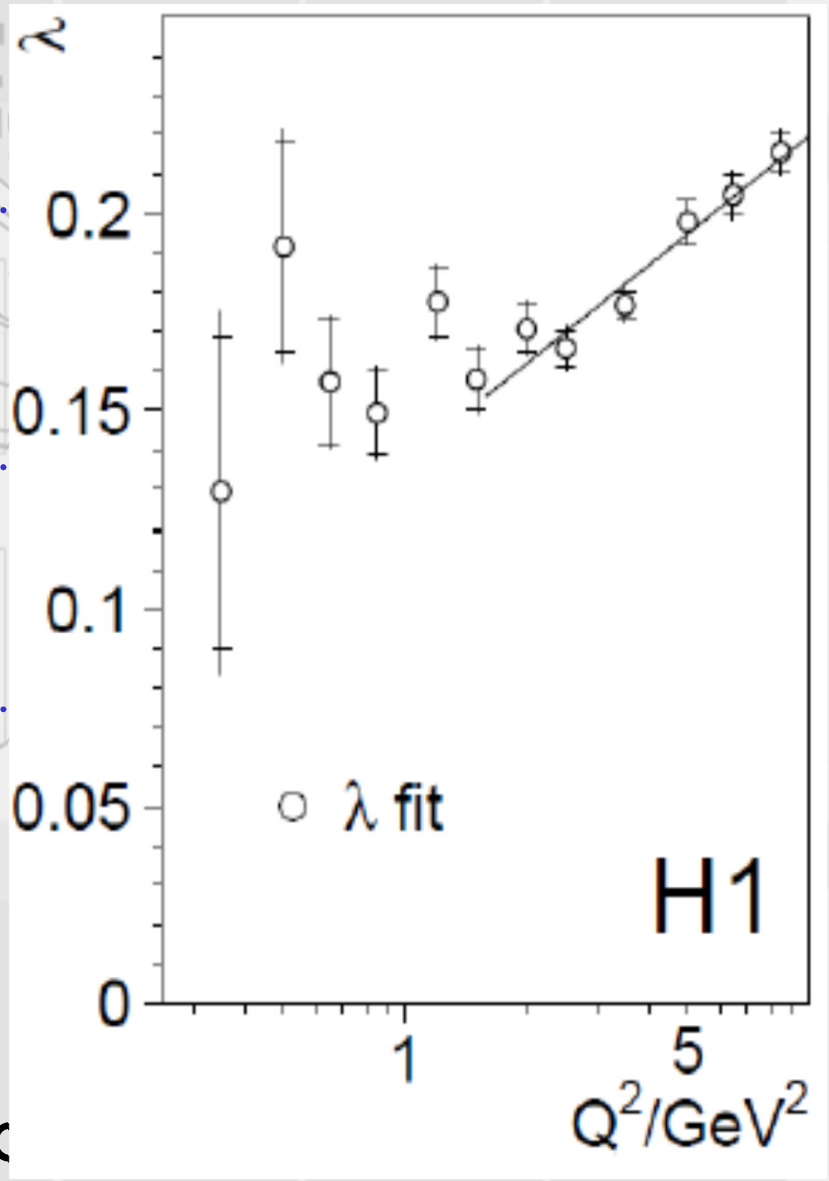


lower x higher x

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

smaller λ larger ?

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



?

Colour Conundrum

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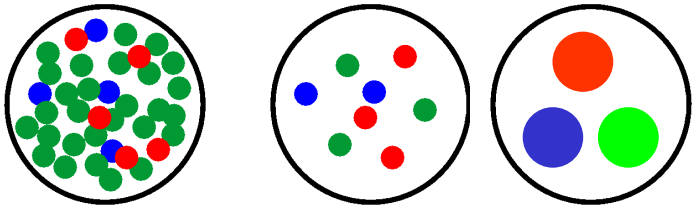

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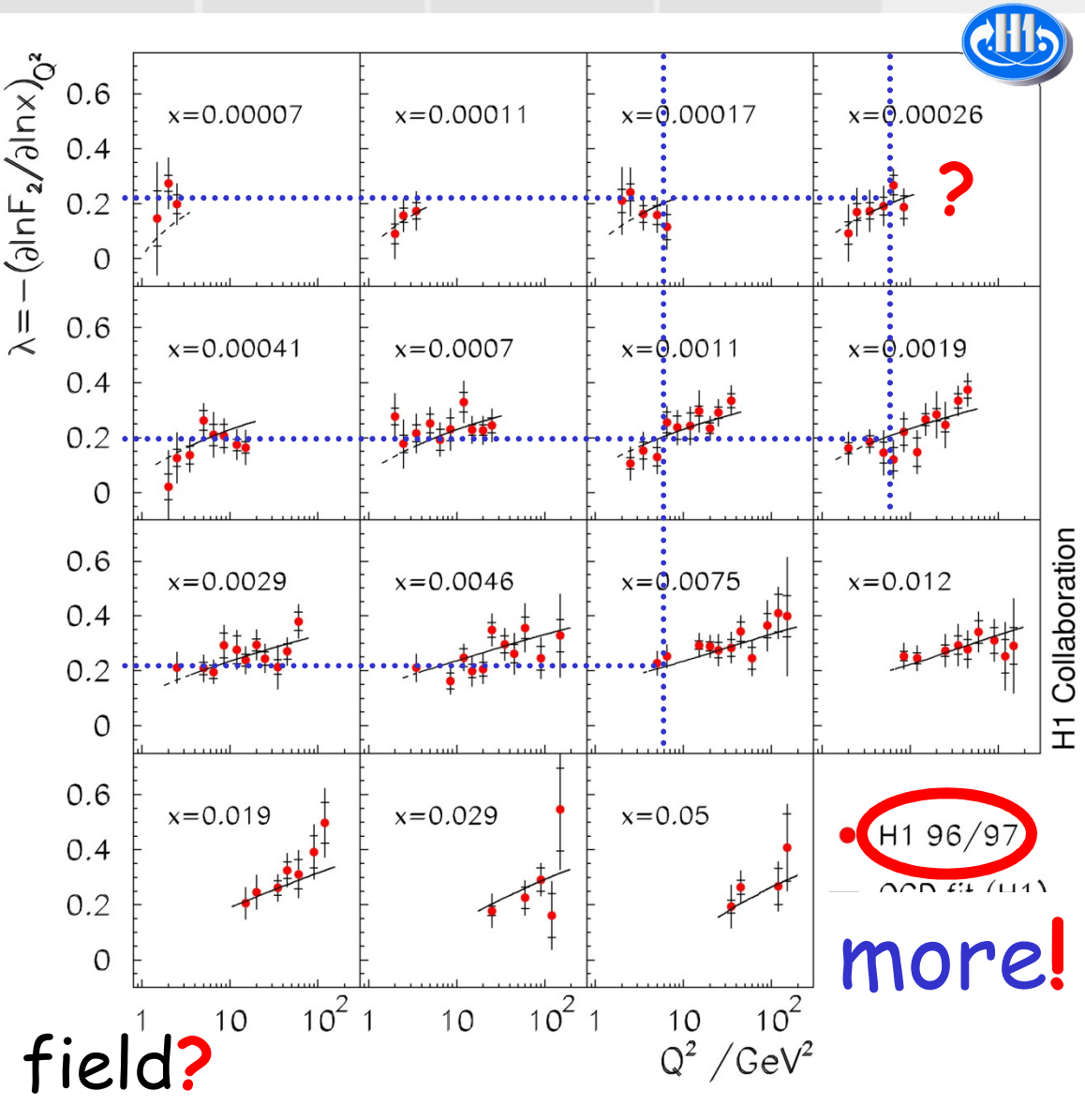

Colour Dynamics

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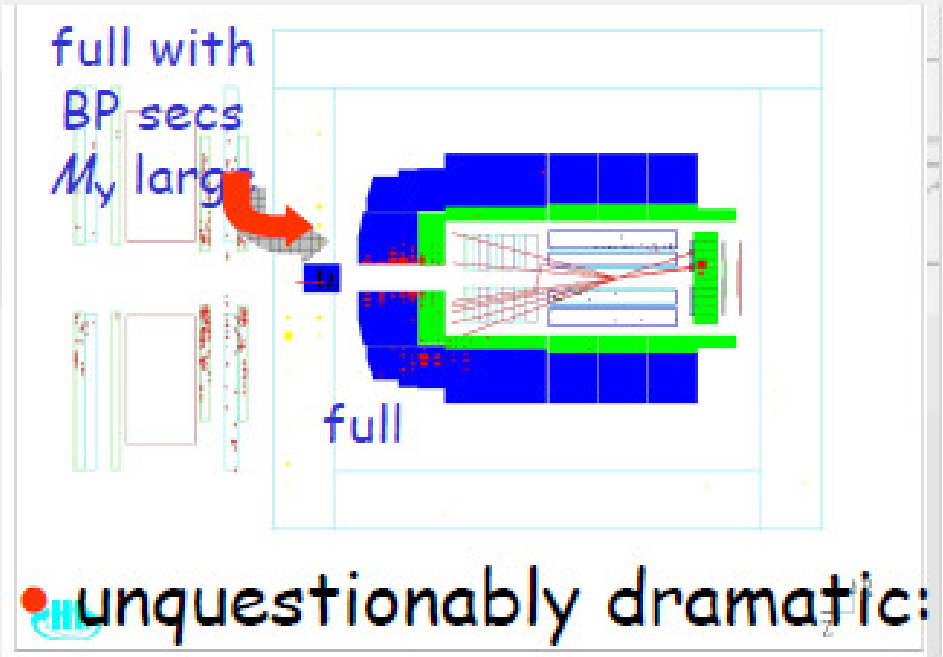
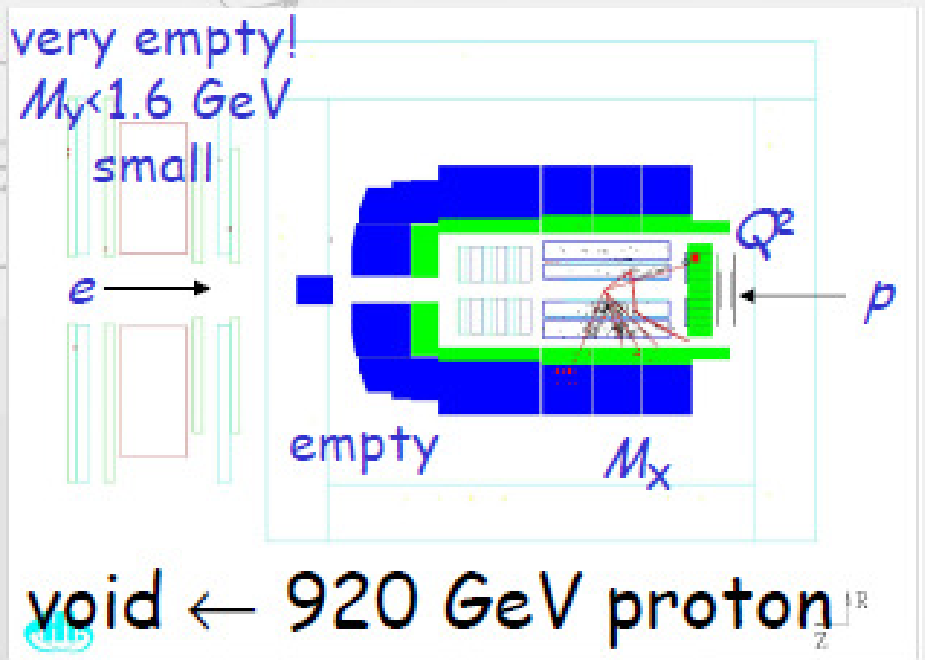
- experiment $ep \to eXY$ with $Q^{-1} < 50$ am
  - p isolated in rapidity
  - forward hadrons $M_Y^2 < 2.5$ GeV^2 isolated in rapidity

} gap → precisely defined x-section





- unquestionably dramatic: void ← 920 GeV proton

Colour Dynamics

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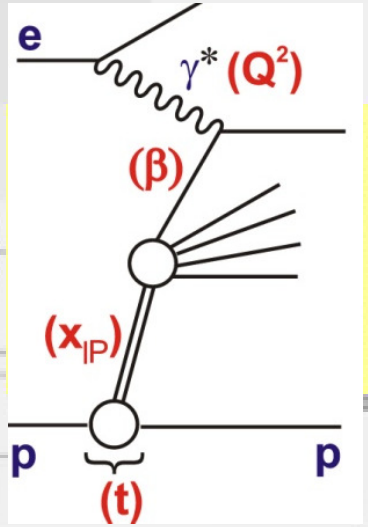
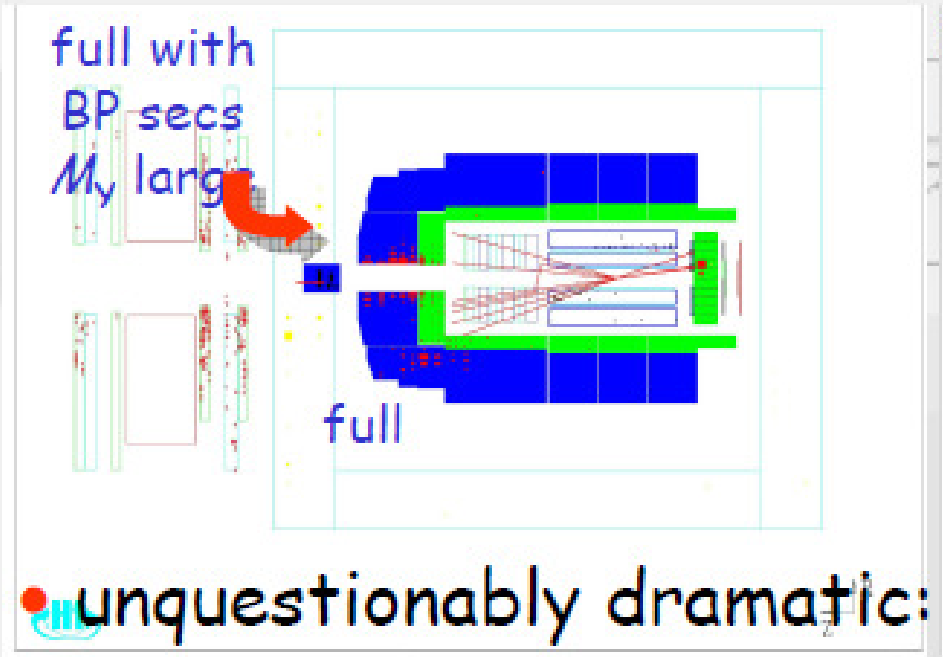
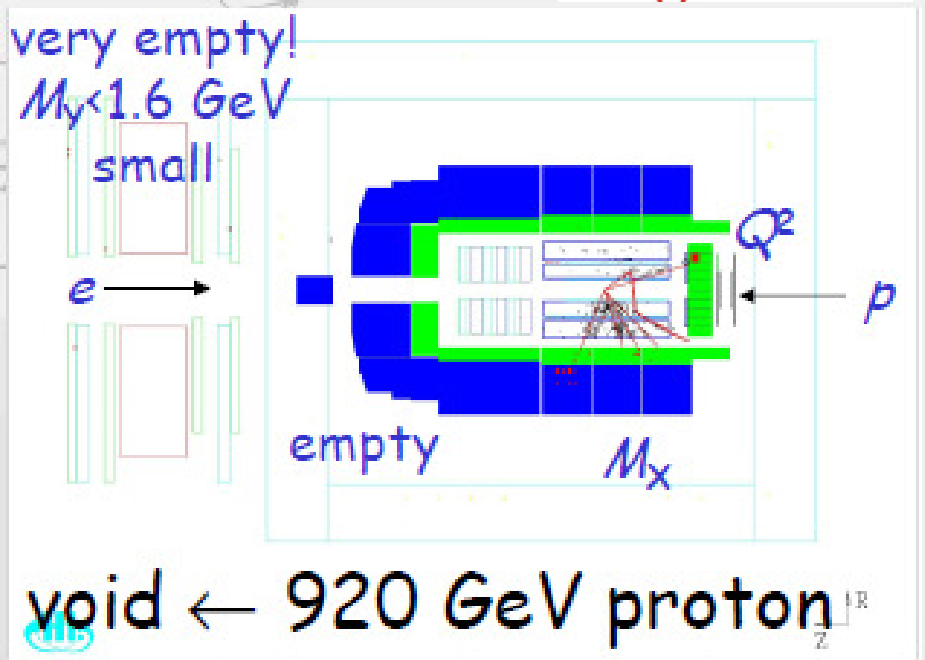
- experiment $ep \to eXY$ with $Q^{-1} < 50$ am
  - p isolated in rapidity
  - forward hadrons $M_Y^2 < 2.5$ GeV^2 } gap
  - isolated in rapidity
  - ↳ probe hadronic interaction







- unquestionably dramatic: void ← 920 GeV proton

Experiment

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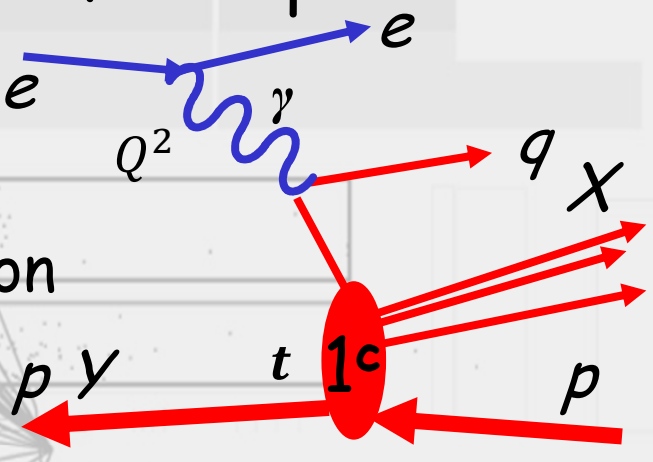
- high energy for precision "Rutherford" probe
  - deep ($Q^2 \gg m_p^2$)
    inelastic ($s \gg m_p^2$)
  - $ep \to e + X + p$
  - space-like factorisation

q from hadronic interaction



$$\sigma_r^{D(4)}(\beta, x_{IP},, t, Q^2) = \frac{Q^4 \beta}{2\pi\alpha_{em}^2 Y_+} \frac{d^2\sigma_r^{D(4)}}{d\beta dx_{IP} dt dQ^2} = F_2^{D(4)} - \frac{y^2}{Y_+} F_L^{D(4)}$$

$F_2^{D(4)} \leftrightarrow$ diffractive parton density

- structure of high energy proton interaction
  = QCD composition of inter-nucleon force
- remnant in beam-pipe $\rightarrow$ rapidity gap

Colour Interaction Dynamics

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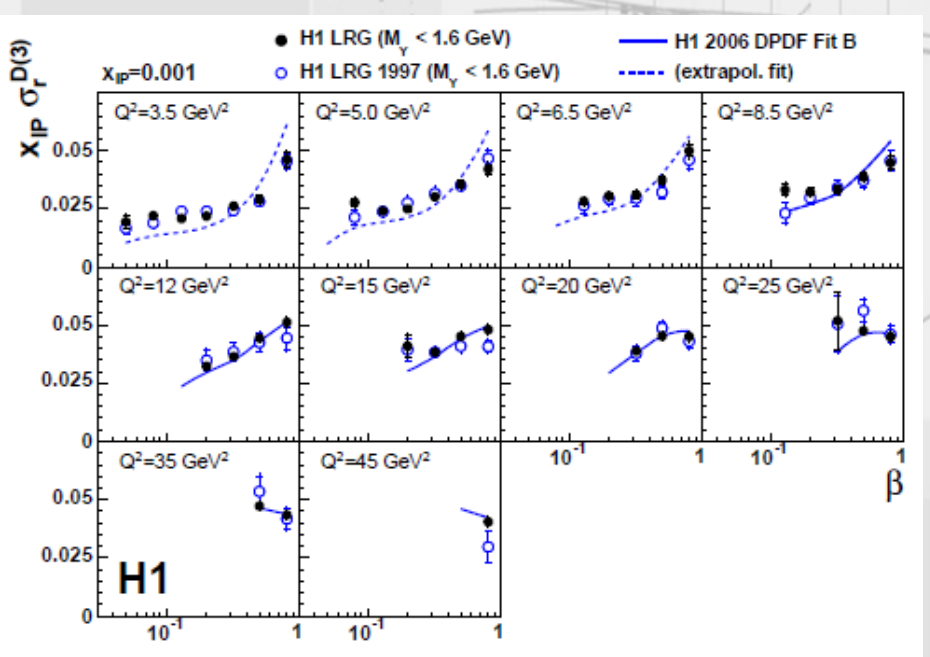
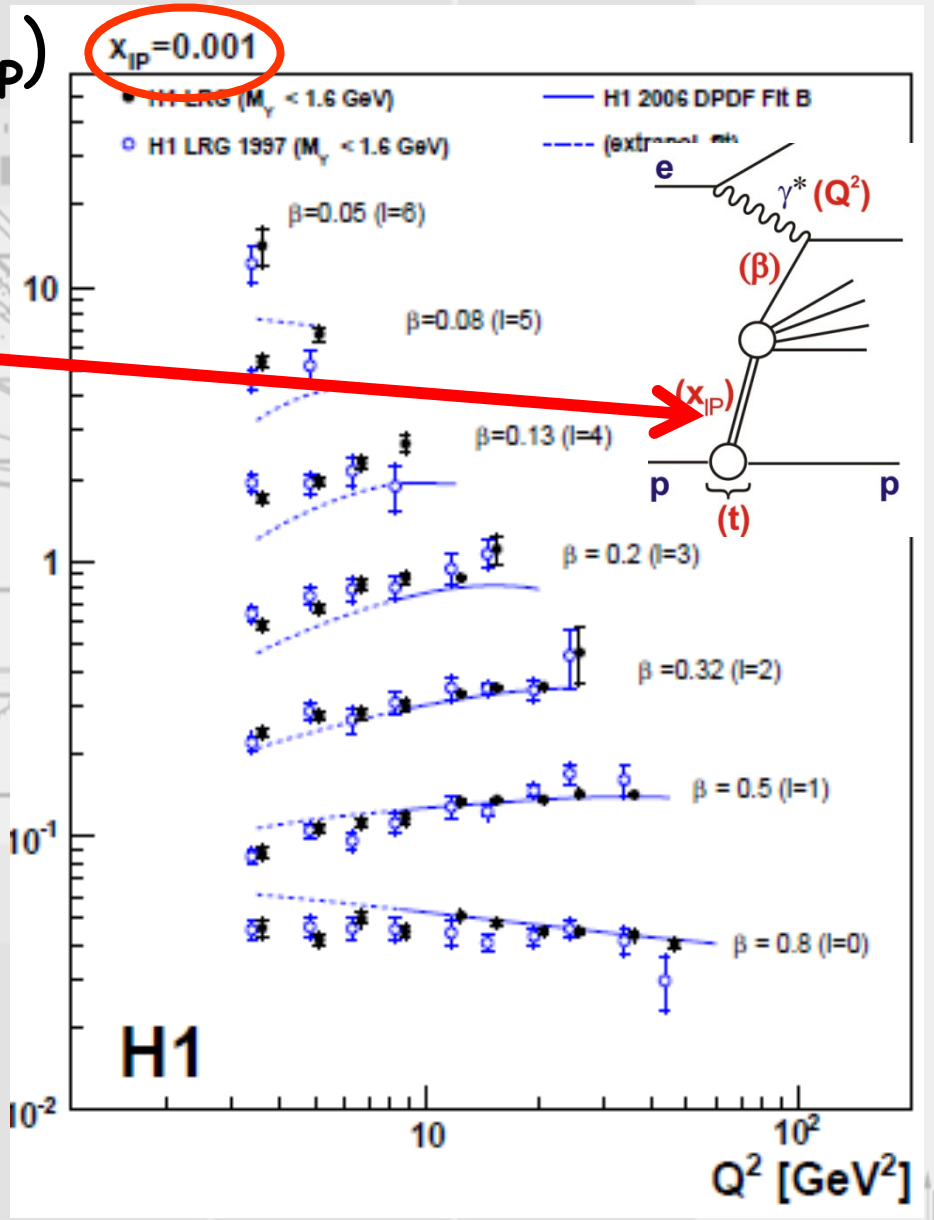
- x-section $x_{IP}\sigma_r \sim F_2(\beta, Q^2, x_{IP})$
  - scaling violations → $1_f(q_s)$ QCD evolution
  - β dep^{c} → $g \to q\bar{q}$





Hadronic Structure

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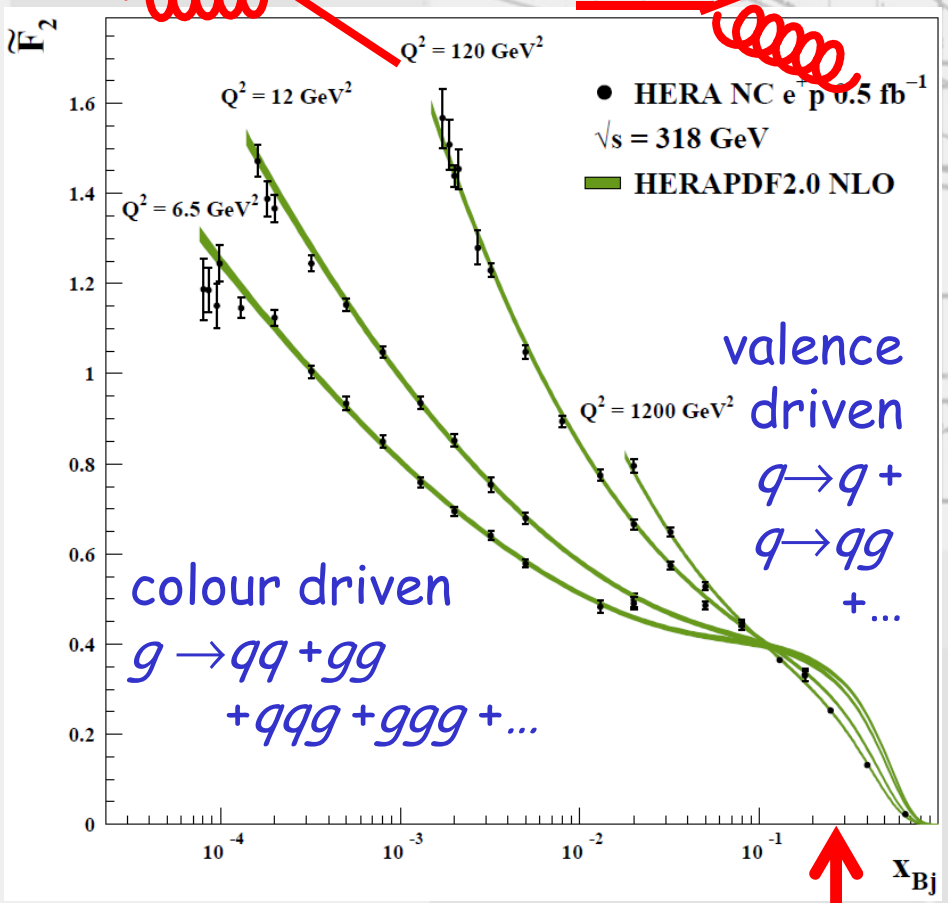
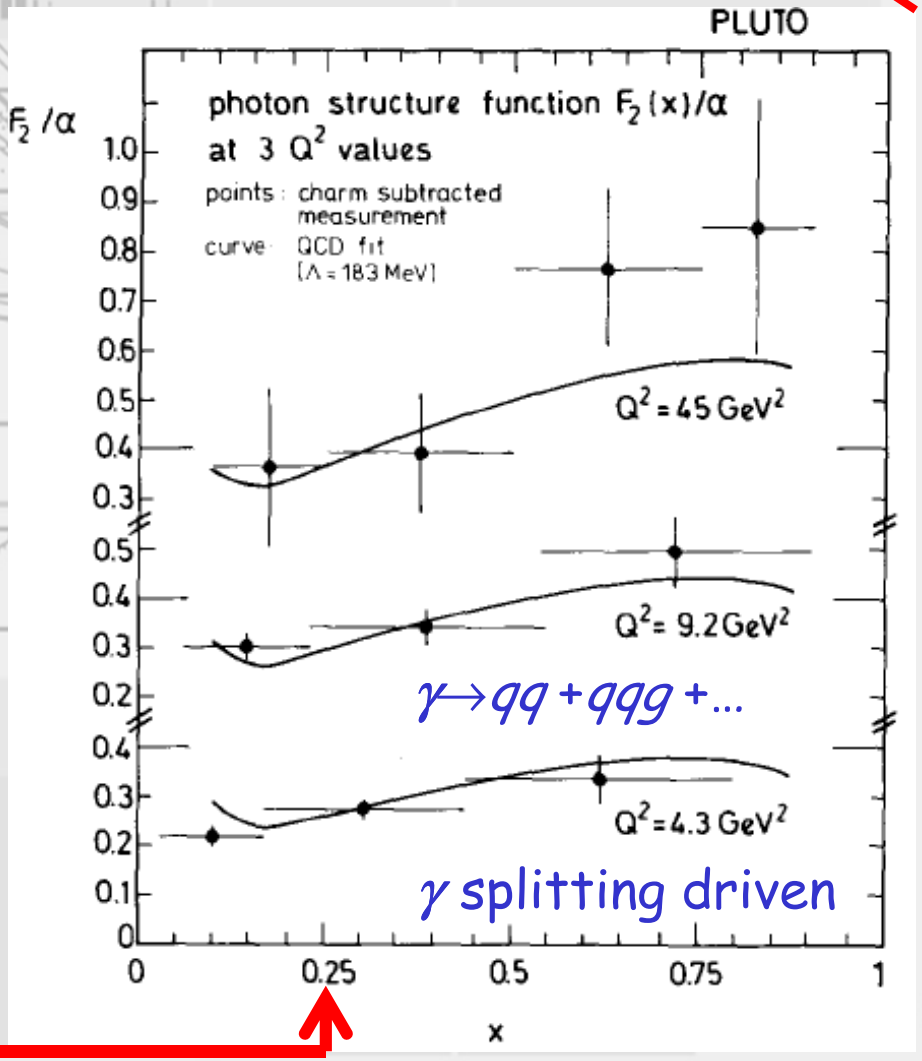
- structure function $F_2(x, Q^2)$
  - QCD and hadron

QFD field + QCD
"γ-splitting"

"g-splitting" "q-splitting"





1_c Interaction Dynamics

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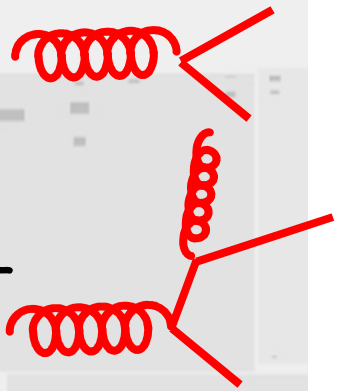
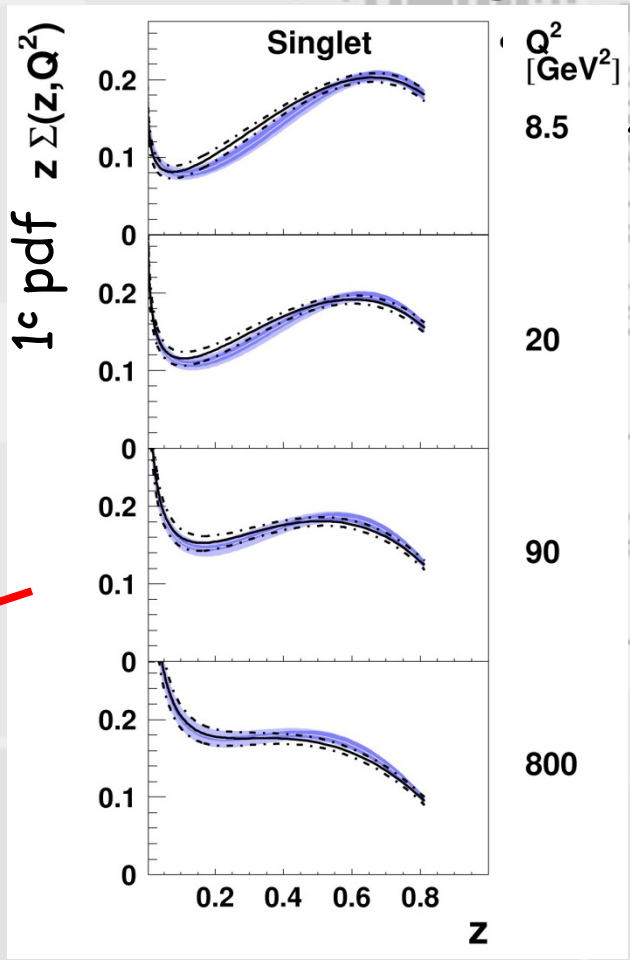
- the colour dynamics of the nucleon interaction
  - NLO $\rightarrow$ 1^c colour singlet inelastic q interaction

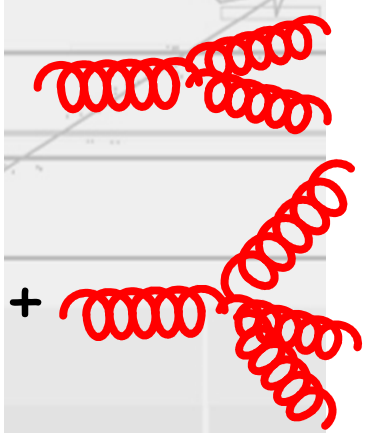
$g \rightarrow q\bar{q}$
$+ g \rightarrow q\bar{q}g$
$+ \ldots$



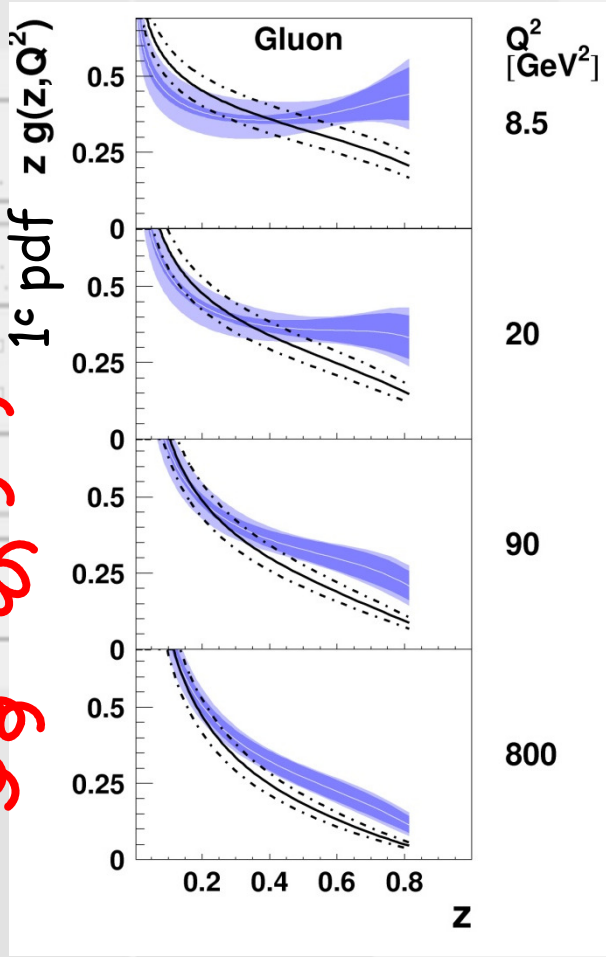
$+ \ldots$



$g \rightarrow gg$
$+ g \rightarrow ggg$
$+ \ldots$



$+ \ldots$



↳ internucleon interaction = gluons = $\frac{\text{gluon splitting}}{\text{quark splitting}} = \frac{9}{4}$ LO

1_c Interaction Dynamics

- the colour dynamics of the nucleon interac
  - NLO $\rightarrow$ 1^c colour singlet inelastic q int rion

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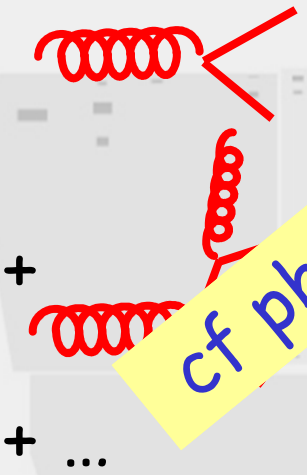
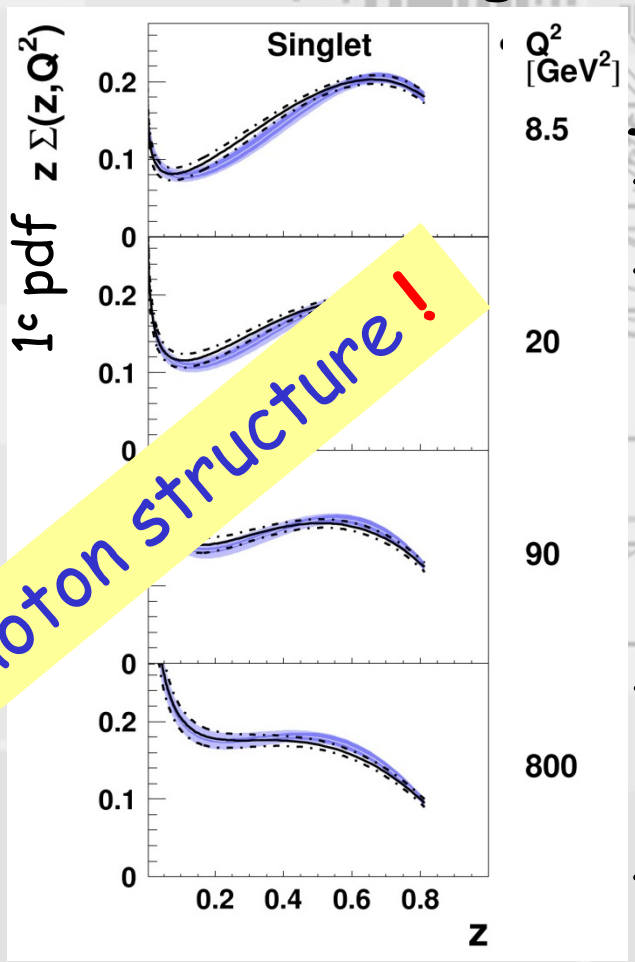
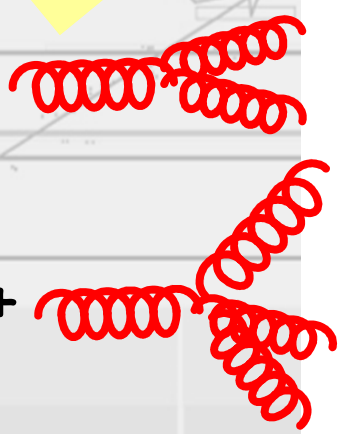


$+$
$+ \ldots$



$g \rightarrow gg$
$+ g \rightarrow$
$+ \ldots$



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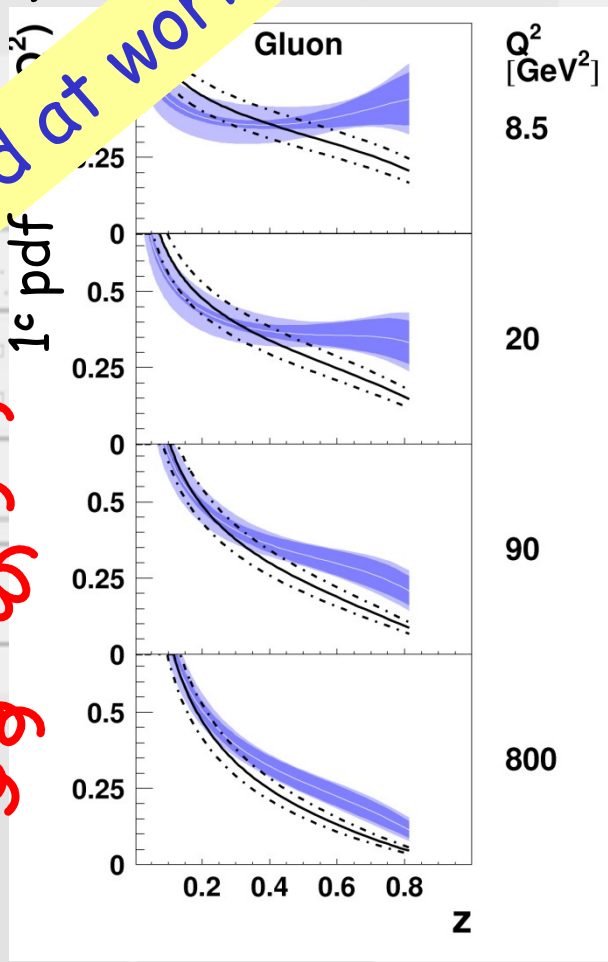

cf photon structure !

QCD field at work with itself

↳ internucleon interaction = gluons = $\frac{\text{gluon splitting}}{\text{quark splitting}} = \frac{9}{4}$ LO

1_c Interaction Dynamics

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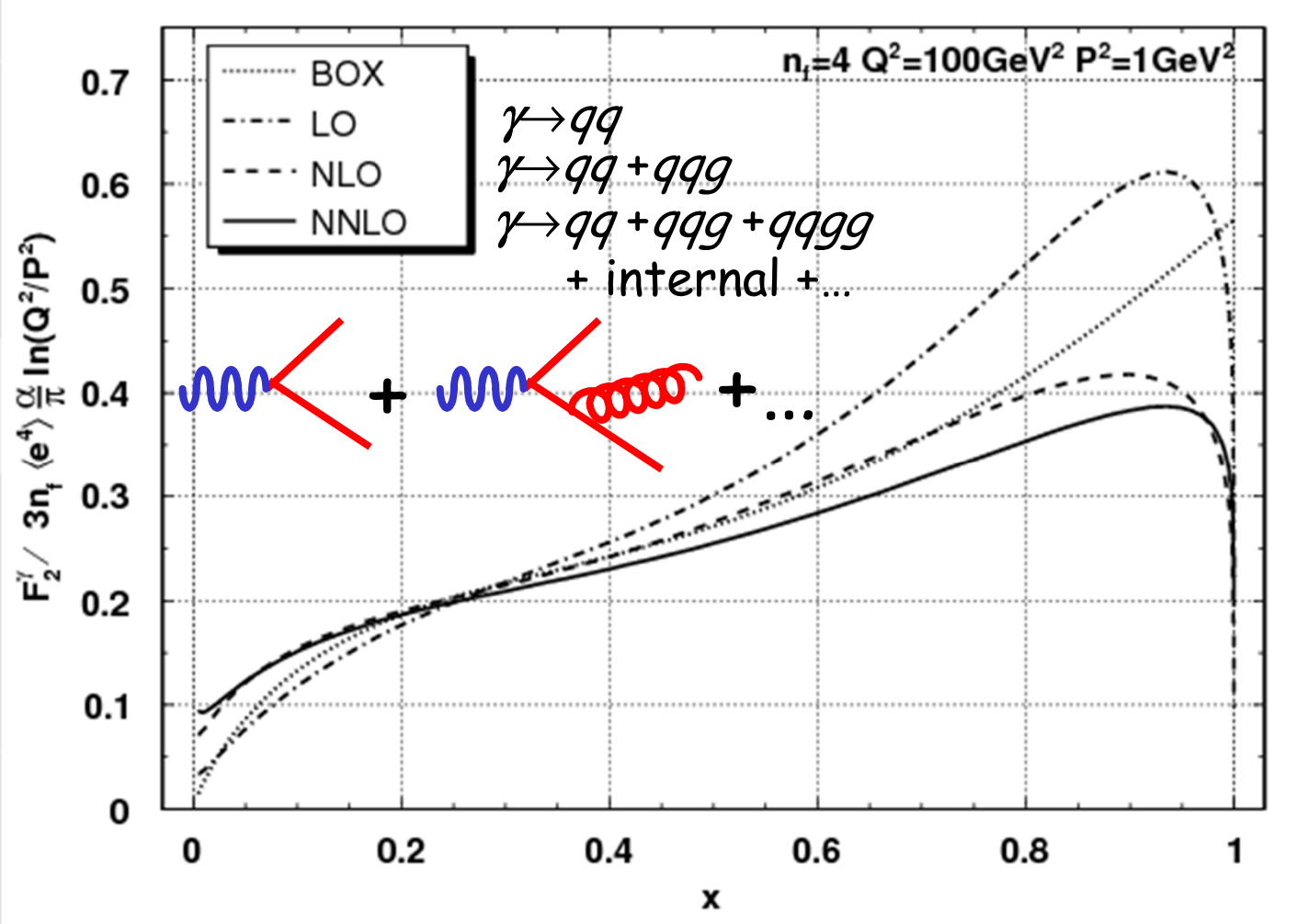
- photon structure function $F_2(x, Q^2)$



↳ QFD+QCD structure = gauge-invariant vector field

1_c Interaction Dynamics

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- high energy for precision "Rutherford" probe
  - deep ($Q^2 \gg m_p^2$)
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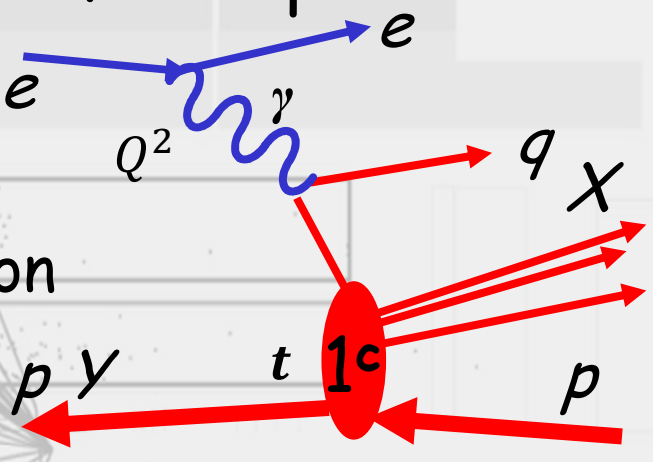
q from hadronic interaction



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$$\langle \sigma_r^{D(3)}(\beta, x_{IP}, Q^2) \rangle_\beta \propto \langle \left(\frac{1}{x}\right)^{\lambda(Q^2)} \rangle_\beta$$

- structure of high energy proton interaction
  = QCD composition of inter-nucleon force
  - multi-gluon exchange ?

1_c Interaction Dynamics

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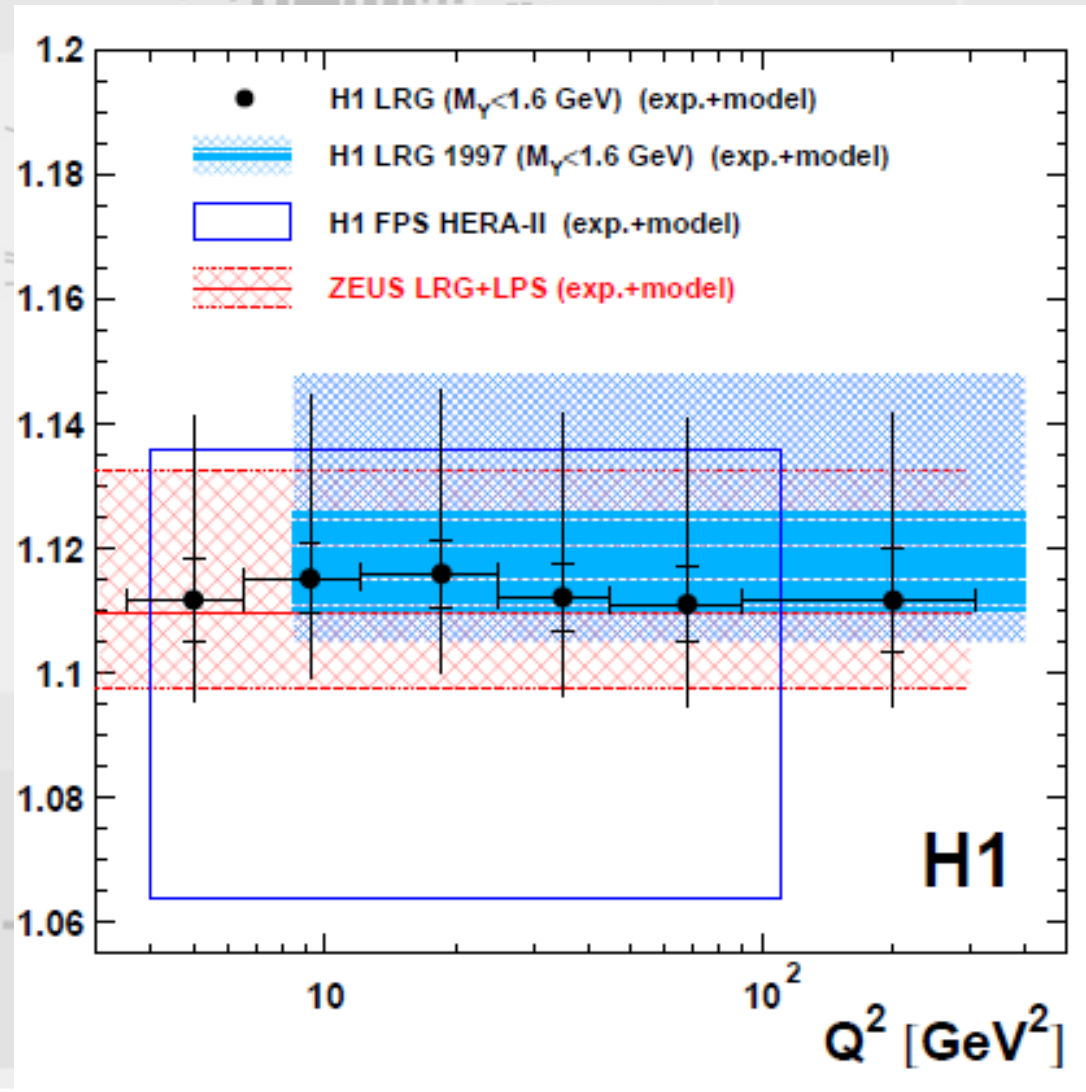
- 1_c dynamics ≡ multi-gluons ~ 8_c dynamics ≡ Lipatov

$\langle 1 + \lambda(Q^2) \rangle_\beta$



1_c Interaction Dynamics

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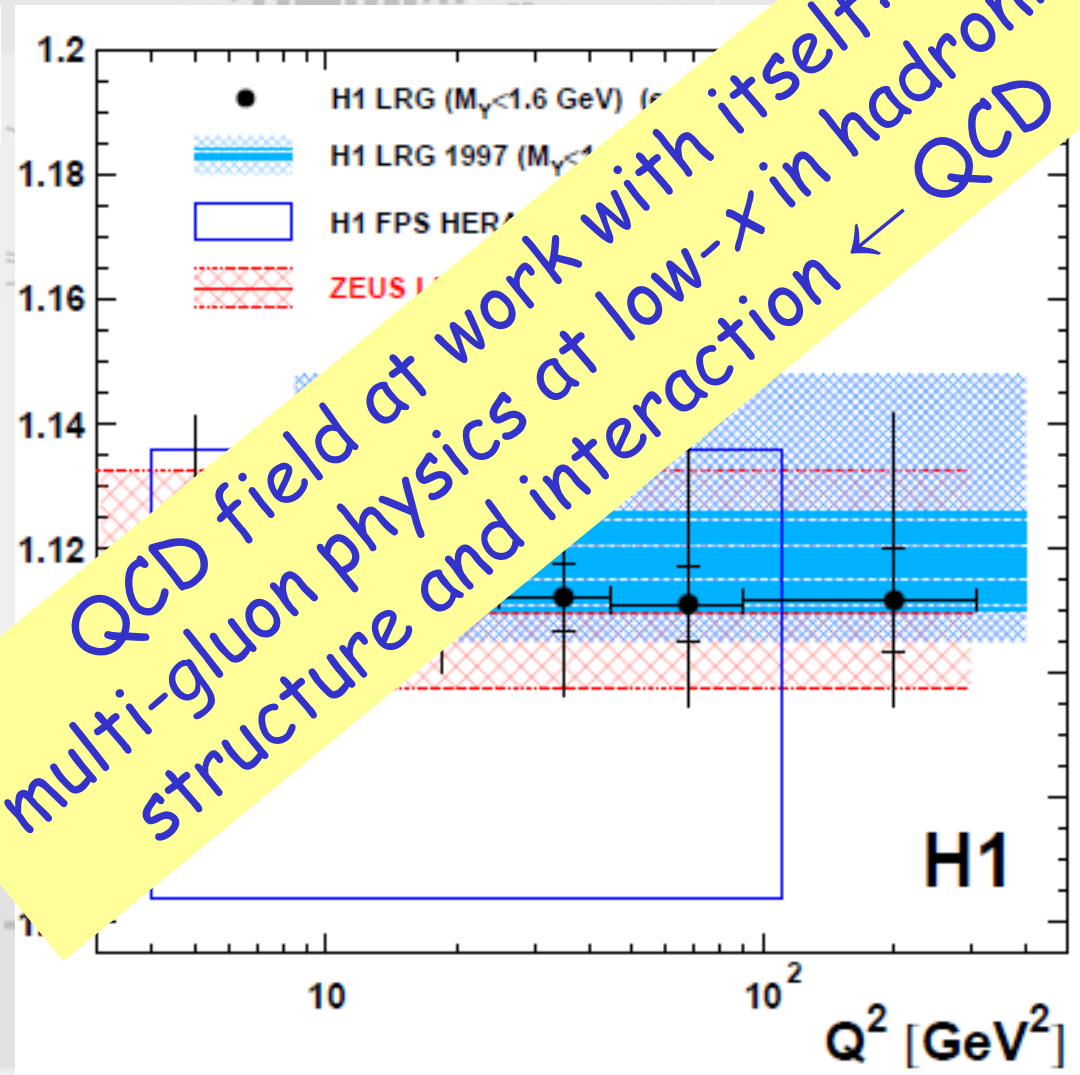

QCD field at work with itself:
multi-gluon physics at low-x in hadronic structure and interaction ← QCD

Shortest Distance

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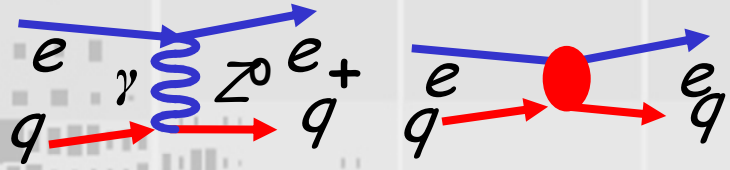
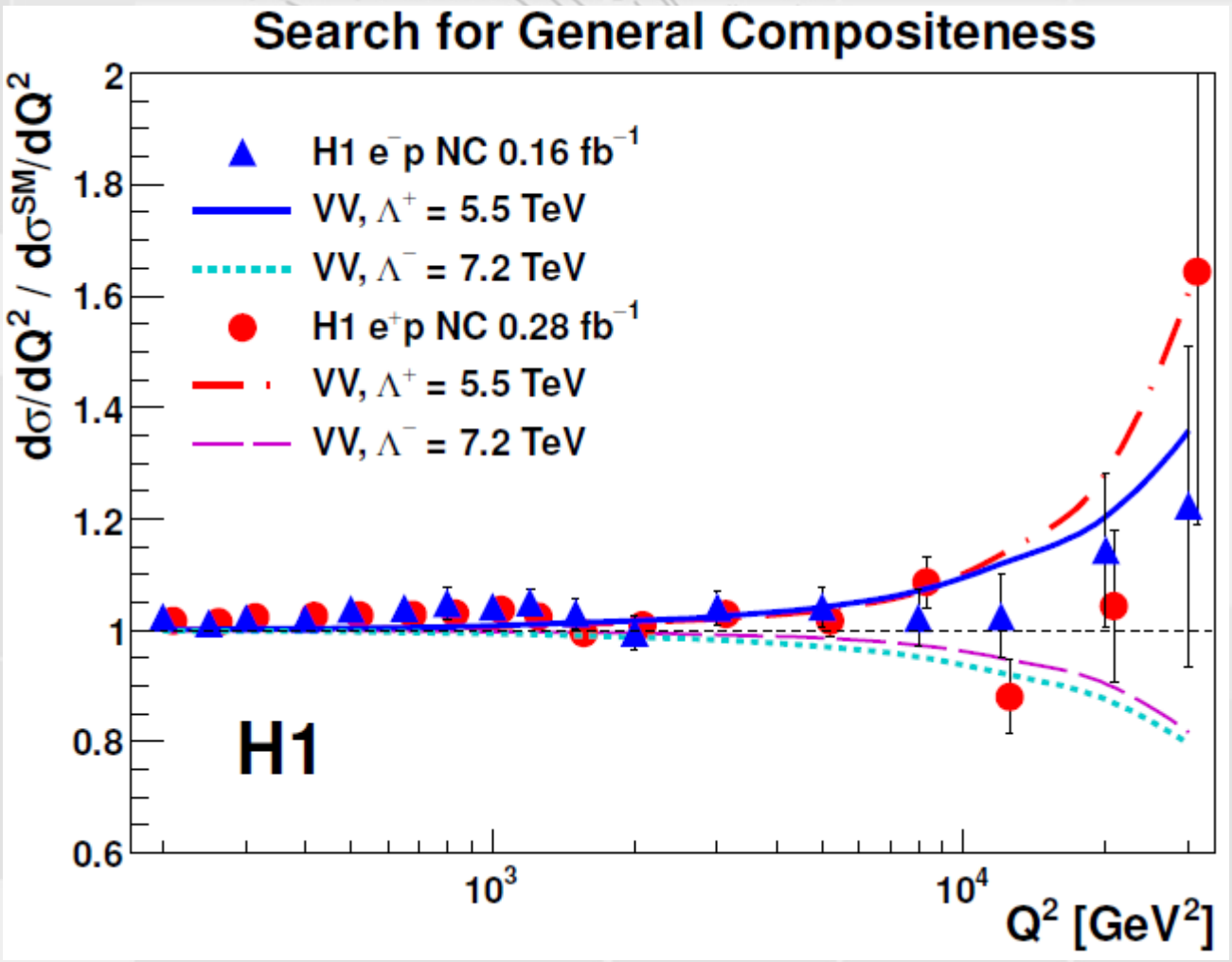
- beyond Dirac quark 

"contact" ?



Shortest Distance

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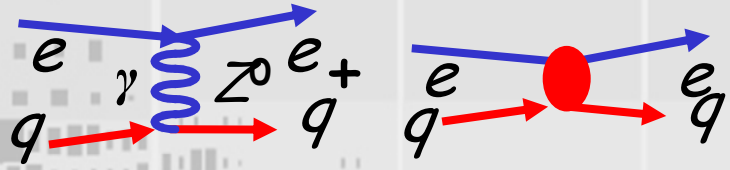
- beyond Dirac quark 

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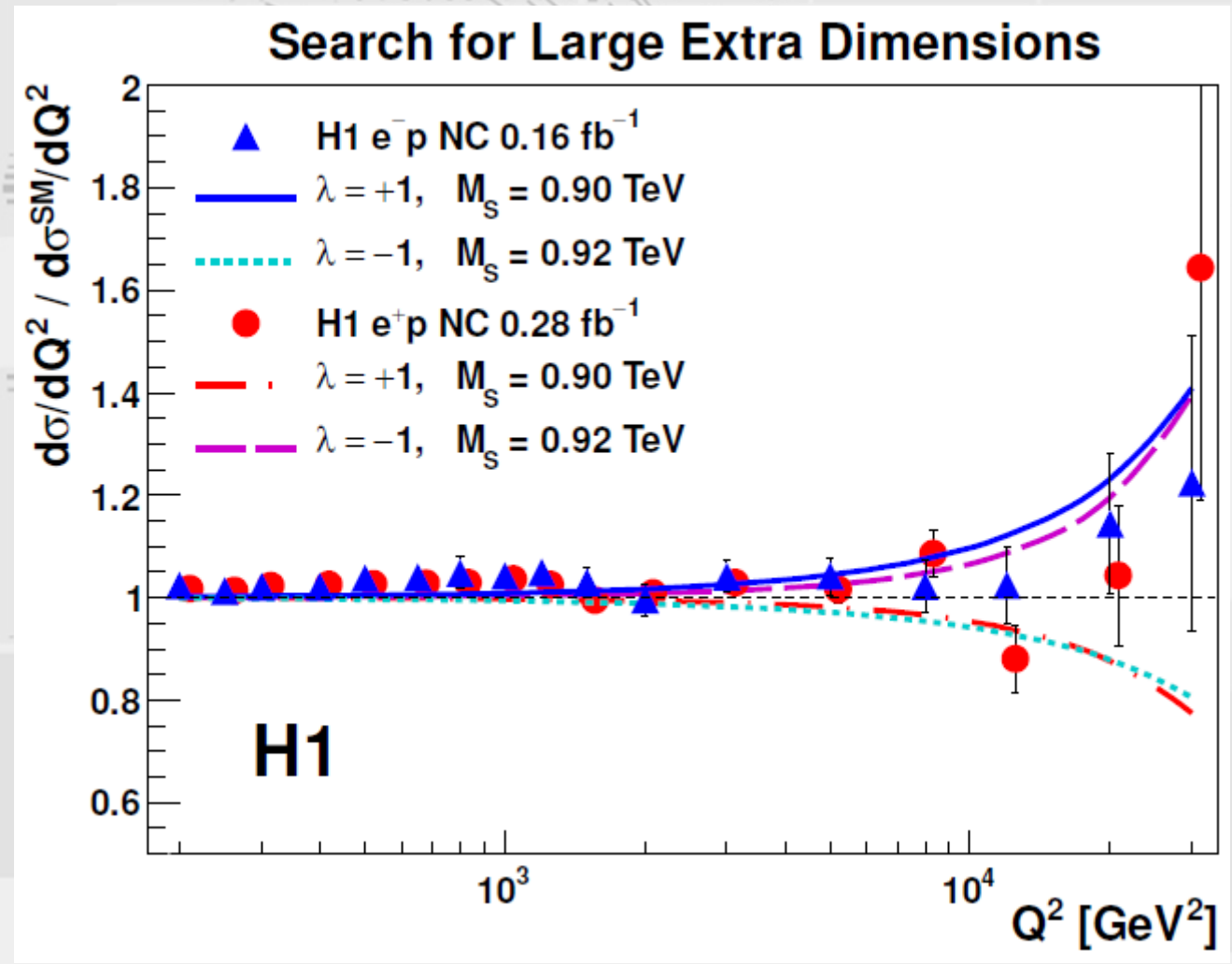

Shortest Distance

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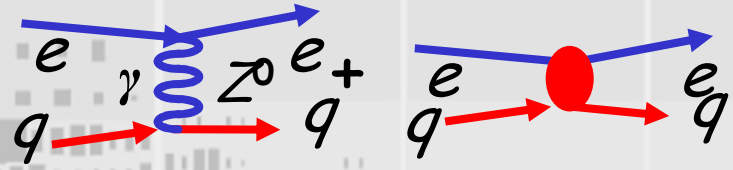
- beyond Dirac quark 

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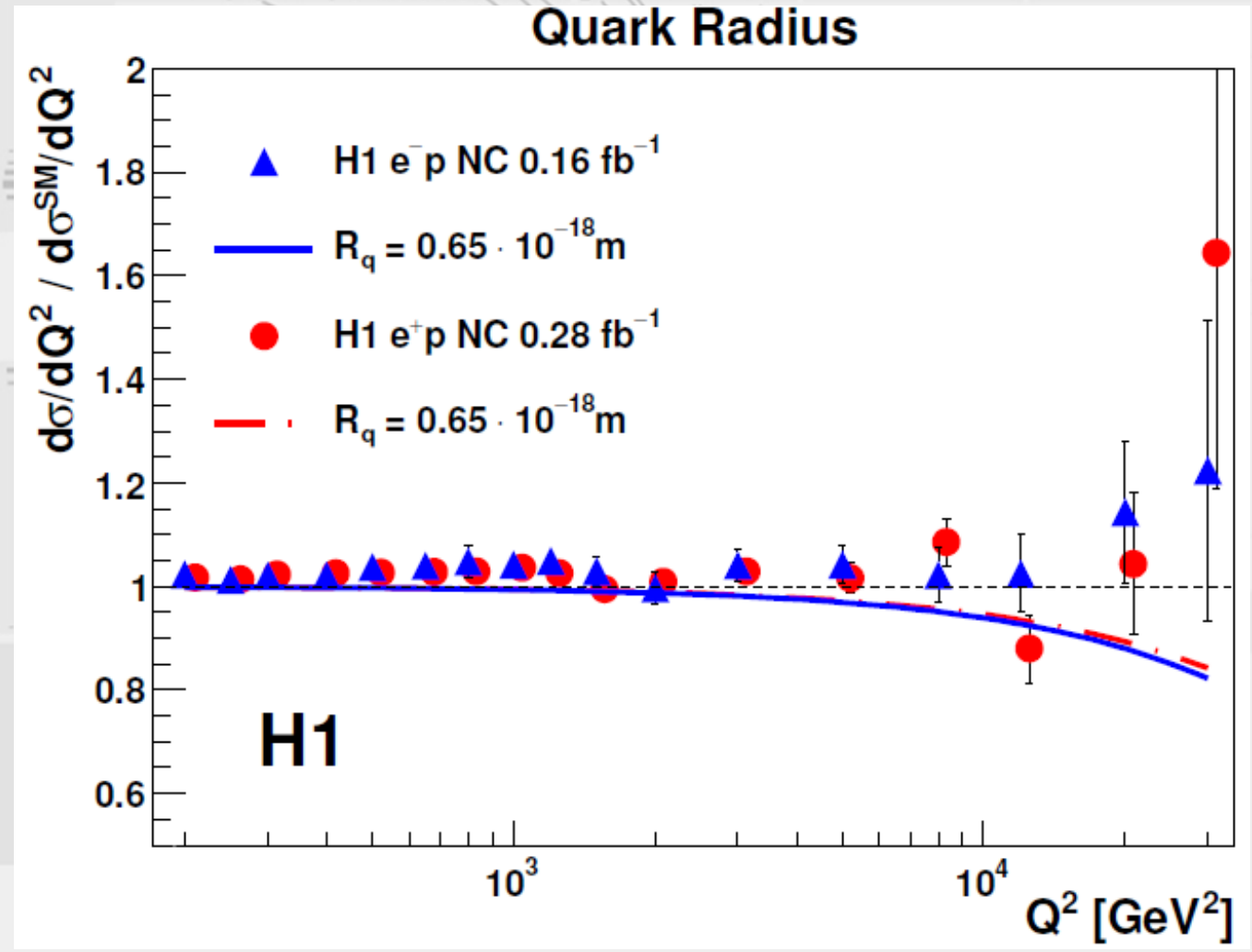

Shortest Distance

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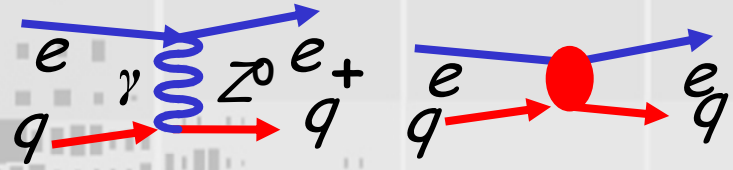
- beyond Dirac quark 

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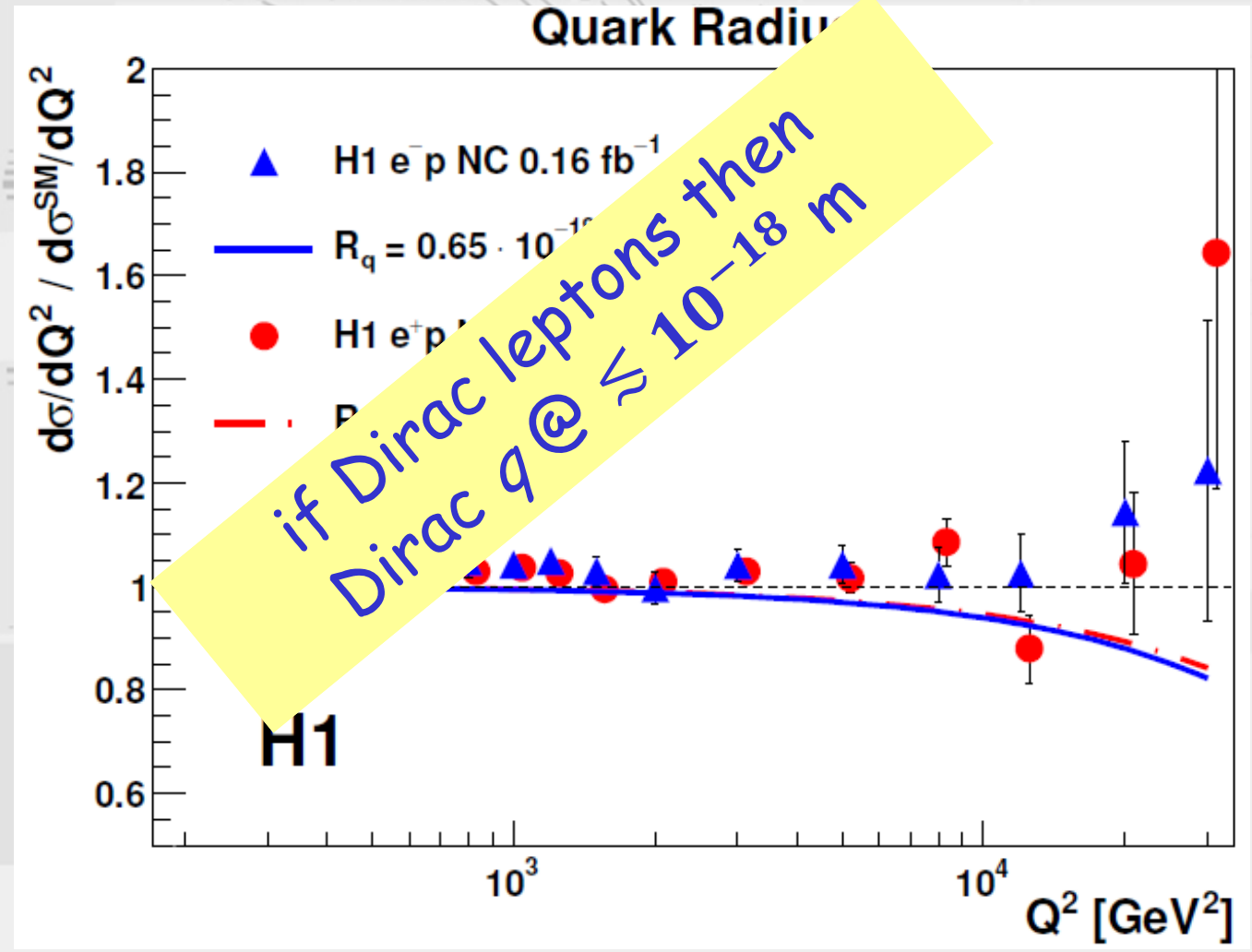

if Dirac leptons then
Dirac q @ $\lesssim 10^{-18}$ m

Landmarks

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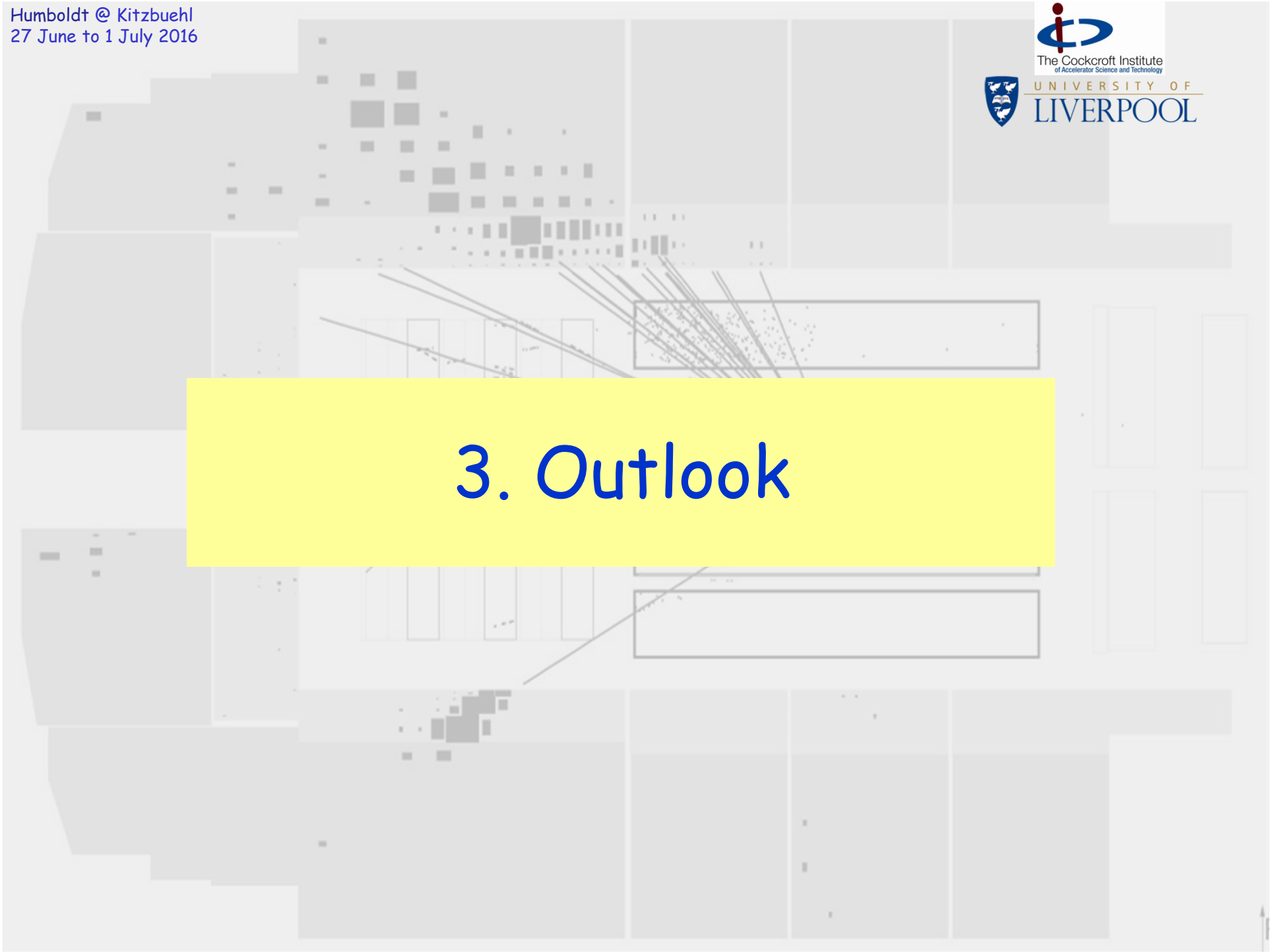
- discoveries reveal the landscape
- measurement defines the landmarks

"(The) history of science has shown that even during that phase of her progress in which she devotes herself to improving the accuracy of the numerical measurements of quantities long familiar, she is preparing the materials for the subjection of new regions, which would have remained unknown if she had been contented with the rough methods of her earlier pioneers."

James Clerk Maxwell

- landmarks signpost and define new discoveries
- paradigm hitherto:
  constituents, currents and colour



3. Outlook

With today's Paradigm ?

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- example: why leptons and quarks ?

THE UNCONFINED QUARKS AND GLUONS

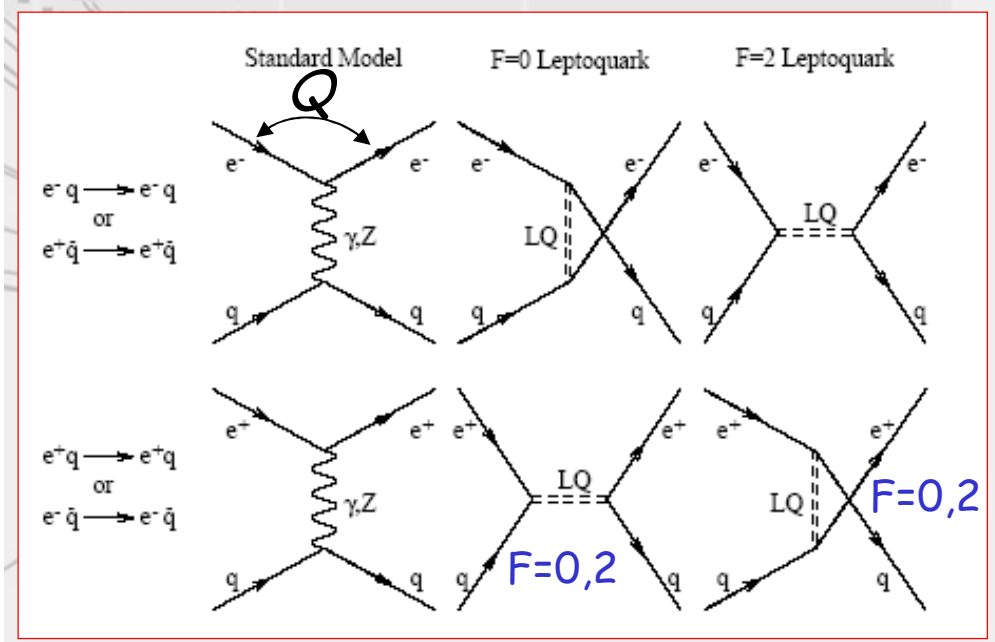
Abdus Salam

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



- further pursuit of landmarks
  - energy frontier
  - intensity frontier

Beyond today's Paradigm ?

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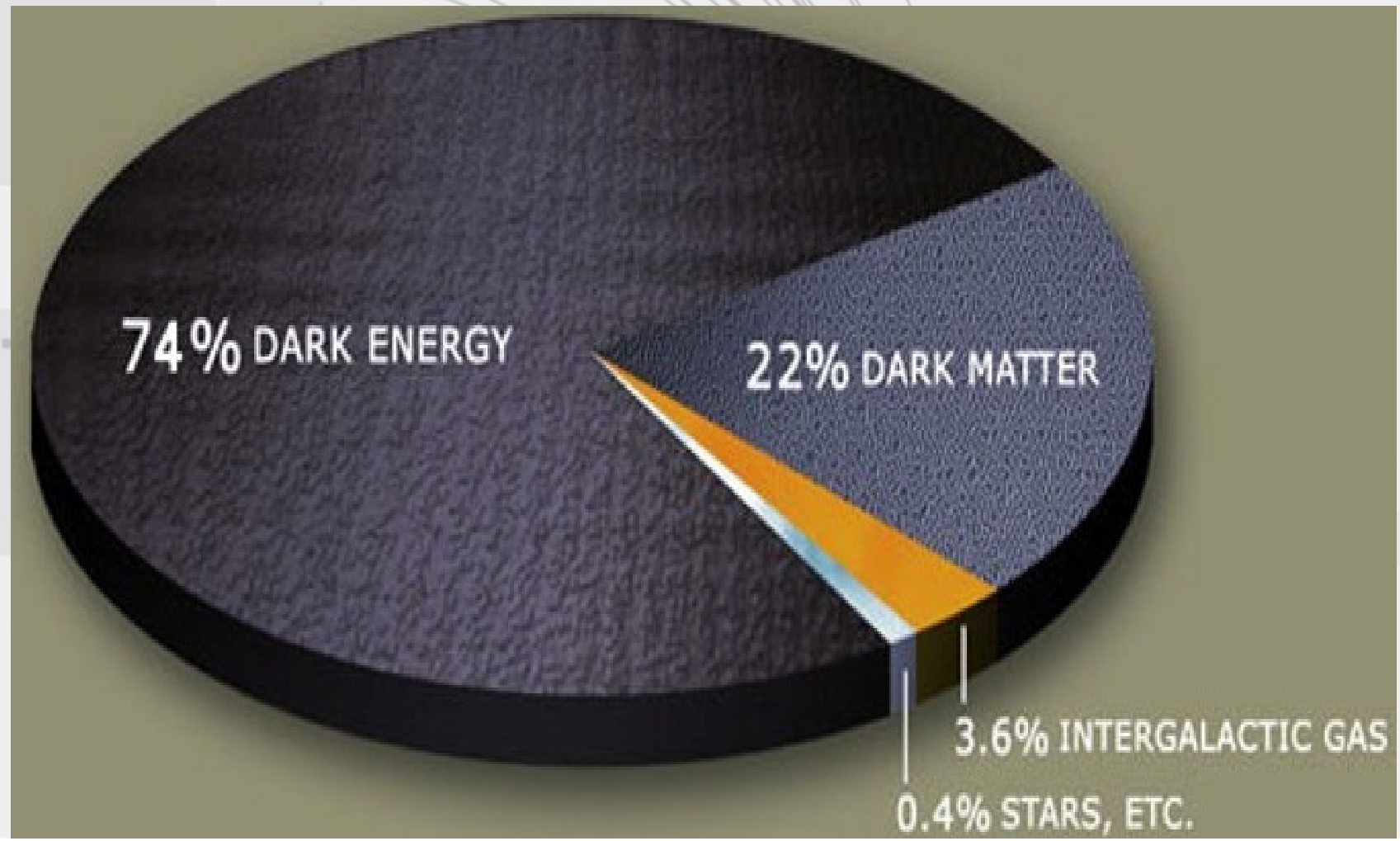
- dark constituents and dark currents ?
- beyond constituents and currents ?



Beyond 1947's Paradigm

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- Dirac 1928
  (n integer j $\frac{1}{2}$-integer)

$$E_{nj} = \frac{mc^2}{\sqrt{1+\left[\frac{1}{\hbar c}\left(\frac{Ze}{n-\left|j+\frac{1}{2}\right|}\right)^2+\sqrt{\left|j+\frac{1}{2}\right|^2-\frac{Z^2e^2}{\hbar c}}\right]^2}}$$

- Lamb-Retherford 1947
  - Dirac+3 ppm observed
  - 3 ppm = 1 GHz splitting

↳ relativity + electron + field quantisation → mode $E_\nu = \left(n+\frac{1}{2}\right)h\nu$

integer — "Zitterbewegung"

↳ relativistic quantum field