V7 – Electroweak measurements at HERA and LEP

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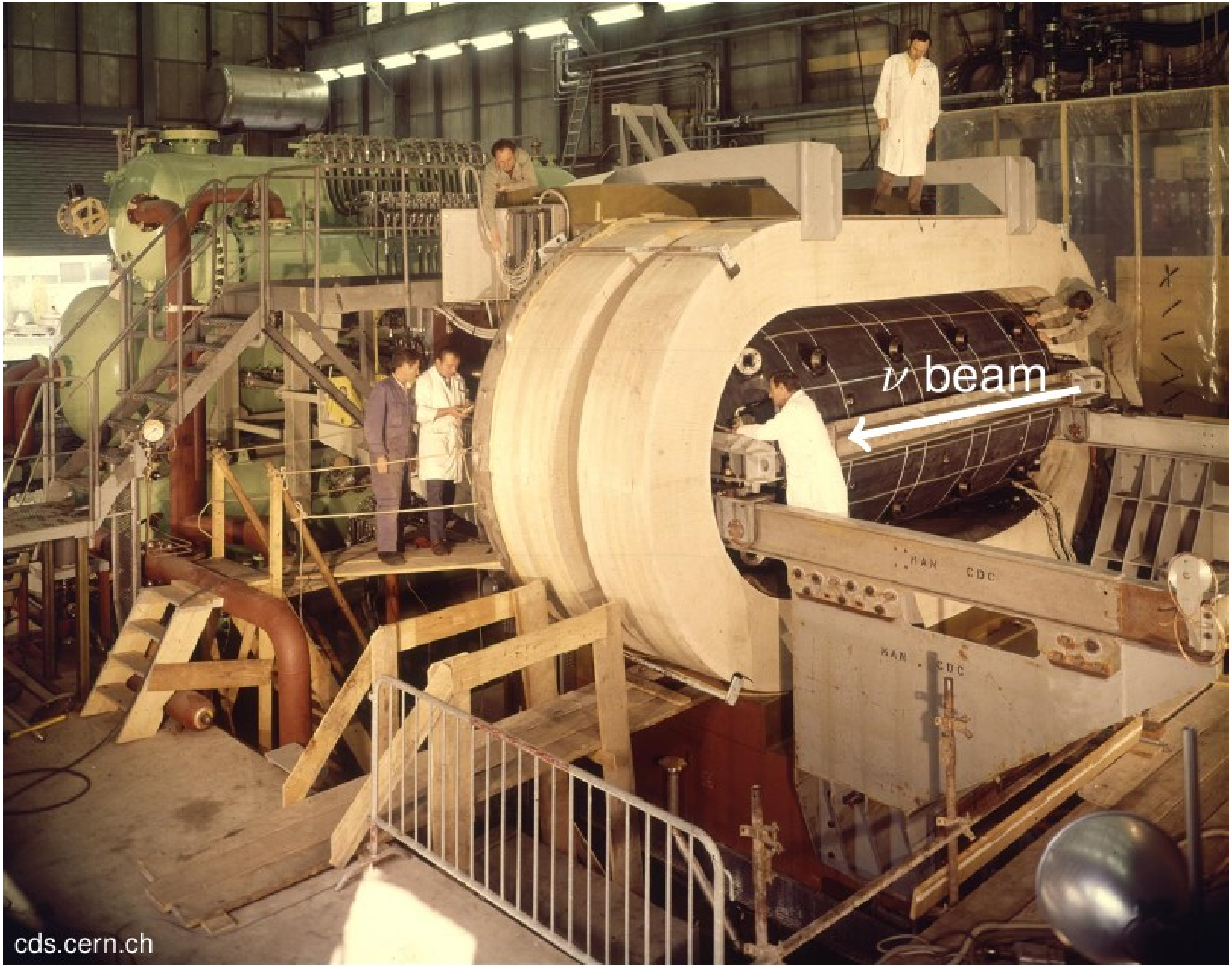
Gargamelle bubble chamber

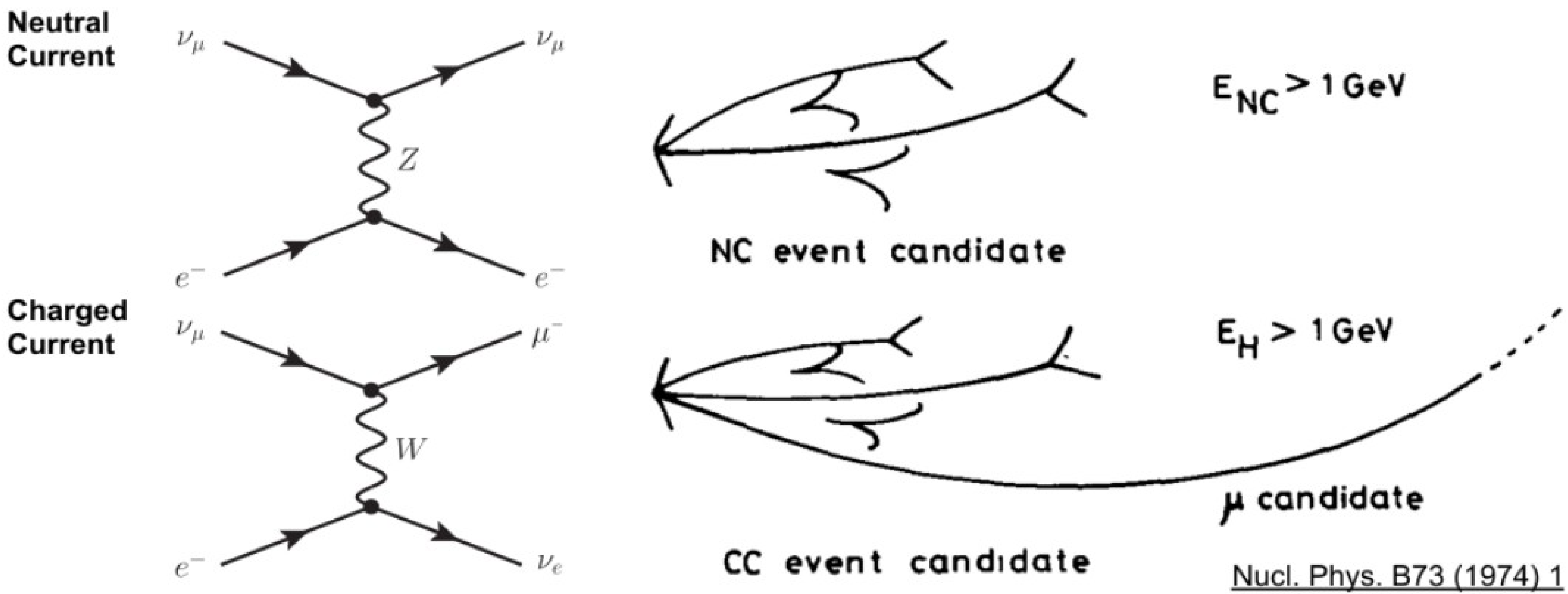
1973



Discovery of neutral currents

- Gargamelle: neutrino beam hits **heavy liquid** (freon)
- Neutrinos interact with **electrons** and atomic **nuclei**

1973

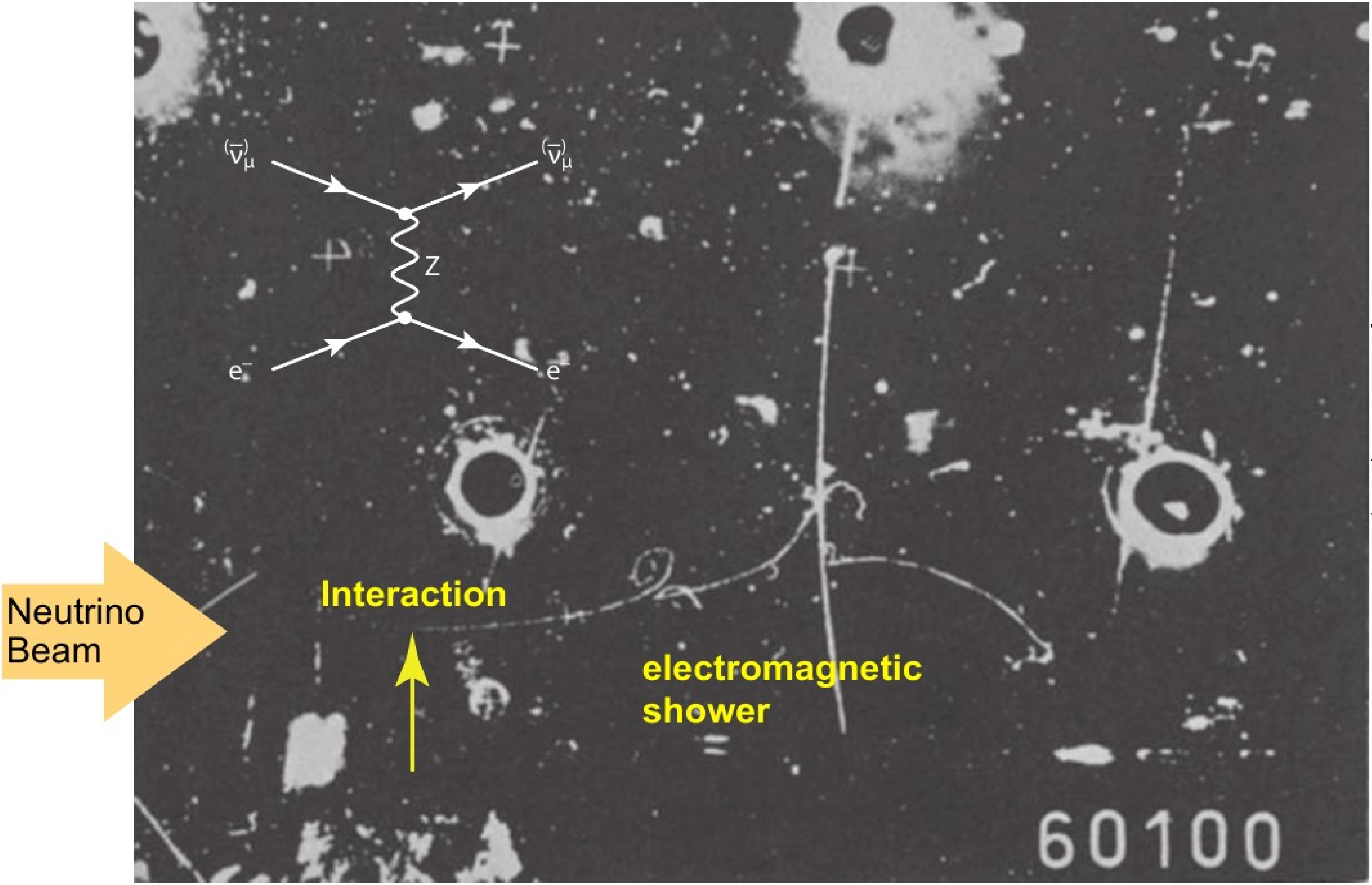


Nucl. Phys. B73 (1974) 1

- **Neutral-current** interaction: scattered electron $\rightarrow$ electromagnetic shower (bremsstrahlung and e^+e^- production)
- **Charged-current** interaction: muon in final state $\rightarrow$ long track

$\nu_\mu e$ neutral currents

1973



Phys. Lett. B46 (1973) 121

SppS collider at CERN

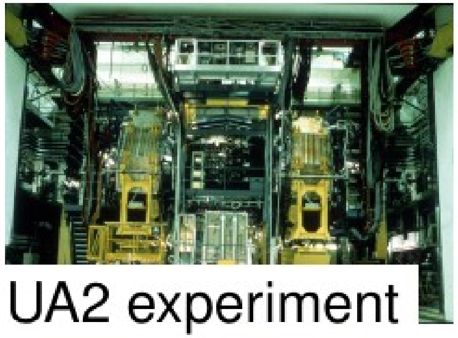
- $p\bar{p}$ collider reach
  - Momentum fractions of colliding valence (anti)quarks $x_1 \approx x_2 \approx 0.2$

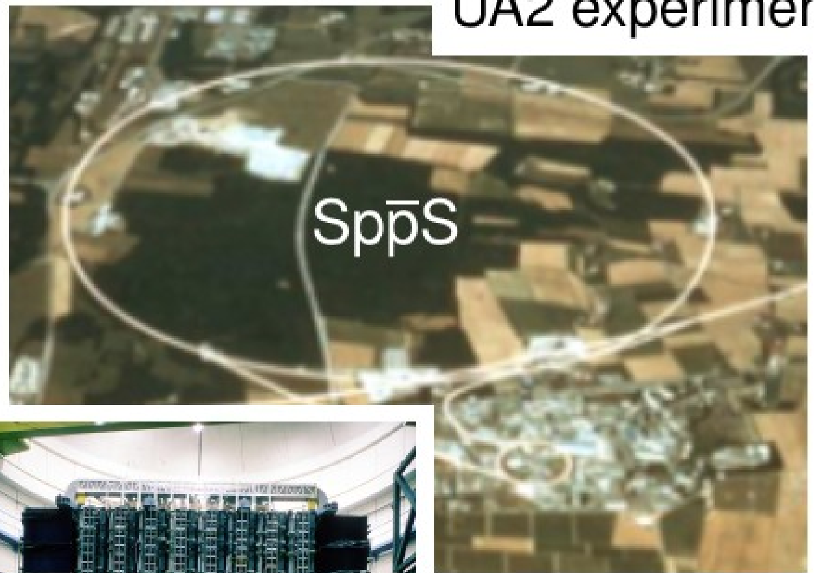
  $\rightarrow$ estimated E_{cms}: $\sqrt{\hat{s}} \approx \sqrt{x_1 x_2 s} \stackrel{!}{=} 100\,\mathrm{GeV} \rightarrow \sqrt{s} = 500\,\mathrm{GeV}$
- SPS (Super Proton Synchrotron) at CERN
  - 6.9 km circumference
  - 400 GeV protons

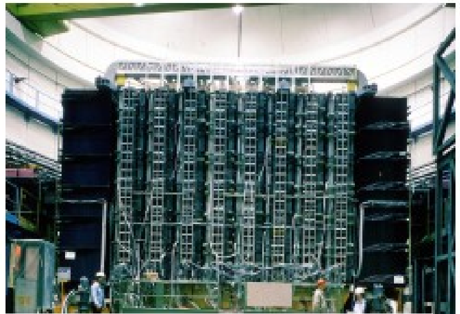
  Idea (C. Rubbia, 1976): upgrade to a $p\bar{p}$ collider

$Sp\bar{p}S$

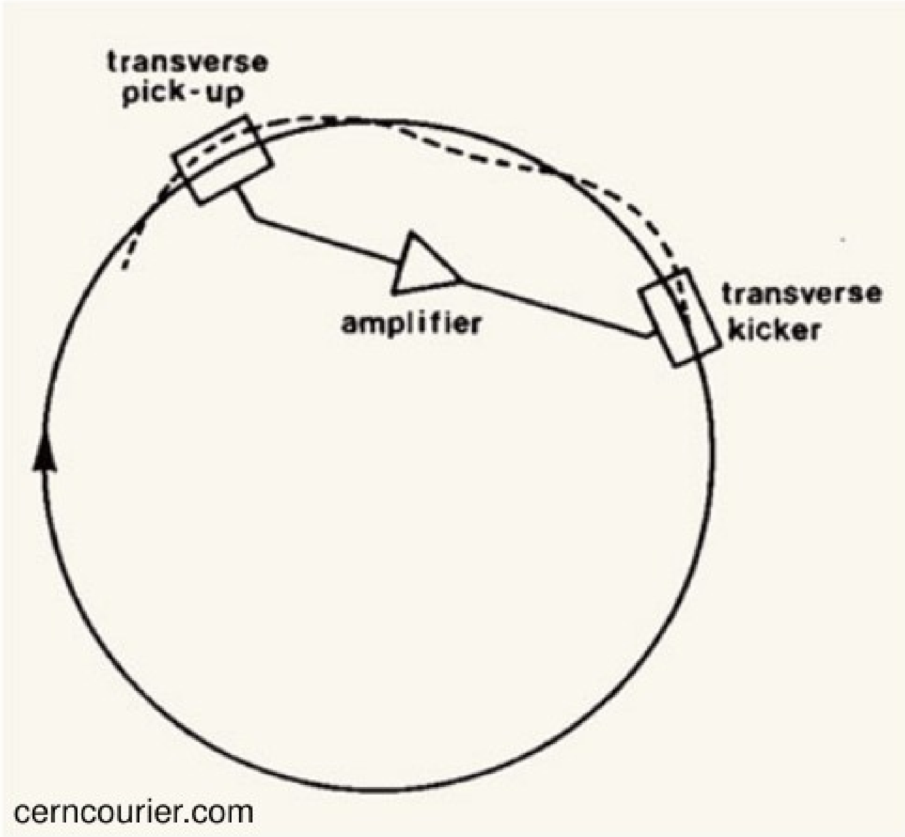
- $E_{\mathrm{cms}} = 540\,\mathrm{GeV}$ initially later upgrade to 630 GeV
- UA1 and UA2 experiments data taking from 1981


UA2 experiment




UA1 experiment

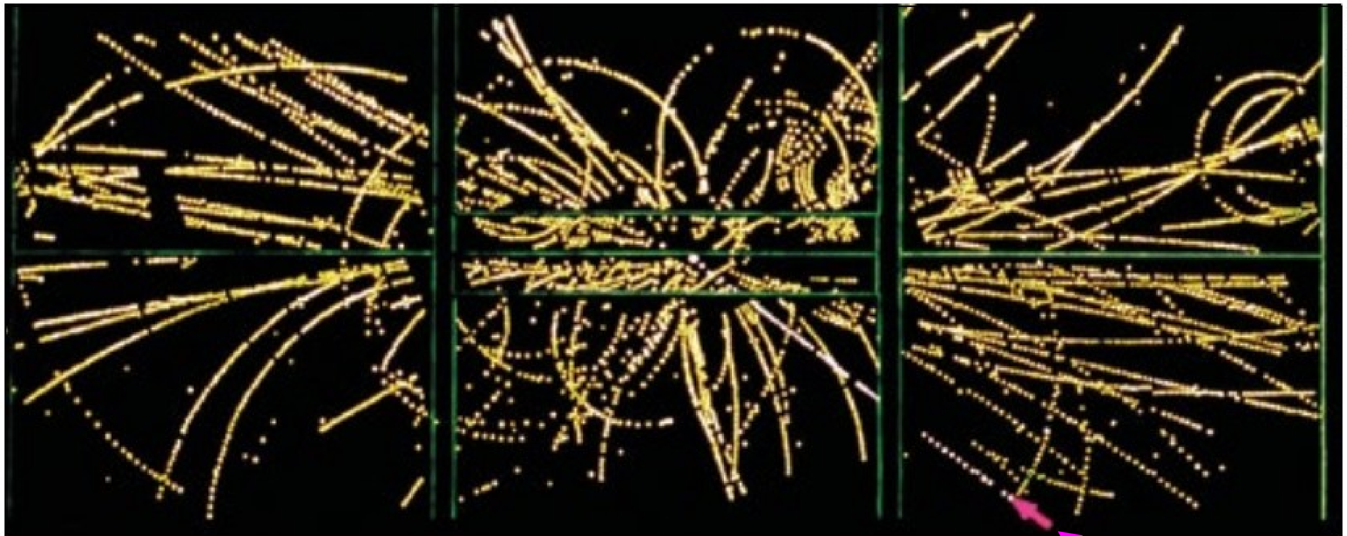
- **Antiprotons**
  - p beam on target: approximately 1 $\bar{p}$ in 10^9 final-state particles
  - Very large **emittance** of $\bar{p}$ beam: reduction without violating Liouville's theorem?
  - Solution (S. van der Meer, 1968): **stochastic cooling**[1] with pick-up and kicker
- Further challenges
  - p and $\bar{p}$ share **same beam pipe**
  - **Hermetic** 4π **detectors** for the first time at hadron colliders



[1] Details e. g. Nucl. Instrum. Meth. A532 (2004) 11

Discovery of the W boson (1983)

- Again nice nistorical perspective in article to celebrate this year the 40$^{\text{th}}$ anniversary of W discovery at CERN
  - Must find charged and neutral weak bosons
  - C. Rubbia initiated SppS with second "p" really an anti-proton!
  - Two experiments: UA1 and UA2; January 1983: 4 and 6 candidates
  - No imaginable background



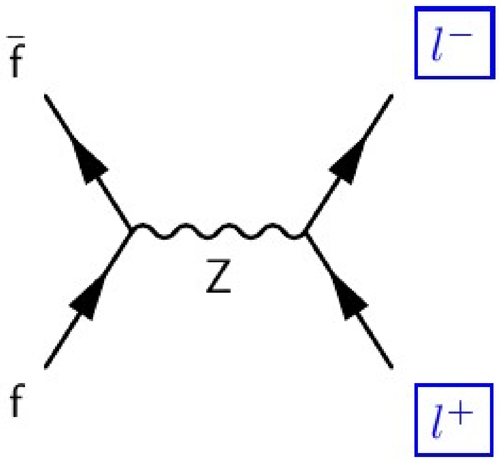
CERN-EX-69576-1

Striking *A W event recorded by UA1 in late 1982, with a high transverse-momentum electron (pink arrow) and only soft particles in opposite directions to it, as expected if an undetected neutrino balances the electron's transverse momentum.*

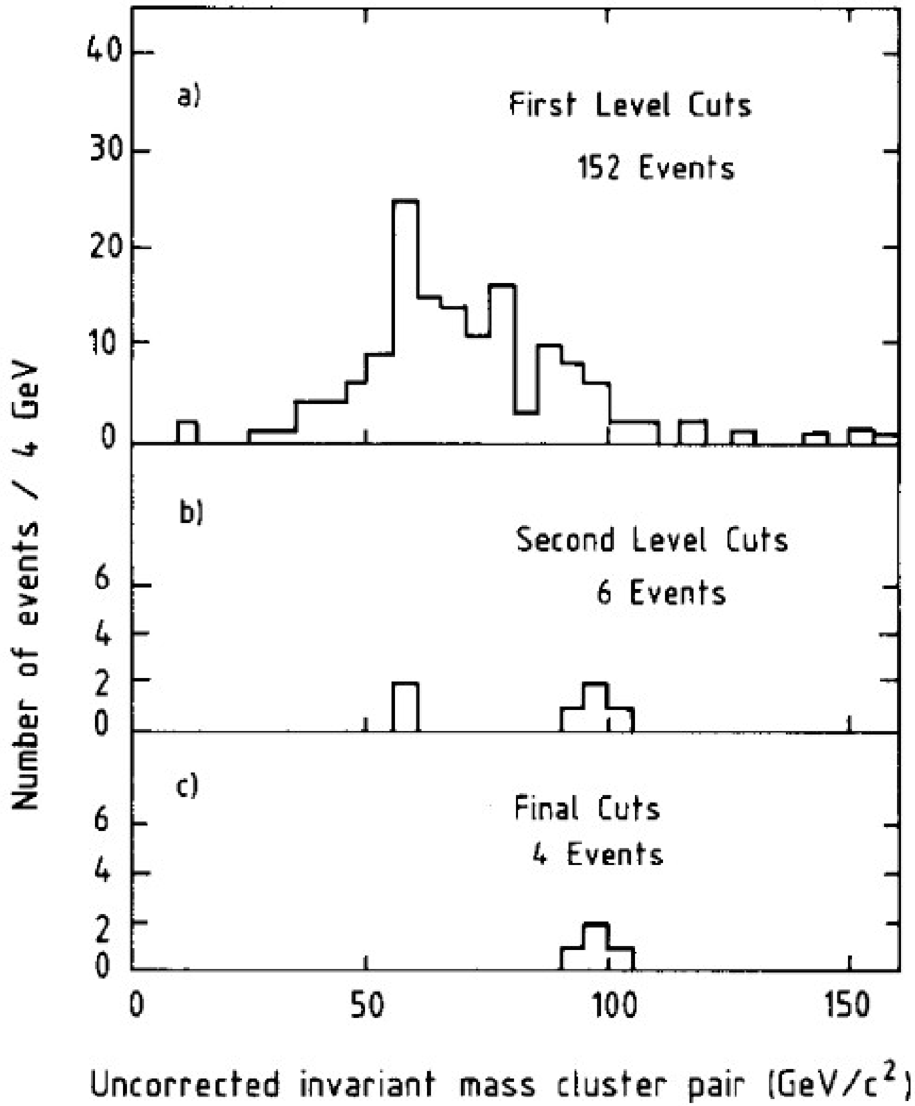
L. Di Lella in CERN Courier Vol. 63 no. 1, Jan/Feb 2023.

Discovery of the Z boson (1983)

- Process $\mathrm{p\bar{p}} \to \mathrm{Z} \to l^+ l^-$ $(l = e, \mu)$



- Analysis strategy: **charged leptons**
  - **Invariant mass** of lepton pair
  - Depends on lepton momenta and opening angle (lepton masses neglected)



Phys. Lett. B126 (1983) 398

$$m_Z^2 \approx 2 \cdot |\vec{p}_{l^+}| \cdot |\vec{p}_{l^-}| \cdot (1 - \cos\phi_{l^+ l^-})$$

Events at CERN

- **Scientific seminar this year at CERN: 31.10.2023**
  - **Celebrate 50 years of discovering neutral currents with Gargamelle**
  - **Celebrate 40 years of discovering W and Z bosons at SppS**

- **Before: Official inauguration of new Science Gateway: 07.10.2023**

Architect R. Piano & CERN DG F. Gianotti

HERA Collider at DESY

HERA: 1992 – 2007

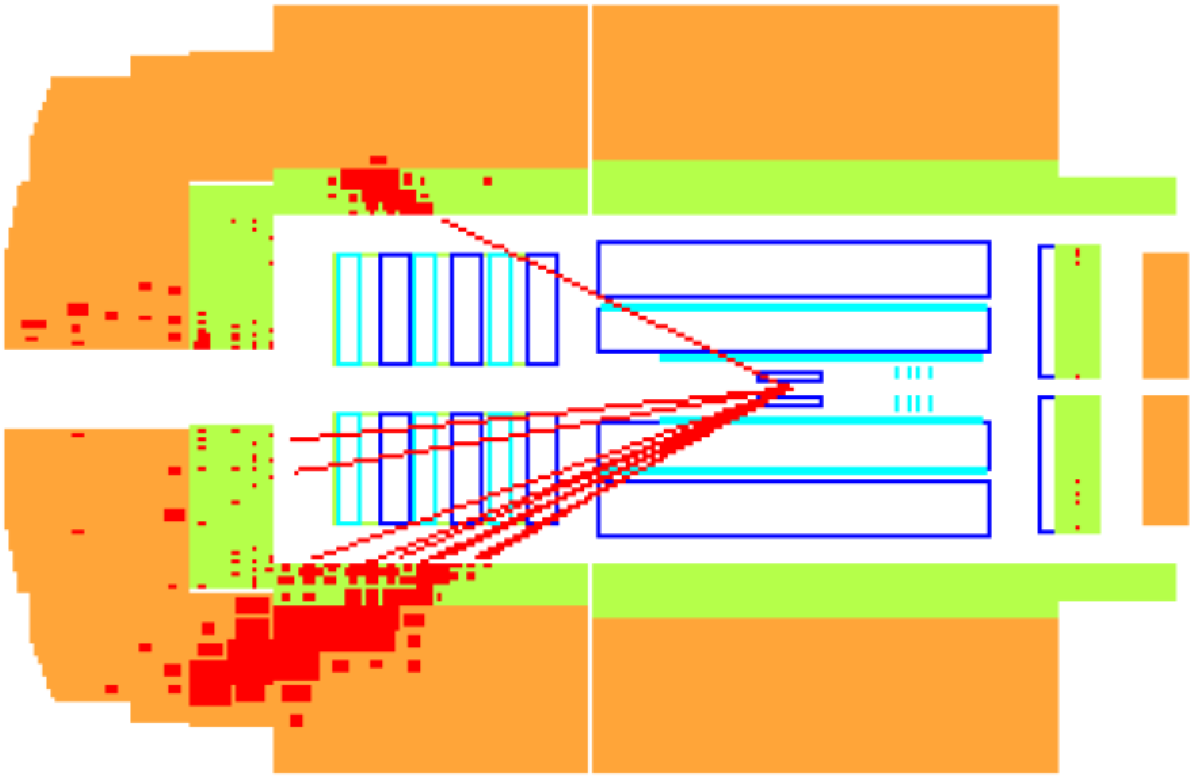
Collisions of e^+-p, e^--p

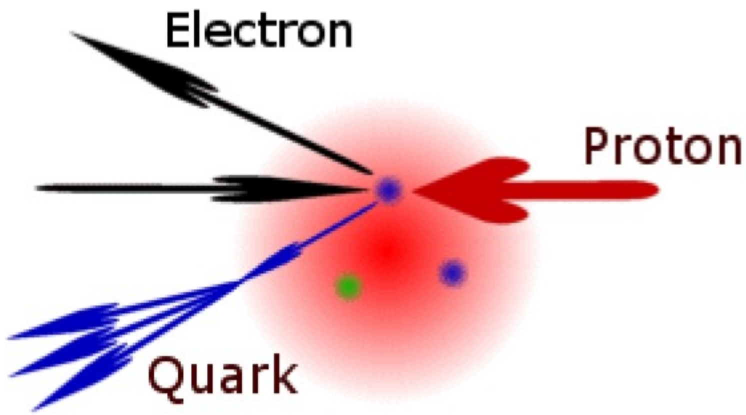
HERA II: E_{cms} = 319 GeV

Electromagnetic reaction:

Backscattering of electron off charged proton constituent

H1 Detector





H1 Event Tutorial, J Meyer, DESY (2005)

DIS kinematics

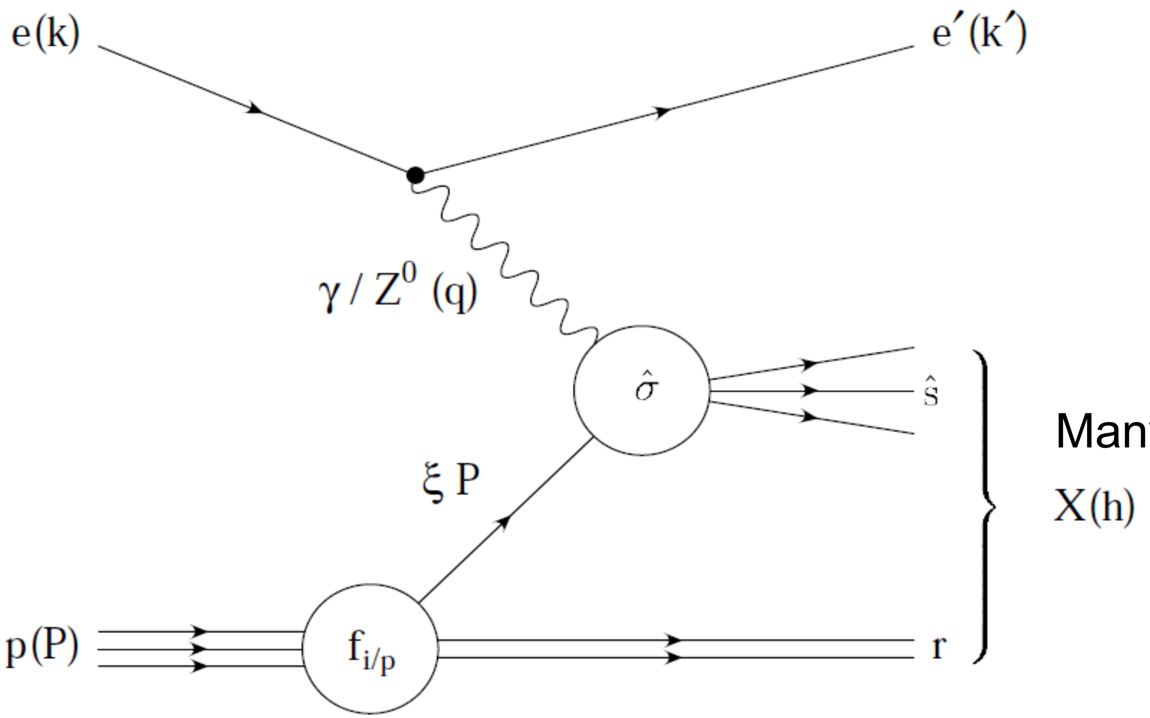
Neglect electron and proton masses: $M_p = M_e = 0$

Center-of-mass energy: $s = (k+P)^2 = 2k \cdot P = 4E_e E_p$

Elastic → one independent variable:

$$Q^2 = -q^2 = (k-k')^2 = 2k \cdot k' = 2E_e E_{e'}(1+\cos(\theta_{e'}))$$

Deep-inelastic scattering (DIS)



Inelastic → 2nd variable:

$$W^2 = (q+P)^2 = 2P \cdot q - q^2$$

Alternative:

Bjorken scaling variable: $x = \dfrac{Q^2}{2P \cdot q}$

Inelasticity: $y = \dfrac{P \cdot q}{P \cdot k}$

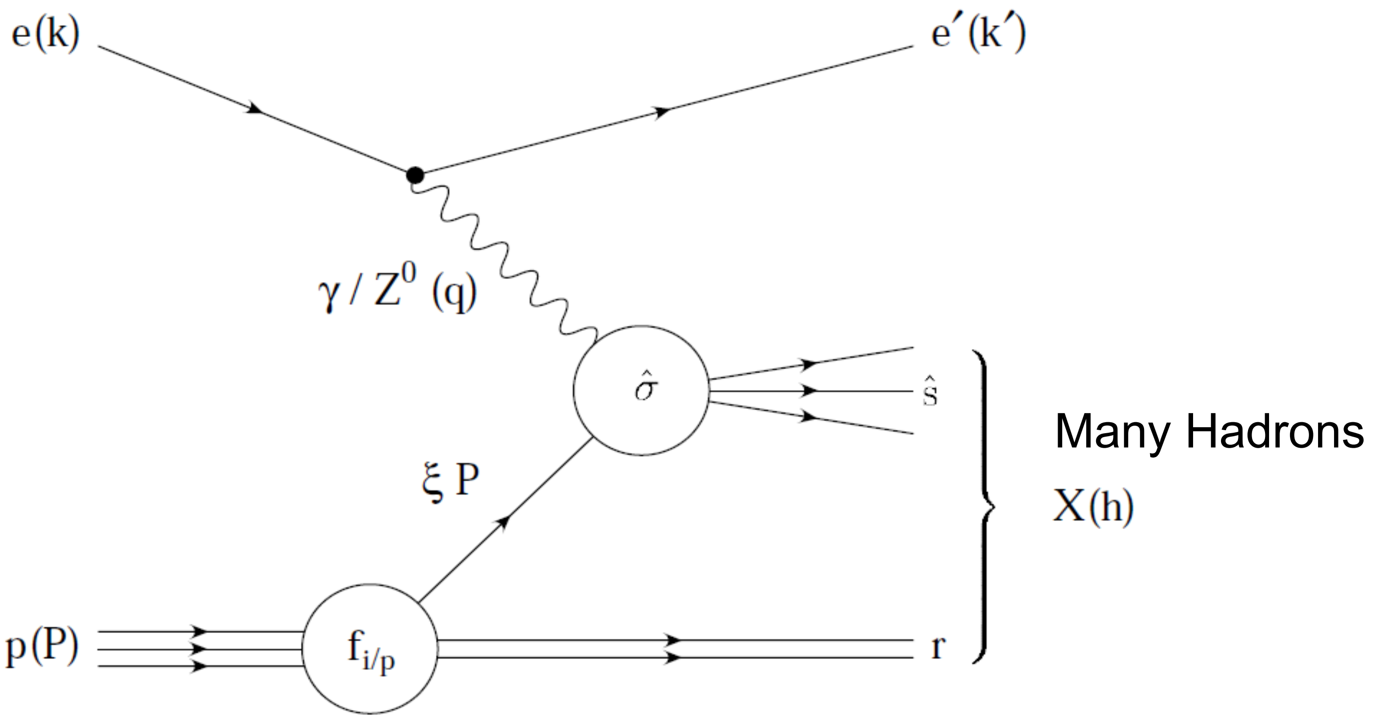
$$0 \leq (x, y) \leq 1$$

Infinite momentum frame

Proton equals collinear stream of fast moving "partons", masses negligible
→ factorised incoherent partonic scatter

$$\hat{s} = (q + \xi P)^2 = 2\xi q \cdot P - Q^2 = \left(\frac{\xi}{x} - 1\right) Q^2$$

Deep-inelastic scattering (DIS)



$$x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

$$0 \leq (x, y) \leq 1$$

Infinite momentum frame

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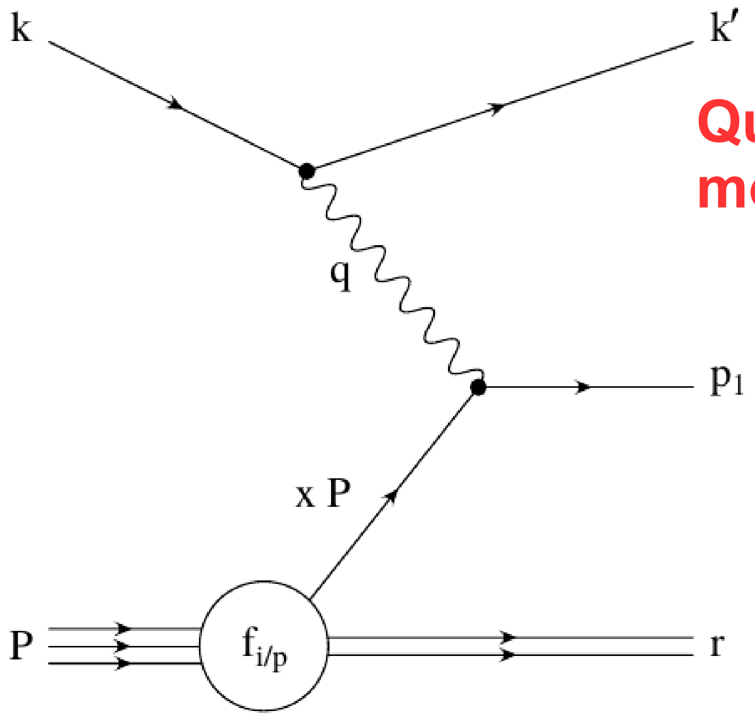
→ factorised incoherent partonic scatter

$$\hat{s} = (q + \xi P)^2 = 2\xi q \cdot P - Q^2 = \left(\frac{\xi}{x} - 1\right) Q^2$$

Deep-inelastic scattering (DIS) at LO $\hat{s} = 0 \rightarrow \xi = x \qquad \xi = \left(1 + \frac{\hat{s}}{Q^2}\right) x$



One parton

Quark parton model (QPM) → scaling variable x: momentum fraction of struck parton in proton

$$x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

$$0 \leq (x, y) \leq 1$$

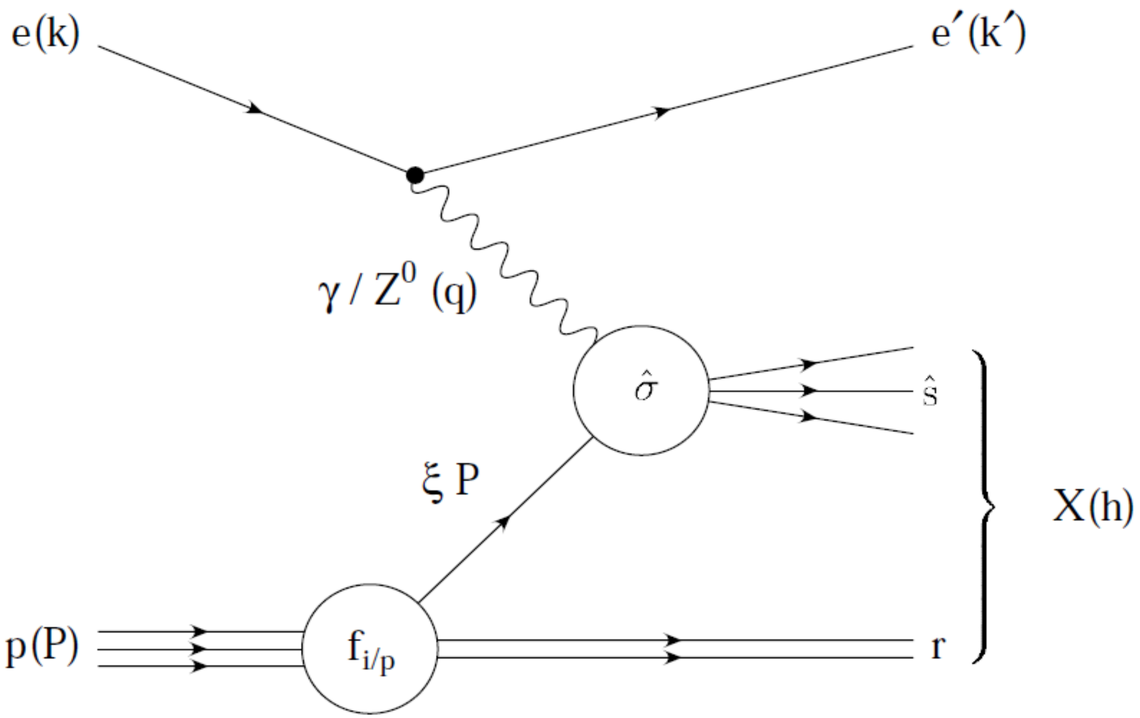
Target rest frame

Inelasticity y is relative energy loss of electron in target rest frame:

$$y = \frac{E_e - E_{e'}}{E_e}$$

Only two of the four invariant variables are independent!

Deep-inelastic scattering (DIS)



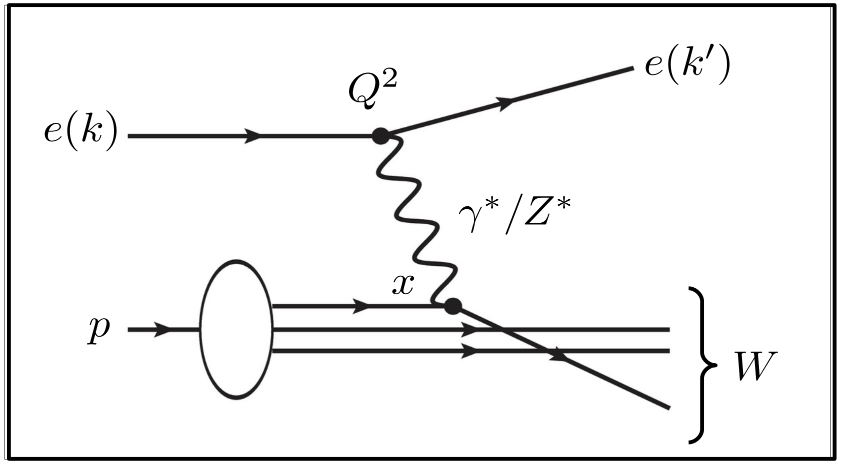
Conversion formulae

$$x = \frac{Q^2}{Q^2 + W^2} \qquad y = \frac{Q^2 + W^2}{s}$$

$$Q^2 = sxy \qquad W^2 = s(1-x)y$$

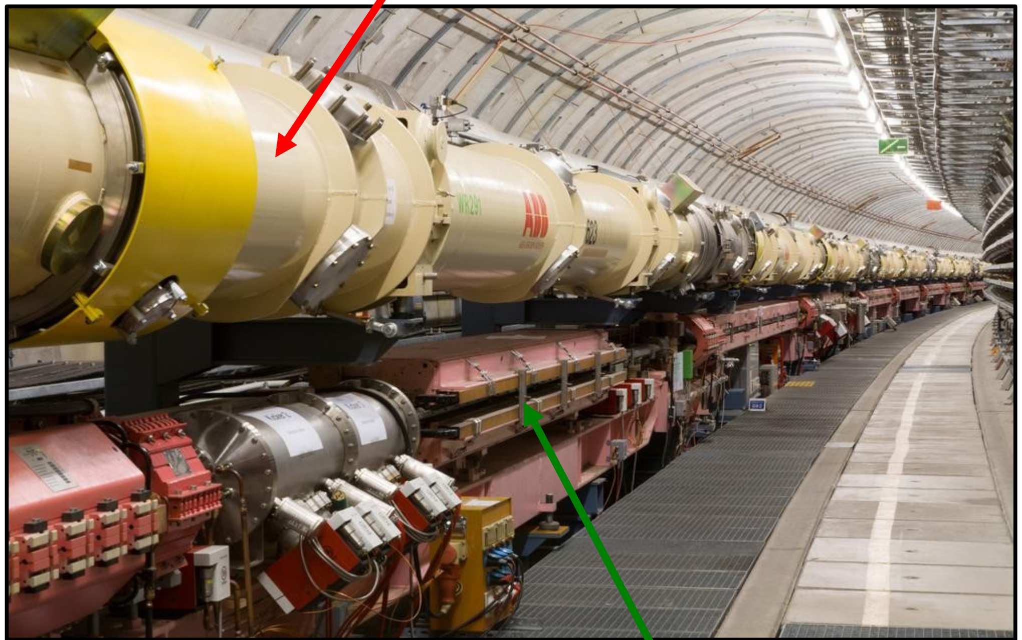
Neutral current DIS

- **HERA e-p collider at DESY**
  - 3 km circumference
  - 27.5 GeV e± on 820 or 920 GeV protons
  - 2 large omni-purpose detectors H1 and ZEUS



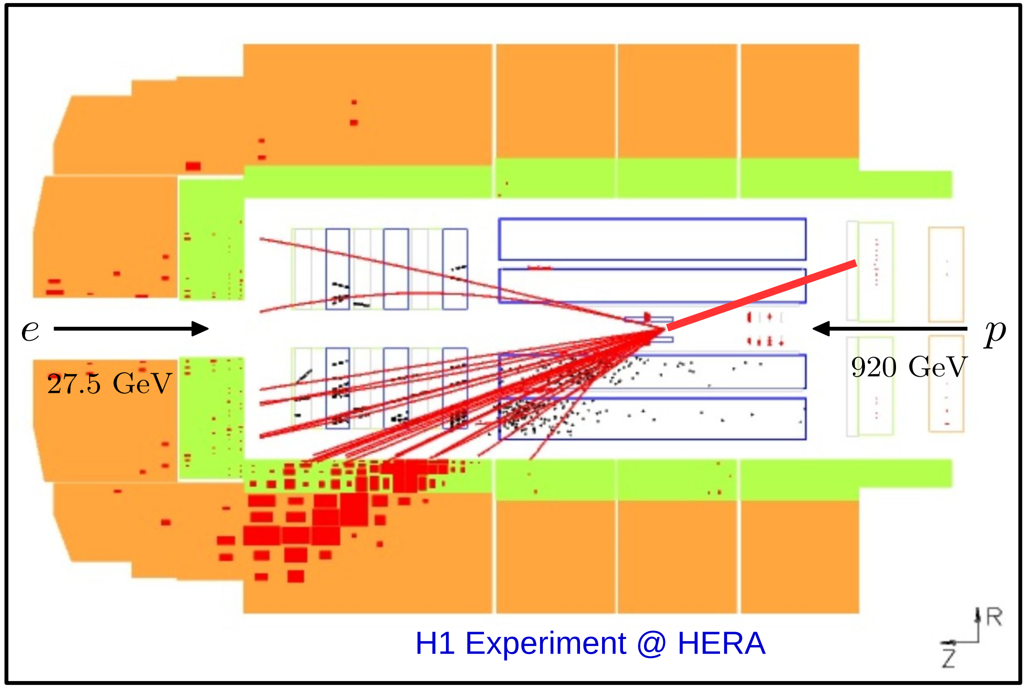
NC DIS: photon exchange

supraconducting: p



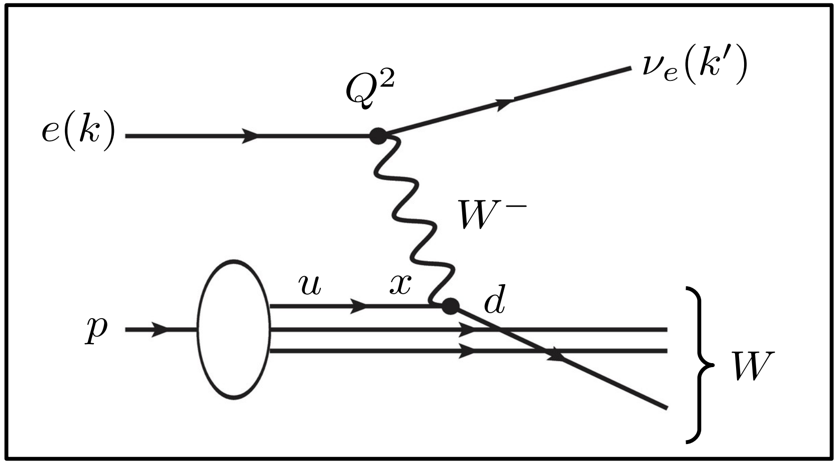
HERA tunnel with magnets

normalconducting: e

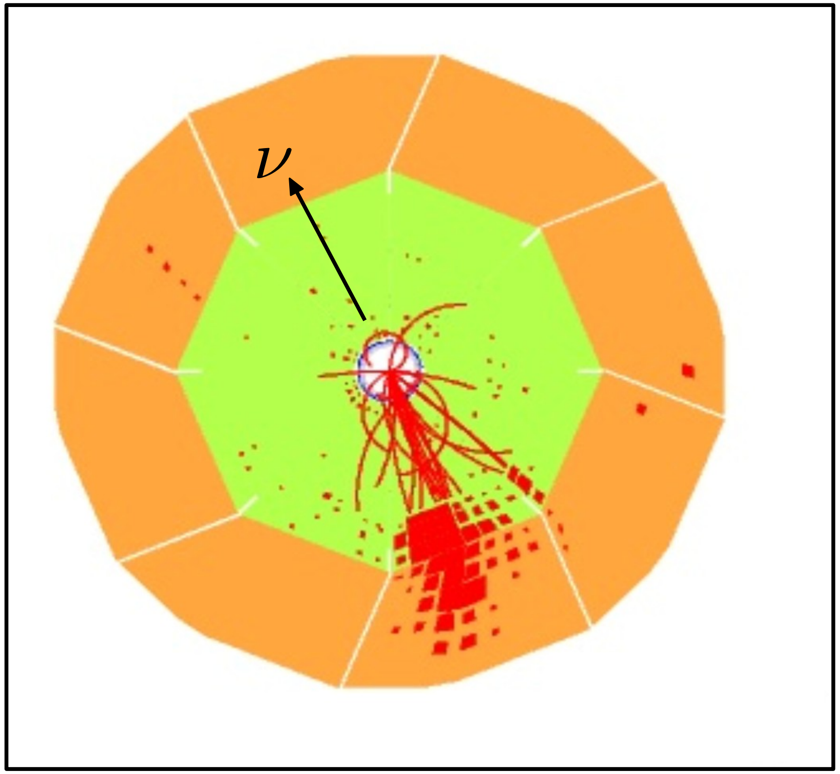


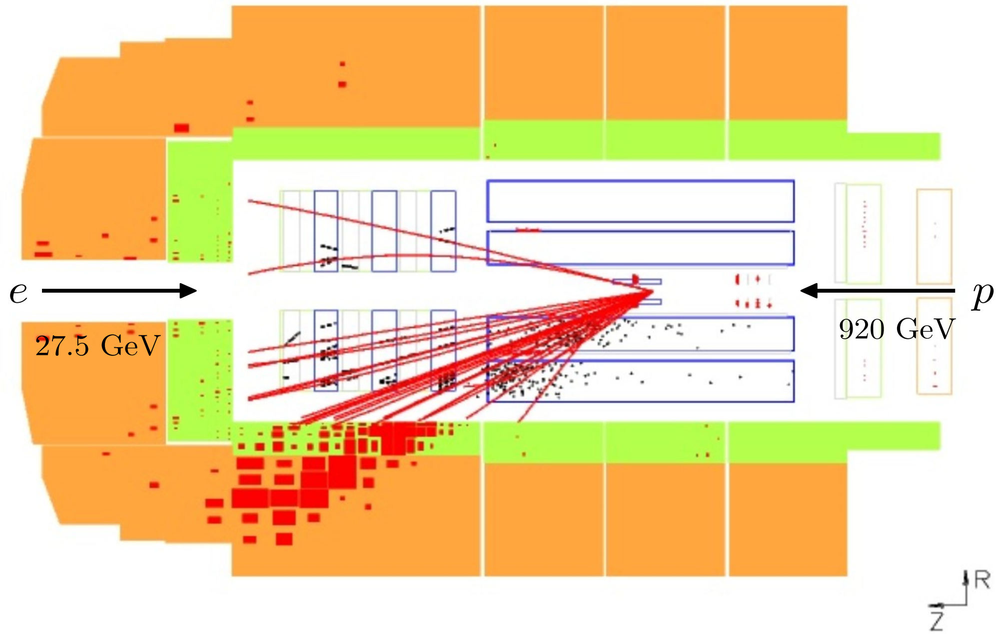
Charged current DIS

- **Exchange of charged boson $W^{\pm}$**
  - **Changes charge and flavour**
  - **Neutrino escapes undetected**
  - **Clear signature of missing transverse energy**



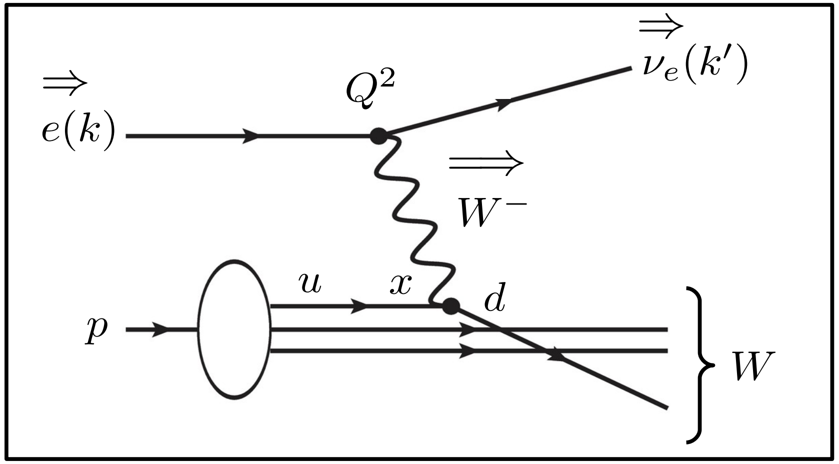
CC DIS: W exchange

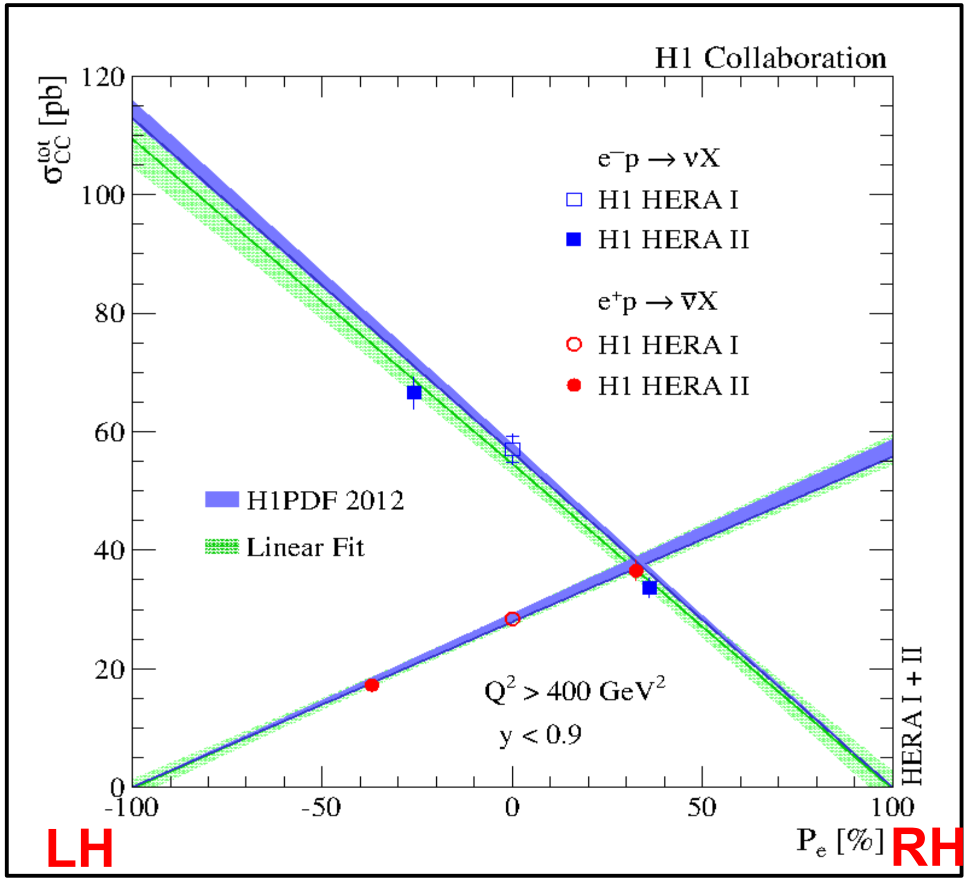




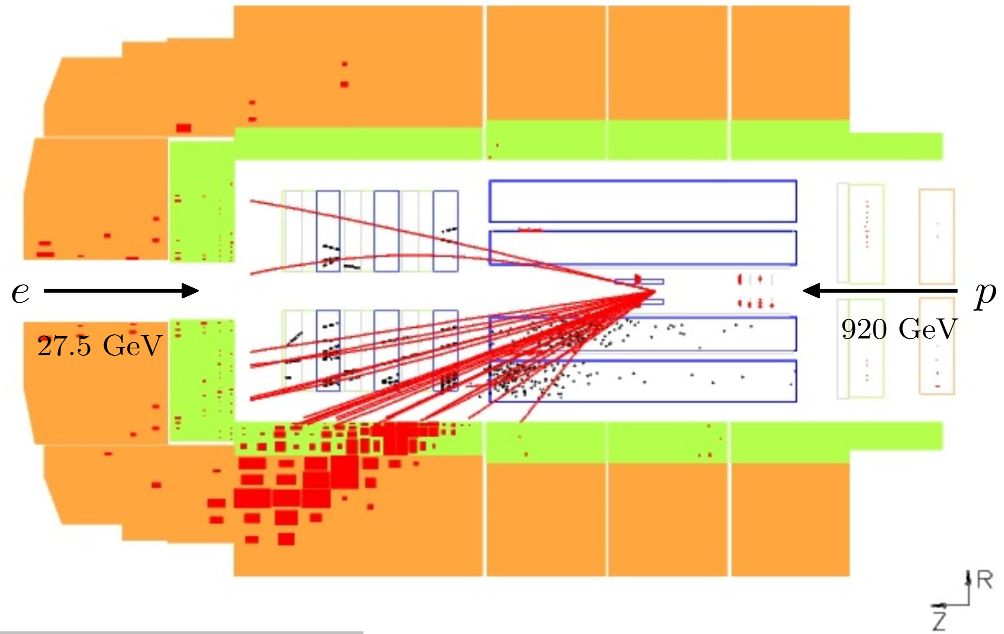
Maximally parity violating

- **Exchange of charged boson $W^\pm$**
  - **W^- couples to left-handed ν_e**
  - **W^+ couples to right-handed anti-ν_e**
  - **HERA provided partially polarised beams of electrons and positrons**



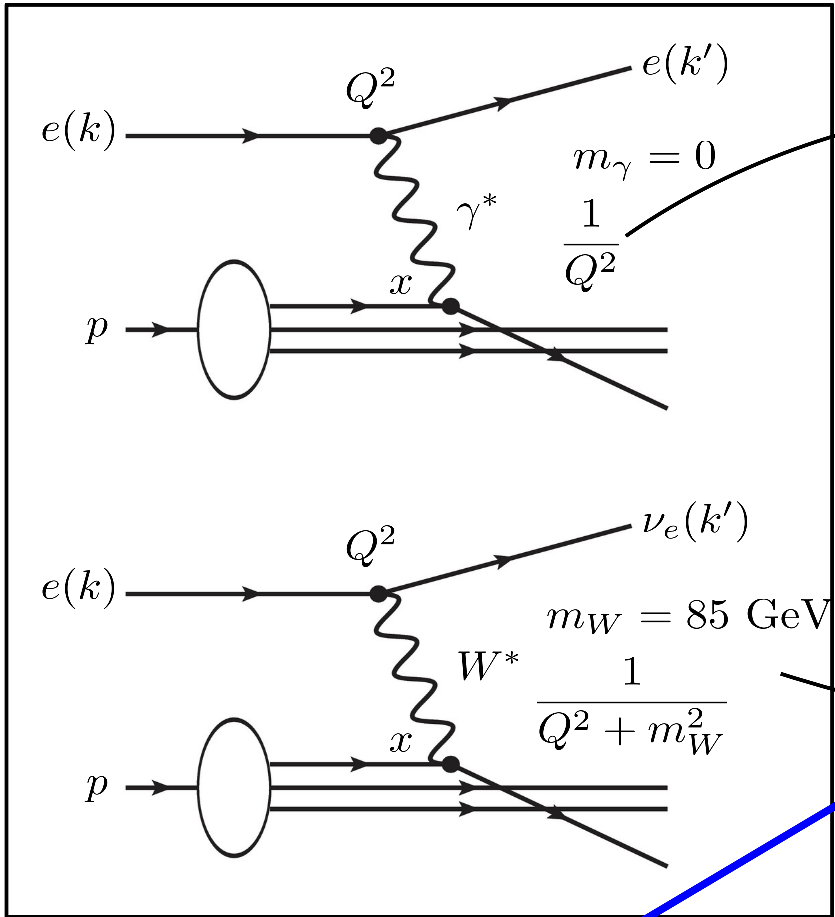


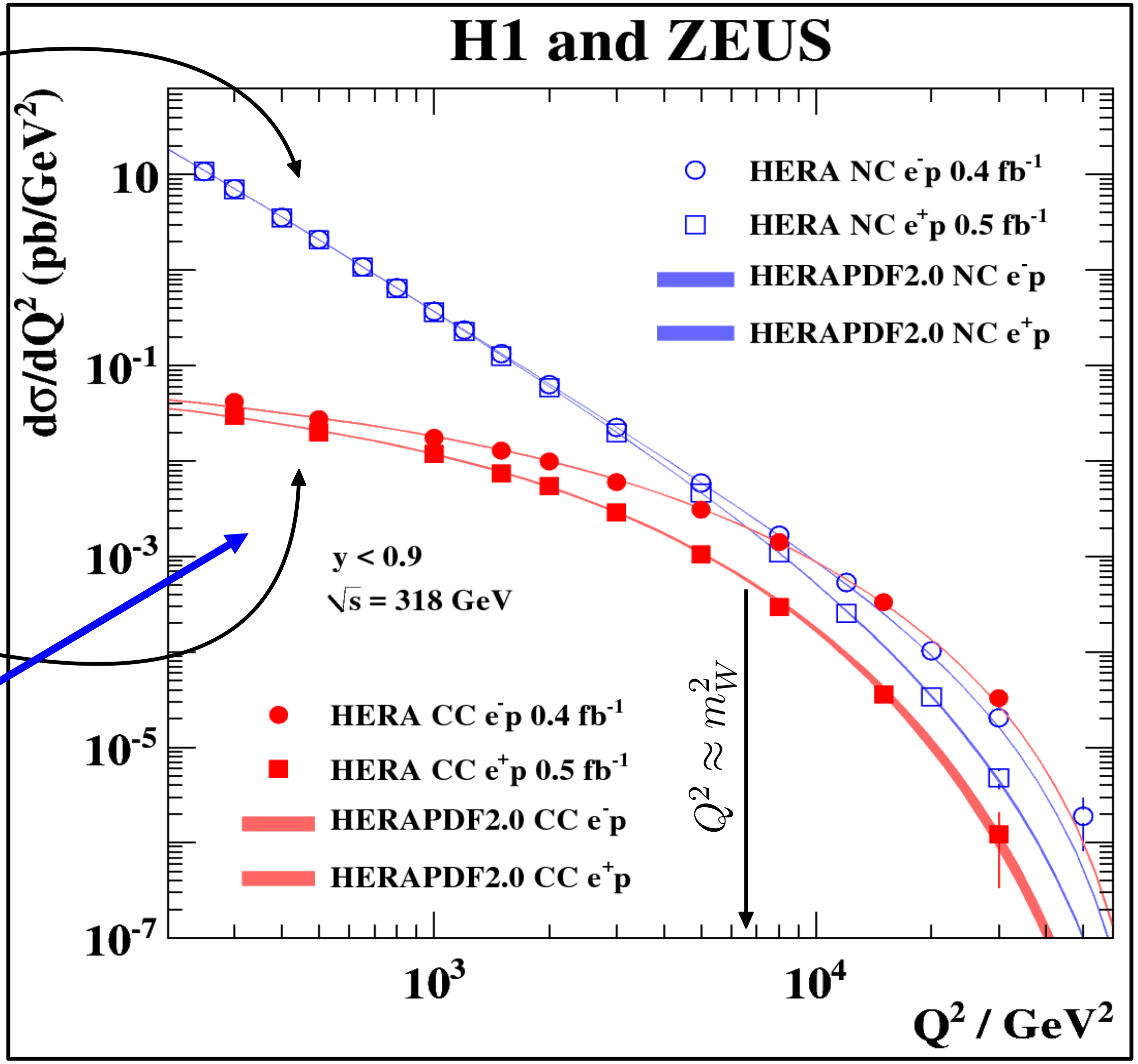
W^- couples to left-handed ν_e



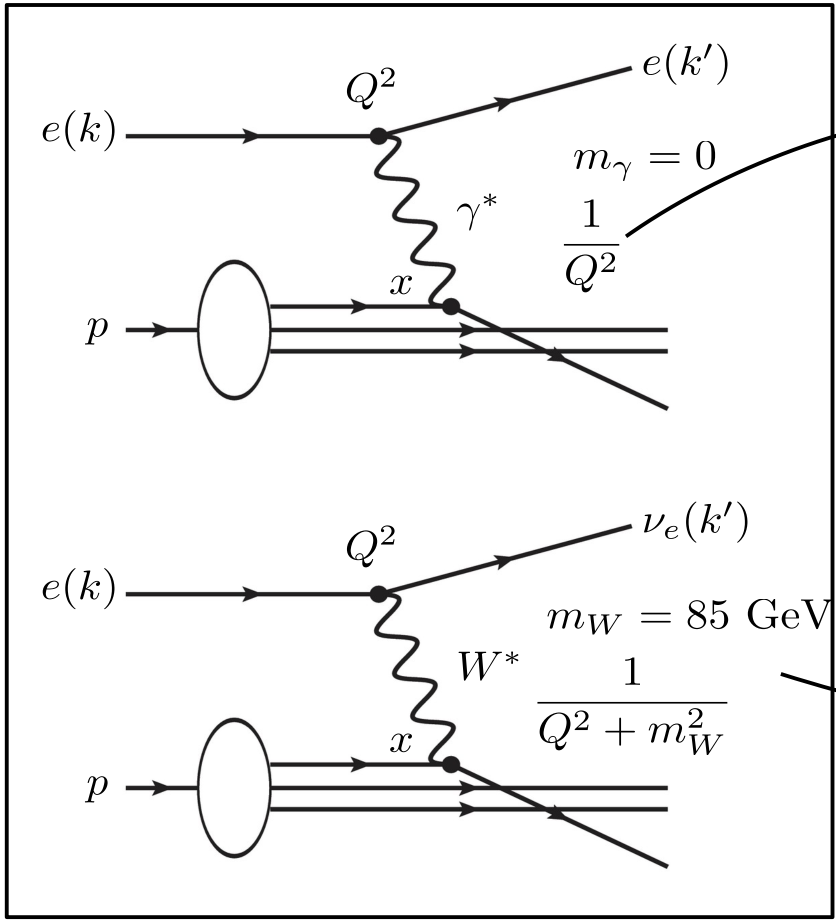
H1, JHEP09 (2012) 061.

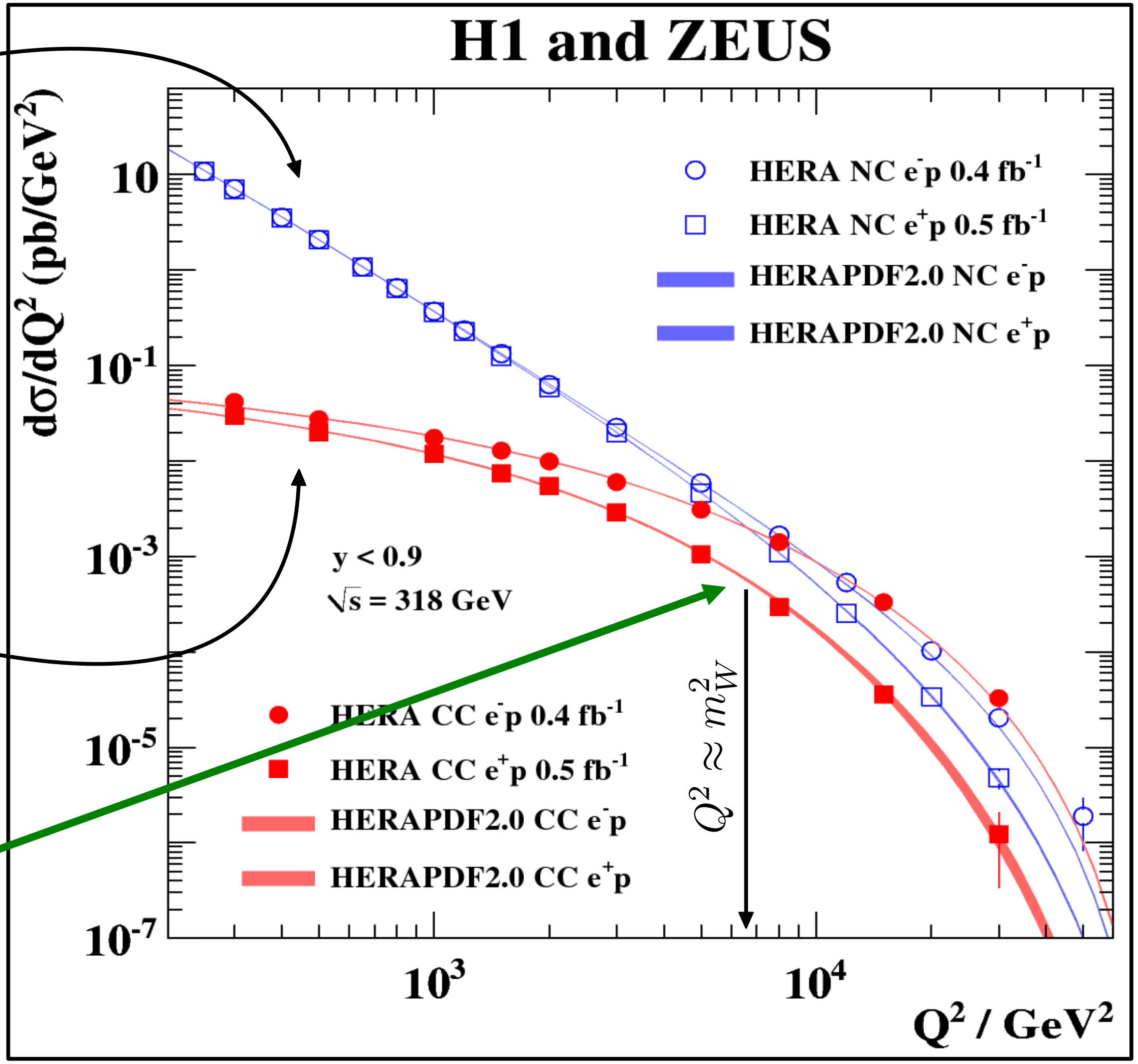
CC and NC cross sections





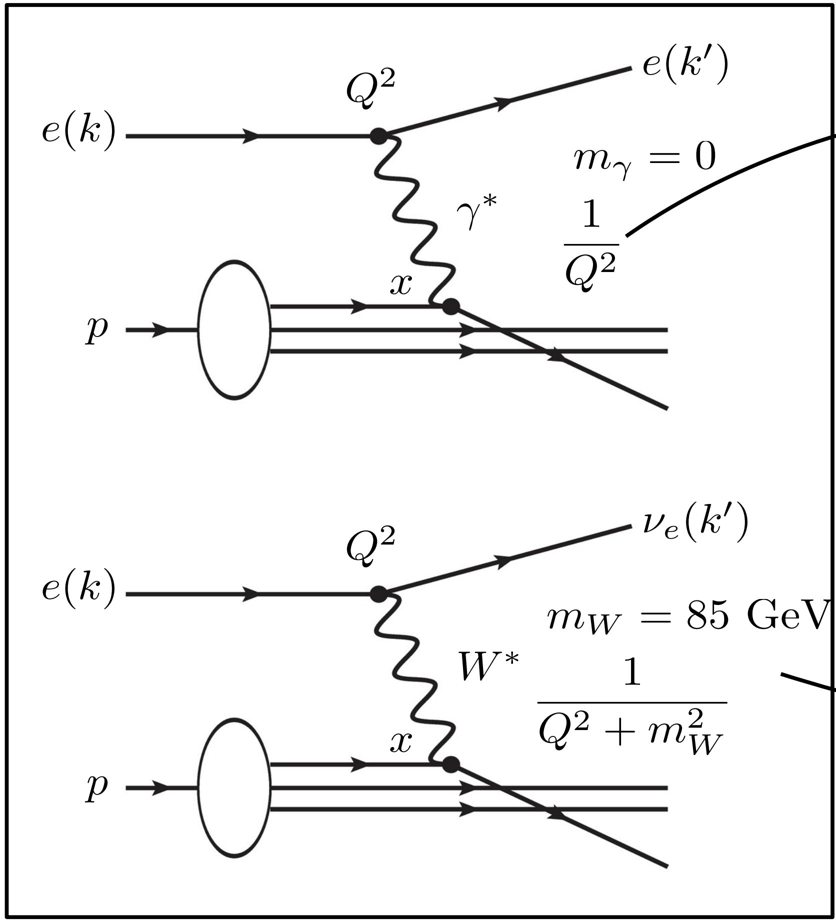
Low Q²: CC almost constant dominated by factor $1/m_W^2$

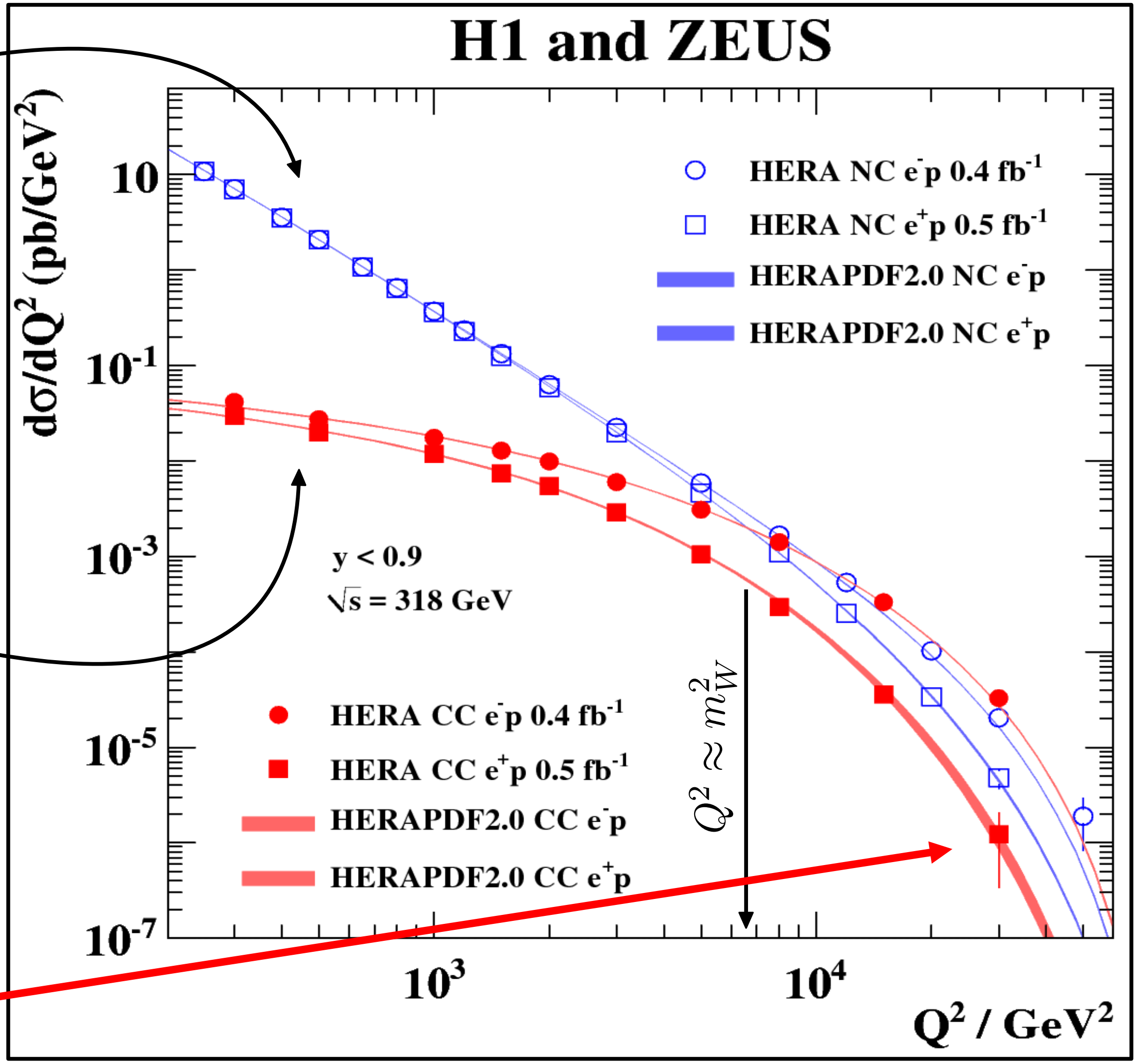




$Q^2 \approx m_W^2$: NC and CC equally strong

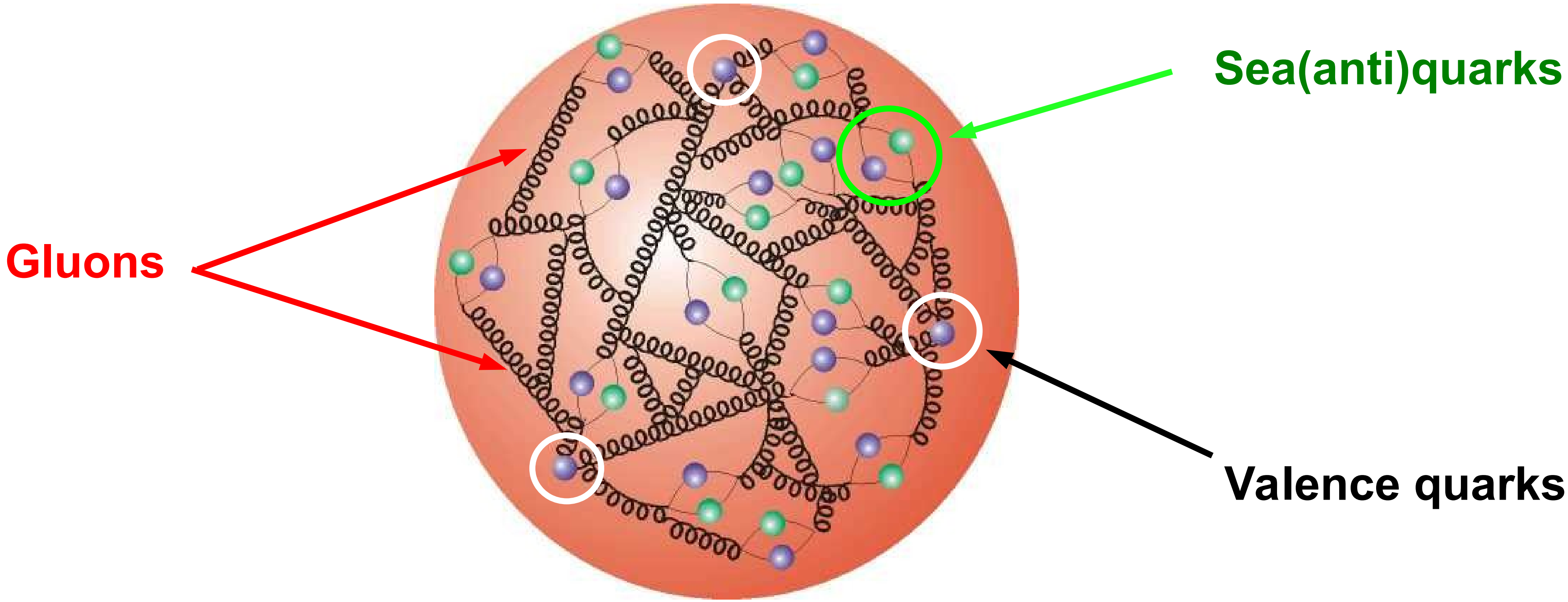
CC and NC cross sections





High Q^2: CC drops off slightly faster since $1/(m_W^2 + Q^2)$ **, BUT ...**

Proton structure



- **Gluons: Do not participate in CC**
- **Low x: Roughly equal numbers of u, d, ubar and dbar (sea)**
- **High x: Valence quarks, $u_v \approx 2 \cdot d_v$**

CC cross sections

- **CC cross section $e^-p \rightarrow \nu_e + X$**
  - Changes charge and flavour
  - Neutrino escapes undetected
  - Clear signature of missing transverse energy

$$\frac{d^2\sigma_{CC}^{e^-p}}{dx\,dQ^2} = \frac{G_F^2 m_W^4}{2\pi(Q^2+m_W^2)^2}\left(\boxed{u(x)} + (1-y)^2\overline{d}(x)\right)$$

e^-p: dominated by u(x)

$$\frac{d^2\sigma_{CC}^{e^+p}}{dx\,dQ^2} = \frac{G_F^2 m_W^4}{2\pi(Q^2+m_W^2)^2}\left(\boxed{(1-y)^2 d(x)} + \overline{u}(x)\right)$$

e^+p: d(x) < u(x) & suppressed by $(1-y)^2$

→ e^-p CC cross section larger than e^+p at large Q^2

Coupling strengths

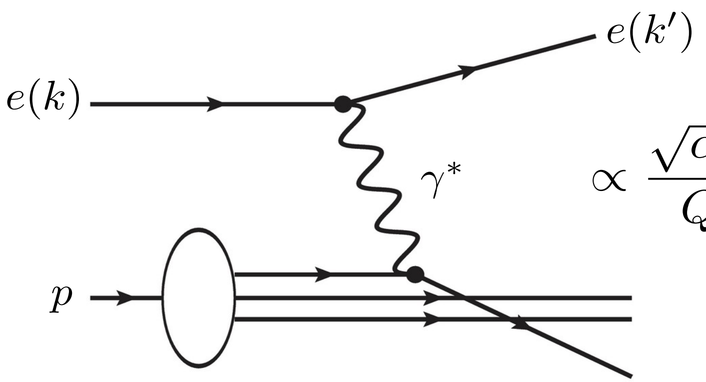
Ratio of weak to electromagnetic coupling

$$\frac{q_e}{g} = \sin\theta_W$$

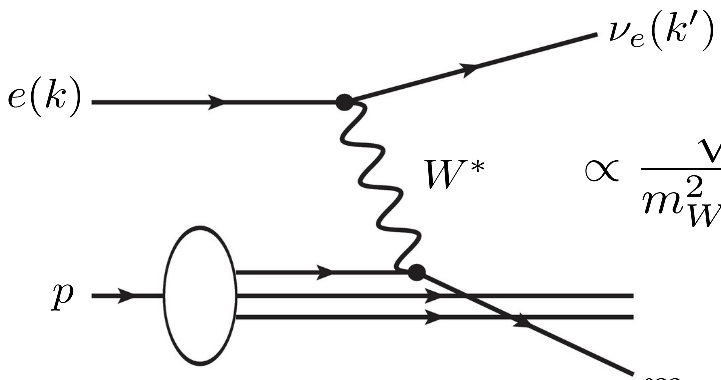
$$\frac{\alpha_{\text{em}}}{\alpha_{\text{w}}} \propto \frac{q_e^2}{g^2} = \sin^2\theta_W$$

$\rightarrow$ Weak coupling even stronger than electromagnetic one!

Relative weakness at low Q^2 stems from propagator of massive W boson



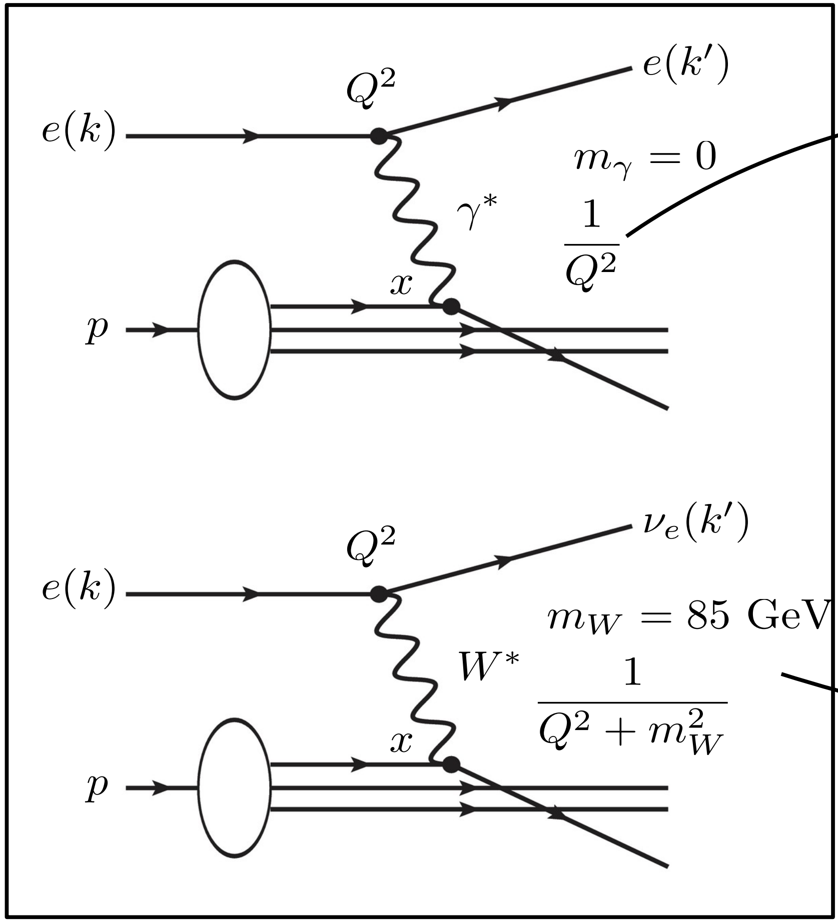
$$\propto \frac{\sqrt{\alpha_{\text{em}}}}{Q^2}$$

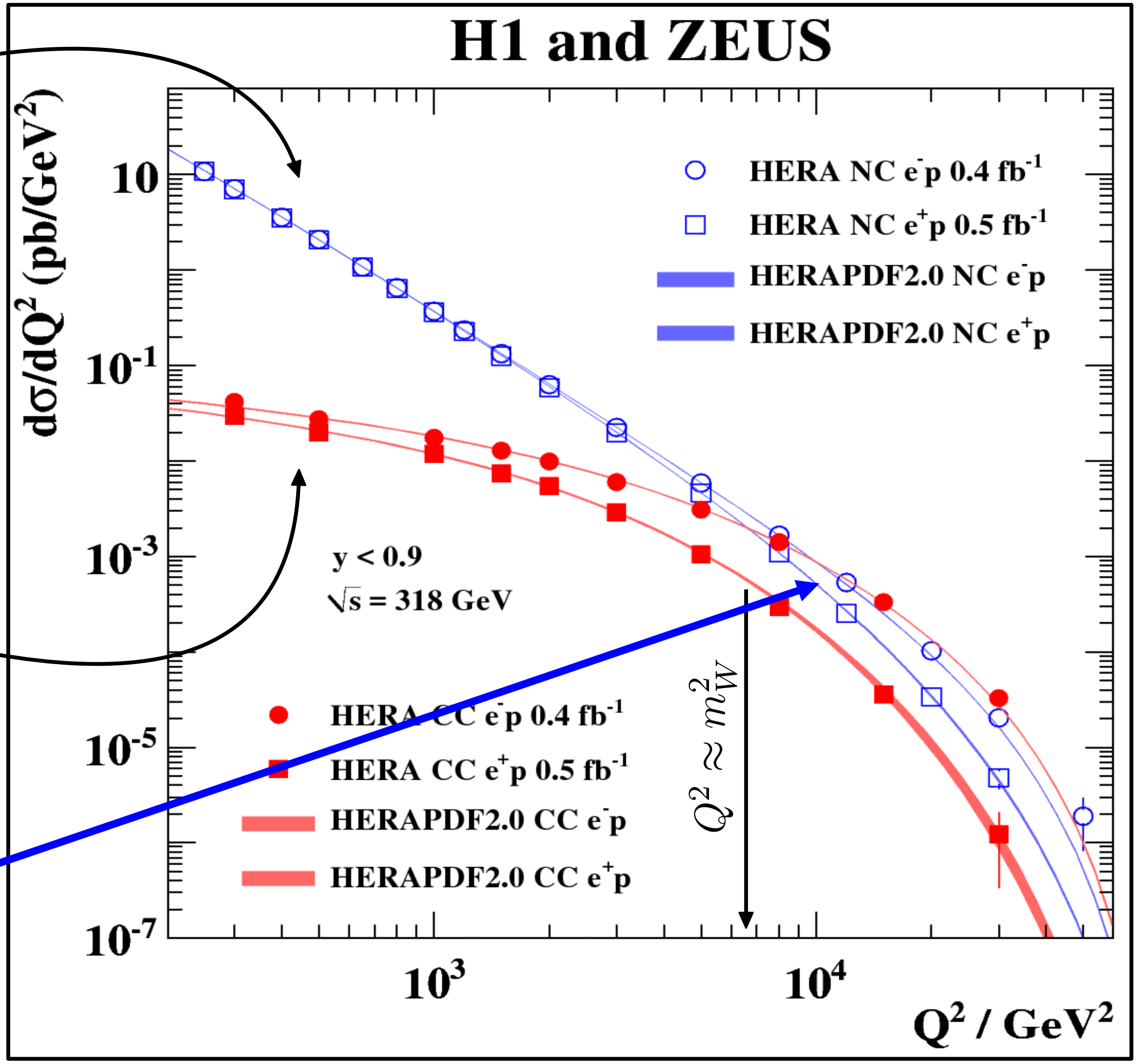


$$\propto \frac{\sqrt{\alpha_{\text{w}}}}{m_W^2 + Q^2}$$

$m_W \approx 80$ GeV

Where is the Z boson (NC) at high Q^2?





High Q^2: NC cross section starts to differ between e^-p and e^+p beyond m_Z^2

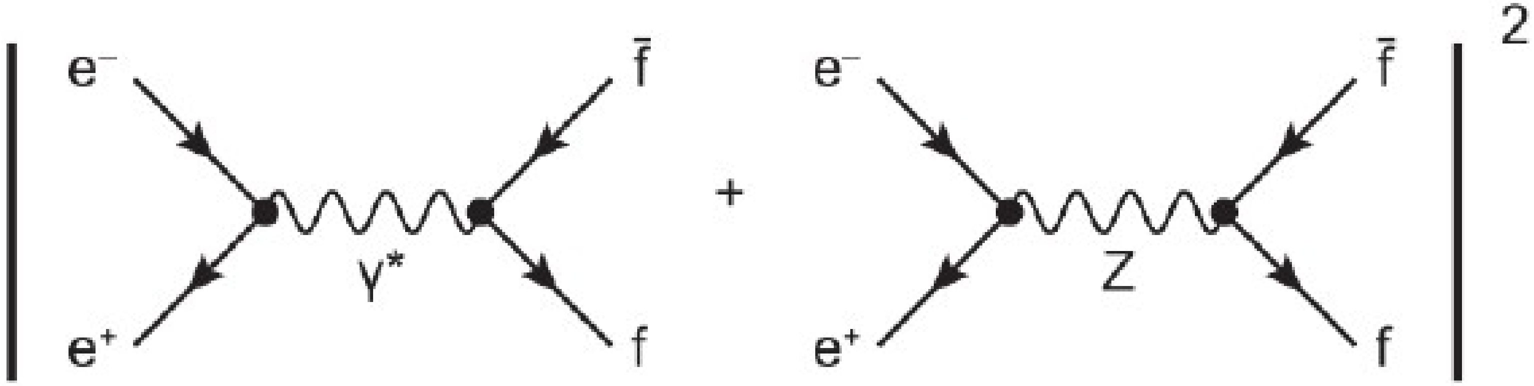
Z production with e^+e^-

- Projects to directly produce Z in huge amounts $e^-p \rightarrow \nu_e + X$
  - e^+e^- colliders with $\sqrt{s} = m_Z \approx 91$ GeV ("at the Z pole")
  - Linac at SLAC (SLC) and ring collider at CERN (LEP)
  - Hermetic "4π" detectors

	LEP (1989-2000)	SLC (1989-1998)
Data-Taking Periods	LEP 1 (1989-1995): $\sqrt{s} \approx m_Z \approx 91$ GeV LEP 2 (1996-2000): $\sqrt{s} = 160\text{–}207$ GeV	$\sqrt{s} \approx m_Z \approx 91$ GeV Polarized electrons since 1992
Experiments	ALEPH, OPAL, DELPHI, L3	Mark II (until 1991), SLD (1992-1998)
Z Boson Decays Recorded	17,000,000	600,000 (polarized)

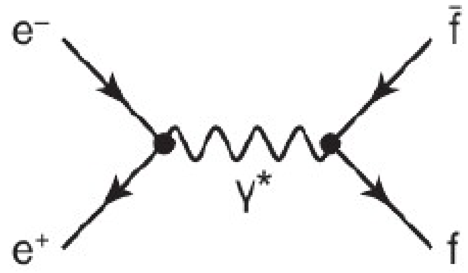
Production cross section

- **Resonant (“s-channel”) production of Z bosons in e^+e^- collisions**
  - **Photon and Z boson have same quantum numbers → interference!**
  - **Add LO matrix elements:**

$|M|^2 =$ 

  - **Cross section:** $\sigma(e^+e^- \to f\overline{f}) = \sigma_{\gamma^*} + \sigma_{\gamma^*-Z} + \sigma_Z$
  - **$\sqrt{s} \ll m_Z$: Photon exchange dominates → only QED effects**
  - **$\sqrt{s} = m_Z$: Z boson exchange dominates**
  - **$\sqrt{s} \gg m_Z$: Both contribute → unification**

$e^+e^- \rightarrow f\bar{f}$ for $\sqrt{s} \ll m_Z$: pure **QED process**



Total cross section: decreasing with 1/(center-of-mass energy)²

$$\sigma_\gamma = N_{C,f}\, Q_f^2\, \frac{4\pi\alpha^2}{3s}$$

- Assumption: all fermion masses can be neglected
- $N_{C,f}$: number of **color degrees of freedom** (3 for quarks, 1 for leptons)
- Q_f: fermion charge in units of elementary charge e
- α: **fine structure constant**

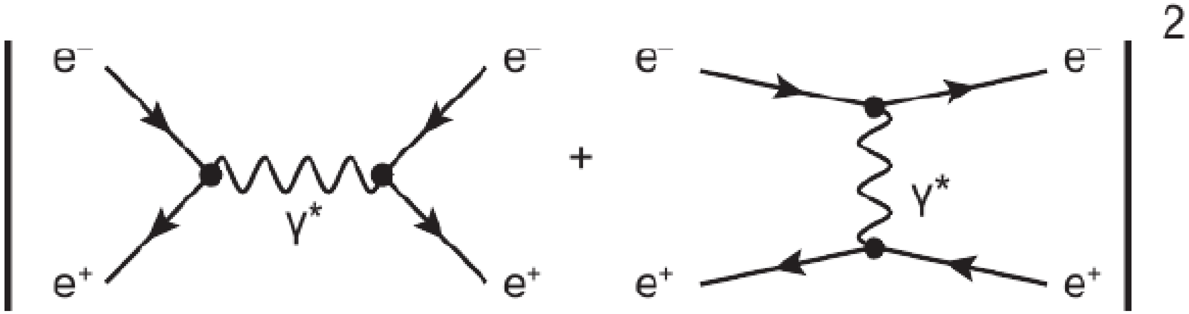
$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$$

$\sqrt{s} \ll m_Z$: Bhaba scattering

Special case: $e^+e^- \to e^+e^-$

- **Identical** particles in initial and final state → t-channel process in addition
- Matrix element:

$$|M|^2 =$$



- t-channel process: **Bhabha scattering** → differential cross section

$$\frac{d\sigma}{d\cos\theta} \sim \frac{1}{\sin^4(\theta/2)}$$

→ dominates for **small scattering angles** (cf. Rutherford scattering)

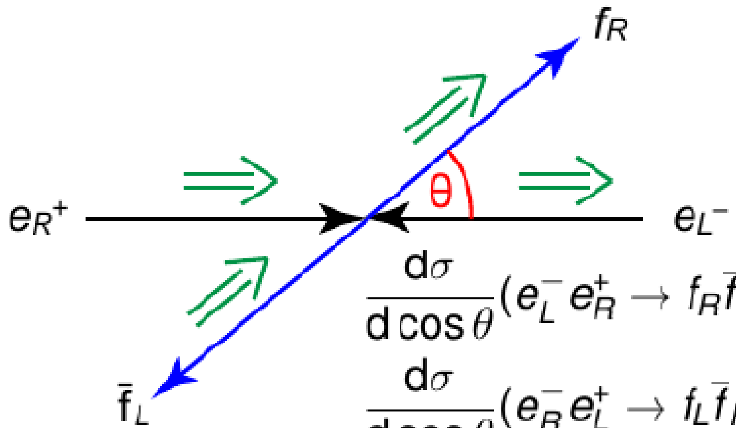
Application at LEP: measurement of **luminosity** (precision: 10^{-3})

- Theory: **pure QED process** → can be calculated very precisely
- Experiment: number of Bhabha events = **3× to 4×** number of Z events

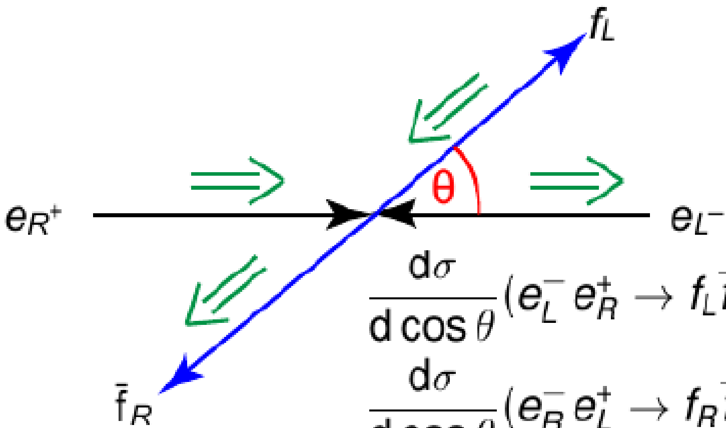
$\sqrt{s} \ll m_Z$: Scattering angle θ

Differential cross section as a function of scattering angle θ:

- Angular dependence from **particle spins**: spin-1 photon exchanged between fermion/antifermion pairs (spin 1/2)



$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_R \bar{f}_L),$$
$$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_L \bar{f}_R):$$
$$\sim (1-\cos\theta)^2$$

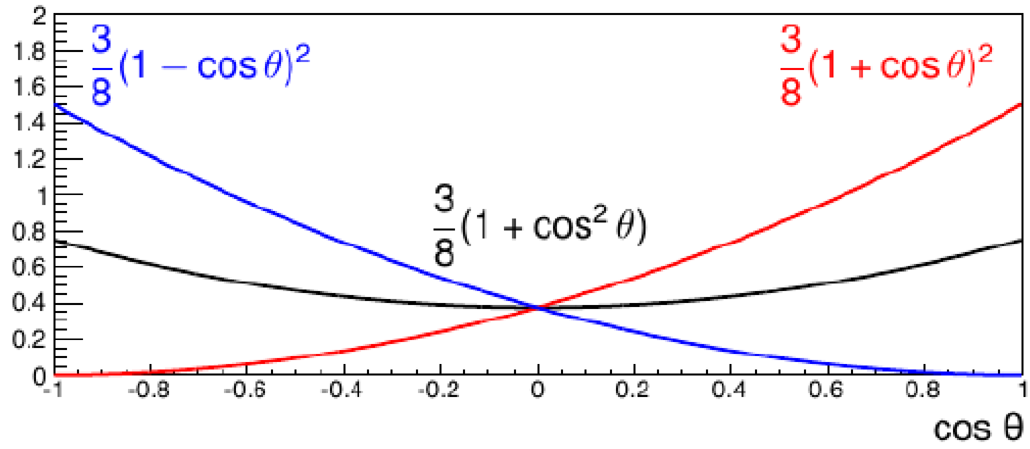


$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_L \bar{f}_R),$$
$$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_R \bar{f}_L):$$
$$\sim (1+\cos\theta)^2$$

Can be derived using Wigner's d-matrices $d^1{}_{1,-1}$ and $d^1{}_{1,1}$

- Superposition of all combinations:

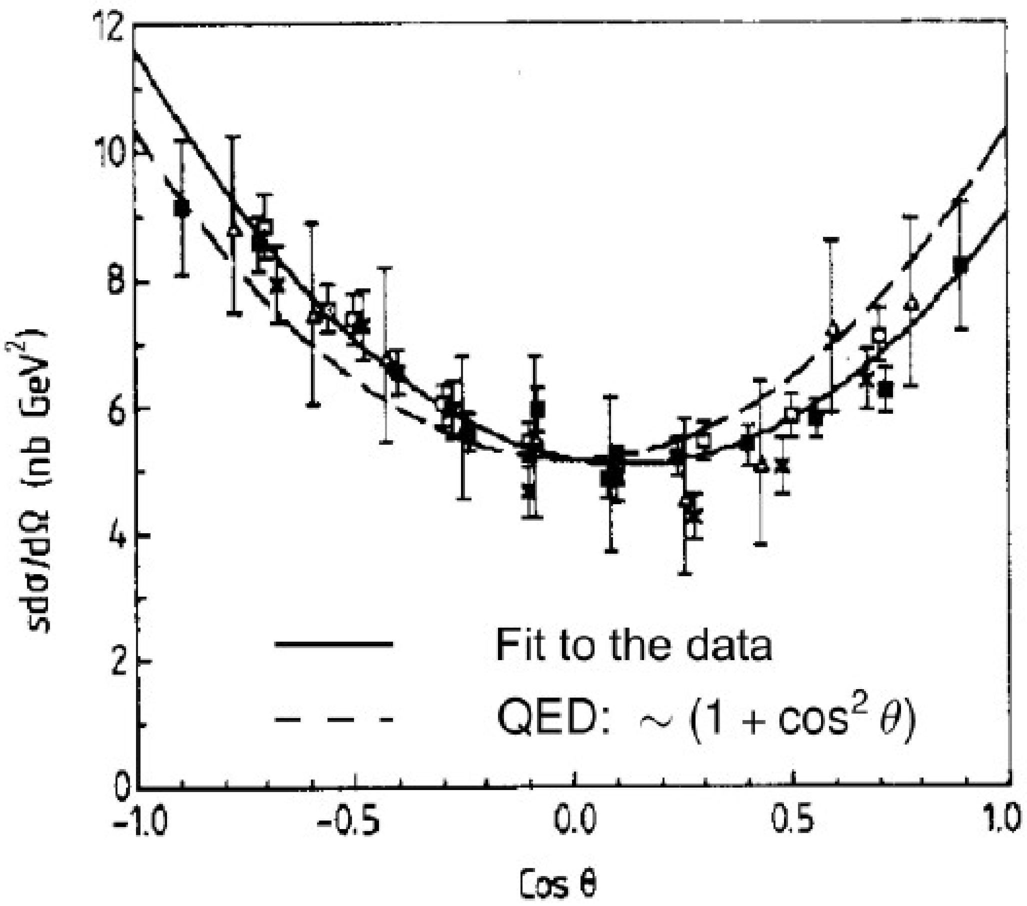
$$\frac{d\sigma_\gamma}{d\cos\theta} = N_{C,f} Q_f^2 \frac{\pi\alpha^2}{2s}(1+\cos^2\theta)$$



Asymmetry: First indications of Z

- **Interference** between γ^* and Z boson exchange already visible for $\sqrt{s} < m_Z$
- Example: **PETRA** (DESY) $\rightarrow$ first deviations from pure QED

PETRA: $\sqrt{s}$ = 29-35.5 GeV



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Asymmetries

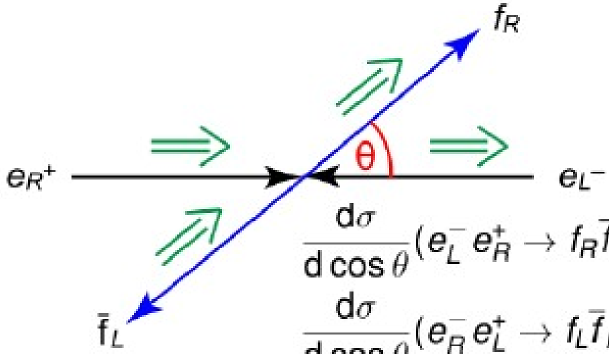
- **Generic definition:**
  - **Divide dataset into two parts X and Y**

$$A = \frac{X - Y}{X + Y}$$

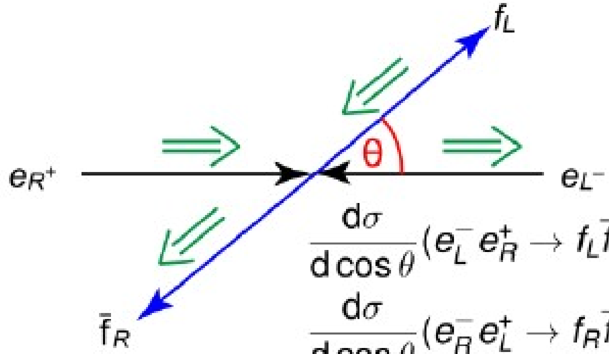
- **Predict and measure asymmetry, which is a ratio!**
  - **Identical or similar backgrounds and systematic uncertainties cancel at least partially!**
  - **Improved sensitivity to small differences**

Again: Scattering angle θ

- Angular dependence from **particle spins**:



$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_R \bar{f}_L)$,
$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_L \bar{f}_R)$:
$\sim (1-\cos\theta)^2$



$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_L \bar{f}_R)$,
$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_R \bar{f}_L)$:
$\sim (1+\cos\theta)^2$

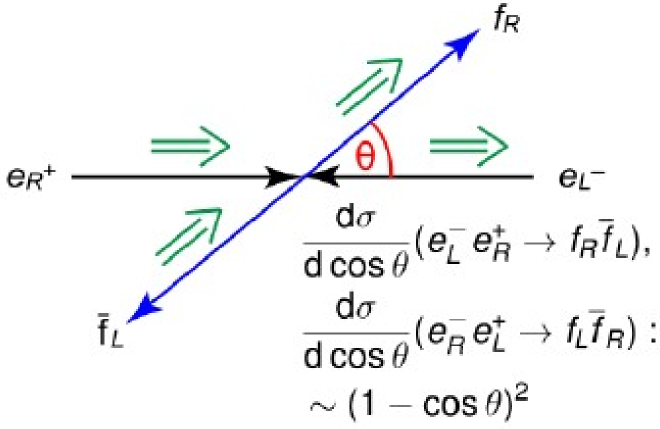
- For pure **QED process**

$$\frac{d\sigma}{d\cos\theta} = N_{C,f} Q_f^2 \frac{\pi\alpha^2}{2s}(1+\cos^2\theta)$$

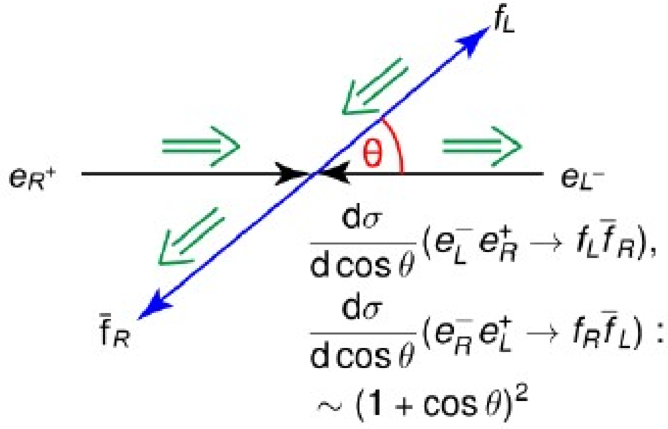
$\rightarrow$ **symmetric in scattering angle**

Now with Z exchange

- Angular dependence from **particle spins**:



$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_R \bar{f}_L)$,
$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_L \bar{f}_R)$:
$\sim (1 - \cos\theta)^2$



$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to f_L \bar{f}_R)$,
$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \to f_R \bar{f}_L)$:
$\sim (1 + \cos\theta)^2$

- For pure **Z exchange**

$$\frac{d\sigma_f}{d\cos\theta} = \frac{3}{8}\sigma_f \left[\boxed{(1 + \cos^2\theta)} + \boxed{(2A_l A_f \cos\theta)} \right]$$

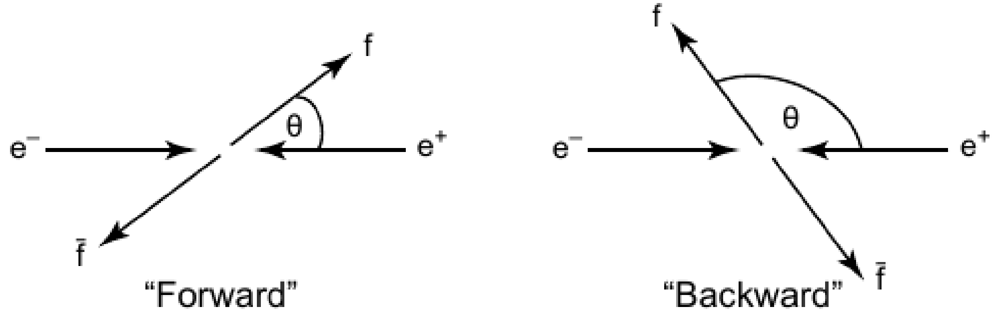
symmetric in $\cos\theta$ asymmetric in $\cos\theta$

with "**asymmetry parameter**"

$$\boxed{A_f = \frac{2\, g_V^f / g_A^f}{1 + (g_V^f / g_A^f)^2} \equiv \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}, \qquad g_{L/R} = g_V \mp g_A}$$

$\to$ **asymmetric in scattering angle?**

- Cross-sections depending on scattering angle of final-state fermion



$$\sigma_F = \int_0^{\pi/2} \frac{d\sigma}{d\cos\theta} d\theta\,, \quad \sigma_B = \int_{\pi/2}^{\pi} \frac{d\sigma}{d\cos\theta} d\theta$$

- **Forward-backward asymmetry**

$$\boxed{A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \ldots = \frac{3}{4} A_e A_f}$$

LEP: $\sqrt{s} = m_Z \pm 2$ GeV