

6. Überblick über die Wechselwirkungen

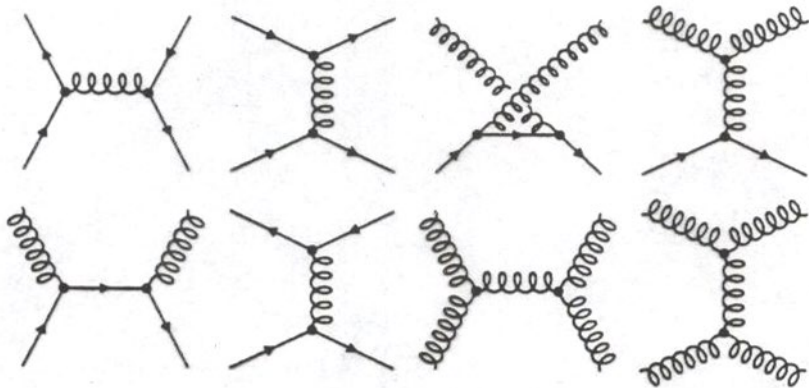
6.1 Elektromagnetische Wechselwirkung

6.2 Quantenchromodynamik

6.3 Schwache Wechselwirkung

6.4 Entdeckung der W- und Z-Bosonen

Beiträge zur QCD qq, qg und gg-Streuung

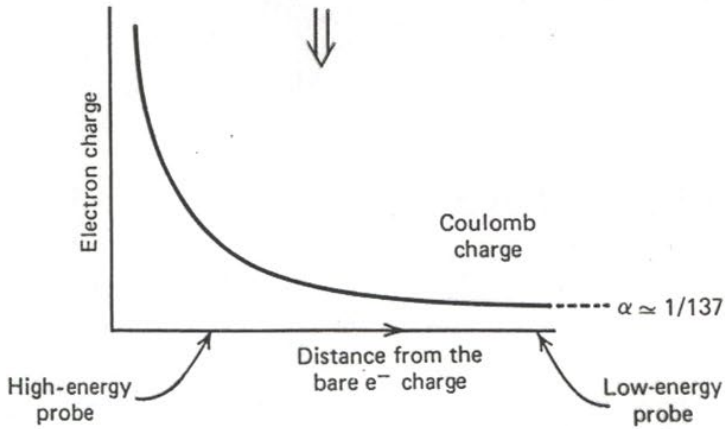
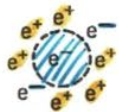
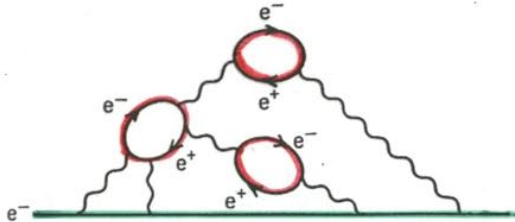


Beiträge führender Ordnung

Table 1. Matrix elements for parton scattering

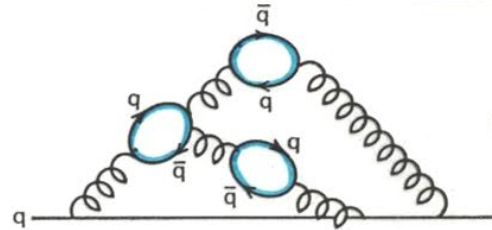
subprocess	$ M ^2$	$\theta^* = \pi/2$
$qq' \rightarrow qq'$	$\frac{4}{9} \frac{s^2+u^2}{t^2}$	2.22
$qq \rightarrow qq$	$\frac{4}{9} \left(\frac{s^2+u^2}{t^2} + \frac{s^2+t^2}{u^2} \right) - \frac{8}{27} \frac{s^2}{ut}$	3.26
$q\bar{q} \rightarrow q'q\bar{q}'$	$\frac{4}{9} \frac{t^2+u^2}{s^2}$	0.22
$q\bar{q} \rightarrow q\bar{q}$	$\frac{4}{9} \left(\frac{s^2+u^2}{t^2} + \frac{t^2+u^2}{s^2} \right) - \frac{8}{27} \frac{u^2}{st}$	2.59
$q\bar{q} \rightarrow gg$	$\frac{32}{27} \frac{u^2+t^2}{ut} - \frac{8}{3} \frac{u^2+t^2}{s^2}$	1.04
$gg \rightarrow q\bar{q}$	$\frac{1}{6} \frac{u^2+t^2}{ut} - \frac{3}{8} \frac{u^2+t^2}{s^2}$	0.15
$gg \rightarrow qq$	$-\frac{4}{9} \frac{u^2+s^2}{us} + \frac{u^2+s^2}{t^2}$	6.11
$gg \rightarrow gg$	$\frac{9}{2} \left(3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2} \right)$	30.38

Quantum electrodynamics (QED)

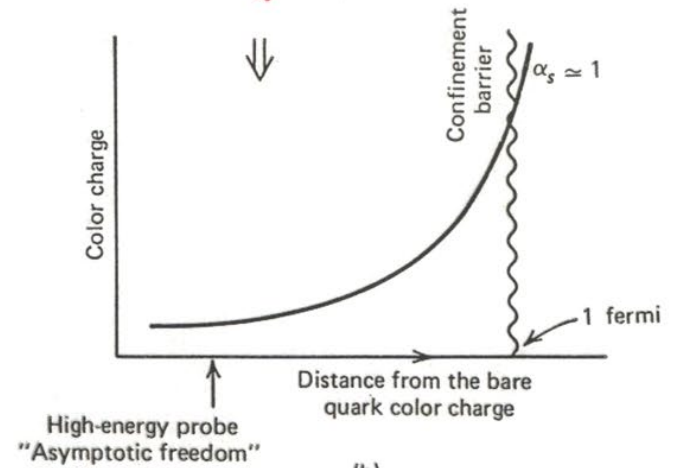
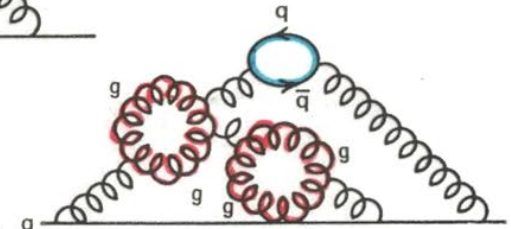


(a)

Quantum chromodynamics (QCD)



but also



(b)

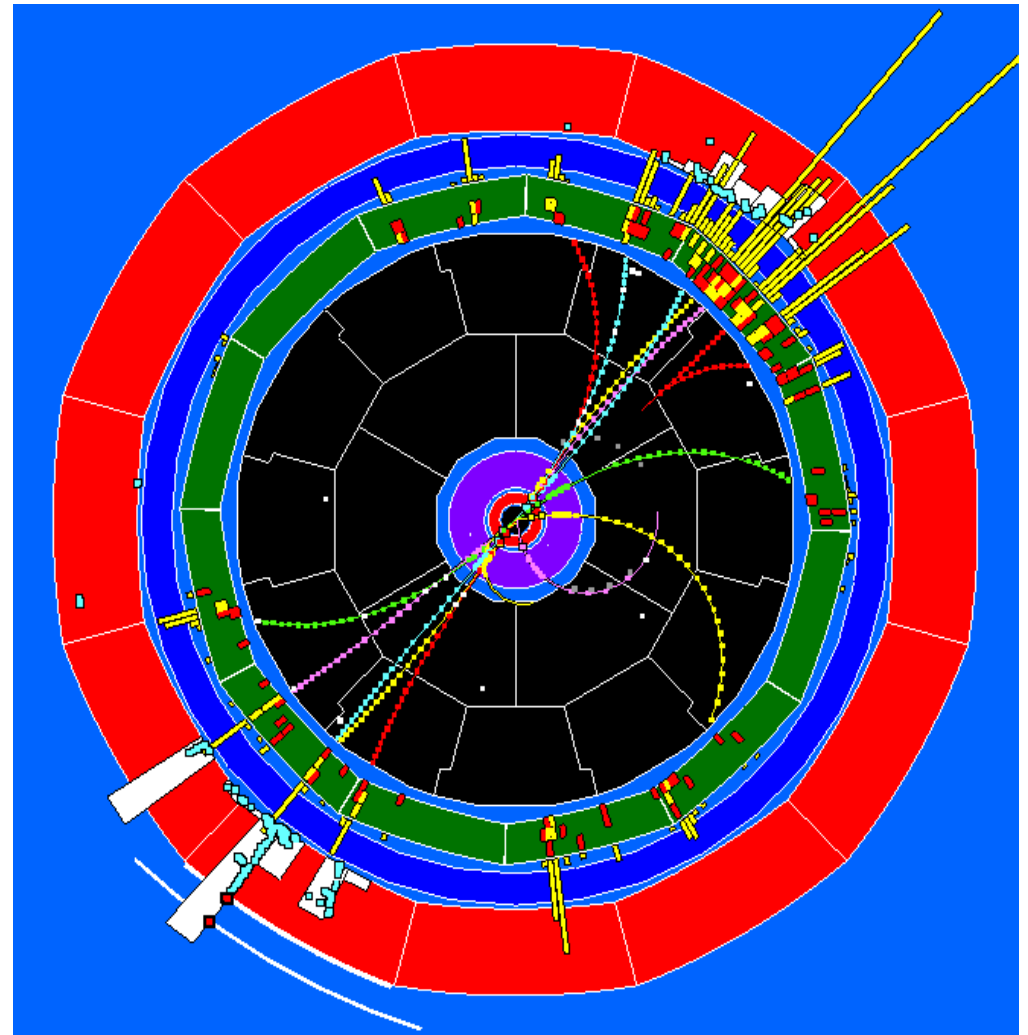
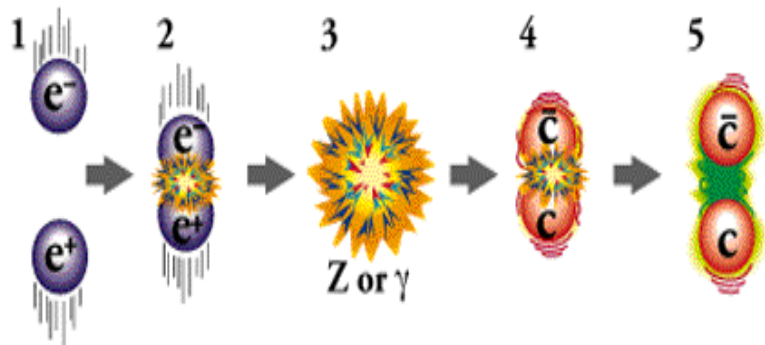
$$e^+e^- \rightarrow q\bar{q}$$

Zwei Teilchenbündel
(Jets) sind entstanden

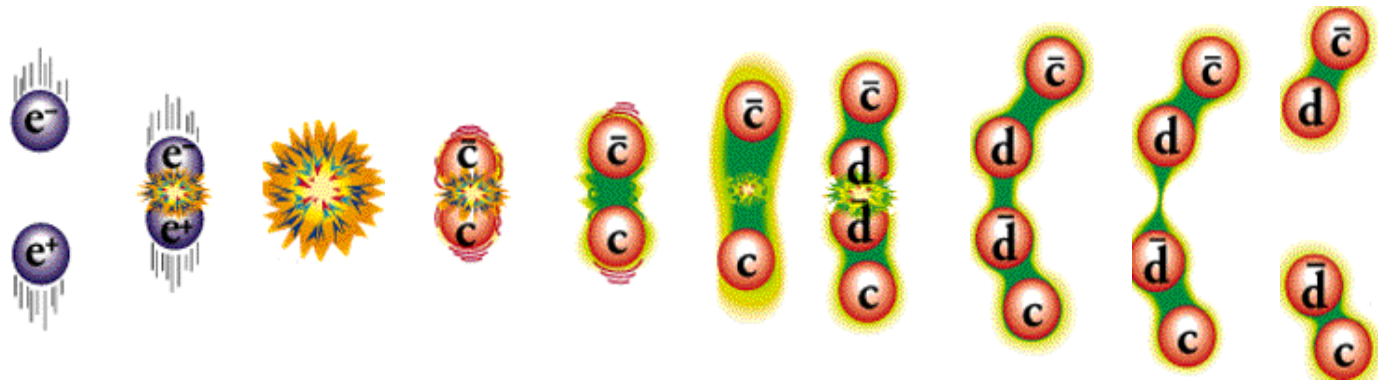


Ursache: Starke Wechselwirkung zwischen Quarks

→ Fragmentation in Hadronen



Die Entstehung der Jets (Teilchenbündel) aus Quarks



- Aus Energie ist ein **Quark-Antiquark Paar** entstanden .
- Die entstandenen Quarks können nicht als freie Teilchen existieren !
- Die starke Wechselwirkung zwischen Quarks führt zur Bildung neuer Quark-Antiquark Paare (aus Energie)
- Aus Quark-Antiquark Paaren oder aus 3-Quark Systemen entstehen die uns bekannten Teilchen (Hadronen)

Entdeckung der Gluonen in Drei-Jet-Ereignissen

DESY, Hamburg (1977)

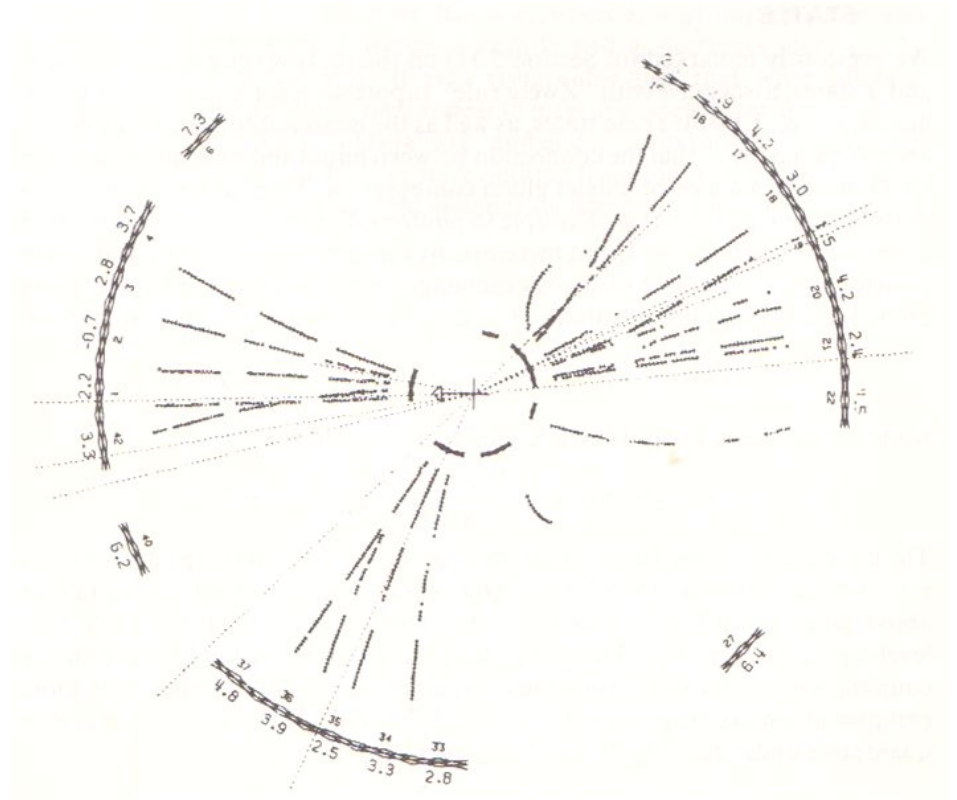
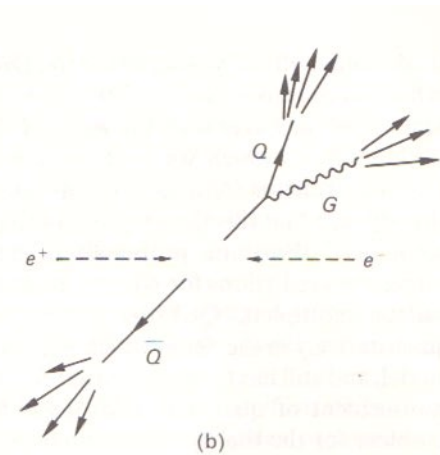
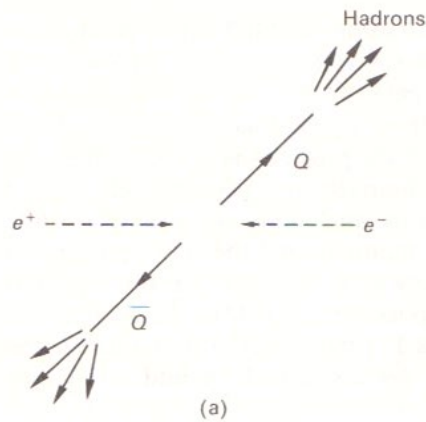


Fig. 8.28 Example of a three-jet event observed in the JADE detector at the PETRA e^+e^- collider (DESY, Hamburg). The total CMS energy in the event is 31 GeV. Such events (in comparison with the more common "two-jet" events of Fig. 2.20, p. 69) are suggestive of the process in Fig. 8.27(b). (Courtesy DESY)

(aus Ref. [8])

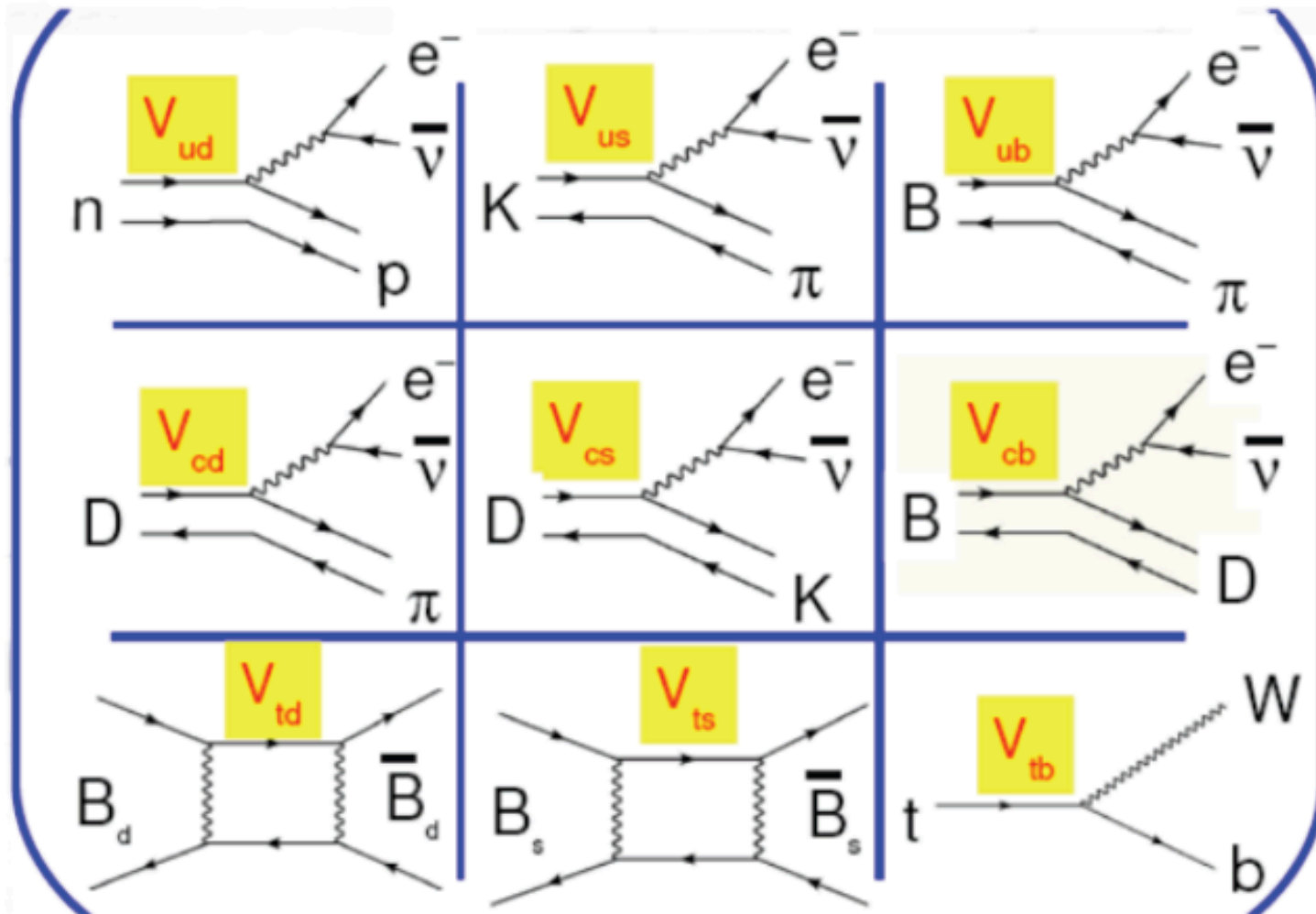
CKM-Matrix

$$V_{\text{CKM}} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

**CKM-Matrix-Elemente müssen experimentell bestimmt werden
(Aus Messungen von Meson Zerfällen)**

Stand: 2008

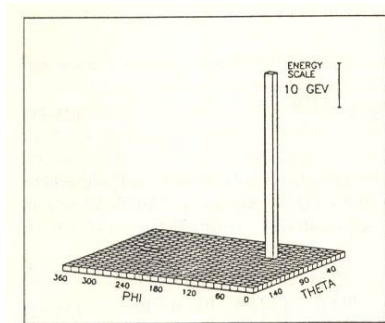
Beispiele für Zerfälle, die zur Vermessung der Größe von CKM-Matrixelementen verwendet werden



Discovery of the W and Z bosons

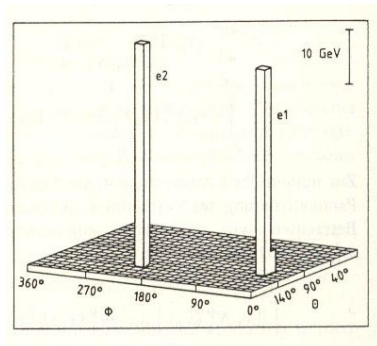
Leptons, photons and missing transverse energy are key signatures at hadron colliders

→ Search for leptonic decays: $W \rightarrow \ell \nu$ (large $P_T(\ell)$, large P_T^{miss})
 $Z \rightarrow \ell \ell$

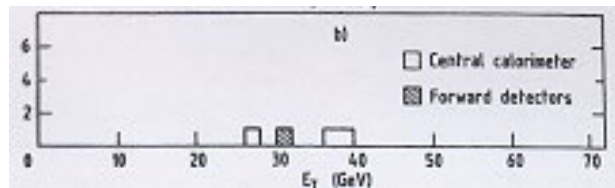


One of the first W events seen;
UA2 experiment

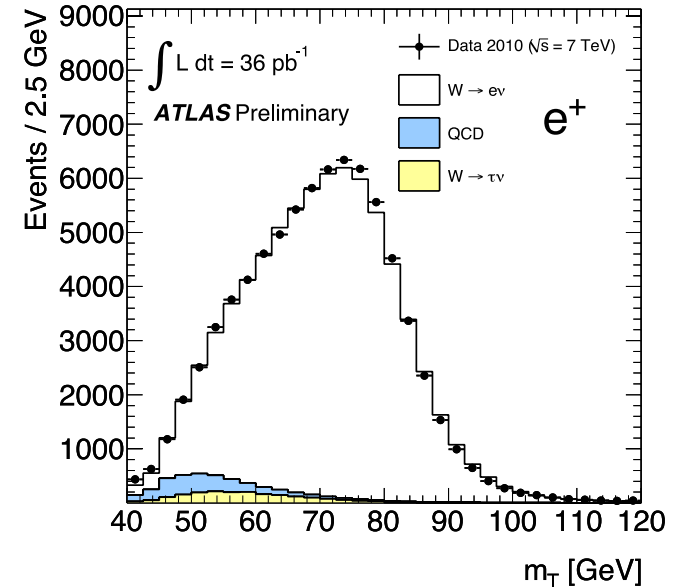
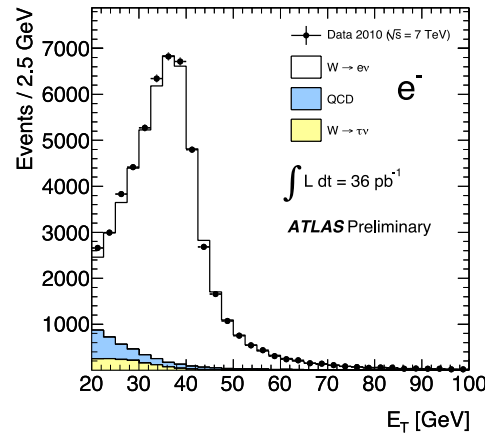
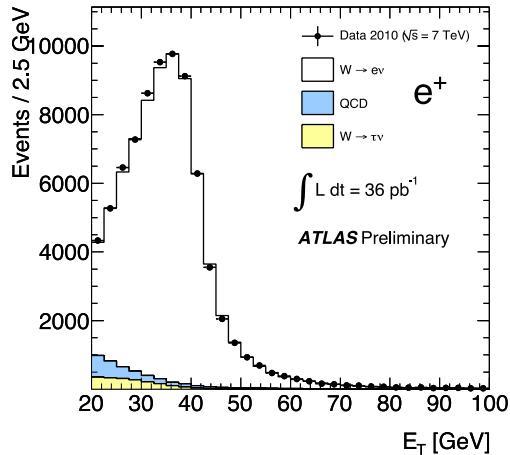
W/Z discovery by the UA1 and UA2 experiments at CERN
(1983/84)



Transverse momentum of
the electrons



Today: W/Z selections in the ATLAS / CMS experiments



Electrons:

- Trigger: high p_T electron candidate in calorimeter
- Isolated el.magn. cluster in the calorimeter
- $P_T > 25 \text{ GeV}/c$
- Shower shape consistent with expectation for electrons
- Matched with tracks

Z $\rightarrow ee$

- $66 \text{ GeV}/c^2 < m_{ee} < 116 \text{ GeV}/c^2$

W $\rightarrow e\nu$

- Missing transverse momentum $> 25 \text{ GeV}/c$
- Transverse mass cut $M_T > 50 \text{ GeV}$

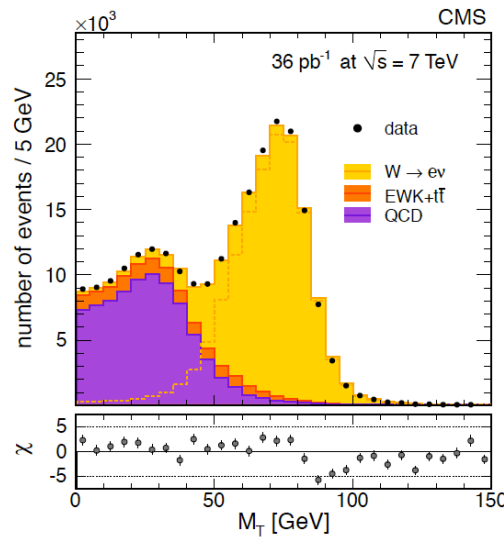
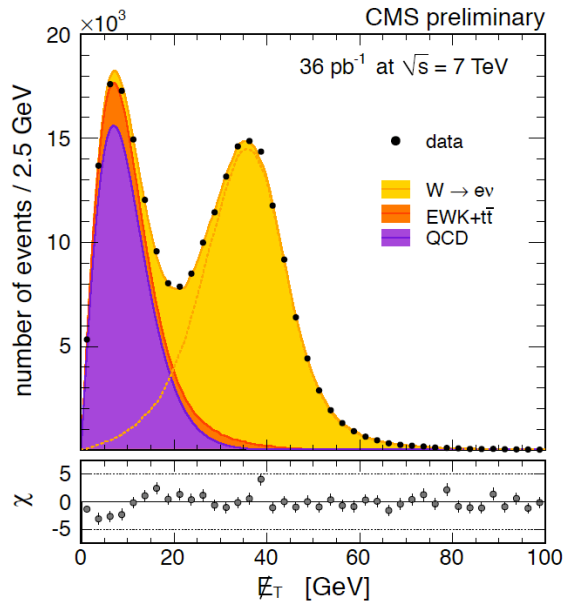
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot (1 - \cos \Delta\phi^{l,\nu})}$$

Transverse mass

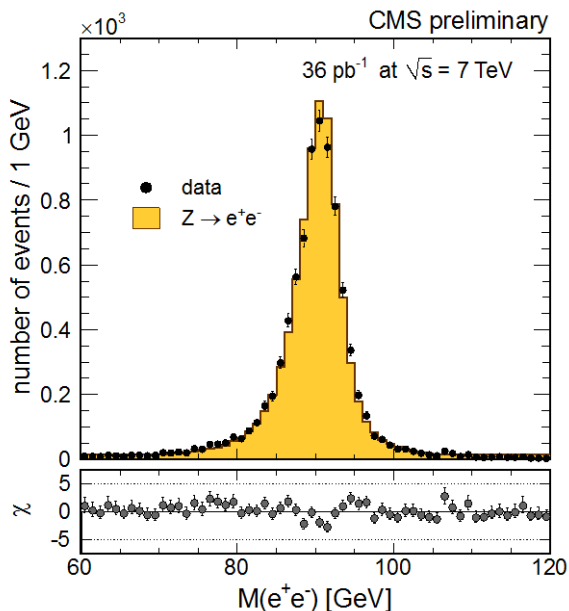
(longitudinal component of the neutrino cannot be measured)



An example: CMS data from 2010: 36 pb⁻¹



Distributions of the missing transverse energy, E_T^{miss} , (left) and transverse mass m_T (right) of electron candidates for data and Monte Carlo simulation, broken down into the signal and various background components.



Distributions of the invariant di-electron mass, m_{ee} , for events passing the Z selection. The data are compared to Monte-Carlo simulation, the background is very small.