QED Prozesse: t- und u-Kanal

OPAL am LEP(CERN):

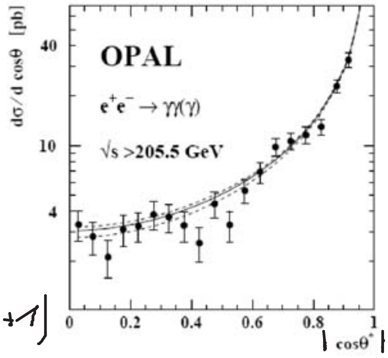
$e^+e^- \rightarrow \gamma\gamma$ bei $\sqrt{s}:=E_{CM} > 205$ GeV

$\langle|\mathcal{M}|\rangle^2 = 2e^4\left(\frac{u}{t}+\frac{t}{u}\right)$

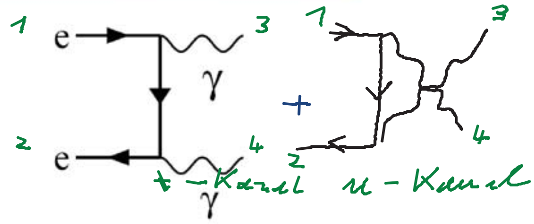
$\int \frac{d\sigma}{d\Omega} d\Omega = \infty$ für $m_e = 0$

weil $m_e \neq 0$

$\sigma = \frac{4\pi\alpha^2}{s}\left(\ln\frac{s}{4m_e^2}+1\right)$



$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Born}} = \frac{\alpha^2}{s}\frac{1+\cos^2\theta}{1-\cos^2\theta}$$



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QED Prozesse: s-Kanal ohne Resonanz

e^+e^- Speicherring PETRA I am DESY (1978-1987)

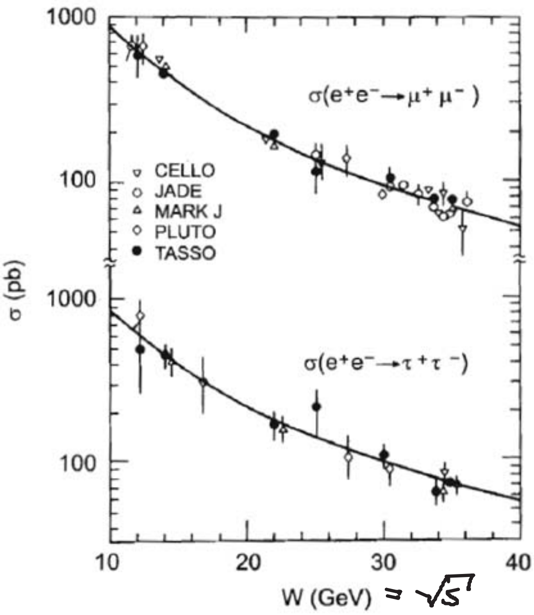
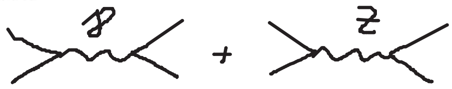
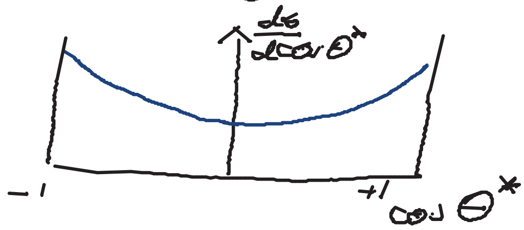


Abb. 8.3: Die Wirkungsquerschnitte für die Reaktionen $e^+e^- \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \tau^+\tau^-$ in Abhängigkeit von der Schwerpunkt-Energie W. Die Kurven bedeuten die Vorhersage der Quantenelektrodynamik [Sö 82].

Bethge-Schröder, Abb. 8.3



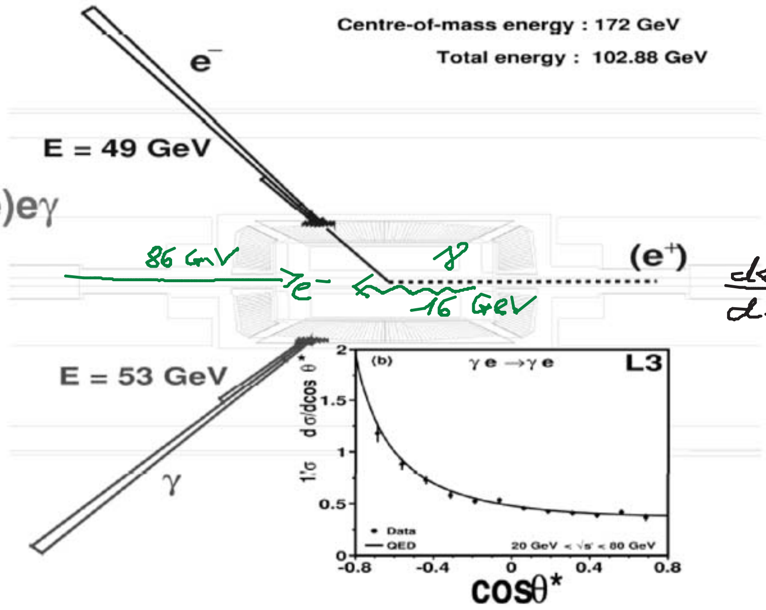
$\sigma = \frac{4\pi}{3}\frac{\alpha_{ew}^2}{s}$

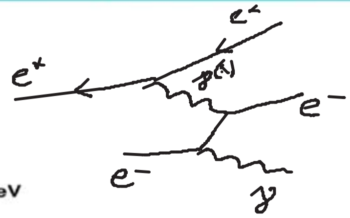


QED Prozesse: s- und u-Kanal

L3 : Highest Energy Compton Scattering

4641 (e)eγ events





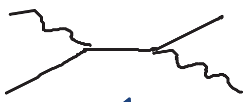
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left(-\frac{u}{s} - \frac{s}{u-m_e^2}\right)$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left(\frac{1+\cos\theta^*}{2} + \frac{2}{1+\cos\theta^* + \frac{2m^2}{s}}\right)$$

vollst. Ausdruck:

BERGER

s- Kanal



$$\uparrow$$

$$\frac{1}{s-m^2}$$

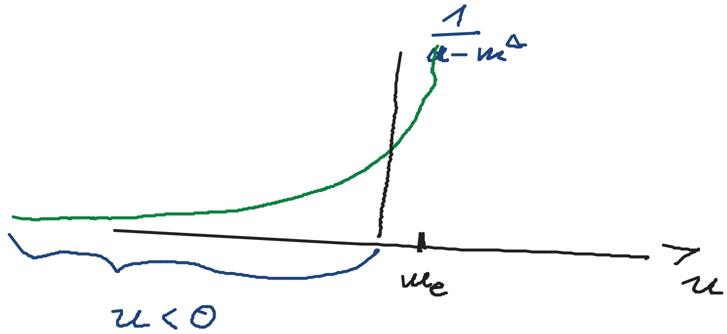
pol bei $s = m^2$

→ sinkt dramatisch mit $s \to \infty$

u- Kanal

$$\uparrow$$

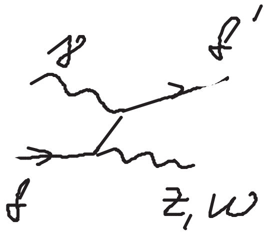
$$\frac{1}{u-m^2}$$



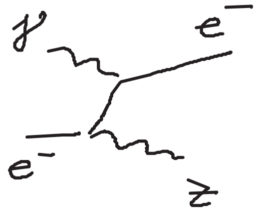
$u \approx 0$ auch für große s möglich

Compton Prozess gilt allgemein für jede Boson–Fermion–Streuung

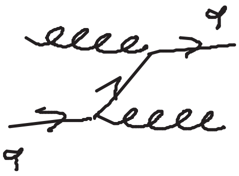
EW



z.B.

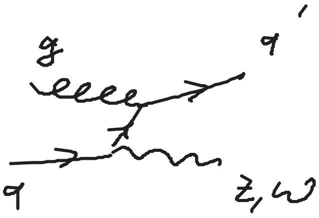


QCD



+ s-Kanal

QCD + EW



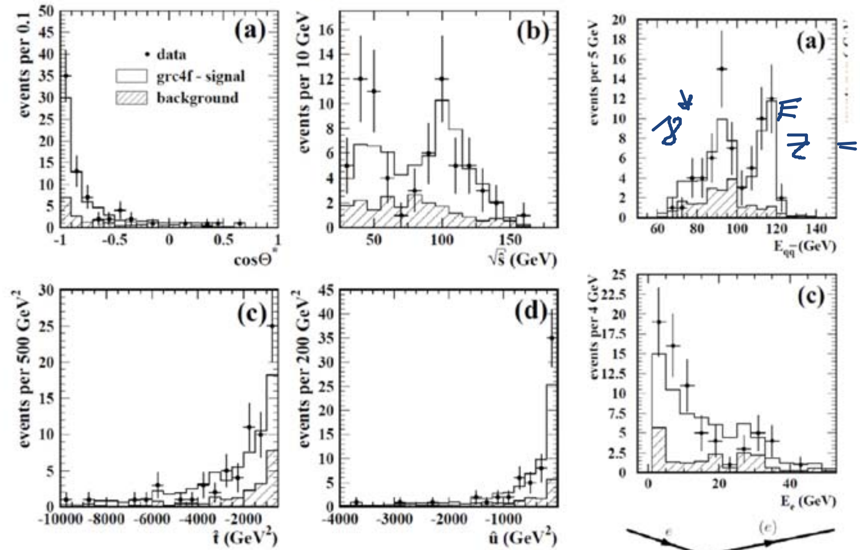
aber u-Kanal bei hoher E dominant

Elektroschwache Z-Erzeugung über Compton-Streuung bei LEP

$\sqrt{s} = 189$ GeV

OPAL

$\approx p_e = 94{,}5$ GeV



$= \sqrt{m_Z^2 + p_Z^2} \approx 120$ GeV

Figure 9: *Distribution of (a) the scattering angle in the eγ rest-frame $\cos\theta^*$, and the kinematic invariants (b) $\sqrt{\hat{s}}$, (c) $\hat{t}$ and (d) $\hat{u}$ after all cuts. The open histogram shows the signal simulated with the grc4f Monte Carlo, the hatched histogram shows the backgrounds from various Monte Carlo simulations and the points the data. Only statistical errors are shown.*

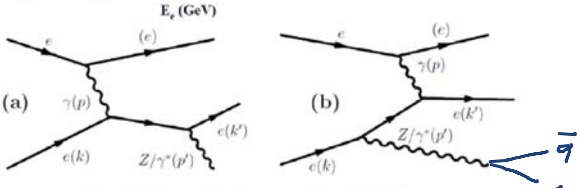
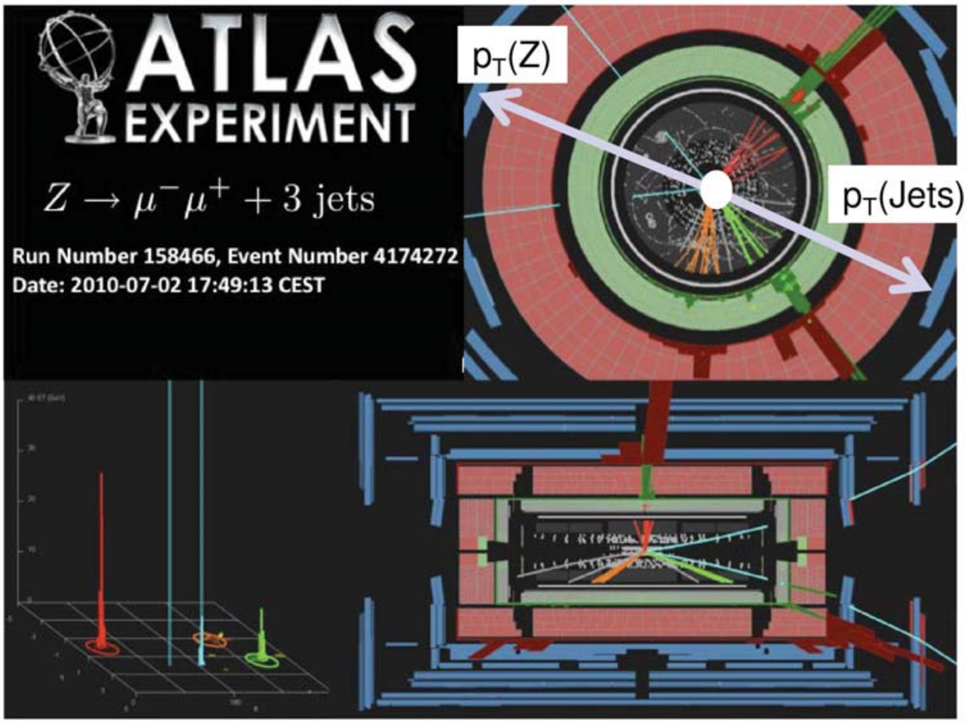
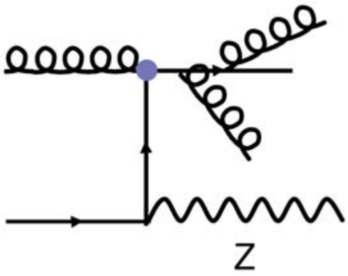


Figure 1: *Diagrams for the process $e^+e^- \to (e)eZ/\gamma^*$.*

Z-Erzeugung über QCD-Compton-Streuung bei LHC





$p_T(Z)$ is balanced against hadronic system

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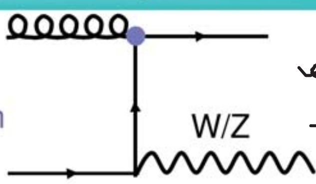
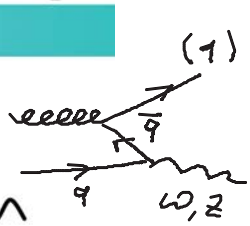
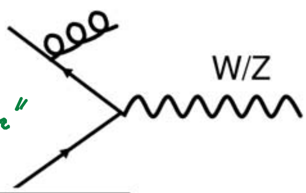
- Sichtweise abhängig von Faktorisierungsskala
- High p_T : W/Z+jet Compton 2->2 → harte Parton-Emission
- Low p_T : s-Kanal Resonanz + weiche gluon Emission
  → Resummierung von Logs, anti-Quark aus pdf

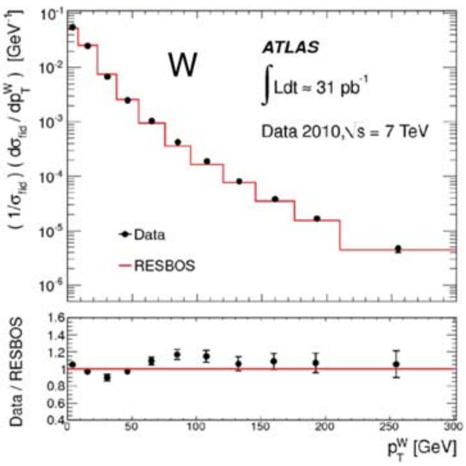


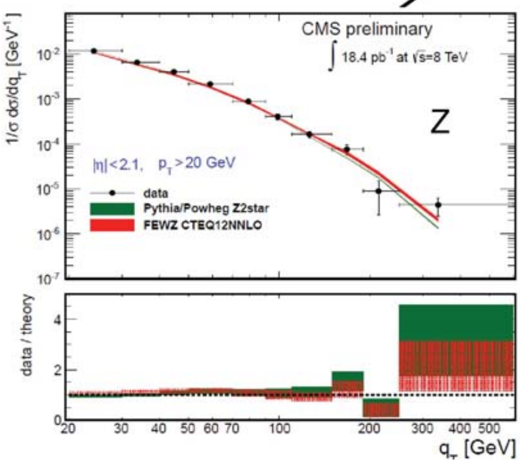




"Drell-Yan"

- Good agreement of data and simulation:



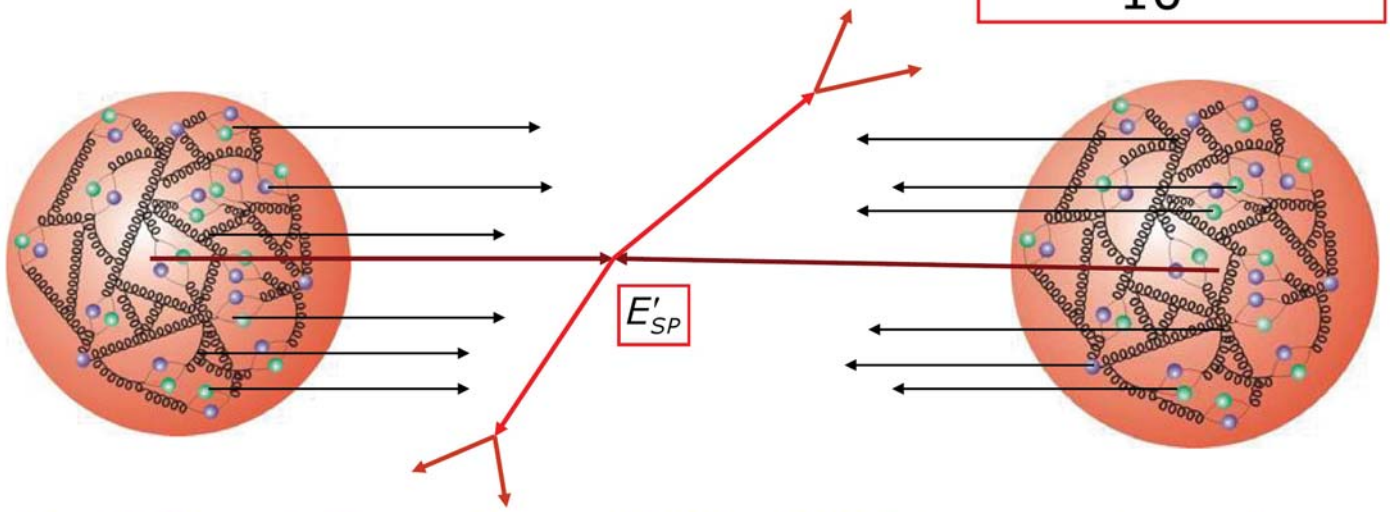


CMS PAS SMP-12-025

Wechselwirkung nur von Bruchteilen des Protons (**Partonen: Quarks und Gluonen**)

Am LHC: Schwerpunktsenergie
der kollidierenden **Partonen** (q, g)

$$\boxed{E'_{SP} \approx \frac{1}{10} E_{SP}(pp)}$$



Neue Teilchen mit **Massen bis zu ~ 1 TeV (ca. 1000 Protonmassen)** erzeugbar

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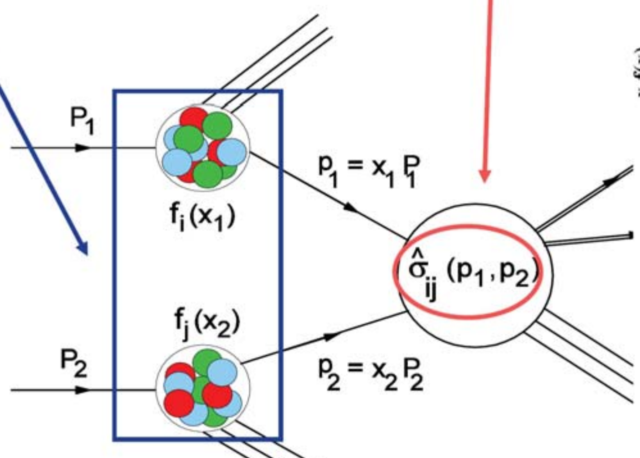
Mathematisch

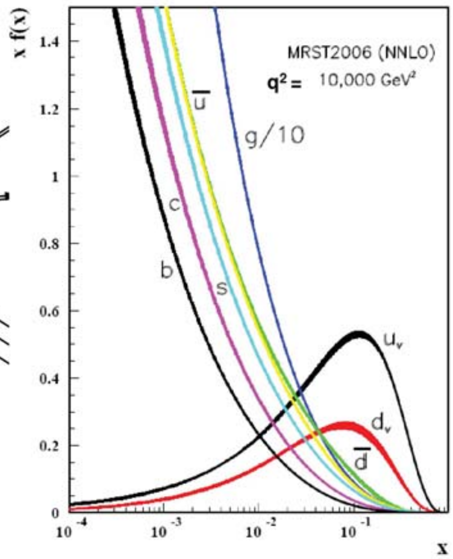
$$\sigma = \sum_{ij} \int \boxed{f_i(x_1) f_j(x_2)} \boxed{\hat{\sigma}_{ij}(p_1, p_2)} dx_1 dx_2$$

Innere Struktur der Protonen

Wechselwirkung der Partonen

Parton:
Bruchteil des Protons
Quark oder Gluon





PROTON BESTEHT DOM. AUS 2u + 1d QUARK U. GLUONEN

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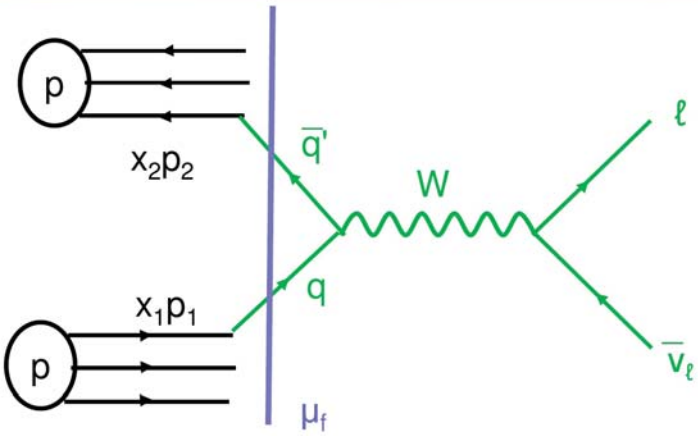
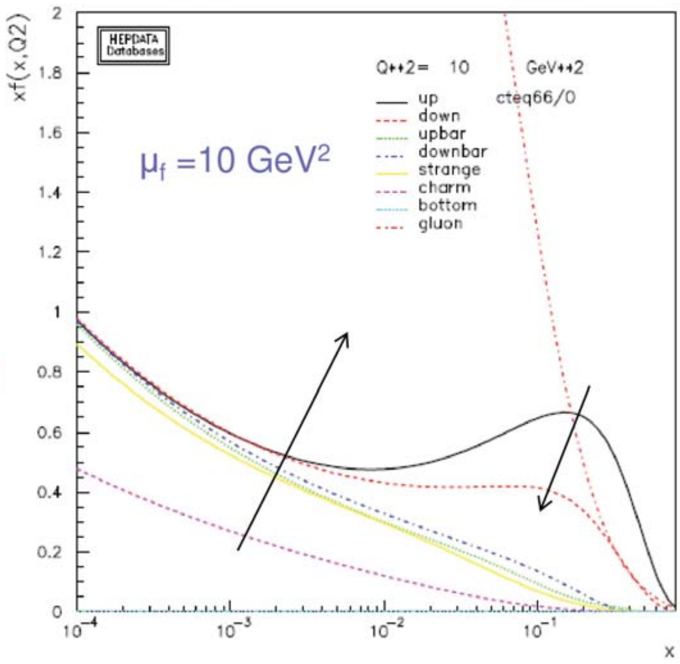
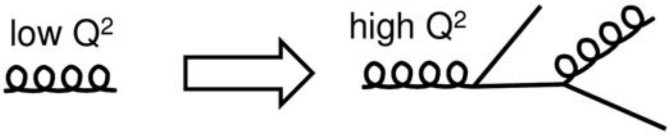




- Factorisation energy scale μ_f
- PDFs are energy scale dependent:



$$\sigma = \sum_{i,j} \int \sigma_{ij}(\hat{s}, \mu_f, \mu_r) \int_0^1 \int_0^1 f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \delta(\hat{s} - x_1 x_2 s) \, dx_1 \, dx_2 d\hat{s}$$

- Partonic cross-section and PDFs must be matched properly

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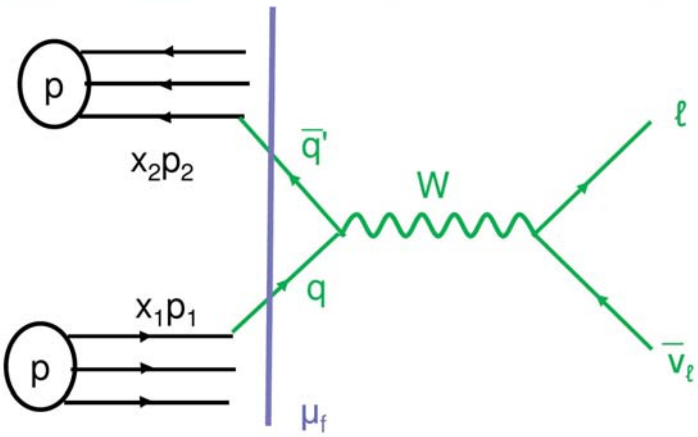

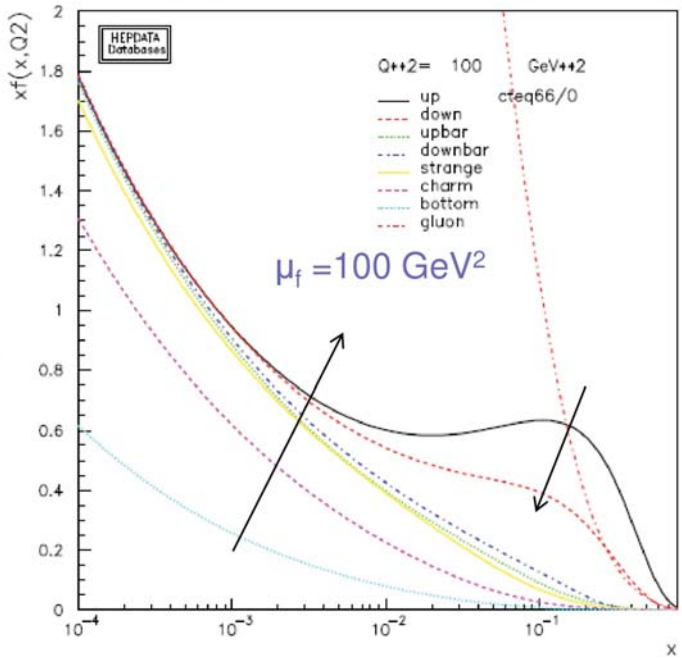

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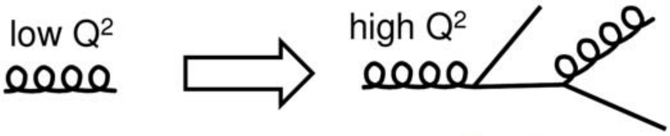
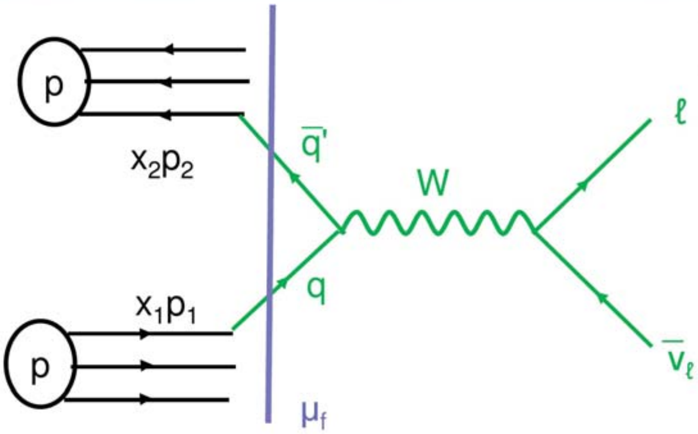
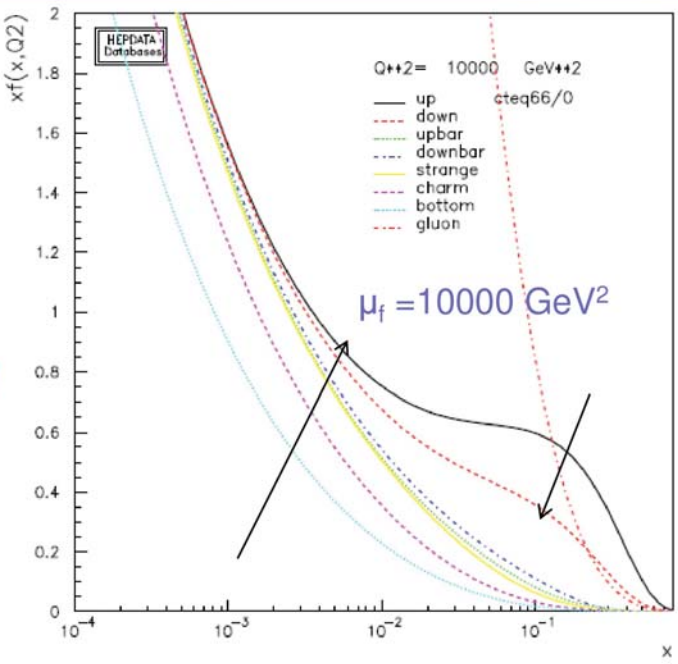


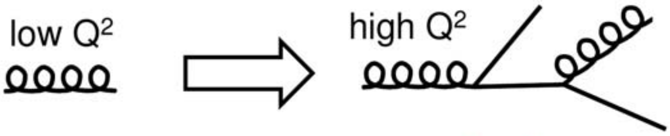
$$\sigma = \sum_{i,j} \int \sigma_{ij}(\hat{s}, \mu_f, \mu_r) \int_0^1 \int_0^1 f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \delta(\hat{s} - x_1 x_2 s) \, dx_1 \, dx_2 d\hat{s}$$

- Partonic cross-section and PDFs must be matched properly





- Factorisation energy scale μ_f
- PDFs are energy scale dependent:

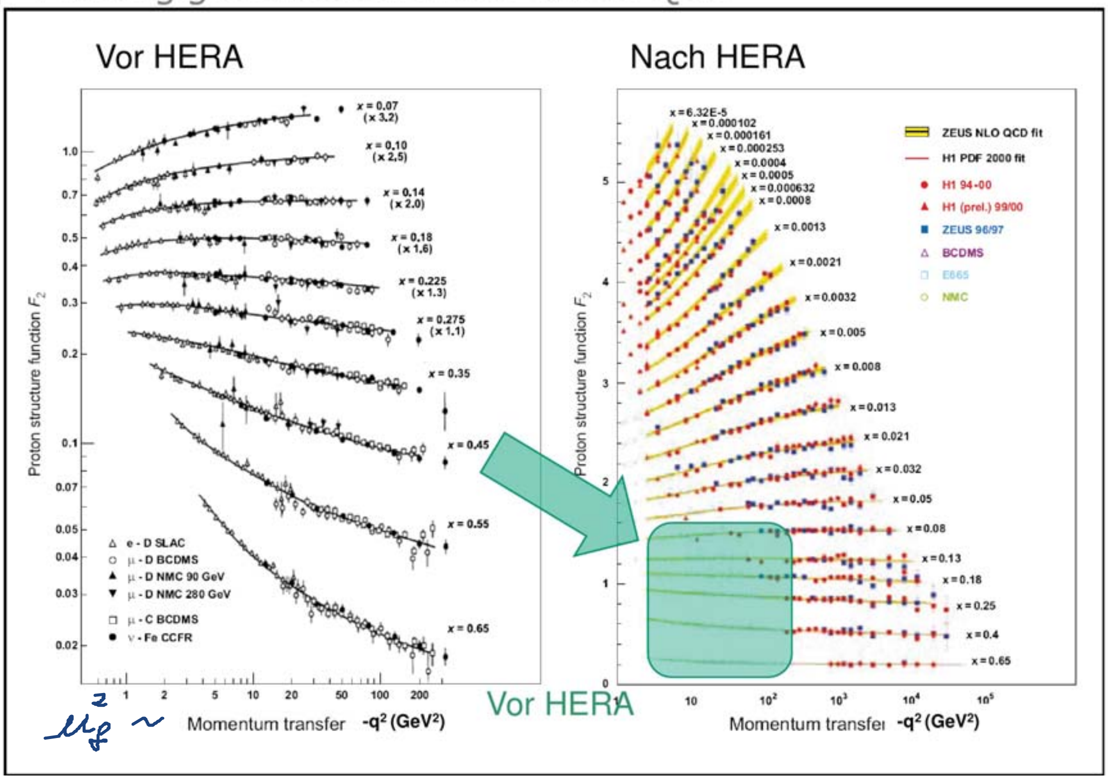


$$\sigma = \sum_{i,j} \int \sigma_{ij}(\hat{s}, \mu_f, \mu_r) \int_0^1 \int_0^1 f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \delta(\hat{s} - x_1 x_2 s)\, dx_1\, dx_2 d\hat{s}$$

- Partonic cross-section and PDFs must be matched properly

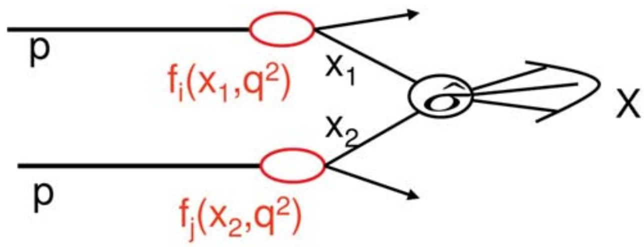
q²-Abhängigkeit beschreibbar durch QCD

Es treten Terme $\sim \ln \frac{q^2}{\mu_f^2}$ auf

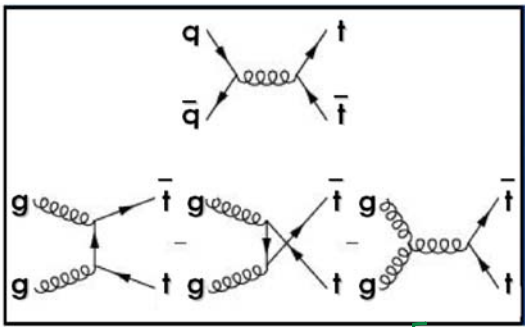


$\mu_f^2 \sim$

$f(x,q^2)$ Parton-Dichte Funktionen (pdf)
bestimmen den Wirkungsquerschnitt

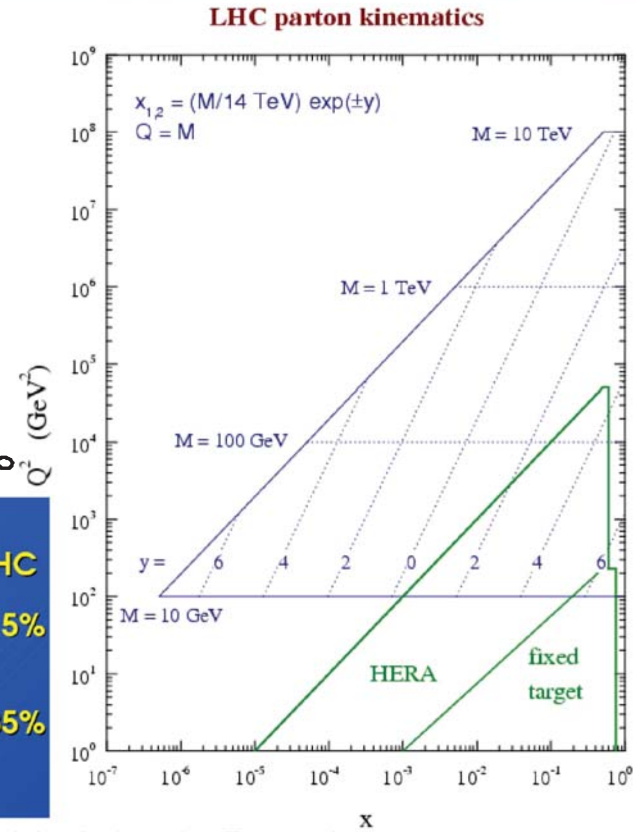


• Vorhersagen über beitragende Prozesse



t u s

	$p\bar{p}$ Tevatron	pp LHC
$q\bar{q}$	~ 85 %	15%
gg	~ 15 %	85%



Unsicherheiten für Extrapolation
von HERA zum LHC

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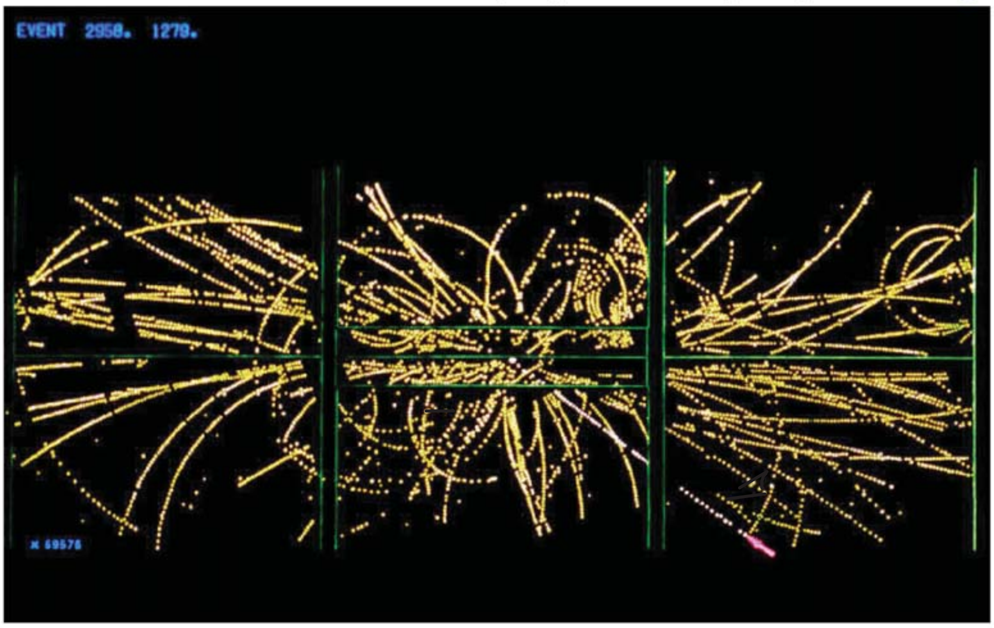
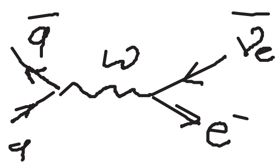
Direkte “on-shell” Erzeugung von W und Z
Entdeckung am Super-Antiproton-Proton Synchrotron (S $\bar{p}$pS) am CERN

Erstes Ereignis $\bar{p}p \rightarrow W + \ldots \rightarrow e\nu + \ldots$
Das Elektron ist durch den roten Pfeil gekennzeichnet
Das Neutrino wird durch fehlenden Transversalimpuls (Summe aller Spuren!) indirekt nachgewiesen





Warum damals $p\bar{p}$ und nicht pp?

Benötige $\sqrt{s_{q\bar{q}}} \gtrsim 80$ GeV $\Longleftrightarrow$ $s_{q\bar{q}} = x_1 x_2 \, s_{p\bar{p}}$

mit Valenzquarks $\langle x_{q_v} \rangle \simeq 0{,}12$

$$\hookrightarrow \sqrt{s_{q\bar{q}}} = \frac{80-90\ \text{GeV}}{0{,}12} = 640-700\ \text{GeV}$$

erreichbar bei SpS

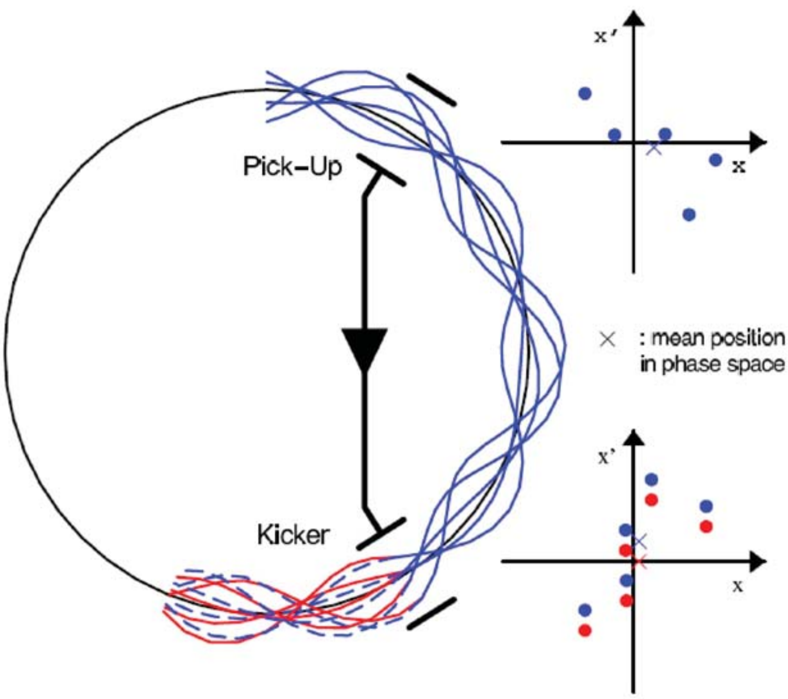
mit pp: $\langle x_{q_v} \rangle = 0{,}12$ $\quad \langle x_{\bar{q}} \rangle \simeq 0{,}04$

$$\sqrt{s_{pp}} = \frac{80-90\ \text{GeV}}{\sqrt{0{,}12}\,\sqrt{0{,}04}} = 1100-1200\ \text{GeV}$$

nicht erreichbar bei SpS

$\rightarrow$ braucht $\bar{p}$ im $Sp\bar{p}S$

Essentiell: Stochastische Kühlung bei $\bar{p}p$ am $S\bar{p}pS$ (Simon van der Meer)



Nobelpreis 1984:
- Carlo Rubbia
- Simon van der Meer

Rekonstruktion über transversale Masse

Beispiele:

links: Drell-Yan W-Produktion bei UA2 (Povh)

rechts: W aus Top-Zerfällen bei LHC (Jana Schaarschmidt, DD)

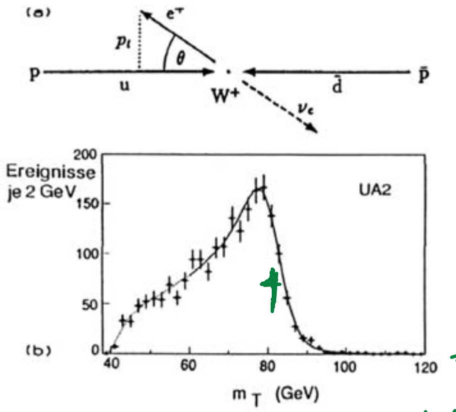
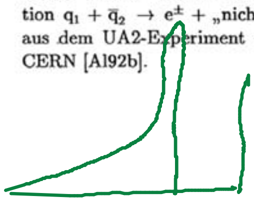
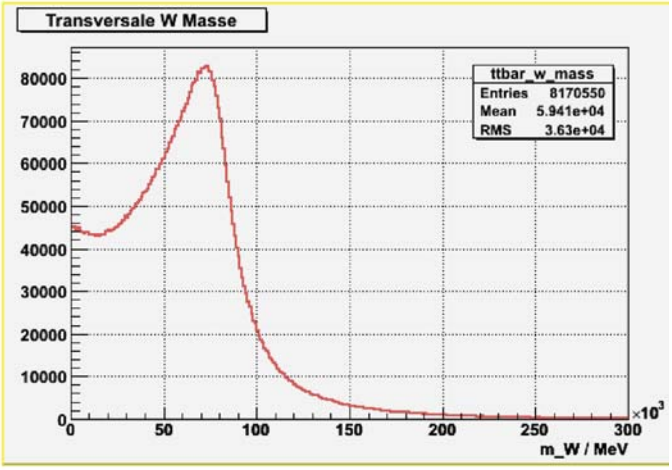


Abb. 11.2. (a) Kinematik des Zerfalls $W^+ \to e^+ + \nu_e$. Der maximal mögliche Transversalimpuls p_t des e^+ ist $M_W c/2$. (b) Verteilung der „transversalen Masse" $m_t = 2p_t/c$ von e^+ und e^- aus der Reaktion $q_1 + \bar{q}_2 \to e^\pm +$ „nichts" aus dem UA2-Experiment am CERN [Al92b].



ohne Detektorauflösung



vollständige W-Masse

$$m_W^2 = (p_\ell^\mu + p_\nu^\mu)^2 = m_\ell^2 + m_\nu^2 + 2E_\ell E_\nu - 2|\vec{p}_\ell||\vec{p}_\nu|\cos\phi_{\ell\nu}$$

$$= 2|\vec{p}_\ell||\vec{p}_\nu|(1-\cos\phi_{\ell\nu})$$

$E \approx p$

Setze $p_{T\nu} = p_{T,miss}$ aber $p_{z\nu} = ?$

$\to$ def. "transversale Masse"

$$\boxed{m_{W_T}^2 = 2|\vec{p}_{T\ell}||\vec{p}_{T\nu}|(1-\cos\underbrace{\phi_{\ell\nu}}_{\text{transv.}}) \le m_W^2}$$

für $\vec{p}_{W_T} = 0 \Leftrightarrow \vec{p}_{T\ell} = -\vec{p}_{T\nu} \Rightarrow m_W^t = 2p_{T\ell}$

Resultat der Entdeckung:

Aus 4 eν Ereignissen:
m_W= (81 +- 5) GeV

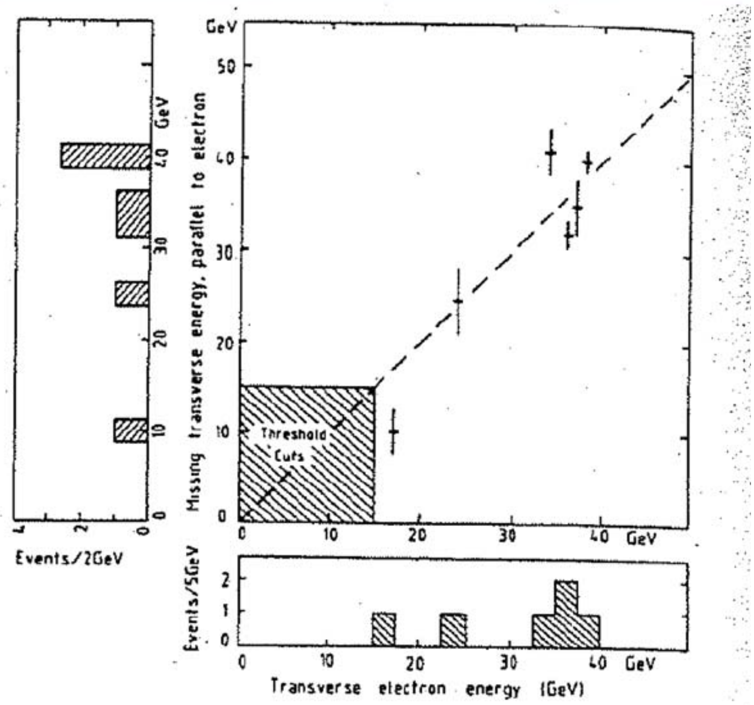


Fig. 8. The missing transverse energy component parallel to the electron, plotted versus the transverse electron energy for the final six electron events without jets (5 gondolas, 1 bouchon) All the events in the gondolas appear well above the threshold cuts used in the searches.

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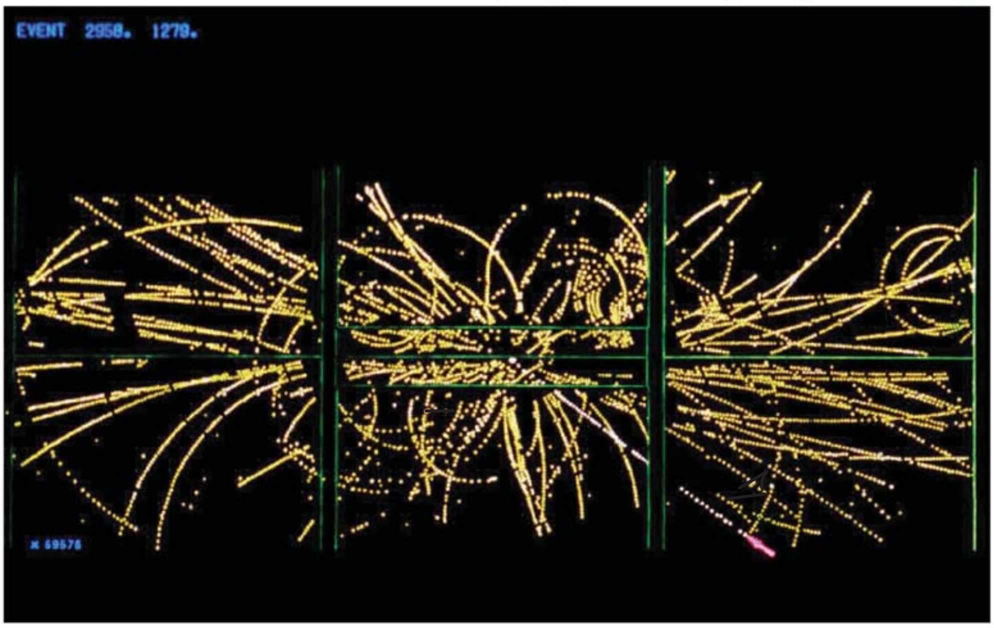
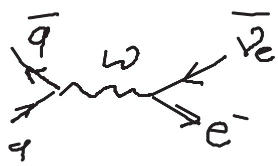
Das Elektron ist durch den roten Pfeil gekennzeichnet
Das Neutrino wird durch fehlenden Transversalimpuls (Summe aller Spuren!) indirekt nachgewiesen





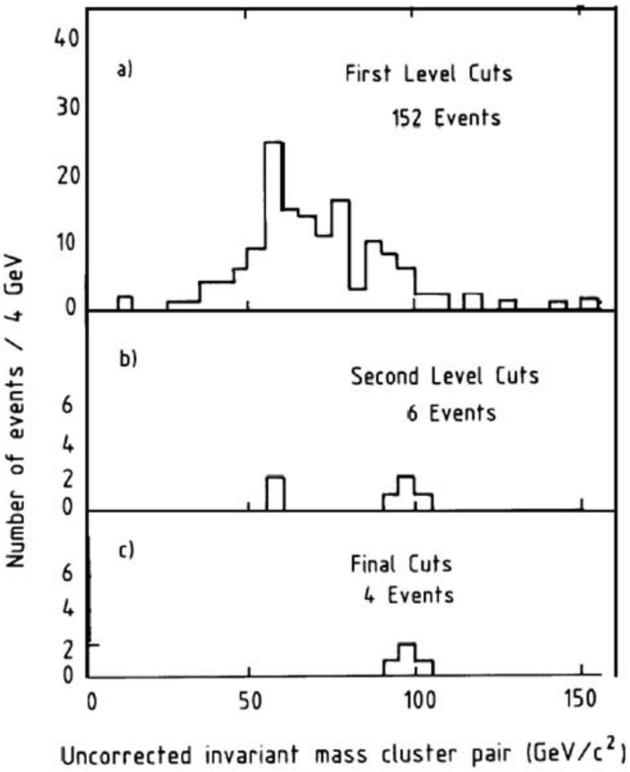


Fig. 24. **Invariant mass distribution (uncorrected) of two electromagnetic clusters: a) with $E_T>25$** GeV; b) as above, and a track with $p_T>7$ GeV/c and projection length of more than 1 cm pointing to the cluster. In addition, a small energy deposition in the hadron calorimeters immediately behind (<0.8 GeV) ensures the electron signature. Isolation is required with $\Sigma p_T<3$ GeV/c for all other tracks pointing to the cluster. c) The second cluster also has an isolated track.

Entdeckung (1983, links):
m_Z = (94 +-3) GeV

Volle Datensätze (1984, unten)

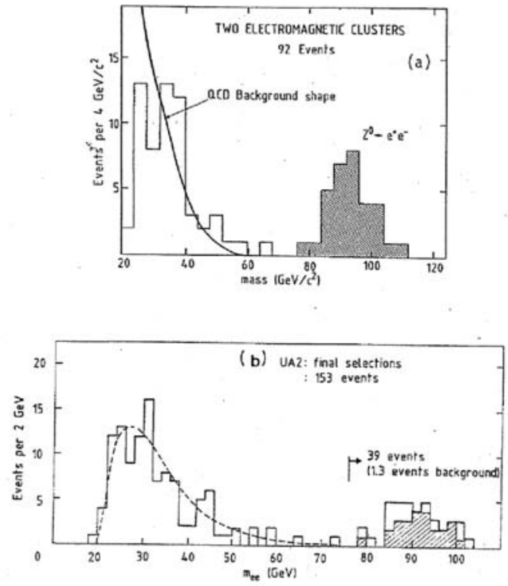


Figure 12.5: (a) The invariant mass distribution for e^+e^- pairs identified through electromagnetic calorimetry in the UA-1 detector. (Figure supplied by UA-1 Collaboration) (b) The analogous plot for the UA-2 data (Ref. 12.12). In both data sets, the Z appears well-separated from the lower mass background.

Die Entdeckung des Z^0 bei UA1, 1983

Das Z wird über seinen Zerfall in $\mu\mu$ (weiße Spuren) und ihrer invarianten Masse rekonstruiert