Electroweak physics and the discovery of the W/Z bosons

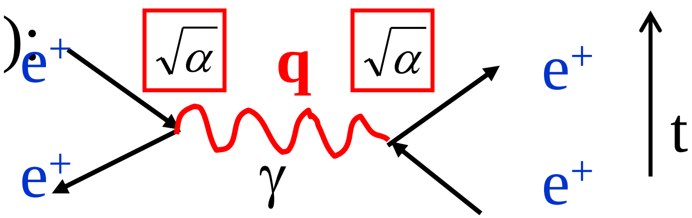
(perhaps the most beautiful, experimentally confirmed, physics theory)

Facts:

-electromagnetic interactions:

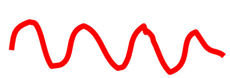
interaction between charged particles mediated by a neutral electromagnetic vector field . Make the theory relativistic and quantized.

The quantized field is the photon with spin 1 and null mass (infinite range):



$$\alpha = \frac{e^2}{4\pi\hbar c}$$

The mediator (the photon) is neutral and the effect of the electromagnetic potential (Coulomb) is described by the propagator:

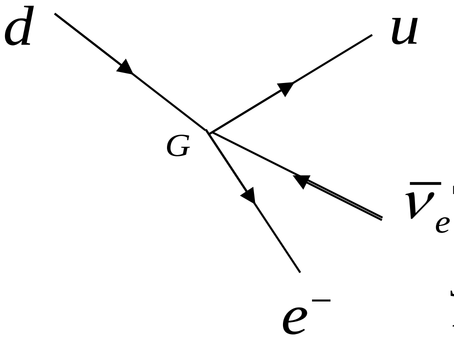


$$\Rightarrow \frac{1}{q^2}$$

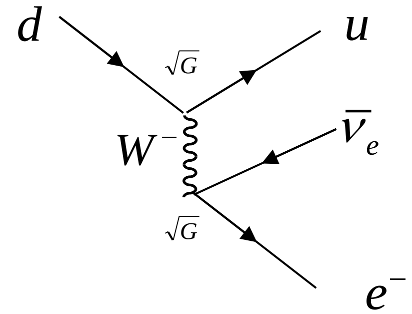
-The weak interactions:

The first one measured: the beta decay:

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$d \rightarrow u + e^- + \bar{\nu}_e$$
$$^3H \rightarrow {}^3He + e^- + \bar{\nu}, {}^6He \rightarrow {}^6Li + e^- + \bar{\nu}$$



The Fermi theory: just the product of two currents multiplied by a constant: G (contact interaction)



$$M = \frac{G}{\sqrt{2}} \langle u | J_\mu | d \rangle \langle e \bar{\nu} | J^\mu | 0 \rangle$$

Hadronic weak current (quarks) — leptonic weak current

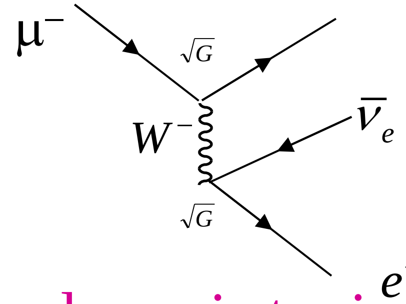
The matrix element M is a constant:

The Phase Space determines the rate : $N(E)dE = E^2 (E_0 - E)^2 dE \Rightarrow N = \int_0^{E_0} N(E)dE = \frac{E_0^5}{30}$

$$\Rightarrow W \propto G^2 E_0^5, \; E_0 = \text{max electron energy} = m_n - m_p$$

$$W = \frac{G^2}{2\pi^3} \int_0^{p_{max}} N(p)dp \propto G^2$$

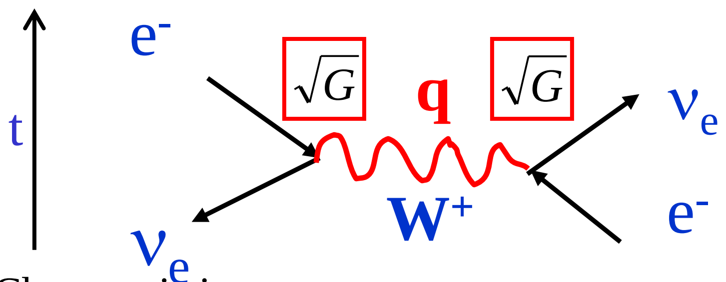
The muon decay is the simplest purely leptonic decay:



$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$\boxed{\frac{1}{\Gamma_\mu} \equiv \tau_\mu = \frac{192\pi^3}{G^2 m_\mu^5}}$$

The m⁻⁵ dependence is typical of any weak decay (neglecting the final particle masses)



Charged weak interaction 2→ 2

Characteristics:

-fermions: leptons and quarks can interact weakly: universal interaction;

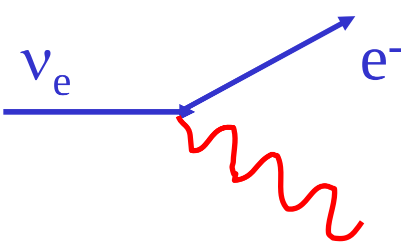
-There is a new neutral particle involved: **the neutrino**;

-The mediator is a spin 1 field but with a mass (short range force) $\to \prec \frac{1}{q^2 - M_W{}^2 + (i\Gamma M_W)}$

-At low interaction energy the intensity of the weak interaction is much lower than the electromagnetic one but it increases with energy (propagator effect).

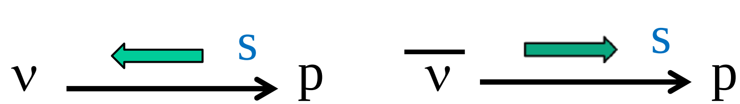
-Weak interactions violate spatial parity: interacting neutrino is left-handed and antineutrino is right-handed

Weak charged current :



$$J^\mu = \frac{g}{\sqrt{2}} \bar{u}(e)\gamma^\mu \frac{1}{2}(1-\gamma^5)u(\nu_e)$$

Difference From QED: (V-A) instead of V



Muon lifetime: τ_μ=2.197 10^{-6} s, m_μ=0.105658 GeV

G = 1.166 10^{-5} GeV^{-2}

$$\text{with} \quad \frac{G}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}, \mathrm{M_W} \approx 80\,\mathrm{GeV} \Rightarrow \mathrm{g_W} = 0.66, \alpha_W = \frac{g_W^2}{4\pi} = \frac{1}{129}$$

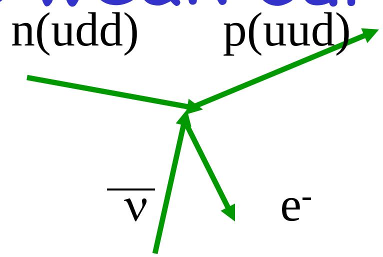
The weak interactions are "weak" because the mediator (W) is very heavy and at low Q^2 it dominates the coupling

Se $Q^2 \sim M_W^2$ (80 GeV)^2 the weak interaction become comparable to the electromagnetic ones:

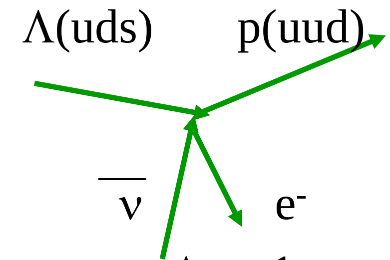
Unifications?

Hadronic weak currents

Experimental evidence of
two beta-like decays

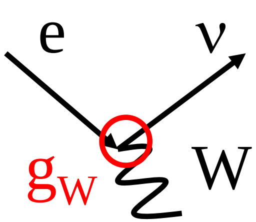


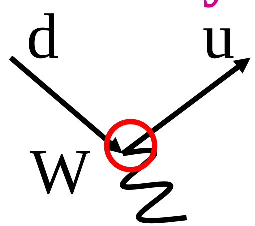
$\Delta s=0$: $d \rightarrow u$

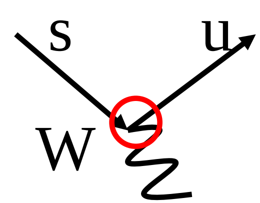


$\Delta s=1$: $s \rightarrow u$

Universality of the beta-decay?







Leptonic : $\mathbf{g_W}$ hadronic $\Delta s=0$: $\mathbf{g_W \cos\theta_c}$ hadronic $\Delta s=1=\Delta Q$: $\mathbf{g_W \sin\theta_c}$

Cabibbo: $\sin\theta_C=0.23$ ($\theta=13^o$) **not predicted**: just an experimental result.

Current still (V-A) $(1-\gamma_5)$. But the quark wavefunctions entering the interaction are:

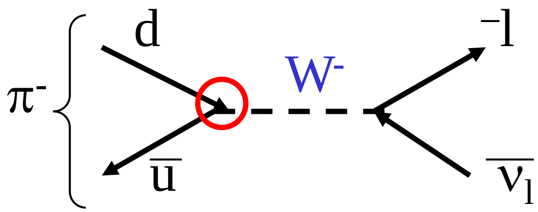
$$d' = d\cos\theta + s\sin\theta$$
$$s' = -d\sin\theta + s\cos\theta$$

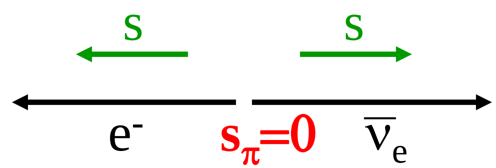
$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$

As in the leptonic case, the charged weak interaction makes the transition between elements of a a weak doublet:

$$\begin{bmatrix} u \\ d' \end{bmatrix} \text{equivalent to} \begin{bmatrix} \nu_e \\ e^- \end{bmatrix}$$

Charged weak interactions of quarks : $\pi^- \to l^- \nu_l$ decay





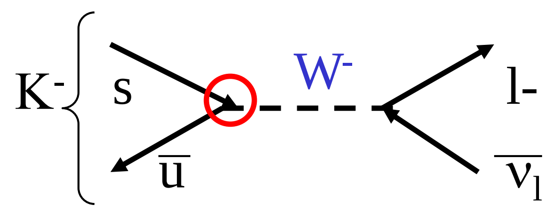
The electron has a "wrong" helicity (+1) disfavoured as:

$$P(\lambda=+1)=1-\beta_{e^-}=\frac{2m_e^2}{m_\pi^2+m_e^2}$$

$$\Rightarrow \Gamma_\pi=\frac{f_\pi^2}{\pi m_\pi^3}\left[\frac{g_W}{4M_W}\right]^4 m_l^2\left[m_\pi^2-m_l^2\right]^2=\frac{f_\pi^2}{\pi m_\pi^3}\frac{G^2}{8}m_l^2\left[m_\pi^2-m_l^2\right]^2$$

$$ansatz: f_\pi = m_\pi \cos\theta_C$$

Similarly : $K^- \to \mu^- \bar{\nu}_\mu (BR = 63.44\%)$



$$\Rightarrow \Gamma_K=\frac{G^2 f_K^2}{8\pi}\frac{1}{m_K^3}m_\mu^2\left[m_K^2-m_\mu^2\right]^2$$

$$ansatz: f_K = m_K \sin\theta_C$$

from the measured π and K lifetimes : τ_π, τ_K $(\tau = 1/\Gamma_{tot})$

$$tan^2\theta_C = 0.63\frac{\tau_\pi}{\tau_K}\frac{m_K^3}{m_\pi^3}\frac{(m_\pi^2-m_\mu^2)^2}{(m_K^2-m_\mu^2)^2} \Rightarrow \begin{cases} sin\theta_C = 0.265 \\ cos\theta_C = 0.964 \end{cases}$$

Cabibbo Kobayashi Maskawa matrix (CKM)

1973: Cabibbo theory generalization with 3 quark doublets : **at least three quark generations needed to provide a CP violation (i.e an irriducible phase).**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The matrix V is complex: 18 elements, but it is also unitary:

$$V^{+}_{\alpha\beta} V_{\beta\alpha} = \delta_{\alpha\beta} \text{ (9 equations)} \Rightarrow 9 \text{ elements}$$

There is ans arbitrary phase at each particle: 9-3*2=3, but still a common phase factor remains :3+1= **4 independent elements (1 phase)**

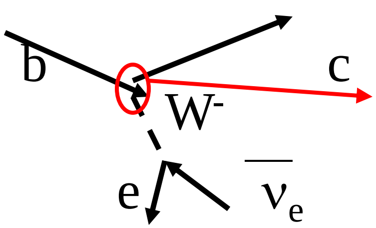
Standard parametrization (PDG): 3 angles θ_{ij} (θ_{12} Cabibbo angle) + a phase: δ_{13}

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

N.B. V cannot be predicted theoretically:its elements extracted from the experiments:



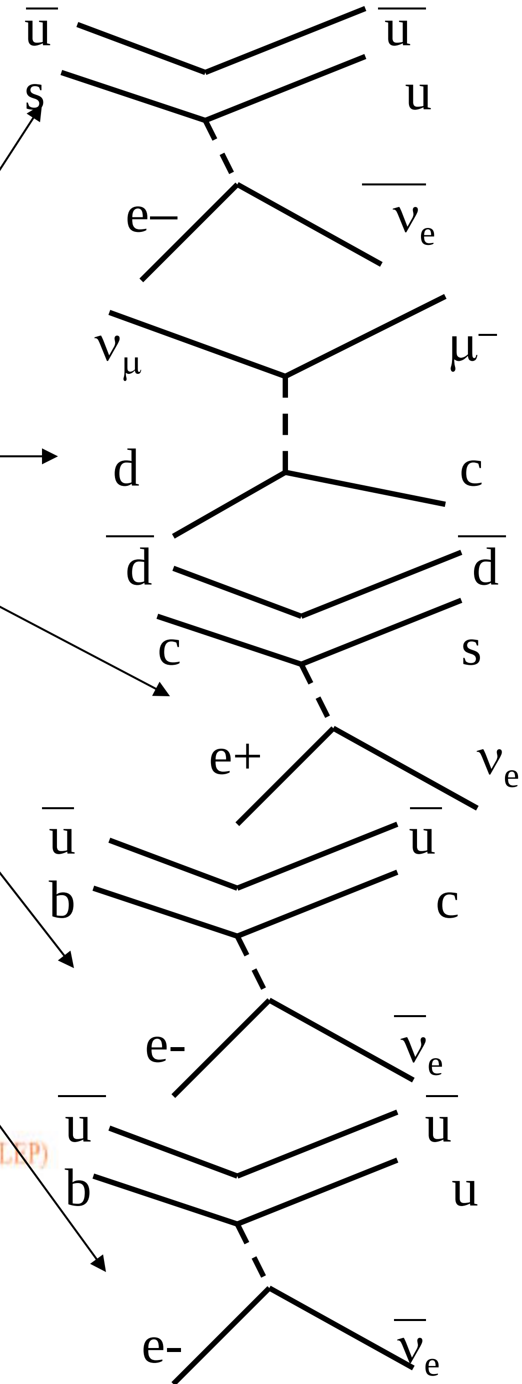
V_{cb}

$$\Gamma(b \to c e^- \bar{\nu}_e) = \frac{G^2 m_b^5}{192\pi} \left| V_{cb} \right|^2 \; F(m_c / m_b)$$

$F(m_c/m_b)$ is a phase-space factor (=1 if you neglect the final state particle masses)

V_{ij} DETERMINATIONS

CKM entry	Value	Source
$\lvert V_{ud}\rvert$	0.9740 ± 0.0005	Nuclear β decay
	0.9731 ± 0.0015	$n \to p e^- \bar{\nu}_e$
	0.9739 ± 0.0005	
$\lvert V_{us}\rvert$	0.2196 ± 0.0026	$K \to \pi e^- \bar{\nu}_e$
$\lvert V_{cd}\rvert$	0.224 ± 0.016	$\nu d \to c X$
$\lvert V_{cs}\rvert$	1.04 ± 0.16	$D \to \bar{K} e^+ \nu_e$
	0.97 ± 0.11	$W^+ \to c\bar{s}$
$\lvert V_{cb}\rvert$	0.0421 ± 0.0021	$B \to D^* l \bar{\nu}_l$
	0.0414 ± 0.0011	$b \to c l \bar{\nu}_l$
	0.0416 ± 0.0020	
$\lvert V_{ub}\rvert$	0.0033 ± 0.0005	$B \to \rho l \bar{\nu}_l$
	0.0041 ± 0.0006	$b \to u l \bar{\nu}_l$
	0.0036 ± 0.0005	
$\lvert V_{tb}\rvert / \sqrt{\sum_q \lvert V_{tq}\rvert^2}$	$0.97^{+0.16}_{-0.12}$	$t \to bW / qW$



$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0006$$

$$\sum_j \left(|V_{uj}|^2 + |V_{cj}|^2 \right) = 2.039 \pm 0.025 \quad \text{(LEP)}$$

A third doublet is required

From experiments:

$$V_{CKM} = \begin{vmatrix} 0.97427 & 0.22534 & 0.00351 \\ 0.22520 & 0.97344 & 0.04120 \\ 0.00867 & 0.0404 & 0.999146 \end{vmatrix}$$

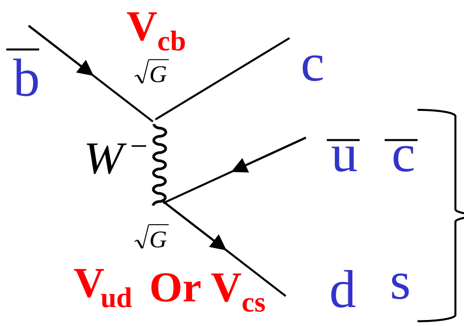
Unitarity puts contraints on rows and colums elements, ex:

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$

Note:

The matrix is nearly diagonal:

In particular ,the off diagonal elements of the 3° row and column are very small: the III generation (t,b) is almost decoupled: The b-quark lifetime is large despite the large mass.



x3 : summed up on the three quark colors

Are there additional quark doublets?

Generalization to n quark generations

$$\frac{n(n-1)}{2} \text{ angles} ; \frac{(n-1)(n-2)}{2} \text{ phases.}$$

The Z boson total width: Γ_Z and the number of neutrinos (families)

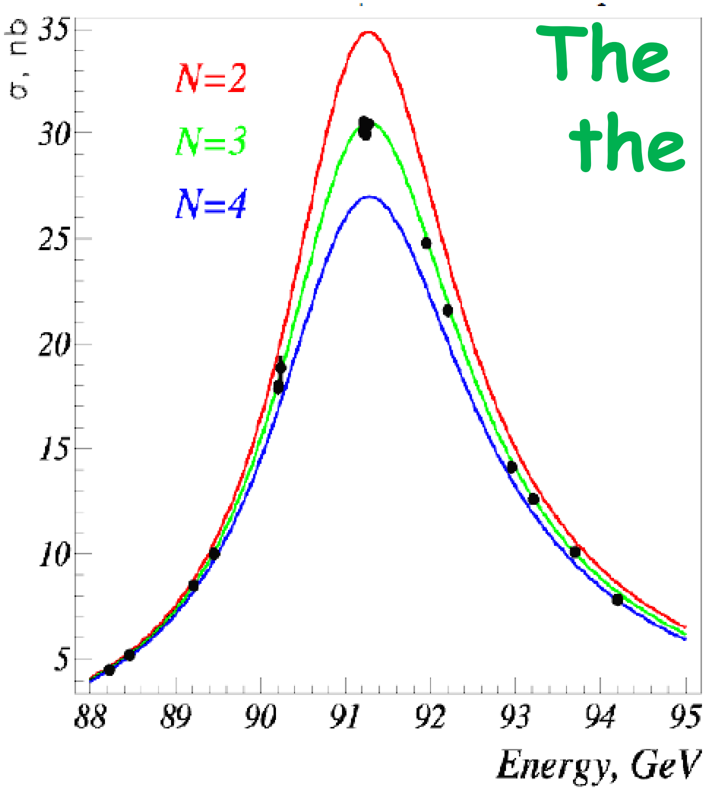


Fig.2. The shape of the Z^0 resonance yields information on the number of light neutrino types [three and only three].

$$P(m) = \frac{1}{2\pi} \frac{\Gamma}{\Gamma^2/4 + (m - m_0)^2}$$

$$\Gamma_Z = \Gamma(e^+e^-) + \Gamma(\mu^+\mu^-) + \Gamma(\tau^+\tau^-) + \\ + \Gamma(u\bar{u}) + \Gamma(d\bar{d}) + \Gamma(s\bar{s}) + \Gamma(c\bar{c}) + \Gamma(b\bar{b}) + \\ + N_\nu \times \Gamma(\nu\bar{\nu})$$

N_ν number of neutrino types (with $m_\nu < M_Z/2$) $(\Gamma(\nu\bar{\nu}) = 166.2\ \text{MeV if } m_\nu = 0)$

The Z width is a measure of the neutrinos number

$$N_\nu = 2.984 \pm 0.008 (\text{PGD LEP data})$$

6 leptonis+ 6 quarks spin ½ ,masses from :
0.5 MeV to 175 GeV/c^2 (+ neutrino masses: eV?)
For weak interactions, fermions are organized in doublets (weak isospin 1/2)

Leptons : e^-, μ^-, τ^- m=0.51, 106, 1777 MeV

$\nu_e, \quad \nu_\mu, \quad \nu_\tau$ m~ eV?????

Quarks : $u, \quad c, \quad t$

$u, \quad c, \quad t$ m ~1, 1500, 175000 MeV

$u, \quad c, \quad t$

$d, \quad s, \quad b$

$d, \quad s, \quad b$ m=1, 170, 5000 MeV

$d, \quad s, \quad b$

3 "color" charges

To build an unified EW theory we need also a weak neutral interaction

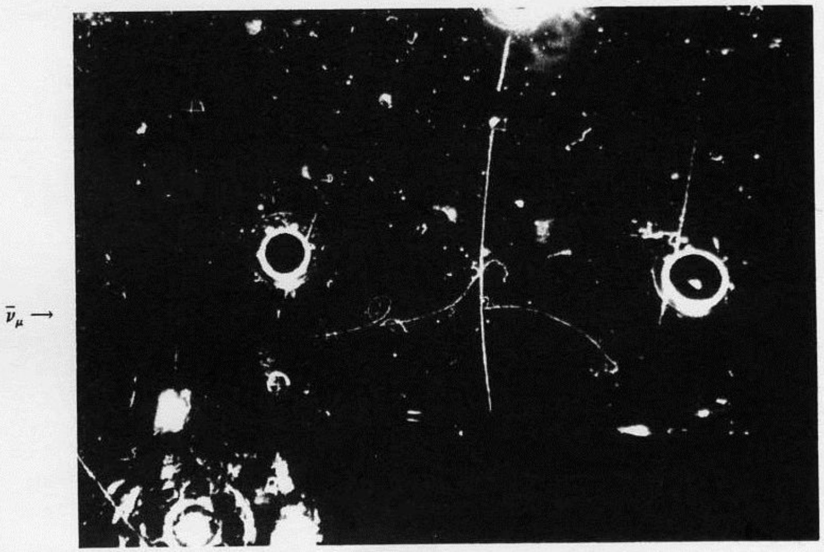
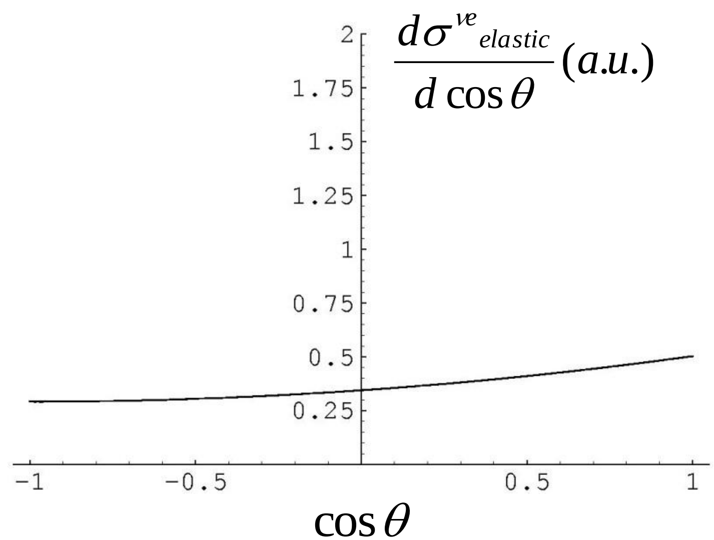


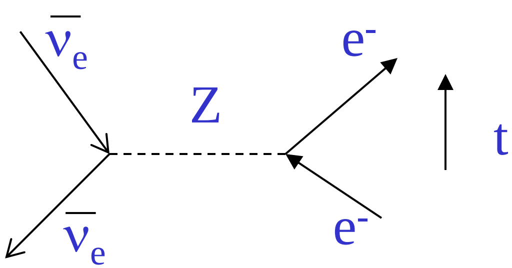
Figure 10.6 The first picture of a neutral weak process ($\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$). The neutrino enters from the left (leaving no track), and strikes an electron, which moves off horizontally to the right, emitting two photons (which show up in the picture only when they subsequently produce electron-positron pairs) as it slows down and spirals inward in the superimposed magnetic field. (Photo courtesy CERN.)

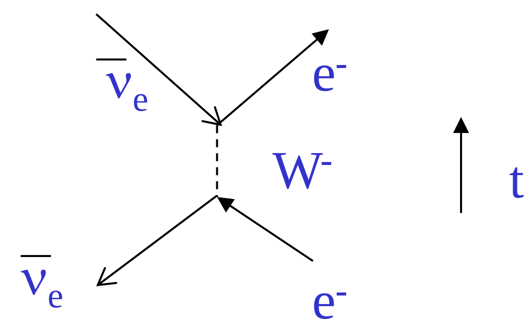
A neutral current event in bubble chamber (1973)

$$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$$

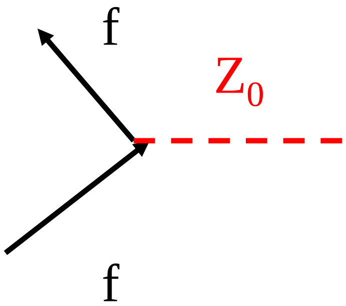


Note that in the scattering $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ would contribute both the neutral current interaction (Z) and the charged current one (W)





Basics of weak neutral currents

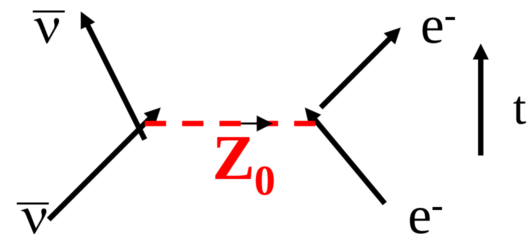


Mediated by an heavy neutral boson : Z_0

Initial and final fermions are the same:

$\mu^- \not\to e^- Z_0$; $s \not\to d\ Z_0$

1973: events mesured in bubble chamber (Gargamelle)



$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$ event with only one electron

$\bar{\nu}_\mu N \to \bar{\nu}_\mu N;\ \nu_\mu N \to \nu_\mu N$ event with only hadrons (no muon)

Facts: neutral current cros sections are ≈1/3 of those equivalent of charged currents
Moreover the current is not pure (V-A): ($\gamma_\mu(1-\gamma_5)$): the coefficient of the vector and axial parts are not the same

$$-i\frac{g_Z}{2}\gamma_\mu\left[C_V^f - C_A^f\gamma_5\right]$$

The coefficients C_V e C_A depend on fermion type

A unified elctro week model has to be built (GWS): a new parameter : θ_W

Connecting "g_W", "g_Z" and "e":

$$g_e = e;\ g_W = \frac{g_e}{\sin\theta_W};\ g_Z = \frac{g_e}{\sin\theta_W\cos\theta_W}$$

Leptons and quarks organized in weak isospin doublets (T, T_3):

$$T_3 = 1/2 \qquad T_3 = -1/2$$

$$\begin{bmatrix}\nu_e \\ e\end{bmatrix}\begin{bmatrix}\nu_\mu \\ \mu\end{bmatrix}\begin{bmatrix}\nu_\tau \\ \tau\end{bmatrix}\quad\begin{bmatrix}u \\ d\end{bmatrix}\begin{bmatrix}c \\ s\end{bmatrix}\begin{bmatrix}t \\ b\end{bmatrix}$$

Towards an electroweak unification

There is a general principle in particle quantum field theory:

the local gauge invariance:

-For the electrodynamics this imply the invariance of the lagrangian if the particle wave functions are multiplied by a local phase: $e^{\theta(x)}$. This corresponds to a symmetry invariance of the group U(1)

-For the weak interactions the wave function is a doublet ex: (ν,e) and the invariance is for rotations in the space of the weak isotopic spin (same algebra of the ordinary ½ spin) : the corresponding symmetry group is SU(2).

For an unified electroweak theory the lagrangian should be invariant for both:

U(1) x SU(2)

Electric charge conservation
(Hypercharge: $Y=Q-T_3$)

Weak isospin, T conservation

Basics The GWS unification model

U(1) implies a isosinglet massles boson B_μ

SU(2) implies a isovector triplet: $\vec{W} = (W_\mu^1, W_\mu^2, W_\mu^3)$

SU(2)xU(1) is broken : **the neutral state (B,W^3) mix to give the physical states**

$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$

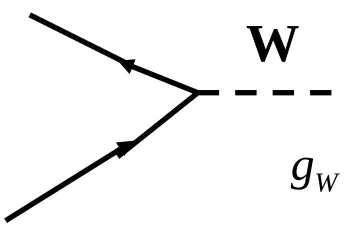
$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

A_μ e Z_μ are the physical observable states,
sinθ_W is a free parameter

$\nu_e\ \nu_\mu\ \nu_\tau$ u c t

↕ ↕ ↕ ↕ ↕ ↕

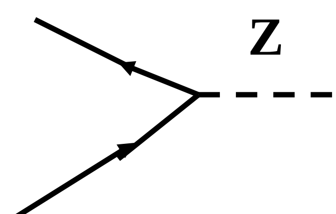
e, μ, τ d s b



Universal charged current connects lepton and quark doublets with coupling g_W (V-A) : $g_W(1-\gamma_5)$

$$g_W = \frac{e}{\sin\theta_W} \quad \gamma^5 == \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad \frac{1}{2}(1-\gamma^5) = \begin{bmatrix} 0\,0 \\ 0\,1 \end{bmatrix} \Rightarrow \text{select spinor of given helicity,:} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}$$

$\nu_e\nu_\mu\nu_\tau$e,μ,τ, q



$\nu_e\nu_\mu\nu_\tau$e,μ,τ, q

Neutral current connects the same flavour leptons and quarks depending on charge , isospin , sin θ_W and with coupling :

g_Z (V-Aγ_5) $g_Z = \dfrac{e}{\sin\theta_W \cos\theta_W}$, $V = T_3 - 2q\sin^2\theta_W$, $A = T_3$

Minimal model

$$g_W = \frac{e}{\sin\theta_W}, g_Z = \frac{e}{\sin\theta_W \cos\theta_W}, \frac{g_W^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}, M_Z = \frac{M_W}{\cos\theta_W}$$

$$Parameter\,\rho = \left(\frac{g_Z^2}{M_Z^2}\right) \Big/ \left(\frac{g_W^2}{M_W^2}\right) = 1$$

Particles mediating the interactions $W^{\pm}, Z, \gamma$ massless so far!!!

An additional scalar field doublet, the Higgs, is required to provide masses to W and Z (see Marumi Kado lecture)

The model parameters are 3, ex : $\alpha, G_F, \sin^2\theta_W$

Theory is determined

$$\alpha = \frac{e^2}{4\pi\hbar c} = \frac{1}{137.035999074(44)} \text{ (a } Q^2 = m_e^2\text{) } 0.000032 \text{ ppm (atomic physics)}$$

$$G_F = 1.1663787(6) \times 10^{-5}\,GeV^{-2} \text{ (muon decay) } 0.5\text{ppm}$$

$$\sin^2\theta_W(M_Z) = 0.23116(12)\ 520 \text{ ppm}$$

if $we : know : \alpha, G_F, \sin^2\theta_W$

we can predict :

$$M_W = \left[\frac{\pi\alpha}{\sqrt{2}G_F}\right]^{\frac{1}{2}} \frac{1}{\sin\theta_W} \approx 78\,GeV$$

$$M_Z = \frac{M_W}{\cos\theta_W} \approx 89\,GeV$$

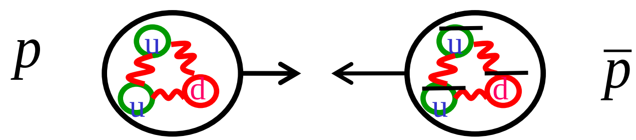
The search for W/Z bosons

Masses ~ 80-90 GeV.
1980: highest accelerator cms energy √s, at fixed target (SPS at CERN):

$$\sqrt{s} = \sqrt{2m_N E} \approx 30GeV(E = 450\,GeV)$$

But if you collide head-on: $\sqrt{s} = 2E \approx 900GeV$

Use SPS as proton-antiproton Collider (Rubbia- Van Der Meer)



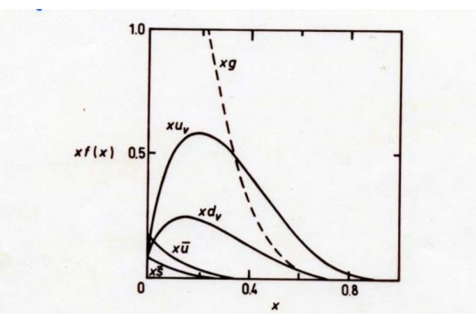


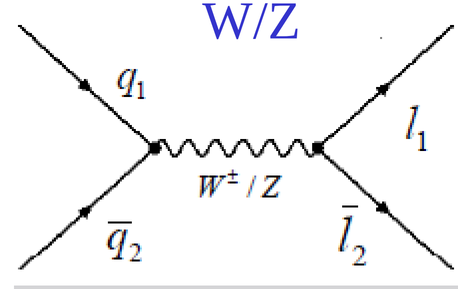
Fig. 2.9. Parton momentum distribution functions for the proton, $xf(x)$. (From Gen. Ref. 3.)

50% momentum carried by quarks and
50% by gluons. Average momentum budget :

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} \xrightarrow{\text{balanced momenta } x_1 = x_2 = x} x\sqrt{s}$$

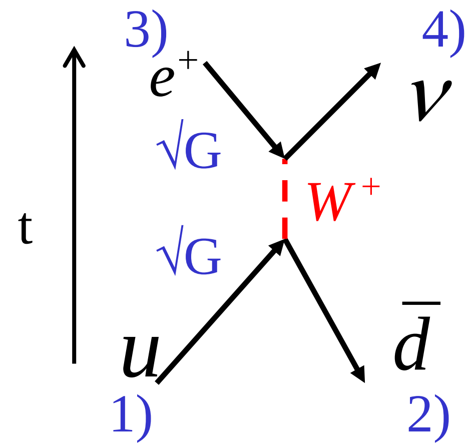
$$\xrightarrow{x=1/6} \frac{900}{6} = 150GeV$$

Annihilate quark and antiquark to produce W/Z

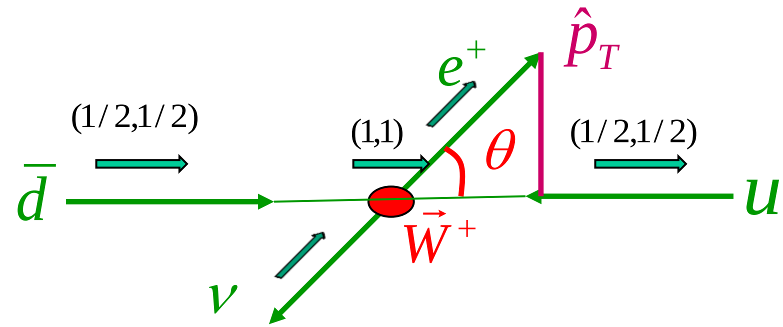


W-measurement

$u\bar{d} \rightarrow W^+ \rightarrow e^+\nu$

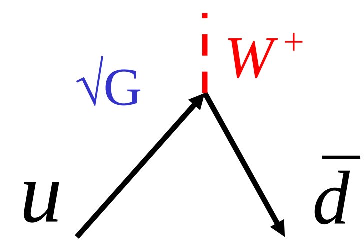


in the center of mass $u\bar{d}$



Angular distribution $\frac{d\sigma}{d\cos\theta} \propto (1+\cos\theta)^2$ (angular momentum conservation effect)

Inclusive cross section for W production $u\bar{d} \rightarrow W^+$



Rough order of magnitude of cross section: “G” :G has dimension GeV^{-2}

We need a cross section: cm^2

a length can be expressed in GeV^{-1} :

$\lambda_C = \hbar/mc$ if $mc^2 = 1GeV, 1GeV^{-1} \approx 0.2\cdot 10^{-13} cm; 1GeV^{-2} \approx 4\cdot 10^{-28} cm^2$

$$\sigma(u\bar{d} \rightarrow W^{+}) \approx (?)G \approx 10^{-5} GeV^{2} \approx 10^{-33} cm^{2} = 1nb$$

Better calculation: take into account PDF's, available phase space, angular distribution,...

$p\bar{p}, \sqrt{s} = 630\,\text{GeV}, \sigma(\text{W}^{\pm}) \approx 3\,\text{nb}$ (ud)

$p\bar{p}, \sqrt{s} = 2\,\text{TeV}, \sigma(\text{W}^{\pm}) \approx 20\,\text{nb}$ (ud)

$pp, \sqrt{s} = 7\,\text{TeV}, \sigma(\text{W}^{+}) \approx 56\,\text{nb}$

$pp, \sqrt{s} = 7\,\text{TeV}, \sigma(\text{W}^{-}) \approx 40\,\text{nb}$

$pp, \sqrt{s} = 14\,TeV, \sigma(W^{\pm}) \approx 150\,nb\ \ (u\bar{d} + \bar{d}u)$

Measure the leptonic decay: $\text{W} \rightarrow e\,\nu$

further 0.1 factor (leptonic BR)

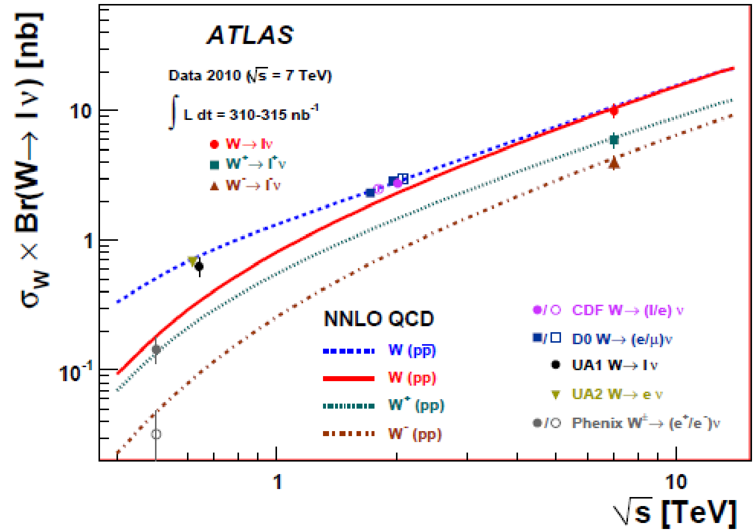


Fig. 12: *The measured values of* $\sigma_W \cdot \text{BR}\,(W \rightarrow \ell\nu)$ *for* W^+, W^- *and for their sum compared to the theoretical predictions based on NNLO QCD calculations (see text). Results are shown for the combined electron-muon results. The predictions are shown for both proton-proton (W^+, W^- and their sum) and proton-antiproton colliders (W) as a function of* $\sqrt{s}$. *In addition, previous measurements at proton-antiproton and proton-proton colliders are shown. The data points at the various energies are staggered to improve readability. The CDF and D0 measurements are shown for both Tevatron collider energies,* $\sqrt{s} = 1.8$ *TeV and* $\sqrt{s} = 1.96$ *TeV. All data points are displayed with their total uncertainty. The theoretical uncertainties are not shown.*

Note that the difference of crosssections $p\bar{p}$ and pp tend to vanish as energy increases

Questions:

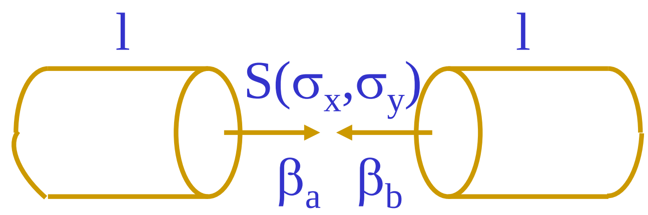
- How to realize a p-pbar collider
- At a collider the collision rate is :

$$R = \sigma \cdot L, L \equiv \text{luminosity}: \text{cm}^{-2} s^{-1}; \Rightarrow if\ \sigma = 10^{-33} cm^{2} and\ R = 1 s^{-1}$$

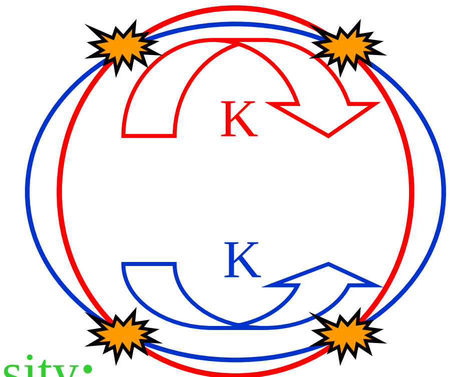
$$\Rightarrow L = 10^{33}\,\text{cm}^{-2} s^{-1}$$

L depends on the accelerator and is proportional to the numebr colliding particles: how to get a sufficient number of antiprotons??

The colliding beams
are structured in bunches
of particles



$$L = \frac{n_a n_b}{4\pi\sigma_x\sigma_y} K \cdot f$$



We introduce also an integrated luminosity:

$$N = \sigma \int L dt \quad \left(\int L dt : \text{dimension cm}^{-2}\right)$$

Ex. $n_a = n_b = 10^{10}$

$K = 2$

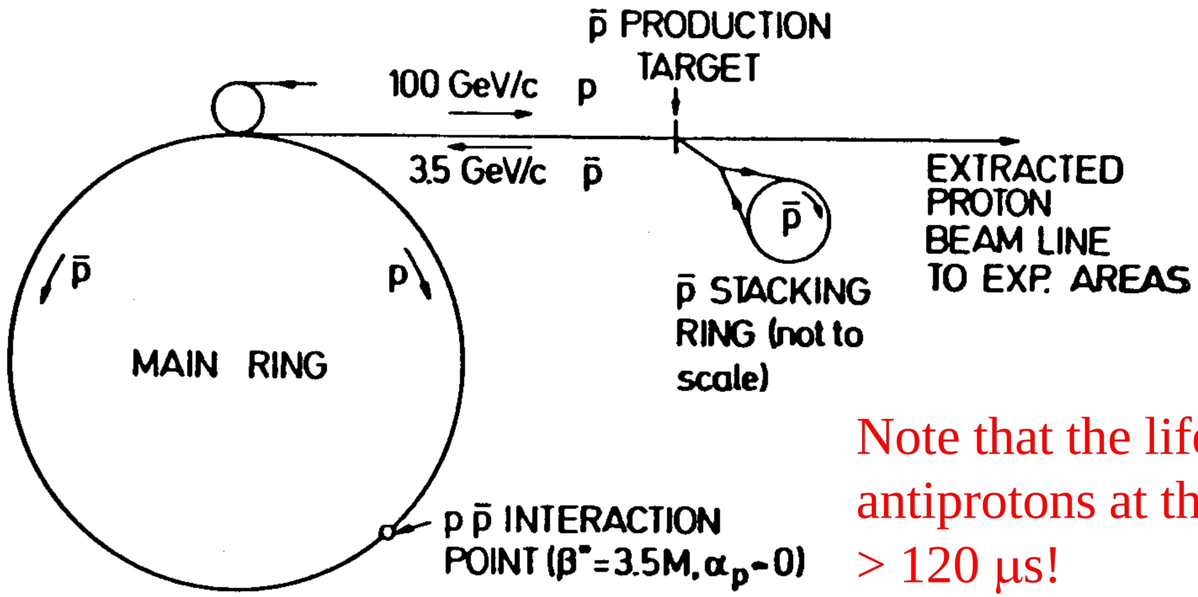
$\sigma_x = \sigma_y = 1$ mm

$f = 43$KHz

→ **$L \sim 10^{30}$ cm^{-2} s^{-1}**

The proposed PBAR-P collider

Scheme to trasform a fixed targed accelerator into a p-pbar collider : C. Rubbia, D.Cline e P. Mac Intyre for the Main Ring of 450 GeV at Fermilab in 1974.



Note that the lifetime of antiprotons at that time was only > 120 μs!

Fig. 5. General layout of the pp̄ colliding scheme, from Ref. [9]. Protons (100 GeV/c) are periodically extracted in short bursts and produce 3.5 GeV/c antiprotons, which are accumulated and cooled in the small stacking ring. Then p̄'s are reinjected in an RF bucket of the main ring and accelerated to top energy. They collide head on against a bunch filled with protons of equal energy and rotating in the opposite direction.

The PBAR-P COLLIDER OF THE CERN SpS

Need to build:

-an antiproton source
-a system to compact antiprotons both in angle and momentum:
the stochastic cooling

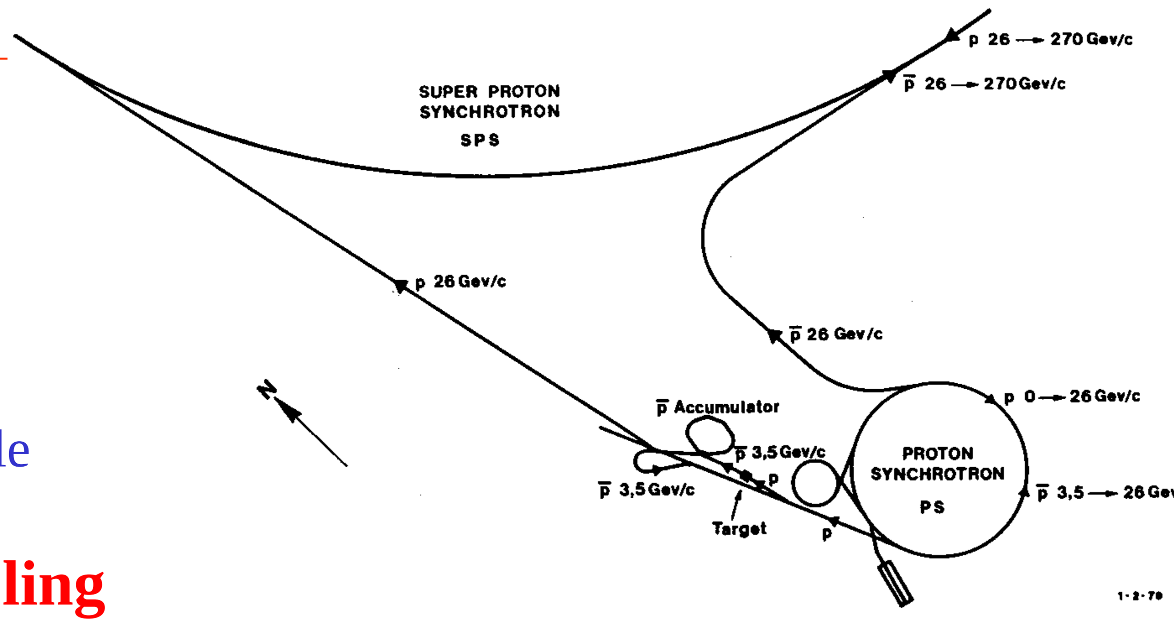


Fig. 1. Overall layout of the $p\bar{p}$ project.

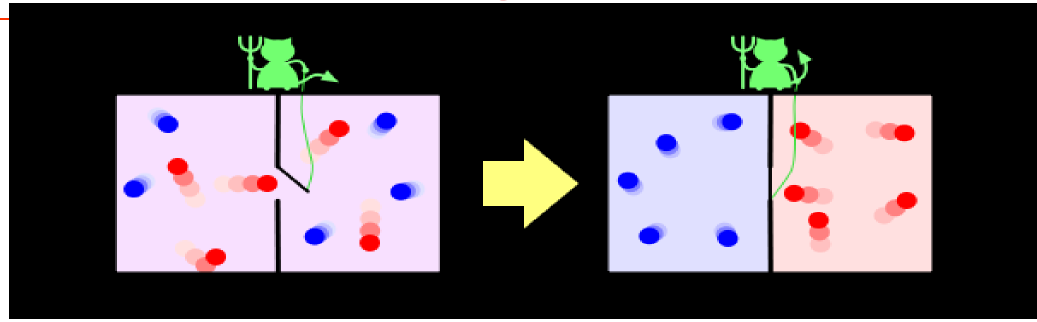
$$Linac\ 50\ MeV \rightarrow Booster\ 800\ MeV \rightarrow PS\ 26\ GeV$$

$$\rightarrow \text{Target} : \frac{\bar{p}}{p} \approx 10^{-6} \rightarrow \text{magnetic lens} \rightarrow$$

$$\rightarrow AA + AC(\approx 10^{12}\ \bar{p}/day) \rightarrow SpS\ 315\ GeV$$

Moel et al., Physics Reports 58, No.2 (1980), p.73.

Stochastic cooling (Maxwell's demon)



Two pick-up measure the transverse and longitudinal deviation of particles from the ideal orbit. A correction signal (kicker)is applied , in average after an appropriate delay on the orbit of the particles

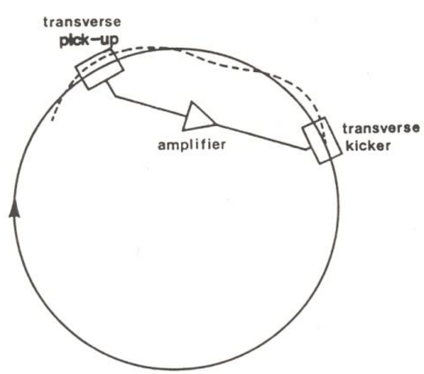


FIG. 2. Cooling of the horizontal betatron oscillation of a si gle particle.

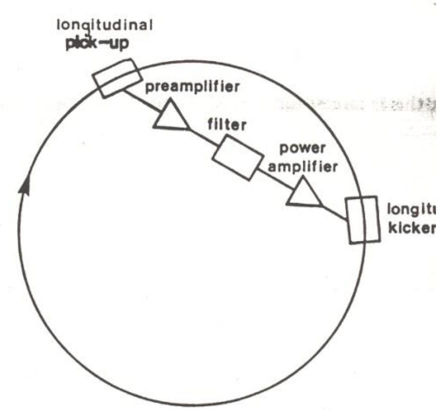
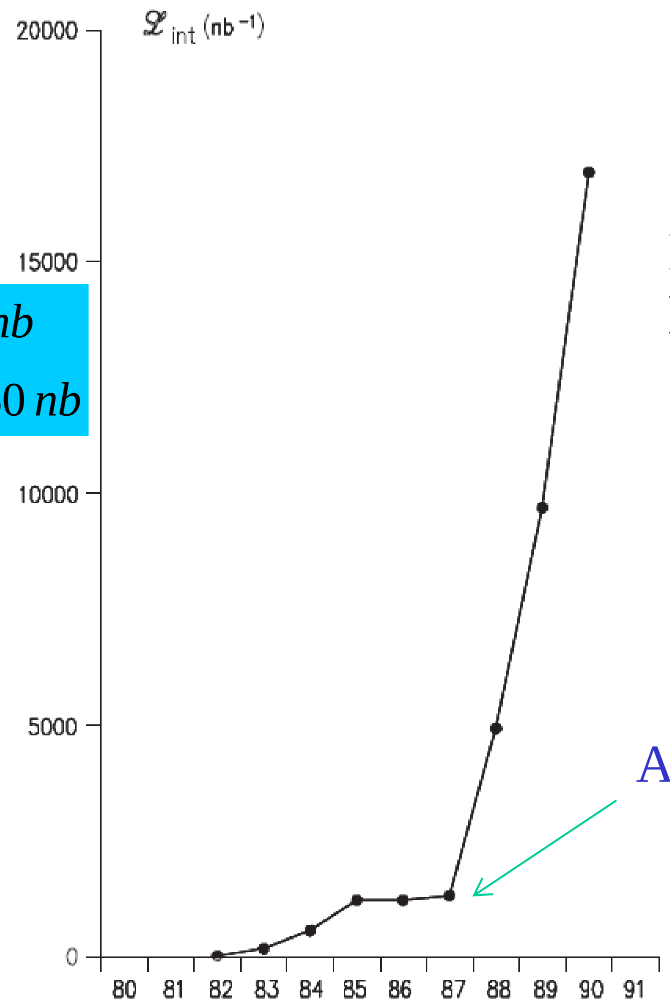


FIG. 7. Filter cooling.

D. Mohl, Stochastic Cooling for Beginners, CERN 84-15, 1984, p.97
S.van der Meer, Stochastic Cooling and the Accumulation of Antiprotons, Rew. Mod. Physics, Vol 57,No.3, part1, July 1985.

Integrated luminosity at the SPS collider

$$\sigma(\bar{p}p \rightarrow Z(Z \rightarrow e^+e^-) + X) \sim 0.05\, nb$$
$$\sigma(\bar{p}p \rightarrow W^+(W^+ \rightarrow e^+\nu) + X) \sim 0.50\, nb$$



Max instantaneous luminosity:
3 10^{30} cm^{-2} s^{-1}

AC+ low beta

Fig. 8. Integrated luminosity of the SPS Collider, from 1982 (first year of routine operation) to 1990 (last full operation). 1980 was the year of AA running-in, 1981 of Collider and detector tests. The luminosity integrated over 1982 and 1983 appears tiny, but sufficed to detect the W and Z and bring the Nobel prize 1984 to CERN. The break in 1986 was due to the repair of UA1 and the beginning of AC installation. AC running-in was completed in 1987, with only a short Collider run at the end of the year. From 1988 onwards, the effect of the AC and the improvements made to the SPS came to bear.

SPSC Collider story

Year	Collision Energy (GeV)	Peak luminosity (cm^{-2} s^{-1})	Integrated luminosity (cm^{-2})
1981	546	$\sim 10^{27}$	2.0×10^{32}
1982	546	5×10^{28}	2.8×10^{34} ← W discovery
1983	546	1.7×10^{29}	1.5×10^{35} ← Z discovery
1984-85	630	3.9×10^{29}	1.0×10^{36}
1987-90	630	$\sim 2 \times 10^{30}$	1.6×10^{37}

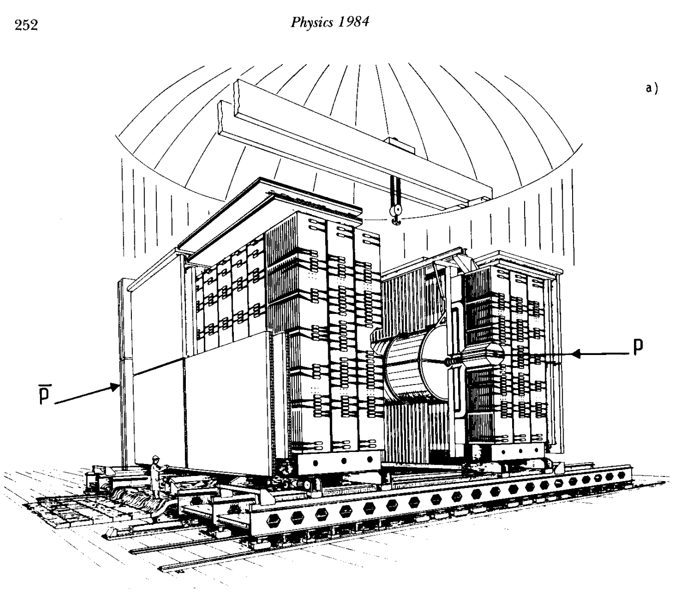
1991: END OPERATIONS

Two detectors at the SpSC to measure W/Z

Measure the leptonic decays of $W \rightarrow e\nu_e, \mu\nu_\mu, Z \rightarrow e^+e^-, \mu^+\mu^-$

UA1, calorimeters and central dipolar magnetic field + muon detection

UA2, calorimeters ,no central magnetic field



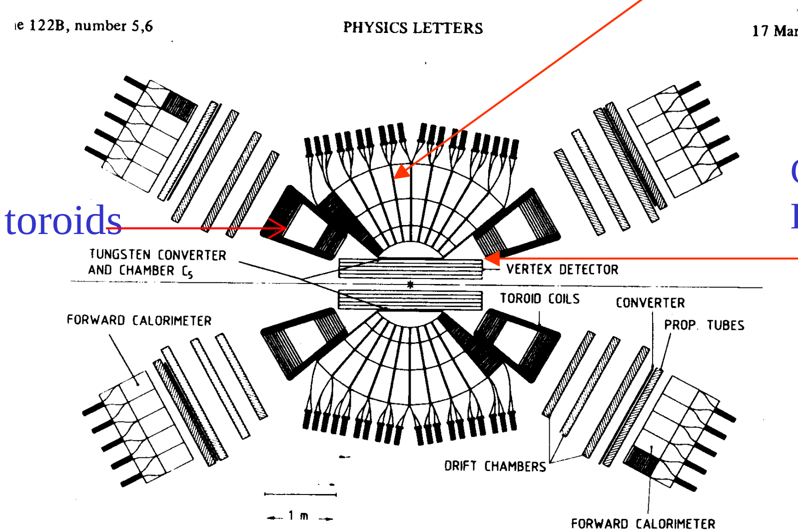
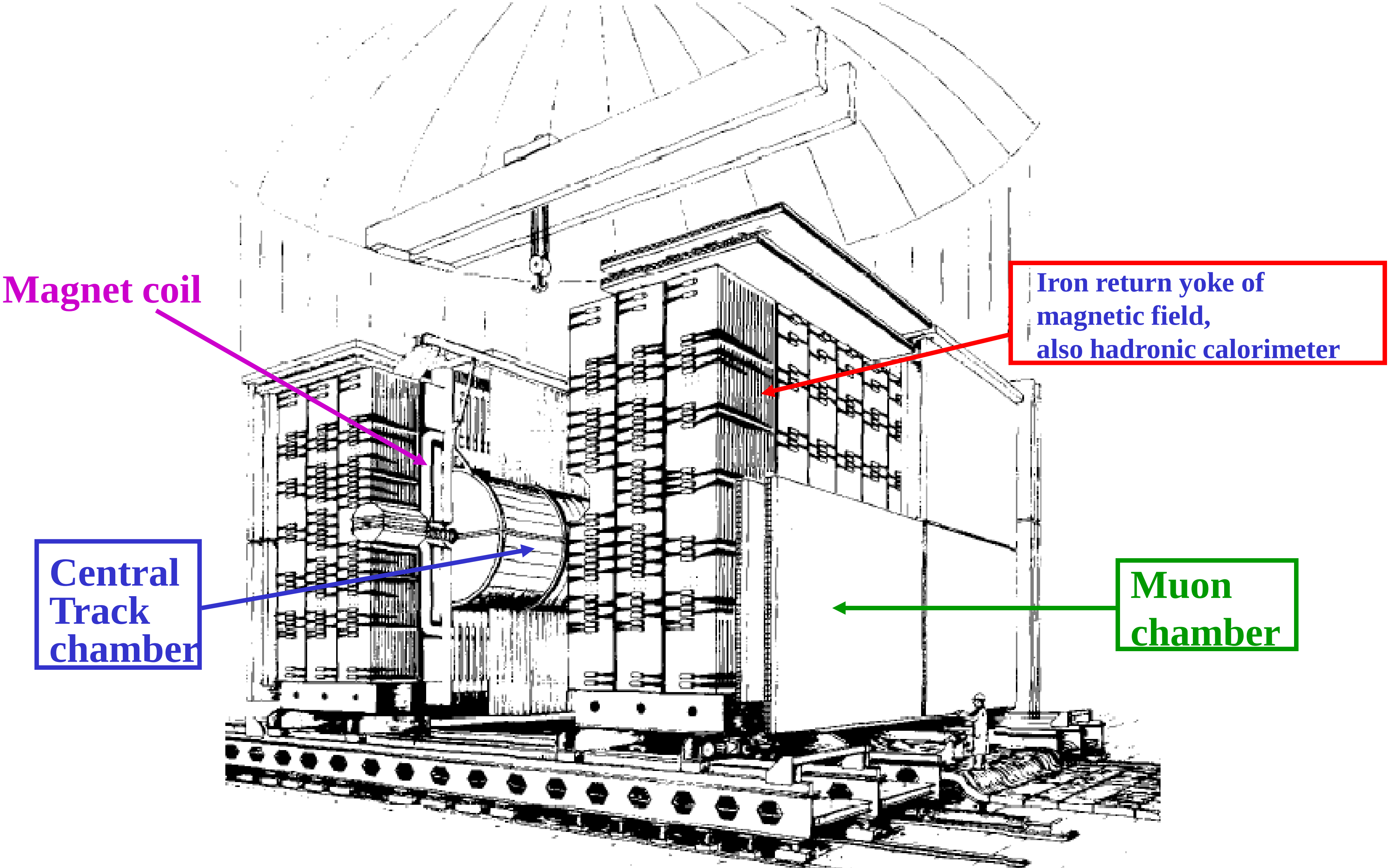


Fig. 1. The UA2 detector: Schematic cross section in the vertical plane containing the beam.

The detector UA1

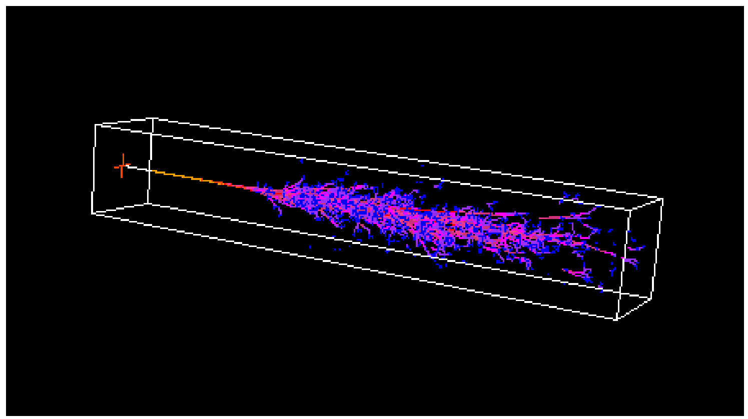


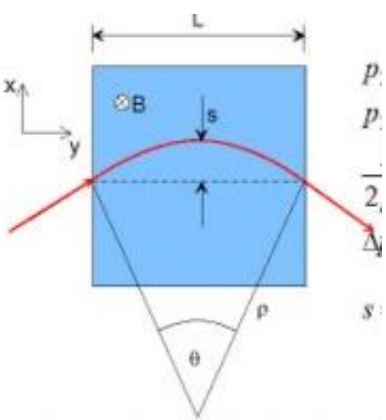
(in the figure the two halves of the dipolar magnet are open)

Electromagnetic calorimeters to measure electrons and magnetic spectrometer for muons

Calorimeter: typical energy resolution (at that time) of an electromagnetic calorimeter: (UA2)

$$\frac{\Delta E}{E} = \frac{0{,}15}{\sqrt{E(GeV)}} = 1{,}5\% \; at \; E = 100 \; GeV \left(ATLAS: \frac{\Delta E}{E} = \frac{0{,}10}{\sqrt{E(GeV)}} \right)$$





Magnetic spectrometer

$$\frac{\Delta p}{p} = \frac{\Delta E}{E} = 10^{-3} E(GeV) \; at \; E = 100 \; GeV, \frac{\Delta E}{E} = 10\%$$

$$\approx 10^{-4} (at \; LHC)$$

Measurements in UA1

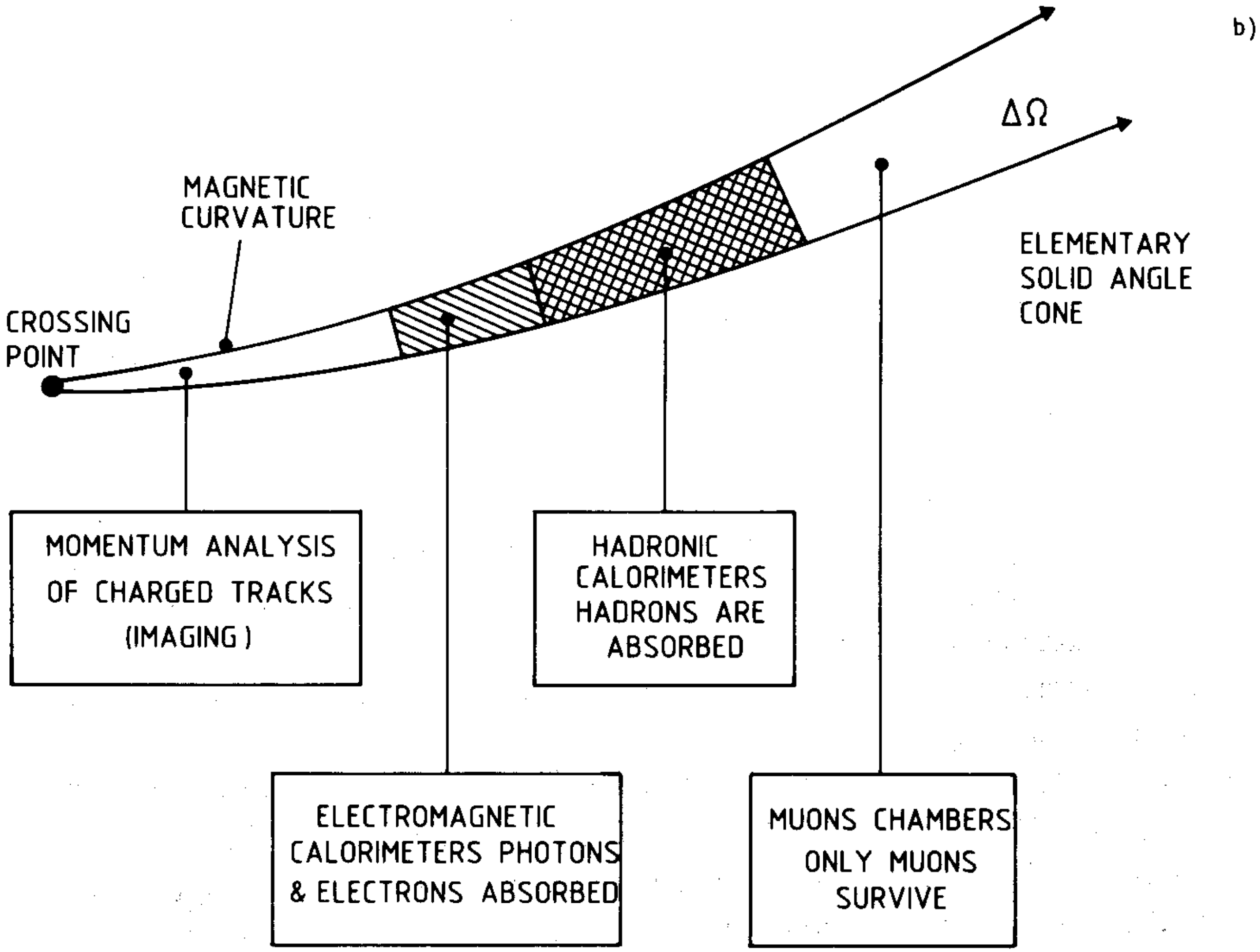
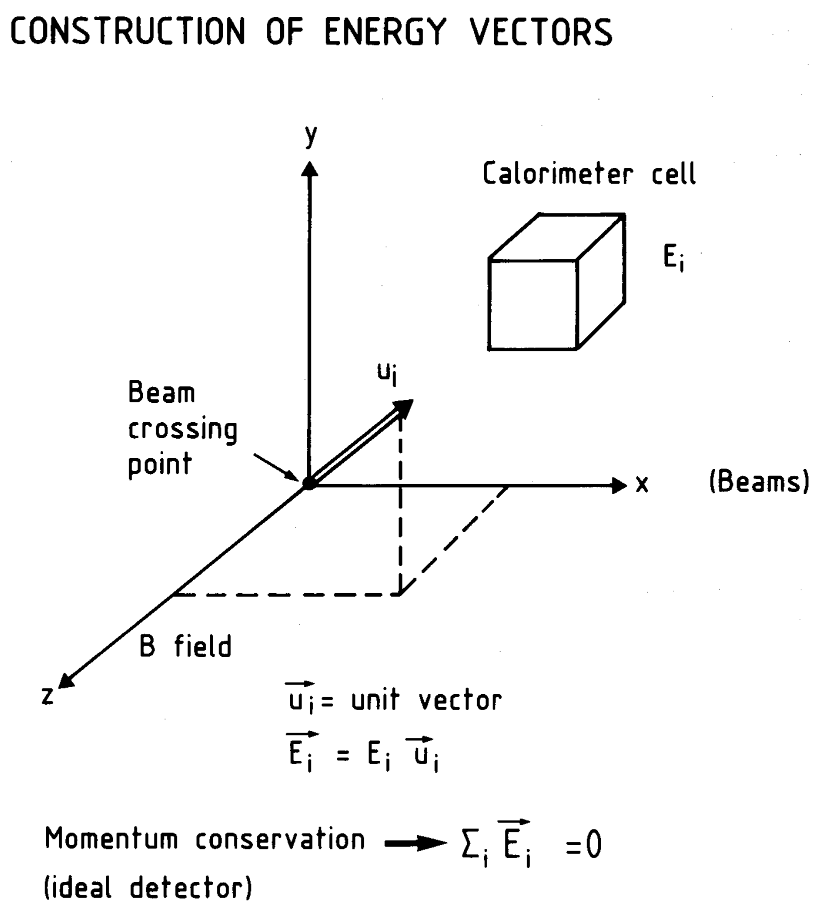


Fig. 8b. The schematic functions of each of the elementary solid-angle elements constituting the detector structure.

Neutrino transverse energy

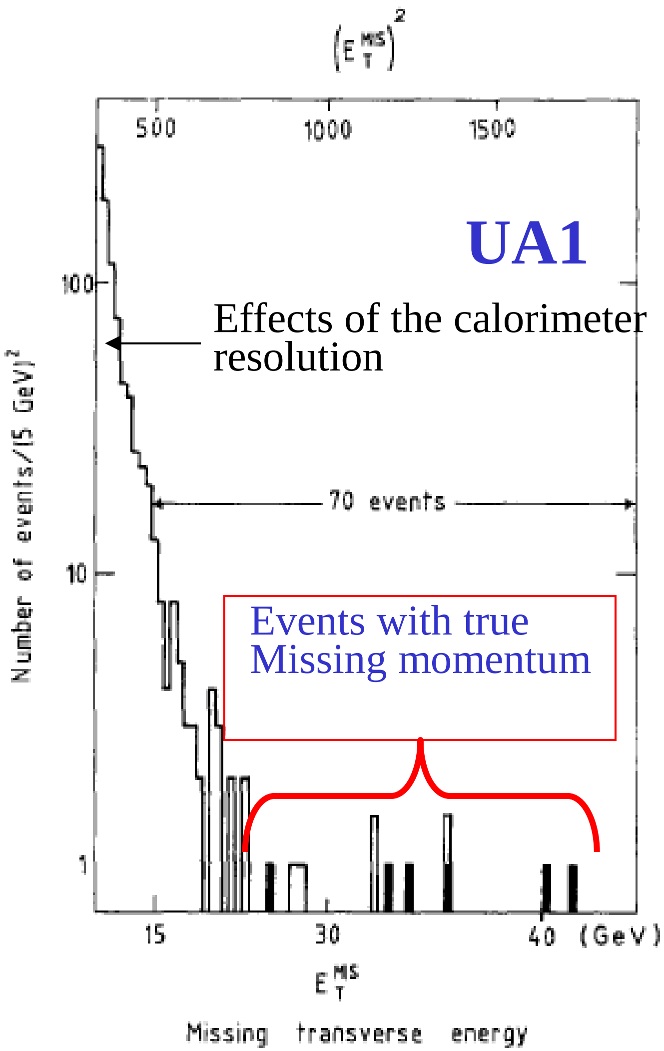


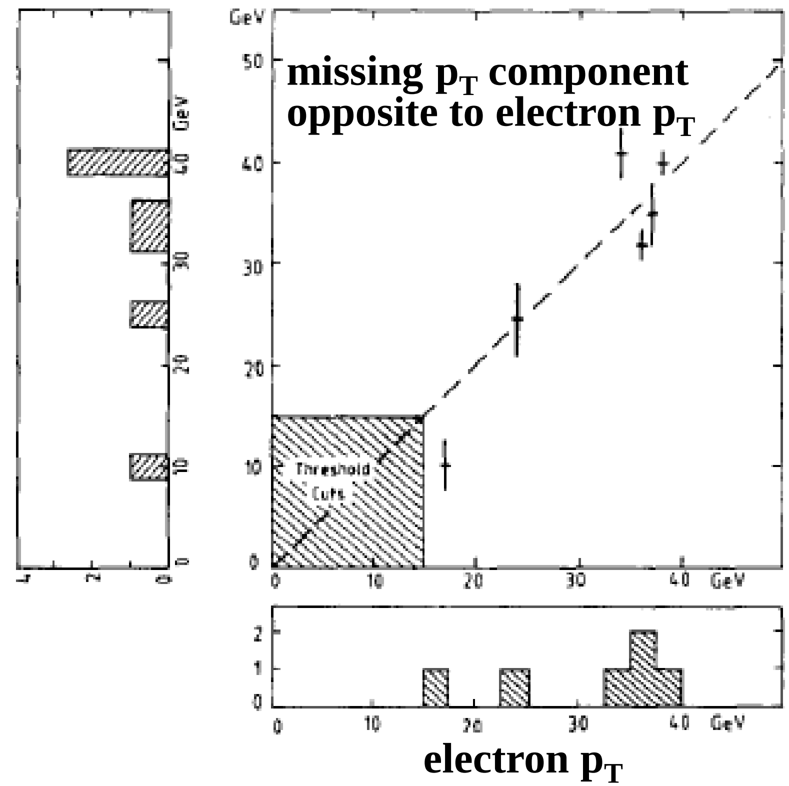
Momentum balance is possible only
for tranverse component:
in fact a large fraction
of the longitudinal momentum is lost
(with large fluctuations) in the vacuum
tube of the beams.

More complete (4 π, hermetic)
and accurate is the calorimeter
coverage,better is the measurement
of the missing transverse momentum.

$$\vec{E}_{t,\nu} = -\sum \vec{E}_{t,cells(i)} \qquad \sum \left| \vec{E}_{t,i} \right| \equiv H_t = \text{"event temperature"}$$

First W's mesured in UA1

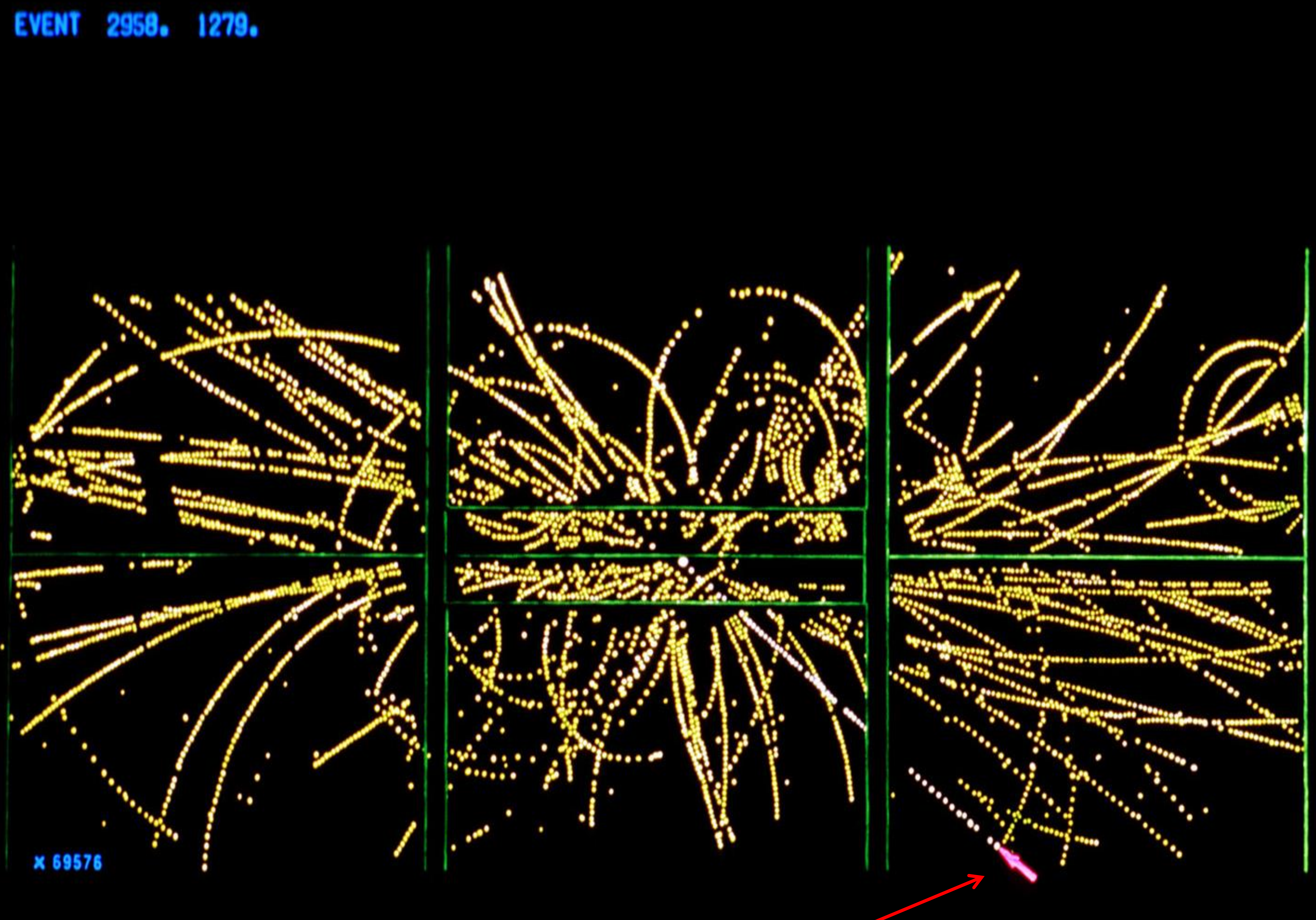




Six events with a large electron p_T electron balanced by large missing p_T

consistent with W → e n decays

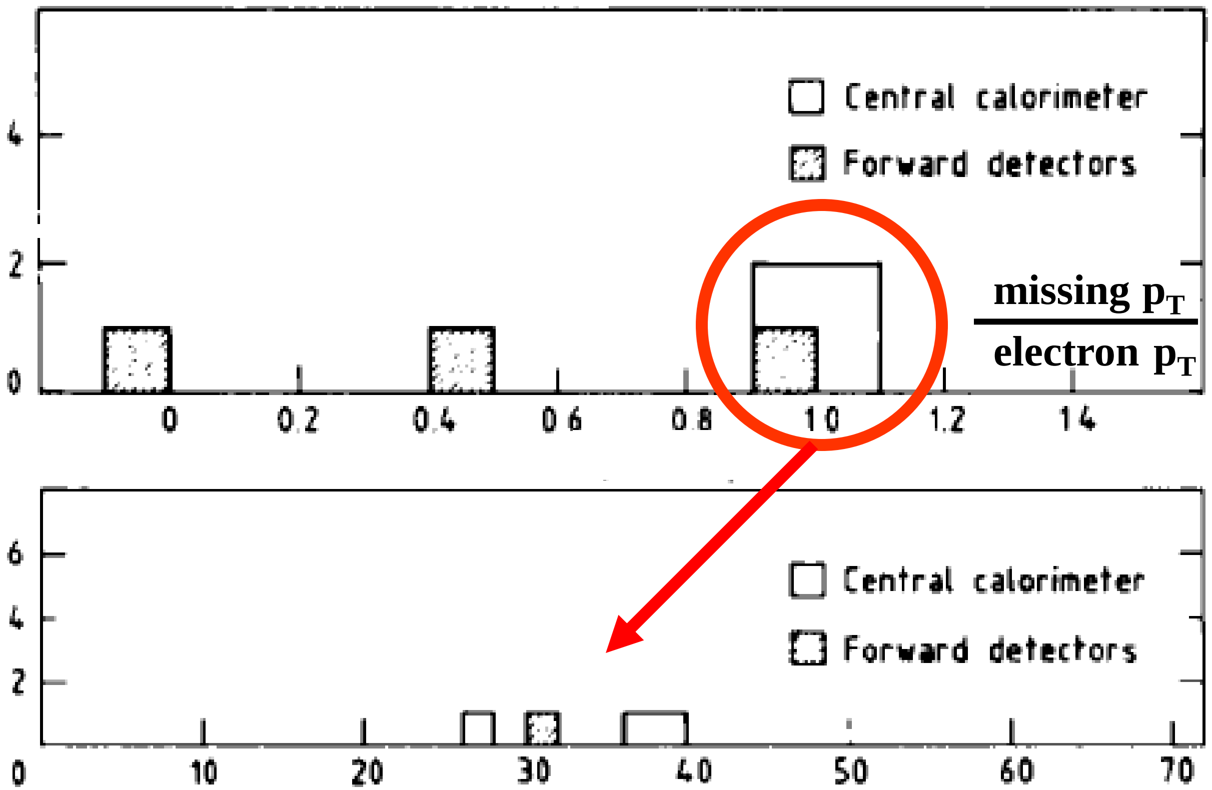
(CERN seminar 20 January , 1983)



Large pT electron from W→eν

UA2: result presented at CERN on January 1983

Six events with an electron with $p_T > 15$ GeV



electron p_T (GeV)

"Iacobian peak"

UA2 first and second generation

…e 122B, number 5,6 PHYSICS LETTERS 17 Marc…

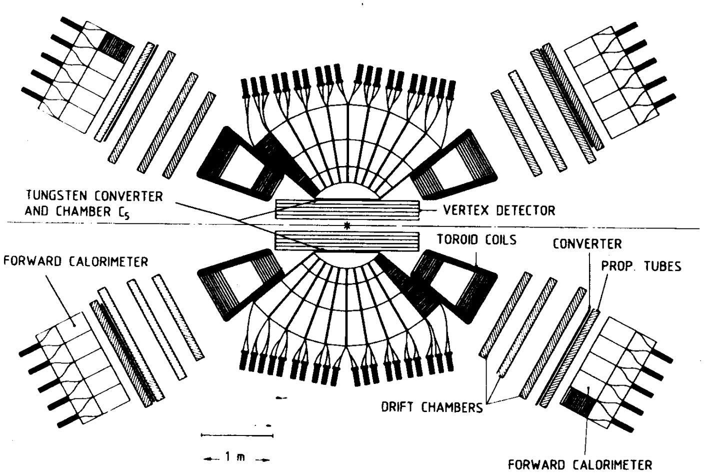
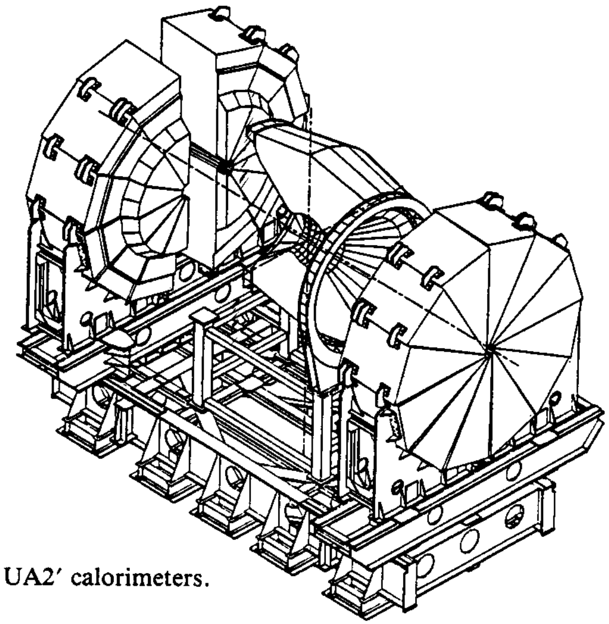
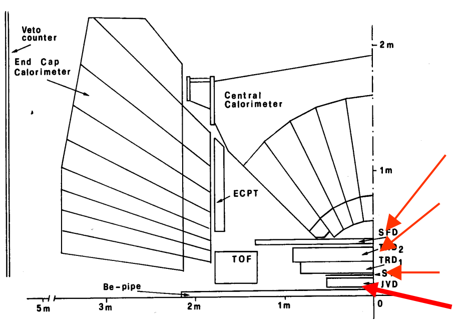


Fig. 1. The UA2 detector: Schematic cross section in the vertical plane containing the beam.



the UA2′ calorimeters.



Scintillating fibres

Silicon detector

Drift chamber vertex chamber

34

Particle segnature in UA2

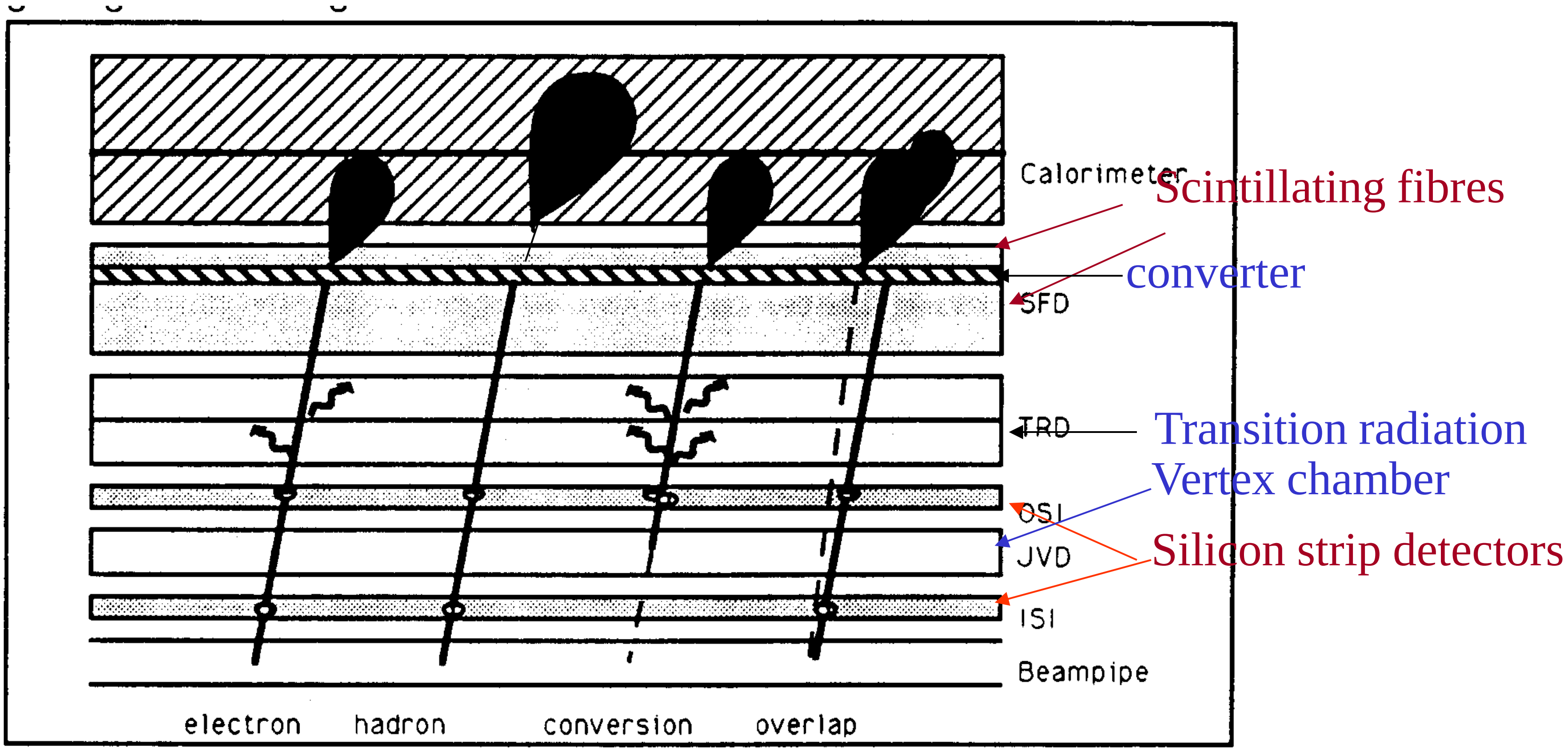


Fig. 1 Particle Identification with the Central Detector

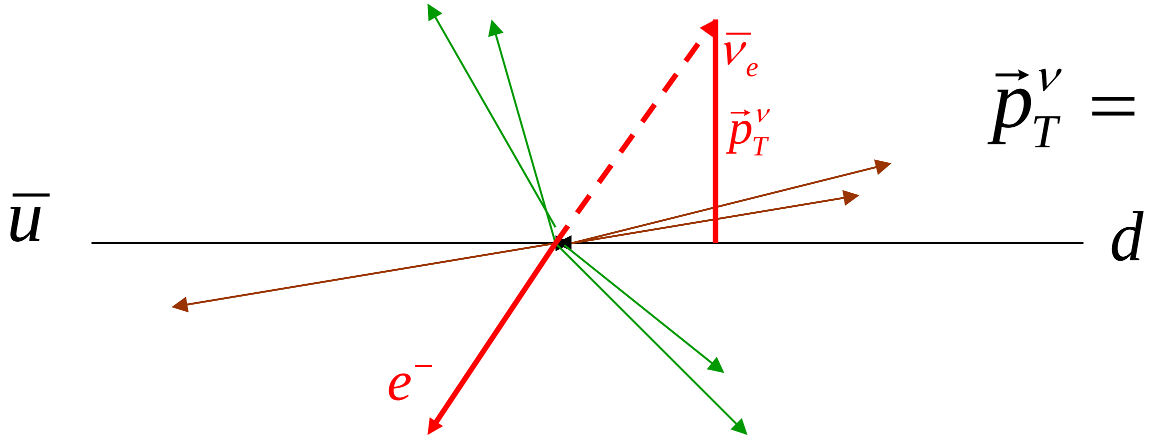
How can we measure W and Z?

Easy for Z's: leptonic channels: $Z \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ (B.R. ~ 3.3%)

⇒Both particles from the decay can be measured
⇒and the invariant mass can be calculated

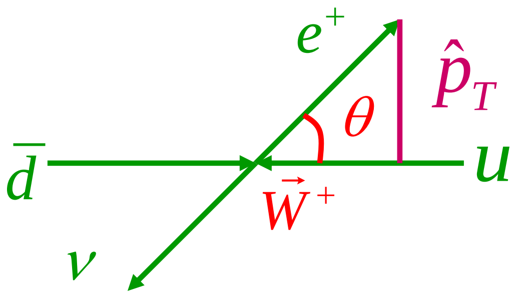
Leptonic decay channels of W(B.R. 11%) $W^- \rightarrow e^-\overline{\nu}_e, \mu^-\overline{\nu}_\mu, \tau^-\overline{\nu}_\tau$

Only the charged lepton is directely measured,, of the neutrino, is only measured the **trasverse momentum as missing momentum.**



$$\vec{p}_T^{\,\nu} = -\sum_i \vec{p}_{T,meas}^{\,i}$$

The annichilation process



$$\hat{p}^2{}_T = \frac{\hat{s} \cdot \sin^2 \hat{\theta}}{4}$$

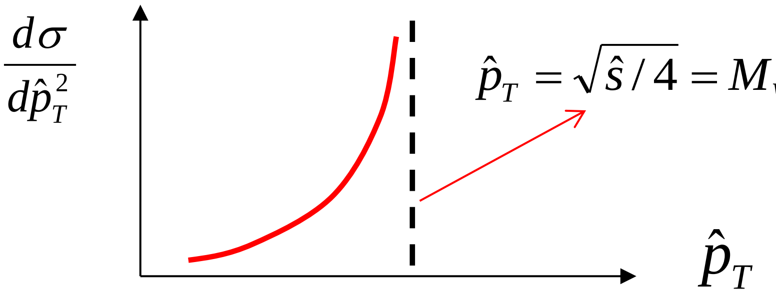
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\cos\hat{\theta}} = K(1+\cos\hat{\theta})^2 (\text{note: it is null at } \theta = \pi, \textit{helicity})$$

$$\cos\hat{\theta} = \left(1 - \frac{4p_T^2}{\hat{s}}\right)^{1/2} \Rightarrow \frac{d\cos\hat{\theta}}{d\hat{p}_T^2} = -\frac{2}{\hat{s}}\left[1 - \frac{4\hat{p}_T^2}{\hat{s}}\right]^{-1/2} = \frac{-2}{\hat{s}\cos\hat{\theta}} \quad \Rightarrow \frac{d\sigma}{d\hat{p}_T^2} = K\frac{(1+\cos^2\hat{\theta})}{\cos\hat{\theta}}$$

Note: the linear term in cos θ vanish: opposite contribute at θ and (π–θ) but the same p_T

$$\frac{d\sigma}{d\hat{p}_T^2} = K\frac{(1-2\hat{p}_T^2/\hat{s})}{(1-4\hat{p}_T^2/\hat{s})^{1/2}}$$

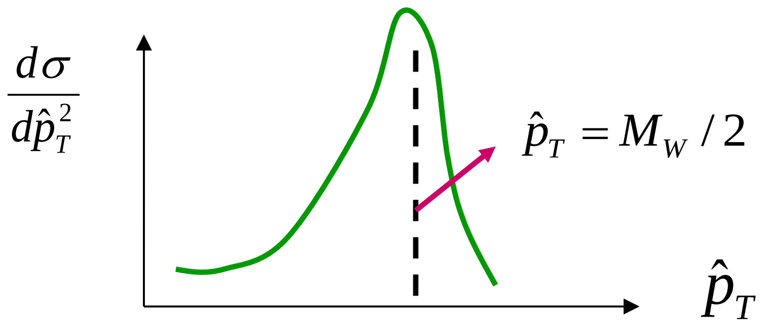
diverges at $\hat{\theta} = \frac{\pi}{2}$, or $\hat{p}_T = \frac{\sqrt{\hat{s}}}{2} \sim M_W/2$



Iacobian peak

The Iacobian peak

N.B. $\hat{p}_T = p_T^{lab}$ In the lab divergence "diluited" by the fact that $\frac{d\sigma}{d\hat{p}_T^2}$
must be convoluted with the resonance shape (BW) which depends
on $\hat{s}$=x_1x_2s, moreover p_T^W is not null
+ experimental effects(resolution).



Iacobian peak

The position of the Iacobian peak provides also the W-mass

The tranverse mass

Define: $$m_T^2(e,\nu) = \left[|\vec{p}_T^{\,e}| + |\vec{p}_T^{\,\nu}| \right]^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2 = 2|\vec{p}_T^{\,e}||\vec{p}_T^{\,\nu}|(1-\cos\phi_{e\nu})$$

$$0 \le m_T \le M_W ;\text{se } p_T^W = 0, \vec{p}_T^{\,e} = -\vec{p}_T^{\,\nu} \Rightarrow m_T = 2|\vec{p}_T^{\,e}| = 2|\vec{p}_T^{\,\nu}|$$

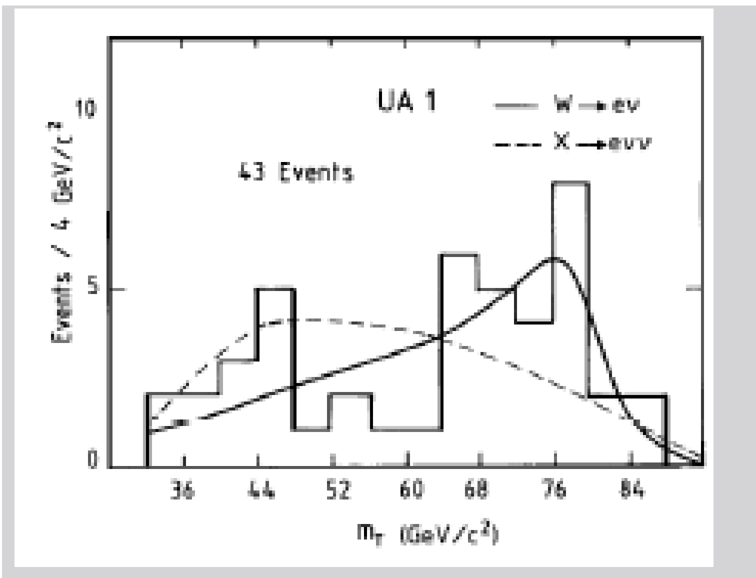
The m_T distribution is less sensitive than that in p_{Te},$p_{T\nu}$,**to the trasverse motion of W you have corrections** $\propto$ β_{TW}^2 not to β_{TW}

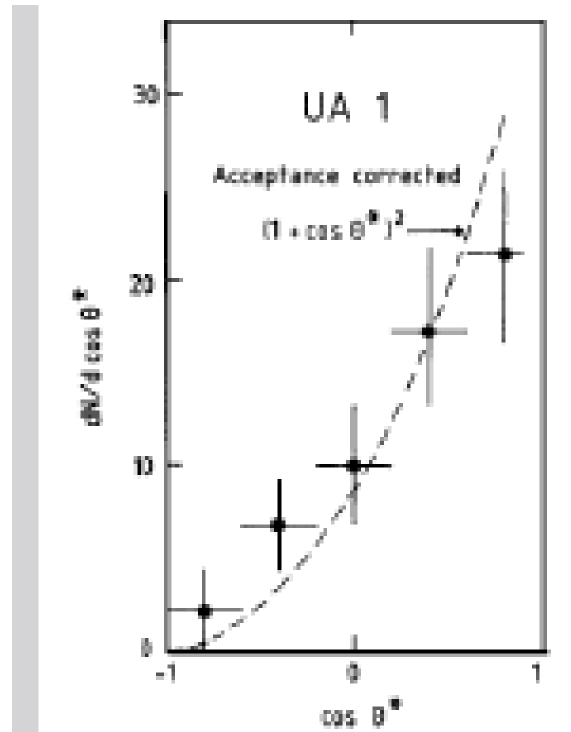
Similarly with the distribution in p_{Te}

$$\frac{d\sigma}{dm_T^2} = \frac{|V_{qq'}|^2}{4\pi}\left[\frac{GM_W^2}{\sqrt{2}}\right]^2 \frac{1}{(\hat{s}-M_W^2)+(\Gamma_W M_W)^2} \frac{2-m_T^2/\hat{s}}{(1-m_T^2/\hat{s})^{1/2}}$$

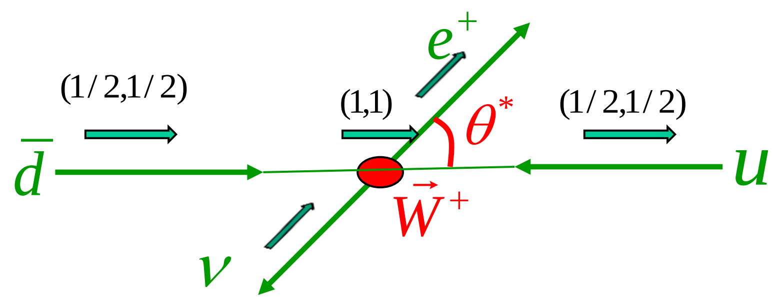
Iacobian peak at $\hat{s} = M_W^2 \sim m_T^2$

The UA1 Iacobian Peak





$$M_W = 80.9 \pm 1.5 GeV$$

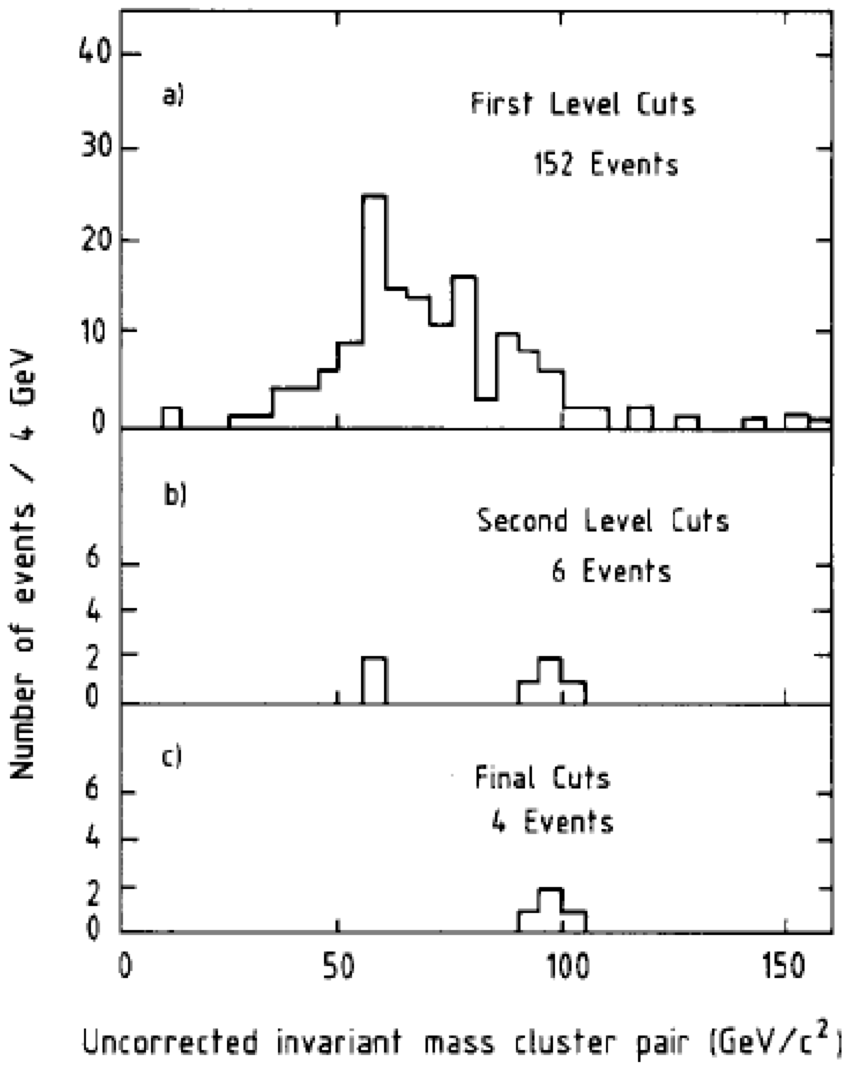


$$PDG : \mathrm{M_W} = 80.385 \pm 0.015\, GeV,$$

$$\Gamma_W = 2.085 \pm 0.042\, GeV$$

UA1: observation of $Z \to e^+ e^-$

(May 1983)

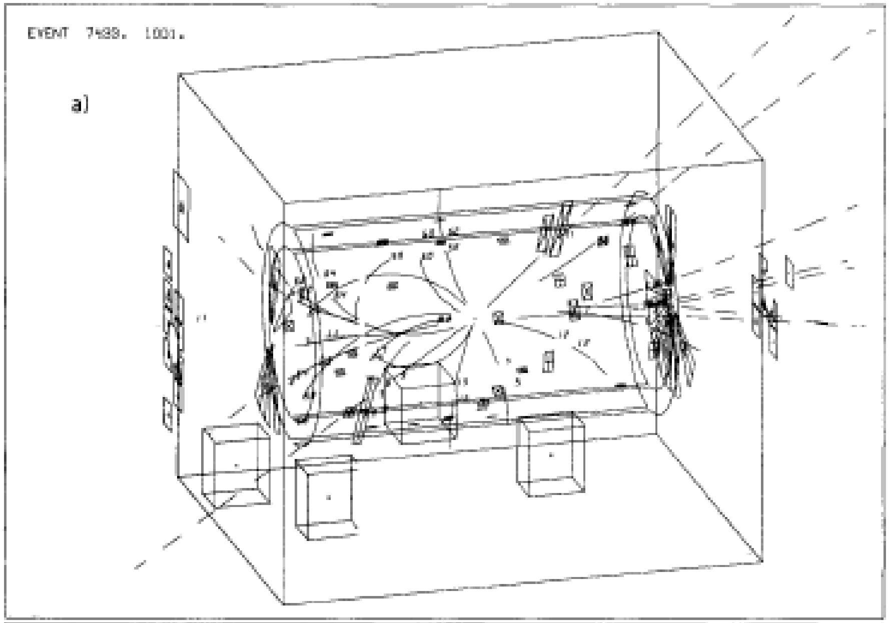


Two localized deposits of energy in the electromagnetic calorimeter (electrons or photons)

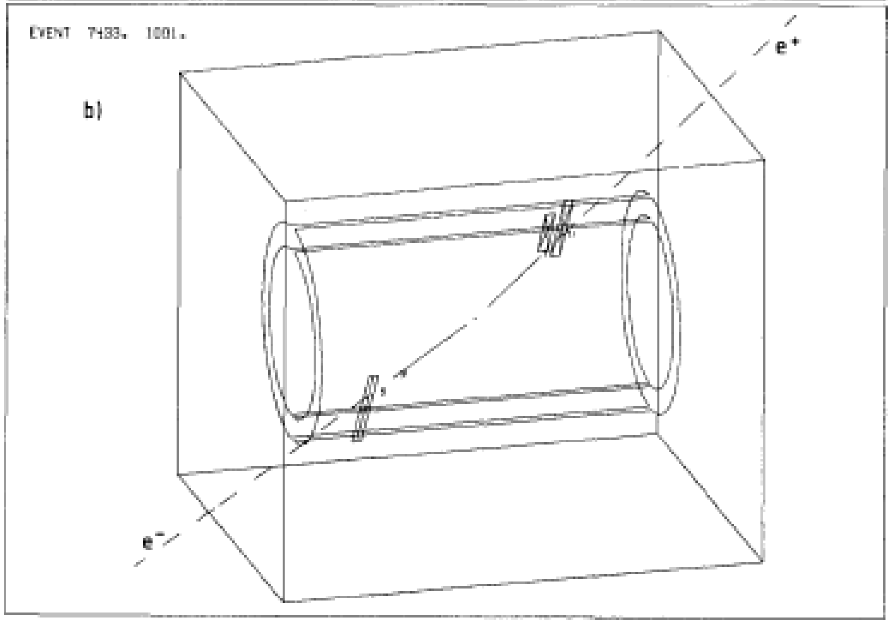
Isolated charged tracks with p_T > 7 GeV
At least one should point to the electromagnetic cluster

<u>Both tracks with</u> p_T > 7 GeV
Point to an electromagnetic cluster

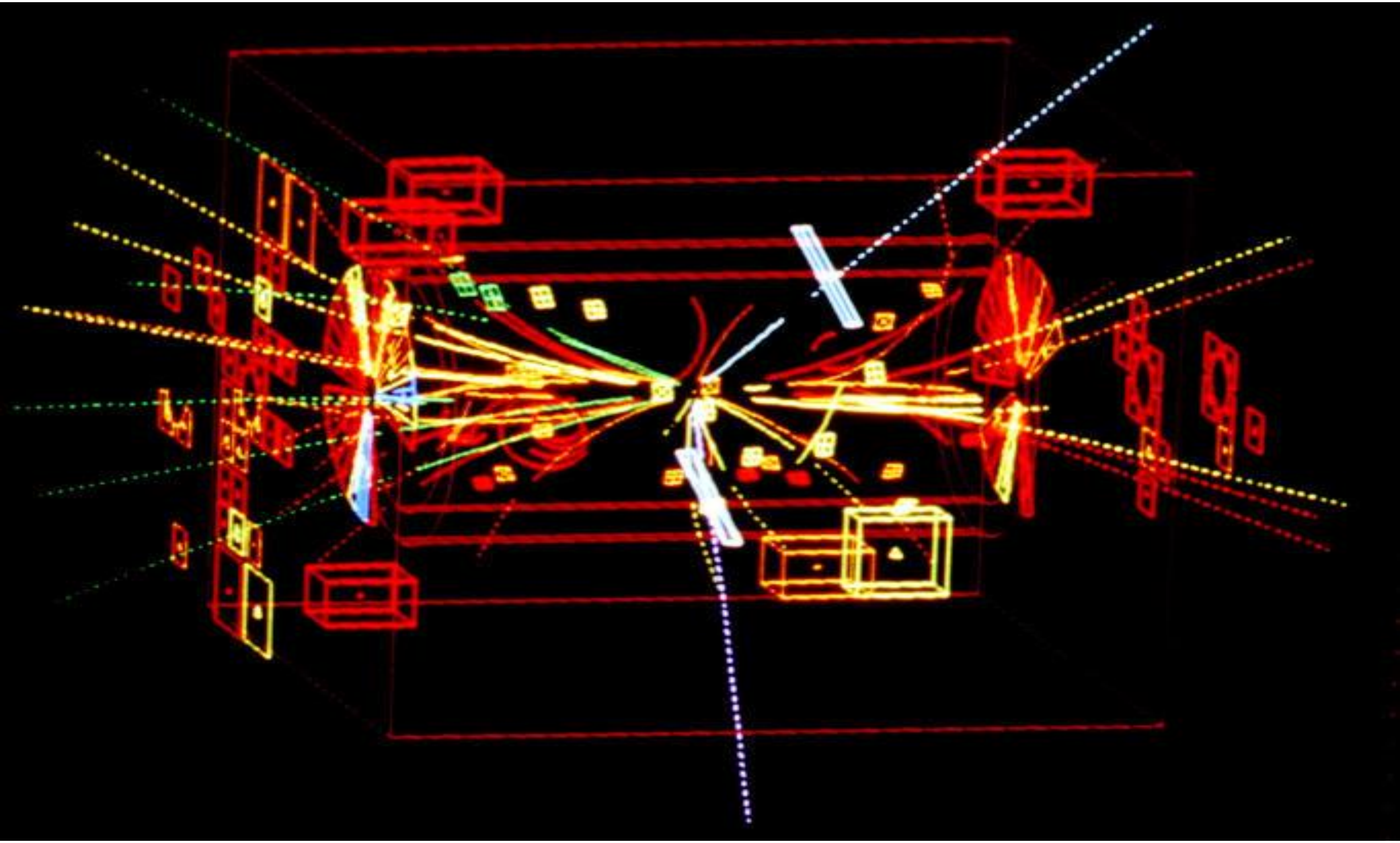
UA1 Z $\rightarrow e^{+} e^{-}$ event



Event with all tracks and Electromagnetic deposits

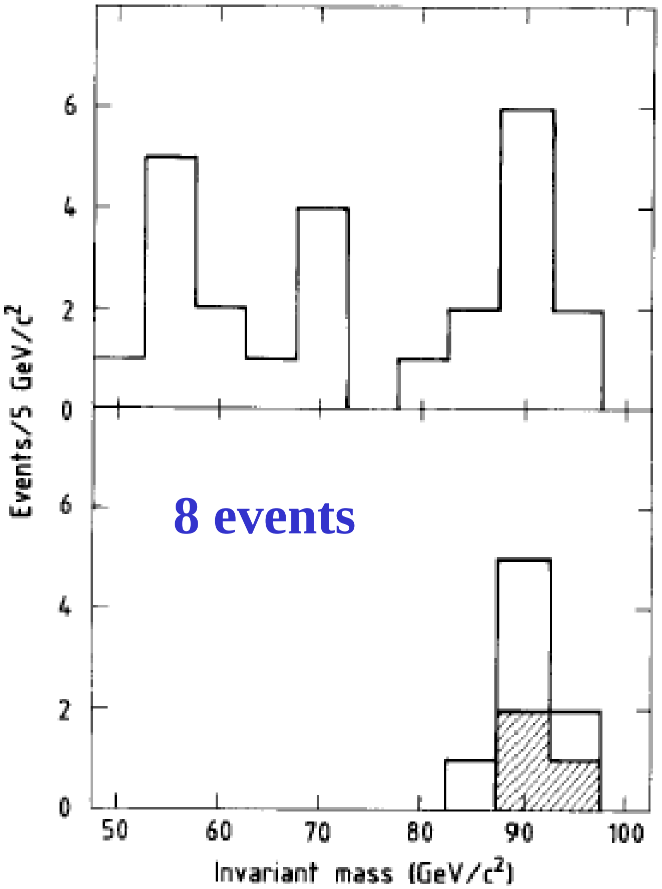


Require tracks with p_T > 2 GeV



UA2: observation of $Z \rightarrow e^+ e^-$

June 1983)



Two localized electromagnetic clusters with p_T > 25 GeV (electrons or photons)

Require at least a charged track pointing to the elctromagnetic cluster

▨ Track identified as an isolated electron pointing to both energy clusters

$$m_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV}$$

(stat) (syst)

The discovery of W e Z

The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Carlo Rubbia

1/2 of the prize

Italy

CERN
Geneva, Switzerland

b. 1934

Simon van der Meer

1/2 of the prize

the Netherlands

CERN
Geneva, Switzerland

b. 1925

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of the weak interaction"

UA2 final results of the W mass (13 pb^{-1})

Phys. Lett. B 276 (1992) 354-364

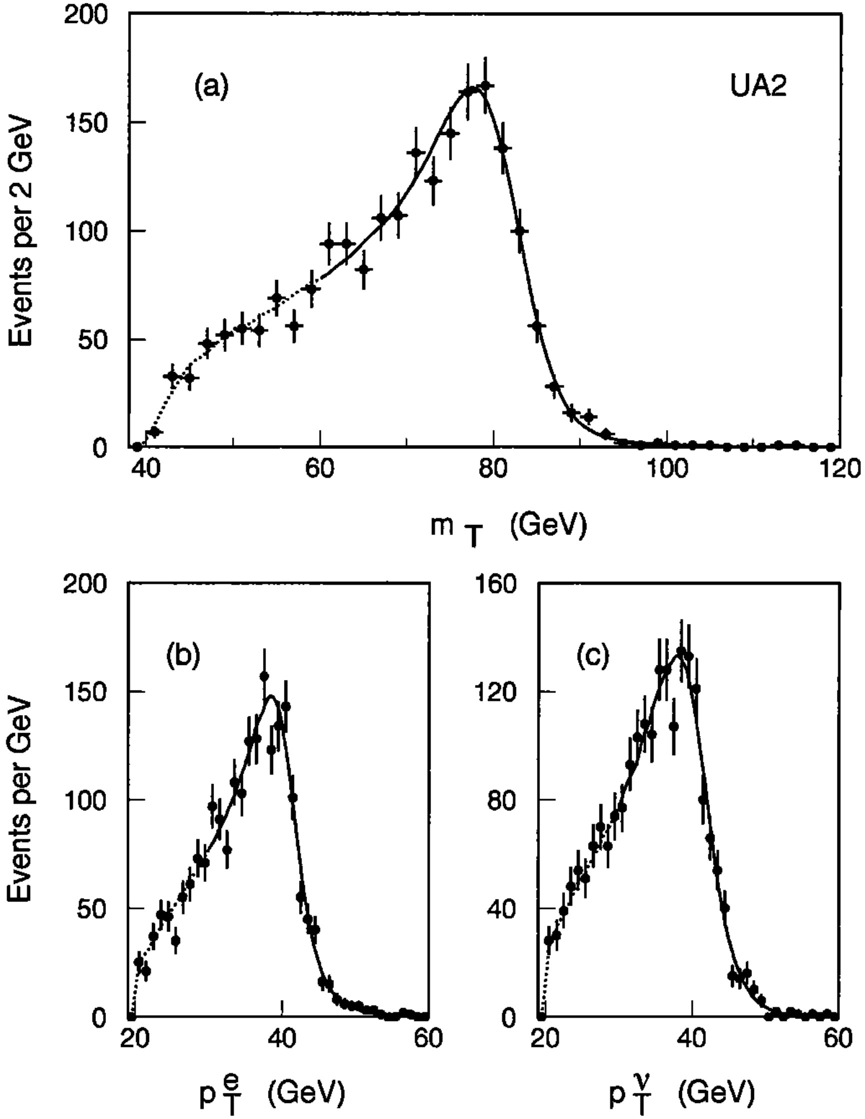


Figure 4: Fits for m_W to (a) the m_T spectrum, (b) the p_T^e spectrum and (c) the p_T^ν spectrum. The points show the data, while the curves show the fit results with the solid portions indicating the ranges over which the fits are performed.

	m_W(GeV)	Γ_W(GeV)
m_T	80.84 ± 0.22	2.1 (fixed)
fit	80.83 ± 0.23	2.2 ± 0.4
p_T^e	80.86 ± 0.29	2.1 (fixed)
fit	80.79 ± 0.30	2.8 ± 0.6
p_T^ν	80.73 ± 0.32	2.1 (fixed)
fit	80.70 ± 0.34	2.3 ± 0.7

$\pm 0.17(sys) \pm 0.81(scale)$

$$m_W/m_Z = 0.8813 \pm 0.0036(\text{stat}) \pm 0.0019(\text{syst})$$

Rescaled with M_Z mesured at LEP

(to divide out the energy scale error)

$$M_Z = 91.195 \pm 0.021\ GeV:$$

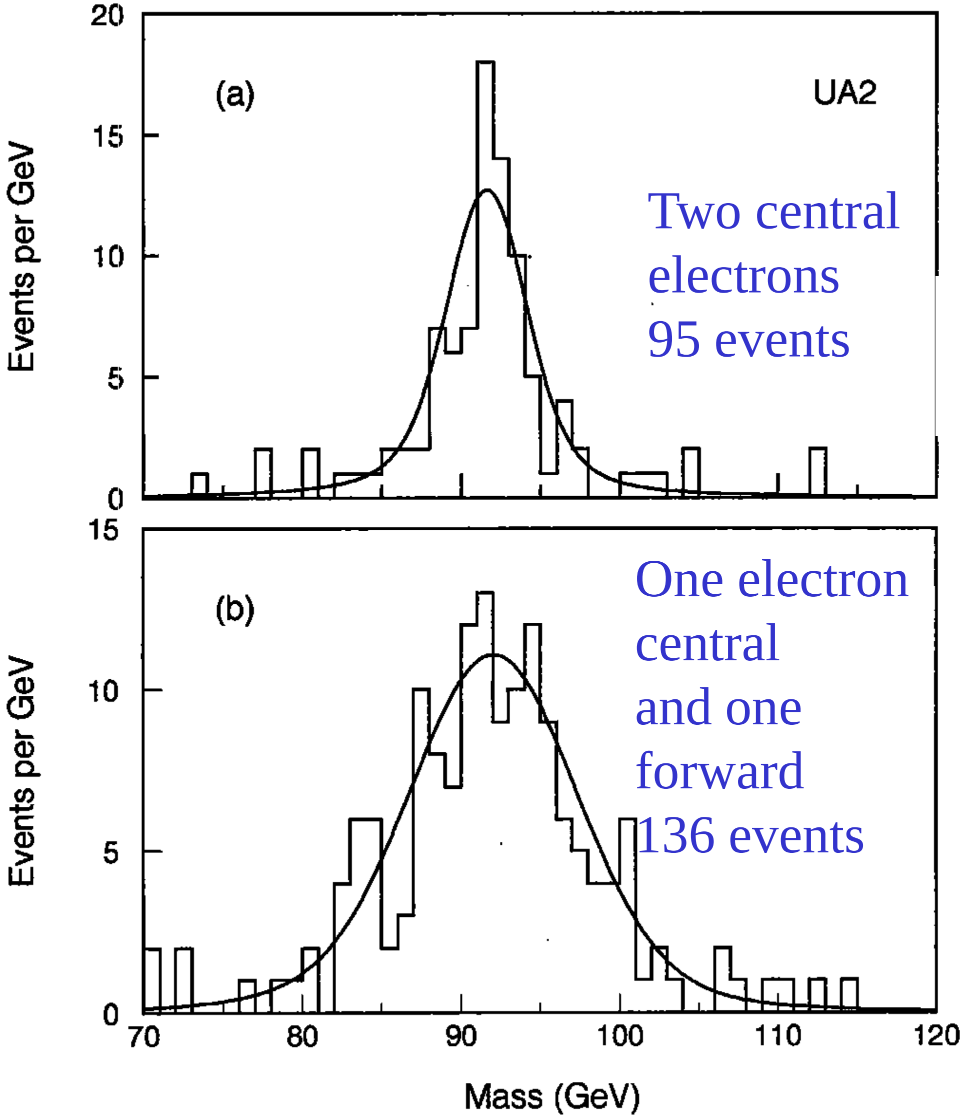
$$m_W = 80.35 \pm 0.33(\text{stat}) \pm 0.17(\text{syst})\ \text{GeV}.$$

$$\sin^2\theta_W \equiv 1 - m_W{}^2/m_Z{}^2,$$

$$\sin^2\theta_W = 0.2234 \pm 0.0064 \pm 0.0033.$$

UA2 final results Z mass (13 pb^{-1})

Phys. Lett. B 276 (1992) 354-364



igure 1: Fits for m_Z to (a) the central sample and (b) the pt-constrained sample. 'he curves show the fits, while the histograms show the data.

Fit max likelihood with relativistic BW convoluted with the resolution σ e and weighted with the partonic luminosity $e^{-\beta m'}$

Input :m_{ee} , σ, output : m_Z , Γ_Z

Probability density function:

$$f(m_{ee},\sigma,m_Z,\Gamma_Z) \propto \int dm' \frac{m'^2 e^{-\beta m'}}{(m'^2 - m_Z{}^2)^2 + m'^4\Gamma_Z^2/m_Z{}^2} e^{-(m_{ee}-m')^2/2\sigma^2}$$

	m_Z(GeV)	Γ_Z(GeV)
central sample	91.65 ± 0.34	2.5 (fixed)
	91.67 ± 0.37	3.2 ± 0.8
p_T-constrained sample	92.10 ± 0.48	2.5 (fixed)
	92.15 ± 0.52	3.8 ± 1.1

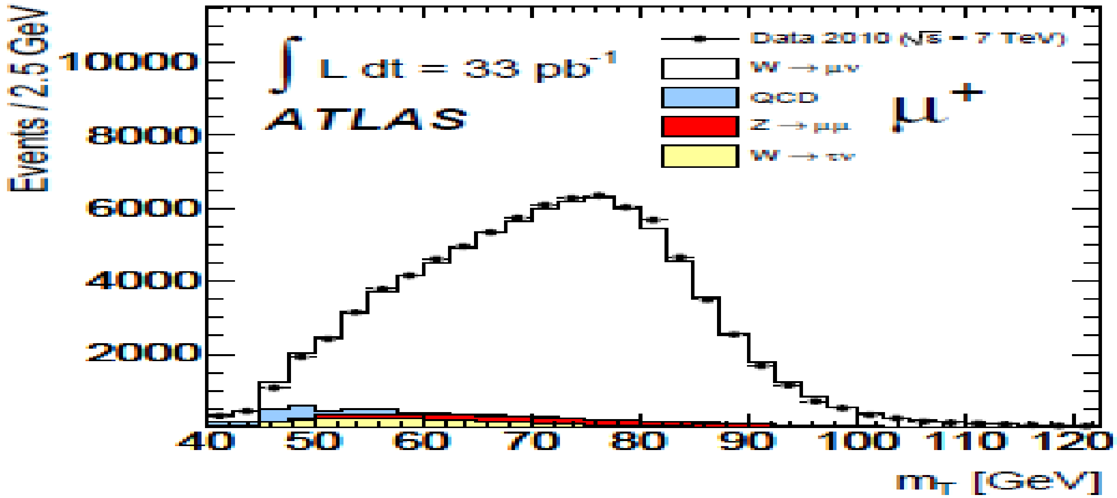
$\pm 0.12(sys) \pm 0.92(scal$

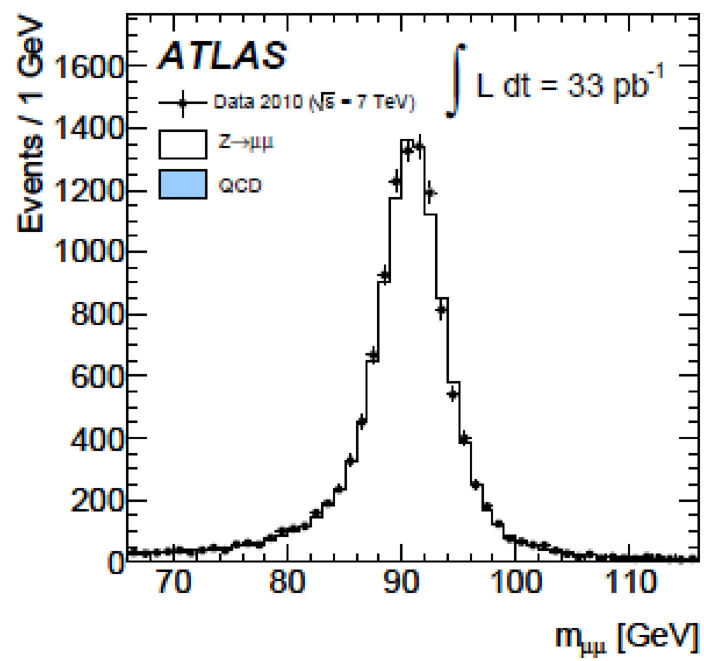
QCD background <1%

$$PDG: M_Z = 91.1896 \pm 0.0021\, GeV,$$

$$\Gamma_Z = 2.4952 \pm 0.0023\, GeV$$

W/Z at LHC

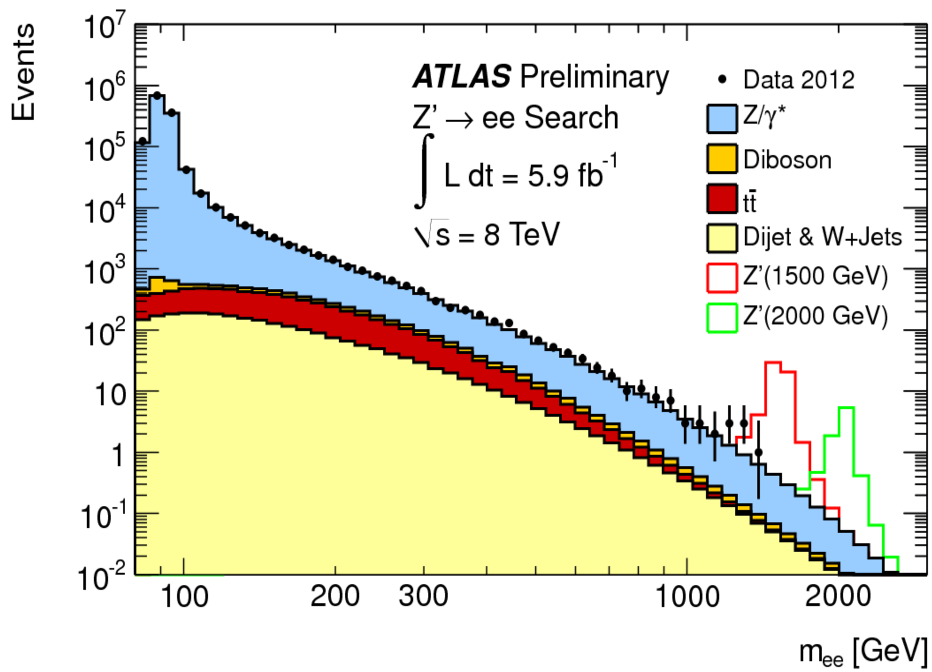




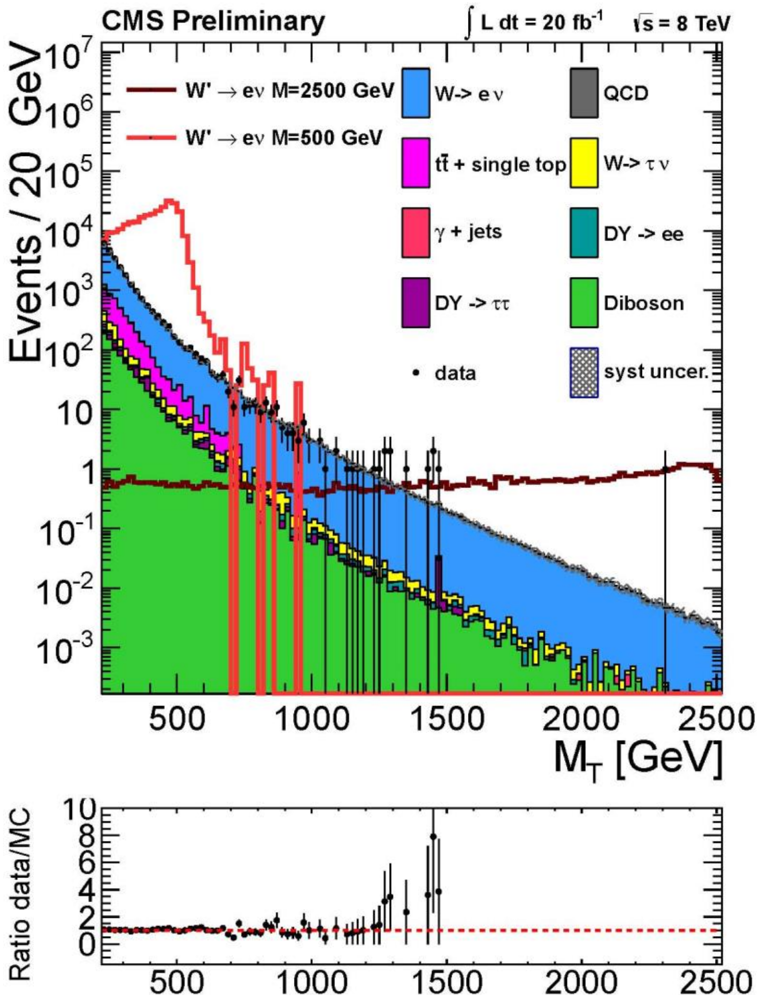
At an integrated luminosity comparable with that of the ppbar Collider

~30 times more Z's

New W/Z bosons ??(U(1)',SU(2)')



Z' with same couplings to fermions as Z excluded at 95% CL for $M_{Z'} < 2.39$ TeV



W' with same couplings to fermion as W (SSM) excluded at 95% CL for $M_{W'} < 3.20$ TeV

Why it is important to measure precisely M_W

In the Standard Model the relationship between fundamental contants

$$g_W^2 = \frac{e^2}{\sin^2\theta_W}; g_W^2/4\pi = \frac{\alpha}{\sin^2\theta_W};$$

$$\frac{G}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}; M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G\sin^2\theta_W}}$$

$$g_z^2 = \frac{e^2}{\sin^2\theta_W\cos^2\theta_W}; g_Z^2/4\pi = \frac{\alpha}{\sin^2\theta_W\cos^2\theta_W};$$

$$M_W = M_Z\cos\theta_W$$

Only 3 parameters are independent, ex:

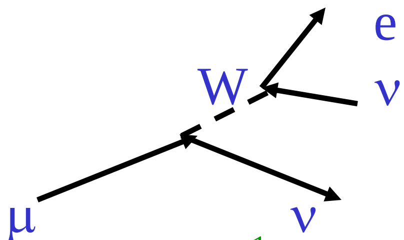
$$\alpha, \left[\frac{\Delta\alpha}{\alpha}\right] = 0.0007\cdot 10^{-6}\ (\text{a } Q^2 = 0)\ \text{from atomic energy levels;}$$

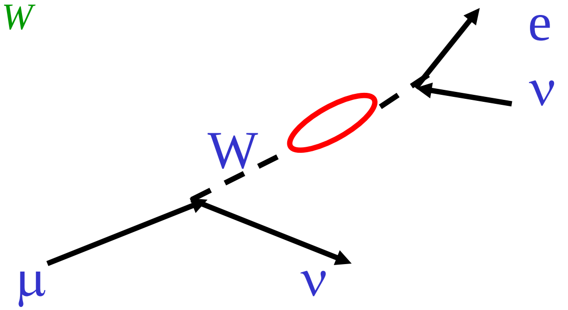
$$G, \left[\frac{\Delta G}{G}\right] = 05\cdot 10^{-6}\ (\text{from the decay } \mu \to e\nu\nu);$$

$$M_W, \left[\frac{\Delta M_W}{M_W}\right] = 19\cdot 10^{-6}; \sin^2\theta_W, \left[\frac{\Delta\sin^2\theta_W}{\sin^2\theta_W}\right] = 52\cdot 10^{-6}$$

But relations at tree level are modified by radiative corrections:

$$\frac{G}{\sqrt{2}} = \frac{g_W^2}{8M_W^2} \rightarrow \frac{G}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}(1-\Delta r)$$



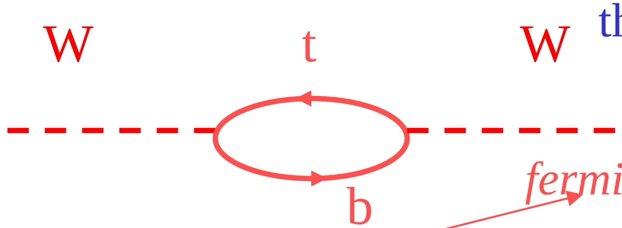


$$M_W = \frac{\left(\pi\alpha/\sqrt{2}G_F\right)^{\frac{1}{2}}}{\sin\theta_W} \equiv \frac{A}{\sin\theta_W} \qquad \Rightarrow M_W = \frac{A}{\sin\theta_W\sqrt{1-\Delta r}}$$

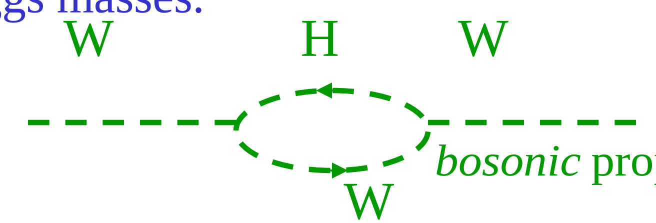
$$A = 37.2810 \pm 0.0003\,\text{GeV}$$

$$\Delta r \sim \Delta\alpha + \frac{G}{8\sqrt{2}\pi^2}\left(-3\cot^2\theta_W m_t^2 + \frac{11}{3}M_W^2 \ln\frac{M_H^2}{M_W^2}\right) + \ldots \qquad \Delta\alpha \cong 1 - \frac{\alpha}{\alpha(M_Z^2)} \approx 0.06$$

Corrections to M_W come from loops with t-quark and Higgs and then they are sensitive to the t-quark and Higgs masses.



fermionic prop.: $1/q$



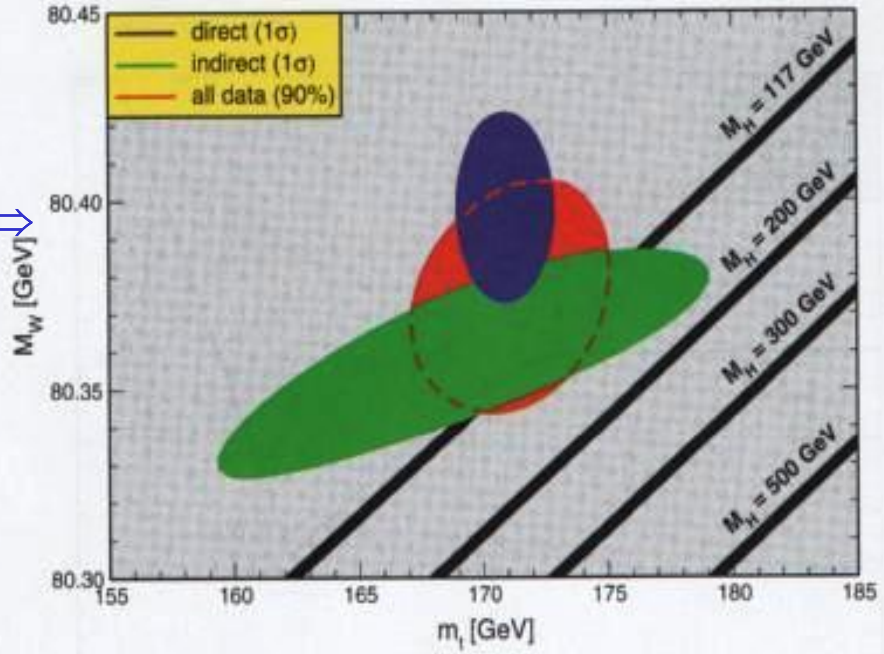
bosonic prop.: $1/q^2$

$$\delta M^2 \sim \int d^4q/q^2 \sim \int q^3 d\ q/q^2 \sim \int^m q\,dq \sim m^2$$

$$\delta M^2 \sim \int d^4q/(q^2)^2 \sim \int q^3 d\ q/q^4 \sim \int^M dq/q \sim \ln(M)$$

Higgs mass from top and W masses (prior to the Higgs discovery)

A displacement of
5 GeV of the top mass ⇒
22 MeV displacement
of M_W (positive)



A displacement of
100 To 1000 GeV
of the Higgs mass
⇒
130 MeV displacement
of M_W (negative)

Figure 10.3: One-standard-deviation (39.35%) region in M_W as a function of m_t for the direct and indirect data, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. The SM prediction as a function of M_H is also indicated. The widths of the M_H bands reflect the theoretical uncertainty from $\alpha(M_Z)$.

M_W vs M_{top} provides predictions on the Higgs mass:

Low Higgs masses favoured (and found).

The Higgs mechanism to provide mass to particles

see the Marumi Kado lecture

Based on the vacuum expectation value of a field (the Higgs) different than zero

With the Higgs discovery everything is understood?

Higgs field and energy of the vacuum

$$V(\phi) = \mu^2\phi^+\phi + \lambda(\phi^+\phi)^2$$

Minimum of V: $$\frac{\partial V}{\partial(\phi^+\phi)} = 0 \Rightarrow \mu^2 + 2\lambda(\phi^+\phi) = 0 \Rightarrow$$

$$\Rightarrow \text{minimum if } \mu^2 < 0 \text{ at } \phi^+\phi = -\frac{\mu^2}{2\lambda} = \frac{v^2}{2}$$

The value of the potential at minimum is then: $V_0 = \frac{\lambda v^4}{4}$ with

$$v = \frac{2M_W}{g_W} = \frac{1}{\sqrt[4]{2}\sqrt{G_F}} \sim 246\,\text{GeV} \Rightarrow \text{V}_0 \sim 0.9\cdot 10^9\,\lambda\,\text{GeV}^4$$

Density of visible matter in the universe:

$\approx \frac{1p}{m^3}$ the total one (dark matter and energy)

≈ 100 the visible one :

total energy density $\approx 10^{-4}\,\frac{GeV}{cm^3}$

$1\,\text{GeV}^{-1} = 0.2\cdot 10^{-13}\,cm \Rightarrow 1\,\text{GeV}^3 = 1.3\cdot 10^{41} cm^{-3}$

$\lambda = m_H^2 / v^2$,

$m_H = 125 GeV, v = 246\, GeV\,(from G_F)$

$\Rightarrow \lambda \approx 0.25$

If λ ~ 0.25 energy of the Higgs field:

$$V_0 \sim 3\cdot 10^{49}\, GeV / cm^3$$

53 orders of magnitude larger than that observed

Of course we can add a constant term to cancel V_0

but this term is to be calibrated $1/10^{53}$!!! **(Hint for new physics???)**

From AA(antiproton accumulator) to Z

(seminar of C. Rubbia at CERN, 1983)

From Z/W to Higgs (2012)

(triumph of the EW model)

From Higgs to ???

The answer (we hope) with the new LHC run: 2015

Back up slides

Fenomenologically there is a hierarchy among the CKM matrix:

Diagonal elements are ≈ 1,

$|V_{us}| \approx |V_{ud}| \approx 0.2$,

$|V_{ts}| \approx 10^{-2}$,

$|V_{ub}| \approx |V_{td}| \approx 10^{-3}$ then, with great accuracy the independent elementa are :

$s_{12} = |V_{us}|$, $s_{13} = |V_{ub}|$, $s_{23} = |V_{cb}|$, δ

Wolfenstein parametrizations. Define :

$$s_{12} = \lambda, \quad s_{13} e^{i\delta} = A\lambda^3(\rho - i\eta)$$
$$s_{23} = A\lambda^2$$

$$\Longrightarrow \quad \eta = \frac{s_{13}}{s_{12}s_{23}} \sin\delta, \qquad \rho = \frac{s_{13}}{s_{12}s_{23}} \cos\delta,$$

By substitution in the standard parametrization we obtain (to λ^4):

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3[1 - \rho - i\eta] & -A\lambda^2 & 1 \end{pmatrix}$$

We exploit the following (out of 9) unitarity relation:

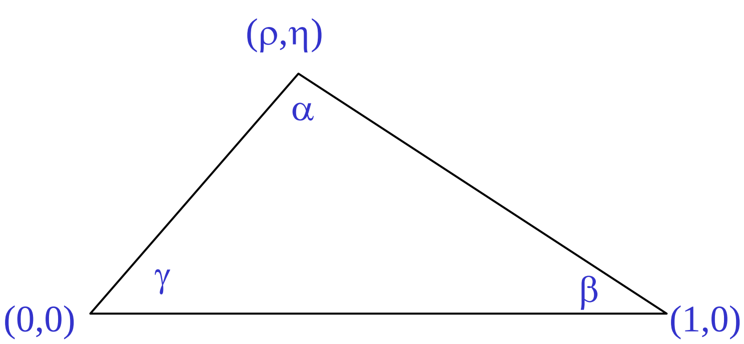
$$V_{ud}V_{ub}^{\ *} + V_{cd}V_{cb}^{\ *} + V_{td}V_{tb}^{\ *} = 0 \Rightarrow 1 + \frac{V_{td}V_{tb}^{\ *}}{V_{cd}V_{cb}^{\ *}} + \frac{V_{ud}V_{ub}^{\ *}}{V_{cd}V_{cb}^{\ *}} = 0$$

This relation define a triangle in the complex plane (unitarity triangle)

Redefine:

$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right), \quad \bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right) \longrightarrow 1 + \frac{V_{td}V_{tb}^{\ *}}{V_{cd}V_{cb}^{\ *}} = \bar{\rho} + i\bar{\eta} + O(\lambda^4)$$

Is the vertex of the triangle:



$$\sin 2\alpha = \frac{2\bar{\eta}(\bar{\eta}^2 + \bar{\rho}^2 - \bar{\rho})}{(\bar{\eta}^2 + \bar{\rho}^2)((1-\bar{\rho}^2) - \bar{\eta}^2)}$$

$$\sin 2\beta = \frac{2\bar{\eta}(1-\bar{\rho}^2)}{(1-\bar{\rho}^2) + \bar{\eta}^2}, \qquad CA = R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

$$\sin 2(\gamma = \delta) = \frac{2\bar{\rho}\bar{\eta}}{\bar{\eta}^2 + \bar{\rho}^2}, \qquad BA = R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

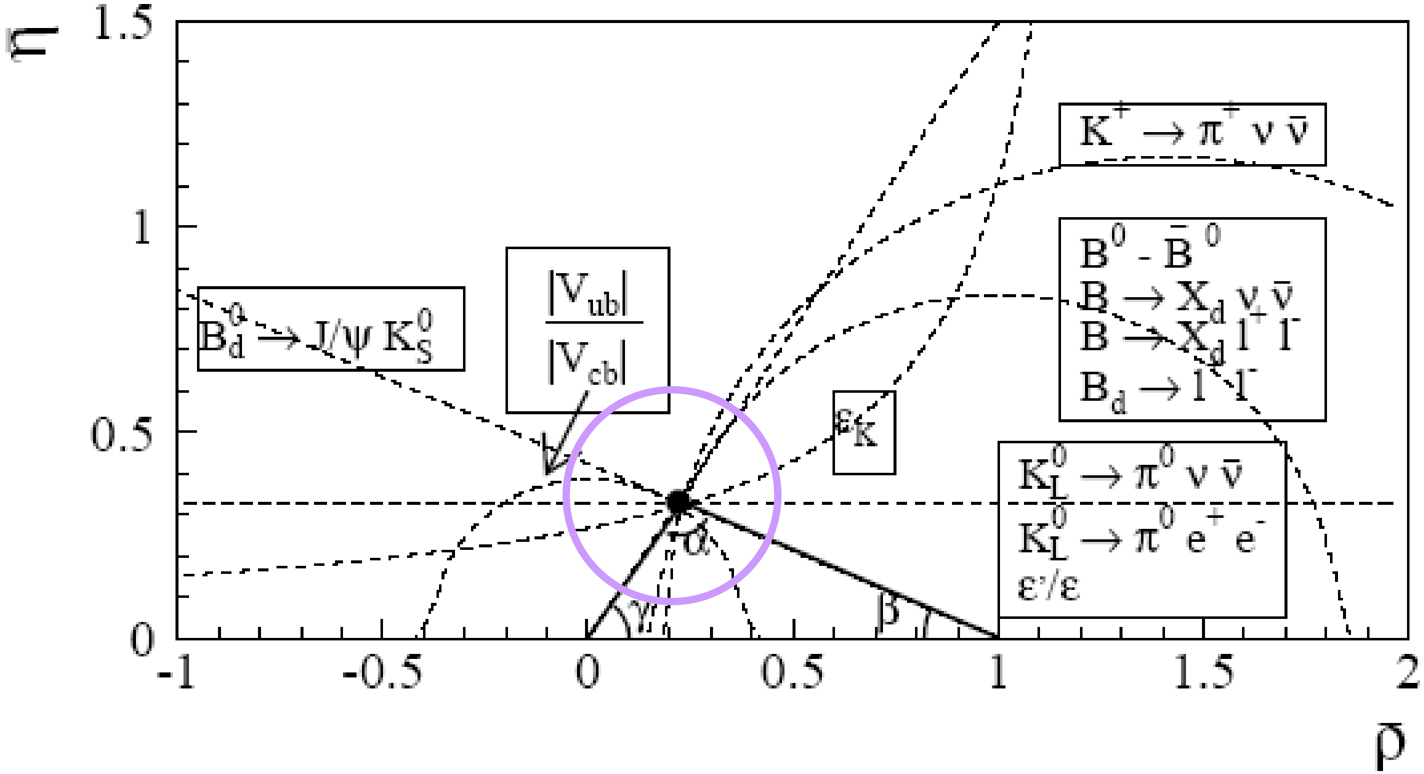
$$V_{td} = |V_{td}|e^{-i\beta},$$

$$V_{ub} = |V_{ub}|e^{-i\gamma},$$

$$R_b e^{i\gamma} + R_t e^{-i\beta} = 1$$

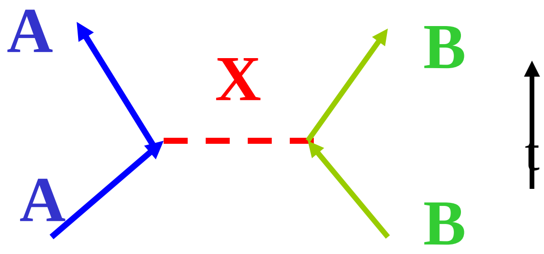
From the unitarity triangle, with |Vus| e |Vcb|, we can extract the full CKM matrix,

Moreover if the experimental results provide deviation from the triangle, would indicate new physics



η
1.5
1
0.5
0
-1
-0.5
0
0.5
1
1.5
2
ρ̄
$K^+ \to \pi^+ \nu \bar{\nu}$
$B^0 - \bar{B}^0$
$B \to X_d \nu \bar{\nu}$
$B \to X_d l^+ l^-$
$B_d \to l^+ l^-$
$B_d^0 \to J/\psi K_S^0$
$\frac{|V_{ub}|}{|V_{cb}|}$
ε_K
$K_L^0 \to \pi^0 \nu \bar{\nu}$
$K_L^0 \to \pi^0 e^+ e^-$
ε'/ε
α
β
γ

Range of elementary forces



A + B ⟶ A + B

We can parametrize the process saying that A emits X

$$A(M_A,\vec{0}) \to A(E_A,\vec{p}) + X(E_X,-\vec{p})$$

$$\text{with } E_A = \sqrt{M_A^2 + p^2},\ \ E_X = \sqrt{M_X^2 + p^2}$$

The final-initial energy ΔE can be written as:

$$\Delta E = E_X + E_A - M_A = \sqrt{M_X^2 + p^2} + \sqrt{M_A^2 + p^2} - M_A > M_X$$

Therefore from the uncertainty principle the process can occur in a time **τ** :

$$\boxed{\tau \approx \frac{\hbar}{\Delta E} \le \frac{\hbar}{M_X}}$$

The maximum propagation distance of the particje X ,R, can be:

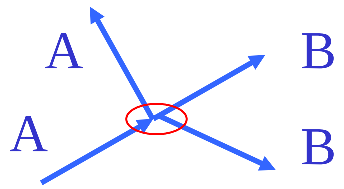
$$R = c \cdot \tau \le \frac{\hbar c}{M_X} \ (range)$$

If M_X=0 the photon) R $\longrightarrow \infty$, but also ΔE $\longrightarrow$ 0 and $\tau \longrightarrow \infty$:
The virtuality time goes to infinity: **the photon is real**

In the case of the weak interactions M_X=M_Z=90 GeV.:

$$R \le \frac{\hbar c}{M_Z} = \frac{0.197 \cdot GeV \cdot fm}{M_Z} \sim 2 \cdot 10^{-3} \ fm$$

If the momentum of the particle, p, of particle A (or B) e' is such as the De Broglie wave lengthλ_B>>R, we can approximate as a "contact interaction" (Fermi theory):



Questions

-Why you don't need a proton cooling (LHC)?
-it is convenient to measure

$Z \to e^+ e^-$,

measuring electrons with a spectrometer or a calorimeter?

$$da : M_W^2 = \frac{\pi\alpha}{G \sin^2\theta_W \sqrt{2}} \to \sin^2\theta_W \cos^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right)\frac{M_W^2}{M_Z^2} = \frac{\pi\alpha(M_Z)}{\sqrt{2} G M_Z^2 (1 - \Delta r)}$$