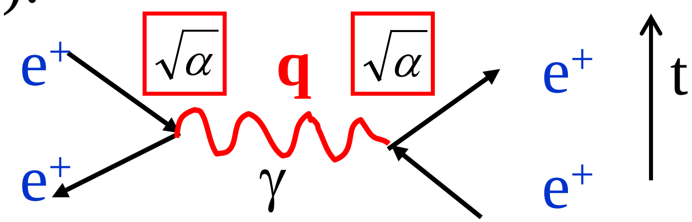
Electroweak physics and the discovery of the W/Z bosons

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):



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

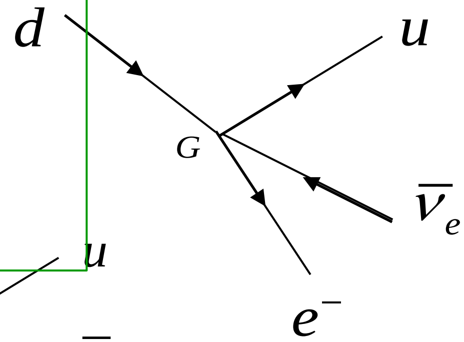
The mediator (the photon) is neutral and the effect of the electromagnetic potential (Coulomb) is described by the propagator:

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

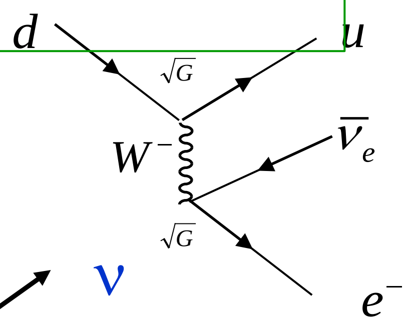
-The weak interactions:

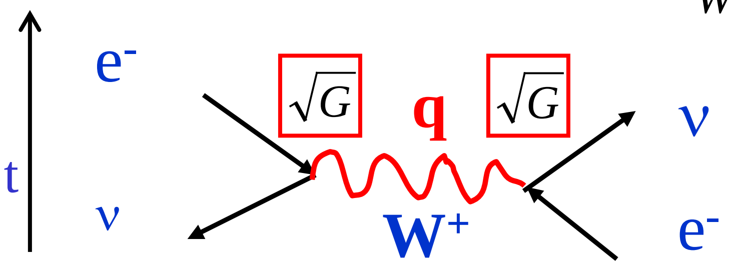
The first one measured: the beta decay:

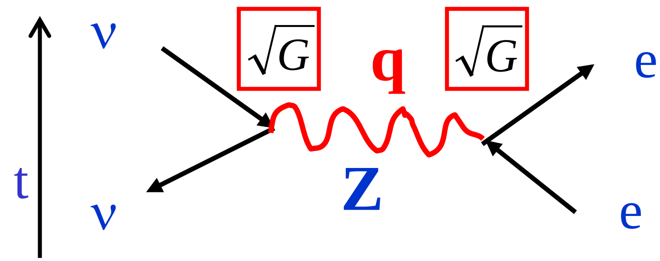
$$n \rightarrow p + e^{-} + \overline{\nu}_e$$
$$d \rightarrow u + e^{-} + \overline{\nu}_e$$
$$^{3}H \rightarrow {}^{3}He + e^{-} + \overline{\nu},\ {}^{6}He \rightarrow {}^{6}Li + e^{-} + \overline{\nu}$$



The Fermi theory: just the product of two currents multiplied by a constant: G







Characteristics:

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

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

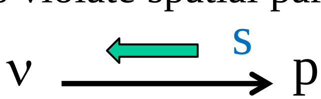
-The mediator is a spin 1 field but with a mass

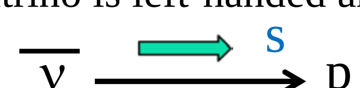
-Exists also a neutral mediator (as in the case of photon) but with mass **: the Z**

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

$$\rightarrow \prec \frac{1}{q^2 - M^2 + (i\Gamma M)}$$

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





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

Towards an electroweak unification

There is a general principle in particle quantum field theory: **the local gauge invariance:**

-for the electrodymamics this imply the invariance of the lagrangian if the particle wave function 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 spin) : the corresponding group is SU(2).

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

U(1) x SU(2)

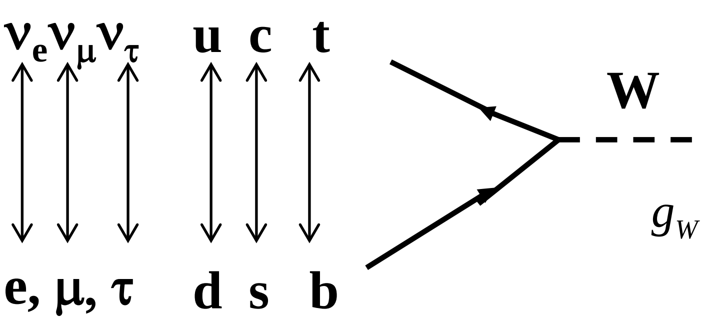
Electric charge conservation (Ypercharge) Weak isospin conservation

The GWS unification model

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

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

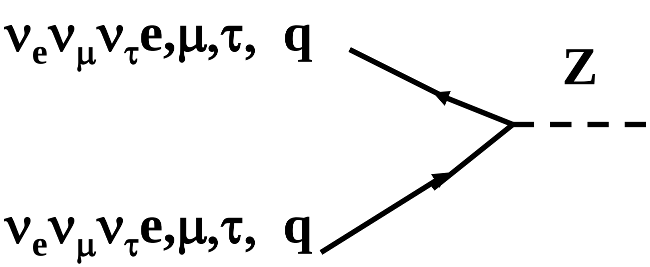
A_μ e Z_μ are the physical observable states, sinθ_W is a free parameter



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

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

(For quark sector see the Benoit Clement lectures)



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

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

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 $W^{\pm}, Z, \gamma$ (+ H (Higgs))

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

Theory is determined

$\alpha = \frac{e^2}{4\pi\hbar c} = \frac{1}{137.03599976(50)}$ (a $Q^2 = m_e^2$) 0.0068 ppm (atomic physics)

$G_F = 1.16639(1) \times 10^{-5} GeV^{-2}$ (muon decay) 9 ppm

$\sin^2\theta_W = 0.23118 \pm 0.0006$(charged neutral current ratio in ν interactions)

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

we can predict :

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

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

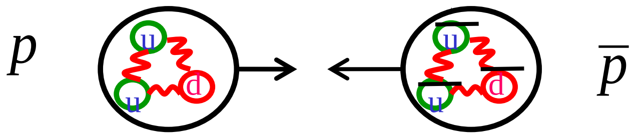
The search for W/Z bosons

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)



Annihilate quark and antiquark to produce W/Z

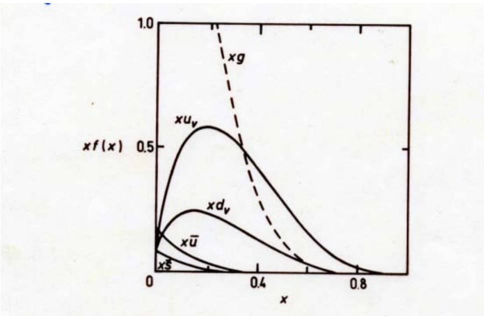
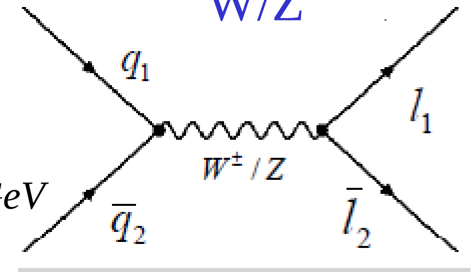


Fig. 2.9. Parton momentum distribution functions for the proton, $xf(x)$. (From Gen. Ref. 3.)

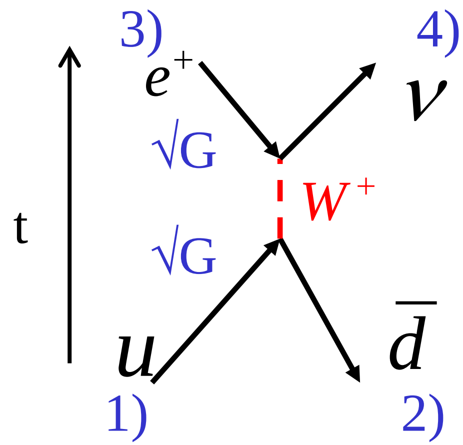
50%momentum carried by quarks and
50% by gluons. Average momentum budget :

$$\sqrt{\hat{s}} = \sqrt{x_1 s \cdot x_2 s} \xrightarrow{\text{balanced momenta}} x\sqrt{s} \xrightarrow{x=1/6} \frac{900}{6} = 150GeV$$

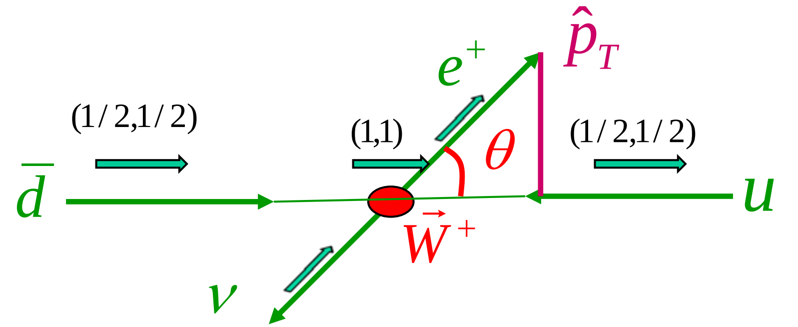


W-measurement

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

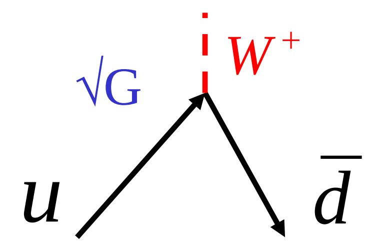


in the center of mass $u\bar{d}$



Angular distribution $\frac{d\sigma}{d\cos\theta} \propto (1-\lambda\cos\theta)^2$ where λ is the helicity of the boson (-1 in case of W^+)

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



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} :

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

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

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

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

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

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

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

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

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

further 0.1 factor (leptonic BR)

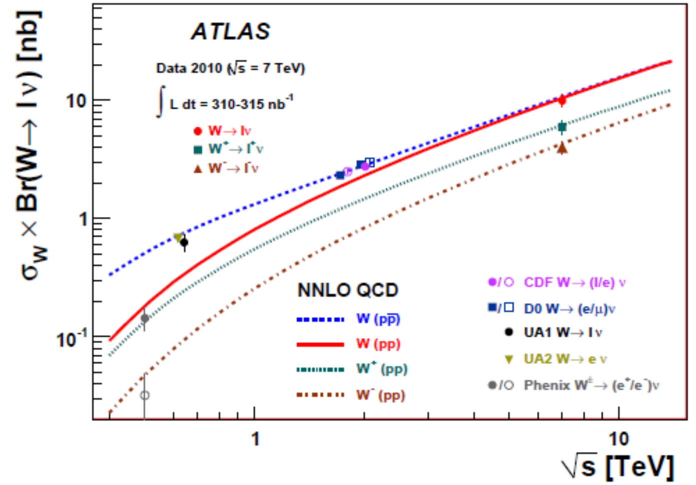


Fig. 12: *The measured values of $\sigma_W \cdot BR\,(W \rightarrow \ell\nu)$ for W^+, W^- and for their sum compared to the theoretical predictions based on NNLO QCD calculations (see text). Results are shown for the combined electron-muon results. The predictions are shown for both proton-proton (W^+, 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:

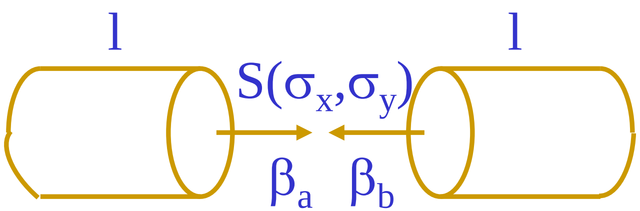
- How to realize a collider p-pbar
- For a collider the collision rate is :

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

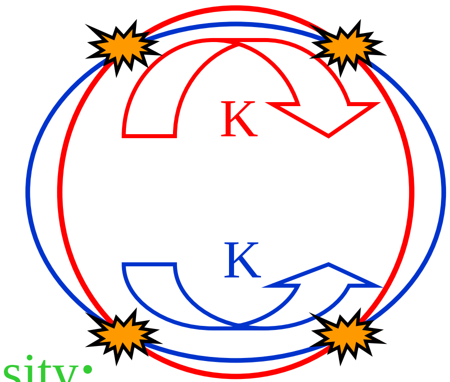
$$\Rightarrow L = 10^{33} \text{cm}^{-2} s^{-1}$$

L depends on the accelerator and is proportional to the numebr colliding particles how to have 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:

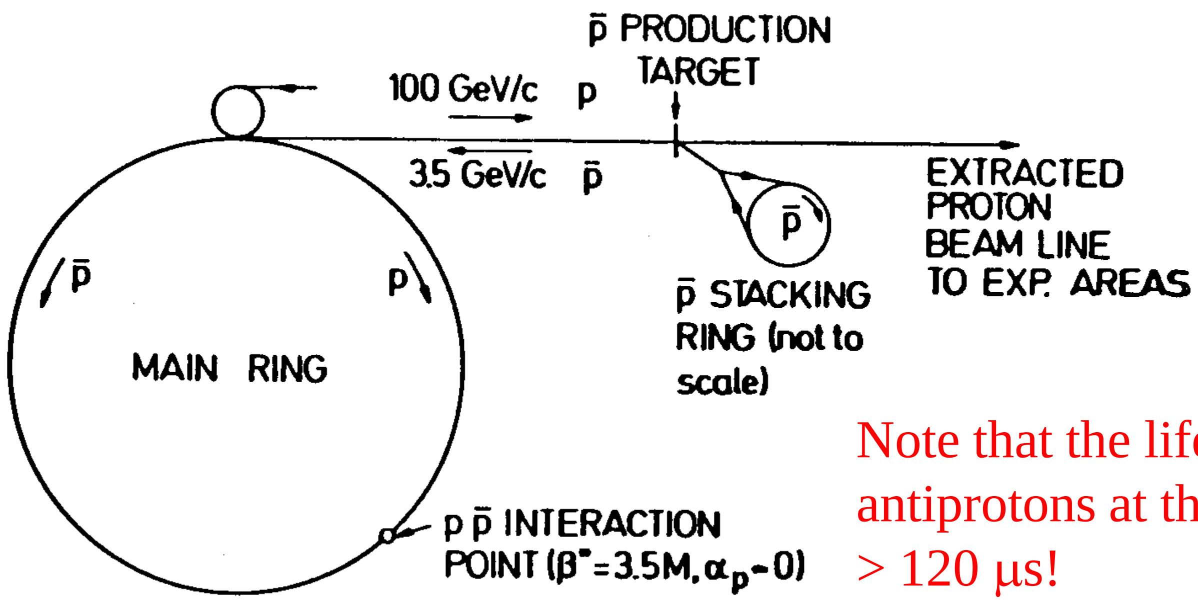
$$N = \sigma \int L dt \quad \left(\int L dt : \text{dimension} \quad cm^{-2}\right)$$

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 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 the antiprotons both in angle and momentum:
the stochastic cooling

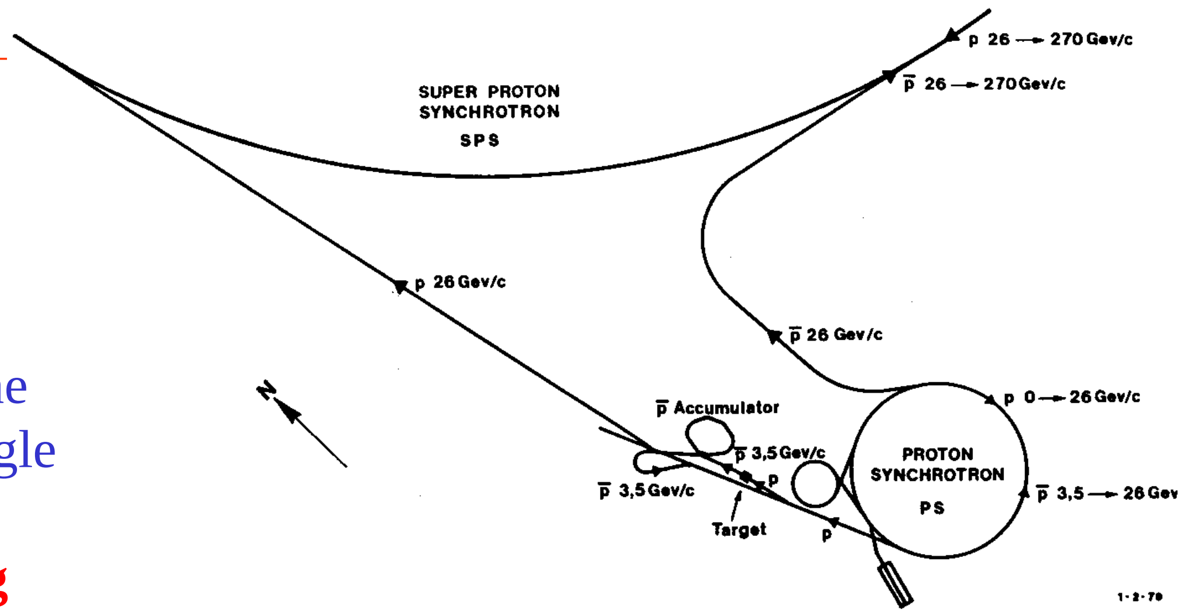


Fig. 1. Overall layout of the $p\bar{p}$ project.

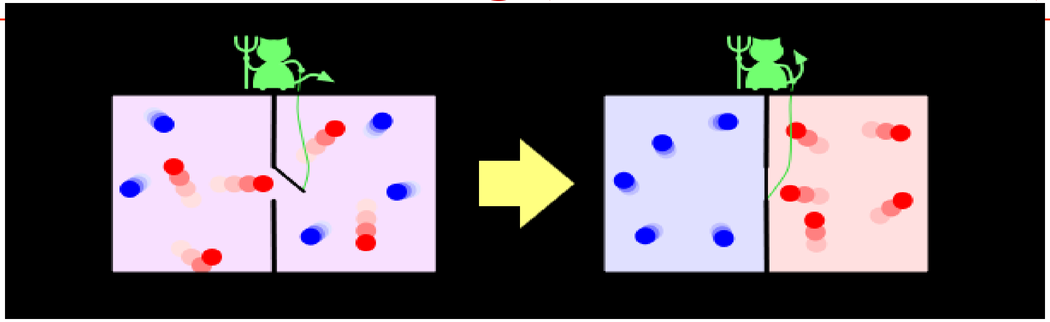
$$Linac\ 50\ MeV \rightarrow Booster\ 800\ MeV \rightarrow PS\ 26\ GeV$$

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

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

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

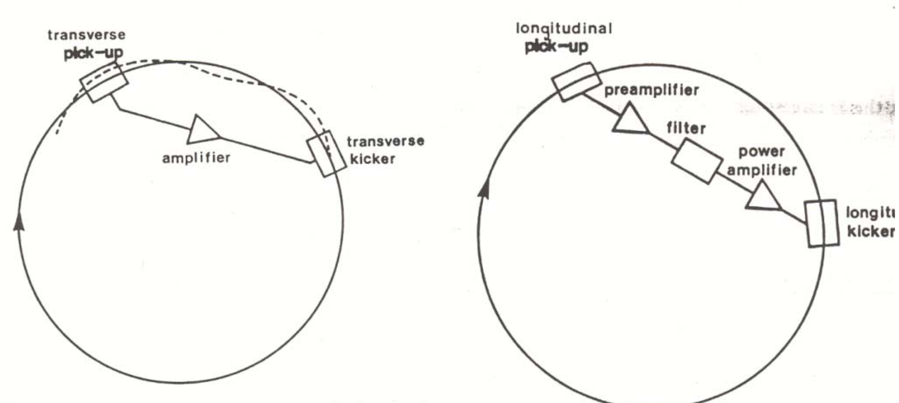


FIG. 2. Cooling of the horizontal betatron oscillation of a si gle particle.

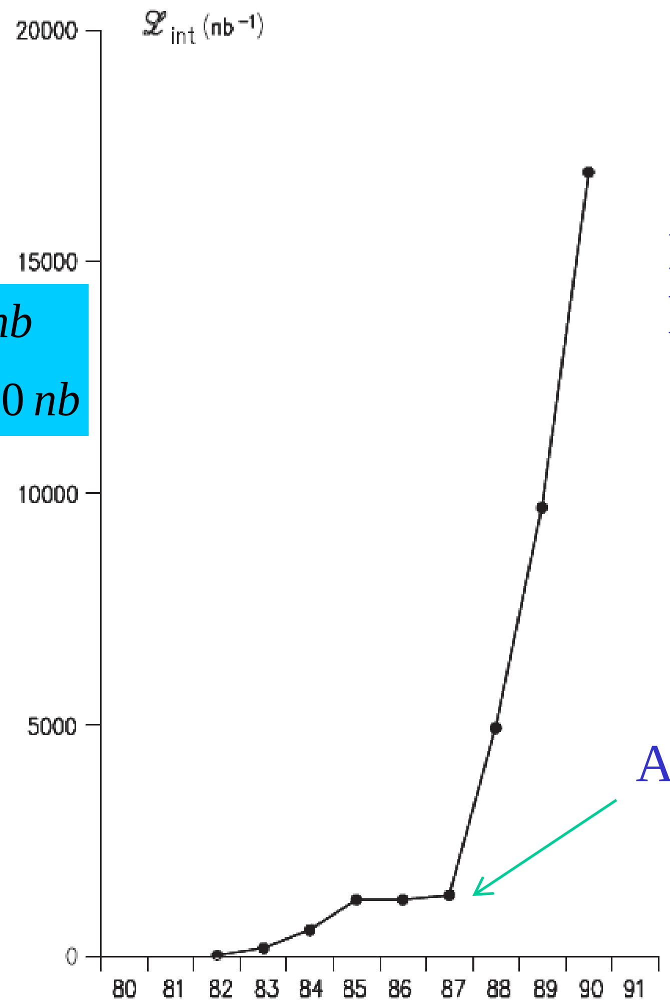
FIG. 7. Filter cooling.

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

$$\sigma(\bar{p}p \to Z(Z \to e^+e^-) + X) \sim 0.05\, nb$$

$$\sigma(\bar{p}p \to W^+(W^+ \to e^+\nu) + X) \sim 0.50\, nb$$



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	~10^{27}	2.0 x 10^{32}
1982	546	5 x 10^{28}	2.8 x 10^{34}
1983	546	1.7 x 10^{29}	1.5 x 10^{35}
1984-85	630	3.9 x 10^{29}	1.0 x 10^{36}
1987-90	630	~2 x 10^{30}	1.6 x 10^{37}

W discovery

Z discovery

1991: END OPERATIONS

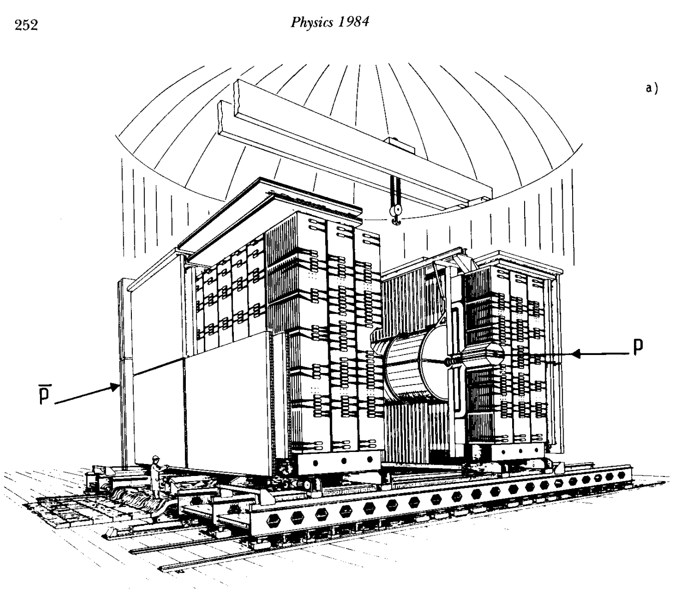
Two detectors at the SpSC to measure W/Z

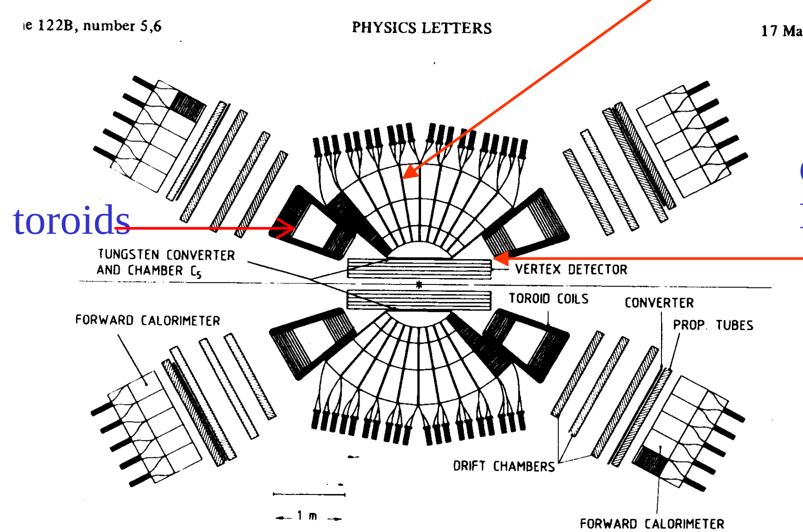
Measure the leptonic decays of $W \rightarrow e\nu_e, \mu\nu_\mu, Z \rightarrow e^+e^-, \mu^+\mu^-$

UA1, calorimeters and central dipolar magnetic field + muon detection

UA2, calorimeters ,no central magnetic field

Calorimeter with projective towers

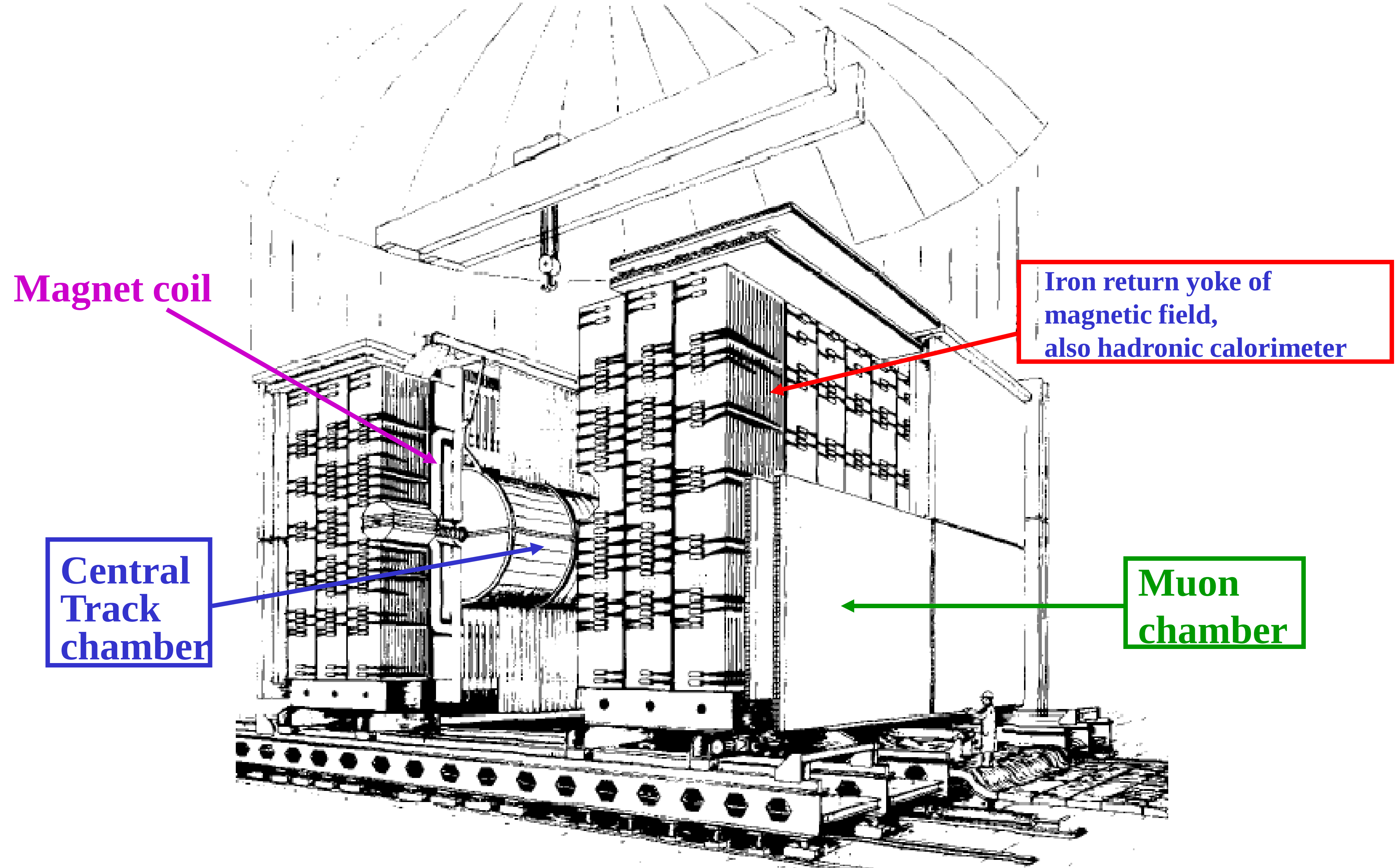




Cylindrical Drift chambers

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

The detector UA1

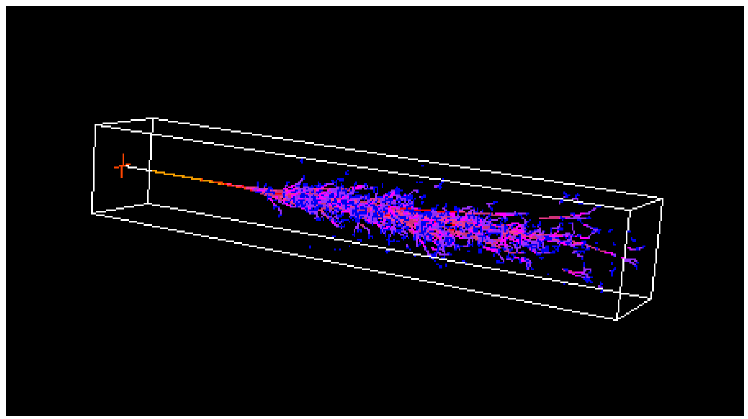


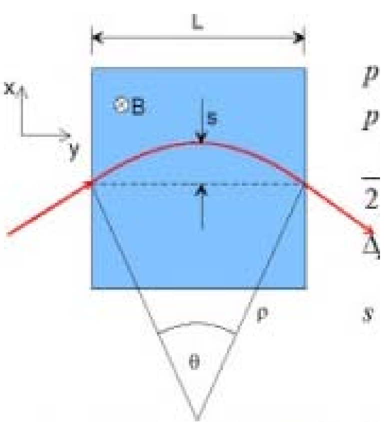
(in the figure the two halves of the dipolar magnet are open)

Electromagnetic calorimeters to measure electrons and spectrometer for muons

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

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





Magnetic spectrometer

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

Measurements in UA1

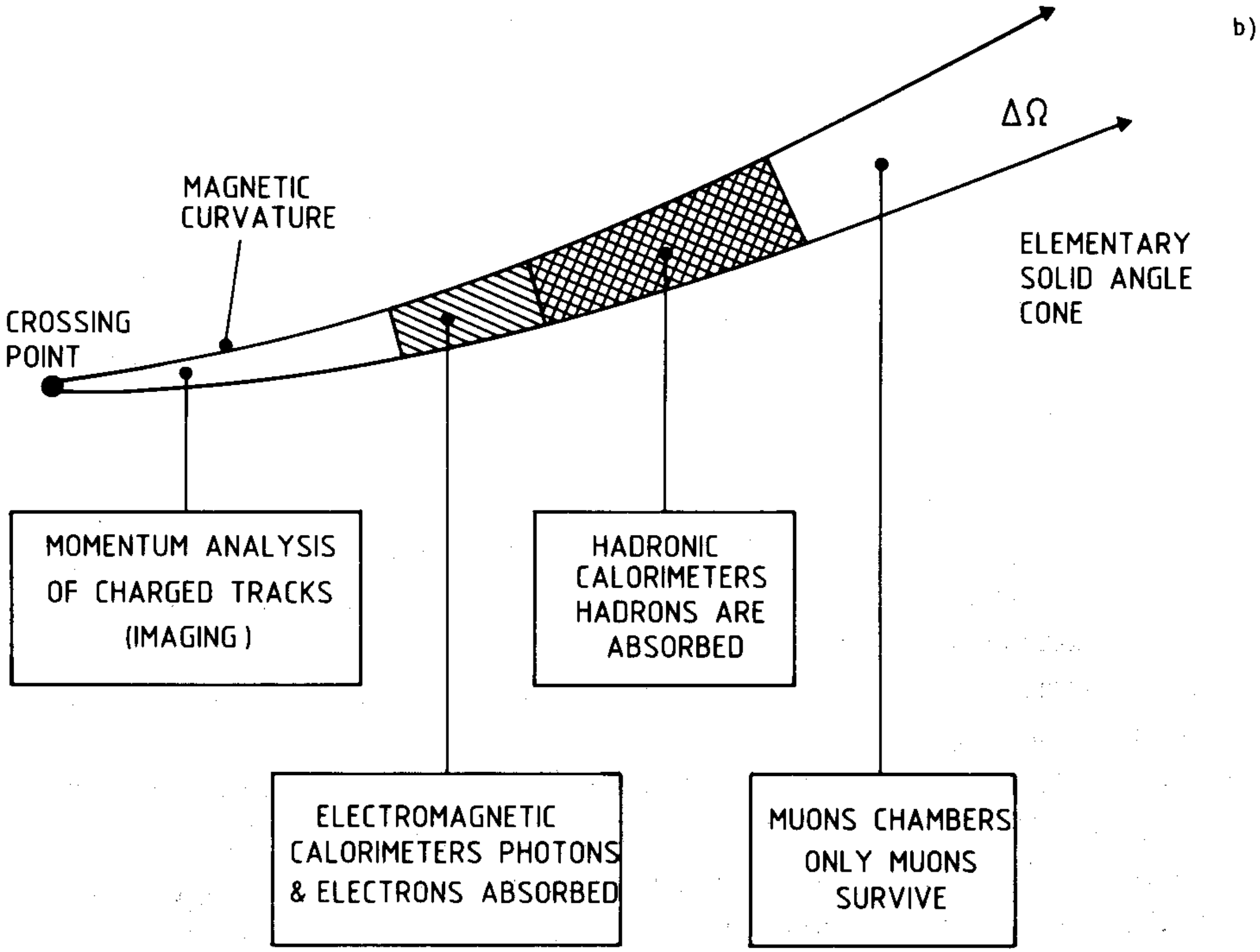
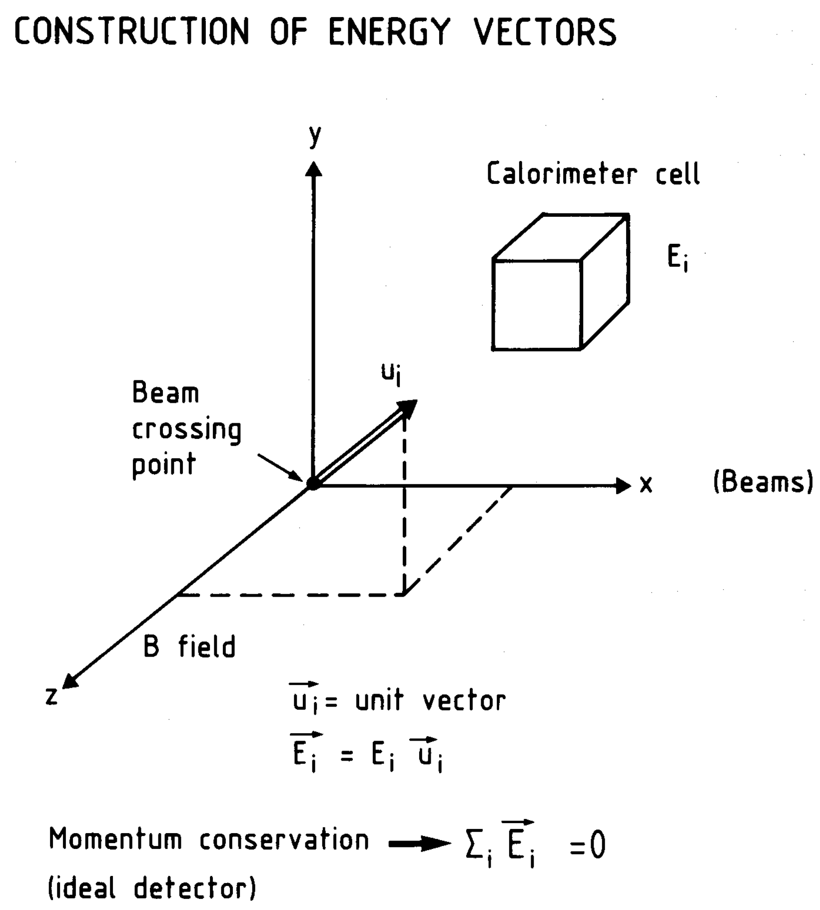


Fig. 8b. The schematic functions of each of the elementary solid-angle elements constituting the detector structure.

Neutrino transverse energy

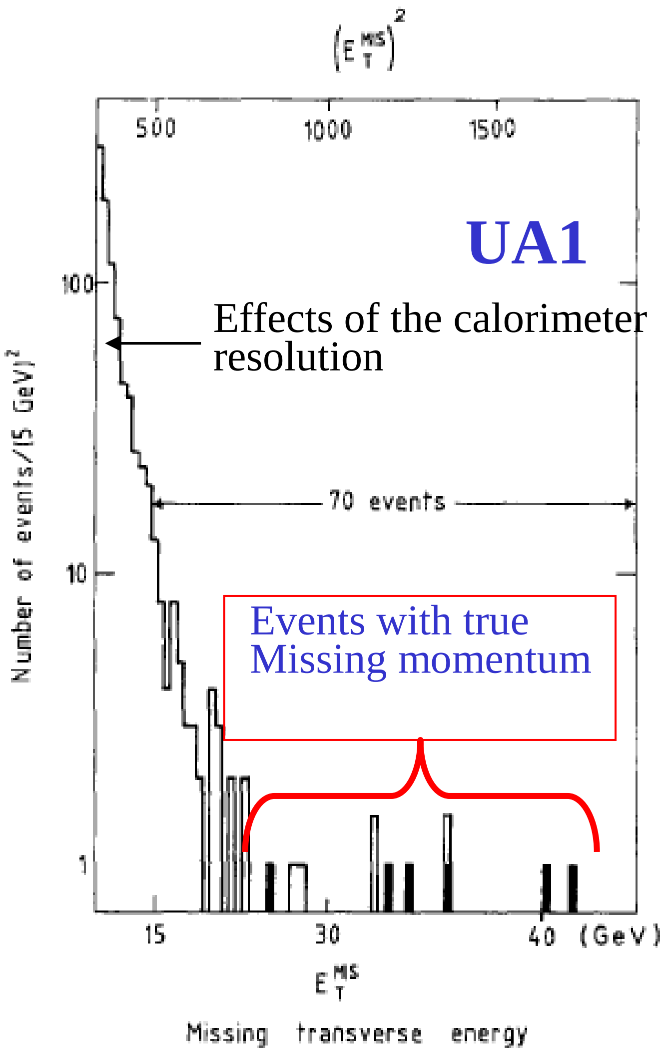


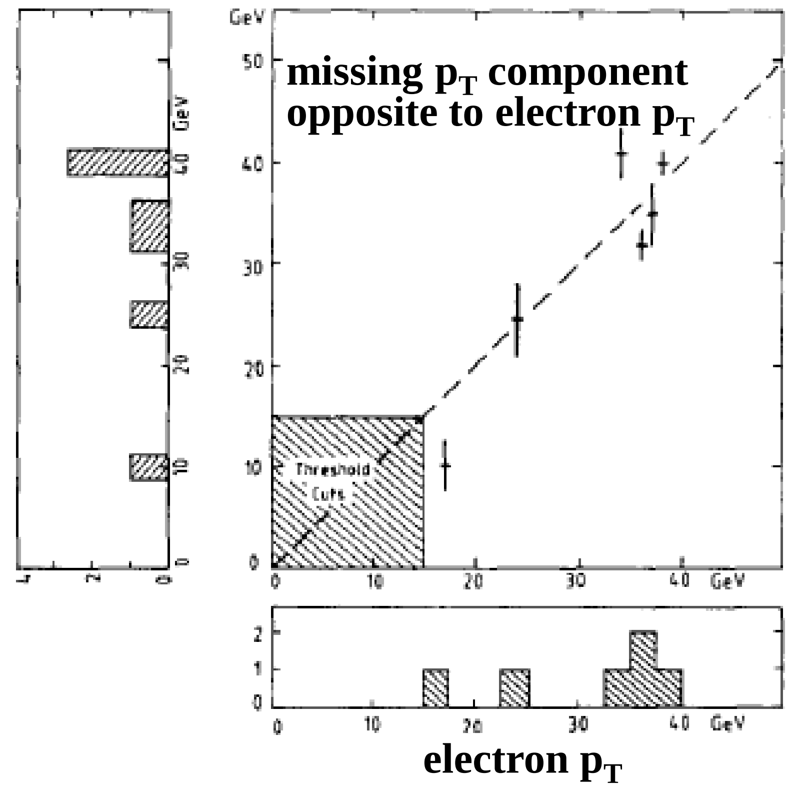
Momentum balance is possible only for tranverse component: in fact a large fraction of the longitudinal momentum is lost (with large fluctuations) in the vacuum tube of the beams.

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

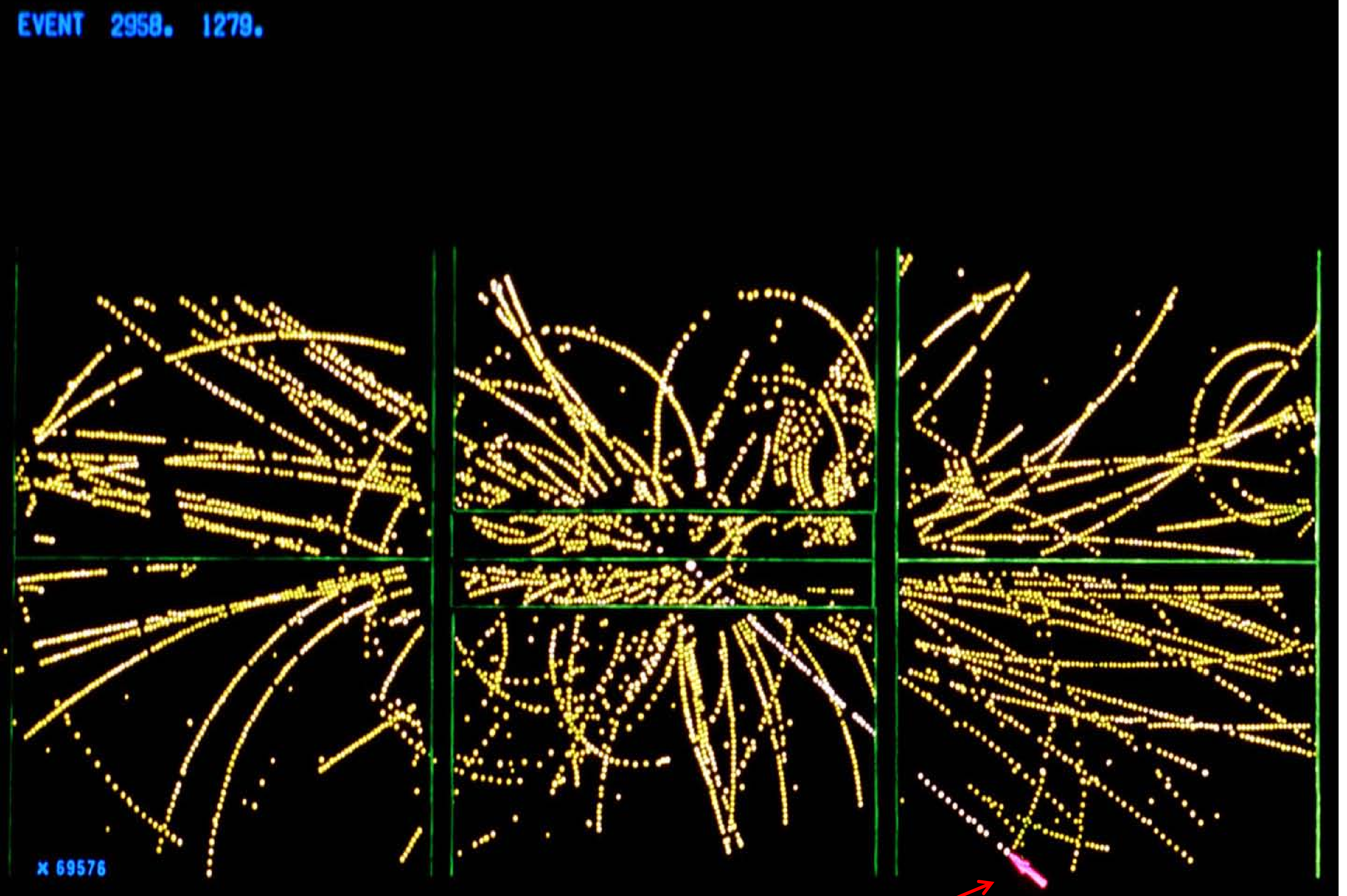




Six events with a large electron p_T electron balanced by large missing p_T

consistent with $W \rightarrow e\ n$ decays

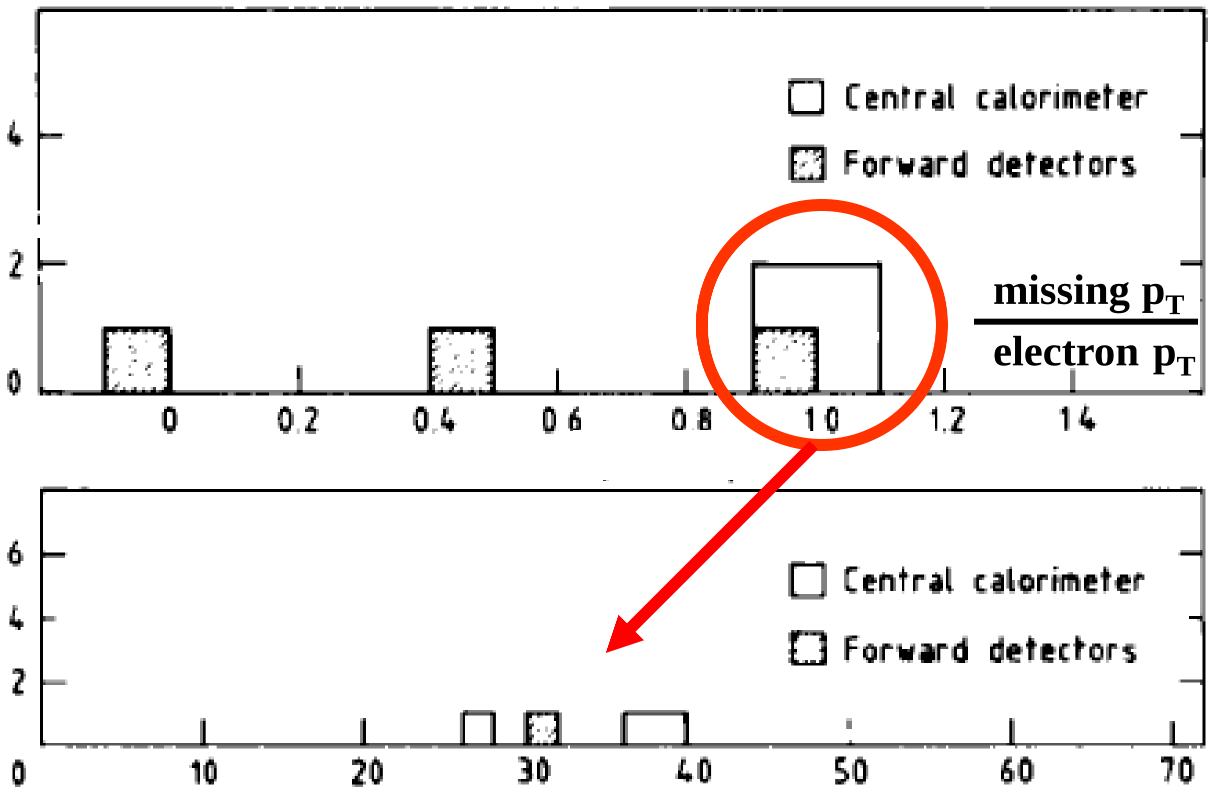
(CERN seminar 20 January , 1983)



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

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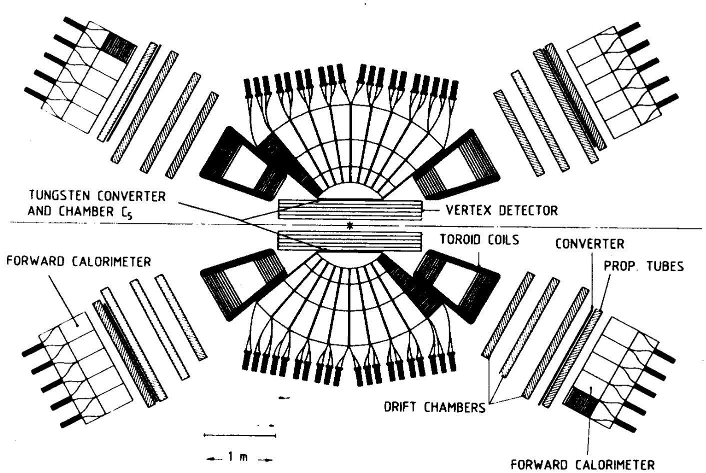

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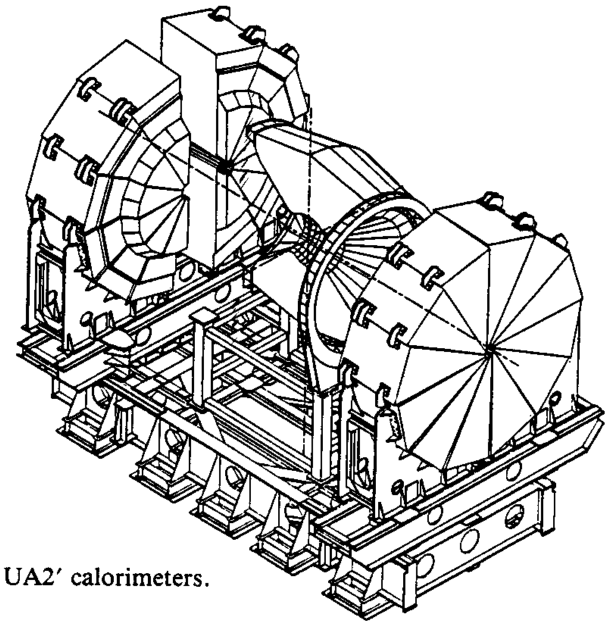
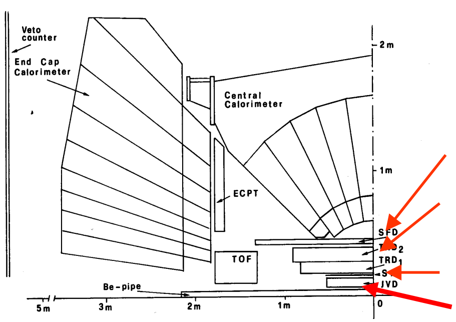


the UA2′ calorimeters.



Scintillating fibres

Silicon detector

Drift chamber vertex chamber

24

Particle segnature in UA2

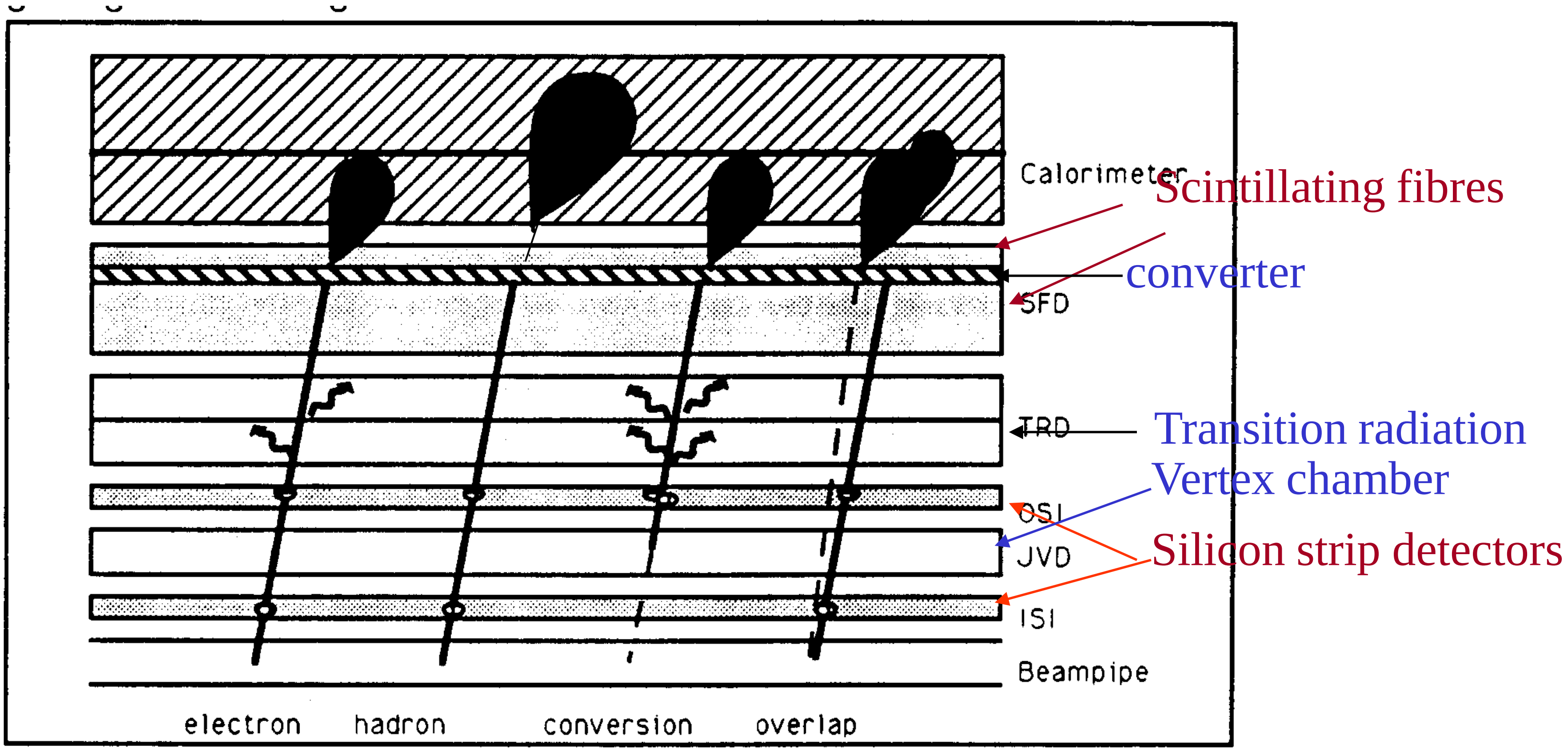


Fig. 1 Particle Identification with the Central Detector

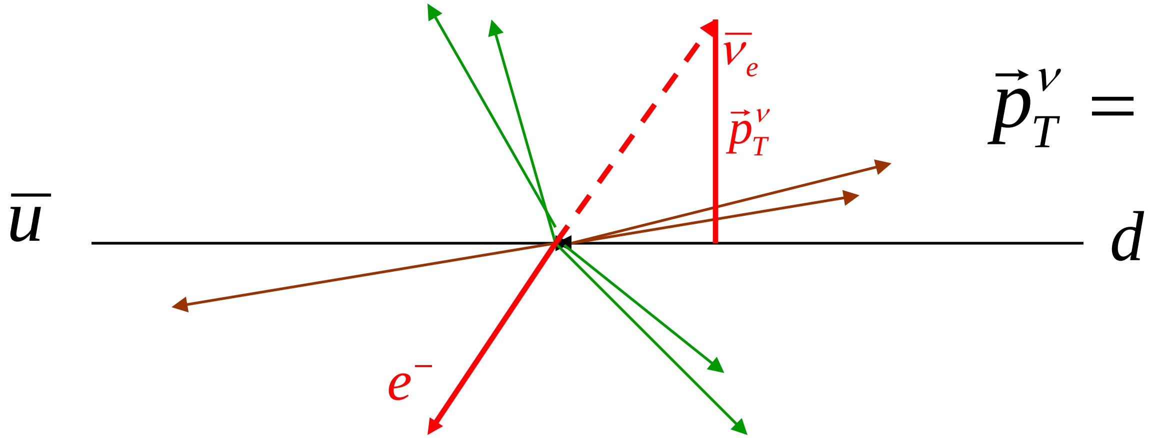
How can we measure W and Z?

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

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

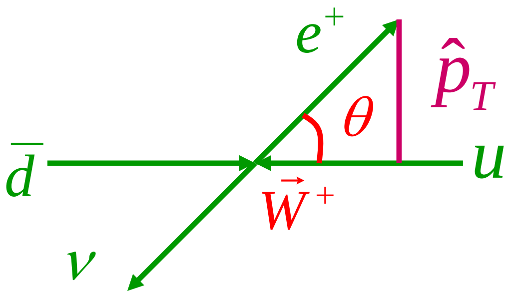
Leptonic decay channels of W(B.R. 11%) $W^- \to e^-\overline{\nu}_e, \mu^-\overline{\nu}_\mu, \tau^-\overline{\nu}_\tau$

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



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

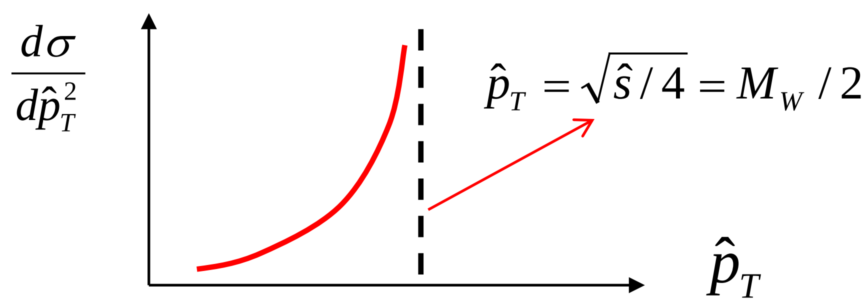
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\cos\theta} = K(1+\cos\hat{\theta})^2 (\text{note: it is null at } \theta = \pi, \textit{helicity})$$

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

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

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

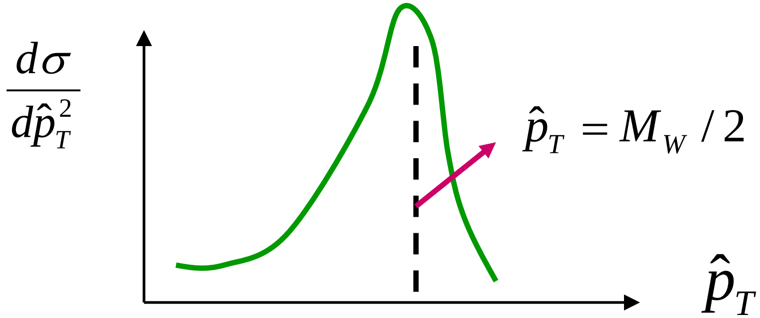
diverges at $\hat{\theta} = \frac{\pi}{2}$, or $\hat{p}_T = \frac{\sqrt{\hat{s}}}{2} \sim M_W/2$



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

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

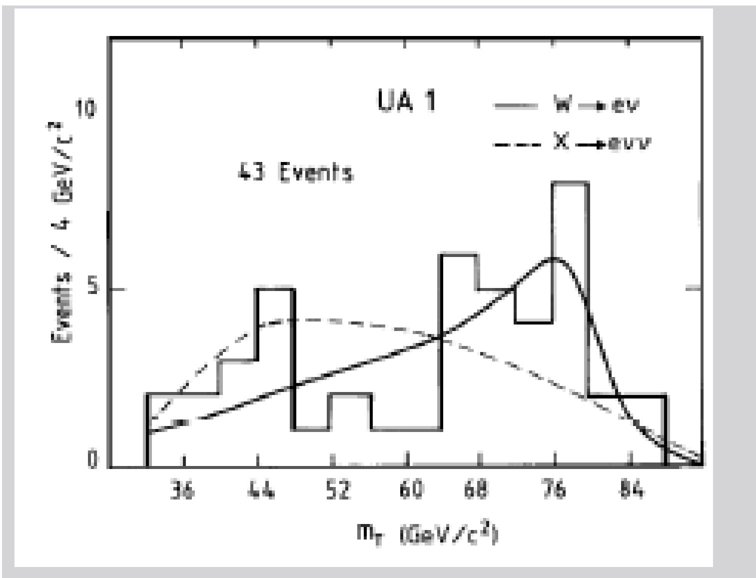
The m_T distribution is less sensitive than that in p_{Te},$p_{T\nu}$,**to the trasverse motion of W you have corrections $\propto$** β_{TW}^2 not to β_{TW}

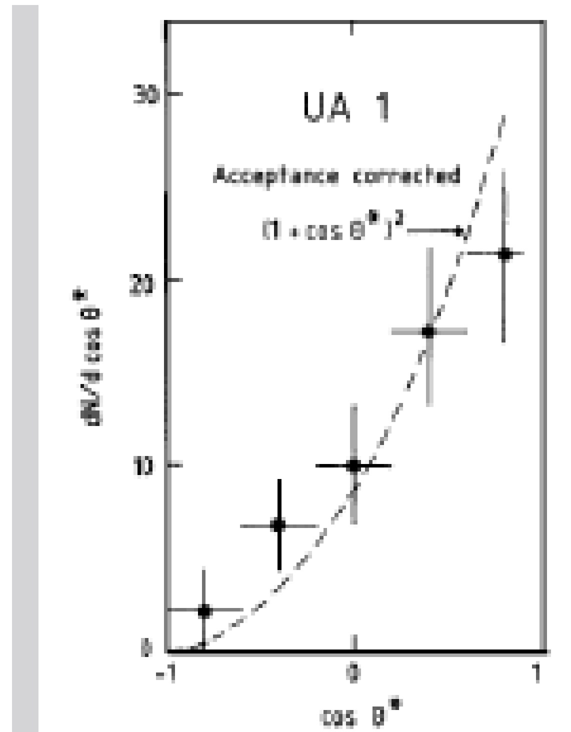
Similarly with the distribution in p_{Te}

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

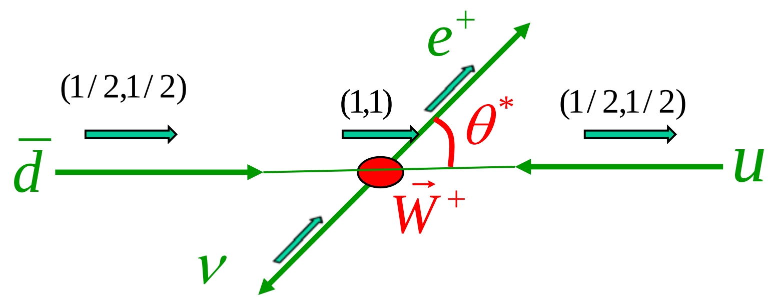
Iacobian peak at $\hat{s} = M_W^2 \sim m_T^2$

The UA1 Iacobian Peak





$M_W = 80.9 \pm 1.5 GeV$

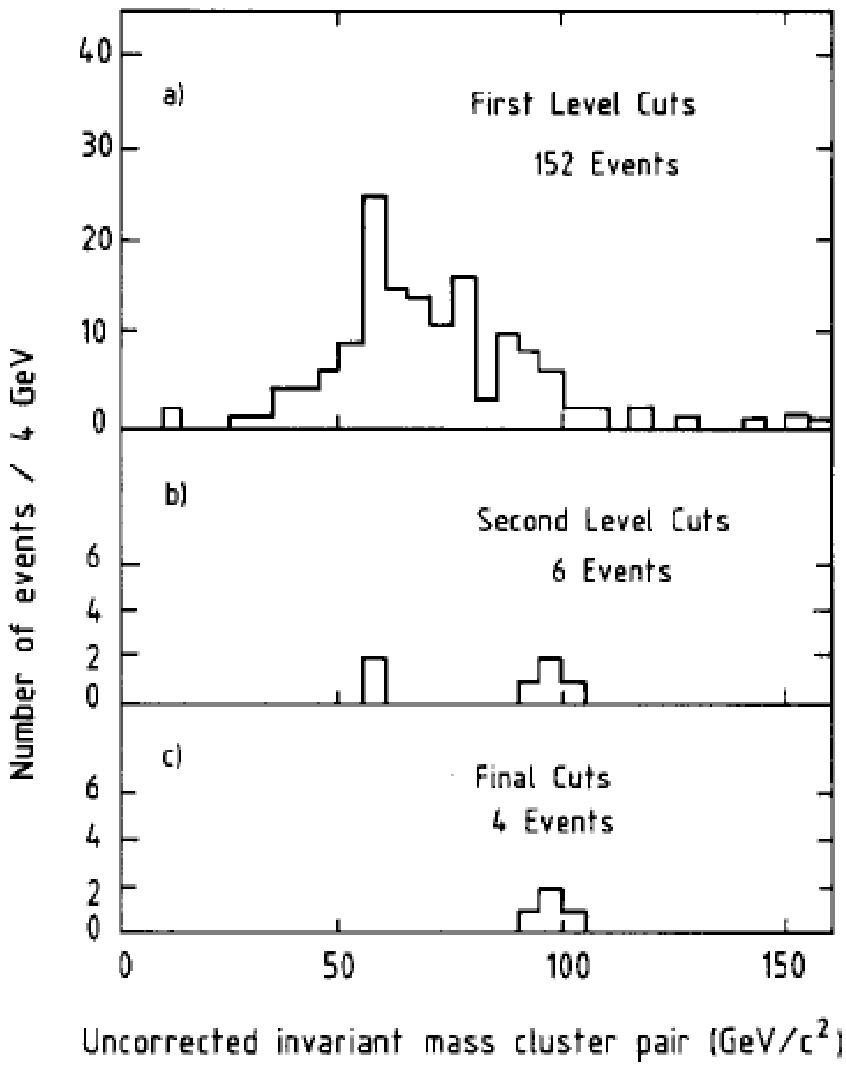


$$PDG: \mathrm{M_W} = 80.398 \pm 0.025\, GeV,$$

$$\Gamma_W = 2.141 \pm 0.041\, GeV$$

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

(May 1983)

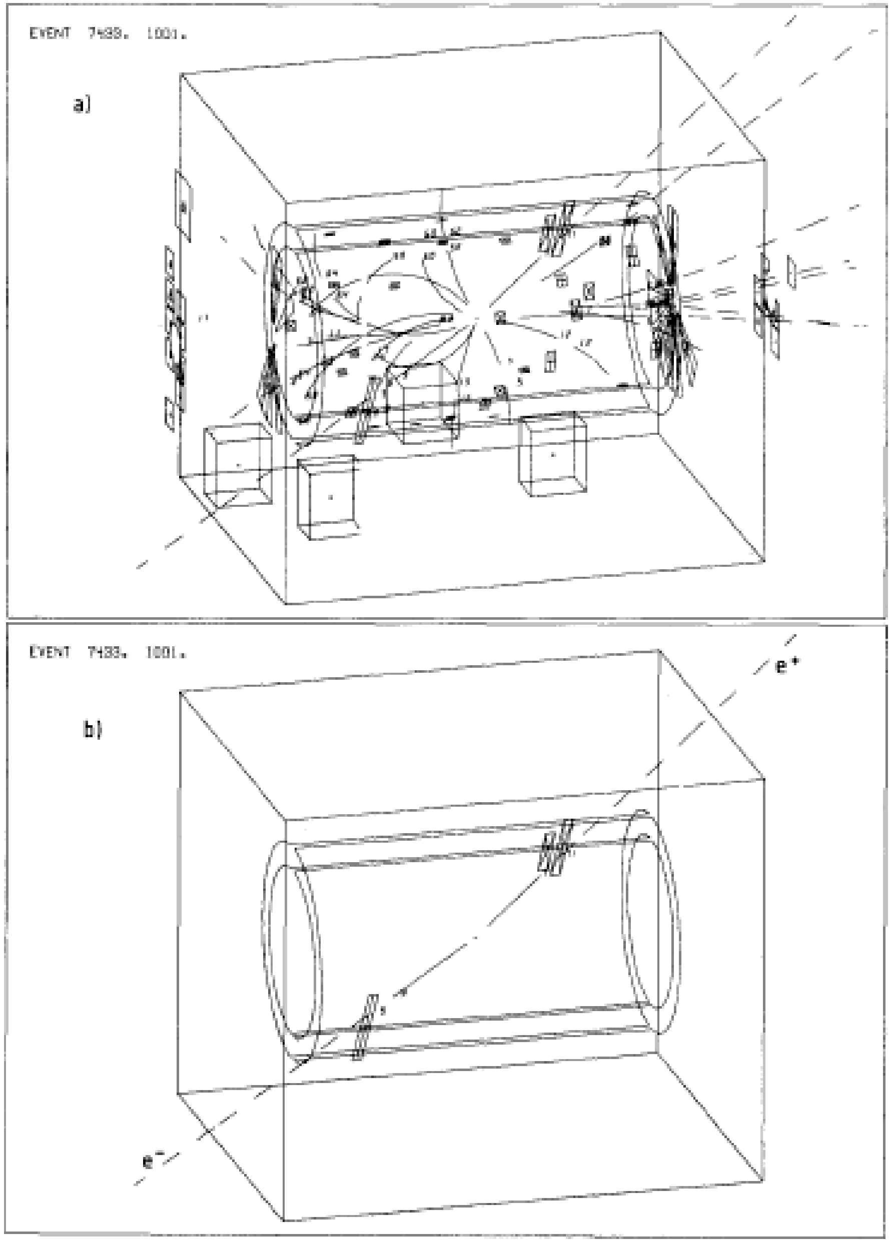


Two localized deposits of energy in the electromagnetic calorimeter (electrons or photons)

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

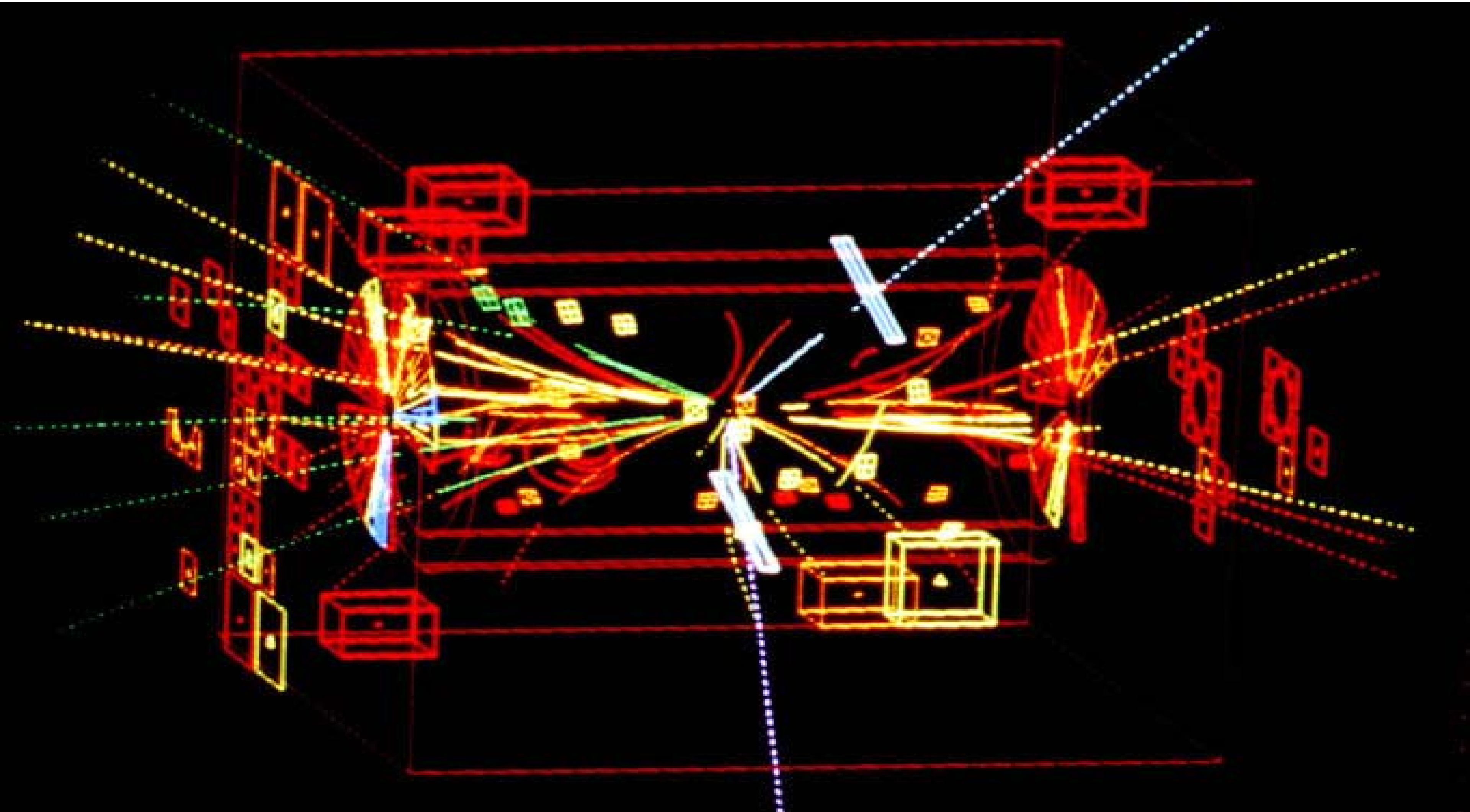
<u>Both tracks with</u> p_T > 7 GeV
Point to an electromagnetic cluster

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



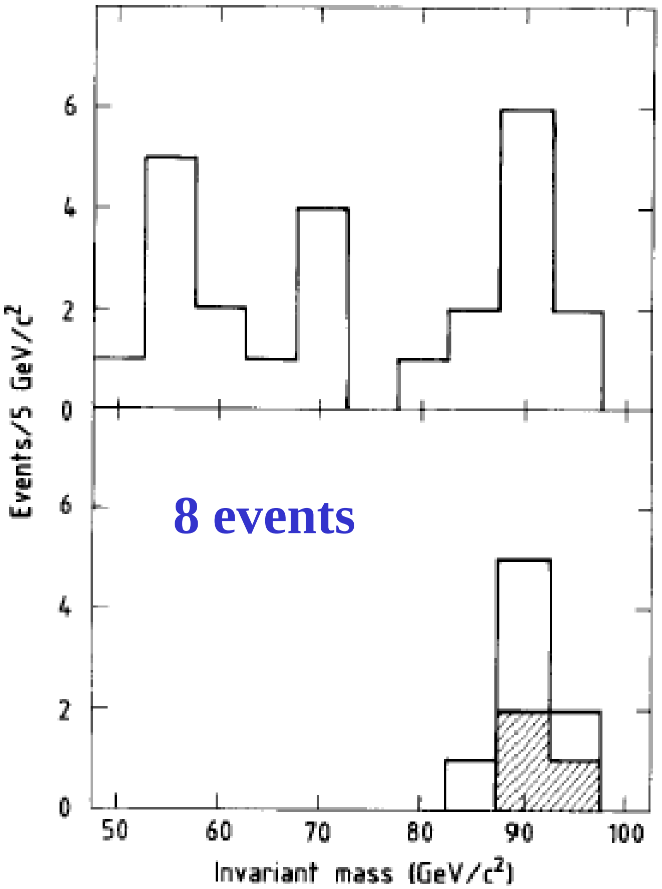
Event with all tracks and Electromagnetic deposits

Require tracks with p_T > 2 GeV



UA2: observation of Z → $e^+ e^-$

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

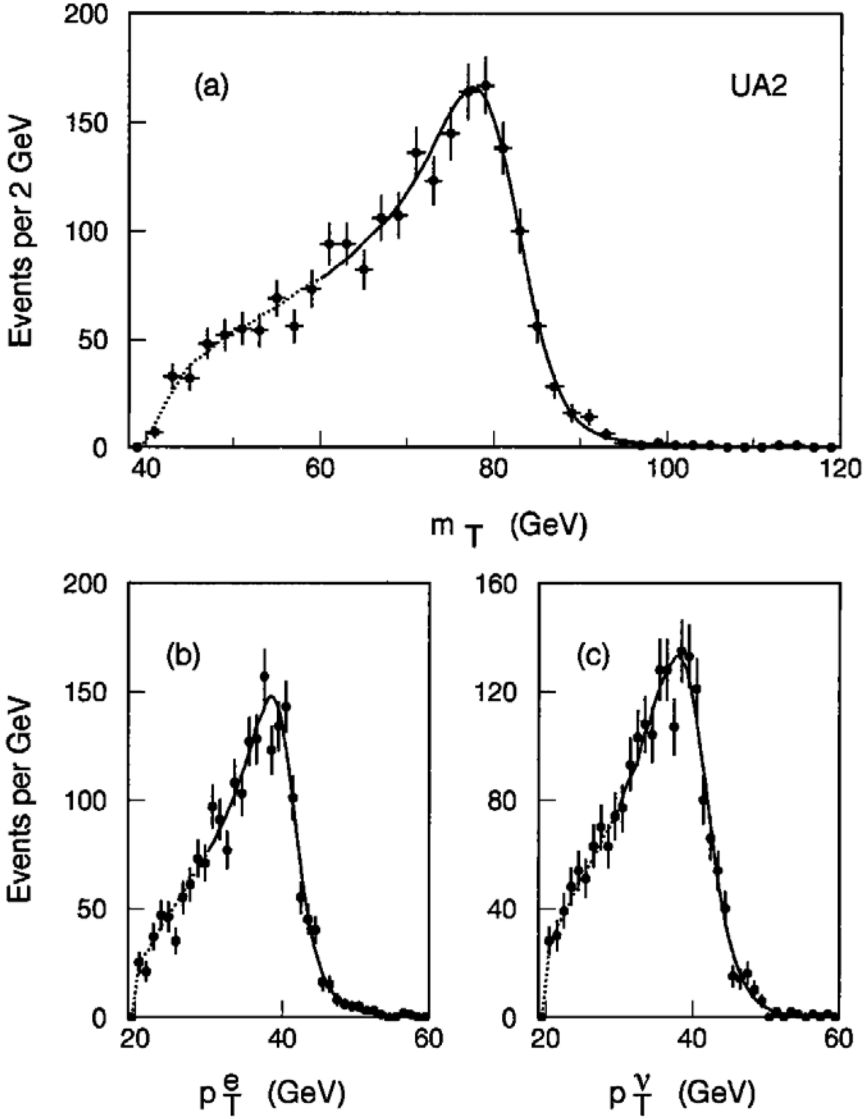


Figure 4: Fits for m_W to (a) the m_T spectrum, (b) the p_T^e spectrum and (c) the p_T^ν spectrum. The points show the data, while the curves show the fit results with the solid portions indicating the ranges over which the fits are performed.

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

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:

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

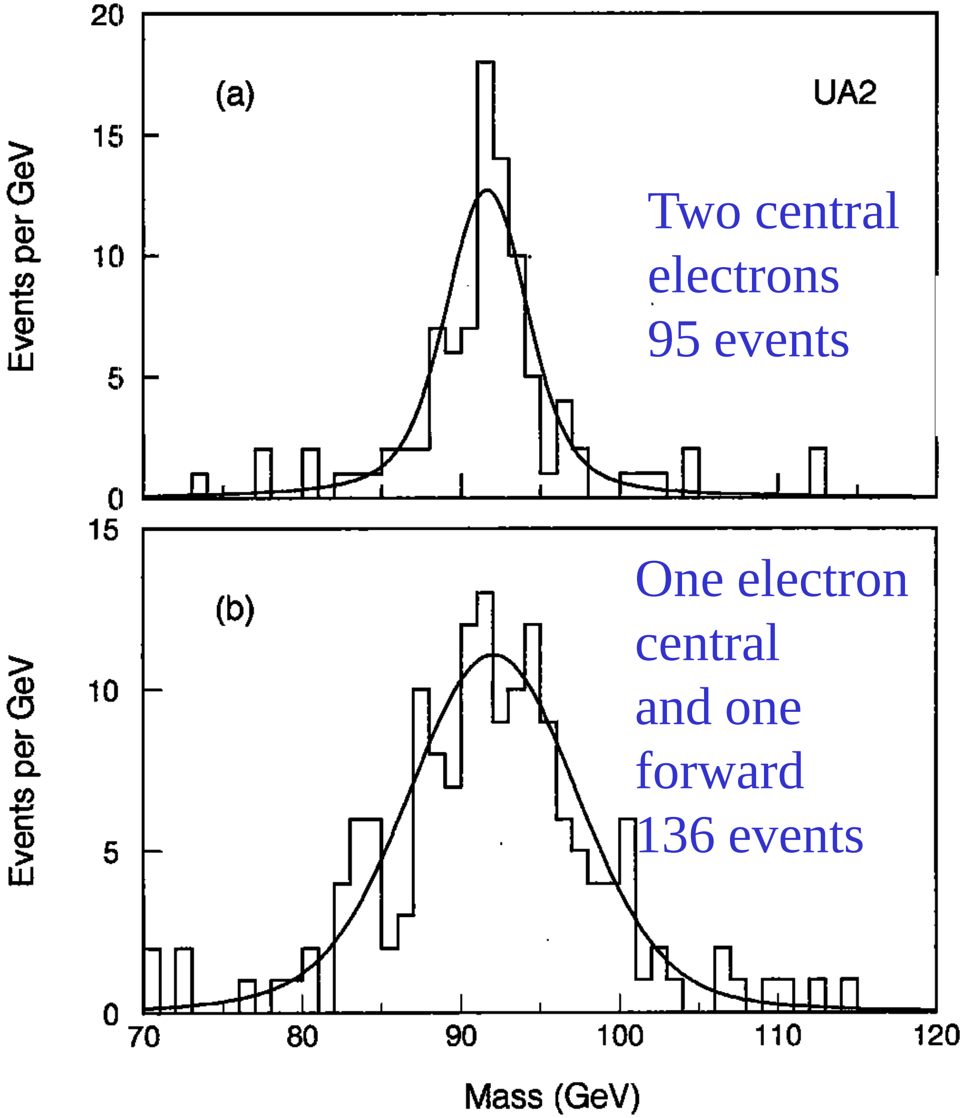


Figure 1: Fits for m_Z to (a) the central sample and (b) the pt-constrained sample. The curves show the fits, while the histograms show the data.

	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

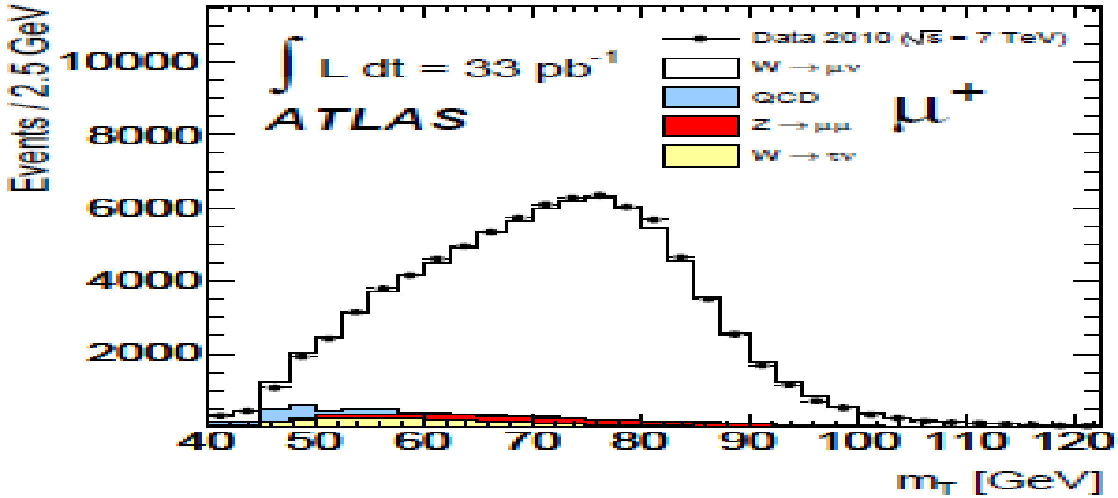
$\pm 0.12(sys) \pm 0.92(scal$

QCD background <1%

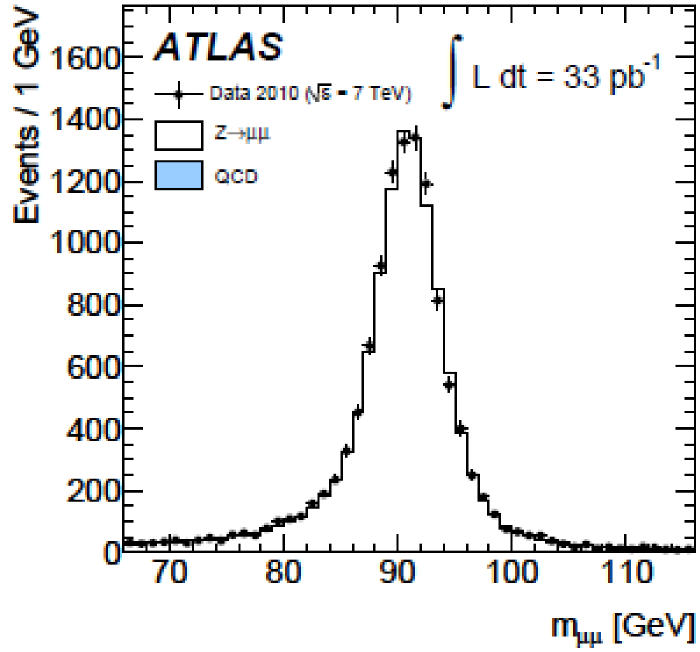
$$PDG : M_Z = 91.1896 \pm 0.0021\, GeV,$$

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

W/Z at LHC



$\int L\, dt = 33\ pb^{-1}$
ATLAS
Data 2010 ($\sqrt{s}$ = 7 TeV)
$W \to \mu\nu$
QCD
$Z \to \mu\mu$
$W \to \tau\nu$
μ^+
Events / 2.5 GeV
10000
8000
6000
4000
2000
40
50
60
70
80
90
100
110
120
m_T [GeV]



ATLAS
$\int L\, dt = 33\ pb^{-1}$
Data 2010 ($\sqrt{s}$ = 7 TeV)
$Z \to \mu\mu$
QCD
Events / 1 GeV
1600
1400
1200
1000
800
600
400
200
0
70
80
90
100
110
$m_{\mu\mu}$ [GeV]

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 parameter are independent, ex:

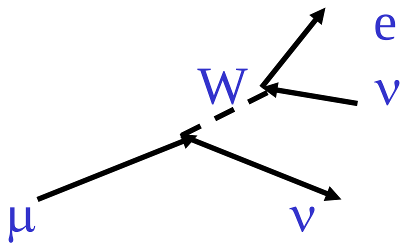
$$\alpha, \left[\frac{\Delta\alpha}{\alpha}\right] = 0.0007\cdot10^{-6}\ (\text{a } Q^2=0)\ \text{dai livelli atomici;}$$

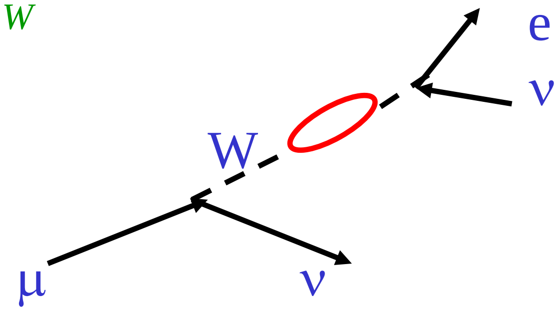
$$\mathrm{G}, \left[\frac{\Delta \mathrm{G}}{\mathrm{G}}\right] = 9\cdot10^{-6}\ (\text{from the decay } \mu\rightarrow e\nu\nu);$$

$$\mathrm{M_W}, \left[\frac{\Delta M_W}{M_W}\right] = 360\cdot10^{-6}; \sin^2\theta_W, \left[\frac{\Delta\sin^2\theta_W}{\sin^2\theta_W}\right] = 650\cdot10^{-6}$$

But relations at tree level are modified by radiative corrections:

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

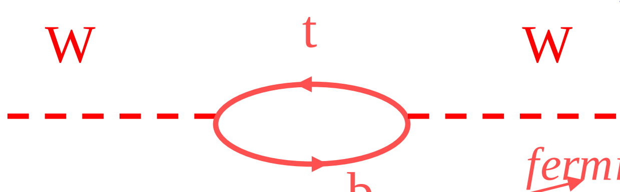




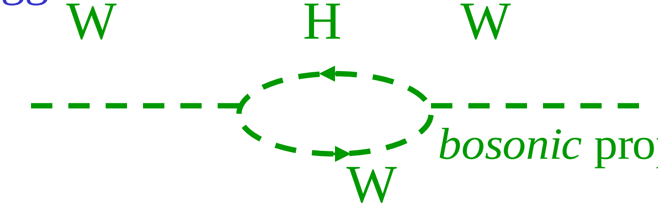
$$da: M_W^2 = \frac{\pi\alpha}{G\sin^2\theta_W\sqrt{2}} \rightarrow \sin^2\theta_W\cos^2\theta_W = \left(1-\frac{M_W^2}{M_Z^2}\right)\frac{M_W^2}{M_Z^2} = \frac{\pi\alpha(M_Z)}{\sqrt{2}GM_Z^2(1-\Delta r)}$$

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

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



fermionic prop.: $1/q$



bosonic prop.: $1/q^2$

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

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

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)

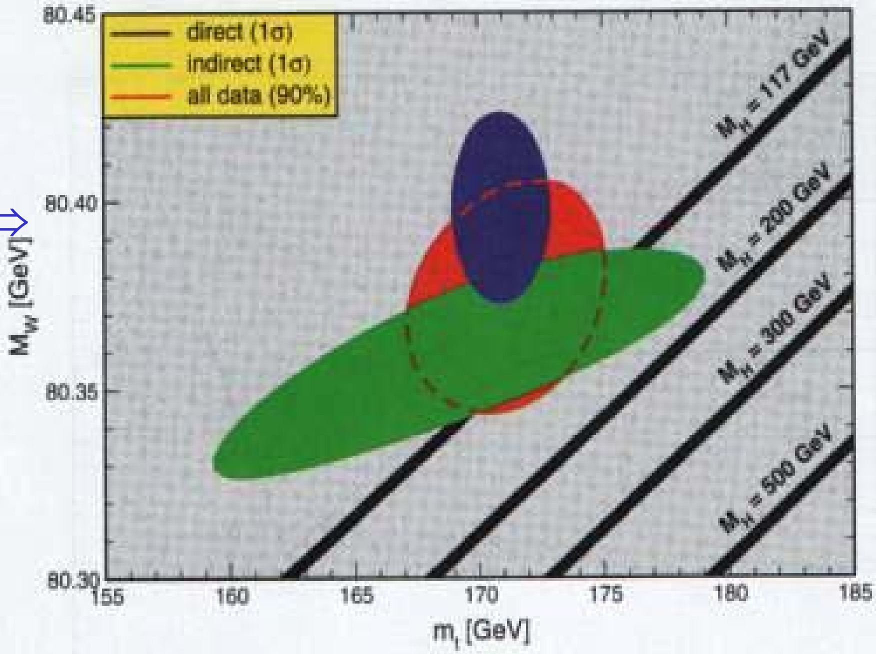


Figure 10.3: One-standard-deviation (39.35%) region in M_W as a function of m_t for the direct and indirect data, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. The SM prediction as a function of M_H is also indicated. The widths of the M_H bands reflect the theoretical uncertainty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

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

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

Low Higgs masses favoured.

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

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

The value of the potential at minimum is then: $V_0 = -\frac{\lambda v^4}{2}$ with

$$v = \frac{\sqrt{2} M_W}{g_W} \sim 174 \text{ GeV} \Rightarrow \text{V}_0 \sim 2 \cdot 10^9 \lambda \text{ GeV}^4$$

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 $\approx 10^{-4} \frac{GeV}{cm^3}$

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

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

$m_H = 125 GeV, v = 174 GeV (from G_F)$

$\Rightarrow \lambda \approx 1$

If λ ~ 1 energy of the Higgs field:

$$V_0 \sim 2.6 \cdot 10^{50}\, GeV / cm^3$$

54 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^{54} !!!

From AA to Z

(seminar of C. Rubbia at CERN, 1983)

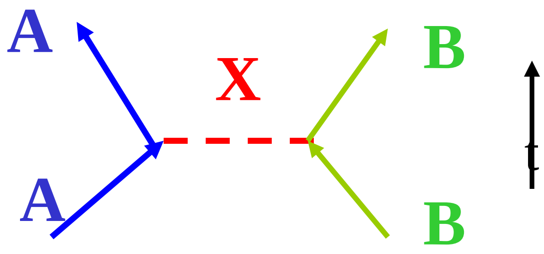
From Z/W to Higgs (2012)

From Higgs to ???

Still a lot of work (theory and experiments) to be done: your future job, good luck!

Back up slides

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:

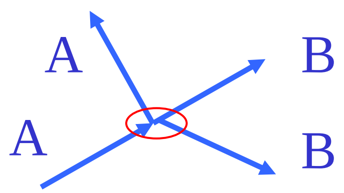
$$R = c \cdot \tau \le \frac{\hbar c}{M_X} \ (range)$$

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?