HASCO 2017

Electroweak physics, an introduction

Together with the Quantum Chromodymamics is
the "Standard Model" of the particle interactions,
very nicely confirmed by many precise experiments,
the last one: the Higgs discovery)

Summary:

-Basics of the electro-weak unification;

-electroweak interactions of leptons;

-electroweak interactions of quarks;

-the discovery of the electroweak mediators: the W and Z bosons;

-The characteristics and self interactions of the W-Z bosons

-Search for new physics in the trilinear gauge boson couplings

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Unify electrodynamics and weak interaction

-**electromagnetic interactions**:

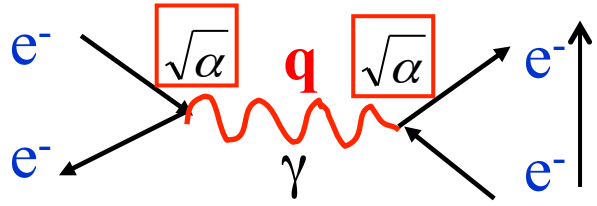
interaction between charged particles mediated by a neutral electromagnetic vector field .

To make the theory relativistic and quantized, we need :

-a coupling constant: **the electric charge: √α**;

-a mediating field: a neutral massless spin 1 particle: **the photon: γ**

Ex: $e^- + e^- \longrightarrow e^- + e^-$



The electromagnetic current:

$$J^\mu = \frac{e}{\sqrt{2}}\bar{u}(e)\gamma^\mu u(e) \qquad \alpha = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137}$$

$u, \bar{u}$: Dirac spinors: 4-component vectors

$\gamma^\mu (\mu = 1-4)$ the (4×4) Dirac matrices

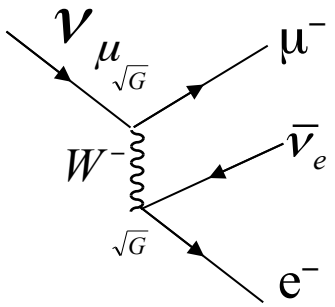
The mediator (the photon) is neutral and the effect of the electromagnetic potential (Coulomb) is described by the propagator:

$$\Rightarrow \frac{1}{q^2}\text{(infinite range force)}$$

-The (charged) weak interactions:

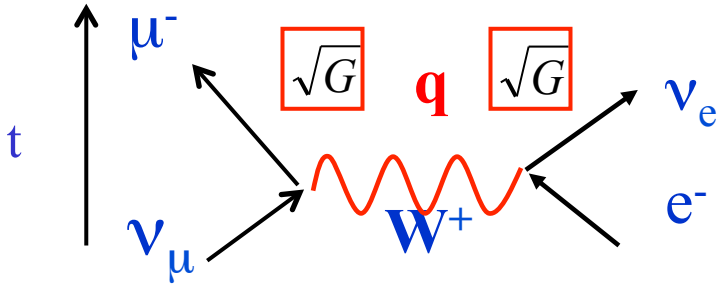
The muon decay is the simplest purely leptonic weak decay:

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



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

The $\underline{m^{-5}}$ dependence is typical of any weak decay (neglecting the final particle masses)



Charged weak interaction $2 \rightarrow 2$

Ex: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$

Properties of the (charged) weak interactions

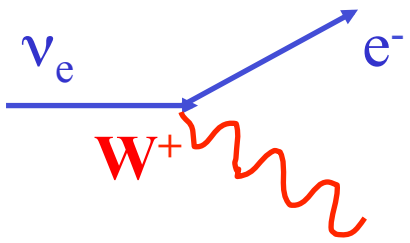
-Fermions: leptons and quarks can interact weakly: universal interaction;

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

-The **mediator, W, is a spin 1 MASSIVE field** (short range force)→ $\propto \frac{1}{q^2 - M_W^{\ 2} + (i\Gamma M_W)}$

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

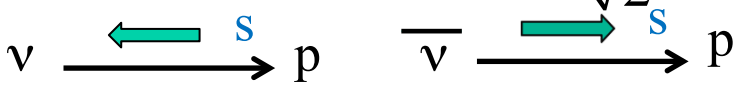
-**Weak interactions violate spatial parity and charge conjugation simmetries**:
the interacting neutrino is left-handed and antineutrino is right-handed.



The "elementary fermions" are doublets, ex:

$$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix}$$

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



$$\gamma^5(4\times 4) = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix},$$

$\gamma^\mu \equiv vector; \quad \gamma^\mu\gamma^5 \equiv axial\ vector$

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

From the muon lifetime measurement:
$\tau_\mu = 2.197\ 10^{-6}$ s and $m_\mu = 0.105658$ GeV

⟹ **Extract $G = 1.166\ 10^{-5}$ GeV^{-2}**

Equivalence between the adimensional weak constant g_W^2 and the "old" Fermi constant G

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

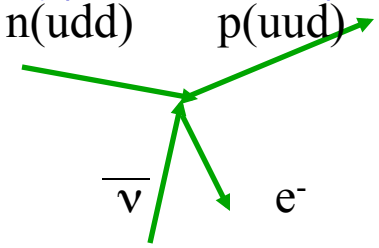
The weak interactions are "weak" because the mediator (W) is very heavy and, at low Q^2, it dominates the coupling

At $Q^2 \sim M_W^2$ $(80\ \text{GeV})^2$ the weak interaction becomes comparable to the electromagnetic ones:

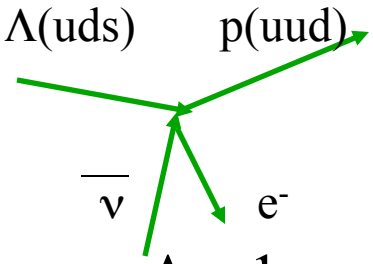
Unification?

Hadronic weak currents

Experimental evidence of two beta-like decays

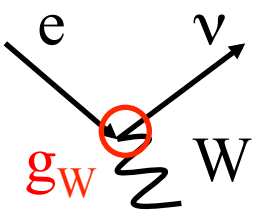


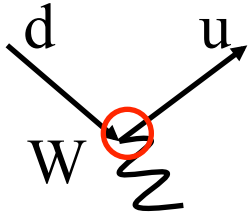
$\Delta s=0$: d→u

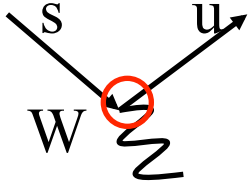


$\Delta s=1$: s→u

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.

Weak current still (V-A): $(1-\gamma_5)$. But the quark 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 weak doublet:

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

The Cabibbo Kobayashi Maskawa (CKM) mixing matrix

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

$$\begin{bmatrix} u \\ d \end{bmatrix}\begin{bmatrix} c \\ s \end{bmatrix}\begin{bmatrix} t \\ b \end{bmatrix}$$

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

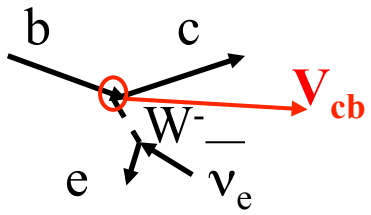
The matrix V is complex: 18 elements, but it is also unitary: 4 irriducible elements

Standard parametrization (PDG): 3 angles θ_{ij} ($\theta_{12}$is the 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 : its elements extracted from the experiments, ex:



$$\text{e.g.}: \Gamma(b \to ce^-\bar{\nu}_e) = \frac{G^2 m_b^5}{192\pi} |V_{cb}|^2 F(m_c/m_b)$$

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

From experiments:

$$V_{CKM} = \begin{vmatrix} 0.97434 & 0.22506 & 0.00357 \\ 0.22492 & 0.97355 & 0.0411 \\ 0.00875 & 0.0403 & 0.99915 \end{vmatrix}$$

Uncertainties: ~10^{-3} - 10^{-4}

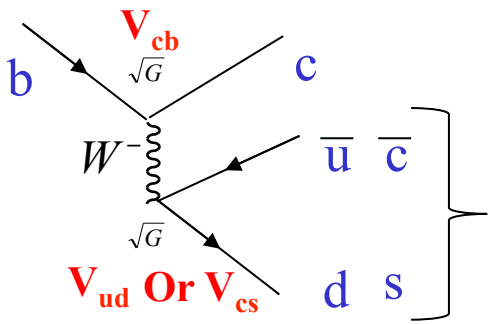
Unitarity puts constraints on rows and colums elements, ex:

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

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 (~ 5 GeV): **τ_{B+}=(1.641 ·10^{-12} ±0.008) s, a fortune for experiments!**



x3 :
summed up on the three quark colors

Are there additional quark doublets?
Generalization to n quark generations

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

6 leptons+ 6 quarks spin ½ ,masses from :
0.5 MeV to 170 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

ν_e, ν_μ, ν_τ m~ eV?????

Quarks : u, c, t

u, c, t m ~1, 1500, 175000 MeV

u, c, t

3 "color" charges

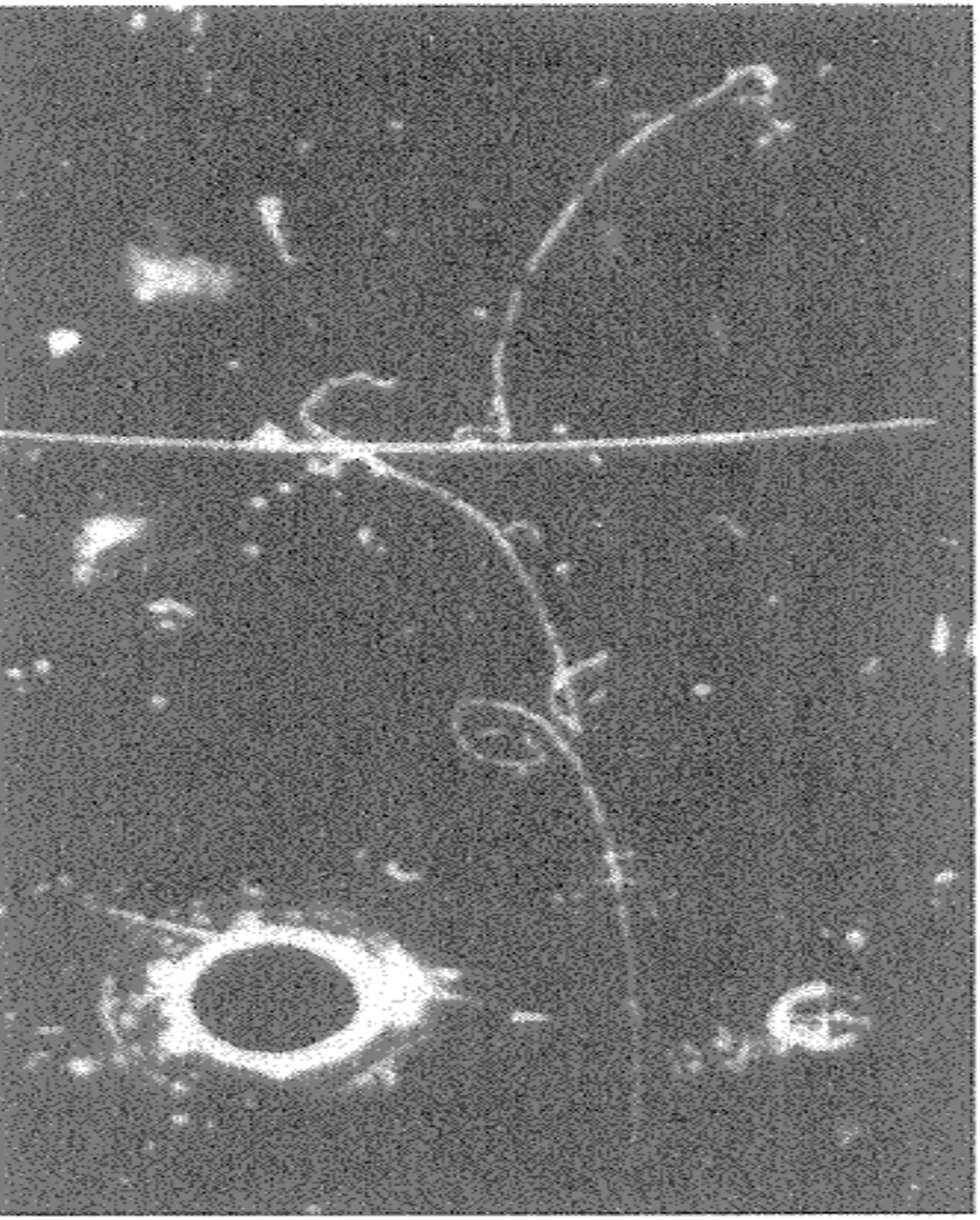
d, s, b

d, s, b m=1, 170, 5000 MeV

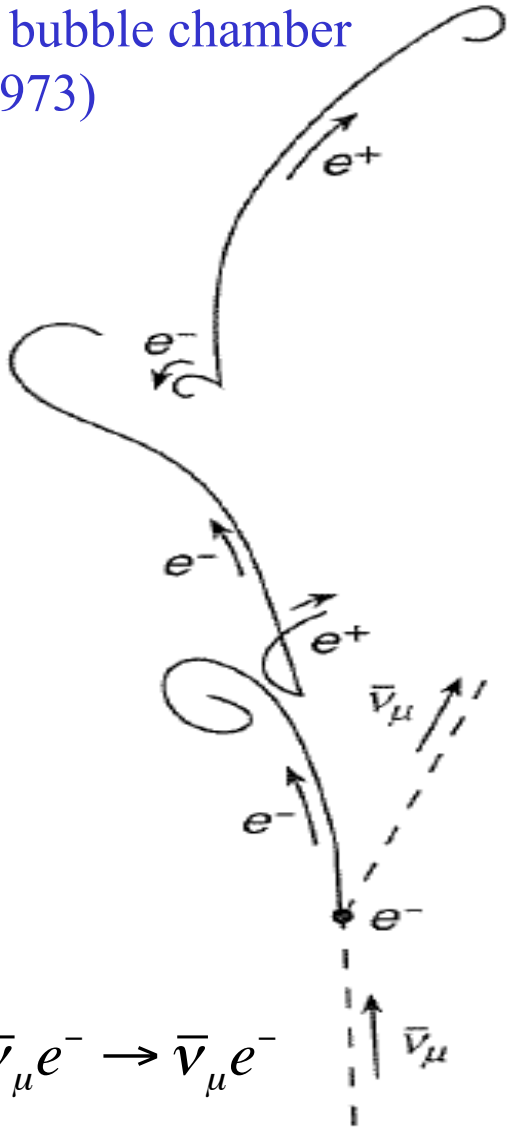
d, s, b

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

First evidence for weak neutral currents: $\overline{\nu}_\mu e^- \rightarrow \overline{\nu}_\mu e^-$

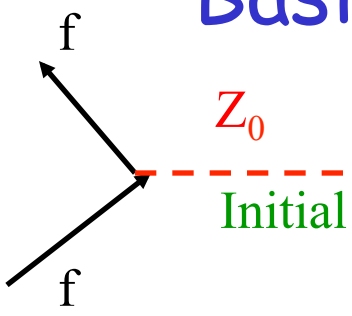


A neutral current event in bubble chamber (1973)



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

Basics of weak neutral currents



Mediated by an heavy neutral boson : Z_0

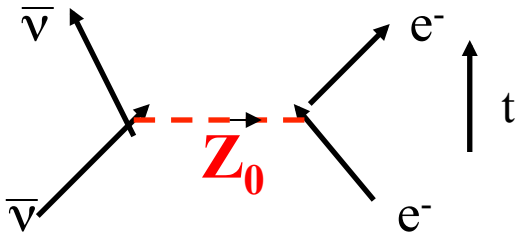
Initial and final fermions are the same (no flavour changing NC) :

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

1973: events mesured in bubble chamber (Gargamelle)

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

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



Facts: neutral current cross 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 (charge+ Isotopic spin T_3) and on a new parameter: θ_W:

In the GWS theory : : θ_W connects "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):

$$T_3 = 1/2 \qquad \begin{bmatrix}\nu_e\\ e\end{bmatrix}\begin{bmatrix}\nu_\mu\\ \mu\end{bmatrix}\begin{bmatrix}\nu_\tau\\ \tau\end{bmatrix} \quad \begin{bmatrix}u\\ d\end{bmatrix}\begin{bmatrix}c\\ s\end{bmatrix}\begin{bmatrix}t\\ b\end{bmatrix}$$

$$T_3 = -1/2$$

$$C_V = T_3 - 2q\sin^2\theta_W, C_A = T_3$$

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 the existence of a isosinglet massless boson B_μ

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

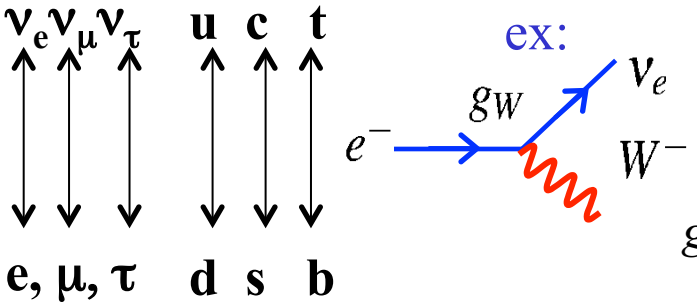
$$\Rightarrow \text{two charged bosons}: W^{\pm}_\mu = \frac{1}{\sqrt{2}}\left[W^1_\mu \mp W^2_\mu\right] \text{ and one neutral: } W^3_\mu$$

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

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

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

A_μ e Z_μ are the physical observable states, **$\sin\theta_W$** is a free parameter

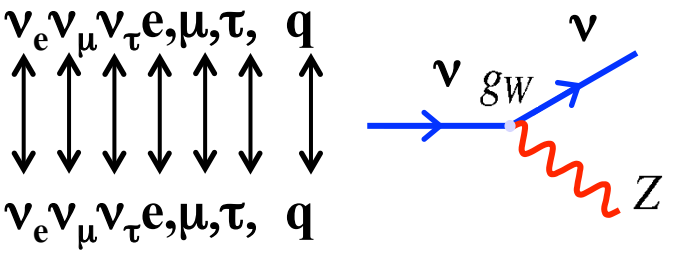


Universal charged current connects lepton and quark doublet components with coupling :

g_W (V-A) : $g_W(1-\gamma_5)$,

for quarks q,q' weighted by the CKM factor $V_{qq'}$

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



Neutral current connects the **same flavour** leptons and quarks depending on charge , isospin , $\sin\theta_W$ and with coupling :

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

Minimal model

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

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

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

To provide masses to W/Z (and keep the photon massless) will be the task of the Higgs boson (see lecture of Aurelio Juste Roza)

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

The theory is determined

$$\alpha = \frac{e^2}{4\pi\hbar c} = \frac{1}{137.035999139(31)}$$ (a $Q^2 = m_e^2$) 0.00023 ppm (atomic physics)

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

$\sin^2\theta_W(M_Z) = 0.23129(5)$ 220 ppm

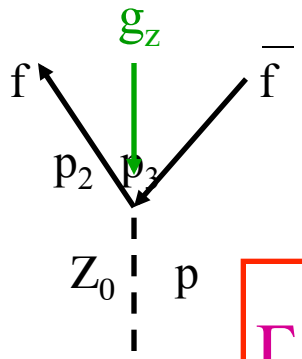
if *we : know*: $\alpha, G_F, \sin^2\theta_W$

we can predict (tree level):

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

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

Interactions of Z and W with fermions



$$M = \frac{-ig_Z}{2}\varepsilon^{\mu}\left[\bar{u}(p_2)\gamma_{\mu}(C_V^f - C_A^f\gamma_5)v(p_3)\right]$$

Make the square of the amplitude and sum on spin of final fermions and average on Z polarization, ε_μ

$$\Gamma_Z = \frac{G}{6\sqrt{2}\pi}M_Z^3\left[C_A^{f\,2} + C_V^{f\,2}\right]$$

Sensitive to coefficients C_A^f e C_V^f

With the appropriate C_A e C_V of fermions in final state:

$$\Gamma(\nu\bar{\nu}) = \frac{GM_Z^3}{6\sqrt{2}\pi}\left[\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2}\right)^2\right] \quad \textbf{color} \quad = 166.2 \text{ MeV}$$

$$\Gamma(l\bar{l}) = \text{"} \left[\left(-\frac{1}{2}\right)^2 + \left(-\frac{1}{2} + 2\sin^2\theta_W\right)^2\right] \quad = 83.5 \text{ MeV}$$

$$\Gamma(u\bar{u}, c\bar{c}) = \text{"} \left[\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2} - \frac{4}{3}\sin^2\theta_W\right)^2\right] \times 3 \quad = 295 \text{ MeV}$$

$$\Gamma(d\bar{d}, s\bar{s}, b\bar{b}) = \text{"} \left[\left(-\frac{1}{2}\right)^2 + \left(-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W\right)^2\right] \times 3 \quad = 381 \text{ MeV}$$

: Γ_Z(tot)=2.478 GeV (exp. 2.4952±0.0023 leptonic ≈ 3.3%,, hadronic (quarks)≈69%.

Are there other lepton families?

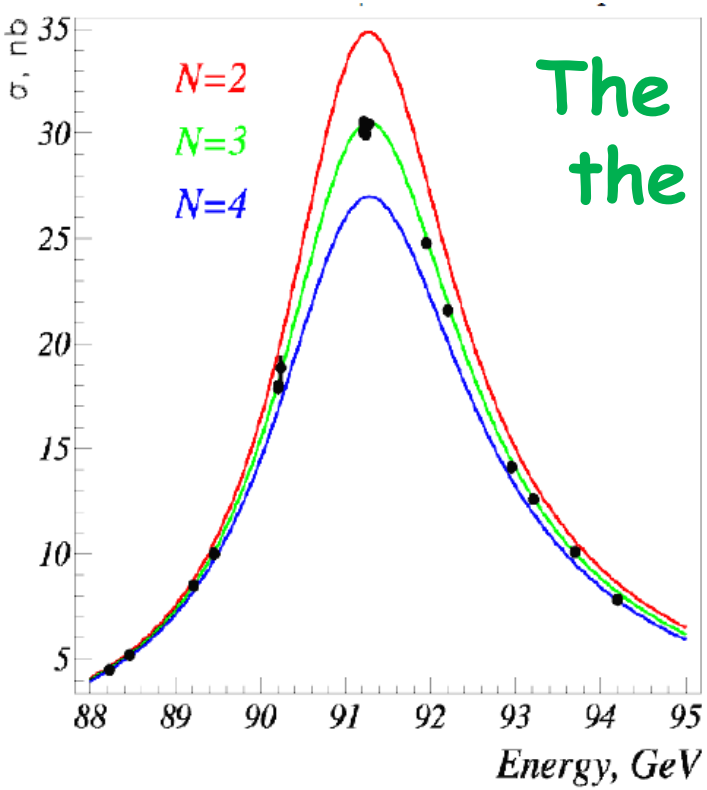


Fig.2. The shape of the Z^0 resonance yields information on the number of light neutrino types [three and only three].

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

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

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

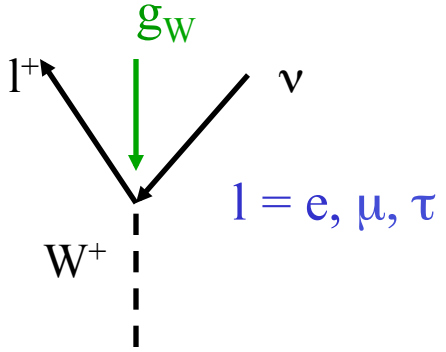
LEP: e^+e^- energy scan around Z-mass

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

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

Similarly for W partial widths



$l = e, \mu, \tau$

$$\Gamma(W^+ \to l^+ \nu_l) = \frac{G M_W^3}{6\sqrt{2}\pi} \approx 226\ \text{MeV}$$

For quark: pairs multiply by color factor and CKM matrix element

$$\Gamma(W^+ \to u\bar{d}) = 3\frac{G M_W^3}{6\sqrt{2}\pi}\left[|V_{ud}|^2\right] \approx 707\ MeV$$

$$\to c\bar{s}$$

$$\Gamma_W(tot) \approx 2100\ \text{MeV}\ (\text{exp.}\ 2.08 \pm 0.07\ \text{GeV})$$

$\to t\bar{b}$ Forbidden kinematically

The leptonic channel is 11%, that one hadronic (quark) is 67%

The Standard Model Lagrangian

Gauge boson (W/Z) self interactions

Gauge boson(W/Z)-lepton interactions

Gauge boson(W/Z)-quark interactions

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \quad \text{(U(1), SU(2) and SU(3) gauge terms)}$$

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu i D_\mu e_R + \bar{\nu}_R\sigma^\mu i D_\mu \nu_R + (\text{h.c.}) \quad \text{(lepton dynamical term)}$$

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right] \quad \text{(electron, muon, tauon mass term)}$$

$$-\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right] \quad \text{(neutrino mass term)}$$

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu i D_\mu u_R + \bar{d}_R\sigma^\mu i D_\mu d_R + (\text{h.c.}) \quad \text{(quark dynamical term)}$$

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right] \quad \text{(down, strange, bottom mass term)}$$

$$-\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right] \quad \text{(up, charmed, top mass term)}$$

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. \quad \text{(Higgs dynamical and mass term)}$$

Questions remaining at 1979 (when WSG awared the Nobel prize)

-Experimental proof of the existence of the electroweak mediators W/Z

-Why the SU(2)xU(1) is broken?

-Why B e W^3 mix up to generate the physical bosons Z e A through sin θ_W?

-Why photon is massless while W and Z are massive? Does the Higgs boson exist?

-Why there are 3 lepton and quark families?

-Why quarks and leptons have the masses they have

-How to unify also strong interactions and gravity?

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 particles head-on: $\sqrt{s} = 2E \approx 900GeV$

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

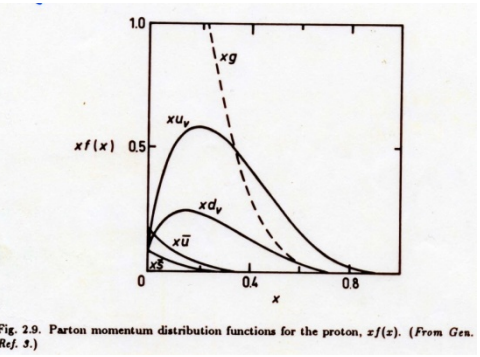
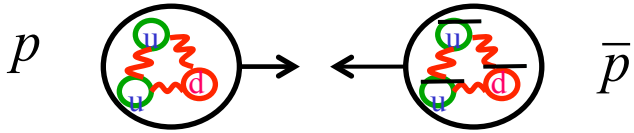


Fig. 2.9. Parton momentum distribution functions for the proton, $xf(x)$. (*From Gen. Ref. 3.*)

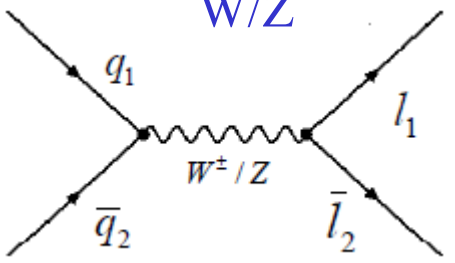


50%momentum carried by quarks and
50% by gluons. Average momentum budget :

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

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

Annihilate quark and antiquark to produce W/Z



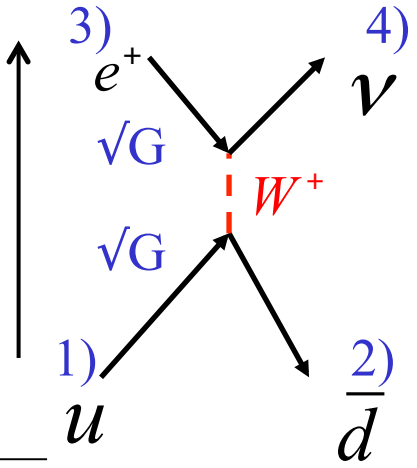
Roughly: at x>0.05 valence quarks dominate
x< 0.05 sea quarks dominate

W-measurement

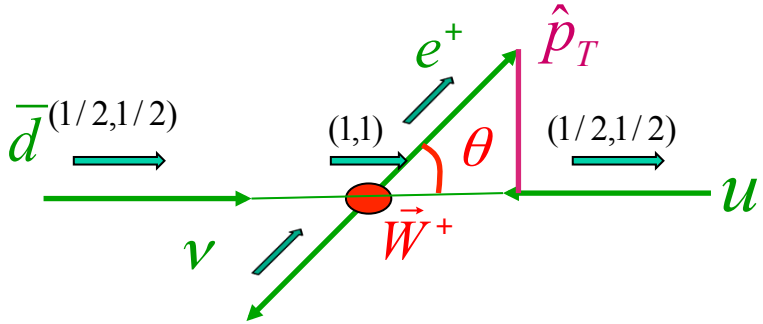
$u\bar{d} \to W^+ \to e^+\nu(11\%BR)$

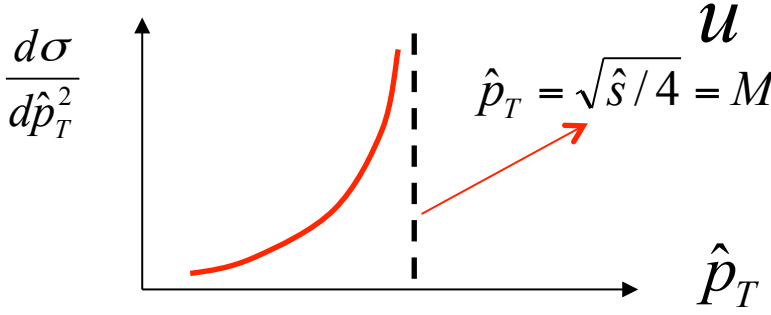
$u\bar{d} \to W^+ \to q\bar{q}'(ex\ u\bar{d}(65\%BR))$

but very large background from QCD

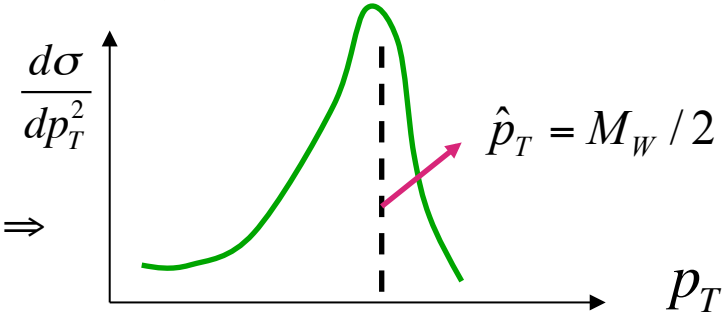


in the center of mass $u\bar{d}$



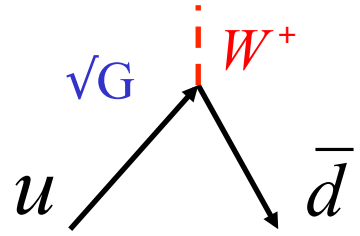


In the lab including experimental effects ⇒



Iacobian peak from W-> e ν

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



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

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

We need a cross section: cm^2

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

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

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

$$\sigma(p_a + p_b \to W^+ + X) = \frac{1}{3}\int_0^1 dx_a \int_0^1 dx_b \sum_{a,b} q(x_a)\bar{q}'(x_b)\hat{\sigma}^W$$

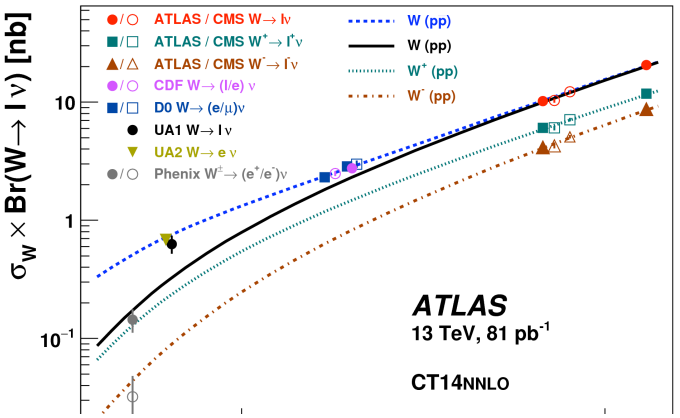
W

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

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

$$pp, \sqrt{s} = 13\,TeV\ , \sigma(W^+) \approx 107\,nb,$$

$$\sigma(W^-) \approx 80\,nb\,(u\bar{d} + \bar{d}u)$$

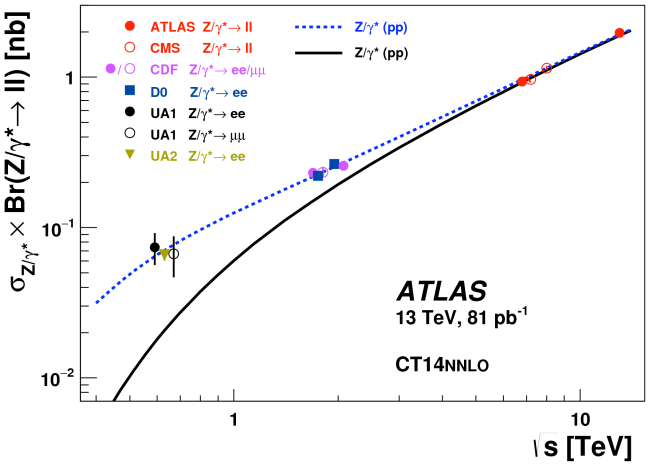


Z

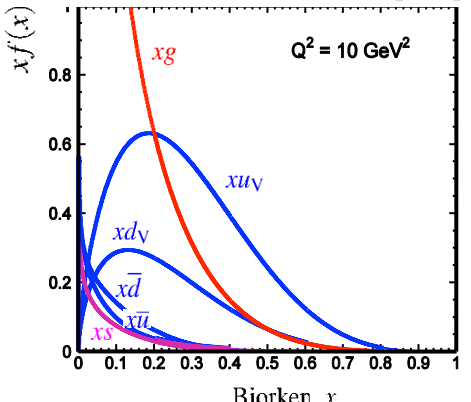
$$p\bar{p}, \sqrt{s} = 630\ \text{GeV}, \sigma(\text{Z}) \approx 1.8\ \text{nb}\ \ (u\bar{u} + d\bar{d})$$

$$p\bar{p}, \sqrt{s} = 2\ \text{TeV}\ , \sigma(\text{Z}) \approx 6.4\ \text{nb}\ \ \text{"}$$

$$pp, \sqrt{s} = 13\,TeV\ , \sigma(Z) \approx 60\,nb\ \ (u\bar{u} + d\bar{d})$$



The W-Z-cross sections increase with energy both for a larger rapidity interval available to W and Z , when energy increases: $\Delta y_{W/Z} \sim \ln \sqrt{s}$, and for different contributions from PDF: as energy increase x of partons decreases



$$ex: x_a x_b = M_W^2 / s,\ if\ \ x_a = x_b \equiv x,$$

$x = M_W / \sqrt{s} = 0.13$ valence quarks CERN ppbar Collider , $|y_W| < 2$

0.04 sea and valence quarks at the Tevatron

0.006 sea quarks at LHC (13 TeV) , $|y_W| < 5.1$

From a fixed target proton accelerator (SpS) to a p-pbar collider for the W/Z discovery

Need to build:

-an antiproton source
-a system to compactify the antiprotons both in angle and momentum:

the stochastic cooling

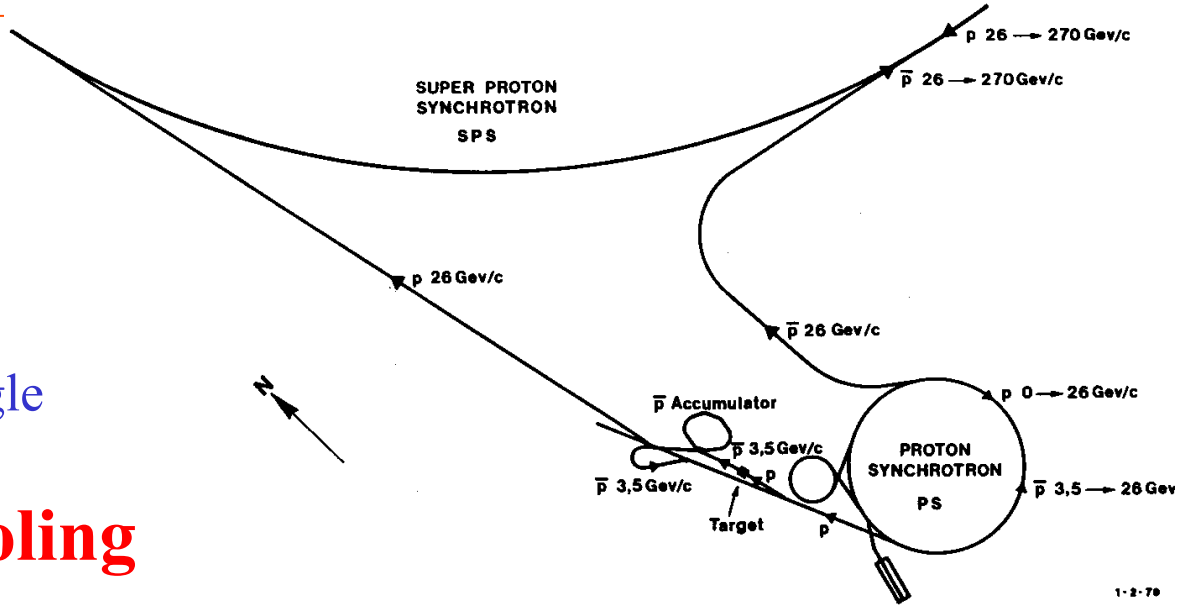


Fig. 1. Overall layout of the p$\bar{p}$ project.

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

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

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

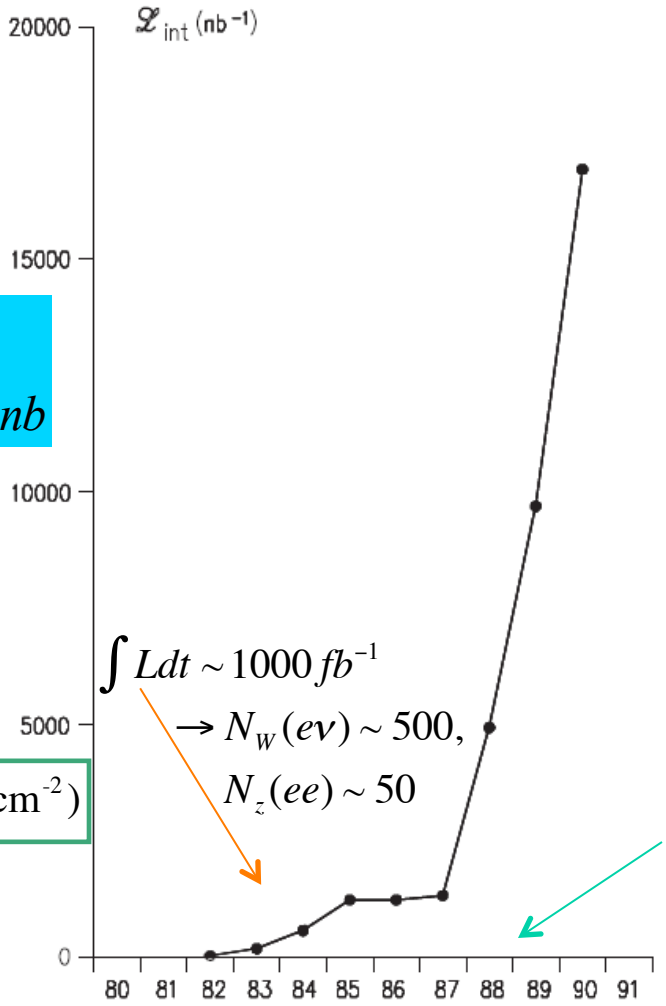
Moel et al., Physics Reports 58, No.2 (1980), p.73.

Integrated luminosity at the SPS collider

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

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

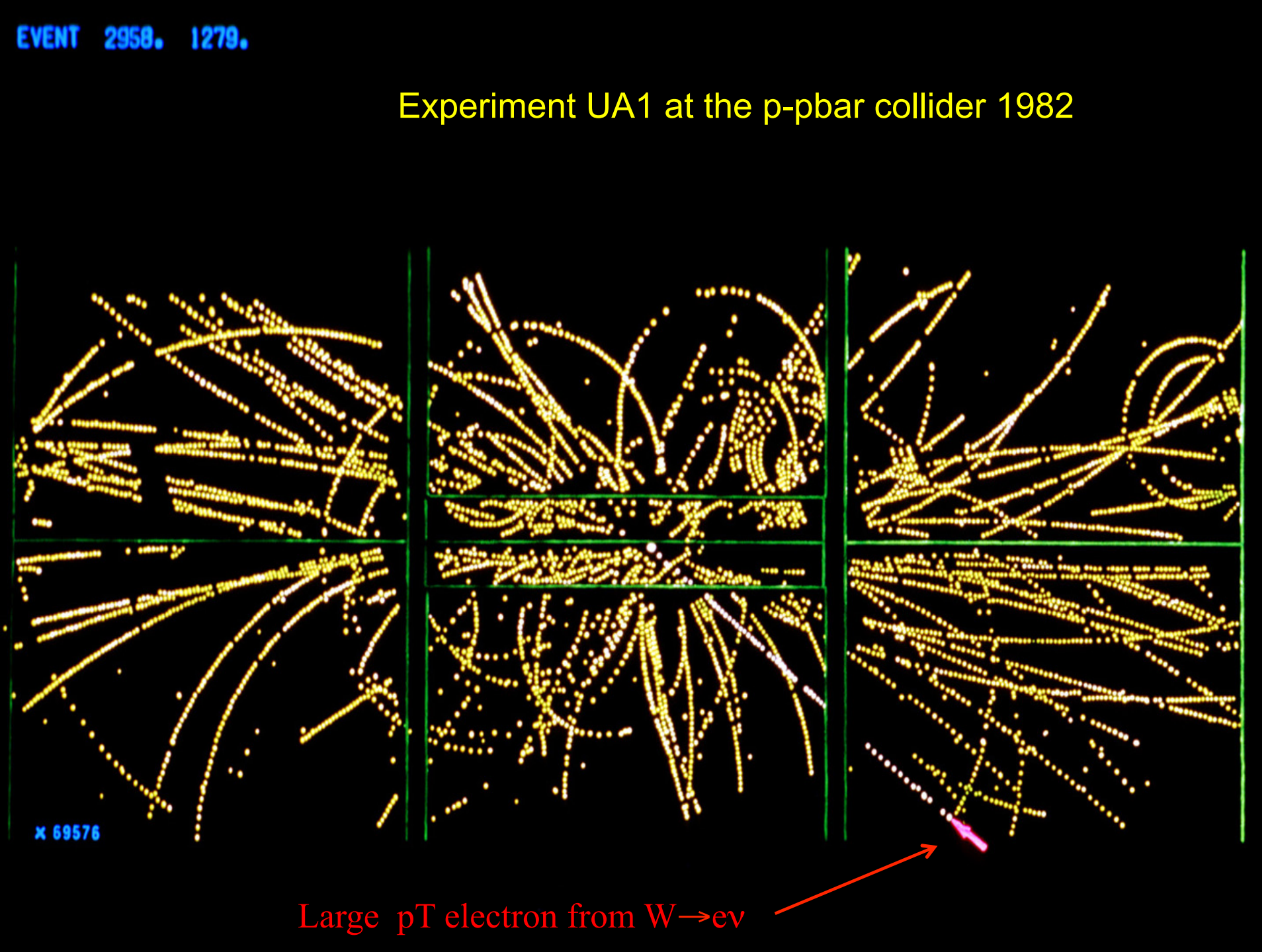
$$N_{W/Z} = \sigma_{W/Z} \int L\,dt \quad (\int L\,dt : \text{dimension: cm}^{-2})$$



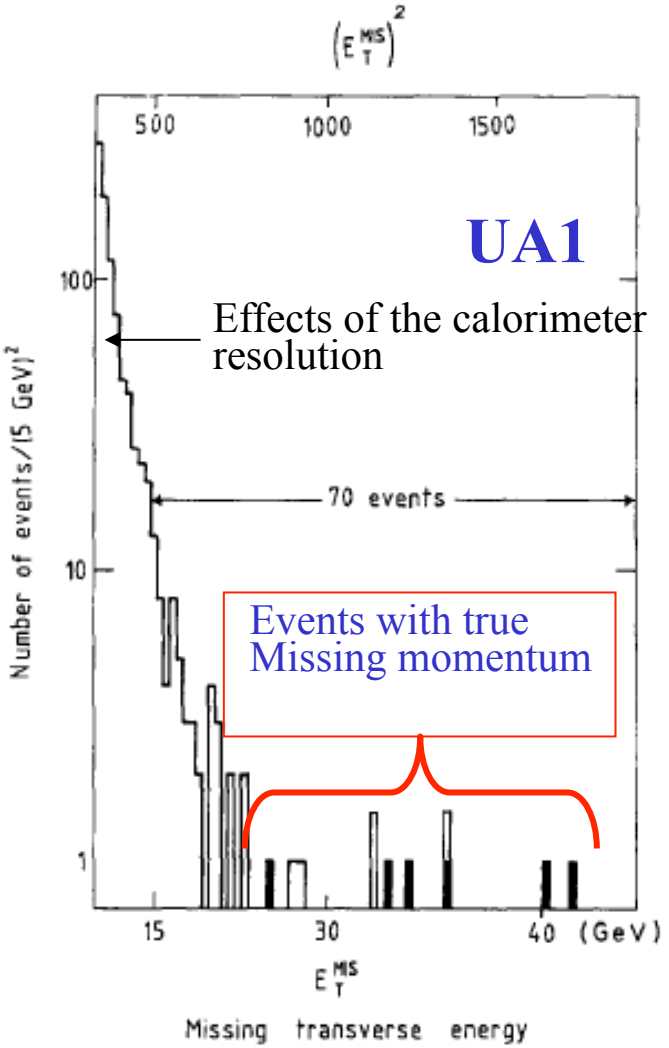
Max instantaneous luminosity:
3 10^{30} cm^{-2} s^{-1}

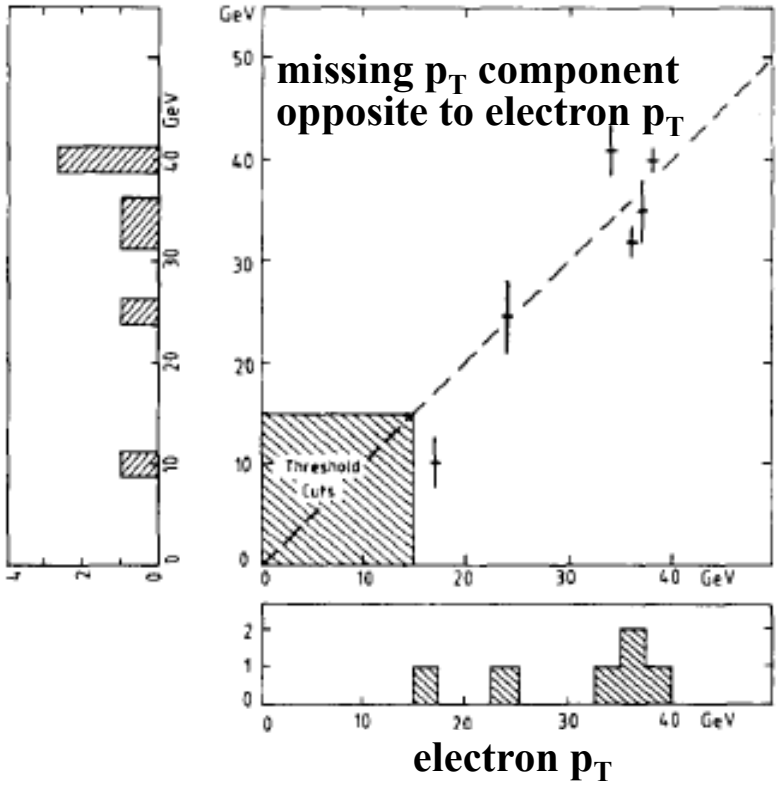
AC+ low beta

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.


EVENT 2958. 1279.
Experiment UA1 at the p-pbar collider 1982
× 69576
Large pT electron from W→eν

First W's mesured in UA1





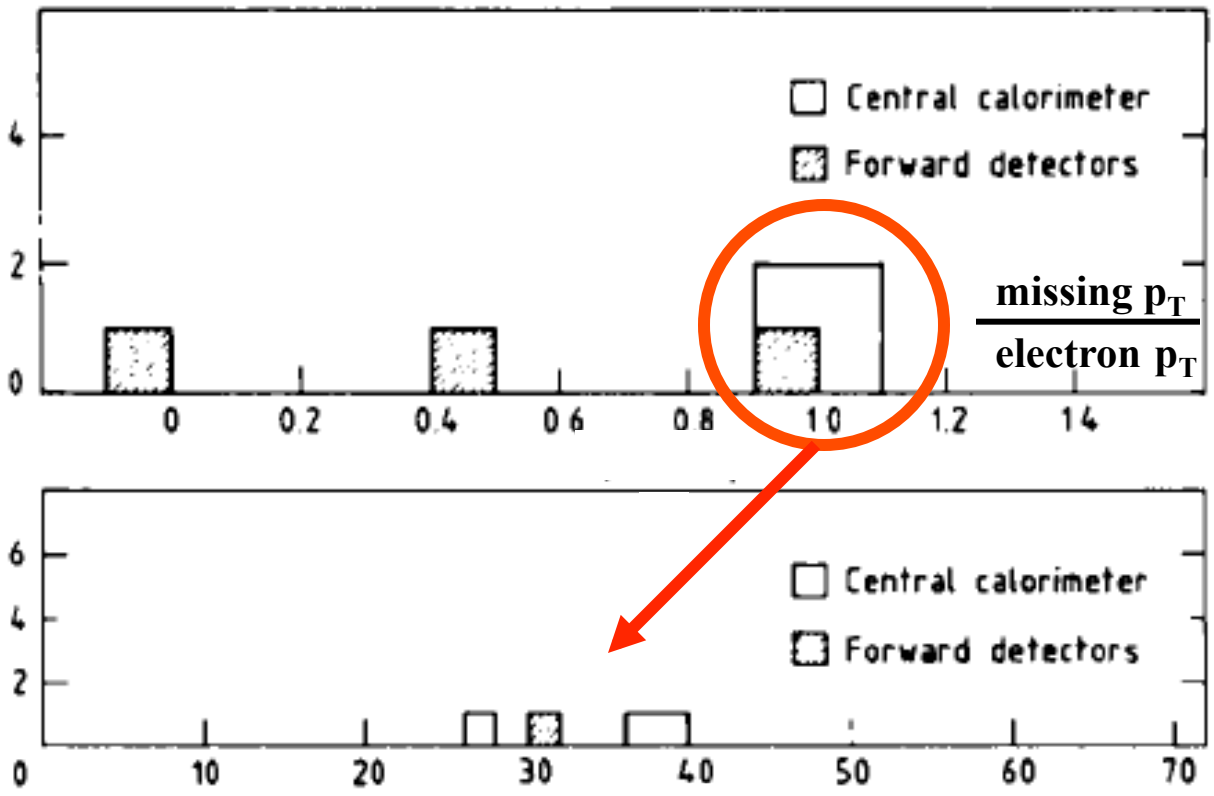
$$\vec{p}_T^{\,\nu} = \vec{p}_T^{\,miss} = -\sum_i \vec{p}_{T,meas}^{\,i}$$

Six events with a large electron p_T electron balanced by large missing p_T consistent with W → e ν decays

(CERN seminar 20 January , 1983)

UA2: result presented at CERN on January 1983

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

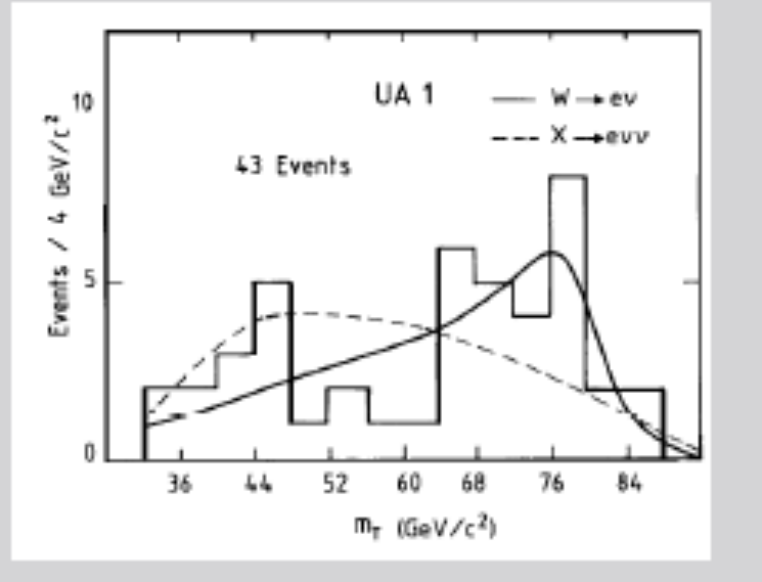


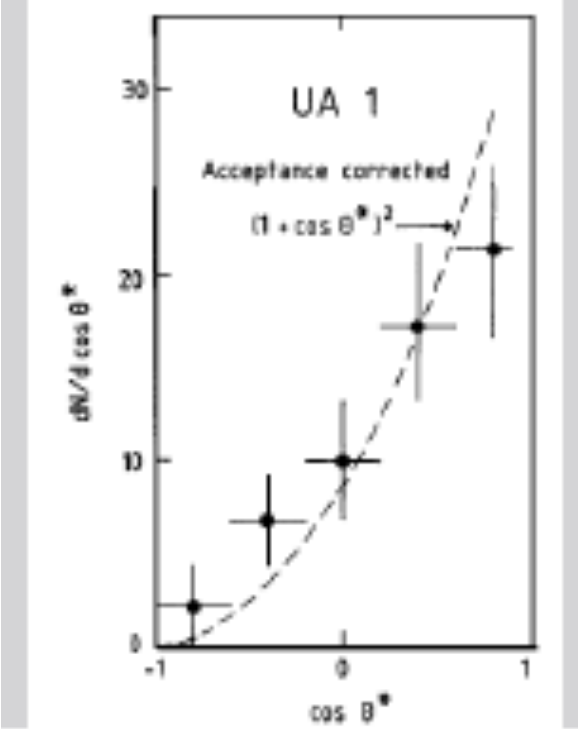
"Iacobian peak"

The UA1 Iacobian Peak

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

Iacobian peak at $m_T = m_W$

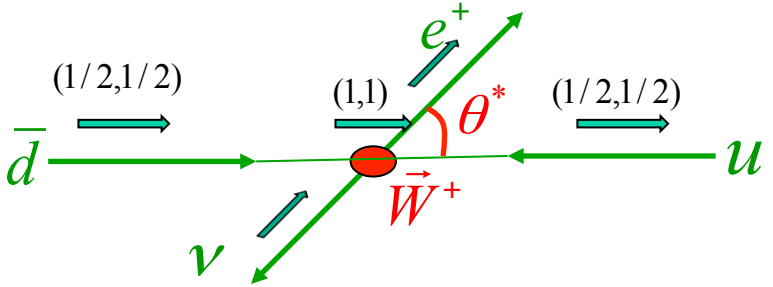


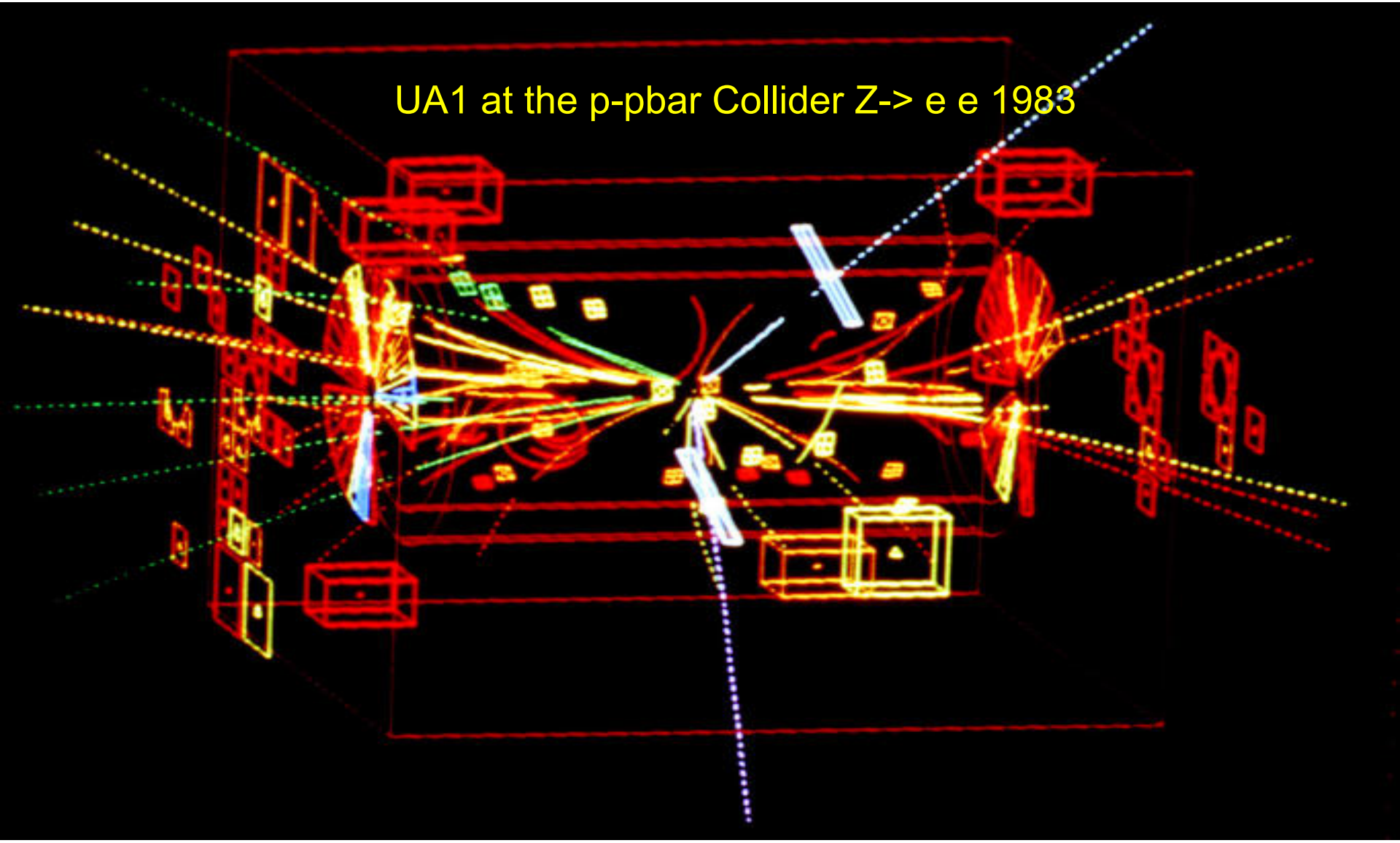


$$M_W = 80.9 \pm 1.5 GeV$$

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

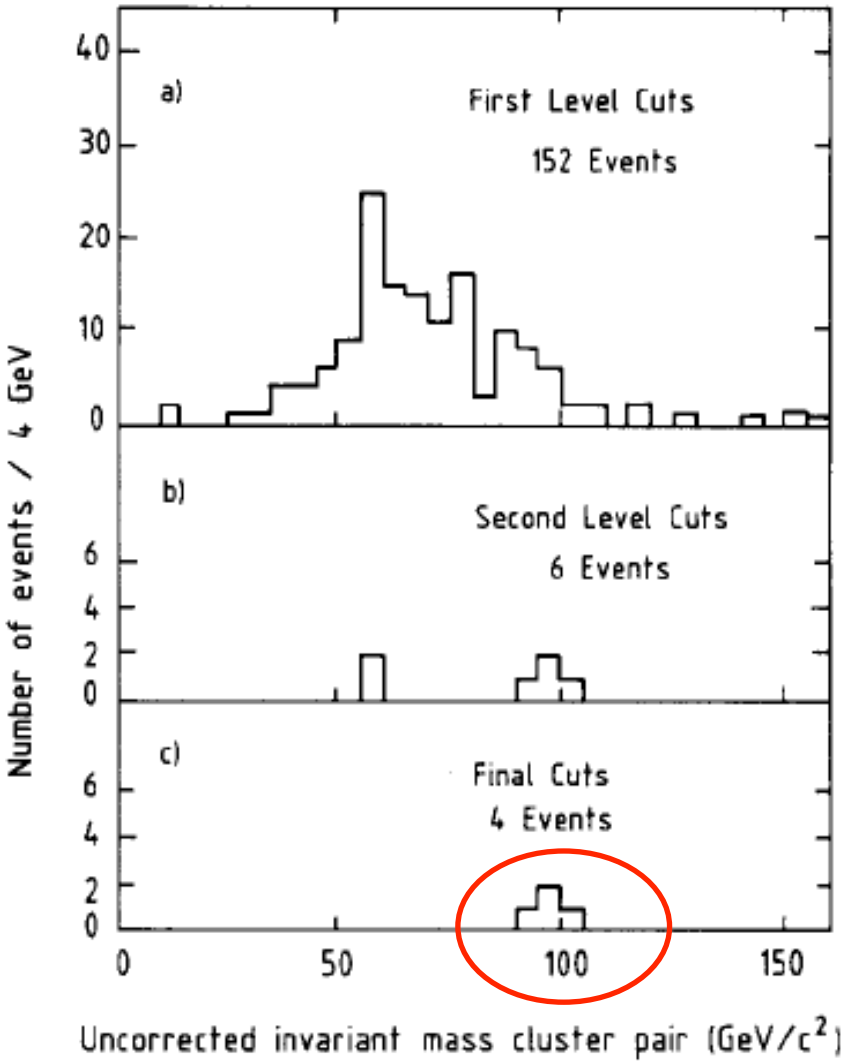
$$\Gamma_W = 2.085 \pm 0.042\, GeV$$




UA1 at the p-pbar Collider Z-> e e 1983

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

(May 1983)



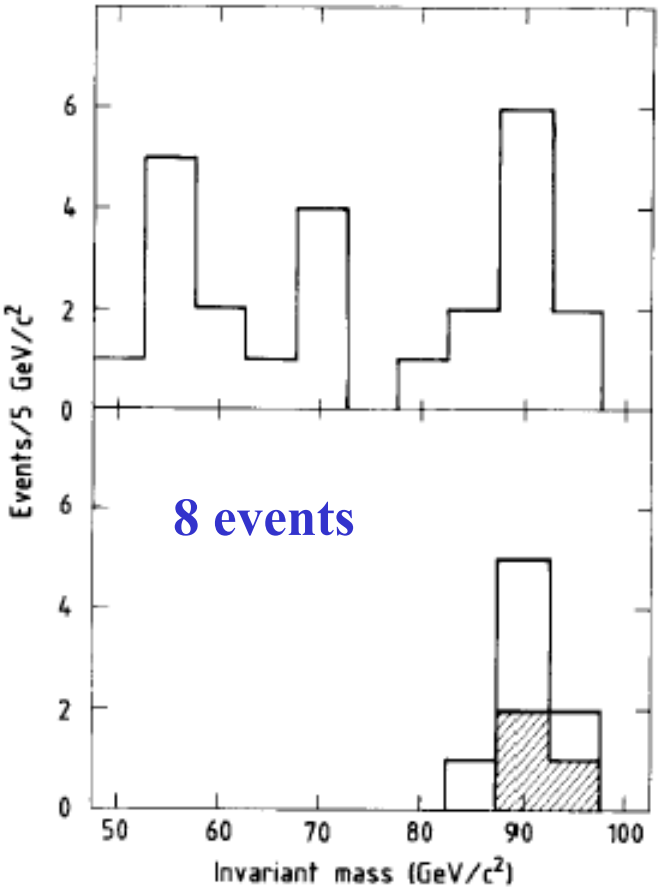
Two localized deposits of energy in the electromagnetic calorimeter (electrons or photons)

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

Both tracks with $p_T > 7$ GeV
Point to an electromagnetic cluster

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

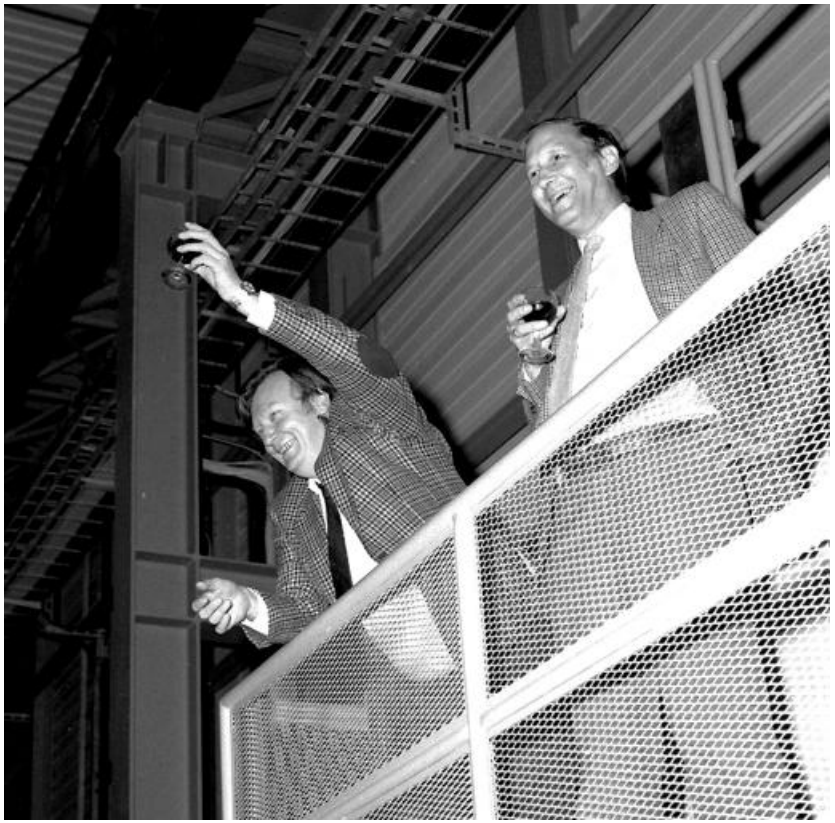
Simon van der Meer

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"

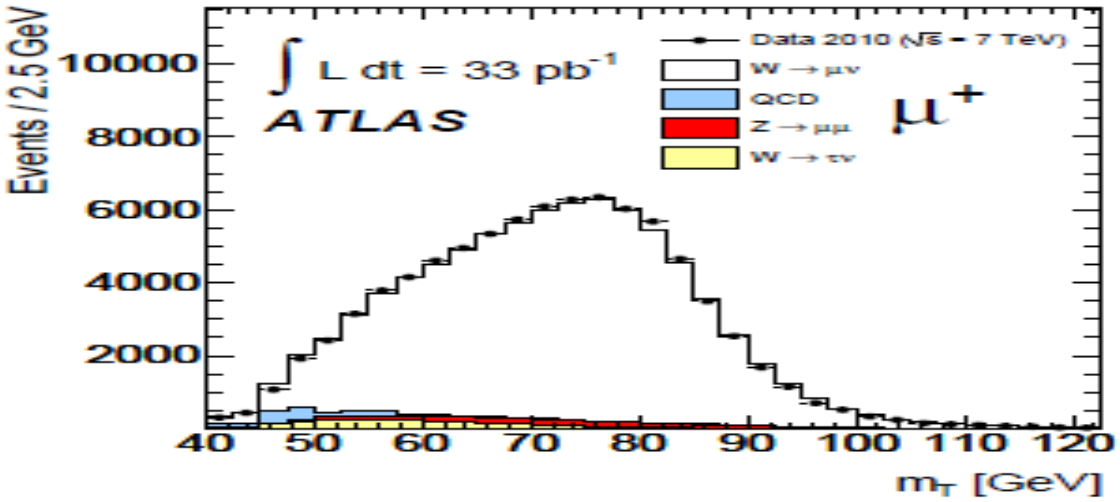
W/Z at LHC

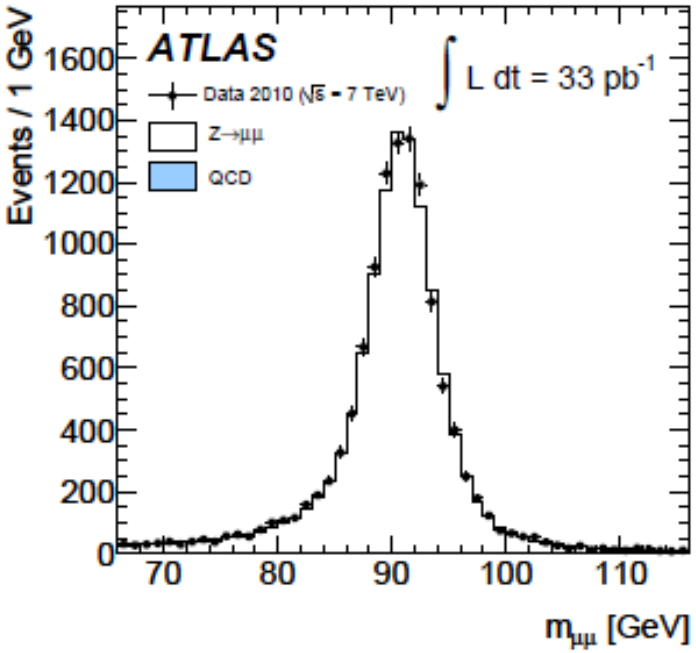
$\mu - \nu$ mass with transverse variables, $\vec{p}_T^{\,\mu}, \vec{p}_T^{\,\nu}$:

$$m_T^2(\mu,\nu) = \left[\left|\vec{p}_T^{\,\mu}\right| + \left|\vec{p}_T^{\,\nu}\right|\right]^2 - (\vec{p}_T^{\,\mu} + \vec{p}_T^{\,\nu})^2 =$$

$$= 2\left|\vec{p}_T^{\,\mu}\right|\left|\vec{p}_T^{\,\nu}\right|(1 - \cos\varphi_{e\nu})$$

Iacobian peak at $m_T = m_W$

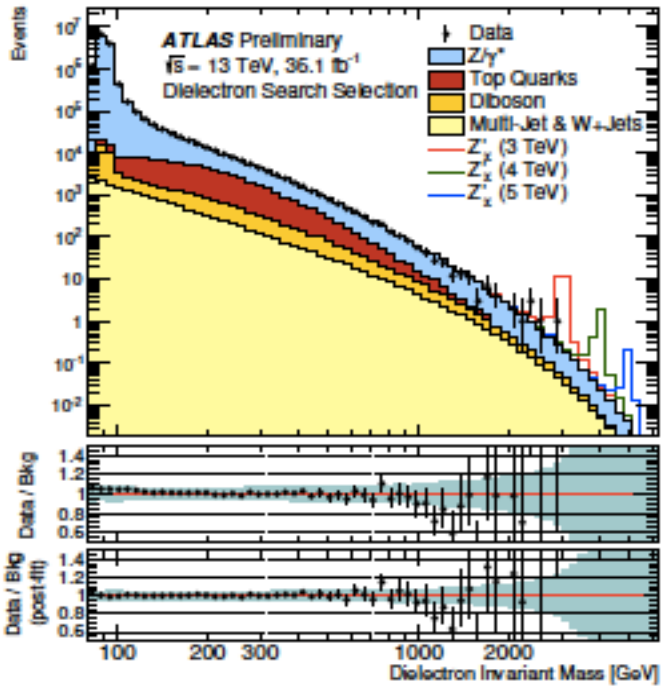




At an integrated luminosity comparable with that of the ppbar Collider

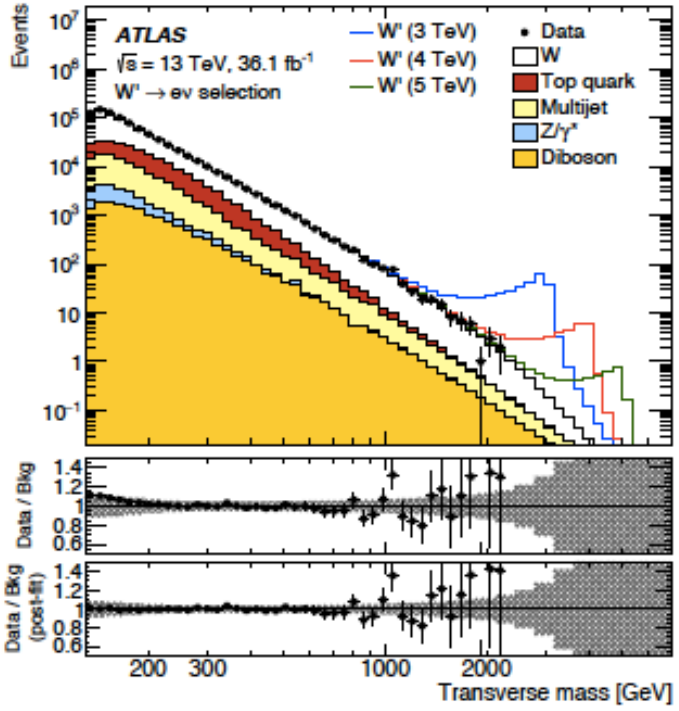
~30 times more Z's (cross section is 30 times larger)

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



(a)

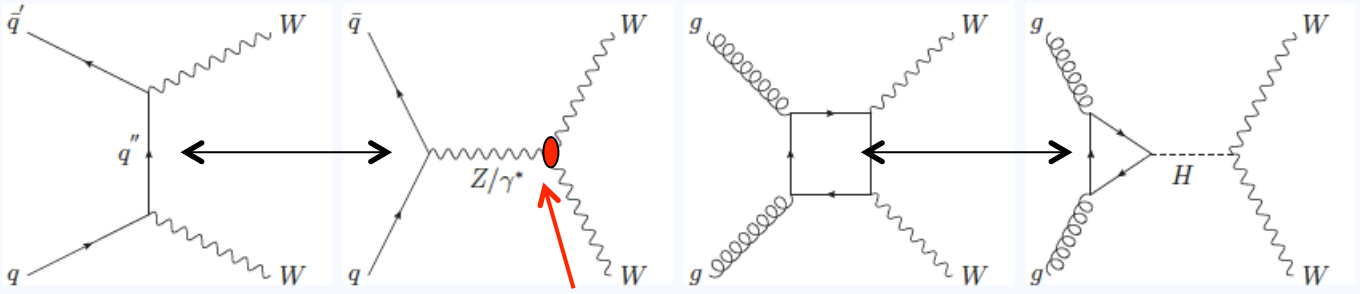
Z' with same couplings to fermions as Z excluded at 95% CL for $M_{Z'} < 4.1$ TeV



W' with same couplings to fermion as W (SSM) excluded at 95% CL for $M_{W'} < 5.1$ TeV

Gauge Boson self interactions

σ~110 pb at √s=13 TeV **WW Production** σ~15 pb at √s=13 TeV

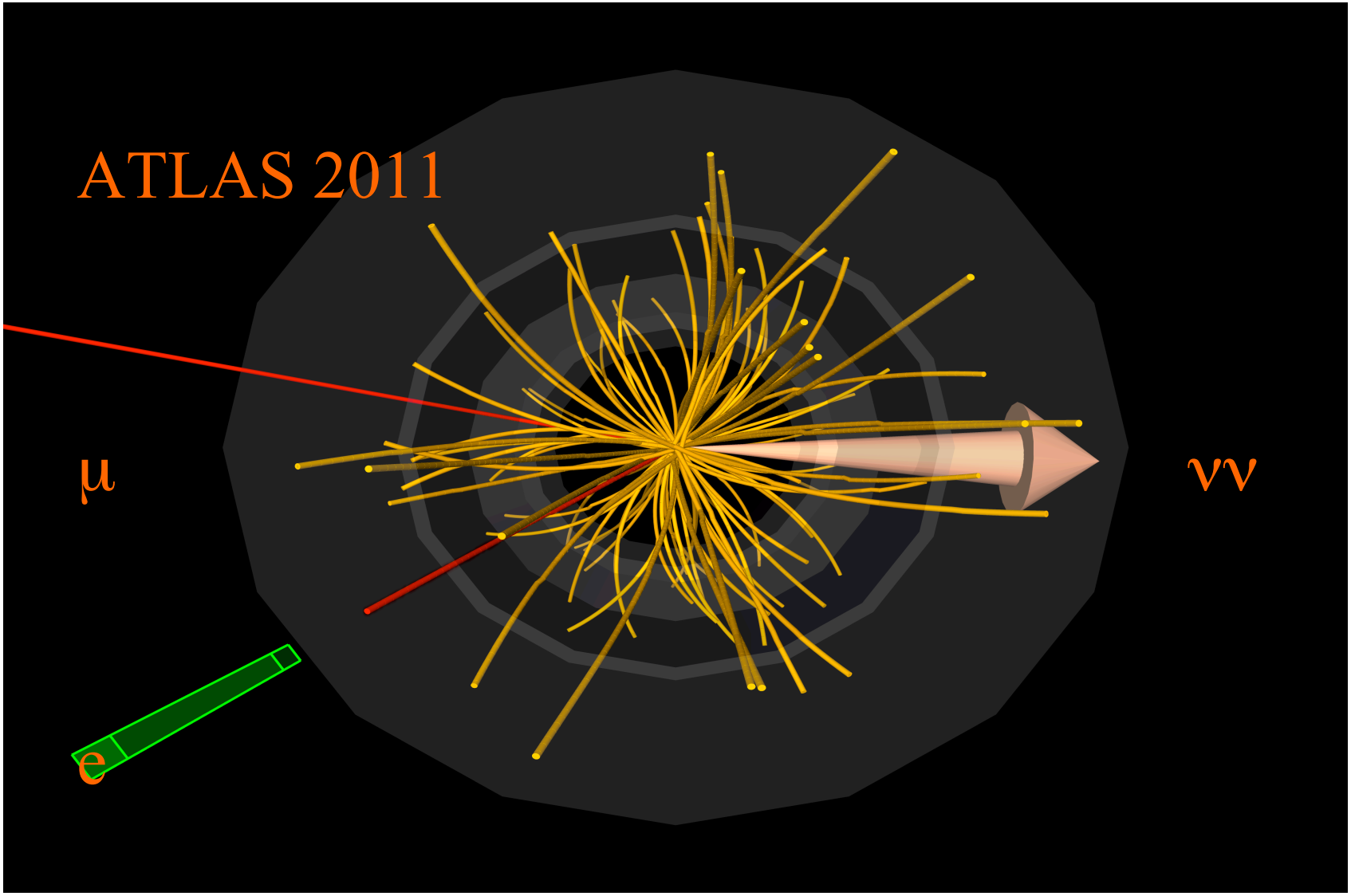


(a) *t*- channel (b) *s*- channel (TGC vertex) (c) gluon fusion (d) Higgs boson production

WZ Production

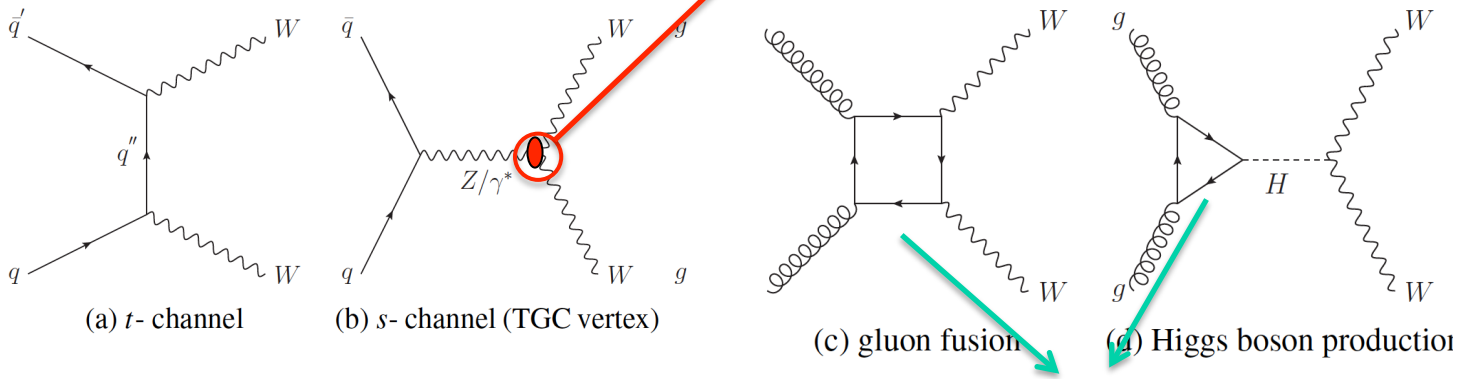
- Major background to SM Higgs → WW search
- Sensitive to new physics through anomalous TGC
- Experimental signature: two isolated leptons with large MET
- Major backgrounds: W/Z + jets, ttbar, single top

An event $W^+W \rightarrow e\nu\mu\nu$



pp➔W$^+$ W$^-$("gauge boson self coupling")

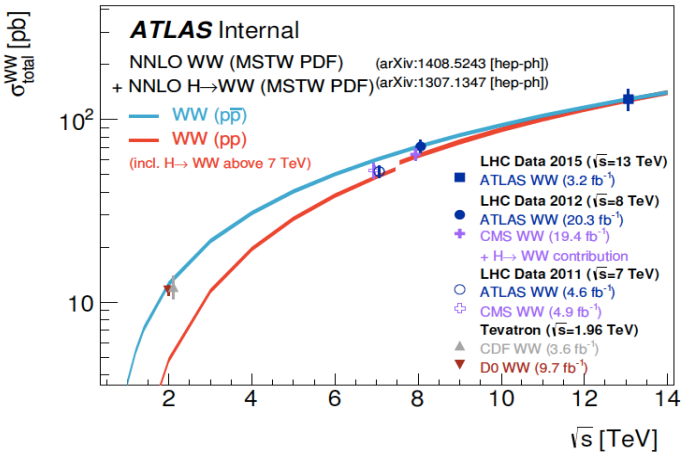
"TGC": Triple Gauge Coupling



quark loops

$$\hat{\sigma} \prec \frac{1}{\hat{s}} \ln\left(\frac{\hat{s}}{M_W^2}\right)$$ (Barger/Phillips: "Collider Physics")

$$\sigma(p_a + p_b \to W^+ + X) = \frac{1}{3}\int_0^1 dx_a \int_0^1 dx_b \sum_{a,b} q(x_a)\bar{q}'(x_b)\hat{\sigma}^W$$



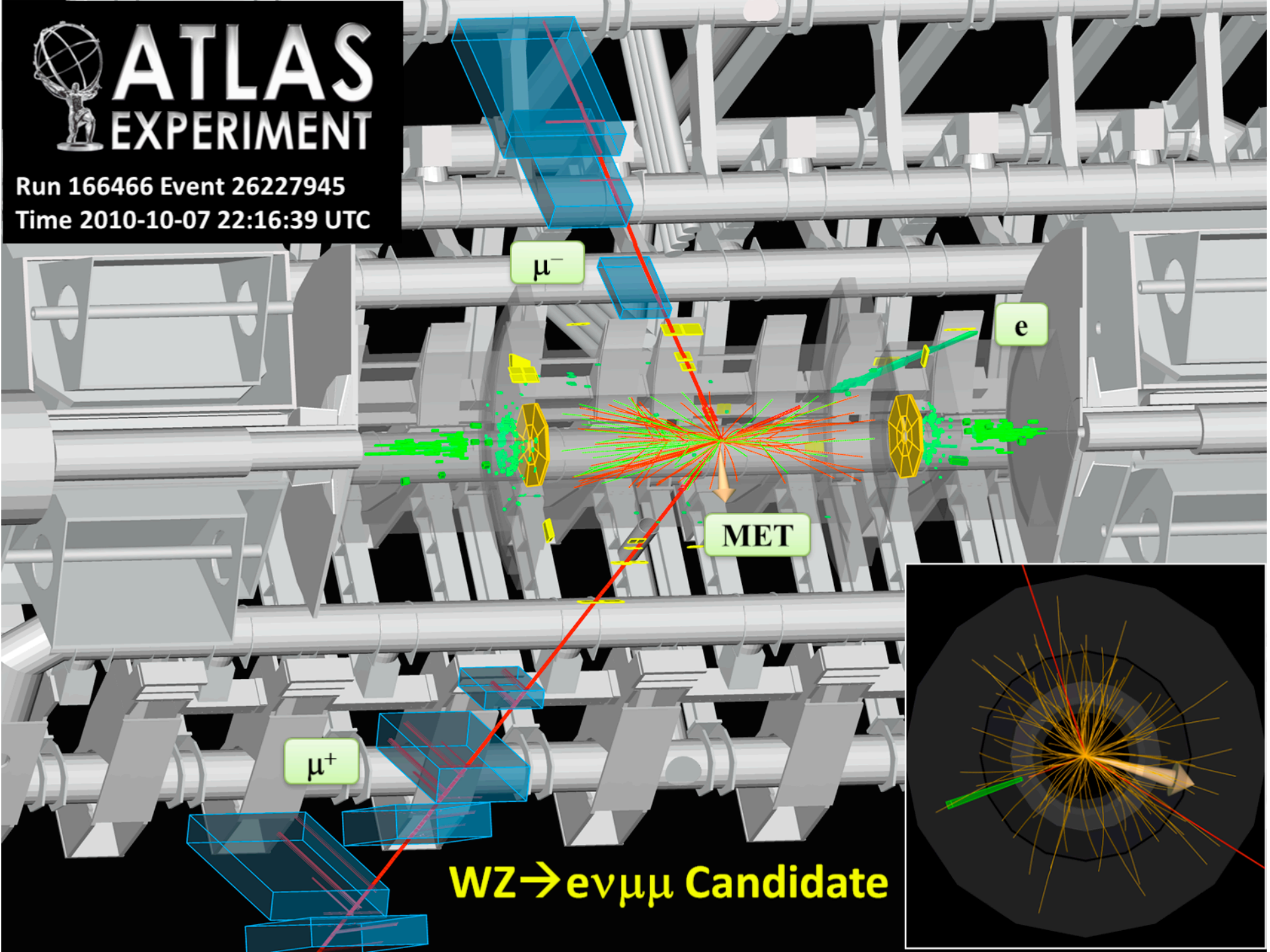
Experimental result :

σ_{WW} (~ 10^{-35} – $10^{-34} cm^2$) and

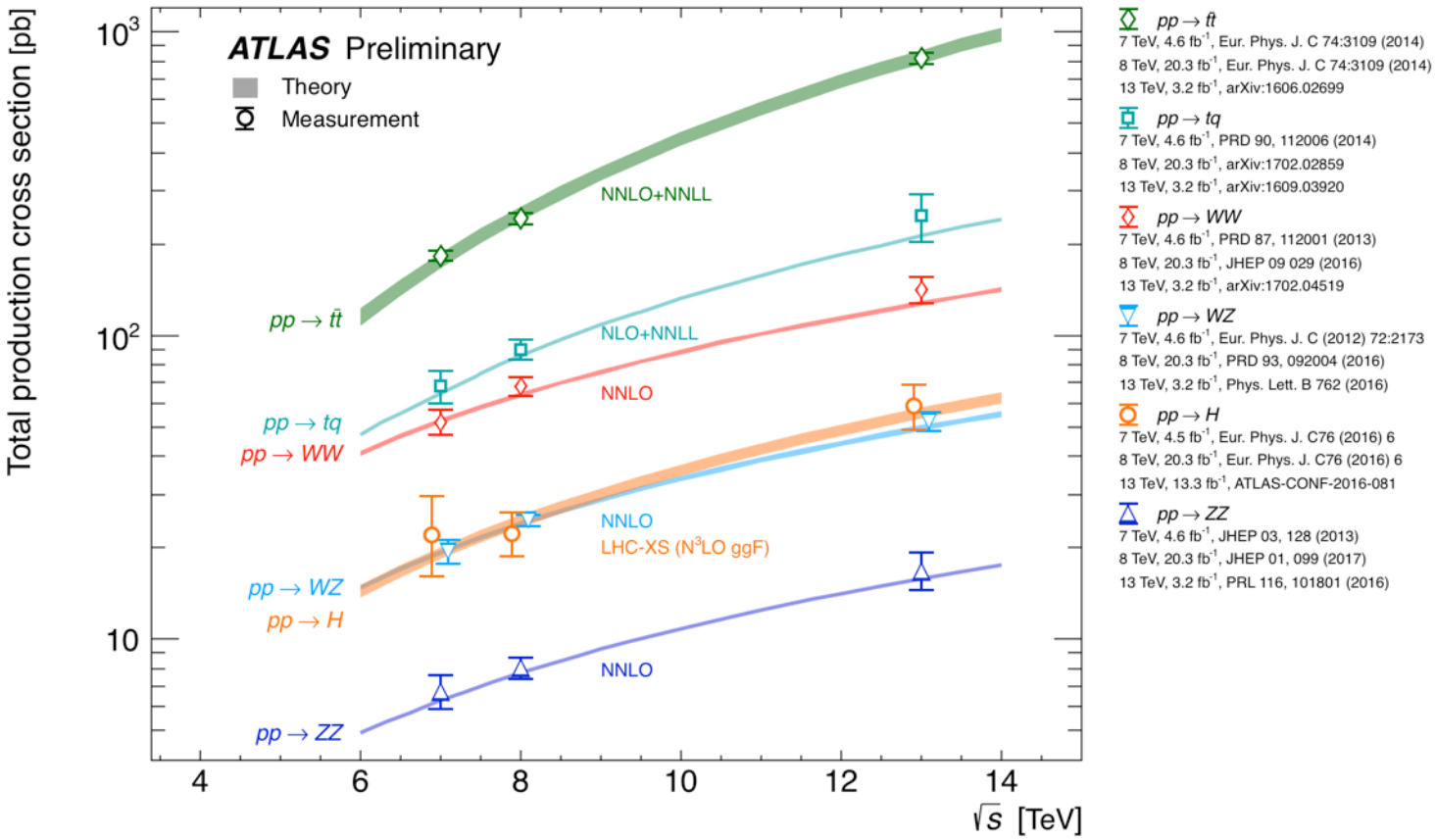
it increases with pp energy ($\sqrt{s}$)

mostly due to the lower x of PDF,

(as for W and Z cross seections)


ATLAS
EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate

WW, WZ, ZZ production cross sections at the LHC



$pp \to t\bar{t}$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb^{-1}, arXiv:1606.02699

$pp \to tq$
7 TeV, 4.6 fb^{-1}, PRD 90, 112006 (2014)
8 TeV, 20.3 fb^{-1}, arXiv:1702.02859
13 TeV, 3.2 fb^{-1}, arXiv:1609.03920

$pp \to WW$
7 TeV, 4.6 fb^{-1}, PRD 87, 112001 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 09 029 (2016)
13 TeV, 3.2 fb^{-1}, arXiv:1702.04519

$pp \to WZ$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb^{-1}, PRD 93, 092004 (2016)
13 TeV, 3.2 fb^{-1}, Phys. Lett. B 762 (2016)

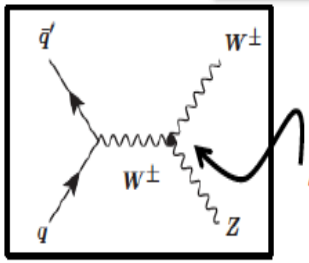
$pp \to H$
7 TeV, 4.5 fb^{-1}, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C76 (2016) 6
13 TeV, 13.3 fb^{-1}, ATLAS-CONF-2016-081

$pp \to ZZ$
7 TeV, 4.6 fb^{-1}, JHEP 03, 128 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 01, 099 (2017)
13 TeV, 3.2 fb^{-1}, PRL 116, 101801 (2016)

Search for anomalous triple gauge boson couplings

- The triple gauge coupling is strictly related to the non-abelian nature of the EWK gauge theory.
- Limits are given with respect to the expected SM coupling: charged (WWZ,WWγ) neutral (ZZγ,ZZZ)

Charged

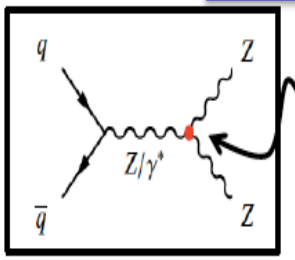


Effective Lagrangian

$\Delta g_1^Z \; \kappa_1^Z \; \lambda_Z$

Neutral

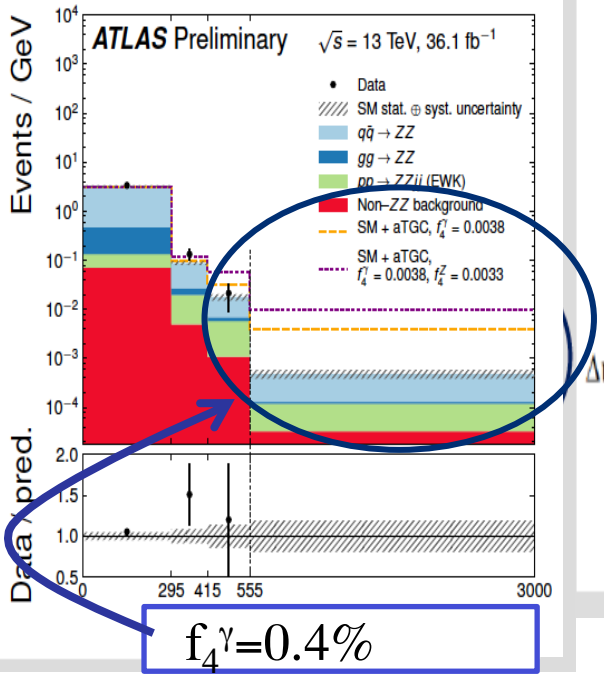
Not allowed In SM



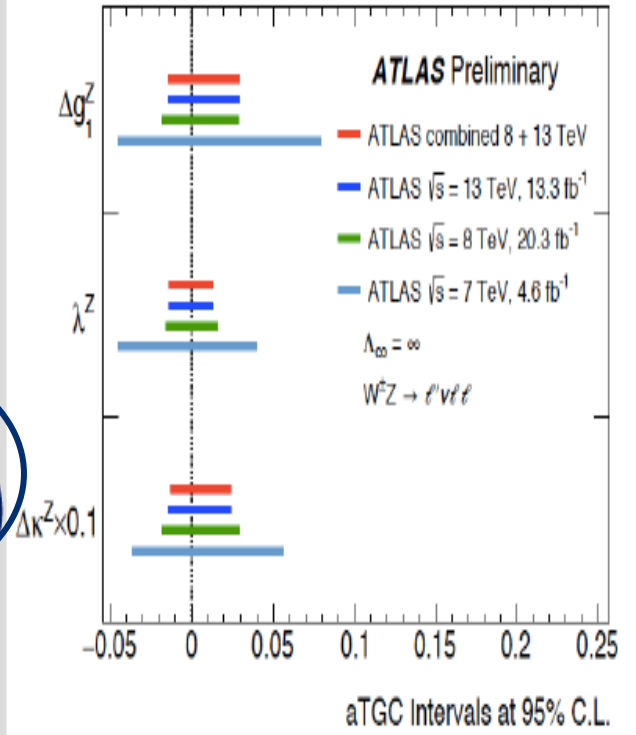
Effective Vertex

$f_4^{Z/\gamma} \; f_5^{Z/\gamma}$

$ZZ - p_T^{Z_1}$



f_4^γ=0.4%

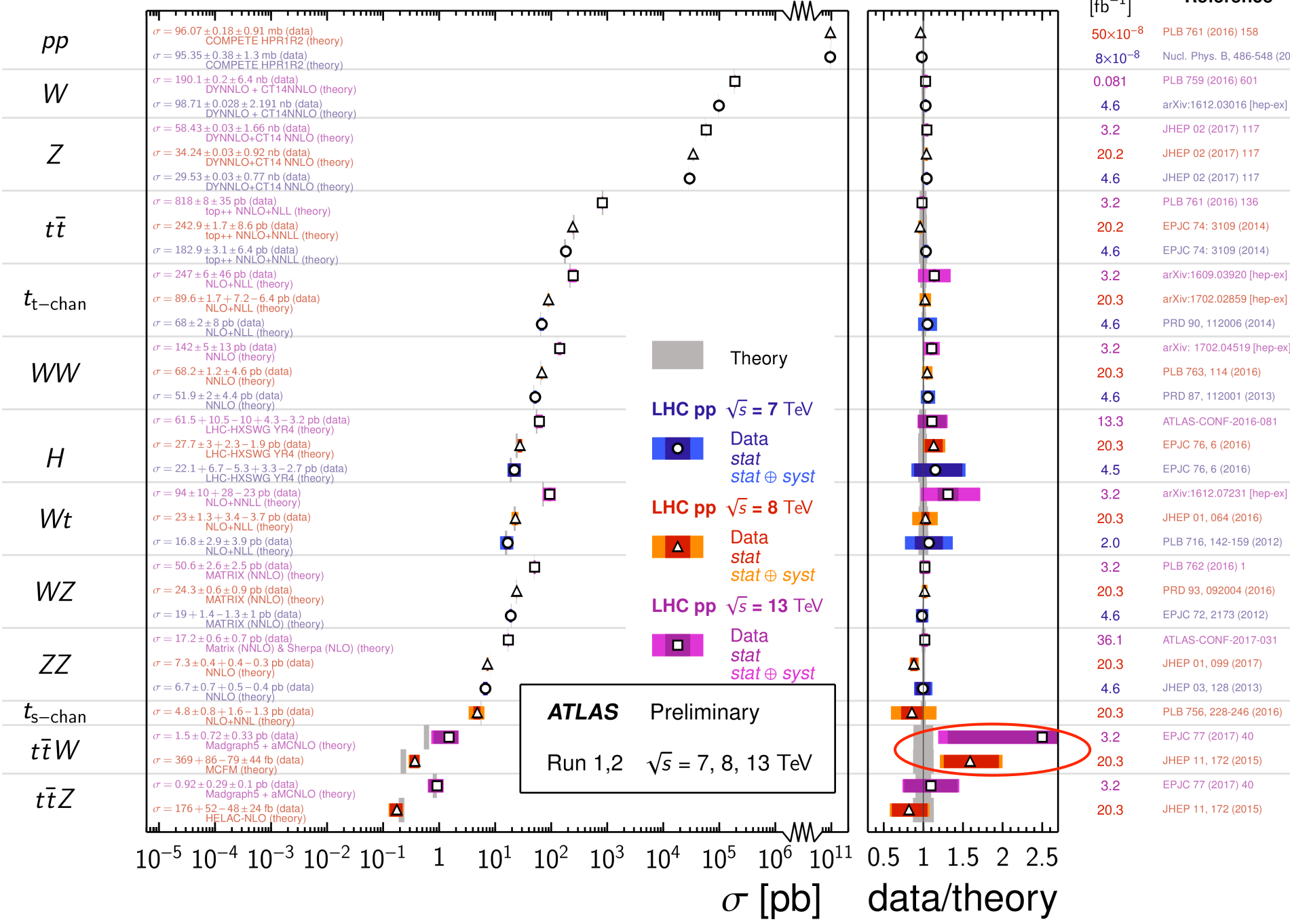


Notice that $Z/\gamma^* \to ZZ$ is allowed, but $Z/\gamma^* \to \gamma\gamma$ is not!

Limits in the region of few percent for charged couplings, fractions of percent for neutral coupling

Standard Model Total Production Cross Section Measurements

Status: May 2017

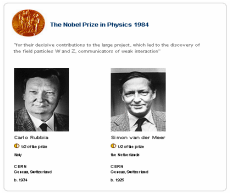


$\int \mathcal{L}\,dt$ [fb^{-1}]	Reference
50×10^{-8}	PLB 761 (2016) 158
8×10^{-8}	Nucl. Phys. B, 486-548 (20
0.081	PLB 759 (2016) 601
4.6	arXiv:1612.03016 [hep-ex]
3.2	JHEP 02 (2017) 117
20.2	JHEP 02 (2017) 117
4.6	JHEP 02 (2017) 117
3.2	PLB 761 (2016) 136
20.2	EPJC 74: 3109 (2014)
4.6	EPJC 74: 3109 (2014)
3.2	arXiv:1609.03920 [hep-ex]
20.3	arXiv:1702.02859 [hep-ex]
4.6	PRD 90, 112006 (2014)
3.2	arXiv: 1702.04519 [hep-ex]
20.3	PLB 763, 114 (2016)
4.6	PRD 87, 112001 (2013)
13.3	ATLAS-CONF-2016-081
20.3	EPJC 76, 6 (2016)
4.5	EPJC 76, 6 (2016)
3.2	arXiv:1612.07231 [hep-ex]
20.3	JHEP 01, 064 (2016)
2.0	PLB 716, 142-159 (2012)
3.2	PLB 762 (2016) 1
20.3	PRD 93, 092004 (2016)
4.6	EPJC 72, 2173 (2012)
36.1	ATLAS-CONF-2017-031
20.3	JHEP 01, 099 (2017)
4.6	JHEP 03, 128 (2013)
20.3	PLB 756, 228-246 (2016)
3.2	EPJC 77 (2017) 40
20.3	JHEP 11, 172 (2015)
3.2	EPJC 77 (2017) 40
20.3	JHEP 11, 172 (2015)

Milestones in building the EW theory

1960->1979 :Electroweak model construction: WGS theory+ BEH mechanism (neutral weak currents discovered ,W/Z and Higgs particles predicted)

1976 :proposal to convert CERN SPS (and Fermilab Main Ring) to a proton-antiproton collider



1983: discovery of W and Z

1984: first proposal to build a very high energy pp collider ,LHC

2012 discovery of the Higgs boson at LHC

(see lecture of Aurelio Juste Roza)

2015->: LHC Run 2, many confirmations of the ew model

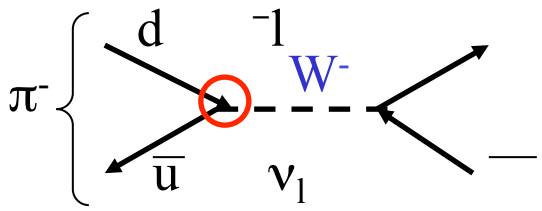
Despite the EW theory success,

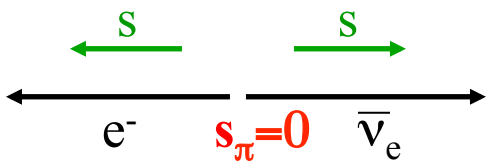
there are still many questions unsolved…

(see lecture **of** Mario Martinez-Perez)

Back up slides

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





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

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

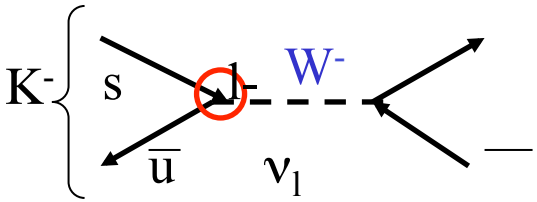
Phase Space $R_2 = \frac{m_\pi^2 - m_l^2}{2m_\pi^2}\pi$ $\left(R_2 = \int \frac{d\vec{p}_2}{2E_2(2\pi)^3}\frac{d\vec{p}_3}{2E_3(2\pi)^3}\delta(E_1-E_2-E_3)\right)$

would have preferred electrons : $\frac{R_2^e}{R_2^\mu} = \frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2} = 2.3$

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

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

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



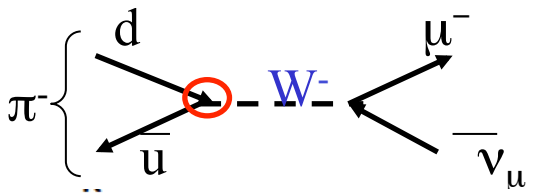
$$\Rightarrow \Gamma_K = \frac{G^2 f_K^2}{8\pi}\frac{1}{m_K^3} m_\mu^2\left[m_K^2 - m_\mu^2\right]^2$$

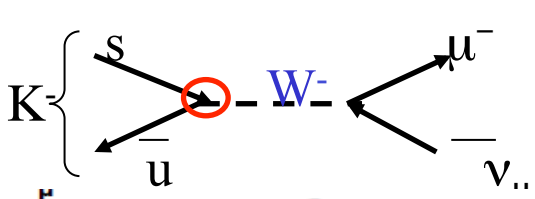
$ansatz : f_K = m_K \sin\theta_C$

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

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

Ex: Charged weak interactions of quarks : $\pi^- \to \mu^- \nu_\mu$, $K^- \to \mu^- \nu_\mu$ decays





Ratio of $\dfrac{\Gamma(K^- \to \mu^- \bar{\nu}_\mu)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)}$ from the measured π and K lifetimes: τ_π, τ_K $(\tau = 1/\Gamma_{tot})$

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

11

1973: Cabibbo theory generalization with 3 quark doublets : **at least three quark generations needed to provide CP violation (i.e an irriducible phase).** $\begin{bmatrix} u \\ d \end{bmatrix}\begin{bmatrix} c \\ s \end{bmatrix}\begin{bmatrix} t \\ b \end{bmatrix}$

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

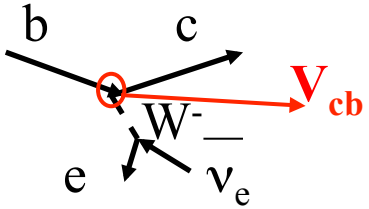
The matrix V is complex: 18 elements, but it is also unitary: 4 irriducible elements

Standard parametrization (PDG): 3 angles θ_{ij} (θ_{12} is the 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 : its elements extracted from the experiments, ex:



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

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

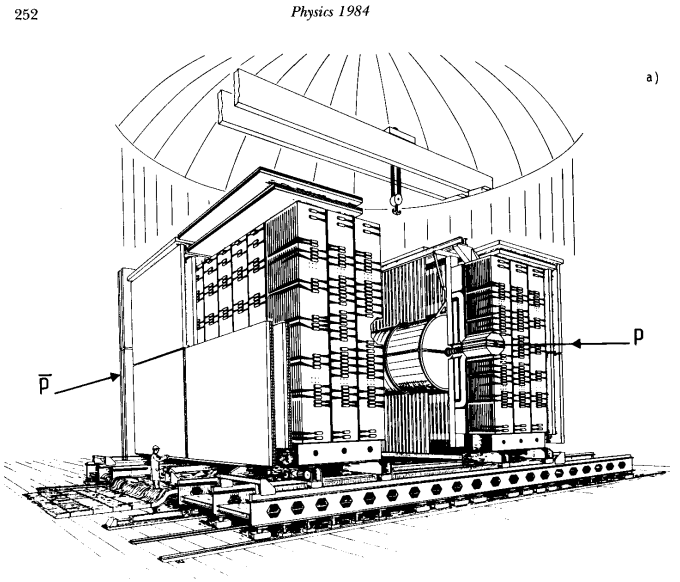
Two detectors at the SpSC to measure W/Z

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

UA1, calorimeters and central dipolar magnetic field + muon detection

UA2, calorimeters ,no central magnetic field

Calorimeter with projective towers



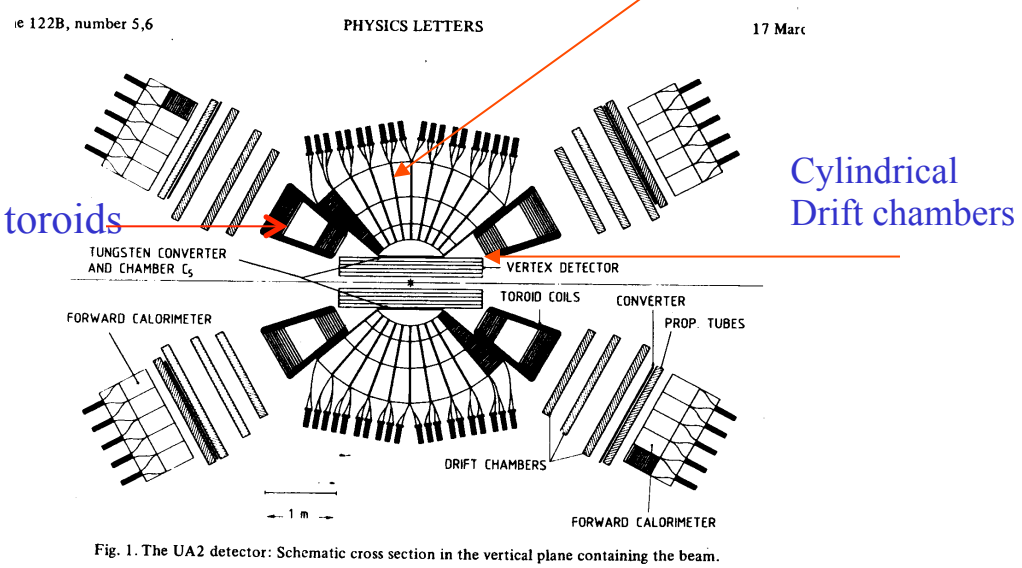
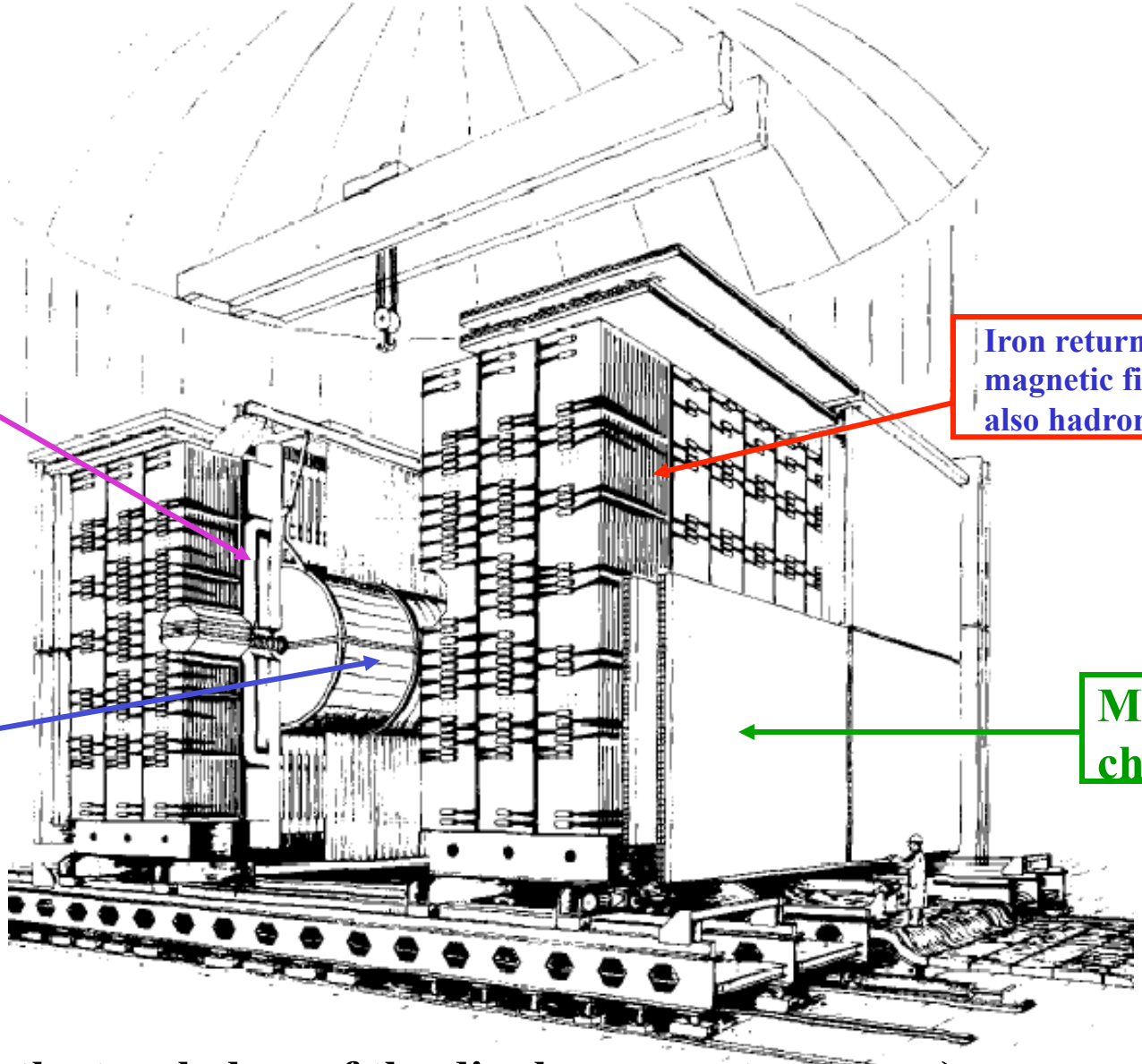


Fig. 1. The UA2 detector: Schematic cross section in the vertical plane containing the beam.

The detector UA1

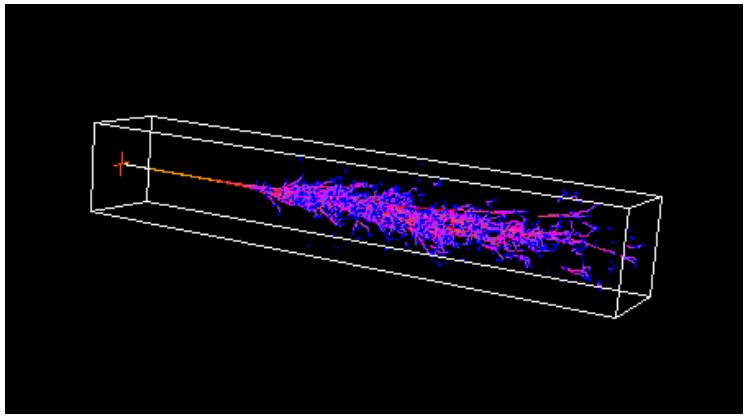


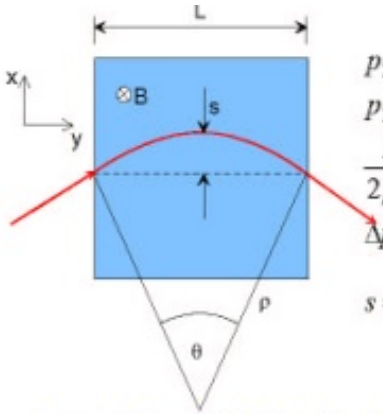
(in the figure the two halves of the dipolar magnet are open)

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

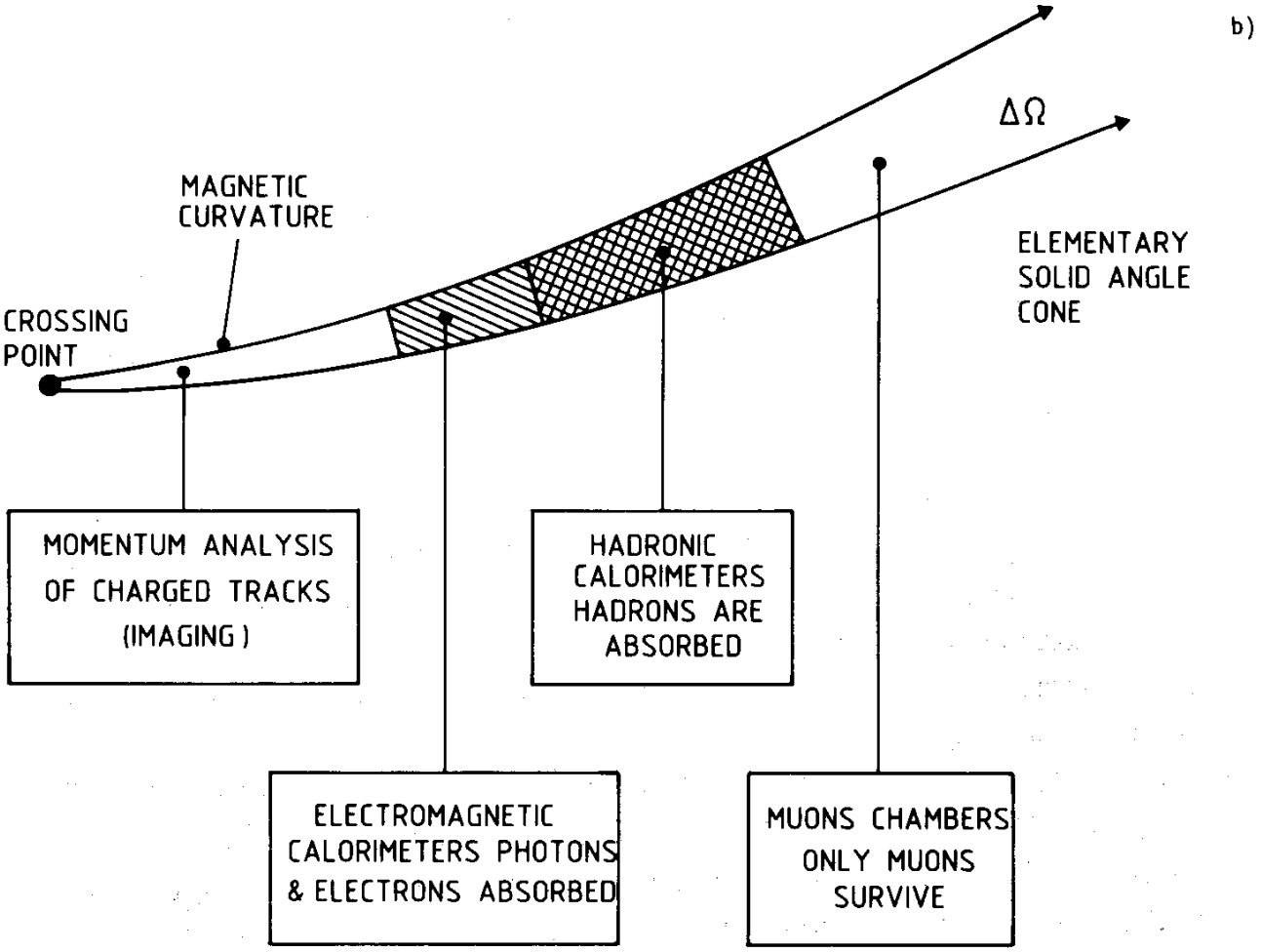


Fig. 8b. The schematic functions of each of the elementary solid-angle elements constituting the detector structure.

UA2 first and second generation

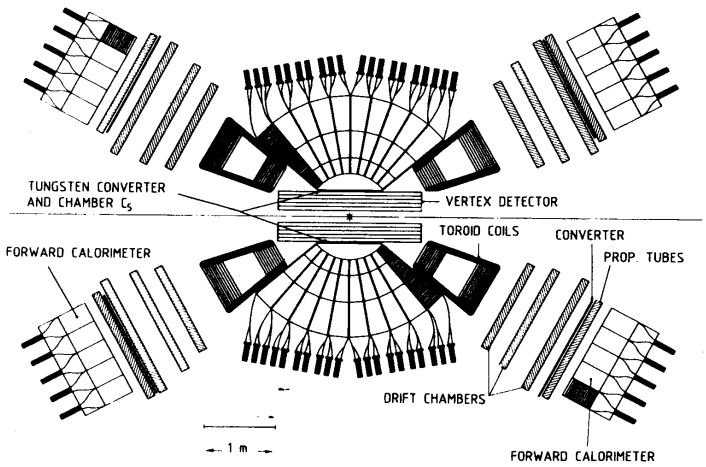
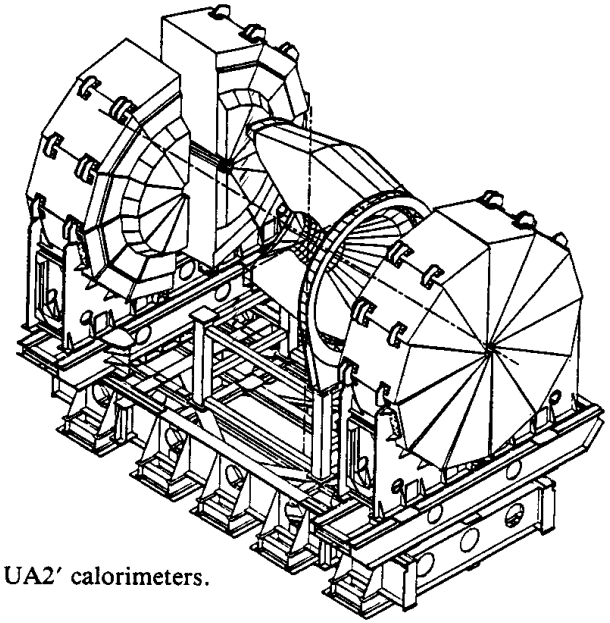
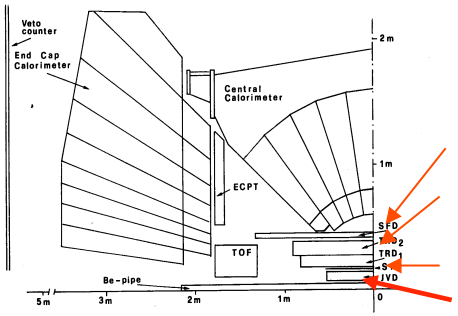


Fig. 1. The UA2 detector: Schematic cross section in the vertical plane containing the beam.



the UA2′ calorimeters.



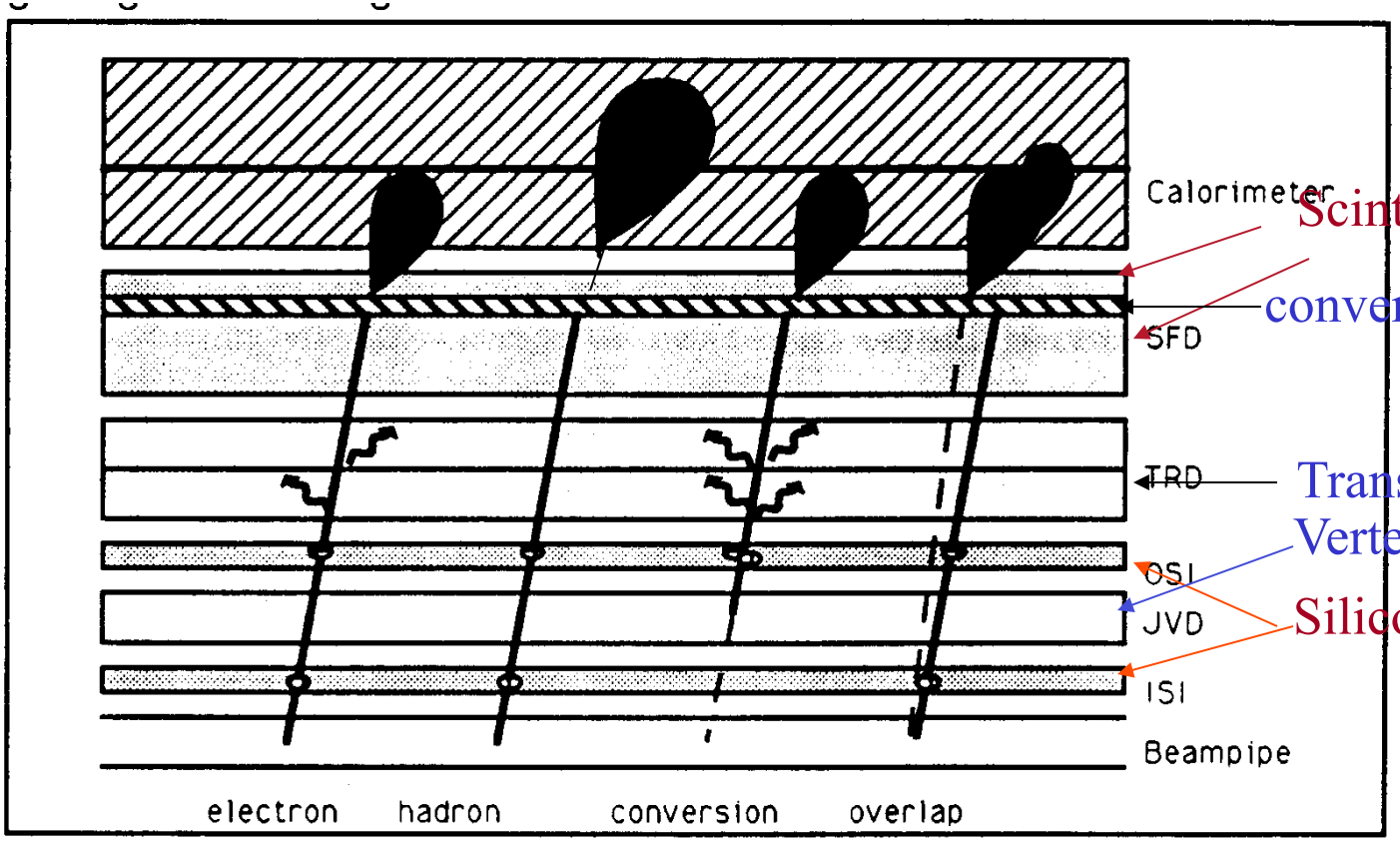
Scintillating fibres

Silicon detector

Drift chamber vertex chamber

50

Particle segnature in UA2



Scintillating fibres

converter

Transition radiation

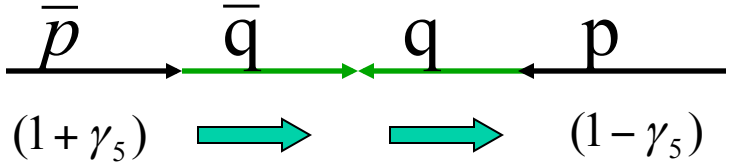
Vertex chamber

Silicon strip detectors

Fig.1 Particle Identification with the Central Detector

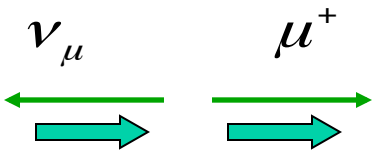
Charge asymmetry in W± decay (V-A structure)

Valence quark dominance:

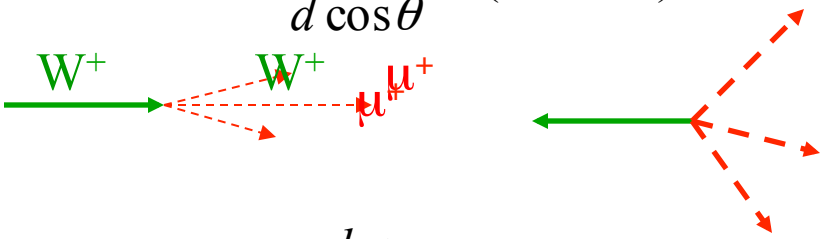


W polarized with helicity h=+1 o h=-1

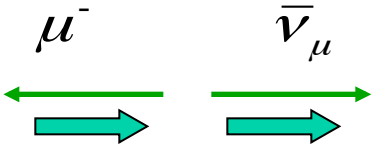
W⁺, θ=angle between $\bar{q}$ ($\bar{p}$) and μ⁺: in cm $\frac{d\sigma}{d\cos\theta} \propto (1+\cos\theta)^2$



In the lab:



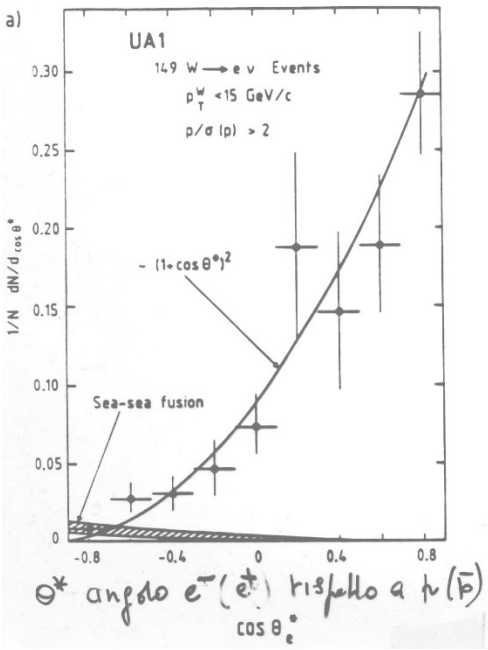
W⁻, θ=angle between q (p) and μ⁻: in cm $\frac{d\sigma}{d\cos\theta} \propto (1+\cos\theta)^2$

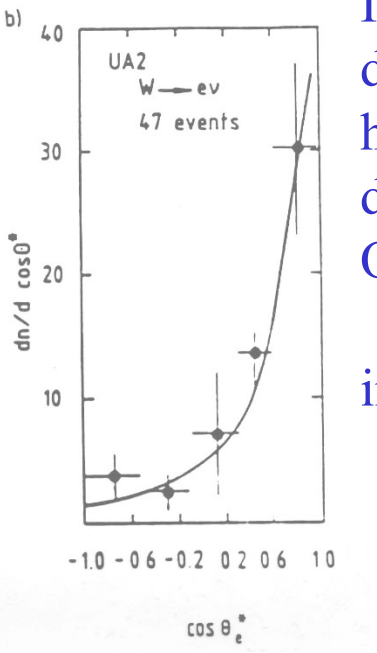


In the lab:

In the decay leptons (μ^- and ν_μ) are emitted preferentially opposite to the W polarization and vice versa for antileptons (μ^+ and $\bar{\nu}_\mu$)

To verify the form $(1+\cos\theta)^2$ we have to go in the W cms , this imply that p^μ e p^ν. However we know only the transverse momentum of the (as missing momentu $p_L{}^\nu$ can be found by imposing: $2(|\vec{p}_\mu| \cdot \sqrt{p_{T\nu}^2 + p_{L\nu}^2})(1 - \vec{p}_{T\mu} \cdot \vec{p}_{T\nu} - p_{L\mu} p_{L\nu}) = M_W^2$





It is interesting to note that $(1+\cos\theta)^2$ does not discriminate V-A from V+A: all helicities change sign and the the angular distributions are the same.
One should measure the helicity of the τ−lepton. For example: in the decay: $W^- \to \tau^- \bar{\nu}_\tau, \tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

μ^- is emitted preferencially backward with respect to the τ^- polarization (V-A).

W spin (M.Jacob N.Cimento 9,826 (1958)): for a particle with spin J≠0 generated by a pair of particles with global helicity μ (for W^+ the $u\bar{d}$) decaying into a particle pair with helicity λ (e.g. $e^+\nu$)

$$\left\langle \cos\theta^* \right\rangle = \frac{\langle \lambda \rangle \cdot \langle \mu \rangle}{J(J+1)}$$

$$(\text{V - A})\ \text{implies} \langle \mu \rangle = -1, \langle \lambda \rangle = -1 \Rightarrow \left\langle \cos\theta^* \right\rangle = 0.5 \text{ if J} = 1;$$

$$\leq 1/6 \text{ se J} \geq 2.$$

$$\text{experimental result}: \left\langle \cos\theta^* \right\rangle = 0.43 \pm 0.07 \text{ (UA1)}$$

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):

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

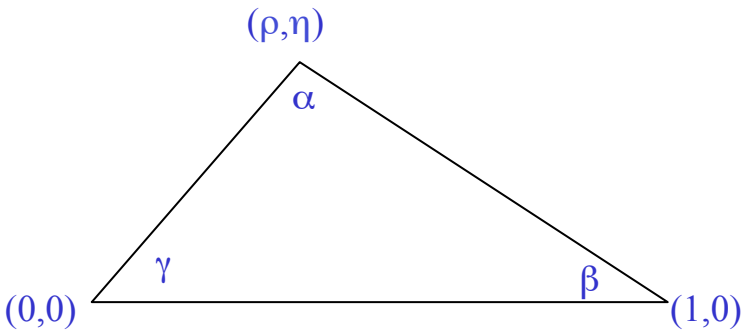
We exploit the following (out of 9) unitarity relation:

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

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:



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

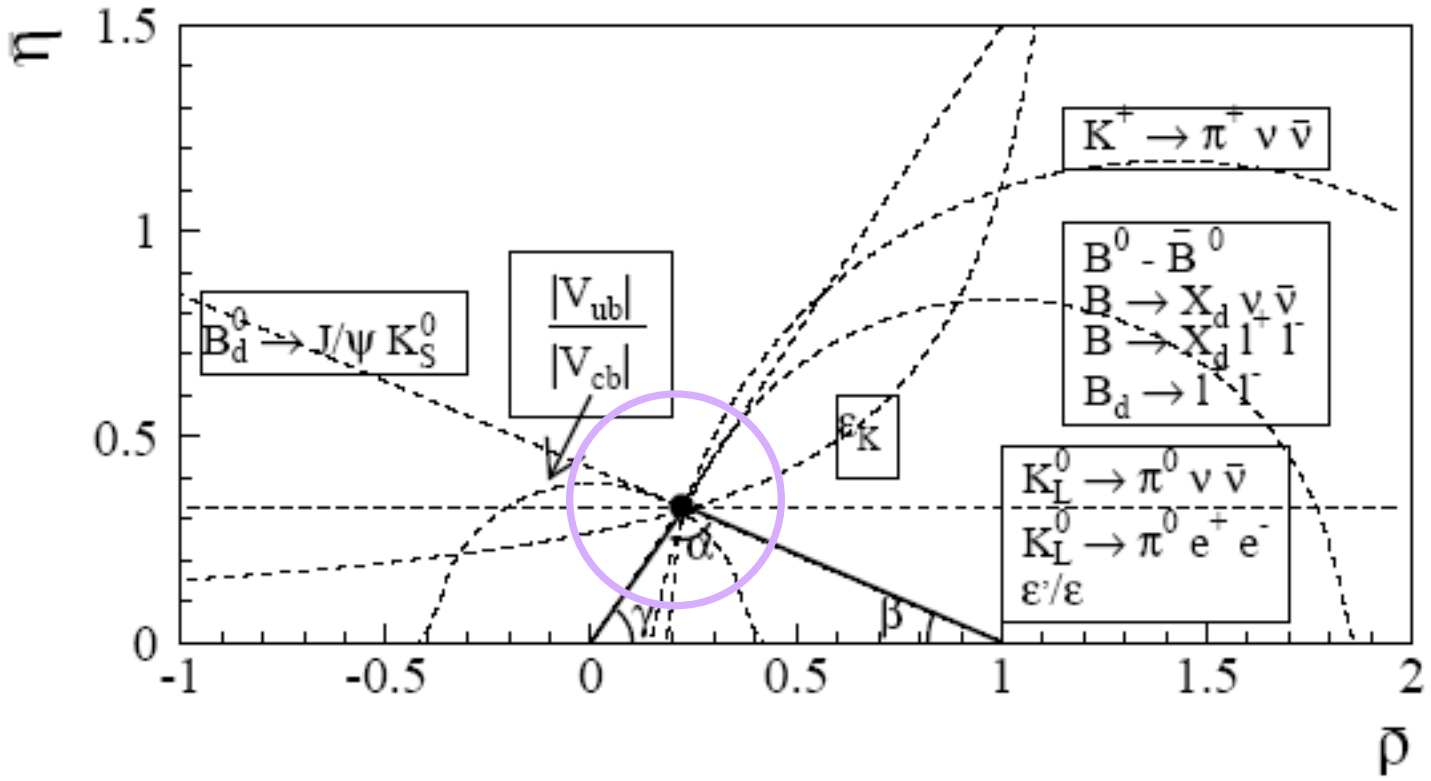
$$\sin 2\beta = \frac{2\bar{\eta}(1-\bar{\rho}^2)}{(1-\bar{\rho}^2) + \bar{\eta}^2}, \qquad CA = R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

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

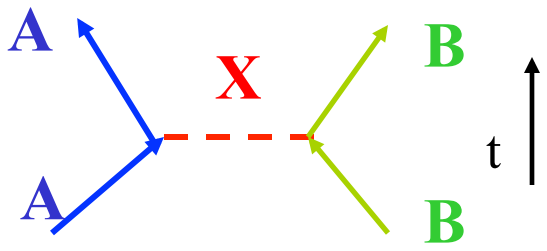
$$V_{td} = |V_{td}|e^{-i\beta}, \qquad R_b e^{i\gamma} + R_t e^{-i\beta} = 1$$

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

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
ρ̄
1.5
1
0.5
0
-1
-0.5
0
0.5
1
1.5
2
$K^+ \to \pi^+ \nu \bar{\nu}$
$B^0 - \bar{B}^0$
$B \to X_d \nu \bar{\nu}$
$B \to X_d l^+ l^-$
$B_d \to l^+ l^-$
$B_d^0 \to J/\psi K_S^0$
$\frac{|V_{ub}|}{|V_{cb}|}$
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



$$\mathbf{A + B \longrightarrow A + B}$$

We can parametrize the process saying that A emits X

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

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

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** :

$$\tau \approx \frac{\hbar}{\Delta E} \leq \frac{\hbar}{M_X}$$

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

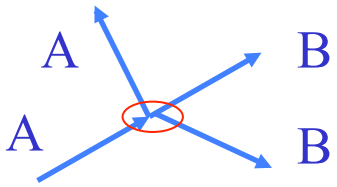
$$R = c \cdot \tau \leq \frac{\hbar c}{M_X} \quad (range)$$

If M_X=0 the photon) R $\longrightarrow \infty$, but also $\Delta E \longrightarrow 0$ 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.:

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

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):



Triple Gauge Coupling - backup

$$\mathcal{L}_{WWV} = ig_{WWV}\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right]$$

$V = Z, \gamma$

$g_{WW\gamma} = -e$

$g_{WWZ} = -e\cot\theta_W$

$\partial_\mu W_\nu - \partial_\nu W_\mu$

$$\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$$

$\rightarrow$ Parameterize deviation form SM using **4 parameters**: f_4^Z, f_4^γ (CP-violating), f_5^Z, f_5^γ (CP-conserving).