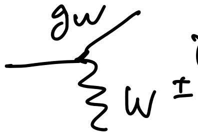
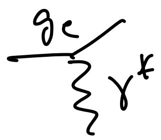
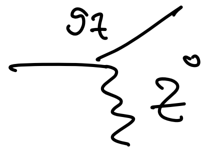
# Glashow - Weinberg - Salam Electroweak theory

| $f$ | $c_V$ | $c_A$ |
|---|---|---|
| $\nu_e, \nu_\mu, \nu_\tau$ | $\frac{1}{2}$ | $\frac{1}{2}$ |
| $e^-, \mu^-, \tau^-$ | $-\frac{1}{2} + 2\sin^2\theta_w$ | $-\frac{1}{2}$ |
| $u, c, t$ | $\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$ | $\frac{1}{2}$ |
| $d, s, b$ | $-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$ | $-\frac{1}{2}$ |




$\gamma^\mu(1-\gamma^5)$




$g_Z \gamma^\mu (C_V - C_A\gamma^5)$

$\theta_W$: weak mixing angle.

GWS $\Rightarrow$ predicts $g_e, g_W, g_Z$

$$g_e = \sqrt{\alpha} = \frac{e}{\sqrt{4\pi}} \qquad g_W = \frac{g_e}{\sin\theta_W} \qquad g_Z = \frac{g_e}{\sin\theta_W \cos\theta_W}.$$

$$\underbrace{\begin{pmatrix} Z^0 \\ A \end{pmatrix}}_{\text{physical gauge bosons.}} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \underbrace{\begin{pmatrix} W_3 \\ B \end{pmatrix}}$$

$\rightarrow$ Bosons of $SU(2)_L \times U(1)_{EM}$ gauge symm.

$A = \underline{A} \rightarrow \gamma$ field $\qquad \theta_W \simeq 29^\circ \qquad \sin\theta_W \simeq 0.23$

$$M_W = M_Z \cos\theta_W \quad \Rightarrow \quad \sin^2\theta_W = 1 - \left(\frac{M_W}{M_Z}\right)^2$$

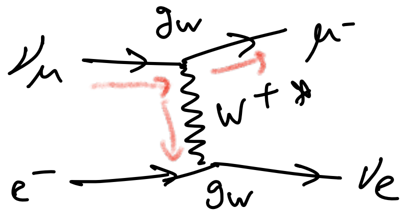
To verify GWS theory

1) measure quantities sensitive to $C_V, C_A \longrightarrow g, \cos\theta_W, \sin\theta_W$.

2) measure $M_W, M_Z$

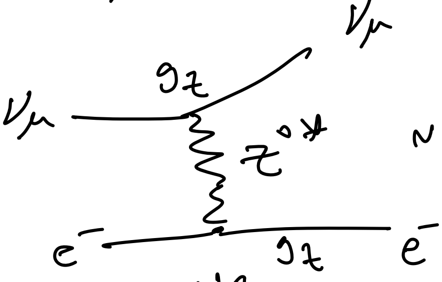
1) mesure $C_V, C_A$ :

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




CC

$\nu_\mu + e^- \longrightarrow \nu_\mu + e^-$




NC

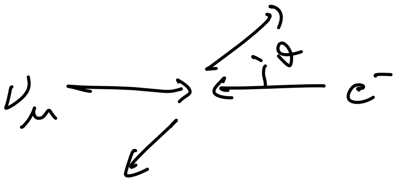
$$\sim \frac{1}{q^2 - m_Z^2} \simeq \frac{1}{m_Z^2}$$

$$\sigma(\nu_\mu + e^- \rightarrow \nu_e + \mu^-) = \sigma(g_W) = \sigma(g, \sin\theta_W)$$

$$\sigma(\nu_\mu + e^- \rightarrow \nu_\mu + e^-) = \sigma(g_Z) = \sigma(g, C_V, C_A) = \sigma(g, \sin\theta_W, \cos\theta_W)$$

Griffiths 9.6

In the center of mass




$E \gg m_e, m_\mu$
$q^2 \ll M_Z^2$

$$\sigma(NC) \sim \left(\frac{g_Z}{m_Z}\right)^4 E^2 \left(C_V^2 + C_A^2 + C_V C_A\right)$$

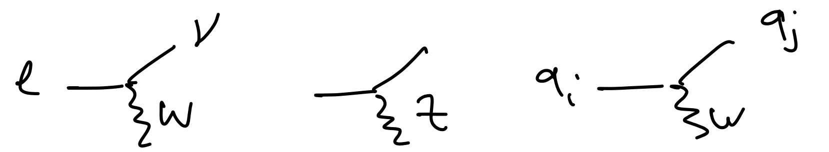
$$\frac{\sigma(NC)}{\sigma(CC)} = \frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^2\theta_W = 0.09 \quad \text{theory prediction.}$$

Experimental mesurement $= 0.11$

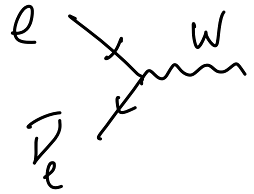
$\#$ events $= \sigma \cdot \mathcal{L} \cdot \Delta t = N$ produced.

$$N_{observed} = N_{produced} \times \varepsilon_{acceptence} \times \varepsilon_{detection}$$

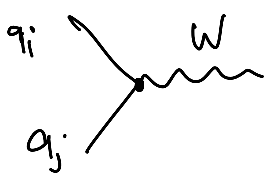
2) Produce W and Z on shell. (Direct evidence)

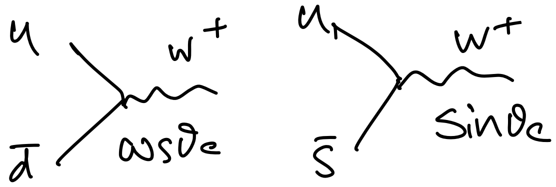



From Fermi theory $G_F = 10^{-5}\ \text{GeV}^{-2} \Rightarrow M_W \simeq 80$ GeV




not feasible



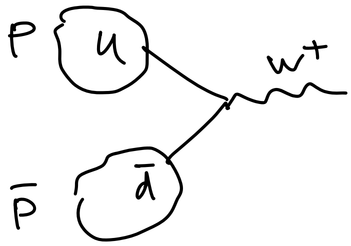



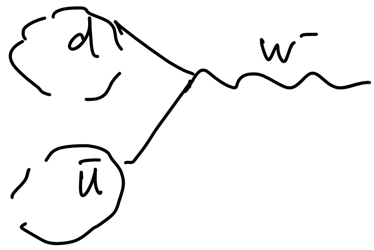

$\pi^+ : u\bar{d}$
$\pi^- : \bar{u}d$

$p + p \rightarrow \pi^+\pi^- + p + p$
$\tau_\pi \simeq 10^{-8}$ s

$p : uud$ $\quad \bar{p} : \bar{u}\bar{u}\bar{d}$

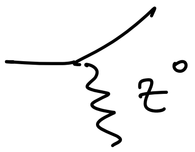
$p + \bar{p} \rightarrow W^+ + X$
$\qquad\quad\; W^- + X$

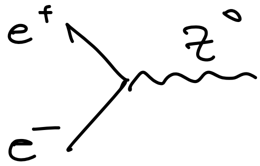


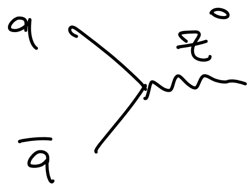

$p + p \rightarrow p + p + p + \bar{p}$

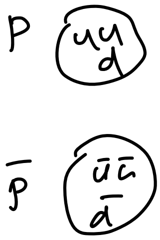
What about $Z^0$ ?

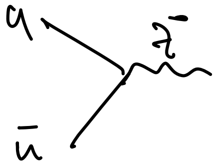


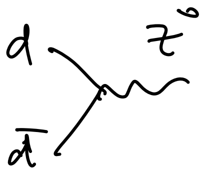




$\sqrt{s} = 2E_{beam} = 90 \text{ GeV} \Rightarrow E \simeq 45 \text{ GeV}.$

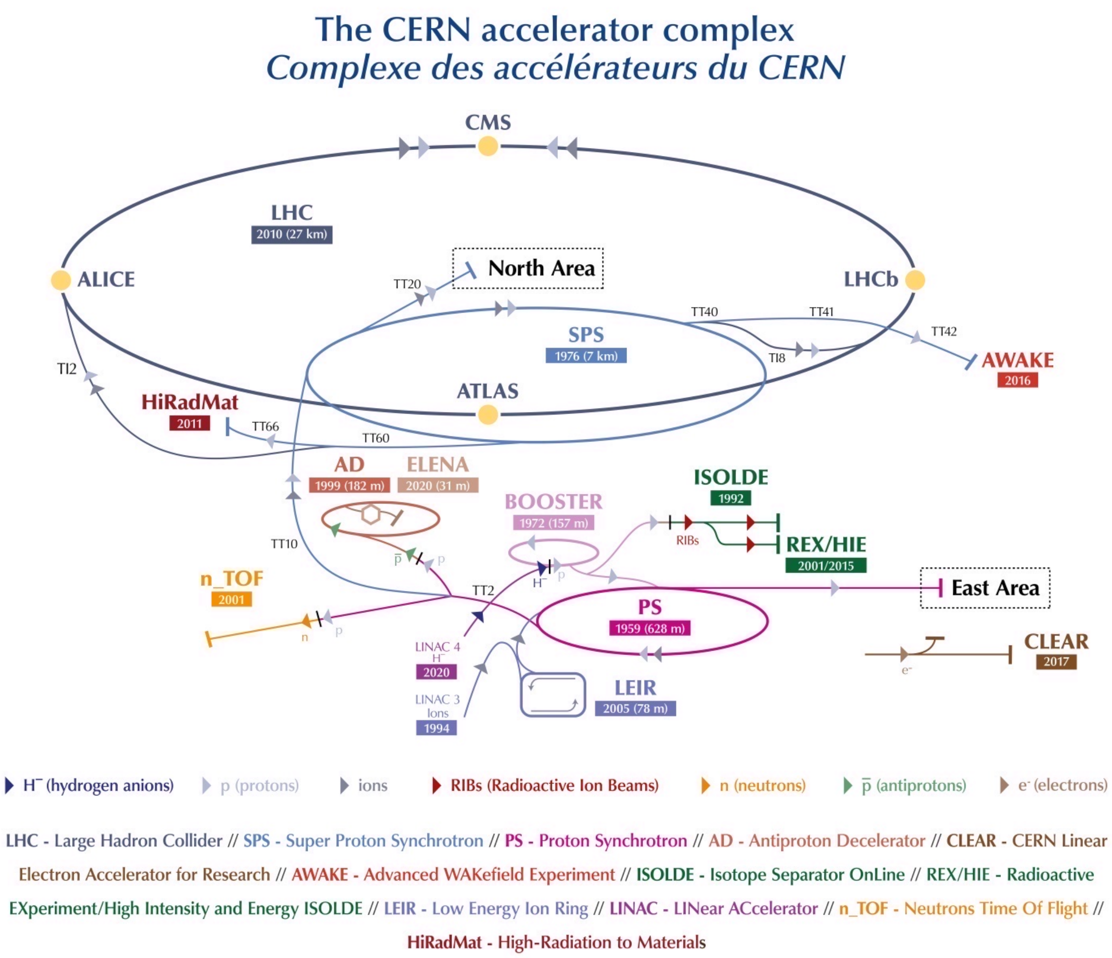


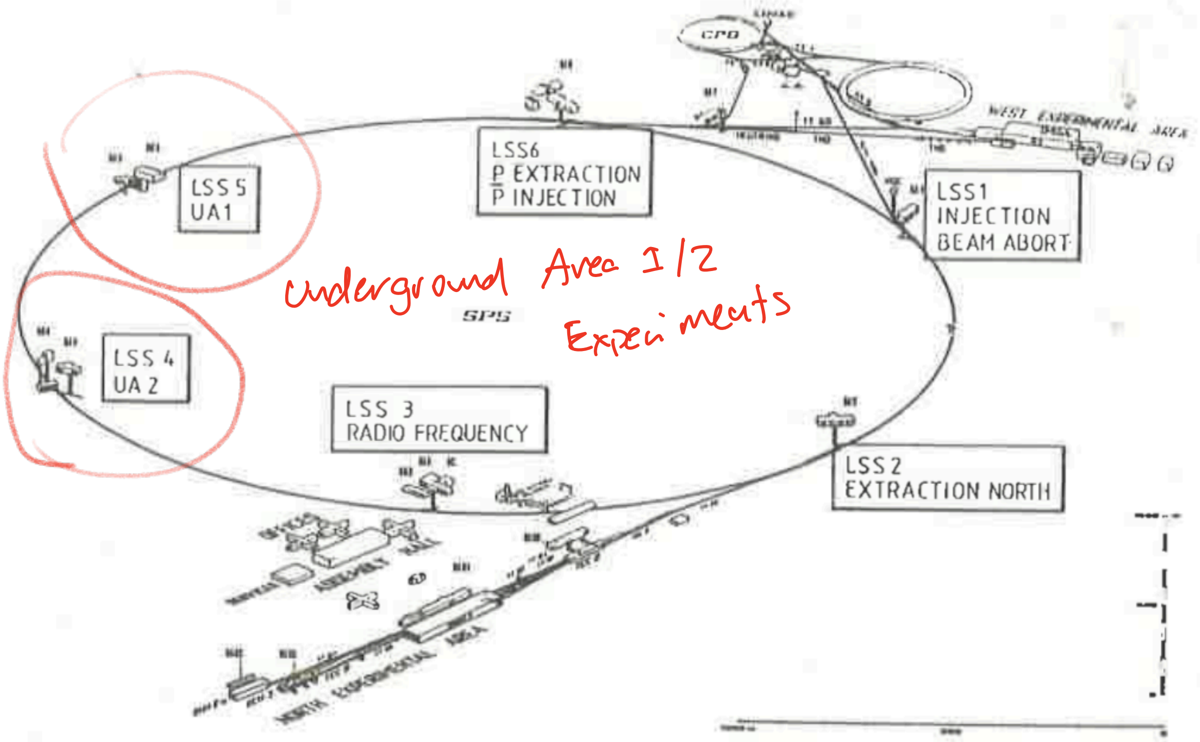




$p + \bar{p} \rightarrow Z^0 + X.$






Convert SPS $\longrightarrow$ $Sp\bar{p}S$ collide $p + \bar{p}$.

$u$, $\bar{d}$ $\to$ $W$ $\qquad \sqrt{s} \geq m_W$

$\{u\,u\,d\}$ $\vec{P} \longrightarrow$ $\qquad \longleftarrow -\vec{P}$ $\{\bar{u}\,\bar{u}\,\bar{d}\}$

$(E, E, 0, 0) \qquad (E, -E, 0, 0)$

$P_u = xP \qquad x \in [0,1]$ parton density function.

$$\bar{x} = \frac{1}{3}$$

$$\sqrt{s} = \sqrt{(P_1 + P_2)^2} = 2E \equiv \simeq \left(\frac{1}{3}E\right) \times 2$$

$$\sqrt{s_{\text{quark}}} \simeq \frac{1}{3}\sqrt{s_{p\bar{p}}}$$

$$\sqrt{s_{p\bar{p}}} = 540 \text{ GeV} \Rightarrow \sqrt{s_{q\bar{q}}} \simeq 170 \text{ GeV} > m_W, m_Z$$

$u \longrightarrow \; \longleftarrow \bar{d} \qquad \bar{u} \longrightarrow \; \longleftarrow d \qquad \longrightarrow \; \longleftarrow \qquad \longrightarrow Z$

$\Rightarrow \qquad \Leftarrow \qquad \Leftarrow$

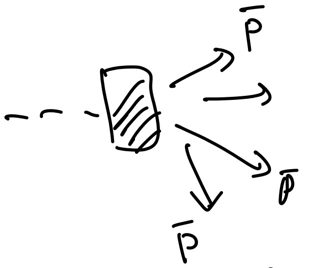
Lorentz boost

Lorentz boost only along z axis. $(P_p + P_{\bar{p}})_T = 0$.

final state $\rightarrow$

$$\Sigma_i \vec{P_{T_i}} = \vec{0}$$

$p + p \longrightarrow p + p + p + \bar{p}$




reduce transverse momentum of $\bar{p}$ after production

1976: SPS $\rightarrow$ $Sp\bar{p}S$ Rubbia, Simon van der Meer

Nobel Prize 1984

stochastic cooling of $\bar{p}$

$$P_{\bar{p}} = P_{L\bar{p}} + P_{T\bar{p}} \longrightarrow \sim P_{L\bar{p}}$$

2 detectors: UA1 and UA2.

to observe $\Rightarrow$ measure invariant mass.

**$W^+$ DECAY MODES**

$W^-$ modes are charge conjugates of the modes below.

| | Mode | | Fraction ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|---|
| $\Gamma_1$ | $\ell^+\nu$ | [a] | $(10.86 \pm 0.09)$ % | |
| $\Gamma_2$ | $e^+\nu$ | | $(10.71 \pm 0.16)$ % | |
| $\Gamma_3$ | $\mu^+\nu$ | | $(10.63 \pm 0.15)$ % | |
| $\Gamma_4$ | $\tau^+\nu$ | | $(11.38 \pm 0.21)$ % | |
| $\Gamma_5$ | hadrons | | $(67.41 \pm 0.27)$ % | |
| $\Gamma_6$ | $\pi^+\gamma$ | | $< 7 \times 10^{-6}$ | 95% |
| $\Gamma_7$ | $D_s^+\gamma$ | | $< 1.3 \times 10^{-3}$ | 95% |
| $\Gamma_8$ | $cX$ | | $(33.3 \pm 2.6)$ % | |

**Z DECAY MODES**

| | Mode | | Fraction ($\Gamma_i/\Gamma$) | Scale factor/ Confidence level |
|---|---|---|---|---|
| $\Gamma_1$ | $e^+e^-$ | [a] | $(3.3632 \pm 0.0042)$ % | |
| $\Gamma_2$ | $\mu^+\mu^-$ | [a] | $(3.3662 \pm 0.0066)$ % | |
| $\Gamma_3$ | $\tau^+\tau^-$ | [a] | $(3.3696 \pm 0.0083)$ % | |
| $\Gamma_4$ | $\ell^+\ell^-$ | [a,b] | $(3.3658 \pm 0.0023)$ % | |
| $\Gamma_5$ | $\mu^+\mu^-\mu^+\mu^-$ | | | |
| $\Gamma_6$ | $\ell^+\ell^-\ell^+\ell^-$ | [c] | $(4.55 \pm 0.17) \times 10^{-6}$ | |
| $\Gamma_7$ | invisible | [a] | $(20.000 \pm 0.055)$ % | |
| $\Gamma_8$ | hadrons | [a] | $(69.911 \pm 0.056)$ % | |

$X \rightarrow 1 + 2$.

$$M_{12} = \sqrt{(\underline{P}_1 + \underline{P}_2)^2} = \sqrt{\underline{P}_1^2 + \underline{P}_2^2 + 2\,\underline{P}_1 \cdot \underline{P}_2}$$

$$= \sqrt{m_1^2 + m_2^2 + 2E_1E_2 - 2\vec{P_1} \cdot \vec{P_2}}$$

$m_1, m_2 \simeq m_e, m_\mu, m_q$

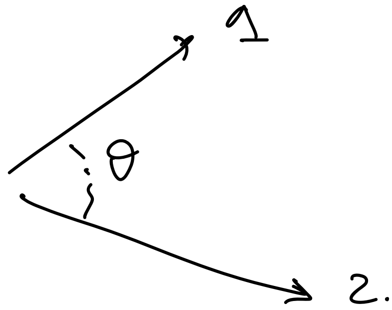
$p + \bar{p} \rightarrow W + X$

$\quad \hookrightarrow 1 + 2$

$E_{1,2} \simeq \frac{M_W}{2} \simeq 40\text{ GeV} \gg m_i$

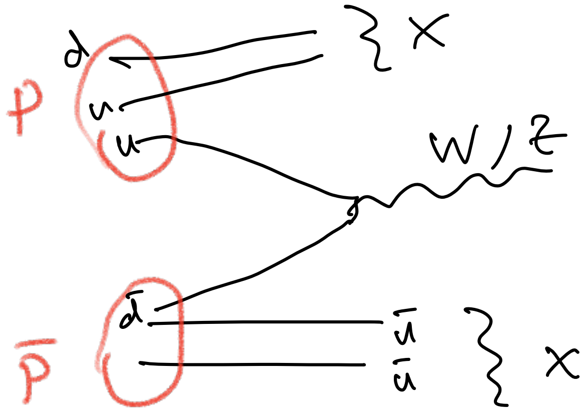
$\Rightarrow$ massless particles. $E_1 = P_1 \quad E_2 = P_2$.

$$m_{12} = \sqrt{2E_1E_2(1-\cos\theta)}$$

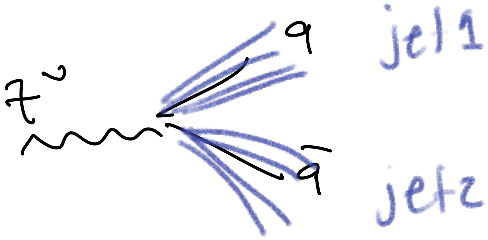



$$p+\bar{p} \longrightarrow W, Z + \underset{\pi^\pm,\, \pi^0,\, K^\pm,\, K^0,\, \ldots \text{ hadrons.}}{X}$$

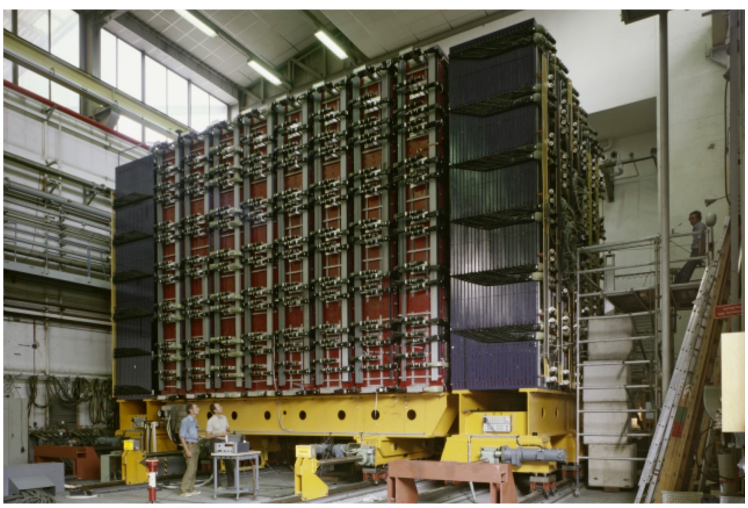
$\hookrightarrow e\nu,\ q_i q_j$

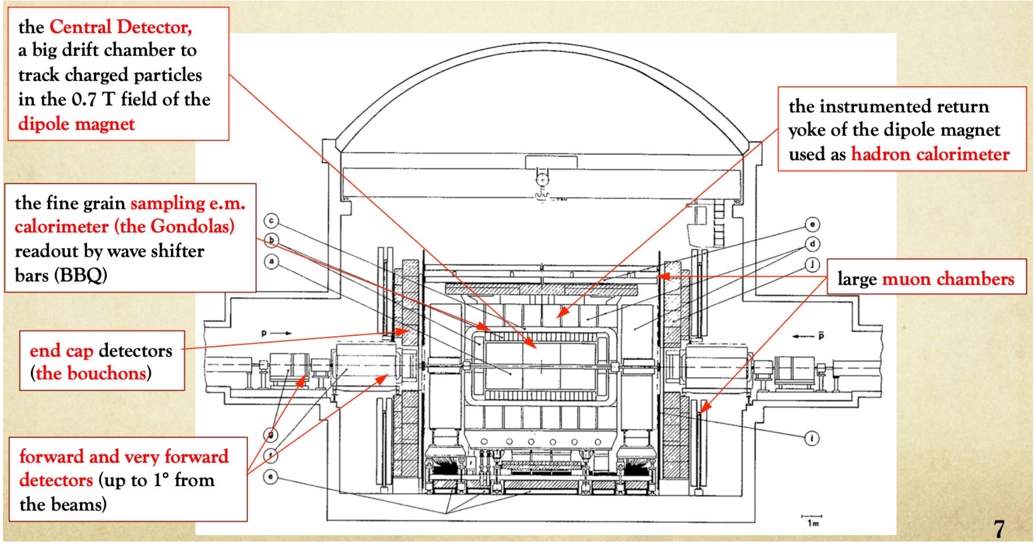


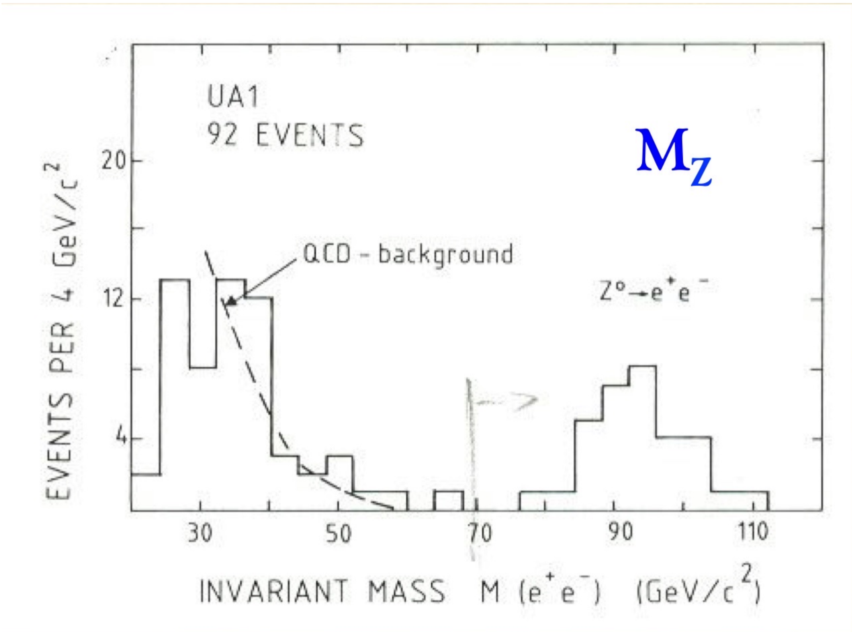

Experimentally $m_{12}$: $\underbrace{m_{e\nu}}_{W}$, $\underbrace{m_{\ell^+\ell^-}}_{Z^0}$, $\underbrace{m_{q\bar{q}},\ m_{q_iq_j}}_{\substack{m_{jj} \\ Z^0, W}}$ (hadronic jets), $m_{\nu\bar{\nu}}$

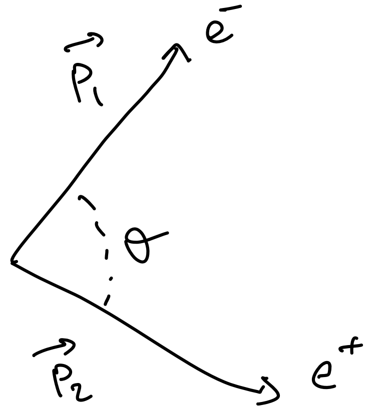



worse experimental resolution then $m_{\ell^+\ell^-}$

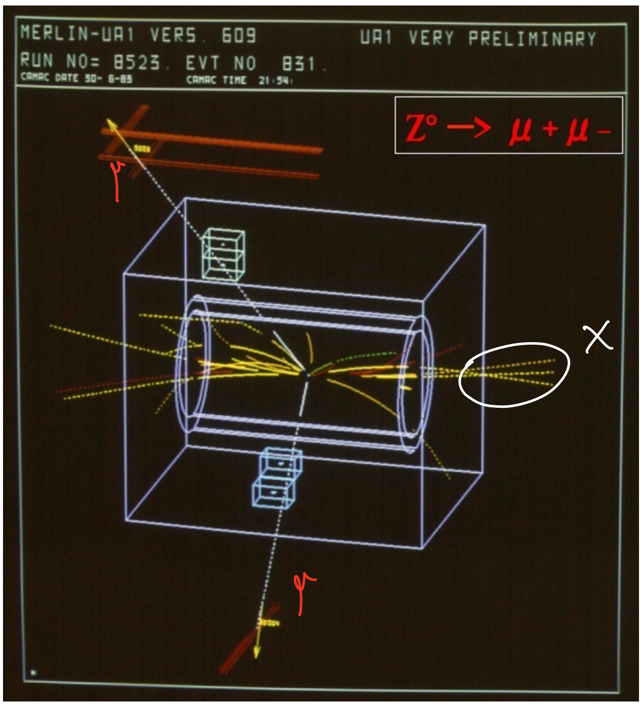


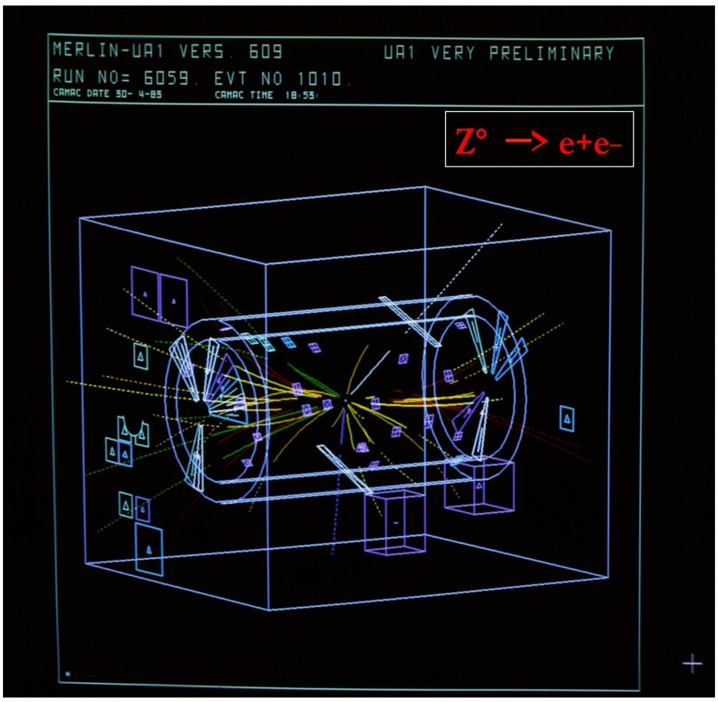


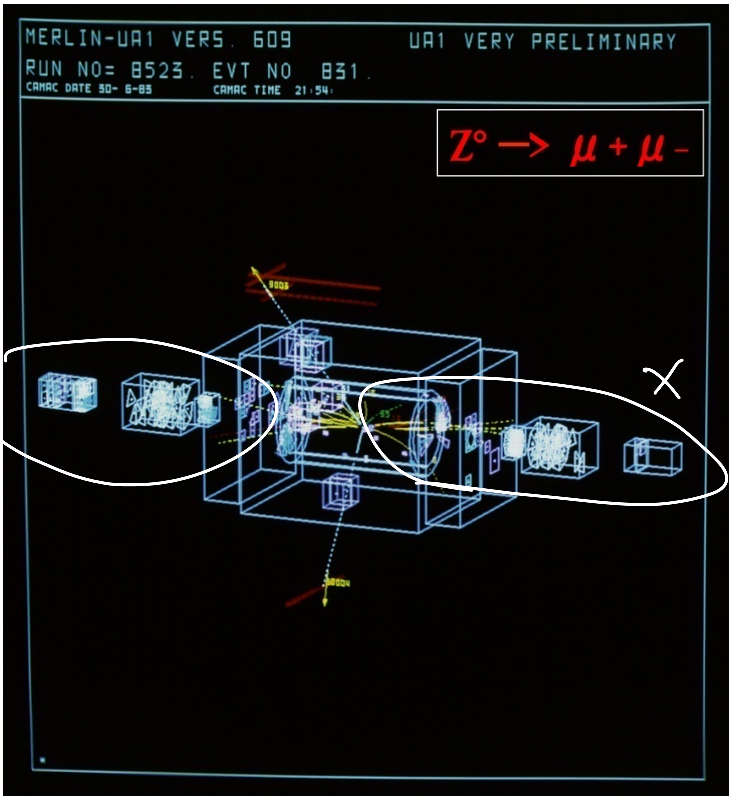



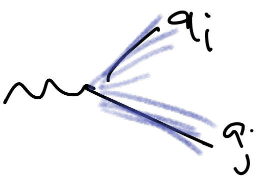

$$M_{ee} = \sqrt{2 E_e^1 E_e^2 (1 - \cos\vartheta)}$$



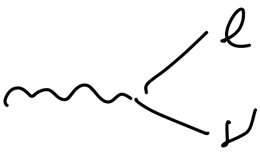



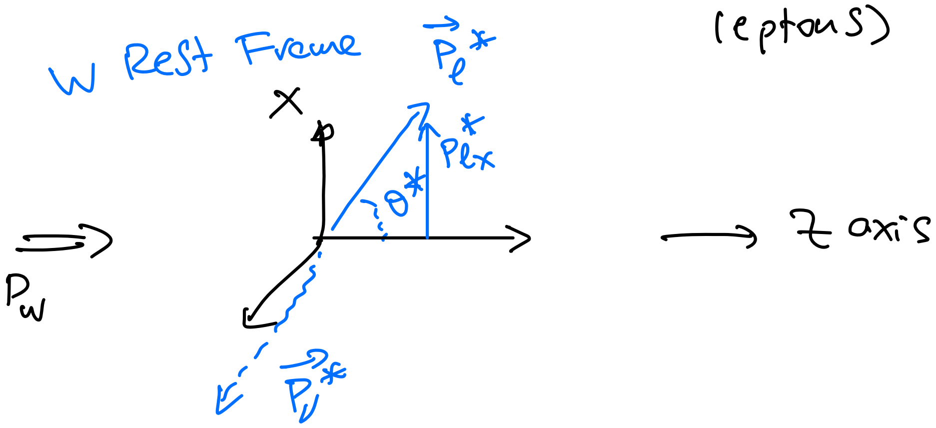



## W peak




$m_{j_1 j_2}$ requires reconstruction of hadronic jets (which have worse resolution than leptons)



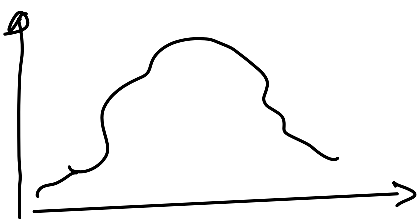




$$W^-$$
$$\nu \longleftarrow \bullet \longrightarrow \ell$$

$$E_\ell^* = E_\nu^* = \frac{M_W}{2} \Rightarrow P_\nu^* = \frac{M_W}{2}$$

$$P_{\ell x}^* = \frac{M_W}{2} \sin\theta^* = P_{\ell x} \text{ in LAB } (\perp \text{ to boost})$$

$$\frac{dn}{dP_{\ell x}} = \#\text{ events}$$



$$\frac{dn}{dP_{ex}} = \underbrace{\frac{dn}{d\theta^*}}\ \underbrace{\frac{d\theta^*}{dP_{ex}}}$$

ang. mom. conserv. (spherical harmonics).

$$\frac{dP_{ex}}{d\theta^*} = \frac{M_W}{2}\cos\theta^*$$

$$\cos\theta^* = \sqrt{1-\sin^2\theta^*}$$

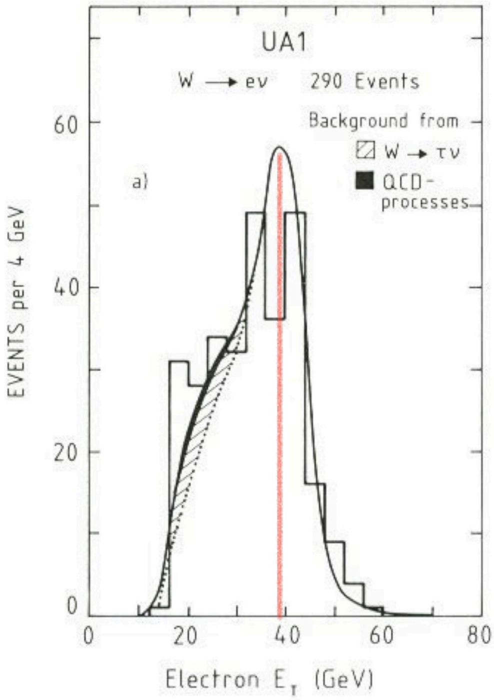
$$\sin\theta^* = \frac{P_{ex}}{M_W/2}$$

measured exp

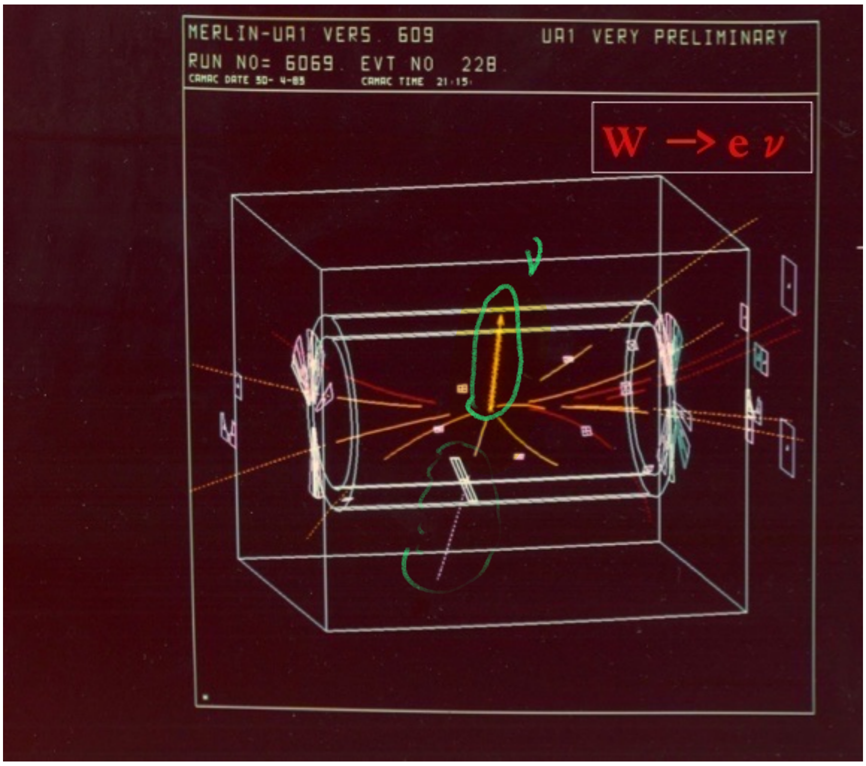
$$\frac{dn}{dP_{ex}} = \frac{dn}{d\theta^*}\ \underbrace{\frac{1}{\sqrt{\left(\frac{M_W}{2}\right)^2-(P_{ex})^2}}}_{\text{Jacobian Peak}}$$

Singularity/peak for $P_{ex} \to \frac{M_W}{2}$

$P_{ex}^{electron} \simeq E_T$ transverse energy.

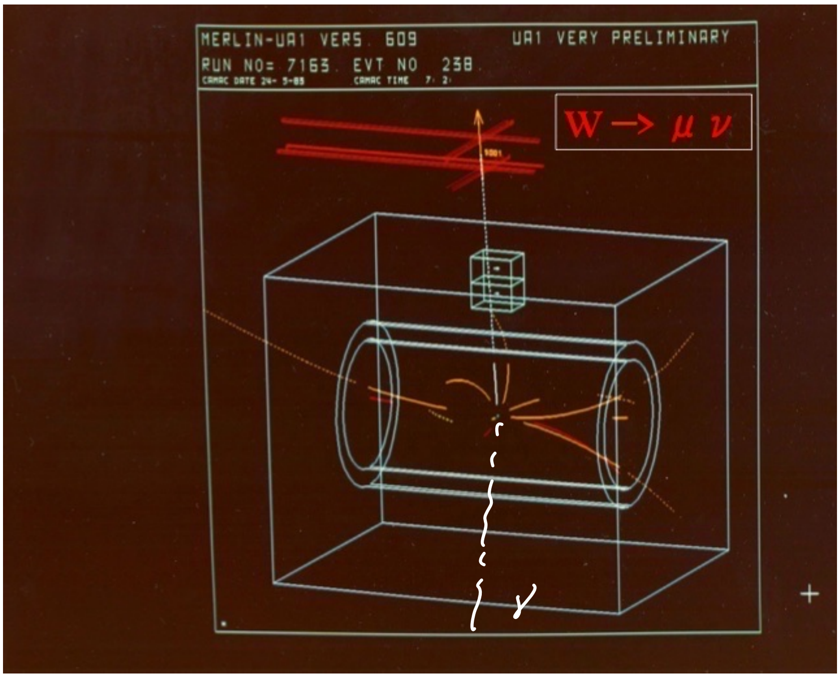



$M_W/2$



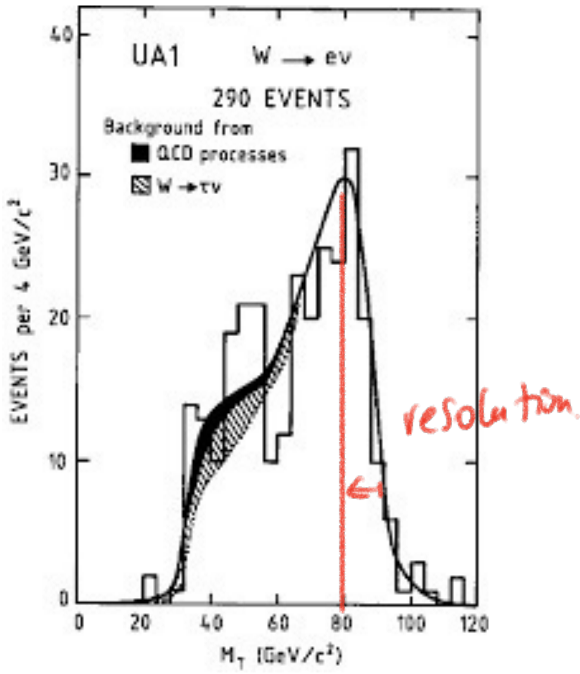

final state particles.

$$\vec{P}_{T\nu} = -\sum_i P_{T_i}$$




Estimate (indirect measurement) of ν momentum from all other particles in the event.

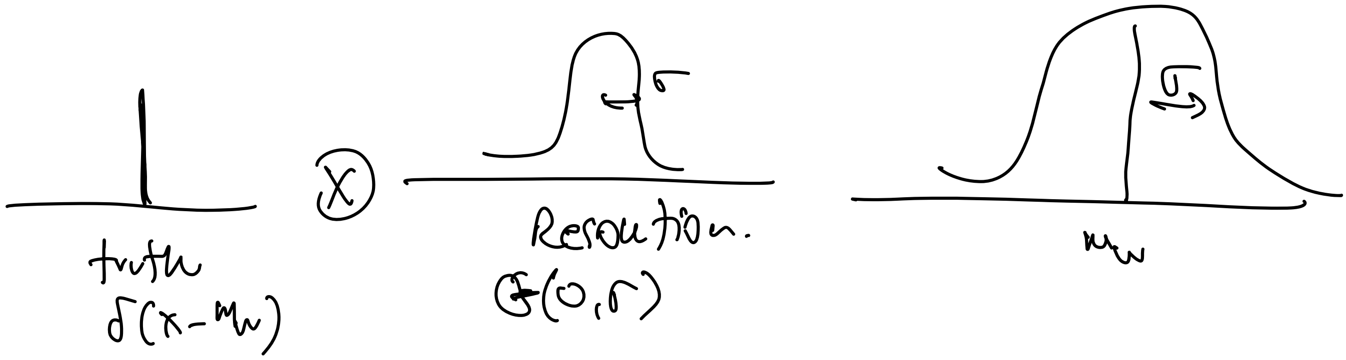
$\vec{P}_{e_T}$ measured.
$\vec{P}_{\nu_T}$ estimated $\Rightarrow$ $m_{e\nu_T}$




$M_T \leq m_W$

$P_{\nu_T}^{estimated} \leq P_{\nu_T}^{true}$

$\tau^- \to e^- \bar{\nu}_e \nu_\tau$.




$W \to e^- + \not{E}$

$W \to \tau^- + \not{E}$
$\quad \hookrightarrow e^- + \not{E}$

$\tau^- \longleftrightarrow \bar{\nu}_e$

$\bar{\nu}_e \; \nu_\tau \leftarrow \overset{\tau^-}{\bullet} \rightarrow e^-$