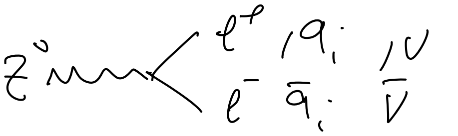
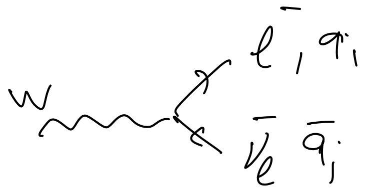
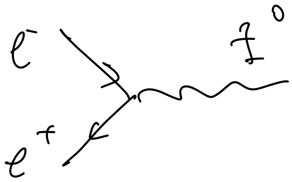
Discovery of W, Z





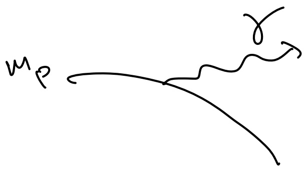
G_F measurement $\Longrightarrow$ $M_W, M_Z \simeq 80-100$ GeV.
μ, decay.
neutron decay

to produce Z

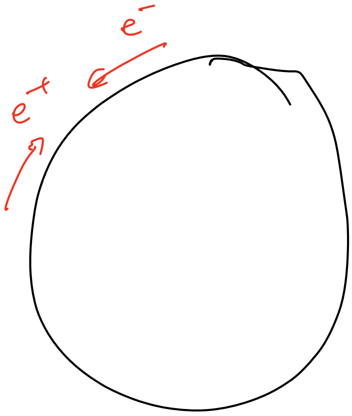


$e^+e^- \to Z^0$
$\mu^+\mu^- \to Z^0$
$\tau^+\tau^- \to Z^0$

$E_{beam} = \frac{M_Z}{2}$



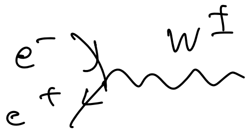
$P_{em.} \propto \frac{1}{m_p^5}$

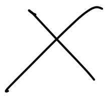


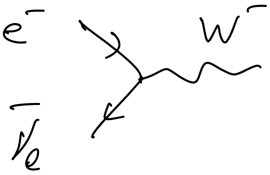
$\mu^+\mu^-$ collision.
has many advantage. But not enough technology yet.

e^+e^- good candidate.

NO

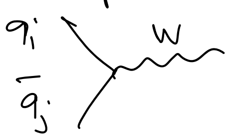


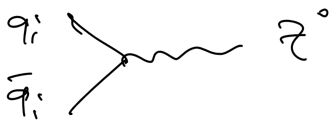




$n \to p e^- \bar{\nu}_e$

the only to produce both Z, W.





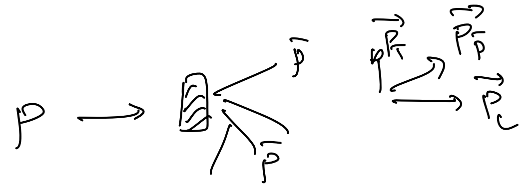
i : flavors.
$u, d, \cancel{s}$

p: uud n: udd. no acceleration for n.

p: uud. only.

$\bar{p}$: $\bar{u}\bar{u}\bar{d}$ experimental challenge. many $\bar{p}$.
accelerate them.

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

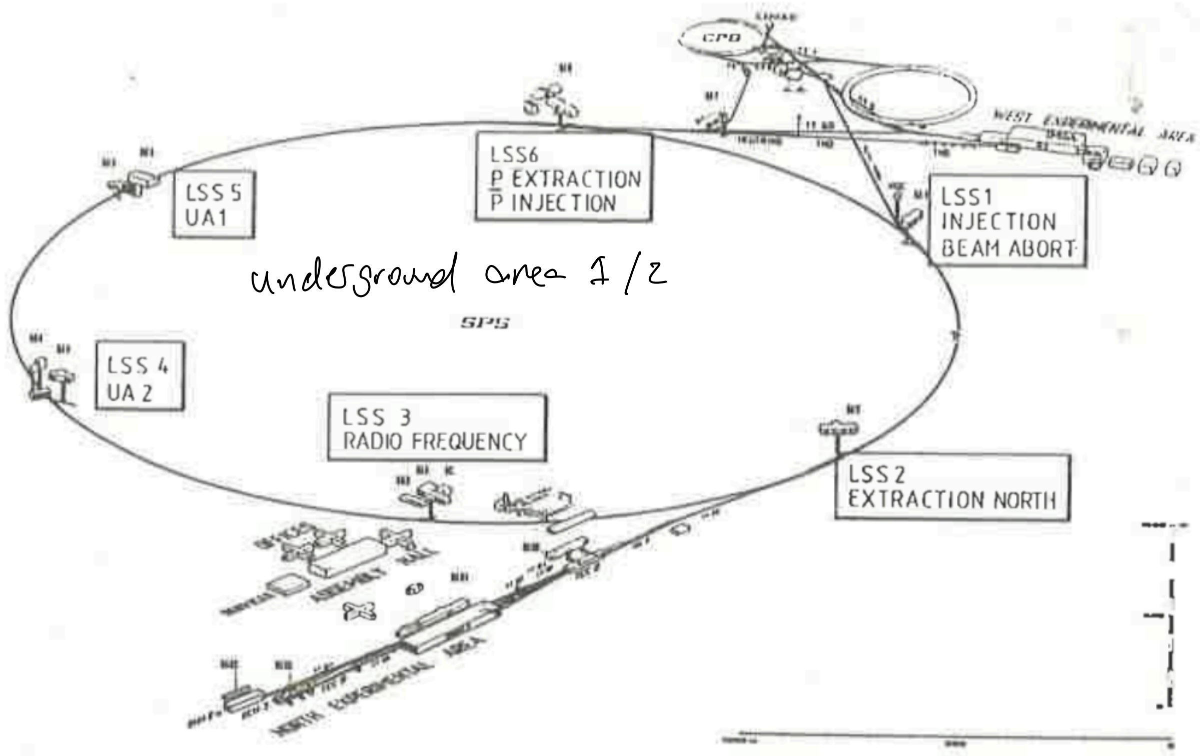


Simon Van der Meer: stochastic cooling of $\bar{p}$

minimize P_T of $\bar{p}$, here $\vec{P_{\bar{p}}} \simeq \vec{P_L}$

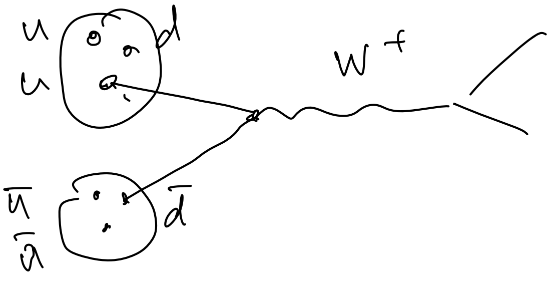
1970's: SPS @ CERN. $\xrightarrow[1976]{\text{Rubbia}}$ $Sp\bar{p}S$

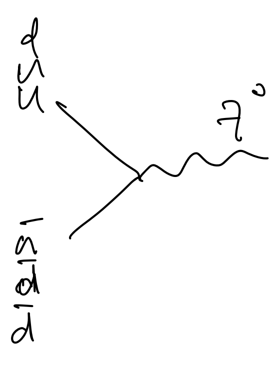
super proton synchrotron. super proton. anti-proton synch.



1984 Nobel: Vander Meer / Rubbia.

$p+\bar{p} \rightarrow W/Z + X$.





No elementary particles

$\longrightarrow x$ $\qquad u \xrightarrow{P_1} \quad \xleftarrow{P_2} \bar{d} \qquad \sqrt{s} = \sqrt{(P_1 + P_2)^2}$

$P_1 = (E_1, E_1, 0, 0) \qquad P_2 = (E_2, -E_2, 0, 0)$

$\sqrt{s} = \sqrt{(E_1 + E_2, E_1 - E_2, 0, 0)^2} \simeq E_1 + E_2.$

$E_1 E_2$: energy of quarks $u, \bar{d}$.

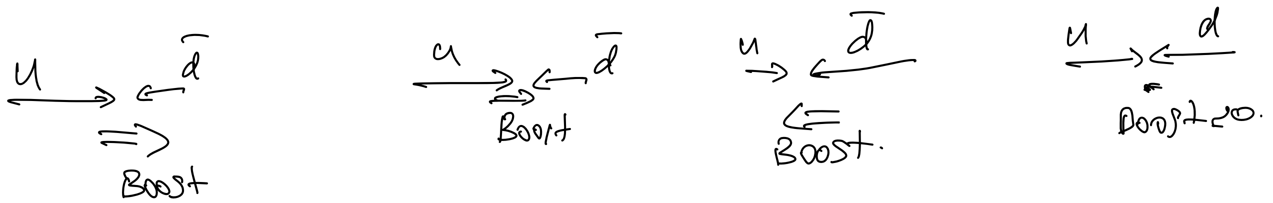
$E_p \neq E_1 E_2$

$E_1, E_2 \simeq \frac{1}{3} E_{beam}.$

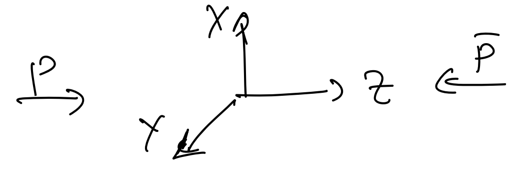
$\sqrt{s_{u\bar{d}}} \simeq \frac{1}{3}(E_p + E_{\bar{p}})$

SppS: $\sqrt{s_{p\bar{p}}} = E_p + E_{\bar{p}} = 540$ GeV.

$\sqrt{s_{q_i \bar{q}_j}} \simeq \frac{1}{3} 540 > M_W, M_Z.$



Boost not know event by event.



Boost $\parallel \hat{z}$.

Boost $\perp \hat{x}, \hat{y}$

$p \longrightarrow \longleftarrow \bar{p} \qquad \vec{P_T} = \vec{0}$ initial state. $P_{\bar{p}}(E, 0, 0, -E).$

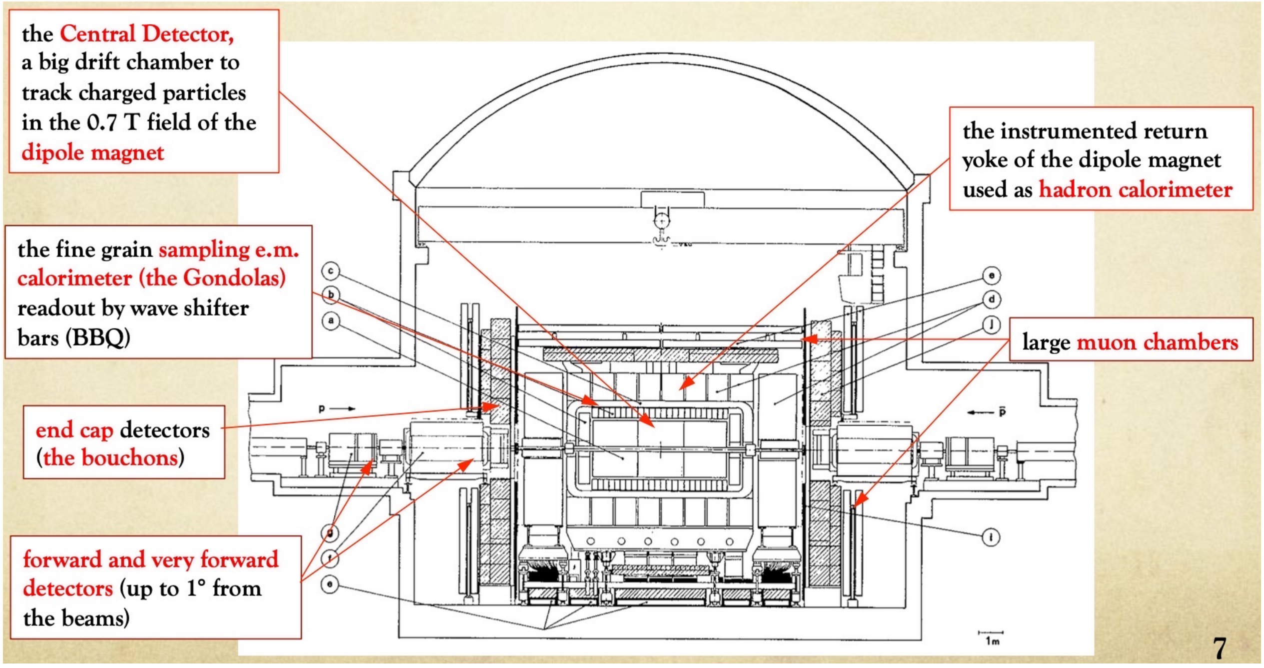
$P_p(E, 0, 0, E)$
$\quad x \; y \; z$

Final state $\sum_i^{\text{particles}} \vec{P_{T_i}} = 0$

$p + \bar{p} \longrightarrow W, Z + X$

- $\bar{b} e \bar{t}$ $q_i \bar{q}_i$ — hadronization of broken $p, \bar{p}$ $\quad \pi^{\pm}, \pi^0, K^{\pm}, K^0, p, \bar{p}$
- $\rightarrow e\bar{\nu}, q_i \bar{q}_j$

UA1 @ SPPS.



produce $Z \to \ell^+ \ell^-$

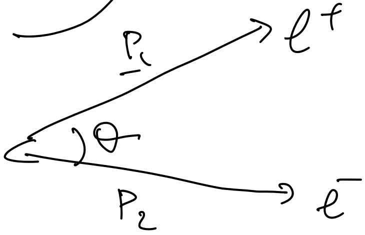
LAB frame: boost unknown.

measure $|\vec{P}|, \theta$ of $\ell^+\ell^-$ $\Rightarrow$ measure $\underline{P}_1, \underline{P}_2$ in LAB.

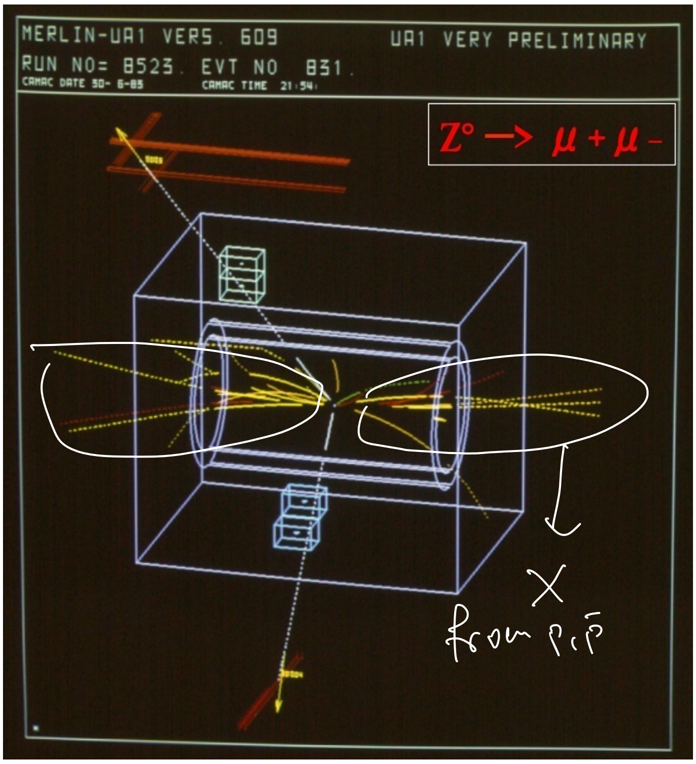
$\ell^+ \leftarrow \overset{Z}{\circ} \rightarrow \ell^-$ Rest frame: $E_{max} = \frac{M_Z}{2}$

$\rightarrow$ μ, e^- are massless. $E \gg m$.

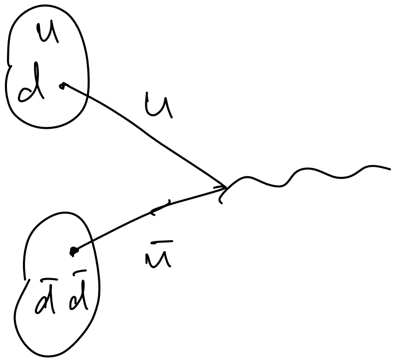
$$\sqrt{s_{\ell^+\ell^-}} = \sqrt{(\underline{P}_1 + \underline{P}_2)^2} = \sqrt{\underbrace{P_1^2 + P_2^2}_{2m_e^2} + 2(E_1E_2 - E_1E_2\cos\theta)}.$$

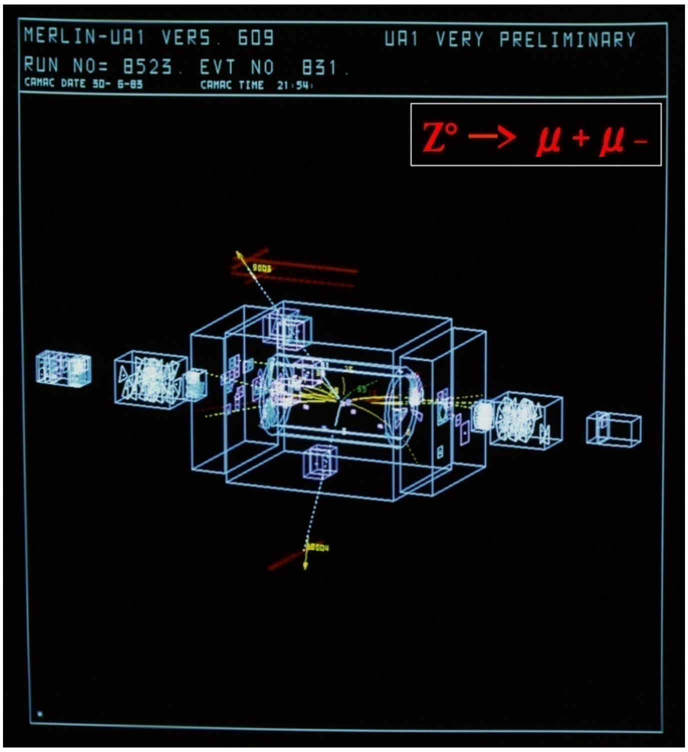


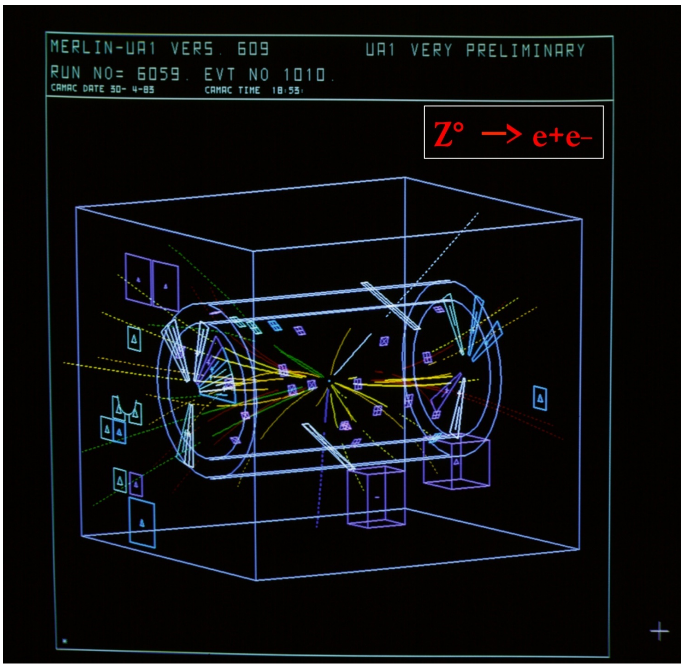
$$\simeq \sqrt{2E_1E_2(1-\cos\theta)}$$



$$p + \bar{p} \rightarrow Z + X$$
$$\hookrightarrow \mu^+\mu^-$$

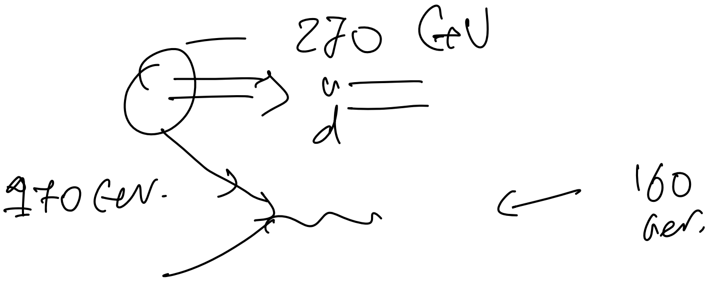


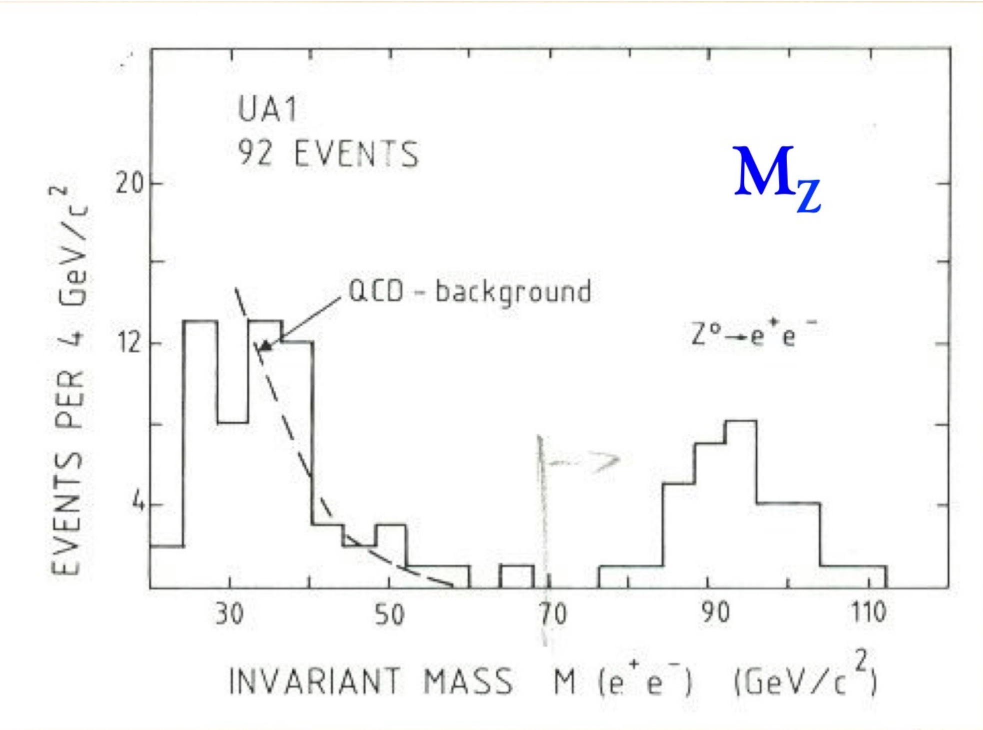




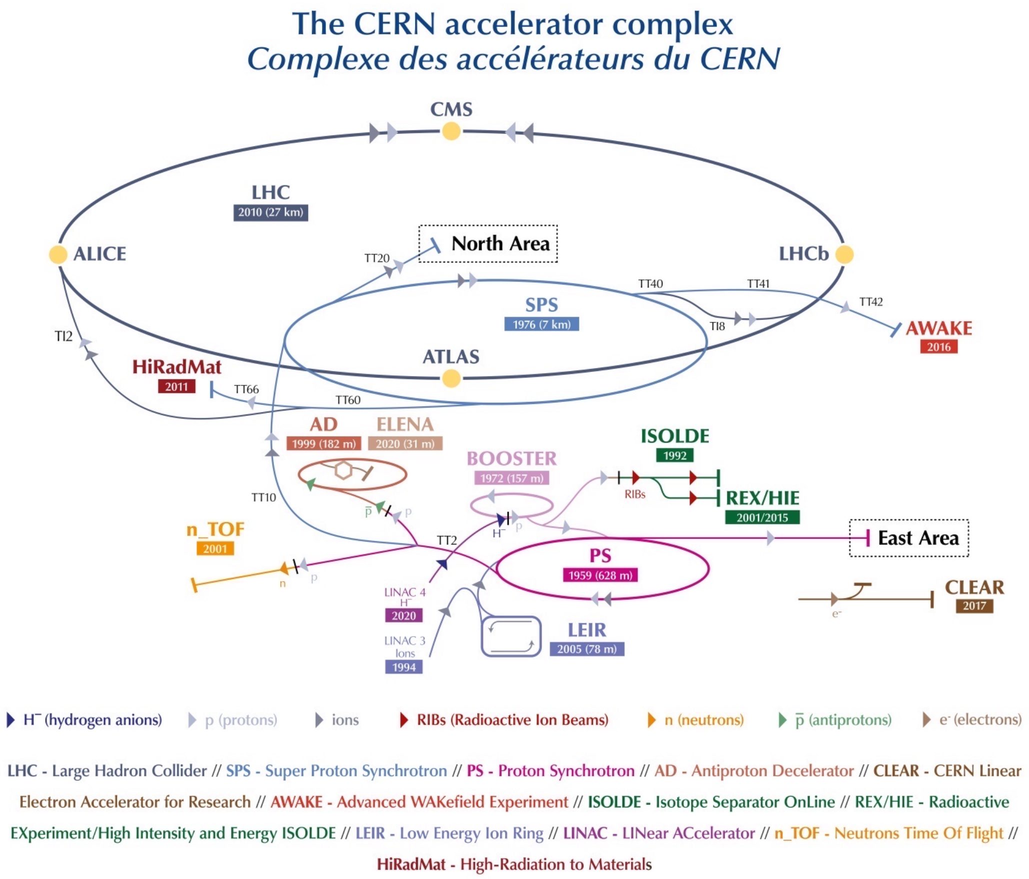
$$p + \bar{p} \rightarrow Z + X$$
$$\hookrightarrow e^+e^-$$

$$X: \ \pi^+ \rightarrow \mu^+ \nu_\mu.$$



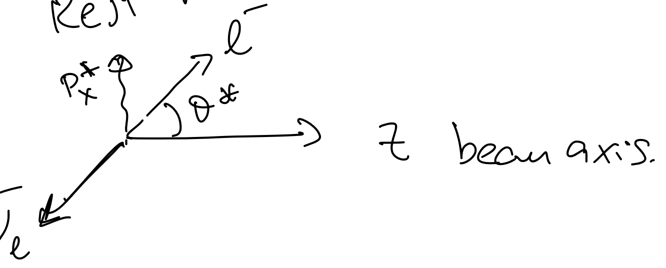


$$\sqrt{s} = \sqrt{2E_1E_2(1-\cos\theta)}$$



W peak

Rest frame.



Boost unknown ~~so~~ $\Rightarrow$ No Lorentz transformation.

W : Spin 1. particle. massive

$e^- \Leftarrow\!\!\longleftarrow \cdot \Longrightarrow\!\!\longrightarrow \bar{\nu}_e$ $\quad P(\theta^*)$ depends on spin.

C-G coeff.

spherical harm.

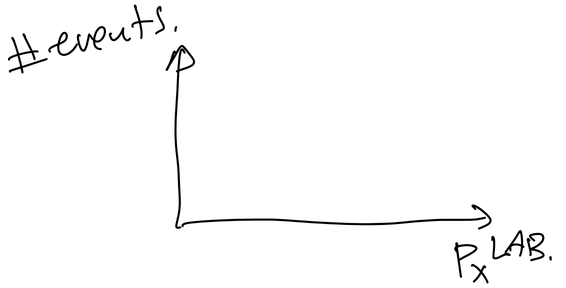
E_ℓ^* in rest frame of W

$$E_\ell^* = \frac{M_W}{2} \qquad P_X^* = \frac{M_W}{2} \sin\theta^* .$$

$$P_X^{LAB} = P_X^* = \frac{M_W}{2} \sin\theta^* .$$

↪ measure with detector.

$$P_X^{LAB} \equiv E_X^{LAB}$$



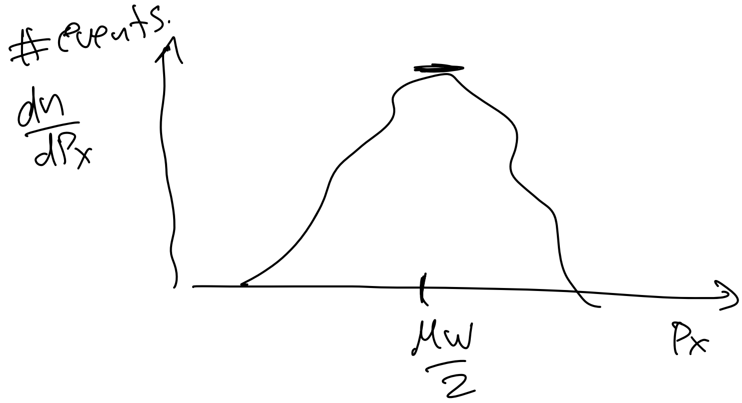
$$\frac{dn}{dP_X} = \underbrace{\frac{dn}{d\theta^*}}_{\text{Computable from spin. ang. mom}} \frac{d\theta^*}{dP_X}$$

$$\frac{d\theta^*}{dP_X} : \qquad \frac{dP_X}{d\theta^*} = \frac{M_W}{2} \cos\theta^* .$$

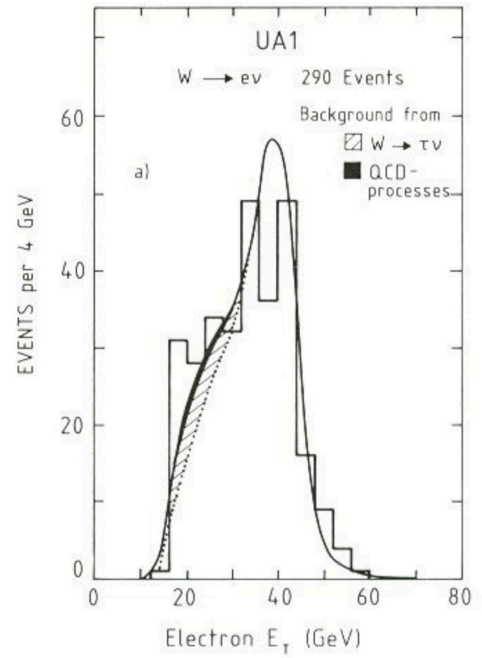
$$\left(\frac{M_W}{2}\right)^2 - \left(\frac{M_W}{2}\right) \cos\theta^{*2} = \underbrace{\left(\frac{M_W}{2}\right)^2 \sin\theta^{*2}}_{(P_X^{LAB})^2} .$$

$$\underbrace{\left(\frac{M_W}{2}\right)^2 \cos\theta^{*2}}_{\left(\frac{dP_X}{d\theta^*}\right)^2} = \left(\frac{M_W}{2}\right)^2 - (P_X^{LAB})^2$$

$$\frac{dn}{dP_x} = \frac{dn}{d\theta^*} \frac{1}{\sqrt{\left(\frac{M_W}{2}\right)^2 - \left(P_x^{LAB}\right)^2}}.$$



$max = \frac{M_W}{2}.$



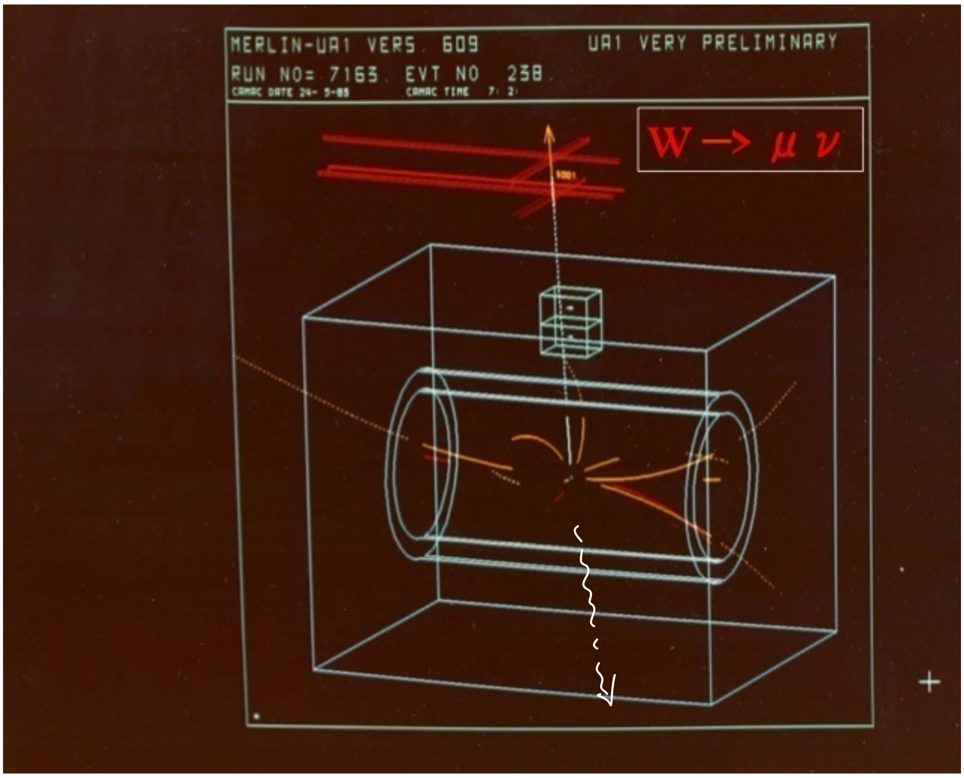
$W^- \longrightarrow \tau^- \bar{\nu}_\tau$

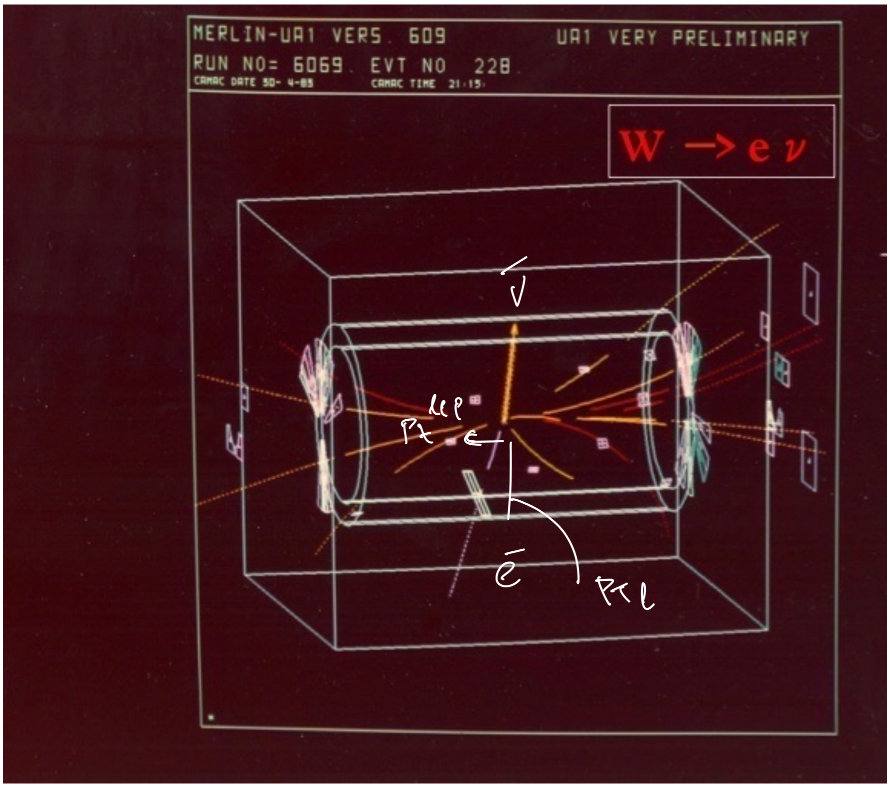
$\hookrightarrow e^- \bar{\nu}_e \nu_\tau$

$W^- \rightarrow e^- \bar{\nu}_\tau \bar{\nu}_e \nu_\tau.$

Compare to

$W^- \longrightarrow e^- \bar{\nu}_e$





final. particles

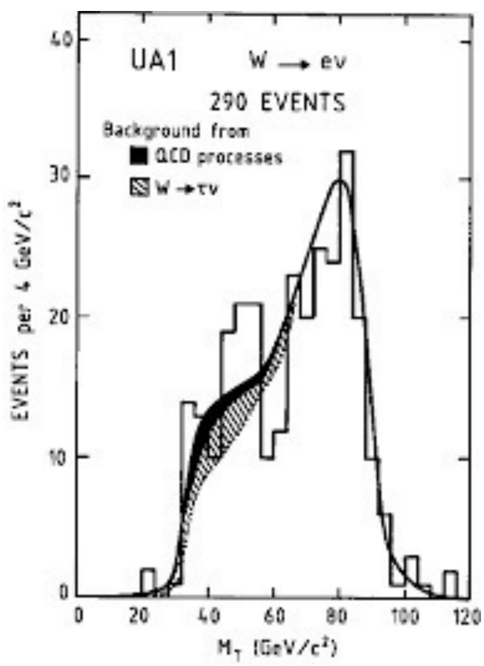
$$\sum_i \vec{P_T} = 0 \qquad P_T = (P_x^{LAB}, P_y^{LAB})$$

$$= \sum_i^{\text{charged particles}} P_T + \vec{P}_{T\nu} = 0.$$

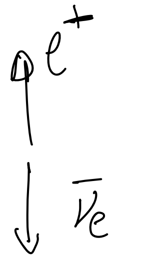
$$\Rightarrow \hat{P}_{T\bar{\nu}} = -\sum_i^{\text{particles}} \vec{P}_{T_i}$$

best estimate of $\vec{P_T}$ of $\bar{\nu}$

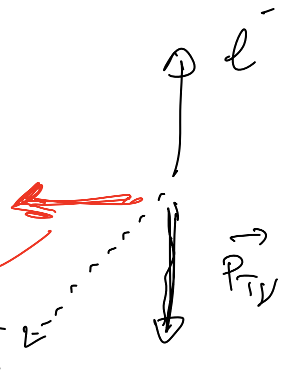
Transverse invariant mass: $\sqrt{s_T} = \sqrt{(P_\ell + P_{T\nu})^2}$



$M_W \sim 80$ GeV



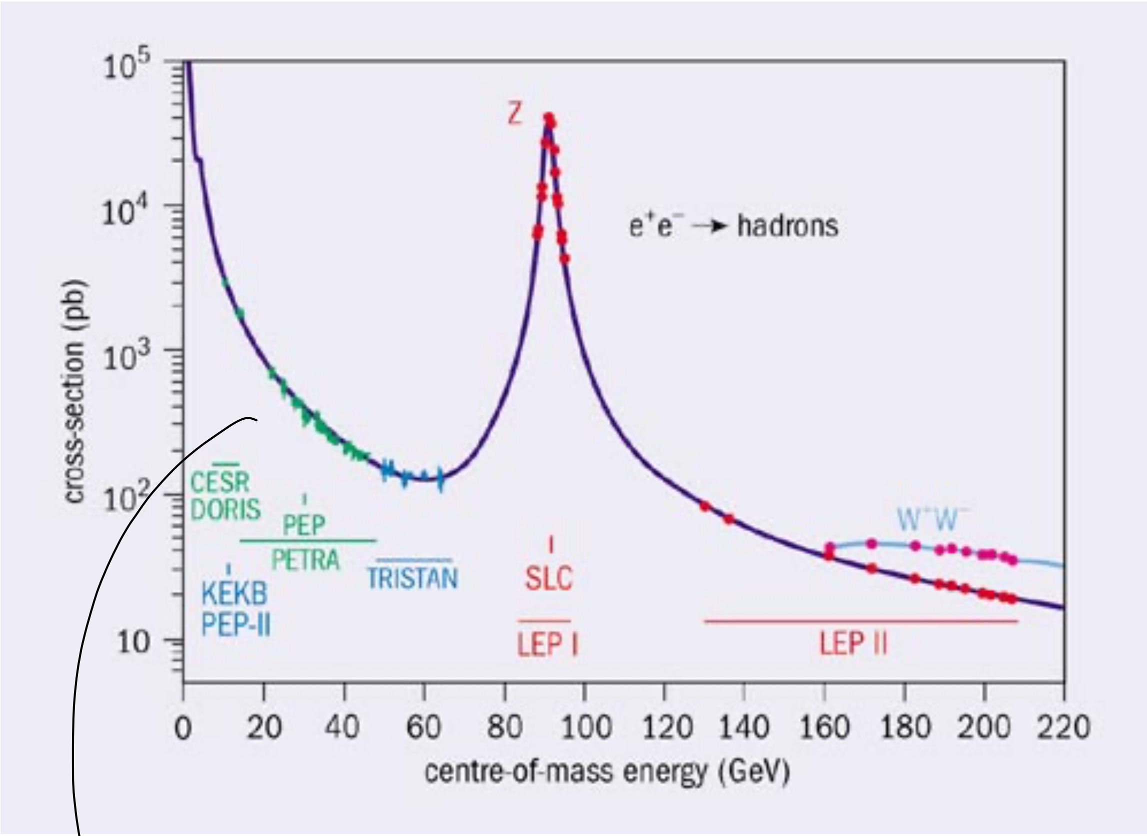
$M_W \sim 20$ GeV.

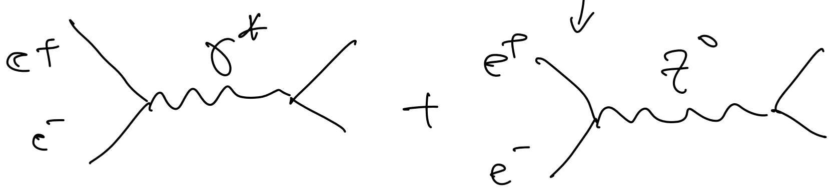


longitudinal $P_{\bar{\nu}_L}$

Discovery of W, Z 1983.

LEP operating in 1989. $e^+e^- \to Z^0 \to \begin{array}{l} e^+e^- \\ \mu^+\mu^- \\ \tau^+\tau^- \\ q_i\bar{q}_i \end{array}$





$\sqrt{s} \le 2M_W$. $e^+e^- \to Z^0 \to f\bar{f}$

$\sqrt{s} \ge 2M_W$ $e^+e^- \to W^+W^-$