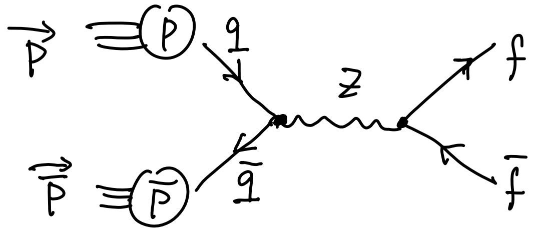
Z玻色子

*) 在强子对撞机上，Z-boson 通过 Drell-Yan 过程产生



	p	$\bar{p}$
价夸克	$u\,d$	$\bar{u}\,\bar{d}$
海夸克	$\bar{u}\,\bar{d}\,s\bar{s}$ $c\bar{c}, b\bar{b}$	$u\,d\,s\bar{s}$ $c\bar{c}, b\bar{b}$

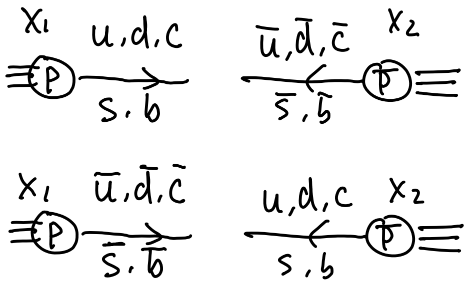
1983年 Z^0 首次在 UA1 实验的 e^+e^- 衰变末态中发现，

至1986年 e^+e^- mode：UA1：32 事例；UA2：37 事例

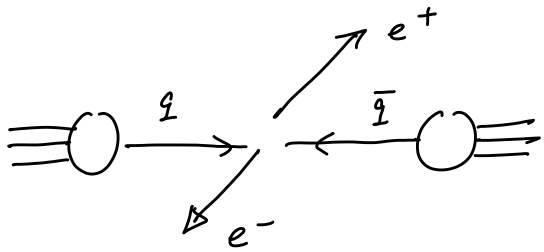
$\mu^+\mu^-$ mode：UA1 19 事例

$$\sigma(p\bar{p}\to q\bar{q}\to Z\to f\bar{f})$$

$$
\begin{aligned}
= \int dx_1 \int dx_2 \Big\{ & f_{u/p}(x_1)\, f_{\bar{u}/\bar{p}}(x_2)\, \hat{\sigma}\big(u(x_1 p)\bar{u}(x_2\bar{p})\to Z\to f\bar{f}\big) \\
& + f_{\bar{u}/p}(x_1)\, f_{u/\bar{p}}(x_2)\, \hat{\sigma}\big(u(x_2\bar{p})\bar{u}(x_1 p)\to Z\to f\bar{f}\big) \\
& + f_{d/p}(x_1)\, f_{\bar{d}/\bar{p}}(x_2)\, \hat{\sigma}\big(d(x_1 p)\bar{d}(x_2\bar{p})\to Z\to f\bar{f}\big) \\
& + f_{\bar{d}/p}(x_1)\, f_{d/\bar{p}}(x_2)\, \hat{\sigma}\big(d(x_2\bar{p})\bar{d}(x_1 p)\to Z\to f\bar{f}\big) \\
& + f_{c/p}(x_1)\, f_{\bar{c}/\bar{p}}(x_2)\, \hat{\sigma}\big(c(x_1 p)\bar{c}(x_2\bar{p})\to Z\to f\bar{f}\big) \\
& + f_{\bar{c}/p}(x_1)\, f_{c/\bar{p}}(x_2)\, \hat{\sigma}\big(c(x_2\bar{p})\bar{c}(x_1 p)\to Z\to f\bar{f}\big) \\
& + f_{s/p}(x_1)\, f_{\bar{s}/\bar{p}}(x_2)\, \hat{\sigma}\big(s(x_1 p)\bar{s}(x_2\bar{p})\to Z\to f\bar{f}\big) \\
& + f_{s/p}(x_1)\, f_{\bar{s}/\bar{p}}(x_2)\, \hat{\sigma}\big(s(x_2\bar{p})\bar{s}(x_1 p)\to Z\to f\bar{f}\big) \\
& + f_{b/p}(x_1)\, f_{\bar{b}/\bar{p}}(x_2)\, \hat{\sigma}\big(b(x_1 p)\bar{b}(x_2\bar{p})\to Z\to f\bar{f}\big) \\
& + f_{b/p}(x_1)\, f_{\bar{b}/\bar{p}}(x_2)\, \hat{\sigma}\big(b(x_2\bar{p})\bar{b}(x_1 p)\to Z\to f\bar{f}\big) \Big\}
\end{aligned}
$$

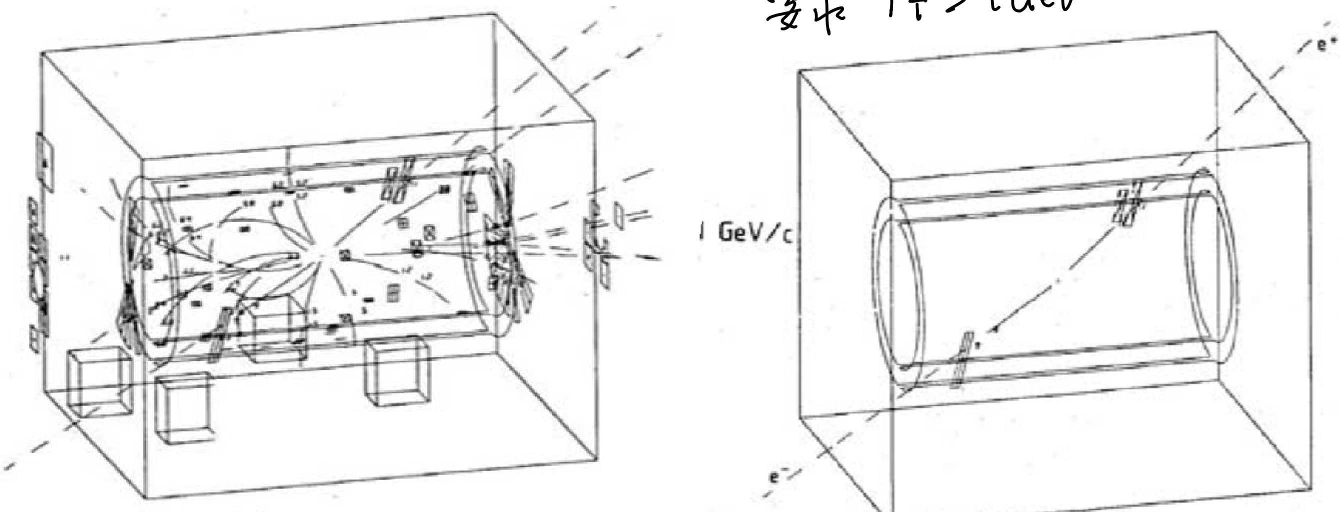


*) Z 玻色子的实验信号



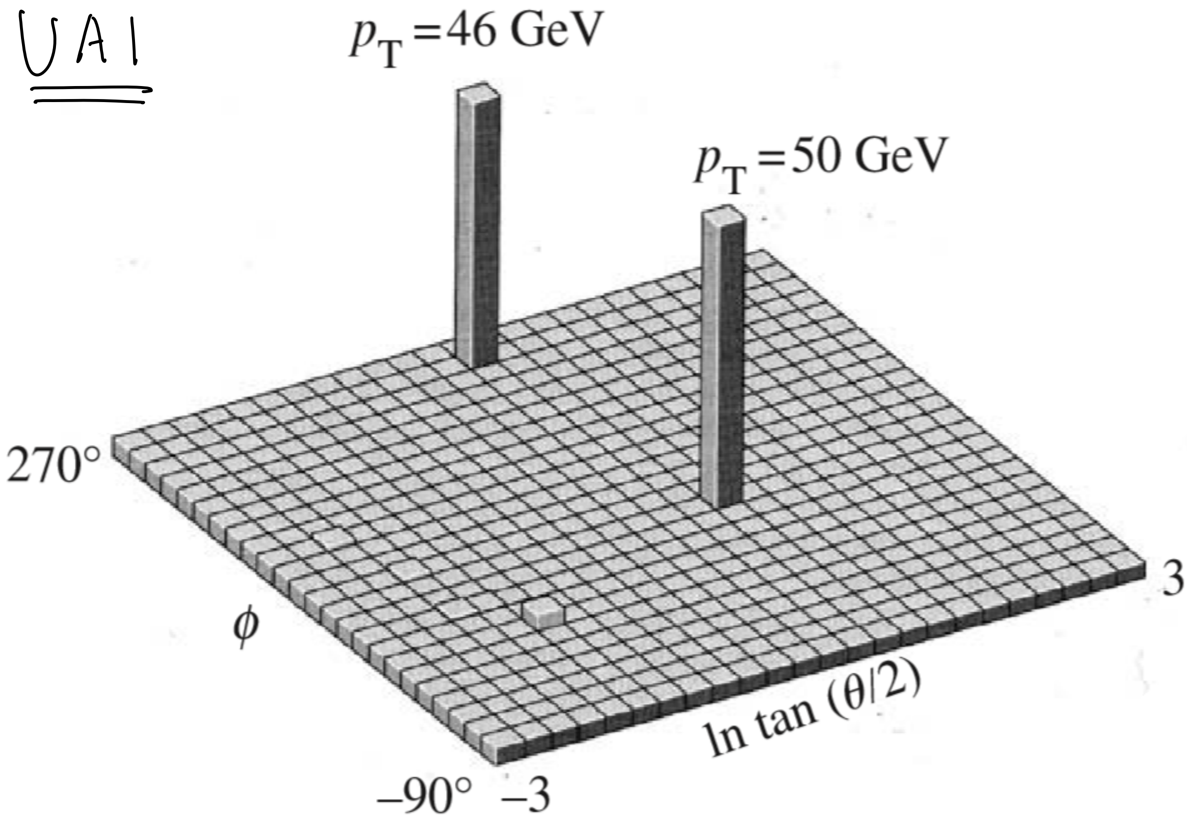
两个大P_T的正负荷电轻子

要求 $P_T^e > 1GeV$



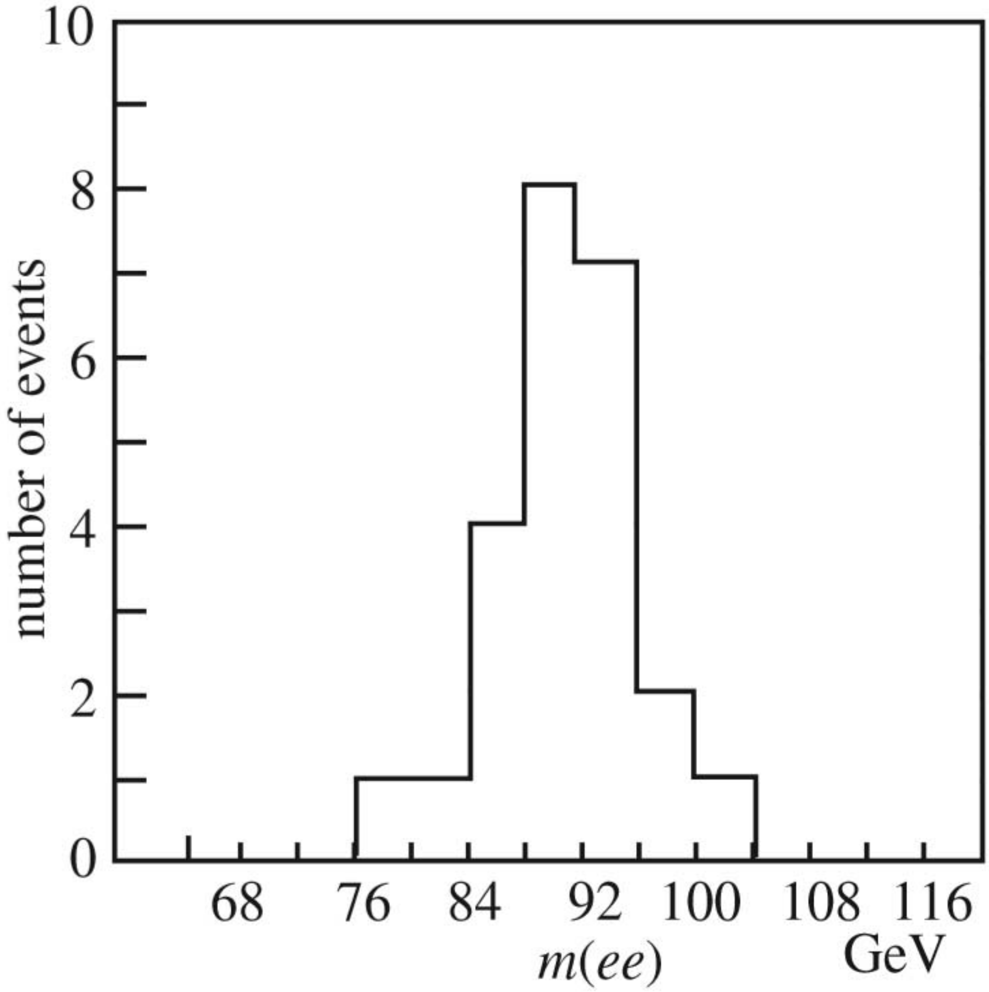
(a)

UA1

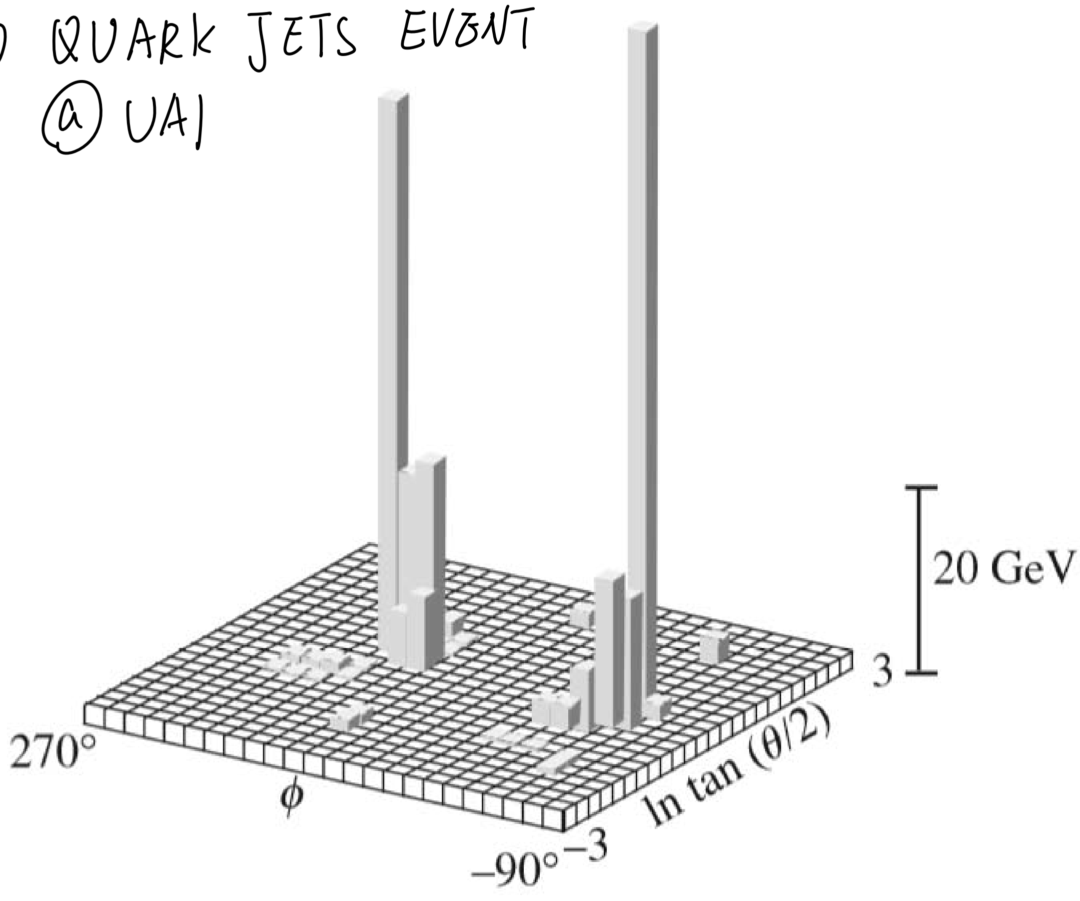


Z-3

24 EVENTS @ UA1



TWO QUARK JETS EVENT @ UA1



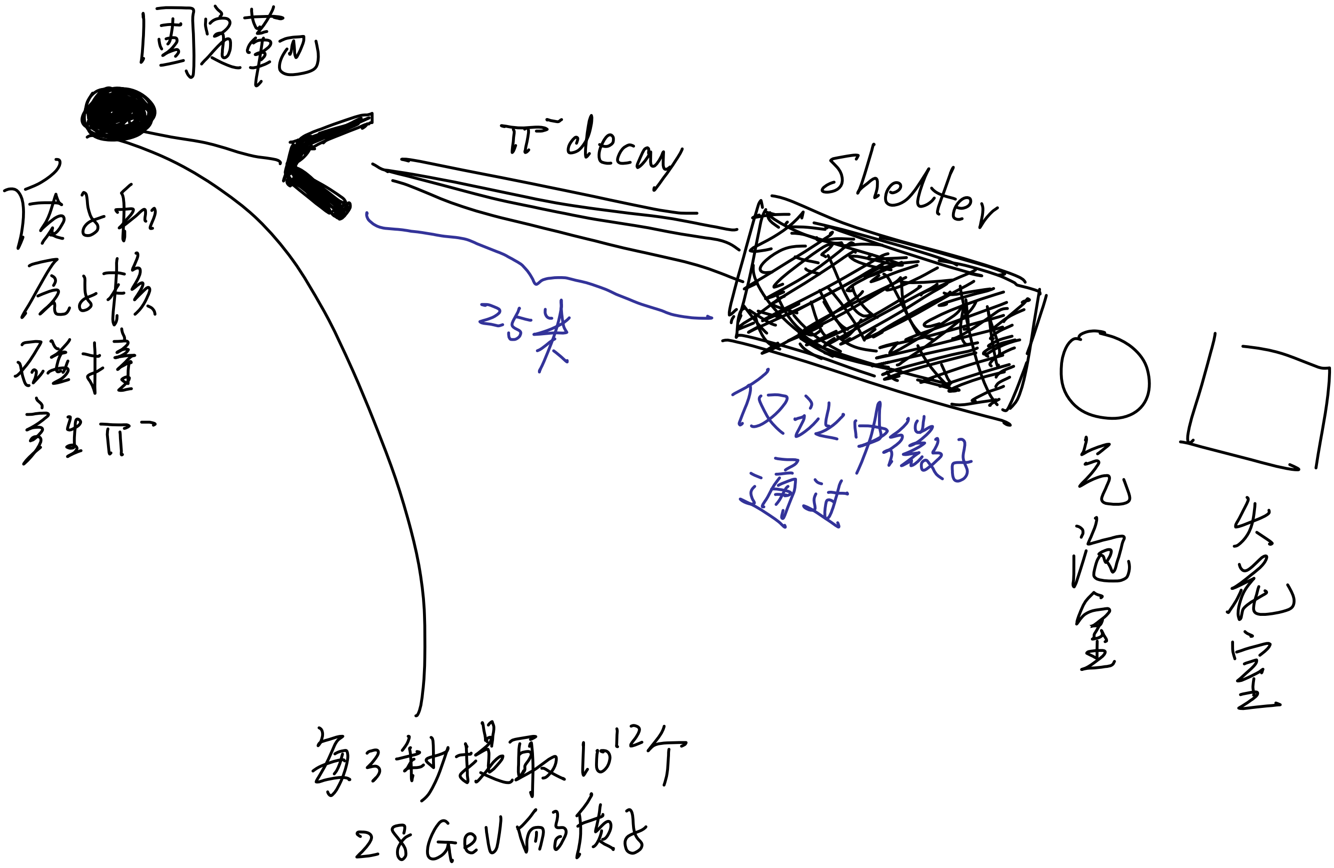
*) $\sin\theta_W$ 测量

1) 方法1: $m_W, m_Z \Longrightarrow \sin\theta_W$

$$\rho = \frac{m_W}{m_Z\cos\theta} = 1 \Longrightarrow \sin\theta_W = \sqrt{1-\frac{m_W^2}{m_Z^2}}$$

误差很大

2) 中微子散射实验

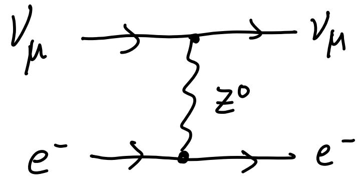


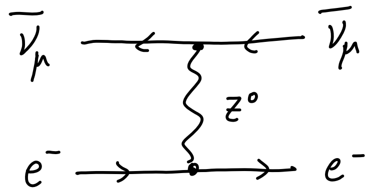
X) 轻子的中性流相互作用

考虑如下两个散射过程

$$\begin{cases} \nu_\mu e \to \nu_\mu e \\ \bar{\nu}_\mu e \to \bar{\nu}_\mu e \end{cases}$$

满足轻子数守恒
仅能由中性流诱导

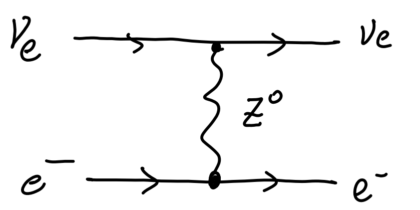


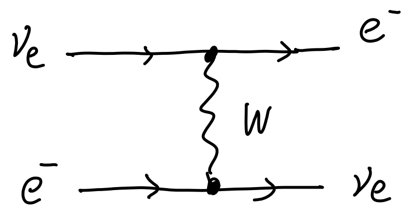


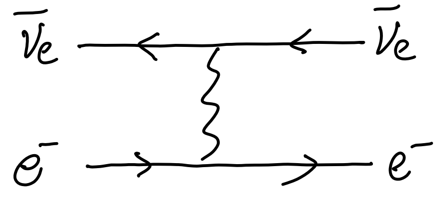
及另外两个过程

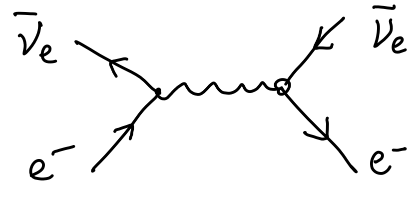
$$\begin{cases} \nu_e e \to \nu_e e \\ \bar{\nu}_e e \to \bar{\nu}_e e \end{cases}$$

带电流和中性流

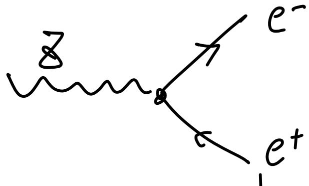








Note:



$i\gamma^\mu(V_e + a_e\gamma_5)$

$V_e = \frac{1}{2}(L_e + R_e)$

$a_e = \frac{1}{2}(L_e - R_e)$

标准模型中 $a_e = -\frac{1}{2}$, $V_e = -\frac{1}{2} + 2x_W$, $x_W = \sin^2\theta_W$

容易计算得

$$\sigma(\nu_\mu e \to \nu_\mu e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2+av+v^2}{3}\right)$$

$$\sigma(\bar{\nu}_\mu e \to \bar{\nu}_\mu e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2-av+v^2}{3}\right)$$

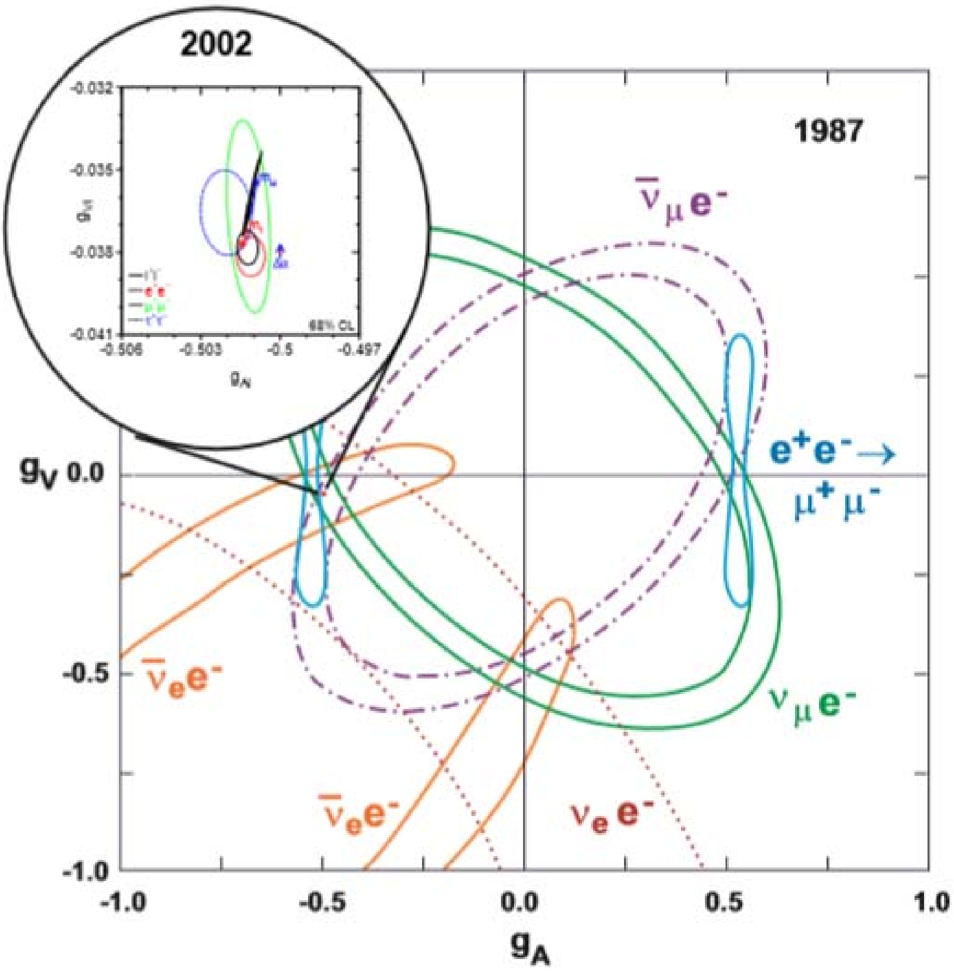
$$\sigma(\nu_e e \to \nu_e e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2+av+v^2}{3} + a+v+1\right)$$

$$\sigma(\bar{\nu}_e e \to \bar{\nu}_e e) = \frac{2G_F^2 mE}{\pi}\left(\frac{a^2-av+v^2+a+v+1}{3}\right)$$

其中 $a \equiv a_e$, $v \equiv v_e$

$\Rightarrow$ 上述4个过程的散射截面具有 $v \leftrightarrow a$ 对称性

$\nu_\mu e$ 和 $\bar{\nu}_\mu e$ 还有正负号任意性，但 $\nu_e e$ 和 $\bar{\nu}_e e$ 可消除此不确定性



ALEPH, DELPHI, L3, OPAL, SLD, the LEP EWWG, the SLD EW&HQ WG

Phys. Rept. 427, 257 (2006)

Fig 1.15

(*) 中微子实验允许

$a=0$, $v=-\frac{1}{2}$

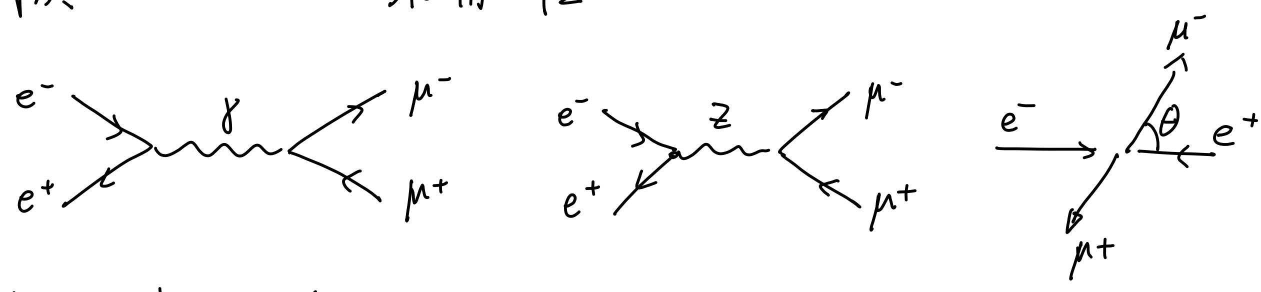
或

$a=-\frac{1}{2}$, $v=0$

*) 正负电子对撞实验

$$e^+e^- \to \mu^+\mu^-,\ \tau^+\tau^-,\ e^+e^-$$

解决了 $v \leftrightarrow a$ 的不确定性



忽略初末态轻子质量.

$$\frac{d\sigma}{d\cos\theta}(e^+e^-\to\mu^+\mu^-)$$

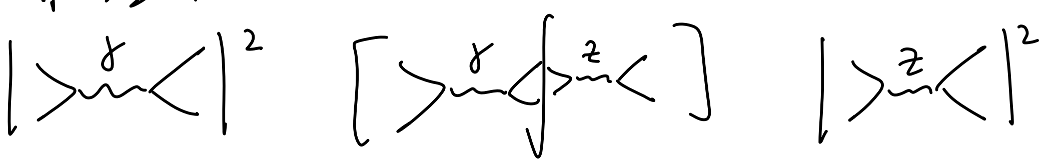
$$= \frac{\pi\alpha^2 Q_\mu^2}{2s}(1+\cos^2\theta)$$

$$-\frac{\alpha Q_\mu G_F M_Z^2 (s-M_Z^2)}{8\sqrt{2}\,[(s-M_Z^2)^2+M_Z^2\Gamma_Z^2]}\left[(R_e+L_e)(R_\mu+L_\mu)(1+\cos^2\theta)+2(R_e-L_e)(R_\mu-L_\mu)\cos\theta\right]$$

$$+\frac{G_F^2 M_Z^4 s}{64\pi\,[(s-M_Z^2)^2+M_Z^2\Gamma_Z^2]}\left[(R_e^2+L_e^2)(R_\mu^2+L_\mu^2)(1+\cos^2\theta)+2(R_e^2-L_e^2)(R_\mu^2-L_\mu^2)\cos\theta\right]$$

注:

a) 在不同质心系能量下,每一项贡献大小不同



$E_{cm}\lesssim 20\,\text{GeV}$ $20\,\text{GeV}\lesssim E_{cm}\lesssim 60\,\text{GeV}$ $60\,\text{GeV}\lesssim E_{cm}\sim M_Z$

当 $E_{cm}\ll m_Z$ 时, 仅有 $|M_\gamma|^2$ 和 $M_{\gamma,Z}$ 干涉项贡献, 而 $|M_Z|^2$ 可略

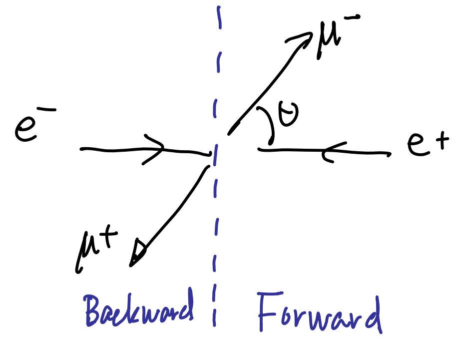
b) v 和 a 对散射截面贡献不同, 例如

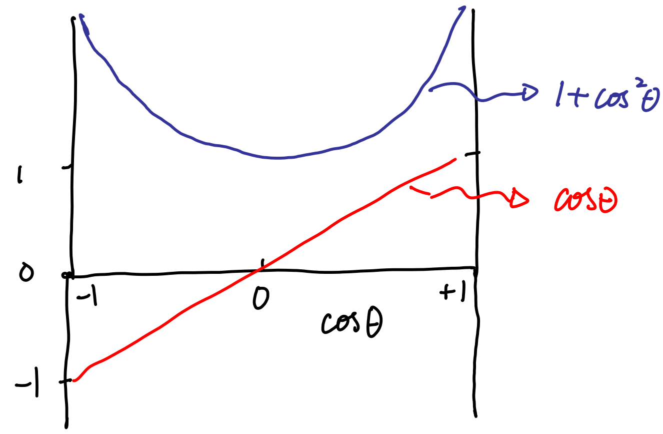
$$M_{\gamma,Z}\ \text{干涉项} \propto v_e v_\mu (1+\cos^2\theta) + 8 a_e a_\mu \cos\theta$$

$\Longrightarrow$ 末态轻子角分布的前后不对称性

*) A_{FB} (Forward-Backward Asymmetry)

在对撞上测量宇称破坏效应的物理观测量





$$A_{FB} \equiv \frac{\int_0^1 d\cos\theta \frac{d\sigma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\sigma}{d\cos\theta}}{\int_0^1 d\cos\theta \frac{d\sigma}{d\cos\theta} + \int_{-1}^0 d\cos\theta \frac{d\sigma}{d\cos\theta}} = \frac{\sigma_F(\cos\theta>0) - \sigma_F(\cos\theta<0)}{\sigma_{total}}$$

$$\frac{d\sigma}{d\cos\theta} \sim a + b\cos^2\theta + c\cos\theta$$

$$\Rightarrow \sigma_{tot} \sim 2a + \frac{2b}{3}, \quad \sigma_F - \sigma_B \sim c$$

$$\Rightarrow A_{FB} \sim \frac{c}{2a+\frac{2b}{3}}$$

在低能区,

$$\lim_{\frac{s}{m_Z^2}\to 0} A_{FB} = \frac{3G_F s}{16\pi\alpha Q_\mu \sqrt{2}} (R_e - L_e)(R_\mu - L_\mu)$$

$$\approx -6.7\times 10^{-5} \left(\frac{s}{1\,\mathrm{GeV}^2}\right)(R_e - L_e)(R_\mu - L_\mu)$$

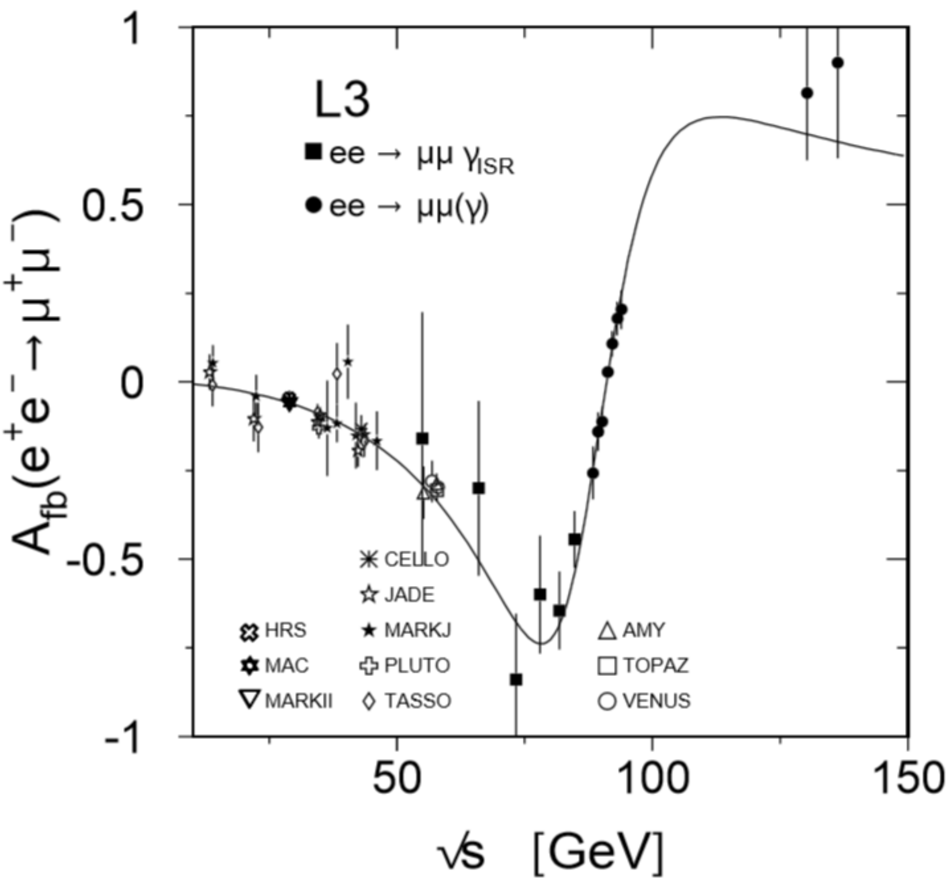
$$\approx -6.7\times 10^{-5} \left(\frac{s}{1\,\mathrm{GeV}^2}\right) \qquad \left(\begin{array}{l}\text{in SM} \\ R_e - L_e = R_\mu - L_\mu = +1\end{array}\right)$$

当 $\sqrt{s} = 50\,\mathrm{GeV}$ 时, $A \approx -17\%$

在一般性的理论中

$$A(s \ll m_Z^2) = -\frac{3G_F s a^2}{4\pi\alpha\sqrt{2}}$$

L3 collaboration, Phys. Lett. B 374, 331 (1996)



从一系列实验中，人们可以得到 $a_e a_\mu$

例，$\sqrt{s} = 29\ \text{GeV}$，$a_e a_\mu = 0.23 \pm 0.03$

$a_e a_\tau = 0.21 \pm 0.05$

In SM

$a_e a_\mu = a_e a_\tau = 0.25$

假设弱相互作用是 universal 的，

则有 $a_\ell \approx \sqrt{a_e a_\mu} \sim \sqrt{a_e a_\tau} \approx \pm 0.5$

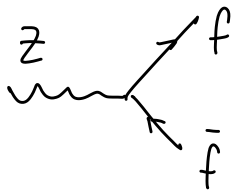
$\Rightarrow$ 和 ν_e 实验结果相比较，可得

$a \approx -\frac{1}{2},\ v \simeq 0$

*) $\sin^2\theta_W$ 测量

在固定靶实验 (Electron 是静止的)

$$\begin{cases} \nu_\mu e^- \longrightarrow \nu_\mu e^- & (NC) \\ \bar{\nu}_\mu e^- \longrightarrow \bar{\nu}_\mu e^- & (NC) \end{cases}$$



$$\frac{ig}{2\cos\theta_W}\gamma_\mu[g_V - g_A\gamma_5]$$

f	g_V	g_A
ν	$\frac{1}{2}$	$\frac{1}{2}$
e^-	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}$

$$\sigma_{tot} = \frac{G_F^2 m_e E_\nu}{2\pi}\left(A+\frac{B}{3}\right),$$

E_ν : lab Energy of ν

$m_e \lll E_\nu \ll M_Z$

$$\begin{cases} A = (g_V+g_A)^2 \\ B = (g_V-g_A)^2 \end{cases} \quad \text{for } \nu_\mu e^- \to \nu_\mu e^-$$

$$\begin{cases} A = (g_V-g_A)^2 \\ B = (g_V+g_A)^2 \end{cases} \quad \text{for } \bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$$

The ratio of

$$\frac{\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{\sigma(\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-)} \sim f(\sin^2\theta_W)$$

$$\Longrightarrow \sin^2\theta_W = 0.23$$

*) Z-boson 衰变宽度

$\Gamma_Z \simeq 2.5\ \mathrm{GeV}$

$Br(Z^0 \to \nu_e\bar{\nu}_e) \sim 6.6\% \quad \times\ N_\nu = 3 \quad (\nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau)$

$Br(Z^0 \to e^+e^-) \sim 3.3\% \quad \times\ 3 \quad (\mu^+\mu^-, \tau^+\tau^-)$

$Br(Z^0 \to u\bar{u}) \sim 12\% \quad \times\ 2 \quad (c\bar{c})$

$Br(Z^0 \to d\bar{d}) \sim 15\% \quad \times\ 3 \quad (s\bar{s}, b\bar{b})$

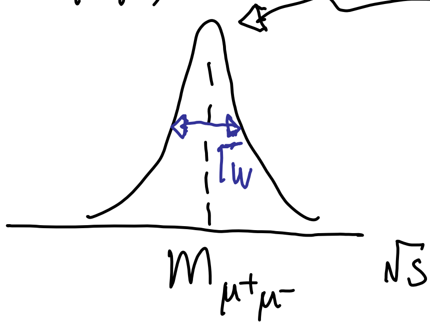
Z 可以衰变到一对正反中微子，但我们无法直接观测到 $\nu\bar{\nu}$。

那我们如何知道在 Z 衰变末态中有多少种中微子呢？ $N_\nu = ?$

1) line-shape method

We can easily do this measurement near Z^0-peak

$\frac{d\sigma}{ds}(e^+e^- \to \mu^+\mu^-)$



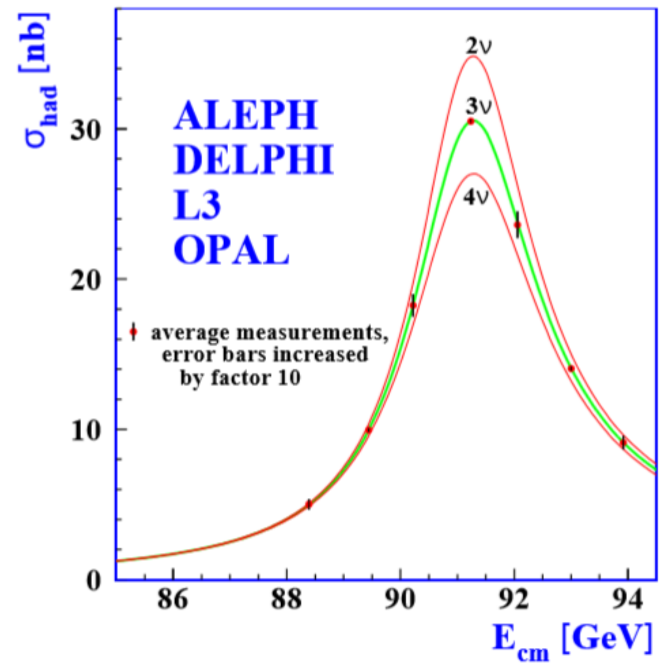
* $M_{\mu^+\mu^-}$ 不变质量峰高度 $\sim \frac{1}{\Gamma_Z^2}$

Height $\to \Gamma_Z \to \Gamma_\nu \to N_\nu$

* N_ν 大则 Γ_W 大

用 Breit-Wigner 共振态形状来拟合实验测得的 $M_{\mu^+\mu^-}$ 分布

$\Longrightarrow M_Z, \Gamma_Z$ 和 N_ν



$\Longrightarrow N_\nu = 3$

仅有3个无质量中微子

也叫 "active neutrino"

hep-ex/0509008
(2006年)

Fig 1.12 和 Fig 1.13

2) 共振态的产生和衰变截面是

$$1+2 \longrightarrow R \longrightarrow \text{out}$$

$$\sigma_{BW}(E) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \underbrace{\frac{C_R}{C_1 C_2}}_{\text{color factors}} \frac{\pi}{k^2} \frac{Br^{in} Br^{out} \Gamma_{tot}^2}{(E-E_R)^2 + \frac{\Gamma_{tot}^2}{4}}$$

k : c.m. momentum

E : energy

Br : Branching Ratio

For Z-peak,

$$\sigma_{BW}^{peak}(s) \simeq (12\pi) \frac{\Gamma_{Z\to e^+e^-} \Gamma_{Z\to f\bar{f}}}{(s-M_Z^2)^2 + M_Z^2 \Gamma_Z^2} (1-\delta_{rad})$$

Radiative Correction factor

$$\equiv \sigma_f^0 (1-\delta_{rad})$$

$$\Gamma_Z = N_\nu \Gamma_\nu + 3\Gamma_{ee} + \Gamma_{had}$$

3) 另一种作法是测量所有可观测末态 $Z\to f\bar{f}$ $(f\neq\nu)$，得

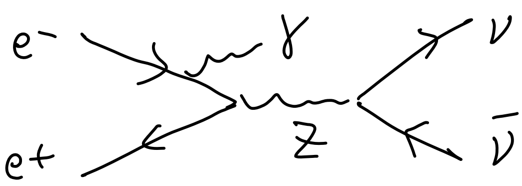
$$\Gamma_{vis} \equiv \sum_{f\neq\nu} \Gamma(Z\to f\bar{f})$$

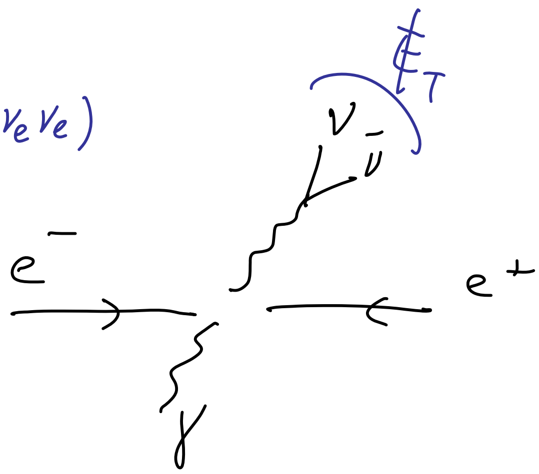
再从 Γ_Z^{tot} 中扣除 Γ_{vis}，从而有

$$N_\nu = \frac{\Gamma_{tot} - \Gamma_{vis}}{\Gamma(Z\to\nu_e\bar{\nu}_e)}$$

4) 单光子 + 大 $\not{E}_T$

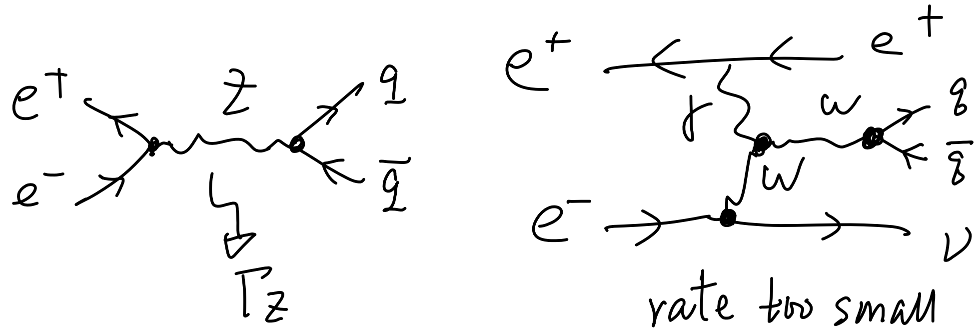
$$\sigma(\gamma + \not{E}_T) = N_\nu \, \sigma(\gamma + Z\to\nu_e\bar{\nu}_e)$$



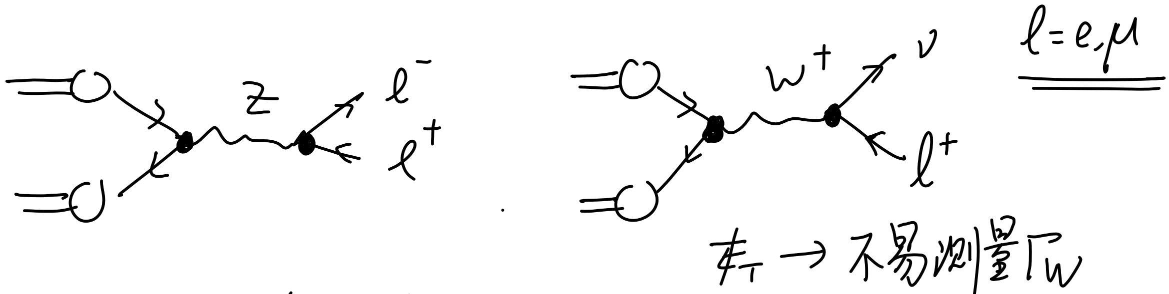


*) Γ_Z 和 Γ_W

a) Z-boson 可以在 e^+e^- 对撞机上产生，但 $W^\pm$ 却很难



b) 强子对撞机上仅有轻子衰变末态可用



但可以利用比值方法

$$\frac{\sigma(p\bar{p}\to W^+\to l^+\nu)}{\sigma(p\bar{p}\to Z\to l^+l^-)}=\frac{\sigma(p\bar{p}\to W^+)\,Br(W^+\to l^+\nu)}{\sigma(p\bar{p}\to Z)\,Br(Z^0\to l^+l^-)}$$

$$=\underbrace{\frac{\sigma(p\bar{p}\to W^+)}{\sigma(p\bar{p}\to Z)}}_{\substack{\text{calculated}\\ \text{(PDFs)}}}\times\frac{\Gamma_Z}{\Gamma_W}\times\underbrace{\frac{\Gamma(W^+\to l^+\nu)}{\Gamma(Z\to l^+l^-)}}_{\text{calculated}}$$

$\Rightarrow$ 可知 $\frac{\Gamma_Z}{\Gamma_W}$

1) 利用LEP测得 $\Gamma_Z \Rightarrow \Gamma_W$

2) 假设标准模型耦合顶点，则此比值给出 N_ν。