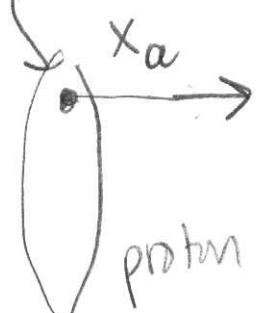


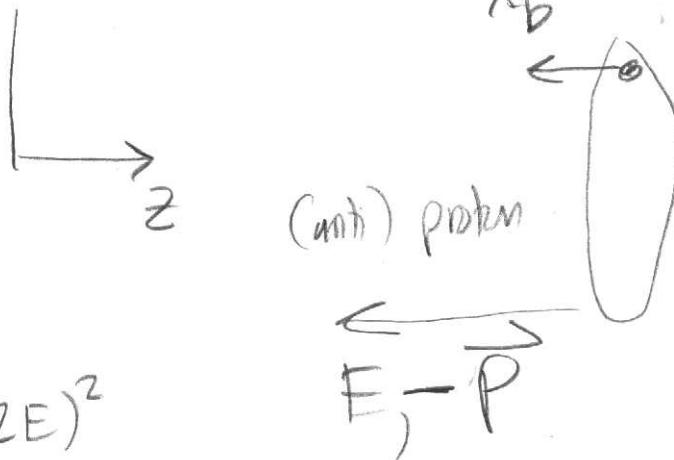
(anti) parton

# Proton - Proton Collisions

parton of interest, a

$$\vec{E}, \vec{P}$$

$$s = (2E)^2$$



a, b :  $g, u, d, \bar{u}, \bar{d}, s, \bar{s}, \dots$

$$|\vec{p}_1| = |\vec{p}_2| \quad \text{but not for}$$

$$x_1 \vec{p}_1 + x_2 \vec{p}_2$$

4-vectors

parton a

$$x_a E(1, 0, 0, 1)$$

$$b : x_b E(1, 0, 0, -1)$$

$$p_a + p_b = ((x_a + x_b)E, 0, 0, (x_a - x_b)E)$$

$$\begin{aligned} \hat{s} &= (p_a + p_b)^2 = [(x_a + x_b)^2 - (x_a - x_b)^2] E^2 \\ &= 4x_a x_b E^2 \end{aligned}$$

$$\hat{s} = x_a x_b s \quad \sqrt{\hat{s}} = \sqrt{x_a x_b} \sqrt{s}$$

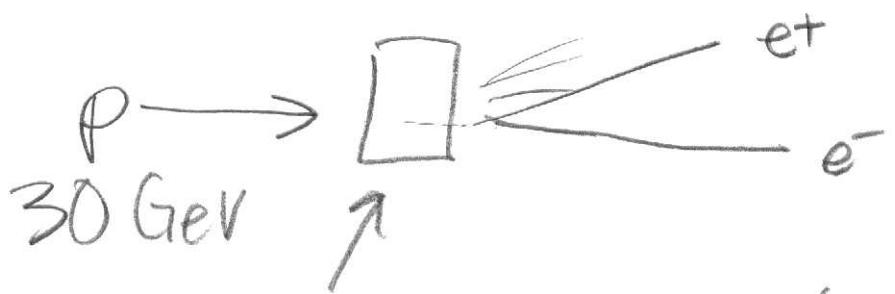
Proposal Time

variety available

notes: 1) momentum transverse to the beam neglected.  
 $(\approx \text{OK})$

2) The system with  $M = \sqrt{s}$  is usually born with a boost, when  $x_a \neq x_b$

The most famous "benchmark" process is "Drell-Yan"  $\Rightarrow$  Discovery of the J at Brookhaven  $\sim 1974$



Target

Beryllium

$p p(\text{or} n) \rightarrow X e^+ e^-$   
 $\nu^+ \nu^-$

called

"Drell-Yan"

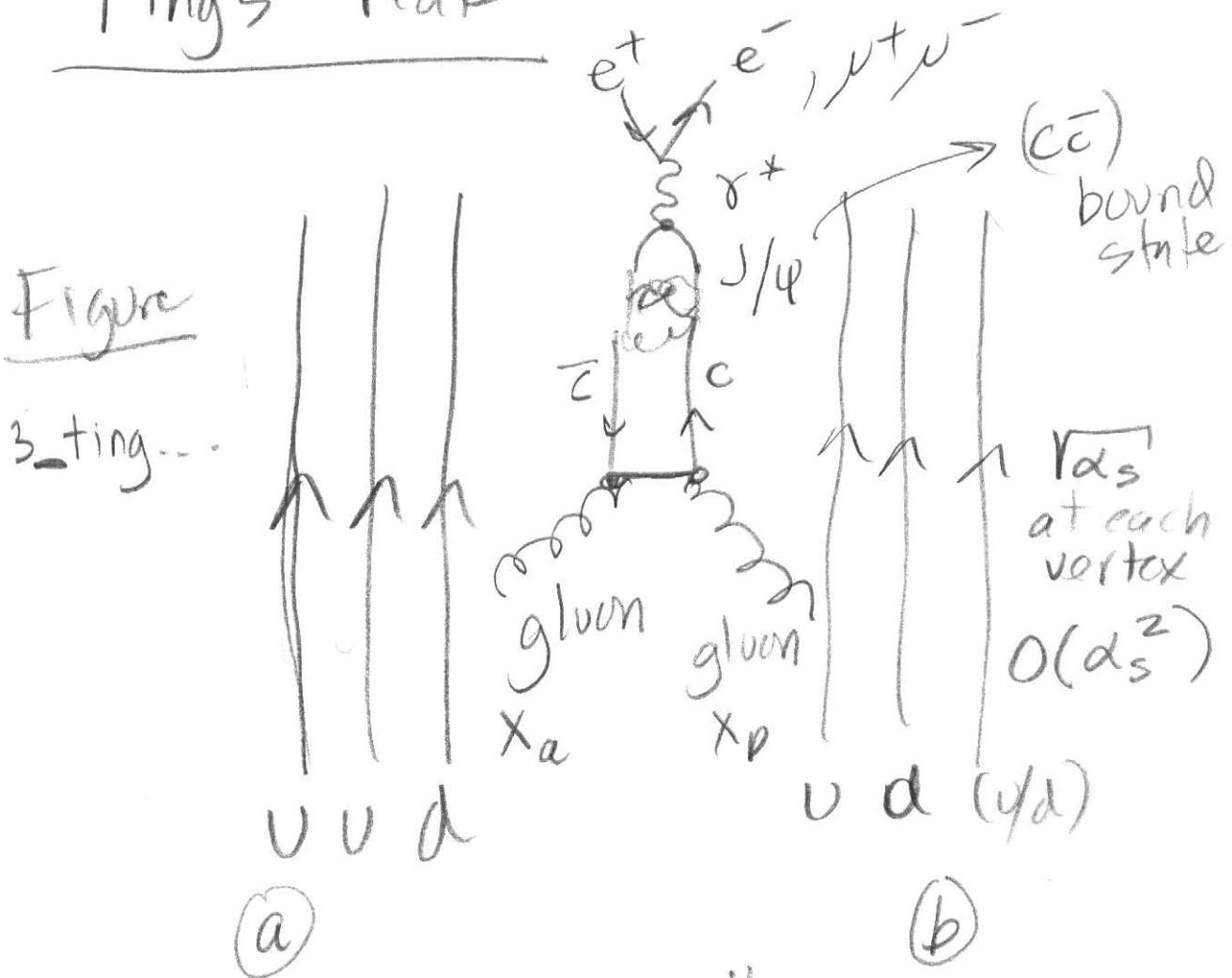
1974

Ting (unexpectedly) discovered the  $J/\psi \approx e^+ e^- \rightarrow \psi \rightarrow \text{final state}$

# Ting's Peak

Figure

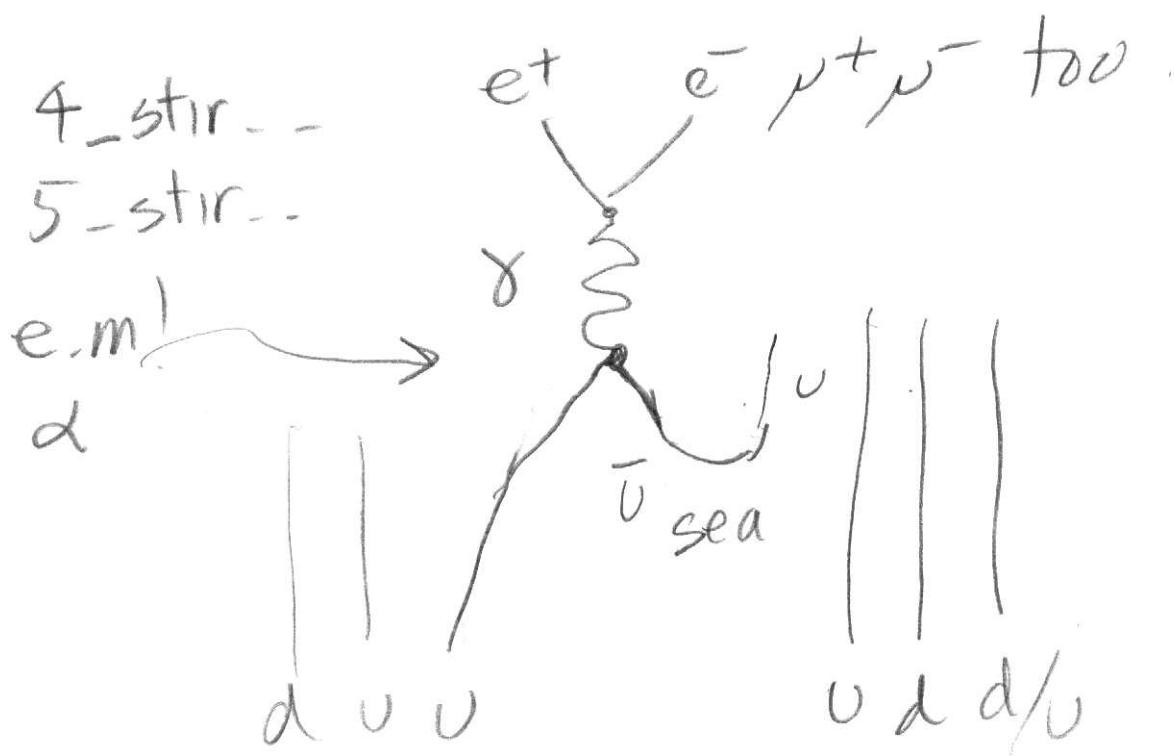
3-ting...



(a)

(b)

"Classic Drell-Yan"



# General Formula For X-section

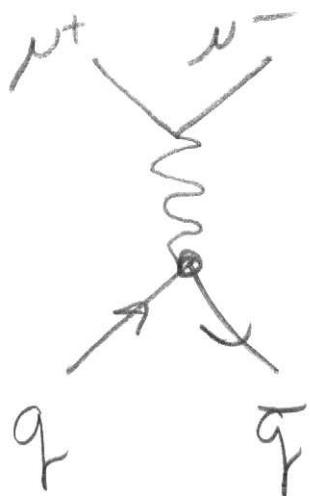
$$\sigma(p\bar{p} \rightarrow X)$$

$$= \iint dx_a dx_b f_1(x_a) f_2(x_b) \sigma(a+b \rightarrow X)$$

structure  
functions for  
partons involved

Frequently,  $\sigma(a+b \rightarrow X)$  is just a function of  $\hat{s}$

example: Classic Drell-Yan



$$\sigma = \frac{4\pi\alpha^2 e_q^2}{3 \hat{s}} \frac{1}{2}$$

$$\hat{s} = M_{\nu\nu}^2$$

$$\sigma(p\bar{p} \rightarrow X \nu \bar{\nu}) = \frac{4\pi\alpha^2}{3M_{\nu\nu}^4} \iint dx_a dx_b \delta(\sqrt{x_a x_b} - \sqrt{\hat{s}}) \sum_a e_a^2 f_1(x_a) f_2(x_b)$$

"electromagnetic luminosity"

Can also do for:

$$gg \rightarrow X, \quad gq \rightarrow X$$

$$q\bar{q} \rightarrow X \quad (\text{via strong})$$

6-lumipp.pdf      Discuss

AMPAQ  
22-141 50 SHEETS  
22-142 100 SHEETS  
22-144 200 SHEETS



Meaning: "Instantaneous Luminosity"

$$\text{Tevatron} \simeq 3 \cdot 10^{32} \frac{1}{\text{cm}^2 \text{s}}$$

$$\begin{aligned} \text{in } 10^7 \text{ s} & \simeq 3 \cdot 10^{39} \frac{1}{\text{cm}^2 / \text{year}} \\ (\text{1 year}) & = 3 \frac{1}{\text{fb}} / \text{y} \quad \text{or} \quad 3000 \frac{1}{\text{pb}} / \text{y} \end{aligned}$$

$$10^{-24} \text{ cm}^2 = 1 \text{ barn}$$

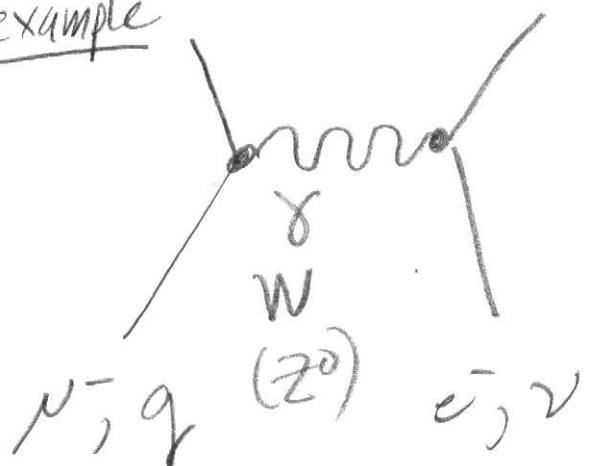
$$\begin{aligned} 10^{-34} \text{ cm}^2 & = 10^{-15} \text{ barn} = 1 \text{ fb} \\ & = 1000 \text{ pb} \end{aligned}$$

1 year  $\rightarrow$  Tev gets to  $\simeq 1 \text{ TeV}$

LHC:  $10^{34} \rightarrow 30 \times$  more than TeV  
"reach"  $\simeq 6-8 \text{ TeV}$

To go further, must understand parton-parton cross sections

example



Let's now always work in CM frame.

$$a+b \rightarrow c+d$$

$$m_a m_b \rightarrow m_c m_d$$

elastic:  $m_a = m_c, m_b = m_d, \text{etc.}$

Golden Rule:

$$d\sigma = \frac{2\pi}{\lambda v_i} |M_{if}|^2 \rho_f$$

$\rho_f$   $\rightarrow$  density of final states

ultrarelativistic limit:  $v_i = c$   
(relative)

$$\rho_f = -\frac{\rho_e^2 d\omega_f}{(2\pi\hbar)^3} \frac{d\rho_e}{dE} \quad E = \text{total energy}$$

$\hbar = 1 \quad = \sqrt{s} \text{ c.m}$

$$p_f = E/2$$

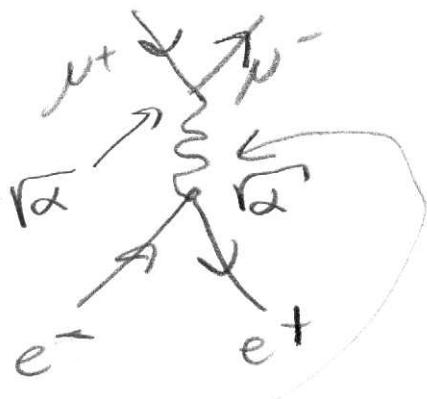
$$\frac{dp_f}{dE} = \frac{1}{2}$$

$$S_f = \frac{(E/2)^2 d\Omega}{(2\pi)^3} \cdot \frac{1}{2} = \frac{E^2}{2^6 \pi^3}$$

$$\frac{d\sigma}{d\Omega} = \frac{2\pi}{2^6 \pi^3} |M_{if}|^2 E^2$$

$$= \frac{1}{2^5 \pi^2} |M_{if}|^2 E^2$$

First look at  $e^+ e^- \rightarrow \mu^+ \mu^-$



$$M_{if} = \frac{4\pi \alpha}{s} < q^2, \text{ really}$$

NEGLECTING  
ANGULAR  
DEPENDENCE

$$(\sqrt{s}, 0, 0, 0)$$

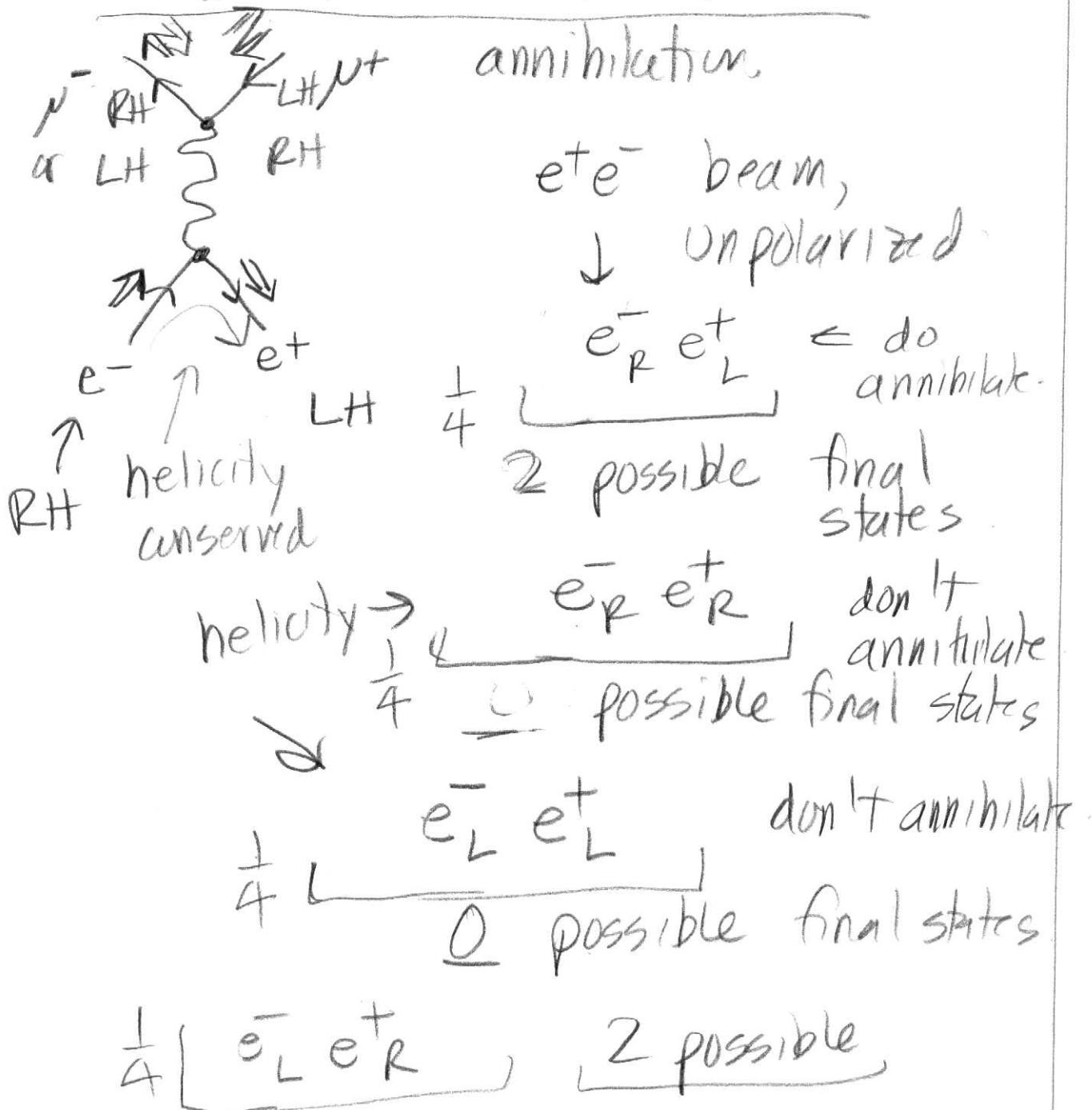
center of  
momentum

$$q^2 = s = E^2$$

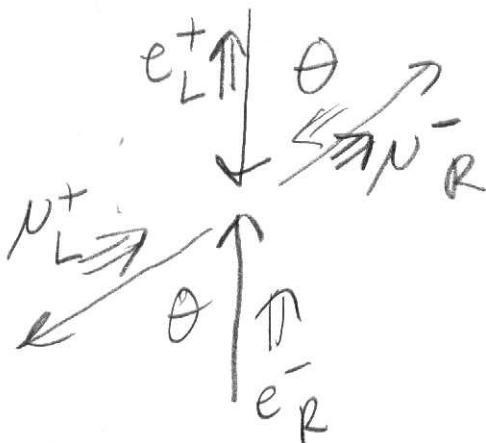
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \frac{\alpha^2}{E^4} E^2$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \frac{\alpha^2}{E^2} = \frac{1}{2} \frac{\alpha^2}{s}$$

# ANGULAR DEPENDENCE



$\rightarrow$  average over initial  
 $\rightarrow$  sum over final



$$\propto |d_{11}(\theta)|^2$$

$$\propto |\frac{1}{2}(1+\cos\theta)|^2$$



$$\propto |\frac{1}{2}(1-\cos\theta)|^2$$

They don't interfere (distinguishable)

contribute

$$\frac{1}{4}(1+\cos\theta)^2 + \frac{1}{4}(1-\cos\theta)^2$$

$$= \frac{1}{2}(1+\cos^2\theta)$$

$$\frac{2}{4} \cdot 2 \cdot \frac{1}{2}(1+\cos^2\theta)$$

↑

↗  
average  
over  $m$

sum  
over  
final

$$= \frac{1}{2}(1+\cos^2\theta)$$

so,

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} \frac{\alpha^2}{s} (1 + \cos^2 \theta)$$

## CROSSING

$$a + b \rightarrow c + d \quad ? \quad \text{Mif}$$



add antimatter to both sides!  
 $(-q \text{ momentum})$

$$a + \cancel{(b\bar{b})} \rightarrow \bar{b} + c + d$$

$$a \rightarrow \bar{b} + c + d \quad \} \text{ same matrix element}$$

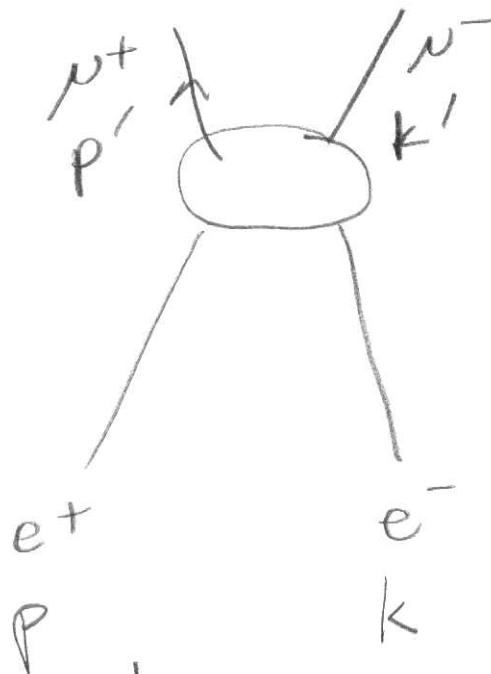
$$a + \bar{c} \rightarrow \bar{b} + d \quad \text{same!}$$

What is different?

$\Rightarrow$  Phase Space

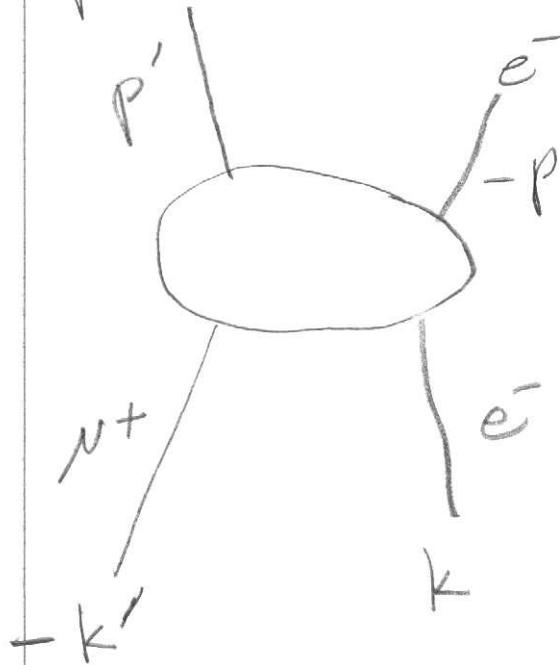
$$\underbrace{\bar{c} + \bar{d}}_{\text{heavy}} \rightarrow \underbrace{\bar{a} + \bar{b}}_{\text{light}}$$

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



$$\begin{aligned} s &= (p+k)^2 \\ t &= (k-k')^2 \\ u &= (p'-k)^2 \end{aligned}$$

CROSS



$$\begin{aligned} s_c &= (-k'+k)^2 = + \\ t_c &= (-p-k)^2 \\ &= (p+k)^2 = s \\ u_c &= (p'-k)^2 = u \end{aligned}$$

$$e^- \bar{\nu}^+ \rightarrow e^- \bar{\nu}^+$$

$$\mathcal{M}(e^+ e^- \rightarrow \mu^+ \mu^-) = f(s, t, u)$$

$$\text{then } \mathcal{M}(e^- \bar{\nu}^+ \rightarrow e^- \bar{\nu}^+) = f(t, s, u)$$