$$\Gamma = \frac{1}{8\pi}\,\frac{1}{m_a}\,\frac{1}{m_a}\,|M|^2\,|\vec{p}|$$ Decay width

in a ref. frame.

$a \to b + c$

$M^2 = |\langle f|H_I|i\rangle|^2$

$p_b = p_c = p$

$p = |\vec{p}|$

$$\Gamma = \frac{1}{\tau}$$

correct from dimensional analysis

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

Fundam. particles

$$\begin{array}{cccc} & 1^{st} & 2^{nd} & 3^{rd} \\ \begin{array}{c}-1\\0\end{array} & \begin{pmatrix} e^- \\ \nu_e \end{pmatrix} & \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} & \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \end{array}$$ leptons

Q_e $$\begin{array}{cccc} \begin{array}{c}+\frac{2}{3}\\-1/3\end{array} & \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} t \\ b \end{pmatrix} \end{array}$$ quarks

$\longrightarrow$ mass

leptons: EM, weak

quarks: EM, weak, strong

Nature: hadrons: composite particles of quarks.

Baryons: $q_1 q_2 q_3$

Mesons: $q_1 \bar{q}_2$

e^+: anti-particle of e^-

$\bar{u}$ antiparticle of u: $Q_{\bar{u}} = -2/3$

$$\begin{pmatrix} \bar{\nu}_e \\ e^+ \end{pmatrix} \begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix} \begin{pmatrix} \bar{\nu}_\tau \\ \tau^+ \end{pmatrix}$$

$$\begin{array}{cccc} \begin{array}{c}+1/3\\-2/3\end{array} & \begin{pmatrix} \bar{d} \\ \bar{u} \end{pmatrix} & \begin{pmatrix} \bar{s} \\ \bar{c} \end{pmatrix} & \begin{pmatrix} \bar{b} \\ \bar{t} \end{pmatrix} \end{array}$$ antiquarks

$\mu^- \to e^- \bar{\nu}_e \nu_\mu$
$\pi^- \to \mu^- \bar{\nu}_\mu$ } unstable particles.
$n \to p e^- \bar{\nu}_e$

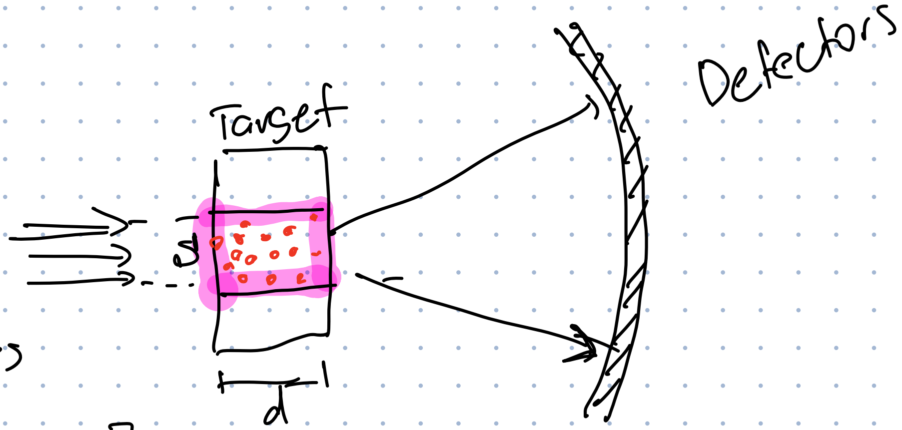
$\pi^- : \bar{u} d$

$Q = -\frac{2}{3} + \left(-\frac{1}{3}\right) = -1$

$\alpha = {}^4_2He \quad Q = +2$

collision:

beam of particles



$a + b \longrightarrow c + d + \cdots + ?$

$$\frac{dN_r}{dt} \equiv \frac{N_{reactions}}{time} = \sigma \frac{dN_p}{dt} n_b d$$

Cross section.

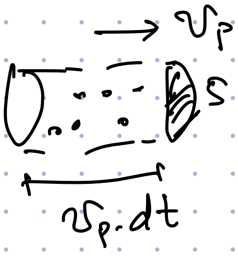
$(n_b) = L^{-3} \qquad \frac{\#}{Volume}$

$[d] = L$

Has to do with nature of interaction.

$$\frac{dN_r}{dt} = \sigma \cdot \frac{dN_p}{dt} \underbrace{n_b \cdot d \, S}_{} \cdot \frac{1}{S} = \sigma \, N_B \underbrace{\frac{dN_p}{dt \cdot S}}_{\Phi_p}$$

N_B : number of targets.



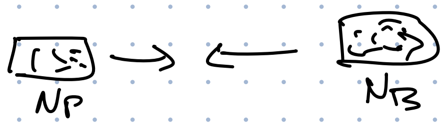
$\Phi_p = n_p \cdot v_p$

$$\underbrace{\frac{1}{N_B} \frac{dN_r}{dt}}_{} = \sigma \cdot \Phi_p$$

$\propto$ probability of interaction.

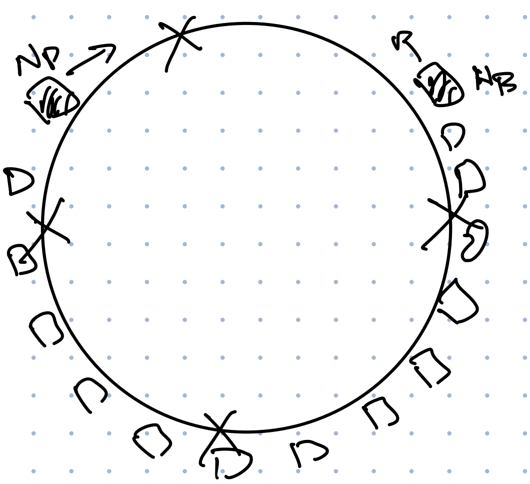
$\Gamma(i \to f)$ prob./unit time

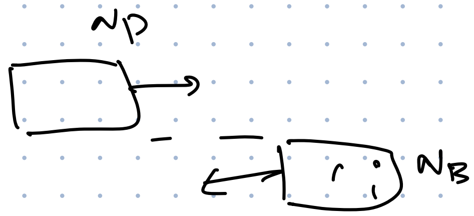
Colliding beams:



$10^{11} p$

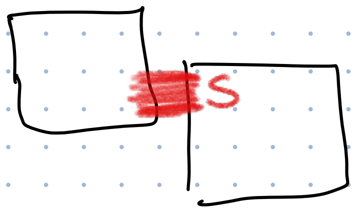
$\sim \mu m - cm$





$$\frac{dN_r}{dt} = \sigma N_B \Phi_p = \sigma N_B \frac{N_p}{S} f_{rev}$$

$$= \underbrace{\sigma}_{\text{physics of interaction.}} \underbrace{\frac{N_B N_p}{S} f_{rev}}_{\text{machine.}}$$



$$\frac{dN_r}{dt} = \sigma \cdot \mathcal{L}$$

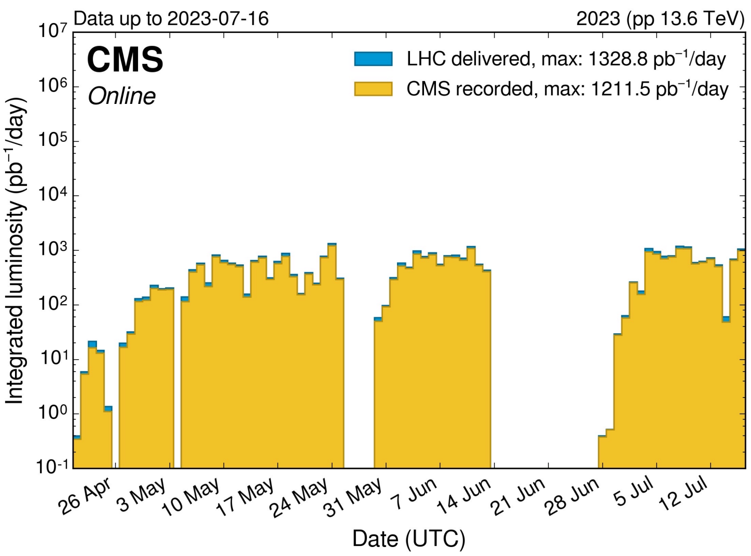
↳ instantaneous luminosity of the machine.

σ ↳ cross section. cm^2 L^2

$$1b = 10^{-24}\, cm^2 = 10^{-28}\, m^2$$

$$[\mathcal{L}] = cm^{-2} s^{-1} = b^{-1} s^{-1}$$

$$N_{events} = \frac{dN_r}{dt}\Delta t = \sigma \cdot \underbrace{\mathcal{L}_{inst} \cdot \Delta t}_{\text{integrated luminosity.}} = \sigma \cdot L$$

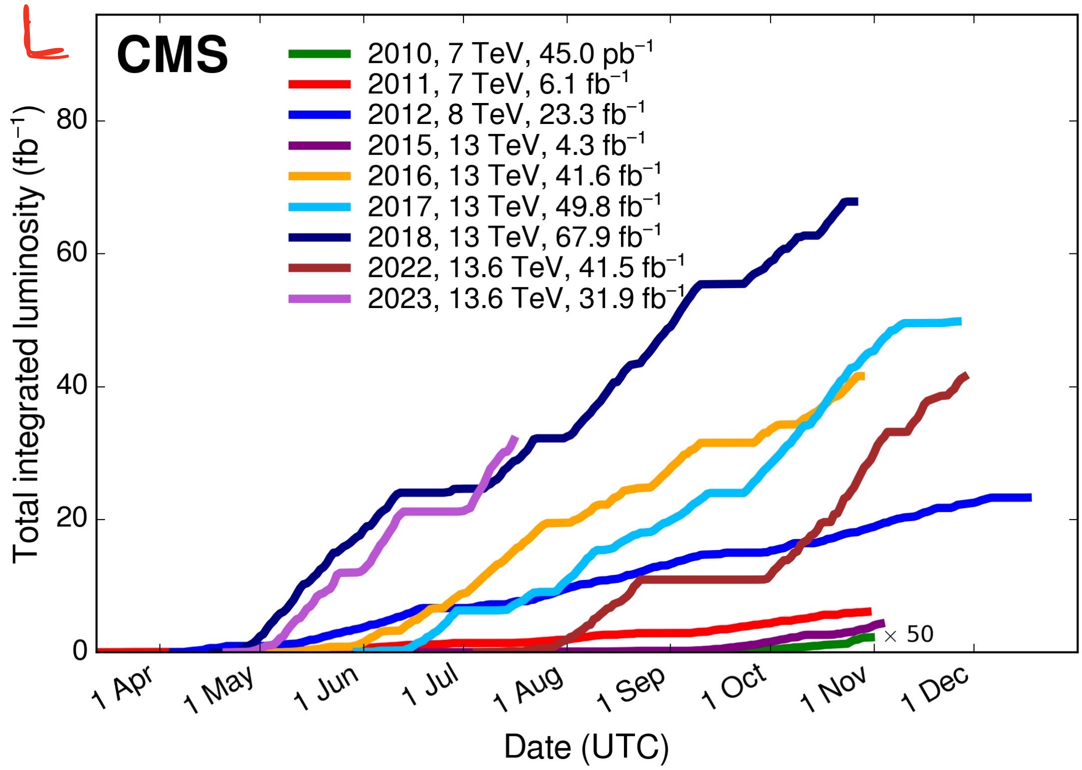


$$pb = 10^{-12}\, b$$

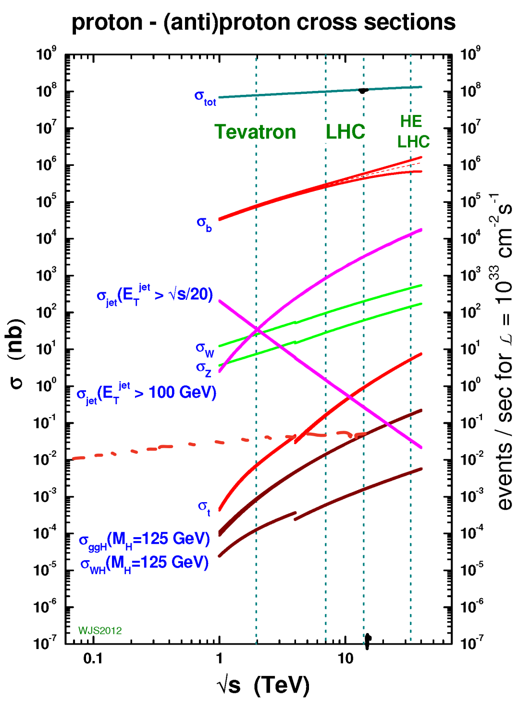
$[\sigma]$ barn.

$[L]$ $barn^{-1}$

L



$L = \mathcal{L} \cdot \Delta t$



$P_1 = (E, \vec{p})$ $\quad$ $P_2 = (E, -\vec{p})$

$p \longrightarrow \quad \longleftarrow p$ symm. collider.

$\sqrt{s} = \sqrt{(P_1 + P_2)^2}$

$= \sqrt{(2E)^2} = 2E$

@ LHC now: $E = 6.5$ TeV

$\sigma_{tot} = 10^8$ nb.

$L = 1\,nb^{-1}$

$\Rightarrow$ # events $= 10^8$

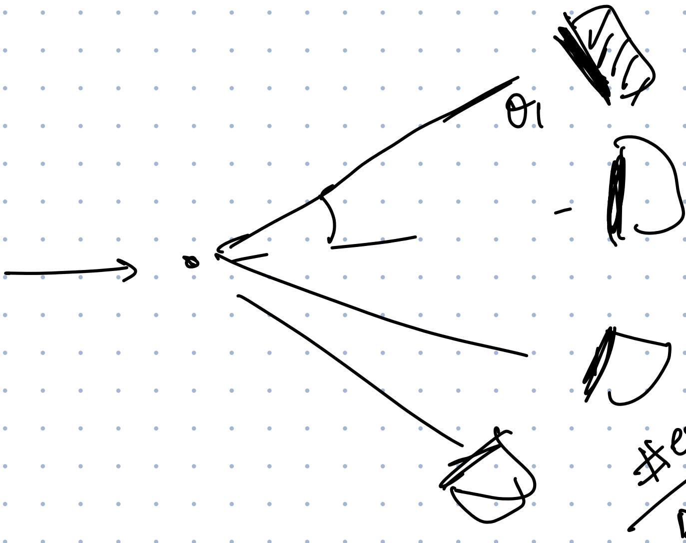
$\sigma(p+p \longrightarrow H+X) = 10^{-2}$ nb.

$\Rightarrow$ 1 Higgs boson $\Rightarrow$ 100 nb^{-1} data.

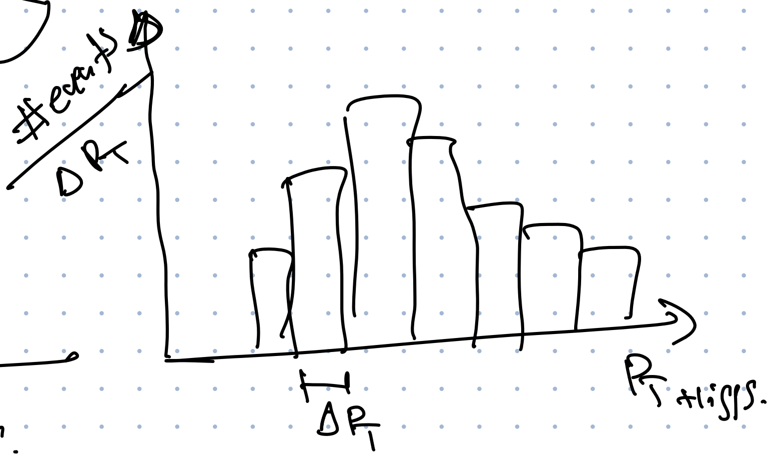
$\sigma(p+p \longrightarrow H+X)$ inclusive cross section.

$\sigma(p+p \longrightarrow p+p+p+\bar{p})$: Exclusive cross section.

Detectors.



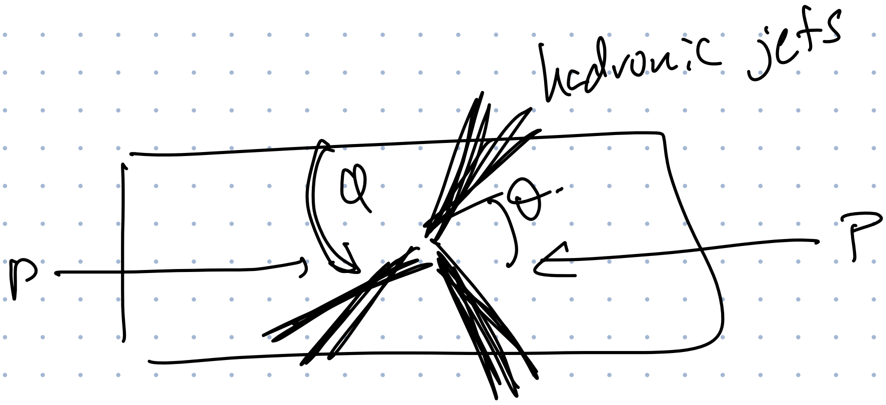
$$\left.\begin{array}{c}\frac{dN}{d\theta}\\[6pt]\frac{dN}{d\Omega}\end{array}\right\}\ \text{Differential cross section.}$$

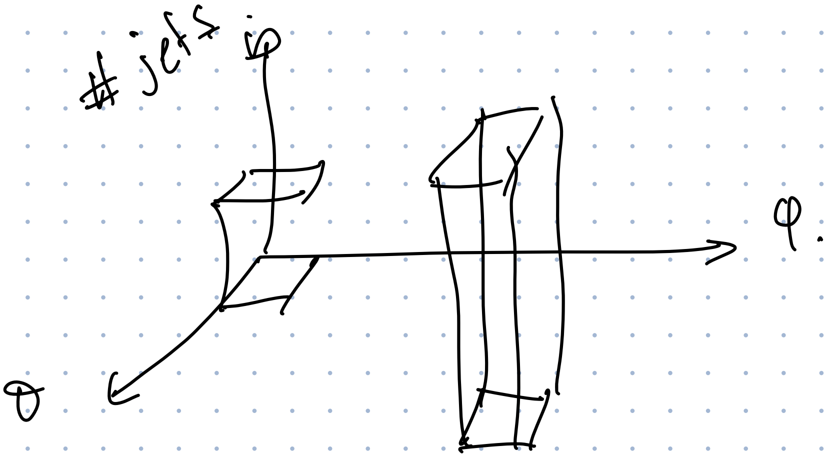


$p+p \rightarrow H+X.$

$$\frac{d\sigma}{dp_{T\,H}} = \frac{\#\,\text{Higgs}}{\Delta P_{T\,\text{Higgs}}}$$

$$\frac{dN}{dp_T\, d\theta\, d\varphi}$$





$$\frac{dN_{jets}}{d\theta\, d\varphi}.$$

$p+p \rightarrow H+X$

$\quad \hookrightarrow Z^0\ Z^0$

$\qquad\quad \hookrightarrow \ell^+\ell^- \qquad \ell^- = e^-, \mu^-, \tau^-$

$\qquad \hookrightarrow \ell^+\ell^-$

$$N(p+p \rightarrow H+X \rightarrow 4\ell+X) = \sigma_H \cdot L \times BF(H\rightarrow ZZ) \times BF(Z\rightarrow \ell\ell) \times BF(Z \rightarrow \ell\ell)$$

$a \rightarrow$ Channel 1.

Chan 2

$\vdots$

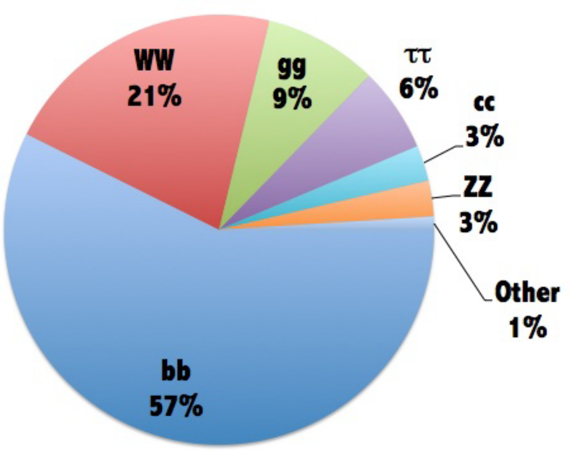
$H \rightarrow$

$b\bar{b}$	Γ_1
$c\bar{c}$	Γ_2
ZZ	Γ_3
$\gamma\gamma$	Γ_4

$$\frac{1}{\tau} = \Gamma_{tot} = \sum_i \Gamma_i \qquad BF_i = \frac{\Gamma_i}{\Gamma_{tot}}$$

$$BF(H \to ZZ) = \frac{\Gamma(H \to ZZ)}{\sum_i \Gamma_i (H \text{ decays})}$$

Higgs decays at m_H=125GeV



Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-		(3.363 $\pm$0.004) %	
Γ_2	$\mu^+\mu^-$		(3.366 $\pm$0.007) %	
Γ_3	$\tau^+\tau^-$		(3.370 $\pm$0.008) %	
Γ_4	$\ell^+\ell^-$	[a]	(3.3658$\pm$0.0023) %	
Γ_5	invisible		(20.00 $\pm$0.06) %	
Γ_6	hadrons		(69.91 $\pm$0.06) %	
Γ_7	$(u\bar{u}+c\bar{c})/2$		(11.6 $\pm$0.6) %	
Γ_8	$(d\bar{d}+s\bar{s}+b\bar{b})/3$		(15.6 $\pm$0.4) %	
Γ_9	$c\bar{c}$		(12.03 $\pm$0.21) %	
Γ_{10}	$b\bar{b}$		(15.12 $\pm$0.05) %	
Γ_{11}	$b\bar{b}b\bar{b}$		(3.6 $\pm$1.3) $\times 10^{-4}$	
Γ_{12}	ggg		< 1.1 %	CL=95%
Γ_{13}	$\pi^0\gamma$		< 5.2 $\times 10^{-5}$	CL=95%
Γ_{14}	$\eta\gamma$		< 5.1 $\times 10^{-5}$	CL=95%
Γ_{15}	$\omega\gamma$		< 6.5 $\times 10^{-4}$	CL=95%
Γ_{16}	$\eta'(958)\gamma$		< 4.2 $\times 10^{-5}$	CL=95%
Γ_{17}	$\gamma\gamma$		< 5.2 $\times 10^{-5}$	CL=95%
Γ_{18}	$\gamma\gamma\gamma$		< 1.0 $\times 10^{-5}$	CL=95%
Γ_{19}	$\pi^\pm W^\mp$	[b]	< 7 $\times 10^{-5}$	CL=95%

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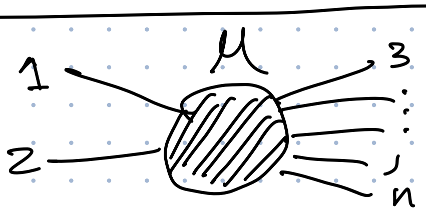
$$\# \; p+p \to H+X \to (4\mu)+X = \sigma \cdot L \cdot (3\times10^{-2})(3\times10^{-2})(3\times10^{-2})$$

$$\simeq \sigma \times L \times 3 \times 10^{-5}$$

Fermi Golden Rule for Scattering

$$\mathcal{M} = \langle 3..n | H_I | 12 \rangle$$



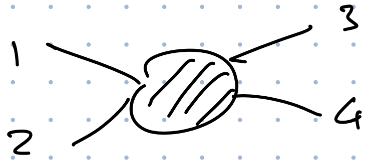
$1+2 \rightarrow 3+\dots+n.$

Stat. factor

$$\sigma = \frac{S}{4\sqrt{(p_1 \cdot p_2)^2 - (m_1 m_2)^2}} \int |\mathcal{M}|^2 (2\pi)^4 \delta^4(p_1+p_2-p_3-\dots-p_n) \times \prod_{j=3}^{n} \frac{1}{2\sqrt{p_j^2+m_j^2}} \frac{d^3\vec{p}_j}{(2\pi)^3}$$

$$p_j = |\vec{p}_j|$$

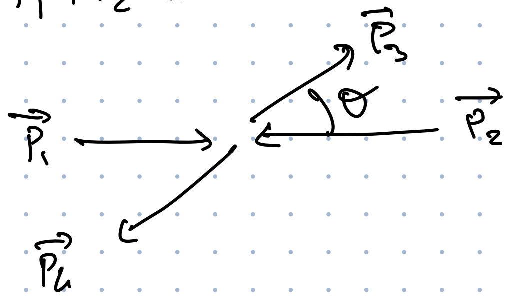
$a+b \to ccc+dd.$ $\qquad S=\frac{1}{N_c!}\,\frac{1}{N_d!}$



Example: $1+2 \to 3+4.$ in Center of mass.

Center of mass: Reference Frame $\qquad \vec{p}_1+\vec{p}_2=\vec{0}$

$$\vec{P}_1+\vec{P}_2=0=\vec{P}_3+\vec{P}_4.$$



$P_1=P_2=P_{in}$

$P_3=P_4=P_{out}\equiv P_f$

$$\Gamma=\frac{1}{4\sqrt{(\underline{P}_1\cdot\underline{P}_2)^2-(m_1m_2)^2}}\int |M|^2\,\delta^4(\underline{P}_1+\underline{P}_2-\underline{P}_3-\underline{P}_4)\,(2\pi)^4\times\frac{1}{(2\pi)^6}\,\frac{d^3\vec{P}_3}{\sqrt{P_3^2+m_3^2}}\,\frac{\cancel{d^3\vec{P}_4}}{\sqrt{P_4^2+m_4^2}}$$

$$P_{in}^2(E_1+E_2)^2$$

$$\delta(E_1+E_2-E_3-E_4)\,\delta^3(\underbrace{\cancel{\vec{P}_1+\vec{P}_2}}_{=\phi}-\vec{P}_3-\vec{P}_4)\Rightarrow \vec{P}_3=-\vec{P}_4$$

$P_3=P_4=P_{out}.$

$$\frac{\delta(E_1+E_2-E_3-E_4)}{\sqrt{P_{out}^2+m_3^2}\,\sqrt{P_{out}^2+m_4^2}}\,d^3\vec{P}_{out}$$

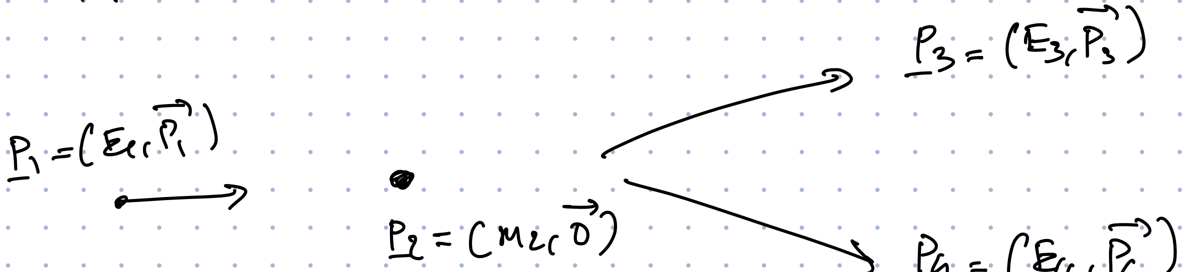
$u=E_3+E_4.$ $\qquad P_{out}\to u$ change variable.

$$d^3\vec{P}_{out} = P_{out}^2\, dP_{out}\, \underline{d\Omega} \qquad d\Omega = \sin\theta\, d\theta\, d\varphi$$

$$\frac{d\sigma}{d\Omega} = \frac{S}{64\pi^2}\frac{1}{(E_1+E_2)^2}\frac{|\vec{P}_{out}|}{|\vec{P}_{in}|}|\mathcal{M}|^2$$

$1+2 \rightarrow 3+4$ in center of mass.

Example



$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2}\frac{1}{m_2^2}\frac{|\vec{P}_{out}|}{|\vec{P}_{in}|}|\mathcal{M}|^2$$

Rutherford: $\alpha + N \longrightarrow \alpha + N$. $\quad m_\alpha / m_N \simeq \frac{4}{79}$

$\gamma + e^- \longrightarrow \gamma + e^-$

$e^- + p \longrightarrow e^- + p$. $\quad m_e/m_p \simeq 1862$

Rutherford exp: $K = 5$ MeV. non relativistic $m = 3.7$ GeV.

electron beam: $K = 5$ MeV. relativistic $m_e = 0.5$ MeV.