PHY 711 Classical Mechanics and Mathematical Methods
10-10:50 AM MWF in Olin 103

Notes for Lecture 3 based on Chap. 1 of F&W

Scattering theory – Coordinate frames

Center of mass and laboratory frames

Course schedule

(Preliminary schedule -- subject to frequent adjustment.)

	Date	F&W Reading	Topic	Assignment	Due
1	Mon, 8/22/2022		Introduction	#1	8/26/2022
2	Wed, 8/24/2022	Chap. 1	Scattering theory		
3	Fri, 8/26/2022	Chap. 1	Scattering theory	#2	8/29/2022
4	Mon, 8/29/2022	Chap. 1	Scattering theory		

PHY 711 – Assignment #2

08/24/2022

Consider a particle of mass m moving in the vicinity of another particle of mass M, initially at rest, where $m << M$. The particles interact with a conservative central potential of the form

$$V(r) = V_0 \left(\left(\frac{r_0}{r} \right)^2 - \left(\frac{r_0}{r} \right) \right),$$

where r denotes the magnitude of the particle separation and V_0 and r_0 denote energy and length constants, respectively. The total energy of the system E is constant and $E = V_0$.

(a) First consider the case where the impact parameter $b = 0$. Find the distance of closest approach of the particles.

(b) Now consider the case where the impact parameter $b = r_0$. Find the distance of closest approach of the particles.

Scattering theory:

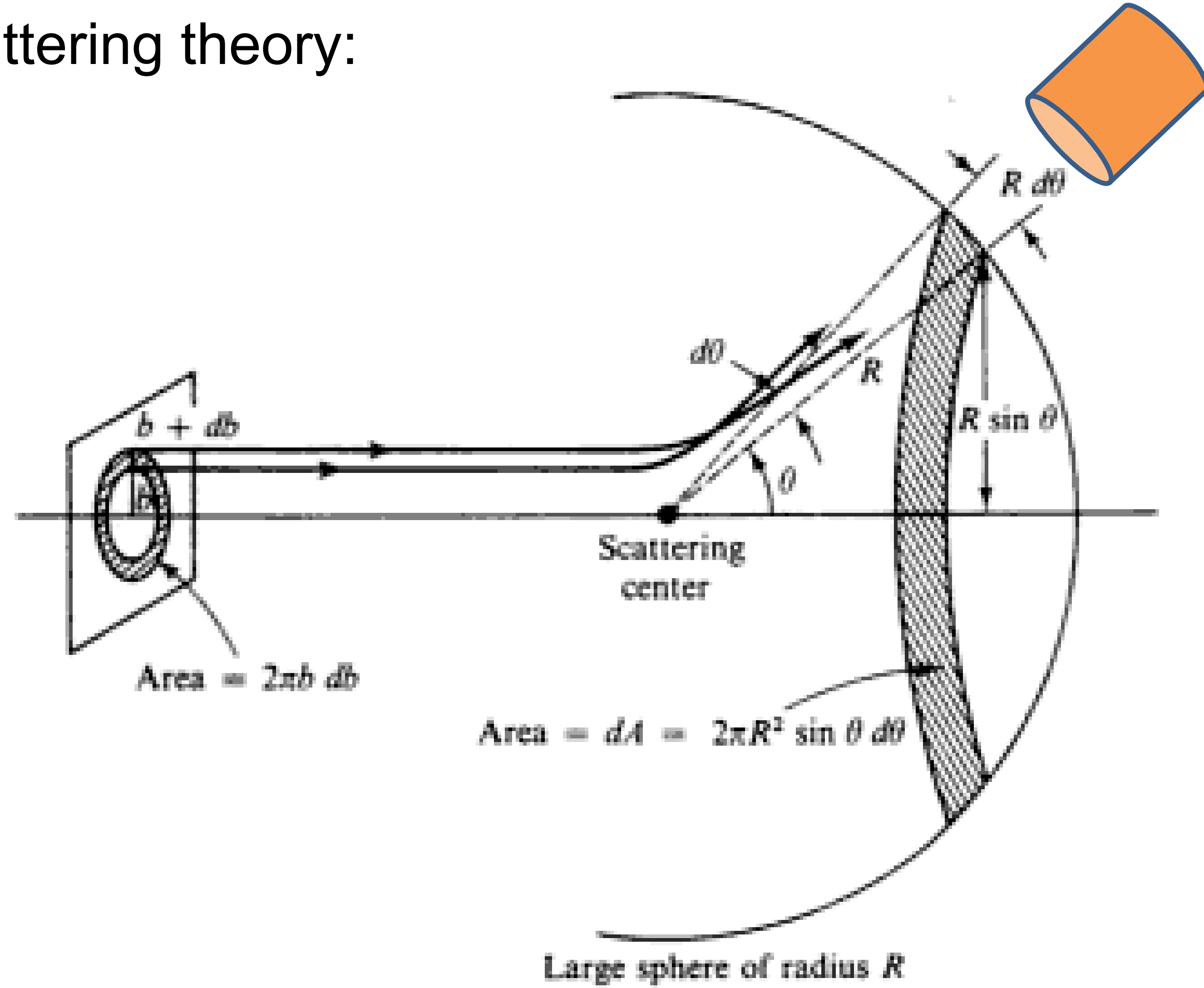


Figure 5.5 The scattering problem and relation of cross section to impact parameter.

Can you think of examples of such an experimental setup?

Other experimental designs –

At CERN https://home.cern/science/experiments/totem

the study of highly energetic proton-proton scattering is designed in the center of mass frame of reference by accelerating two proton beams focused to collide head on in the Large Hadron Collider LHC facility.

Figure from CERN website

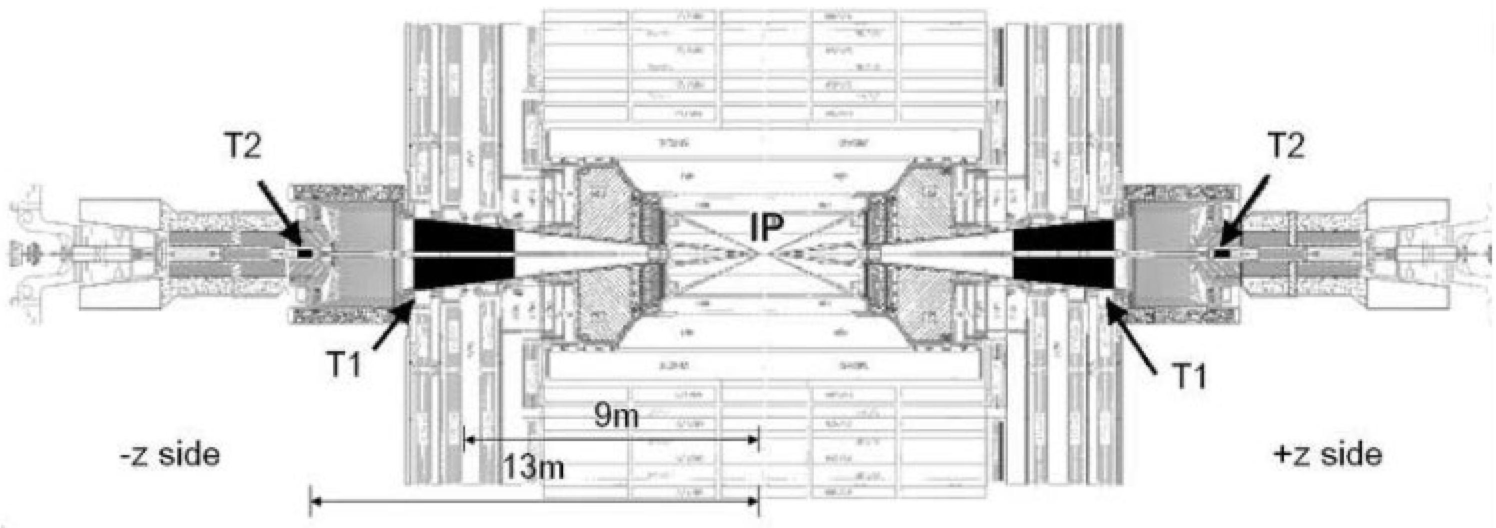


Figure 1.17: View of the inelastic forward trackers T1 and T2 inside the CMS detector.

What might be the advantage/disadvantage of this design?

What are the benefits/disadvantages of expressing the scattering cross section in the laboratory frame of reference vs center of mass frame of reference? (When or why to use a particular frame of reference)

Advantages of Lab frame

1. Natural experimental design.
2. Some targets are more naturally at rest.
3. ??

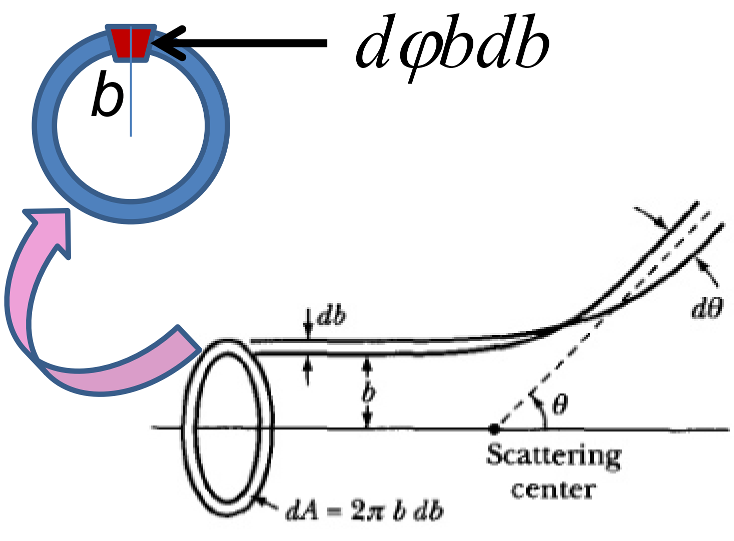
Advantages of CM frame

1. Analysis is done in CM frame.
2. Experiment is more energy efficient.
3. ??

Differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right)=\frac{\text{Number of detected particles at }\theta\text{ per target particle}}{\text{Number of incident particles per unit area}}$$

$$=\text{Area of incident beam that is scattered into detector at angle }\theta$$

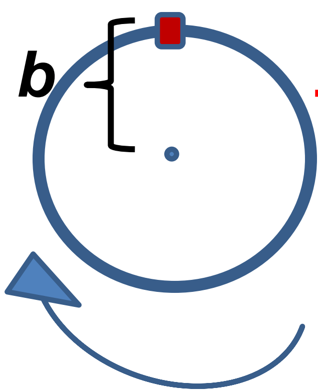


$$\left(\frac{d\sigma}{d\Omega}\right)=\frac{d\varphi\, b\, db}{d\varphi \sin\theta\, d\theta}=\frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

Figure from Marion & Thorton, Classical Dynamics

More details --

We imagine that the beam of particles has a cylindrical geometry and that the physics is totally uniform in the azimuthal direction. The cross section of the beam is a circle.

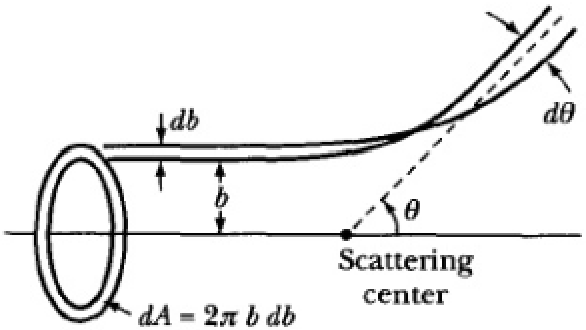


←This piece of the beam scatters into the detector at angle θ

This logic leads to the notion that b is a function of theta and we will try to find b(θ) for various cases.

$$\varphi \equiv \text{azimuthal angle}$$

Note: The notion of cross section is common to many areas of physics including classical mechanics, quantum mechanics, optics, etc. Only in the **classical mechanics** can we calculate it from a knowledge of the particle trajectory as it relates to the scattering geometry.



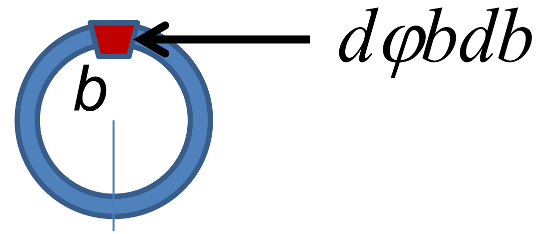
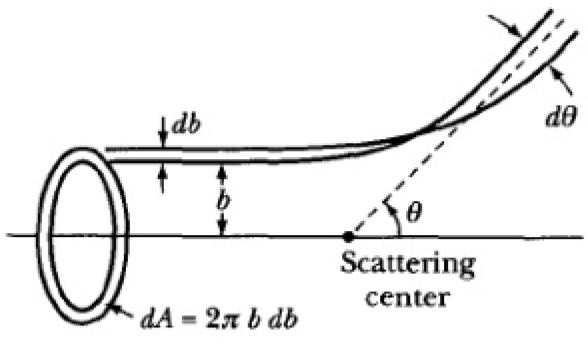


Figure from Marion & Thorton, Classical Dynamics

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{d\varphi\, b\, db}{d\varphi \sin\theta\, d\theta} = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

Note: We are assuming that the process is isotropic in ϕ

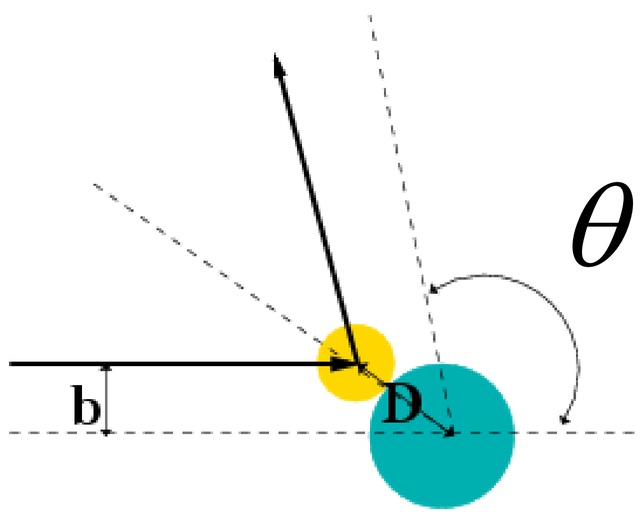
Simple example – collision of hard spheres



$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

Microscopic view:

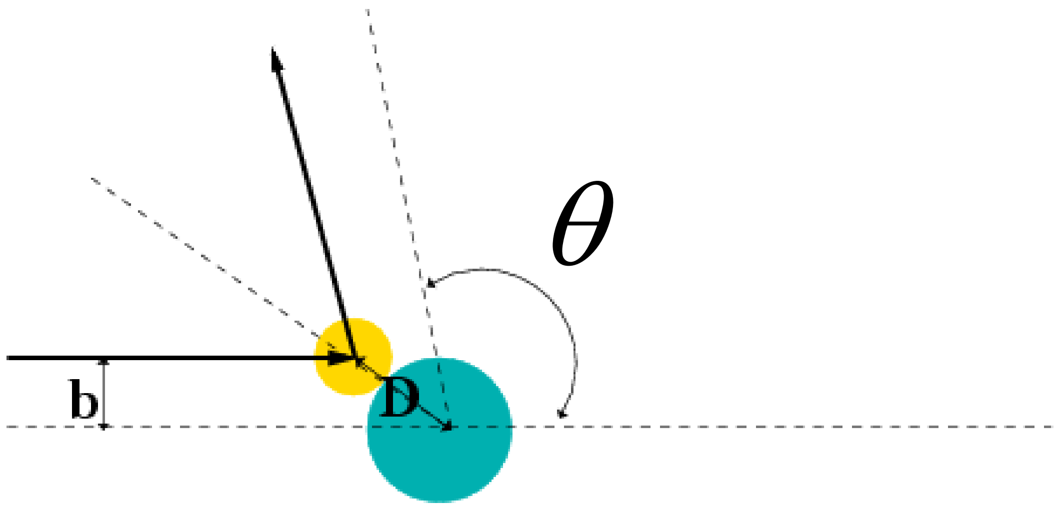
$$b(\theta) = ?$$

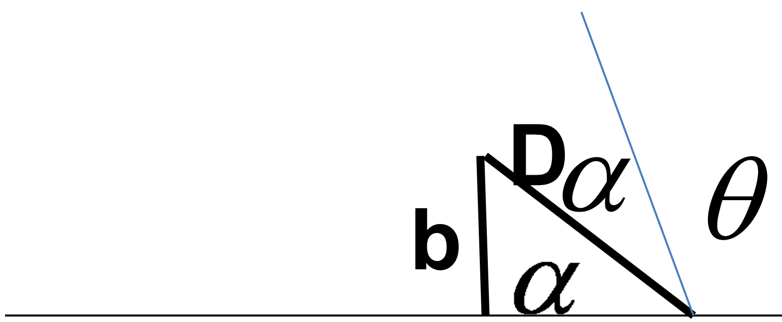


$$b(\theta) = D\sin\left(\frac{\pi}{2} - \frac{\theta}{2}\right)$$

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{D^2}{4}$$

Some more details of form of $b(\theta)$

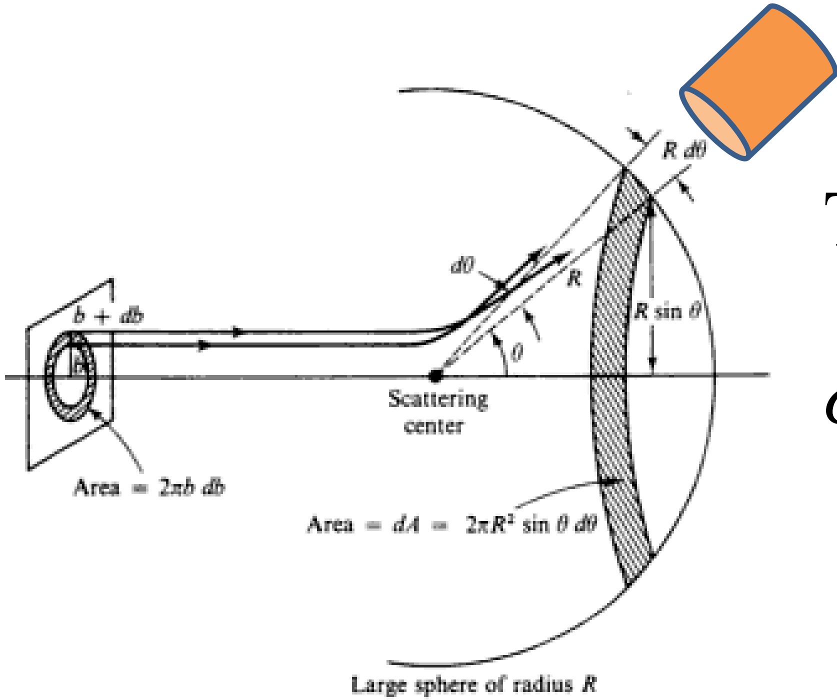




$$b = D \sin\alpha = D \sin\left(\frac{\pi}{2} - \frac{\theta}{2}\right)$$

$$2\alpha + \theta = \pi$$

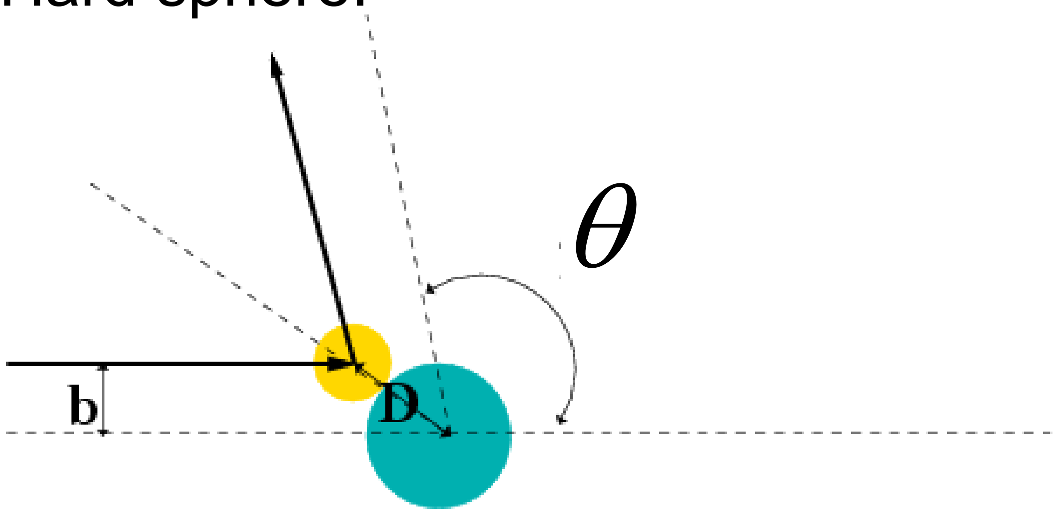
Simple example – collision of hard spheres -- continued



Total scattering cross section:

$$\sigma = \int \left(\frac{d\sigma}{d\Omega} \right) d\Omega$$

Hard sphere:



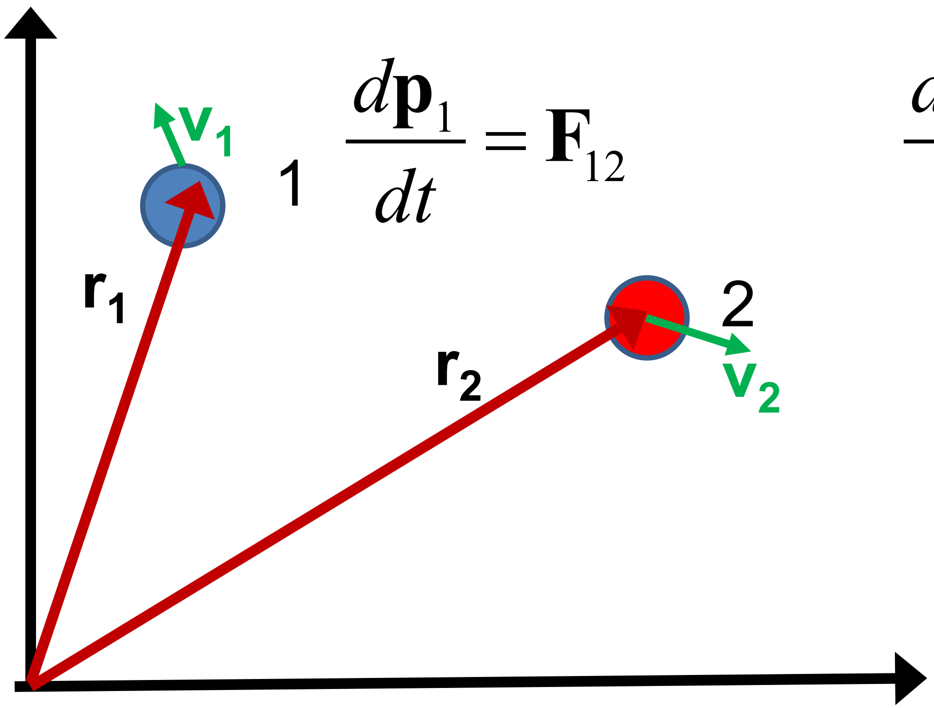
$$\left(\frac{d\sigma}{d\Omega} \right) = \frac{D^2}{4}$$

$$\sigma = \pi D^2$$

Now consider the more general case of particle interactions and the corresponding scattering analysis.

Scattering theory can help us analyze the interaction potential *V(r).* First, we need to simply the number of variables.

Relationship of scattering cross-section to particle interactions -- Classical mechanics of a conservative 2-particle system.



$$\frac{d\mathbf{p}_1}{dt} = \mathbf{F}_{12} \qquad \frac{d\mathbf{p}_2}{dt} = \mathbf{F}_{21}$$

$$\mathbf{F}_{12} = -\nabla_1 V\left(\mathbf{r}_1 - \mathbf{r}_2\right) \qquad \Rightarrow E = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 + V\left(\mathbf{r}_1 - \mathbf{r}_2\right)$$

Relationship between center of mass and laboratory frames of reference. At a time *t*, the following relationships apply --

Definition of center of mass $\mathbf{R}_{CM}$

$$m_1\mathbf{r}_1 + m_2\mathbf{r}_2 = (m_1 + m_2)\mathbf{R}_{CM}$$

$$m_1\dot{\mathbf{r}}_1 + m_2\dot{\mathbf{r}}_2 = (m_1 + m_2)\dot{\mathbf{R}}_{CM} = (m_1 + m_2)\mathbf{V}_{CM}$$

Note that $\dot{\mathbf{r}} \equiv \frac{d\mathbf{r}}{dt}$

$$E = \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 + V(\mathbf{r}_1 - \mathbf{r}_2)$$

$$= \frac{1}{2}(m_1 + m_2)V_{CM}^2 + \frac{1}{2}\mu|\mathbf{v}_1 - \mathbf{v}_2|^2 + V(\mathbf{r}_1 - \mathbf{r}_2)$$

where: $\mu \equiv \frac{m_1 m_2}{m_1 + m_2}$

Classical mechanics of a conservative 2-particle system -- continued

$$E = \frac{1}{2}(m_1 + m_2)V_{CM}^2 + \frac{1}{2}\mu|\mathbf{v}_1 - \mathbf{v}_2|^2 + V(\mathbf{r}_1 - \mathbf{r}_2)$$

For central potentials: $V(\mathbf{r}_1 - \mathbf{r}_2) = V(|\mathbf{r}_1 - \mathbf{r}_2|) \equiv V(r_{12})$

Relative angular momentum is also conserved:

$$\mathbf{L}_{12} \equiv \mathbf{r}_{12} \times \mu \mathbf{v}_{12}$$

$$E = \frac{1}{2}(m_1 + m_2)V_{CM}^2 + \frac{1}{2}\mu v_{12}^2 + \frac{L_{12}^2}{2\mu r_{12}^2} + V(r_{12})$$

Simpler notation:

$$E = \frac{1}{2}(m_1 + m_2)V_{CM}^2 + \frac{1}{2}\mu \dot{r}^2 + \frac{\ell^2}{2\mu r^2} + V(r)$$

Simpler notation:

$$E = \frac{1}{2}\left(m_1 + m_2\right)V_{CM}^2 + \frac{1}{2}\mu\dot{r}^2 + \frac{\ell^2}{2\mu r^2} + V\left(r\right)$$

constants

vary in time

For scattering analysis only need to know trajectory **before** and **after** the collision. We also generally assume that the interaction between particle and target *V(r)* conserves energy and angular momentum.

Comment: The impact parameter *b* is a useful concept in the general case.

$$E_{total} = \underbrace{\frac{1}{2}(m_1+m_2)V_{CM}^2}_{E_{CM}} + \underbrace{\frac{1}{2}\mu\dot{r}^2 + \frac{\ell^2}{2\mu r^2} + V(r)}_{E_{rel}}$$

$$E_{rel} = \frac{1}{2}\mu\dot{r}^2 + \frac{E_{rel}b^2}{r^2} + V(r)$$

In what situations do particles undergo inelastic scattering, rather than elastic scattering?

Comment – elastic scattering means $E_{initial}=E_{final}$

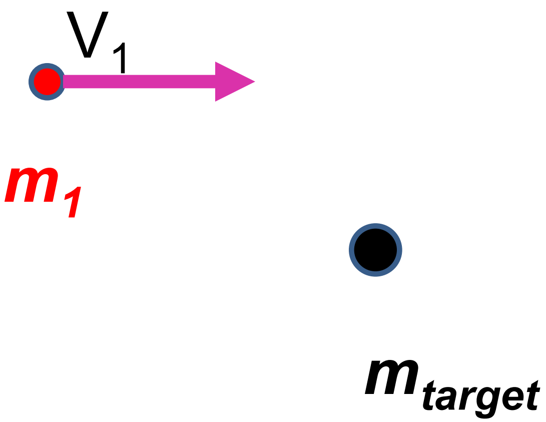
Typically, elastic scattering occurs when two fundamental particles interact (as long as the final kinetic energy of both particles is taken into account).

Elastically bouncing ball

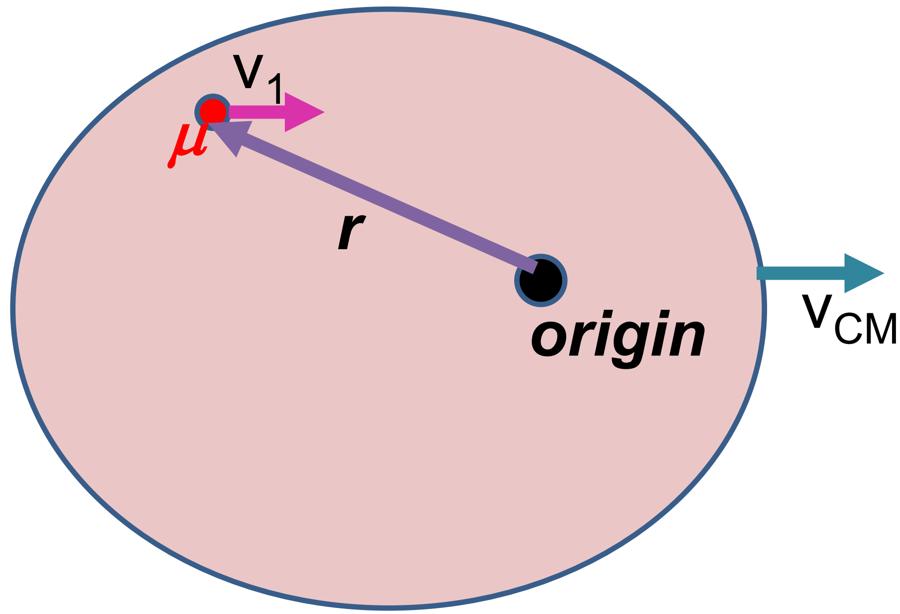
Inelastically collision

Note: The following analysis will be carried out in the center of mass frame of reference.

In laboratory frame:



In center-of-mass frame:



$$\mu = \frac{m_1 m_{\text{target}}}{m_1 + m_{\text{target}}}$$

$$\ell = \left| \mathbf{r} \times \mu \mathbf{v}_1 \right|$$

Typically, the laboratory frame is where the data is taken, but the center of mass frame is where the analysis is most straightforward.

Previous equations --

$$E = \frac{1}{2}(m_1 + m_2)V_{CM}^2 + \frac{1}{2}\mu\dot{r}^2 + \frac{\ell^2}{2\mu r^2} + V(r)$$

constant

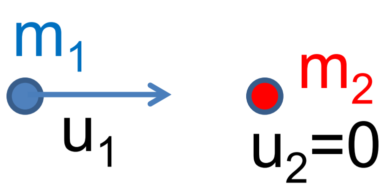
relative coordinate system; visualize as “in” CM frame

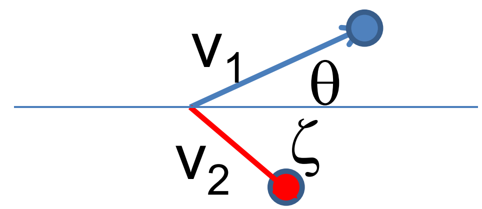
It is often convenient to analyze the scattering cross section in the center of mass reference frame.

Relationship between normal laboratory reference and center of mass:

Laboratory reference frame:

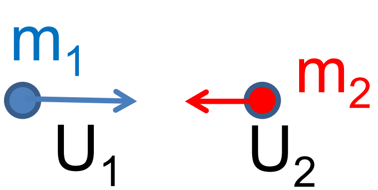
Before | After

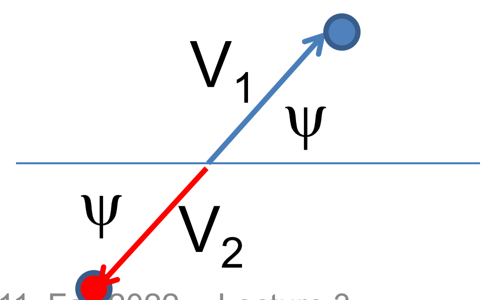




Center of mass reference frame:

Before | After





Relationship between center of mass and laboratory frames of reference -- continued

Since m_2 is initially at rest in lab frame:

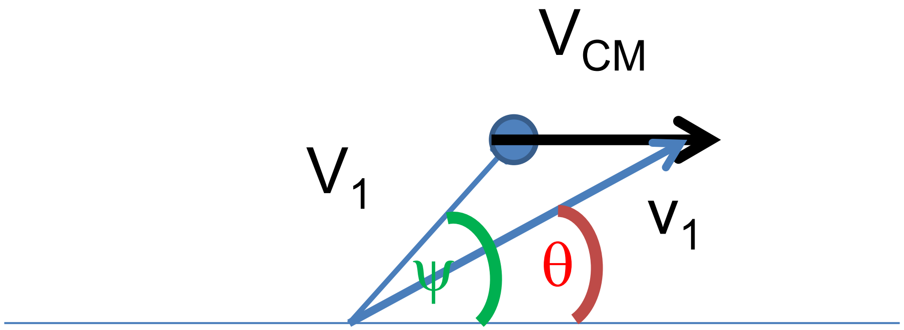
$$\mathbf{V}_{CM} = \frac{m_1}{m_1 + m_2}\mathbf{u}_1 \qquad \mathbf{u}_1 = \mathbf{U}_1 + \mathbf{V}_{CM} \qquad \Rightarrow \mathbf{U}_1 = \frac{m_2}{m_1 + m_2}\mathbf{u}_1 = \frac{m_2}{m_1}\mathbf{V}_{CM}$$

$$\mathbf{u}_2 = \mathbf{U}_2 + \mathbf{V}_{CM} \qquad \Rightarrow \mathbf{U}_2 = -\frac{m_1}{m_1 + m_2}\mathbf{u}_1 = -\mathbf{V}_{CM}$$

$$\mathbf{v}_1 = \mathbf{V}_1 + \mathbf{V}_{CM}$$

$$\mathbf{v}_2 = \mathbf{V}_2 + \mathbf{V}_{CM}$$

Relationship between center of mass and laboratory frames of reference for the scattering particle 1



$$\mathbf{v}_1 = \mathbf{V}_1 + \mathbf{V}_{CM}$$

$$v_1 \sin\theta = V_1 \sin\psi$$

$$v_1 \cos\theta = V_1 \cos\psi + V_{CM}$$

$$\tan\theta = \frac{\sin\psi}{\cos\psi + V_{CM} / V_1} = \frac{\sin\psi}{\cos\psi + m_1 / m_2}$$

For elastic scattering

Digression – elastic scattering

$$\tfrac{1}{2}m_1U_1^2+\tfrac{1}{2}m_2U_2^2+\tfrac{1}{2}(m_1+m_2)V_{CM}^2$$
$$=\tfrac{1}{2}m_1V_1^2+\tfrac{1}{2}m_2V_2^2+\tfrac{1}{2}(m_1+m_2)V_{CM}^2$$

Also note:

$$m_1\mathbf{U}_1+m_2\mathbf{U}_2=0 \qquad\qquad m_1\mathbf{V}_1+m_2\mathbf{V}_2=0$$

$$\mathbf{U}_1=\frac{m_2}{m_1}\mathbf{V}_{CM} \qquad\qquad \mathbf{U}_2=-\mathbf{V}_{CM}$$

$$\Rightarrow |\mathbf{U_1}|=|\mathbf{V_1}| \quad \text{and} \quad |\mathbf{U_2}|=|\mathbf{V_2}|=|\mathbf{V_{CM}}|$$

Also note that : $\quad m_1|\mathbf{U_1}|=m_2|\mathbf{U_2}|$

So that : $\quad V_{CM}/V_1=V_{CM}/U_1=m_1/m_2$

Summary of results --

$$\mathbf{v}_1 = \mathbf{V}_1 + \mathbf{V}_{CM}$$

$$v_1 \sin\theta = V_1 \sin\psi$$

$$v_1 \cos\theta = V_1 \cos\psi + V_{CM}$$

$$\tan\theta = \frac{\sin\psi}{\cos\psi + V_{CM} / V_1} = \frac{\sin\psi}{\cos\psi + m_1 / m_2}$$

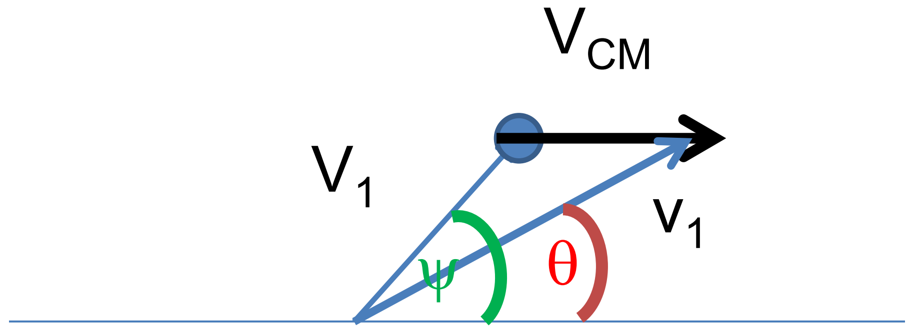
General case

Special case of elastic scattering

For elastic scattering

$$V_{CM} / V_1 = m_1 / m_2$$

Relationship between center of mass and laboratory frames of reference – continued (elastic scattering)



$$\mathbf{v}_1 = \mathbf{V}_1 + \mathbf{V}_{CM}$$

$$v_1 \sin\theta = V_1 \sin\psi$$

$$v_1 \cos\theta = V_1 \cos\psi + V_{CM}$$

$$\tan\theta = \frac{\sin\psi}{\cos\psi + V_{CM}/V_1} = \frac{\sin\psi}{\cos\psi + m_1/m_2}$$

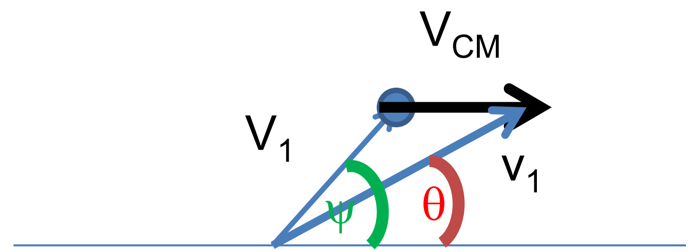
Also: $$\cos\theta = \frac{\cos\psi + m_1/m_2}{\sqrt{1 + 2m_1/m_2\cos\psi + \left(m_1/m_2\right)^2}}$$

More details -- from the diagram and equations --

$$\mathbf{v}_1 = \mathbf{V}_1 + \mathbf{V}_{CM}$$

$$v_1 \sin\theta = V_1 \sin\psi$$

$$v_1 \cos\theta = V_1 \cos\psi + V_{CM}$$



Take the dot product of the first equation with itself

$$v_1^2 = V_1^2 + 2V_1V_{CM}\cos\psi + V_{CM}^2$$

$$\text{or } \frac{v_1}{V_1} = \sqrt{1 + 2\frac{V_{CM}}{V_1}\cos\psi + \frac{V_{CM}^2}{V_1^2}} = \sqrt{1 + 2\frac{m_1}{m_2}\cos\psi + \left(\frac{m_1}{m_2}\right)^2}$$

$$\Rightarrow \quad \cos\theta = \frac{\cos\psi + m_1/m_2}{\sqrt{1 + 2m_1/m_2\cos\psi + (m_1/m_2)^2}}$$

Differential cross sections in different reference frames

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right) = \left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right)\frac{d\Omega_{CM}}{d\Omega_{LAB}}$$

$$\frac{d\Omega_{CM}}{d\Omega_{LAB}} = \left|\frac{\sin\psi}{\sin\theta}\frac{d\psi}{d\theta}\right| = \left|\frac{d\cos\psi}{d\cos\theta}\right|$$

Using:

$$\cos\theta = \frac{\cos\psi + m_1/m_2}{\sqrt{1+2(m_1/m_2)\cos\psi + (m_1/m_2)^2}}$$

$$\left|\frac{d\cos\theta}{d\cos\psi}\right| = \frac{(m_1/m_2)\cos\psi + 1}{\left(1+2(m_1/m_2)\cos\psi + (m_1/m_2)^2\right)^{3/2}}$$

Differential cross sections in different reference frames – continued:

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right) = \left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right)\left|\frac{d\cos\psi}{d\cos\theta}\right|$$

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right) = \left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right)\frac{\left(1+2m_1/m_2\cos\psi+(m_1/m_2)^2\right)^{3/2}}{(m_1/m_2)\cos\psi+1}$$

where: $\tan\theta = \frac{\sin\psi}{\cos\psi + m_1/m_2}$

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right)=\left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right)\frac{\left(1+2m_1/m_2\cos\psi+\left(m_1/m_2\right)^2\right)^{3/2}}{\left(m_1/m_2\right)\cos\psi+1}$$

where: $\tan\theta=\dfrac{\sin\psi}{\cos\psi+m_1/m_2}$

Example: suppose $m_1 = m_2$

In this case: $\tan\theta=\dfrac{\sin\psi}{\cos\psi+1} \quad \Rightarrow \theta=\dfrac{\psi}{2}$

note that $0\le\theta\le\dfrac{\pi}{2}$

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right)=\left(\frac{d\sigma_{CM}(2\theta)}{d\Omega_{CM}}\right)\cdot 4\cos\theta$$

Summary --

Differential cross sections in different reference frames – continued:

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right)=\left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right)\left|\frac{d\cos\psi}{d\cos\theta}\right|$$

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right)=\left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right)\frac{\left(1+2m_1/m_2\cos\psi+(m_1/m_2)^2\right)^{3/2}}{(m_1/m_2)\cos\psi+1}$$

where: $\tan\theta=\dfrac{\sin\psi}{\cos\psi+m_1/m_2}$

For elastic scattering

Hard sphere example – continued

$m_1 = m_2$

Center of mass frame

Lab frame

$$\left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right) = \frac{D^2}{4}$$

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right) = D^2 \cos\theta \quad \theta = \frac{\psi}{2}$$

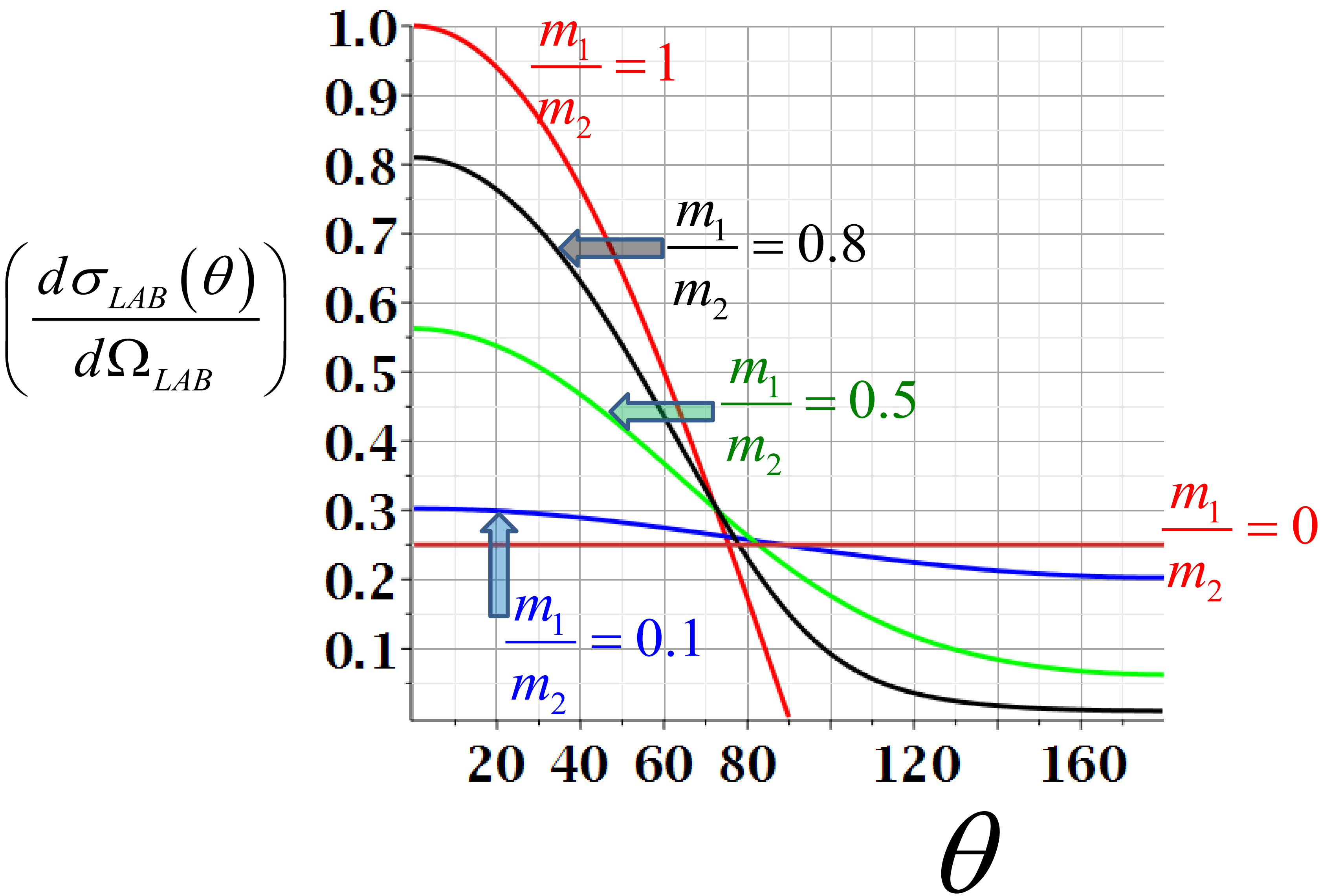
$$\int \frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}} d\Omega_{CM} =$$

$$\frac{D^2}{4} 4\pi = \pi D^2$$

$$\int \frac{d\sigma_{lab}(\theta)}{d\Omega_{lab}} d\Omega_{lab} =$$

$$2\pi D^2 \int_0^{\pi/2} \cos\theta \, \sin\theta d\theta = \pi D^2$$

Scattering cross section for hard sphere in lab frame for various mass ratios:



For visualization, is convenient to make a "parametric" plot of

$$\left(\frac{d\sigma_{LAB}}{d\Omega}(\theta)\right) \text{ vs } \theta(\psi)$$

$$\left(\frac{d\sigma_{LAB}(\theta)}{d\Omega_{LAB}}\right) = \left(\frac{d\sigma_{CM}(\psi)}{d\Omega_{CM}}\right)\frac{\left(1+2m_1/m_2\cos\psi+(m_1/m_2)^2\right)^{3/2}}{(m_1/m_2)\cos\psi+1}$$

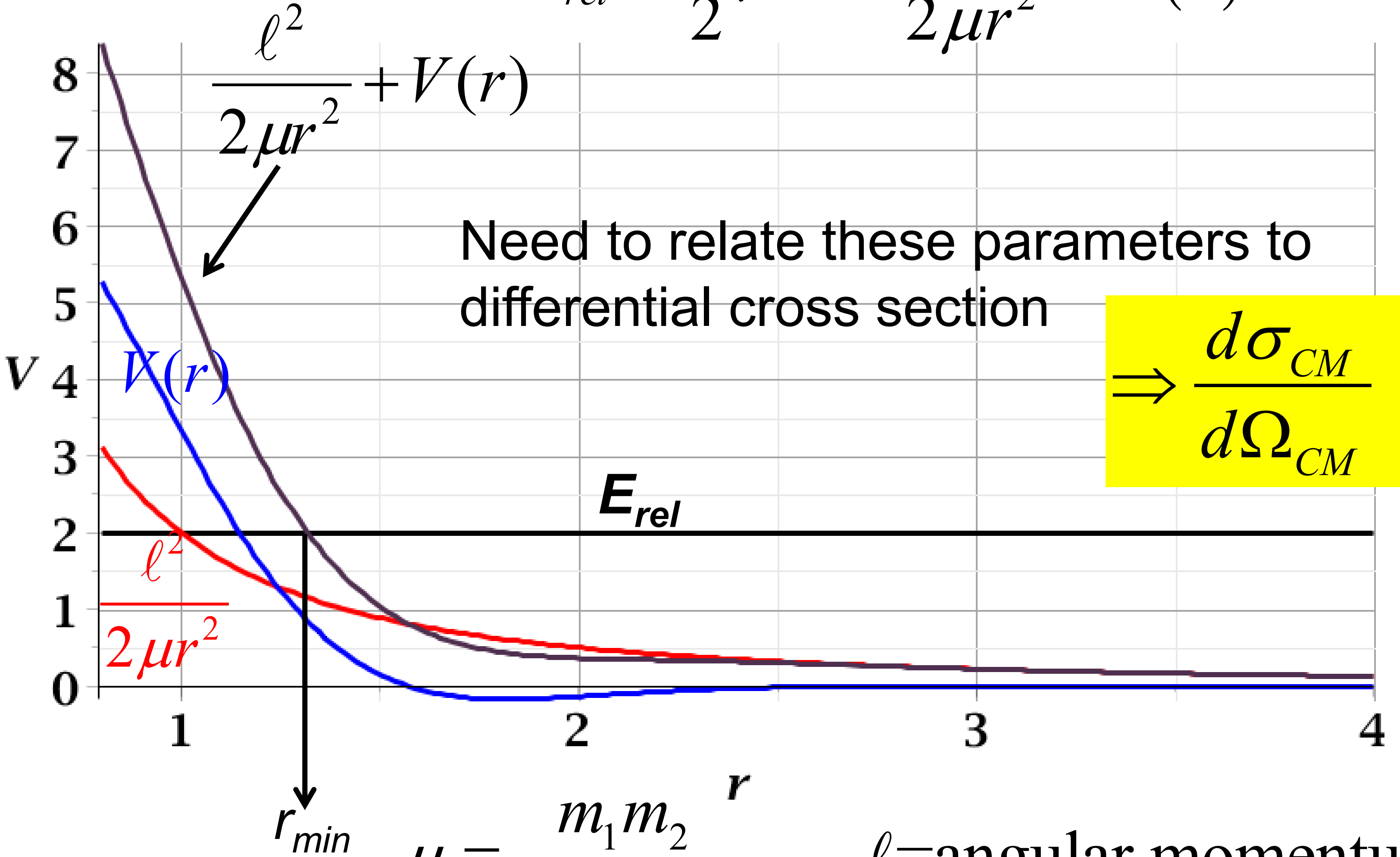
where: $\tan\theta = \dfrac{\sin\psi}{\cos\psi + m_1/m_2}$

Maple syntax:

```
> plot( { [psi(theta, 0), sigma(theta, 0), theta = 0.001 ..3.14], [psi(theta, .1), sigma(theta, .1), theta
     = 0.001 ..3.14], [psi(theta, .5), sigma(theta, .5), theta = 0.001 ..3.14], [psi(theta, .8),
    sigma(theta, .8), theta = 0.001 ..3.14], [psi(theta, 1), sigma(theta, 1), theta = 0.001 ..3.14]},
    thickness = 3, font = ['Times','bold', 24], gridlines = true, color = [red, blue, green, black,
    orange])
```

For a continuous potential interaction in center of mass reference frame:

$$E_{rel} = \frac{1}{2}\mu\dot{r}^2 + \frac{\ell^2}{2\mu r^2} + V(r)$$



Need to relate these parameters to differential cross section

$$\Rightarrow \frac{d\sigma_{CM}}{d\Omega_{CM}}$$

$$\mu \equiv \frac{m_1 m_2}{m_1 + m_2}$$

ℓ=angular momentum