Modelling Hadron Rescattering Cross Sections Within Sherpa

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Contents

The Aim

- We are interested in $\nu + N \rightarrow$: A Hadronic rescattering causing a quantum billiard system. Produced hadrons undergo multiple rescatterings inside the nucleus.
- Hadronic rescattering is crucial because it connects the initial neutrino interaction to what detectors actually observe
- We want to use physics informed neural networks and machine learn scattering cross sections.

What are baryons and mesons?

- Baryons and mesons are hadrons and bound states of multiple quarks
- Baryons have 3 quarks (qqq)
- Mesons have 1 quark and 1 antiquark, or a superposition of quark-antiquark pairs ($q\bar{q}$ or $\frac{1}{\sqrt{2}}(q\bar{q} + q'\bar{q}')$)

Cross Section and Rescattering

- The cross section, σ, is a measure of the effective area of interaction for some collision experiment
- It is common to think of it as a likelihood of an interaction, as the bigger the target, the easier it is to hit said target.
- A vital parameter for $\nu + N \rightarrow$ is the total cross section denoted by σ_{tot}
- Rescattering can be thought of as hadrons undergoing multiple collisions inside the nucleus, similar to balls scattering on a snooker table
- Rescattering probability is given by

$$P(b) = P_0 e^{\frac{-b^2}{b_0^2}}, \tag{1}$$

where $b_0 = \sqrt{\frac{\sigma_{total}}{P_0 \pi}}$, b is the shortest distance between two interacting particles (the impact parameter)

Baryon-Baryon Total Cross Sections

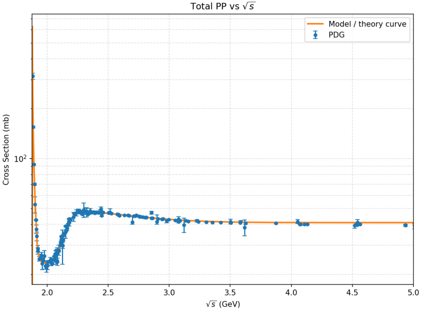
- Below 5 GeV, fit to data.
- Above 5 GeV, we use the HPR_1R_2 parameterization

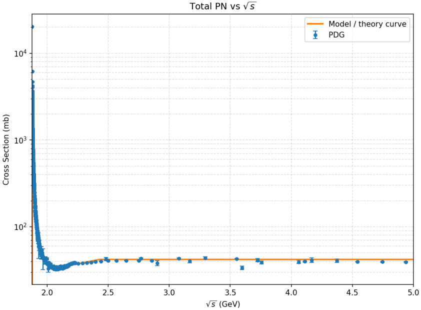
$$\sigma_{tot} = P + Hlog^2\left(\frac{s}{s_0}\right) + R_1\left(\frac{s}{s_0}\right)^{\eta_1} + R_2\left(\frac{s}{s_0}\right)^{\eta_2},$$

where $s_0 = (m_A + m_B + M)^2$. P, R_1 and R_2 are parameters which depend on the particle, and H, η_1 and η_2 are constant parameters.

Cugnon, J. and Vandermeulen, J. and L'Hote, D. 'Simple parametrization of cross-sections for nuclear transport studies up to the GeV range' (1996)

Baryon-Baryon Total Cross Section vs Centre of Momentum Energy





Baryon-Baryon Elastic Cross Sections

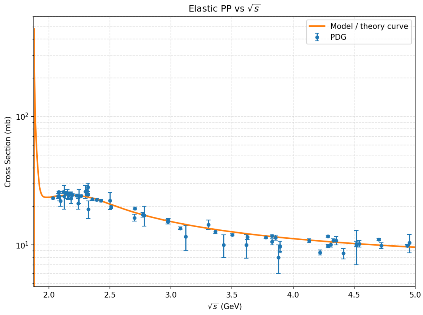
- Elastic: $A + B \to A + B$, no new particles
- Again, below 5 GeV, fit to data.
- The elastic cross section has a similar looking parameterization above 5 GeV, given by the CERN/HERA parameteriation

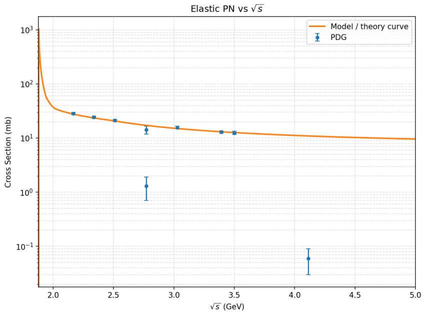
$$\sigma_{\mathrm{HERA}}(p) = a + b\, p^n + c\, \log^2 p + d\, \log p. \tag{2}$$

with a, b, c, and d all parameters depending on the particle species, p is the lab momenta.

Cugnon, J. and Vandermeulen, J. and L'Hote, D. 'Simple parametrization of cross-sections for nuclear transport studies up to the GeV range' (1996)

Baryon-Baryon Elastic Cross Section vs Centre of Momentum Energy





Baryon-Antibaryon Cross Sections

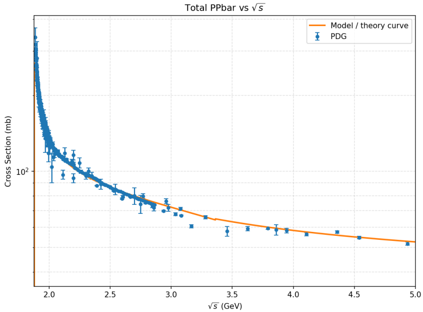
- For $B\bar{B}$, we parameterise the cross section for $p\bar{p}$ below $p_{\mathrm{CM}} < 6.5\ \mathrm{GeV}$

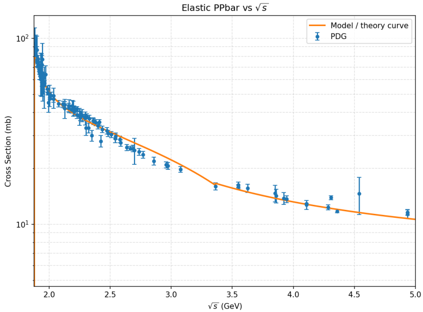
$$\sigma_{\mathrm{tot}}(p\bar{p}) = \begin{cases} 271.6\, e^{-1.1p^2}, & p < 0.3, \\ 75.0 + 43.1\, p^{-1} + 2.6\, p^{-2} - 3.9\, p, & 0.3 < p < 6.5. \end{cases} \tag{3}$$

- For $p_{\mathrm{CM}} > 6.5\ \mathrm{GeV}$, we use HPR_1R_2. For other $B\bar{B}$ cases, we use a scaling factor
- The elastic parameterisation is much the same style of fitting.

Sjöstrand, Torbjörn and Utheim, Marius, 'A Framework for Hadronic Rescattering in pp Collisions' (2005)

Proton-Antiproton Cross Section Cross Section vs Centre of Momentum Energy





Baryon-Meson Cross Sections

- In the few-GeV regime, scattering processes are dominated by resonance production

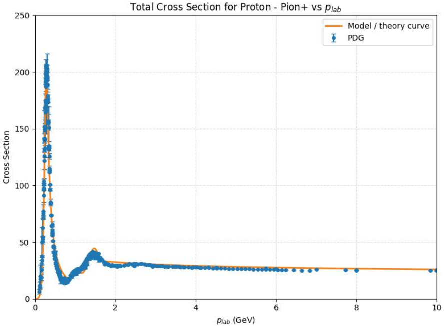
$$\sigma_{AB\to R} = \frac{\pi}{p_{cm}^2} \frac{(2S_R+1)}{(2S_A+1)(2S_B+1)} \frac{\Gamma_{AB\to R}\Gamma_R}{(m_R-\sqrt{s})^2+\frac{1}{4}\Gamma_R^2} \quad (4)$$

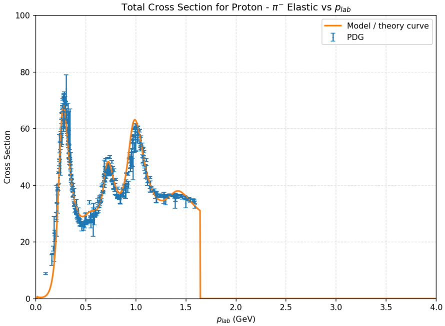
  Where $S_{A,B}$ are the spins of the colliding particles. S_R is the spin of the resonant particle. Γ_R is the total decay width, and $\Gamma_{R\to AB}$ is the partial width.
- Resonances are Δ and N for $N\pi$ interactions, and Σ and Λ for NK interactions.

What are these resonant particles?

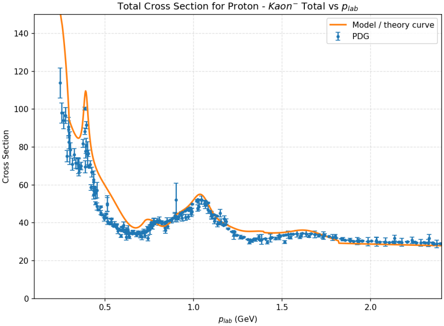
- These resonant particles are 'intermediate' within the interaction. They then go onto decay into the final state particles we can then measue with a detector. These particles can either be excitations, or have completely different quark structure entirely.
- N or nucleon resonances have the same quark structure as the proton (uud) and neutron (udd), but they are excited states which have higher masses.
- $\Delta^{++} = uuu$, $\Delta^{+} = uud$, $\Delta^{0} = udd$, $\Delta^{-} = ddd$.
- Δ^{+} and Δ^{0} are different to the proton and neutron as the Δ's are spin-3/2, whereas protons and neutrons are only spin-1/2
- For example, for $p + \pi^{+}$, proton has uud and π^{+} has $u\bar{d}$, then resonance has $\Delta^{++} = uuu$. Then $\Delta^{++} \to p + \pi^{+}$.
- $p + \pi^{+} \to \Delta^{++} \to p + \pi^{+}$

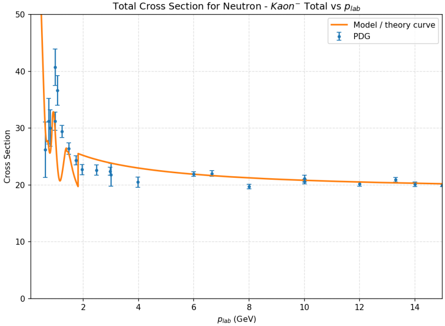
Baryon-Meson $p\pi^+$ and $p\pi^-$ Cross Section vs Lab Momentum



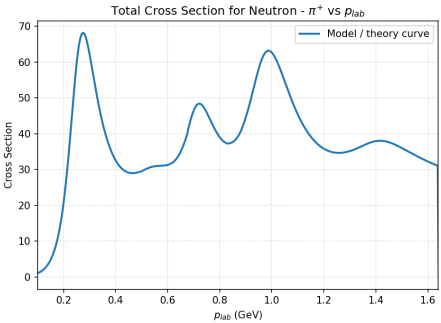


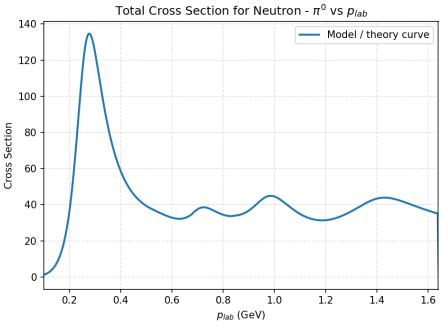
Baryon-Meson pK^+ and nK^+ Cross Section vs Lab Momentum





Baryon-Meson $n\pi^+$ and $n\pi^0$ Cross Section vs Lab Momentum





Meson-Meson Cross Sections

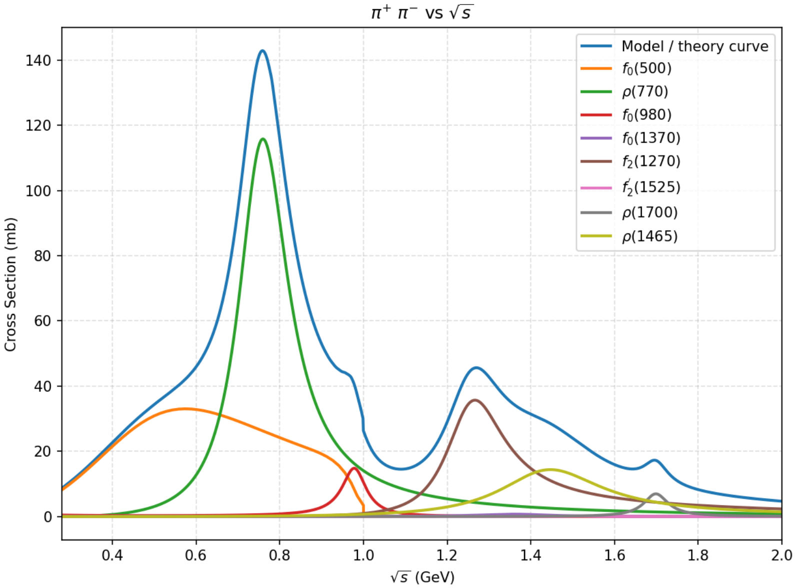
- The meson-meson cross sections is build out of the possible resonances from the colliding particles, given by the same UrQMD parameterisation given used before on baryon-meson interactions. The cross section is again given by Eq. 4
- The resonances for these implemented collisions are mesons such as the f, ω and ρ mesons

Sjöstrand, Torbjörn and Utheim, Marius, 'A Framework for Hadronic Rescattering in pp Collisions' (2005)

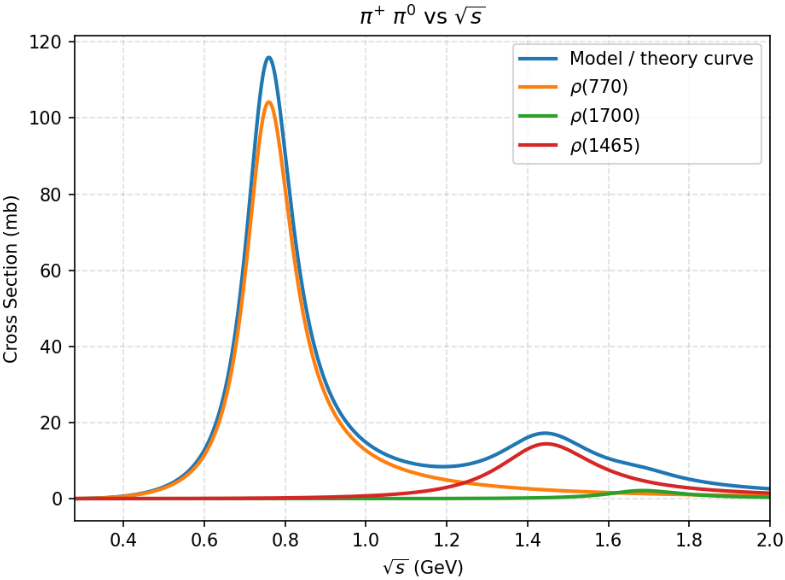
Meson-Meson resonant particles

- The $\rho(770)$, $\rho(1465)$, $\rho(1700)$ all have the same quark structure, they are just excitations of one another.
- The ρ and ω mesons are spin 1, they have very similar quark structure to the pions discussed before.
- $\rho^+ = u\bar{d}$, $\rho^- = d\bar{u}$, $\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$, $\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$.
- Lastly, the $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_2(1270)$ and the $f_2^{'}(1525)$. The subscript gives the spin.
- The quark structure of these are a bit more messy as the quarks mix between up, down and strange quarks.
- $f = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})cos(\theta) + (s\bar{s})sin(\theta)$ where θ is the mixing angle.

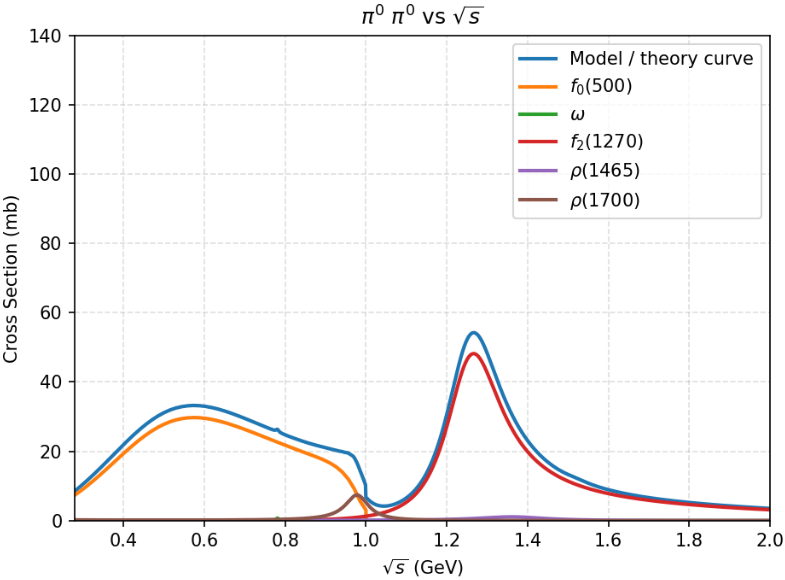
$\pi^+\pi^-$ Cross Section vs Centre of Momentum Energy



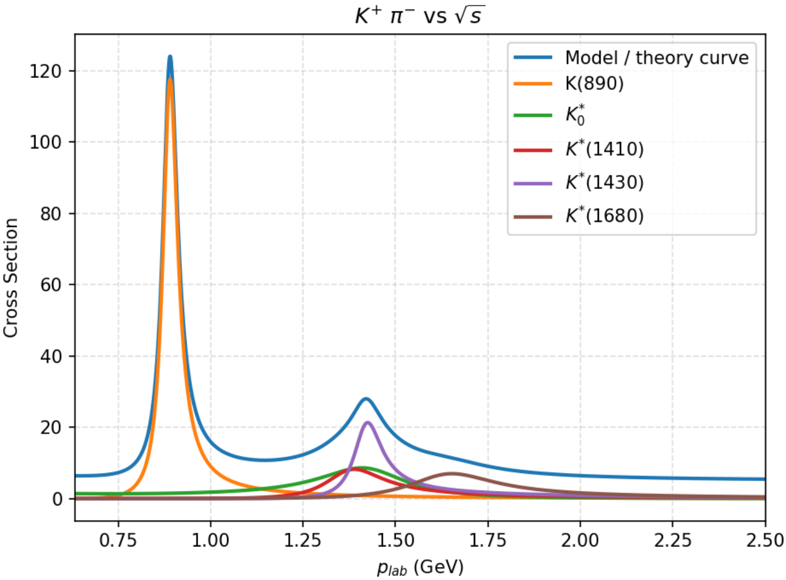
$\pi^+\pi^0$ Cross Section vs Centre of Momentum Energy



$\pi^0\pi^0$ Cross Section vs Centre of Momentum Energy

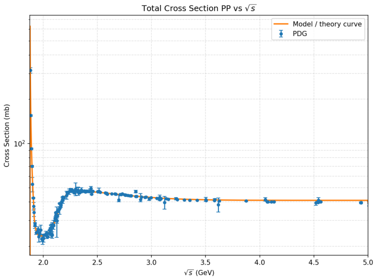


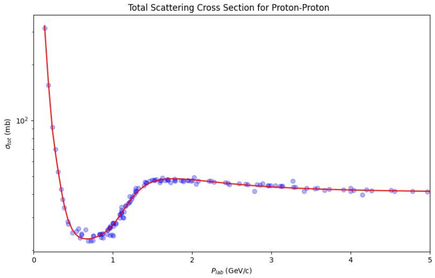
$K^+\pi^-$ Cross Section vs Centre of Momentum Energy



Machine Learning Cross Section vs Centre of Momentum Energy (left) and Lab Momentum (right)

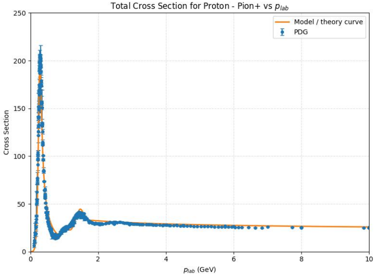
- Without physics informed neural networks and just three linear layers, machine learning can plot the cross sections with the help from experimental data. For example for proton-proton...

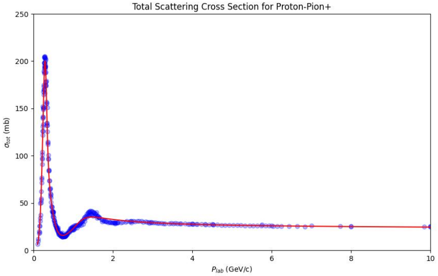




Machine Learning Cross Section vs Lab Momentum

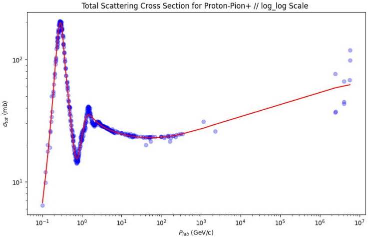
- ...and for proton-π^+

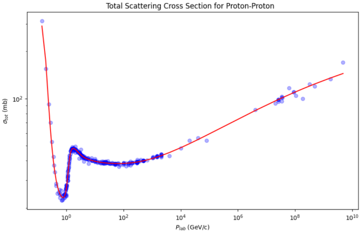




Total Scattering Cross Section vs Lab Momentum

... and all regions





What's Next?

- Machine learn this system to calculate the cross sections for these processes
- Implement deep inelastic scattering
- $\nu + N \rightarrow$: quantum billiard our hadrons (hence rescattering) and calculate the cross section. Hopefully compare with some experimental data within a few years!