



CNAO2025: first observation of fast target fragmentation process

INFN Milano

From the last physics meeting: Mass reconstruction using P and ToF

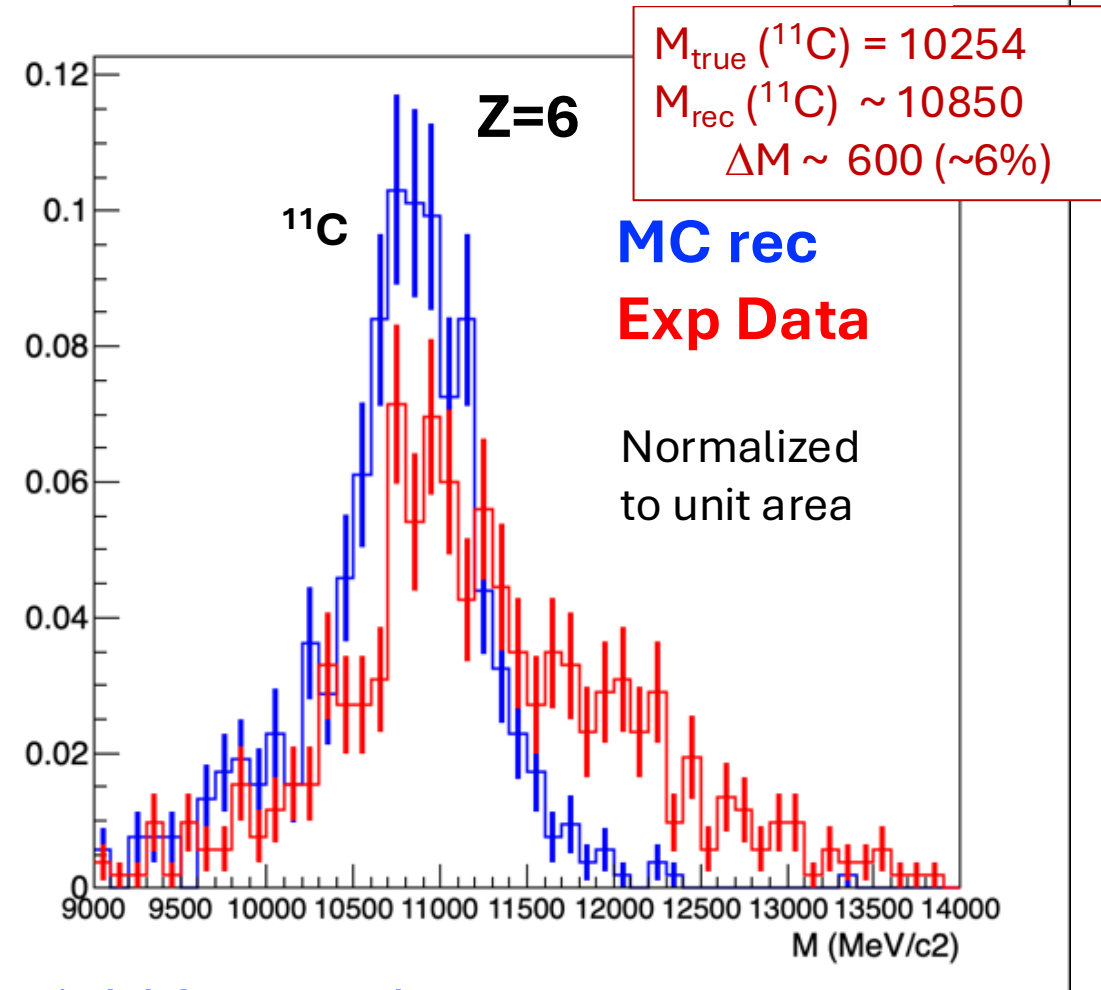
A number of Z=6 were indentified both in data and MC

but at least 2 global tracks were required in event selection!

In these events there are 1 Z=6 track and 1 Z=1
→ $Z_{\text{tot}} = 7$ and this is not a mistake

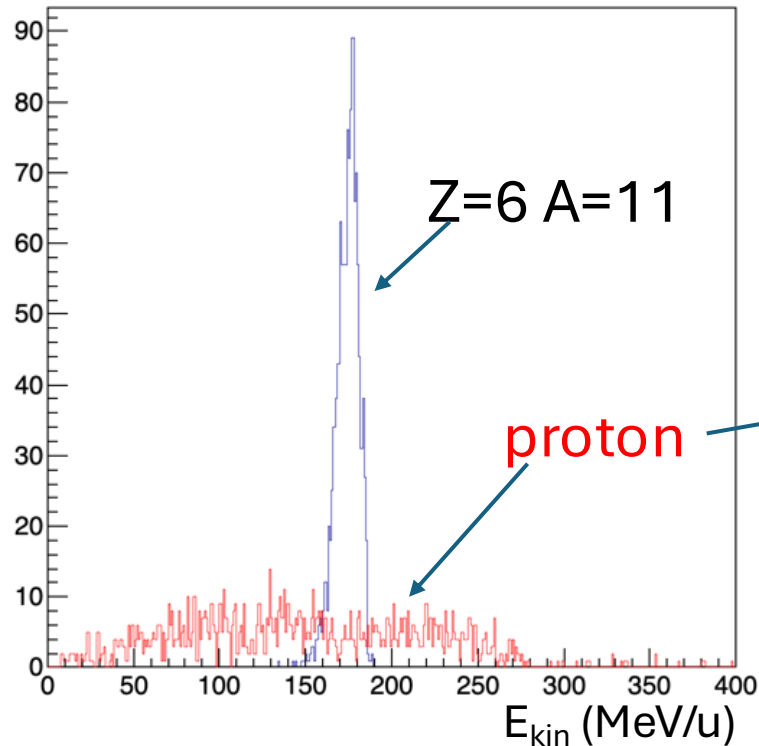
Actually, the naive assumption that fast charged tracks are all coming from projectile fragmentation is not exact:

target fragmentation in N-N collisions can yield fast nucleons

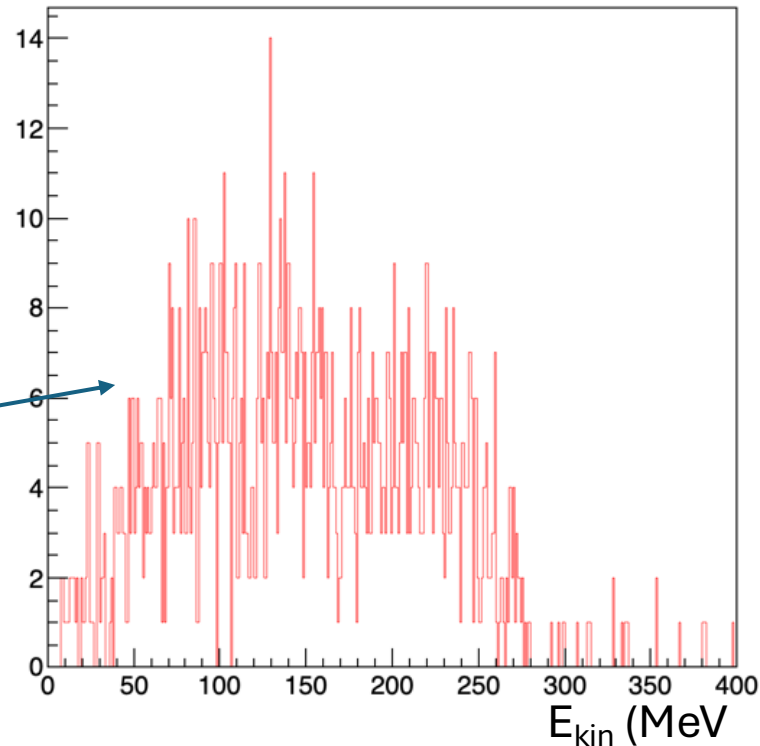


MC prediction: E_{kin} of fragments arriving at TW from target in the same event

E_{kin}/u Z=6 in 11-C events



E_{kin} Z=1 in 11-C events

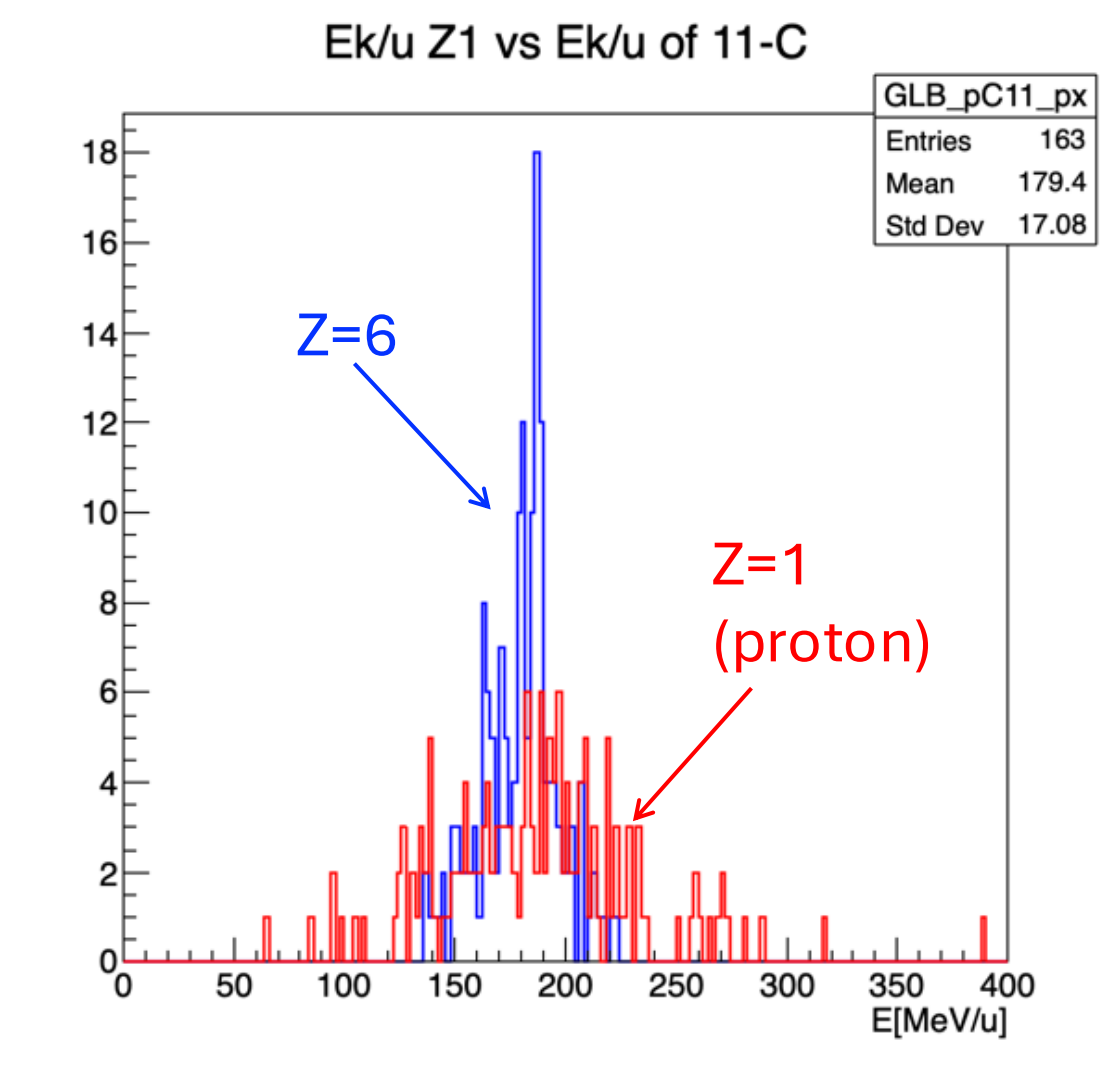


Notice:

Nuclear fragment, evidently coming from projectile fragmentation, has an energy/nucleon close to projectile's one

The accompanying proton has an energy reaching 350 MeV and beyond

Data reconstruction



Also in exp. data the accompanying Z=1 has an energy reaching 350 MeV and beyond

Recalling the mechanisms of N-N collisions at FOOT energies

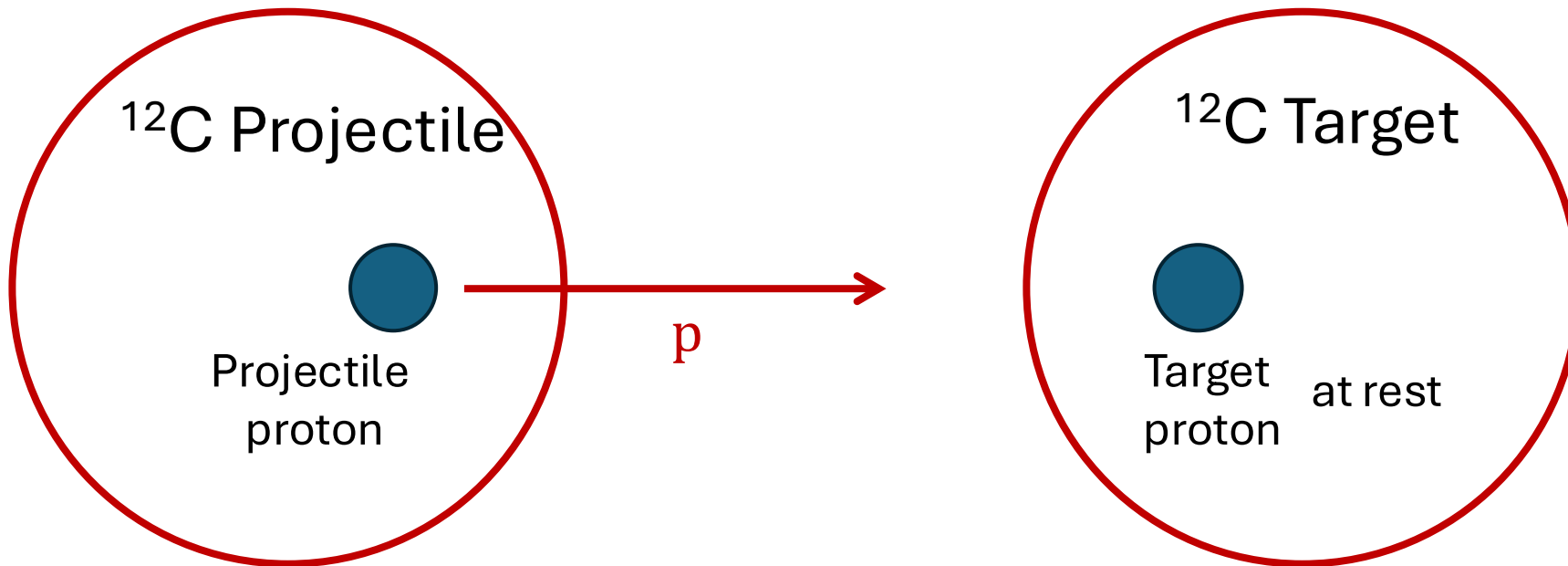
See G.B.'s talk at 2022 Coll. Meeting in Perugia

At our energies, Nucleus-Nucleus collisions proceed at first as a number of elastic binary nucleon-nucleon collisions. The energy released in these collisions will fragment both projectile and target, delivering also fast nucleons

All this is what intranuclear cascade or QMD or AMD or BME models describe using different assumptions and paths (*Further emission of nucleons, at lower energy, will follow in a second step after pre-equilibrium and nuclear evaporation stages*)

Let us now consider in more detail the kinematics of the fast nucleon-nucleon collisions

The collision in the Lab frame (200 MeV/u)



Projectile proton in average
(= forgetting Fermi momentum)

$$E_{\text{tot}} = 200 + 938.3 = 1138.3 \text{ MeV}$$

$$P = 644.5 \text{ MeV}/c, \quad \beta = 0.5662, \quad \gamma = 1.2132$$

Proton-Proton collision
in the CM frame

$$s = (E_1 + E_2)^2 - (P_1 + P_2)^2$$

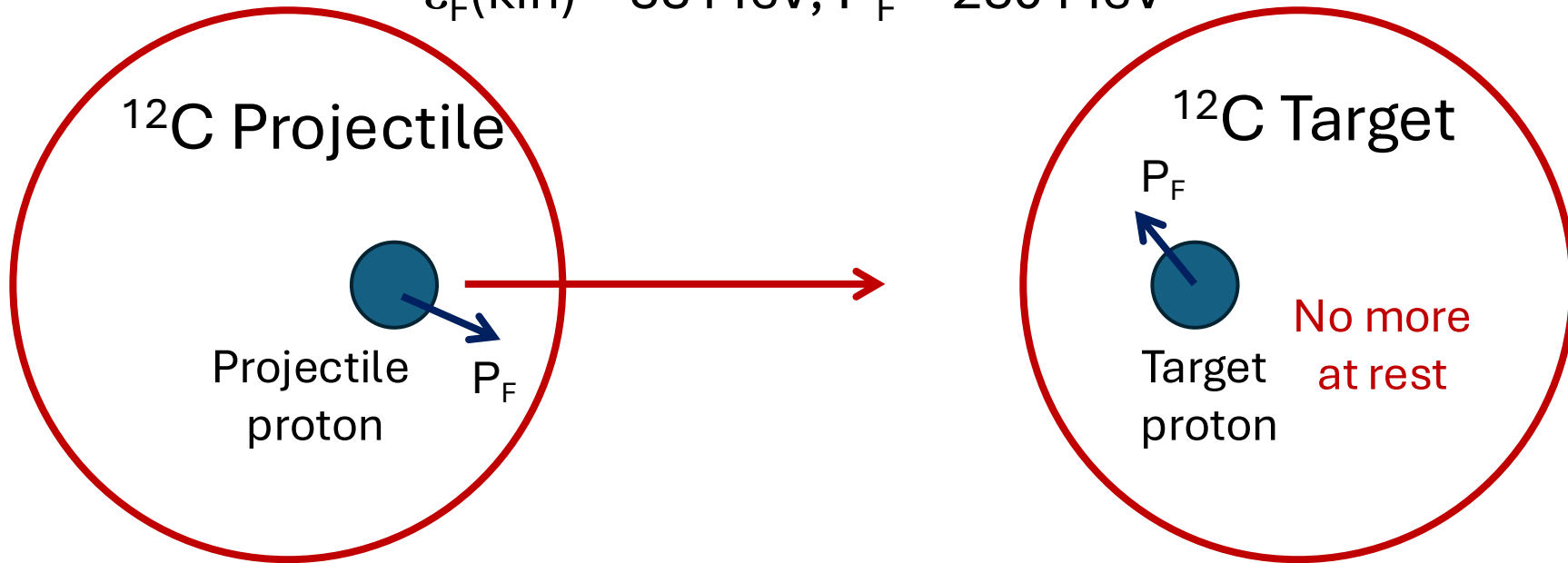
$$P^* = \sqrt{(s - 4m^2)} / 2$$

$$\sqrt{s} = 1975.3 \text{ MeV}$$

$$P^* = 306.3 \text{ MeV}/c \quad E^* = 987.0 \text{ MeV}$$

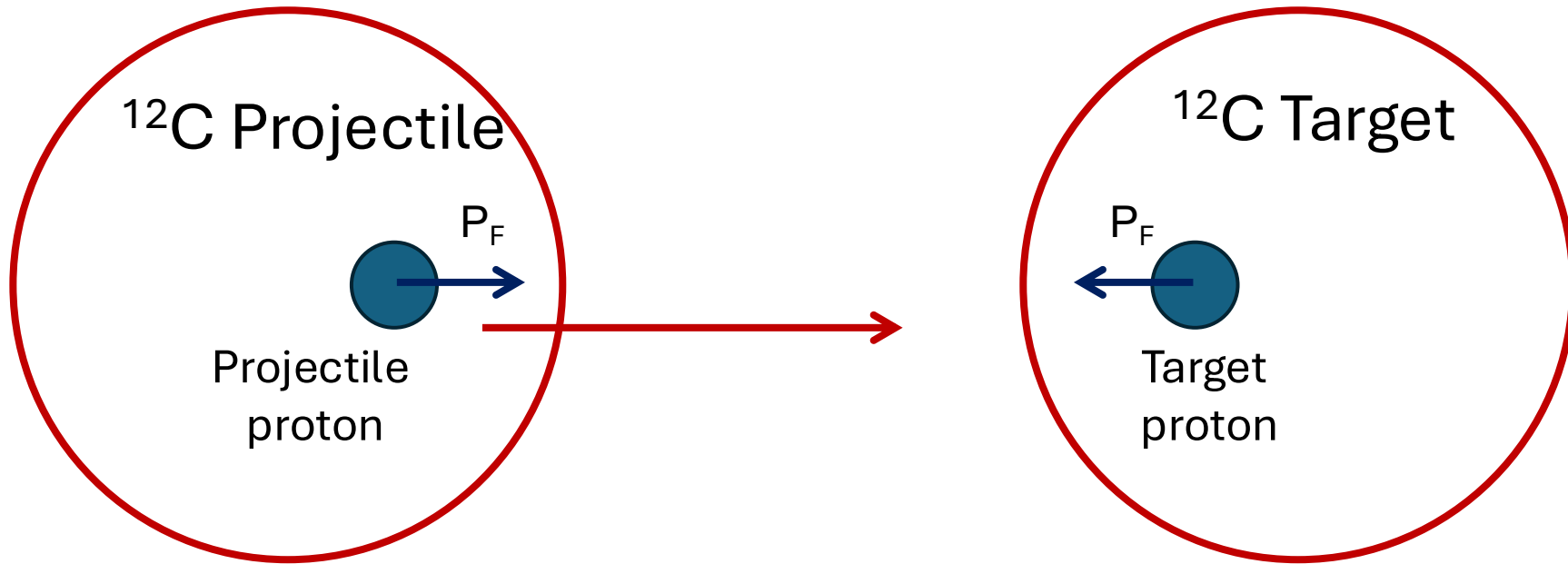
Considering Fermi Momentum

$$\varepsilon_F(\text{kin}) \sim 33 \text{ MeV}; P_F \sim 250 \text{ MeV}$$



Limiting ourselves to 0° or 180° scattering in the CM frame of nucleon-nucleon collision, we have now **4 extreme cases**

Case A

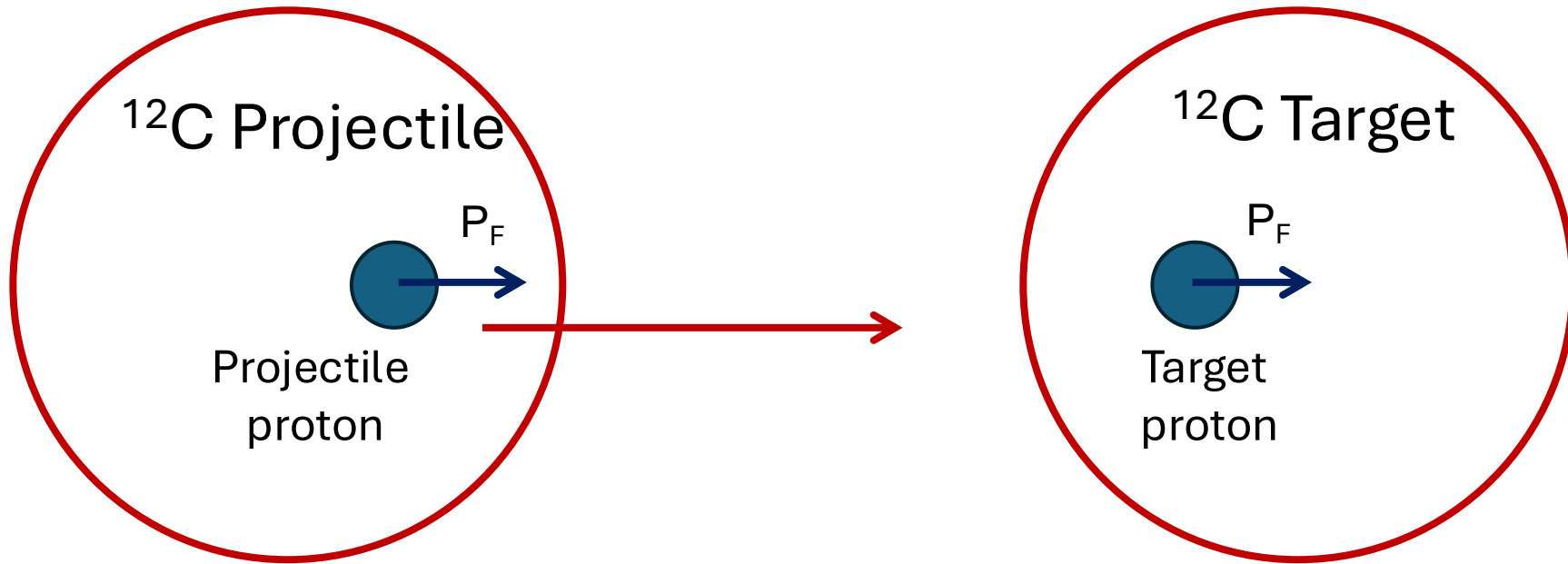


Projectile proton: $p_z = 894.5 \text{ MeV}/c$

Target proton: $p_z = -250 \text{ MeV}/c$

$$\sqrt{s} = 2173.9 \text{ MeV} \quad P^* = 548.7 \text{ MeV}/c \quad E^* = 1086.9 \text{ MeV}$$

Case B



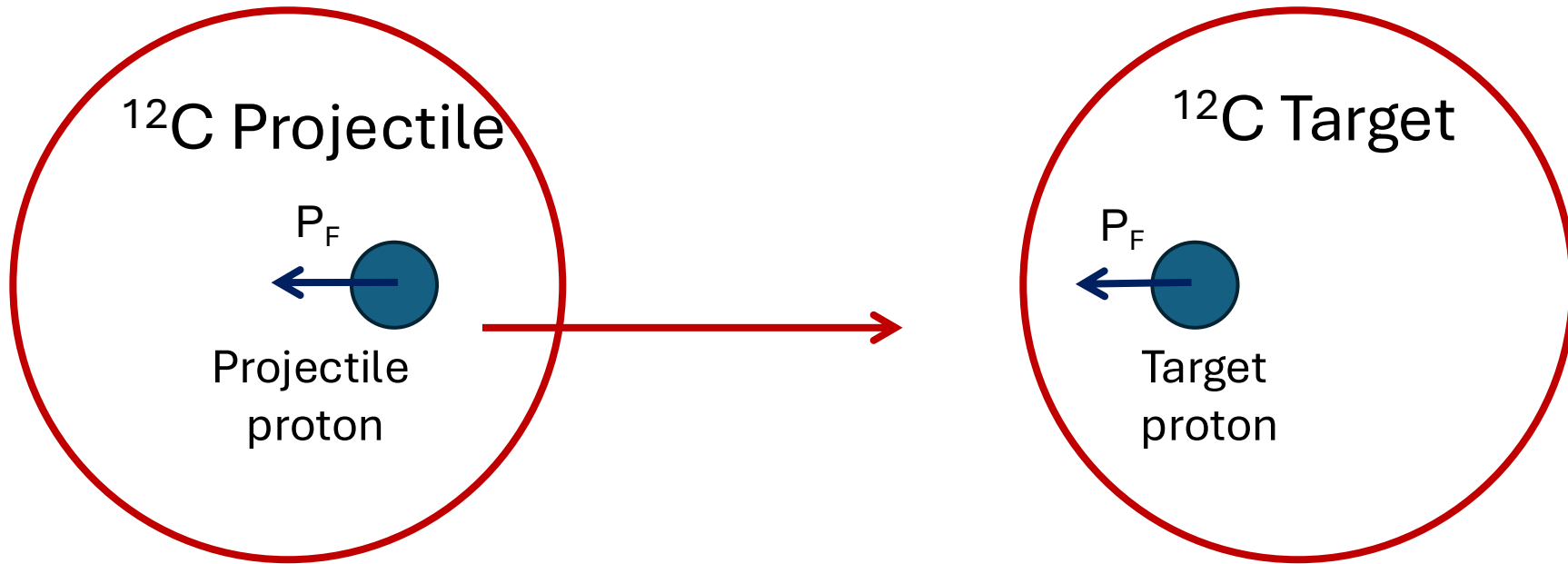
Projectile proton: $p_z = 894.5 \text{ MeV}/c$

Target proton: $p_z = +250 \text{ MeV}/c$

$$\sqrt{s} = 1957.4 \text{ MeV} \quad P^* = 278.2 \text{ MeV}/c \quad E^* = 978.7 \text{ MeV}$$

close to average case

Case C



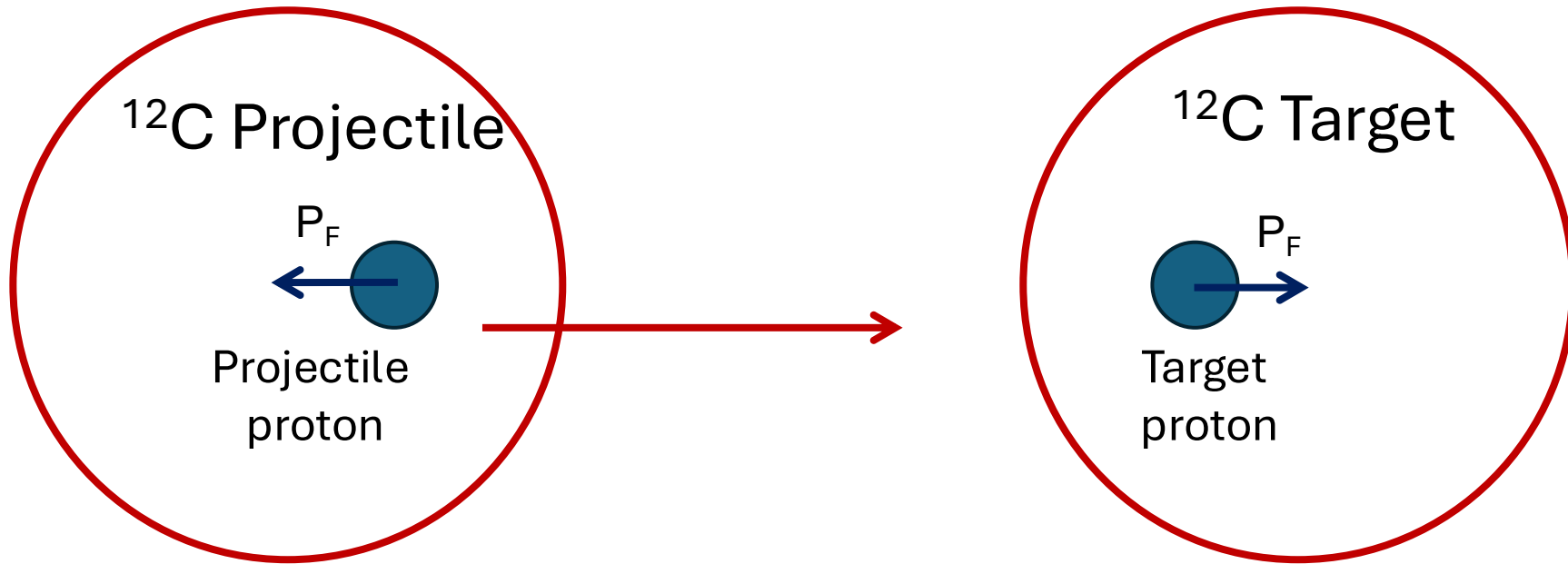
Projectile proton: $p_z = 394.5 \text{ MeV}/c$

Target proton: $p_z = -250 \text{ MeV}/c$

$$\sqrt{s} = 1983.6 \text{ MeV} \quad P^* = 321.4 \text{ MeV}/c. \quad E^* = 991.8 \text{ MeV}$$

close to average case

Case D



Projectile proton: $p_z = 394.5 \text{ MeV}/c$

Target proton: $p_z = +250 \text{ MeV}/c$

$$\sqrt{s} = 1881.6 \text{ MeV} \quad P^* = 68.4 \text{ MeV}/c \quad E^* = 940.8 \text{ MeV}$$

The minimum \sqrt{s} case

Boosting from CM to Lab system

$$\vec{\beta}_{\text{CM}} = (\vec{P}_1 + \vec{P}_2)/(E_1 + E_2), \quad \gamma_{\text{CM}} = (E_1 + E_2)/\sqrt{s}$$

$$E_{\text{lab}} = \gamma_{\text{CM}} (E^* \pm \beta_{\text{CM}} P^*) \quad + \text{ for } \theta^*=0^\circ, - \text{ for } \theta^*=180^\circ$$

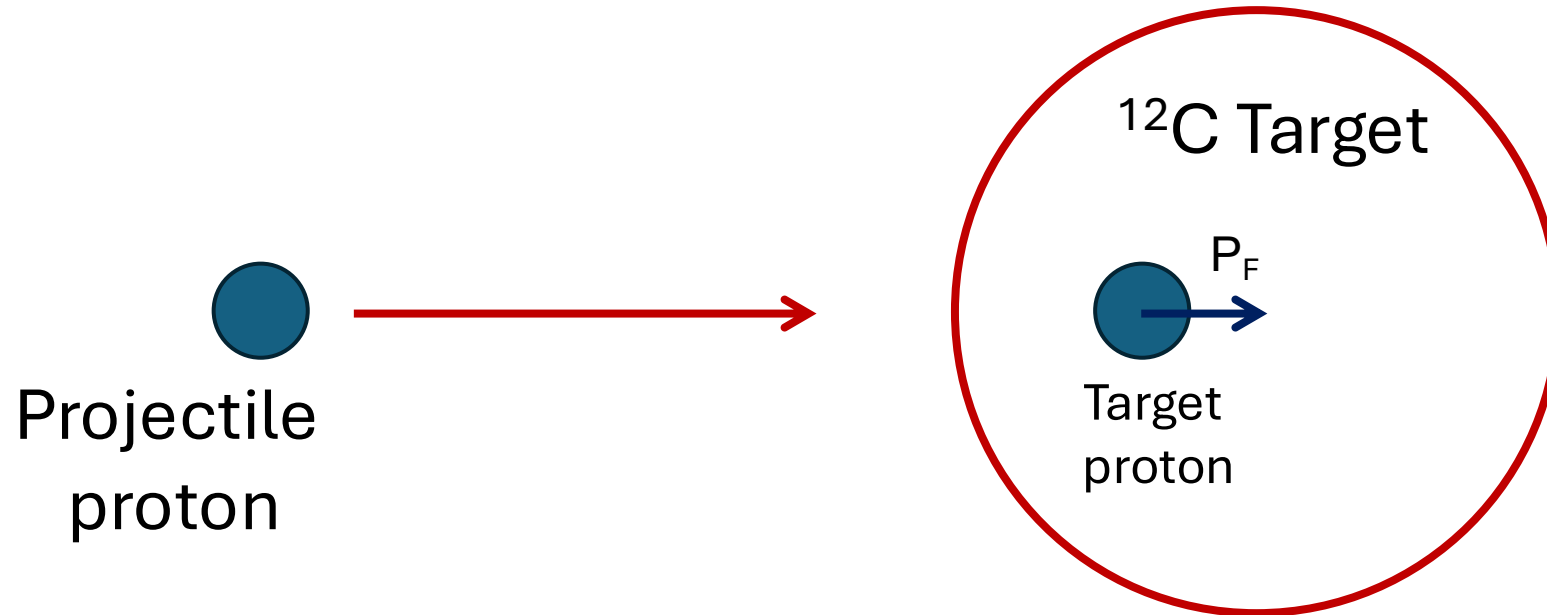
Case A (max \sqrt{s}): $p^* = 548.7 \text{ MeV}/c$, $\beta_{\text{CM}} = 0.2842$, $\gamma_{\text{CM}} = 1.0430$

$$\theta^*=0^\circ \rightarrow \text{Max } E_{\text{lab}} = 1296.4 \text{ MeV} \quad \text{Max } T_{\text{lab}} \sim 358 \text{ MeV} \leftarrow$$

$$\theta^*=180^\circ \rightarrow \text{Min } E_{\text{lab}} = 971.1 \text{ MeV} \quad \text{Min } T_{\text{lab}} \sim 33 \text{ MeV}$$

Case B gives the same results, Cases C and D give $\text{Max } T_{\text{lab}} \sim 80 \text{ MeV}$

Notice: that is different from target fragmentation occurring in proton-Nucleus!



In this case $T_{\max} \sim 200 \text{ MeV} \sim \text{equal to Projectile } T$

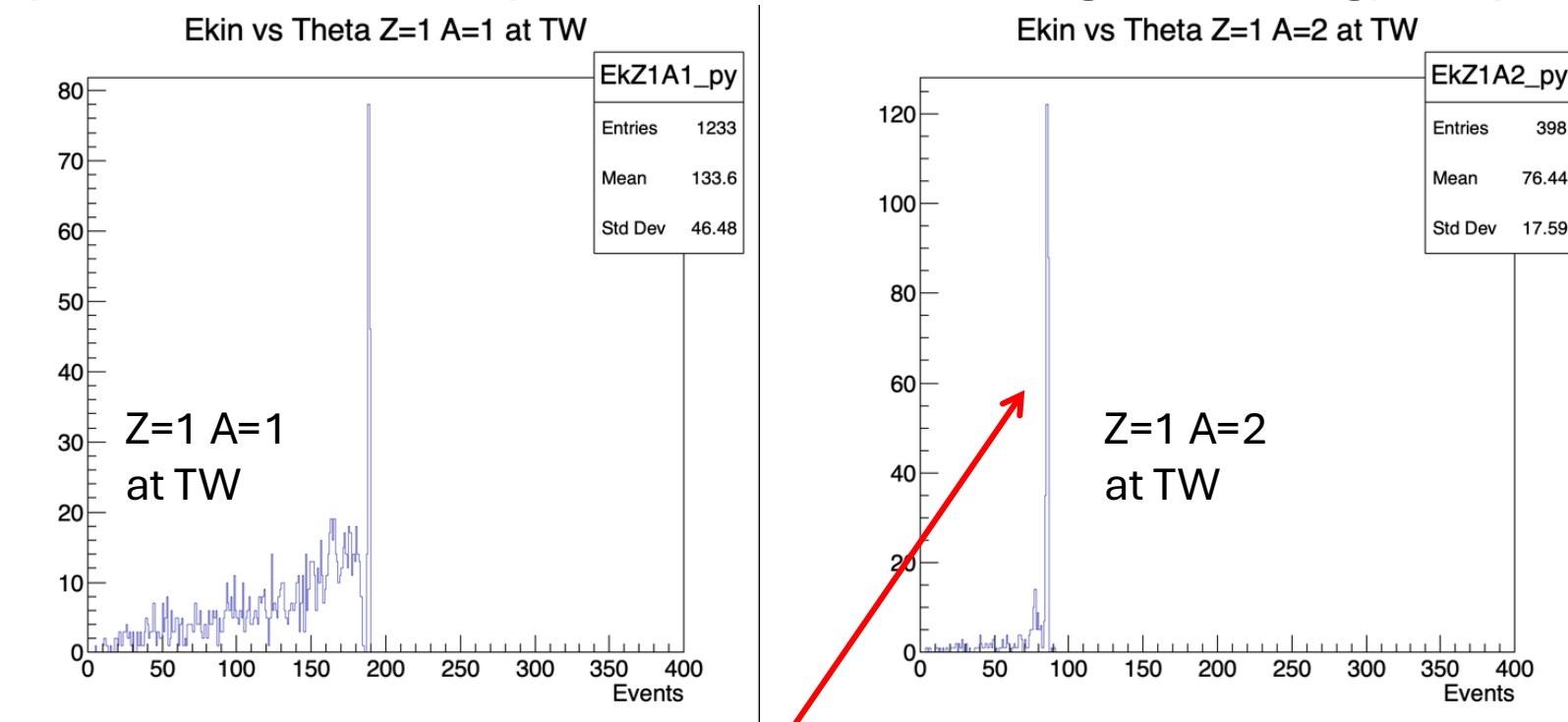
Therefore:

- We are experimentally observing a tail of the (fast) target fragmentation process in N-N collisions
- This confirms the essential role of the binary nucleon-nucleon interaction mechanism in the N-N interactions of our interest
- We cannot use this kind of observation to measure a cross section, but it can be important to validate models
- In all our reconstructed events (not only those with $Z=6$) there will be always a fraction of them containing at least 1 proton from target fragmentation (deuterons can reach \sim half the max. energy of protons). **This is some background for $Z=1$ cross section**
- This process could be probably studied with higher efficiency by means of emulsions
- Of course, there also fast neutrons from the same mechanism. At this energy there is \sim no difference between p and n
- Of course we cannot detect, in direct kinematics, target nucleon emission deriving from later stages of N-N interaction (such as pre-equilibrium and evaporation)

A dream for the future:

- Using a proton beam we should be able (efficiency allowing...) to observe the same kind of process, but with protons not exceeding the energy of primary

MC truth



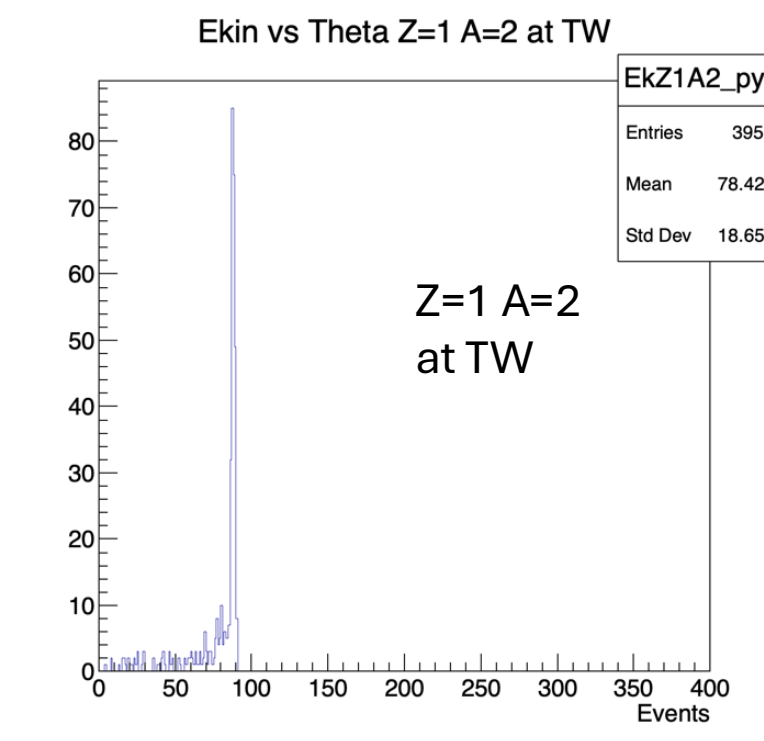
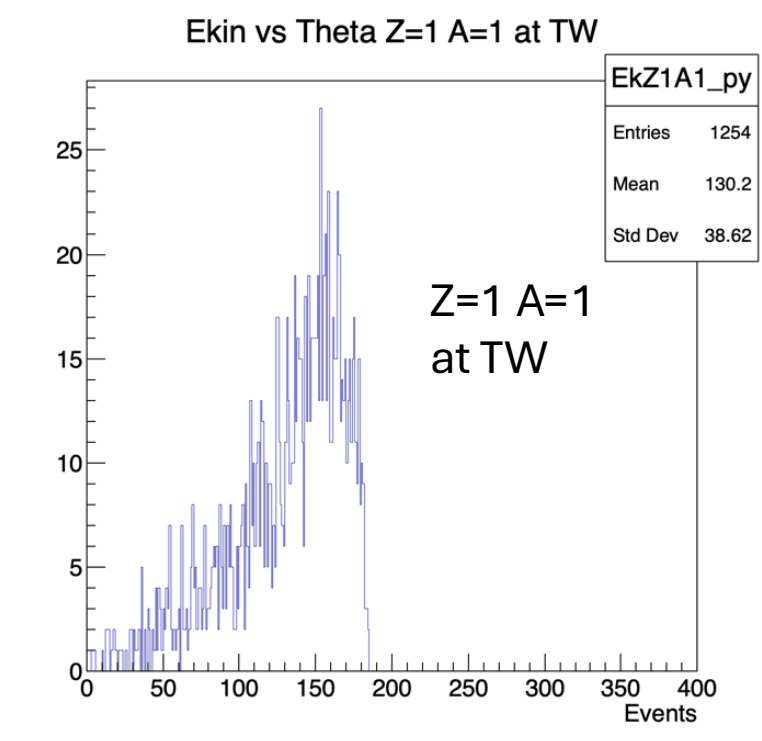
- Again, emulsions would be a good candidate
- With a proton beam one could also study other interesting processes in target fragmentation, like **deuteron knock-out** *(to be illustrated in a future talk)*

A more ambitious dream:

A proton beam has the problem of the large background from non interacted primaries and from elastic scattering

A 100-200 MeV **neutron beam** (~unfeasible in practice) would be ideal: **a much cleaner identification of fast charged fragments from target!**

MC truth





Cinderella sings: “A dream is a wish your heart makes
When you're fast asleep...”