CNAO2025: measurement of primary P

INFN Milano

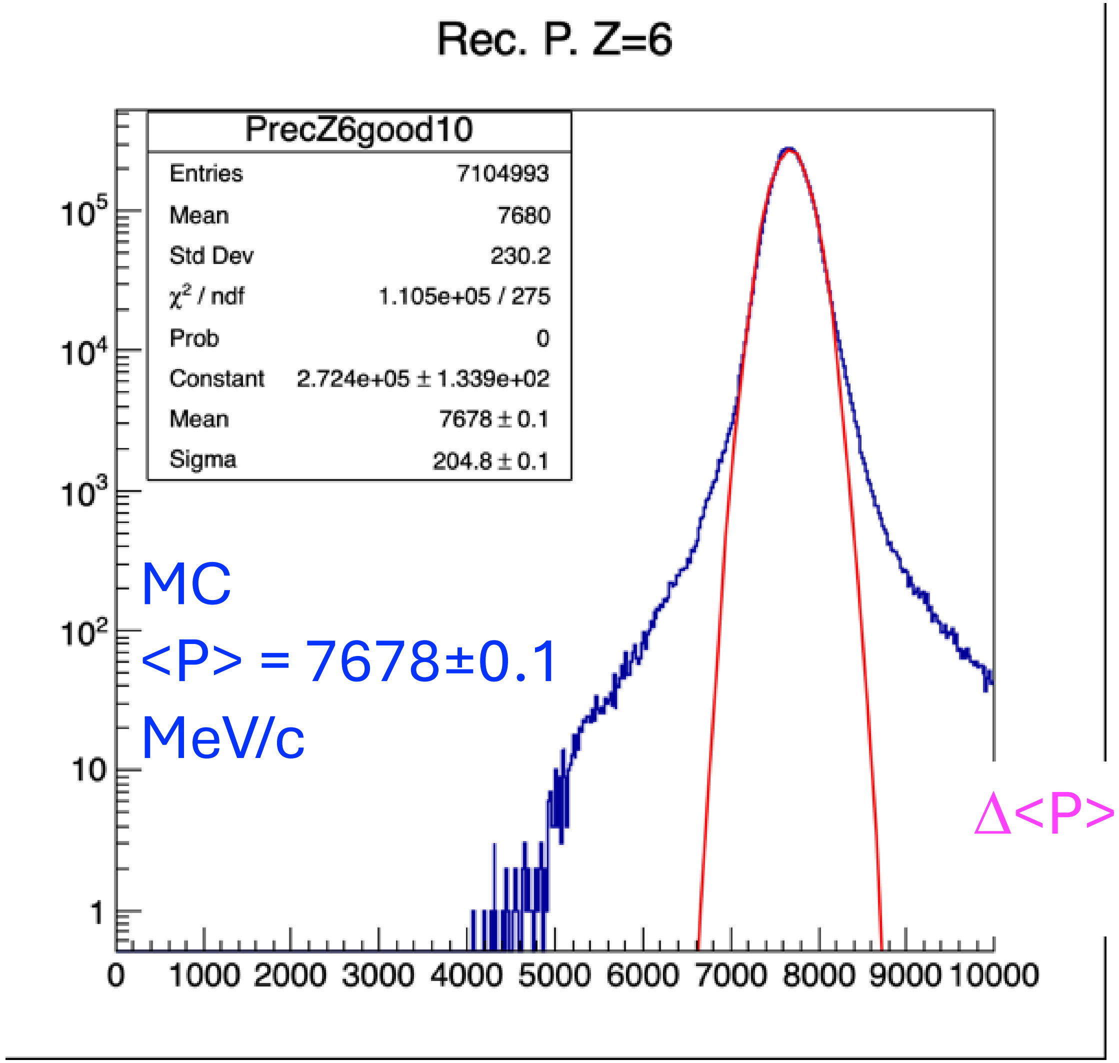
Introduction and outline

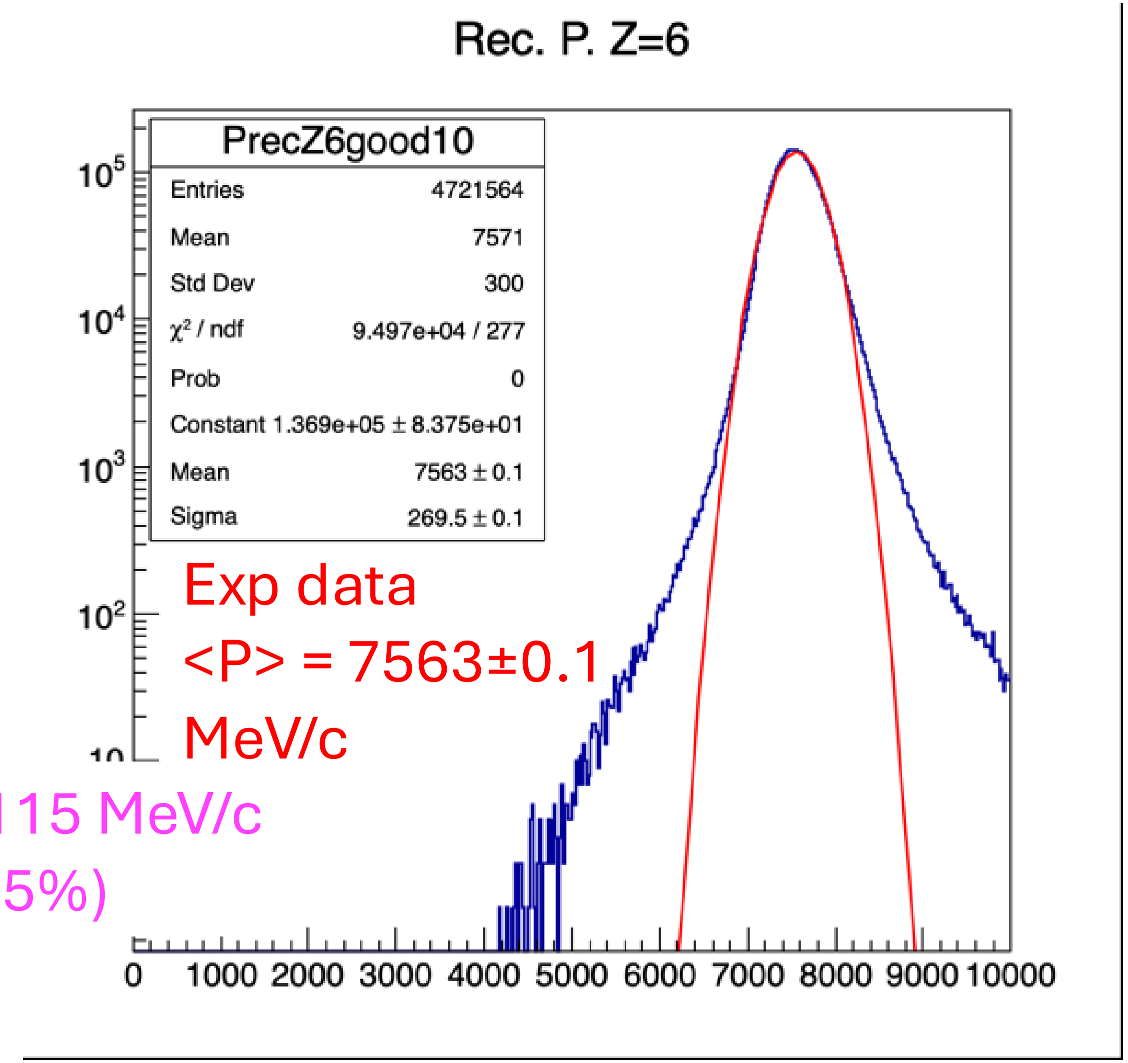
- At the last meeting we showed mass reconstruction from the combination of P and ToF for secondary fragments
- The need to correct for some P overestimation was confirmed
- The question of checking P reconstruction for the primary particles was left open. Here we present results on this subject
- Spoiler: we might have some unexpected systematics

1st Analysis: Runs with C target

- Genfit reconstruction
- Event Selection: ≥1 reconstructed global track and Z_{id} = 6 in TW and MSD
- Tracks with ≥10 points
- P obtained from glbtrck->GetTgtMomentum() ➔ in the case of primaries, momentum is estimated at the center of target

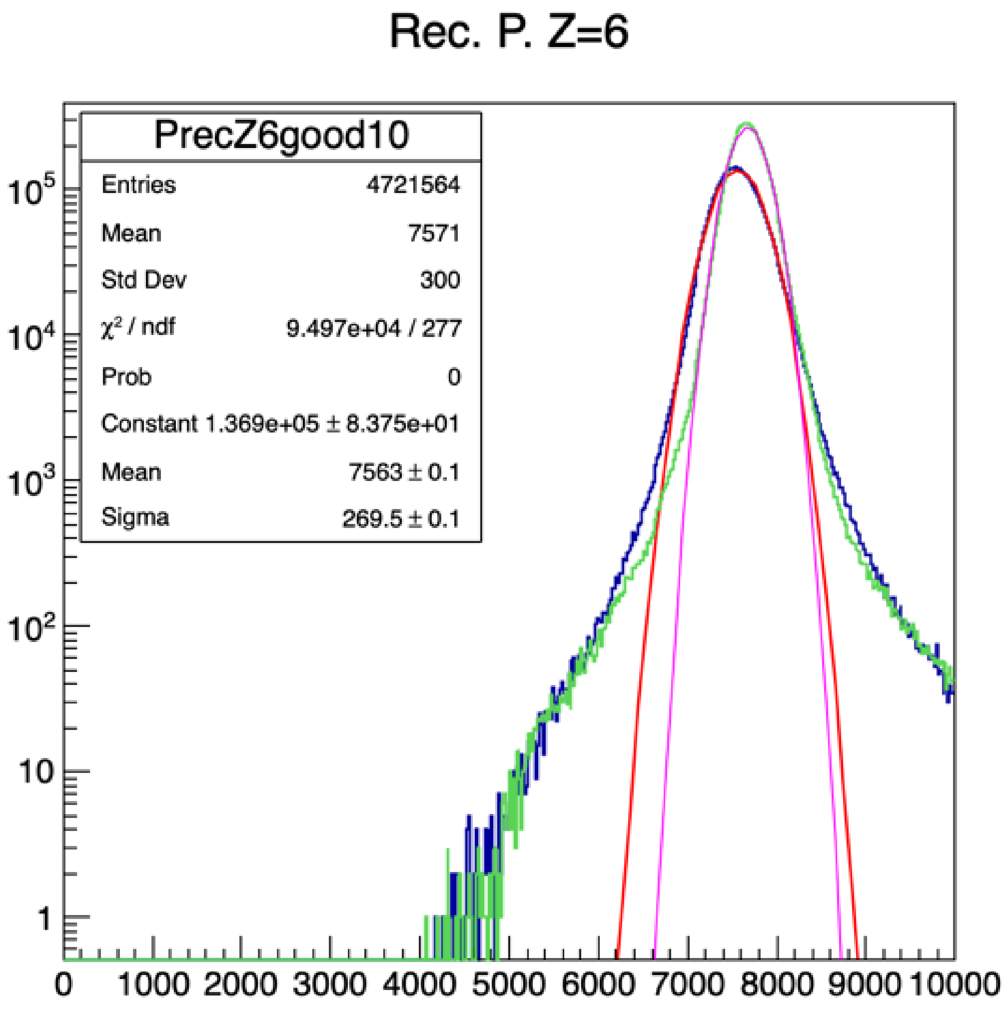
Data – MC comparison (C target)





Δ<P> = 115 MeV/c
(1.5%)

We are assuming to have taken data at 200 MeV/u (actually 200.61 MeV/u)



Of course, MC follows the same assumption

Peak of Data corresponds to **193.2 MeV/u**

Peak of MC corresponds to **198.6 MeV/u**

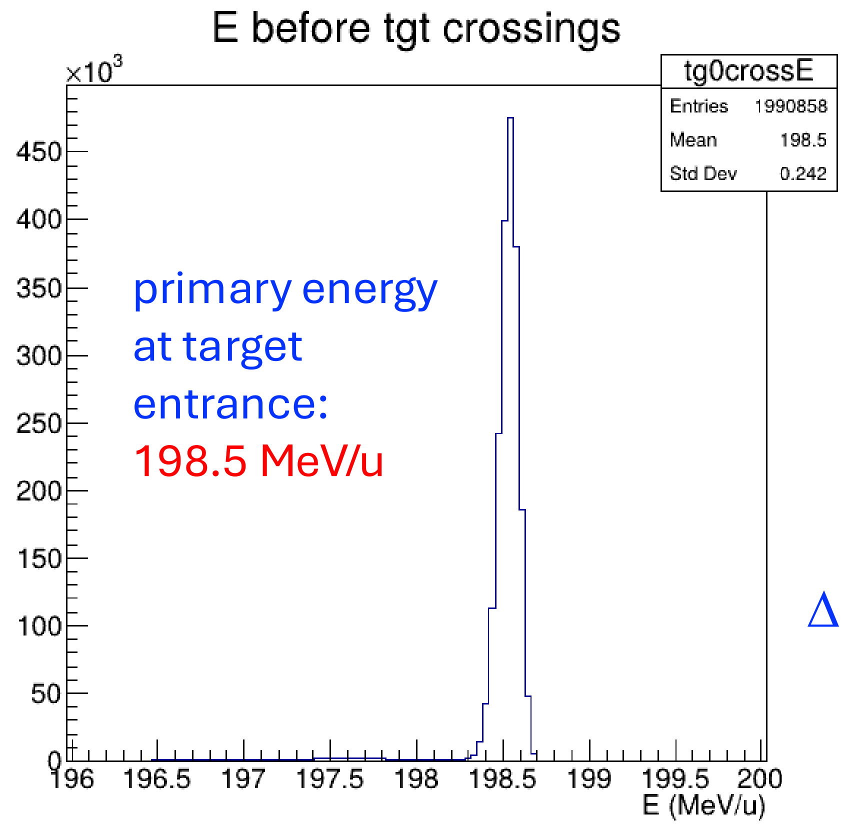
ΔE (MC-Data) = 5.4 MeV/u
+2.7%
(the relation betwee P and E is not linear)

Other observation:
σ_P(MC) = 205 MeV/c
σ_P(Data) = 270 MeV/c

But in the following we shall discuss only the ΔE issue

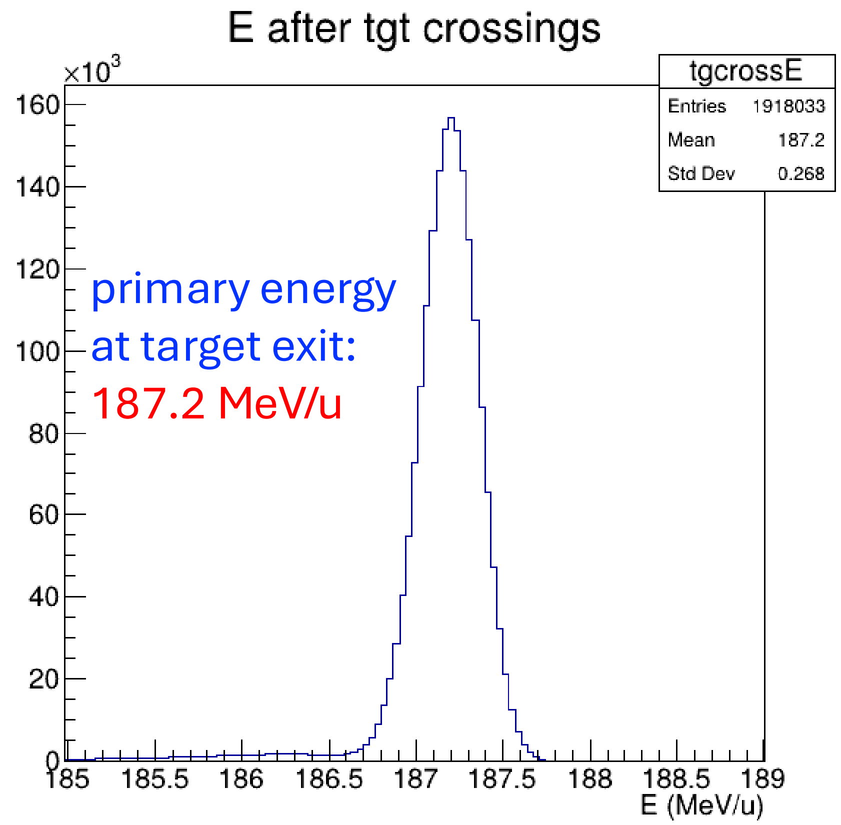
Question 1: is the MC consistent?

Starting from the assumed energy value in the beam pipe (200.61 MeV/u)



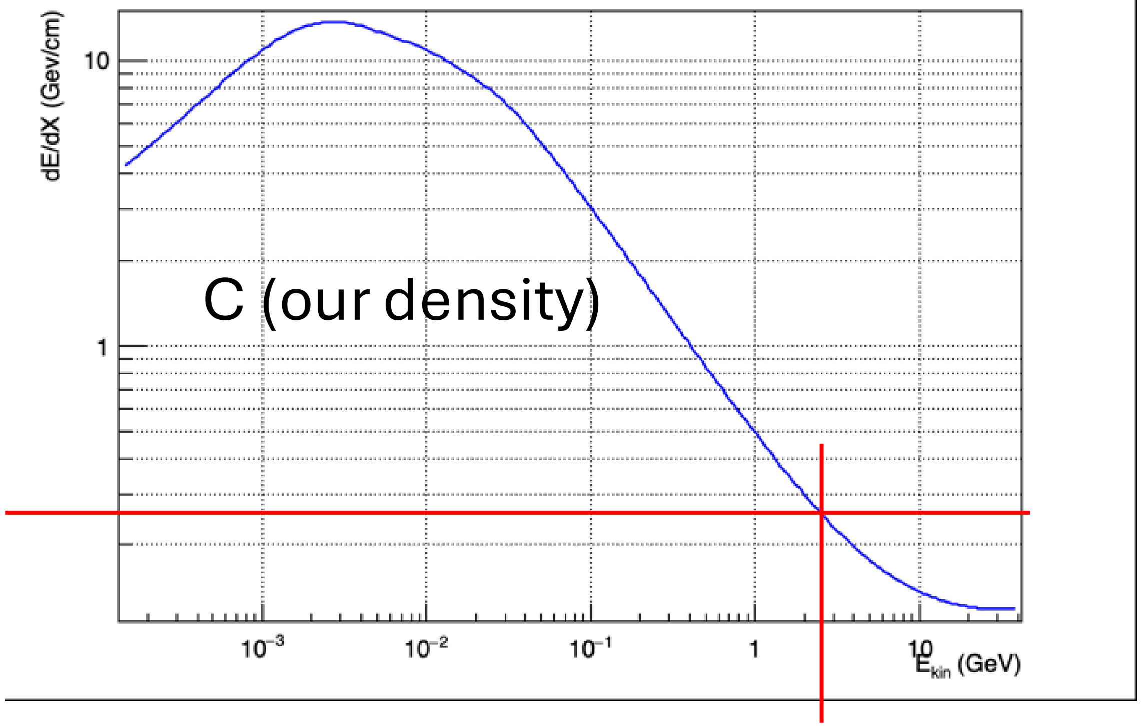
MC truth

ΔE = 11.3 MeV/u



At **target center** ➔ E = 192.9 MeV/u

dE/dx vs total Ekin for ^{12}C in C



At 200 MeV/u (2400 MeV): dE/dx~ 266 MeV (total)/cm = 26.6 MeV/mm ~ 2.2 MeV/u/mm

➔ Energy loss in target is consistent

➔ Energy at target center ~192.8 MeV/u ➔ P ~ 7553.9 MeV/c

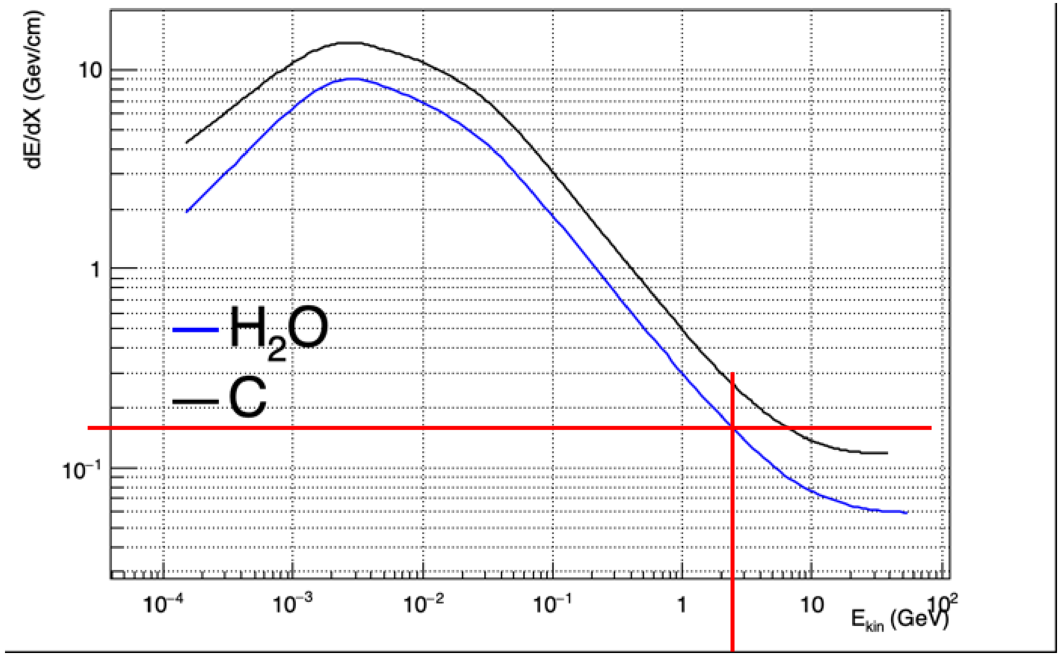
➔ Erec = 198.6 MeV/u, Prec = 7678 MeV/c, but we already know (from previous analyses) that Rec. P is overestimated by 1 - 2%

➔ the MC reconstruction is consistent

Question 2: is the MC input energy assumption correct?

Warning: at present we are not considering the C-fiber window at beam exit of the beam pipe

dE/dx vs total Ekin of ^{12}C in C and H_2O



C-fiber window estimated to be equivalent to ~1 mm H_2O

(M. Pullia, private communication)

At 200 MeV/u (2400 MeV): dE/dx~ 160 MeV (total)/cm = 16 MeV/mm ~ 1.3 (MeV/u)/mm

➔ this is not enough to reconcile MC and data (you would need ~196 MeV/u at the entrance of ST and ~194.6 MeV at Target entrance)

Something more about the energy assumption

From CNAO ^{12}C beam library

Energy (MeV/u)	mm H_2O
195.18	80
197.91	82
200.61	84
203.29	86
205.95	88

A step of Bragg peak position of 2 mm corresponds to a change of energy of the order of ~2.7 MeV/u

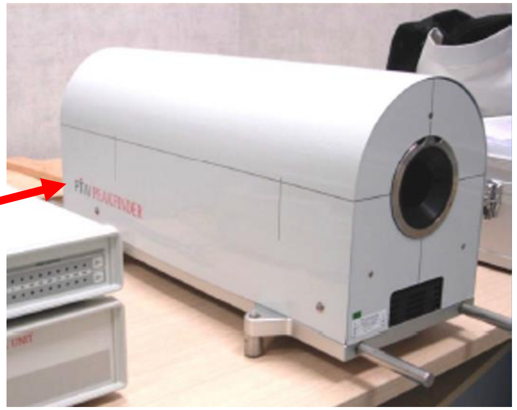
Our nominal energy at CNAO2025

These values are supposed to be the energy in the beam pipe

According to the convention used at CNAO, this number represents the position of Bragg Peak

➔ Bragg Peak position in Water is what was **actually measured during the commisioning**

Bragg Peak measurement at CNAO



At CNAO, to measure the Bragg peak, a PTW "peak finder" is used. It measures the ratio between an entrance chamber and a depth chamber in a "water column" (variable position with excellent resolution in the order of 10 microns)

- The peak finder is placed at the isocenter.
- **Dose delivery is in and with carbon, ripple filters are inserted.**

In FOOT we do not have Dose Delivery chambers and Ripple Filters

The measured peak position is then set back by ~3 mm to compensate the effect of Dose Delivery with ripple filters

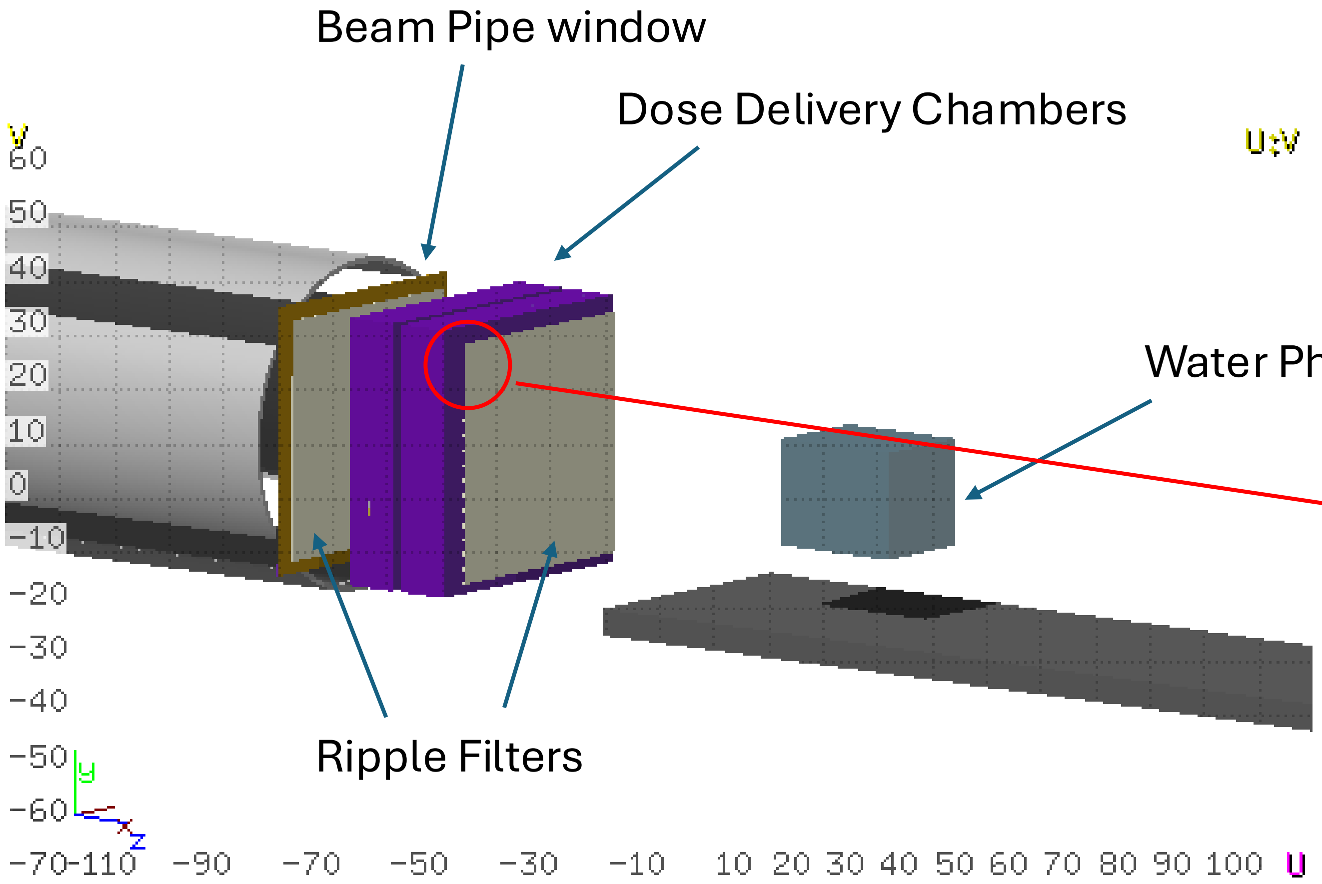
For example: if you send a "30 mm" beam, the peak position is found at 27 mm depth. Without it, it would be 30 mm.

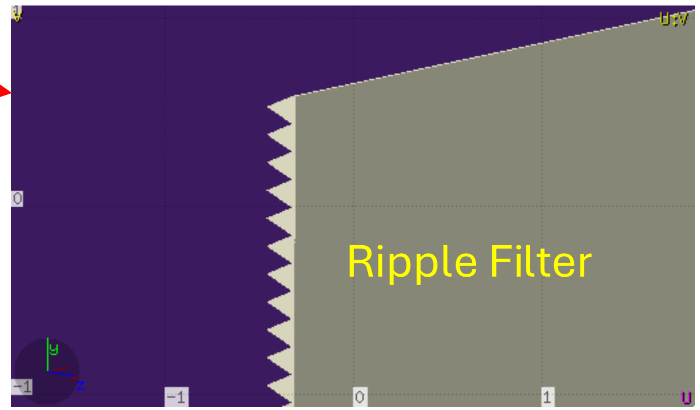
(M. Pullia, private communication)

Simulation check: geometry

The Dose Delivery and Ripple Filter geometry in FLUKA was prepared years ago at CNAO.

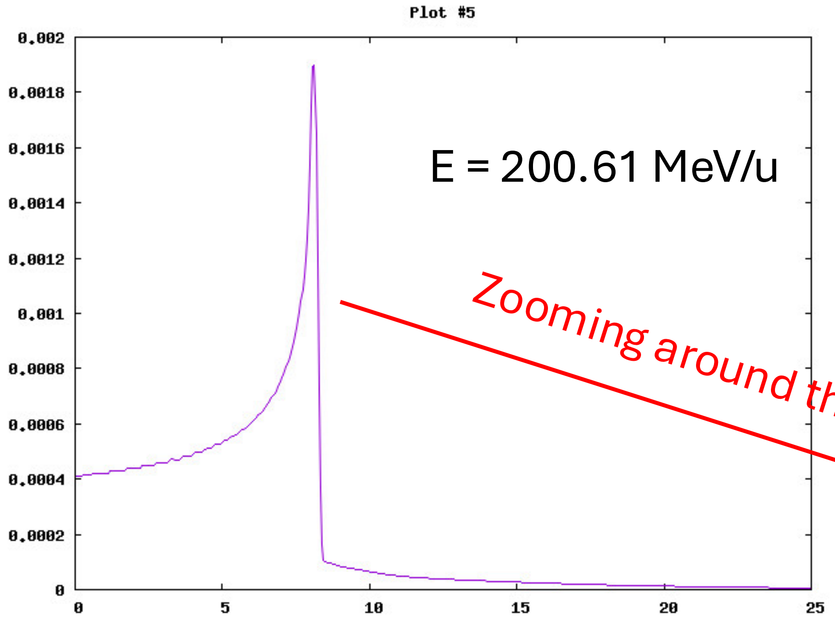
We use it, for instance, for the INSIDE clinical trial





We use as energy inside the vacuum pipe the 200.61 MeV/u value

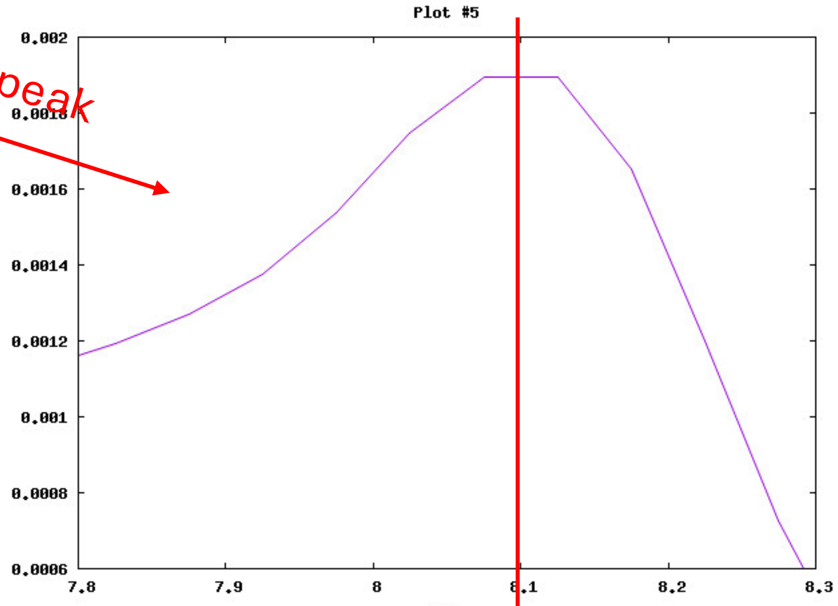
Simulation check: results



Zooming around the peak

Bragg Peak location predicted at 81 mm

➔ by adding 3 mm you get the expected 84 mm



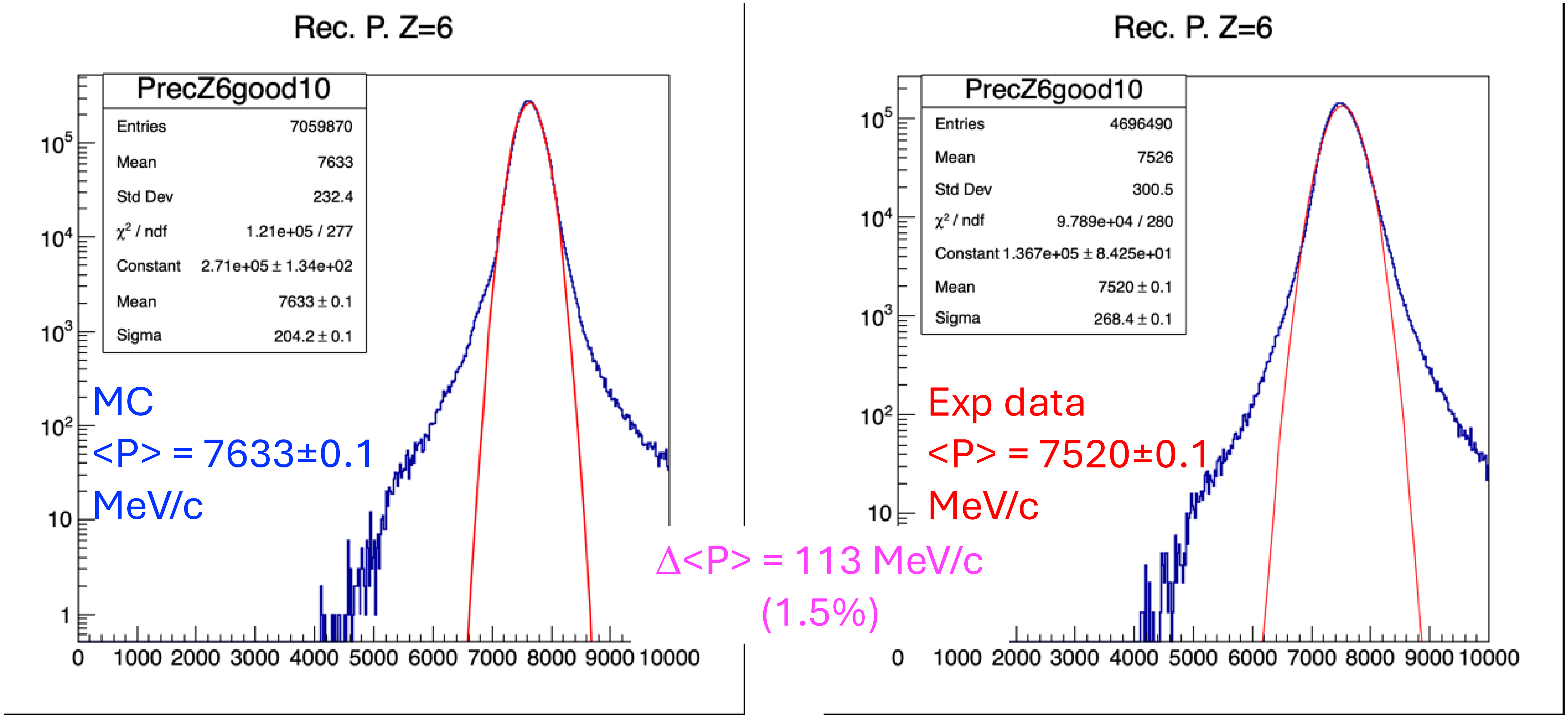
not a novelty: measurements and FLUKA MC results were checked during CNAO commissioning

➔ Therefore it is correct to assume that the input energy is the value to be used inside the beam pipe

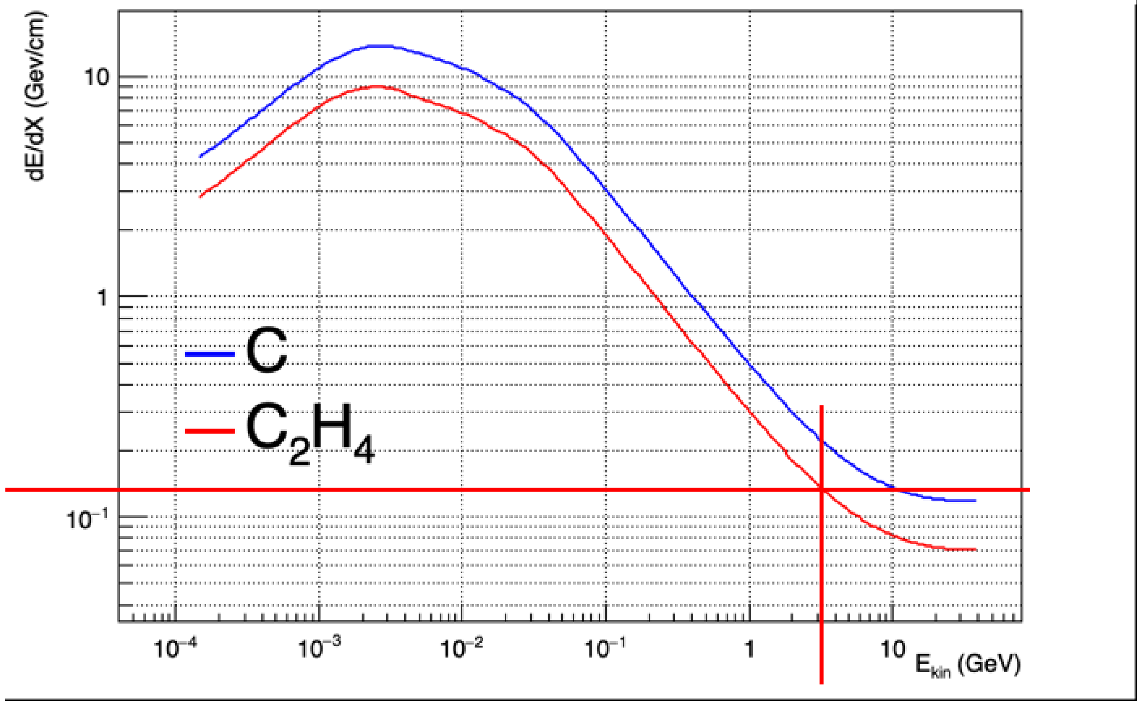
2nd Analysis: Runs with C_2H_4 target

- Exactly the same selection cuts and procedure as for the C target case

Data – MC comparison (C_2H_4 target)



dE/dx vs total Ekin of ^{12}C in C and C_2H_4



At 200 MeV/u (2400 MeV): dE/dx~ 162 MeV (total)/cm = 16.2 MeV/mm ~ 1.35 (MeV/u)/mm

very similar to H_2O, but target is thicker by a factor of 2

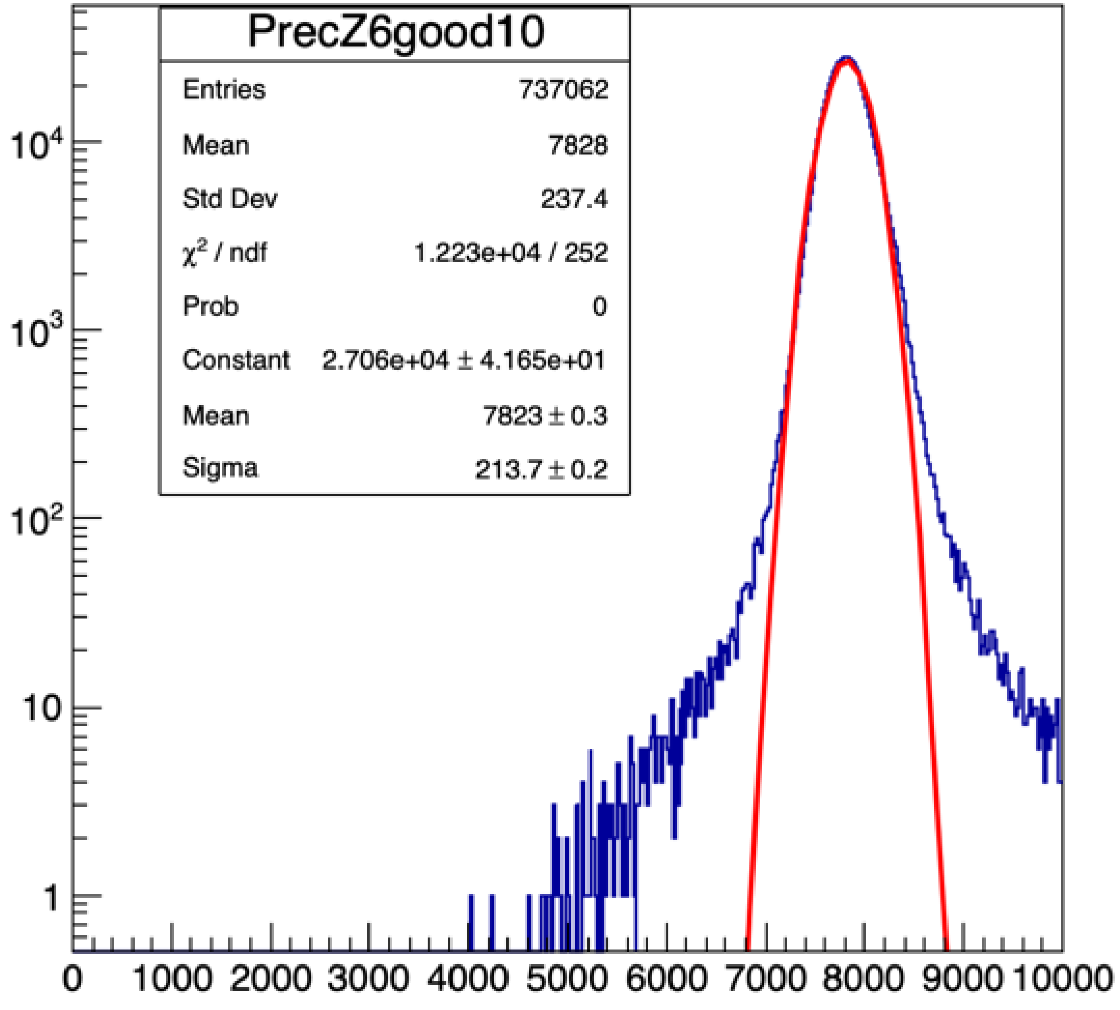
➔ Energy at target center is now ~191.6 MeV/u ➔ P ~ 7528 MeV/c (slightly lower than for C target). ➔ Reconstruction overestimated by 1.4%

➔ Both MC and exp. data appear to scale with target ~in agreement with expectations

3rd Analysis: Runs with no target

- Only 4 runs to be considered safe: 8017, 8018, 8019, 8020, ~128600 triggers
- Exactly the same selection cuts and procedure as for the C target case

MC



<P> = 7823±0.3 MeV/c
E = 205.5 Mev/u

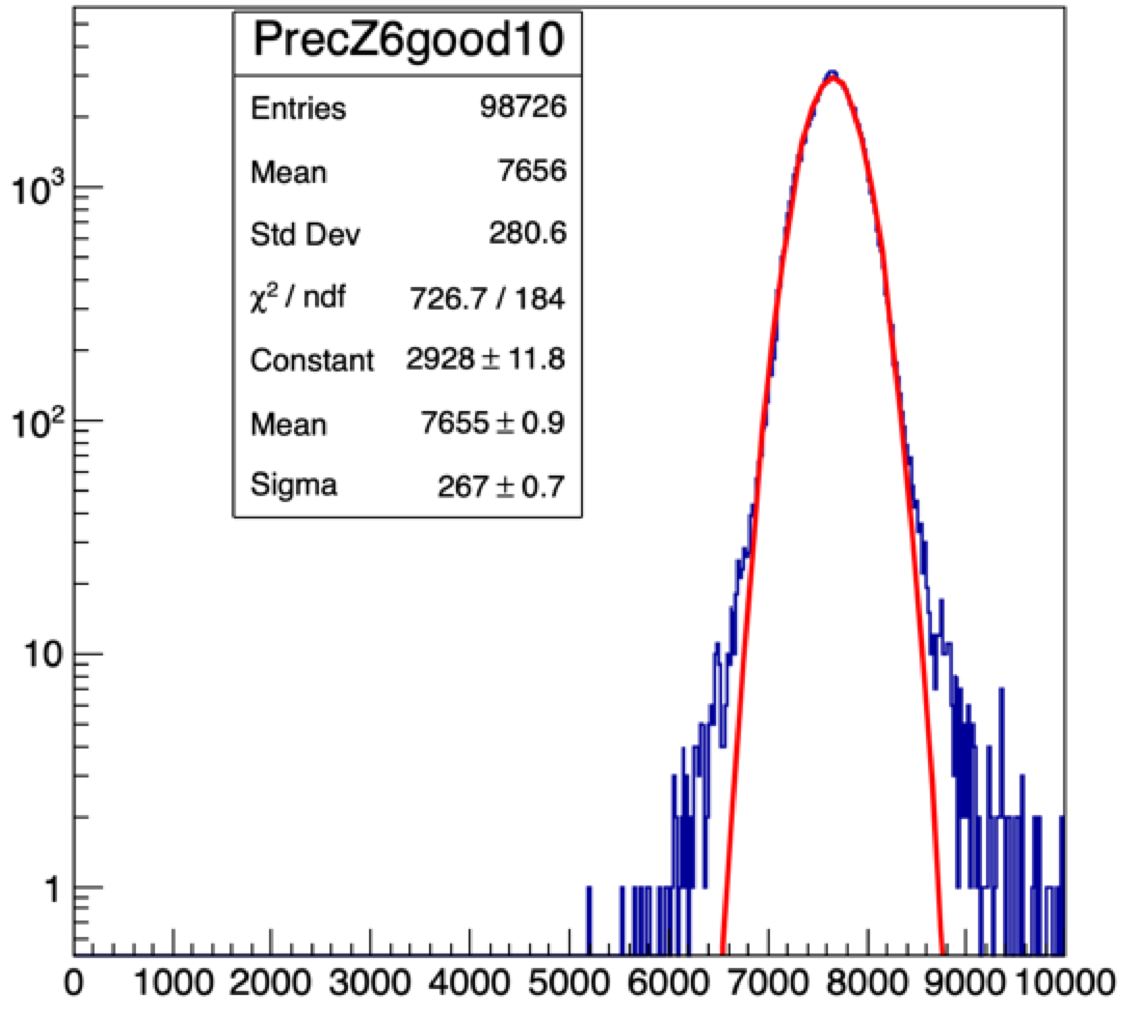
Obviously too high!
(MC truth = 198.5 MeV/u)

~199.7 MeV/u after correction for possible P overestimation by 1.6%

~198.2 MeV/u after correction for possible P overestimation by 2%

Much closer to MC truth

Exp. data



<P> = 7655±0.9 MeV/c

E = 197.5 Mev/u

Assuming the same correction for P overestimation as in MC, we get **~192 MeV/u**

Again, it is too low (~6.5 MeV/u)

Material budget along primary tracks (C target)

From Beam Exit to Target	1.15 mm H_2O
From Target to VT:	8.72
From VT to IT:	0.9
From IT to MSD:	1.07 / 1.75
From MSD to TW:	3.28
Total:	**15.1 / 15.8 mm H_2O**

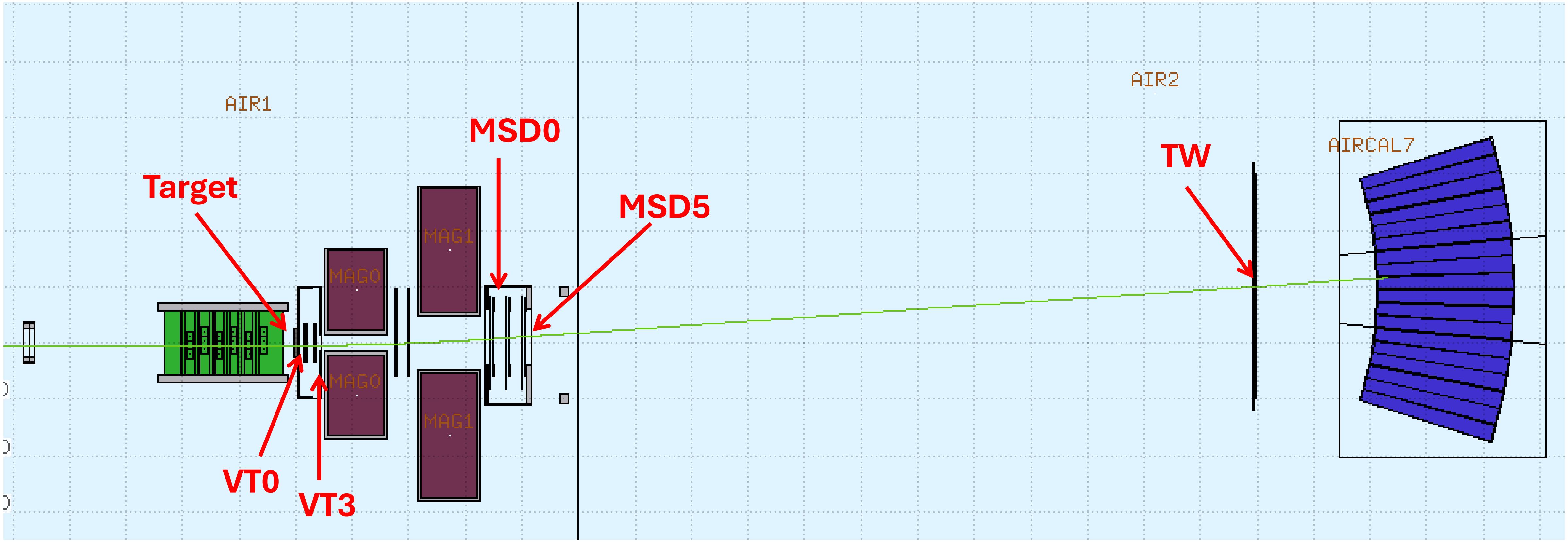
Even primary tracks may cross either **1** or **2** IT ladders

In order to reconcile MC and Data we need an additional thickness of **~4.2 mm H_2O** in the total material budget (**+27 - 28% !!**).

Where?

We can check the evolution of P along the tracks

P evaluated at different depths



Test on C target: <P> from gaussian fit at each position (MeV/c)

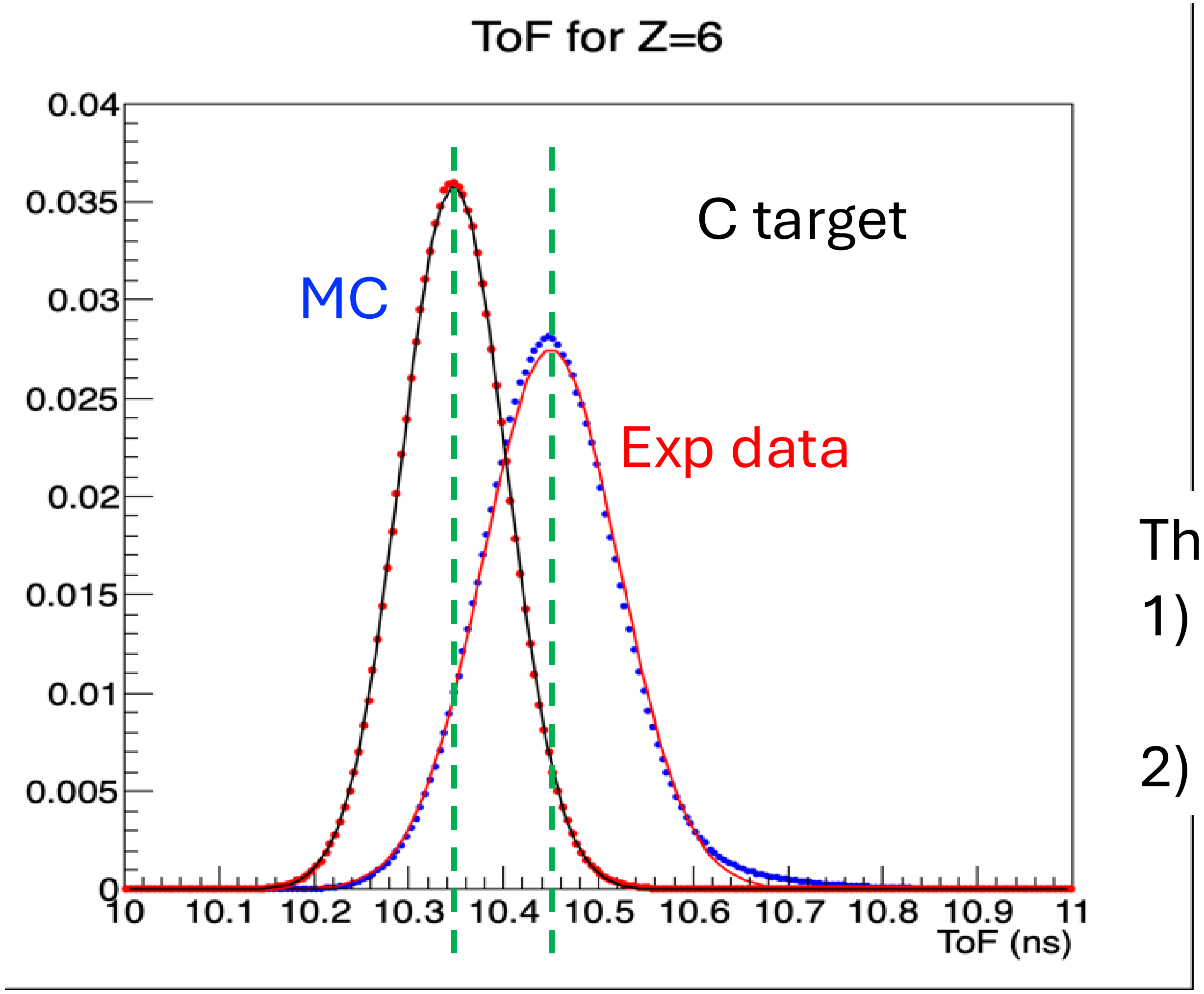
	MC		DATA		MC -DATA	
	P (MeV/c)	E (MeV/u)	P (MeV/c)	E (MeV/u)	ΔP (MeV/c)	ΔE (MeV/u)
Target	7678.0	198.6	7563.0	193.2	115.0	5.4
VT0	7558.0	193.0	7439.0	187.5	119.0	5.5
VT3	7547.0	192.5	7430.0	187.1	117.0	5.4
MSD0	7526.0	191.5	7407.0	186.0	119.0	5.5
MSD5	7481.0	189.4	7360.0	183.8	121.0	5.6
TW	7388.0	185.1	7264.0	179.5	124.0	5.7

Fit error on P is always of the order 0.1 MeV/c

Apart from small variations of the order of few MeV/c (~1‰)
ΔP(MC-Data) is ~constant along the track

➔Tracks see the ~same material budget in both MC and Data

A last P-independent check: ToF comparison



Gaussian fits

MC: <ToF> = 10.3474 +/- 2e-05 ns

Data: <ToF> = 10.4497 +/- 3e-05 ns

Δ<ToF> = 0.102 ns

This could perfectly compatible with:

1) a difference in kinetic energy of ~5.5 MeV/u

OR

2) a mismatch, or error, in TW distance of ~2 cm

But ToF is not yet calibrated in CNAO2025: there is still the 2024 calibration

Warning: there might be also some circularity

The ToF we are considering in analysis is:
ToF(TW – SC) – ToF(Target – SC)

ToF(Target – SC) is not measured, it is calculated on the basis of the assumption on initial energy

At present, in both MC and Data analysis we were using:
ToF(Target-SC) = 47.15 cm/ beta(E=200.61 MeV/u) c ~ 2.767 ns
A difference of 5 MeV/u would imply a correction of the order of ~0.03 ns

Summary and conclusions(?)

- There is a difference of ~1.5% in the value of P reconstruction between MC and data

  Is this important?

- An independent ToF measurement could confirm this, but geometry has to be double checked and calibration for CNAO2025 has to be completed
- MC is demostrated to be self-consistent *(although this does not necessarily mean that FOOT simulation is correct)*
- The choice of input energy inside the beam pipe turned out to be consistent with CNAO measurements and assumptions
- Reconstruction scales consistently with target properties on both MC and Data
- P evolves ~in the same way along the track both in MC and Data: we have the material budget under control
- At present we remain with no explanation, *unless..*

Hypotheses and questions for discussion

<u>Assuming that</u> SHOE reconstruction behaves exactly in the same way for MC and Data:

But this would be quite a big thickness!

1. We are missing some material (~4.2 mm H_2O) of in the description of FOOT <u>upstream of the target</u> *(1 mm H_2O can be accounted by the beam window)*
2. OR there is some subtle problem with the magnetic field *(Yun suggests also the possible role of alignment of the magnetic system).* An independent ToF comparison could exclude this problem, after calibration and geometry check
3. OR could this be due to some wrong parameter in geometry? Or a difference in geometry beween MC and reconstruction?
4. OR for some unknown reason, the beam energy is not what it's supposed to be (lower by ~5 - 6 MeV/u)
5. OR ….???