Measurements of secondary particle production induced by particle therapy ion beams impinging on a PMMA phantom

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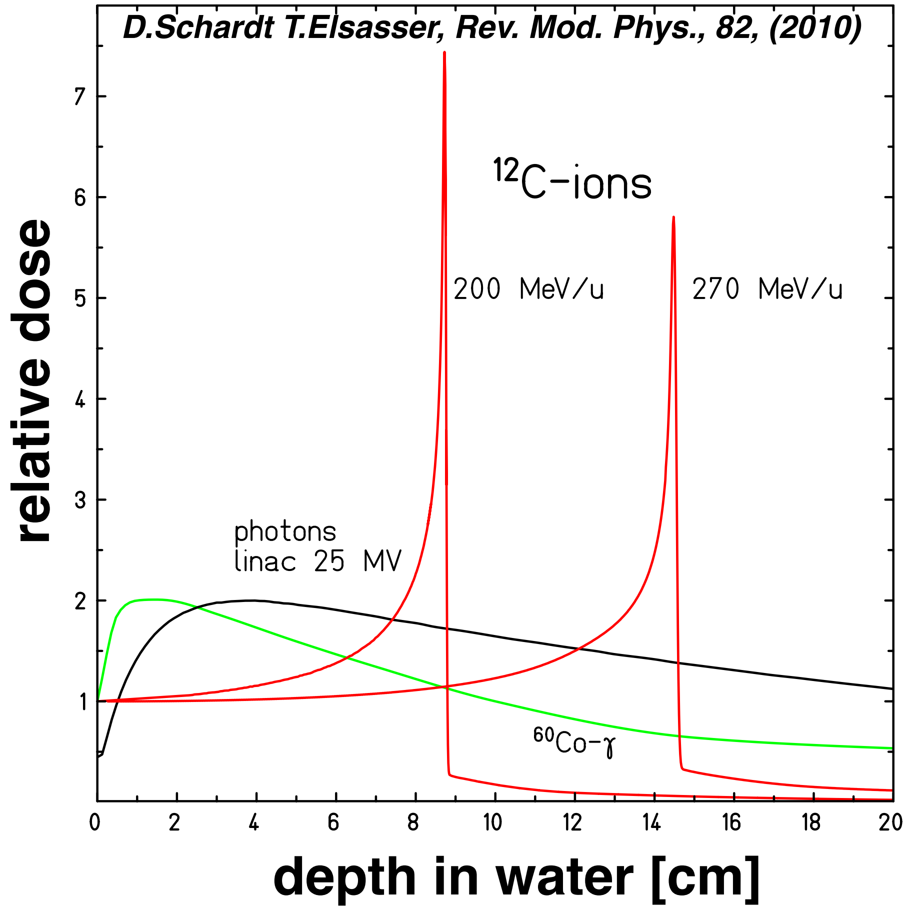
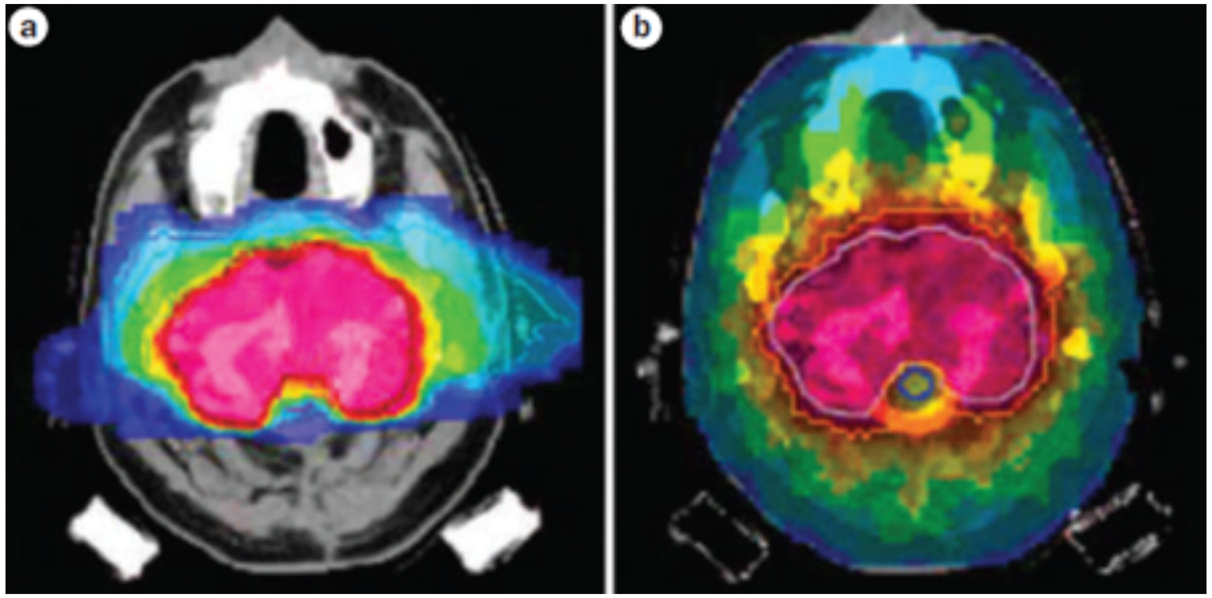
Particle therapy (PT)

- **In PT accelerated light ions ($Z \leq 8$) are used for the treatment of tumors (p,^{12}C)**
- Advantages of PT with respect to conventional Radiotherapy (with photons):
  - ➡ Highly localized dose deposition (Bragg Peak)
  - ➡ Higher biological efficiency (RBE)
  - ➡ Treatment of highly radiation resistent tumors, sparing surrounding organs at risk (OAR)



PT | **Radiotherapy**



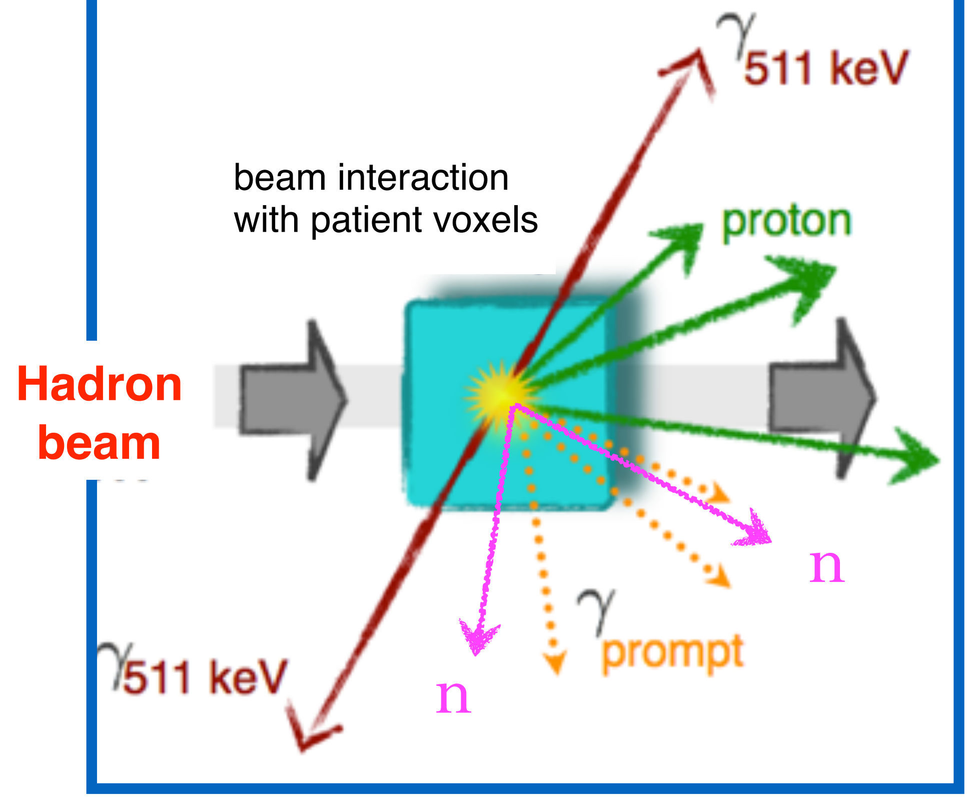
^{12}C (2 fields) | **photons (9 fields)**

M.Durante and J.S.Loeffler, Nat. Rev. Clin. Oncol., 7, 37-43 (2010)

- **Due to the highly localized dose deposition in PT a high precision monitoring is needed**
- So far, we are still lacking a standard on-line monitoring procedure widespread in clinical use

The online monitoring challenge

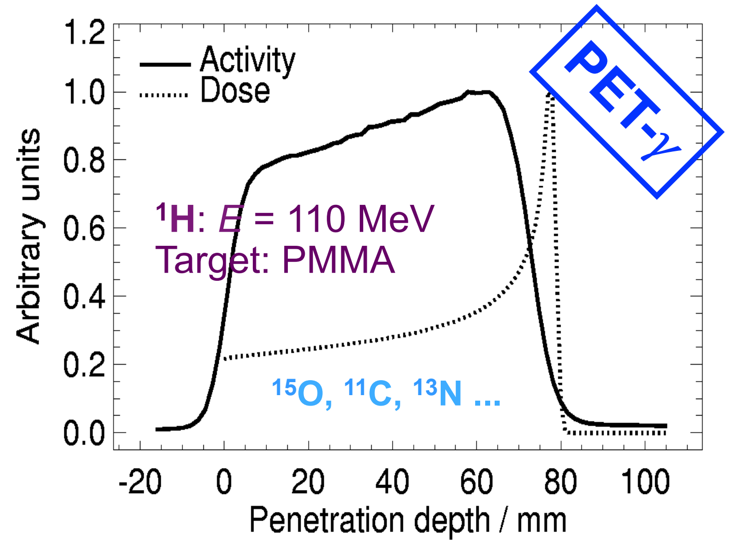
- **On-line monitoring: not an easy task!**
  - ➡ Beam is stopped inside the patient (BP)
  - ➡ Monitor has to provide fast feedback to act on the beam control and prevent damage to OARs
- **<u>Possible solution</u>: exploit the secondaries emitted in the nuclear interaction processes btw ion beam and the target nuclei**
  - ➡ possibility to correlate the emission point of secondary particles with the dose release and BP position!
- Achievable resolution depends on:
  - ➡ Abundance of secondaries production
  - ➡ interaction inside the patient
  - ➡ detection efficiency (limited by external constraints such as the integration within the treatment room…)



Beyond p and ^{12}C there's a growing interest in other "heavy" ions (^{4}He, ^{16}O) beam applications: an improved characterization of the secondaries production for these beams is becoming crucial for their deployment in treatment centers

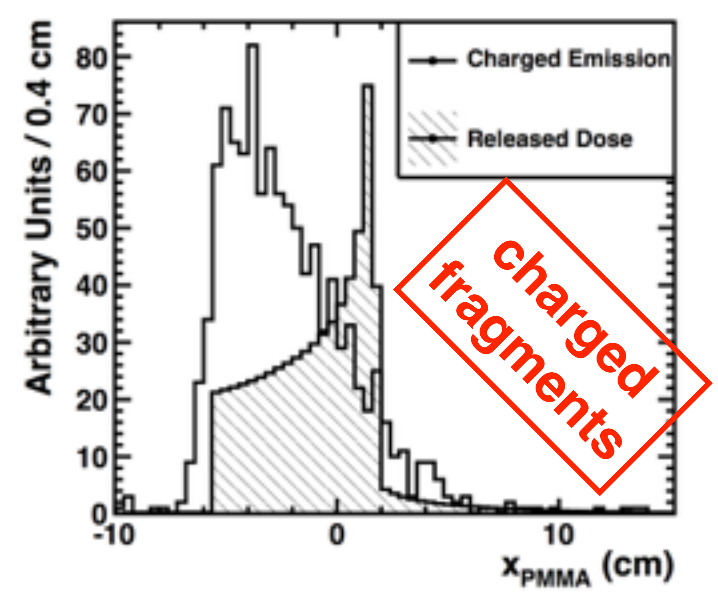
PT monitoring with different secondaries

- Three type of secondary particles have been exploited until now:
  - ➡ **Prompt-γ** (comes from fragments nuclear de-excitation)
  - ➡ **PET-γ** (comes from β+ emitters fragments)
  - ➡ **Charged fragments** (mainly ^{1}H,^{2}H,^{3}H. The heavier ions are absorbed in patient body/PMMA target)



K.Parodi et al., IEEE TNS, Vol. 52, N. 3, (2005)

- For each type of secondary particle is necessary to:
  - ➡ correlate the emission point with the dose release and the BP position
  - ➡ compute the production fluxes



220 MeV/u ^{12}C on PMMA

[1] L. Piersanti et al. - Phys. in Med. and Biol., vol. 59, no. 7, p. 1857, (2014)

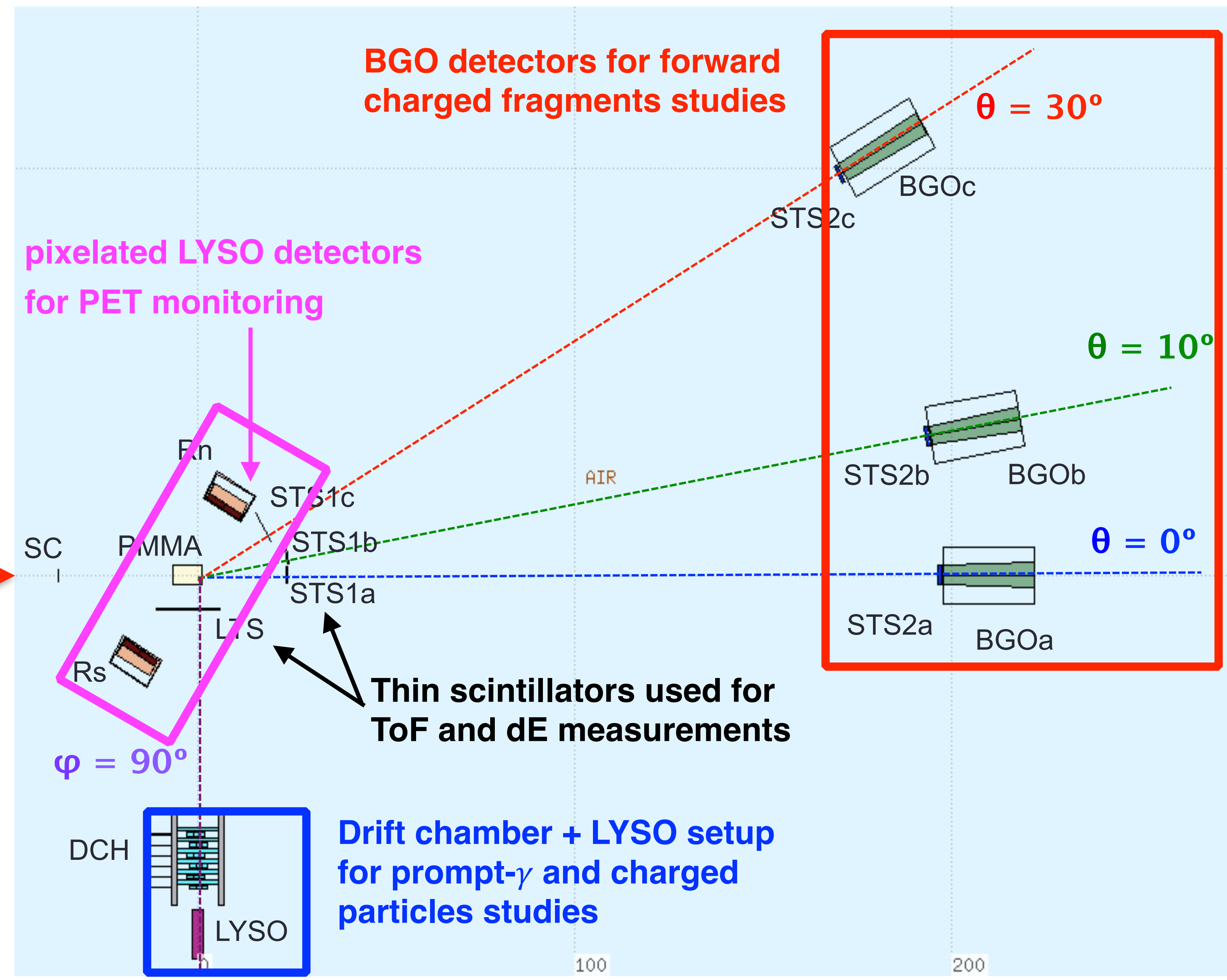
In 2014 we performed an experiment @ HIT facility (**H**eidelberg **I**on-Beam **T**herapy Center) in order to measure secondary particles produced in the interaction of **He, C and O beams** (with therapeutical energies) **against a thick PMMA target**

The HIT experimental setup

beam direction

beam direction

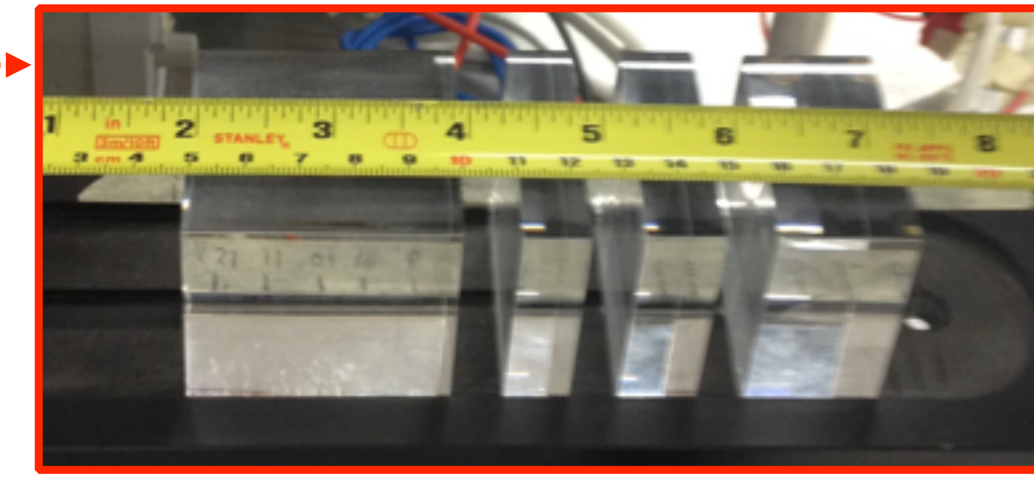
- Collected several millions of collisions with different beam energies, **different geometrical configurations**, and **fixed** distance btw BP and PMMA exit window



- A MC simulation of the full setup has been developed with FLUKA for efficiencies and solid angle studies

Dataset, beam conditions

- Different PMMA blocks have been assembled (for different beam energies) in order to have a target ensuring:
  - ➡ a **fixed BP position** in our experimental reference frame (z=0 with the beam along the z axis)
  - ➡ a **fixed distance btw BP and PMMA exit window**, to ease the systematics treatment for the fragmentation studies
- The PET monitoring system was full functional only for He beams

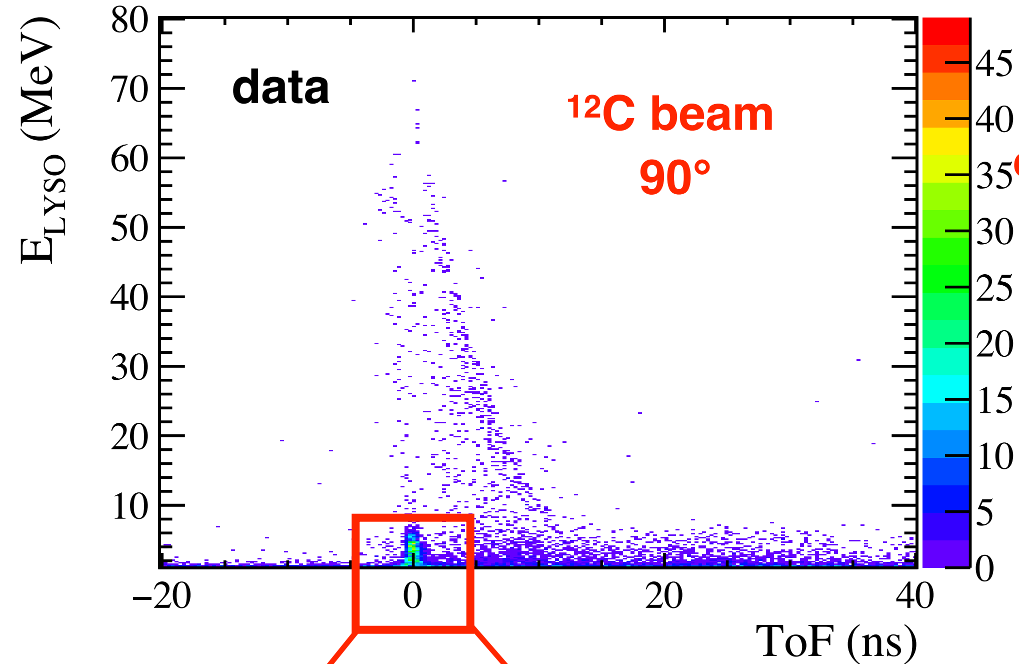


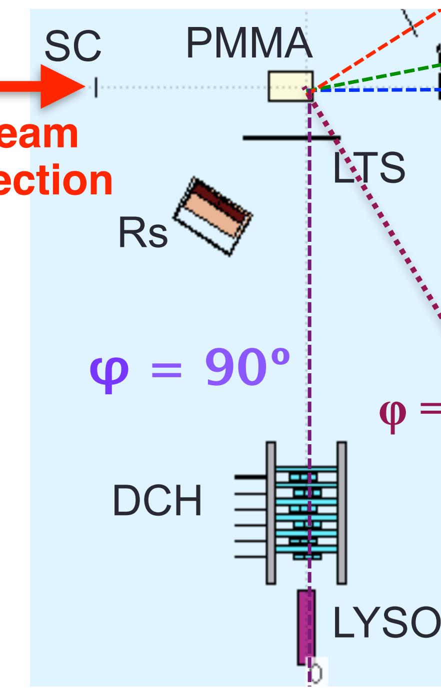
- The data analysis is still ongoing
- In the following I'll show only prompt-γ emission spectra, raw fluxes and preliminary secondary particles emission profiles

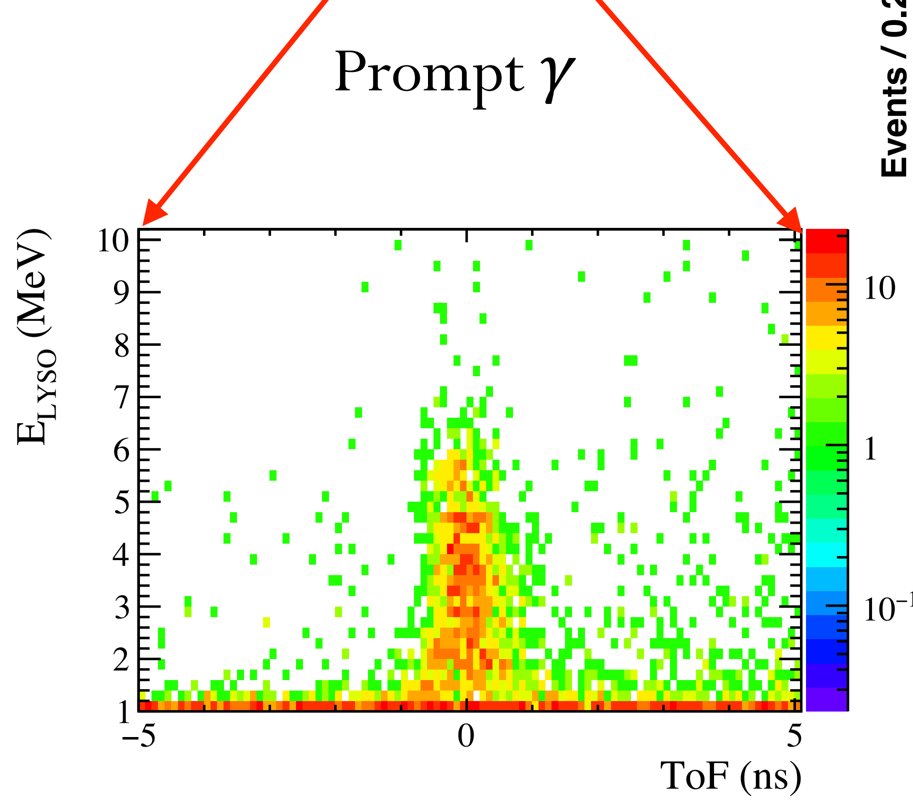
Beam	Energy (MeV/u)	PMMA (cm)	Config	#ions (x 10^8) 90° [60°]
He	102	7.65	90°, 60°	28.8 [33.2]
	125	10	"	32.4 [32.2]
	145	12.65	"	32.3 [31.9]
O	210	7.65	"	23.9 [15.4]
	260	10	"	12.5 [12.3]
	300	12.65	"	29.9 [18.3]
C	120	12.65	90°	15.3
	160	"	"	9.9
	180	"	"	6.4
	220	"	"	8.2

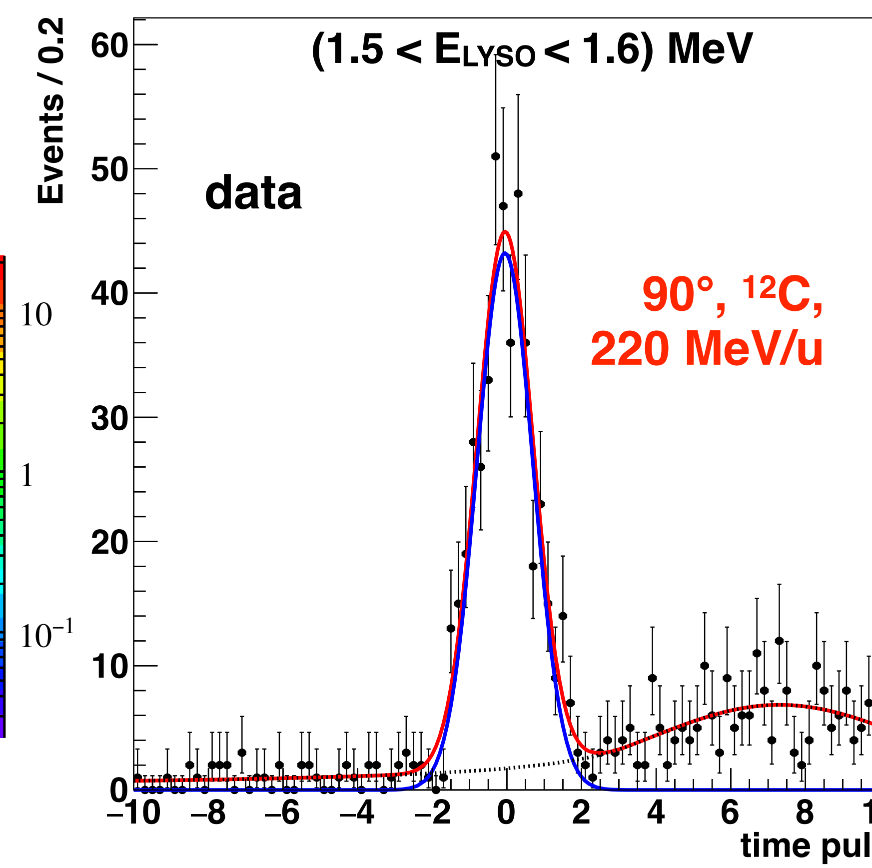
Prompt-γ production

- Prompt γ are mainly produced by the fragments de-excitations and are selected using E vs "ToF" (time of flight computed as t_{LYSO} - t_{SC})
- N_γ is computed from an unbinned likelihood fit to the time pull distribution in E_{LYSO} slices:
  - ➡ the background is modeled using the sum of a flat component (from LYSO internal radiation) and a peaking one, on the right (mainly due to neutrons)



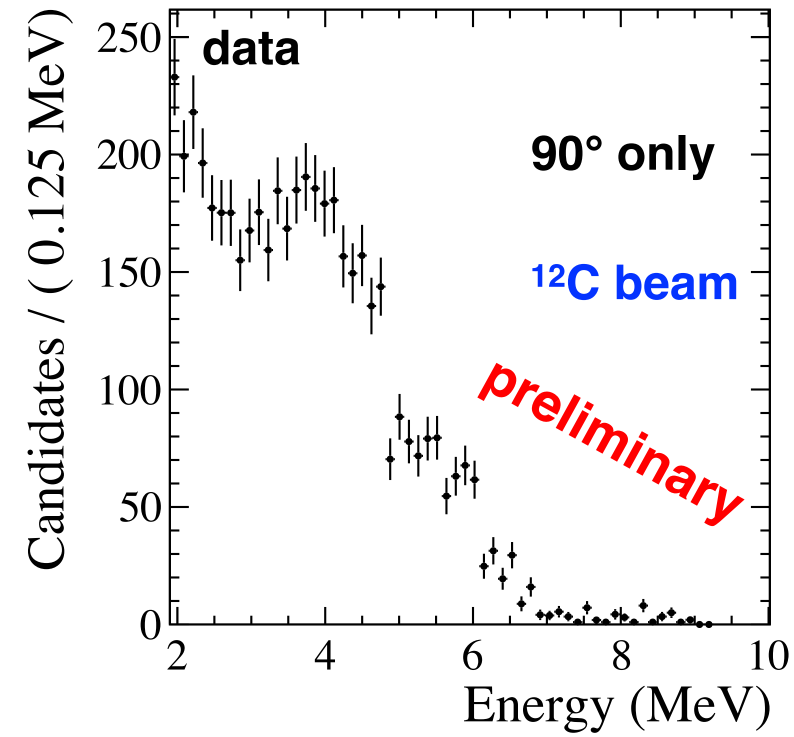


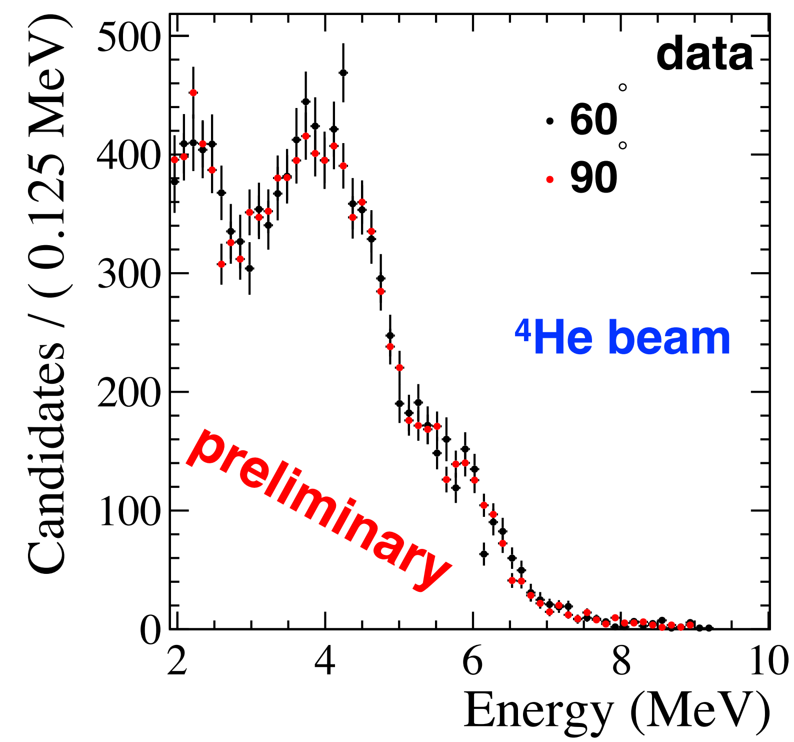




Detected prompt-γ spectra

- **Prompt γ production was observed for all the beams**
- Emission spectra consistent with what already measured with LYSO detector @ LNS, GSI
- Broad peaks: convolution of prompt-γ from different isotopes
- Emission spectra for 60° and 90° for He and O beams have been compared, normalizing them to have the same area.





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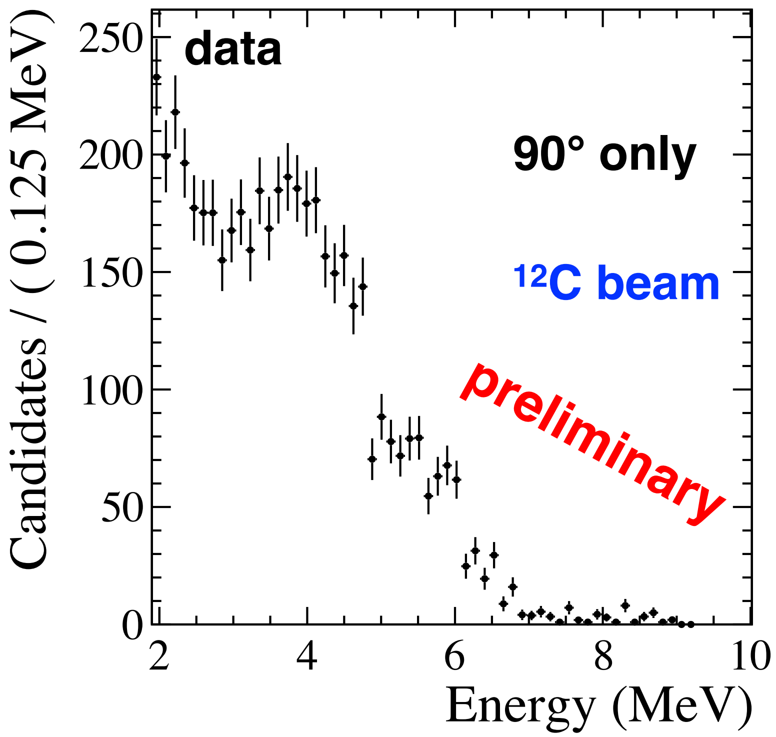
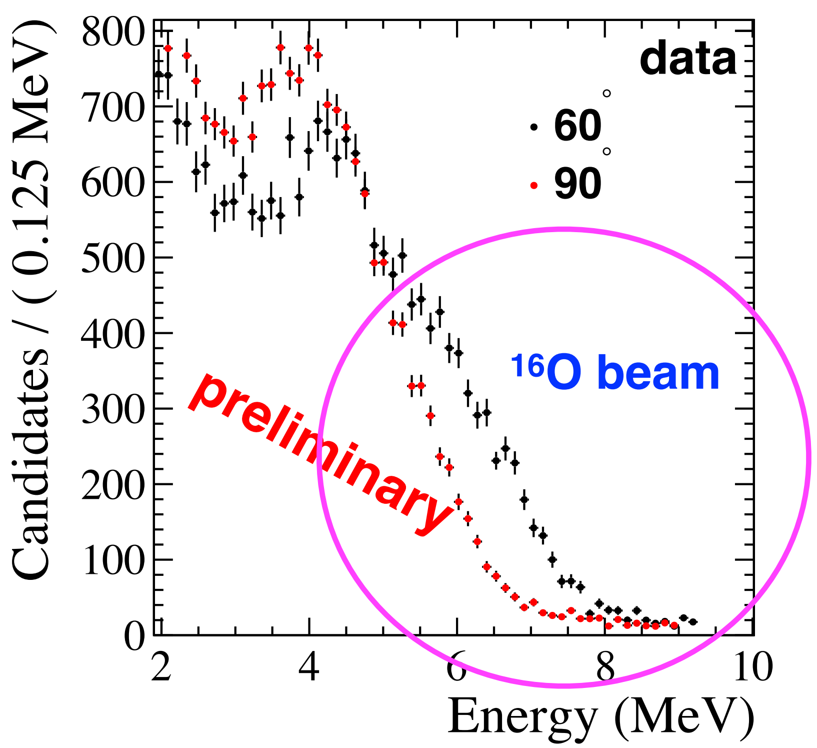
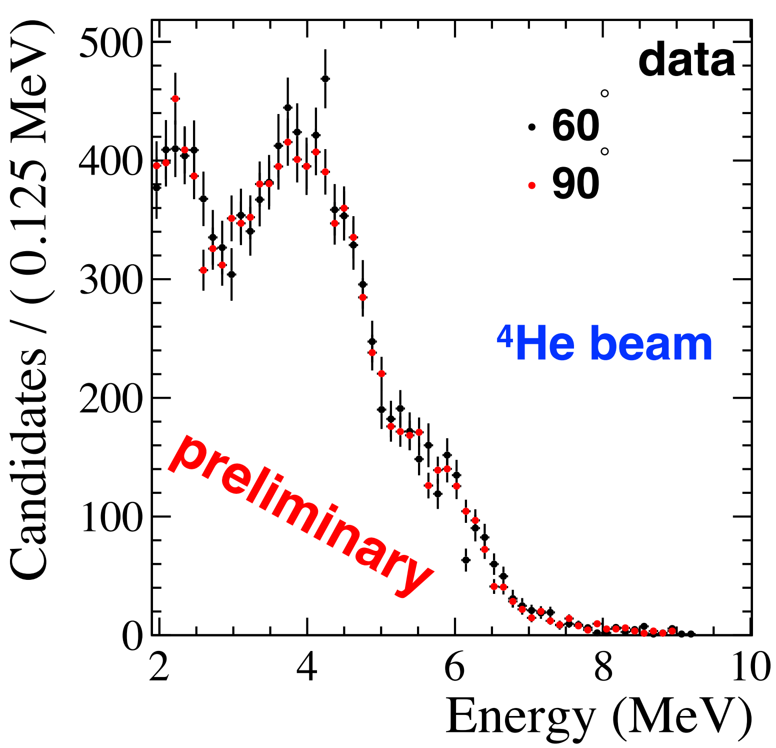


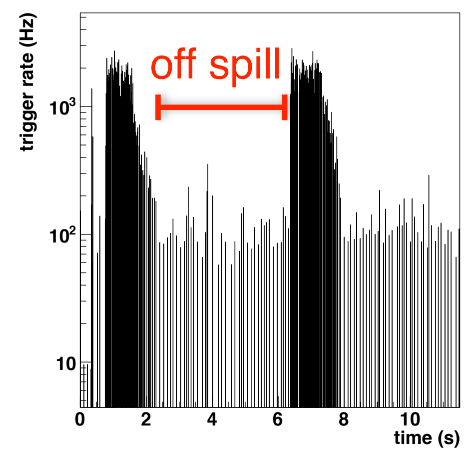
➡ For prompt γ produced by ^{16}O beam, **we observe an asymmetry** that is related to the prompt γ production in the projectile fragmentation (and thus affected by the projectile boost)



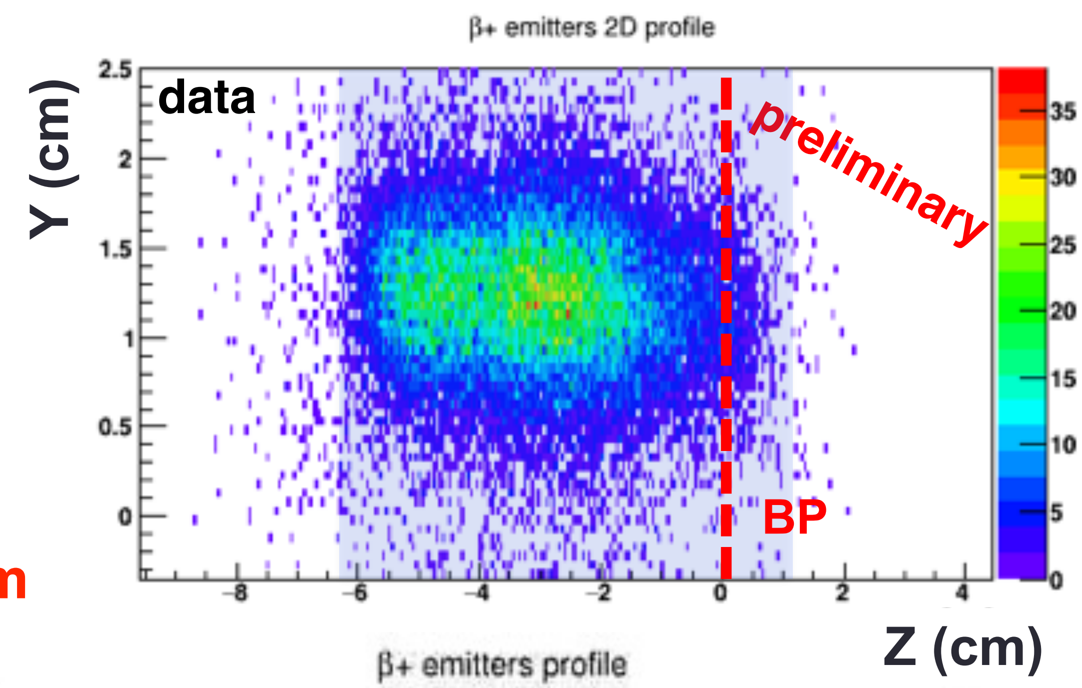


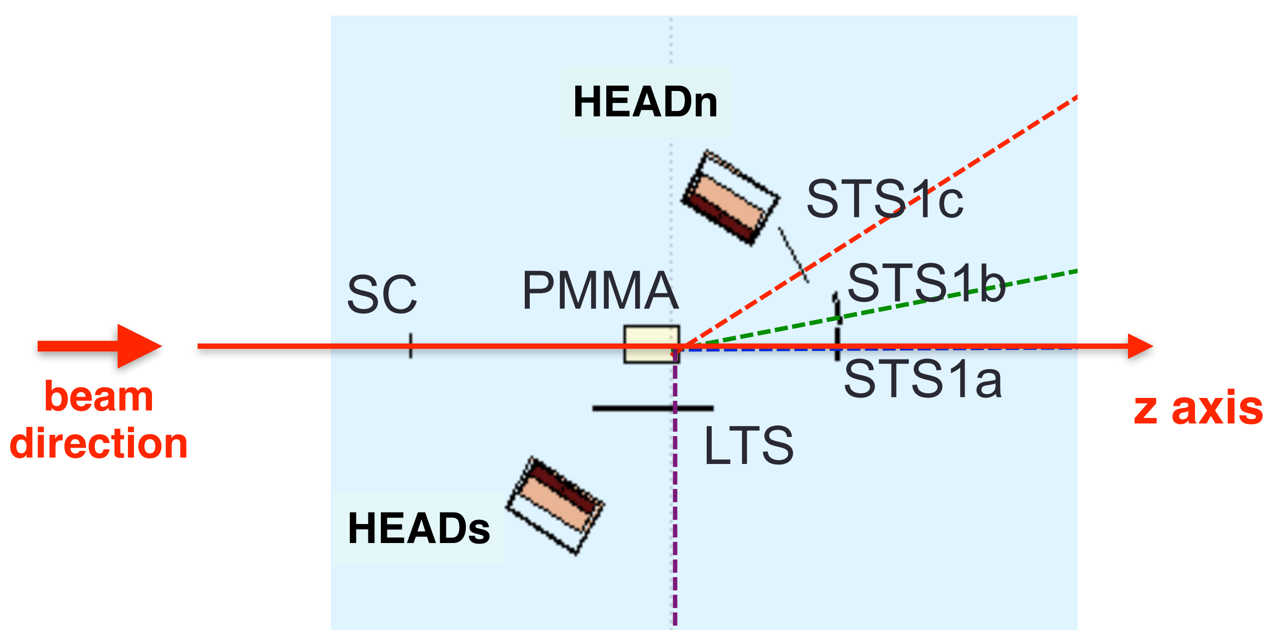
PET-γ production

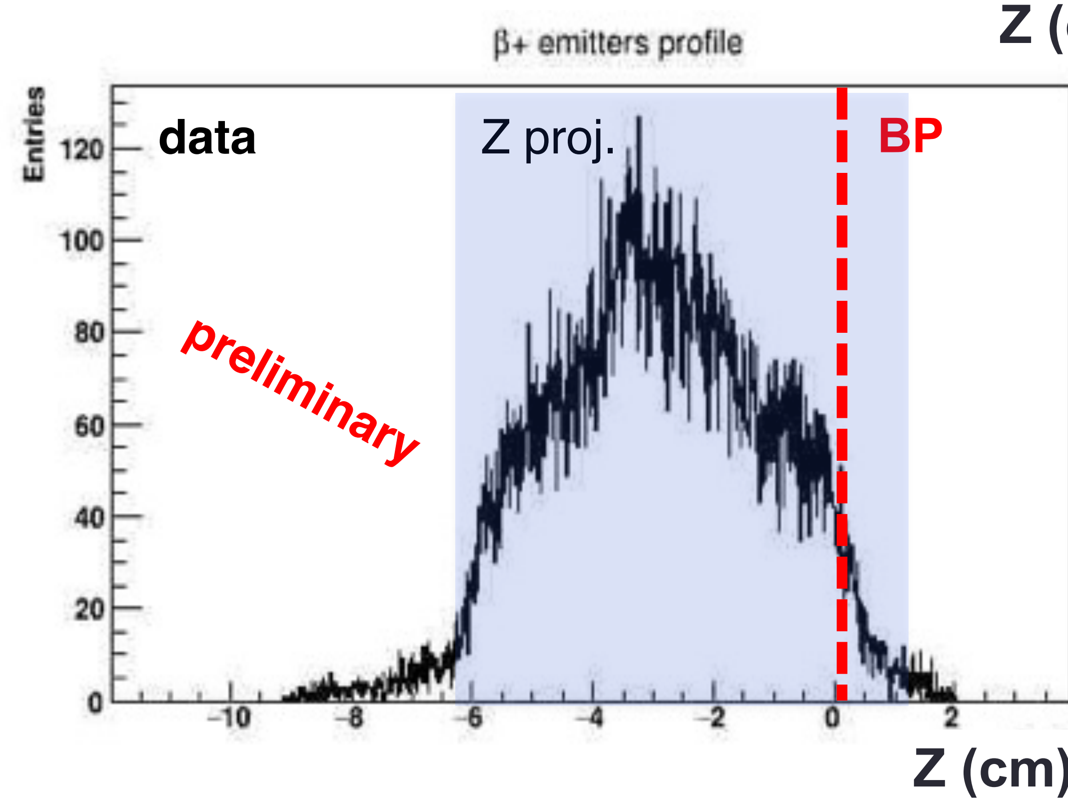
- The PET γ emission point is reconstructed only for helium beam
- PET γ are identified requiring E around the 511 keV peak and $\Delta t < 3\sigma(t)$ for off spill events
- Still missing the ε corrections



102 MeV/u He beam

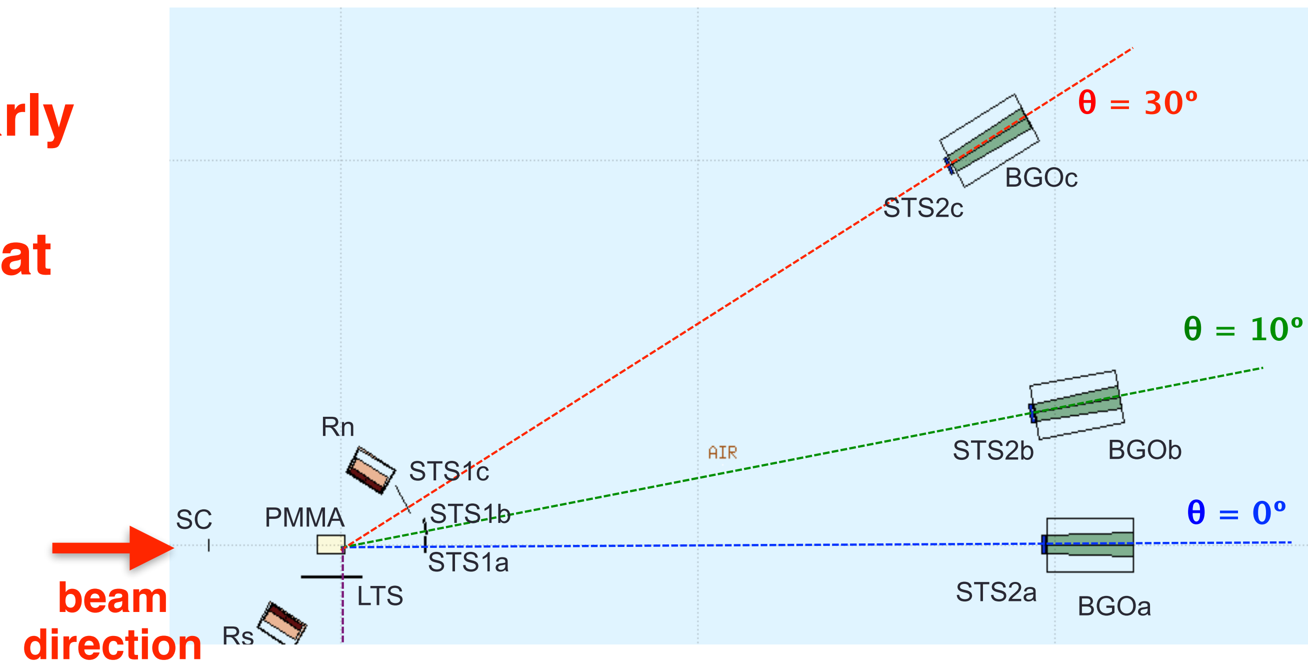


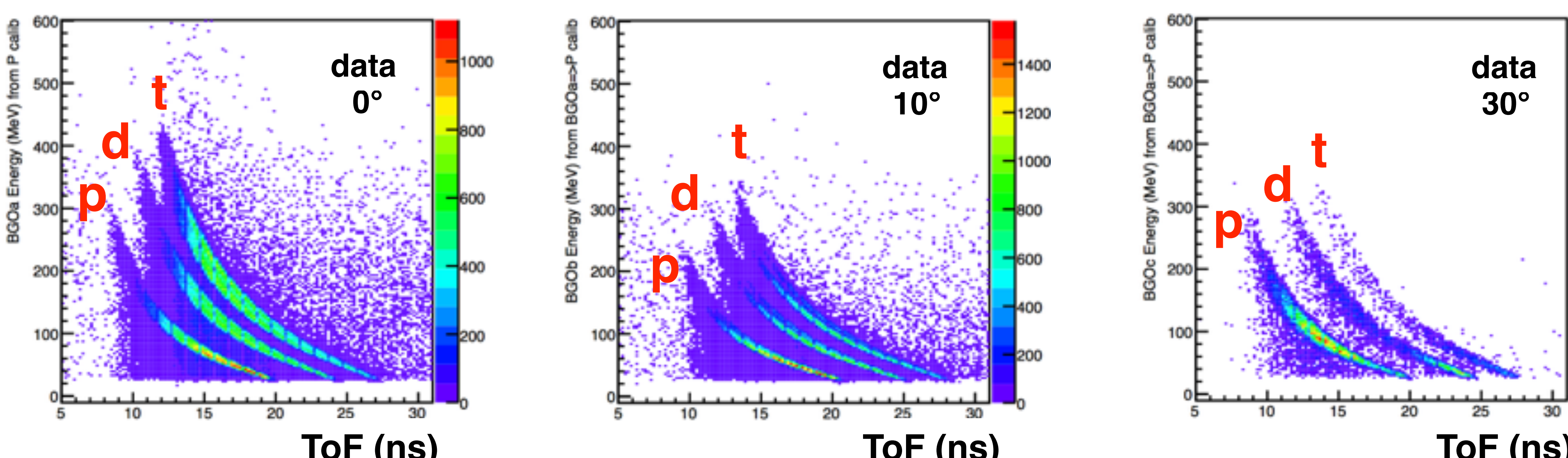




Charged fragments - small angles

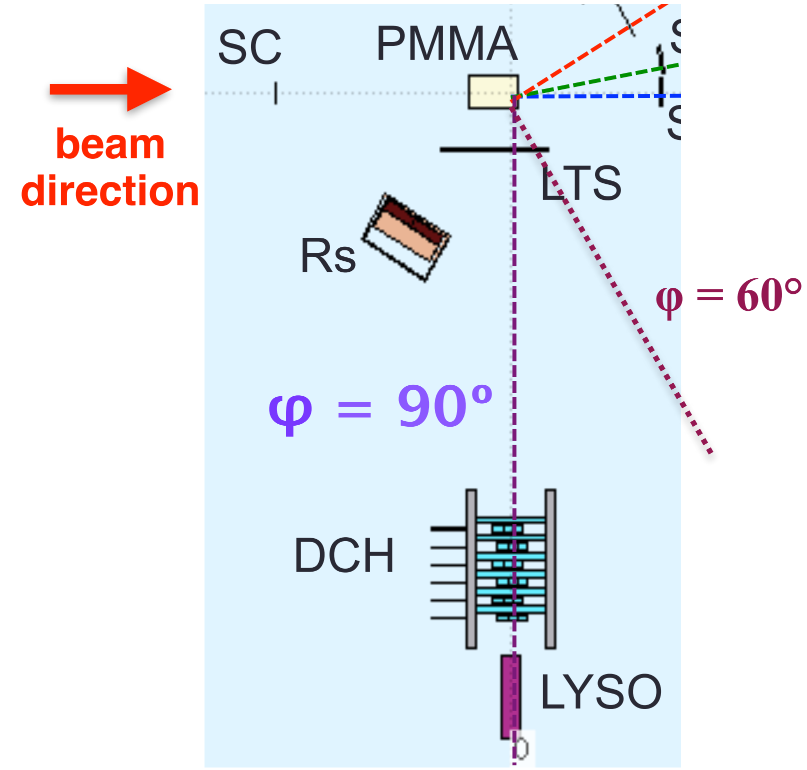
- Started with analysis of He beams (plots are shown for 102 MeV/u beam).
- **Proton, deuteron and triton bands are clearly visible for He fragmentation at all beam energies, with non negligible contribution at large angles**
- The energy calibration of BGO detectors has been performed with p beams
- Nice agreement of E vs ToF distributions is observed with the predictions from Fluka MC simulation

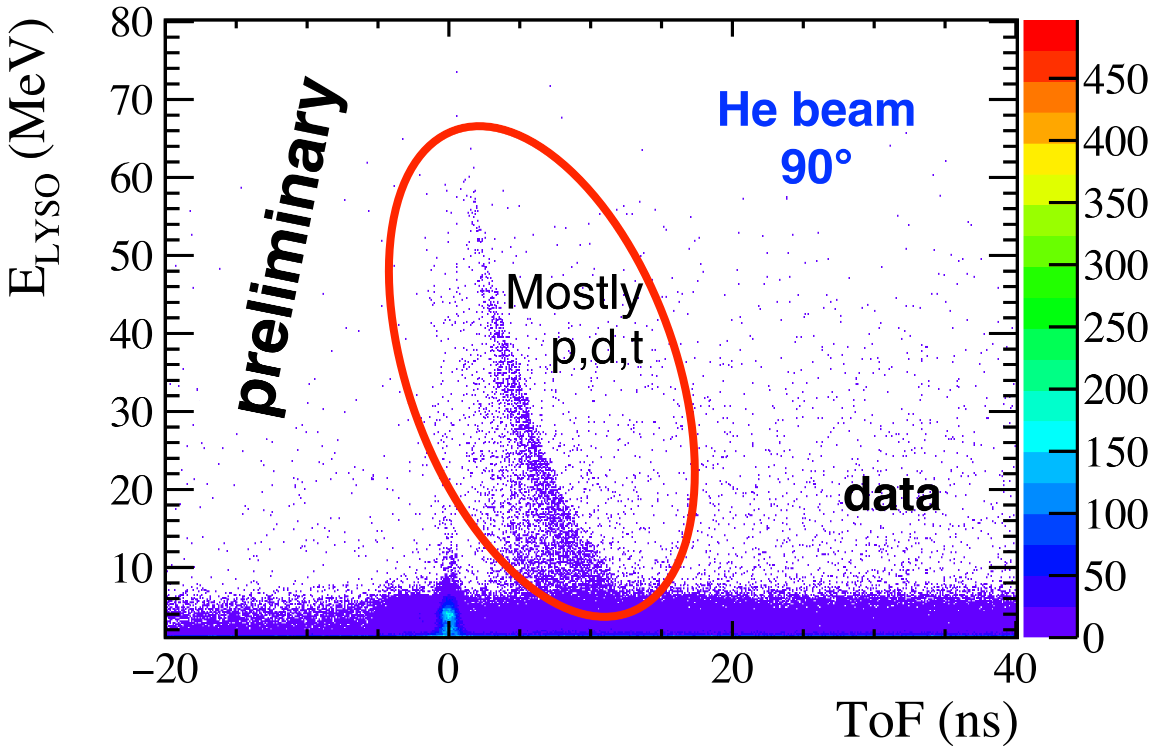


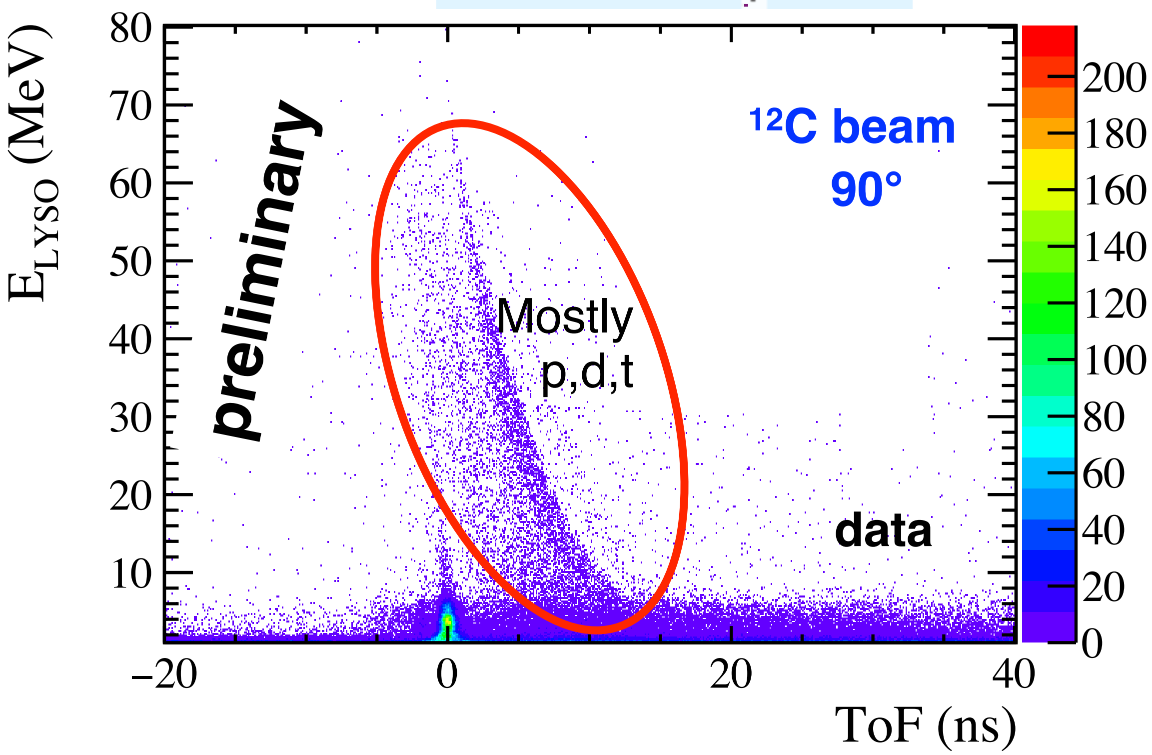


Charged fragments - large angles

- Tracks reconstructed by the DCH
  - ➡ Detector alignment done with aluminum table fixed positions (± 1mm)
  - ➡ DCH center aligned with fixed BP positions (x_{PMMA} = 0, ~1.5 cm before exit window)
  - ➡ $\Omega \sim 6 \cdot 10^{-5}$ sr, $\varepsilon_{det} > 90\%$
  - ➡ DCH trk resolution @ emission point **~ 1mm**





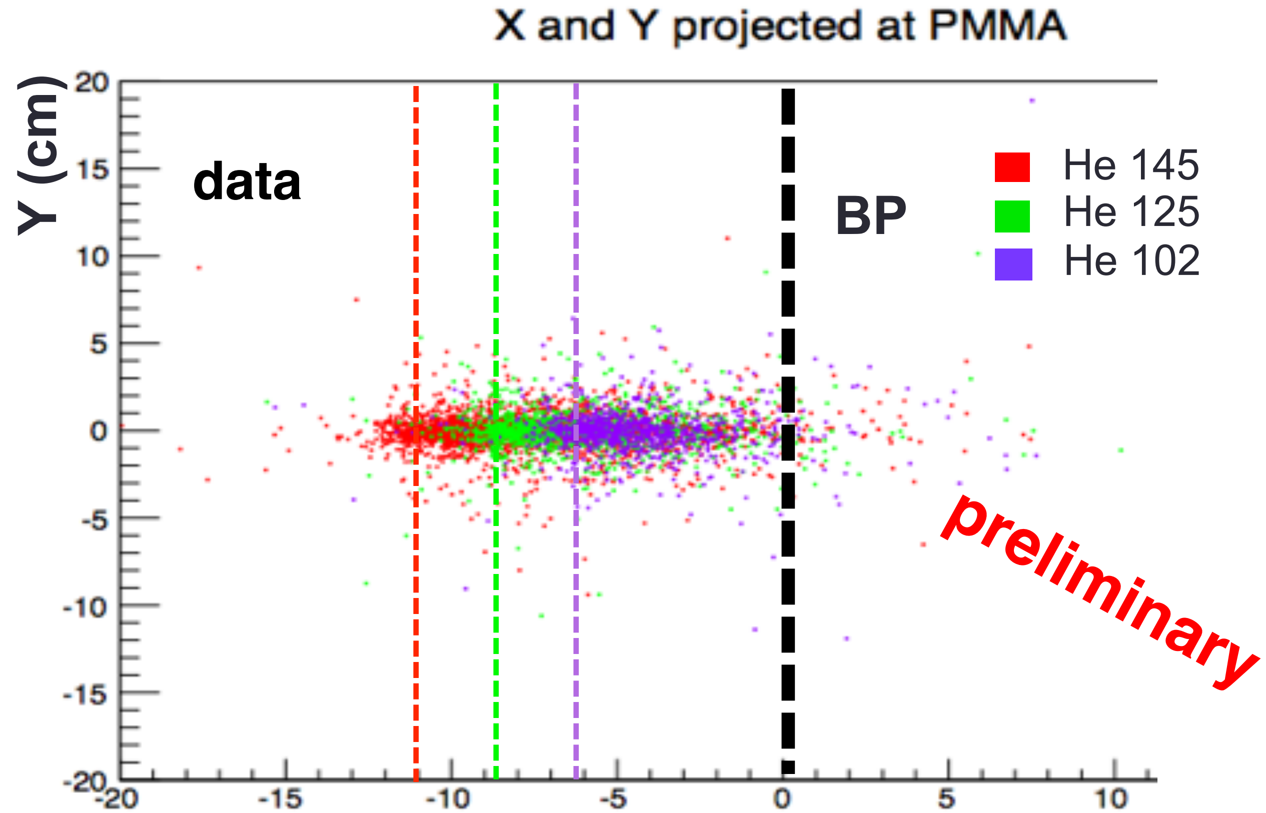


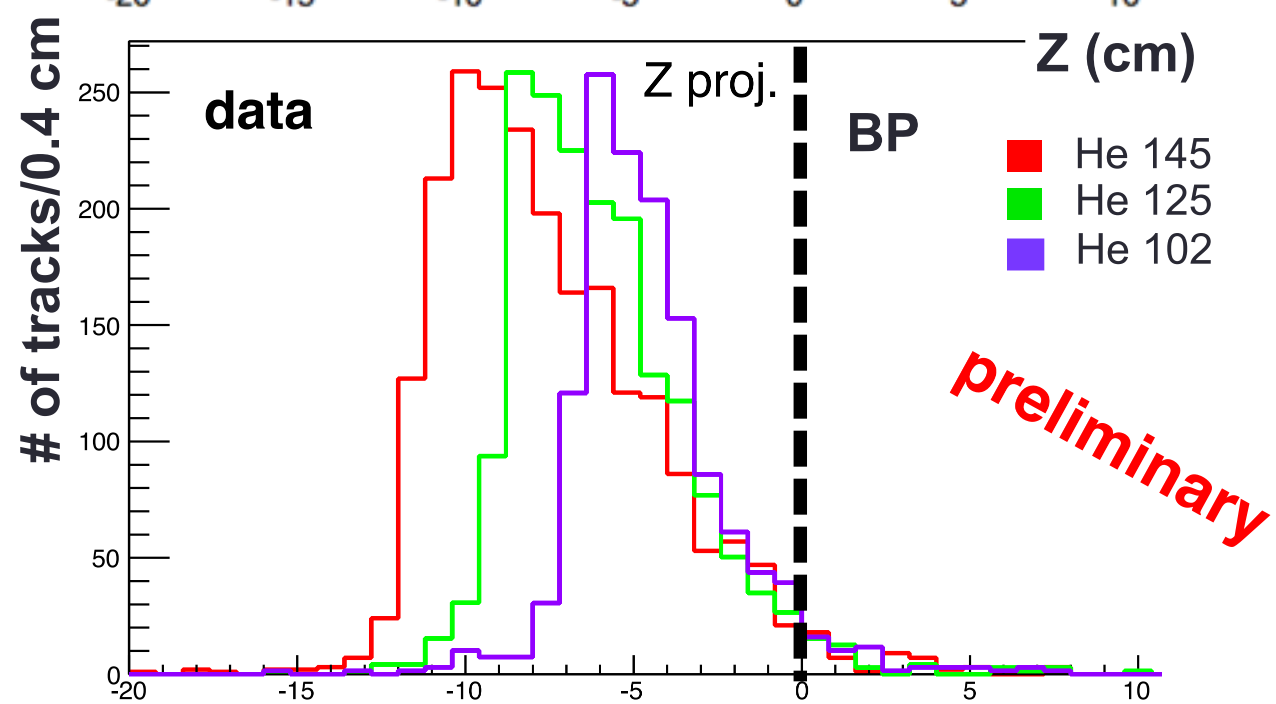
BP monitoring on He beams

- A non negligible production of charged particles at large angles is observed for all beam types
- The emission shape is correlated to the beam entrance window and BP position as already measured with ^{12}C
- $\phi = dN_{all}/(N_{ions}\, d\Omega)$

Beam type/E	φ 90° (10^{-3})
He 102	0.6
He 125	0.7
He 145	1
C 160	1
C 180	2
C 220	3
O 210	3
O 260	5
O 300	10

preliminary

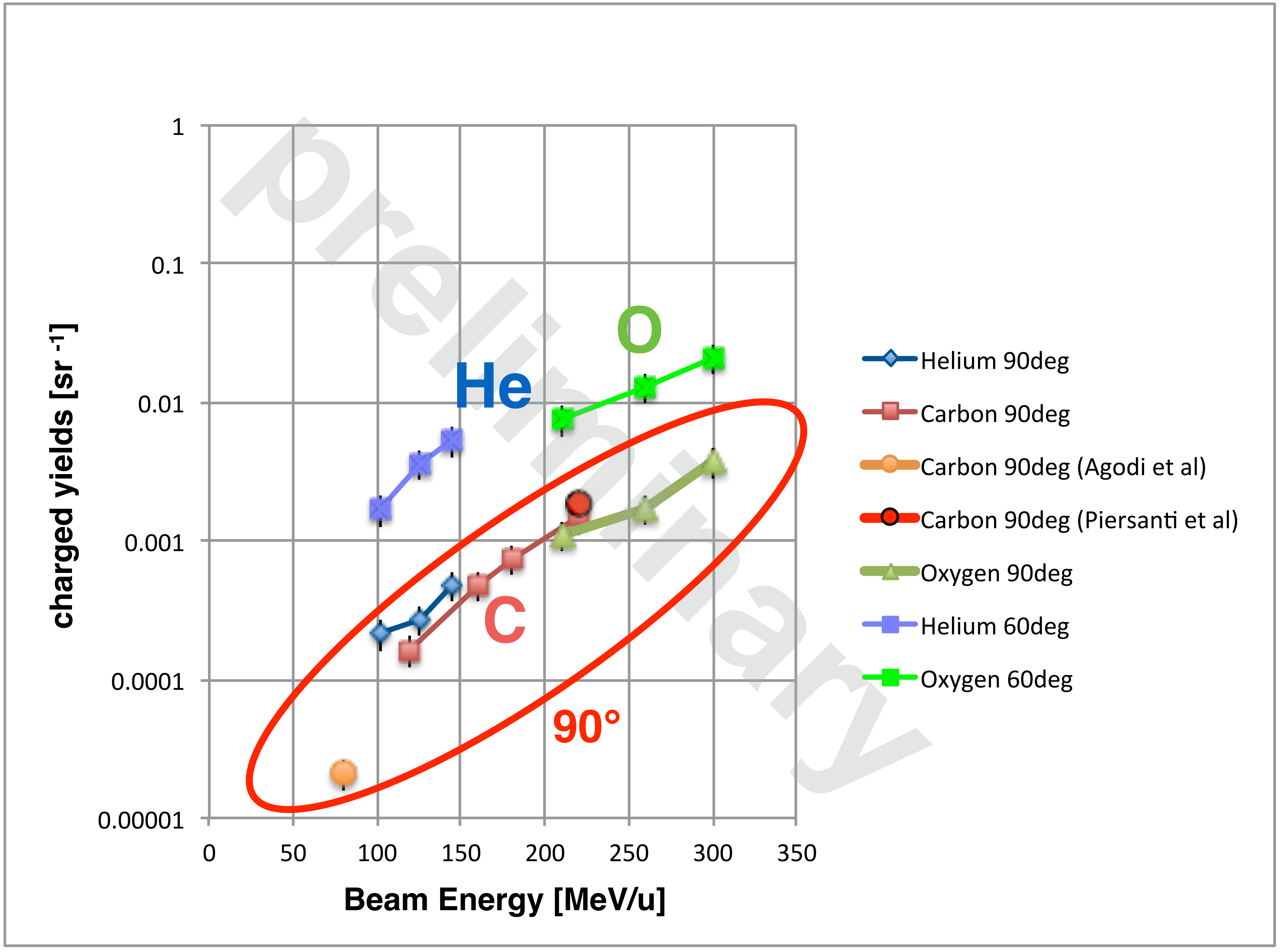




different PMMA thickness !!

Comparison of charged measurement at 90°

Very preliminary charged yields comparison at 90° for different energy and ion beams btw HIT data and previous data acquisition campaigns @ GSI and LNS of our group



Conclusions

- The study of secondary particles production from He, C and O beams impinging on a thick PMMA target is well advanced! With the few millions of events collected at the HIT facility we already observed:
  - ➡ **A significant production of charged particles for all beam types**. Results obtained for ^{12}C beam are in agreement with what already published and confirm the feasibility of a dose monitor based on the charged particles detection!
  - ➡ A significant forward fragmentation of ^{4}He beams (p, d, t)
  - ➡ A significant prompt-γ production, with a spectra that has the same properties of what already observed in previous experiments.
    - ➡ The contribution from projectile fragments de-excitation has been observed using the ^{16}O beam.
  - ➡ PET-γ emission profile exploiting the He beam