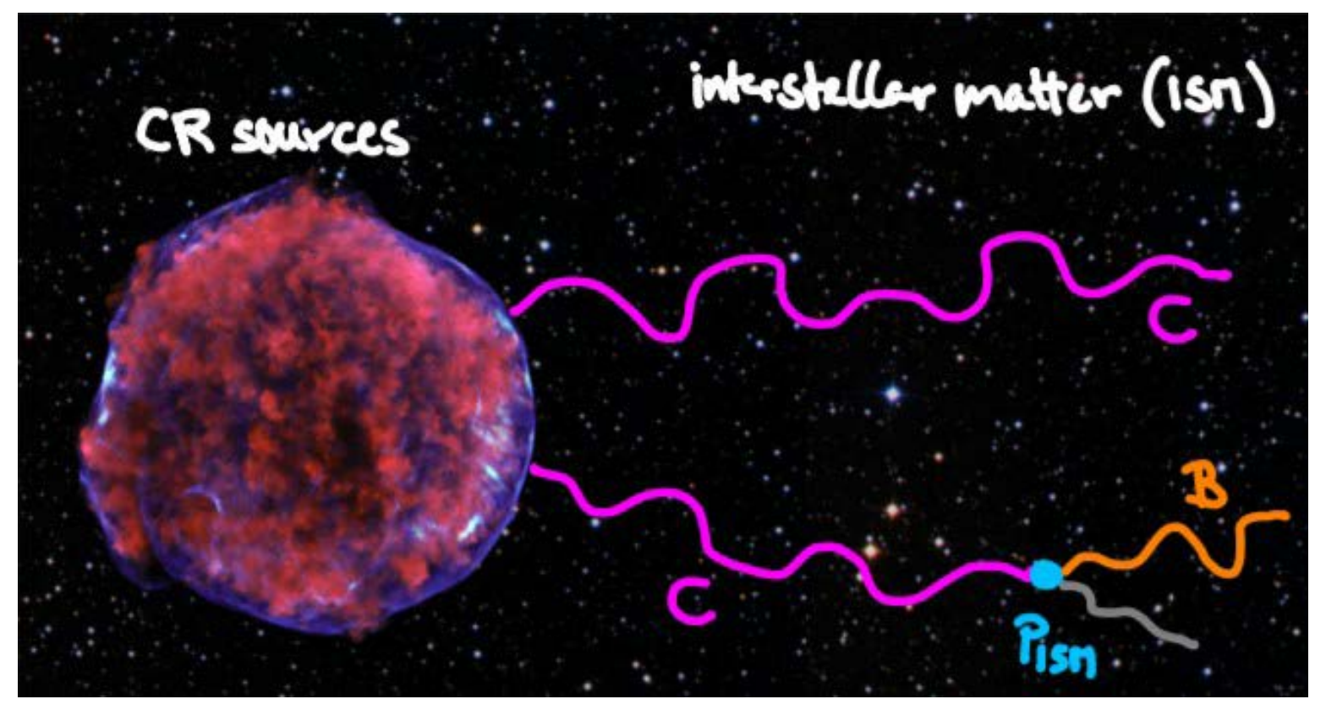
Nuclear fragmentation processes in heavy ion collisions necessary to understand propagation of cosmic rays in the Galaxy

Yuliia Balkova
University of Silesia in Katowice, Poland
yuliia.balkova@cern.ch

National Science Center, Poland
grant # 2018/31/G/ST2/03910

Cosmic ray propagation



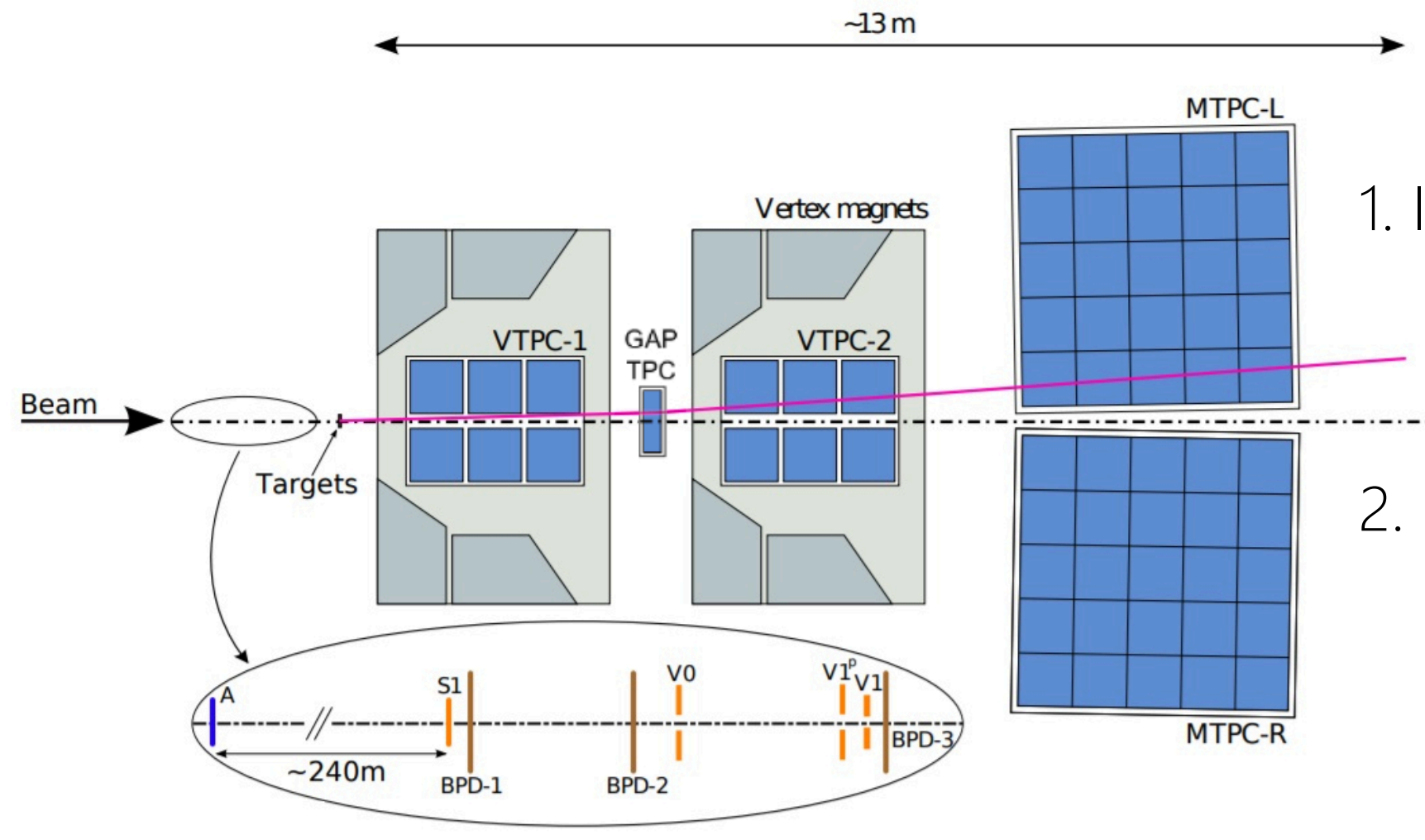
- protons and most of the nuclei in CR are referred to as primaries
- when primary species propagate through the galaxy they can scatter on the interstellar gas and create so-called secondary cosmic ray:

$$^{12}C + p \xrightarrow{frag.} B + X$$

$$^{12}C + p \xrightarrow{frag.} {}^{11}C + X \xrightarrow{decay} B + Y$$

- secondary production mode is very important for certain nuclei like **lithium**, **beryllium** and **boron**
- a large fraction of **antimatter** in CR is believed to be of secondary origin
- knowledge of **fragmentation cross-sections** is crucial for CR propagation modelling

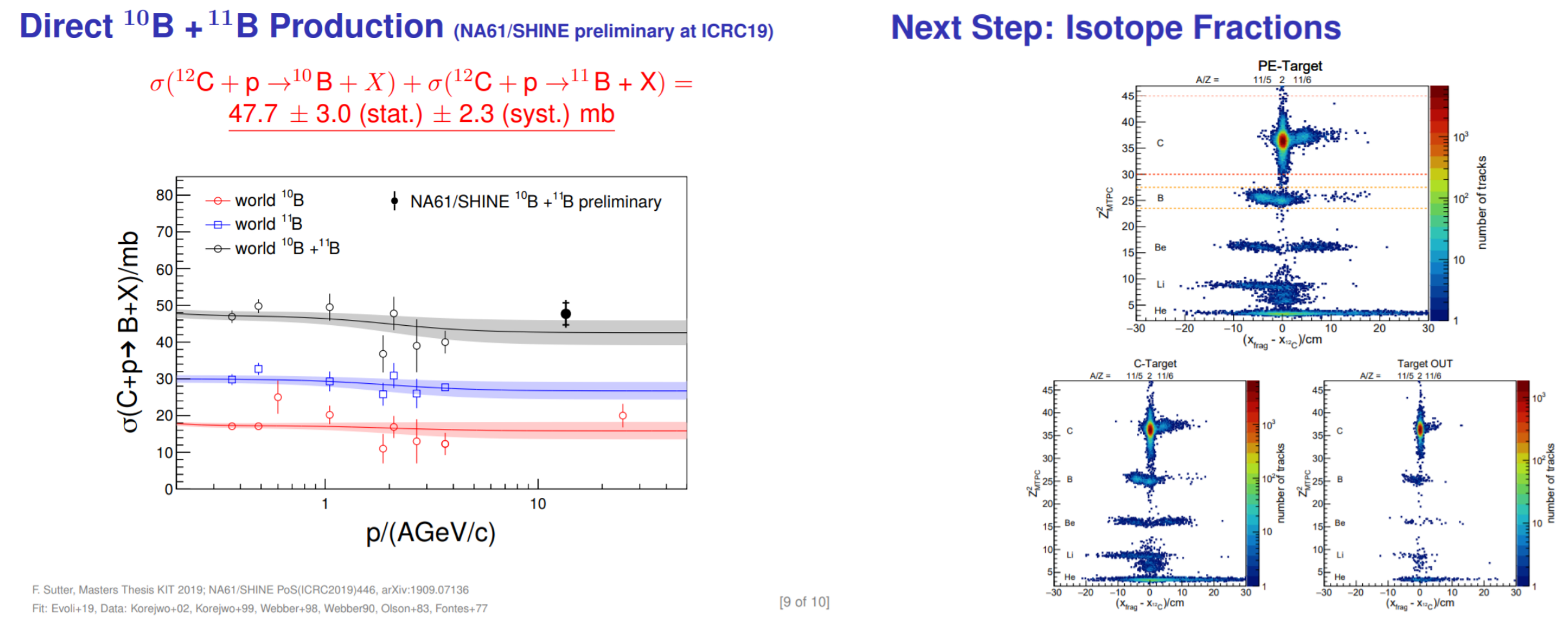
Experimental setup of NA61/SHINE at CERN SPS



1. Identification of **beam particles**:
   - time of flight → mass number of particle (A)
   - energy loss → squared charge of particle (Z^2)
2. Identification of **fragments**:
   - energy loss → squared charge of fragment (Z^2)
   - path curvature → A/Z ratio of fragment

N. Abgrall et al., [NA61/SHINE Collab.] JINST 9 (2014) P06005

Preliminary NA61/SHINE results on boron production and next step of data analysis



Direct ^{10}B + ^{11}B Production (NA61/SHINE preliminary at ICRC19)

$\sigma(^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{10}\mathrm{B} + X) + \sigma(^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{11}\mathrm{B} + \mathrm{X}) =$
$47.7 \pm 3.0\ (\mathrm{stat.}) \pm 2.3\ (\mathrm{syst.})$ mb

Next Step: Isotope Fractions

F. Sutter, Masters Thesis KIT 2019; NA61/SHINE PoS(ICRC2019)446, arXiv:1909.07136
Fit: Evoli+19, Data: Korejwo+02, Korejwo+99, Webber+98, Webber90, Olson+83, Fontes+77

[9 of 10]

Broad peaks of isotopes → **distribution overlap**! What are the possible reasons?

1. beam ions properties?
   - not exact momentum (momentum smearing by Fermi motion)
   - not a point source
2. beam rescattering in the target (length dependent)?
3. physics properties of fragments?

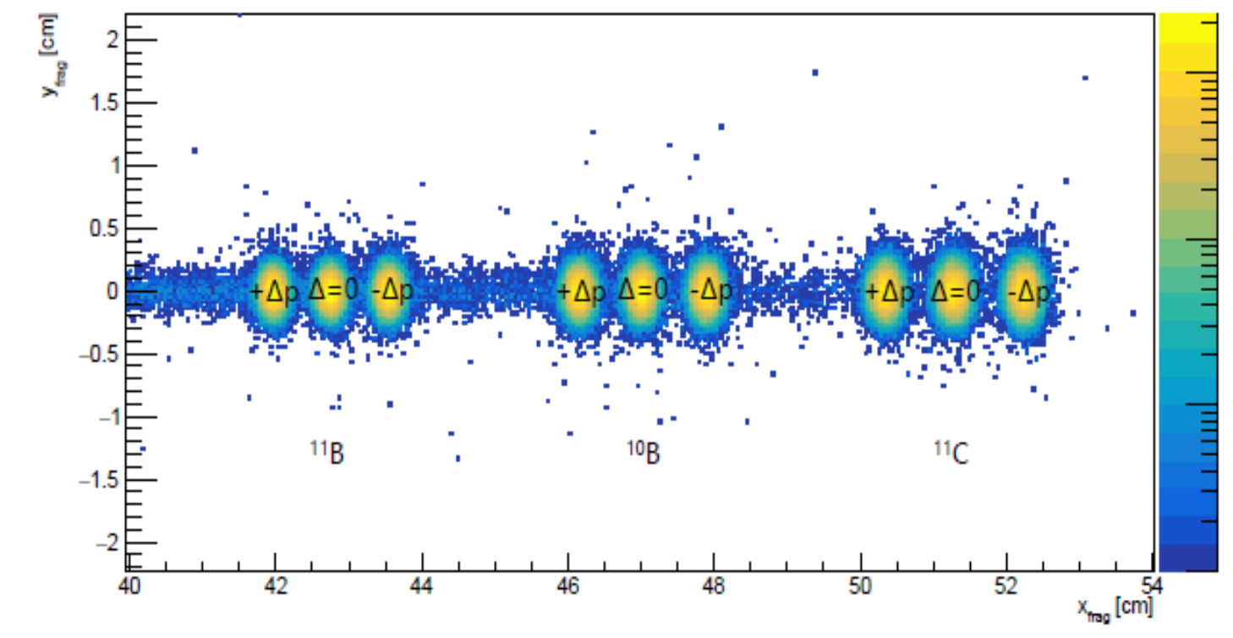
Simulations to check!

Simulation framework

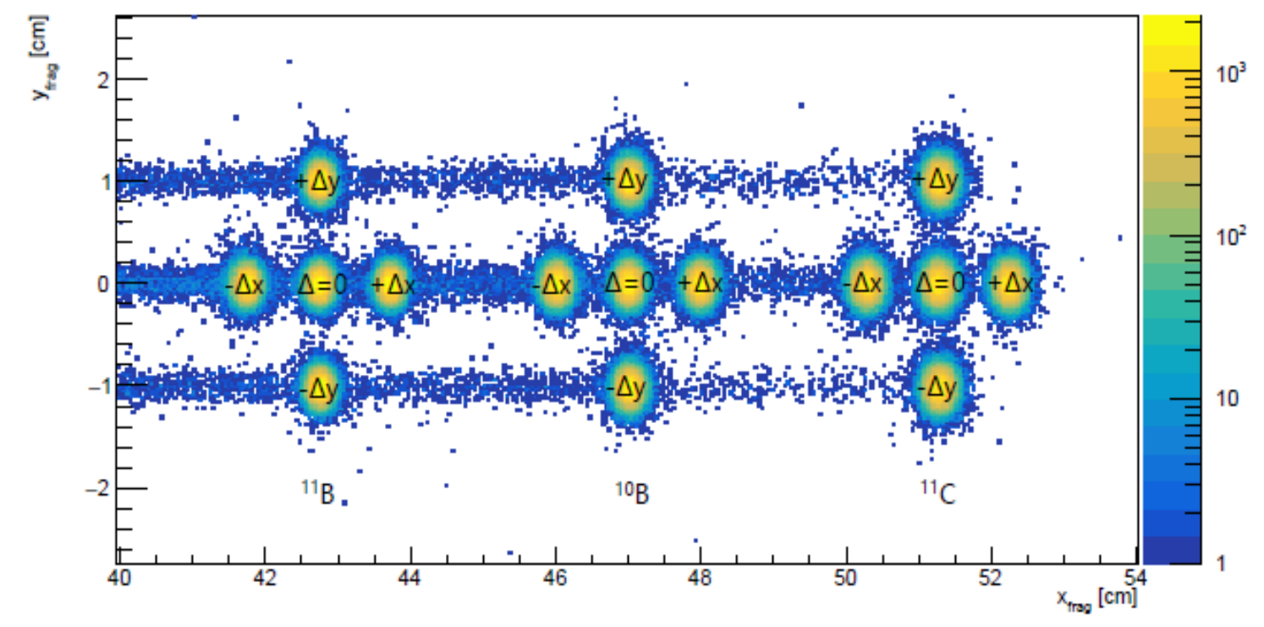
- **GEANT 4** with geometry of NA61/SHINE detector
- **QGSP_INCLXX** physics list used (Quark Gluon String Model with Precompound nucleus + Liege Intranuclear Cascade)
- two targets implemented: **C** and **PE** + target removed mode
- two modes of simulation:
  - **particle gun mode** – no target, propagation of selected isotopes through detector (defined parameters, start in target position); simulation with simple assumptions to check basic effects
  - **beam fragmentation mode** – C or PE target, mix of isotopes is produced as result of fragmentation, simulation of fragments' propagation through detector

1. Analysis of beam ions properties

- simulation in particle gun mode
- ^{10}B+^{11}B+^{11}C XY position distributions as **output**
- **no overlap** present for given momentum and position blur



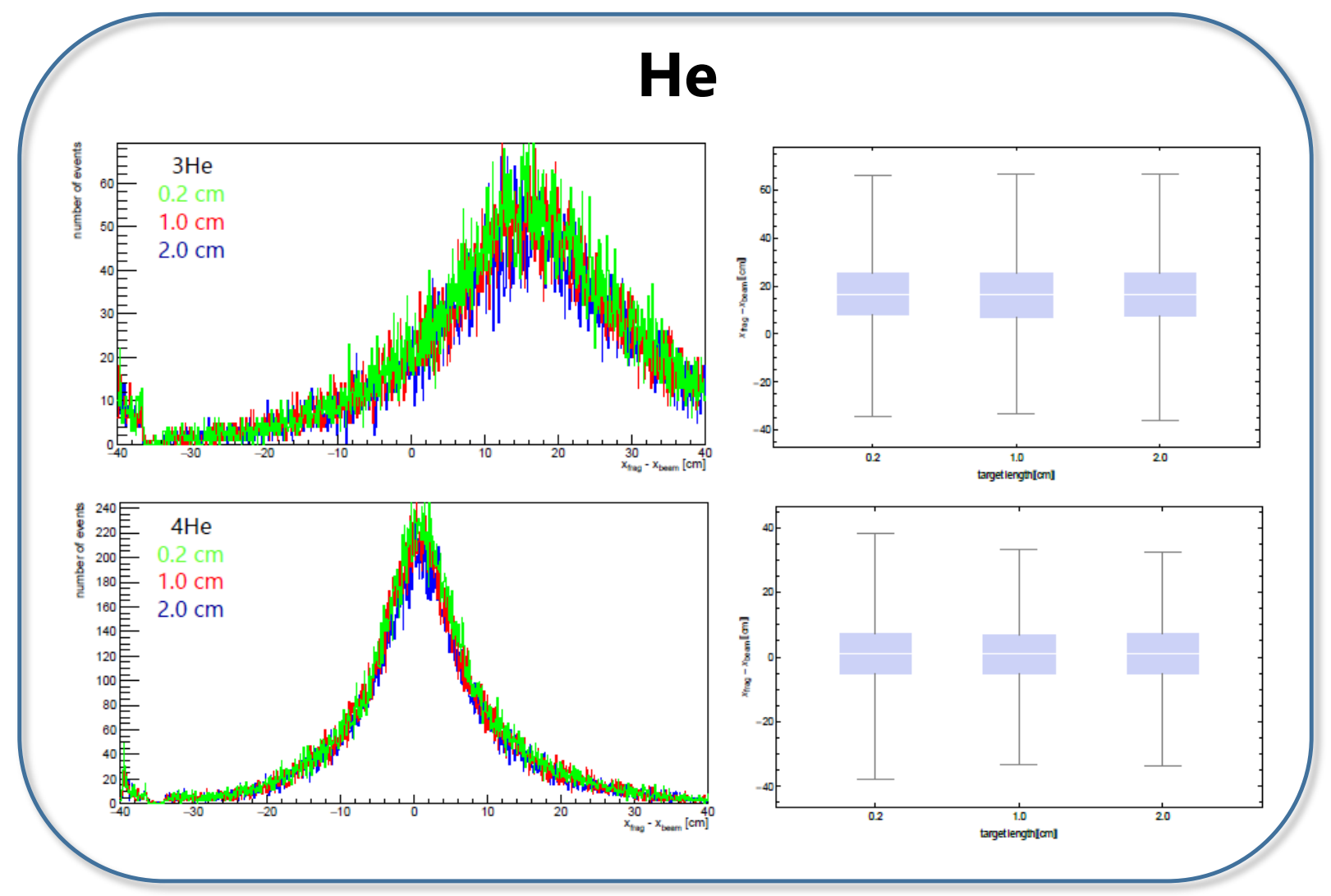
momentum blur ±250*A* GeV/c



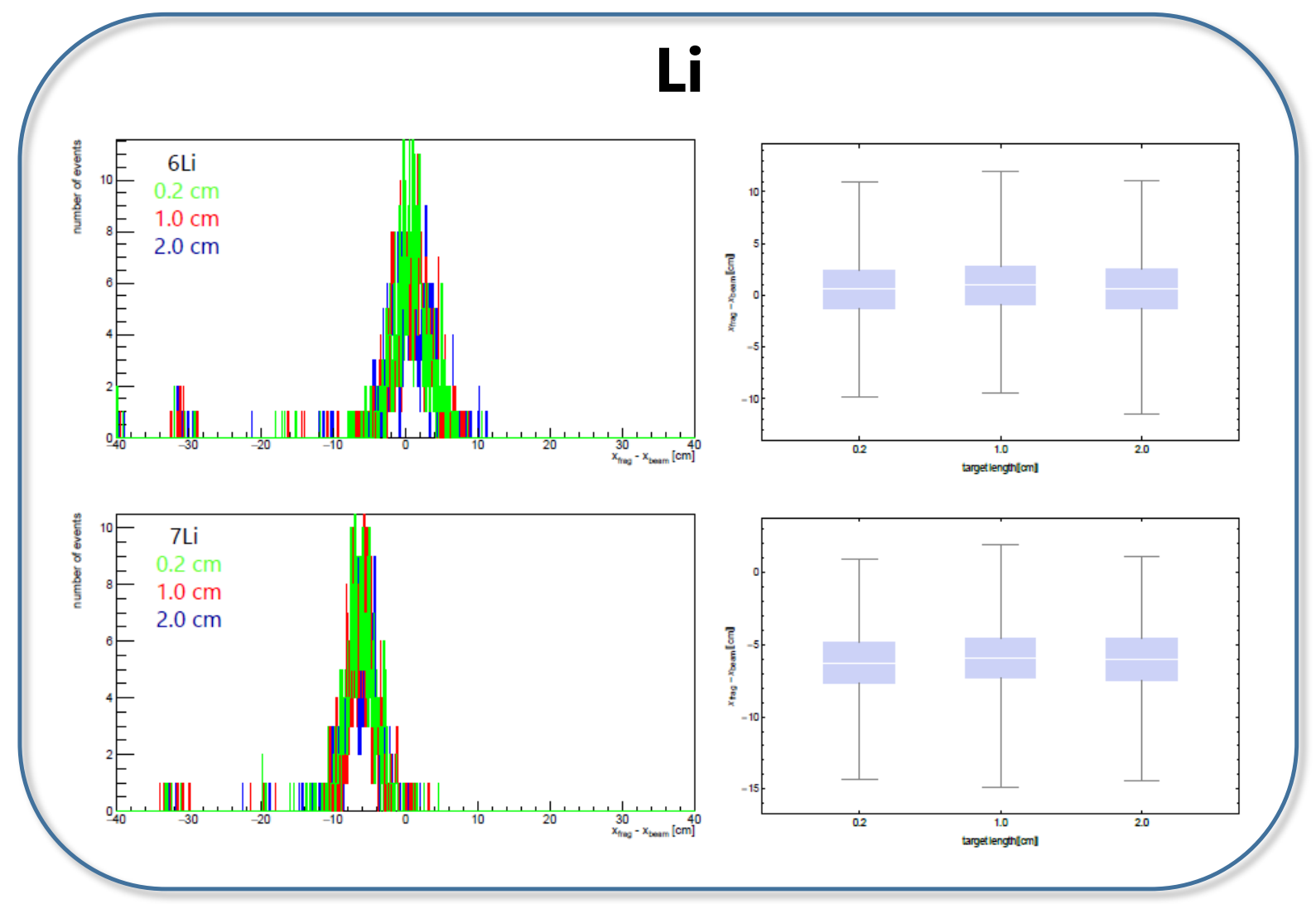
beam origin position blur ±1 cm

2. Analysis of beam rescattering in the target

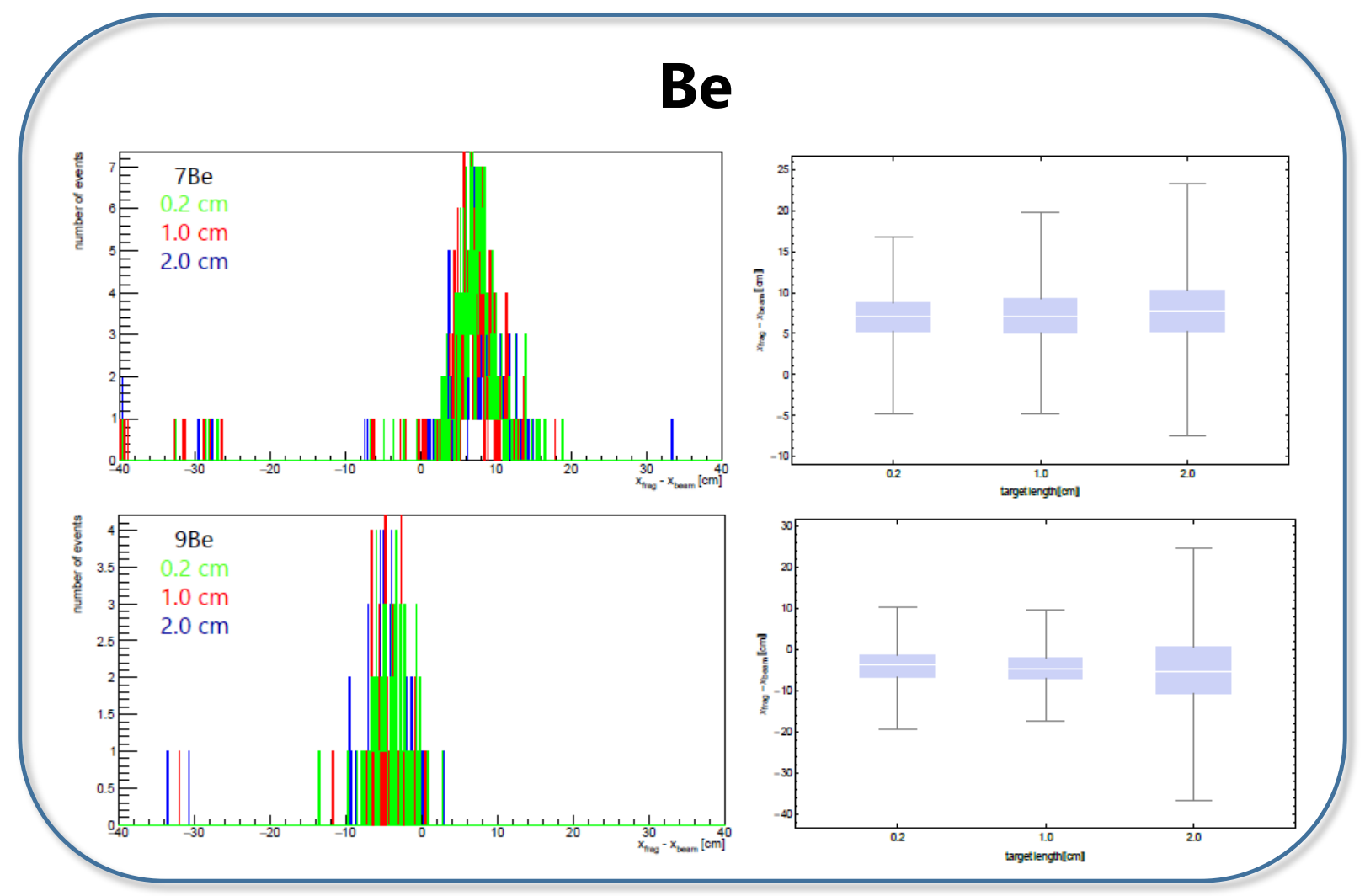
- simulation in beam fragmentation mode for three different target lengths
- normalized to beam X position distributions of fragments from C+C simulation as **output**
- **no dependence** on target length



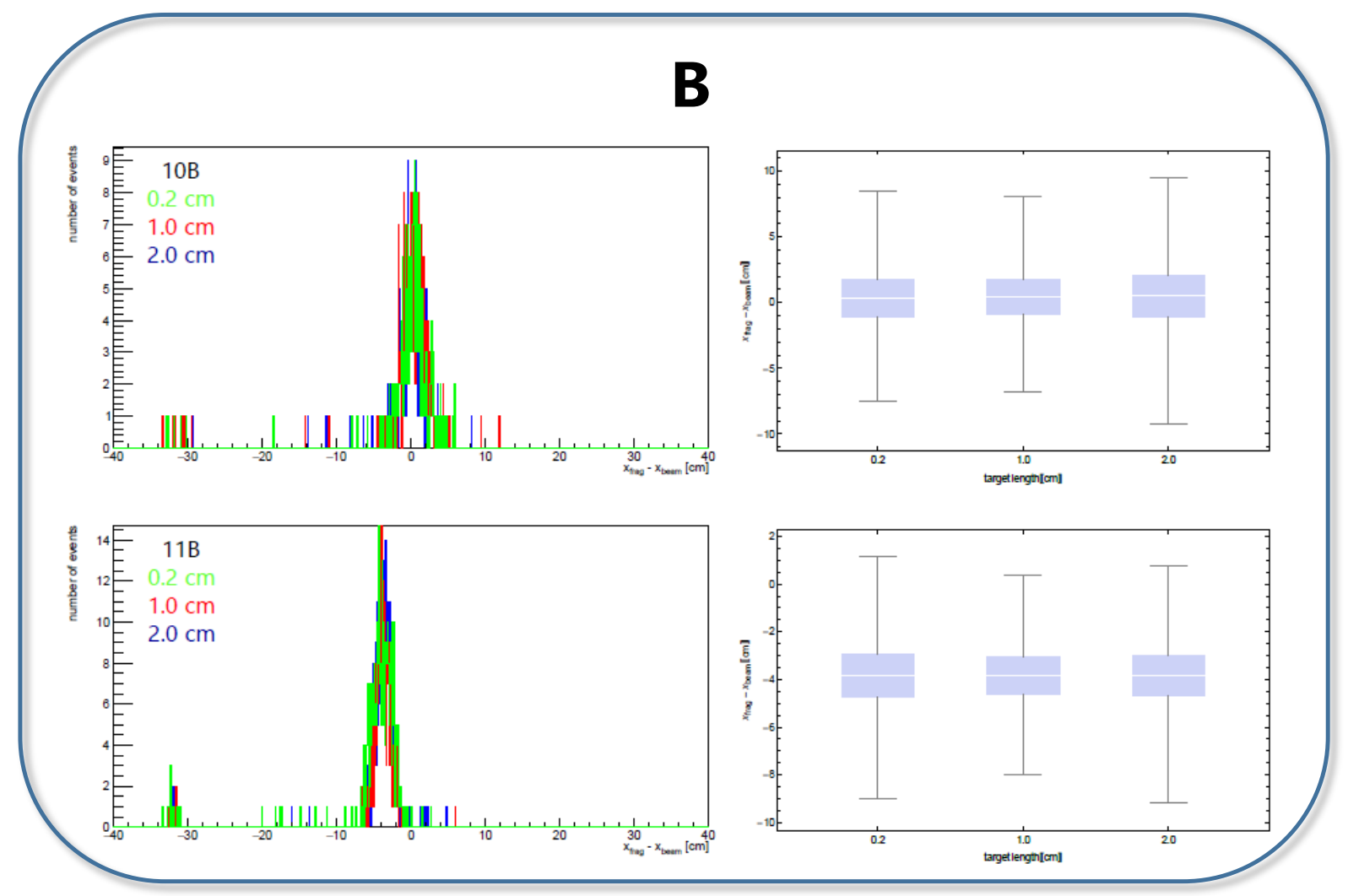
He



Li



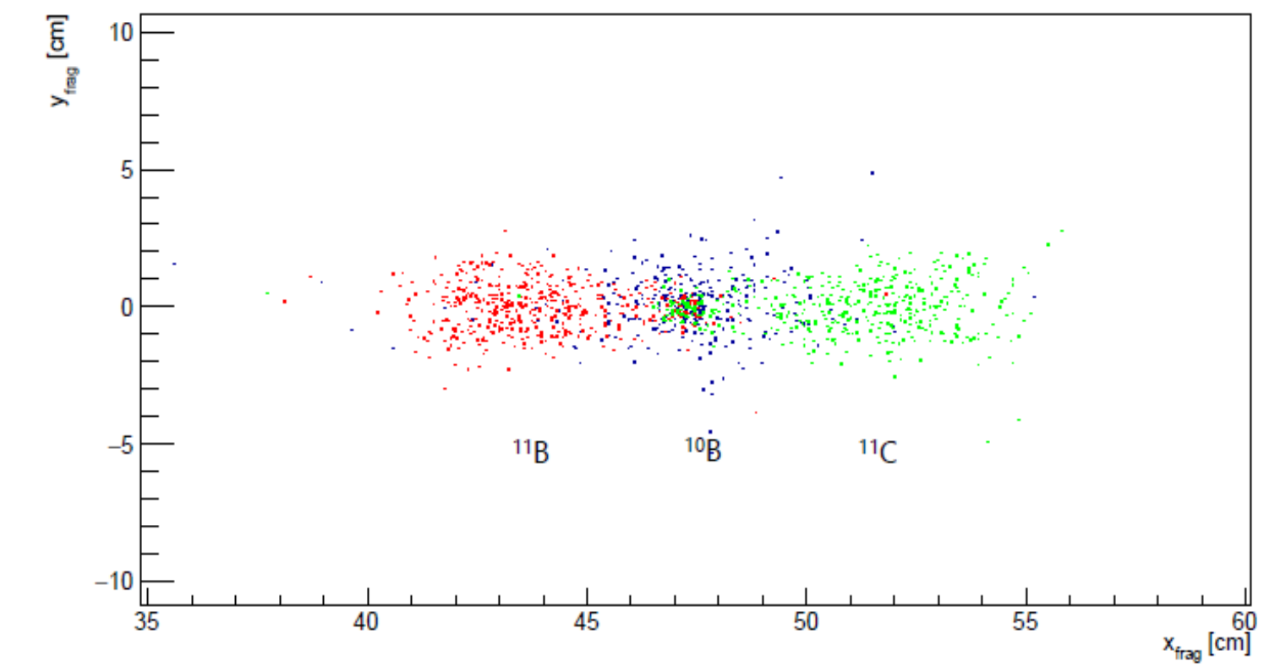
Be



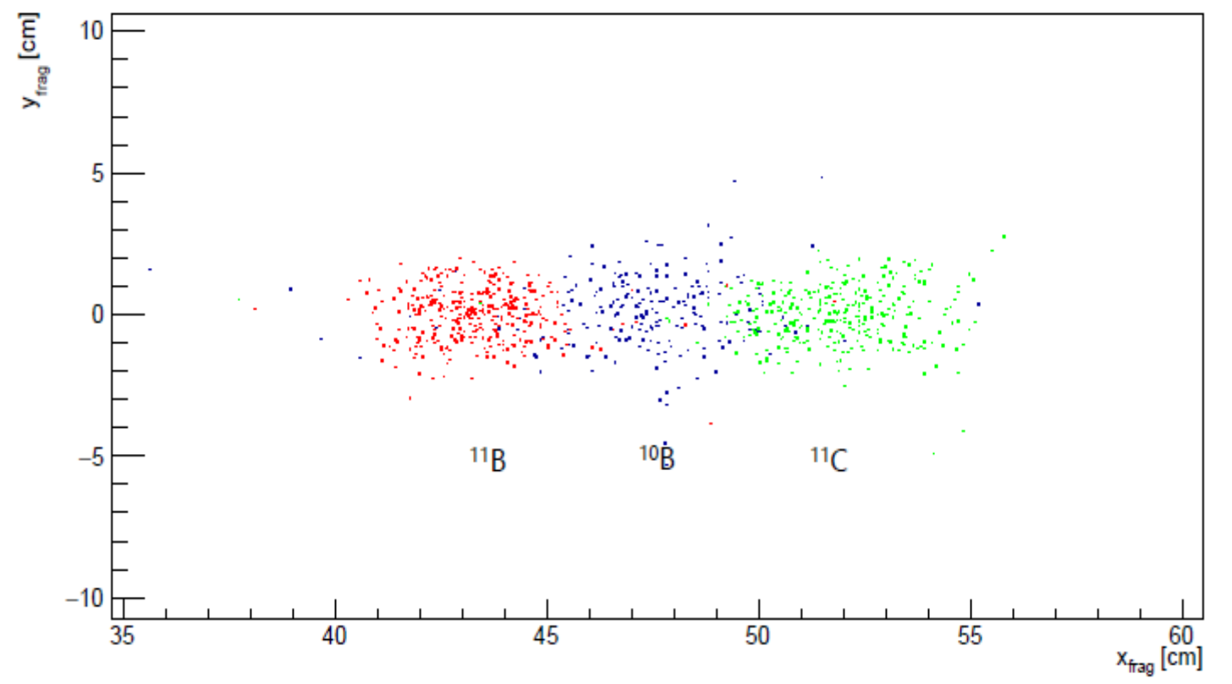
B

3. Analysis of physics properties of fragments

- simulation in beam fragmentation mode
- ^{10}B+^{11}B+^{11}C XY position distributions from C+C simulation as **output**
- **overlap is present** with peak in ^{10}B position!
- it is possible to reduce off-target production by cuts implying



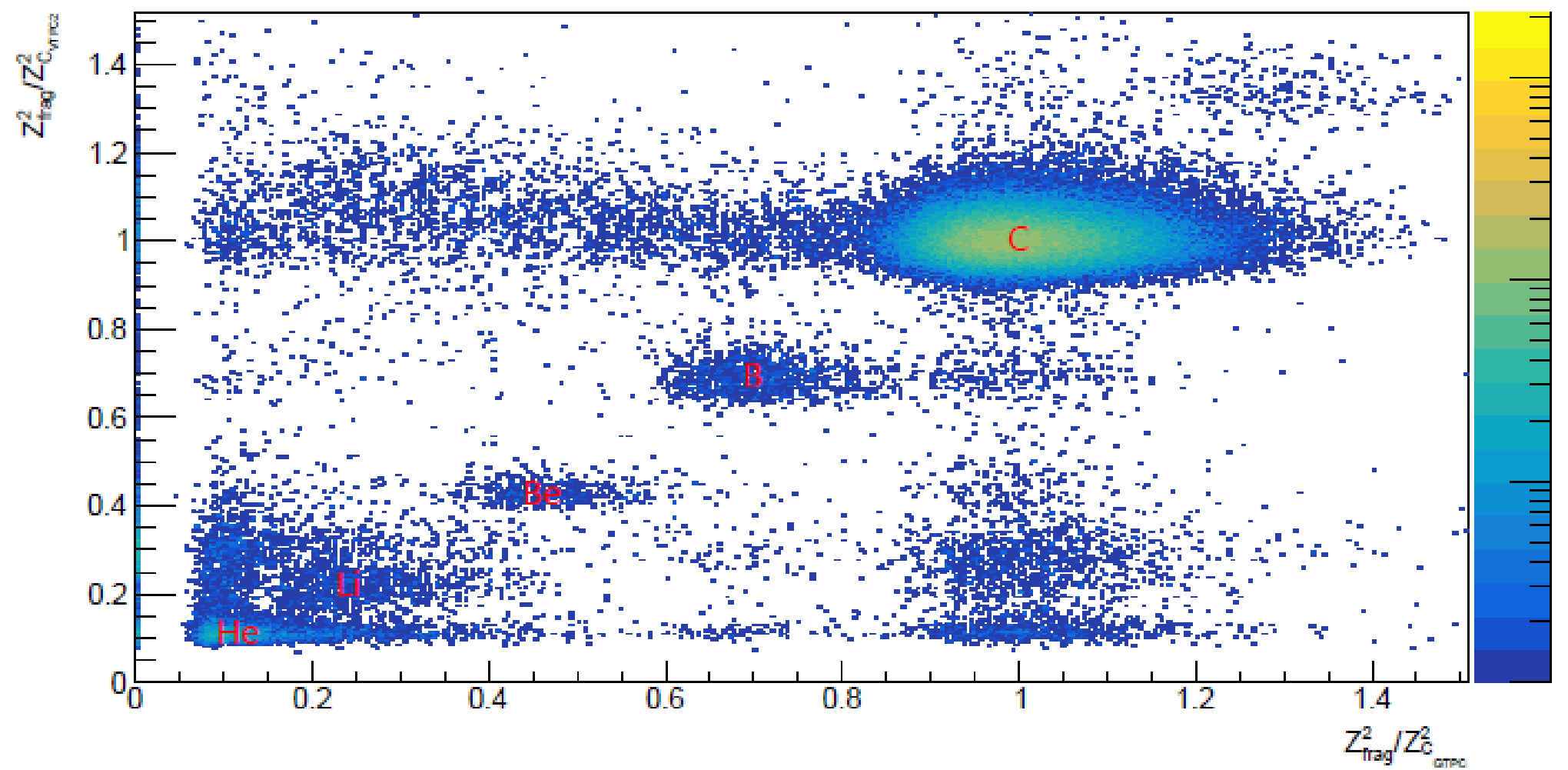
no cut: fragments are originated both from target and detector
(in-target + off-target interactions)



in-target cut: fragments are originated only from target
(in-target interactions)

Comparison of simulation with actual data

In order to reveal the best possible cut for off-target fragment production reduction, the actual data was compared to simulation in beam fragmentation mode.



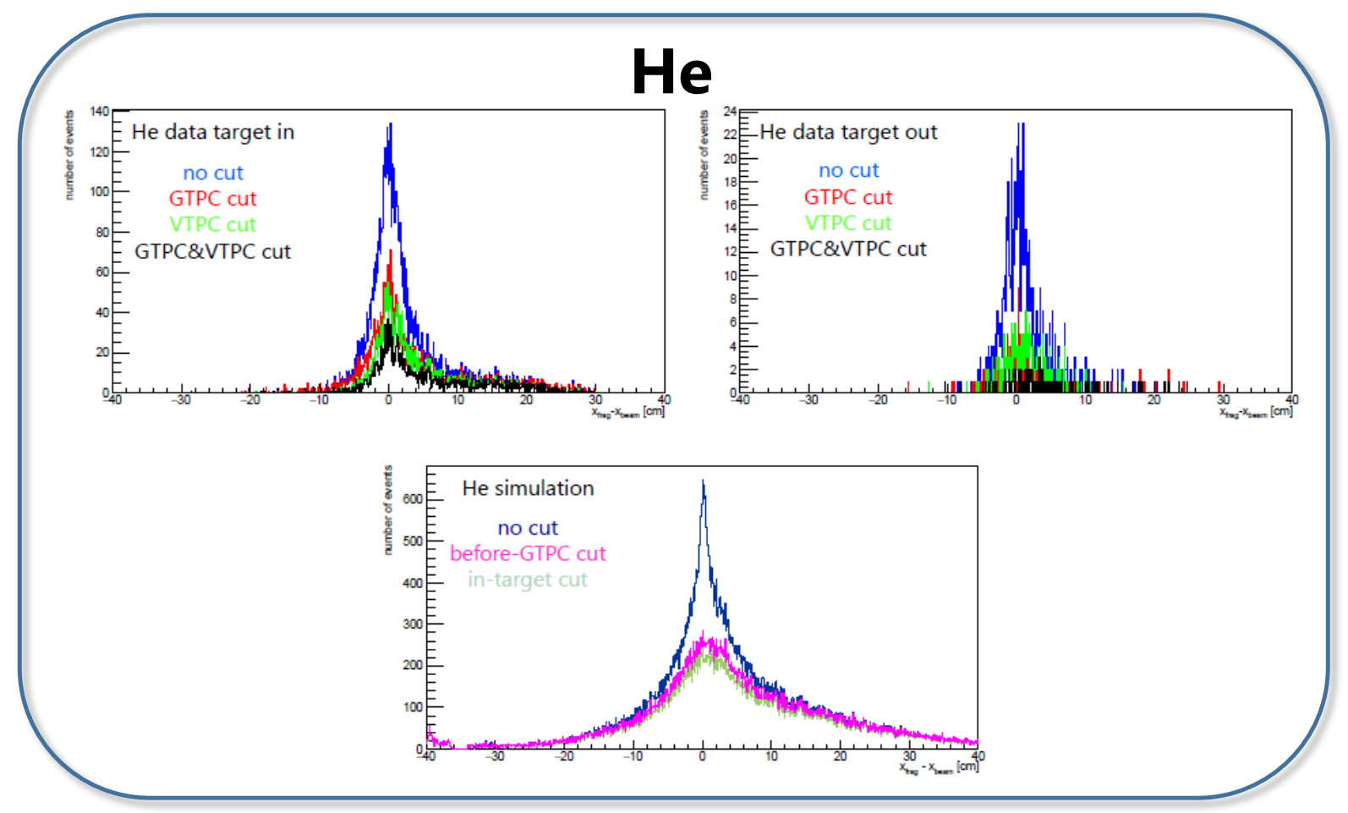
identification of fragments in GTPC and VTPC2

data cuts

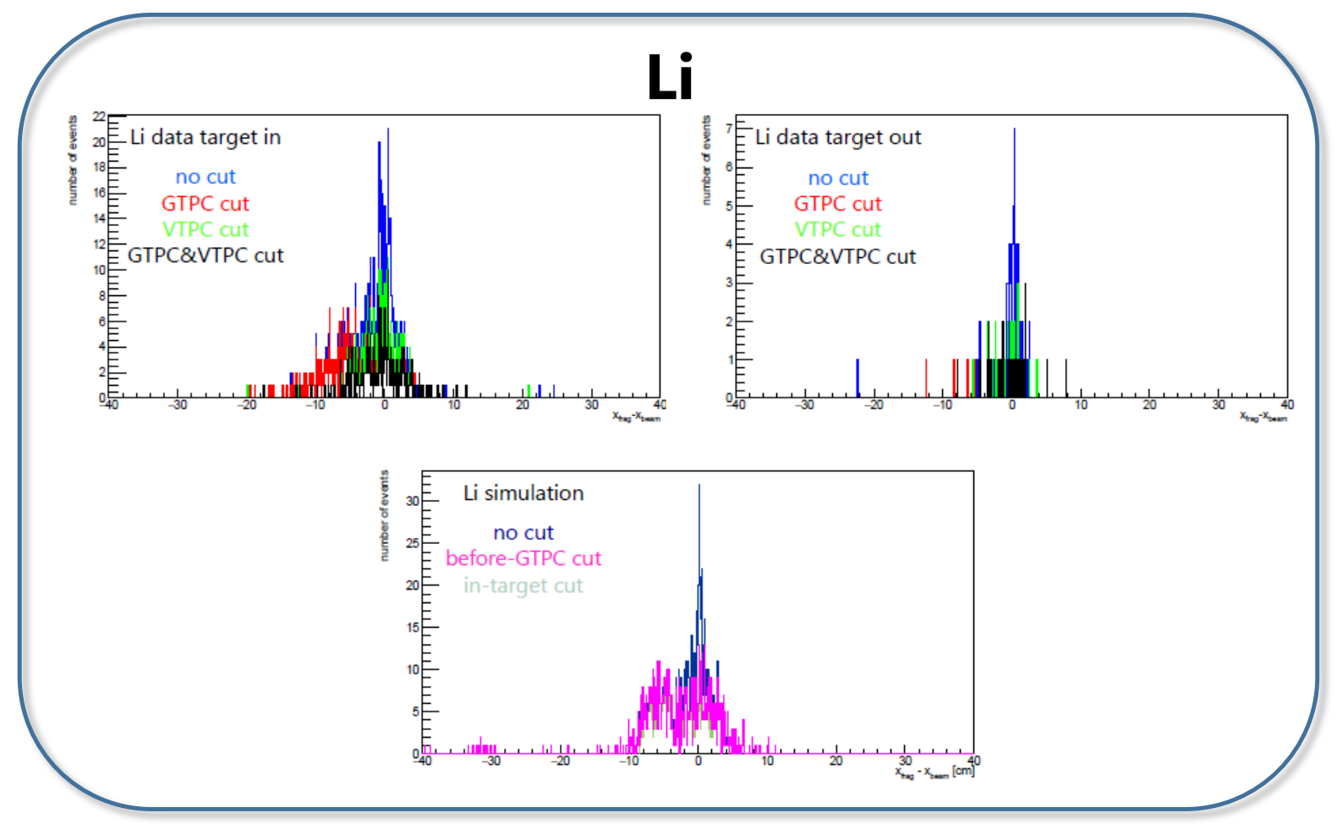
- no cut: Z^2_{MTPC}
- GTPC cut: $Z^2_{MTPC} \approx Z^2_{GTPC}$
- VTPC cut: $Z^2_{MTPC} \approx Z^2_{VTPC}$
- GTPC&VTPC cut: $Z^2_{MTPC} \approx Z^2_{GTPC} \approx \approx Z^2_{VTPC}$

simulation cuts

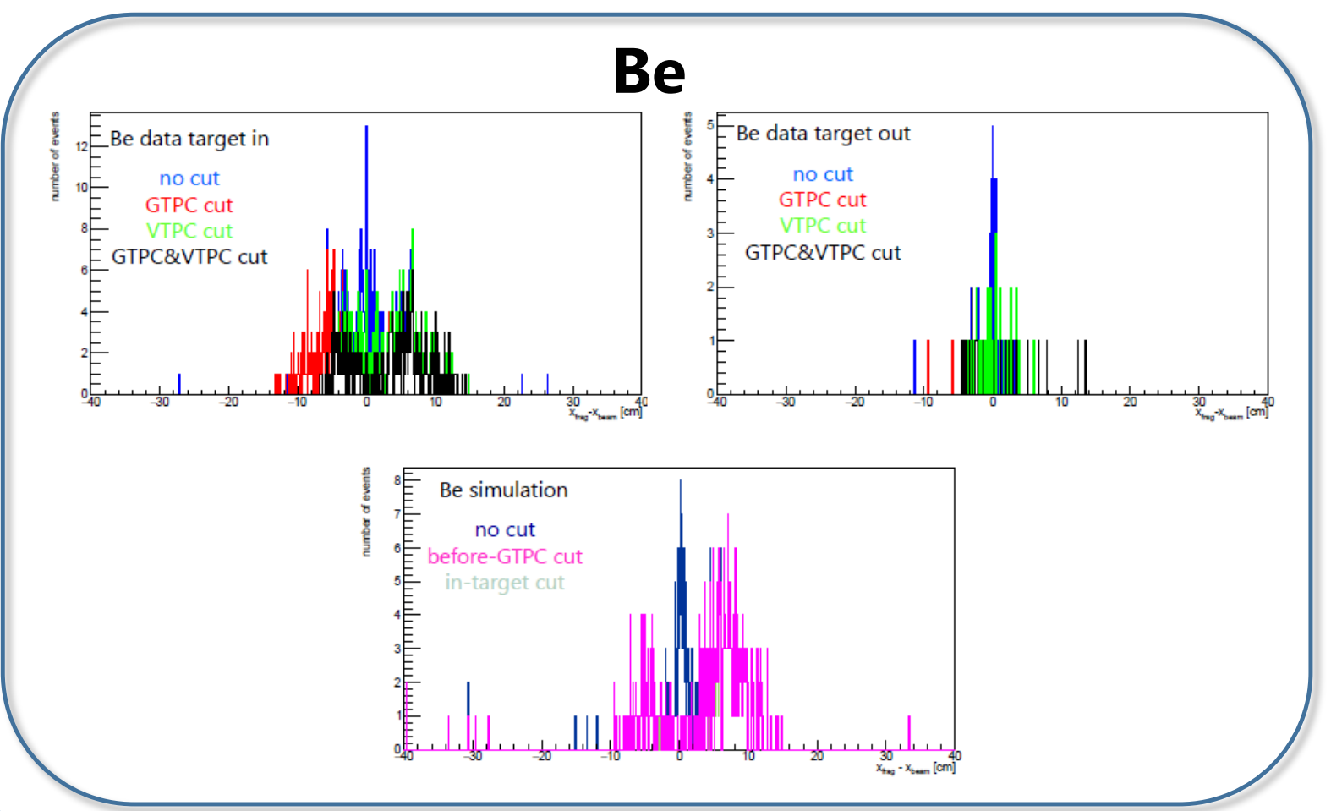
- no cut: Z^2_{MTPC}
- GTPC cut: Z^2_{MTPC} originated from up to GTPC
- in-target cut: Z^2_{MTPC} originated from target



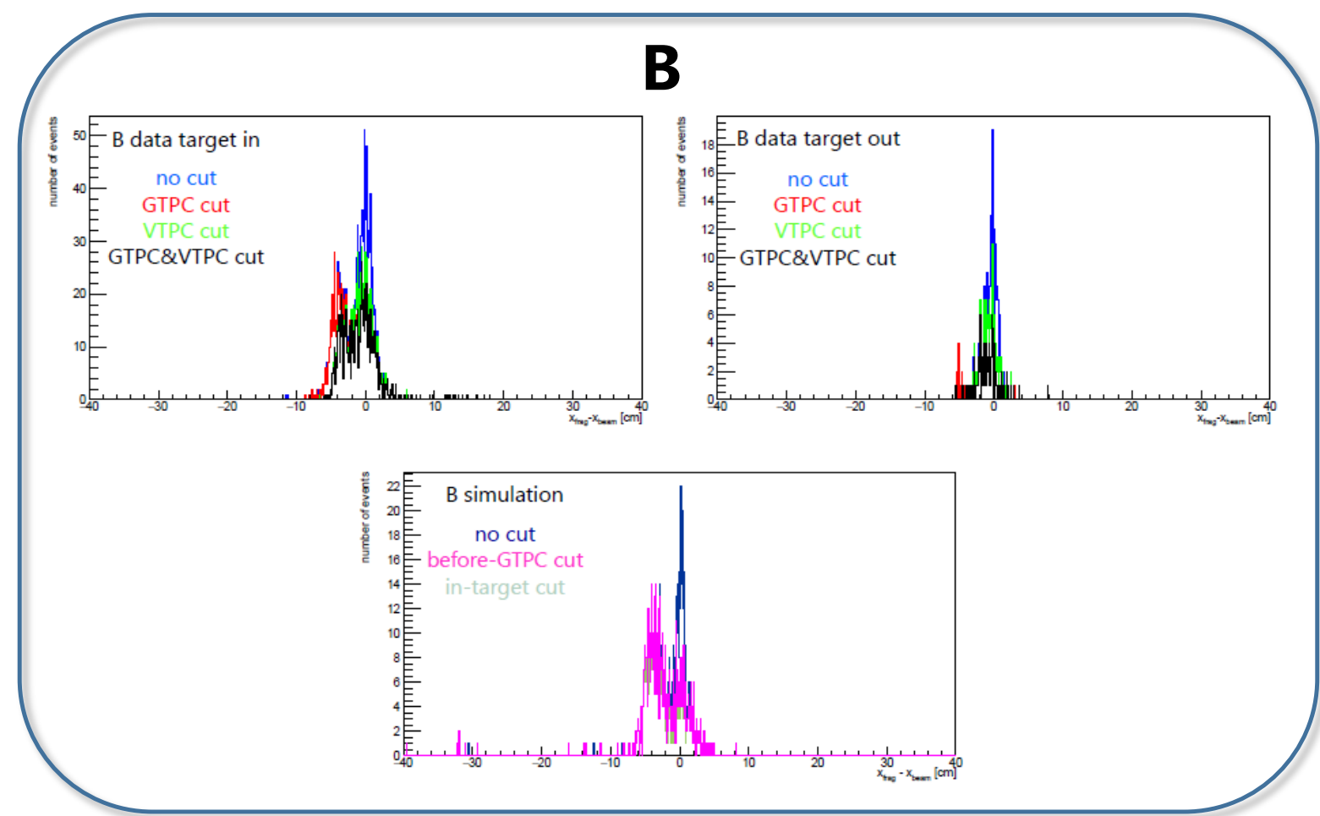
He



Li



Be



B

Calculation of fragmentation elemental cross-sections

Due to poor statistics of target out data, it was necessary to develop a method for off-target fragment production reduction. Two different approaches were developed:

- **based on simulations**. In the simulation it is precisely known how many and where the different fragments were produced. Therefore, it is possible to calculate efficiency of the before-GTPC cut in the simulation. Then it is assumed that the before-GTPC cut in the simulation has the same efficiency as the GTPC cut in the data and the in-target fragment production is estimated.
- **based on the target out data**. It is proposed to scale the available statistics in order to reduce the off-target fragment production. It is expected that quantitatively, the fragment production downstream of the GTPC should be the same both in target in and target out data, thus, it becomes possible to introduce a scaling factor and express the in-target fragment production.

Performance of both methods is verified by the **test calculation** of the fragmentation elemental cross-sections and its further comparison with available data in this energy range [A. Korejwo et al. J. Phys. G, vol. 26, pp. 1171–1186]:

Reaction ^{12}C →	$\boldsymbol{\sigma_{C+p\rightarrow X}[mb]}$ I method	$\boldsymbol{\sigma_{C+p\rightarrow X}[mb]}$ II method	$\boldsymbol{\sigma_{C+p\rightarrow X}[mb]}$ @ 3.66 GeV/A
He	77.1±0.93	113.59±7.37	185±25
Li	9.66±0.36	16.57±2.62	34.0±4.6
Be	8.86±0.33	9.75±1.90	21.0±2.7
B	48.6±0.77	41.50±5.07	40.6±3.1
X (Z < 6)	143.35±1.2	179.56±11.79	

For both methods the calculated cross-section values appear to be underestimated. It should be mentioned that both methods are very sensitive to implied cuts and the wider cuts were used for second method. Overall, the result can be explained by the imperfection of proposed methods and the inaccuracy of the detector calibration.