Measurement of ^{12}C ions fragmentation cross sections on a gold thin target with the FIRST apparatus

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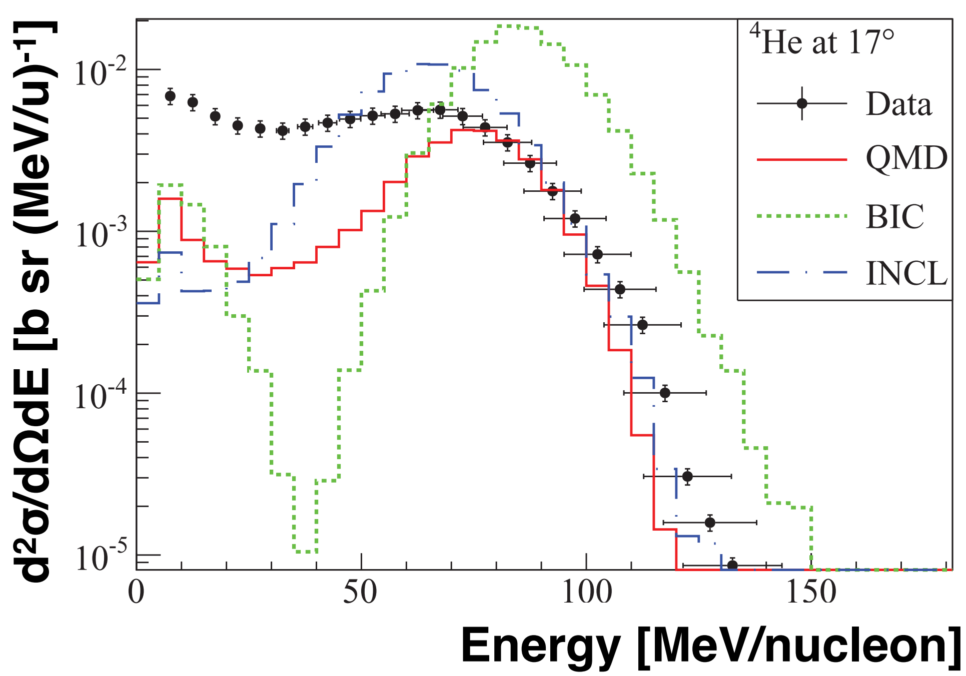
54th International Winter Meeting on Nuclear Physics
25-29 January 2016, Bormio (Italy)

FIRST experiment purposes

- The study of the nuclear fragmentation processes in the interaction of highly energetic ions in matter is of great interest in:
  1. Basic research: To improve our knowledge of nucleus-nucleus collisions (e.g. hadronic shower induced by ions in the atmosphere)
  2. Applied physics: in particular in particle therapy for the treatment of tumors and in space radiation protection
- Accurate measurements of fragmentation cross sections of light ions interacting with elemental and composite targets are crucial to benchmark and improve the nuclear interaction models implemented in Monte Carlo (MC) simulation codes.

- **The current discrepancies between MC codes and experimental data are mainly due to the lack of available data and to their limited precision.**

Data: E600 (GANIL)C+C @ 95 MeV/nucleon
MC simulation: GEANT
J.Dudouet et al., Phys. Rev. C 89, (2014)



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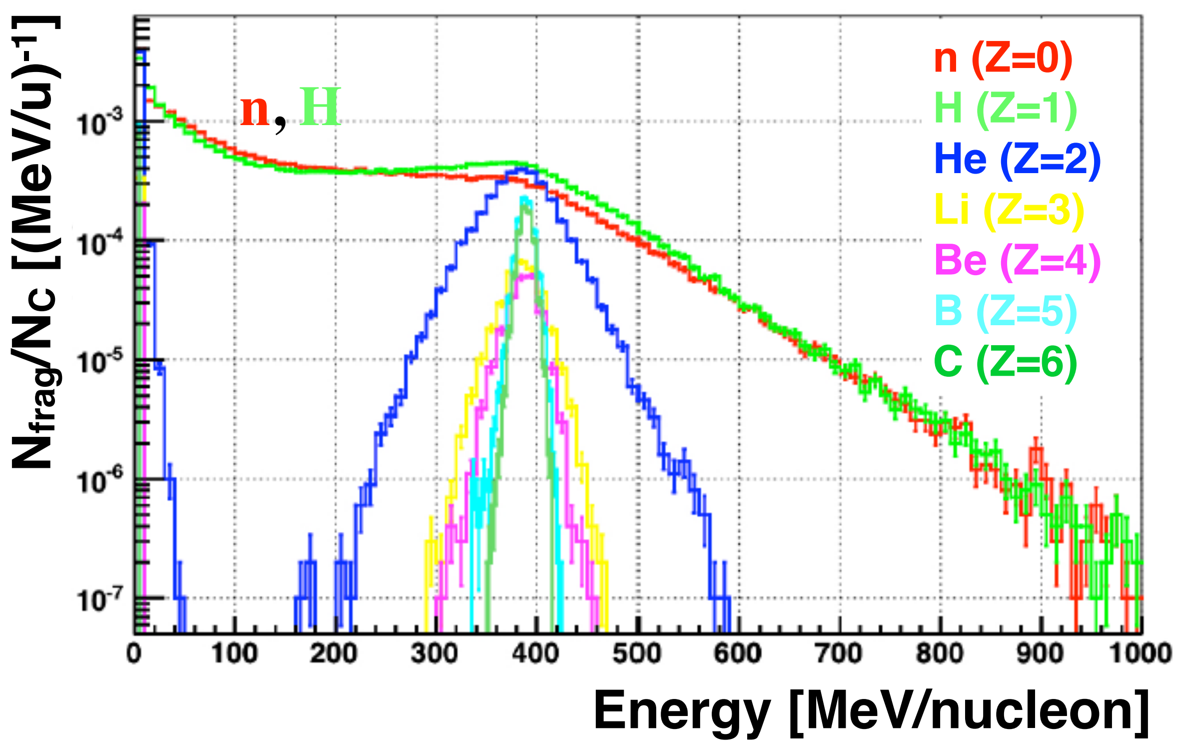
- The FIRST (**F**ragmentation of **I**ons **R**elevant for **S**pace and **T**heraphy) experiment at SIS accelerator of GSI measured the fragmentation cross sections of a ^{12}C beam on thin targets
- Collected 5 M events of **^{12}C @ 400 MeV/nucleon impinging on a 0.5 mm Gold target**
- **Differential cross sections measured for fragments emitted in the forward region (with polar angle θ wrt the beam axis < 5°)**

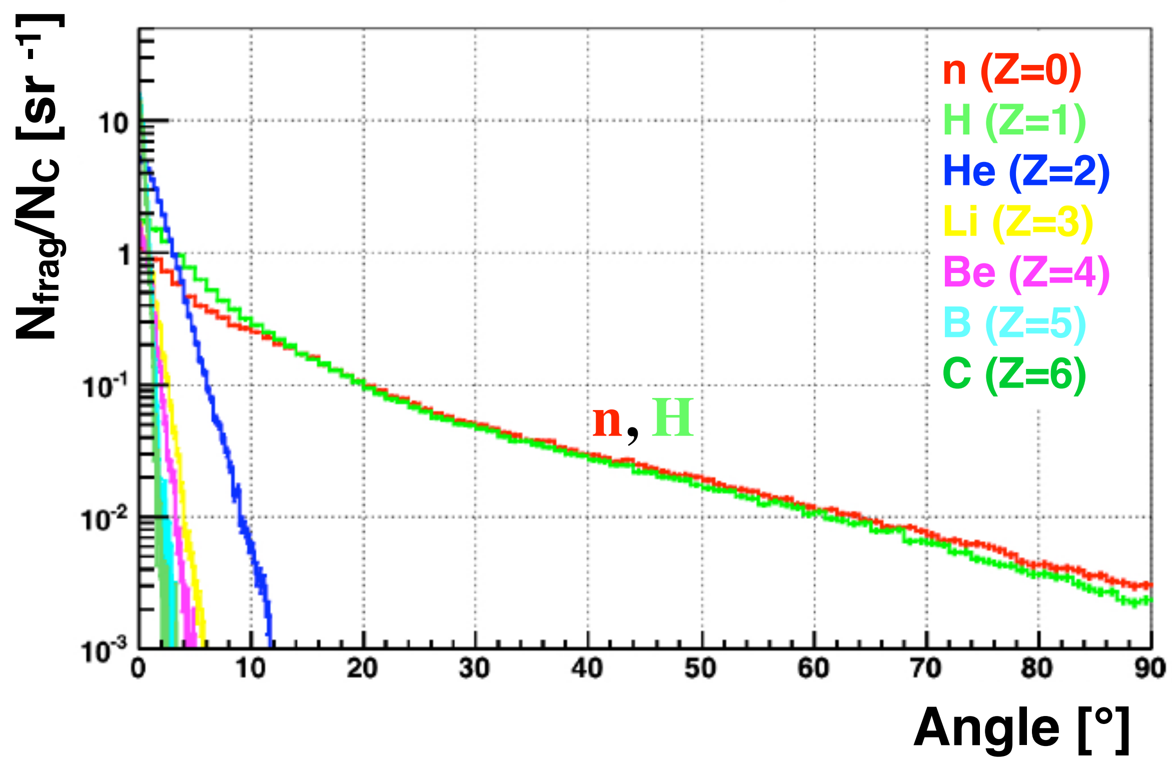
FIRST detector optimization

- **A MC simulation of a ^{12}C beam at 400 MeV/nucleon on a 8 mm carbon target has been developed using the FLUKA code, to design the detector:**
  - ➡ Z > 2 fragments ~ same velocity of the ^{12}C ions. Emitted in forward direction
  - ➡ Protons & neutrons are the most abundant fragments: wide β spectrum 0<β<0.6 and wide angular distribution
- The dE/dx loss by the fragments spans from 2 to 100 m.i.p.

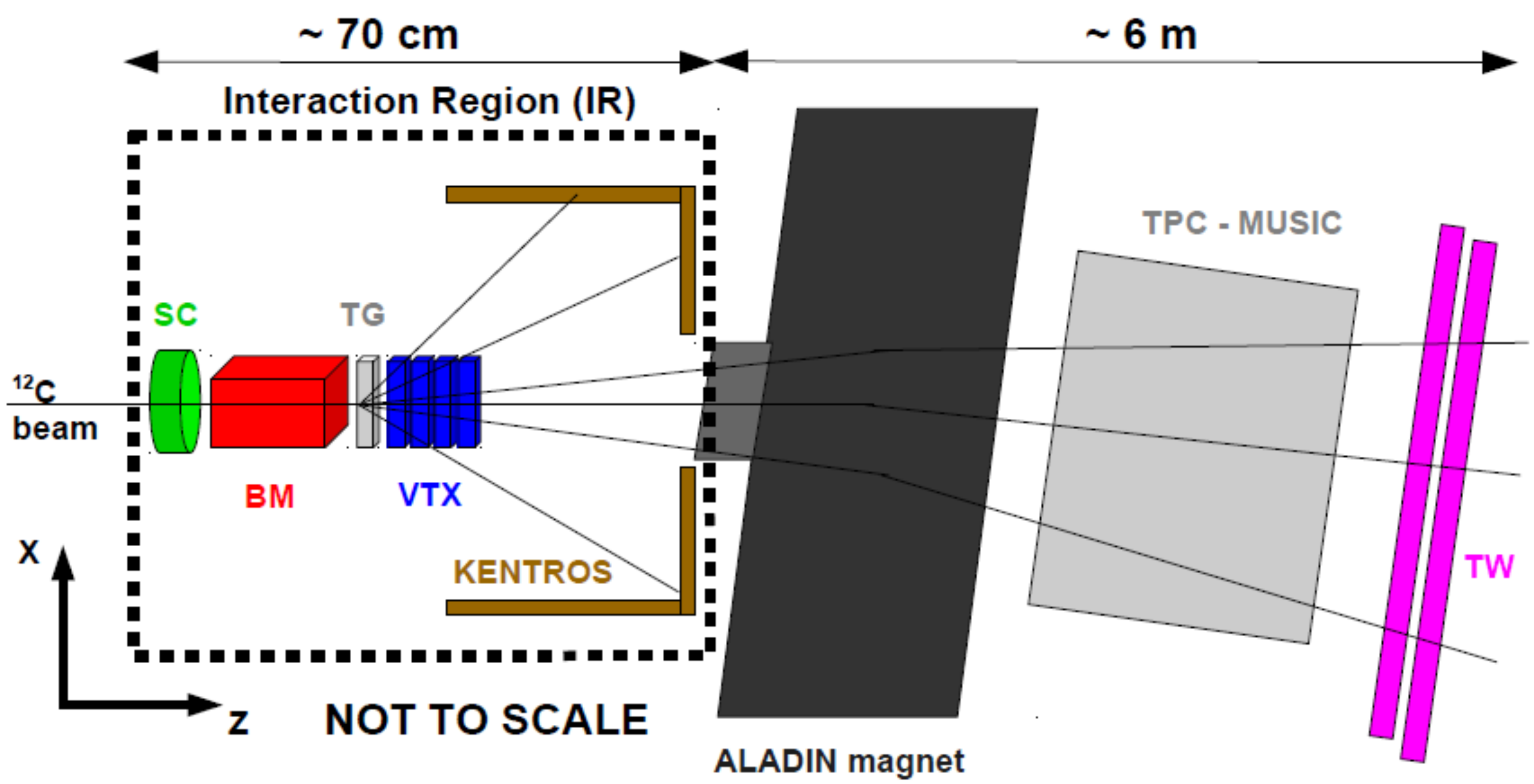
FLUKA simulation: Energy distribution



FLUKA simulation: Angular distribution



The FIRST apparatus



The TPC didn't work during the data acquisition.

The KENTROS detector (scintillators and fibers for ToF, E_{loss} and tracking measurements) has not been used in this analysis focused on forward emitted fragments only ($\theta < 5°$)

Start Counter (SC): thin scintillator. N_C, ToF and trigger

Beam Monitor (BM): drift chamber for beam direction and impact point on target

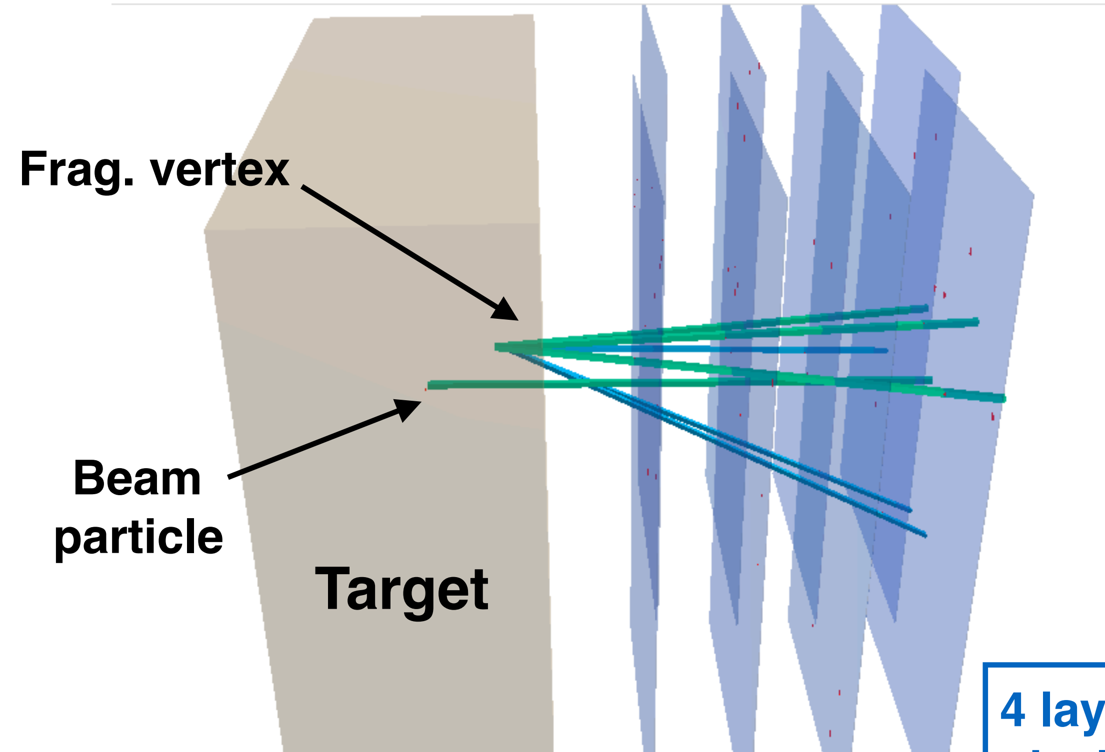
Vertex Detector (VTX): 4 layers of pixel silicon detectors. Tracks direction ($\theta < 40°$)

ToF Wall (TW): two layers of plastic scintillator (192 vertical slats). X, Y, Z, E_{loss} and ToF

The FIRST **reconstruction challenge** is to match **the VTX and the TW (~6 m apart) information for the forward fragments** (passing through the magnet region).

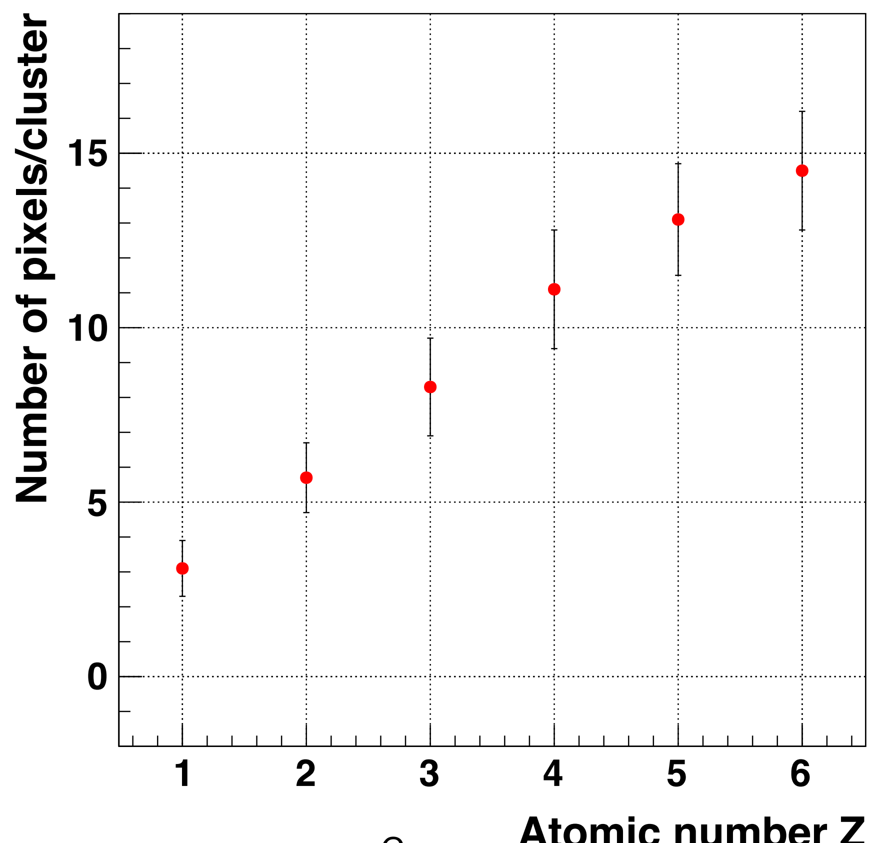
The Vertex detector

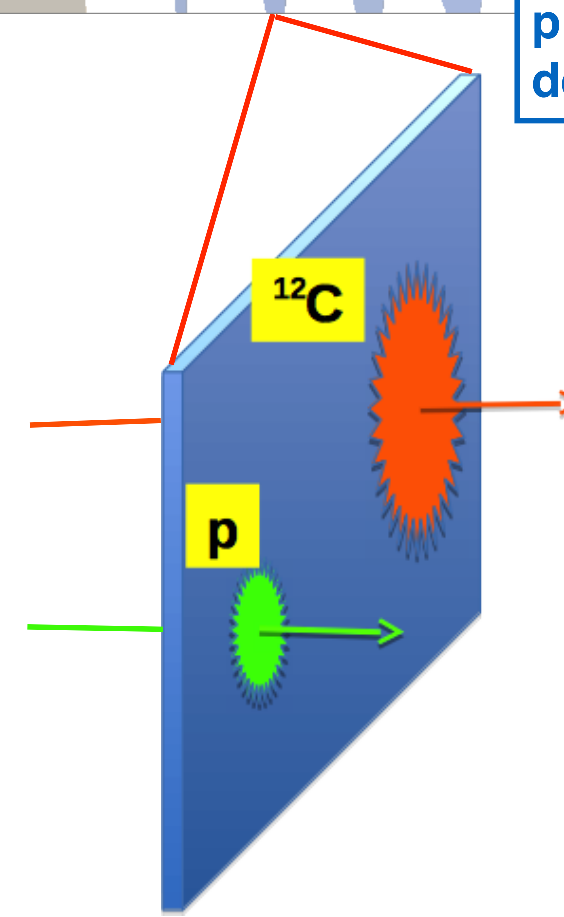
- High tracking efficiency and vertex reconstruction efficiency (~ 99%)
- Excellent tracking resolution < 10 μm (x,y) and vertexing resolution < 10 μm (x,y) and < 50 μm (z): **fundamental when extrapolating the fragment tracks along ~6 m to the ToF Wall**



4 layers of pixel silicon detectors

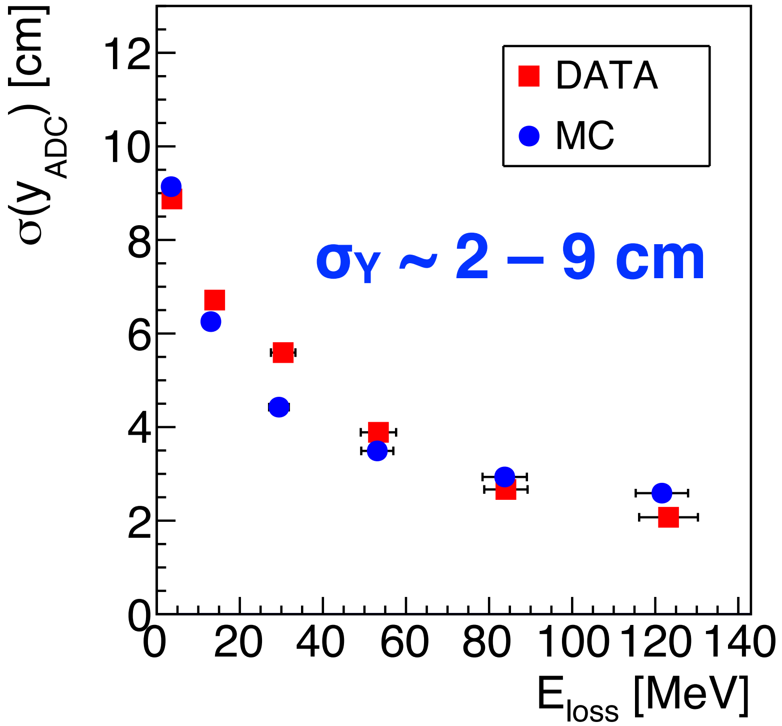
- The VTX slow integration time (115 μs) causes some pile-up that was taken into account
- **The VTX can provide also information on the fragment charge looking at the number of fired pixels per cluster**

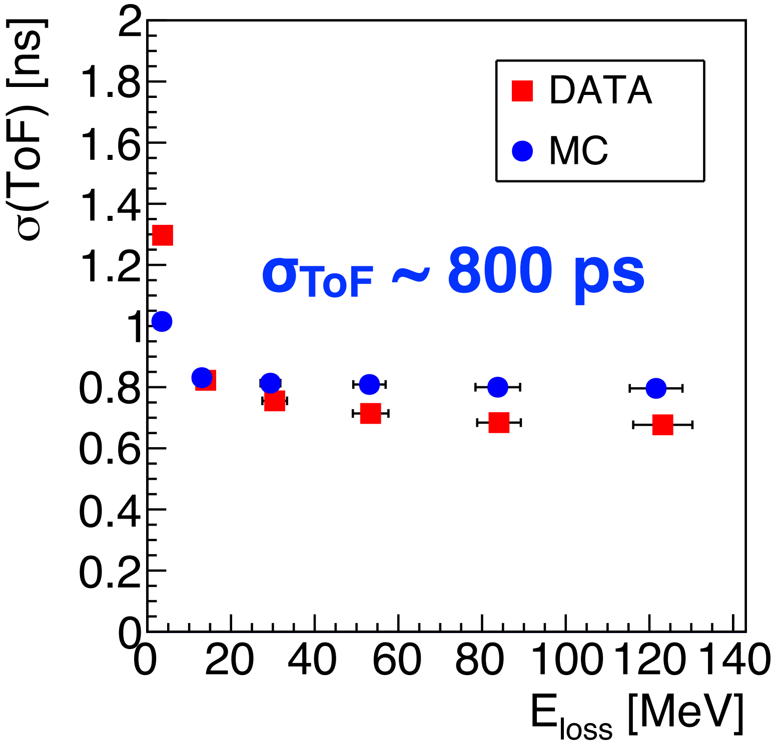




The ToF-Wall detector

- Two planes of 192 plastic scintillators (slat dimension: 1.10 m x 2.5 cm x 1 cm)
- **The resolutions have been estimated (on data) by comparing the position, ToF and Energy loss values measured for hits in the two TW planes that are associated to the same incoming fragment**
- **X & Y hit position resolution: $\sigma_X \sim 0.7$ cm, $\sigma_Y \sim 2 - 9$ cm**
- **ToF resolution: $\sigma_{ToF} \sim 800$ ps**
- **E_{loss} resolution: $\sigma_E \sim (2–12)$ MeV**





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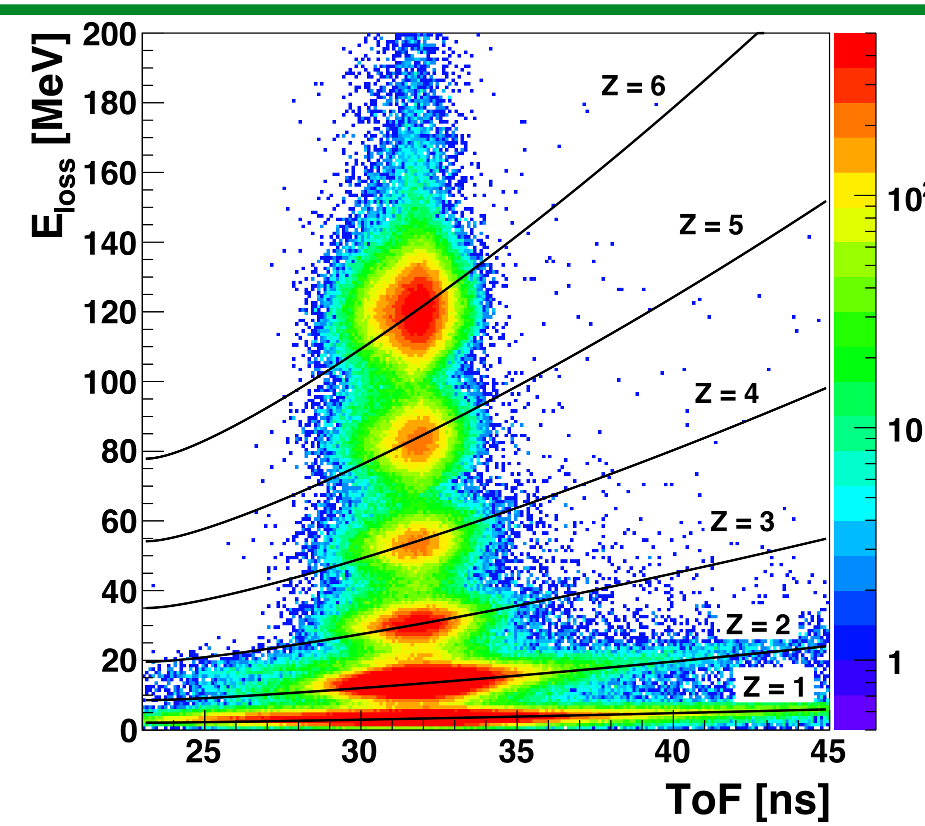
Fragment charge identification (ZID) is performed using an algorithm based on detected dE/dX in the TW vs Tof



Global reconstruction strategy

- **Fragments are reconstructed using an iterative procedure that matches VTX tracks and TW hits**
- A minimization algorithm determines pc/Z and the track trajectory L
- Fragment velocity from ToF:

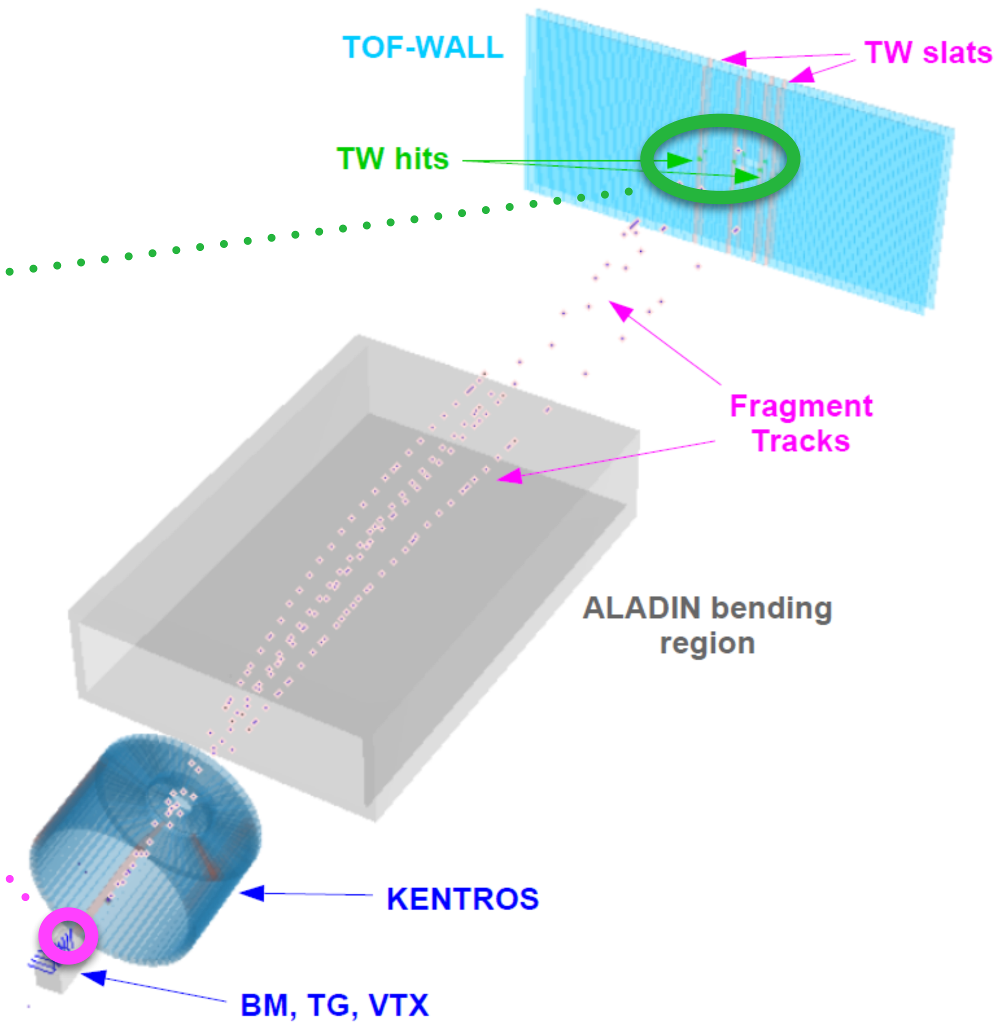
$$\beta = \frac{L}{\mathrm{ToF} \cdot c}$$

- Fragments mass:

$$\boxed{Mc^2 = \frac{pc}{\beta \cdot \gamma}}$$

- Mass resolution:

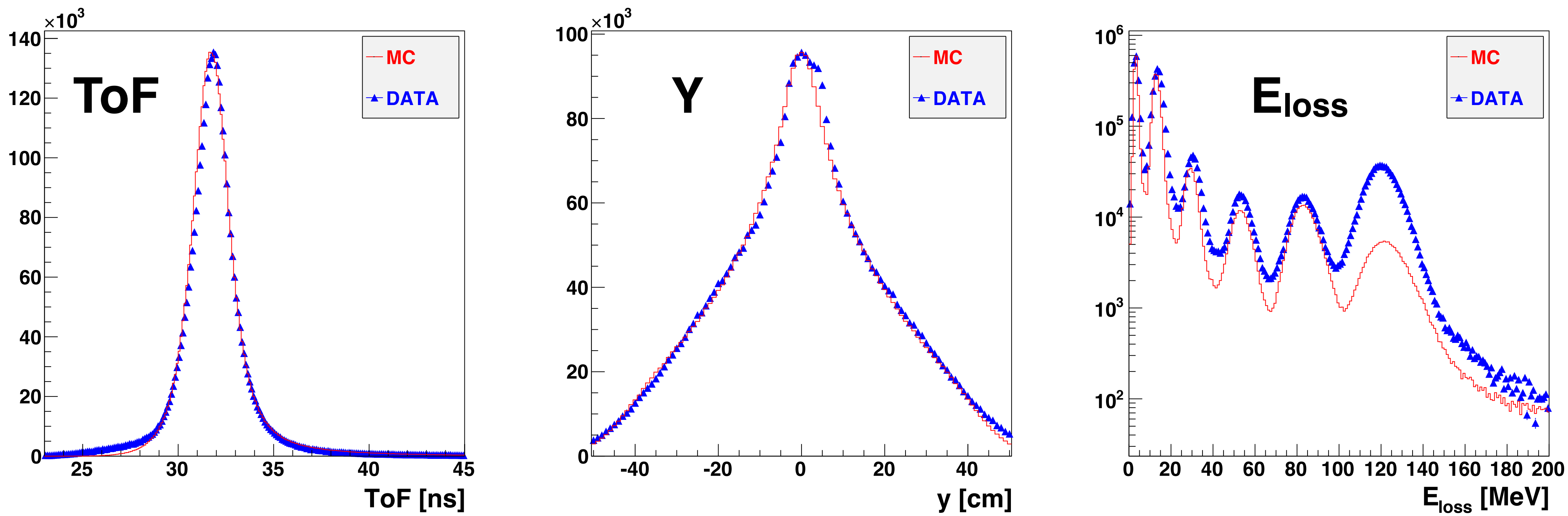
$$\frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta p}{p}\right)^2 + \left(\gamma^2 \frac{\Delta t}{t}\right)^2}$$



A scoring function based on both Y and global charge (from VTX and TW) is used to **rate the combinations of VTX / TW tracks** and to **select the best track candidate**

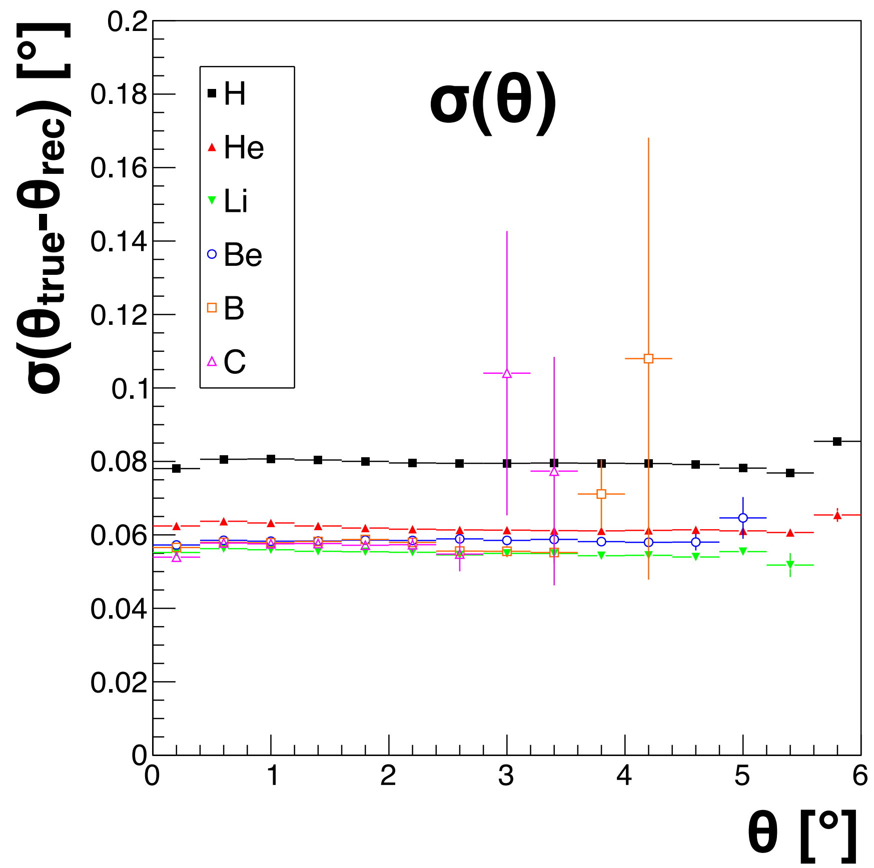
MC simulation

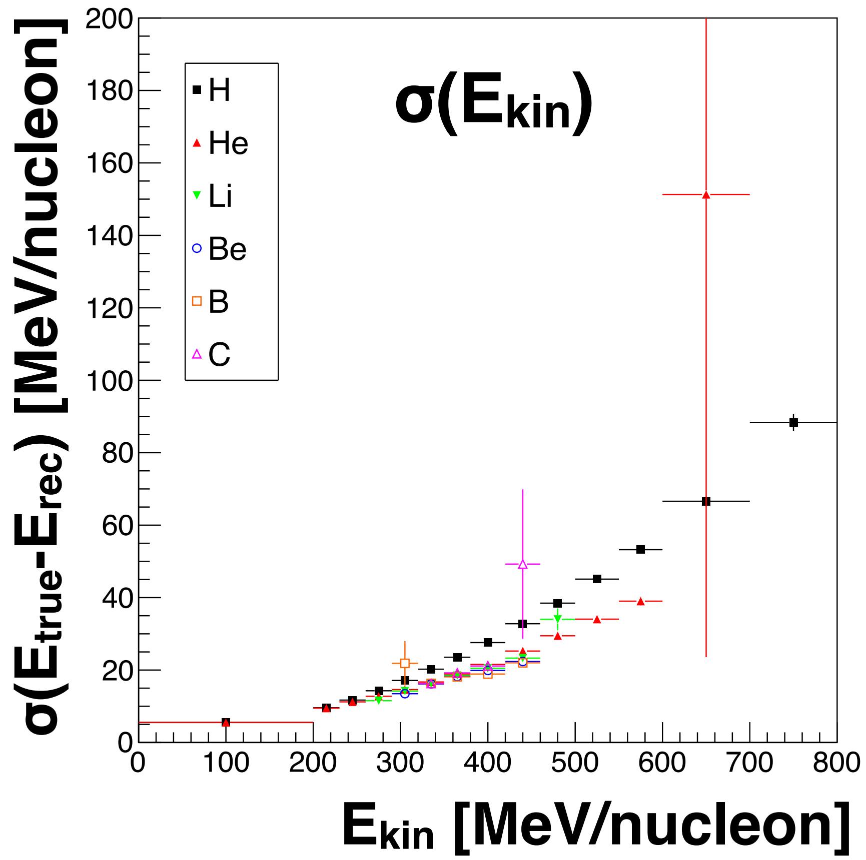
- A detailed ***MC simulation*** of a ^{12}C beam @ 400 MeV/nucleon impinging on a 0.5 mm gold target, has been developed with FLUKA **for the evaluation of the efficiencies, the resolutions and the background** PDF modeling / cross feed subtraction
- The comparison of E_{loss}, ToF and Y coordinates measured from the TW detector for DATA and MC events has been obtained for events in which a fragmentation occurred (number of tracks associated to a reconstructed vertex greater than 1)



FIRST performances: resolution

- **The global reconstruction algorithm has been benchmarked against the MC simulation**
- Angular and kinetic energy resolutions have been measured to evaluate possible bias introduced by the reconstruction algorithm and to optimize the binning choice for differential cross section measurements





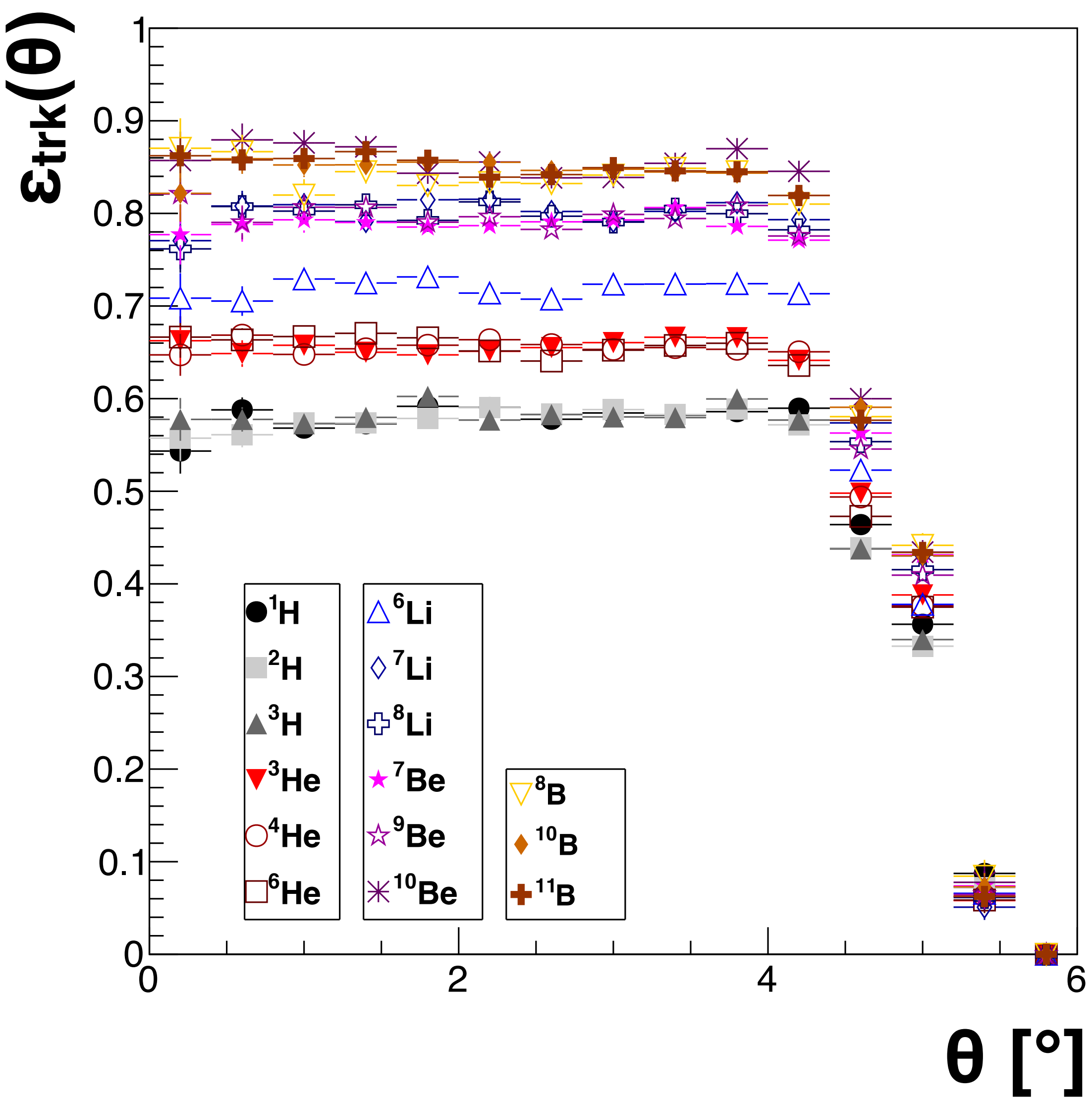
- The E_{kin} resolution increases as a function of fragment E_{kin} as expected
- We need to unfold the spectrum (Used the RooUnfold Tool with Bayesian approach)

FIRST performances: efficiencies

- **Tracking efficiencies are evaluated using a MC simulation for each fragment produced in the interaction of the ^{12}C beam with the gold target**

$$\boldsymbol{\varepsilon_{trk} = n_{REC} / n_{PROD}}$$

- $\mathbf{n_{PROD}}$: fragments emerging from the target in the magnet acceptance
- $\mathbf{n_{REC}}$: reconstructed tracks built using the true VTX and TW hits belonging to the true MC tracks under study



Cross Section Measurements

- Differential cross section, with respect to kinetic energy and angle, for the i-th isotope ${}^{Z}_{A}X$ with charge Z and mass number A

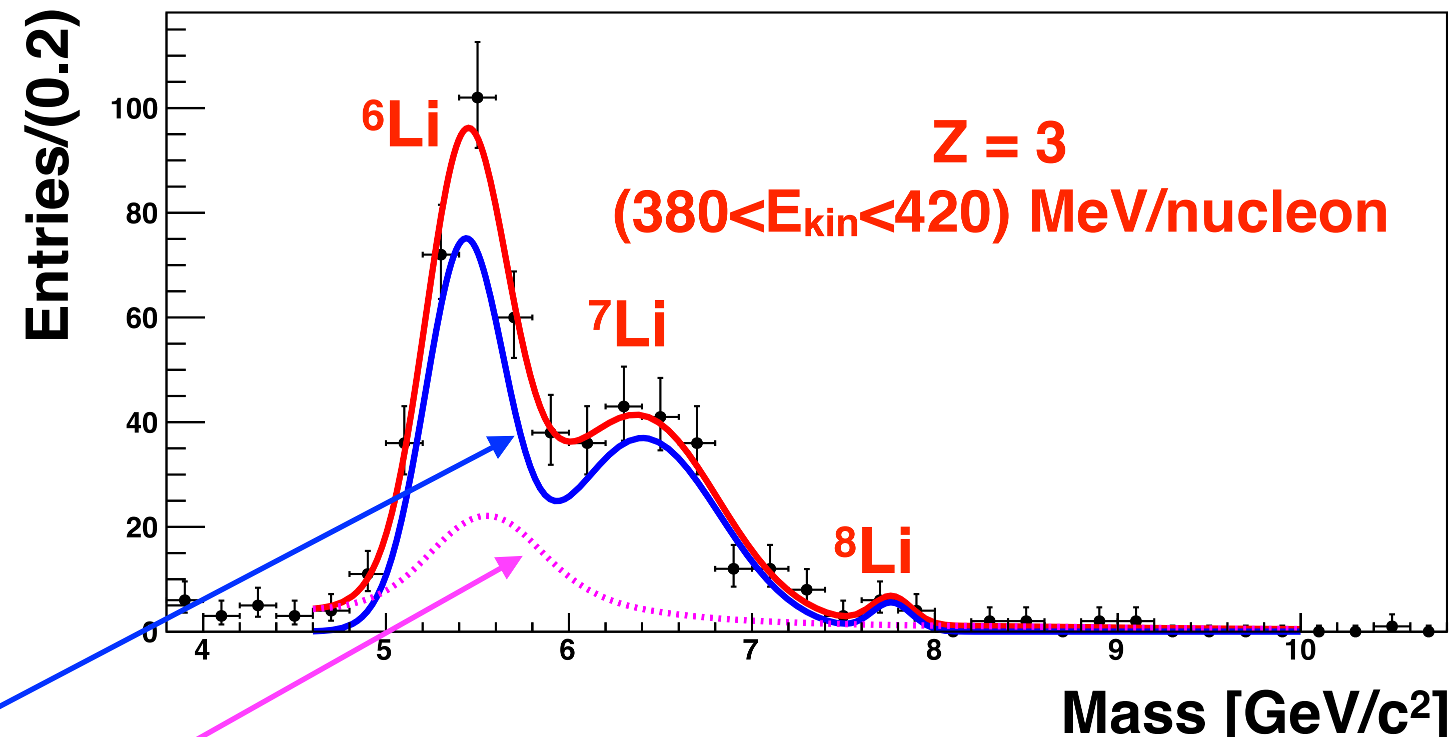
$$\frac{d\sigma_i}{d\Omega}(\theta) = \frac{Y_i(\theta)}{N_C \times N_{TG} \times \Delta\Omega \times \epsilon^i_{trk}(\theta)}$$

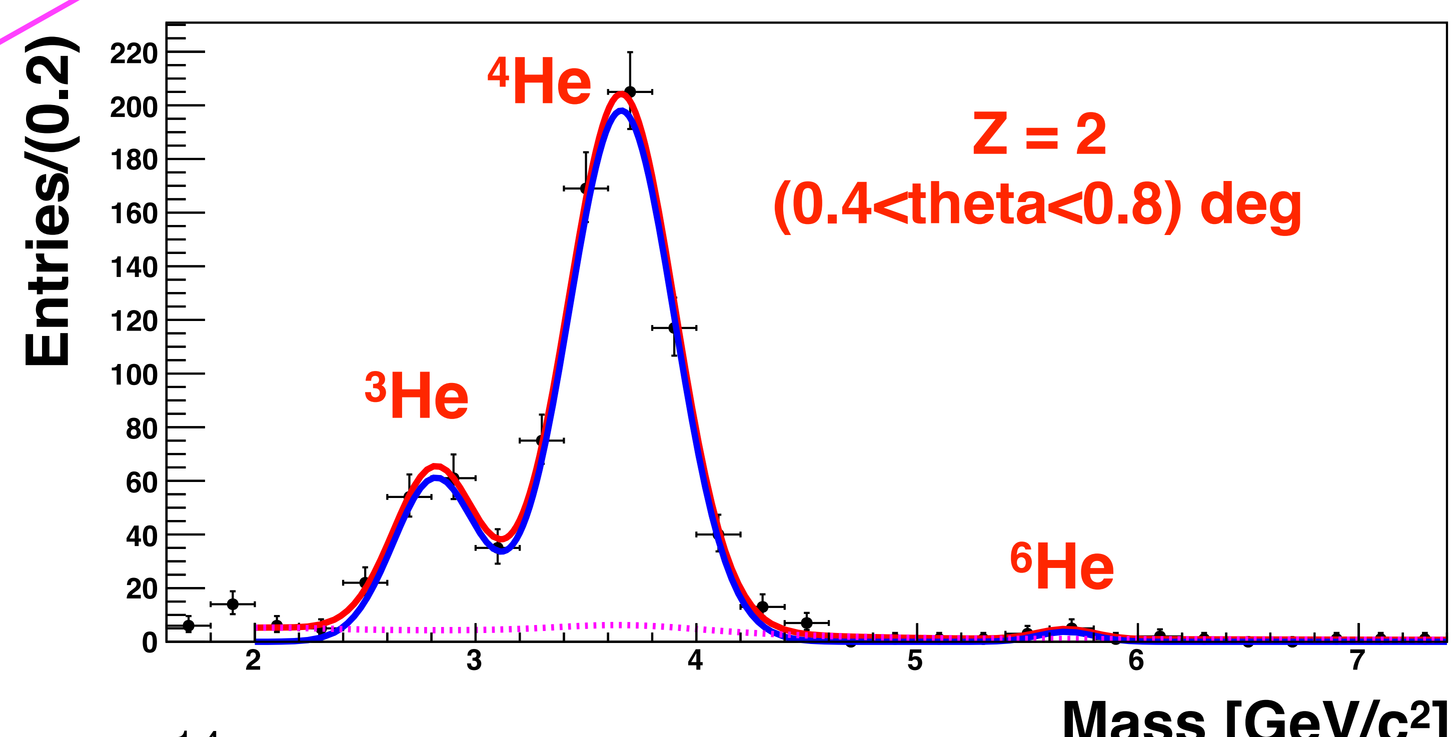
$$\frac{d\sigma_i}{dE_{kin}}(E_{kin}) = \frac{Y_i(E_{kin})}{N_C \times N_{TG} \times \Delta E_{kin} \times \epsilon^i_{trk}(E_{kin})}$$

- N_{TG} : number of atoms in the target per unit surface ($\rho \times d \times N_A / A$)
- N_C : number of total ${}^{12}C$ impinging on the target from Start Counter
- $\varepsilon_{trk}(\theta)$ / $\varepsilon_{trk}(E_{kin})$: tracking reconstruction efficiency per angular/energy bin for each isotope (as defined in previous slide)
- **$Y_i(\theta)$ / $Y_i(E_{kin})$: fragment yields for a given isotope ${}^{Z}_{A}X$ in an angular / energy bin $\Delta\Omega$ / ΔE_{kin}, measured from mass fits**

Fragment yields measurements

- **The reconstructed mass spectra are fitted, for each charge and angular (energy) bin ΔΩ (ΔE) to measure the fragment yield Y_i for each isotope $^{Z}_{A}X$**
- The Y_i yield are measured using an unbinned extended maximum likelihood fit: we get the yields of signal and background with uncertainties
- Signal (for each isotope) is modeled with Gaussian signal PDF
- Background PDFs are taking into account the combinatorial background
- **In the MC study, a fragment is marked as <u>combinatorial background</u> candidate whenever a track from VTX is paired with a hit from TW that does not belong to the SAME fragment.**





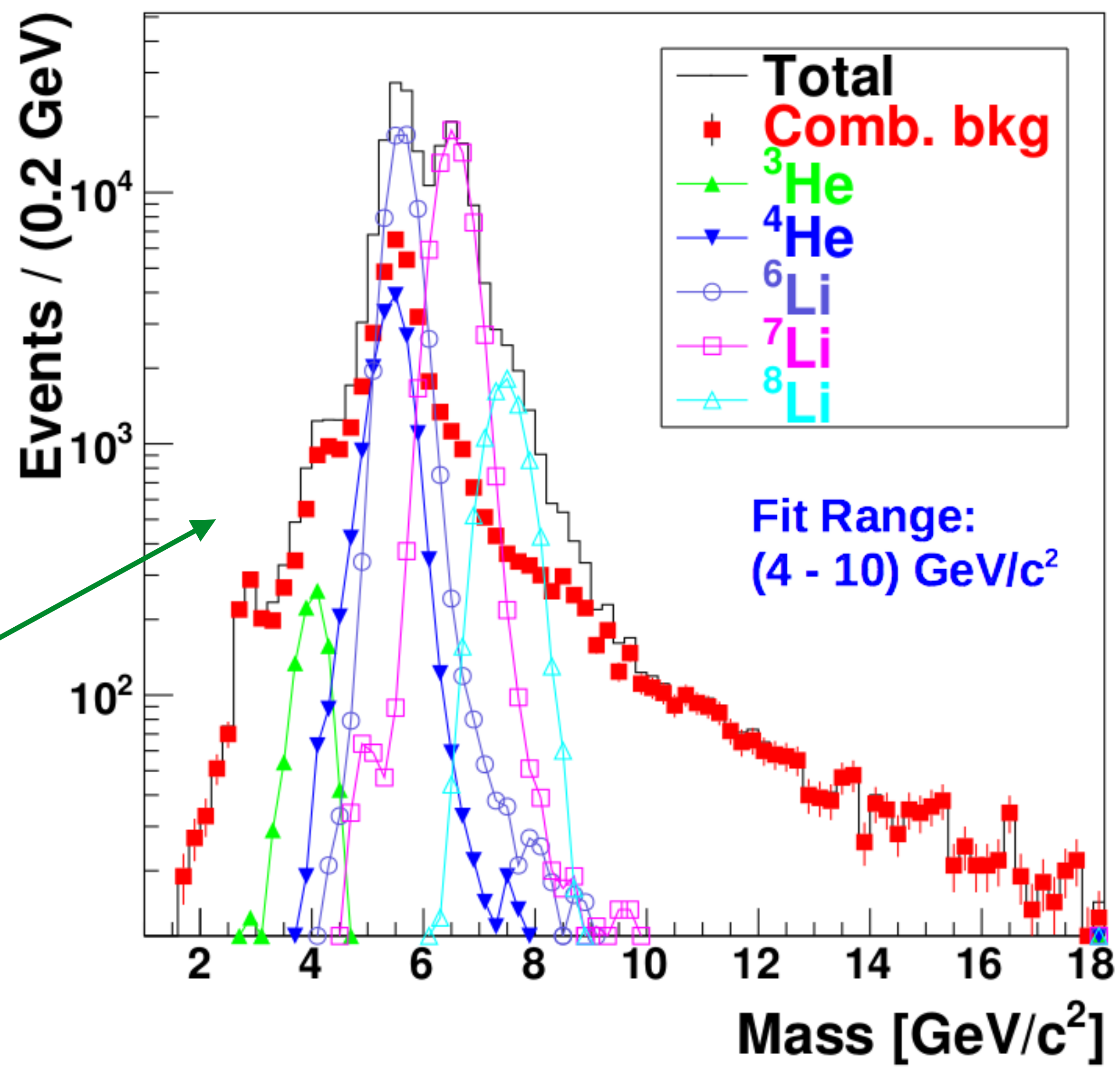
Cross feed background

- **Cross feed: global tracks, properly matched, that have a wrong charge ID**
- Not all the isotopes are contributing (in fact we have max 2 isotopes in a given fit that have to be considered, and usually we have JUST 1 isotope under a given mass peak)
- In the plot the **reconstructed mass for Lithium** in an energy bin is shown:

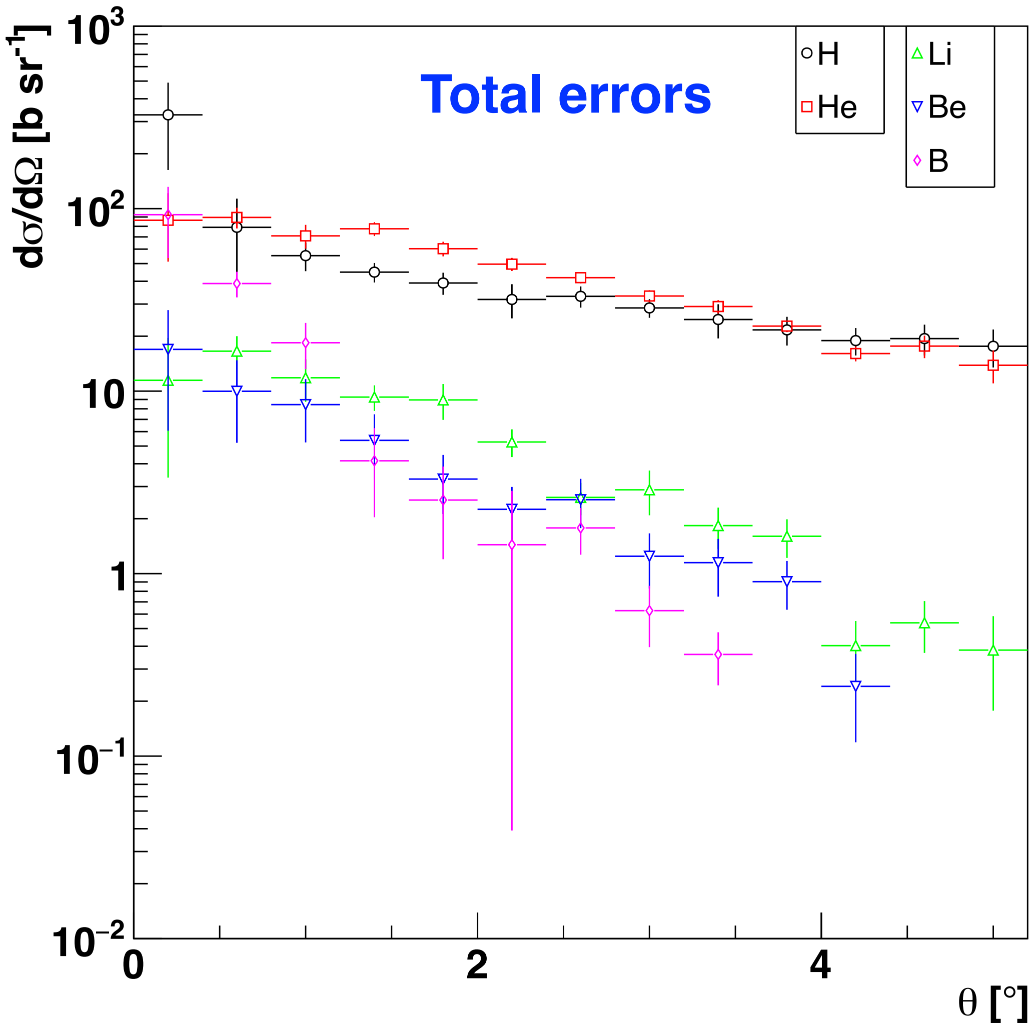
  In red is the combinatorial background

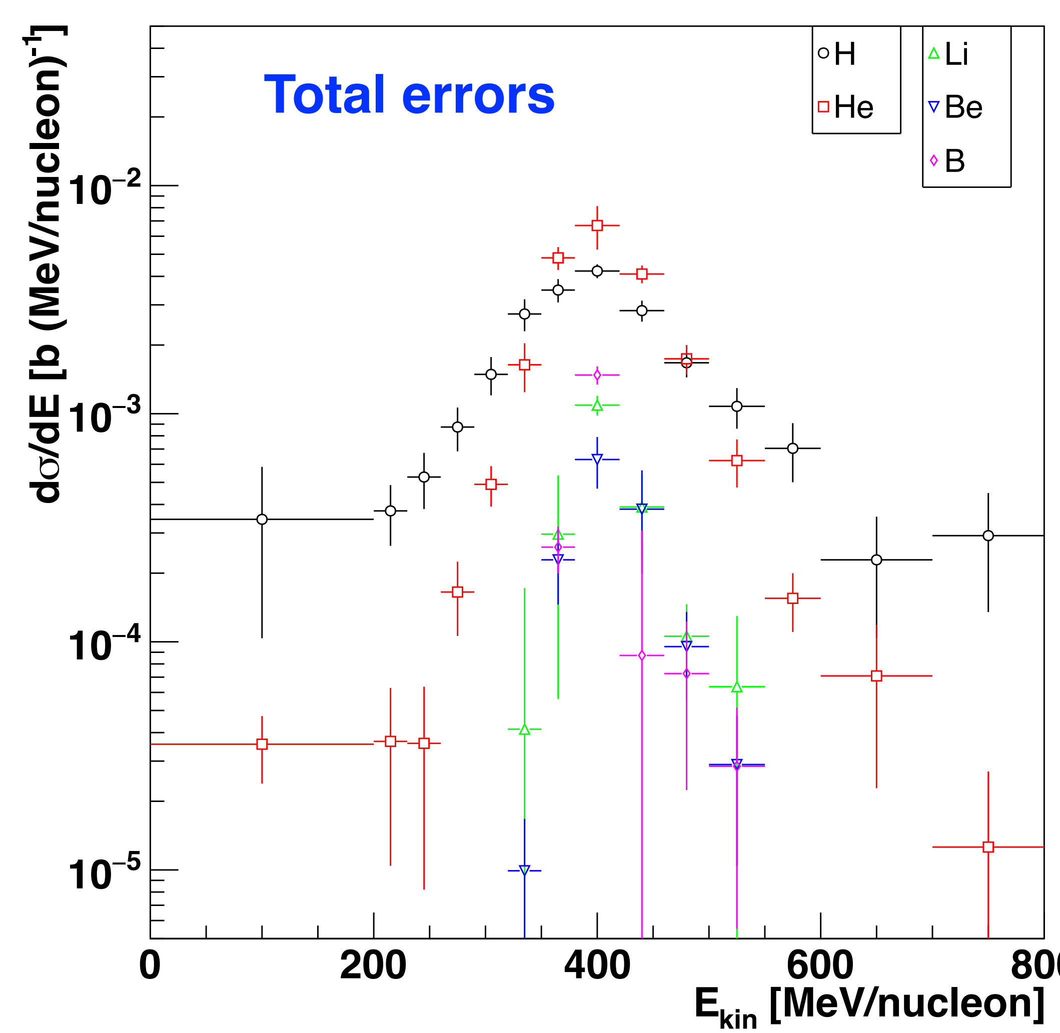
  The signal are ^{6}**Li**, ^{7}**Li** and ^{8}**Li**

  The crossfeed correction accounts for the ^{4}**He** contamination under the ^{6}**Li** peak.



Fragmentation cross sections

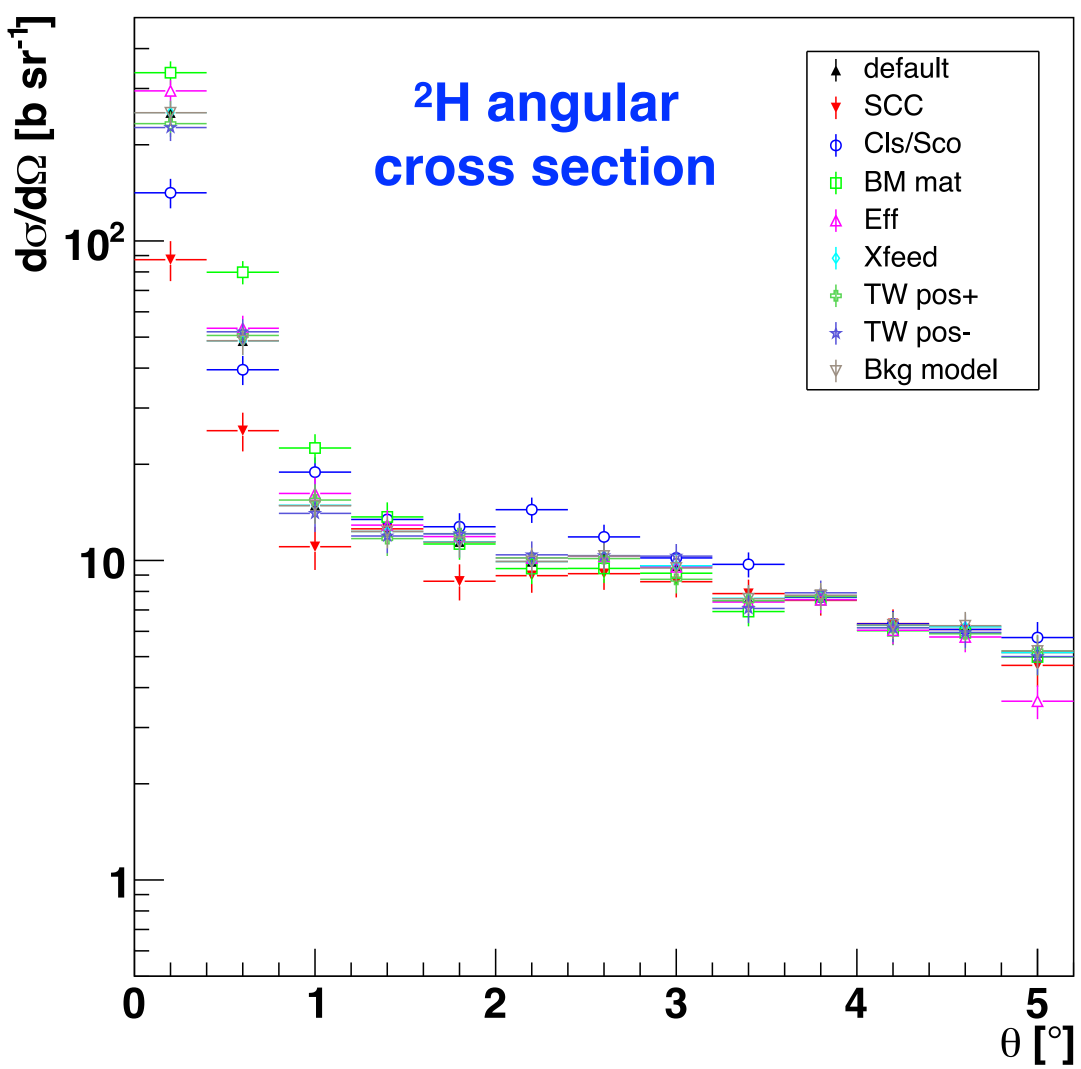


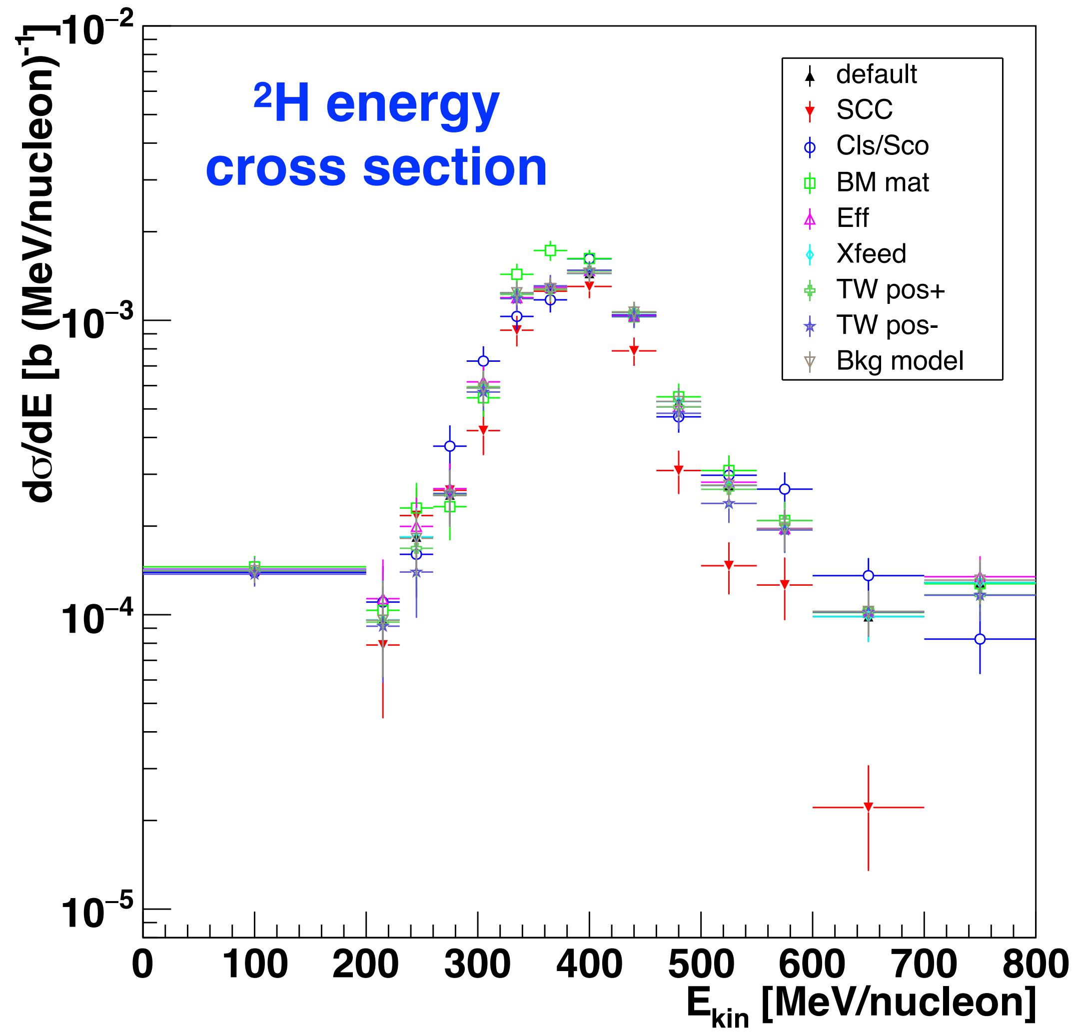


- **Left: Angular elemental cross sections.**
- **Right: Energy elemental cross sections unfolded to take into account the detector resolution**

Systematic uncertainties

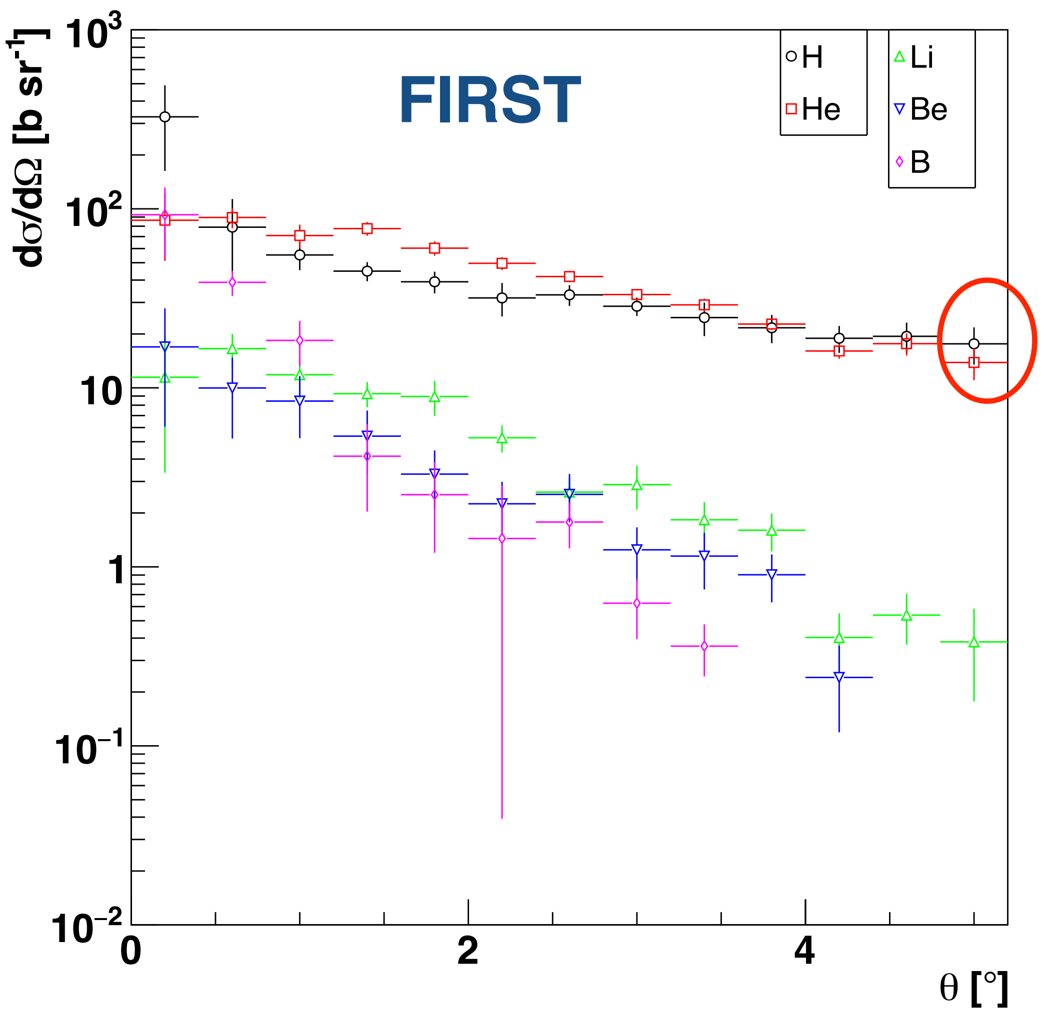
- The systematic uncertainties have been evaluated changing the reconstruction algorithms (local and global), the calibration and geometrical parameters, the corrections and the background subtraction procedure
- The systematic uncertainty has been computed as spread of the different results with respect to the “default” one

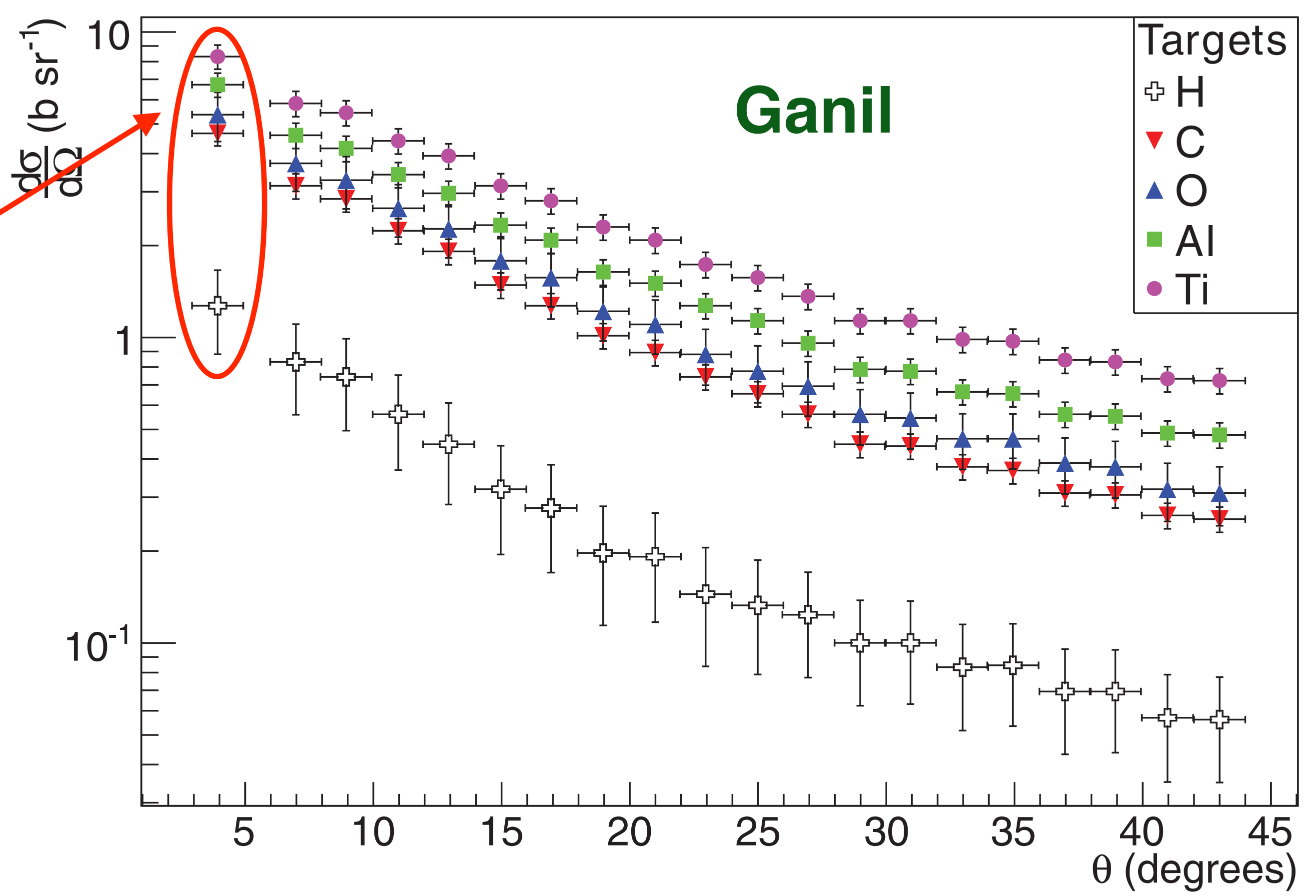




Comparison with Ganil results

- It is possible to compare FIRST results with a recent experiment at Ganil that measured the fragmentation of a ^{12}C beam @ 95 MeV/nucleon (different energy!) on different thin targets (the heavier one is the Titanium: Z = 22)
- Ganil results can be used to check the order of magnitude of the cross section at 5° (the only experimental point in common between the two experiment)
- e.g. for H ions at θ=5°: **$(d\sigma/d\Omega)_{FIRST}$ = (18± 3) b sr^{-1}** and **$(d\sigma/d\Omega)_{GANIL}$ (H - Ti) ≈ (1 - 9) b sr^{-1}**



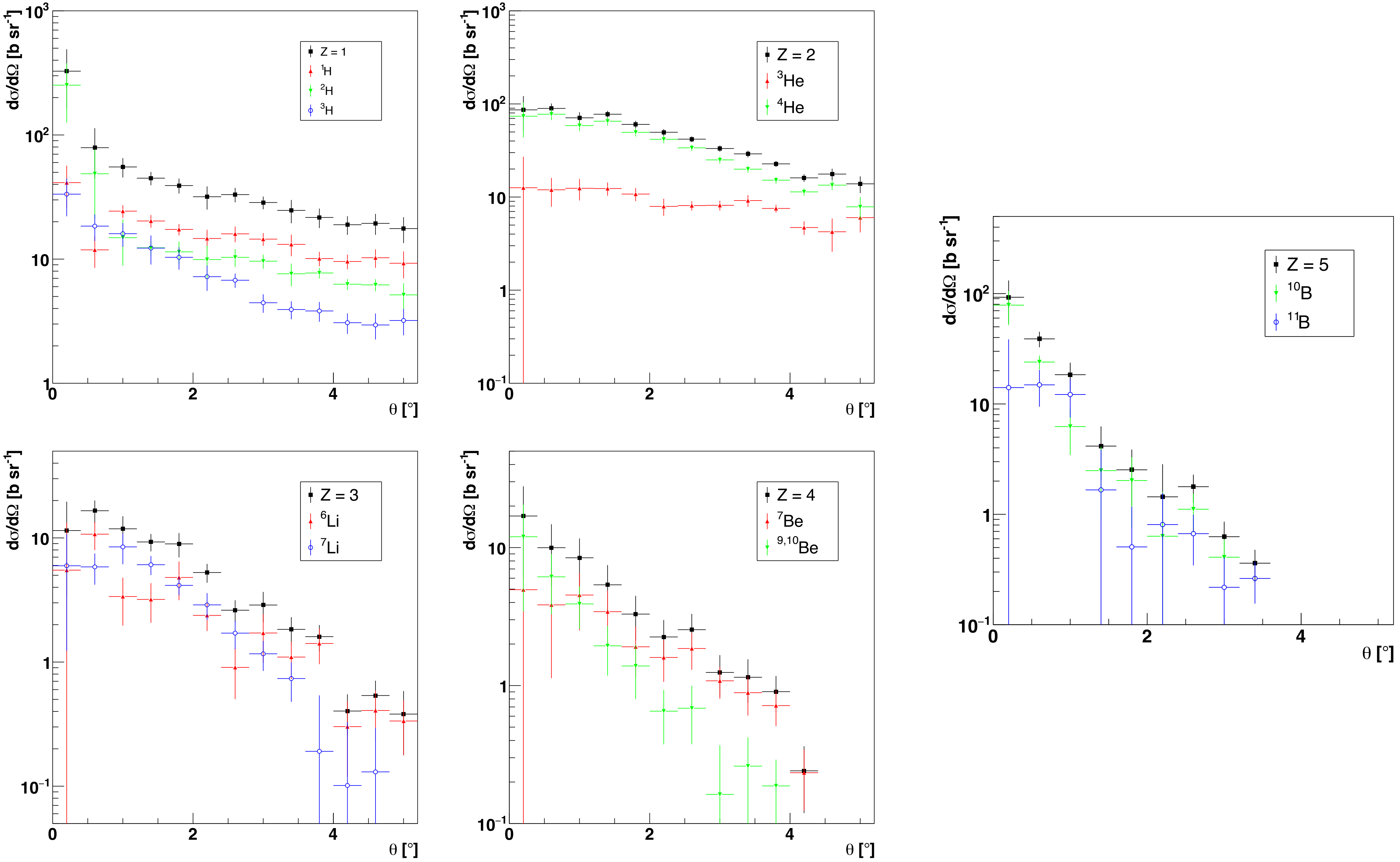


Conclusions

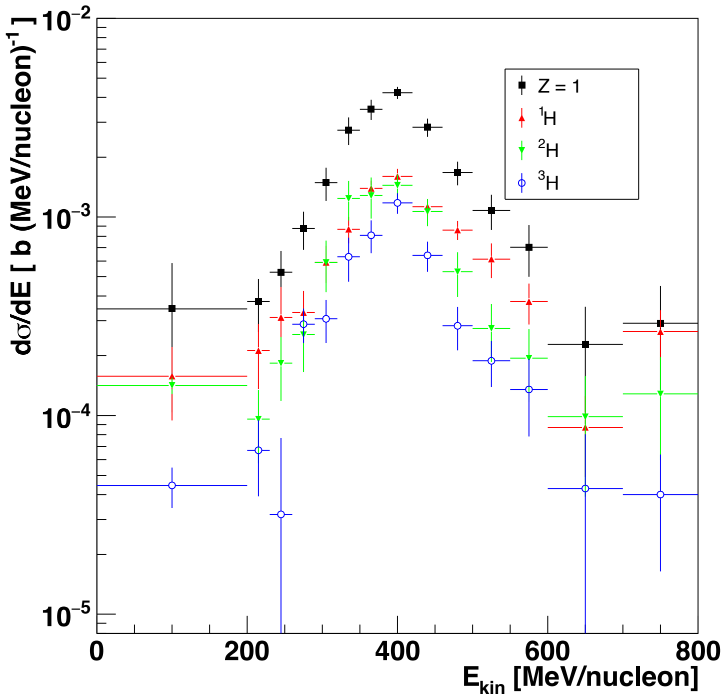
- **FIRST measured the differential cross section of ^{12}C @ 400 MeV/nucleon on a thin gold target for all the detected fragments with $1 < Z < 5$, emitted in the angular acceptance of the magnet ($\theta < 5°$)**
  - ➡ Most precise C+Au fragmentation cross section measurement so far!
  - ➡ Measured both the elemental and the isotopic cross sections
  - ➡ The results have been cross checked with the Ganil results for the fragmentation of a ^{12}C beam @ 95 MeV/nucleon on different target
  - ➡ **A Paper has been submitted to PRC**
- The obtained CS results will be used for the benchmarking of nuclear models implemented in MC codes (Fluka, Geant, …)

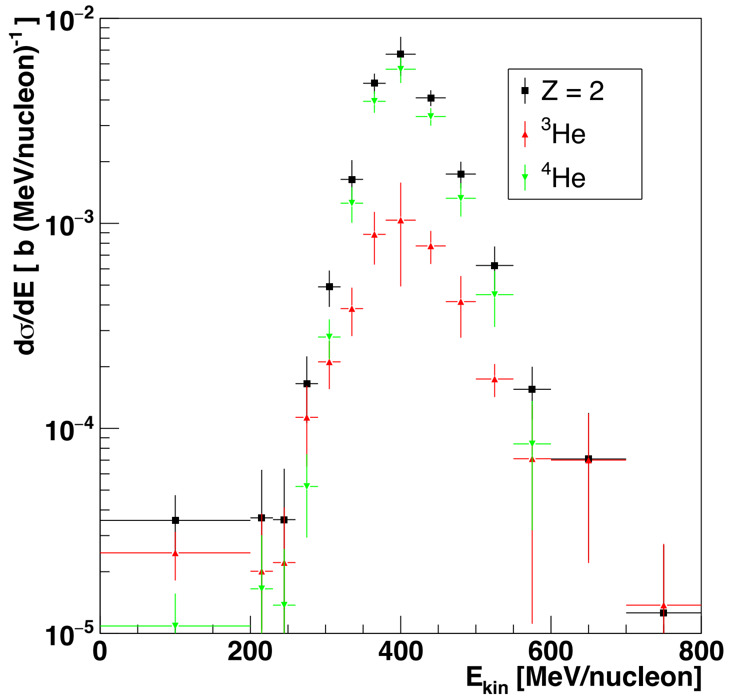
SPARES SLIDES

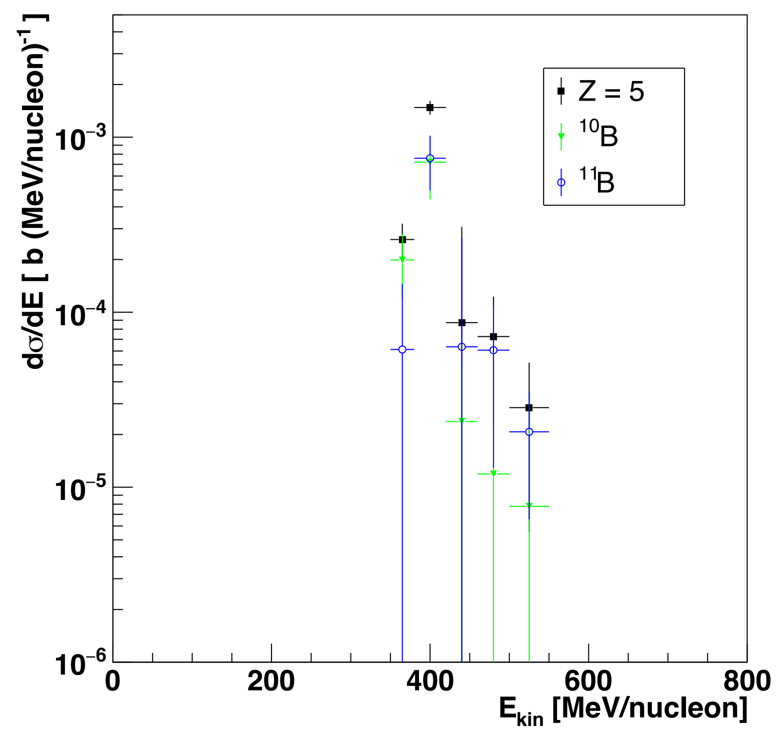
Angular isotopic cross sections

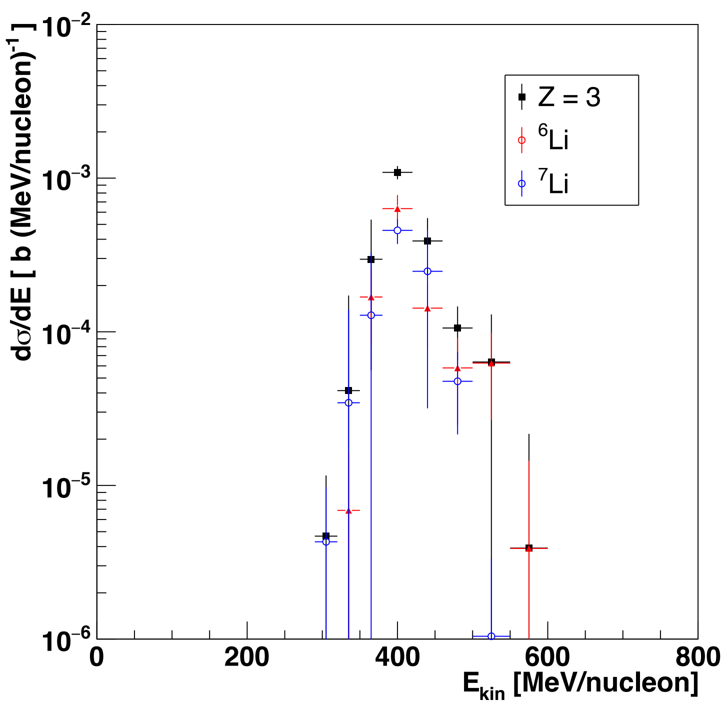


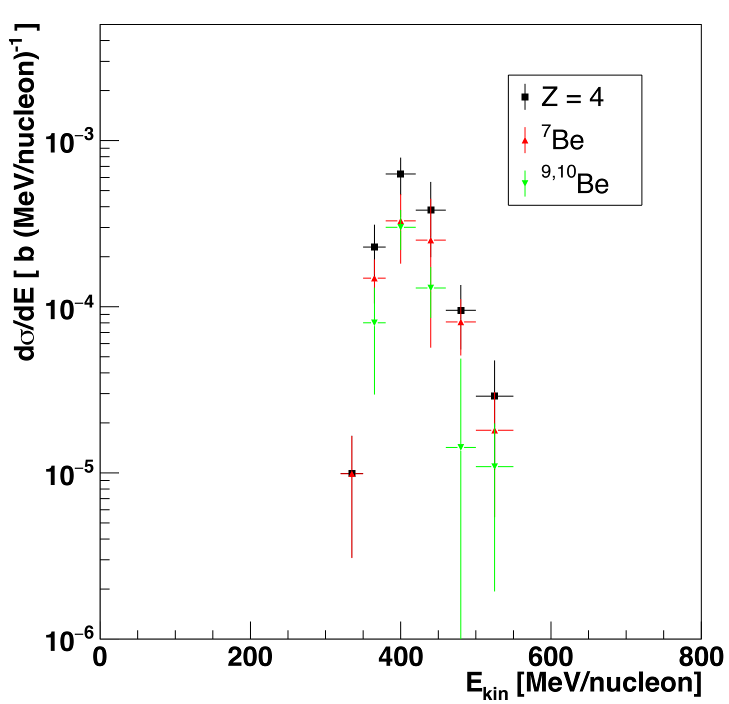
Energy isotopic cross sections





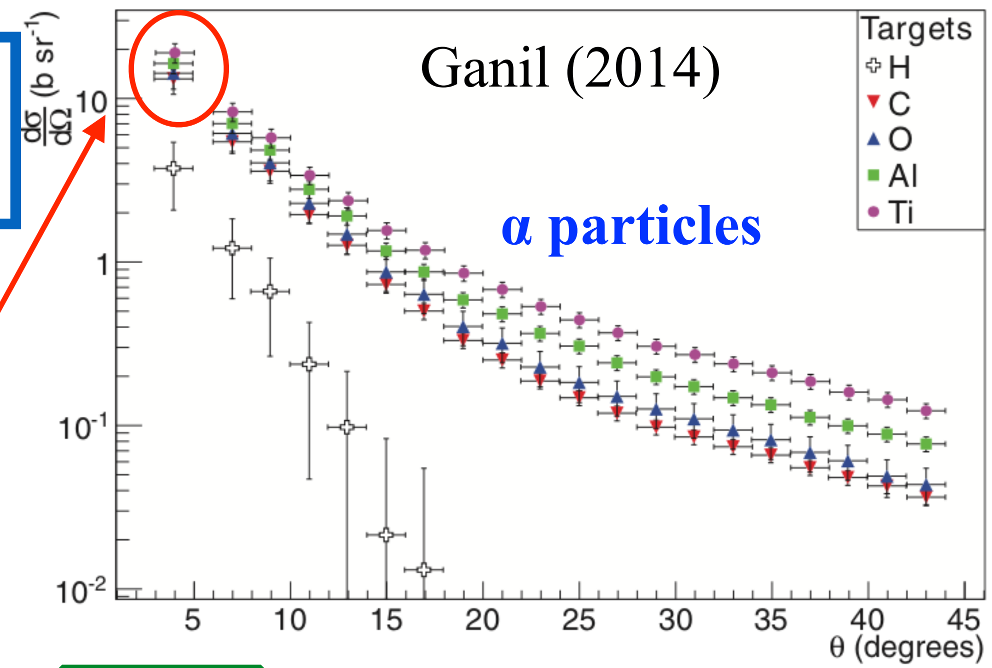


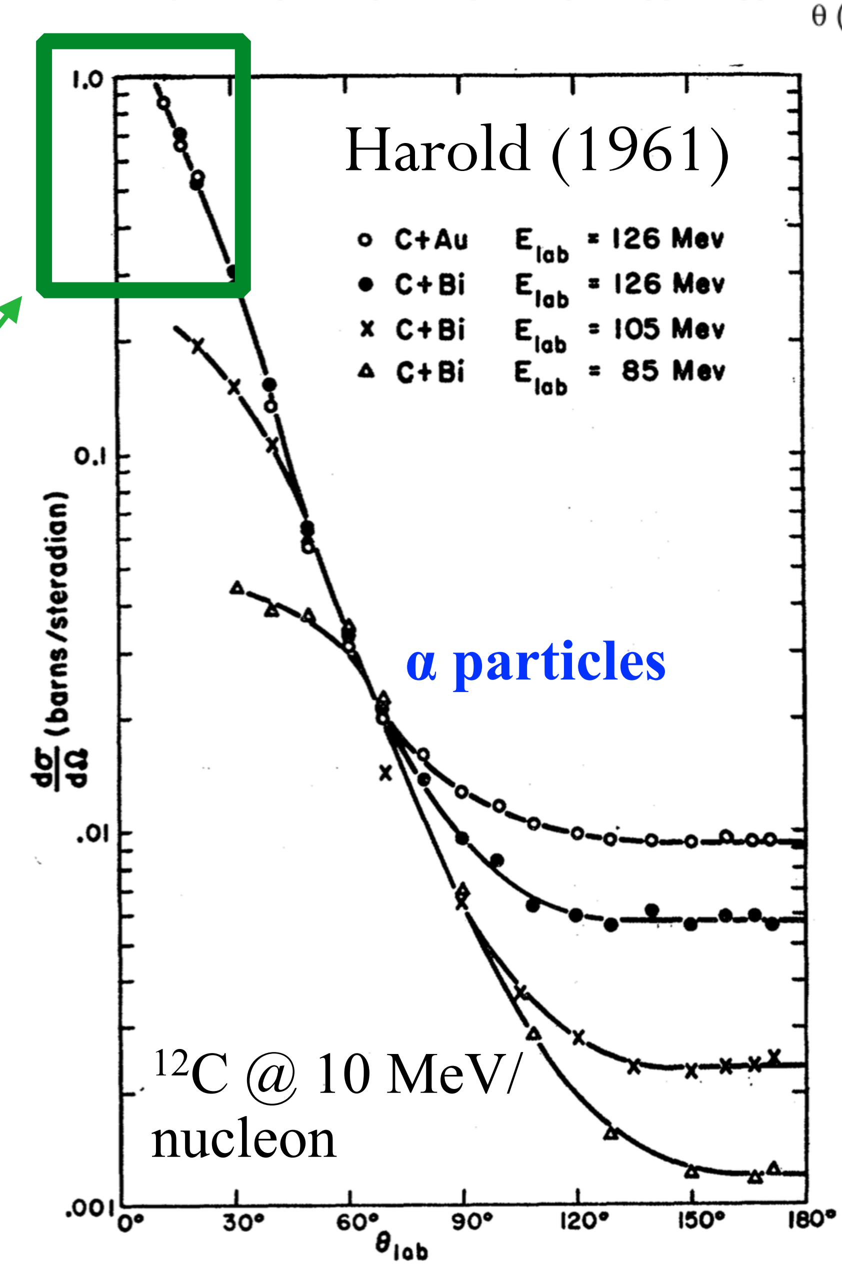




Comparison with other results

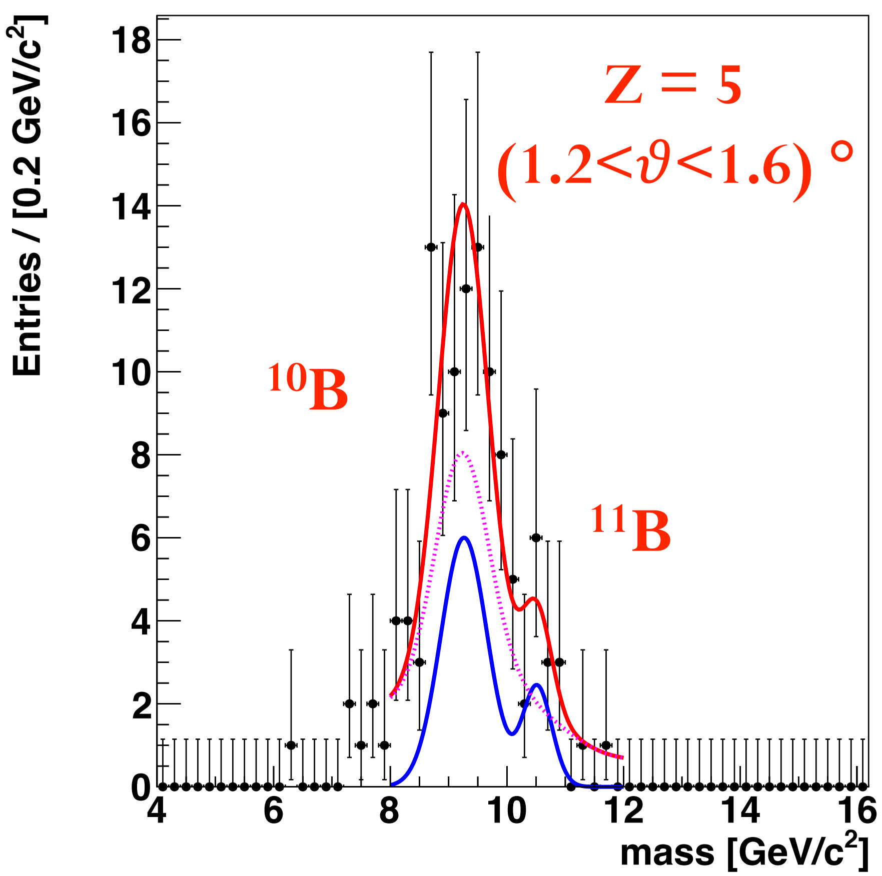
- FIRST measurement: α particle production @ 5° is (14 ± 3) b sr^{-1}
- Compared this result with data from:
  - ➡ Ganil [^{12}C on different targets @95 MeV/nucleon]: check last bin from FIRST against first bin from Ganil (on Ti) to check for correct order of magnitude (saturation is observed from C to Ti targets around 15 - 20 b sr^{-1})
  - ➡ Harold [^{12}C on Au, @10 MeV/nucleon]: check extrapolation from large angles (> 10°) to verify order of magnitude [$d\sigma/d\Omega(\theta=10°) \approx 1$ b sr^{-1}]

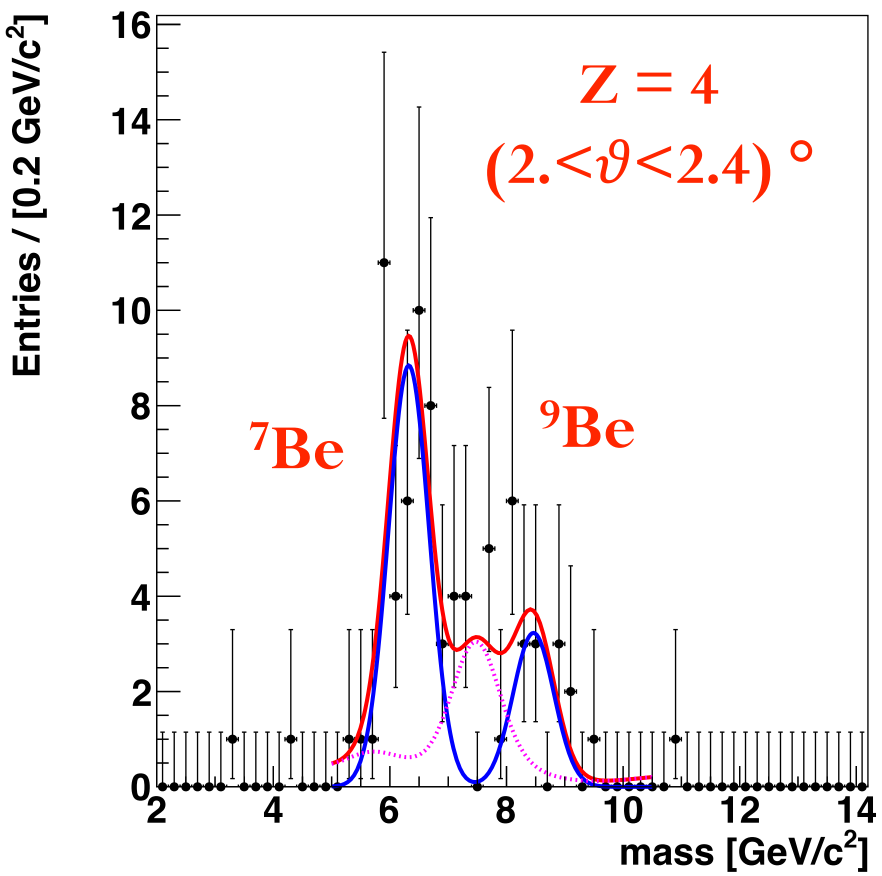




Mass fits tuning

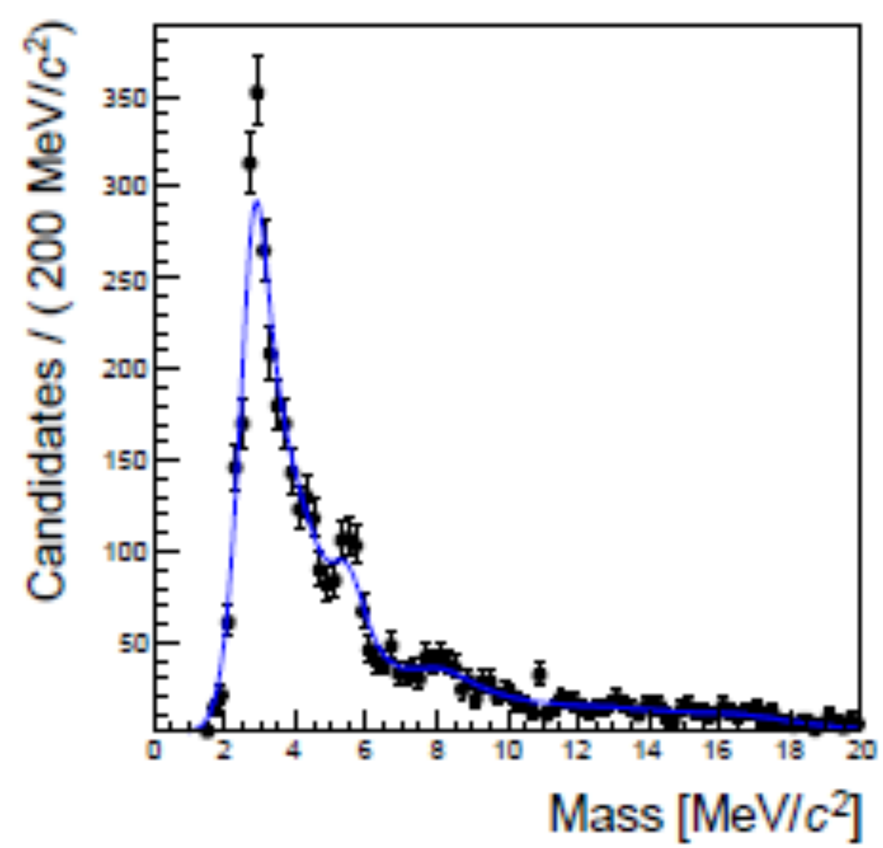
- For fragments with high Z it is more difficult to properly model/fit the observed distributions: results are affected by a **larger statistical uncertainty** BUT are also **more dependent on the choice of fit range** and allowed parameters range [leading to a larger systematic uncertainty].





Combinatorial background

- In the MC study, a fragment is marked as combinatorial background candidate whenever a track from VTX is paired with a hit from TW that does not belong to the SAME fragment.
- The combinatorial background has to be taken into account and subtracted from the fully reconstructed track sample:
  - ➡ Taking the shape from MC,
  - ➡ **Fitting the normalization of combinatorial background directly on data, using the mass distribution**
- The combinatorial background PDFs to be used in the mass fits are obtained, for each charge and for each angular/energy bin, from a MC sample in which all the WRONG combinations are selected at MC truth level.
- The background PDF component has been modeled using a kernel estimation algorithm (Cranmer KS. Computer Physics Communications 136:198-207,2001)



Combinatorial background

- The reconstruction algorithm computes the rigidity R = pc/Z
- The rigidity is proportional to the radius of curvature r in the magnetic field B (r ~ R/B)
- The momentum measurement, and so the mass, is fixed by the charge assignment: pc = R · Z
- In the example:
  - ➡ The “true” Helium (at VTX) is matched with the Lithium hit (at TW) and so, Z =3 (from TW alg) and its rec mass is: M ~ 6 GeV/c^2 (that is the Lithium mass ~ 2* Z), beeing the two rigidity about the same. So the combinatorial background in the Lithium bins will show a peak at ~ 6 GeV/c^2