Status of Simulation and Physics Performances Studies

G. Battistoni

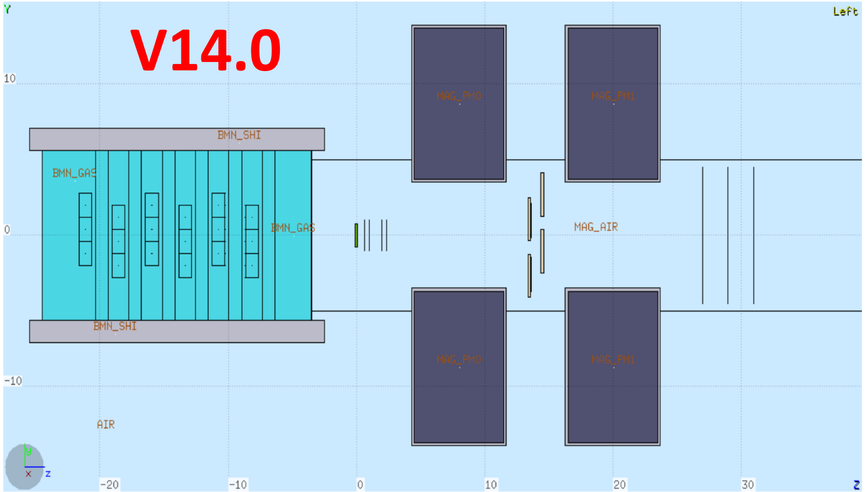
On behalf of many others

Simulation Update: V14

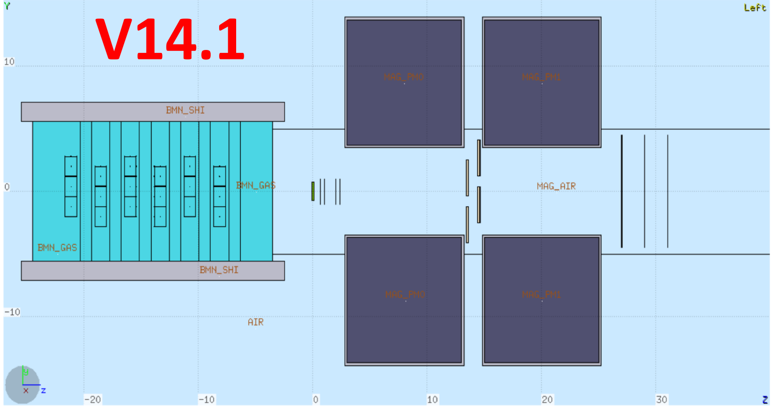
Geometry of Electronic Setup fully handled by the SHOE software: ***(S. Valle + M. Franchini)***

- in **/Simulation/foot_geo.h** → constants, positions, distances, etc
- in **/libs/src/TA*DET*base/TA*DET*parGeo.cxx** and **.h** → methods to write geometry for each detector (both root and FLUKA geo)
- **/Simulation/MakeGeo.cxx** → main code that produces FLUKA geo (recalls methods described in the libraries).
- **In this way the reconstruction software is ready to reconstruct the events with the same geo used to produce simulations**
- ***Of course from now on the management of simulation geometry is less immediate and some dedicated training is necessary***

Studies in view of magnet definition

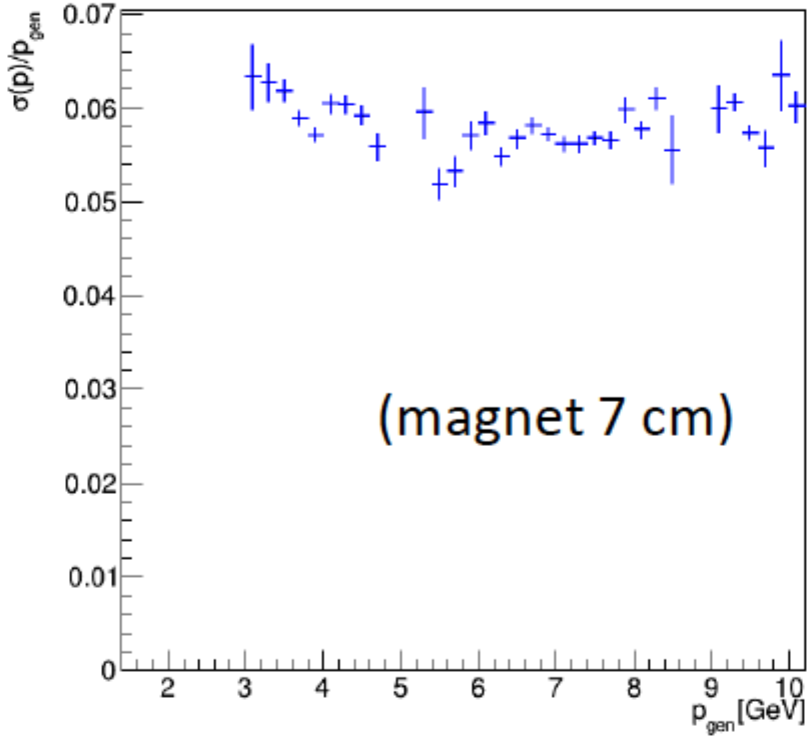


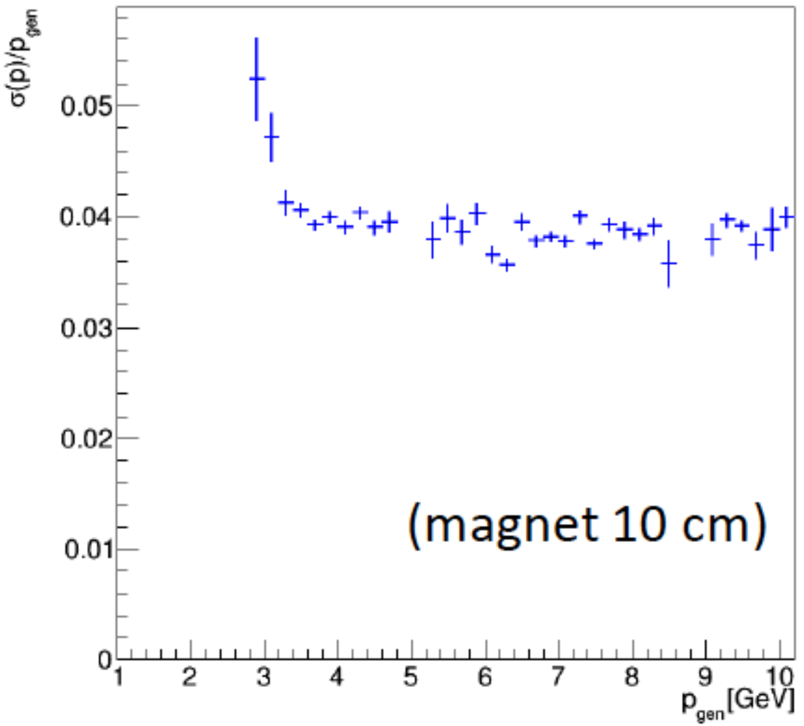
- Single magnes length 7 cm
- Center-to-center distance of magnetes: 12 cm



- Single magnet length 10 cm
- Center-to-center distance of magnets: 12 cm (gap btw magnets ~2cm, not realistic)

Importance of B•dl: improvement in p resolution with 10 cm magnet *(M. Franchini et al.)*

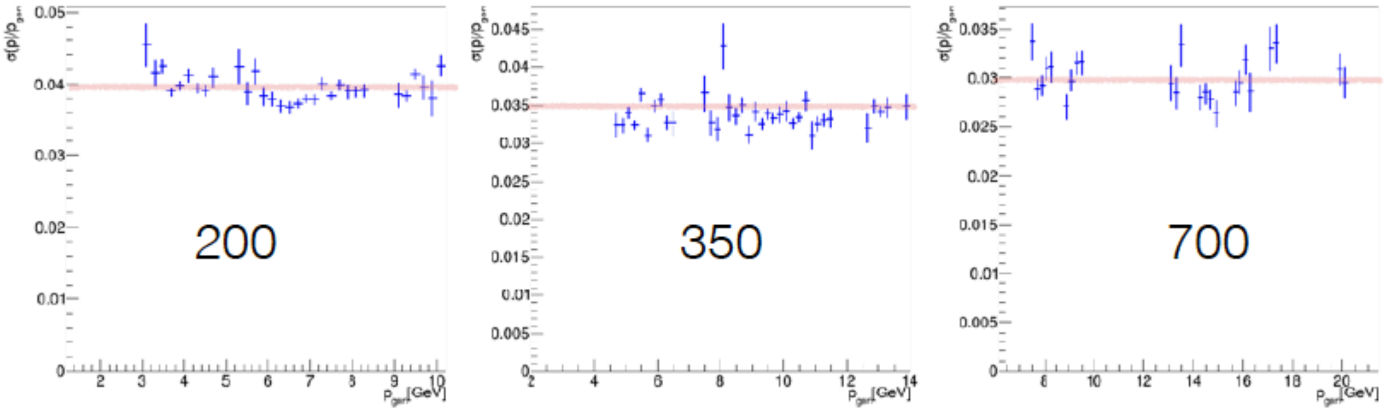




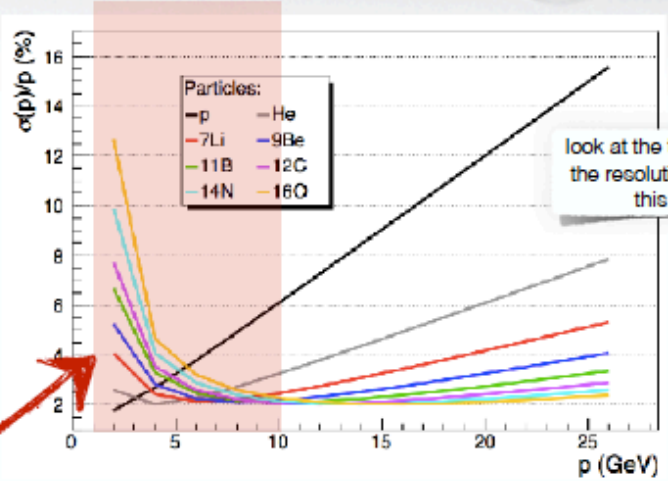
Momentum resolution for higher energies

- v14.2: 10cm magnets, 5cm between magnets;
- more the p, more the resolution —> seems we're dominated by MS that decrease with increasing p. Kalman seems then good at fitting also poorly bended tracks.

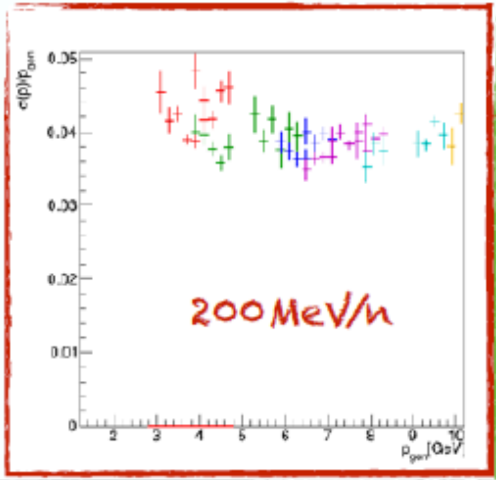
- **VT** xy Reso: 0.0006cm
  z Reso: 0.005cm
- **IT** xy Reso: 0.0006cm
  z Reso : 0.005cm
- **MSD** xy Reso: 0.003cm
  z Reso : 0.01cm

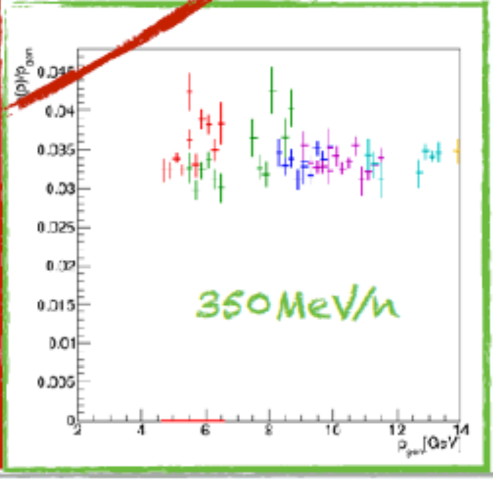


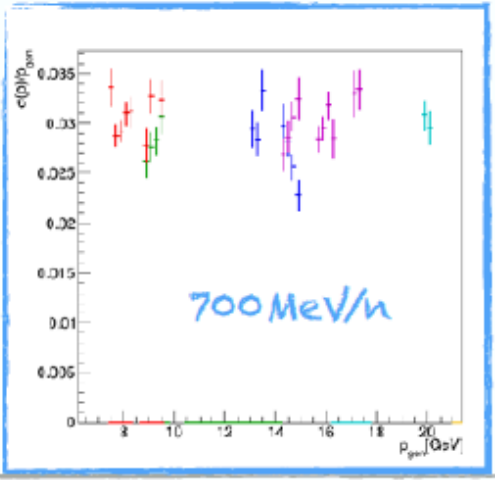
- At 200MeV/n, all elements are in the "decreasing" part, dominated by MS contribution;
    - **heavy-elements** have high p so almost at minimum (that is at lower-p), MS not so high anymore;
- At 700MeV/n, all in region dominated by spatial resolution;
    - **light elements** (steeper growth, lower-p minimum) have low p; still close to the minimum
    - **heavy elements** (grows slower, higher-p minimum) have higher p but still close to the minimum



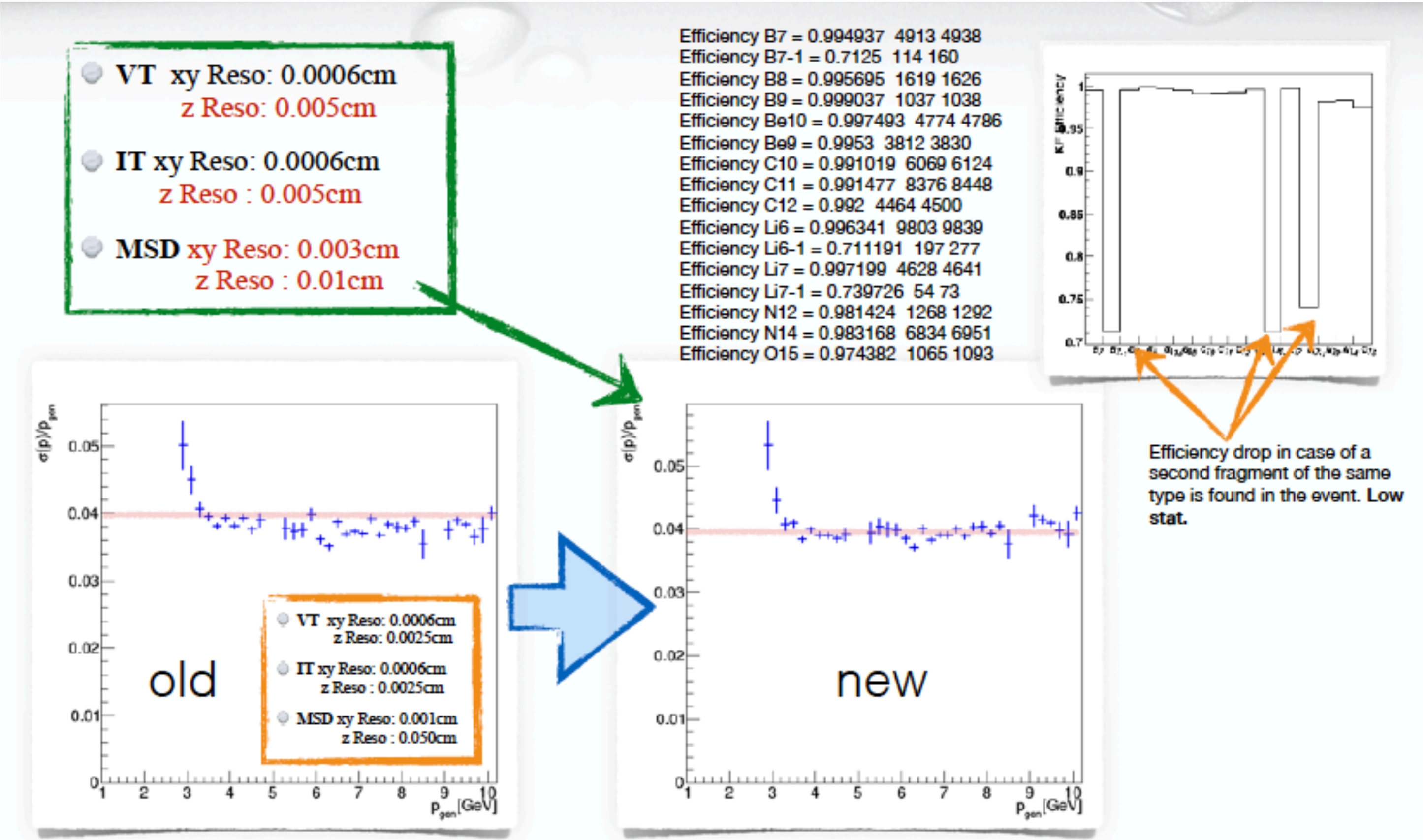
look at the **trend** not at the resolution value in this plot



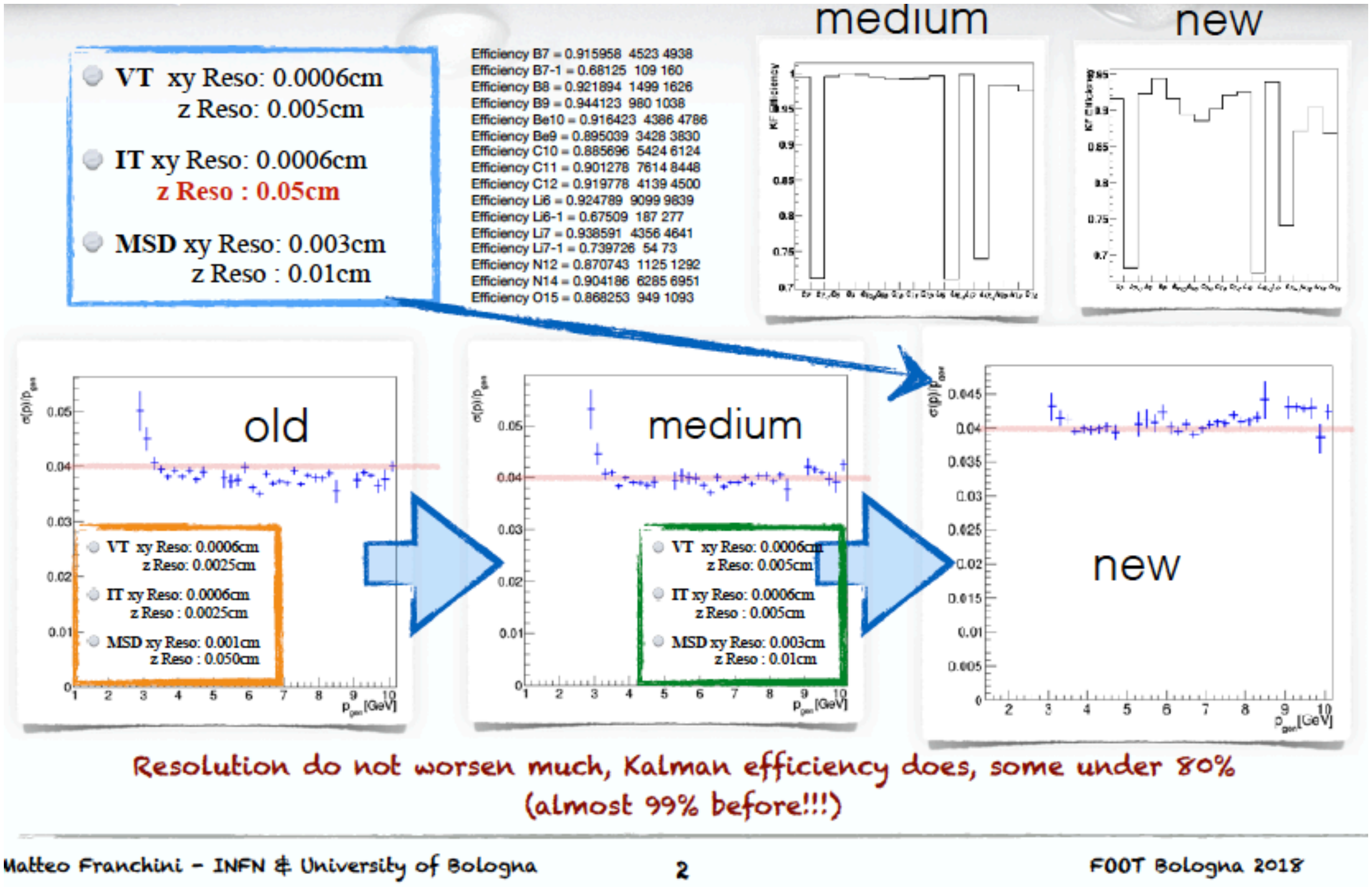




Impact of detector resolution

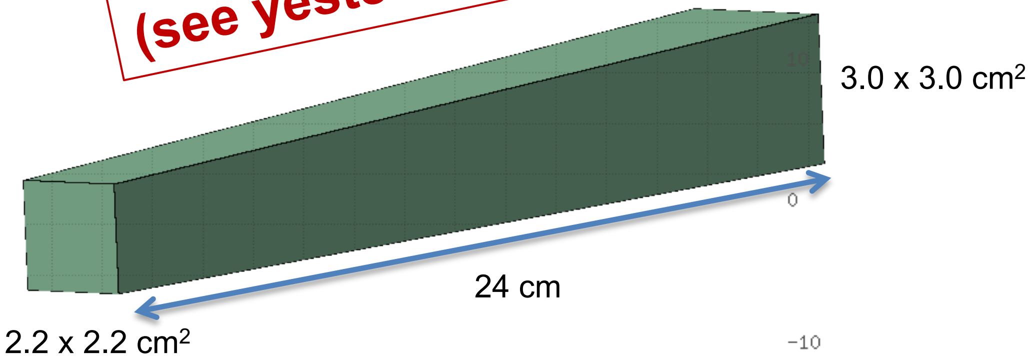


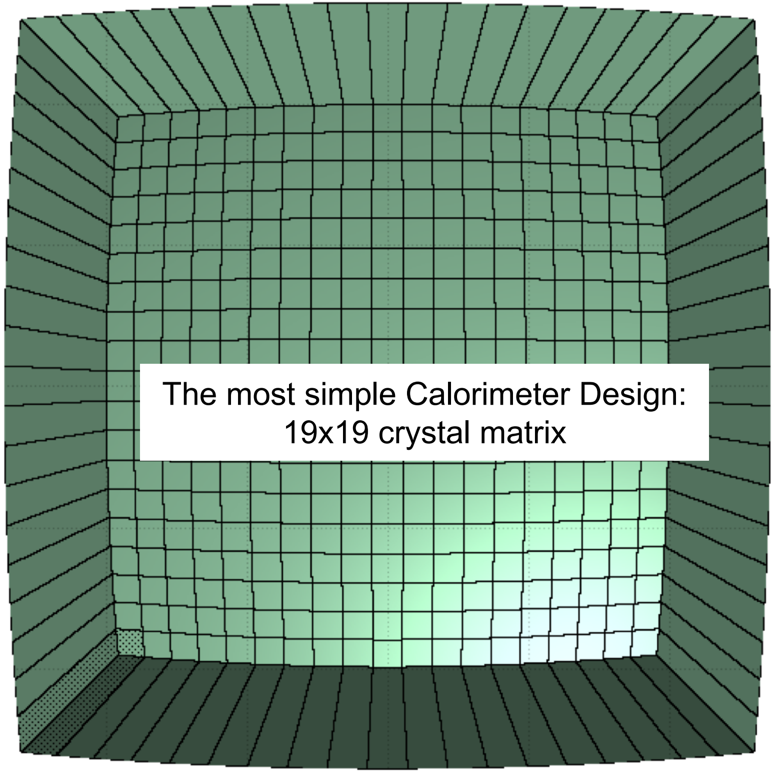
Impact of detector resolution



New BGO Crystals (truncated pyramid)

Initial guess: to be modified!!!
(see yesterdays's talk about calo)

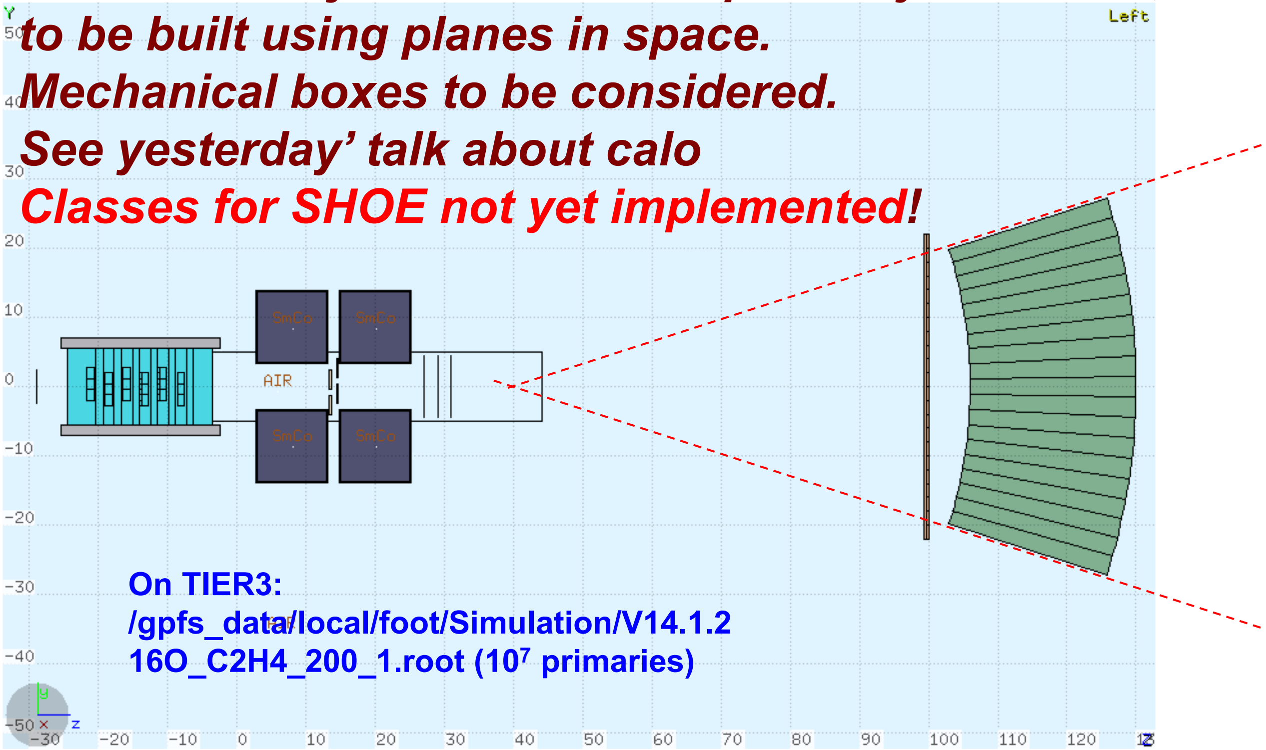




Some specific simulation study is in progress in view of next test beam activity to be performed at CNAO

V14.1.2: very first implementation of new calorimeter design in FLUKA geometry

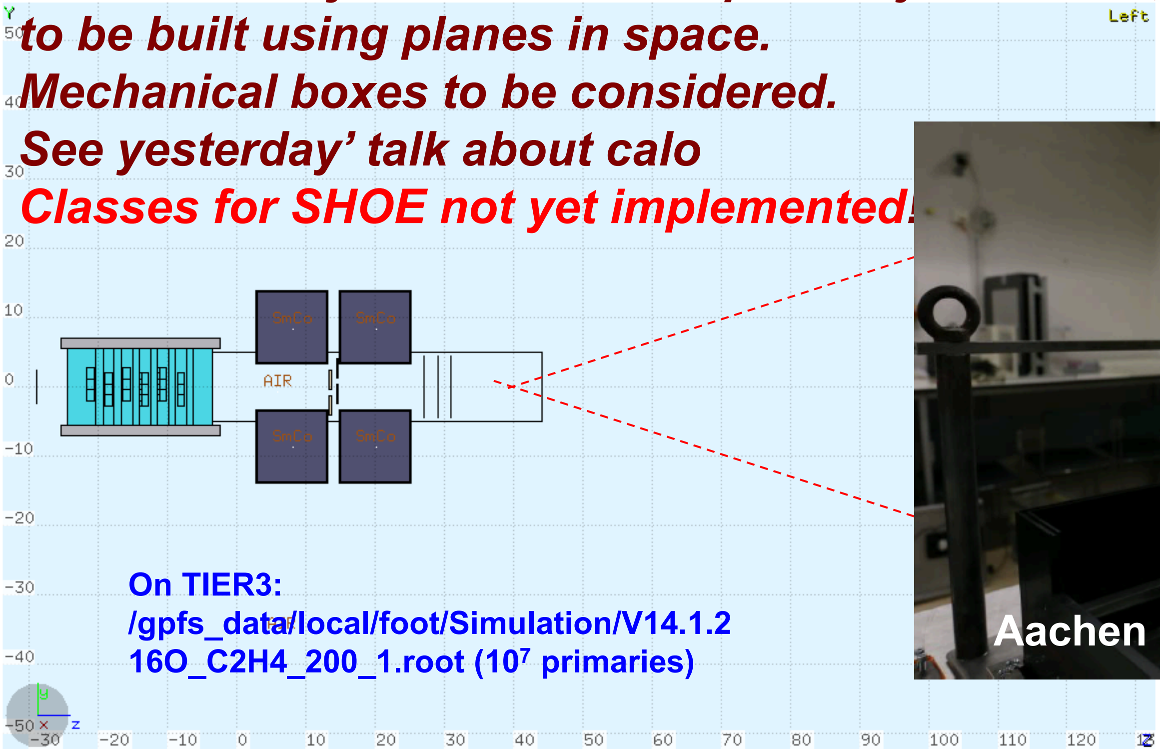
More difficult job: it's not a simple body in FLUKA, it has to be built using planes in space.
Mechanical boxes to be considered.
See yesterday' talk about calo
Classes for SHOE not yet implemented!



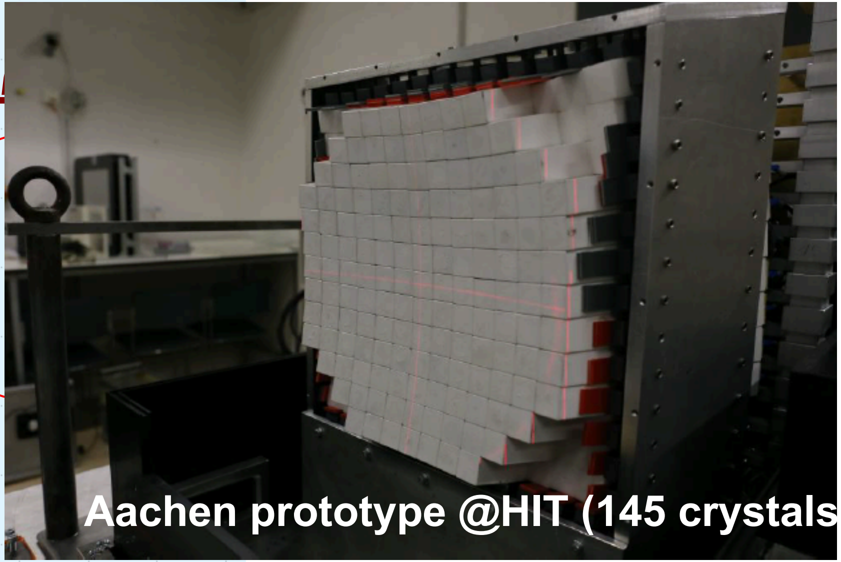
On TIER3:
/gpfs_data/local/foot/Simulation/V14.1.2
16O_C2H4_200_1.root (10^7 primaries)

V14.1.2: very first implementation of new calorimeter design in FLUKA geometry

More difficult job: it's not a simple body in FLUKA, it has to be built using planes in space.
Mechanical boxes to be considered.
See yesterday' talk about calo
Classes for SHOE not yet implemented!



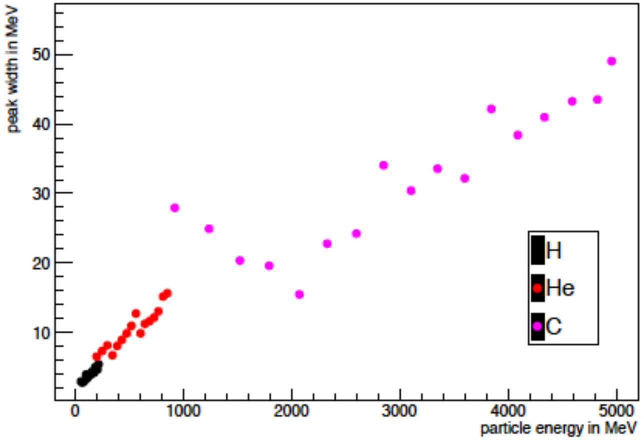
On TIER3:
/gpfs_data/local/foot/Simulation/V14.1.2
16O_C2H4_200_1.root (10^7 primaries)



Analysis of Aachen prototype results *(as presented on May 8, M.Emde & R. Hetzel)*

Energy Resolution

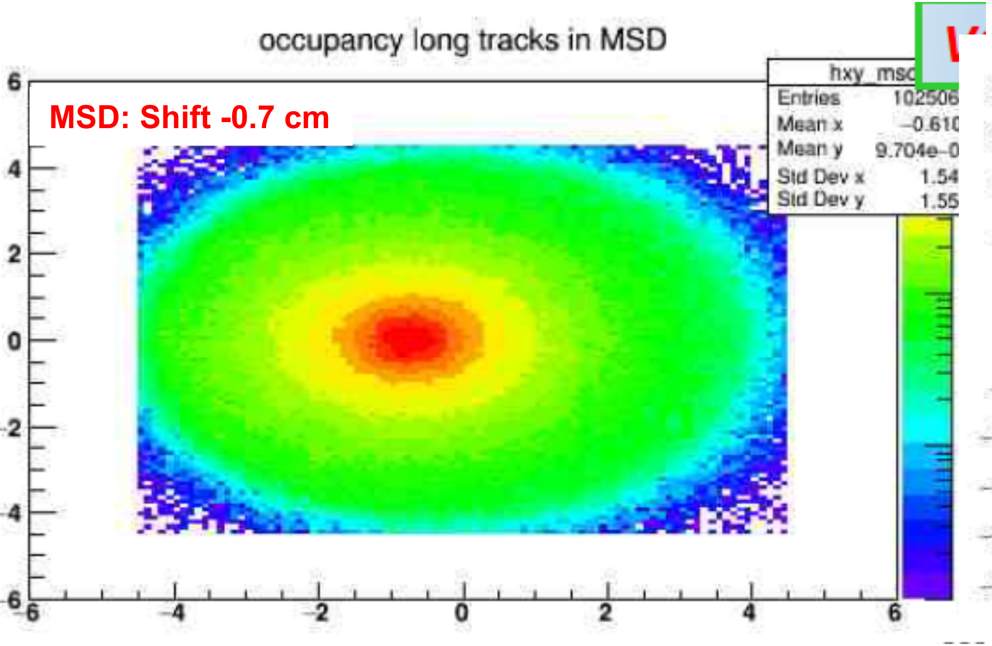
- Energy corrected for losses before reaching calorimeter
- From peak width of spectra
- Includes contributions from beam energy spread, detector and electronics
- Reaches 1 % to 3 %

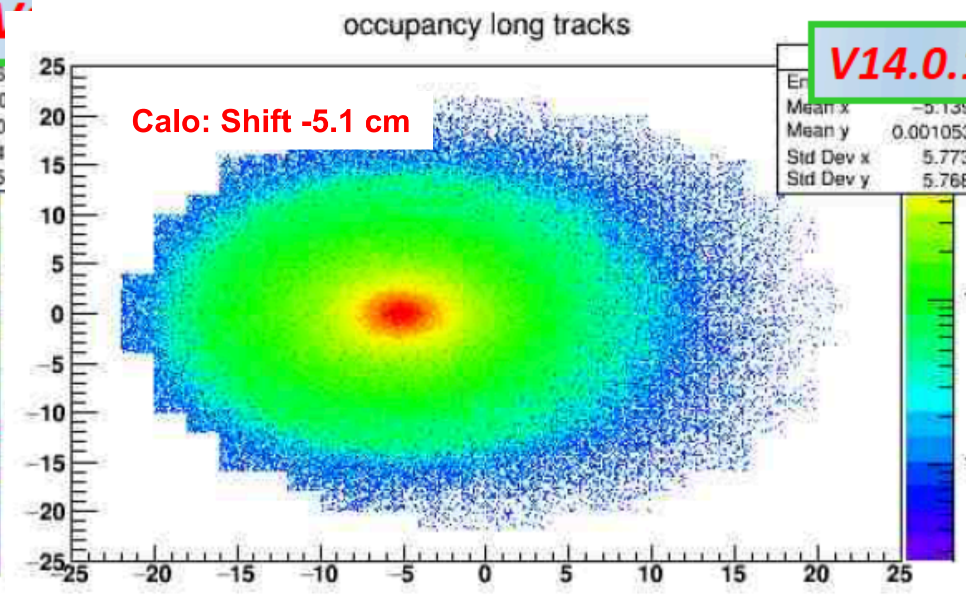


Some issues recently emerged which could affect the expected performance:

1) Magnetic deflection and possible loss of detector acceptance in the downstream region
2) Longer magnets: how to recover angular acceptance
3) Effect of uncertainties in the knowledge of magnetic map (position, alignement,…)
4) Stability of B field of permanent magnets and radiation damage
5) Actual resolution along z coordinate of Intermediate Tracker

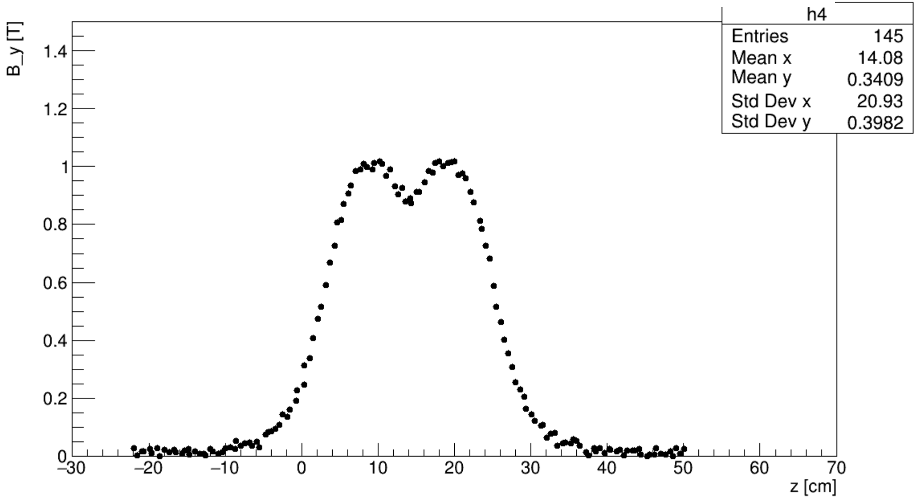
Deflection in the case of 2 magnets with aligned B: possible loss of efficiency *(R. Spighi)*



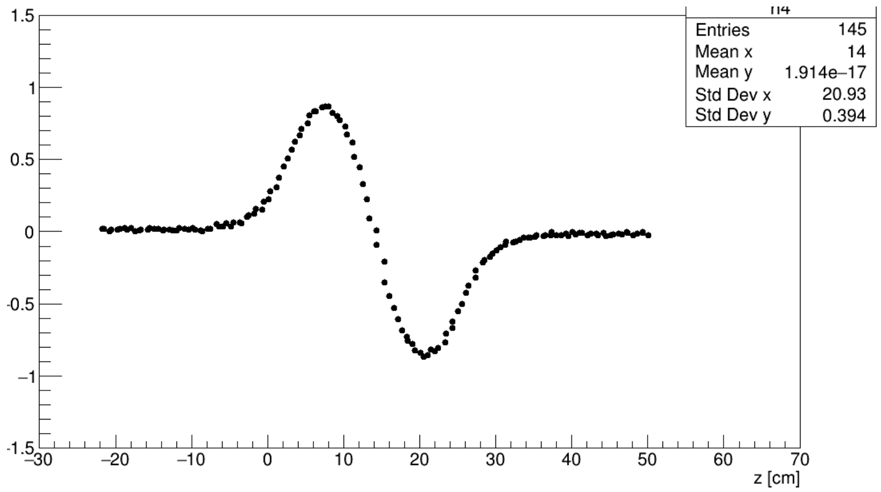


Possible alternatives for the field orientation of the two magnets

2nd magnet with same magnetic field orientation as 1st magnet



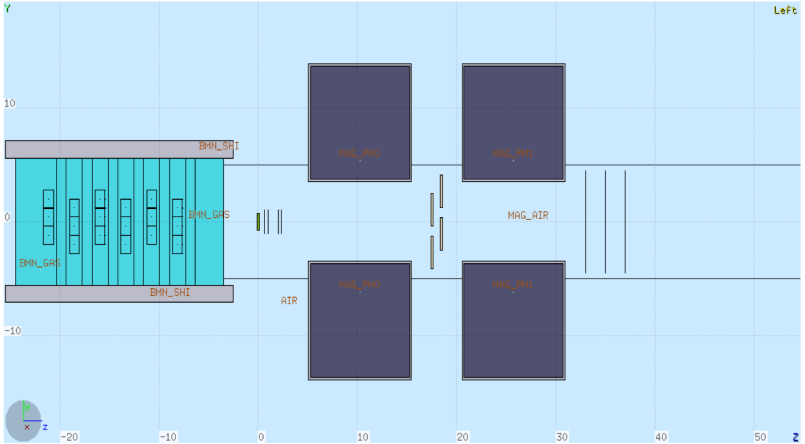
2nd magnet with opposite magnetic field orientation with respect to 1st magnet

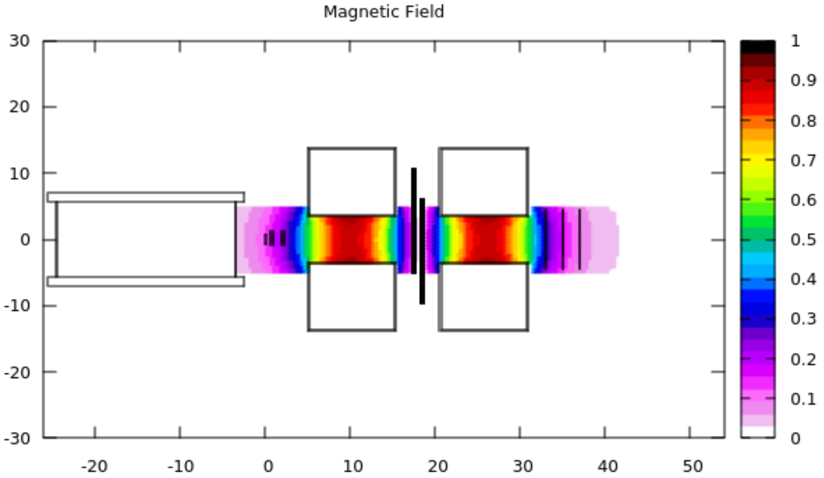


Under investigation

V14.2

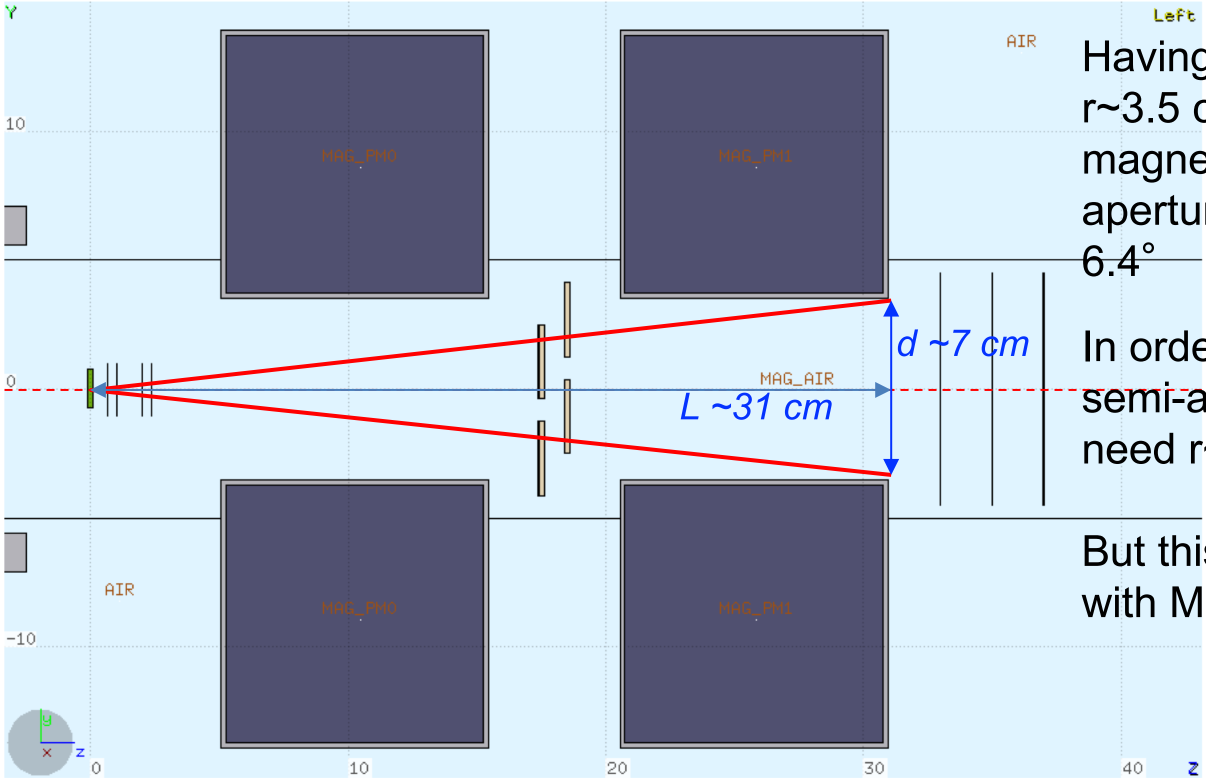
- Single magnet length 10 cm
- Center-to-center distance of magnetes: 15 cm, gap ~5 cm, as recommended after FOOT Mech Meeting
- ITR and MSD shifted downstream





Suddenly we realize a problem…

Angular acceptance vs Magnetic Lenght vs Tracking Detector Size



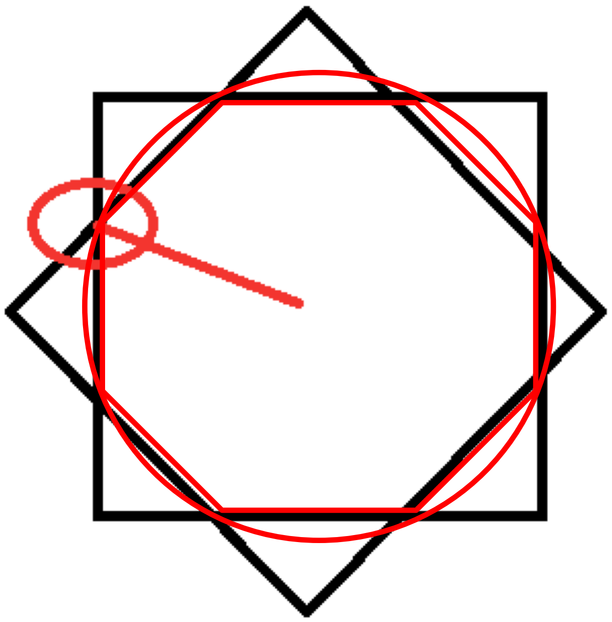
Having kept constant to r~3.5 cm the radius of the magnet bore reduces semi-aperture of the cone to ~ 6.4°

In order to recover 10° semi-aperture we would need r~ 5.5 cm

But this would be useless with MSD size of 9x9 cm^2

A possible suggestions for MSD in case of larger diameter of magnet bore:

Increase number of detector layers from 3 to 4, alternating the following 45° rotation *(L. Servoli)*:

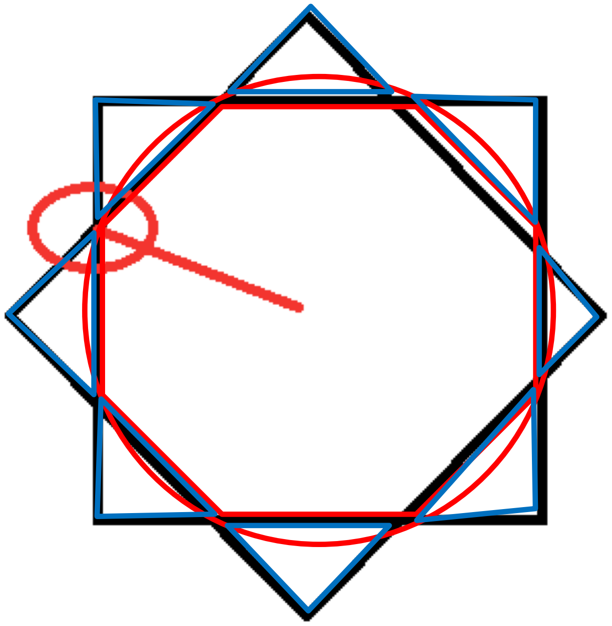


4 point coverage

The mimimum diameter of the circle covering at least 2 points is ~10.6 cm

A possible suggestions for MSD in case of larger diameter of magnet bore:

Increase number of detector layers from 3 to 4, alternating the following 45° rotation *(L. Servoli)*:

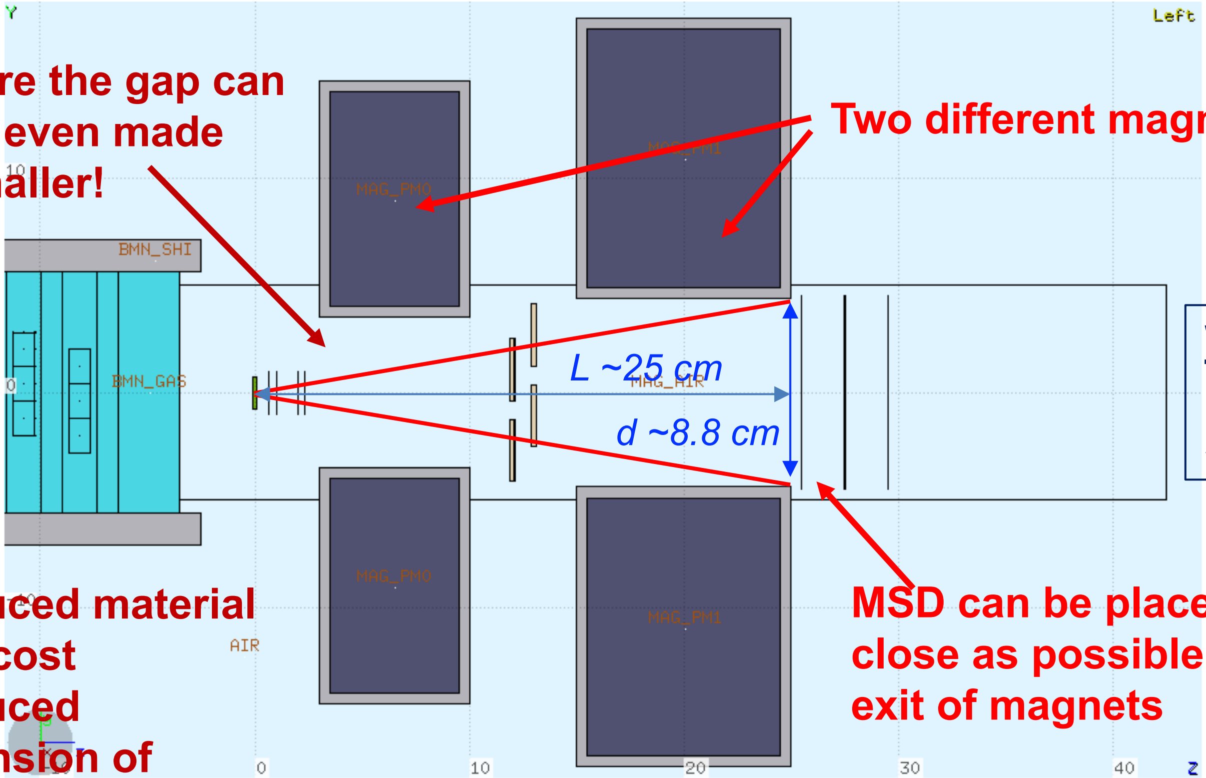


2 point coverage

4 point coverage

The mimimum diameter of the circle covering at least 2 points is ~10.6 cm

Alternative magnet design:



Here the gap can be even made smaller!

Two different magnets

Warning:
maybe we loose something in B•dl

Reduced material and cost
Reduced extension of fringe field

MSD can be placed as close as possible to the exit of magnets

Initial studies on the uncertainties on mag field
(Mi+Bo)

- 500 μm uncertainty on Intermediate Tracker long coordinate: no significant effect on resolution. A small bias in momentum reconstruction
- 1 degree disalignment between the two magnets: no significant effect
- Alternate alignement of magnets
- Systematic error in magnetic map coordinates

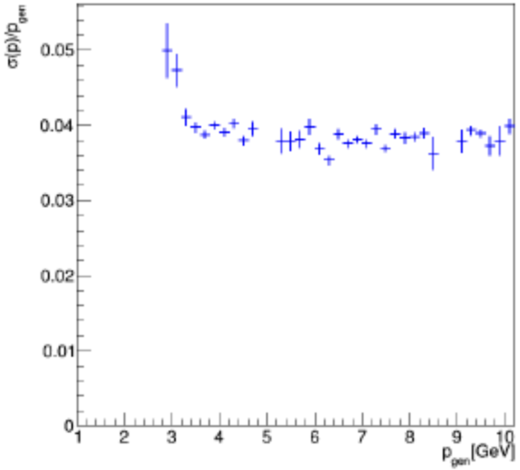
Different studies still in progress

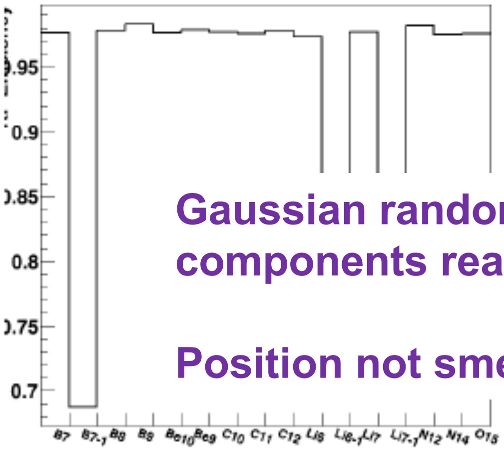
Smearing tests *(M. Franchini)*

- **VT** xy Reso: 0.0006cm
  z Reso: 0.0025cm
- **IT** xy Reso: 0.0006cm
  z Reso : 0.0025cm
- **MSD** xy Reso: 0.001cm
  z Reso : 0.050cm

V14.0.1
Magnets: 10 cm
5% smearing

5%
Efficiency B7 = 0.975901 4819 4938
Efficiency B7-1 = 0.6875 110 160
Efficiency B8 = 0.97786 1590 1626
Efficiency B9 = 0.982659 1020 1038
Efficiency Be10 = 0.976389 4673 4786
Efficiency Be9 = 0.978329 3747 3830
Efficiency C10 = 0.976486 5980 6124
Efficiency C11 = 0.975852 8244 8448
Efficiency C12 = 0.978 4401 4500
Efficiency Li6 = 0.973066 9574 9839
Efficiency Li6-1 = 0.700361 194 277
Efficiency Li7 = 0.976514 4532 4641
Efficiency Li7-1 = 0.739726 54 73
Efficiency N12 = 0.981424 1268 1292
Efficiency N14 = 0.974968 6777 6951
Efficiency O15 = 0.975297 1066 1093





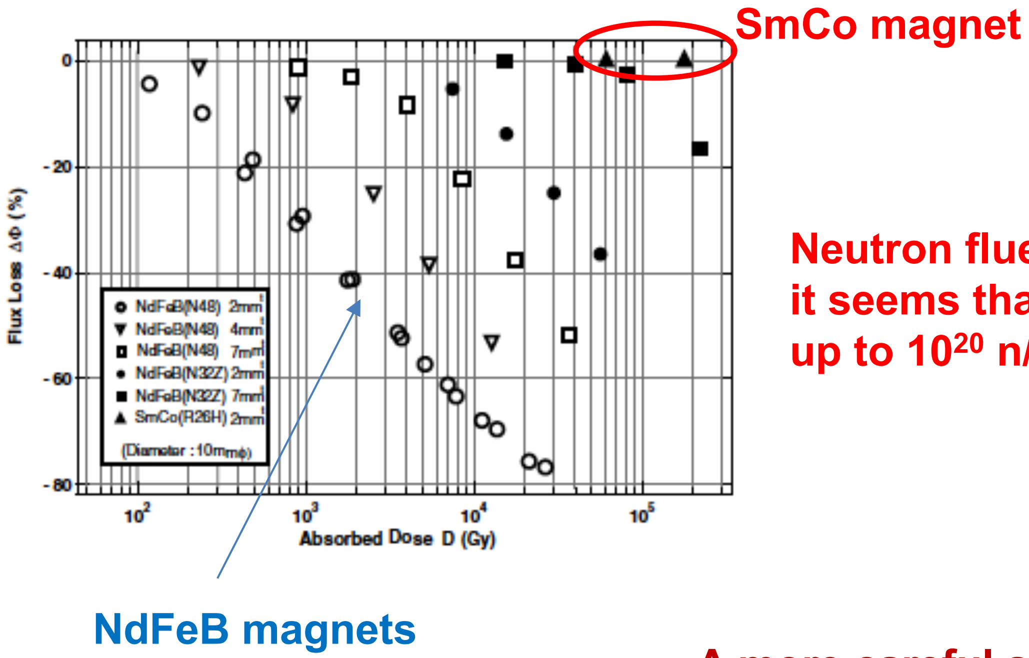
Gaussian random smearing on the magnetic field components read from the magnetic map

Position not smeared

Radiaton Damage in Permanent Magnets

- We have been recently made aware that permanent magnet may suffer magnetization variations under irradiation *(For ex.: M. Schanz et al «High energy proton induced radiation damage of rare earth permanent magnet quadrupoles», Rev. Sci. Instr. 88 (2017) 125103)*
- Some literature available: mostly related to e.m. radiation but also to neutrons and in few cases to protons
- Apparently the damage is ~independent from the nature of radiation. It is of course related to dose/fluence in the magnet
- Mainly two different materials: Nd-Fe-B and Sm-Co. The latter (our initial choice) is reported to be much more radiation resistant

For a review: A.J. Samin «A review of radiation induced demagnetization of permanent magnets», Journal of Nuclear Materials 503 (2018) 42-55
Specific paper on 200 MeV protons: Ito et al, NIM B183 (2001) 323)



Neutron fluence:
it seems that SmCo magnets can tolerate up to 10^{20} n/cm^2

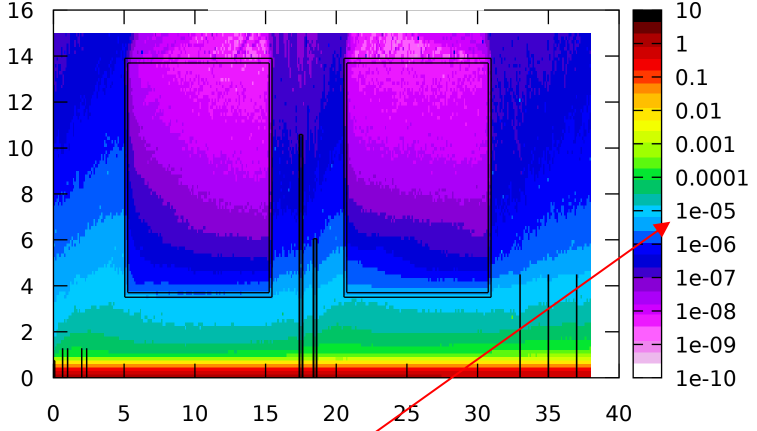
- **A more careful study is however recommended**
- **Should we organize an irradiation test on a sample?**

Dose in the magnets. Preliminary simulation study

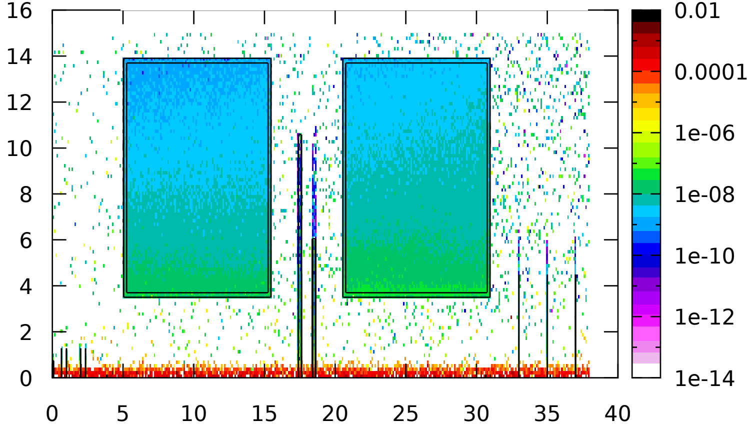
^{16}O beam @ 200 MeV/u, (SmCo magnets)

Dose maps in cylindrical coordinates (integrated in Phi)

All hadrons



Neutron contribution



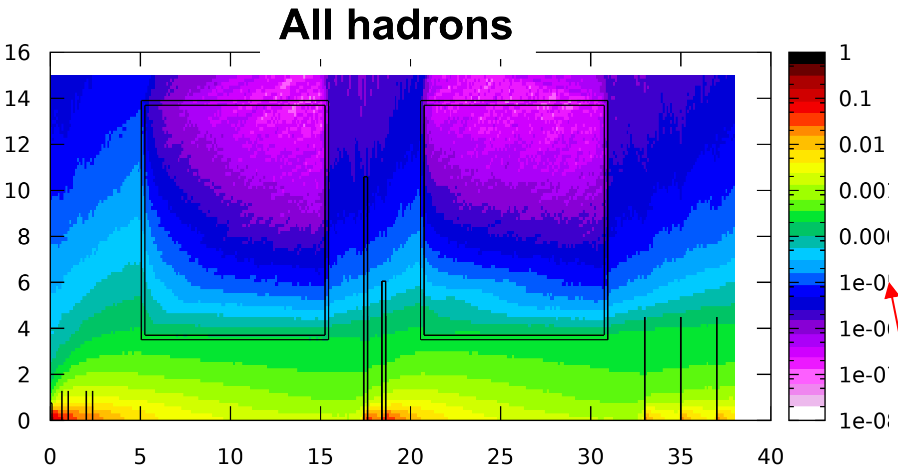
Scale is in GeV/g/primary. To get Gy multiply by 1.602 10^{-7}

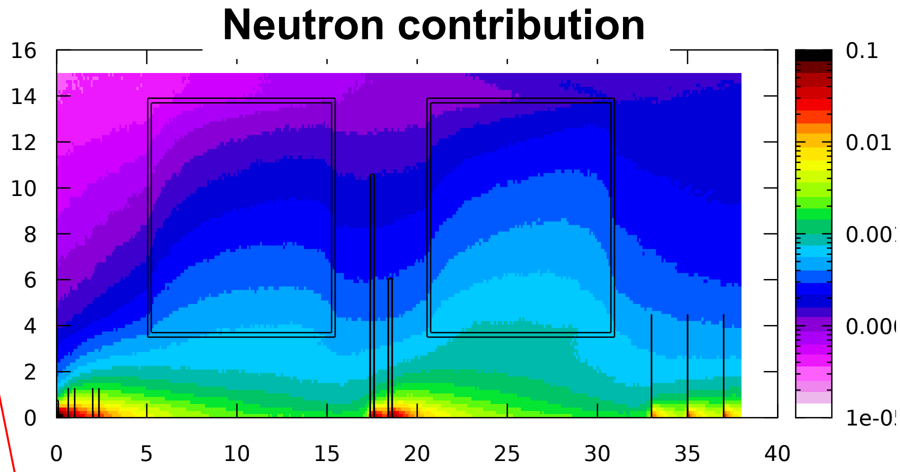
The integral is 8.8 10^{-11} Gy/primary in the first magnet and 1.2 10^{-10} Gy/primary in the second. Neutron contribution is ~4%

Considering runs with 10^7 - 10^8 primaries we shoul be on the safe side…

However: not fully realistic environment, no beam halo has been considered!

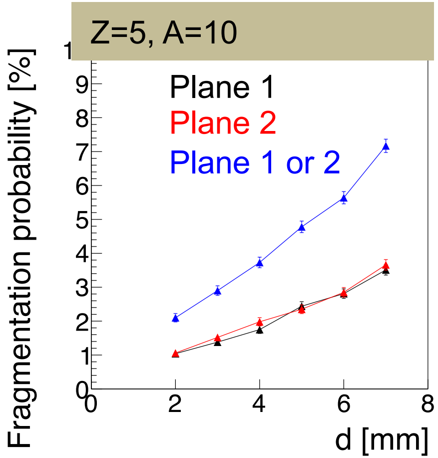
Fluence in the magnets. Preliminary simulation study

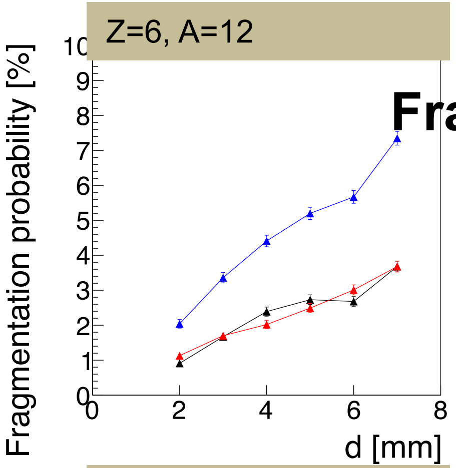




Scale is in particles/cm^2/primary.

Study of Fragmentation in Scintillator *(A. Kraan)*



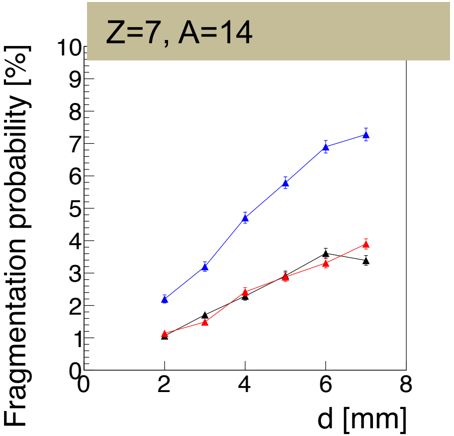


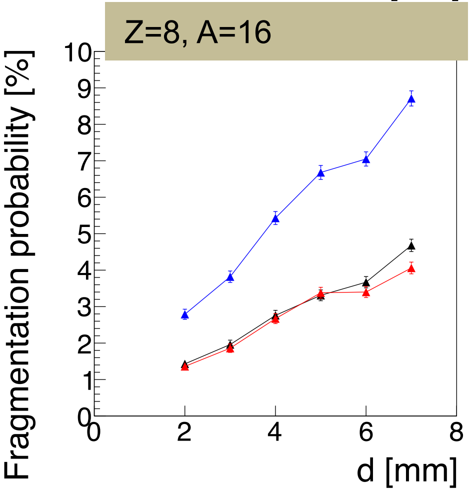
Fragmentation vs bar thickness

Fragmentation grows with thickness

Small thickness (3 mm):
+ less fragmentation
- Landau shape for Z=1, 2, 3 at all energies (not shown)

Large thickness (6 mm):
- More fragmentation
- More expensive
+ More gaussian shape: Z=4 already ok

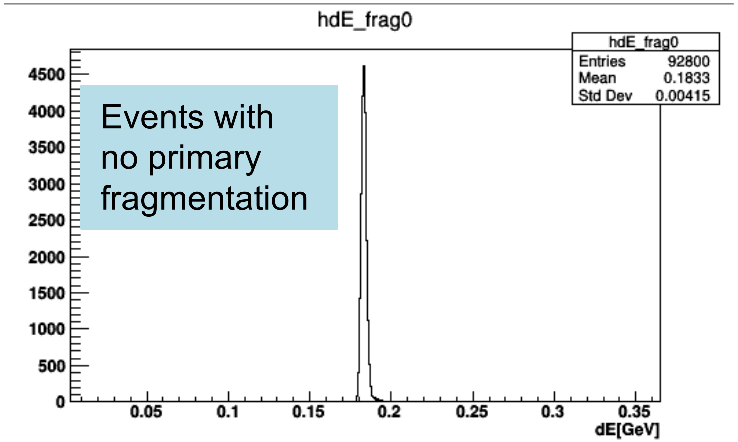


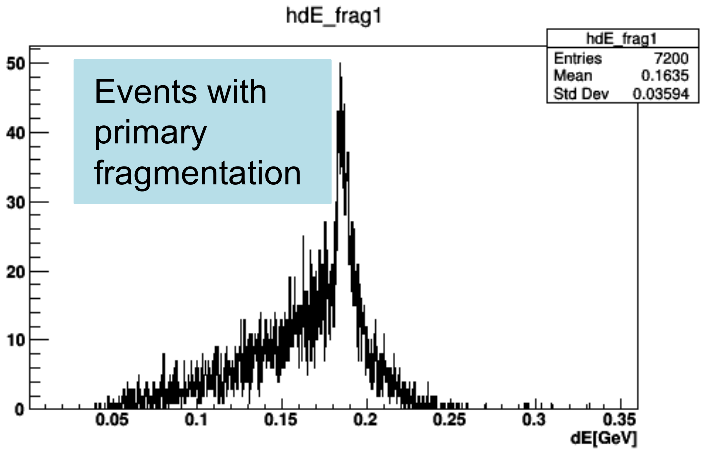


Fragmentation vs bar thickness

- Compare energy deposition in scintillator for events with and without primary fragmentation

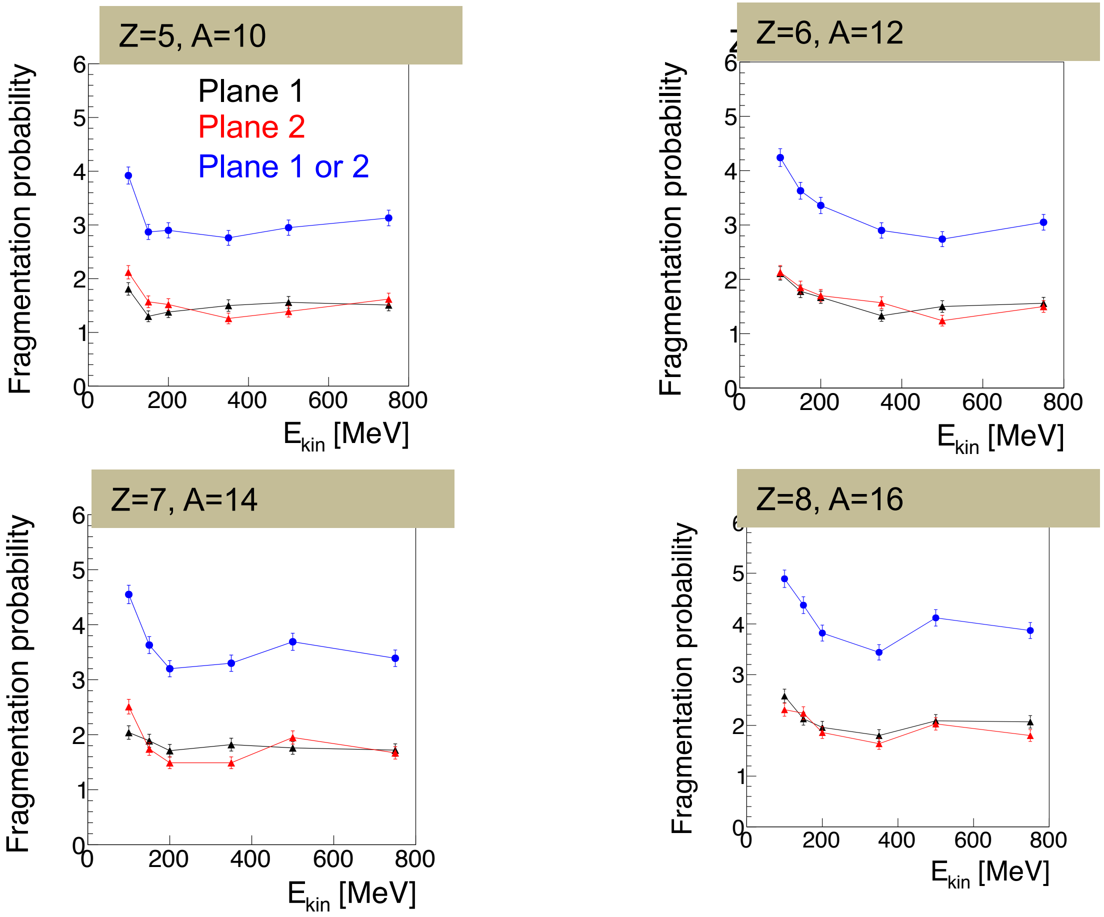
Z=8, A=16, E=200 MeV/n, d=6 mm



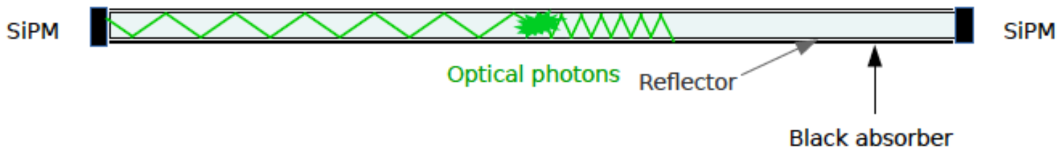


Deposits are much more variable, can be up to 250 MeV (but rare)

Fragmentation vs energy



Simulation of the optical transport in the scintillator bars *(E. Ciarrocchi)*



$$\overline{N}_{ph,det} = \overline{N}_{ph,\ gen} \cdot PDE \cdot \varepsilon_{geom,transport}$$

$\overline{N}_{ph,\ gen} = \Delta E \cdot Y$

FLUKA

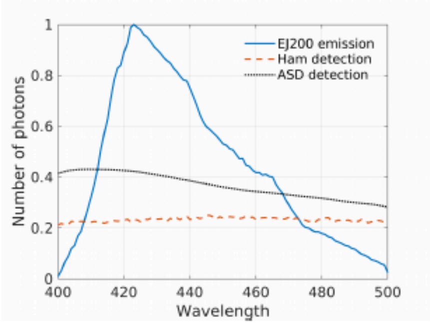
10^4 ph/MeV

~23% for Ham SiPM

~10% per side @ detector center (Geant4)

Comparison with experimental data:

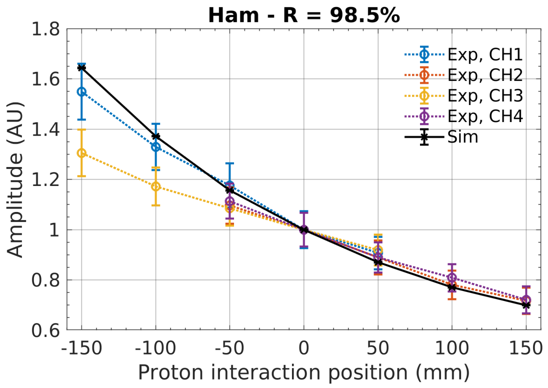
- Optical attenuation with proton interaction position along the bar
- Absolute number of detected photons
- Exp data for two scintillator bars and for two types of SiPMs
- Comparison only for protons

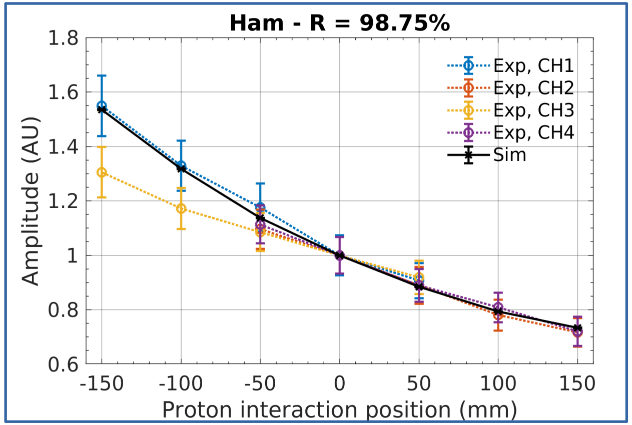


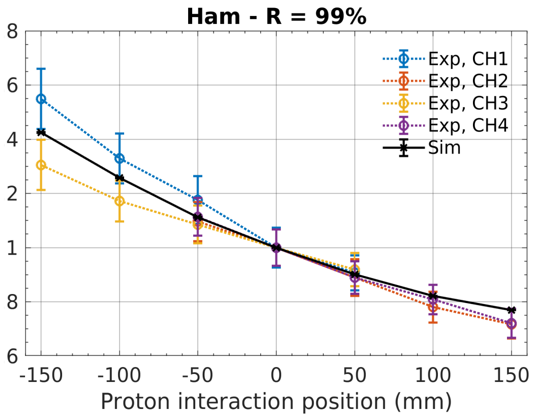
<u>Matlab</u>

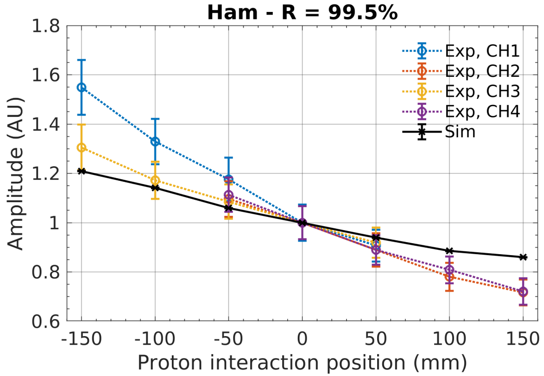
- Given nr. of emitted photons
- EJ212 emission spectrum
- HAM/ASD spectral PDE
- Probability of a photon of given energy to be detected

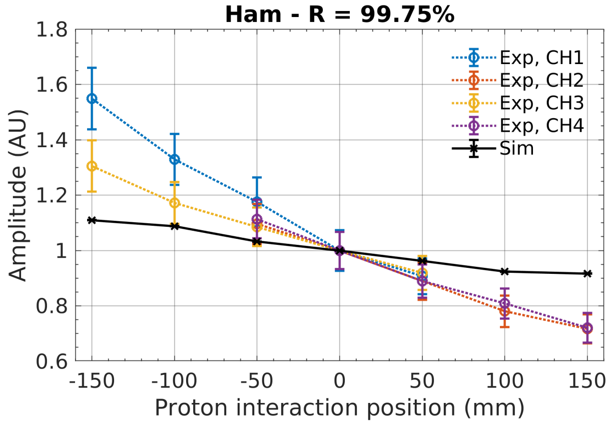
Optical attenuation: Hamamatsu





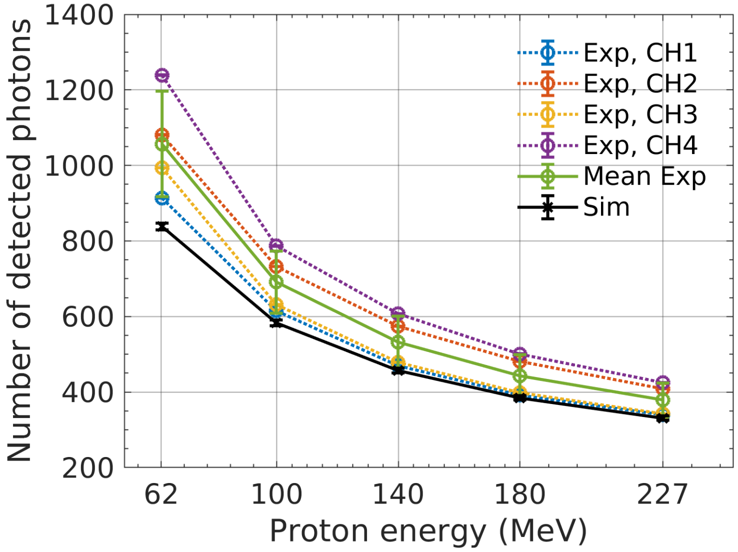


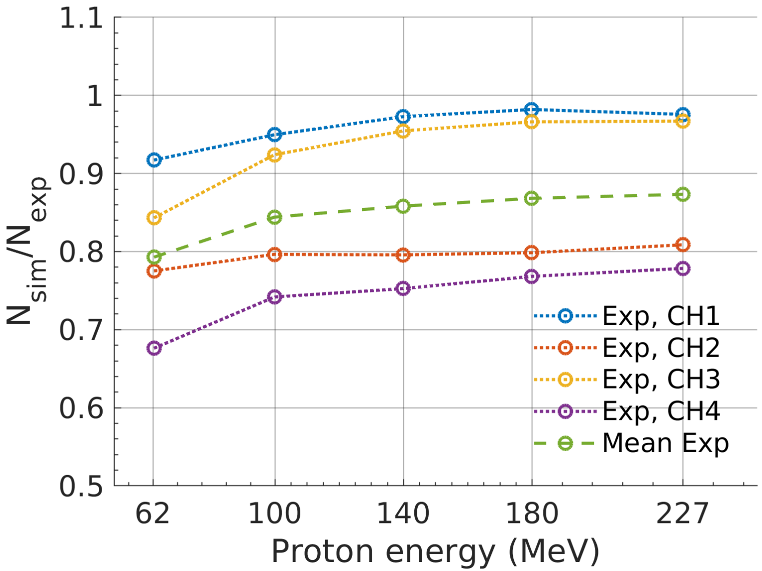




R = bar reflection coefficient

Absolute number of photons (Hamamatsu)





- Only Hamamatsu
- Simulation does not account for noise factors
- High uncertainty on gain used to determine exp nr of photons

Summary of Studies of FOOT Performance on charge reconstruction and Fragment Identification

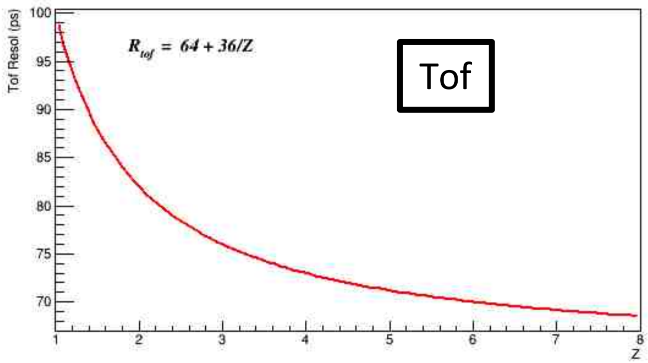
(R. Spighi et al.)

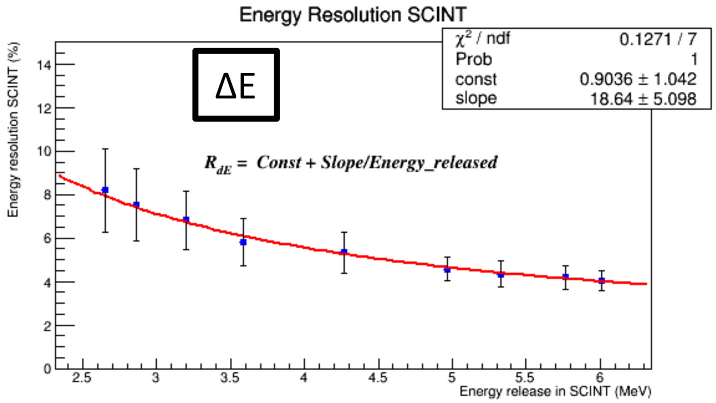
INPUT DATA

- 4×10^7 primaries
- Projectile: ^{16}O (200 MeV/u)
- Target: C_2H_4 (2mm)
- Selected tracks that pass all the subdetectors

INPUT RESOLUTIONS:

- Momentum (tracking) → 4.5%
- Kinetic Energy (Calo) → 1.5%
- Tof : [70:100] ps depending on Z
- ΔE (scint): [3:10]% depending on energy released



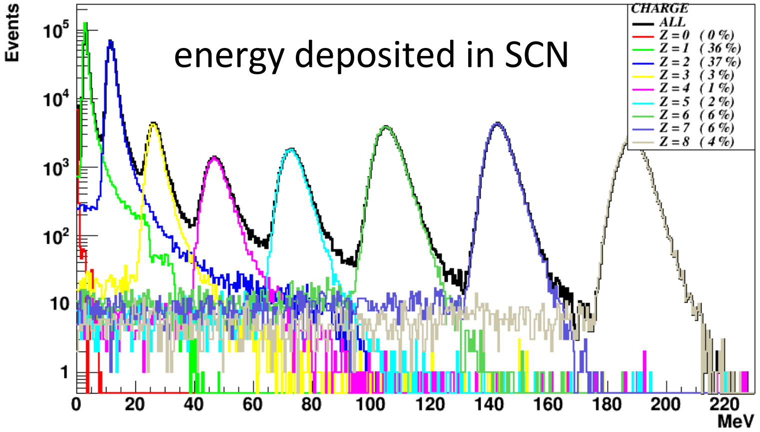


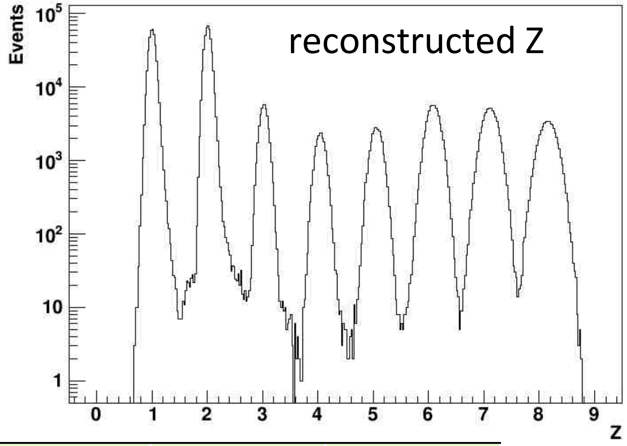
Z reconstruction

SCN

$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A}\,\frac{4\pi\,N_A\,m_e c^2}{M_U}\left(\frac{e^2}{4\pi\epsilon_0\,m_e c^2}\right)^2 \frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

TOF





Z Resolution

^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N	^{16}O
1	2	3	4	5	6	7	8
1.01±0.06	2.01±0.06	3.02±0.07	4.05±0.09	5.06±0.10	6.09±0.12	7.11±0.14	8.15±0.16

Resol: 6% 3% 2.0%

Z Resolution: [2-6%] << minimum distance between charges (~10% between 7 and 8)

Charge completely identified (wrong assignment < %), possible to improve with MSD

A Identification

RECO

TRACKER

$$A_1 = \frac{m}{U} = \frac{p}{U\,\beta\,\gamma}$$

TOF

CALO

$$A_2 = \frac{m}{U} = \frac{E_{kin}}{U(\gamma - 1)}$$

TOF

TRACKER

$$A_3 = \frac{m}{U} = \frac{p^2 - E_{kin}{}^2}{2E_{kin}}$$

CALO

FITS

Standard χ2

$$f = \left(\frac{(tof_{reco} - t)}{\sigma tof_{reco}}\right)^2 + \left(\frac{(p_{reco} - p)}{\sigma p_{reco}}\right)^2 + \left(\frac{(T_{reco} - T)}{\sigma T_{reco}}\right)^2 + (A_1 - A \quad A_2 - A \quad A_3 - A)\begin{pmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{pmatrix}\begin{pmatrix} A_1 - A \\ A_2 - A \\ A_3 - A \end{pmatrix}$$

$$C = (A \cdot A^T)^{-1} \qquad A = \begin{pmatrix} \frac{\partial A_1}{\partial t}dt & \frac{\partial A_1}{\partial p}dp & 0 \\ \frac{\partial A_2}{\partial t}dt & 0 & \frac{\partial A_2}{\partial T}dT \\ 0 & \frac{\partial A_3}{\partial p}dp & \frac{\partial A_3}{\partial T}dT \end{pmatrix}$$

Augmented Lagrangian Method

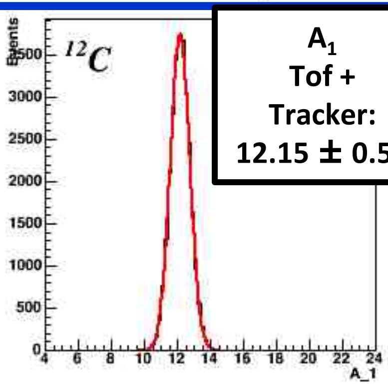
$$\tilde{\mathcal{L}}(\vec{x};\lambda,\mu) \equiv f(\vec{x}) - \sum_a \lambda_a c_a(\vec{x}) + \frac{1}{2\mu}\sum_a c_a^2(\vec{x}).$$

Studied fragments, one per charge

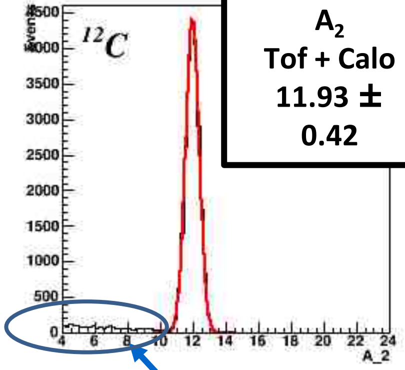
	^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N	^{16}O
Z	1	2	3	4	5	6	7	8
A	1	4	7	9	11	12	14	16

Reconstruction methods

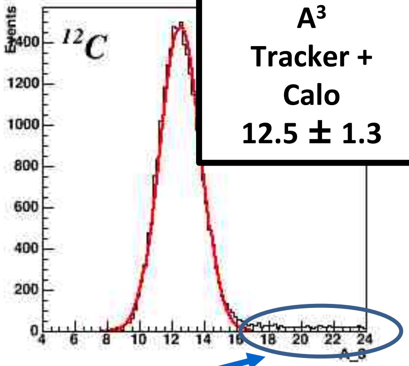
Example: A of ^{12}C



A_1
Tof + Tracker:
12.15 ± 0.59



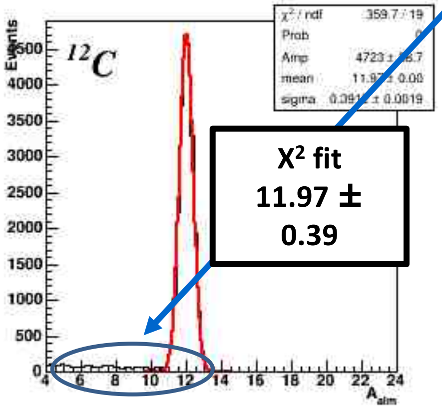
A_2
Tof + Calo
11.93 ± 0.42



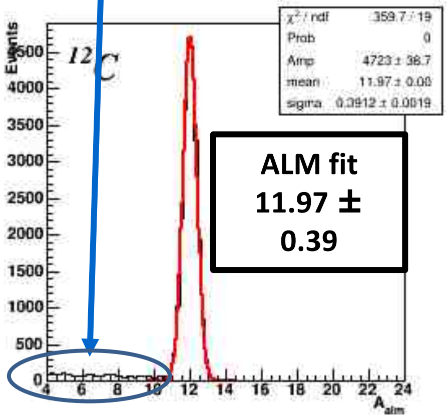
A^3
Tracker + Calo
12.5 ± 1.3

Cal: Tail due to energy taken away off the calo in nuclear interactins

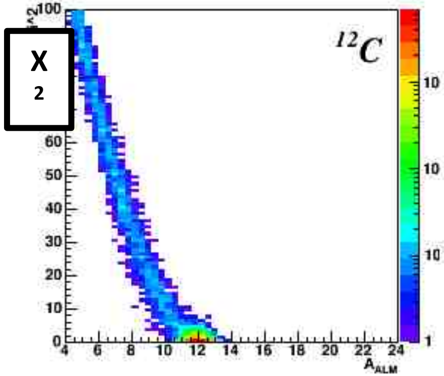
Fit methods



X^2 fit
11.97 ±
0.39



ALM fit
11.97 ±
0.39

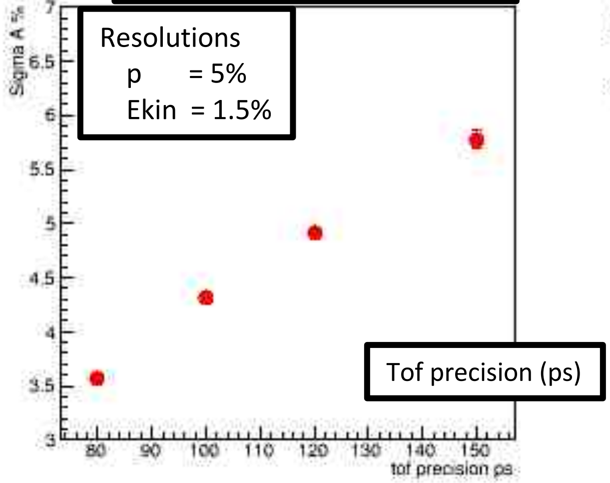


X
2

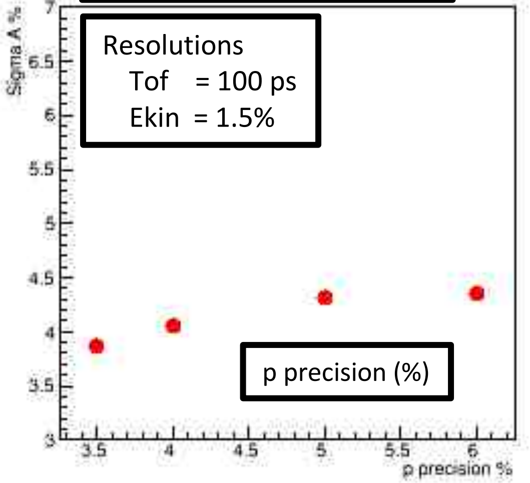
Possibility to eliminate the tail with a χ^2 cut

Systematic on A resolution (example ^{12}C)

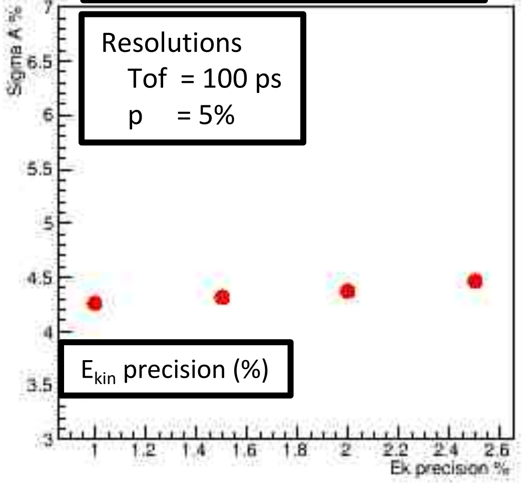
σ_A (%) vs Tof precision



σ_A (%) vs p precision

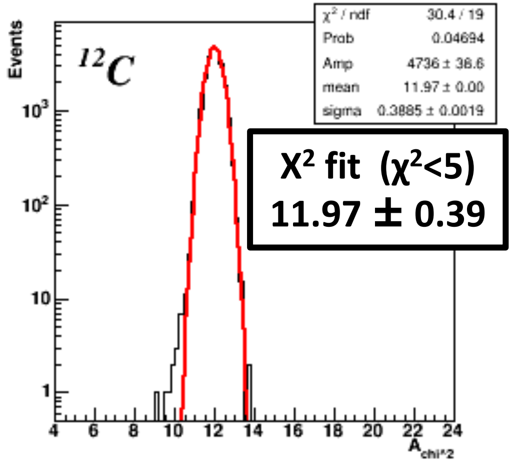


σ_A (%) vs E_{kin} precision

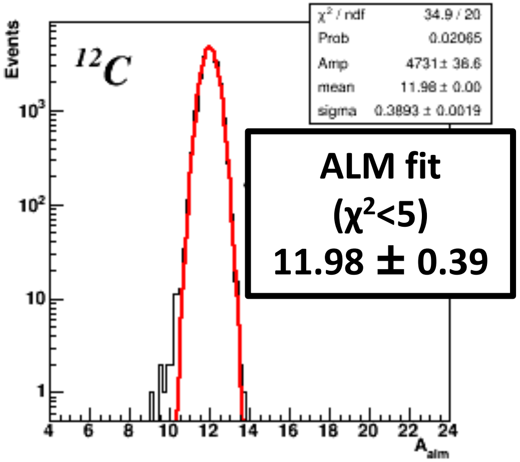


- **A Resolution**
  - **Large dependence on the Tof Resolution**
  - **Week dependence on the p and E_{kin} resolution**

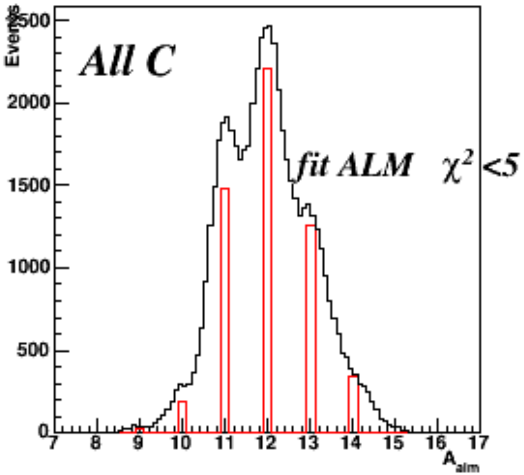
A identification: example on Carbon (cut on χ^2)



X^2 fit (χ^2<5)
11.97 ± 0.39



ALM fit
(χ^2<5)
11.98 ± 0.39

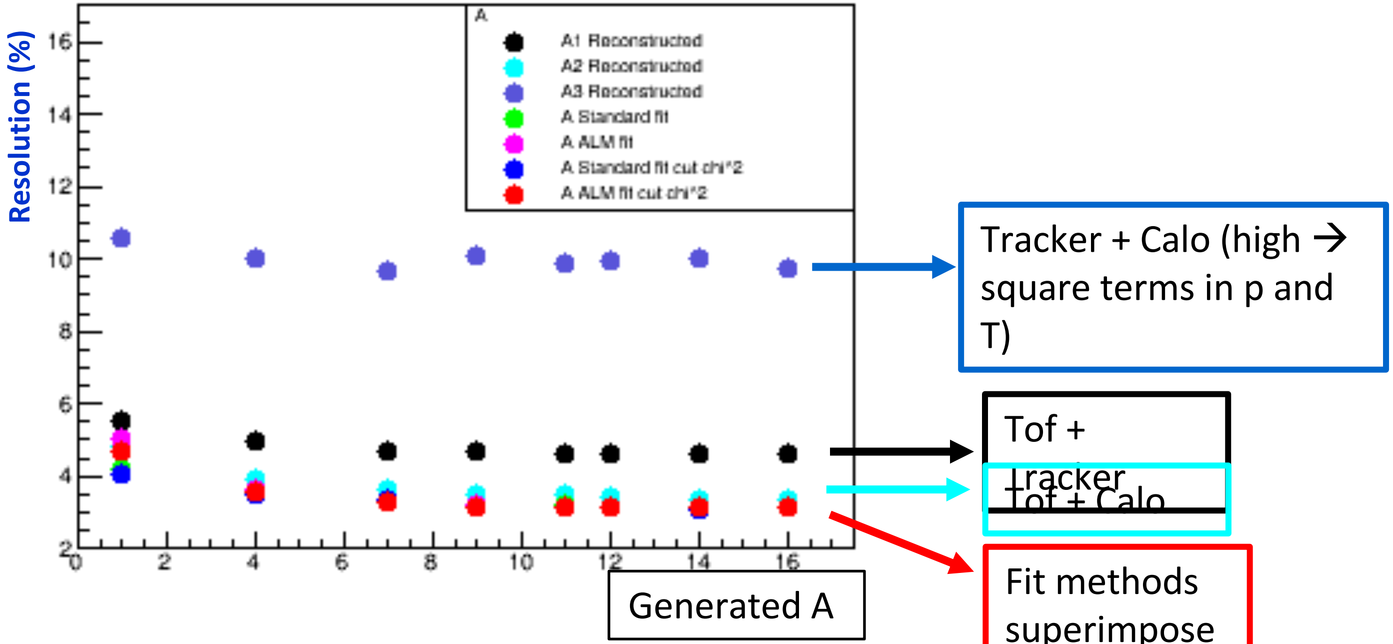


With these resolution we begin to disentangle the various isotopes

A Resolution (%)

	^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N	^{16}O
Z	1	2	3	4	5	6	7	8
A	1	4	7	9	11	12	14	16

Studied fragments



Mass Number (A) resolution with Fit methods at level of 3%

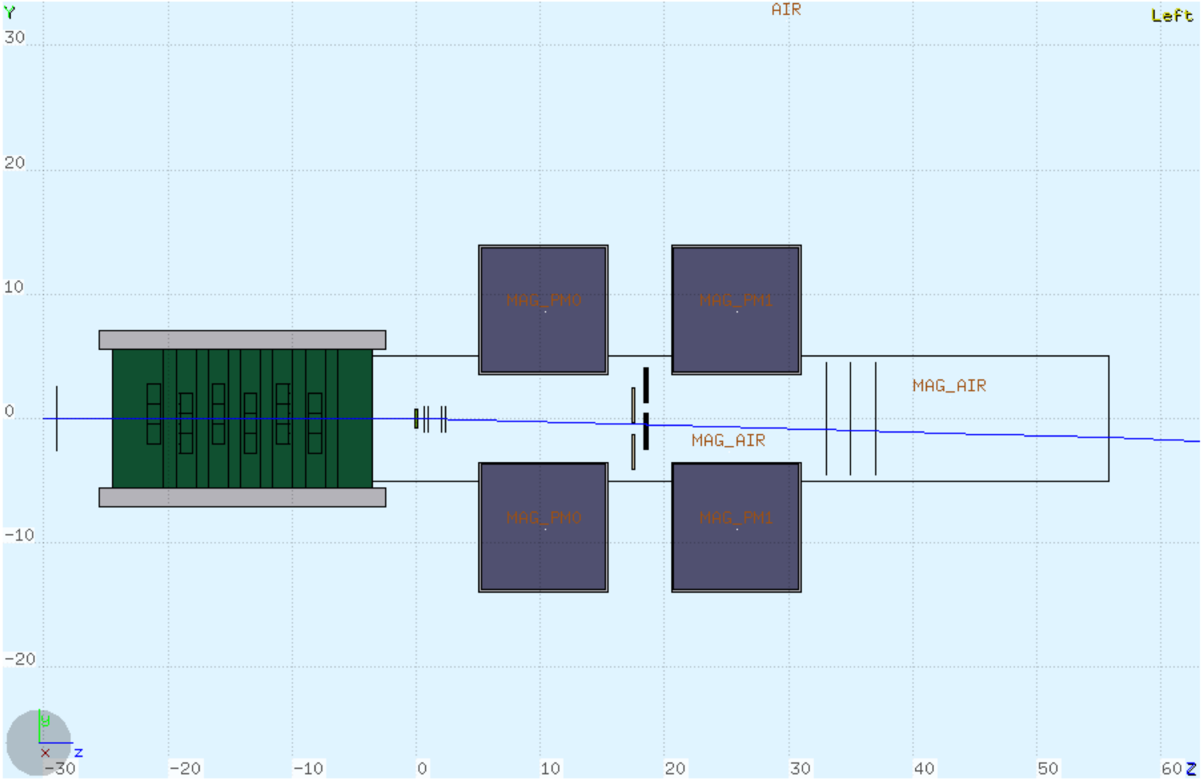
- **Reconstruction → best performance from Tof + Calo**
- **Fit → slightly improvement of the performances, remove tails**

Elastic scattering in the target

- In C_nH_m targets the primary nucleus can undergo elastic scattering on H (reversed kinematics of p-C or p-O elastic scattering)
- This results in the following pattern:
  - The primary undergoes a small deflection
  - The recoiling proton has very low energy and is generally absorbed in the target
- Can be easily confused with a reaction like, for instance, $^{12}C \rightarrow {}^{11}C + n$
- A preliminary study yields ~1.3 10^{-3} elastic ev/primary in C_2H_4 against ~10^{-2} ev/primary inelastic interactions
- Not an issue in pure C targets

Elastic scattering in the target

Event example (notice that this view is the non bending one):



A lot of work has been done but there is a lot more still to do…

- Different distances, materials and parameters for Intermediate Tracker (see talk by E. Spiriti)
- Gap between scintillator bars (see talk by M. Morrocchi)
- New geometry of calorimeter, plastic boxes,… (see talk by P. Cerello)
- Different thickness of MSD, spacing, layout… (see talk by L. Servoli)
- Soon we shall hopefully have a new magnetic system layout
- …

Man power with the proper training is unsufficient. This is now a bottleneck

Tutorial about basic handling of simulation of FOOT: 13-14 June in Milano (two days are not enough anyway). Only 2 people are surely coming…