UPDATE ON THE ANALYSIS OF GSI ^{16}O@200MEV/N DATA TAKING

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28/05/2025, XVIII General MAECI MOFFIITS FOOT Meeting

MAECI MOFFIITS

Ministero dell'Università e della Ricerca

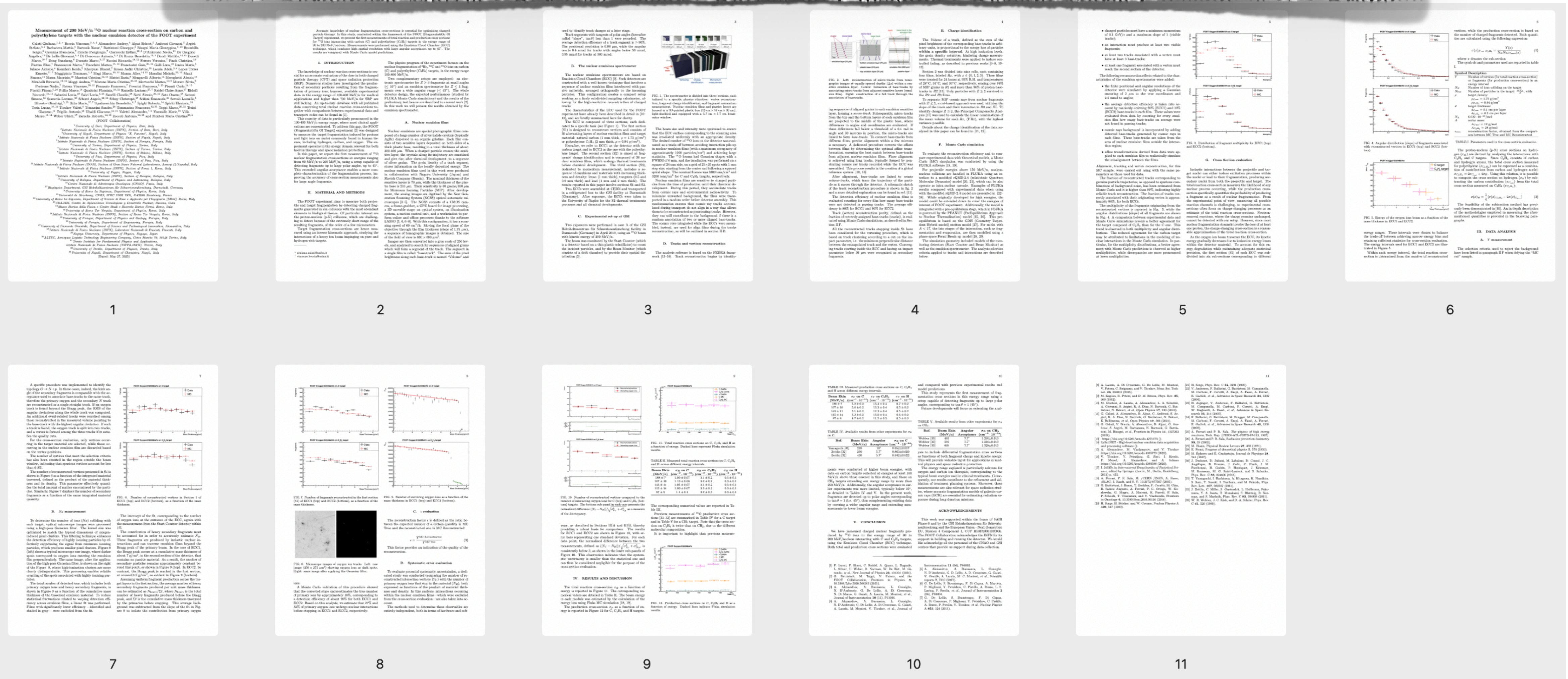
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Finanziato dall'Unione europea NextGenerationEU

Paper READY! (already sent to the EB)

Measurement of 200 MeV/n ^{16}O nuclear reaction cross-section on carbon and polyethylene targets with the nuclear emulsion detector of the FOOT experiment

Galati Giuliana,[1,2,*] Boccia Vincenzo,[3,4,†] Alexandrov Andrey,[4] Alpat Behcet,[5] Ambrosi Giovanni,[5] Argirò



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- Introduction
- Material and methods
  - Nuclear emulsion films
  - The nuclear emulsions spectrometer
  - Experimental set-up at GSI
  - Tracks and vertices reconstruction
  - Charge identification
- Monte Carlo simulation
- **Cross Section evaluation**
- **Data analysis**
  - Y measurement
  - N_B measurement
  - ε evaluation
  - Systematic error evaluation
- **Results and discussion**
- Conclusion

To be submitted on **Physical Review C**

Cross section evaluation

What’s new:

- xsec evaluated layer by layer
- Weighted mean for each subsection

Total Cross Section Measurement

$$\sigma|_{C\ or\ C_2H_4} = \frac{Y}{N_B N_{TG}\, \epsilon_{reco}}$$

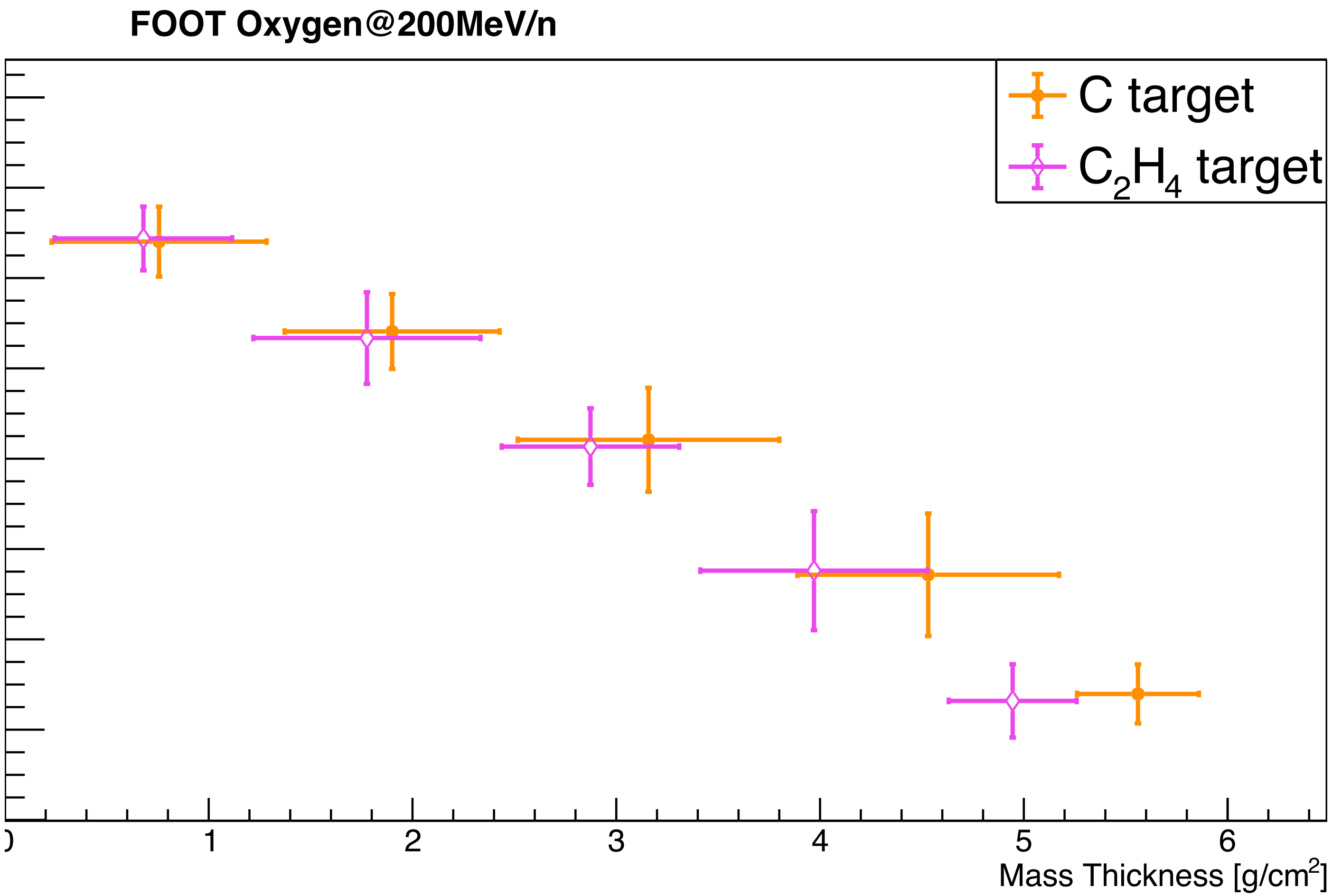
$$\sigma(x)_H = \frac{1}{4}\left[\sigma(x)_{C_2H_4} - 2\sigma(x)_{C_{\mathrm{nat}}}\right]$$

- Y = # of vertices (total xsec) or fragments (production xsec)
- N_B = # of ions colliding on the target (includes the efficiency on beam reconstruction)
- N_{TG} = # of particles in the target: $\frac{\rho d N_A}{A}$, with:
  - ρ = target density:
    $\rho_C = 1.73 g/cm^3$
    $\rho_{C_2H_4} = 0.94 g/cm^3$
  - d = target thickness:
    $d_C = 0.1cm$ per layer
    $d_{C_2H_4} = 0.2cm$ per layer
  - $N_A = 6.022 \cdot 10^{23}/mol$
  - A = molar mass:
    $A_C = 12 g/mol$
    $A_{C2H4} = 28 g/mol$
- ϵ_{reco} = reconstruction factor

One detector… many measurements!

- The energy loss within S1 is not negligible
- We divide S1 into sub-sections
- x denotes the sub-section

$$\sigma(x)_{C\ or\ C_2H_4} = \frac{Y(x)}{N_B N_{TG} \epsilon_{\mathrm{reco}}(x)}$$



C:

- (188 ± 8) MeV/n
- (168 ± 8) MeV/n
- (144 ± 11) MeV/n
- (114 ± 13) MeV/
- (88 ± 13) MeV/n

C_2H_4:

- (188 ± 7) MeV/n
- (167 ± 10) MeV/n
- (143 ± 8) MeV/n
- (116 ± 13) MeV/n
- (88 ± 8) MeV/n

H:

- (188 ± 8) MeV/n
- (168 ± 10) MeV/n
- (144 ± 11) MeV/n
- (115 ± 13) MeV/n
- (88 ± 8) MeV/n

Reconstruction efficiency

The **reconstruction factor** ϵ is defined as the ratio between the expected number of a certain quantity in MC True and the reconstructed one in MC Reconstructed

Error evaluation

Y = counting

$N_b = a + bx$

$\epsilon = \frac{RMC}{MC}$ (counting)

$$\sigma|_{C\ or\ C_2H_4} = \frac{Y}{N_B N_{TG} \epsilon_{reco}}$$

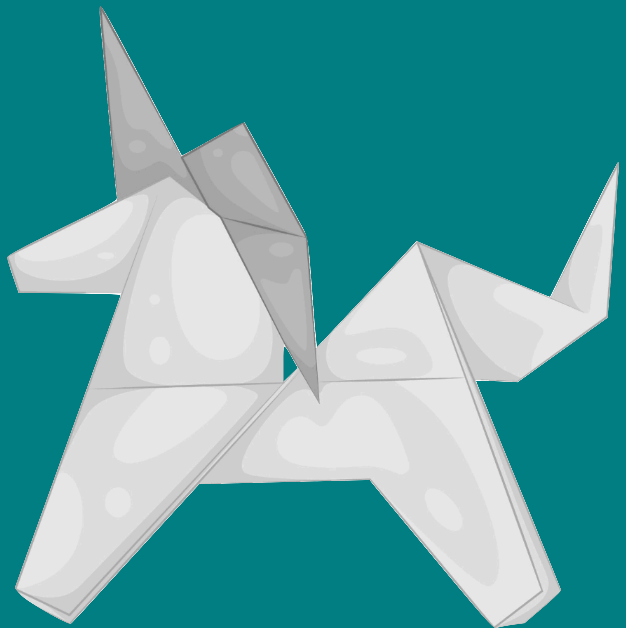
$$\text{sigma}_\sigma = \sqrt{\frac{Y}{(N_B \cdot N_{TG} \cdot \epsilon)^2} + \left(\frac{Y}{N_B^2 \cdot N_{TG} \cdot \epsilon}\right)^2 \left((\Delta a)^2 + x^2(\Delta b)^2 + 2x\,\mathrm{Cov}(a,b)\right) + \left(\frac{Y}{N_B \cdot N_{TG} \cdot \epsilon^2}\right)^2 \left(\frac{\mathrm{RMC}}{\mathrm{MC}^2} + \left(\frac{\mathrm{RMC}}{\mathrm{MC}^2}\right)^2 \cdot \mathrm{MC}\right)}$$

Number of vertices and number of produced fragments

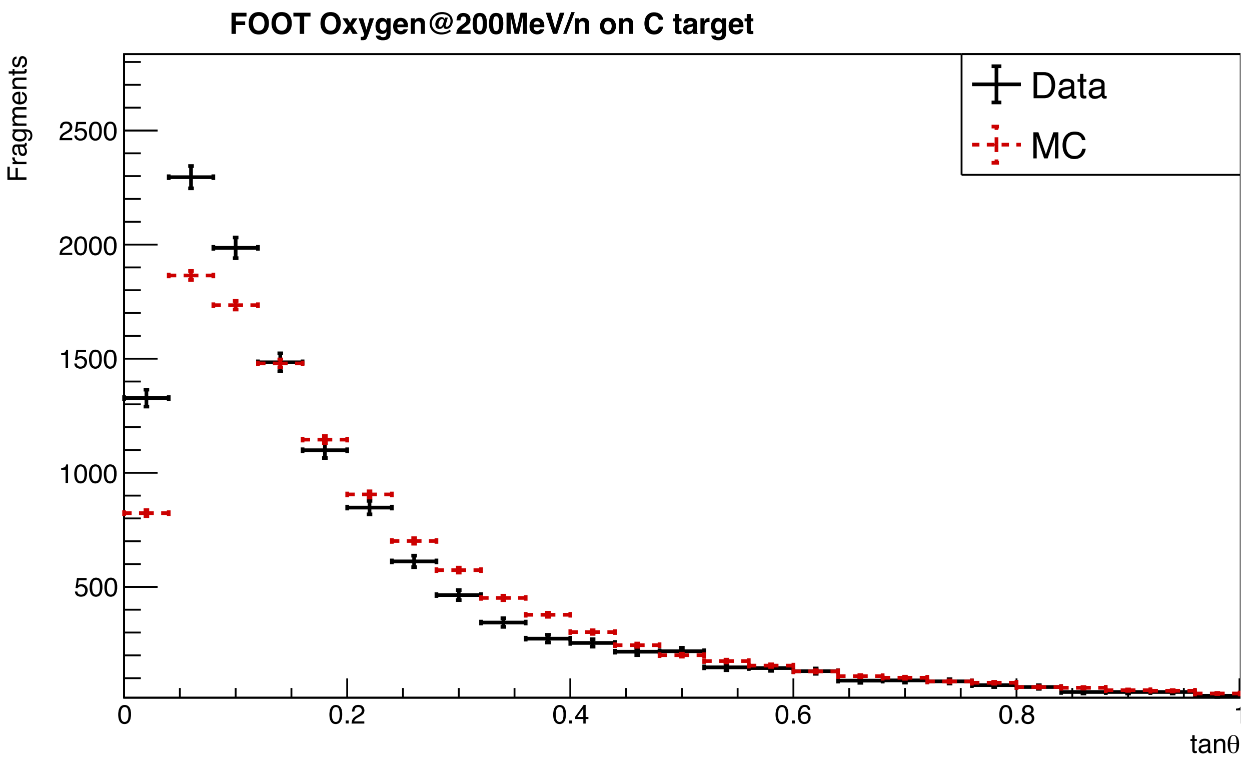
Y

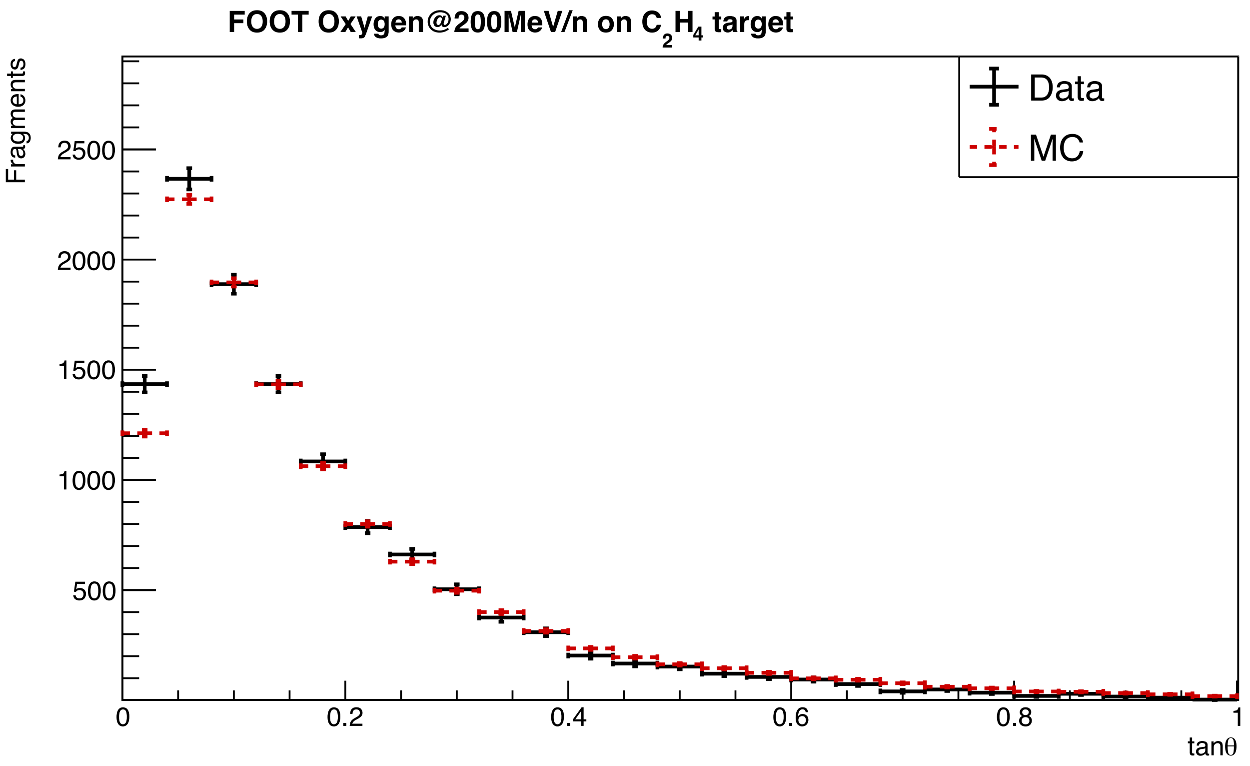
What's new:

- tracking parameters improved → higher efficiency



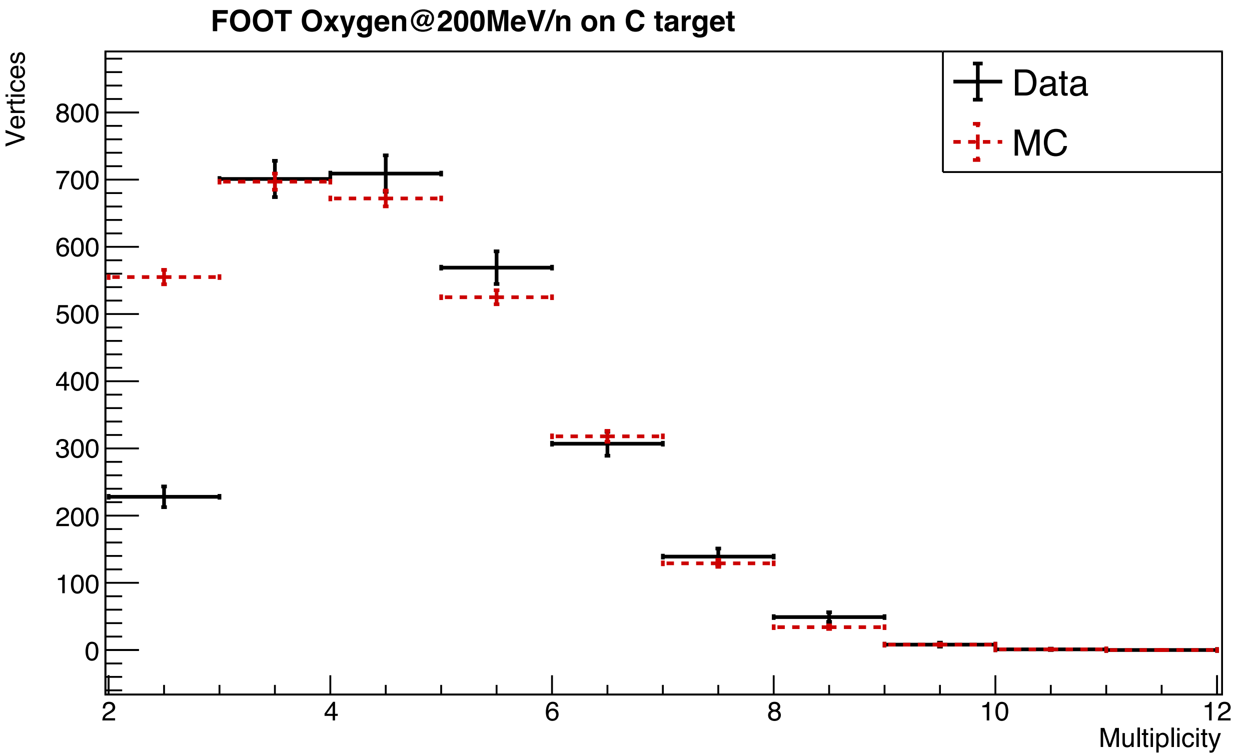
Angular distribution of fragments associated with reconstructed vertices

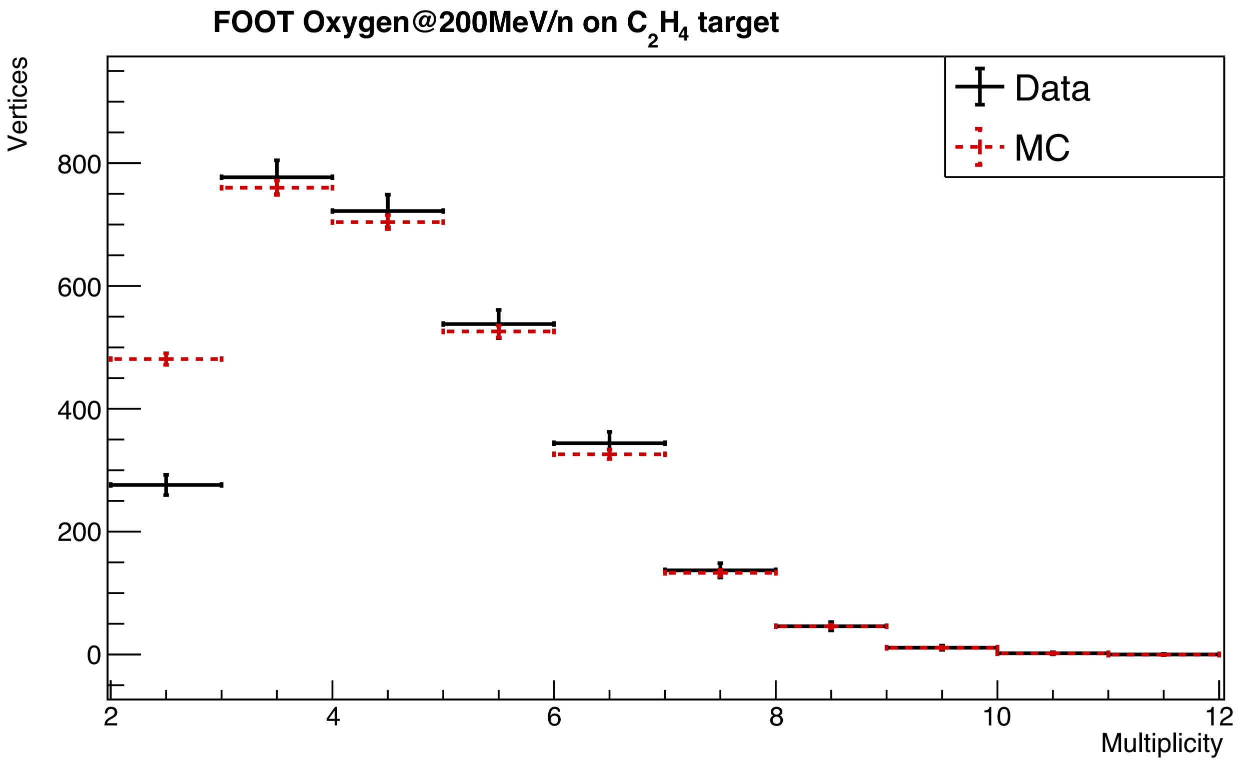




- Better agreement for the C_2H_4 target than for the C one
- The reduced agreement for the carbon target may be attributed to limitations in the modelling of nuclear interactions in the Monte Carlo simulation

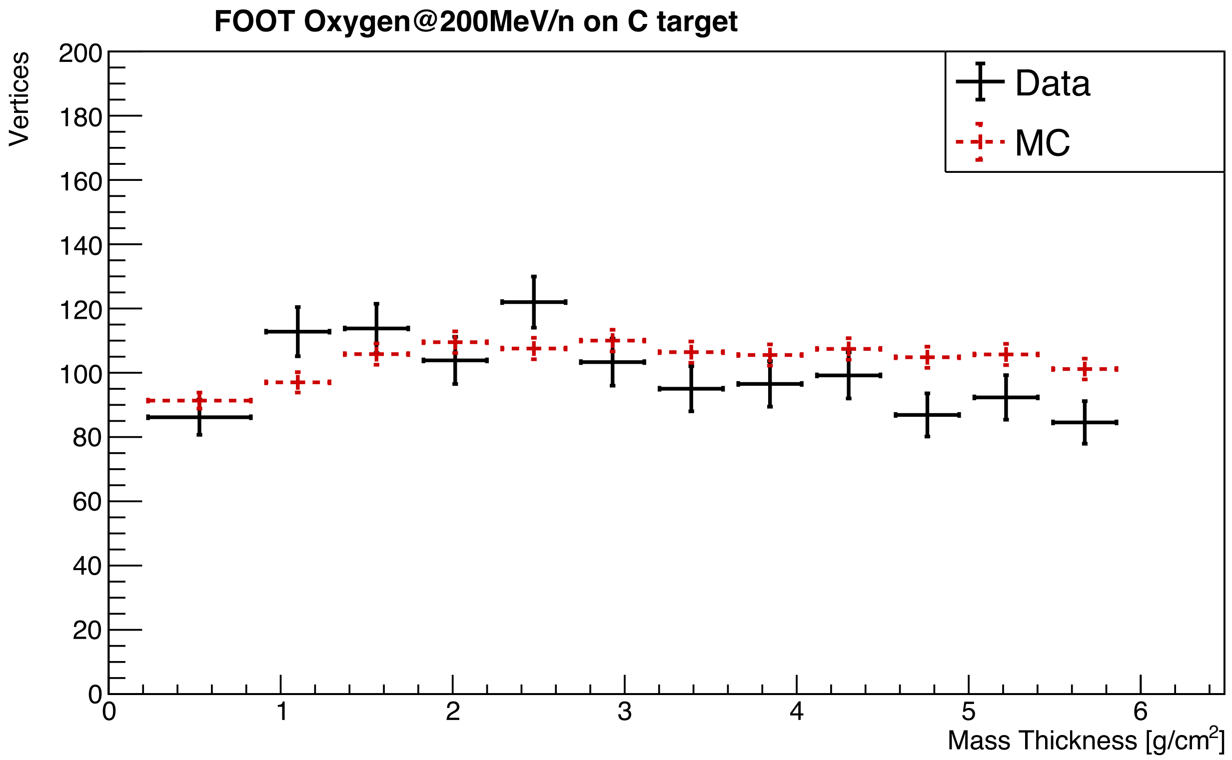
Distribution of fragment multiplicity

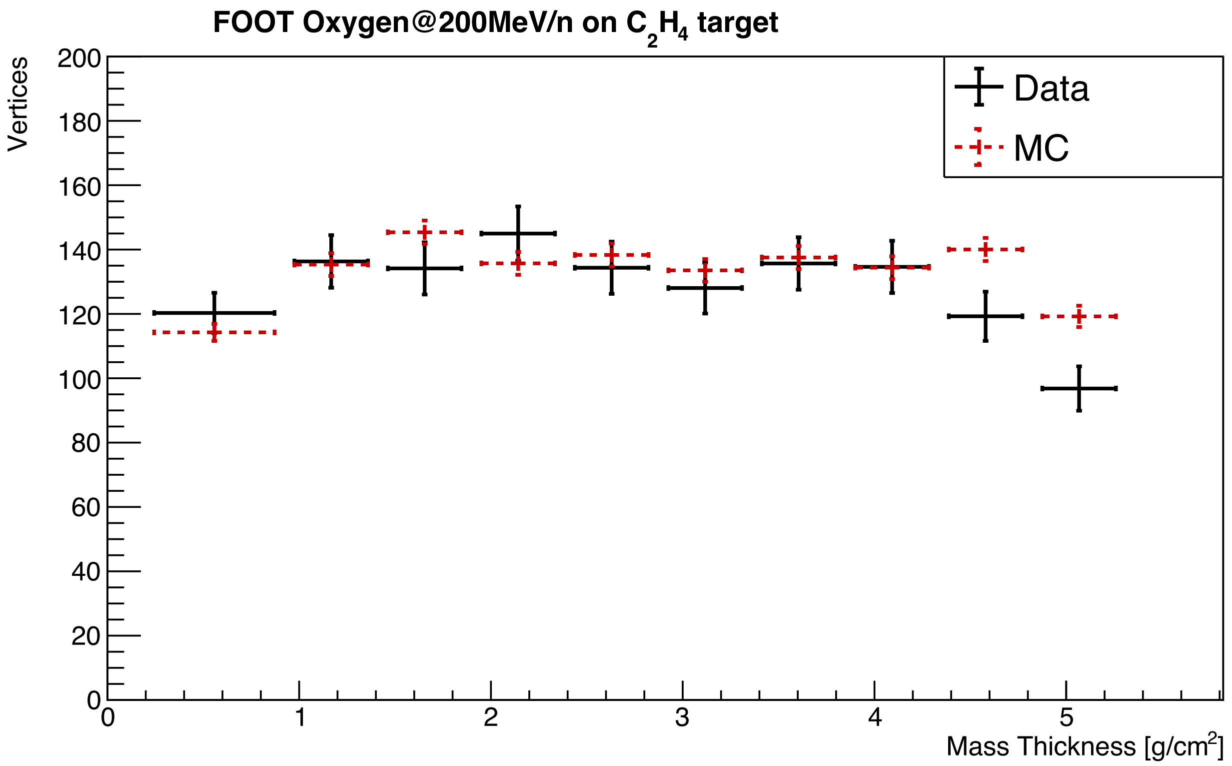




- Better agreement for the C_2H_4 target than for the C one
- The reduced agreement for the carbon target may be attributed to limitations in the modelling of nuclear interactions in the Monte Carlo simulation

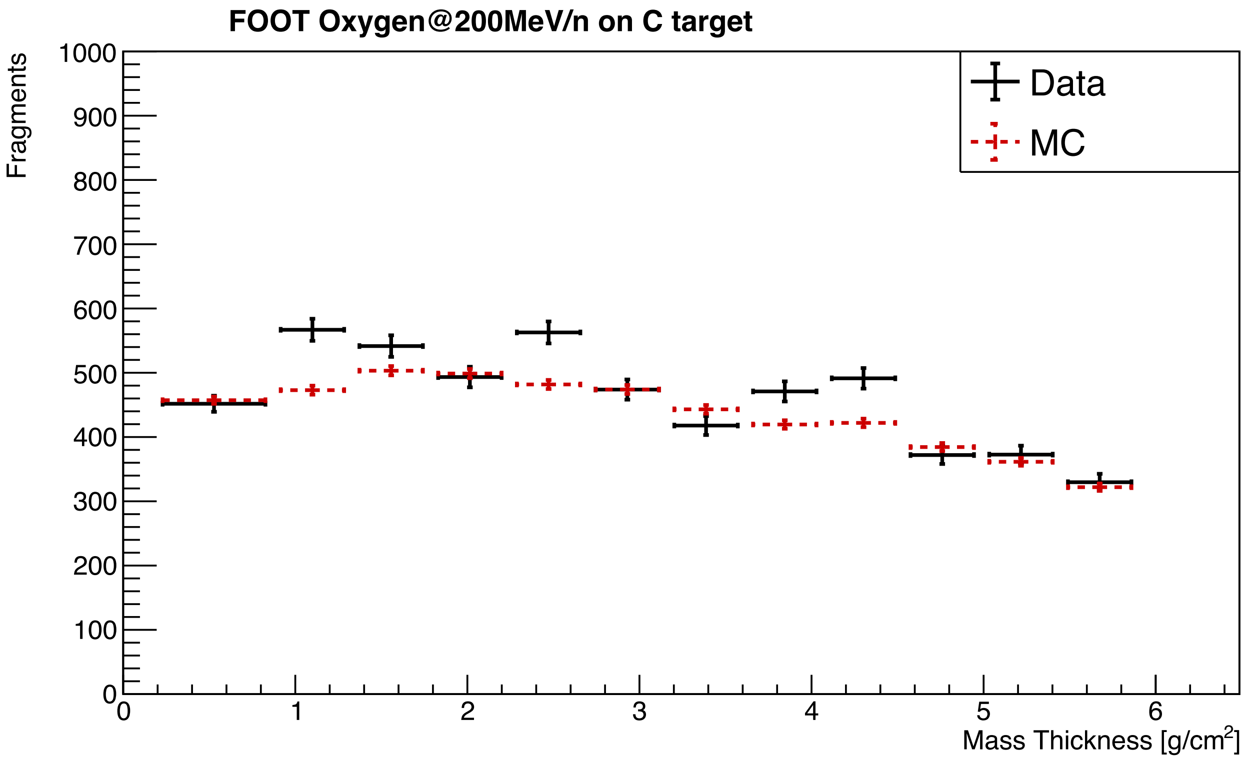
Number of reconstructed vertices in Section 1

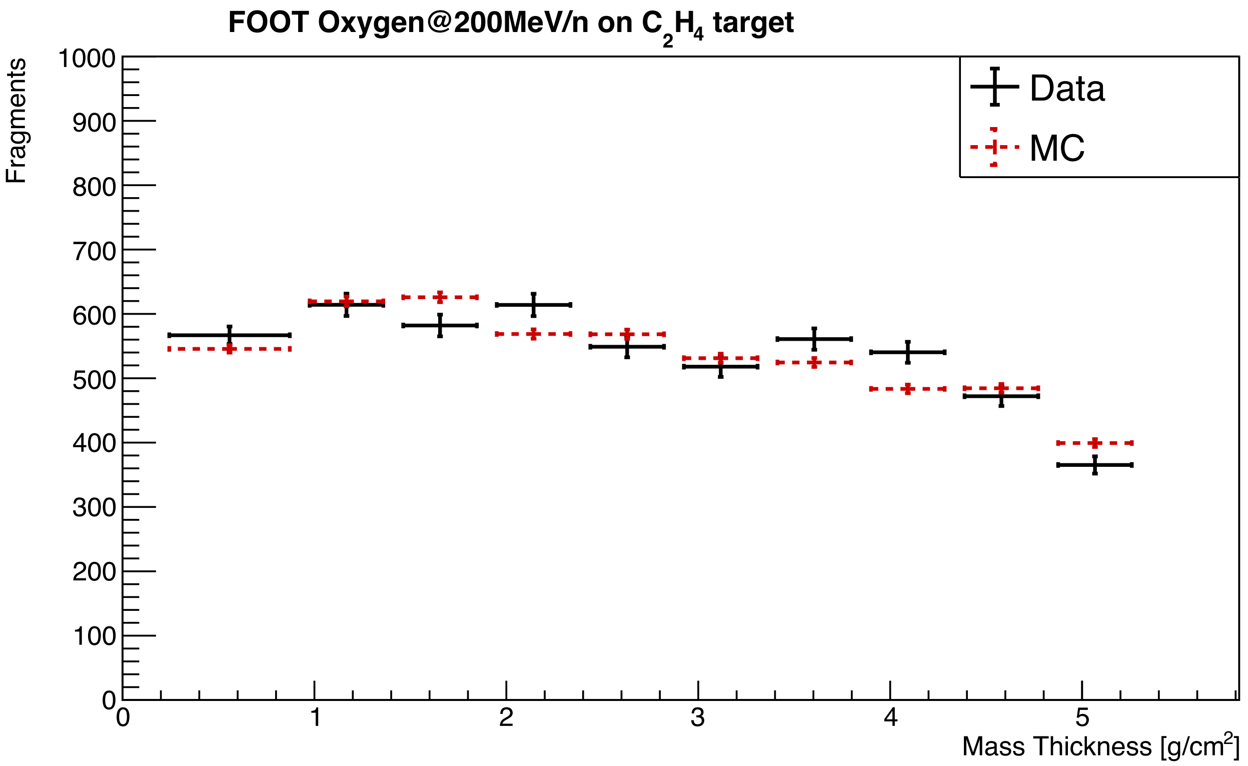




- The number of reconstructed vertices presented in S1 is shown as a function of the integrated material traversed, defined as the product of the material thickness and its density. This parameter effectively quantifies the total amount of matter encountered by the particles.

Number of fragments reconstructed in Section 1

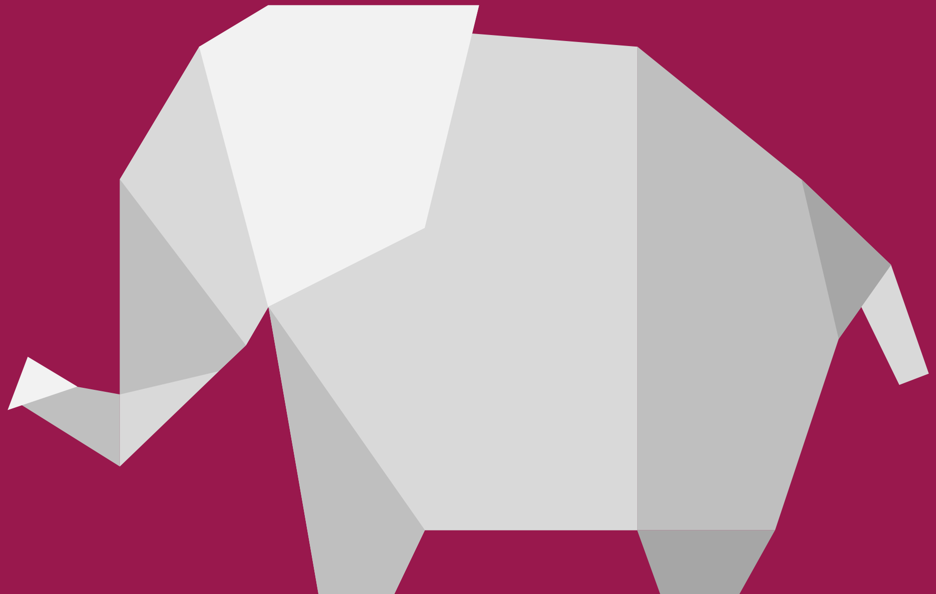




- The number of reconstructed vertices presented in S1 is shown as a function of the integrated material traversed, defined as the product of the material thickness and its density. This parameter effectively quantifies the total amount of matter encountered by the particles.

Number of beam particles

$$N_B$$



N_B evaluation

$$\sigma_i|_{C\ or\ C_2H_4} = \frac{Y_i}{N_{B_i}\, N_{TG_i}\, \epsilon^i_{reco}}$$

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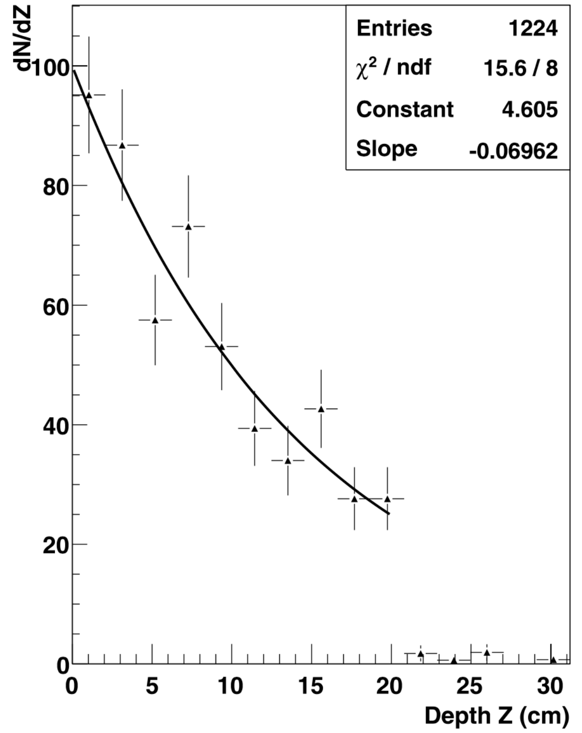
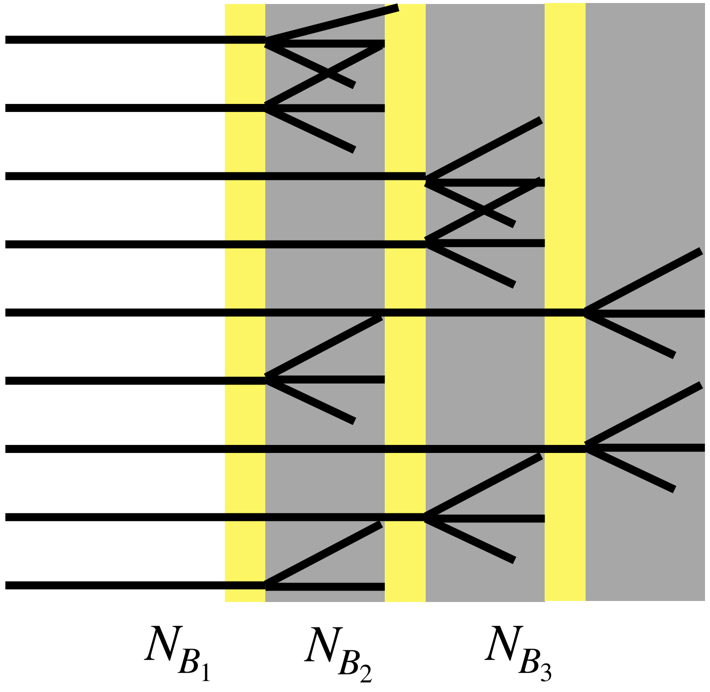


Fig. 2. Fraction of the remnant Carbon beam as a function of the traversed ECC material

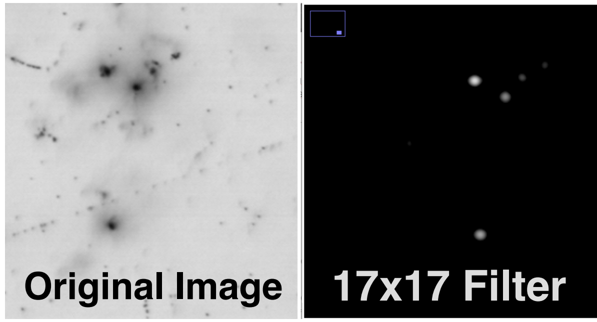


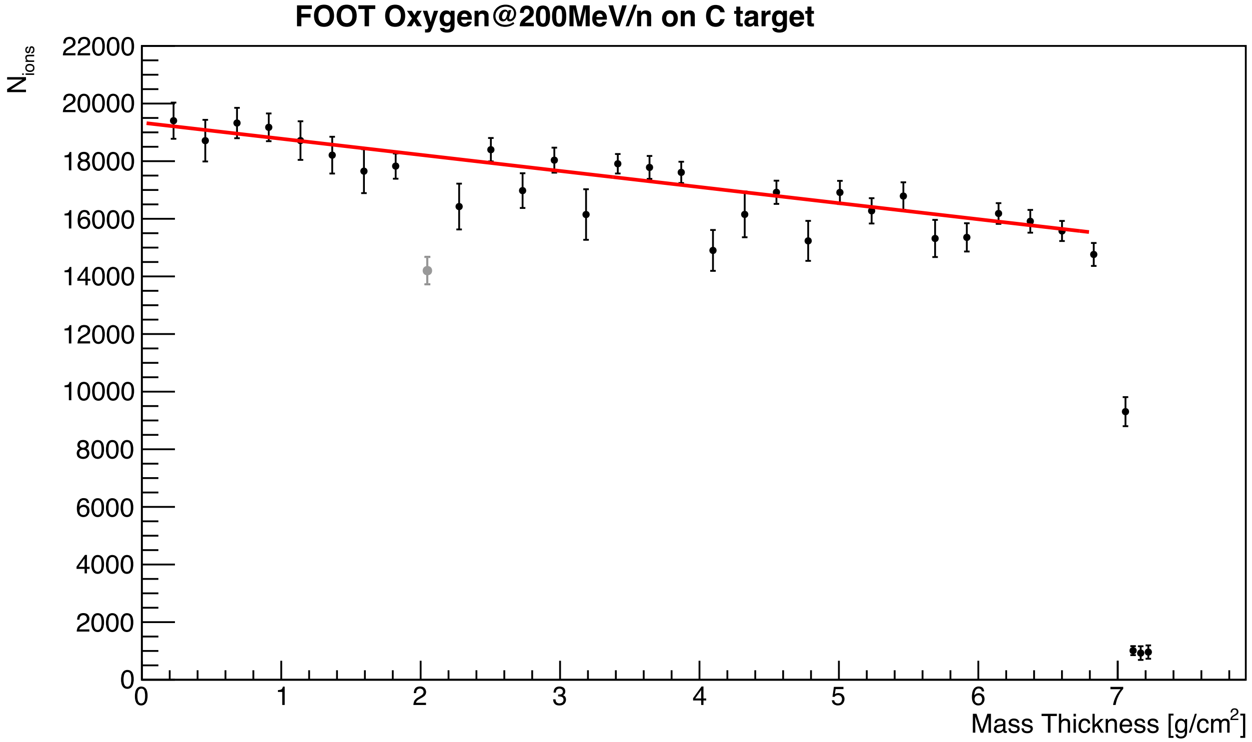
- Each passive material layer can be considered a “new measurement”
- The number of incident beam particle on each layer has to be evaluated and is affected by its efficiency
- New approach: estimation from oxygen tracks

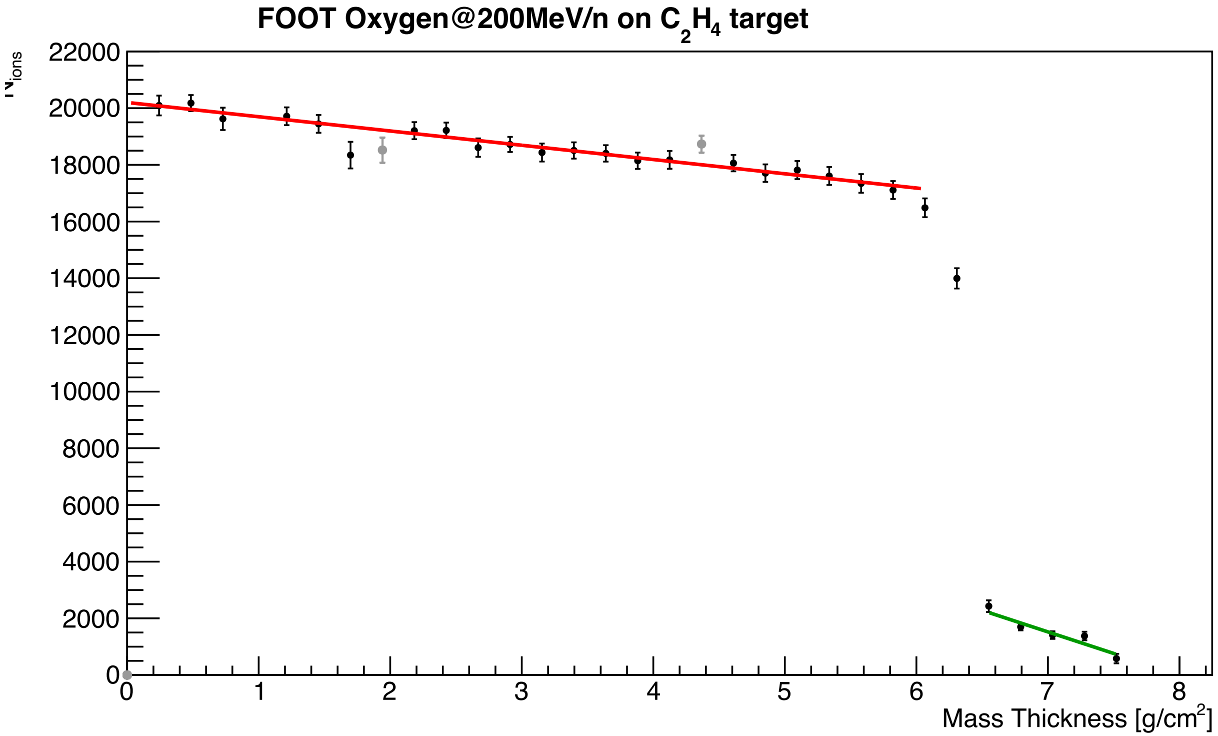
Evaluation of the number of beam particles for each subsection

For more details: https://agenda.infn.it/event/44578/contributions/250785/attachments/129107/191445/VB_PhysMeet_Dec24.pdf

- To determine the number of ions colliding with each target, optical microscope images were processed using a high-pass Gaussian filter, whose kernel size was optimized to match the typical dimensions of oxygen-induced pixel clusters.
- **Plates outside 2σ** from the fit have been removed and the fit performed again
- Assuming uniform fragment production across the target layers in S1, the average number of heavy secondary fragments produced can be estimated and subtracted from the slope of the fit to isolate the contribution from primary oxygen ions
- Monte Carlo validation gives 90% efficiency



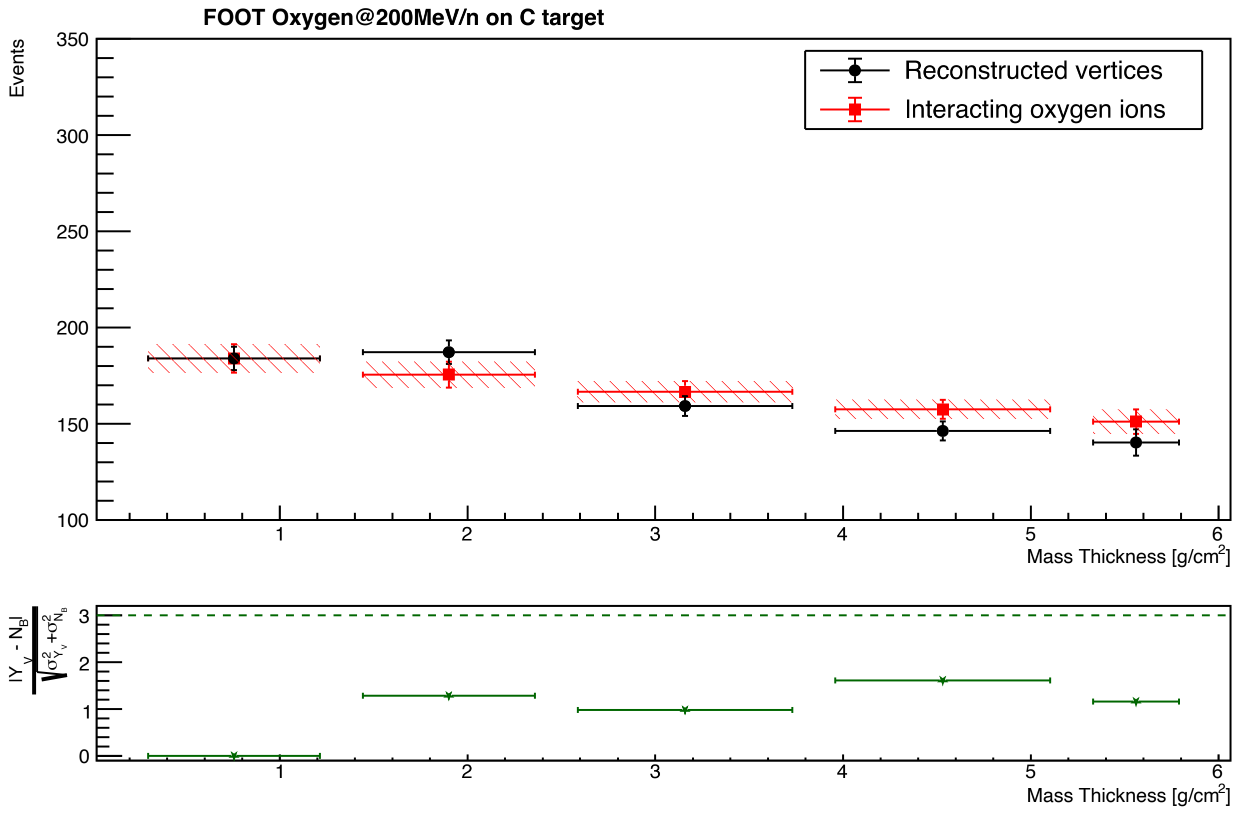


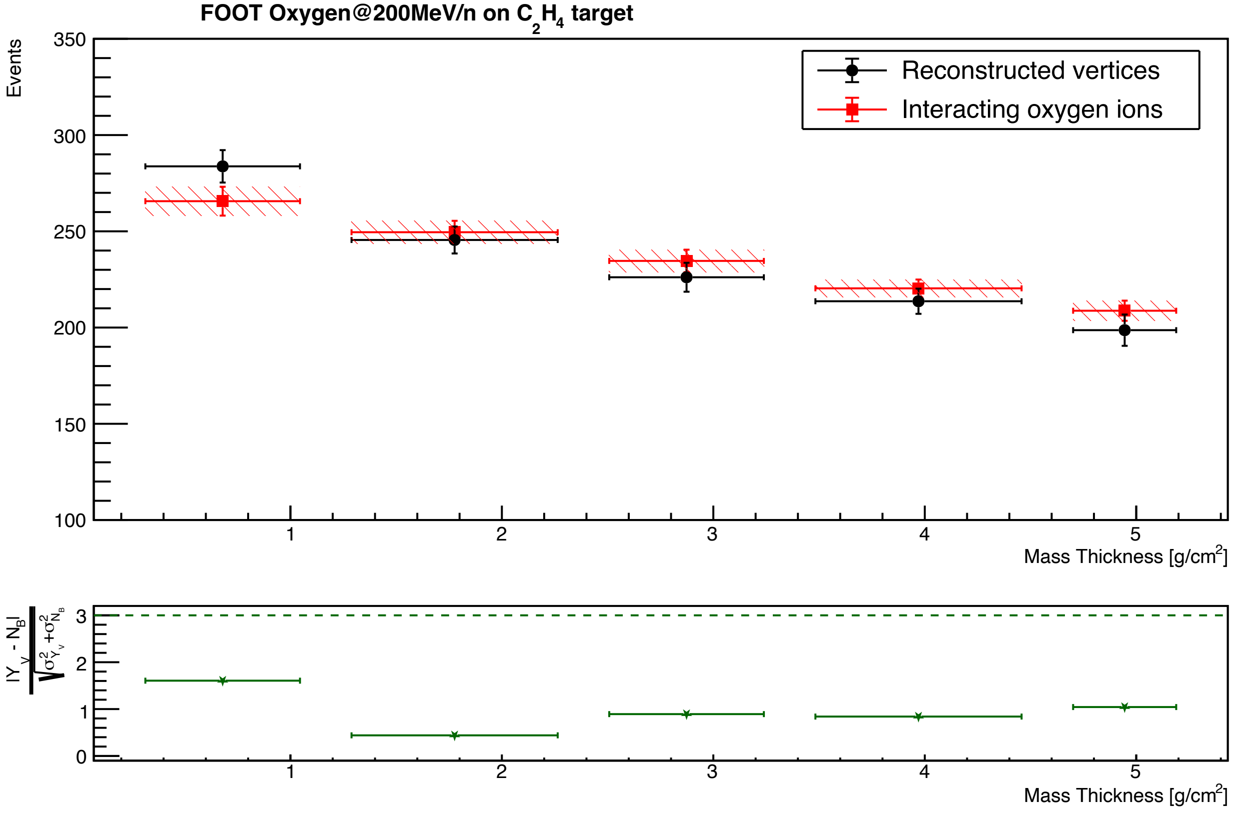


Systematic error evaluation

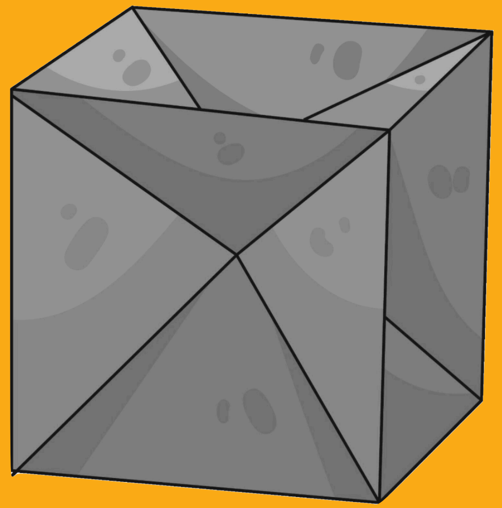
- Comparison of the number of disappearing beam oxygens and the number of reconstructed vertices(*)
- Double check for cross section with **completely independent methods** (both in terms of hardware and software)
- Normalized difference between the two measurements is always below 3, indicating that the systematic uncertainty is smaller than the statistical one and can thus be considered negligible

$$\frac{|Y_V - N_B|}{\sqrt{\sigma^2_{Y_V} + \sigma^2_{N_B}}}$$





* vertices in the nuclear emulsion film considered in this sample



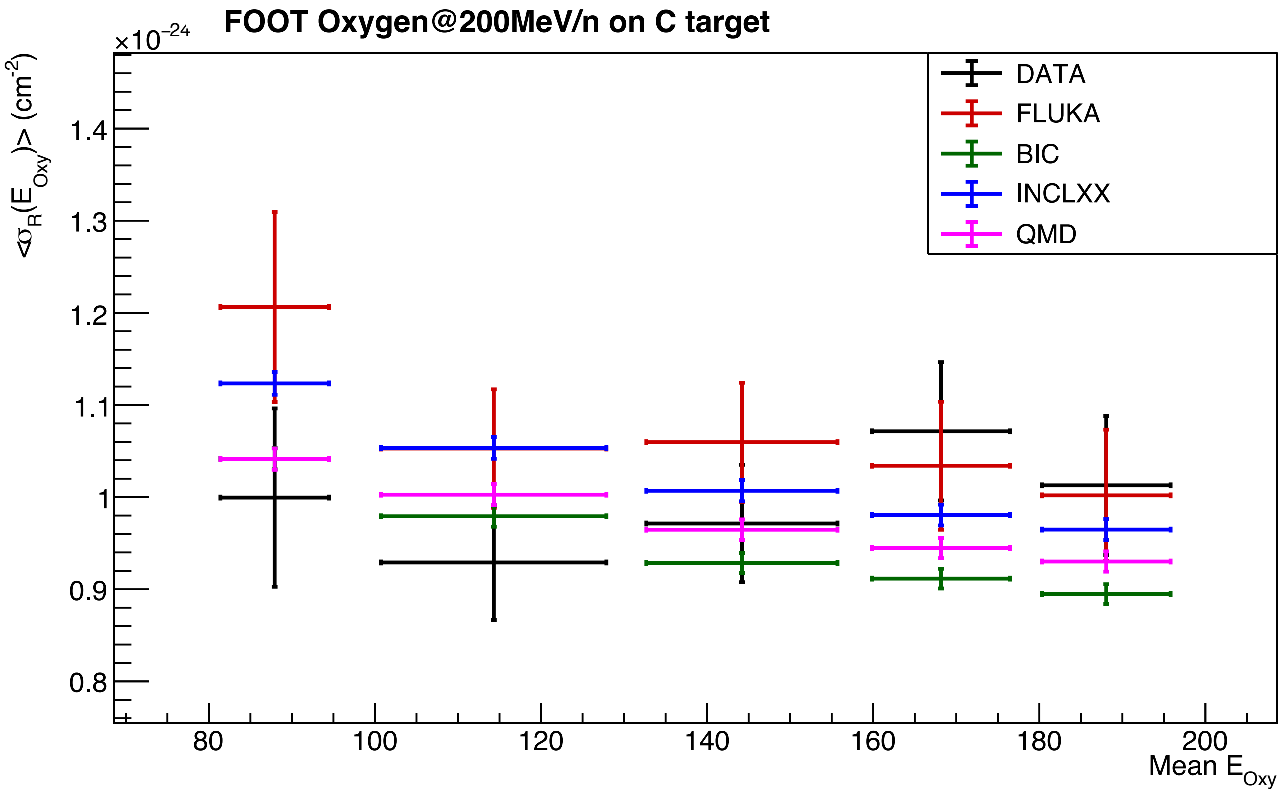
Results and discussion

What’s new:

- Comparison with Geant4

Total reaction cross section on C

$Y = <\#\text{ of vertices}>$



- FLUKA: 10^5 events (full detector)
- GEANT: 10^6 events (1mm target)

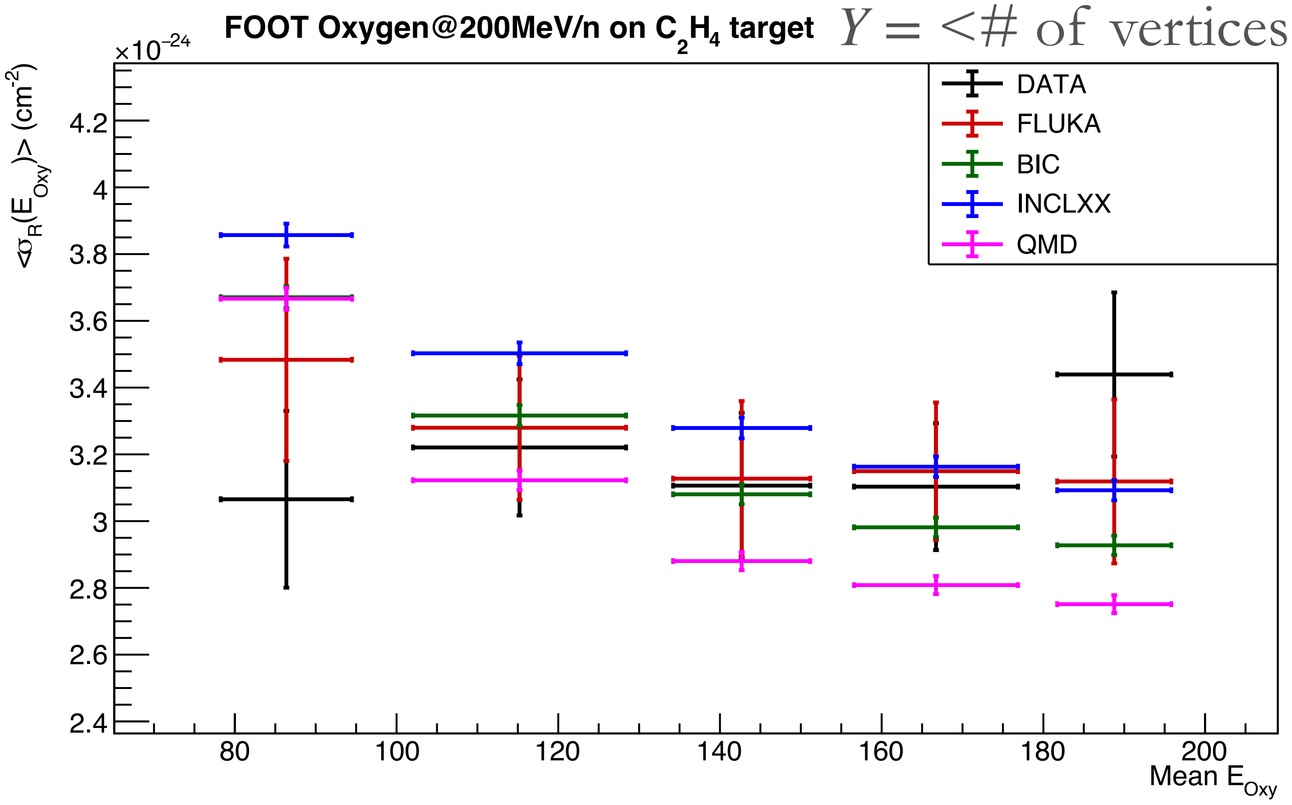
TABLE II. Measured total reaction cross sections on C, C_2H_4 and H across different energy intervals.

Beam Ekin (MeV/n)	σ_R on C $(cm^{-2} \cdot 10^{-24})$	σ_R on C_2H_4 $(cm^{-2} \cdot 10^{-24})$	σ_R on H $(cm^{-2} \cdot 10^{-24})$
188 ± 7	1.00 ± 0.07	3.1 ± 0.2	0.3 ± 0.1
167 ± 10	1.10 ± 0.08	3.2 ± 0.2	0.3 ± 0.1
143 ± 11	1.05 ± 0.07	3.1 ± 0.2	0.3 ± 0.1
115 ± 14	1.00 ± 0.07	3.3 ± 0.2	0.3 ± 0.1
87 ± 8	1.1 ± 0.1	3.2 ± 0.3	0.3 ± 0.1

TABLE IV. Available results from other experiments for σ_R on C.

Ref.	Beam Ekin (MeV/n)	Angular Acceptance	σ_R on C $(cm^{-2} \cdot 10^{-24})$
Yamaguchi [31]	288	10°	0.852±0.017
Zeitlin [32]	290	5.7°	0.863±0.020
Zeitlin [32]	400	5.7°	0.842±0.022

Total reaction cross section on C_2H_4



$Y = <\#\text{ of vertices}>$

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115 ± 14	1.00 ± 0.07	3.3 ± 0.2	0.3 ± 0.1
87 ± 8	1.1 ± 0.1	3.2 ± 0.3	0.3 ± 0.1

- FLUKA: 10^5 events (full detector)
- GEANT: 10^6 events (2mm target)

TABLE V. Available results from other experiments for σ_R on CH_2.

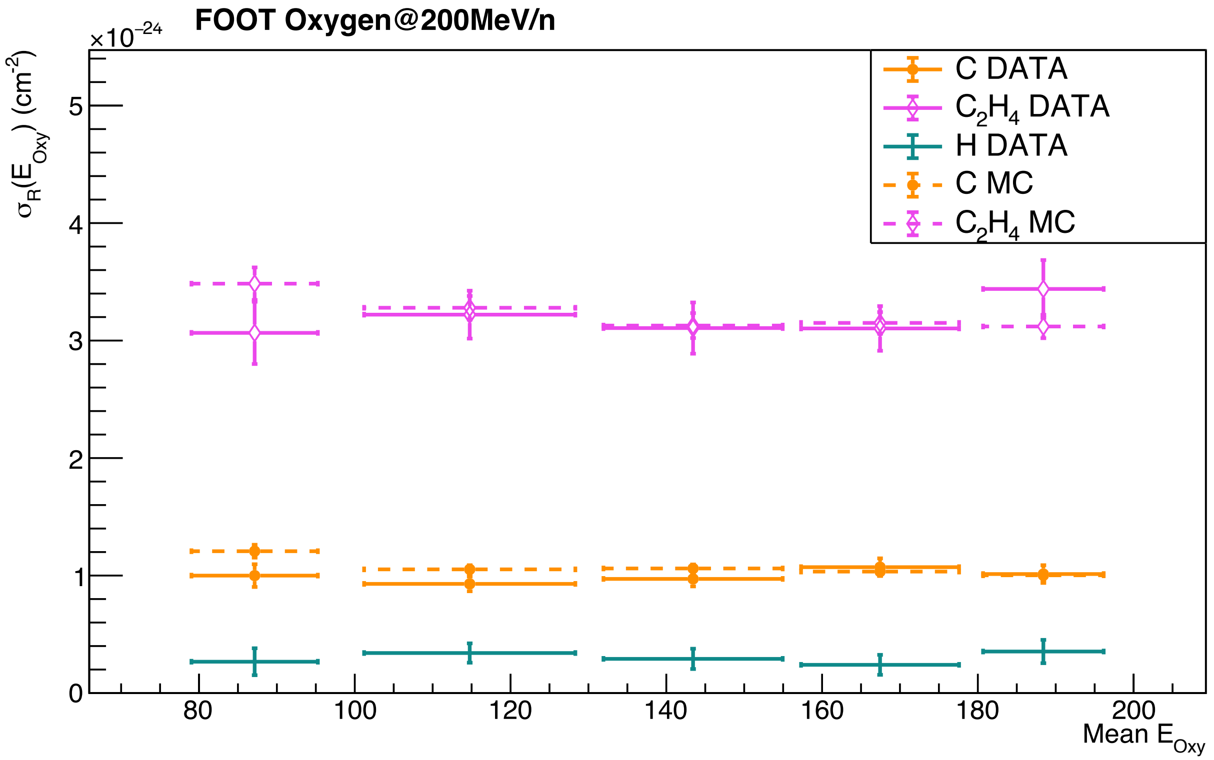
Ref.	Beam Ekin (MeV/n)	Angular Acceptance	σ_R on CH_2 ($cm^{-2} \cdot 10^{-24}$)
Webber [33]	441	7.7°	1.260±0.013
Webber [33]	591	7.7°	1.316±0.013
Webber [33]	669	7.7°	1.328±0.013

Note that the cross section on C_2H_4 is twice that on CH_2

Integrated cross section H

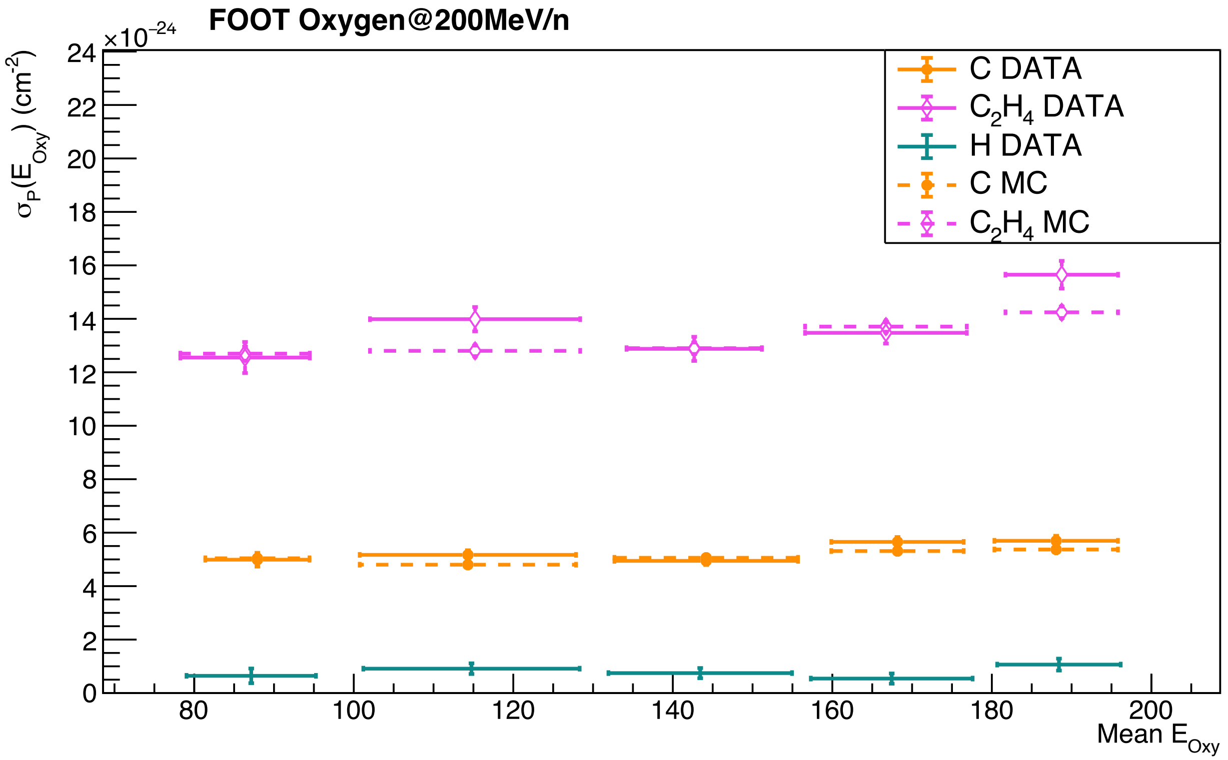
Total reaction cross section

$$Y_i = \text{<\# of vertices>}$$



Total production cross section

$$Y_i = \text{<\# of fragments>}$$



Conclusions

In the present work, fragments are detected up to polar angles corresponding to $\tan\theta = 1$ (i.e. 45°), thus complementing existing data by covering a wider angular range and extending measurements to lower beam energies

To do list for the next days:

- Include Geant4 simulations in the paper
- Receive comments from EB
- Circulate to the Collaboration
- Send to PRC

THANK YOU!