Total Reaction Cross-Section Measurements in the S444 Commissioning Experiment

Lukas Ponnath

R3B Week - Catania
November 2022

Status of Cave-C in 2019

Total Reaction Cross-Section Measurement

Next Steps & Outlook

Supported by BMBF 05P21WOFN1 and 05P19WOFN1.

The results presented here are based on the experiment s444/s473, which was performed at the beam line/infrastructure Cave C at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the frame of FAIR Phase-0.

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2094 – 390783311.

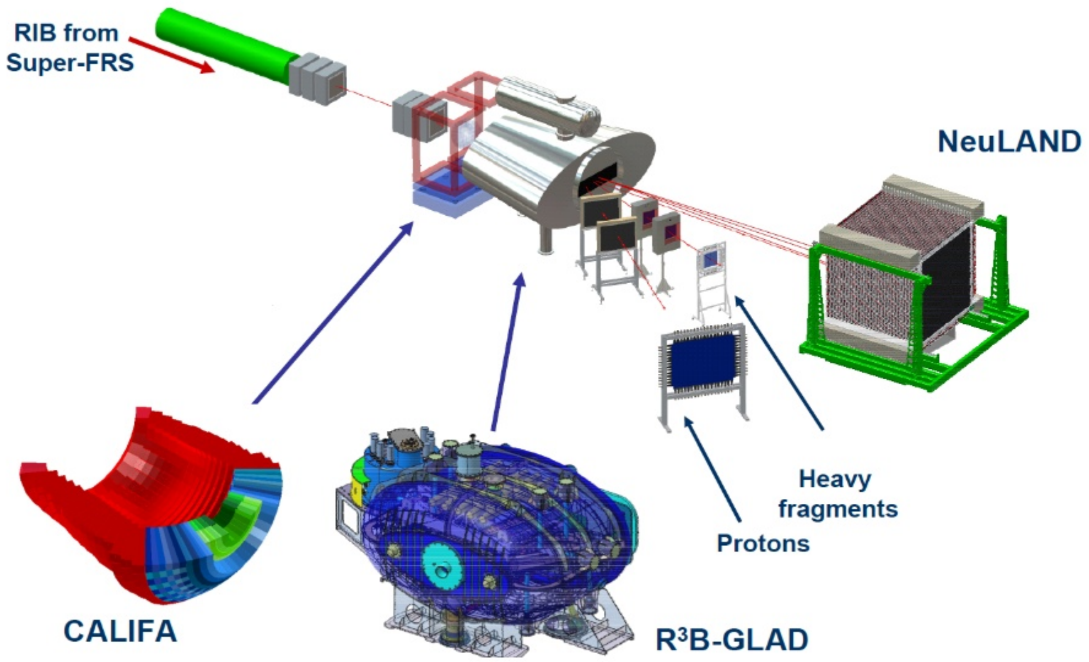
ORIGINS Excellence Cluster

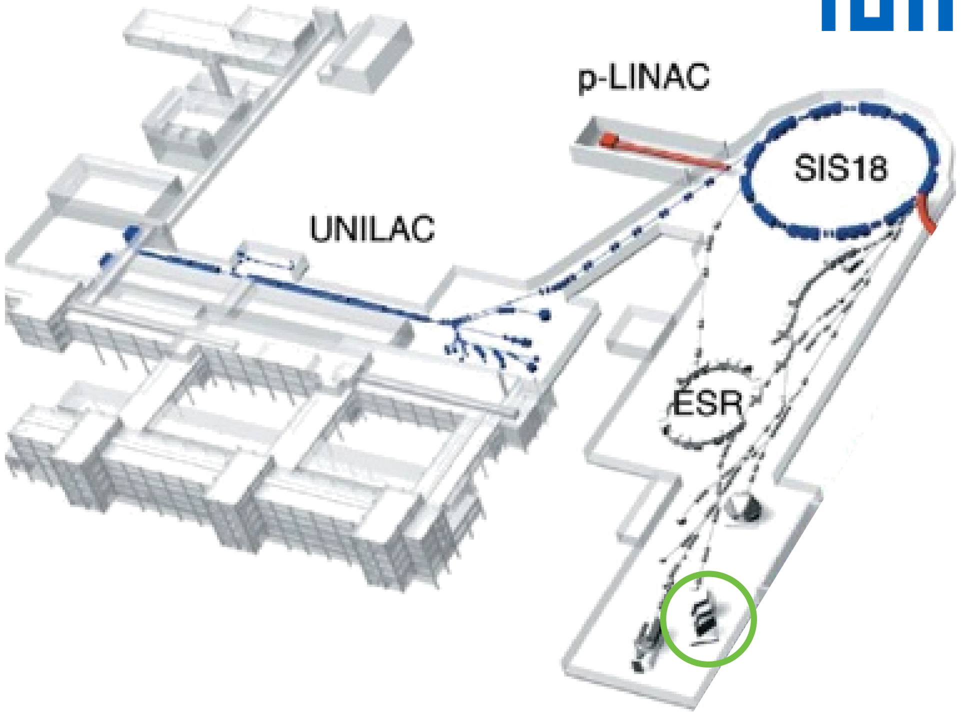
GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

GSI

FAIR Phase 0 Research Program

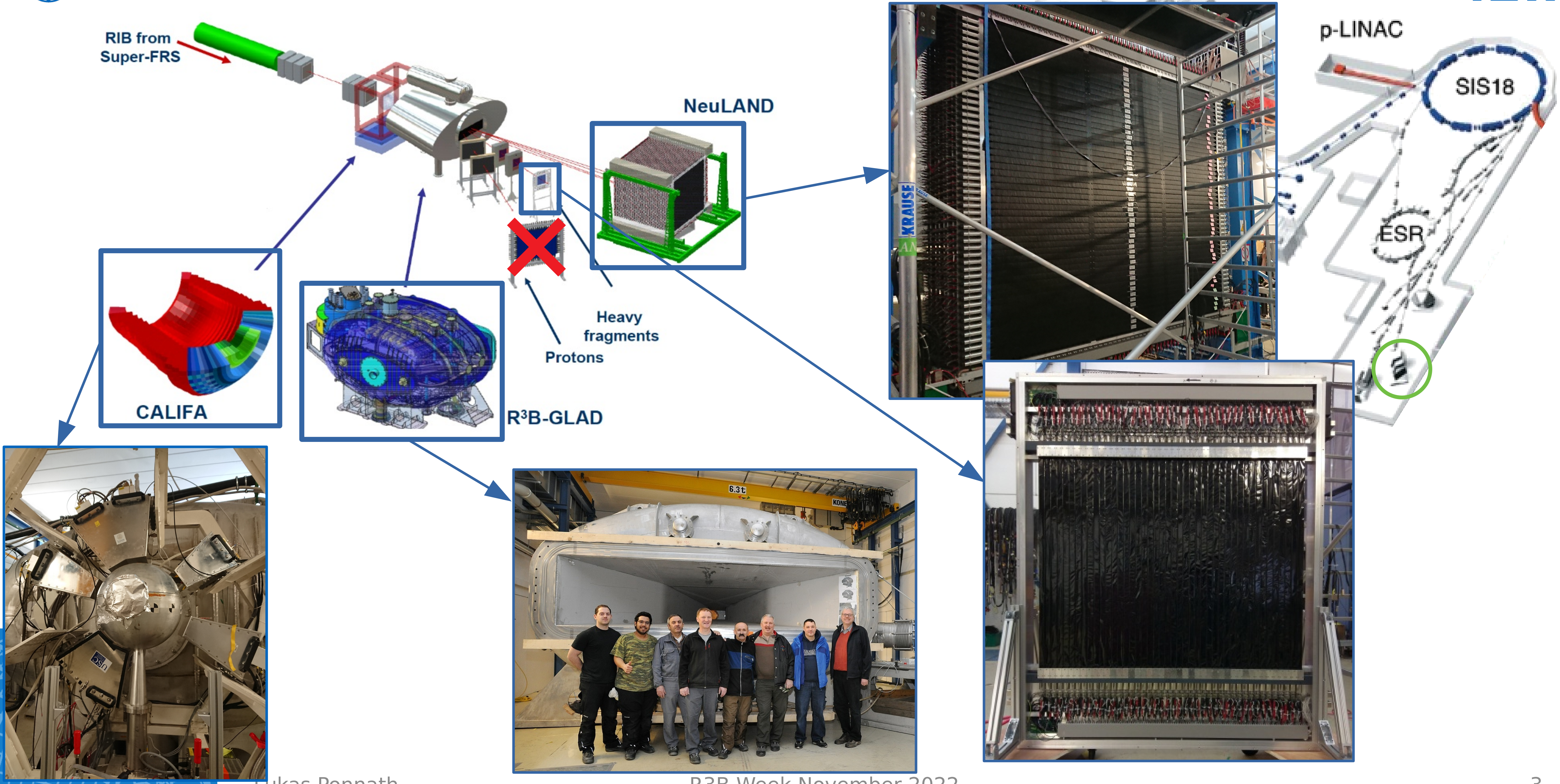
R^3B Detectors in Cave-C at GSI 2019





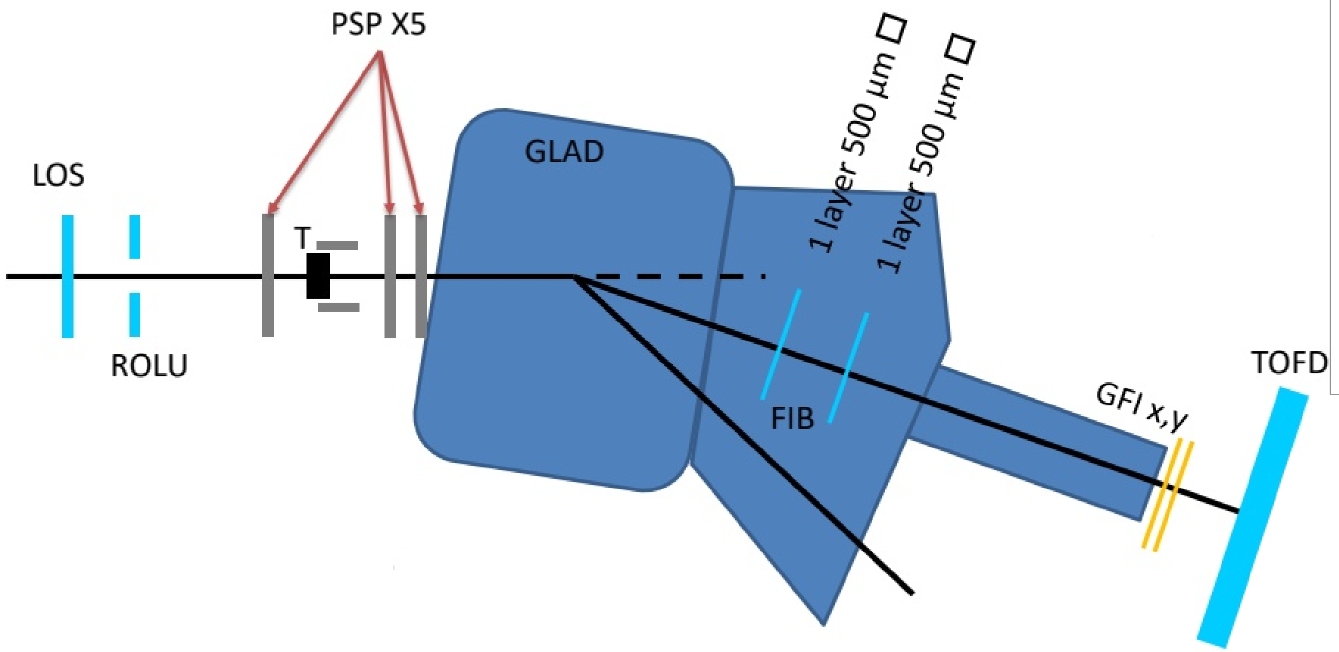
R^3B Detectors in Cave-C at GSI 2019

40% of NeuLAND



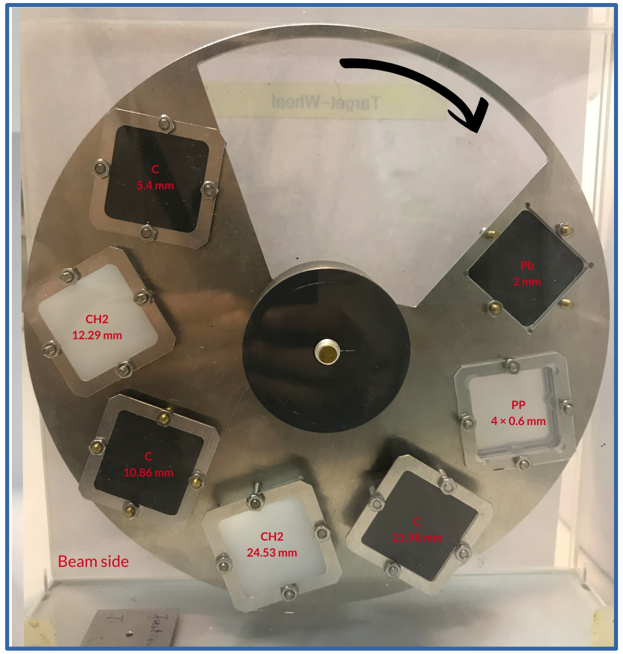
S444 Commissioning Experiment

First common operation of GLAD and R^3B detectors



- Beam: 400 – 1000 AMeV ^{12}C
- Targets: C, CH_2 (different thickness)

Benchmark Reaction: **$^{12}C(p,2p)^{11}B$**



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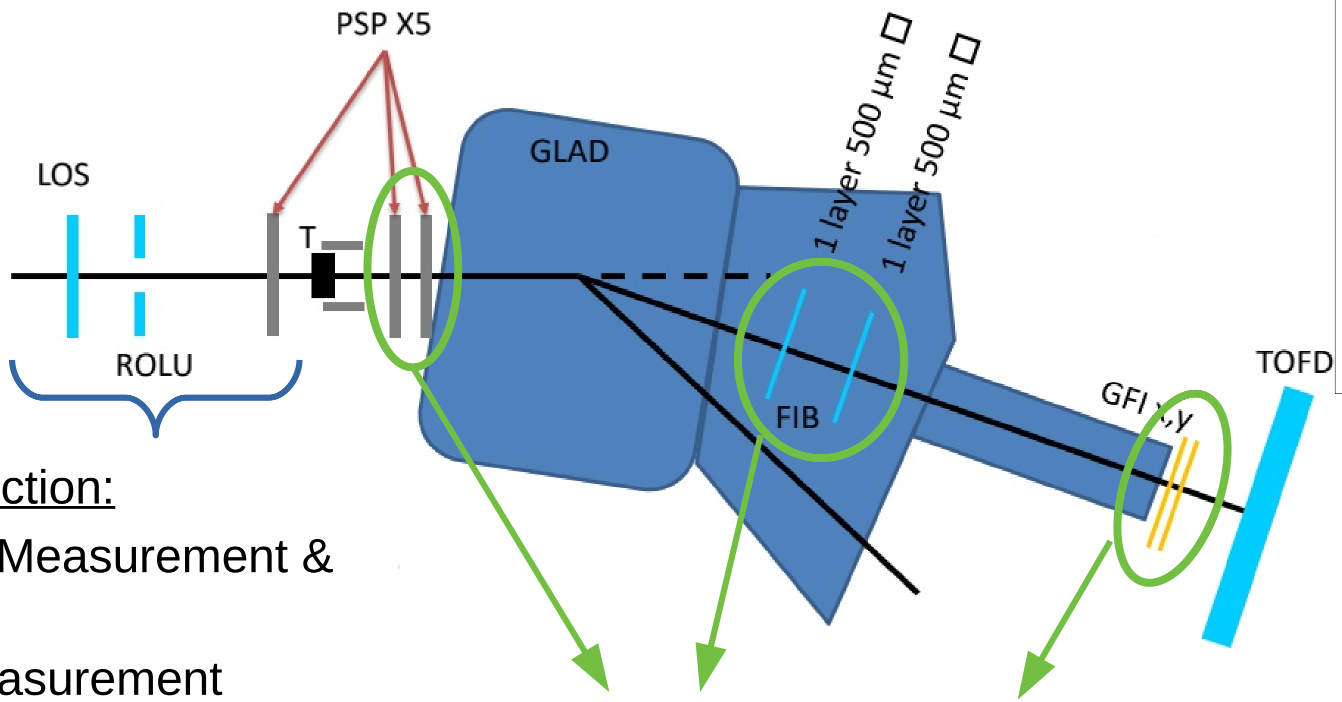

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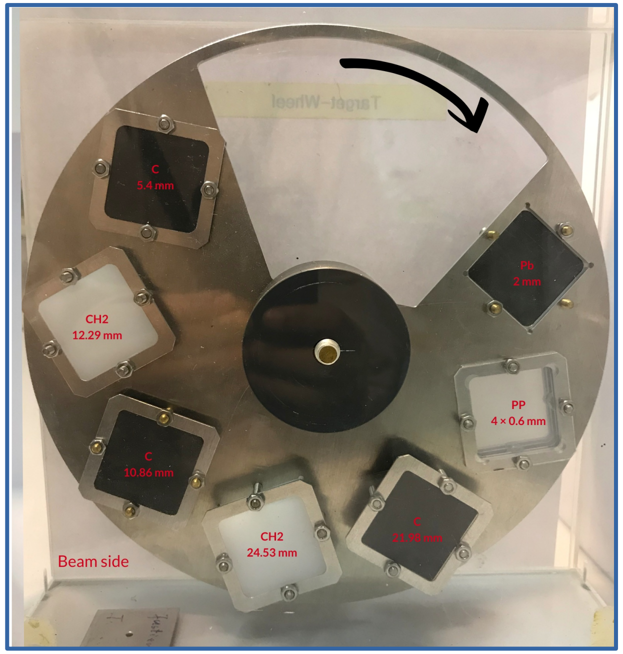


<u>Event-Selection:</u>

- Position Measurement & Veto
- Time Measurement
- Charge Identification

<u>Silicon- & Fiber-Tracking:</u>

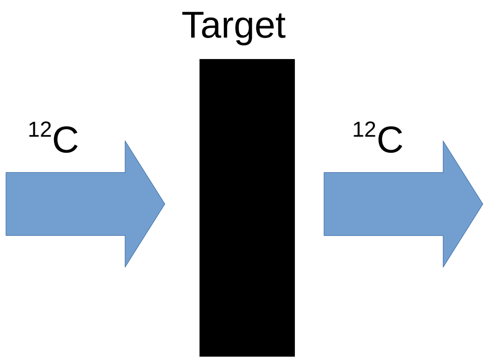
- Position Measurement
- Charge Identification after the target

Total Reaction Cross-Section

Precision Measurement:

Energy dependence of the total reaction cross-section of $^{12}C \rightarrow {}^{12}C$

(Tom Aumann)



Total reaction cross-section: $\sigma_R = \sigma_I + \sigma_{inel}$

Total interaction cross-section σ_I:

The projectile changes its identity.

At least one nucleon is removed.

Total inelastic cross-section σ_{inel}:

The projectile is excited to a bound state. No nucleon is removed.

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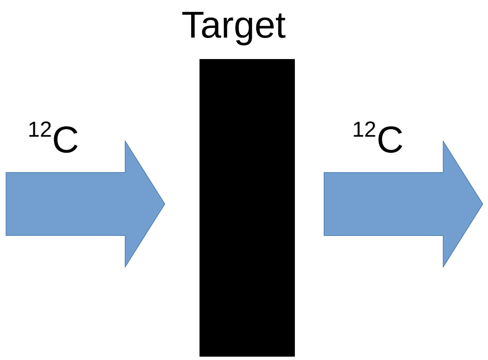

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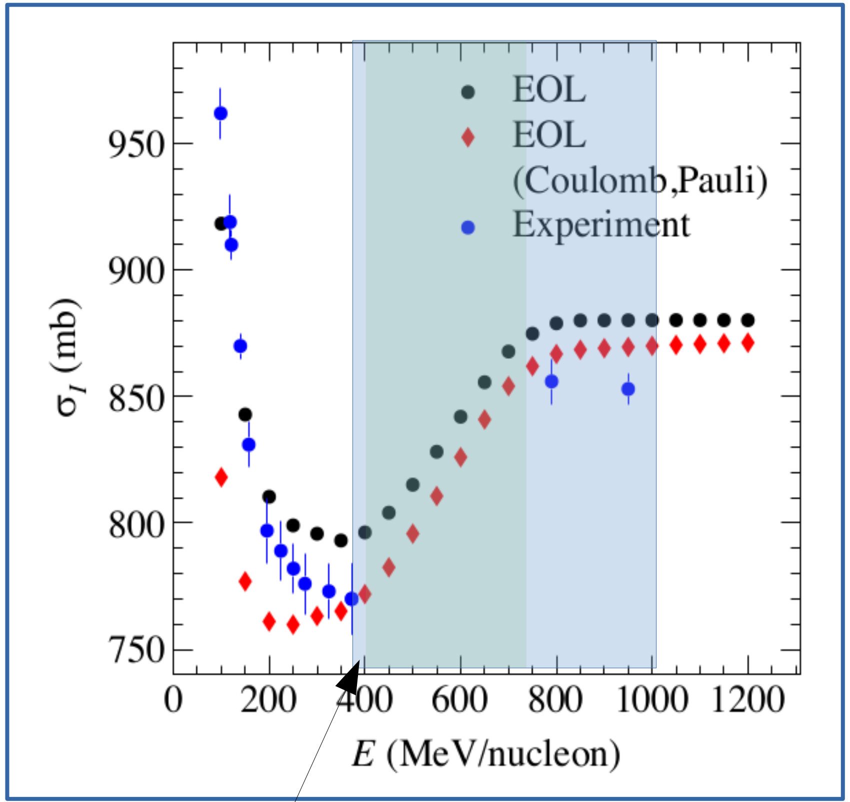


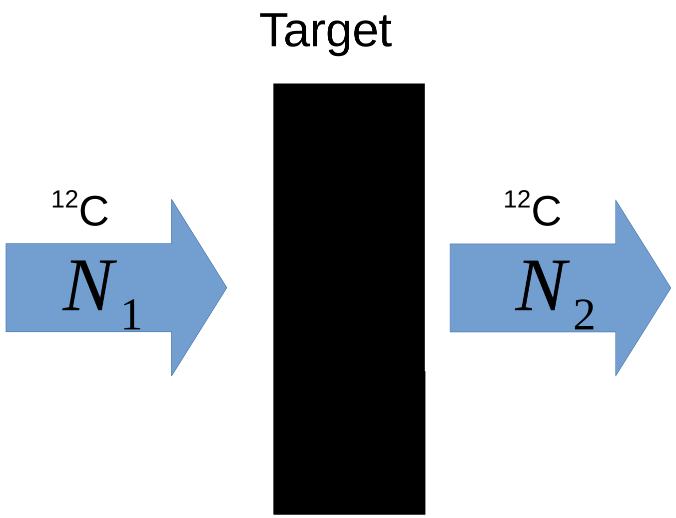
F. Schindler, PhD Thesis, TU Darmstadt (2017)

^{12}C Beam Energies in S444 Experiment:

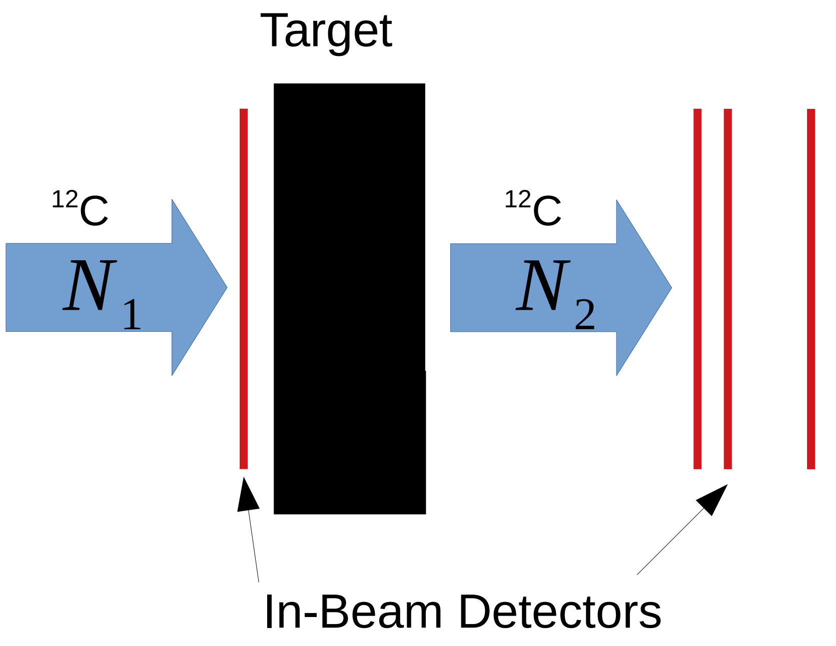
400, 550, 650, 800 & 1000 AMeV

Measurement Concept

Surviving-Probability: $$P_{surv.} = \frac{N_2}{N_1} = e^{-N_t \cdot \sigma_R}$$



Measurement Concept



Surviving-Probability: $P_{surv.} = \frac{N_2}{N_1} = e^{-N_t \cdot \sigma_R}$

Exclude reactions in Setup: $\frac{\overbrace{N_2^i / N_1^i}^{\text{Target-In}}}{\underbrace{N_2^o / N_1^o}_{\text{Target-Out}}} = e^{-N_t \cdot \sigma_R}$

Transmission method:

$$\sigma_R = -\frac{1}{N_t} \ln\left(\frac{N_2^i / N_1^i}{N_2^o / N_1^o}\right)$$

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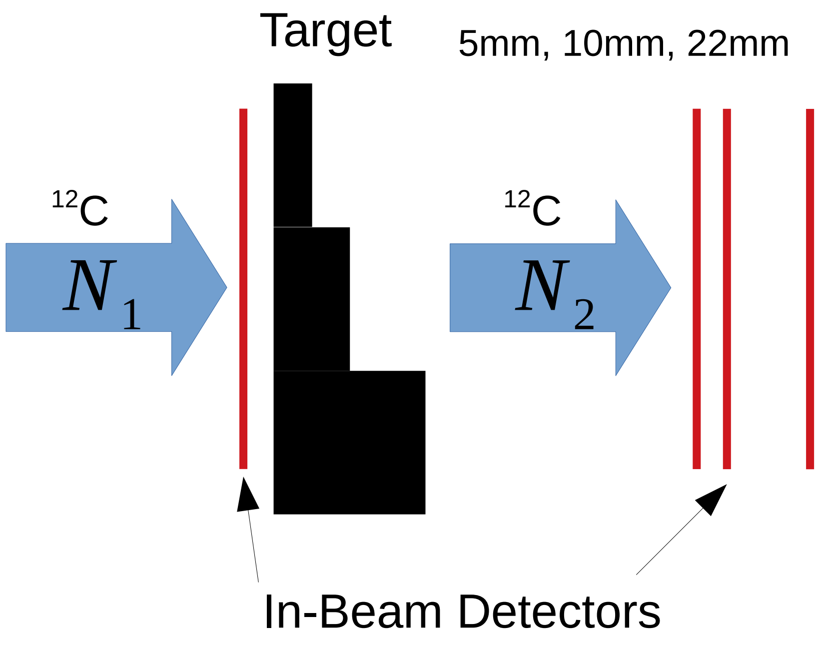
<u>Transmission method:</u>

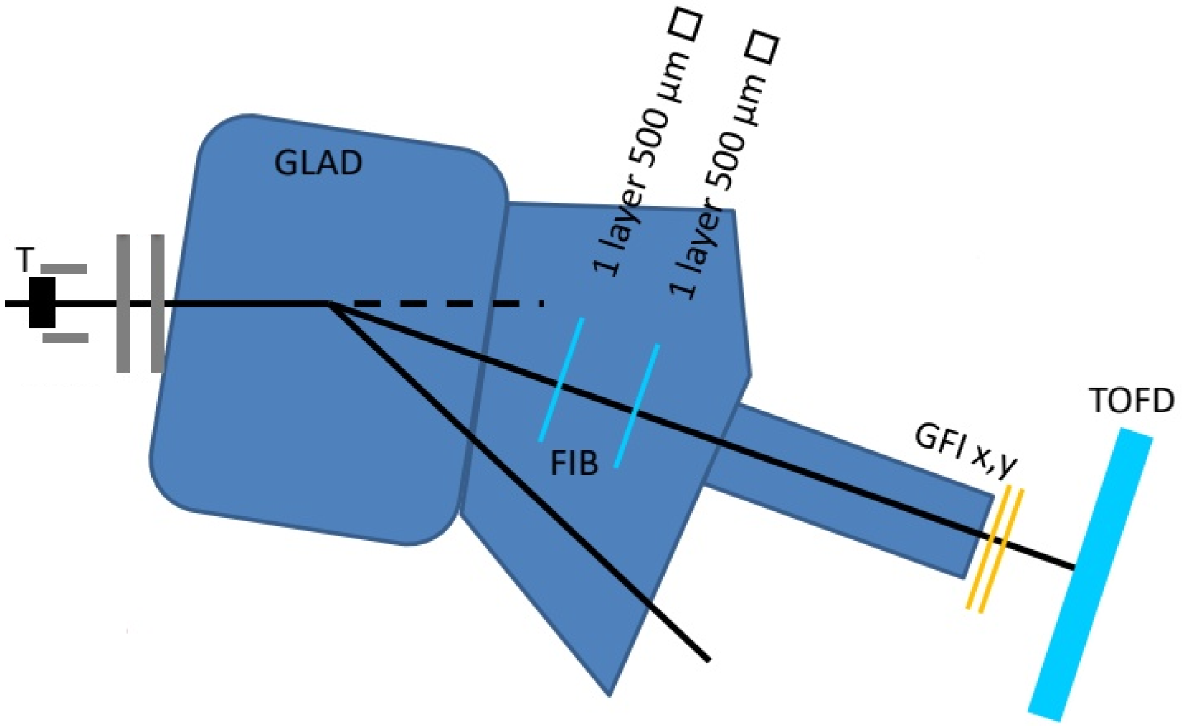
$$\sigma_R = -\frac{1}{N_t} \ln\left(\frac{N_2^i / N_1^i}{N_2^o / N_1^o}\right)$$

Challenge: Time- & Rate-depended Efficiency & geometrical Acceptance of Detectors



- → N_t is a target specific constant (density, Thickness)
- → N_1, number of incident ^{12}C nuclei (stable beam, Event-Selection)
- → N_2, number of non-reacting ^{12}C nuclei, identified after the target (that's our big challenge)

Number of non-reacting Nuclei



Strategy: minimize systematic uncertainties → minimize Number of detectors

1. Count the number of all Carbon (Q=6) isotopes with TOFD $N_{Q=6}$

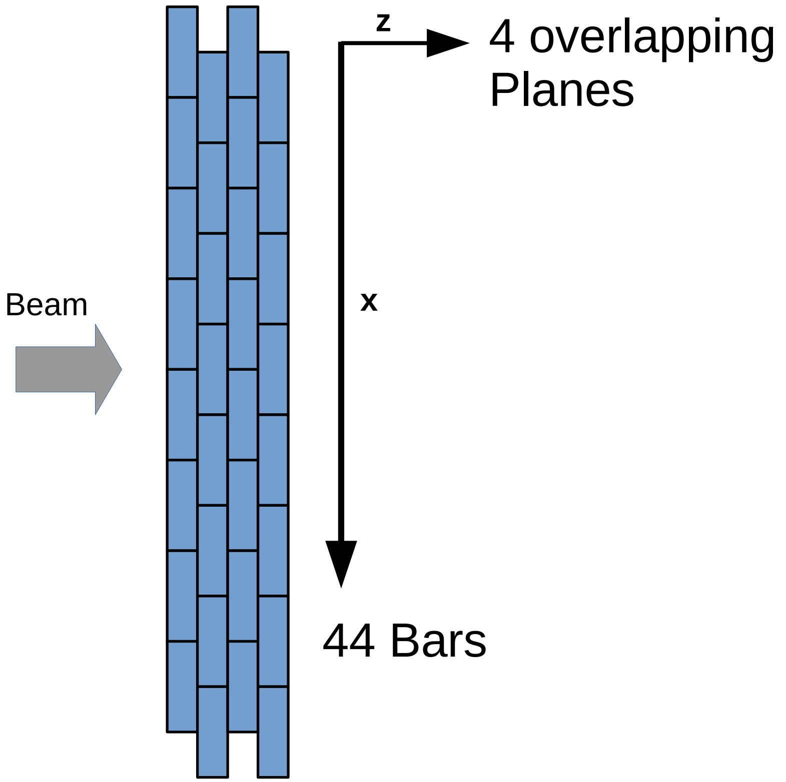
2. Define Correction factors:

   2a. Ratio of ^{12}C to all identified Carbon isotopes $R\left(^{12}C\right)$

   2b. Correction of variable geometrical acceptance A

Non-reacting ^{12}C nuclei: $$N_2^{i/o} = \frac{N_{Q=6}^{i/o} \cdot R^{i/o}\left(^{12}C\right)}{\mathrm{A}^{i/o}}$$

Carbon Identification



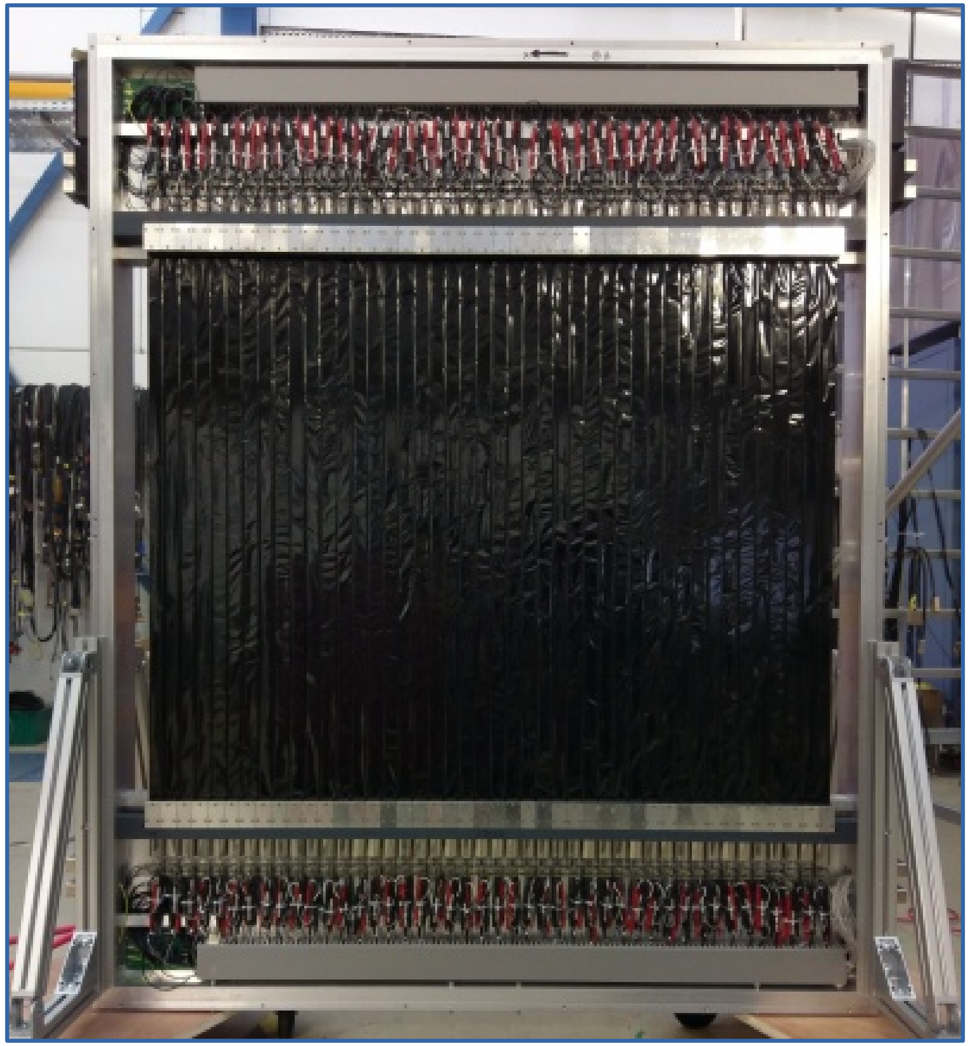
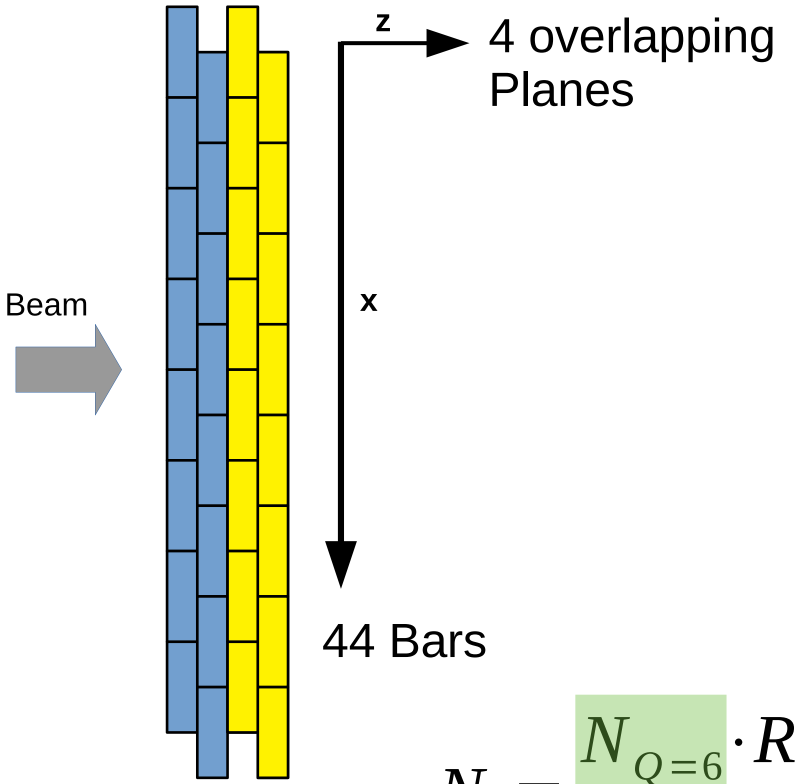
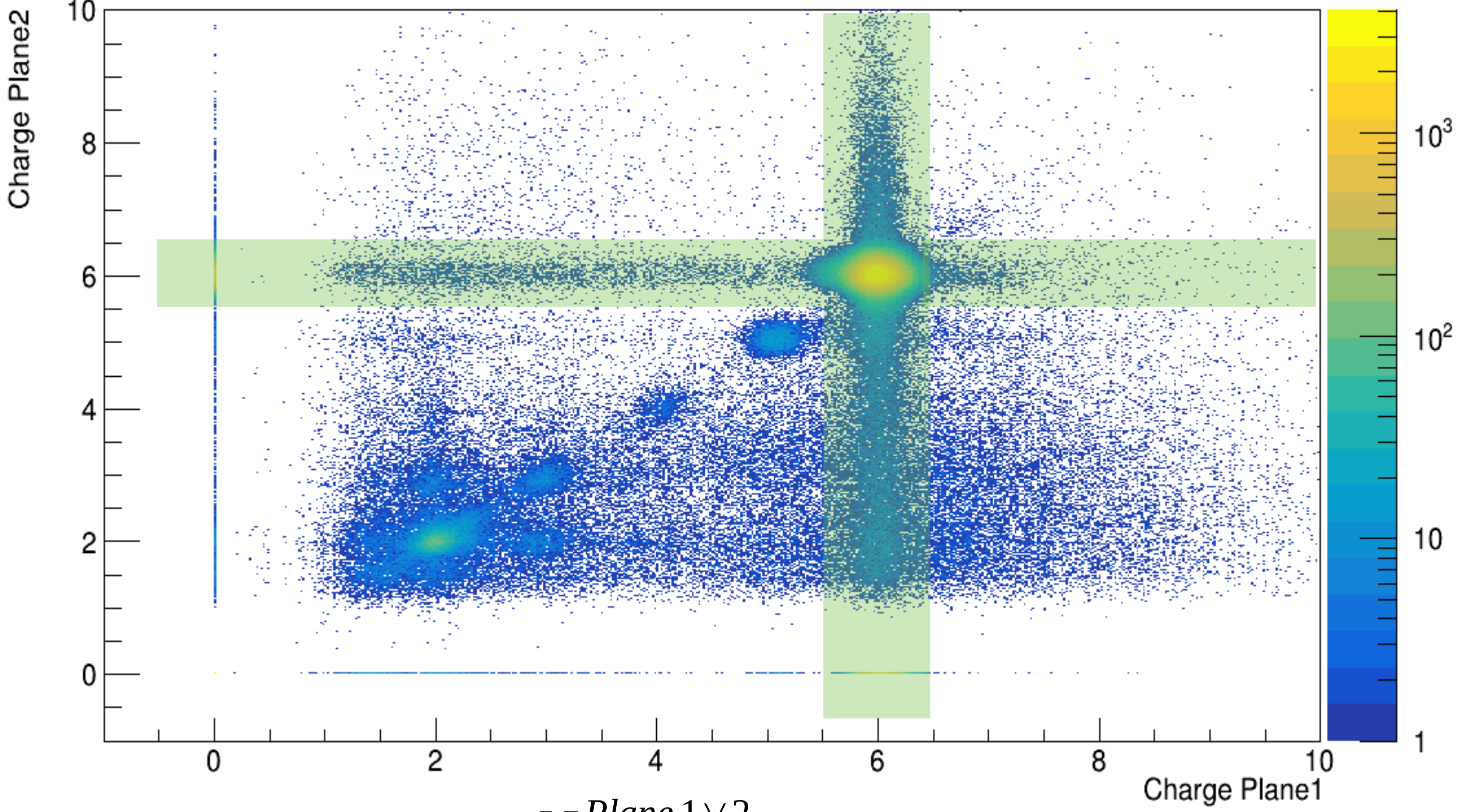


Photo by Michael Heil et al

Carbon Identification



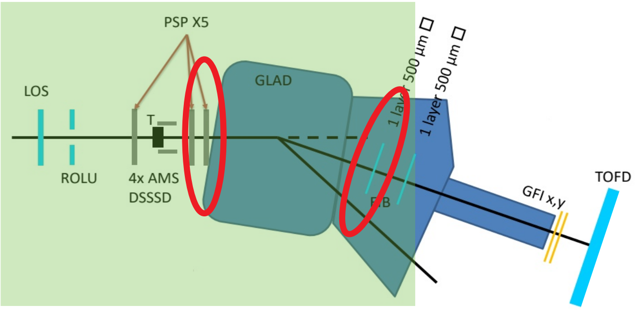
$N_{Q=6}$ = Plane1 or Plane2 saw a particle with Q = 6. +/- 0.5 (>99.9993 %)

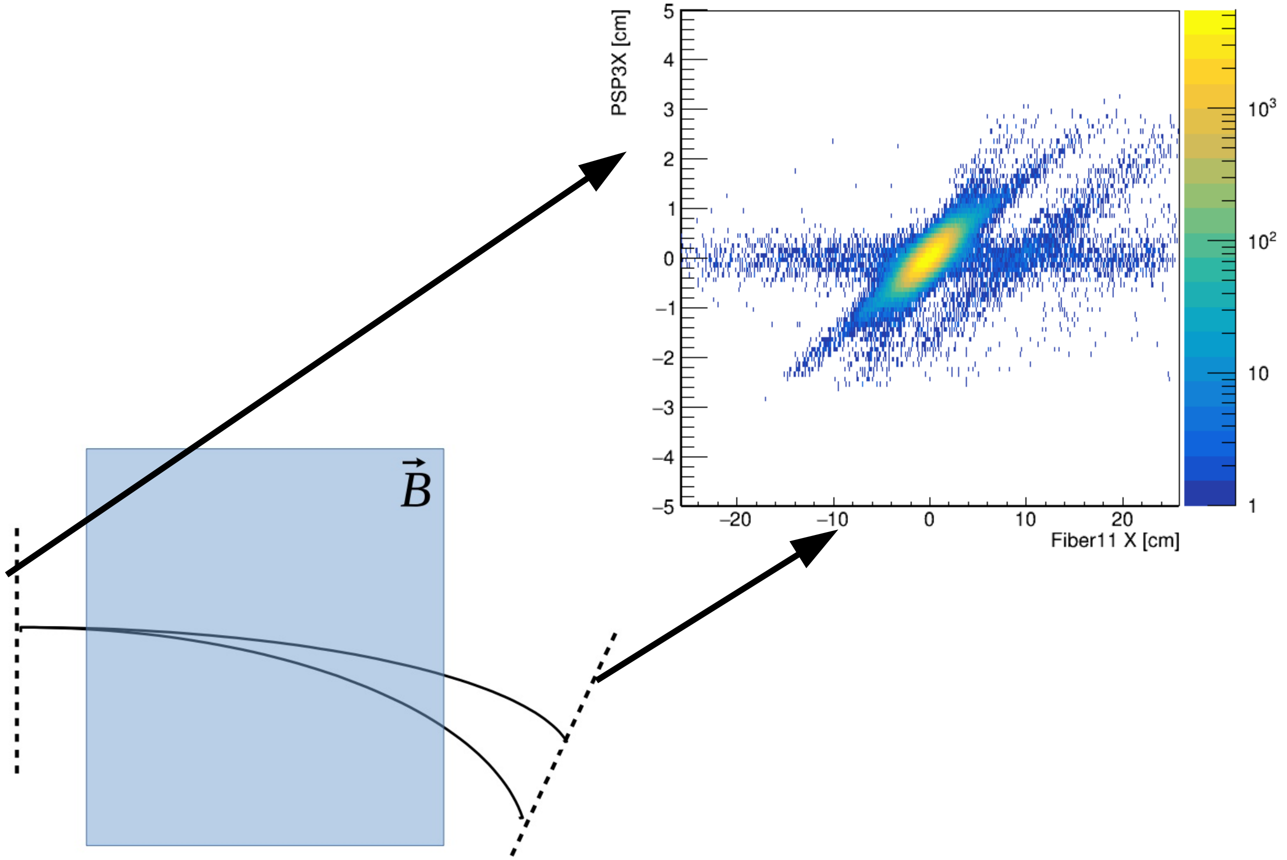


$$N_2 = \frac{N_{Q=6} \cdot R(^{12}C)}{A}$$

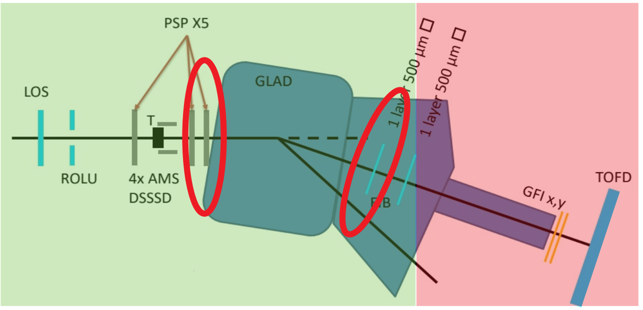
Check efficiency of Carbon identification: $\varepsilon = \frac{N_{Q=6}^{Plane\,1 \vee 2}}{N_{Q=6}^{Plane\,3 \wedge 4}} = 0.999916(17)\%$

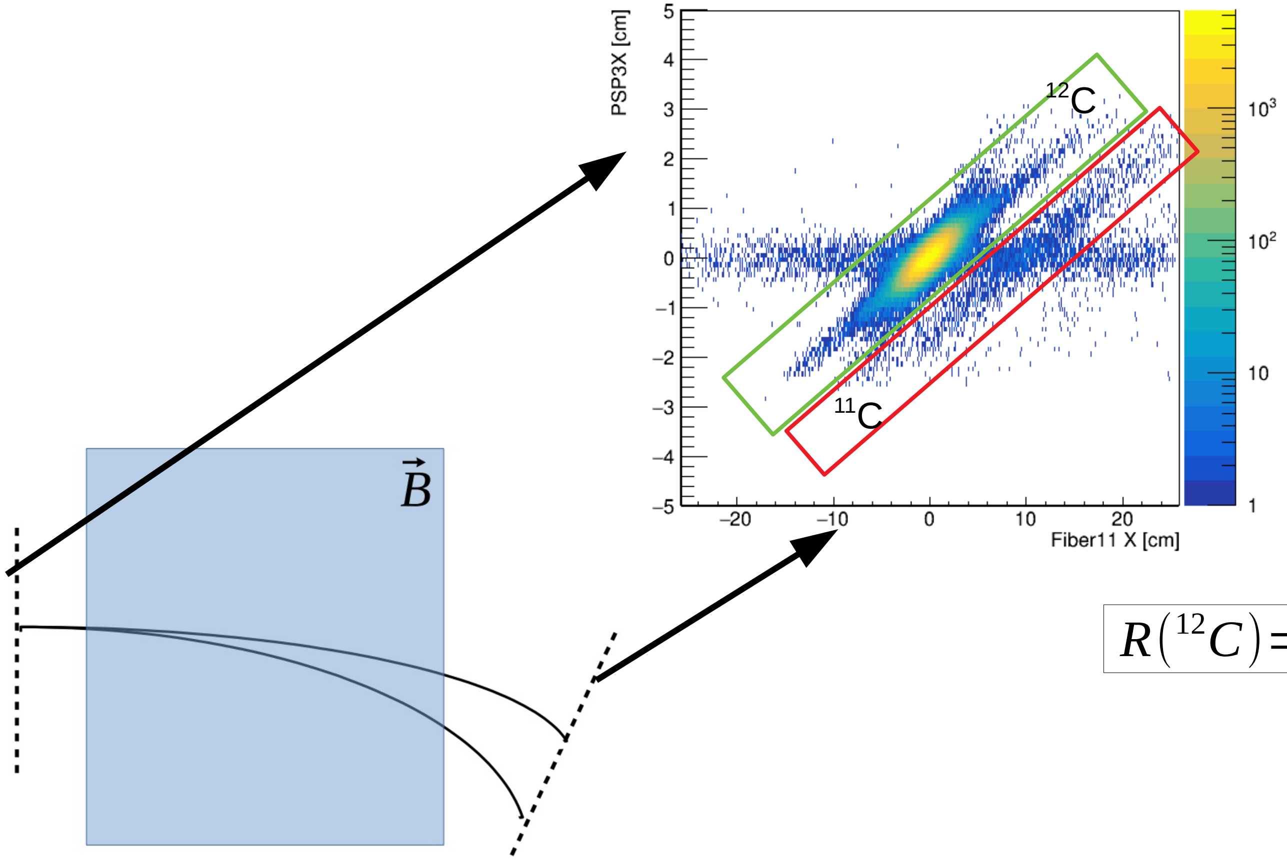
Isotope-Correction



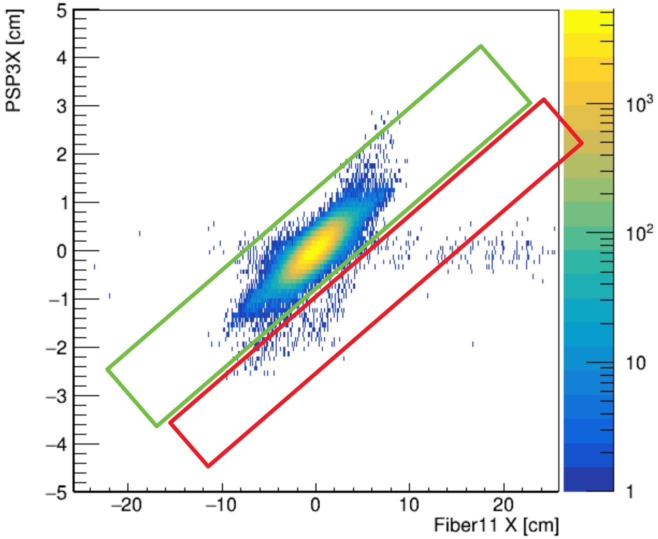


Isotope-Correction





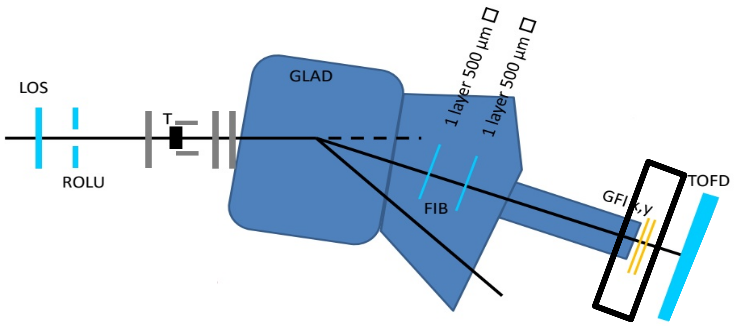
TOFD Q=6



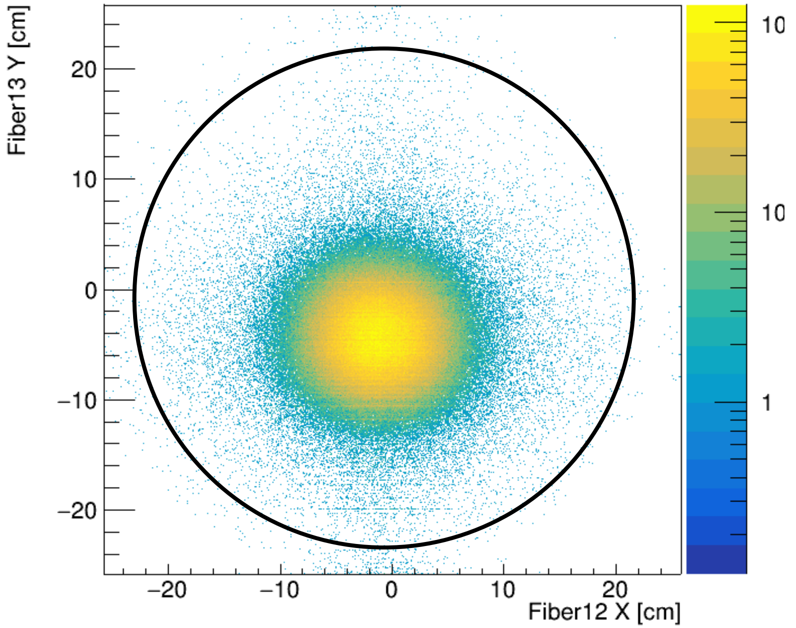
$$R\left(^{12}C\right)=0.99950\left(5\right)\%$$

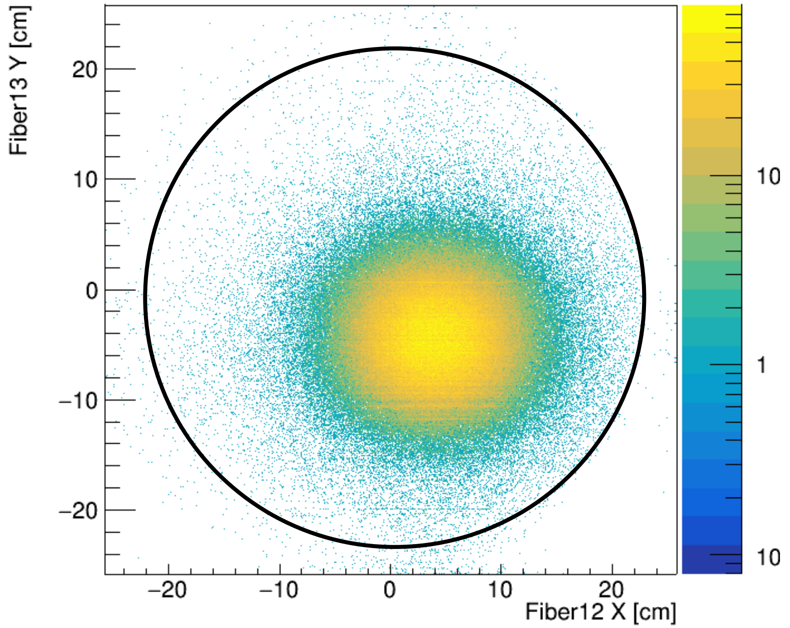
$$N_2=\frac{N_{Q=6}\cdot R\left(^{12}C\right)}{A}$$

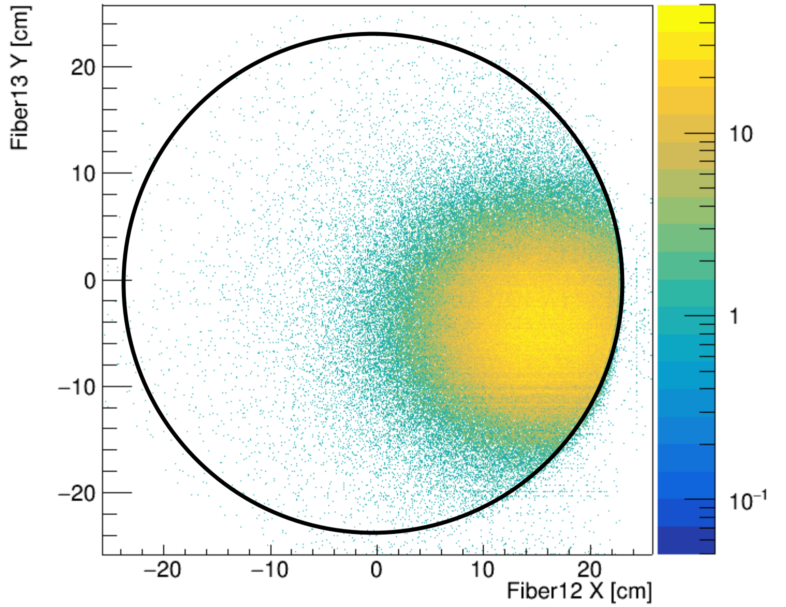
Acceptance-Correction



Beam-Energy 400 AMeV





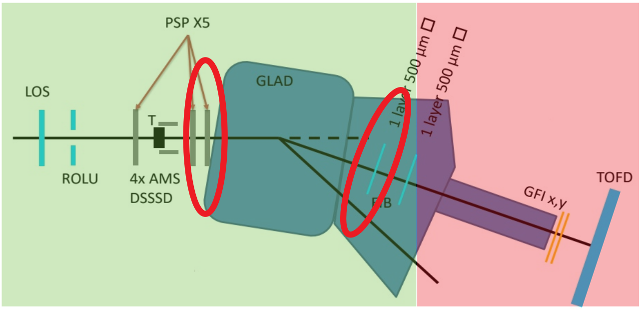


Target Thickness: 5.451 mm | 10.793 mm | 21.928 mm

Beam-Energy 400 AMeV

Loss due to geometrical acceptance

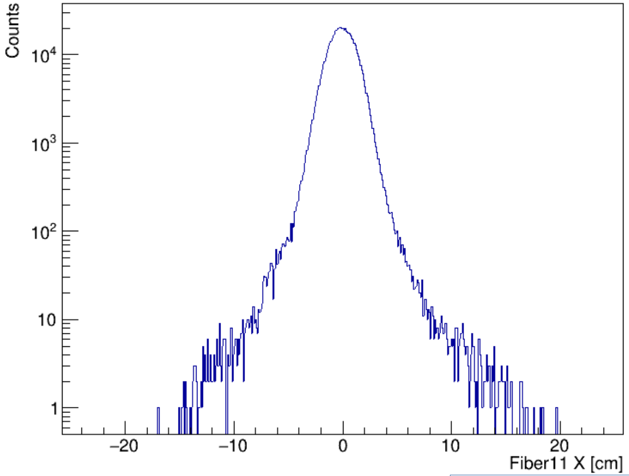
Acceptance-Correction



$$A = \frac{\int_{-25.8\,cm}^{25.8\,cm} g(x)}{\int_{-25.8\,cm}^{25.8\,cm} S \cdot f(x)}$$

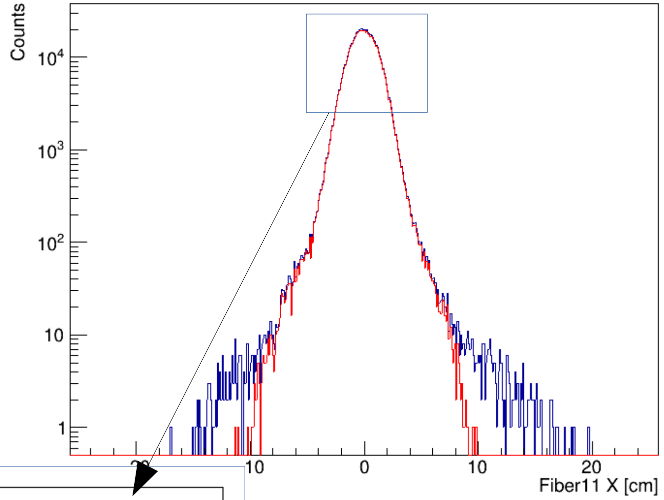
Scaling-Factor

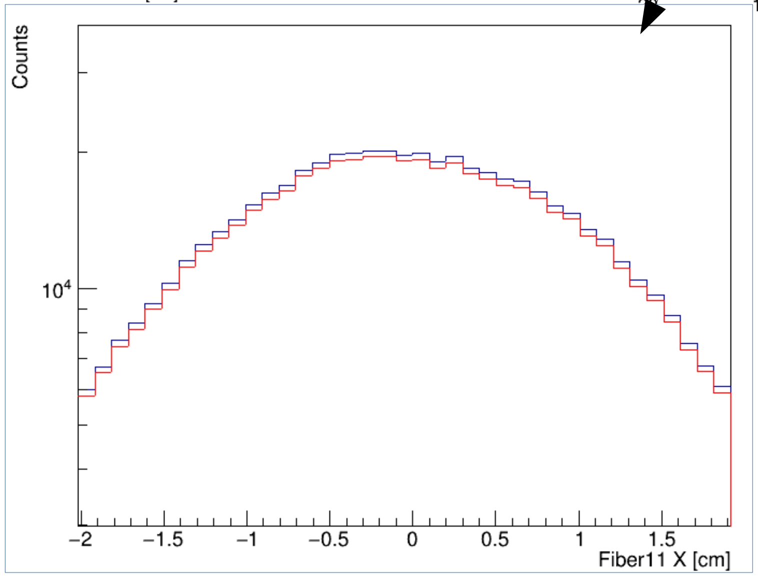
Position-Distribution of ^{12}C f(x)



TOFD Q=6

Position-Distribution of ^{12}C with TOFD g(x)





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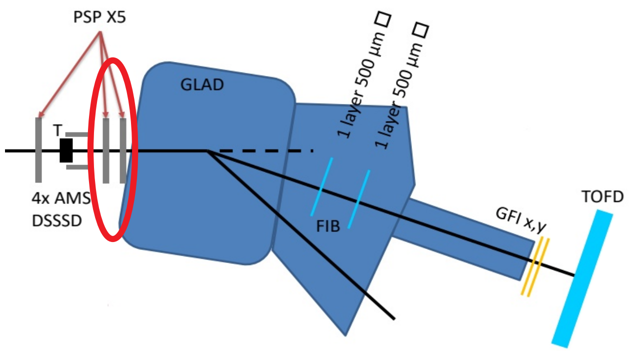
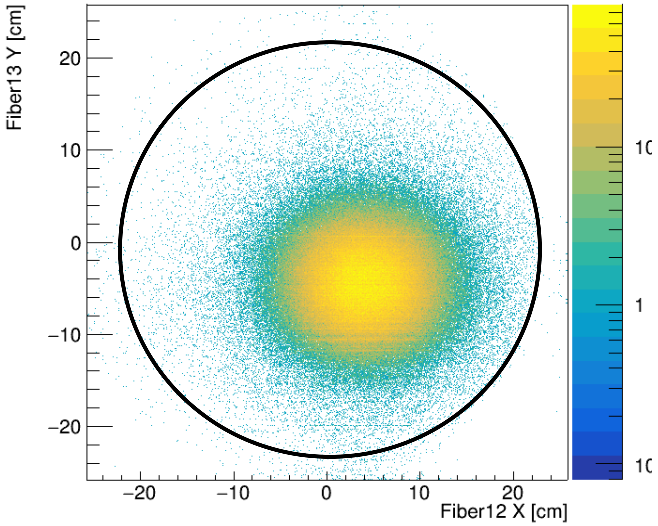
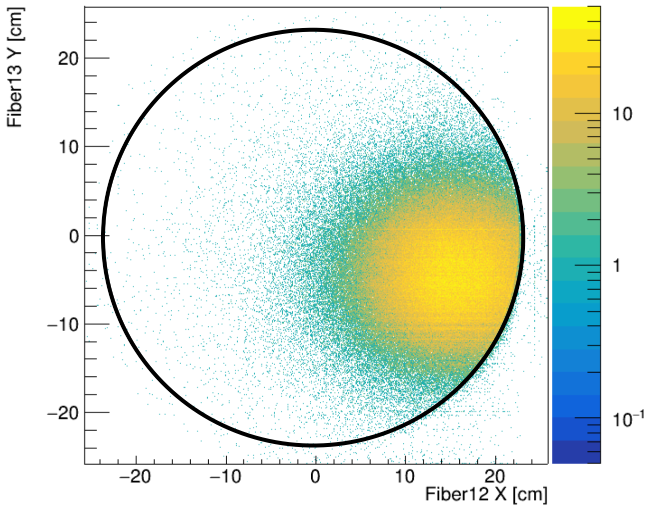


The Scaling-Factor represents reactions within the setup material –
not the limited geometrical acceptance!

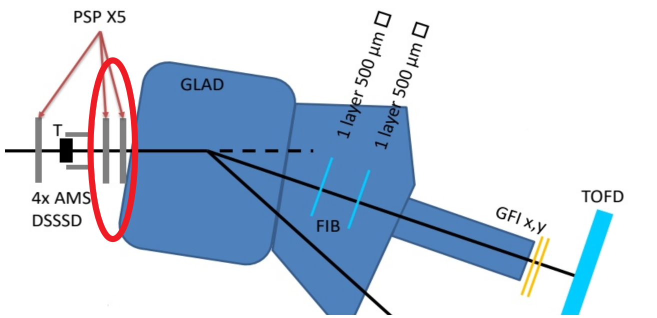


10.793 mm



21.928 mm

Scaling-Factor



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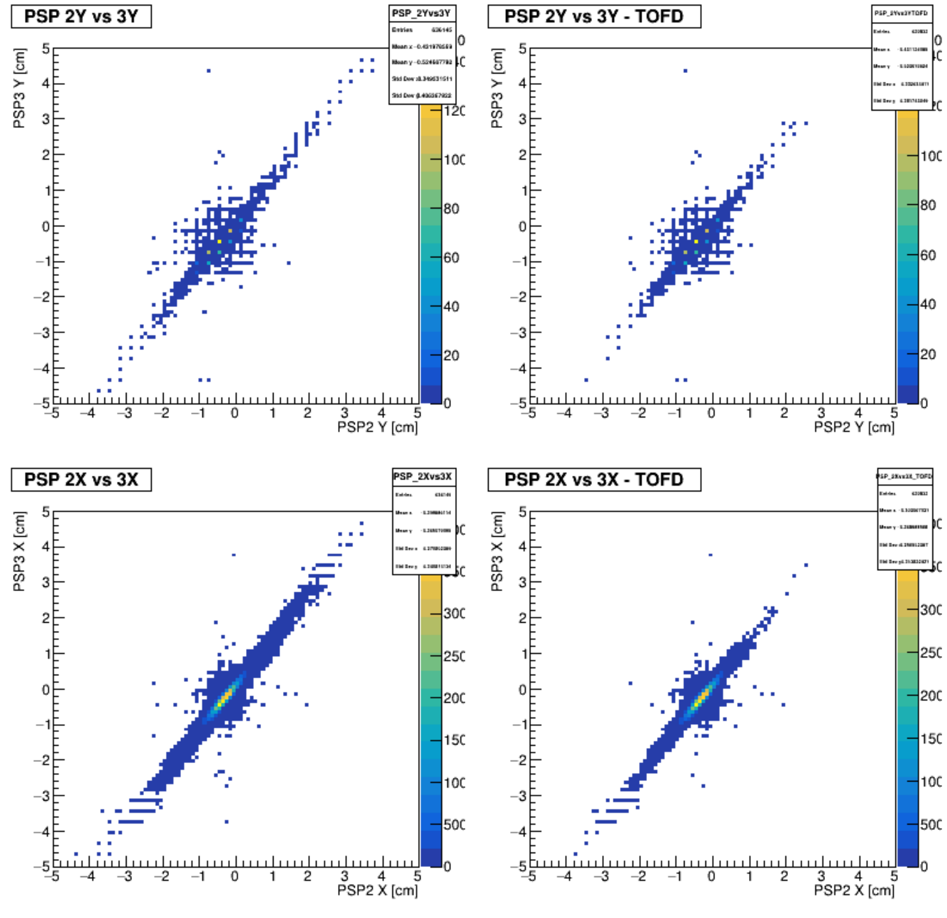
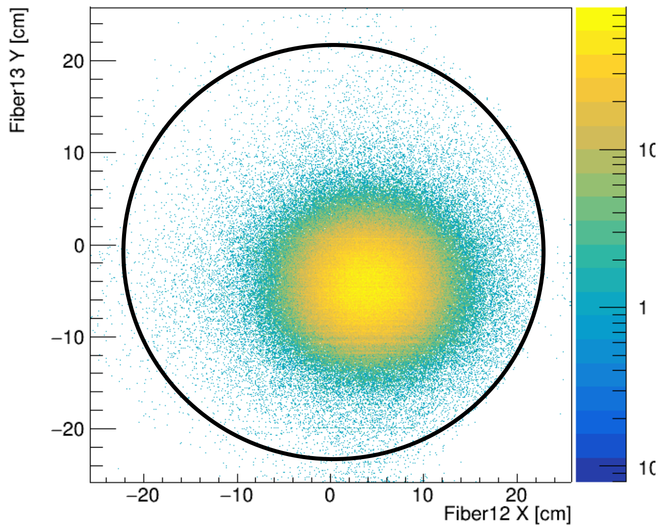
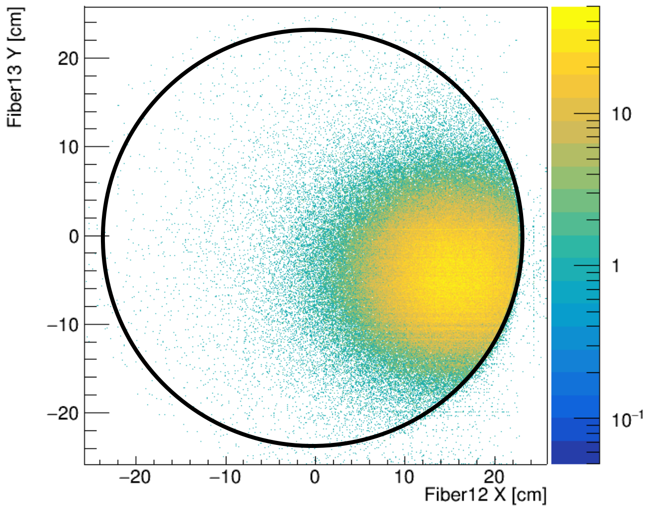
→ We need a subset of the same data-set for the Scaling-Factor:





10.793 mm



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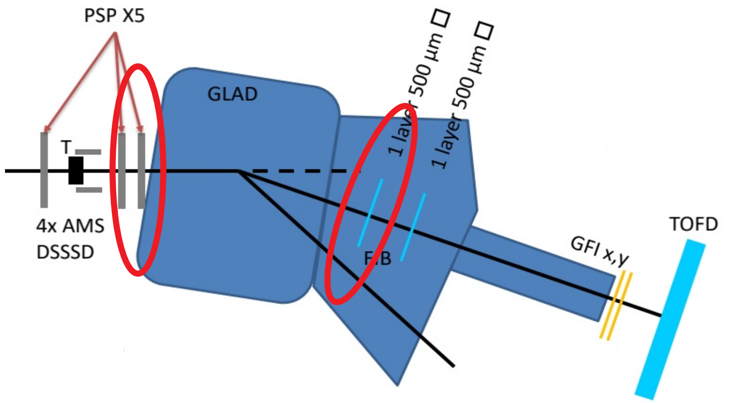
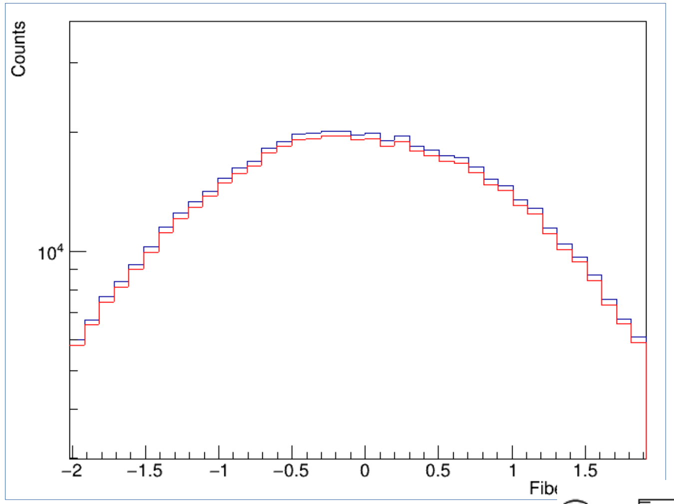
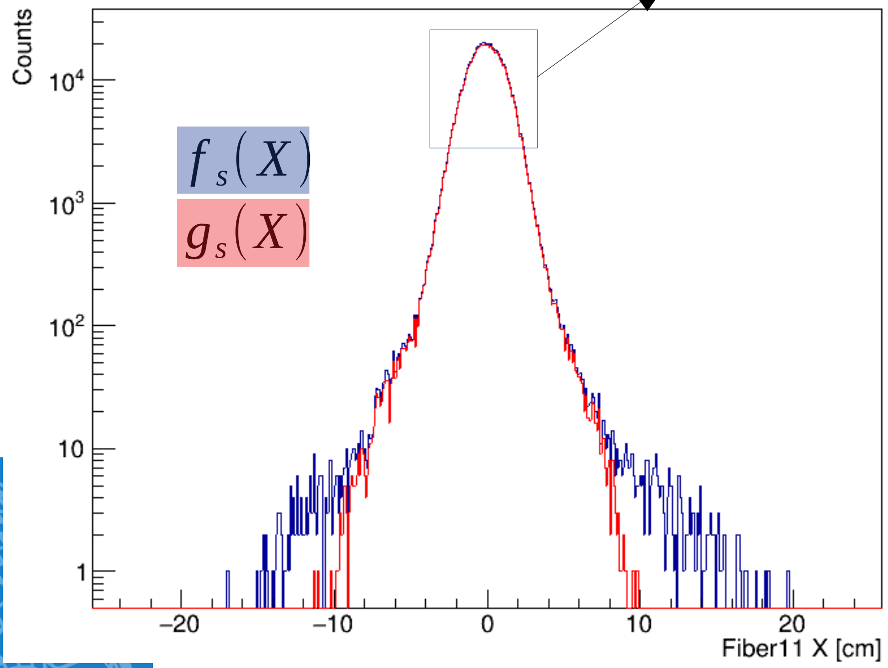
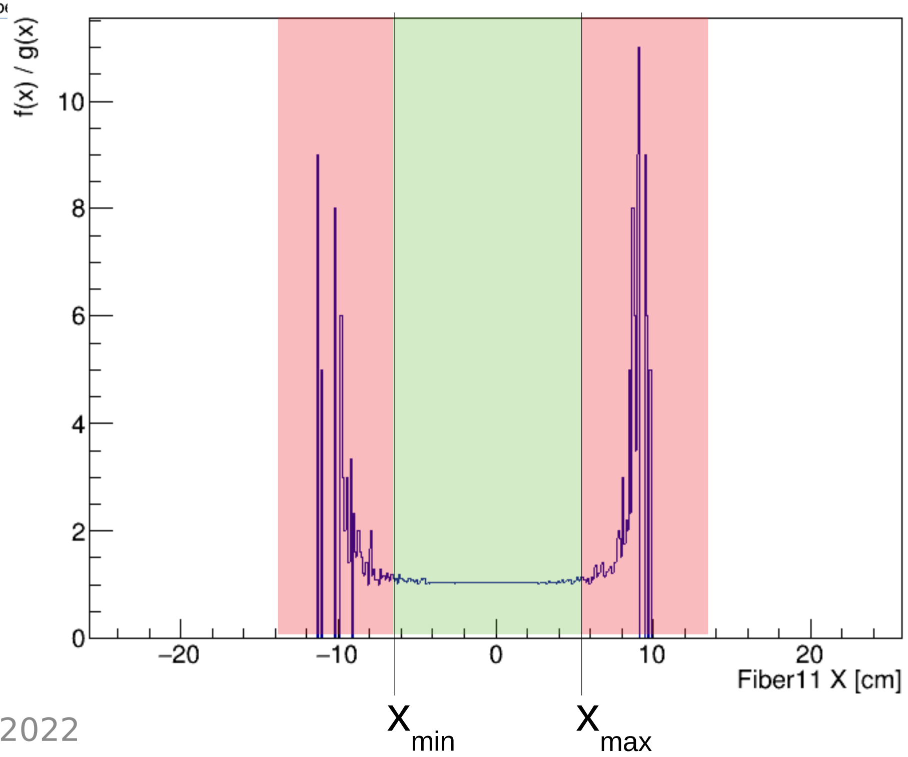




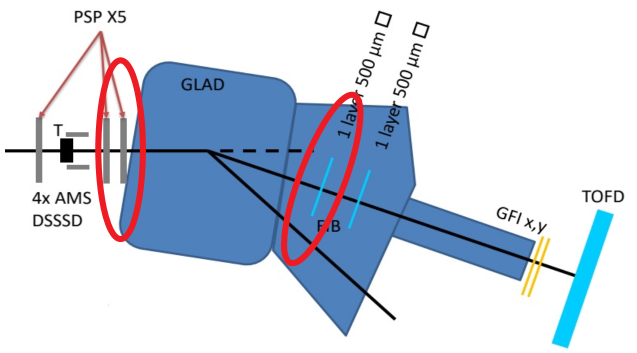


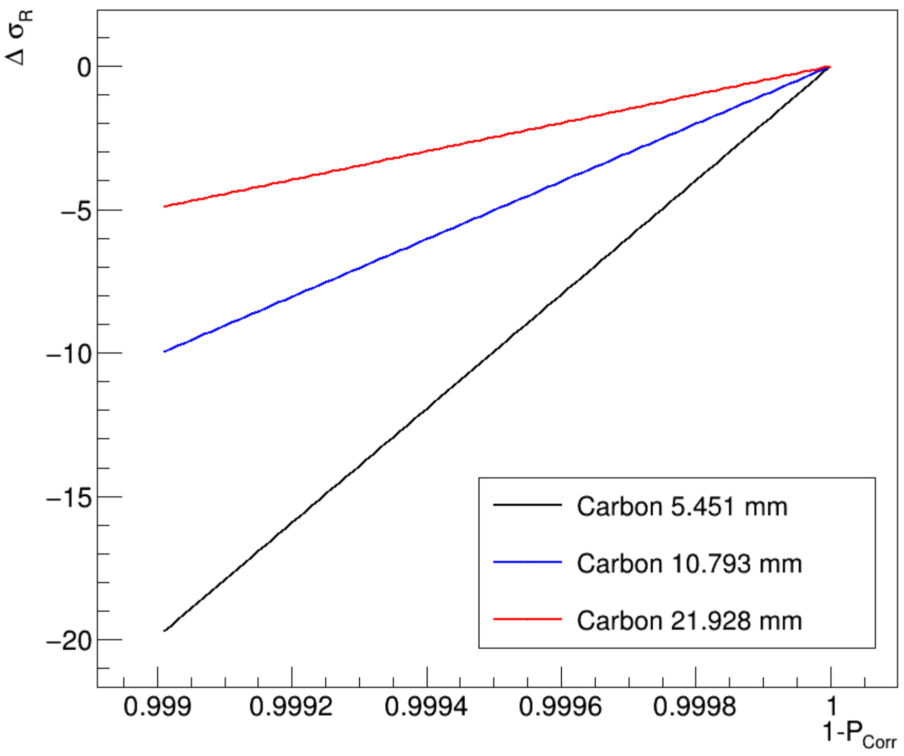
$$S = \frac{\int_{x_{min}}^{x_{max}} g_s(x)}{\int_{x_{min}}^{x_{max}} f_s(x)}$$

Dividing both distribution



Systematic Uncertainty





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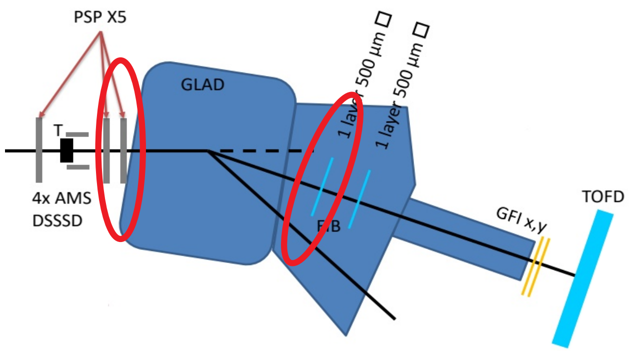
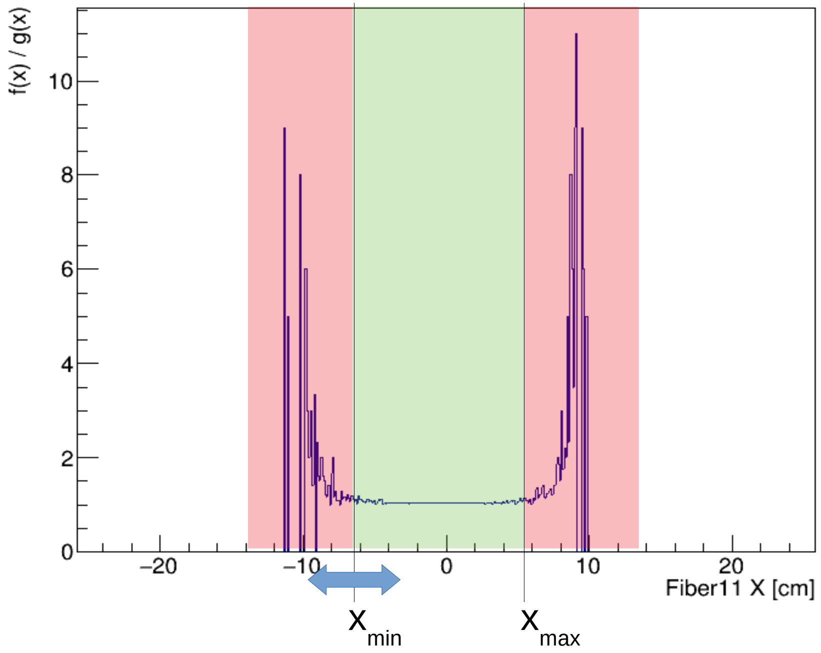
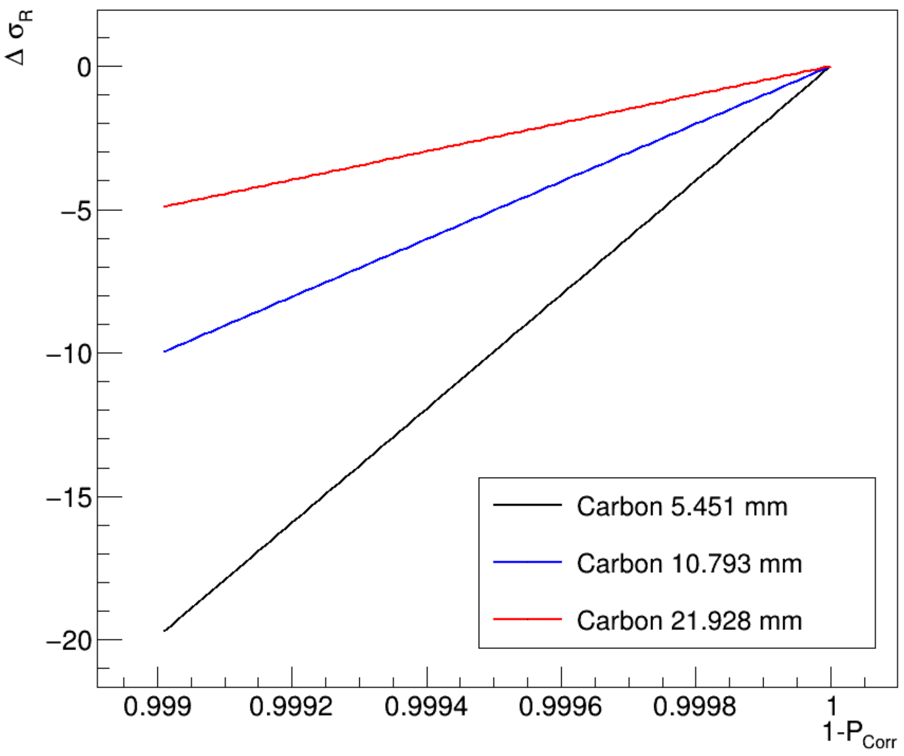
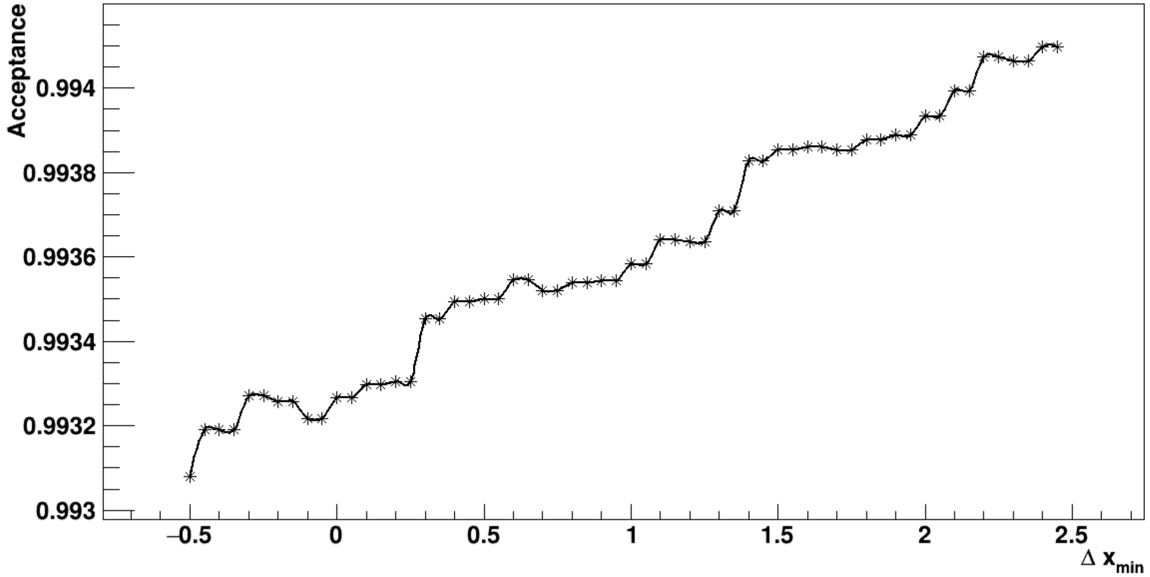


Dividing both distribution







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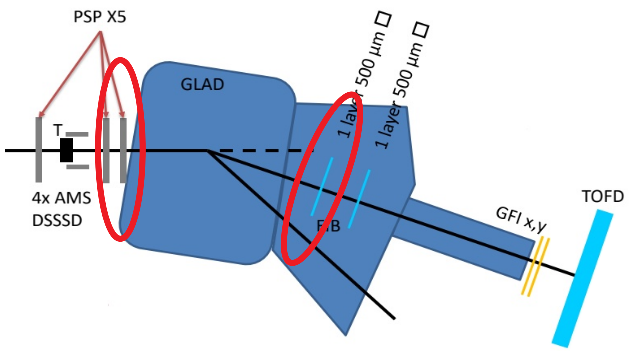
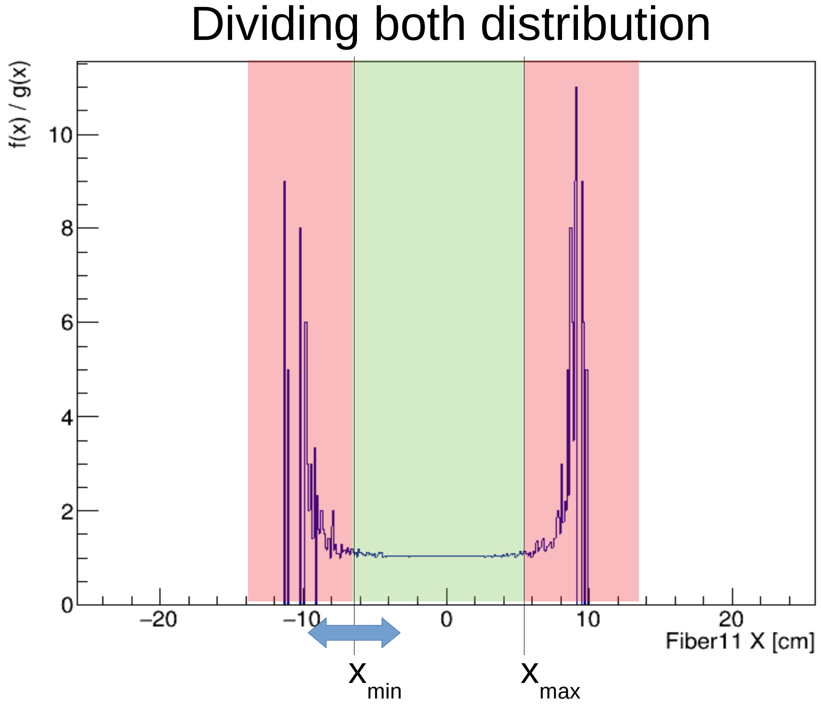
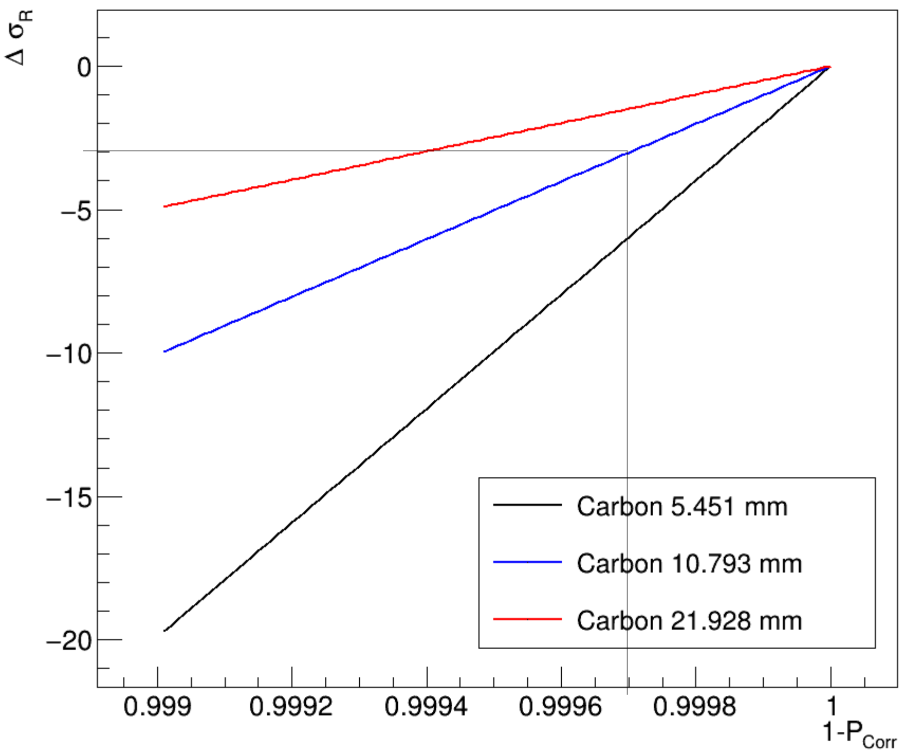
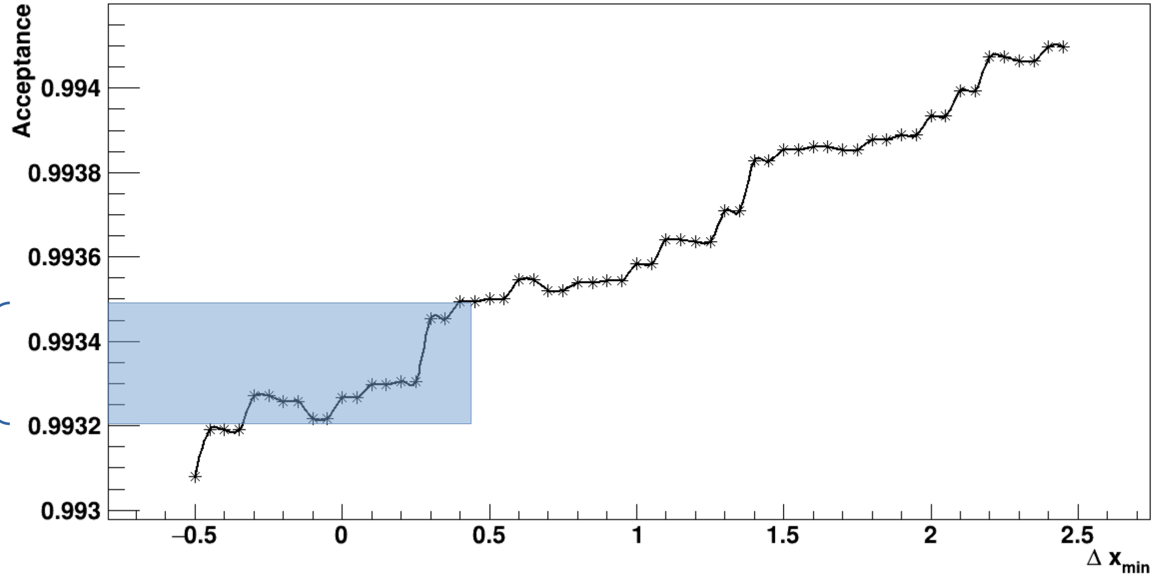




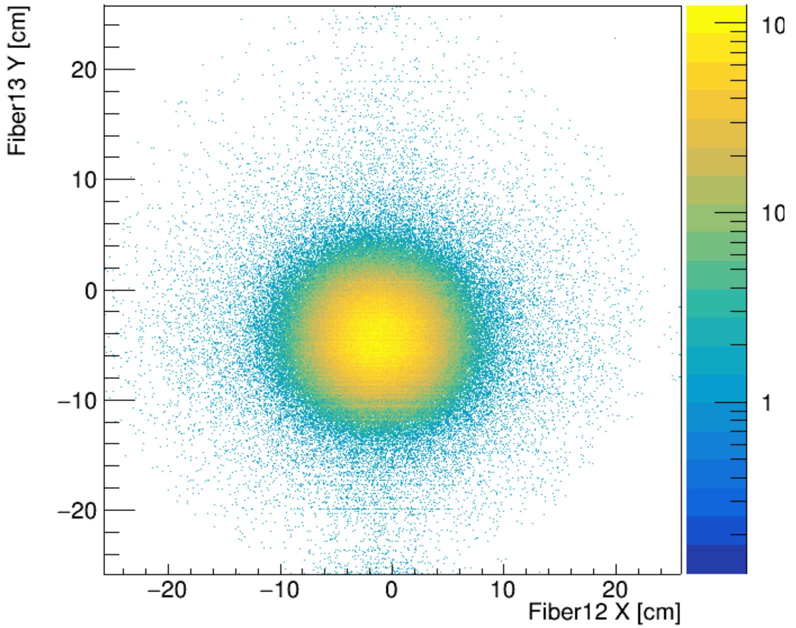


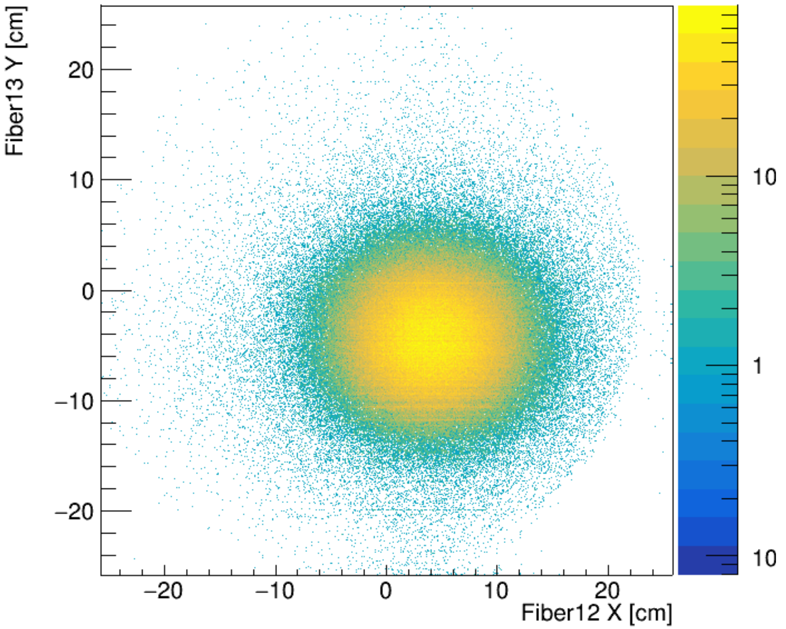
$$\Delta A_{Corr} = 0.0003$$

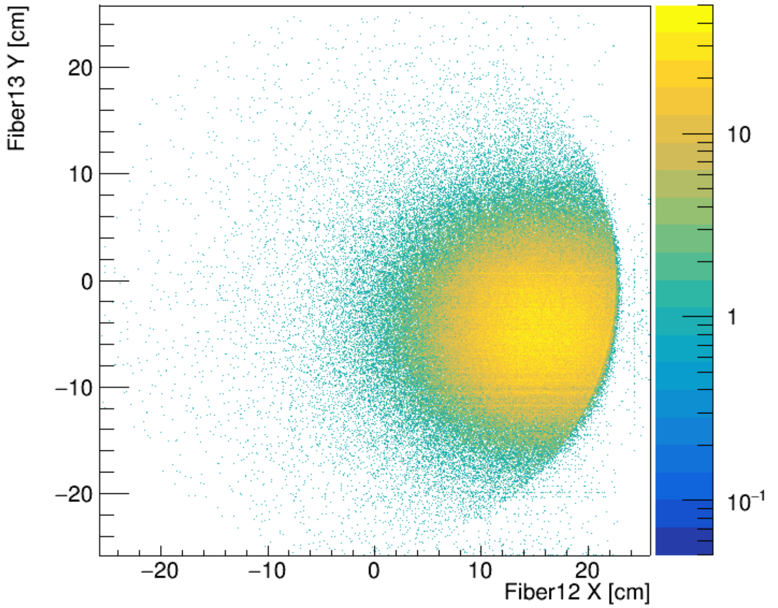


Acceptance-Correction

Beam-Energy 400 AMeV



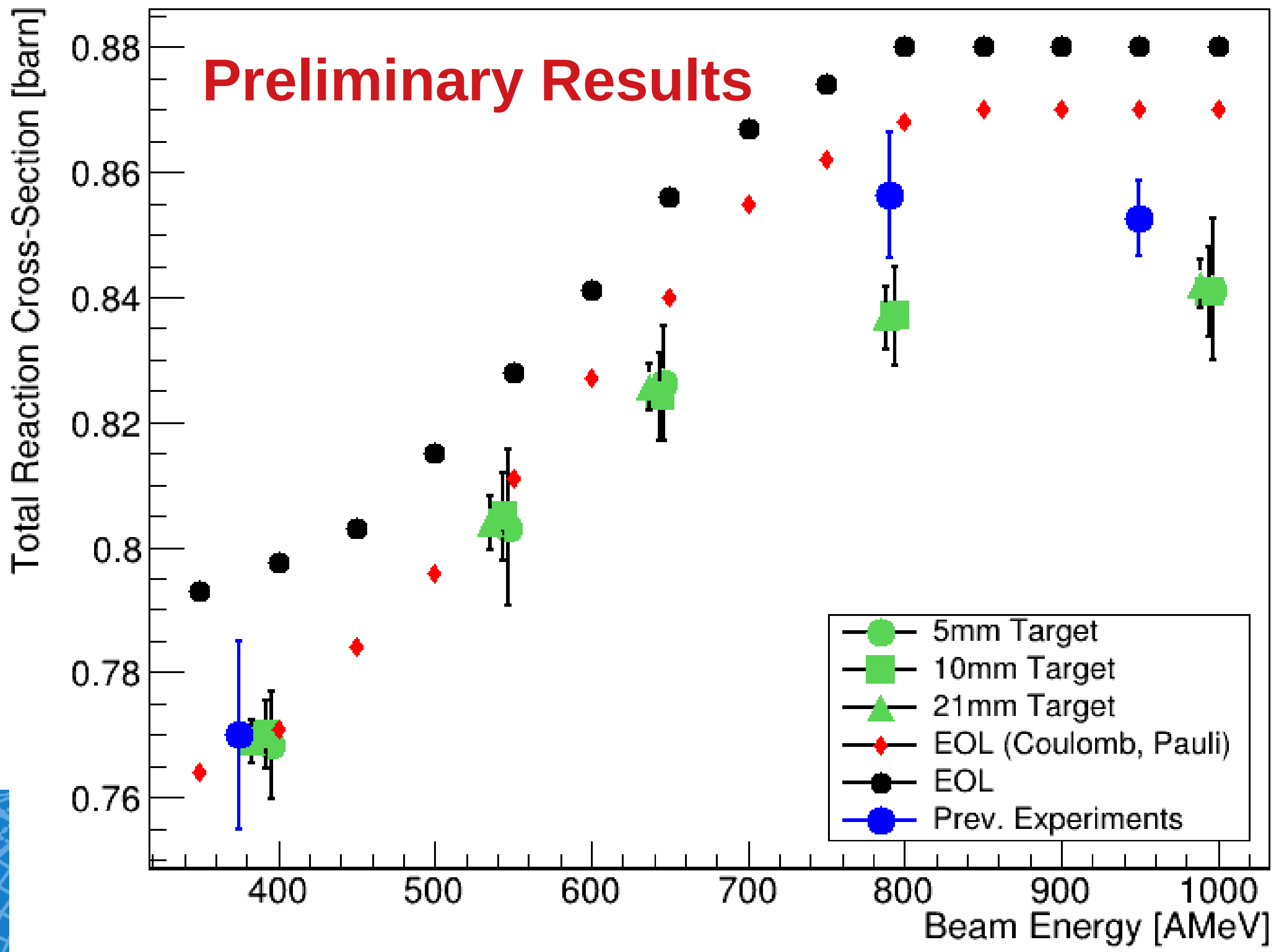




Target Thickness:	5.451 mm	10.793 mm	21.928 mm
Acceptance:	**0.997115**	**0.993424**	**0.841181**

$$N_2 = \frac{N_{Q=6} \cdot R(^{12}C)}{A}$$

Total Reaction Cross-Section



Status:

- Experimental results are in agreement with previous experiments at low energies
- Theory overestimates exp. results at high energies
- Estimation of systematic uncertainties:

400 AmeV ^{12}C – 21mm ^{12}C Target

$$\sigma_R = 768.87 \underbrace{\pm 2.44}_{\text{Statistical}} \underbrace{\pm 0.04}_{\text{Efficiency}} \underbrace{\pm 0.21}_{\text{Isotope Corr}} \underbrace{\pm 1.45}_{\text{Acceptance Corr}} mb$$

Outlook:

- Analysis-Report in progress!

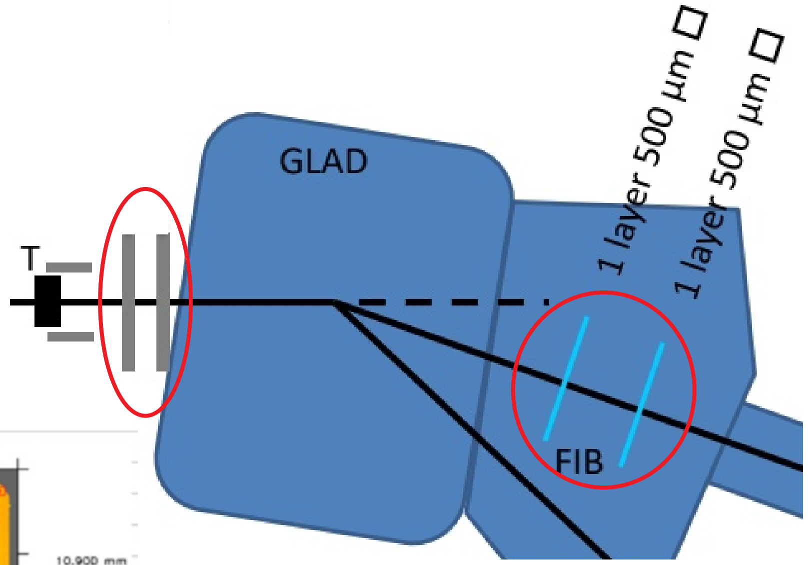
Thank you!

CALIFA @ Technical University of Munich (TUM)

Roman Gernhäuser, Philipp Klenze, Lukas Ponnath, Tobias Jenegger

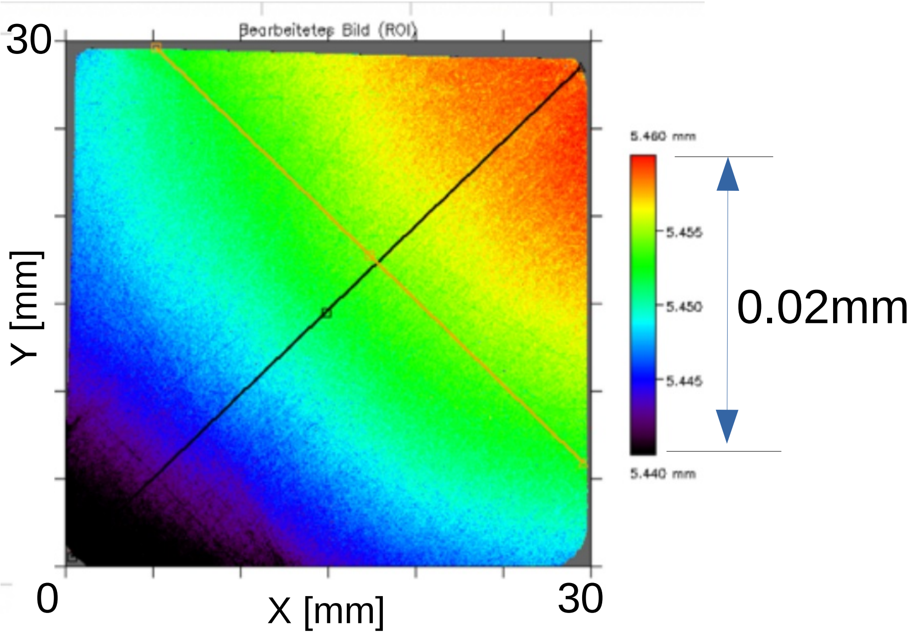
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

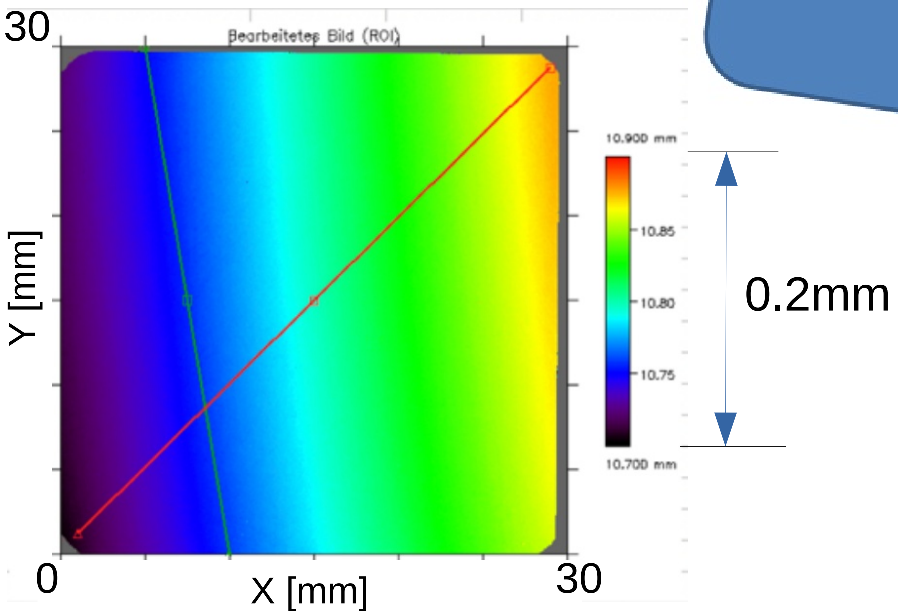
Next Steps & Outlook



- Detailed investigation of Acceptance-Correction
  - ➔ Compare all PSP-Fiber-Combinations

- Error estimation for target thickness & Acceptance Correction



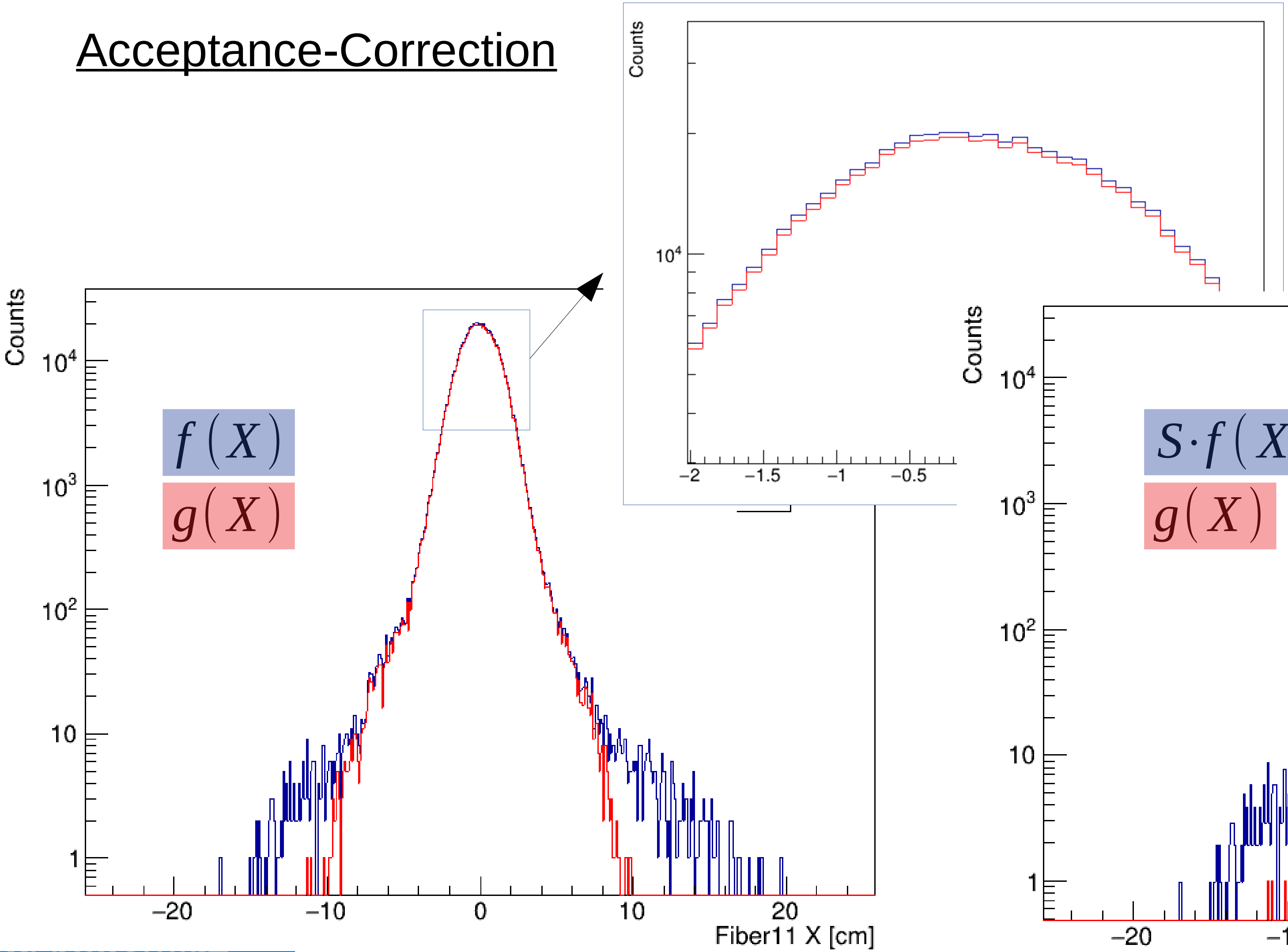


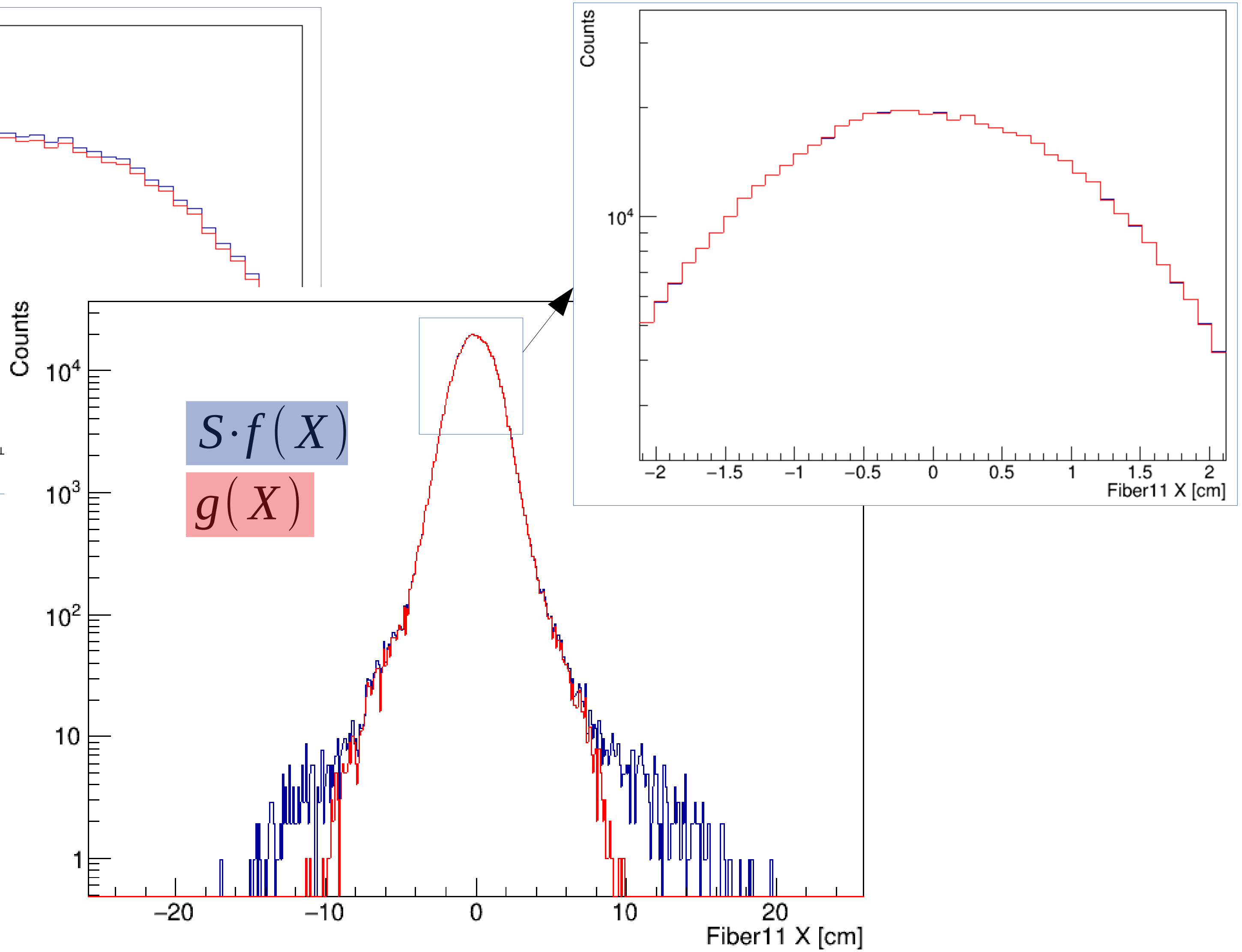
- Investigation of inelastic scattering contribution
  - ➔ S444 Experiment in 2020 (Full CALIFA Barrel) for Gamma detection

- Outlook: Measurement of total reaction cross-section of ^{12}C on a p-Target

Total Reaction Cross-Section

Acceptance-Correction



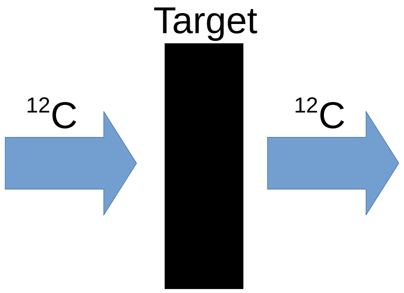


Total Reaction Cross-Section

Precision Measurement:

Energy dependence of the total reaction cross-section of $^{12}C \rightarrow {}^{12}C$

(Tom Aumann)



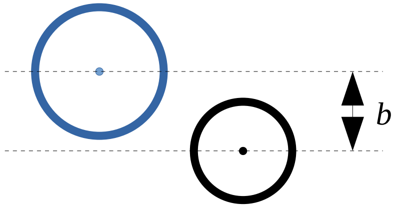
Total reaction cross-section: $\sigma_R = \sigma_I + \sigma_{inel}$

Total interaction cross-section σ_I**:**

The projectile changes its identity. At least one nucleon is removed.

Total inelastic cross-section σ_{inel}**:**

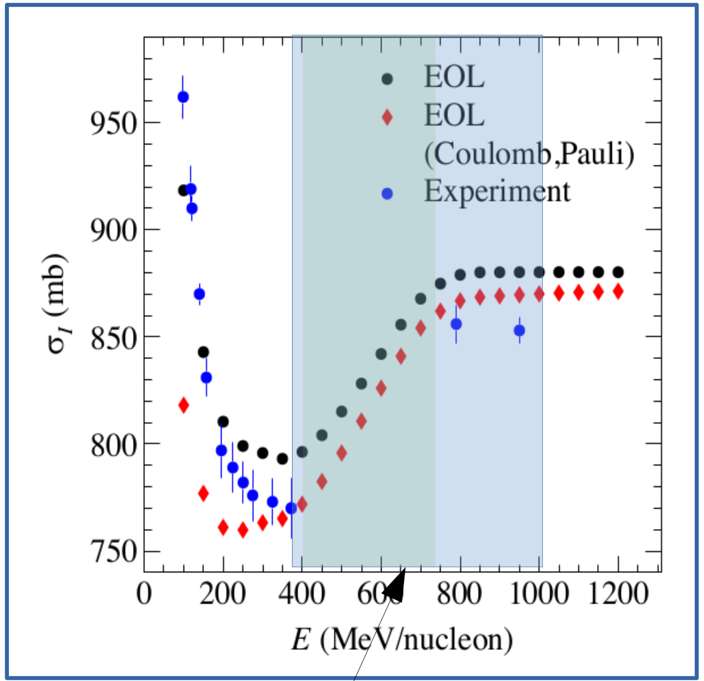
The projectile is excited to a bound state. No nucleon is removed.



Eikonal approximation in Glauber theory:
Projectile passes field of the target on straight-line trajectory until interaction. ($E >> |V_0|$)

Optical-Limit representation:
Single nucleon-nucleon-interaction is replaced by an averaged interaction.
$V_{OL}(\vec{b}) \propto \sigma_{NN} \cdot \int \rho_P(\vec{r}) \rho_T(\vec{r} - \vec{b})$

Extension of Glauber model:
Coulomb repulsion, Pauli blocking



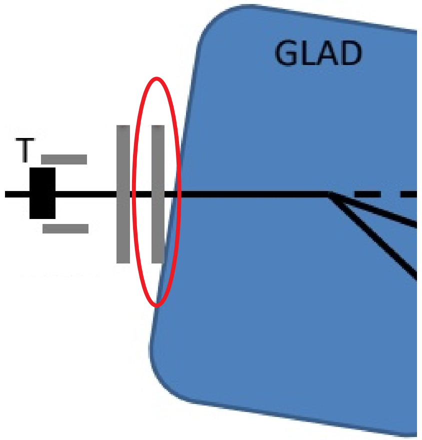
F. Schindler, PhD Thesis, TU Darmstadt (2017)

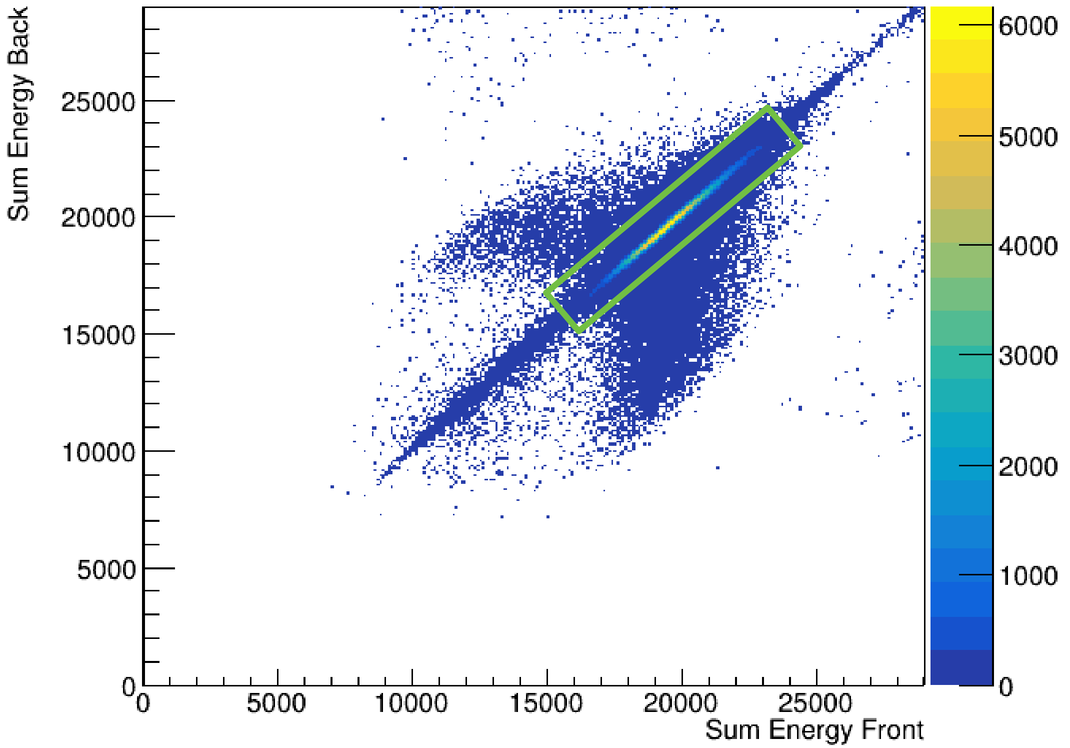
^{12}C Beam Energies in S444 Experiment:

400, 550, 650, 800 & 1000 AMeV

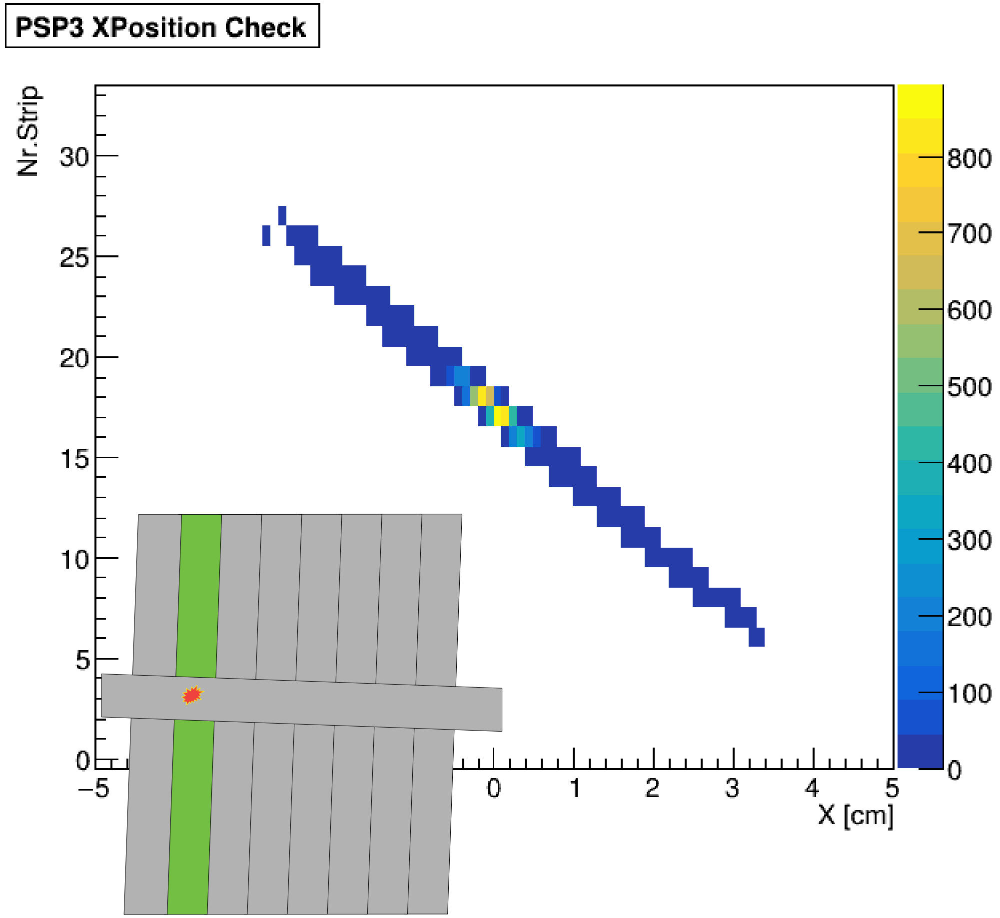
Total Reaction Cross-Section

PSP Detector - X-Position



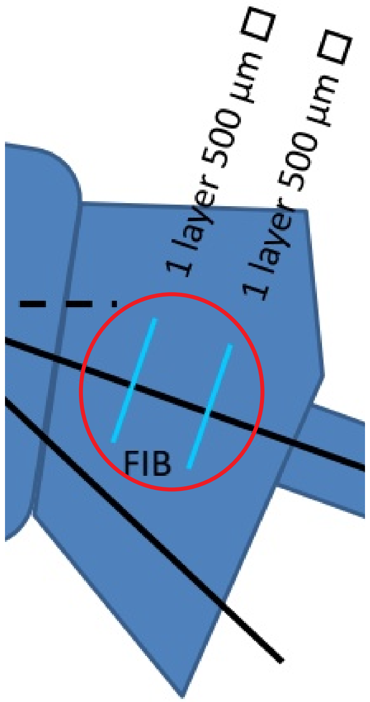


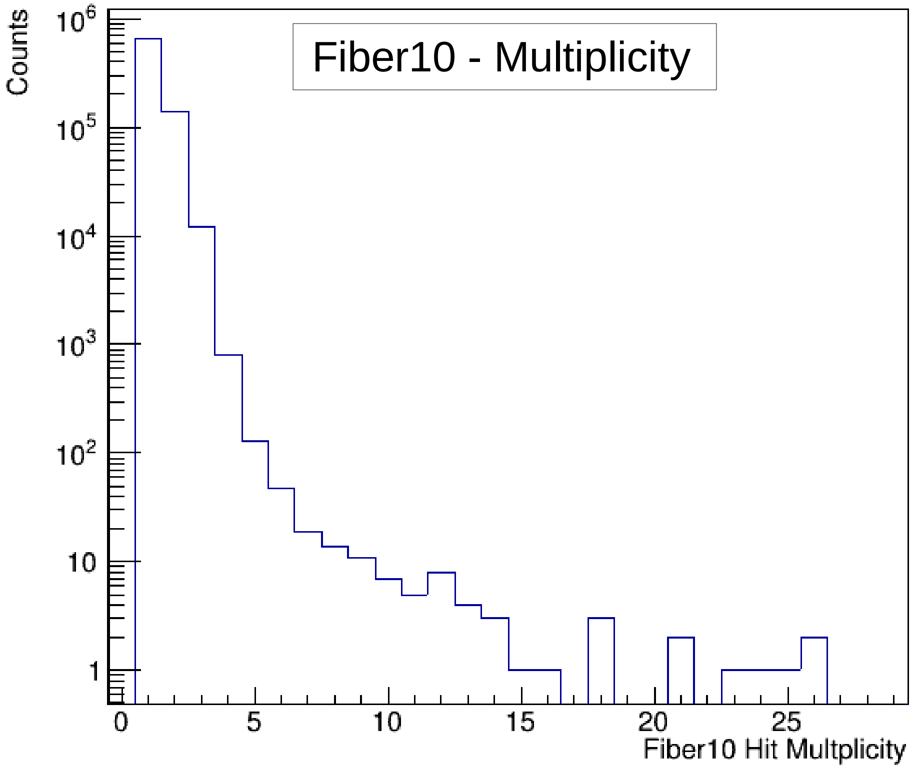
- Multplicity=1 on Front- & Back-Layer
- Same Energy (Q=6) Deposition in both Layers

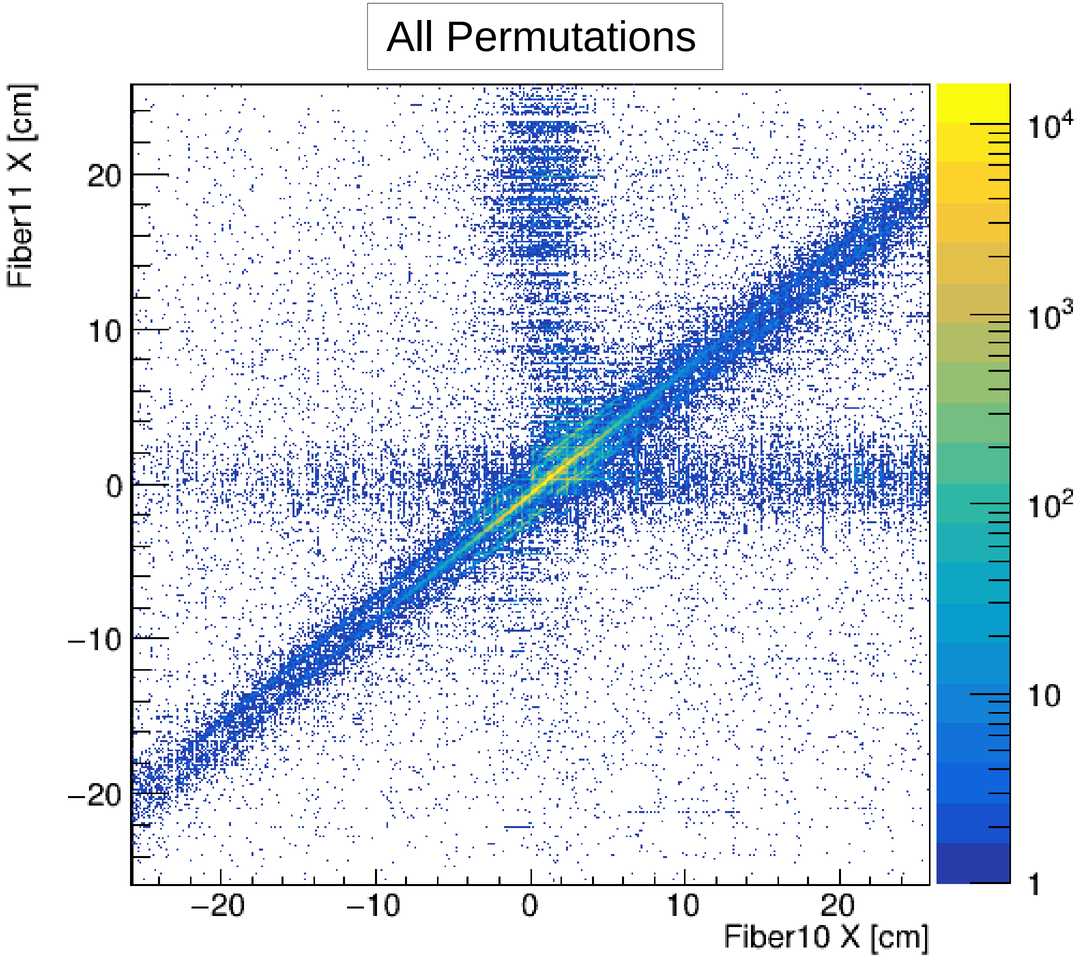


We can cross-check the x-position with the Strip-Nr. of the Front-Layer

Fiber Detector - X-Position



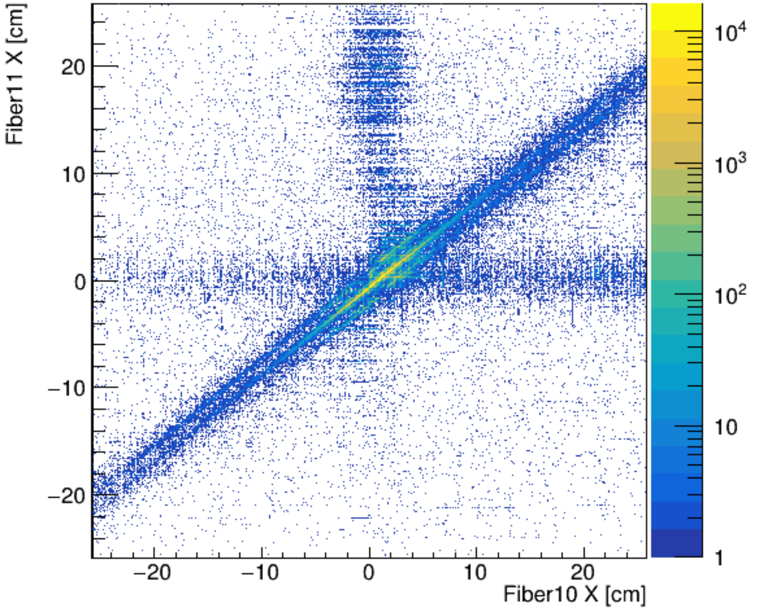


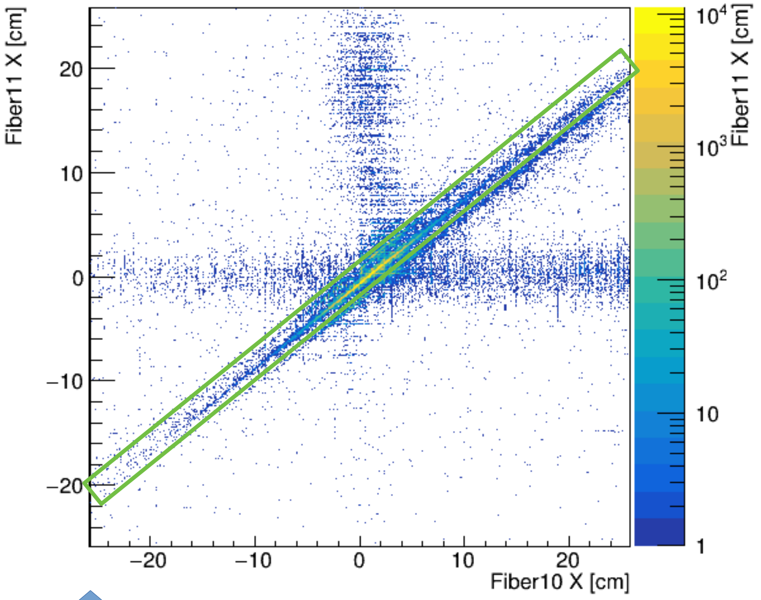


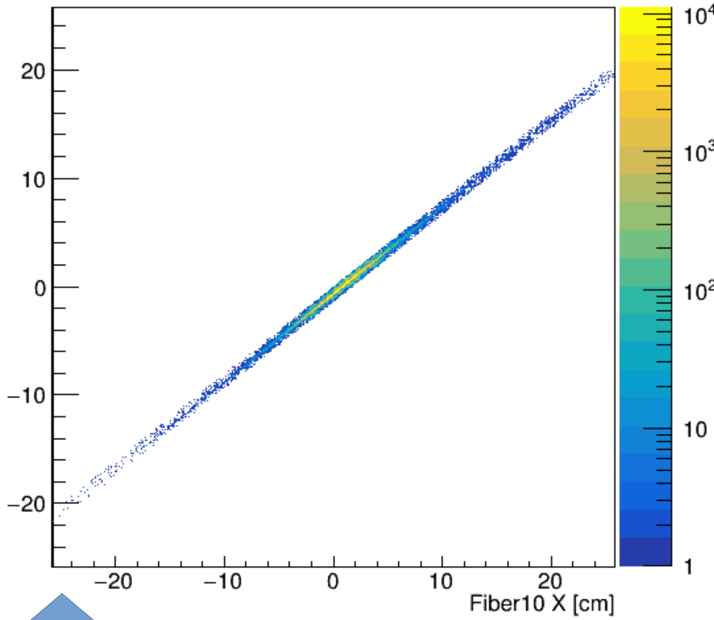
Problem: High Multiplicity due to light cross-talk
How can we find the correct Hit / the correct X-Position?

Total Reaction Cross-Section

Fiber Detector - X-Position





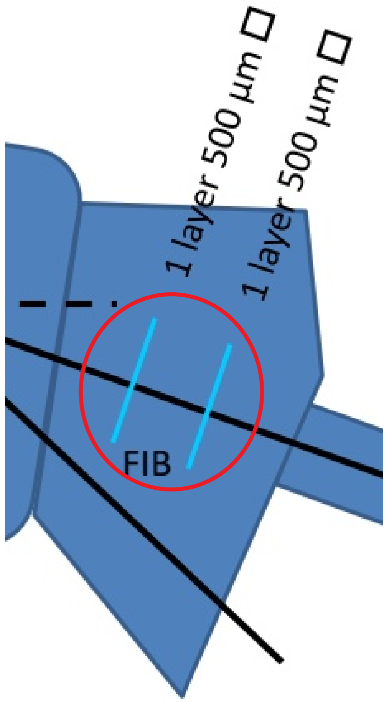


Conditions:
- Time Coincidence
- PSP Q=6

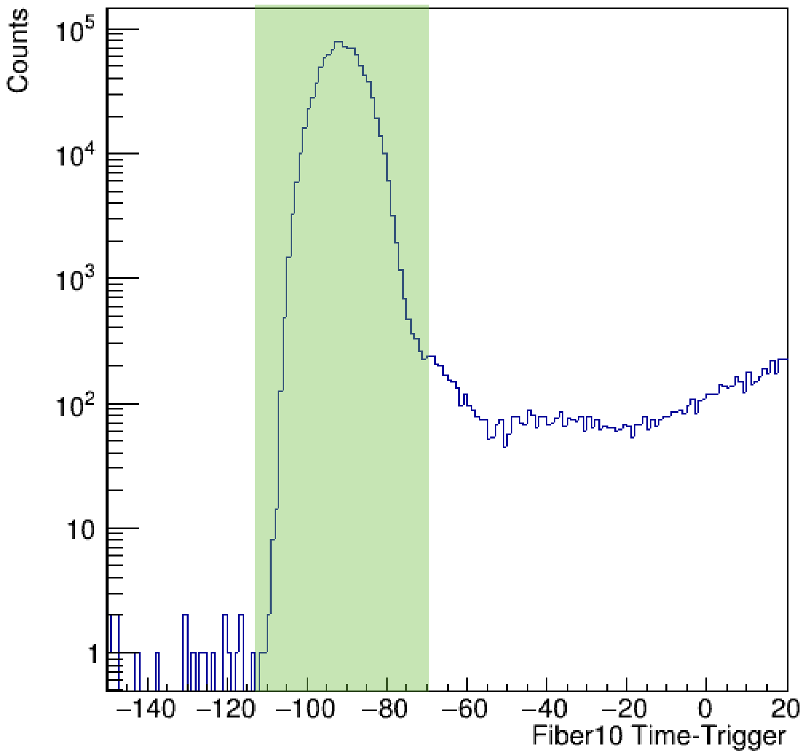
Conditions:
- Position Correlation Fib10&11
- Highest Energy loss

Total Reaction Cross-Section

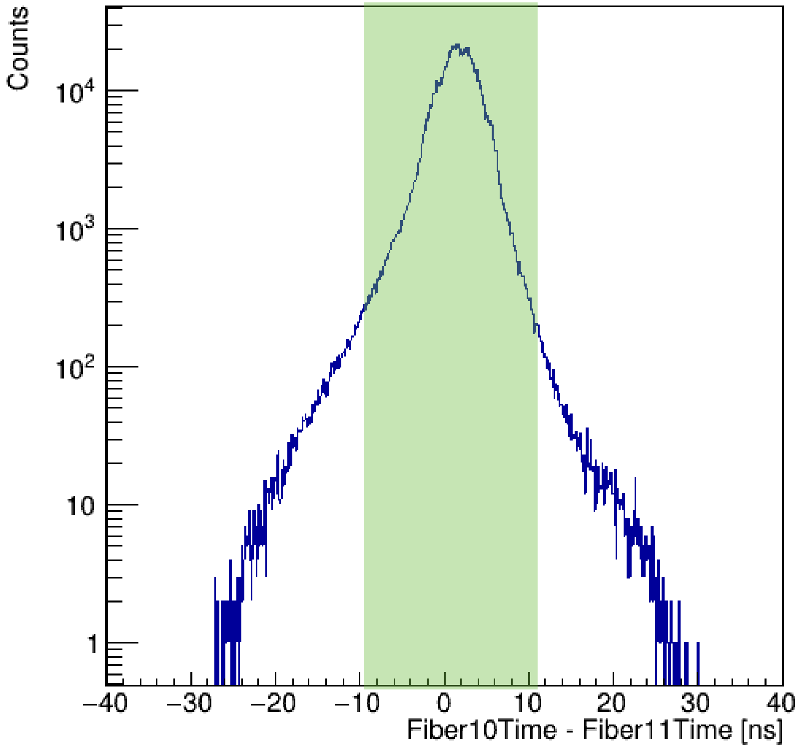
Fiber Detector - X-Position



Time Difference to Readout-Trigger



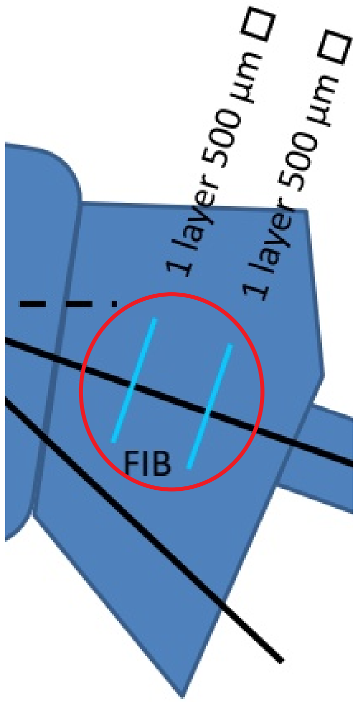
Coincidence between both Detectors

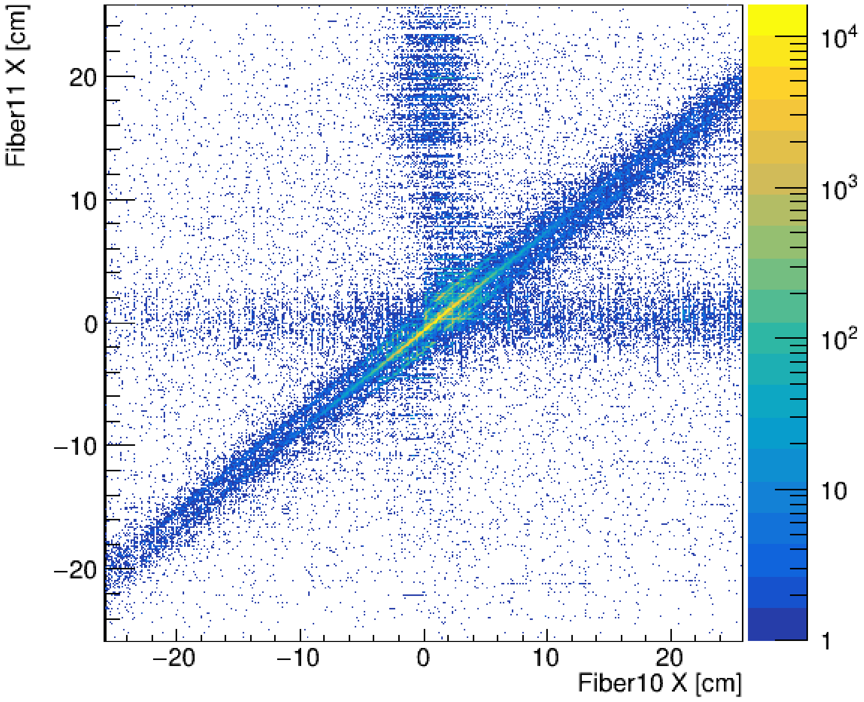


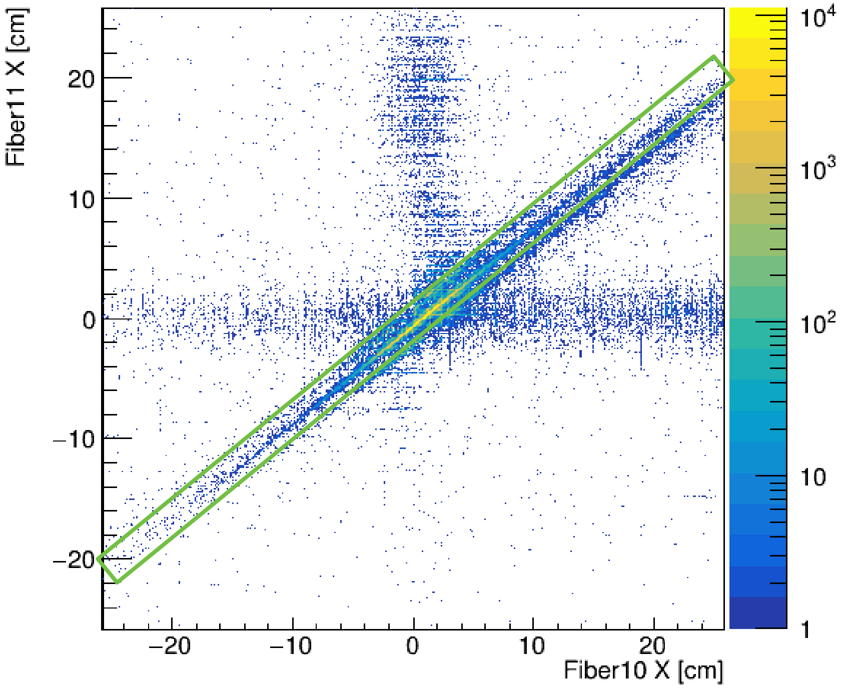
We are choosing a small Time-Difference to the Readout-Trigger for both Fiber-Detectors and defining a Coincidence-Window for both Hits.

Total Reaction Cross-Section

Fiber Detector - X-Position







Conditions:
- Time Coincidence
- PSP Q=6

In the last step we ask for a position correlation between Fiber10 & 11 (large enough to include large angles ~5mrad) and choose the Hit with the highest Energy loss.

Total Reaction Cross-Section

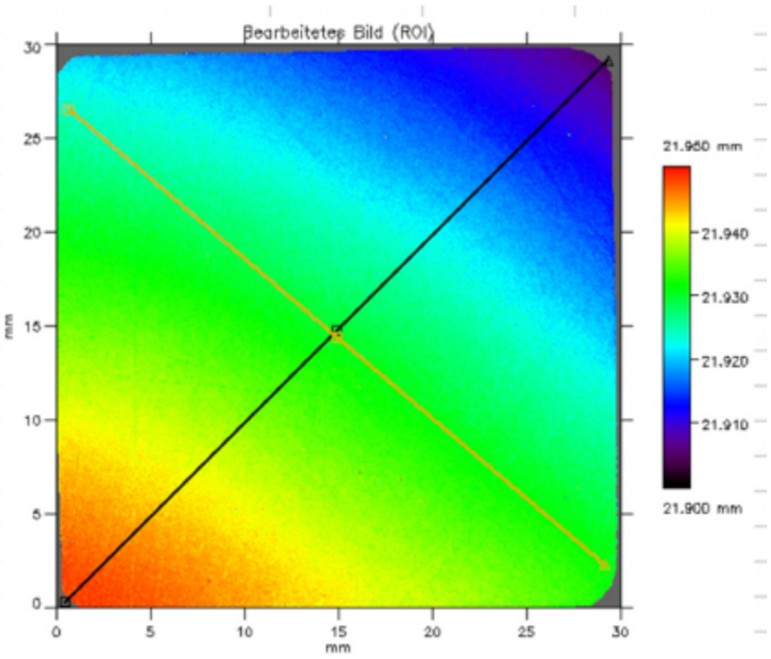
<u>Number of target scattering centers:</u>

$$N_t = \frac{\rho_t \cdot d_t \cdot N_A}{A_t}$$

where

- ρ_t is the volume density of the target (1.84 g/cm^3)
- d_t is the target thickness
- N_A is Avogadro's constant (6.02214*10^{23} mol^{-1})
- A_t is the molar mass of the target (12.0107 u)

$$\sigma_R = -\frac{1}{N_t} \ln\left(\frac{N_2^i / N_1^i}{N_2^o / N_1^o}\right)$$



Dt [cm]	Nt
0.5451	5.50334*10^{23}
1.0793	1.09904*10^{24}
2.1928	2.120248*10^{25}