Constraining the Symmetry-Energy via Total Reaction Cross-Section Measurements

Lukas Ponnath

PSI Seminar
May 2023

Physics with R^{3}B

Equation of State of Asymmetric Nuclear Matter

The Glauber-Model

Total Reaction Cross-Section Measurement

Supported by BMBF 05P21WOFN1 and 05P19WOFN1.

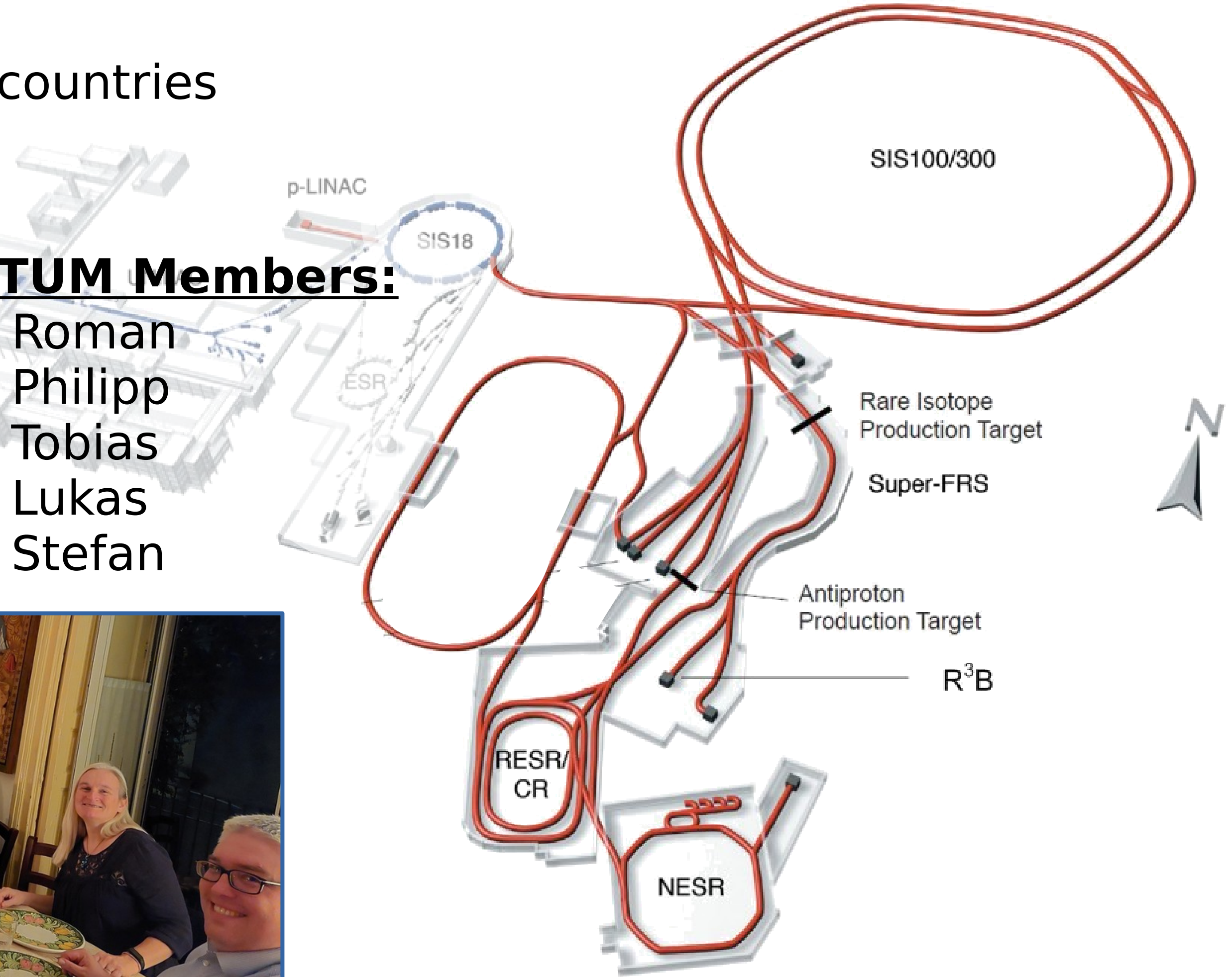
The results presented here are based on the experiment s444/s473, which was performed at the beam line/infrastructure Cave C at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the frame of FAIR Phase-0.

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

Reactions with **R**elativistic **R**adioactive **B**eams

- Collaboration with > 200 scientists over 20 countries

TUM Members:
Roman
Philipp
Tobias
Lukas
Stefan



GSI / FAIR

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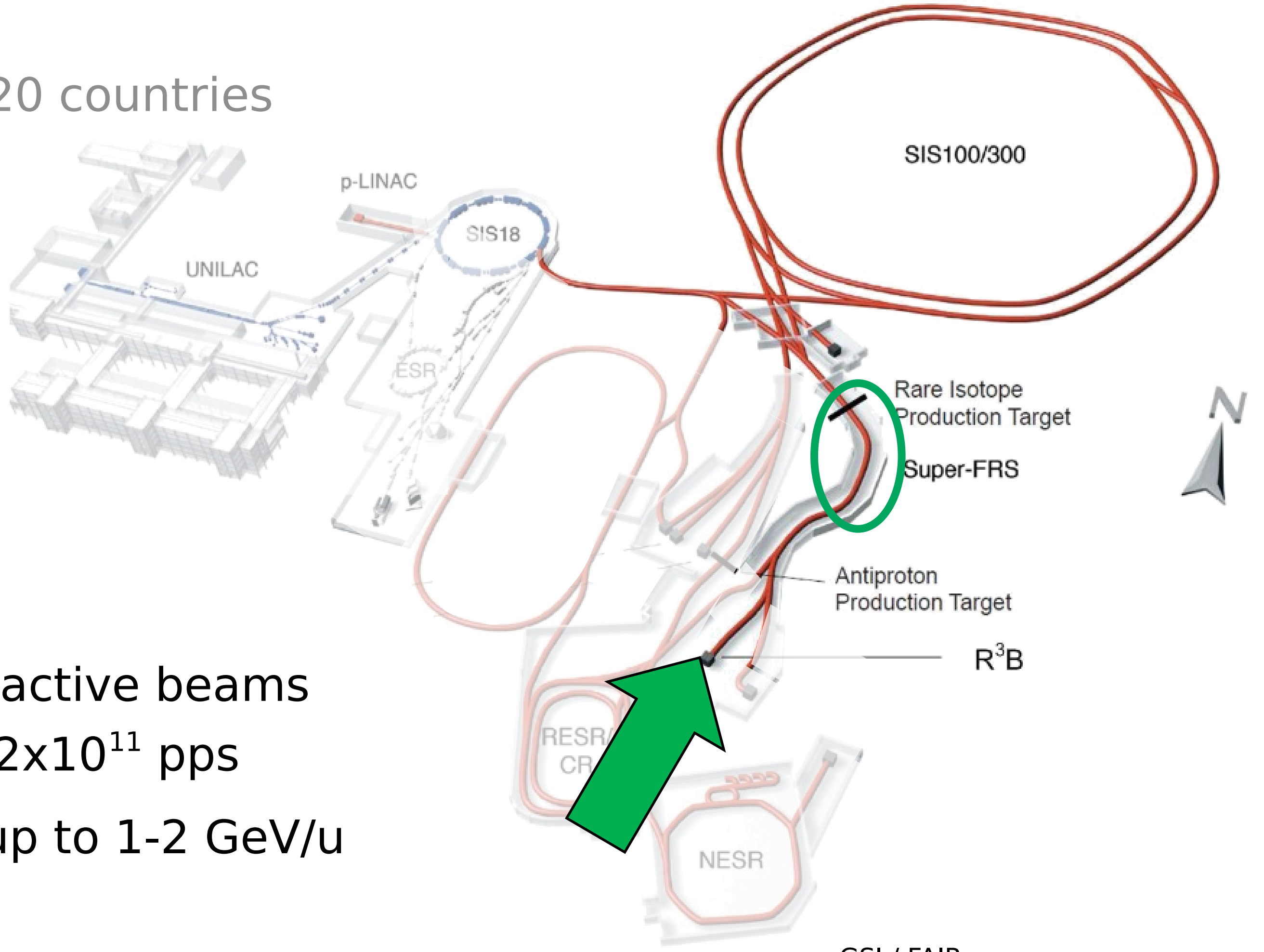
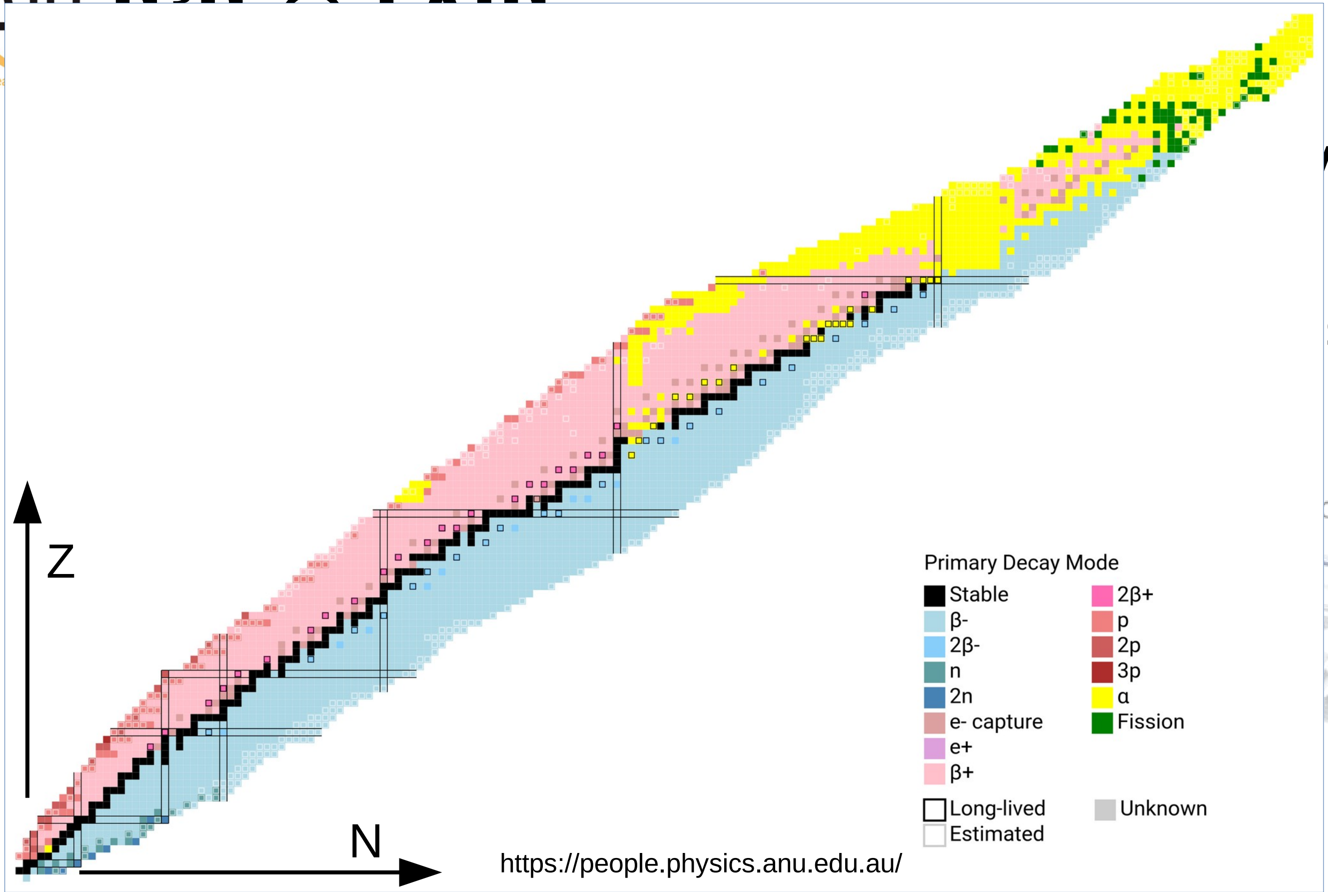


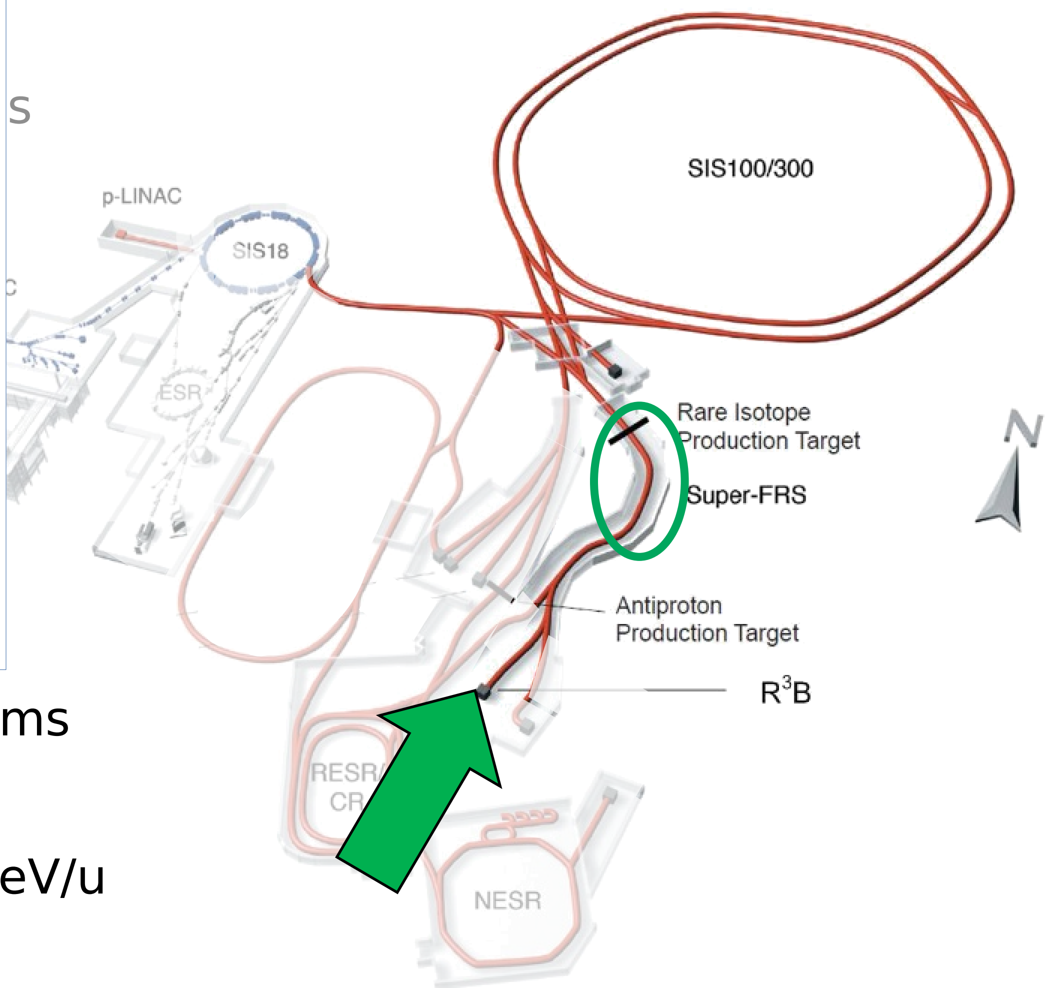
GSI / FAIR

- In-Flight Production of radioactive beams
- Primary-Beam Intensities ~2x10^{11} pps
- Secondary-Beam Energies up to 1-2 GeV/u

R³B @ FAIR

…istic **B**eams





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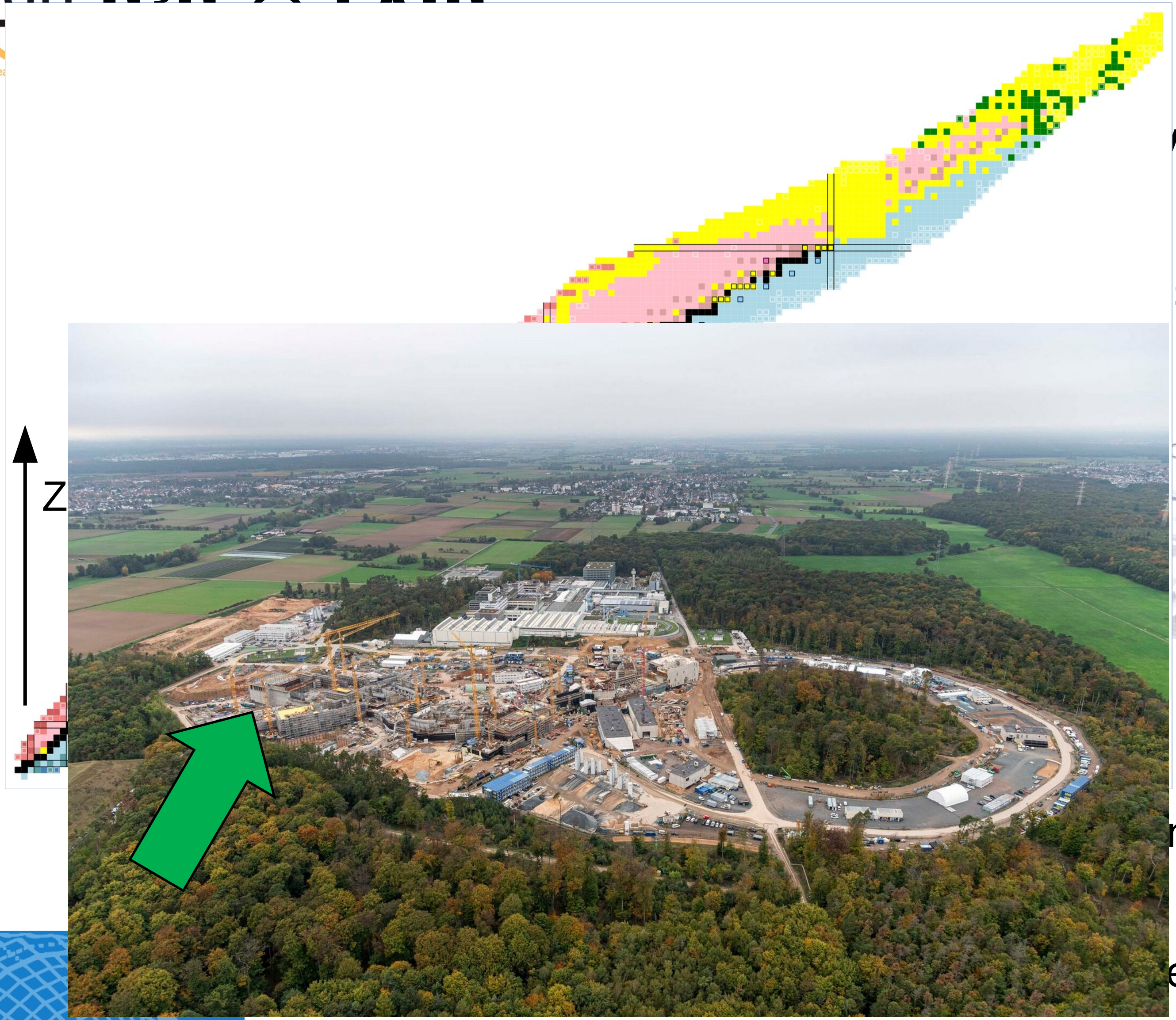
R³B @ FAIR

istic **B**eams

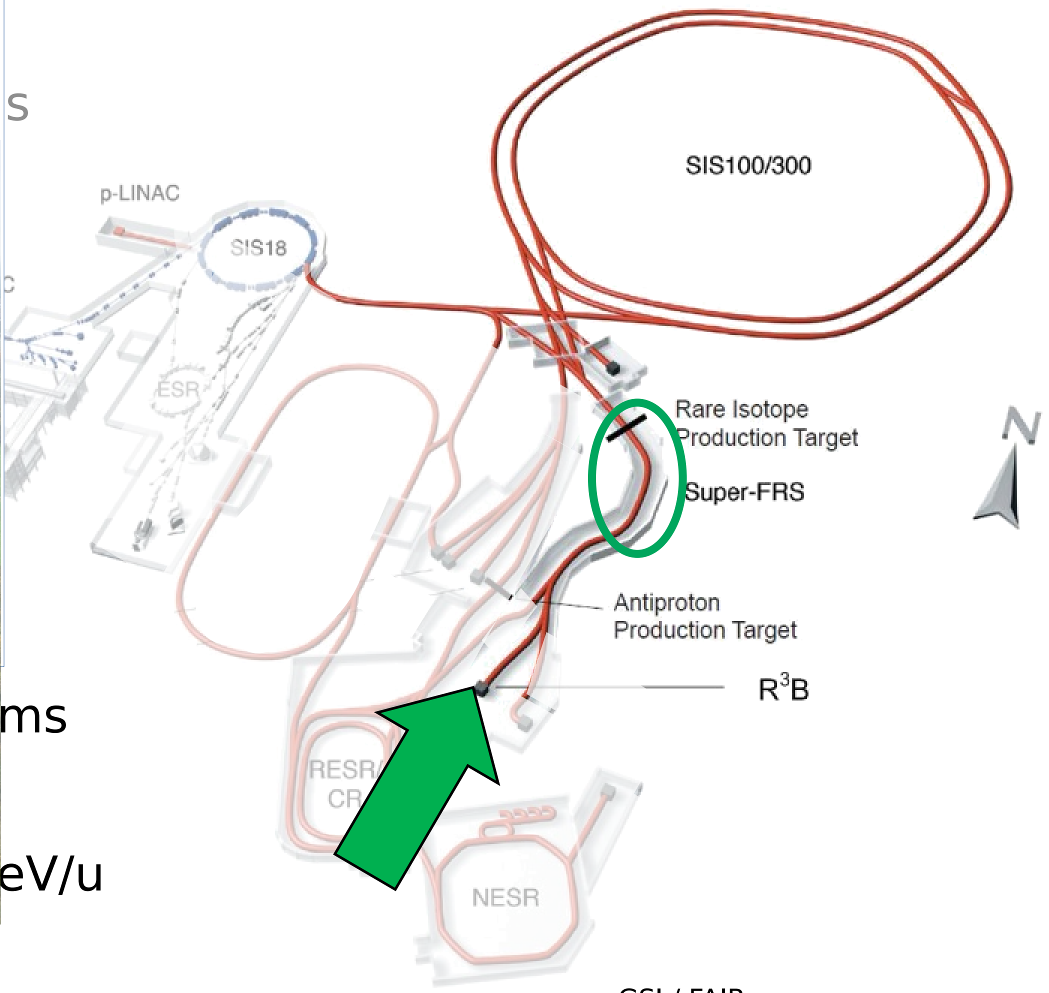
s

ms

eV/u

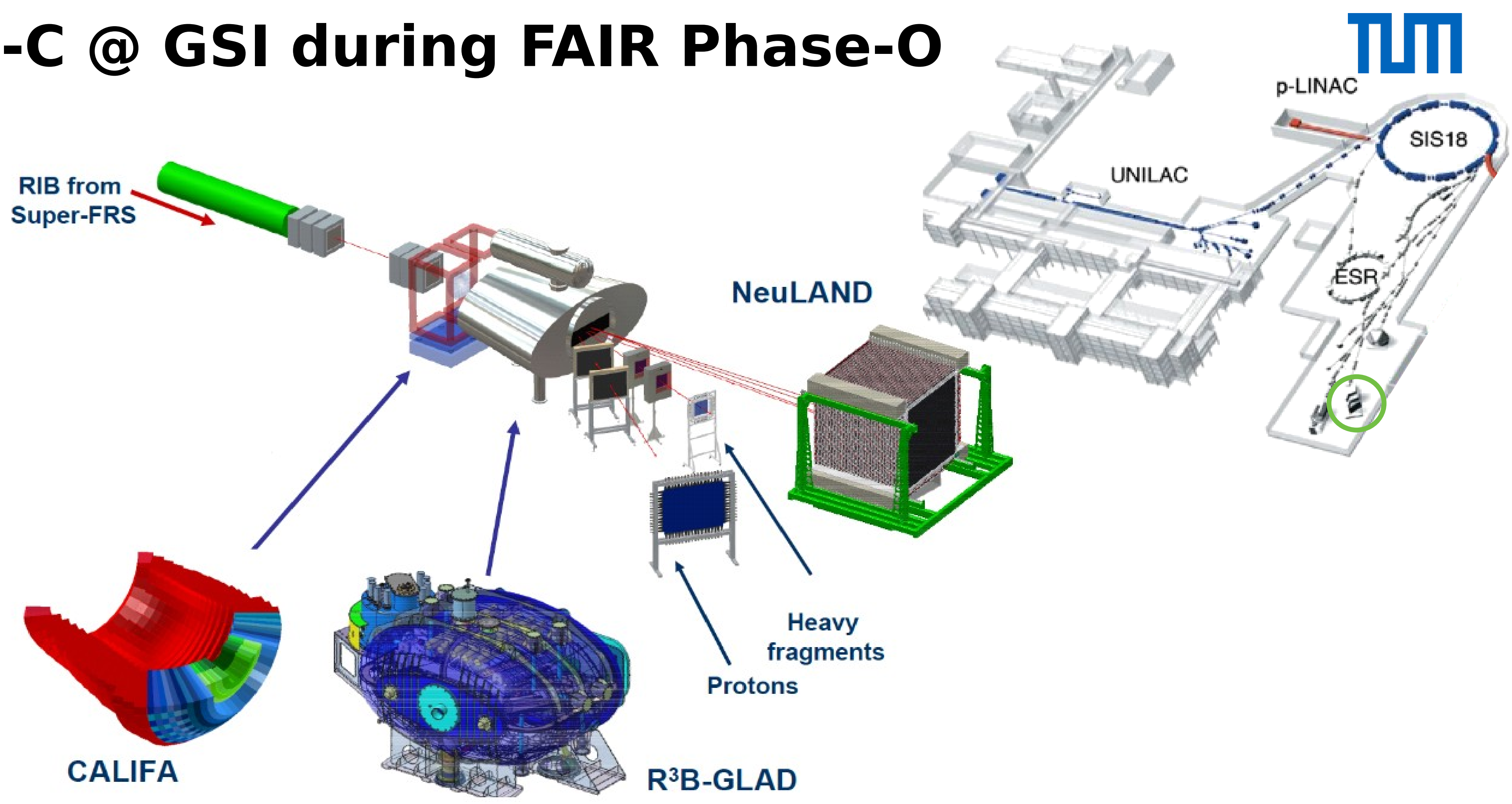


D. Fehrenz, M. Konradt, GSI/FAIR (LinkedIn) November 2022



GSI / FAIR

R³B in Cave-C @ GSI during FAIR Phase-0



The R^{3}B Experimental Setup during FAIR Phase-0
- A magnetic Spectrometer -

R³B in Cave-C @ GSI during FAIR Phase-0

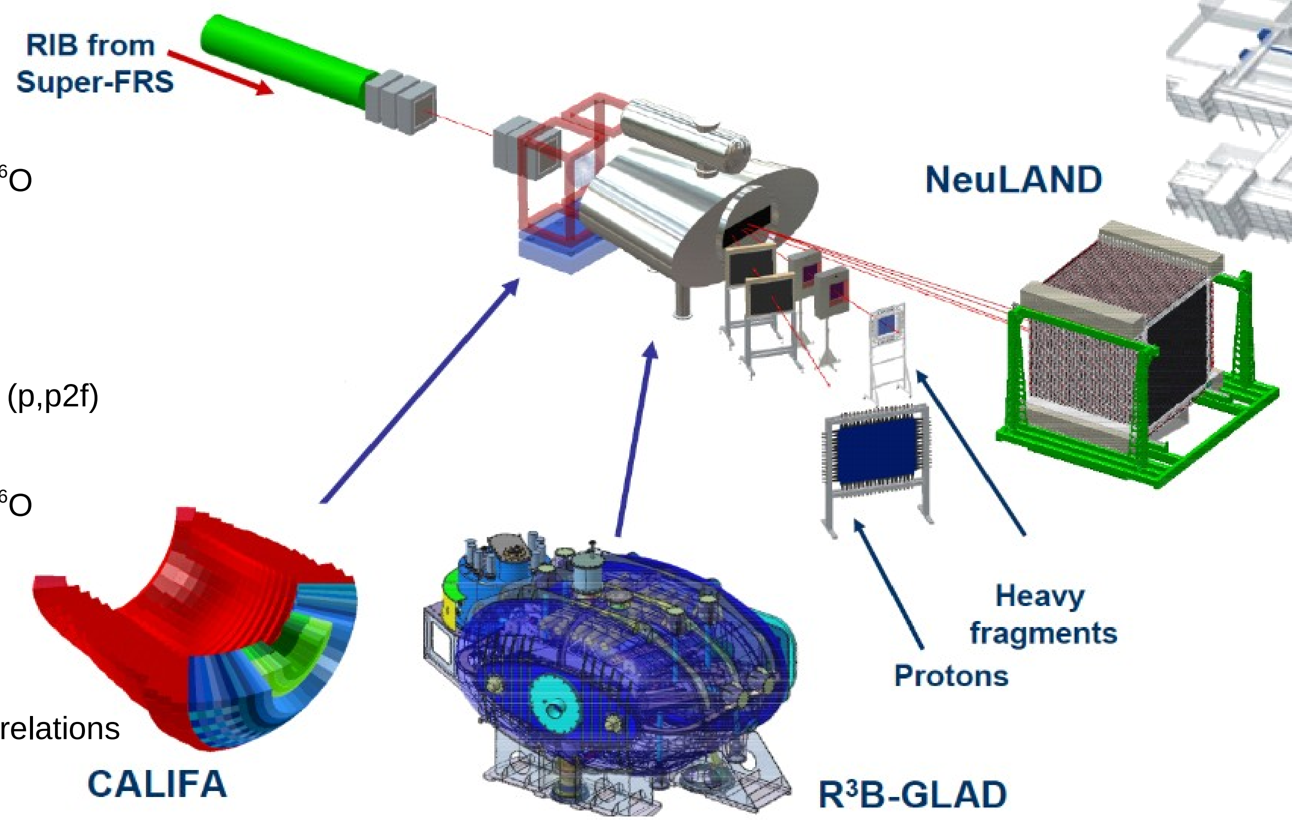
2019
- **S444** - Commissioning
- S473 - Charge- and Neutron-removal Cross-Section of Sn
- S454 - Coulomb Dissociation of ^{16}O

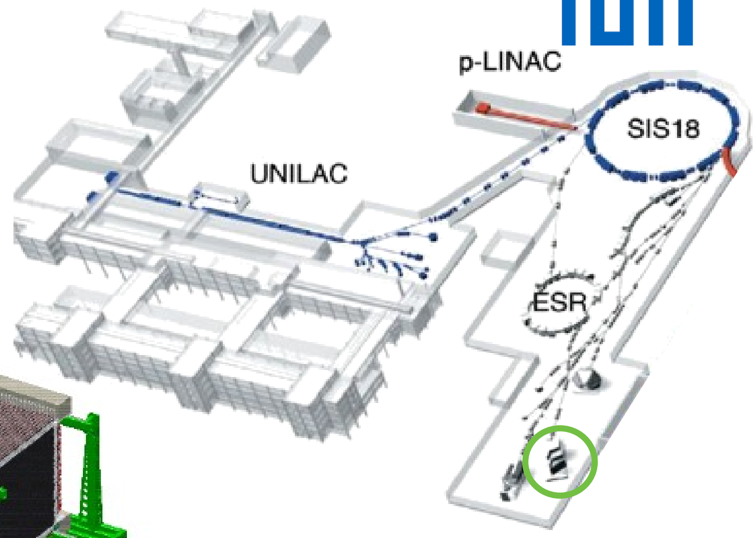
2020
- S467- Shell evolution along Z=20

2021
- S455 - Investigation of fission via (p,p2f)
- S494 - Coulomb Dissociation of ^{16}O
- S515 - Charge- and Neutron-removal Cross-Section of Sn

2022
- S509 - Study of multi-neutron correlations
- S522 - Short-Range Correlations

...





The R^{3}B Experimental Setup during FAIR Phase-0
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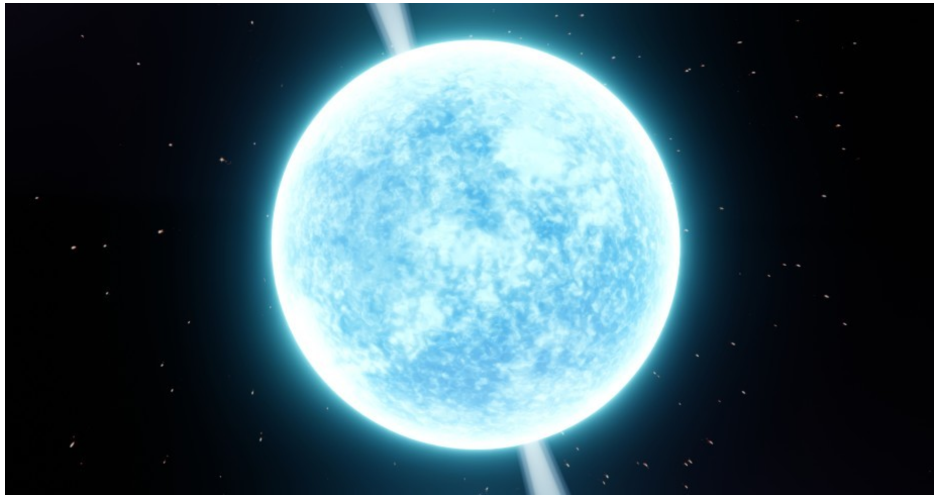
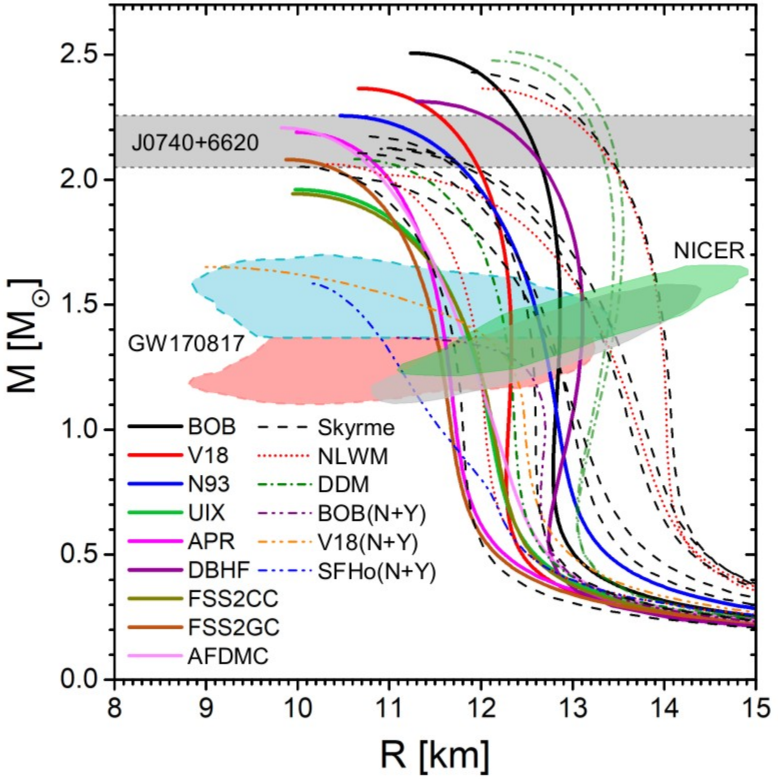
Asymmetric Nuclear Matter - Neutron Stars



https://www.uis.no/en/research/in-the-core-of-a-neutron-star



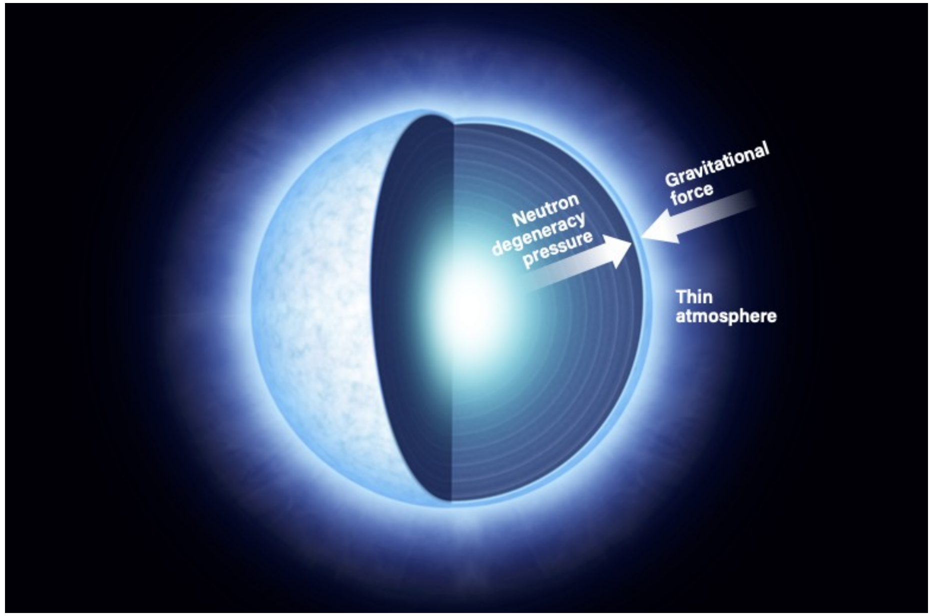
G.F. Burgio et al. Progress in Particle and Nuclear Physics 120(12):103879 (2021)

Stellar parameters:

- **Mass** $M_{J0740+6620} = 2.14^{+0.10}_{-0.09} M_{solar}$
  - Binary systems (Kepler's third law + post-Keplerian parameters)
- **Radius** $R_{J0030+0451} = 12.71^{+1.14}_{-1.19} km$
  - X-ray bursts (depend on the distance to the NS)
- **Tidal deformations**
  - Gravitational waves
- ….

Asymmetric Nuclear Matter - Neutron Stars

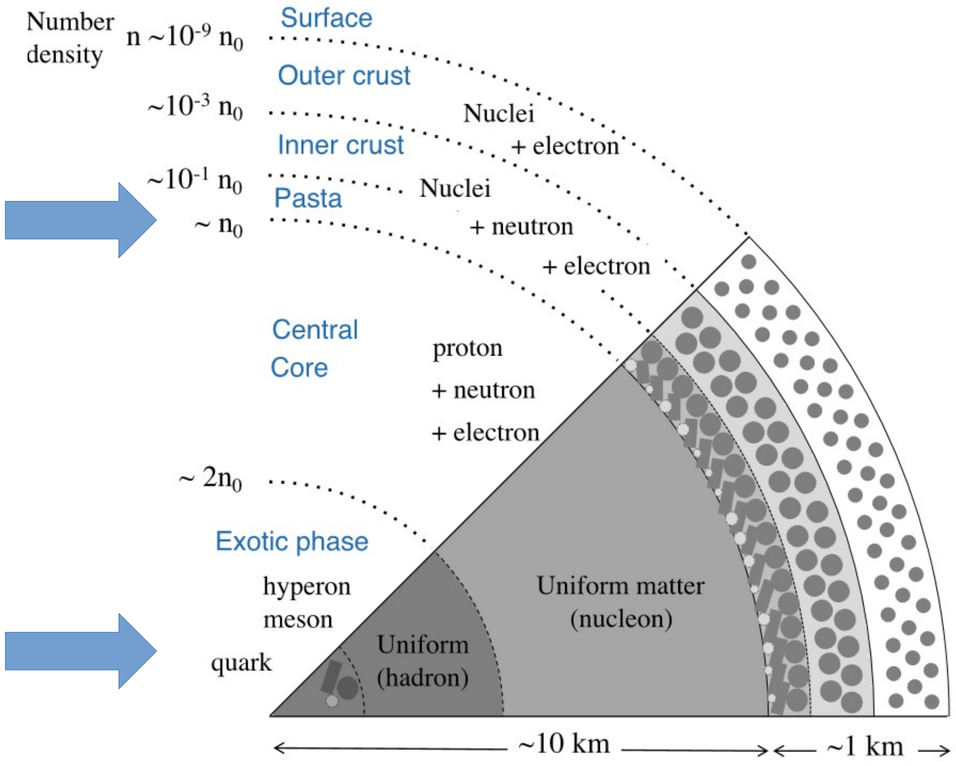
Equilibrium between gravitational force and pressure



https://astronomy.com/magazine/news/2021/10/neutron-stars-a-cosmic-gold-mine

GSI / FAIR

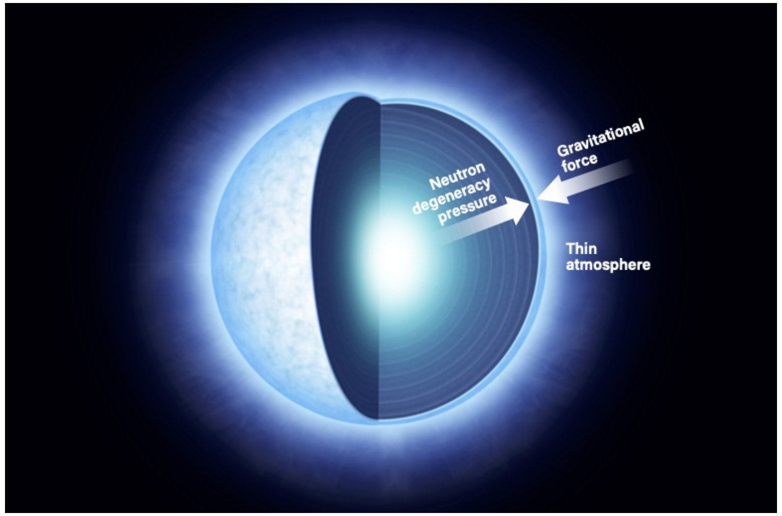
ALICE



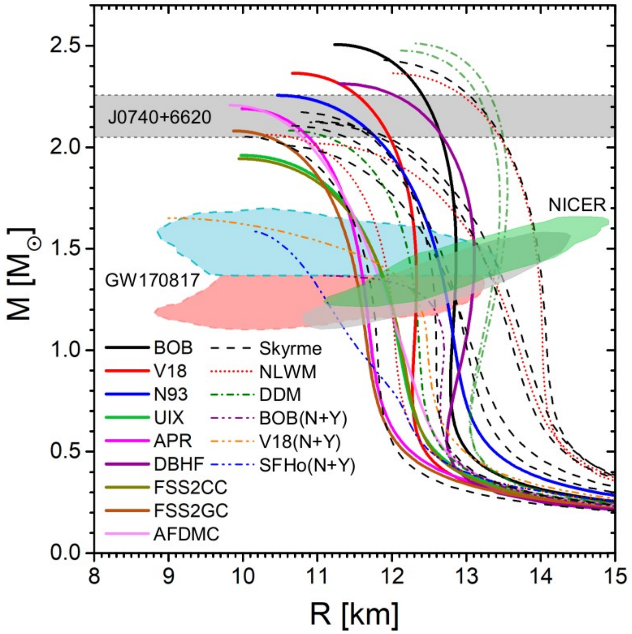
K. Sumiyoshi, The Puzzle of Supernova Explosions Unraveled by Nuclear Physics (2018)

Asymmetric Nuclear Matter - Neutron Stars

Equilibrium between gravitational force and pressure



https://astronomy.com/magazine/news/2021/10/neutron-stars-a-cosmic-gold-mine



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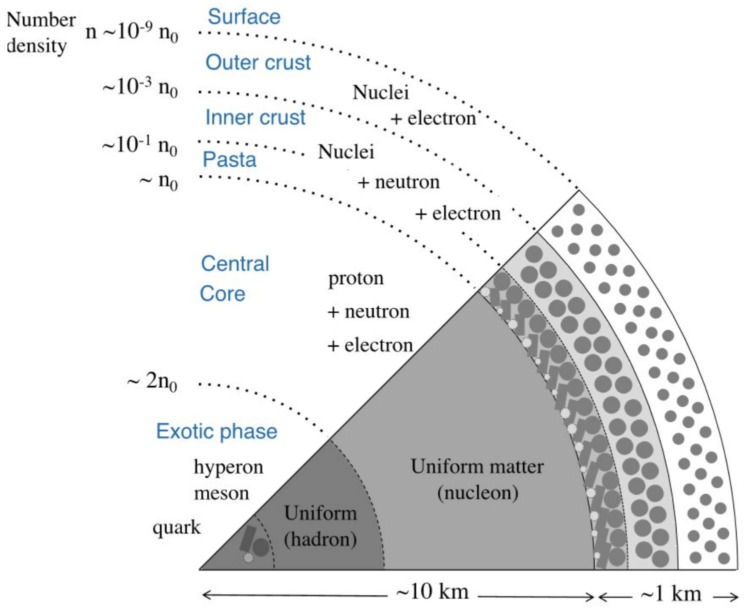

K. Sumiyoshi, The Puzzle of Supernova Explosions Unraveled by Nuclear Physics (2018)

Tolman-Oppenheimer-Volkoff (TOV) equation:

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{\rho(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{M(r)}\right)\left(1-\frac{2GM(r)}{r}\right)^{-1}$$

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)$$

Boundary conditions:

$P(0)=P_0 \quad M(0)=0$

$P(R)=0 \quad M(R)=M_{max}$

Equation of State

Equation of State

Energy per nucleon:

$$E(\rho,\delta)=E(\rho,0)+\underbrace{S(\rho)}\delta^2+O(\rho^4)$$

Asymmetry parameter:

$$\delta=(\rho_n-\rho_p)/\rho$$

Symmetry energy:

$$S(\rho)=J+\frac{L}{3}\alpha+\frac{1}{18}K_{sym}\alpha^2+O(\alpha^3)$$

Density-shift parameter:

$$\alpha=(\rho-\rho_0)/\rho_0$$

Highly model dependent!

Input for TOV-equation:

$$P=\rho_B^2\left(\frac{\partial E}{\partial \rho_B}\right) \qquad T=\left(\frac{\partial E}{\partial s}\right) \qquad \mu_i=\left(\frac{\partial E}{\partial Y_i}\right)$$

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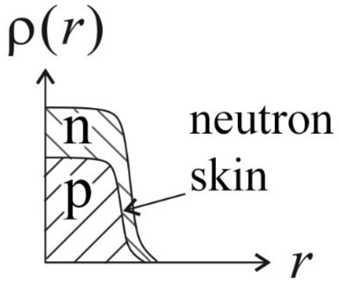

$$\Delta r_{np}=\langle r_n^2\rangle^{1/2}-\langle r_p^2\rangle^{1/2}$$

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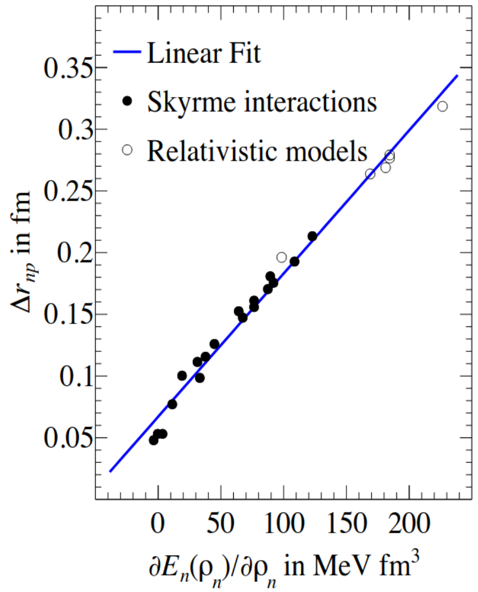
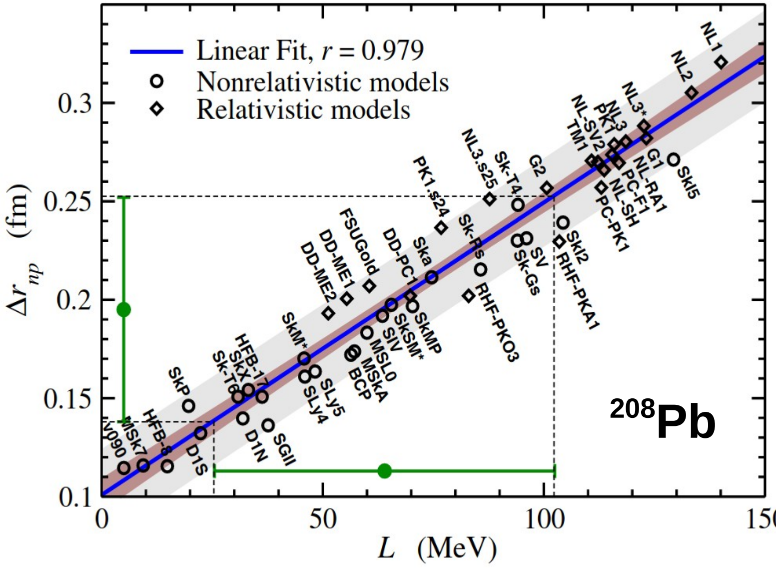
$$P=\rho_B^2\left(\frac{\partial E}{\partial\rho_B}\right)\qquad T=\left(\frac{\partial E}{\partial s}\right)\qquad \mu_i=\left(\frac{\partial E}{\partial Y_i}\right)$$

Constraining the slope parameter L experimentally via neutron-skin thickness

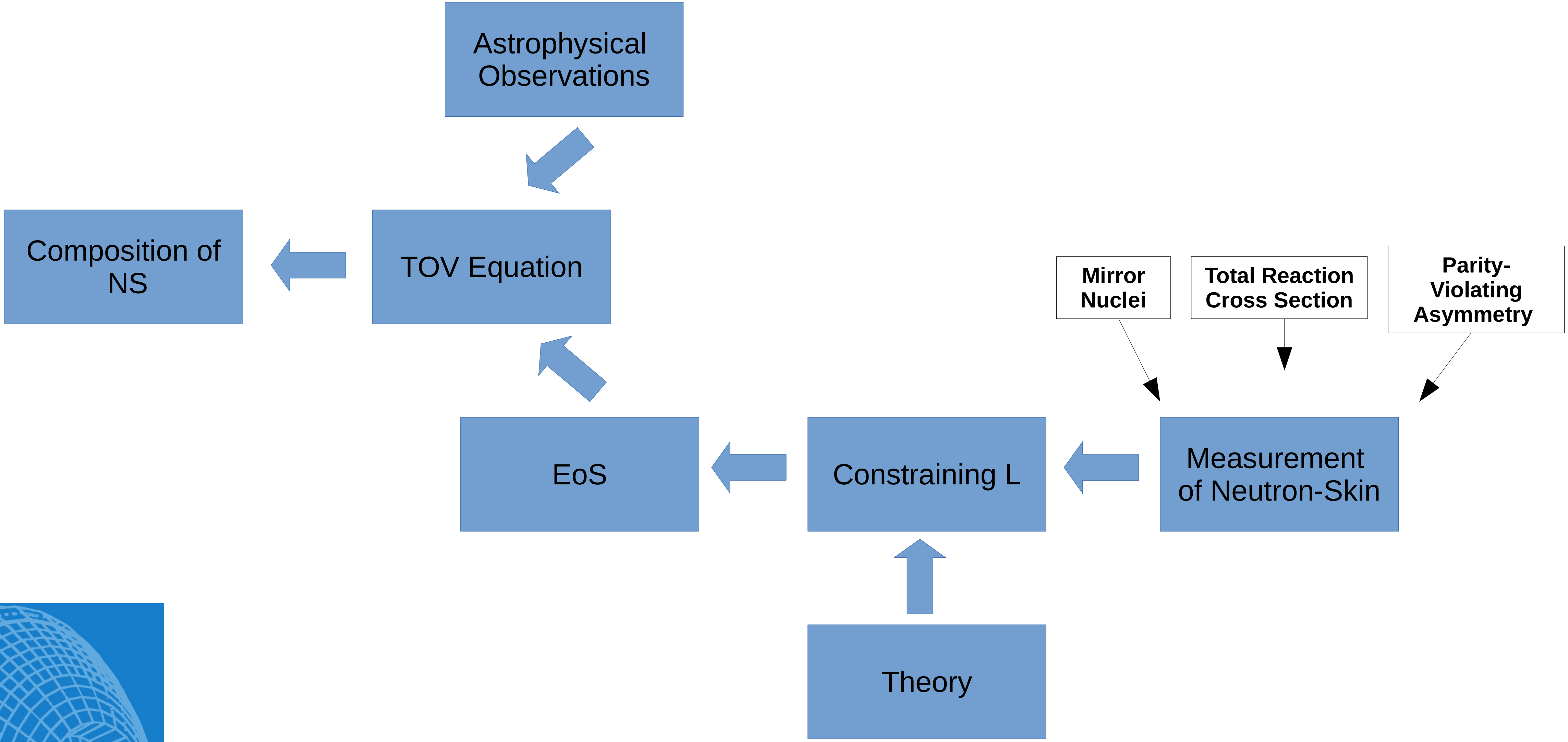


S. Typel, B.A.Brown, Phys.Rev.C 64, 027302 (2001)



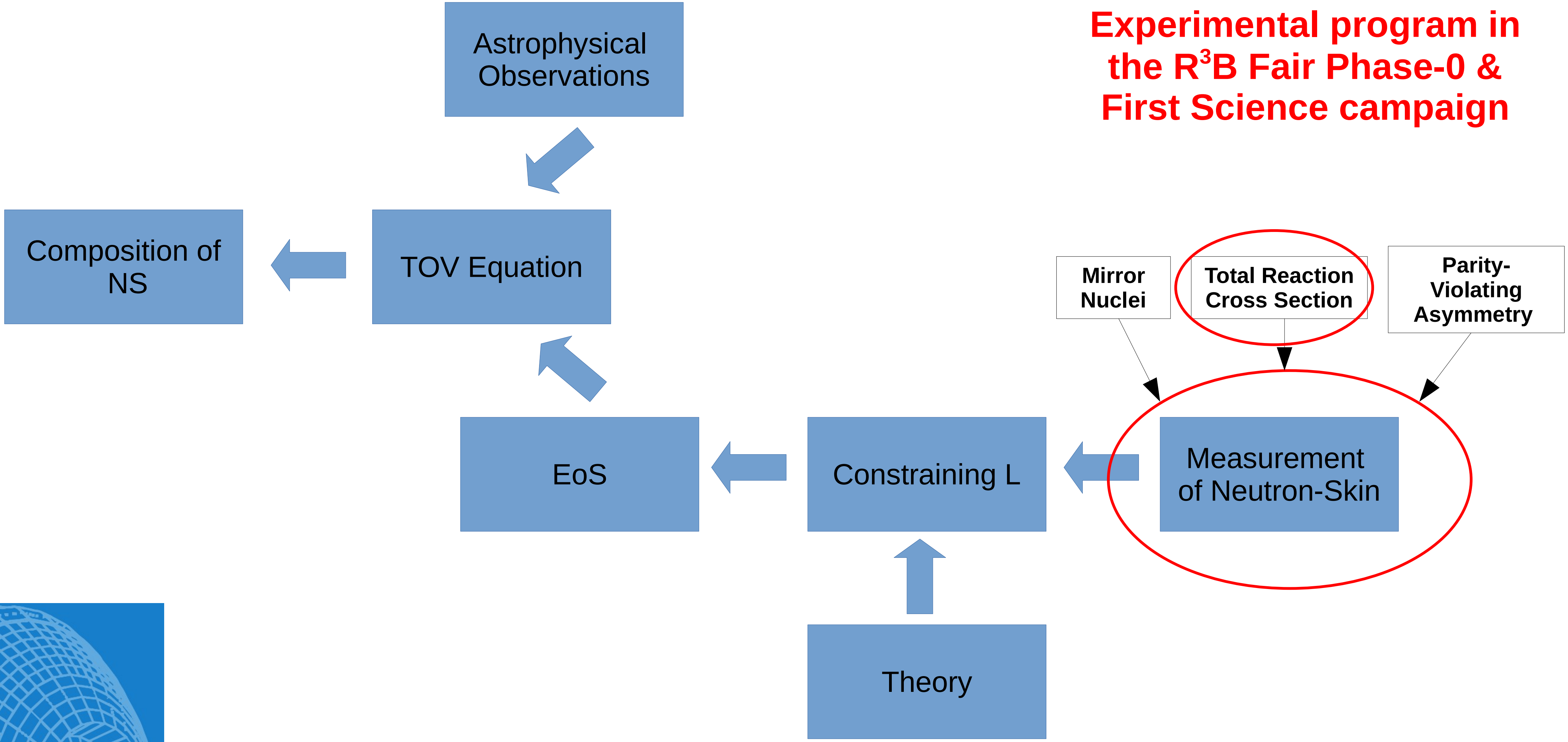
X. Roca-Maza et a. Phys.Rev.Lett. C 106, 252501 (2011)

First Summary



First Summary

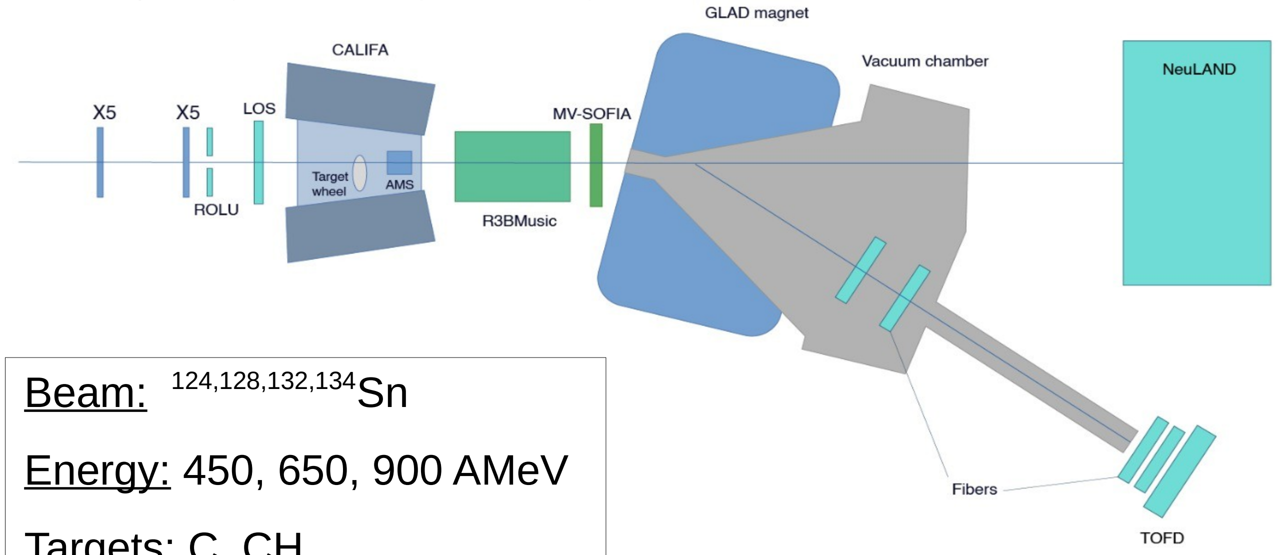
Experimental program in the R^{3}B Fair Phase-0 & First Science campaign



S473 Neutron Skin thickness @ GSI during FAIR Phase-0

Constraining energy-density functionals and the density-dependence of the symmetry energy

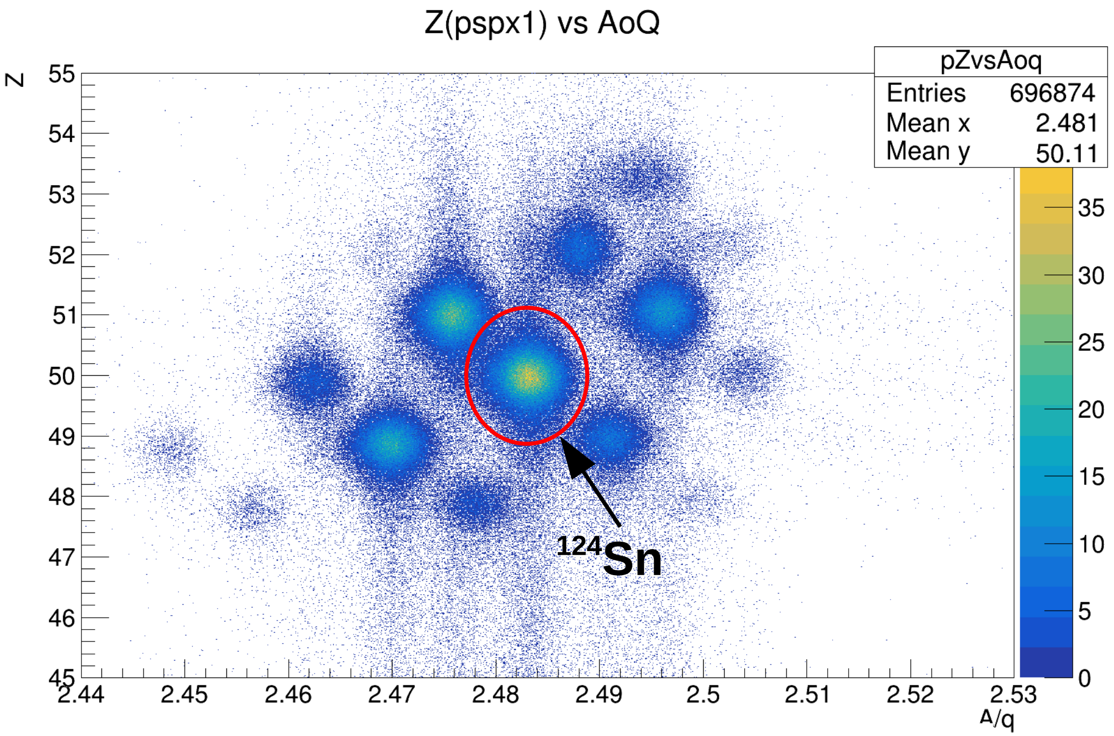
Proposed by Tom Aumann (TU Darmstadt)



<u>Beam:</u> ^{124,128,132,134}Sn

<u>Energy:</u> 450, 650, 900 AMeV

<u>Targets:</u> C, CH_2



Analysis by: Eleonora Kudaibergenova – TU Darmstadt AG Aumann

<u>Challenge & Motivation:</u>

- Measurement of total reaction, charge-changing and neutron removal cross sections along the tin isotopic chain ^{124,128,132,134}Sn
- A direct comparison of cross sections to predictions based on Glauber theory leads to neutron density distribution

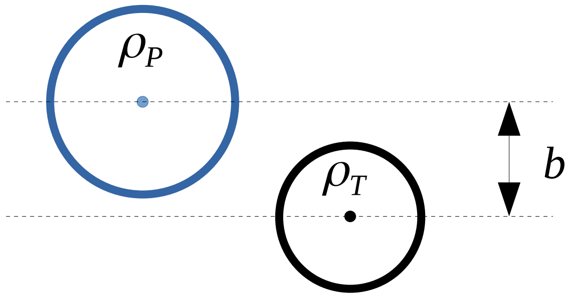
$$\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$$

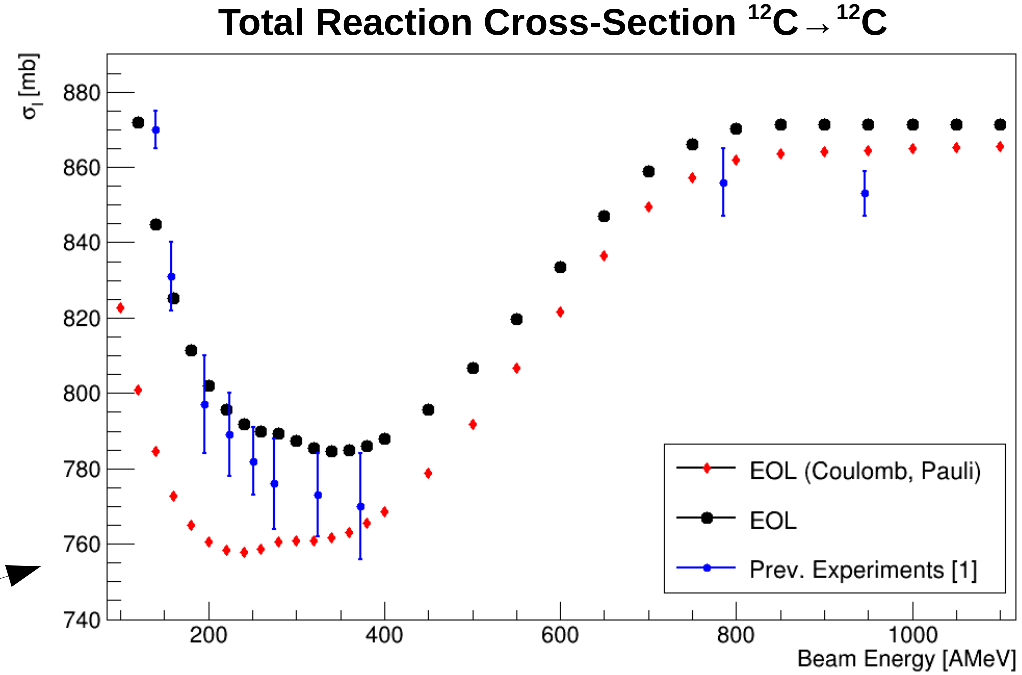
The Glauber-Model

<u>Reaction processes & integrated cross sections</u>

- **σ_{el} : Total elastic cross section**
  The projectile stays in its ground state
- **σ_{inel} : Total inelastic cross section**
  The projectile is exited to a bound state
- **σ_{I} : Total Interaction cross section**
  The projectile changes its identity = $\boldsymbol{\sigma_{\Delta Z} + \sigma_{\Delta N}}$

→ **σ_R : Total reaction cross section= $\sigma_{inel} + \sigma_I$**





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 [Bertulani, de Conti]

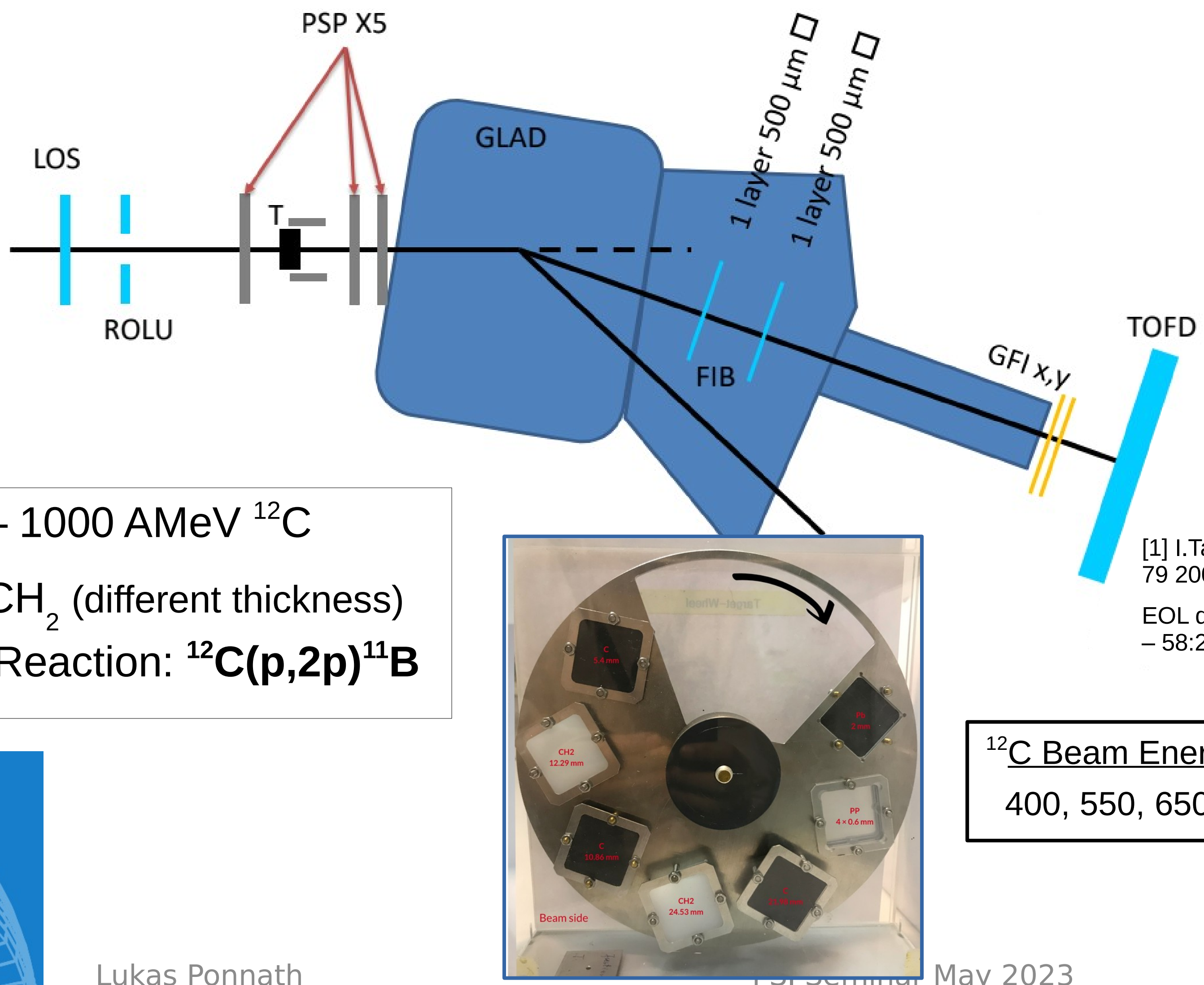
→ For medium to heavy nuclei collective excitations become relevant

[1] I.Tanihata et al. (Radioactive Nuclear Beams 1990), M. Takechi et al. (PRC – 79 2009) , A. Ozawa et al. (Nuc. Phy. A – 691 2001)

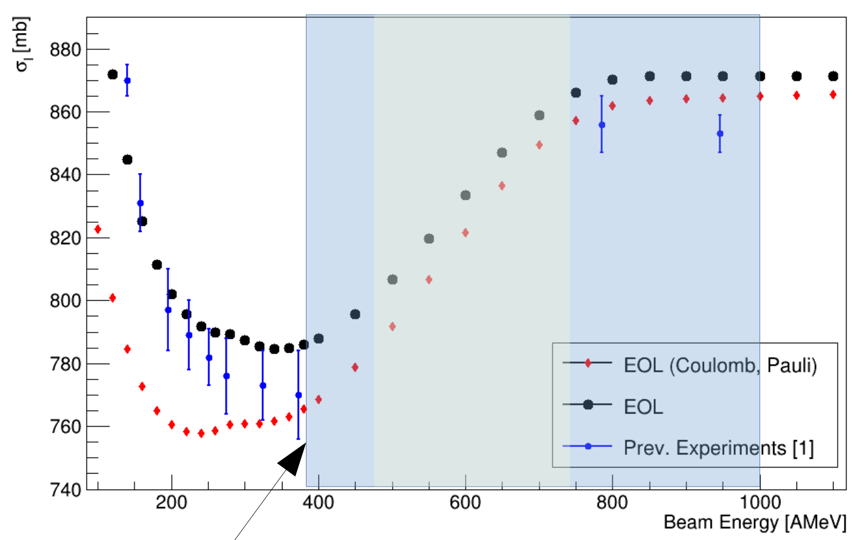
EOL data: E.A. Teixeira, T. Aumann, C.A. Bertulani, B.V. Carlson (Eur. Phys. J.A – 58:205 2022)

S444 Commissioning Experiment

First common operation of GLAD and R^3B detectors



Total Reaction Cross Section $^{12}C \rightarrow {}^{12}C$



Beam: 400 – 1000 AMeV ^{12}C

Targets: C, CH_2 (different thickness)

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

[1] I.Tanihata et al. (Radioactive Nuclear Beams 1990), M. Takechi et al. (PRC – 79 2009) , A. Ozawa et al. (Nuc. Phy. A – 691 2001)

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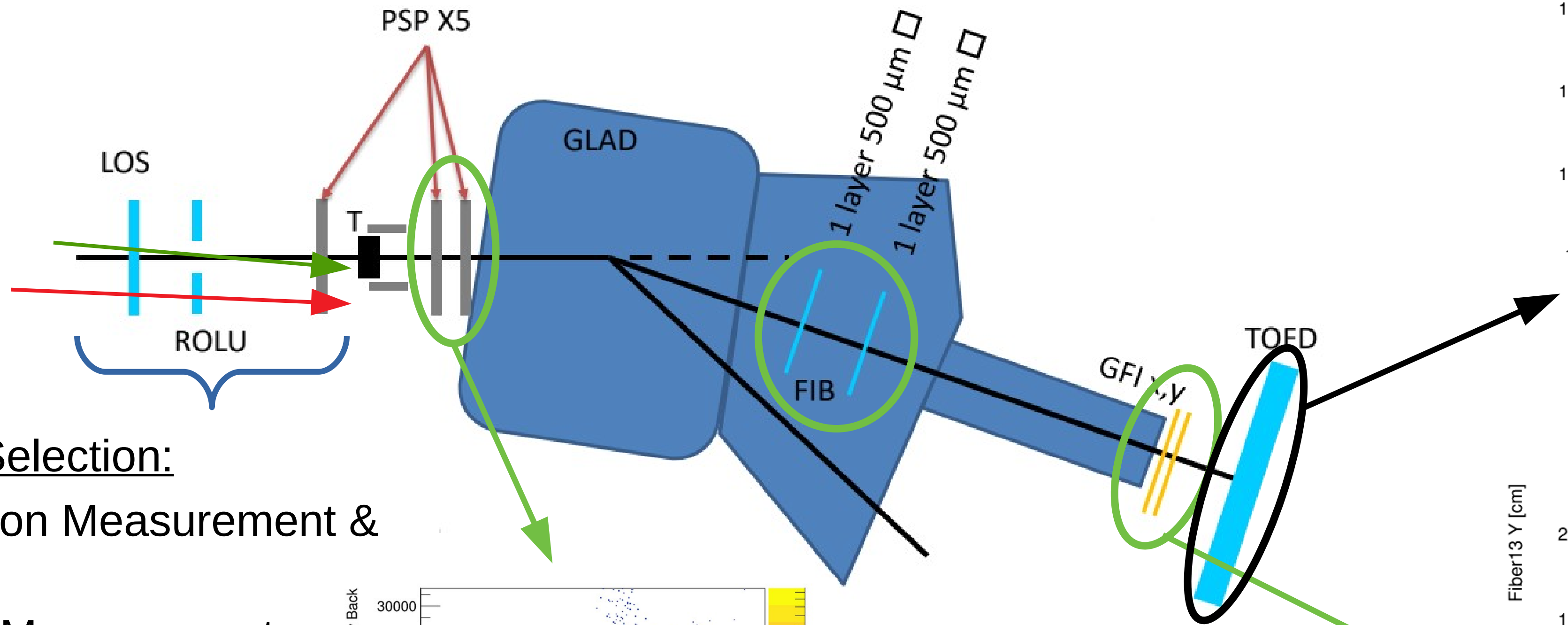
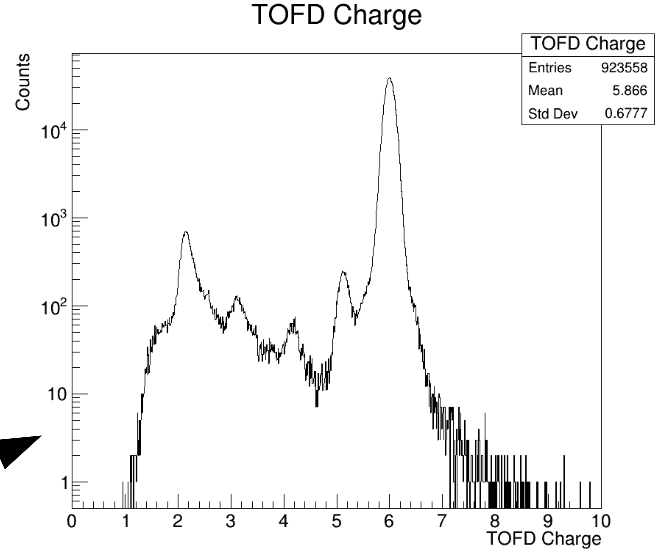
^{12}C Beam Energies in S444 Experiment:

400, 550, 650, 800 & 1000 AMeV

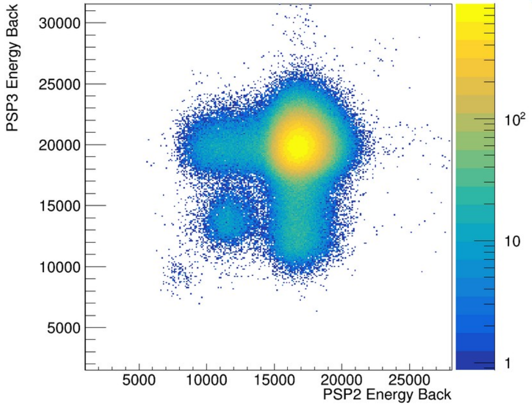
S444 Commissioning Experiment





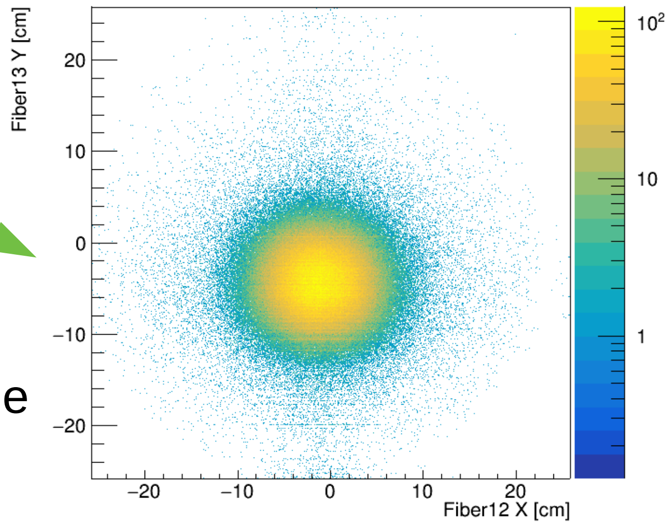
Event-Selection:

- Position Measurement & Veto
- Time Measurement
- Charge Identification

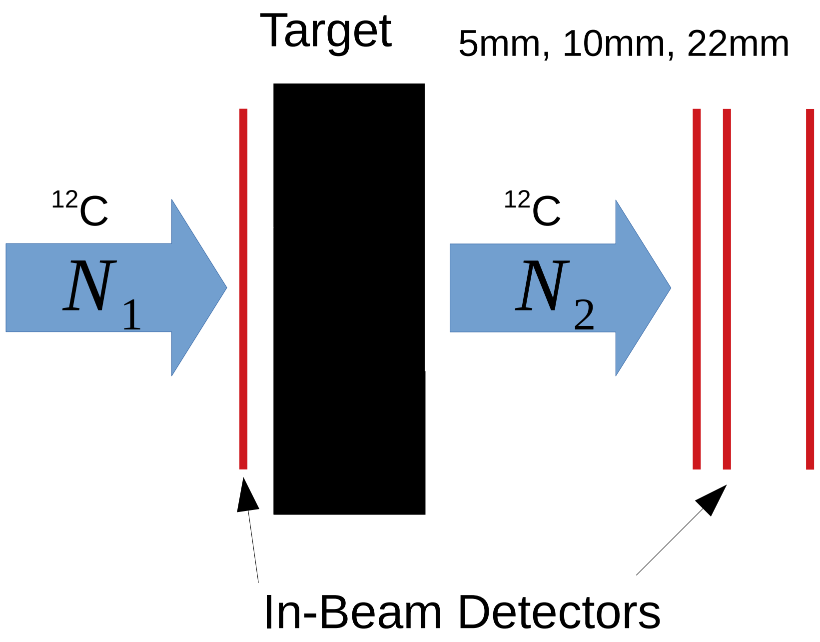


Silicon- & Fiber-Tracking:

- Position Measurement
- Charge Identification after the target



Total Reaction Cross-Section



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

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

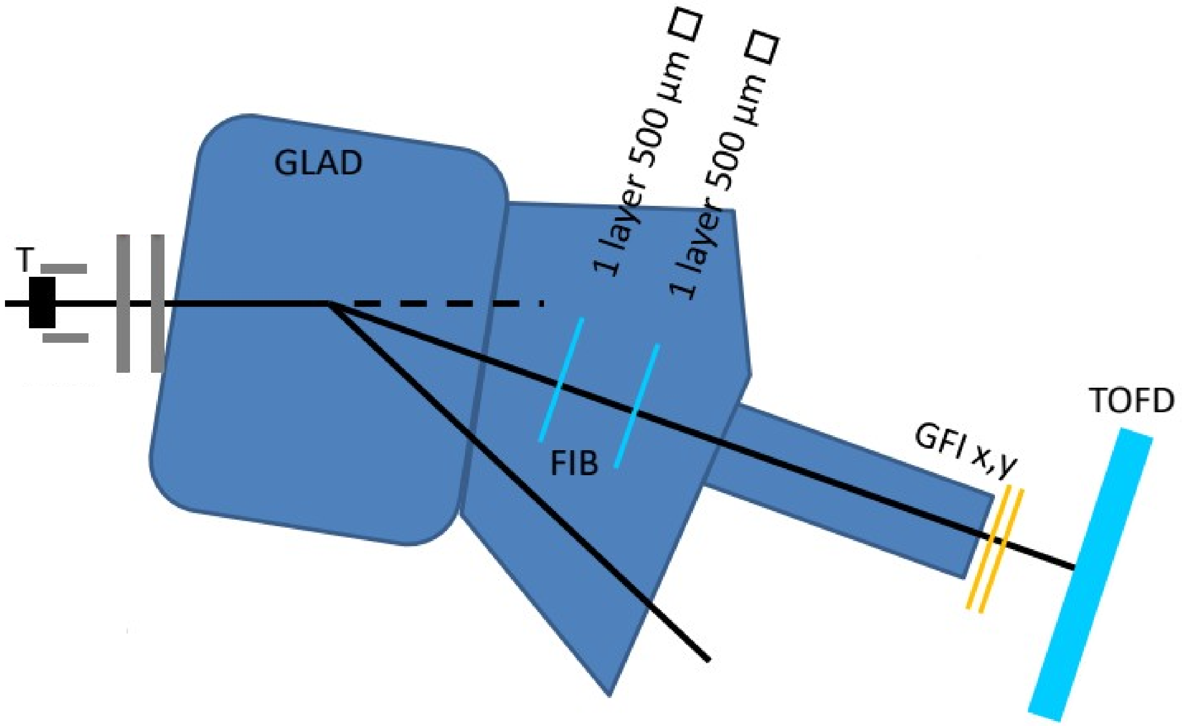
Transmission method:

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

- 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)

Challenge of Total-Reaction Cross-Section Measurements:
Reactions in Setup,Efficiency & Acceptance of Detectors

Number of non-reacting Nuclei



Strategy: minimize systematic uncertainties → minimize Number of detectors

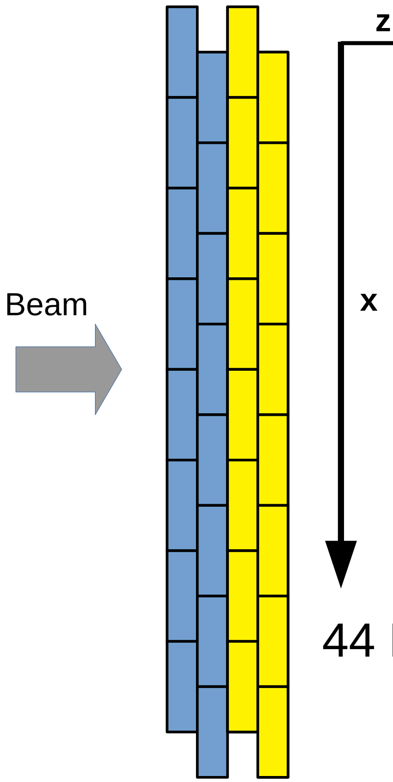
1. Count the number of all Carbon (Q=6) isotopes with TOFD $N_{Q=6}$
2. Identify the efficiency of Carbon-identification with TOFD ε
3. Define Correction factors:

   3a. Ratio of ^{12}C to all identified Carbon isotopes $R\left({}^{12}C\right)$

   3b. Correction for lack of acceptance A

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

Carbon Identification

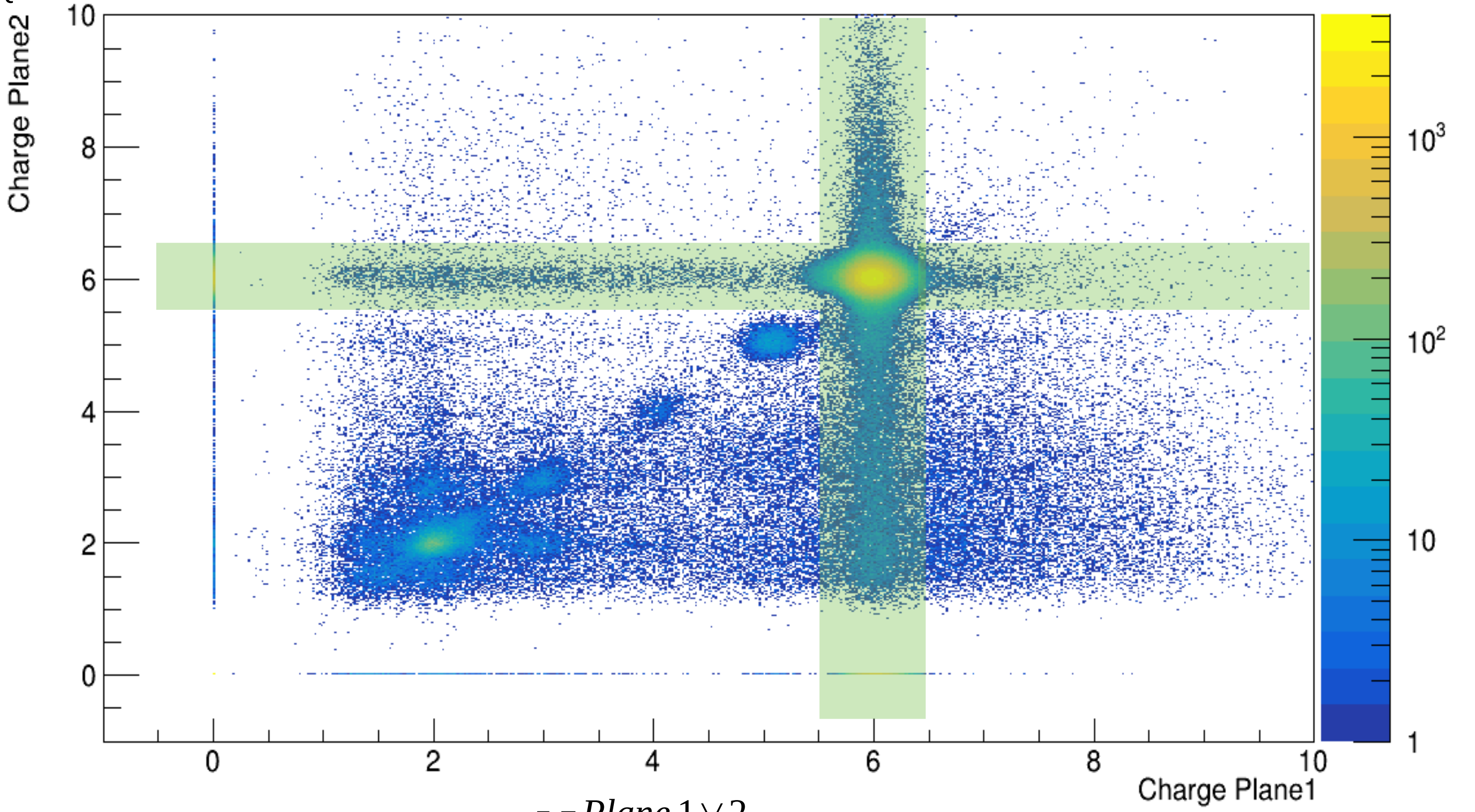


4 overlapping Planes

44 Bars

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

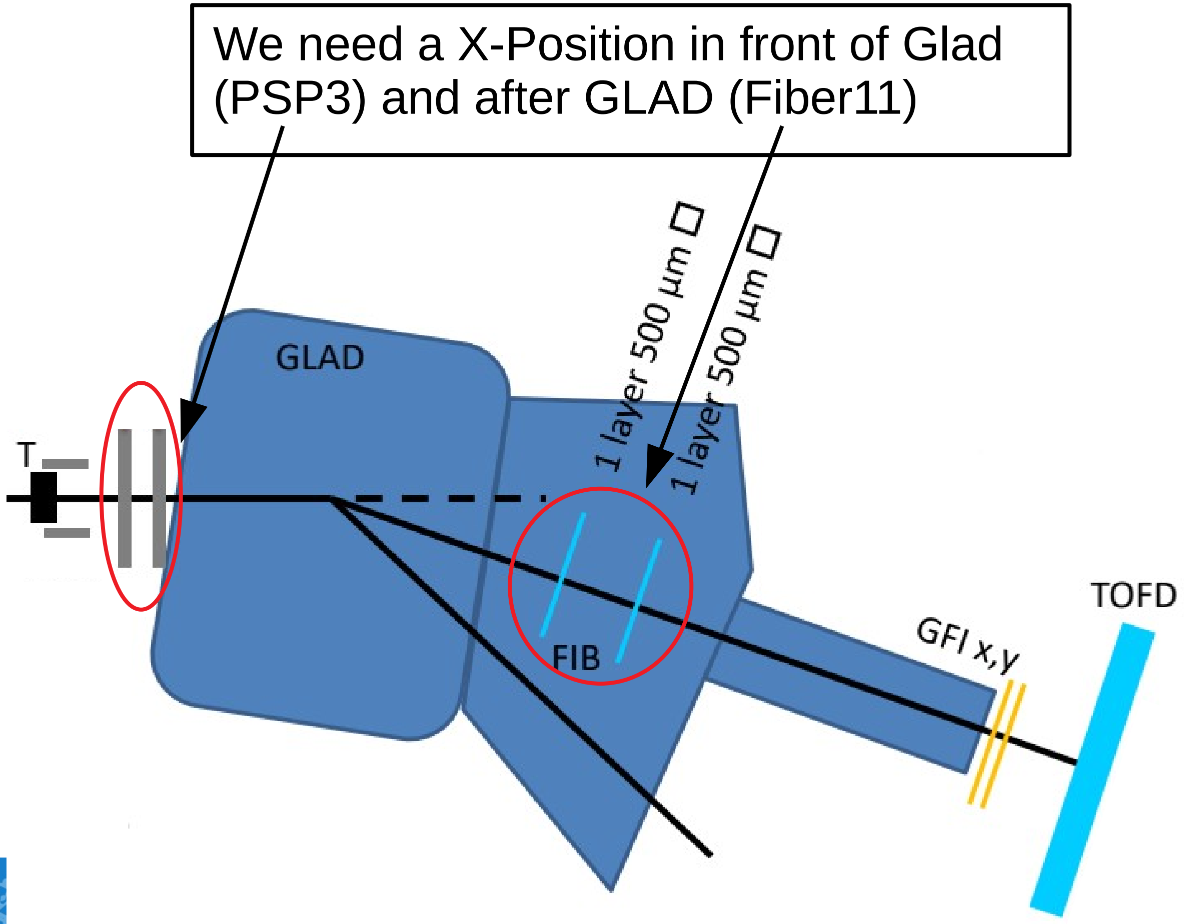
$N_{Q=6}$ = Plane1 <u>or</u> Plane2 saw a particle with Q = 6. +/- 0.5 (>99.9993 %)



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

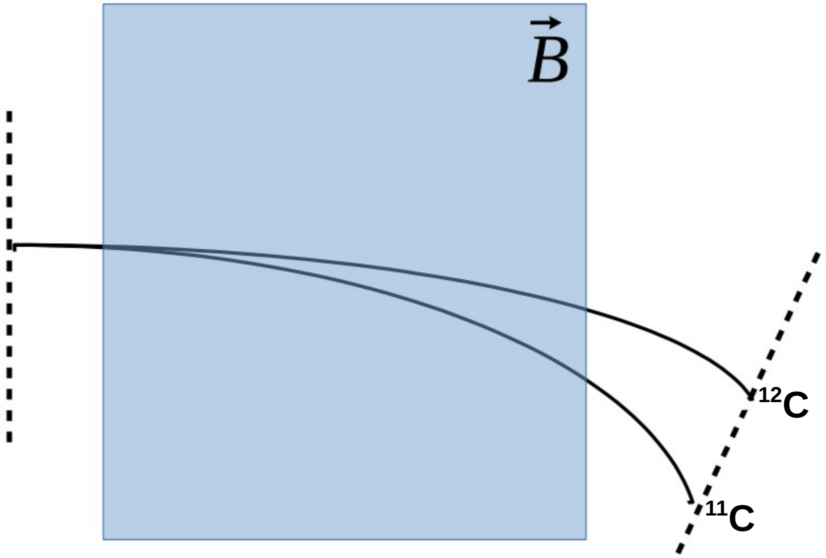
Isotope-Correction

We need a X-Position in front of Glad (PSP3) and after GLAD (Fiber11)

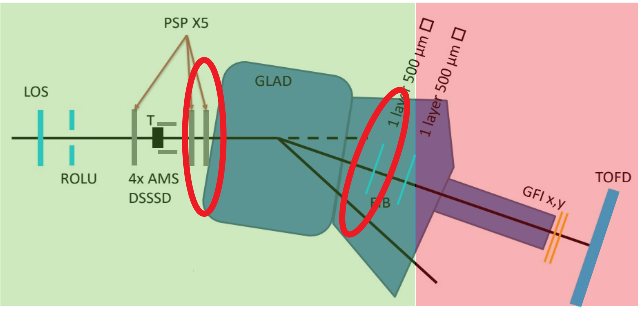


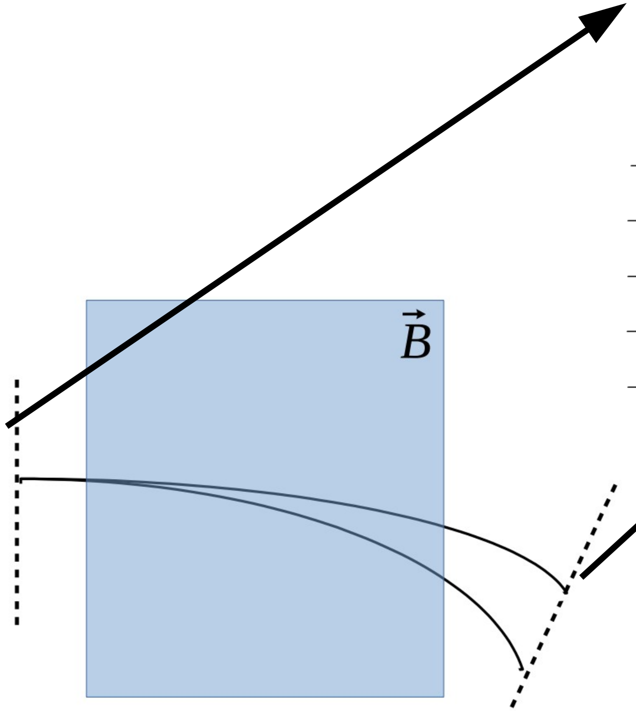
Isotopes with different mass (A) have a different bending-radius (ρ) in a const. Magentic field (B) .

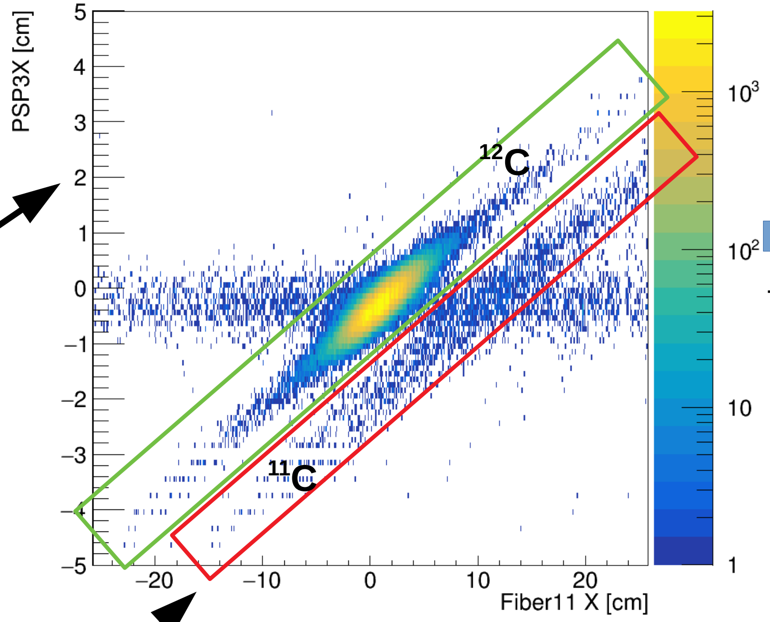
$$B\rho = \frac{A}{q} \cdot c \cdot \gamma \cdot \beta$$



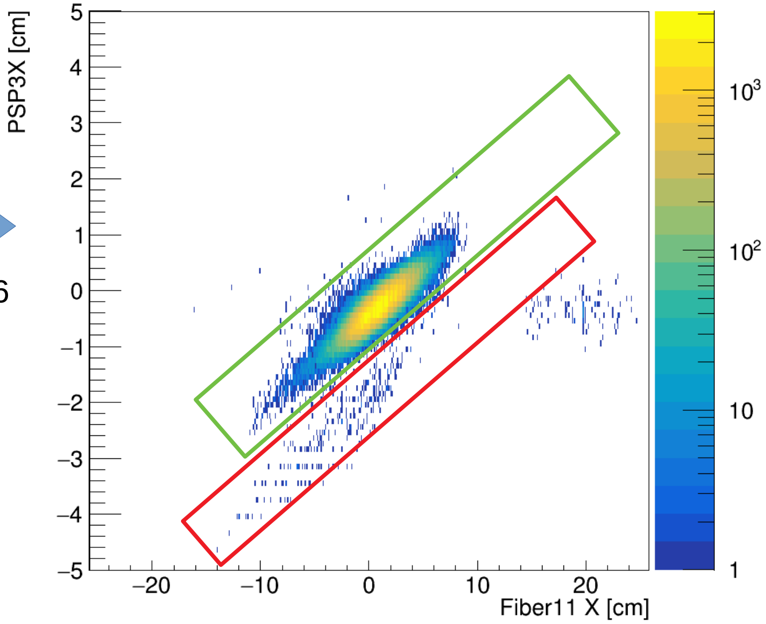
Isotope-Correction







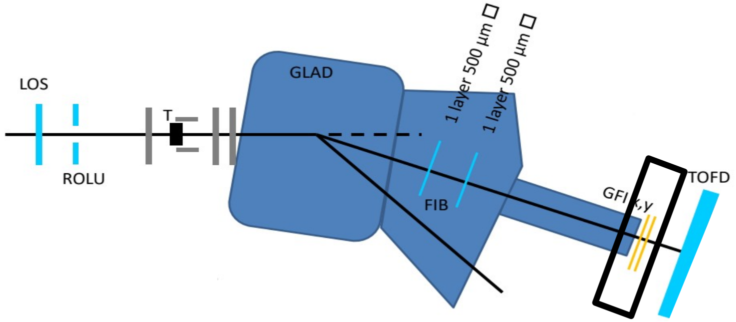
TOFD Q=6



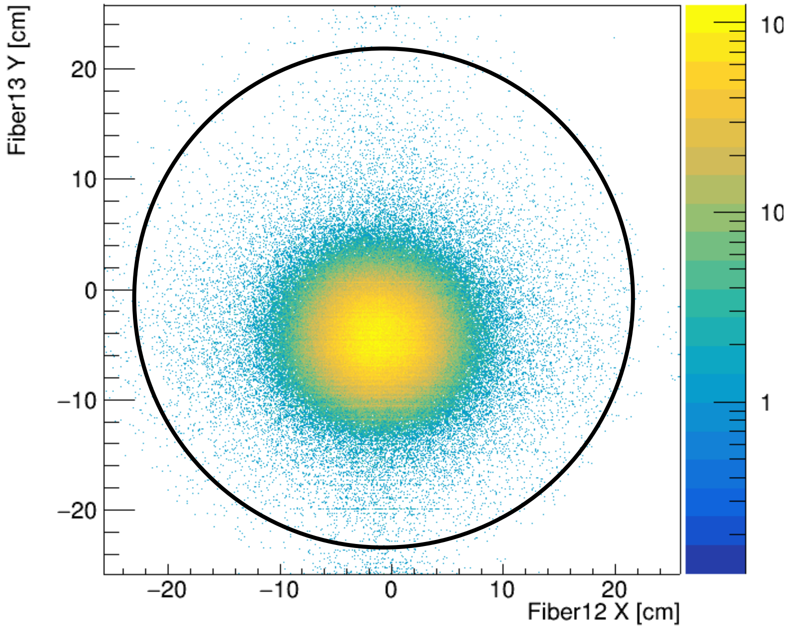
$$R(^{12}C) = 0.99950(5)$$

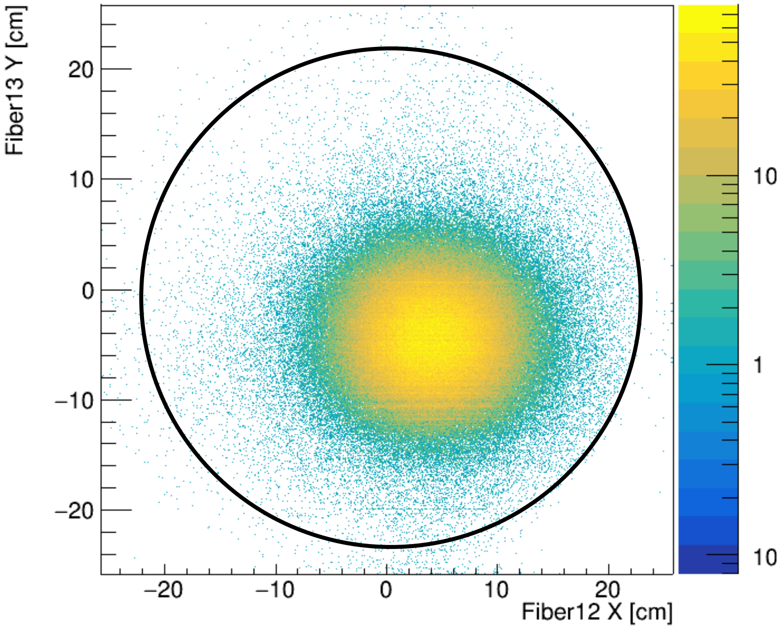
$$N_2 = \frac{N_{Q=6} \cdot R(^{12}C)}{\varepsilon \cdot A}$$

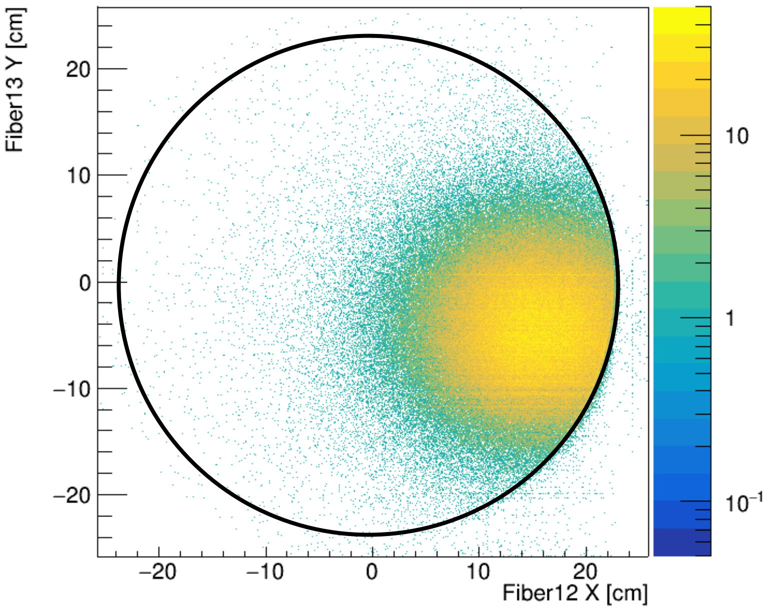
Acceptance-Correction



Beam-Energy 400 AMeV





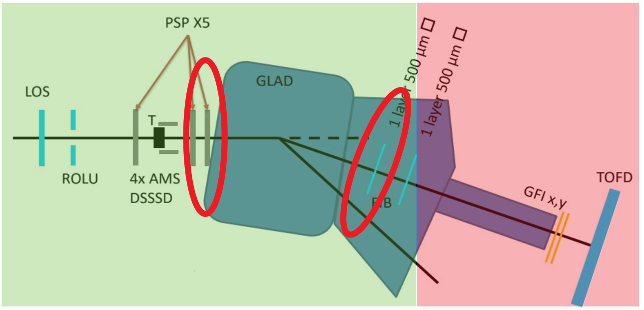


Target Thickness: 5.451 mm 10.793 mm 21.928 mm

Loss due to geometrical acceptance

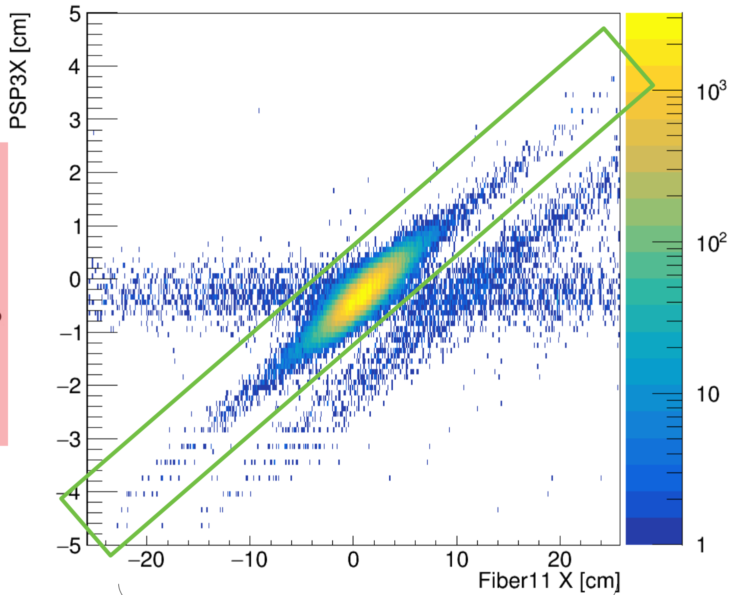
$$B\rho = \frac{A}{q} \cdot c \cdot \gamma \cdot \beta$$

Acceptance-Correction



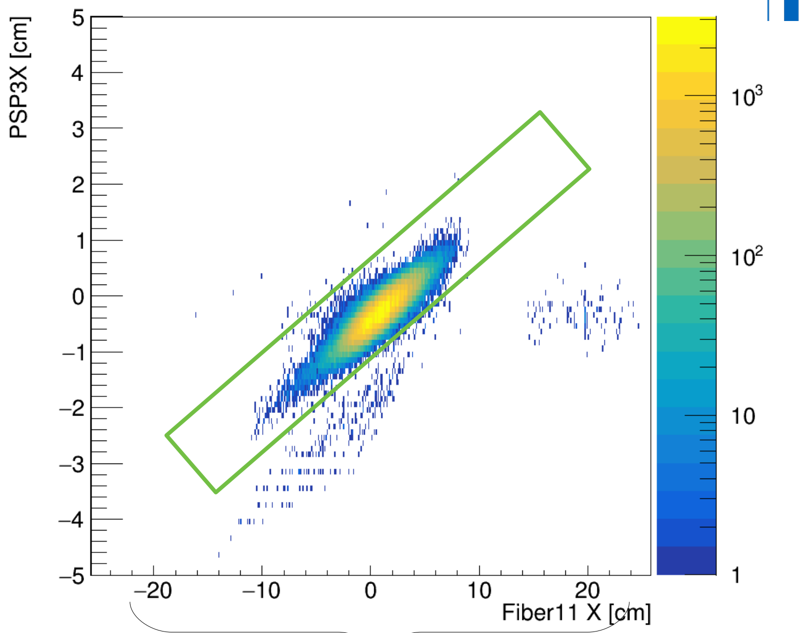
$$A = \frac{\int_{-25.8\,cm}^{25.8\,cm} g(x)}{\int_{-25.8\,cm}^{25.8\,cm} S \cdot f(x)}$$

Scaling-Factor

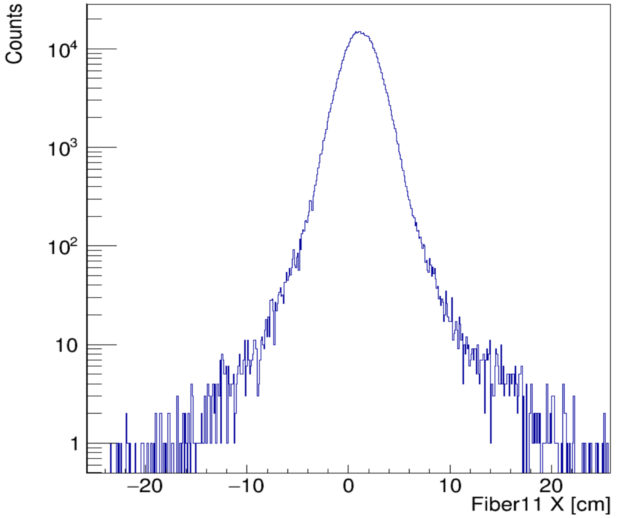


Position-Distribution of ^{12}C f(x)

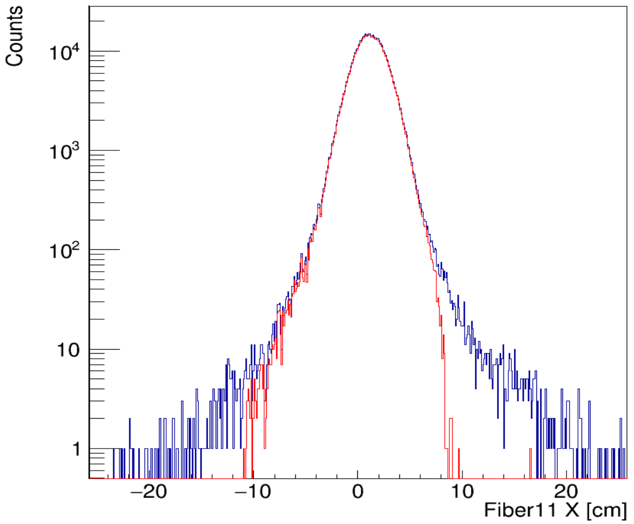
TOFD Q=6



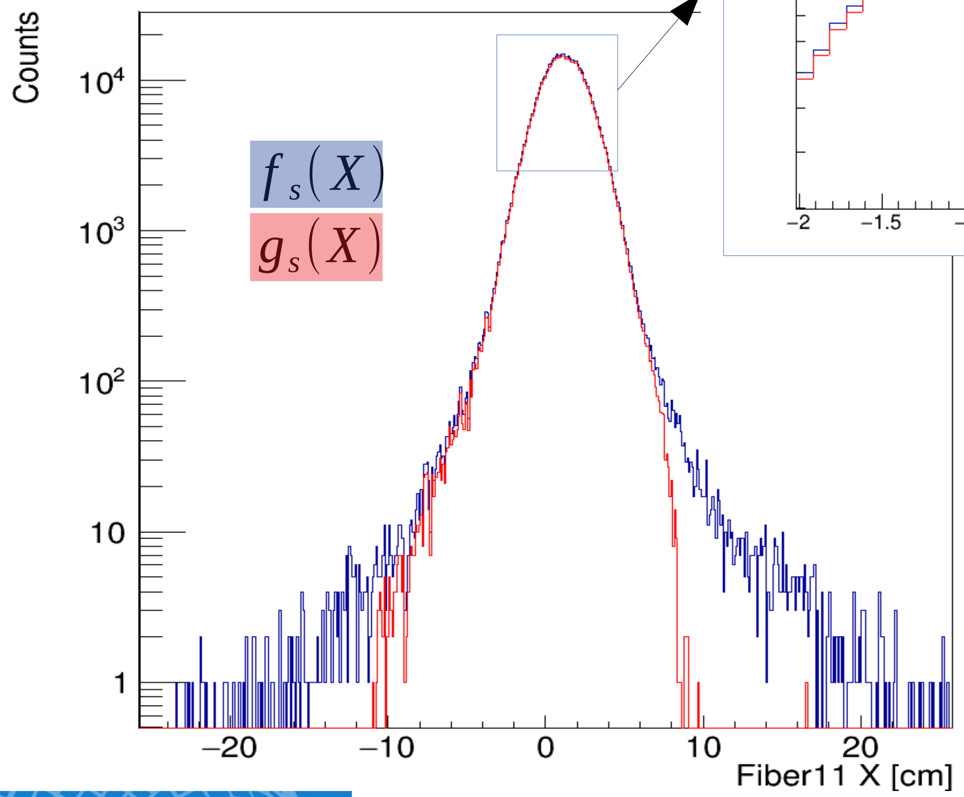
Position-Distribution of ^{12}C with TOFD g(x)

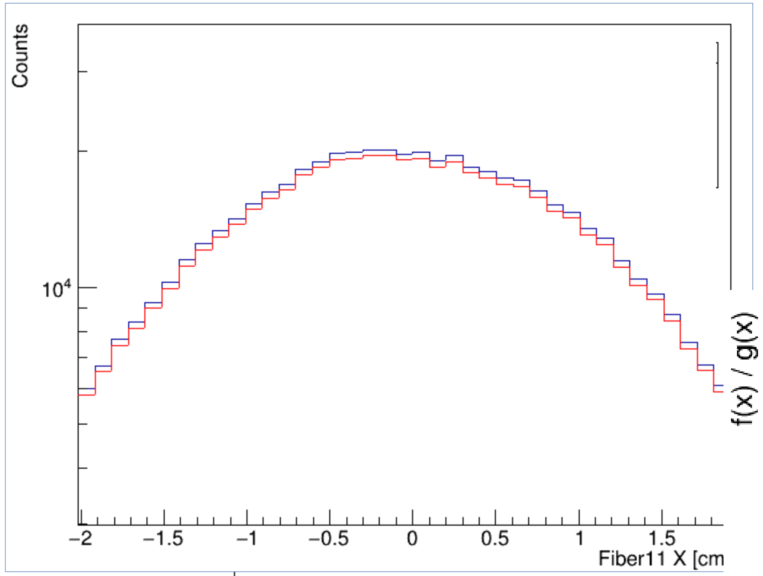


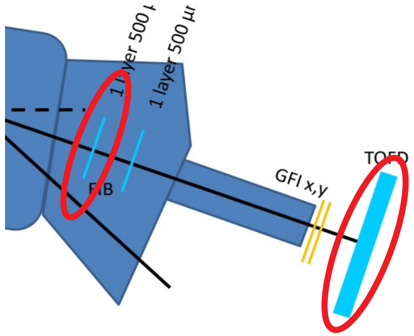
TOFD Q=6



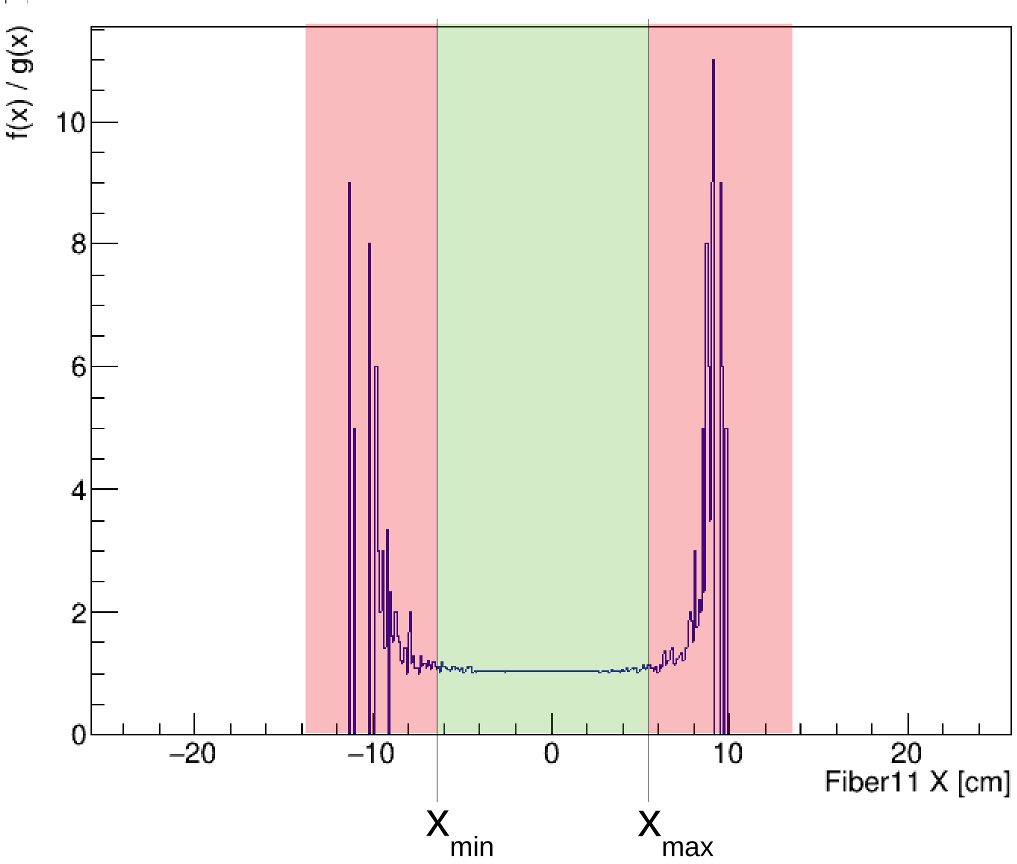
Scaling-Factor





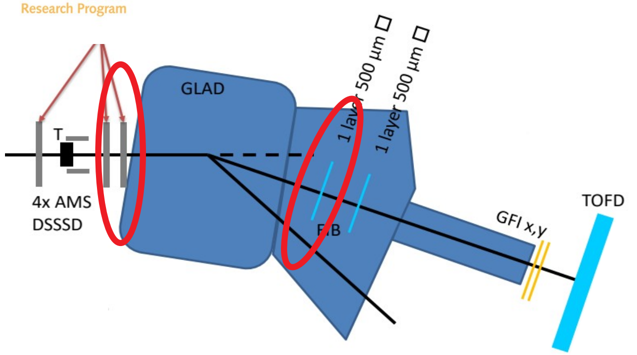


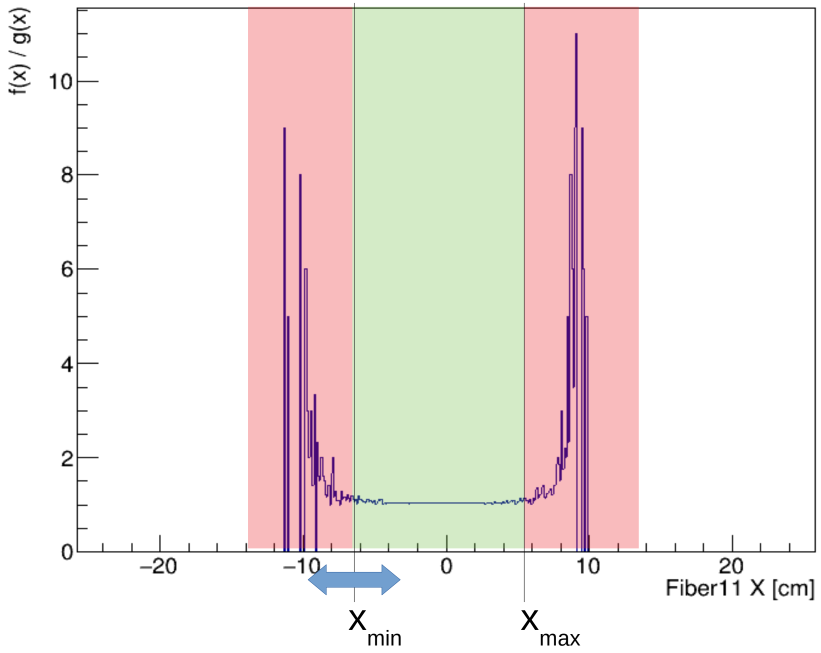
Dividing both distribution

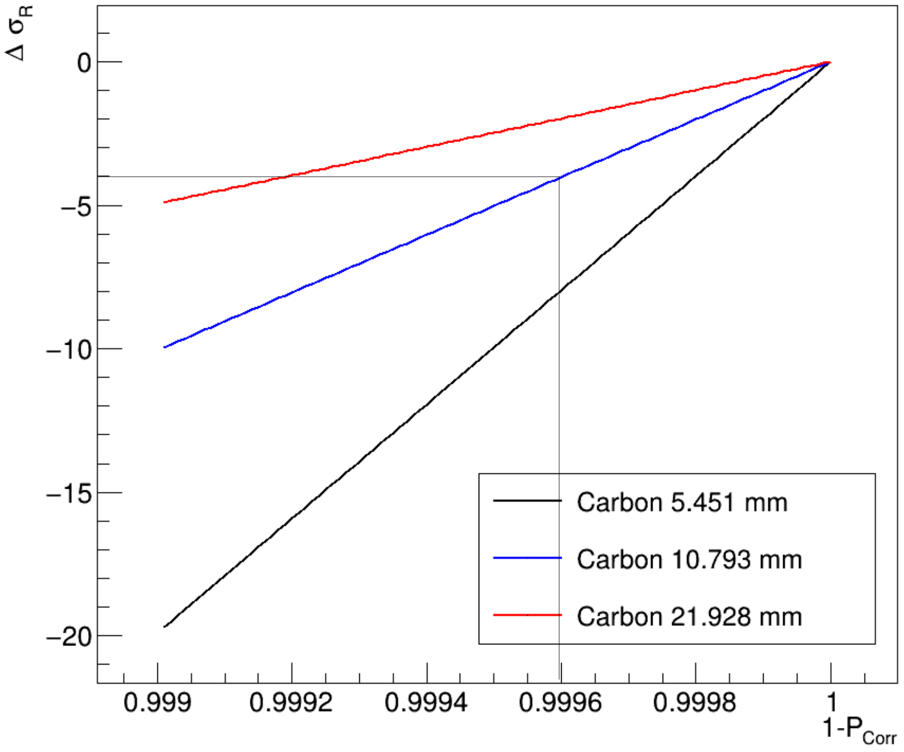


$$S = \frac{\int_{x_{min}}^{x_{max}} g_s(x)}{\int_{x_{min}}^{x_{max}} f_s(x)}$$

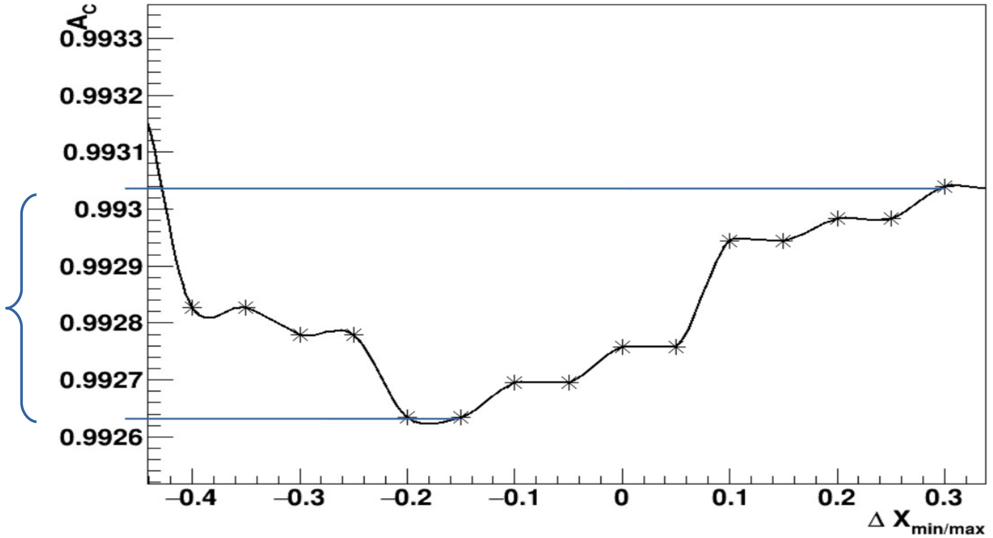
Systematic Uncertainty





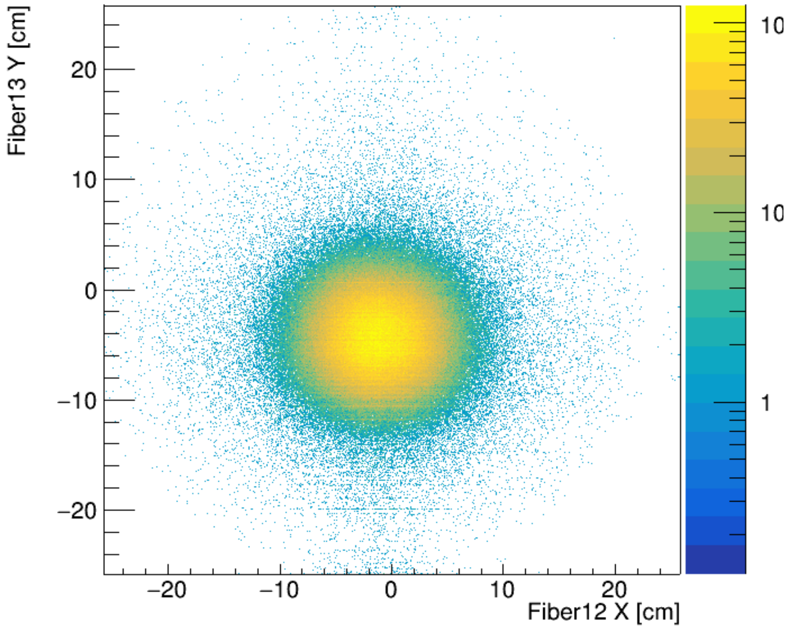


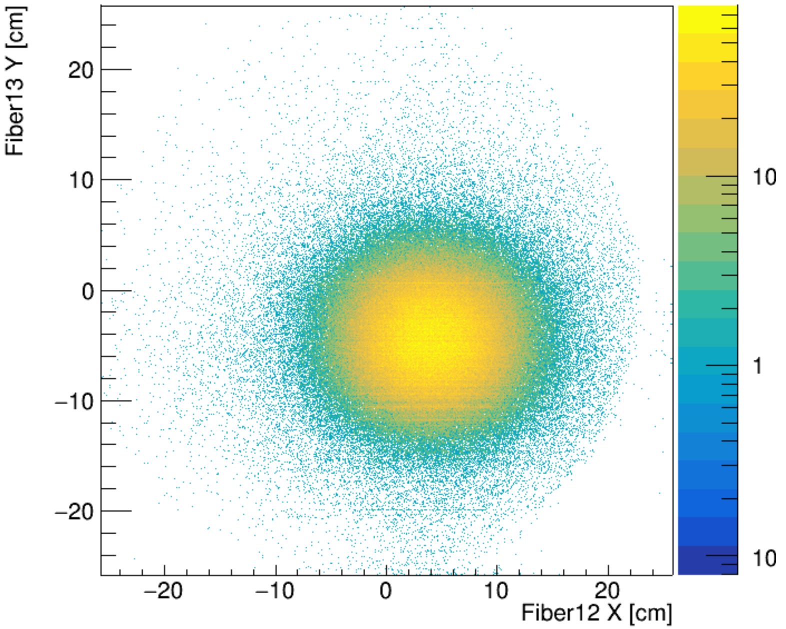
$$\Delta A_{Corr} = 0.0004$$

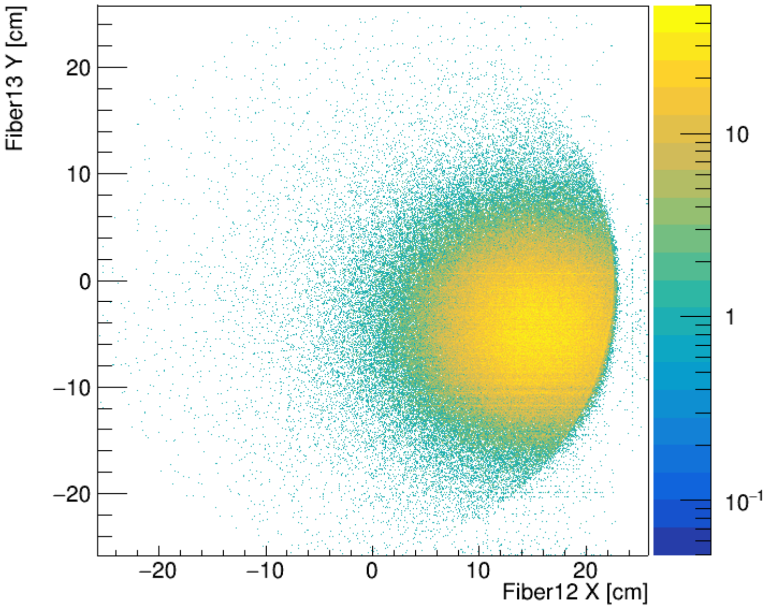


Acceptance-Correction

Beam-Energy 400 AMeV



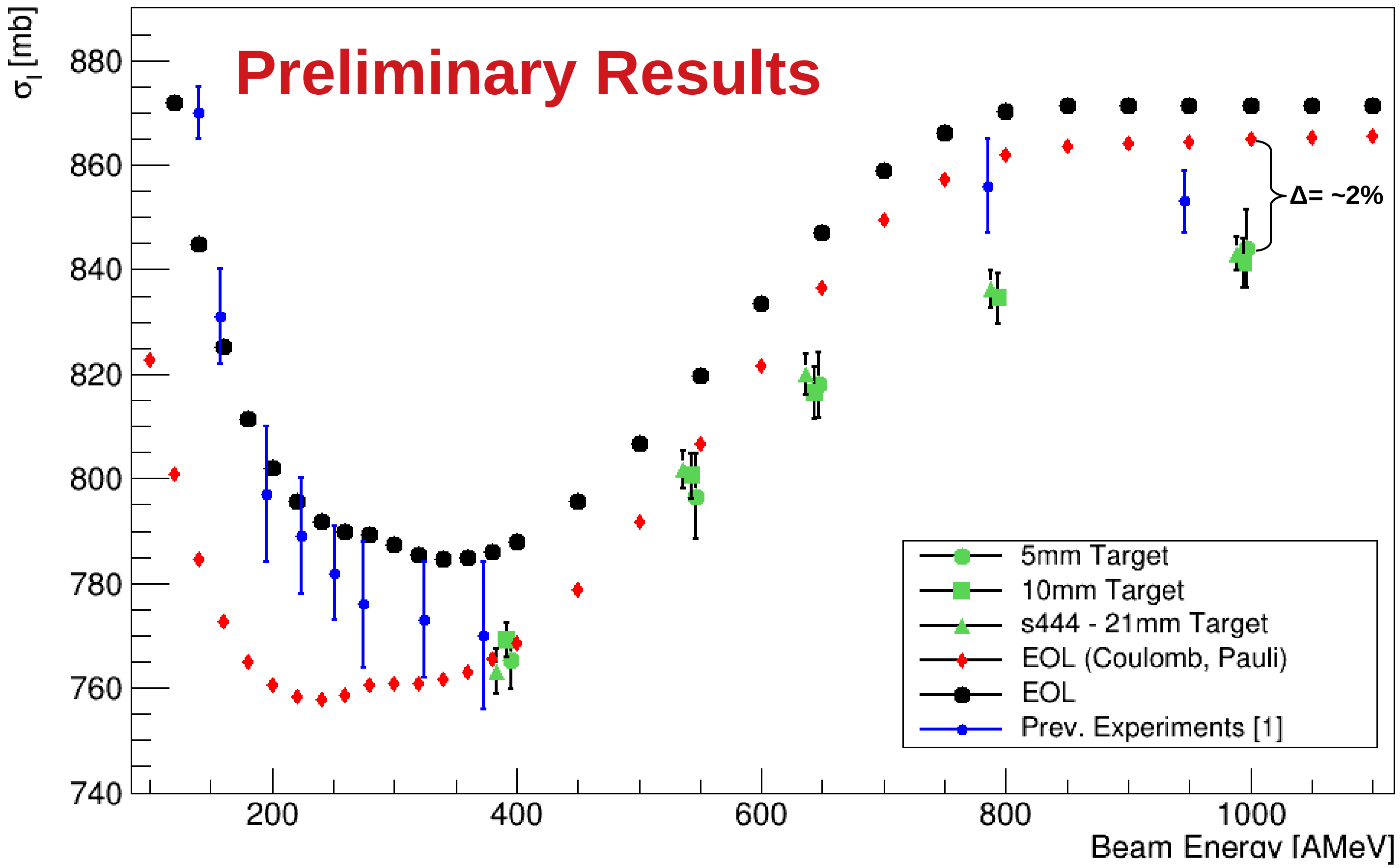




Target Thickness:	5.451 mm	10.793 mm	21.928 mm
Acceptance:	0.998358	0.99523	0.842726

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

Total Reaction Cross Section



[1] I.Tanihata et al. (Radioactive Nuclear Beams 1990), M. Takechi et al. (PRC – 79 2009) , A. Ozawa et al. (Nuc. Phy. A – 691 2001)

EOL data: E.A. Teixeira, T. Aumann, C.A. Bertulani, B.V. Carlson (Eur. Phys. J.A – 58:205 2022)

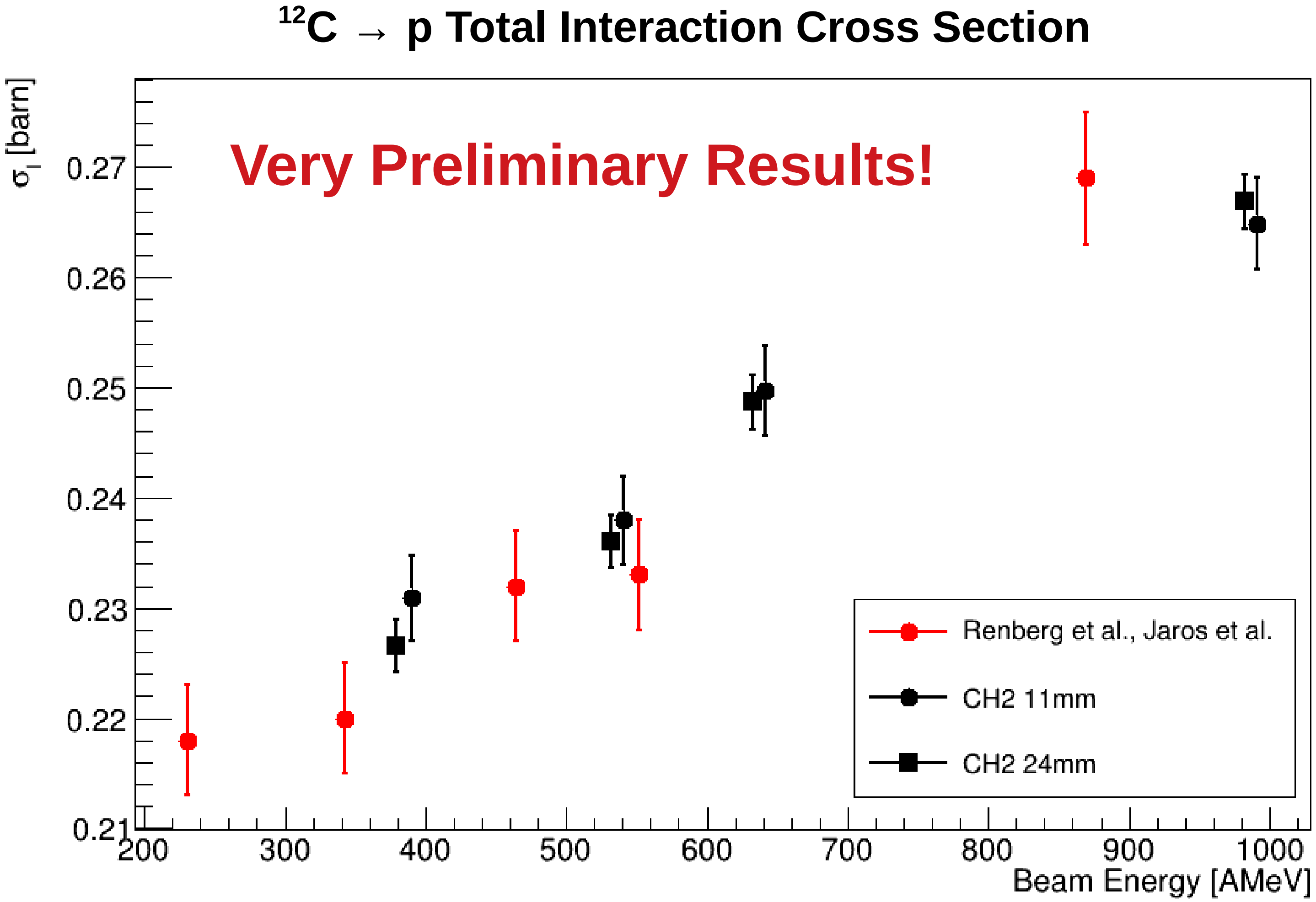
Status:

- Experimental results are in agreement with previous experiments at low energies
- Theory overestimates exp. results at high energies (~2%)
- Estimation of systematic uncertainties:

400 AMeV ^{12}C – 21mm ^{12}C Target

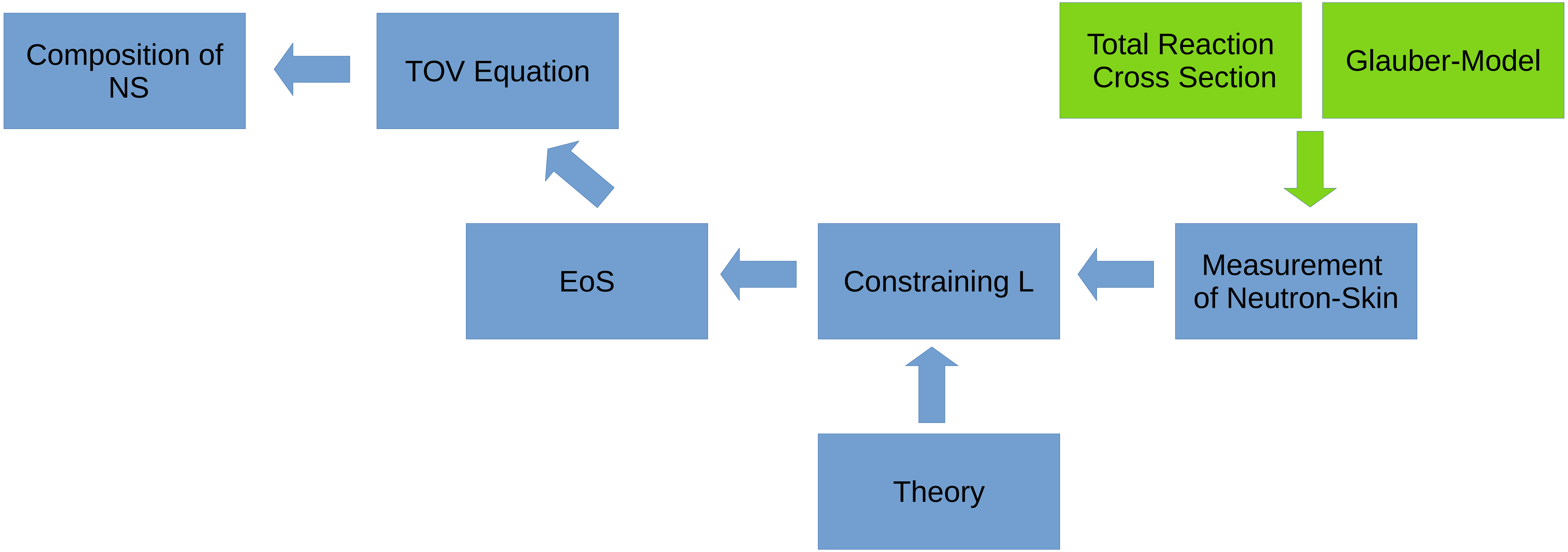
$$\sigma_R = 768.87 \pm \underbrace{2.44}_{\text{Statistical}} \pm \underbrace{0.04}_{\text{Efficiency}} \pm \underbrace{0.21}_{\text{Isotope Corr}} \pm \underbrace{1.45}_{\text{Acceptance Corr}} \, mb$$

Total Reaction Cross Section



P. Renberg et al. Nuclear Physics A 183 (1972) 81-104

Summary


Composition of NS
TOV Equation
Total Reaction Cross Section
Glauber-Model
EoS
Constraining L
Measurement of Neutron-Skin
Theory

Thank you!

CALIFA @ Technical University of Munich (TUM)

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GEFÖRDERT VOM
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