



# R<sup>3</sup>B Commissioning Experiments with Final CALIFA Setup



Supported by BMBF 05P15WOFNA 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.

GEFÖRDERT VOM

## Tobias Jenegger

R<sup>3</sup>B Experiment @ GSI

PSI Seminar  
16.06.2021

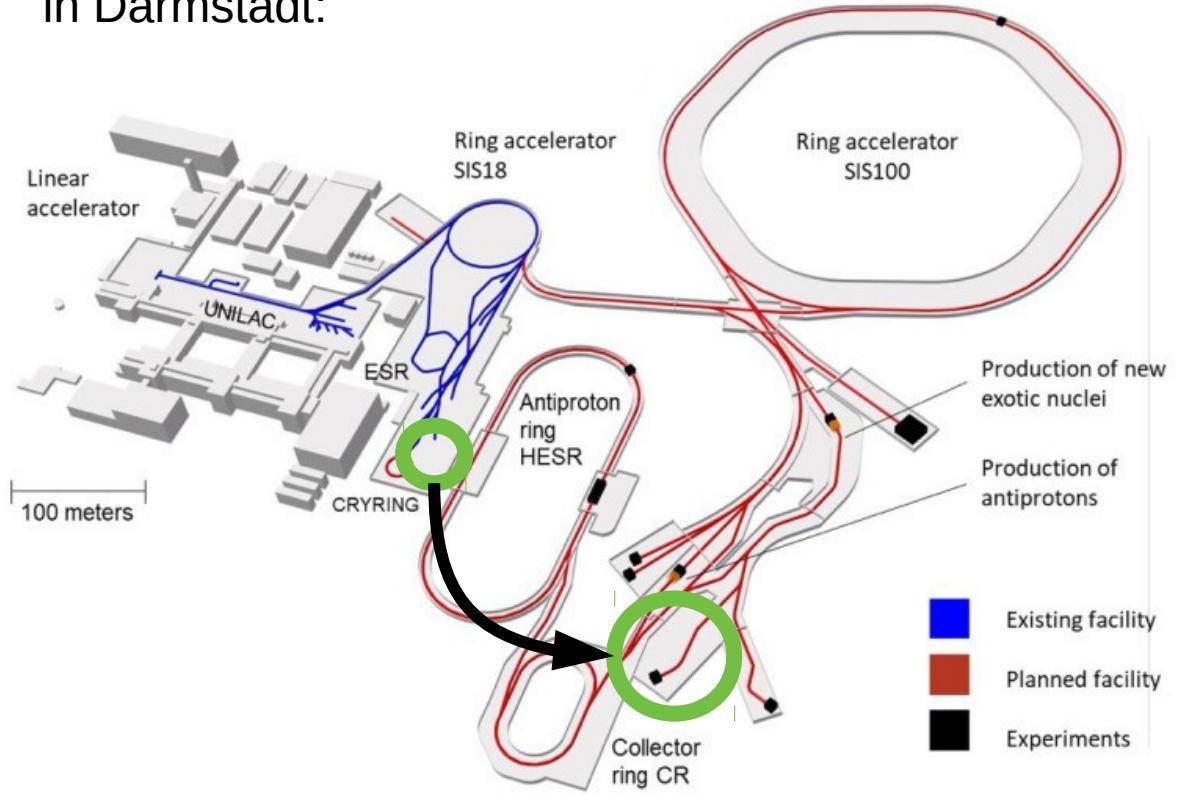
CALIFA - Design and Upgrades

12C(p,2p)11B reaction from Commissioning

QFS Analysis

TUM Members:  
Roman Gernhäuser, Lukas Ponnath, Philipp Klenze, Tobias Jenegger

R<sup>3</sup>B as part of the  
Facility for Antiproton and Ion Research (FAIR)  
in Darmstadt:



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- 2 mio. m<sup>3</sup> of earth excavated
- 600,000 m<sup>3</sup> of concrete
- 65,000 tons of steel



5,000 single family homes



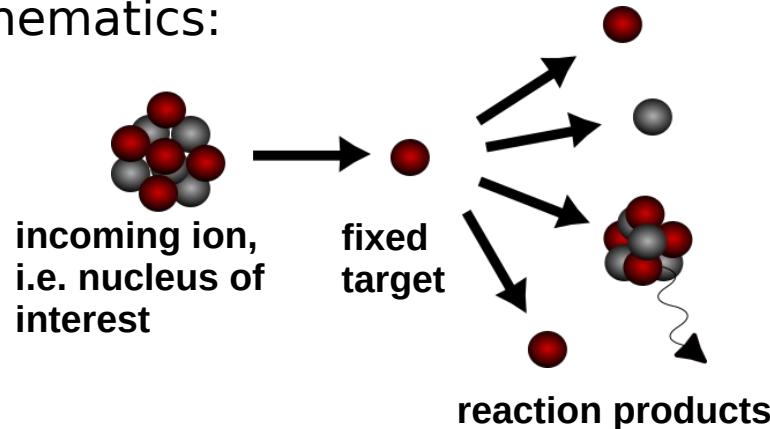
eight Frankfurt soccer stadiums



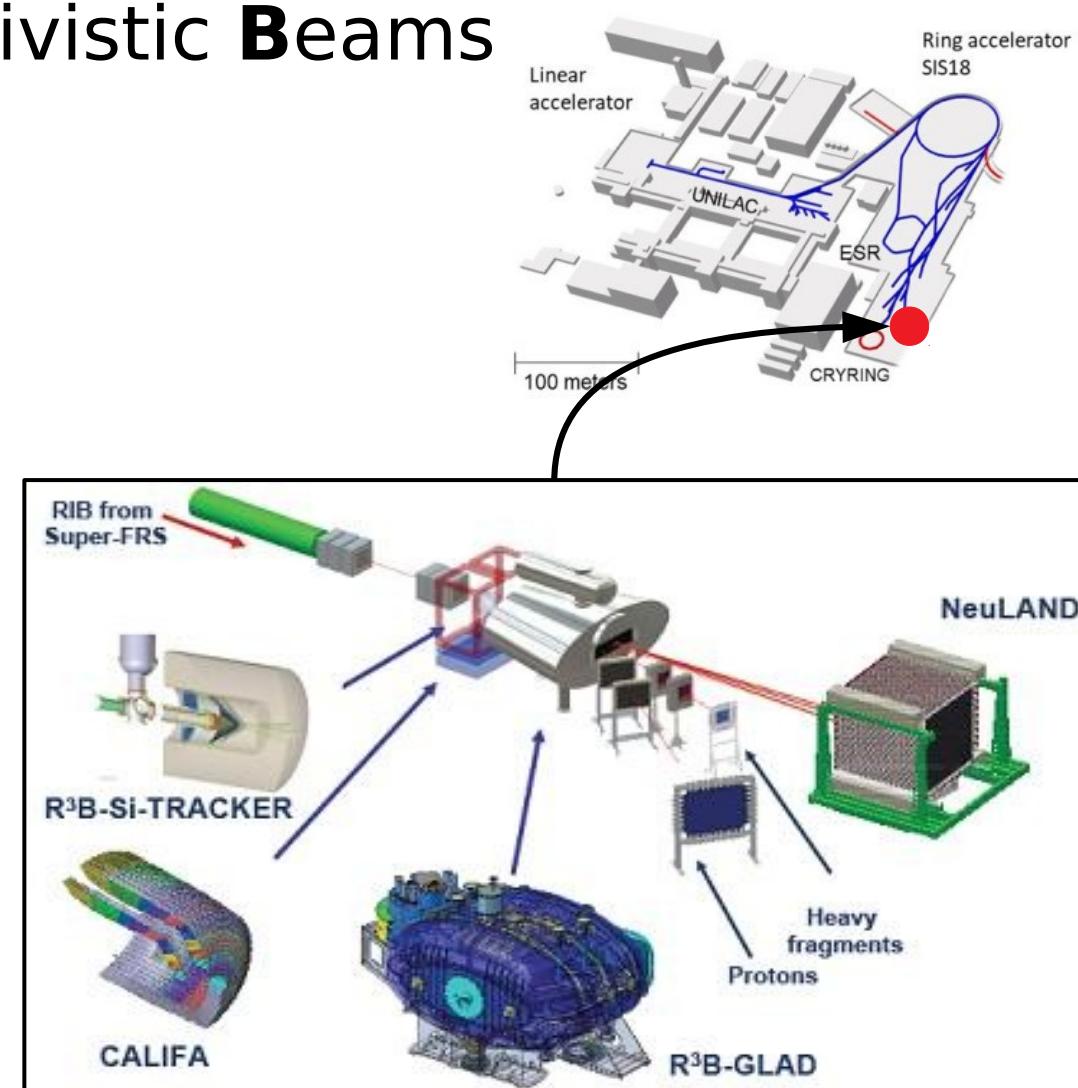
nine Eiffel Towers

## Reactions with Radioactive Relativistic Beams

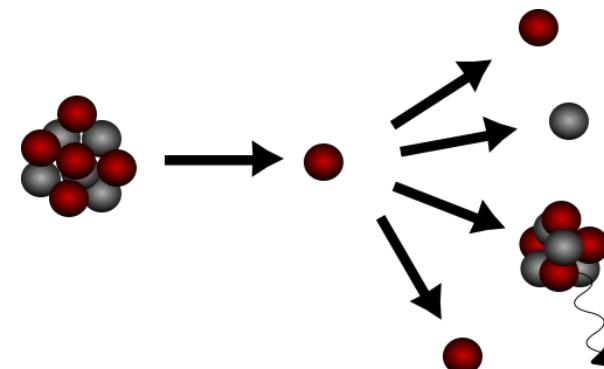
- Physics program on exotic nuclei in inverse kinematics:



- In flight production of exotic nuclei from fragment separator Super-FRS
- kinematically complete measurements
- Flexible setup, extensive physics schedule  
(despite pandemic restrictions)



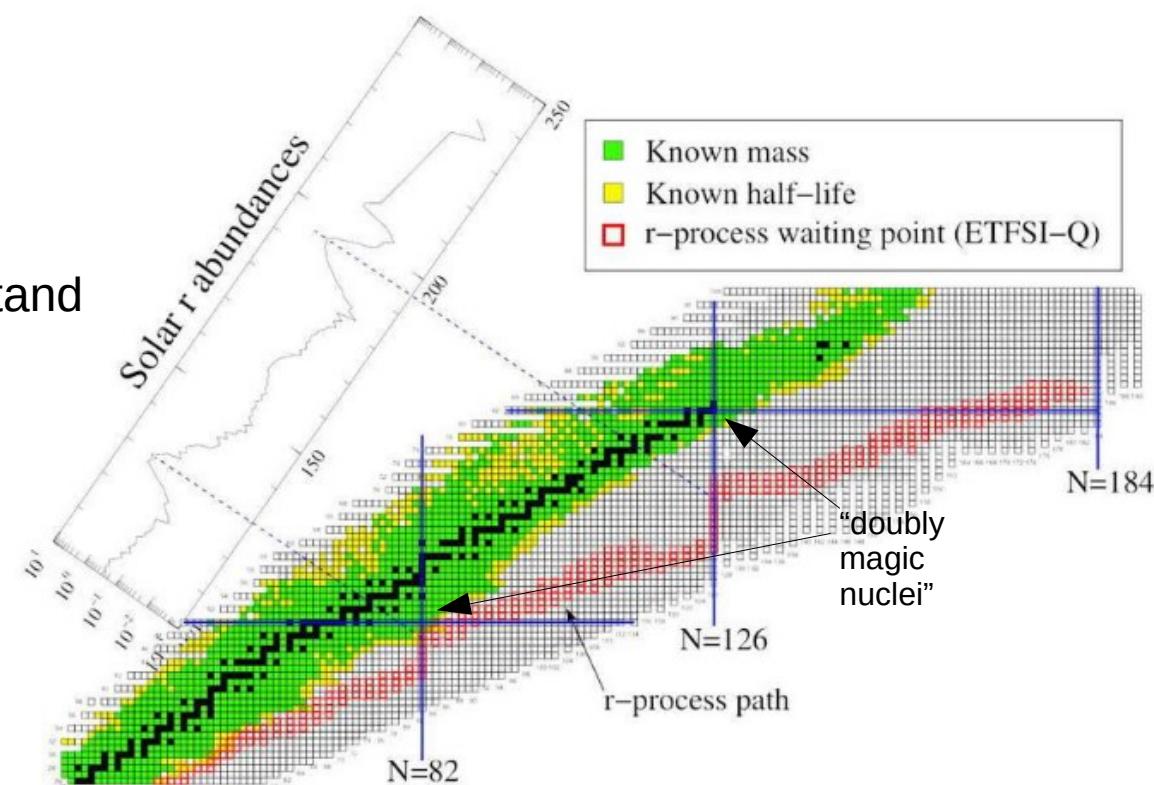
- Quasi Free Scattering (QFS)/Knockout reactions
  - study single particle properties inside nuclei
  - analyze shell evolution far off stability
  - measurement of Fermi-momentum, separation energy, ...

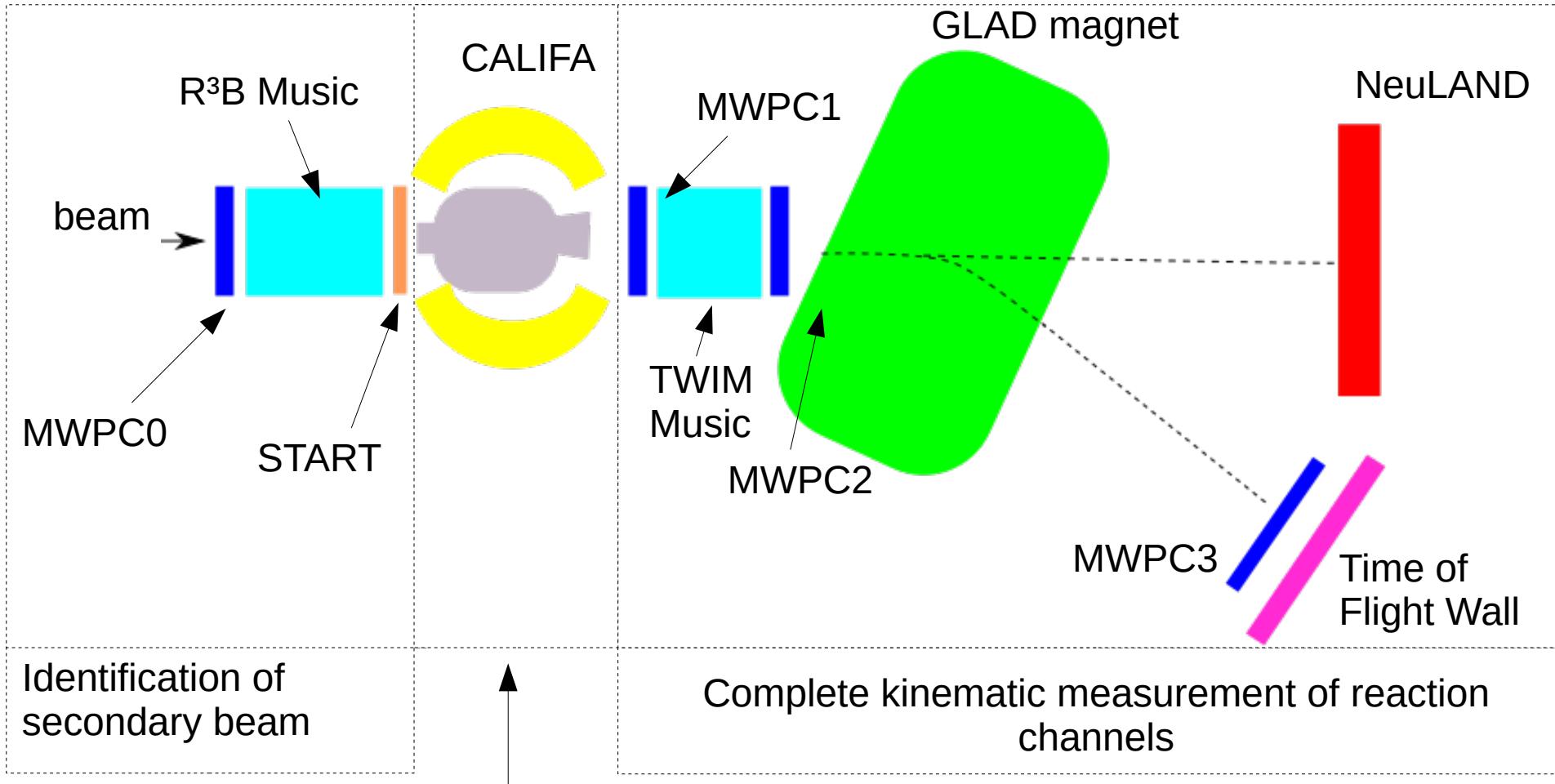


- Collective excitations in neutron rich exotic nuclei via Coulomb excitation

- Fission Studies (up to uranium)

- fission barriers on heavy neutron rich nuclei to understand e.g. final r-process abundance
- fission yields: symmetry/asymmetry of fission products

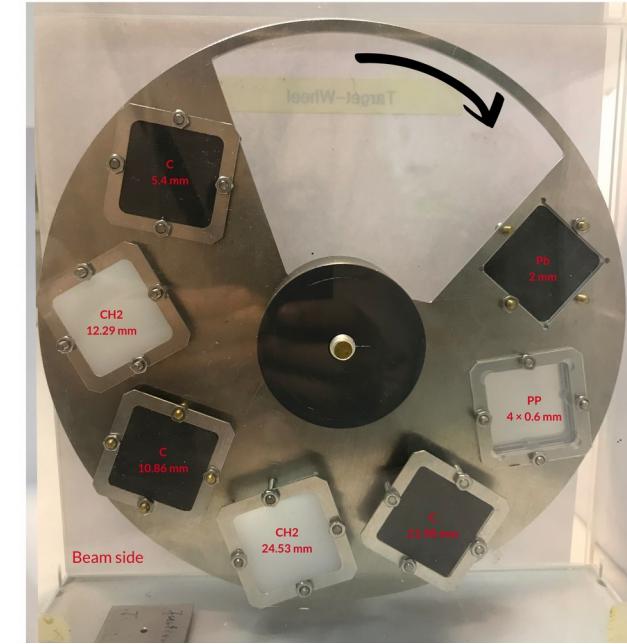






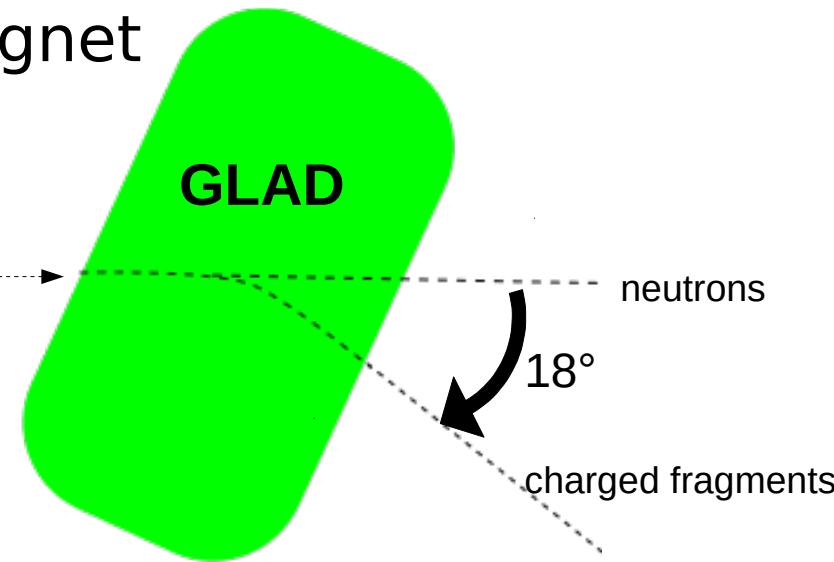
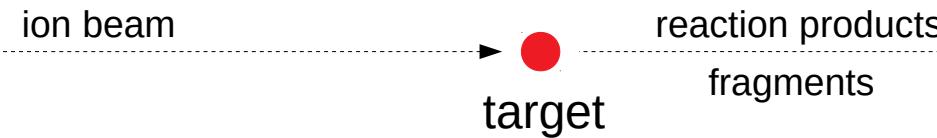
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Target Wheel



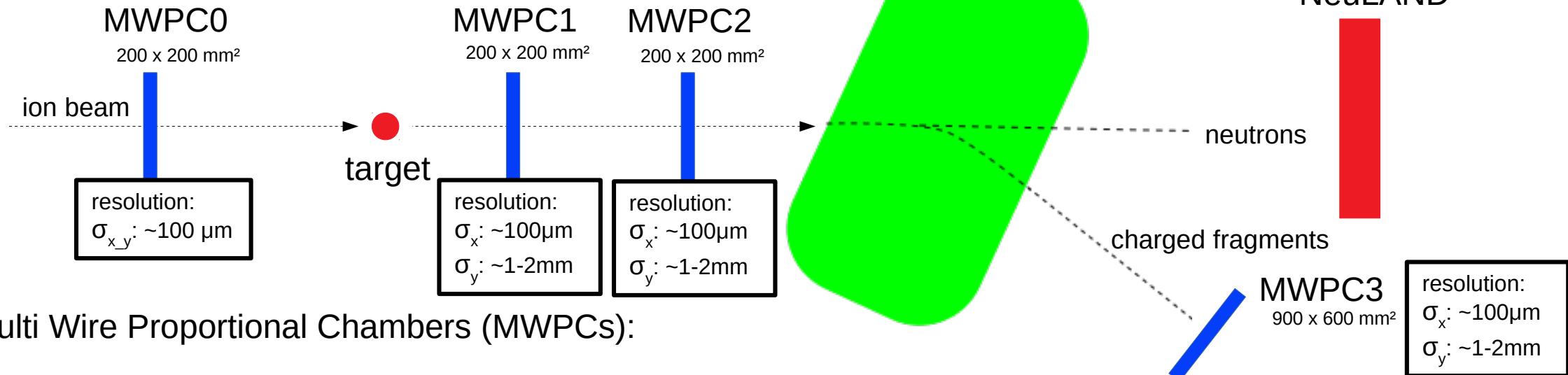
## Targets:

- C with length:  
5.4 / 10.86 / 21.98 mm
- CH<sub>2</sub> with length:  
12.29 / 24.53 / 24 mm
- Pb with length:  
2 mm

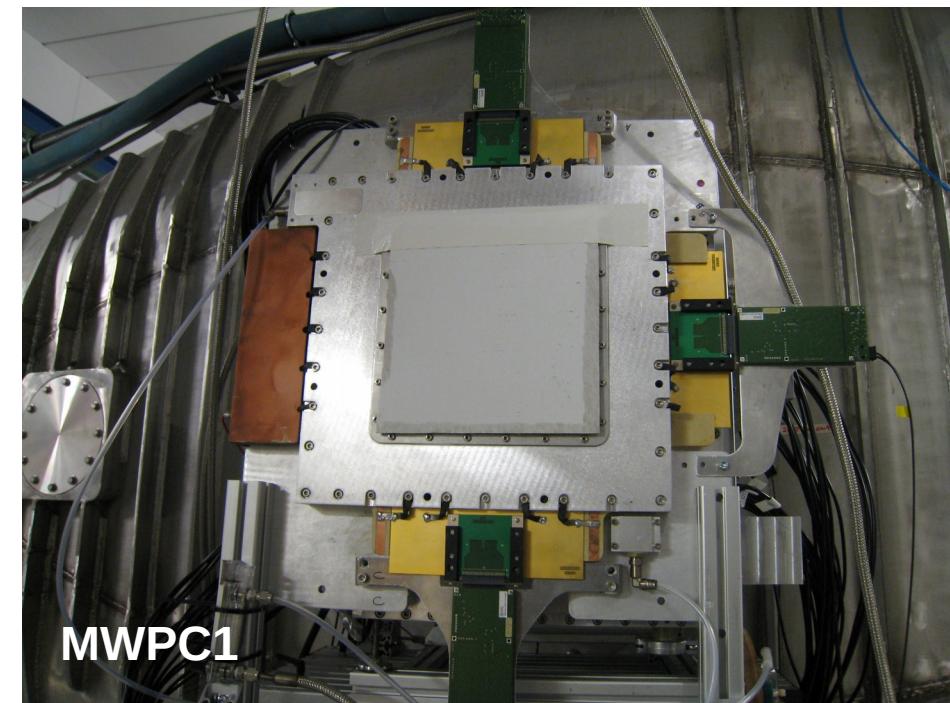
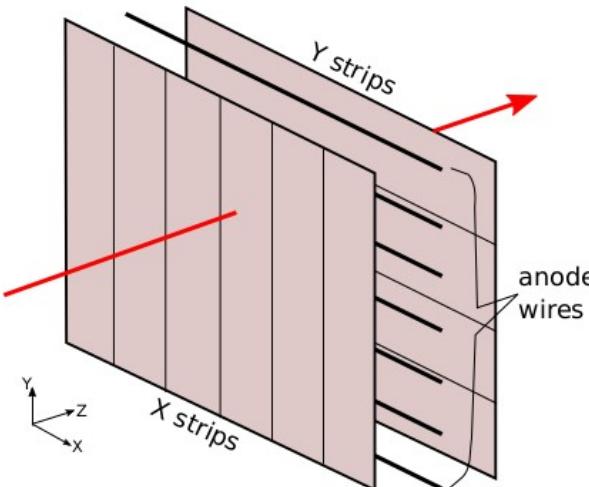


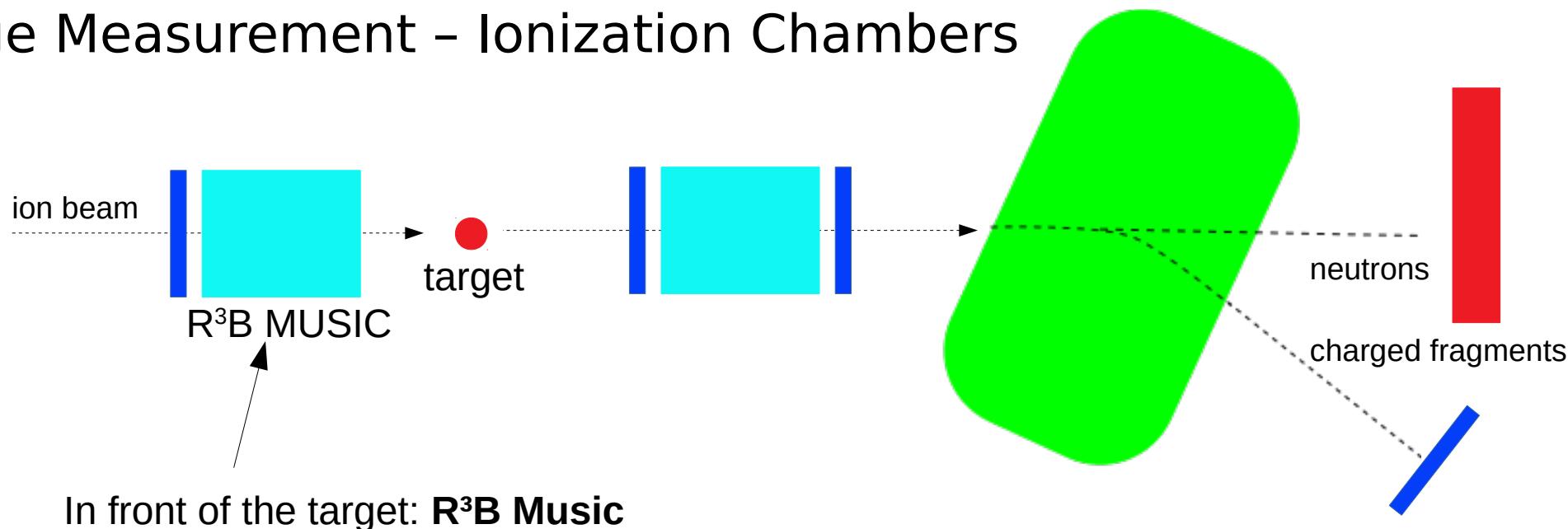
- large vertical gap (+-80 mrad) for neutrons
- high bending angle of 40°
- field integral of about 5 Tm
- momentum resolution  $\Delta p/p$  of around  $10^{-3}$

# Tracking Detectors



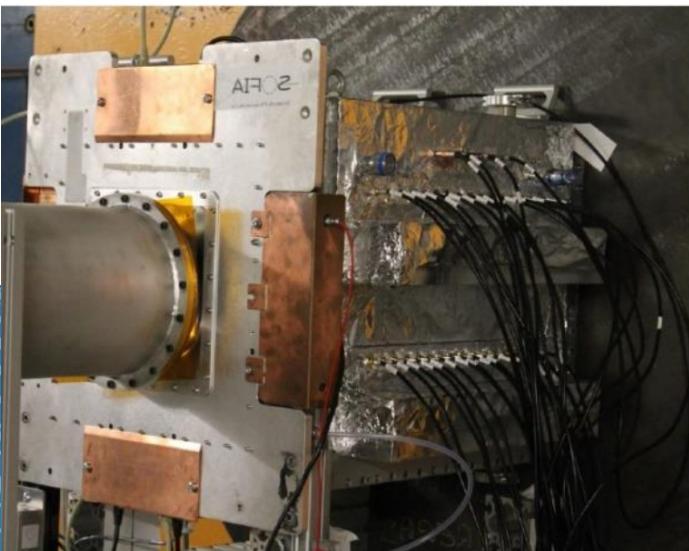
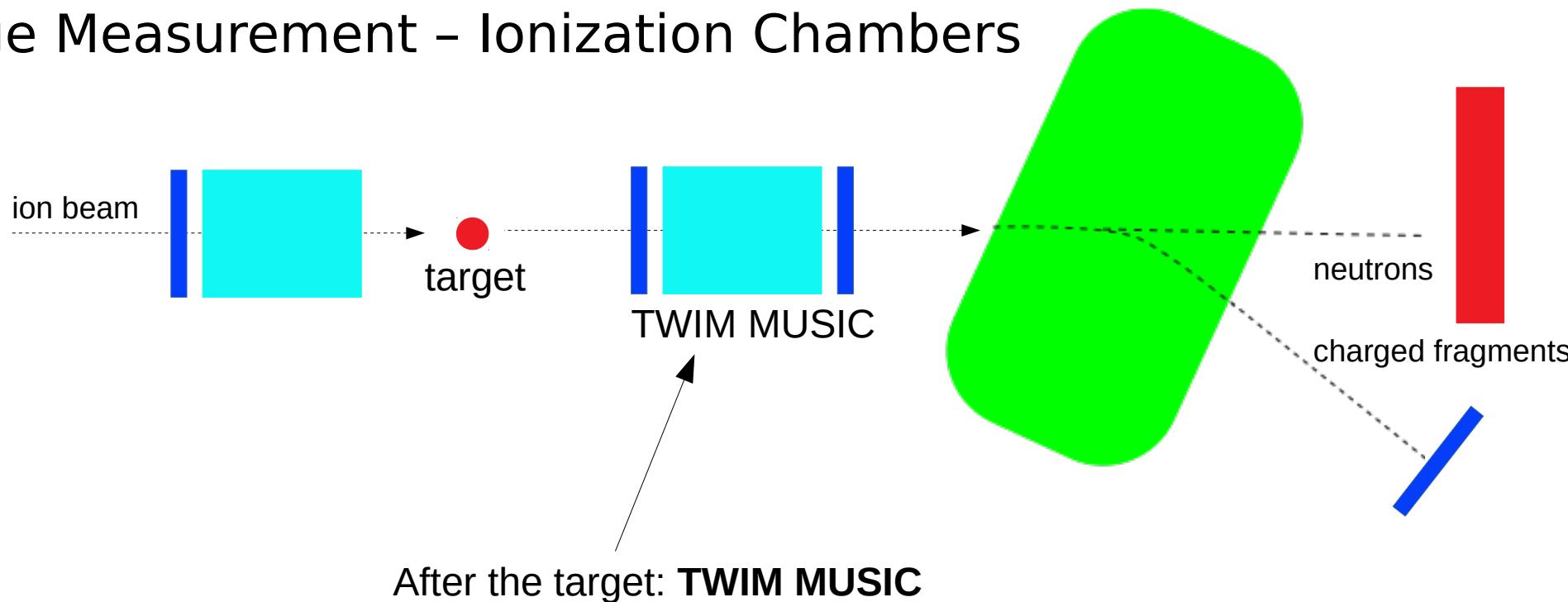
- vertical/horizontal wires:  $50 \mu\text{m}$  diameter,  $2.5 \text{ mm}$  spacing
- vertical/horizontal pads:  
Al-deposited on a  $12 \mu\text{m}$  Mylar foil,  
 $5/3.125 \text{ mm}$  width (vertical/horizontal)
- gas mixture: 84% Ar, 16% CO<sub>2</sub>
- pad readout





51 x 54 x 53 cm<sup>3</sup>  
Cathode left side -  
Anode right side  
Gas mixture:  
Ar 25%, CH4 75%





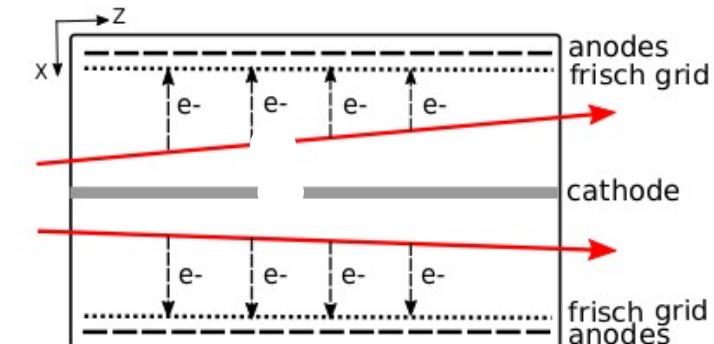
43 x 48 x 55 cm<sup>3</sup>

Double ionization chamber with central cathode and two anode planes

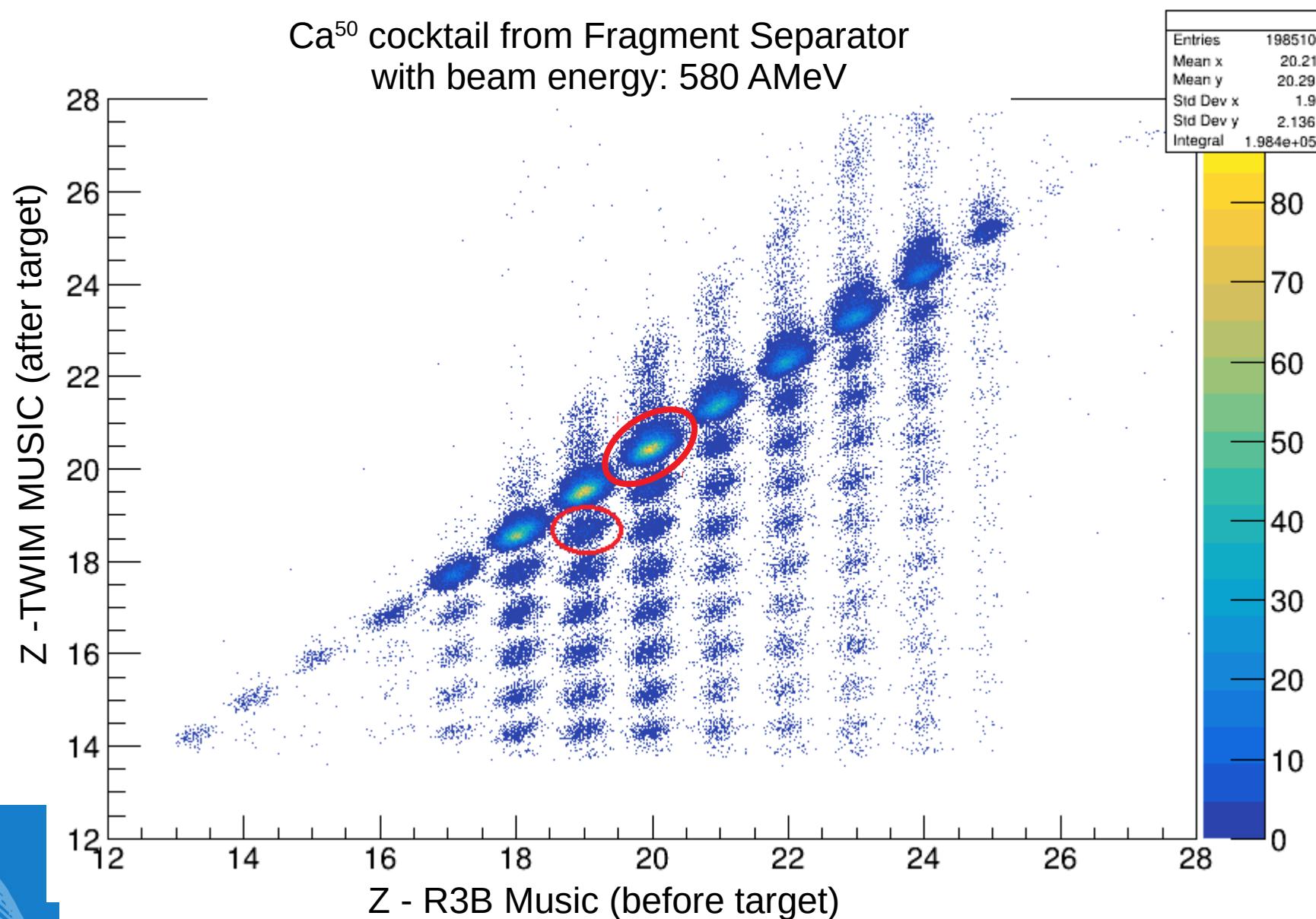
Frisch grid for better signal quality and time resolution

Gas mixture:

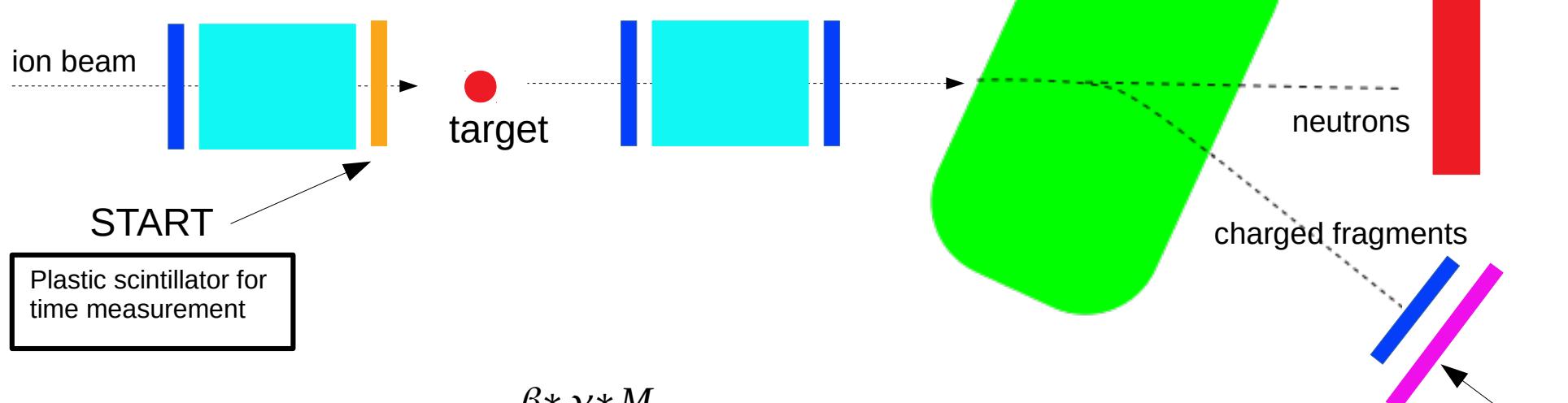
Ar 25%, CH<sub>4</sub> 75%



# $\text{Ca}^{50}$ cocktail from Fragment Separator with beam energy: 580 AMeV



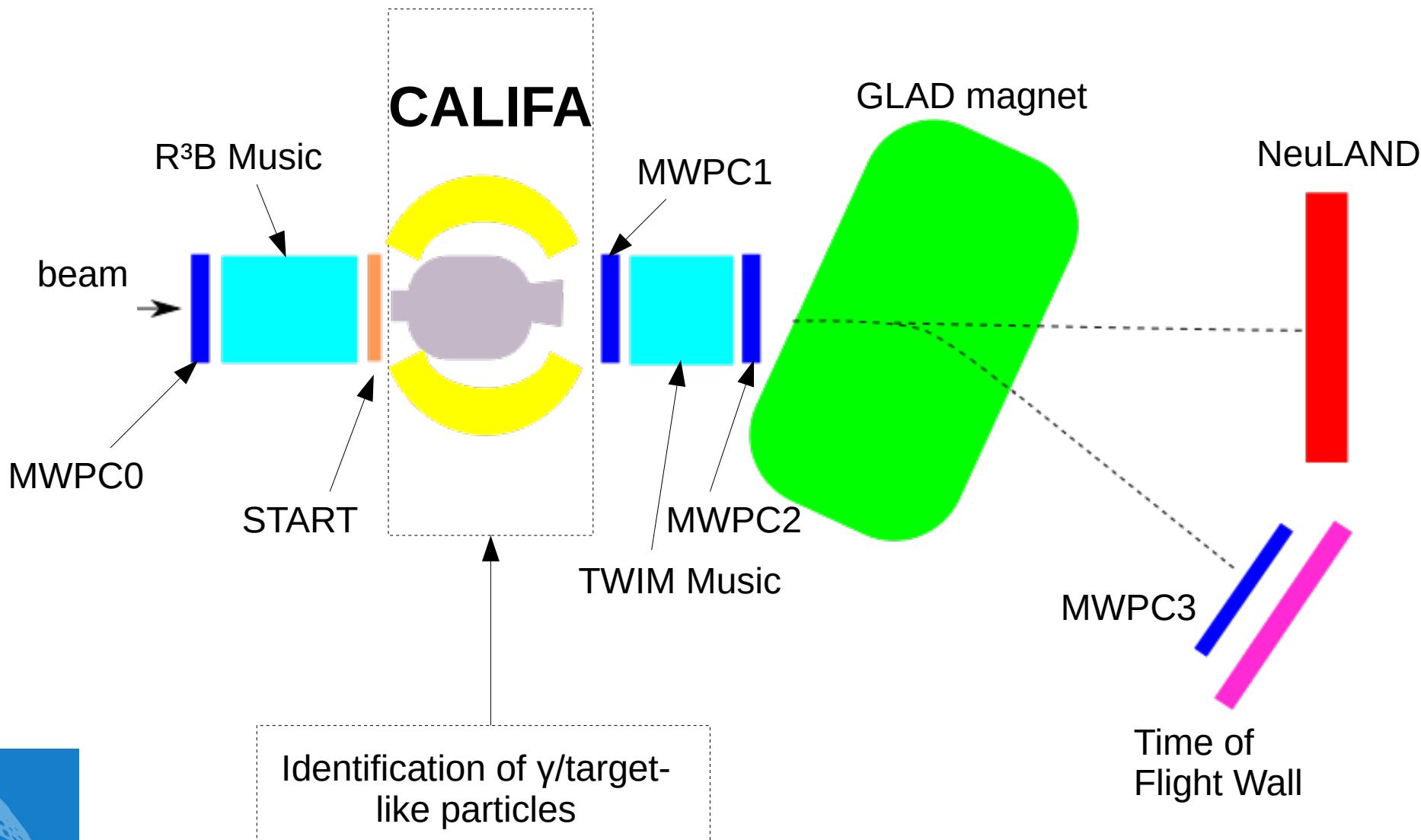
# Time Measurement - START & ToFW



Particle Identification:  $B*\rho = \frac{\beta*\gamma*M}{q}$

- ToF measurement: START to TOFW
- flight-path reconstruction: tracking detectors
- charge measurement: TWIM MUSIC





CALorimeter for the In Flight detection of  $\gamma$ -rays and light charged pArticles

## Endcap:

### iPhos:

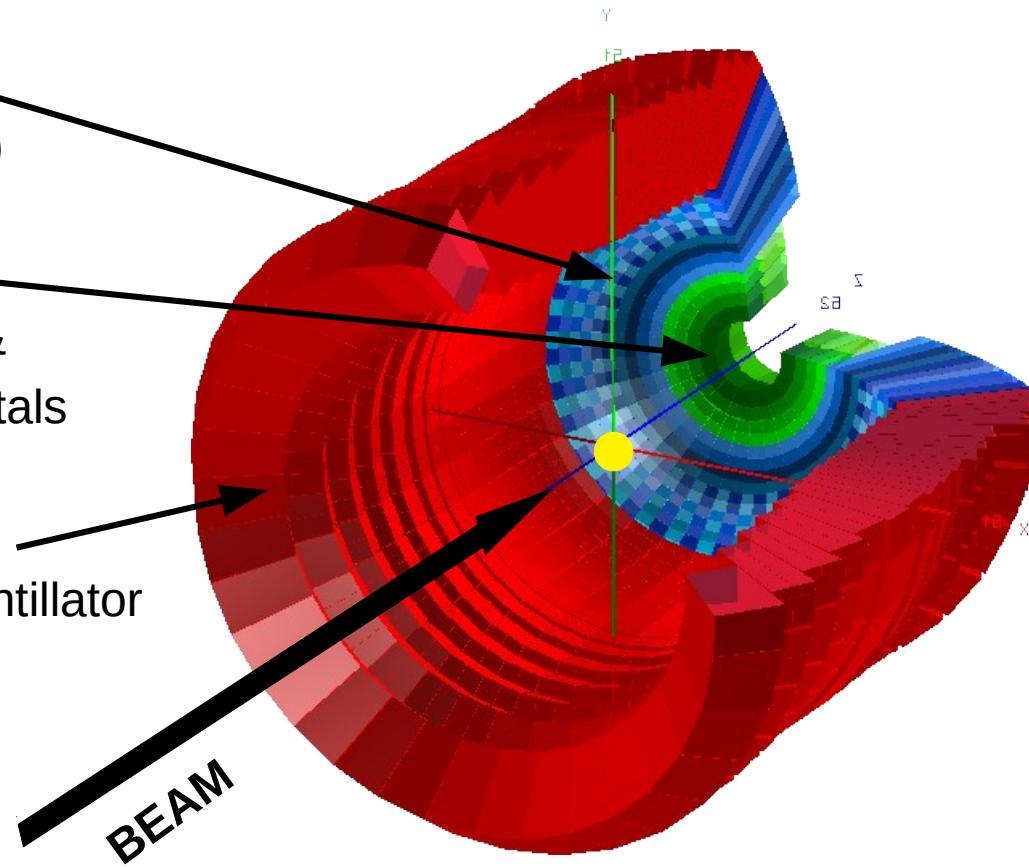
512 CsI(Tl)  
crystals

### CEPA:

96 LaBr<sub>3</sub> &  
LaCl<sub>3</sub> crystals

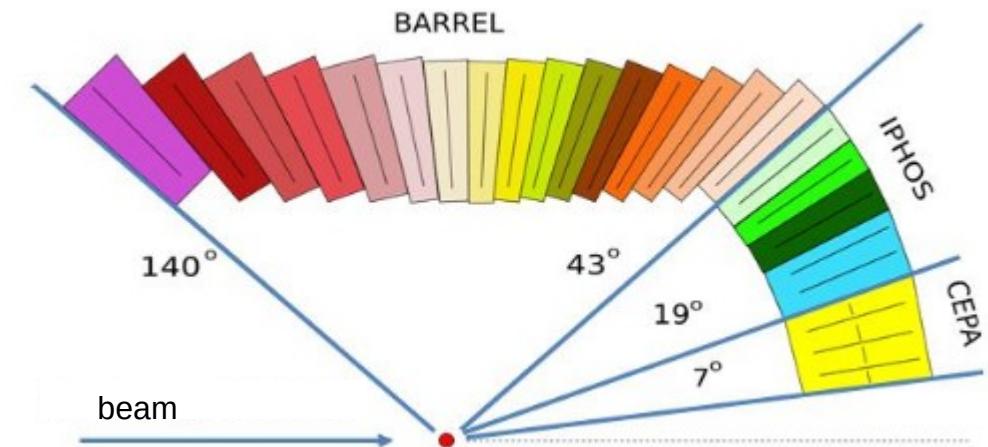
## Barrel:

1952 CsI(Tl) scintillator  
crystals



## Requirements:

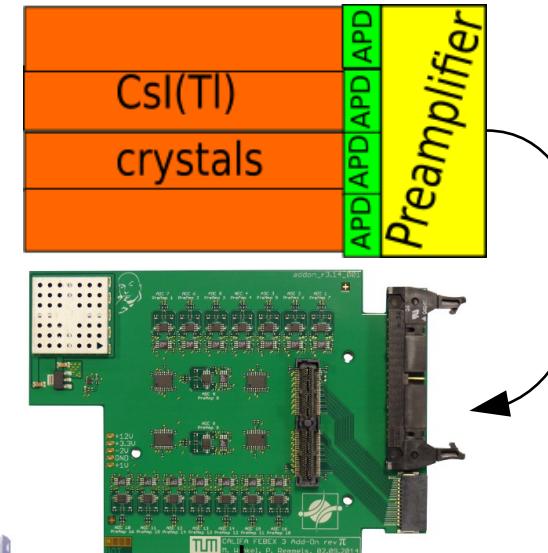
- high dynamic range:  
100 keV  $\gamma$ -rays – 700 AMeV charged particles
- high efficiency
- high granularity → Doppler correction
- particle identification



# Signal Processing @ CALIFA

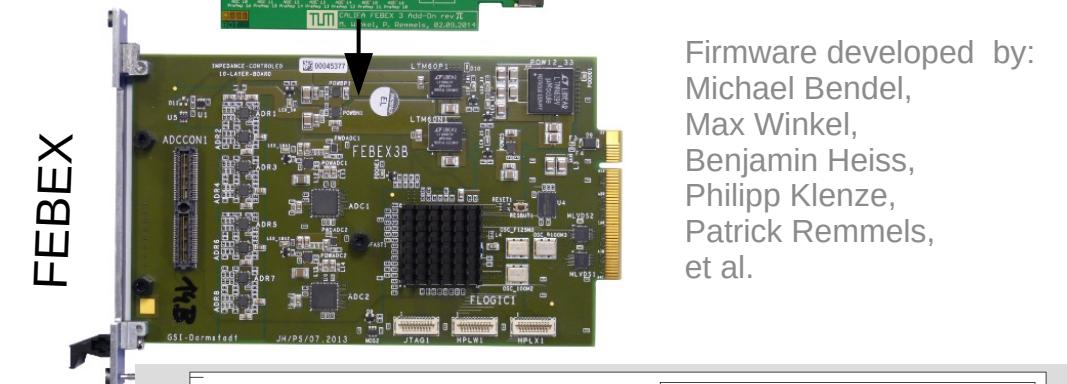
$\gamma$ /particle interaction in **crystal** → scintillatorlight (550nm)  
Every crystal connected to one **APD** → signal current  
Preamplifier: generates HV for APD bias +  
amplifies/integrates signal

## Add-on Board: Filtering



Add-on Board

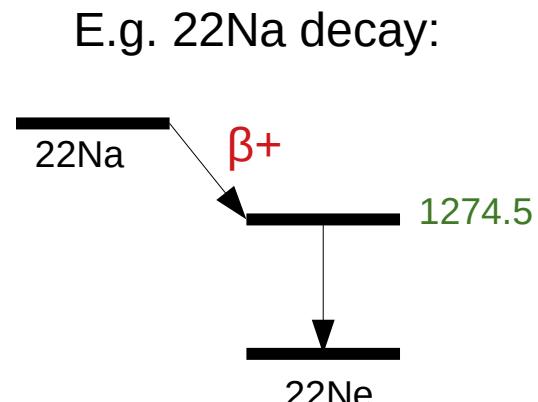
## FEBEX Module: ADC + energy & particle identification



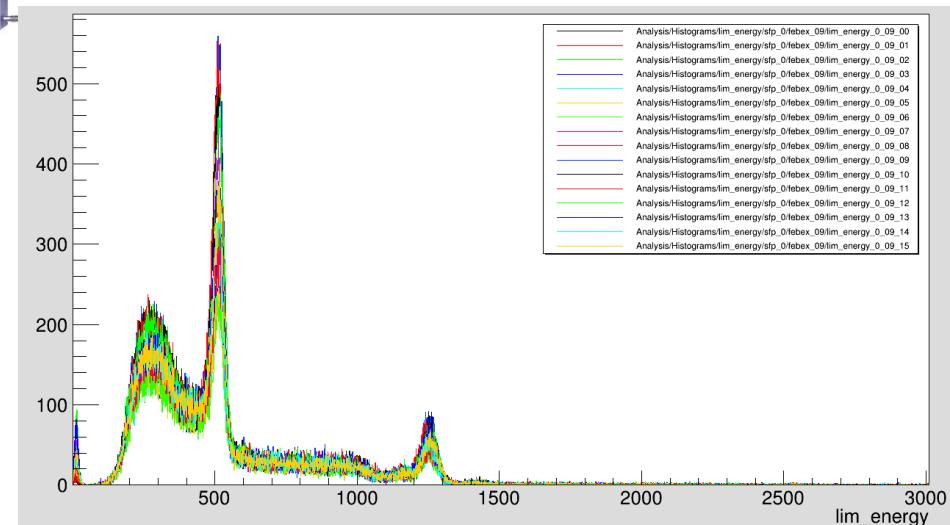
Firmware developed by:  
Michael Bendel,  
Max Winkel,  
Benjamin Heiss,  
Philipp Klenze,  
Patrick Remmels,  
et al.

## Automated APD Gain matching routine:

- ensures that all channels cover same range
- already pre-calibrated



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# Electronics for CALIFA



Each rack:  
→ 1024 channels

→ 50 MHz  
continuous  
sampling rate

Dead-time free  
readout design:

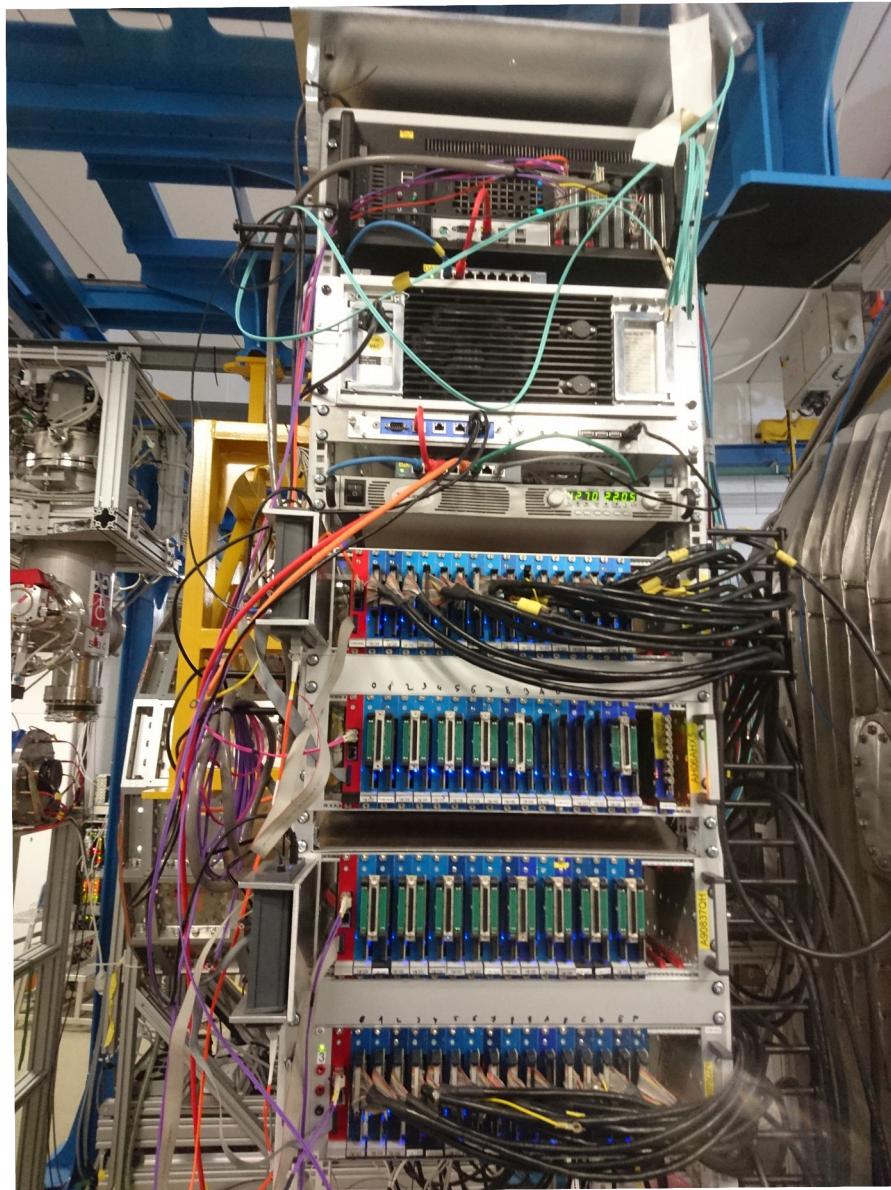
→ PEXOR card

→ TRIXOR card

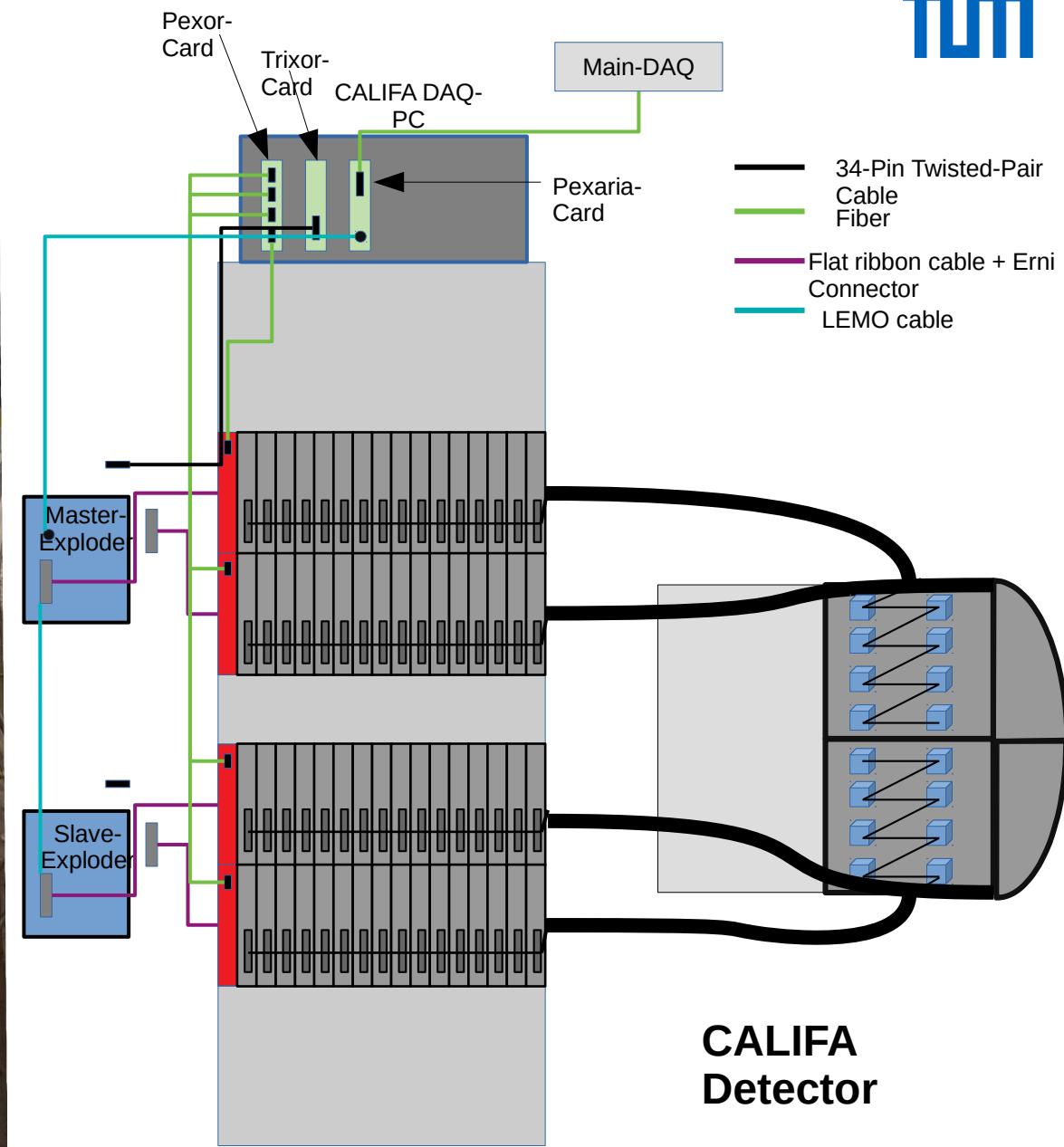
→ EXPLODER

→ PEXARIA  
(white

Rabbit  
timestamp)



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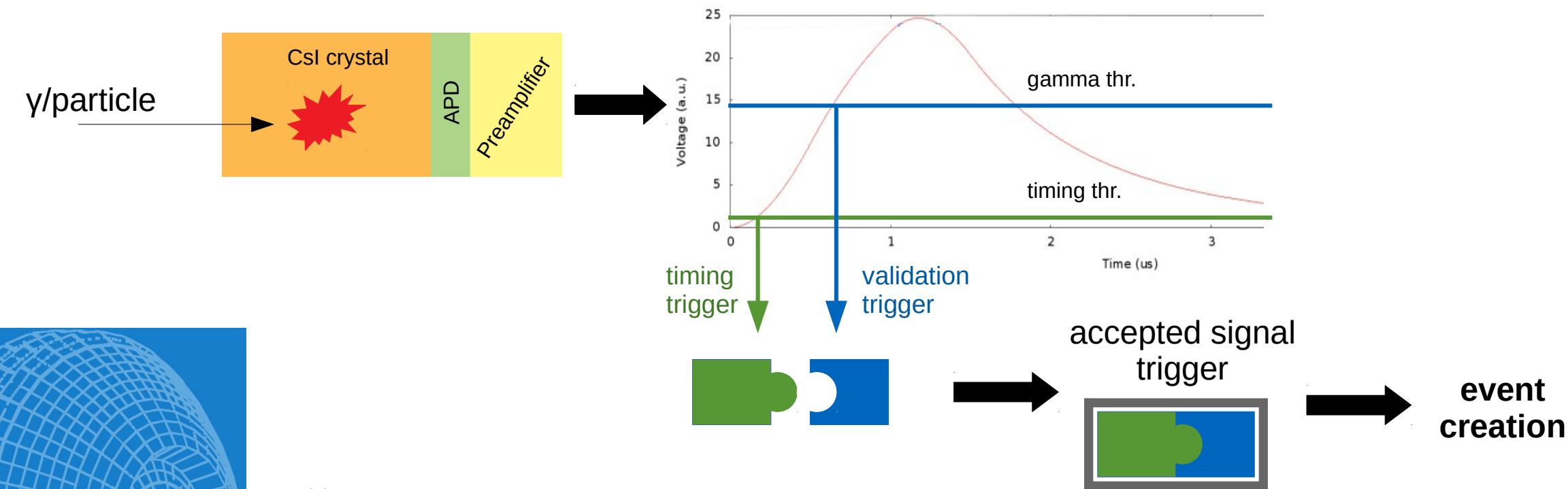


CALIFA  
Detector

Trigger-Discriminator Logic:

- **Timing Trigger**: event time assignment
- **Gamma Trigger**: event validation
- **Proton Trigger**: external trigger

Intuitive event building logic (free running mode):

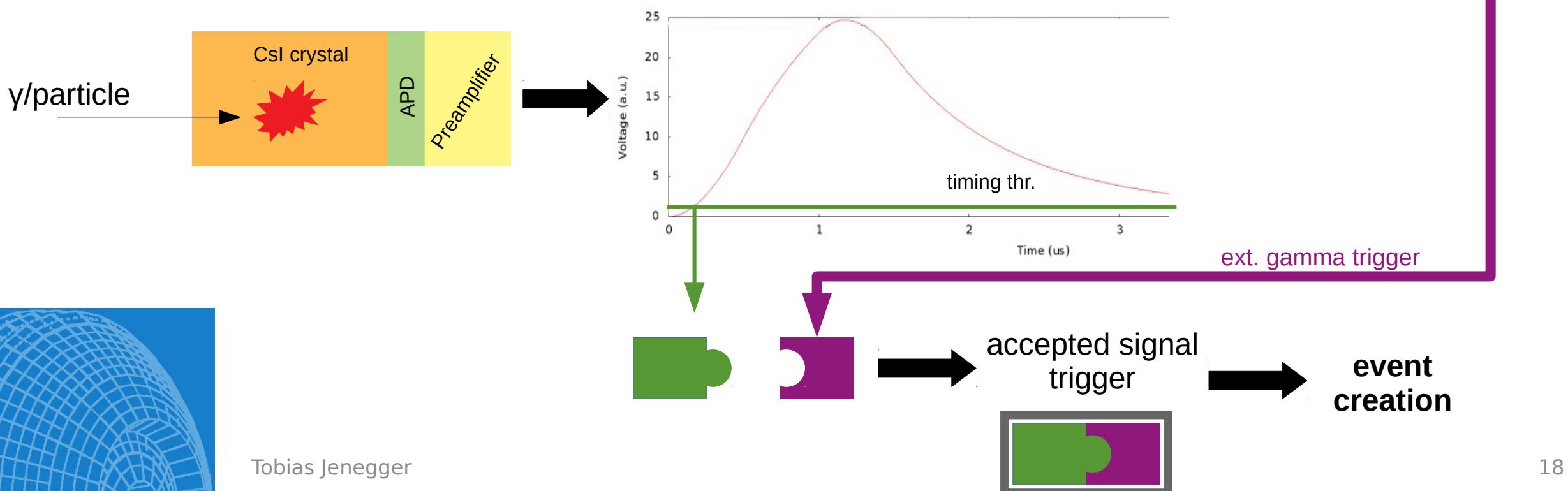


Trigger-Discriminator Logic:

- **Timing Trigger**: event time assignment
- **Gamma Trigger**: event validation
- **Proton Trigger**: external trigger

Ext.  
Detector

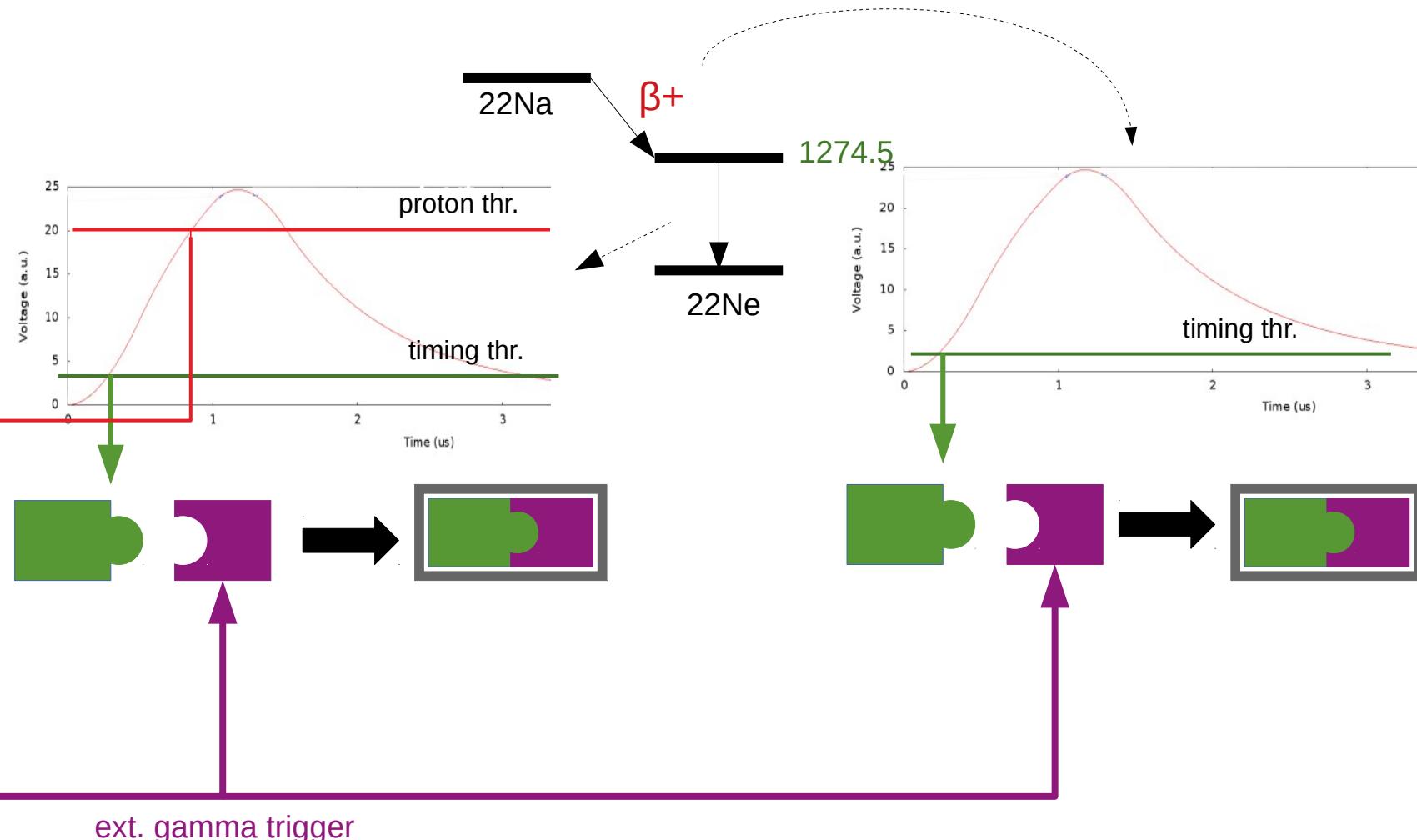
synchronous and coincident trigger mode (ext. validation trigger):



- for experiment in May 2021 with He test beam
- ext. gamma trigger from START detector

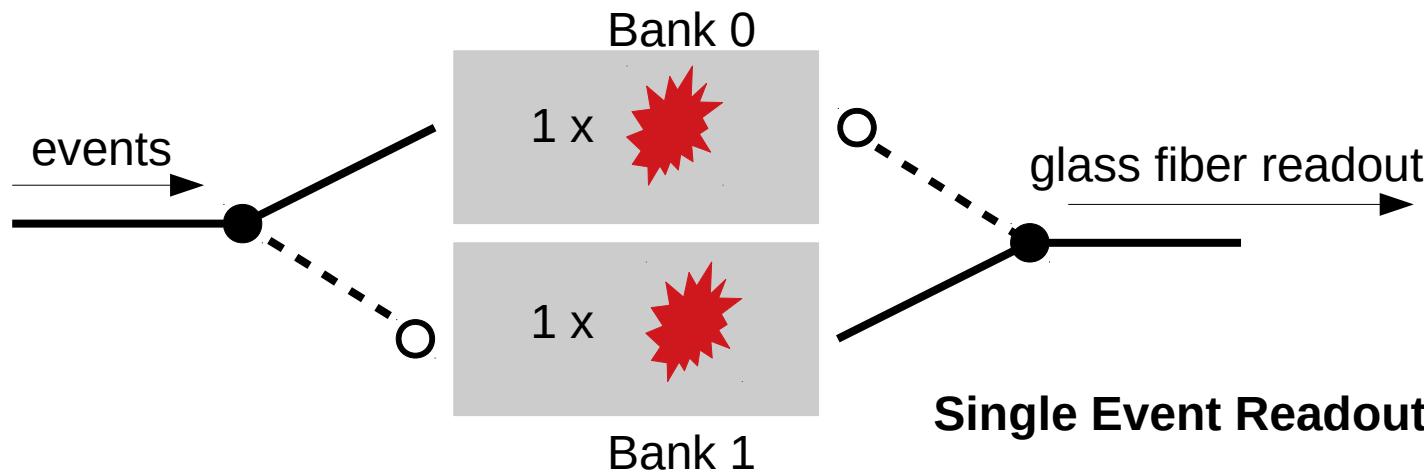
## Testing:

- › 22Na source
- ›  $\gamma$  - 1274.5 keV as proton trigger
- › redirect proton trigger as external gamma trigger



Exploder

# CALIFA Readout Modes

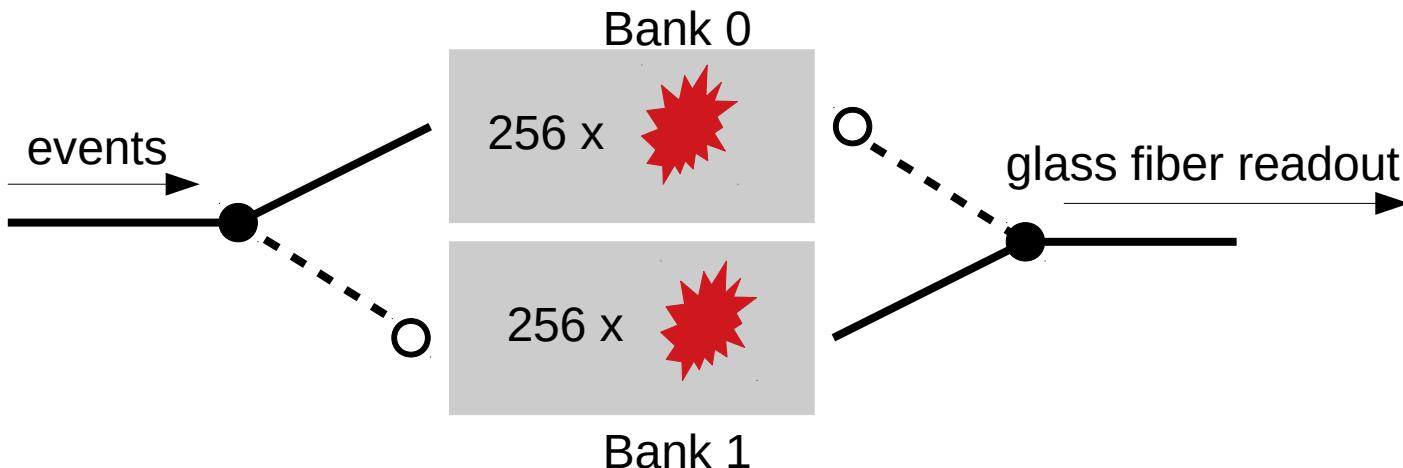


## Single Event Readout (std. Firmware):

- data is read out after each accepted signal trigger
- **dead time:**
  - if 2 events in  $\Delta t <$  readout time
- readout speed depends on data size:
  - larger data blocks increase readout speed (max. 190MB/s)



# CALIFA Readout Modes



## Multi Event Readout (free running mode) :

- max. 256 events saved on each FEBEX bank
- **(almost) no dead time!**
- not until 512 events in  $\Delta t <$  readout time

Given: 100kHz reaction rate at target

**How many crystals can be hit per reaction event ?**

$$190 \text{ MB/s} = 40 \text{ Byte} * 10^5 * x$$

↓                    ↓                    ↓                    ↓

max. readout speed per glass fiber      data size of single event      reaction rate      max. crystal hits per reaction event:  
 $\approx 45$

For final design we have  
10 glass fiber lines

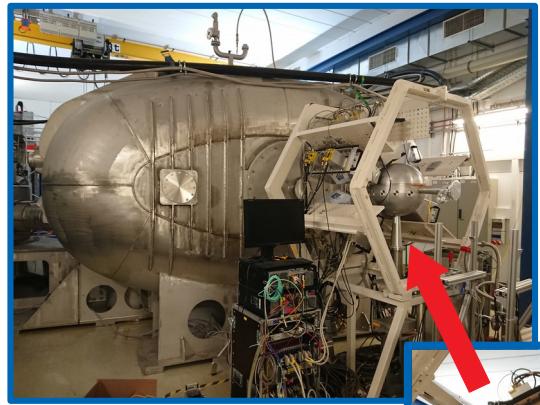
↓  
max. 450 crystal hits for  
100kHz reaction rate



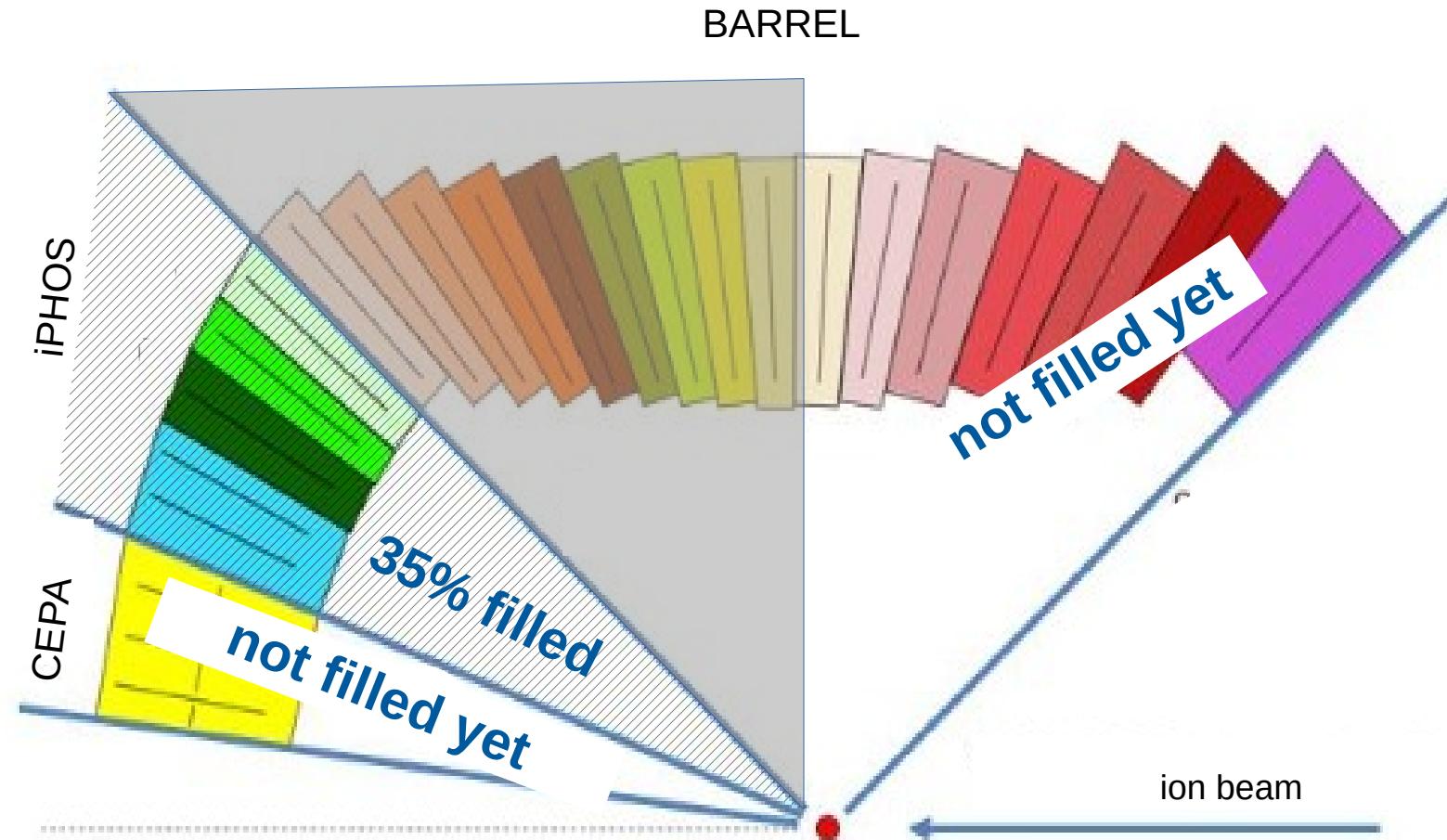
# CALIFA Upgrade 2021

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# From Demonstrator to Final Setup



experiment of Lukas Ponnath



**UPGRADE: iPHOS region fully filled!**



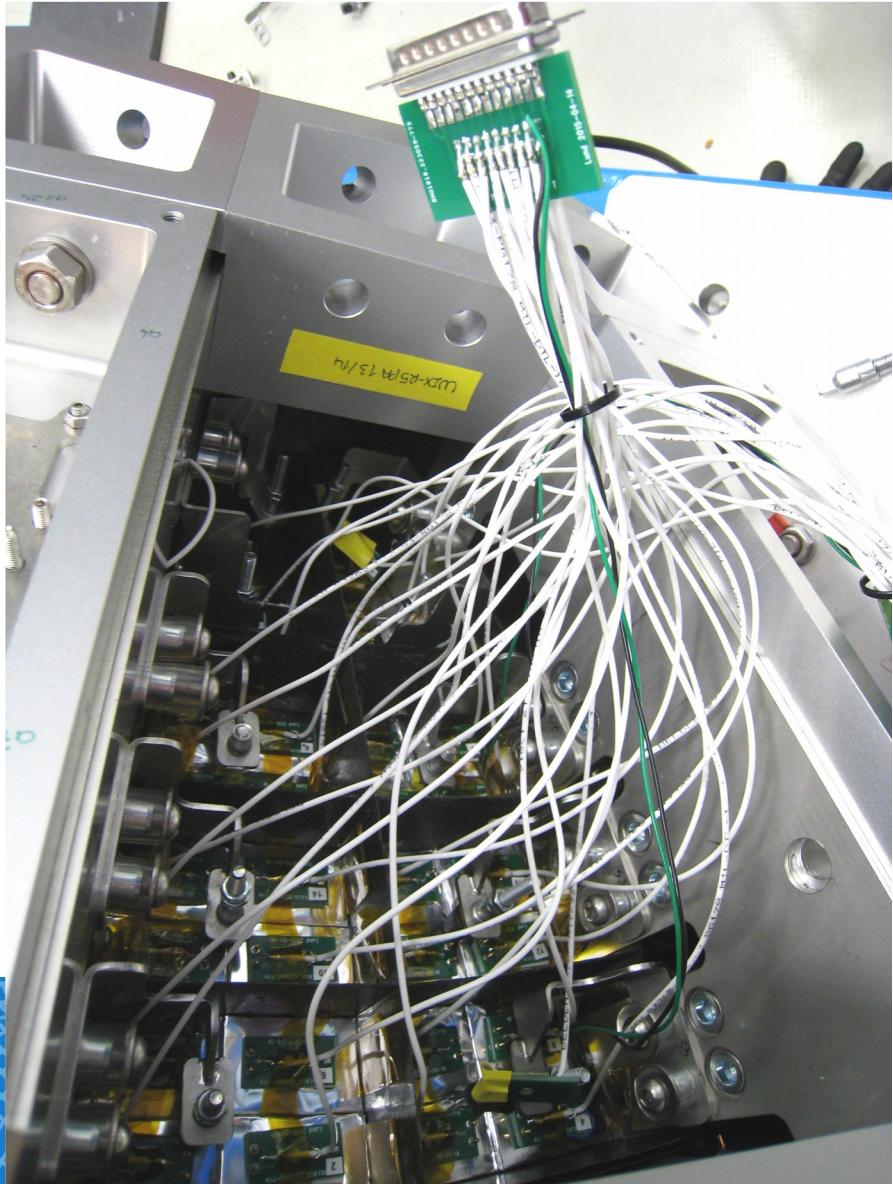
unmounting:



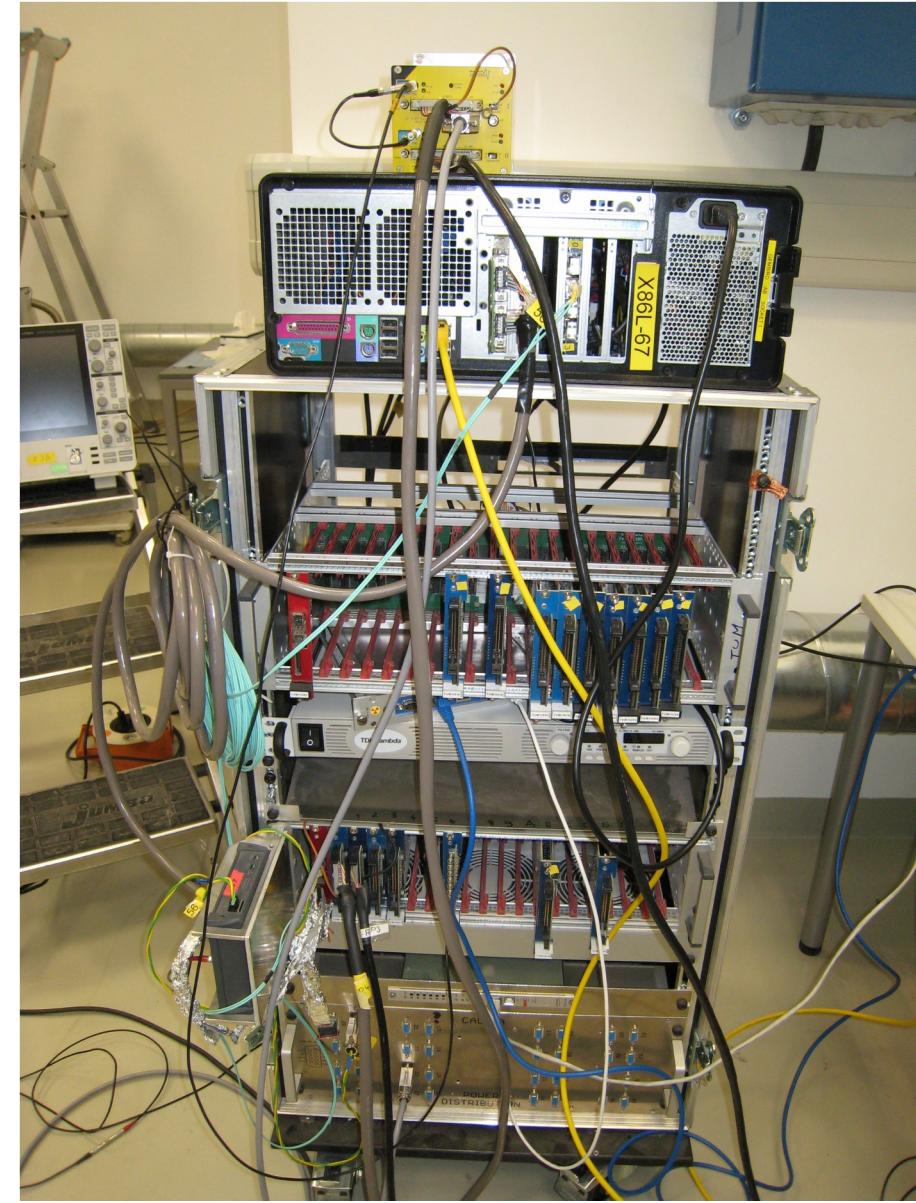
open tiles & measure crystals:



## crystal filling:



## testing with mobile DAQ:



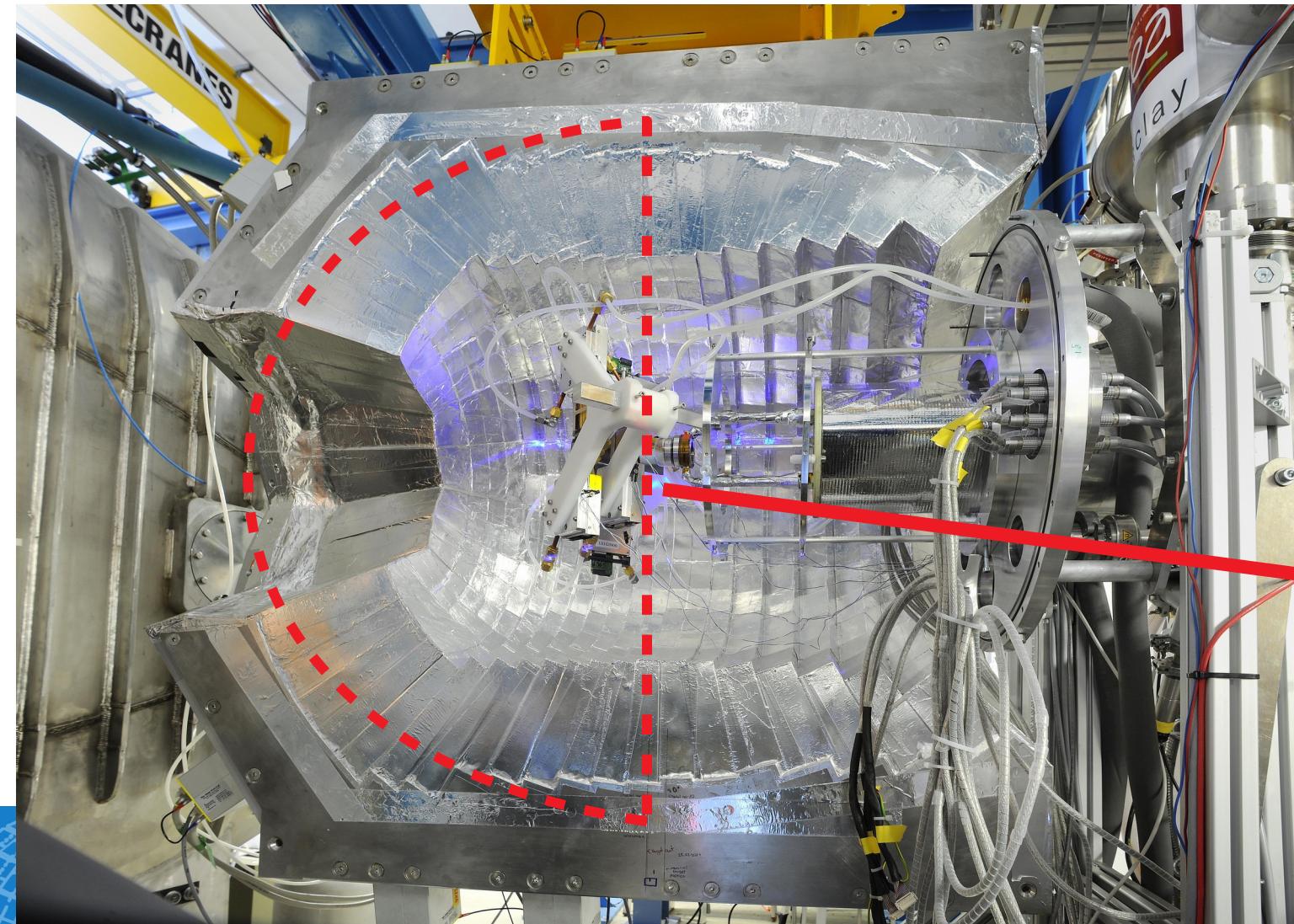
bring back to Cave C:

**1.2 tons !**

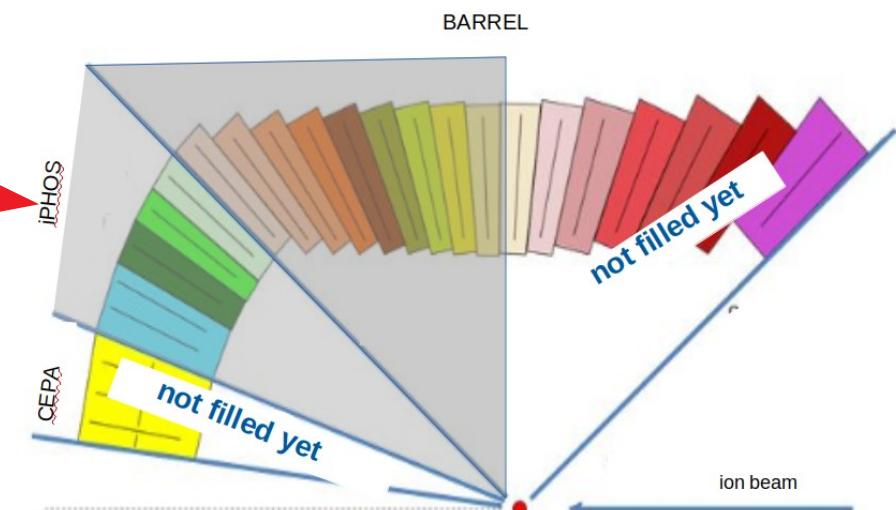


mount and align:



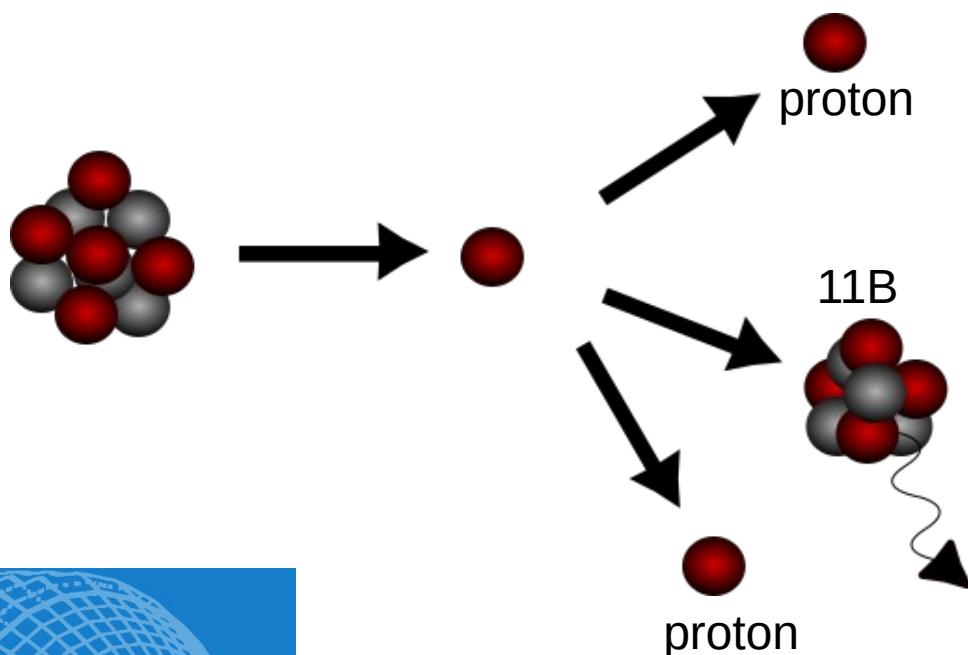


Fully filled forward half !

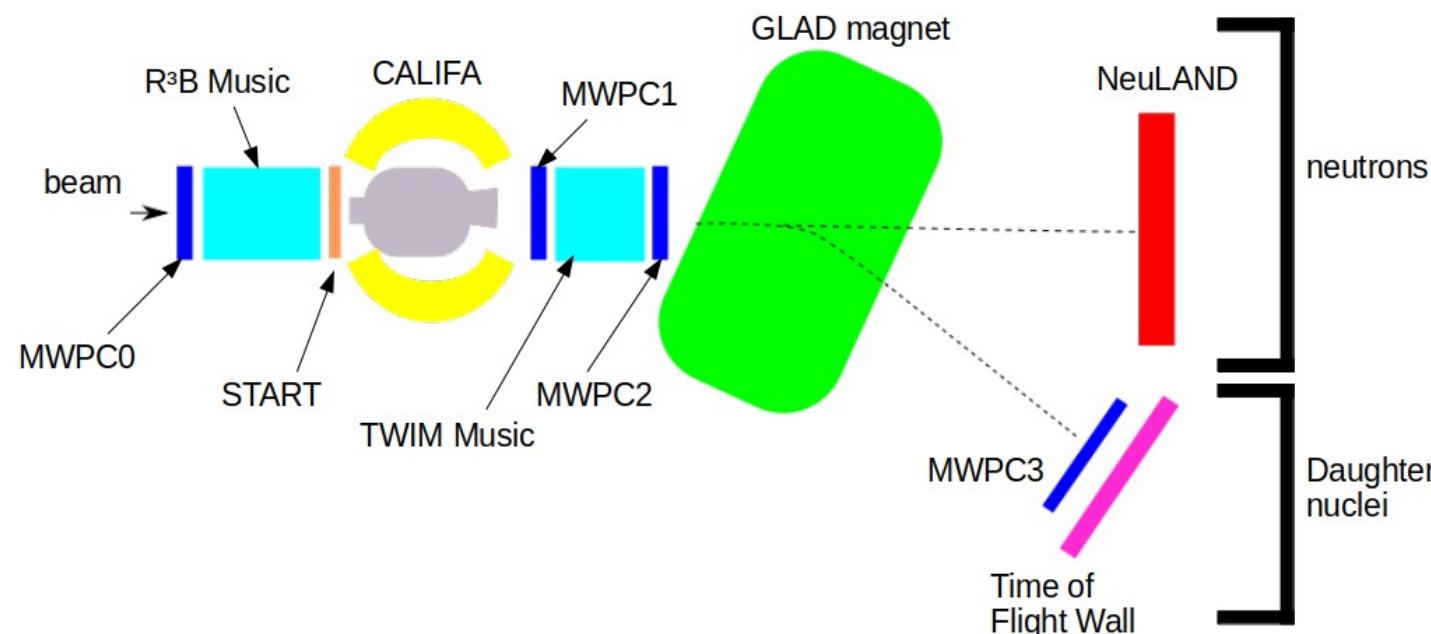


**12C(p,2p)11B reaction:**

- 12C beam
  - proton like target
- 2 protons
- 11B fragment (spectator)

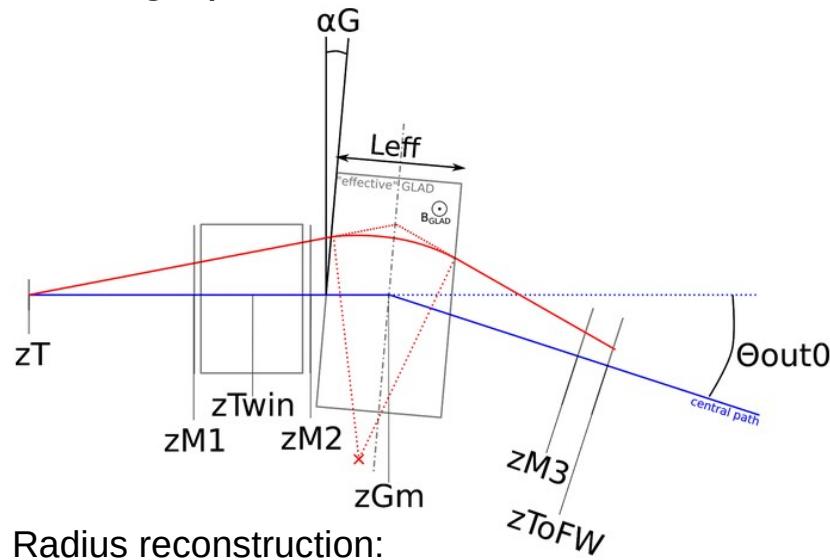
**SETUP:**

Beam energy: 400 AMeV  
Beamtype: C<sup>12</sup>  
Target: CH<sub>2</sub>



# Fragment Particle Identification

Flightpath reconstruction:



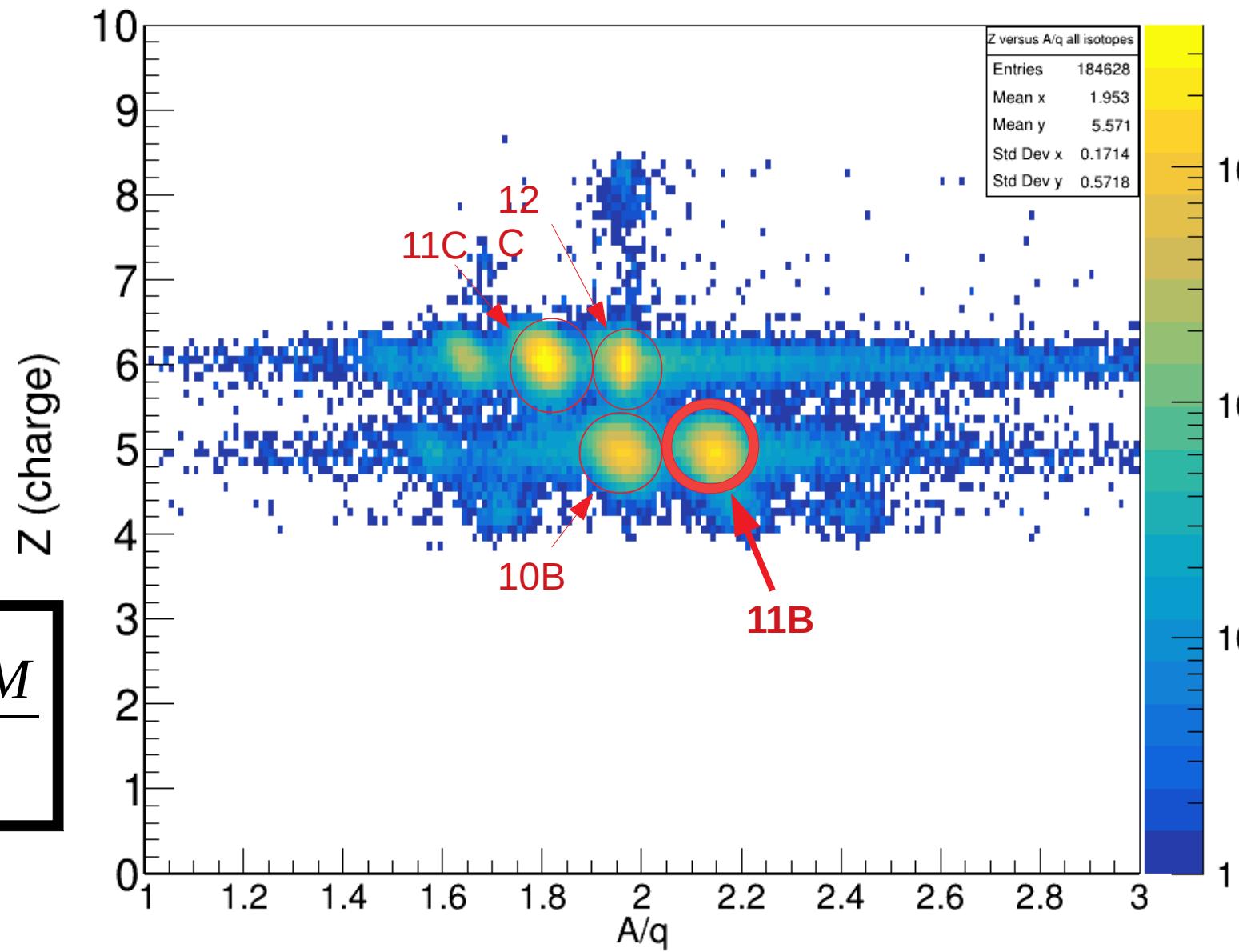
Radius reconstruction:

$$R = \frac{L_{eff}}{2 \sin\left(\frac{\theta_{in} + \theta_{out}}{2}\right)}$$

$$B * \rho = \frac{\beta * \gamma * M}{q}$$

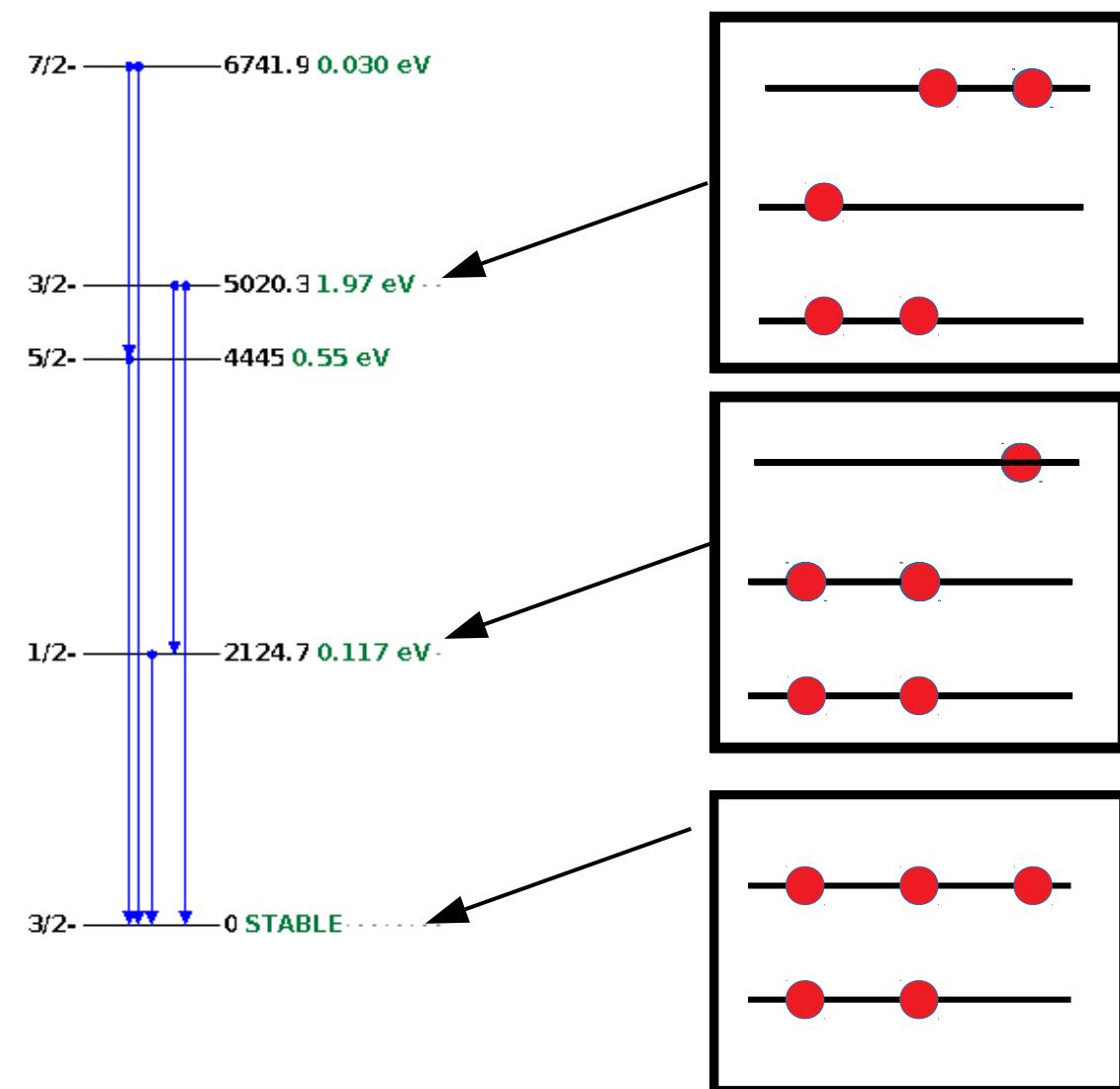
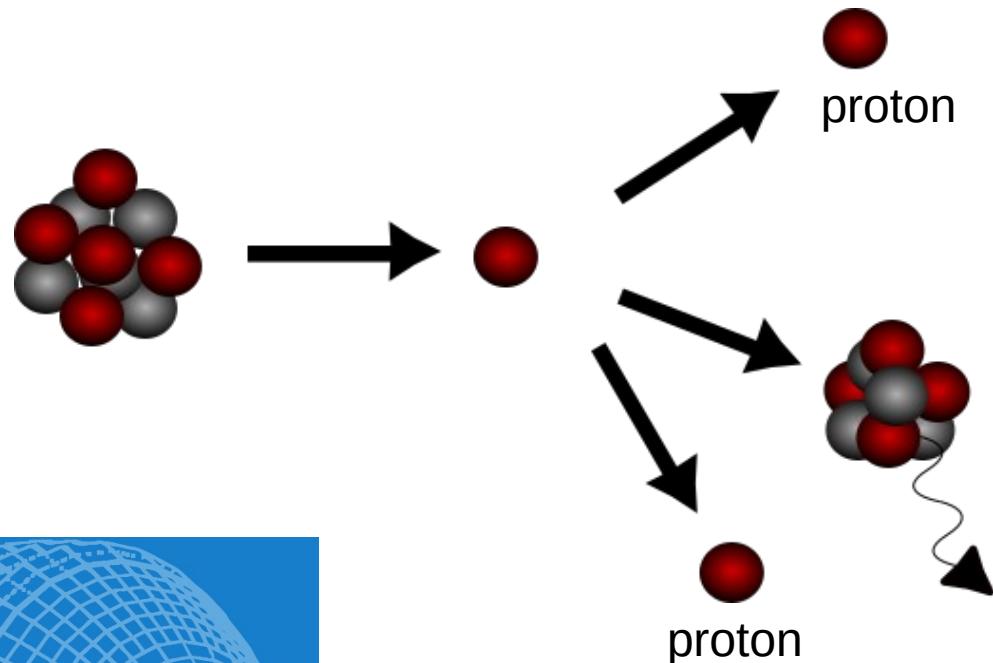


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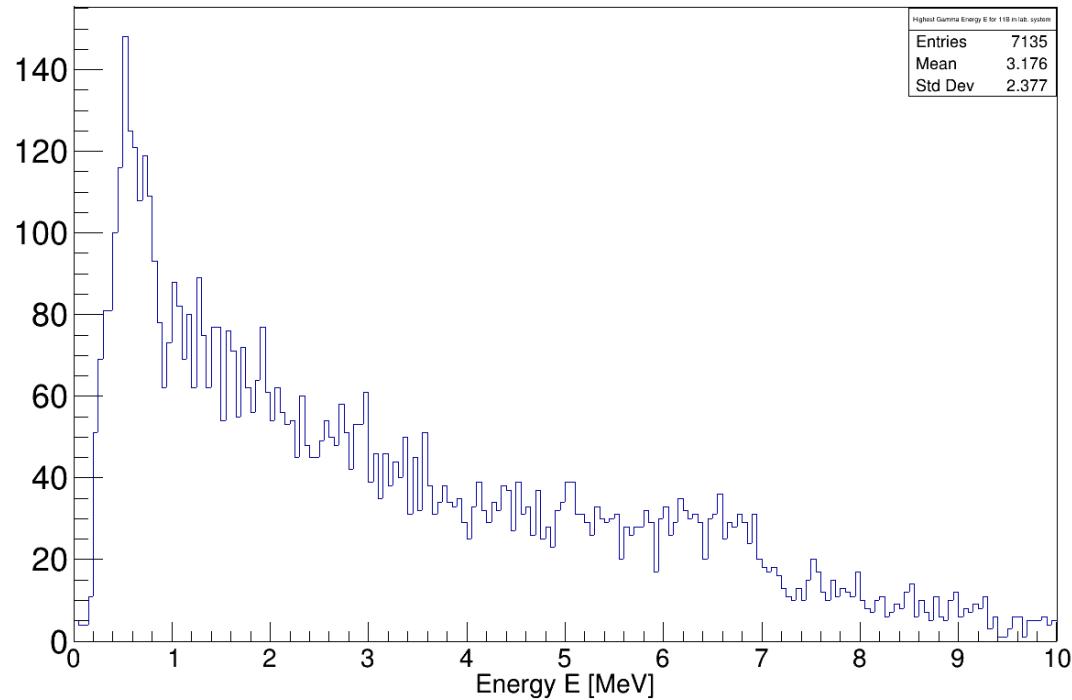
# $^{12}\text{C}(\text{p},2\text{p})^{11}\text{B}$ reaction

**Two Proton Identification:**  
→ two hits with  $E_{\text{hit}} > 30 \text{ MeV}$



# Gamma Spectrum of $^{11}\text{B}$

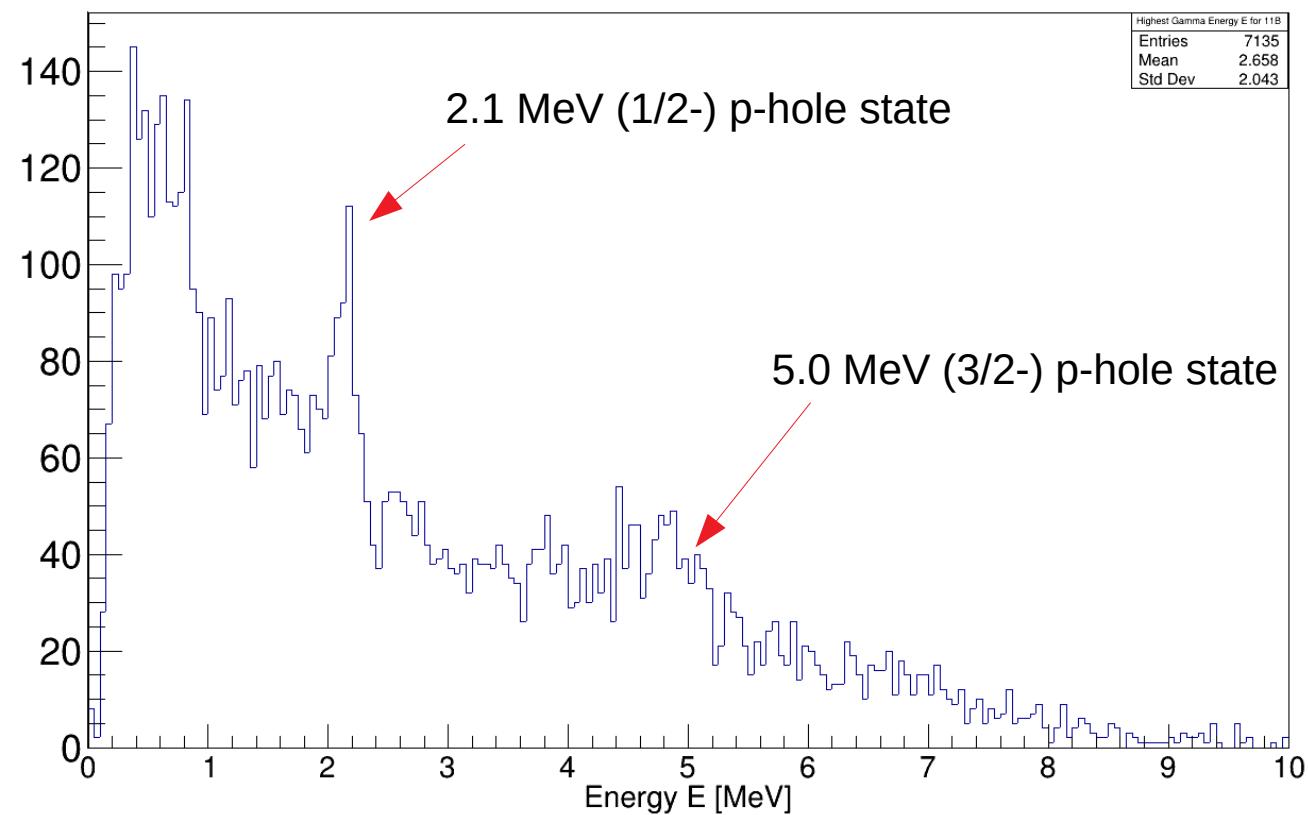
laboratory system



Doppler Correction:

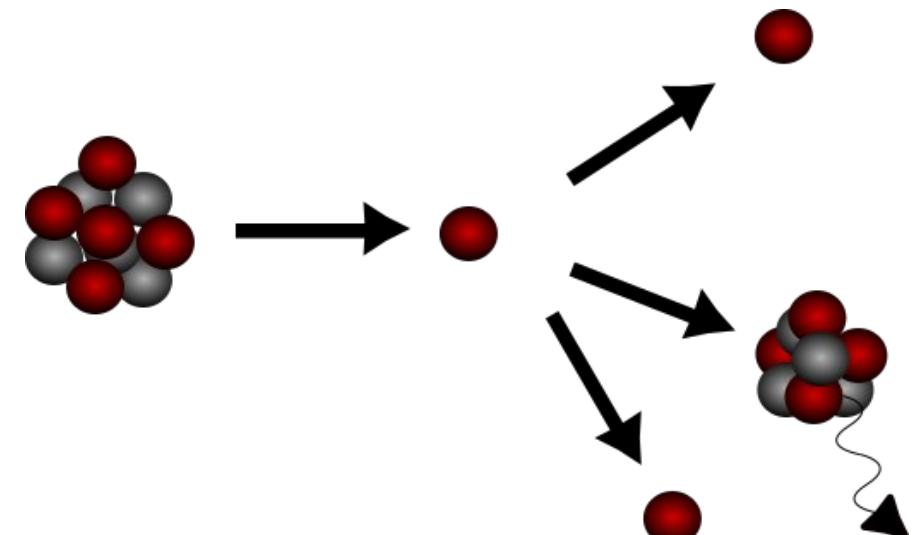
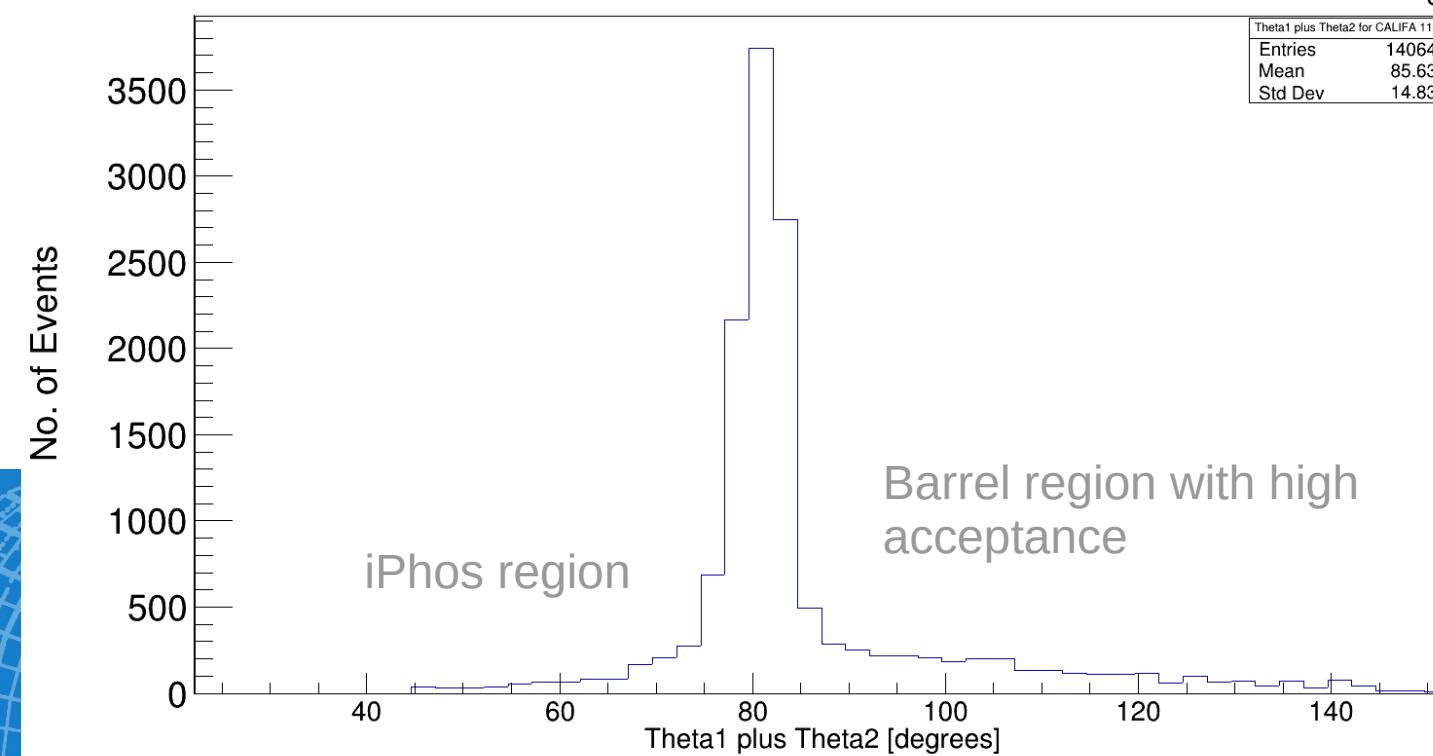
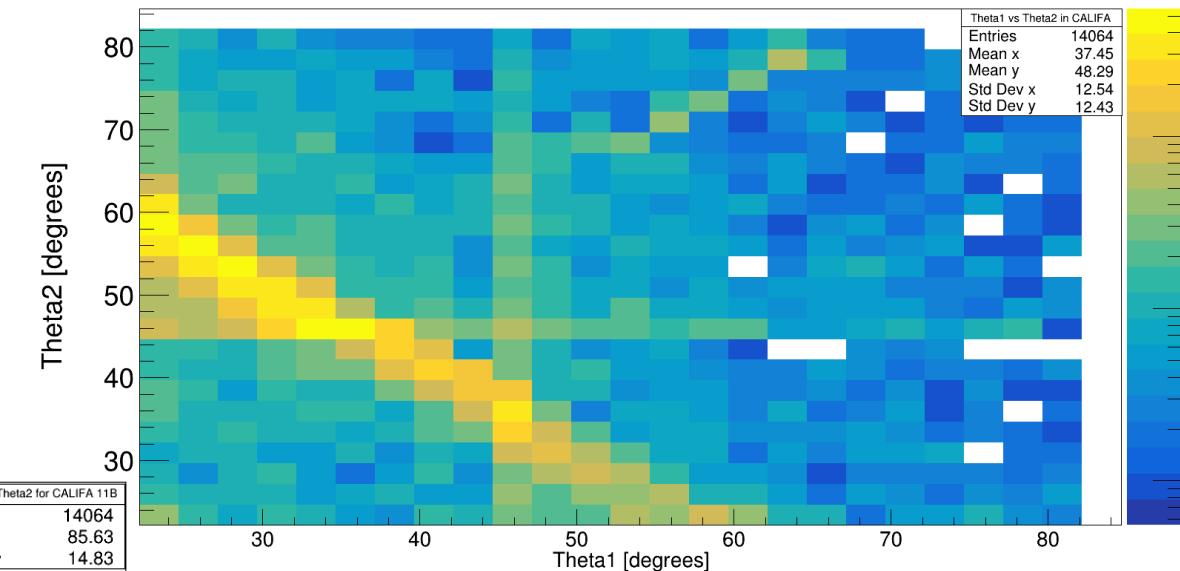
$$E_{\gamma} = \gamma E_{lab} (1 - \beta \cos(\theta))$$

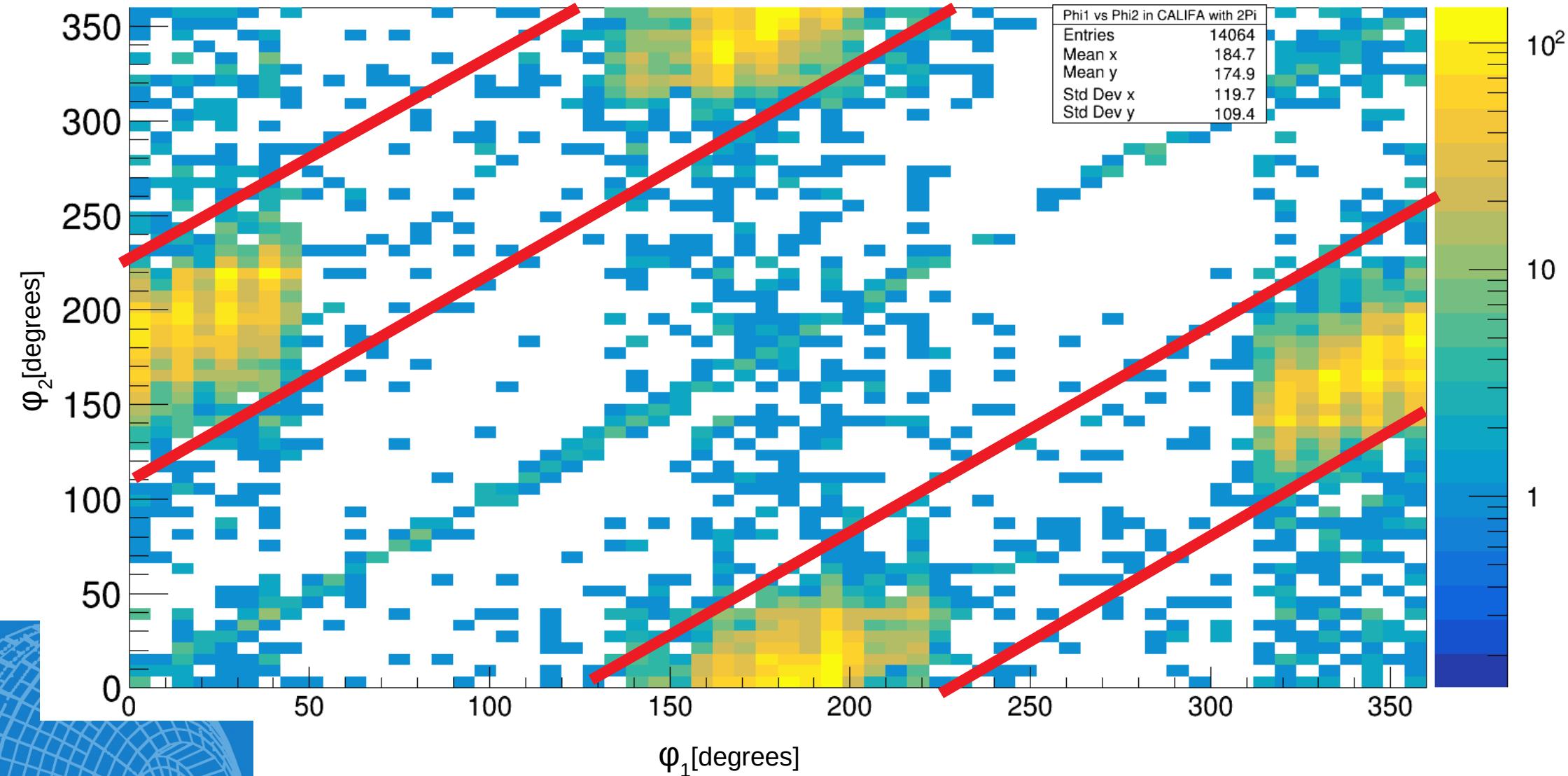
12C rest frame



# Polar Angular Distribution of protons for $^{12}\text{C}(\text{p},2\text{p})^{11}\text{B}$

Theta1 vs Theta2 in CALIFA

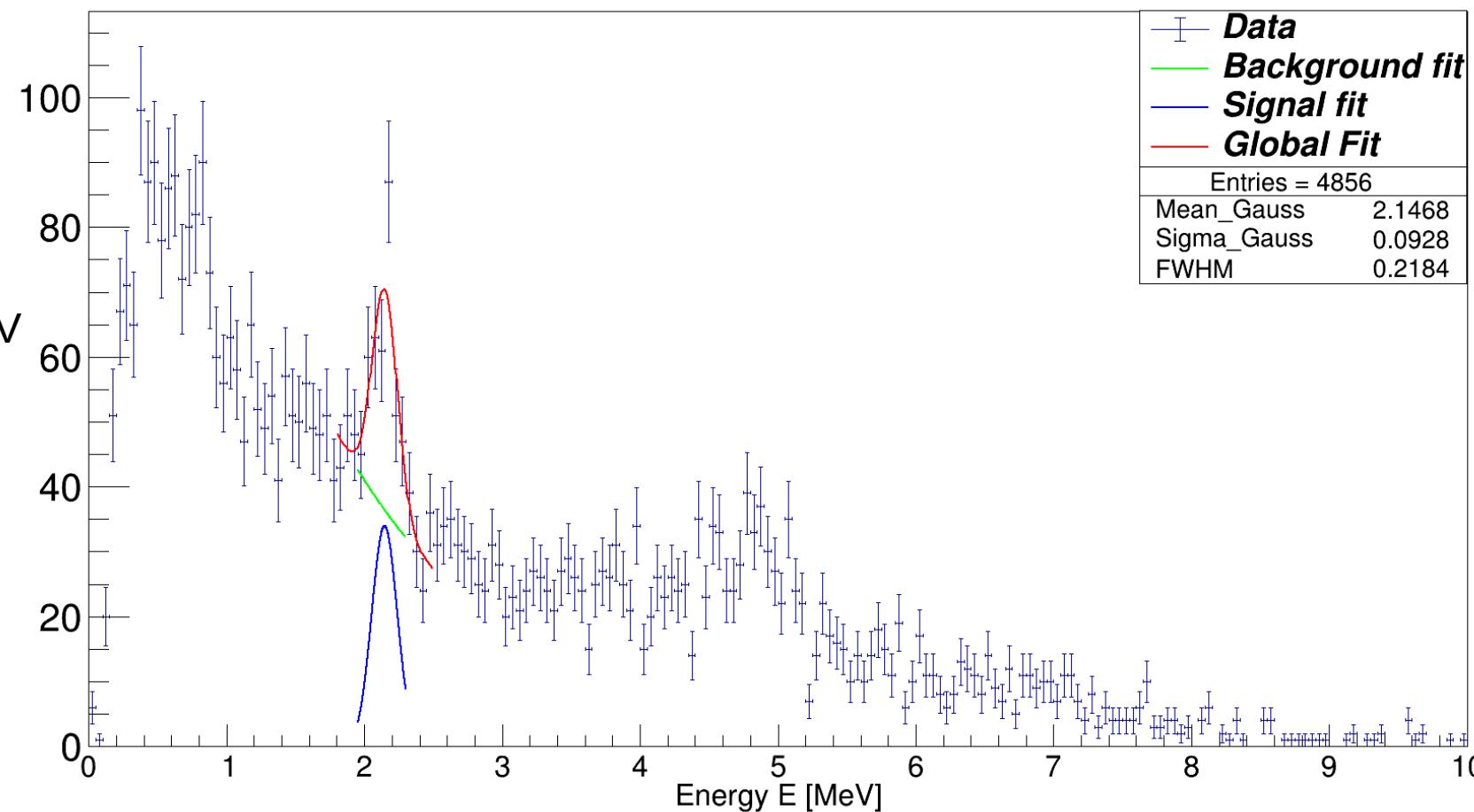




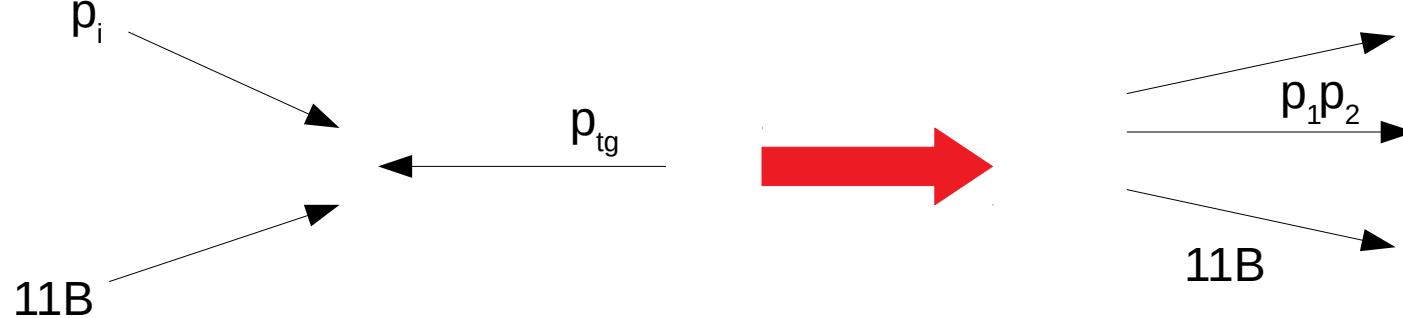
CALIFA Gamma Energy Spectrum

Event selection criteria for CALIFA:

- 11B fragment identification
- two hits (protons) with  $E_{\text{hit}} > 30 \text{ MeV}$
- $\theta_1 + \theta_2 < 90^\circ$
- $\Delta\phi = 180^\circ \pm 40^\circ$



# Reconstruction of Inner Momenta



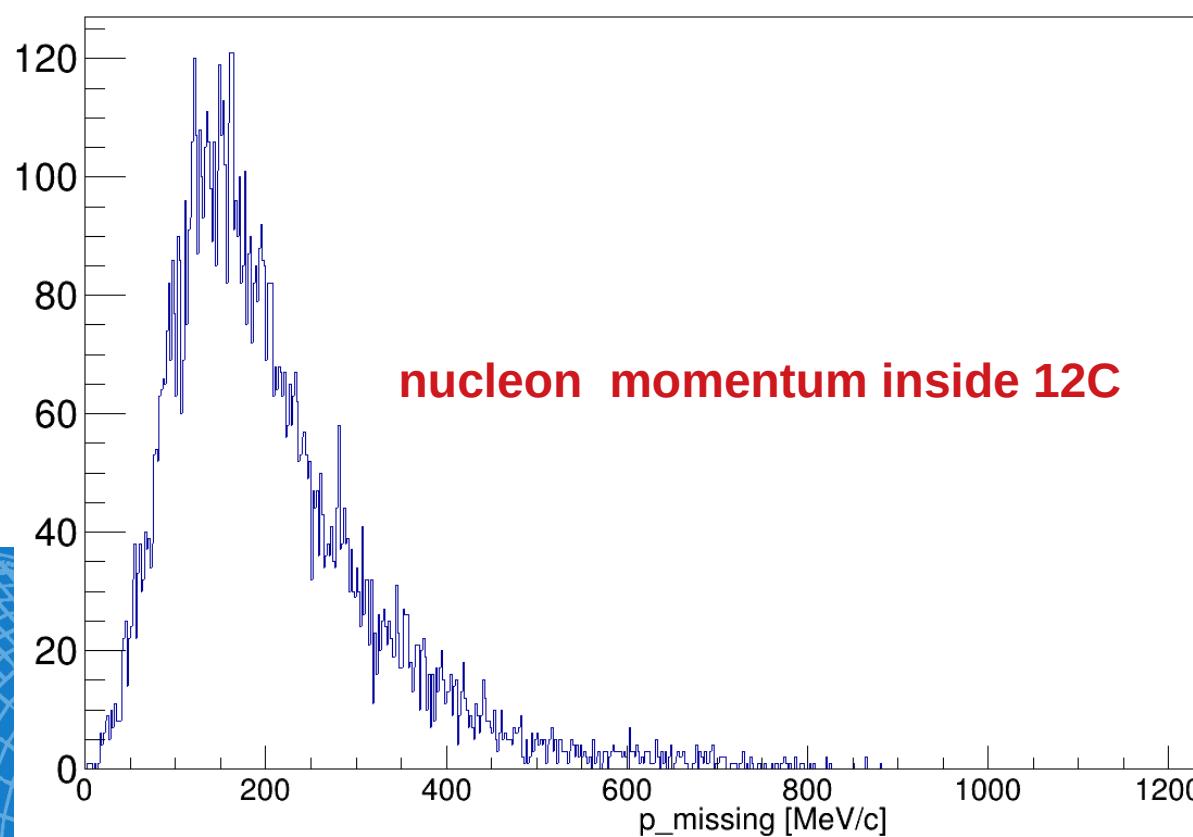
Momentum conservation relation:

$$p_{^{12}\text{C}} + p_{tg} = p_1 + p_2 + p_{^{11}\text{B}}$$

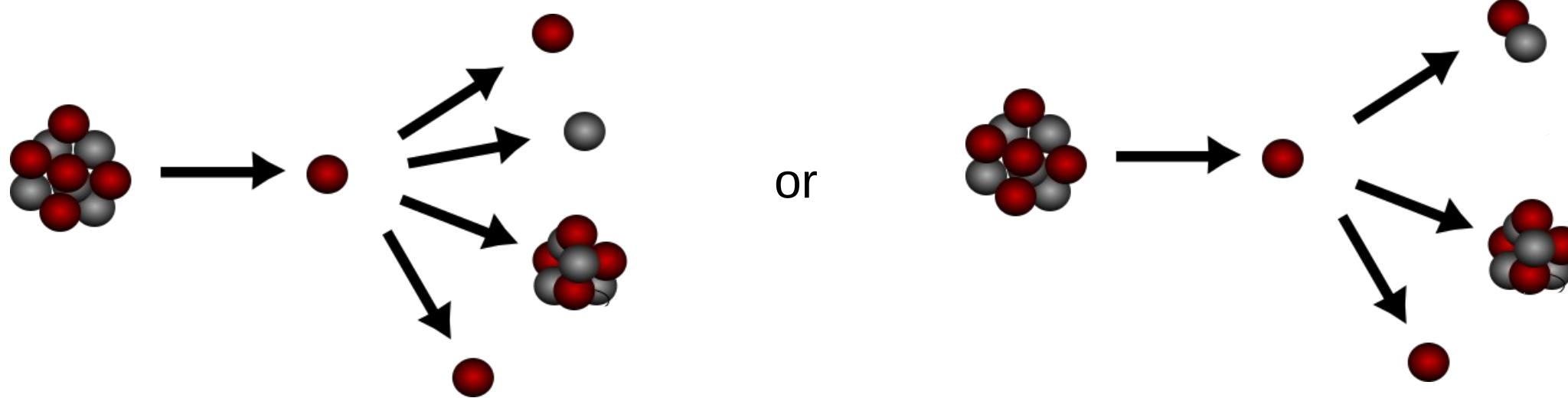
assuming QE scattering in mean field potential:

$$p_{^{12}\text{C}} = p_i + p_{^{11}\text{B}}$$

$$p_i \approx p_{missing} = p_1 + p_2 - p_{tg} \quad (\text{no ISI/FSI})$$

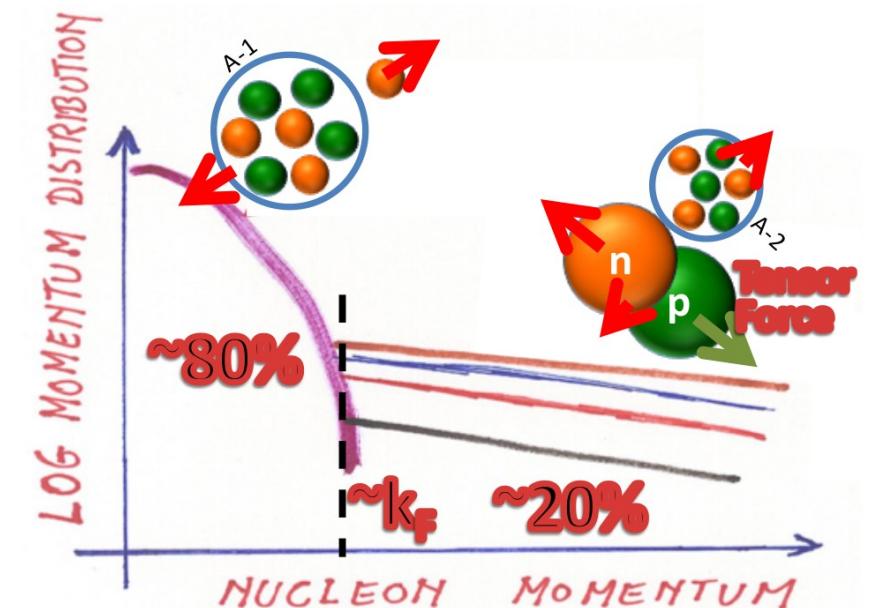


# $^{12}\text{C}(\text{p},\text{pn/d})^{10}\text{B}$ reaction



## Short Range Correlations (SRC):

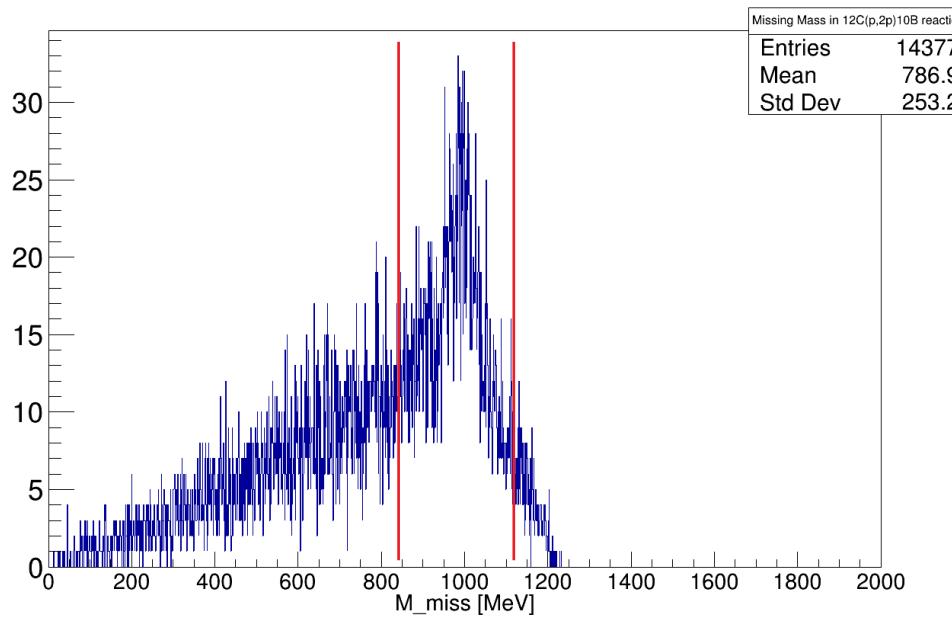
- Possible explanation for EMC - effect
- nucleon pairs with high relative and low c.m. momentum (compared to Fermi momentum  $k_F$ )
- SRC exist in nuclei and account for about 20% of nucleons



# First Angular and Momentum Plots ...

Making cut on the reconstructed neutron:

$$M^2_{missing} = (p_{12C} + p_{tg} - p_1 - p_2 - p_{10B})$$

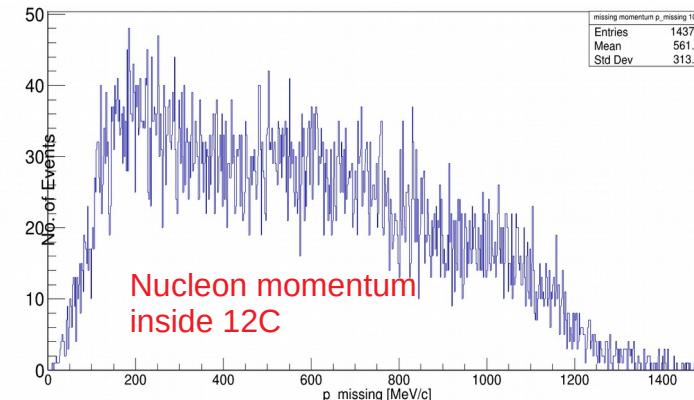


**M<sub>missing</sub> cut**  
850 MeV < M<sub>missing</sub> < 1100 MeV

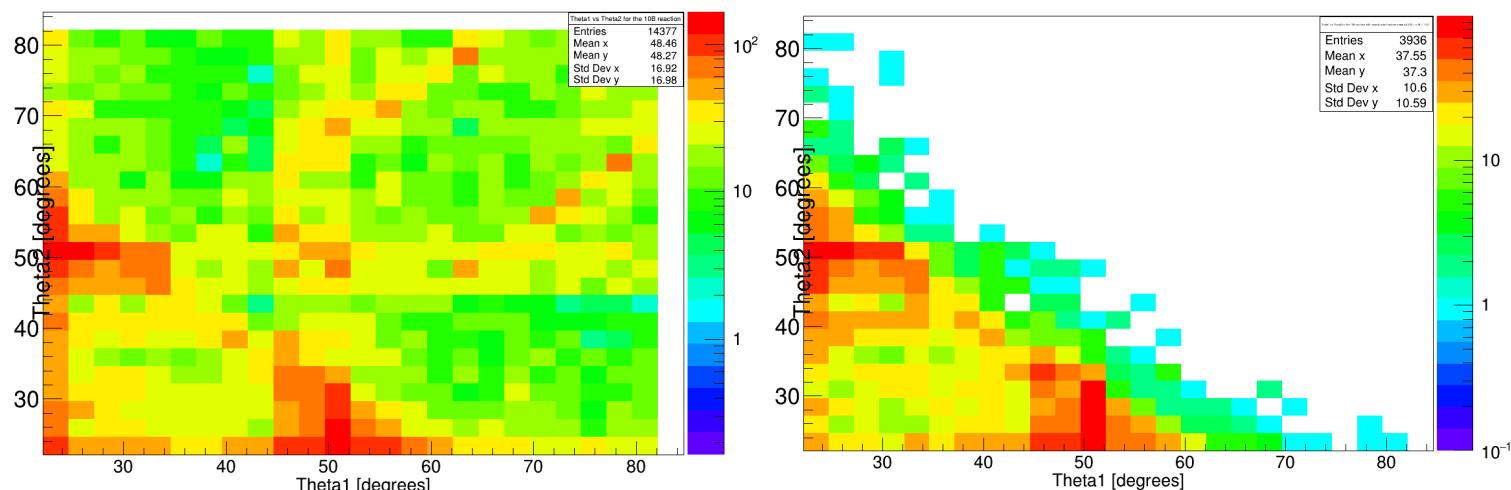


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Without cut:



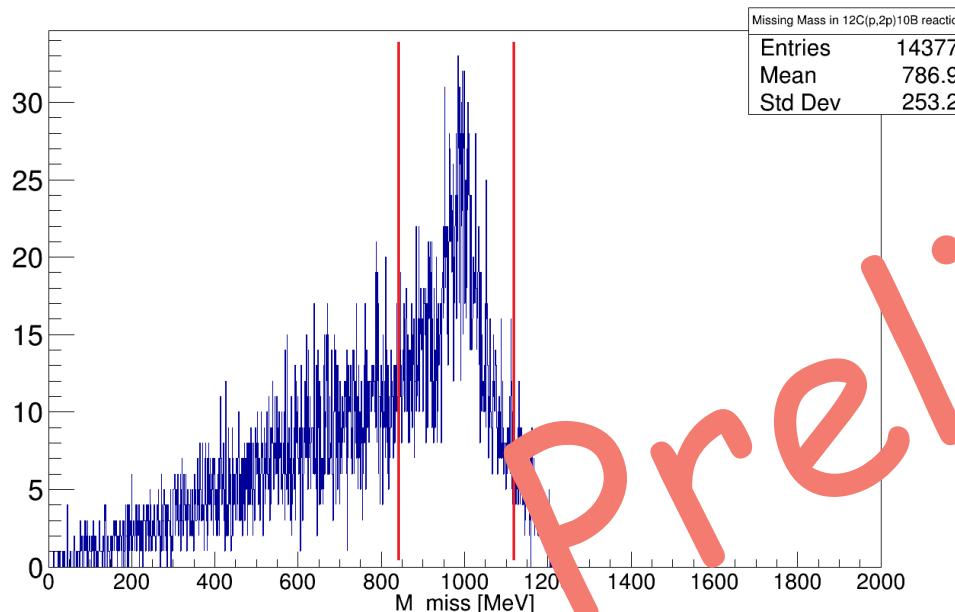
With reconstructed neutron mass cut:



# First Angular and Momentum Plots ...

Making cut on the reconstructed neutron:

$$M^2_{missing} = (p_{12C} + p_{tg} - p_1 - p_2 - p_{10B})$$

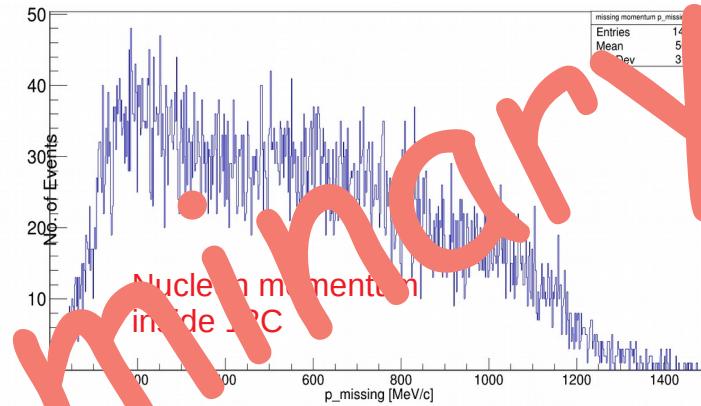


$M_{missing}$  cut  
850 MeV <  $M_{missing}$  < 1100 MeV

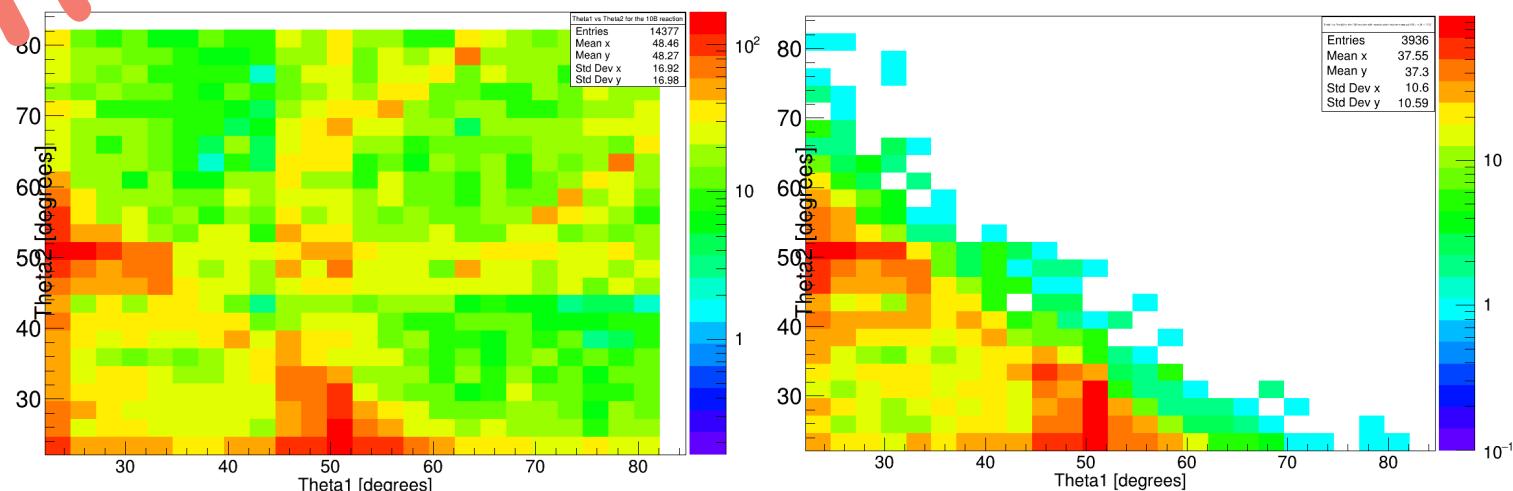


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Without cut:



With reconstructed neutron mass cut:





# Summary & Outlook





R<sup>3</sup>B



# Thank you!

**CALIFA @ Technical University of Munich (TUM)**

Roman Gernhäuser, Lukas Ponnath, Philipp Klenze, Tobias Jenegger



Tobias Jenegger

Particle Identification in R<sup>3</sup>B





# Backup

