



R³B 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

R³B Experiment @ GSI

PSI Seminar
16.06.2021

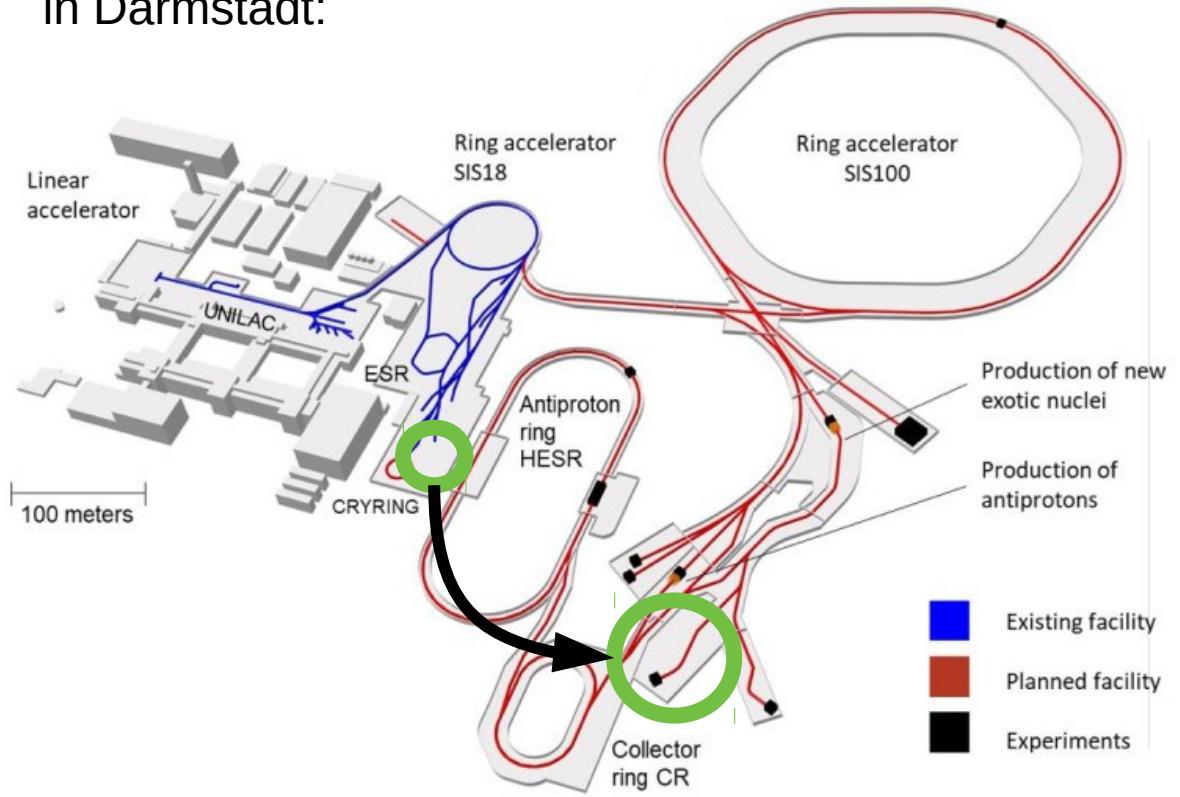
CALIFA - Design and Upgrades

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

QFS Analysis

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

R³B as part of the
Facility for Antiproton and Ion Research (FAIR)
in Darmstadt:



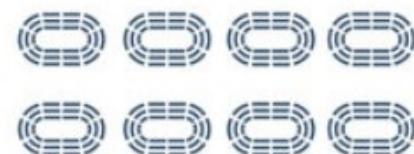
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- 2 mio. m³ of earth excavated
- 600,000 m³ of concrete
- 65,000 tons of steel



5,000 single family homes



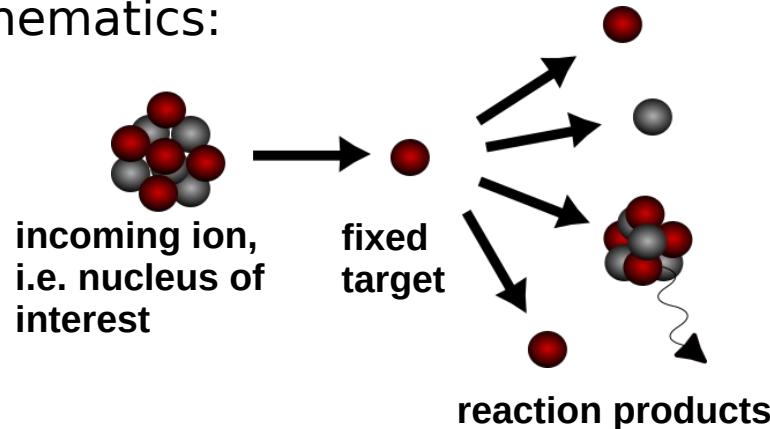
eight Frankfurt soccer stadiums



nine Eiffel Towers

Reactions with Radioactive Relativistic Beams

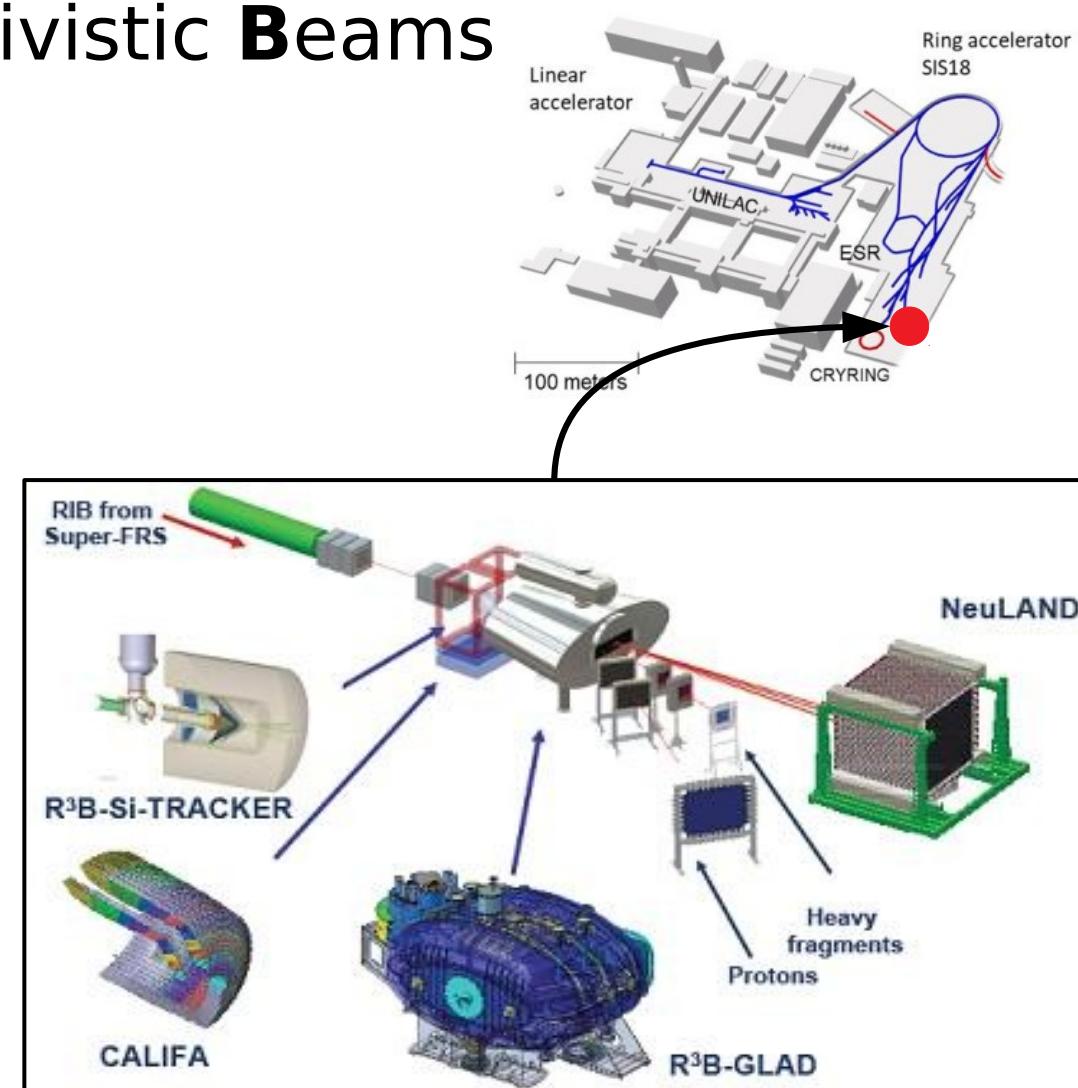
- Physics program on exotic nuclei in inverse kinematics:



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



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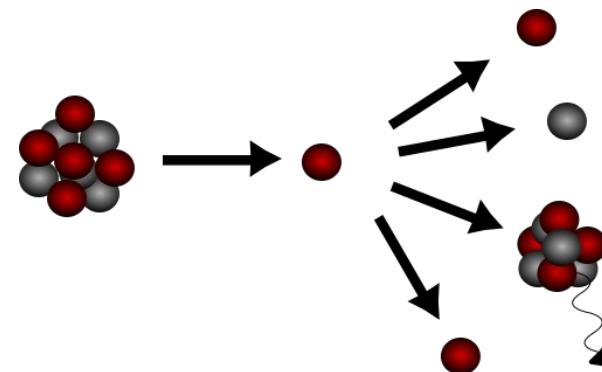




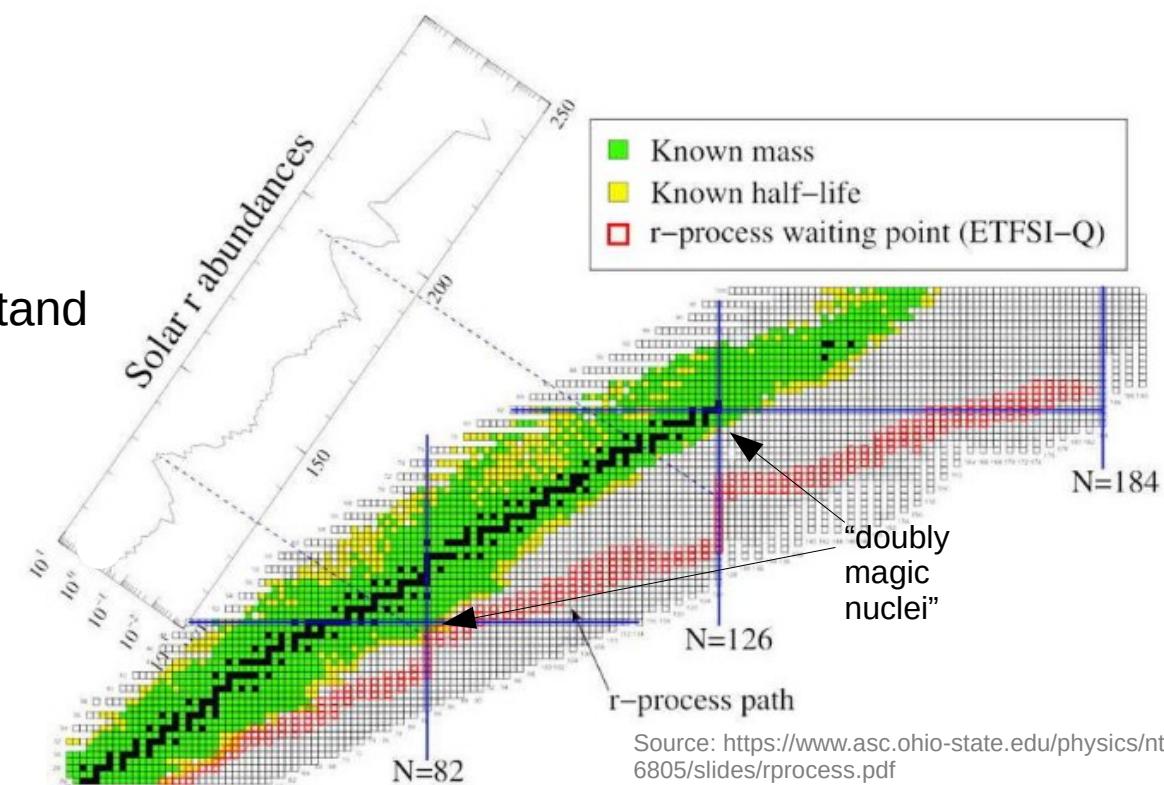
Physics program @ R³B



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



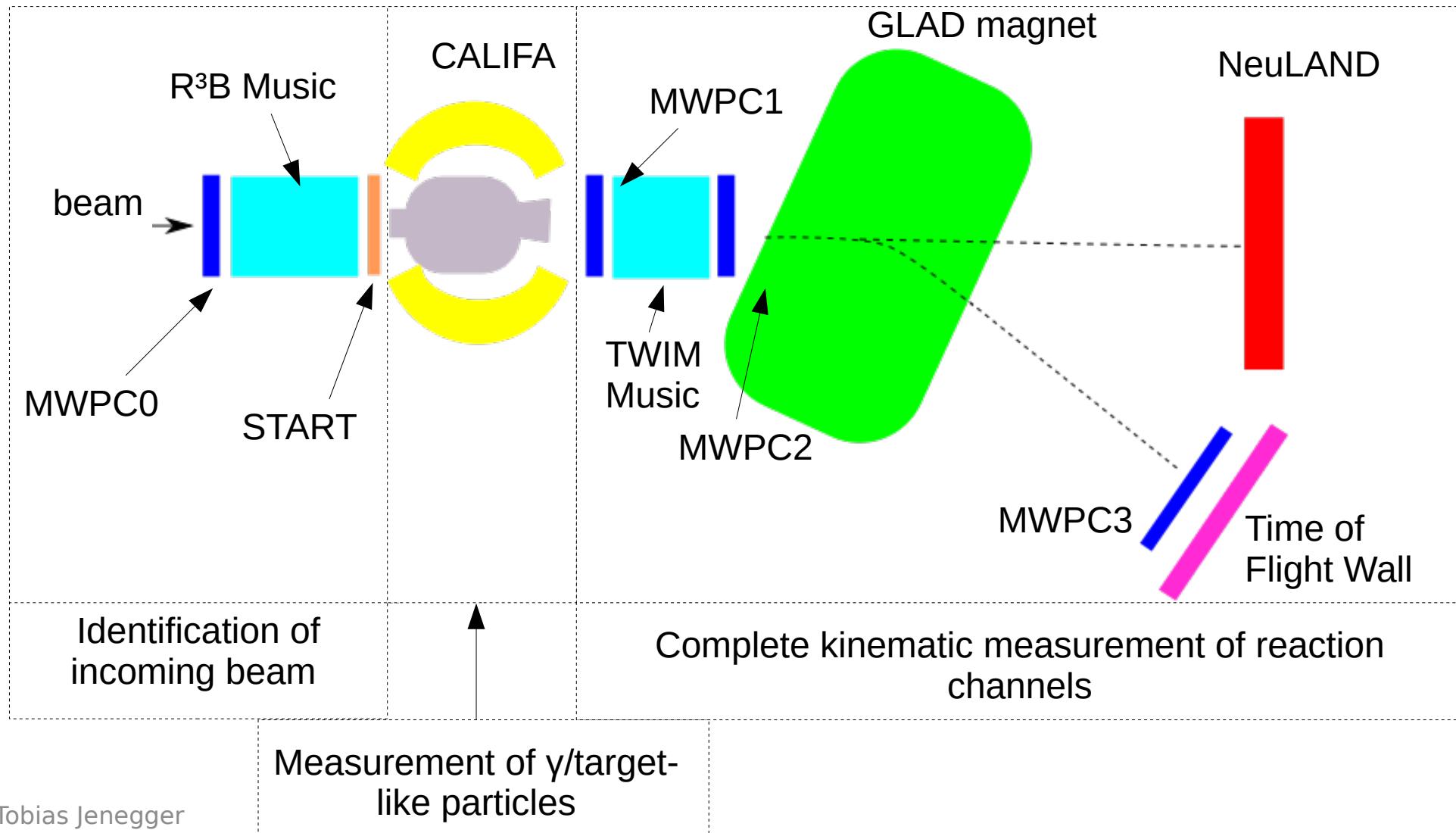
- Collective excitations in neutron rich exotic nuclei via Coulomb Excitation
- Fission Studies (up to uranium)
 - fission barriers on heavy neutron rich nuclei to understand e.g. final r-process abundance
 - fission yields: symmetry/asymmetry of fission products

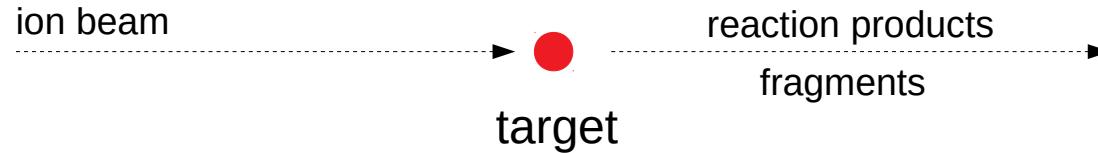


R³B Setup for Experiments S444/467 (2020)

S444: Commissioning Run with ^{12}C beam

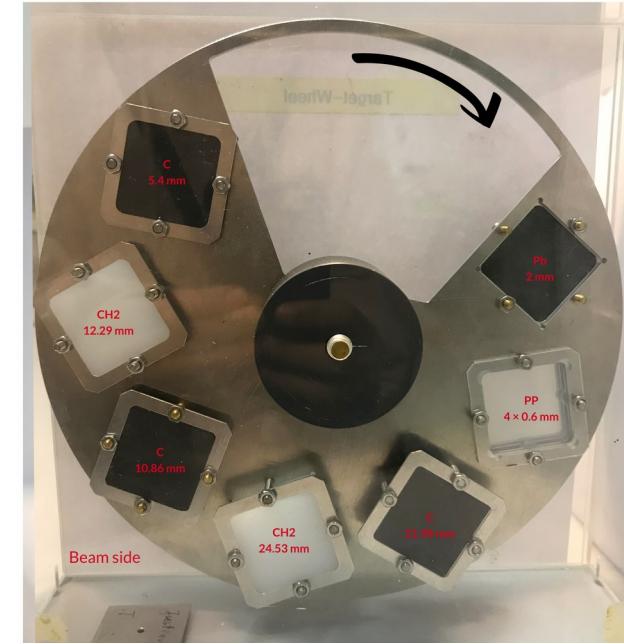
S467: Physics Run with neutron rich Ca isotopes beam





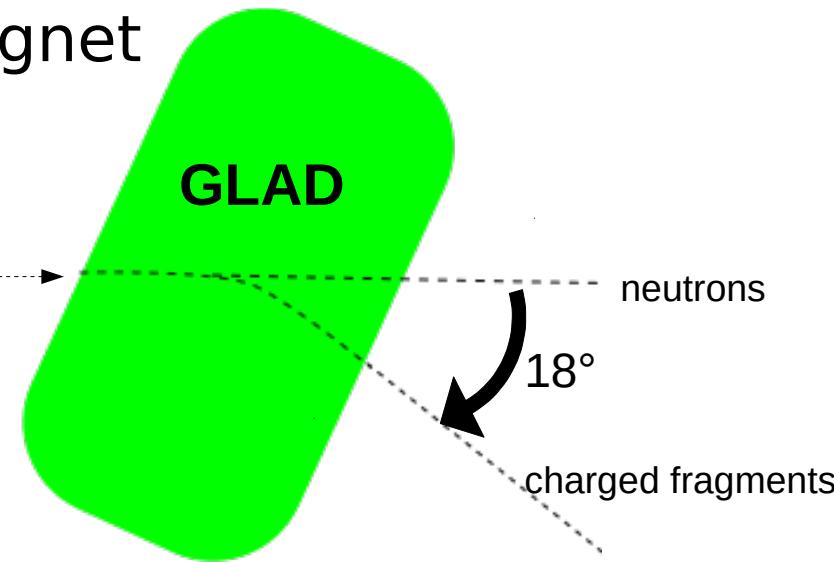
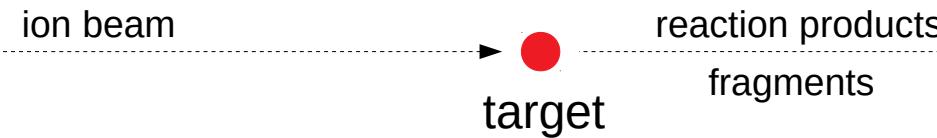
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Target Wheel



Targets:

- C with length:
5.4 / 10.86 / 21.98 mm
- CH₂ with length:
12.29 / 24.53 / 24 mm
- Pb with length:
2 mm



- large aperture (+-80 mrad) for neutrons
- high bending range from 0° - 40°
- field integral of about 5 Tm
- momentum resolution $\Delta p/p$ of around 10^{-3}



Tracking Detectors



MWPC0

200 x 200 mm²

ion beam

resolution:
 $\sigma_{x,y} \approx 100 \mu\text{m}$

MWPC1

200 x 200 mm²

target

resolution:
 $\sigma_x \approx 100 \mu\text{m}$
 $\sigma_y \approx 1-2 \text{ mm}$

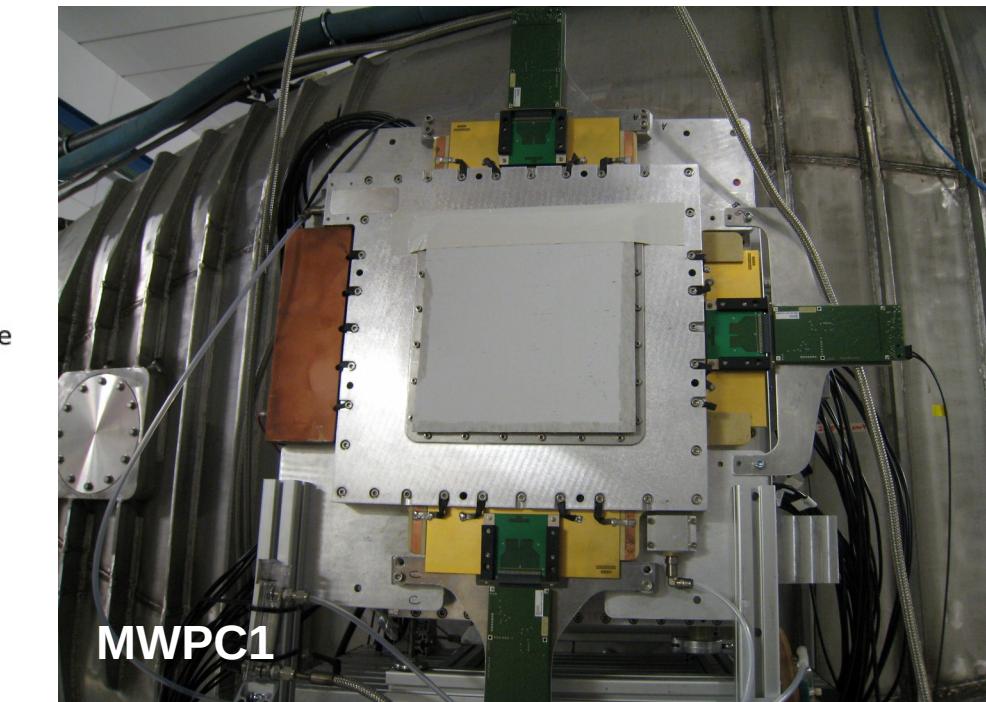
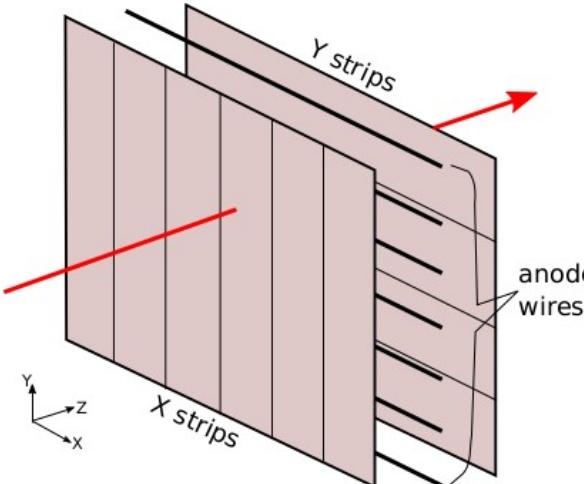
MWPC2

200 x 200 mm²

resolution:
 $\sigma_x \approx 100 \mu\text{m}$
 $\sigma_y \approx 1-2 \text{ mm}$

Multi Wire Proportional Chambers (MWPCs):

- horizontal wires: 50 μm diameter, 2.5 mm spacing
- vertical/horizontal pads:
Al-deposited on a 12 μm Mylar foil,
5/3.125 mm width (vertical/horizontal)
- gas mixture: 84% Ar, 16% CO₂
- pad readout



NeuLAND

resolution:
 $\sigma_x \approx 100 \mu\text{m}$
 $\sigma_y \approx 1-2 \text{ mm}$

MWPC3
900 x 600 mm²

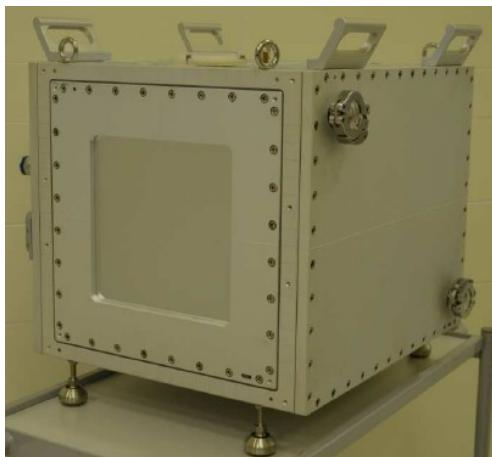
neutrons

charged fragments

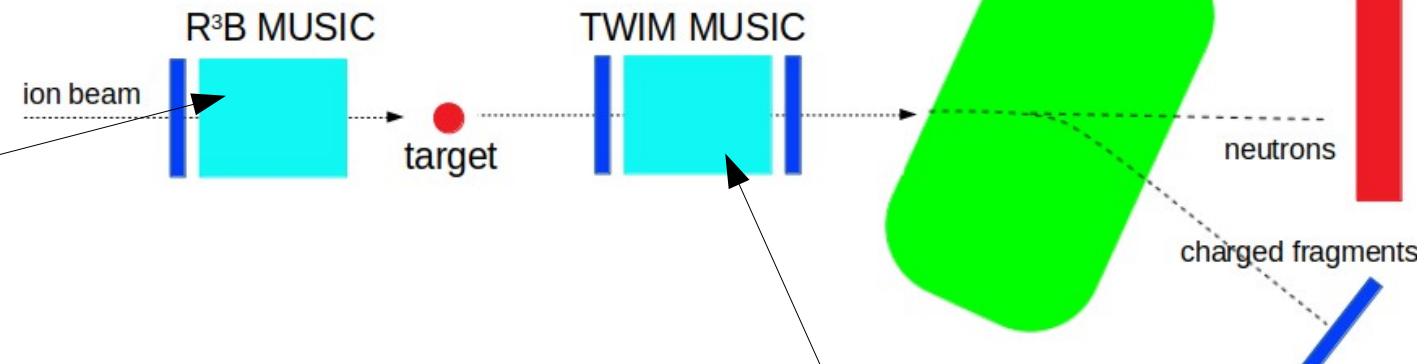
resolution:
 $\sigma_x \approx 100 \mu\text{m}$
 $\sigma_y \approx 1-2 \text{ mm}$

Charge Measurement - Ionization Chambers

Before the target: **R³B MUSIC**



51 x 54 x 53 cm³
Cathode left side -
Anode right side
Gas mixture:
Ar 25%, CH₄ 75%

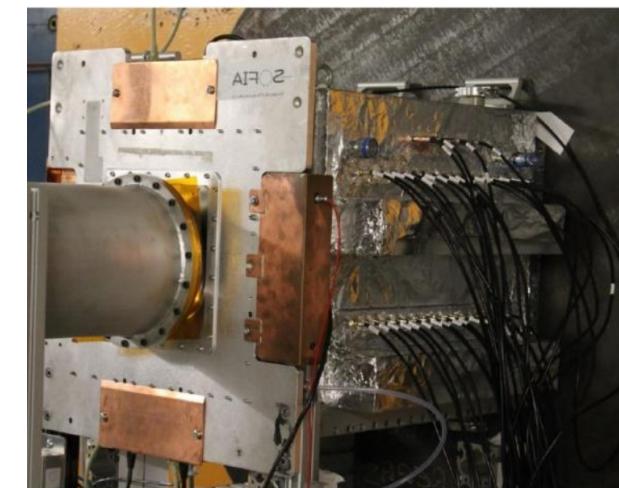


High resolution measurements of:

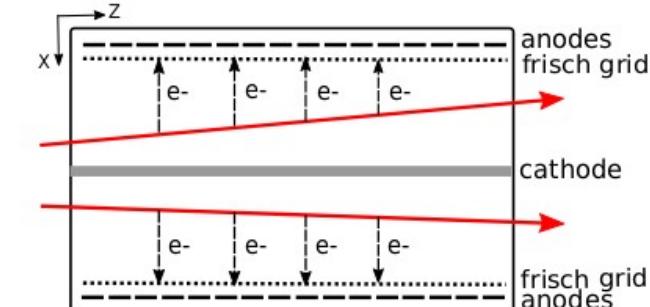
- energy loss ΔE
→ **charge**

- drift time of e^- from ionization
→ **horizontal angle**

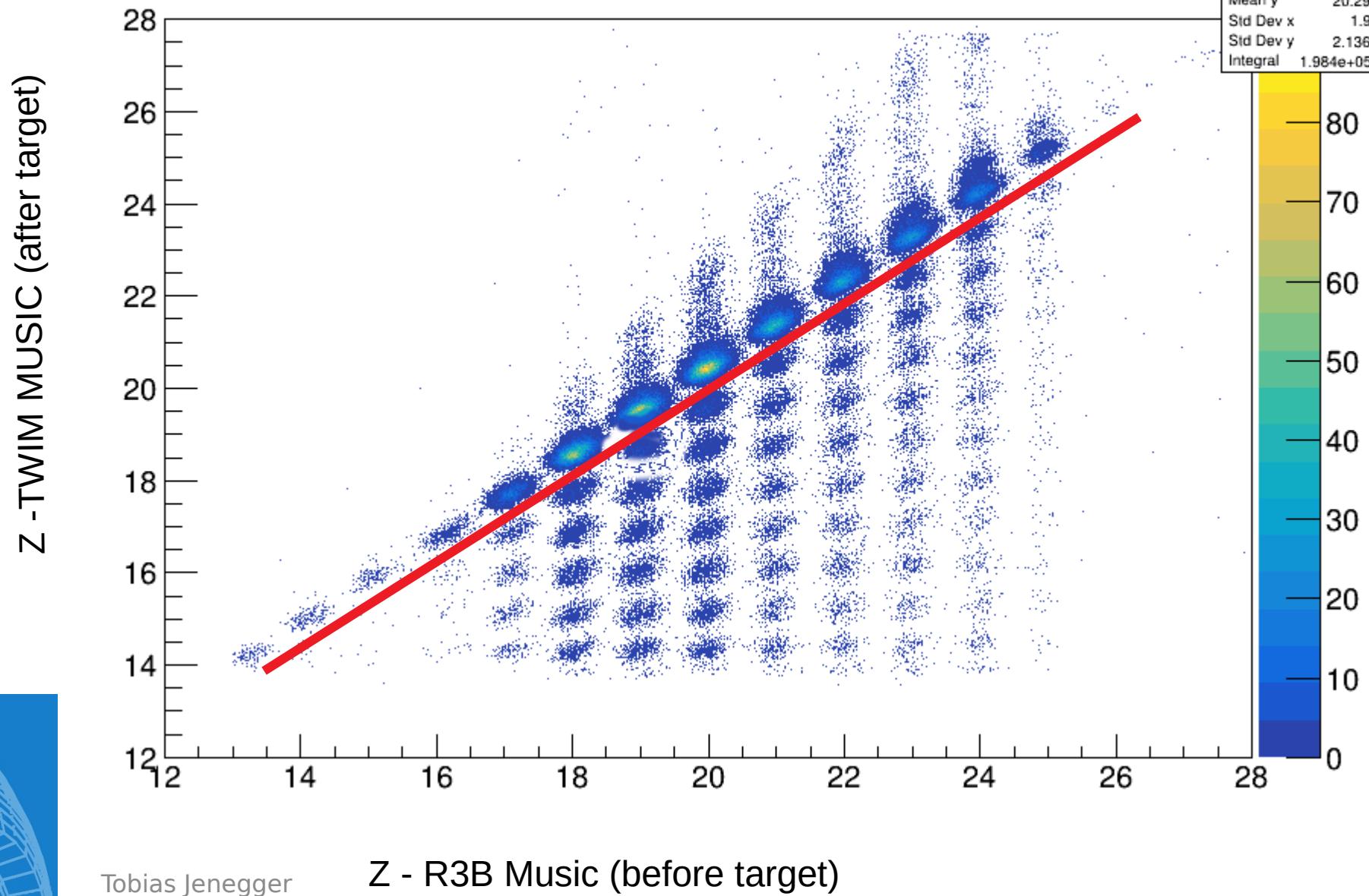
After the target area: **TWIM MUSIC**



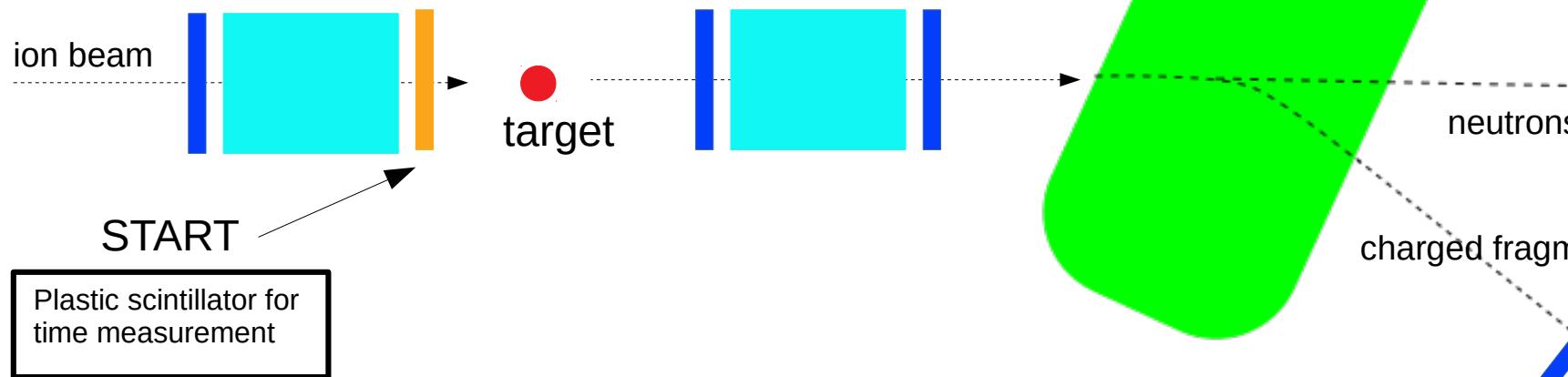
43 x 48 x 55 cm³
Double ionization chamber
Frisch grid for better signal quality and time resolution
Gas mixture:
Ar 25%, CH₄ 75%



Ca^{50} cocktail from Fragment Separator
with beam energy: 580 AMeV



Time Measurement - START & ToFW



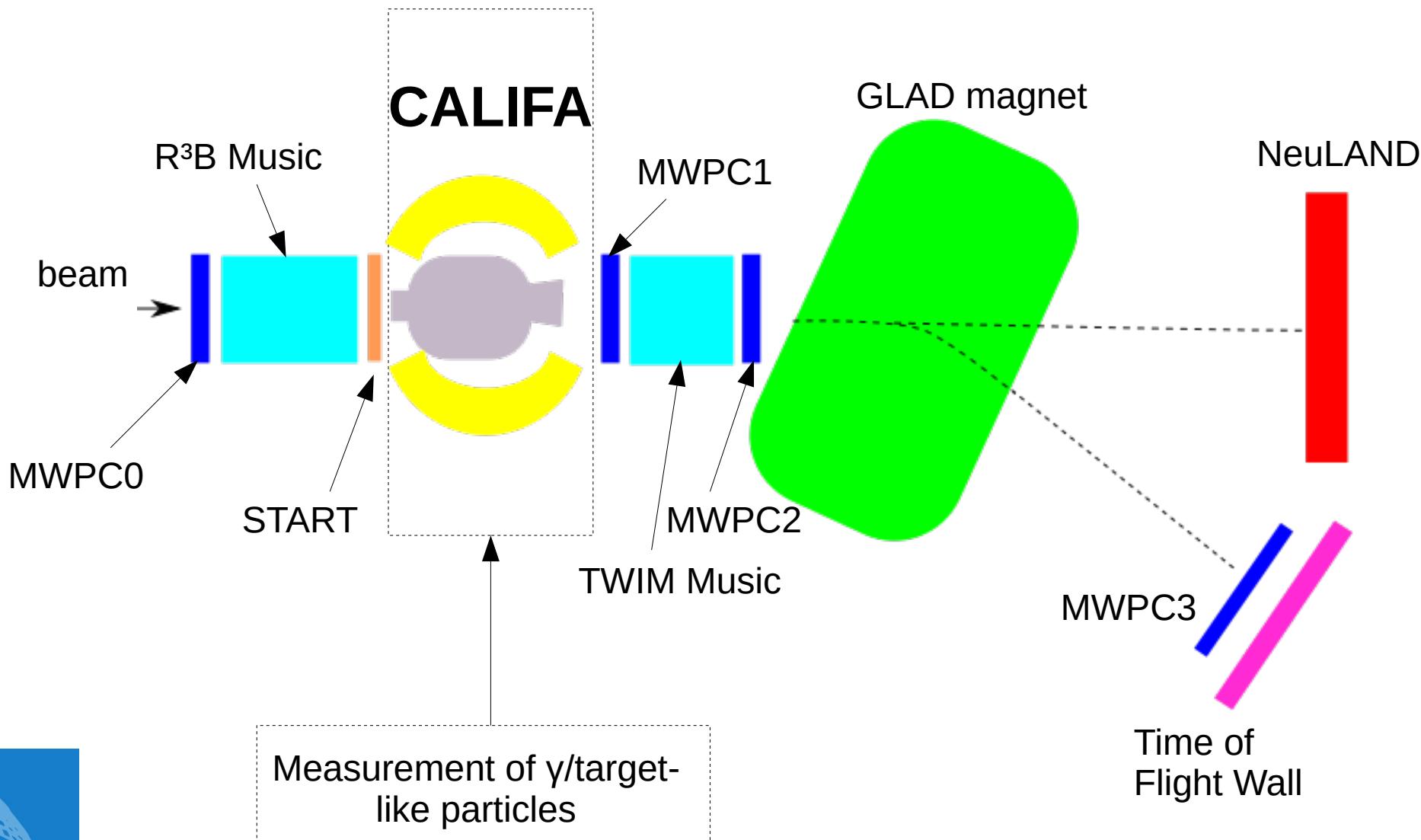
Mass Identification:

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

- ToF measurement: START to TOFW
- flight-path reconstruction: tracking detectors
- charge measurement: R3B Music &

TWIM MUSIC





CALorimeter for the In Flight detection of γ -rays and light charged pArticles

Endcap:

iPhos:

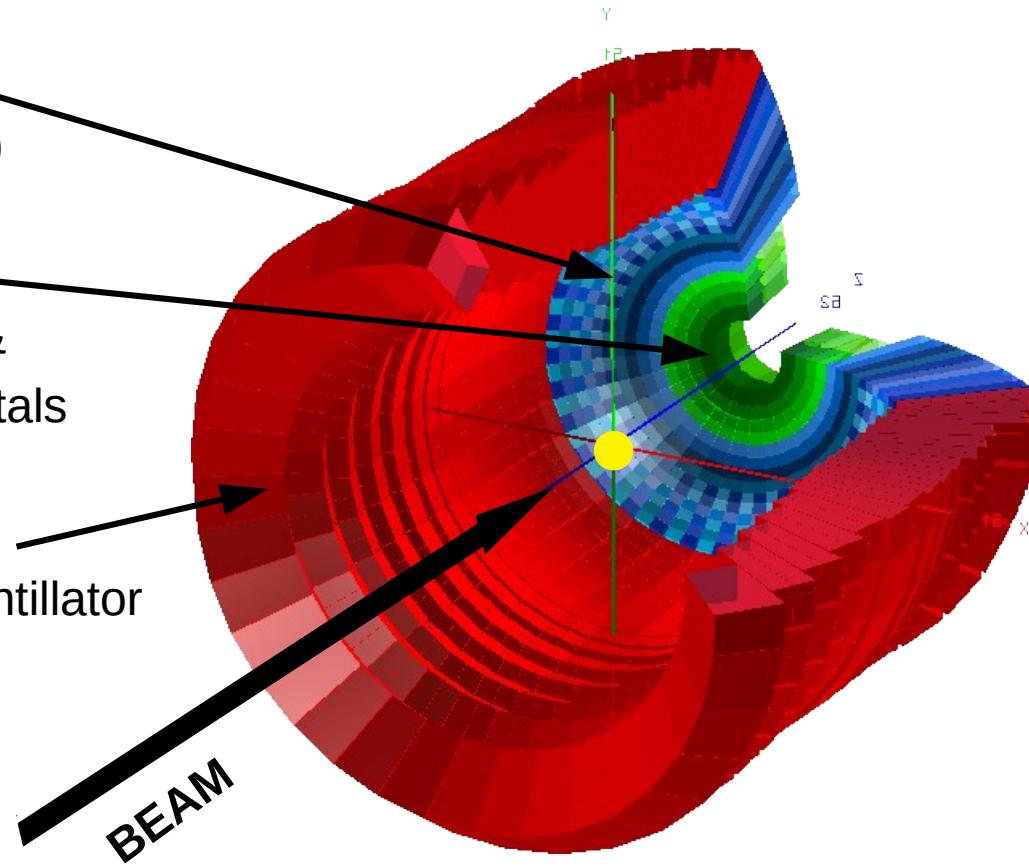
512 CsI(Tl)
crystals

CEPA:

96 LaBr₃ &
LaCl₃ crystals

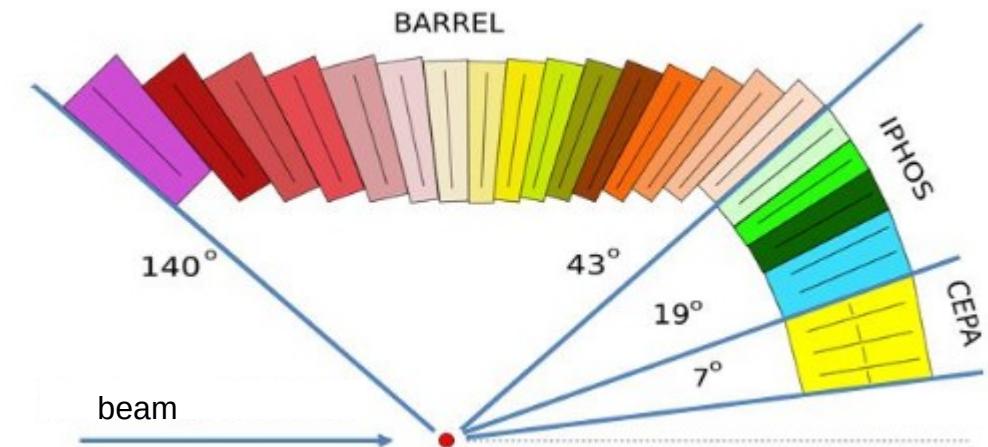
Barrel:

1952 CsI(Tl) scintillator
crystals



Requirements:

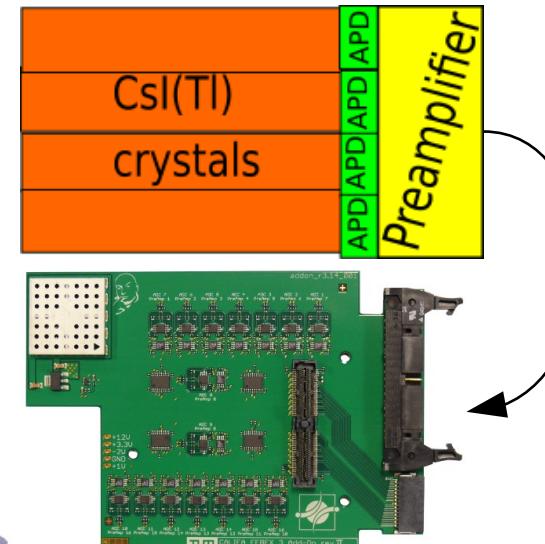
- high dynamic range:
100 keV γ -rays – 700 AMeV charged particles
- high efficiency
- high granularity → Doppler correction
- particle identification



Signal Processing @ CALIFA

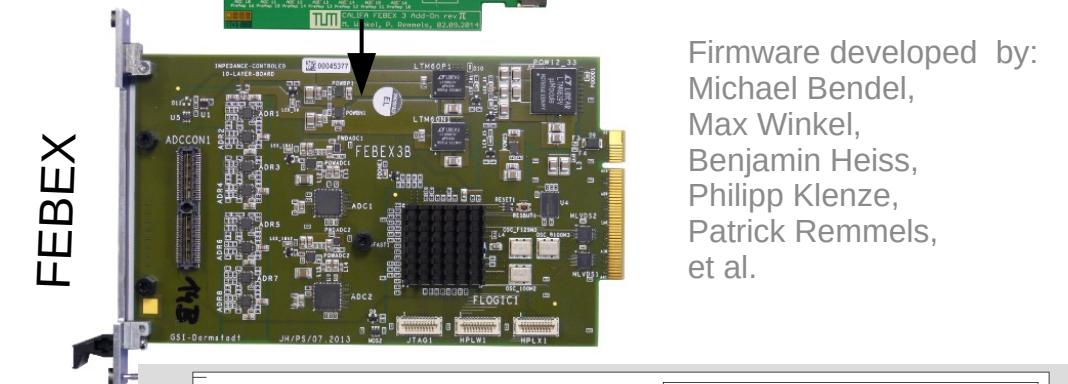
γ /particle interaction in **crystal** → scintillatorlight (550nm)
Every crystal connected to one **APD** → current gain ≈ 50
Preamplifier: generates HV for APD bias +
amplifies/integrates signal

Add-on Board: Filtering



Add-on Board

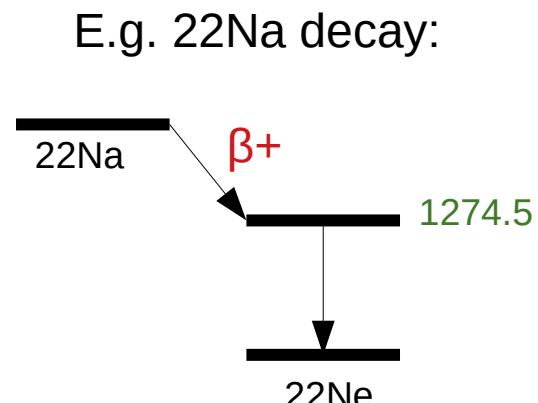
FEBEX Module: ADC + energy & particle identification



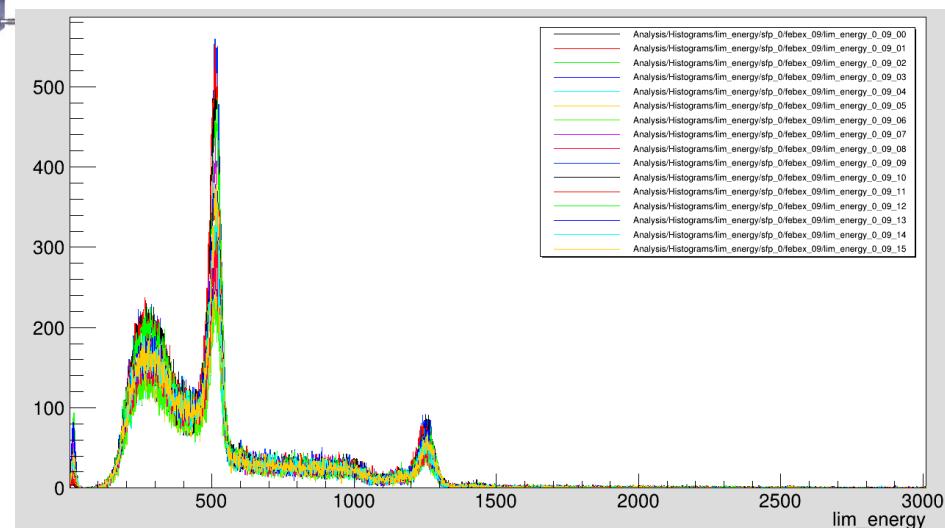
Firmware developed by:
Michael Bendel,
Max Winkel,
Benjamin Heiss,
Philipp Klenze,
Patrick Remmels,
et al.

Automated APD Gain matching routine:

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



Tobias Jenegger





Electronics for CALIFA



Each rack:
→ 1024 channels

→ 50 MHz
continuous
sampling rate

Dead-time free
readout design:

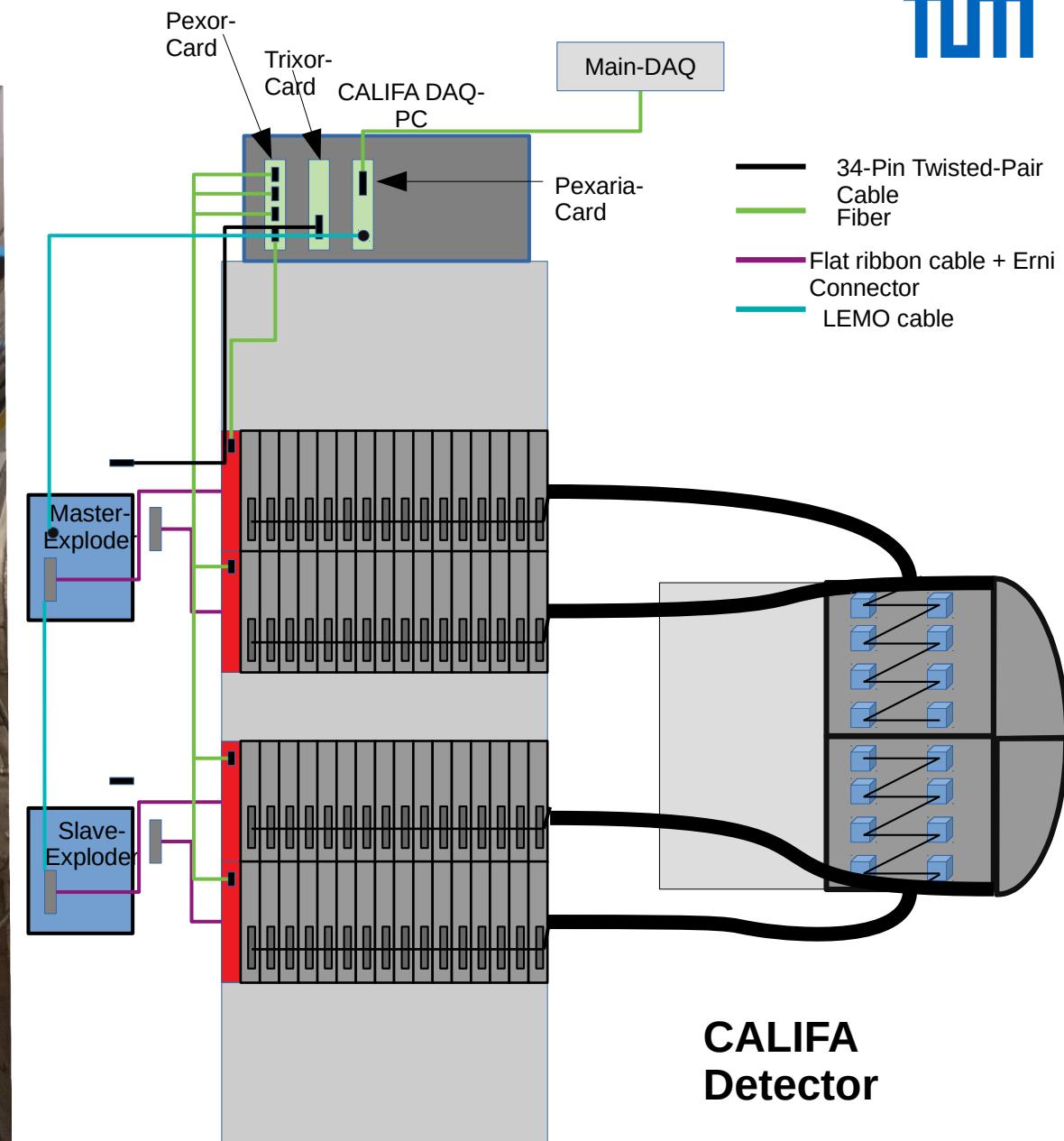
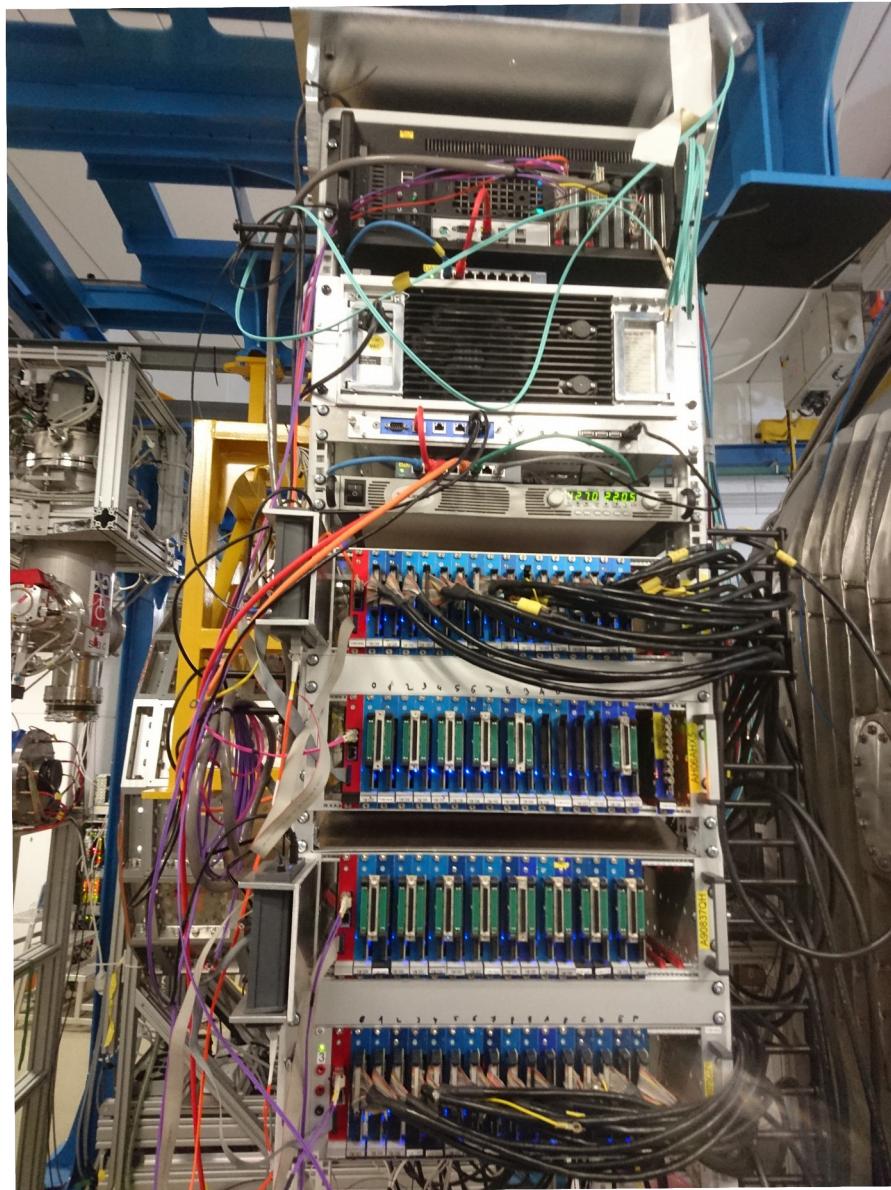
→ PEXOR card

→ TRIXOR card

→ EXPLODER

→ PEXARIA
(white

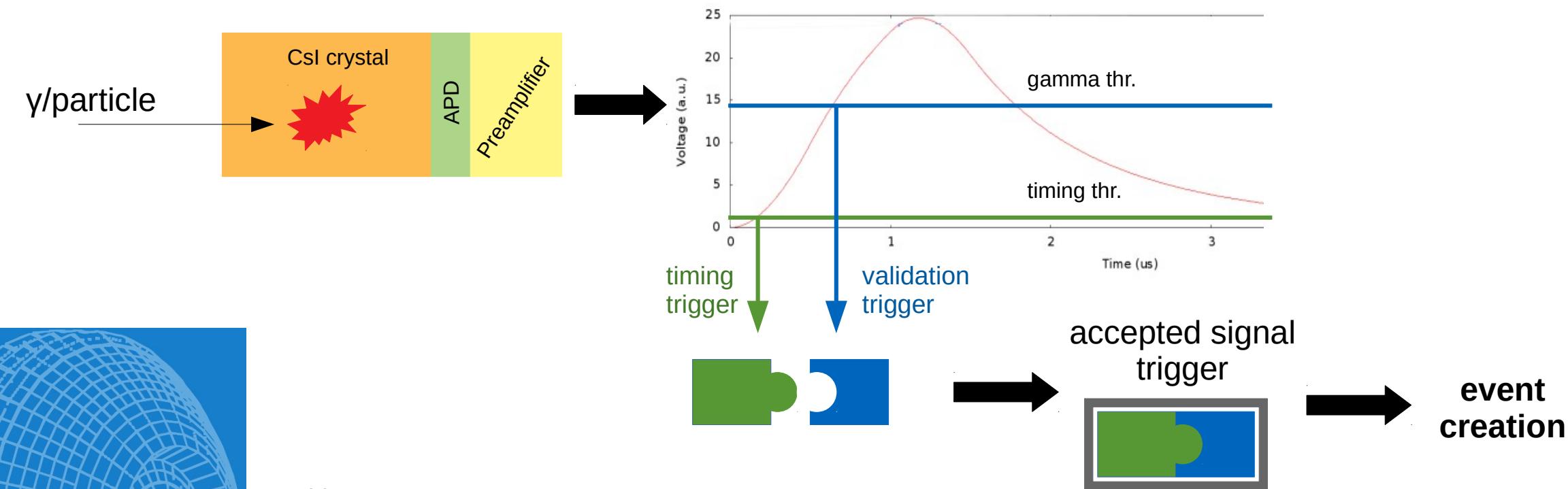
Rabbit
timestamp)



Trigger-Discriminator Logic:

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

Intuitive event building logic (free running mode):

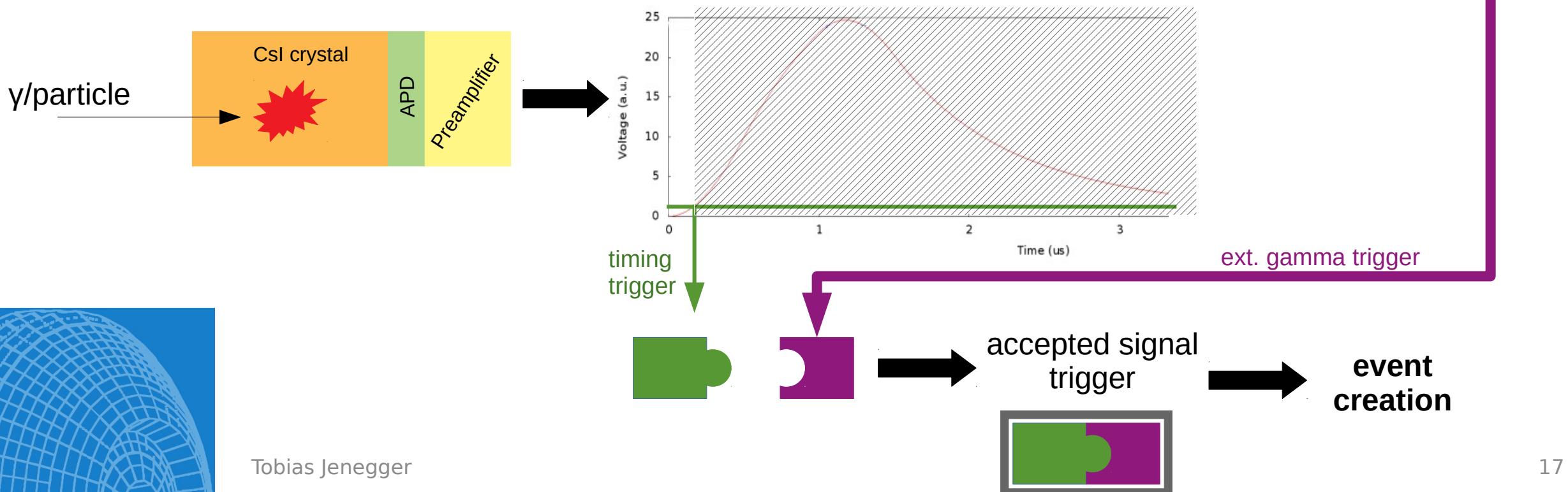


Trigger-Discriminator Logic:

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

Ext.
Detector

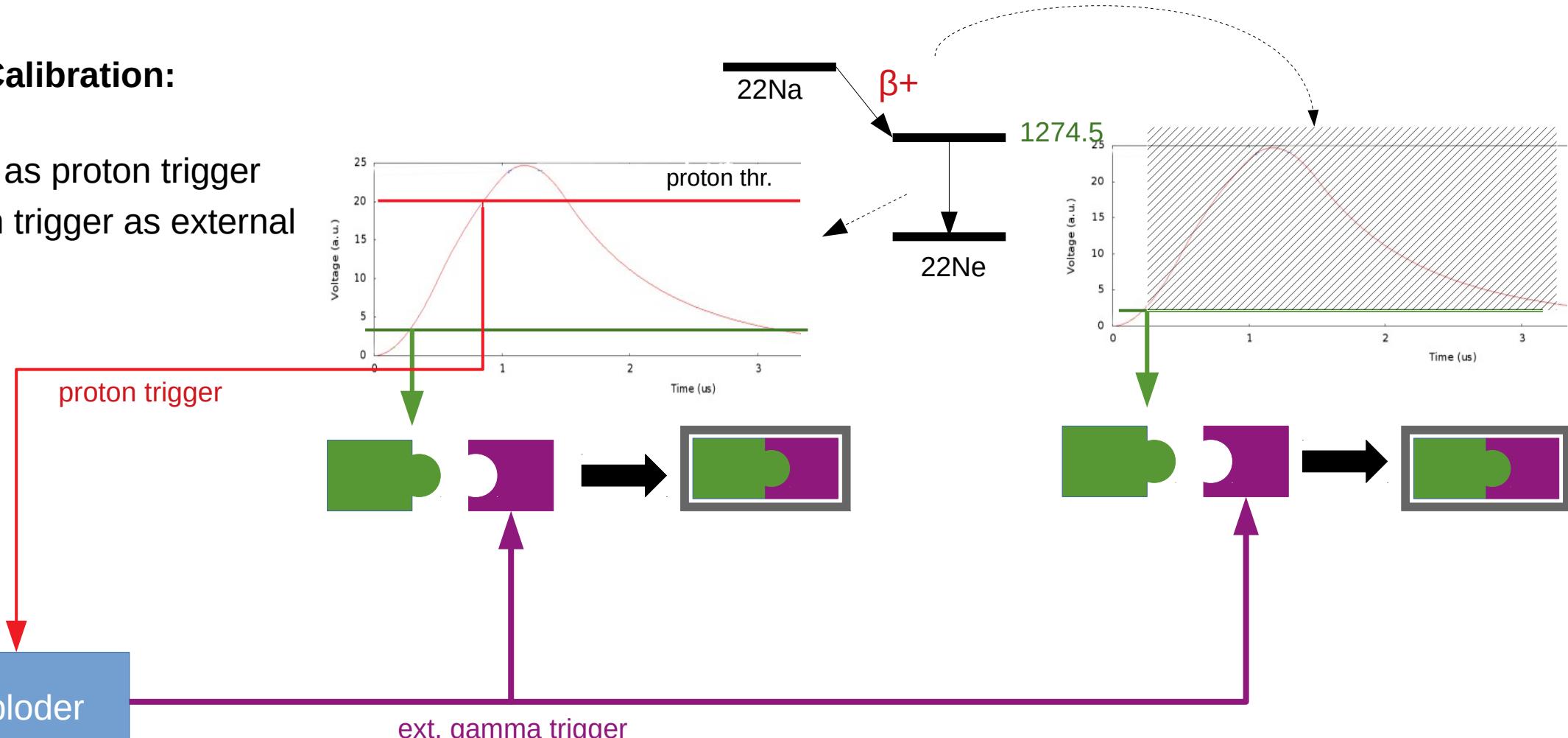
synchronous and coincident trigger mode (ext. validation trigger):



- For upcoming experiments we switched to coinc. trigger mode
- ext. gamma trigger from START detector

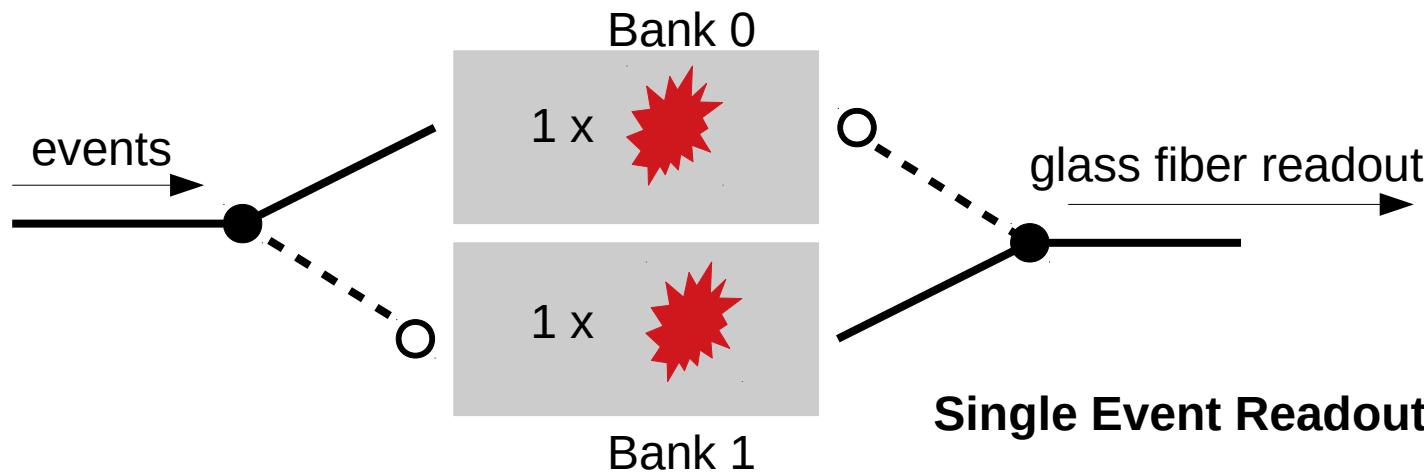
For Calibration:

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



Exploder

CALIFA Readout Modes

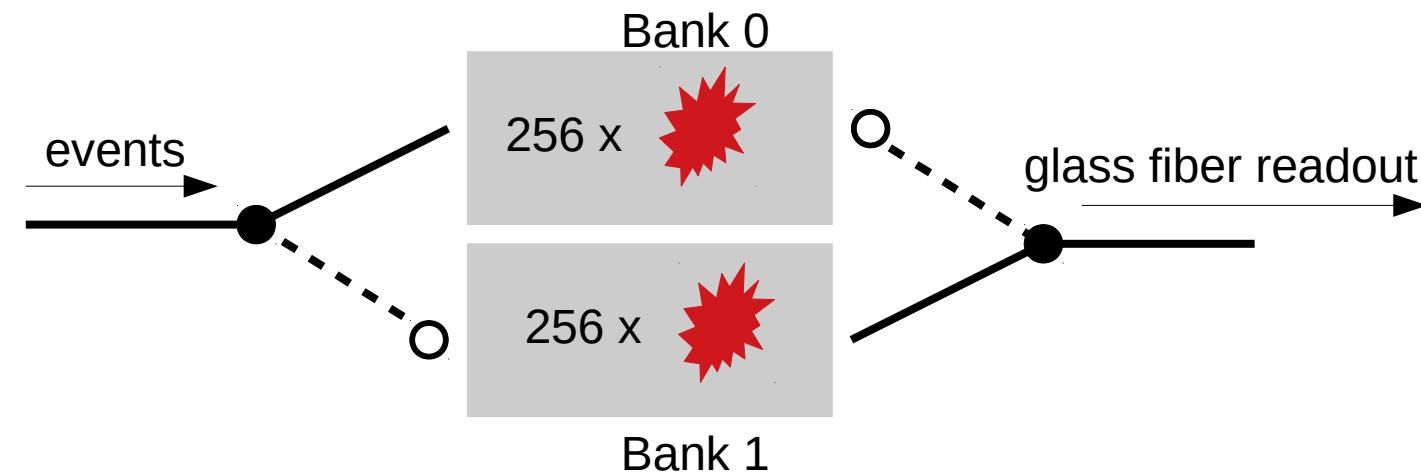


Single Event Readout (std. Firmware):

- 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

What is our rate limit?

max. readout speed per
glass fiber

$$\frac{190 \text{ MByte/s}}{40 \text{ Byte}} \approx 4 \text{ Mio. Hits/s}$$

data size of single
event

For final design we have
10 glass fiber lines



max. 40 Mio. Hits in total !

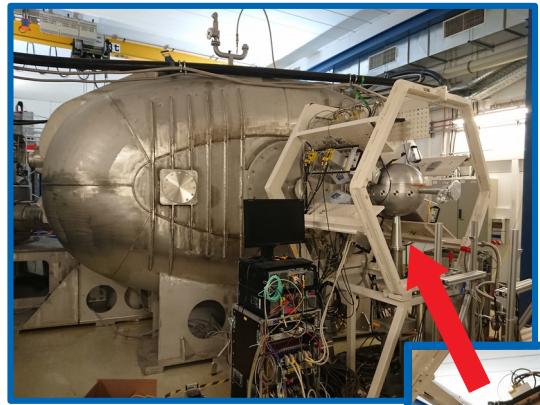
CALIFA is fast !!



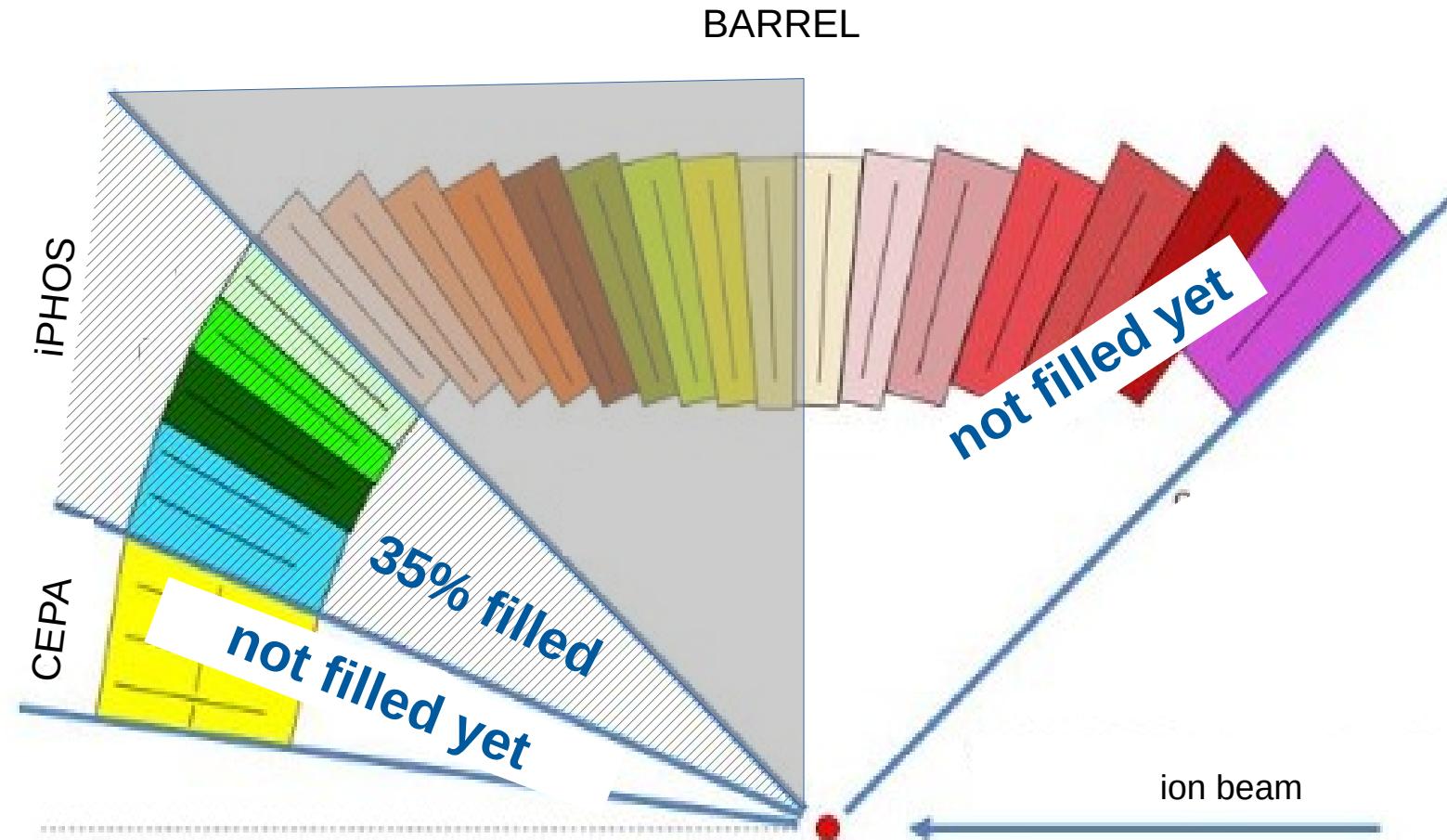
CALIFA Upgrade 2021

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From Demonstrator to Final Setup



experiment of Lukas Ponnath



UPGRADE: iPHOS region fully filled!



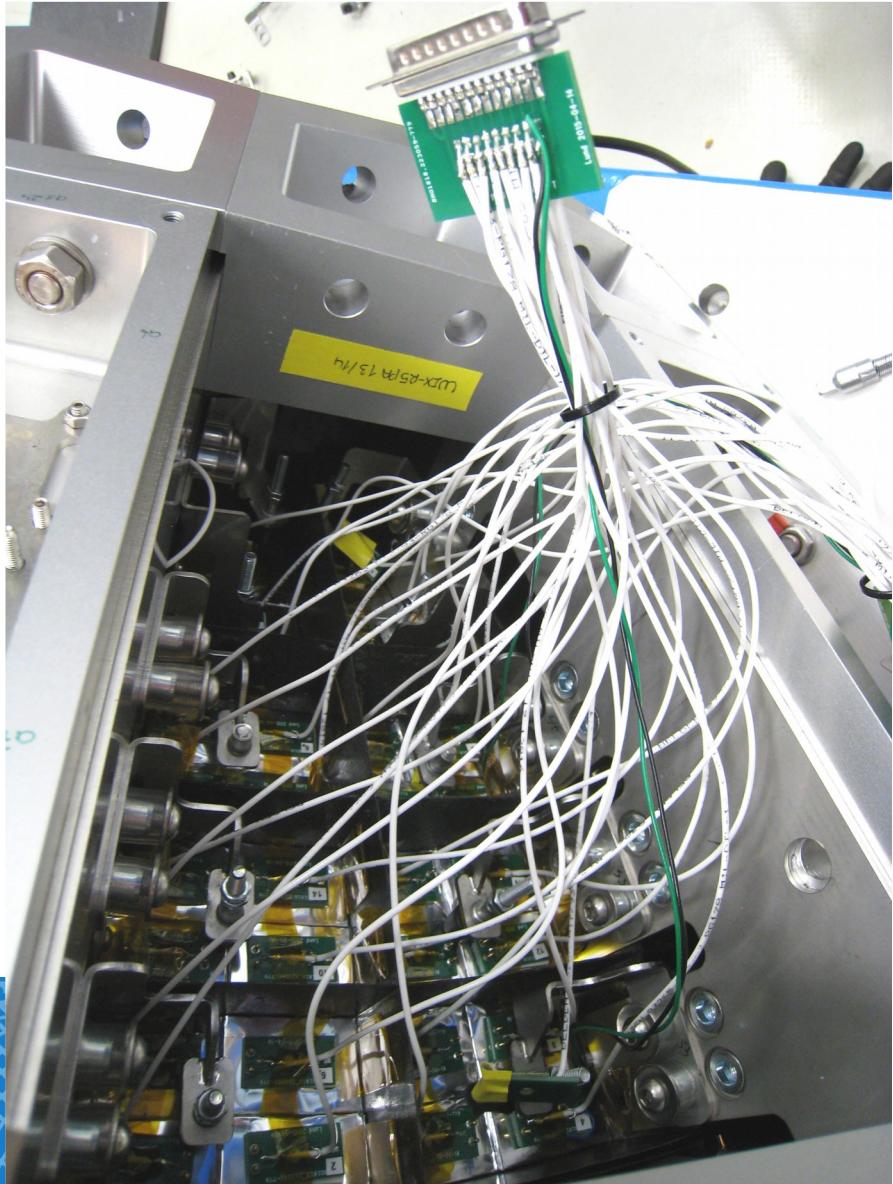
unmounting:



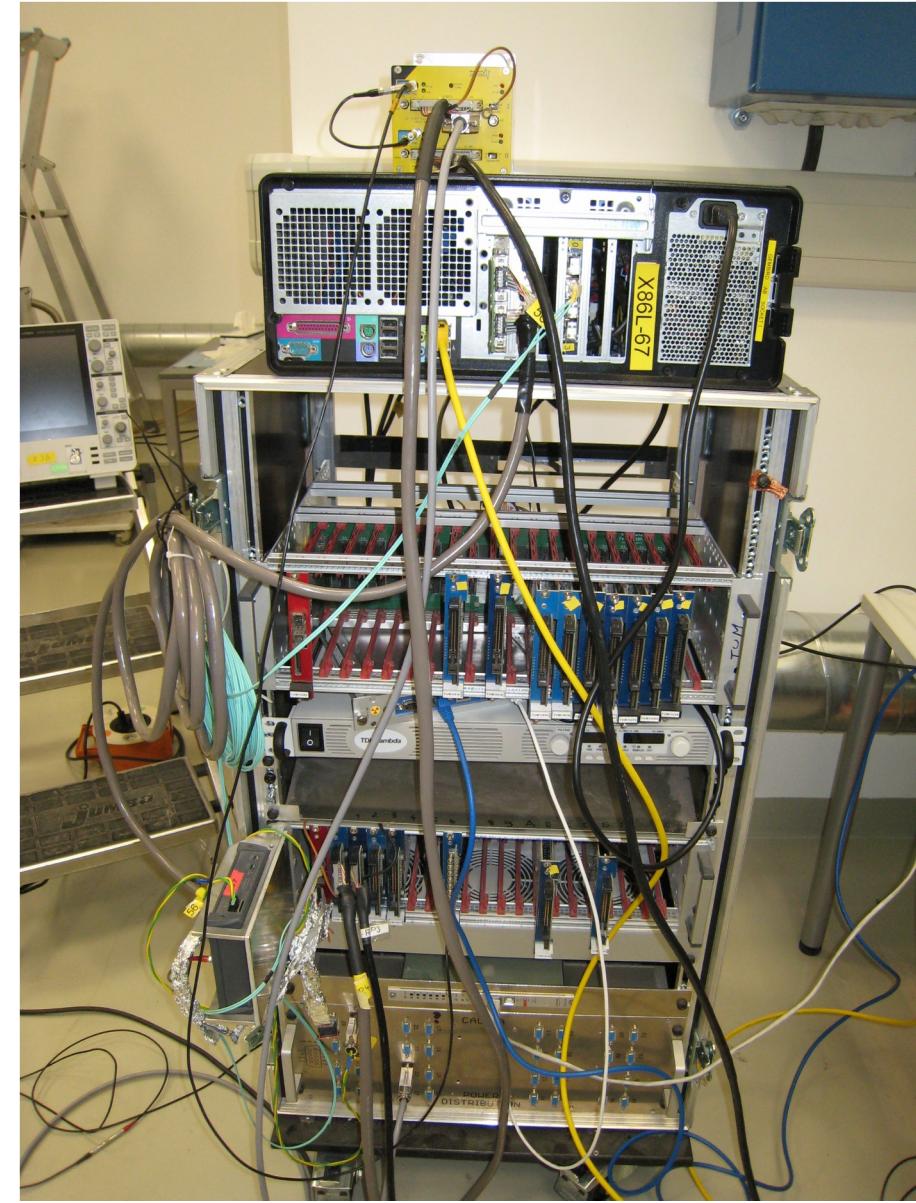
open tiles & individual crystal check:



crystal filling:



testing with mobile DAQ:



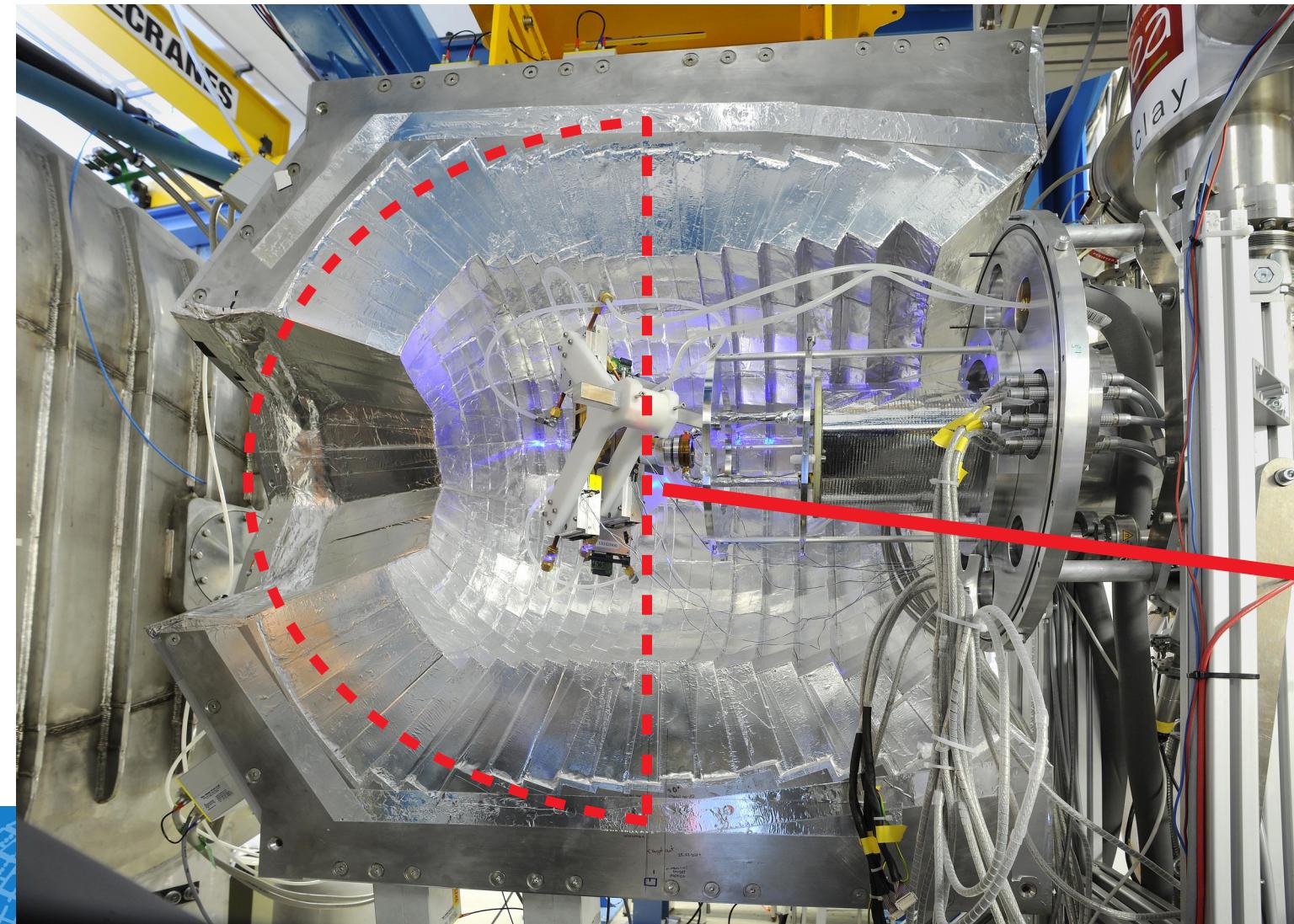
bring back to Cave C:

1.2 tons !

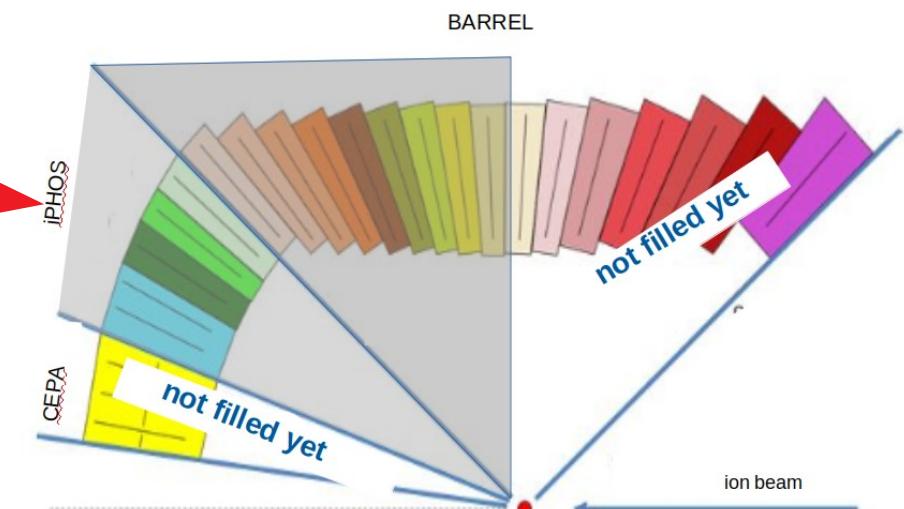


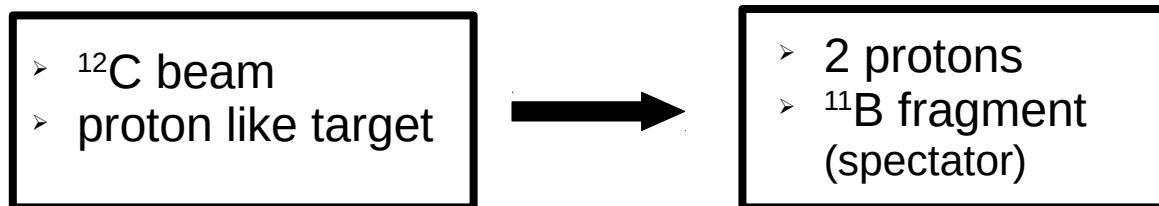
mount and align:



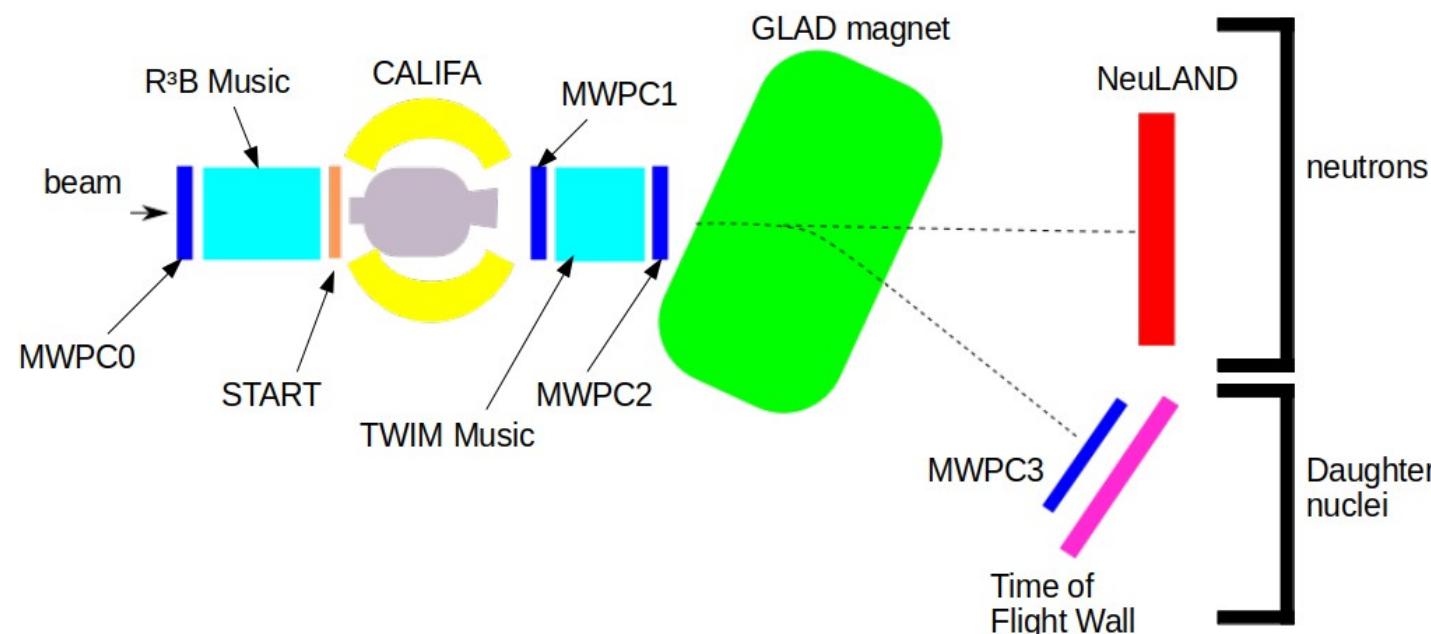
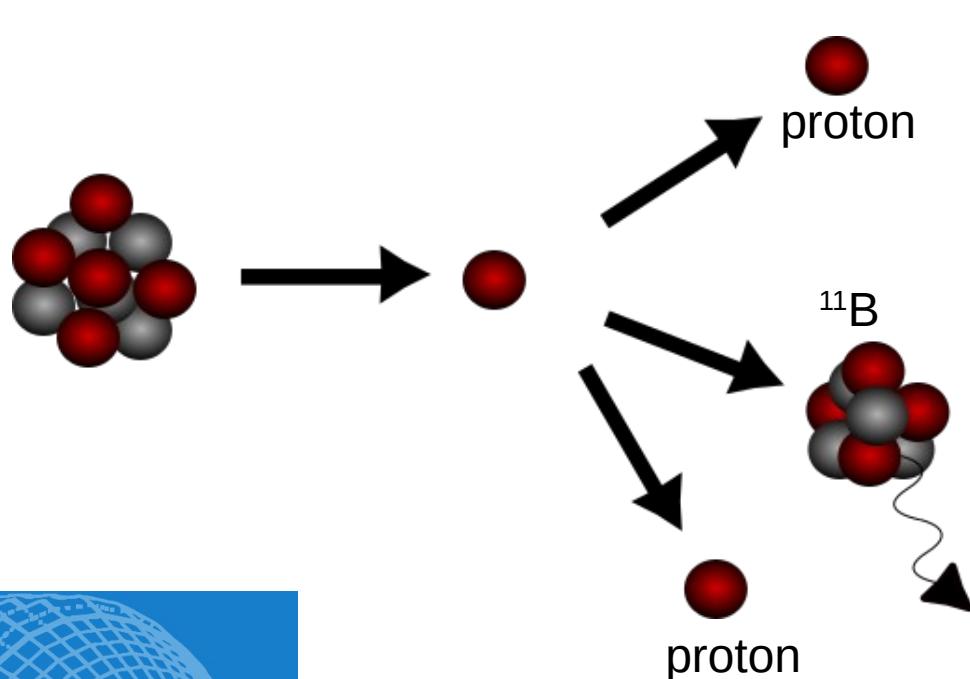


Fully filled forward half !



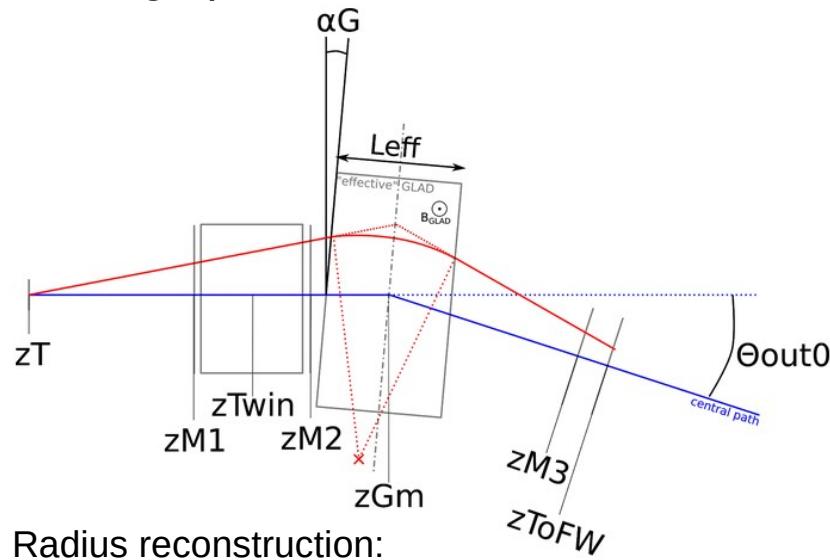
12C(p,2p)11B reaction:**SETUP:**

Beam energy: 400 AMeV
Beamtype: ^{12}C
Target: CH_2



Fragment Particle Identification

Flightpath reconstruction:



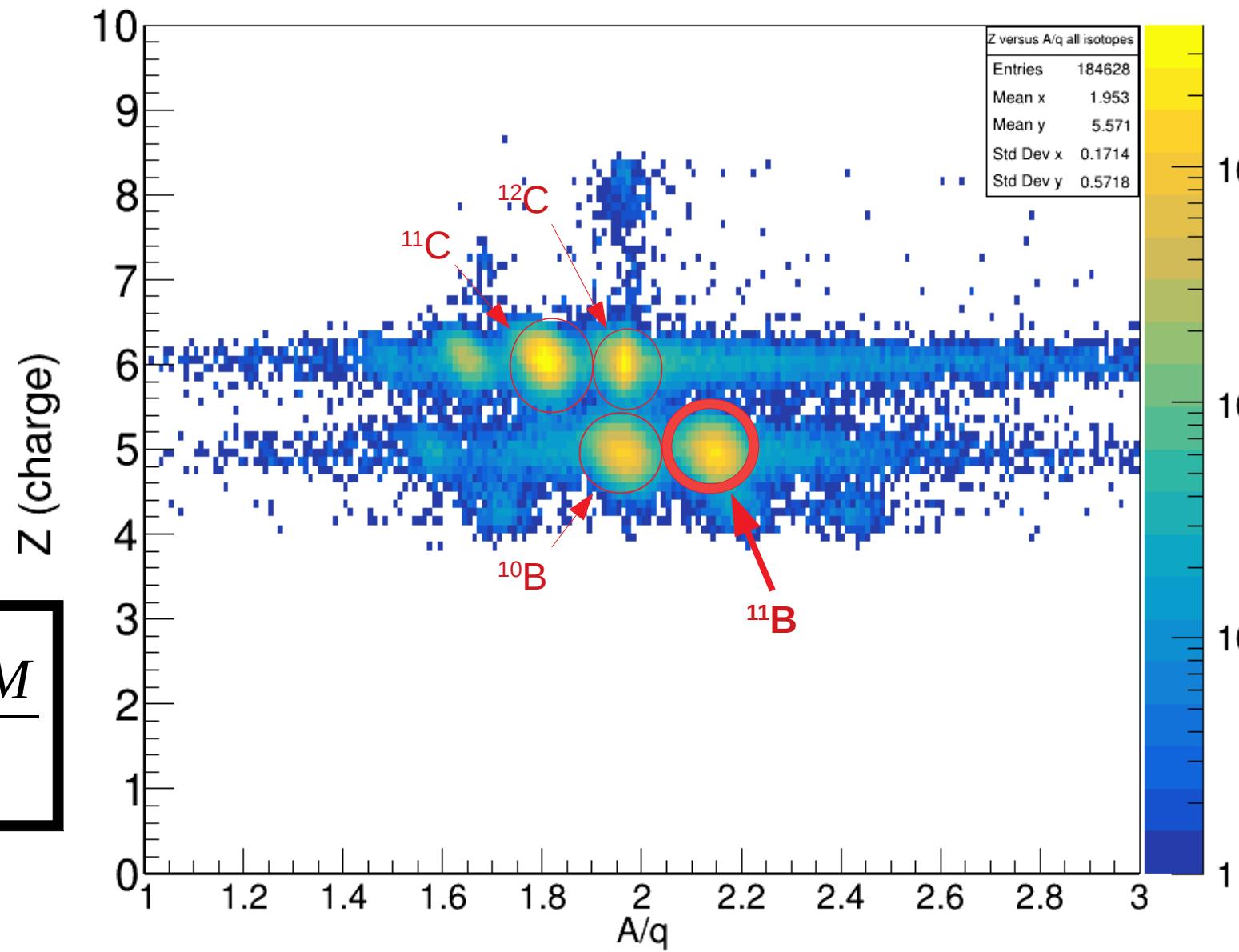
Radius reconstruction:

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

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

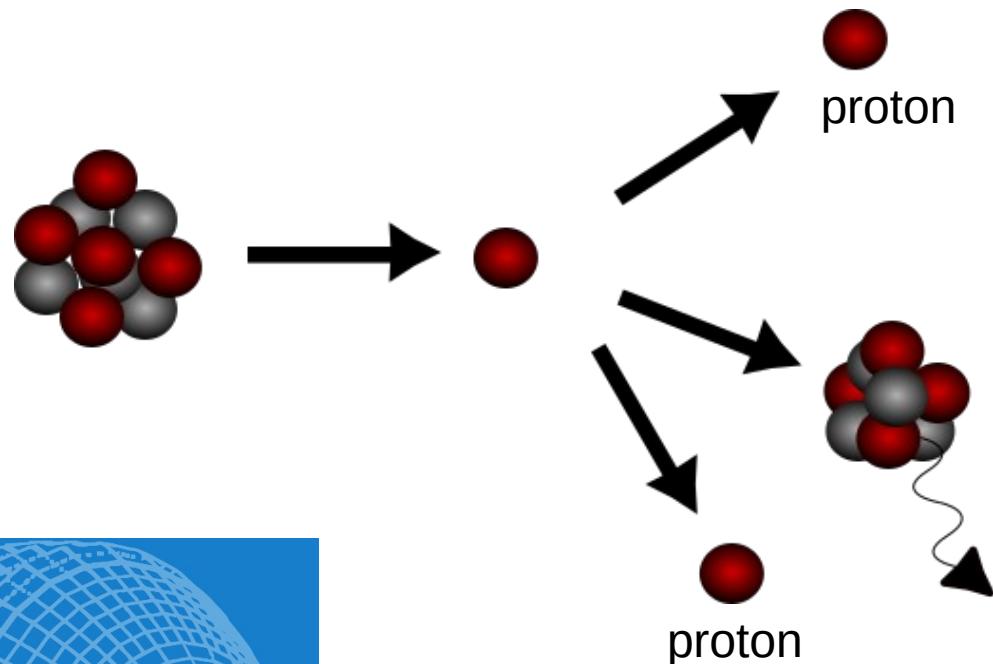


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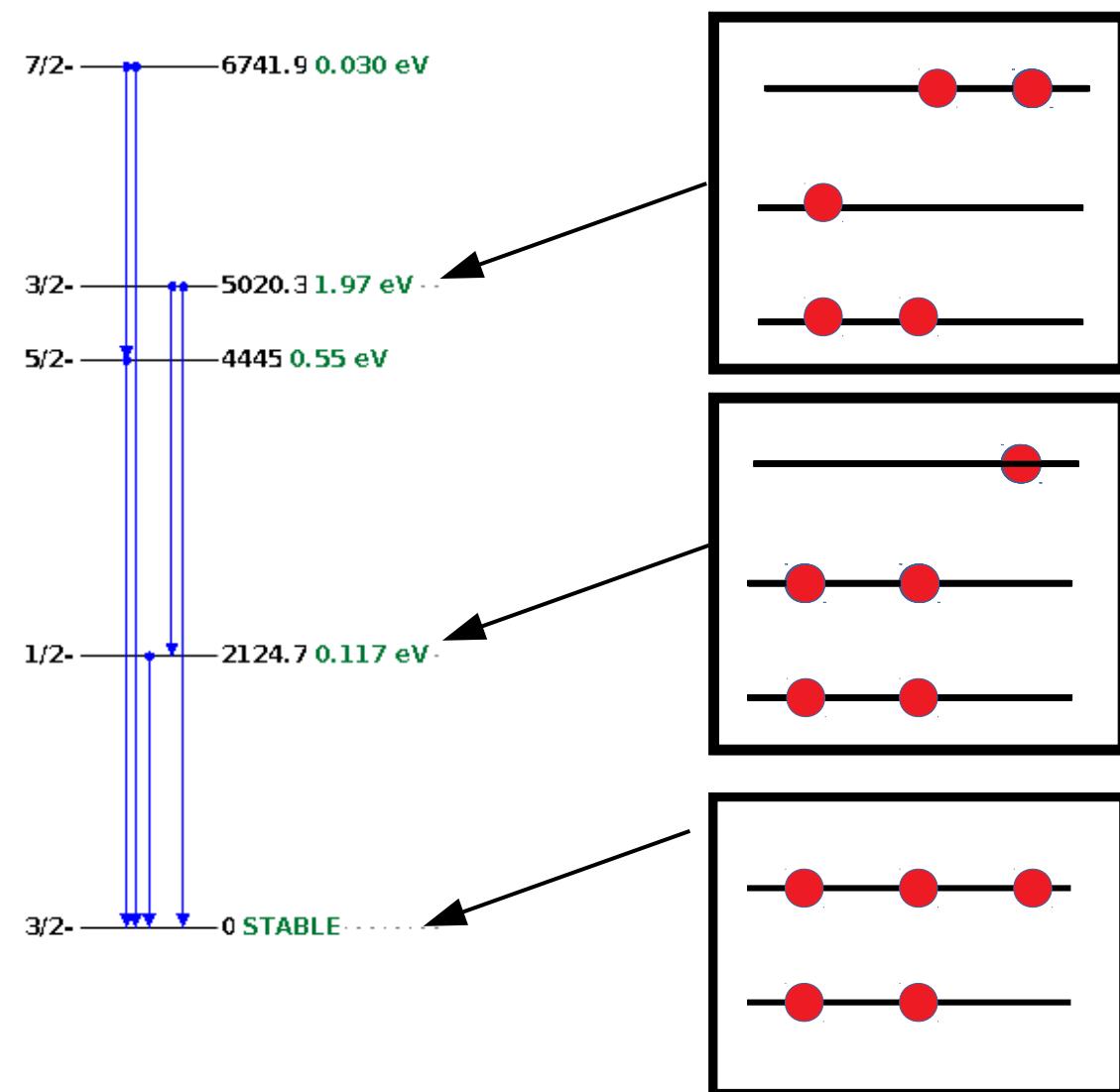


$^{12}\text{C}(\text{p},2\text{p})^{11}\text{B}$ reaction

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



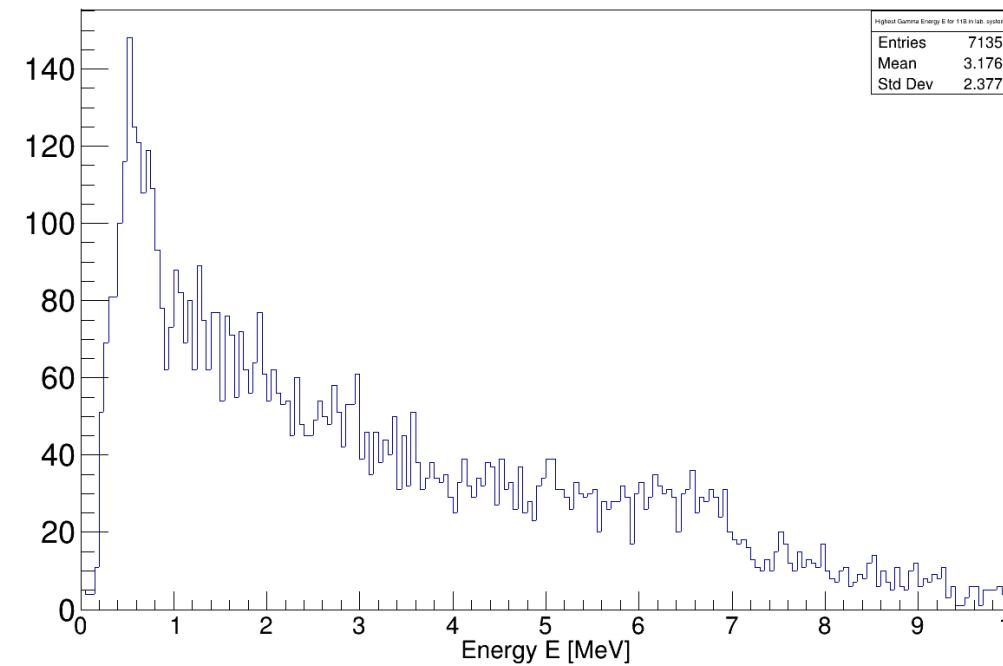
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Gamma Spectrum of ^{11}B

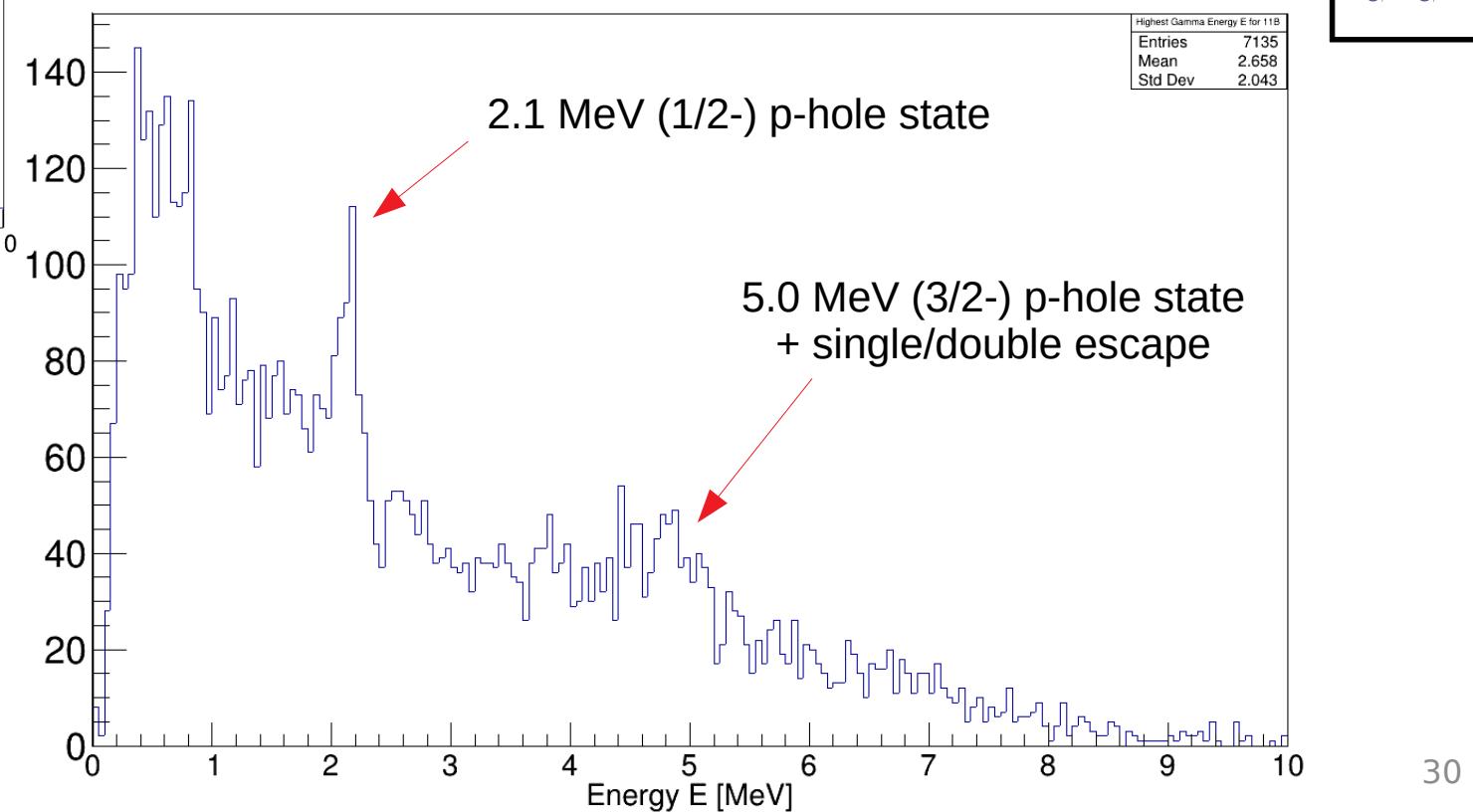
laboratory system



Doppler Correction:

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

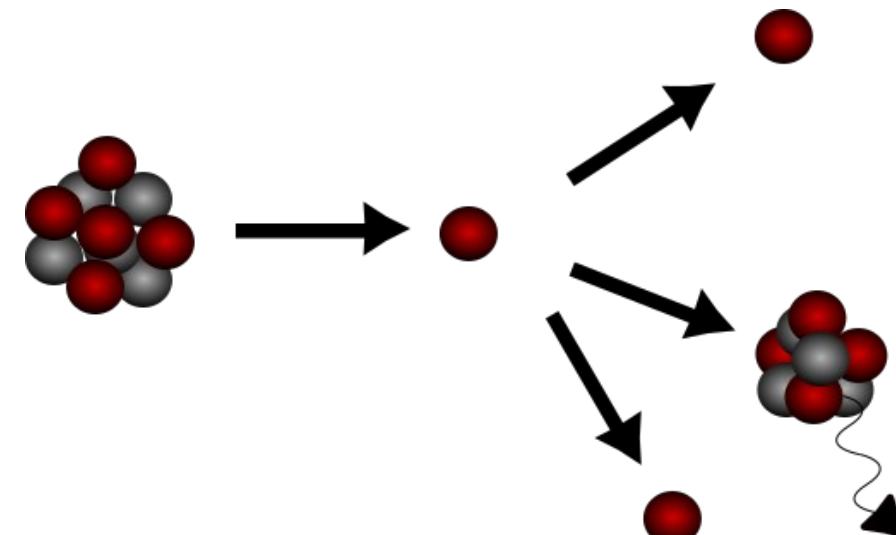
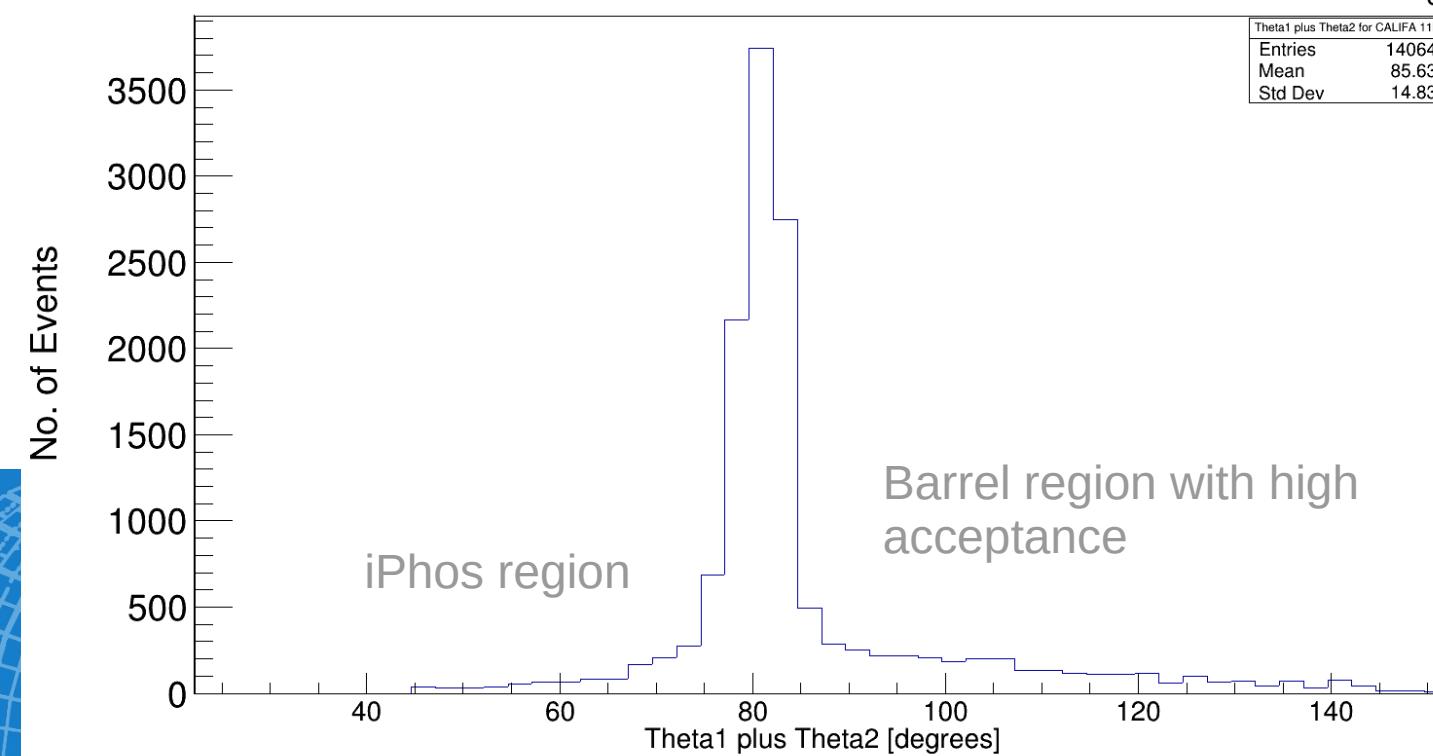
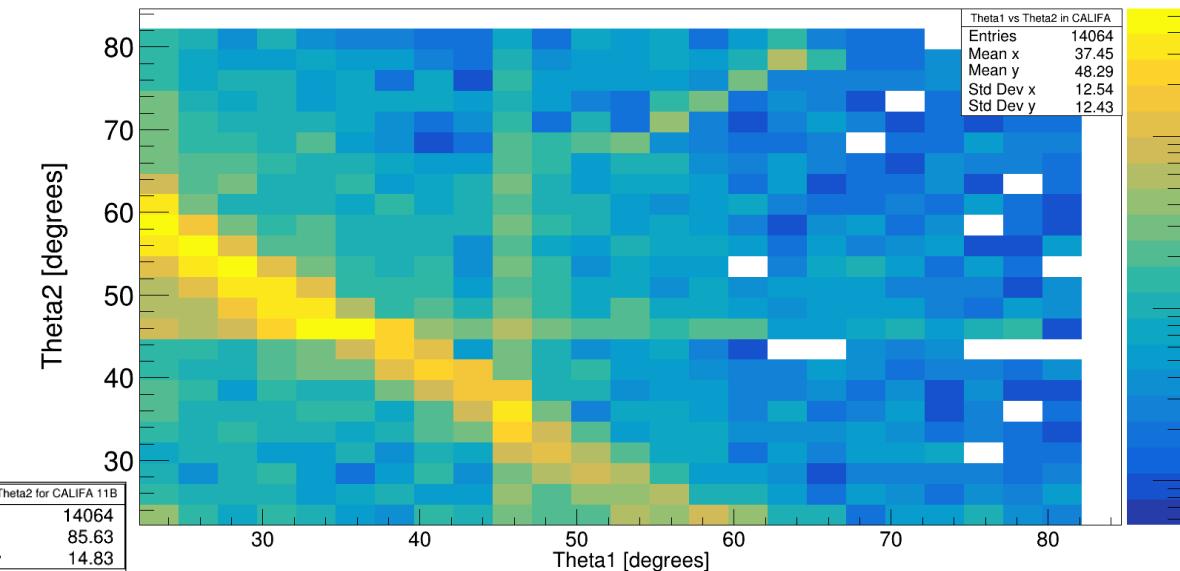
^{11}B rest frame

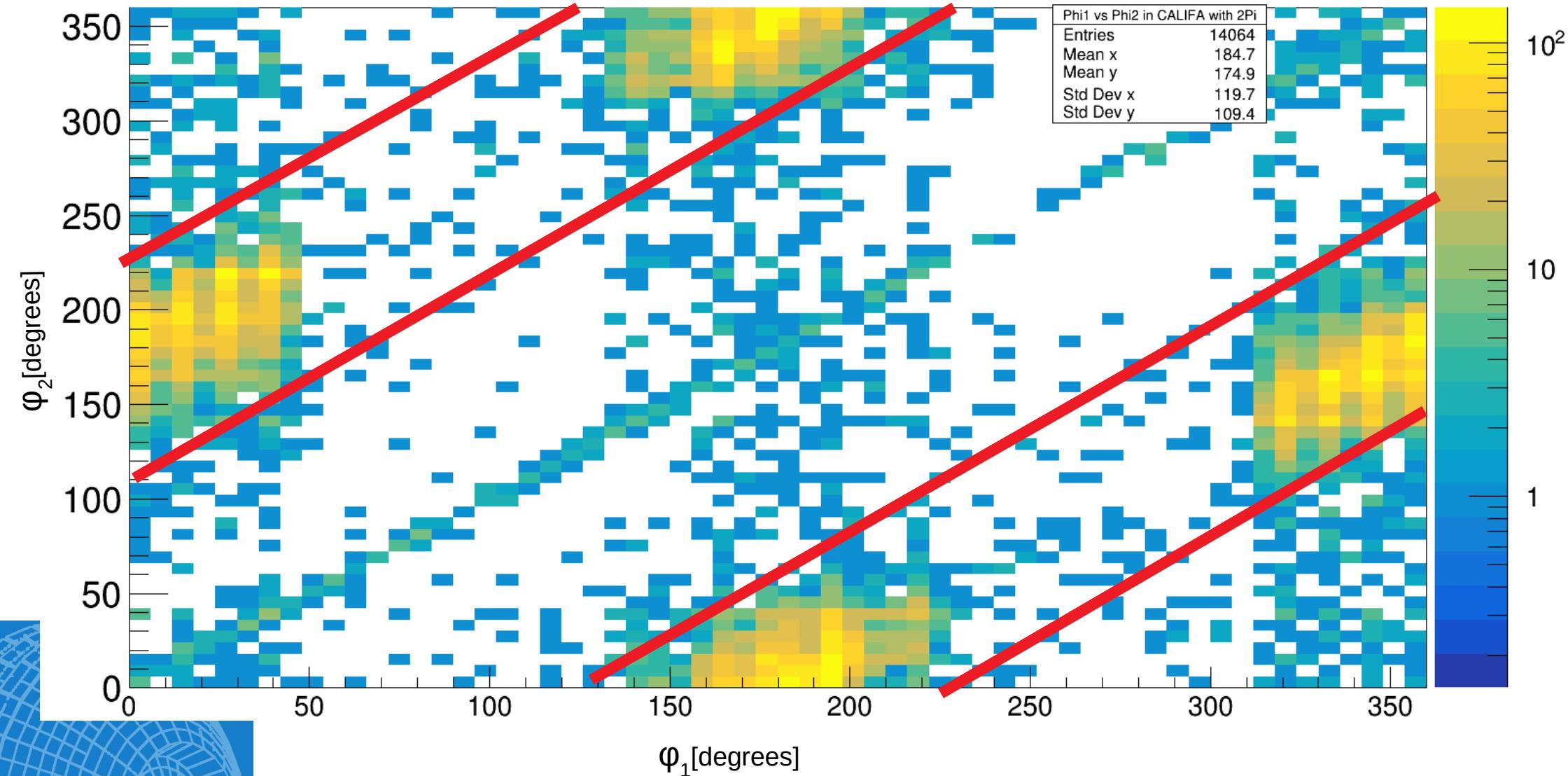


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Polar Angular Distribution of protons for $^{12}\text{C}(\text{p},2\text{p})^{11}\text{B}$

Theta1 vs Theta2 in CALIFA

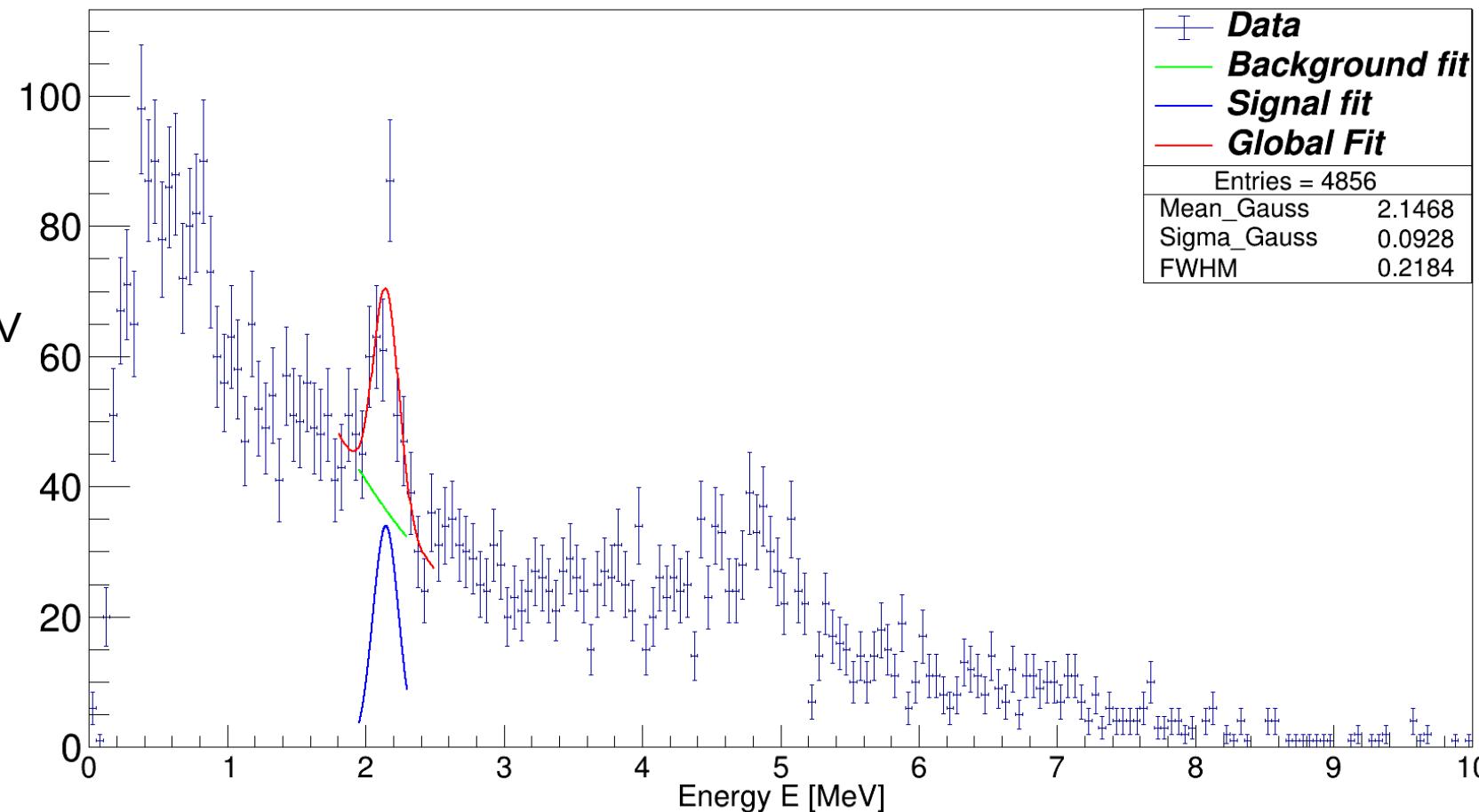




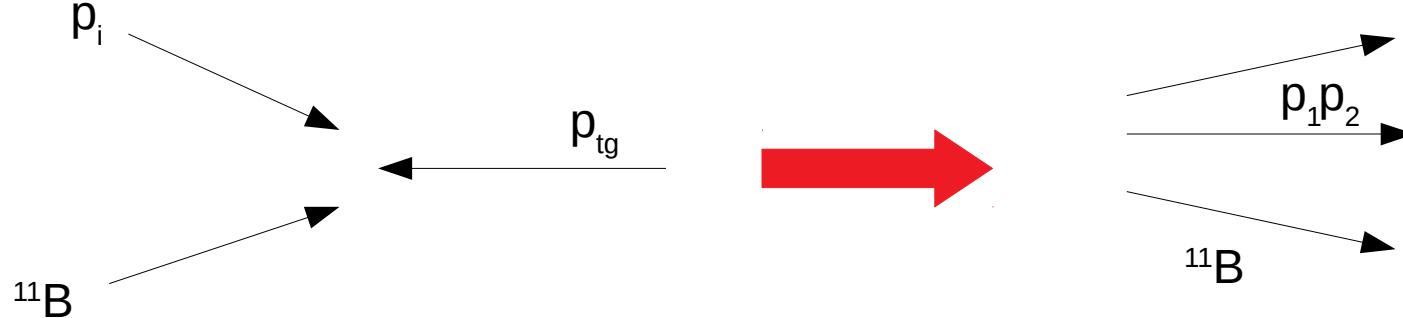
CALIFA Gamma Energy Spectrum

Event selection criteria for CALIFA:

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



Reconstruction of Inner Momenta



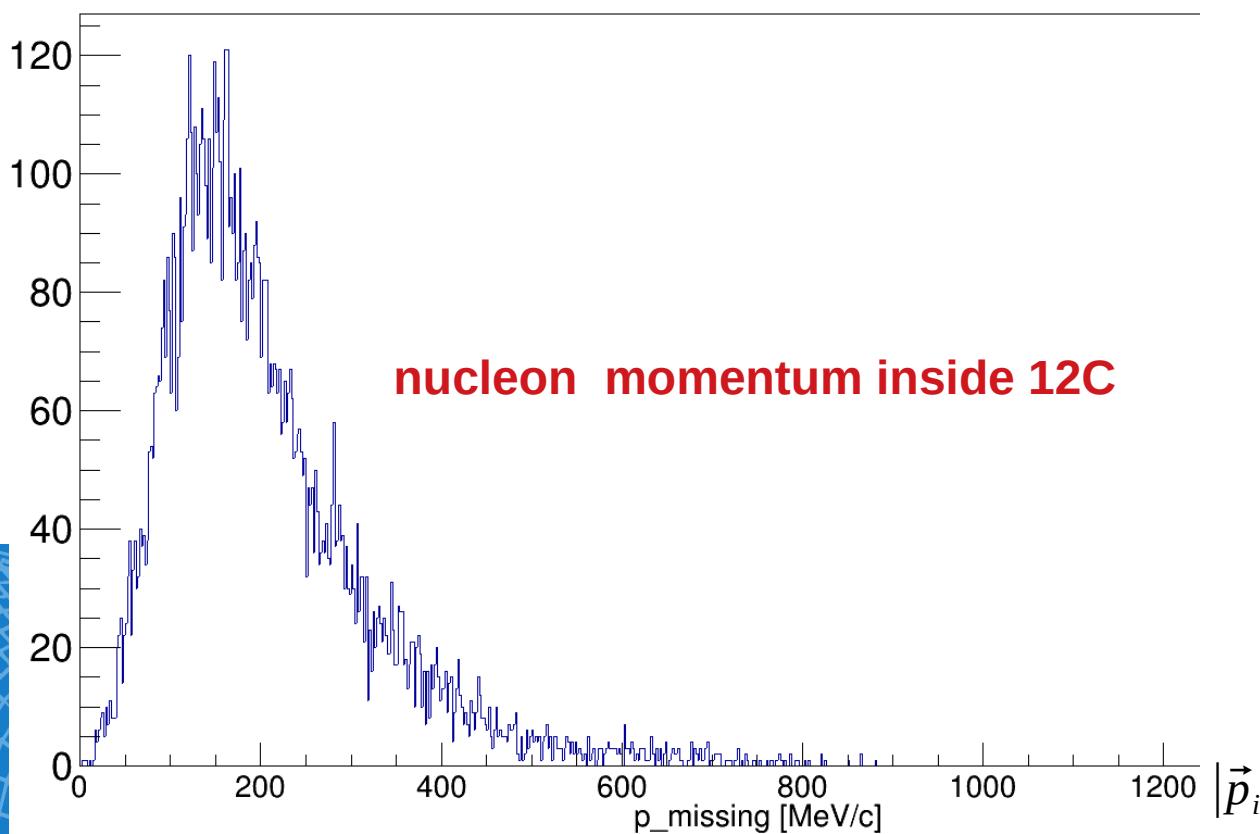
Momentum conservation relation:

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

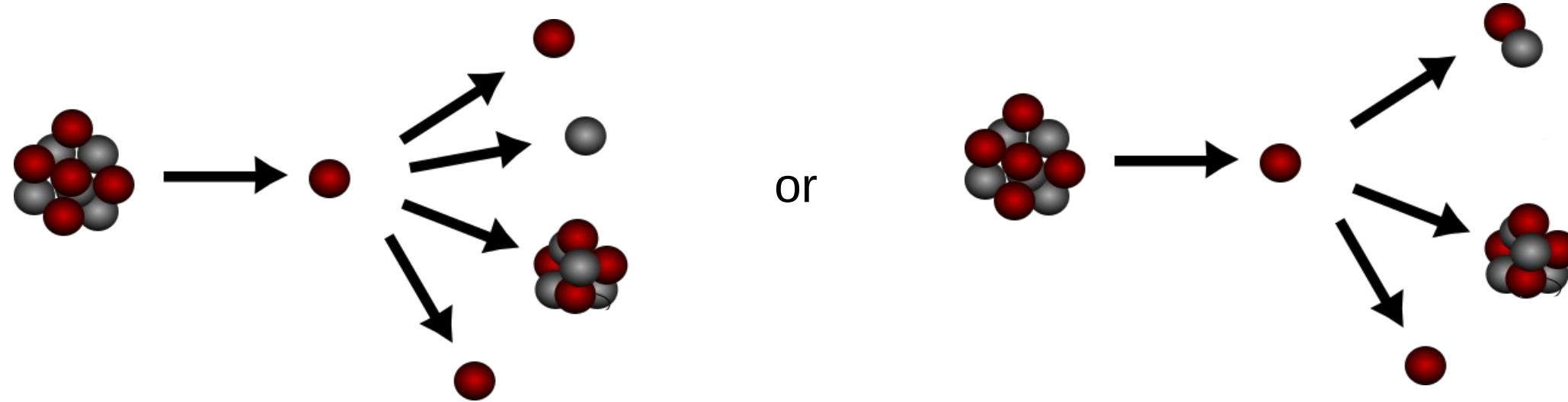
assuming QE scattering in mean field potential:

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

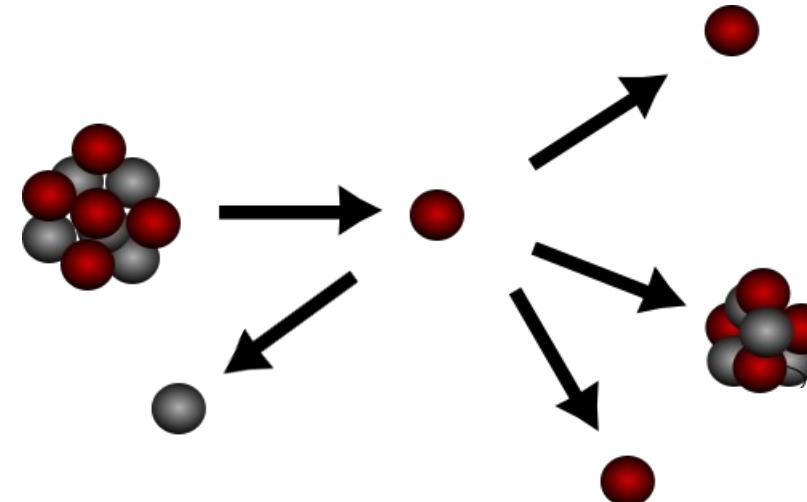
$$p_i \approx p_{\text{missing}} = p_1 + p_2 - p_{tg} (\text{no ISI/FSI})$$



$^{12}\text{C}(\text{p,ppn/pd})^{10}\text{B}$ Reaction

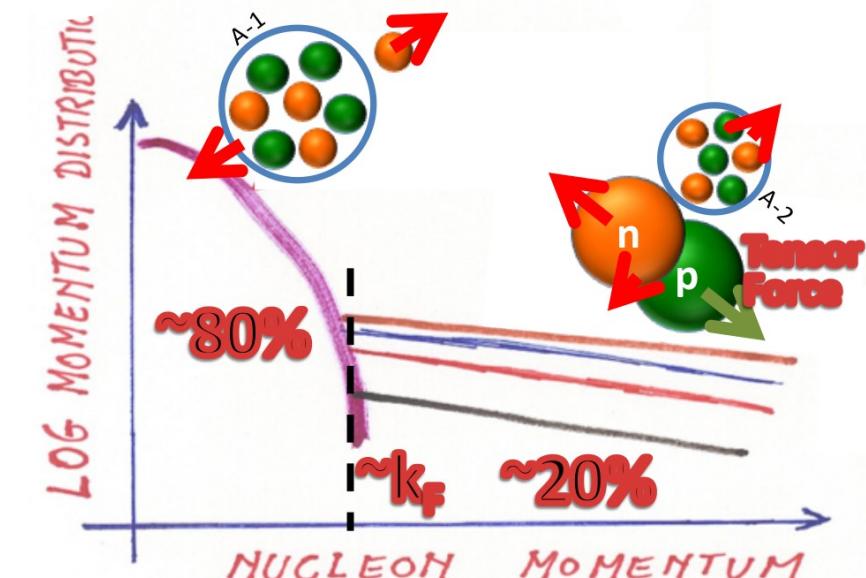


$^{12}\text{C}(\text{p},\text{ppn/pd})^{10}\text{B}$ Reaction



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



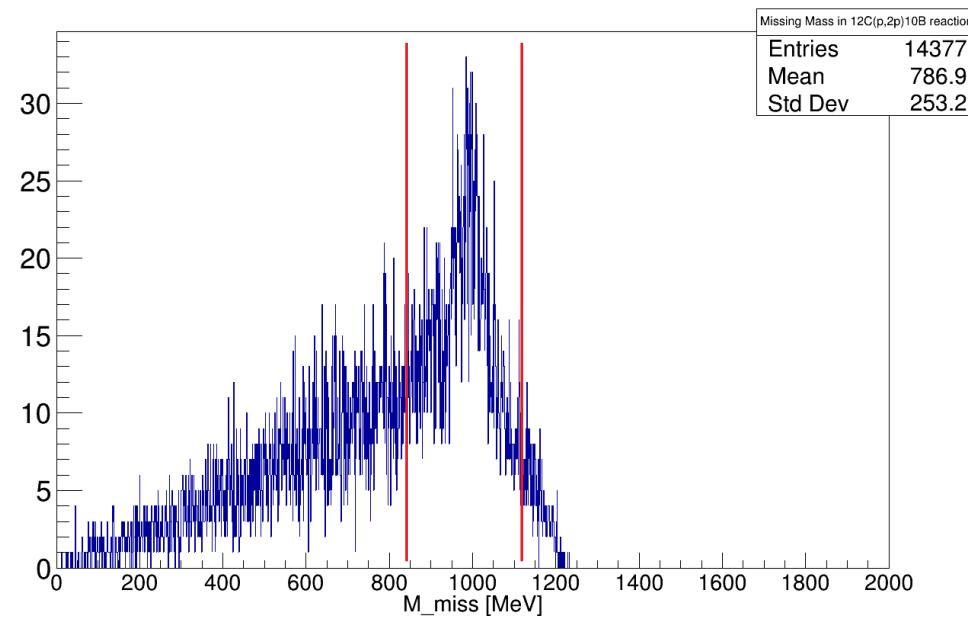
Source:
https://www.int.washington.edu/talks/WorkShops/int_18_2a/People/Hen_O/Hen.pdf



First Angular and Momentum Plots ...

Making cut on the reconstructed neutron:

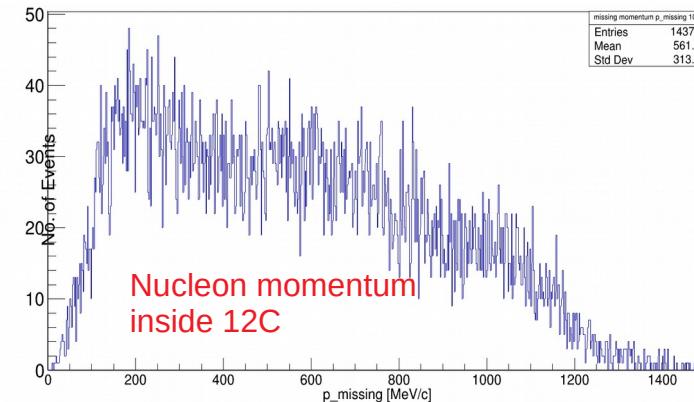
$$M^2_{missing} = (p_{12C} + p_{tg} - p_1 - p_2 - p_{10B})$$



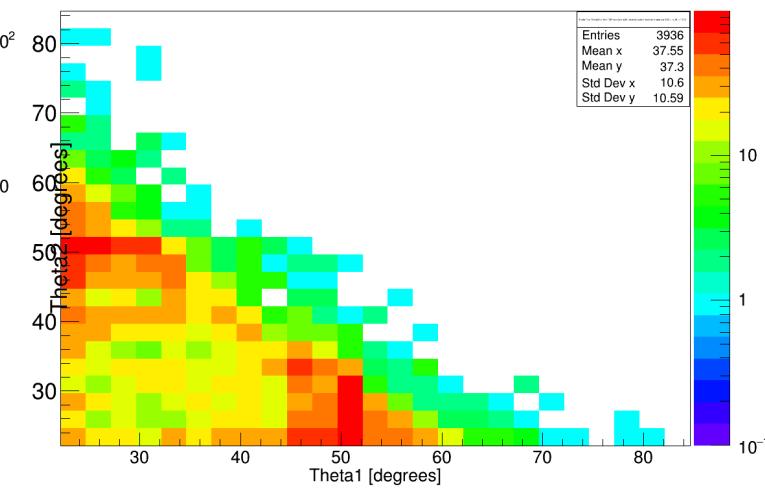
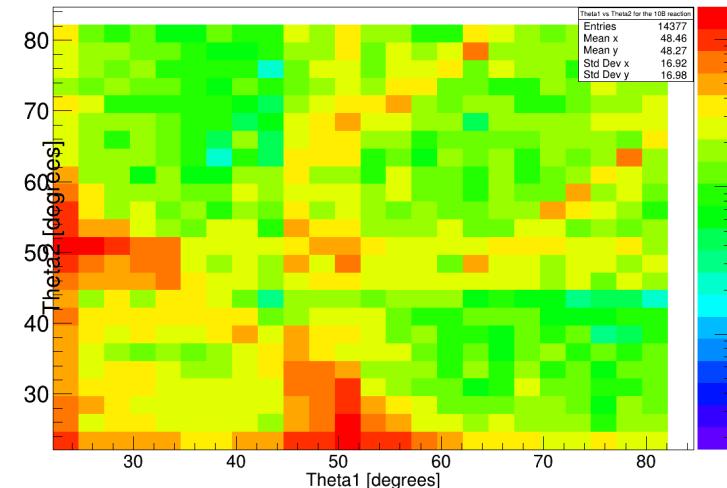
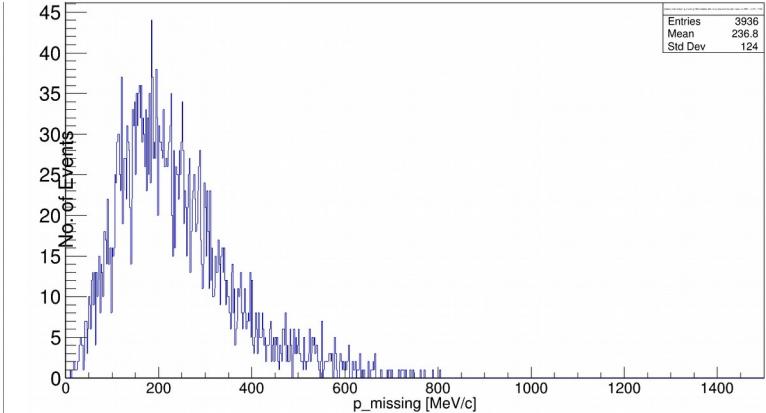
M_{missing} cut
850 MeV < M_{missing} < 1100 MeV

Tobias Jenegger

Without cut:



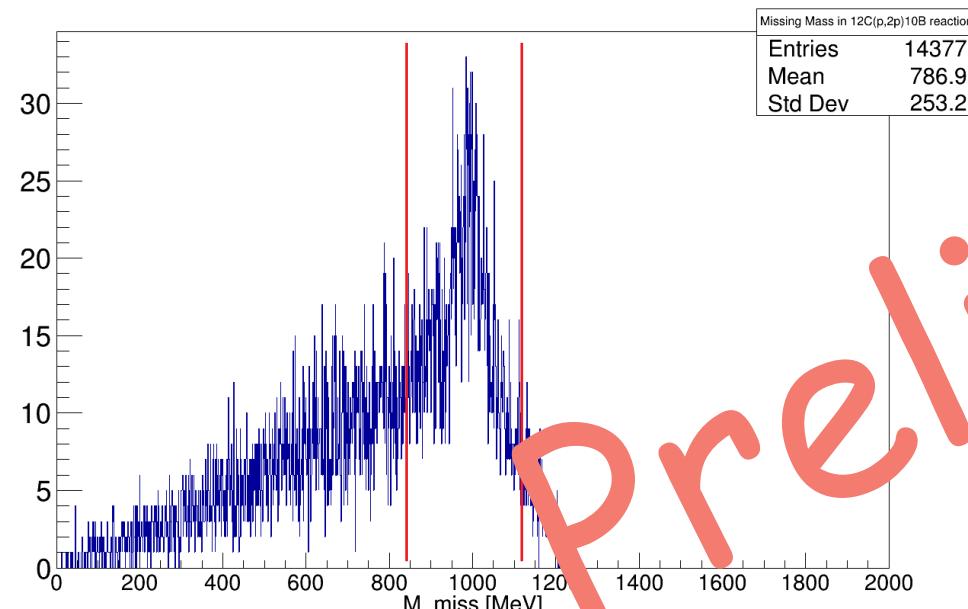
With reconstructed neutron mass cut:



First Angular and Momentum Plots ...

Making cut on the reconstructed neutron:

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

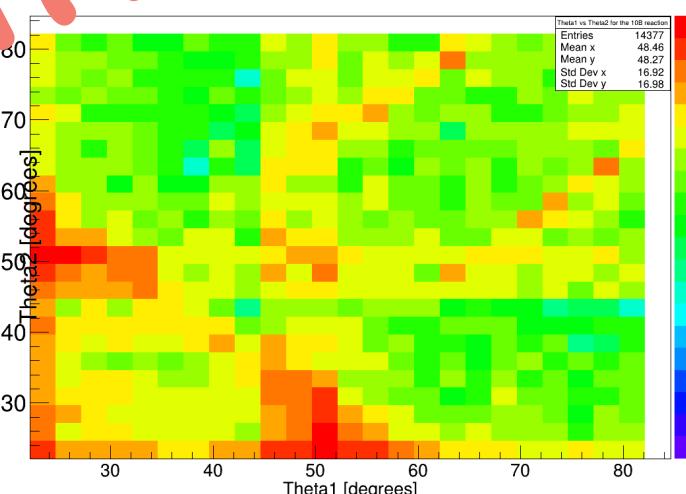
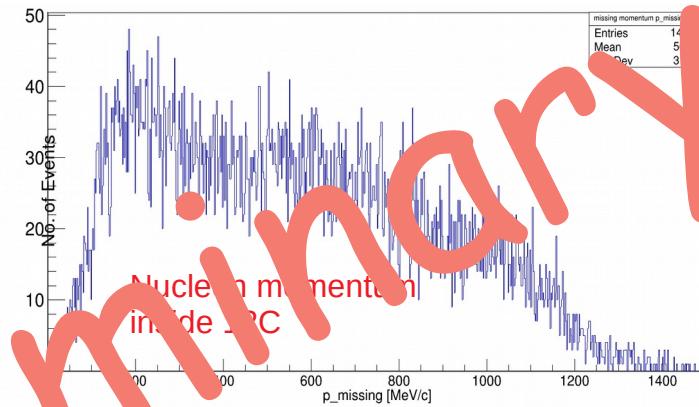


M_{missing} cut
850 MeV < M_{missing} < 1100 MeV

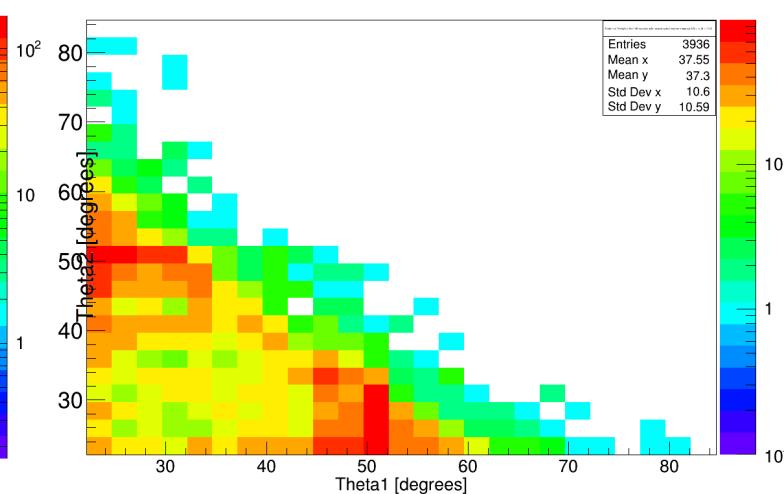
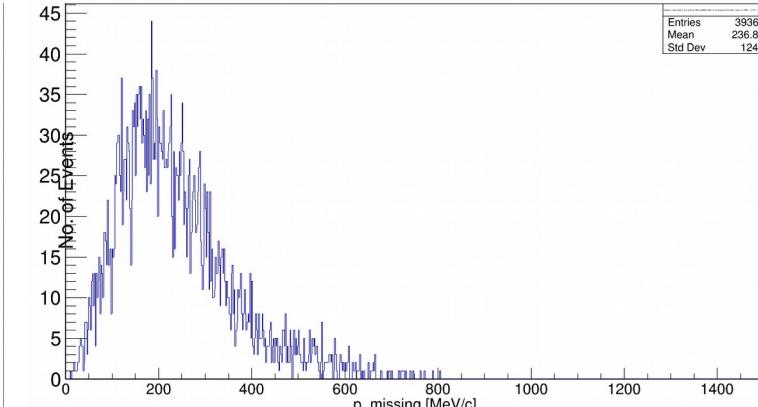


Tobias Jenegger

Without cut:

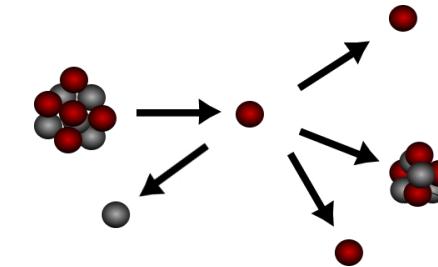


With reconstructed neutron mass cut:

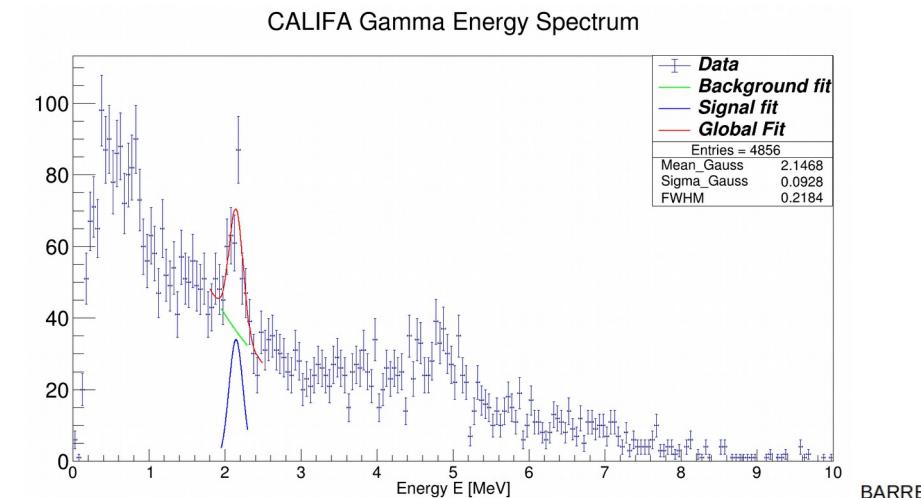


Summary & Outlook

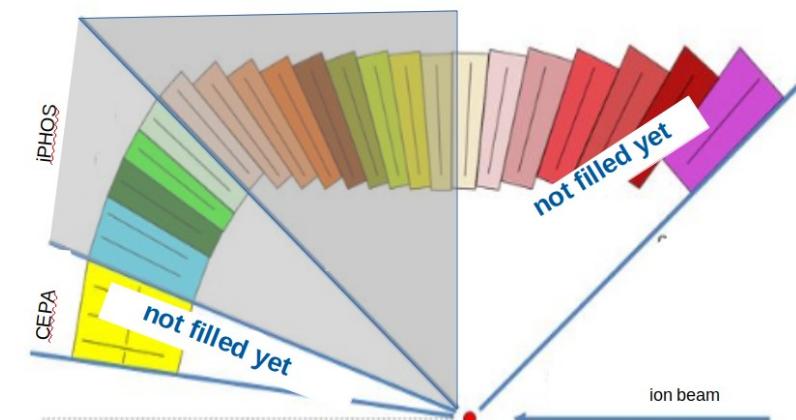
→ further investigations for the $^{12}\text{C}(\text{p},\text{ppn}/\text{pd})^{10}\text{B}$ reaction channel needed



→ promising first analysis results from $^{12}\text{C}(\text{p},2\text{p})^{11}\text{B}$ reconstruction



→ looking forward to exciting upgrade of CALIFA filling the Barrel (backward) region and the most forward CEPA region





Thank you!

CALIFA @ Technical University of Munich (TUM)

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Tobias Jenegger

GEFÖRDERT VOM



Bundesministerium
für Bildung
und Forschung





Backup





CALIFA Doppler reconstruction



High and well-defined segmentation
→ Doppler reconstruction

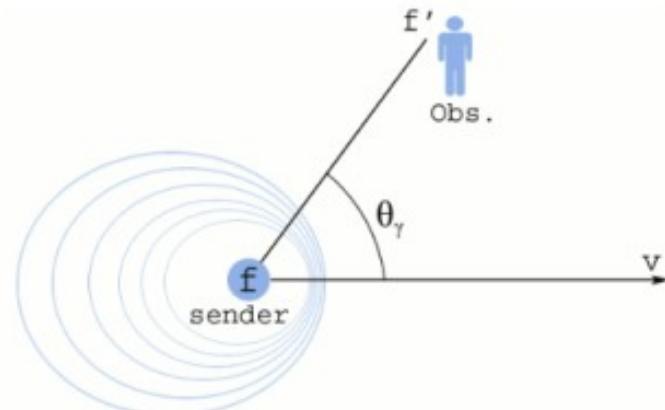
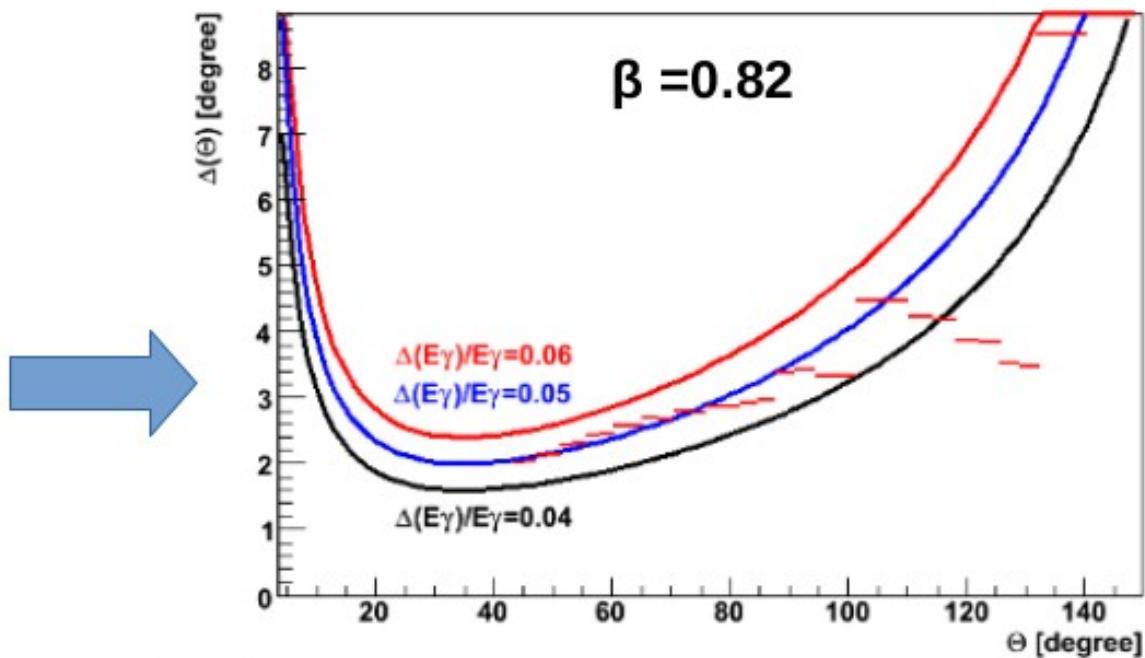
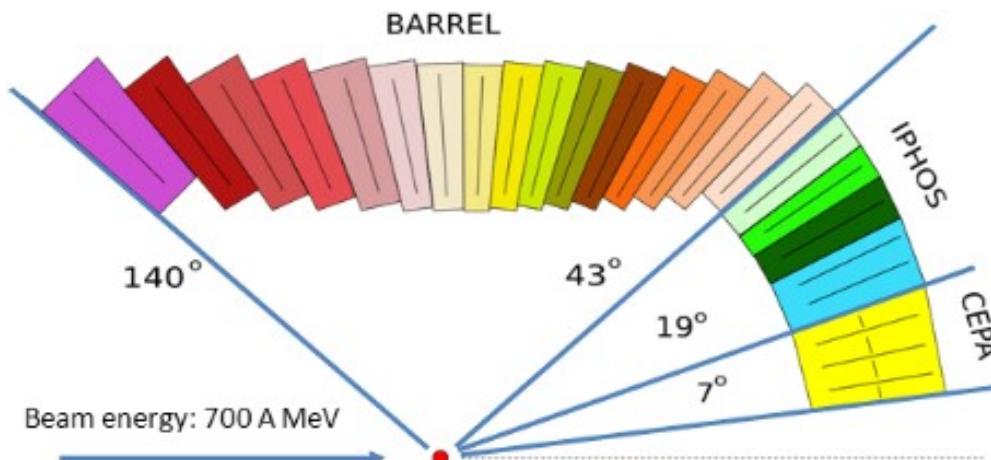


Figure taken from [1]

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

→ shape and angles of crystals provide constant relative resolution:



[1] AliAli-Adili: Simulations of Doppler Effects in NuclearReactions for AGATA CommissioningExperiments (2009)