Investigation of Fission in quasi-free-scattering experiments at R³B

Tobias Jenegger

DPG Mainz
29.03.2022

Fission via (p,2pf) reaction

R³B Setup at GSI

First Analysis Steps

Outlook

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.

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

Fission via quasi-free scattering ^{238}U(p,2pf)

→ Fission Process: how does it look like, components.. (make a sketch)
→ What do we want to measure (first of all: fission barrier; also fission yield)

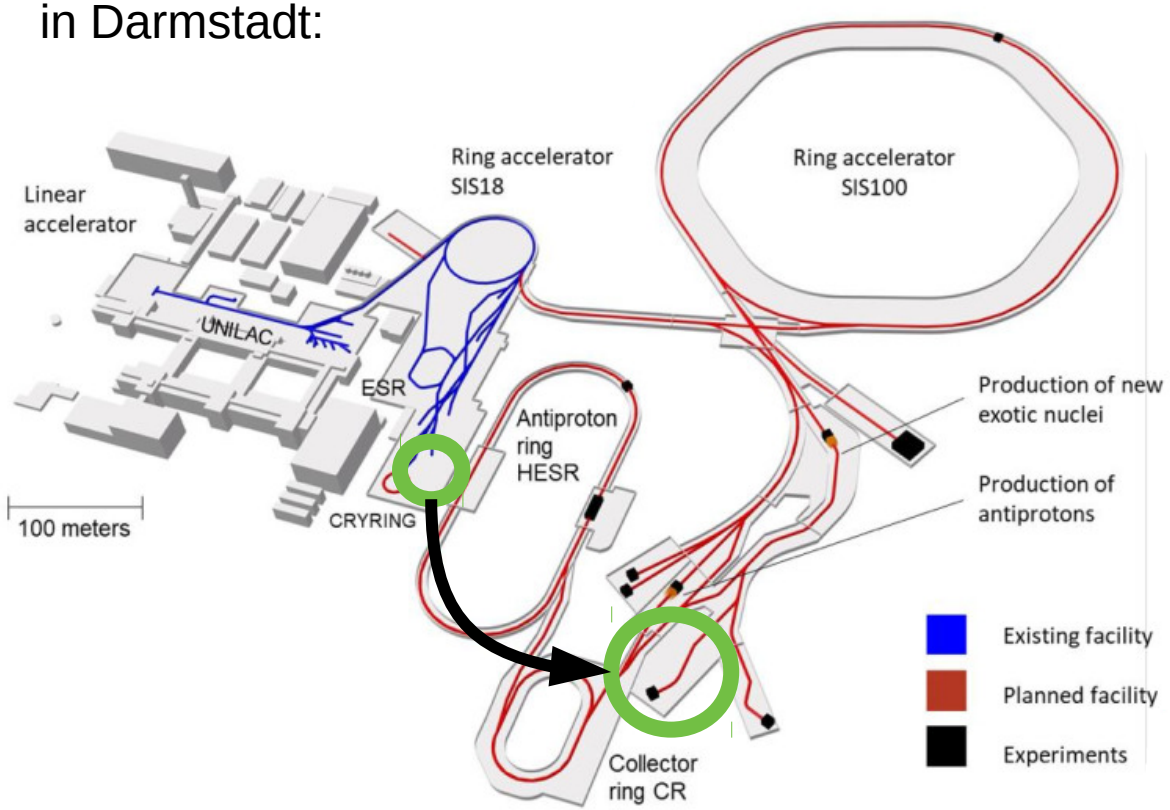
Why fission via quasi free scattering ?

Show other methods – pros and cons
Coulomb Fission
Energy reconstruction
Velocity construction

-p2pf → Full reconstruction of energy of all constituents
-Dedicated setup needed

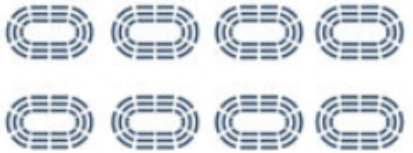
R³B @ GSI

R³B as part of the
Facility for **A**ntiproton and **I**on **R**esearch (**FAIR**)
in Darmstadt:



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

5,000 single family homes



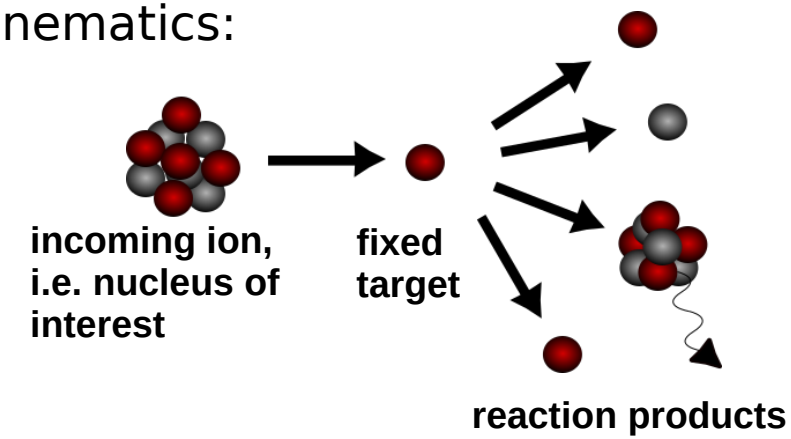
eight Frankfurt soccer stadiums

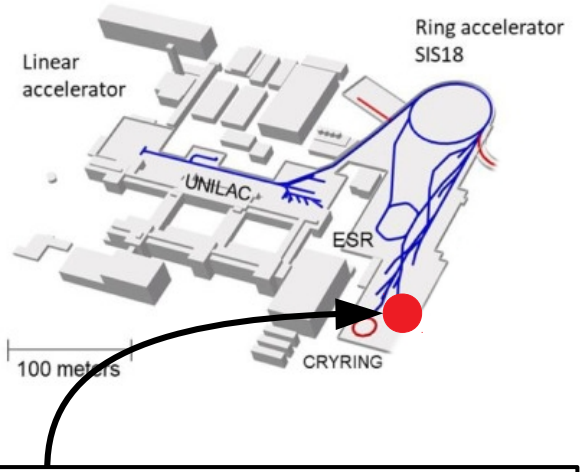
nine Eiffel Towers

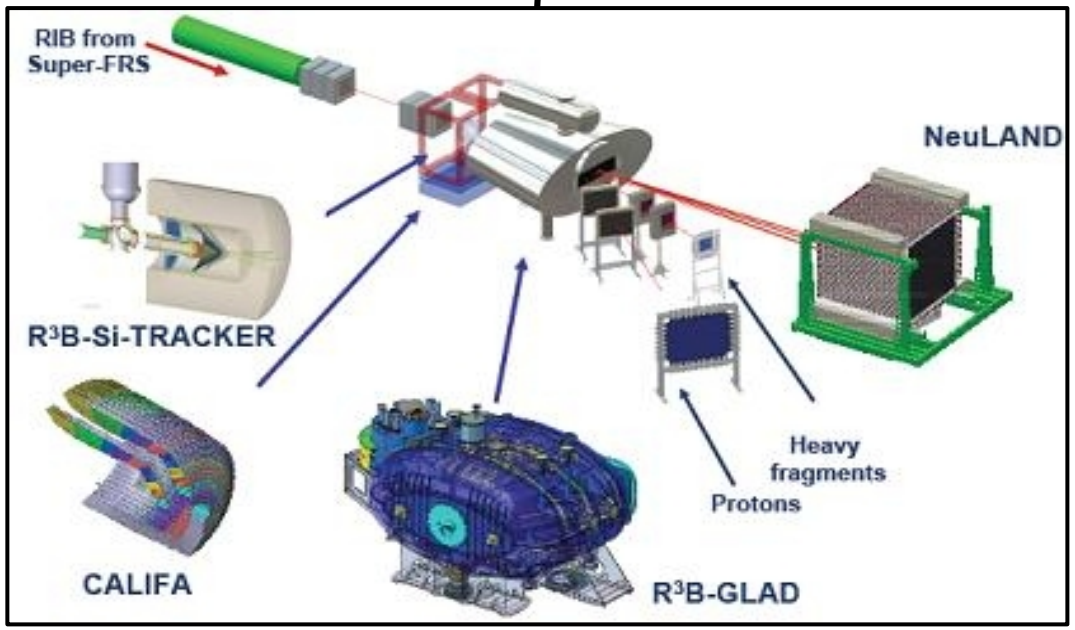
R³B Experiment @ GSI

Reactions with Radioactive Relativistic Beams

- Physics program on exotic nuclei in inverse kinematics:



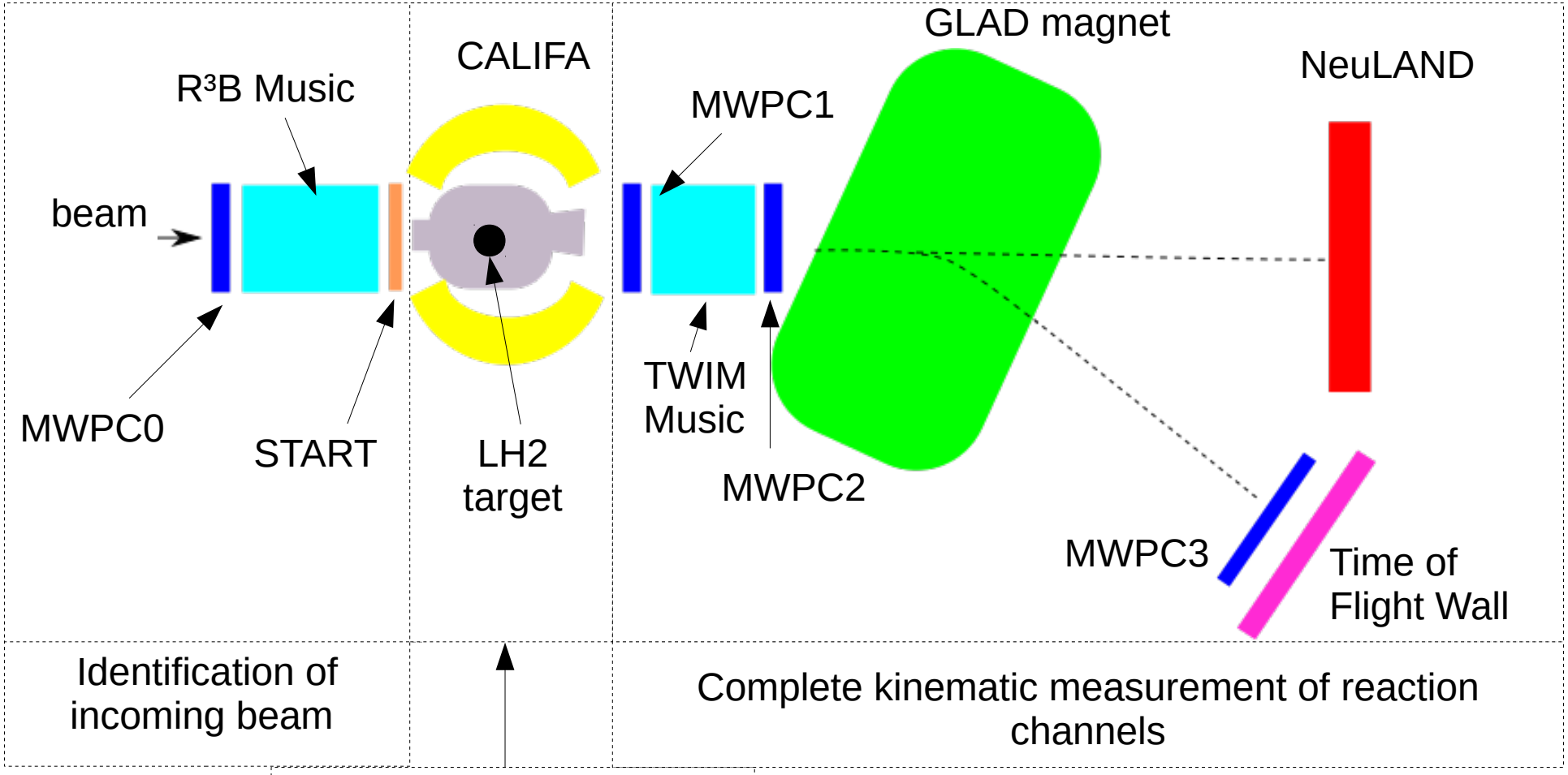




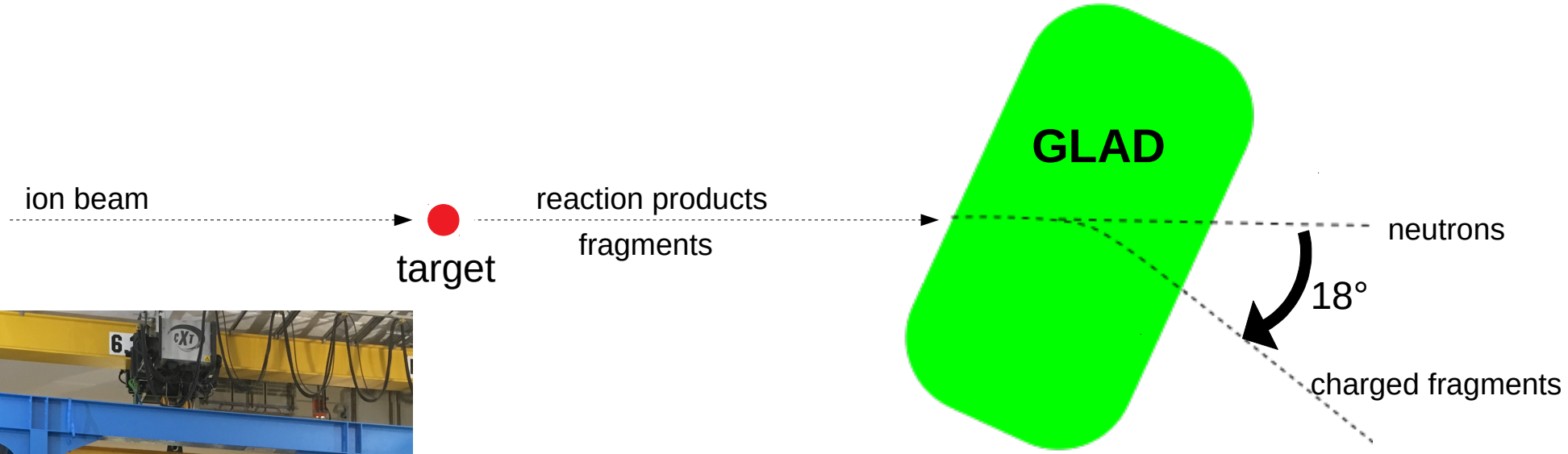
- In flight production of exotic nuclei from fragment separator Super-FRS
- kinematically complete measurements
- Flexible setup, extensive physics schedule (despite pandemic restrictions)

R³B Setup for Pilot Experiments (2021)

Beam: ^{238}U beam, 637 AMeV beam energy
Target: liquid hydrogen



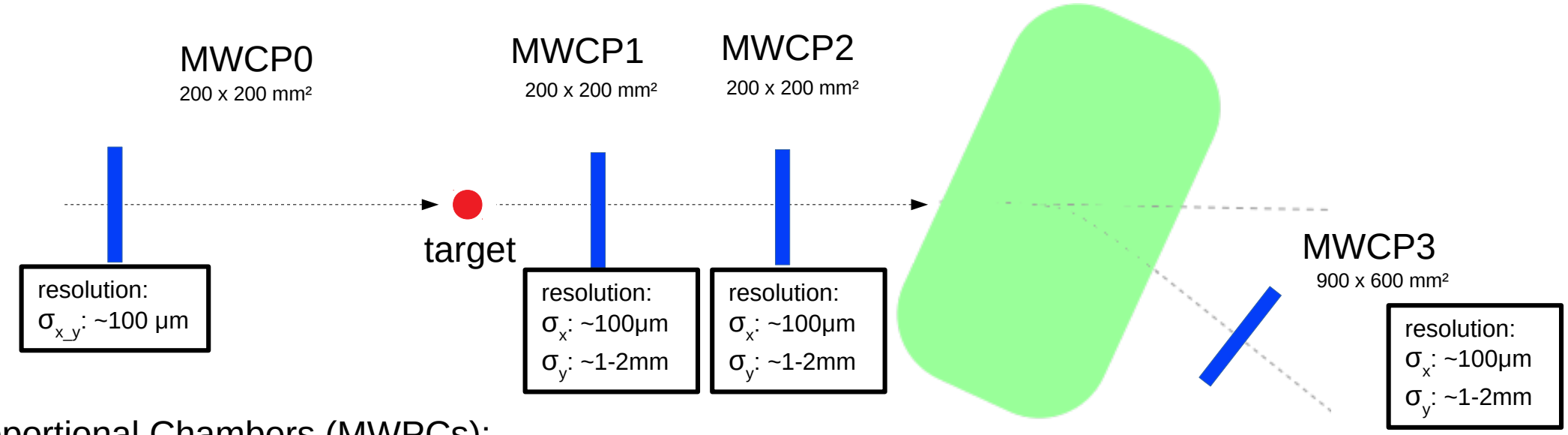
GLAD Superconducting Dipole Magnet



- 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}

I am not happy with those bullet points!

Tracking Detectors



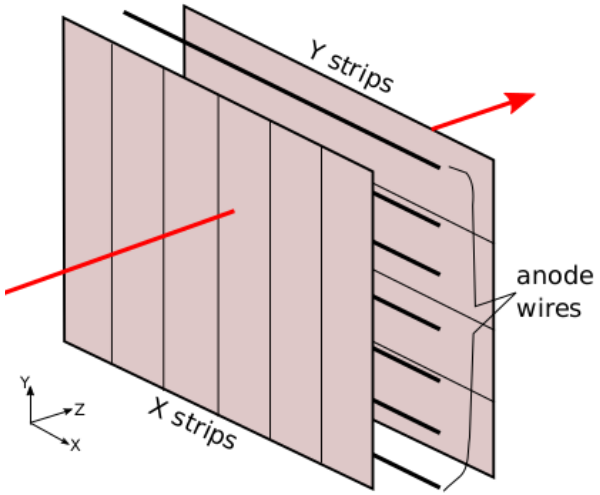
Multi Wire Proportional Chambers (MWPCs):

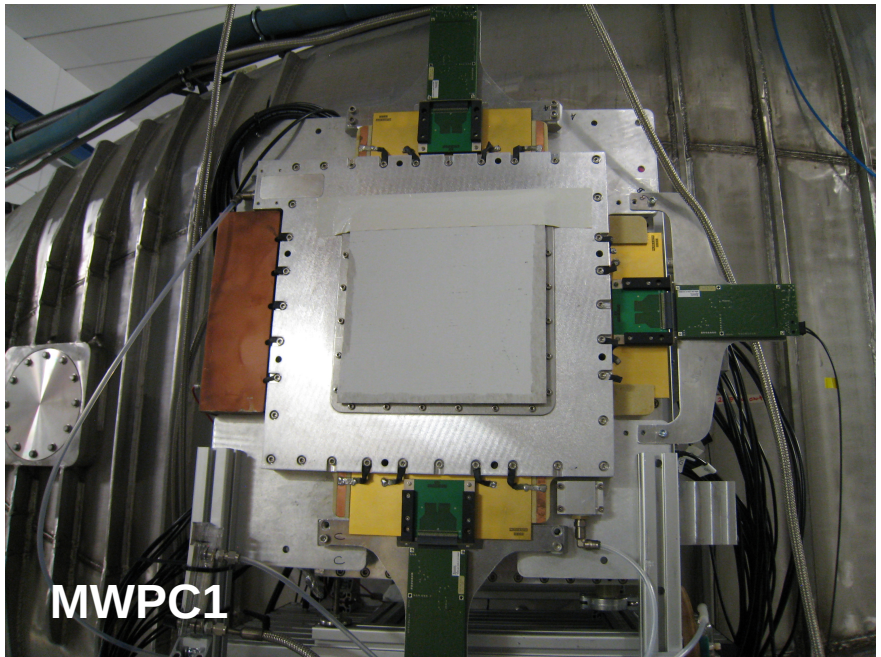
→ horizontal wires: 50 µm diameter, 2.5 mm spacing

→ vertical/horizontal pads:
Al-deposited on a 12 µm Mylar foil,
5/3.125 mm width (vertical/horizontal)

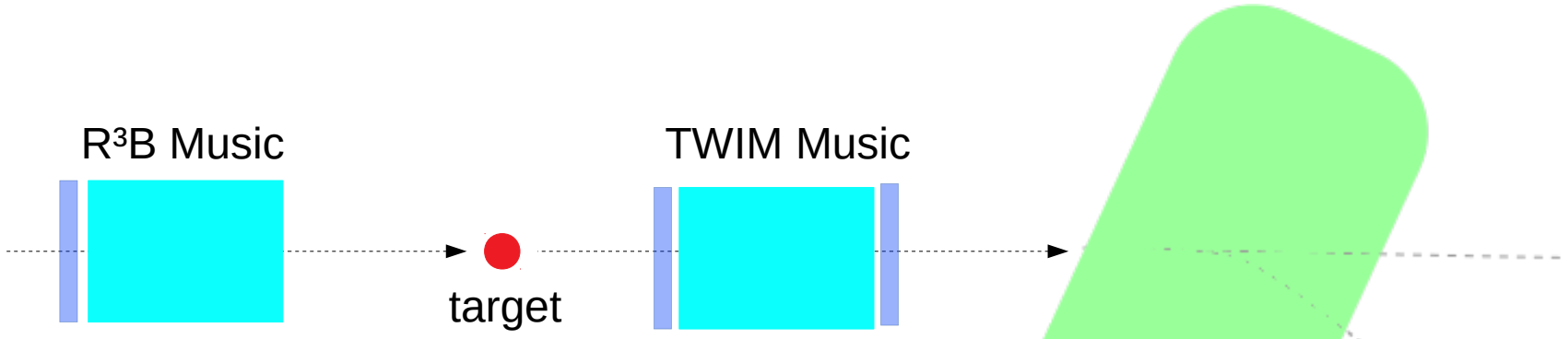
→ gas mixture: 84% Ar, 16% CO2

→ pad readout





Charge Measurement – Ionization Chambers



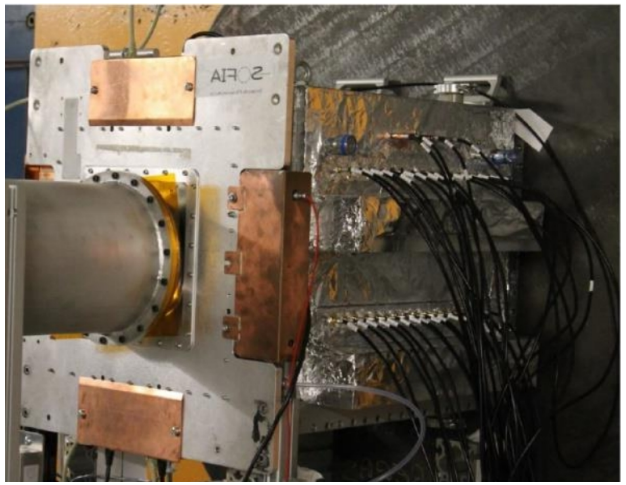
43 x 48 x 55 cm³

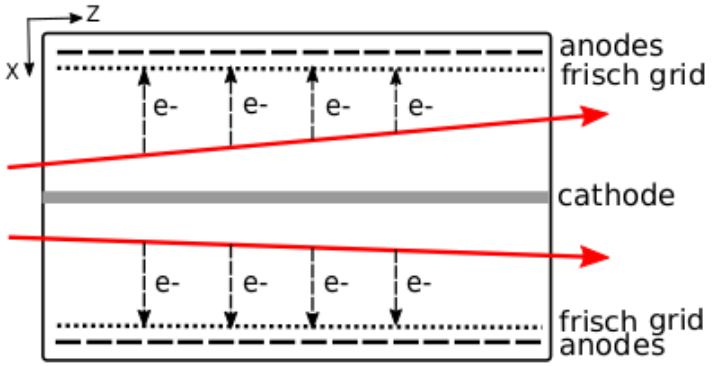
Double ionization chamber

Frisch grid for better signal quality and time resolution

Gas mixture:

Ar 25%, CH4 75%





High resolution measurements of:

→ energy loss ΔE

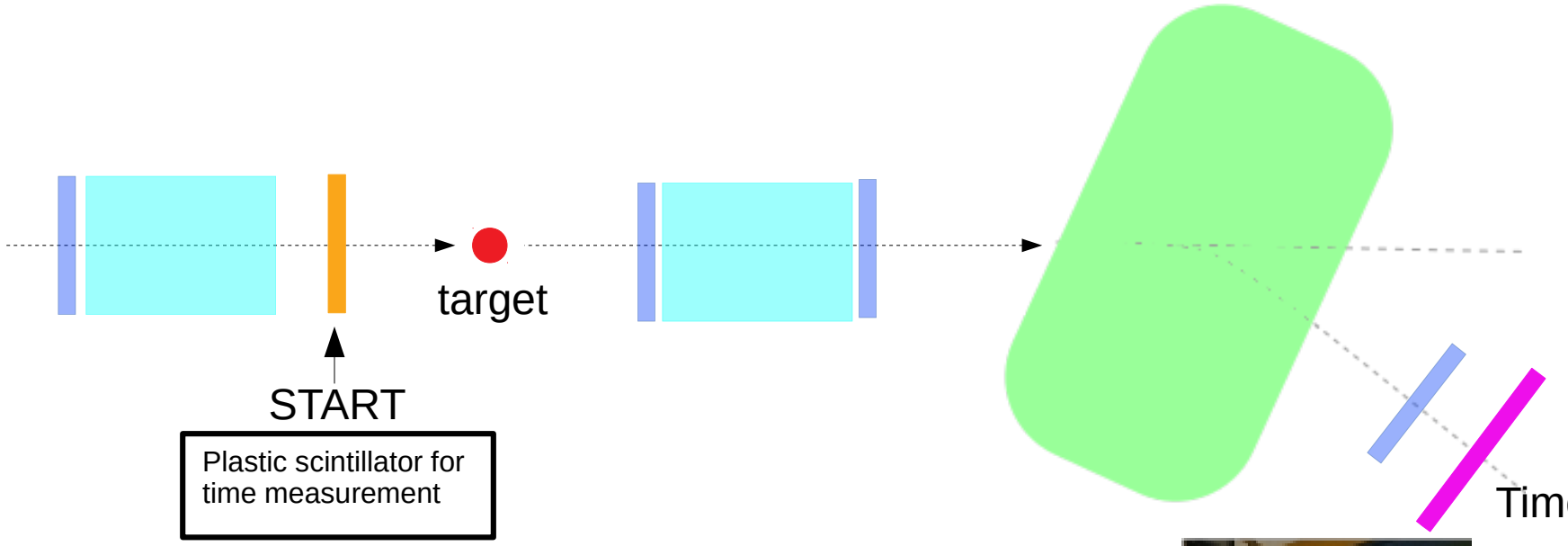
charge

->drift time of e^- from ionization

horizontal angle

TODO: not happy with bullet points!!

Charge Measurement – Ionization Chambers



Mass Identification:

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

27 vertical scintillators (each 30 x 600 x 5 mm)

time and position measurement

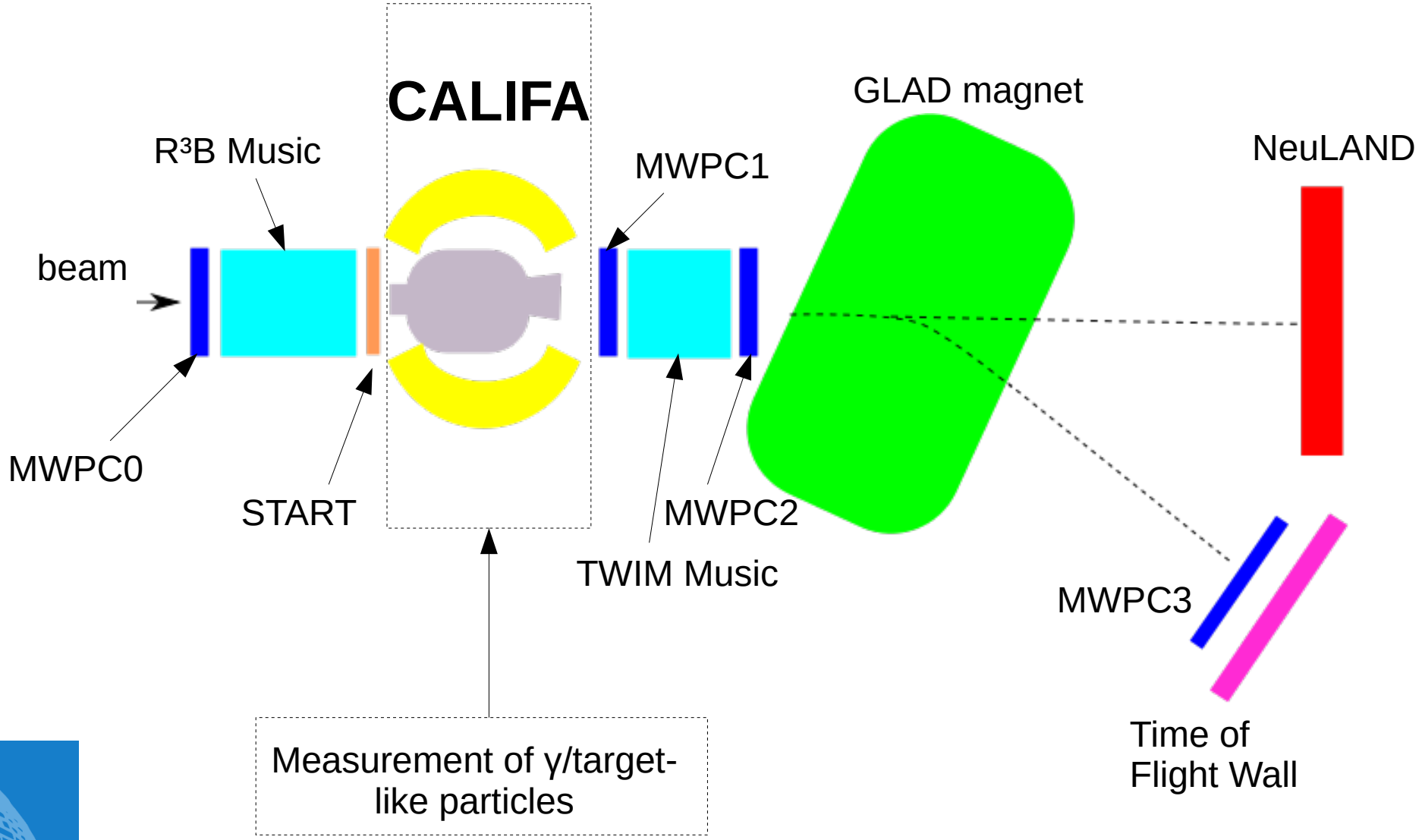
→ ToF measurement: START to TOFW

→ flight-path reconstruction: tracking detectors

→ charge measurement: R3B Music &

TWIM MUSIC

TODO: not happy witht bullet points!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Measurement of γ/target-
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CALIFA Detector @ R³B

CALorimeter for the **I**n **F**light detection of γ-rays and light charged p**A**rticles

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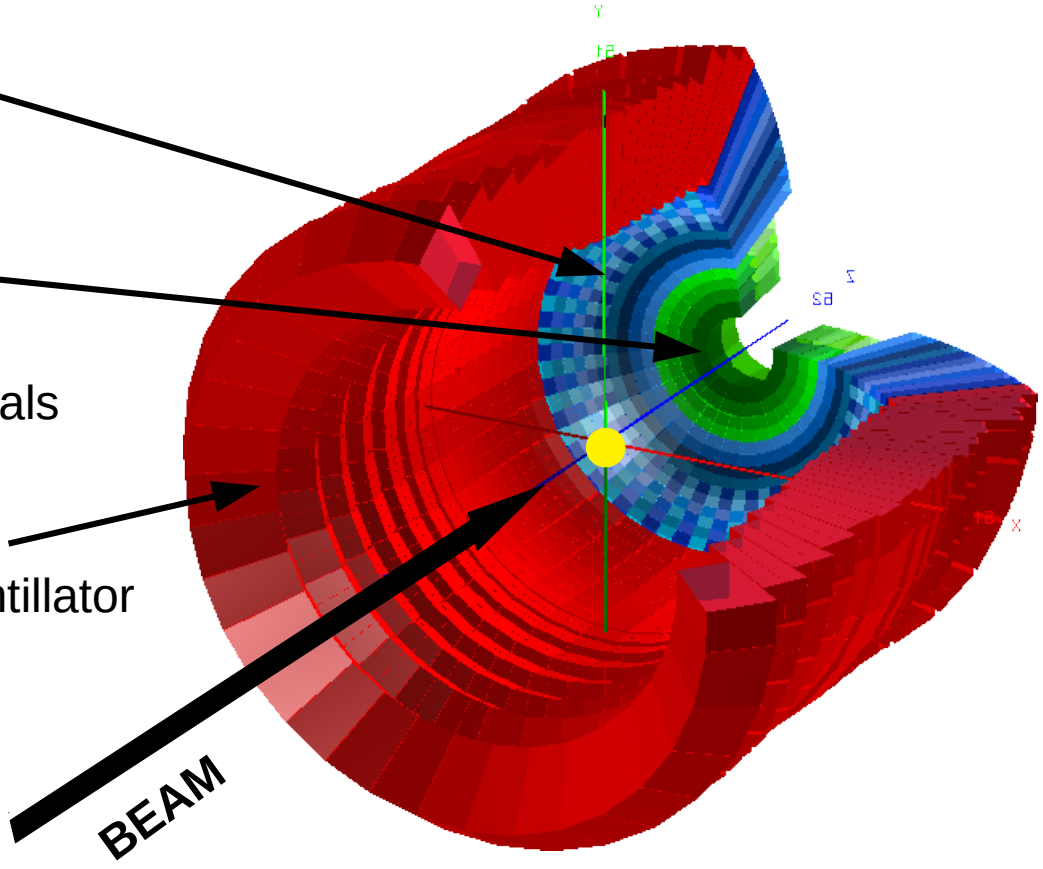
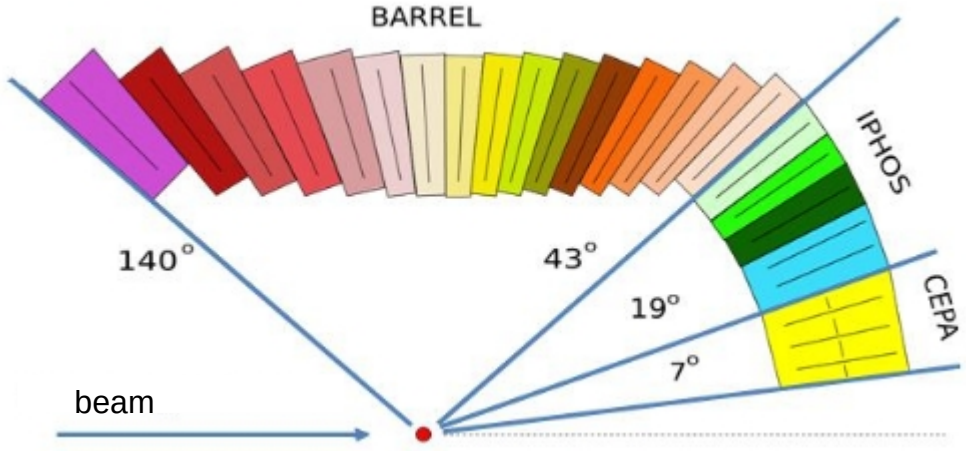


Requirements:
-high dynamic range:
100 keV γ-rays – 700 AMeV charged particles
-high efficiency
-high granularity → Doppler correction
-particle identification



QFS anaylsis in CALIFA

238U(p,2pf) reaction → find the two protons in CALIFA

→ precalibratrion of TWIM Music → cut on Z = 91

→ CALIFA CUTS, delta theta, delta phi, energy, (wrts)

→ show plots from cut on Z and from theta_sum using the cuts
(and also from some simulation)

→ say something about the cross section, what we expect, simulate

ANTIA & Gabriels analysis

.....

Gamma spectrum in CALIFA

Idea: cut on one FF with Z=50 (tin)
Look at the gamma specrum → interesting to understand how energies are shared between the FF

→ show the interesting isotopes of tin
→ show the cuts you did and the gamma spectrum

MW12 vs MW3 vs tof? Maybe….

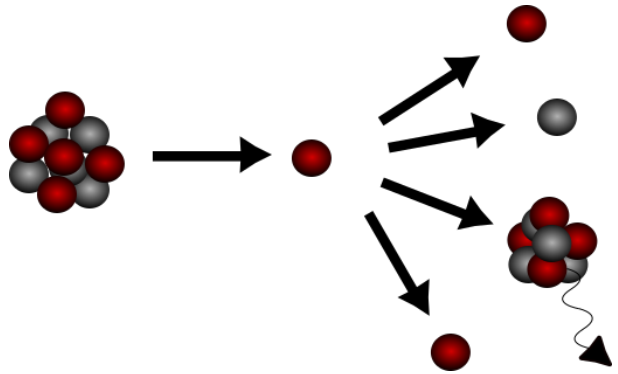
Can I see the different isotopes of tin?? would be nice

Outlook

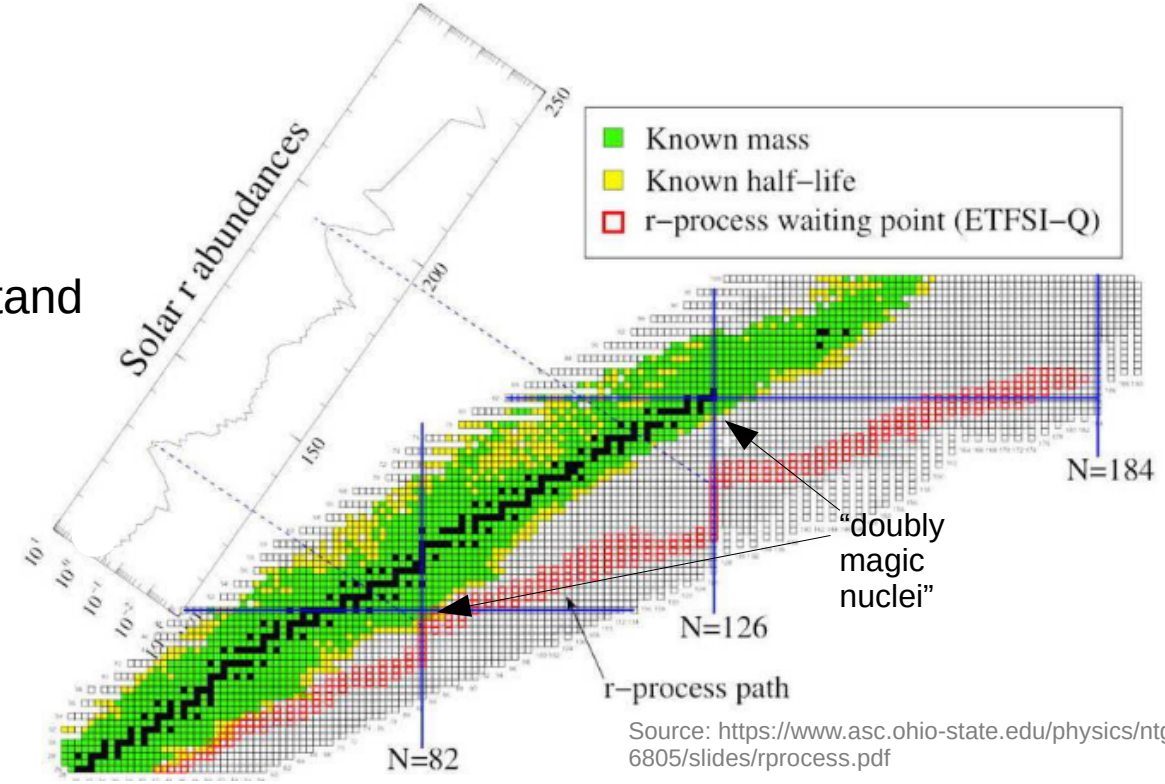
→ calibration of TWIM Music, track reconstruction is essential for clear separation of isotopes
→ make also full energy reconstruction
→ fission barrier /spectra of excited FF

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

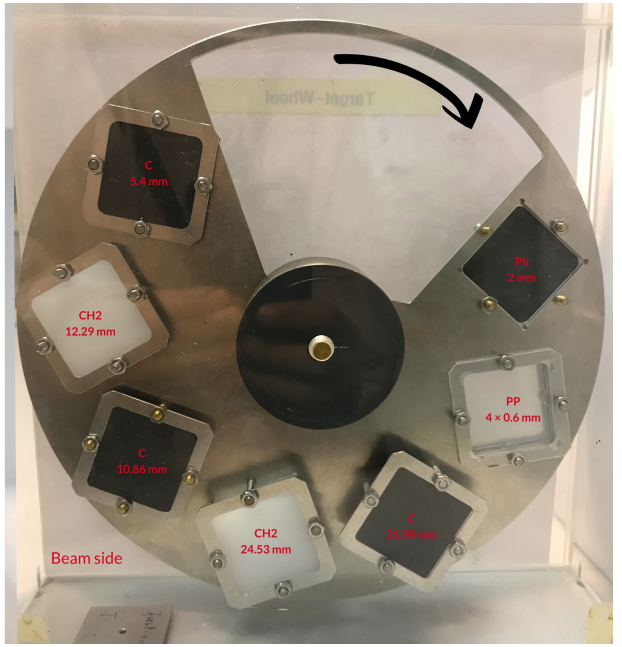


Source: https://www.asc.ohio-state.edu/physics/ntg/6805/slides/rprocess.pdf

R³B – Setup and Detectors

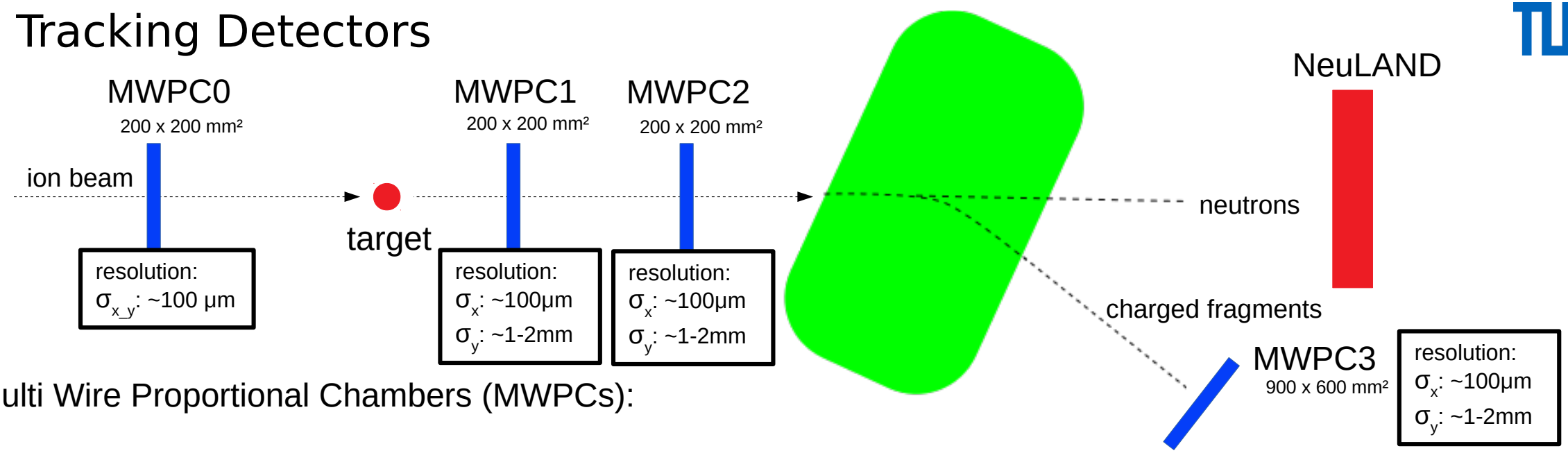
LH2 targets
with length:
15 / 50 / 150 mm

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

Tracking Detectors



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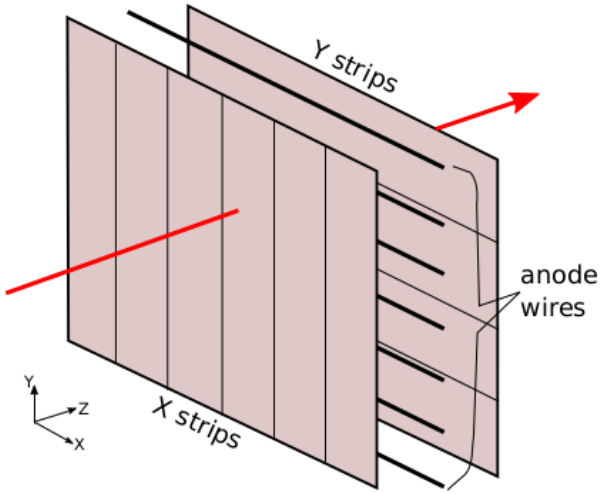

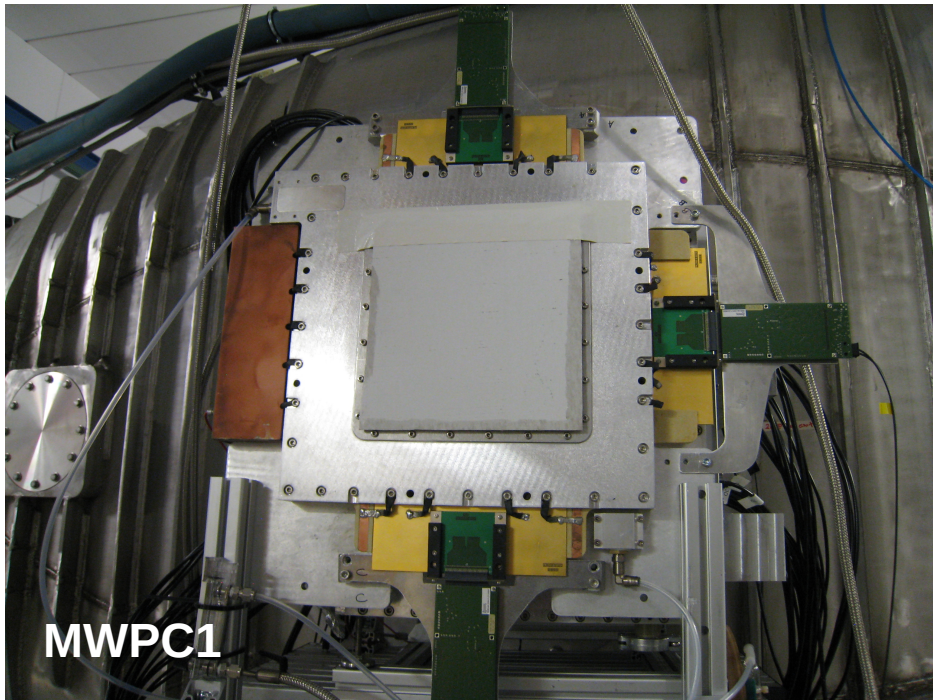

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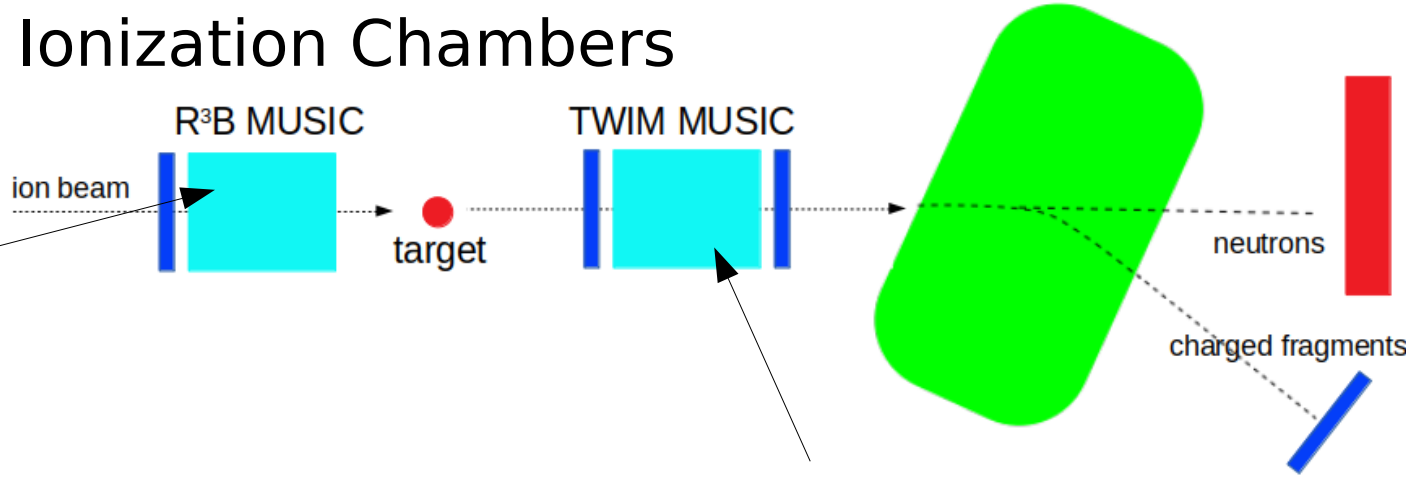


Before the target: **R³B Music**

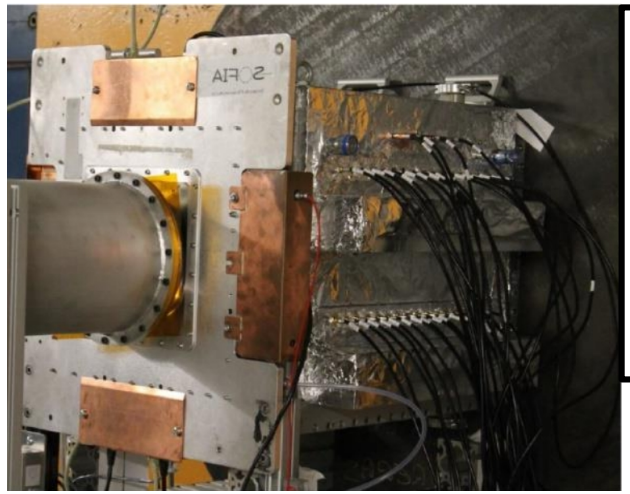
51 x 54 x 53 cm³
Cathode left side - Anode right side
Gas mixture:
Ar 25%, CH4 75%

High resolution measurements of:

→ energy loss ΔE
➡ **charge**

→ drift time of e⁻ from ionization
➡ **horizontal angle**

After the target area: **TWIM MUSIC**



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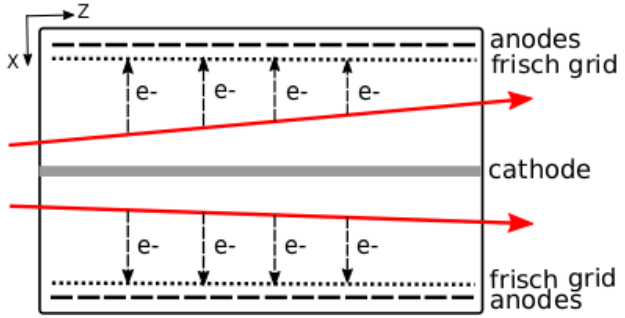
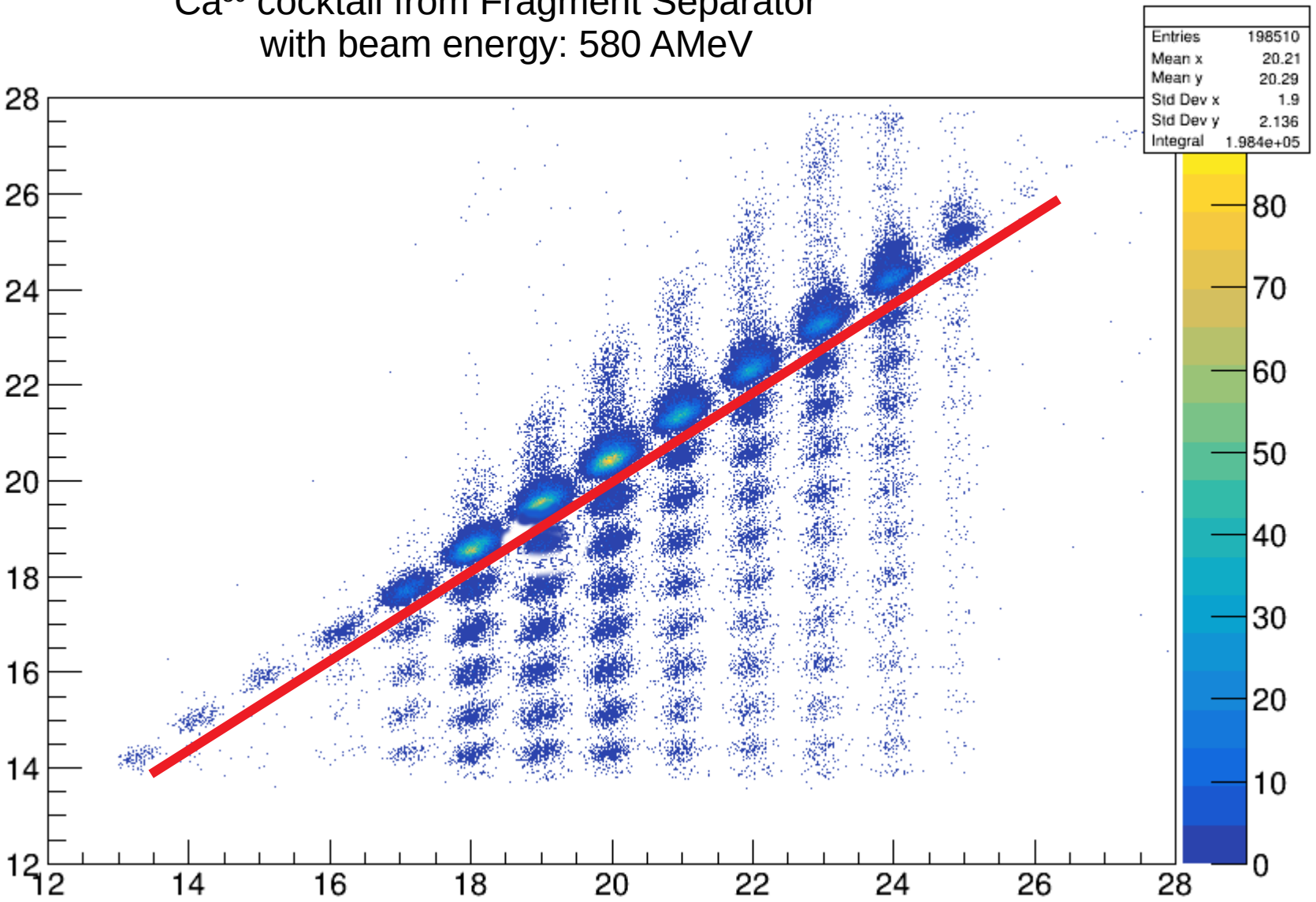
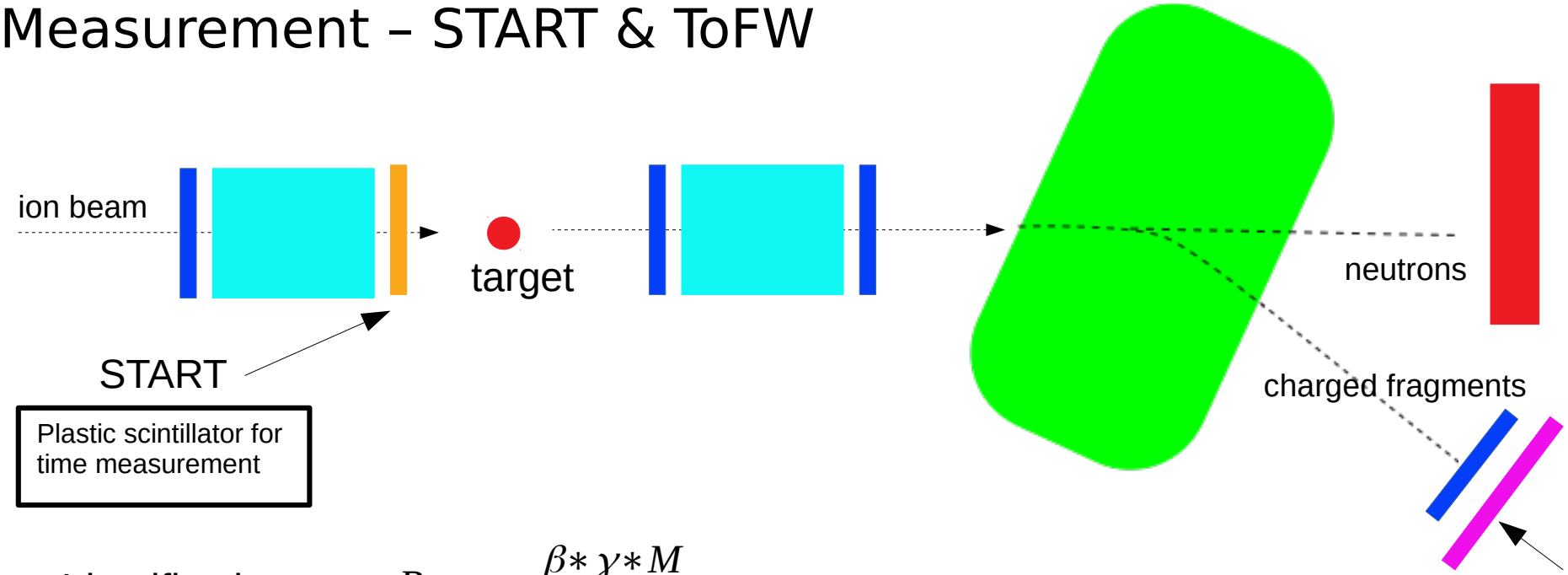


Ca^{50} cocktail from Fragment Separator with beam energy: 580 AMeV



Time Measurement – START & ToFW



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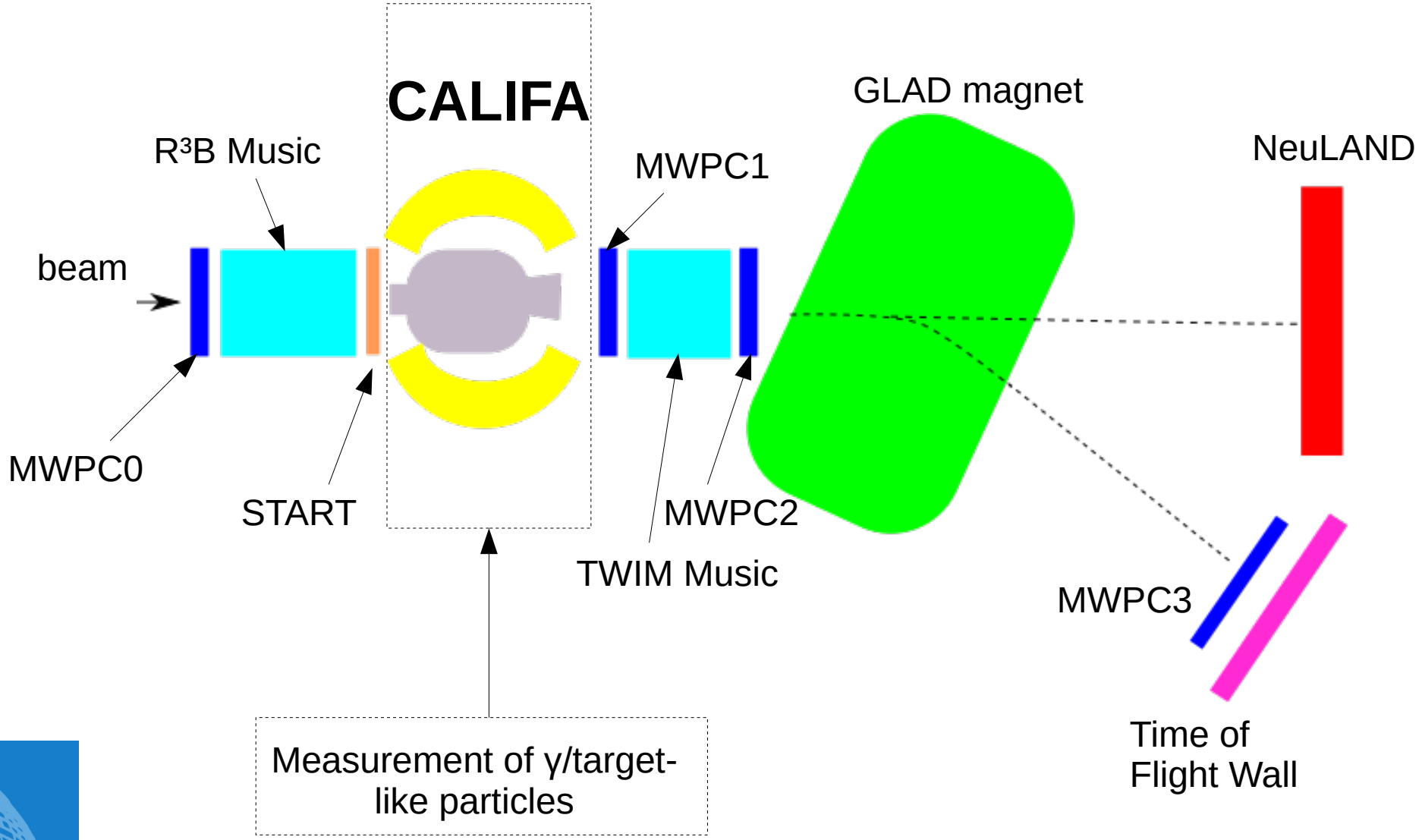
→ ToF measurement: START to TOFW

→ flight-path reconstruction: tracking detectors

→ charge measurement: R3B Music &
TWIM MUSIC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CALorimeter for the **I**n **F**light detection of γ-rays and light charged p**A**rticles

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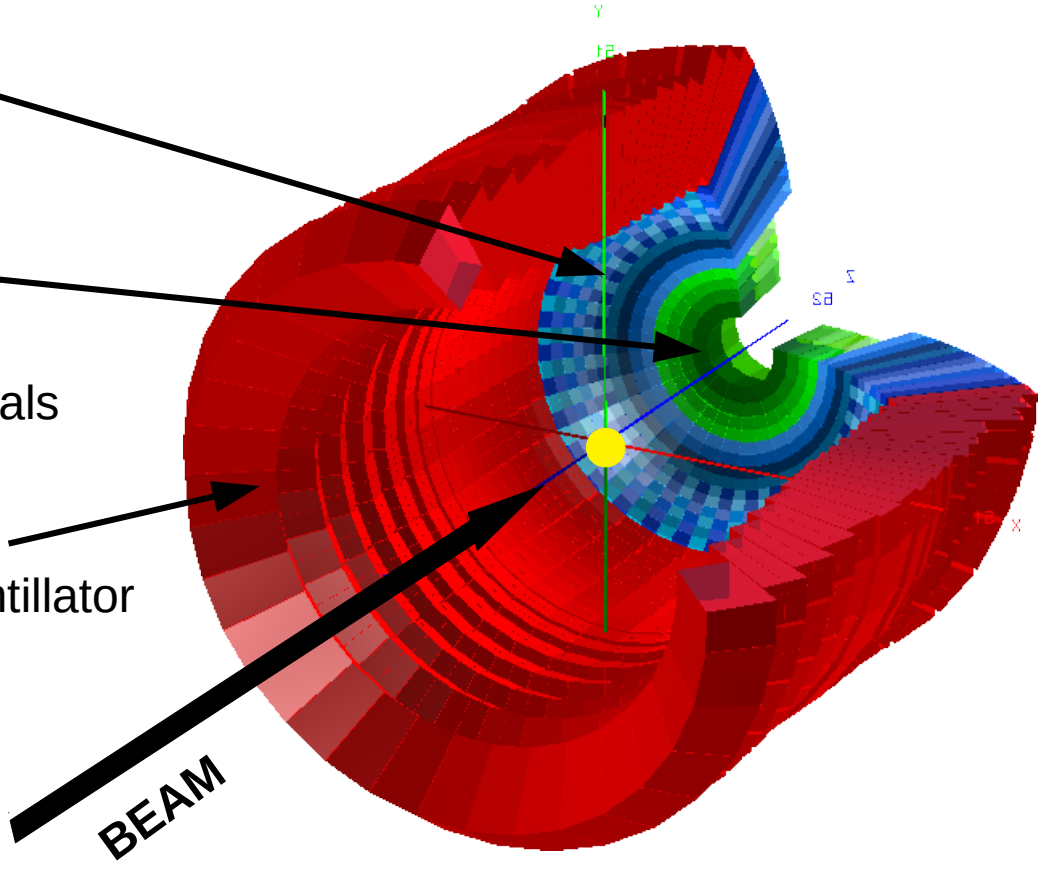

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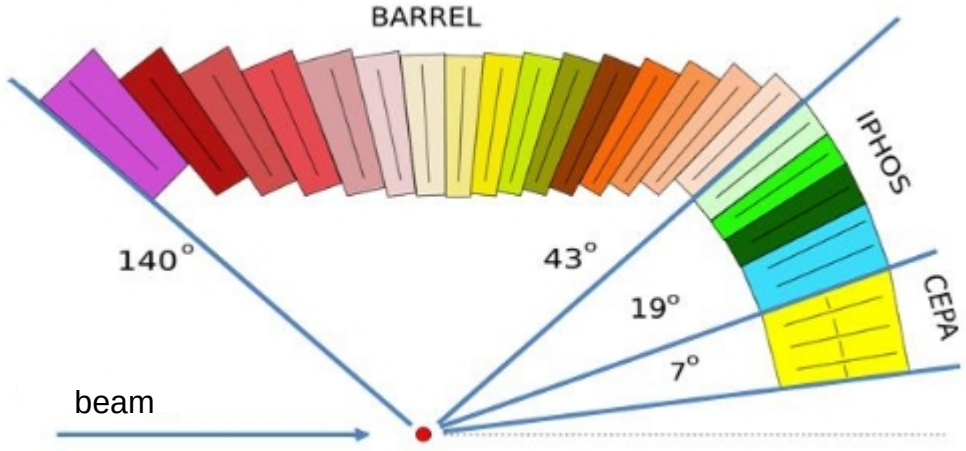
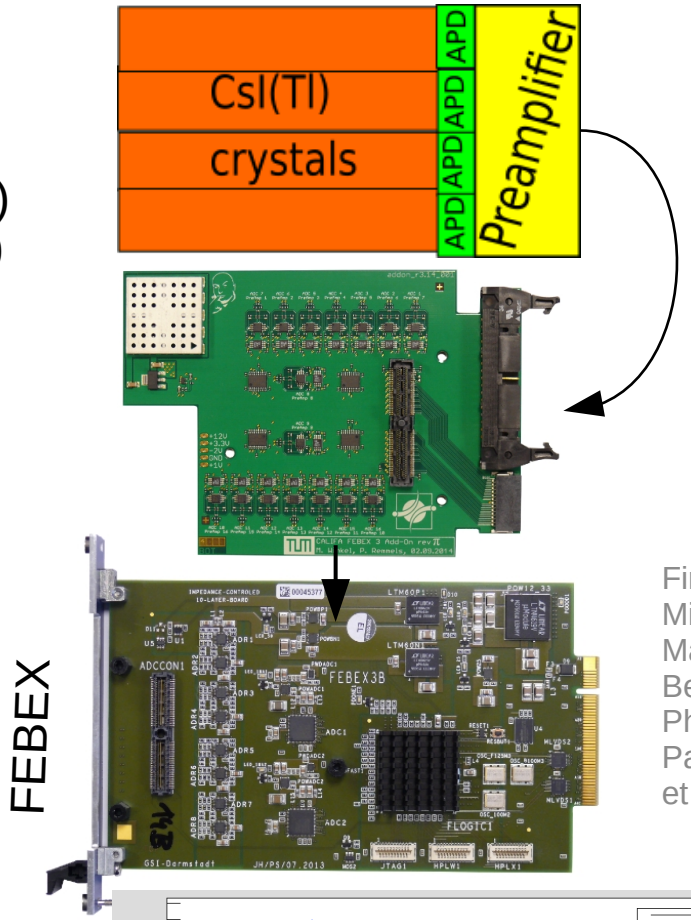


Signal Processing @ CALIFA

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

FEBEX Module: ADC + energy & particle identification



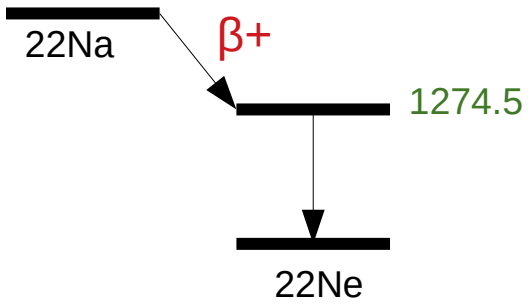
Firmware developed by:
Michael Bendel,
Max Winkel,
Benjamin Heiss,
Philipp Klenze,
Patrick Remmels,
et al.

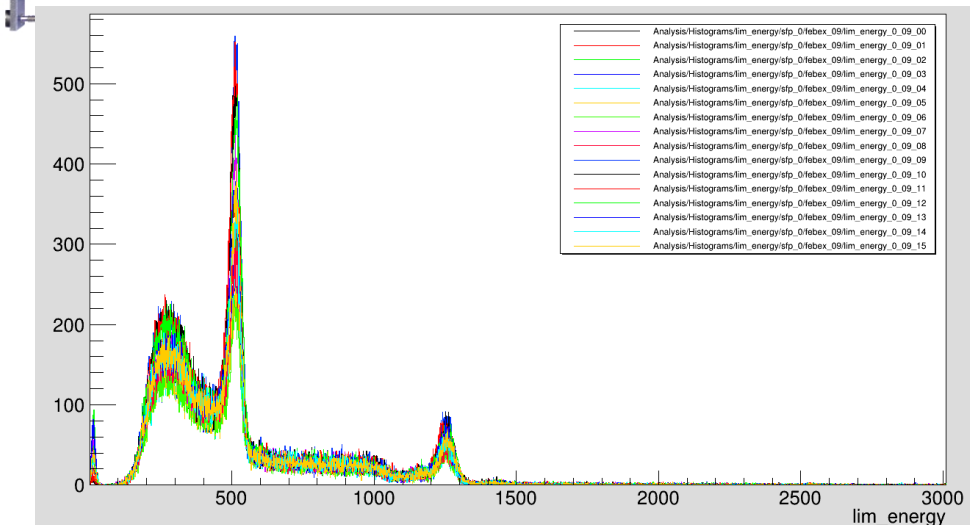
Automated APD Gain matching routine:

→ ensures that all channels cover same range

→ already pre-calibrated

E.g. 22Na decay:





Electronics for CALIFA

Each rack:

→ 1024 channels

→ 50 MHz continuous sampling rate

Dead-time free readout design:

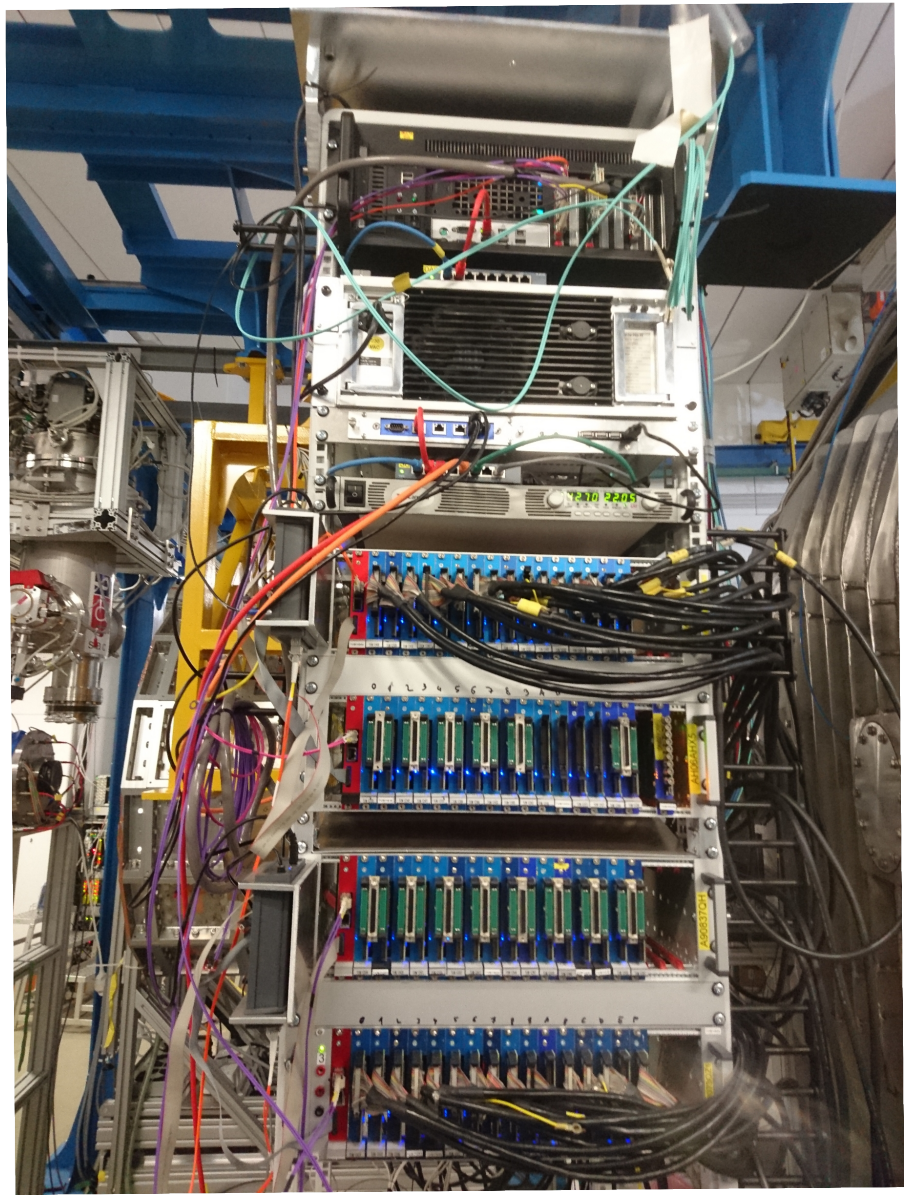
→ PEXOR card

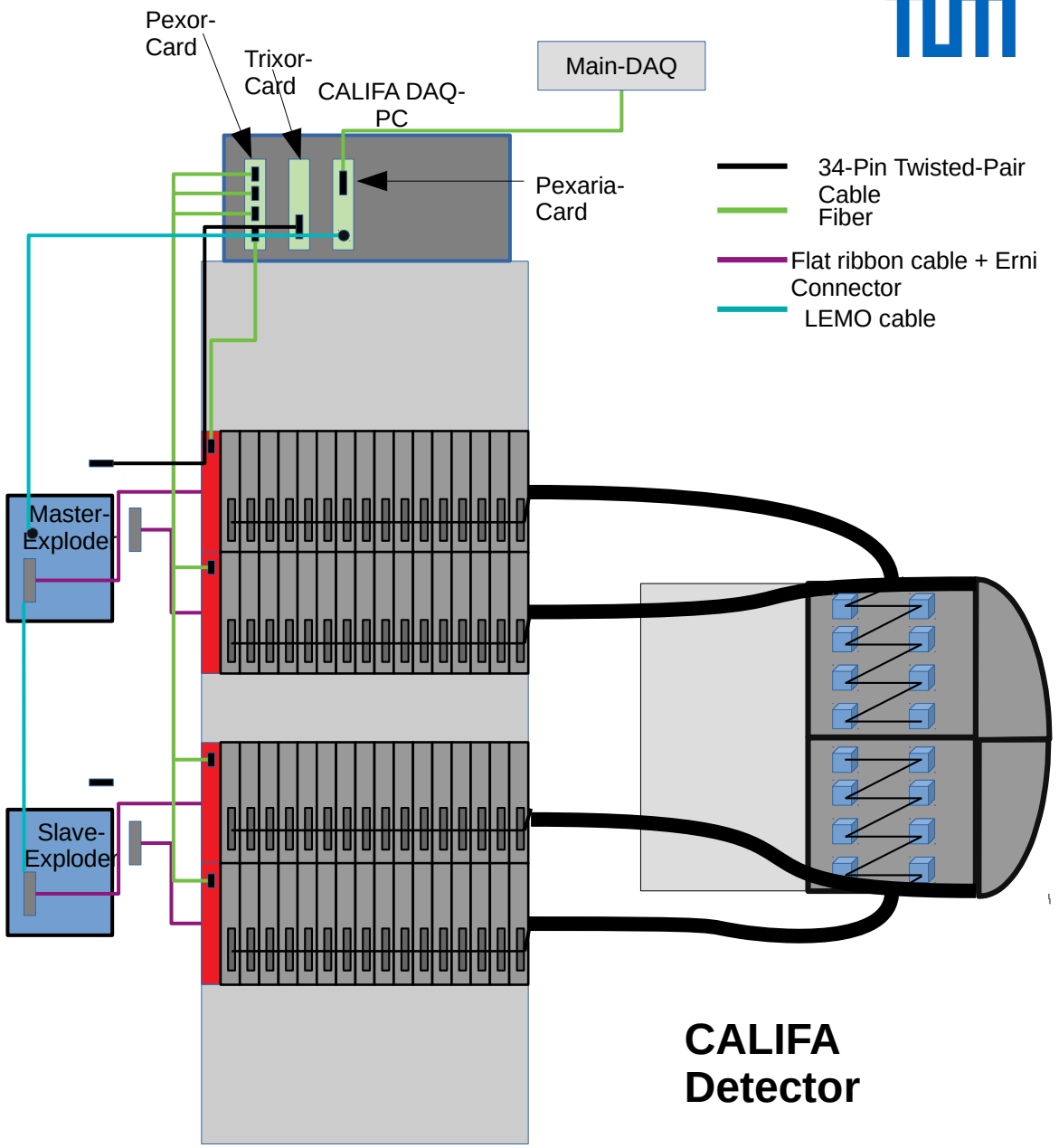
→ TRIXOR card

→ EXPLODER

→ PEXARIA (white

Rabbit timestamp)



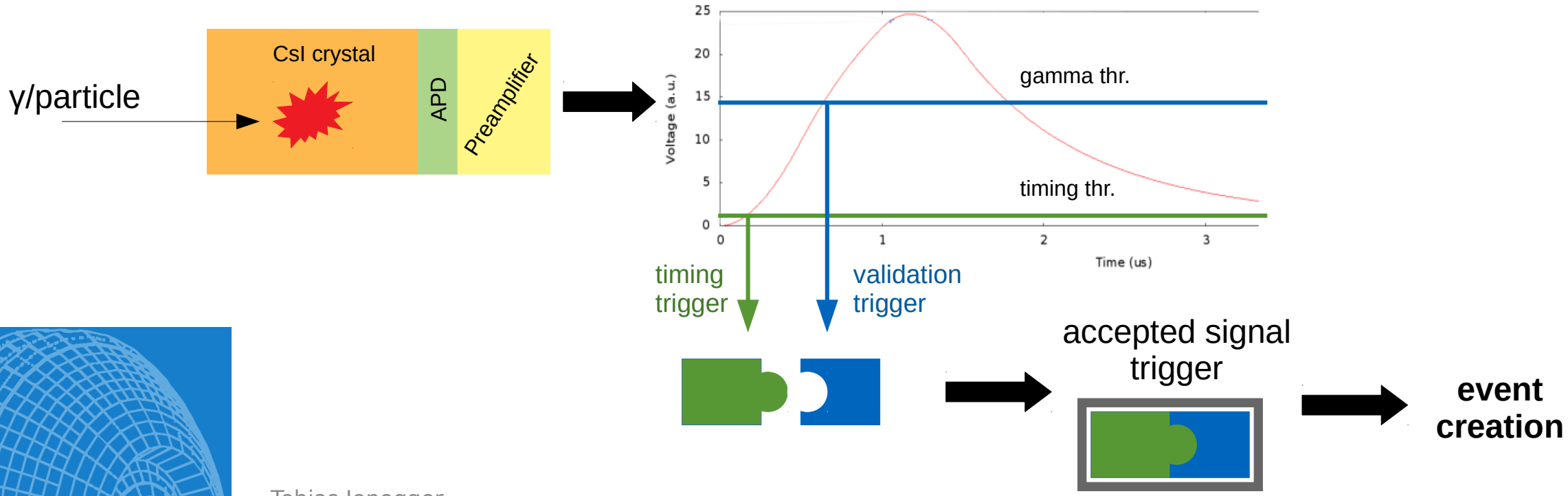


CALIFA Trigger Logic for event building

Trigger-Discriminator Logic:

→ Timing Trigger: event time assignment
→ Gamma Trigger: event validation
→ Proton Trigger: external trigger

Intuitive event building logic (free running mode):



CALIFA Trigger Logic for event building

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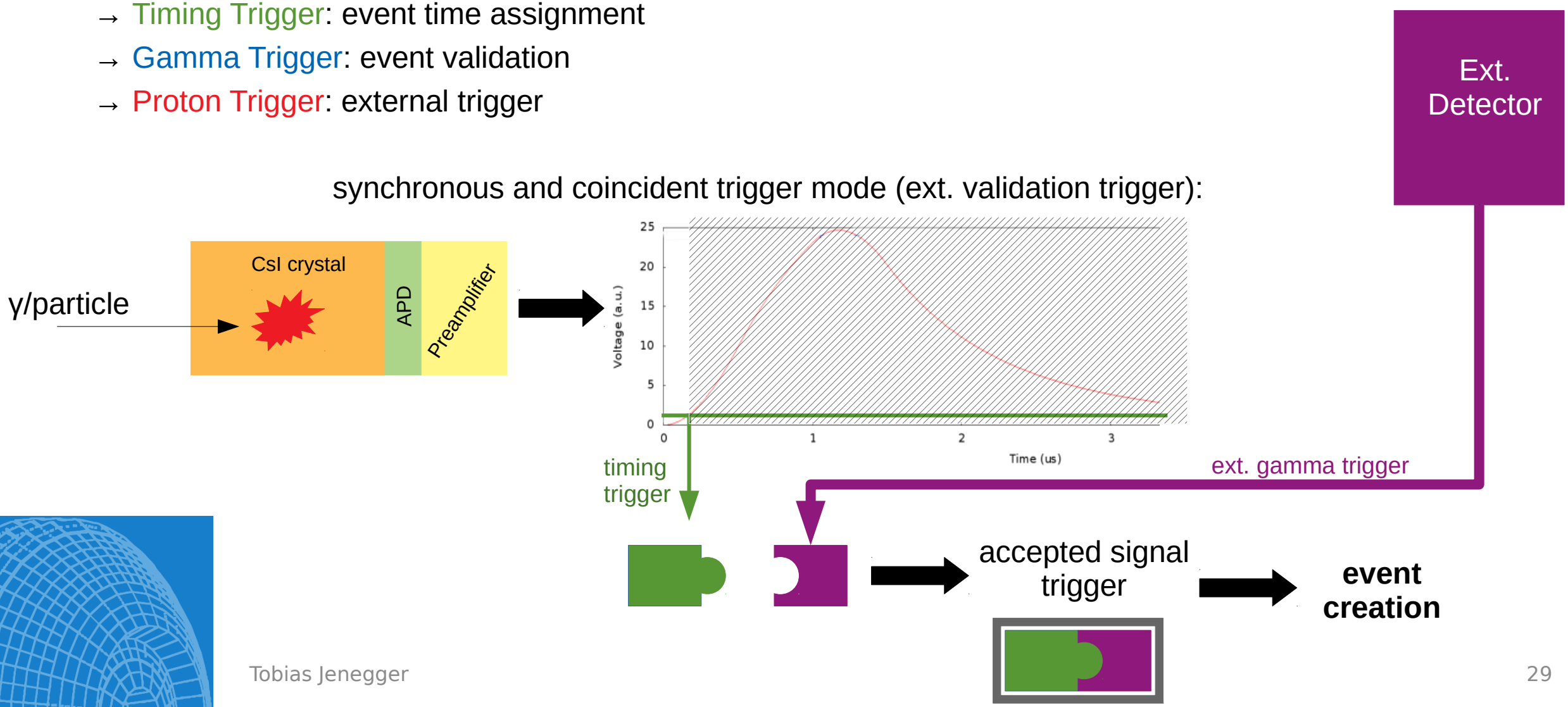
synchronous and coincident trigger mode (ext. validation trigger):

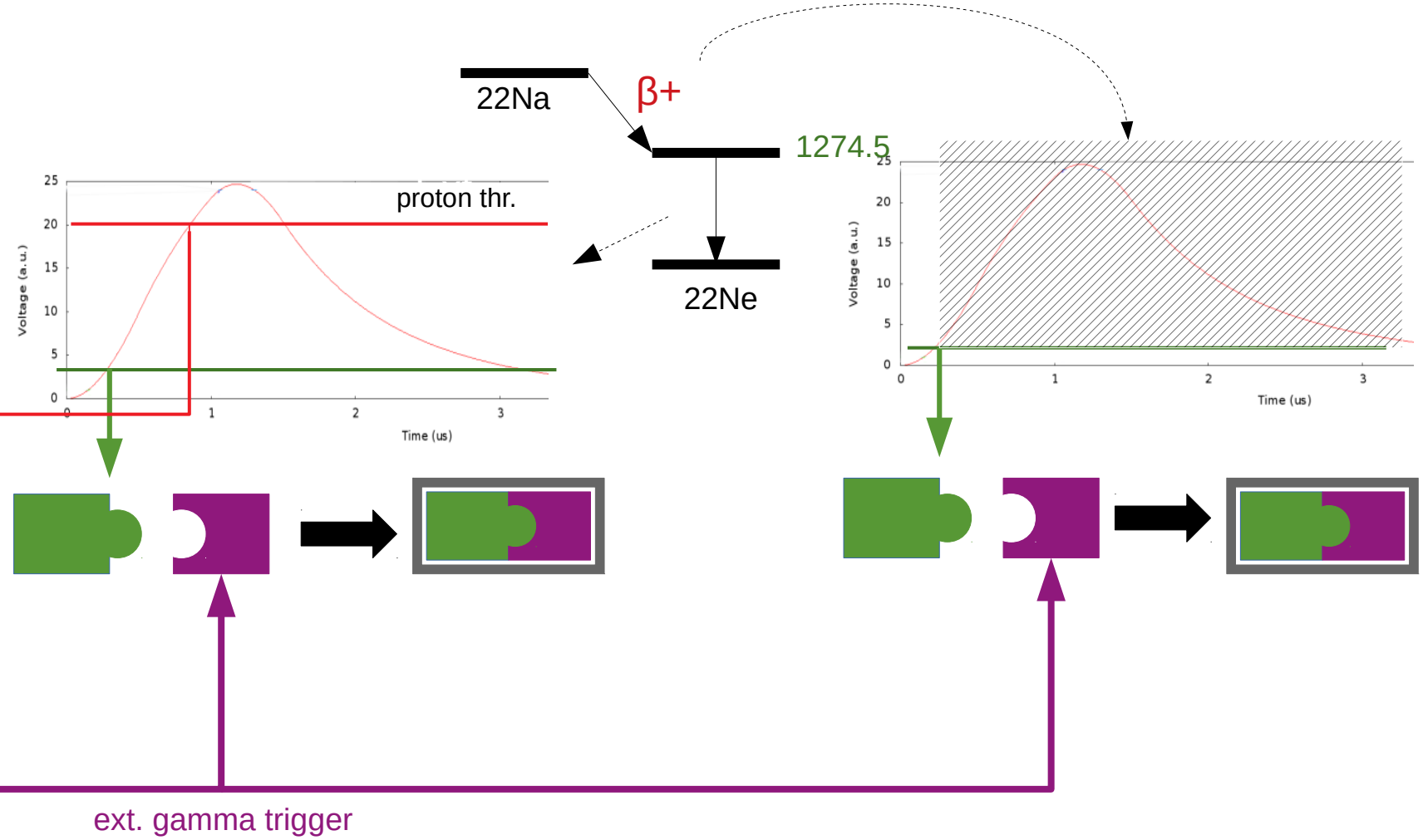


Setting to Synchronous and Coincident Trigger Mode

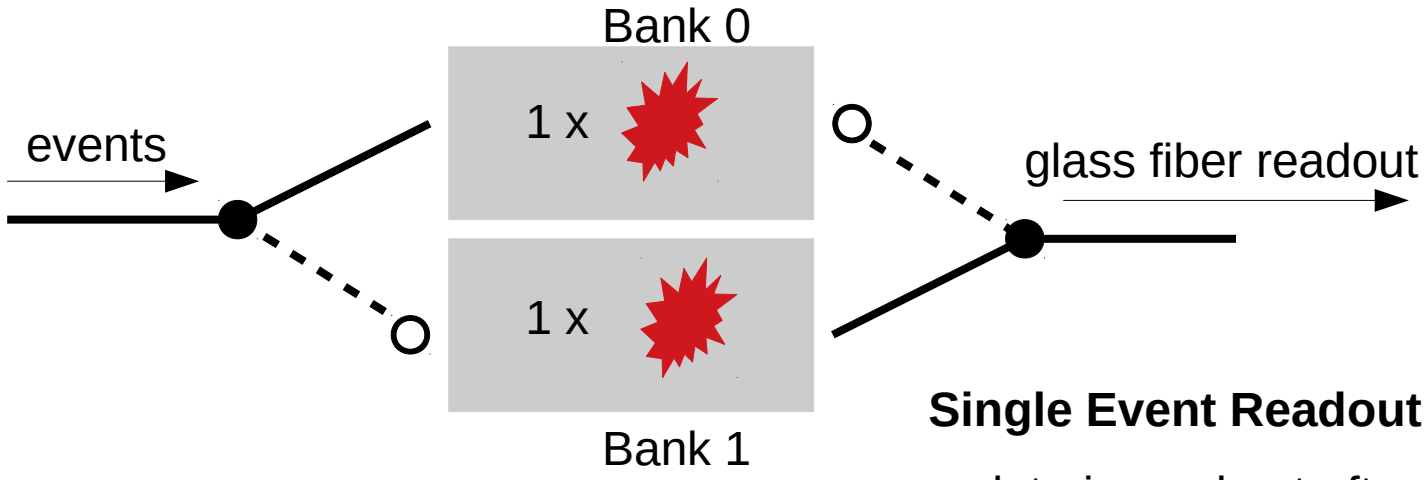
→ For upcoming experiments we switched to coinc. trigger mode
→ ext. gamma trigger from START detector

For Calibration:

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



CALIFA Readout Modes



Single Event Readout (std. Firmware):

→ data is read out after each accepted signal trigger

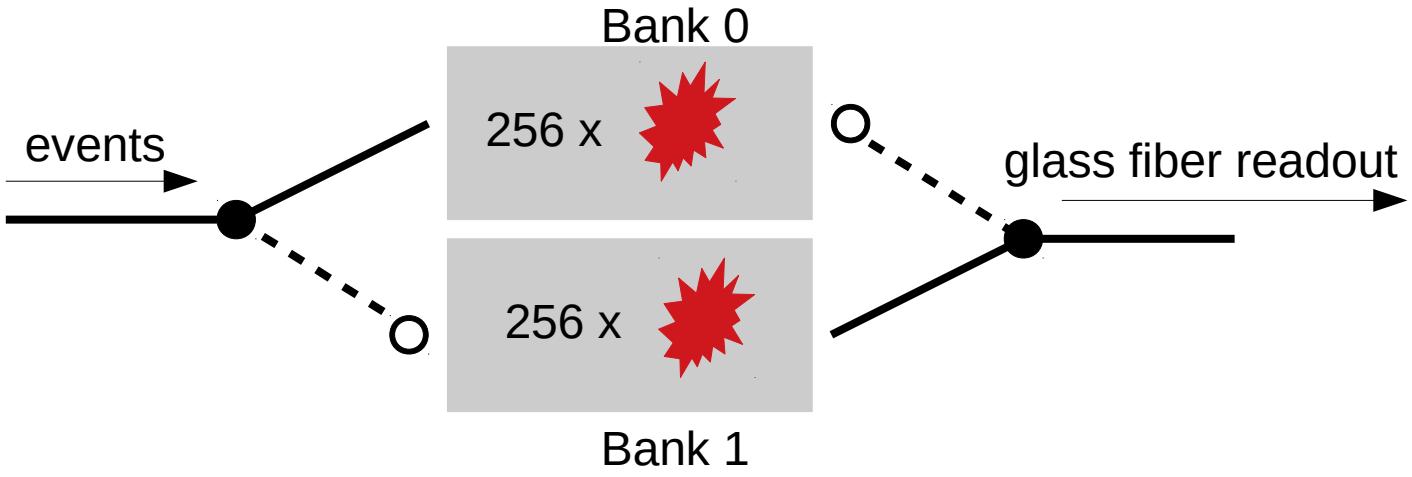
→ **dead time:**

if 2 events in Δt < 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 Δt < readout time

What is our rate limit?

max. readout speed per glass fiber

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

data size of single event

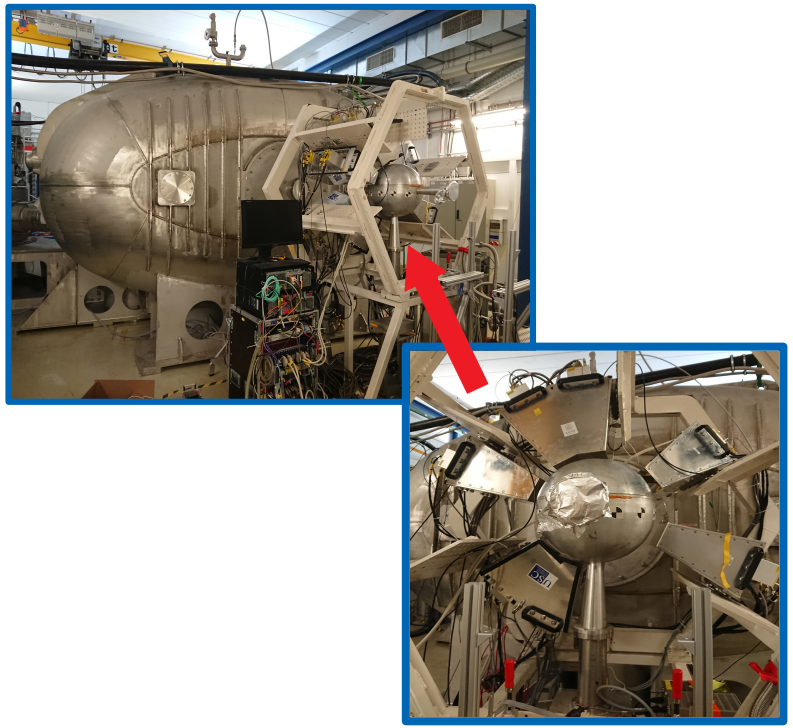
For final design we have 10 glass fiber lines

max. 40 Mio. Hits in total !

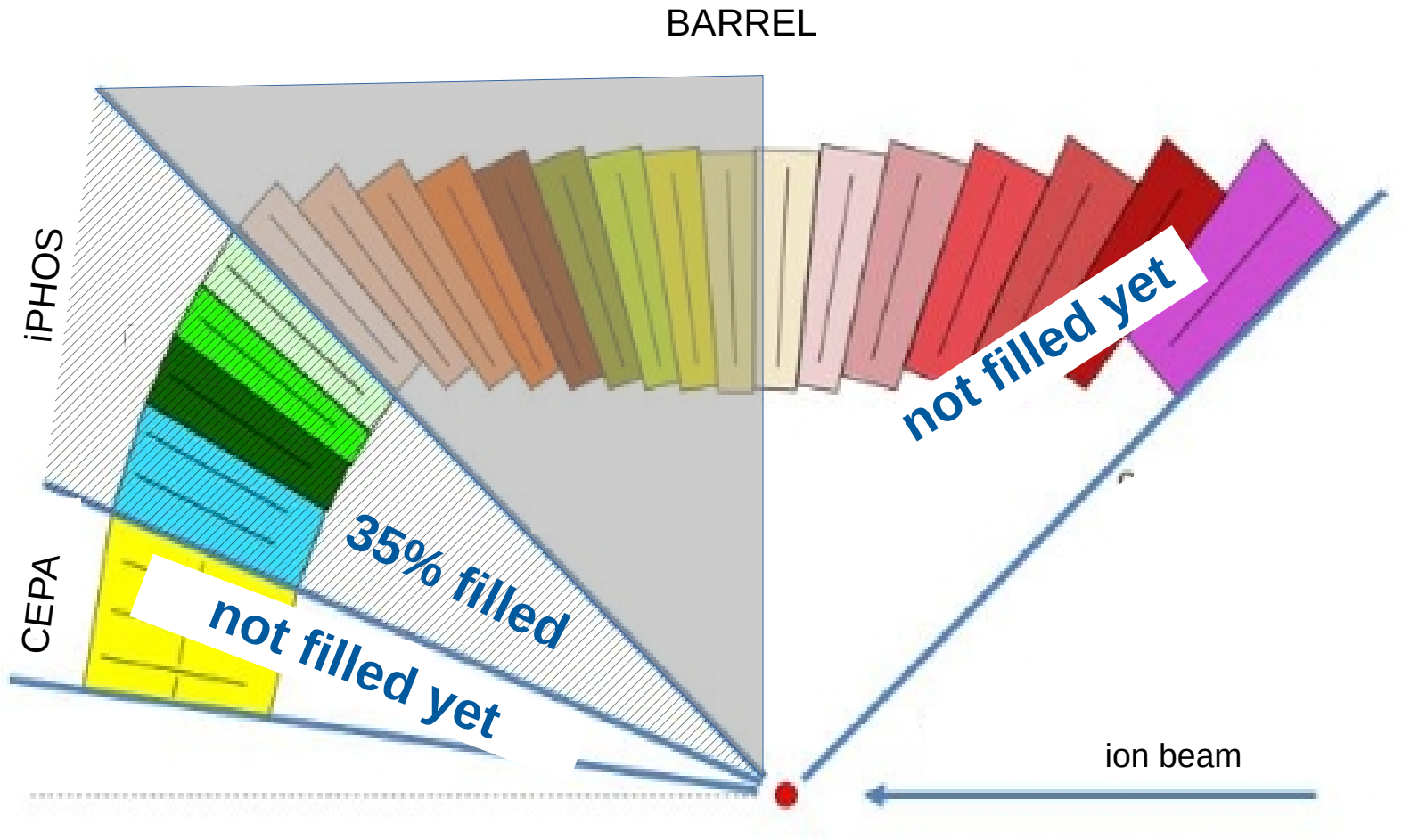
CALIFA is fast !!

CALIFA Upgrade 2021

From Demonstrator to Final Setup



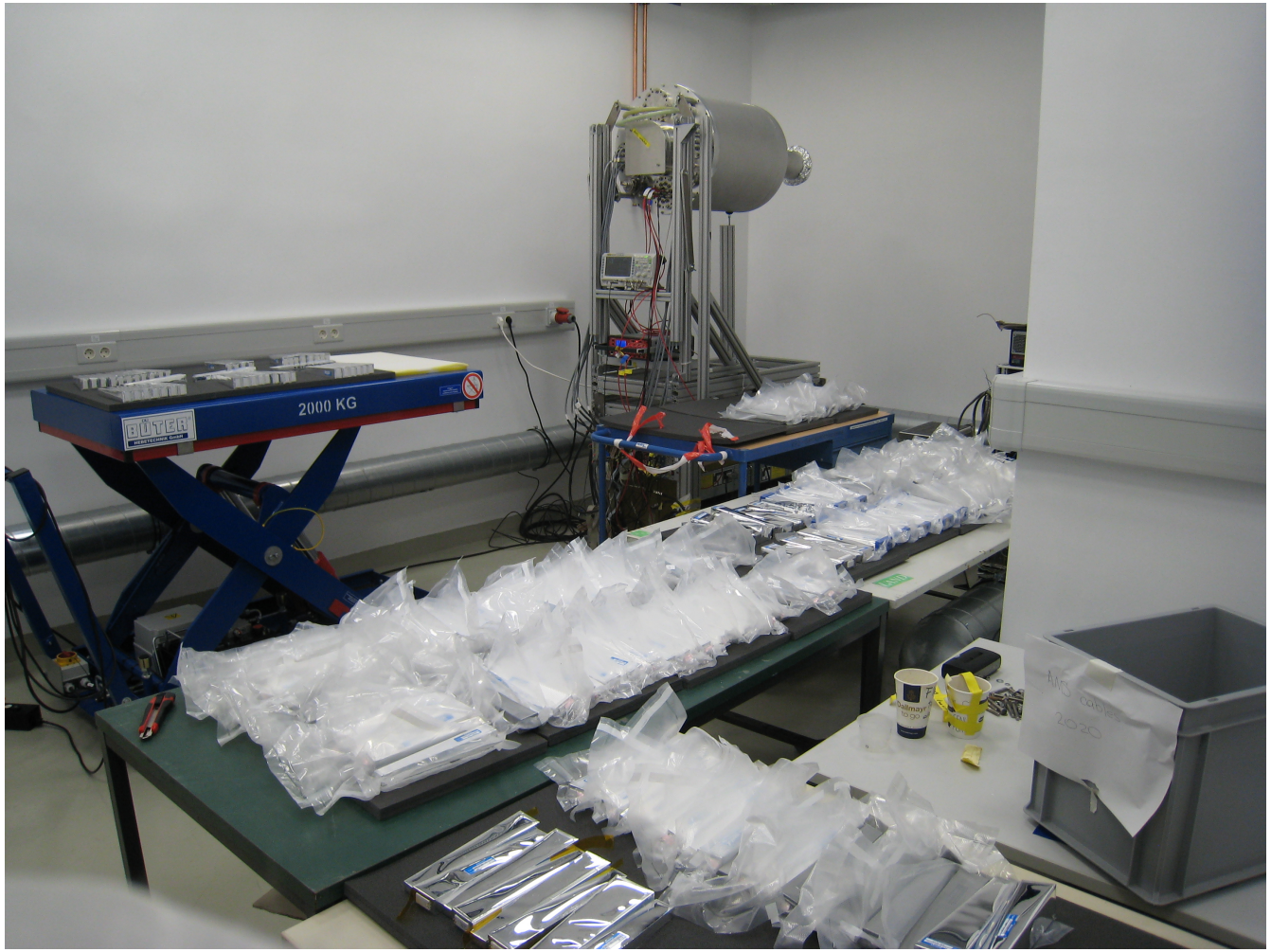
experiment of Lukas Ponnath



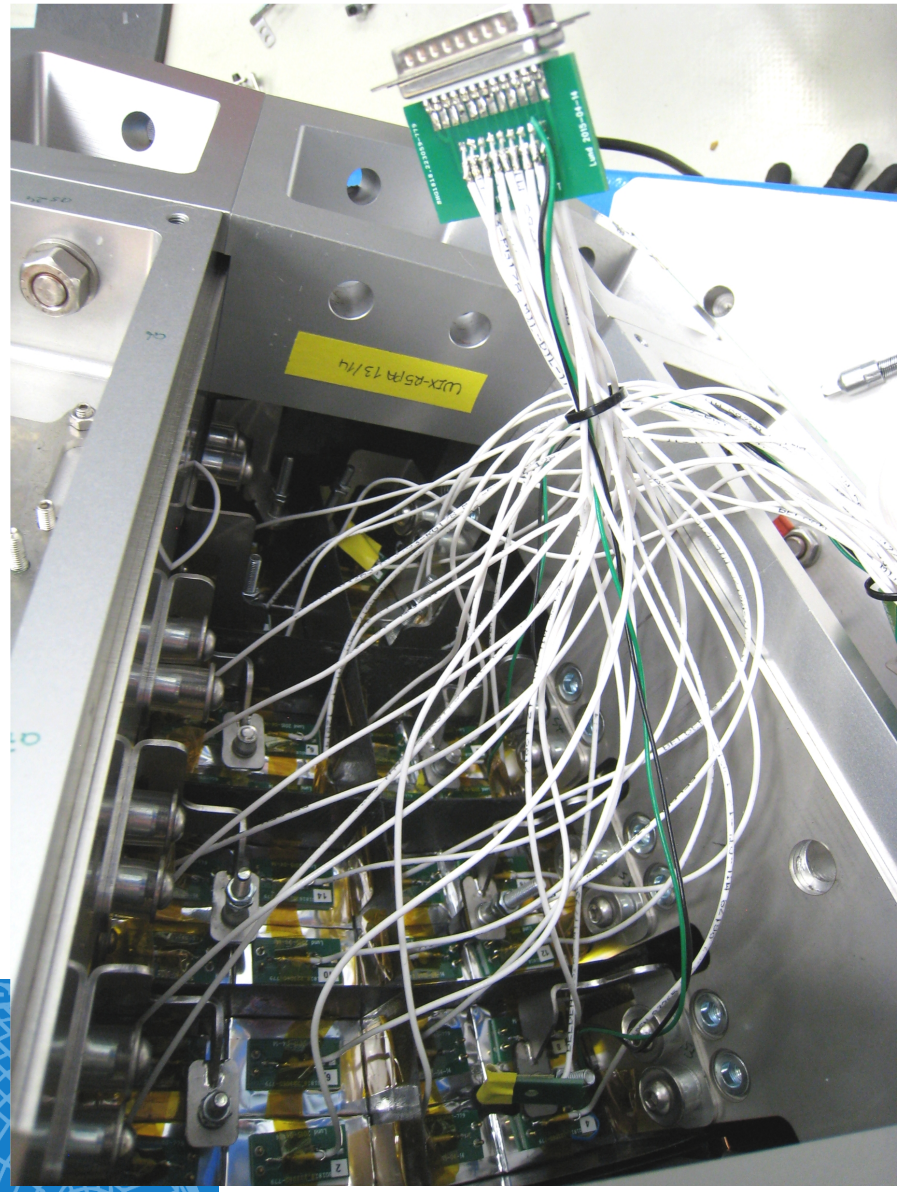
UPGRADE: iPHOS region fully filled!

unmounting:

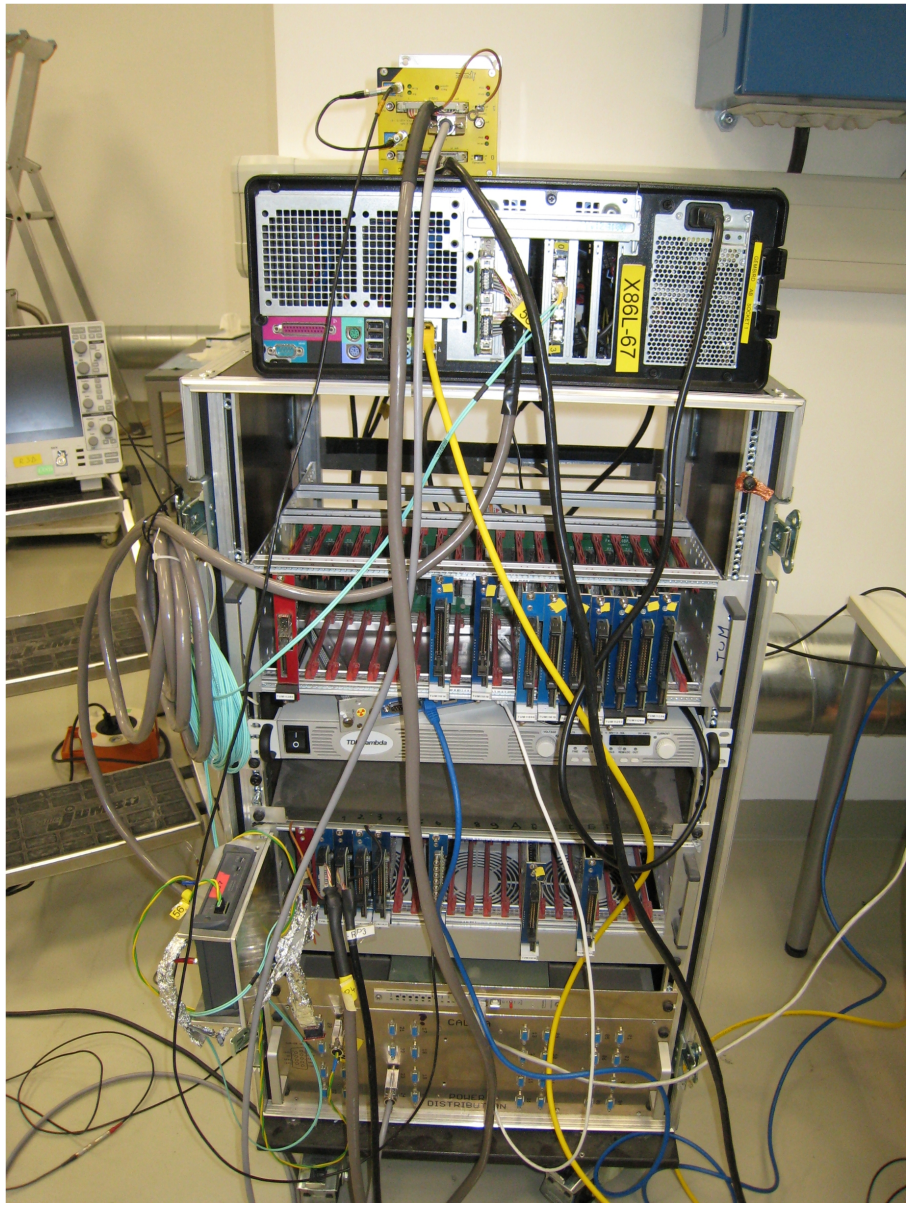
open tiles & individual crystal check:



crystal filling:



testing with mobile DAQ:

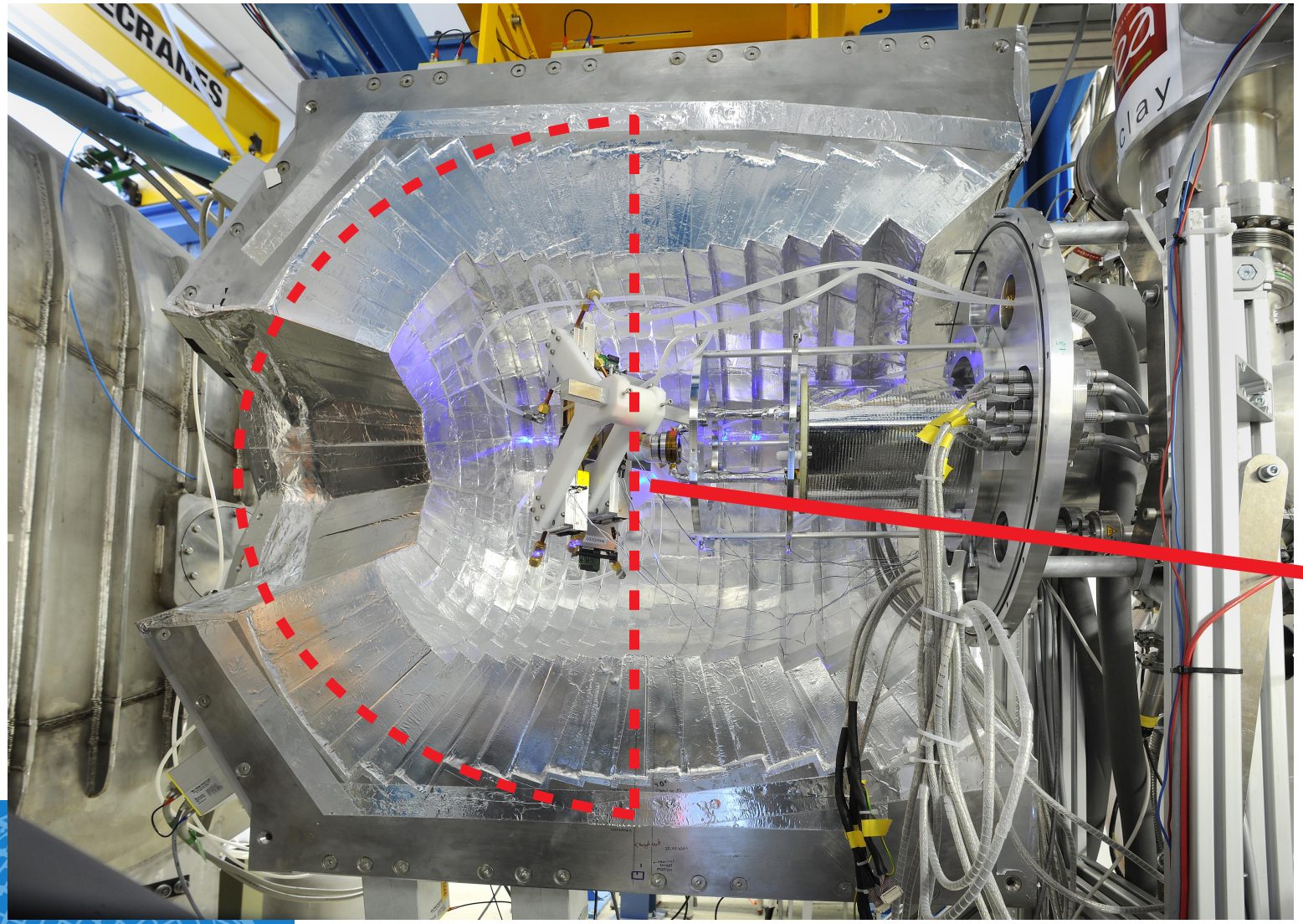


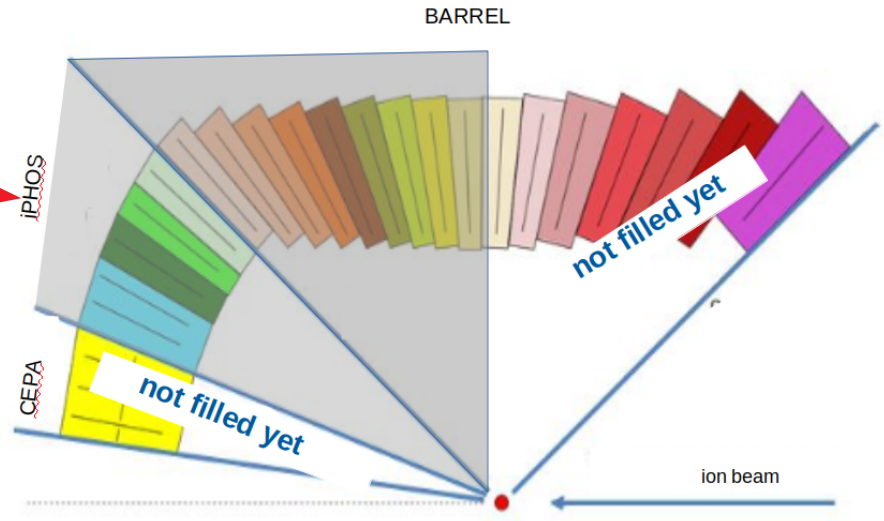
bring back to Cave C:

1.2 tons !

mount and align:

Fully filled forward half !





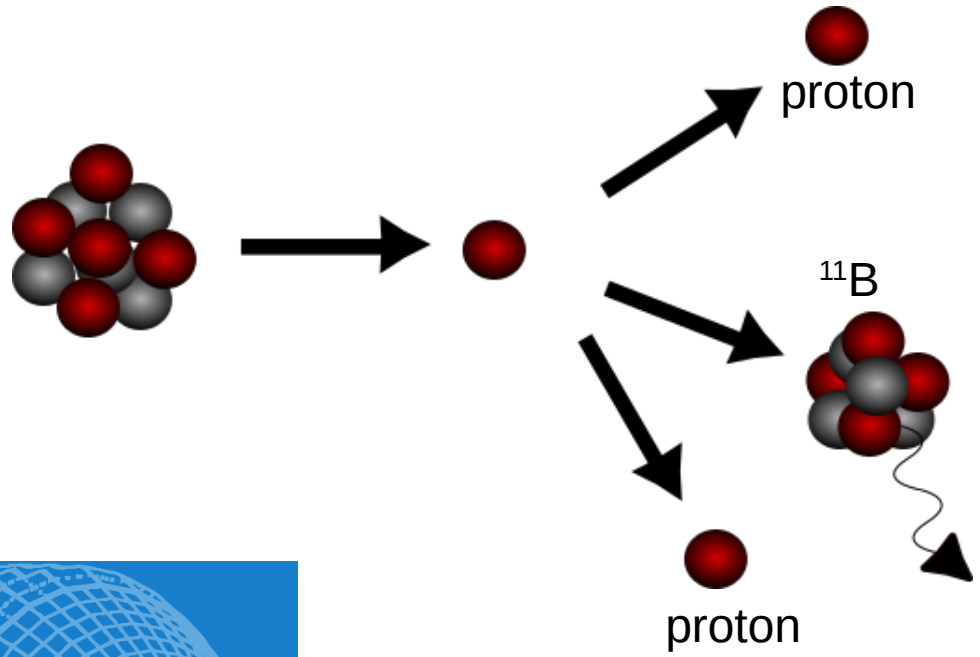
Quasi Free Scattering Analysis with Experiment S444/467 (2020)

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

- ^{12}C beam
- proton like target

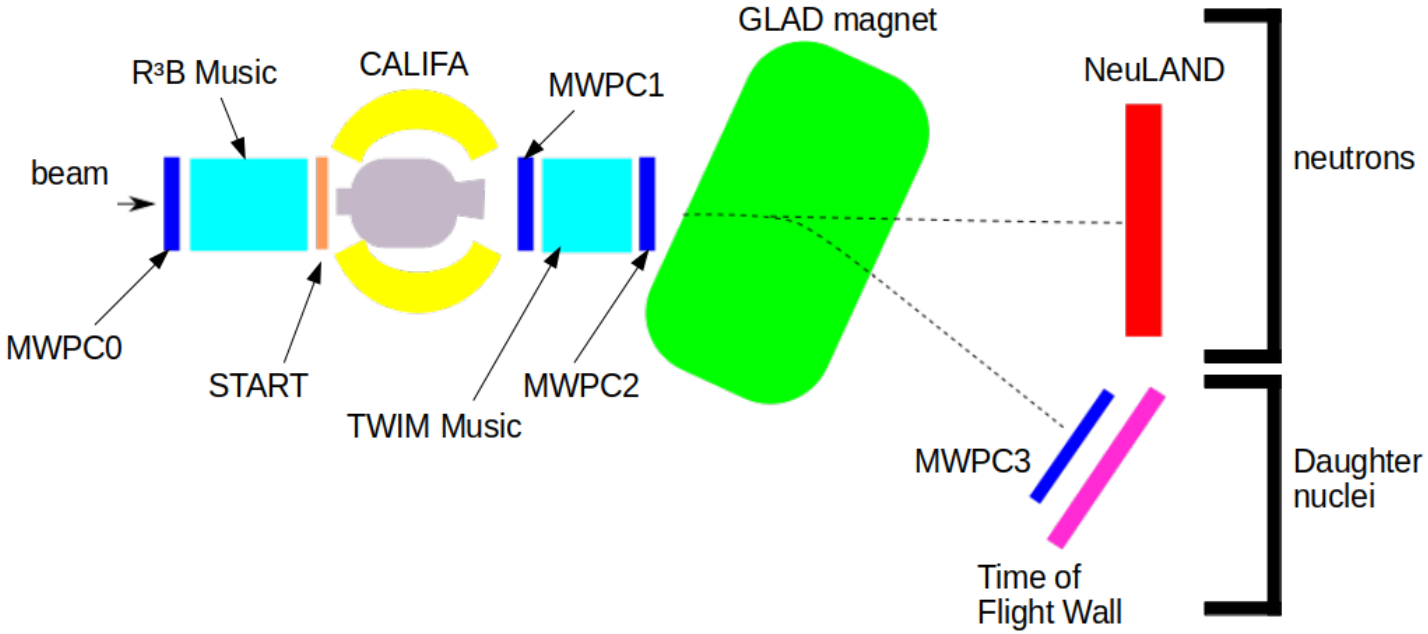
→

- 2 protons
- ^{11}B fragment (spectator)



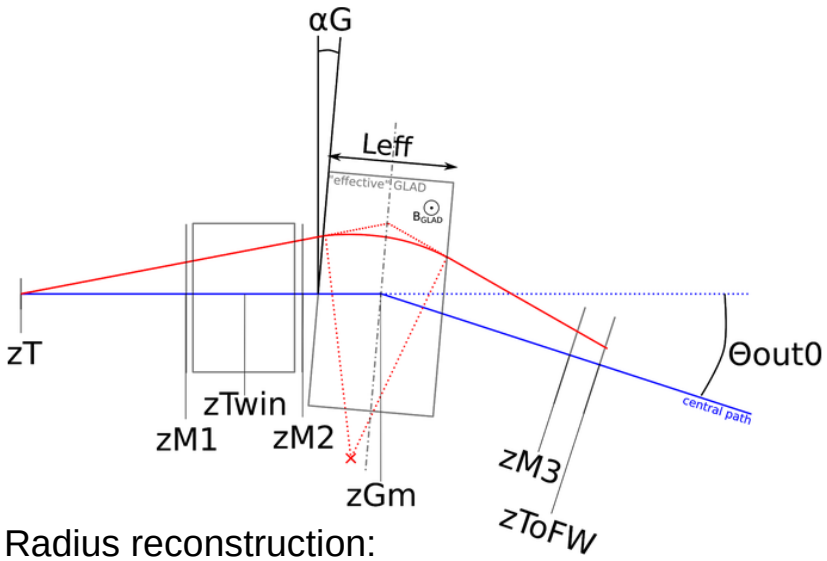
SETUP:

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



Fragment Particle Identification

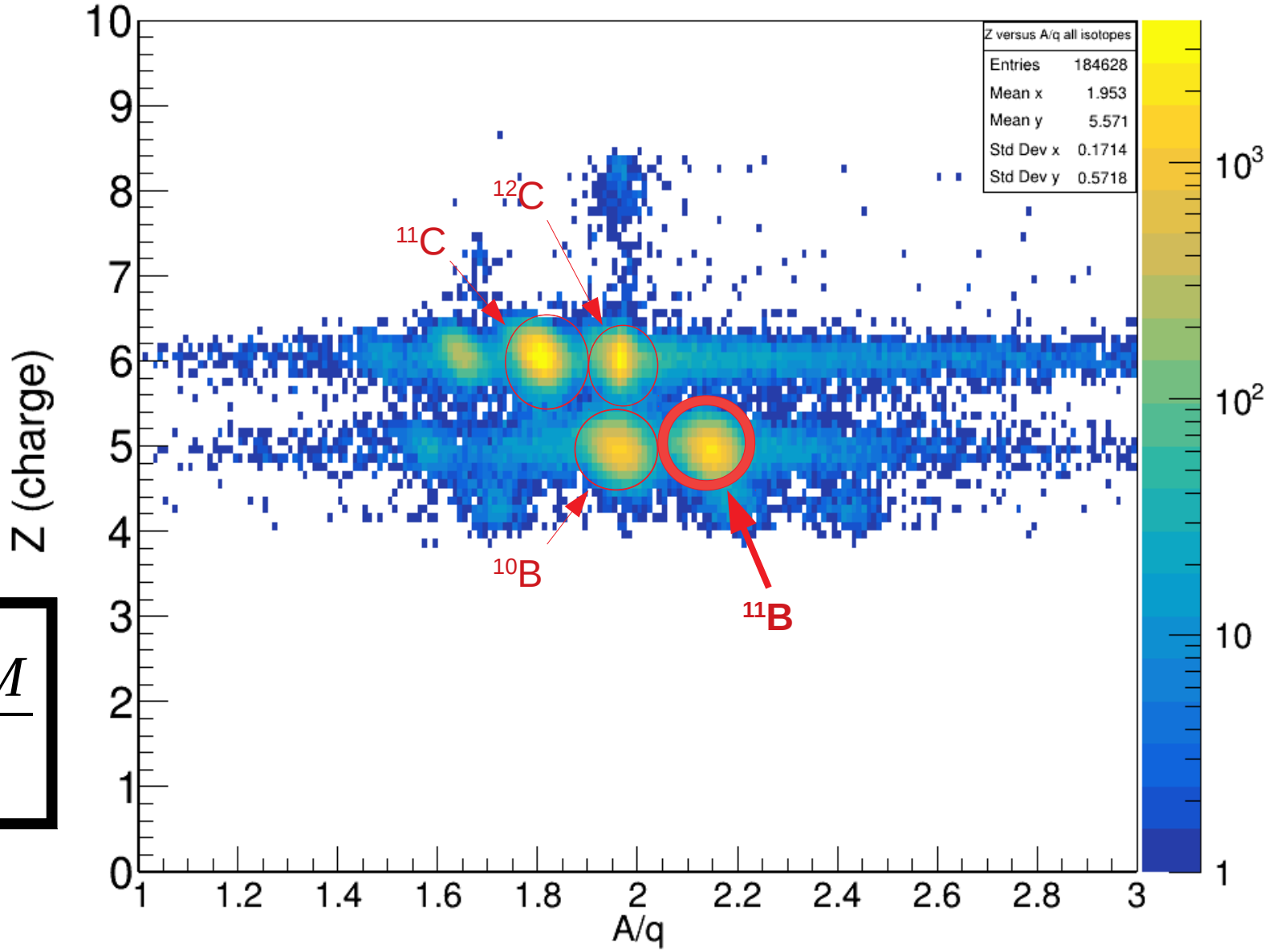
Flightpath reconstruction:



Radius reconstruction:

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

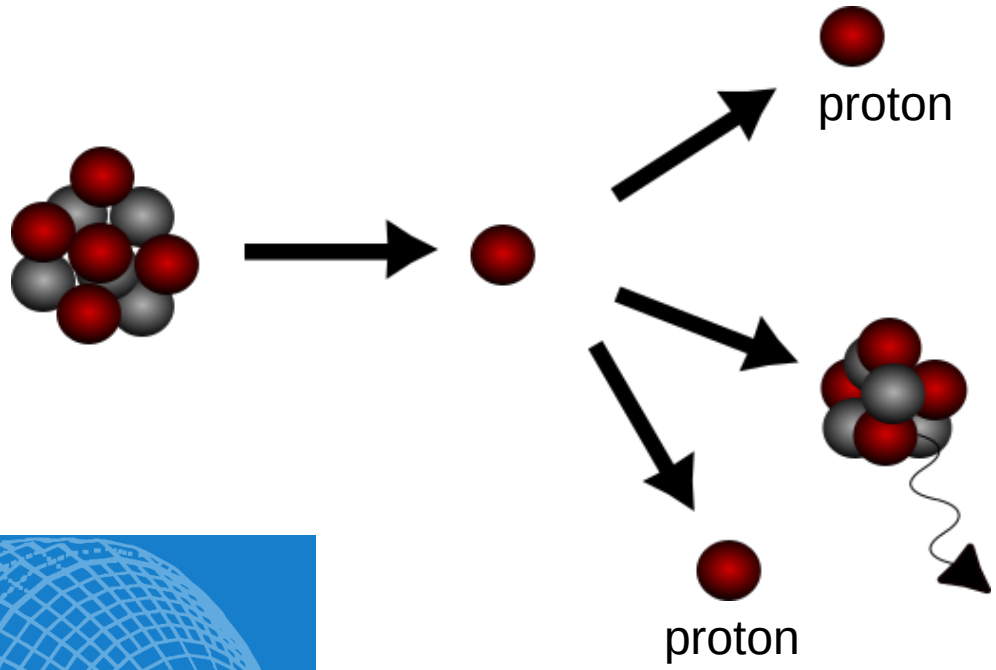
$$B * \rho = \frac{\beta * \gamma * M}{q}$$

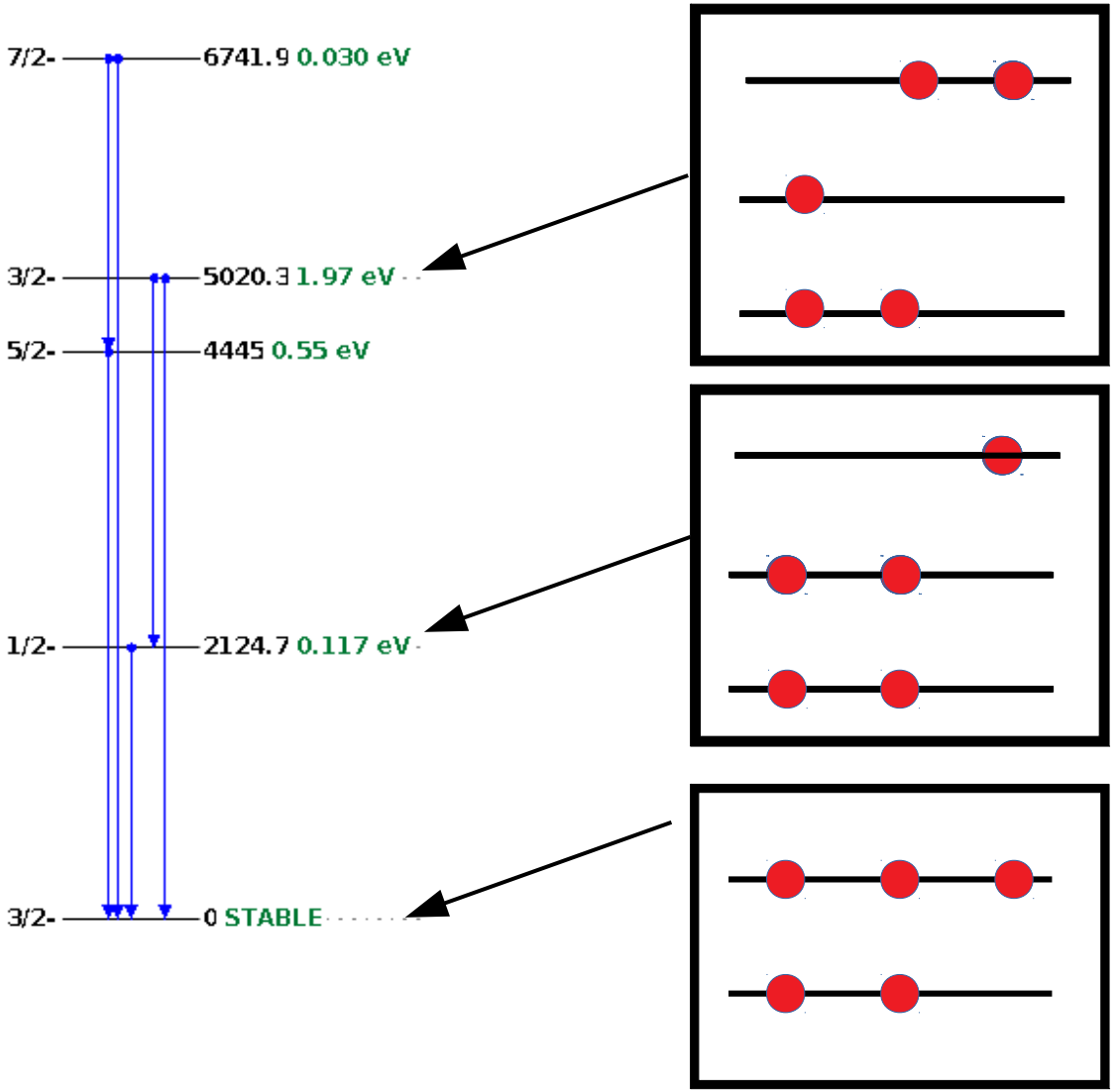


12C(p,2p)11B reaction

Two Proton Identification:

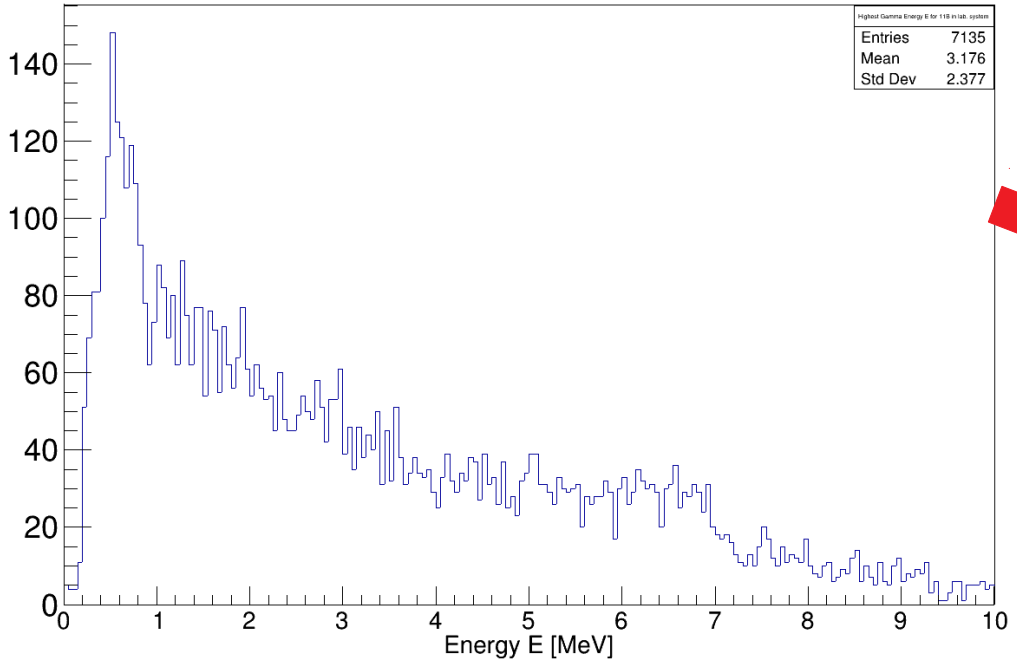
→ two hits with E_{hit} > 30 MeV





Gamma Spectrum of 11B

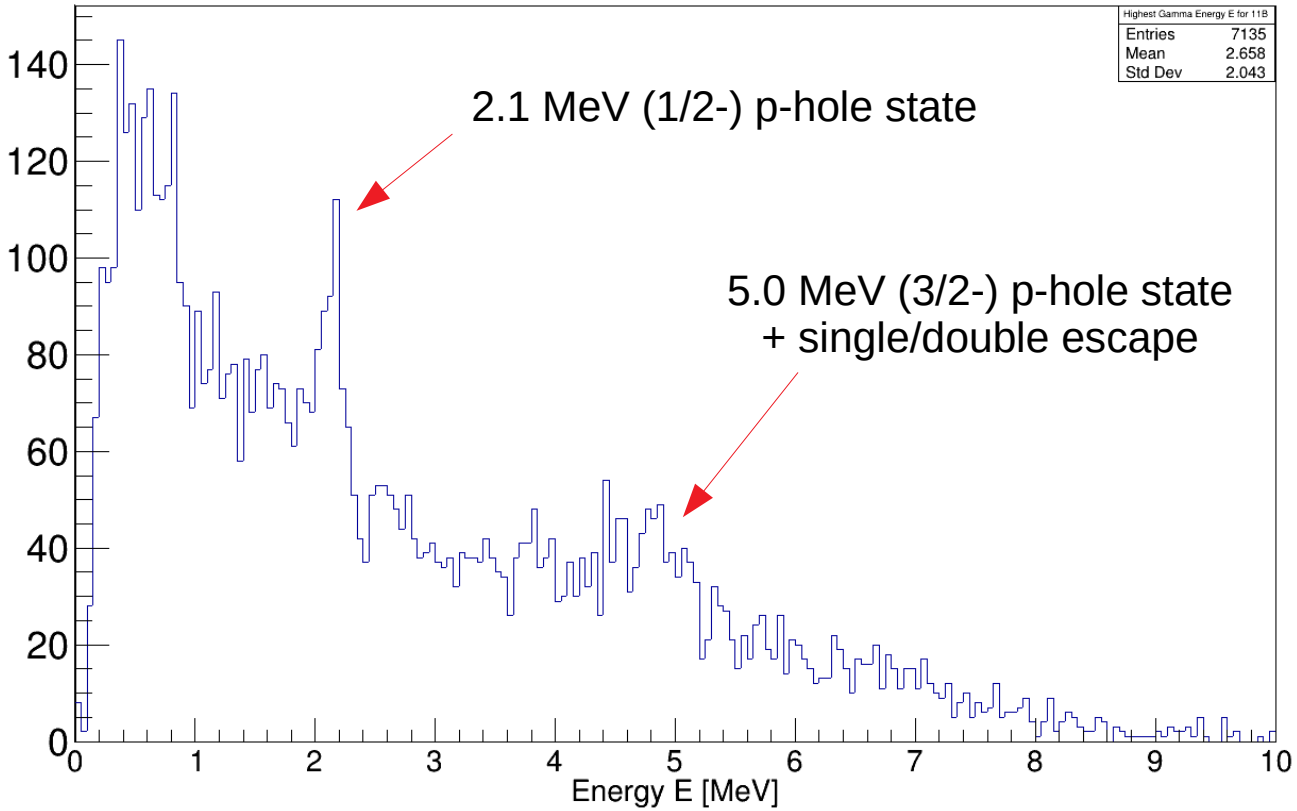
laboratory system

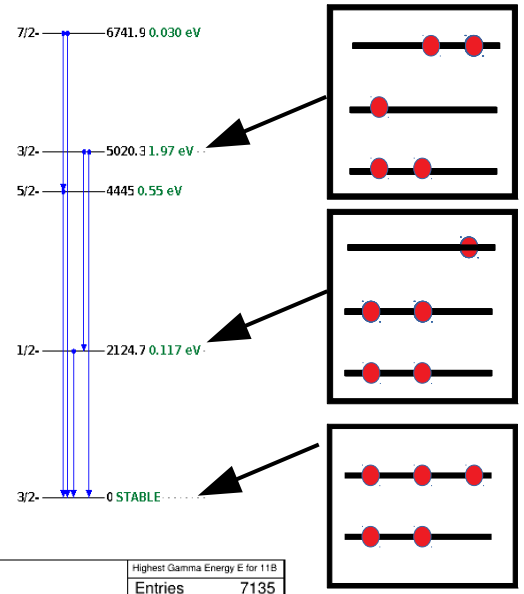


Doppler Correction:

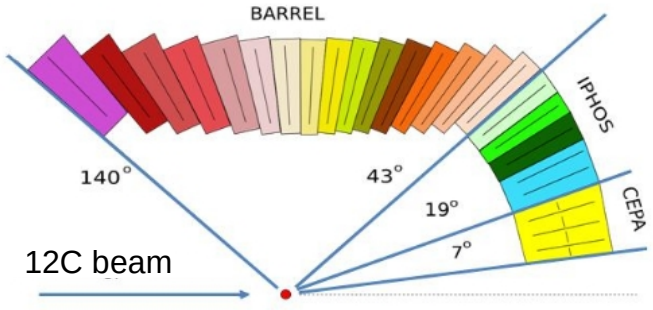
$$E_\gamma = \gamma E_{lab}\left(1-\beta\cos\left(\theta\right)\right)$$

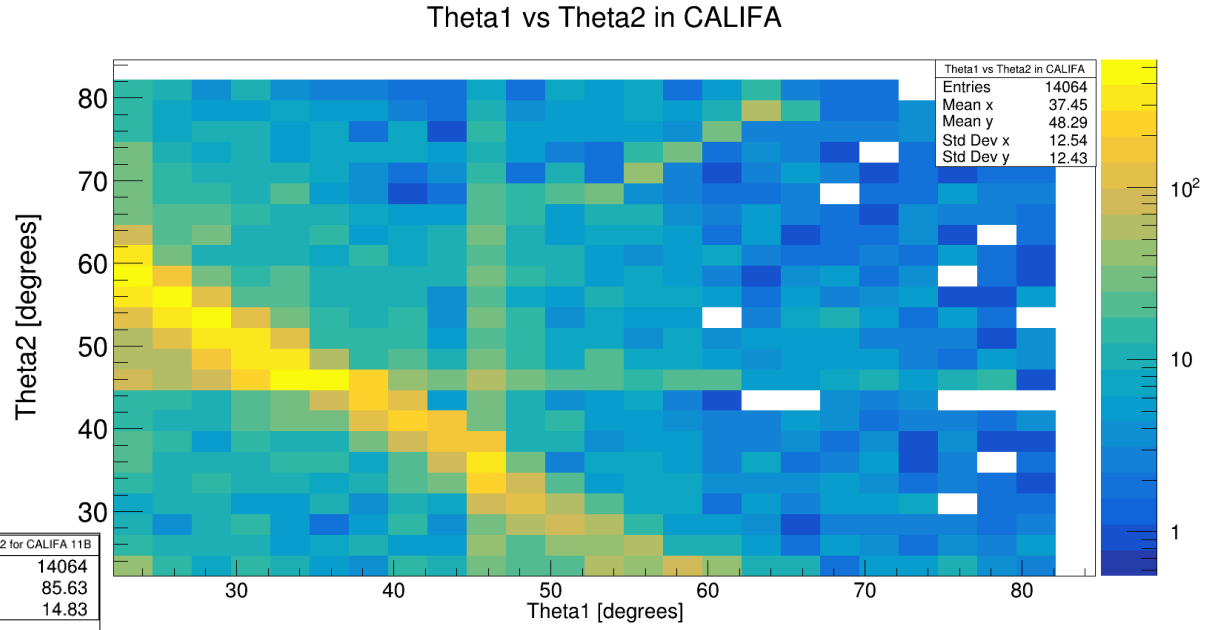
^{11}B rest frame

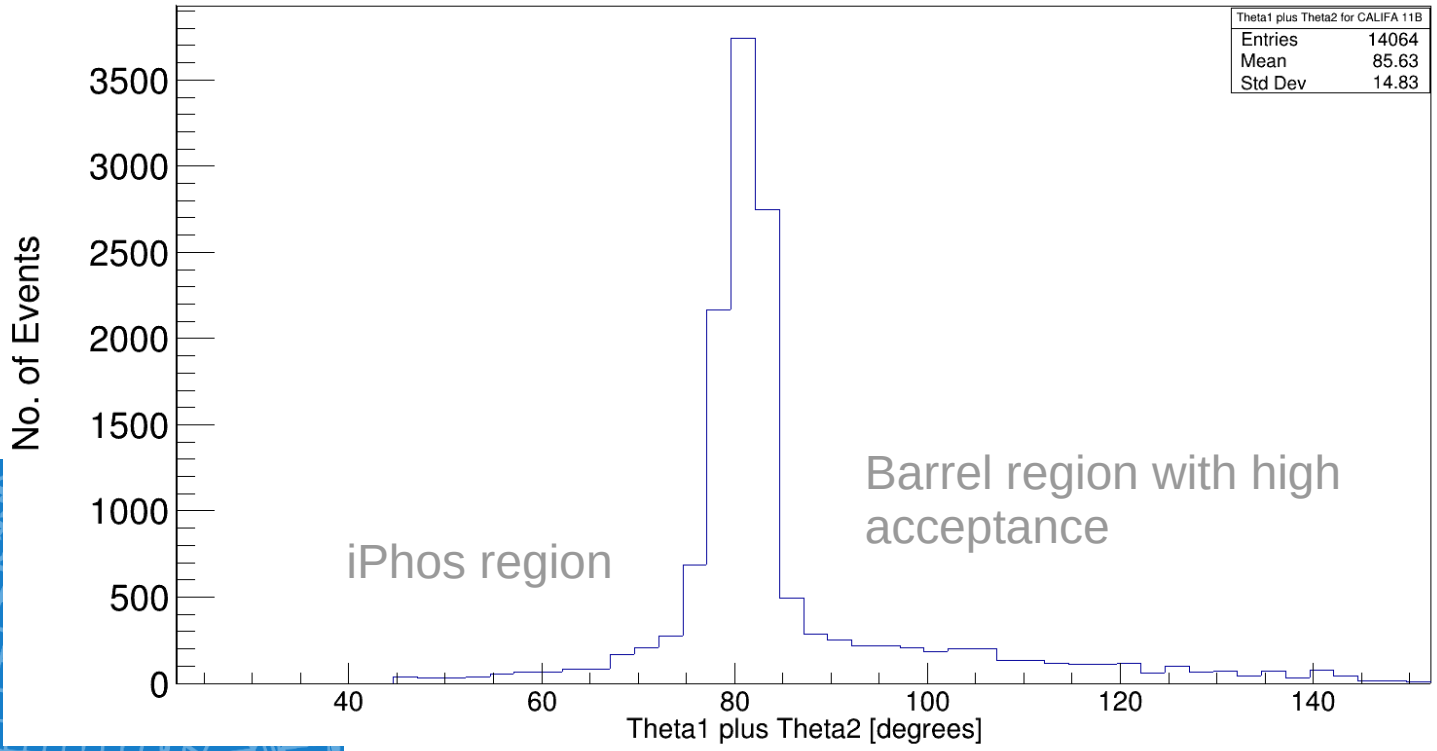


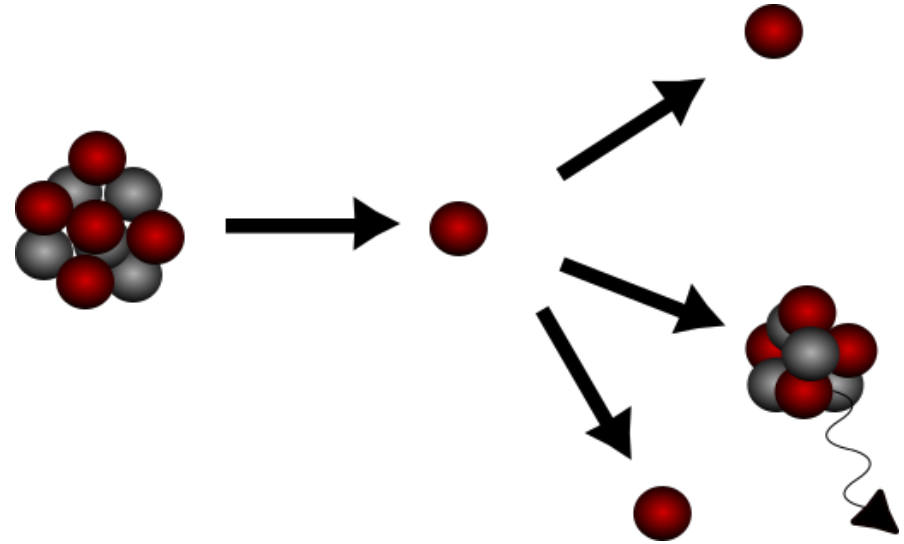


Polar Angular Distribution of protons for 12C(p,2p)11B

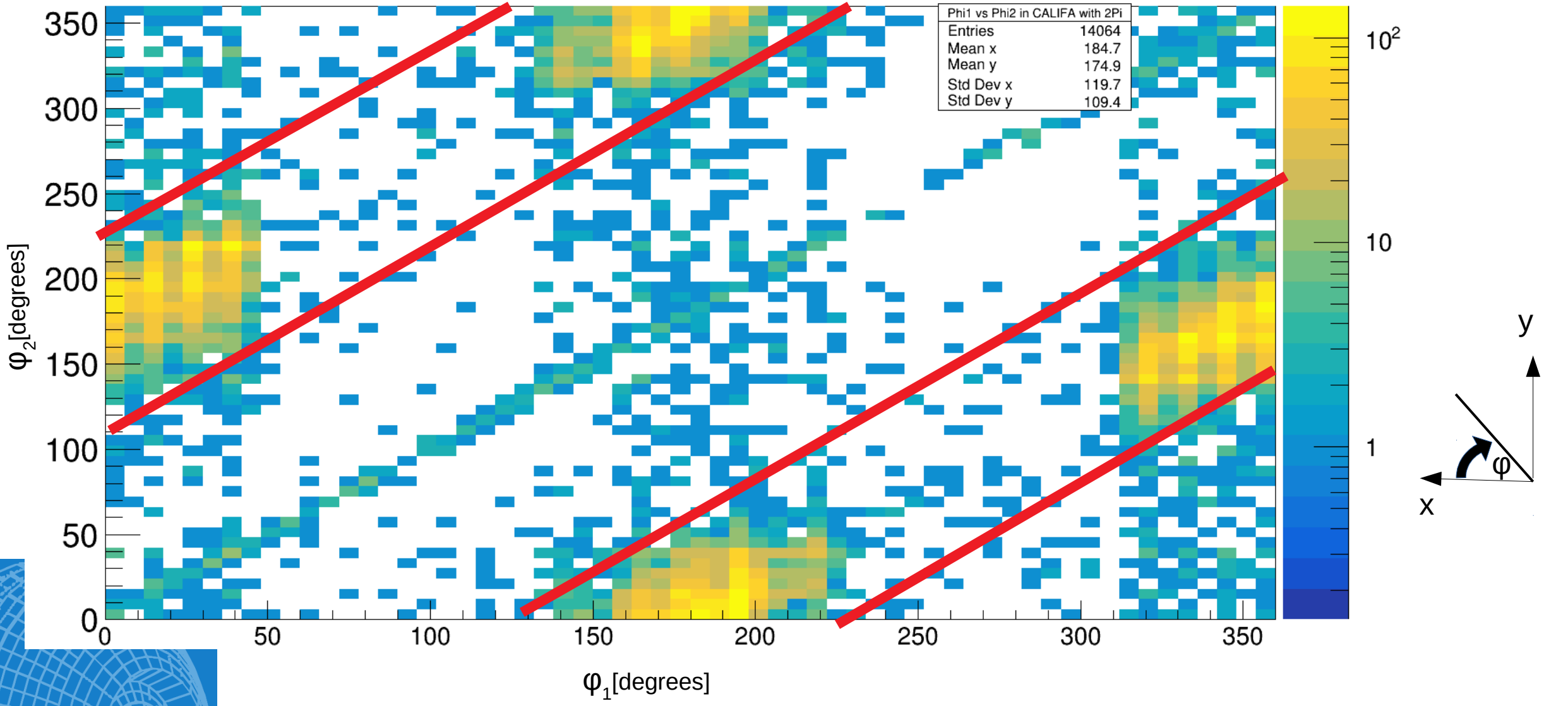








Arzimuthal Distribution of protons for 12C(p,2p)11B



Gamma Spectrum with Angular Cuts

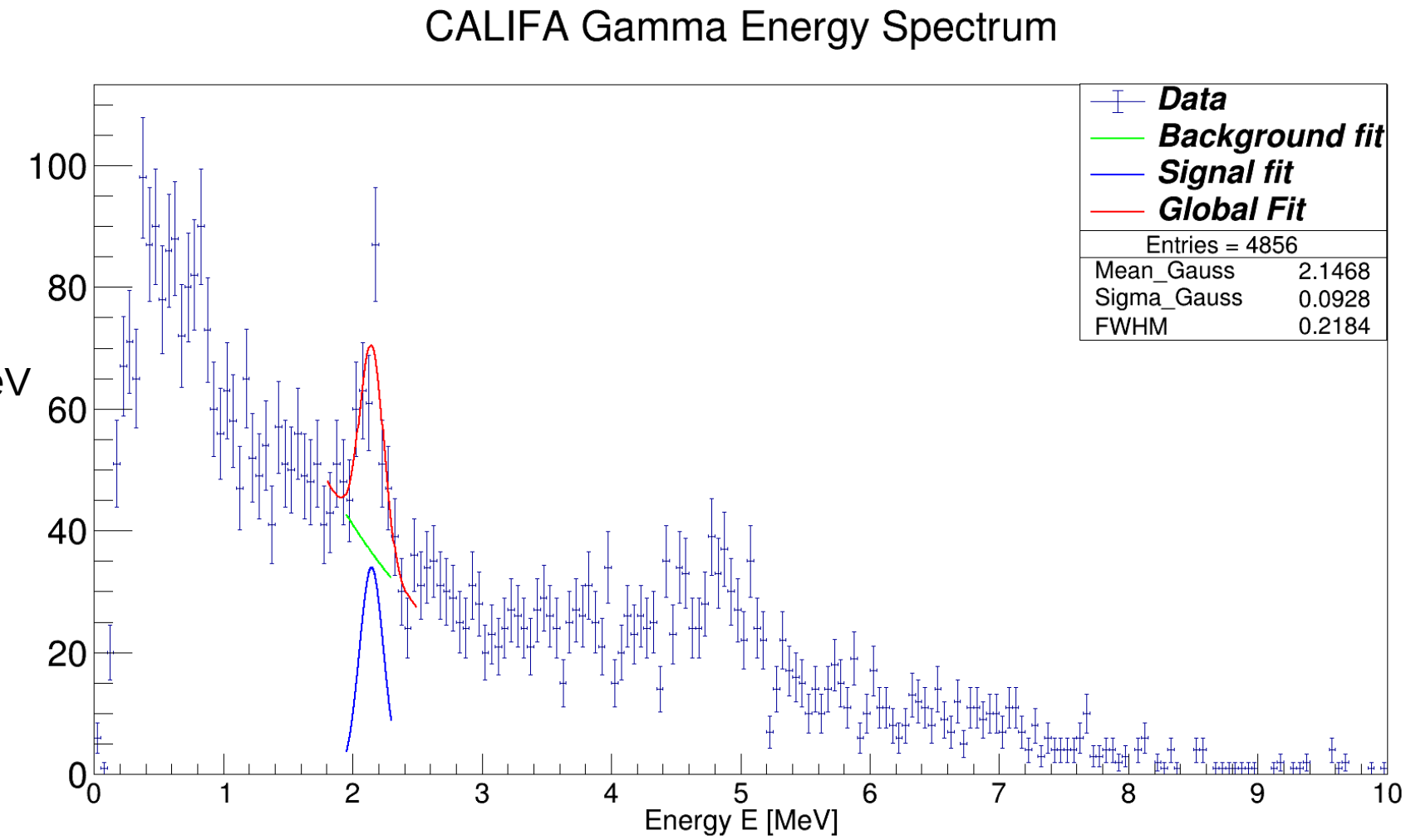
Event selection criteria for CALIFA:

→ 11B fragment identification

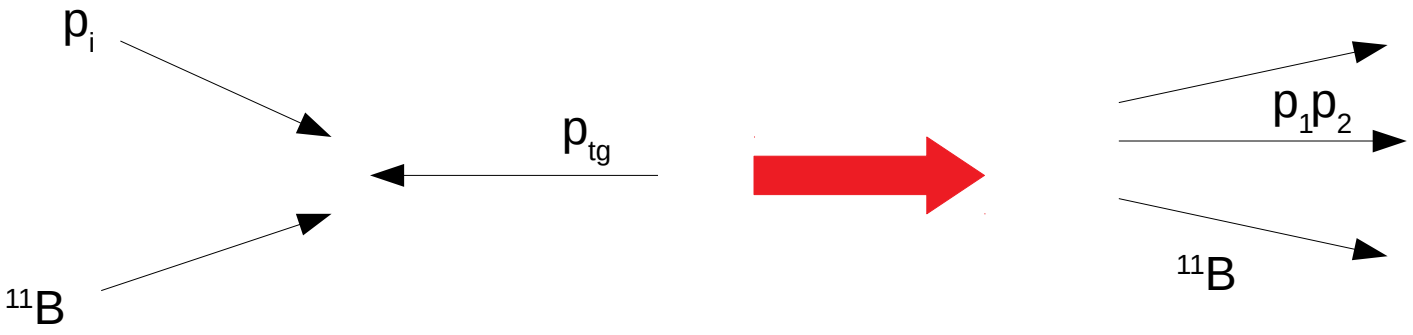
→ two hits (protons) with E_{hit} > 30 MeV

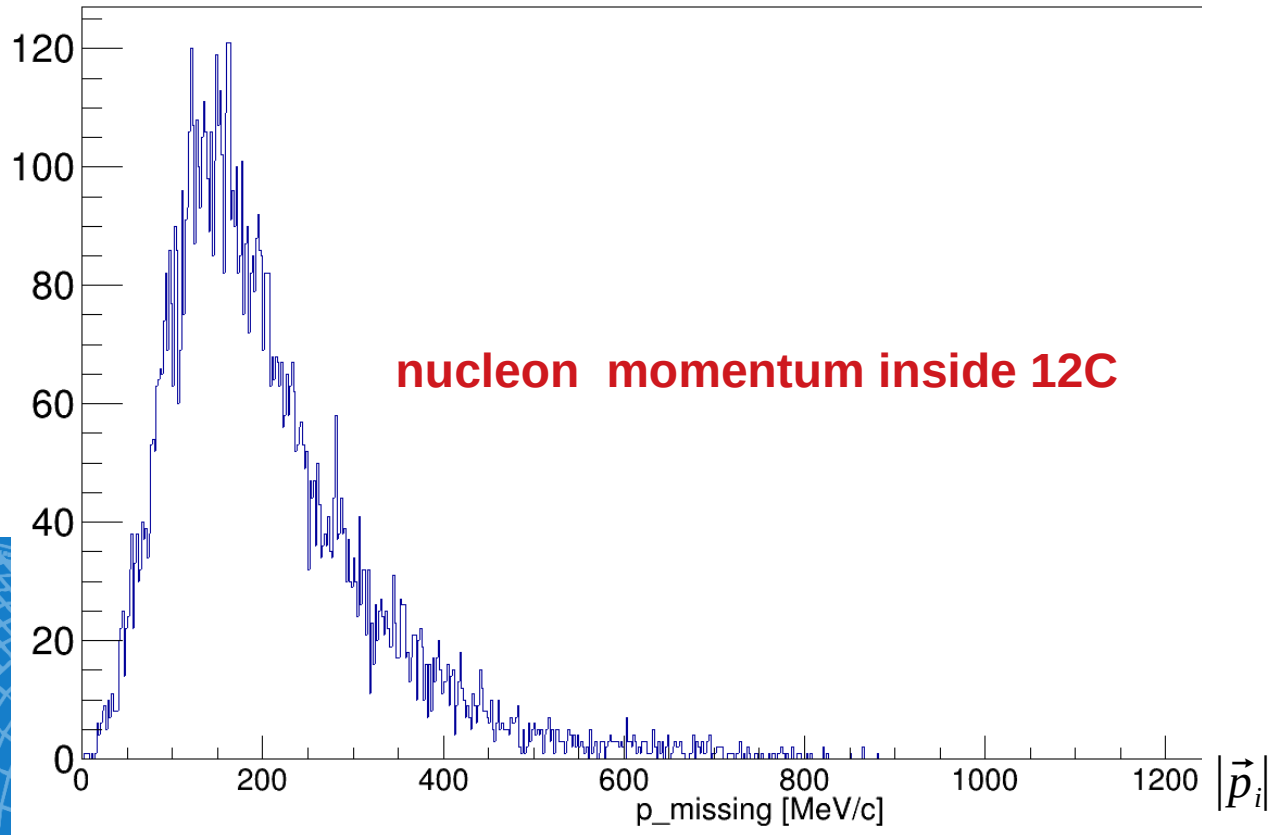
→ θ1 + θ2 < 90°

→ Δφ = 180° +- 40°



Reconstruction of Inner Momenta





nucleon momentum inside 12C

Momentum conservation relation:

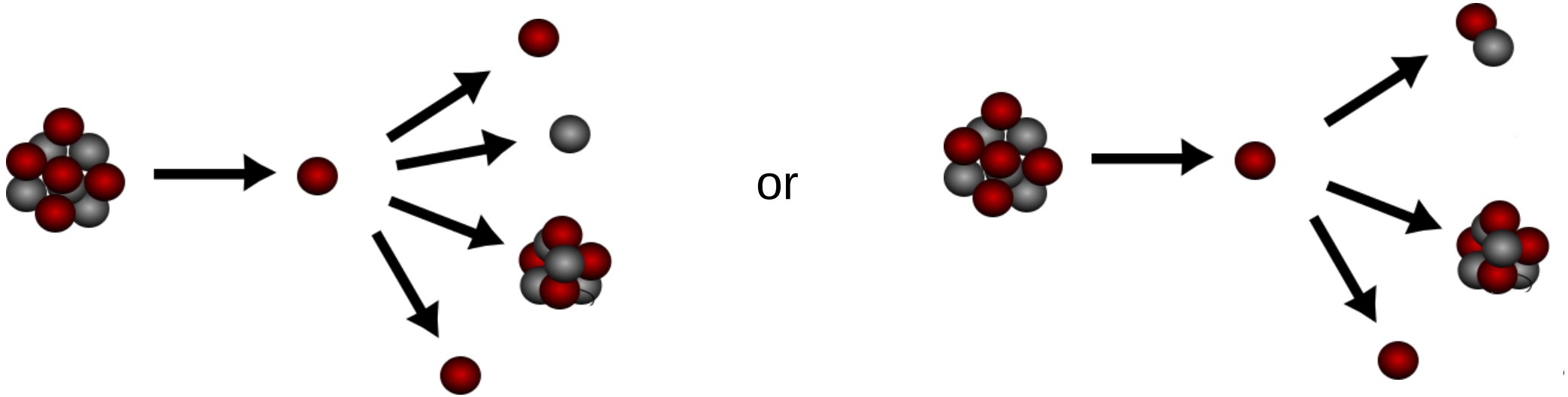
$$\boldsymbol{p}_{12\,C} + \boldsymbol{p}_{tg} = \boldsymbol{p}_1 + \boldsymbol{p}_2 + \boldsymbol{p}_{11\,B}$$

assuming QE scattering in mean field potential:

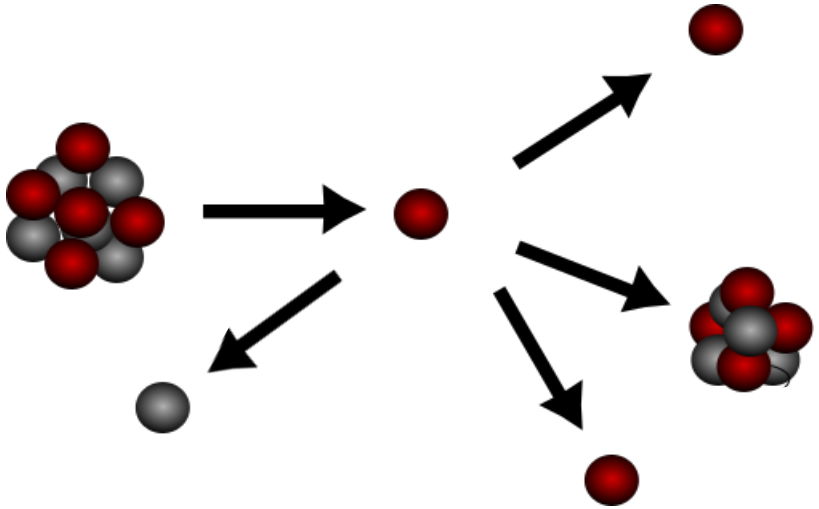
$$\boldsymbol{p}_{12\,C} = \boldsymbol{p}_i + \boldsymbol{p}_{11\,B}$$

$$\boldsymbol{p}_i \approx \boldsymbol{p}_{missing} = \boldsymbol{p}_1 + \boldsymbol{p}_2 - \boldsymbol{p}_{tg} \left(no\ ISI\,/\,FSI \right)$$

12C(p,ppn/pd)10B Reaction



12C(p,ppn/pd)10B Reaction

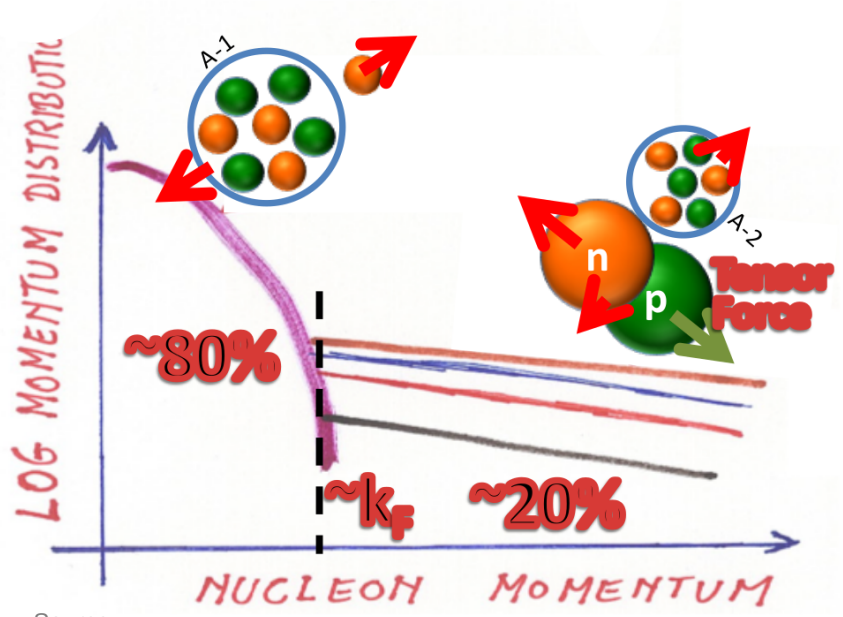


Short Range Correlations (SRC):

→ 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

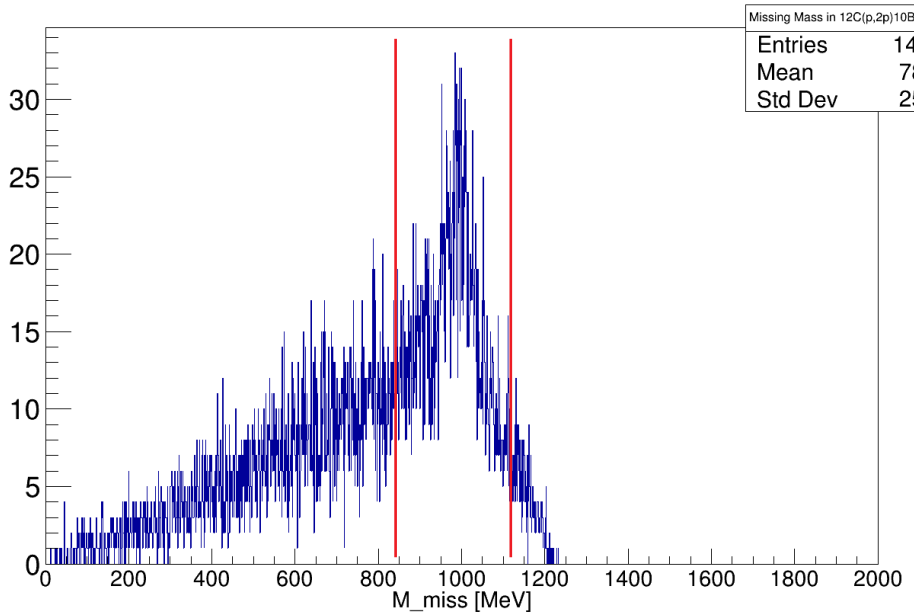


Source: https://www.int.washington.edu/talks/WorkShops/int_18_2a/People/Hen_O/Hen.pdf

First Angular and Momentum Plots …

Making cut on the reconstructed neutron:

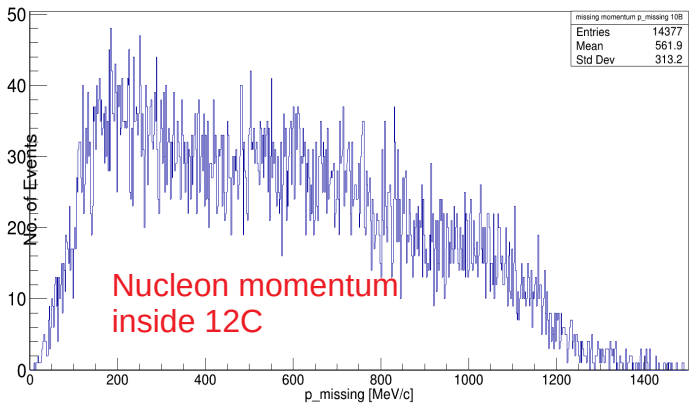
$$M^2_{missing} = (p_{12C} + p_{tg} - p_1 - p_2 - p_{10B})$$



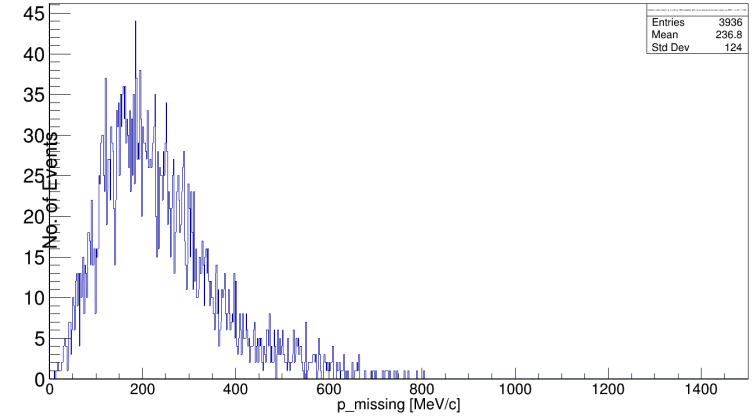
$M_{missing}$ cut

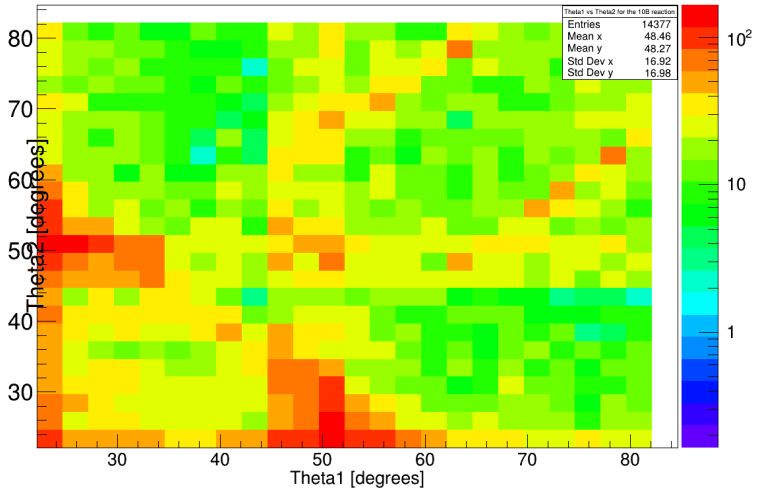
850 MeV < $M_{missing}$ < 1100 MeV

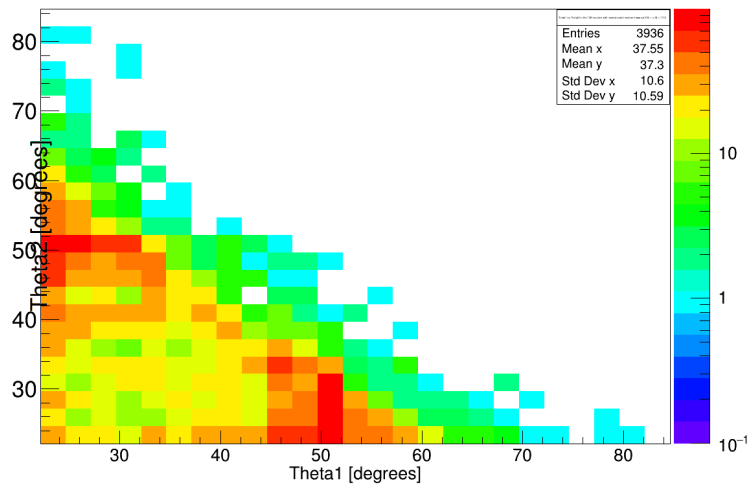
Without cut:



With reconstructed neutron mass cut:



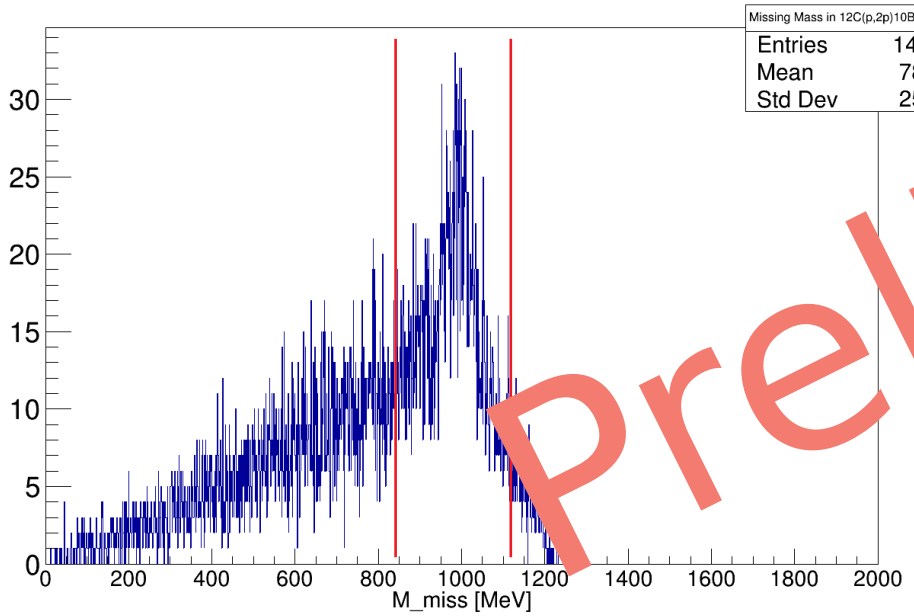




First Angular and Momentum Plots …

Making cut on the reconstructed neutron:

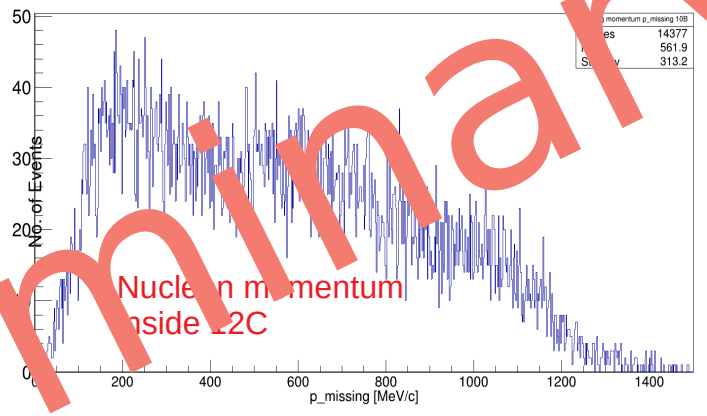
$$M^2_{missing} = (p_{12C} + p_{tg} - p_1 - p_2 - p_{10B})$$



$M_{missing}$ cut

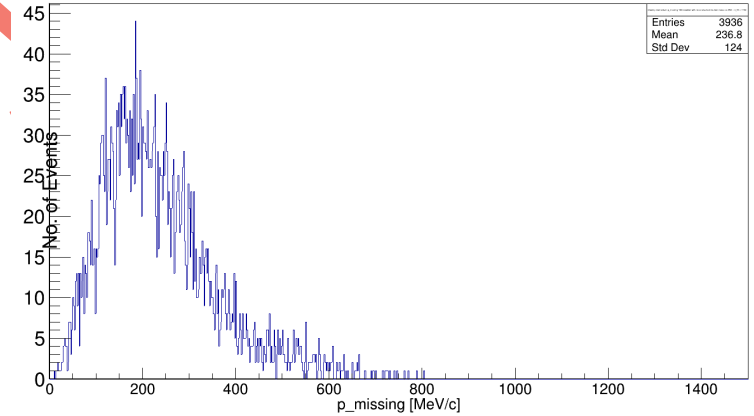
850 MeV < $M_{missing}$ < 1100 MeV

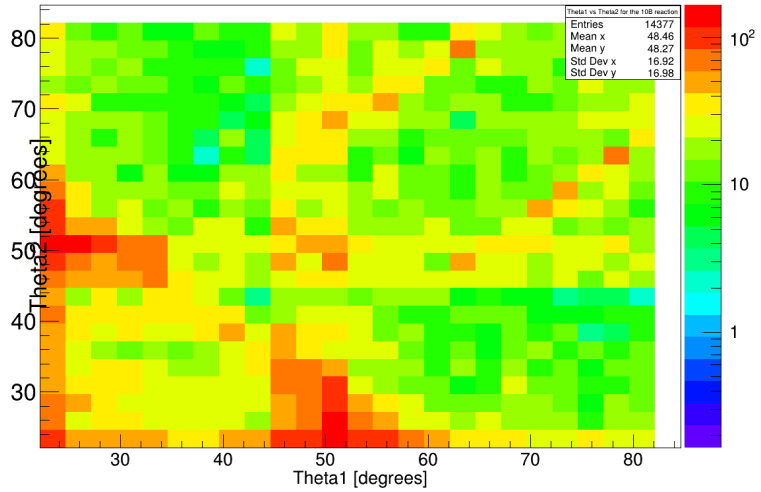
Without cut:

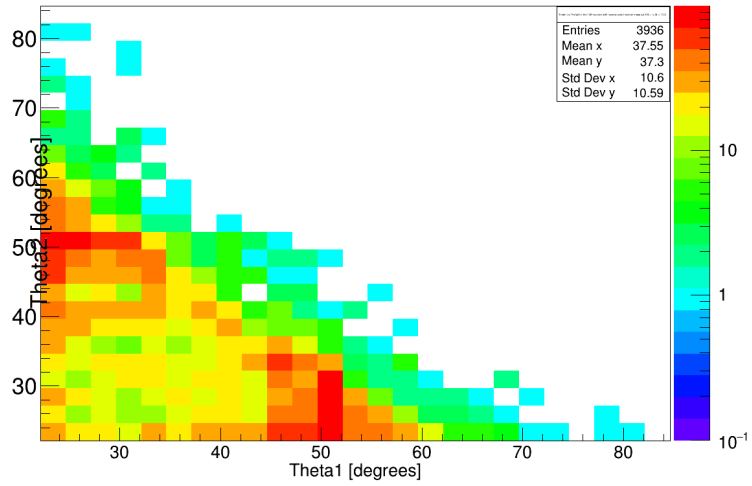


Nucleon momentum inside 12C

With reconstructed neutron mass cut:

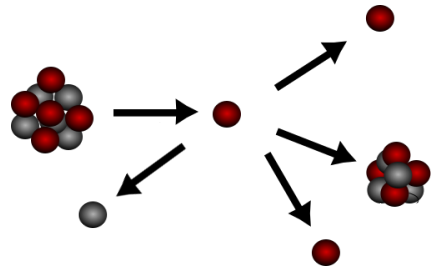




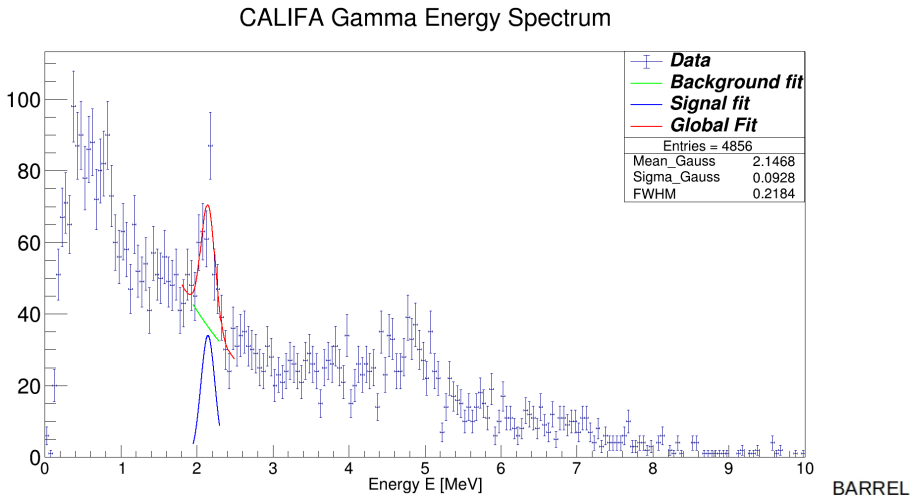


Summary & Outlook

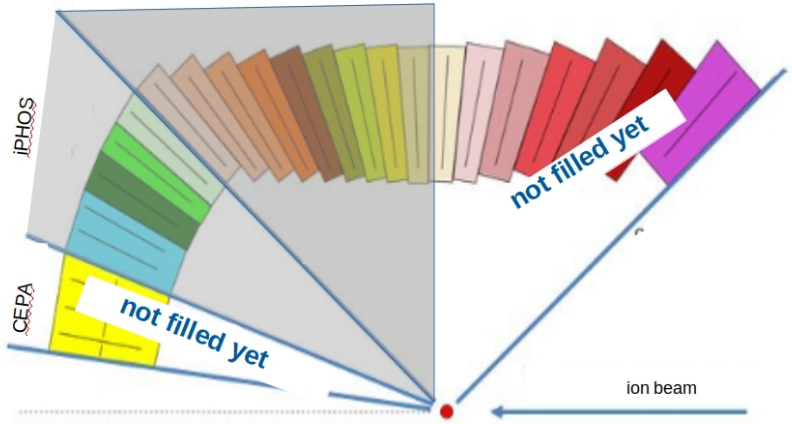
→ further investigations for the 12C(p,ppn/pd)10B reaction channel needed



→ promising first analysis results from 12C(p,2p)11B 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)

Roman Gernhäuser, Lukas Ponnath, Philipp Klenze, Tobias Jenegger

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Backup

CALIFA Doppler reconstruction

High and well-defined segementation

→ Doppler reconstruction

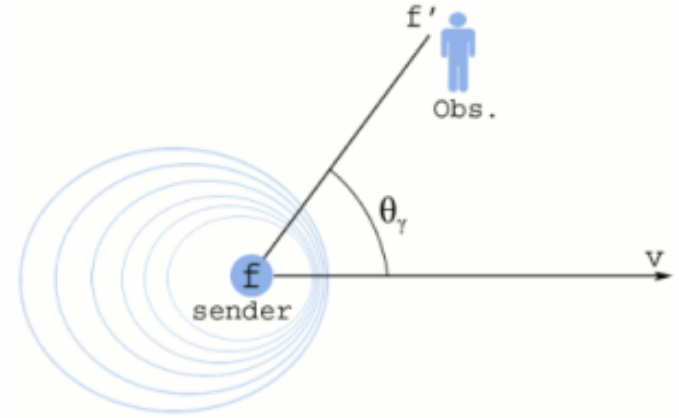
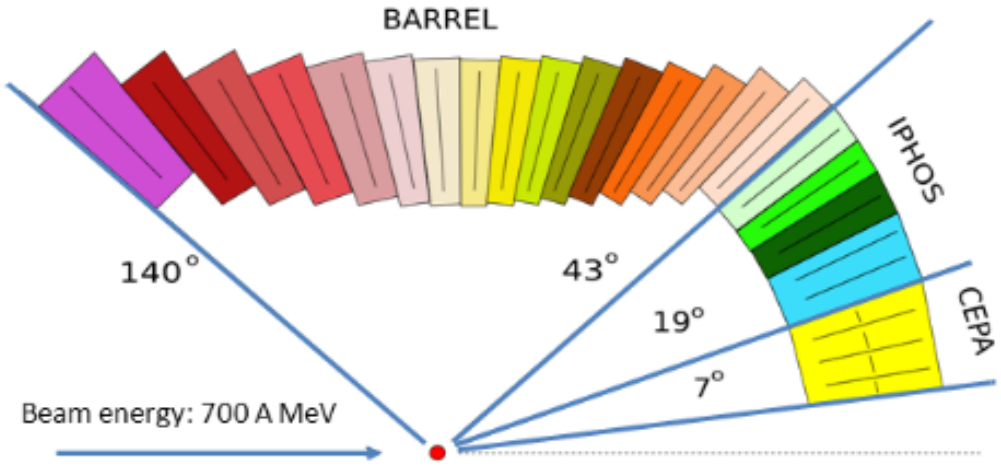
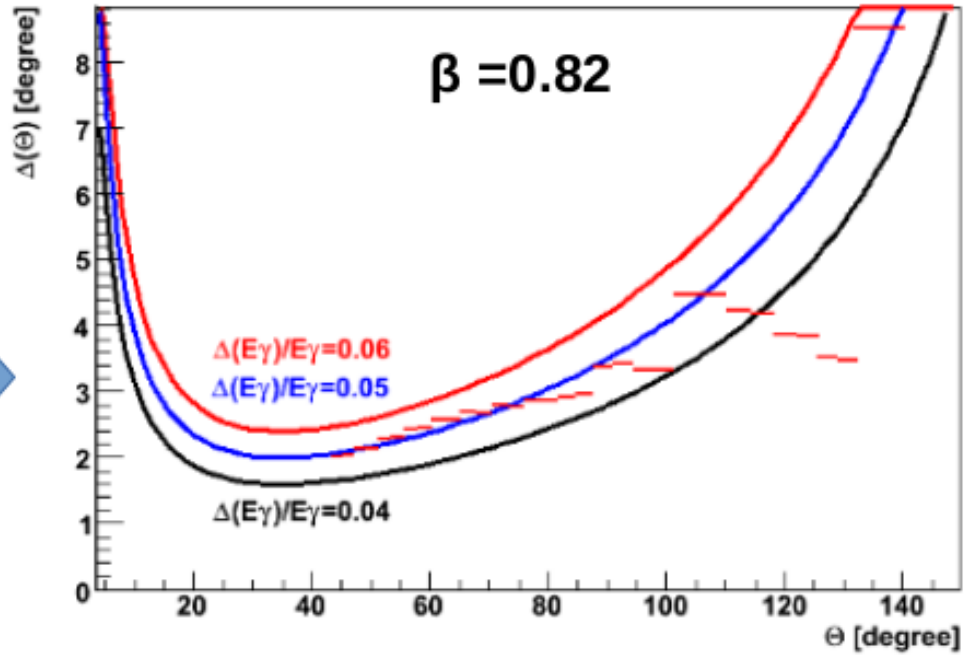


Figure taken from [1]

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

→ shape and angles of crystals provide constant relative resolution:





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