Cherenkov light in vacuum beam monitors for crystal-assisted beam manipulations

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OUTLINE

- √ A briefly introduction on crystal channeling
- √ The CpFM for Crystal assisted collimation in the UA9 experiment
  - √ CpFM requirements and layout.
  - √ CpFM commissioning during operations: first functionality test and detector characterization.
  - √ CpFM in situ ri-calibration.
- √ The Slow Extraction CpFM for Slow crystal assisted extraction @ SPS
  - √ SE-CpFM requirements and layout.
  - √ SE-CpFM: calibration of the whole detection chain @ H8-SPS.
  - √ SE-CpFM first operation: results and outcomes

CRYSTAL CHANNELING

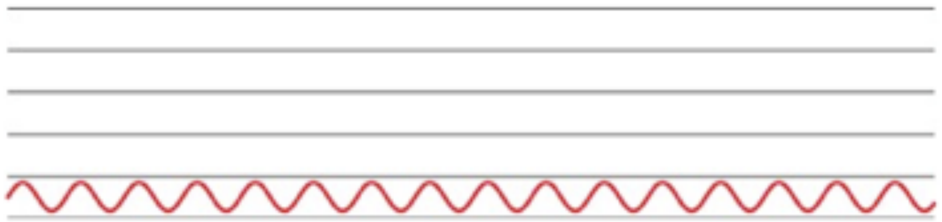
If the protons have $p_T < U_{max}$

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

Critical angle in Si

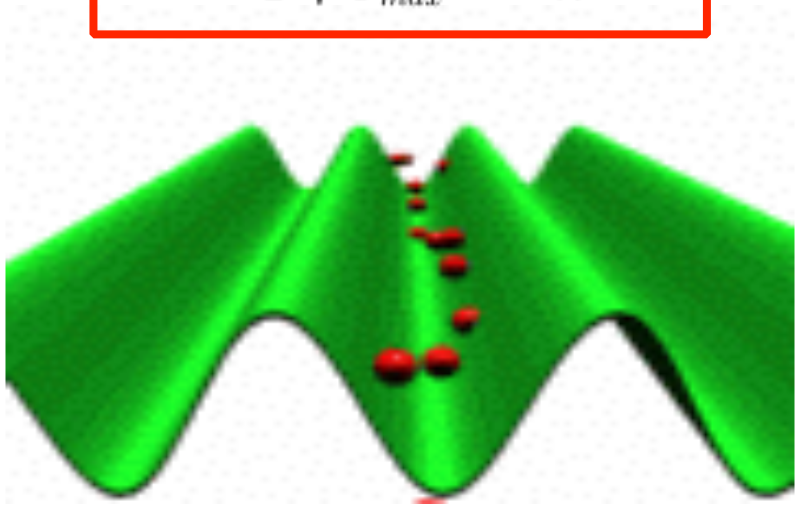
Case	Energy [GeV]	θ_c [μrad]	λ [μm]
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

Straight crystal: hadron "trapped" between planes

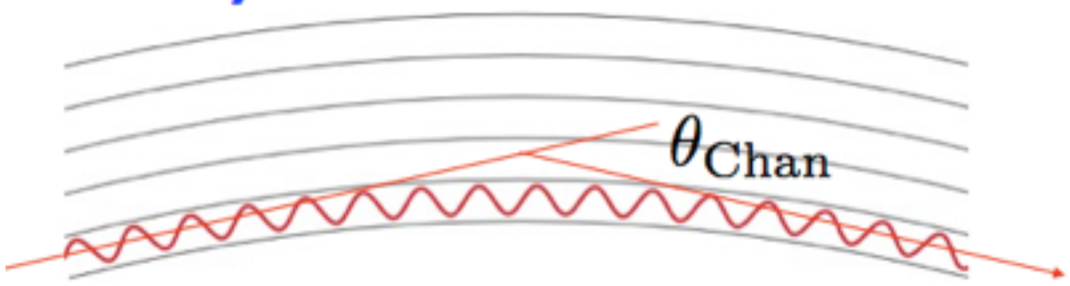


Forced to oscillate between crystalline planes

$$x(z) = \frac{d_p}{2}\sqrt{\frac{E_t}{U_{max}}}\sin(\frac{2\pi z}{\lambda} + \phi)$$



Bent crystal

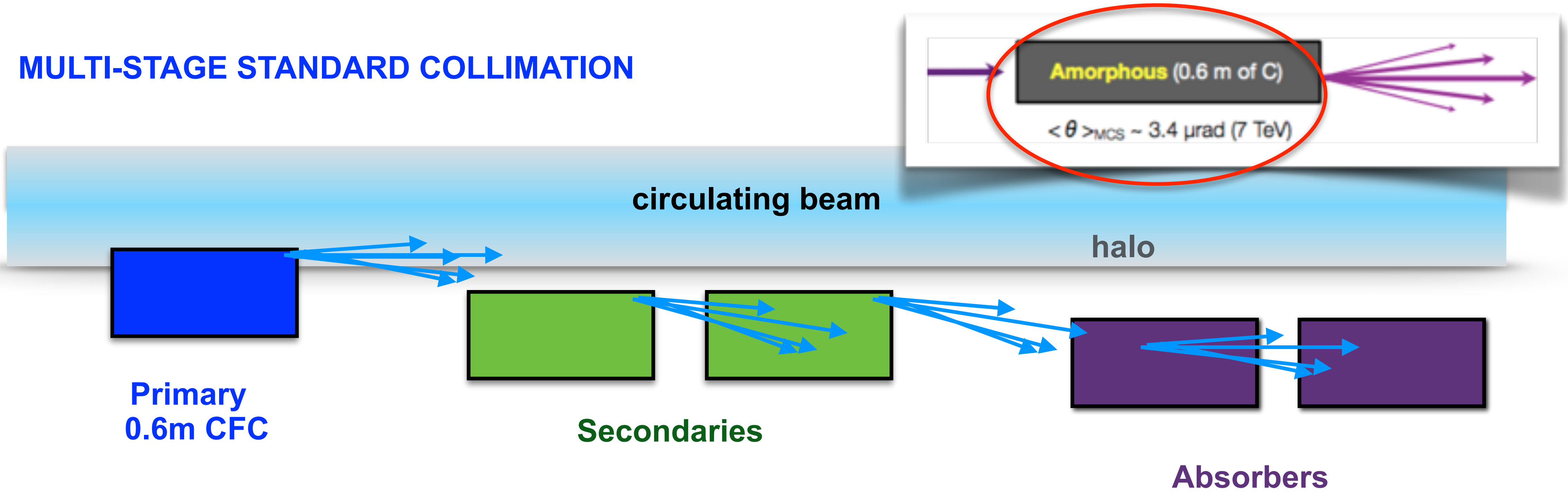


4 mm Si Crystal with a bending angle of 50urad produces the same kick of a 310T magnet!

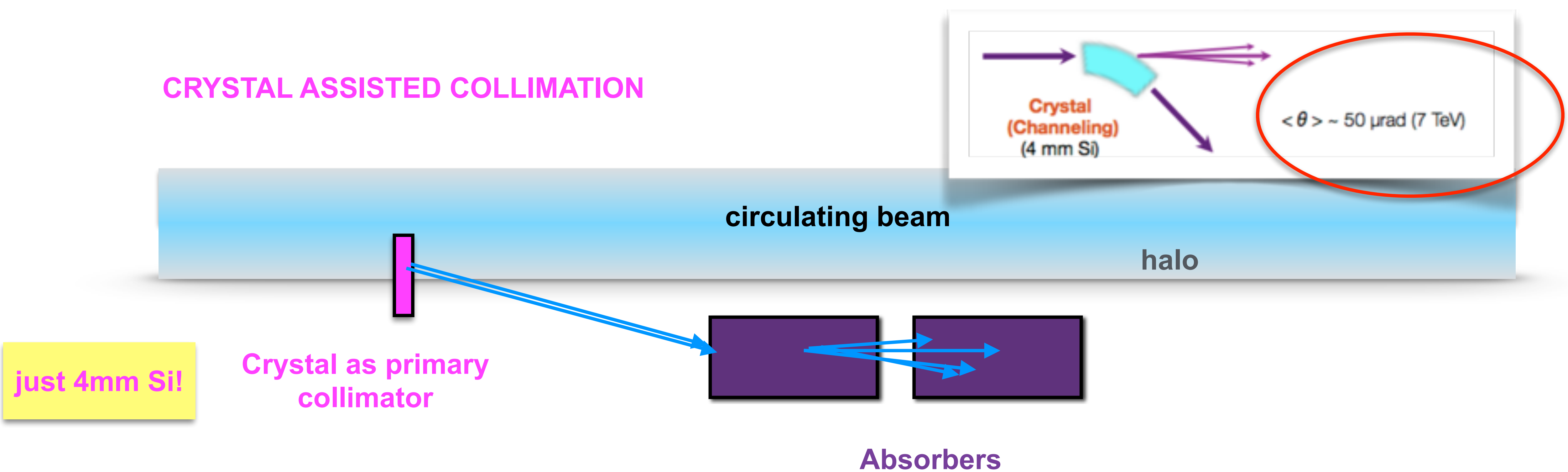
UA9 EXPERIMENT PURPOSE

The main purpose of UA9 experiment at CERN-SPS is to demonstrate the feasibility of a bent crystal assisted collimation for hadron colliders

MULTI-STAGE STANDARD COLLIMATION



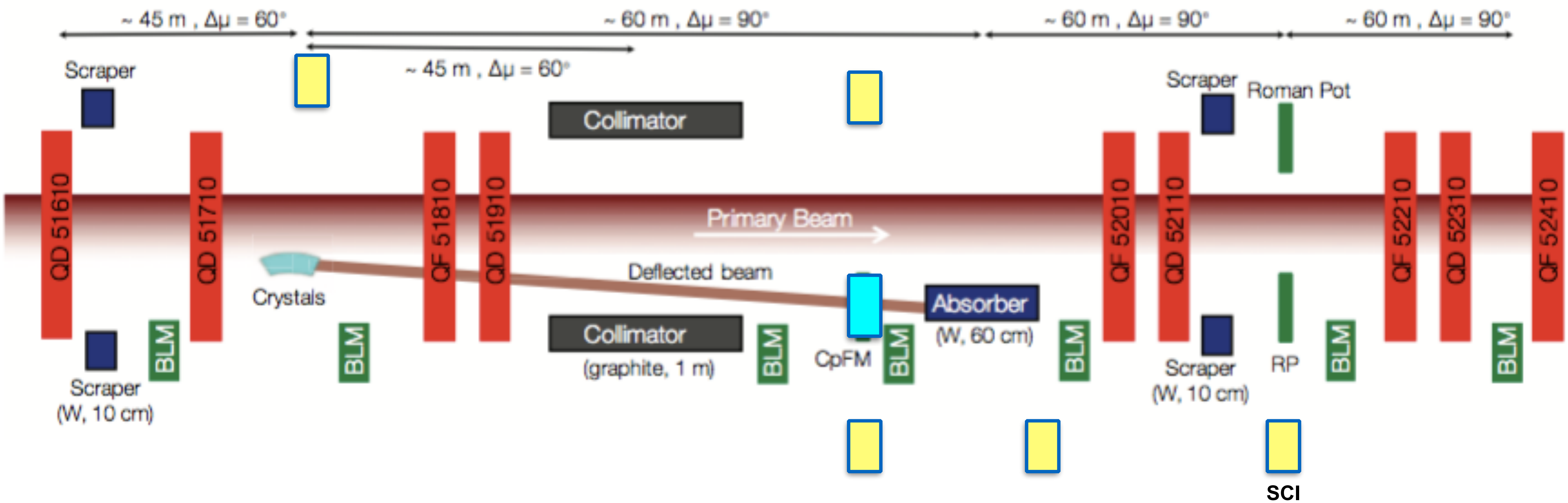
CRYSTAL ASSISTED COLLIMATION



The Cherenkov for proton Flux Measurement detector for UA9 experiment

THE CERENKOV proton Flux Measurement detector for UA9 experiment

To monitor the deflected halo a new concept in-vacuum detector is needed, sensitive to the single proton.

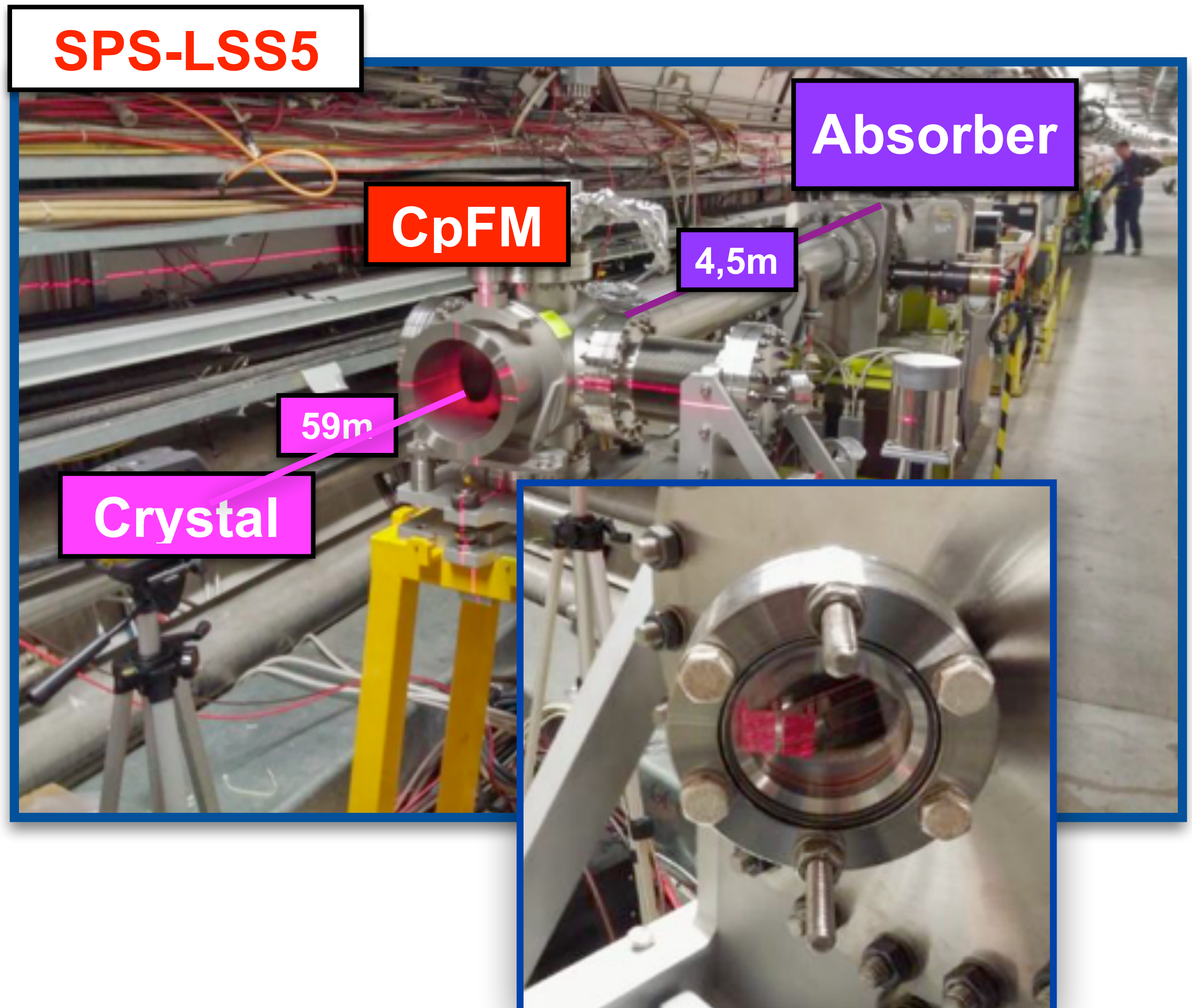


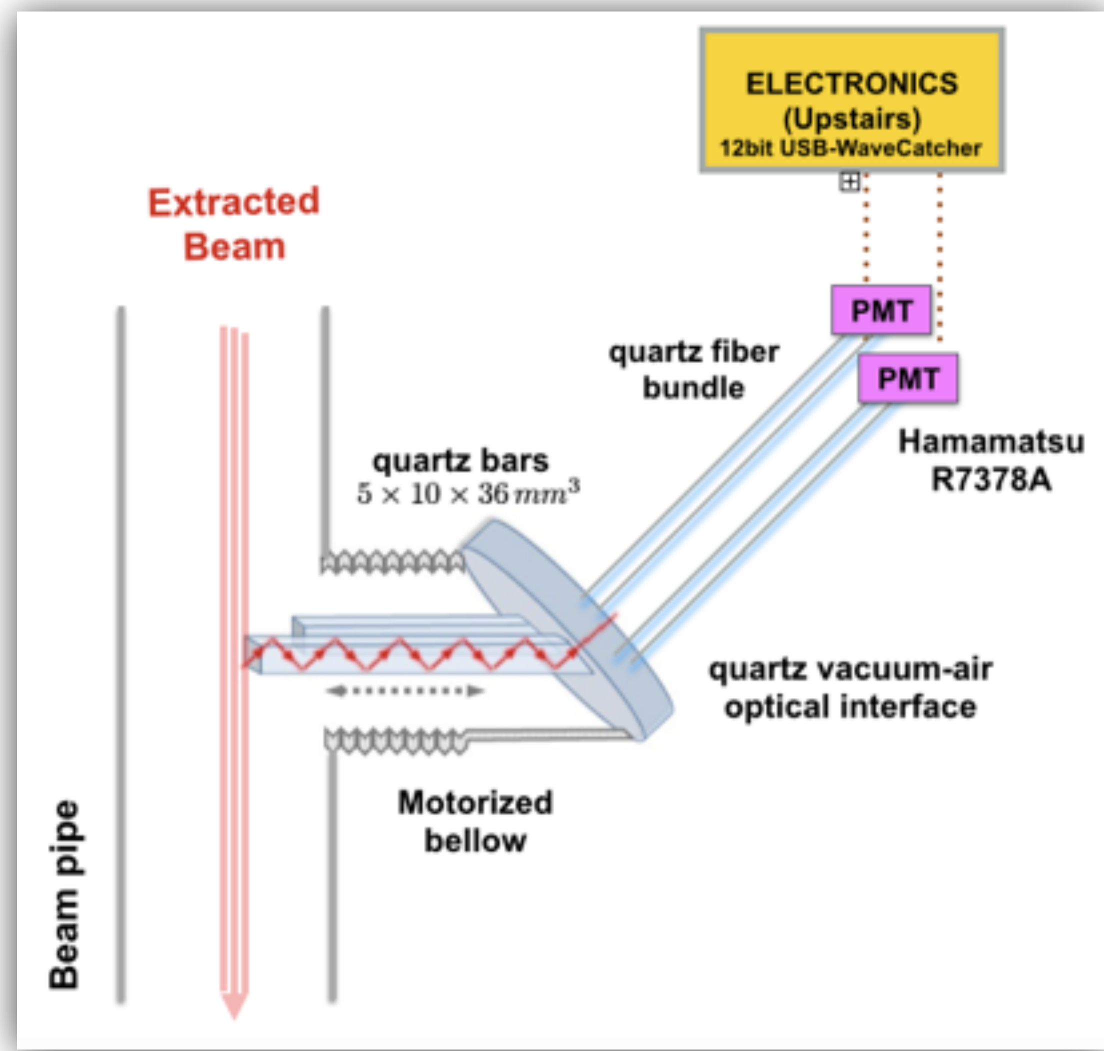
CpFM design requirements:

- materials with no degassing (location: inside the primary vacuum)
- Radiation hardness of the detection chain (~ 100 Gy, 10^12 1-MeV-eq. neutrons/cm^2 per year)
- Timing: 3 ns bunches, bunch spacing 25 ns
- Dynamic range: 1÷200 protons per pulse.
  (extracted ~ 10^5-10^7 protons/s; Trev = 23 μs)

The Cerenkov proton Flux Measurement detector for UA9 experiment

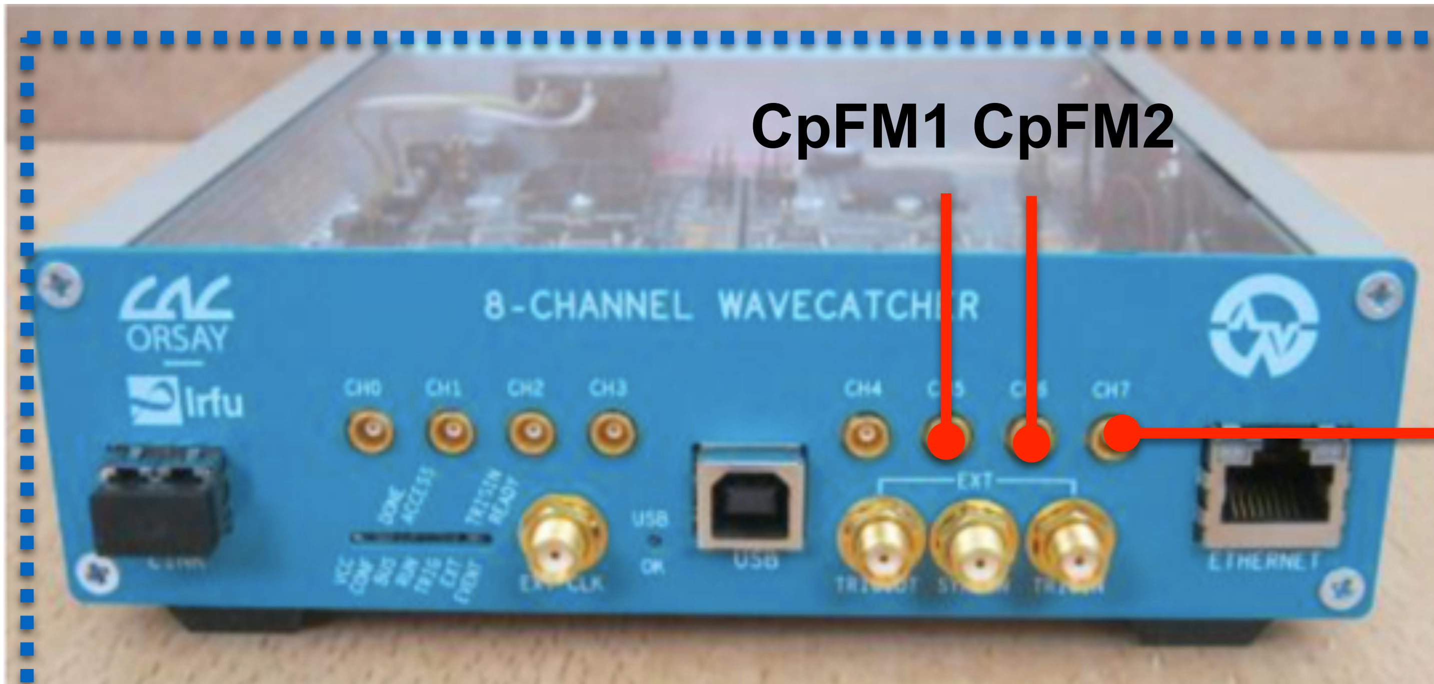
CpFM detector has been installed in UA9 experimental area in LSS5 since December 2014





Calibrated at BTF with 500MeV/c electrons: efficiency to single electron = 63%

CpFM READOUT ELECTRONICS AND DAQ SYSTEM



DOWN-SCALED 43 HZ TRIGGER

(Revolution freq signal)

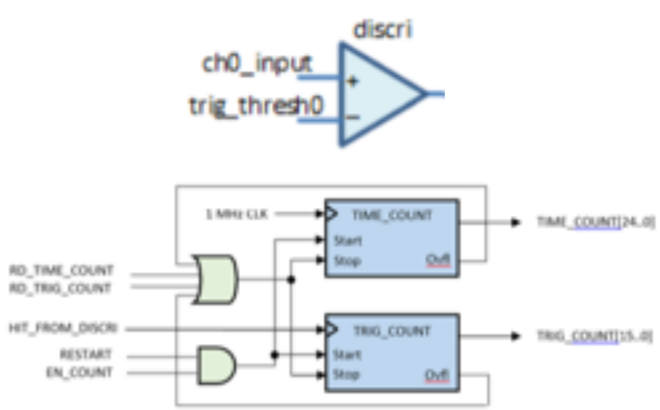
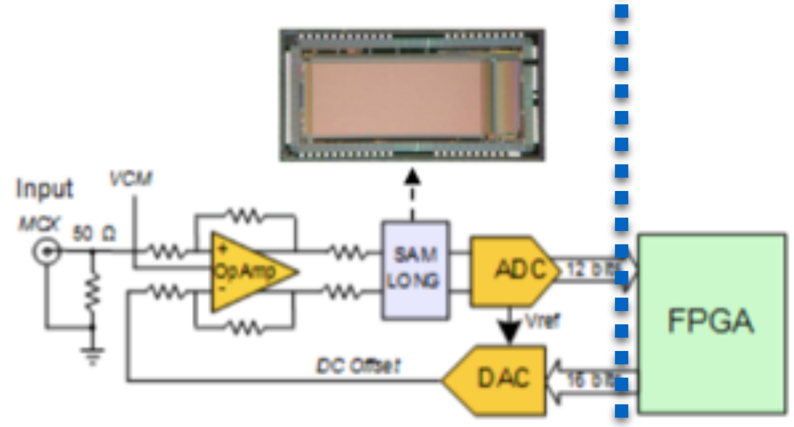


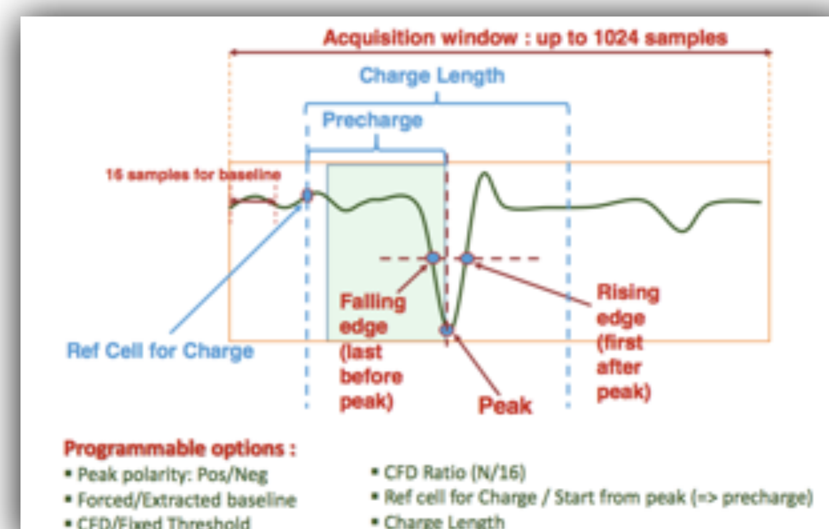
Figure 2.10: block diagram of the hit rate monitor

HIT MONITOR



WAVEFORM DIGITIZER + MB

MEASUREMENT BLOCK

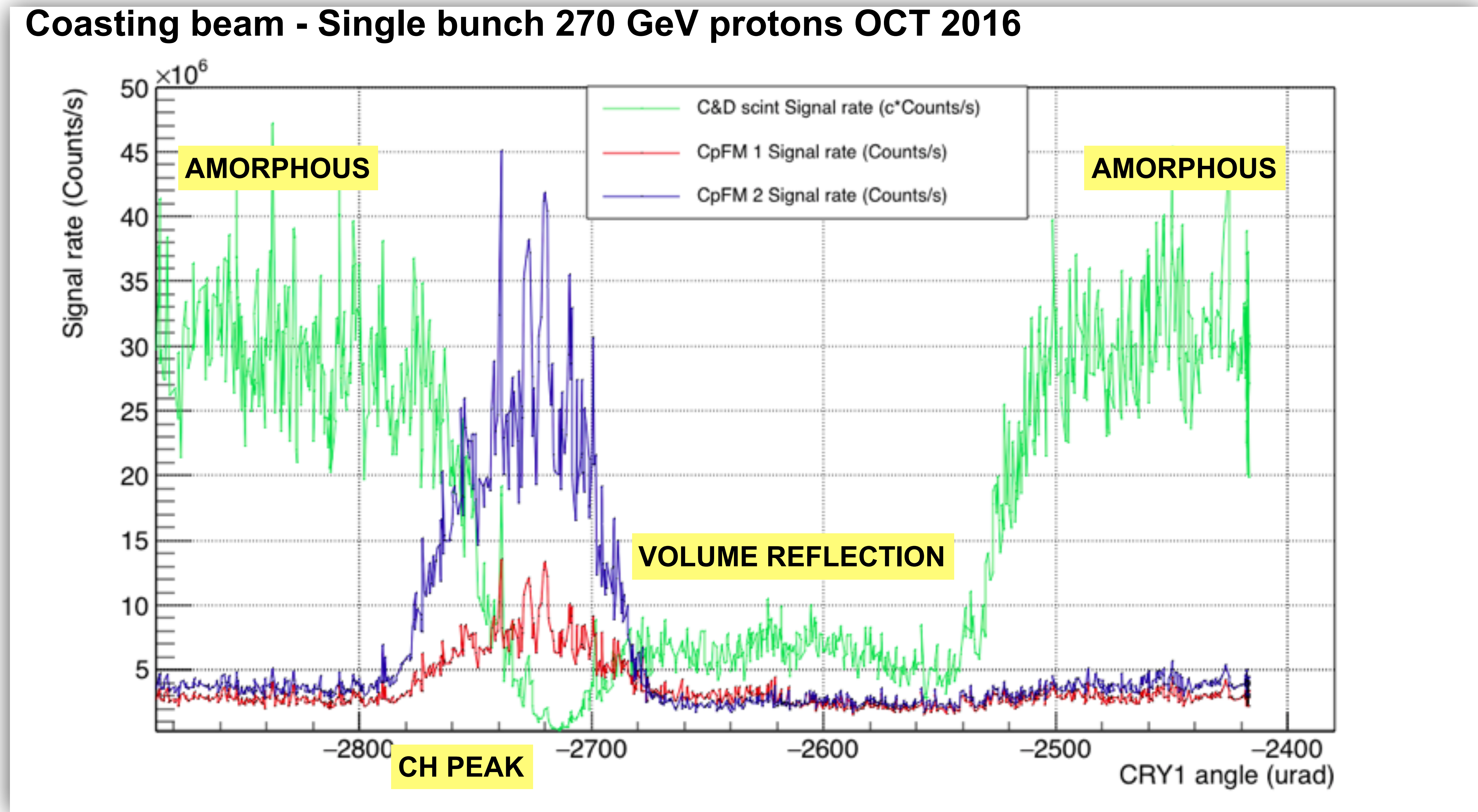


Programmable by the User

COUNTS/S

SAMPLED WF + INFORMATIONS FROM THE SIGNAL

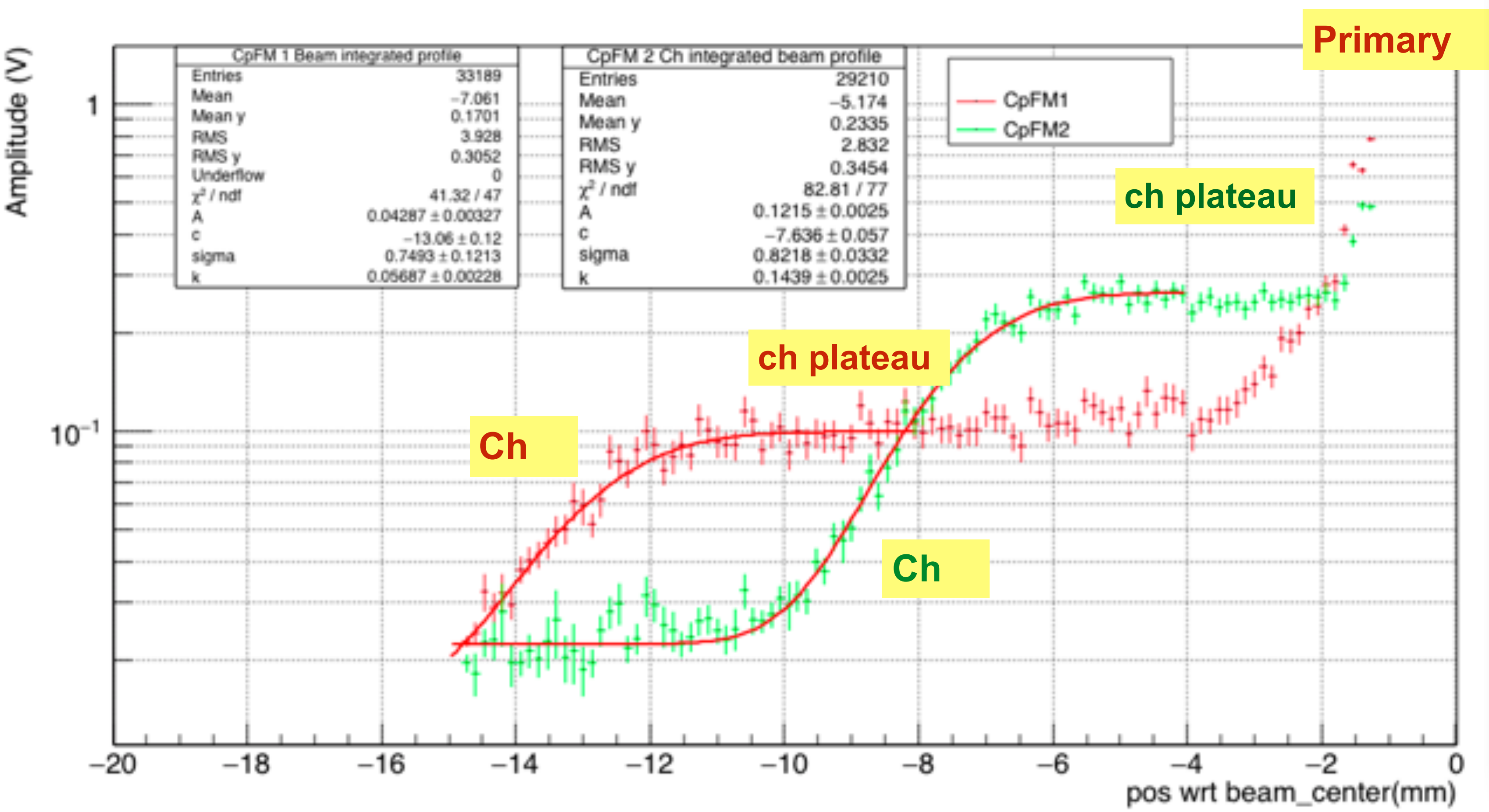
CpFM COMMISSIONING&OPERATION: ANGULAR SCAN

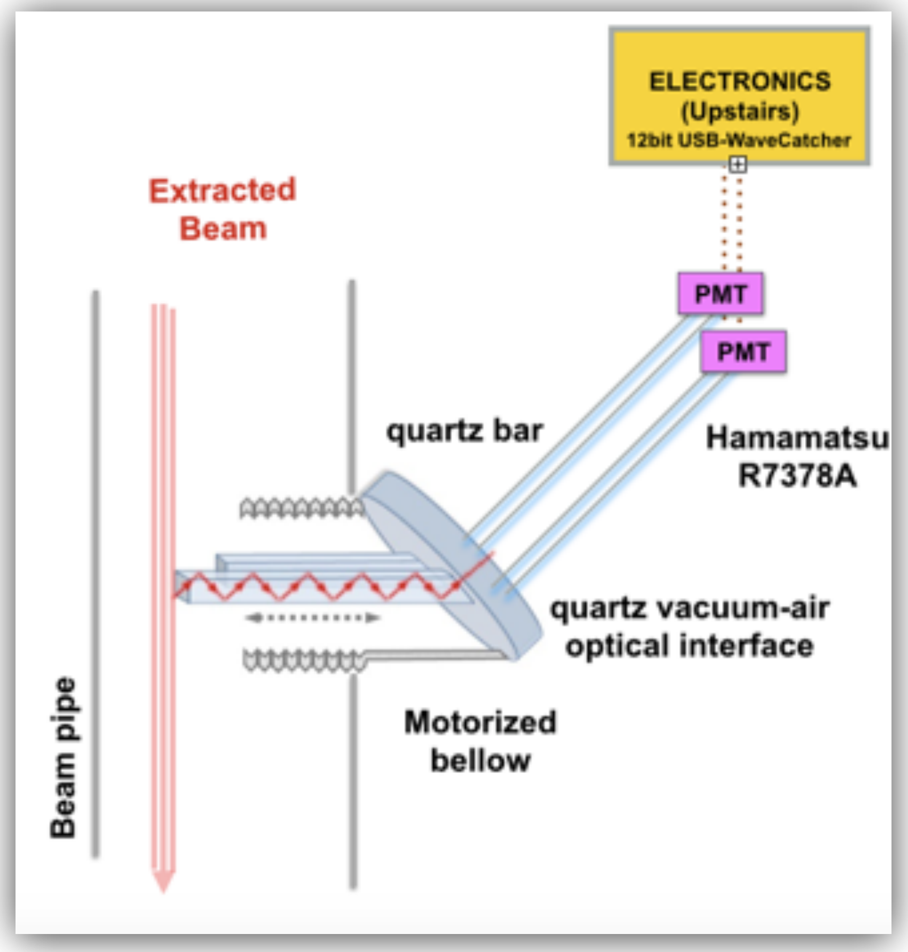


Angular scan: performed to find the optimum channeling orientation of the crystal wrt to the halo beam. The Channeling orientation appears as a depression in the losses (green curve) and as signal peak on the CpFM intercepting the channeled beam.

CpFM COMMISSIONING&OPERATION: LINEAR SCAN

Coasting beam - Single bunch 270 GeV protons OCT 2015

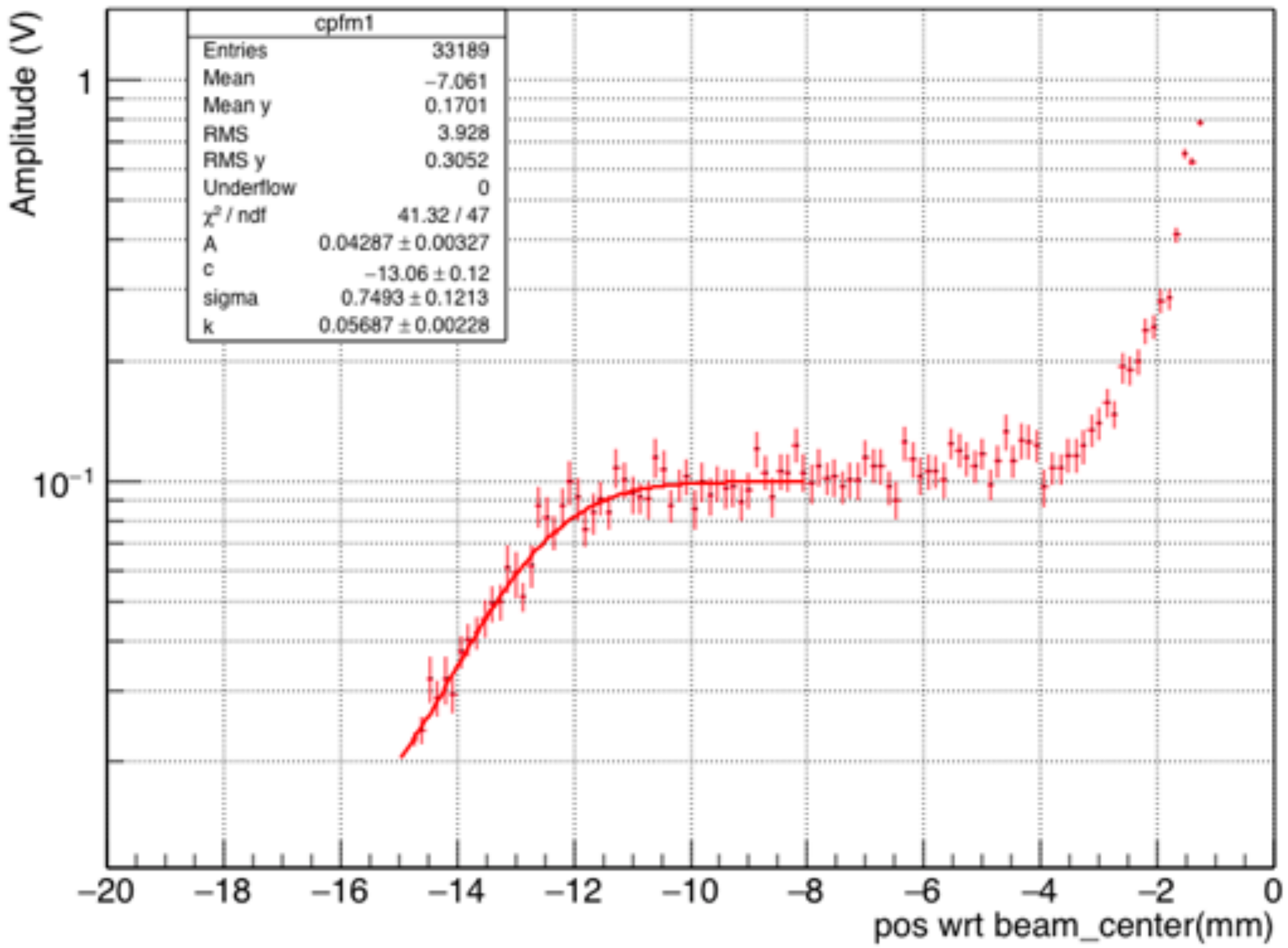


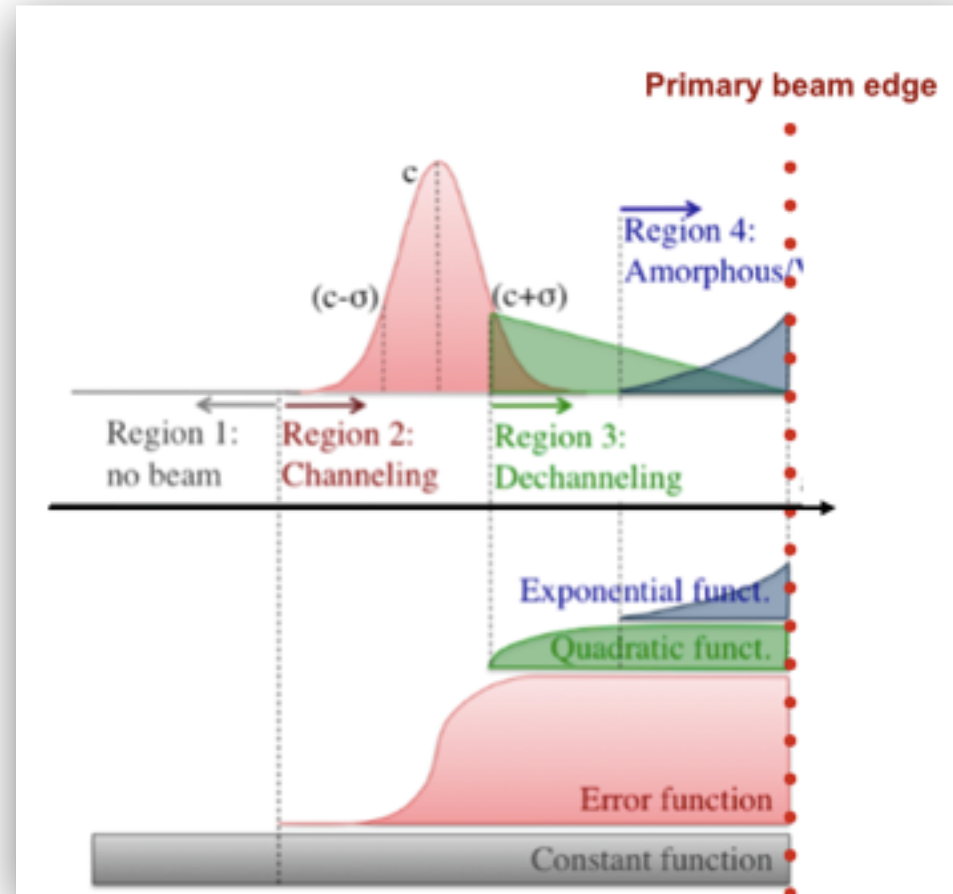


UA9 Crystal as a primary collimator. As the bars approach the channeled beam, the amplitude of the signal increases, until the channeled beam is fully intercepted. Moving the bars further, the first one touches the edge of the primary beam.The shift of the fit peaks is due to the relative shift of the bars (5,5 mm)

CpFM FUNCTIONALITY TEST:CHANNELED BEAM PARAMETERS EXTRAPOLATION

Coasting beam - Single bunch 270 GeV protons OCT 2015





Fitting function: $A \cdot \frac{1}{\sigma\sqrt{2\pi}} \int_0^x e^{-\frac{(t-c)^2}{2\sigma^2}} dt + k$

- ✓ **The amplitude distribution in the channeling region can be fitted with an error function. The derivative of this function corresponds to the gaussian profile of the channeled beam. From the sigma value is possible derive the angular spread of the channeled beam that, in our case, well reproduce the critical angle for 270 GeV protons(12.2 urad).**

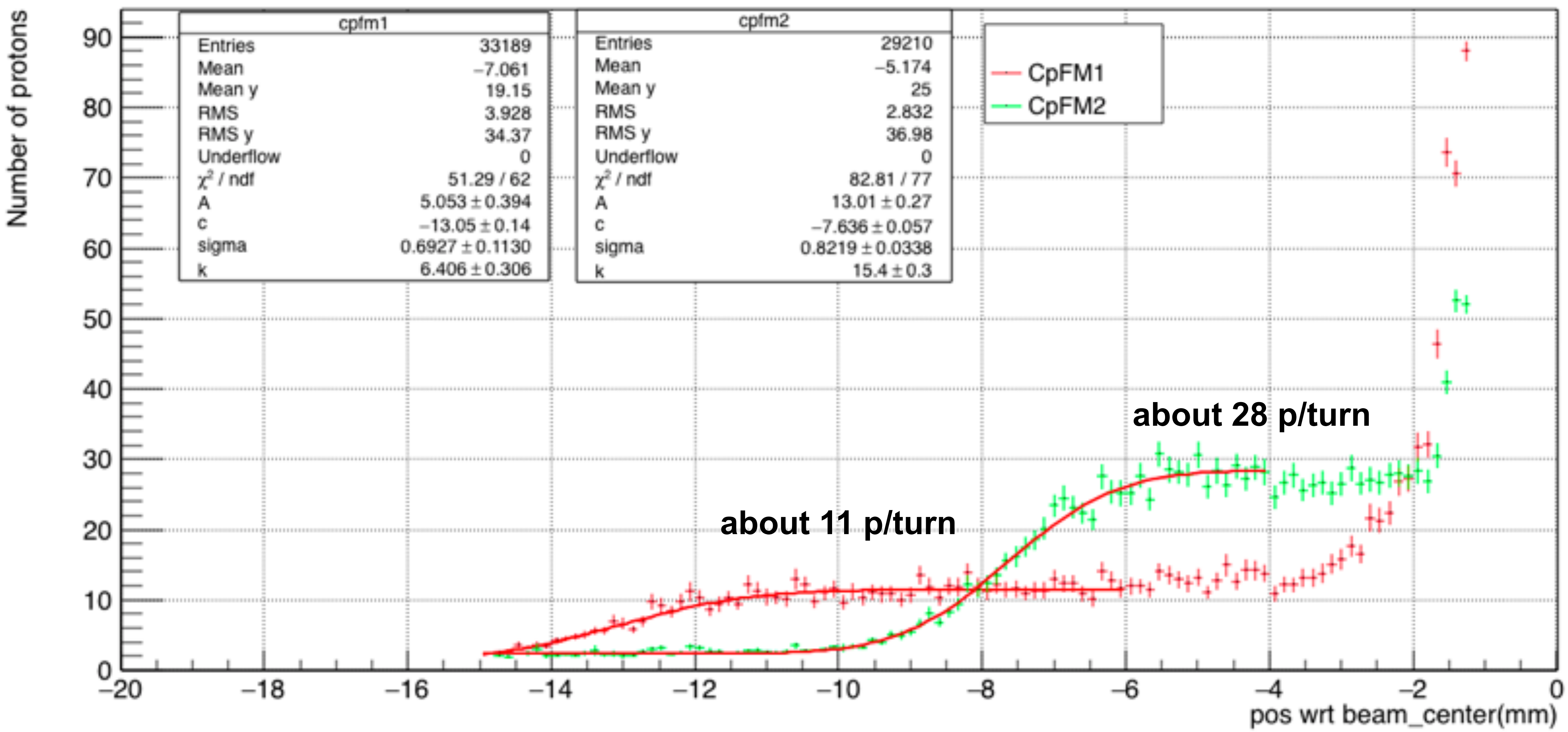
$$\theta_{spread} = (12,8 \pm 1,3)\mu rad$$

- ✓ **Estimation of the bending angle through the knowledge of the channeling peak position.**

$$\theta_{ch(cry4)} = (153 \pm 11)\mu rad$$

CpFM COMMISSIONING&OPERATION: FLUX MEASUREMENT

Single bunch 270 GeV protons -OCT 2105



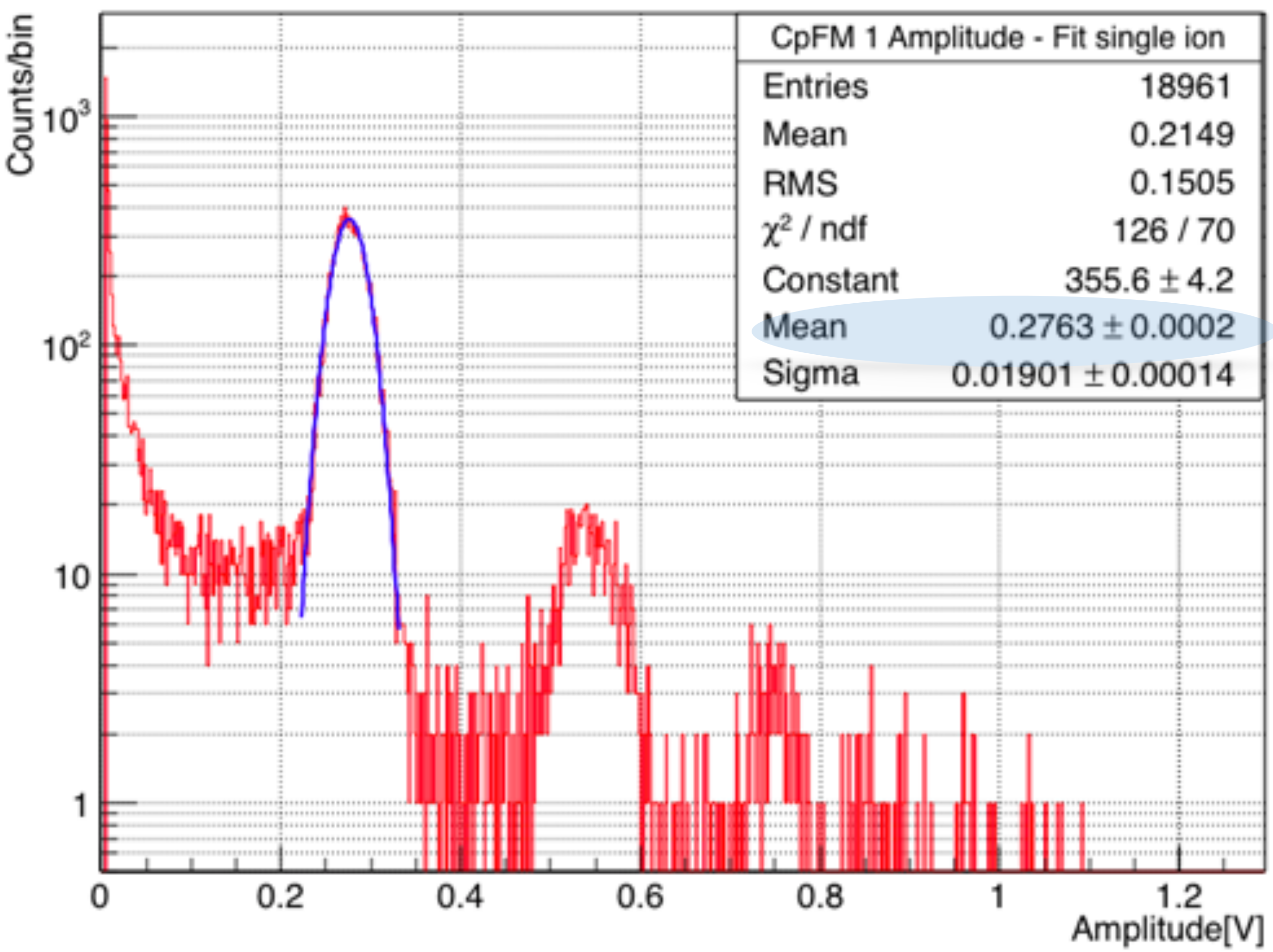
- CpFM 1 counts about 11 extracted protons/turn
- CpFM 2 counts about 28 extracted protons/turn
- BCTDC (Beam Current Transformer) counts about 135 extracted protons/turn (%5-10 resolution for this flux)

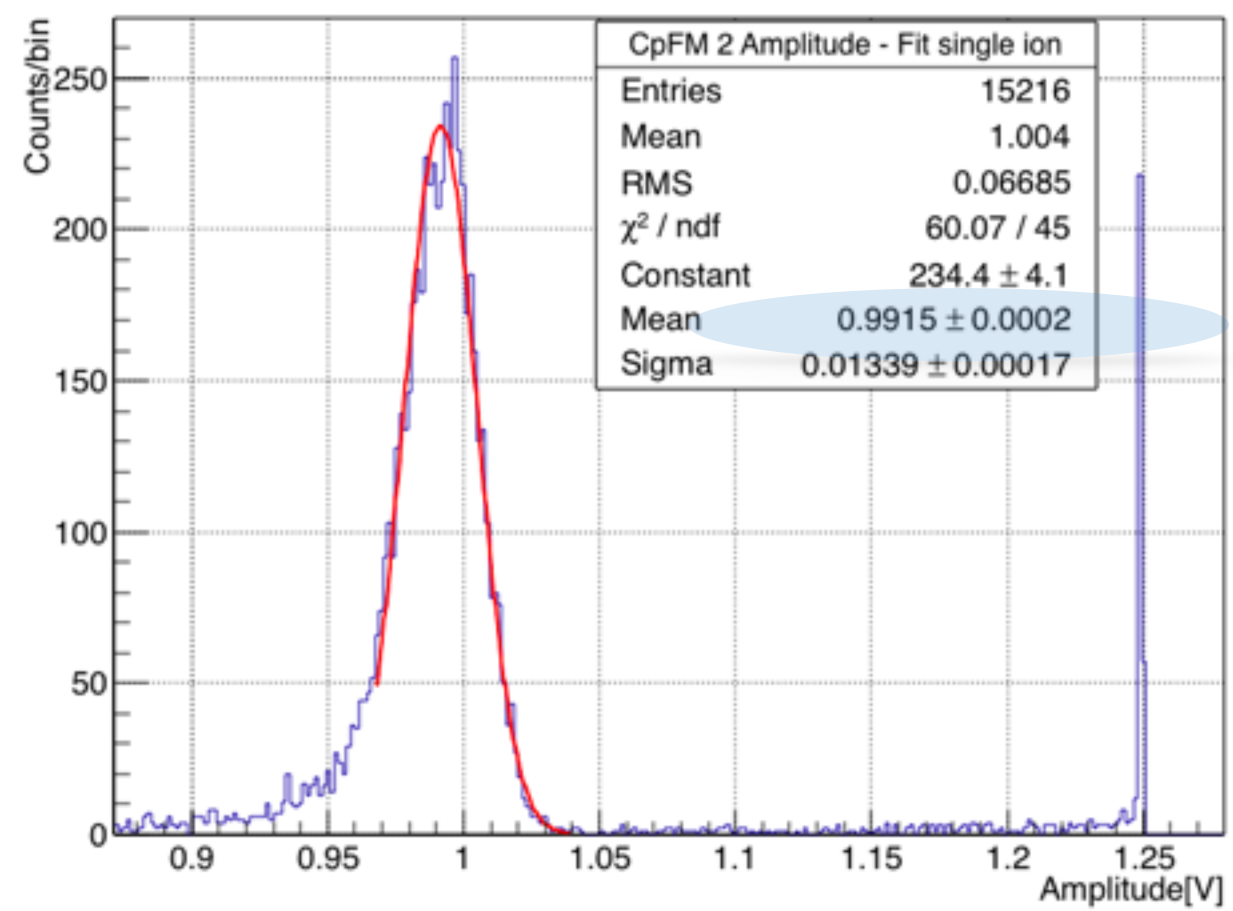
- Why CpFM 1 and CpFM 2 measured a different flux?
- Why CpFM1&2 flux measurement it is so different from the BCTD measurement?

Hp: CpFM 1&2 EFFICIENCY LOSS

CpFM : IN SITU CALIBRATION WITH Pb IONS BEAM

Coasting beam - Multi-bunch ions - Nov 2016





CALIBRATION STRATEGY TO CALCULATE NEW CALIBRATION FACTORS:

$$\mathbf{SIGNAL\ AMP}_{\mathbf{single\ ion}} = Z^2_{Pb} \times ph.e.yield/p \times ph.e(mV)$$

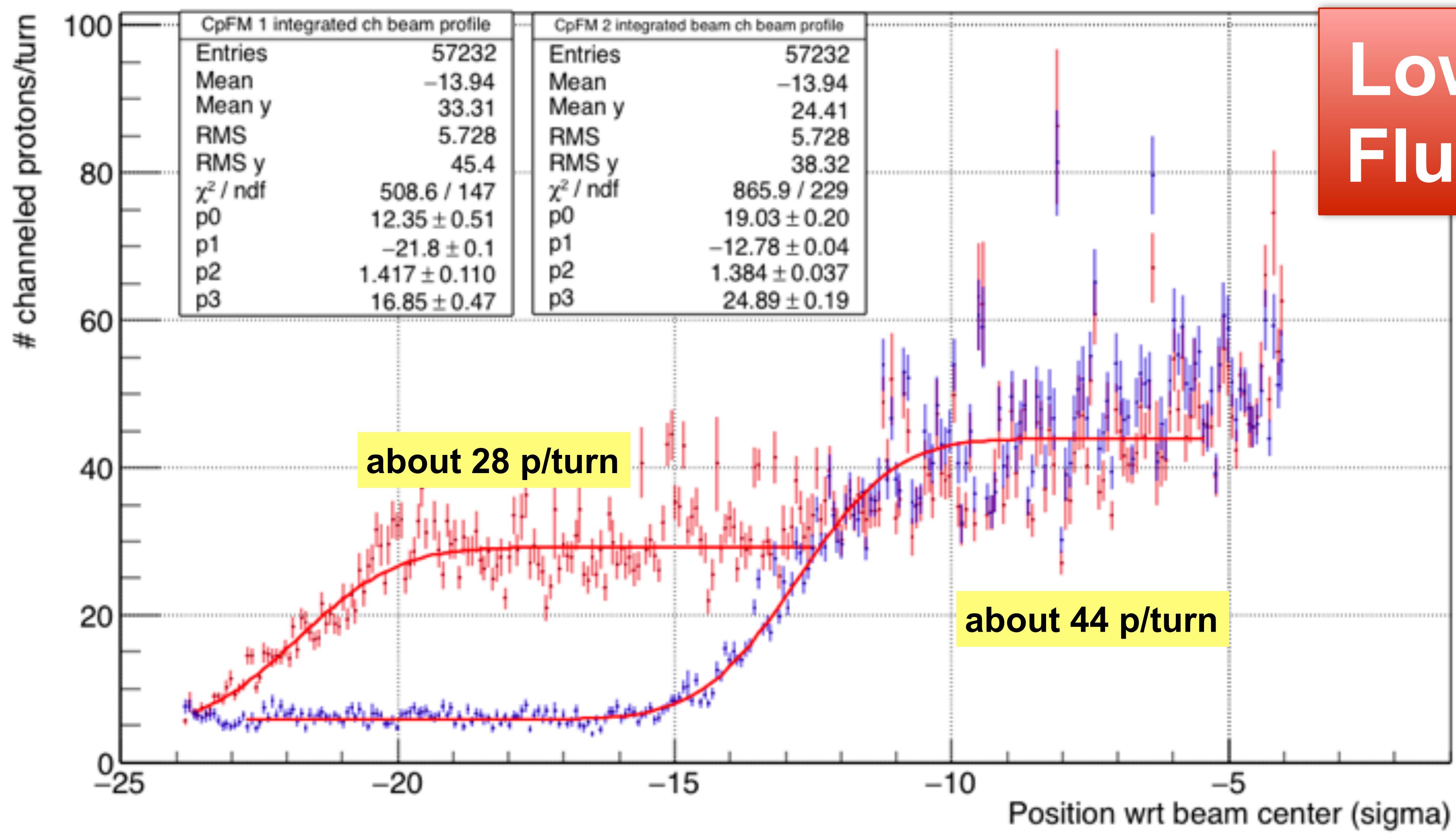
CpFM DESIGN EFFICIENCY per proton : 60%
(as measured in BTF)

OBSERVED CpFM 1 = 6%

OBSERVED CpFM 1 = 18%

CpFM FLUX MEASUREMENT AFTER RECALIBRATION

Coasting beam - Single bunch 270 GeV protons OCT 2016



Low Flux

On going discussion on the estimation of the error on the CpFM flux

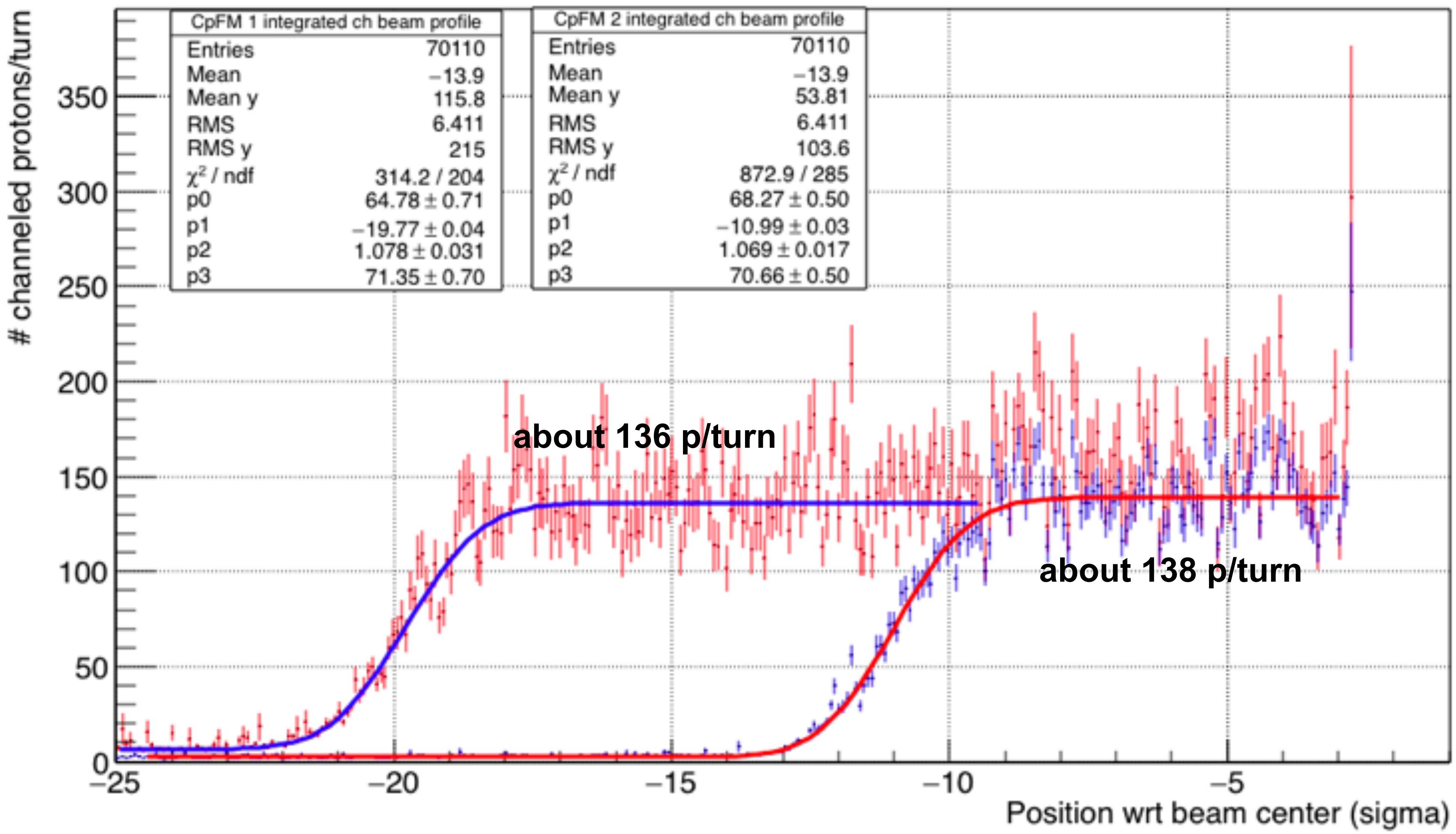
If the extracted flux is low (BCTDC counted 58 protons with 30% of resolution), only the CpFM 2 is efficient (efficiency>99%) and in agreement, considering the errors, with the BCTDC. For the same reason it's not possible to equalize the detectors applying the new calibration factor.

In fact, considering the dependance of the efficiency on the number of protons extracted, the CpFM 1 it's 90% efficient for a flux of 40 protons, reaching the 99% efficiency just for more than 100 p

CpFM FLUX MEASURMENT AFTER RI-CALIBRATION

Coasting beam - Single bunch 270 GeV protons OCT 2016

High Flux



On going discussion on the estimation of the error on the CpFM flux

If the extracted flux is high (BCTDC counted 180 p with 15% of resolution), the CpFM 1 efficiency is >99%. The signals are now perfectly equalized even if not completely in agreement with the BCTDC (considering just the error of the BCTDC).

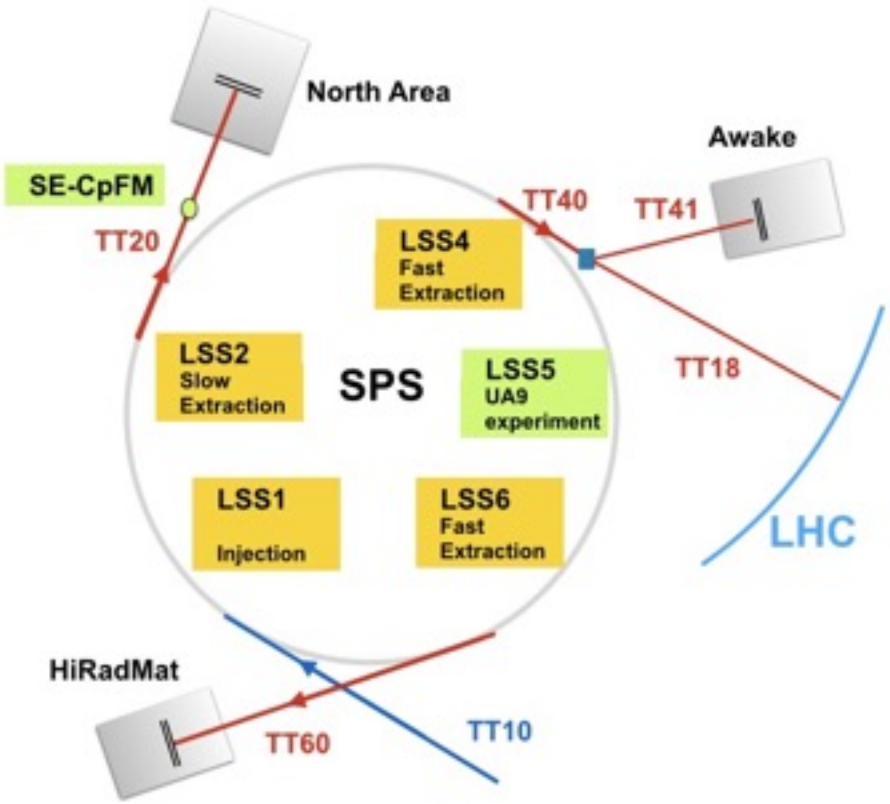
SUMMARY: CpFM FOR THE UA9 EXPERIMENT

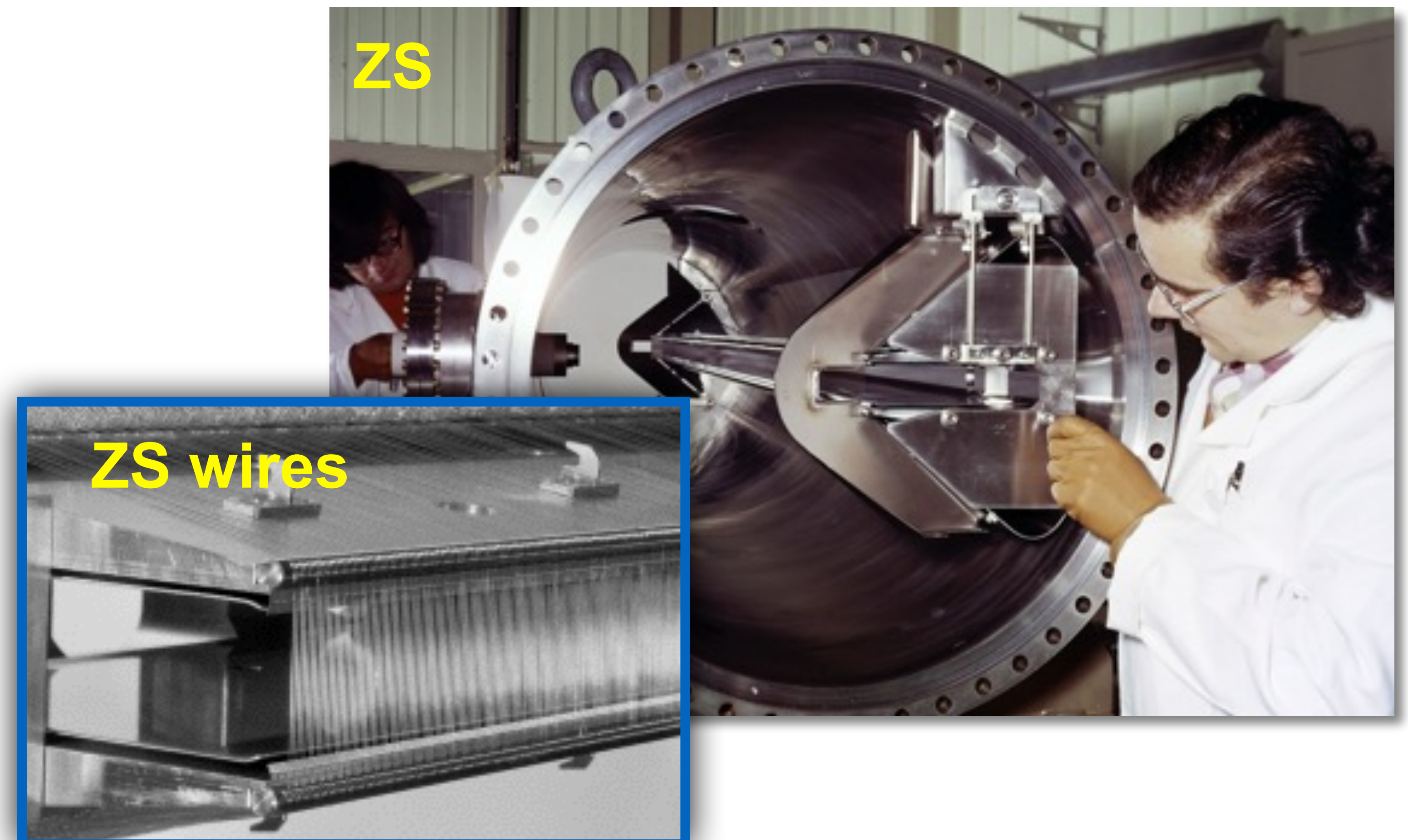
- ✓ A new concept of Cherenkov detector has been designed to perform proton flux measurements in the framework of UA9 experiment.
- ✓ The device has been commissioned during 2015 and 2016: Linear scan and angular scan procedures have been used for both, testing the functionality of the CpFM detector and to support during the UA9 operations.
- ✓ During the commissioning an efficiency loss was observed. An in situ calibration of the detector has been performed with Pb ions beam in Nov 2016 (Efficiency per single proton from 60% to 6% for CpFM1 and from 60% to 18% for the CpFM2)
- ✓ The new calibration confirmed that CpFM 1&2 were not sensitive to the single proton. For theCpFM1, efficiency>99% if #p>100, while for the CpFM2 if #p>20. Discussion on the estimation of the resolution of the CpFM are still on going.
- ✓ In January 2017 we dismounted the detector to understand the causes responsible for the efficiency loss and it was found out a bad polishing of the quartz bars
- ✓ In January 2018 a new version of the detector will be installed, without fiber bundle and with a pyramidal shaped bar.

The Slow Extraction CpFM for Slow Crystal assisted extraction @ SPS

SPS SLOW EXTRACTION: CURRENT LAYOUT

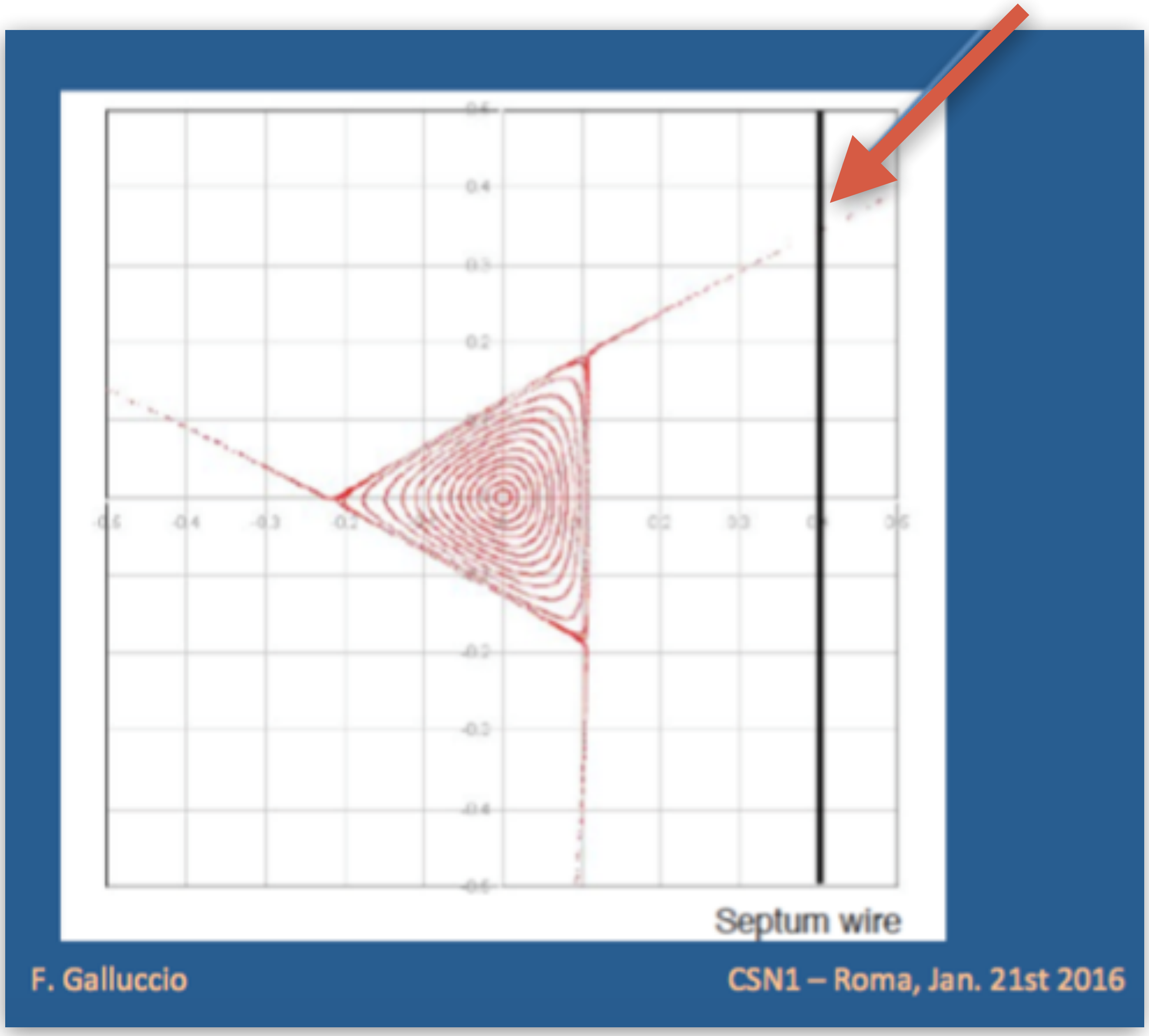
Currently the slow extraction @ SPS toward the NA (Fixed Target Physics) is a RESONANT SLOW EXTRACTION and it is performed through 5 Electrostatic Septa ZS (bending needed to match the extraction channel 5x73urad)





The main problematic issue of this extraction process regards the small fraction of the beam (1%) lost on the wires of the ZS ▶ activation of the SPS, limitation in the delivered beam intensity

CRYSTAL-ASSISTED RESONANT SLOW EXTRACTION

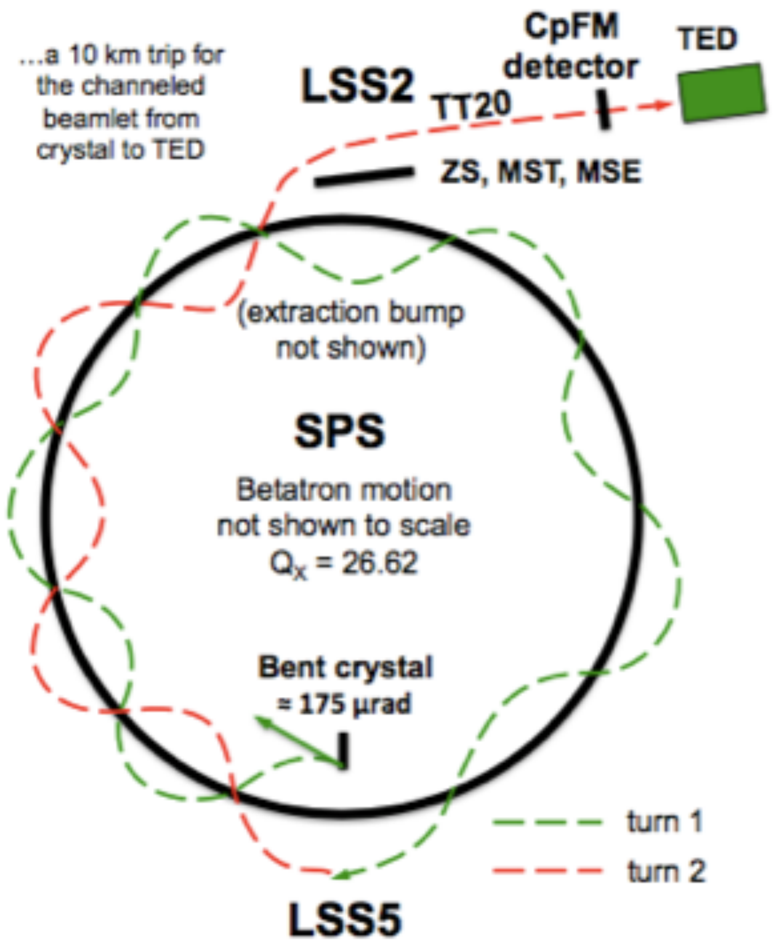


SHADOWING SCENARIO:

Bent crystal used to shape a gap along the separatrix to shadow the wires of the ZS during a conventional resonant slow extraction.

CRYSTAL-ASSISTED SE: PROOF OF PRINCIPLE EXPERIMENT

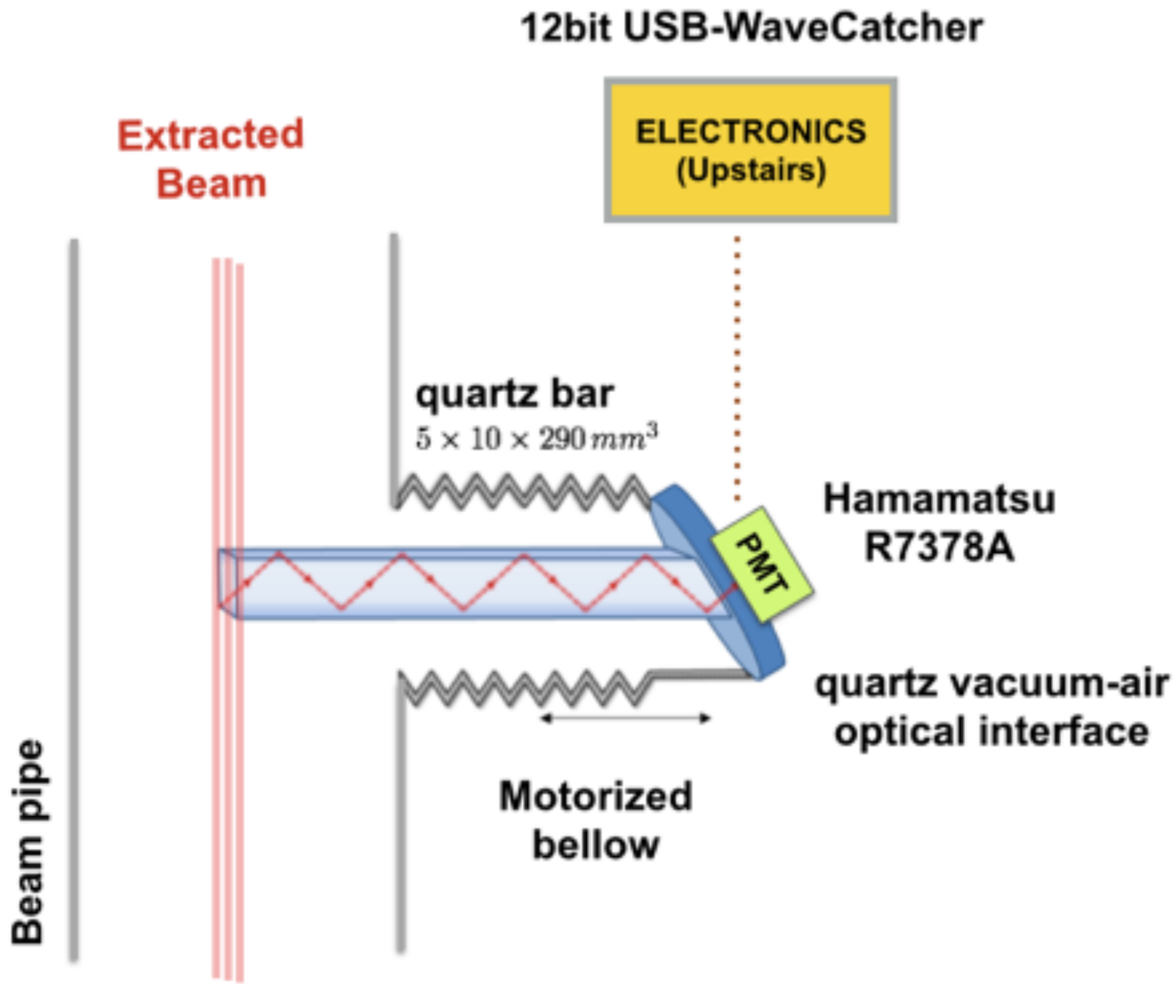
As a first step, a proof of principle experimental campaign started in the end of 2016, with the aim to demonstrate the possibility to use bent crystals in conjunction with the ZS system to perform a crystal assisted extraction from the SPS to the TT20 extraction line. In this frame the SE-CpFM detector was needed to detect and characterize the extracted beam directly in TT20



Proof of principle experiment:
it consists of very low intensity and bunched extraction. The halo of a low intensity (10^10p) LHC-type single bunch (270 GeV) is extracted at each turn (every 23 us) from the circulating beam by a UA9 crystal (LSS5).

SLOW EXTRACTION CpFM REQUIREMENTS & LAYOUT

SE-CpFM detector has been installed in LSS2 since January 2016



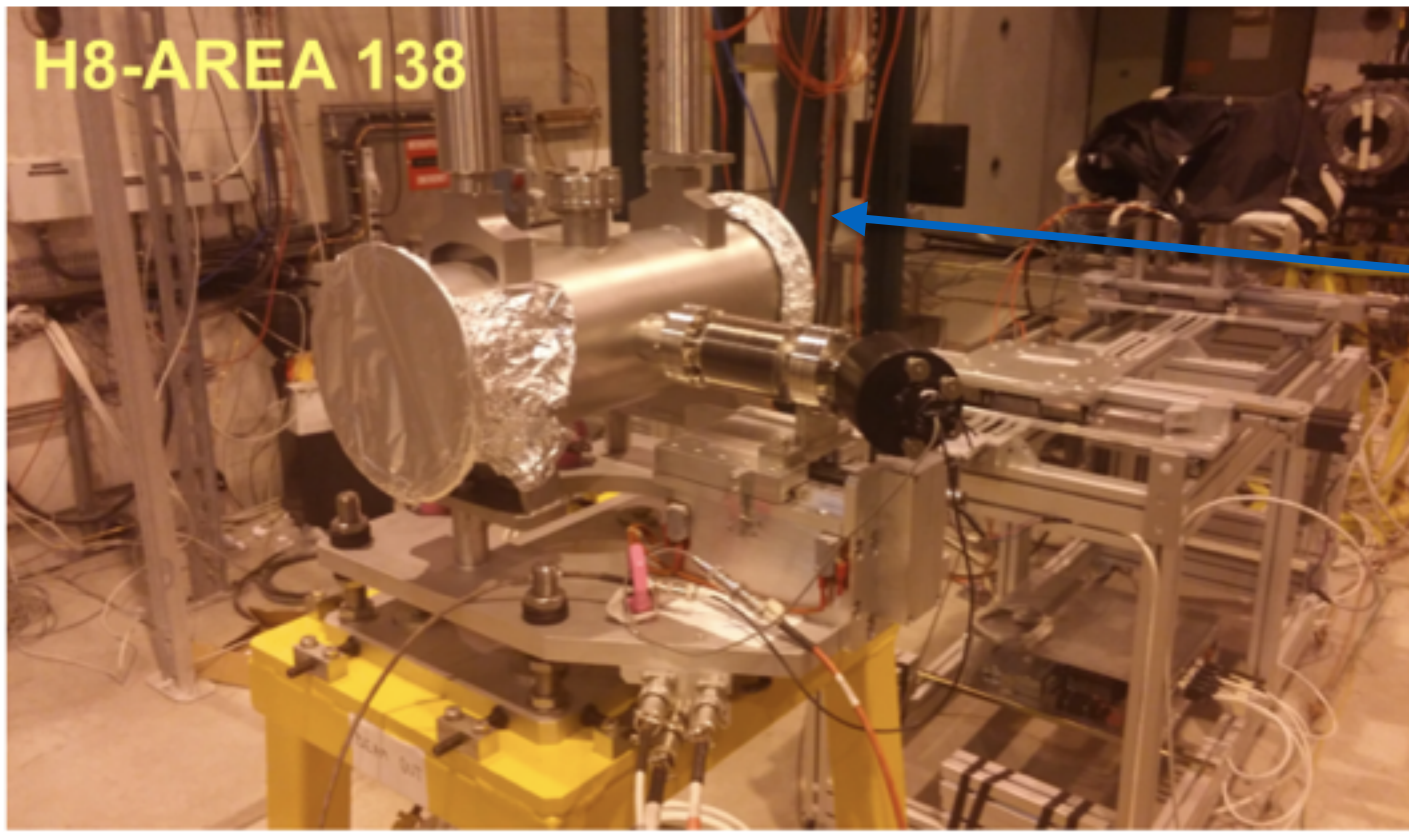
DIFFERENCES WRT THE UA9-CpFM:

- ✓ **Bundle remotion to maximize the ph.e yield/p of the detector**
- ✓ **Single bar with a reshaped holder to improve the optical coupling between the bar and the quartz window of the viewport.**
- ✓ **Radiation environment more challenging for the PMT but periodical checks on the PMT are foreseen**

Essentially it has to fulfill the same requirements of the UA9-CpFM using therefore a similar layout. In fact, it has to perform the flux measurement on a beam with the same characteristics (bunched, low intensity beam).

SE-CpFM CHARACTERIZATION TEST

The whole detector chain was tested in H8-SPS extraction line, with 180 GeV pions beam (2-5 10^5 pions in 4.5 s spill)

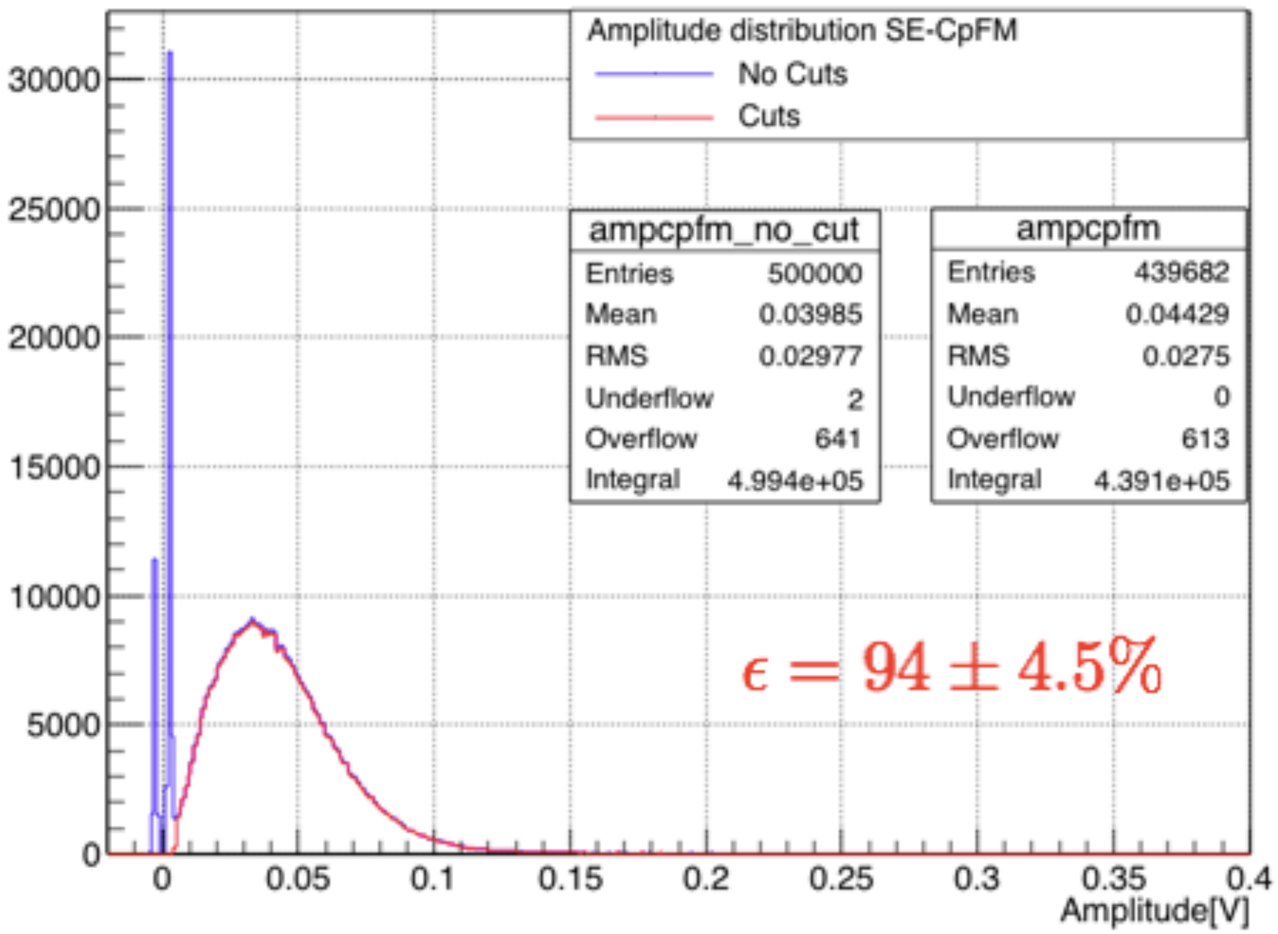


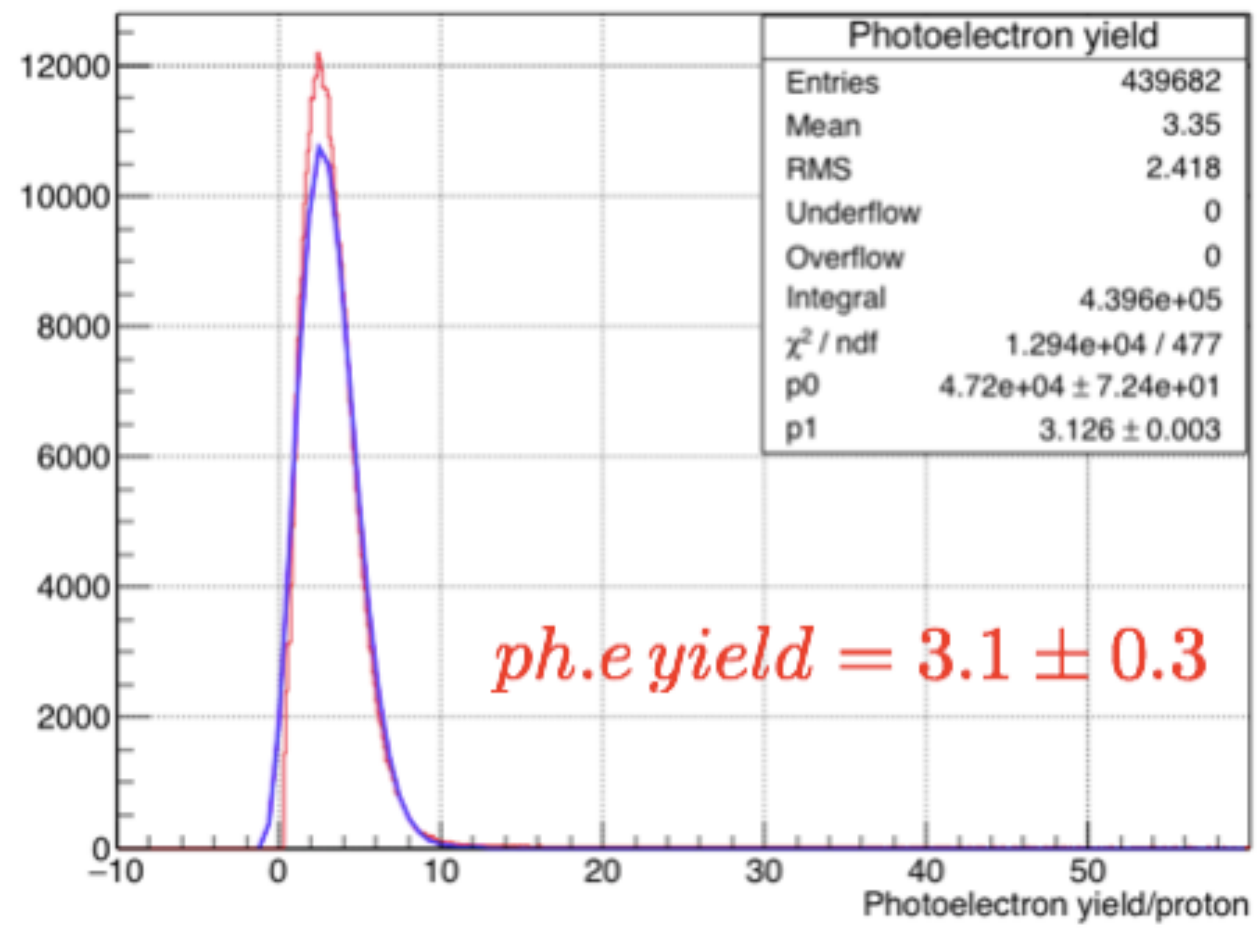
5 mm x 10 mm x 30 mm scintllator bar readout by SiPMs

AIM OF THE TEST: SINGLE PROTON EFFICIENCY AND SINGLE PROTON LIGHT YIELD

SE-CpFM CHARACTERIZATION TEST

SE-CpFM has better performances wrt the UA9 CpFM. This is mainly due to the removal of the bundle and to the better polishing of the bar.





single particle efficiency

SE-CpFM 94%

UA9-CpFM1 6%

UA9-CpFM1 18%

Single particle light yield

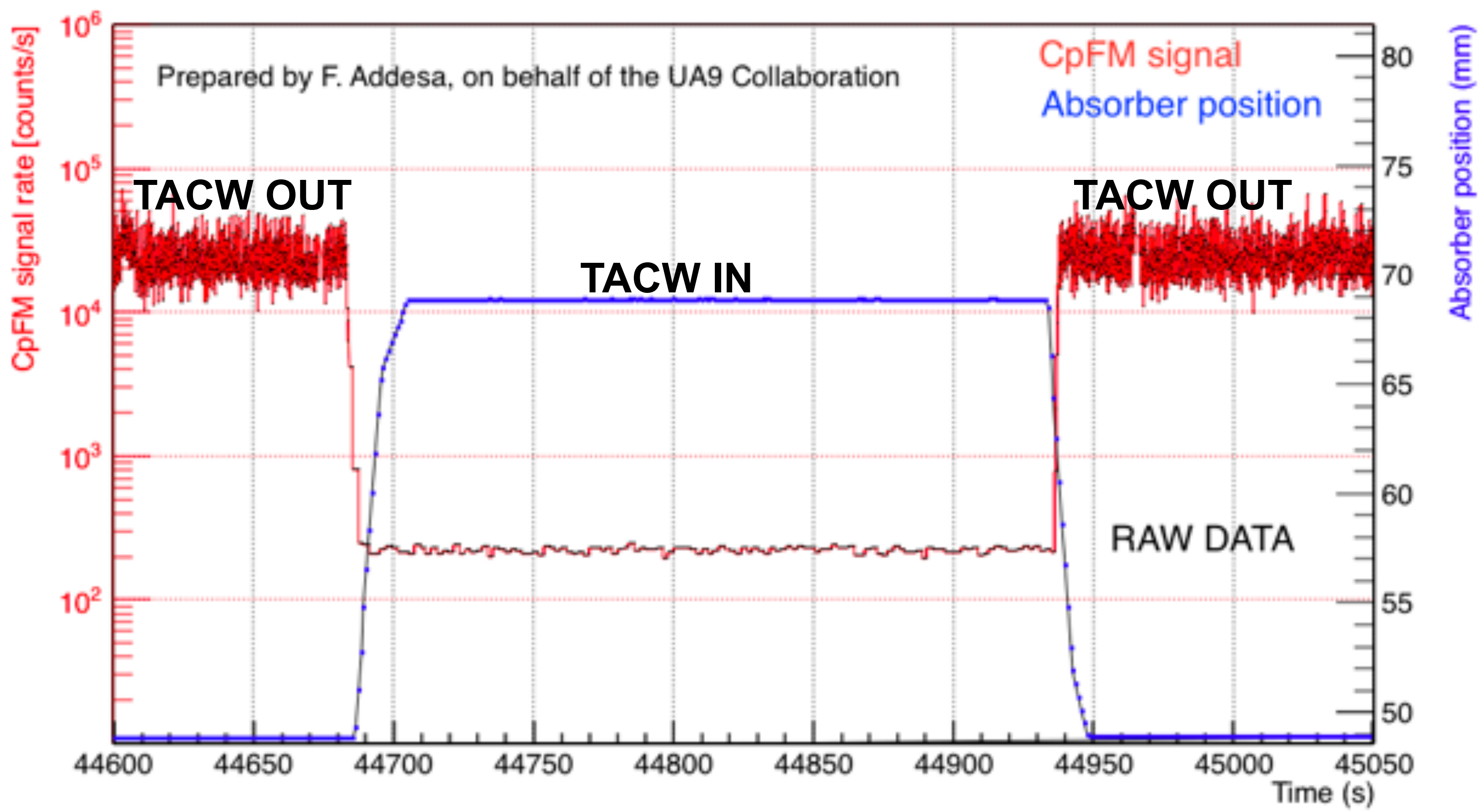
UA9-CpFM1 0.06ph.e

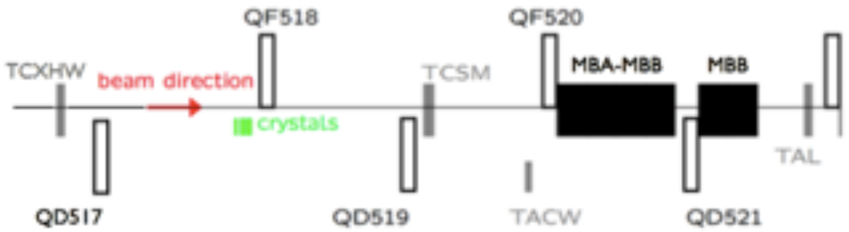
SE-CpFM 3.1 ph.e

UA9-CpFM2 0.18ph.e

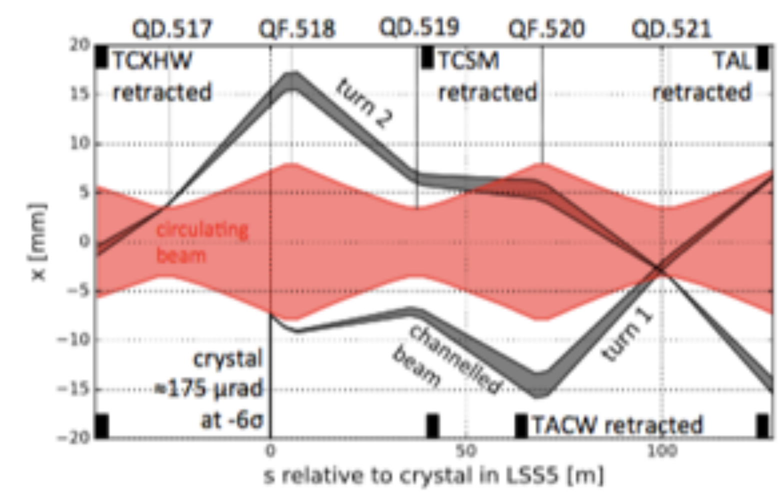
PROOF OF PRINCIPLE EXPERIMENT FIRST RESULTS

Coasting beam - Single bunch 270 GeV protons OCT 2016

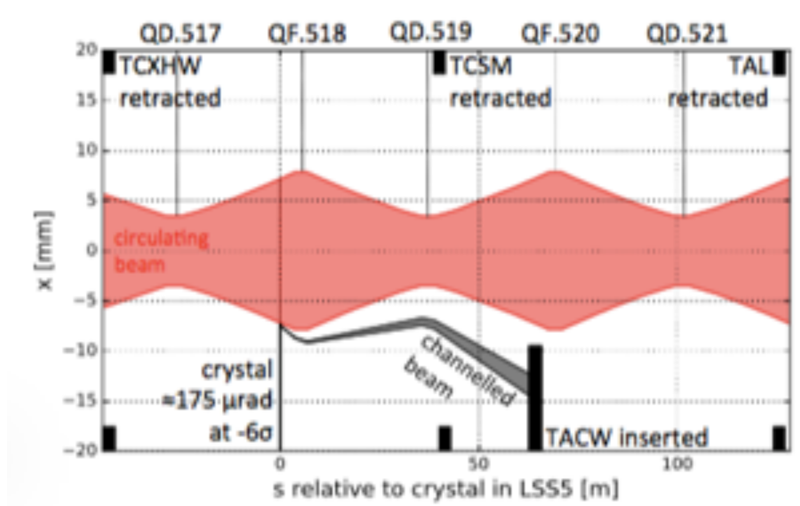




TACW OUT



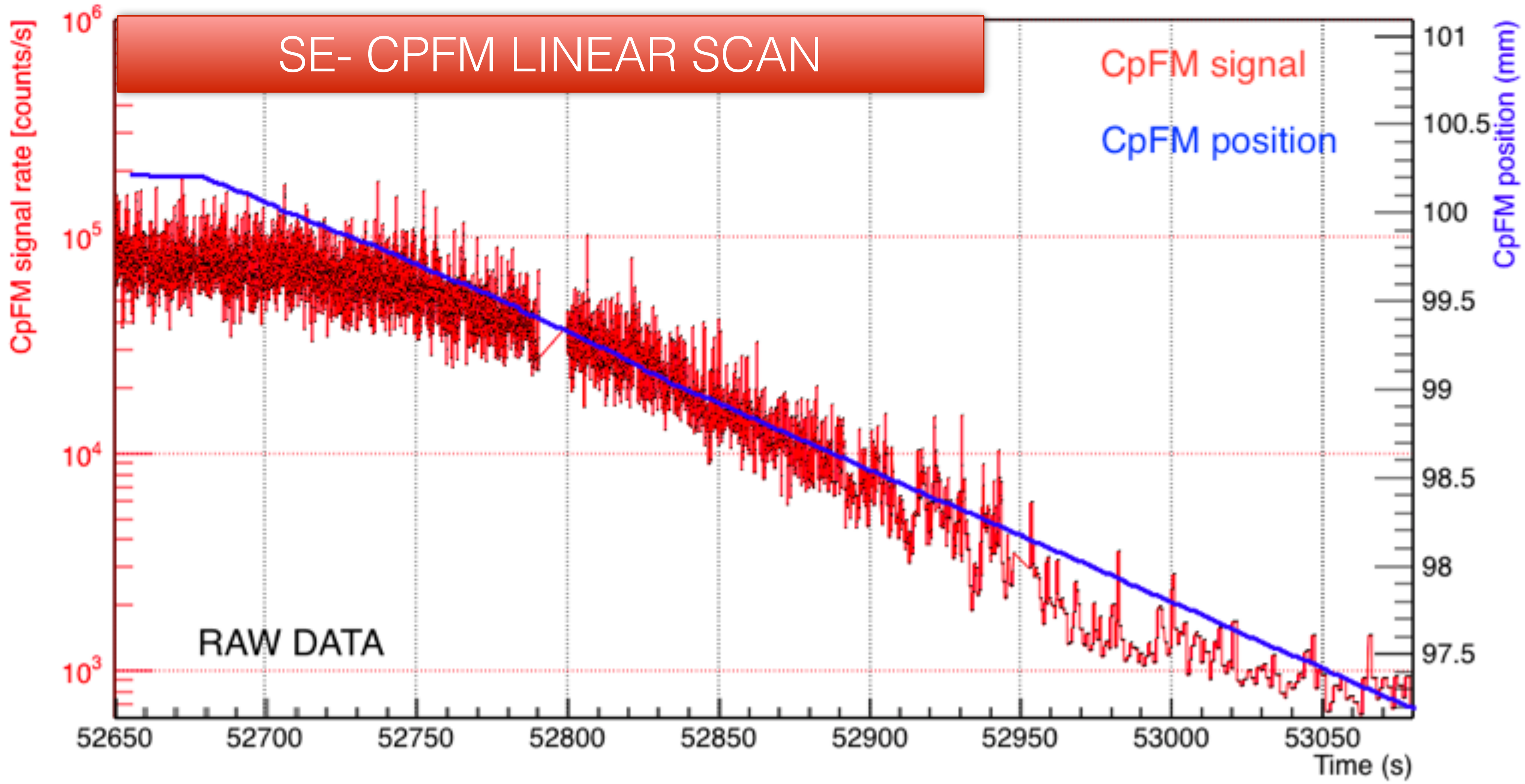
TT20 CpFM signal rate (red) vs TACW absorber position (blu). When the TACW is retracted the channeled beam is free to circulate and to be extracted toward TT20 where the CpFM detects it. As the TACW is inserted the channeled beam is stopped in LSS5 and the signal rate measured by the CpFM drops

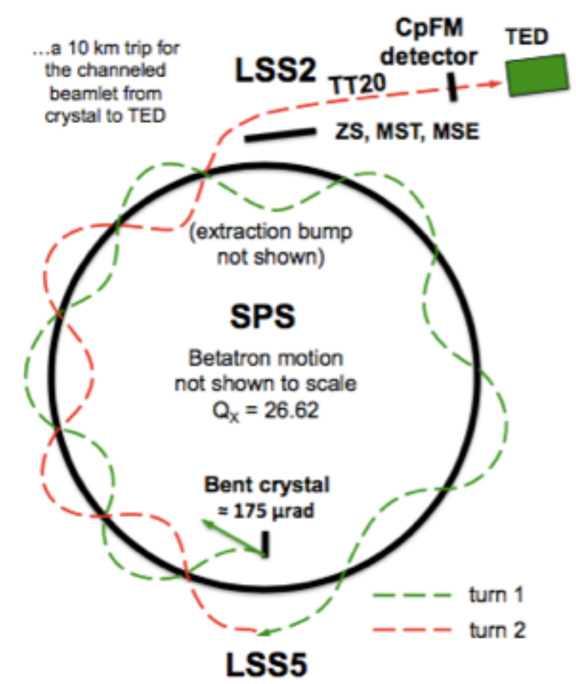


TACW IN

PROOF OF PRINCIPLE EXPERIMENT FIRST RESULTS

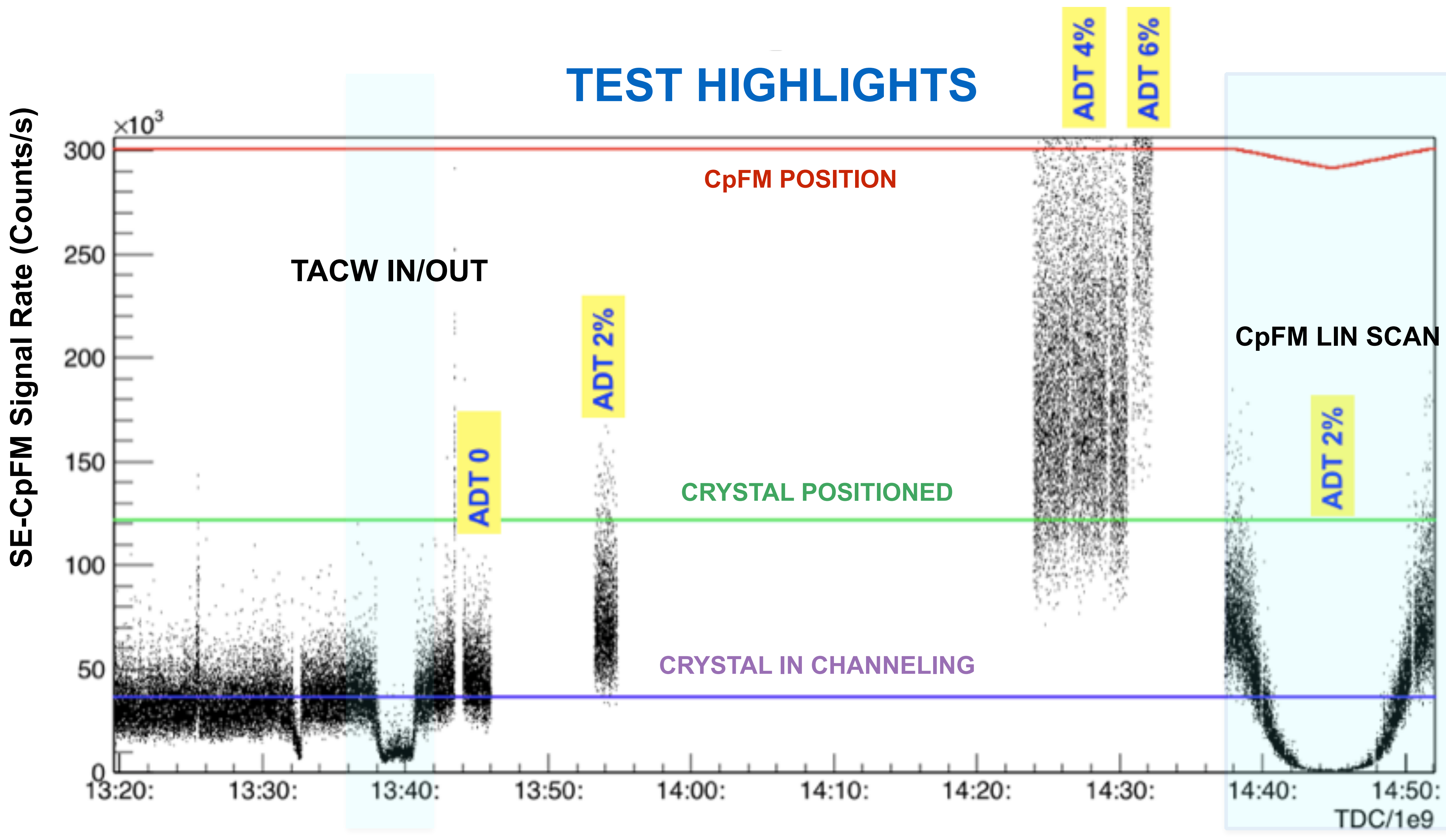
Coasting beam - Single bunch 270 GeV protons OCT 2016





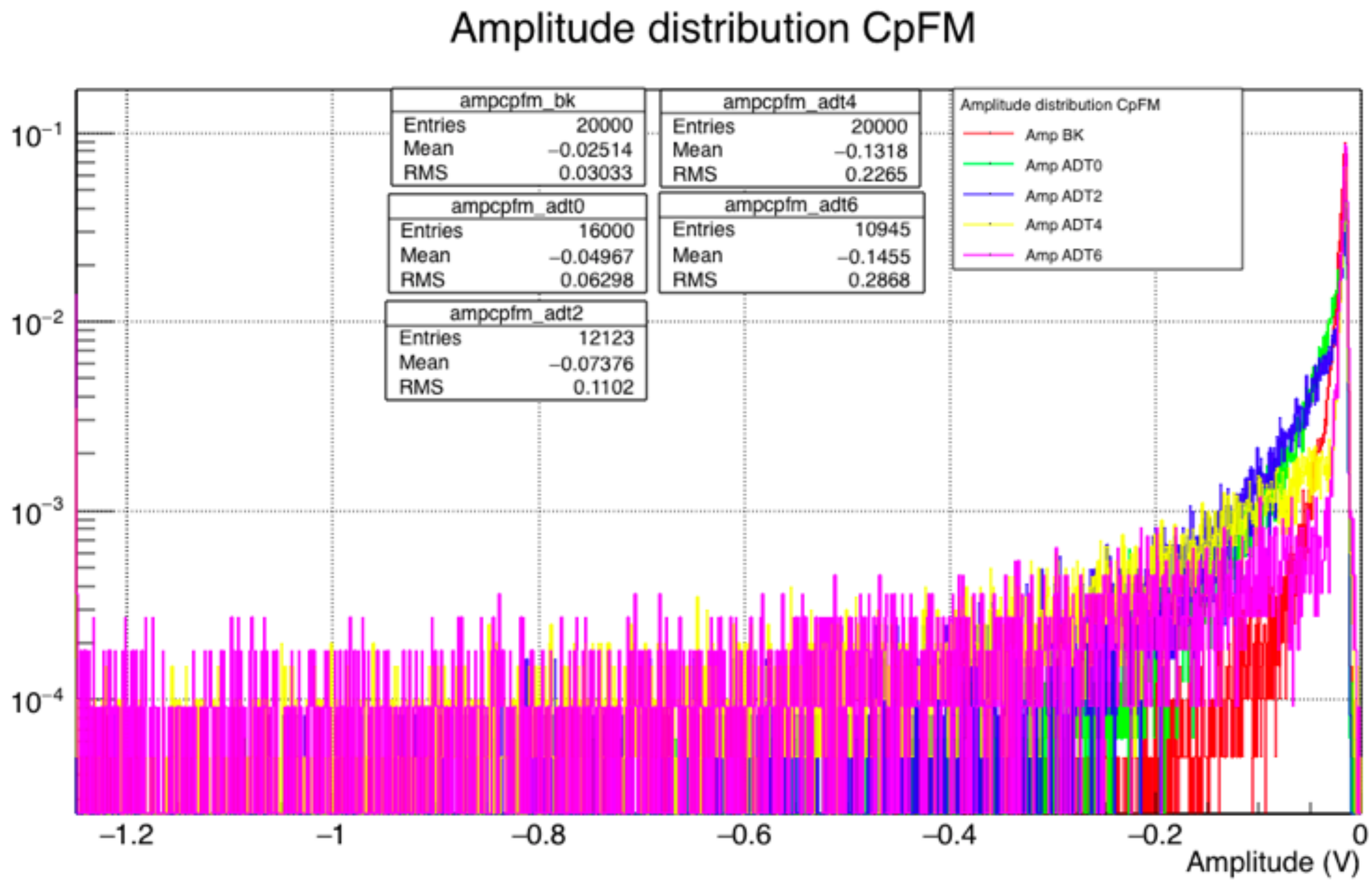
TT20 CpFM signal rate (red) and position (blue) vs time as it is moved out of the extracted beam

PROOF OF PRINCIPLE EXPERIMENT FIRST RESULTS: FLUX MEASUREMENT



After the SE-CpFM position was optimized wrt the extracted beam, data were acquired switching on the ADT (Adiabatic Transversal Dumper). The effect of the ADT is to move the beam from the core to the halo, increasing the flux diffusing to the crystal and consequently the crystal extraction rate.

PROOF OF PRINCIPLE EXPERIMENT FIRST RESULTS: FLUX MEASURMENT



SE-CPFM detected the increase of the extraction rates but unfortunately it was unable to count. In fact the SE-CpFM signal was auto-triggered because the SPS-reference signal was not yet installed. Even if a careful study of the auto-trigger threshold was performed using the background acquisition (with no beam in TT20), the condition during the extraction were different and the detector settings were not optimal anymore. An SPS-reference signal has been now installed and we are waiting for the next beam time!

Summary: SE-CpFM to monitor the slow extraction spill of SPS

- ✓ A second version of the CpFM detector has been designed to study the feasibility of the crystal-assisted slow extraction from the SPS to the TT20 extraction line (SPS-North Area, Fixed Target Physics).

- ✓ The whole detector chain has been succesfully tested with 180 GeV/C pions beam at H8. The detector efficiency per single proton was evaluated in 94% and the ph.e. yield per proton in 3.1.

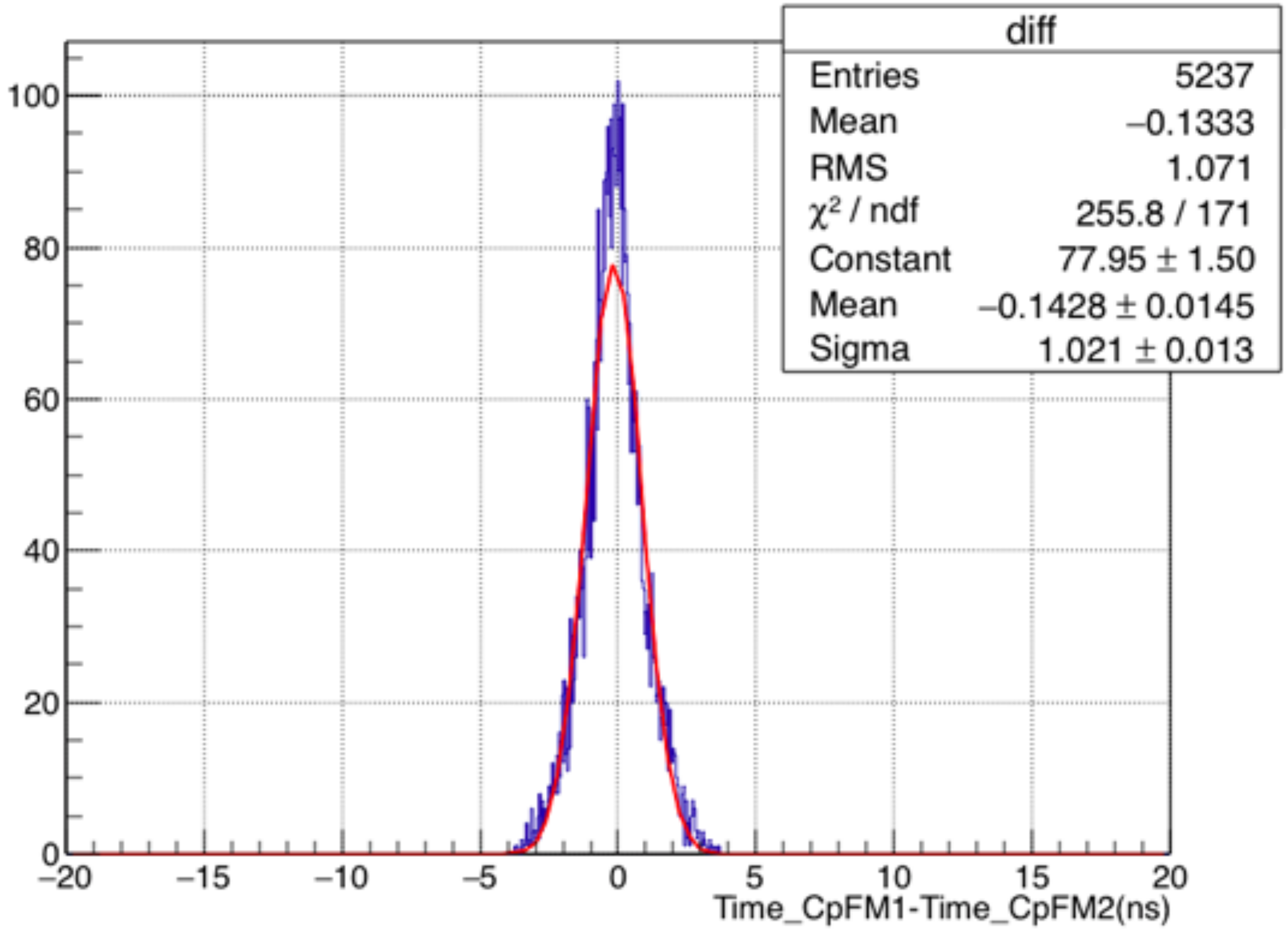
- ✓ The device has been installed in May 2016 in TT20-SPS transfer line and the full commissioning is still ongoing

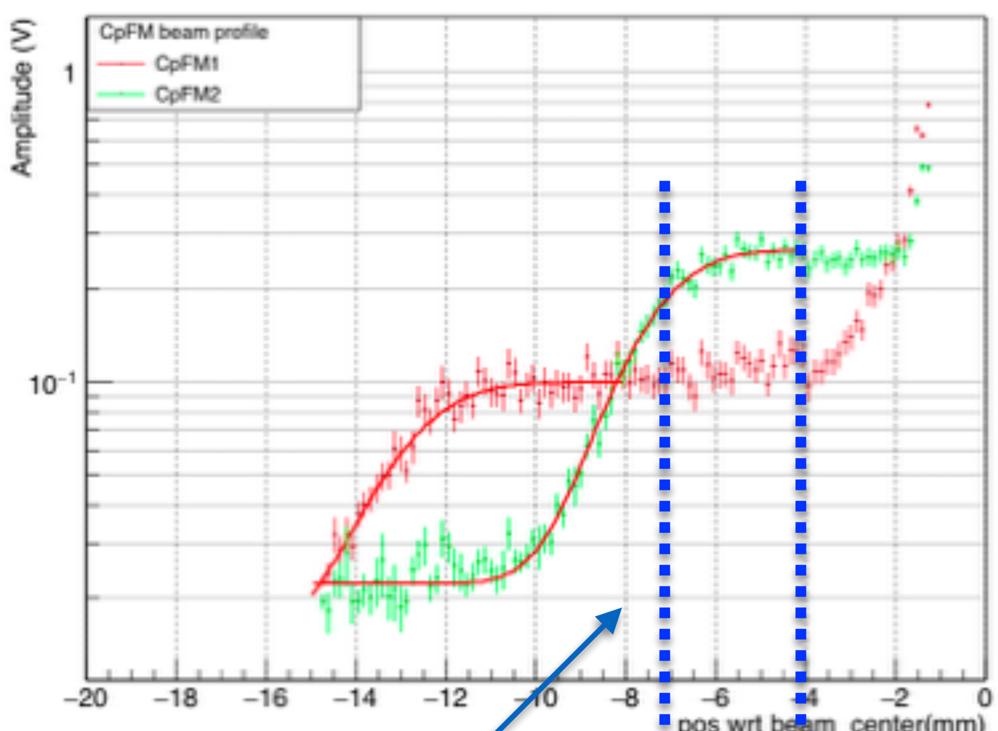
- ✓ In October 2016, the SE-CpFM has been fundamental to prove the first crystal assisted proton extraction @ the SPS.

- ✓ In June 2017 we have installed an SPS beam synchronous signal to improve the signal-to-noise ratio. We are now waiting for new beam time!

BACK UP

CpFM detector characterization: Time resolution





To extrapolate time resolution we need to be sure that both the bars detect the same particles so we need to consider just the case in which both bars intercept the whole channelled beam (plateau position). Supposing that the time resolution for the two bars is the same:

Time resolution of CpFM= $(722 \pm 9)ps$

Bending angle formula

We assume on-momentum particles hitting the edge of the crystal at their maximum betatron extension:

$$\begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}_{cry} = \begin{pmatrix} x_{cry} \\ -\frac{\alpha_{cry}}{\beta_{cry}} x_{cry} \end{pmatrix} \tag{3.16}$$

where x_{cry} is the aperture of the crystal and α_{cry}, β_{cry} are the twiss parameters at the crystal location. After a kick θ_k from the crystal, the coordinates at the crystal are:

$$\begin{pmatrix} x_1 \\ x'_1 \end{pmatrix}_{cry} = \begin{pmatrix} x_{cry} \\ -\frac{\alpha_{cry}}{\beta_{cry}} x_{cry} + \theta_k \end{pmatrix} \tag{3.17}$$

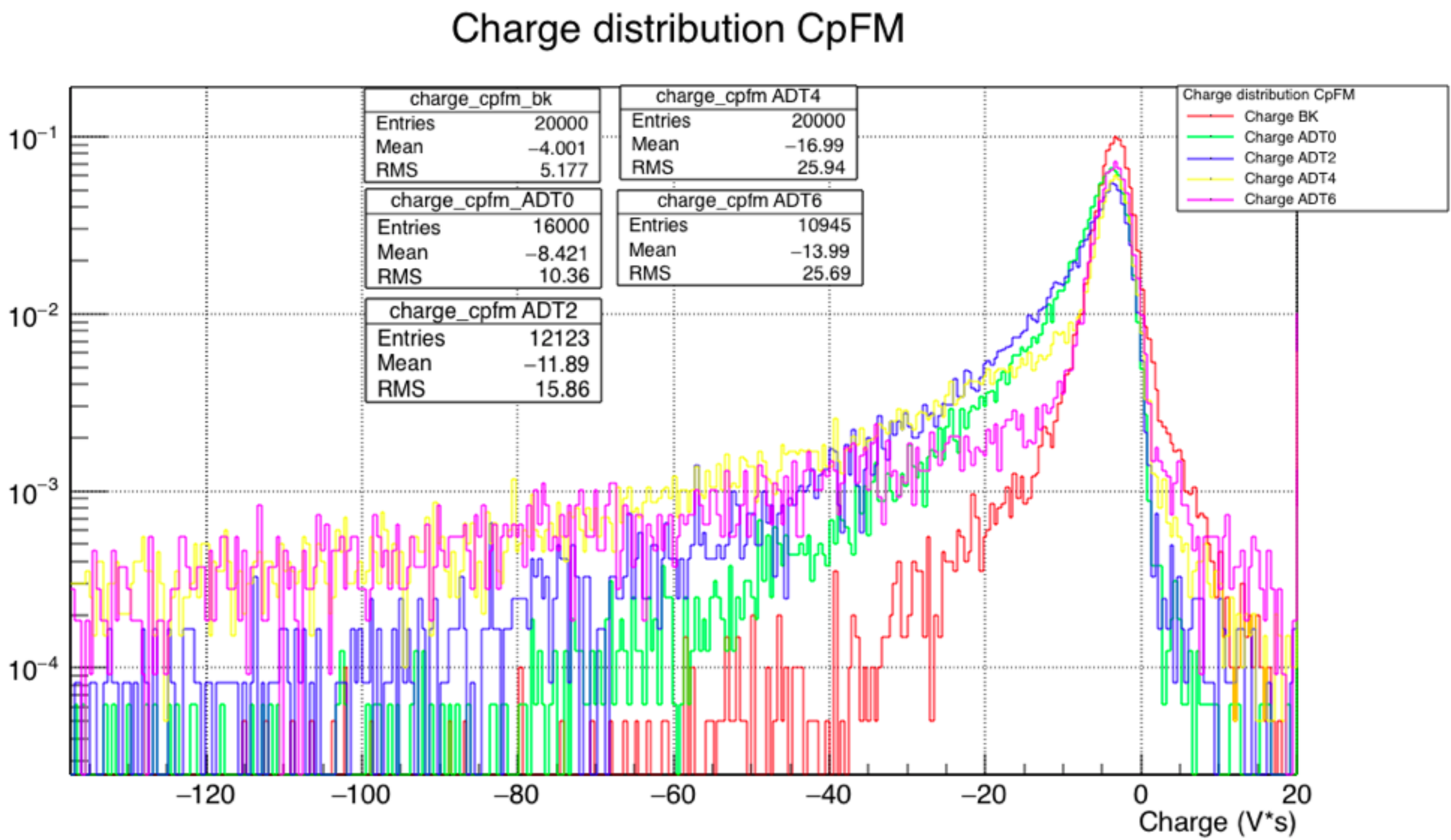
One can calculate the transverse coordinate $x(s_{coll})$ at the collimator location applying the standard transformation matrix M

$$M = \begin{pmatrix} \sqrt{\frac{\beta_{coll}}{\beta_{cry}}}(\cos\Delta\phi + \alpha_{cry}\sin\Delta\phi) & \sqrt{\beta_{cry}\beta_{coll}}\sin\Delta\phi \\ \frac{(1+\alpha_{coll}\alpha_{cry})\sin\Delta\phi+(\alpha_{coll}-\alpha_{cry})\cos\Delta\phi}{\sqrt{\beta_{cry}\beta_{coll}}} & \sqrt{\frac{\beta_{cry}}{\beta_{coll}}}\cos\Delta\phi - \alpha_{coll}\sin\Delta\phi \end{pmatrix} \tag{3.18}$$

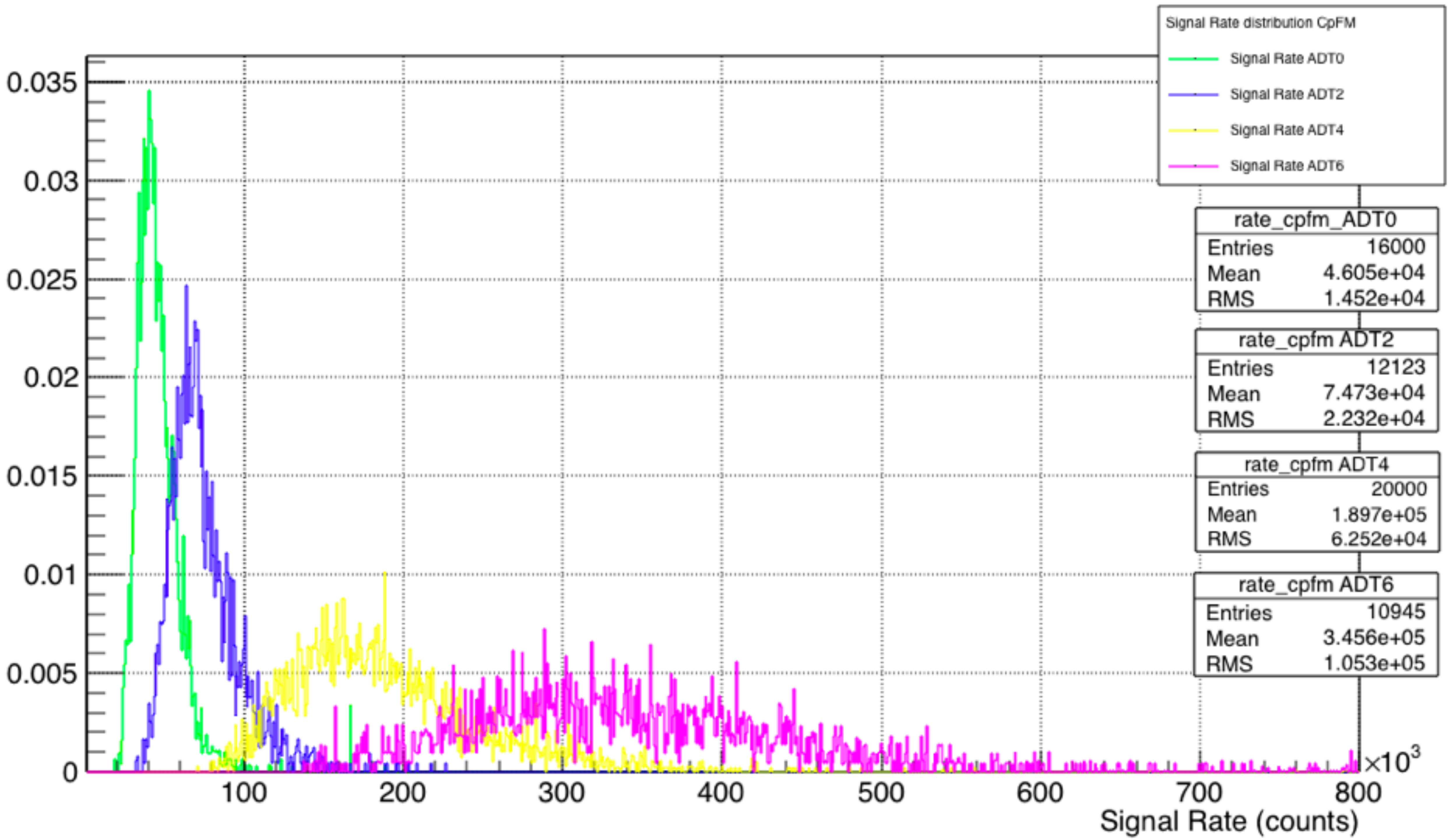
$$\theta_k(s_{coll}) = \frac{x(s_{coll}) - \sqrt{\beta_{coll}/\beta_{cry}}\, x_{cry}\cos(\Delta\phi)}{\sqrt{\beta_{cry}\beta_{coll}}\sin(\Delta\phi)} \tag{3.20}$$

By calculating the equivalent kick associated to the center of the channeling peak c, one then obtains the channeling angle $\theta_{chan} = \theta_k(c)$.

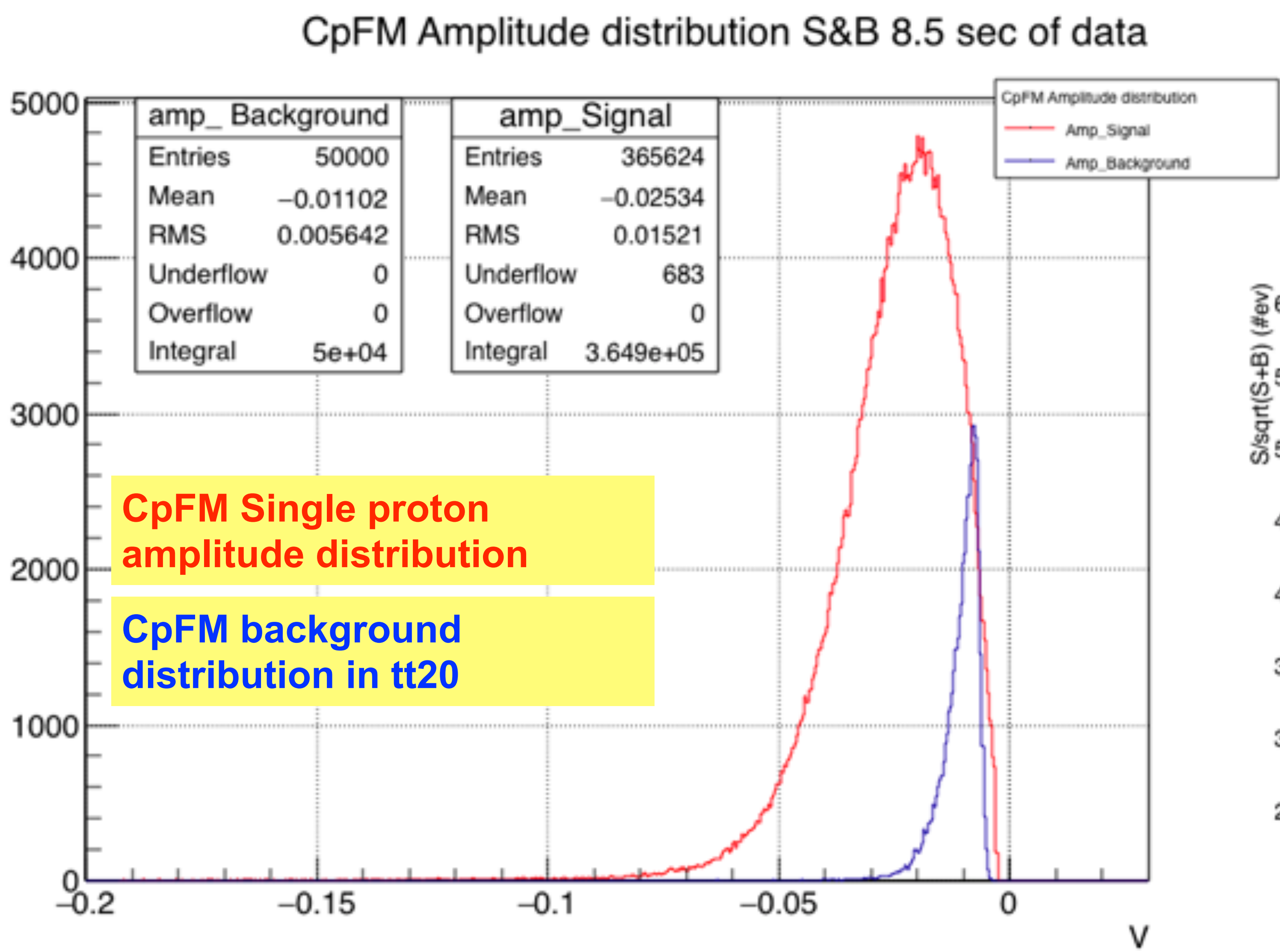
CPFM CHARGE DISTRIBUTION- ZOOM

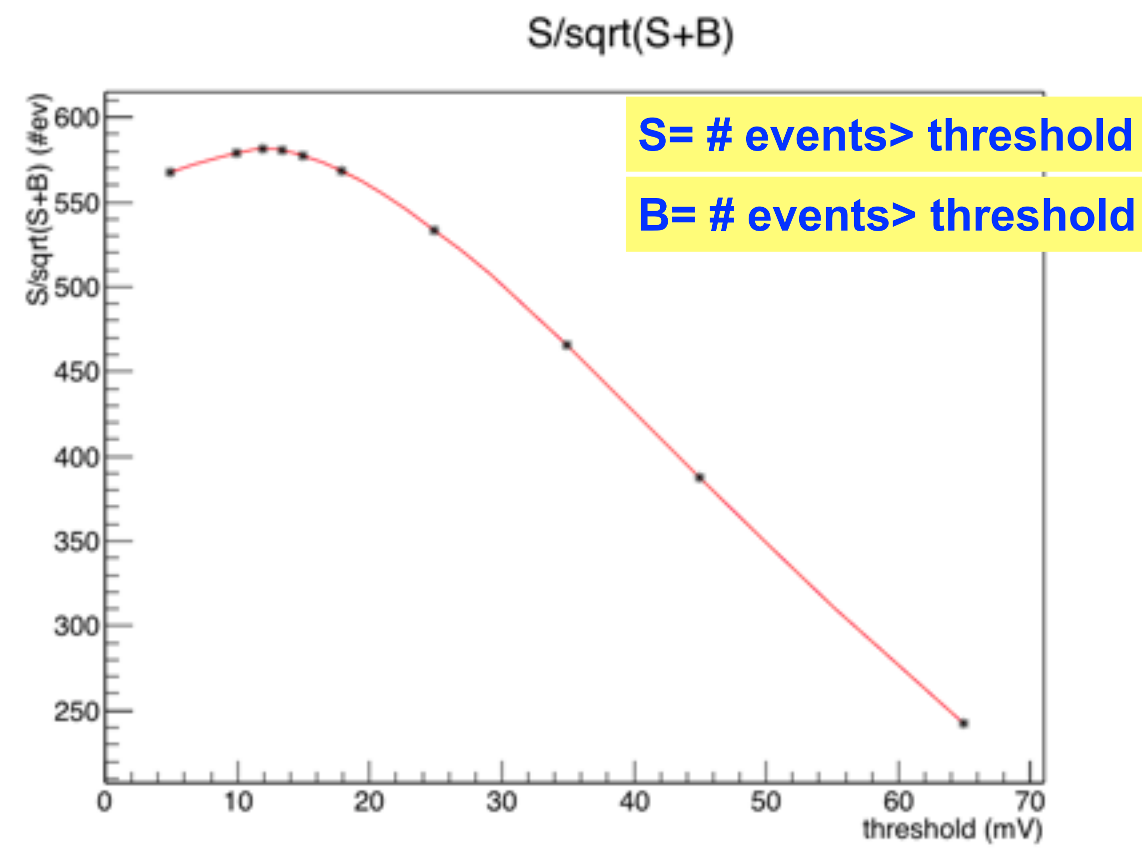


CPFM RATE DISTRIBUTION



CpFM S/B RATIO OPTIMIZATION IN TT20





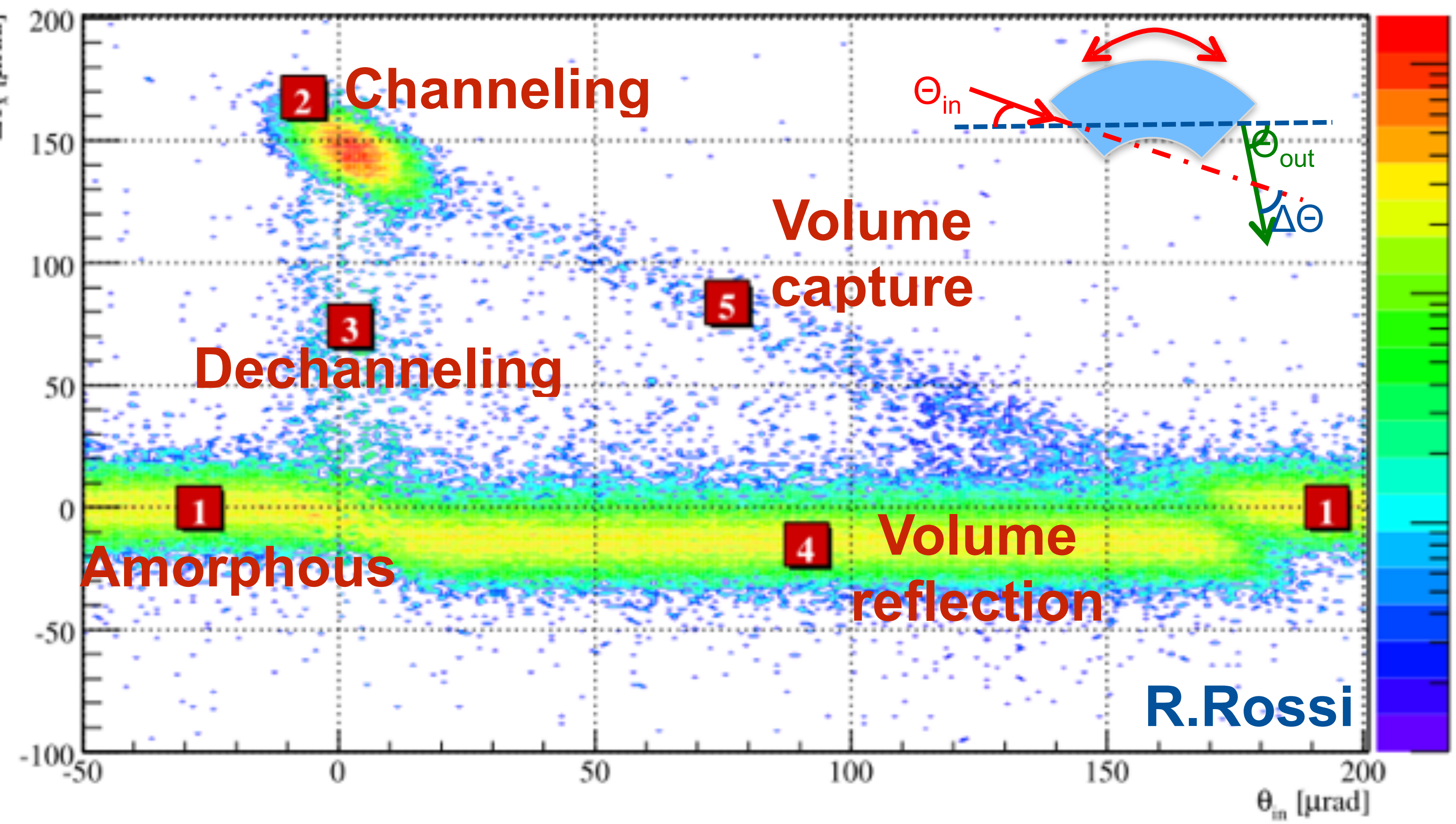
S/sqrt(S+B) vs discriminator threshold

Best choice of the discriminator thereshold -12 mV

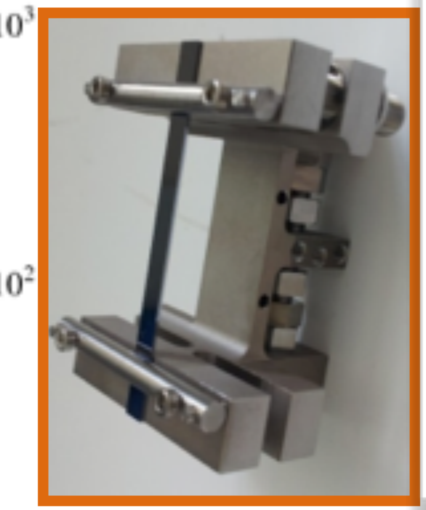
UA9 Experiment: Single-pass measurements observation of channeling in SPS-H8

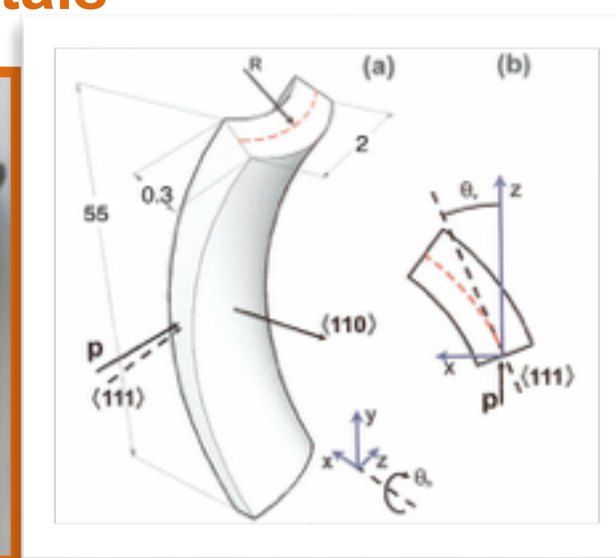
Since 2009 the UA9 Experiment investigates channeling effect and the feasibility to use bent crystals to steer hadron beams at CERN-SPS.

400 GeV protons H8 beam test

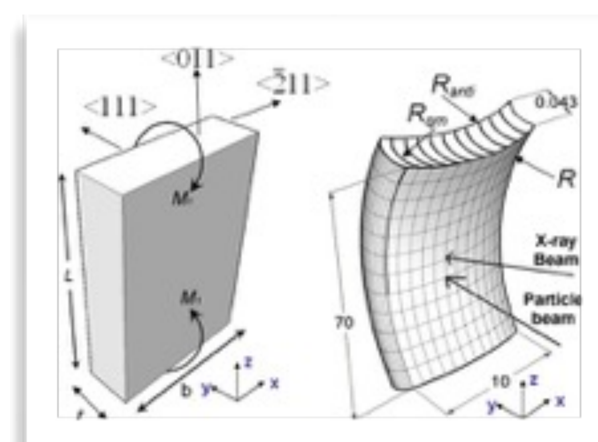


Strip Crystals





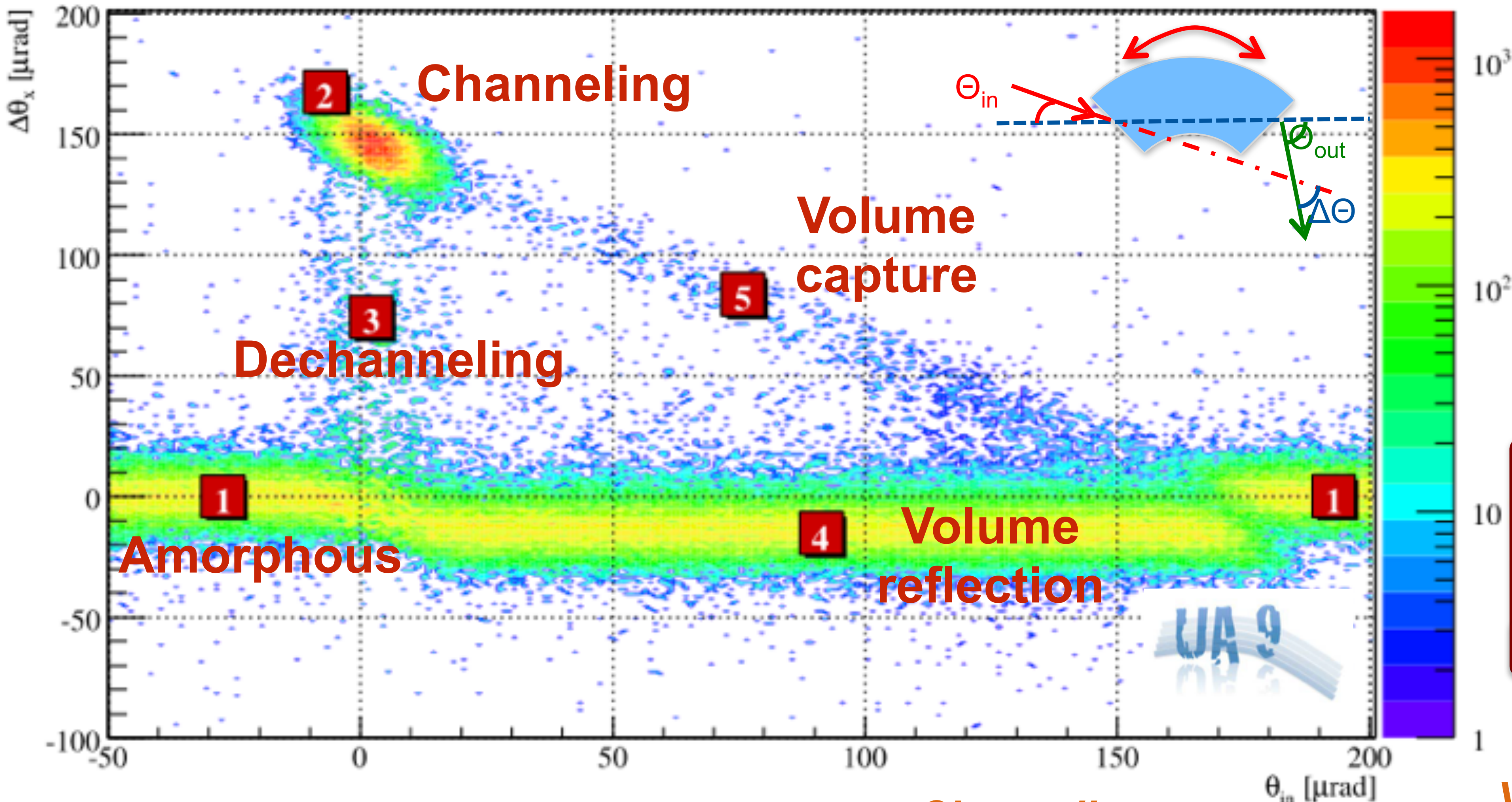
Quasi-mosaic crystals



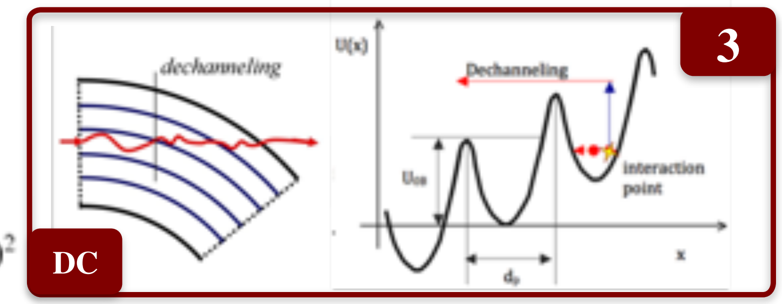
For a LHC designed crystal the channeling efficiency measured in H8 is around 60%

Other Charge particle interactions in bent crystals

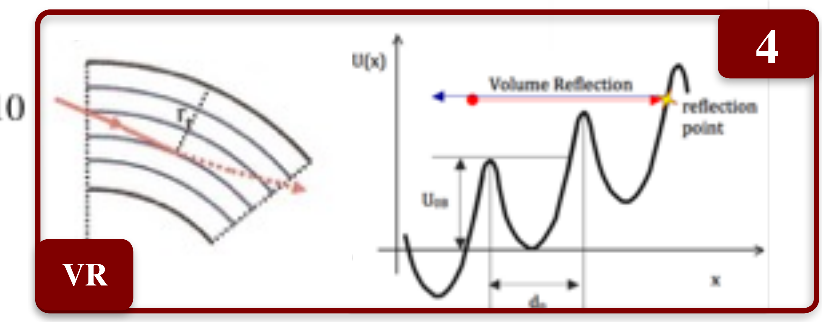
Single-pass measurements in H8-SPS extraction line - UA9 Experiment



Dechanneling



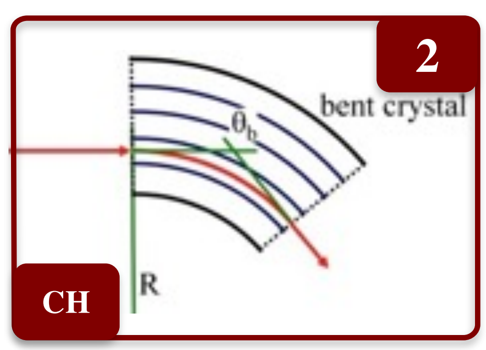
Volume reflection



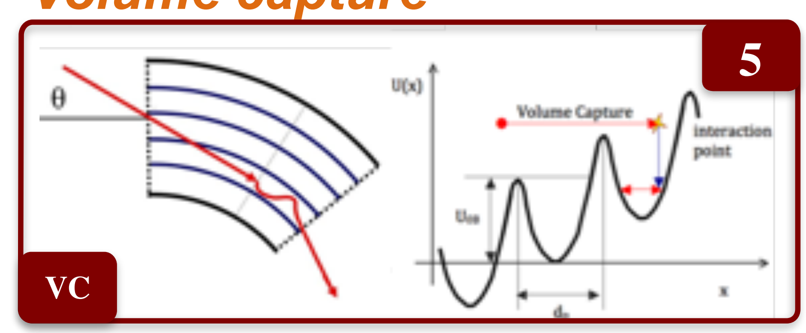
Amorphous

1
- multiple scattering
- inelastic interactions

Channeling



Volume capture



SPS-BA5 setup