Beam merging techniques assisted by curved crystals

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Ph.D. in Accelerator Physics
Cycle XXXVIII

Outline of the Presentation

1) Beam Merging with bent crystals
   - Idea and implementation in H8

2) UA9 Experimental setup design and simulations
   - Experiment KPI (Key Performance Indicators)
   - Merging efficiency after introducing imperfections

3) TimePix3 measurements for Channeling detection in SPS H8 NA
   - Differential Data Analysis
   - TimePix3 detector measurements (standalone & with UA9 tracker)

4) Conclusions

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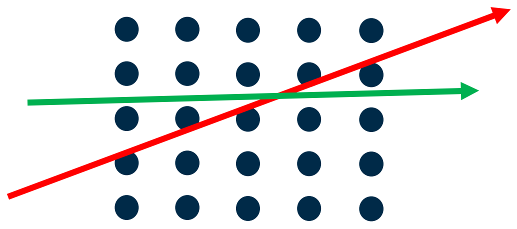
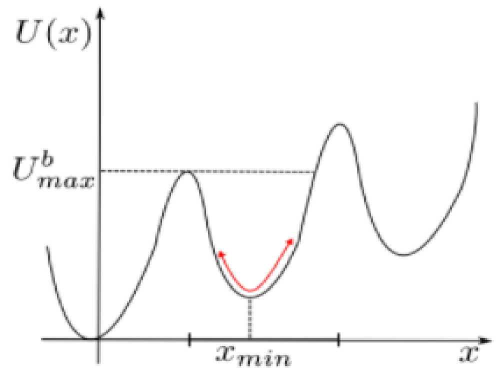
Beam Merging with bent crystals

Coherent processes in bent crystals (1/2)

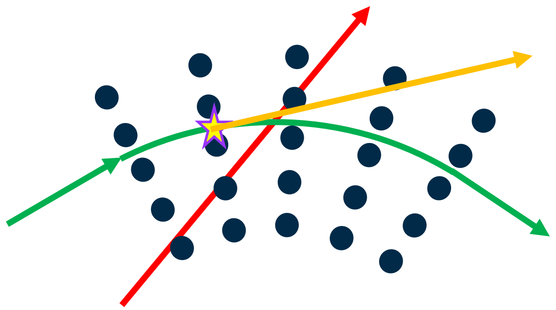
- A particle impinging on a crystal behaves differently depending on its alignement wrt crystal structure
  - Amorphous or Coherent Behaviour



- Particle aligned with the crystal planes
  - Critical Angle $\theta_c = \sqrt{2U/E}$ for Channeling
  - capture inside the tunnel if particle imapcts Cry with $\theta < \theta_c$

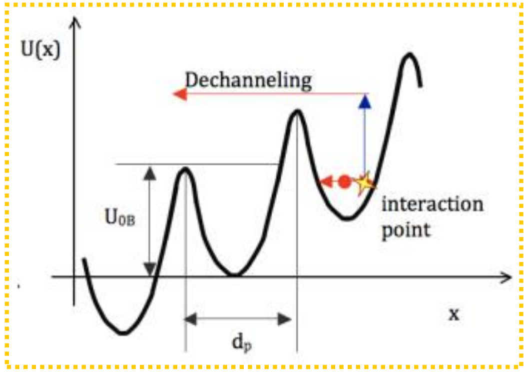


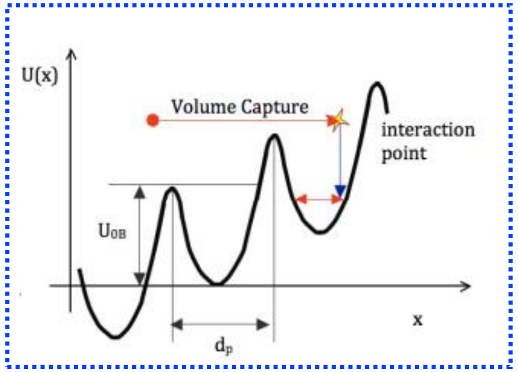
- Bent crystal → Particle deflection
- If the particle leaves the Channeling condition
  - Dechanneling

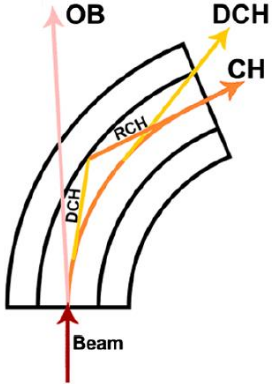


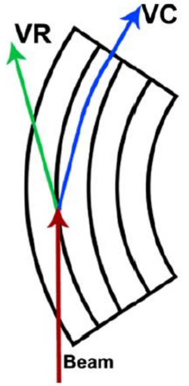
Coherent processes in bent crystals (2/2)

- Dechanneling (DCH), Volume Capture (VC) and Rechanneling (RCH)
  - No more CH condition DCH can happen (sometimes followed by RCH)
  - VC conceptually similar to RCH

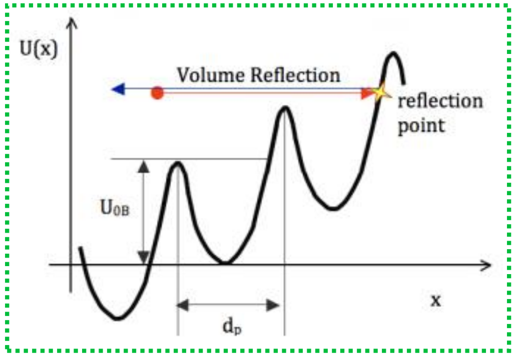








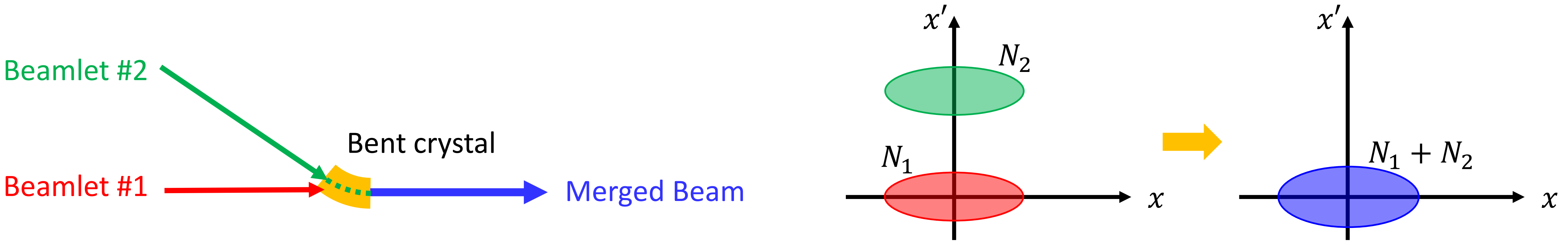
- Volume Reflection (VR)
  - Charghed particles reflected by the crystal potential barrier



- Is it possible to exploit Coherent Processes to merge beams?

Beam merging Idea

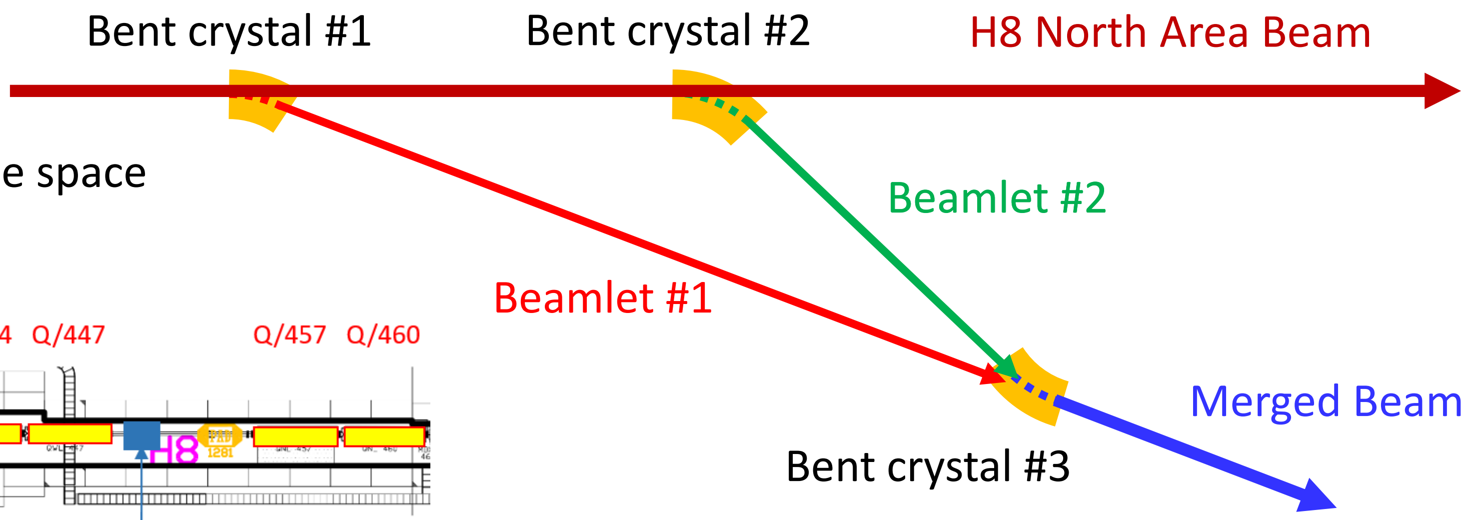
- Two beams incoming from different directions, merged by bent crystal
- A bent crystal act as an «Angular Filter», deflecting particles by Channeling
  - No dramatic emittance increase after merging!
  - Beamlet #1 → AM/VR → wider divergence after crystal   Beamlet #2 → Channeling
  - Main scheme and (x, x') phase space plots in the ideal case



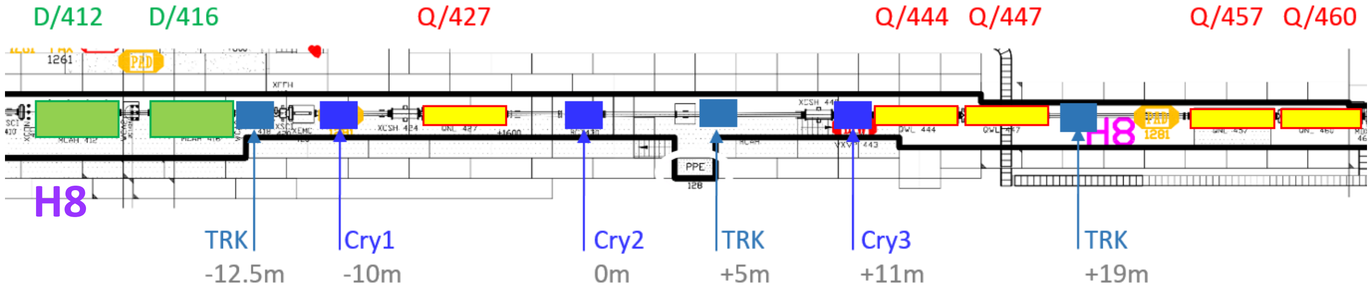
  - How is it possible to implement this merging scheme?

Beam merging proposed setups

- Problem: A Two-Converging Beamlines setup does not exist
  - Solution: Bent crystals → create two beamlets which will converge at another point
  - Third crystal at the convergence point → here the merge will happen!
- CERN SPS H8 extracted Beamline is the UA9 experimental site since decades



Main limitation to this design:
The H8 Beamline Footprint define the available space
~30 m clearance with magnets along the line



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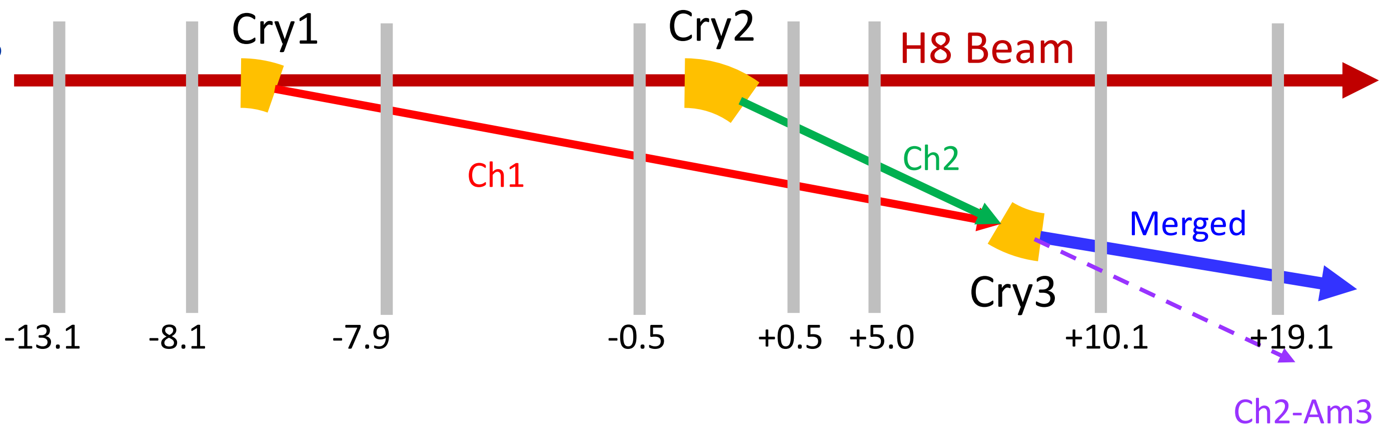
UA9 Experimental setup design and simulations

From the idea to the simulations

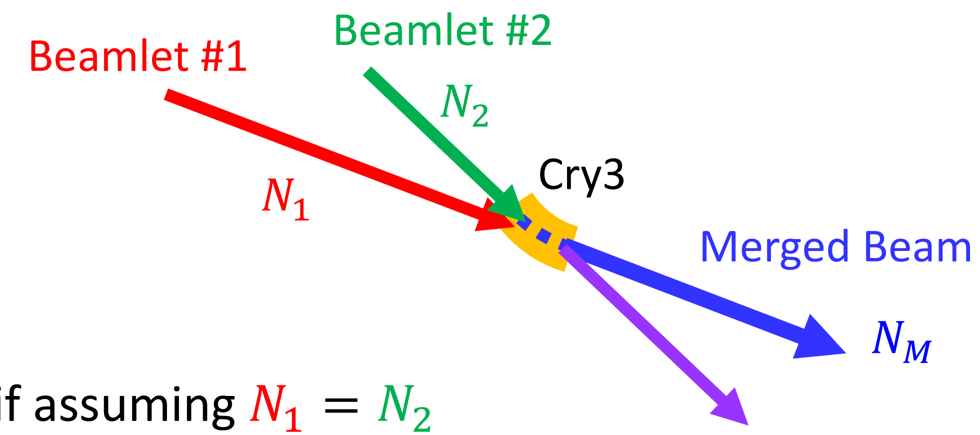
- Geant4 Toolkit used to perform the simulation of the UA9 merging setup
  - Channeling implemented by E.Bagli et al (INFN-Fe) since G4 10.05.p01
- Simulations campaign carried on BEFORE decicing the effective UA9 setup
- «Baseline» unperturbed Configuration scheme
  - Reference frame centered on Cry2 → Cry1 and Cry3 placed at -8 m and +10 m
  - Bending Angles: $\theta_{b1} = 1\ \mu rad, \theta_{b2} = 1.8\ \mu rad, \theta_{b3} = -0.8\ \mu rad$ to close the «triangle»

- Realistic H8 Beamline Parameters
  - Beam Spot: $2 \times 2\ mm^2$ RMS
  - Divergence: $40 \times 30\ \mu rad$
  - Energy: $180\ GeV$



Beam Merging Efficiency

- Focus only on the Beamlets #1 and #2 and the Cry3
  - Beam #1 enters Cry3 in AM/VR → Fully passes through Cry3 an go almost straigth
  - Beam #2 enters Cry3 in Channeling → Some particles will be bent, some other will go in AM
- Beamlet #1 and #2 are already in Cry3 Acceptance
  - Same crystal entry face width for all the crystals. Beamlets #1 and #2 have $\sigma'_x = \theta_c$
- Merging Efficiency $\varepsilon_M = \frac{N_M}{N_{Ch1}+N_{Ch2}}$



✓ For the Baseline Configuration → $\varepsilon_M = 85\%$

- Which is quite good! Lose only 30% of Beam #2, if assuming $N_1 = N_2$

Introducing perturbation

- What happens if there are Bending errors $\delta\theta_b$ on the crystal
  - Small $\delta\theta_b \rightarrow$ The ε_M and N_M will be reduced
  - Big $\delta\theta_b \rightarrow$ Beam #1 and/or #2 could not impact Cry3 anymore
  - Cry3 should be shifted laterally if $\delta\theta_b$ is too big

- How to modify the UA9 setup if bending errors on the crystals are present
- How can the baseline configuration be recovered
  - Bending errors can be compensated by changing the crystals orientation $\delta\theta_r$

- Rotations must NOT be too high
  - otherwise less particles impinging the crystals will be into their Channeling Acceptance
  - The Beamlet #1 or #2 or the Merged one would be less populated for big rotation angles

Introducing perturbation

- Apply Bending errors $\delta\theta_b$ and rotations $\delta\theta_r$ to the crystals
  - Study how merging efficiency (ε_M) andmerged beam population (N_M) will be reduced
  - θ_{rms} → Quadrature sum of all the source of angular errors

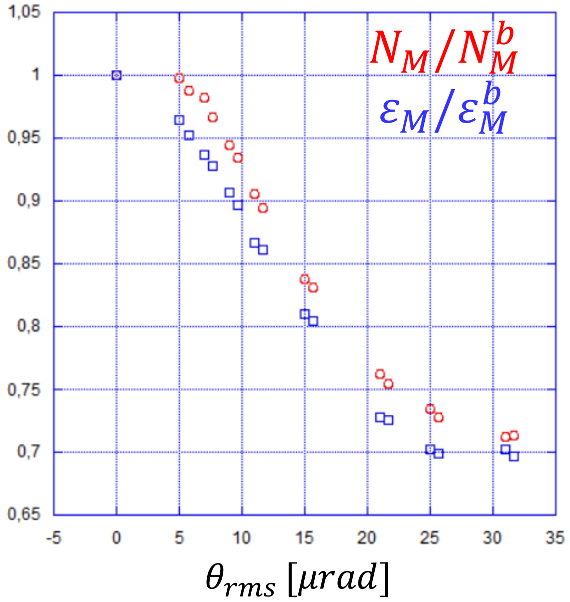
N_M/N_M^b → Ratio of the merged beam population when applying the angular perturbations with respect to the Baseline case (no perturbations applied)

$\varepsilon_M/\varepsilon_M^b$ → Same but for the merging efficiency

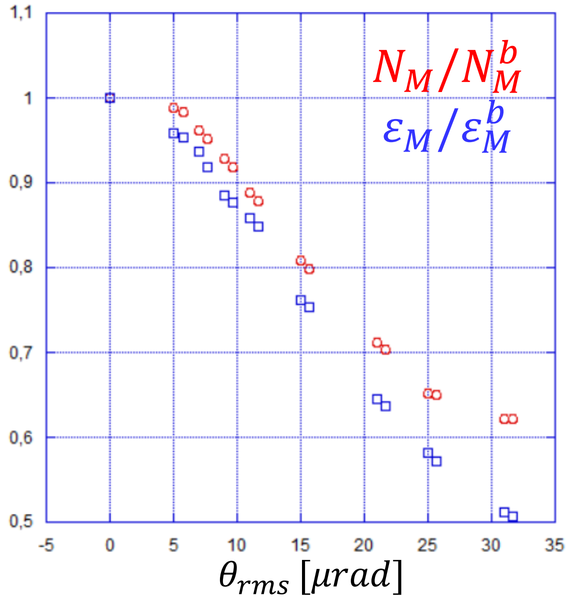
ε_M and N_M are still acceptable (30% losses wrt Baseline) only if $\theta_{rms} < 15 \div 25\ \mu rad$

Keep crystal $\delta\theta_b$ BELOW $\sim 20\ \mu rad$

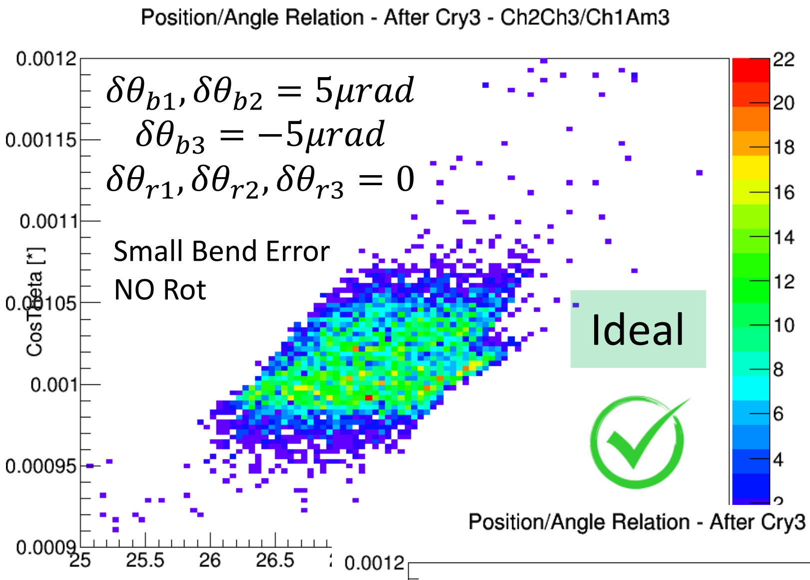
Bending Errors Only

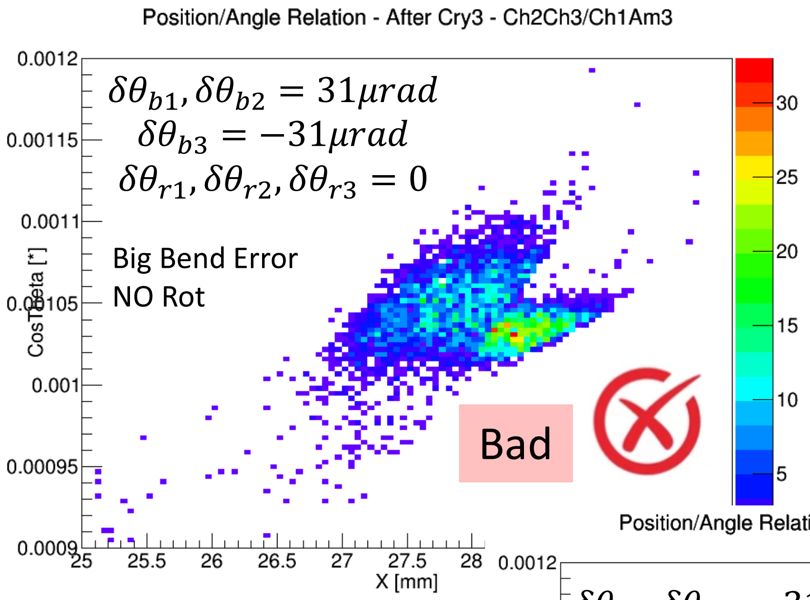


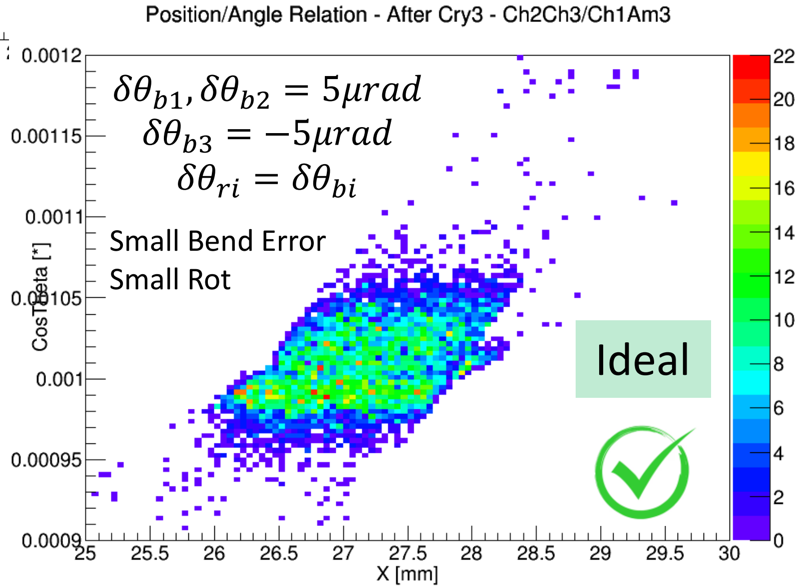
Bending Errors & Rotation



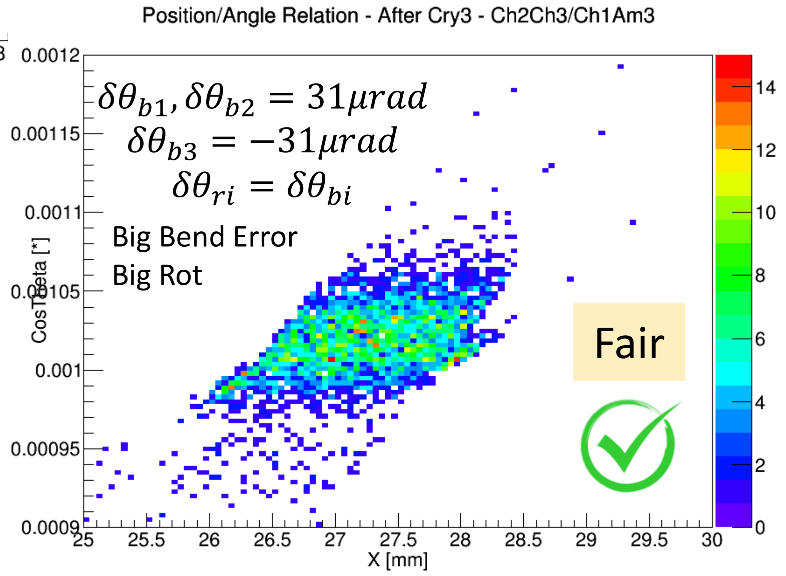
Recombined beam in the phase space







Fewer particles in the Merged Beam…



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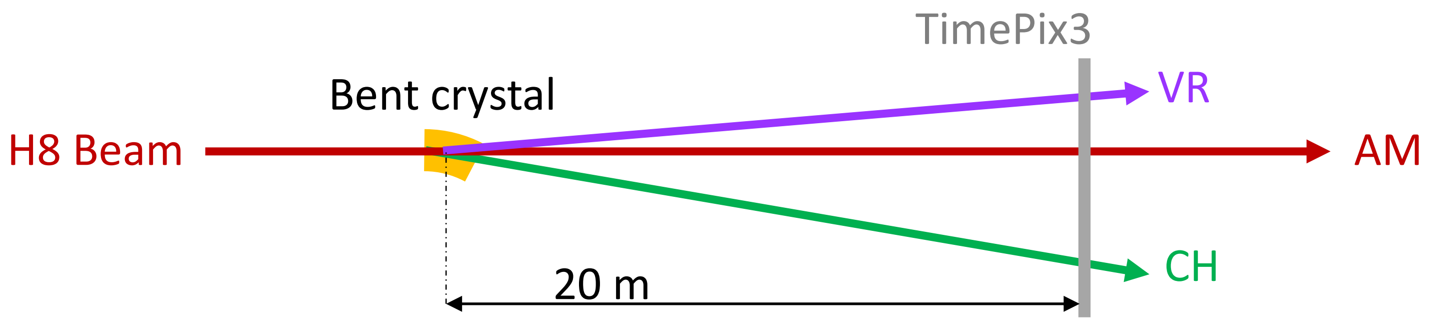
TimePix3 measurements for Channeling detection in SPS H8 NA

The TimePix3 in a nutshell and its application

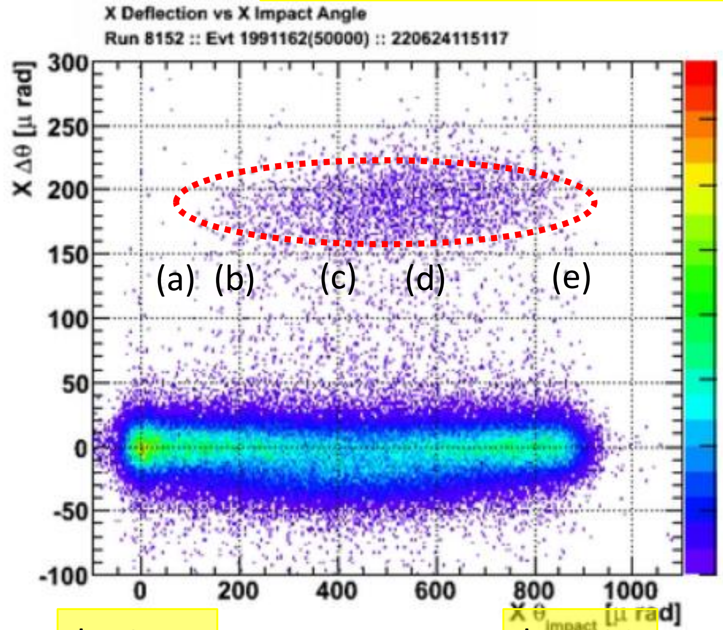
- Small and portable detector
  - 14x14 mm^2 sensitive area, 256x256 pixels, 55 μm pixel pitch, 100 μm thick Si sensor
  - ToA, ToT, Itot functionalities → Beam X/Y Profiles, Time distribution and energy deposit
  - Acquisition in «Single Frame» or «Cumulative» mode (stacking more frames per single DAQ)
- TimePix3 can be used as online beam monitor
- Useful to perform the Angular Scan
  - Cumulative mode → See how the beam spot size and morphology change over time
  - Real time CH/VR peak emerging from the Background when rotating the crystal (June 2024)
  - Scheme of the setup



TimePix3 angular scan – Compare with Tracker

- Angular Scan performed using the TimePix3 and the UA9 Tracker Standalone
  - Large impact angle acceptance bigger than $\theta_c \rightarrow$ Twisted crystal
  - At different time, different parts of the crystal are in Channeling

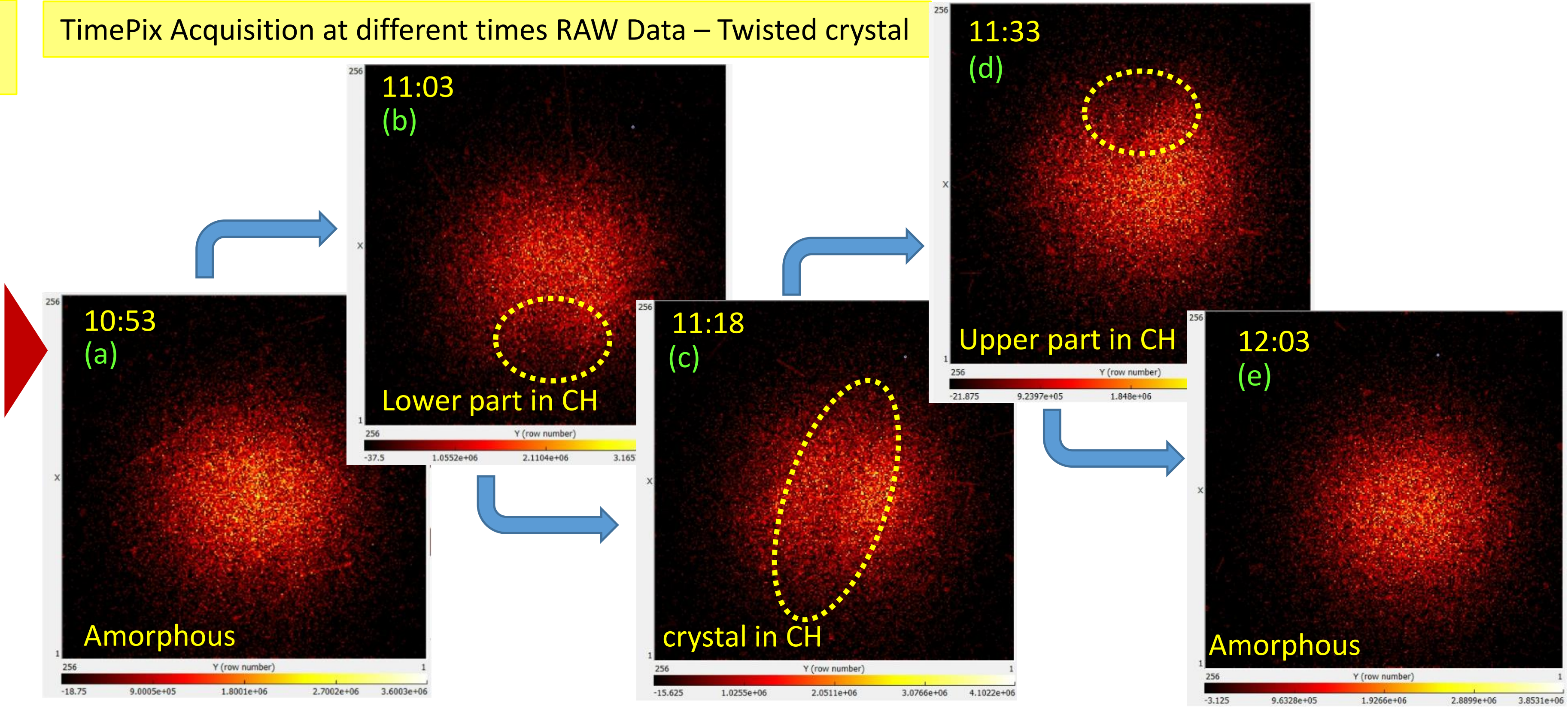
Angular Scan with the Tracker
Twisted crystal



h 10:47
START SCAN

h 12:06
END SCAN

TimePix Acquisition at different times RAW Data – Twisted crystal

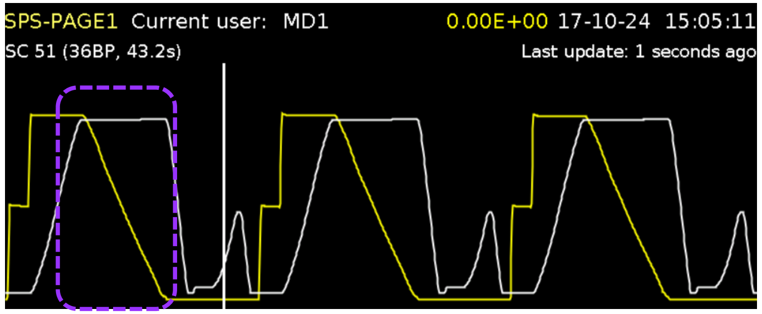


Bending Angle measurement with TimePix3

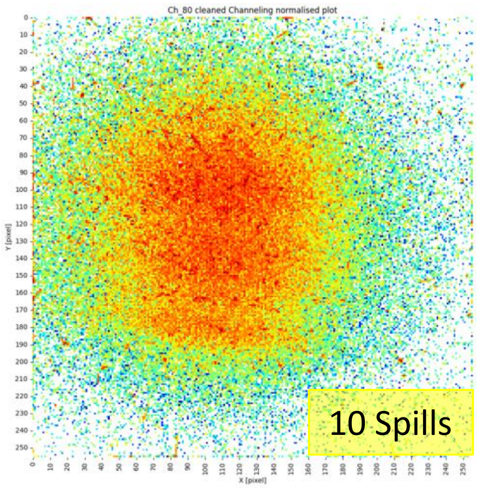
- Readout in «Frame» mode → Beam X/Y distribution
  - Mandatory to record almost 10 Spills, otherwise the SNR is too low and data cannot be analyzed (more spills is better, i.e. 100)
  - The two Runs are cleaned, normalized, and then subtracted.

✓ Crystal bending angle: 170 μrad from previous UA9 measurements

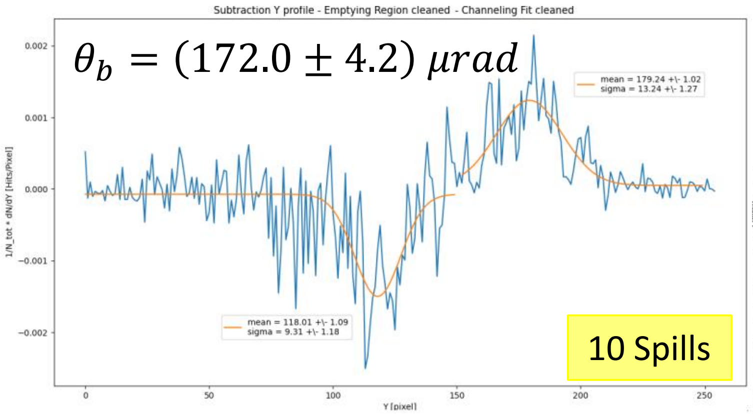
SPS Page 1 – SFTPRO Supercycle



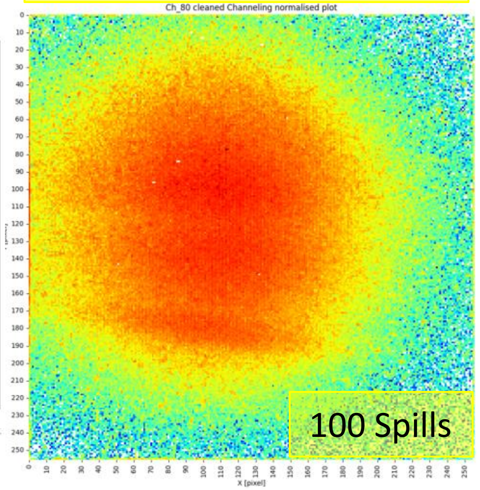
2d-plot Run Channeling



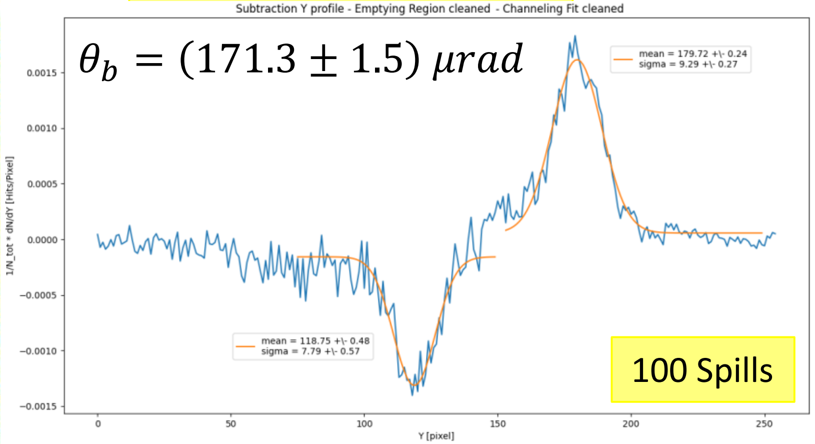
Subtraction Y-Profile



2d-plot Run Channeling



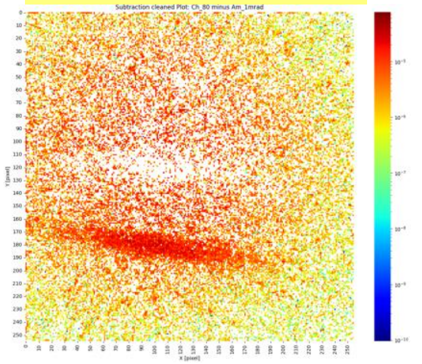
Subtraction Y-Profile



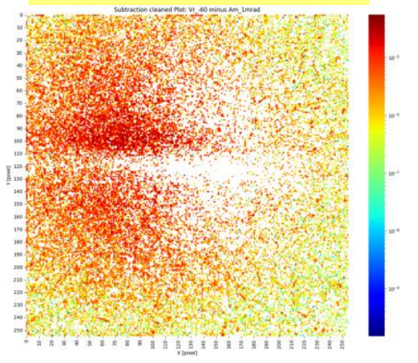
100 Spills best CH and VR Runs

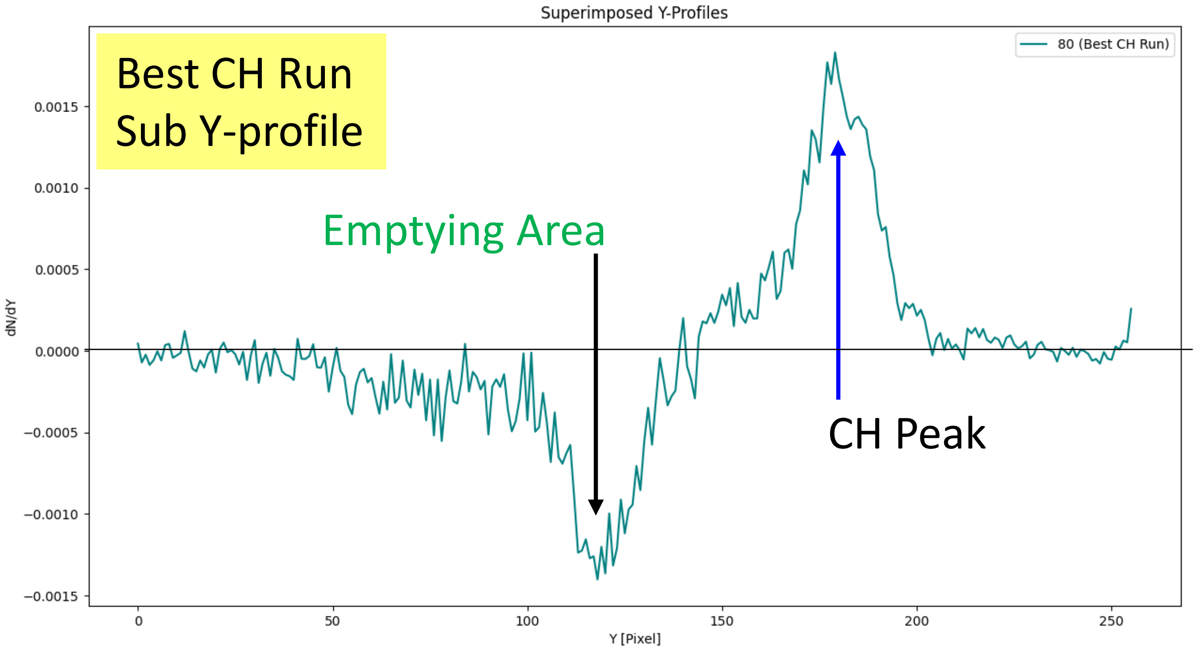
- These two Runs are the best in CH and VR orientation
  - TimePix3 can be used to measure precisely CH and VR angle
  - In these plot the CH/VR-AM subtraction is applied
  - VR Angle measurement: $\theta_{VR} = (52.7 \pm 3.2)\ \mu rad$

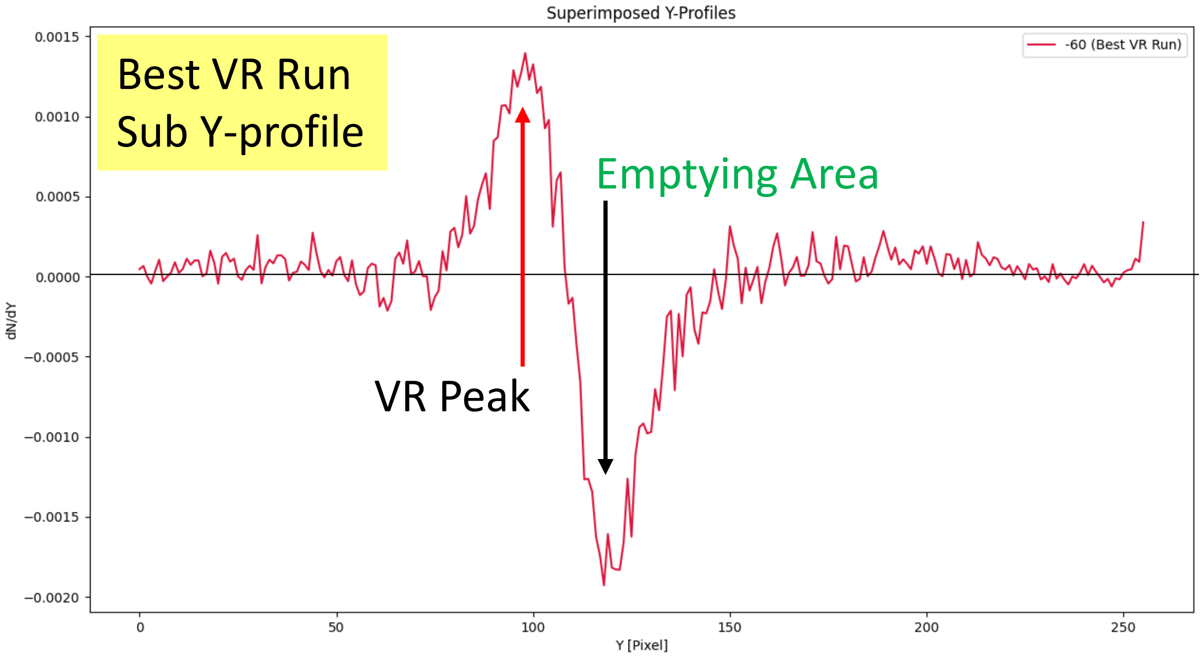
Best CH Run 2D Sub



Best VR Run 2D Sub

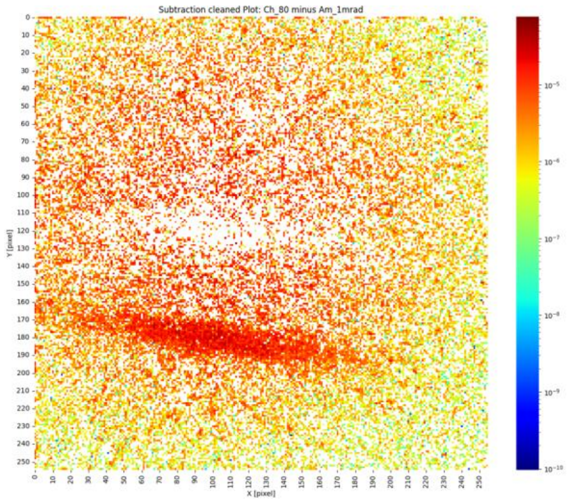




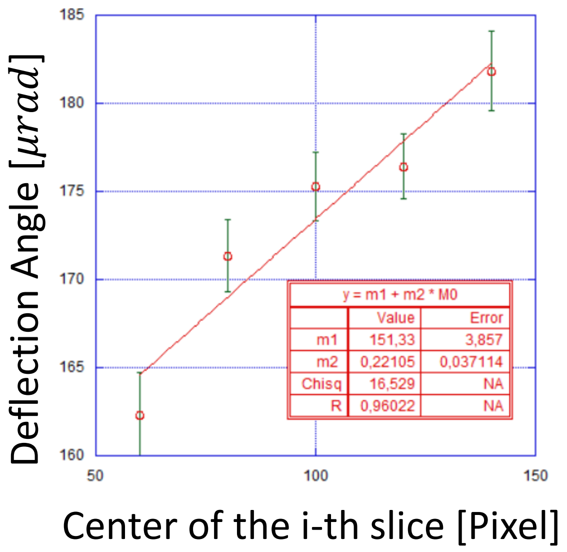


Crystal Torsion measurement with TimePix3

- SPS-Type Crystal with known torsion defect
  - measured with UA9 Tracker: $T \sim 4\ \mu rad$ (September 2023 – May/June 2024)
- Beam impacts on the crystal at different heights
  - CH particles are deflected at different angles despite Cry Channeling angle is the same!
  - This means there is a Twist effect!
  - Key goal: Obtain bending angle slice-by-slice to compute the torsion



5 Slices



Slope $(0.22 \pm 0.04) \mu rad/pxl$

Torsion $(4.04 \pm 0.07) \mu rad/mm$

Compatible with Tracker

4
Conclusions

Now this is not the End

It is not even the Beginning of the End

But it is, perhaps, the End of the Beginning

- W.Churchill 10 Nov 1942

Conclusions

- The beam recombination scheme with crystals can be implemented in NA H8
  - From simulations → Merging efficiency is 85% in the unperturbed case
  - Maximum tolerance for bending errors and crystal rotation shoud not exceed $15 \div 25\ \mu rad$
- TimePix3 detector can be used «in parallel» with the Tracker or either standalone
  - Excellent results while performing the Angular Scan
  - Easily allows to identify AM, VR, CH and Transition regions
  - Differential Analysis → Powerful tool to measure crystal CH/VR angle
  - All the results obtained are compatible with the one obtained by the UA9 Tracker
- Plans for the future
  - Implement in H8 the Cry2/Cry3 Chicane (Oct 2024) and the full setup (Early 2025)

Thank You for your attention

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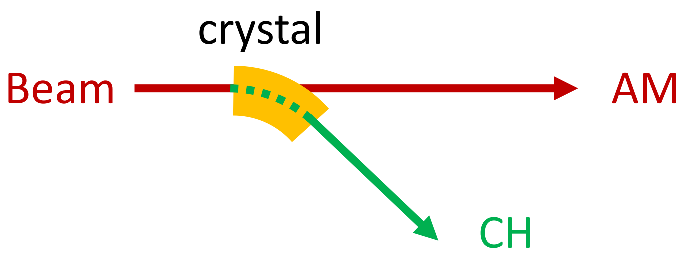
Many thanks to my Ph.D. Supervisors for their precious advices, passion and dedication

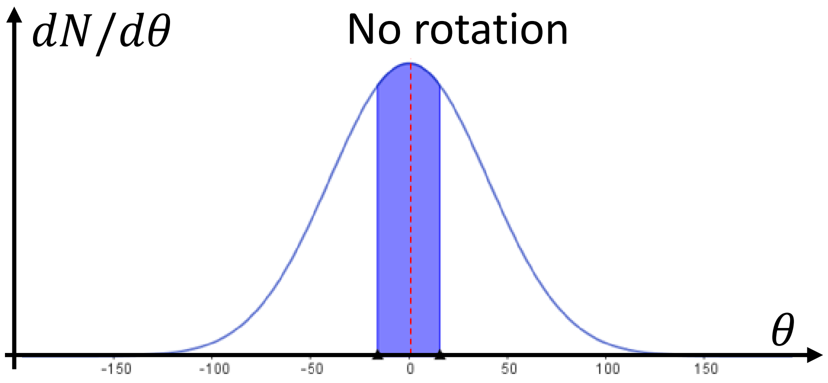
Many thanks to GC,LS (and DDR former) for the smooth administrative operation of our Ph.D.

Backup Slides

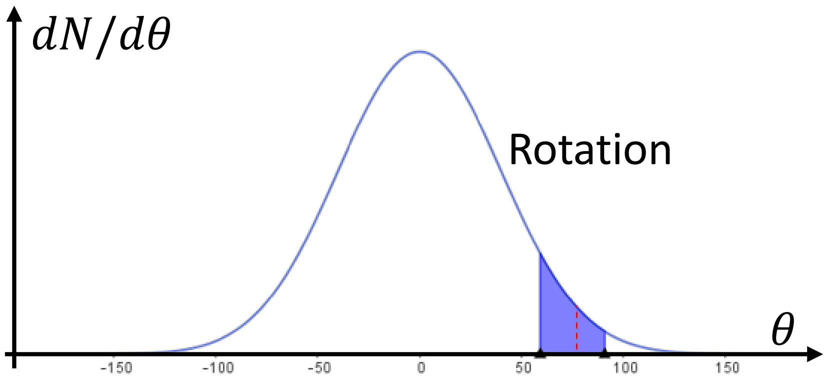
Single-crystal KPI



- Determine Single-crystal Channeling Efficiency
  - Beam $\sigma'_x = 40\ \mu rad$; crystal $\theta_c = 15.8\ \mu rad$.
  - Only 30.7% of the beam in the CH Acceptance
  - Deflection efficiency for Cry1,2,3 is in range $\sim 60 \div 70\%$

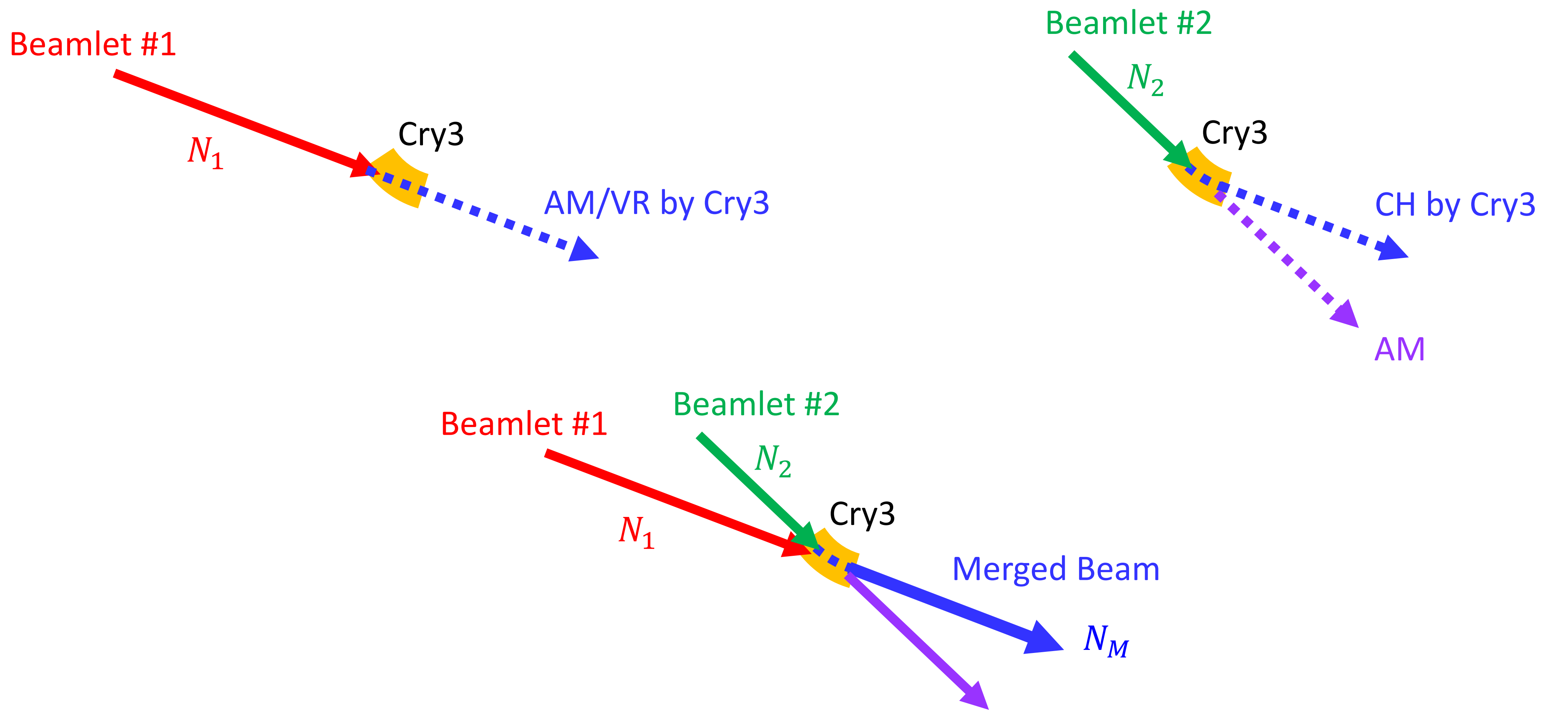


- Effect of Cry Rotation on ε_{CH}
  - Even less particles in the Acceptance
  - i.e. rotatyng Cry by $75\ \mu rad$ only 5% of particles in Acceptance

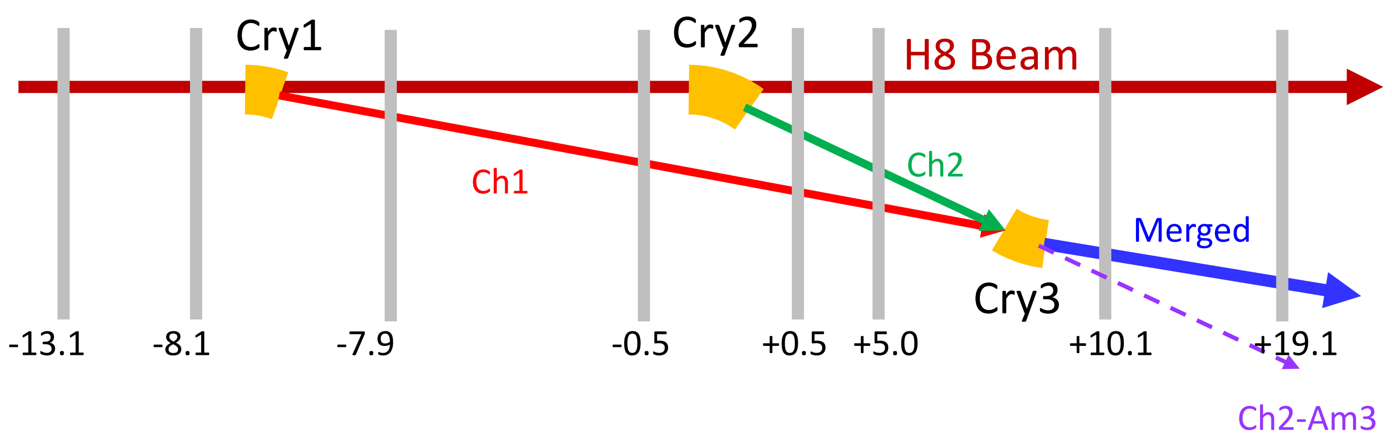


- Effect of Cry Bending on ε_{CH}
  - Sligthly increased Dechanneling if curvature radius get smaller

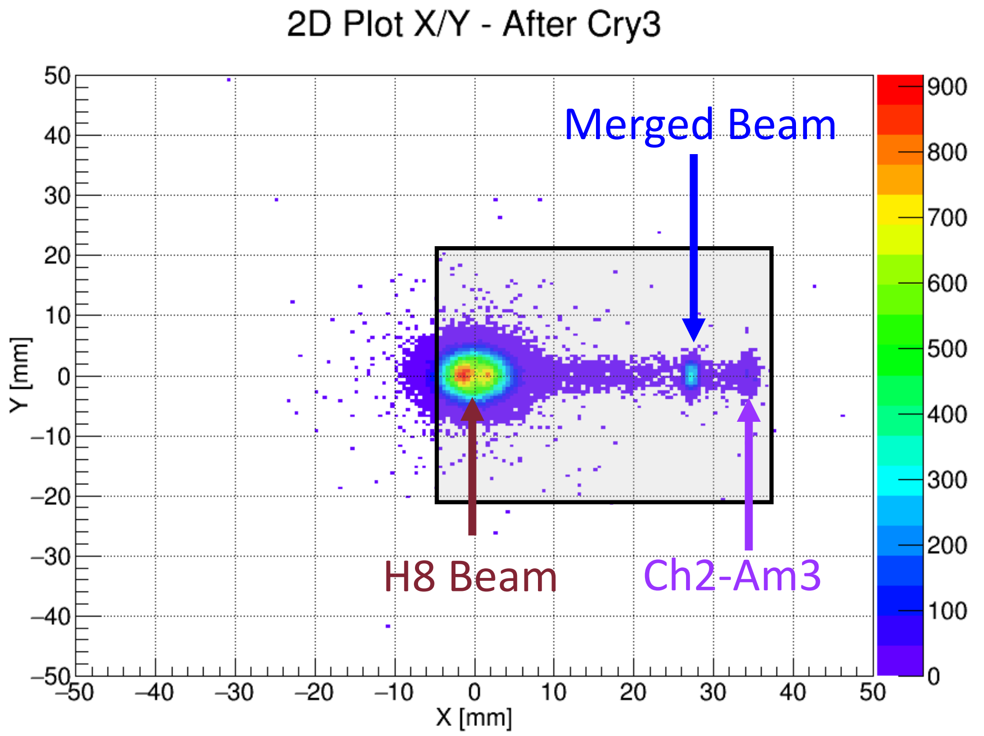
Beam Merging scheme



Beams seen by the Tracker P6 (+19.1 m)

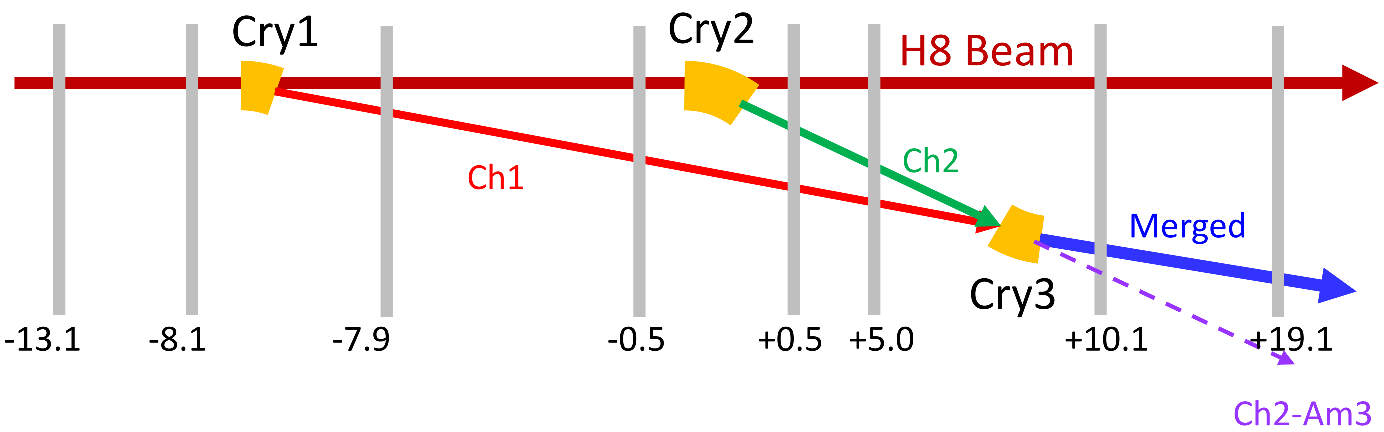


- Geant4 Setup
  - Tracker Stations $42 \times 42\ mm^2$
  - This constrain bending angles

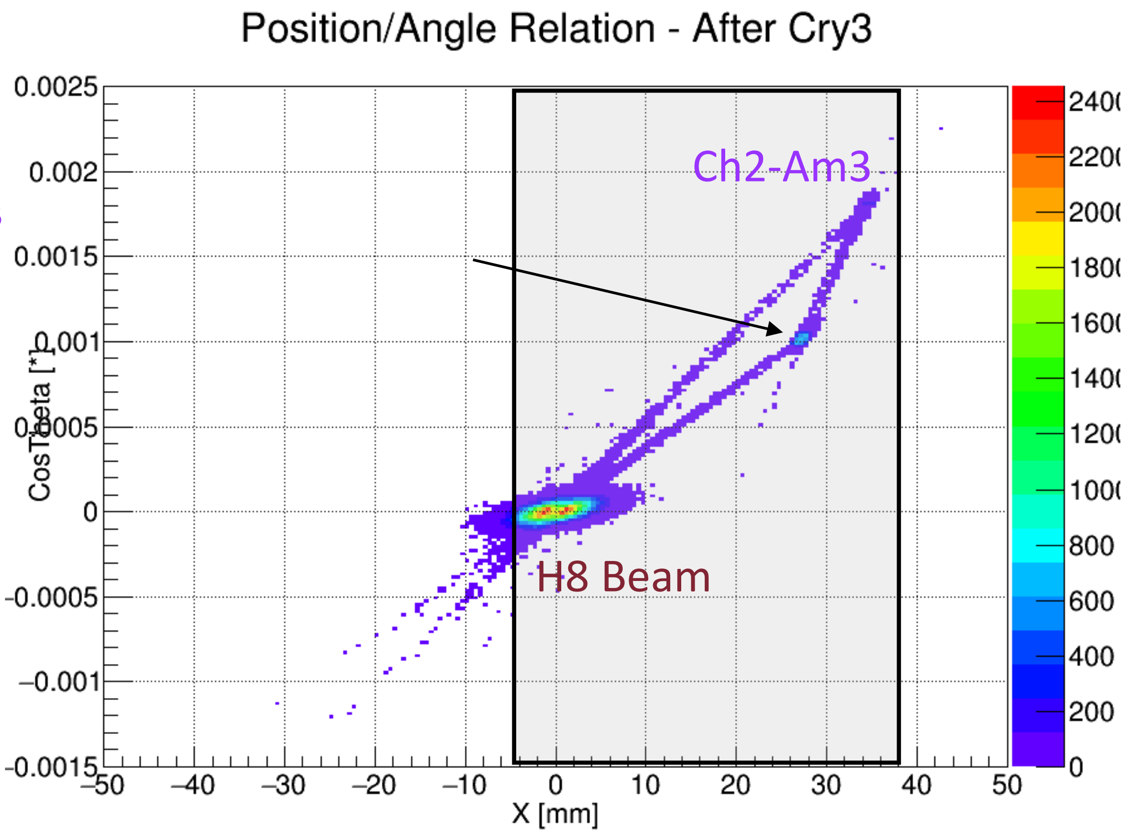


- What does the most downstream Tracker Station observe (X-Y 2d-Plot)
  - H8 Circulating Beam
  - Merged Beam (Ch1-AM/VR3 + Ch2-Ch3)
  - AM componet of B2 after Cry3 (Ch2-AM3)

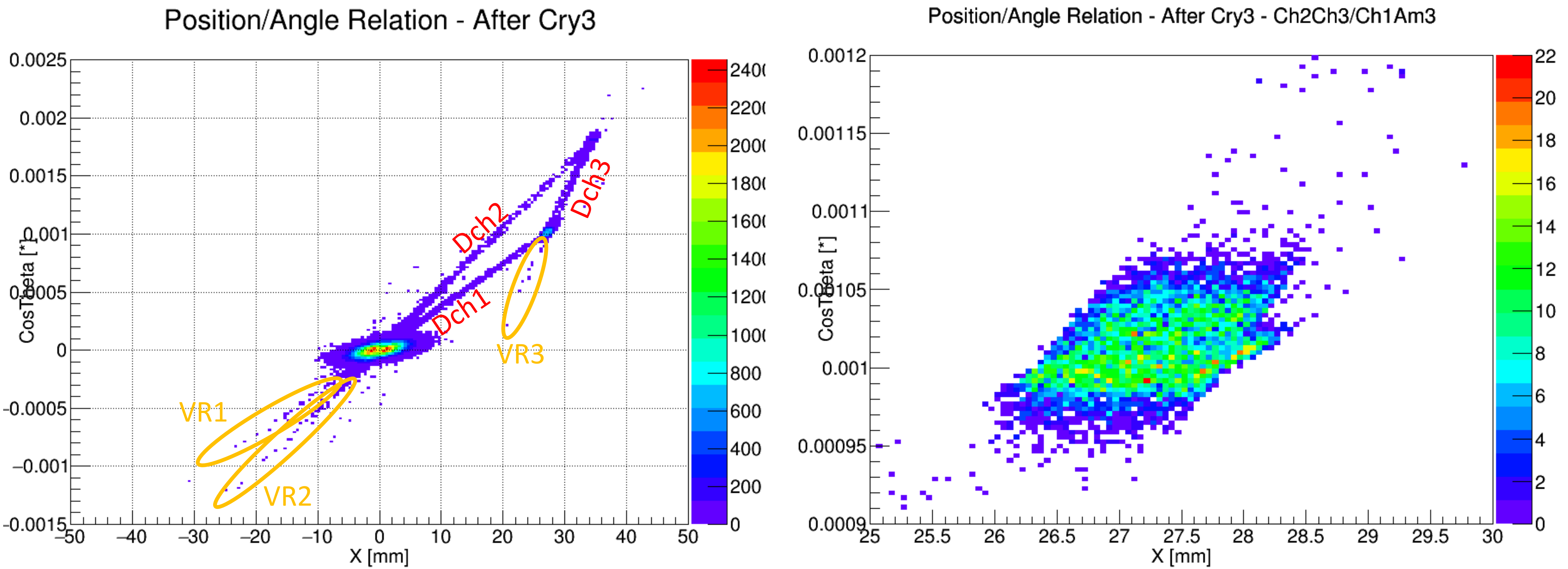
Phase Space plot at P6 (+19.1 m)



- The Circulating Beam goes straight
  - $\cos\theta \approx 0$ and $x \approx 0$
- The Ch1-Am/VR3 Beam goes at 1 $mrad$
  - Impacts Plane6 in $x = 27.1\ mm$
- The Ch2-Am3 Beam goes at 1.8 $mrad$
  - Impacts Plane6 in $x = 34.8\ mm$

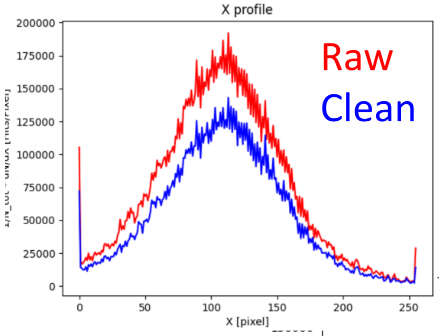


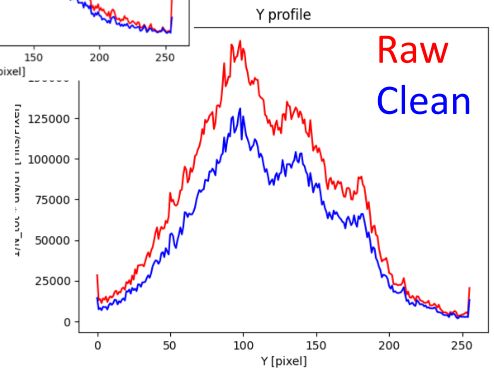
Phase Space plot at P6 (+19.1 m)



TimePix3 Differential Data Analysis

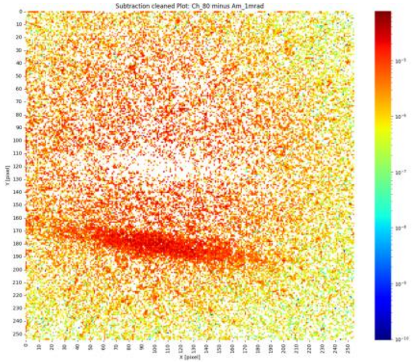
- Necessary Runs to perform the Analysis
  - DAQ in «Frame» mode → One Run with Crystal in AM and one in CH or VR orientation
  - Clean (eliminate frames with spikes) & normalize the two Runs separately
  - Subtract the 2d cleaned beam distributions
  - Obtain the Y profile → Fit the CH or VR peak and the Emptying Region → Compute CH/VR Angle



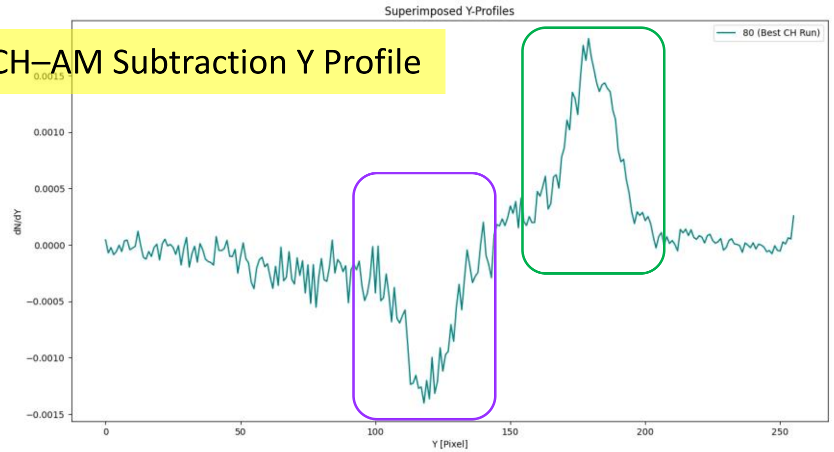


Raw and Cleaned data
X/Y Profiles for CH Run

CH–AM Subtraction 2d Plot



CH–AM Subtraction Y Profile



Transition Regions

- One Run (-60) is pure VR, the other three Runs (30, 40, 50) are at CH/VR Transition

Very effective to check the crystal alignment in real time if the Tracker does not work