Analysis of the T-980 experimental data

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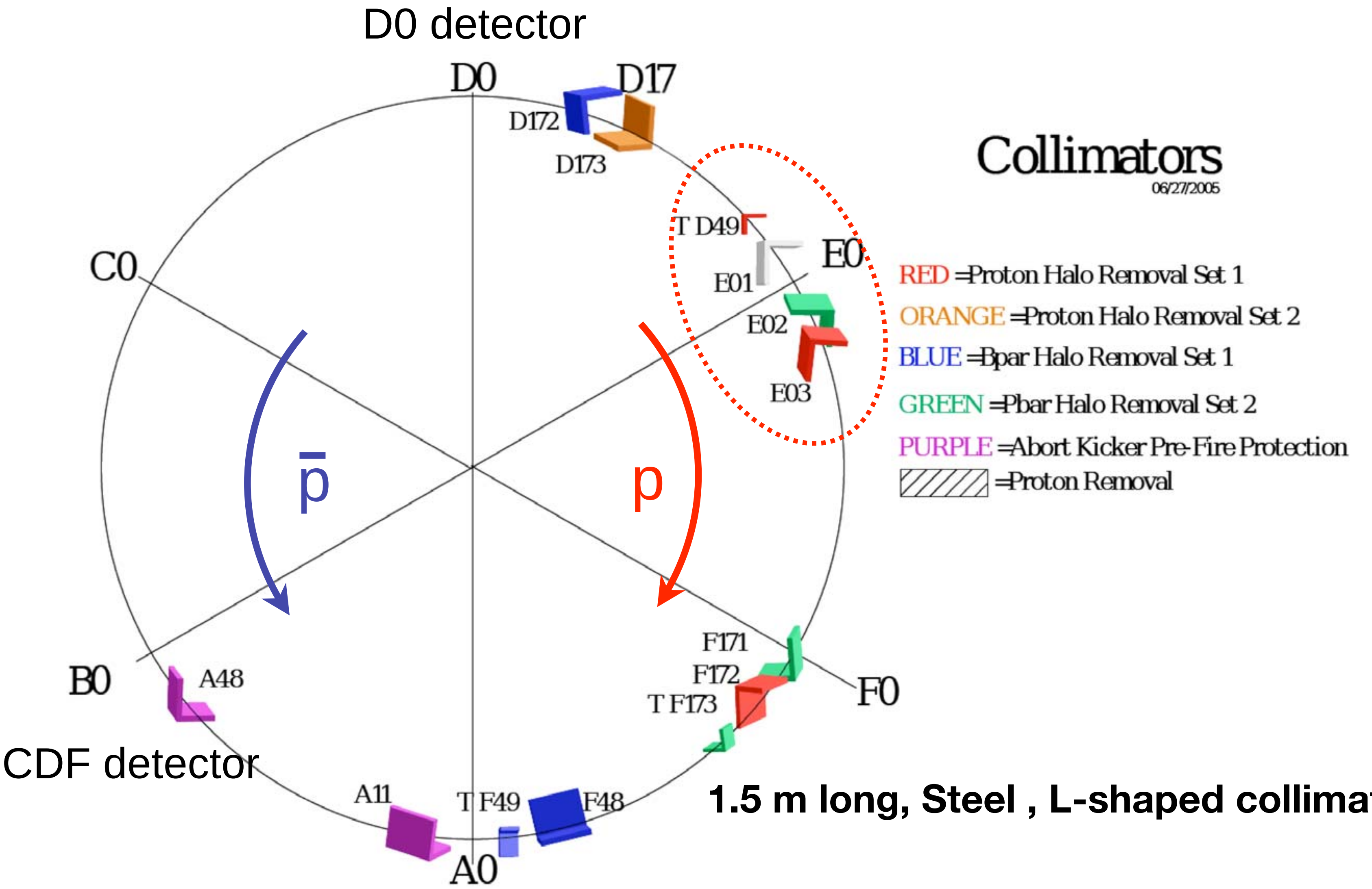
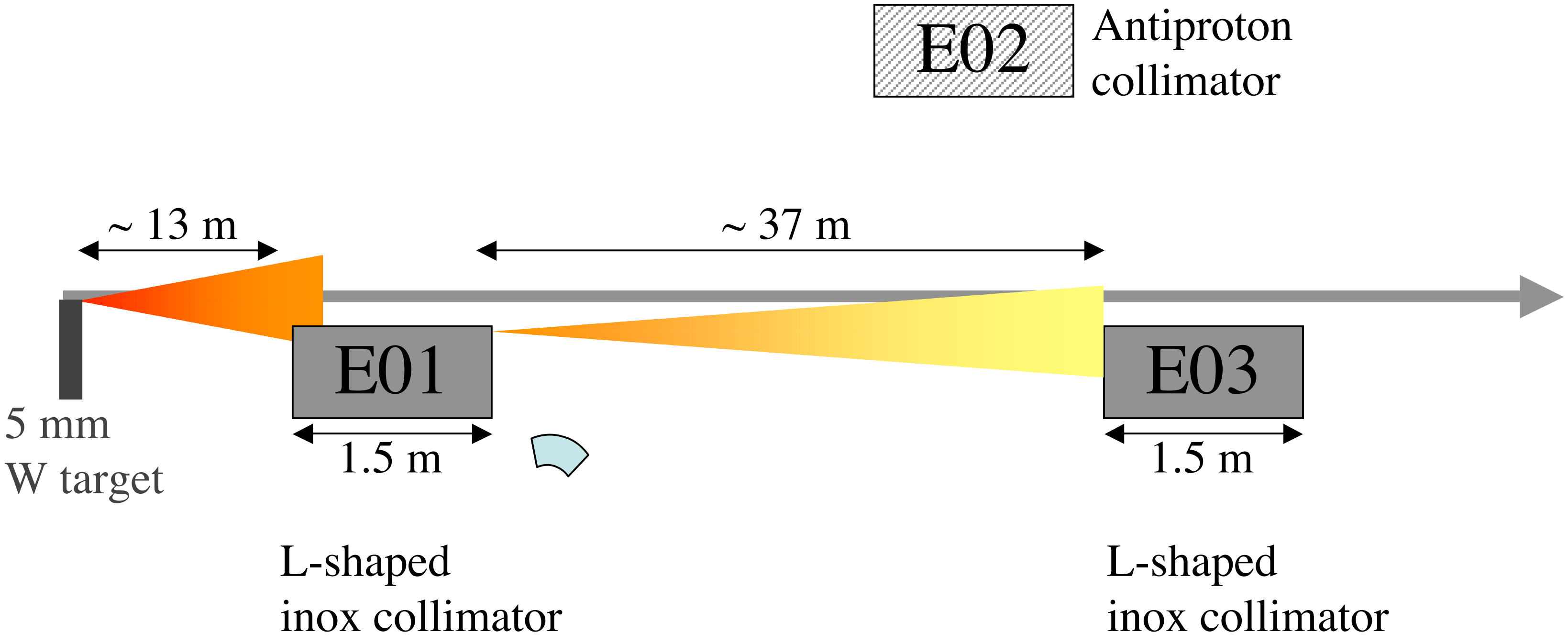
Tevatron: the collimation system

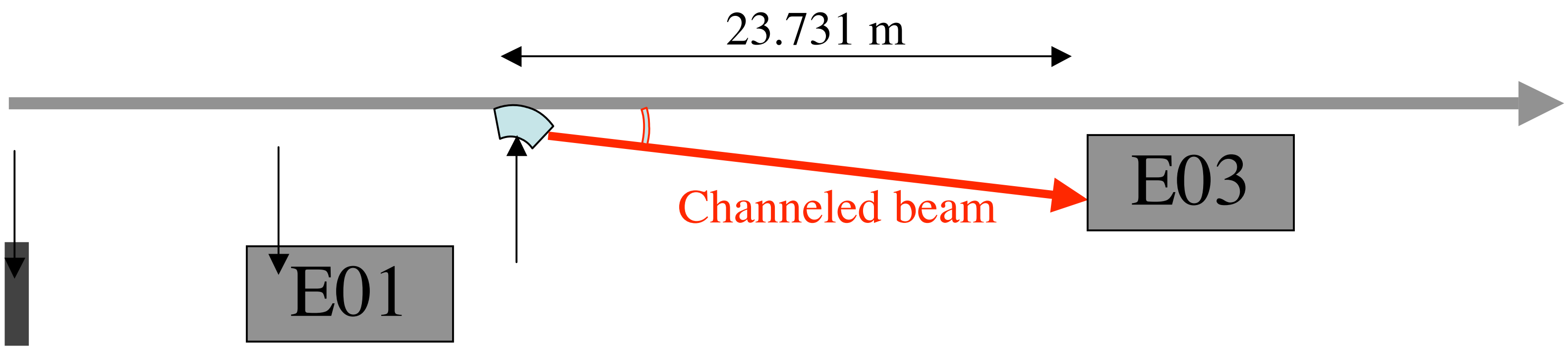


1.5 m long, Steel , L-shaped collimators

Layout of T-980

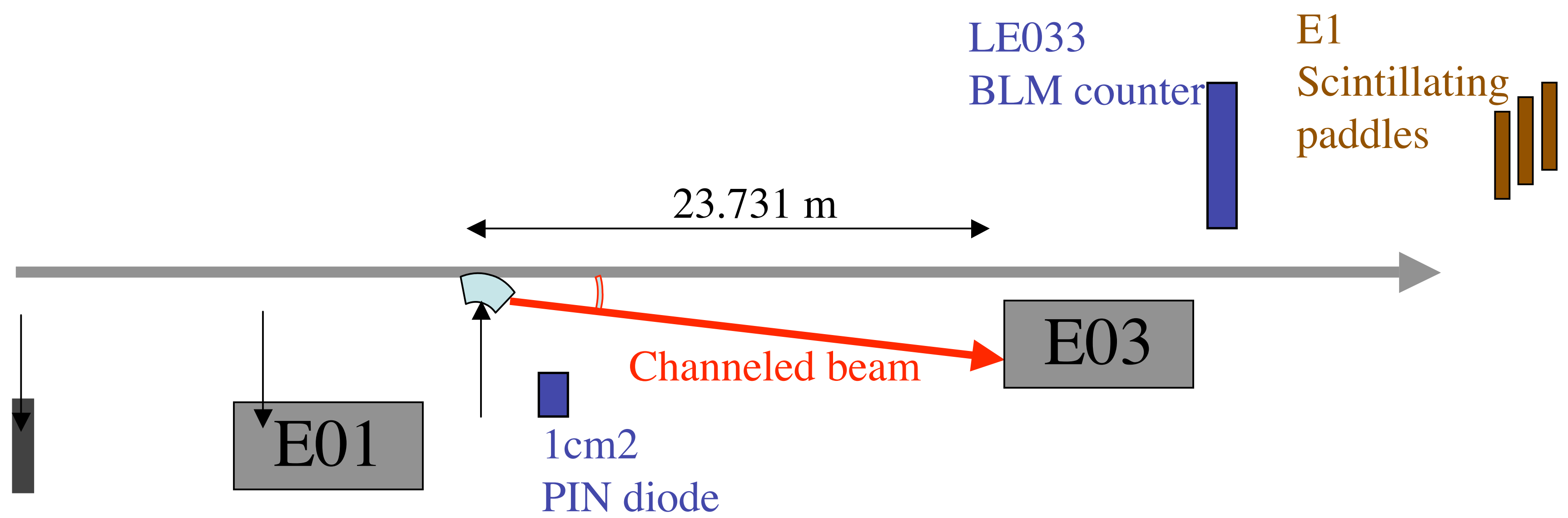


Layout of T-980



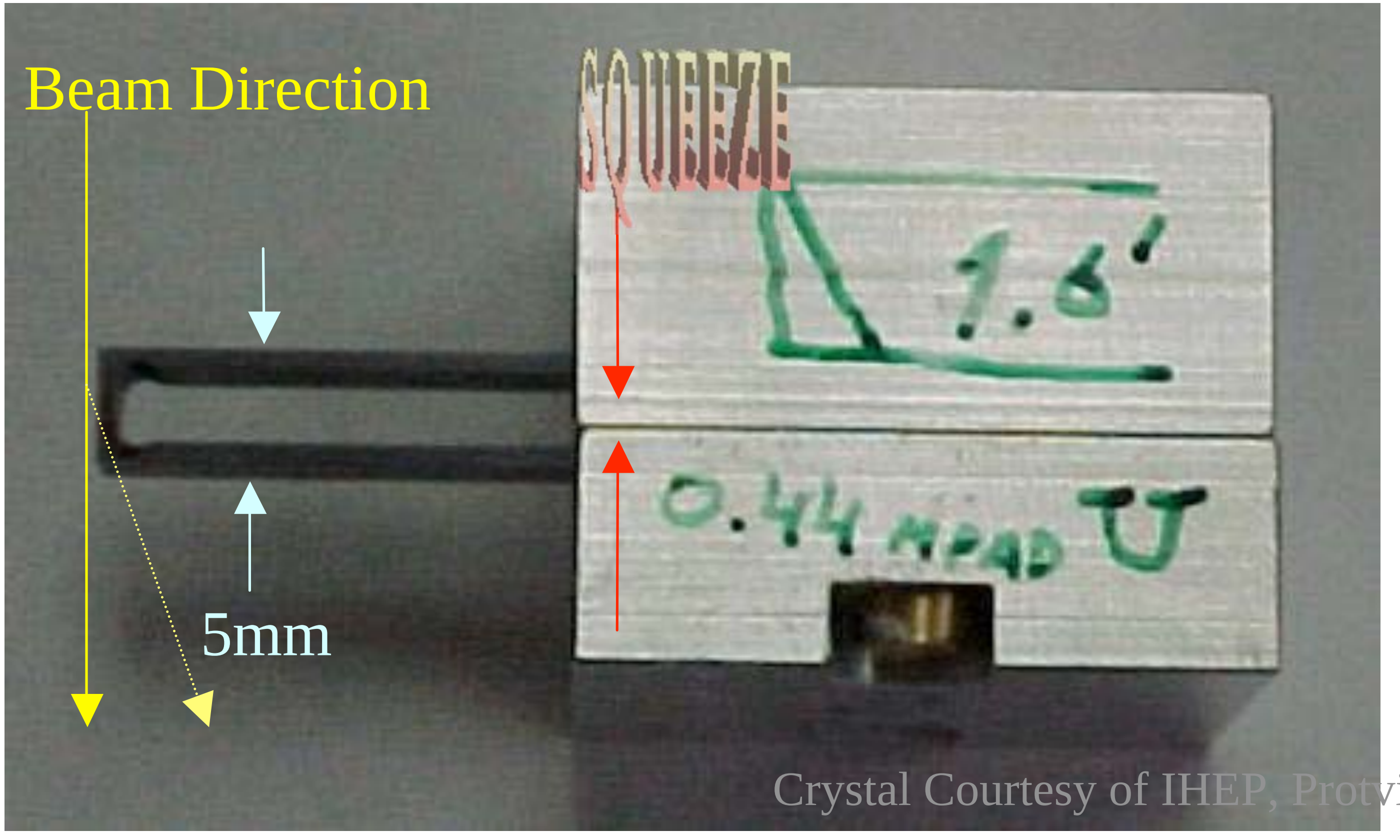
- Remove the W target and insert the Crystal
- The halo particles are channeled on the E03 collimator

Layout of T-980



- Remove the W target and insert the Crystal
- The halo particles are channeled on the E03 collimator
- *Detectors*:
  - *Pin diode:* immediately downstream of the crystal. It measures the total inelastic interactions at the crystal location
  - *LE033 BLM counters* : immediately downstream of the collimator. It measures the total losses at the E03 collimator location
  - *E1 scintillating paddles*: **gated** counters for losses at the E03 collimator. They can discriminate between bunched and abort gap beam.

The Crystal



- Si o-shaped crystal, 5 mm long
- 410 μrad bending angle (9.5 mm displacement at E03 collimator)
- 1.4 mrad of mis-cut angle

My work at fermilab

- Experimental part:
  - Taking part in 3 different “end of storage” (EOS) studies
    - October 29th
    - November 20th
    - December 10th
  - Analyzed the data from the three MDs plus old data (september, beginning of october) and some data from 2005 for comparison.
- Simulations:
  - Retrieve the tevatron optics and convert it in MADX format (yet to be checked)
  - Retrieve the tevatron aperture file and convert it with a formato compliant to the BeamLossPattern program (yet to be finished)
  - Adapt Sixtrack for the Tevatron Lattice

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The EOS beam studies: standard procedure

1. **Crystal as leading edge:**

   we retract all the collimators but the crystal and the E03 collimator. (and some collimators for kicker pre-fire error protection)

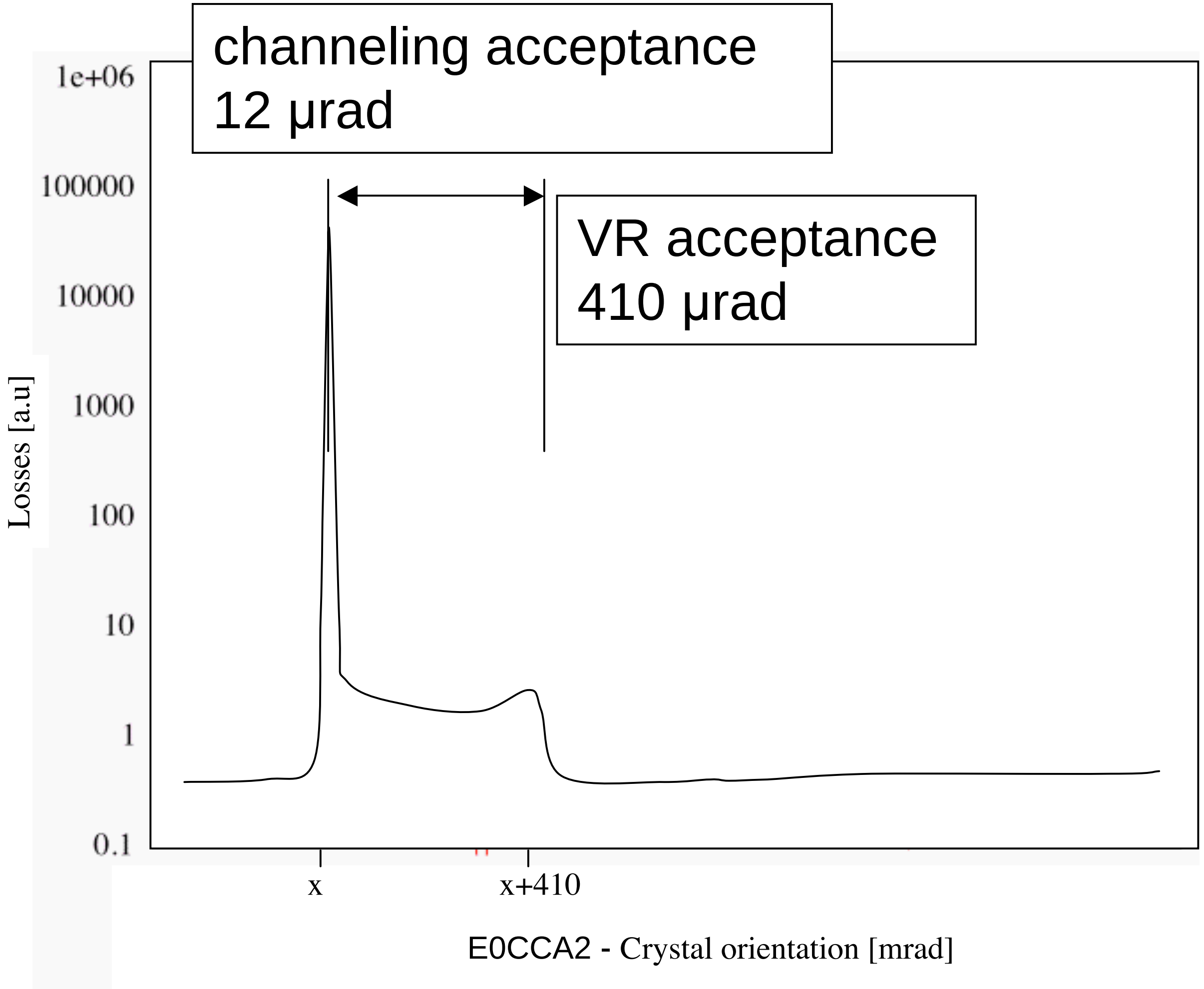
2. **Angular scan:** change the crystal orientation and measure losses at the E03 collimator

   The crystal behavior depends on the relative angle between the incident particles and the crystaline planes! First task: find the right crystal orientation

3. **Collimator scan:** keep the angle of the crystal fixed, and change the horizontal position of the collimator E03

   We expect to observe a precise displacement of the halo beam in channeling position.

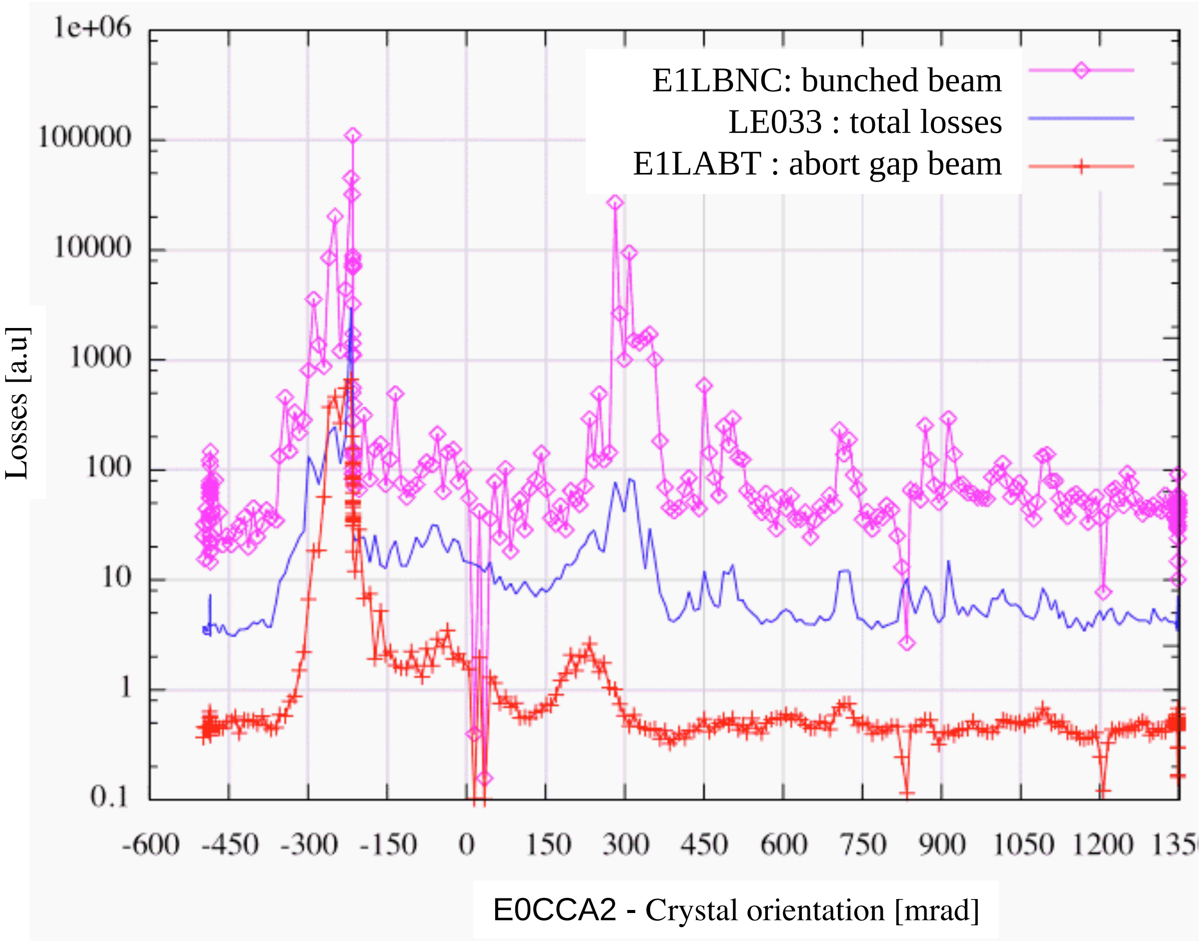
2. Angular scan: what we expected…



The ideal behavior:

- clear channeling region, width of 2*critical angle (12 µrad)
- clear volume reflection region, acceptance = channeling angle (410 µrad)
- maybe a bump at the end of the VR region (as foreseen by simulations)

Angular scan: what we found…

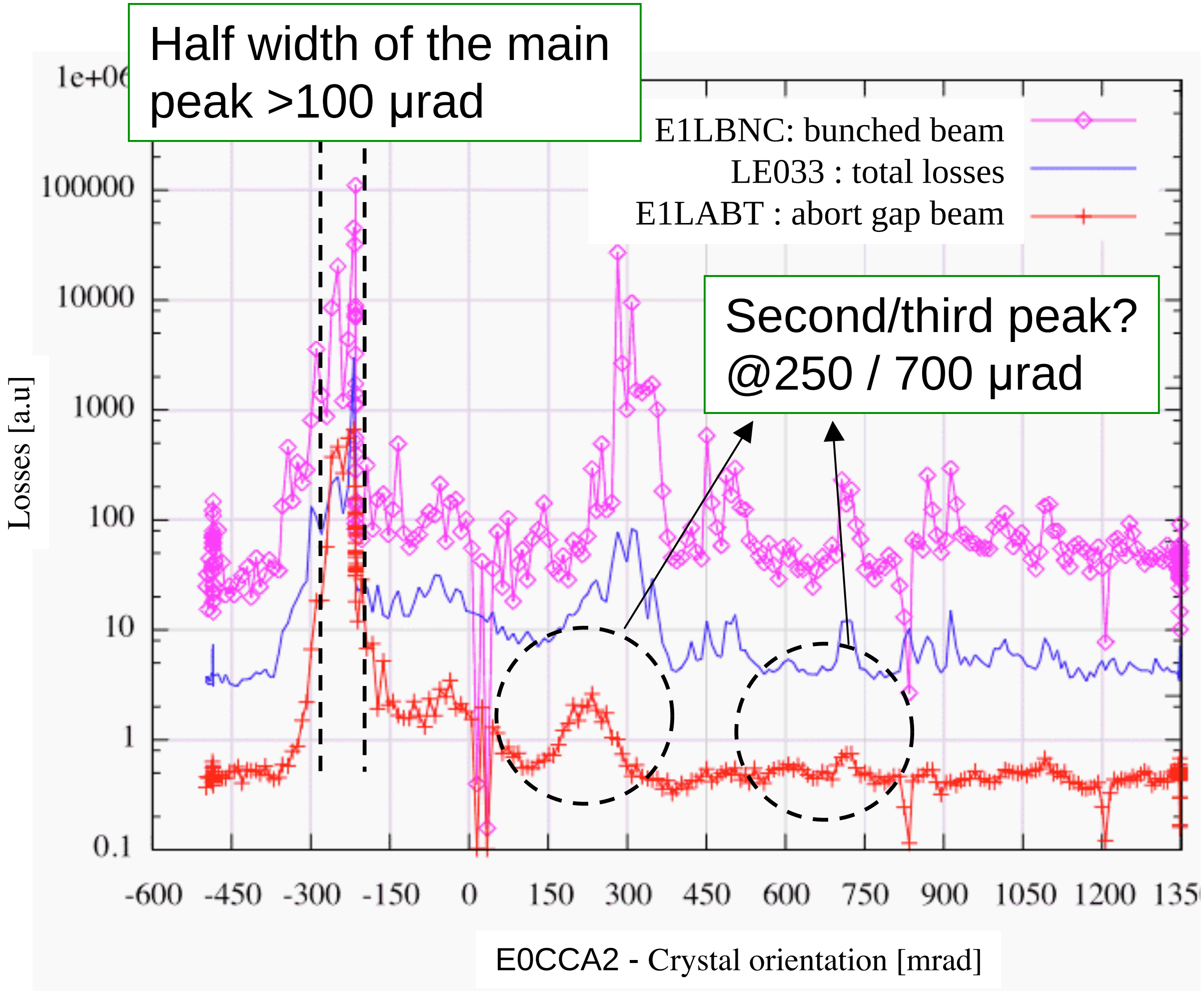


The real behavior

There is a clear peak at -240 μrad (channeling?).

The signal for bunched beam is noisy.

Angular scan: what we found…



The real behavior

There is a clear peak at -240 μrad (channeling?).

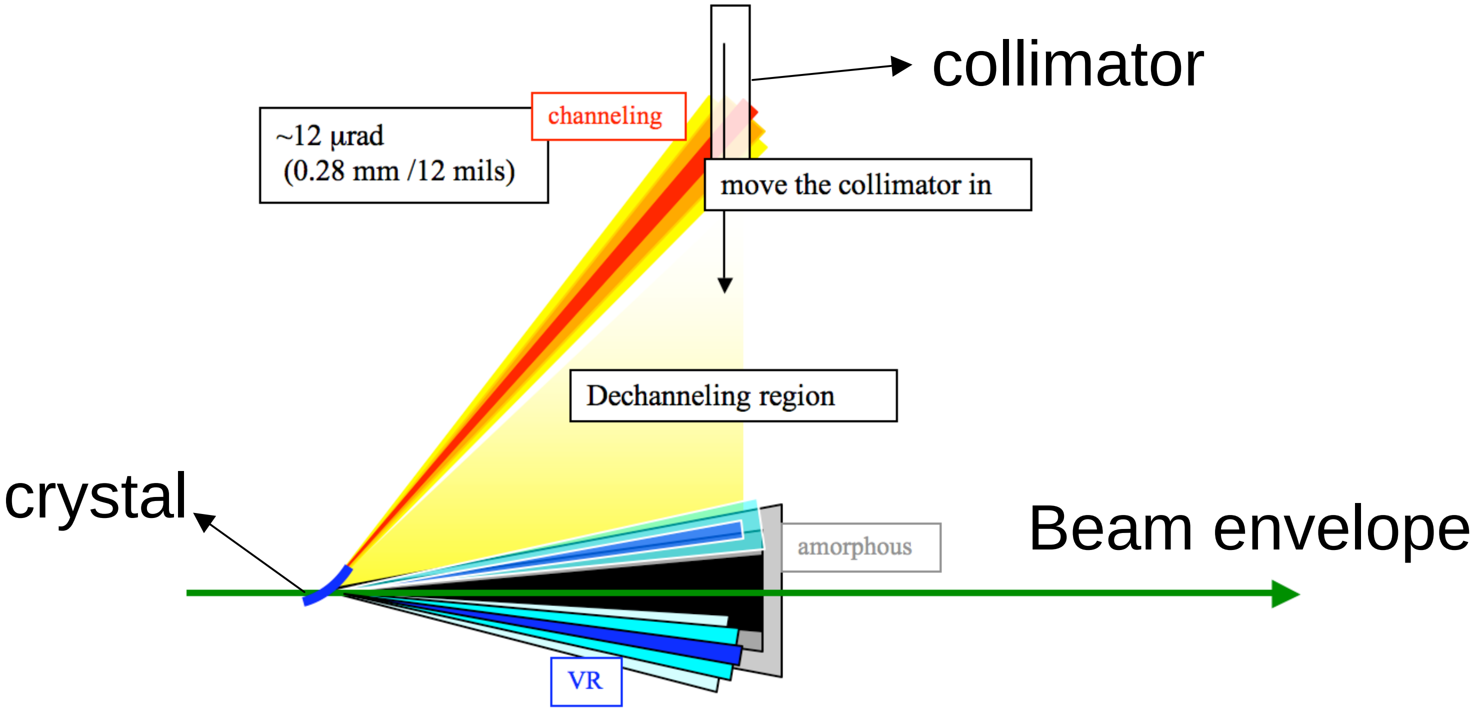
The signal for bunched beam is noisy.

PUZZLING:

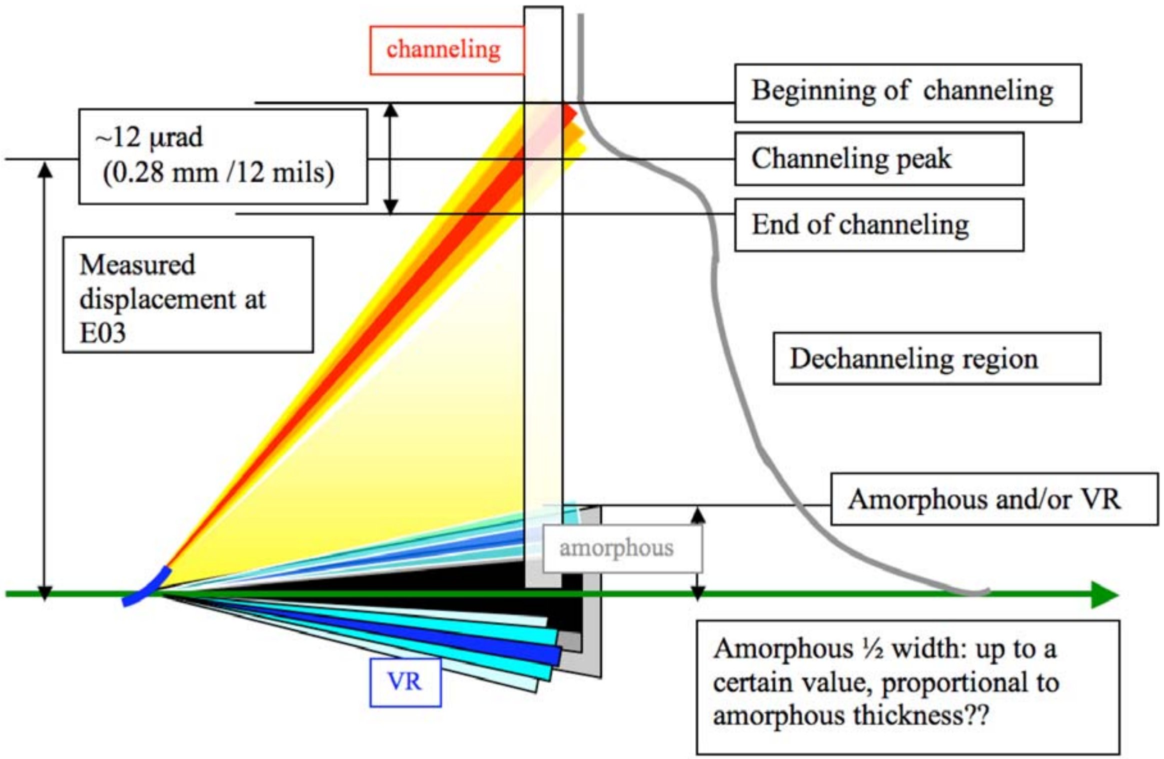
The measured acceptance of channeling is >100 μrad : **much larger than expected! (~12 μrad).**

What is the peak @250urad?

3. Collimator scan



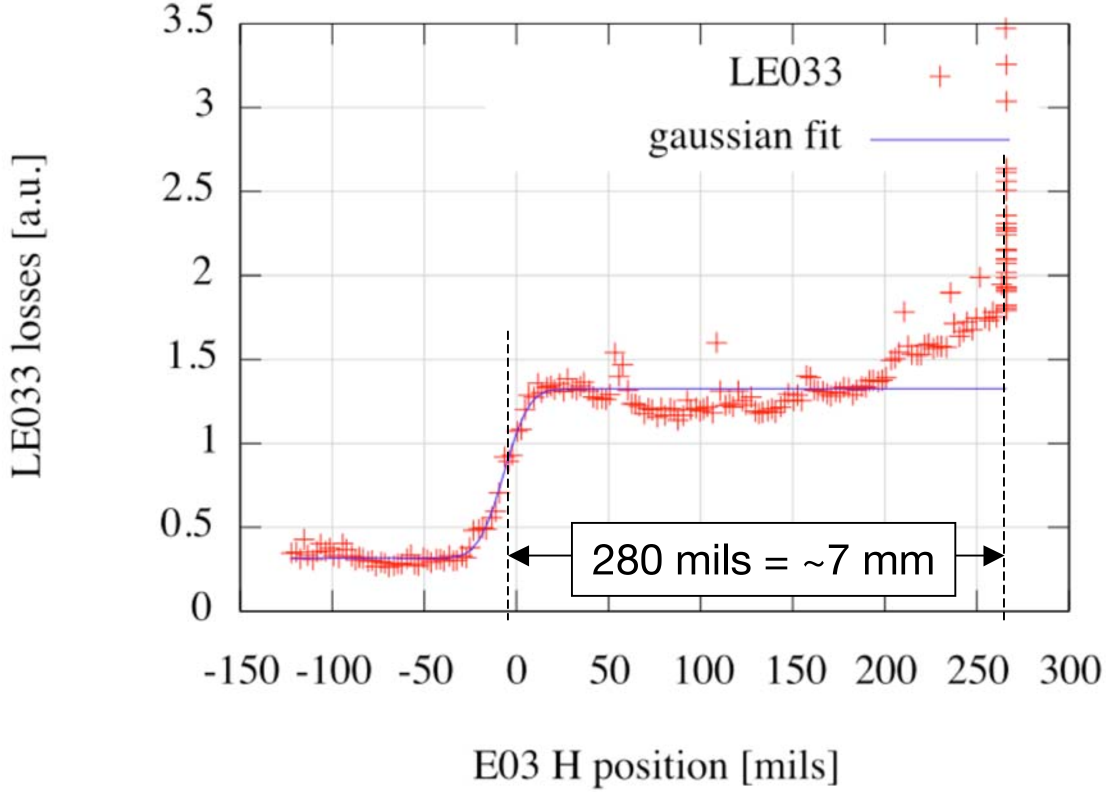
Collimator scan



- The collimator scan allows understanding the profile of the incoming beam
- We can measure the displacement between the channeled and the non-channeled beam
- The expected displacement (for 410μrad kick) is 9.5 mm

Collimator scan

in the middle of channeling peak



The measured displacement (~7 mm) is much lower than expected.

The displacement is evaluated by fitting the channeling signal with an error function

$$f(x) = a \cdot erf\left(\frac{(x-c)}{\sqrt{2}s}\right) + b$$

```
Final set of parameters            Asymptotic Standard Error
=======================            =========================

a               = 0.505231         +/- 0.009469      (1.874%)
b               = 0.821607         +/- 0.008615      (1.049%)
c               = -6.84432         +/- 0.5168        (7.551%)
s               = 10.8197          +/- 0.6928        (6.403%)
```

What we could not understand:

1. Angular scan:
   1. **Angular spread**: Why is the channeling peak acceptance much larger (>100 μrad) than expected (~12 μrad)?
   2. **No VR:** Why we do not see a clear VR effect?
   3. **Secondary peaks:** What is the peak at ~250/300 μrad in the angular scan? Is there a third peak around ~700 μrad?
2. Collimator scan:
   1. **Reduced displacement:** Why the measured displacement (~7 mm) for the channeling peak is lower than the expected one (9.6 mm)?

Hypothesis

Different attempt have been done to explain these features. Two hypothesis:

1. Feature of the beam (momentum offset)
   - Off momentum particles have a different incoming angle: can this explain the channeling peak width?
   - Off momentum particles have a different displacement at the collimator location: how much is the difference?
2. Feature of the crystal (mis-cut angle)
   - What is the effect of the mis-cut on the channeling acceptance?
   - What is the effect of the mis-cut on the observed displacement at the collimator location?

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Off-momentum particles

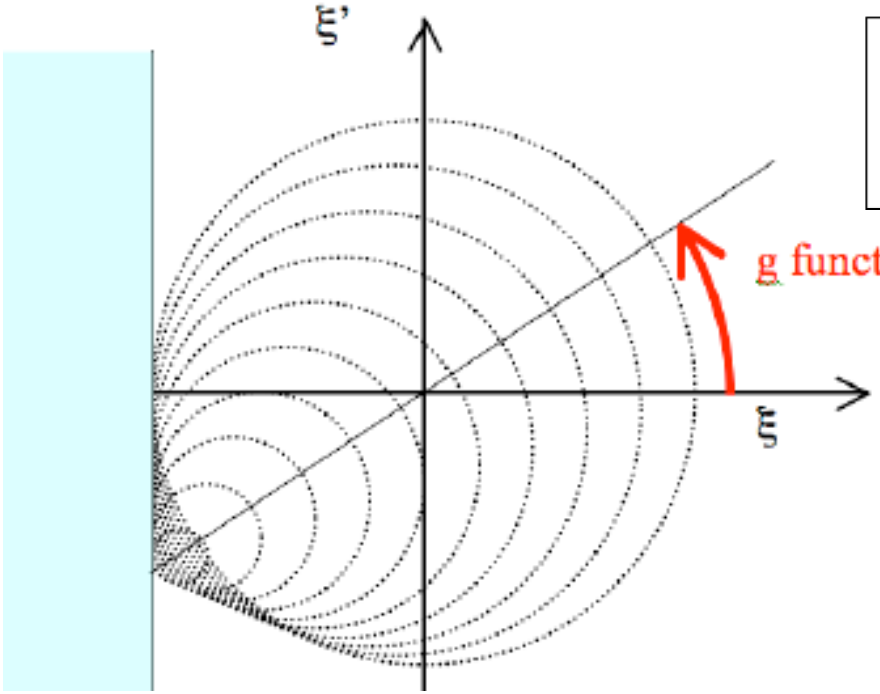
Taking into account that:

- the dispersion at the crystal (and at the collimator) is quite high (2m!)
- we are channeling also the abort gap beam
- the abort gap beam has high $\Delta p/p$ values

We tried to evaluate the effect of dealing with large off-momentum particles

For reference:
1 $\sigma p/p$ in the tevatron is 140 MeV
The RF bucket height is 450 MeV
In the abort gap particles are just outside of the separatrix
electron lens heating is turned on

Off-momentum particles: angular spread



$$n_0(\delta p/p) = n_{cry} - D_{cry} \cdot \frac{\delta p/p}{\sigma_{cry}}$$

$g = 2.9\ 10^{-3}$
$\sigma p/p\ 2.9\ 10^{-3}$

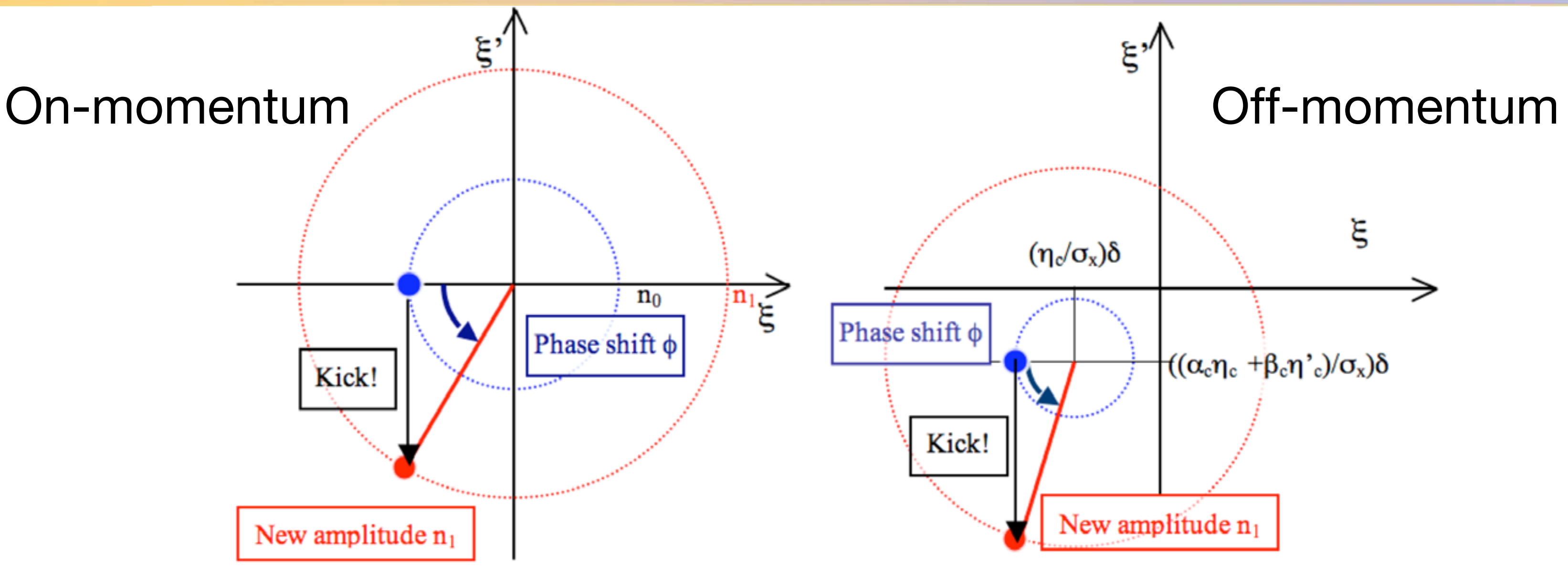
The **grazing condition** requires that, at the crystal location, the *maximum betatron extension* of the particle plus the *offset given by the dispersion* is equal to the x coordinate of the crystal's edge

=> careful: the synchrotron oscillation is neglected (considered slow enough) in this first approximation.

The angular spread is only ~1.2 μrad for particles with $\Delta p/p = 4\ \sigma_p$!

The momentum offset cannot explain a 100 μrad-wide channeling peak

Off-momentum particles: displacement at the collimator

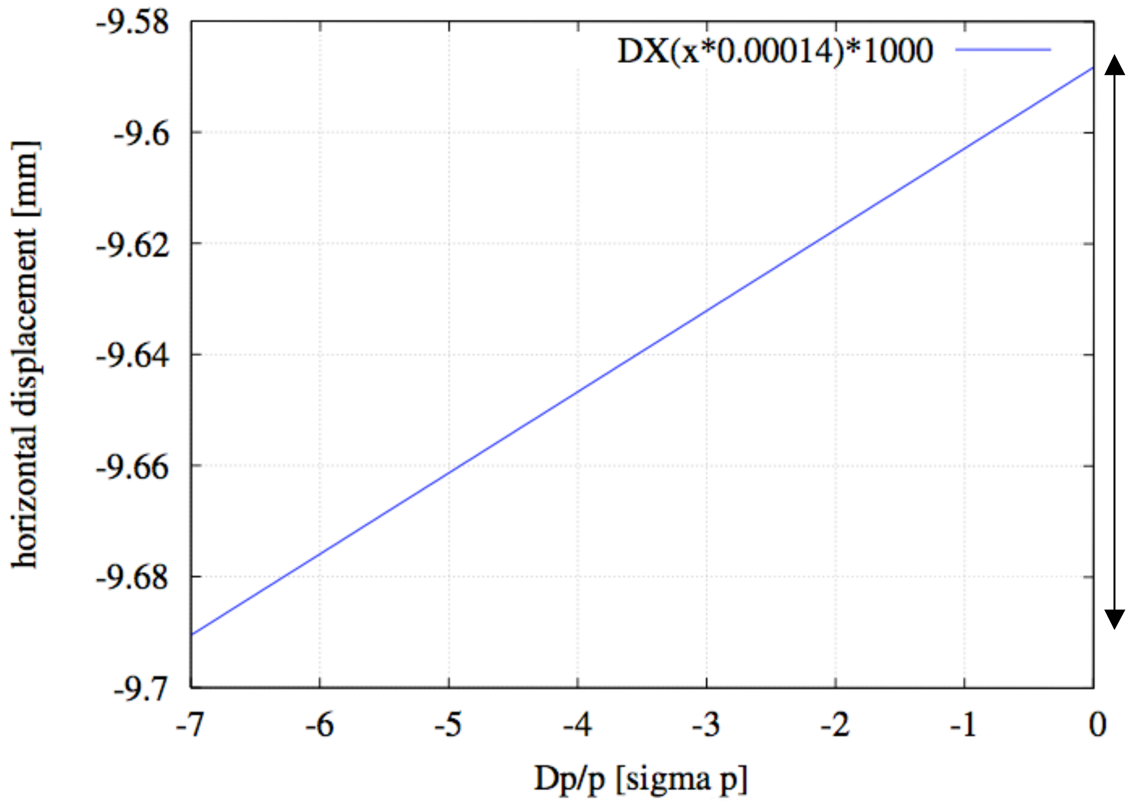


Every kick changes the amplitude and the phase of the particle.
The new amplitude and the phase shift depend on the initial amplitude: different outcomes for particles with different energy!

Particles with higher $\Delta p/p$, will have different amplitude/phase shift in comparison with on momentum particles => they will have different displacement at the collimator. How much?

Off-momentum particles: displacement at the collimator

Assuming the channeling kick of 410 μrad



The displacement is even higher for larger energy offset. (effect in the wrong direction)
Anyway the difference is only 100 μm!!!

The momentum offset cannot explain the reduced displacement observed at E03

Hypothesis

Different attempt have been done to explain these features. Two hypothesis:

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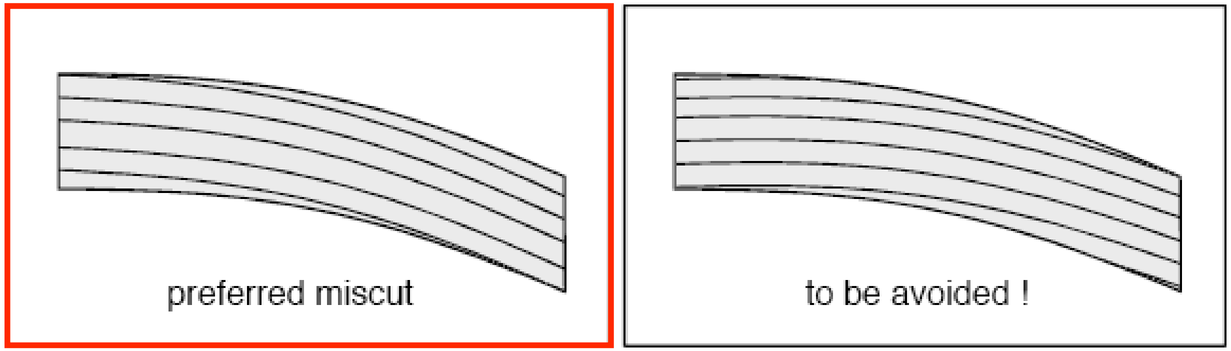
   - Off momentum particles have a different displacement at the collimator location: how much is the difference?
2. Feature of the crystal (mis-cut angle)
   - What is the effect of the mis-cut on the channeling acceptance?
   - What is the effect of the mis-cut on the observed displacement at the collimator location?

Influence of the mis-cut angle

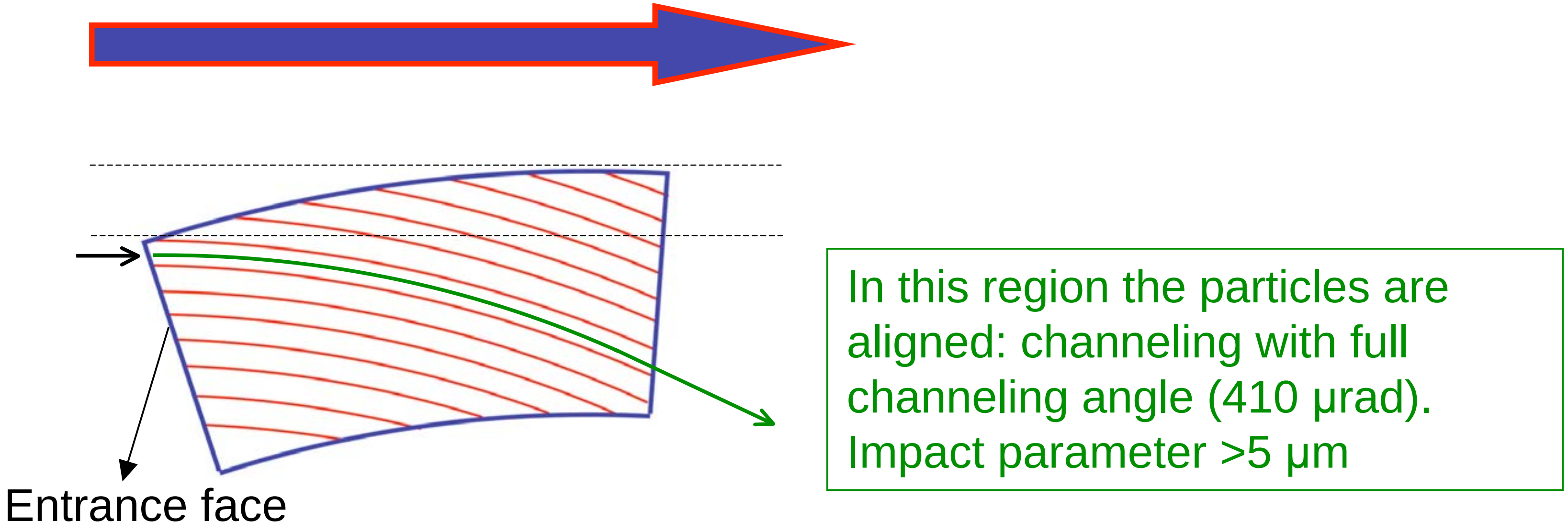
- The mis-cut angle of the crystal is **very large** (1.4 mrad over 0.41 mrad of bending angle)



Even if we are in the “good” orientation, the mis-cut could affect the particle-crystal interactions. In the following we analyze the problem in details.

Positive mis-cut angle:

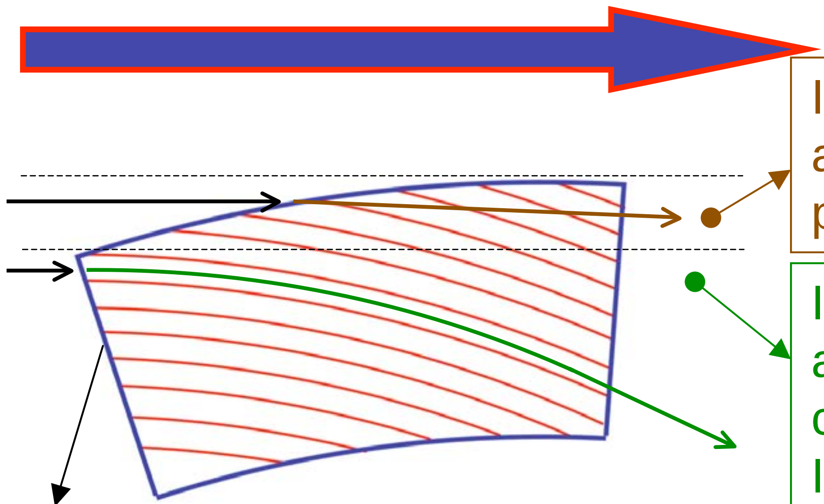
crystal aligned for channeling



- Particles are aligned with the crystal planes at the entrance face

Positive mis-cut angle:

crystal aligned for channeling



In this region the particles are not aligned: amorphous layer. Impact parameter < 5 μm

In this region the particles are aligned: channeling with full channeling angle (410 μrad). Impact parameter >5 μm

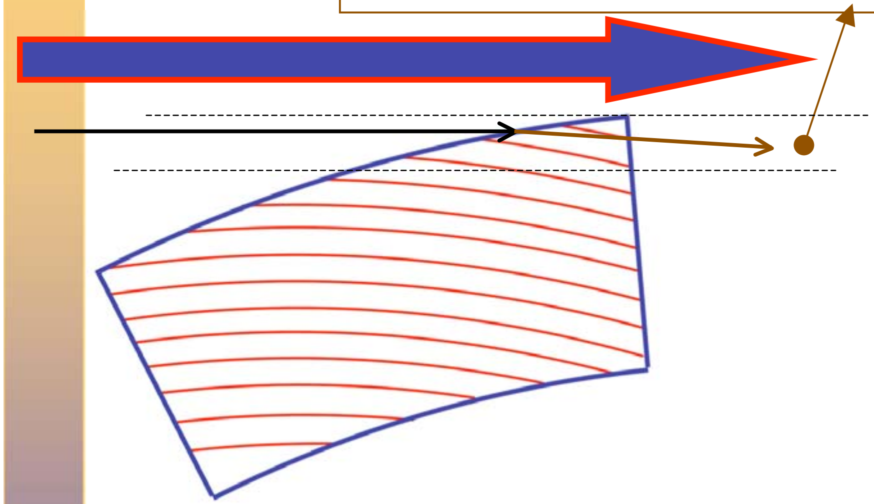
Entrance face

- Particles are aligned with the crystal planes at the entrance face:
  - The closest point to the beam is the end of the crystal
  - They will have to cross ~5 μm of amorphous layer before being channeled

Positive mis-cut angle:

crystal aligned for VR

1.In this region the particles are not aligned: amorphous layer. Impact parameter 0μm < λ_0< 5 μm



Positive mis-cut angle:

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1.In this region the particles are not aligned: amorphous layer.
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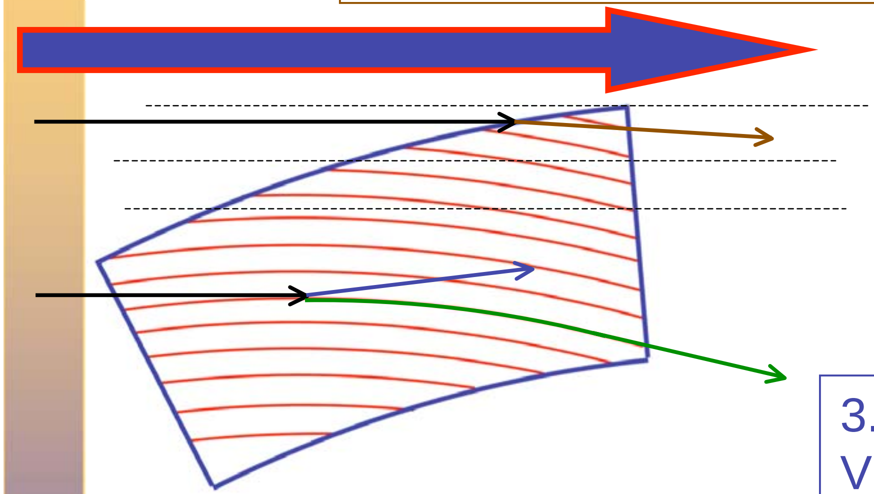

3. In this region the particles are aligned for Volume Reflection / Volume Capture (low probability).
Impact parameter $\lambda > \lambda_0$

Positive mis-cut angle:
crystal aligned for VR

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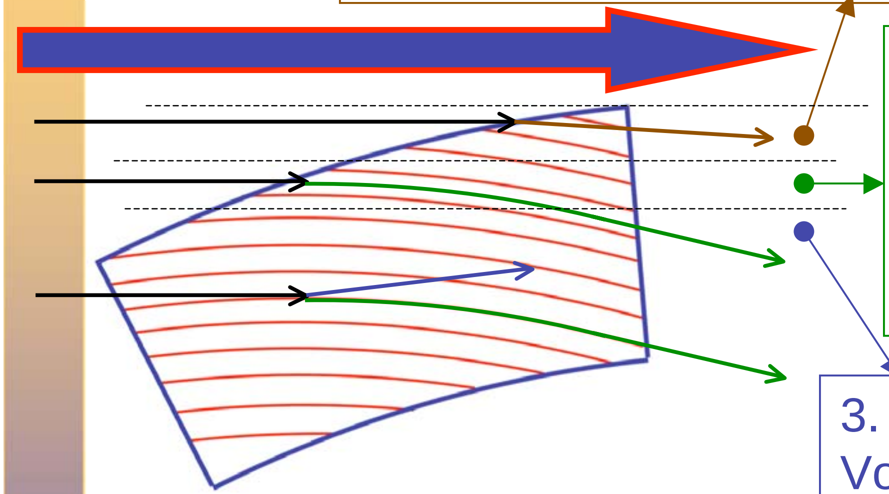
Impact parameter 0µm < λ_0< 5 µm



2. In this region the particles are aligned: channeling with **reduced channeling angle** (<410 µrad).
Impact parameter $\lambda \sim \lambda_0$ parameter.
The width of this region is $\Delta\lambda$~0.25 µm

3. In this region the particles are aligned for Volume Reflection / Volume Capture.
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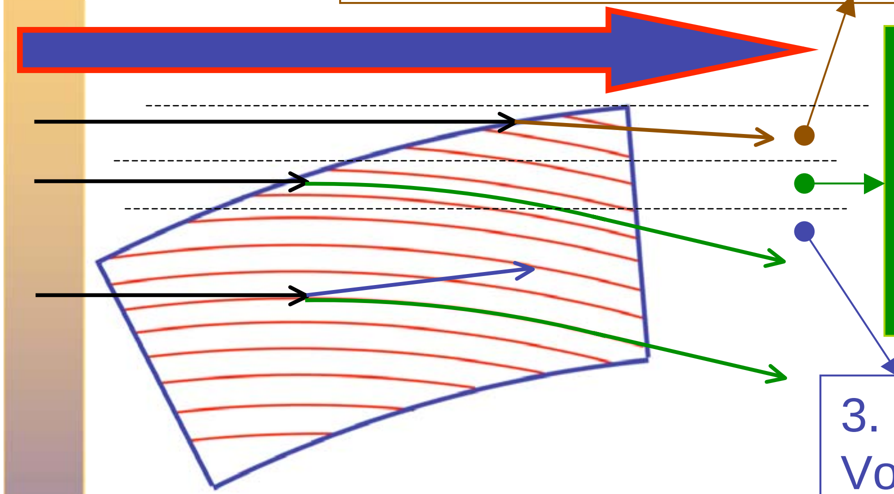

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Impact parameter $\lambda \sim \lambda_0$ parameter.
The width of this region is $\Delta\lambda$~0.25 μm

3. In this region the particles are aligned for Volume Reflection / Volume Capture.
Impact parameter $\lambda > \lambda_0$

For each orientation of the crystal, there will be an impact parameter λ_0 for which the particles are aligned with crystal planes

=> **channeling**, but with a reduced channeling angle! This could explain the reduced displacement at the collimator AND the larger channeling peak.

Positive mis-cut angle:
interpretation of measured data

- For each orientation there will be a superposition of the three effects (reduced channeling, VR, VC)
- **We channel in each orientation, but with reduced channeling angles!** We can calculate this reduced angle, and **predict the displacement** at the collimator.

Positive mis-cut angle: interpretation of measured data

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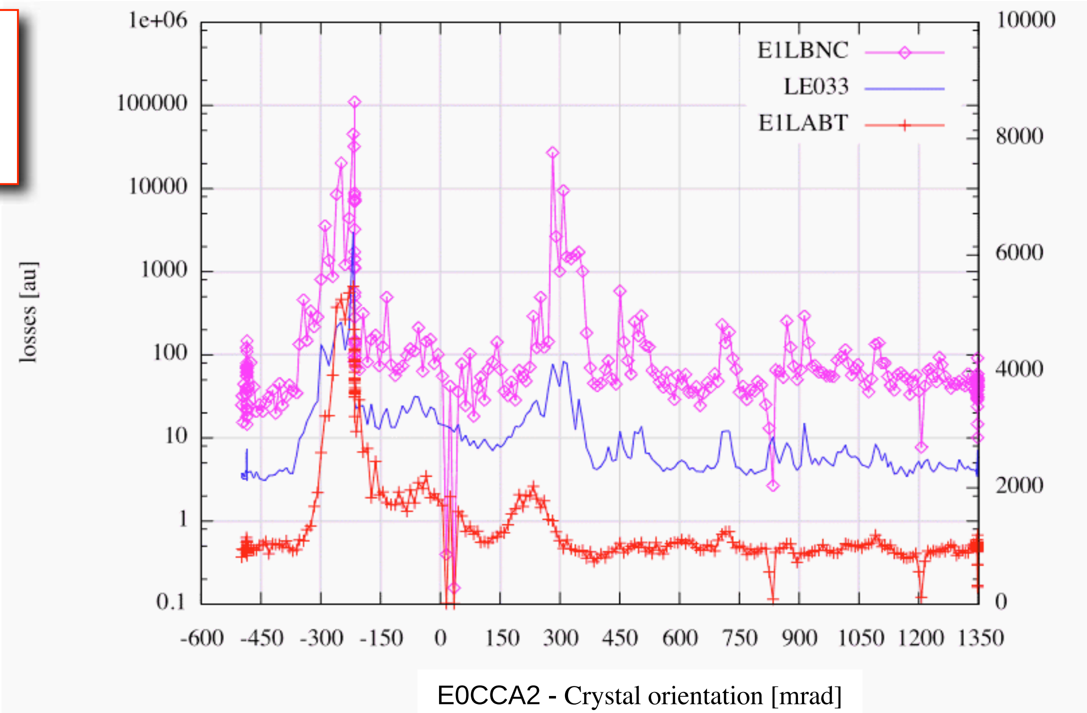
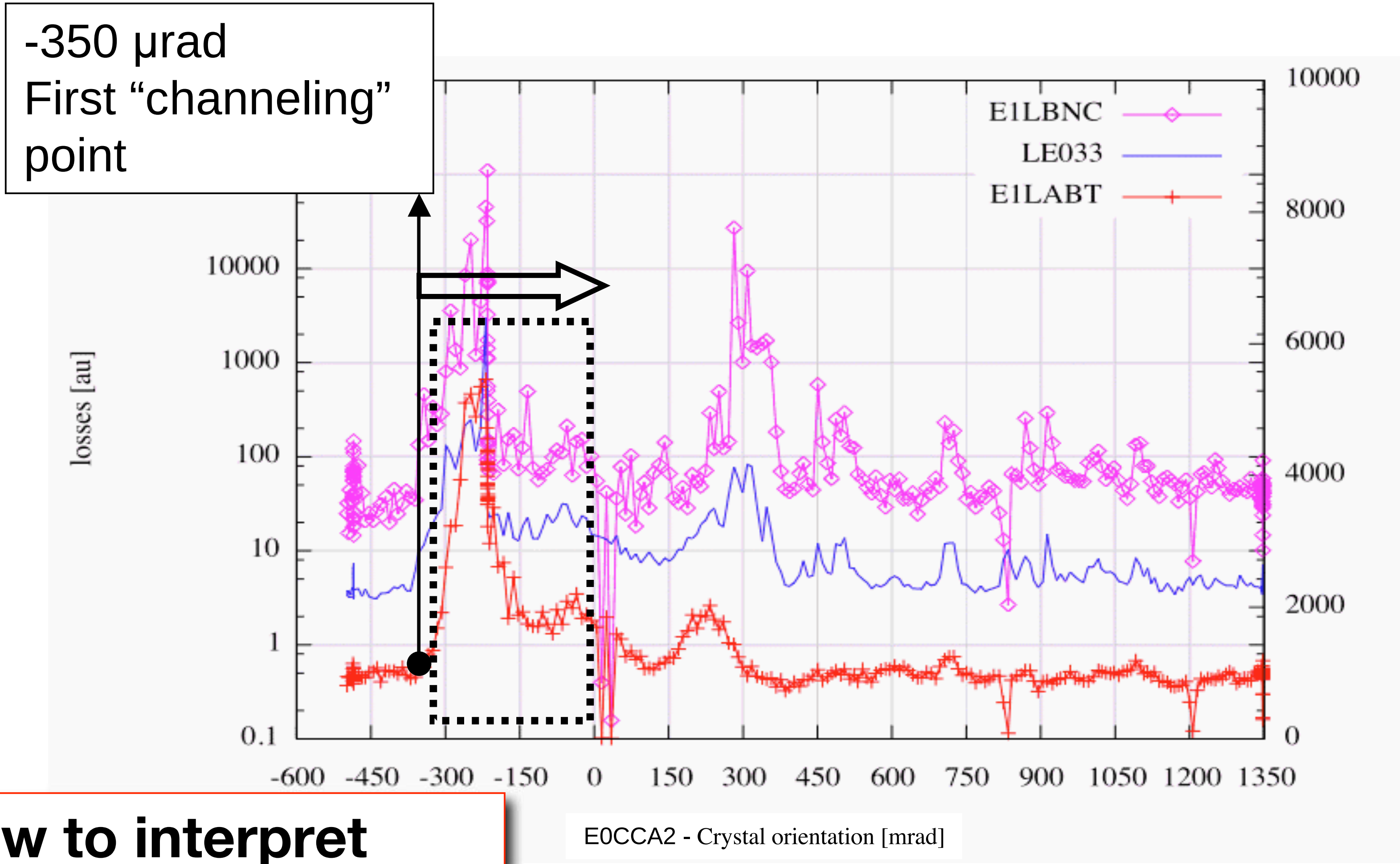
How to interpret our angular scan?



NB: Reduced channeling and Volume Capture give the same kick to the particle, but the channeling probability is much higher.

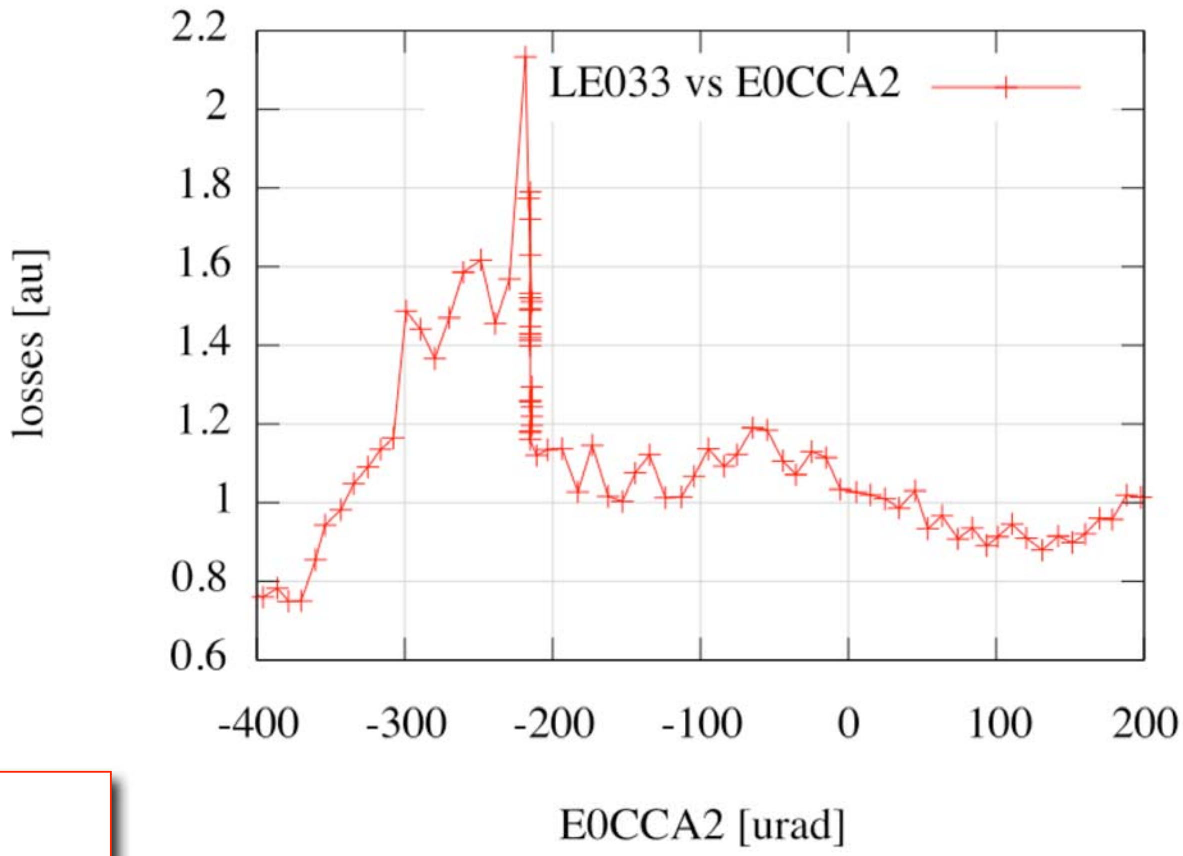
Positive mis-cut angle: interpretation of measured data



How to interpret our angular scan?

Positive mis-cut angle: interpretation of measured data

Zoom of the channeling-VR region - only BLM data



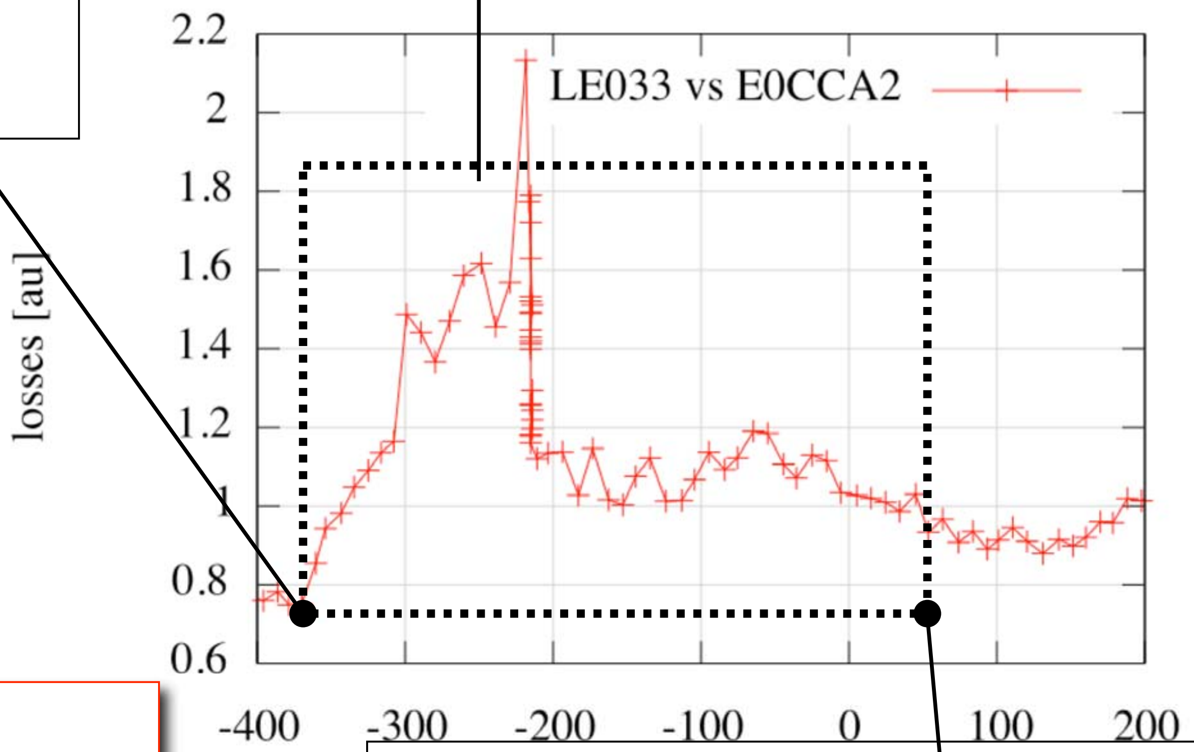
How to interpret our angular scan?

LHC Collimation Project CERN

Positive mis-cut angle: interpreta

-350 μrad < θ <+60 μrad
intermediate orientation: "reduced" channeling kicks are expected (it scales linearly)
also amorphous and channeling should take place

-350 μrad
Beginning of channeling: full channeling kick is expected



Completely new interpretation of the measured data!

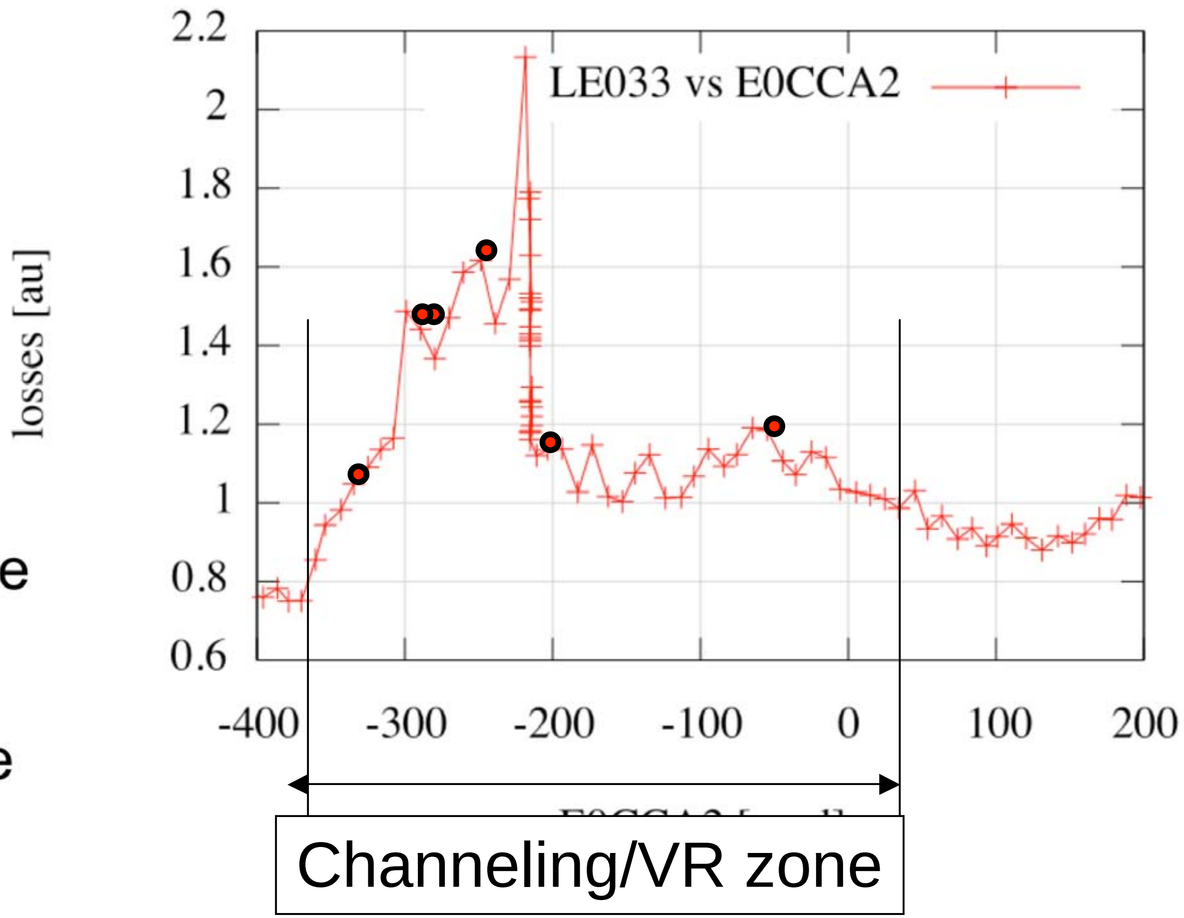
+60 μrad
End of channeling: all the crystal coherent effects should stop

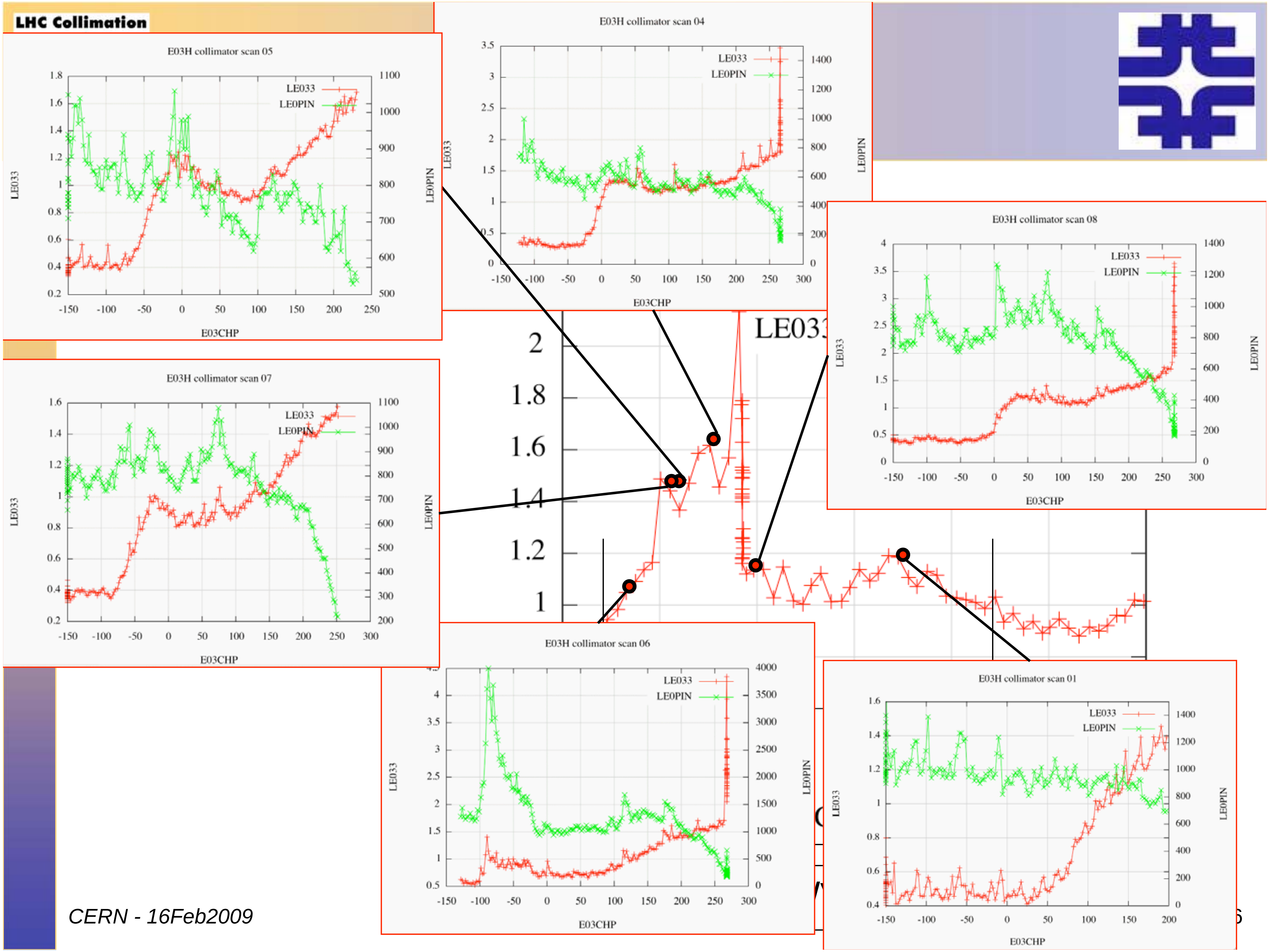
Positive mis-cut angle: comparison with measured data

We selected 6 different orientations for new collimator scans:

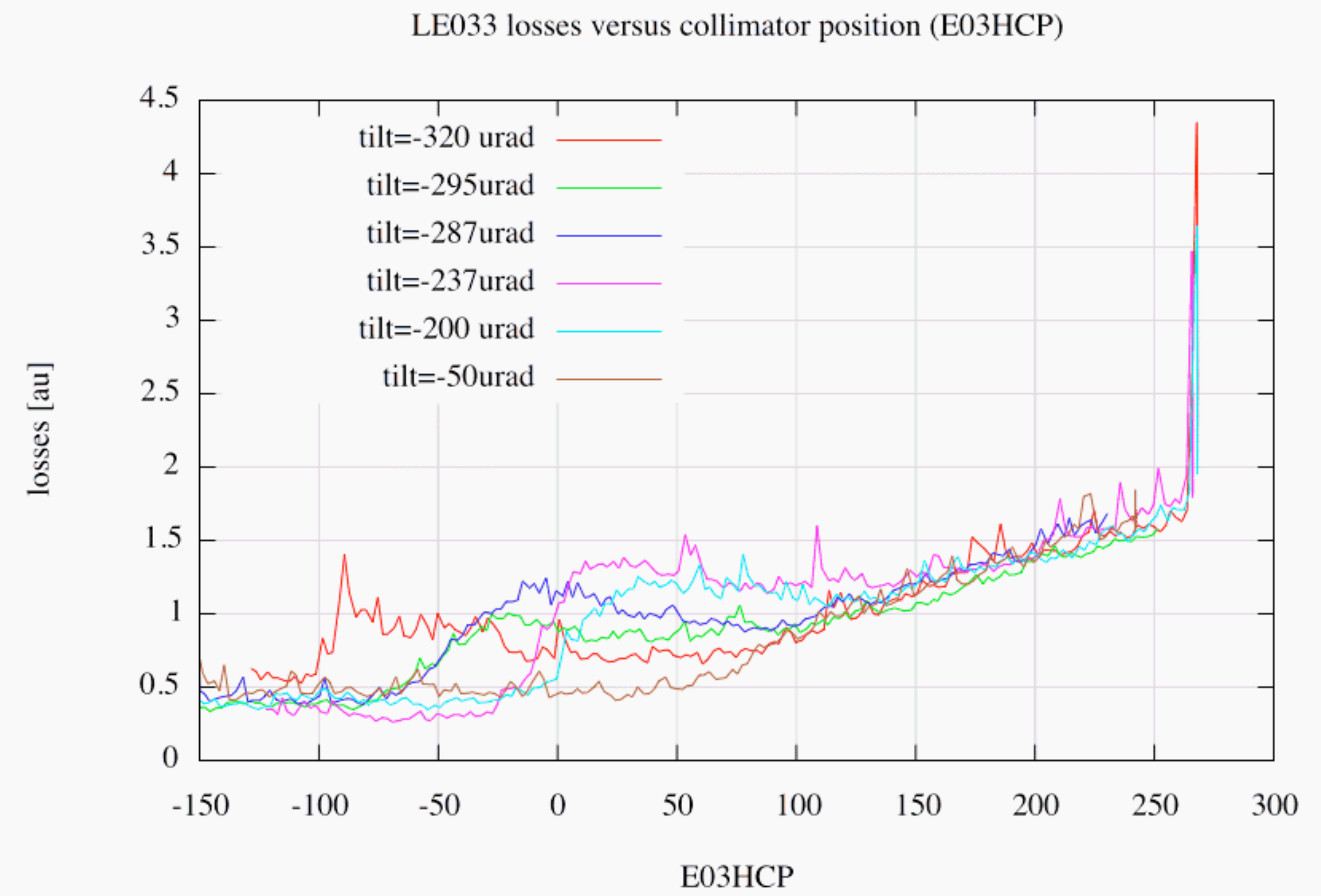
- **- 320 μrad**
- **- 295 μrad**
- **- 287 μrad**
- **- 237 μrad**
- **- 200 μrad**
- **- 50 μrad**

For each point we measure the displacement of the halo at the collimator, and compare it with the expected displacement

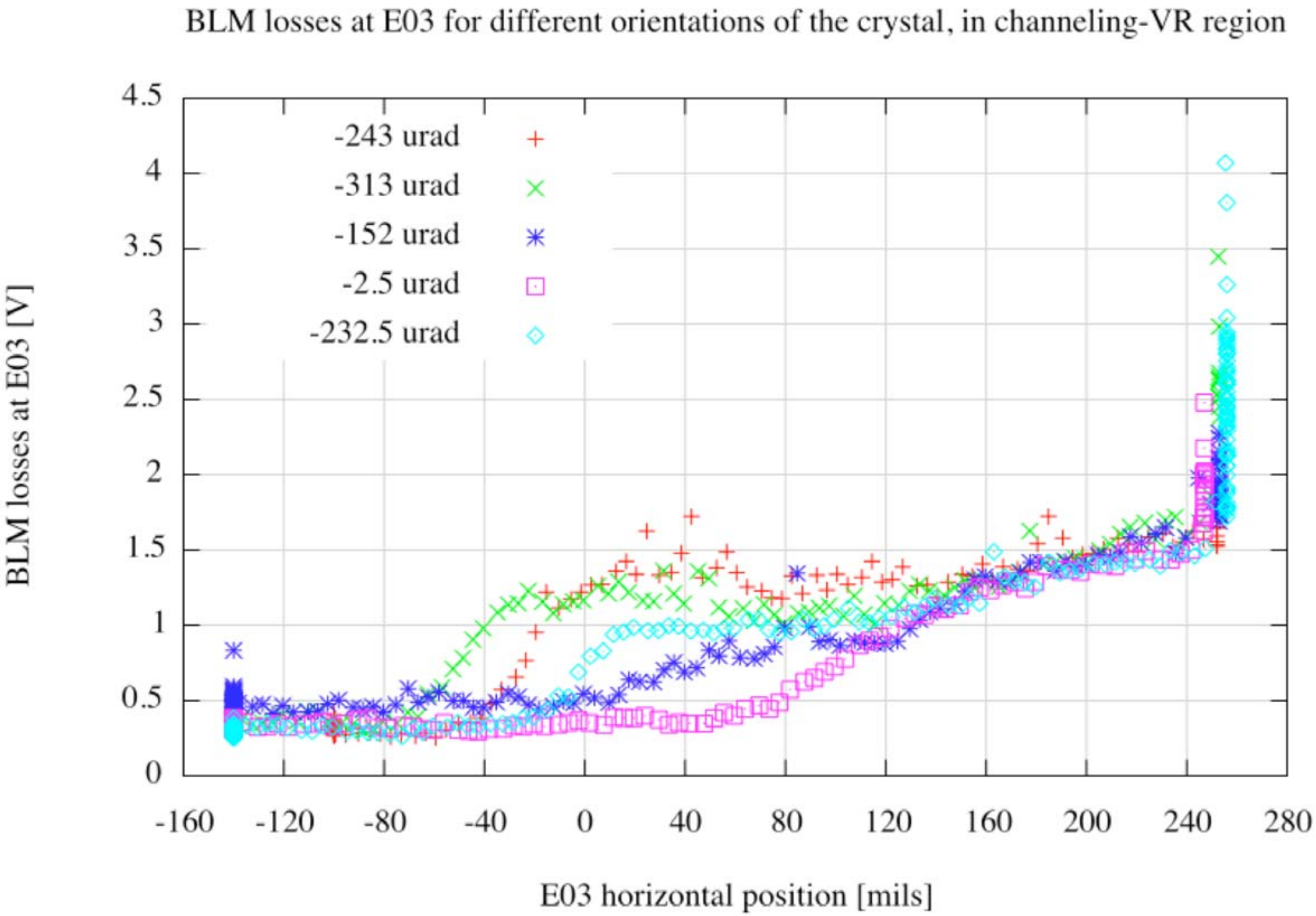



E03H collimator scan 05
E03H collimator scan 04
E03H collimator scan 08
E03H collimator scan 07
E03H collimator scan 06
E03H collimator scan 01
LE033
LE0PIN
E03CHP

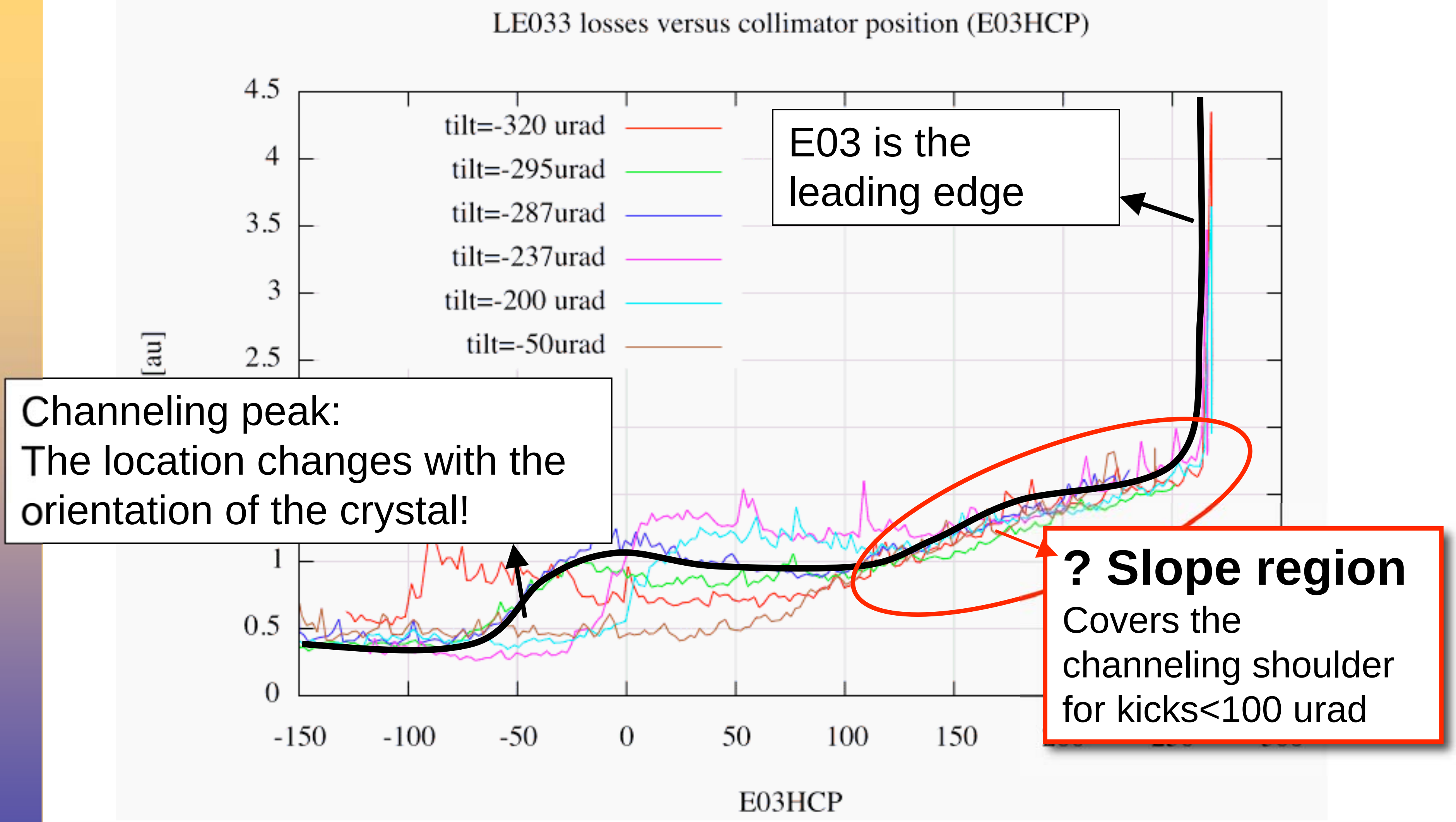
All toghether…



More angular scans…
(dec 10th)

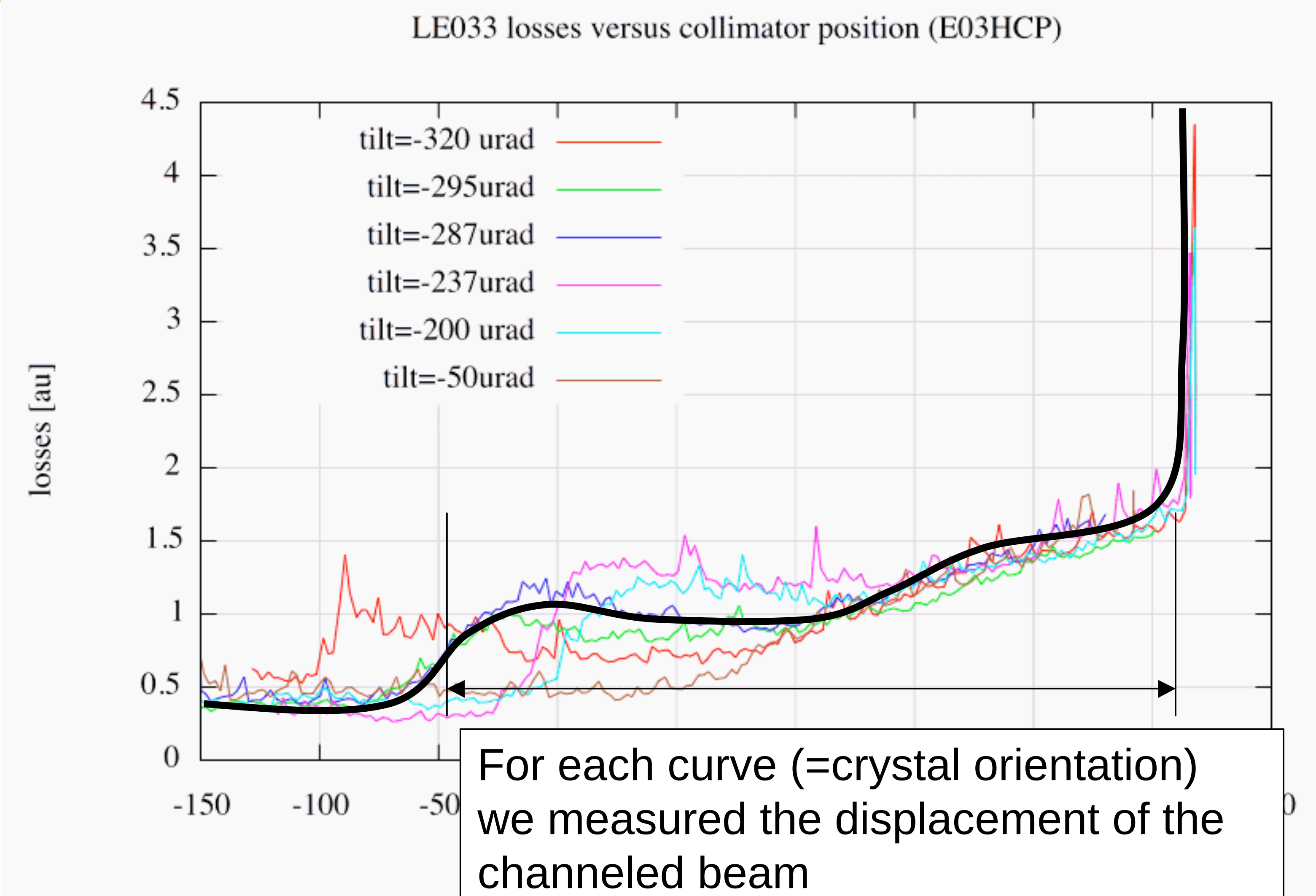


All together…
typical shape of a collimator scan



All together…

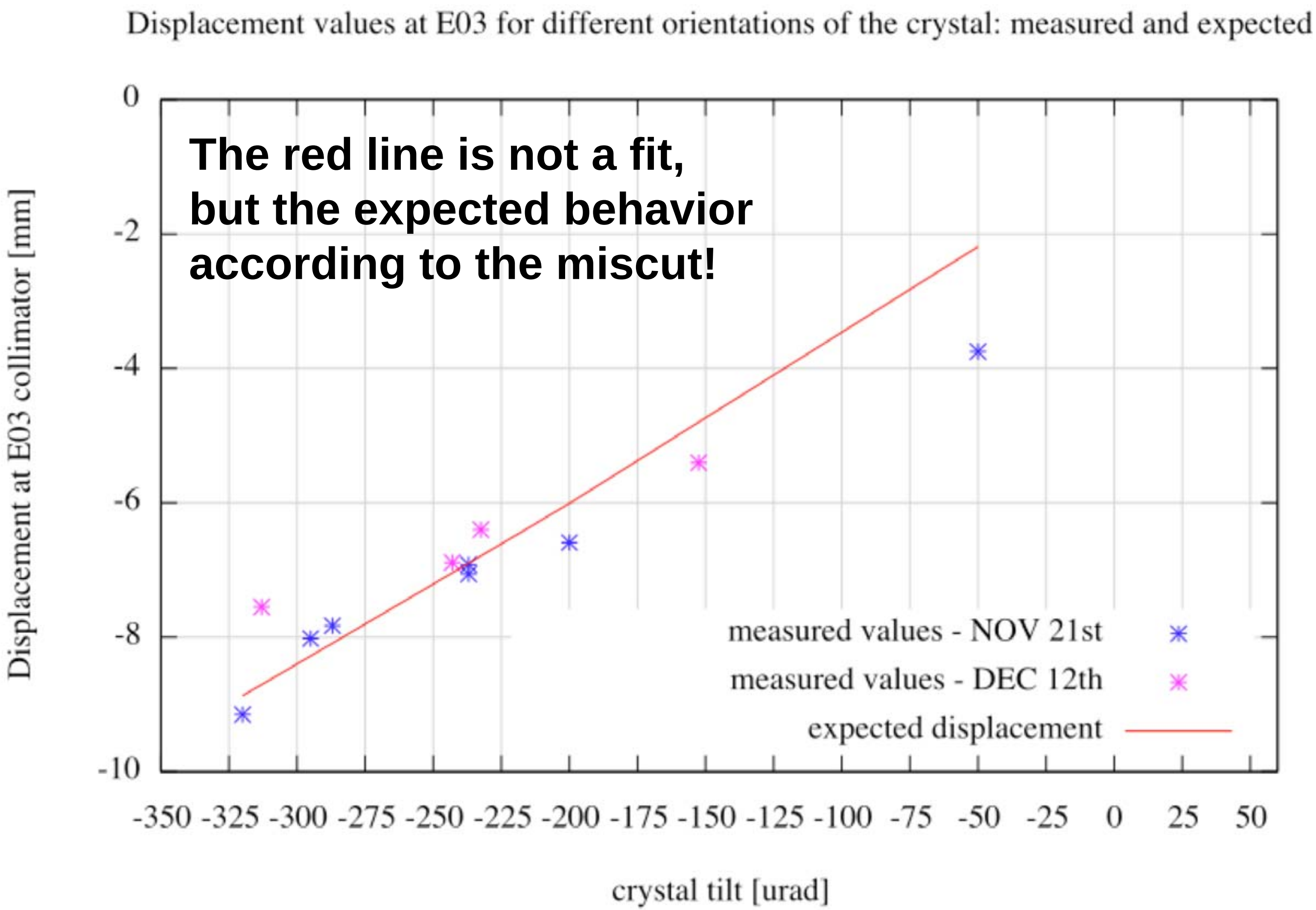
typical shape of a collimator scan



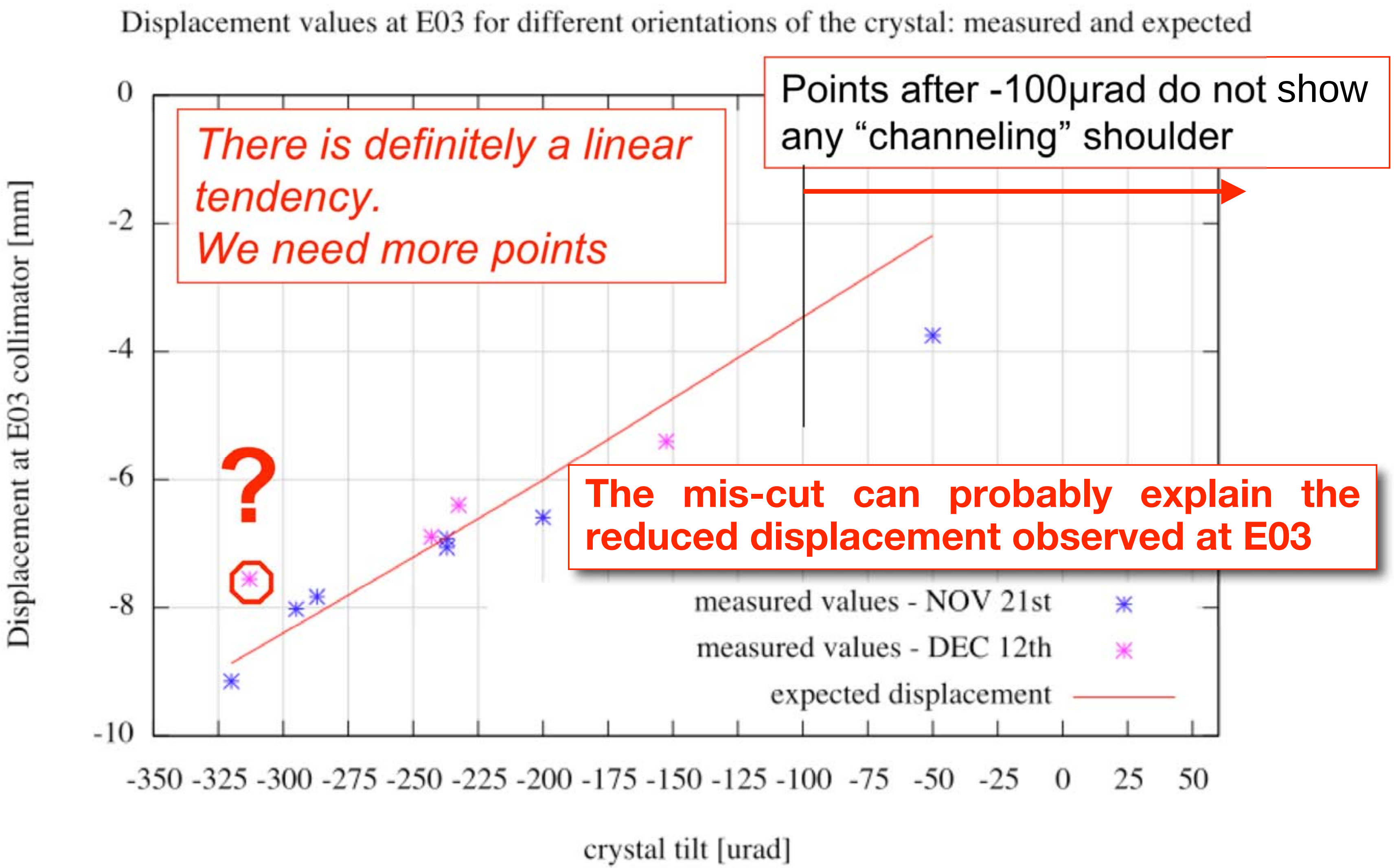
For each curve (=crystal orientation) we measured the displacement of the channeled beam

All together…

Gaussian fits vs theory



Displacement for different orientations of the crystal

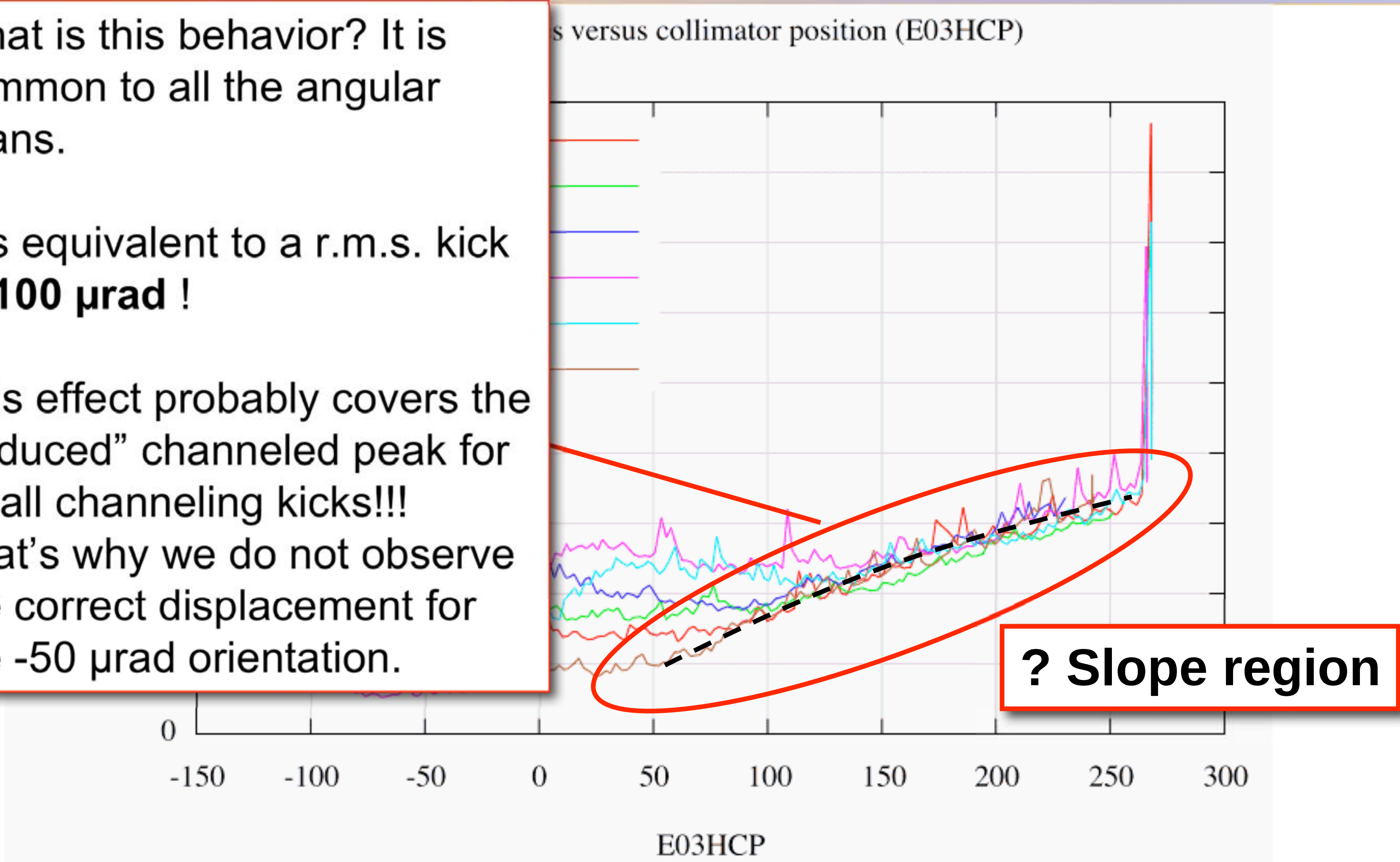


... more questions...
Slope region

What is this behavior? It is common to all the angular scans.

It is equivalent to a r.m.s. kick of **100 µrad** !

This effect probably covers the "reduced" channeled peak for small channeling kicks!!! That's why we do not observe the correct displacement for the -50 µrad orientation.



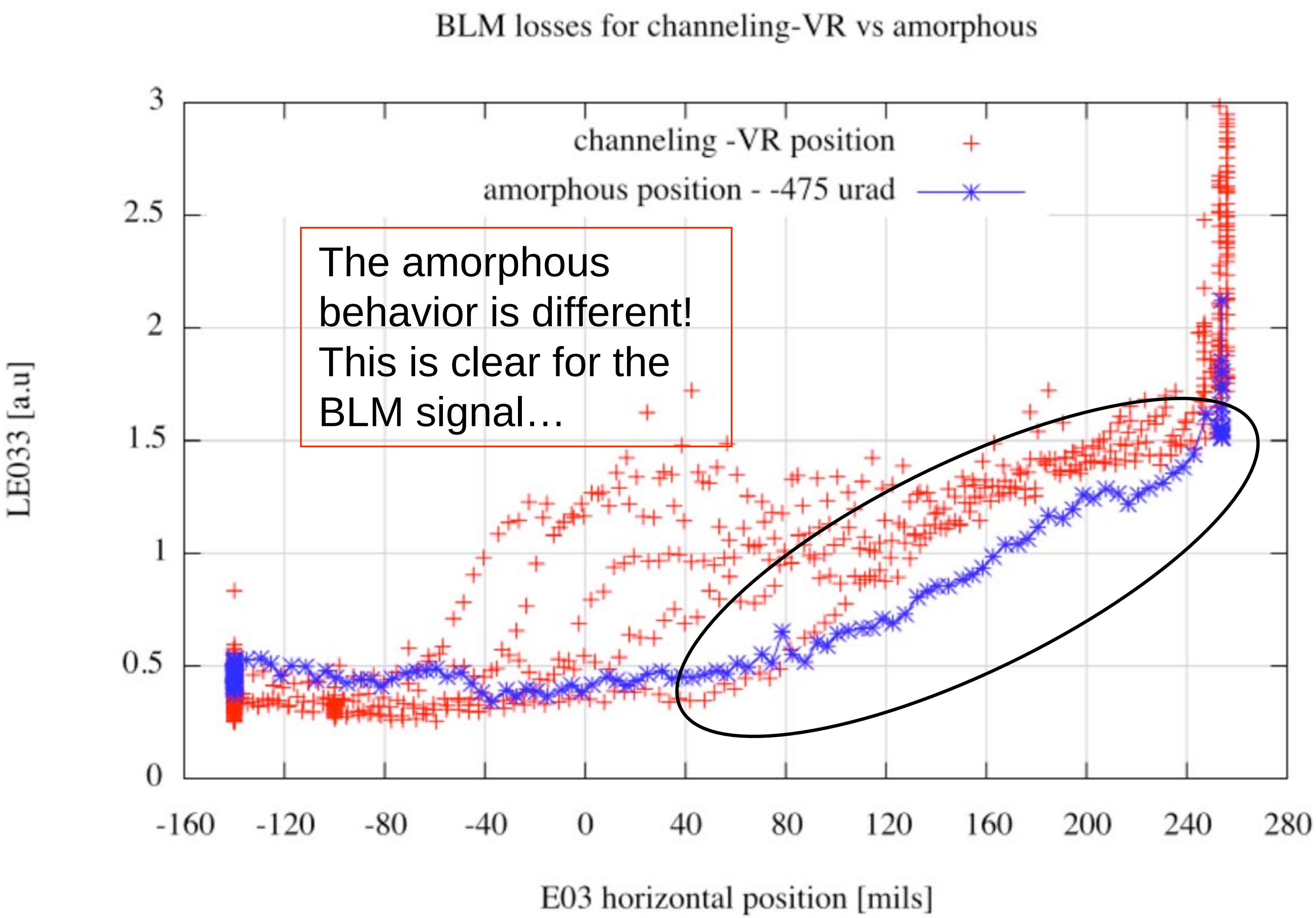
Investigate the 'slope' region

What is the physical process which cause the 'slope' region at the end of the collimator scans?

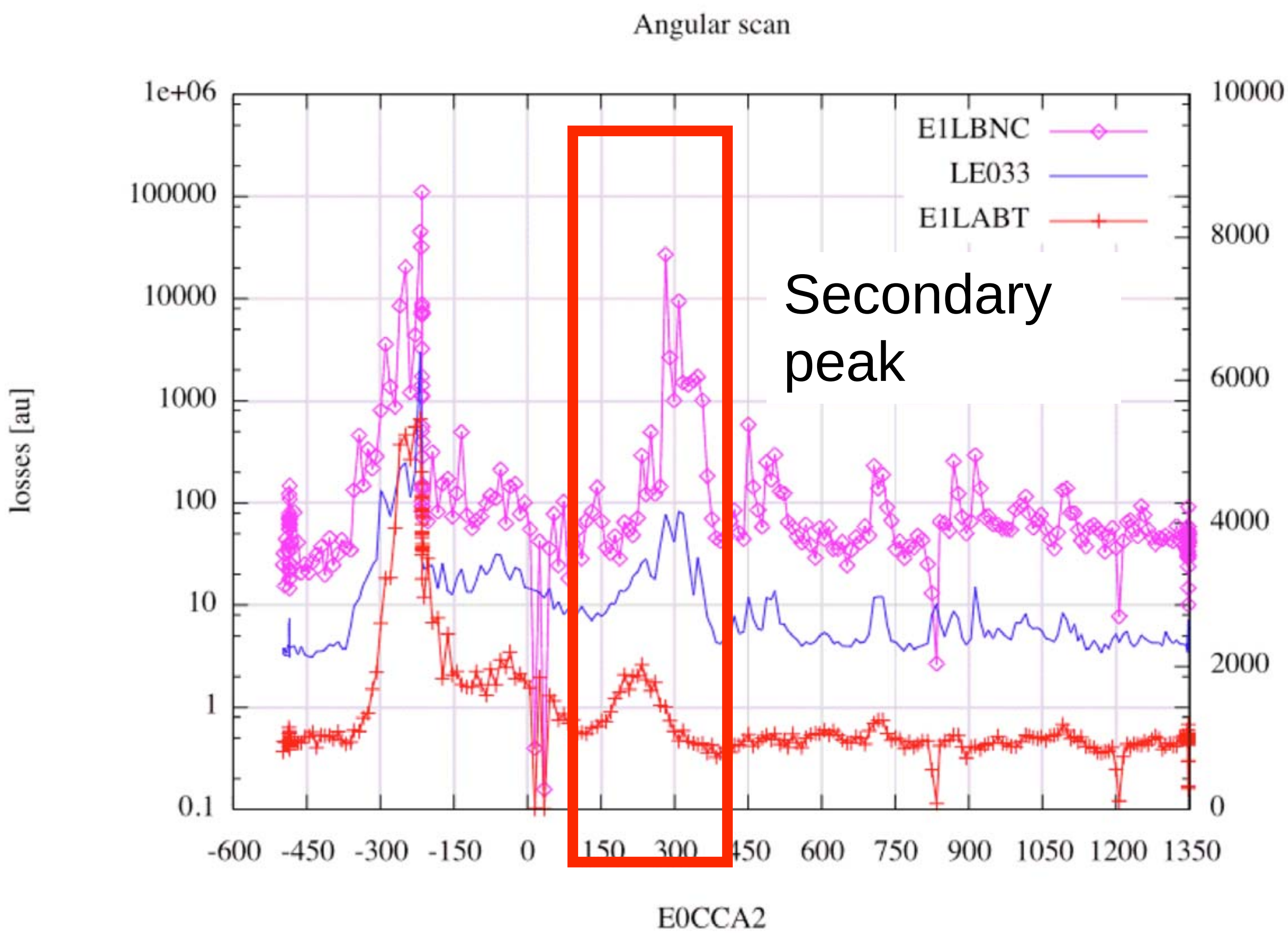
1. Is the 'slope' region due to the **amorphous** behavior of the 'amorphous' layer?
   - In this case, and according to the model of our crystal, the amorphous region should be larger for the crystal closer to 'pure channeling' position -> this is in contraddiction with our data.
2. Cannot be **channeling**: we have detected the channeling 'shoulder'!
3. Cannot be **dechanneling**: the dechanneling kick cannot be larger than the channeling kick!
4. Cannot be **single volume reflection**: the kick is too large (average of ~100 μrad)
5. Could it be **multiple volume reflection**?

Investigate the 'slope' region

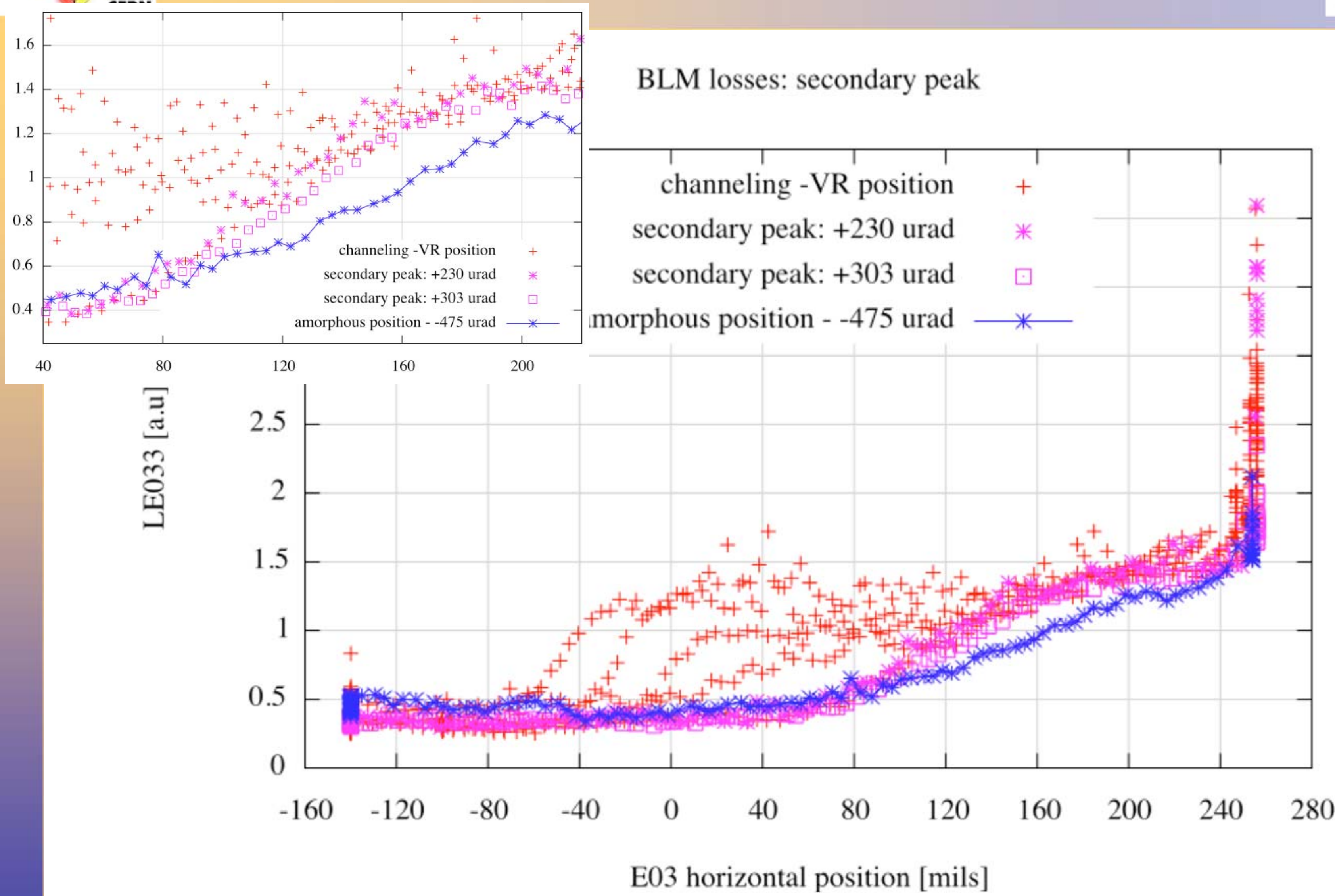
Comparison with amorphous



… more questions…
Secondary peak

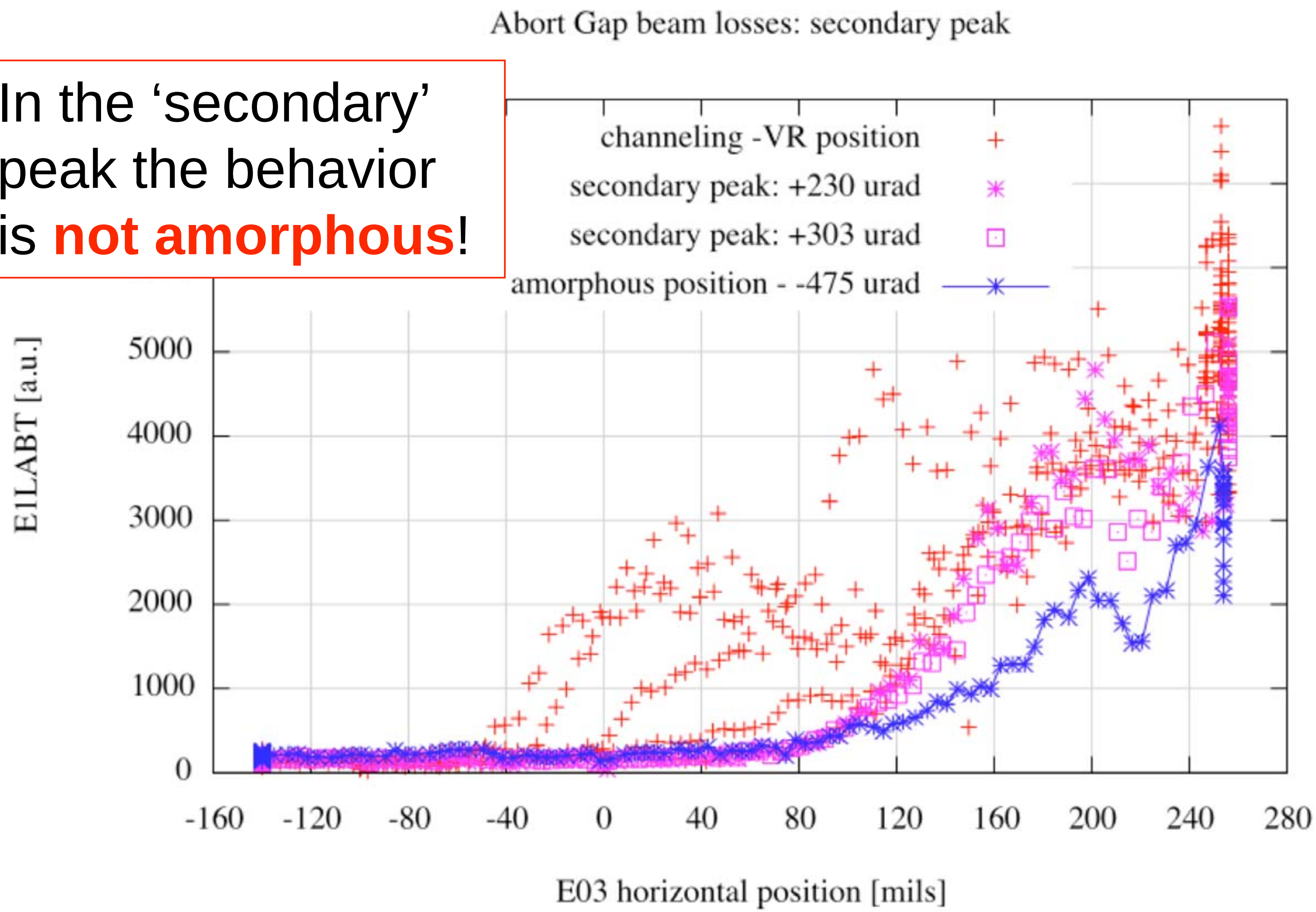


Investigate the secondary peak
E03 coll scan: BLM losses



Investigate the secondary peak

E03 coll scan: DC beam losses



In the 'secondary' peak the behavior is **not amorphous**!

Investigate the secondary peak

conclusion

- In the secondary peak at ~300 μrad there is evidence of some coherent effect in the crystal.
- Cold it be a secondary channeling peak? (with angle < 100 μrad, then covered by the slope region)
- Is the VR region larger than expected? How is this possible? -> we need an exact geometrical description of the crystal.
- What happens in the middle? (between where we believe is the end of VR and the secondary peak). This should be investigated.

More questions?

- What is the effect of the electron lens in the particle-crystal dynamic?
- Is the synchrotron oscillation playing an important role? Is the “grazing” assumption valid? Should we evaluate in more details the impacting angle of off momentum particles?
- What happens if the RF voltage is turned up/down (moving the separatrix)? What happens if the RF frequency itself is slightly changed, shifting the underside of the separatrix slightly up/down?

Conclusions

A lot of open questions…

- We trust the characterization of the crystal made in Ferrara (V. Guidi et al.): we assume the bending angle=410 μrad.
- We observe a channeling acceptance that is far too large.
- We observe a displacement of the channeled beam at the collimator which is lower than expected (= lower kick).
- Different hypothesis to explain this features:
  - Feature of the beam (momentum offset)
  - Feature of the crystal (mis-cut angle)
- The momentum offset does not have significant influence.
- **The mis-cut angle can partially explain the results we observe.**
- Further investigations will be done in the next studies.

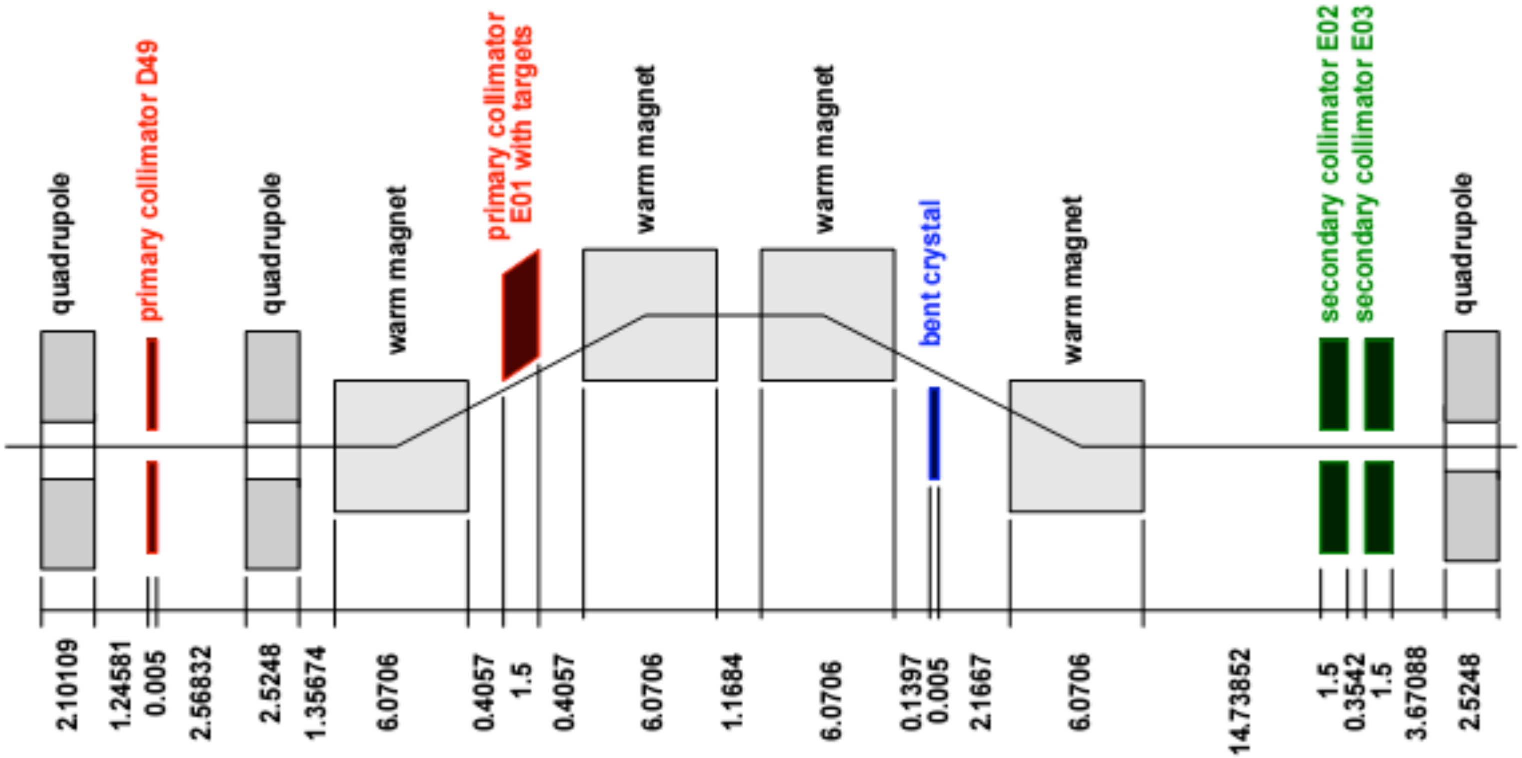
Thanks!

…to you for your attention…

… AND to many colleagues for their help…

Dick Carrigan, Todd Johnson, Nikolai Mokov, Vladimir Shiltev , Satomi Shirai, Rick Tesarek

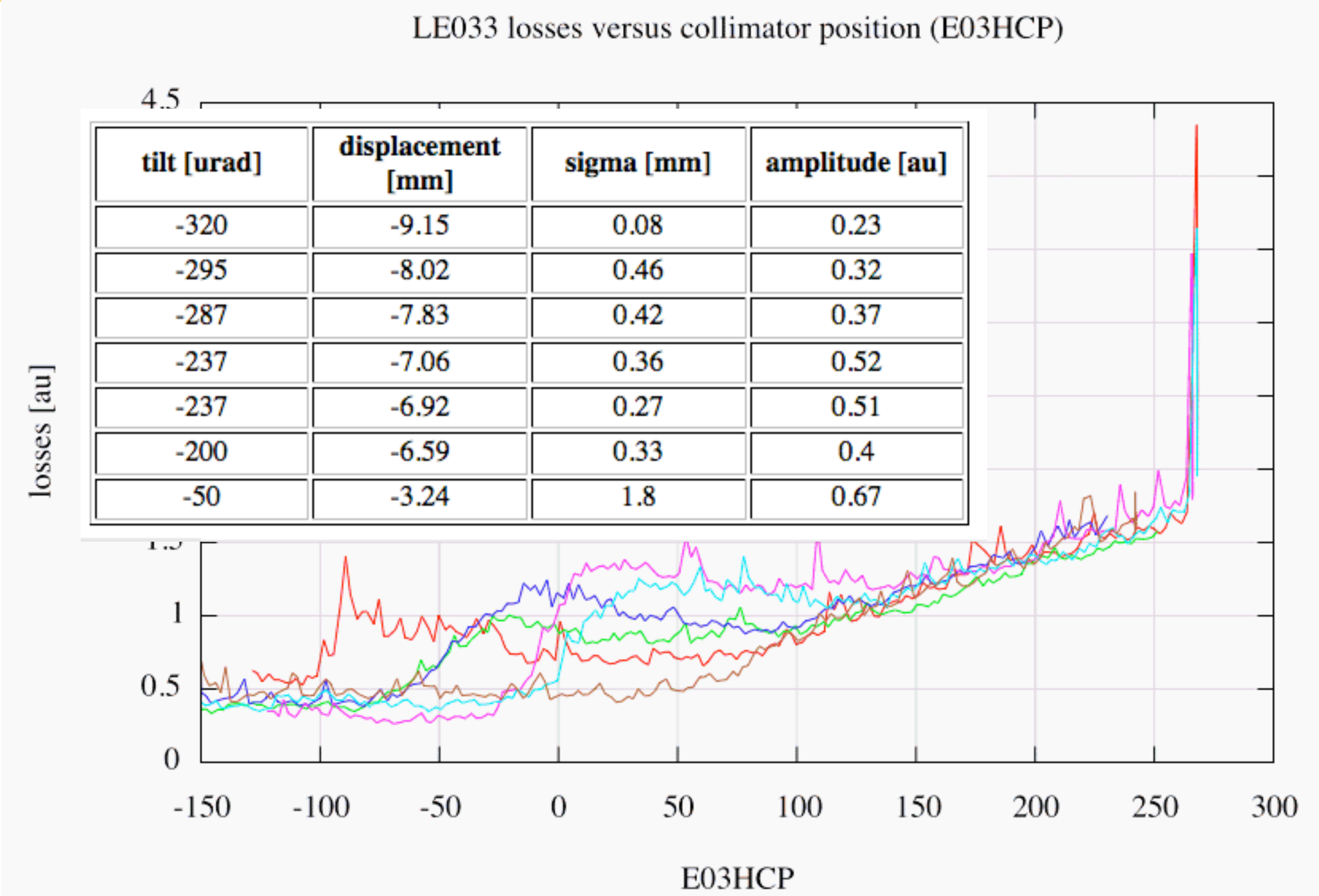
Armen Apyan, Chiara Bracco , Sasha Drozhdin, Guillaume Robert de Molaize, Jeffrey Smith, Rogelio Thomas Garcia, Sasha Valishev, Thomas Weiler, Igor Yazynin



Courtesy of A.Drozhdin, A,Apyan

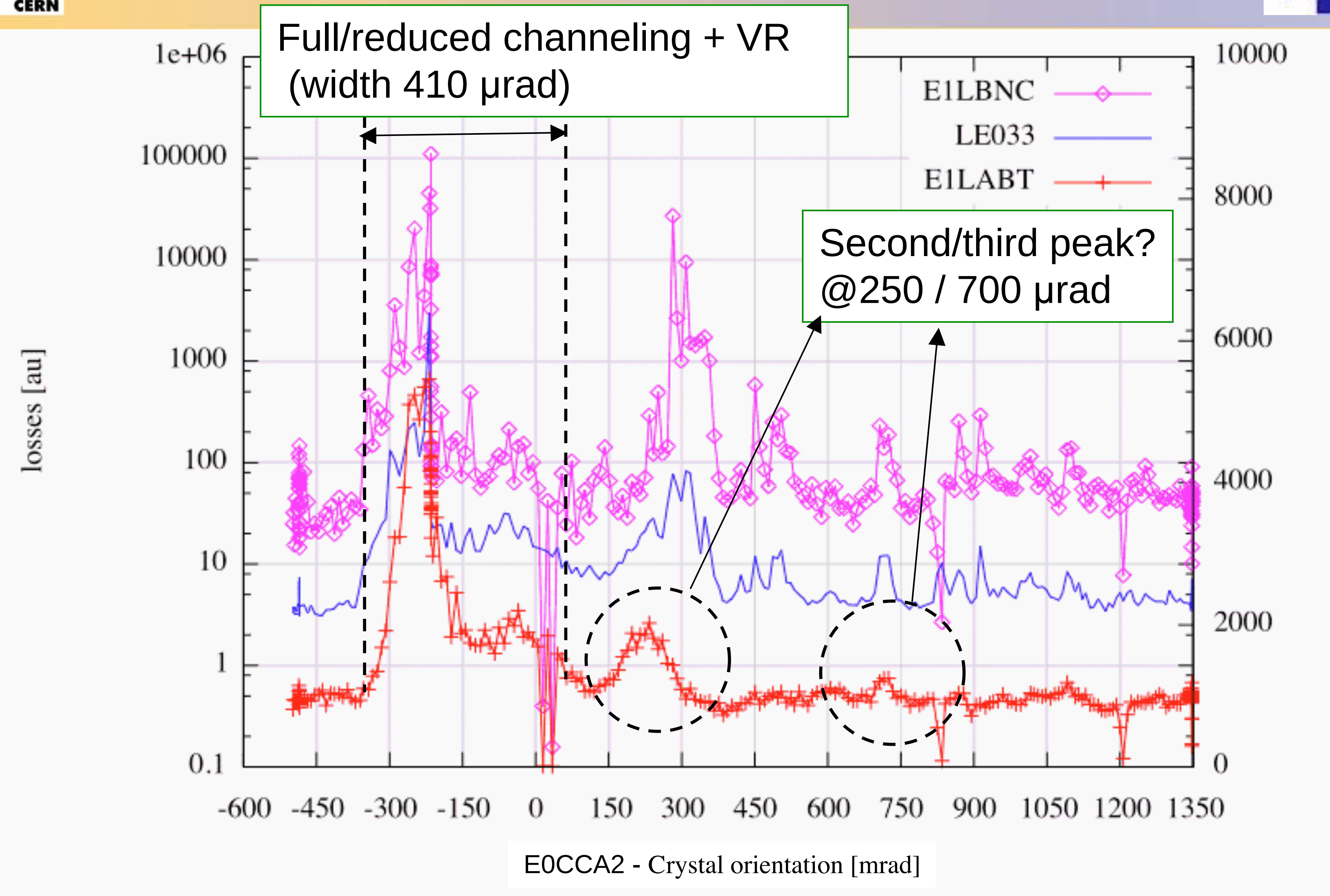
All toghether…

Gaussian fits



tilt [urad]	displacement [mm]	sigma [mm]	amplitude [au]
-320	-9.15	0.08	0.23
-295	-8.02	0.46	0.32
-287	-7.83	0.42	0.37
-237	-7.06	0.36	0.52
-237	-6.92	0.27	0.51
-200	-6.59	0.33	0.4
-50	-3.24	1.8	0.67

Angular scan: a wider view



maybe the crystal is almost aligned in vertical position?