Analysis of the T-980 experimental data

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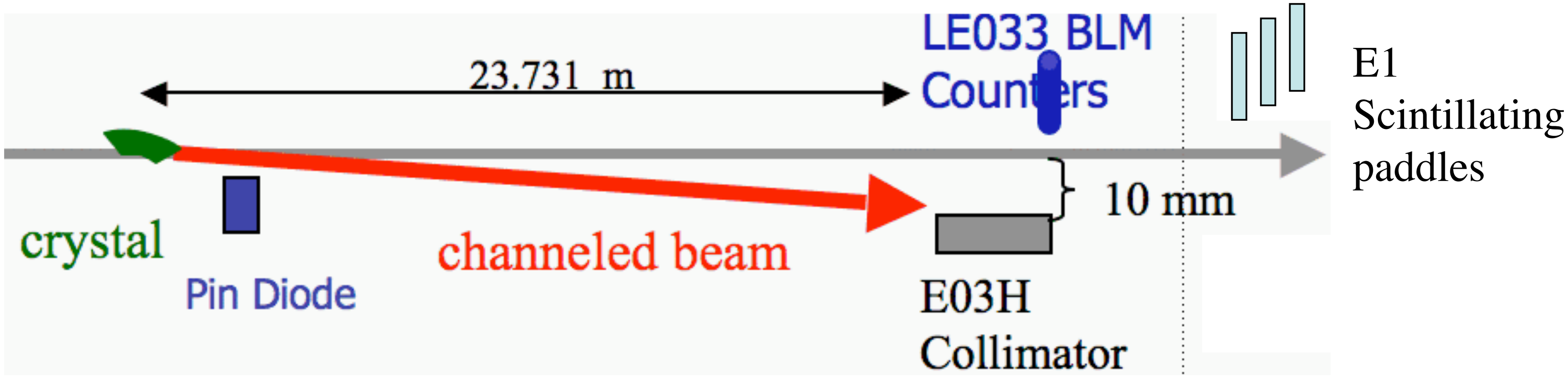
Layout of T-980



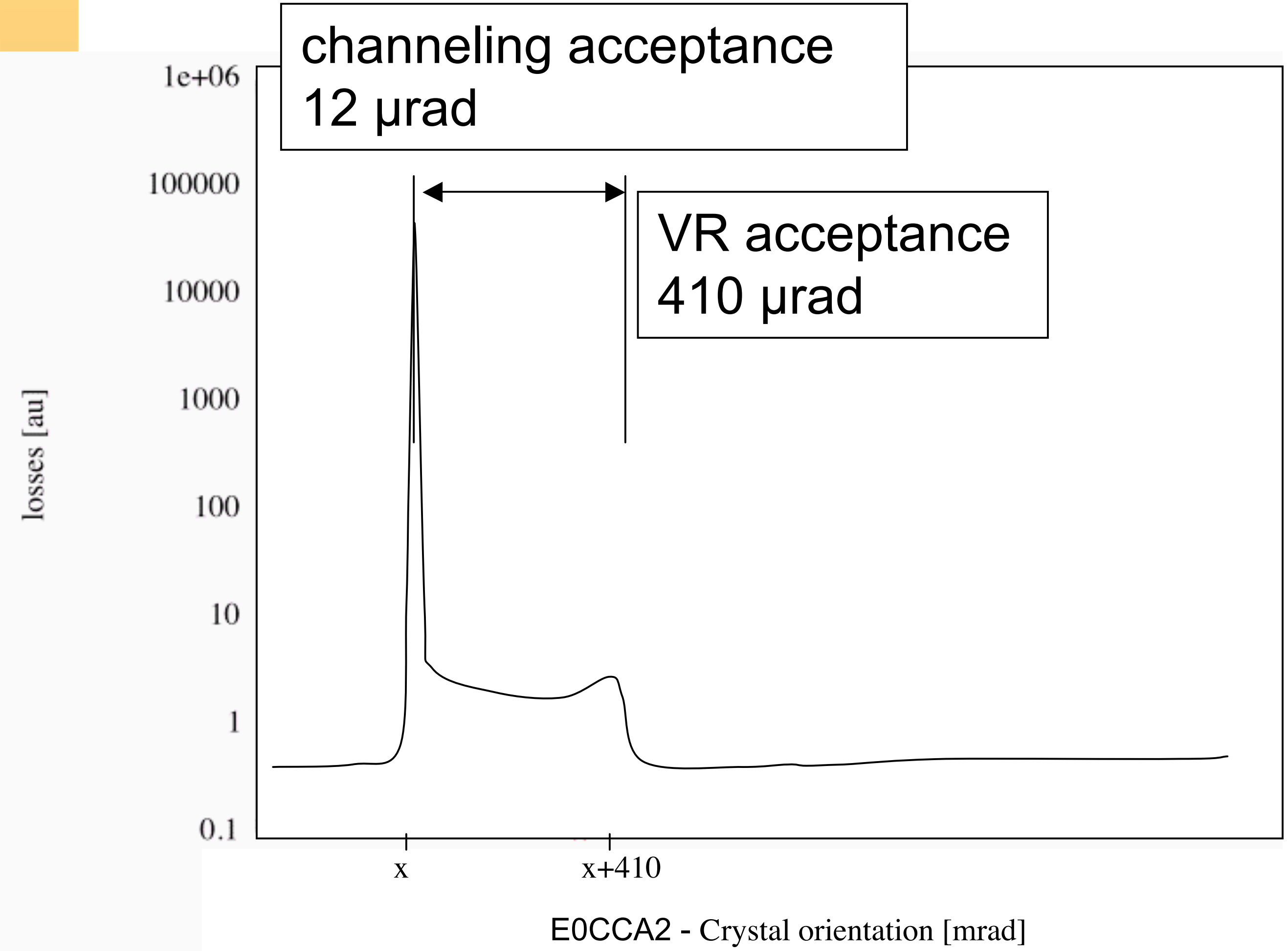
- Si o-shaped crystal, 5 mm long, 410 μrad bending angle
- Pin diode downstream of the crystal, used to measure the inelastic interactions at the crystal location
- Collimator E03 (horizontal, p collimator) 23.7 m downstream
- LE0 BLM counters immediately downstream the collimator: total losses at the collimator location
- E1 scintillating paddles: gated counters for losses at the E03 collimator. They can distinguish between bunched and abort gap beam.

Standard measurement procedure

Once we have the crystal as leading edge, we perform two different measurements:

1. **Angular scan:** change the crystal orientation and measure losses at the E03 collimator
2. **Collimator scan:** keep the angle of the crystal fixed, and change the horizontal position of the collimator E03

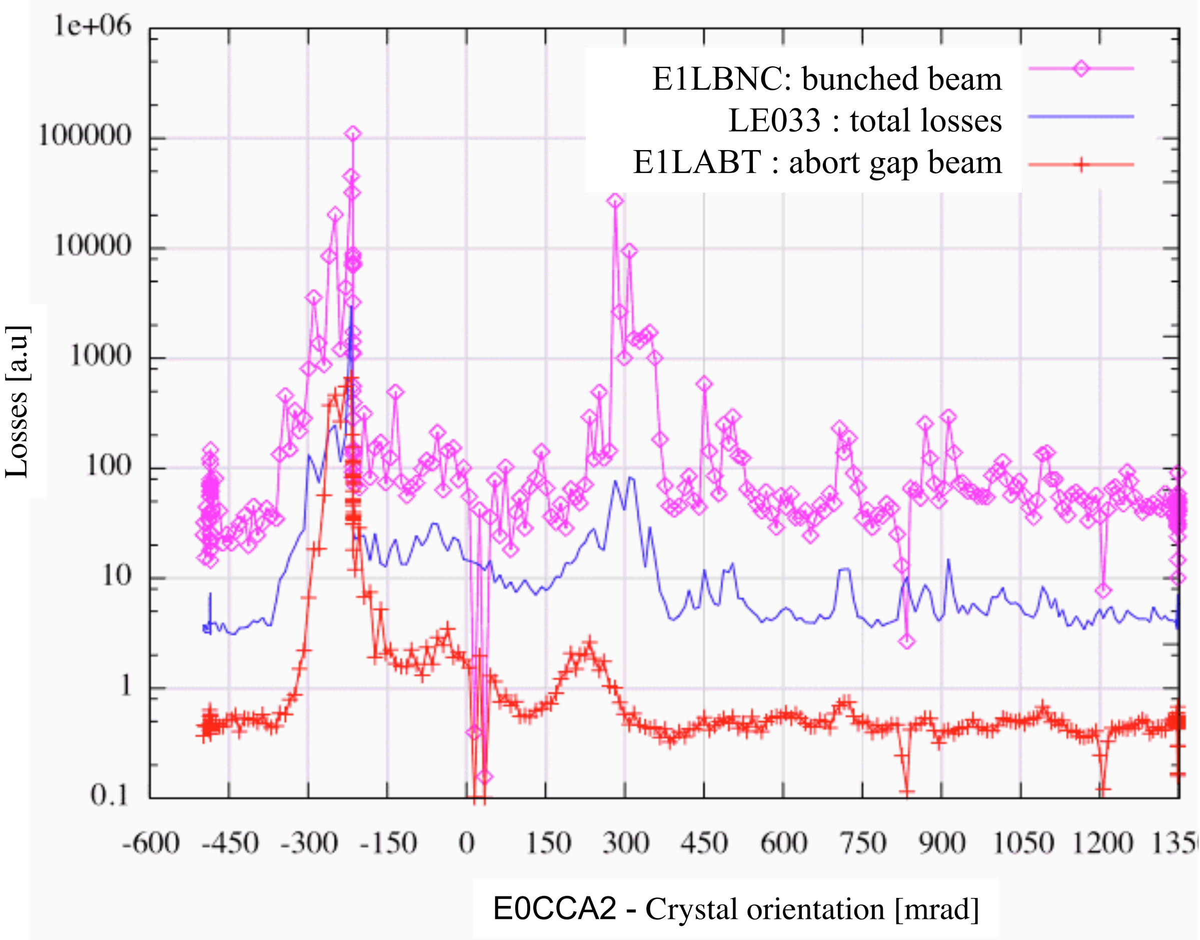
Angular scan: what we expected…



The ideal behaviour:

- 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…



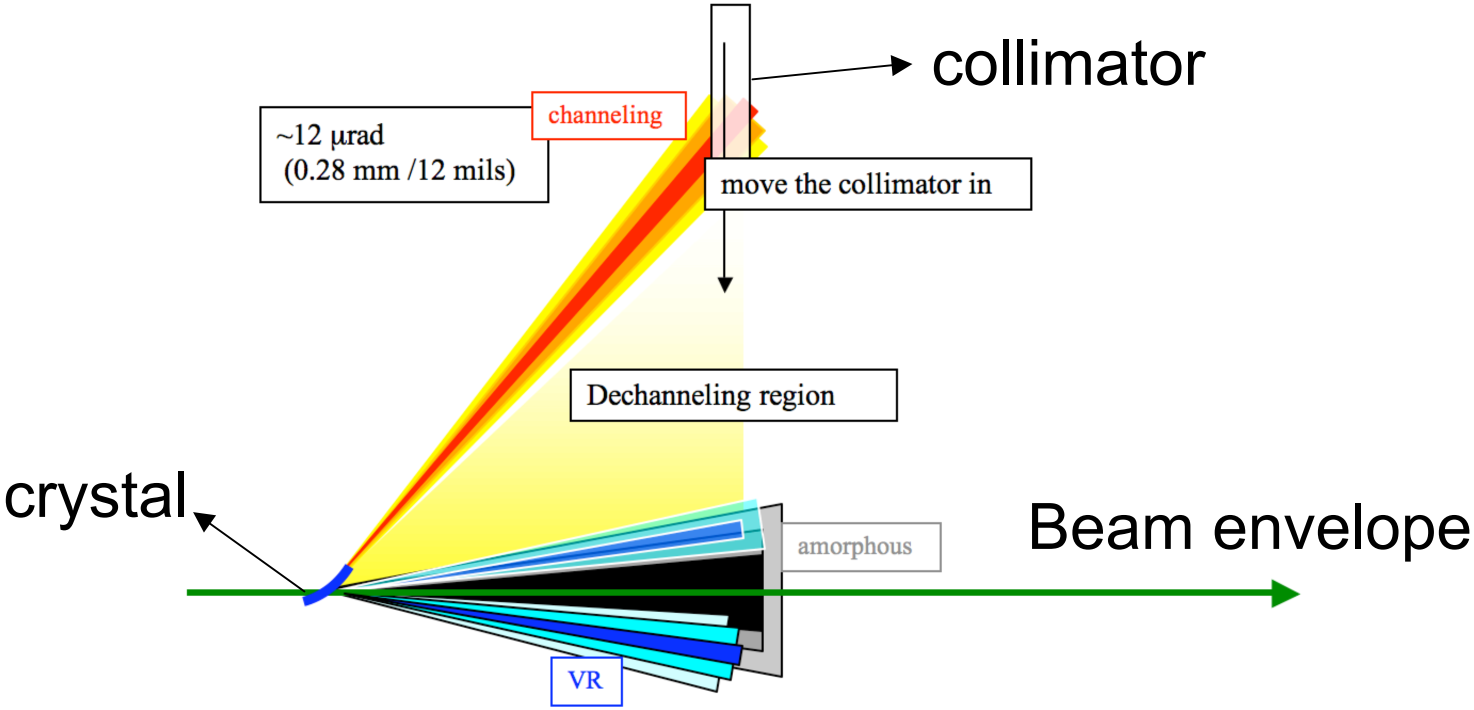
The signal for bunched beam is noisy: a normalization is needed. (how to do it???)

The maximum of the channeling peak is at -240 μrad.

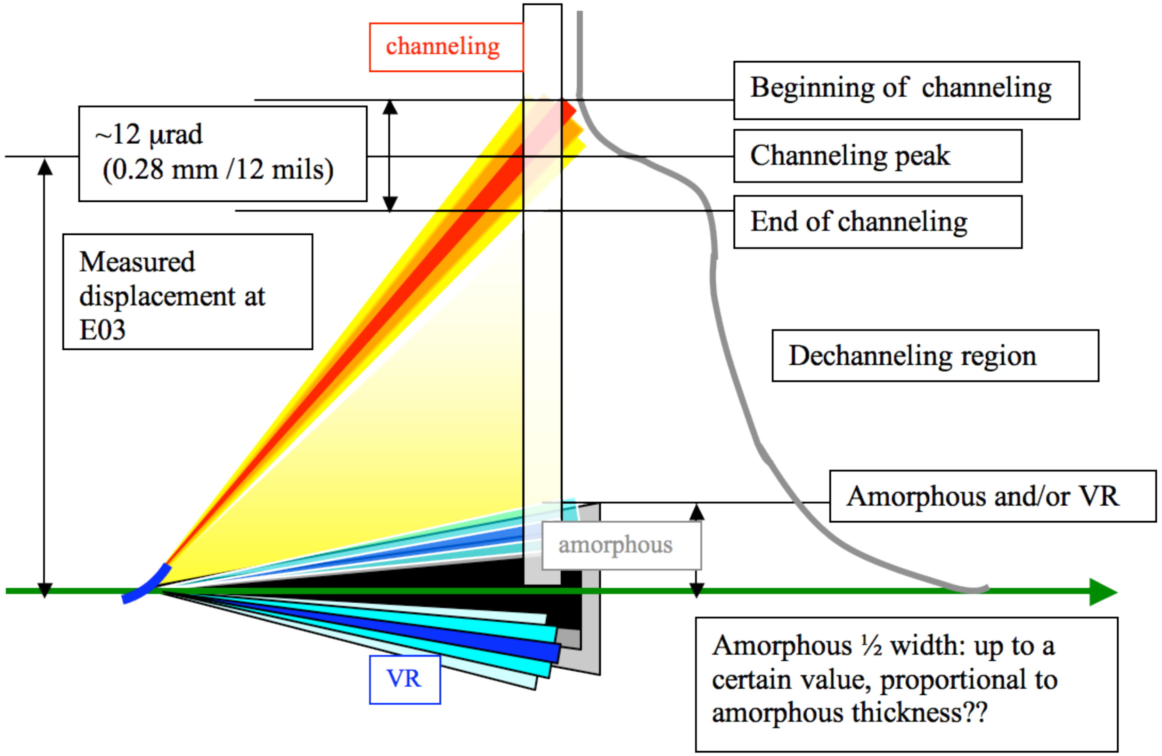
The measured acceptance of channeling is ~200 μrad : **much larger than expected! (~12 μrad).**

Possible reasons are investigated further

Collimator scan



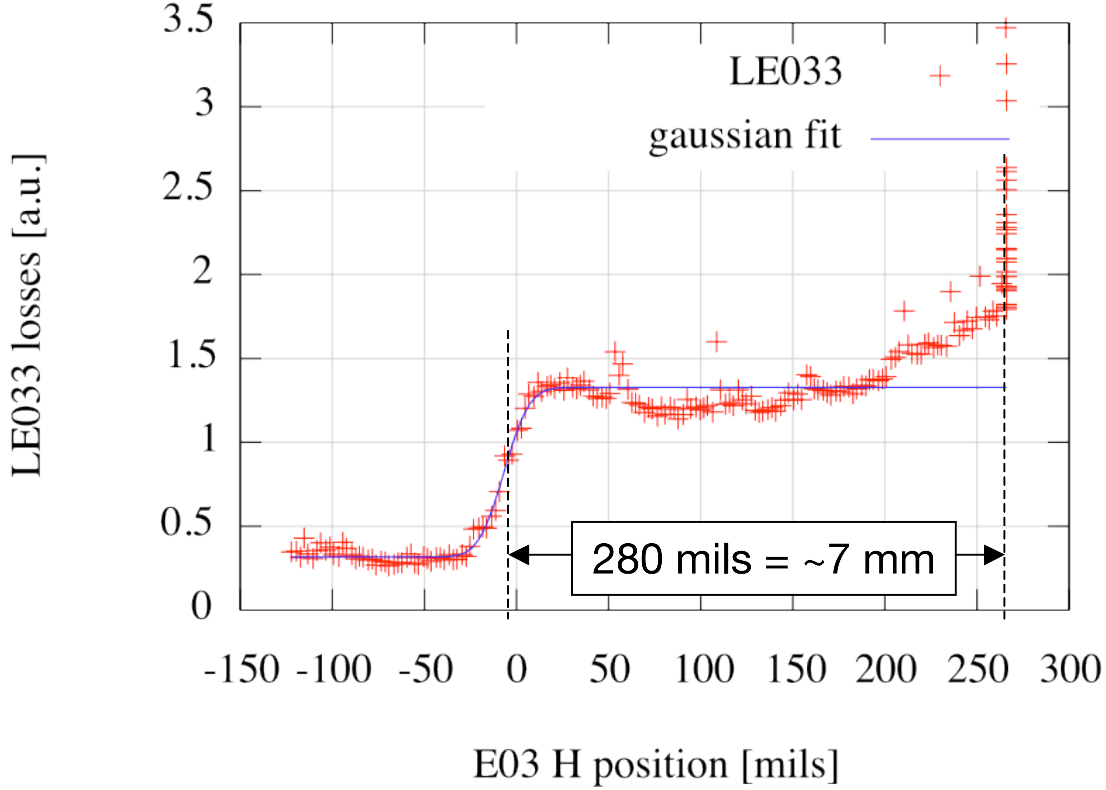
Collimator scan



- 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. Why is the channeling peak acceptance much larger (~200 μrad) than expected (~20 μrad)?
2. Why we do not see a clear VR effect?
3. Why the measured displacement (~7 mm) for the channeling peak is lower than the expected one (9.6 mm)?
4. What is the peak at ~250/300 μrad in the angular scan? Is there a third peak around ~700 μrad?

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

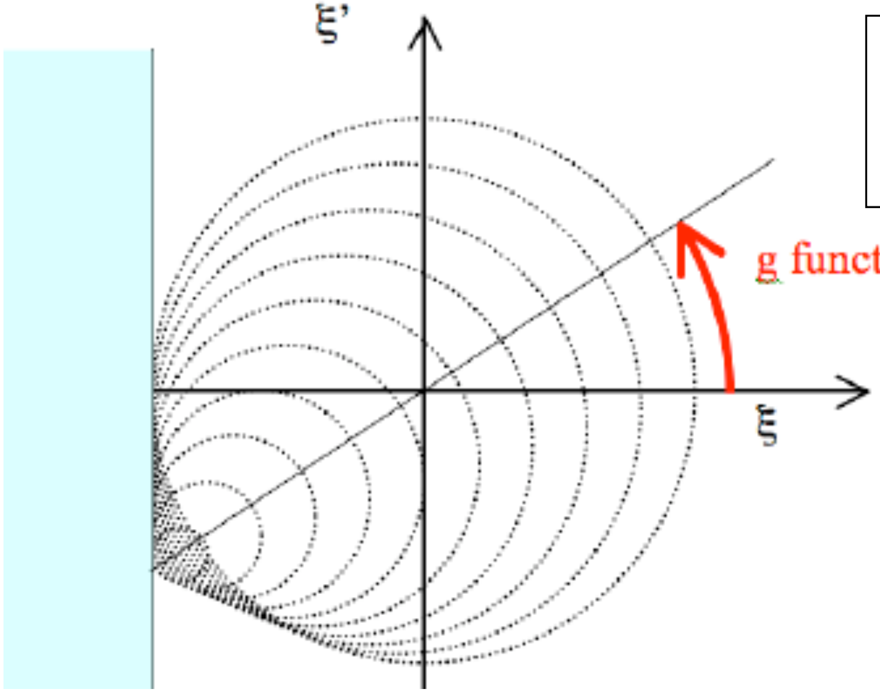
Taking into account that:

- 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}

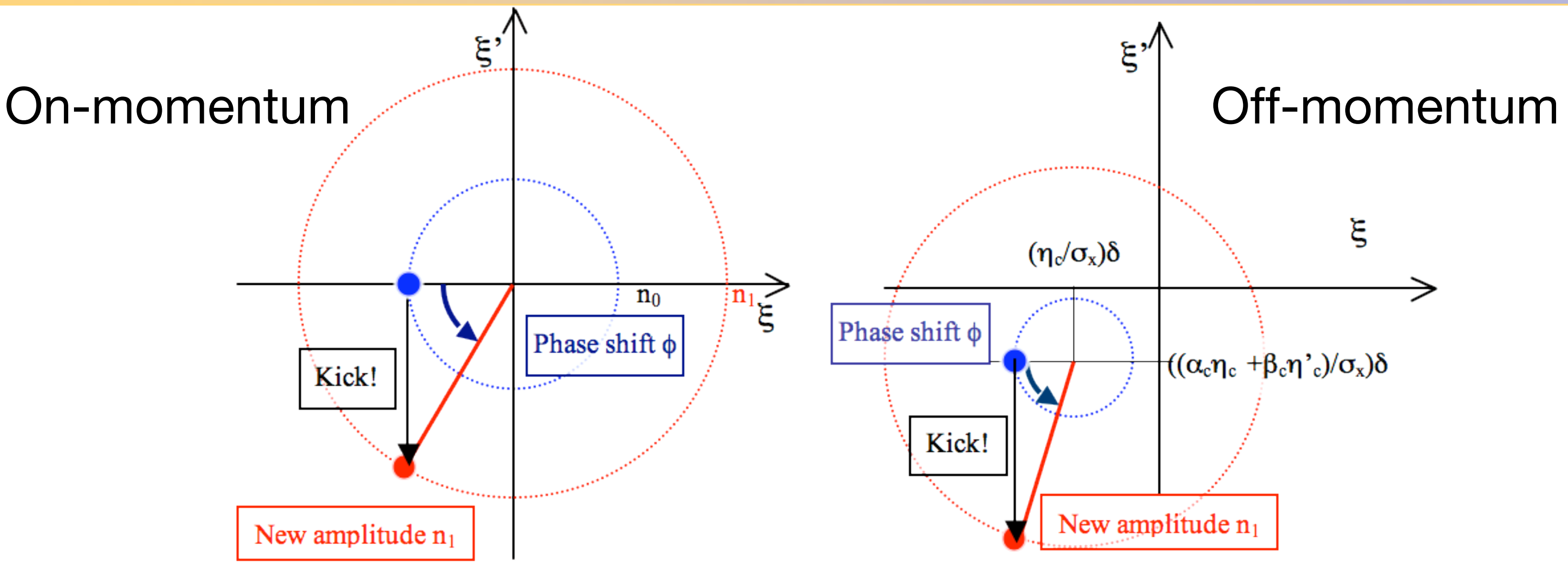
The **grazing condition** requires that, at the crystal location, the *maximum betatron extension* of the particle plus the *offset given by the dispersion* is equal to the x coordinate of the crystal's edge

=> careful: the synchrotron oscillation is neglected in this first approximation.

The angular spread is only ~1.6μrad for particles with $\Delta p/p = 4\ \sigma_p$!

The momentum offset cannot explain a 200 μrad-wide channeling peak

Off-momentum particles:
displacement at the collimator

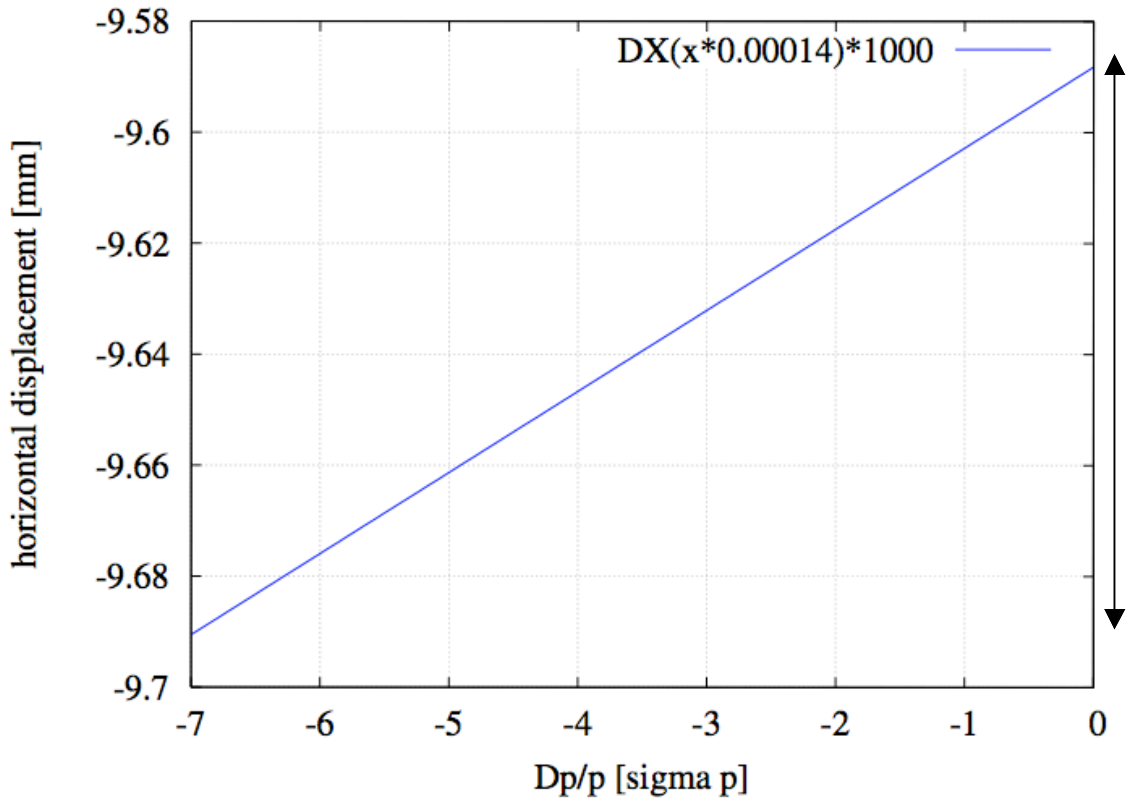


Every kick changes the amplitude and the phase of the particle.
The new amplitude and the phase shift depend on the initial amplitude: different outcomes for particles with different energy!

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 higher for larger energy offset.

Anyway the difference is only 100 μm!!!

The momentum offset cannot explain the reduced displacement observed at E03

Hypothesis

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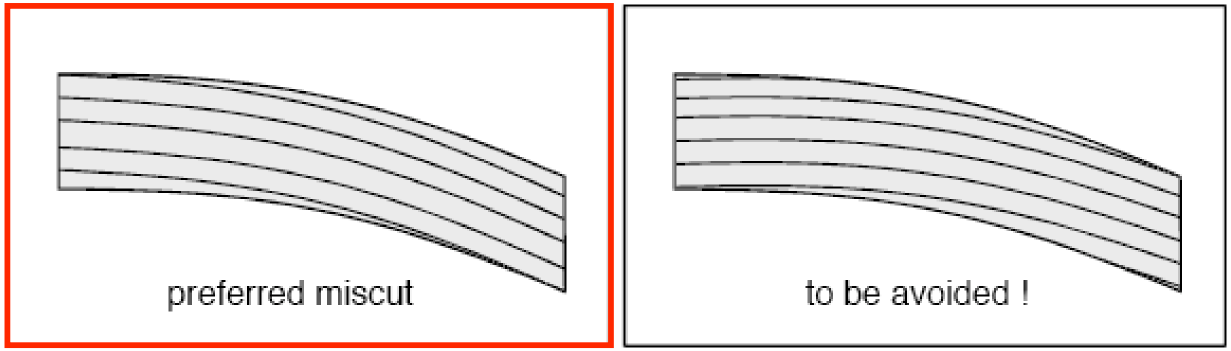
   - Off momentum particles have a different displacement at the collimator location: how much is the difference?
2. Feature of the crystal (mis-cut angle)
   - What is the effect of the mis-cut on the channeling acceptance?
   - What is the effect of the mis-cut on the observed displacement at the collimator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

Influence of the mis-cut angle

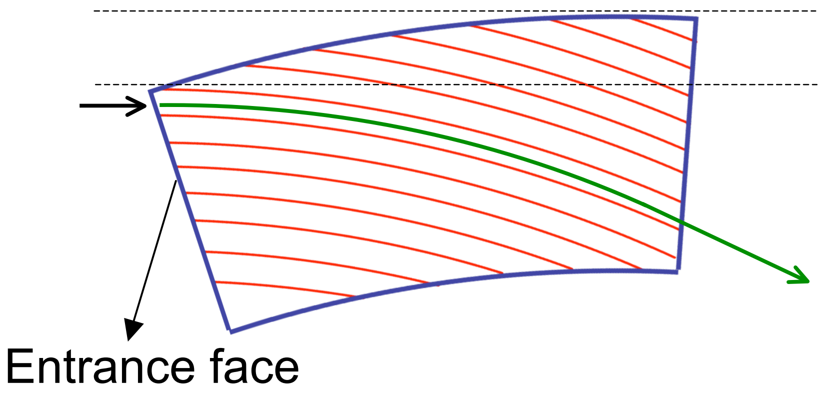
- The mis-cut angle of the crystal is **very large** (1.6 mrad over 0.41 mrad of bending angle)



- 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

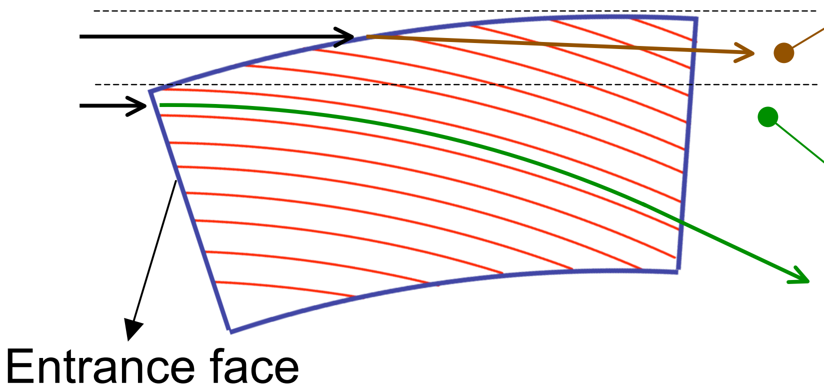


In this region the particles are aligned: channeling with full channeling angle (410 μrad). Impact parameter >5 μm

- 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

- 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

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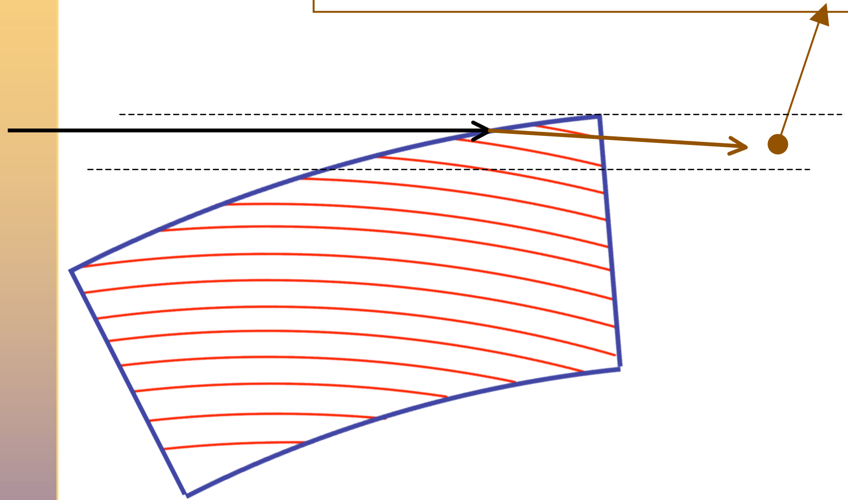
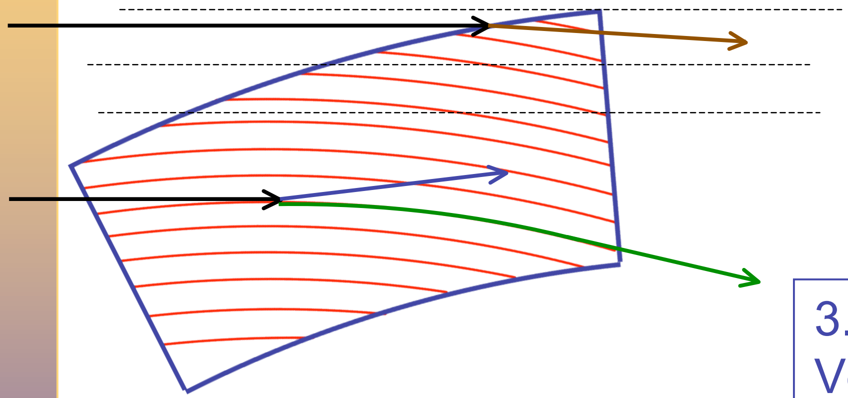
Positive mis-cut angle:
crystal aligned for VR

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



Positive mis-cut angle:
crystal aligned for VR

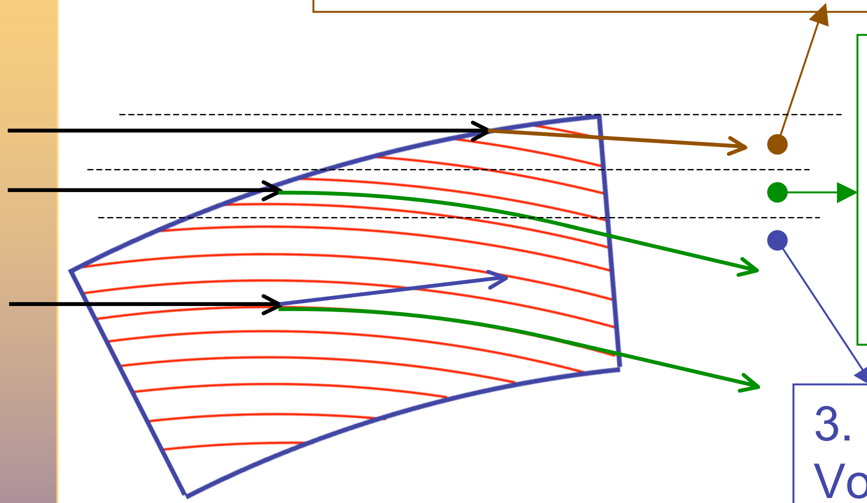
1.In this region the particles are not aligned: amorphous layer.
Impact parameter 0μm < λ_0< 5 μm



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

1.In this region the particles are not aligned: amorphous layer.
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.
Impact parameter $\lambda > \lambda_0$

Positive mis-cut angle:

crystal aligned for VR

1.In this region the particles are not aligned: amorphous layer.
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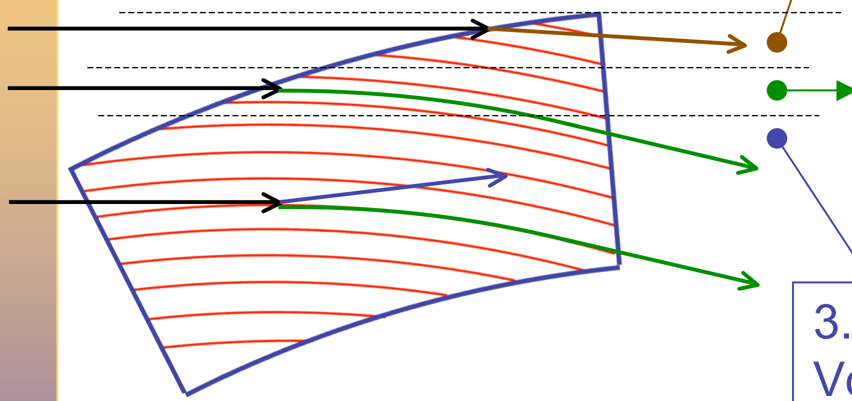
The width of this region is $\Delta\lambda$~0.25 µm



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

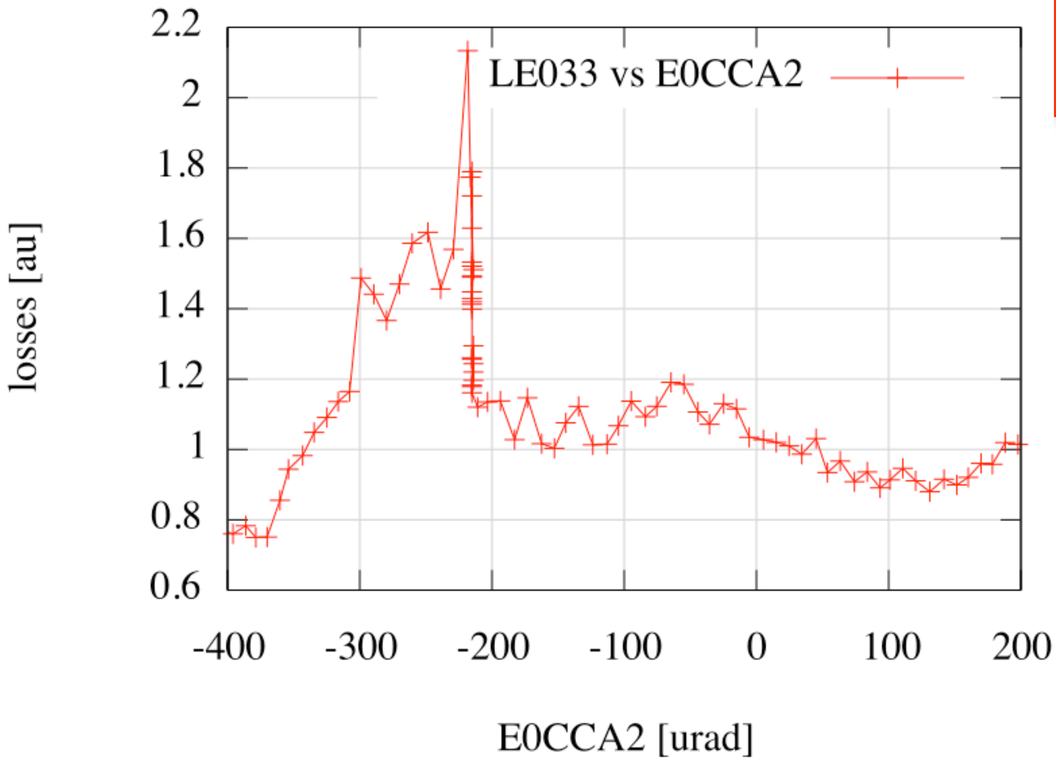
For each orientation of the crystal, there will be an impact parameter λ_0 for which the particles are aligned with crystal planes

=> **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.

How to interpret our angular scan?

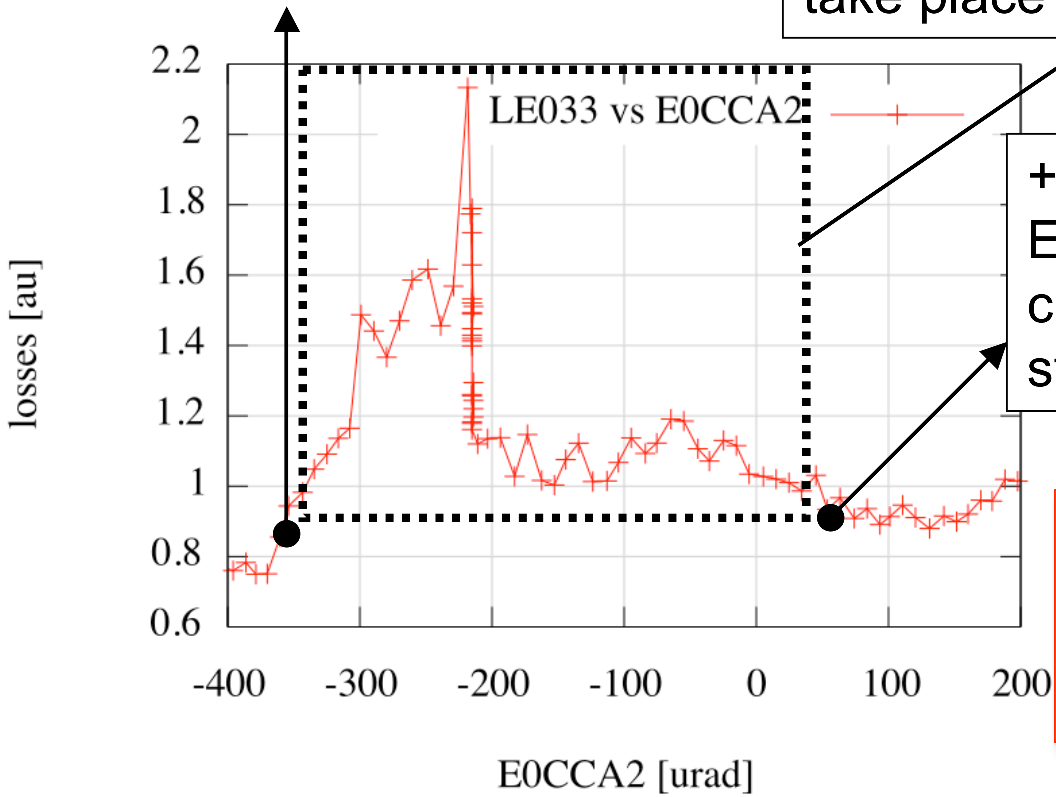


NB: Reduced channeling and Volume Capture give the same kick to the particle, but the channeling probability is much higher.

Positive mis-cut angle:
interpretation of measured data

-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

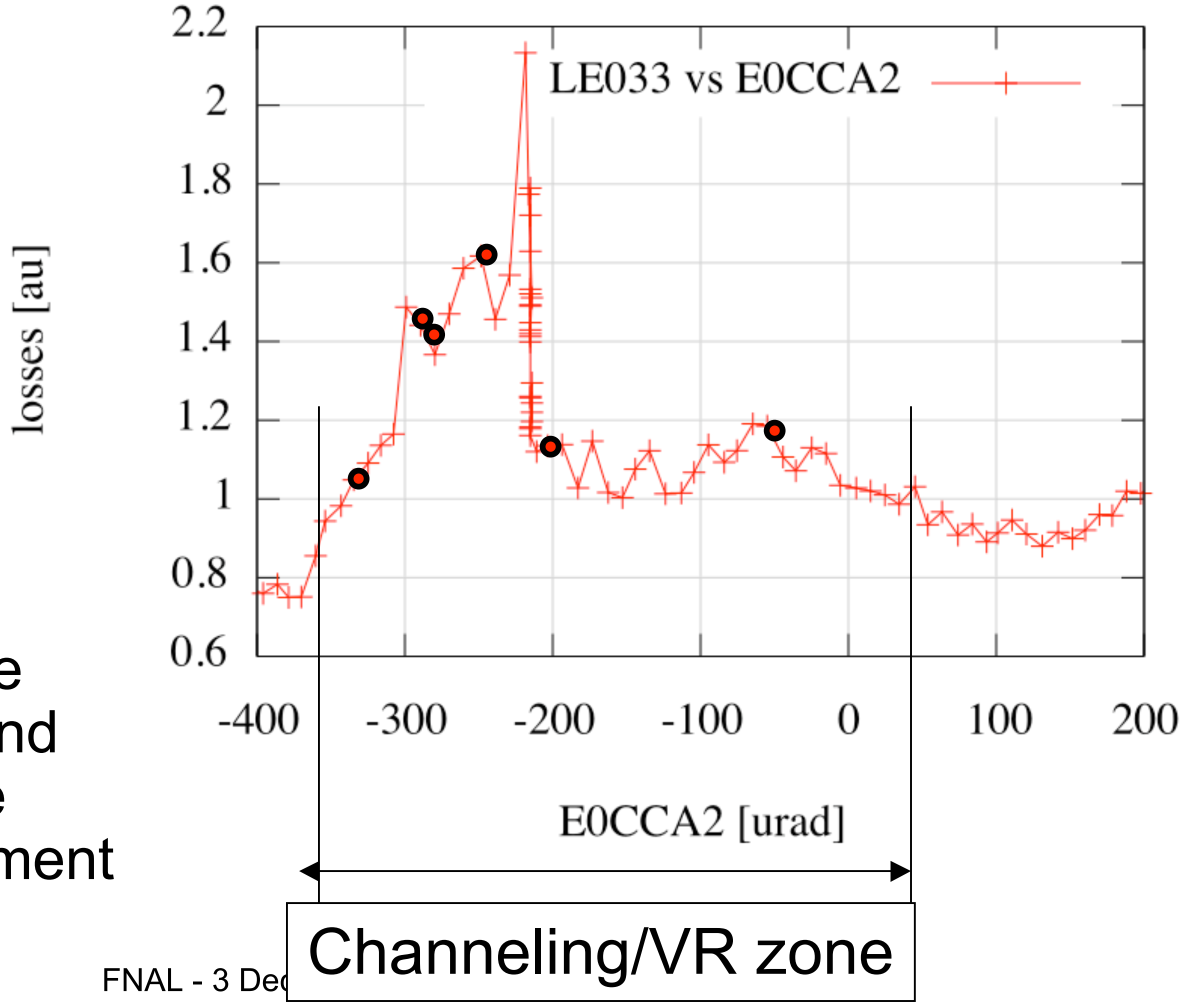


+60 µrad
End of channeling: all the crystal coherent effects should stop

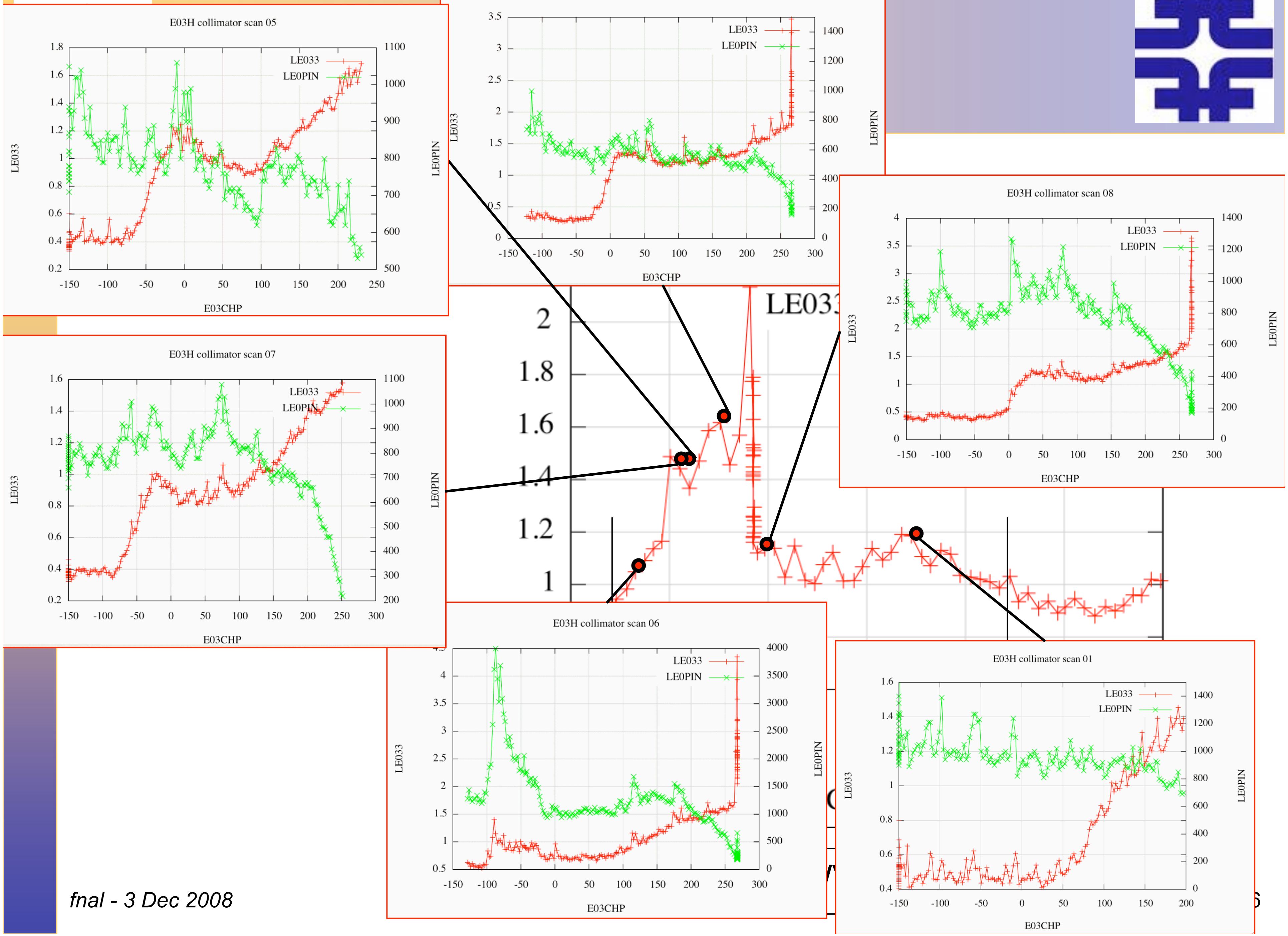
Completely new interpretation of the measured data!

Positive mis-cut angle: comparison with measured data

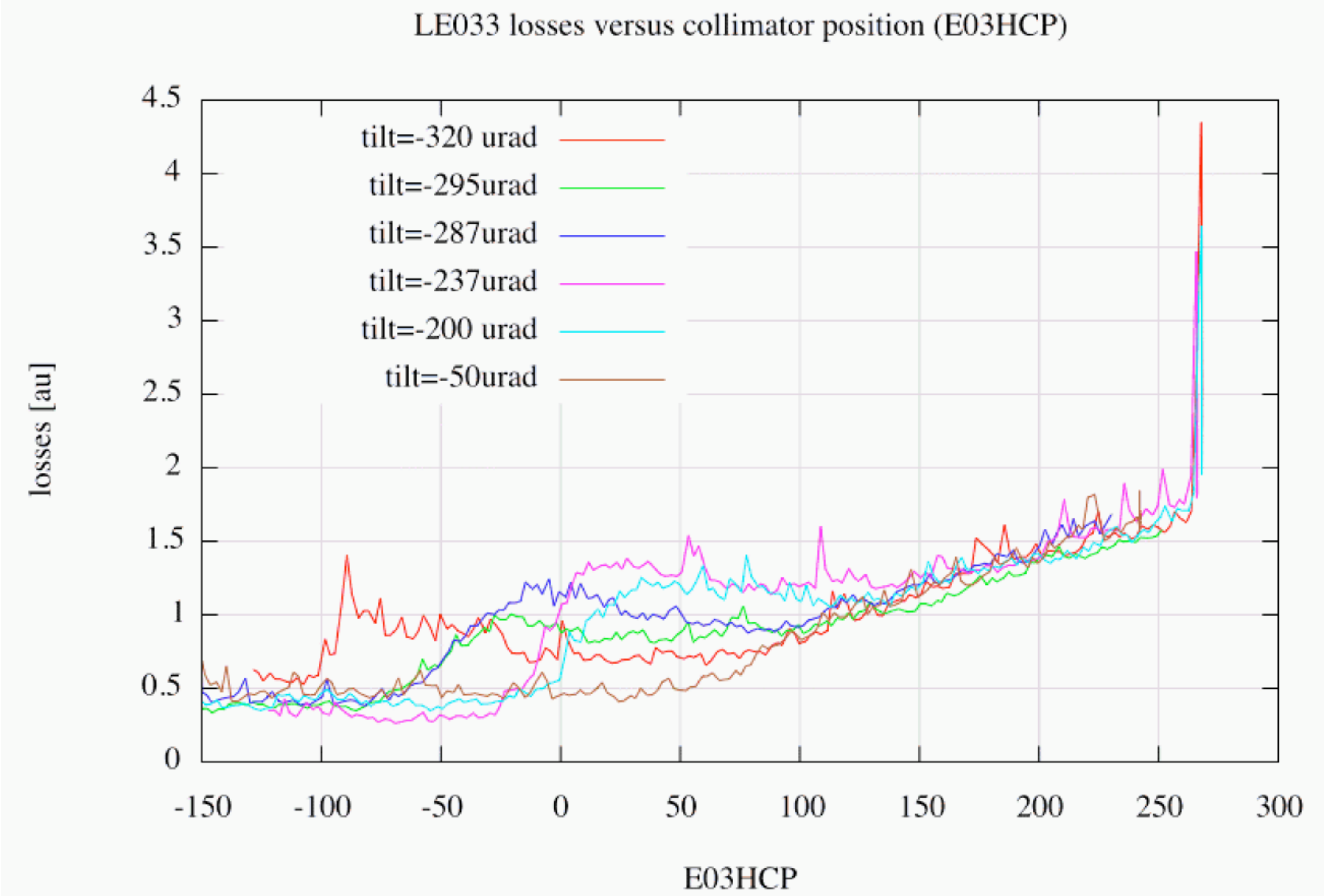
- We selected 6 different orientations for new collimator scans:
  - **- 320 μrad**
  - **- 295 μrad**
  - **- 287 μrad**
  - **- 237 μrad**
  - **- 200 μrad**
  - **- 50 μrad**



- For each point we measure the displacement of the channeled peak, and compare it with the expected displacement

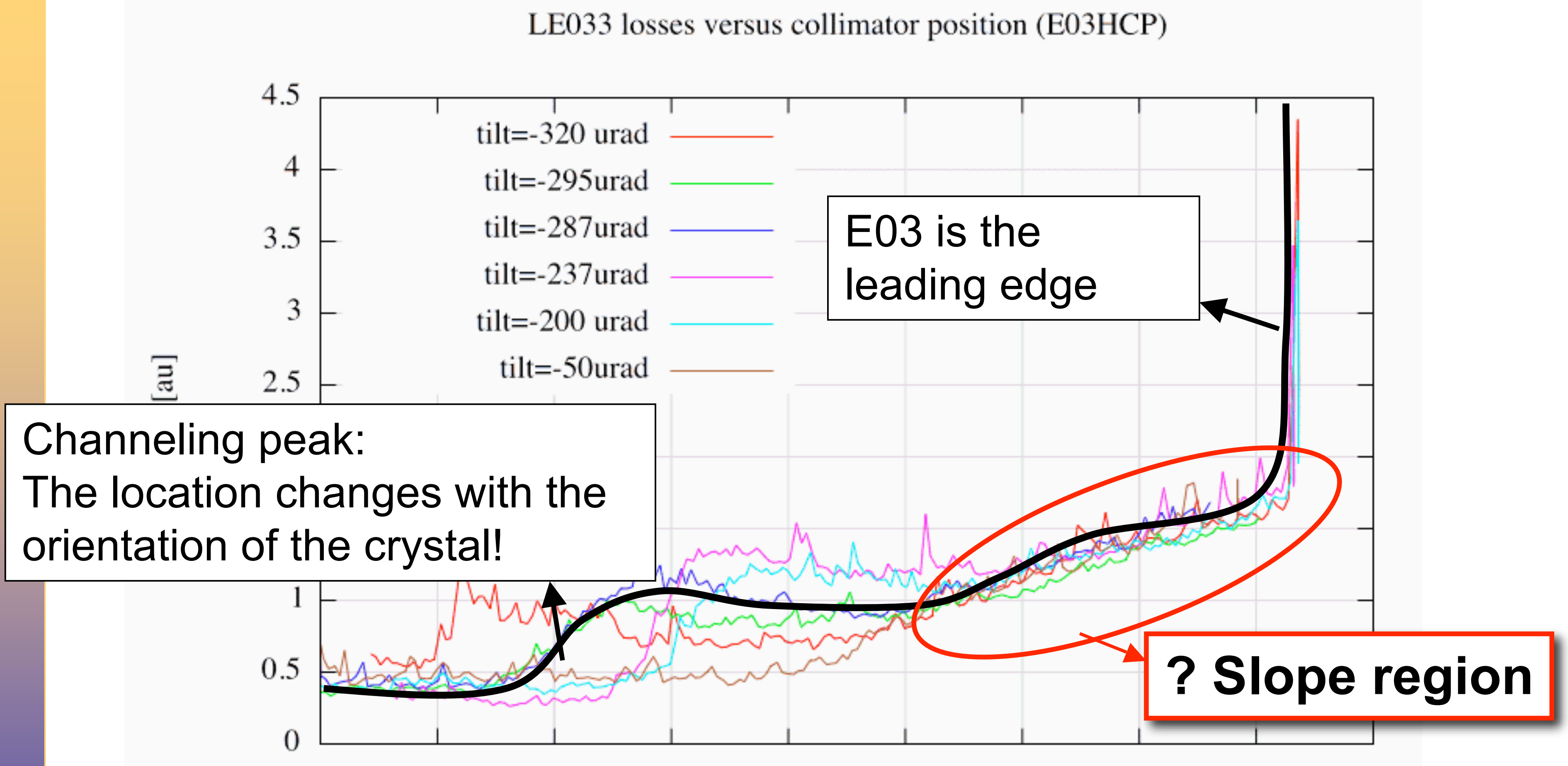

E03H collimator scan 05
E03H collimator scan 04
E03H collimator scan 08
E03H collimator scan 07
E03H collimator scan 06
E03H collimator scan 01
LE033
LE0PIN
E03CHP

All toghether…



All toghether…

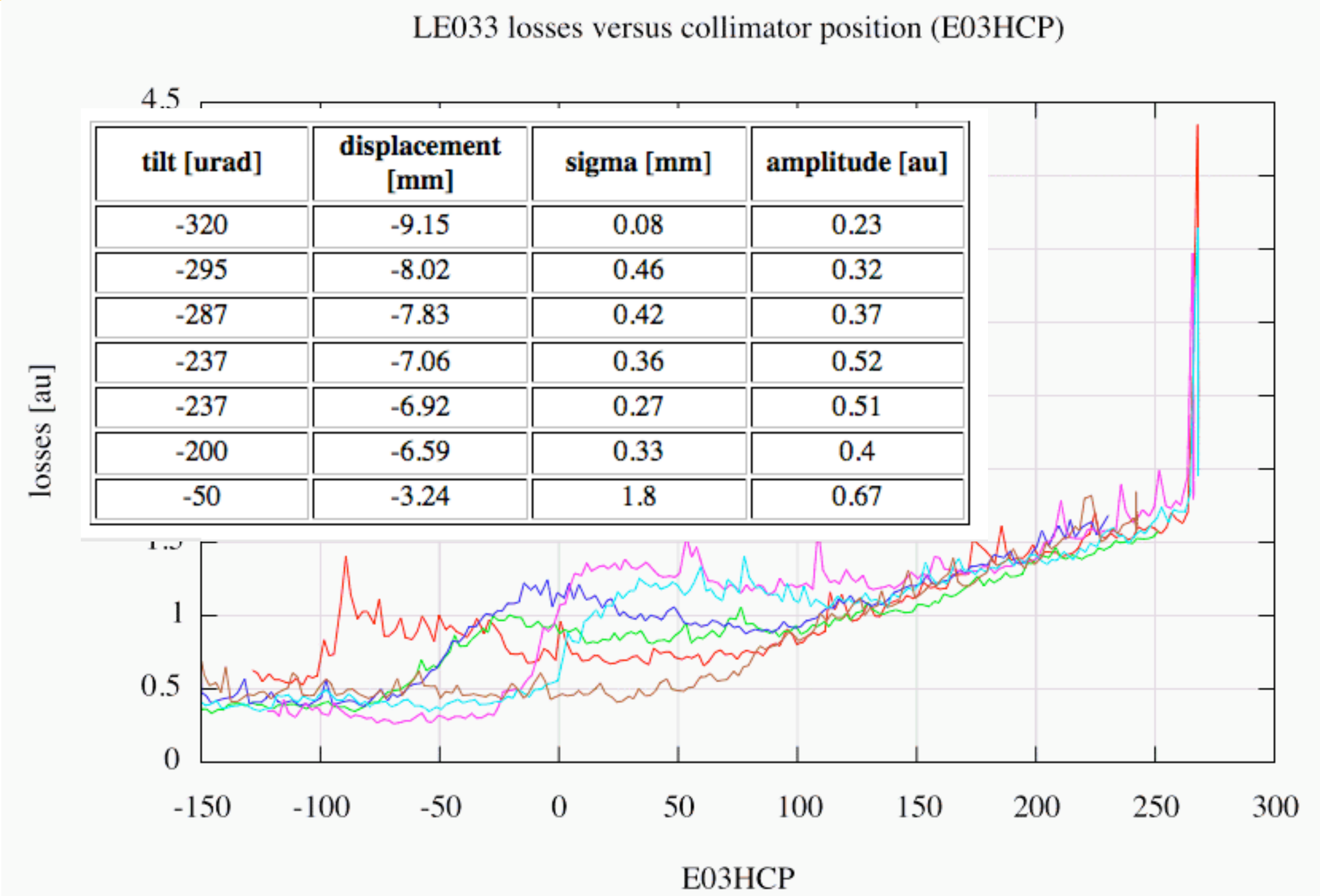
typical shape of a collimator scan



All the E03 scans have the same shape, apart from the scan at -50 μrad, where the channeling peak is not visible

All toghether…

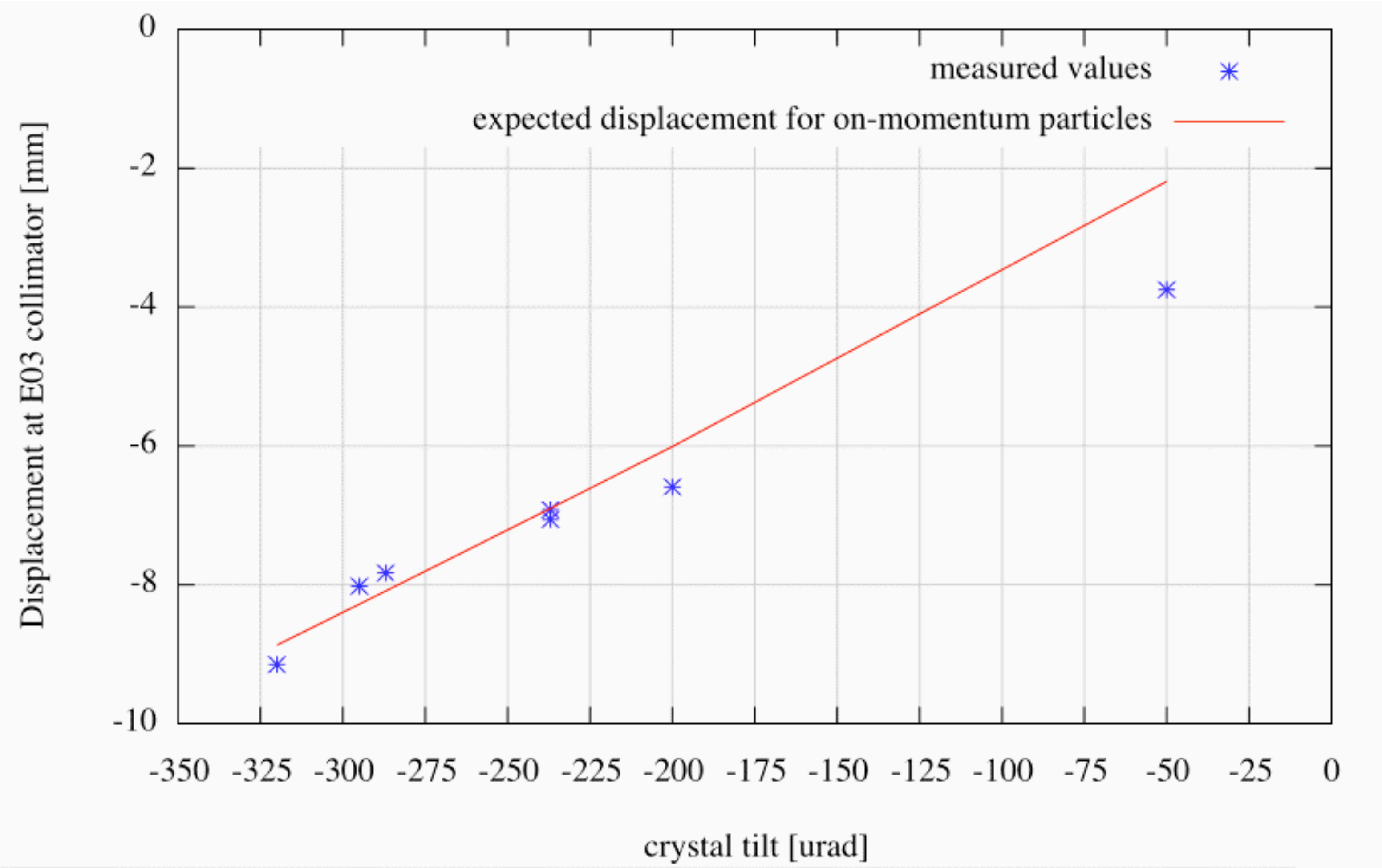
Gaussian fits



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

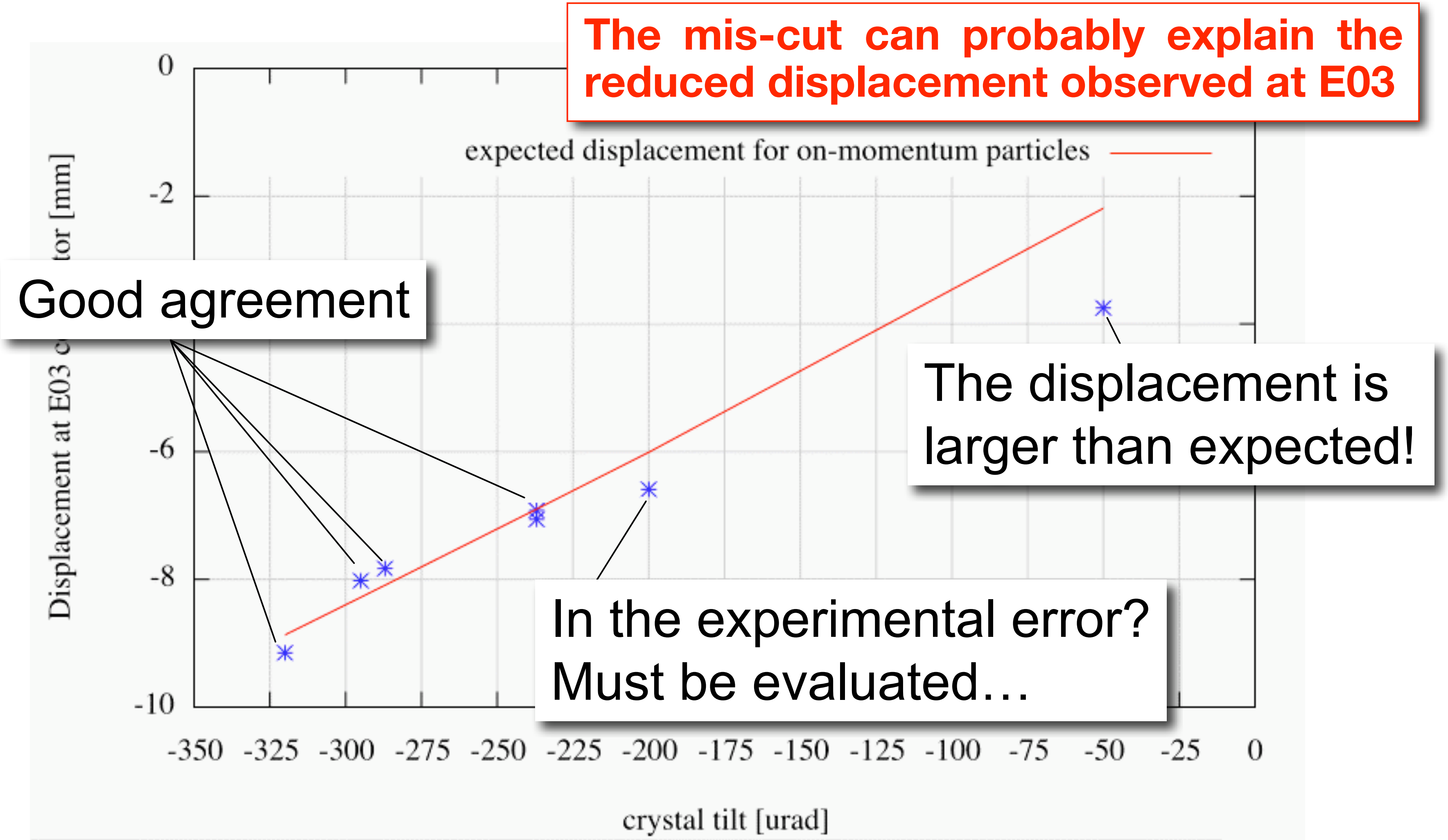
All toghether…

Gaussian fits vs theory



Displacement for different orientations of the crystal

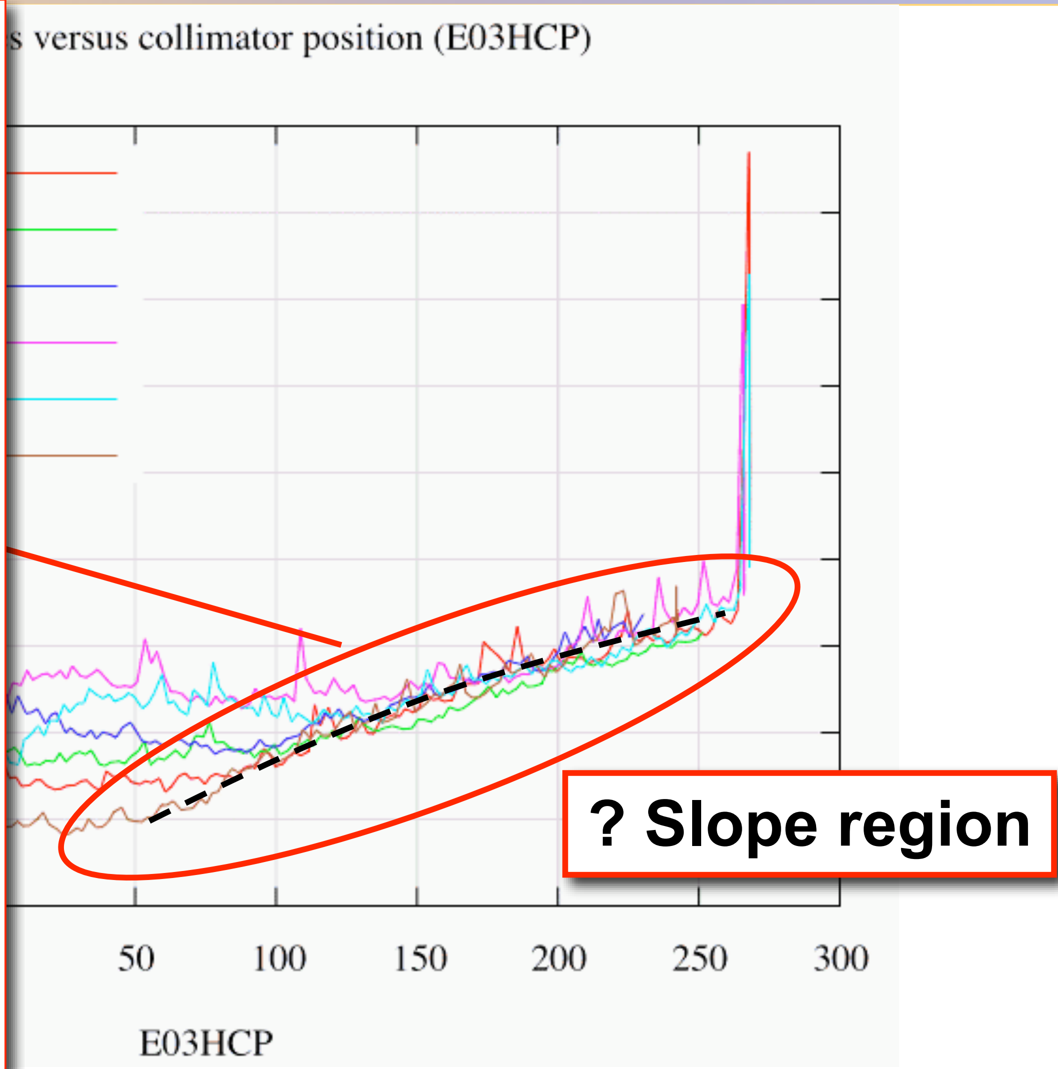
measured and expected



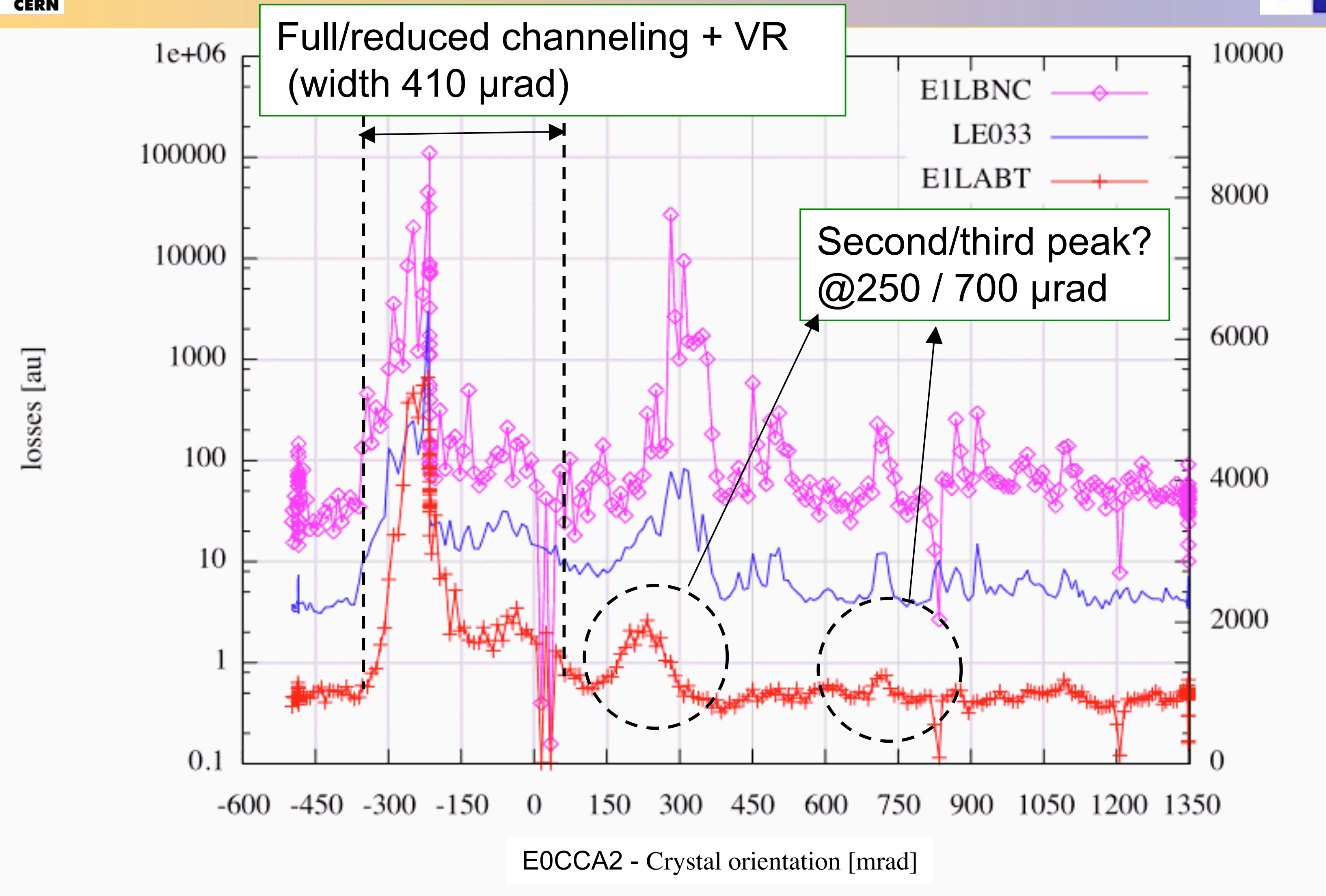
All toghether…

more questions

What is this behavior? It is common to all the angular scans.
It is equivalent to a r.m.s. kick of **100 μrad** ! Cannot be amorphous (typical kick 3.2 μrad) or single VR (-6 μrad).
Cannot be de-channeling (cannot be larger than the channeling kick).
Maybe **multiple volume reflection?**
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.



Angular scan: a wider view



maybe the crystal is almost aligned in vertical position?

More questions?

- What is the peak we see at 250-300 μrad in the angular scan? Is there a third peak at ~700 μrad? Are they channeling peaks? Are we almost aligned in vertical position?
- What is the final slope we observe in each collimator scan, which corresponds to a typical kick of -100 μrad? Is it multiple volume reflection?
- 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?

Even more questions…

(from Steve)

- 1.what would you expect to see in the H8/RD22 single particle line, with this crystal?
- 2.What happens if the electron lens heating is turned off/down?
- 3.What happens if the RF voltage is turned up/down (moving the separatrix)?
- 4.What happens if the RF frequency itself is slightly changed, shifting the underside of the separatrix slightly up/down?
- 5.Synchrotron oscillations MUST be playing a vital role
  - a) in providing lots of time for betatron heating as the protons go oh-so-slowly past the unstable fixed point
  - b) in helping to determine the actual spread of impact parameters as the protons go at normal speed (as in a regular synchrotron oscillation) past the bottom of the RF bucket.

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.