A. Sytov[1,2], E. Bagli[1], L. Bandiera[1], S. Gessner[3], V. Guidi[1], M. J. Hogan[3], R. Holtzapple[4], T. W. Markiewicz[3], A. Mazzolari[1], R. E. Mikkelsen[5], R.J. Noble[3], V.V. Tikhomirov[2], S. Tucker[4], U. I. Uggerhøj[5], U. Wienands[3], T. N. Wistisen[5]

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(on behalf of SLAC E-212 Collaboration)

PLANAR CHANNELING AND QUASICHANNELING OSCILLATIONS IN THE DEFLECTION ANGLE DISTRIBUTION IN A BENT CRYSTAL

The XII International Symposium
«Radiation from Relativistic Electrons in Periodic Structures»
RREPS-17
DESY, Hamburg, September 18-22, 2017

Outline

- **CRYSTAL** simulation code for particle tracking in crystal.

- Planar **channeling** and **quasichanneling oscillations** in the deflection angle distribution
  - Planar channeling oscillations
  - Planar quasichanneling oscillations
  - Simulation examples
  - Observation conditions and constraints

- **Observation of quasichanneling oscillations**

CRYSTAL simulation code*

Main conception – tracking of charged particles in a crystal in averaged atomic potential

Program modes:

- **1D** model – particle motion in an interplanar potential
- **2D** model – particle motion in an interaxial potential

Simulation of the different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.
- **Nuclear scattering**
- **Ionization energy losses**
- **Crystal geometry**

Advantages:

- High calculation speed (up to **10^3 particles/s/core**)
- **MPI** parallelization for high performance computing

Max number of cores used simultaneously by CRYSTAL

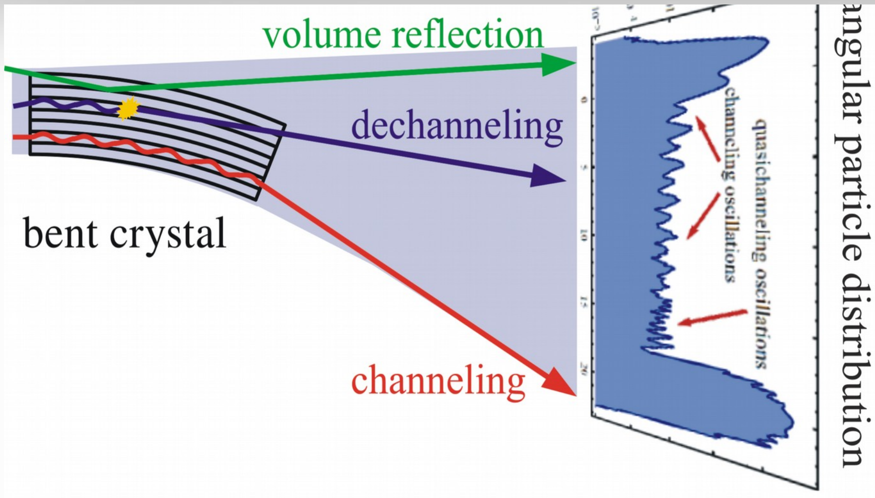
- **FERMI:** **2048**
- **GALILEO:** **768**
- **MARCONI:** **2152**

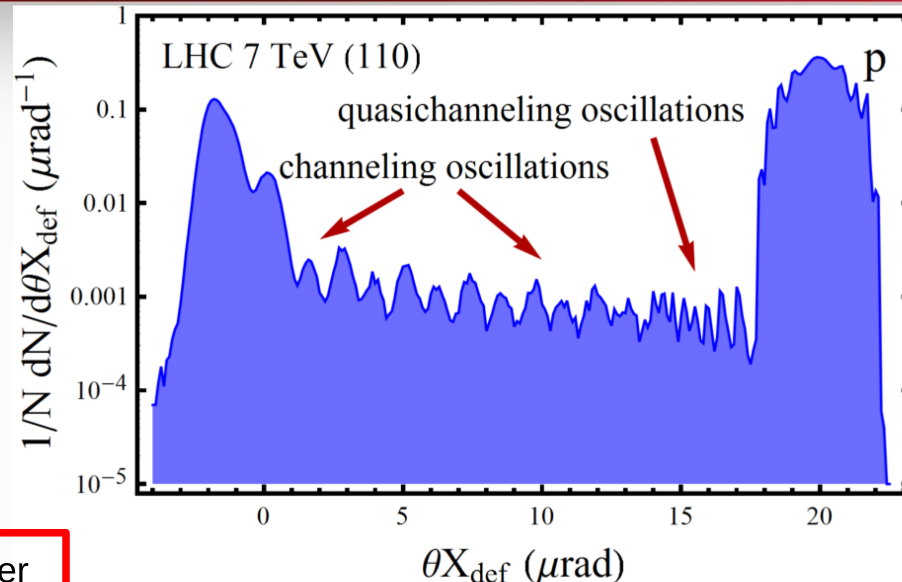
What have we been granted by?

- **FERMI:** **200 kh**
- **GALILEO:** **100 kh**
- **MARCONI:** **400 kh**

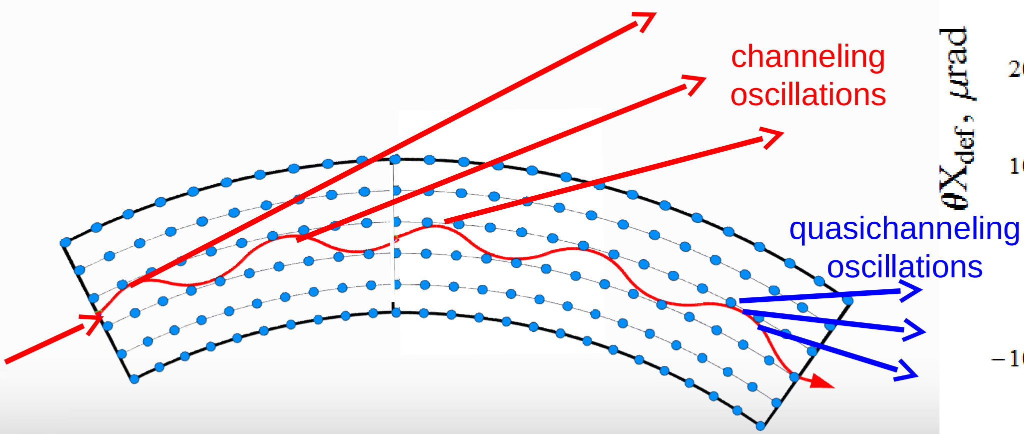
*A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.

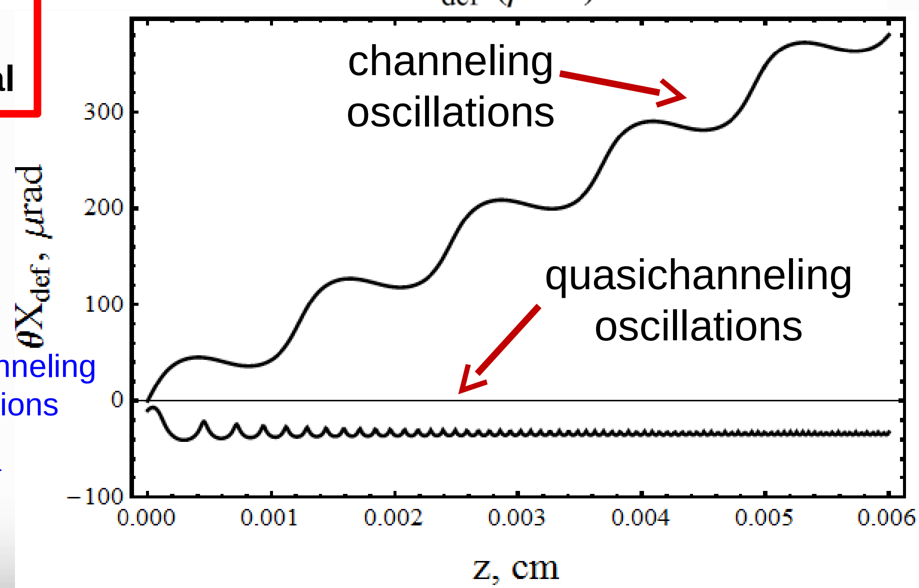
Planar channeling oscillations and quasichanneling oscillations in deflection angle distribution*,**





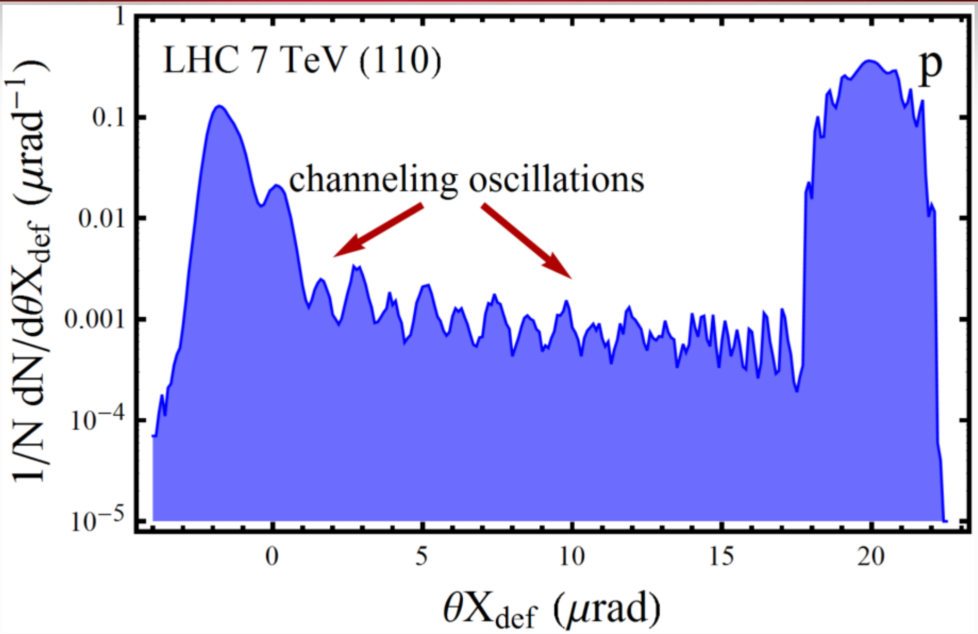
Channeling oscillations manifest themselves clearer an the **start** and the **middle** of the **crystal** while **quasichanneling oscillations** at the **end** of the **crystal**

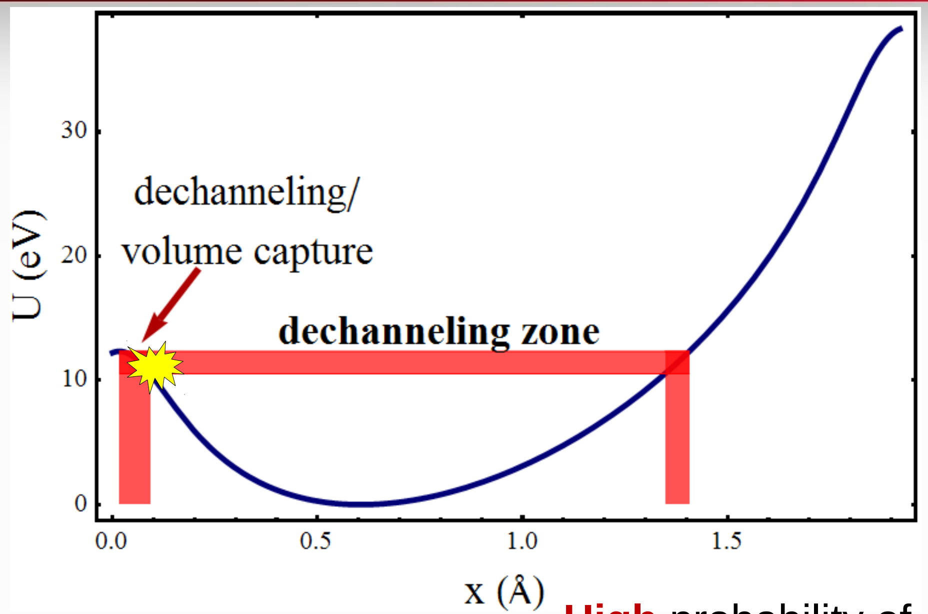


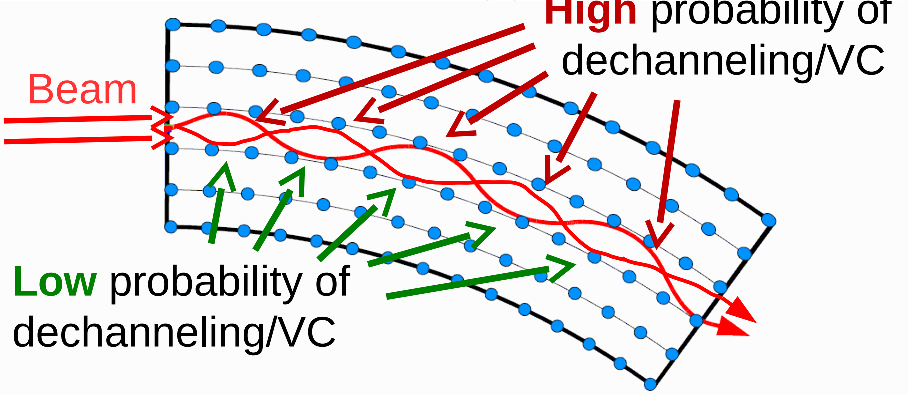


*A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

Planar channeling oscillations in deflection angle distribution (only for positive particles)*,**



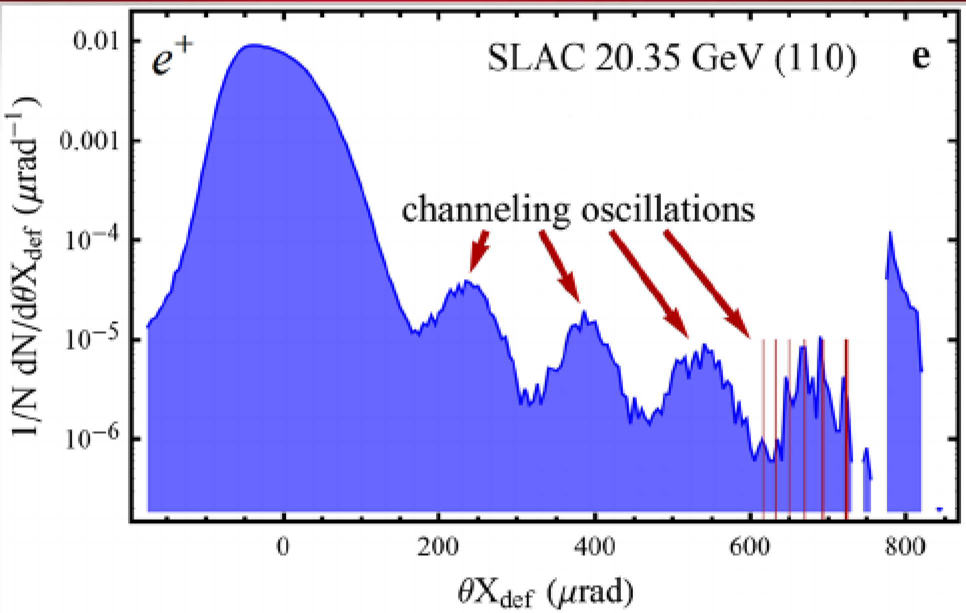


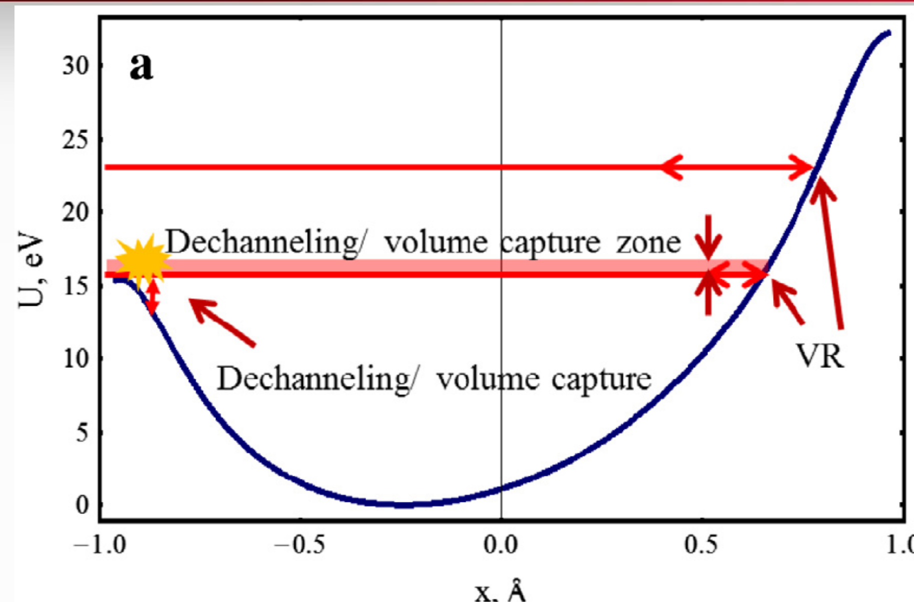


$$\Delta\varphi_{peak} = \frac{\lambda}{2R} = \frac{\pi d_0}{2R}\sqrt{\frac{pv}{2U_0}}$$

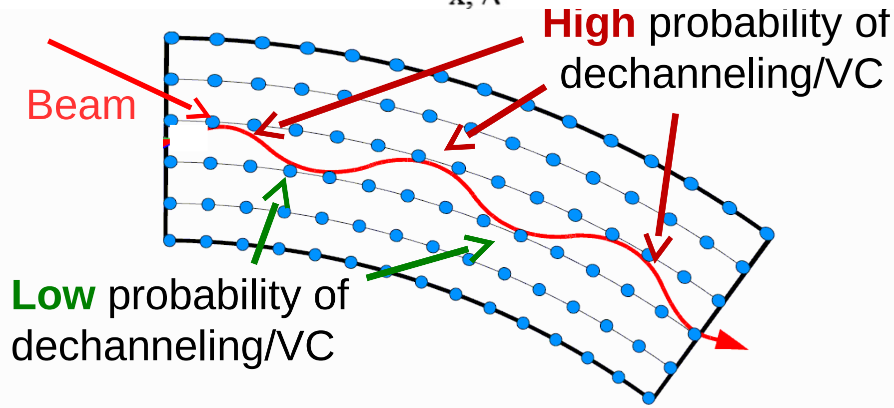
*A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.
**A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

Planar channeling oscillations in deflection angle distribution (only for positive particles), volume reflection alignment*,**



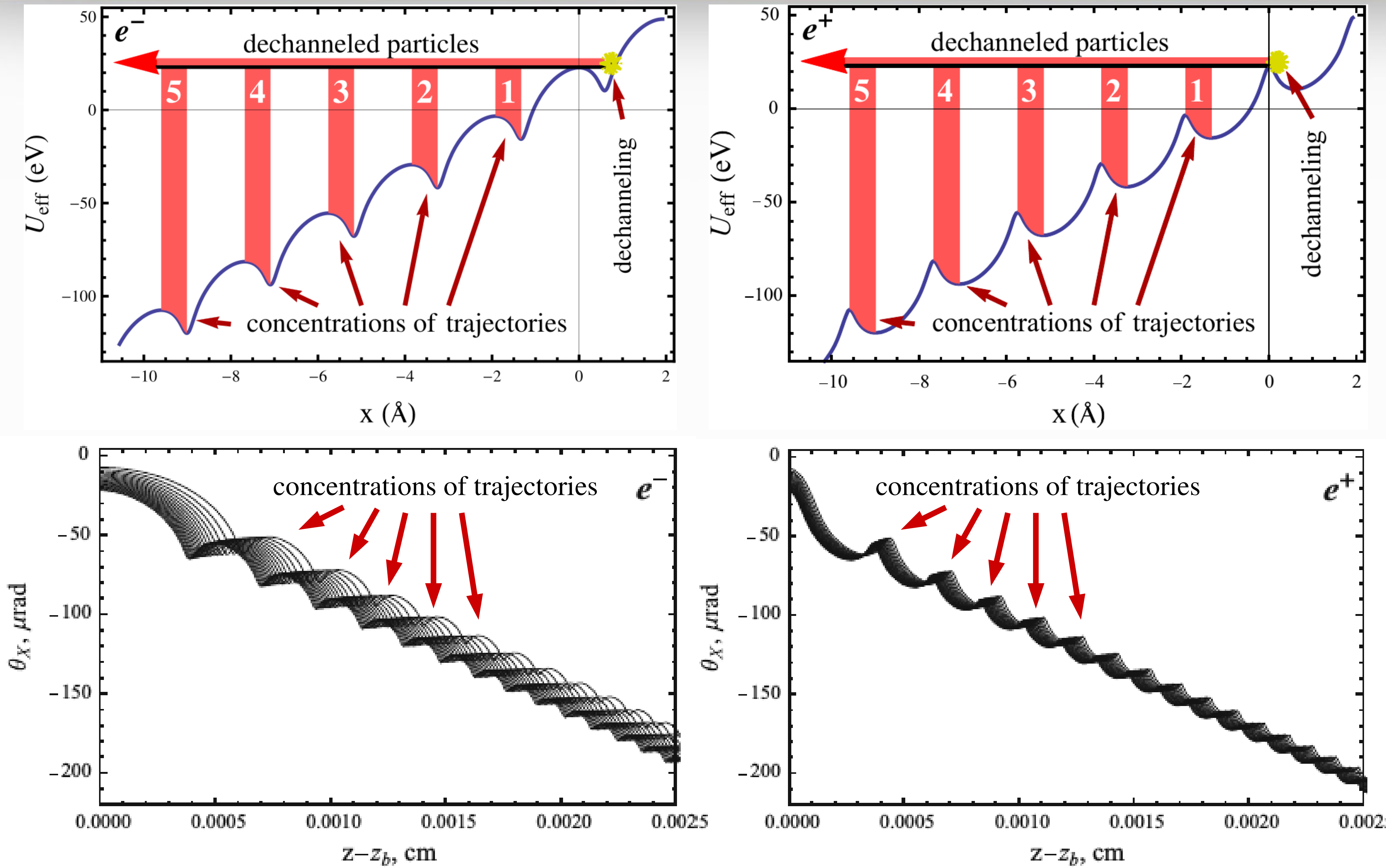


$$\Delta\varphi_{peak} = \frac{\lambda}{\cancel{2}R} = \frac{\pi d_0}{\cancel{2}R}\sqrt{\frac{pv}{2U_0}}$$



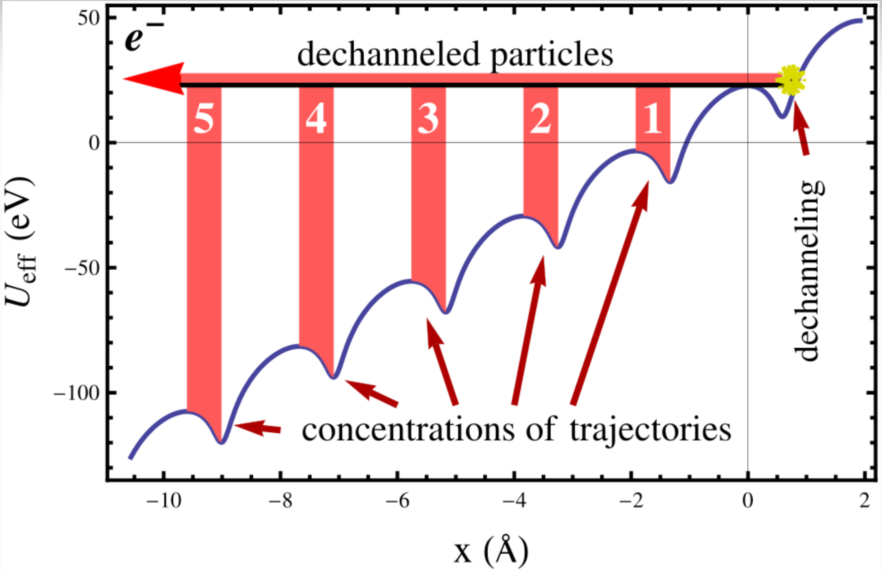
*A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.
**A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

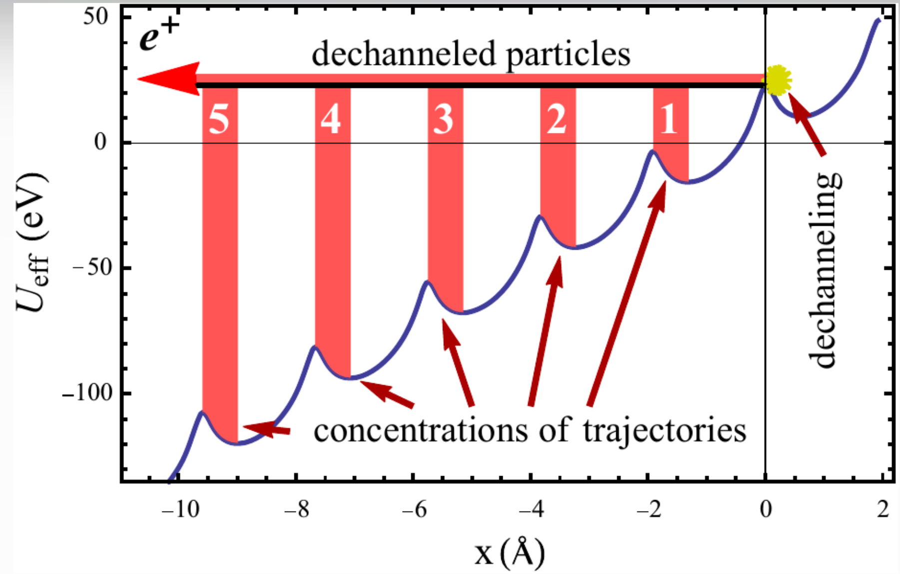
Planar *quasichanneling* oscillations in deflection angle distribution, co-rotating reference system (for any charge of particle)*

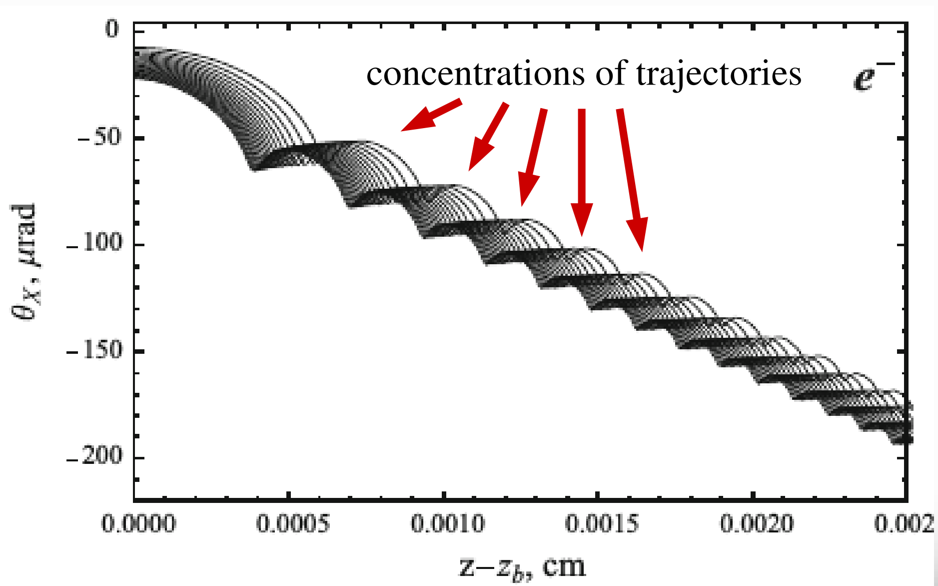


*A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

Planar *quasichanneling* oscillations in deflection angle distribution, co-rotating reference system (for any charge of particle)*







In co-rotating reference system:

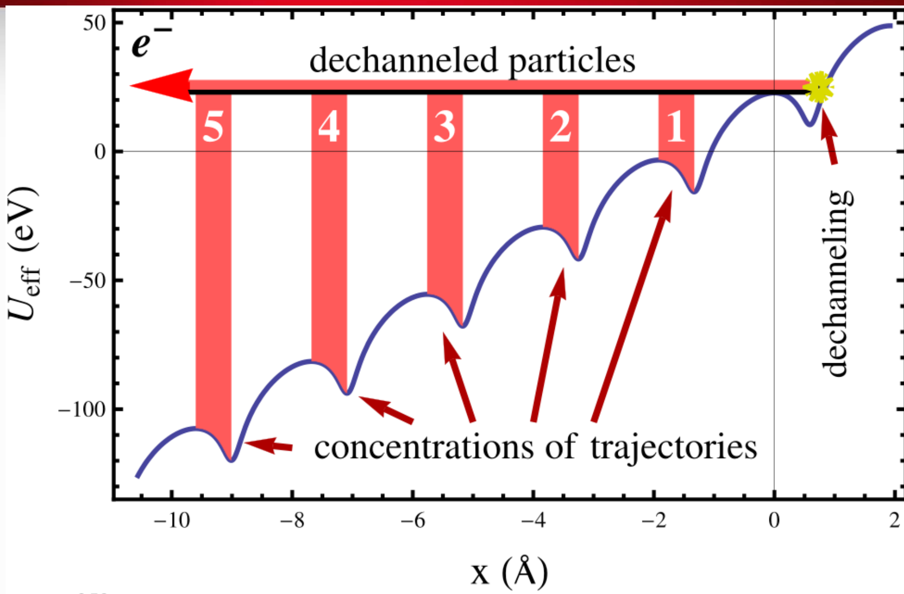
$$\theta_X = -\sqrt{\frac{2(\varepsilon_\perp - U_{eff}(x(z-z_b,\varepsilon_\perp)))}{pv}}$$

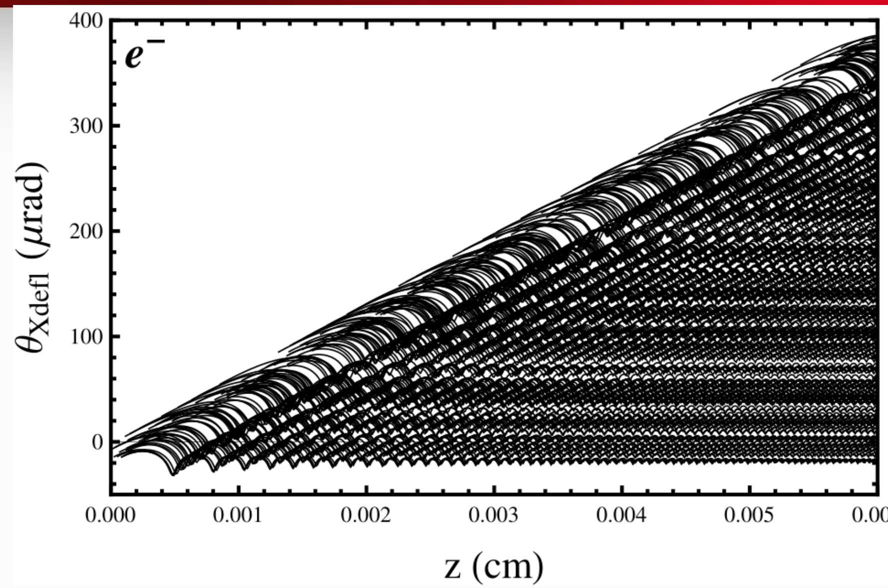
$$\frac{dN}{d\theta_X} = \frac{dN}{dz}\sum_i \frac{1}{|d\theta_X/dz|_i}$$

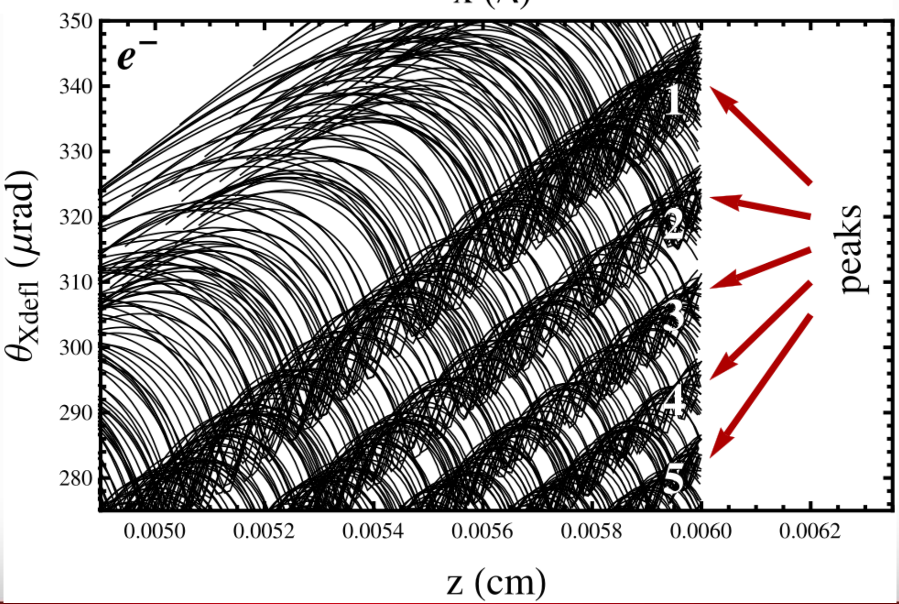
Concentrations of trajectories:

$$\boxed{U'_{eff}(x) = 0} \qquad \frac{d\theta_X}{dz} = 0$$

Planar *quasichanneling* oscillations in deflection angle distribution, laboratory reference system (for any charge of particle)*







In laboratory reference system:

$$\theta_{Xdefl} = \frac{z}{R} - \sqrt{\frac{2(\varepsilon_\perp - U_{eff}(x(z,\varepsilon_\perp)))}{pv}}$$

Concentrations of trajectories:

$$\boxed{U'_{eff}(x) = 0} \Rightarrow \frac{d\theta_{Xdefl}}{dz} = \frac{1}{R}$$

Planar *quasichanneling* oscillations in deflection angle distribution

$$\theta_{Xdefl} = \frac{z}{R} - \sqrt{\frac{2(\varepsilon_\perp - U_{eff}(x(z,\varepsilon_\perp)))}{pv}}$$

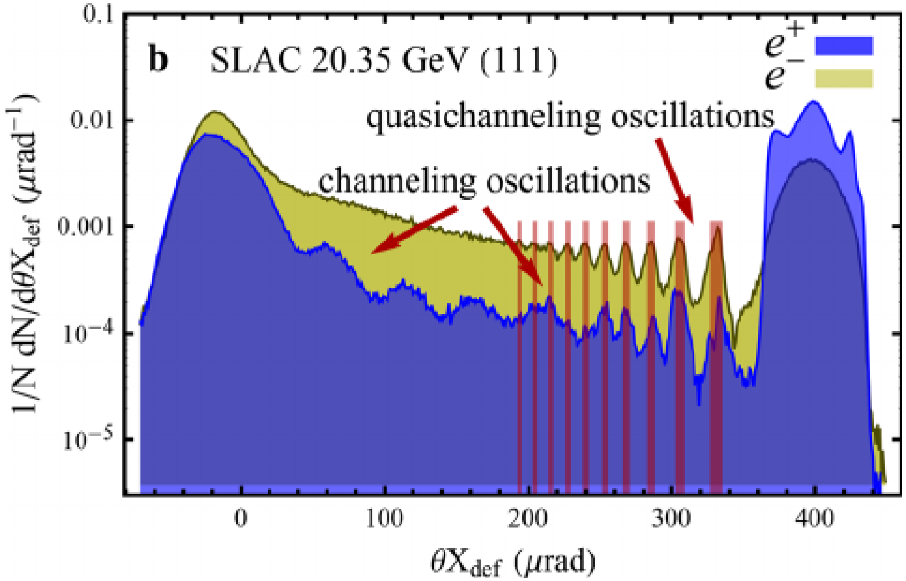
Boundaries of peaks of quasichanneling oscillations:

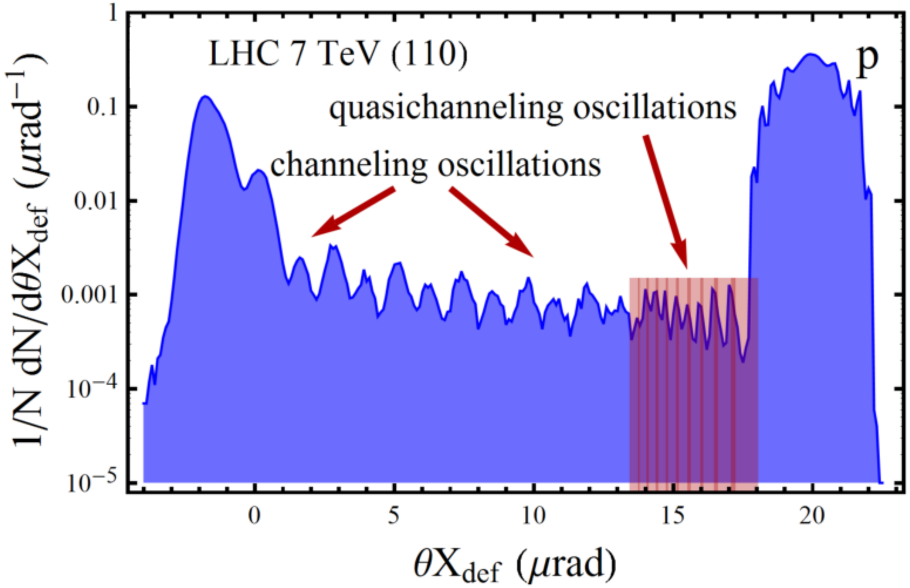
$$\begin{cases} \theta_{Xdefl} = \dfrac{z}{R} - \sqrt{\dfrac{2d_0 n}{R}} \\ \theta_{Xdefl} = \dfrac{z}{R} - \sqrt{\dfrac{2d_0 n}{R} + \dfrac{2\Delta V}{pv}} \end{cases}$$

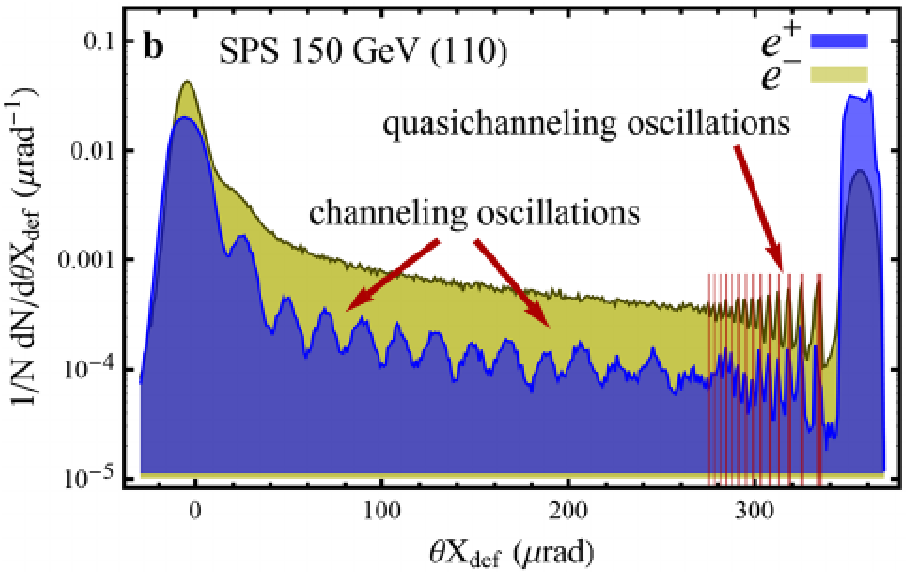
Angular difference between neighbouring of peaks:

$$\Delta\varphi_{peak} = \sqrt{\frac{2d_0}{R} + (\theta_b - \theta_{Xdefl})^2} - (\theta_b - \theta_{Xdefl}) \approx \frac{d_0}{R(\theta_b - \theta_{Xdefl})}$$

Planar channeling and quasichanneling oscillations In the deflection angle distribution*







Interpeak distance

- **Channeling oscilations:**

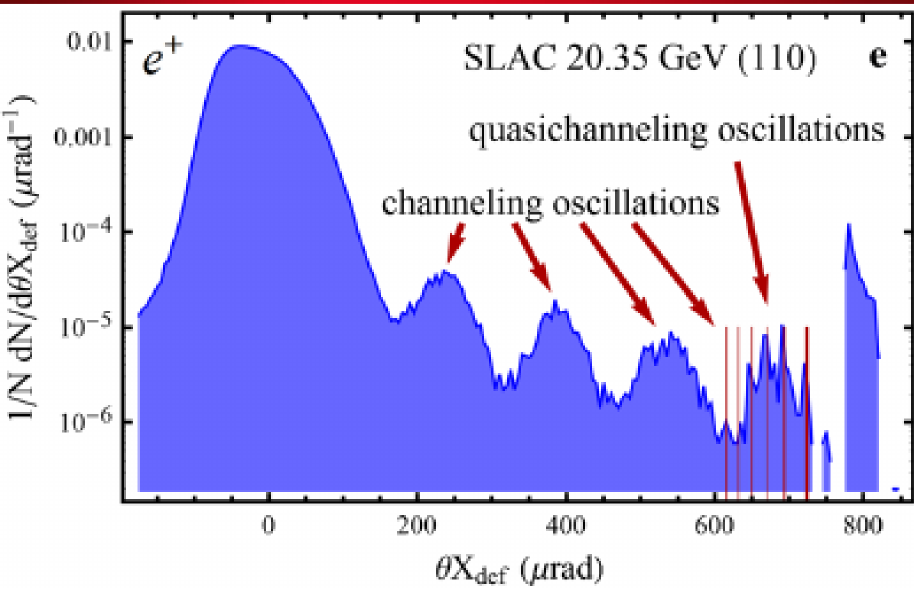
$$\boxed{\Delta\varphi_{peak} = \frac{\lambda}{2R} = \frac{\pi d_0}{2R}\sqrt{\frac{pv}{2U_0}}}$$

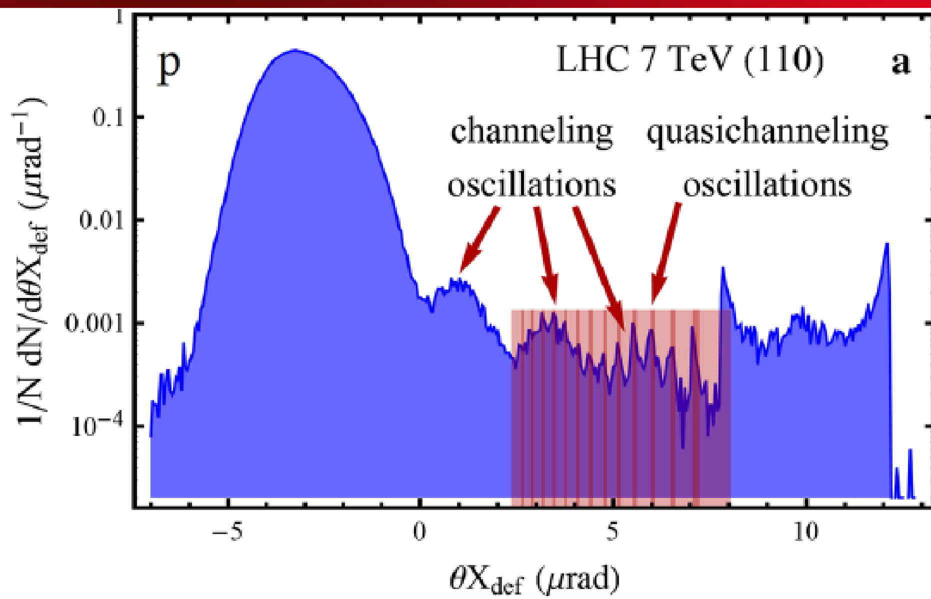
- **Quasichanneling oscilations:**

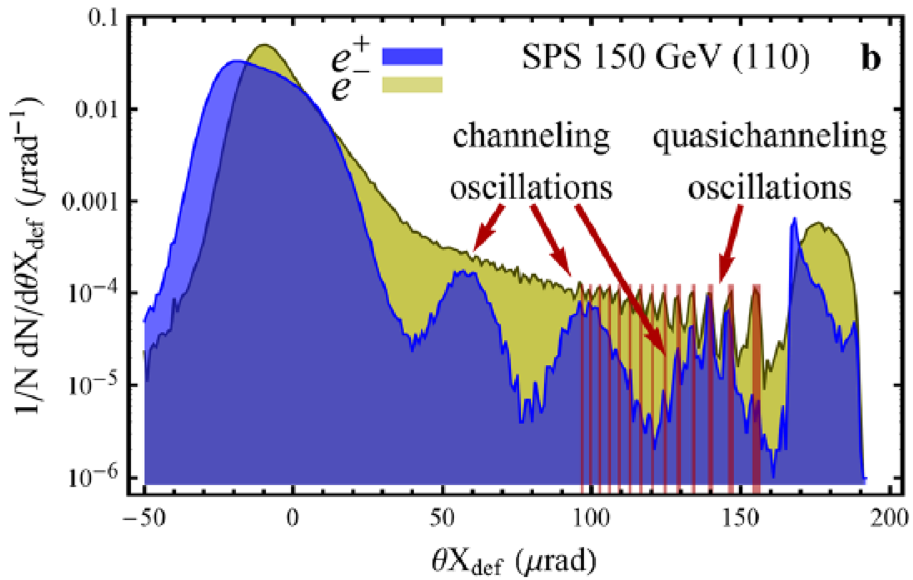
$$\boxed{\Delta\varphi_{peak} = \sqrt{\frac{2d_0}{R} + (\theta_b - \theta_{Xdefl})^2} - (\theta_b - \theta_{Xdefl}) \approx \frac{d_0}{R(\theta_b - \theta_{Xdefl})}}$$

*A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

Planar channeling and quasichanneling oscillations In the deflection angle distribution (VR alignment)*







Interpeak distance

- **Channeling oscilations:**

$$\boxed{\Delta\varphi_{peak} = \frac{\lambda}{\cancel{2}R} = \frac{\pi d_0}{\cancel{2}R}\sqrt{\frac{pv}{2U_0}}}$$

- **Quasichanneling oscilations:**

$$\boxed{\Delta\varphi_{peak} = \sqrt{\frac{2d_0}{R} + (\theta_b - \theta_{Xdefl})^2} - (\theta_b - \theta_{Xdefl}) \approx \frac{d_0}{R(\theta_b - \theta_{Xdefl})}}$$

*A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

Planar channeling and quasichanneling oscillations: observation conditions*

Channeling condition:

$$\frac{R}{R_{cr}} \gtrsim 2$$

Small angular divergence (only for channeling oscillations):

$$\theta_{in\ r.m.s.} < \theta_L/2$$

Interpeak distance w.r.t. the scattering angle:

$$\frac{\Delta\varphi_{peak}}{2\theta_{sc}} \gtrsim 2$$

$$\frac{\Delta\theta_{x0}}{2\sqrt{\sum_i(\frac{\Delta x_{res\ i}}{L_{eff}})^2 + (\frac{\Delta x_{det\ beam}}{L_{eff}})^2 + \theta_{sc}{}^2}} \gtrsim 2$$

detector resolution

angular beam size

scattering on crystal

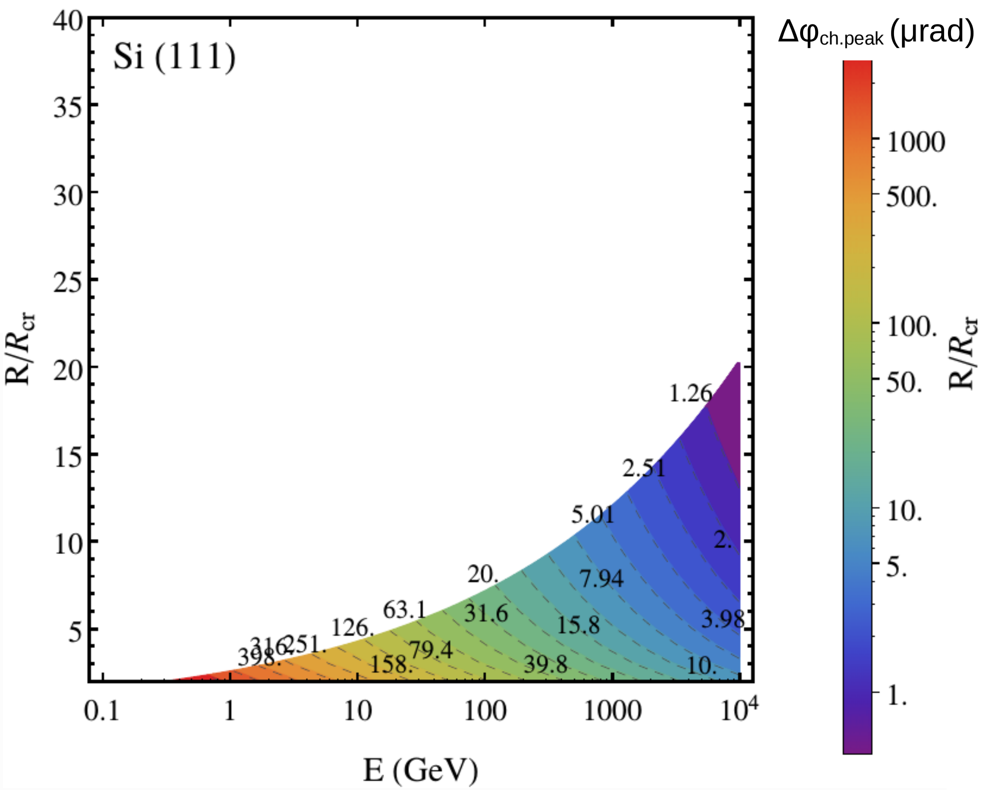
Ch.oscil.: $$\frac{\Delta\varphi_{ch.peak}}{2\theta_{sc}} = \frac{\lambda}{4R}\frac{pv}{13.6MeV \times \sqrt{l_{cr}/X_r} \times (1+0.038 \times ln(l_{cr}/X_r))} > 2$$

Qch.oscil.: $$\frac{\Delta\varphi_{qch.peak}}{2\theta_{sc2}} = \frac{d_0}{R\theta_L}\frac{pv}{13.6MeV \times \sqrt{\lambda/2X_r} \times (1+0.038 \times ln(\lambda/2X_r))} > 2$$

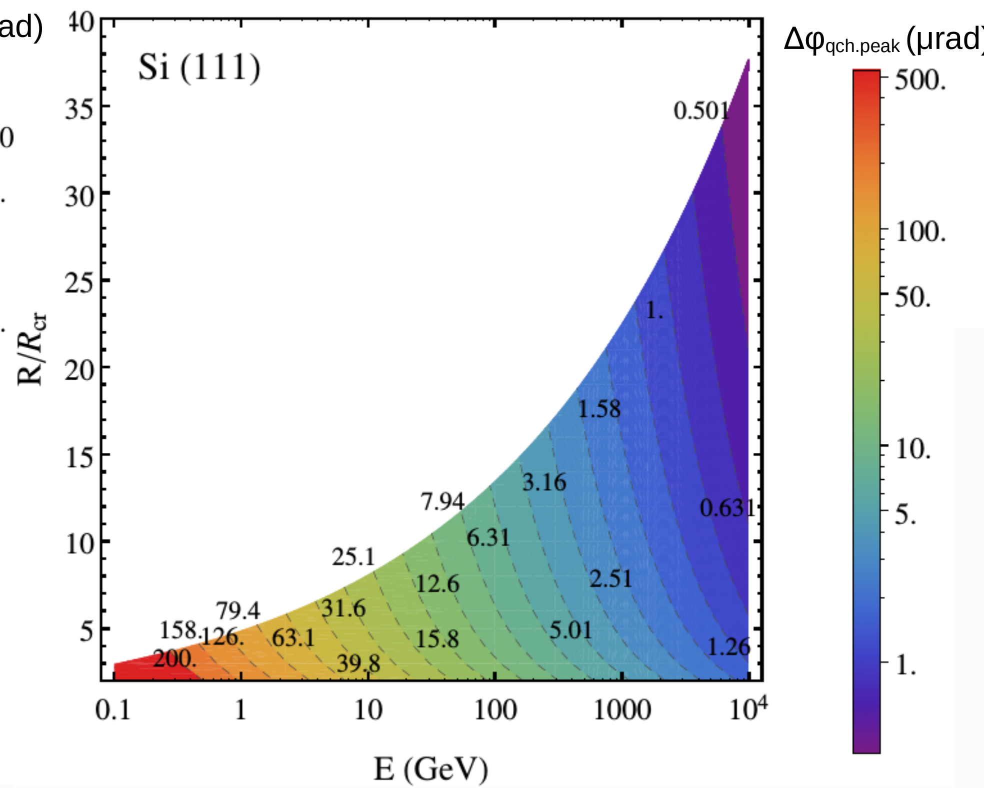
*A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

Channeling and quasichanneling oscillations
Observation conditions w.r.t. beam energy

Channeling oscillations



Quasichanneling oscillations



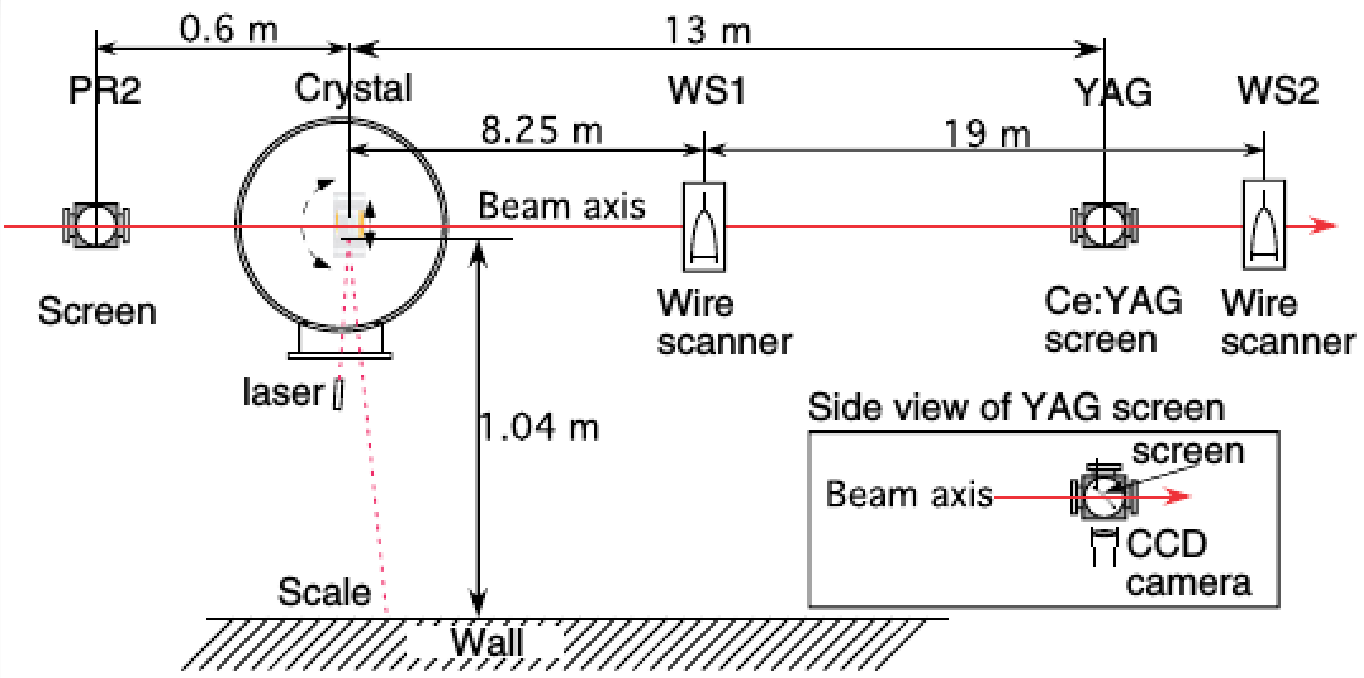
~10^0 GeV => 250–800 μrad
~10^1 GeV => 80–250 μrad
~10^2 GeV => 20–80 μrad
~10^0 TeV => 1–20 μrad

$$\boxed{\Delta\varphi_{ch.peak} \sim 5\ \Delta\varphi_{qch.\ peak}}$$

~10^0 GeV => 40–160 μrad
~10^1 GeV => 16–40 μrad
~10^2 GeV => 5–16 μrad
~10^0 TeV => 0.5–5 μrad

Observation of quasichanneling oscillations at SLAC*: experimental setup**

(on behalf of SLAC E-212 Collaboration)

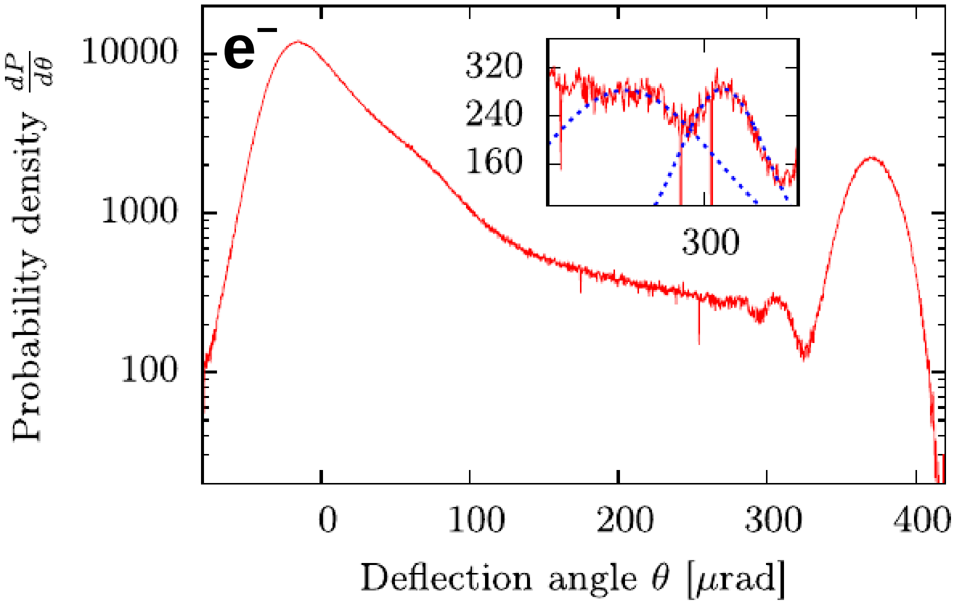


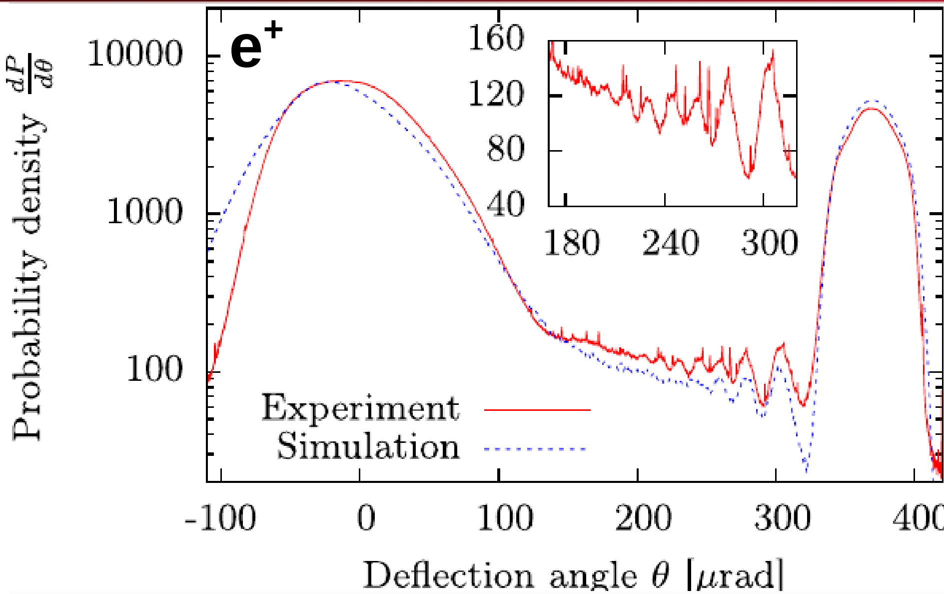
- Particles: **electrons** and **positrons**
- Energy: 20.35 GeV
- Crystal: Si, (111)
- Crystal length: 60 µm
- Bending radius: 15 cm

PI: U. I. Uggerhøj

*T.N. Wistisen et al. Phys. Rev. Lett. 119, 024801 (2017)

Observation of quasichanneling oscillations at SLAC





e⁻ : $\theta^{-}_{\mathrm{qch}} \sim \theta_d - \sqrt{\frac{2d_0 n}{R}}$

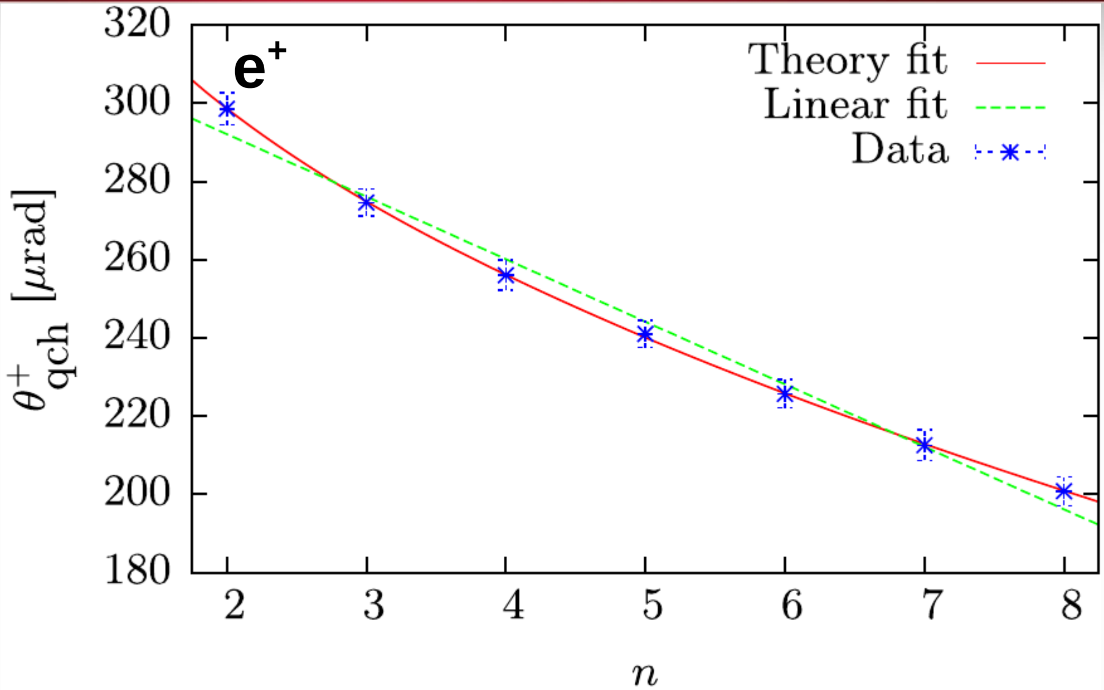
e⁺ : $\theta^{+}_{\mathrm{qch}} \sim \theta_d - \sqrt{\frac{2d_0(n-1)}{R} + \frac{2d_s}{R}}$

$$\Delta\varphi^{exp}_{peak} = 30.5 \pm 2\ \mu\mathrm{rad}$$

$$\Delta\varphi^{theory}_{peak} = (\sqrt{2}-1)\sqrt{2d_0/R} = 26.8\ \mu\mathrm{rad}$$

n	2	3	4	5	6	7	8
θ_{peak} (μrad)	299	275	256	241	226	213	201
σ_{peak} (μrad)	4.1	3.5	3.8	3.5	3.6	3.9	3.7

Fit of quasichanneling oscillations observed at SLAC



$$\theta^+_{\mathrm{qch}} \sim \theta_d - \sqrt{\frac{2d_0(n-1)}{R} + \frac{2d_s}{R}}$$

$$\theta_d - a\sqrt{2(n-1) + \tfrac{1}{2}}$$

$$a = \sqrt{d_0/R}$$

n	2	3	4	5	6	7	8
θ_{peak} (μrad)	299	275	256	241	226	213	201
σ_{peak} (μrad)	4.1	3.5	3.8	3.5	3.6	3.9	3.7

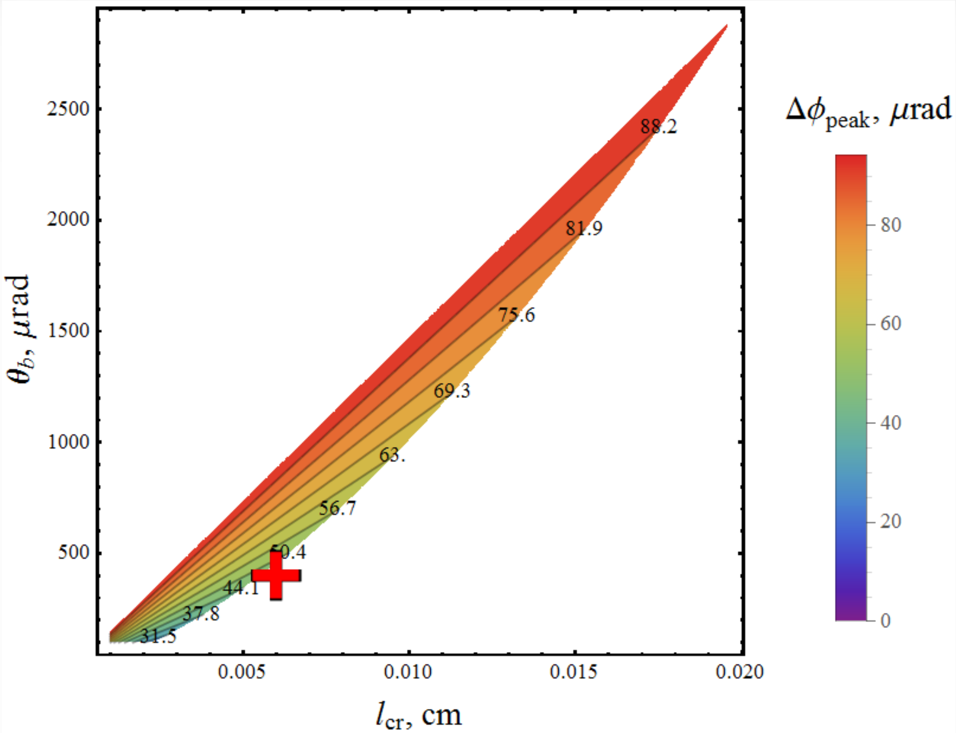
$$a_{\mathrm{exp}} = (4.39 \pm 0.13) \times 10^{-5}$$

$$a_{\mathrm{theory}} = (4.57 \pm 0.06) \times 10^{-5}$$

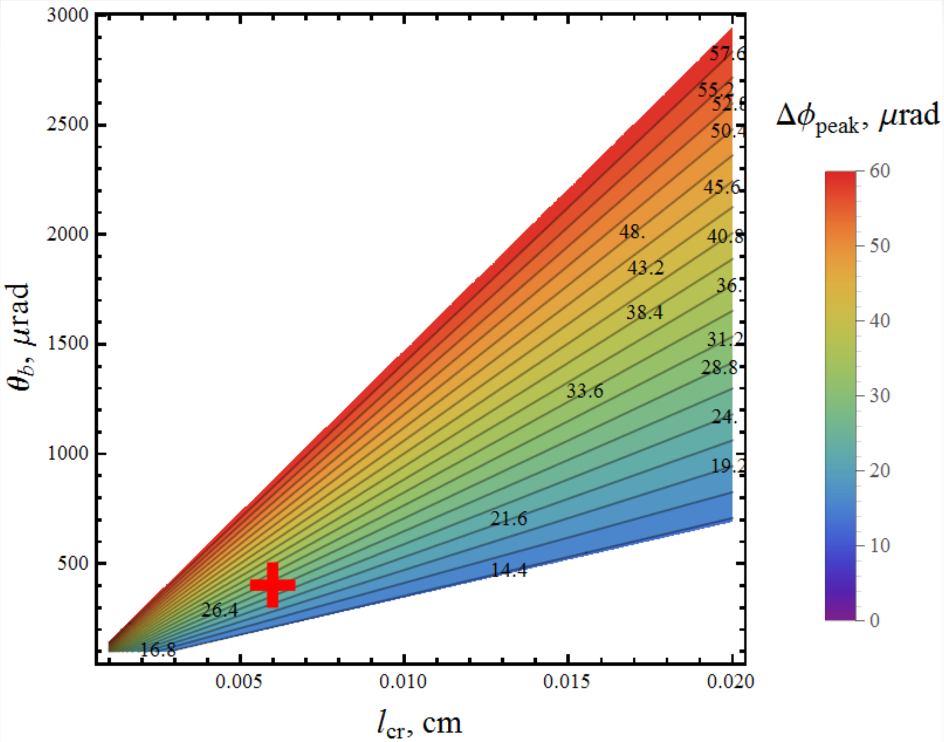
$$\theta_d = (368 \pm 1.8)\ \mu\mathrm{rad}$$

Channeling and quasichanneling oscillations
Optimal conditions for observation at SLAC

Channeling oscillations



Quasichanneling oscillations



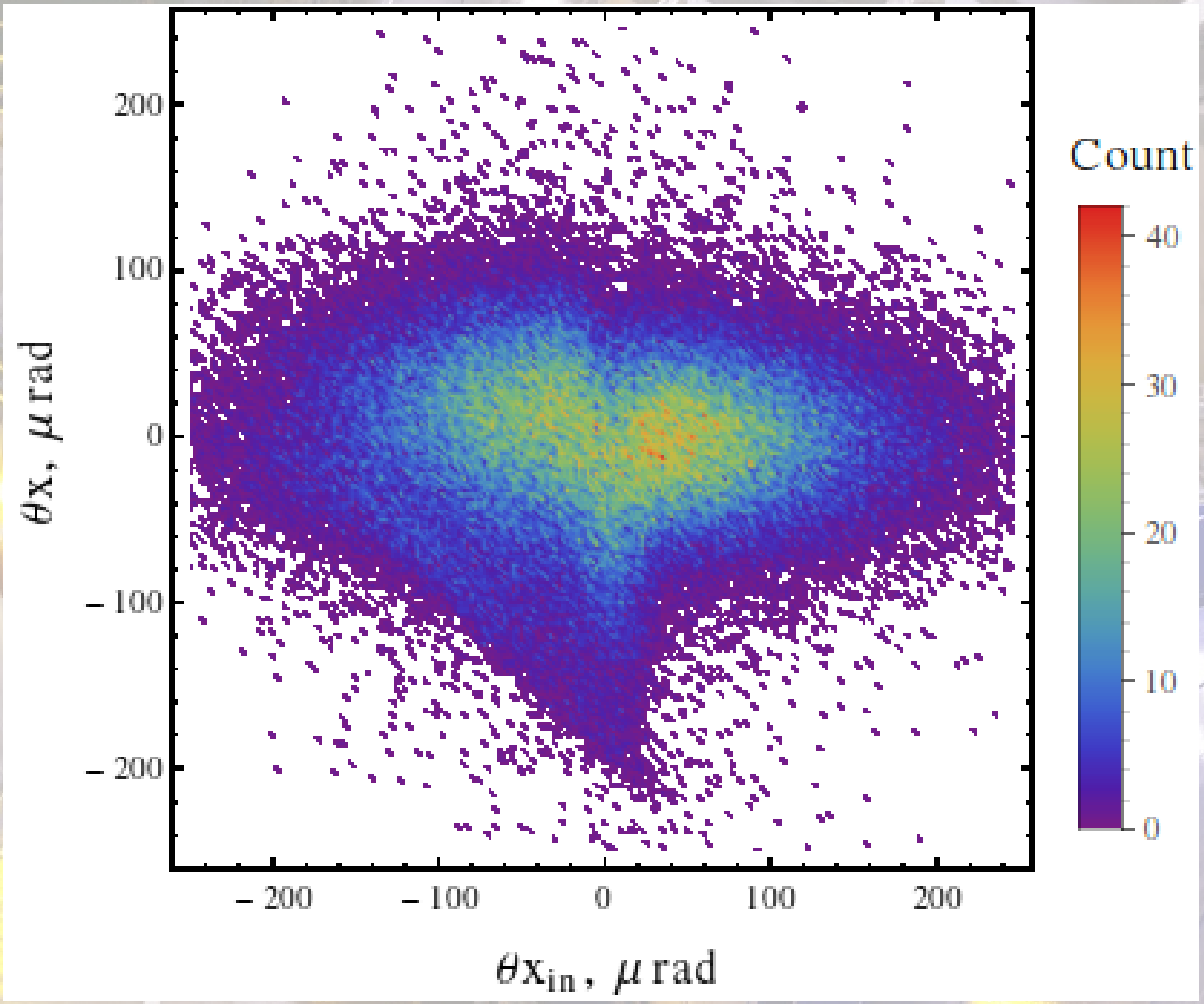
Ch.oscil.: $$\frac{\Delta\varphi_{ch.peak}}{2\theta_{sc}} = \frac{\lambda}{4R}\frac{pv}{13.6MeV\times\sqrt{l_{cr}/X_r}\times(1+0.038\times ln(l_{cr}/X_r))} > 2$$

Qch.oscil.: $$\frac{\Delta\varphi_{qch.peak}}{2\theta_{sc2}} = \frac{d_0}{R\theta_L}\frac{pv}{13.6MeV\times\sqrt{\lambda/2X_r}\times(1+0.038\times ln(\lambda/2X_r))} > 2$$

*A.I. Sytov, V. Guidi, V.V. Tikhomirov et al. Eur. Phys. J. C 76:77 (2016)

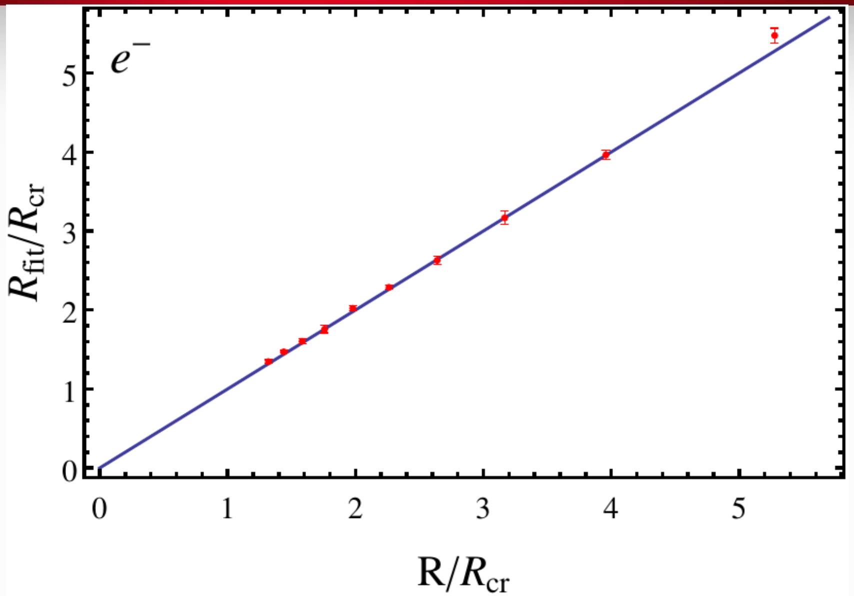
Conclusions

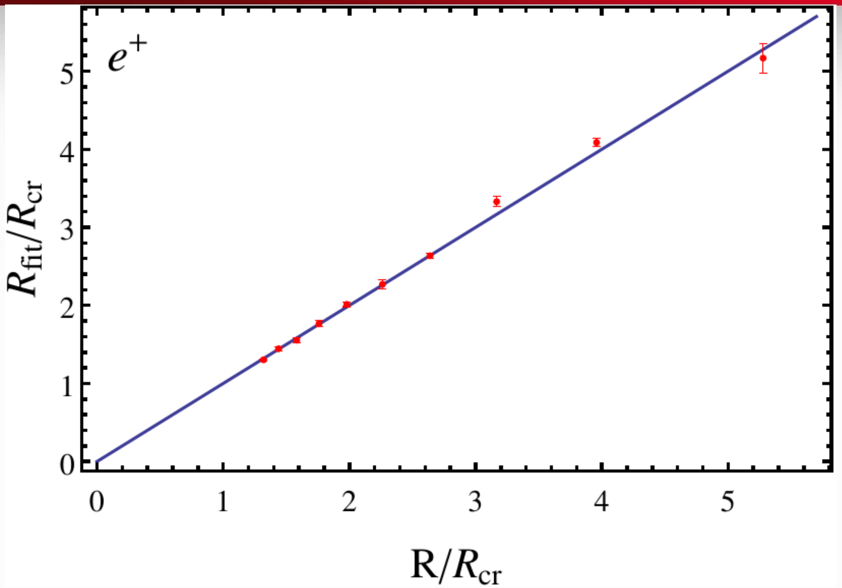
- **Planar channeling** and **quasichanneling oscillations** in the deflection angle distribution allow one to directly observe the channeling and over-barrier oscillations in a bent crystal
- **Channeling oscillations** can be observed only for **positive particles** while **quasichanneling oscillations** for particles of **either sign**.
- Both **effects** have been **predicted** in **CRYSTAL** simulations.
- Both effects can be observed in a wide range of energies from **sub-GeV** up to **TeV** energy.
- **Quasichanneling oscillations** have been **observed at SLAC** for both positrons and electrons in good agreement with expectations, provided by both theoretical model and simulations.

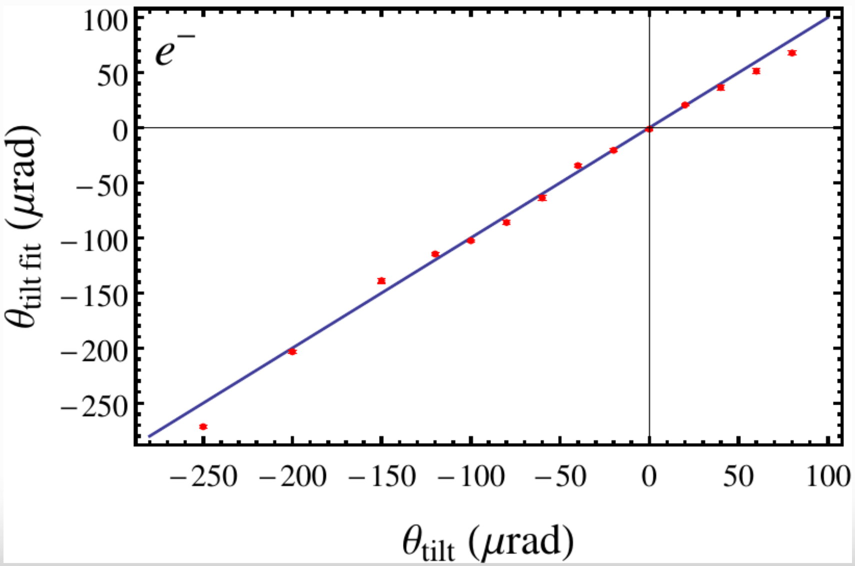


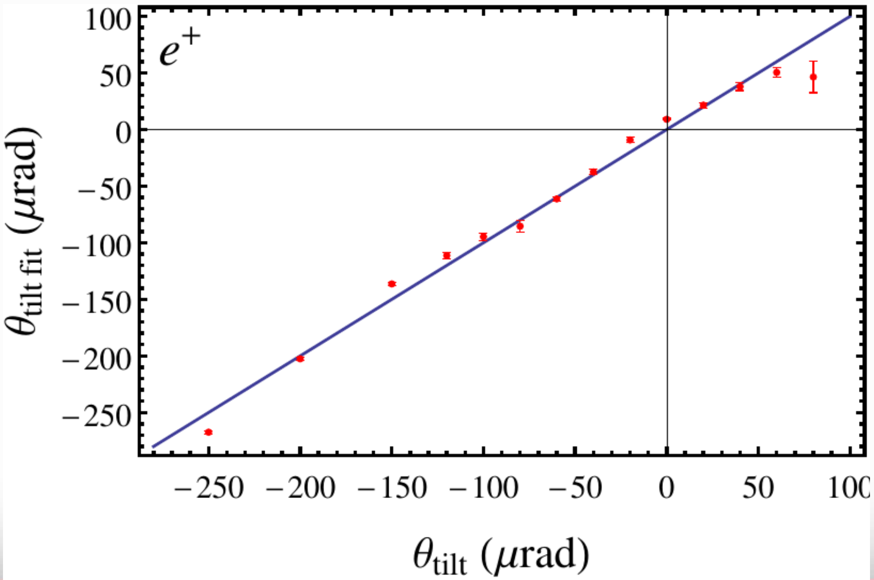
Thank you for attention!

Application of quasichanneling oscillations: crystal alignment





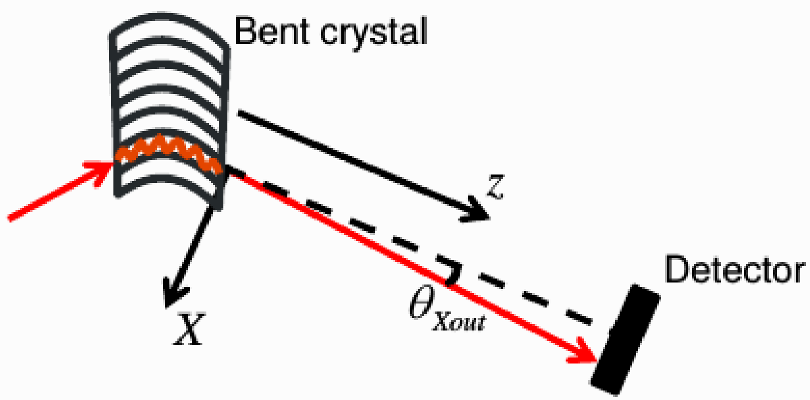




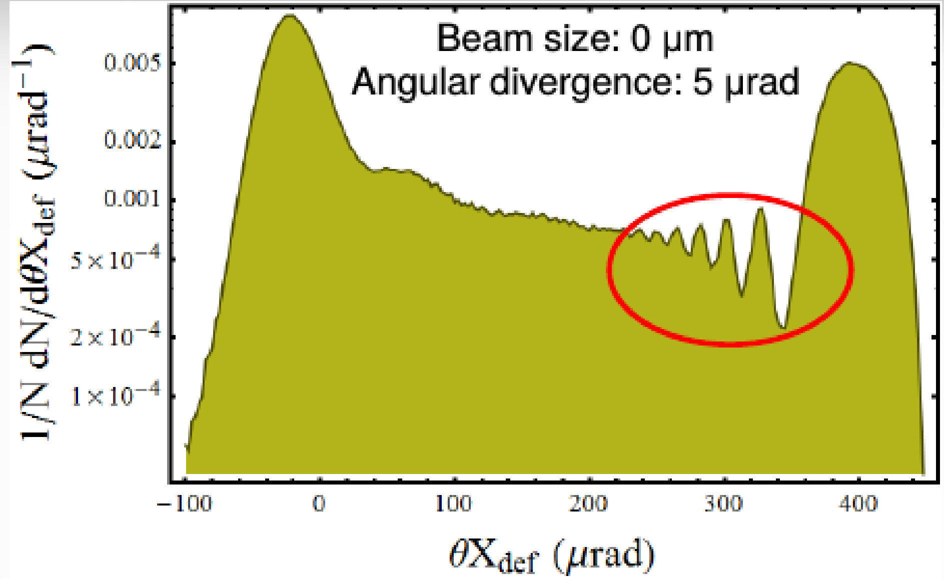
Influence of beam size to quasichanneling oscillations

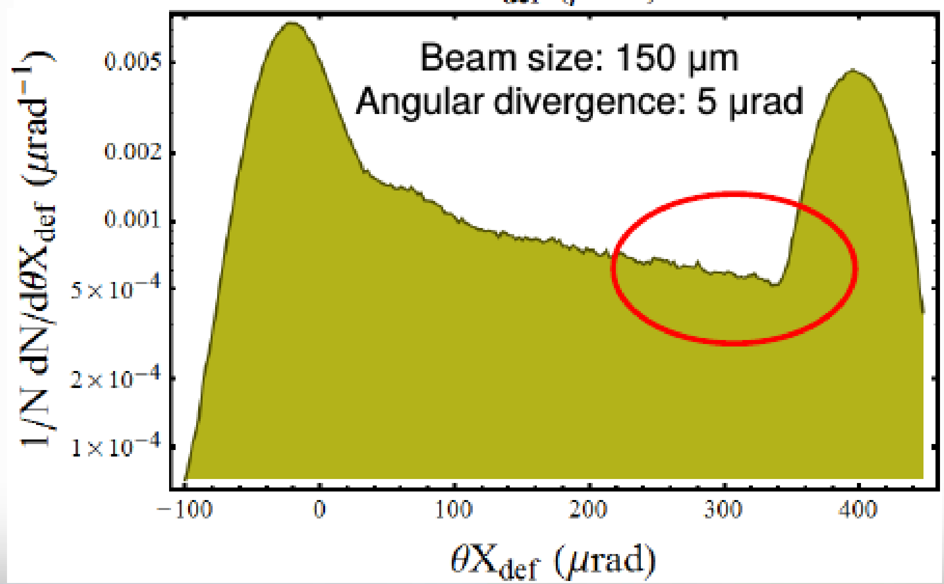
Simulation input parameters:

- Beam energy: 14.7 GeV (electrons)
- Angular divergence: 5 μrad
- Beam size: **150 μm**
- Distance between crystal and detector: 12.882 m
- Crystal thickness: 60 μm
- Crystal bending angle: 400 μrad
- Crystal alignment: 0 μrad (channeling orientation).



$$\theta_{Xdef} = \theta_{Xout} + X / z$$





Recent development and verification of ***simulation methods***

V. Guidi, L. Bandiera, V.V. Tikhomirov, Phys. Rev. A. 86 (2012) 042903

L. Bandiera ... V. Guidi,.. V.V. Tikhomirov , Phys. Rev. Lett. 111 (2013) 255502 .

A. Mazzolari ... V. Guidi, ..V.V. Tikhomirov , Phys. Rev. Lett. 112 (2014) 135503.

L. Bandiera ... V. Guidi,.. V.V. Tikhomirov , Phys. Rev. Lett. 115 (2015) 025504.