Master Degree in Physics of Data
Final Dissertation
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# Simulation studies for a double-crystal channeling experiment at the LHC

Candidate: Chiara Maccani
Supervisor: Massimiliano Ferro-Luzzi
Co-supervisor: Marco Zanetti

Università degli Studi di Padova

# Electromagnetic dipole moments of charmed baryons



- **MDM**: $\boldsymbol{\mu} = g \frac{eQ}{2m} \boldsymbol{s}$, **EDM**: $\boldsymbol{\delta} = d \frac{eQ}{2m} \boldsymbol{s}$

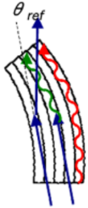
  $$\mathcal{H} = -\boldsymbol{\mu} \cdot \boldsymbol{B} - \boldsymbol{\delta} \cdot \boldsymbol{E} \xrightarrow{P,T} \mathcal{H} = -\boldsymbol{\mu} \cdot \boldsymbol{B} + \boldsymbol{\delta} \cdot \boldsymbol{E}$$

- MDMs provide tests of hadronic structure models
- EDMs are source of possible physics Beyond the Standard Model.

- **Experimental method:**
  given a polarized incoming particle, let it travel through an intense electromagnetic field and measure the spin precession angle

**Polarization precession**

$$\frac{d\boldsymbol{s}}{d\tau} = -\boldsymbol{\mu} \times \boldsymbol{B}^* - \boldsymbol{\delta} \times \boldsymbol{E}^*$$




- For charmed baryons no direct measurements exist due to their short lifetime

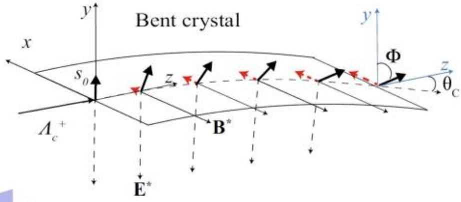
$\rightarrow \Lambda_c^+ = (u, d, c), \quad \tau_{\Lambda_c^+} \sim 10^{-13}\ s$

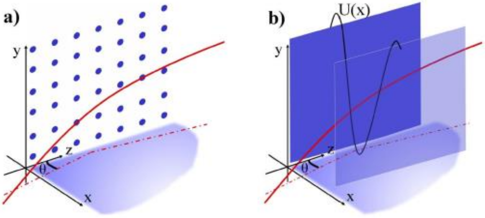
**Fixed target experiment exploiting crystal channeling**

# Channeling in bent crystals



→ Particles can be trapped into the intense crystal interatomic electric field $E{\sim}10^{11}\ V/m$ for Silicon (lab frame)




$\Phi$ Spin precession angle

$\theta_c$ Crystal bending angle

$$s_x \approx s_0 \frac{d}{g-1}(\cos\Phi - 1), \qquad \Phi \approx \frac{g-2}{2}\gamma\theta_c$$

$$\boldsymbol{E}^* \approx \gamma \boldsymbol{E}, \qquad \boldsymbol{B}^* \approx -\gamma\boldsymbol{\beta} \times \frac{\boldsymbol{E}}{c}$$

**→ reconstruct $\Phi$ by analizing the angular distribution of the baryon decay products**

# Double Crystal Experiment at LHC

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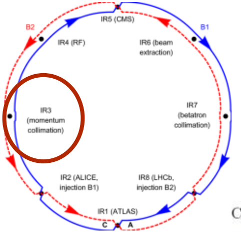
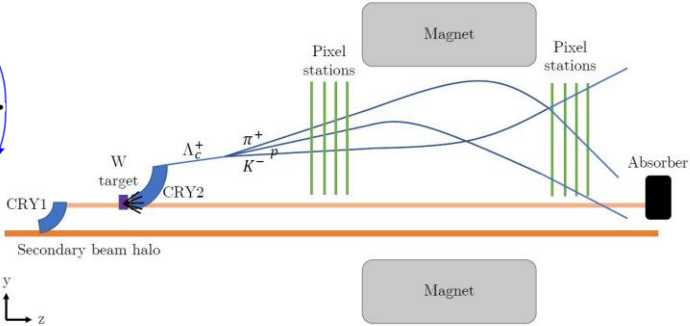
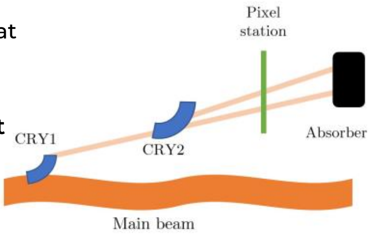
- **CRY1 (Si)** deflects protons from the secondary halo of the main LHC beam ($6.8\ TeV$) onto a **W target**
- **CRY2 (Si)** induces a measurable precession ($7.0\ cm$ long and $\sim 7.0\ mrad$ bent)
- **Detector** to reconstruct the decay products

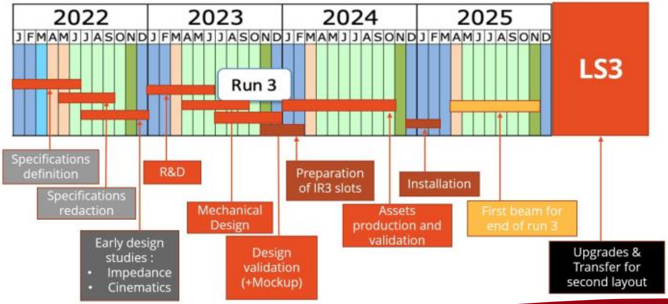


# Proof of principles

- measure the **channeling performance** of CRY2 at energies in the **TeV** range
- improve operational techniques for crystal **alignment**, optimization of the **proton on target rate** and control of the **secondary halo**
- Estimate the **background** for the new IR3 detector

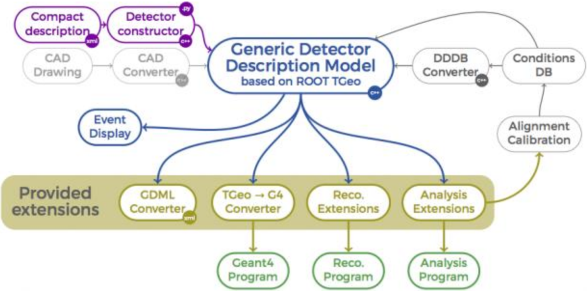



Software tool developed with the aim to have a
**Complete Detector Description**
**Single source of information**

## Main components:

- **ROOT geometry package** (construction and visualization of geometry)
- **Geant4** simulation toolkit




## Data flow:

- The compact description is provided in **XML files**
- DD4hep geometry is **translated to the Geant4 geometry** representation (shapes, materials, volumes and volume placements)
- **DDG4 package:** instantiate the physics setup by means of a set factories
- **Simulation parameters:** provided through a python script, supports **HepMC input** formats

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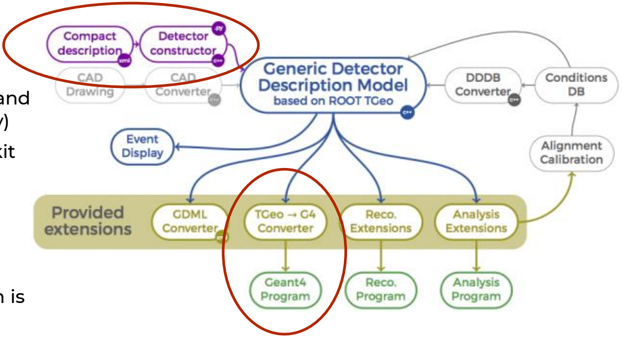


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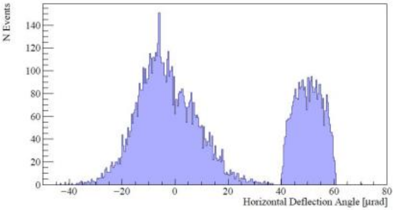
# Geant4 Channeling and DD4hep interface

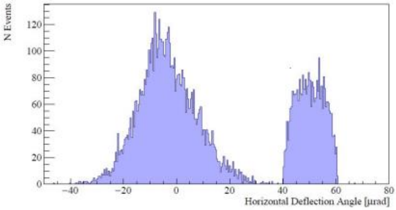
Geant4 Channeling Routine (Bagli 2014)

**Crystal Channeling** properties are contained into:

- Physics List
- Extended volumes
- Extended materials

Geant4 output distribution




DD4hep output distribution

**Channeling was not supported in DD4hep :**
the class responsible of creation of materials and volumes in DD4hep could handle only base versions

✓ UPGRADE
- Materials and volumes extensions are handled using **plugins** that make use of new specialized **factories**
- Information about which plugin to use and on channeling parameters can be specified as input in the **XML** file

Reproduction of **the default example:** $10000$ events of $400\ GeV$ protons shot on a $1.0 \times 70.0 \times 1.94\ mm$ crystal with $R = 38.416\ m$

# Geant4 Channeling and DD4hep interface

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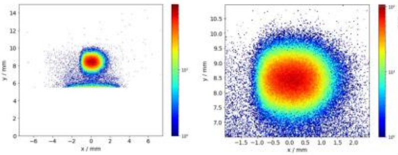
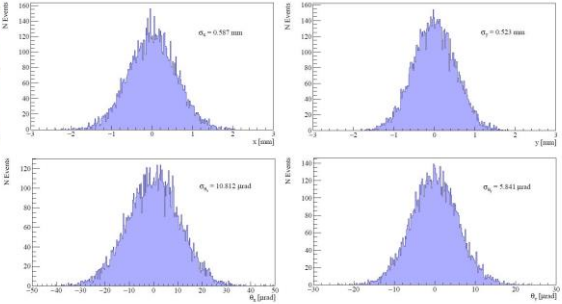
✓ **UPGRADE**

- Development of a DD4hep class to check particle parameters at each step in order to apply configuareble cuts to kill particles

✓ **UPGRADE**

- Introduction of the possibility to simulate beams characterized by a **2D gaussian distribution** of positions $x, y$ and angular directions $\theta_x$, $\theta_y$




| | $\mu$ | $\sigma$ | $3\sigma$ |
|---|---|---|---|
| $x$ | 0.096 mm | 0.583 mm | 1.75 mm |
| $\theta_x$ | 0.852 $\mu$rad | 10.5 $\mu$rad | 31.4 $\mu$rad |
| $y$ | 8.42 mm | 0.525 mm | 1.58 mm |
| $\theta_y$ | 63.0 $\mu$rad | 5.25 $\mu$rad | 15.8 $\mu$rad |

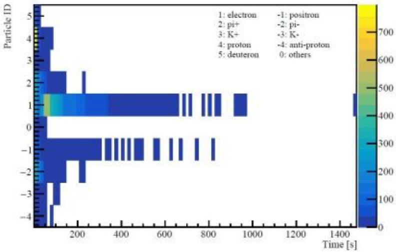
Reproduction of beam distributions obtained with SixTrack simulations of CRY1

# Slowdown problems



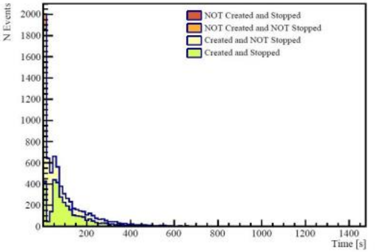
**PRELIMINARY SIMULATION**

to give a rough estimate of the amount of background and signal particles that can be observed in a scoring plane after CRY2 in the conditions of the proof of principles.




First simulation with a minimal setup:

- CRY2
- Proton gun of energy $E_p = 1\,TeV$, Gaussian beam characteristics
- A silicon scoring plane $150 \times 150 \times 0.2\,mm^3$ placed at a distance $d = 1.04\,m$ from the crystal
- $500$ Events



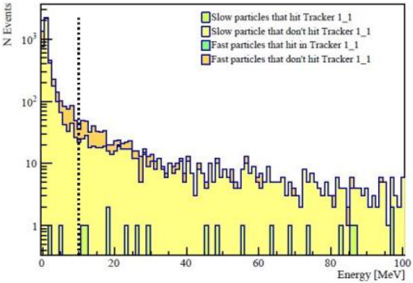

➡ Geant4 Channeling routine is **very slow**

- The run lasted 178 hours

# Cut Analysis

Basing on the 500 event simulation forcast the time reduction if charged particles created in crystal that satisfy a certain cut were killed at the beginning

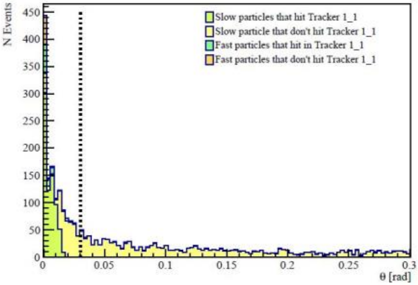
- **Vertex Kinetic Energy**: cut at $E_{k,vert} < 10\ MeV$




**Real test:**

- Time reduction of a factor **7.3**

- **Polar Angle**: cut at $\theta > 0.03\ rad$




**Real test:**

- Time reduction of a factor **12.22**

# 2000 Events Simulation

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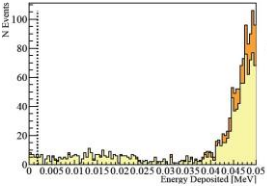
Simulation setup:

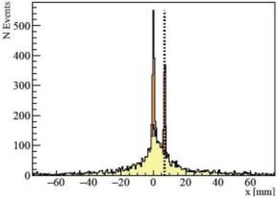
- CRY2
- Proton gun of energy $E_p = 1\,TeV$, Gaussian beam characteristics
- A silicon scoring plane of dimensions $150 \times 150 \times 0.2\,mm^3$ placed at a distance $d = 1.04\,m$ from the crystal
- Vertex kinetic energy **cut of $\mathbf{10}\ \boldsymbol{MeV}$**
- **2000 Events** run in parallel using HTCondor

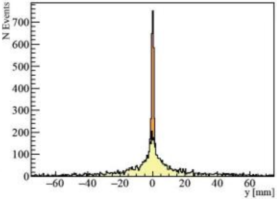
- $273 \times 273$ bins of $550\ \mu m \times 550\ \mu m^2$ (10 pixel)
- **Energy deposit** threshold at $\mathbf{1.8}\ \boldsymbol{keV}$ (cut applied on each particle)

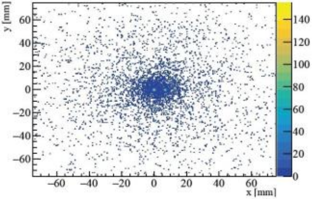



**Signal Hit**: protons coming from CRY1 and splitted by CRY2 that hit the tracker (orange)

**Background Hit**: particles created in interactions of primary protons with Si crystal that hit the tracker (yellow)

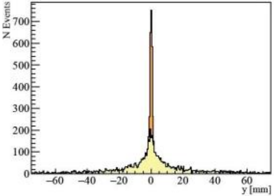


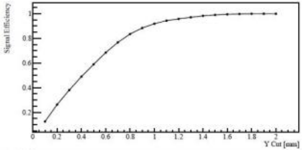



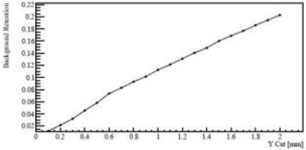
# 2000 Events Simulation - Cuts

- Apply a variable cut on $|y|$ **position**

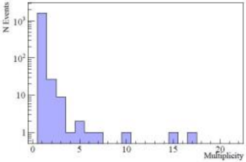


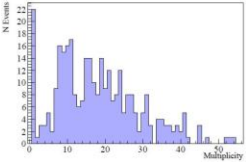

➡ Cut on $|y| < 1.8\,mm$



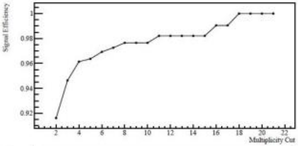



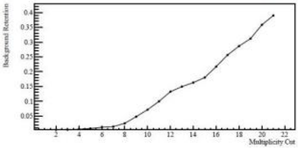

- Apply a variable cut on **particle multiplicity**



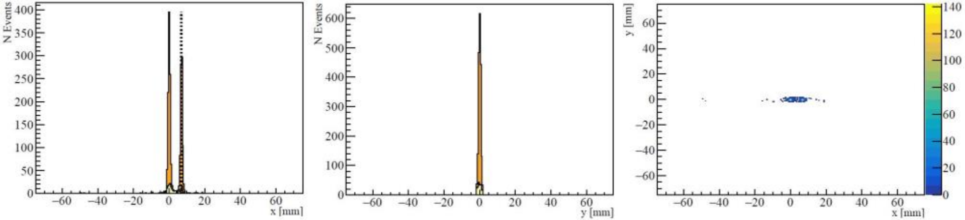

➡ Cut on $N \leq 11$



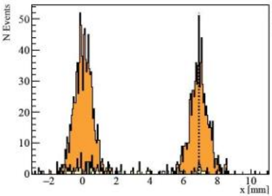



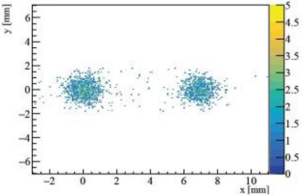
# 2000 Events Simulation – After cuts

Cut at $|y| < 1.8\,mm$ and at $N \leq 11$



**VeloPix dimension:** $14.08 \times 14.08\,mm^2$





$256 \times 256$ bins of dimension $55 \times 55\ \mu m^2$ (1 pixel)

**~ 45 % efficiency**

# Simulations with the target

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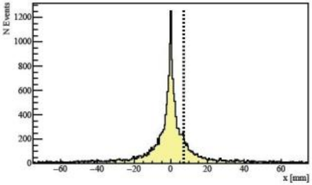
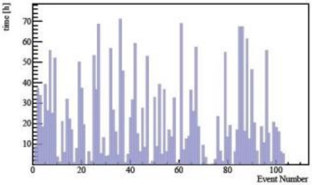
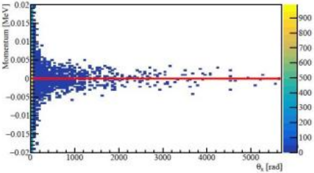
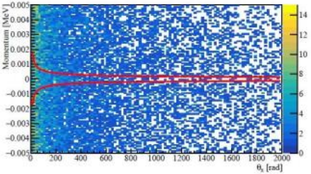
- Tungsten target of $40 \times 80 \times 50\, mm^3$ placed before CRY2
- Primary p-W interactions read from a Pythia Argantyr file, proton energy set to $E_p = 7\, TeV$
- 100 events




## Analytical approach

- Disable Geant4Channeling routine and consider particles at crystal entrance
- Compute the channeling critical angle condition (red curve)

$$\theta_c(pv) = \sqrt{\frac{2U(x_c)}{pv}\left(1 - \frac{pv}{E(x_c)} \cdot \frac{1}{R}\right)}$$

- Compute channeling probability
- Deflect particles that satisfy channeling conditions

➡ At least 42000 events simulation needed to produce a statistically significant bump

# Conclusions

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**The existing Geant4 crystal channeling physics routine was interfaced to DD4hep and can now be used.**

- The **CPU computation time** is very limiting, even after applying cuts

  ***Future work:***
  - Study other types of cuts
  - Try to directly optimize the Geant4 Channeling Routine
  - Circumvent the use of this particular Geant4 channeling routine by implementing a model of the channeling phenomenon based on parametrization

**Proof of principles tests:** the presence of channeled protons should be clearly visible above the background in a VeloPix

- **With the target:** the presence of channeled particles in events with a p-W interaction is much more hidden in the background

  ***Future work:***
  - Study how many tracking planes would be required to be able to identify clearly channeled particles from a p-W interaction

# THANK YOU FOR YOUR ATTENTION

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Dipartimento di Fisica e Astronomia Galileo Galilei

**Channeling condition**

$$\theta_c\,(R_c/R) = \theta_{c,0}\left(1 - \frac{R_c}{R}\right) \qquad \text{where } \theta_{c,0} = \sqrt{\frac{2U(x_c)}{pv}} \text{ and } R_c = \frac{pv}{U'(x_c)}$$

$U(x_c) = 16\text{ eV} = 1.6 \cdot 10^{-5}\text{ MeV} \qquad U'(x_c) = 5.7\text{ GeV/cm} = 5.7 \cdot 10^{3}\text{ MeV/cm}$

Crystal bending radius: $R = 10\text{ m} = 1 \cdot 10^{3}\text{ cm}$

Critical momentum: $p_c = 5.7$ TeV since $R > R_c$

$$\theta_c(pv) = \sqrt{\frac{2U(x_c)}{pv}}\left(1 - \frac{pv}{U'(x_c)} \cdot \frac{1}{R}\right)$$

Assuming $v = c$

$$\theta_c(p) = \sqrt{\frac{2 \cdot 1.6 \cdot 10^{-5}\text{ MeV}}{p}}\left(1 - \frac{p}{5.7 \cdot 10^{3}\text{ MeV/cm}} \cdot \frac{1}{1 \cdot 10^{3}\text{ cm}}\right)$$

**Dechanneling probability**

$$F(\Theta, \rho)/A_S = (1-\rho)^2 \exp\left(-\frac{\Theta}{\Theta_D \rho (1-\rho)^2}\right) \qquad \text{where } \rho = \frac{R_c}{R}$$

$$\Theta_D = \frac{256}{9\pi} \frac{N Z a_{TF} d_p^2}{\ln(2 m_e c^2 \gamma / I) - 1}$$

For Silicon Si(110)

$$\Theta_D = \frac{4.526}{\ln\left(5907.51 \cdot \frac{E}{m}\right) - 1}$$