# Recent Advances in Crystal-Assisted Beam Shadowing for the Mu2e experiment

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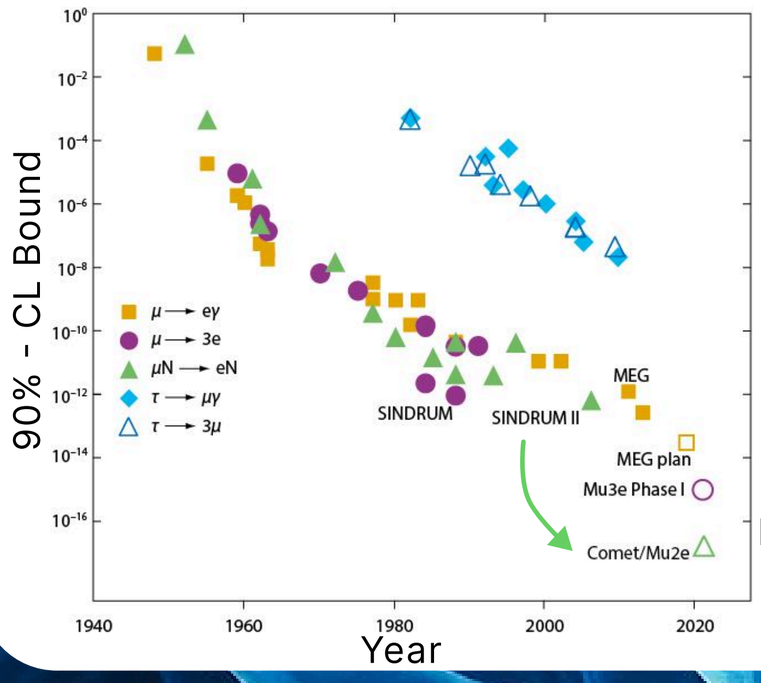
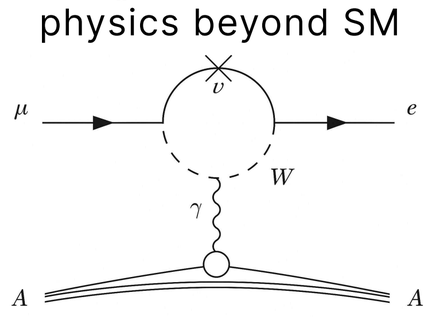
## Mu2e Physics goal



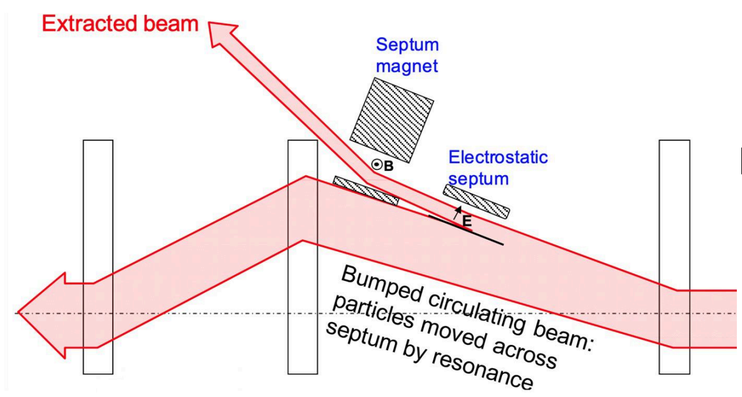

Search for neutrinoless muon-to-electron conversion as a signature of new physics beyond SM




Improvement of current single event sensitivity by a factor $10^4$

## Mu2e requirements

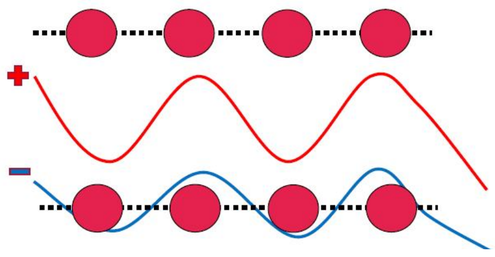
1. High statistics: highest intensity muon beam in the world
2. High background rejection: **pulsed proton beam structure to reject Radiative Pion Capture**
3. High detector precision

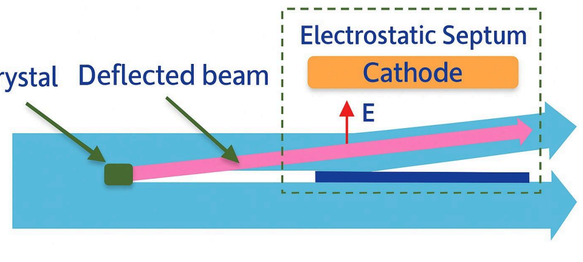



The pulsed proton beam is extracted via resonant extraction. Issue: a fraction of the beam interacts with the septum material, causing about 1.5% of beam losses and unwanted radiation issues. **[1]**

## Septum shadowing with bent crystals

In a **bent crystal** channeled particles **follow the curvature** of the lattice plane which acts as a sort of wave-guide.





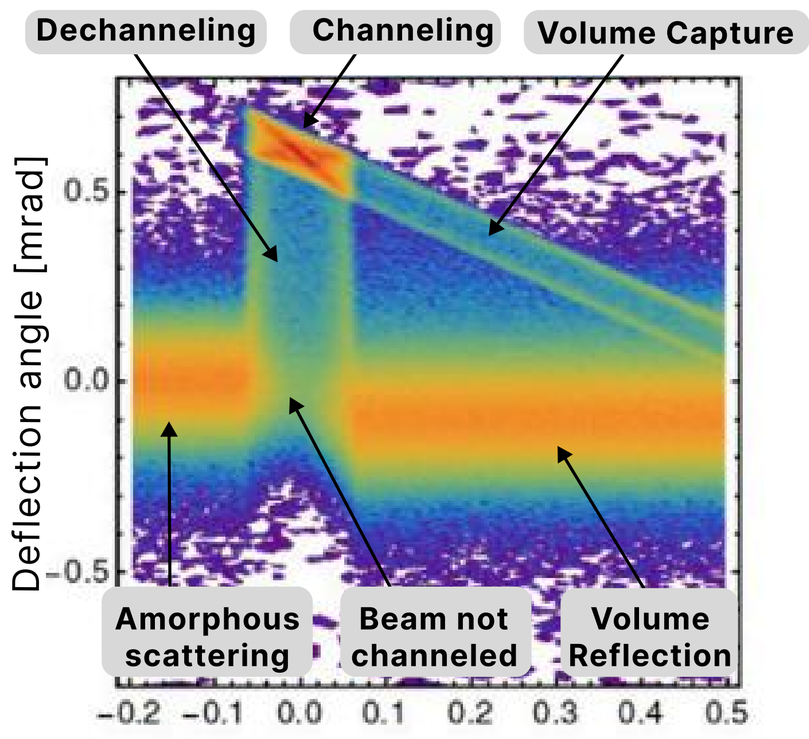

Idea: implement an optimized bent crystal upstream of the electrostatic septum to **reduce particle loss**.

A large steering power can be obtained in **few millimeters of crystal**, equivalent to that of **hundreds of Tesla** magnetic dipole.

| Beam energy (GeV) | Deflection (μrad) | Size (mm) | Equivalent dipole (T) | |
|---|---|---|---|---|
| 6500 | 50 | 4 | 271 | LHC |
| 20.53 | 400 | 0.06 | 456 | |
| 8 | 450 | 2 | 6 | Mu2e |
| 2000 | 14000 | 70 | 1333 | |

## Simulations

*GEANT4 Simulation – Bent Crystal PDF*



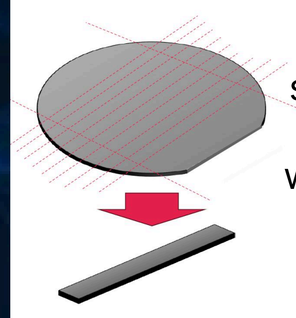

Simulations of a silicon-oriented bent crystal with a 600 μrad bending angle and 3 mm thickness, using Fermilab Delivery Ring beam parameters

**A preliminary beam loss reduction of a factor 3 is estimated for a beam with 40 μrad angular divergence.**

**[2-3]**

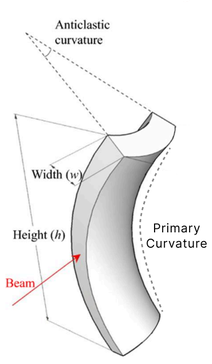
## Silicon bent crystal realization

### 1. Cutting



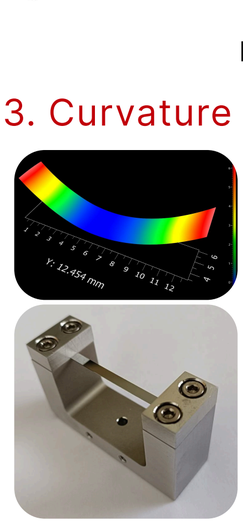
Parallelepiped-shaped samples were obtained with micrometric precision using dicing blades bonded with micro-diamonds.

### 2. Crystal bending scheme



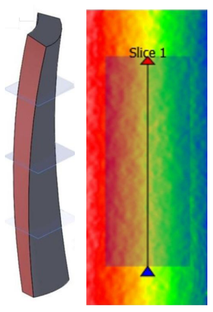

A holder forces the crystal into arched position.
A very uniform secondary anticlastic curvature appear as elastic reaction of silicon.

### 3. Curvature characterization




A 2D measure of surface profile is achieved with nanometric precision with interferometric profilometer

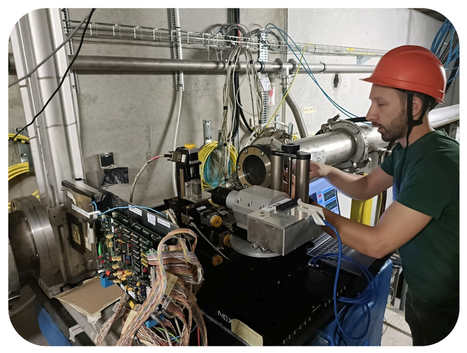
### 4. Torsion Characterization

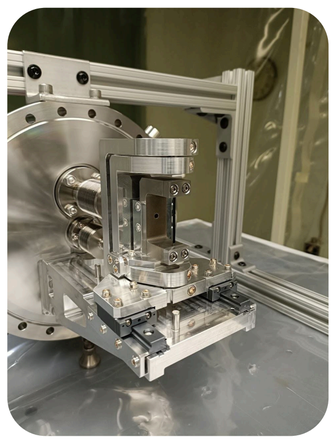



Torsion <10μrad/mm is required for good steering efficiency.
The optical characterization estimates ~5μrad/mm.

## Bent crystal characterization and installation

A sample of 3 bent crystals was characterized at CERN SPS H8 with 180 GeV protons parameter estimated:
1. Deflection angle
2. Channeling efficiency
3. Crystal torsion





All the crystals satisfy the requirements.
The most performant has been installed in the Fermilab delivery ring in February 2026
The commissioning is ongoing

**References:**
**[1] Mu2e Collaboration, Universe 2023, 9(1), 54.**
**DOI: 10.3390/universe9010054**
**[2] V. Nagaslaev, et al., Nucl. Instr. Meth. A, 1058 (2024) 168892.**
**DOI: 10.1016/j.nima.2023.168892**
**[3] S. Miscetti, et al., Nucl. Instr. Meth. A, 1073 (2025) 170257.**
**DOI: 10.1016/j.nima.2025.170257**

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