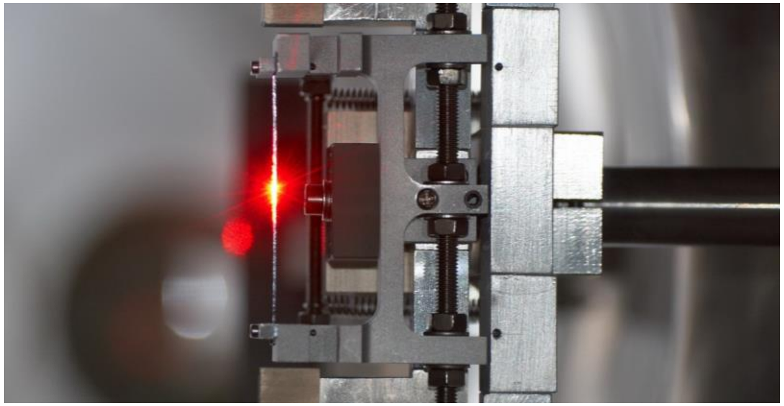
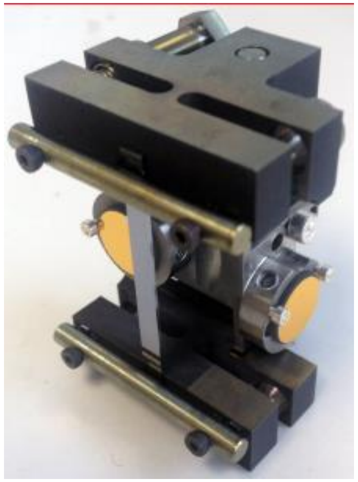




Crystals for beam extractions

Gianluca Cavoto (INFN Roma)

FCC WG on experiments with the injectors, CERN Dec 12th 2014

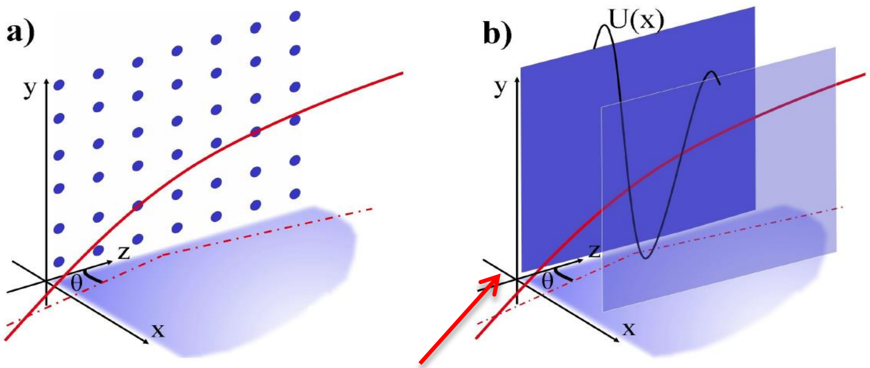
Outline

- ***Aim***: Efficient **crystal** extraction of a multi-TeV hadron beam for *fixed target experiments*
  - *CRYSBEAM(*) project*
- State of the art of crystals on accelerators
  - Crystal collimation and the ***UA9 experiment at CERN***
- What's needed: cutting-edge technology in crystal
- *An application*: Cosmic ray physics with the extracted beam
- Plans

*(*) CRYSBEAM is funded by a **ERC Consolidator Grant GA 615089** (FP7 IDEAS action) with a **2M euro** budget for the period May **2014**- May **2019***

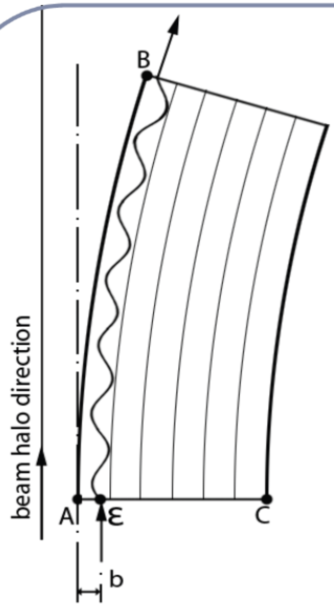
***INFN** is the Host Institution*
Website : http://crysbeam.roma1.infn.it/

Crystal channeling, a coherent interaction



Charged particle direction within a **critical angle** relative to the atomic planes.

Trapped in the lattice electric potential U(x).



If crystal mechanically **bent,**

particles still oscillate inside the "channel".

Particles emerge **deflected** and **parallel** (**low divergence**).

Critical angle

$$\theta_C = \sqrt{\frac{2U_0}{E}}$$

Potential well depth **~Z** [22.7 eV for (110) Si]

Particle energy

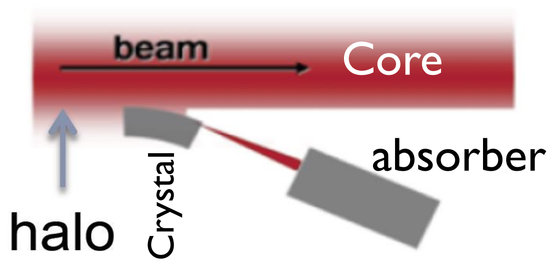
$\theta_C \approx 2.3\mu rad$ at $E \sim 7$ TeV

CRYSBEAM basic idea

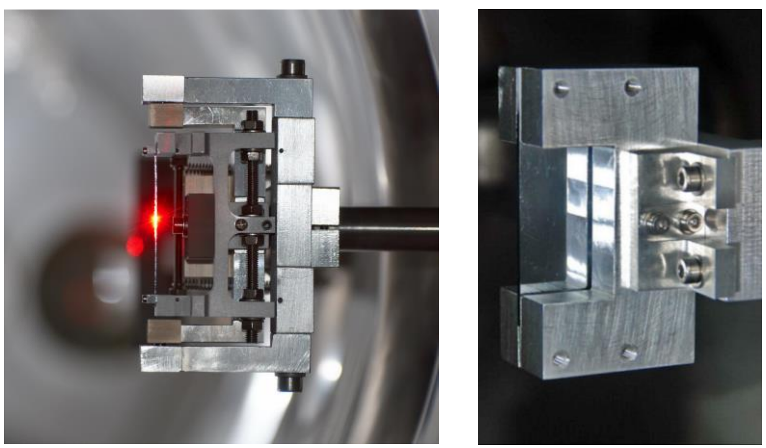
PARASITIC *EXTRACTION of BEAM with* ***a bent crystal*** *in*
channeling orientation

Low background, continuous extraction of the beam halo

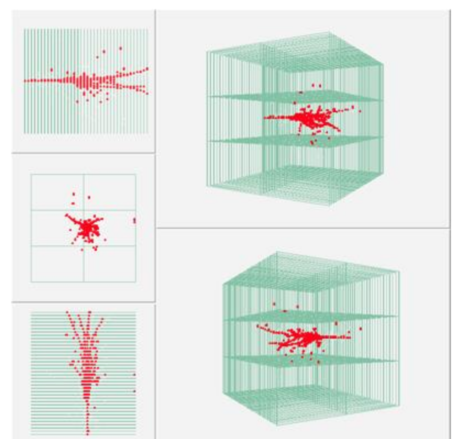
10^8 particle per second might be possible



Instrumented ("smart") absorber to measure the hadronic shower structure



UA9 crystals

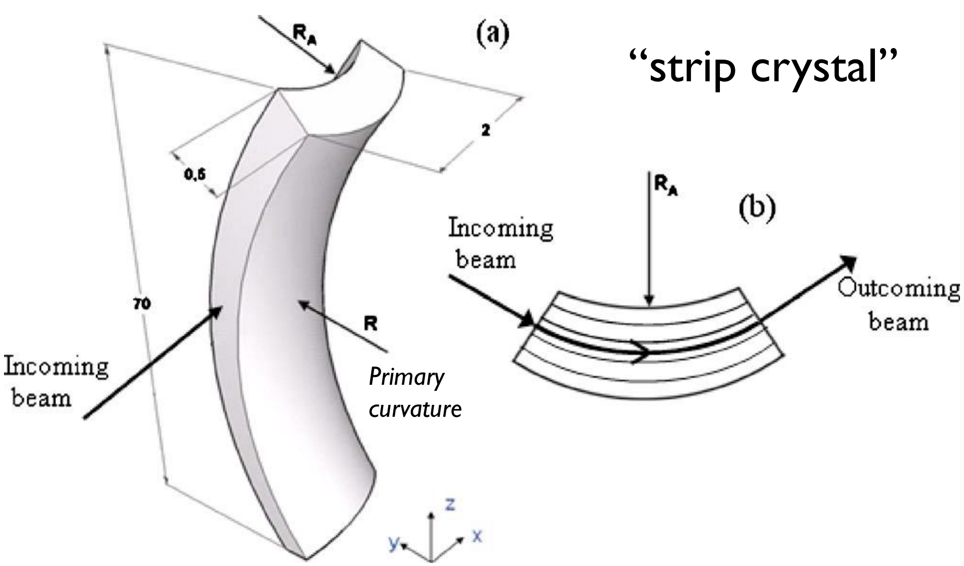


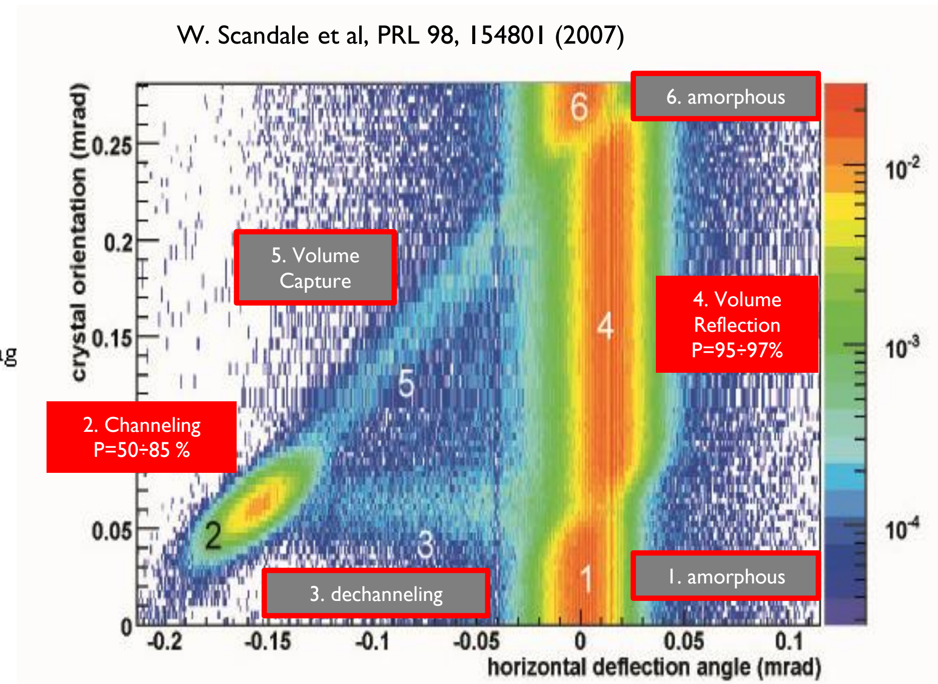
CALICE Digital HCAL

The UA9 experiment at CERN

Coherent interaction studies a

- UA9 leader in producing and testing crystals
  - H8 beam test, X-ray diffraction, RBS, …

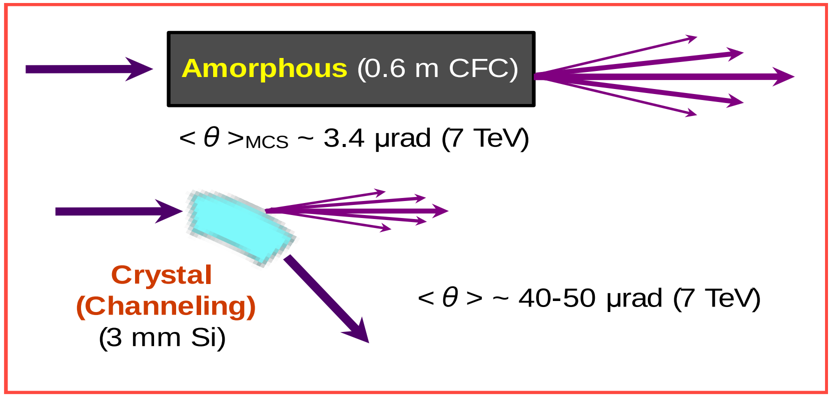


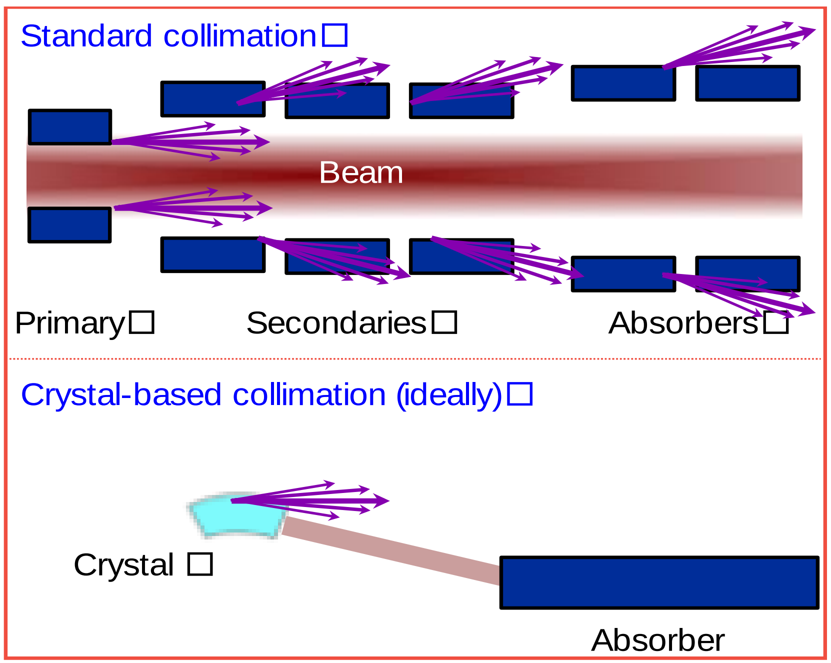


Anticlastic deformation to impart bending

Also quasi-mosaicity used (wider crystals)

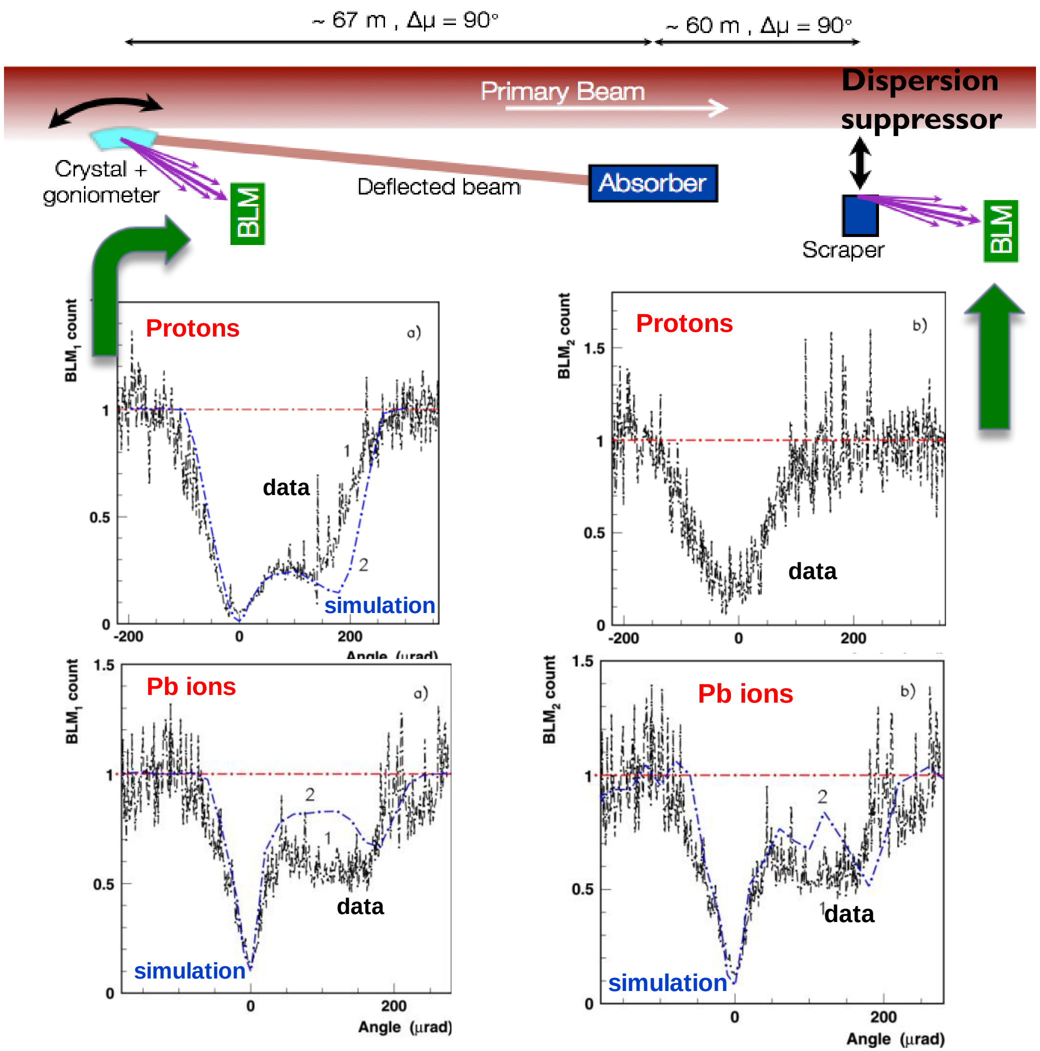
Crystal collimation idea





- Bent crystals as primary collimator
  - Large kick angle even at high energy
  - Reduced hard interaction
    - (diffraction, ion fragmentation, ion em dissociation…)
  - Reduced impedance
    - Reduced number of secondary collimators, larger gaps
- At a price of
  - Relatively small acceptance
  - All the losses on a single absorber

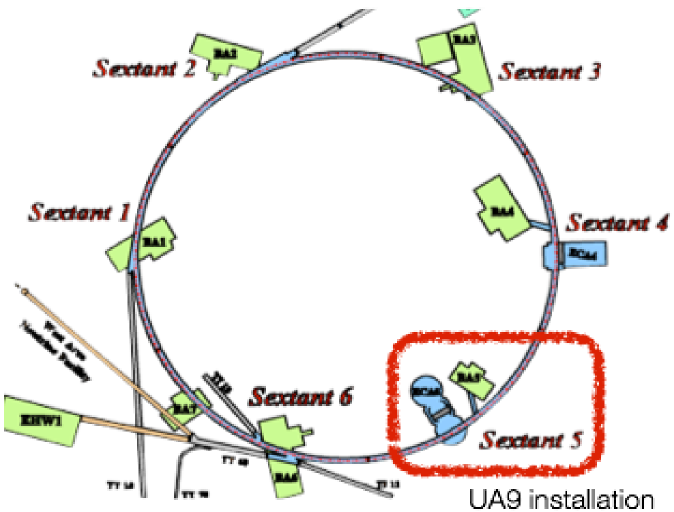
Crystal collimation at SPS

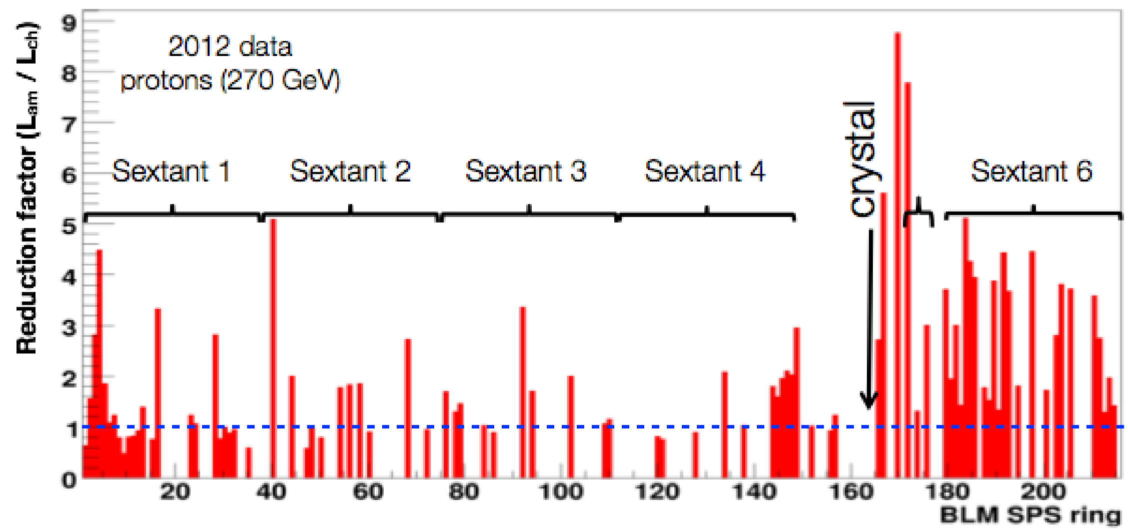


- Extensive tests with 120-270 GeV protons and Pb ions
  - 150 μrad deflection
  - $\theta_C \sim$ 20-13 μrad
  - Single bunch and multi-bunch dedicated beams
- Fast and reproducible crystal alignment
- Clear loss ***reduction with respect to an amorphous orientation***
  - Up to x20 reduction

Losses around the SPS ri

- Consistent reduction in the whole ring

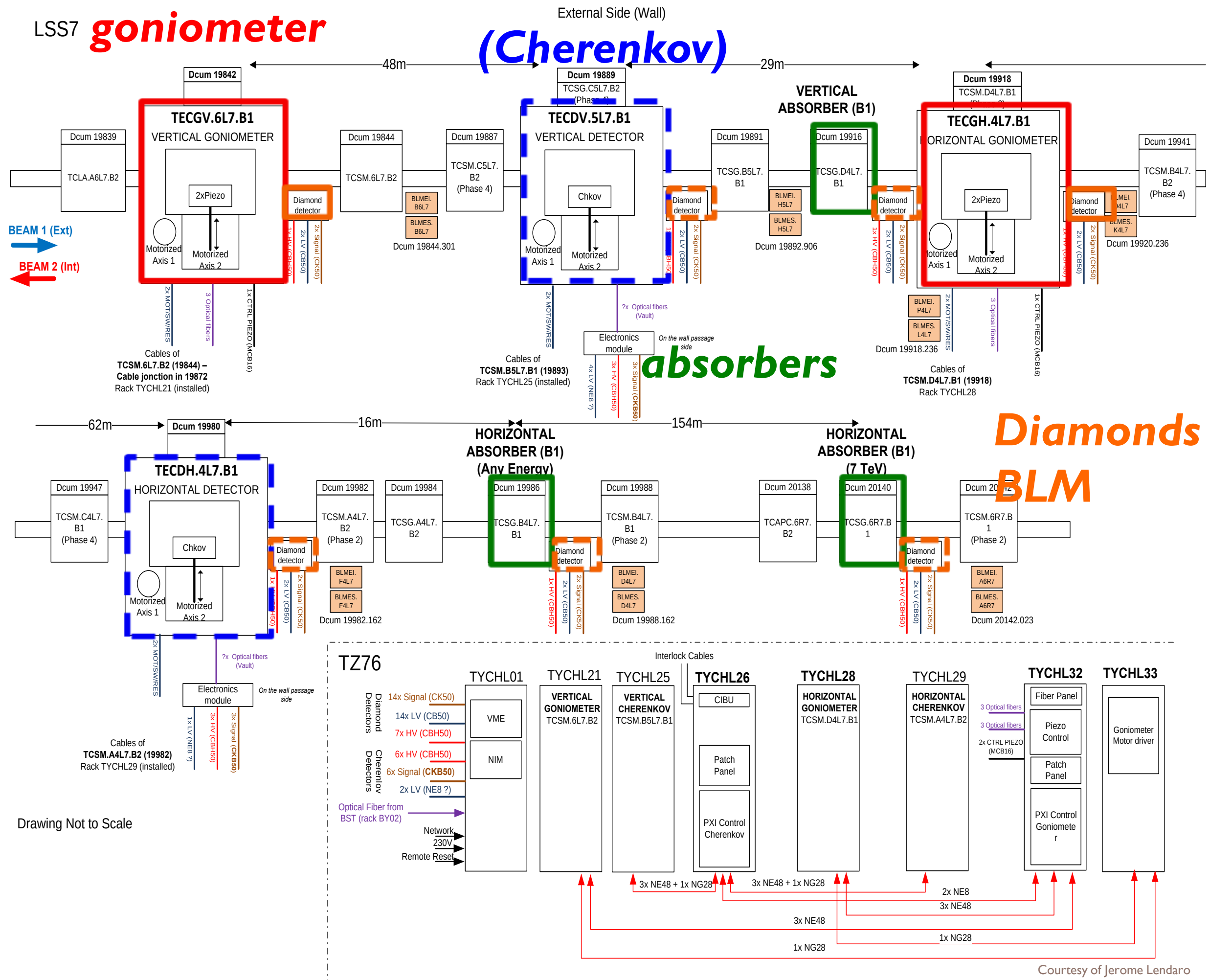




Efficient crystal (i.e. almost all particles are channeled) means low background in the machine

The UA9 test on LHC

- Integration of the crystals in the existing collimation system:
  - installation of the equipment in IR7
  - use of existing collimators (as absorbers) and BLMs.
  - Simultaneous test of horizontal and vertical collimation.



Courtesy of Jerome Lendaro

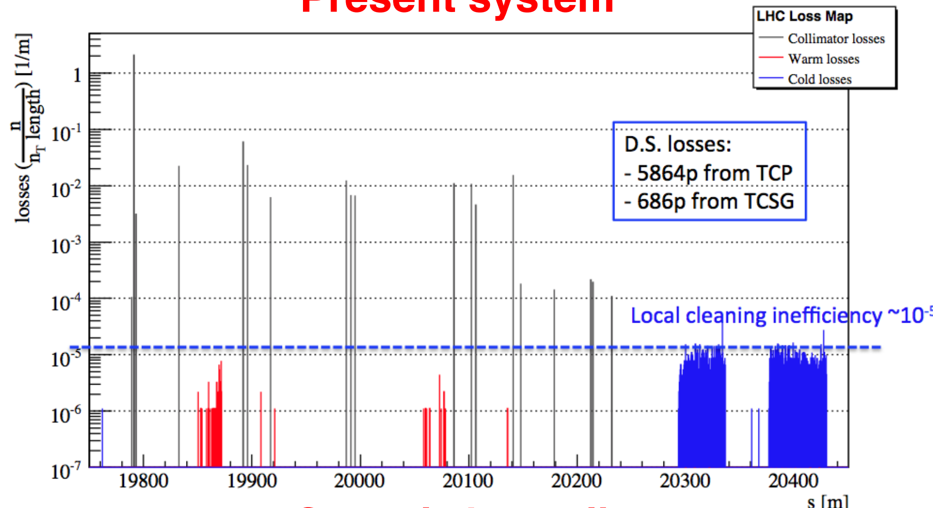
In close collaboration with CERN Collimation Group

Prediction for the LHC test

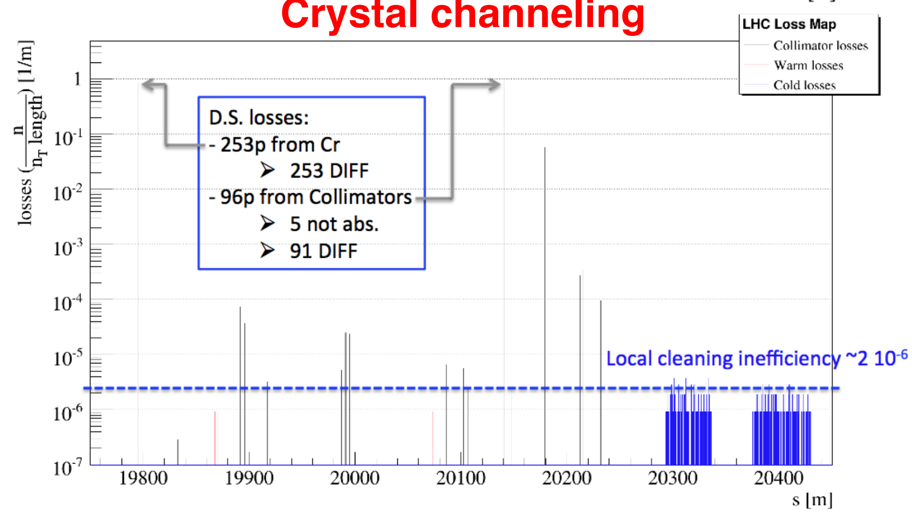
*D. Mirarchi, S. Redaelli, W. Scandale, V. Previtali:
Layouts for Crystal Collimation Tests at the LHC, MOPWO035, IPAC13.

- Layout optimized with complete tracking simulation
  - Vertical crystal: DCUM 19918, horizontal crystal: DCUM 19842
  - Crystal parameters: bending angle 50 μrad, length 0.4 cm
  - local cleaning inefficiency is reduced by 5÷10 times in the dispersion suppressor

Present system



Crystal channeling



The *CRYSBEAM* challenges

SPS extraction, RD-22 experiment

The RD22 Collaboration, CERN DRDC 94-11

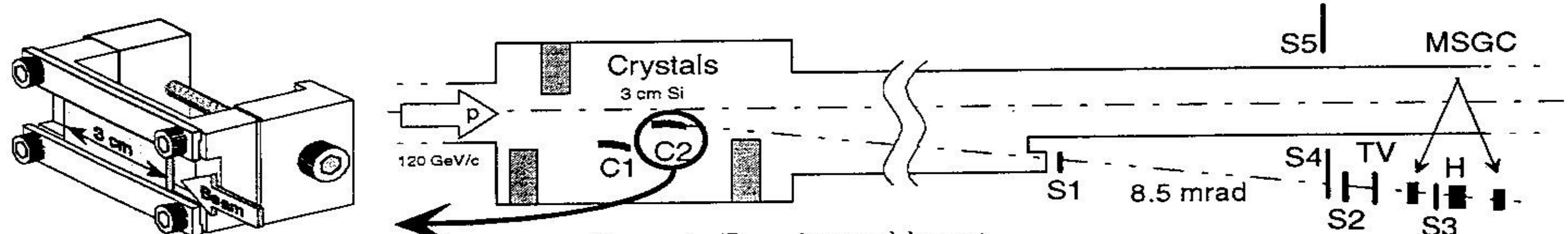
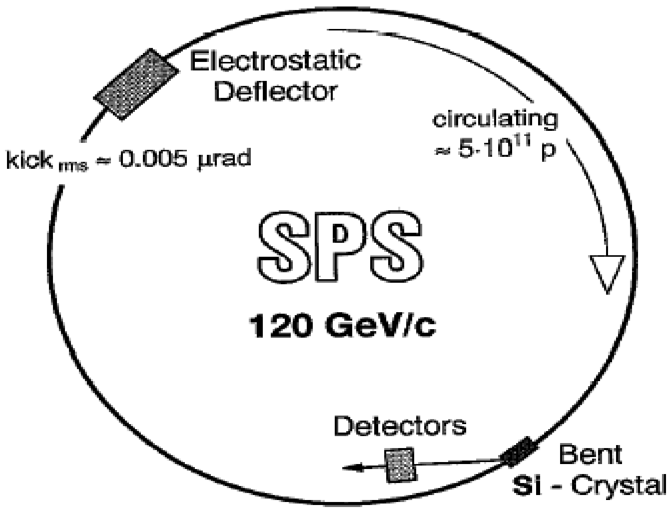


Figure 1: Experimental layout



	Crystal 1	Crystal 2
beam intensity (protons)	$(7.0 \pm 0.1) \cdot 10^{11}$	$(3.7 \pm 0.1) \cdot 10^{11}$
beam lifetime (hrs)	20 ± 2	12 ± 1
protons lost per second	$(6.7 \pm 0.6) \cdot 10^{6}$	$(8.9 \pm 0.7) \cdot 10^{6}$
protons detected per second	$5.6 \cdot 10^{5}$	$6.6 \cdot 10^{5}$
background (%)	5	2
detection efficiency (%)	78 ± 12	78 ± 12
extraction efficiency (%)	**10.2 ± 1.7**	**9.3 ± 1.6**

- Crystal used in other accelerators (U70) in the o(100 GeV) energy range

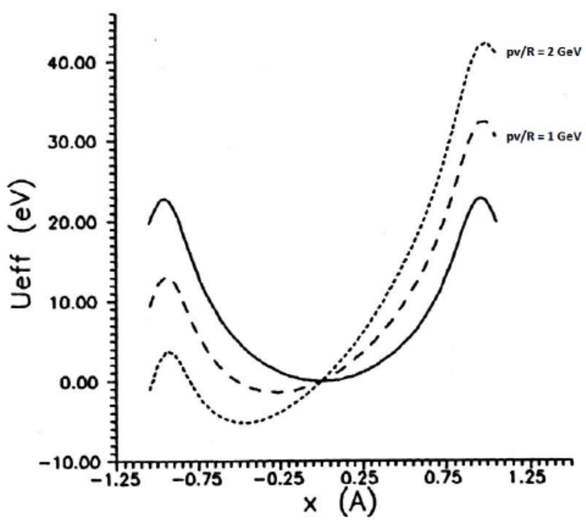
Critical Radius for channeling

- Given a deflection angle Φ **[~1 mrad]**

$$\Phi = L/R$$

where R is crystal curvature radius and
L is the crystal length

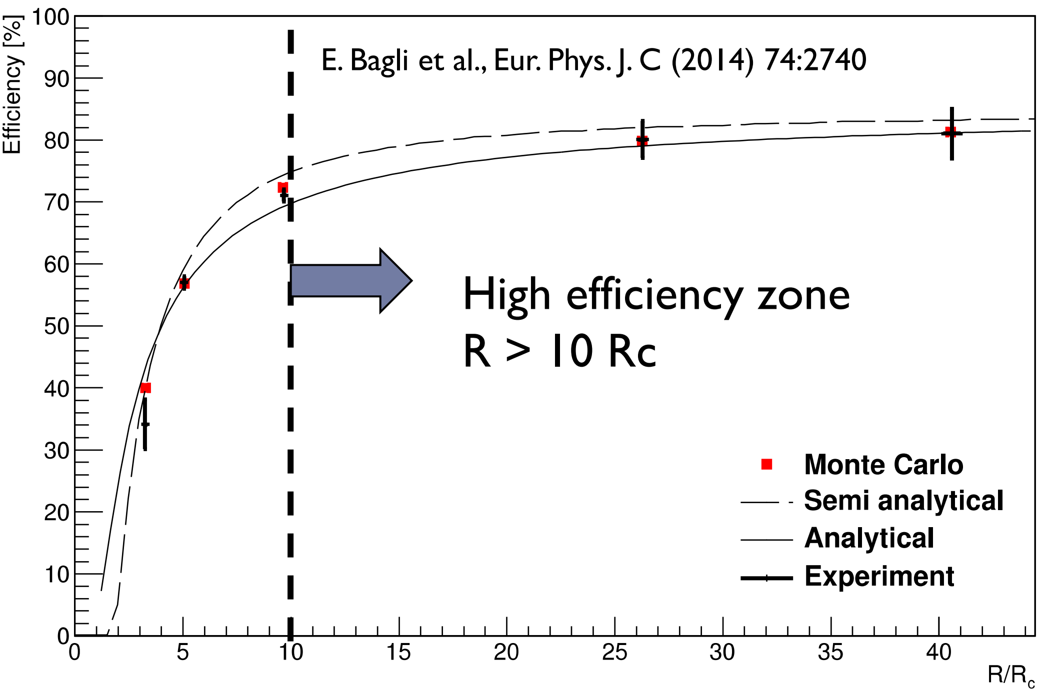
Effective potential in presence of centrifugal force (bending)



Critical radius to have an efficient channeling

$$R_c \approx \frac{\frac{p}{Z_i}\beta}{\pi Z e^2 N d}$$

Channeling efficiency versus Rc



- Experiment (H8 and SPS):
  - Si bent crystal (**L = 0.2cm**)
  - (1 1 0) plane
  - 400 GeV/c protons

Si (110):

R_c = 12m at $p\beta$ = 7 TeV

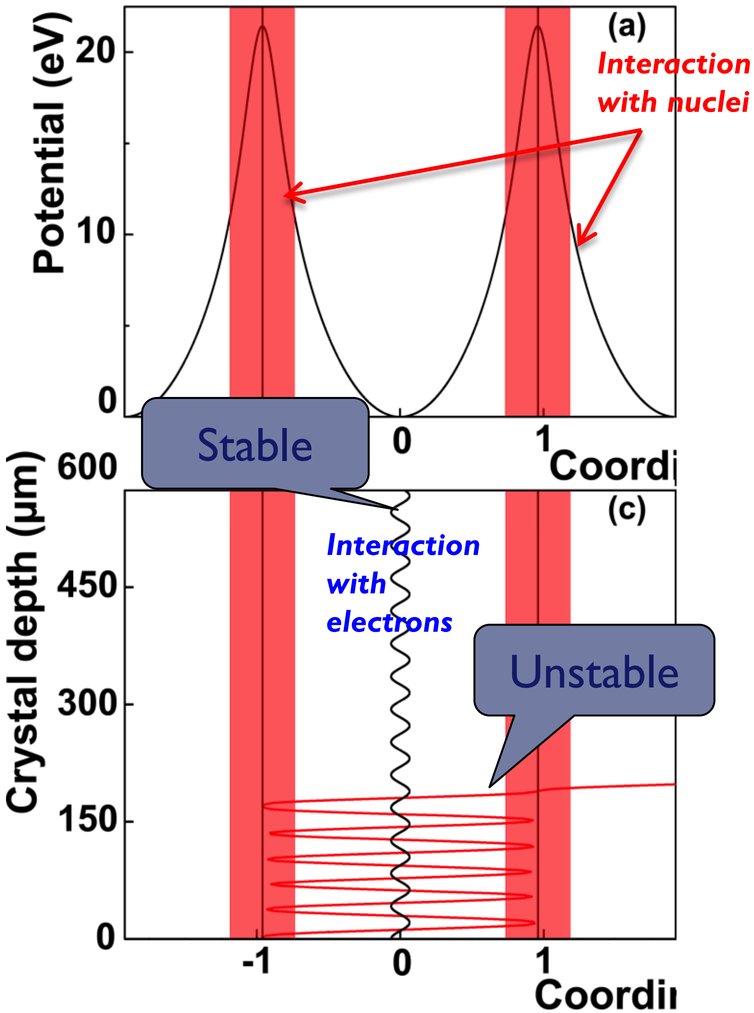
Ge (110):

R_c = 7m at $p\beta$ = 7 TeV

- ~1 mrad deflection requires ~12cm long Si crystal (or 7 cm long Ge crystal)
- Much longer than what UA9 tested and used so far

Dechanneling effects

Scandale et al., PLB 680, 129 (2009)

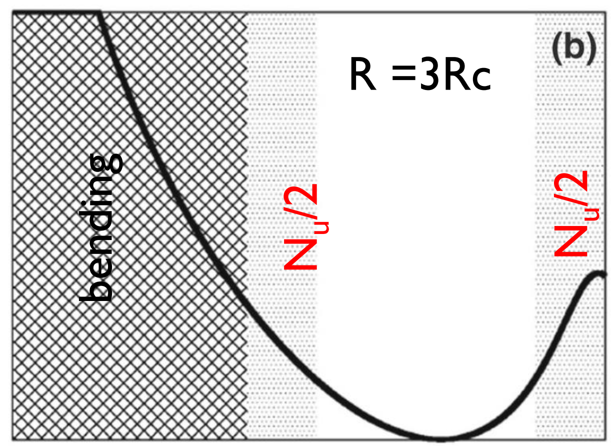


- Nuclear (L_n) and electronic (L_e) dechanneling affecting channeling efficiency

$$N_{ch}(z) \approx N_{unstable} e^{-\frac{z}{L_n}} + N_{stable} e^{-\frac{z}{L_e}}$$

L_n ~ sqrt(p) : at 7 TeV L_n ~ 0.6 cm

L_e ~ p : at 7 TeV L_e ~ 400cm



$$\varepsilon \approx \left(1 - \frac{R_c}{R}\right)^2$$

E. Bagli et al., Eur. Phys. J. C (2014) 74:2740

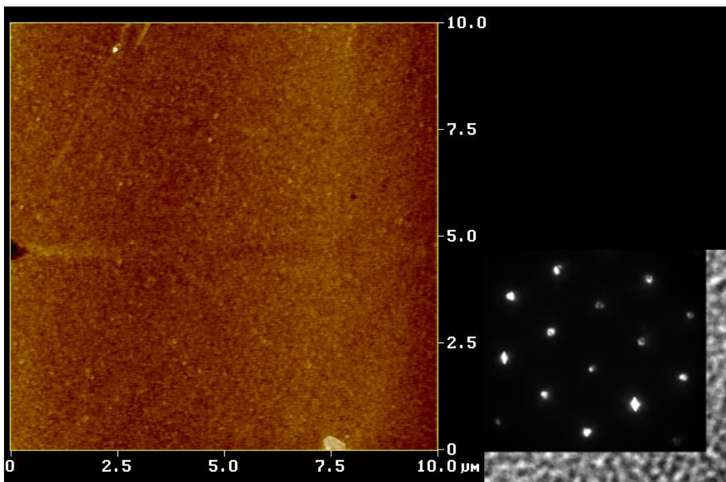
Silicon crystal production and testing

Sensor and Semiconductor Laboratory

University of Ferrara and INFN Ferrara

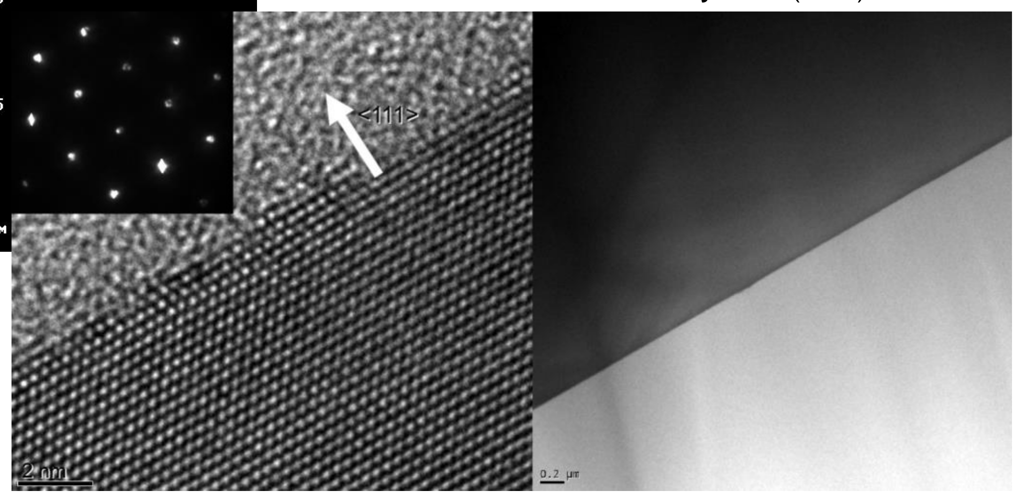
- Anisotropic chemical etching
  - Sub-surface damage free crystal

Lateral surface (AFM)



Entry surface (HRTEM)

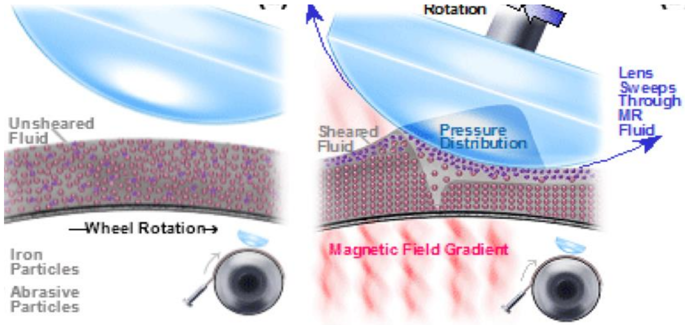
JPD 41 (2008) 245501

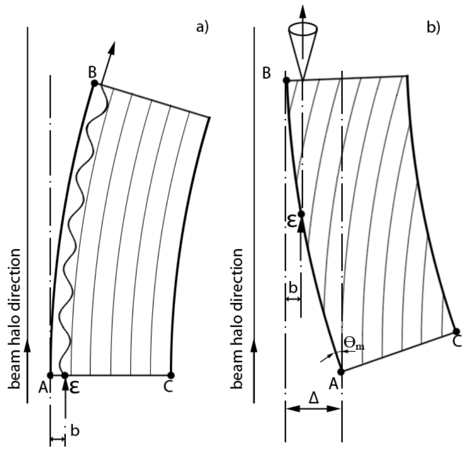


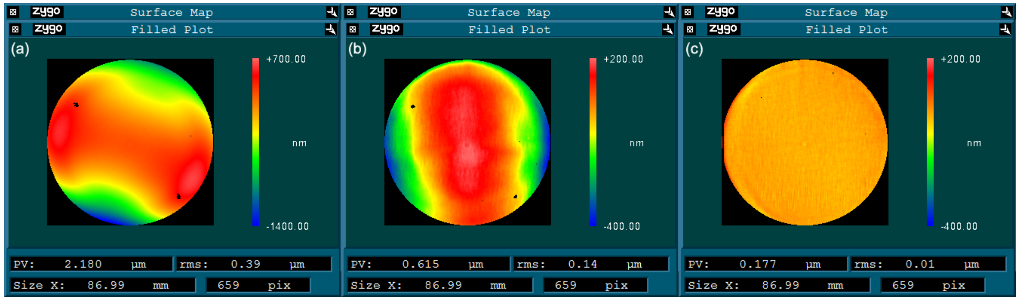
Sub-nm roughness was achieved

Challenges for crystal production

- 6 inch wafer micro-machining
- Low miscut wafer
  - Use magneto-rheologic finishing







Initial surface of the wafer

PV 2.18 um
RMS 0.39 um

Surface after first lapping

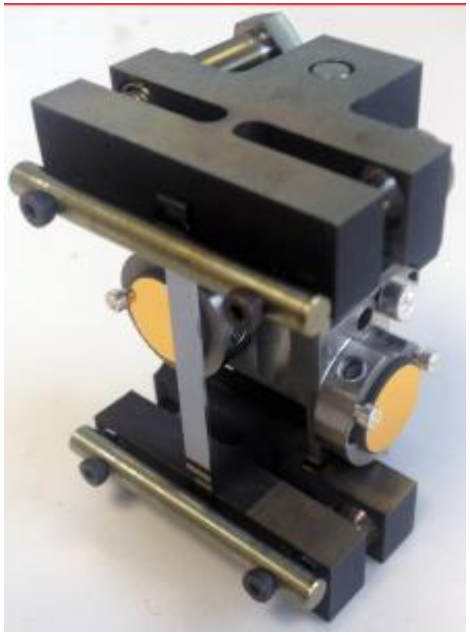
PV 0.615 um
RMS 0.14 um

Final Surface

PV 0.177 um
RMS 0.01 um

- Dislocation (1D and 2D) might be a problem for long crystals
- Ge is now a viable alternative

New Holder technology



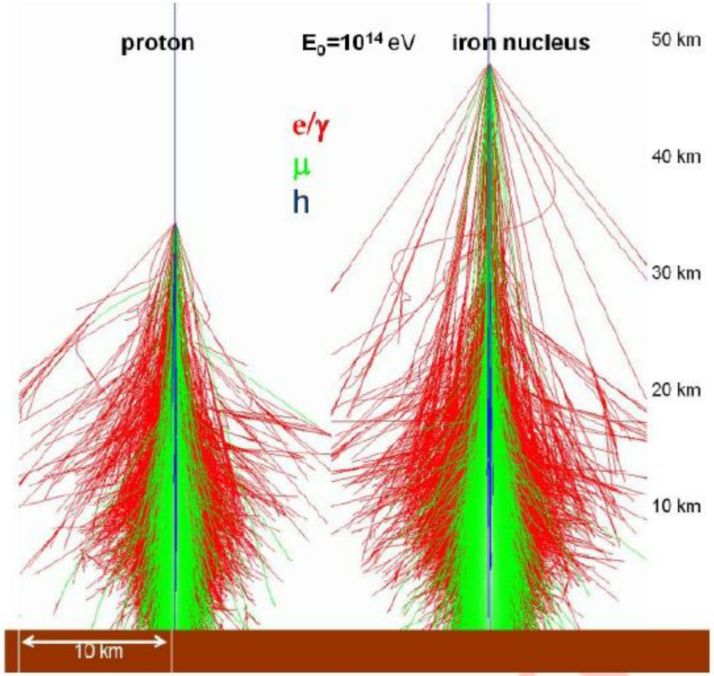
- High grade titanium holder for SPS and LHC crystals

- For a very long crystal (~10 cm), a new holder need be designed!
  - Assisted curvature with **tensile layer deposition**
  - INFN Ferrara labs has infrastructures and know-how

Hadronic showers and Cosmic rays

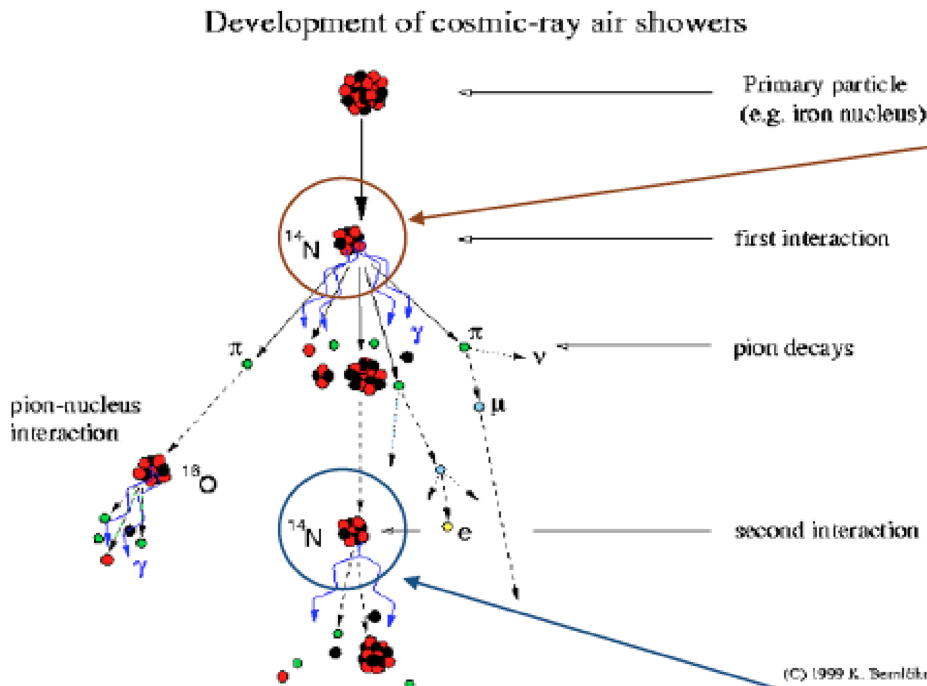
Observations of Cosmic Rays at ground level:

"Extensive Air Showers"



Hadronic interaction in air showers

G.Mitsuka (LHCf coll)



Largest systematic uncertainty of indirect measurement is in first interaction.

E~TeV

1. **Inelastic cross section**
   large → rapid development
   small → deep penetrating
2. **Inelasticity $k = 1 - p_{lead}/p_{beam}$**
   large → rapid development
   small → deep penetrating
3. **Forward energy spectrum**
   softer → rapid development
   harder → deep penetrating
4. **Nuclear effects**
5. **Extrapolation to high energy**
   precise measurements at available energies are crucial

E~GeV

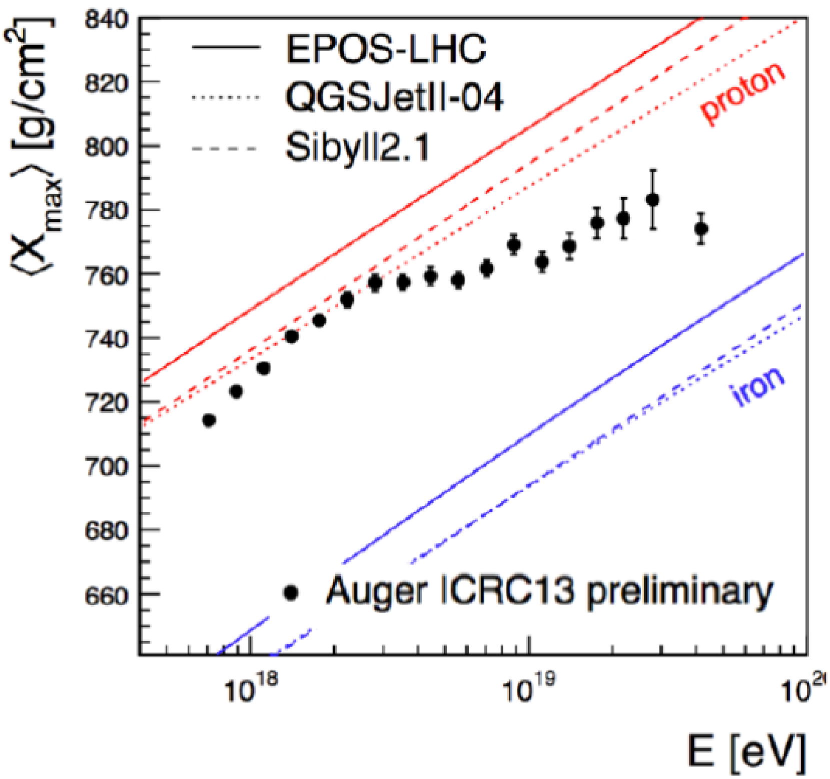
1. **Charge ratio**
2. **Multiplicity**
   number of muons in air shower sensitive to mass composition

- Accelerator based experiments to unravel this (LHC-f, NA61 at CERN,…)

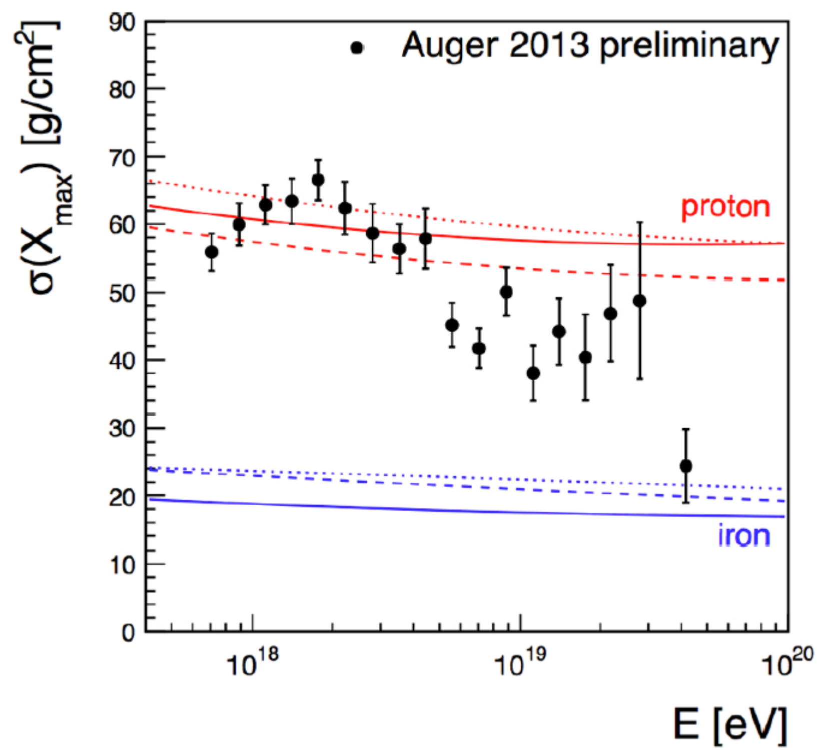
CR Mass composition

Pierre Auger Observatory

Shower maximum position



Cross section

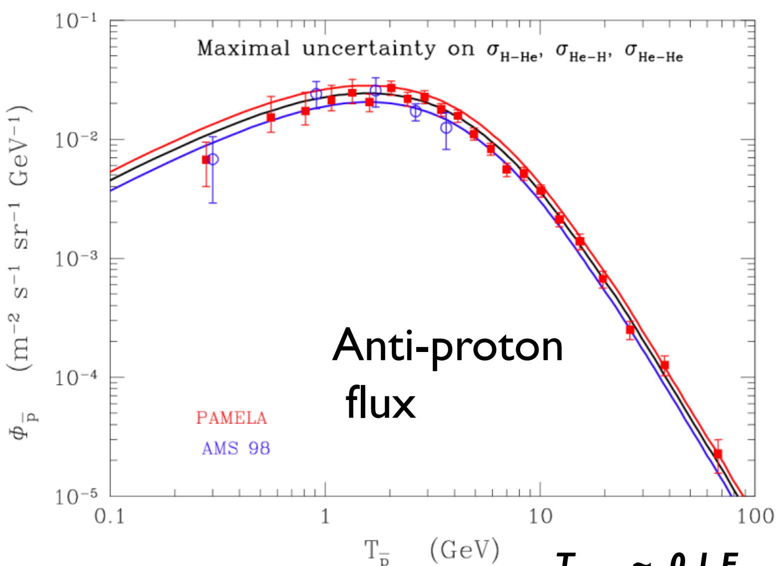


Data interpretation depends on MC used to described the shower

Propagation of Cosmic Rays in Galaxy

- Evidence of anti-matter excess in (galactic) cosmic rays (PAMELA, AMS-02, etc.)
  - Is this a sign of ***Dark Matter annihilating*** in our Galaxy?

F. Donato et al. ApJ 2001, PRL 2009



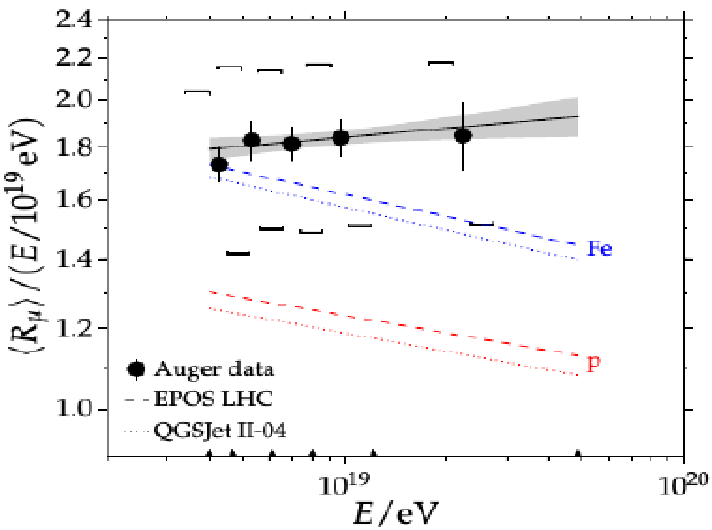
$T_{anti\text{-}p} \sim 0.1\ E_p$

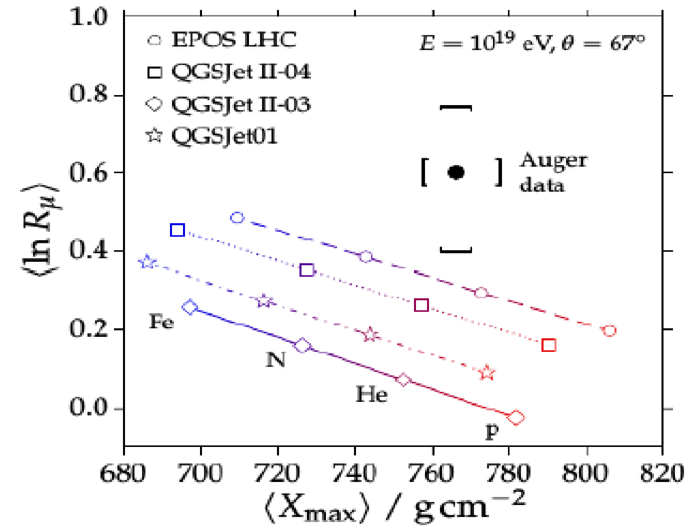
- It might only be due to cosmic rays interaction in interstellar medium
  - ***Improve propagation models*** with more precise cross section measurement
    - (B/C spallation, anti-proton production from He target,…)
  - **Measure p-p and p-He cross sections in the Ep ~1 GeV – few TeV range**

Gianluca Cavoto

Dec 2nd 2014

Muon in cosmic air-showers





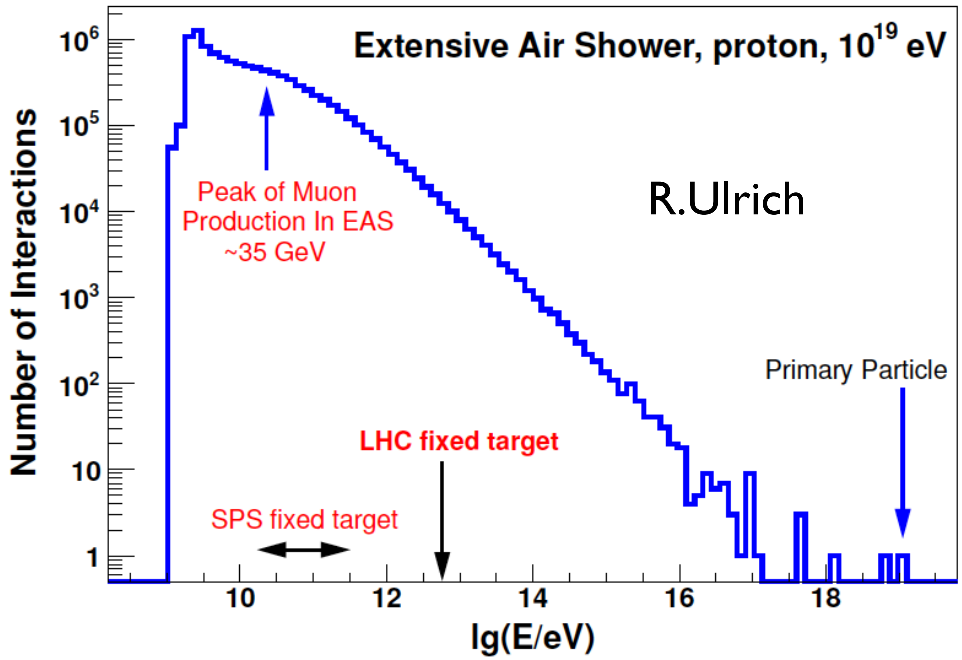
More muons in air-shower data than expected

Auger, arXiv-1408.1421 [atro-ph]

- Can be a problem in interaction physics in air-shower model ?
- Is a muon counting experiment after a beam dump interesting (or enough) to help solving this ?
- Do we need to study **charm** content of a shower ? Access to parton with momentum fraction x→1 in the target.
- Study production of charm from light nuclei directly?

Showers of Cosmic Rays in a lab

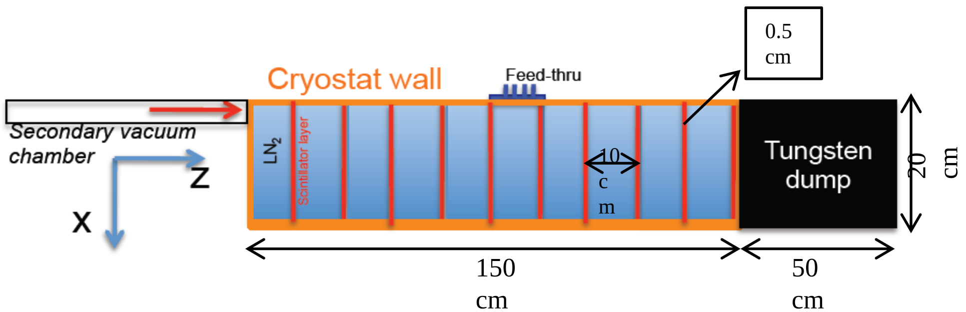
- Sub-showers of UHECR air-shower can be reproduced in lab: compare with MC (*CORSIKA*)
  - Following shower evolution as in air-shower experiment!



- Hadron beam of 10 GeV – 10 TeV (both SPS and LHC)
- Different targets (carbon, water, liq. nitrogen)

A smart absorber experiment

- Dump the extracted beam onto a light element absorber.
  - Possibly change the absorber
  - Count the number of particles crossing thin active layers



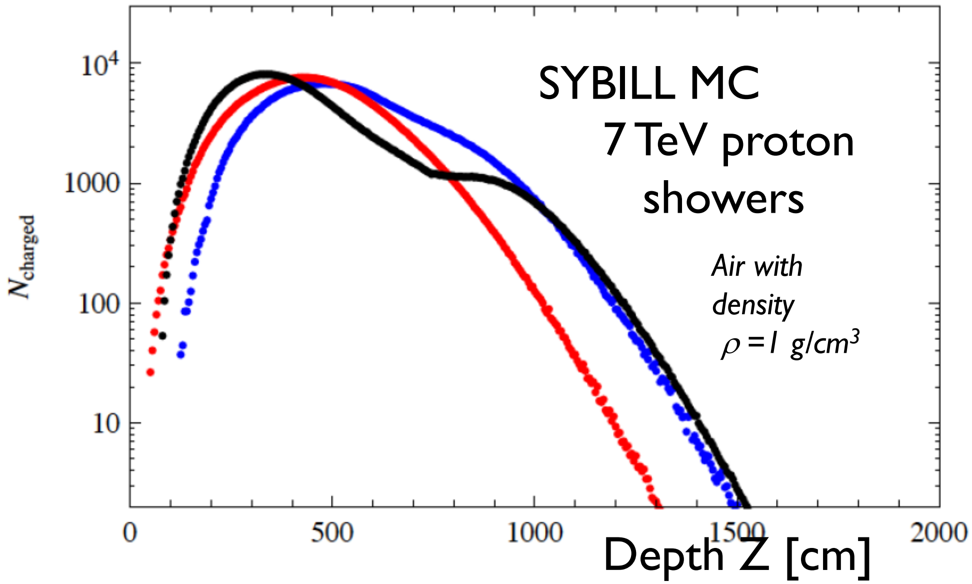
Can be tested on SPS North Area were proton and pion beam are currently available (up to 400 GeV energy)

Eventually moved to LHC (crystal) extracted line

Some synergy with Particle Flow Calorimeter R&D (ILC detector calorimeter)

Hadronic model in air-shower MC

Strategy: use CORSIKA to simulate a dense uniform atmosphere (a "lab" atmosphere) at lab energies.



- Critical measurements
  - Position of first interaction
  - Xmax, RMS(Xmax)
  - Number of ionizing particles

Change hadronic model and compare with experiment

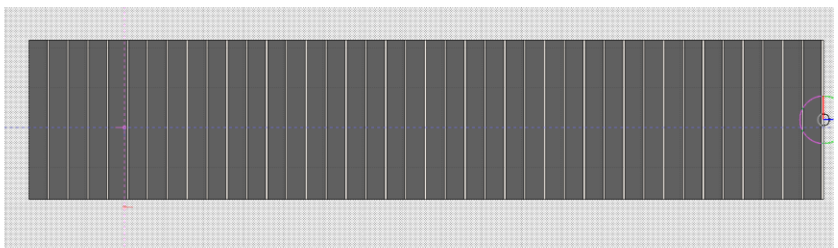
First look at FLUKA vs SYBILL show a 10% discrepancy in Xmax at 400 GeV and 7 TeV.

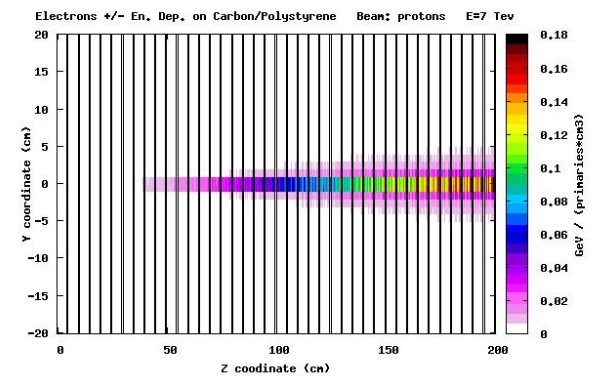
FLUKA simulations

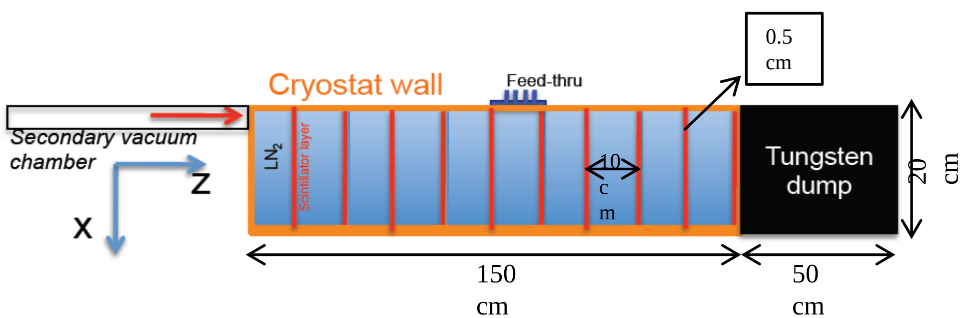
- Detailed tool to study geometry and algorithm to extract cross section information [$\sigma_{tot} = 1/(n\,\lambda_{int})$]

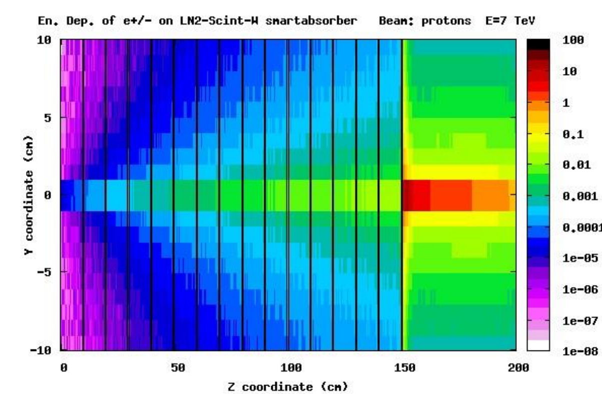
Carbon layers: 43 mm / Scint layers: 7 mm

7TeV protons









Plans

CRYSBEAM objectives

- **Produce crystals** with a large bending angle (~mrad) ***[2015]***
  - Even larger bending for SPS test
- **Test** them in the **North Area** to characterize their performance
  - Reuse UA9 expertise and infrastructure ***[end of 2015 – beg 2016]***
- Design smart *absorber [2015]*
  - Build it (2016) and then test on North Area ***[2016-2017]***
  - Cross section measurement of interest for CR physics might be possible at H8
- Propose a scenario for the halo extraction in the SPS,

  using the UA9 existing infrastructure (LSS5 region) ***[2015]***
- **Test and characterize the halo extraction scheme in the SPS *[2016-2017]***
  - Extracted beam characterization with BLM and Cherenkov detector *[after H8 validation]*
- **Propose of a scenario for an extraction test in LHC [2018]**

A scenario for LHC extraction ?

W. Scandale, Proc. LHC Workshop, eds G. Jarlskog and D. Rein, Aachen, 1990, vol. III p. 760.

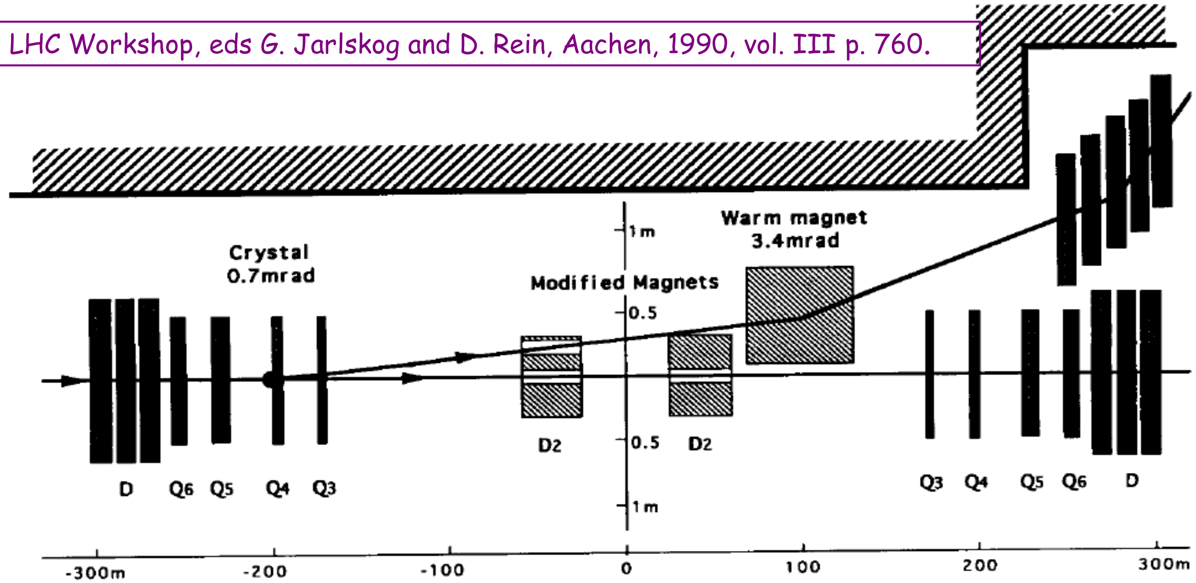


Fig. 2. Schematic layout of vertical halo extraction using channeling in a bent silicon crystal. After the warm septum magnet the extracted beam is bent by a string of five superconducting dipoles of the LHC type [14].

- Discussions just started
  - Crystal can play a substantial role in a realistic extraction scenario

Conclusions

- Experience of crystals with accelerator is well consolidated at CERN with UA9
  - Crystal collimation is as an option for high luminosity in LHC
  - UA9 will cooperate with the Collimation Team in the frame of the Hi-Lumi Programme
  - Test of crystal-assisted collimation could be extended to high-intensity operation
- ***CRYSBEAM*** (and INFN) propose to demonstrate multi-TeV crystal extraction is feasible, hopefully in few years from now.
  - ***CRYSBEAM also*** proposes experiments relevant for Cosmic Rays physics to demonstrate this technique is valid

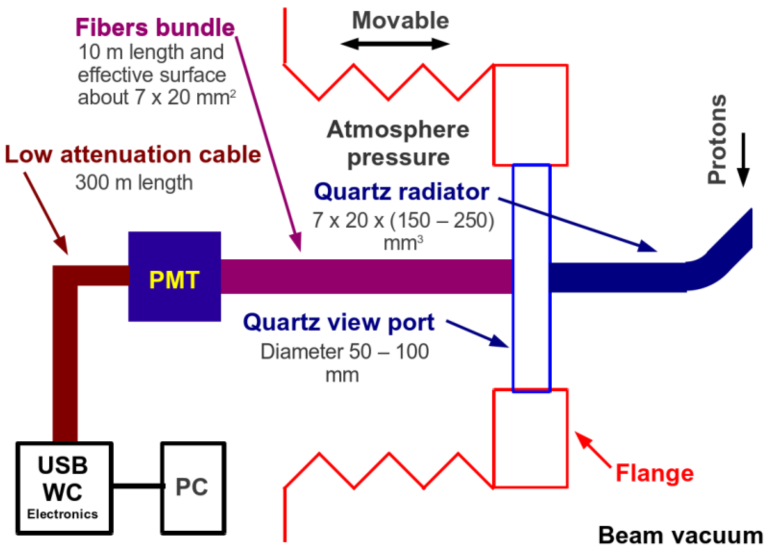
Additional back-up slides

More on beam monitoring

Cherenkov detector

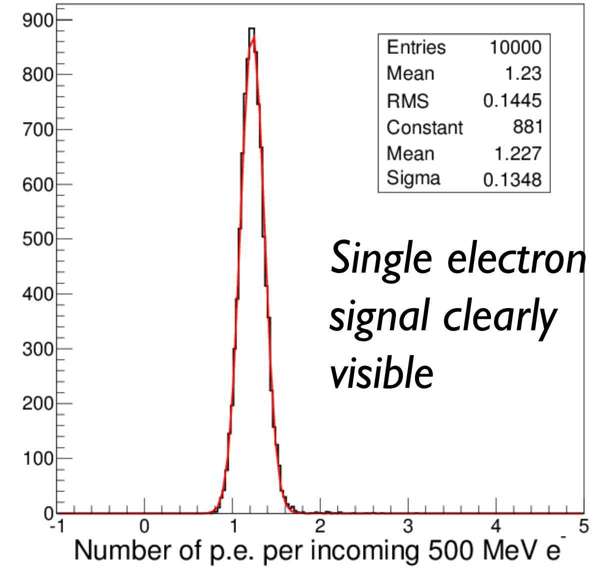
- Exploit **Cherenkov radiation in fused silica** to count deflected particle, measure their time and – with segmentation – beam spot.

UA9 Cherenkov proton flux counter



5-10% resolution on number of incident protons (100) achieved

Test at INFN LNF BTF

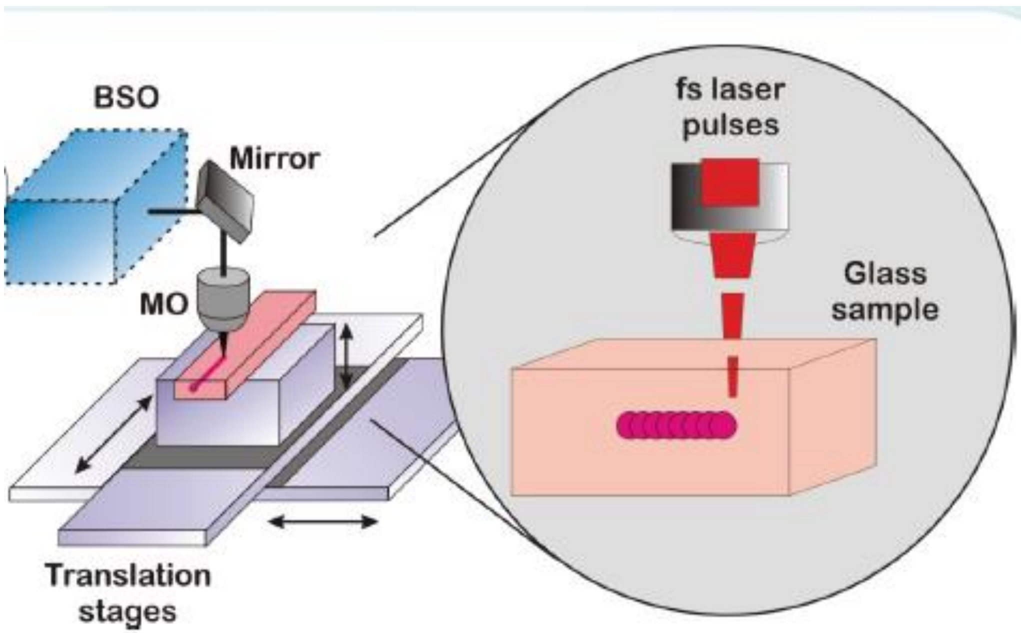


Single electron signal clearly visible

To be installed and tested in SPS UA9 experimental area

Radiator with position sensitivity

- Ultra-fast high power laser writes waveguides!
  - Use to build quantum-optics device



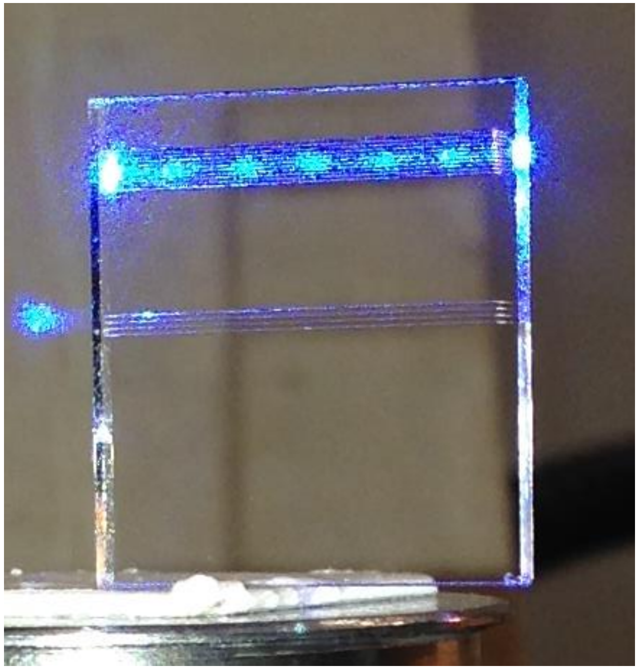
R. Osellame et al., J. Opt. Soc. Am. B 20, 1559 (2003)

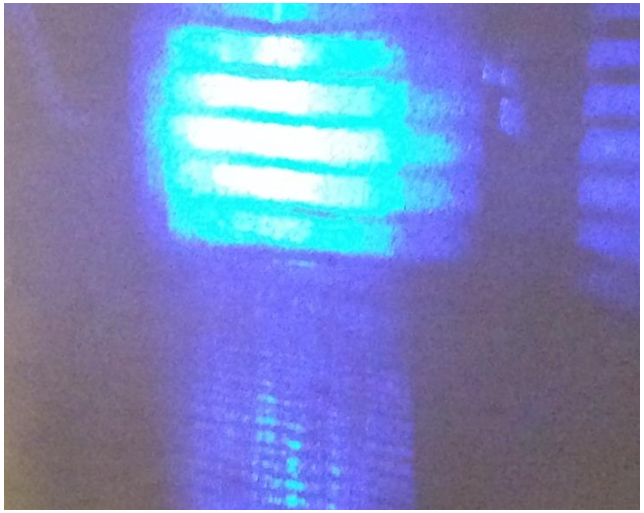
- "write" several optical waveguide to trap Cherenkov light (as a bundle of fibers)
- Connect each waveguide to a separate light sensor (SiPM, APD,…)
- Position information given by which channel fires
  - ***Instrumented beam silica thin window***

Micro-machined fused silica

- Grooves in fused silica: light guide!
- Working on a prototype with small SiPM readout

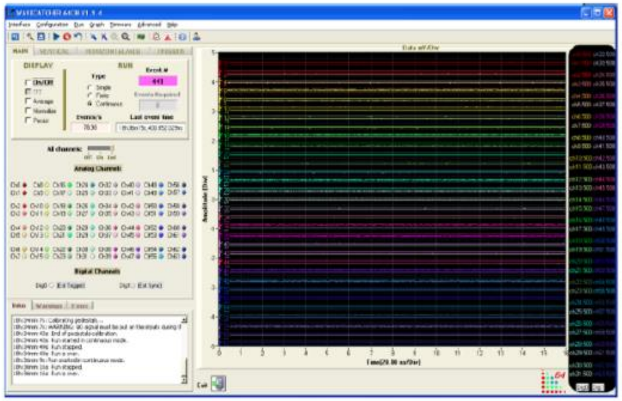
Laser impinging with 45 deg inclination





Timing resolution

- Sub-ns timing resolution:
  - prompt light emission (Cherenkov light)
  - low light dispersion (short propagation distance)
  - High resolution front-end electronics



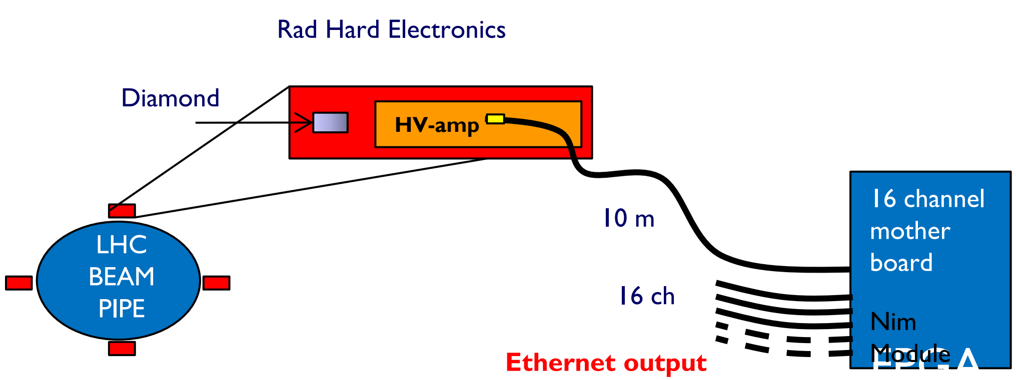
D. Breton, PhotoDet2012

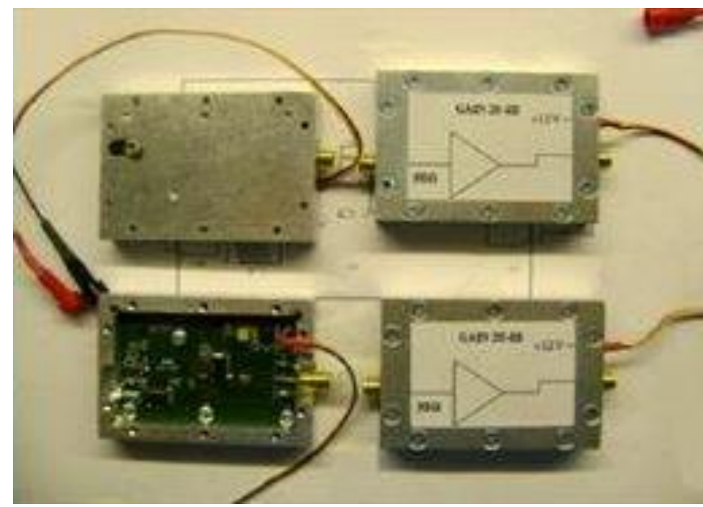
- LAL (Orsay) **WaveCatcher**
  - A waveform digitizer
  - 3.2 Gs/s sampling rate
  - 12 bits
  - < 10ps rms sampling time precision

UA9 already uses this electronics

Diamonds as BLM

- Fast beam loss close to crystal might be important to monitor crystal behaviour.
  - Sensor based on synthetic diamond already used at LHC
  - CRYSBEAM: build an ad-hoc fast electronic chain (preamp+fast disc+FPGA)

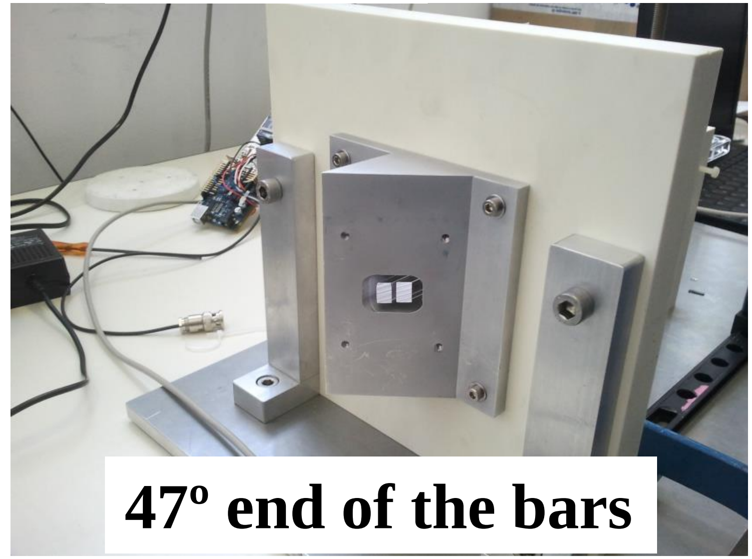




R&D interesting for collimation as well

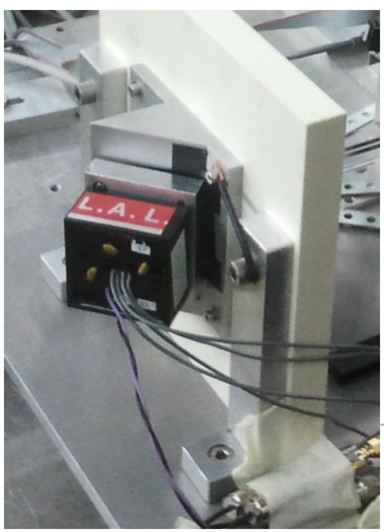
UA9 LNF BTF test

4 Cherenkov bars
(L and I shape)

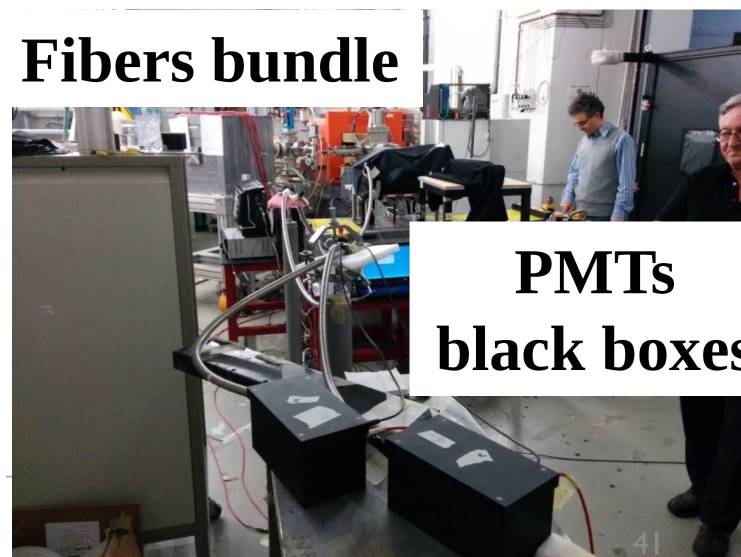


47º end of the bars

MCP-PMT



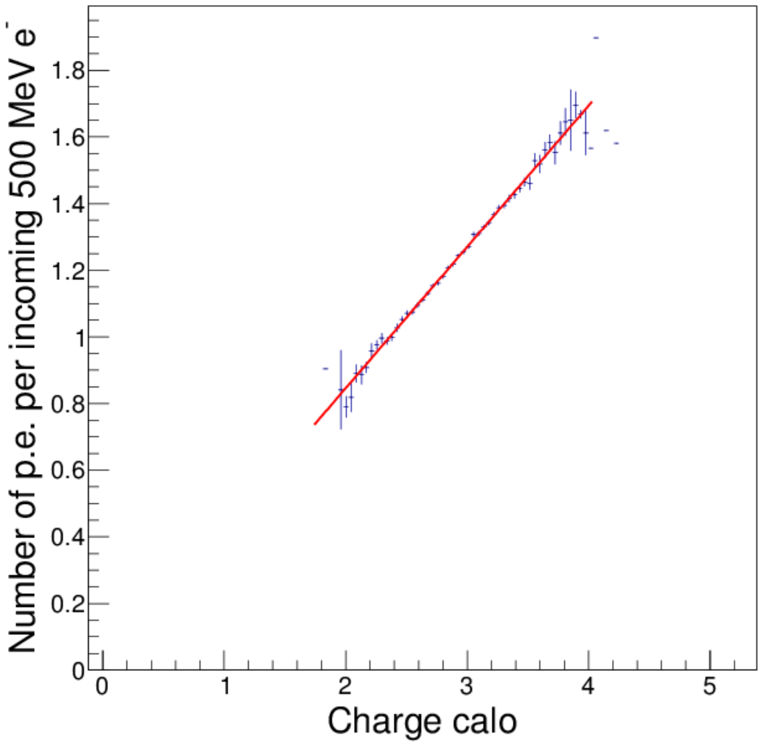
Fibers bundle



Fibers bundle

PMTs
black boxes

UA9 CpFM linearity



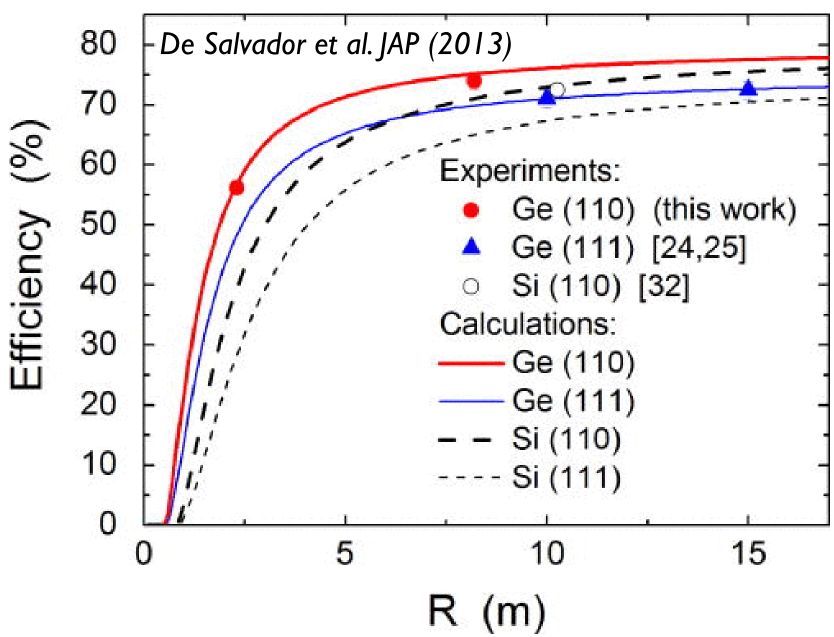
- Measured CpFM charge (normalized on the charge of single p.e.) as a function of BTF calorimeter charge

More on crystals

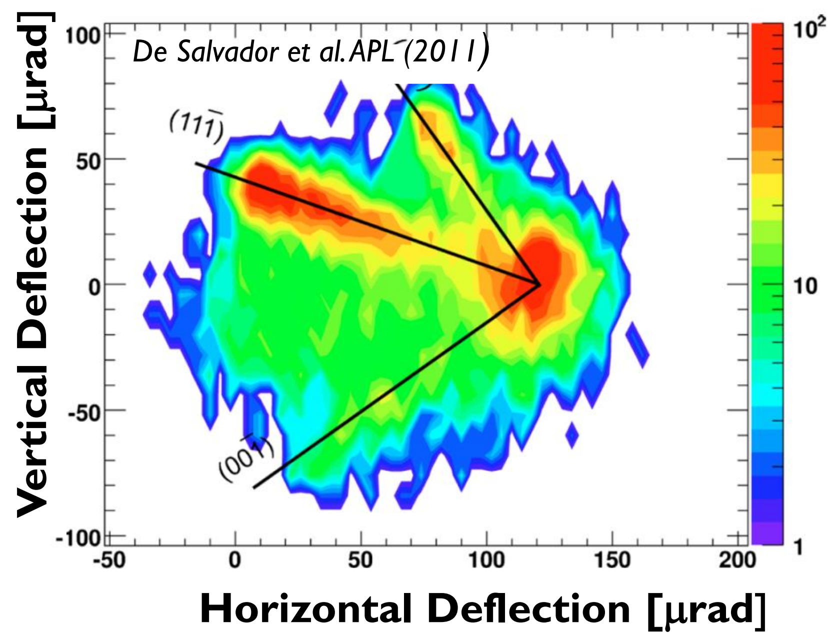
Germanium technology is mature alternative

SPS-H8-CERN 400 GeV Proton

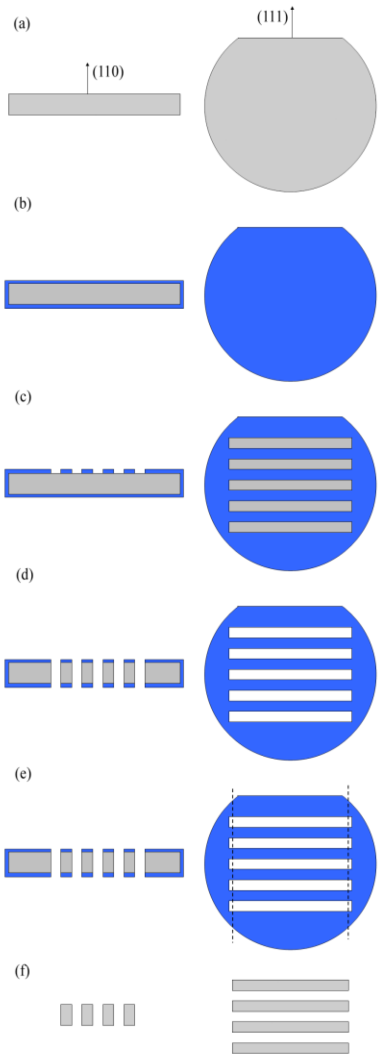
Plannar channeling efficiency



First axial channeling in Ge



Silicon strip manufacturing



Established fabrication technique

a) Starting material: (110) silicon wafer

b) LPCVD deposition of silicon nitride thin layer

c) Silicon nitride patterning (photolithography)

d) Etching of Si in KOH solution, silicon nitride acts as masking layer

e) Silicon strips release   Revisitation needed!

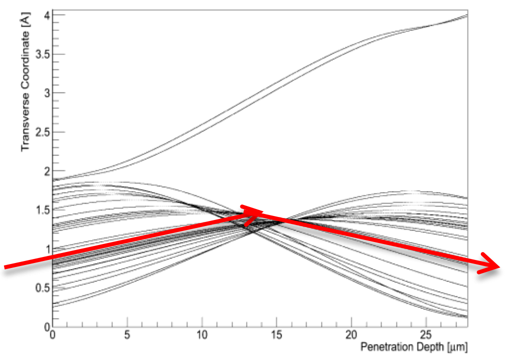
f) Removal of silicon nitride

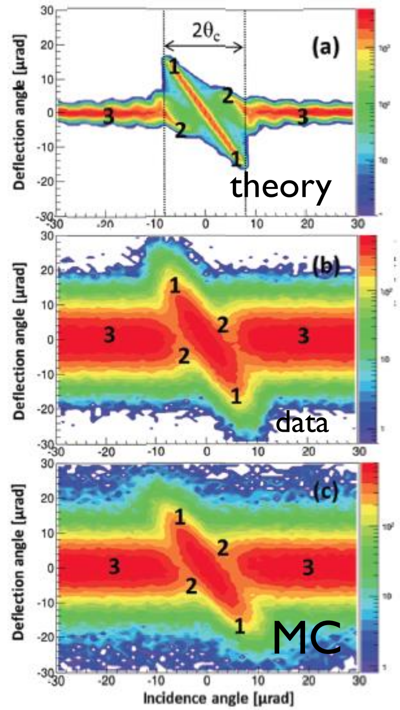
Some recent results on exotic crystals

W.Scandale et al. Phys.Lett. B 734 (2014) 1-6

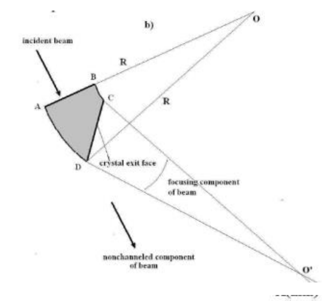
W.Scandale et al. Phys.Lett.B, 733 (2014) 366-372

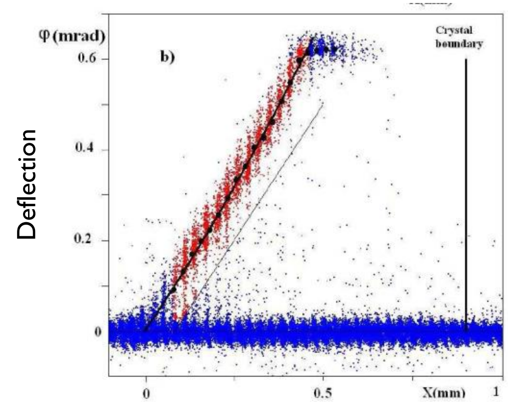
Mirror crystals





Thin (~10 μm) straight crystal (a "membrane")



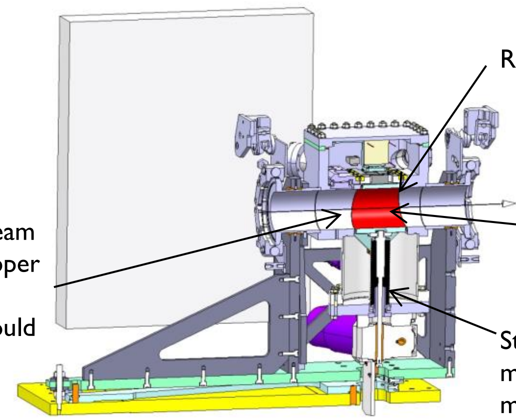


Focusing/ defocusing crystals

- *Crystal manufacturing and coherent interactions models are well mastered by UA9 collaboration*

Piezo-goniometer installed on

- Designed at CERN EN-STI group, realized by CINEL



Linear Stroke: 60 mm

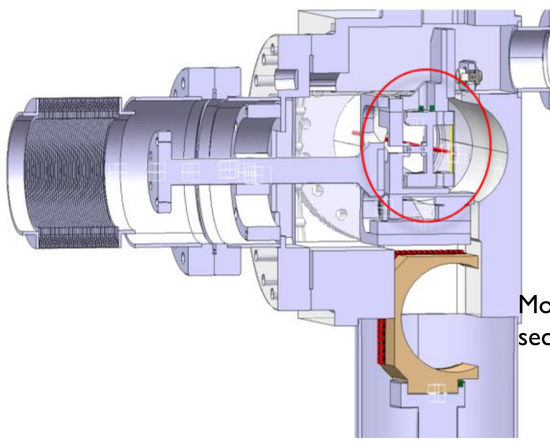
Linear resolution: 5 um

Total angular range : ±10 mrad

Angle resolution: 0.1 µrad

Angle accuracy: ±1 urad

Operational position

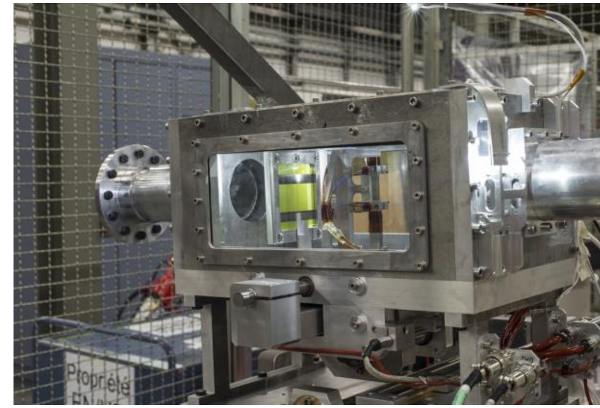


New version under study

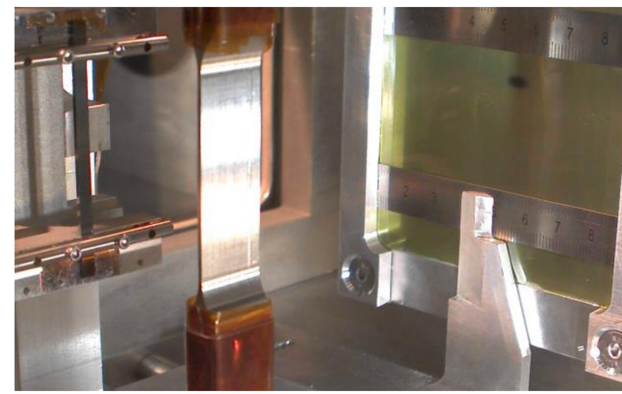
Piezo-electric material with higher Curie point (>200 deg) under investigation

Crystal resistance to irradiation

- **IHEP U-70** (Biryukov et al, NIMB 234, 23-30)
  - 70 GeV protons,
    50 ms spills of **10^{14} protons every 9.6 s**,
    several minutes irradiation
    channeling efficiency unchanged.



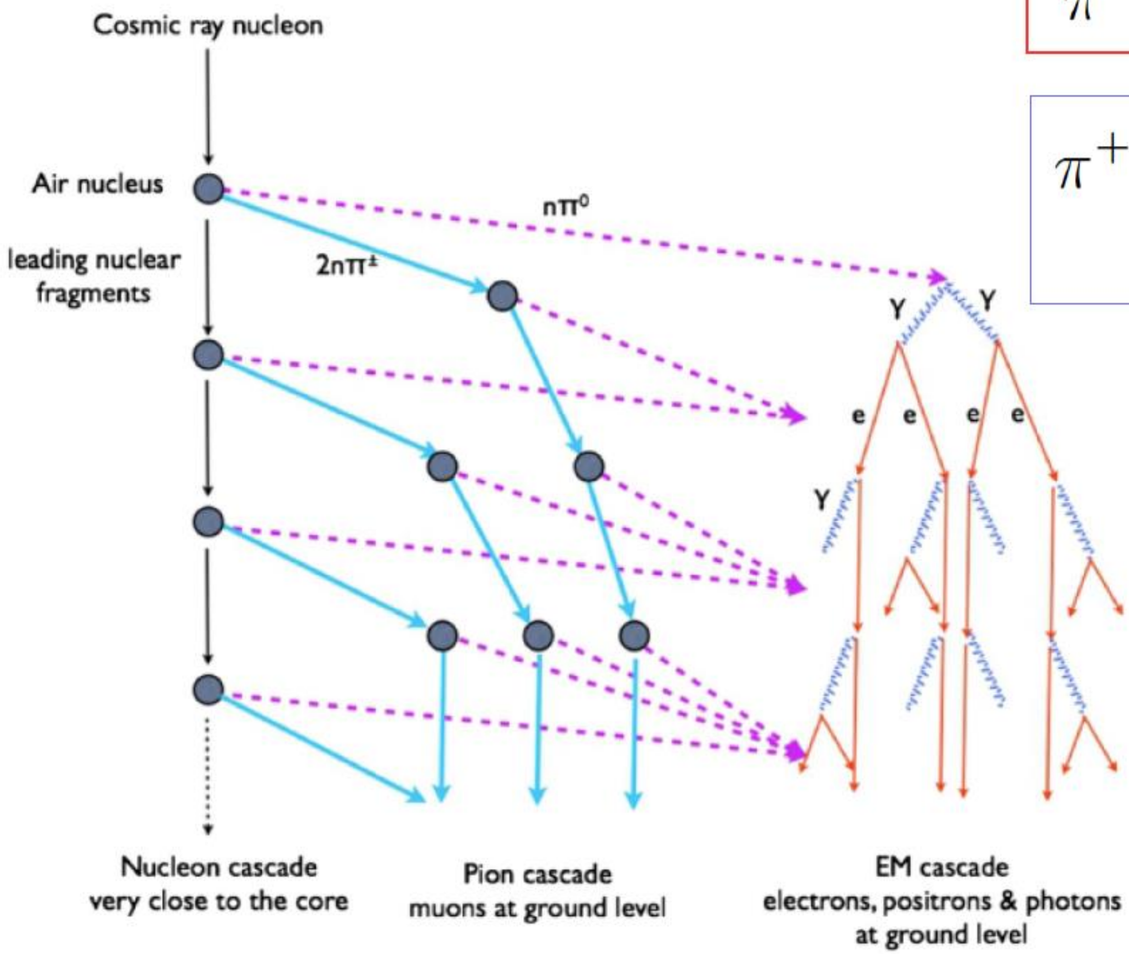
- **SPS North Area** - NA48 (Biino et al, CERN-SL-96-30-EA)
  - 450 GeV protons,
    2.4 s spill of 5 x 10^{12} protons every 14.4 s,
    one year irradiation, **2.4 x 10^{20} protons/cm^2** in total,
    channeling efficiency reduced by 30%.



- **HRMT16-UA9CRY** (HiRadMat facility, **November 2012**):
  - 440 GeV protons, up to **288 bunches in 7.2 μs,**
    1.1 x 10^{11} protons per bunch (3 x 10^{13} protons in total)
    ➒comparable to asynchronous beam dump in LHC
    no damage to the crystal after accurate visual inspection
    more tests planned to assess possible crystal lattice damage
    accurate FLUKA simulation of energy deposition and residual dose

More on CR physics

Development of a hadronic shower

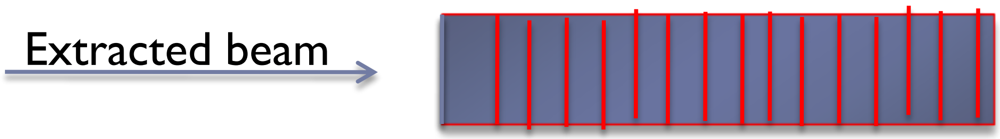


$$\pi^{\circ} \rightarrow \gamma\ \gamma$$

$$\pi^{+} \rightarrow \mu^{+}\ \ \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+}\ \ \nu_{e}\ \ \overline{\nu}_{\mu}$$

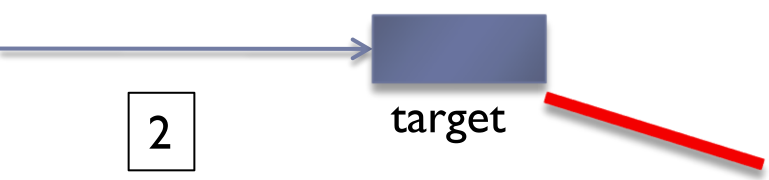
Conceptual experiments with absorber



Segmented absorber
Active layers (pixelated?)
to measure shower properties

1

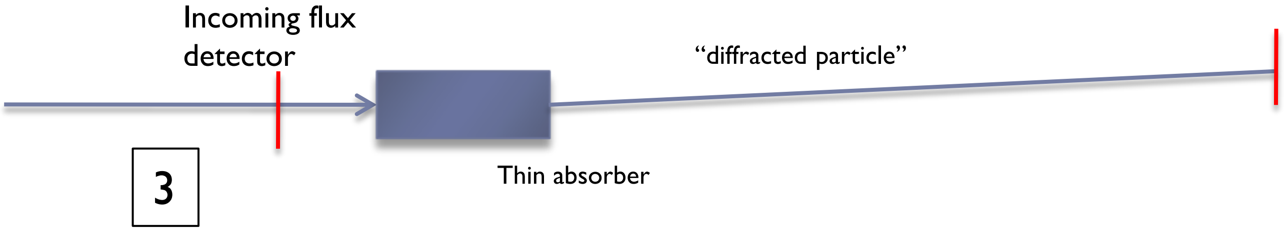
Q: are shower properties sensitive to cross section on absorber material?
(test with FLUKA and SYBILL)



2

Target material can be changed.
Measure
(in a narrow solid angle)
exclusive cross-section
(anti proton, B, C,..)
Detector can be moved at different angles

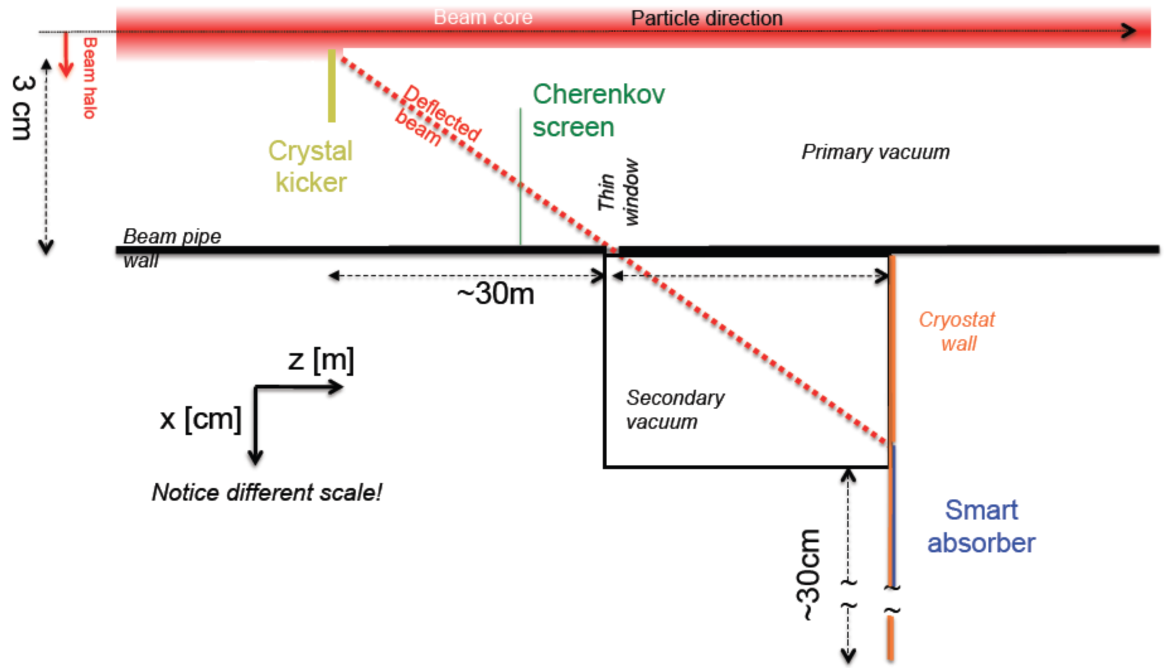
Conceptual experiments (2)



Dispersive region of the accelerator: Detected diffracted particles

Use the accelerator as a spectrometer to measure the momentum of diffractive particles
With two stations, measure angle and momentum
Direct measurement of diffractive cross section on absorber materials

CRYSBEAM conceptual layout



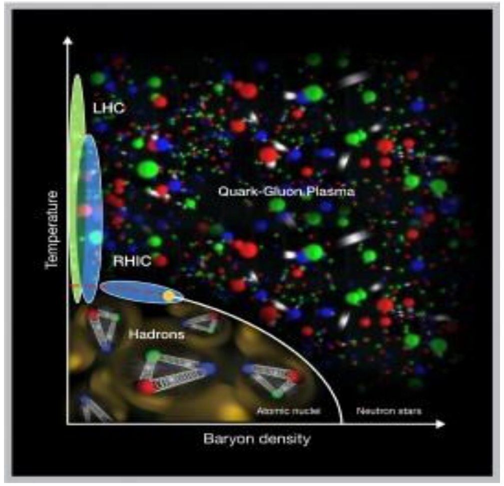
- **Crystal kick about 1 mrad** technically feasible.
- ***Detection and timing*** of deflected/extracted beam at the vacuum/air interface with a detector based on ***Cherenkov*** light emission.
- **Instrumented** beam dump in air.

Requirements and methods of CRYSBEAM

	ELEMENT	REQUIREMENTS	METHODS
	Crystal Kicker	Orient lattice planes parallel to the beam within $\theta_C(7\ TeV) \approx 2\ \mu rad$ with high repeatability inside the vacuum beam pipe.	Finely polished, low miscut silicon crystals. Goniometer for ultra-high vacuum.
	Cherenkov Screen	For deflected particles measure flux at ***5%***, timing ***<1ns***, beam-spot ***≈ 250 µm*** in the beam pipe vacuum.	Fused silica slab transverse to beam. Cherenkov light internally reflected through optical micro-guide to multi-channel plate PMT.
	Smart Absorber	Measure particle cross sections on nucleus A σ_{tot}(p-A) and σ_{tot}(Pb-A) as in Cosmic rays collisions	Several active scintillator layers to follow the hadron shower evolution. In case of Liquid He or liquid N_2 target thin-wall cryostat is required

Physics with a multi-TeV hadron beam

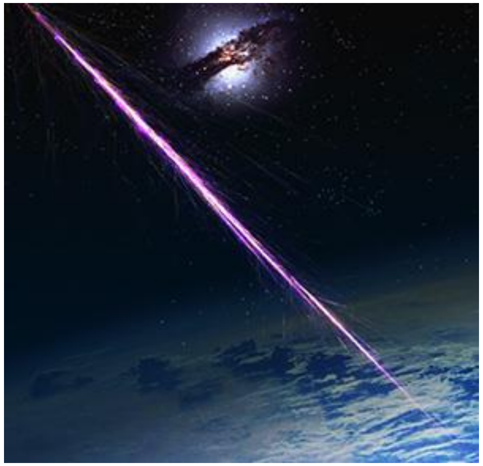
Phase diagram of hadronic matter



- QCD at **unprecedented** laboratory energies and momentum transfers
- Proton spin physics
- ***Quark-gluon plasma excitation in the target rest frame***
- Diffractive physics
- … and more with secondary beams

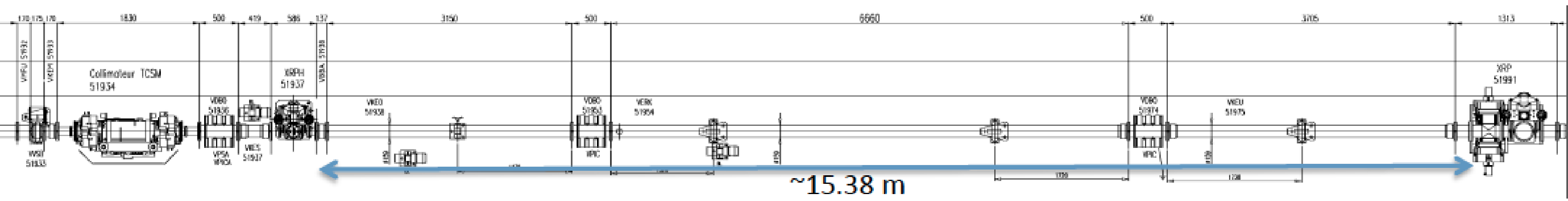
"Physics opportunities of a fixed-target experiment using LHC beams"
S. J. Brodsky, F. Fleuret, C. Hadjidakis, and J. P. Lansberg, Phys. Rep. 522 (2013) 239-255.

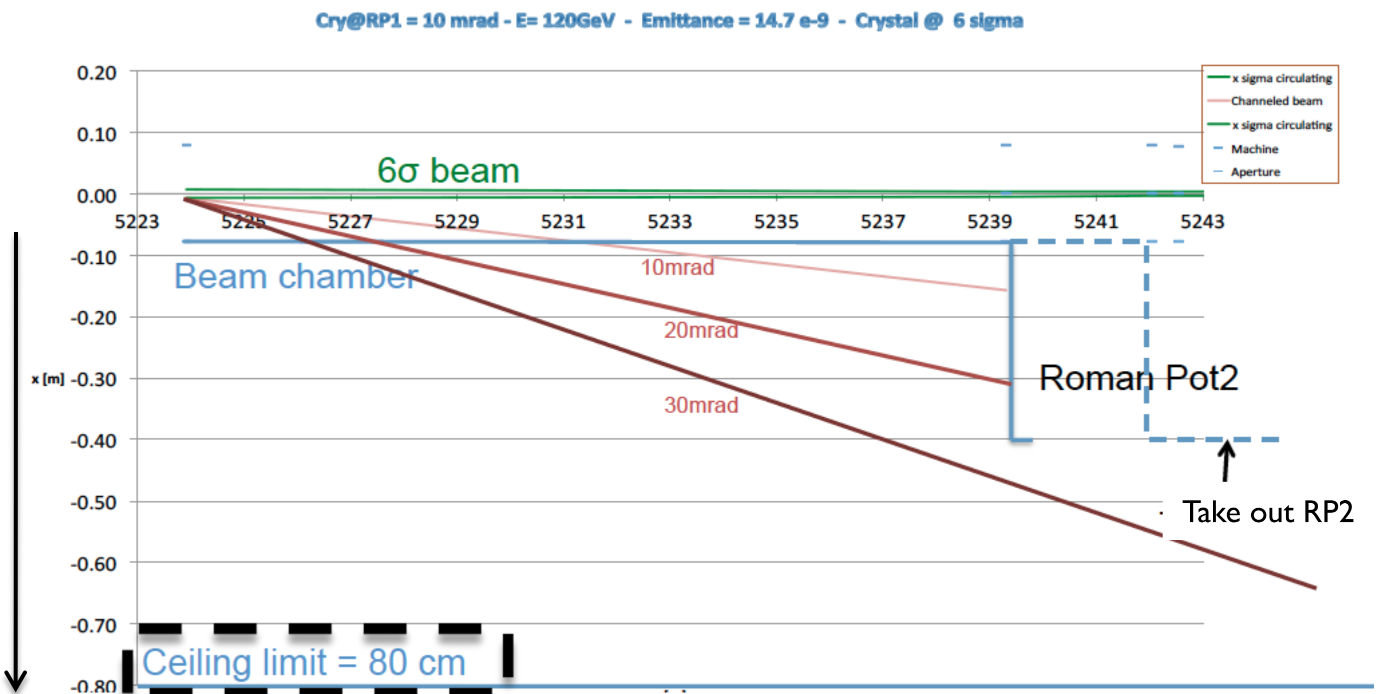
Cosmic ray shower



- What is the nature of the cosmic rays?
- Which the nature of dark matter ?
  - Study interaction of hadrons with **different targets**

SPS extraction test in LSS5

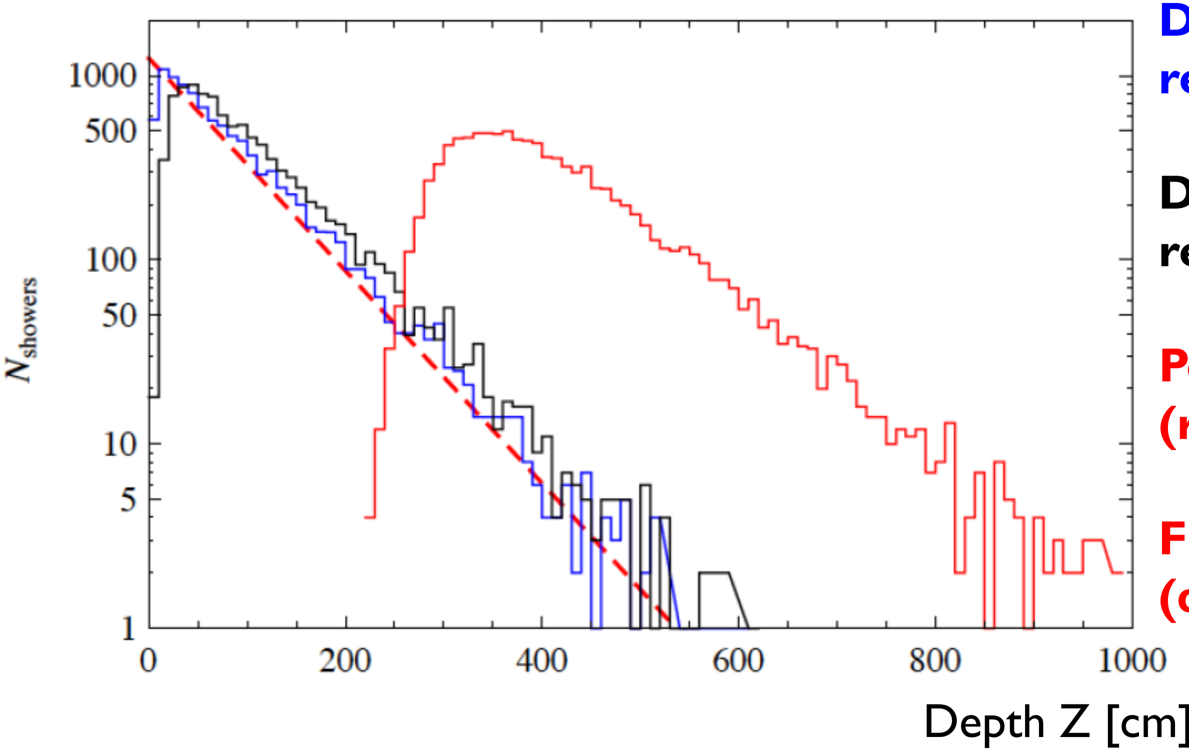




Location of the extraction test-bed in SPS under study.

Vertical extraction (towards to the ceiling of the tunnel) might be possible

Hadronic shower parameters



Depth where 10 particles are registered (blue histo)

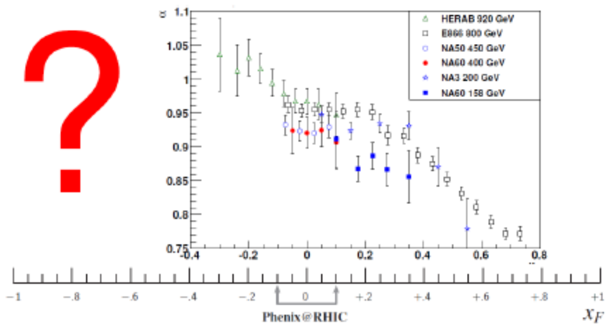
Depth where 100 particles are registered (black histo)

Position of shower maximum (red histo)

First interaction distribution (dashed line)

A broader physics reach, AFTER@LHC

- There is a wider physics case for a LHC fixed target experment
  - High precision study of hadronic physics with either proton or ions extracted and sent to different targets



- large negative-x_F reactions in proton-nucleus collisions;
- the charm and beauty content of the proton;
- the quark and gluon Sivers effect and the proton spin;
- the hard probes of quark-gluon plasma close to the QCD phase transition;
- the large-x gluon distribution in the proton, neutron, deuteron and nuclei;

- This goes ***beyond*** CRYSBEAM activity (a more complex and bigger experiment is needed!)

Recent Workshop at CERN (AFTER@LHC)

https://indico.cern.ch/event/325836/session/0/contribution/0/material/slides/0.pdf

Espression of Interest Letter in preparation