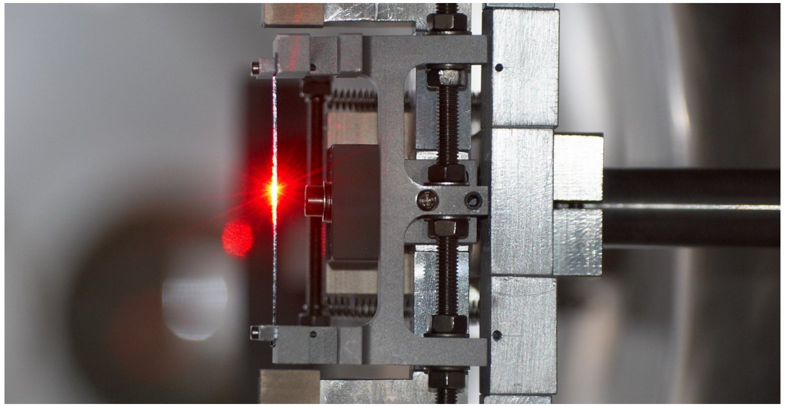
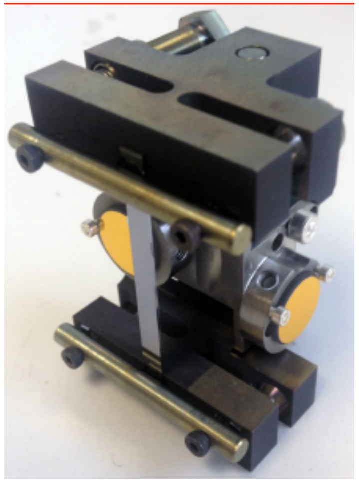




Cosmic rays and accelerator(s), some ideas

Gianluca Cavoto (INFN Roma)

What Next Padova 3rd Dec 2014

Outline

- Few ideas on how to exploit CERN accelerators, in particular an extracted LHC beam.
  - Discussions with several people (P.Lipari, R.Engel, R.Ulrich, F.Donato, O.Adriani, B.Bertucci, …)

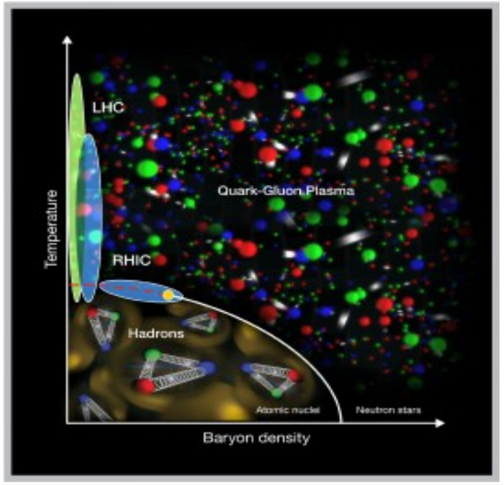
- Part of the subject of CRYSBEAM(*)
  - Efficient **crystal extraction** of a multi-TeV hadron beam for *fixed target experiments*

- *Discuss some scenarios*
  - *with the declared aim to provoke some discussion and (maybe) propose an experiment.*

*(*) CRYSBEAM is funded with 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*

Physics with a multi-TeV hadron beam

Phase diagram of hadronic matter

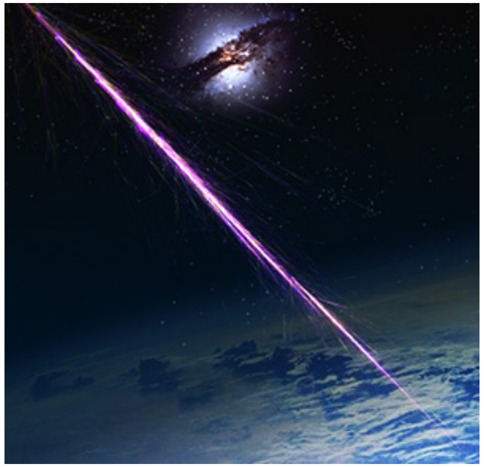


- QCD at **unprecedented** laboratory energies and momentum transfers
- Gluon/heavy flavour at large Bjorken x (**BSM** searches)
- Proton spin physics
- Quarkonia physics
- Heavy ion collisione at large rapidity
- ***Quark-gluon plasma excitation in the target rest frame***
- Diffractive physics
- … 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.

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

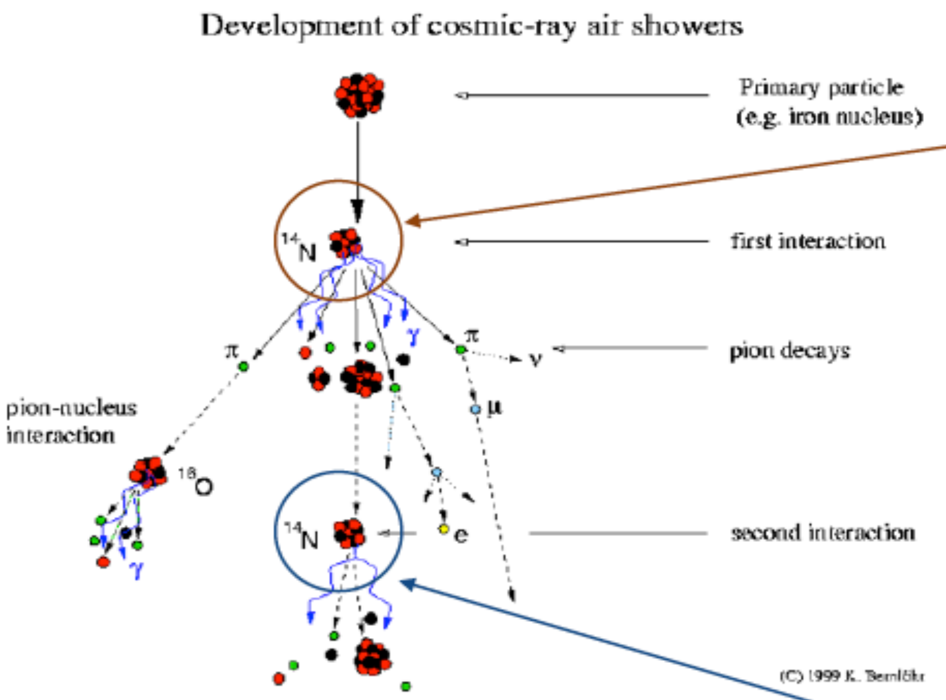
Cosmic ray shower



- Is the study of interaction of multi-TeV hadrons with **different nuclei (C,N,O,…)** **useful for CR physics?**

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

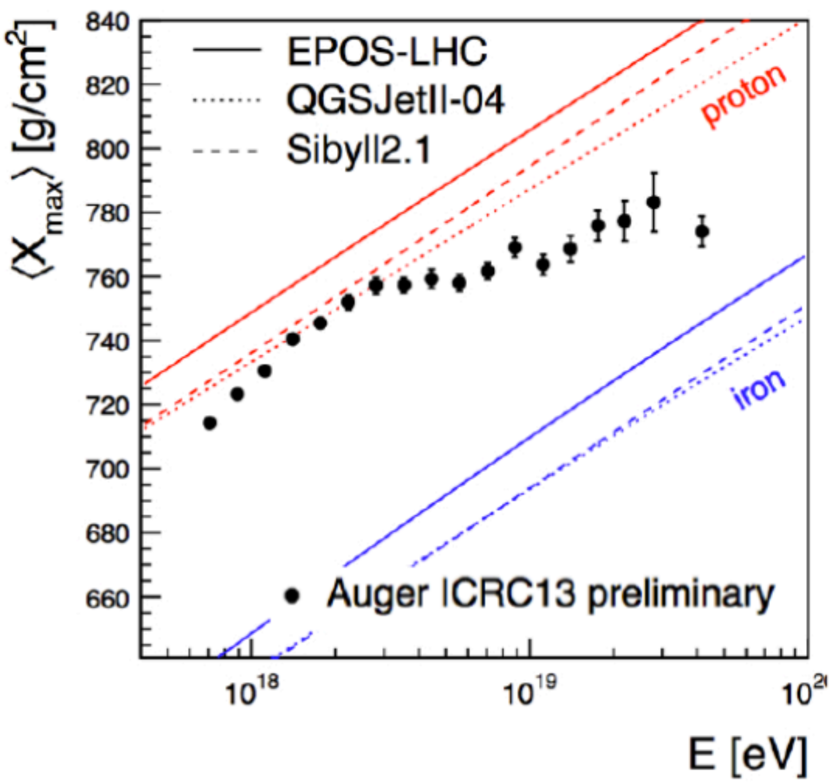
1. **Charge ratio**
2. **Multiplicity**
   number of muons in air shower sensitive to mass composition

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

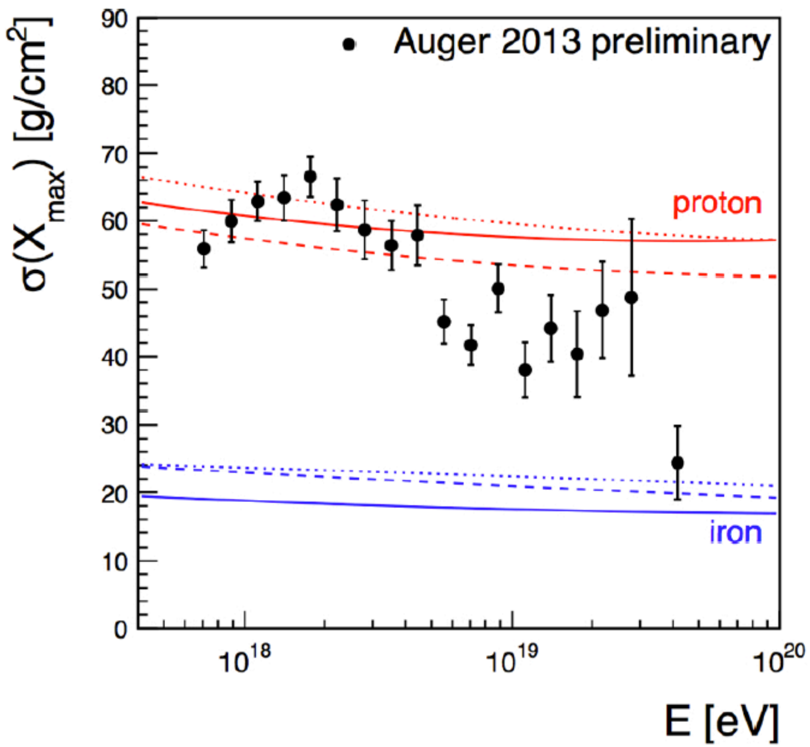
CR Mass composition

Pierre Auger Observatory

Shower maximum position



Cross section



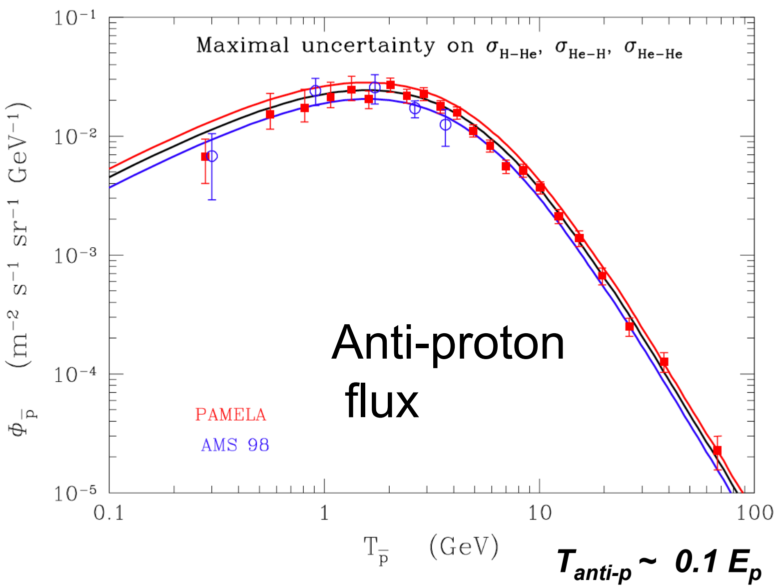
Data interpretation depends on MC used to described the shower

Is it useful to reproduce in lab such showers at (much) lower energy?

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?

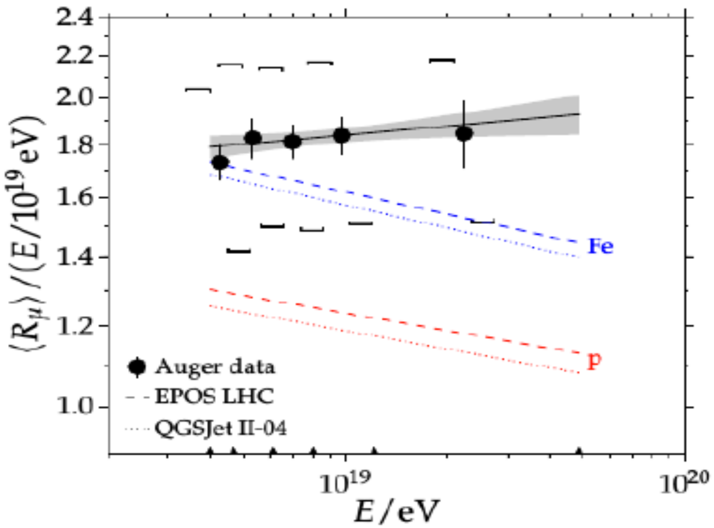
F. Donato et al. ApJ 2001, PRL 2009

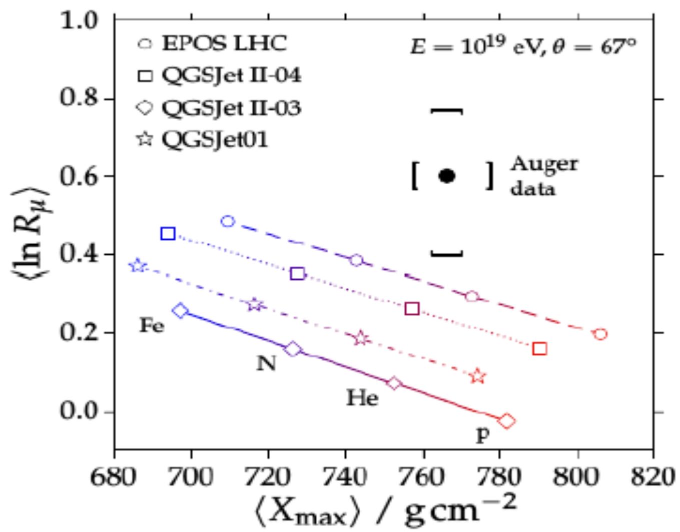


T_{anti-p} ~ 0.1 E_p

- 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**

Muon in cosmic air-showers





More muons in air-shower data than expected Auger, arXiv-1408.1421 [atro-ph]

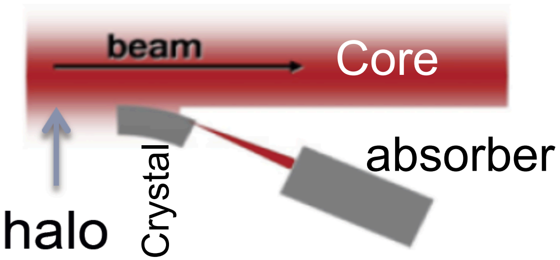
- Can be a problem in interaction physics in air-shower model ?
- Is a muon counting experiment after a beam dump interesting (or enough) to help solving this ?
- Do we need to study **charm** content of a shower ? Access to parton with momentum fraction x→1 in the target.
- Study production of charm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

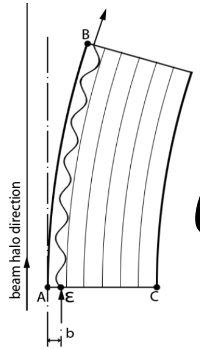
CRYSBEAM basic idea

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

Low background, continuous extraction of the beam halo

10^8 particle per second might be possible



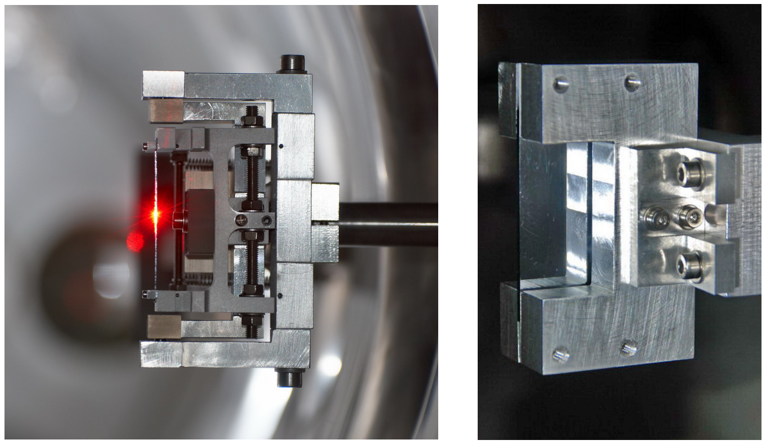


Critical angle

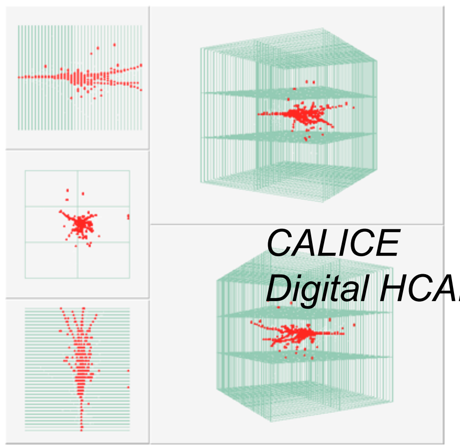
$$\theta_C = \sqrt{\frac{2U_0}{E}}$$

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

Particle energy



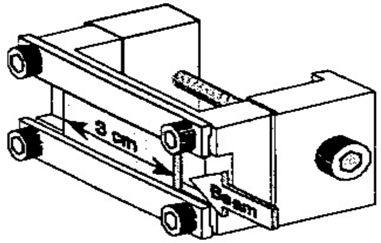
UA9 crystals



Instrumented ("smart") absorber to measure hadronic shower

SPS extraction, RD-22 experiment

The RD22 Collaboration, CERN DRDC 94-11



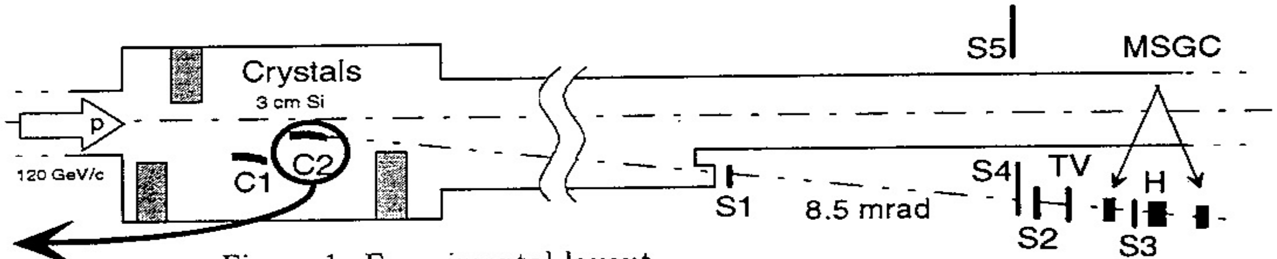
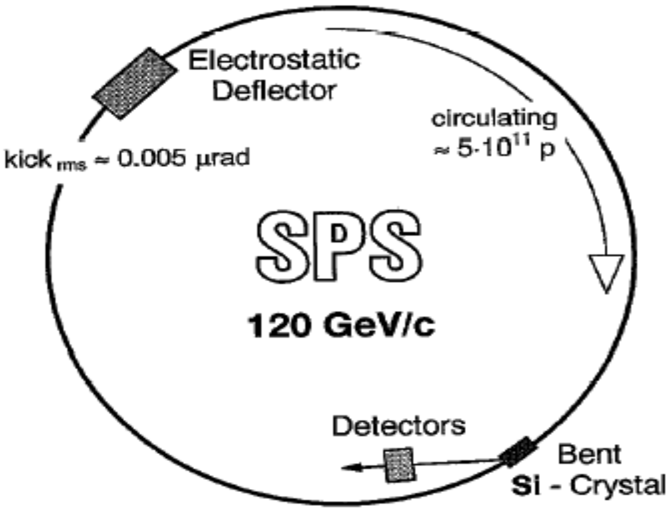


Figure 1: Experimental layout



	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

A scenario for LHC extraction ?

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

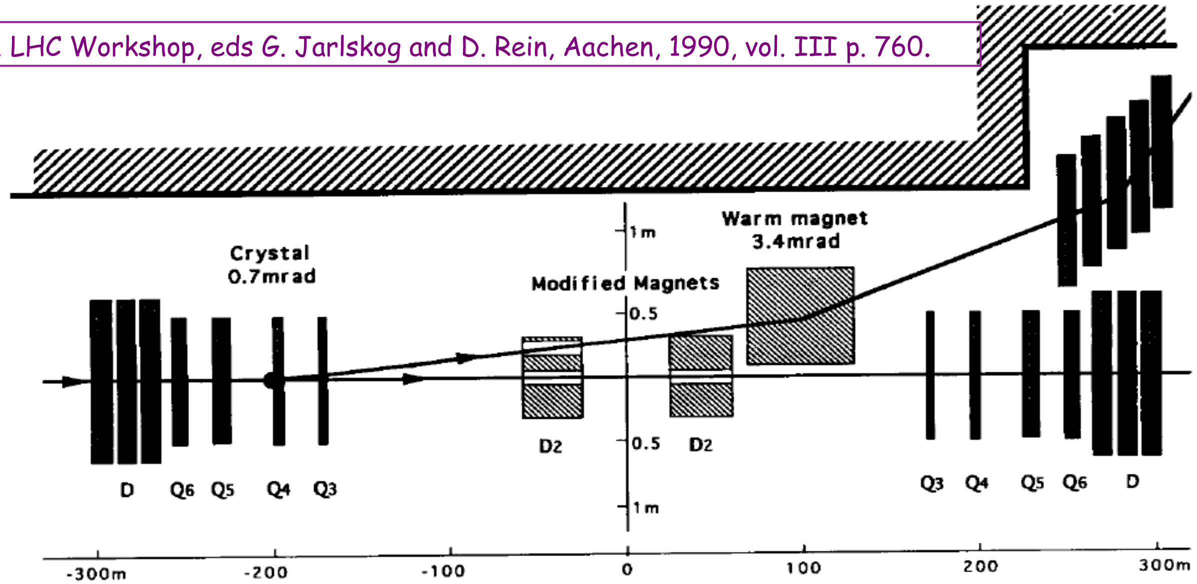
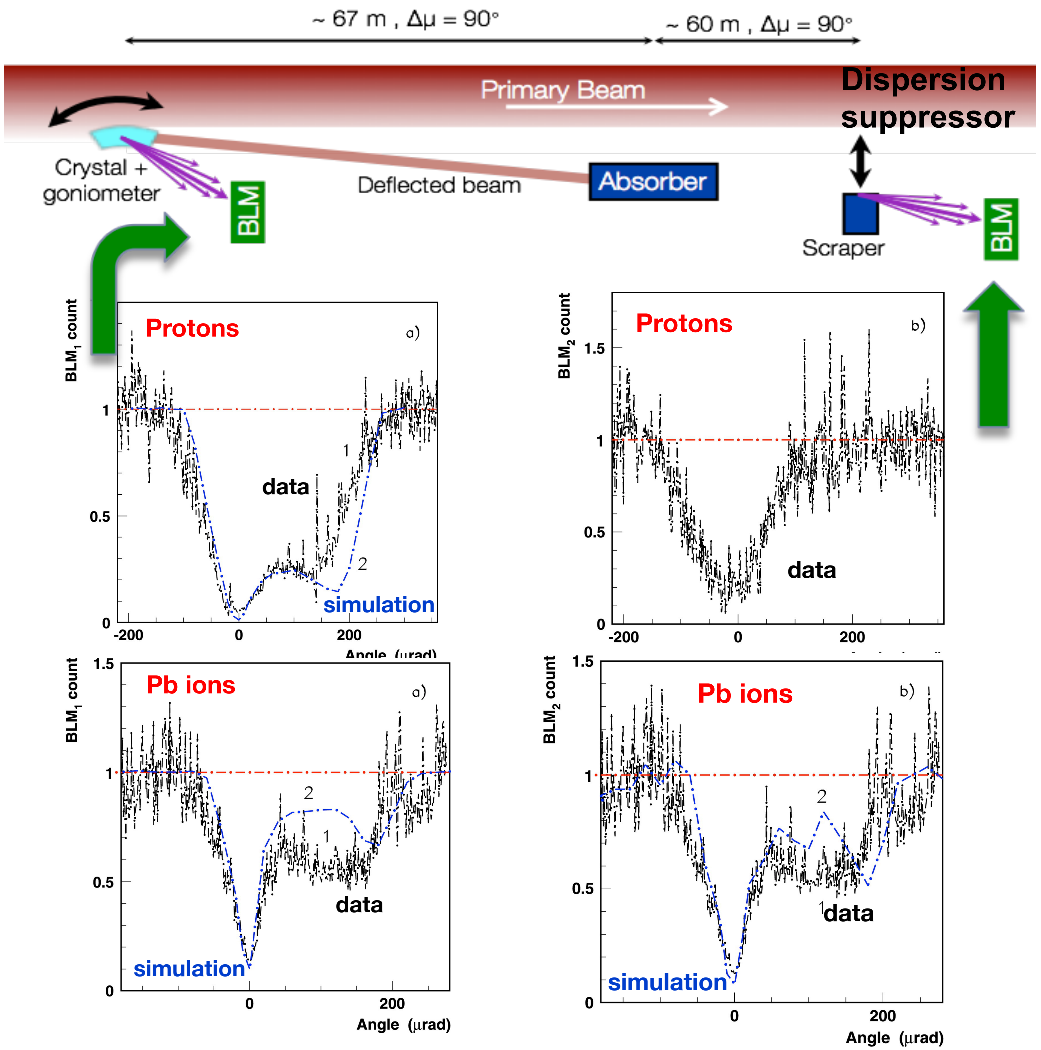


Fig. 2. Schematic layout of vertical halo extraction using channeling in a bent silicon crystal. After the warm septum magnet the extracted beam is bent by a string of five superconducting dipoles of the LHC type [14].

- Discussion with CERN accelerator people just started
  - Crystal can play a substantial role

Crystal collimation at SPS

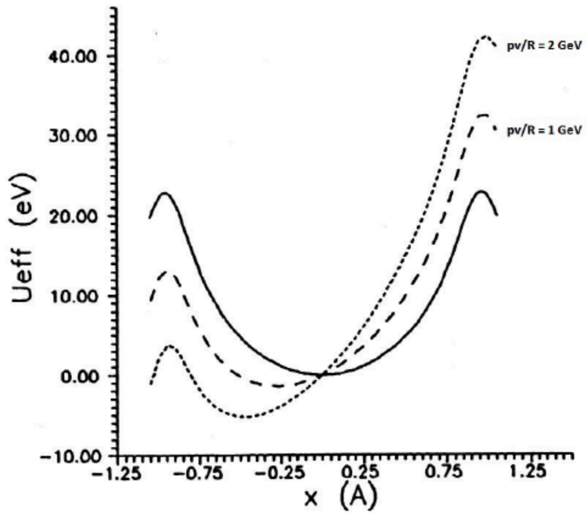


- Extensive tests with 120-270 GeV protons and Pb ions
  - 150 μrad deflection
  - $\theta_C \sim$ 20-13 μrad
  - Single bunch and multi-bunch dedicated beams
- Fast and reproducible crystal alignment
- Clear loss ***reduction with respect to an amorphous orientation***
  - Up to x20 reduction

Critical Radius for channeling, a challenge

- Deflection angle Φ = L/R *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

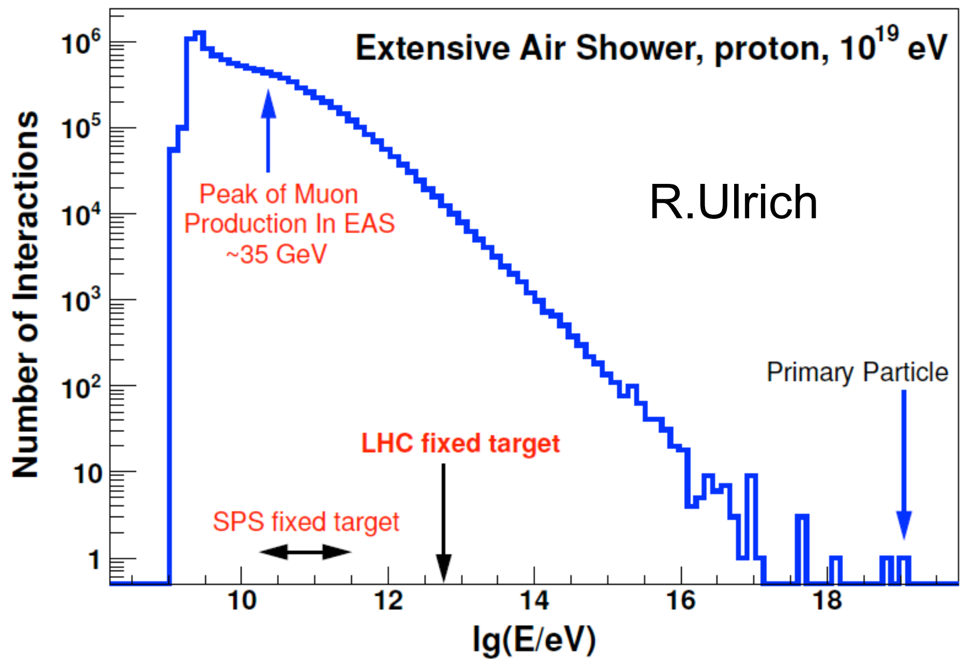
$$R_c \approx \frac{\frac{p}{Z_i}\beta}{\pi Z e^2 N d}$$

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

Possible experiments

Air-showers of Cosmic Rays in a lab

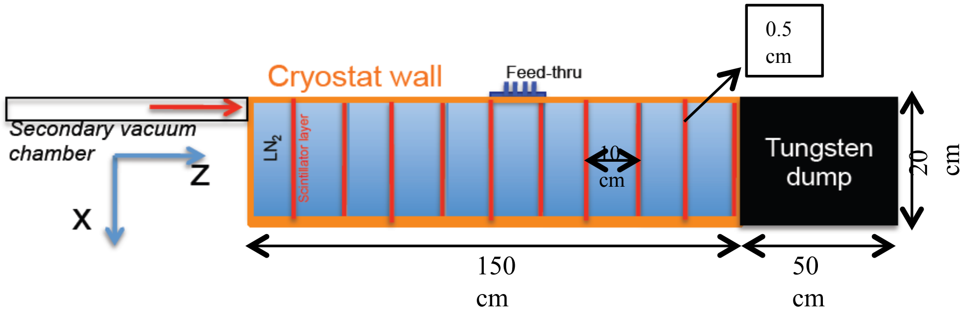
- Strategy: sub-showers of UHECR air-shower can be reproduced in lab: compare with MC (*CORSIKA*)
  - Following shower evolution as in air-shower experiment!



- 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



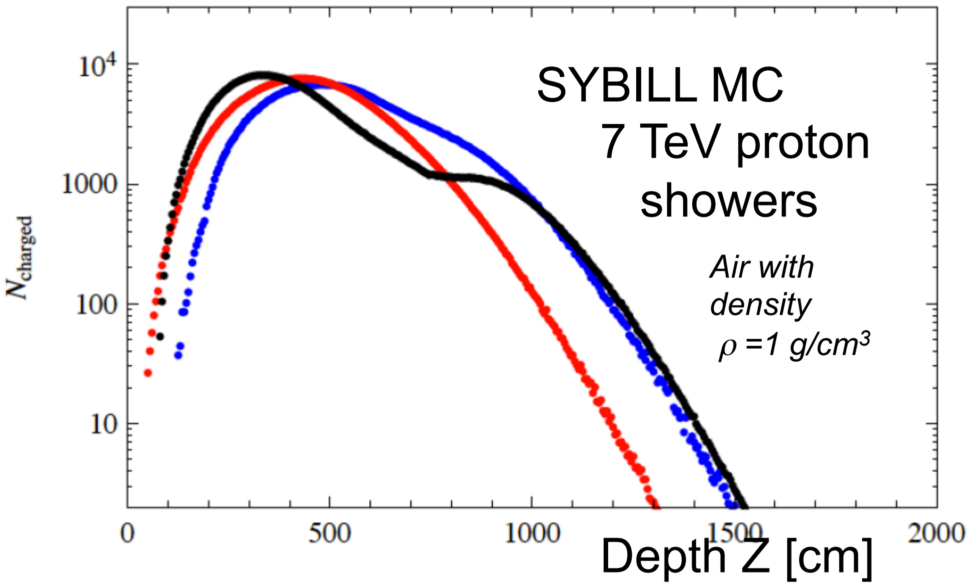
Can be tested on SPS North Area were proton and pion beam are currently available (up to 400 GeV energy)

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

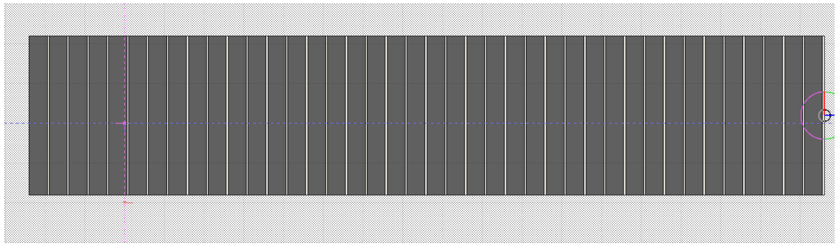
First look at FLUKA vs SYBILL show a 10% discrepancy in Xmax at 400 GeV and 7 TeV.

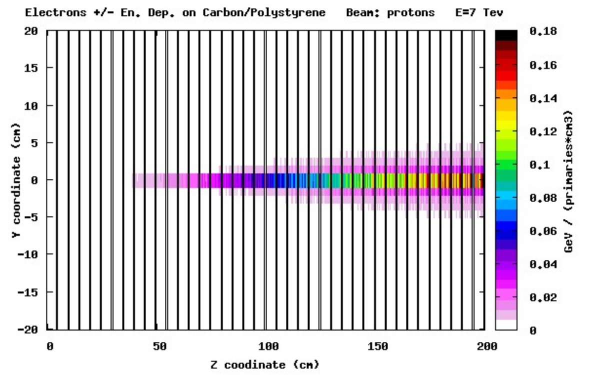
FLUKA simulations

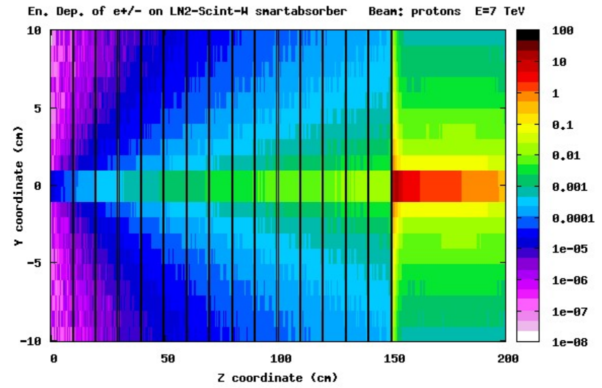
- More detailed tool to study geometry and algorithm to extract cross section information [$\sigma_{tot} = 1/(n\ \lambda_{int})$]

Carbon layers: 43 mm / Scint layers: 7 mm

7TeV protons



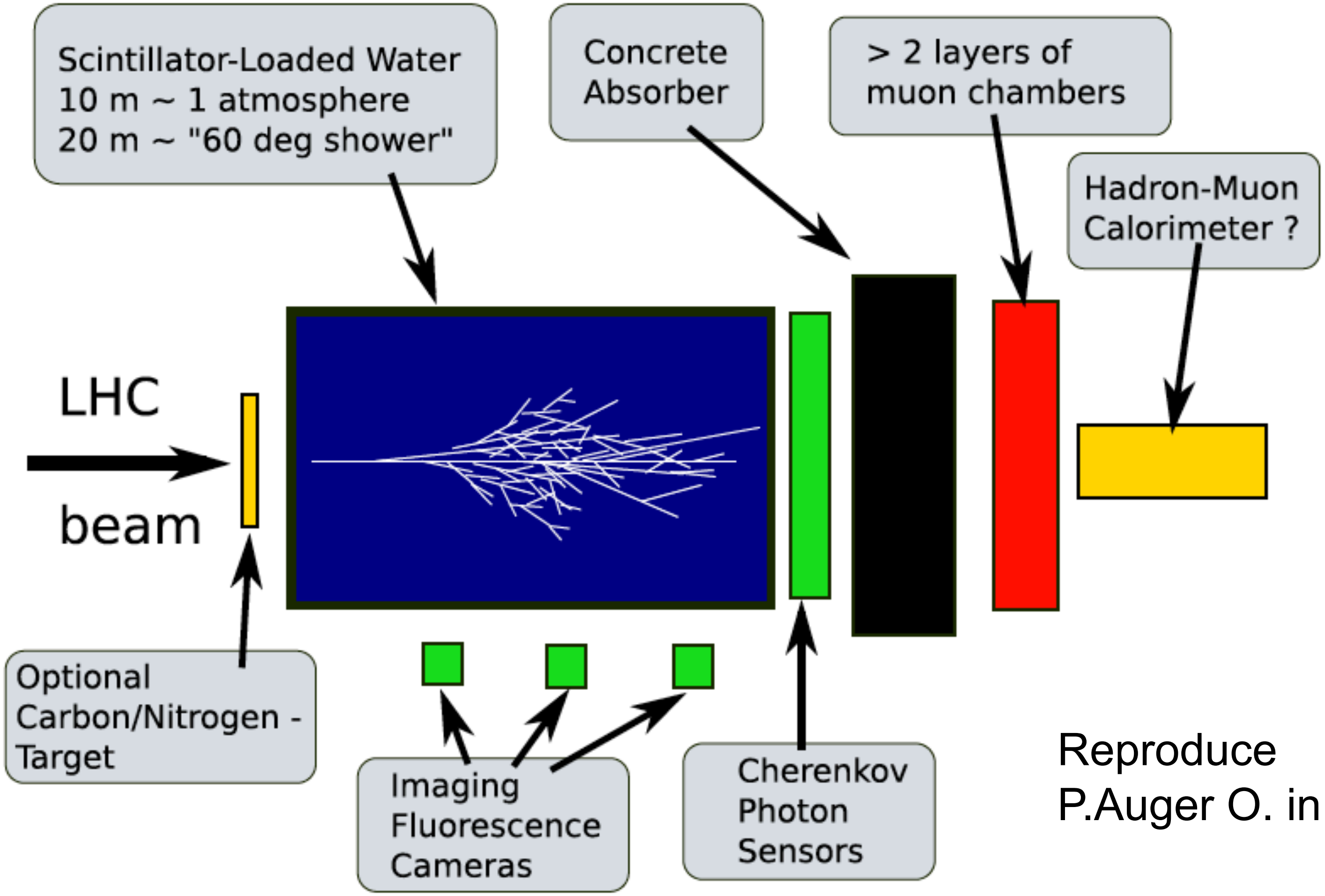




Optimization of the number of active layers
Impose constraint given by available space

Advanced layout

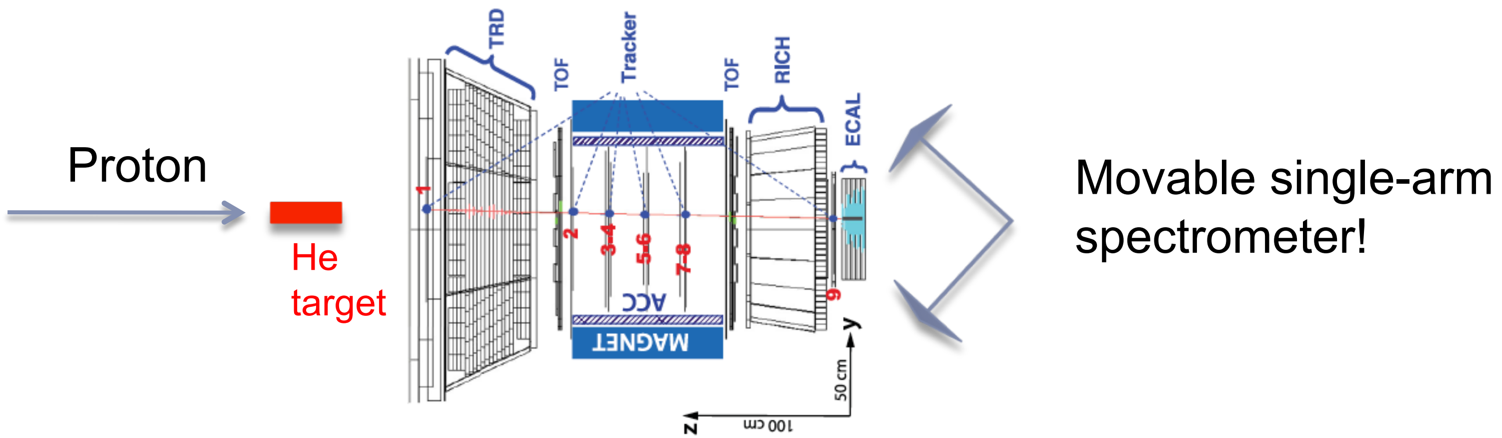
R.Ulrich



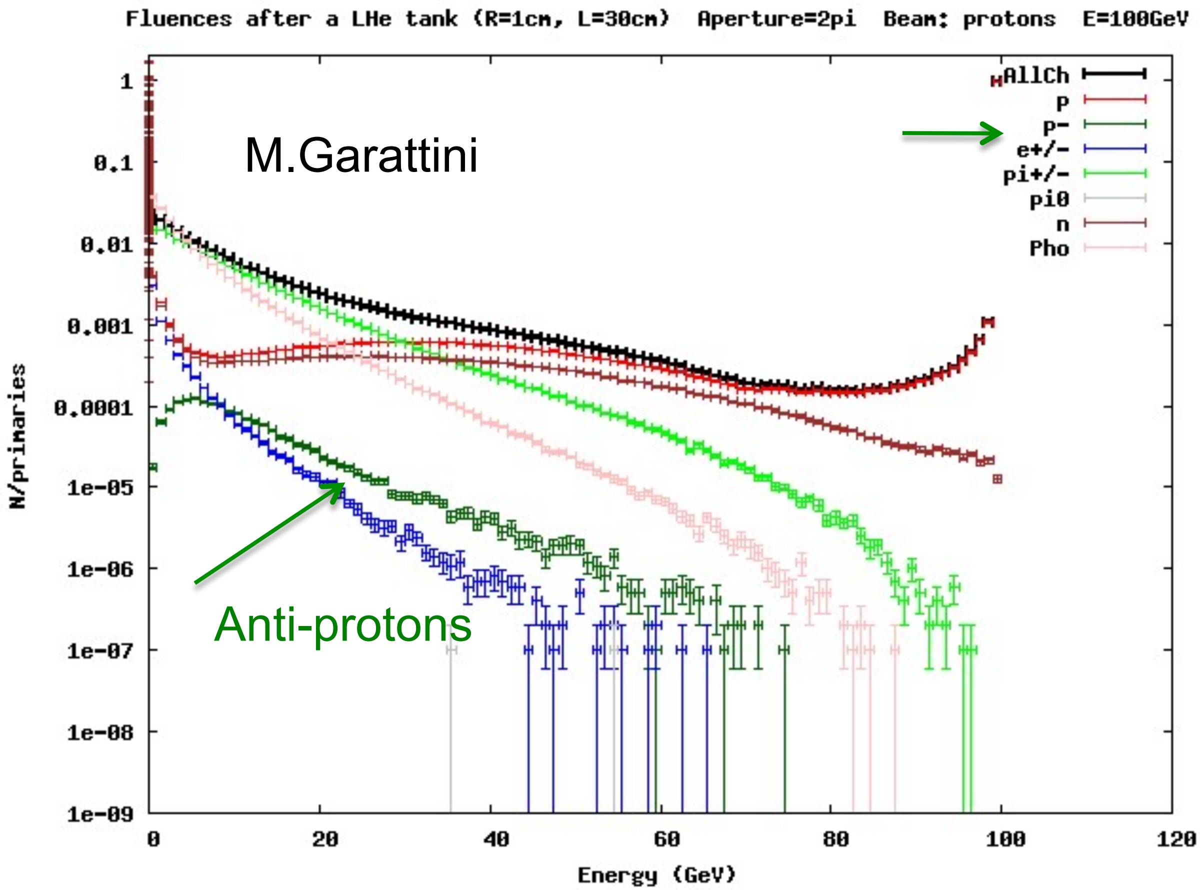
Reproduce P.Auger O. in lab

An experiment for anti-proton

- Hard to cover such a wide range of momentum (few GeV – 1 TeV) with the same apparatus
- Need a tracker in a magnet ($$$)
- Need excellent PID
- Need to be moved from SPS lines to LHC line
- ***… isn't it a copy of AMS-02 itself??***



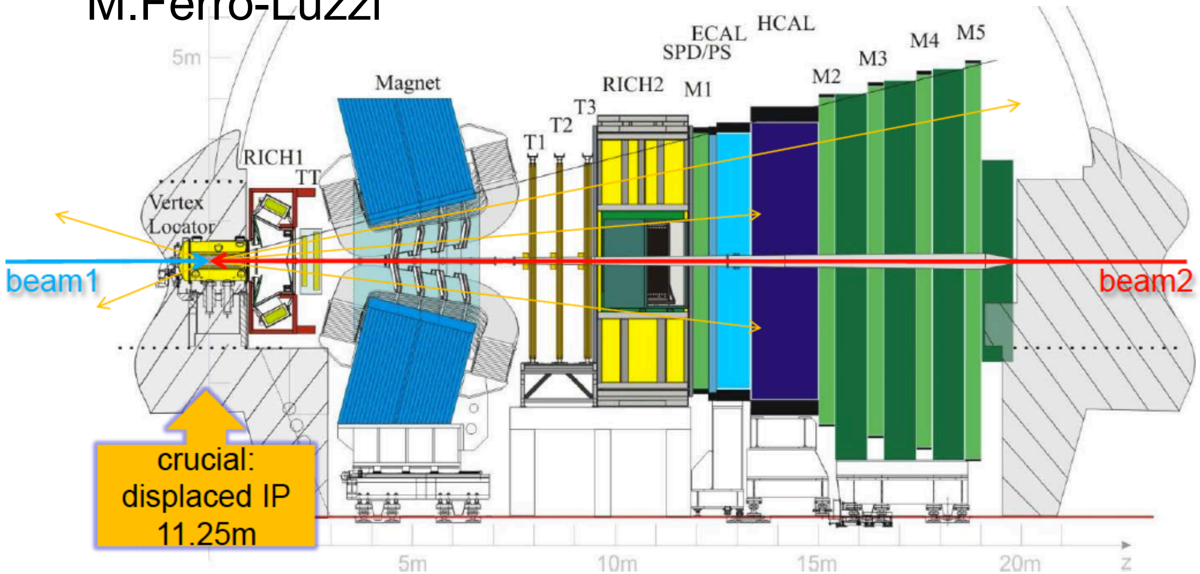
Antiproton production from He (FLUKA)



Optimize
He target
to get
a cross
section
measurement

Internal gas target at LHC-b (SMOG)

M.Ferro-Luzzi



Beam-gas interaction used for luminosity meas. (SMOG)

They injected $\sim 10^{-7}$ mbar Ne in LHC beam pipe (!!!)

Other gases are possible

LHC-b is a naturally forward detector
(its physic core program is beauty and charm physics)

Given its very good tracking and PID capability
could easily measure particle spectra!
(but limited rapidity coverage)

If problem with He in beam pipe a crystal can be used to split the beam!

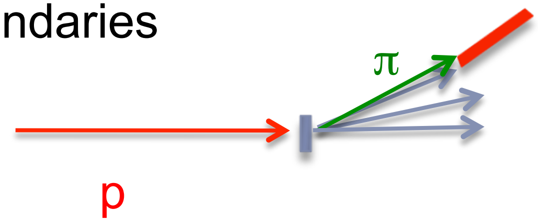
https://indico.cern.ch/event/325836/session/0/contribution/3/material/slides/1.pdf

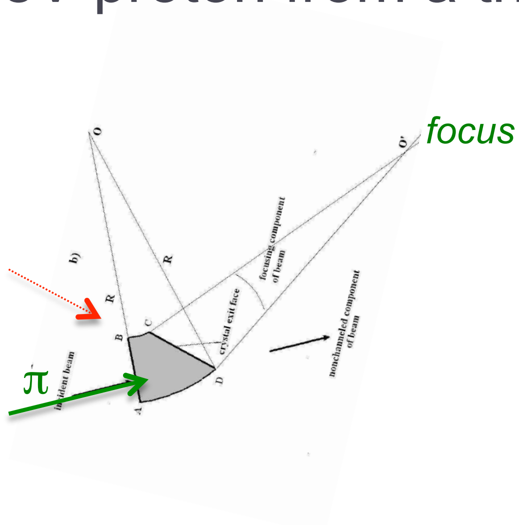
More on the list ?

- A 7 TeV beam can be used for direct calibration
  - Gamma-400 calorimeter, LHC-f.

- Sub-shower in air-shower are mainly due to pions
  - A special crystal can be used to focus secondaries from the interaction of primary 7TeV proton from a thin target

A ***focusing crystal*** can intercept a fraction of the secondaries



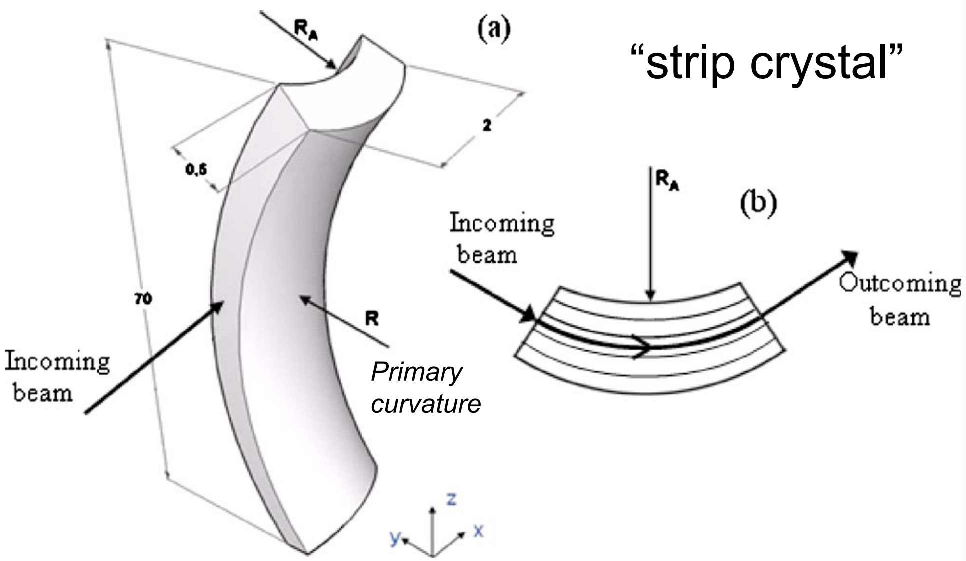


(Today's) Conclusions

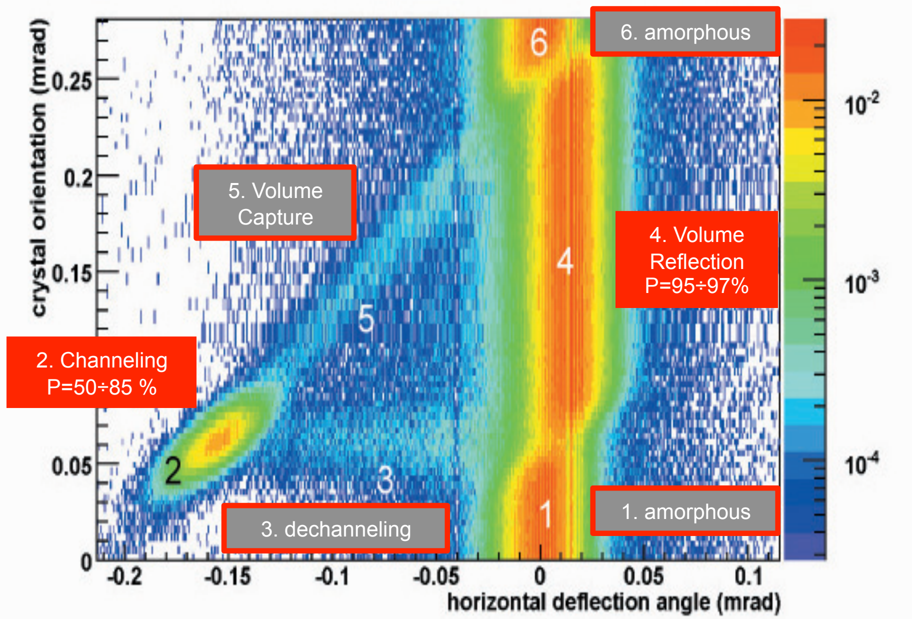
- Measurements with "low" energy probes at CERN are possible
  - SPS North Area lines (up to 400 GeV) are usually available to users.
  - LHC 7 TeV proton (or ion) beam could be extracted parasitically with a crystal in the next coming years.
- Identify crucial measurements is a key-point
  - Reproduce UHECR air-shower in lab
  - Measure anti-proton production from He
  - Muon production
  - …
- I believe CR physics community should be proactive and make realistic proposals
  - Re-use of existing apparatus would certainly help.

Additional back-up slides

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



W. Scandale et al, PRL 98, 154801 (2007)

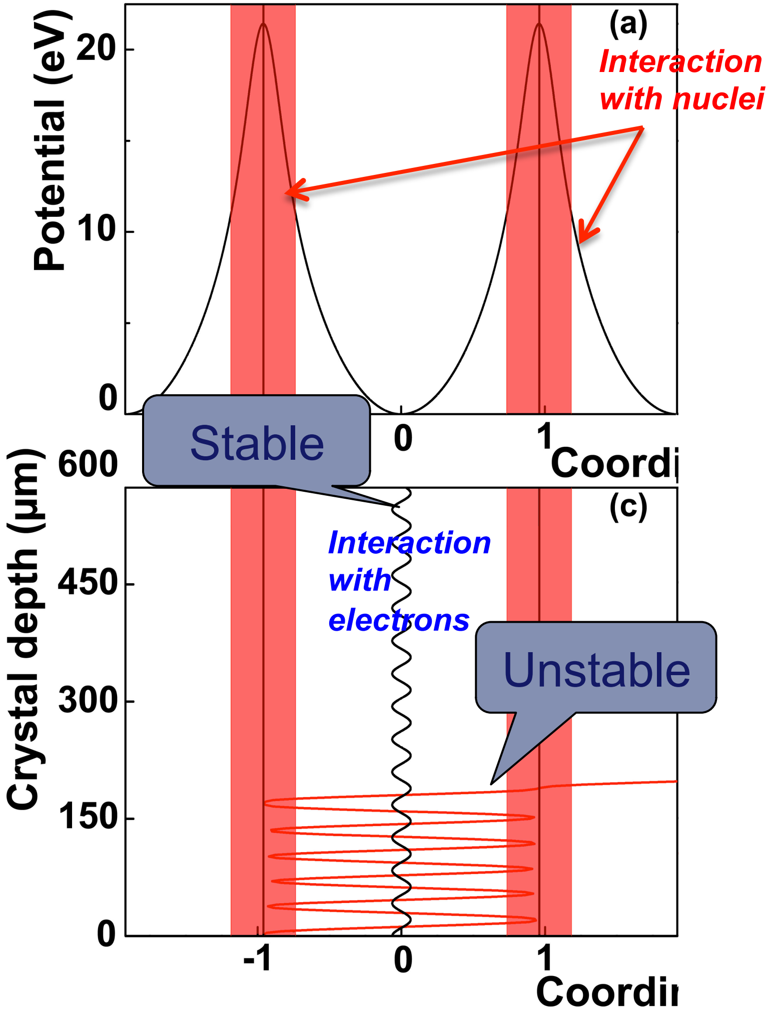


Anticlastic deformation to impart bending

Also quasi-mosaicity used (wider crystals)

Dechanneling effects

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

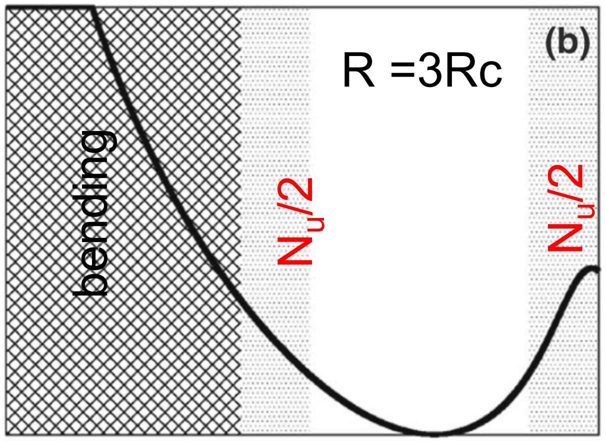


- Nuclear (L_n) and electronic (L_e) dechanneling affecting channeling efficiency

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

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

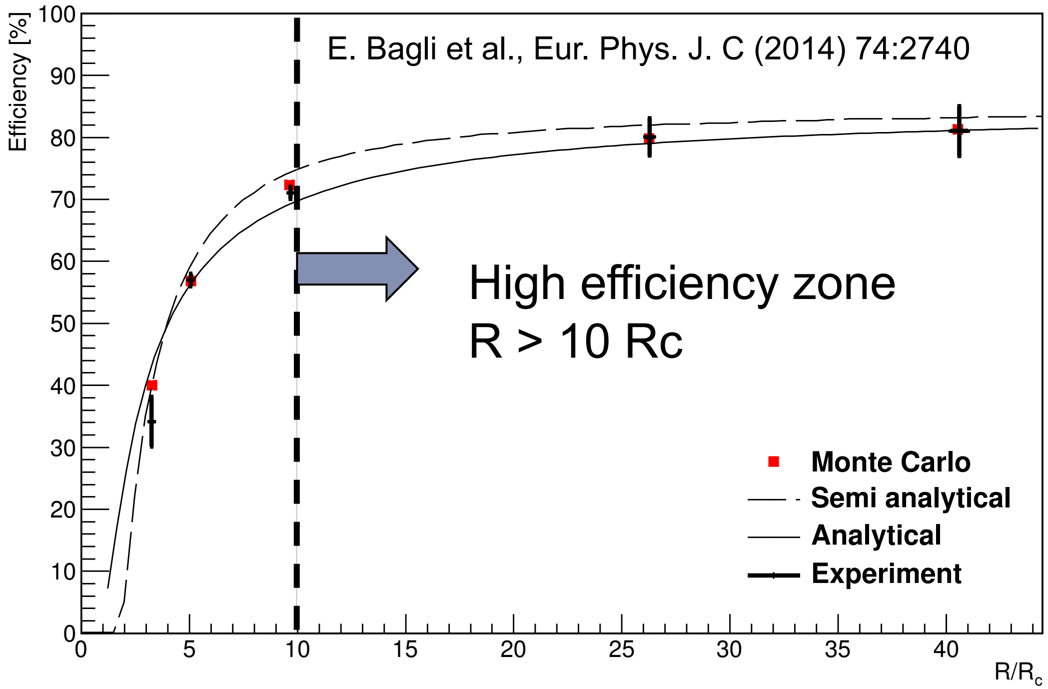
L_e ~ p : at 7 TeV L_e ~ 400cm



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

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

Channeling efficiency versus Rc

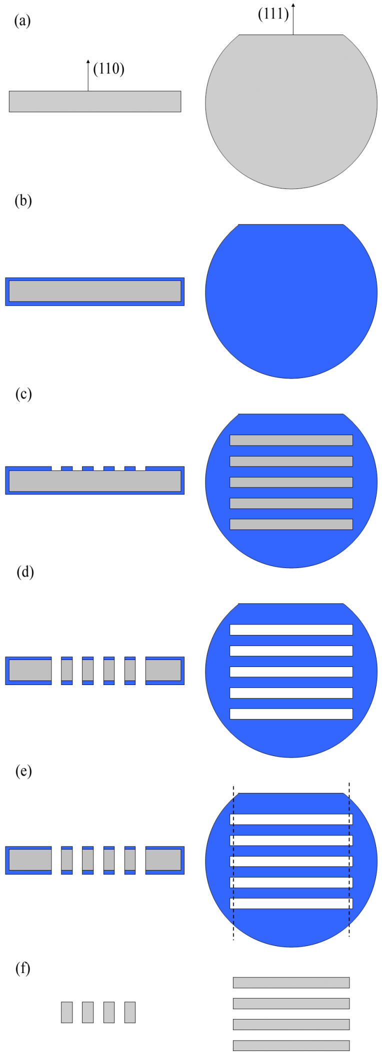


- Experiment (H8 and SPS):
  - Si bent crystal (**L = 0.2cm**)
  - (1 1 0) plane
  - 400 GeV/c protons

Si (110):
R_c = 12m at E = 7 TeV
Ge (110):
R_c = 7m at E = 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

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

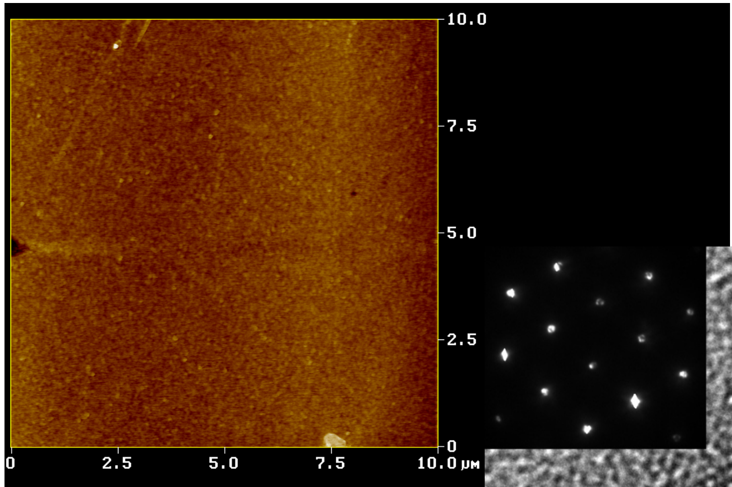
Silicon crystal production and testing

- Anisotropic chemical etching
  - Sub-surface damage free crystal

Sensor and Semiconductor Laboratory

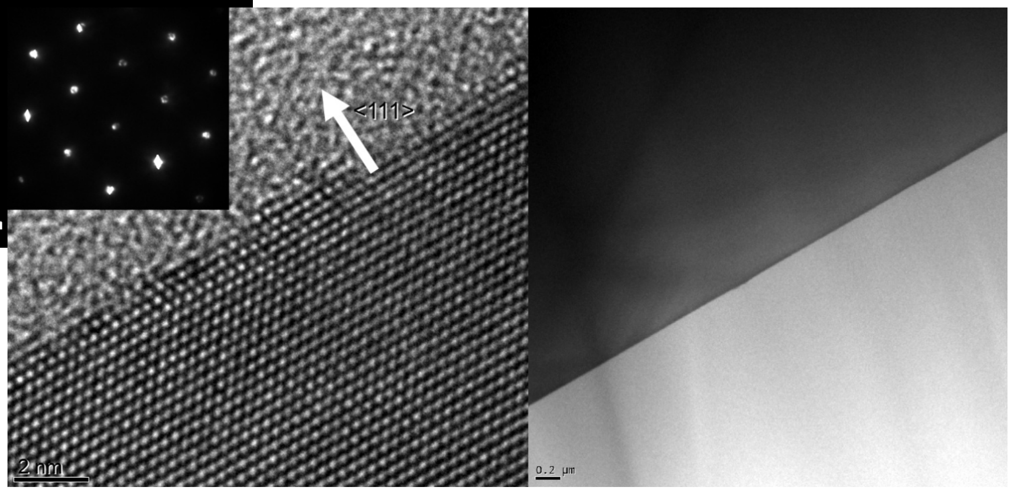
University of Ferrara and INFN Ferrara

Lateral surface (AFM)



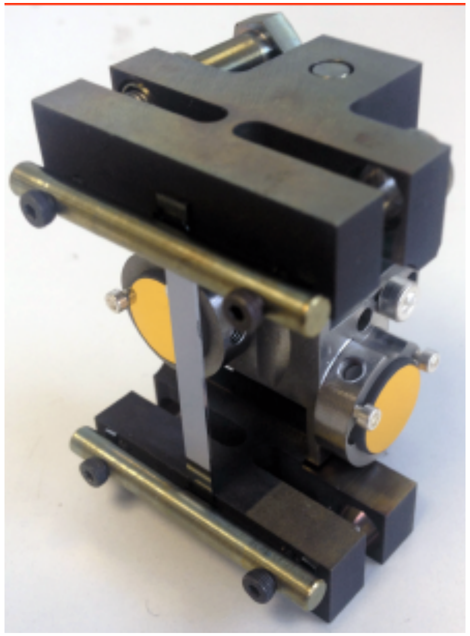
Entry surface (HRTEM)

JPD 41 (2008) 245501



Sub-nm roughness was achieved

New Holder technology



- High grade titanium holder for SPS and LHC crystals

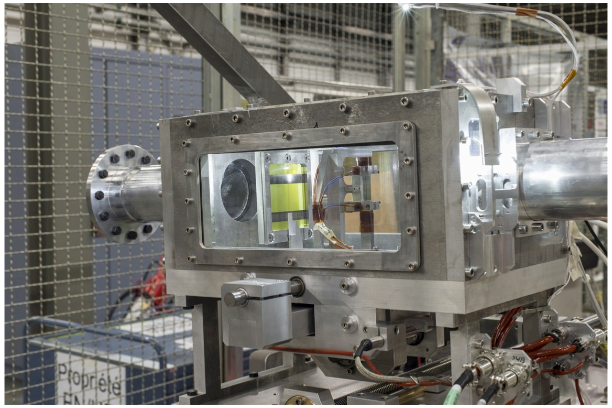
- For a very long crystal (~10 cm), a new holder needs to be designed!
  - Assisted curvature with **tensile layer deposition**
  - INFN Ferrara labs has infrastructures and know-how

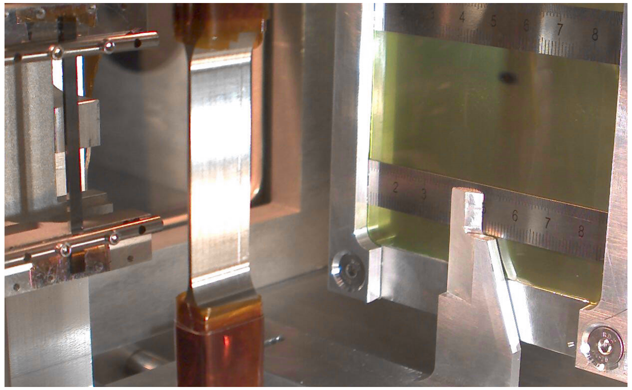
Crystal resistance to irradiation

- **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)
    ➔ comparable 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



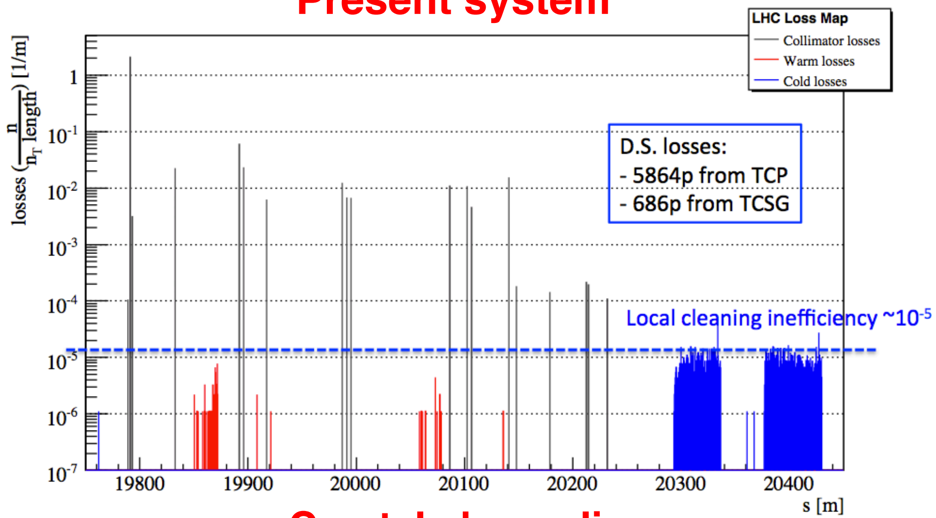


Prediction for the LHC test

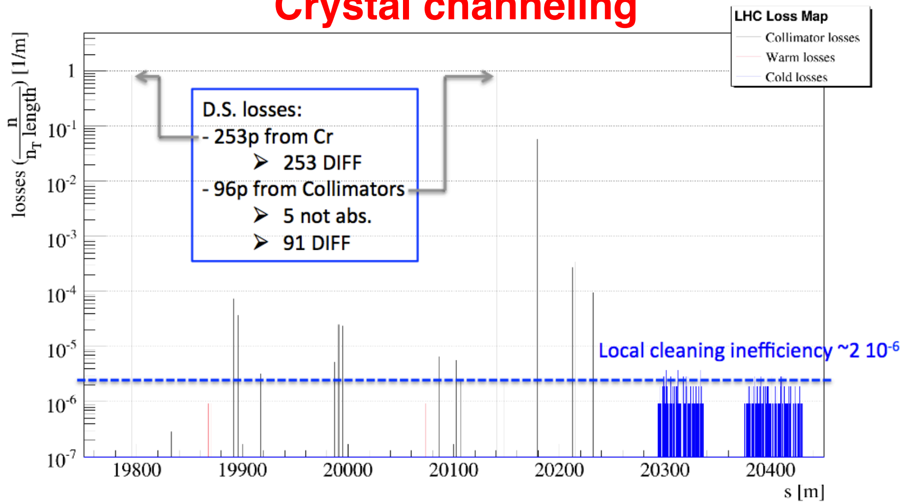
*D. Mirarchi, S. Redaelli, W. Scandale, V. Previtali:
Layouts for Crystal Collimation Tests at the LHC, MOPWO035, IPAC13.

- 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

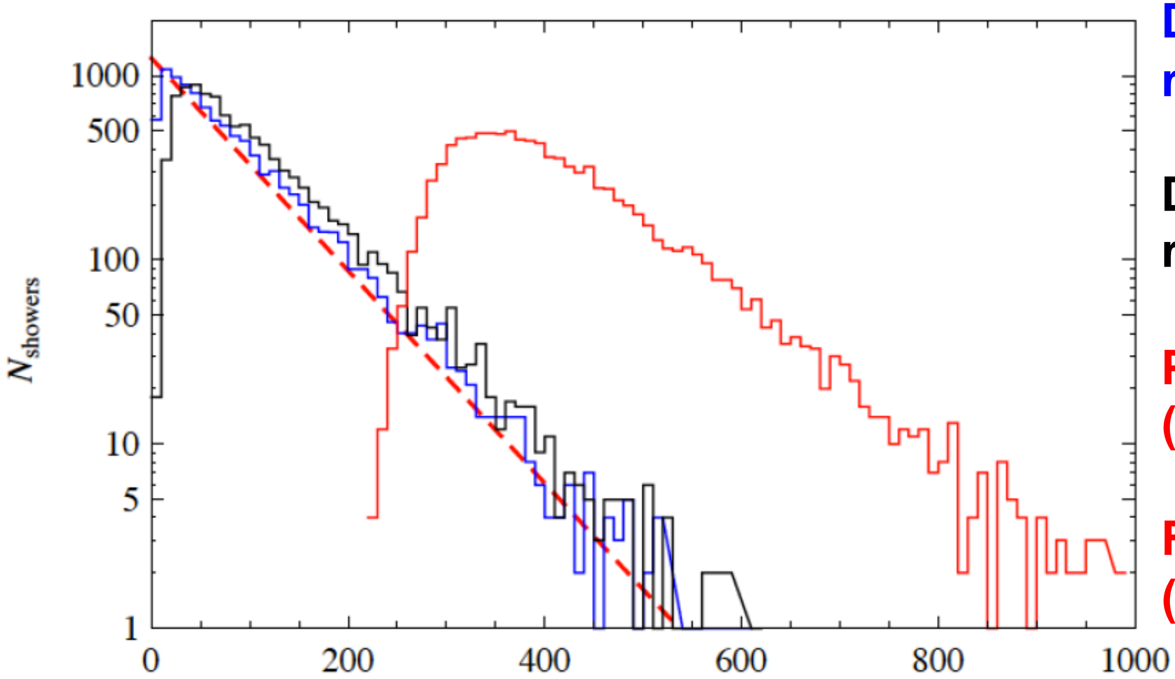


CRYSBEAM objectives

- **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]**

Hadronic shower parameters



Depth Z [cm]

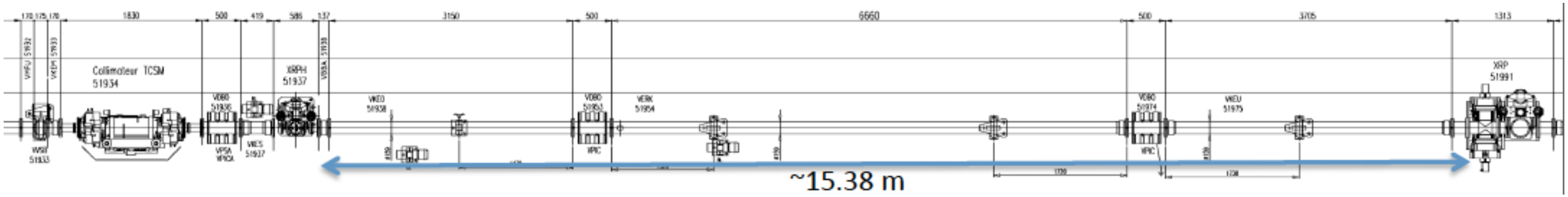
Depth where 10 particles are registered (blue histo)

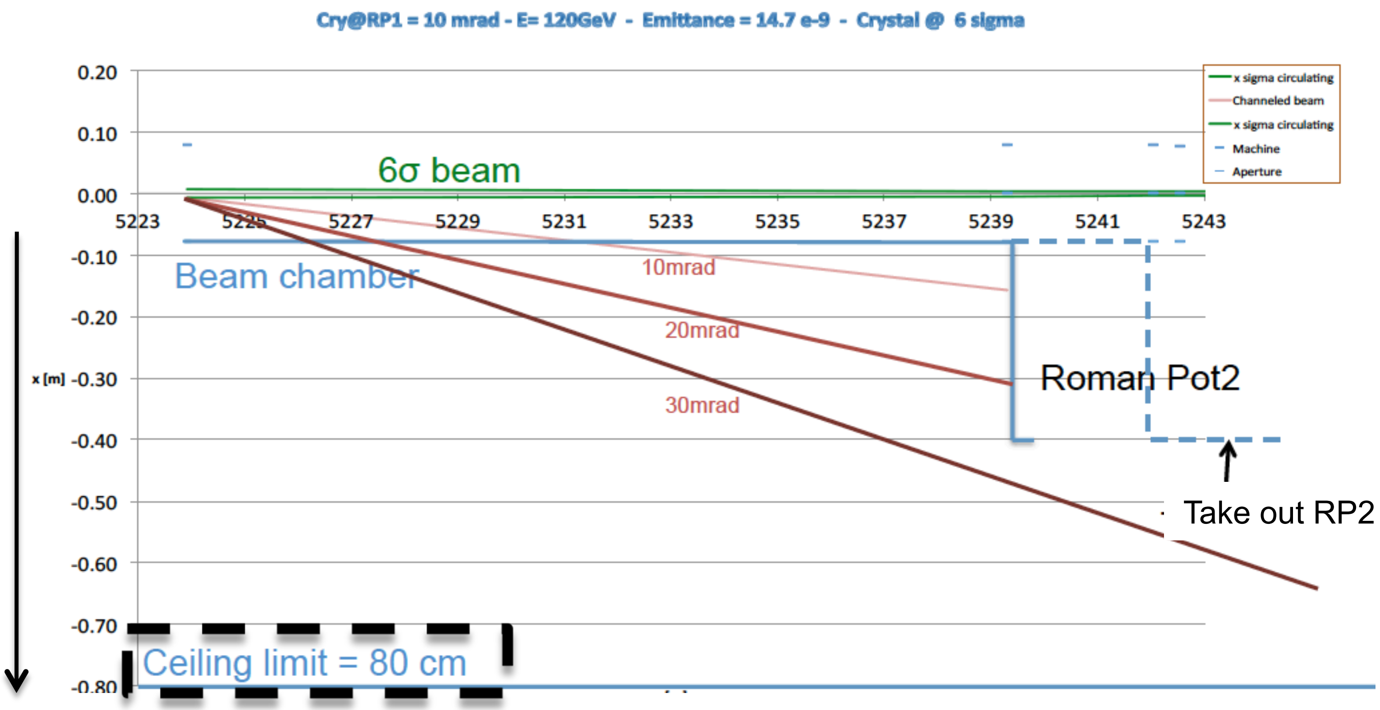
Depth where 100 particles are registered (black histo)

Position of shower maximum (red histo)

First interaction distribution (dashed line)

SPS extraction test in LSS5



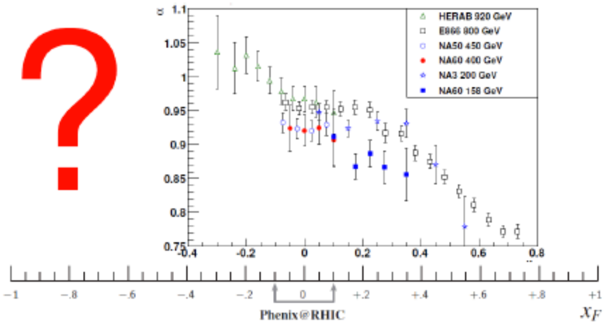


Location of the extraction test-bed in SPS under study.

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

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

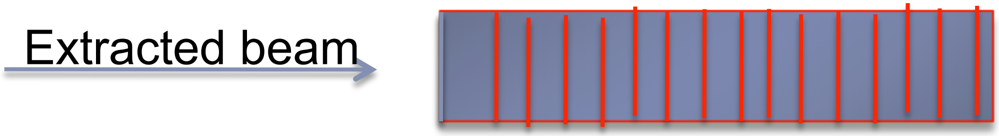


- large negative-x_F reactions in proton-nucleus collisions;
- the charm and beauty content of the proton;
- the quark and gluon Sivers effect and the proton spin;
- the hard probes of quark-gluon plasma close to the QCD phase transition;
- the large-x gluon distribution in the proton, neutron, deuteron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

- This goes ***beyond*** CRYSBEAM activity
  - A more complex (and bigger) experiment is needed!
    - But crystal extraction could be the first piece for this
  - A Letter of Intent for CERN is in preparation

Conceptual experiments

Extracted beam

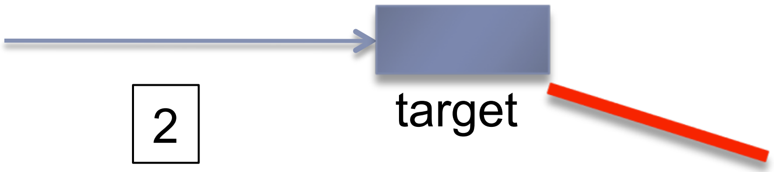


Segmented absorber
Active layers (pixelated?)
to measure shower properties

1

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

Extracted beam



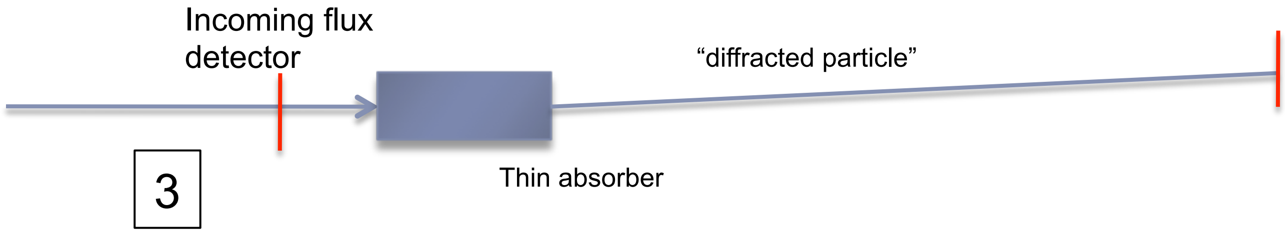
2

target

"single-arm"
detector

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

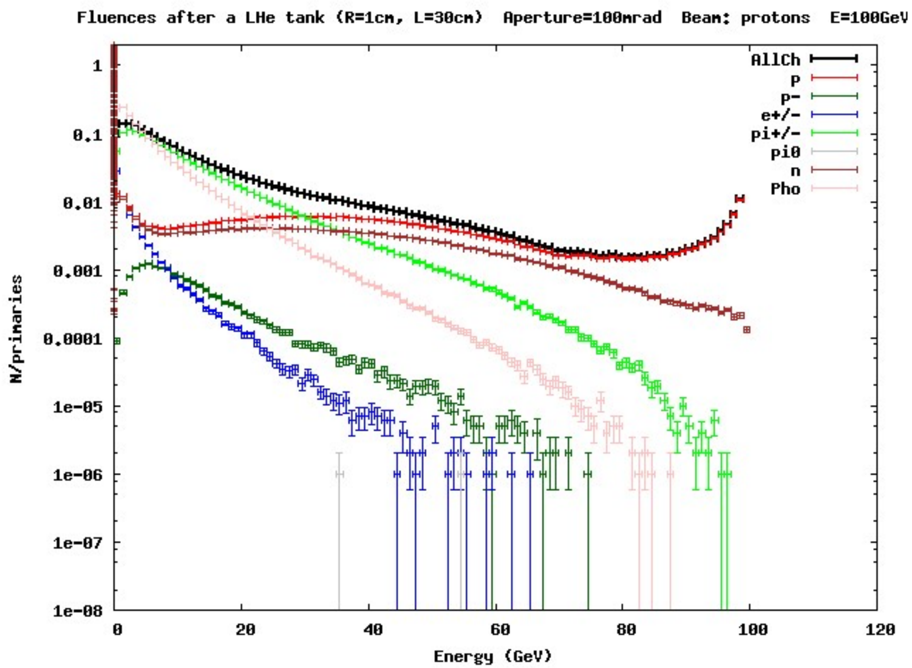
Conceptual experiments (2)

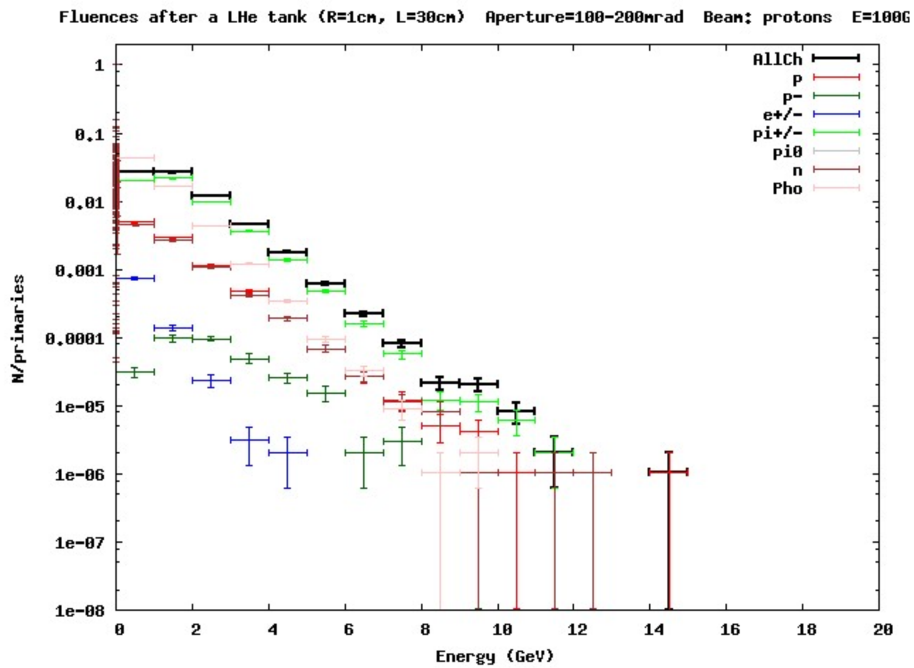


Dispersive region of the accelerator: Detected diffracted particles

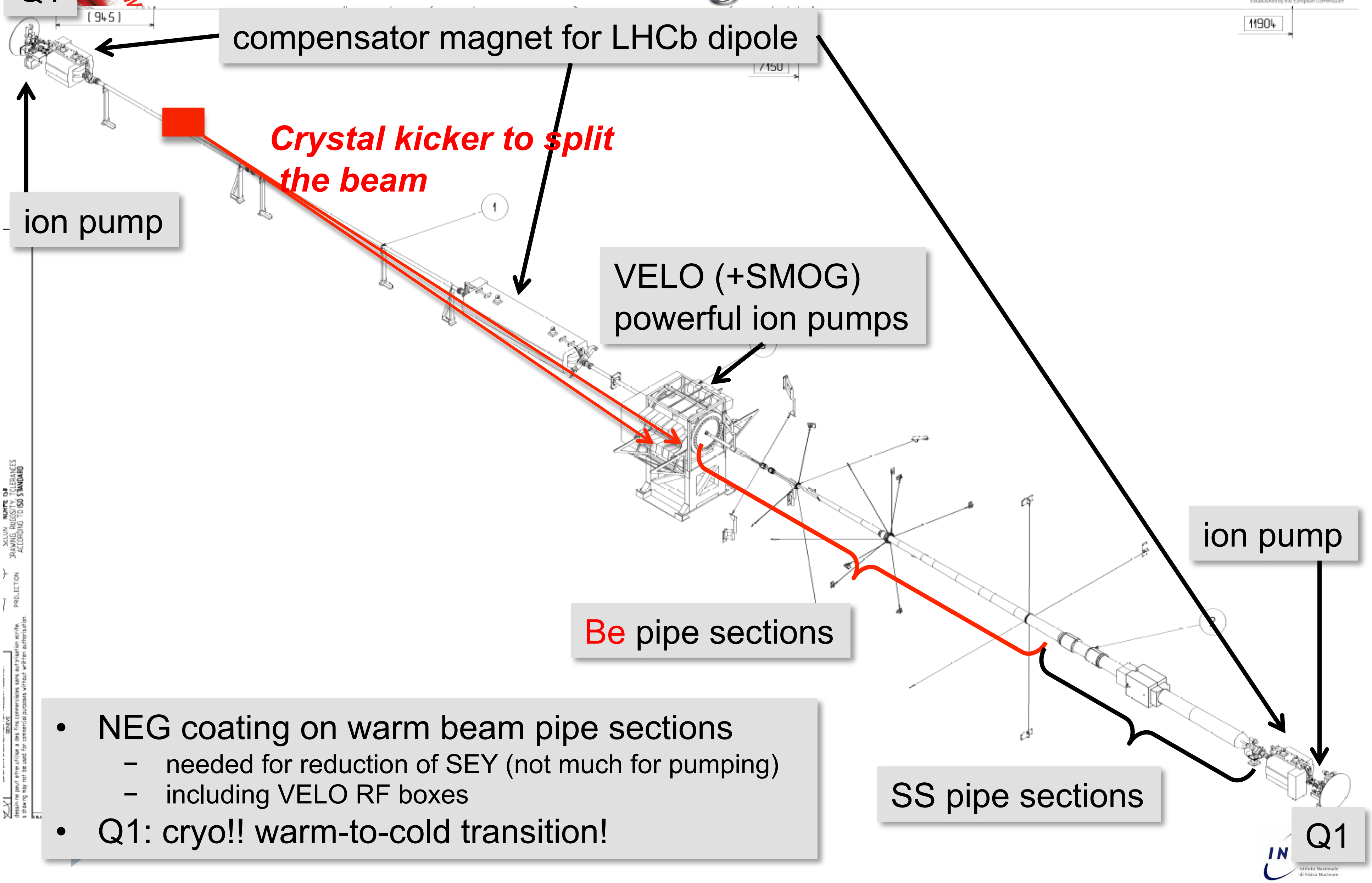
Use the accelerator as a spectrometer to measure the momentum of diffractive particles
With two stations, measure angle and momentum
Direct measurement of diffractive cross section on absorber materials

More on particle fluence from He (FLUKA)





LHC-b vacuum configuration



- NEG coating on warm beam pipe sections
  - needed for reduction of SEY (not much for pumping)
  - including VELO RF boxes
- Q1: cryo!! warm-to-cold transition!