Big thanks to UA9 collaborators, especially M. Garattini, T. James, M. Pesaresi, R. Rossi

Siena Topical Seminar IPRD19
14.10.19

Optimisation of a silicon microstrip telescope for UA9 crystal channeling studies

G. Hall

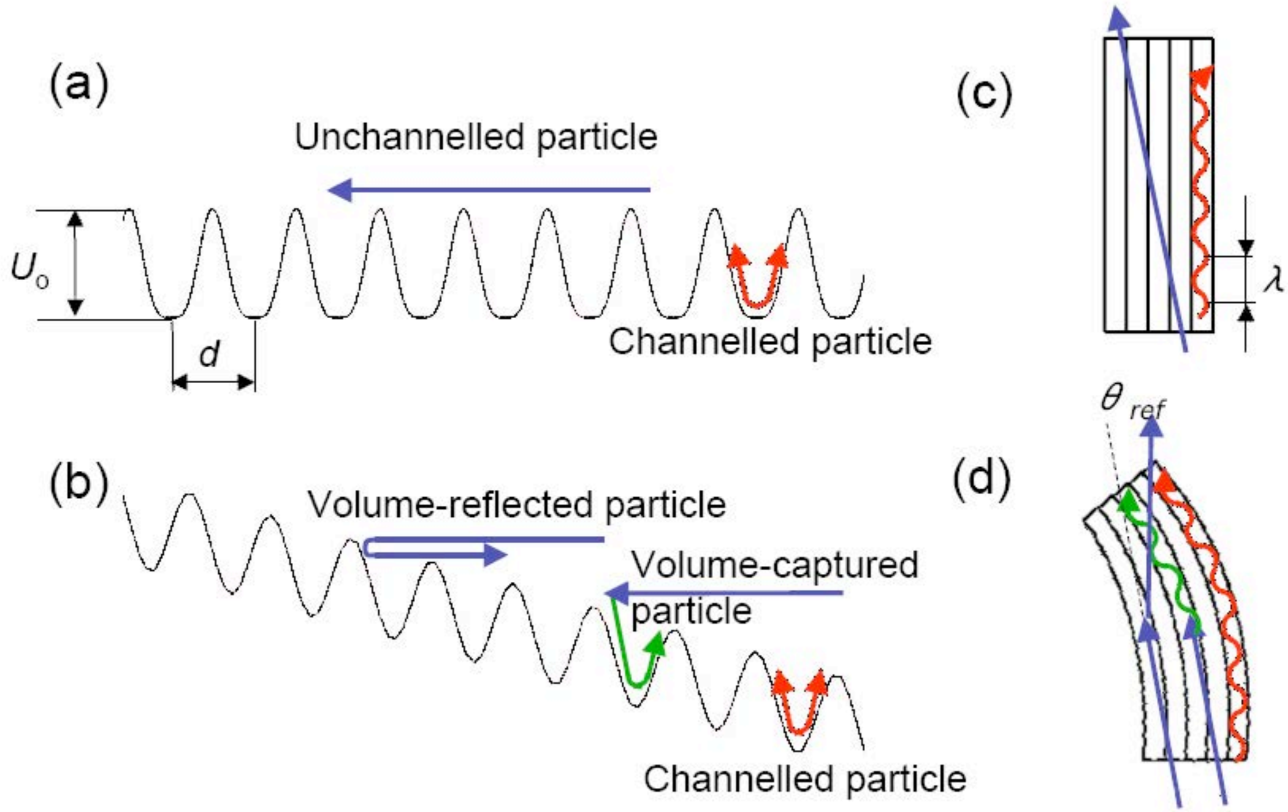
Crystal channeling

- Potential well captures and confines particles within certain p_T range

$$\theta_c \approx \frac{6.3\mu rad}{\sqrt{p[TeV]}} \approx 10\ \mu rad \text{ @ 400 GeV}$$

Possible processes:

- multiple scattering
- channeling
- volume capture
- de-channeling
- volume reflection



UA9 collaboration has been studying this for applications in beam collimation and and control, including ejected LHC beams for future fixed target experiments

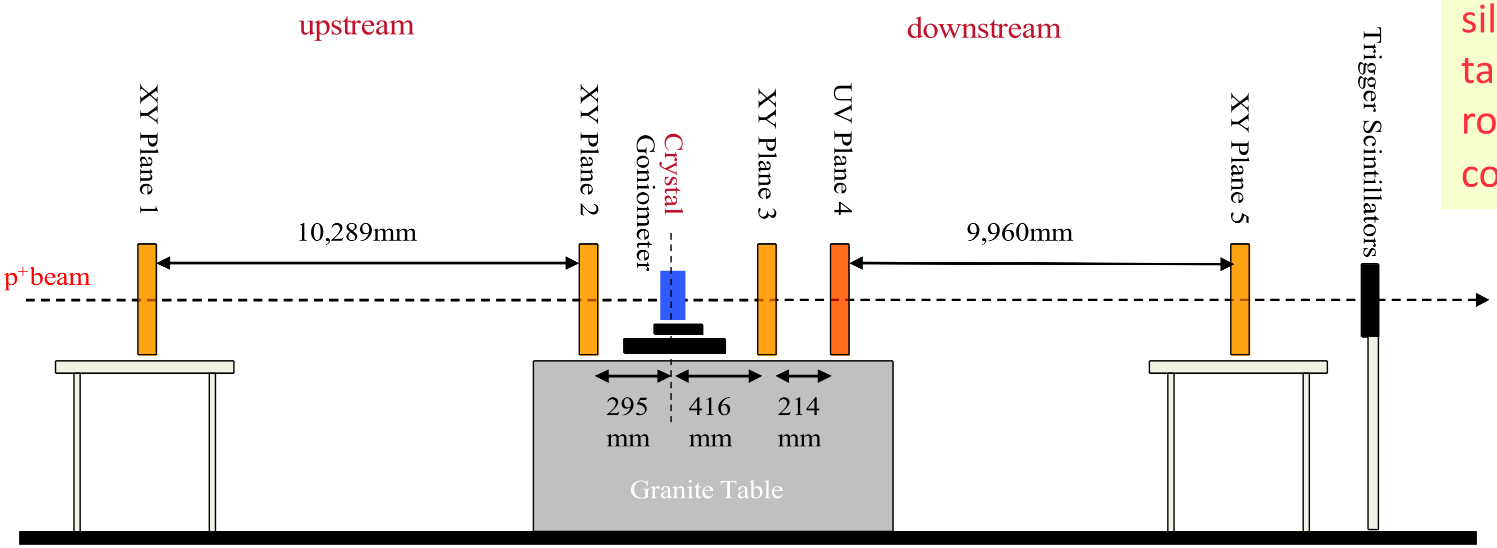
The facility at the CERN H8 beamline has been used to study suitable crystals and to investigate related physics

Original objectives of the telescope

- To measure performance of crystals to be used for LHC beam collimation
  - excellent angular resolution – sufficient to select particles within critical channeling angle
  - limited angular acceptance, both upstream and downstream
  - automated scans from incident direction to channeling angular region
  - (mostly) a single particle in the telescope
  - high data rate during spill to acquire sufficient events
  - rotation of crystal by goniometer between spills
  - beams of protons, pions and heavy ions
- Constraints
  - detector modules and DAQ to be based on existing, or easily acquired, hardware
  - software developed from existing system, with real time histogramming
  - mostly based on CMS tracker system, with customised modules using D0 sensors
- First H8 commissioning: June & September 2010
  - 4k events per spill, reaching 60k with upgraded PC and storage

H8 telescope: "standard" configuration

- Conventional microstrip telescope based on existing components
  - APV25 and FEDs developed by us for CMS tracker, and DAQ. Analogue optical data transfer
  - Planes distributed to achieve high angular resolution, rather than local spatial precision
  - High data taking rate but low occupancy



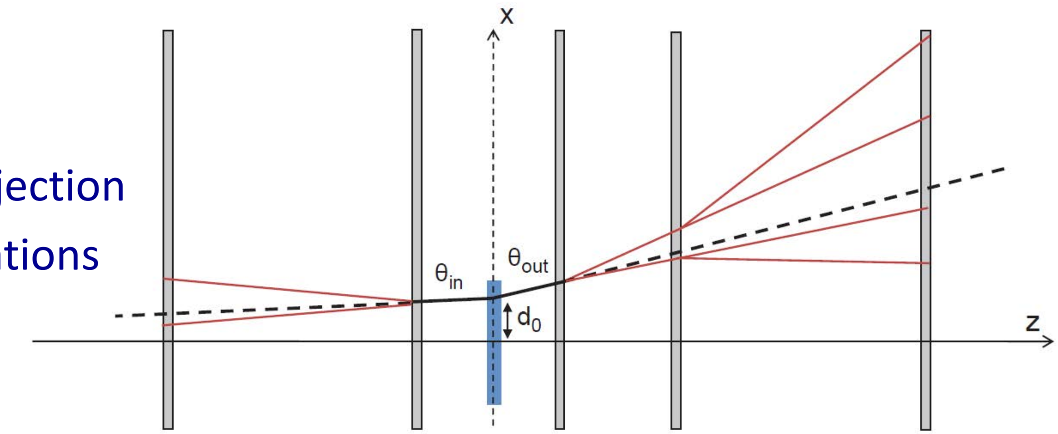
silicon crystal target on precise rotation stage controlled by DAQ

Two measurement arms – each approximately 10m length

- Dominant contribution to angular error from multiple scattering
  - $\sigma(\theta)$ ~2.7 µrad at 400 GeV/c from 700 µm silicon & windows per station
- Outgoing arm uses UV plane to distinguish multiple hits downstream of crystal

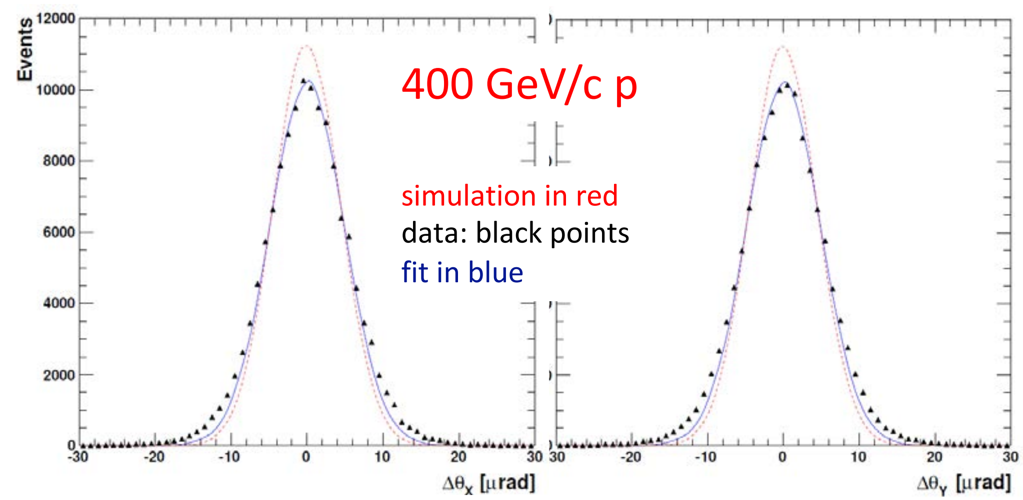
Track reconstruction

- Fitting procedure
  – 2D hit required in each plane
  – Two straight line fits
  – Three parameter fit (θ_{in}, θ_{out}, d_0) per projection
  – includes multiple scattering error correlations
  – χ^2 cut



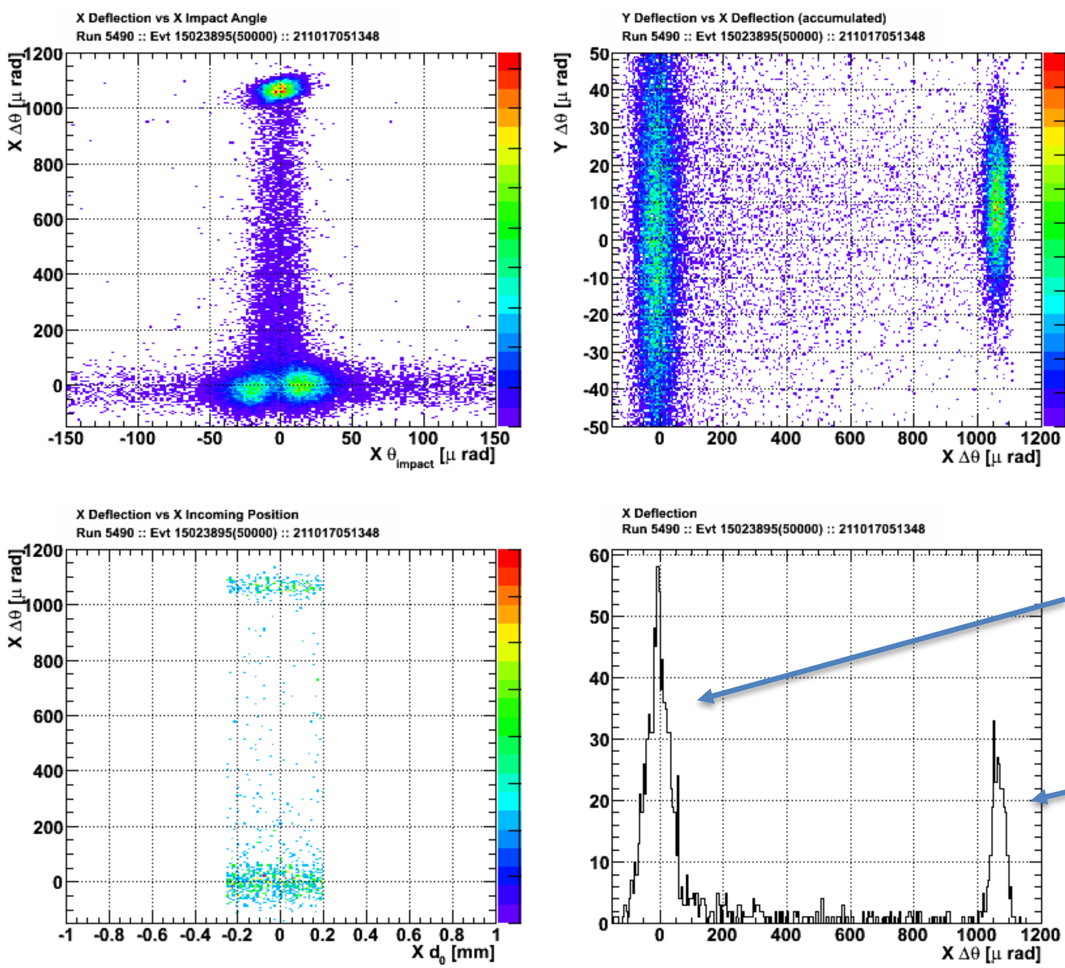
- Special runs requiring layout modifications for acceptance
  – Heavy ions
  – Large angular displacement
  – Nuclear interactions

  – For larger angular acceptance only two downstream planes used – with consequently worse angular resolution



Measurements in H8 beam

- Data taken with range of beam particles
  - 400 GeV/c p, 180 GeV/c π, light and heavy ions, e.g. Pb and Xe
  - Large number of different crystals and types of crystal characterised



180 GeV/c π data

data taking efficiency for channeling in H8 beam depends on beam dispersion, i.e. fraction within θ_c

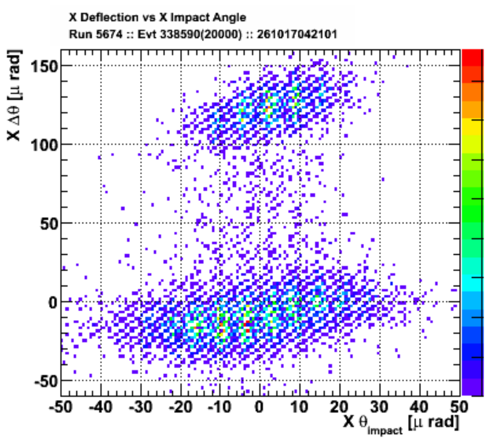
undeflected beam

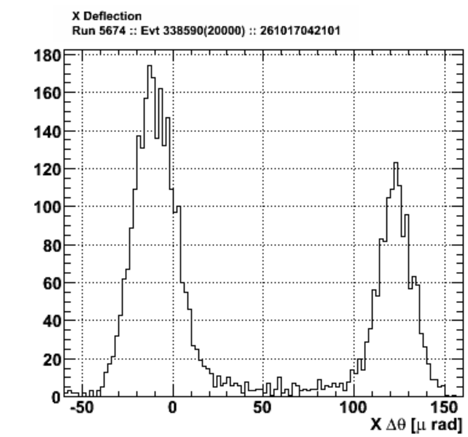
channeled particles

Ion beam measurements

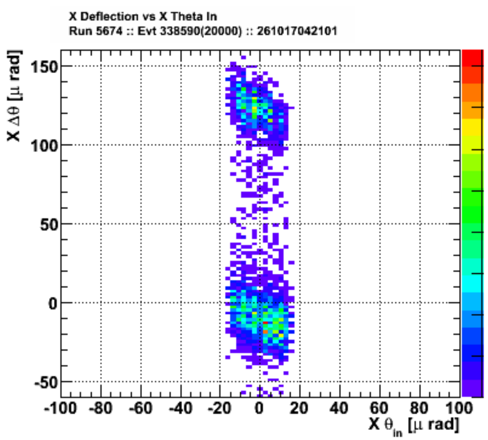
- Special operating conditions needed for ions because of very large dE/dx
  - Signal size = Z^2.MIP => 2916 MIP [Xe] - 6724 MIP [Pb]
  - Amplifier designed for linear operation up to a few MIP signals in 300-500µm silicon

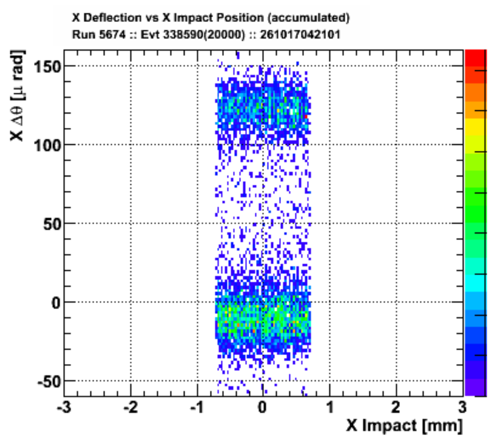
150A GeV/c Xe data

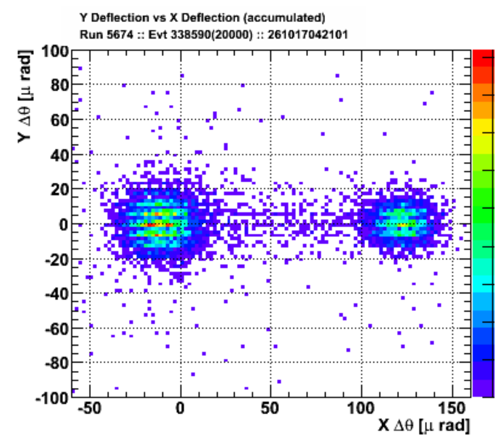




- V_{sensor}= 3.6V (cf. 150V normally)
- include clusters <20 strips (cf. 8)
- peak cluster size ≈ 3 [Xe] (cf. 1-2)
- strip threshold ≈ 5 MIP
- $\sigma(\Delta\theta)$ = 7.7 µrad







Performance

- Observed resolution (some variation in plane locations)

beam		Z	A	p [GeV/c]	σ_{meas} [μrad]	σ_{scaled} [μrad]	σ_{calc} [μrad]
p		1	1	400	5.4	5.4	4.4
Xe	150 GeV/n	54	131.2	19680	7.8	5.9	4.8
Pb	30 GeV/n	82	207.2	6216	29.6	28.5	21.7
π/p		1	1	180	11.3 ± 0.03	12.0	9.3
π/p	4 plane reco	1	1	180	22.1 ± 0.1		23.0
π/p	+8cm Si 4 plane reco	1	1	180	82.2 ± 1.0		73.2

- Comments (Calculations based on V. Karimäki [NIM A410(1998) 284-292] plus MS correlations)
  – generally good agreement, but may be a systematic underestimate (agrees with MC, where done)
  – ion cluster data are essentially binary, not truly analogue, because of signal sizes
  – Calculations do not include:
    - alignment precision: should be ~few μrad
    - uncertainty in beam momentum and spread: ~percent level

Performance with different material budget

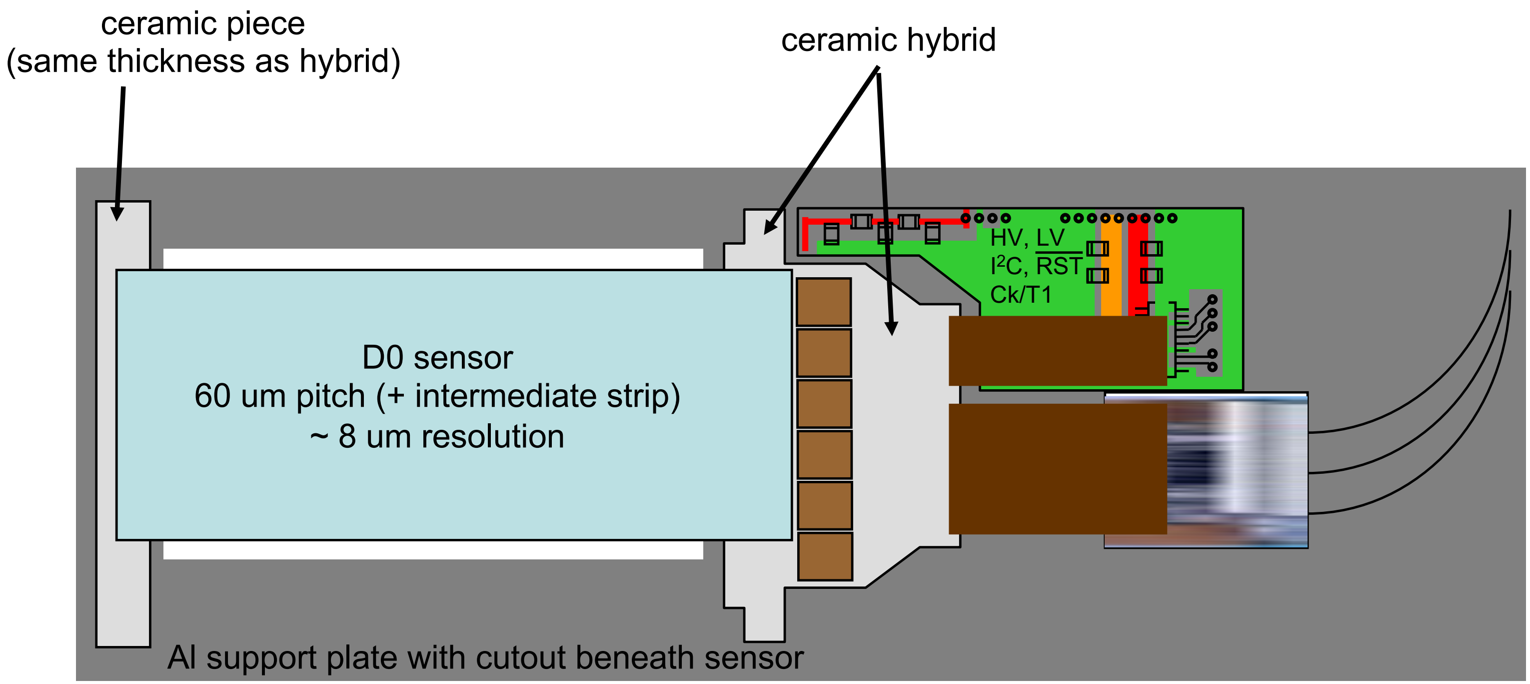
- Expected angular resolution for 5 plane telescope

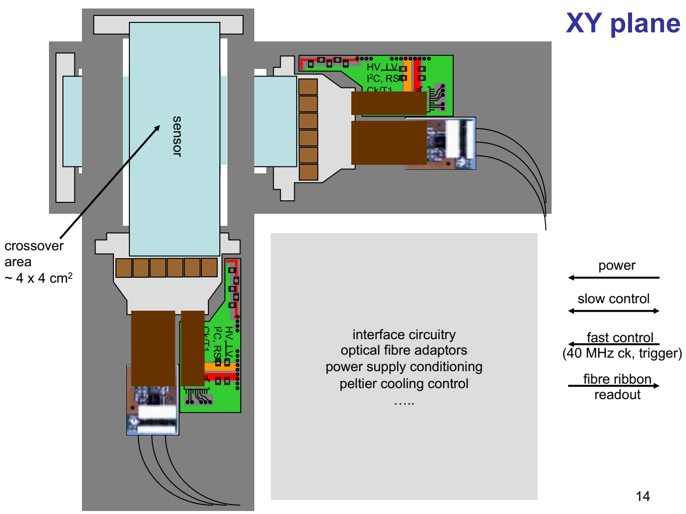
beam	material per plane	p [GeV/c]	σ_{calc} [μrad]
p	350 μm	400	3.3
p	700 μm	400	4.4
p	1400 μm	400	6.2
π/p	350 μm	180	6.5
π/p	700 μm	180	9.3
π/p	1400 μm	180	13.5

scales ~√thickness as expected

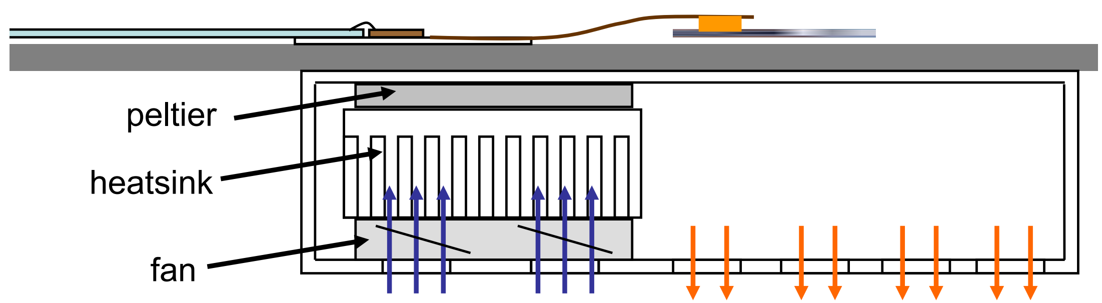
- Comments
  - in practice, difficult to decrease sensor material thickness – availability, sensor design, area, …
  - if material were to increase downstream (see later), upstream planes should remain as at present

telescope sensor module

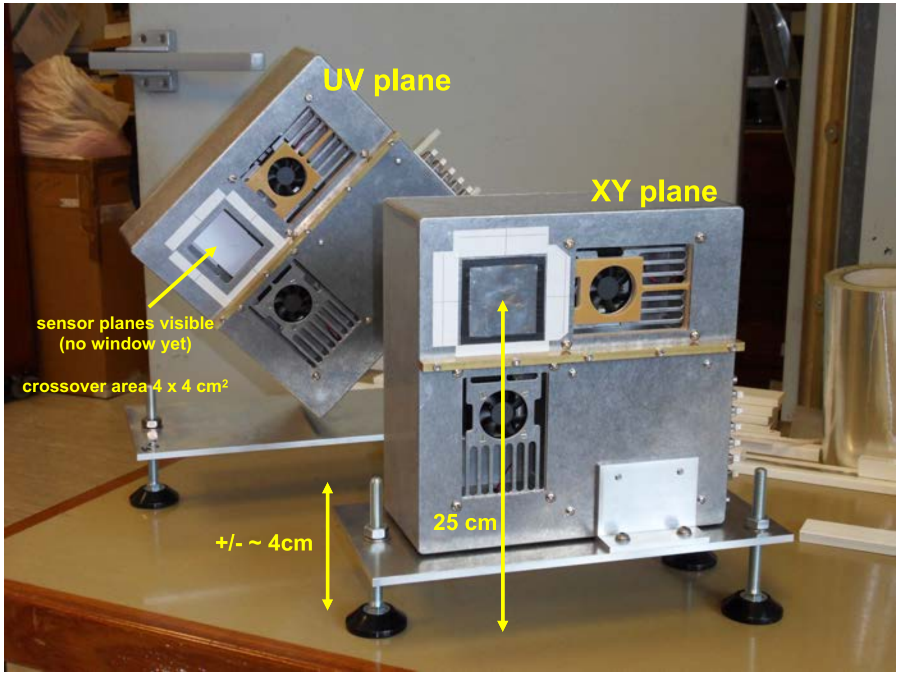




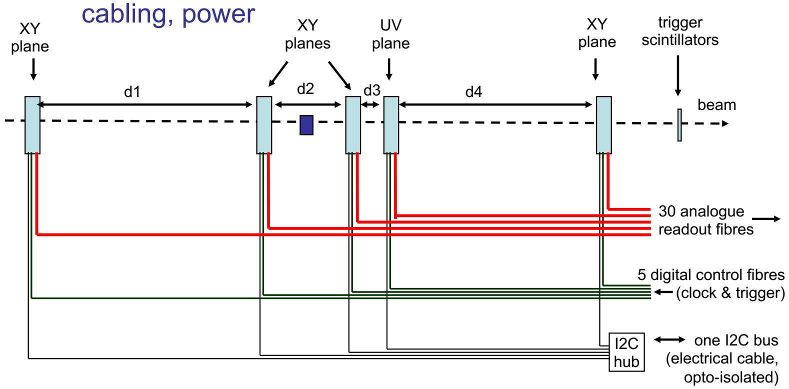
XY plane



More details of telescope



cabling, power



to/from counting room

6 readout fibres per plane => 30 total

1 control fibre per plane = 5 total

1 electrical cable to I2C hub in beam area

electrical fanout to each plane

will need some coax cables for trigger,….

will need 2 mains sockets per plane (LV power, HV supply)

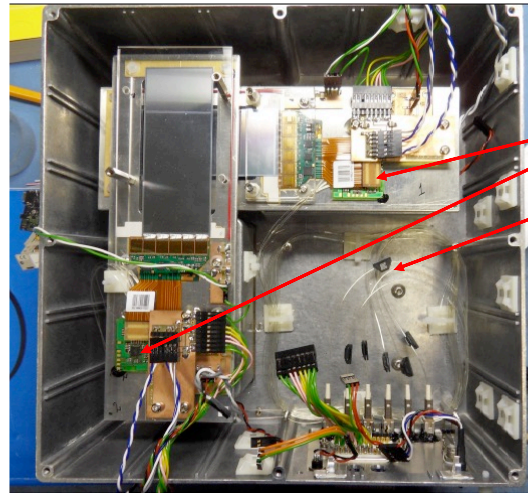
should aim for one multi-socket extension cable per plane (5 total)

note: the integrity of these analogue fibres is crucial to the performance of the telescope (the CMS readout system was designed for a one-off, careful installation)

5

inside the box

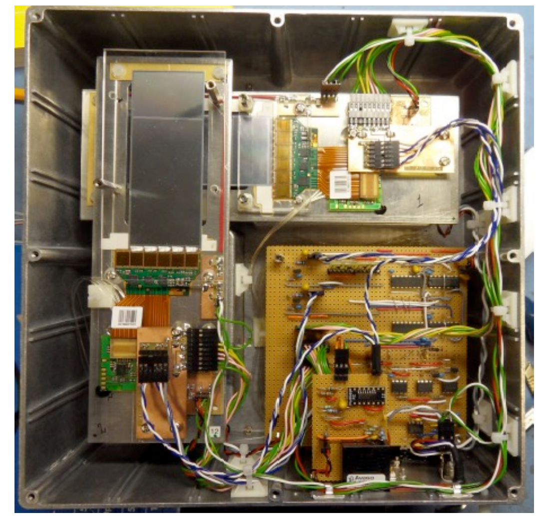
after optical hybrids installed



analogue opto-hybrids

fibres

finished



Some key points:

Sensors procured from D0 (abandoned upgrade)

Several components recycled from CMS

- FE hybrid, optohybrid
- APV25 ASICs

Analogue optical links

Alternatives to present sensors?

- Sensors generally customised for specific projects, so thinner or finer pitch devices not readily available off-the-shelf
  – investment required

- Double-sided µstrips
  – gain in material but still affected by combinatorials, handling and assembly issues

- Pixels? – more complex readout architecture
  – hybrid designs add significant material (sensor + electronic layers)
  – pixel sizes not small enough to match µstrip resolution
    - e.g. CMS 100 x 150 μm^2, ATLAS 50 x 400 μm^2 - both profit from B field

- MAPs – much thinner, and smaller pixels, eg ~30 x 30 μm^2
  – small area devices, limited by reticle size, for fixed target telescope
  – possible frame rate limitations to rolling-shutter design

- Pros and cons to all options but no simple better alternative

Other possible improvements

- The telescope and DAQ hardware have not changed much
  - (and been quite reliable)
  - most of the evolution has been in the DAQ PCs, storage, connectivity and software

- First area for potential improvement
  - data links and module interfaces, DAQ back-end
  - replace analogue links, and intermediate electronics

  - digital electronics has advanced considerably in 10 years

Original DAQ hardware

Some key points:

VME FEDs no longer state-of-art

but essential for compatibility

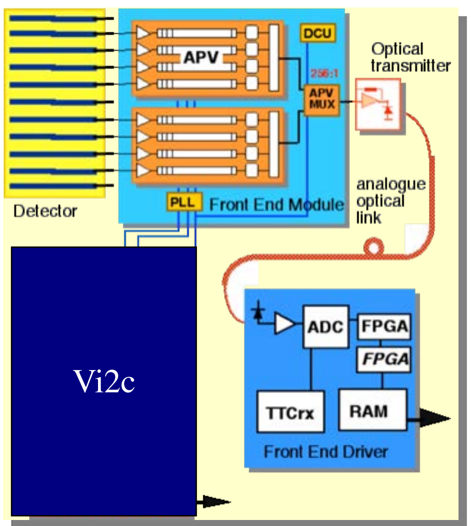
Today would use digital links

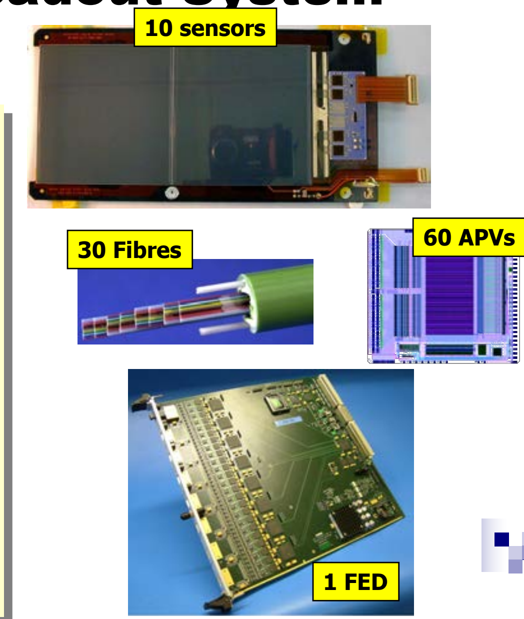
need ADC outside FED

much higher speed links

Control and Readout System

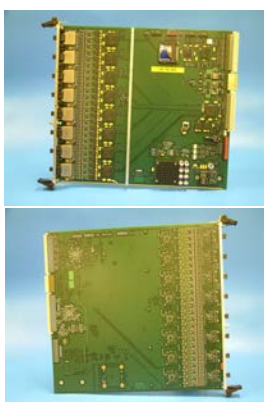
Telescope has 30 channels ~ 7680 strips in 5 planes





Jonathan Fulcher

FED 9U Board

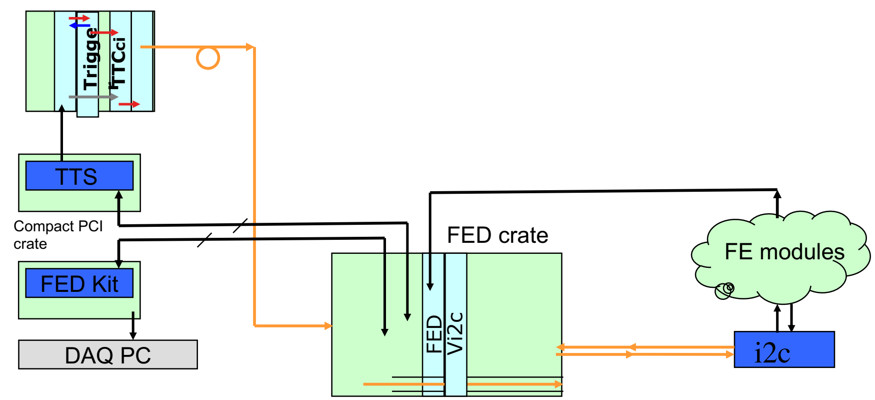


- 9U VME64x
- PCB 14 layers (incl 6 power & ground)
- ~ 6 K components (smallest 0402) ; ~ 25 K tracks
- BGAs largest 676 pins @ 1 mm pitch
- 96 ADC channels :
AD9218 Dual package 10 bit @ 40 MHz
Half Analogue circuitry on Secondary Side

JTAG Boundary Scan

Jonathan Fulcher

Full System Setup



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New DAQ

- Much higher data throughput, and possible real time processing

A telescope with digitization in the planes

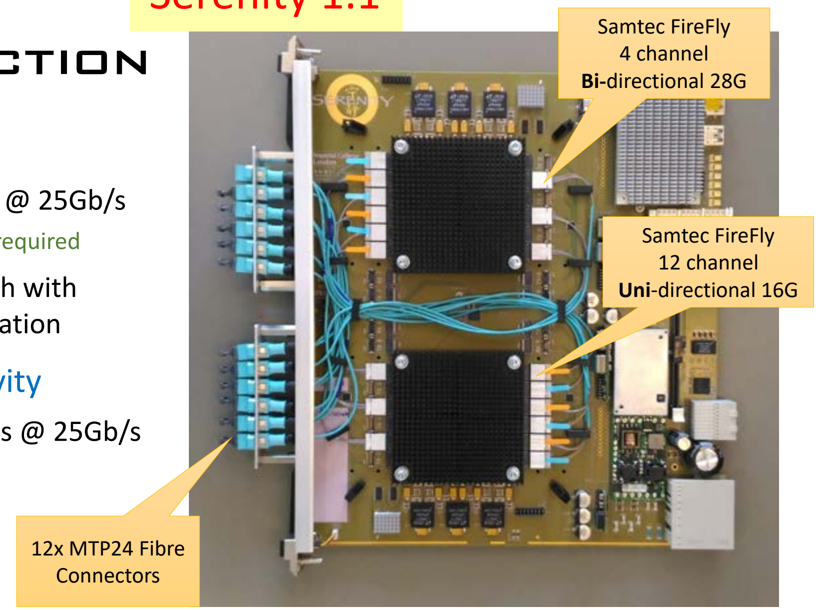
Existing hardware/firmware
- Sensor module interface boards
  - Adapter from mDP to APV hybrid
  - Temperature sensor
  - LDO Voltage regulators
- Digitizer FMC cards
  - Digitizes signals from sensor modules
  - Provides supply voltages for the APVs
  - Peltier driver for temperature control
- FC7 firmware exists, but needs extending:
  - Cluster finding/zero suppresion
  - DAQ integration

Serenity 1.1

CONSTRUCTION

Fibre connectivity
- Up to 288 fibres @ 25Gb/s
  - Upgradeable if required
- 7 Tb/s bandwidth with current configuration

Processor connectivity
- A 64-channel bus @ 25Gb/s links the 2 sites



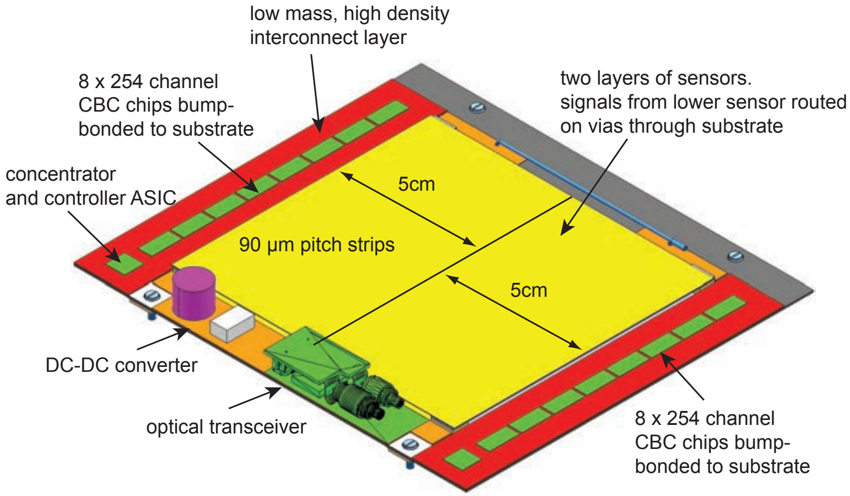
Probably would switch to more advanced DAQ boards in ATCA format

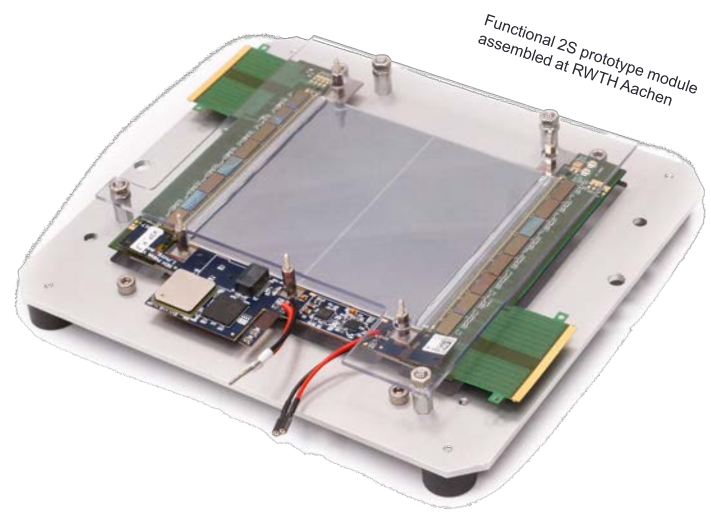
Serenity has huge data processing capability and many high speed links

developed by us for CMS applications, so good infrastructure support

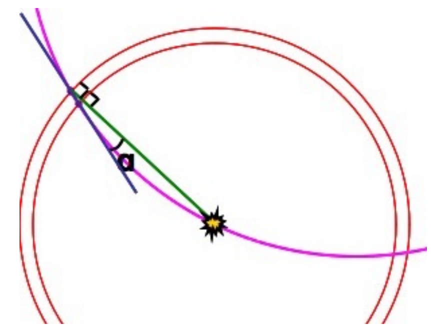
Alternative modules

- Profit from new designs to use data in new ways, cf. CMS



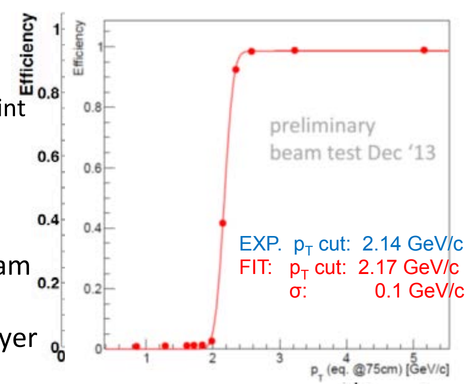


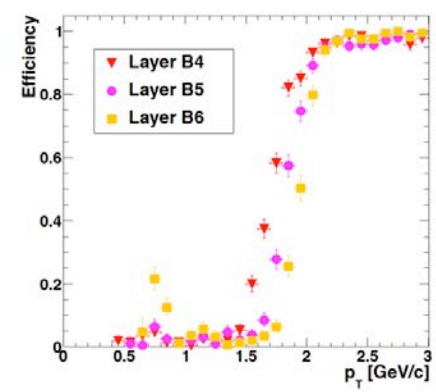
Track finding in real-time in FPGAs
  using "stubs" from hit data in double layer modules
Modules at advanced stage of development
  using RAL-Imperial CBC ASIC
Stacked-tracker principle



- Compare pattern of hits in contiguous sensor elements in closely spaced layers
  - p_T cut set by angle of track in layer
  - primarily depends on layer separation
    - but increasing separation worsens fake combinations
  - details depend on
    - pitch
    - thickness
    - charge sharing
    - track impact point
    - …

data from 2013 beam test
assumes r=75cm layer



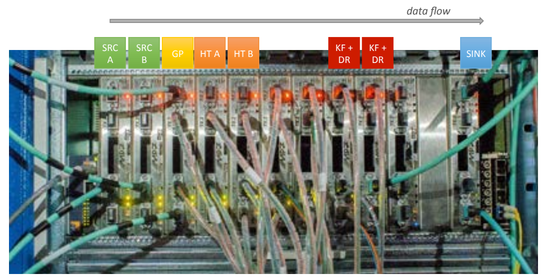


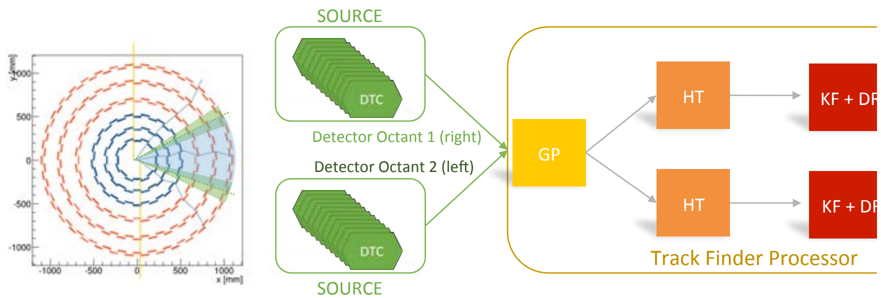
Real-time processing

- Track-finding is **well proven** with previous generation (MP7) hardware since 2016
  - CMS problem of complex event tracking in magnetic field is much more difficult

DEMONSTRATOR OVERVIEW - DATA TAKING

- 8 *daisy-chained* MP7 boards
- Five boards emulate one Track Finder Processor
- Processes Monte Carlo stubs for **any one octant in φ, all of η at once**
- We take take data for all eight octants to **generate hardware results for entire tracker**





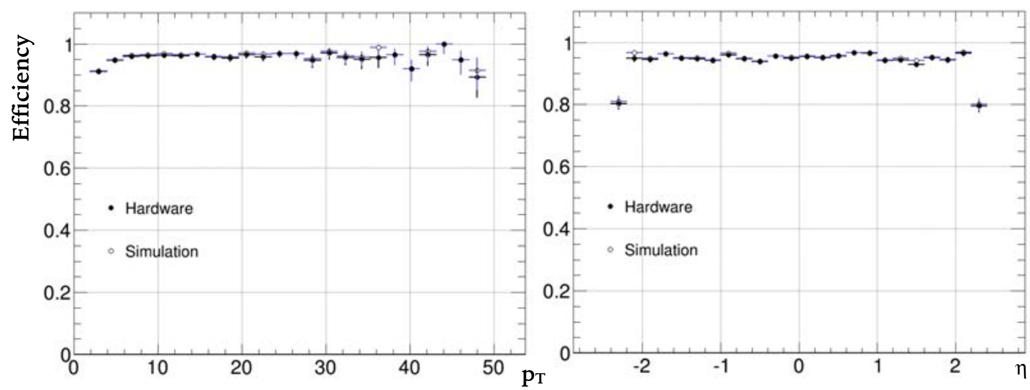
Tom James (Imperial College) TMTT 08/Dec/2016

DEMONSTRATOR RESULTS - TTBAR + 200 PU (1800 EVENTS)

- Highly efficient at finding TTBar inclusive tracks
- Demonstrator matching CMSSW simulation well

	Efficiency (%)	Av Rate	Matched tracks (%)
hw	94.5	76.5	98.7
sw	94.8	79.4	

All results use official matching criteria



Tom James (Imperial College) TMTT 08/Dec/2016 TMTT: L1 Tracking Review 11

Conclusions

- Based on about 10 years of operations:

  – only modest gains easily possible by reducing material budget
    - sensors dominate

  – potential improvements in throughput from digital electronics evolution

  – possibly combined with new double-layer module types
    - permit background hit rejection
    - online cluster-finding and track reconstruction
    - triggering on event topologies

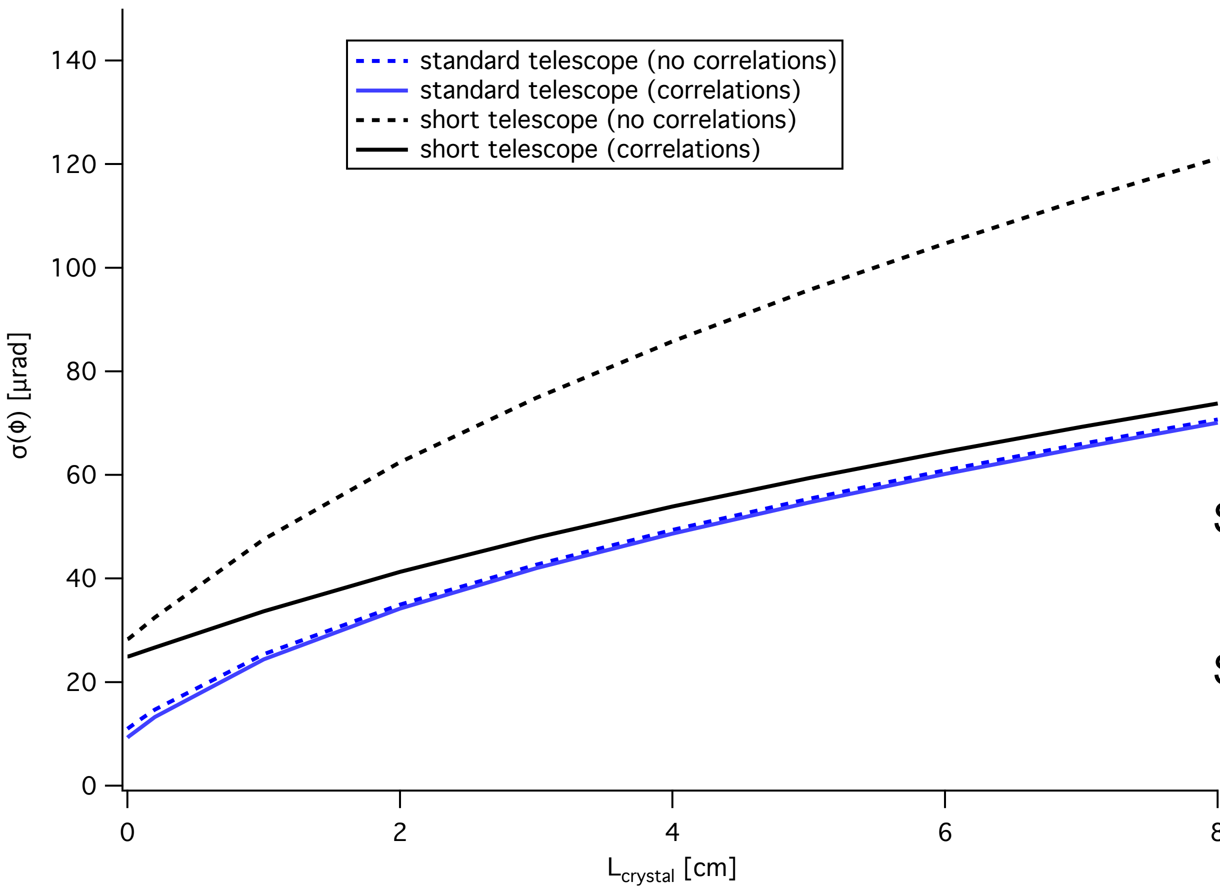
"Design and performance of a high rate, high angular resolution beam telescope used for crystal channeling studies"
M. Pesaresi, W. Ferguson, J. Fulcher, G. Hall, M. Raymond, M. Ryan and O. Zorba.
DOI:10.1088/1748-0221/6/04/P04006
JINST **6**, P04006 (2011).

"A high angular resolution silicon microstrip telescope for crystal channeling studies"
G. Hall, G. Auzinger, J. Borg, T. James, M. Pesaresi and M. Raymond.
DOI:10.1016/j.nima.2018.08.060
Nucl. Instrum. Meth. A **924**, 394 (2019).

Backup

Multiple scattering correlations

- Important to include them in the angular resolution calculations



Crystal causes multiple scattering of non-channeled particles

Standard = ~10 m downstream arm
3 planes

Short = ~0.5 m downstream arm
2 planes