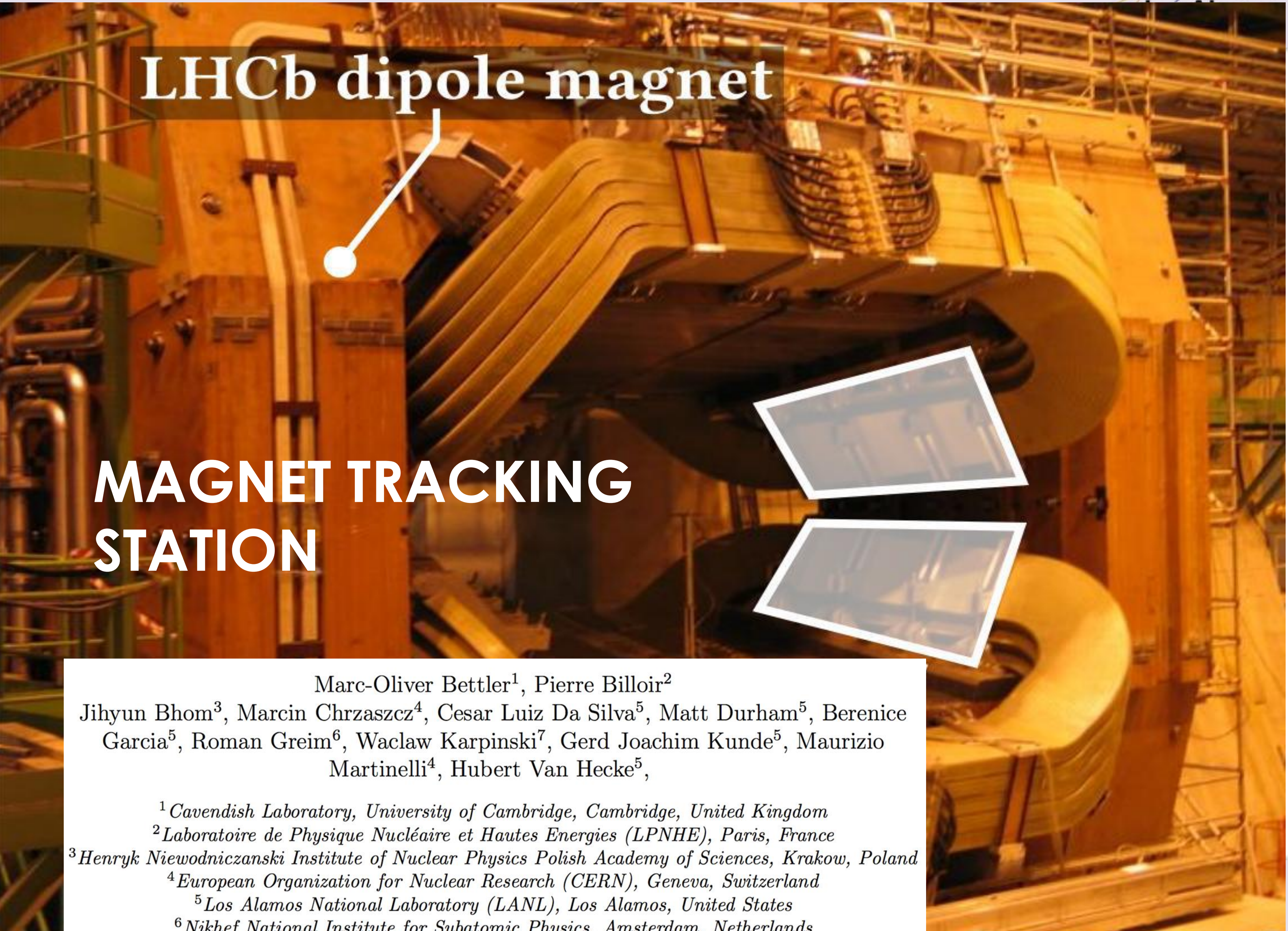

MAGNET TRACKING STATION

Marc-Oliver Bettler[1], Pierre Billoir[2]
Jihyun Bhom[3], Marcin Chrzaszcz[4], Cesar Luiz Da Silva[5], Matt Durham[5], Berenice Garcia[5], Roman Greim[6], Waclaw Karpinski[7], Gerd Joachim Kunde[5], Maurizio Martinelli[4], Hubert Van Hecke[5],

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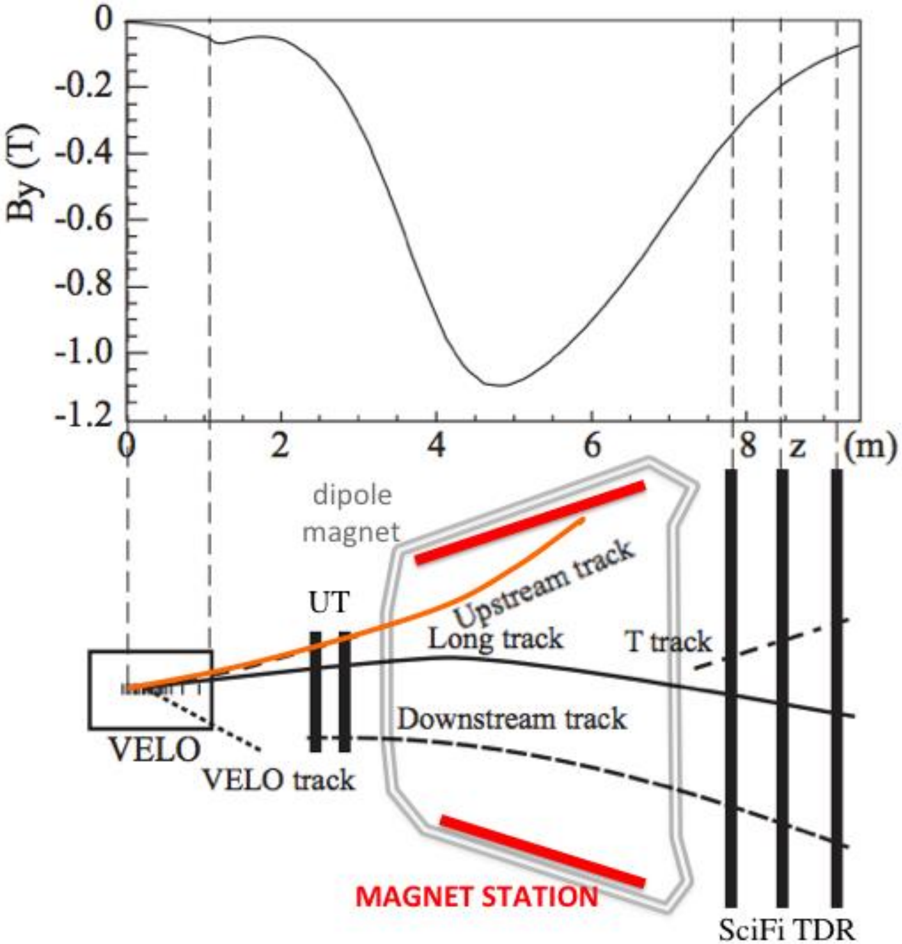
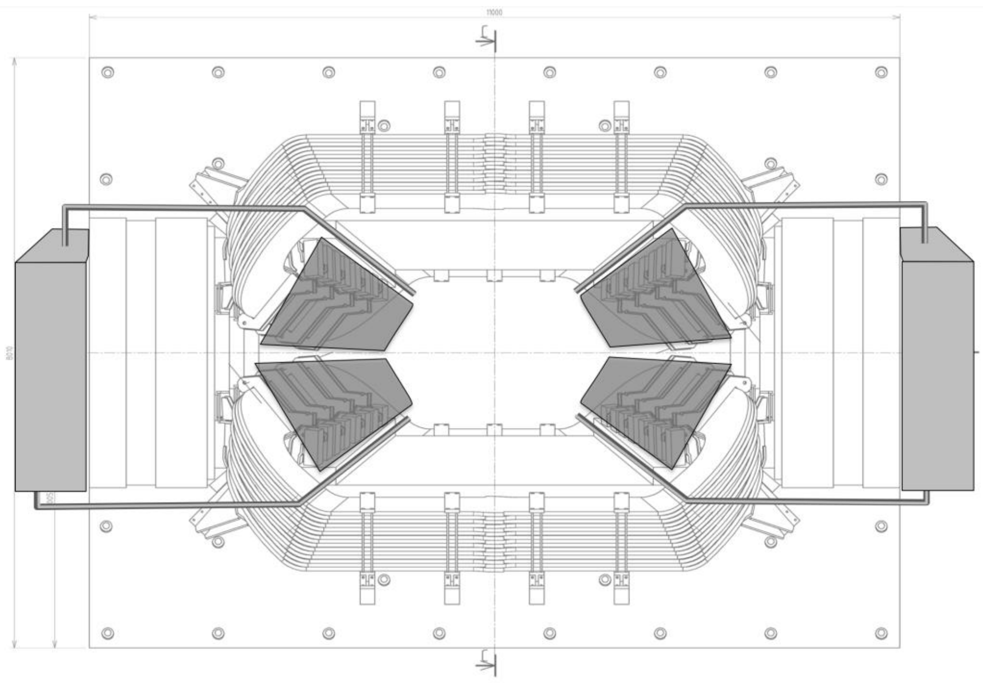
[3] *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[4] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[5] *Los Alamos National Laboratory (LANL), Los Alamos, United States*
[6] *Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*

DETECTOR CONCEPT

Magnet Tracking Station (MTS)

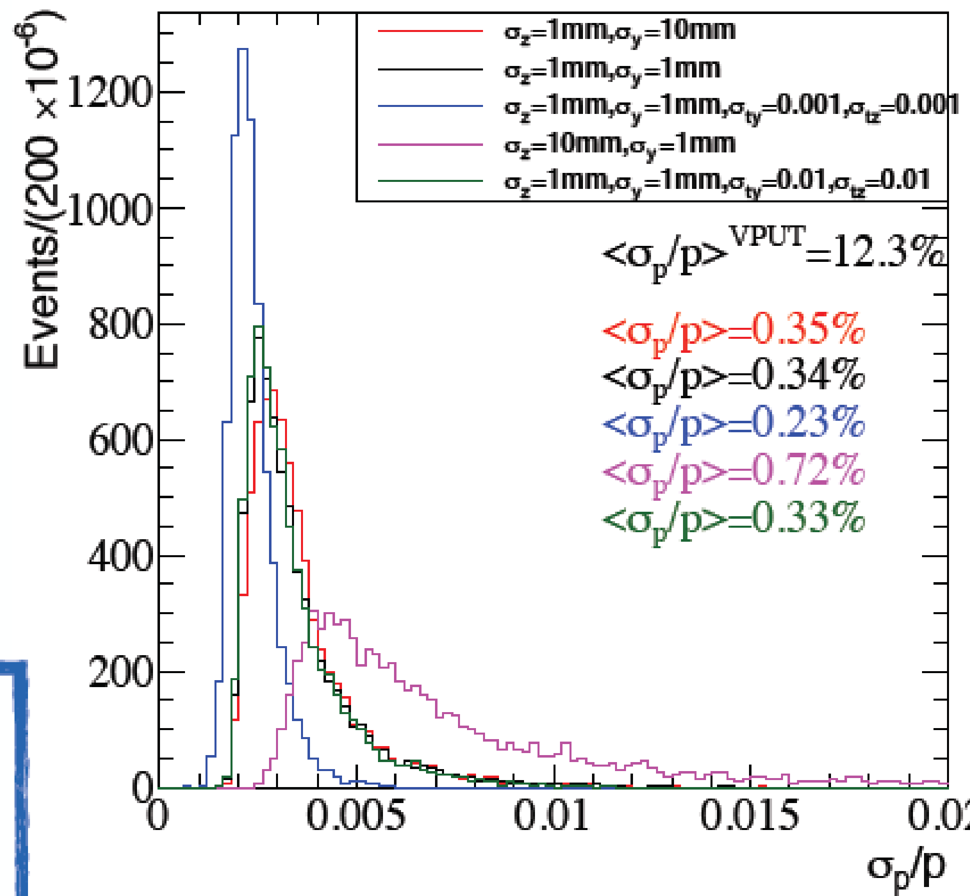




Momentum x Position Resolution

Scenarios

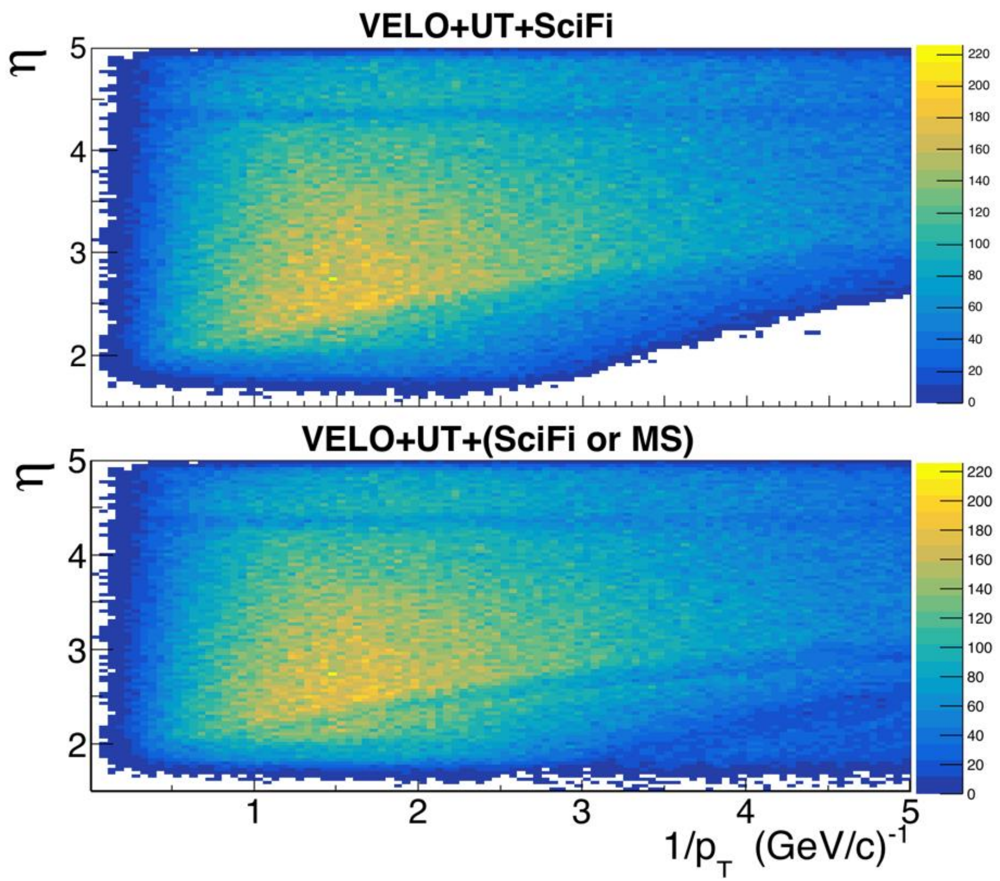
- **Most likely scenario: red**
  σ_z=1mm, σ_y=1cm
- **Very good y-res: black**
  σ_z=1mm, σ_y=1mm
- **Effect of direction angle: blue**
  σ_z=1mm, σ_y=1mm, σ_{ty}=1mrad, σ_{tz}=1mrad
- **Effect of direction angle (realistic): green**
  σ_z=1mm, σ_y=1mm, σ_{ty}=10mrad, σ_{tz}=10mrad
- **"Poor" z-resolution: magenta**
  σ_z=1cm, σ_y=1mm



Even assuming the estimate wrong by 100%, <1% uncertainty seems possible!

σ_Z=1mm , σ_Y=. Occupancies determine segmentation.

High Momentum Resolution Particle Acceptance



~15% more particles with high momentum resolution

2.6 x increase of converted photons w/ hits in UT:

- more pi0 and etas
- gamma+hadron(jet) correlations

May reduce inv. mass combinatorics in ion collisions and high luminosity pp runs.

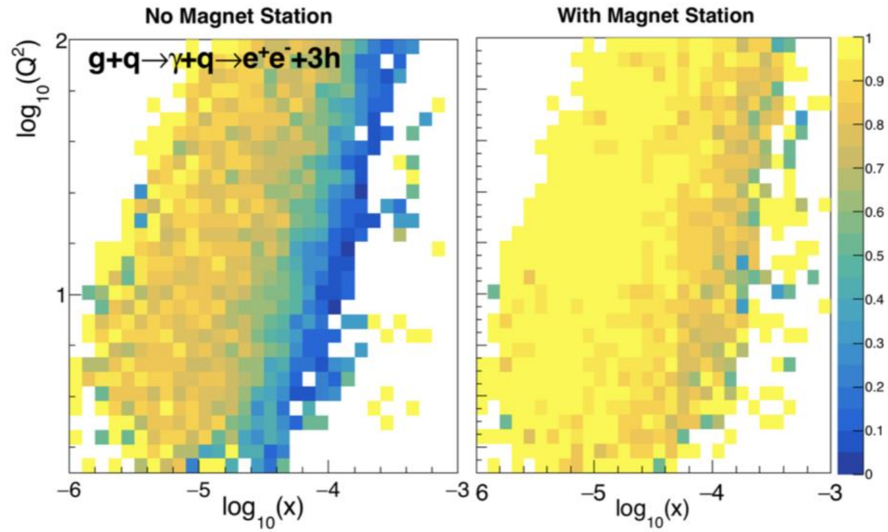
PHYSICS CHANNELS

SLOW DECAY PRODUCTS

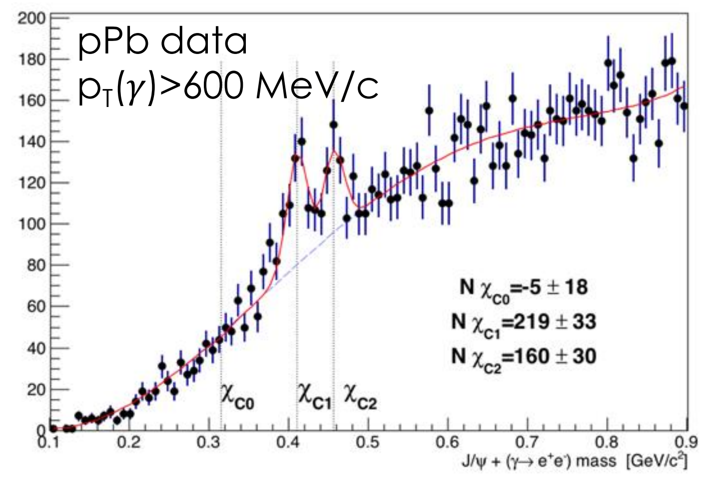
- $D^* \to D(\pi K)\pi_{\text{slow}}$: gain 21 %.
- $\Lambda_b \to \Lambda_c^* \mu\nu,\ \Lambda_c^* \to p\pi_{\text{slow}}\pi_{\text{slow}}$: gain 60 %.
- $B \to D^*\tau\nu$: gain 26 %.
- $\Sigma_b \to \Lambda_b \pi_{\text{slow}}$: gain 29 %.

- $B \to \tau\tau$: gain: 24 %.
- $B \to nK$: gain 10 – 50 %.

PDF, nPDF and gluon saturation



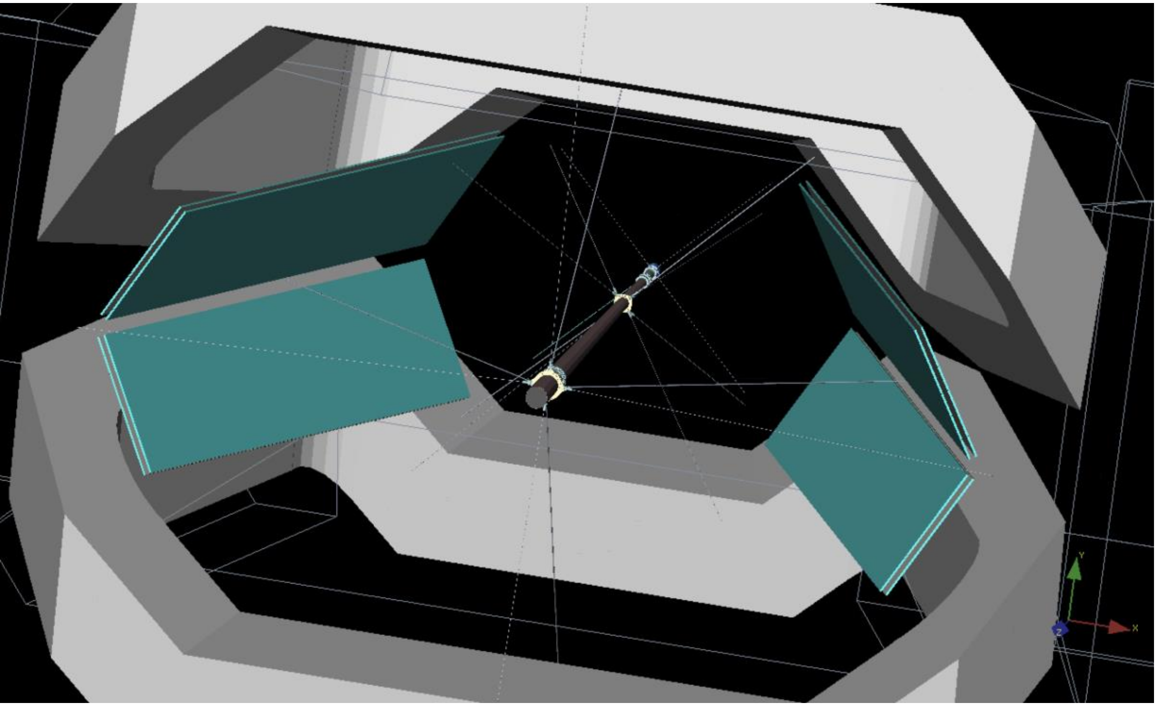
Increase Radiative Decay Acceptance



NEW SIMULATION SETUP

Implementation in Gauss

PANORAMIX



```
TrCutsRunAction("TrCuts").KillLoops = False
TrCutsRunAction("TrCuts").MuonTrCut = 10.0;
TrCutsRunAction("TrCuts").pKpiCut = 0.1;
TrCutsRunAction("TrCuts").NeutrinoTrCut = 0.0;
TrCutsRunAction("TrCuts").NeutronTrCut = 0.0;
TrCutsRunAction("TrCuts").GammaTrCut = 0.03;
TrCutsRunAction("TrCuts").ElectronTrCut = 0.03;
TrCutsRunAction("TrCuts").OtherTrCut = 0.0;
TrCutsRunAction("TrCuts").OutputLevel = 2
```

Minimum cuts for particle selection.

https://gitlab.cern.ch/lhcb-magnet-stations

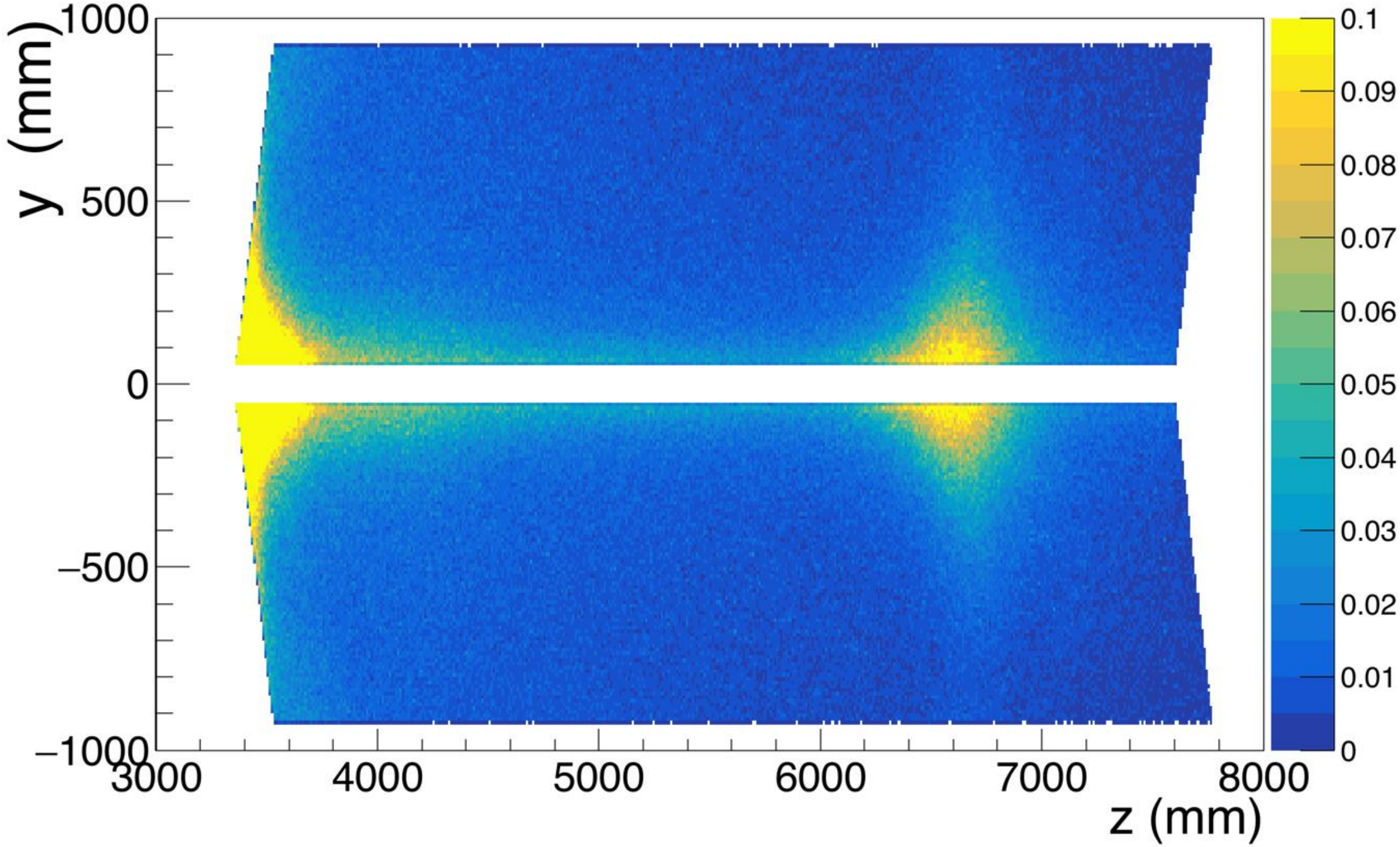
Detector implemented with
- Carbon fiber box
- Tyvek coating
- Scintillator

All available beam pipe support implemented.

10K events
42 collisions per event
(RUN4 Luminosity)

Hit Distribution in one side/plane

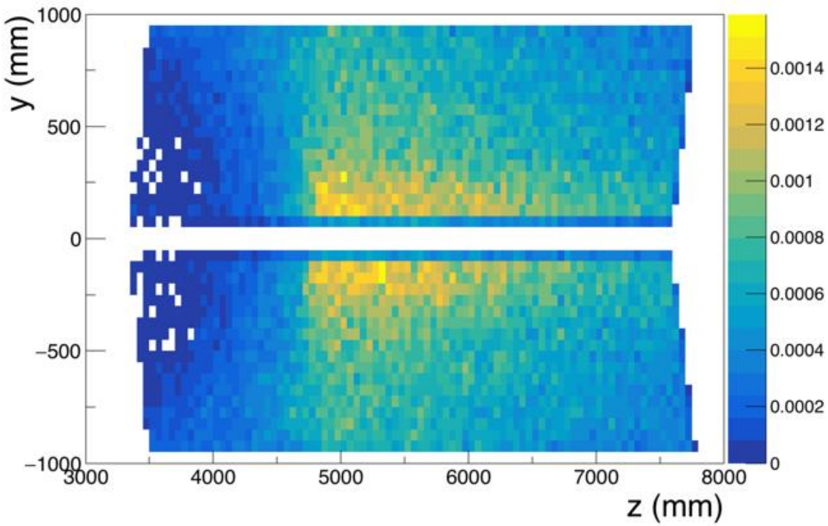
ALL PARTICLES **Hits/bunch/cm^2.**



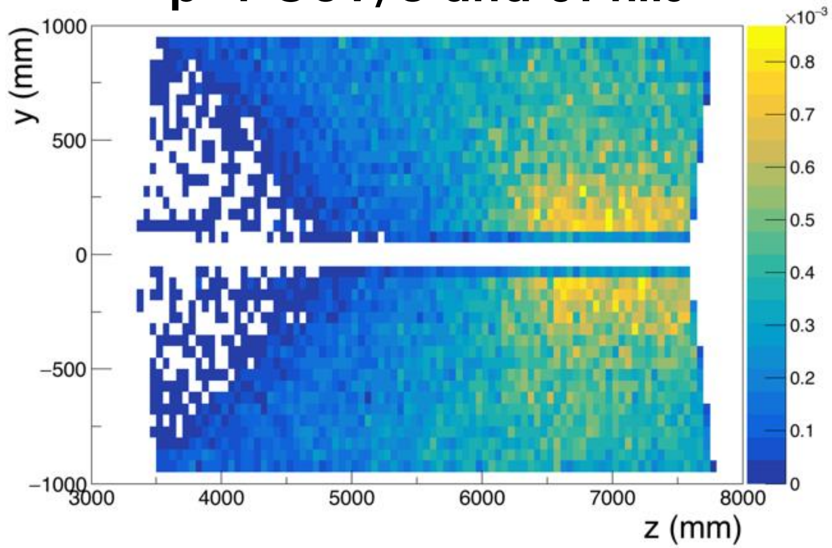
42 collisions per bunch

Particle Acceptance

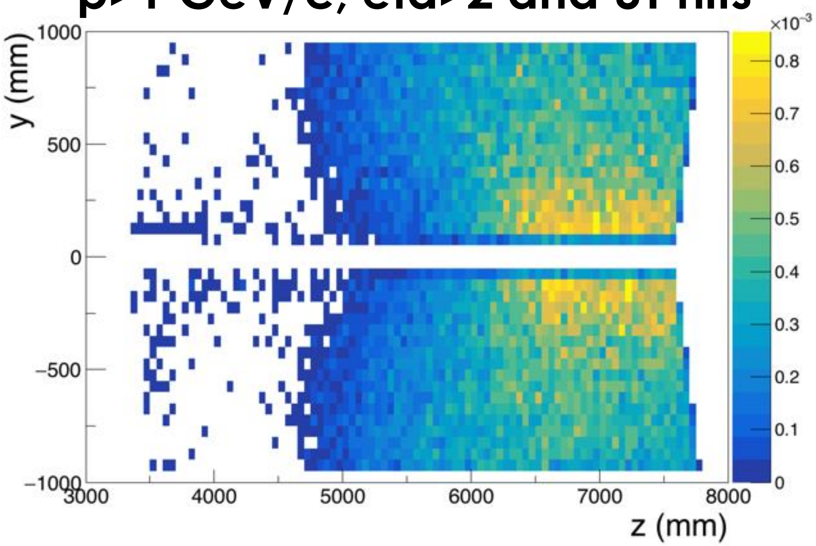
p>0.5 GeV/c and UT hits



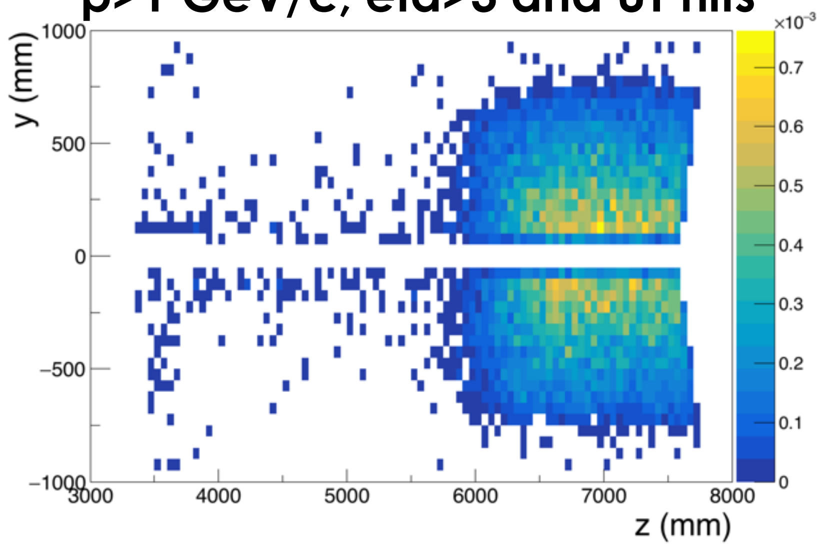
p>1 GeV/c and UT hits



p>1 GeV/c, eta>2 and UT hits

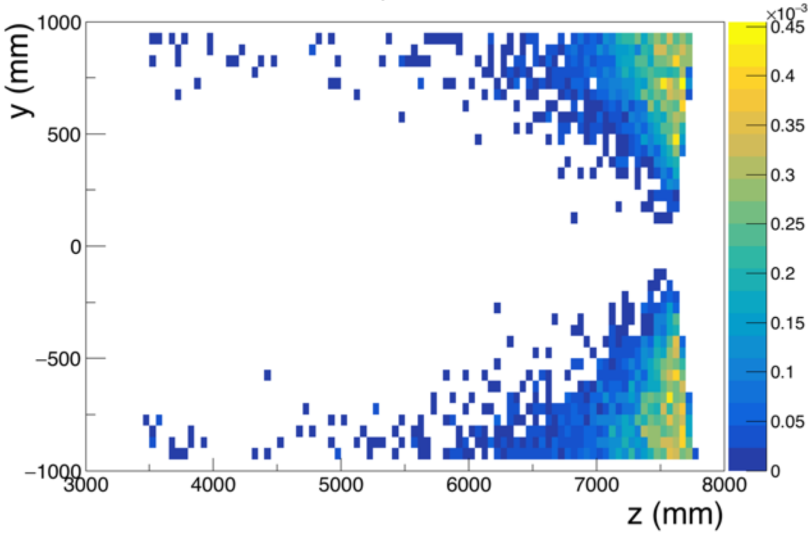


p>1 GeV/c, eta>3 and UT hits

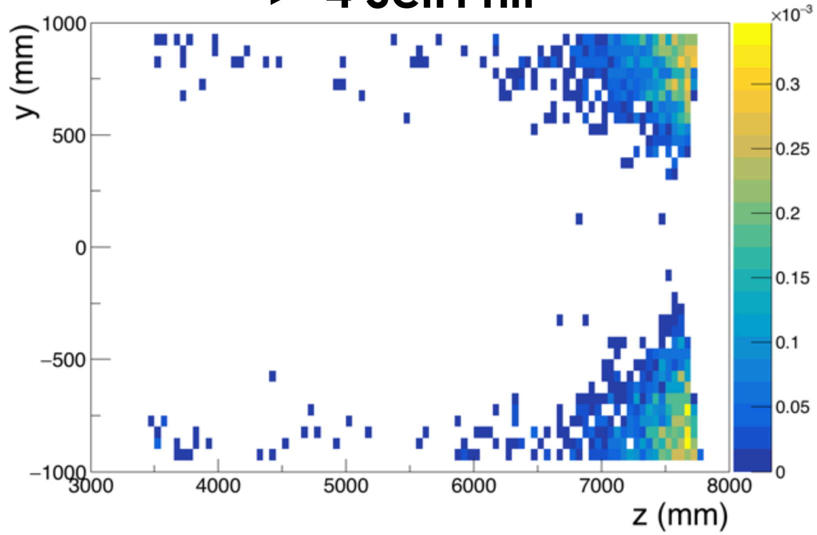


Redundancy with SciFi

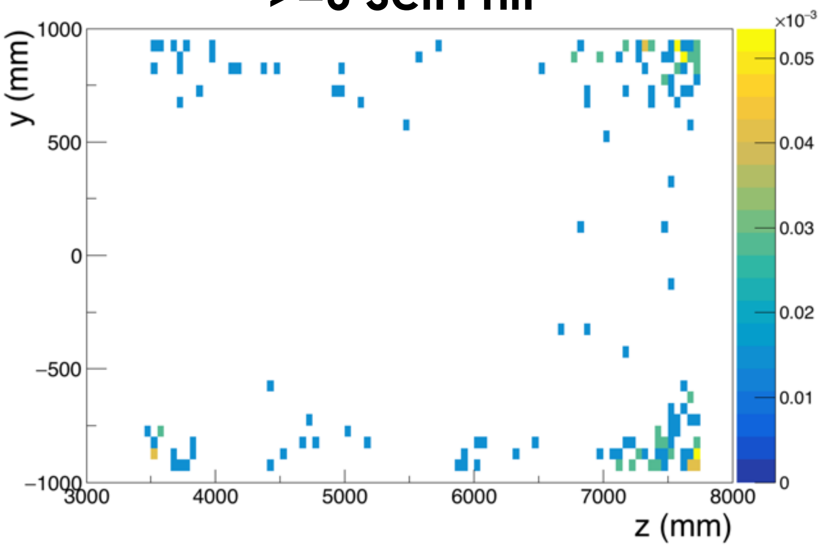
>=1 SciFi hit



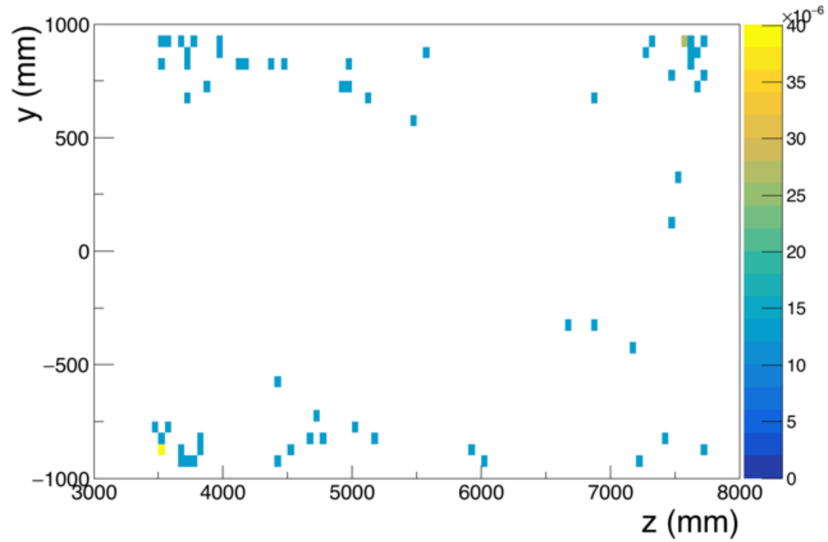
>=4 SciFi hit



>=6 SciFi hit



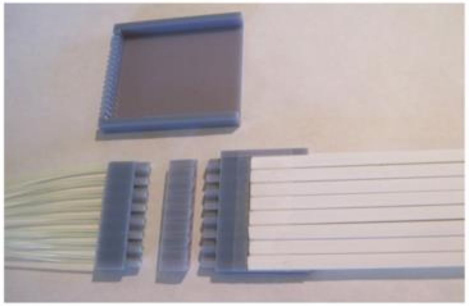
>=8 SciFi hits

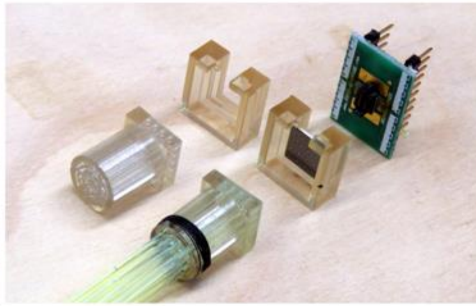


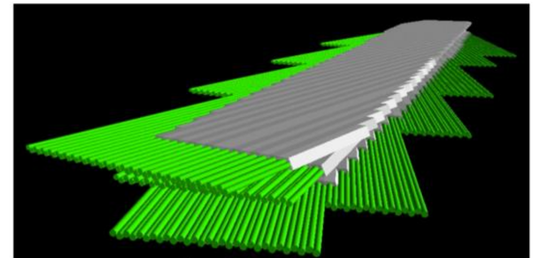
DETECTOR SEGMENTATION/ORIENTATION

Triangular Extruded Scintillating Bars

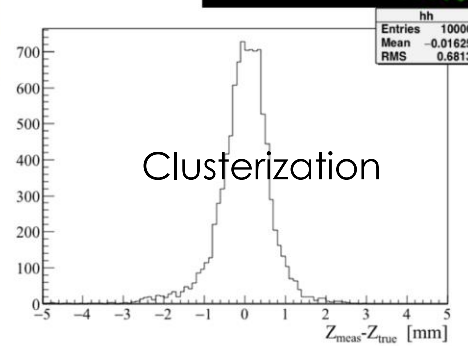
Los Alamos NATIONAL LABORATORY EST. 1943

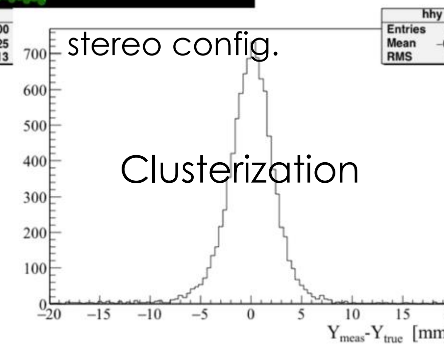




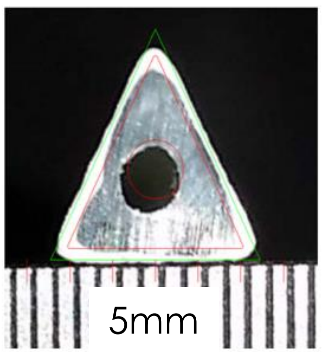


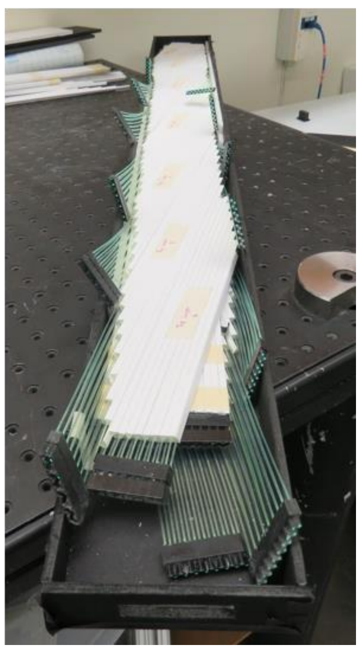
GEANT4





$\sigma_Z = 0.7mm$ $\sigma_y = 3mm$

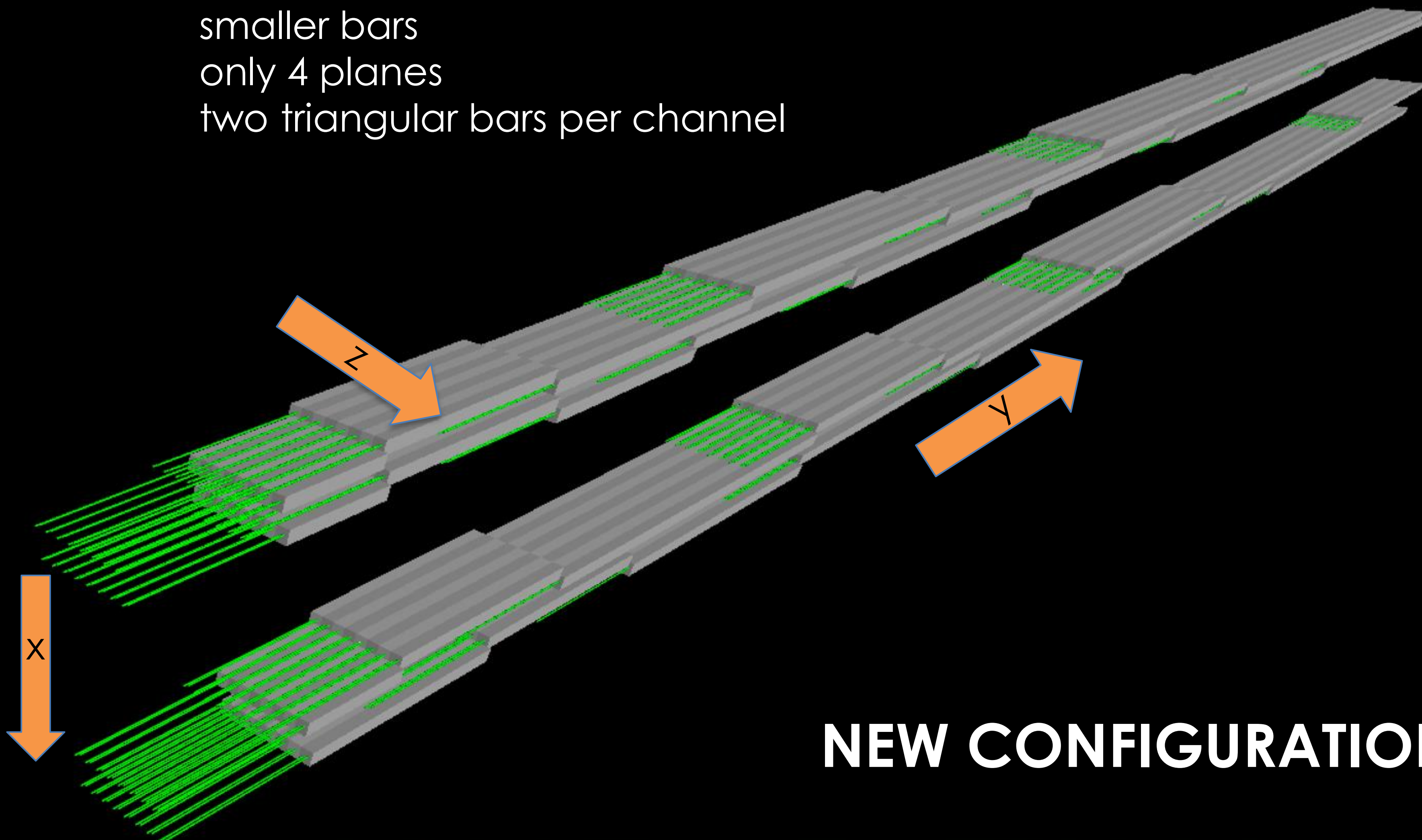




- Ongoing R&D in LANL
- 5mm side triangular bars fabricated at FNAL
- Embed wavelength shifter coupled to clear fibers.
- Similar concept used in DØ.
- Coupling concept well developed
- **5% light yield loss after 10 kGy.**

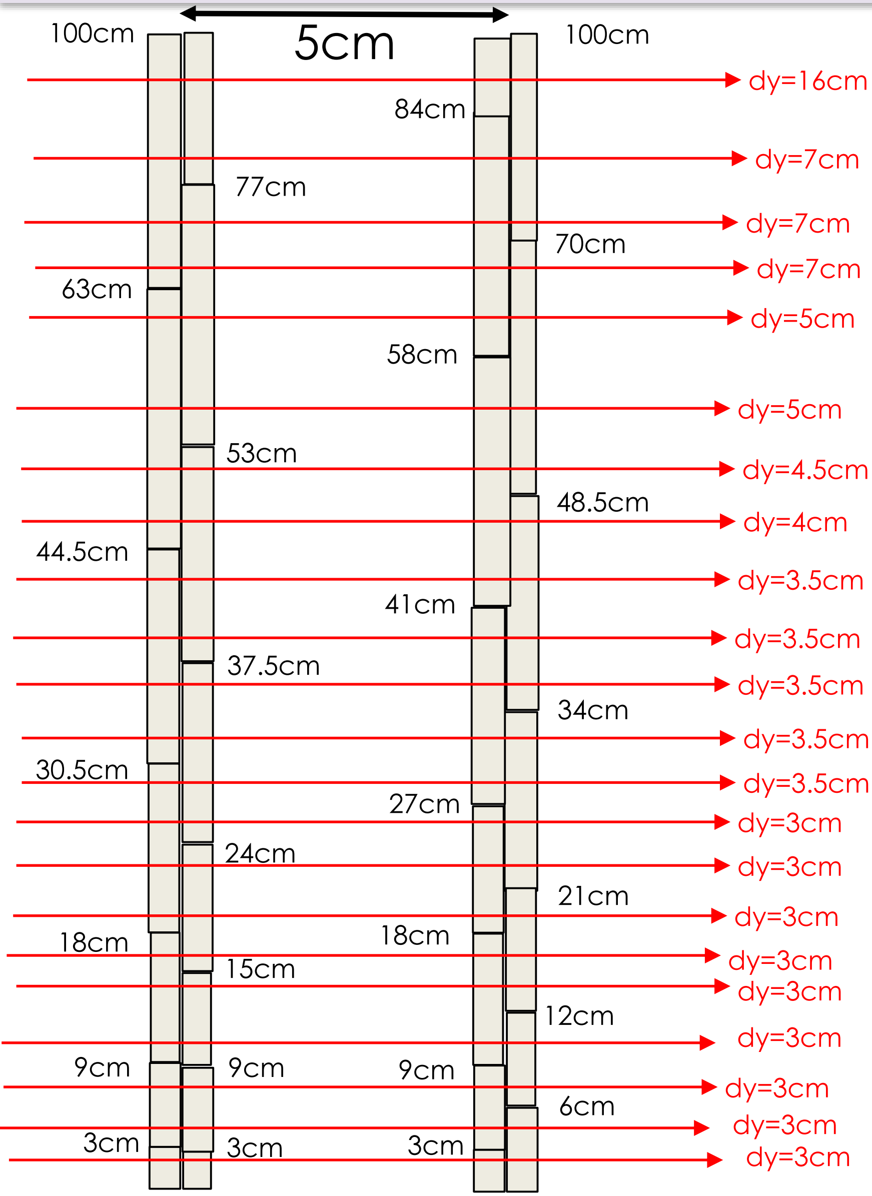
Berenice Garcia (LANL)

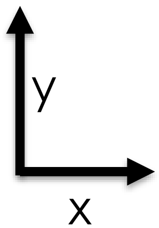
smaller bars
only 4 planes
two triangular bars per channel



NEW CONFIGURATION

Bars Orientation in each Panel

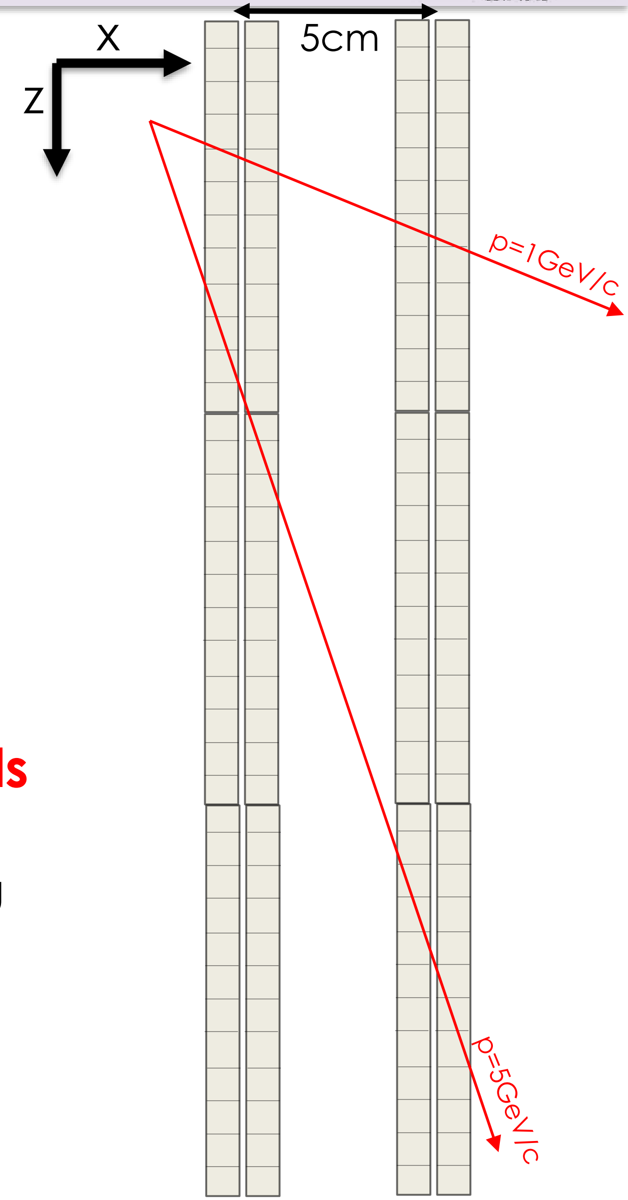




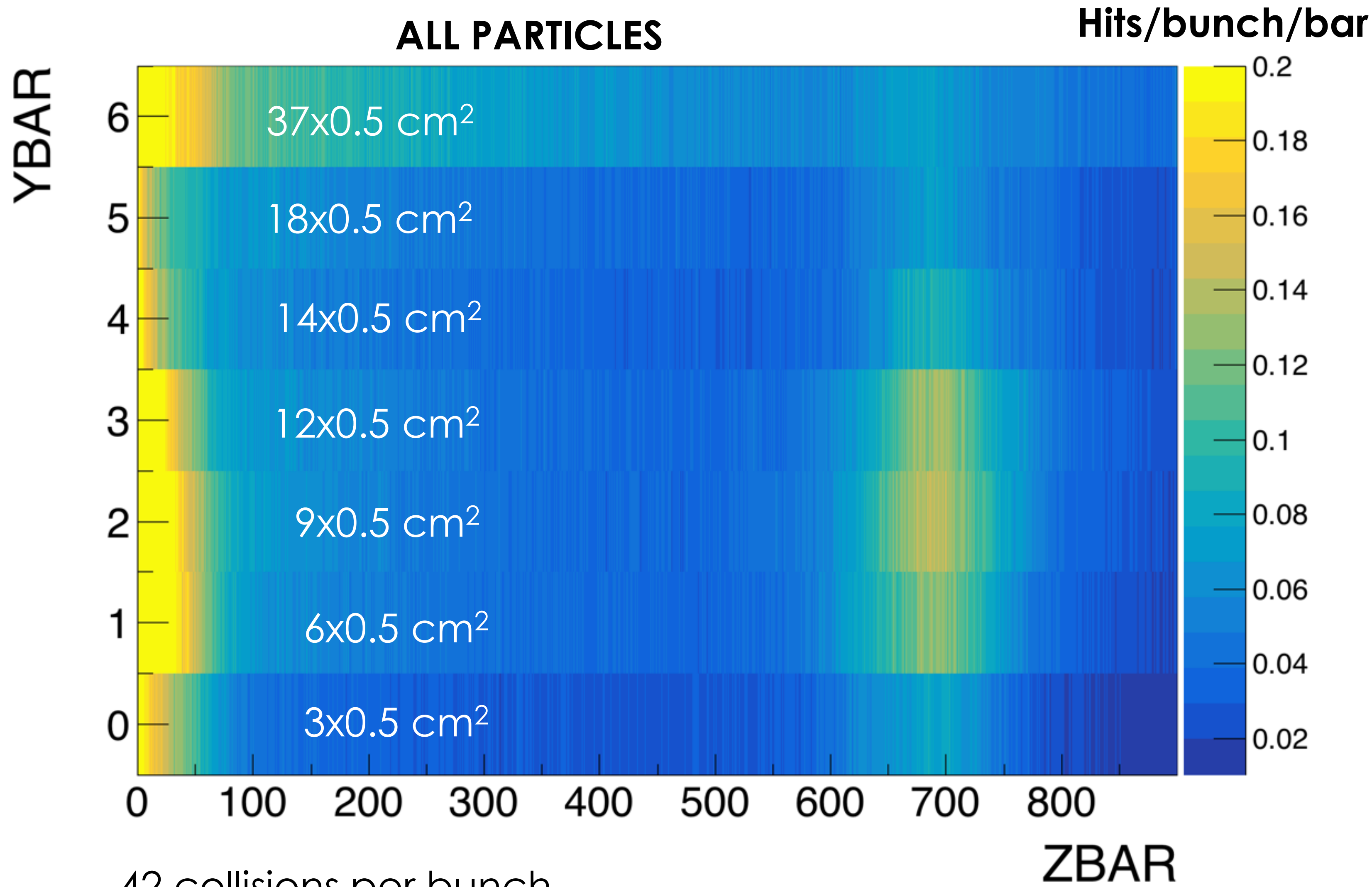
Bars not in scale

30 ybars
*** 4 panels**
*** 600 zbars**
= 72K channels

for all 1x3m² long panels



Bar Hit Distribution in one panel



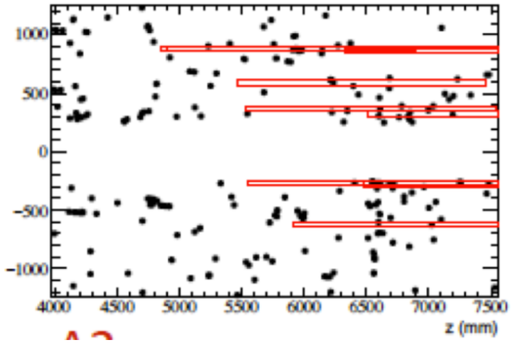
42 collisions per bunch

UT track + MS hit matching

Los Alamos NATIONAL LABORATORY EST. 1943

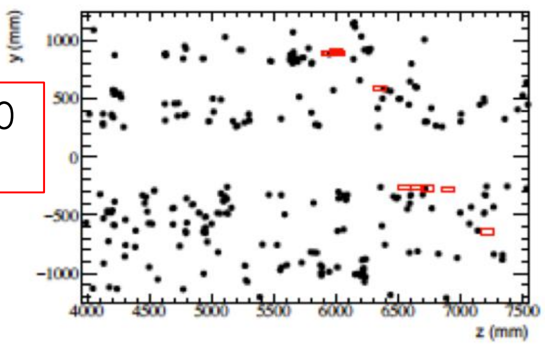
UT projection

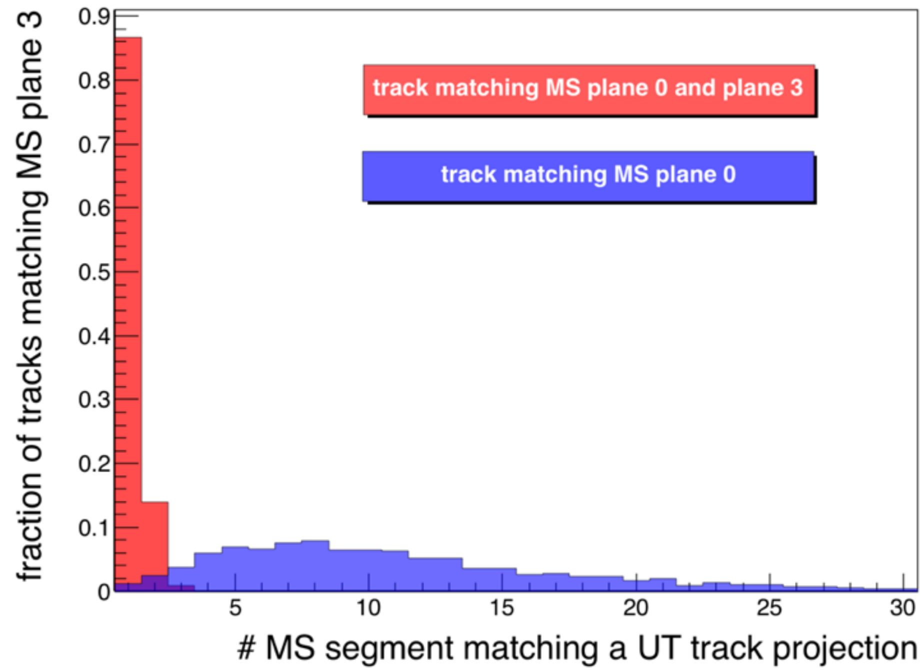
plane 0



UT+MS plane0 projection

plane 3





Robust against occupancies in 42 collisions per bunch.
Further improvements:

- Matching a 4-hit tracklet
- Tracklet clusterization

Radiation Level inside the Magnet

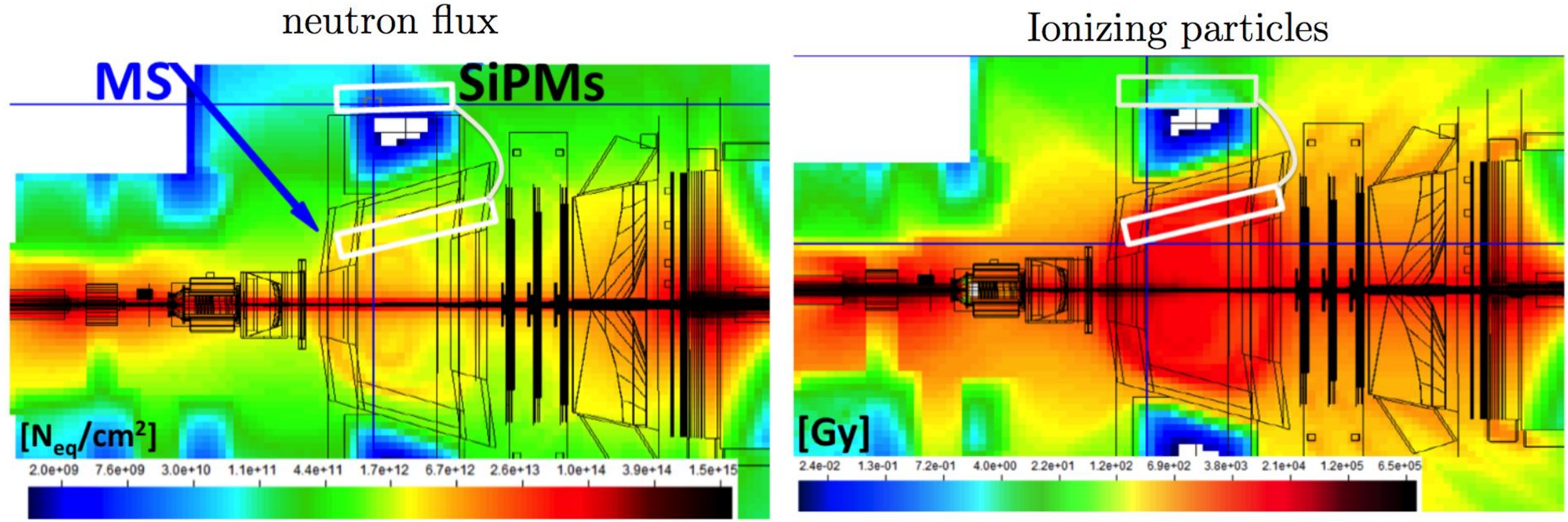


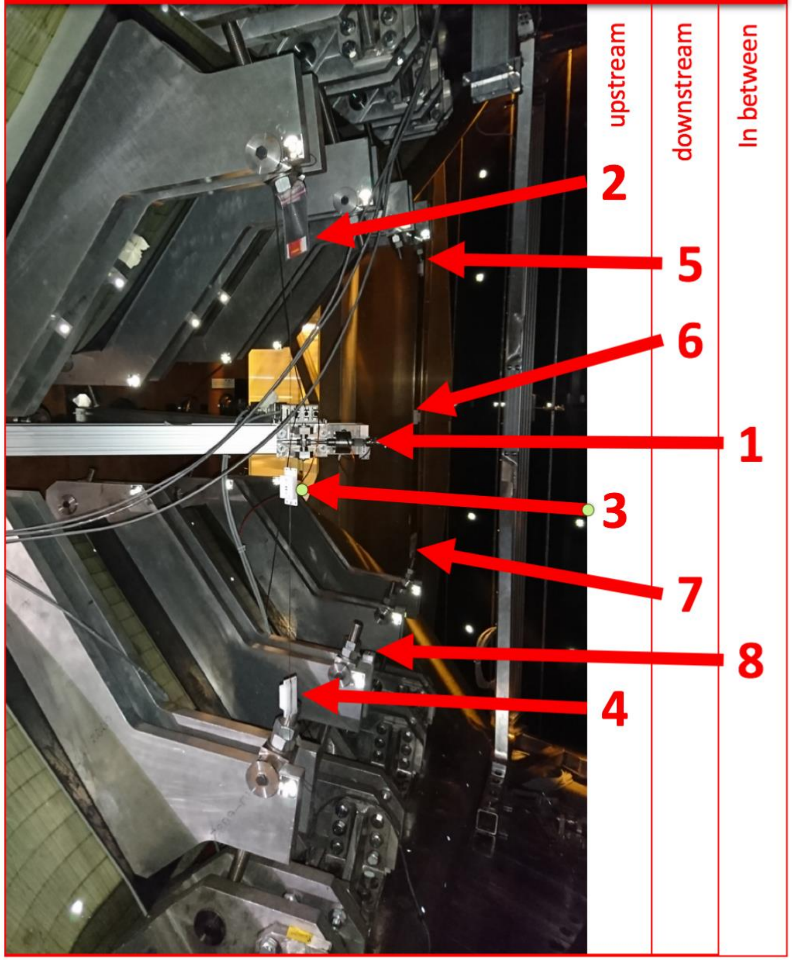
Figure 16: Radiation levels inside the magnet at the beam line plane estimated by Fluka simulations along with the position of the scintillating planes and SiPMs.

Radiation levels and 25 ns detector response determine the choice to use scintillating bars or fibers.

SiPM readout would require shielding + cooling inside the magnet. Moved to outside the magnet, where radiation levels are ~10^{-3} smaller than in SciFi.

Beam support not in FLUKA simulation.

Position Labels



Dosimeters read out in TS2 2017 (Sept.)

The accumulated dose corresponds to an **integrated luminosity of 0.9512 fb^{-1}**

ID	Label	Alanine Dose [Gy]	Simulation Dose [Gy]	Ratio Sim/Al	x [cm]	y [cm]	z [cm]
16211	1	39	79	2.03	190	-3	525
16212	2	18.4	48	2.61	172	42	458
16213	3	129.1	140	1.08	172	-1	458
16214	4	16.6	47	2.83	172	-42	458
16215	5	8.9	18	2.34	245	67	639
16216	6	167.7	96	0.57	245	-1	639
16217	7	11.1	18	1.62	245	-67	639
16218	8	9	17	1.89	190	-58	525

Difference of simulation/measurement within factor of 3 at the evaluated positions

Extrapolation for an **integrated luminosity of 50 fb-1**

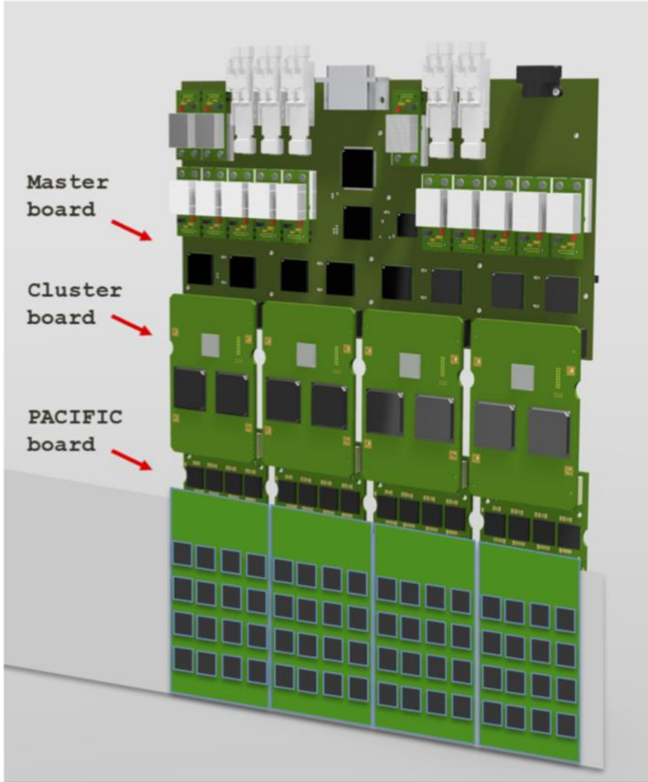
ID	Label	0.95 fb^{-1} Dose [Gy]	50 fb^{-1} Dose [Gy]	x [cm]	y [cm]	z [cm]
16211	1	39	2050.042	190	-3	525
16212	2	18.4	967.1993	172	42	458
16213	3	129.1	6786.165	172	-1	458
16214	4	16.6	872.582	172	-42	458
16215	5	8.9	404.7519	245	67	639
16216	6	167.7	8815.181	245	-1	639
16217	7	11.1	583.4735	245	-67	639
16218	8	9	473.0866	190	-58	525

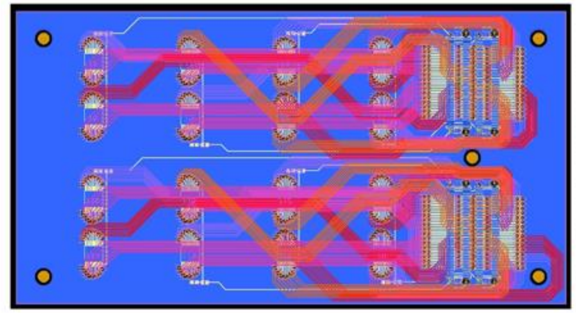
Bars have 5% light yield loss after 10 kGy

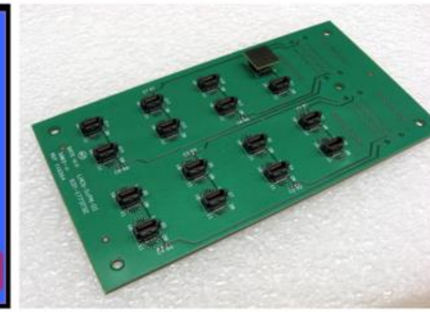
FLUKA overestimate radiation levels in most points.
Should still take a factor of ±3 uncertainty in FLUKA and measurements.

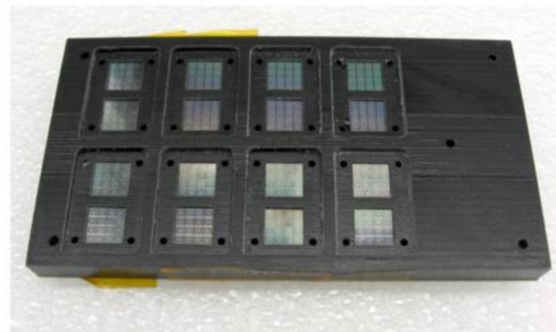
ELECTRONICS AND COOLING

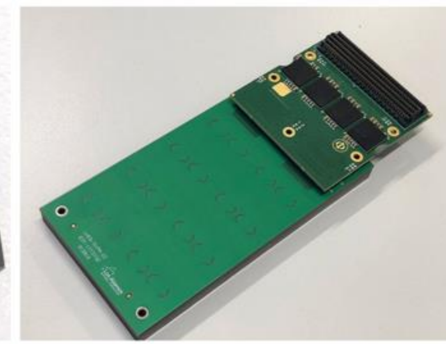
Adapting to the SciFi electronics readout

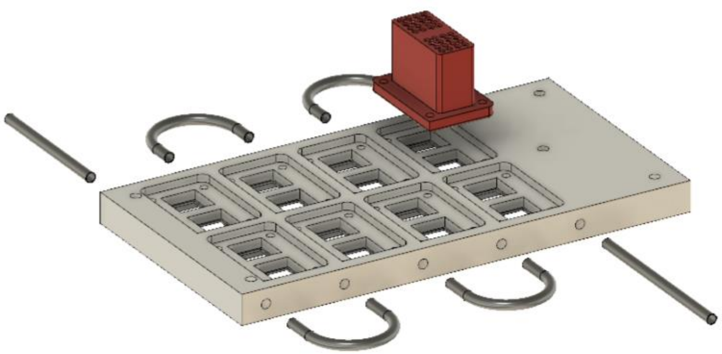








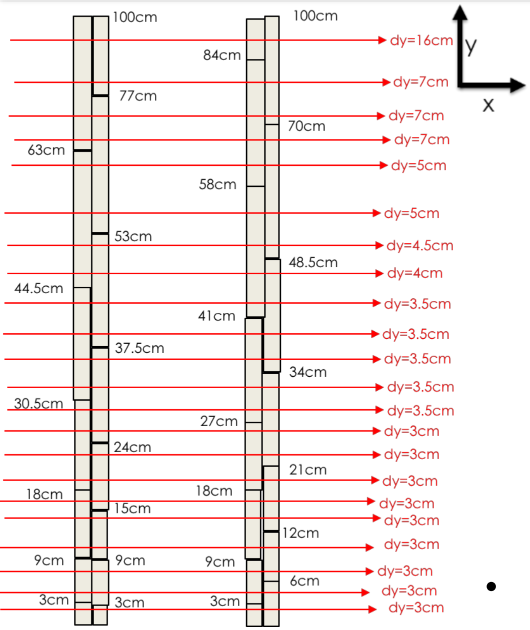


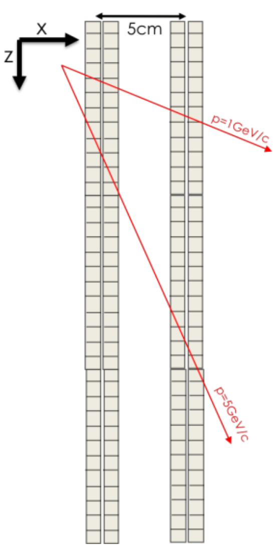


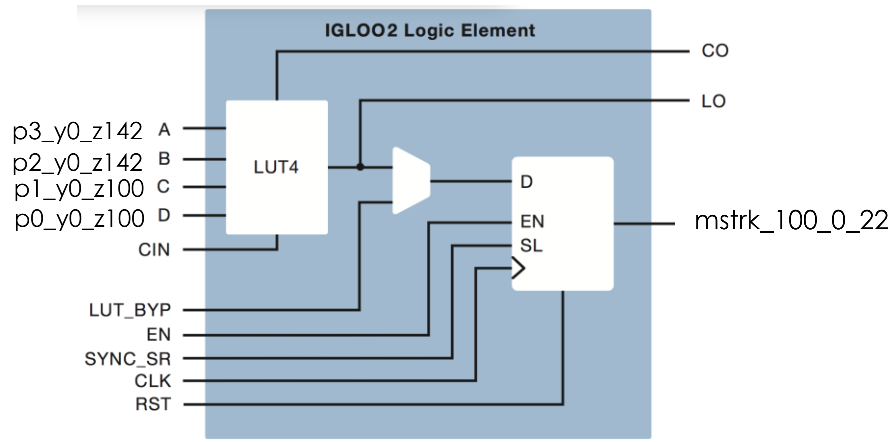
Adapting 16 SiPM arrays (256 channels) to a SciFi/PACIFIC board.

Designed cooling concept for SiPMs array board.

First thoughts about MS tracklet logic







- 22 y segments per z column (particles from vertex don't bend in y direction)
- z0-z2-z3-z4 combinations depends on the distance between planes
- 40 z0-z1-z2-z3 combinations for 1GeV/c < p < 5 GeV/c
- 600 z columns per panel
- ~240k combinations per panel (18 bits ID in the data package)
- 2bit ADC information from each of the 4 bars associated to the track for offline ghost track rejection and track clustering
- 2-3 IGLOO2 FPGAs (150K LE each) per panel

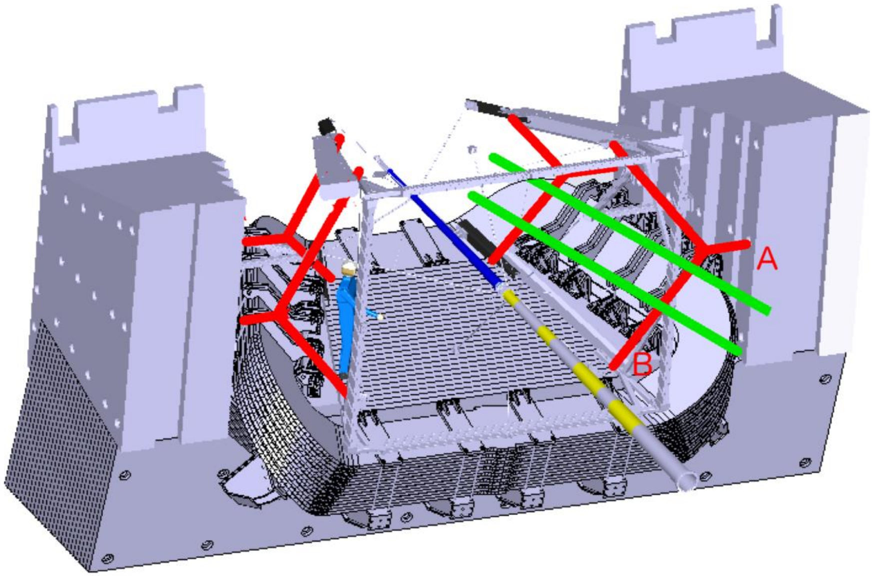
DATA STREAMING

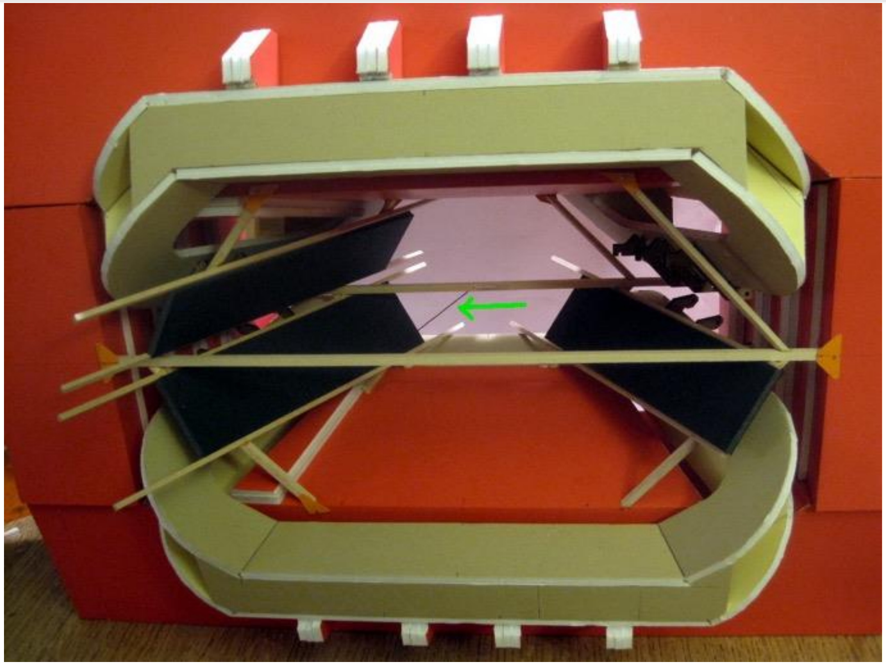
	HIT STREAMING	TRACKLET STREAMING
N entries	900 hits / panel/bunch	~25 tracklets / panel/ bunch
Nbits	15b ID + 2b ADC	18b trackID + 4b total ADC
Bit rate	~ 612 Gb/s	~22 Gb/s
N GBTxs	~200	~ 7

- HEADER: 12-bit bunch crossing ID + truncation bit + [11b(N hits) or 6b(Ntracks)]
- Hit and tracklet activities based on Gauss w/ 42 collisions / bunch
- Z>4m, removing high activity in the entrance of the magnet
- Further track clustering in FPGA can reduce data rates by nearly a factor of 3

MECHANICAL STRUCTURE

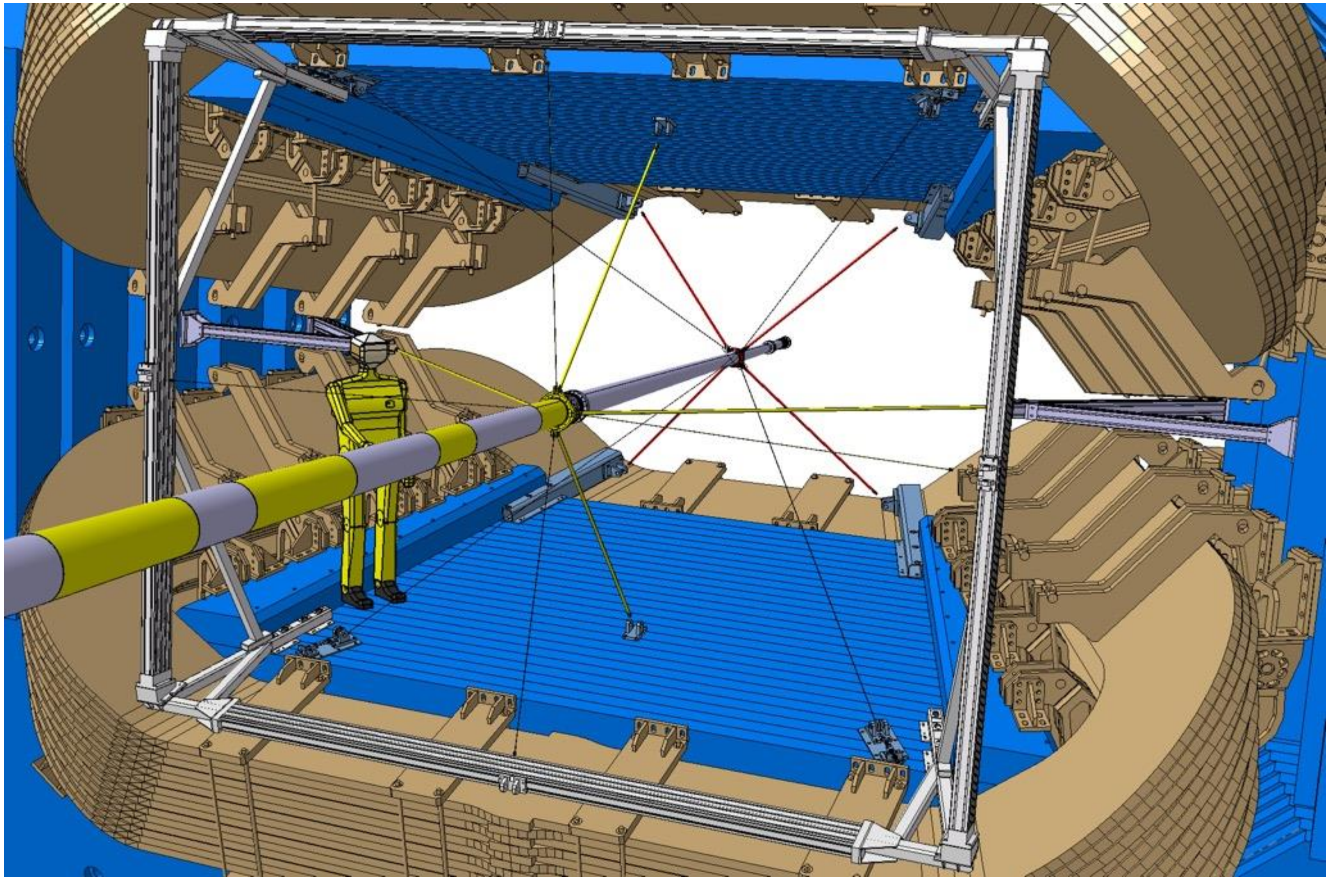
Installation





- Mounted a realistic 1:21 mockup of the magnet in foam board (vertical bars are only to sustain the mockup): study structure and installation procedure
- 4 panels installed on rails from the SciFi side, rails can fold during installation
- Connections with magnet yoke may allow ~1mm freedom for magnet moves when changing polarities.
- LANL mechanical engineer already working on the drawings

MECHANICAL STRUCTURE IN SIMULATION



- No spiderweb support for the beam pipe is implemented (side bars) in the simulation geometry
- No mechanical structure (rails)
- May need another FLUKA

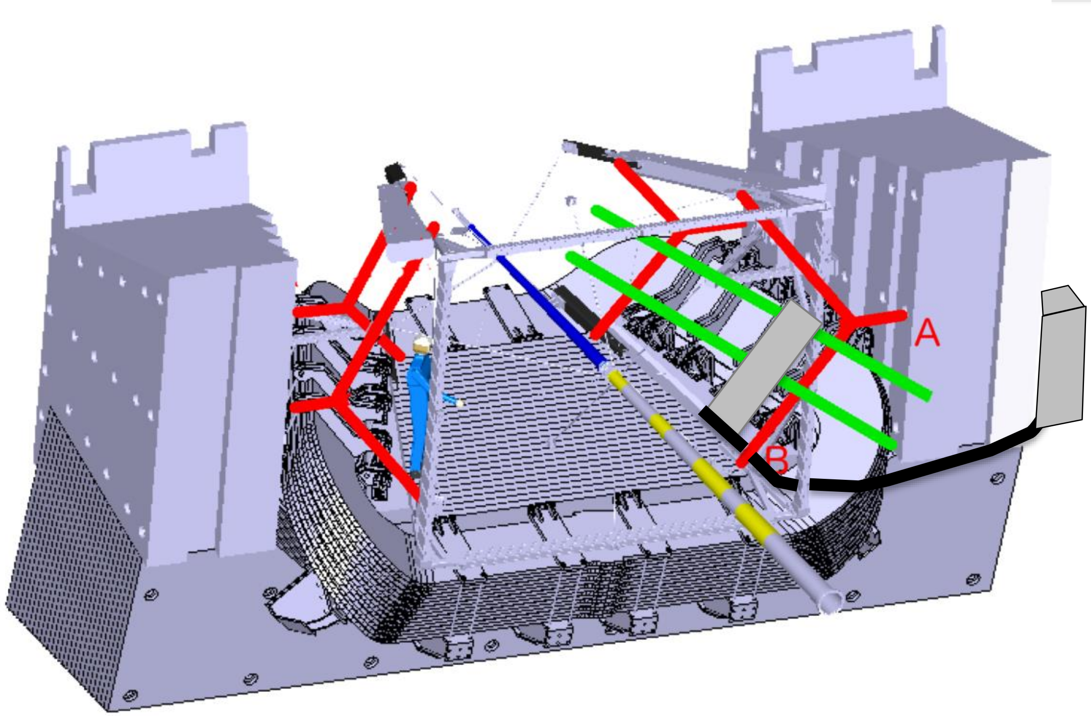
Estimated Costs

Item	Quantity	Cost
Hamamatsu SiPM S13360-1375PE 1.3×1.3 mm^2	1/ch	CHF 7.7 / ch
1mm ø Kuraray scintillating fiber (SCSF-78M)	100 cm/ch	CHF 1.1 / ch
0.5 mm ø Kuraray clear fiber (Clear-PSM)	2 x 5 m/ch	CHF 4.5 / ch
Fiber-clear fiber coupling	1/8ch	CHF 0.13 / ch
Readout electronics	1/ch	CHF 5 / ch
Extruded scintillating bars	30 Km	CHF 200K
Mechanical Structure, crates, cooling		CHF 200K

TOTAL material and services costs for **3m long** detector along Z with 72K channels is **~CHF1.4M.**

No labor costs involved.

Proposal to Install a Prototype During LSII



Full set of rail bars for future installation

A 6-planes 80x100 cm^2 panel prototype (bars configuration)

1024 channels: one SciFi electronic module

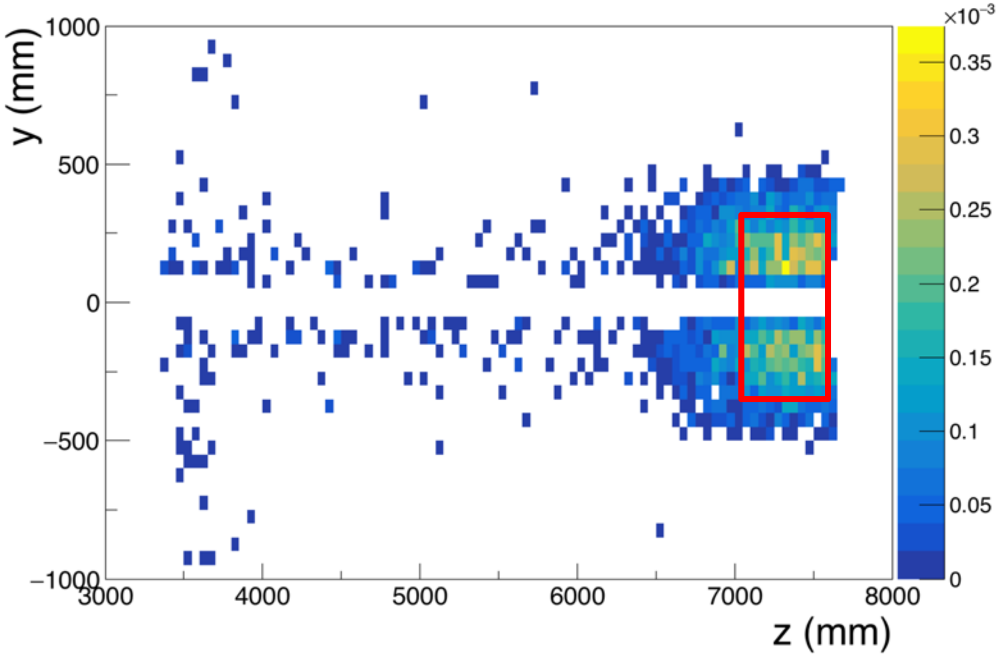
Hall probes attached to the panel.

Funding available for this prototyping.

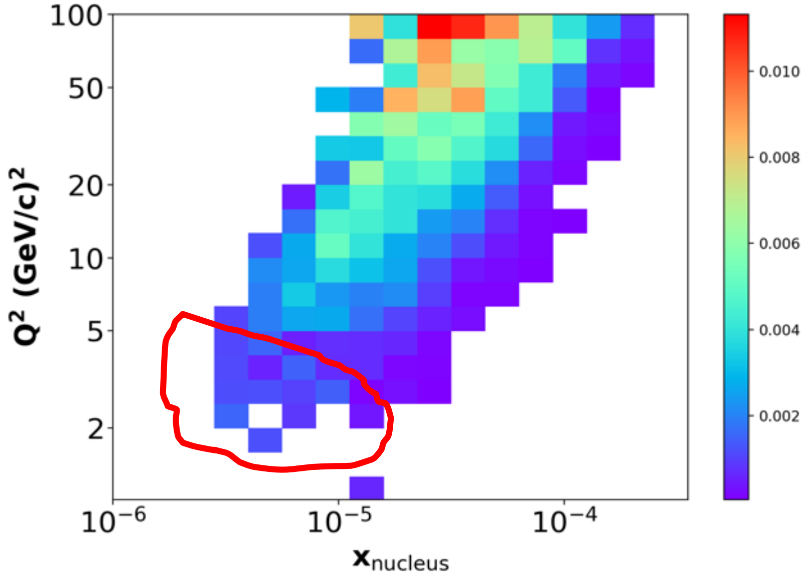
- Much to learn about it:
  - Realistic occupancy levels
  - Aging of bars and fibers
  - Tracking
  - Magnetic field: track projection uncertainties range from 1mm to 10mm in the edges of the magnet (fringe fields)
  - Readout electronics performance

Physics with the prototype ?

Electrons from converted photons
p>1.2 GeV/c, eta>3.5 and UT hits



g+q->gamma+h



Needs to run a dedicated simulation for a confirmation.

Needs more channels and a panel in each side of the detector for e+e- detection.

Summary and Next Steps

- A more realistic detector geometry and digitalization now available in a private Gauss+Boole+Brunel gitlab area
- Simulation can be used to explore more physics channels
- Staying away from stereo planes. New segmentation provides a smaller number of channels and occupancy
- Proposing the installation of a small prototype inside the magnet during LSII for precise detector characterization and maybe small-x physics
- A note was released 2 months ago, now largely outdated. Another version to be released soon.

PARTS OF THE REVIEW REPORT

The proposal relies on well-understood scintillating bar or fibres that have been used in previous projects and exploits existing electronics readout chains. Thus, **assuming the fibres and proposed layouts are found to meet the resolution, occupancy and radiation specifications, the technical risks of this subdetector will be relatively low and thus could be suited to installation in LS3.**

Recommendations for physics and detector simulations

The proponents have clearly demonstrated that there is a significant sample of VELO-UT tracks to which the magnet stations can add additional hits. The panel considers that it is important to show the physics gain of adding the magnet side stations, compared with that available from using the the VELO-UT track alone. **Showing the corresponding improvement on mass resolution for particular decay modes** may be an e↲ective way of demonstrating the improvement.

A prototype of a realistic reconstruction algorithm which includes the **matching of the hits to the VELO-UT tracks within realistic search windows will be an important development**. This will allow the evaluation of the efficiency, ghost level and additional computing time of the magnet station tracks.

Since the performance of the detector depends strongly on the occupancy, it is essential to simulate correctly the distribution of low-momentum particles. It is therefore recommended to check the **Geant parameters (especially cut-off parameters) with experts from the simulation group**.

Recommendations for radiation studies

It is requested to clarify what are the radiation levels and particle densities that are expected from simulation and how these values were informed by local measurements of the radiation dose. The detector occupancy numbers and radiation levels can be checked for consistency, and should be shown for Upgrade I and Upgrade II conditions. **Introducing a small reference volume just in front of the SciFi may facilitate the cross-check.**

To better understand the particle fluxes and the radiation levels the referees support the idea to install a prototype detector during LS2. However, before choosing a technology and constructing a detector a **better understanding of the expected multiplicities** should be gained.

The dose released to scintillating fibres or bars and consequent light yield loss should be computed for the full Run 4-6 operation.
The **radiation damage should also be evaluated for the clear fibre sections** used to transmit the light to the SiPMs.

Recommendations for mechanical issues and related timescale considerations

The readout of the envisaged detectors by SiPMs relies on a good connection between scintillators and clear fibres. In case of the fibre option this could become critical. The quality of the connection achieved should be clearly presented.

It is proposed to fix the chambers on supports which are themselves attached to the yoke of the magnet. Past measurement have shown that the magnet yoke moves with the magnetic field. The **stability of the positioning should be considered and methods adopted for decoupling from the yoke movements**.

The installation of a prototype in LS2 is proposed by the proponents. This would certainly be very advantageous but the timescale is very tight and it must not adversely affect the Upgrade I activities. **The installation of rails before the LHCb beampipe is installed may be necessary. It is suggested that the proponents make a milestone plan for discussion with the experiment's technical coordination team.**

Given the DAQ scheme in Upgrade I the implication on DAQ, ECS and flow and processing of data from the prototype have to be clarified.

Recommendations for project planning and resources

Designing a detector that will be sucessfully operated throughout the full period of Run 4-6 is highly desirable. The data sample planned to be collected in Run 5 and 6 is an order of magnitude larger than that expected in Run 4 alone. Consequently modest gains obtained across the full period may exceed the benefit of major gains in Run 4 alone.

A possible cost range was indicated in the meeting. The price needs to be commensurate with the physics gain. **The committee feels that targeting numbers at the lower end of the range is more likely to result in a detector that can be financed by the proponents and additional collaborators** and not excessively affect the overall cost of Upgrade II. The upper end of the range given is comparable with the cost of subdetector systems in Upgrade I which are essential for LHCb operation (e.g VELO: 5.8 MSF). The number of channels is likely to significantly affect the cost associated with the detector, readout and processing and thus should be carefully optimised.

As the technical studies progress it may also be useful to clarify with the LHCb partners their potential effort and funding levels for the detector construction phase. Partners from outside the collaboration who would be interested in participating in this project would also be very welcome.

Detailed recommendations for physics and simulation studies

The measurement of **low-momentum tracks in heavy ion collisions may be an important element of the physics case**. If this is the case, suitable studies of the performance improvement should be provided.

The note mentions that the addition of the magnet stations could lead to **physics analyses with soft electrons. The panel suggests that this interesting point is followed up with further studies.**

For understandable reasons it is proposed not to instrument the highest occupancy region around the beam plane. However, in order to assess the loss in physics acceptance from this decision it would be interesting to see the distribution of tracks for decays of interest at the sides of the magnet.

It was pointed out in the meeting that the **spiderweb supports of the beam pipe may not be in the simulation. This would be useful to clarify and discuss with the simulation group whether they should be added**.

Further detailed recommendations

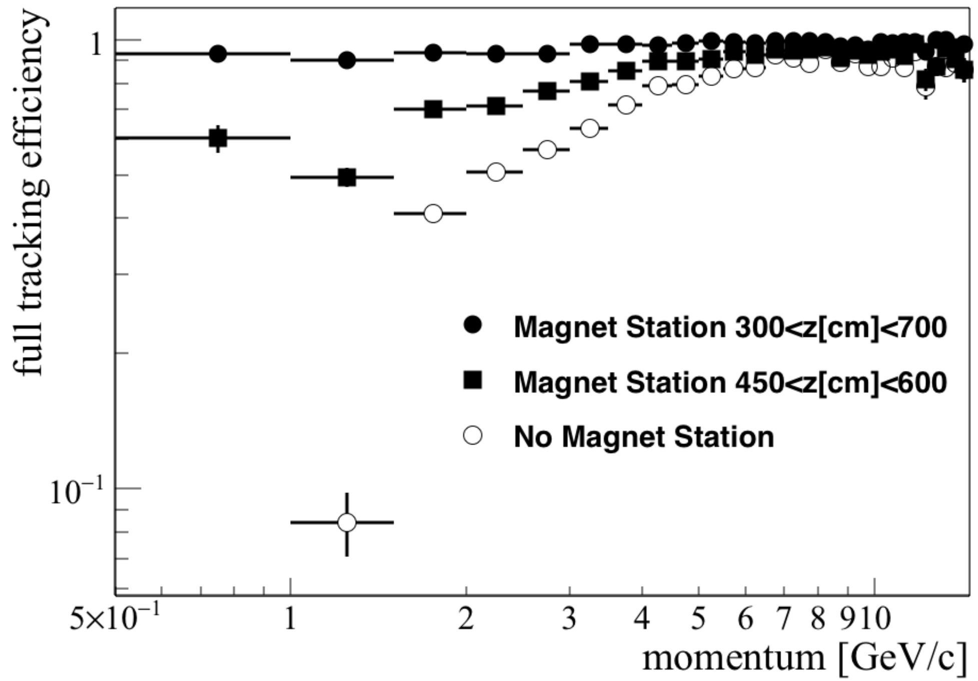
If the prototype goes ahead with installation in LS2, results from its operation will be available by late 2021. The timing of a TDR for this object will need to be considered in light of the availability of these results and the requirements from the proponents' funding agencies.

As part of the future studies of reconstruction performance, **the CPU (or other) resources required to carry out the magnet station clustering and tracking should be estimated, and the associated costs should be factored into the budget**. It will be helpful to discus the cost estimate with the online and RTA groups.

Timescales for LS3 installation are such that it may assist the proponents for them to produce themselves a list of milestones to guide their project design and prototyping studies.

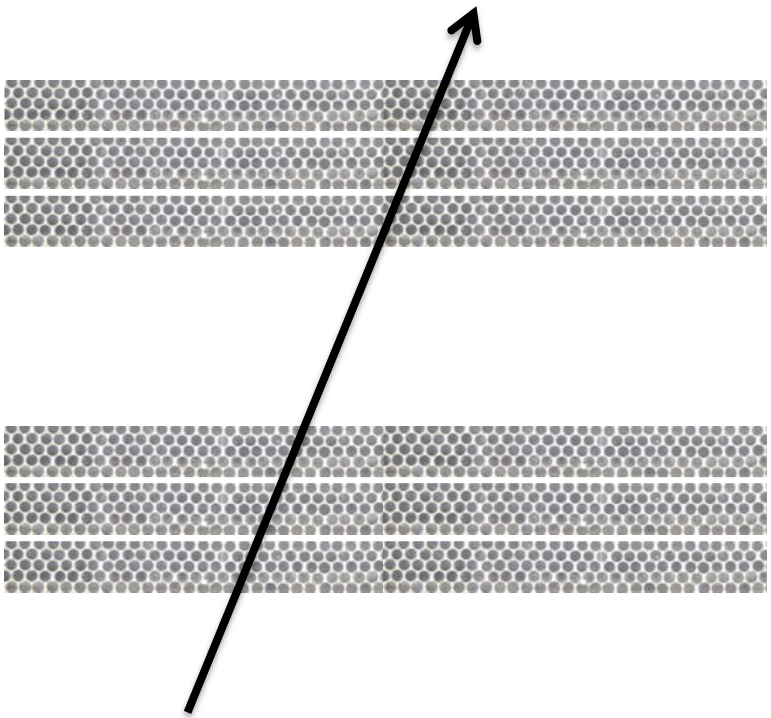
BACKUP SLIDES

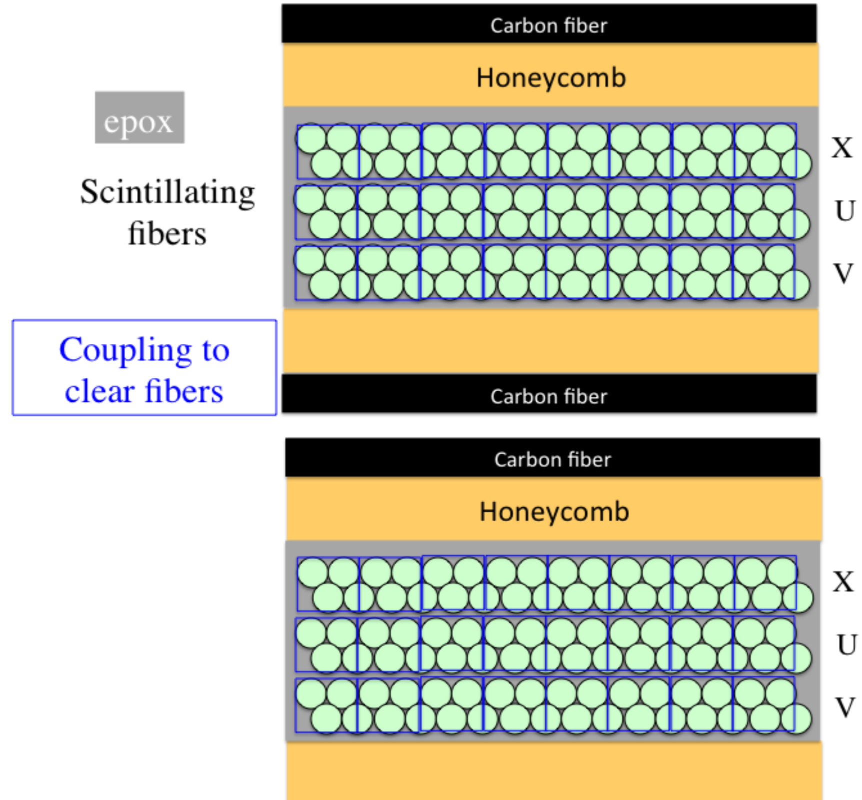
Fast Simulation



Generate particles in PYTHIA
Propagate through LHCb magnet field
Look for the fraction of tracks going to downstream detectors and MTS

Scintillating Fibers

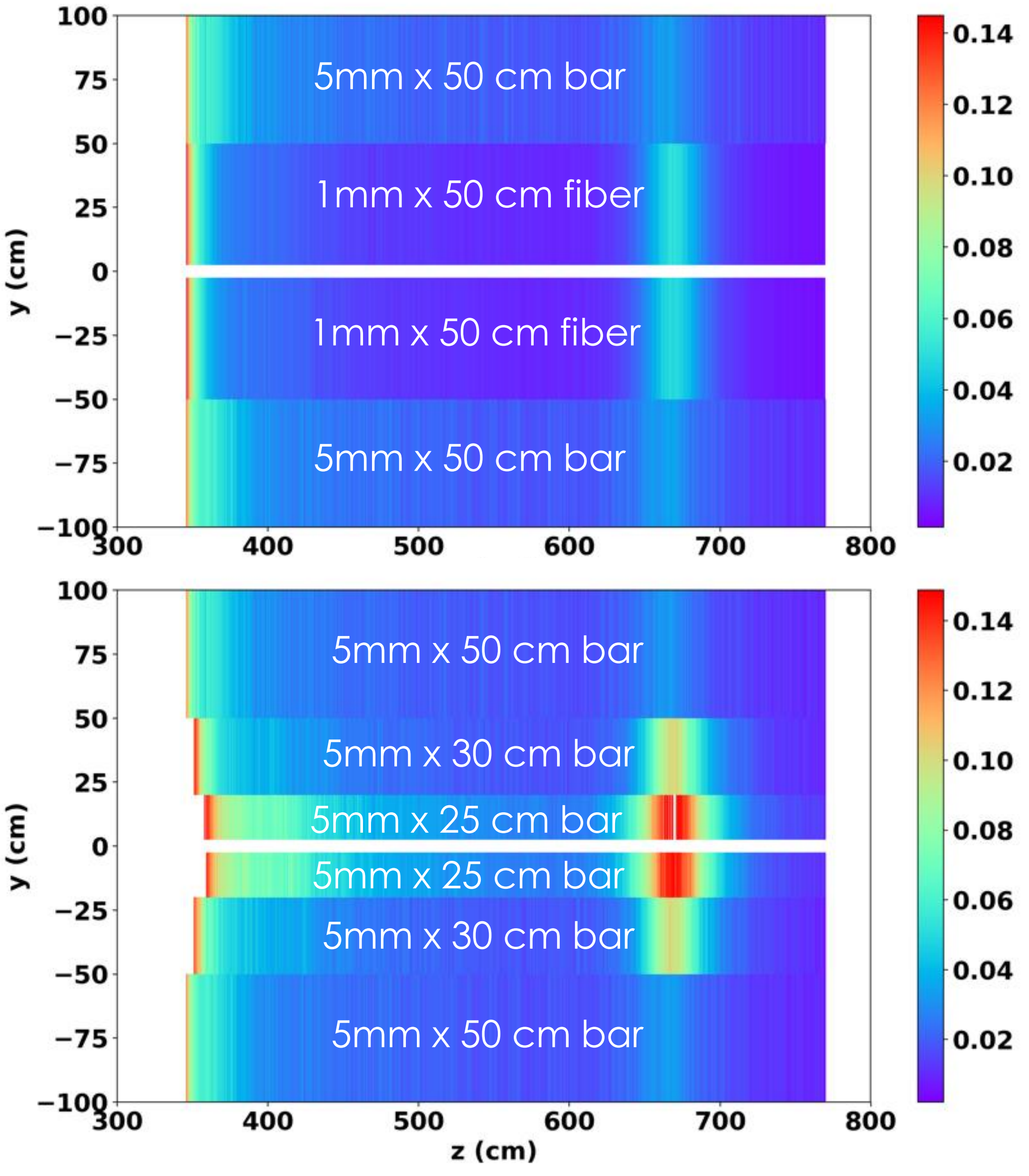




Option using a copy of SciFi panels:
- leverage SciFi technology
- Needs coupling with 1mm clear fiber

Option using a new 1mm fibers panel:
- More reasonable segmentation
- Still challenging coupling

Occupancy per Segment



3m Z extension:
6000 fiber/panel
1200 bars/panel
6 planes x 2 sides

173K channels

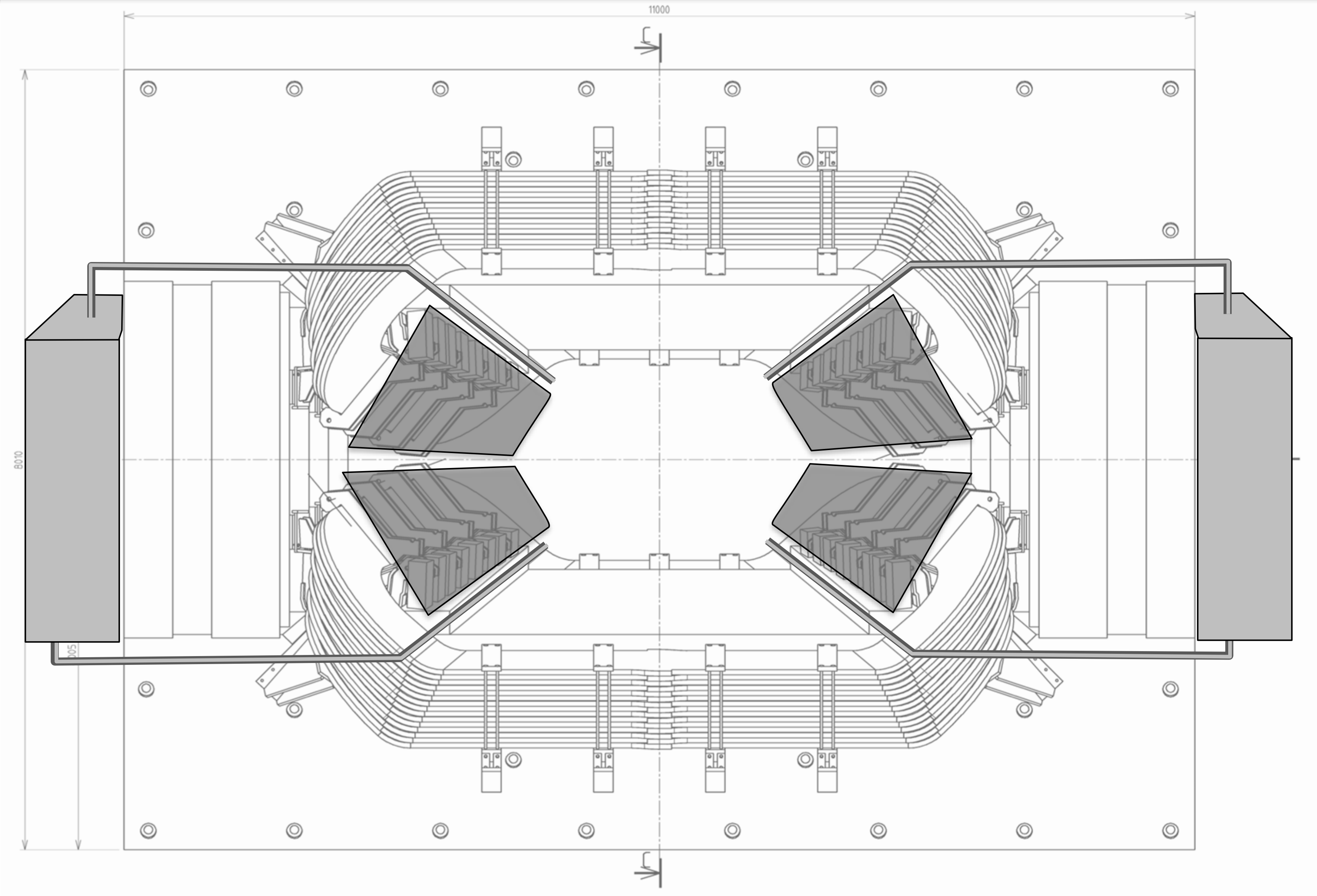
Versions with 6 planes in XUV-XUV configuration

8 collisions per event

86.4K channels

5 cm clearance around y=0 for the beam pipe support.

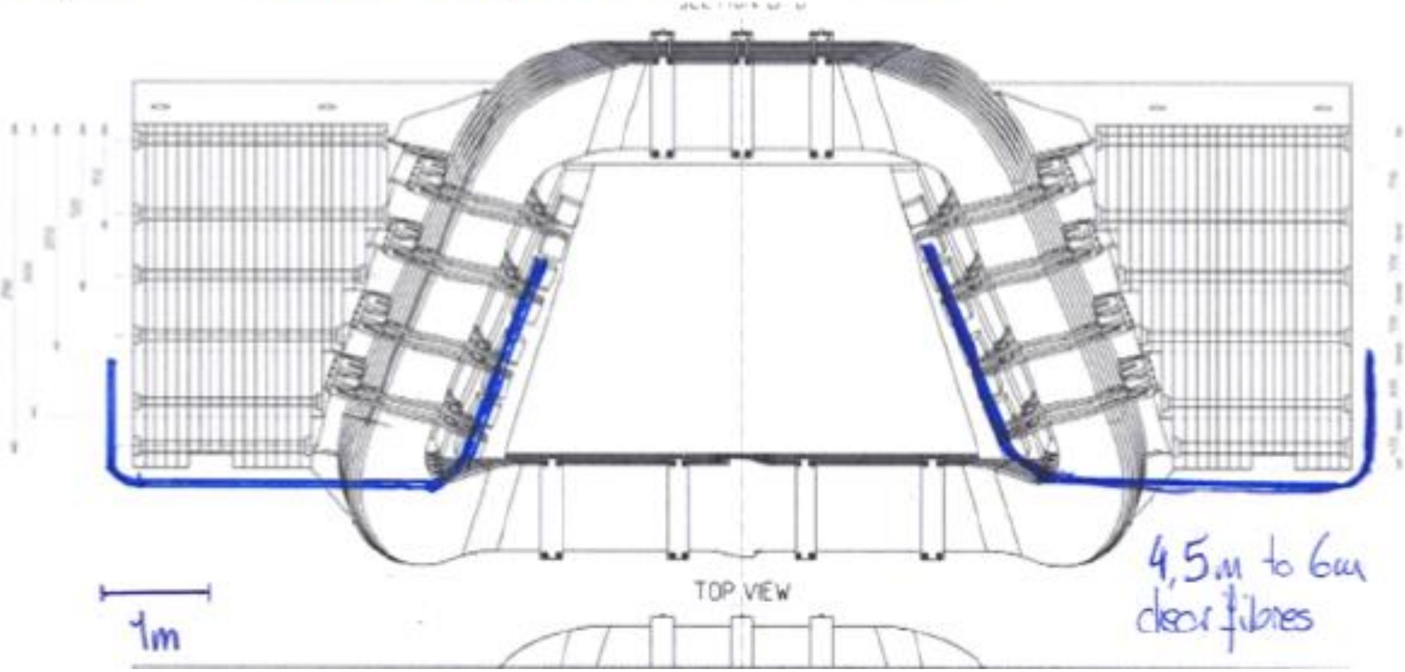
All particles. No minimum energy deposit cut.


11000
8010

Boundary Conditions: Readout

SiPM

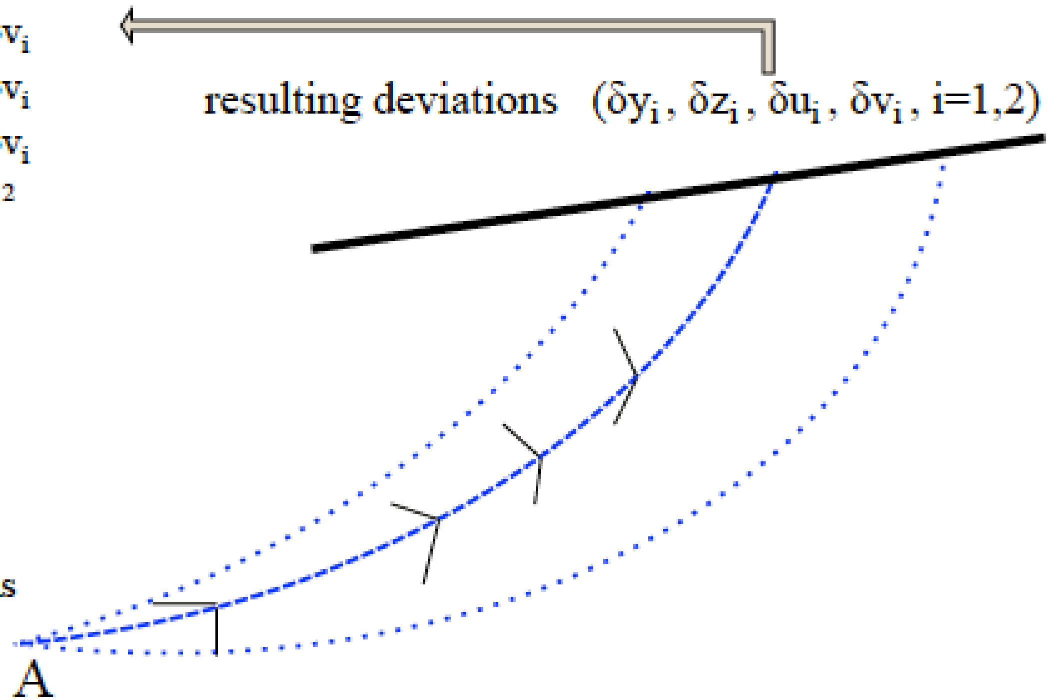
- **Benefit from FT R&D**
- **Insensitive to magnetic field**
- **... but sensitive to radiation damage**
  Estimated 5×10^{12} neq/cm^2 inside magnet → would require shielding and cooling
- **Need to be placed outside the magnet behind iron yoke**
  ~2×10^{10} neq/cm^2 → need to route photons with clean fibres



Performance: Track Propagation

fully numerical approach:

$$C_i = \begin{matrix} \delta y_i^{\,2} & \delta y_i\,\delta z_i & \delta y_i\,\delta u_i & \delta y_i\,\delta v_i \\ \delta y_i\,\delta z_i & \delta z_i^2 & \delta z_i\,\delta u_i & \delta z_i\,\delta v_i \\ \delta y_i\,\delta u_i & \delta z_i\delta u_i & \delta u_i^{\,2} & \delta u_i\,\delta v_i \\ \delta y_i\,\delta v_i & \delta z_i\delta v_i & \delta u_i\,\delta v_i & \delta v_i^{\,2} \end{matrix}$$



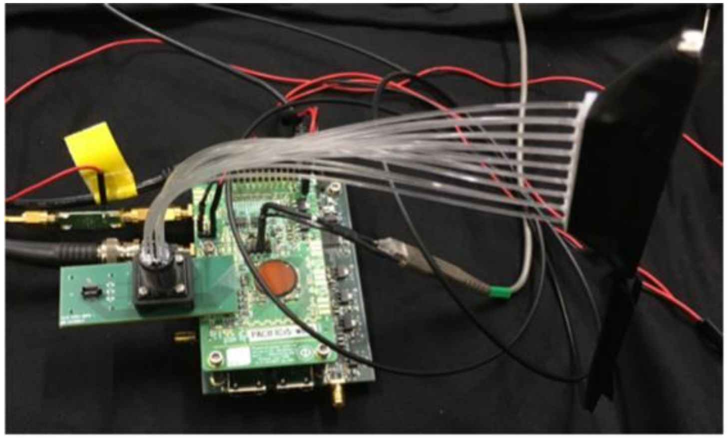
deviations of $\delta\theta = 1$ mrad in two *orthogonal* directions
(may be chosen in an arbitrary way)

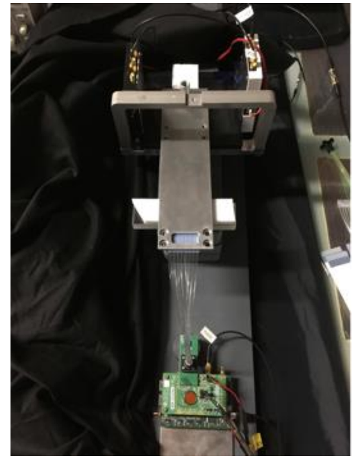
with θ^2_{MS} at point A
➔ contribution $(\theta_{MS}/\delta\theta)^2\,(C_1+C_2)$

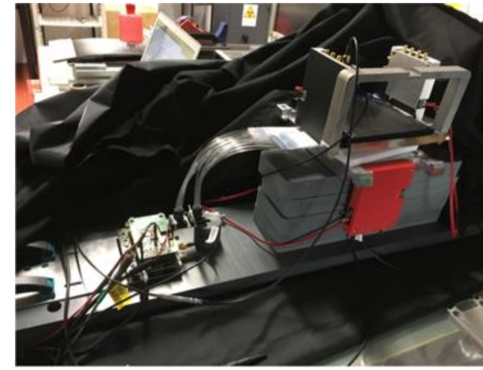
continuous material (e.g. air):
define a sequence of points $\{A_k\}$
sum up the independent contributions
along the trajectory

Pierre Billoir – LPNHE Paris

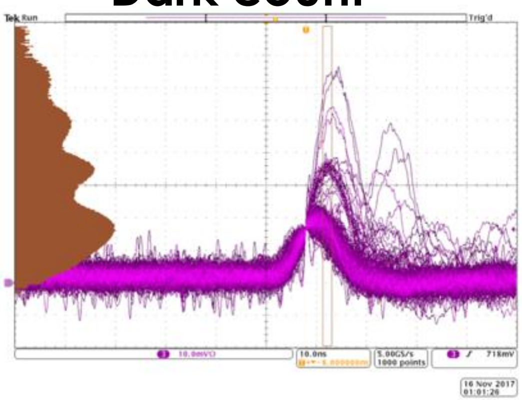
Tests w/ PACIFIC in Heidelberg



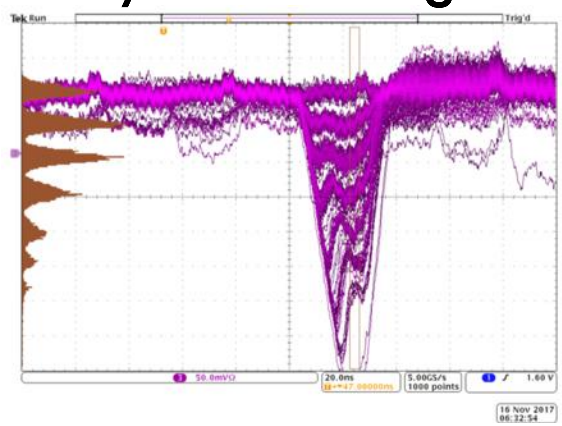




Dark count



Synchronous light



Thanks Albert (Heidelberg)!

- All channels worked
- Dark count signal shaping and gain same as SciFi
- Signal from Sr^{90} close to saturation, but using very short clear fibers
- Observed cosmics, but needs a long run and longer bars (in preparation at LANL)