PLUME: luminosity detector for LHCb

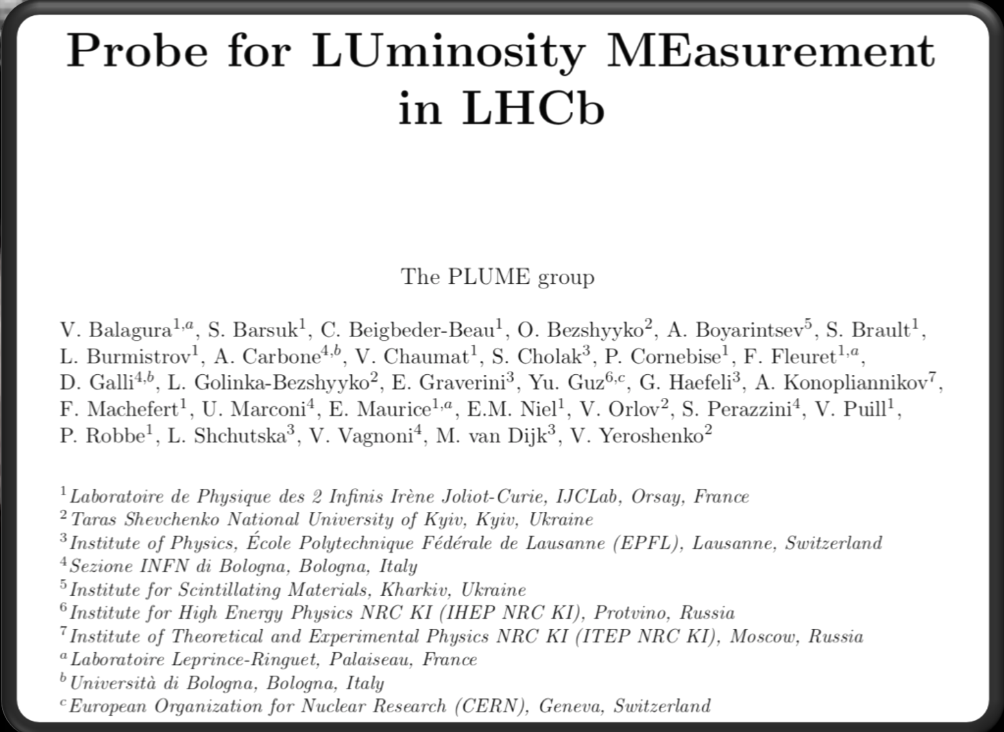
Elisabeth Niel

on behalf of the PLUME group

22/10/2020

French-Ukrainian Workshop

Orsay, France.



Probe for LUminosity MEasurement in LHCb

The PLUME group

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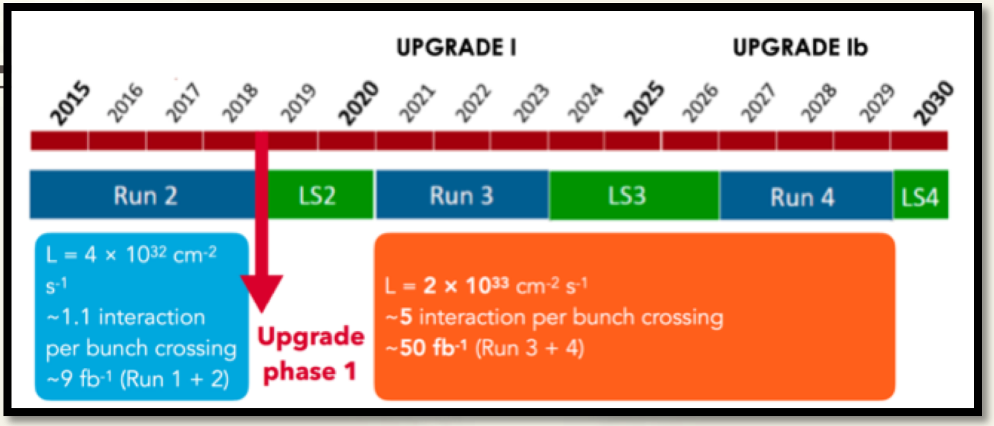
Introduction



From Patrick's talk

Run 1+ 2   2808 proton bunches with up to $1.5{\times}10^{11}$protons, collision rate 20 MHz (until 2016) then 40 MHz. In total $\sim 9\ fb^{-1}$

At LHCb IP (Interaction Point): **luminosity is reduced** by increasing the transverse distance between the beam. « Luminosity levellling »: keep luminosity stable within 5%

Measurement during Run 1 + 2 :

- Calorimeter activity used to infer average μ **(=number of interaction per bunch crossing)**
- Monitor beam induced background using:
  - Radiation Monitoring System (RMS): for inner silicon tracker sensors
  - Beam Condition Monitor (BCM): bunch-by-bunch measurement of background next to IP
  - Beam Loss Scintillators (BLS): trigger beam dump if to high activity next to the beam

Problem: radiation-induced aging.

Run 3:

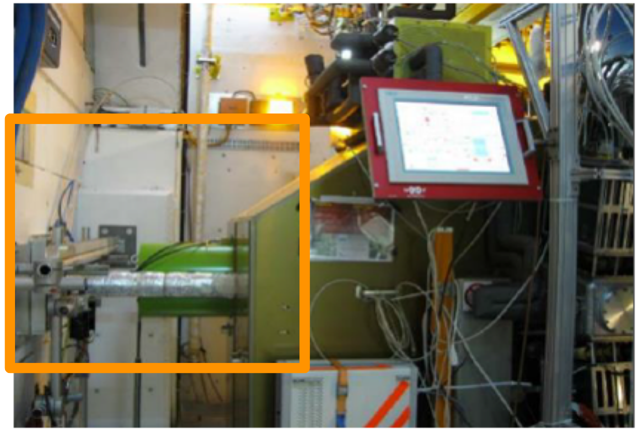
- 5-fold increase of luminosity and pile-up
- side effects: strong variation of luminosity, beam size, machine-induced background, ghost charges, satellites and crossing angles expected
- Software real time trigger→ need stable running conditions determined by the instantaneous luminosity
- Rely on external multiplicity determination for centrality determination of nucleus-nucleus collisions and separation from pp/pN collisions

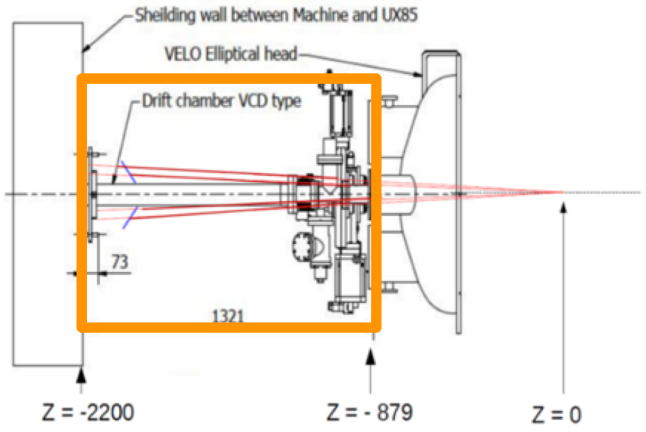
instantaneous luminosity measurement is essential: need dedicated detector

The PLUME detector design

New detector's tasks:

1. Deliver the online luminosity and μ measurements for the luminosity levelling
2. Perform these measurements per bunch
3. Measure the radiation background induced by the accelerator or bad vacuum, produce alarms, measure the level of the ghost charges
4. Cross-check the LHC filling scheme in real time
5. Contribute to the centrality determination in the fixed-target program
6. Provide accurate offline luminosity determination





Need to fit in the available space

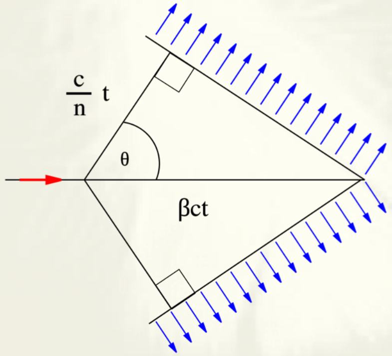
Precision needed:

Statistical error: 1% hits/detector unit at 11kHz(revolution frequency)→ 110Hz events rate.
Accurancy of 3% can be reached in 0.01 seconds.
Sufficient for online purposes
Note: for luminosity levelling need ~1Hz.

Systematics: depends on the stability of the detector, the calibration is crucial.

PLUME working principle

Build a detector based on the measuring of **chernekov radiation** from charged particles going upstream of LHCb



$$c/n < v_p < c$$

$$\beta = v_p/c \quad \cos\theta = \frac{1}{n\beta}$$

Allows signal to be produced and collected within ~10ps

IDEA: set small light detectors around the beam to measure Cherenkov light

START: preliminary studies based on Geant4 simulations, Test Beam at Desy and experience with other luminometer detectors (LUCID at ATLAS)

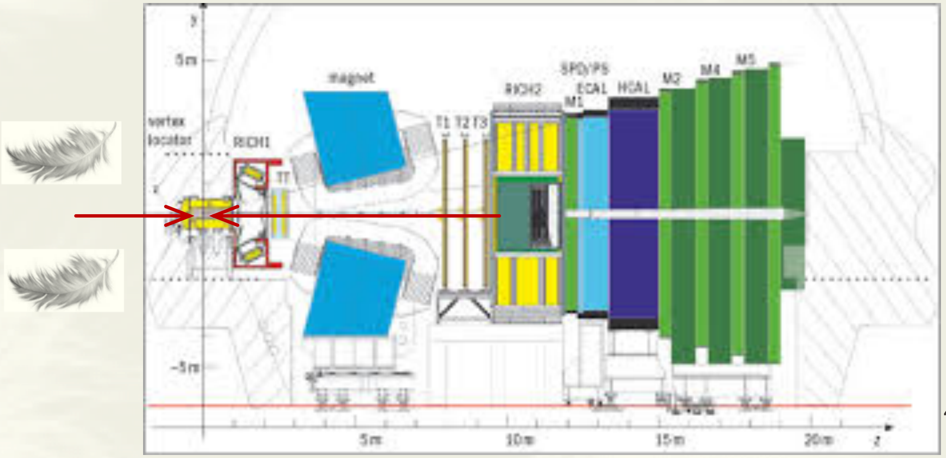
CONSTRAINS:

1. Limited time: need to be installed for Run 3 (2021?)
2. Radiation environment (strongly biasing the design)
3. Restricted space available
4. Integration in the LHCb detectors and DAQ

AVAILABLE OPTIONS:

Radiators: quartz bars, quartz fiber bundles, PMT window itself.

Light extraction: (quartz) optical fibers, optical transmission in the air via a system of mirrors, photon detectors close to the radiator.



PLUME tested options

Test the options at DESY

1. **Quartz fiber bundle as Cherenkov radiator:** can transport light outside high radiation region
2. **Garnet scintillator coupled to a quartz fiber bundle:** crystal+bundles on one side, PMT at the other end, low yield 4 p.e. per incoming electron and long signal
3. **Garnet scintillator coupled directly to a PMT:** 400 p.e. per incoming electron, 14 ns decay time
4. **PMT with a quartz window** : short signal pulse from Cherenkov radiation produced in the PMT window (used by LUCID)
5. **System of parabolic mirrors** to deliver the light produced in a Cherenkov radiator or in a scintillating crystal : would need an optical tuning, space and mechanically complex

Baseline solution

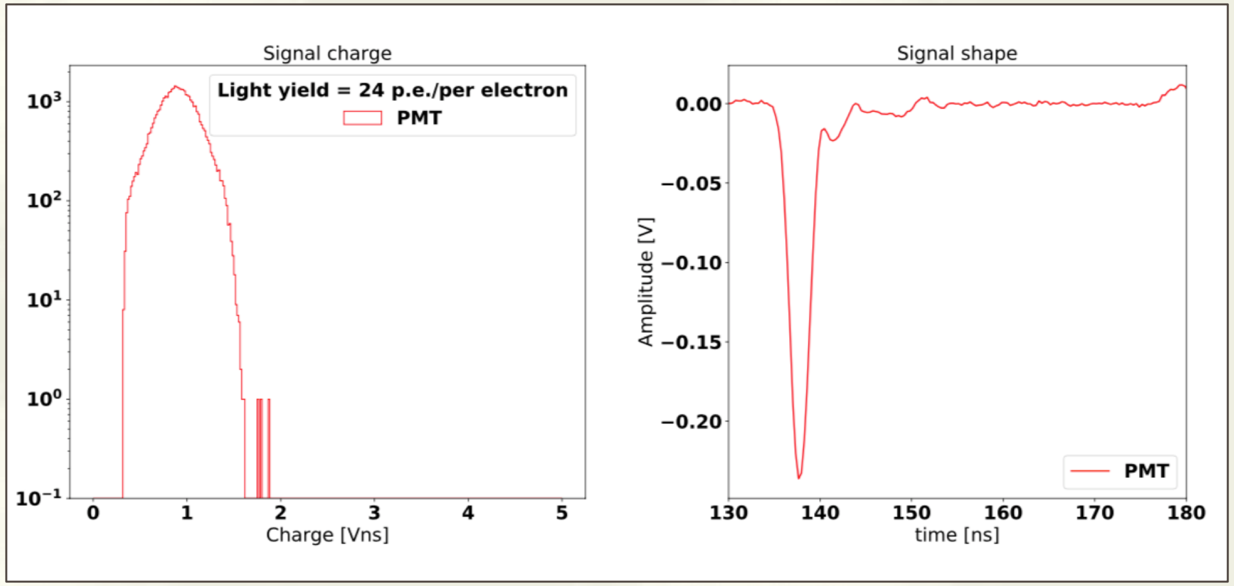
Photodetector: PMT

Radiator: PMT window + **quartz** tablet optically coupled to increase the yield

Backup solution

Radiator: Quartz fiber bundle and transmitting light to photodetetector

Photodetector: (MA)PMTs positioned in low radiation zone

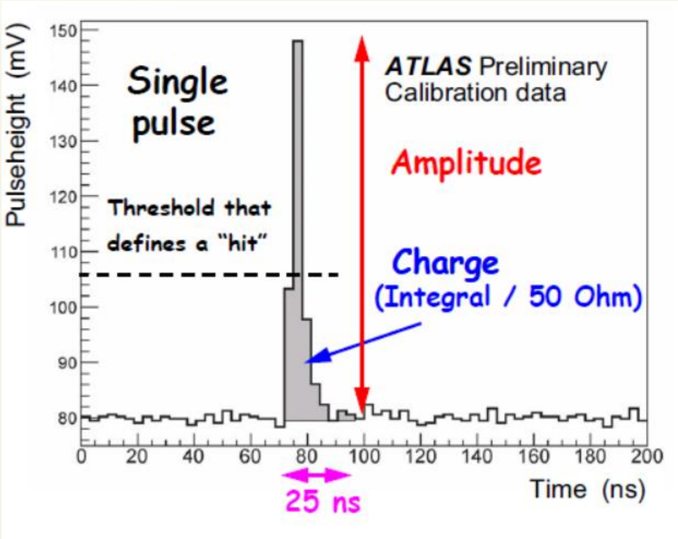


PMT choice

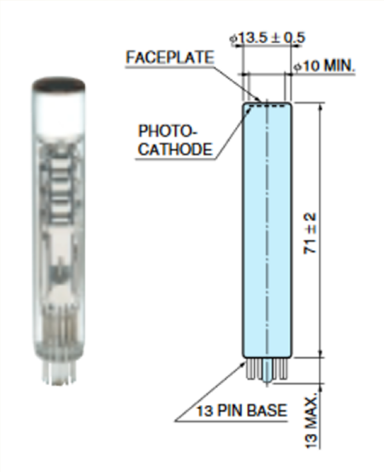
Elementary counters: PMT with 5mm quartz window (Hamamatsu R760) and attached quartz tablet, both acting as radiator to increase the light yield

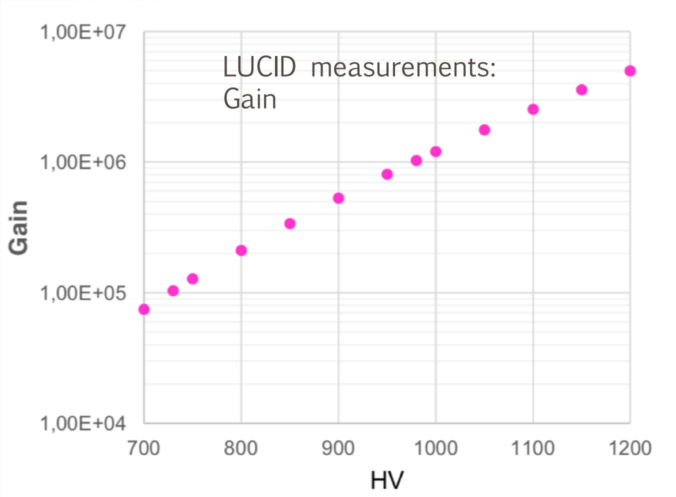
- Measured the integrated charge
- Yes/no response
- Fraction of empty events used to infer luminosity

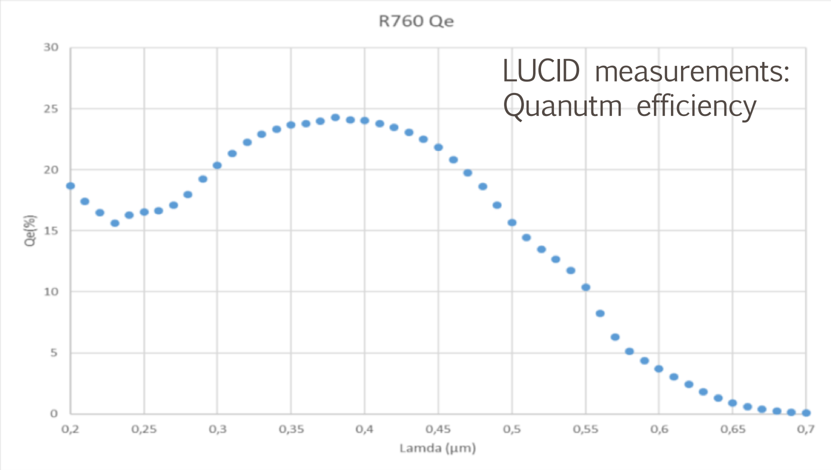
PMT Hamamatsu R760: robust technology and materials (borosilicate, quartz and metal – all radiation resistant), already used by LUCID in ATLAS



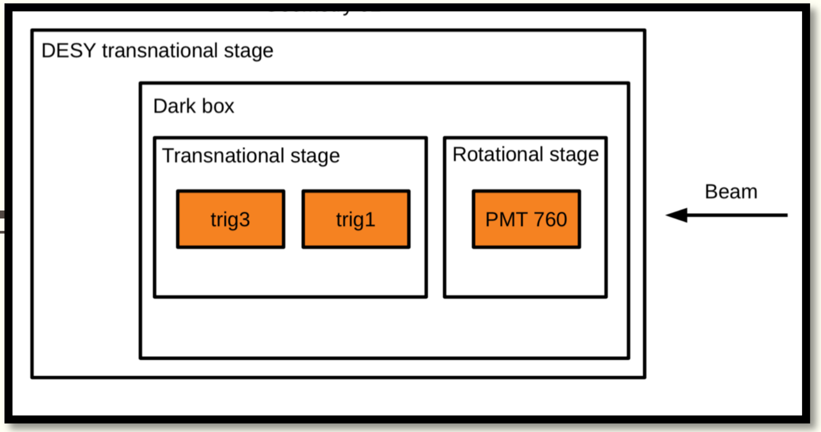
Gain = 10^6
I_d = 1 nA
TT = 22 ns







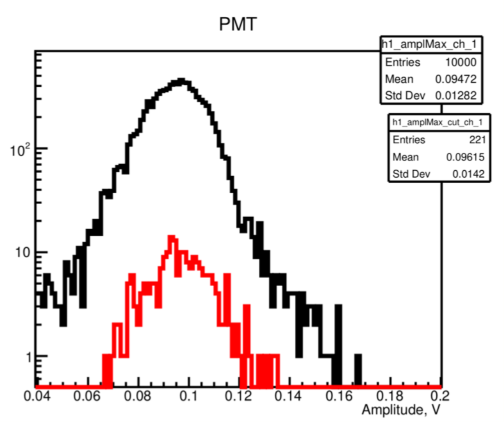
Recent test beam at DESY 10/2020

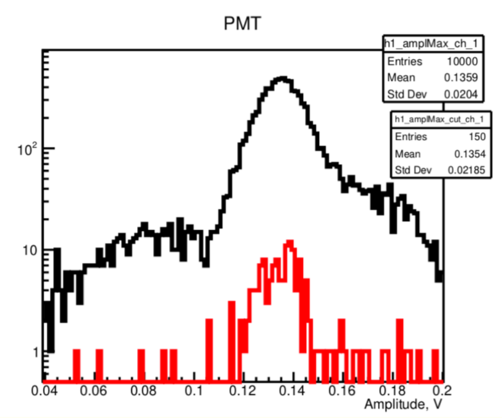


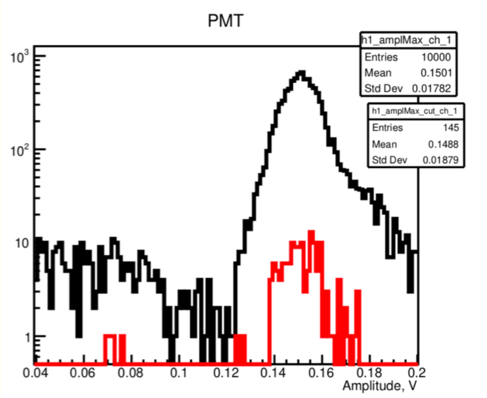
Latest test beam:

- Beam energy 5.4 GeV/c
- Beam in the exit of the collimator : 5 x 5 mm2
- Particle rate in the vicinity of the detector ~200 Hz

Tests: PMT (with about 1.2 mm quartz window thickness) alone or with round (10 mm thick) or rectangular quartz tablets (5 mm thick), with or without the optical grease or glue







signal amplitude from PMT alone is 95 mV.

10 mm tablet: about 130 mV

quartz box (10 x 10 x 5 mm3) + glue : about 150 mV

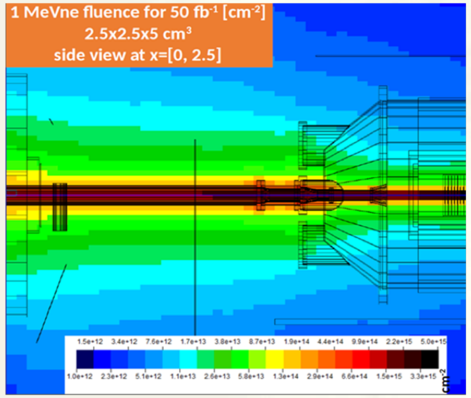
RK: The signal strength does not change significantly when selecting only good trigger events (red curves) with the reduced fraction of secondaries

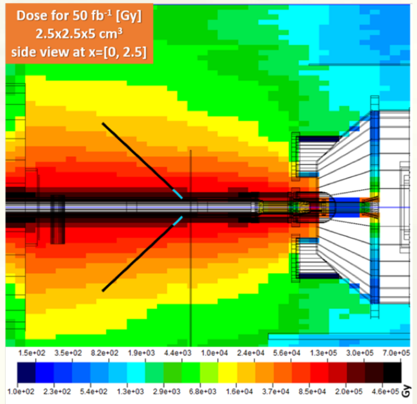
Results far from the expected proportionality to the total quartz thickness.
Hypothesis: attenuation of the Cherenkov short wave-length light in the optical contact and a relatively thick layer of grease/glue
Use of quartz tablet under discussion

PMT radiation resistance

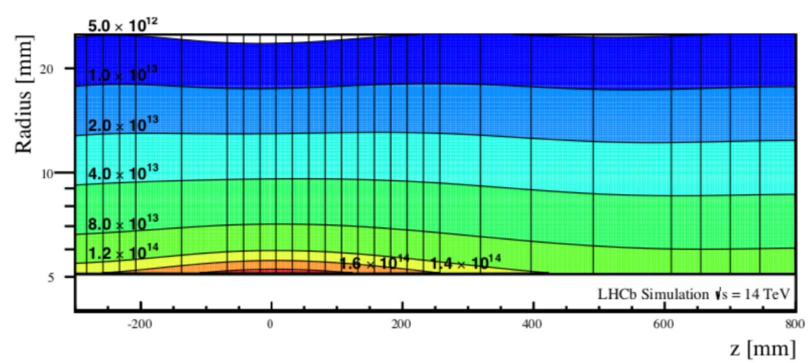
V. Cicero, Neutron radiation resistance of PMT for the LUCID detector

- Total ionizing dose per pp collision, in Gy, in LHC Runs 1+2 conditions



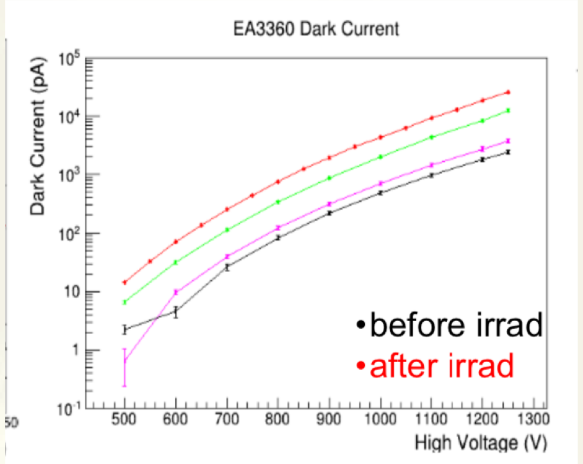


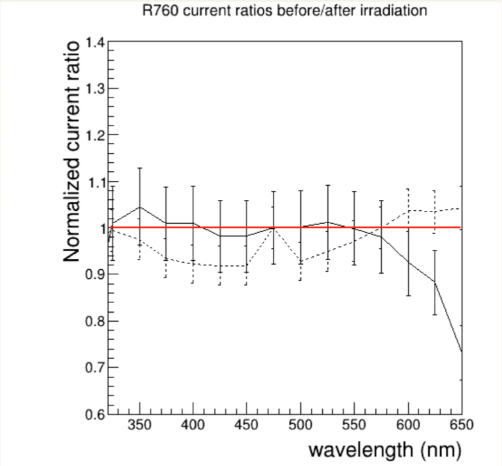
- Estimated radiation dose per fb in upgrade conditions, expressed in 1 MeV neutron equivalents p cm^{-2}



Close to the beam pipe $80 - 200\ kGy$
And neutrons fluence $\sim 10^{13}\ neutrons/cm^2$

Irradiation of R760 PMTs: $200\ kGy\ (\gamma\ ryas)\ /2.7\ 10^{14}\ neutrons/cm^{-2}$

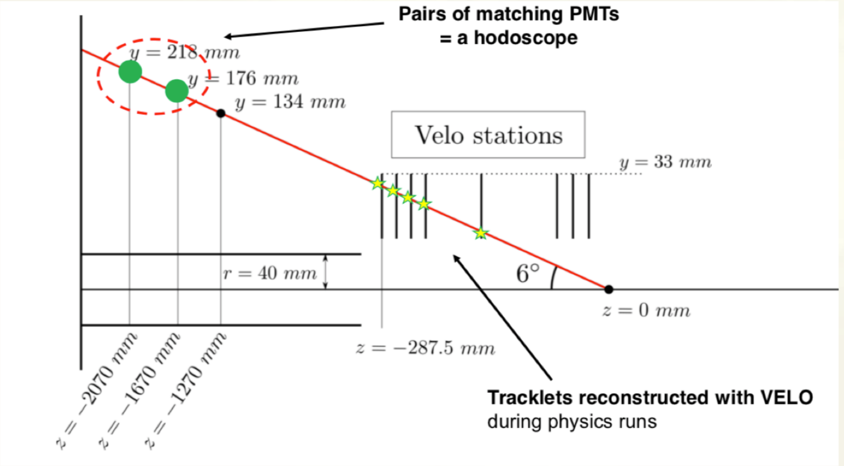


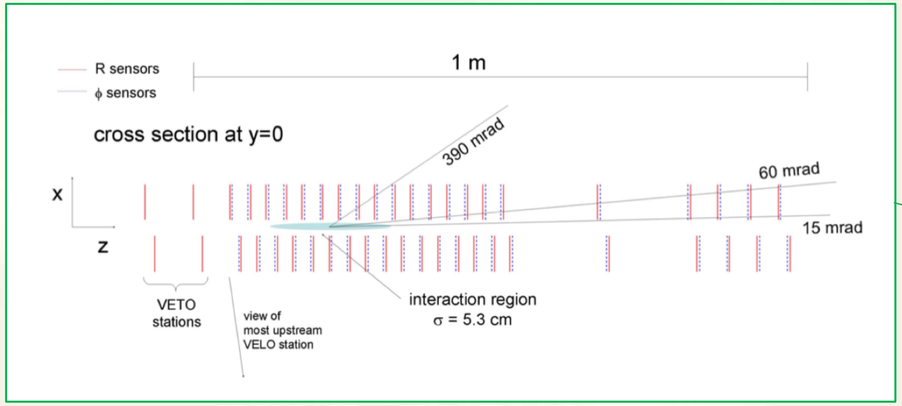


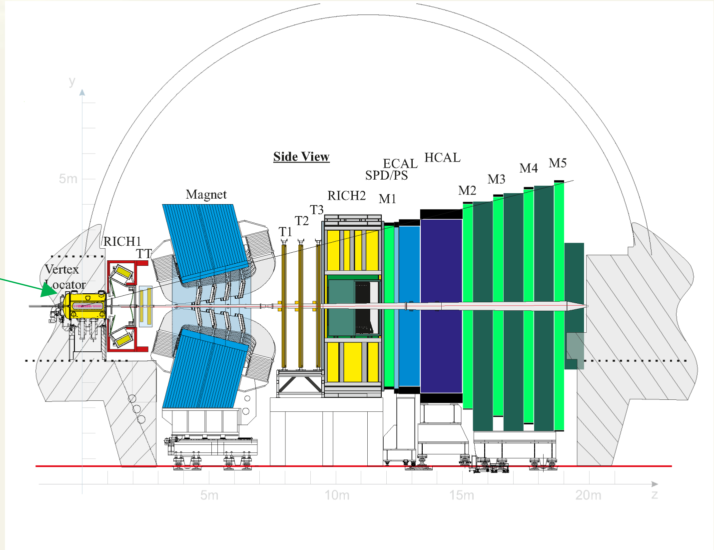
No variation in spectral response and gain, increase of dark current

Recently done (at Kharkiv): study of radiation resistance of optical grease and glue samples with γ and neutrons

Detector positioning



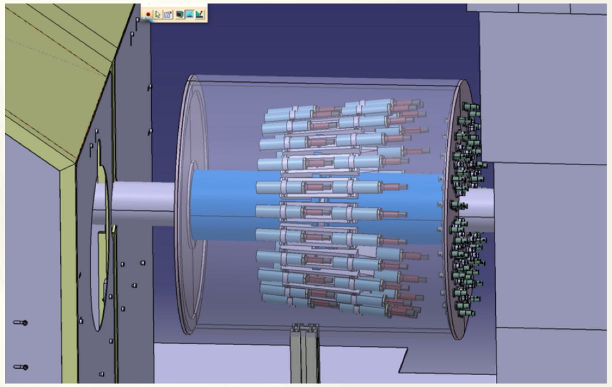




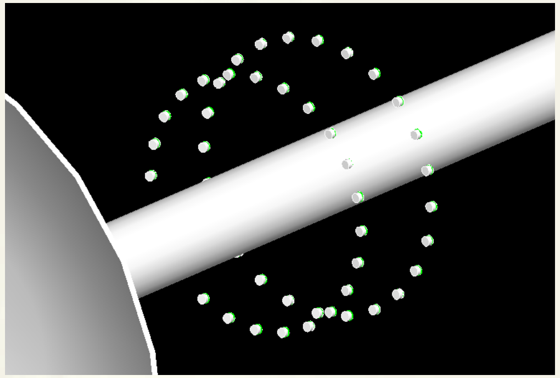
1. Two projective layers to perform coincidence (to reduce secondaries) studied using Geant 4 simulation

2. **Constraint from calibration**: possibility to reconstruct tracklets with upstream VELO stations elementary → detectors need to be at ~5-10°

3. Prefer position with reduced radiation dose level



Geant4 simulation

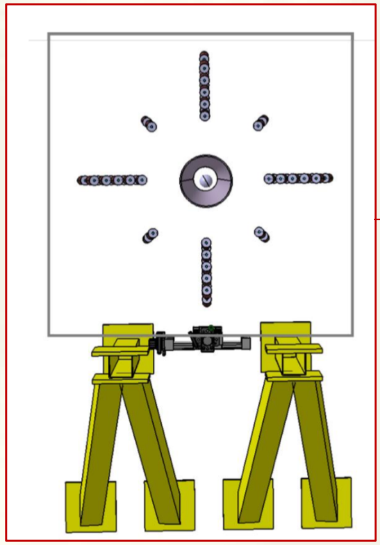


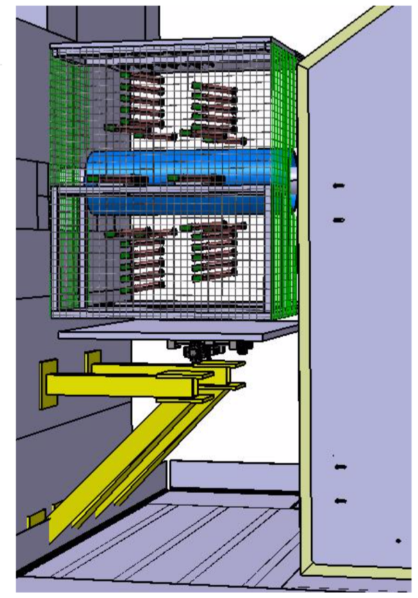
Preliminary positioning

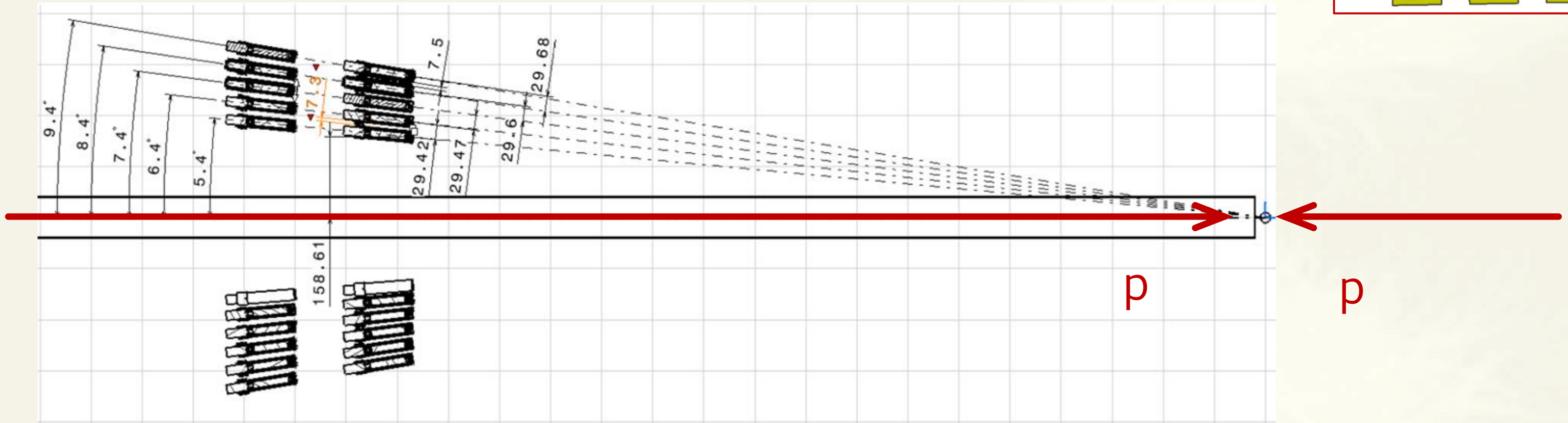
PLUME detector geometry

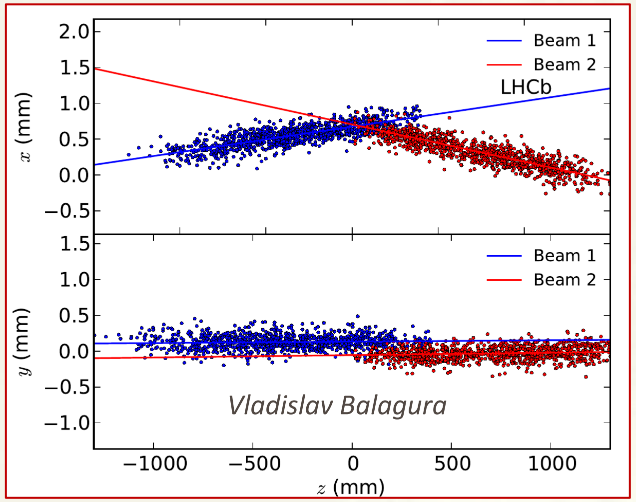
- 2 x 24 elementary counters in projective geometry
- Each hodoscope layer (24 counters) arranged in an almost cross-shaped structure
- Shape: pseudo rapidity determination, crossing angle determination

- Angle coverage with respect to the beam axis: 5-10° pseudorapidity range $2.4 < \eta < 3.1$





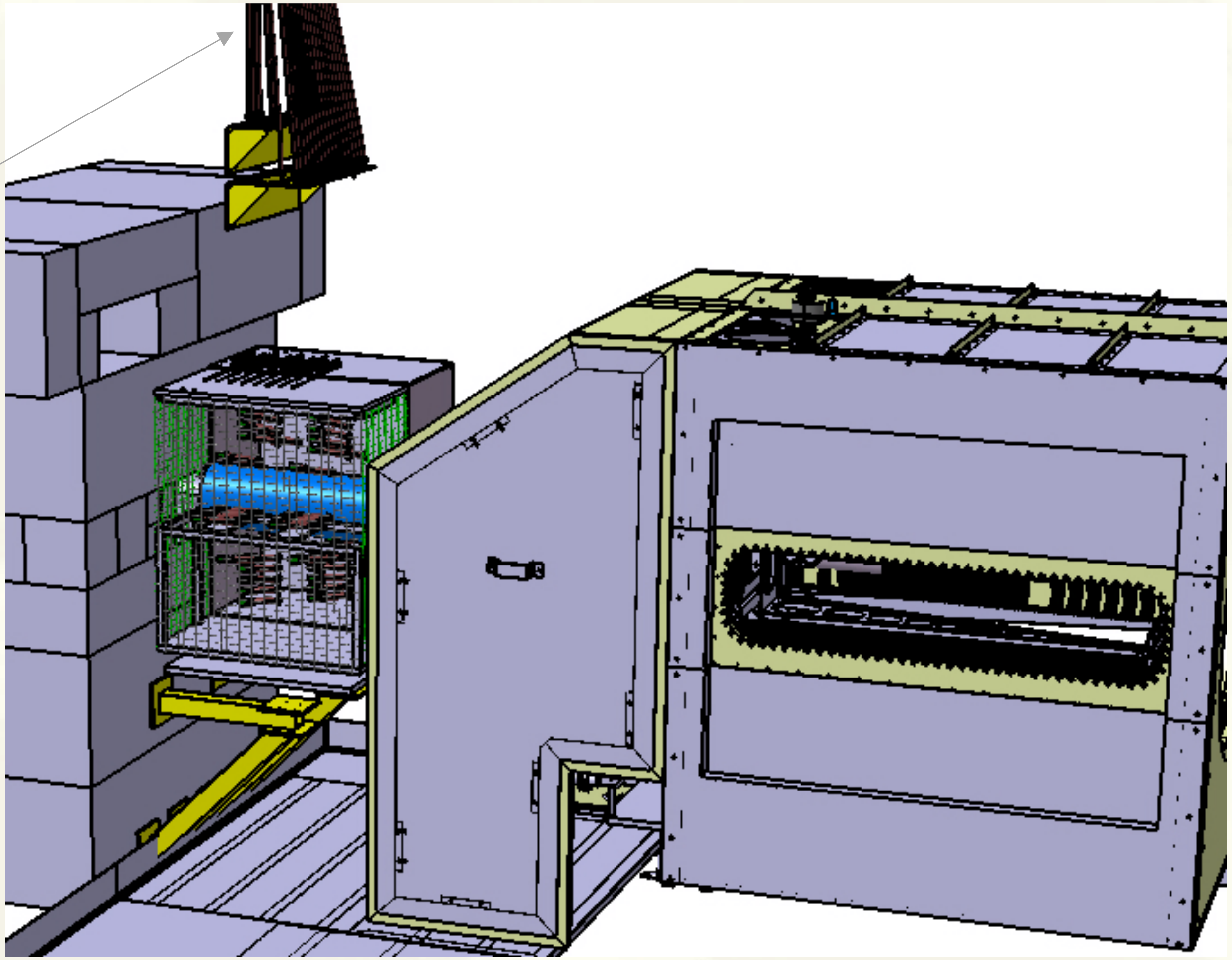




PLUME detector box

- Plume detector box attached to concrete blocks upstream LHCb
- Possibility to rapidly (<1 day) remove the detector to provide VELO emergency access

Patch-panel for cabling: HV and signal cables and quartz fiber per channel



PLUME read-out electronics

- Approaches to front-end electronics (FEE) have been considered for the PLUME detector. Based on the FEE for:
  - ➢ LHCb Calorimeter
  - ➢ LHCb RICH
  - ➢ LUCID detector electronics.

- **Final choice: LHCb calorimeter-like electronics**
  - o It's already adapted to the LHCb data format and event building
  - o A preliminary test showed that ECAL FEBs can readout the expected signal
  - o No need to produce a special board (long), the existing ones are adaptable

✓ Can measure at LHC rate the individual hits and hodoscope coincidences. Also measure integrated charge.

✓ Signals transmitted to Tell40 and processed by PCIe40:

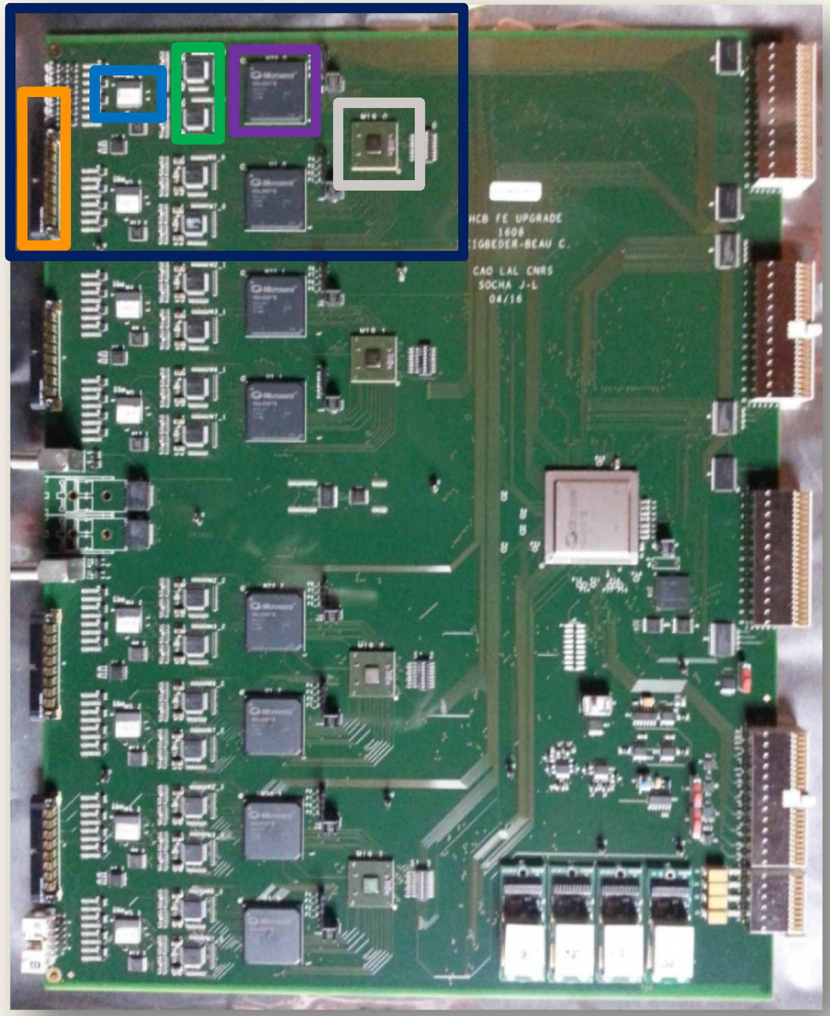
→ generate fast alarm, determine online luminosity from hits and integrated charge information, including luminosity levelling

A custom firmware to be developed to provide instantaneous luminosity to the LHCb control system

✓ Information available offline (as other subdetectors)

ECAL FE Boards

Front-end block



ECAL FEB

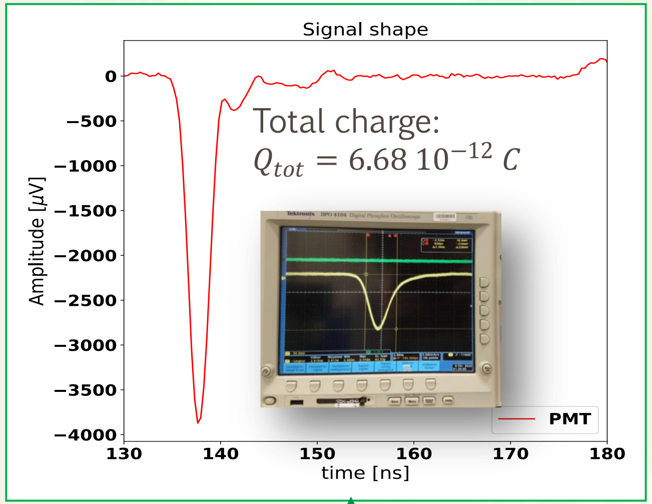
- ➢ Treats 32 channels (4 blocks of 8 channels)
- ➢ ICECAL chip analog part: shape and integrate the signal
- ➢ Digital electronics:
  12 bits Analog to Digital Converter (bandwidth 12x32=364 bits at 40MHz)
- ➢ 8 FPGA Front-End (treating 2 ADCs so 4 channels)
- ➢ GBT output to send data on the optical fiber, gives the clock
- ➢ 4 optical fibers for the readout

- ▪ To be installed on a 9U crate with a home-made backplane
- ▪ Control board: 3CU for clock, fast and slow control with bi-directional optical link
- ▪ MARATON power supply configured for the calorimeter
- ▪ 4 optical fibers for the readout of one board

PCIe40

- Receive RAW data from the detector with one word of 12-bit ADC per channel
- **A custom firmware to be developed to provide instantaneous luminosity to the LHCb control system**
- Count the number of channels with no activity
- Using Bunch Crossing information from RAW data→possible to obtain the luminosity per bunch (histograms of empty events as a function of the BCId)

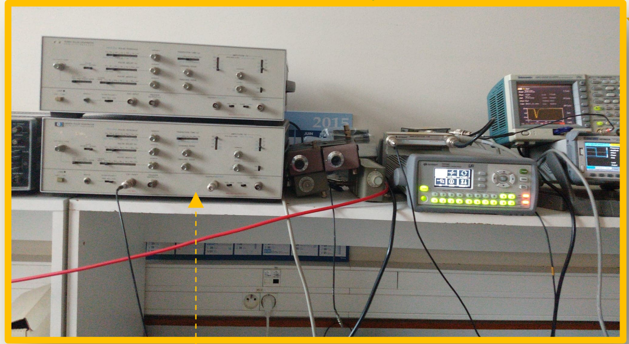
PLUME read-out electronics



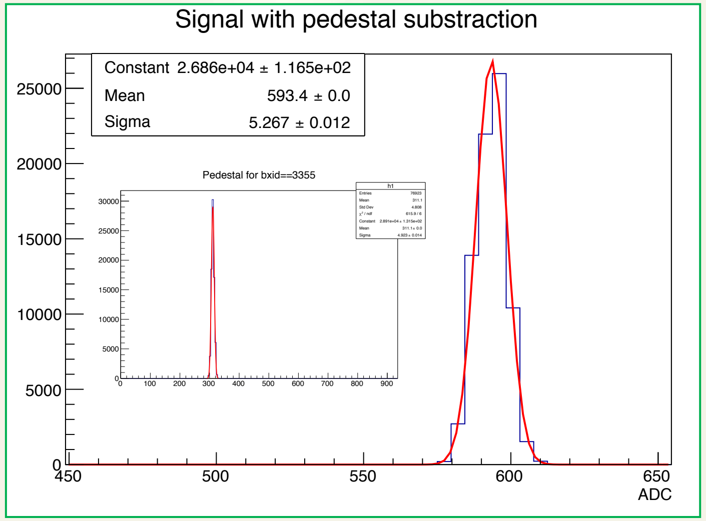
- Inject signal shape from DESY test beams
- Note: the signal is much shorter compared to the 25 ns window of FEB

Conclusion: ECAL electronics can read the expected signal shape

Cable CT50



Generator

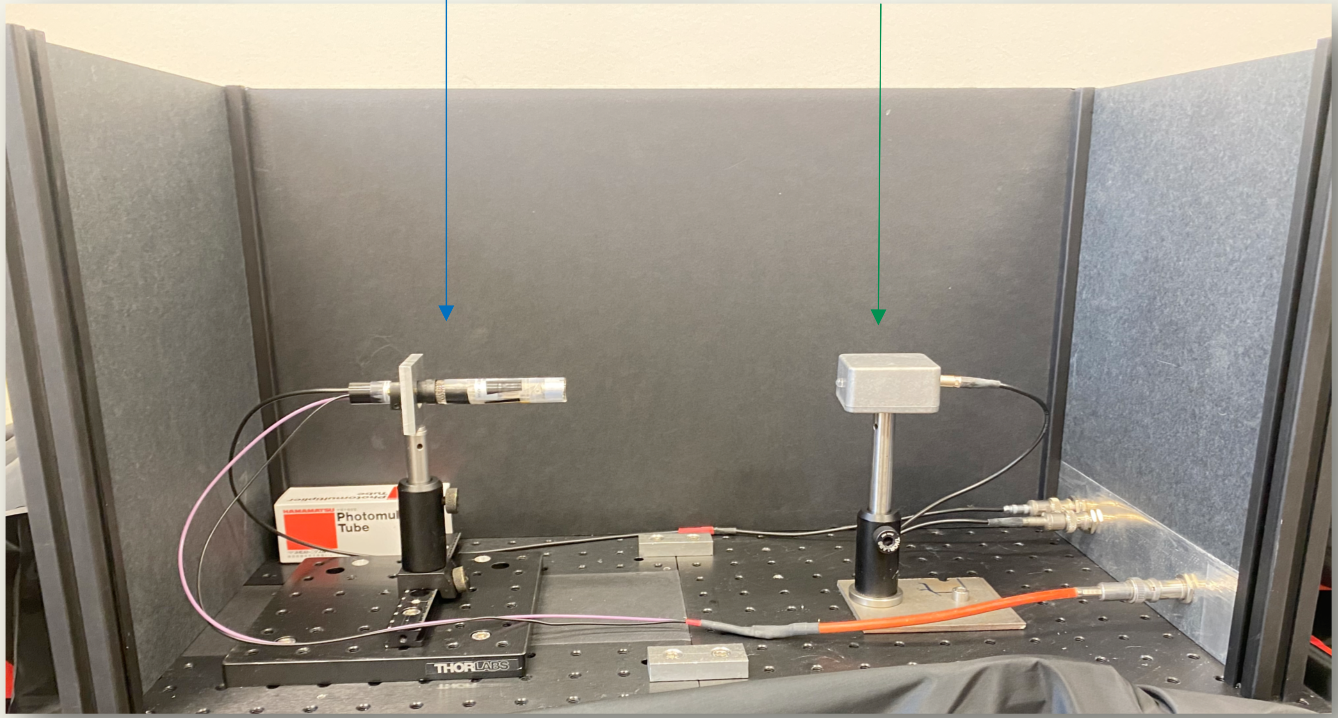


PLUME read-out electronics

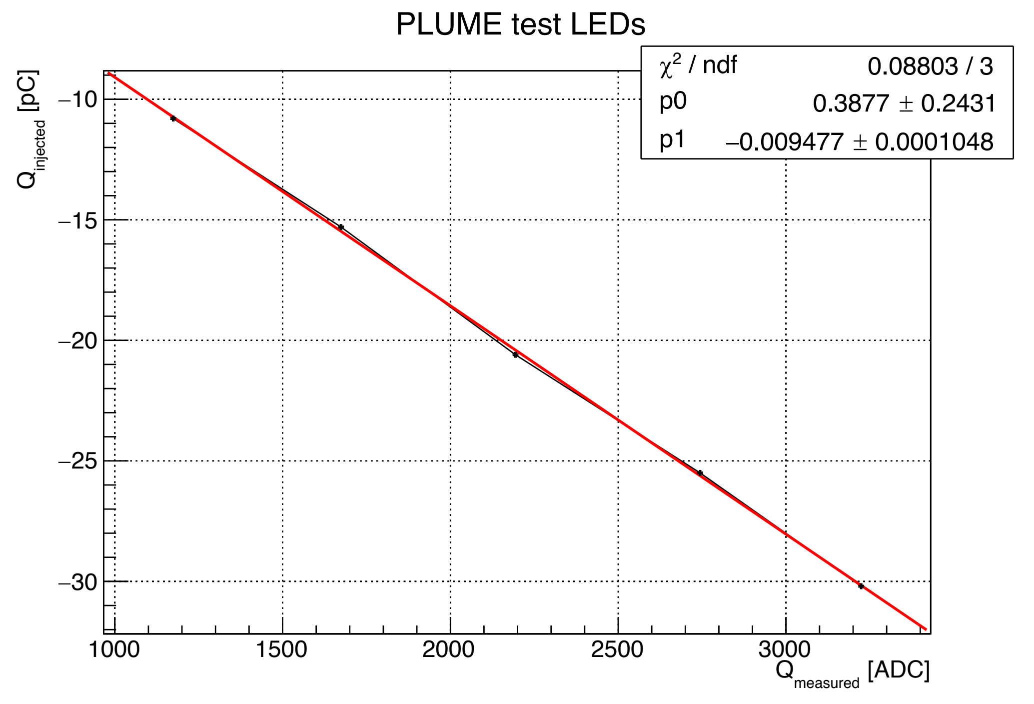
Second test:

measure the signal directly from the PMT

LEDs as light source



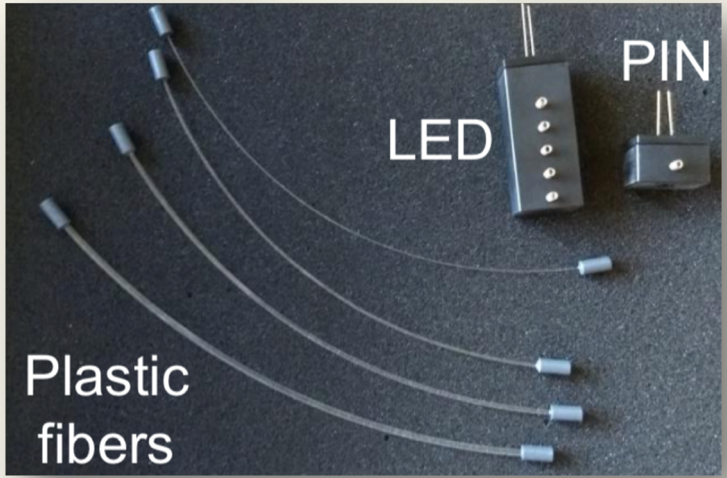
Check linearity



Monitoring and calibration

- PMT gain and hit efficiency expected to vary depending on occupancy, time and radiation dose
  →Need to monitor and apply HV correction to recover the reference value

- Calibrations methods used at LHC:
  - LUCID detector: 207-Bi source drops placed on the PMT quartz window
  - LHCb ECAL: ligth injection with LEDs



PLUME will adopt 2 solutions:
- **Light injection with LEDs**
- **Calibration tracks** coming from the interaction point and reconstructed with **VELO**

Corrections automatically applied on a fill-by-fill basis

Calibration:

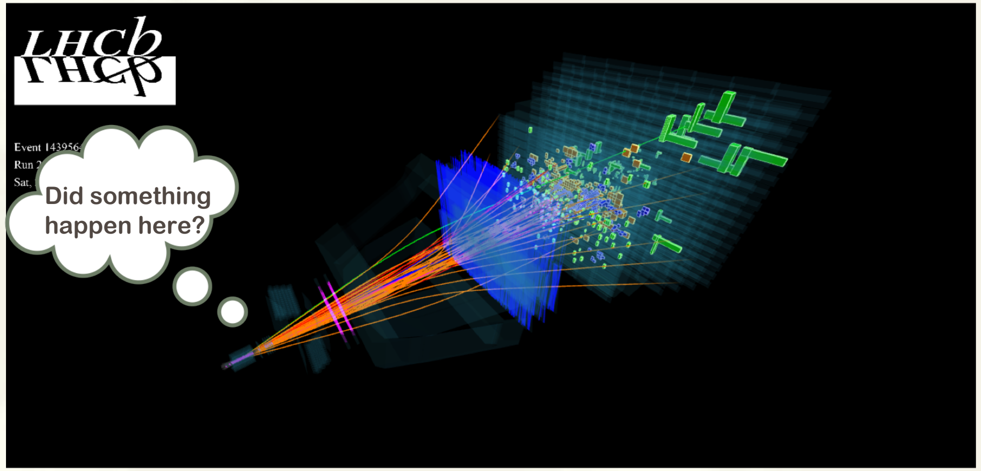
- Perform calibration at beginning + EOF (=End Of Fill) + during empty BX
  - Amplitude histograms to compare with reference data saved every 15 minutes
  - Minimum ΔV applied is 0.5 , $\sim 2\%$ gain variation
  - WinCC daemon applies new recipes at beginning of fill

- LED flash amplitude rather stable but affected by loosening contacts ⟶ monitor LED stability using **PIN photodiode**

Luminosity measurement: logZero method

Method 1: logZero method

Pile-up = μ = N interactions per bunch crossing ~ 1-2.
Poisson law: $\boldsymbol{\mu = -log(P_0)}$
P_0 =fraction of "empty" events,
eg. Number vertexes = 0 or N tracks < 2



$$L = N/\sigma_{vis}$$

where N = number of interactions (integrated μ) and σ_{vis} is the cross section for $pp \rightarrow$events with at least 2 VELO tracks, is determined in dedicated LHC fills from N and L in calibrated samples, where L is measured "directly.

Relies on the assumption: empty event + empty event = empty. This might be not the case e.g. for high thresholds when two events with signals below the threshold, after summing up fire the trigger.

Higher "backgrounds" (populating the region below the threshold, e.g. the signals from the secondary tracks traversing PMT at "wrong" angles) increase the bias

Luminosity measurement: linear mode method

Method 2: linear mode

Accumulates quantities proportional to luminosity measured once per year in vdM or BGI

→ **requires very precise calibration and heavily relies on linearity of the detector**

Can be biased by: drift due to aging and non linearity of busy events

In PMT this quantity could be:

- (PMT ADC signal - pedestal) per BX, need data without pedestal suppression.
  E.g. only in lumi events (30 kHz?), or keep full sum over integration period per BX.
- PMT currents: need external info to subtract be/eb background
- Number of PMT hits: biased for large occupancy, saturates if >1 tracks can hit one PMT, not linear

Luminosity measurement: linear mode method

Method 3:
use not only empty events but also other bins. Fill histrograms with PMT hits and find the μ value. May be a good complement of the other methods.

For more informations on the methods for the luminosity measurement see Vladik's talk of yesterday
https://indico.ijclab.in2p3.fr/event/6532/contributions/20629/attachments/15332/19328/pgf_lumi.pdf

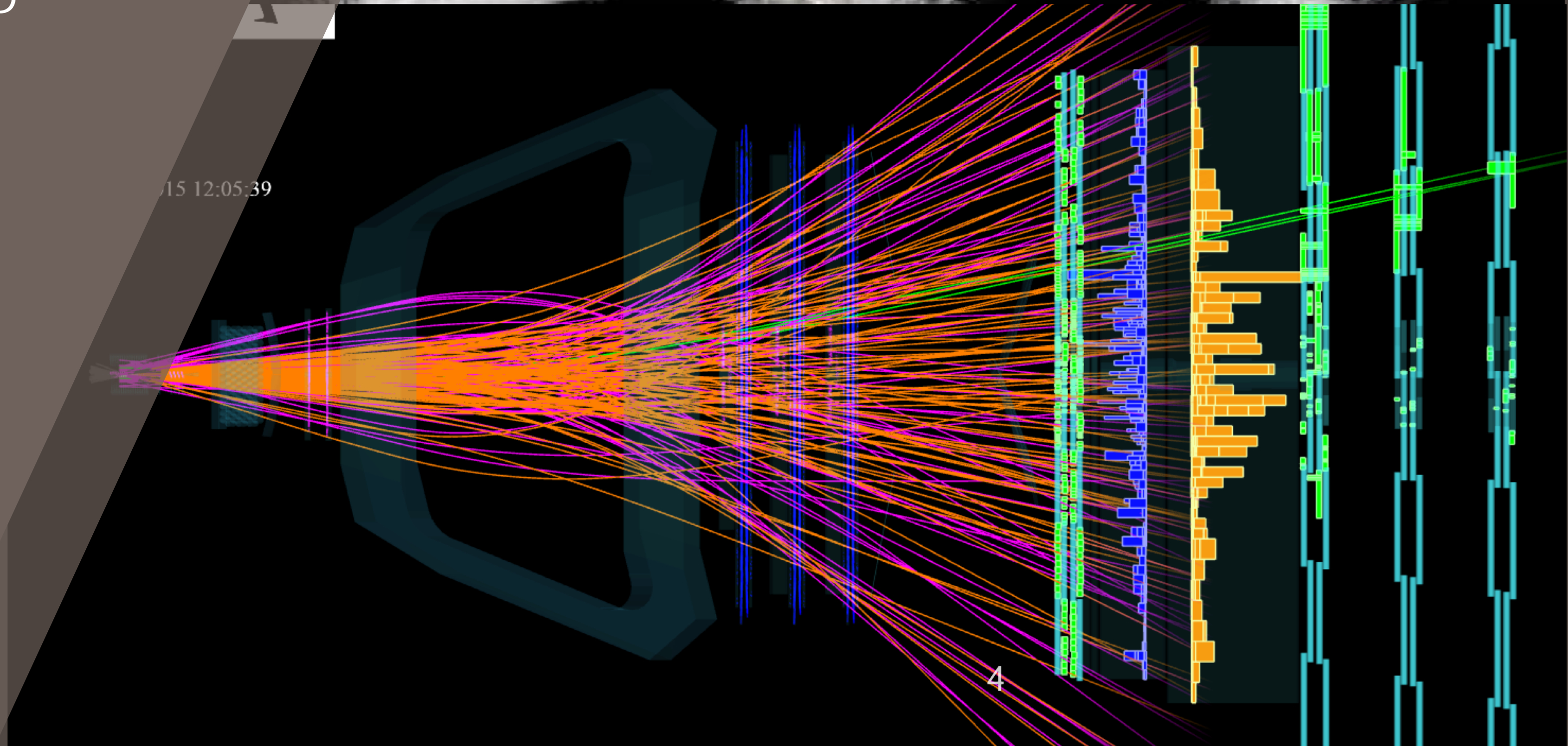
Backgrounds for the luminosity determination:

- In all methods the contribution of backgrounds to μ can be estimated from beam-empty and empty-empty crossing
- Off-time background: activation of surrounding materials negligeable thanks to the Cherenkov light threshold (slow particle don't produce light).
- Secondaries (not produced at the IP): use coincidence and/or VELO tracks

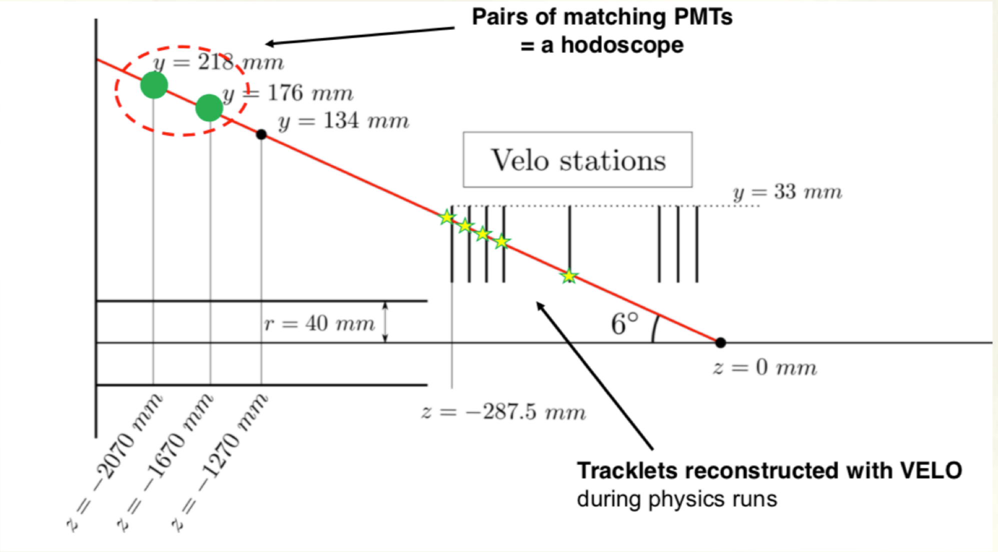
Conclusions

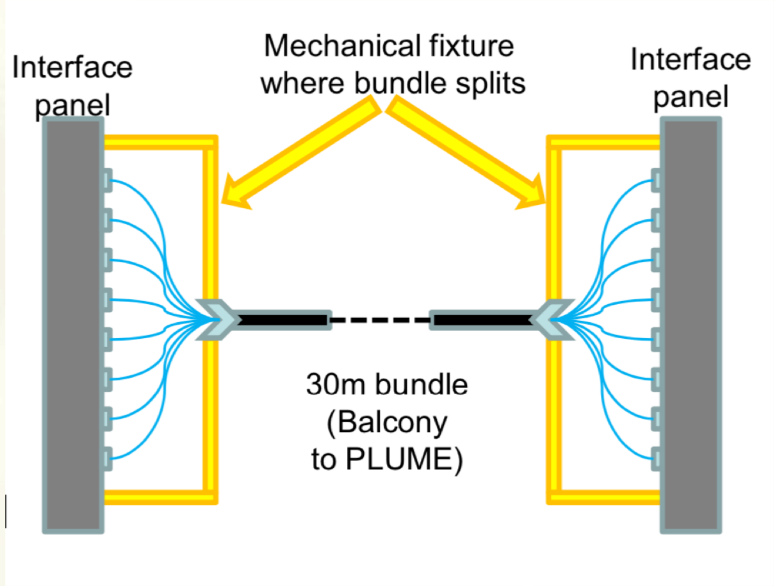
- PLUME is a detector for LHCb luminosity measurement in Run 3
- It is based on Cherenkov light from upstream particles
- The detector choice is inspired by LUCID and is based on Geant4 simulation and Test Beam results at DESY
- Final choice: 2 layers of PMTs
- Electronics from ECAL
- First channels operational late 2021

THANKS



Monitoring and calibration





- Cleaning from secondaries: use coincidences (enough) and tracks from VELO upstream stations when VELO is closed
- Transport LED light to PMTs using quartz fibers
- LHCb DAQ allow injection at 1 kHz but 25-50 Hz is already sufficient
- Light source: Blue LED (Cree LC503)
  - LED flash amplitude rather stable but affected by loosening contacts ⟶ monitor LED stability using **PIN photodiode**
  - Amplify PIN signal to same size as the regular PMT signal before FEB
  - Dedicated FEB for PIN photodiode readout

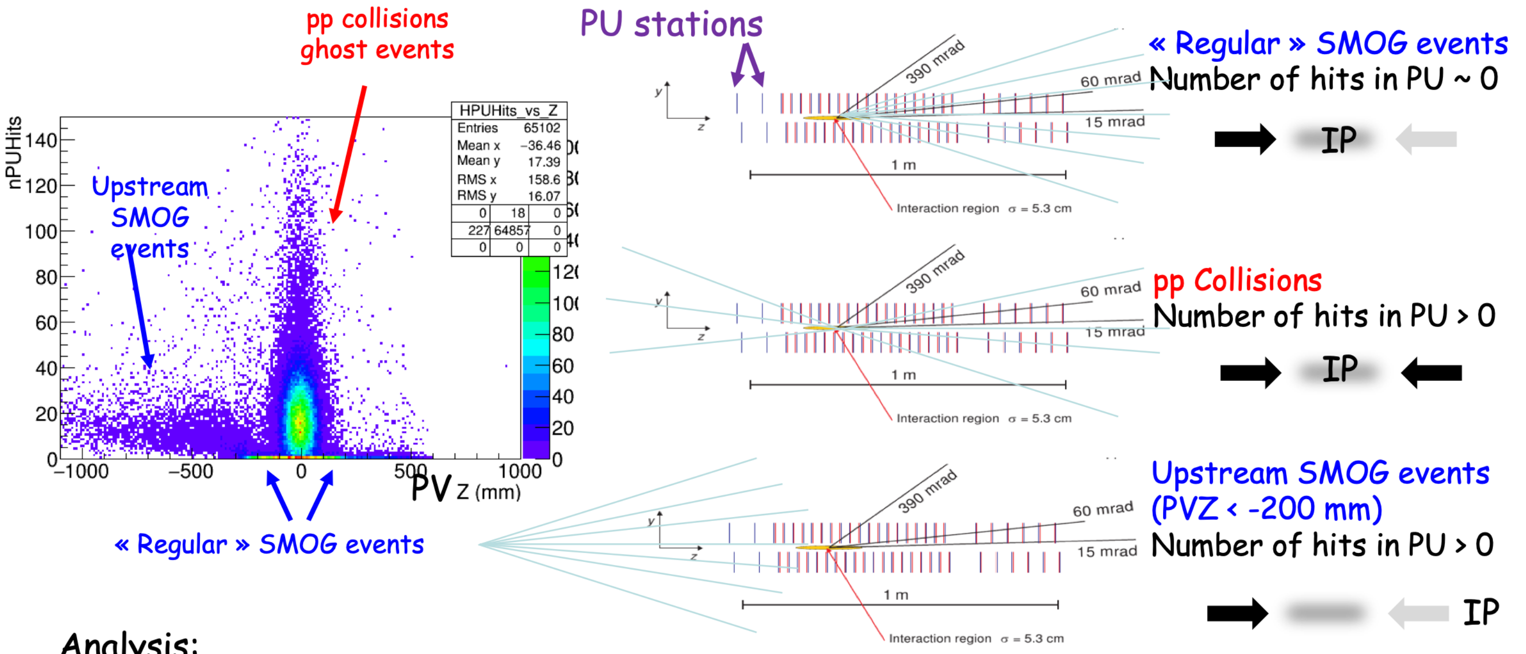
SMOG: current fixed-target configuration

Slide by Sergey Barsuk

- The **gas is injected into the VELO tank** with VELO pumps switched off. The gas **leaks into the LHC tube** until it is pumped at ± 20m from IP

Frédéric Fleuret

- Regular SMOG events are located at -200 < PVZ < 200 mm



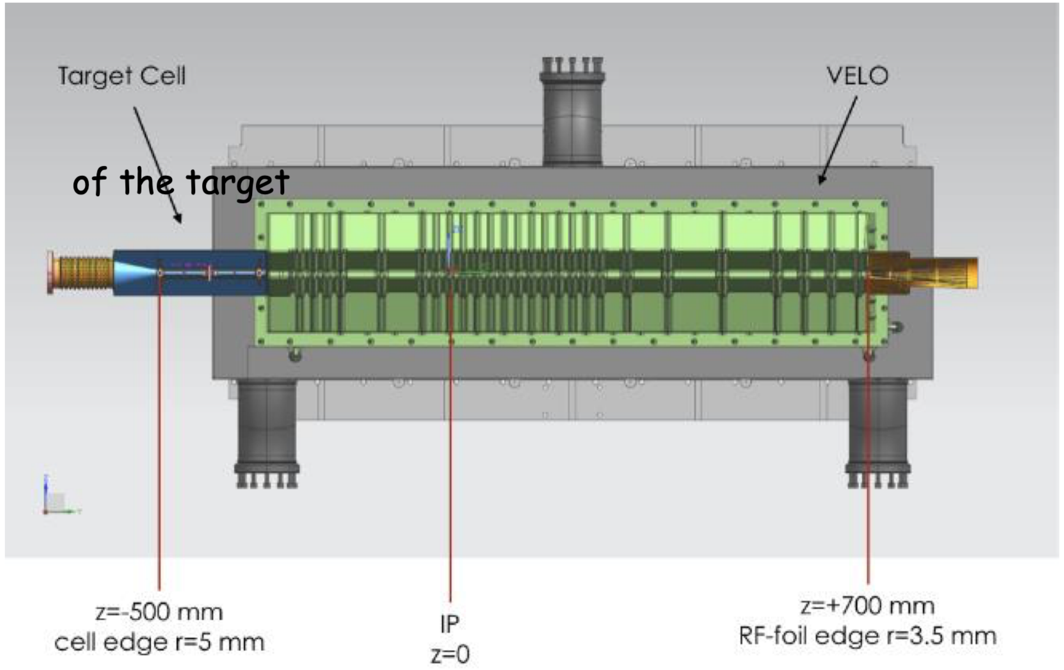
Analysis:

- **pN collisions:** PUHits information is used to separate (remove) pp collisions from regular SMOG.
- **NN collisions:** centrality of the collision is determined with the particle multiplicity and the energy deposited in CALO. PUHits information must be used to remove pileup upstream+regular SMOG events (otherwise, overestimate centrality)

SMOG: upgraded fixed-target configuration

Frédéric Fleuret

- **Gas is injected into the target cell upstream of VELO** with VELO pumps switched on
- Regular SMOG events are located at -500 < PVZ < -300 mm
- **No PU stations** upstream of the target



Analysis:

- **PN collisions:** use PVZ information to separate (remove) pp collisions (PVZ~0) from regular SMOG (-500<PVZ<-300).
- **NN collisions:** centrality of the collision is determined with the particle multiplicity and the energy deposited in CALO. Need an additionnal detector upstream of the target to veto PU upstream+regular SMOG events (otherwise, overestimate centrality). The closer to the target cell, the better.

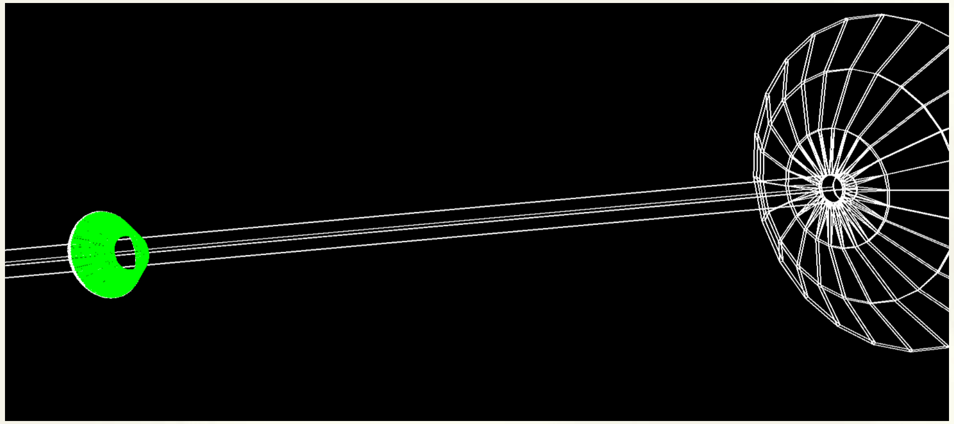
Slide by Sergey Barsuk

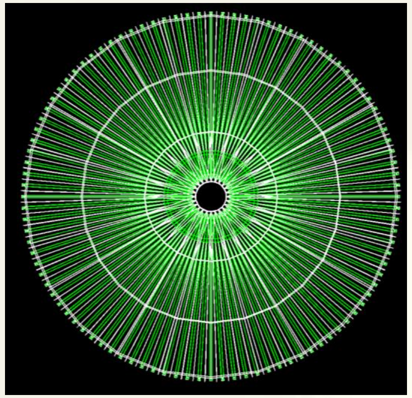
Simulations for quartz bars options

First ideas: quartz-based detector

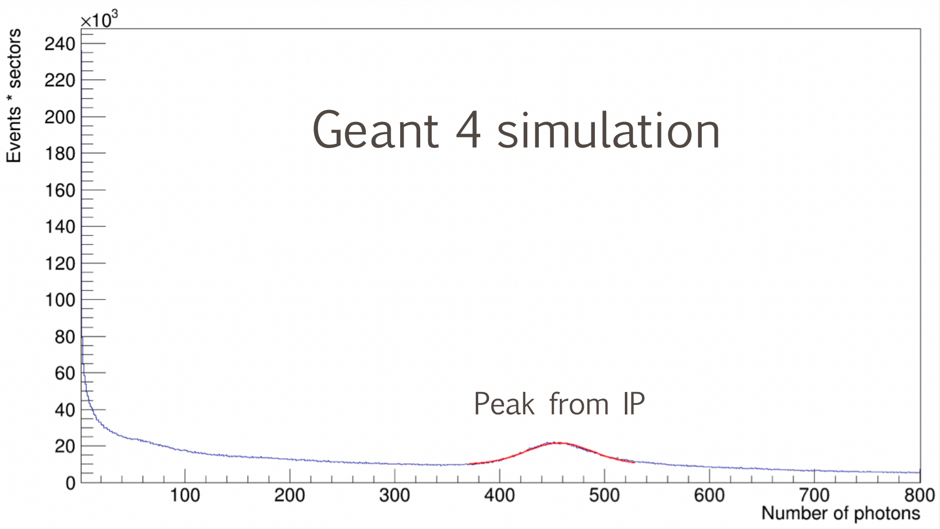
“corona” of 100 quartz bars is positioned at z = −2070 mm at a minimal radius from the beam of 320 mm, with the longer side of the bars inclined at an angle of 47°

Note that at this angle the bars are not pointing to IP and the primary particles traverse in the inner acceptance 14.5 mm of quartz





The background comes from secondaries at random angles



Desy first test beam results

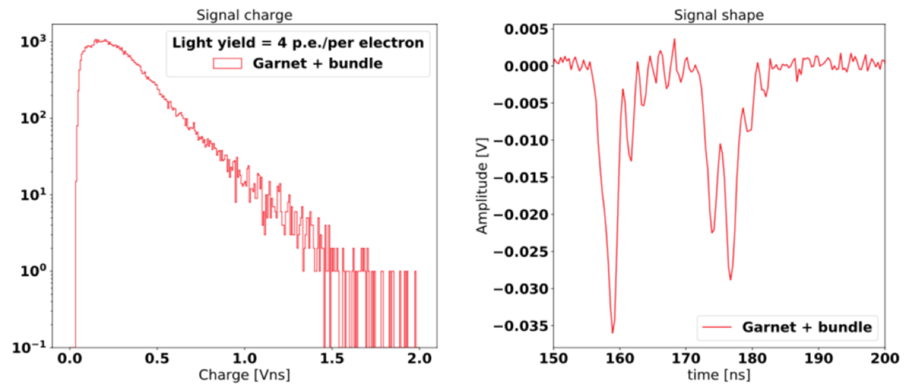


Figure 8: Response (left) and signal shape (right) of the tested quartz fibre bundle, coupled to the Garnet crystal.

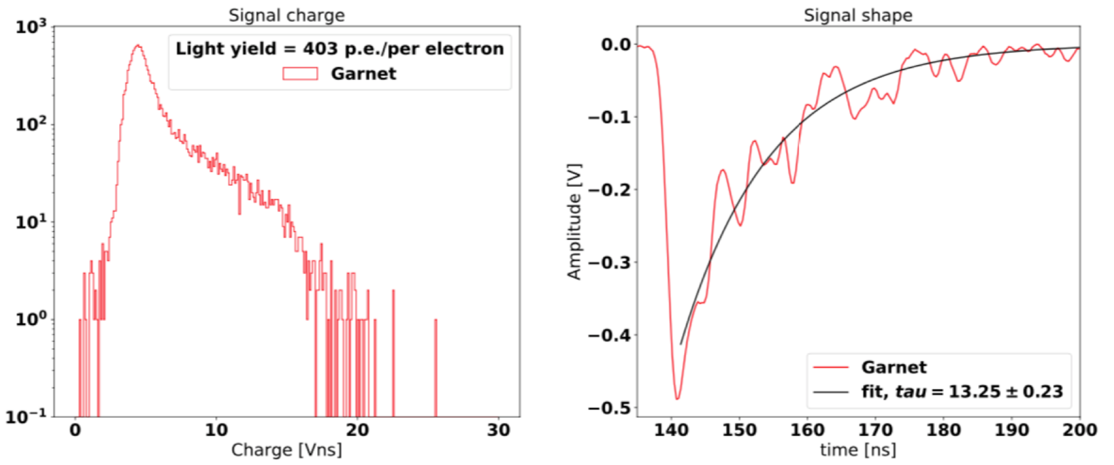


Figure 9: Response (left) and signal shape (right) of the tested Garnet crystal.

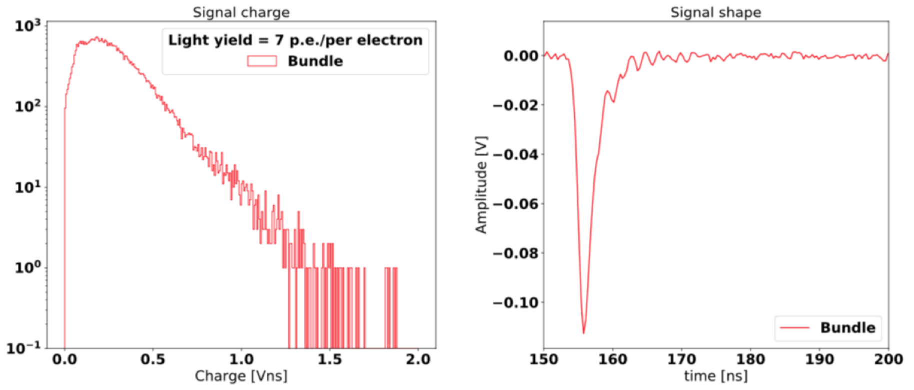


Figure 7: Response (left) and signal shape (right) of the tested quartz fiber bundle.

Desy first test beam results

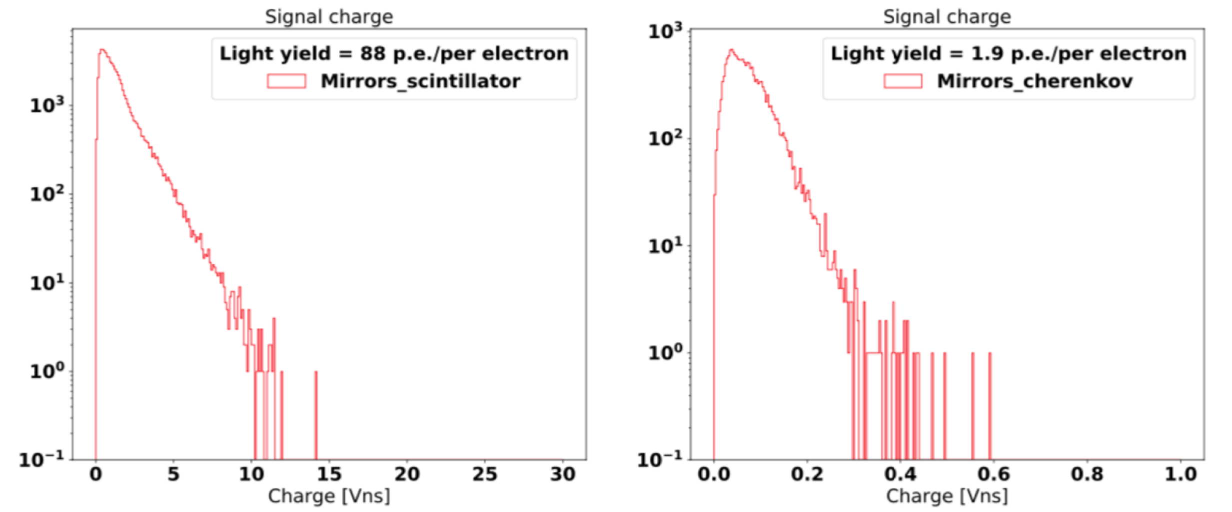


Figure 11: Response with scintillator (left) and with Cherenkov radiator (right) of the Mirrors setup.

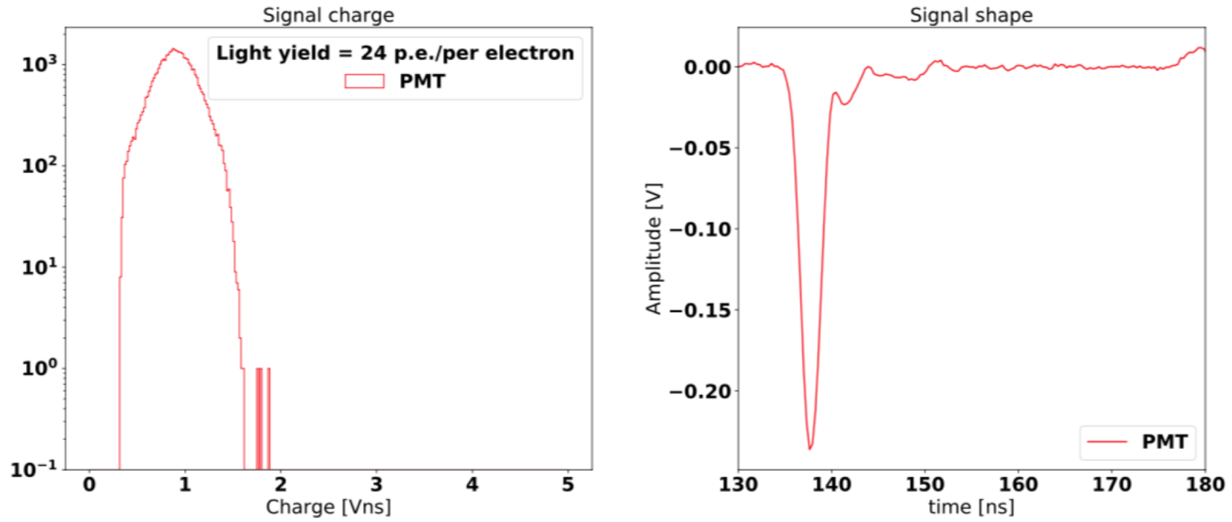


Figure 10: Response (left) and signal shape (right) of the tested PMT with quartz window

PLUME read-out electronics

Infrastructure

- FEE rack located on the balcony close to the VELO
- ECAL 9U crate equipped with a ECAL backplane
- 3 (+1) FEBs: 2 (detector readout) + 1 (pin diode readout) (+ 1 for timing TBC)
- 1 control board (3CU)
- 1 Maraton power supply water cooled at the back of the crate, controlled by 1 Wiener RCM (Remote Control Module)

Fibers:

- 12 individual optical fibers for the readout (4 per FEB)
- 2 individual fibers for the clock and slow control (connected to the 3CU)
- 2 long-distance 12-fiber ribbons between the PLUME readout crate and the TELL40 and SOL40 boards.

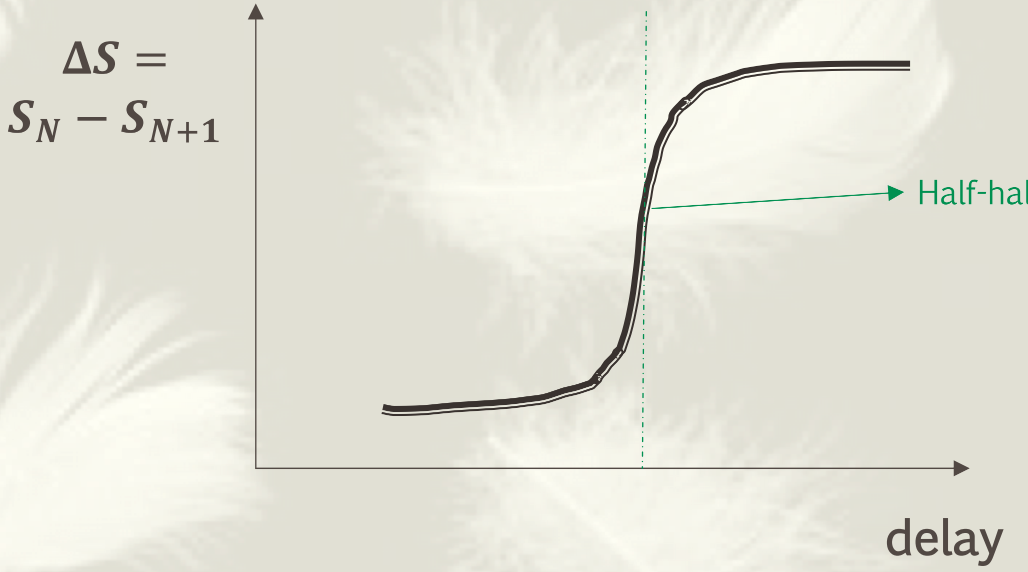
Fig: ECAL Rack

TELL40 (PCIe40)

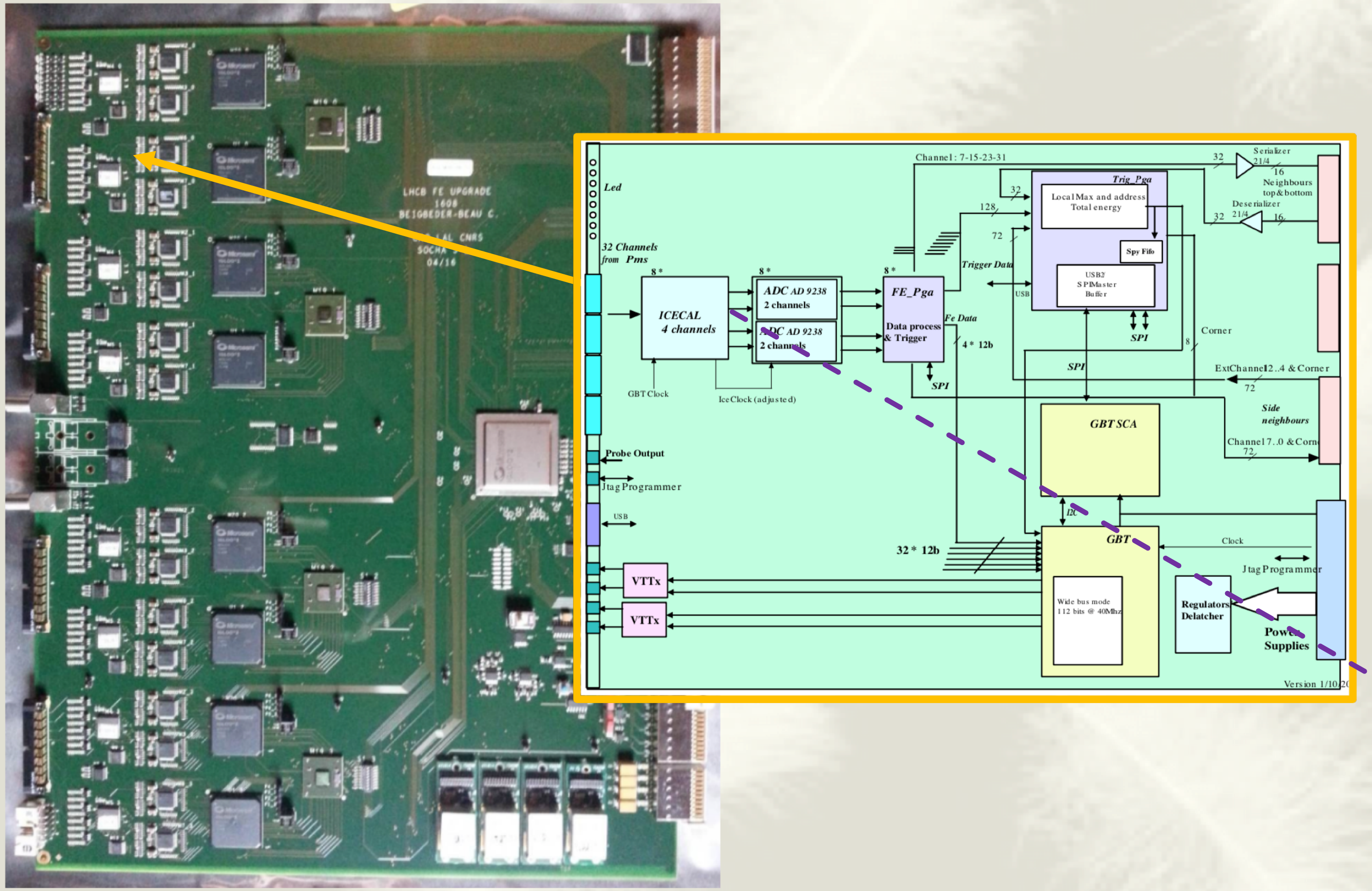
- Receive RAW data from the detector with one word of 12-bit ADC per channel
- A **custom firmware to be developed** to provide instantaneous luminosity to the LHCb control system
- Count the number of channels with no activity
- Using Bunch Crossing information from RAW data→possible to obtain the luminosity per bunch (histograms of empty events as a function of the BCId)

Timing measurement with ECAL electronics

The idea: perform a timing measurment
shift the integration window of the signal (introduce a delay) to perform a timing measurement



Testing the FE for PLUME: front-end block



Front-end block contains:

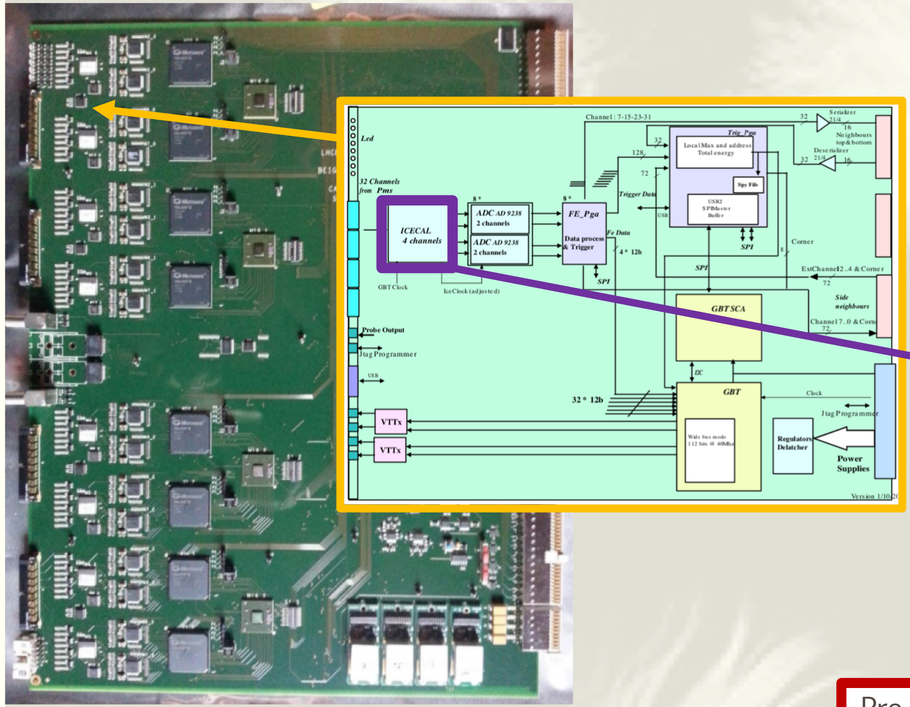
- Analog electronics
- 2 DUAL ADC
- 2 FPGA (Front-end)
- GBT-X
- GBT-SCA slow control

Analog part: PMT signal clipped on the base to contain the pulse in 25 ns window then travel trough a coaxial cable to be injected in the positive input polarity

ICECAL chip: the integration happens here

Testing the FE for PLUME: ICECAL

ICECAL: 2 processing lines at 20 MHz (synchronized with the global clock)



Shape the signal with pole zero compensation

2 integrators working in alternation (one at rest, one integrating)

Store the integrated signal and do the sampling

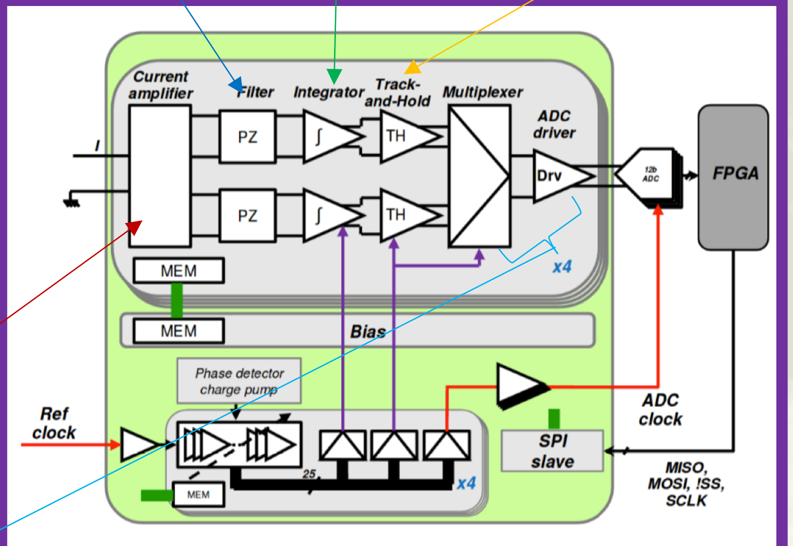


Figure 6: Schematics of the analog electronics.

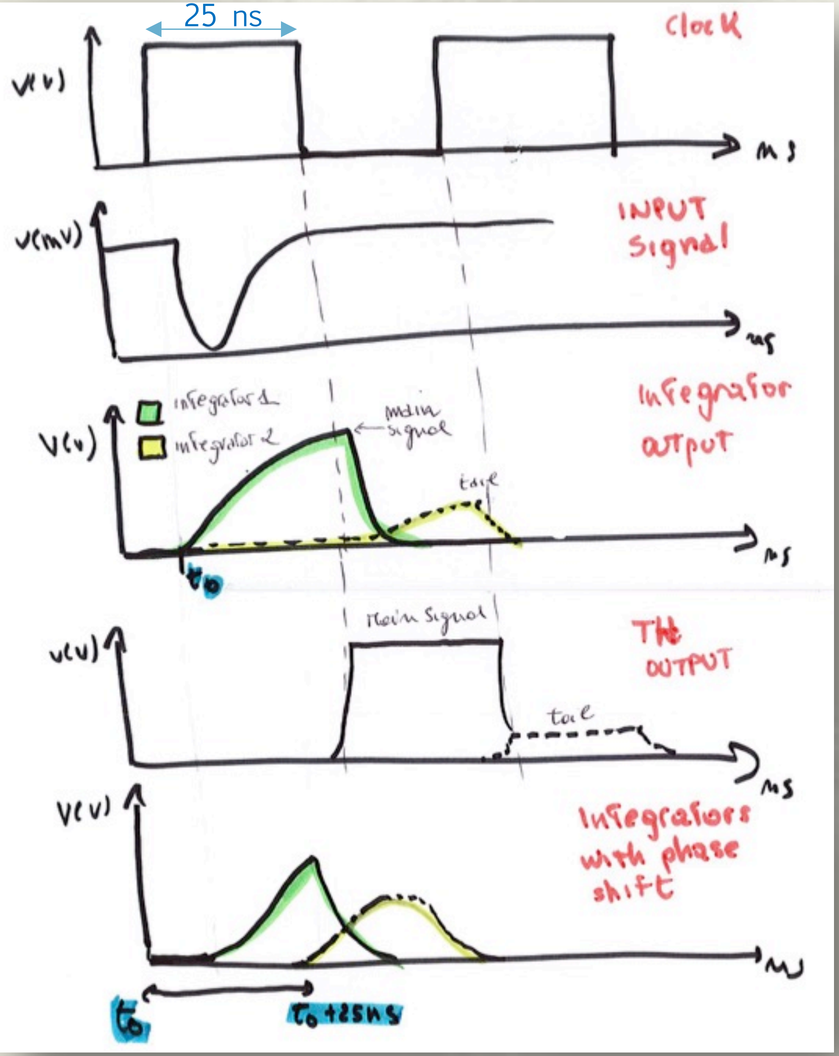
Pre-amplifier

Analogue Multiplexer selecting the correct sub channel + ADC driver to match ADC input impedance

Process:

1. Shape signal with pole zero compensation
2. Integrate signal
3. Store in T/H

Testing the FE for PLUME: ICECAL



What's going on while integrating the signal?

1. First the signal is integrated in subchannel 1
   →Transfer the output charge to the T/H
2. Reset integrator 1 while integrator 2 is integrating the rest of the signal

One integrator has odd bxid the other even (25 ns alternation).

When do we start integrating?

- The clocks come from the GBT-X to the ICECAL
- The ADC needs also need a clock to properly sample the ICECAL output
- We can tune the phase of these 2 clocks: ClockTH and ClockADC (which are linked to each other)
- We also need to set the polarity of the FPGA clock (positive or negative depending on the phase shift)

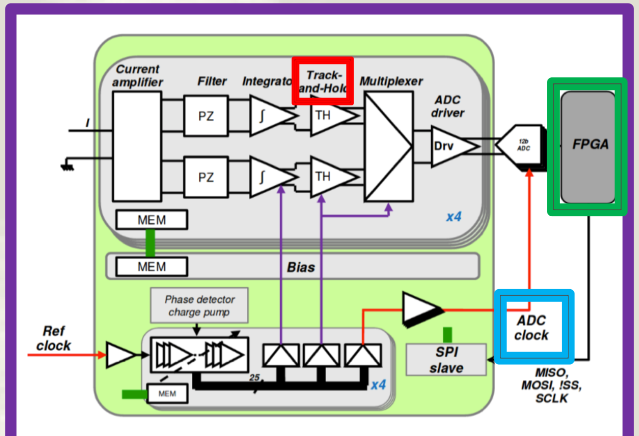


Figure 6: Schematics of the analog electronics.