TORCH - Cherenkov and Time-of-Flight PID Detector for the LHCb upgrade at CERN

Klaus Föhl, CERN

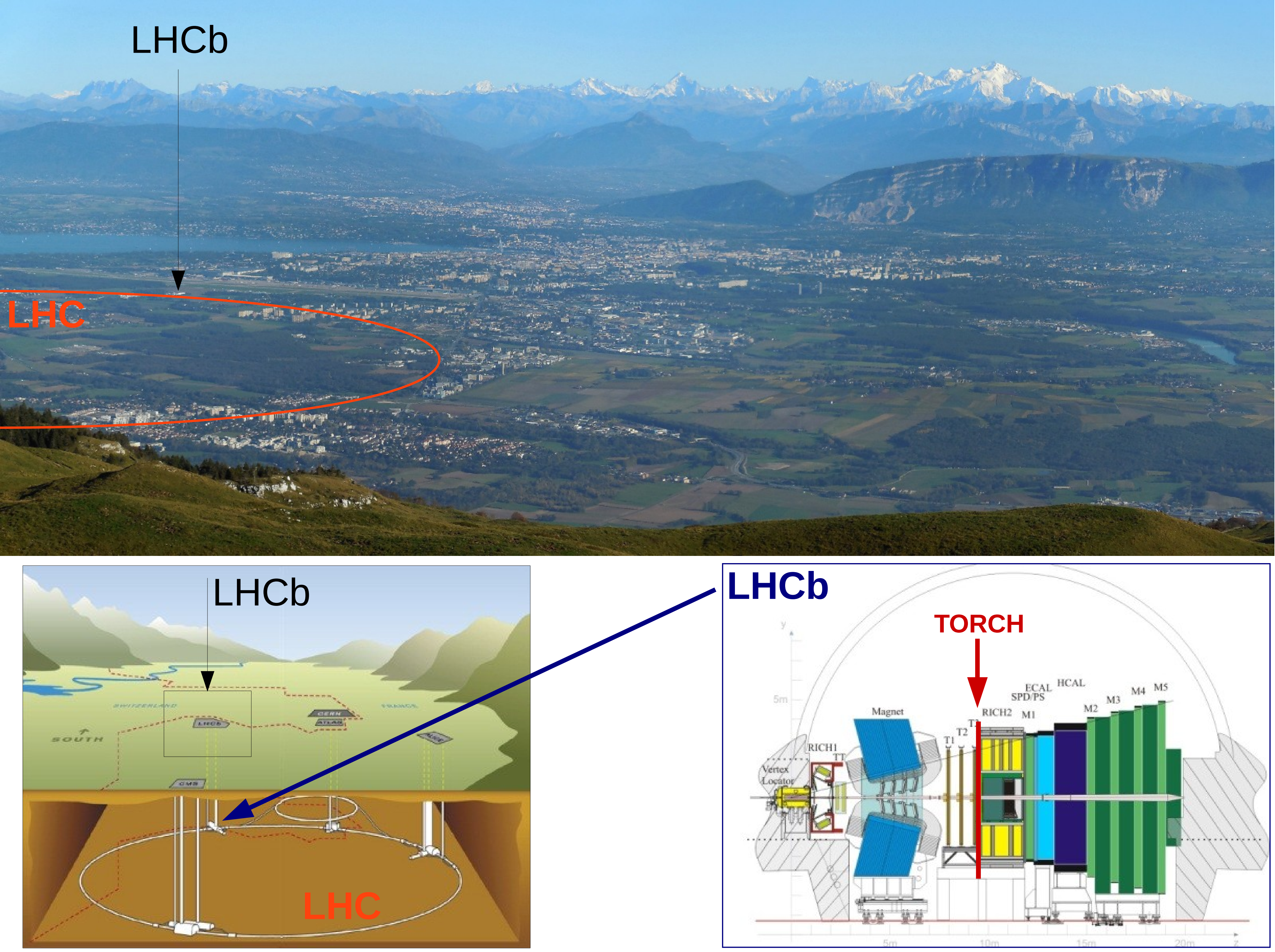
on behalf of the TORCH Collaboration
(University of Bristol, CERN,
UCL, University of Oxford,
with industrial partner Photek)

DIRC2015
Rauischholzhausen
12 November 2015

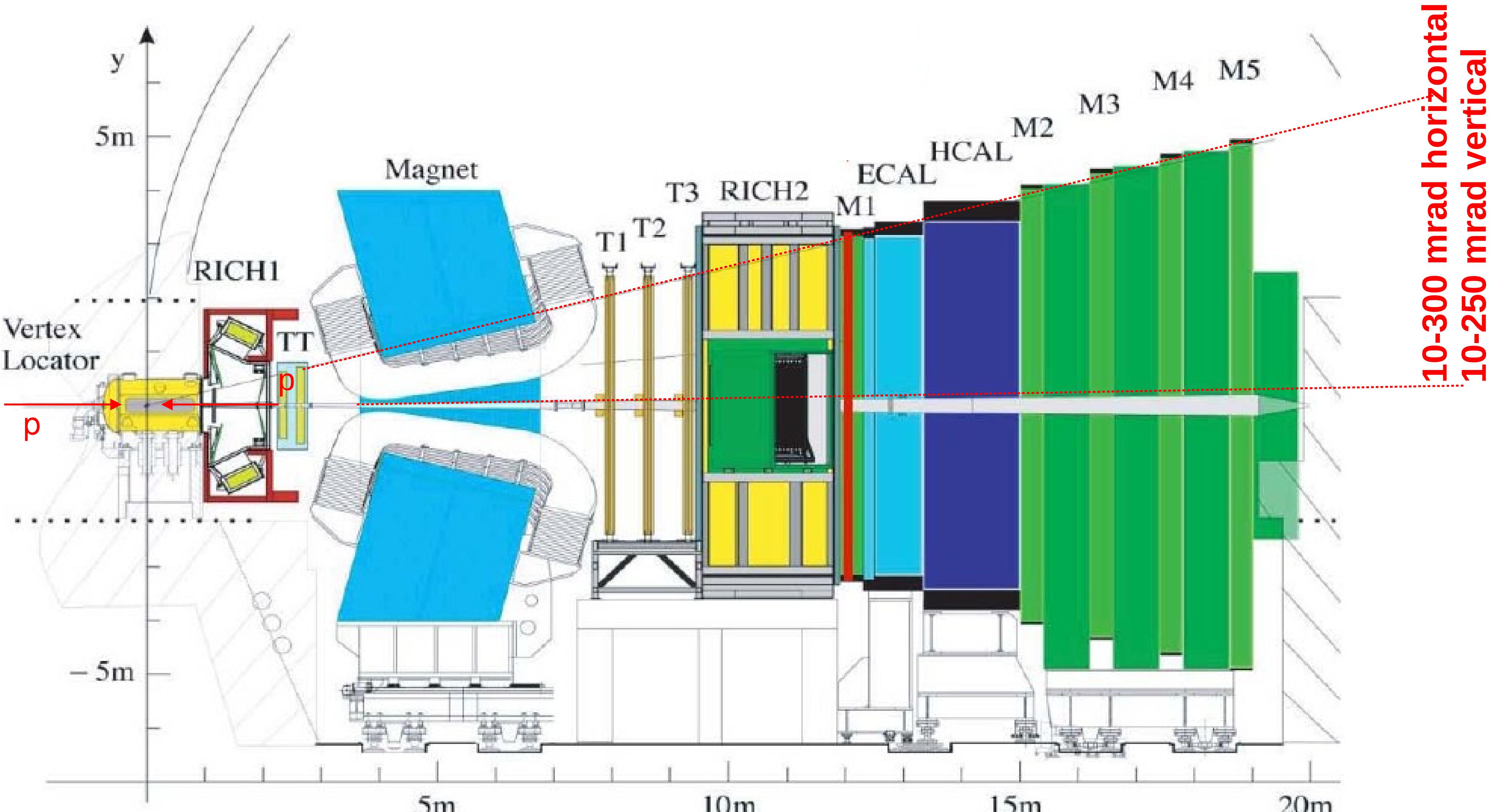
European Research Council
Established by the European Commission

Outline

- TORCH within an upgraded LHCb
- TORCH design and principles
- Photon sensors
- Electronics
- Test beam introduction
- BaBar bar boxes as option

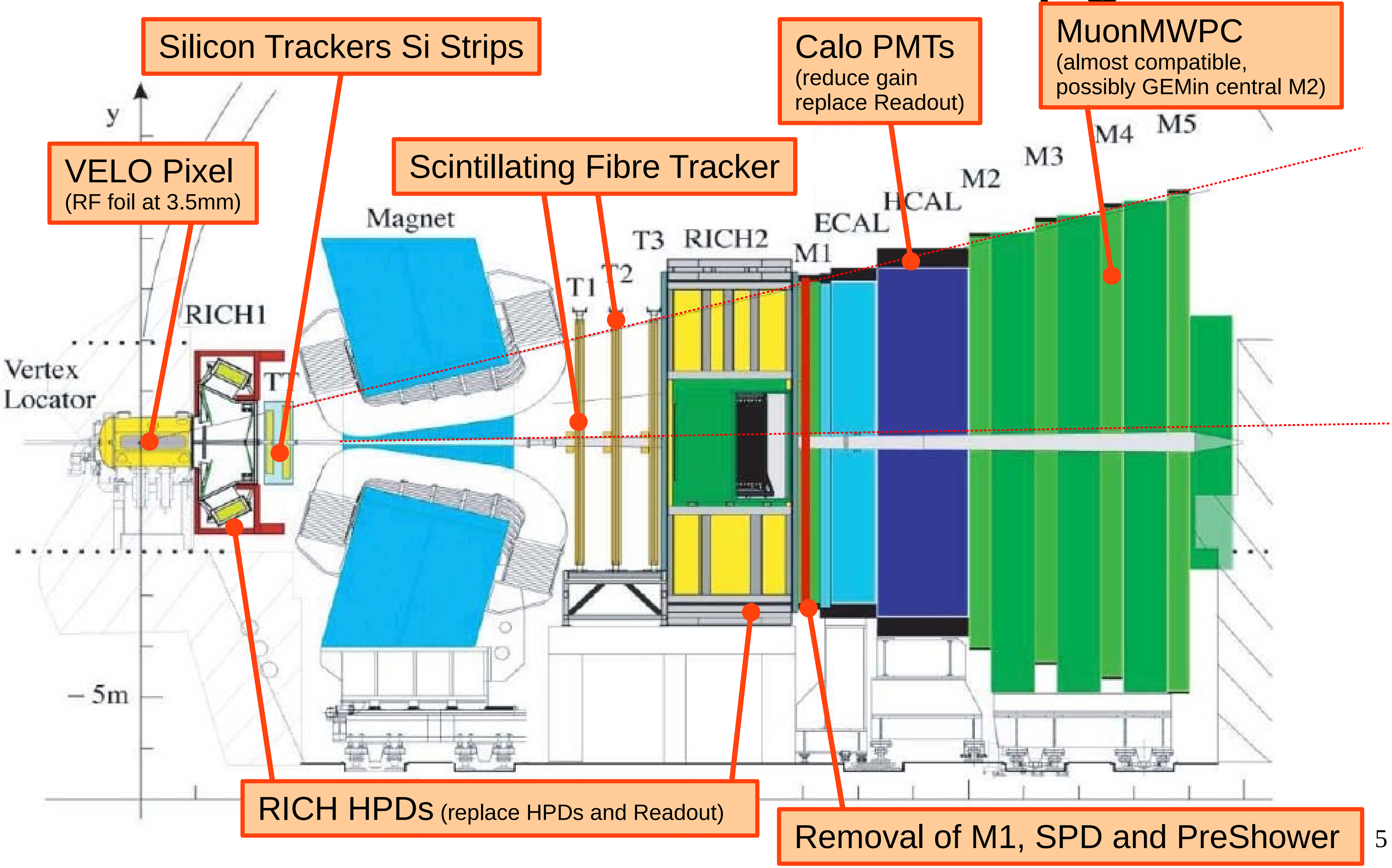

LHCb
LHC
LHCb
SOUTH
LHC
LHCb
TORCH
y
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
ECAL
SPD/PS
HCAL
M1
M2
M3
M4
M5
5m
10m
15m
20m
z

LHCb at CERN



y
5m
– 5m
Magnet
RICH1
Vertex
Locator
TT
p
p
T1
T2
T3
RICH2
M1
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
10-300 mrad horizontal
10-250 mrad vertical

LHCb – LS2 Detector Upgrades

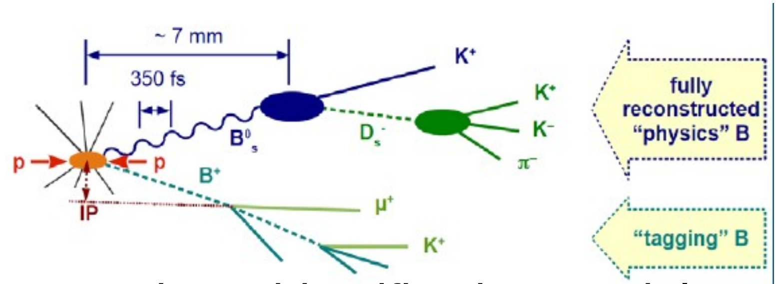


Envisaged upgrades of LHCb during CERN Long Shutdown 2.

LHCb upgrade during LS2

goals:

- Increase statistics by factor of 10
- Improve access to hadronic modes



kaon identification crucial for reconstructing the upstream reaction particles

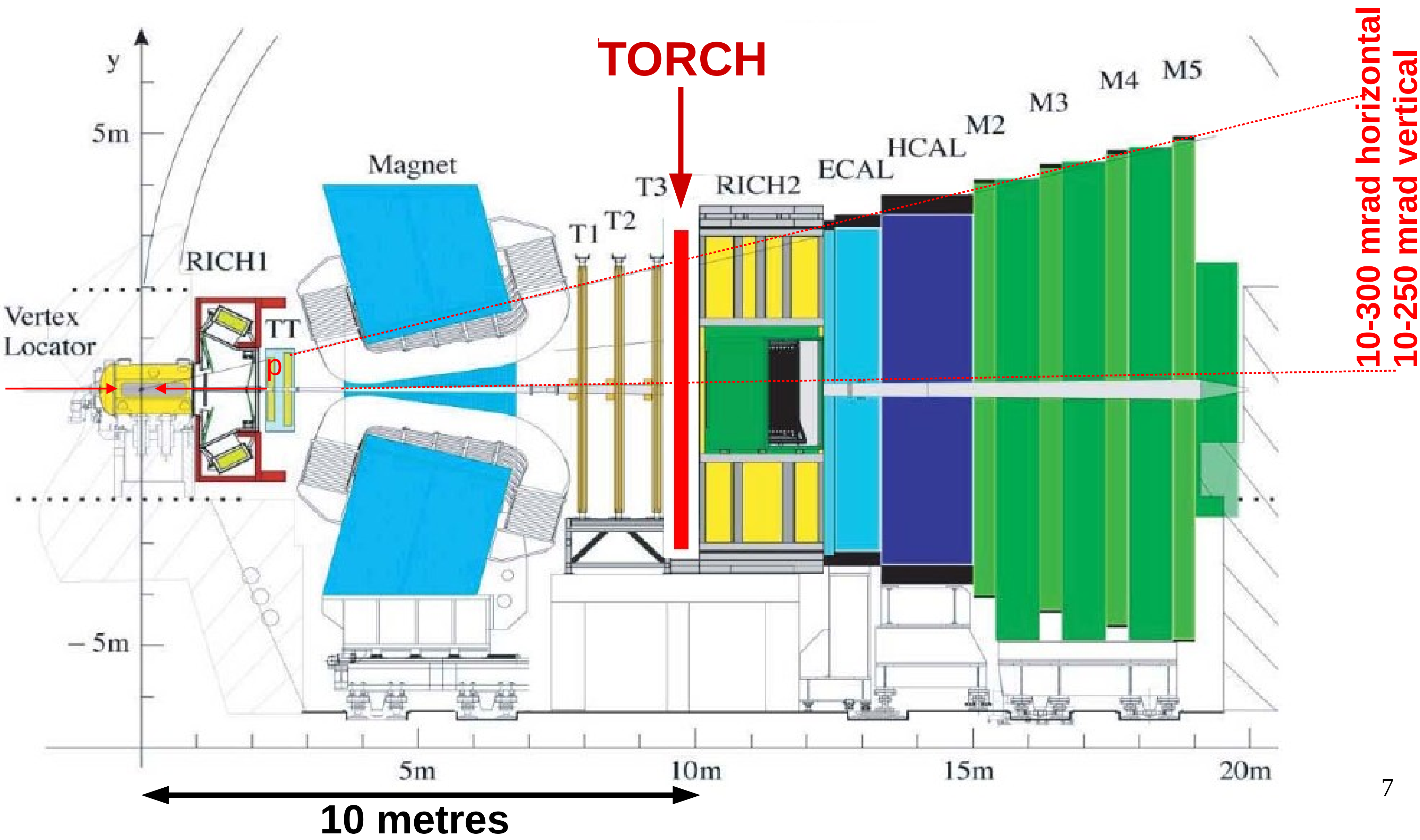
how-to:

- Increase luminosity
  - >100 kHz to 1 MHz of bb-bar pairs at LHCb interaction point
- Increase efficiency of hadronic channels by factor >2
- Improve output bandwidth, fully software trigger and lower p_T

reason:

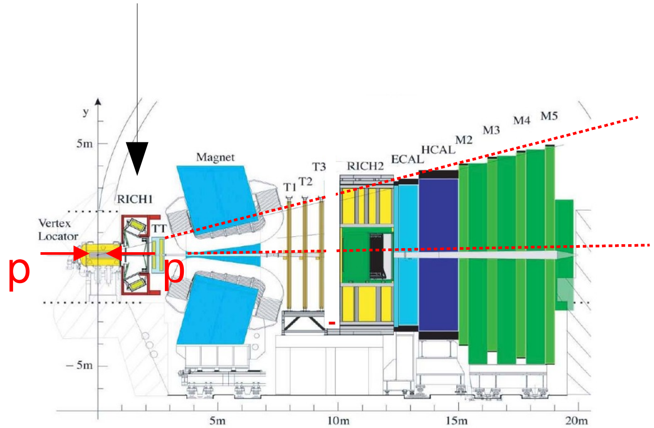
- To give access to new modes and observables

TORCH location within LHCb at CERN



Motivation for TORCH 1

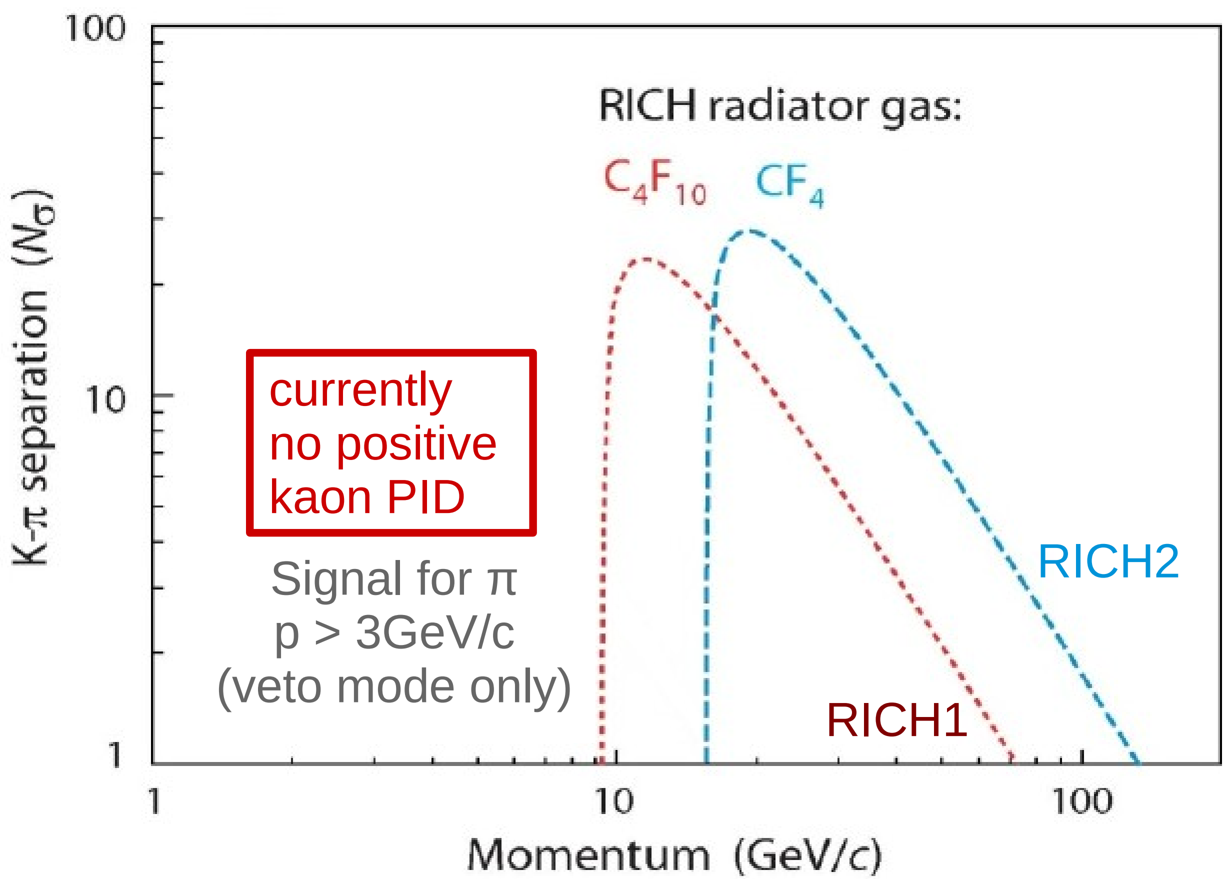
RICH1



Momentum 1-10 GeV/c :

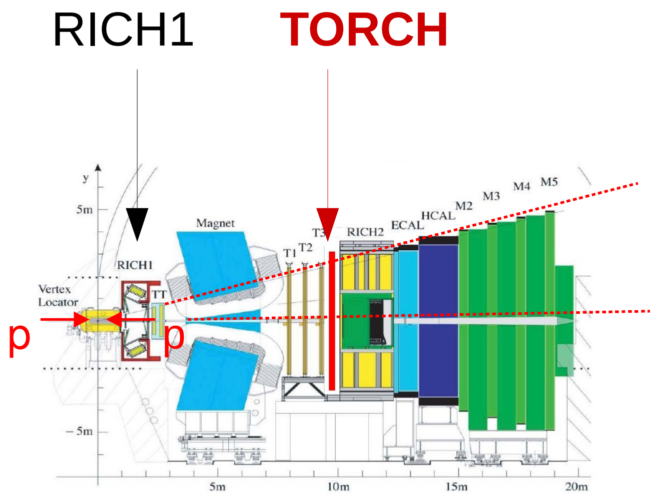
PID not covered in LHCb with aerogel now removed from RICH1 detector

- Low photon yield
- Resolution not as expected
- Added occupancy



Idealised PID Performance of RICH detectors

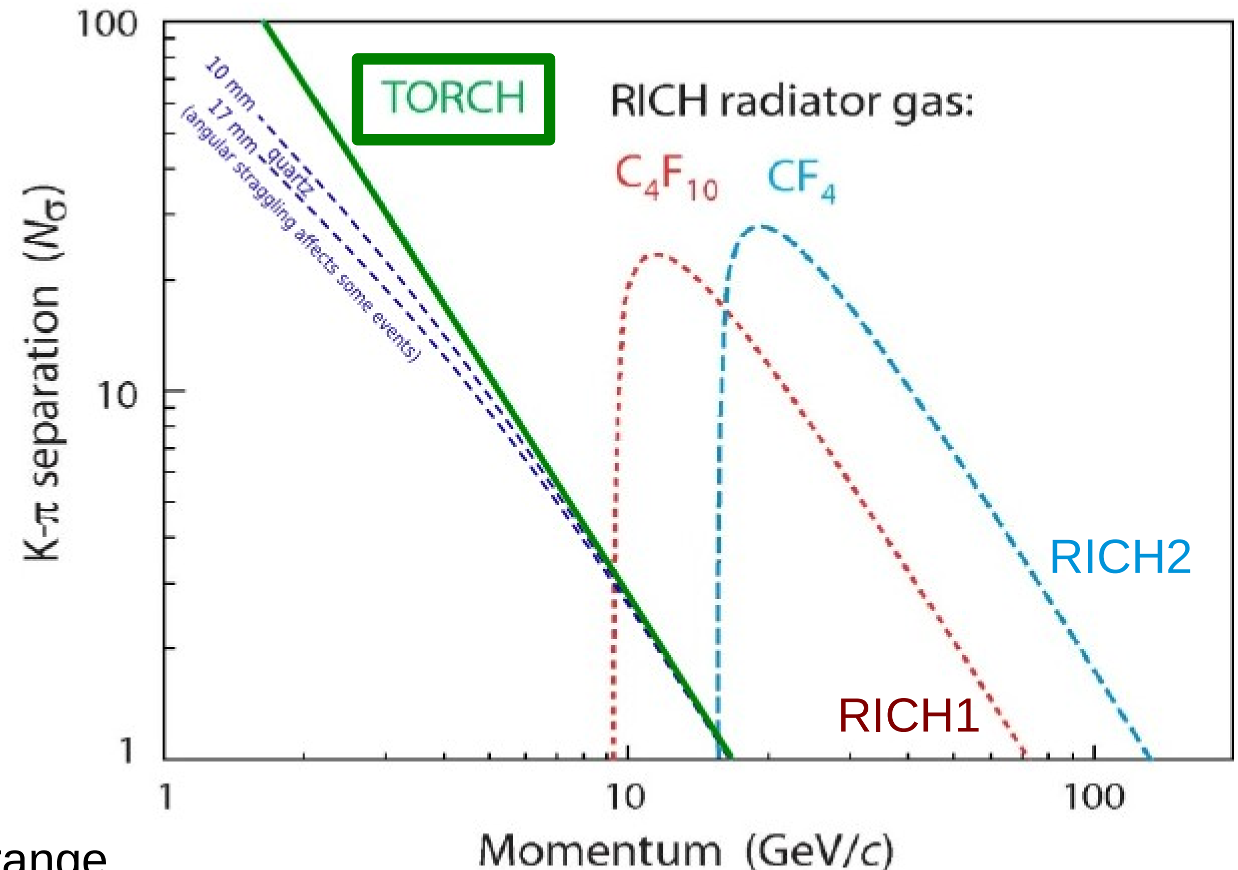
Motivation for TORCH 2



Momentum 1-10 GeV/c :

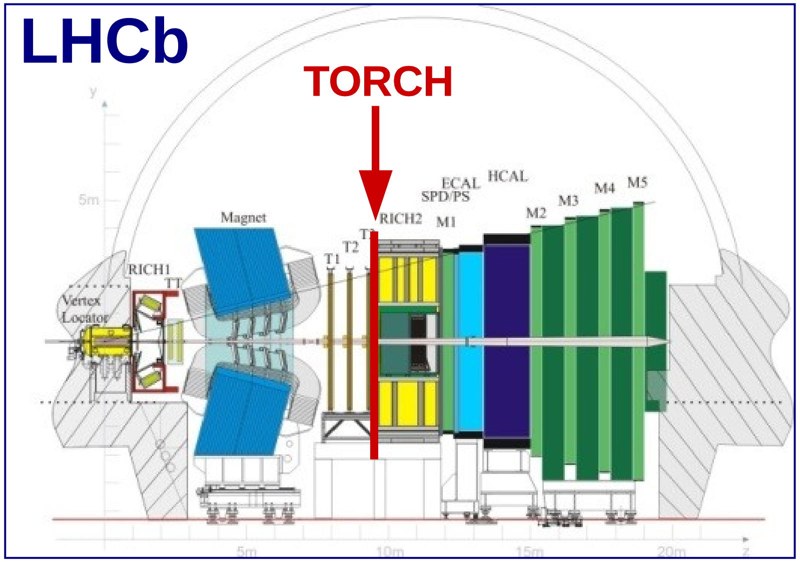
PID not covered in LHCb with aerogel now removed from RICH1 detector

For kaons positive PID in the range p = 1-10 GeV/c can be achieved by adding the TORCH detector

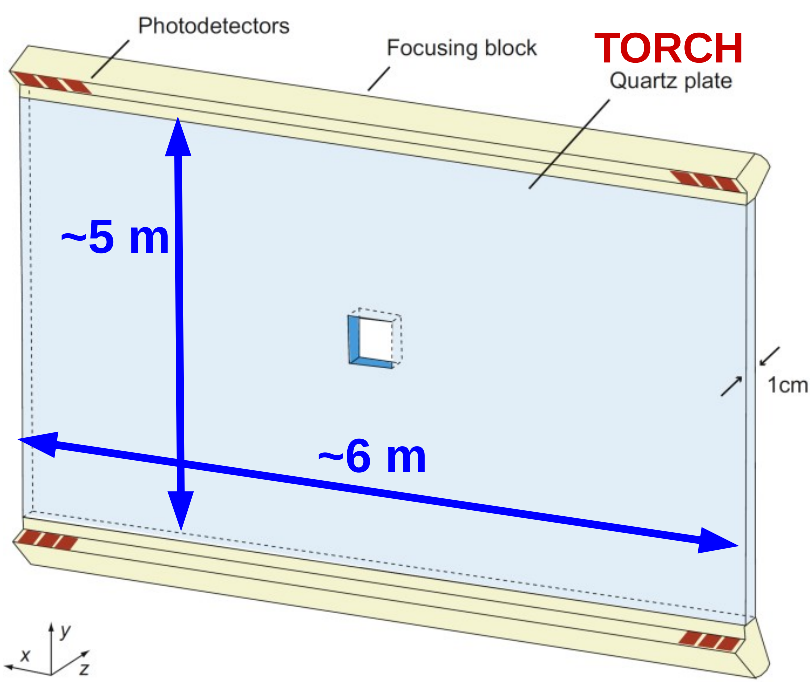


Idealised PID Performance of TORCH alongside RICH detectors

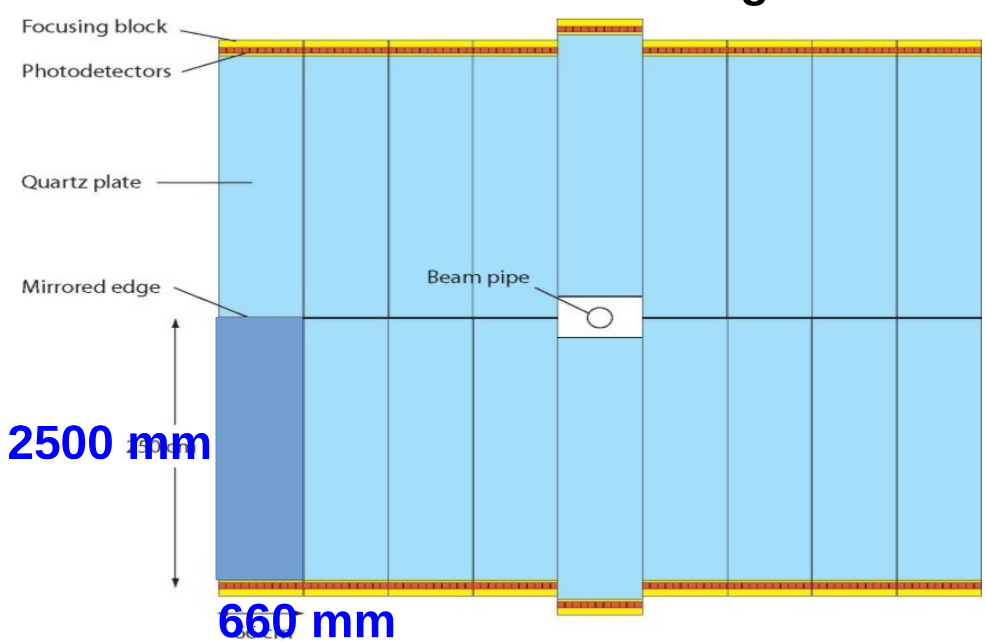
TORCH overall geometry



- Overall area about 6 x 5 m^2
- Plate thickness ~10 mm (~15-17mm still acceptable)
- 18 tiles of 660 x 2500 mm^2 in Modular Design

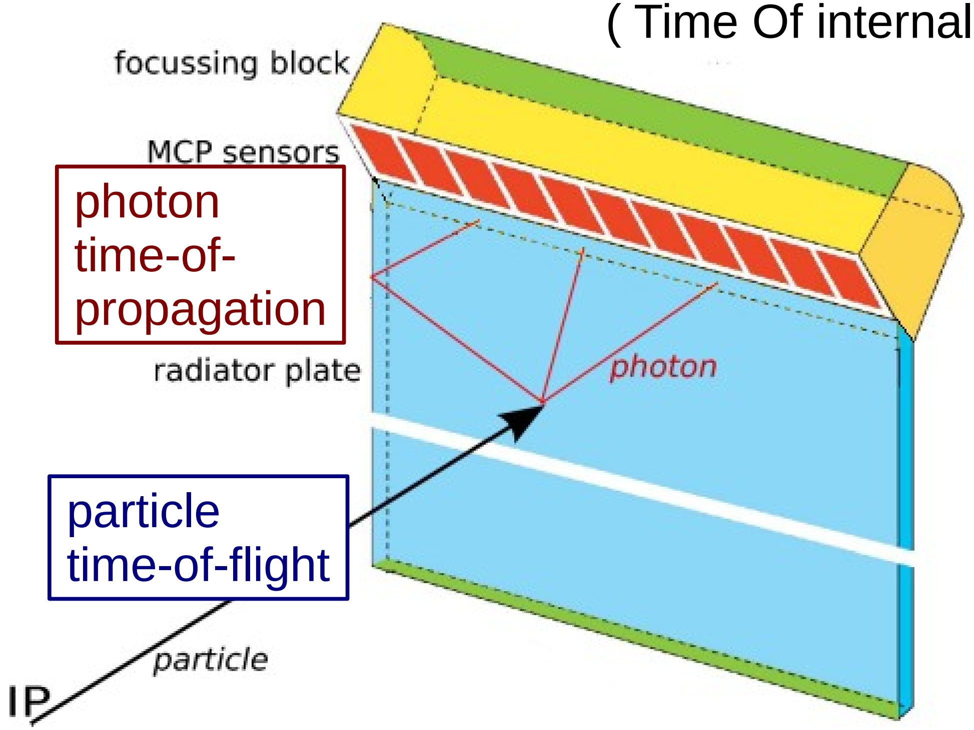


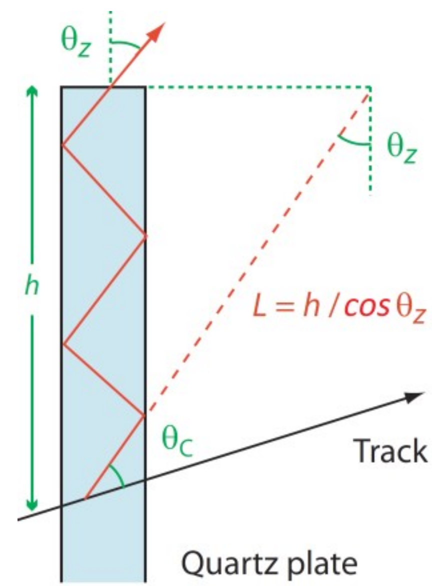
Modular Design

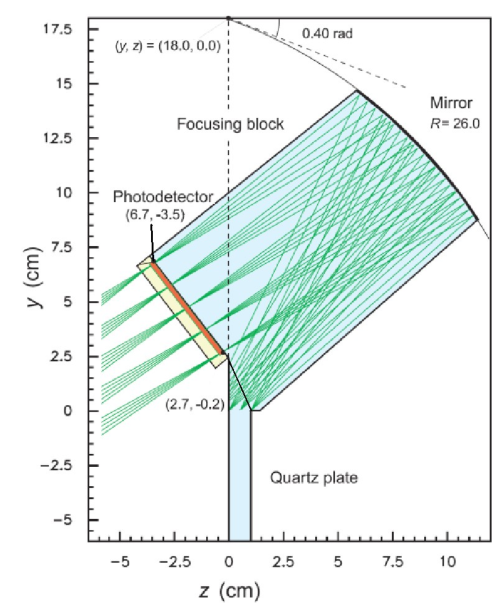


Basics of the TORCH design

(Time Of internally Reflected Cherenkov)



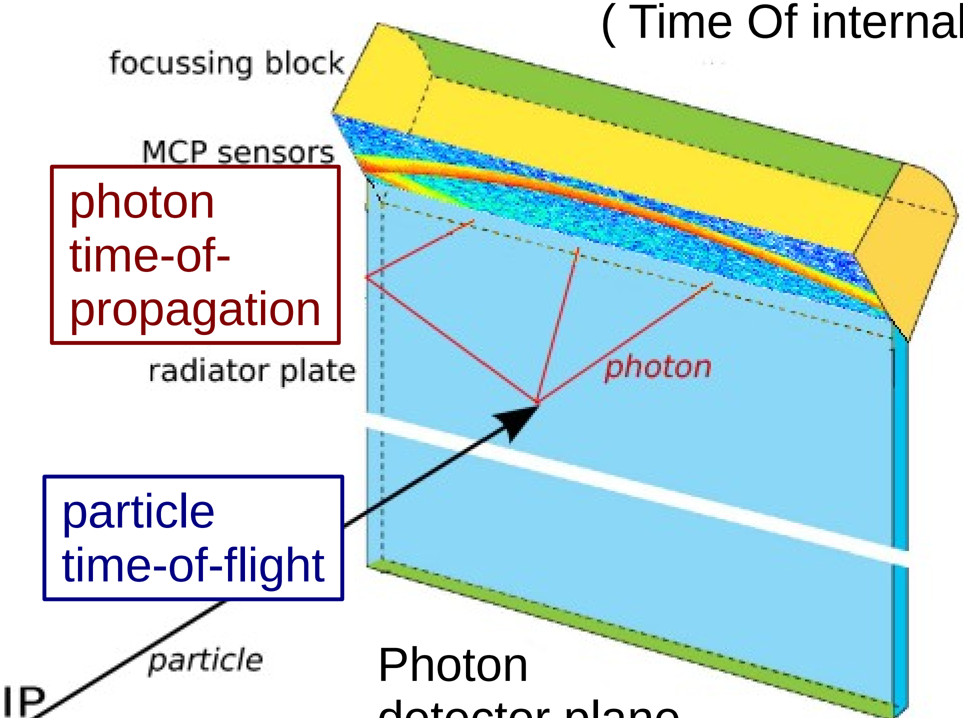


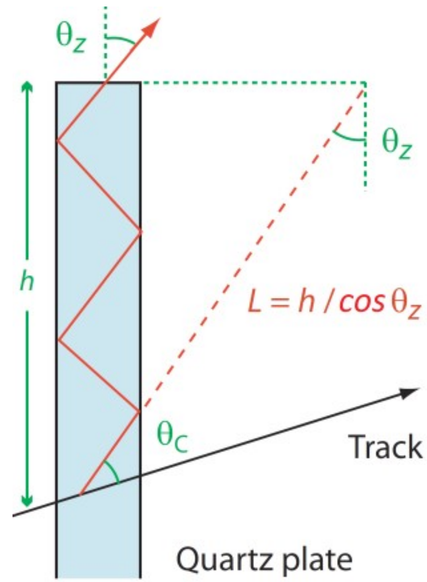


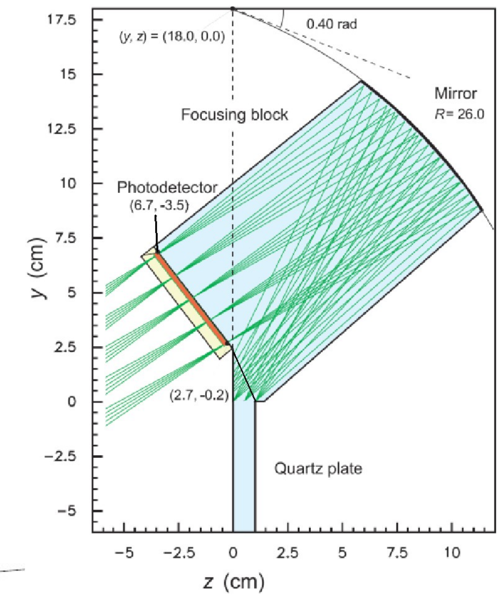
- θ_x measured via horizontal position on MCP sensors
- θ_z measured via cylindrical mirror focussing

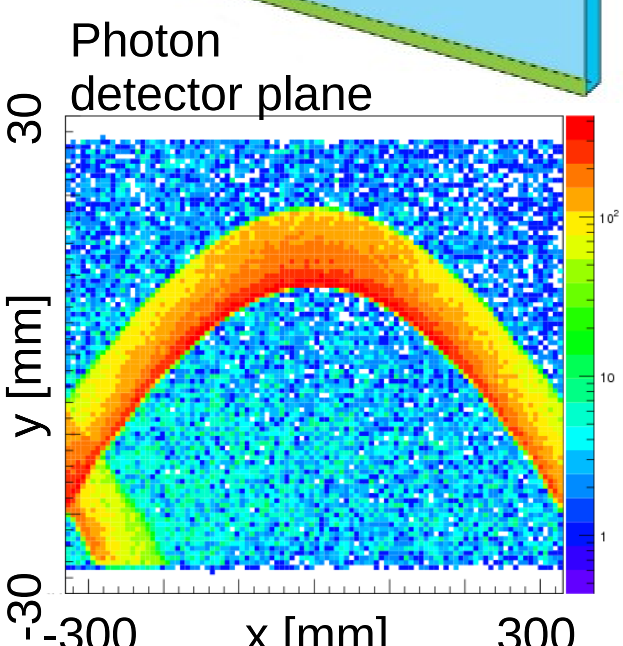
Basics of the TORCH design

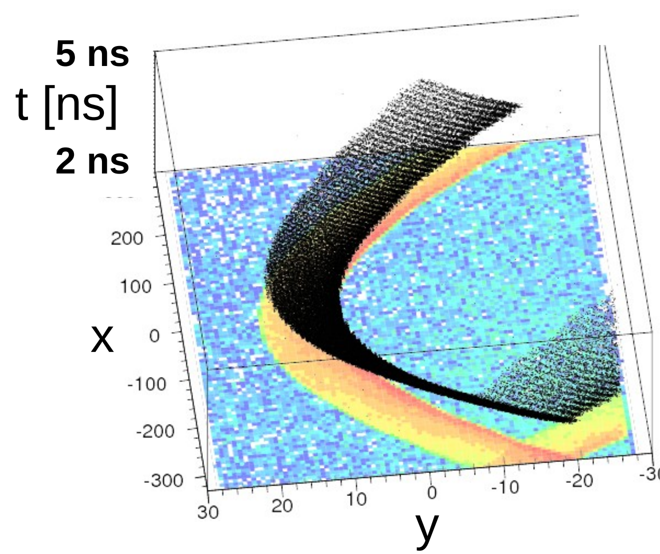
(Time Of internally Reflected Cherenkov)



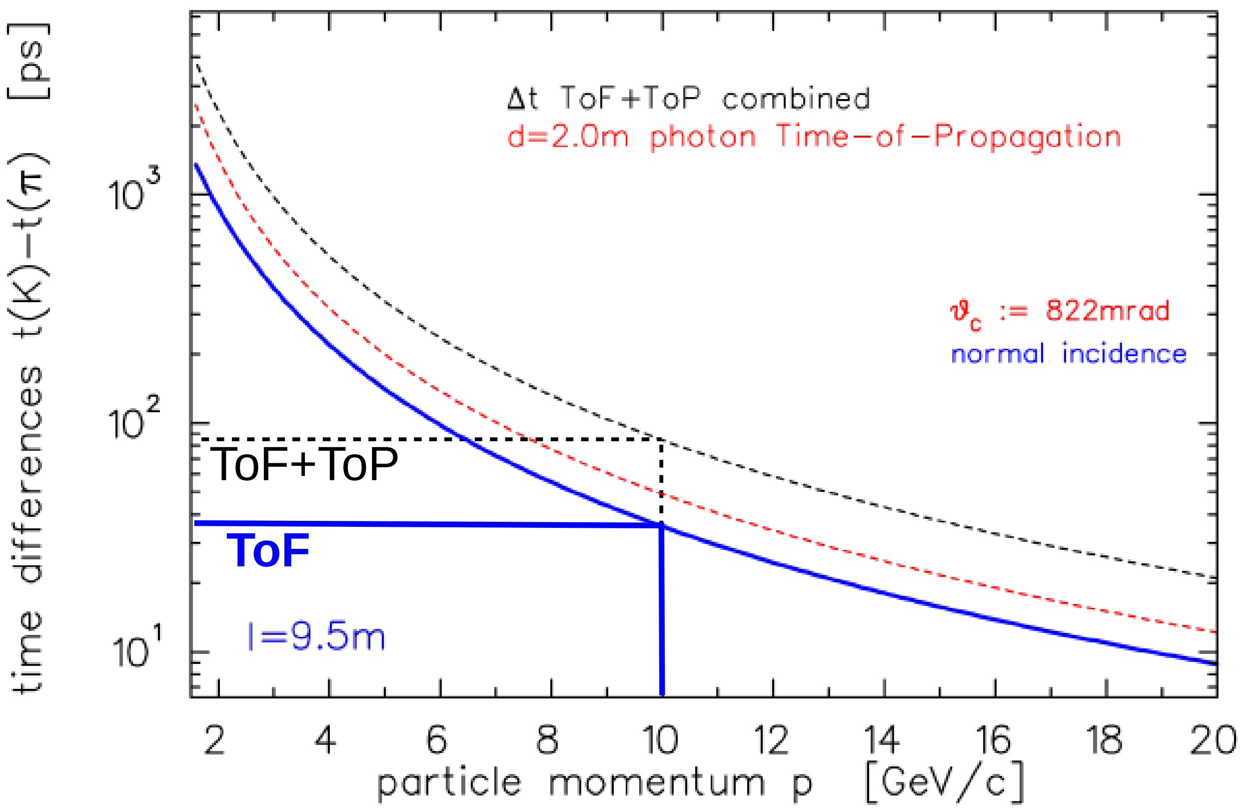


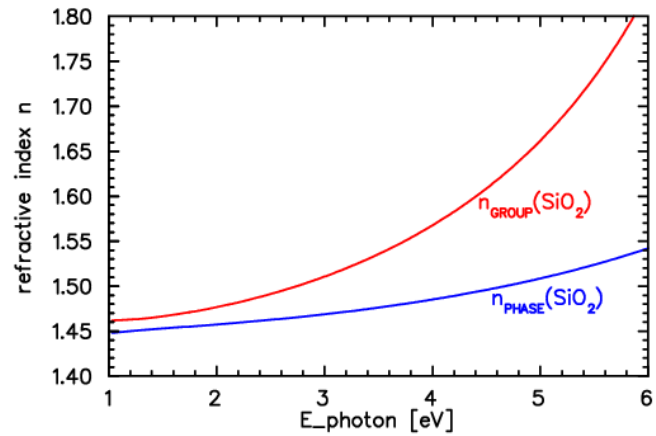






TORCH principle

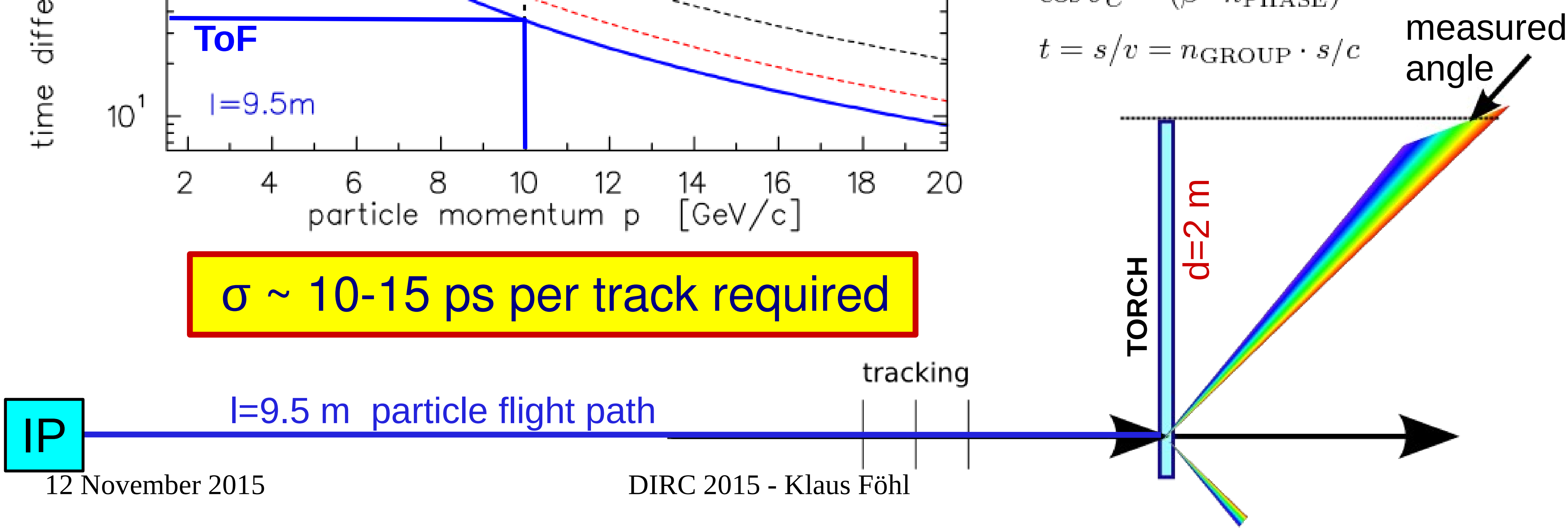




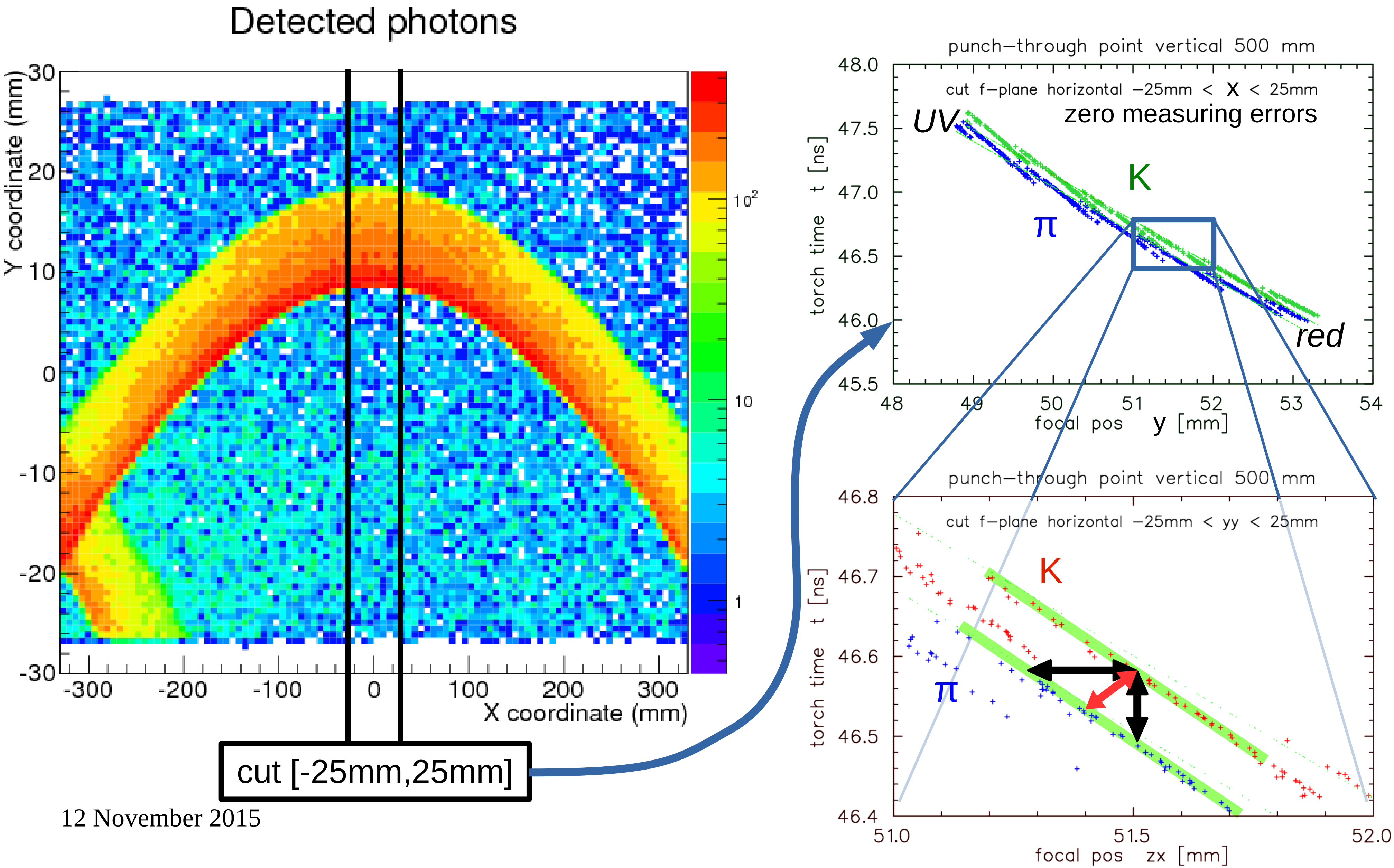
$$\cos\vartheta_C = (\beta \cdot n_{\mathrm{PHASE}})^{-1}$$

$$t = s/v = n_{\mathrm{GROUP}} \cdot s/c$$

σ ~ 10-15 ps per track required



TORCH module simulation



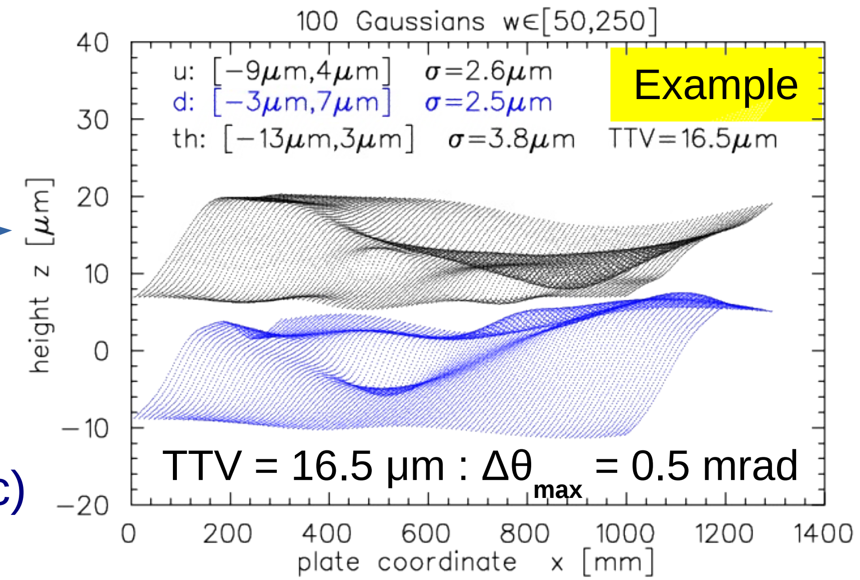
Required resolutions

- <u>Optical resolution ~1 to 2 mrad</u>

  (sigma, all effects combined)
  - Cherenkov material
  - Radiator propagation
    - Angles preserved
    - High photon transmission
    - Low light background
  - Focussing optics
  - Sensor resolution
- <u>Time resolution ~50ps</u>
  - Photon sensors (MCPs)
  - Analog electronics (amplifier)
  - Logical electronics (discriminator)
  - Digital discretisation (TDC)
  - Clock synchronisation

Optical properties

- Material geometry
  - Overall size
  - Surfaces geometry



- Material bulk
  - Refractive index variations (random, systematic)
  - Absorption chemical impurities
  - Absorption physical impurities

- Random / local $\Delta n < 1\ 10^{-4}$
- hence $\Delta n < 1\ 10^{-5}$ averaged
- periodic layers give diffraction patterns

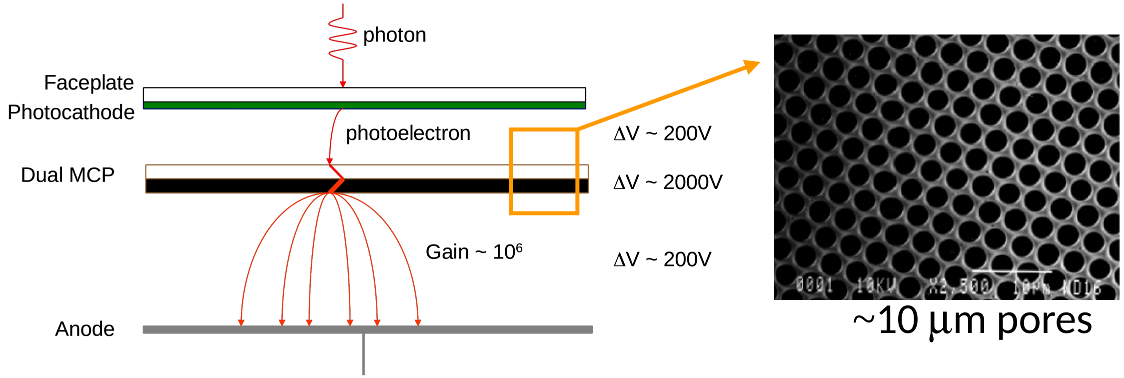
- Material surface
  - Scratches/digs, cracks, sharp edges vs bevels
  - Dirt deposition
  - Surface roughness

Rq=0.5nm / R_{RMS}=0.5nm
incomplete specification

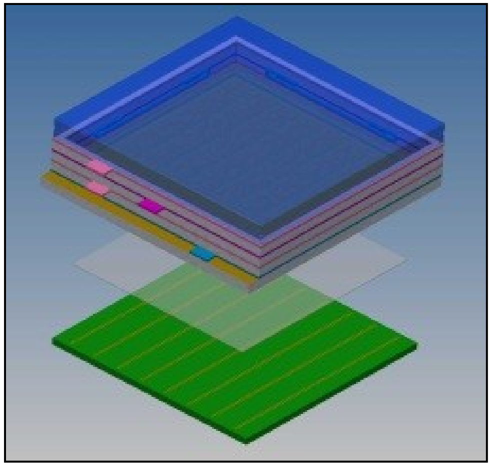
- photon energy range 2 eV to 5.5 eV
- Rq spatial bandwidth 1 mm to 80 nm
- (wider than standard in ISO 10110-8)

Photon sensor (MCP) resolution

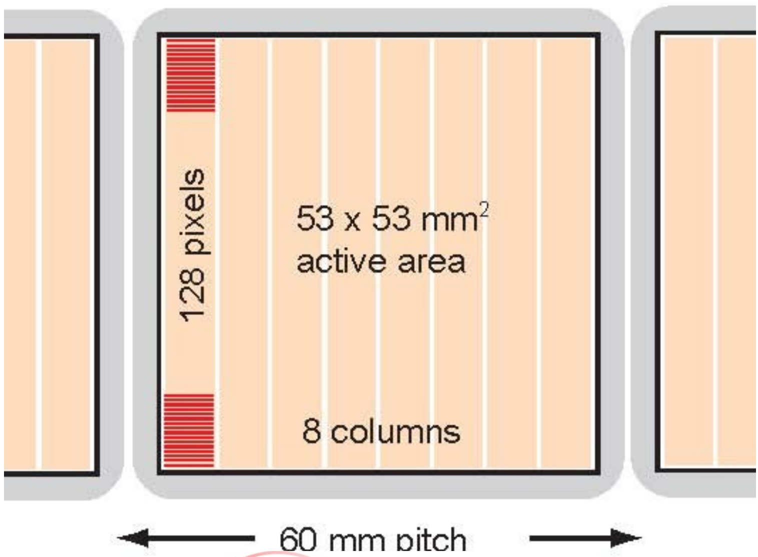
- Time resolution σ = 50-70 ps single photon
  - MCP sensors suitable for the required fast timing



~10 µm pores



- Anode pad structure adjustable
- Range $\Delta\theta_z$= 0.4 rad, resolution ~1mrad
  - 128 pixels (400mrad/(128 √12) ~ 1 mrad)
- Lateral direction requires 6mm pixel width
  - 128x8 pixels required
  - 64x8 if using charge sharing / centroiding



The development of a suitable detector with this layout is a focus of the R&D with industrial partner Photek(UK).

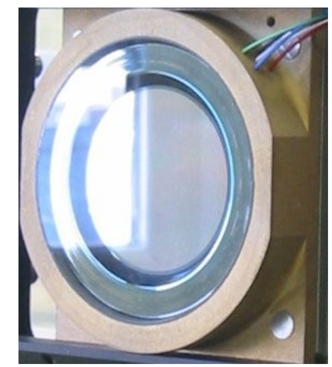
Photek project phases

Fast photon detectors with high spatial resolution and extended lifetime.

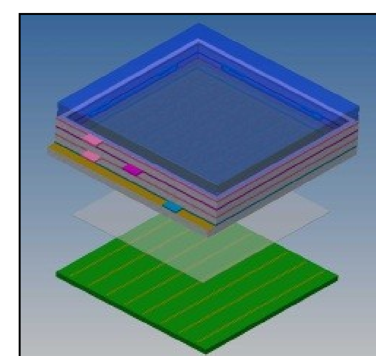
- Phase 1 – Lifetime
  - Aim: 5 C/cm^2 collected anode charge
- Phase 2 – Resolution
  - Demonstrator pad pitch 0.828 mm
- Phase 3 – Square form factor
  - Square body in linearly tileable geometry

→ The TORCH PMT, a close packing, multi-anode, long life MCP-PMT for Cherenkov applications (James Milnes, Photek)

phase 1 tube

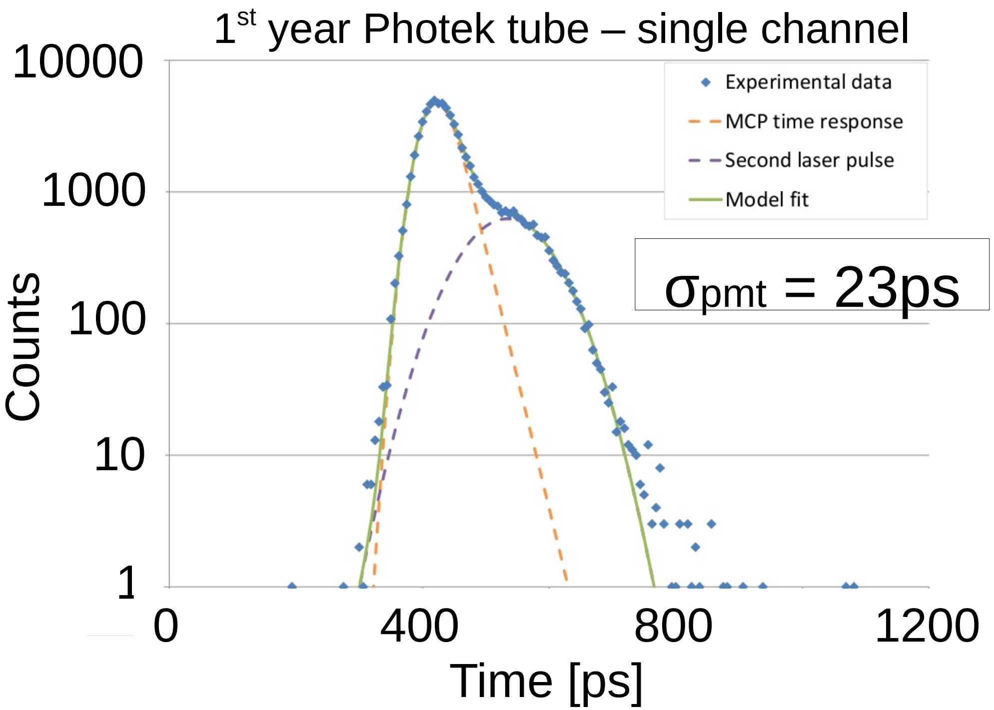


phase 2 tube

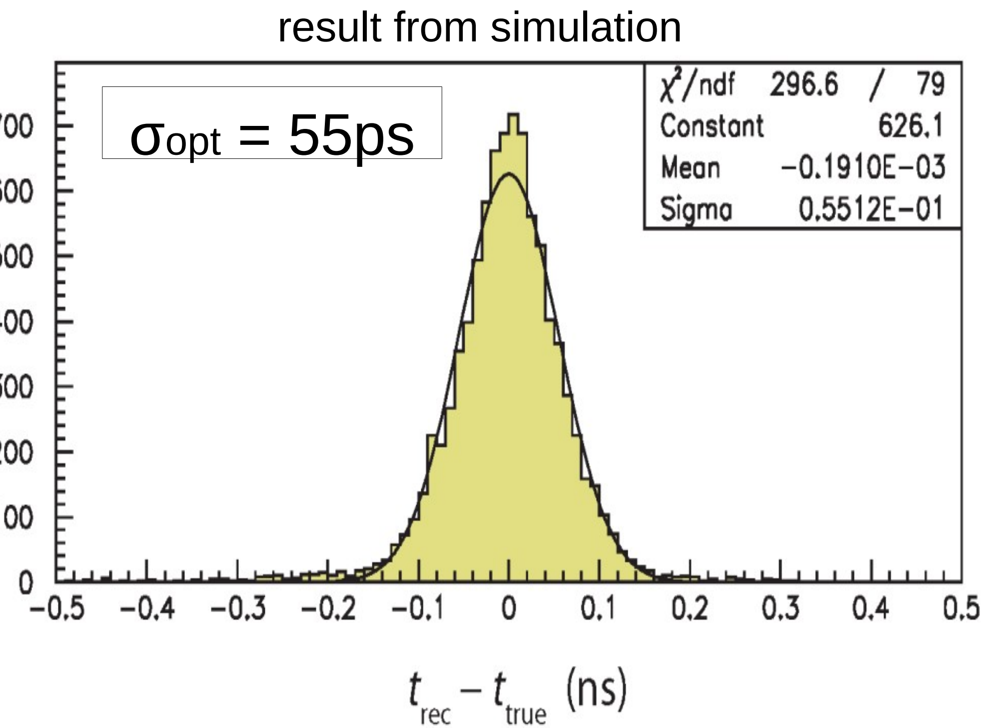


phase 3 tube (visualisation)

Timing – Sensor and Optical



MCP timing distribution



Optics timing distribution (mostly granularity)

$$\sigma_{total} = \sqrt{\sigma^2{}_{pmt} + \sigma^2{}_{opt}} \sim 60ps$$

Development, characterization and beam tests of a small-scale TORCH prototype module (Lucía Castillo García, CERN and EPFL)

Electronics development: Goals

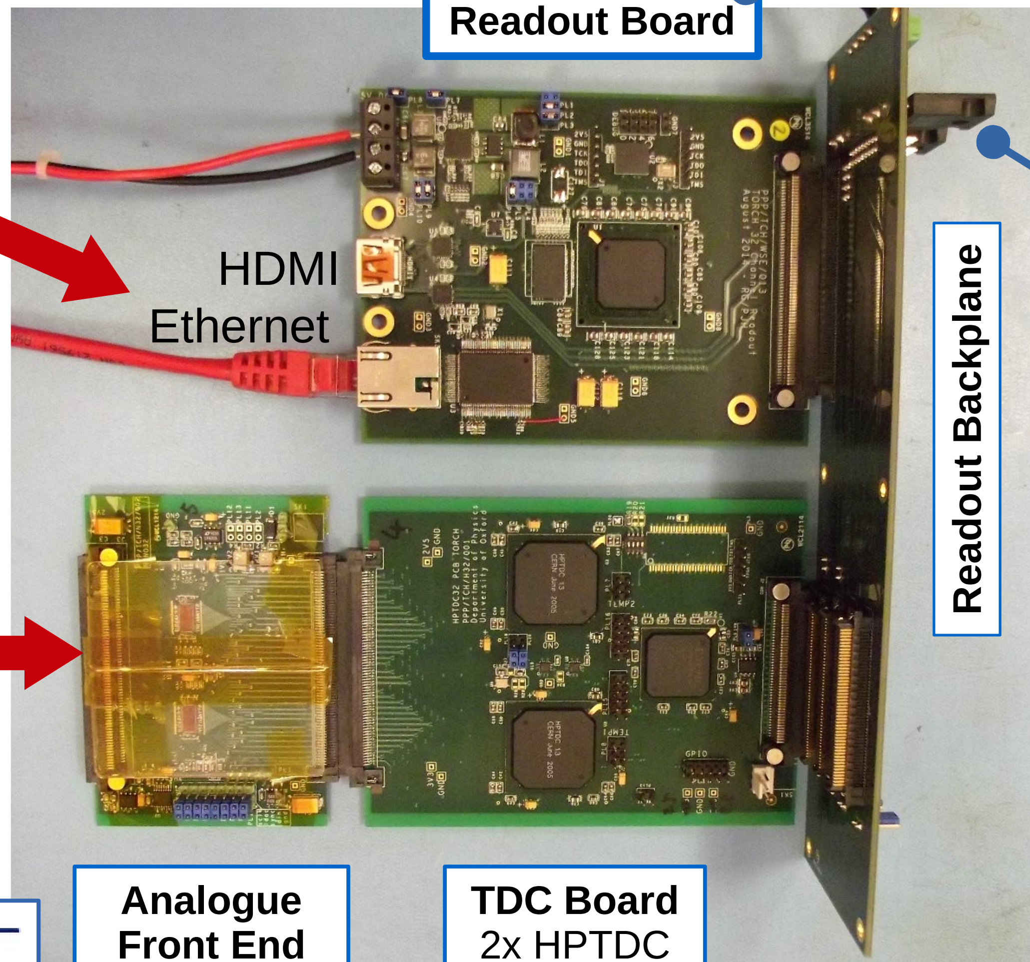
- Time-of-flight measurement of 128x8 channels per MCP (or 64x8 with charge sharing technique applied to achieve the 128x8 equivalent granularity)
- Fit within the 60mm dimension of a photon detector
- Overall timing resolution requirement is 70ps per single photon, electronics and MCP need to provide 50ps per channel
- Scalable design to suit different iterations of MCPs through stages of their development
- Flexible readout to be compatible with an experiment readout framework, e.g. LHCb (25ns beam crossing)

TORCH custom-made electronics

DAQ PC

HDMI
Ethernet

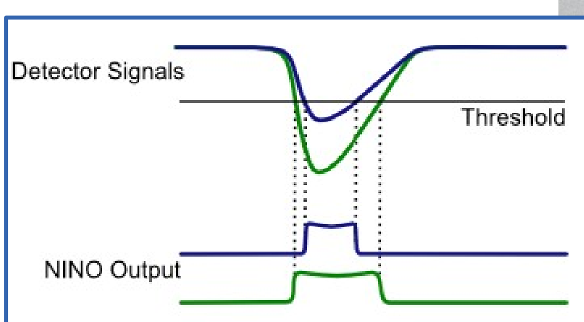
Readout Board



Readout Backplane

Regulators
and Power
Transistors

MCP Sensor

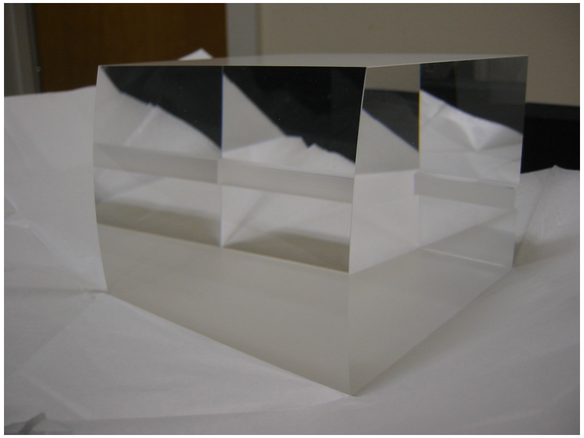


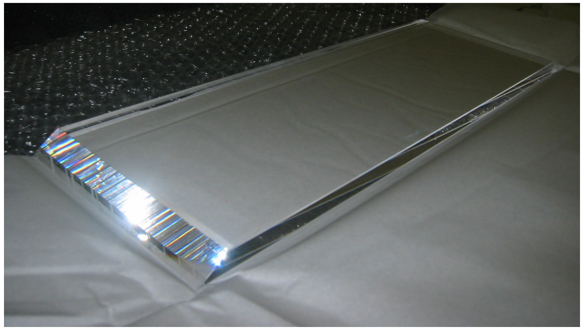
Analogue Front End
2x NINO32

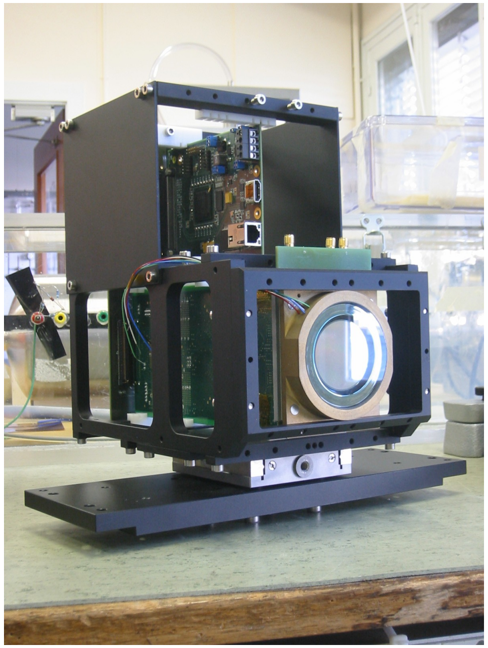
TDC Board
2x HPTDC
FPGA:
Spartan3AN

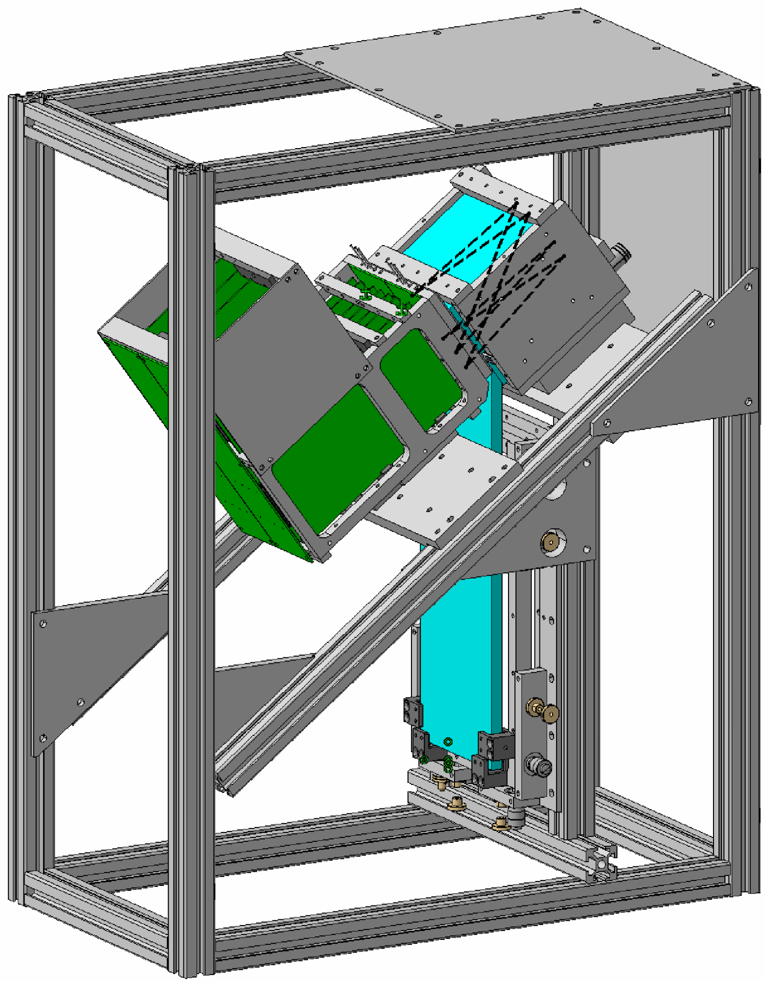
Readout for
4 Front-End
Card Chains
LVDS I/O
4x clocks
4x triggers
36 pairs of
LVDS signals
Standalone
JTAG for
TDC board
Spartan6 LX45T
1Gbit DDR3 RAM
Gigabit Ethernet
HDMI Connector
Single 5V
Power Supply

Test-beam setup


focussing block

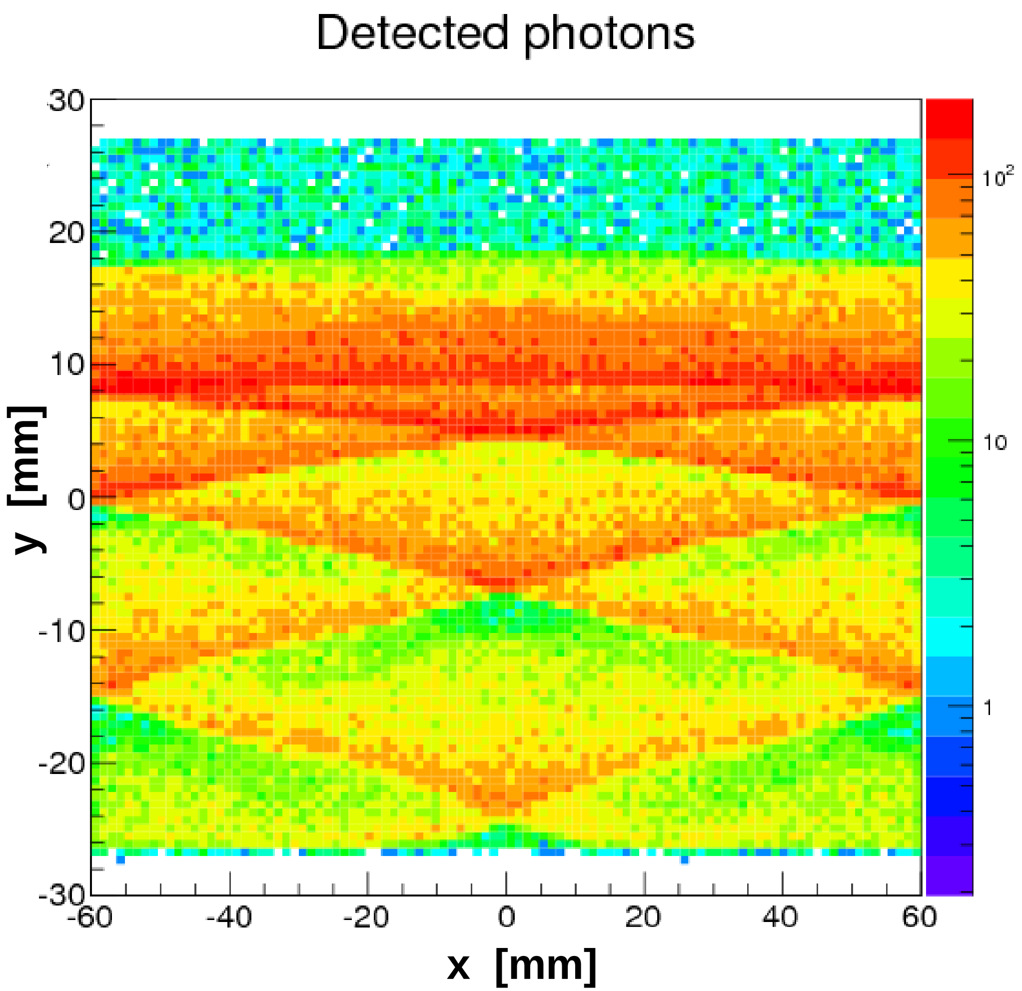

radiator



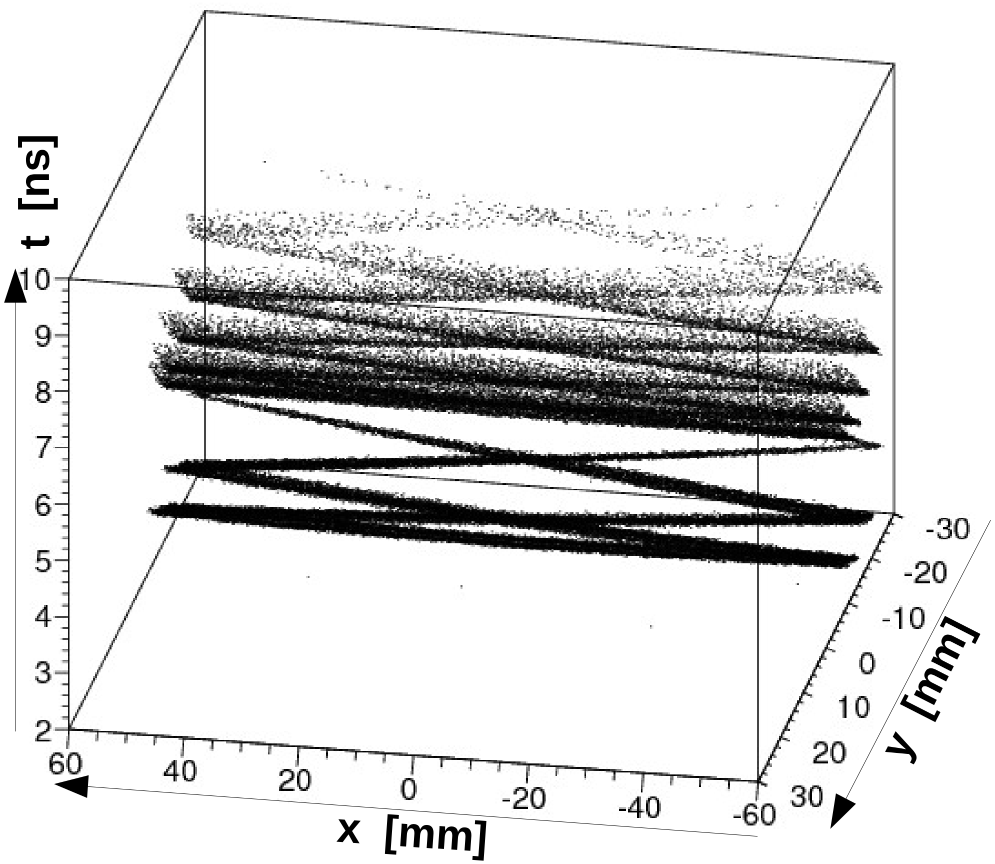


- Beam tests at CERN (SPS-H8 and PS/T9) this year
- Scaled-down version of TORCH module optical components from Schott (CH):
  - Quartz radiator plate (35 x 12 x 1) cm^3
  - Focussing block
- Photek prototype MCP and/or 32 x 32 channel Planacon

Test beam simulations 1



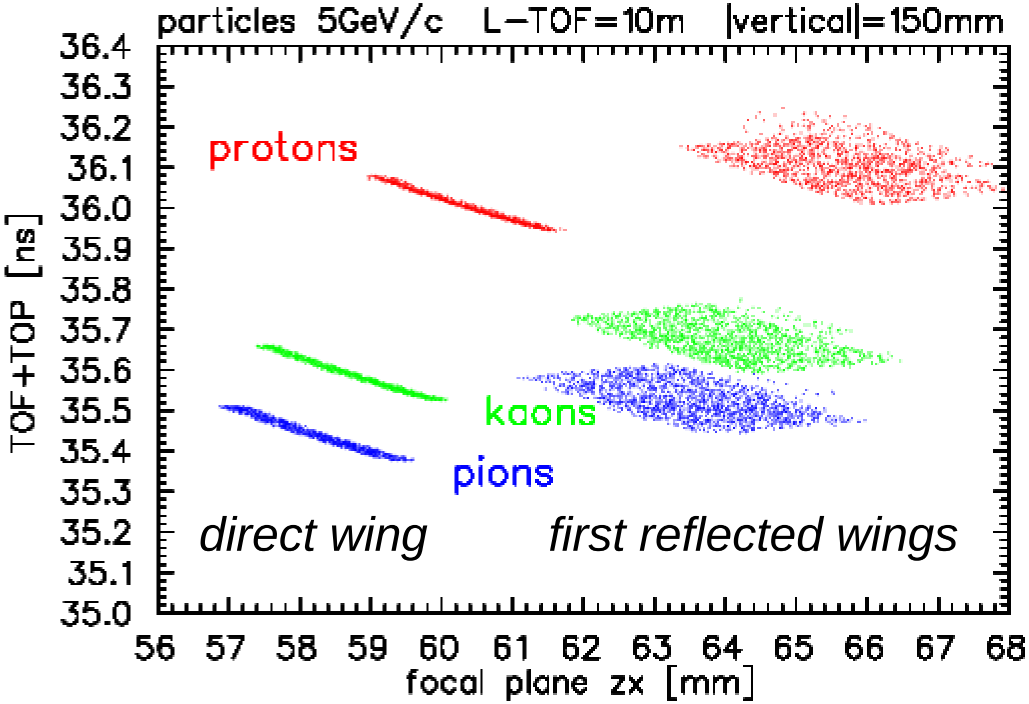
pattern on focal plane

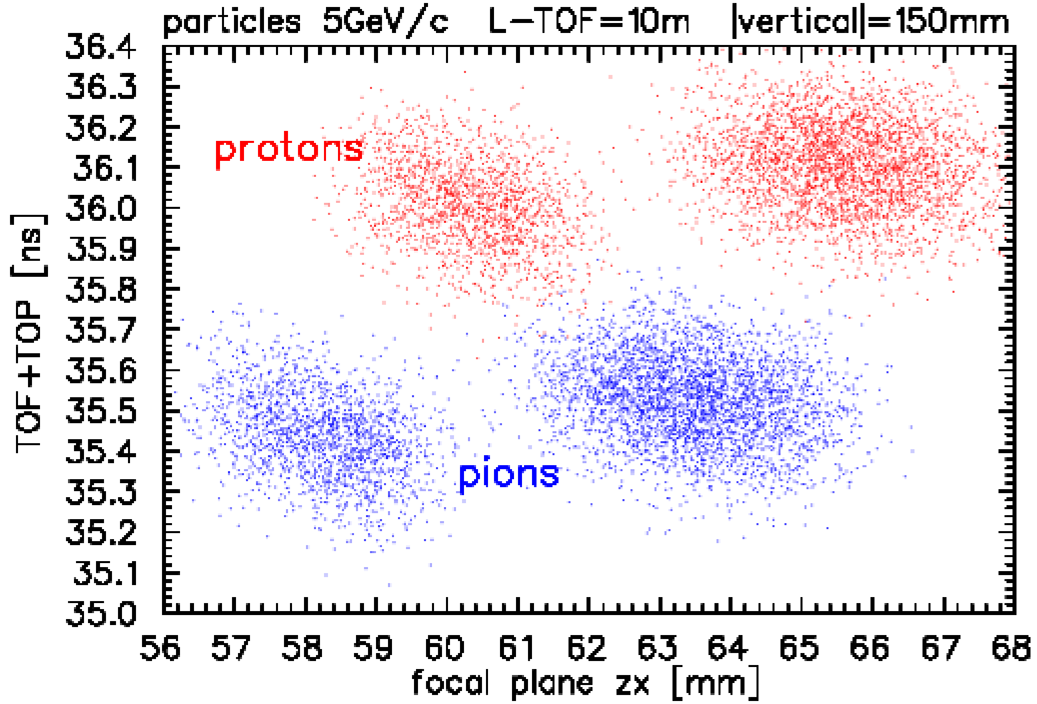


oblique 3-d view including time

Test beam simulations 2

instrumentation of +-12mm slice ; beam close to readout block



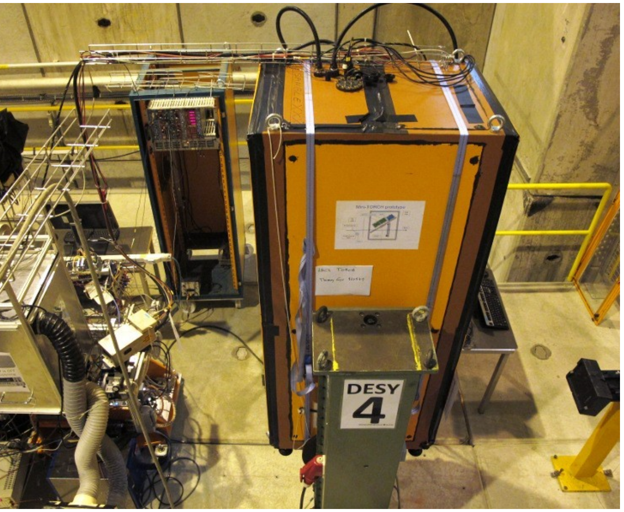


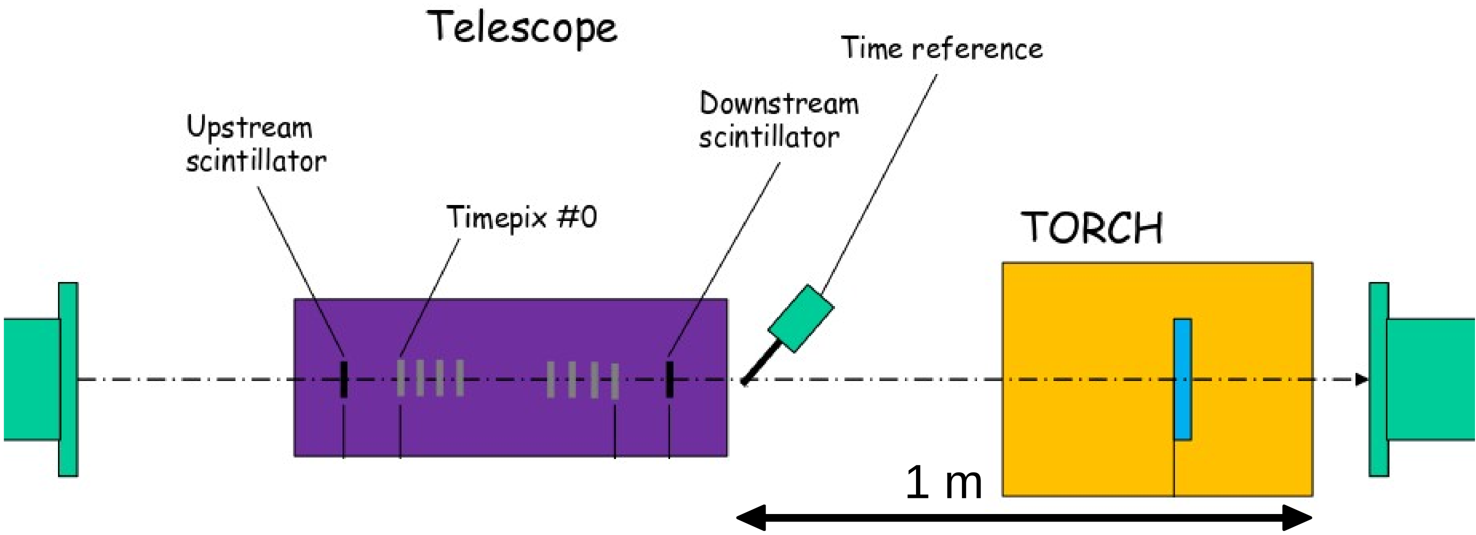
MC truth unsmeared

- horizontal 1.6mm/sqrt(12) Gaussian
- vertical 100 ps Gaussian

SPS overview

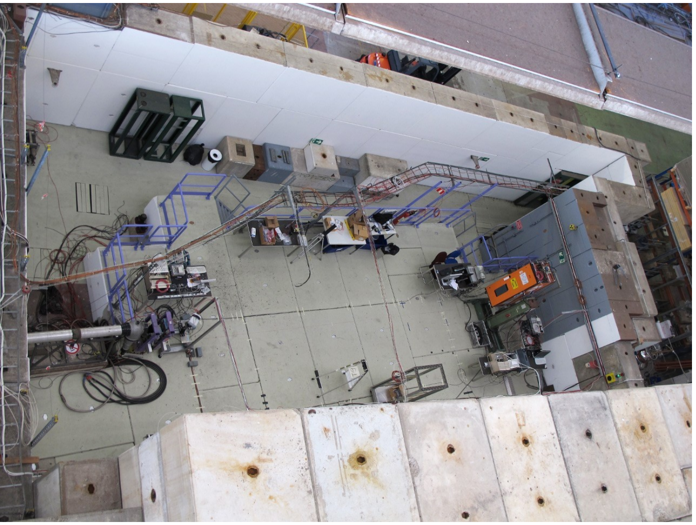
p = 180 GeV/c

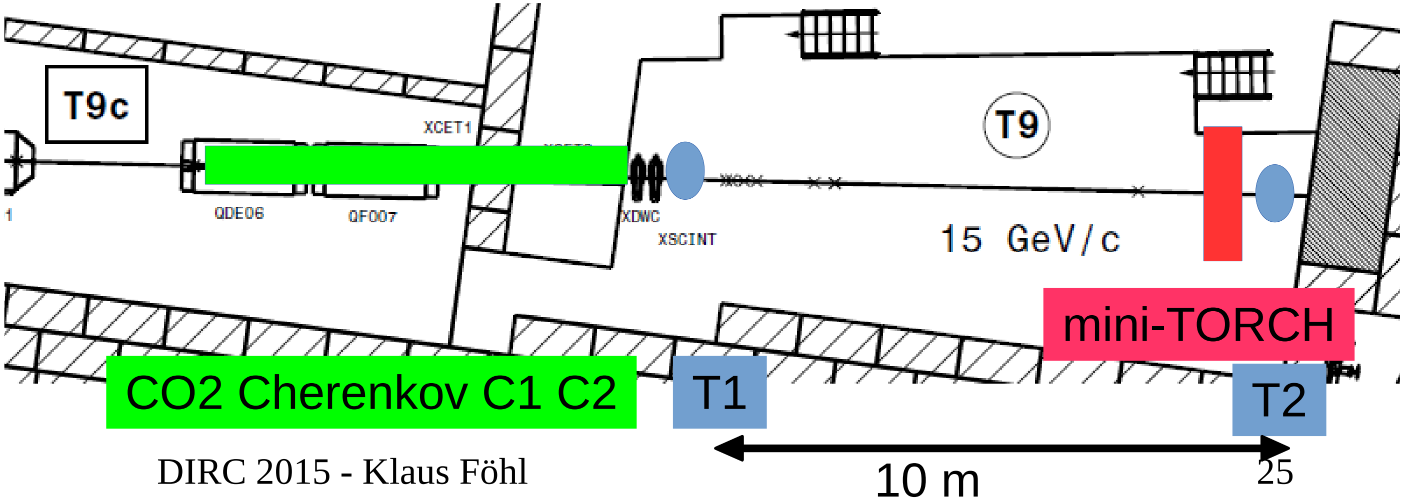




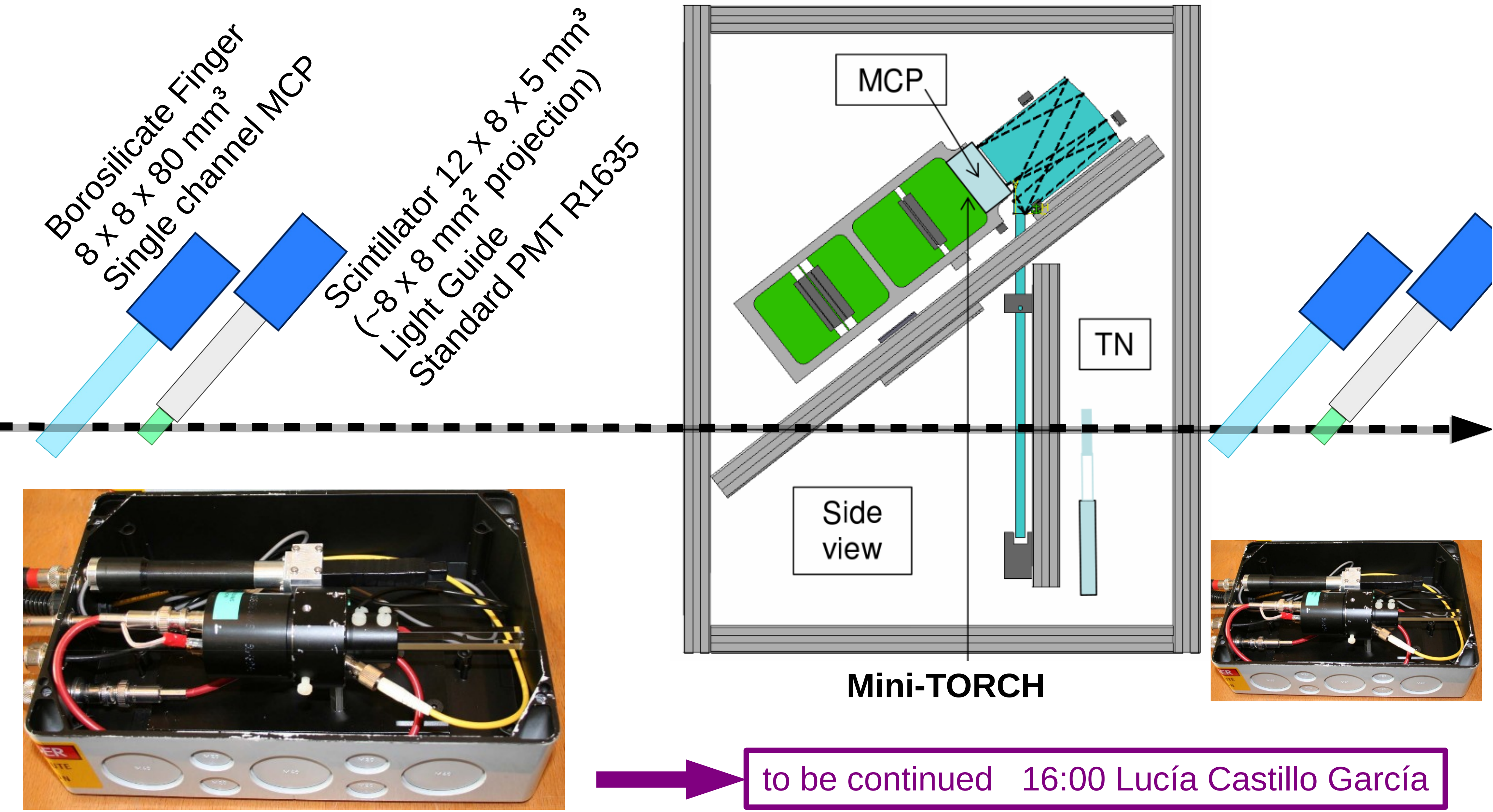
PS overview

p = 3-10 GeV/c





Current CERN PS/T9 test beam

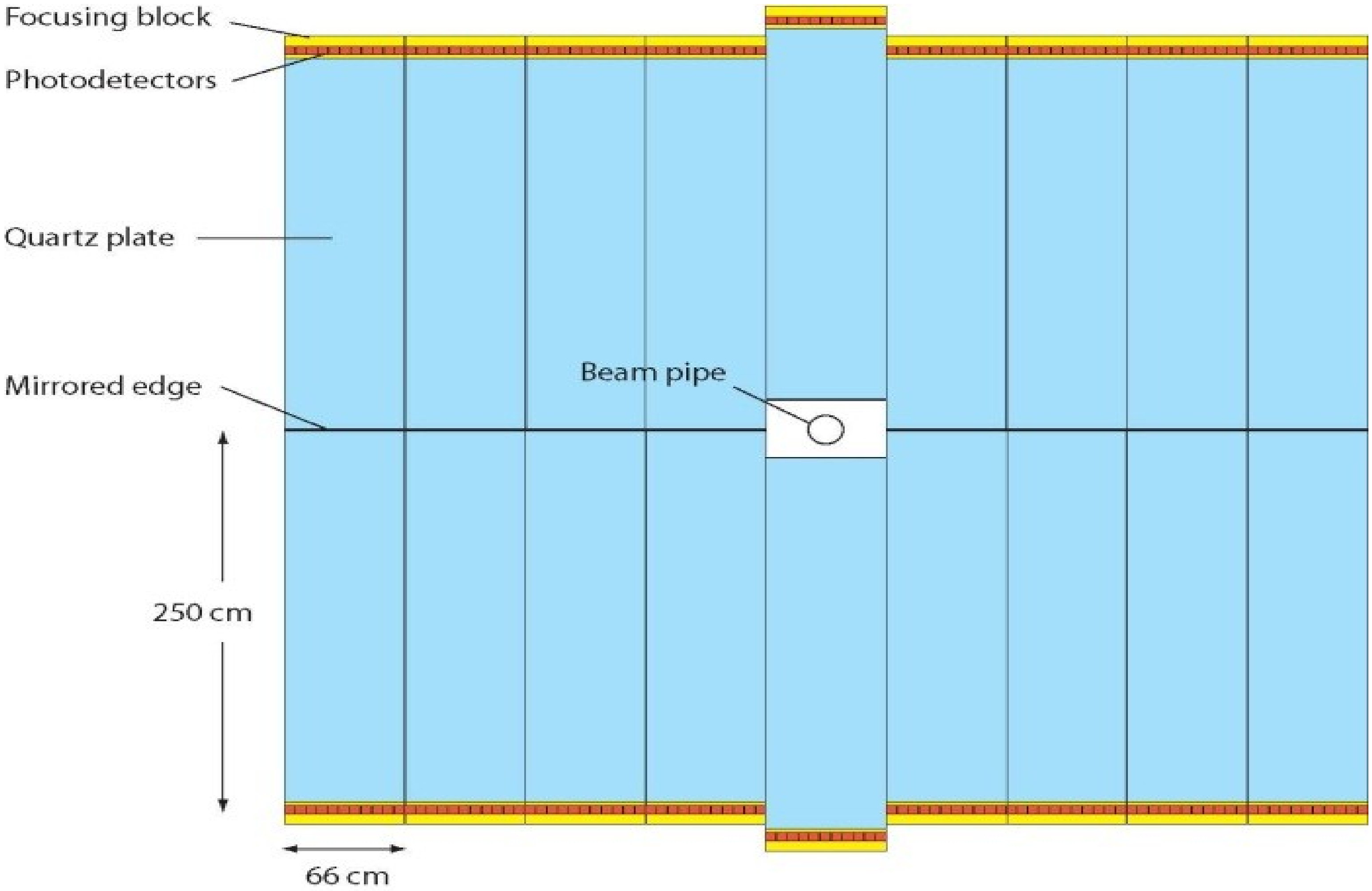


Mini-TORCH

Timing station

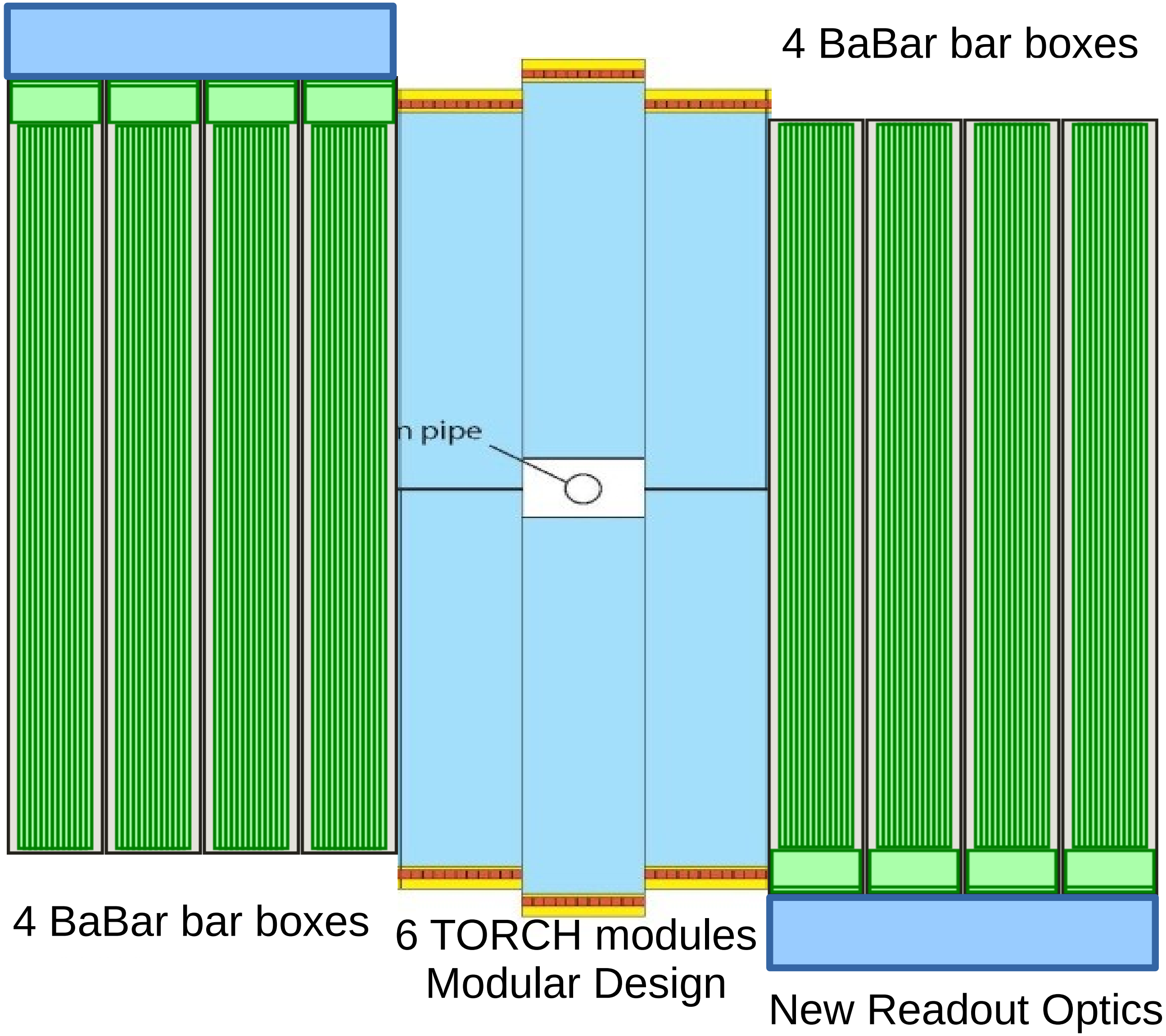
to be continued 16:00 Lucía Castillo García

TORCH Modular Design

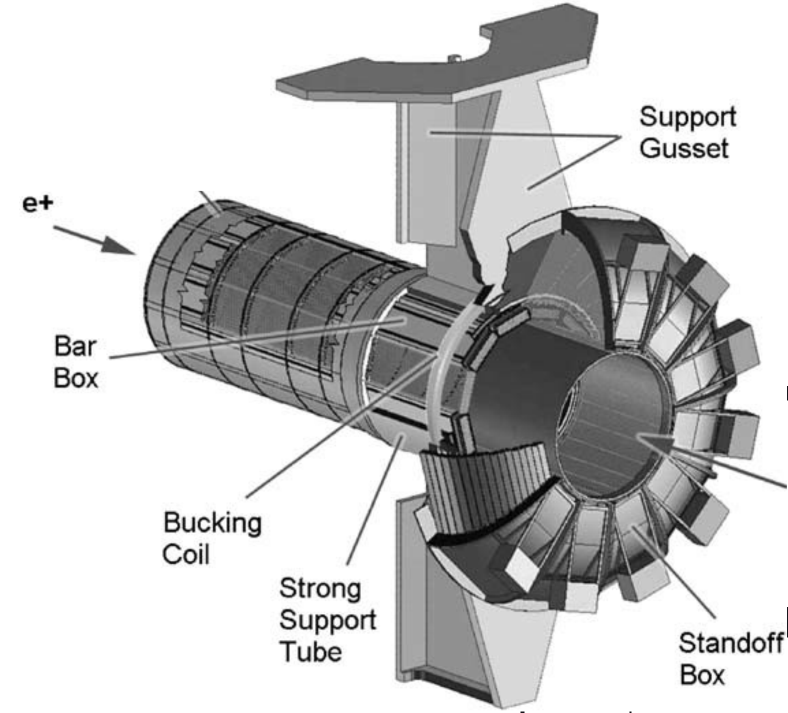


9x2 TORCH modules Modular Design

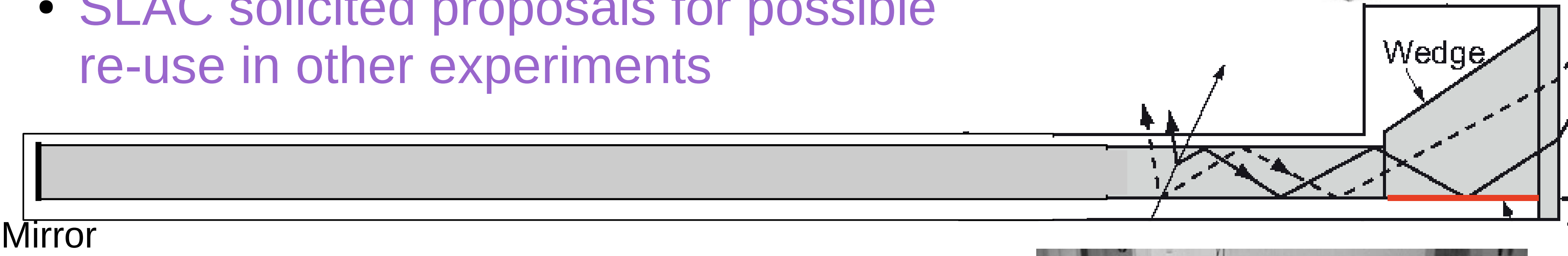
Use BaBar bar boxes within TORCH?



BaBar DIRC re-use?



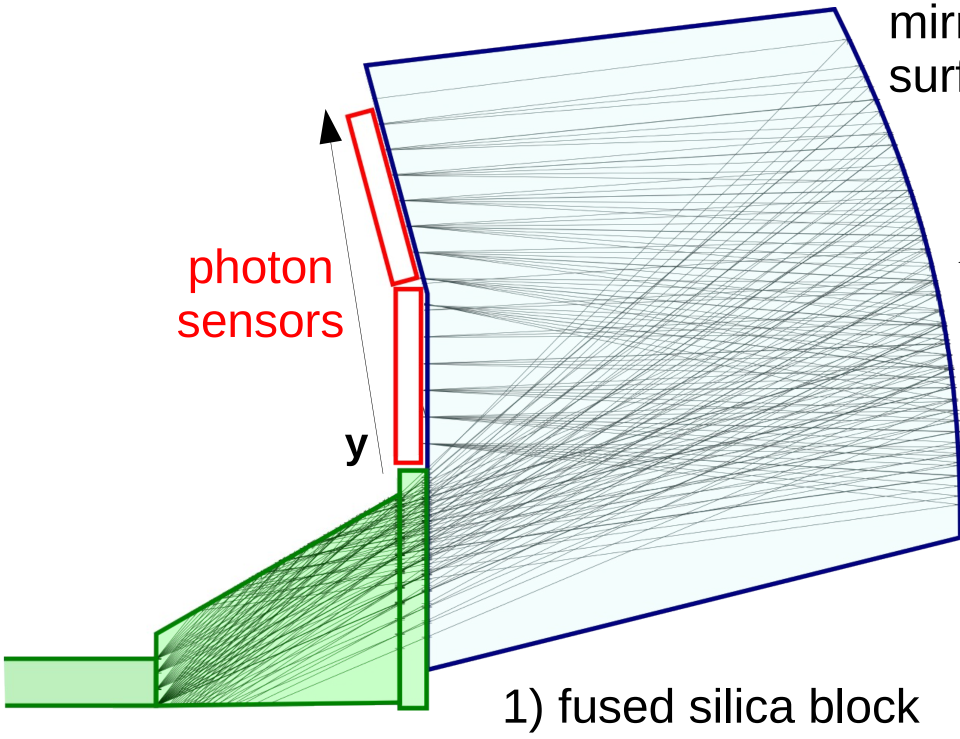
- 12 planar “Bar-Boxes”
  - 12 quartz bars 17 x 35 x 4900 mm³
- If sited at z = 9.5 m the bar length and the total area match
- SLAC solicited proposals for possible re-use in other experiments

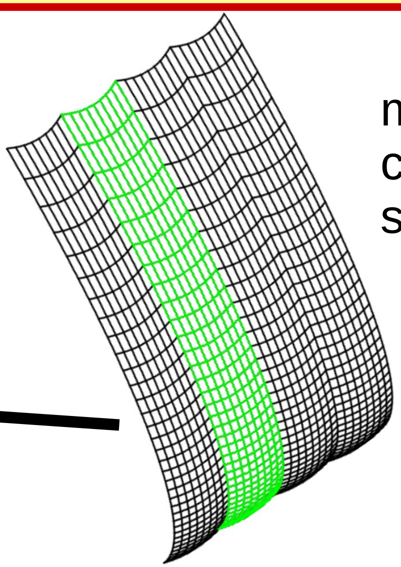


- Potentially very interesting
  - Optics needs to be adapted
  - Focussing in both projections required

New optics onto BaBar boxes 1

Spherical slices mirror – overall cylindrical shape

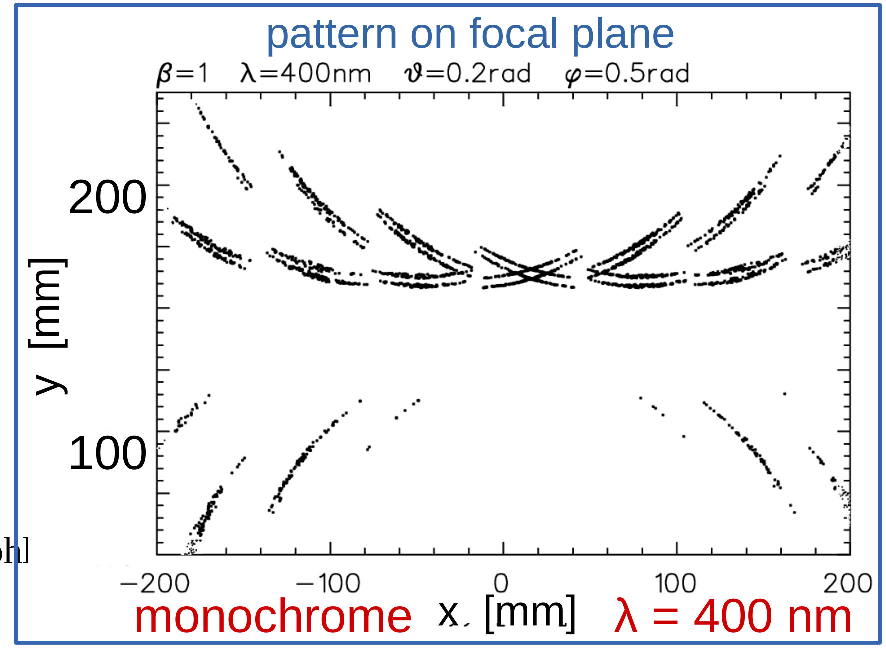




mirror surface composed of spherical slices

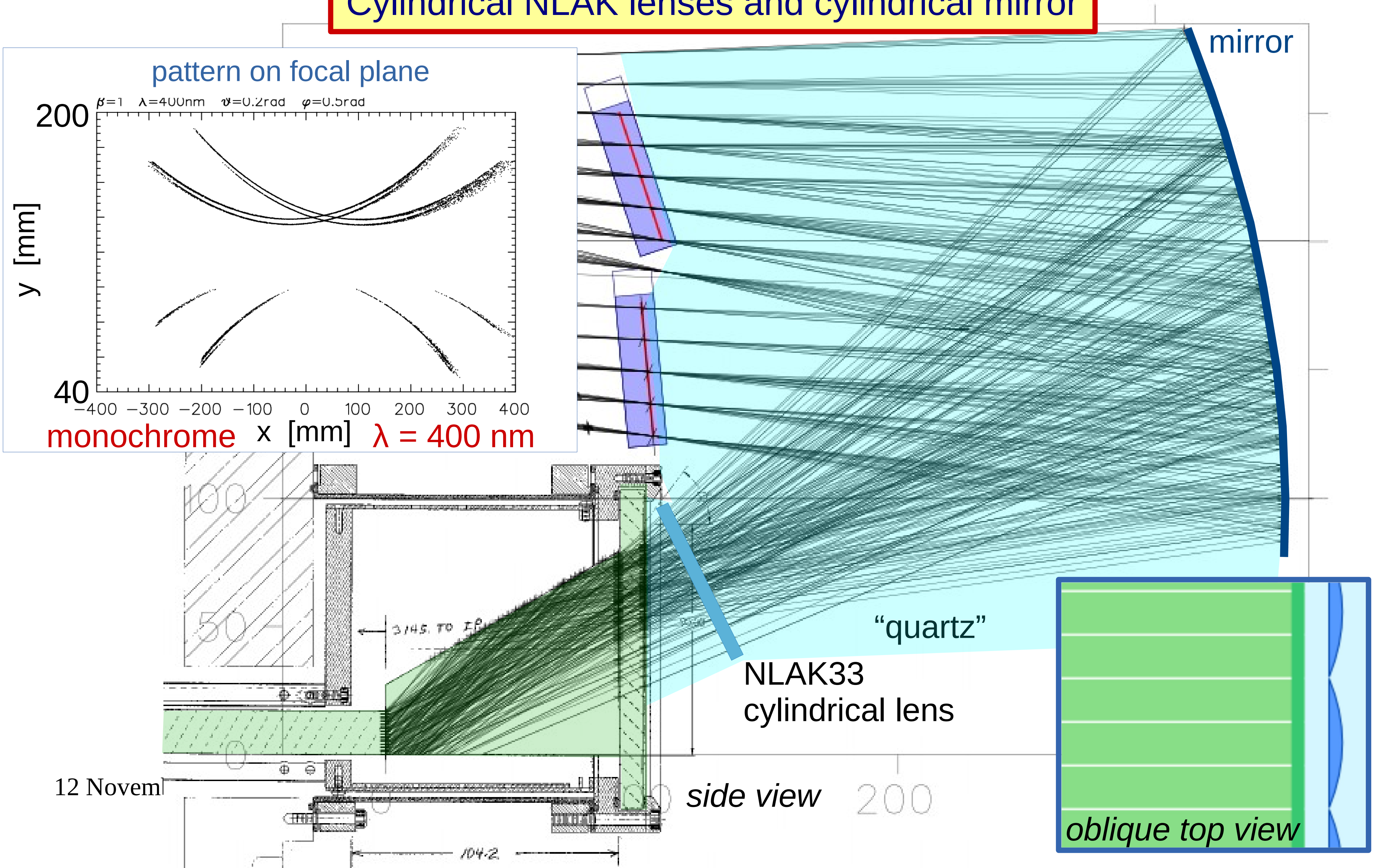
1) fused silica block
or
2) oil-filled volume with immersed mirror

BaBar bar box optics as provided



New optics onto BaBar boxes 2

Cylindrical NLAK lenses and cylindrical mirror



Conclusions

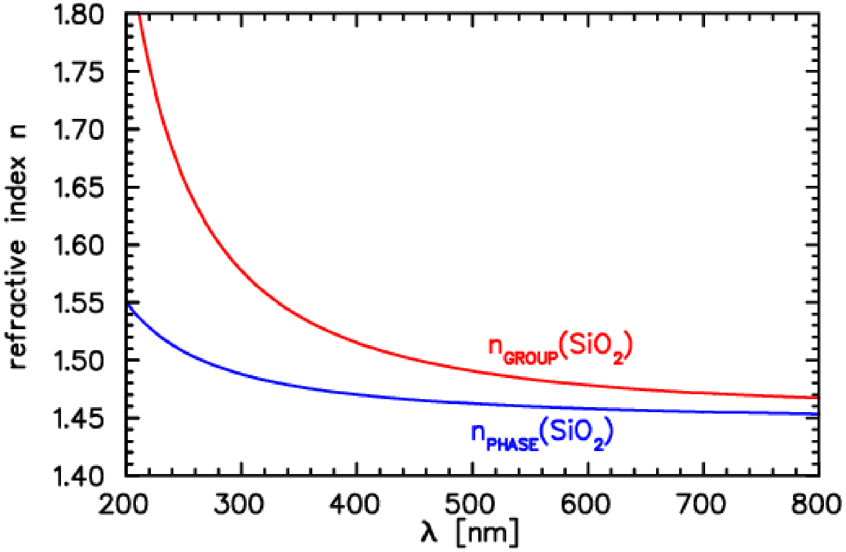
- Introduction to TORCH
  - Kaon PID for LHCb at >3σ up to 10 GeV/c
- Custom MCP Photon sensor development
  - Photek R&D project
  - Phase 1: Lifetime achieved (ALD coating)
  - Phase 2: High granularity – under test
  - Phase 3: next year
- Readout electronics
  - NINO Board, HPTDC Board, and Readout Board
  - Developed successfully, calibration to be completed
- Test beams
  - SPS and PS test beams at CERN - in progress
- Looking into BaBar DIRC components re-use
  - Feasibility assessed, BaBar bax boxes kept as an option

The support of the European Research Council is gratefully acknowledged in this work (ERC-2011-AdG, 291175-TORCH)

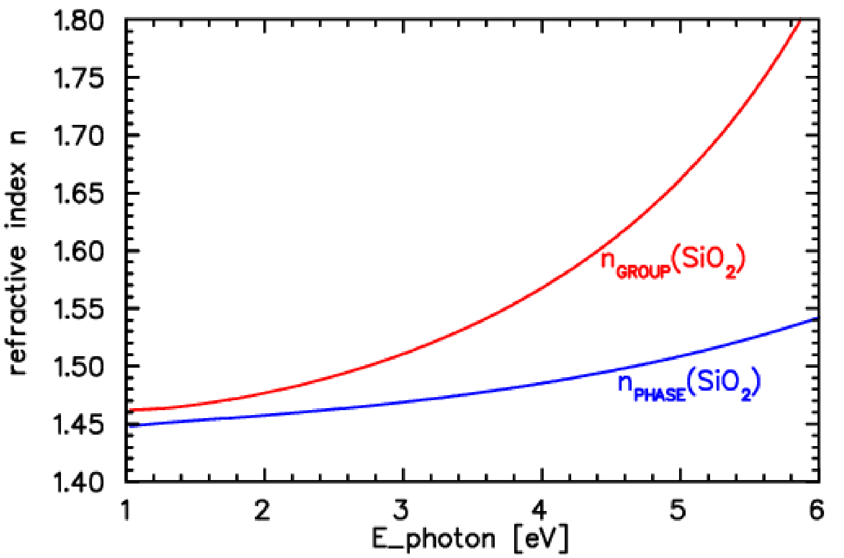
Thank you for your attention

Backup Slides

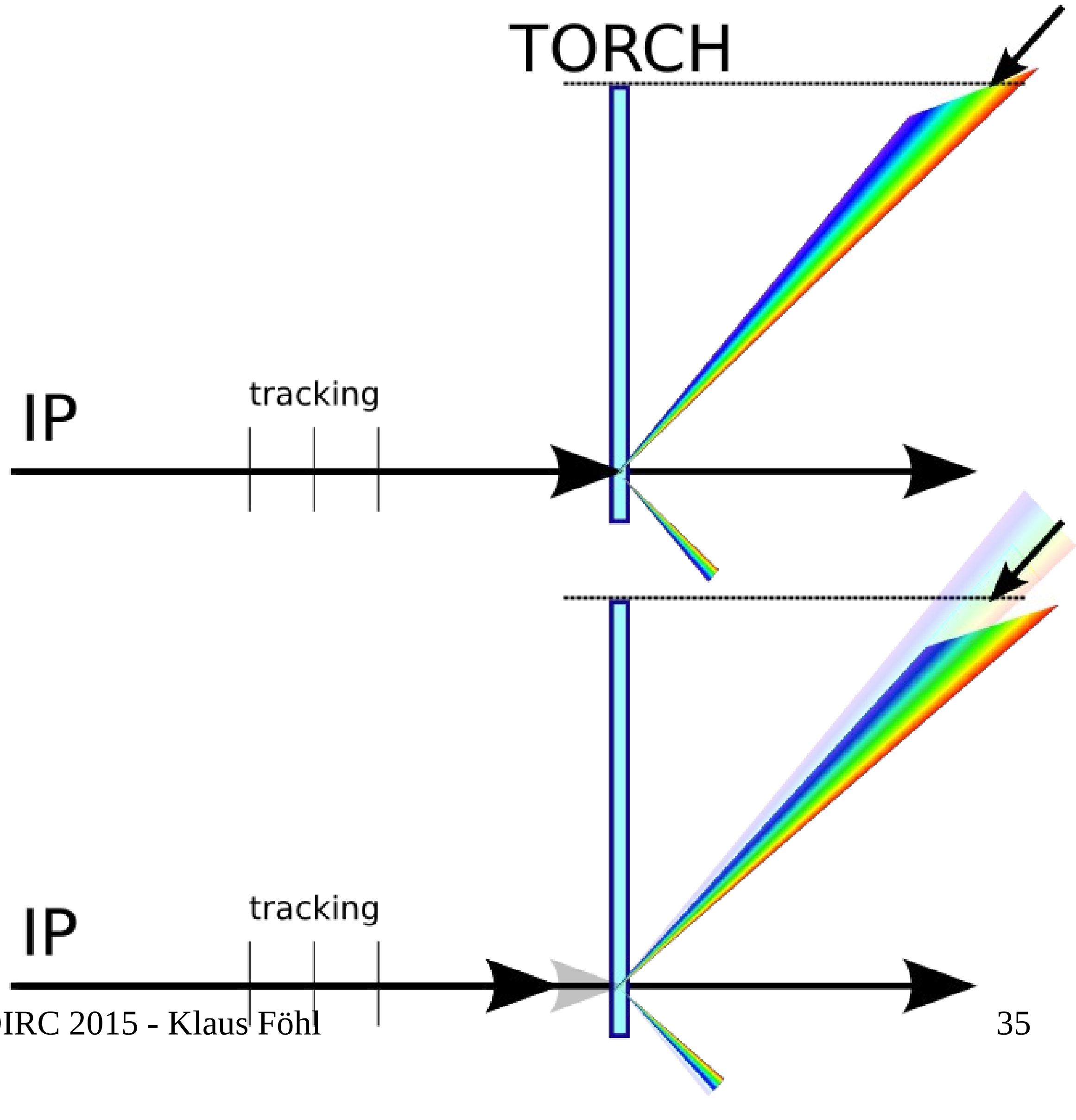
Motivation



refractive index n
λ [nm]
1.80
1.75
1.70
1.65
1.60
1.55
1.50
1.45
1.40
200
300
400
500
600
700
800
$n_{GROUP}(SiO_2)$
$n_{PHASE}(SiO_2)$



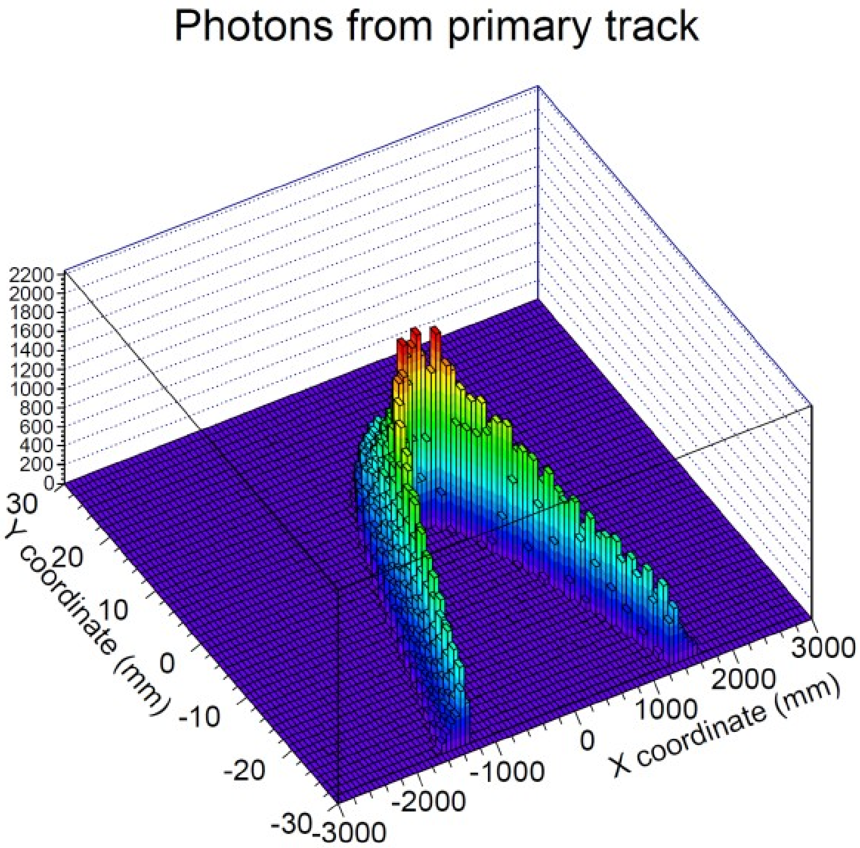
refractive index n
E_photon [eV]
1.80
1.75
1.70
1.65
1.60
1.55
1.50
1.45
1.40
1
2
3
4
5
6
$n_{GROUP}(SiO_2)$
$n_{PHASE}(SiO_2)$

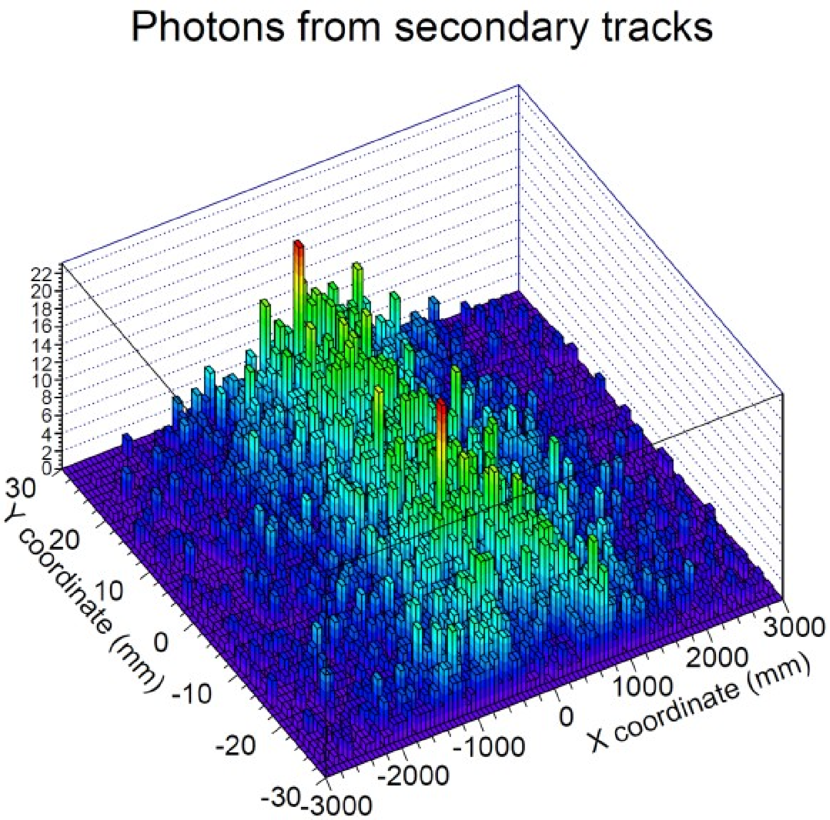


TORCH
IP
tracking
IP
tracking

Full GEANT simulations

- Simulation of accumulated photons for a thousand 10 GeV/c kaons
- Background photons from secondary electrons that also give off Cherenkov radiation
- Width of Cherenkov ring segment is due to chromatic dispersion in quartz medium

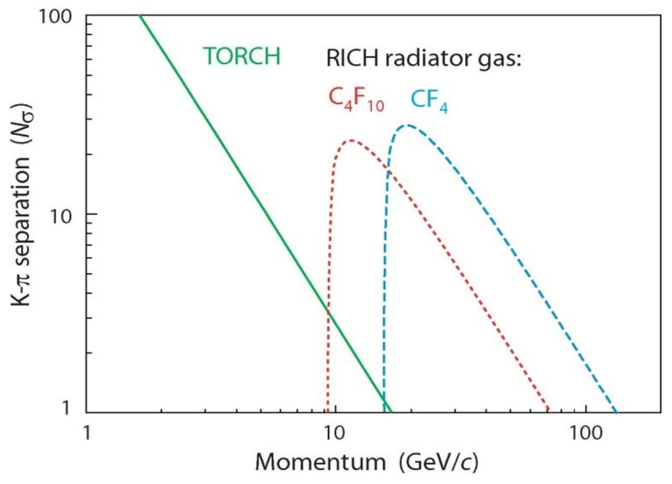




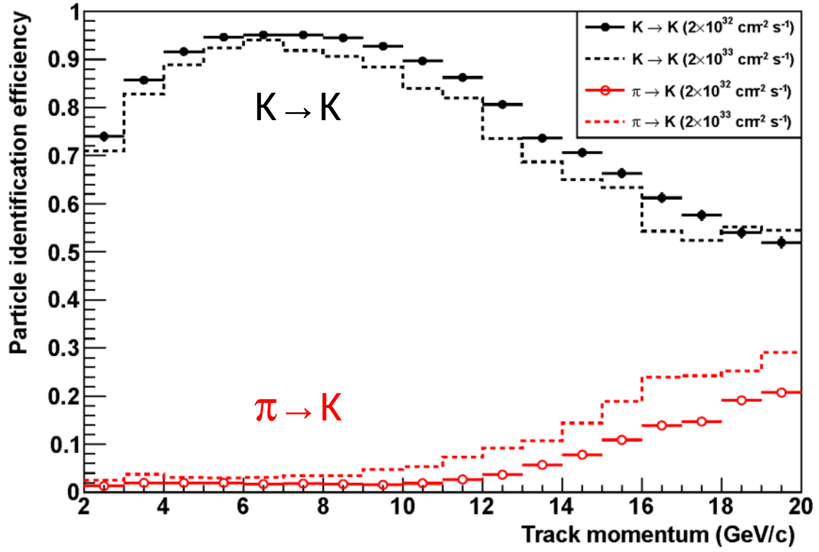
Expected performance

- Complete reconstruction studied including pattern recognition, using a simple simulation of the TORCH detector (single plate) interfaced to full LHCb simulation
- Excellent particle ID performance achieved, up to 10 GeV as required
  Robust against increased luminosity (········ after increase by × 10)
- Full GEANT simulation of TORCH is in progress, and optimization of the modular layout

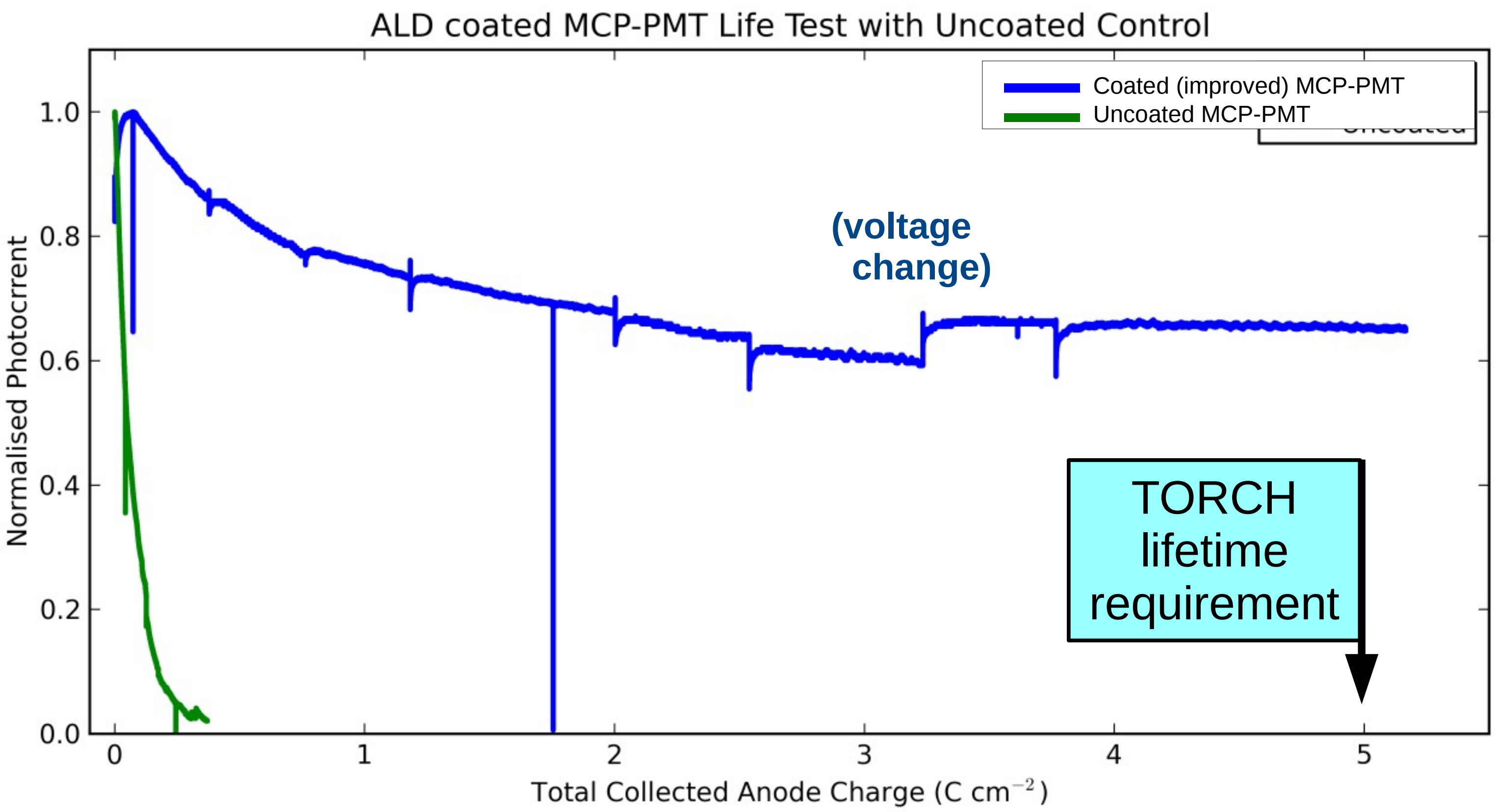
(ideal reconstruction, isolated tracks)



LHCb simulation: efficiency vs. *p*



MCP-PMT lifetime



Photocathode response as a function of collected charge.

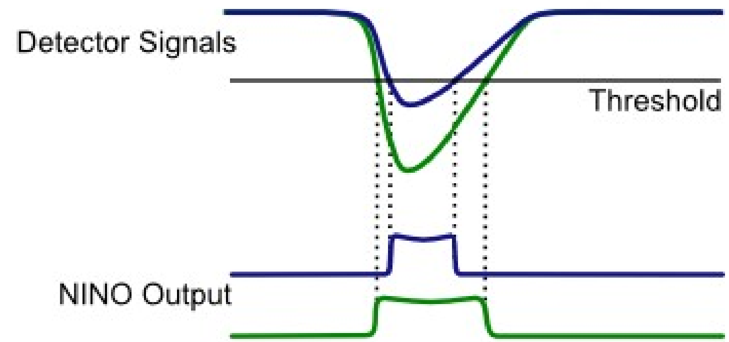
Courtesy Photek Ltd., Ref NIM A 732 (2013) 388391

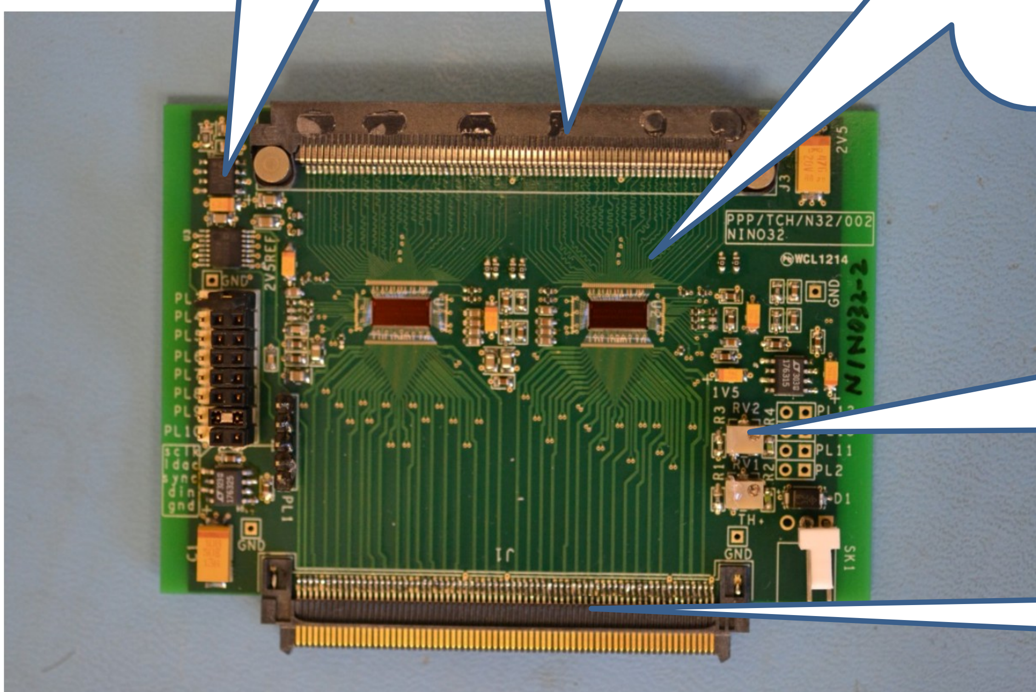
Analogue Front End – NINO

DAC – Setting threshold

Input – negative phase only

2x**NINO** - Time Over Threshold Measurement, 64-ch per board



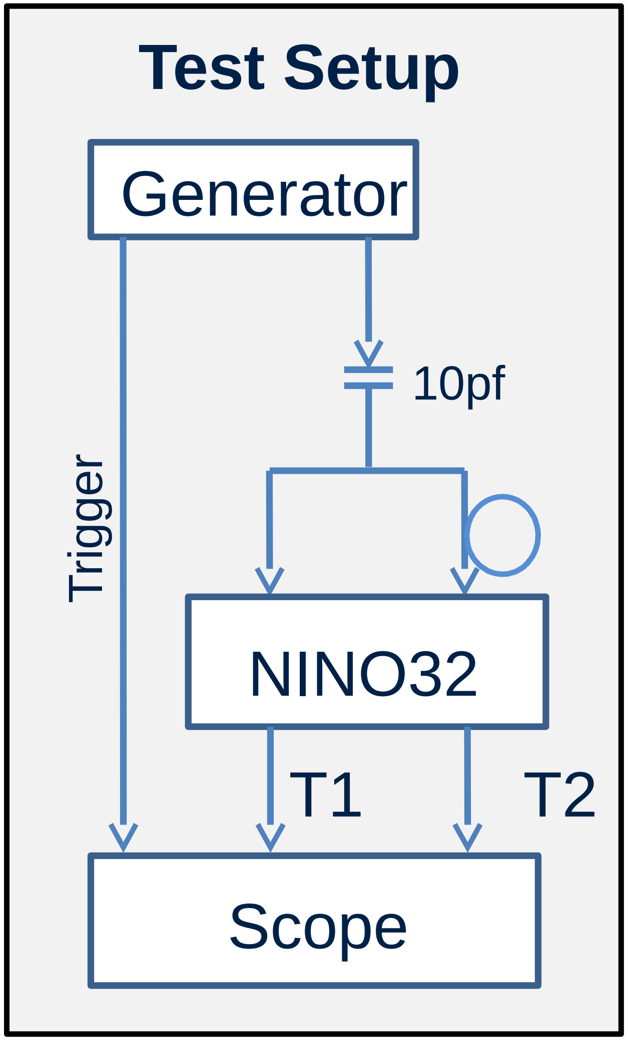


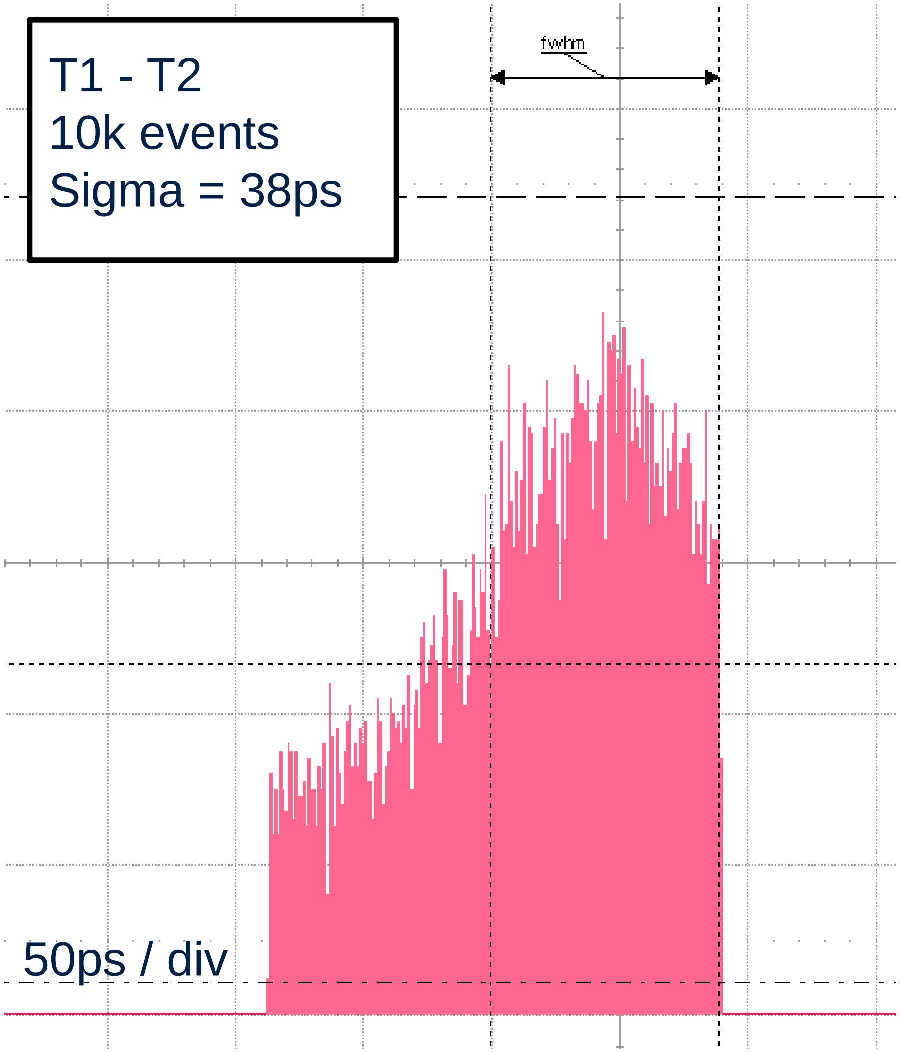
Potentiometer – threshold quick settings

LVDS output

Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

NINO32 Performance





Time resolution = $38/\sqrt{2} = 26.8$ps

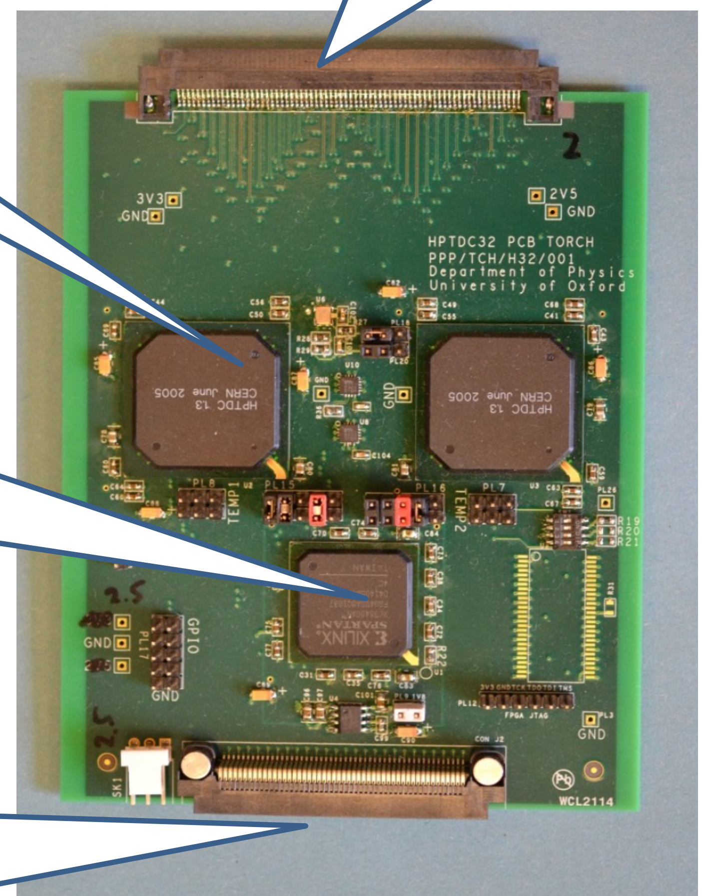
HPTDC Board – Time to Digital Conversion

LVDS input from **NINO**

2x **HPTDC**[4] ASICs 64ch per board

Spartan3AN
HPTDC configuration and control
Data formatting and buffering

Power
Input: clock, trigger, serial slow control, fast control
Output: TDC data, all signals in LVDS



Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

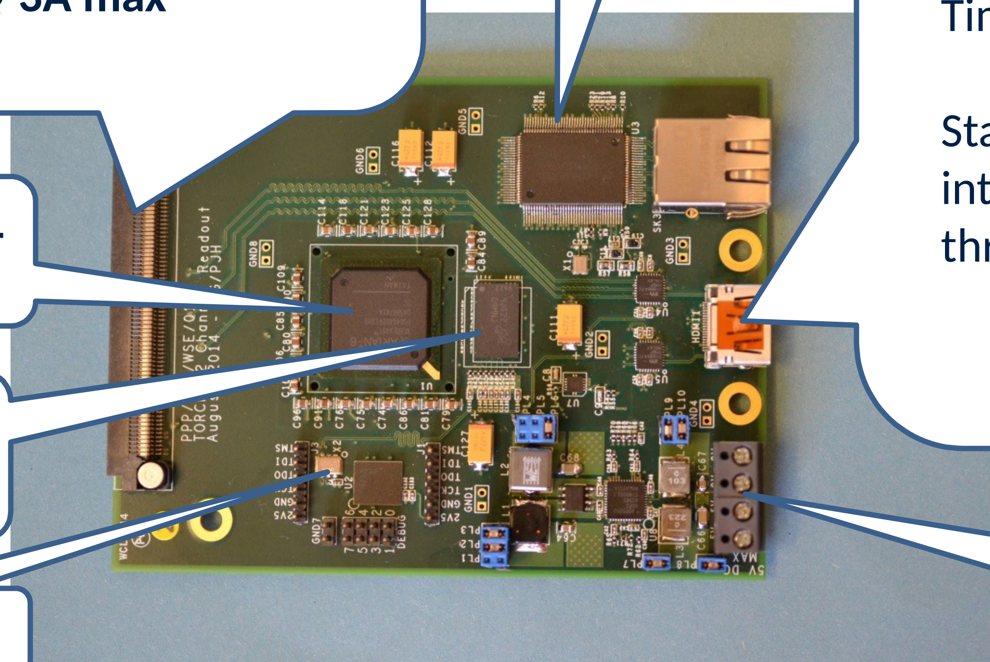
Readout Board

LVDS I/O
Fan out 4 x clocks, 4 x triggers
and 36 pairs of LVDS signals
Standalone JTAG for TDC board
2.5v and 3.3v @ 3A max

Gigabit Ethernet

HDMI Connector
External clock and 3
bi-directional LVDS pairs,
pinout compatible with
Timepix3 Telescope TLU.

Standard LEMO/ SMA
interface are available
through adaptor.



Spartan6 LX45T

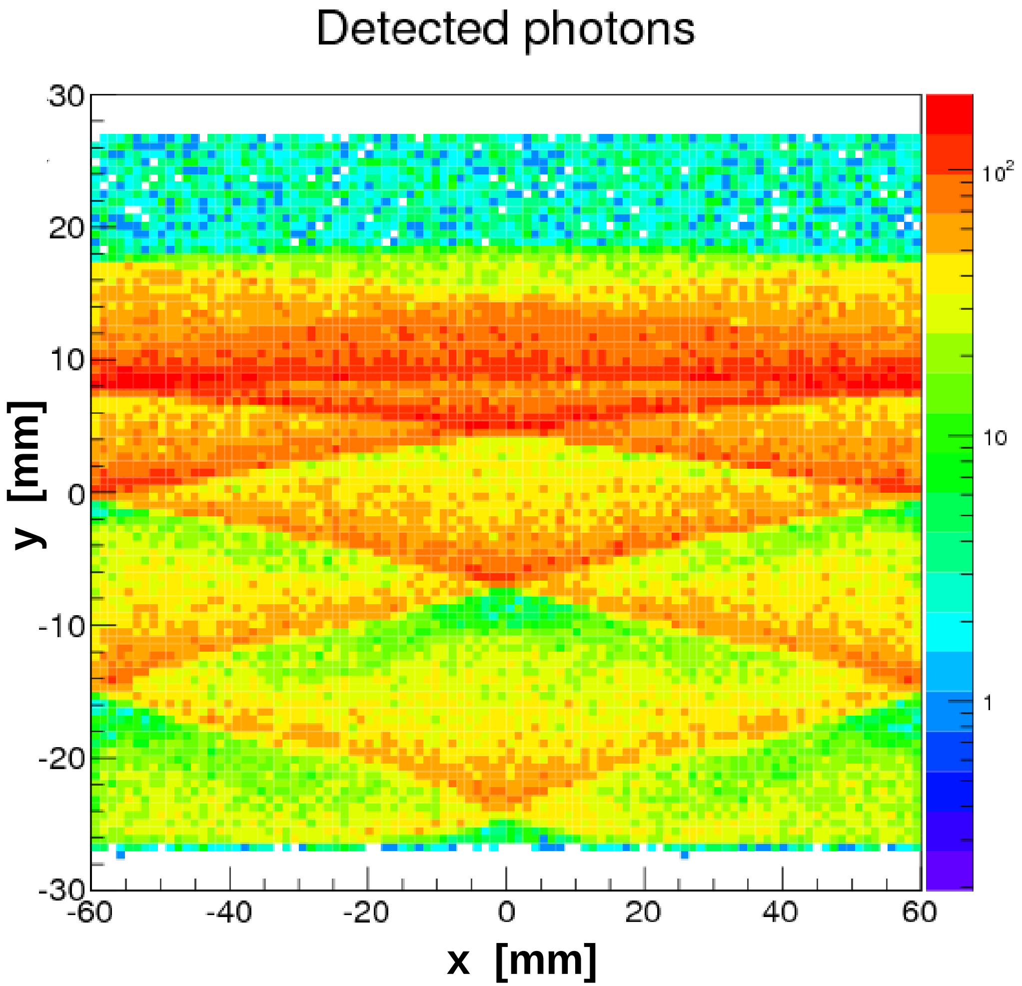
1Gbit DDR3 RAM

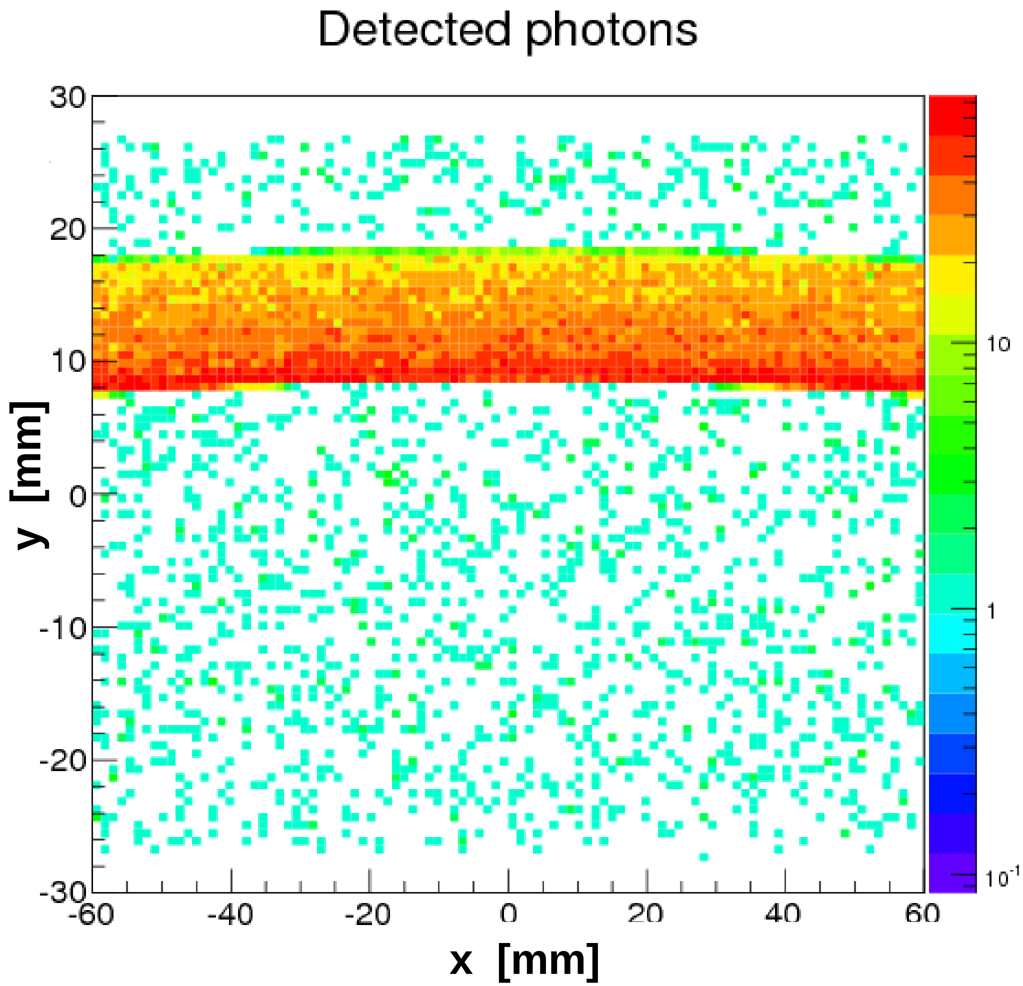
200MHz OSC

Single 5V power supply

Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

Test beam simulations





polished (reflecting) - radiator plate and focussing block sides– **blackened (absorbing)**

TORCH detector environment

- high radiation dose
  - several krad/year, leptonic, hadronic charged, NIEL
- low magnetic field
- small temperature changes, cavern
- atmospheric pressure, not controlled
- radiator plates mounted vertically
- inside light tight housing, clean and dry gas environment
- low seismic activity region