# **GasToF**: Picosecond Resolution Time-of-Flight Detector

L. Bonnet, J. Liao, T. Pierzchala, K. Piotrzkowski and N. Schul (UCLouvain)

As introduction: Motivation for forward proton timing at LHC

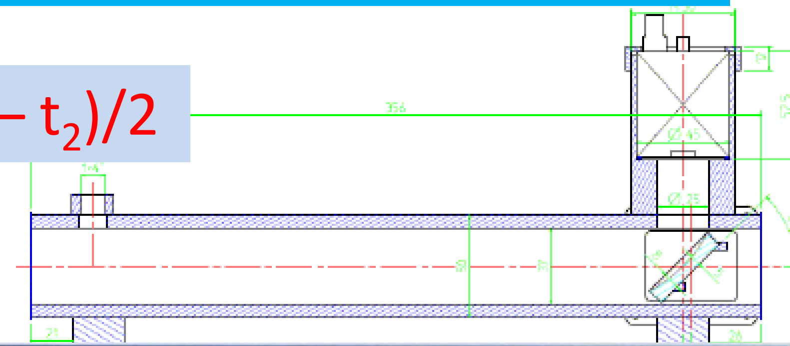
GasToF: Concept, design and prototypes

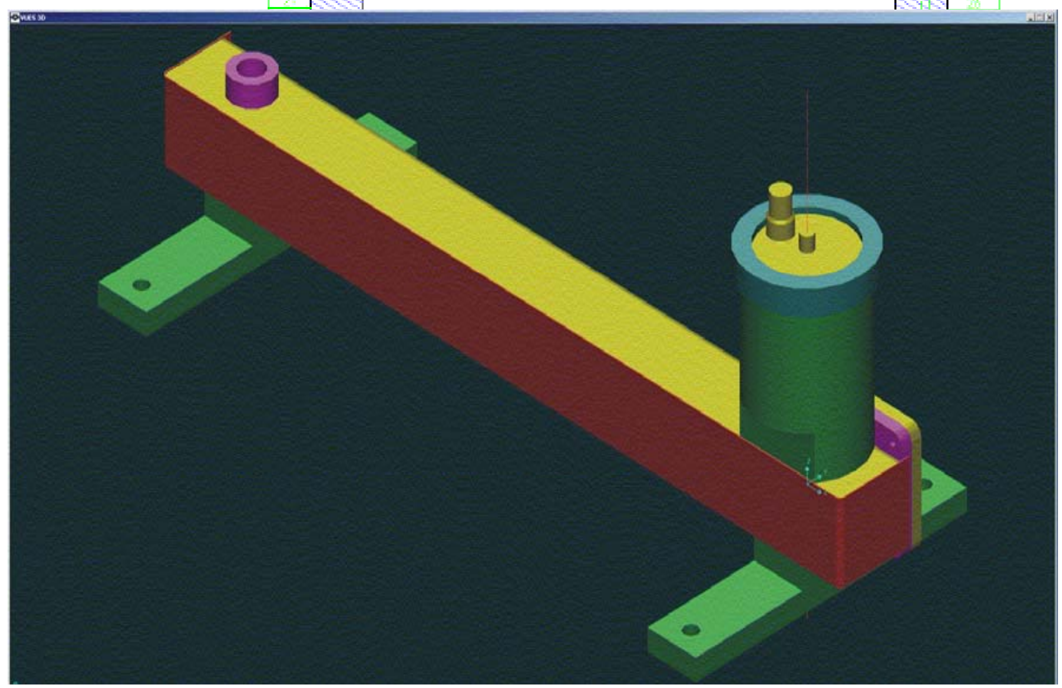
Laser test bench studies and beam tests

Outlook

RICH 2010,
Cassis (France)

$$z = c\,(t_1 - t_2)/2$$





# New forward detectors:

Brief history:

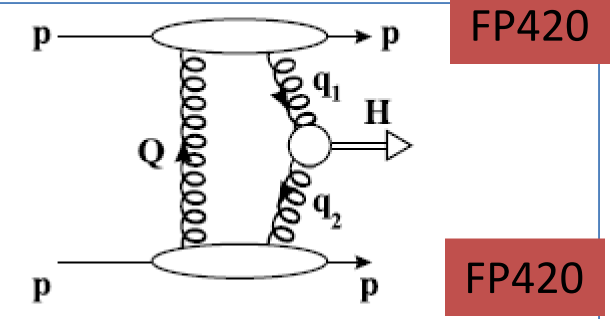
May'05: R&D proposal acknowledged by LHCC

June'08: FP420 Report

Fall'08: First proposals to CMS/ATLAS

In 2009: Adding detectors @220/240 m

HPS project in CMS




Central Exclusive Production (CEP): $pp \rightarrow p + H + p$



**The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC**

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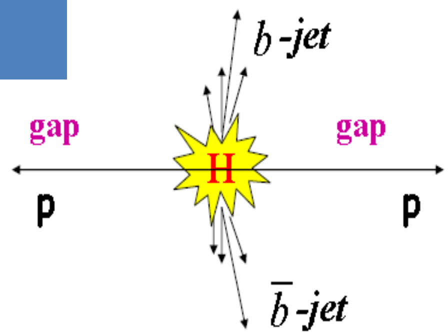
*FP420 R&D Collaboration*

JINST **4** (2009) T10001

# High Precision Spectrometers: Motivation

(1000 Tm bending power $\rightarrow$ $\delta p/p \sim 2.10^{-4}$)




Light Higgs boson case is compelling more than ever – exclusive production provides unique information:

- Higgs quantum numbers (spin-parity filter)
- Direct & precise H mass measurement (event-by-event); $M_H$ resolution of $\approx$ 2 GeV $\rightarrow$ direct limits on Higgs width
- Possibility of detecting H $\rightarrow$ $b\bar{b}$ mode

Detection of SM Higgs boson requires (very) large luminosity ($\sigma_{obs} \approx 0.1–0.2$ fb) and challenging timing detectors to keep backgrounds low (S/B$\approx$1:2); in case of BSM physics HPS could provide discovery channels for Higgs bosons

In addition, HPS offers access to 'guaranteed' and unique studies like electroweak physics in two-photon interactions, or new QCD phenomena in exclusive production, for example.

**Observation of Exclusive Charmonium Production and *γγ → μ+μ- in pp Collisions at √s = 1.96 TeV***

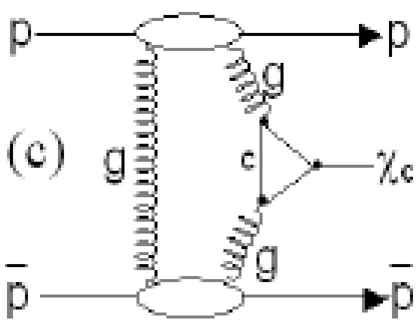
Focus Archive | PNU Index | Image Index | Focus Search

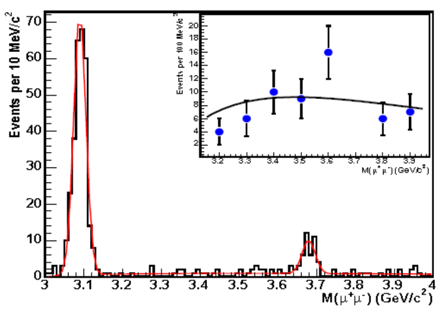
Previous Story / Volume 23 archive

Phys. Rev. Lett. 102, 242001
(issue of 19 June 2009)
Title and Authors

24 June 2009

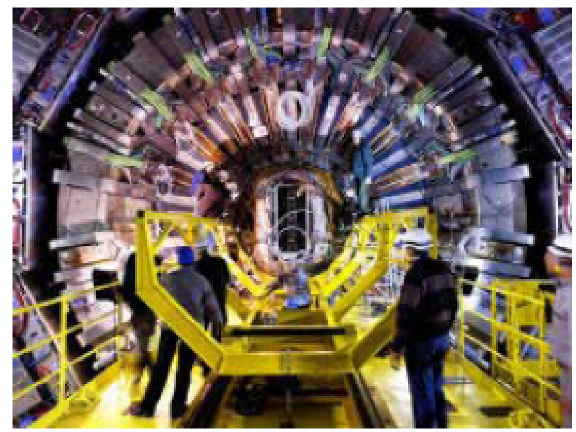
# A Higgs Boson without the Mess




Particle physicists at CERN's Large Hadron Collider (LHC) hope to discover the Higgs boson amid the froth of particles born from proton-proton collisions. Results in the 19 June *Physical Review Letters* show that there may be a way to cut through some of that froth. An experiment at Fermilab's proton-antiproton collider in Illinois has identified a rare process that produces matter from the intense field of the strong nuclear force but leaves the proton and antiproton intact. There's a chance the same basic interaction could give LHC physicists a cleaner look at the Higgs.

A proton is always surrounded by a swarm of ghostly virtual photons and gluons associated with the fields of the electromagnetic and strong nuclear forces. Researchers have predicted that when two protons (or a proton and an antiproton) fly past one another at close range, within



CERN

**Higgs machine.** If CERN's Large Hadron Collider (LHC) can create Higgs bosons, a handful may appear in rare "exclusive" reactions that don't destroy the colliding protons--similar to a reaction now observed at Fermilab. CERN's ATLAS and CMS teams are considering adding equipment to their detectors (CMS shown here) to look for such events (click image to enlarge)

# Forward proton detectors @ (high $\mathscr{L}$) LHC

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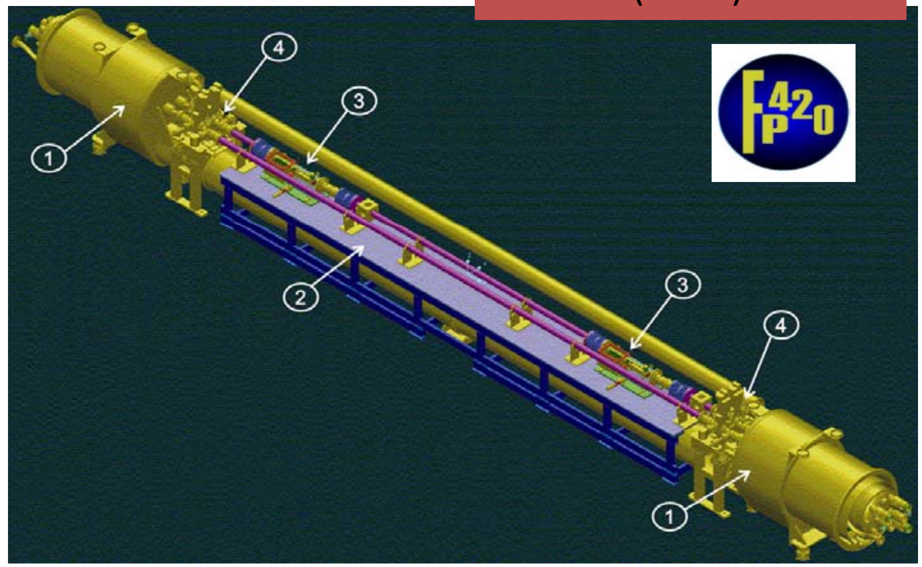
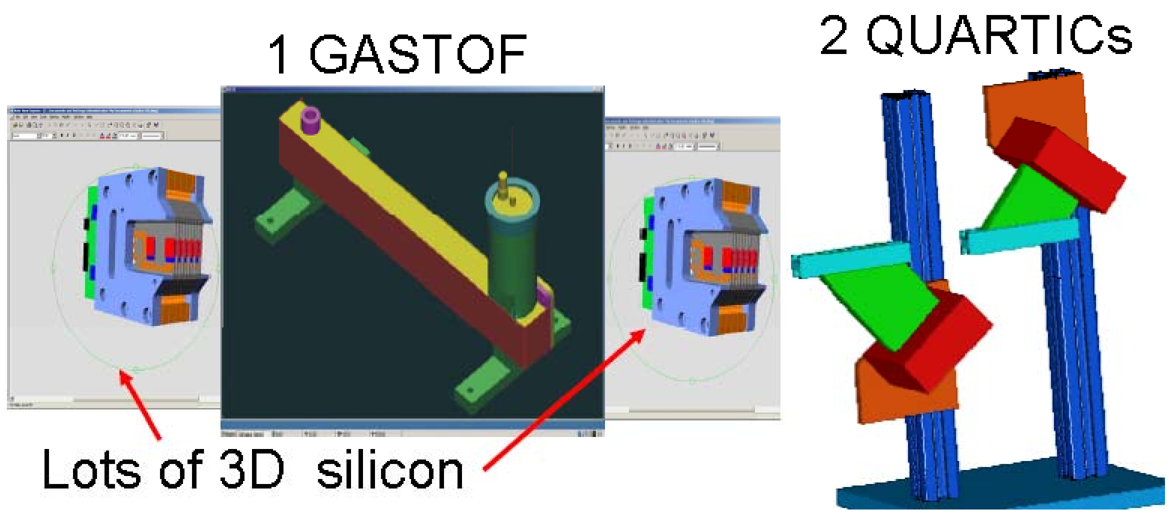


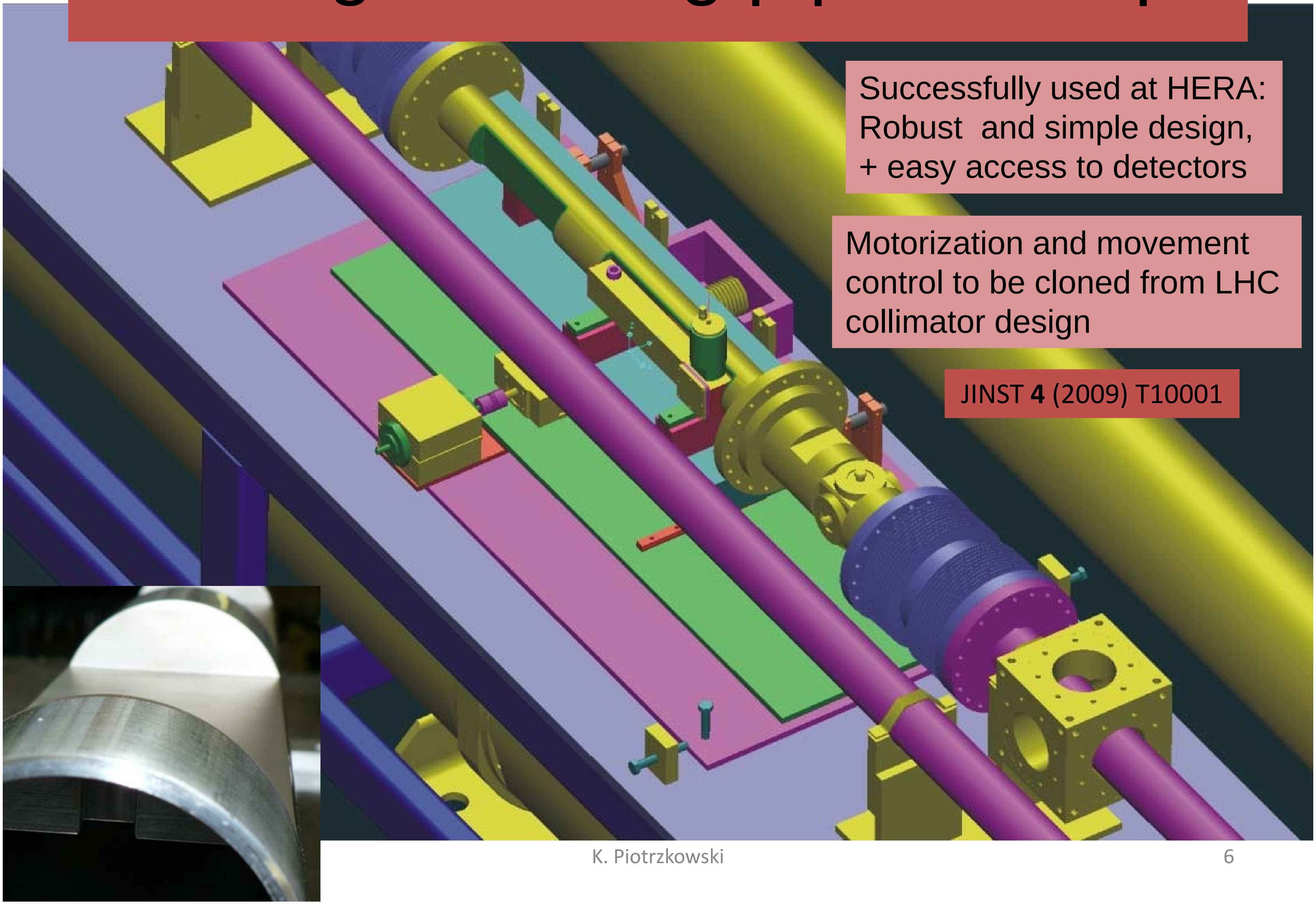
- Installation of Si detectors in cryogenic region of LHC, i.e. cryostat redesign needed
- Strict space limitations rule out Roman Pot technology, use movable beam-pipe instead
- Radiation hardness required of Si is comparable to those at SLHC, use novel 3-D Silicon technology
- To control pile-up background use very fast timing detectors ($\sigma$ ~ 10ps)

Acceptance in fractional energy loss
(at nominal LHC $\beta^*$ = 0.5 m):
**$0.002 < \xi < 0.02$**

**Two detector stations per arm (4 in total): each station contains tracking and timing detectors**



# Moving Hamburg pipe concept



Successfully used at HERA:
Robust and simple design,
+ easy access to detectors

Motorization and movement control to be cloned from LHC collimator design

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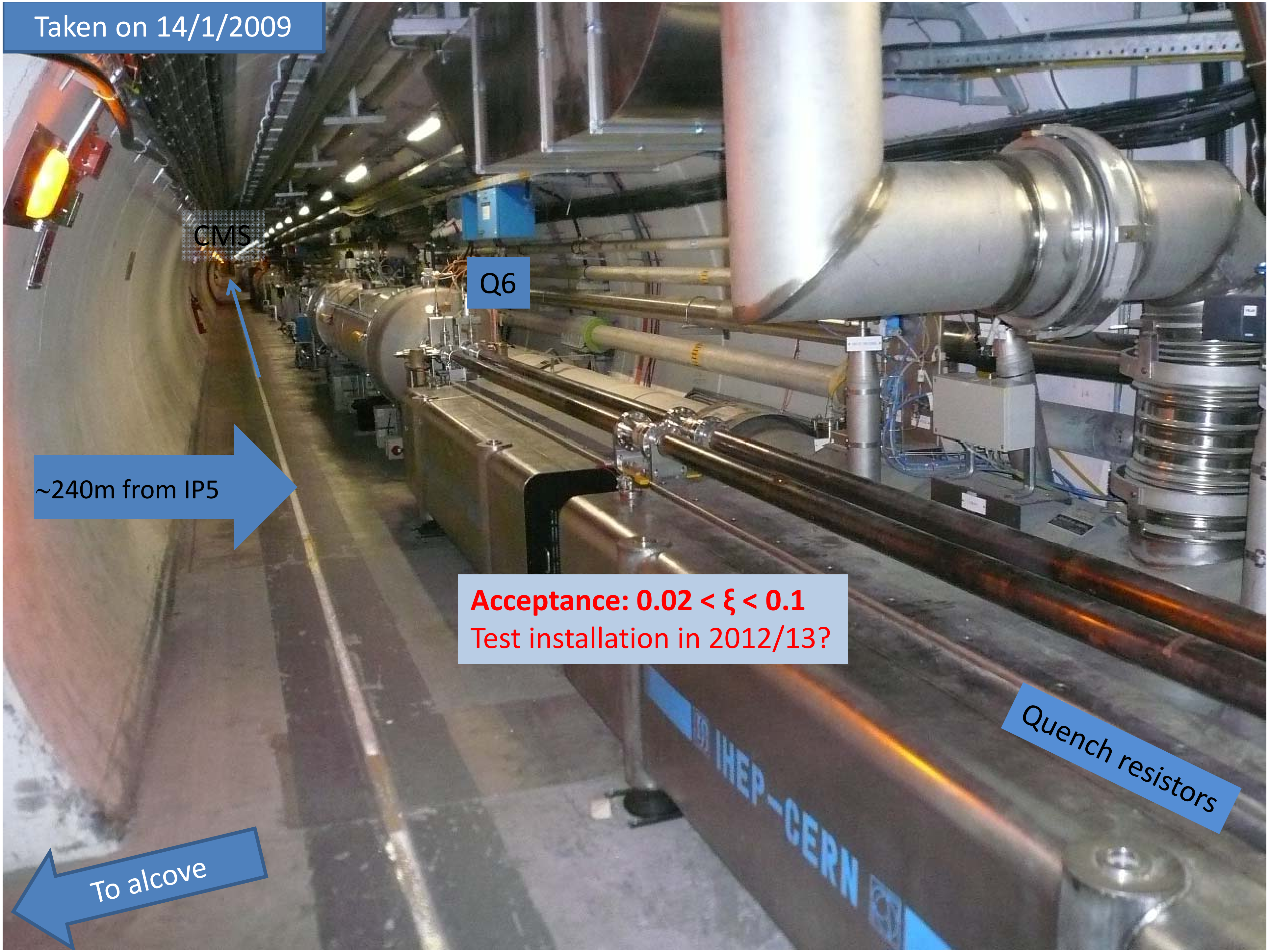
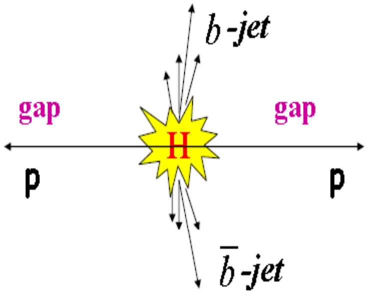

Taken on 14/1/2009
CMS
Q6
~240m from IP5
Acceptance: 0.02 < ξ < 0.1
Test installation in 2012/13?
Quench resistors
To alcove
IHEP-CERN

# Picosecond ToF detectors @ LHC

At nominal luminosity event rate so high @ HPS that accidental overlays (= triple coincidence of an interesting event in central detector + two protons from single diffraction) become major background!




Use very fast ToF detectors to reduce it by matching *z-vertex* from central tracking with *z-by-timing* from proton arrival time difference:
LHC vertex spread is ~50 mm → to reduce significantly backgrounds one needs < 10ps time resolution ( → 2 mm *z-vertex* resolution)!

$z = c\,(t_1 - t_2)/2$

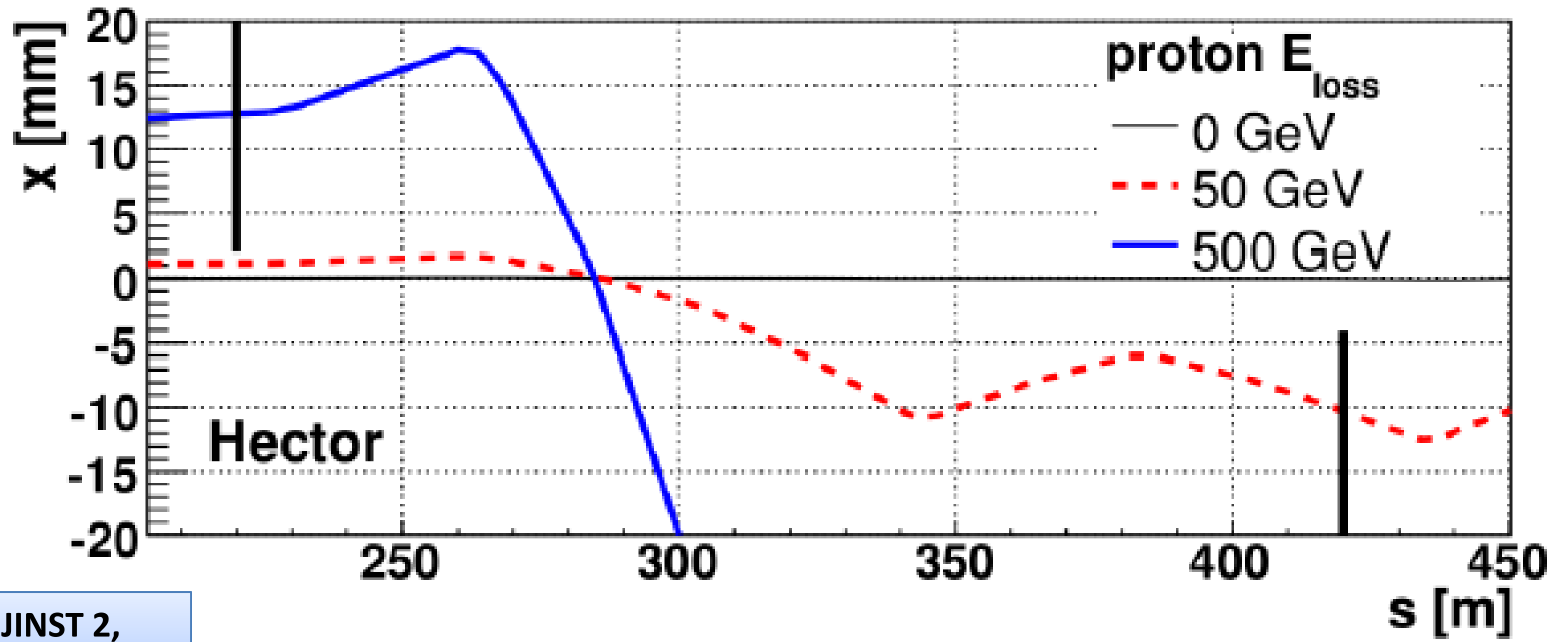
Proposed fast (& small ~10 $cm^2$) timing detectors: Čerenkov radiators + fastest MCP-PMTs

Challenging environment → pushing MCP-PMT performances to limits:
→ High event rates, up to several MHz
→ Running MCP-PMTs close to maximal anode currents
→ Large annual total collected anode charges (up to 10 $C/cm^2$)

GasToF: Gas ($C_4F_{10}$) Čerenkov detector with very fast light pulse (< 1 ps!) → resolution limited by TTS of MCP-PMTs and electronics

Quartic: Quartz based Čerenkov with fine segmentation – multi-hit capability

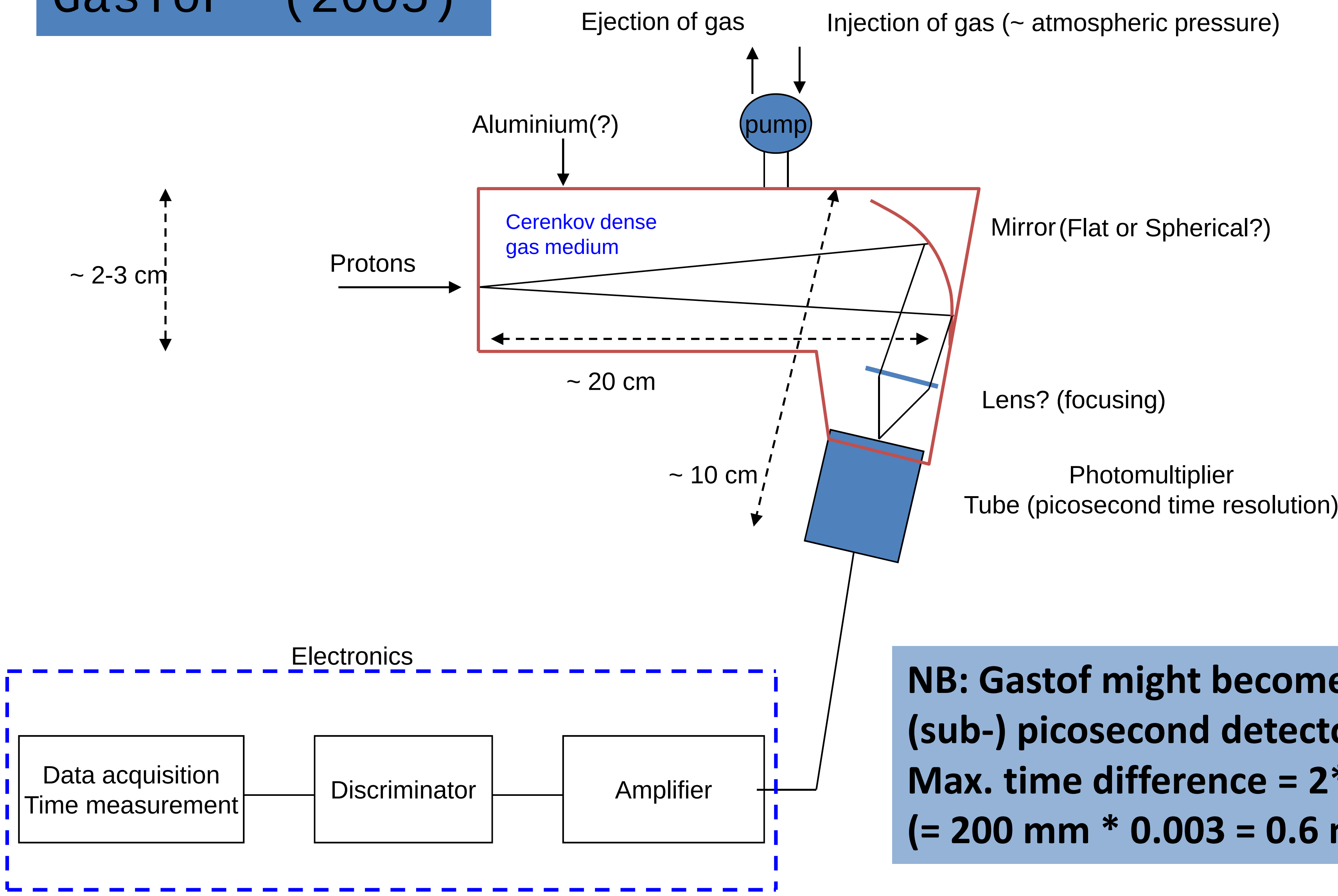
# Forward proton trajectories @ LHC




HECTOR: **JINST 2, P09005 (2007)**

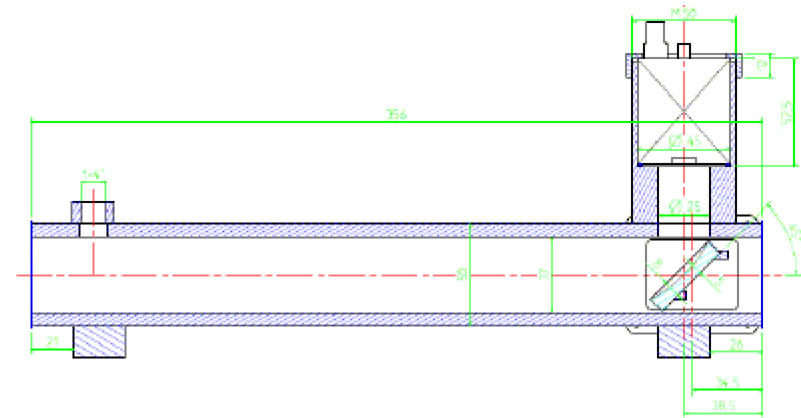
Thanks to very high energy and low scattering angles path length differences are very small for forward protons, below 100 μm! It means that it starts affecting *z-by-timing* only for sub-picosecond measurements!

# GasToF™(2005)



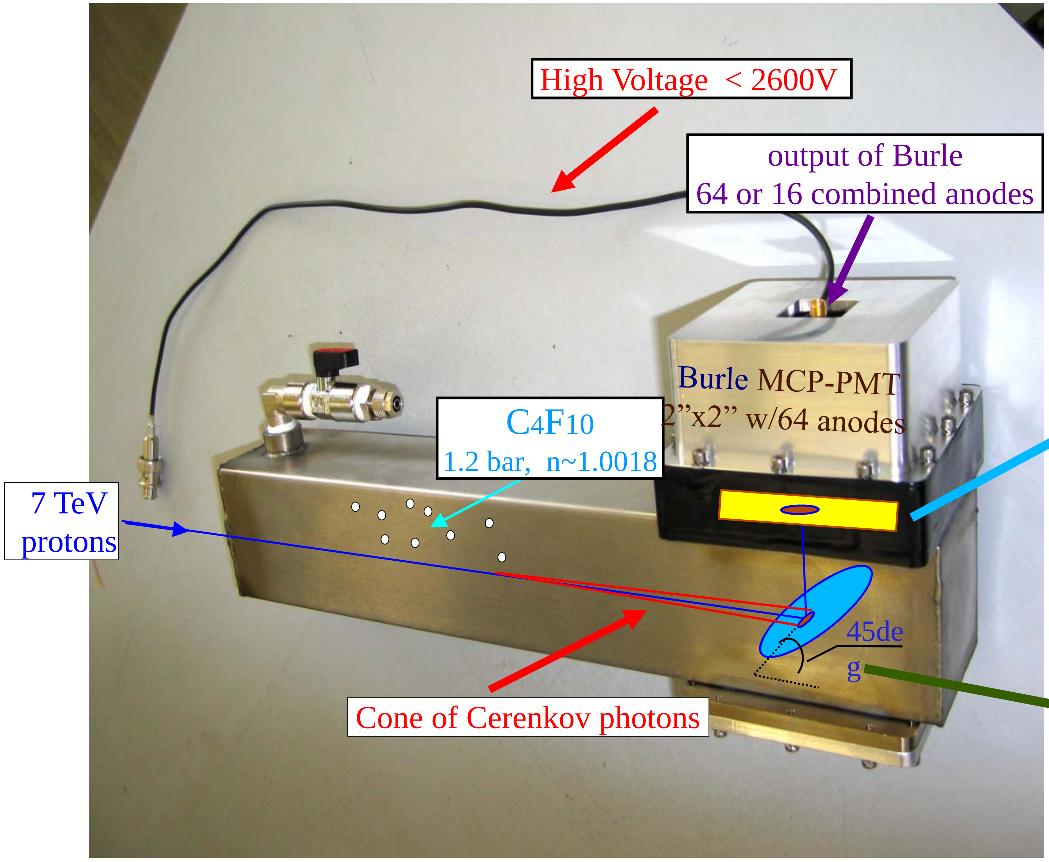

**NB: Gastof might become (sub-) picosecond detector! Max. time difference = 2*L*Δn (= 200 mm * 0.003 = 0.6 mm !)**

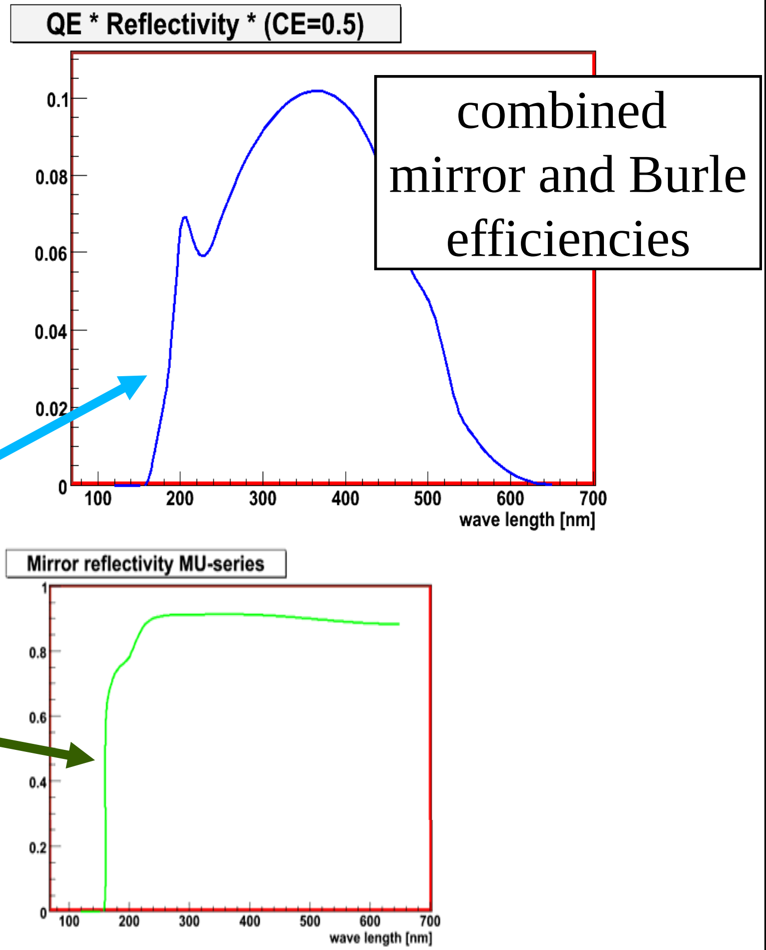
# GasToF Concept



- Intrinsically very fast
- Light detector – can be used with(in) tracking
- Simple (small chromacity) – modeling with ray tracing
- Robust and radiation hard

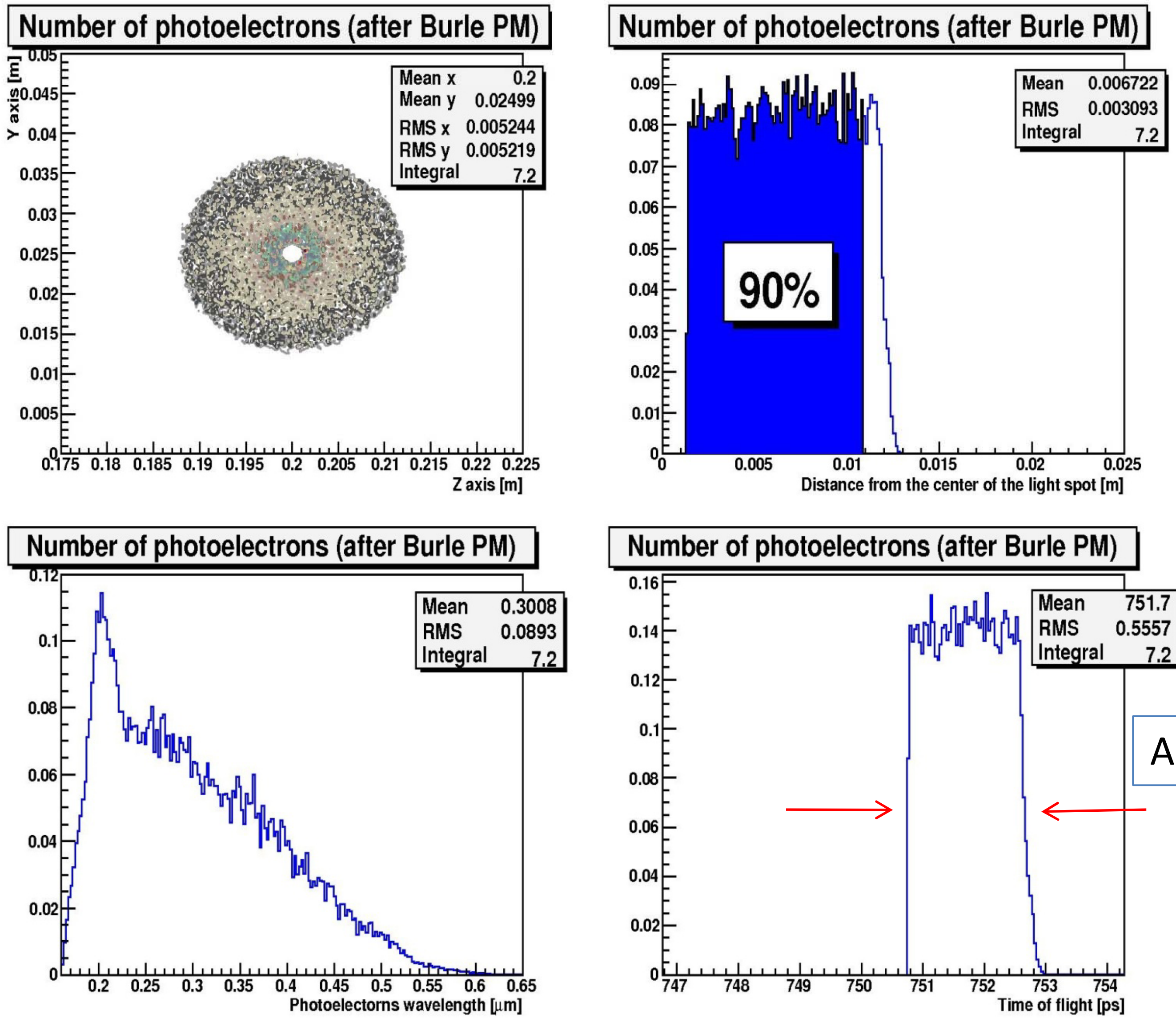
## GasToF **prototyping** with Photonis/Burle 25 μm MCP-PMTs




Our 'workhorse': very robust with timing resolution of ~30 ps (due to TTS) → L. Bonnet *et al.* Acta Phys. Pol. B38 (2007) 447; FP420 Collab., JINST 4 (2009) T10001

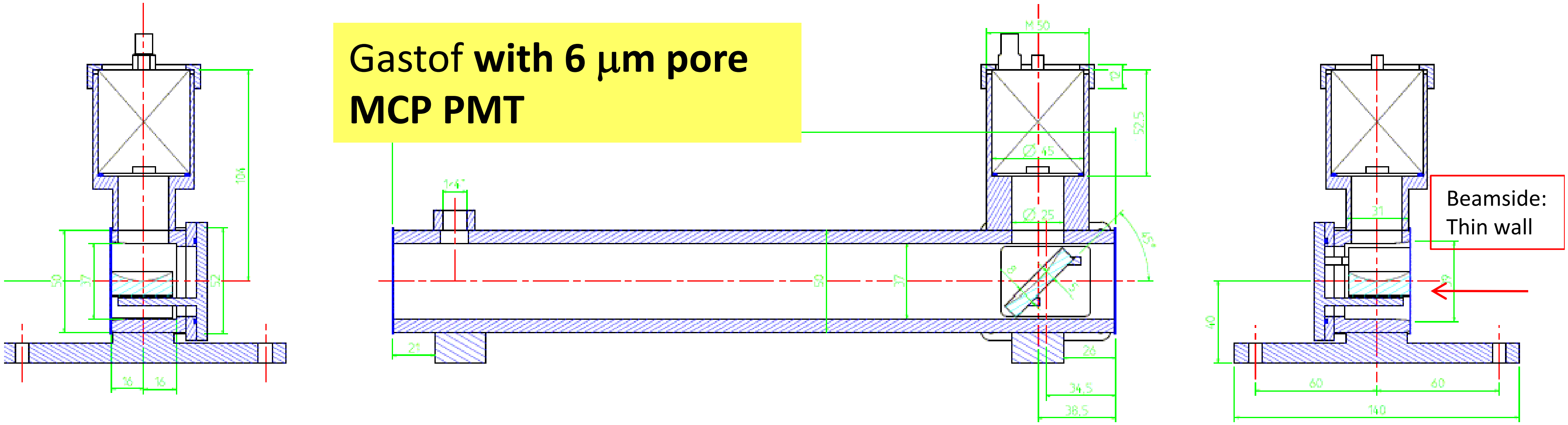
# Simulations with Photonis 25 μm MCP-PMT (T. Pierzchala: raytracing)




All in 2ps !!

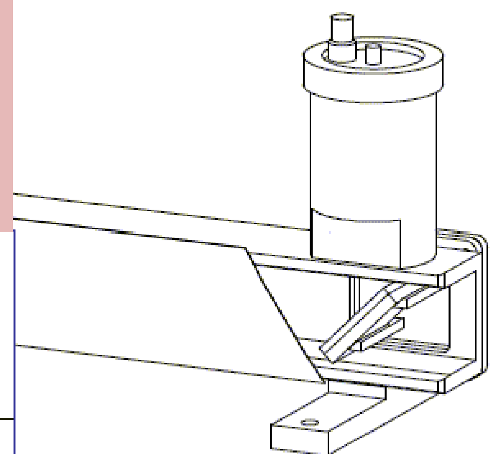
20cm $C_4F_{10}$ + Flat mirror + central protons + 50% CE

Gastof **with 6 μm pore MCP PMT**



Beamside: Thin wall

**Problem:**
**Small 11 mm cathode → use spherical mirror to focus light on MCP-PMT**

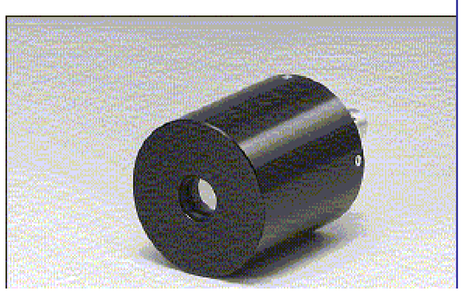


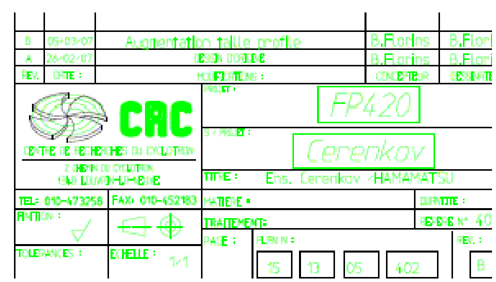
HAMAMATSU

**MICROCHANNEL PLATE-PHOTOMULTIPLIER TUBE (MCP-PMTs)**
**R3809U-50 SERIES**

**Compact MCP-PMT Series Featuring**
**Variety of Spectral Response with Fast Time Response**

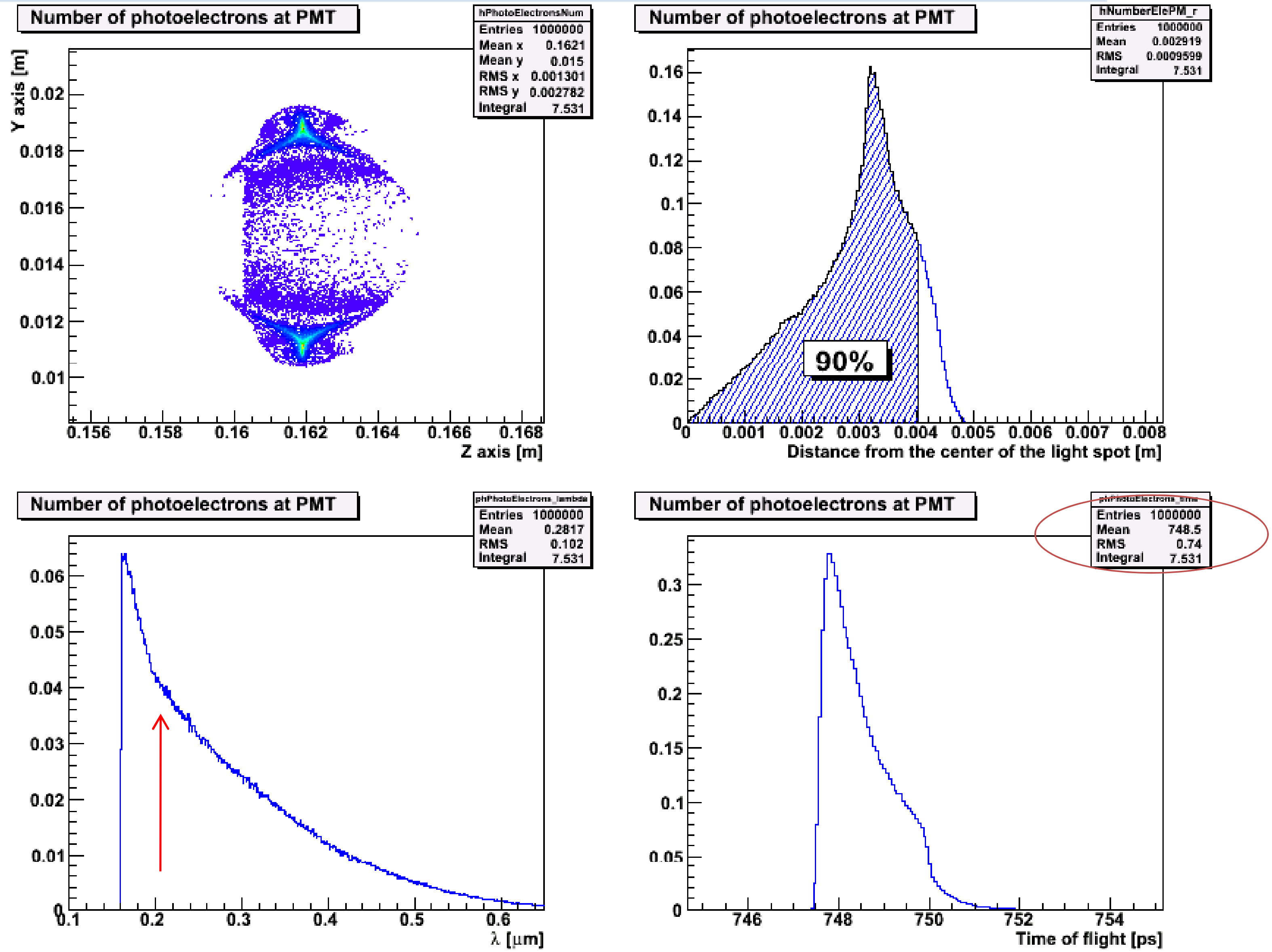
**FEATURES**
- **High Speed**
  Rise Time: 150ps
  T.T.S. (Transit Time Spread)[1]: ≤ 25ps(FWHM)
- **Low Noise**
- **Compact Profile**
  Useful Photocathode: 11mm diameter
  (Overall length: 70.2mm Outer diameter: 45.0mm)





Short GasToF (20cm), reflective beam-wall, R3809U-58 PMT, protons on axis:

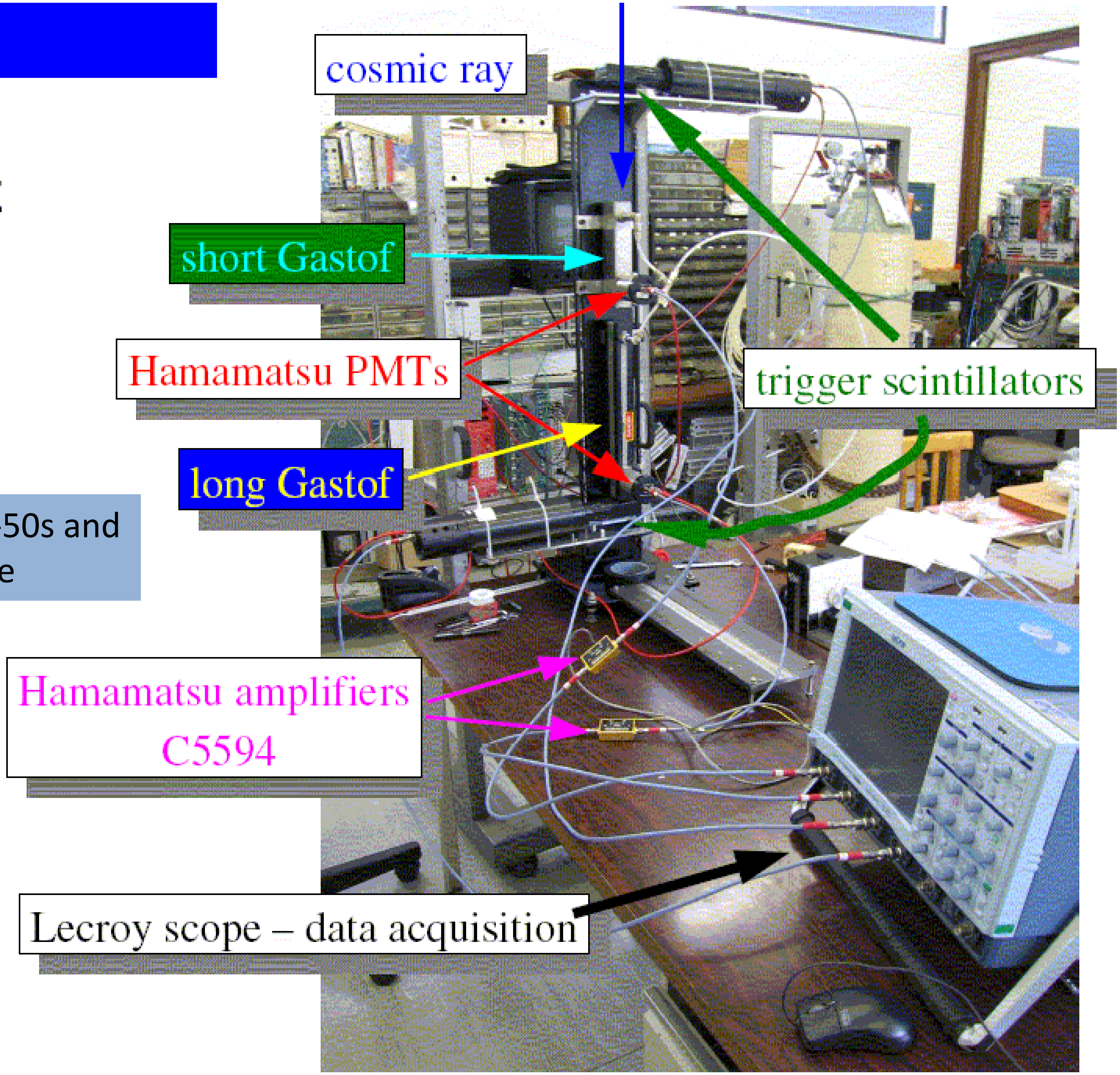
Nicolas Schul



Tomek Pierzchala

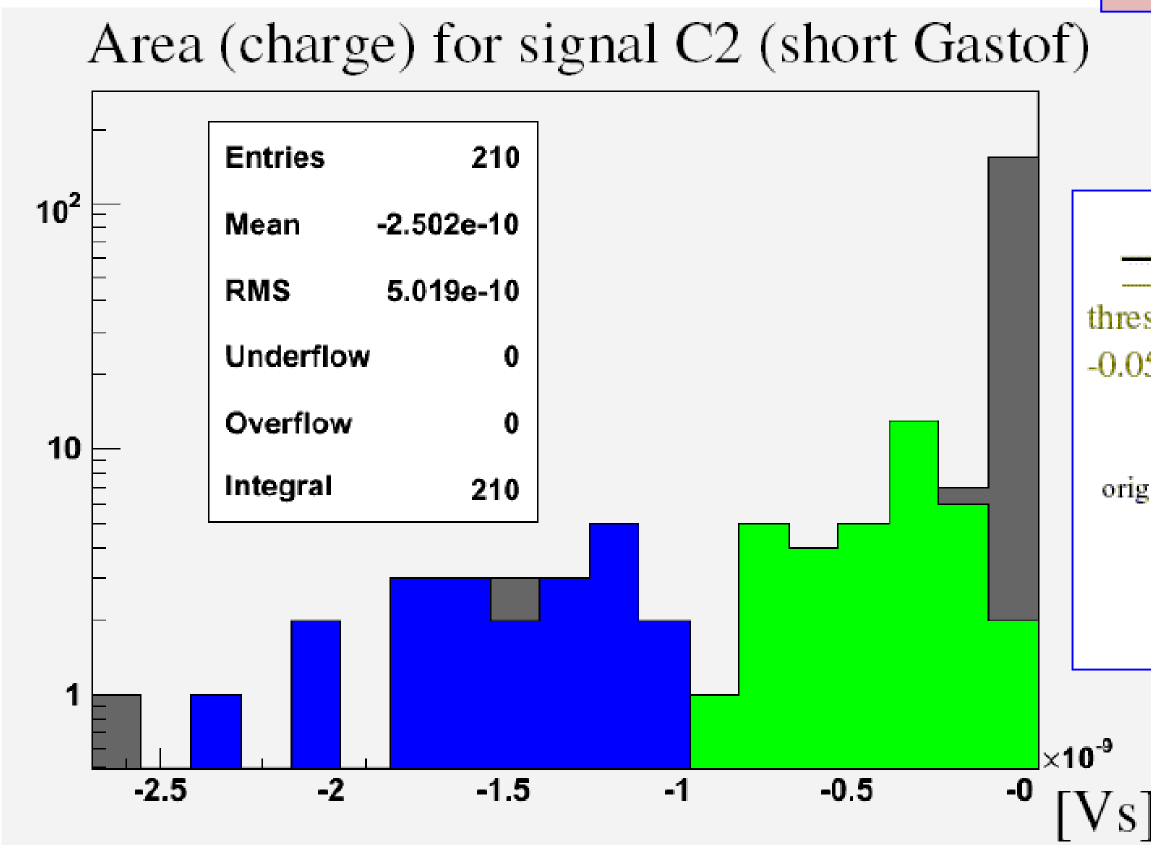
# Cosmic rays test stand

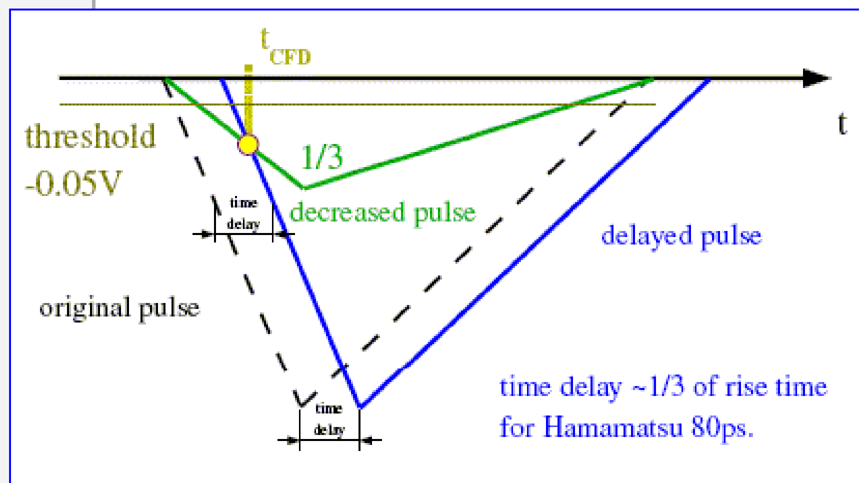
Tests using R3809U-50s and 3 GHz, 20 Gs/s scope



# Charge distributions for the cosmic ray events

**First with air-filled detectors and 1 pe signals (HPK tubes @ 3000 V)**



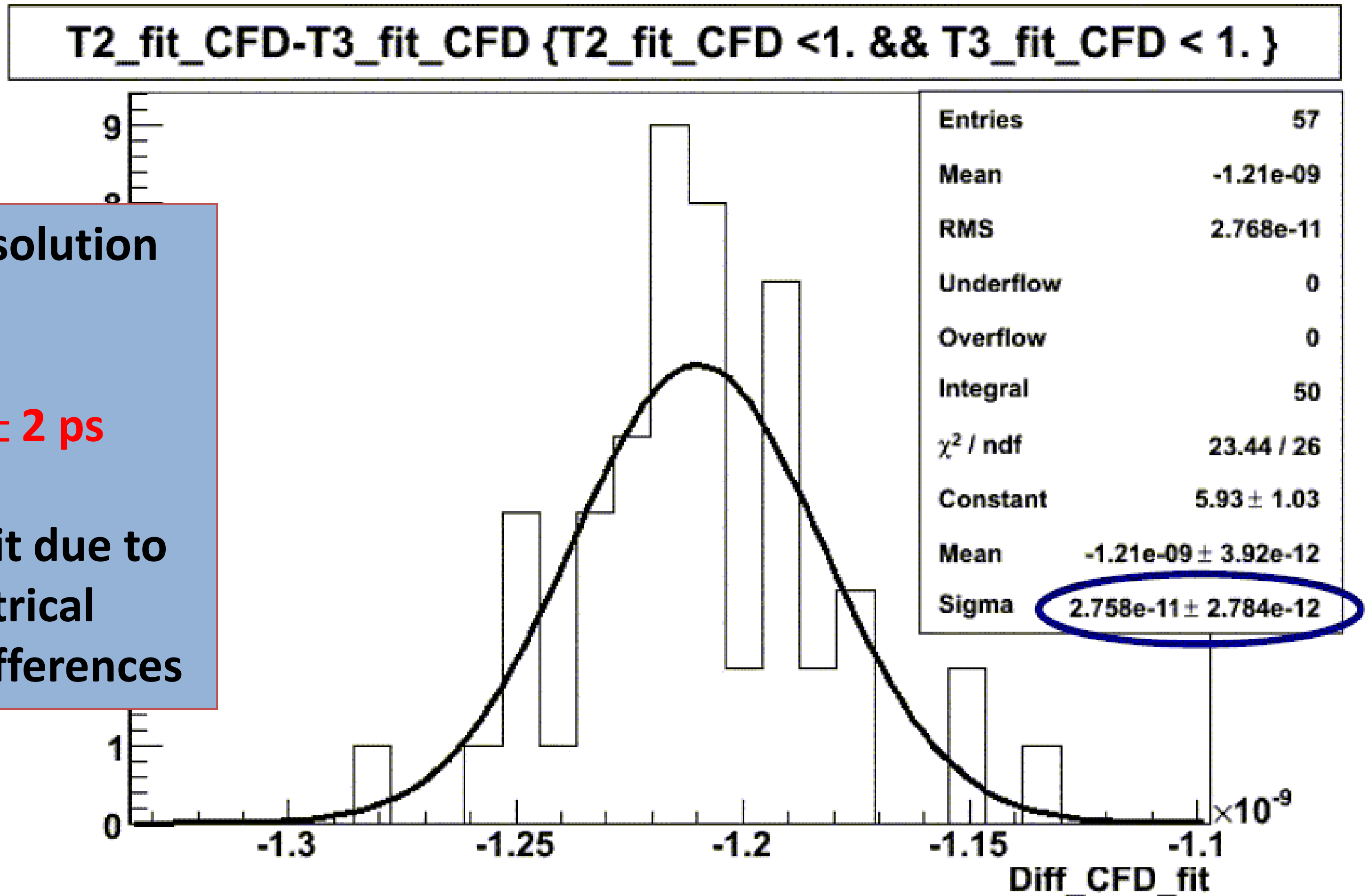




Run offline CFD algorithms (Tomek Pierzchala)

**1 pe, 2 pe, …**

Tomek Pierzchala

**Using CFD algo:**
**Measure spread of time difference (~distance between PMTs)**

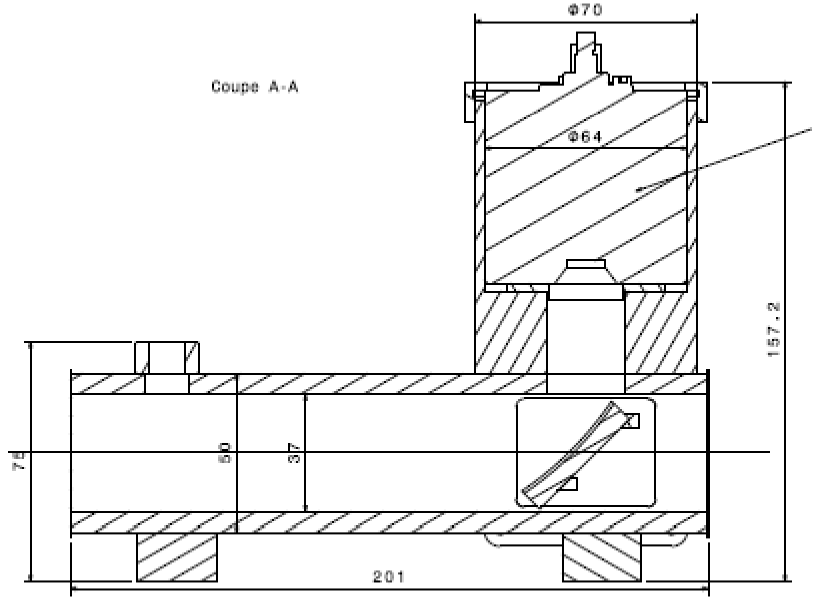



**Derived GasToF resolution (for ~1 pe):**

**< 28 ps/√2 = 19.5 ± 2 ps**

**NB: Just upper limit due to significant 'geometrical spread' of time differences**

## ULTRA FAST PHOTOMULTIPLIERS Photek

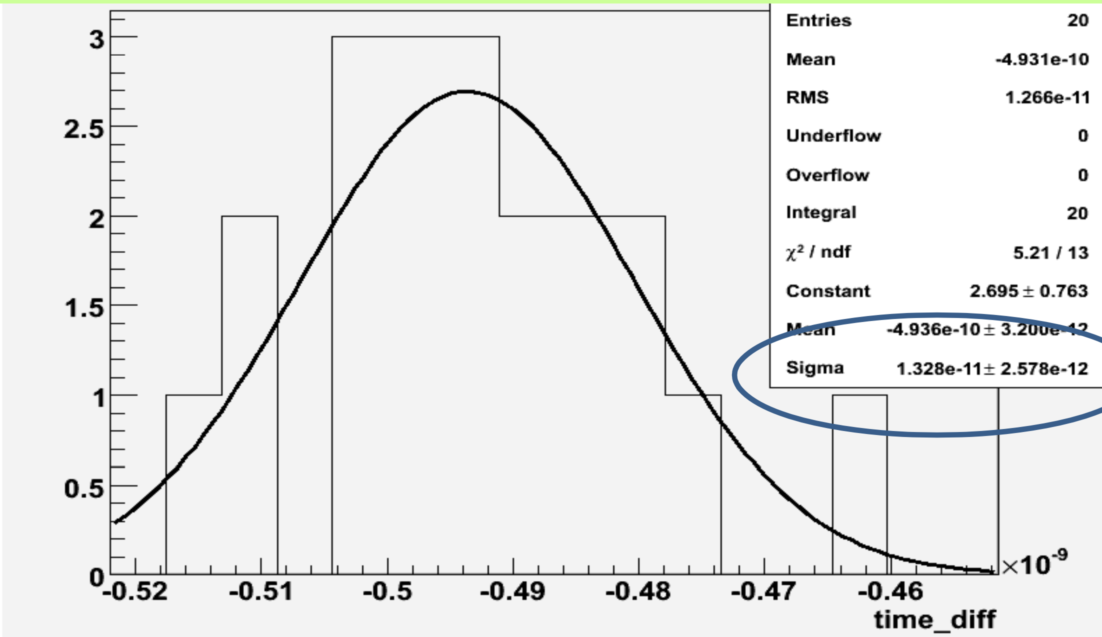



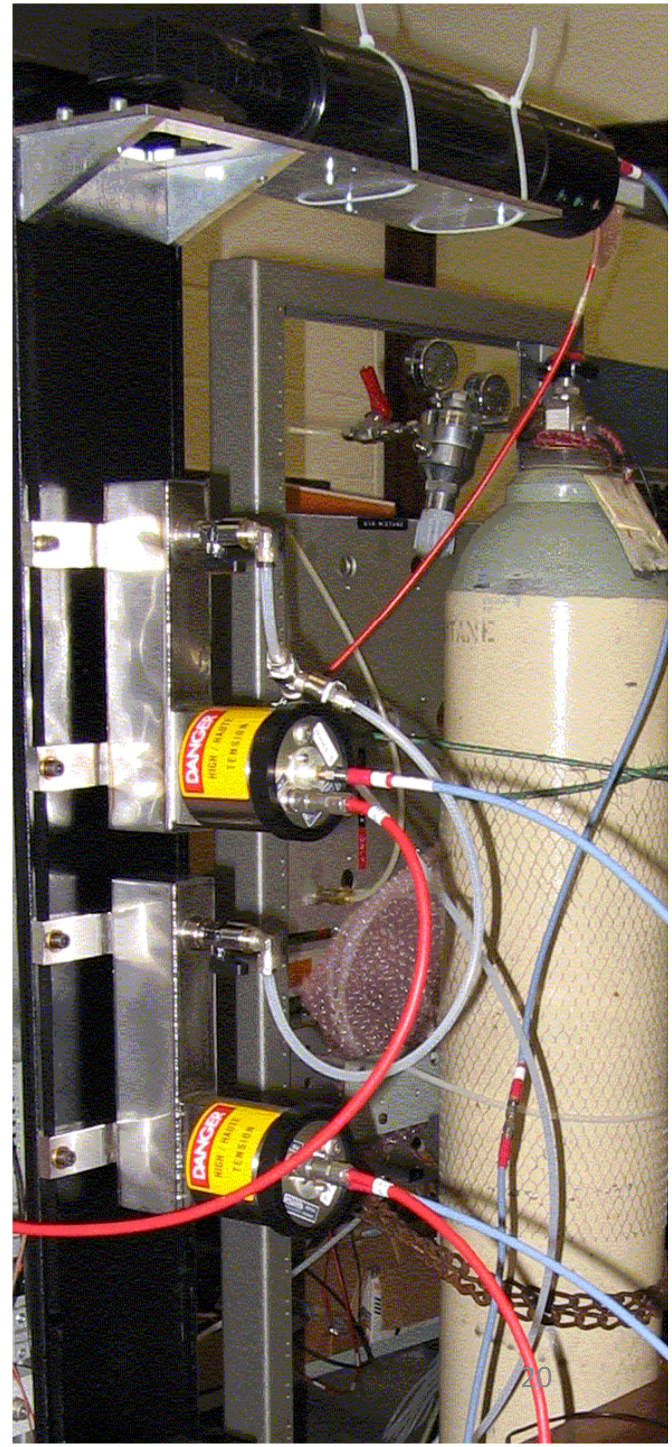

| | PMT210 | PMT212 | PMT325 | PMT340 |
|---|---|---|---|---|
| **Anode Size** | 10 mm | 12 mm | 25 mm | 40 mm |
| **Electron Gain** | $10^6$ | $10^6$ | $10^7$ | $10^7$ |
| **Peak/Valley** | 2:1 | 1.5:1 | 2:1 | 2:1 |
| **Dynamic Range cps** | 40,000 | 40,000 | 40,000 | 40,000 |
| **Pulse Rise Time** | 100 ps | 100 ps | 300 ps | 500 ps |
| **Pulse FWHM** | 170 ps | 170 ps | 800ps-1 ns | 1 ns |
| **Transit Time Jitter** | 30 ps | 30 ps | 100 ps | 100 ps |
| **MCP Pore Size** | 5/6 | 5/6 | 10/12 | 10/12 |

**Received from PHOTEK two $3\ \mu m$ pore MCP-PMTs…**

**…so fast that had to upgrade to yet faster scope…**

## Cosmic rays results for PHOTEK two 3 μm pore MCP PMTS:



Example of time difference measurements of two GasToF detectors with Photek MCP-PMTs ;

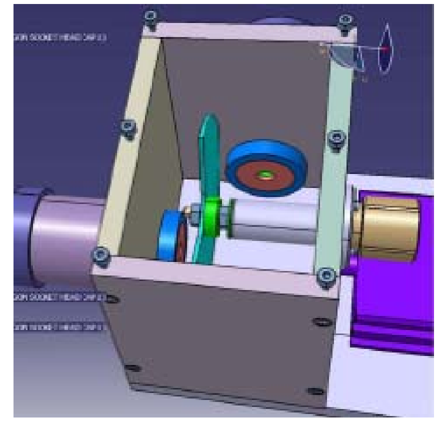
Signal wave-forms were registered on fast scope and CFD algorithms were applied to determine signal arrival times

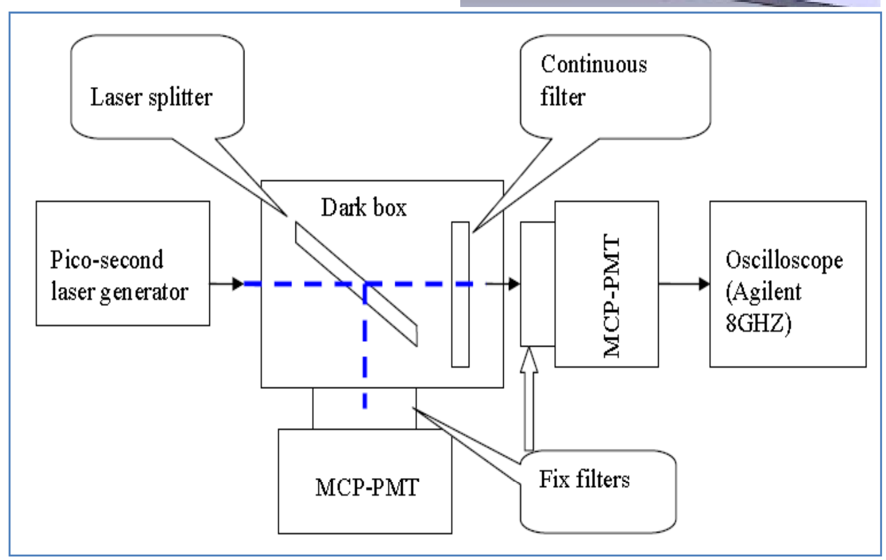
Time difference spread corresponds to < 10 ps time resolution per detector

Dedicated picosecond laser test setup was developed to characterize fastest MCP-PMTs from Photek and Hamamatsu – using Agilent scope with 8 GHz BW and 40 GSamples/s

| PILxxx | wavelength (nm) | tolerance (nm) | spectral width (nm) | pulse width (ps) |
|---|---|---|---|---|
| PIL037 | 375 | ± 10 | < 7 | < 60 |
| PIL040 | 408 | ± 10 | < 7 | < 45 |
| | | | | FWHM |

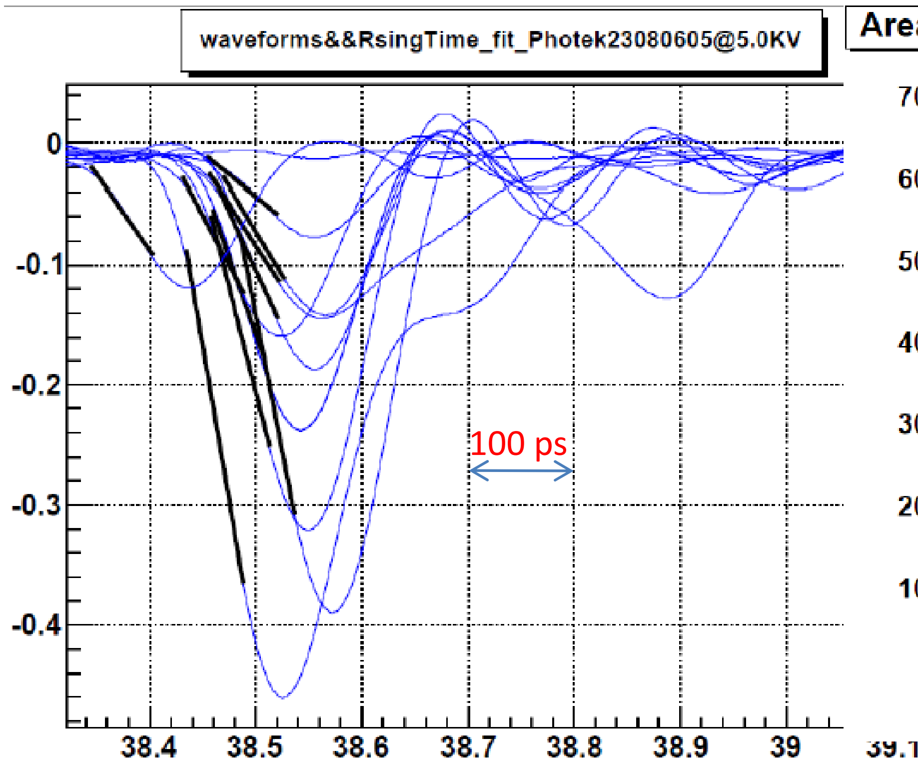

PiLas 408 nm





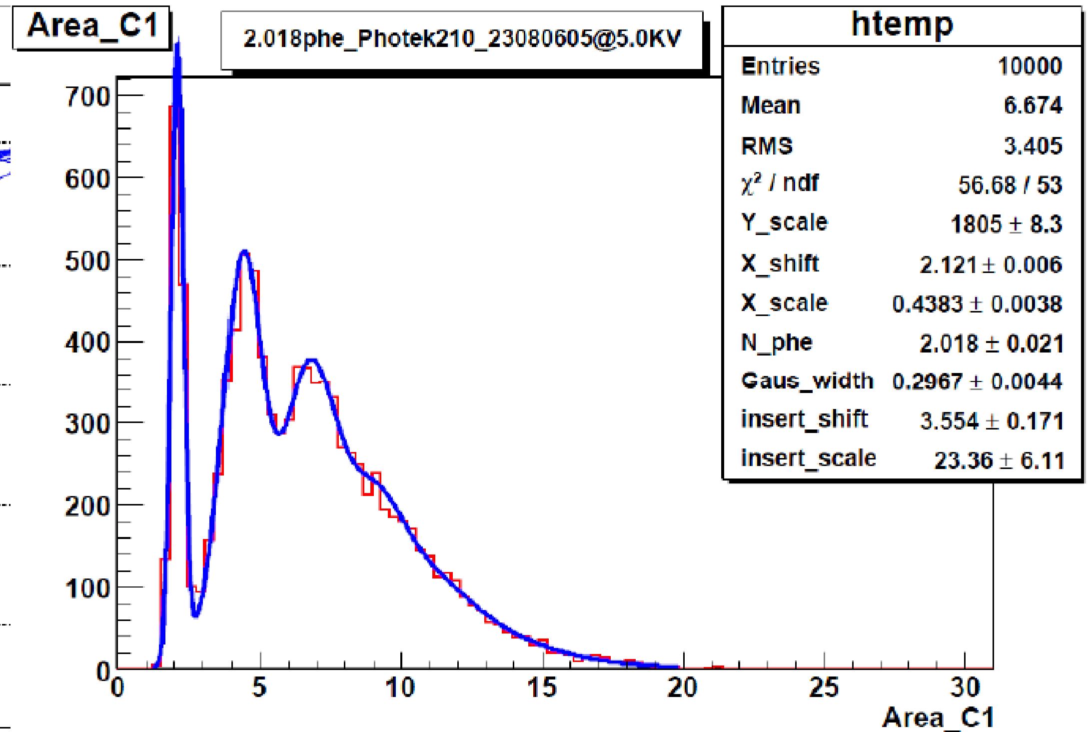
PiLas laser test setup runs up to 1 MHz repetition rate at 408 nm and using 8 GHz Agilent scope with 40 GSa/s

J. Liao




Photek23090605_2.5phe

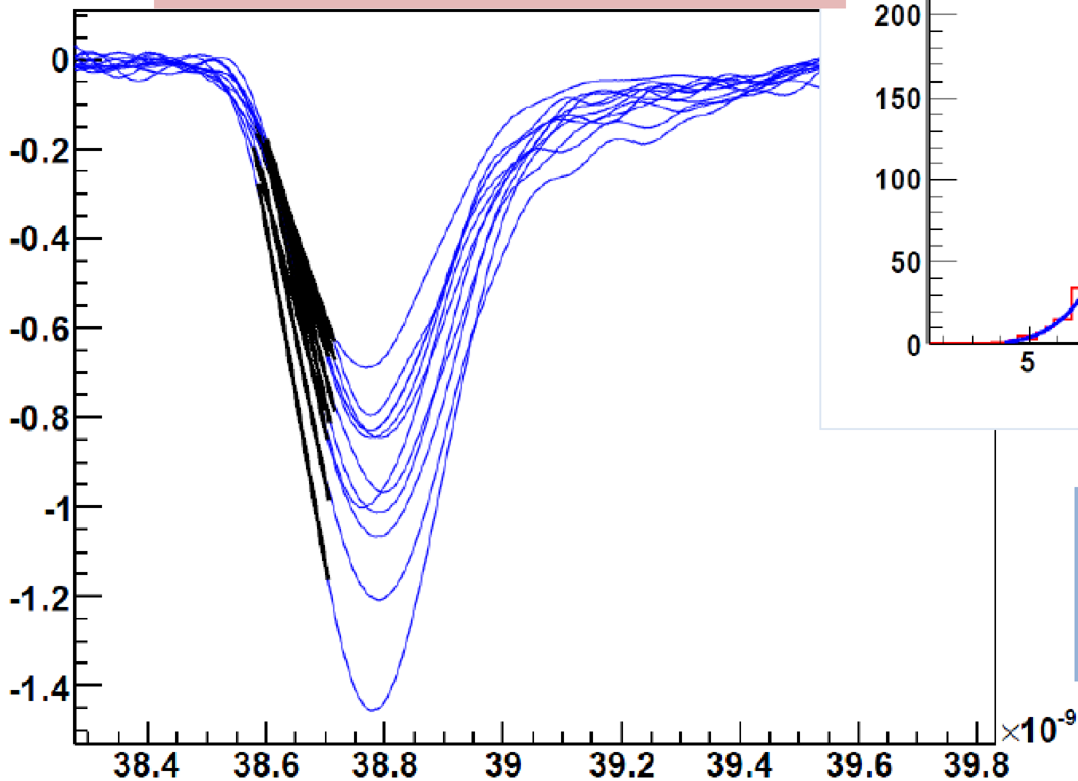
Impressive rise time (10→90%) measured: 80 ps for PHOTEK 3 μm pore PMT210 (and 150 ps for R 3809U-50)

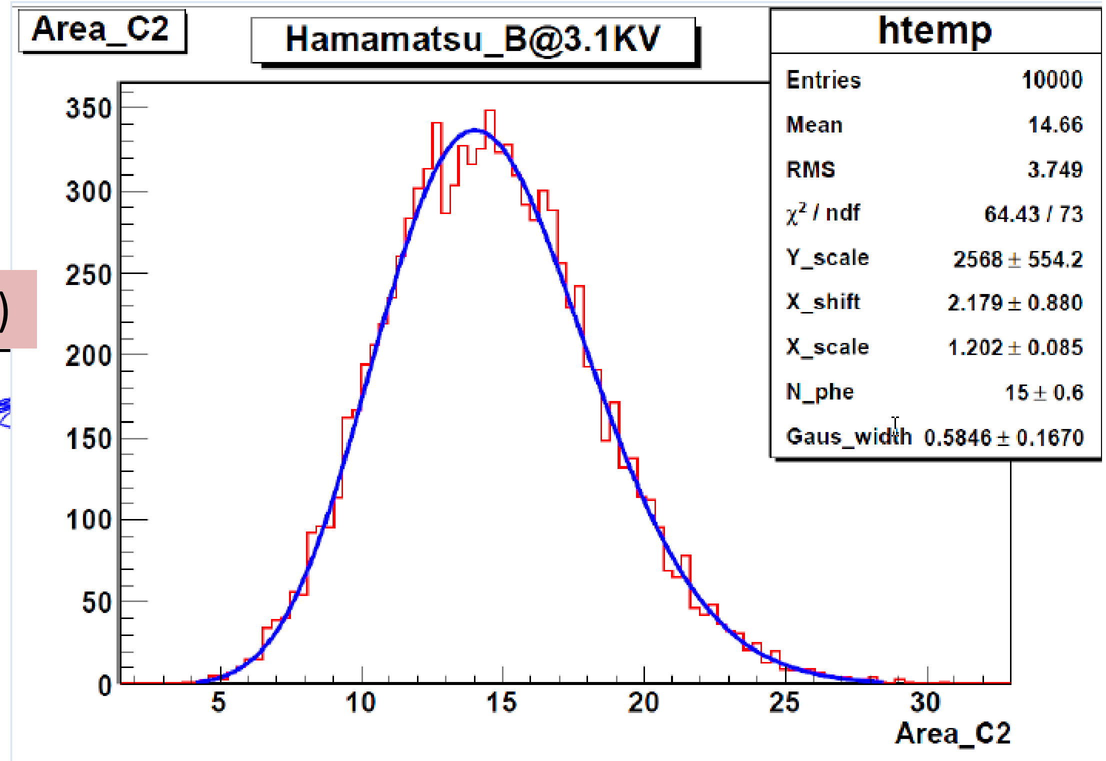



Example of anode charge distribution for low light pulse; 0, 1 and 2 phe peaks are clearly visible; line shows fitted detector response model

# Waveforms and anode charge distribution from Hamamatsu R 3809U-50

Laser test measurements (J. Liao)



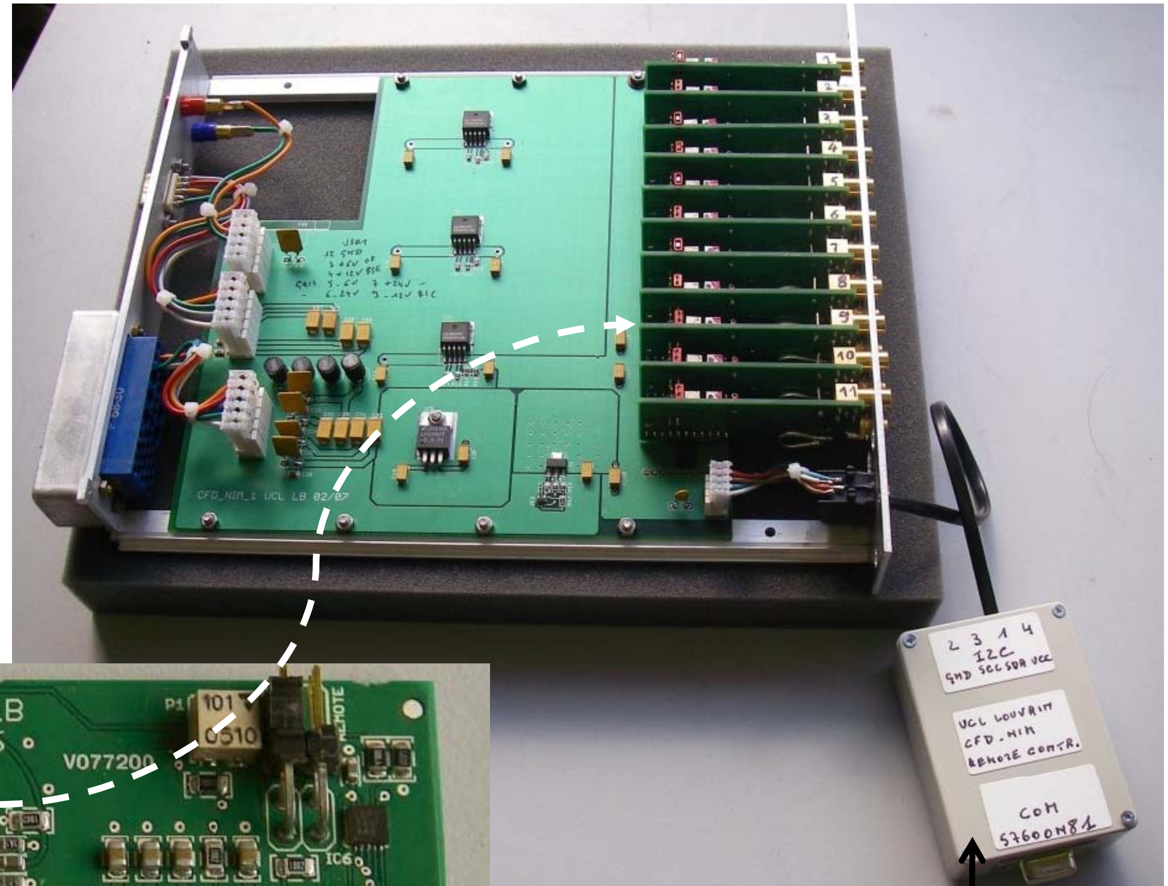

Good understanding of laser tests:
→ Reliable modeling of waveforms
→ Input to MC simulations

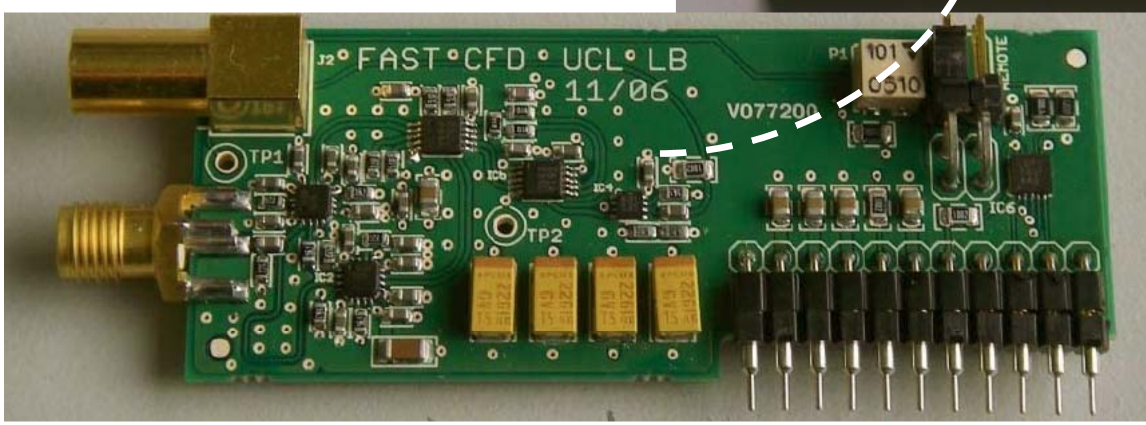
# Fast Constant Fraction Discriminator

L. Bonnet (UCLouvain)

Development of LCFD

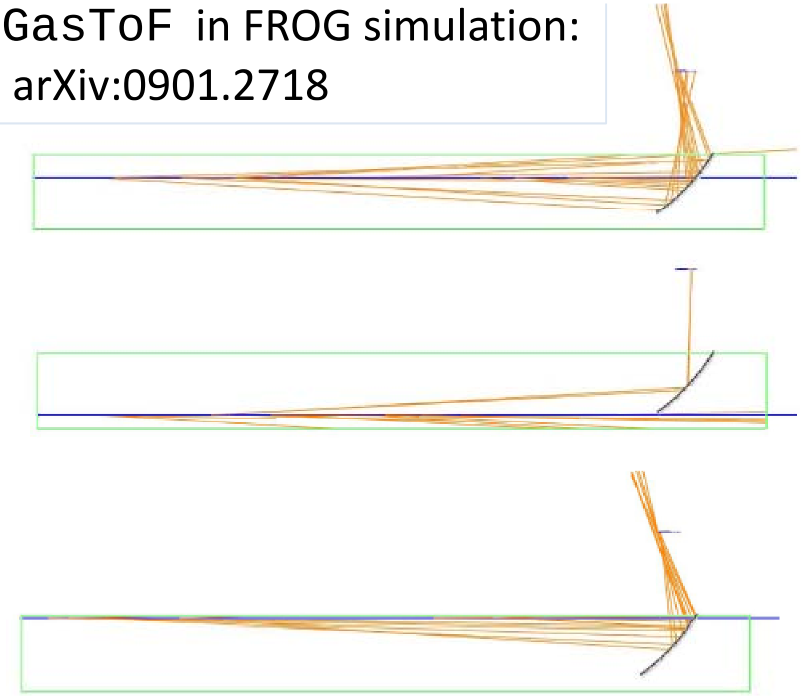
- 12 channel NIM units
- mini-module approach tuned to PMT rise time (HPK/Photek vs Photonis)
- Good performance: < 10 ps resolution for 4 or more phe's (A. Brandt)





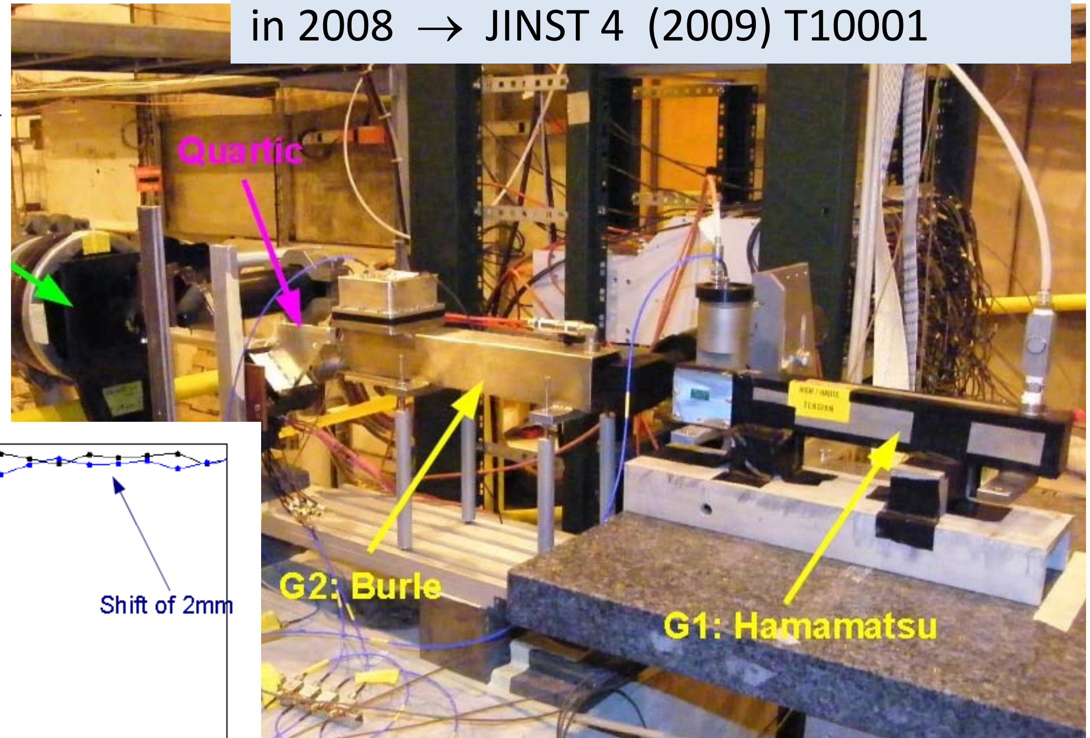

Remote control for threshold

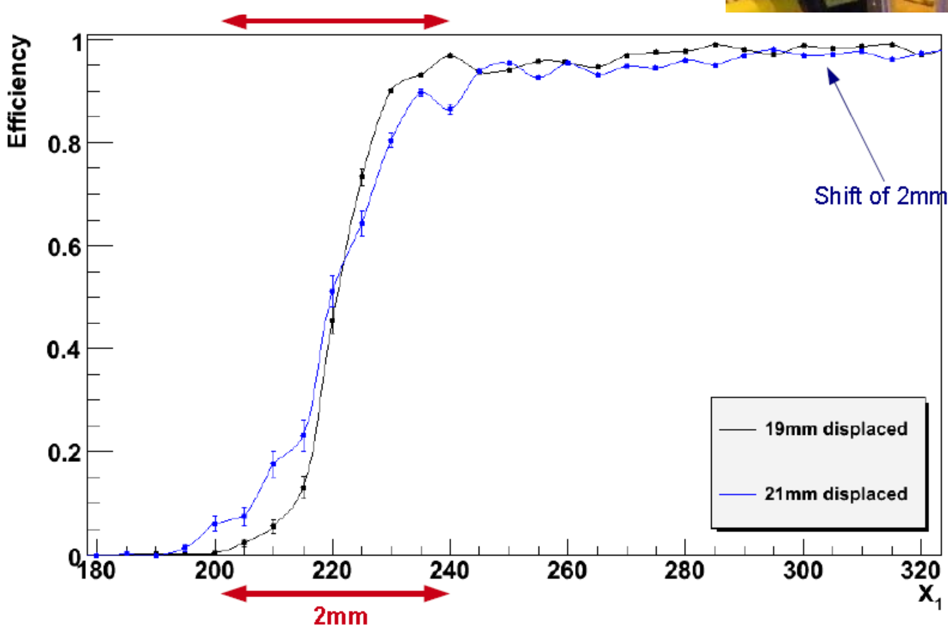
GasToF in FROG simulation:
arXiv:0901.2718



N. Schul

Two GasToF detectors at CERN test beam in 2008 → JINST 4 (2009) T10001




High statistics beam test results:
- High efficiency (~98%), down to close mechanical edge
- Good description by MC

# GasToF: Outlook

- Continue R&D toward 1 ps ToF detectors (also interesting for PID at test beams and fixed target experiments)

- Very exciting, long-term development program is crystallizing

- Start design and prepare tests of GasToF detectors with multi-anode MCP-PMTs – with working mode 1 phe per channel – will check its <u>multi-hit</u> and high rate performance;
NB: need fast multi-channel electronics (is CERN HPTDC chip enough?)

- System performance studies started – need < 5 ps precise reference clock distribution over ~1 km

- Addressing in detail high rate/lifetime issues
  (NB: MCP-PMT radiation hardness already tested)

# GasToF: Outlook

High rate/lifetime issues – two scenarios/setups:

1. Medium luminosity (~$10^{33}$ $cm^{-2}s^{-1}$):
- Use one channel GasToF (with < 1 $cm^2$ PC) and 4–5 pe signal
- No multi-hit capability – event pileup low (double hit ~2%)
- Photon counting rate ~ 4 $MHz/cm^2$
- Total annual anode charge (assuming gain $3.10^5$) is ~2 $C/cm^2$

2. High luminosity (~$10^{34}$ $cm^{-2}s^{-1}$):
- Use multi-channel GasToF (with ~12 $cm^2$ PC) and 8–10 pe total signal, 1 pe single anode signal
- Multi-hit capability – event pileup high (double hit ~20%)
- Extra bonus: Position reconstruction from disc pattern to ~2 mm
- Photon counting rate ~5 $MHz/cm^2$
- Total annual anode charge (assuming gain $5.10^5$) is ~5 $C/cm^2$

GasToF strengths:
- Large part of light pulse on PC around 200 nm – QE drop much suppressed
- Some loss of QE can be easily compensated by increasing gas pressure

(NB. Dark noise not relevant due to high signal rates & only 1 ns wide 'active' window)

# Summary

• Proposal of HPS project for New Physics with forward detectors is well advancing – requires developing small but challenging detectors

• Final GasToF designs for (single anode) HPK and Photek MCP-PMTs are ready

• Modeling GasToF performance and MC simulation well developed

• Laser test setup running (with 8 GHz BW 40 GSa/s scope), and well understood

• Future tests clearly defined – many new results soon to come, also from test beams!

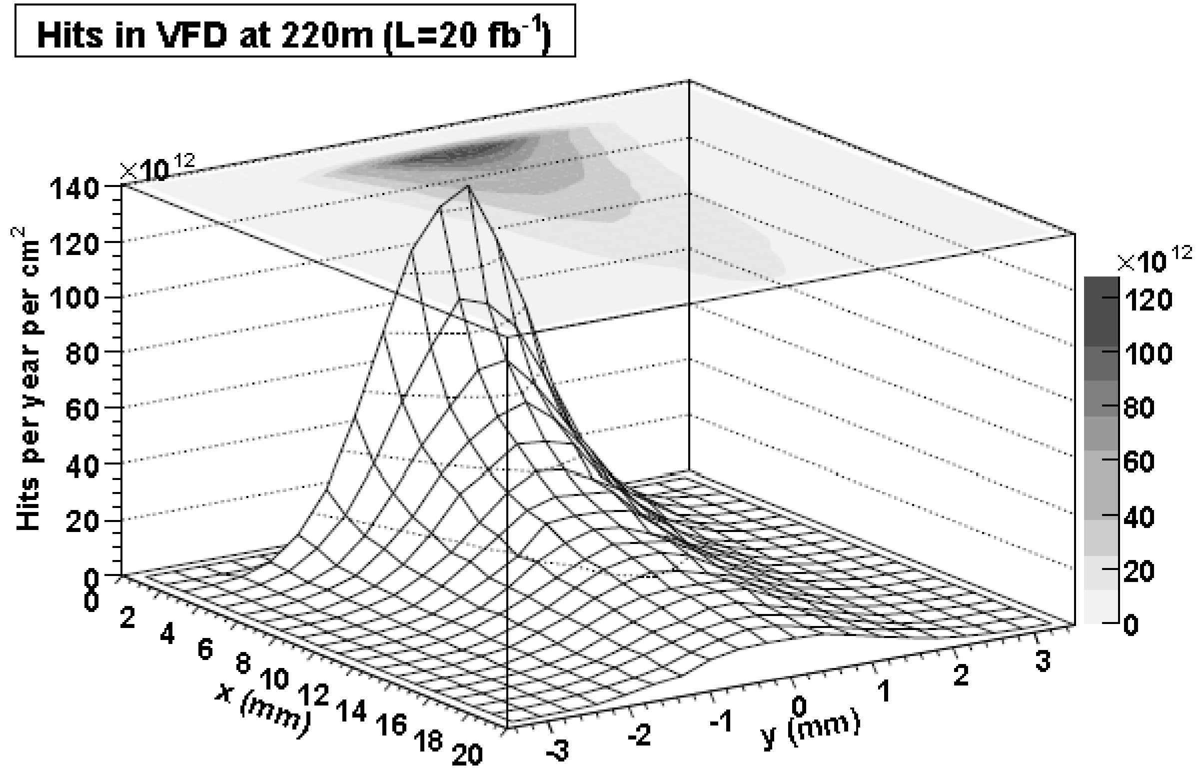
• HPS Technical Design Report in preparation

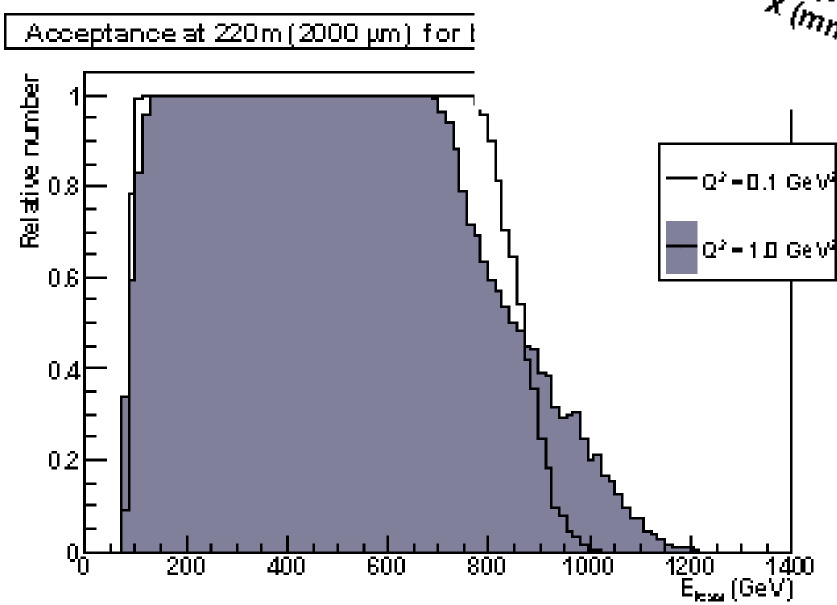
STAY TUNED!

# Extra slides

# Forward proton acceptance @ $\beta^* = 0.5$ m

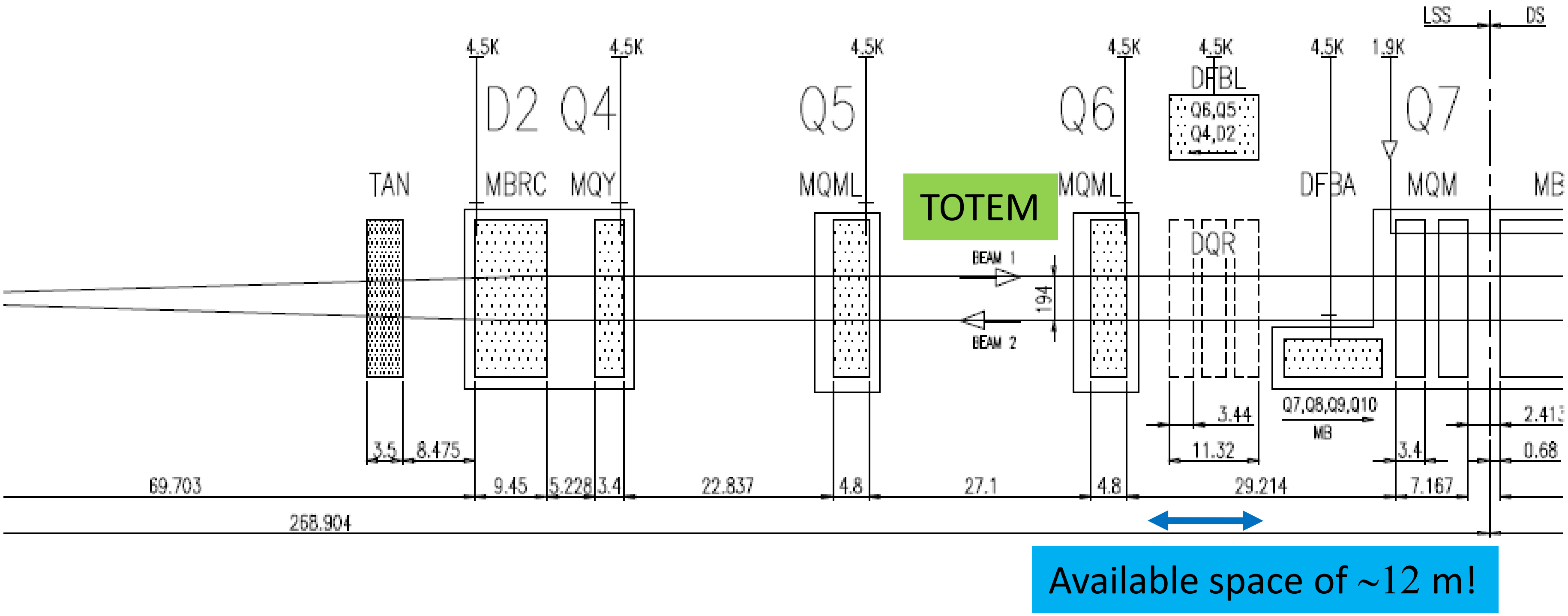
HECTOR: **JINST 2, P09005 (2007)**



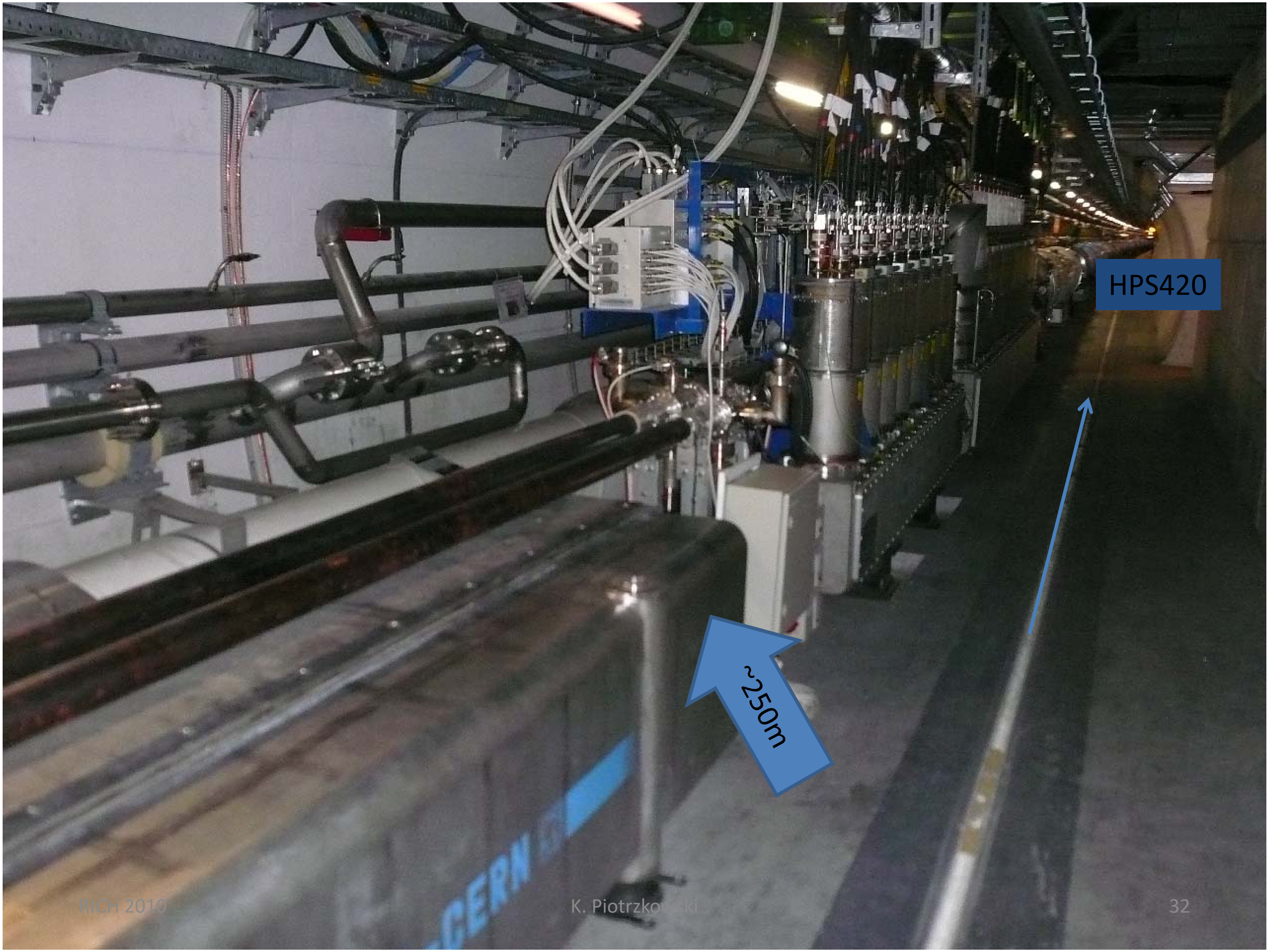

Similar proton lateral distributions to HPS420

# LHC beam-line close to 240 m

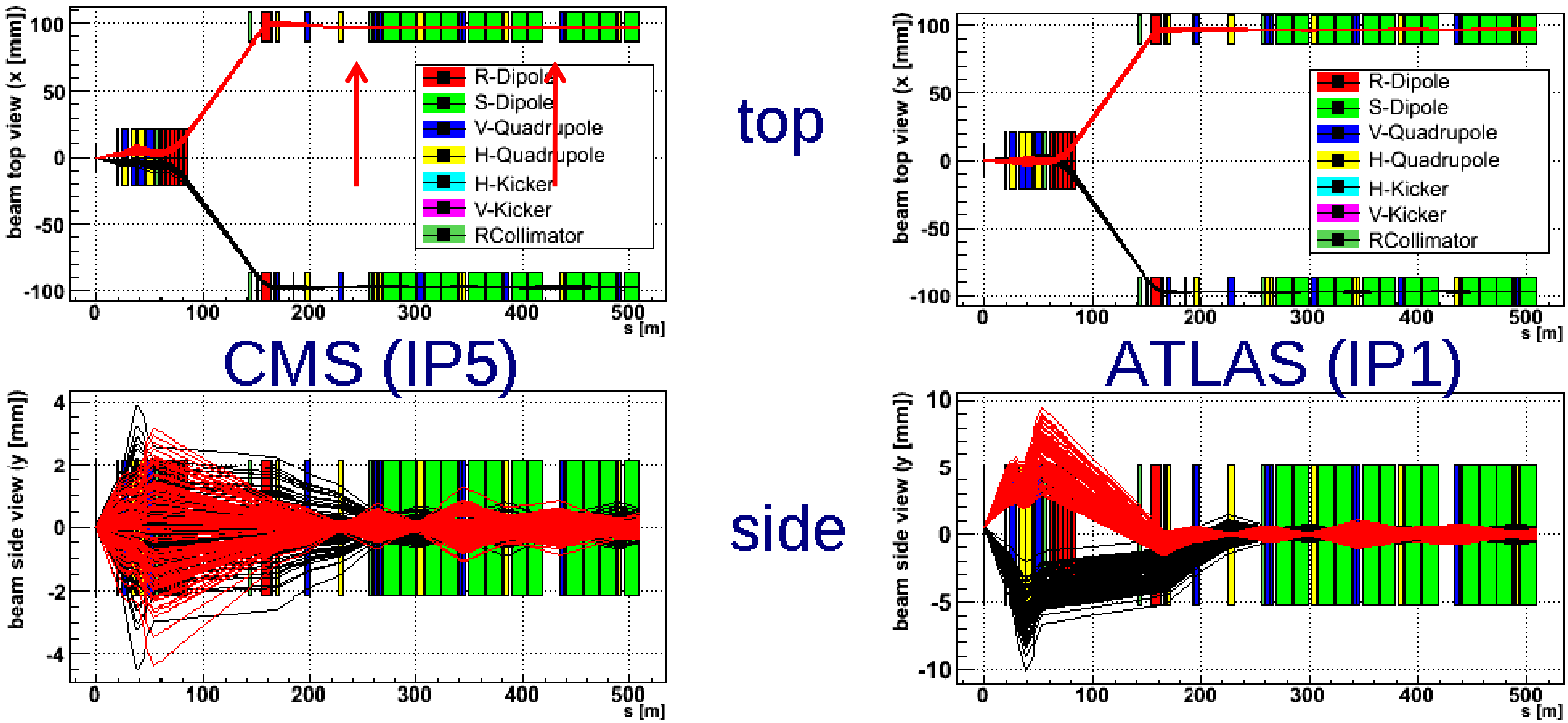



From Detlef:

- Space above quench resistors (QRs) is not reserved yet
- Space between QR and beam pipe ~ 25 cm, and space between QRs ~ 50 cm
- No problem of heat load


HPS420
~250m
CERN

**Optimal places for tagging Central Exclusive Production (CEP) at LHC: @ 220/240m and 420m from IP**

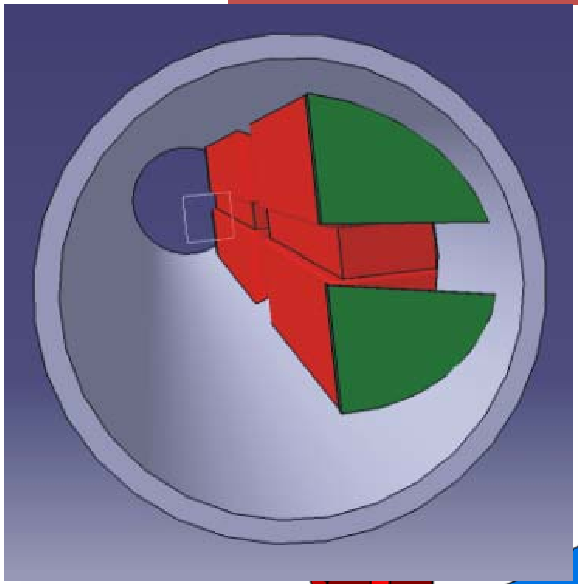



Horizontal crossing plane

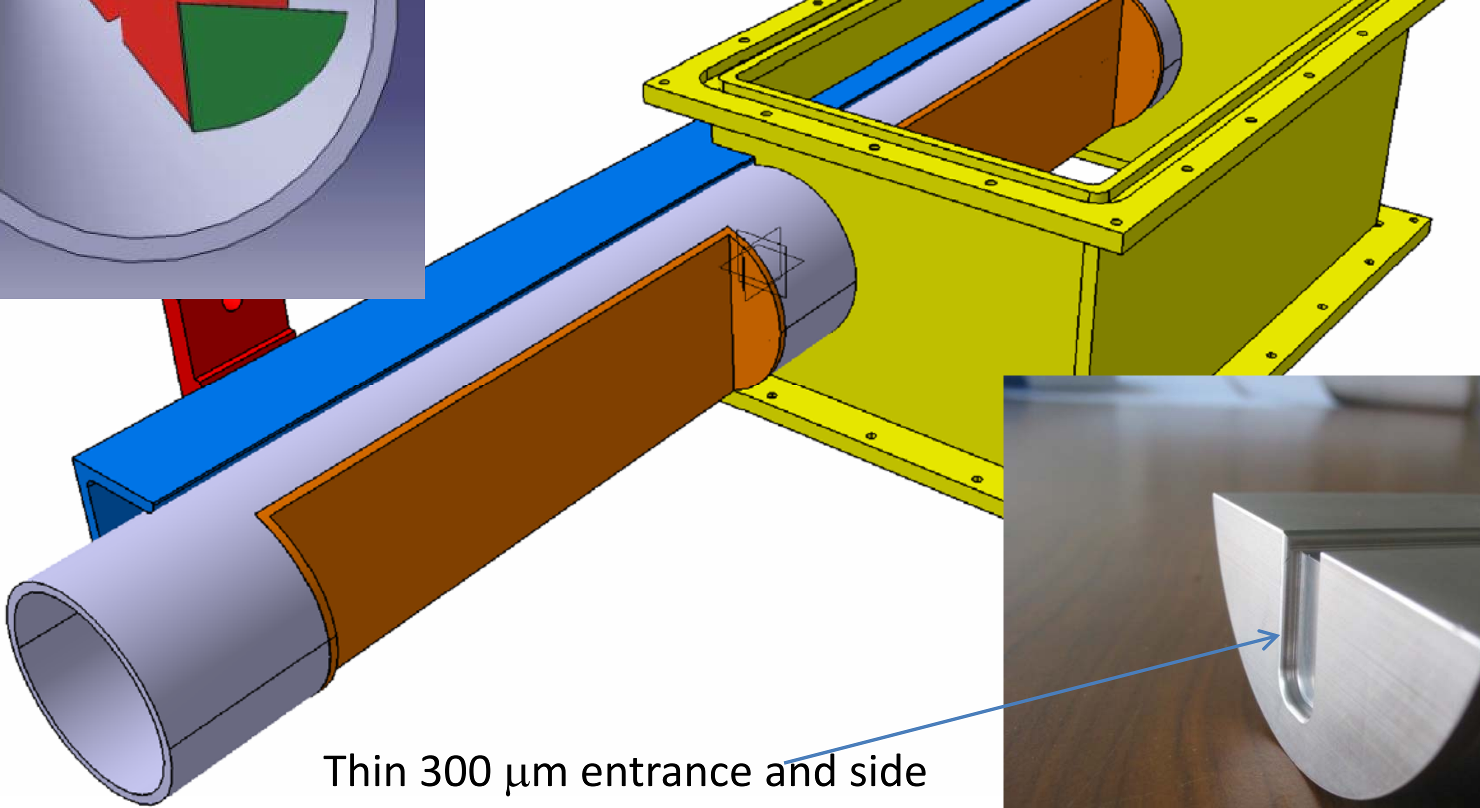
Vertical crossing plane

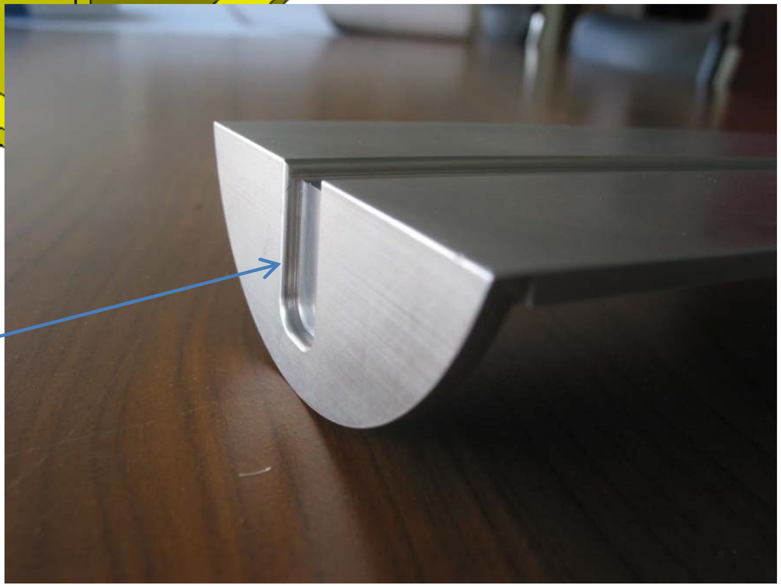
HECTOR: **JINST 2, P09005 (2007)**
**For <u>nominal</u> low-β LHC optics**

# Moving pipe: Detector 'pockets'



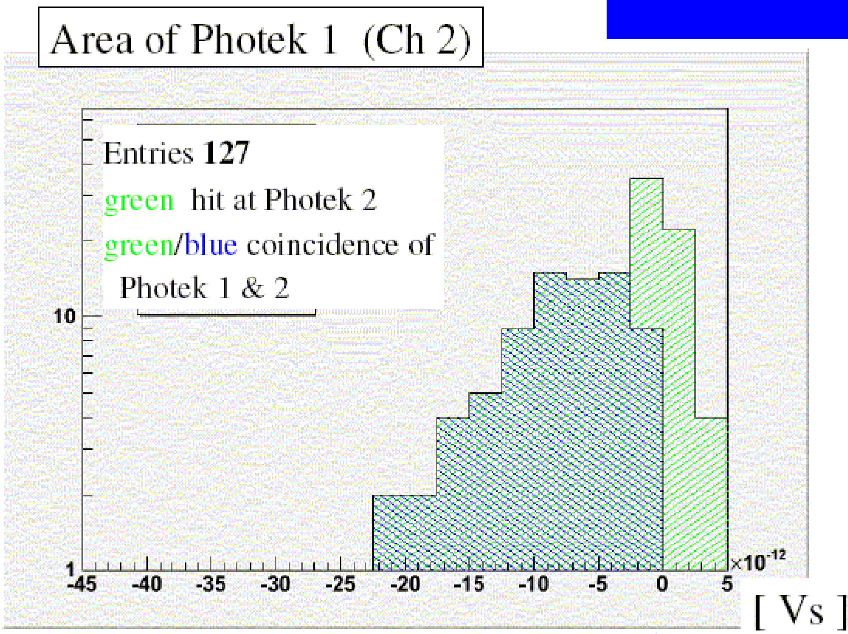
Prepared for beam tests:

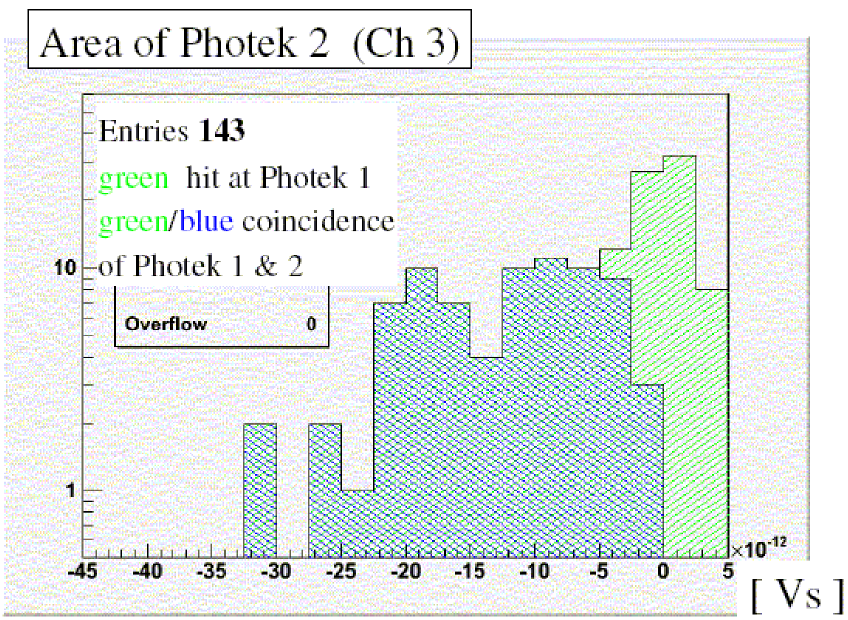


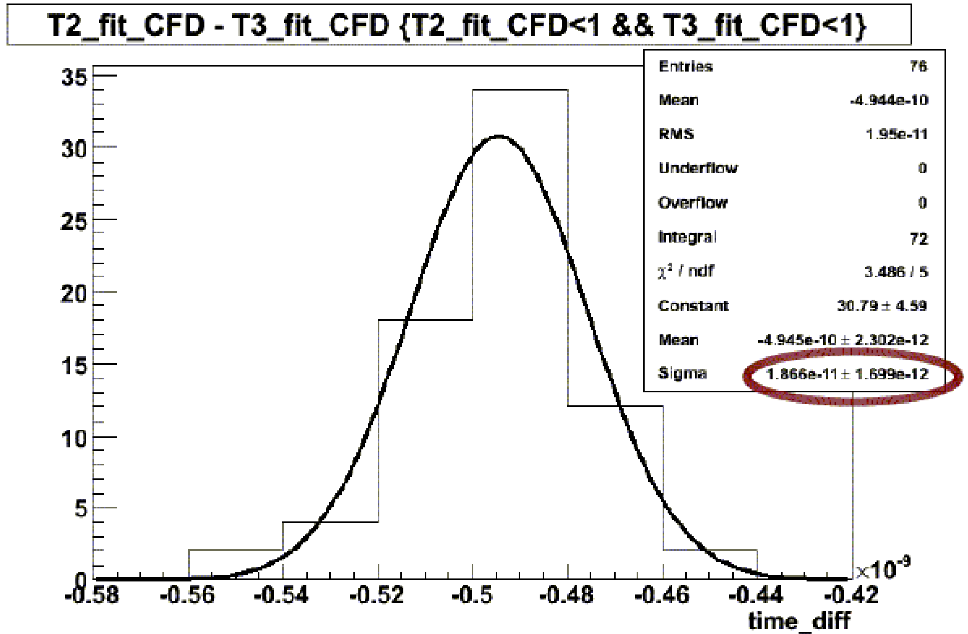


Thin 300 μm entrance and side windows by electro-erosion

Tomek Pierzchala




we measured an uncertainty of time difference:

18.0 ps ± 1.6 ps

and

18.7 ps ± 1.7 ps

both are consistent

taking worst result and assuming to detectors have the same jitter, we have a Gastof jitter:

< **13.2 ps ± 1.2 ps**

# HPS proposal: Adding HPS240 detectors

- Tagging at 420m and 240(220)m is complementary – together $\sim 0.2\text{–}10\%$ energy loss range is covered !
- This leads to significantly higher tagged cross sections
- Both 220 and 240 m locations are 'warm&free' – just bare beam-pipes
- At IP5, locations at 220 m are occupied by TOTEM -> go 240m (as ALFA in ATLAS) - it is still possible to send triggers to CMS!
- One does not need to modify the LHC beamline -> can be done before HPS420 and be treated as a *proof-of-principle* project + interesting physics as a bonus