GasToF: Pico-second Resolution Time-of-Flight Detector

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

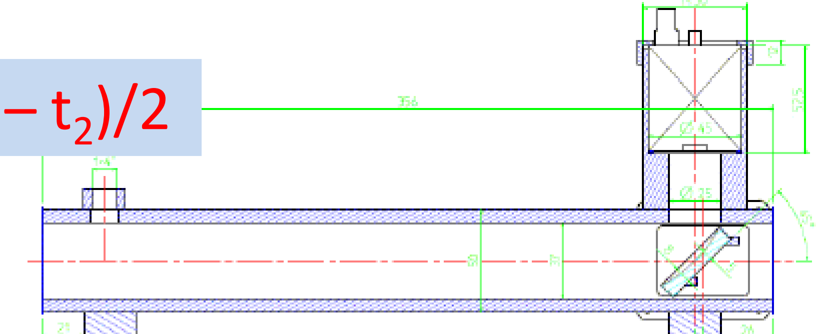
As introduction:
Motivation for forward proton timing at LHC

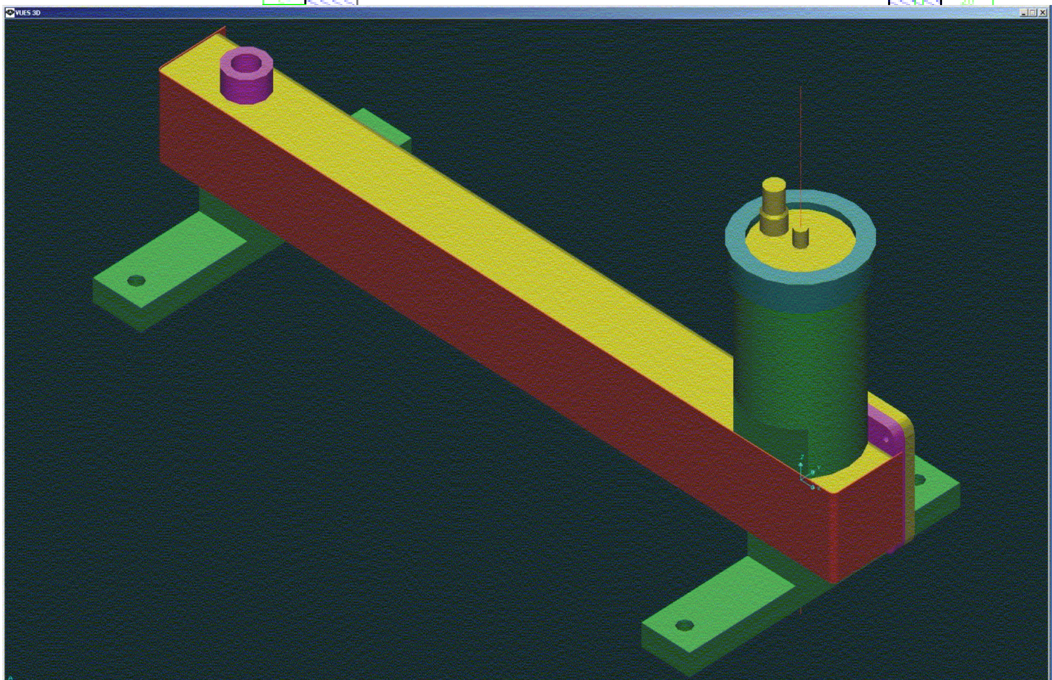
GasToF: Concept, design and prototypes

Laser & beam tests studies

Outlook

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





Workshop on Fast Cherenkov Detectors
Giessen (Germany)

New forward detectors:

Brief history:

May'05: R&D proposal acknowledged by LHCC

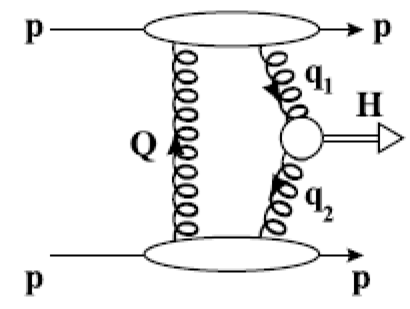
June'08: FP420 Report

Fall'08: Letters of Intend to CMS/ATLAS

In 2009: Adding detectors @220/240 m

HPS project in CMS

FP420



FP420

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

0302v2 [hep-ex] 2 Jan 2009

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

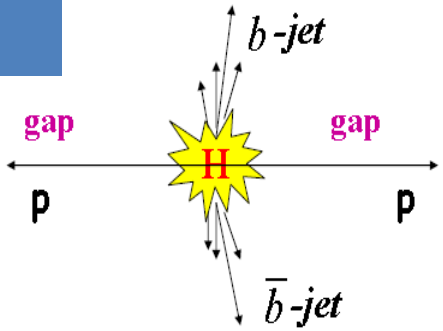
M. G. Albrow[1], R. B. Appleby[2], M. Arneodo[3], G. Atoian[4], I.L. Azhgirey[5], R. Barlow[2], I.S. Bayshev[5], W. Beaumont[6], L. Bonnet[7], A. Brandt[8], P. Bussey[9], C. Buttar[9], J. M. Butterworth[10], M. Carter[11], B.E. Cox[2,], D. Dattola[12], C. Da Via[13], J. de Favereau[7], D. d'Enterria[14], P. De Remigis[12], A. De Roeck[14,6,*], E.A. De Wolf[6], P. Duarte[8,†], J. R. Ellis[14], B. Florins[7], J. R. Forshaw[13], J. Freestone[13], K. Goulianos[15], J. Gronberg[16], M. Grothe[17], J. F. Gunion[18], J. Hasi[13], S. Heinemeyer[19], J. J. Hollar[16], S. Houston[9], V. Issakov[4], R. M. Jones[2], M. Kelly[13], C. Kenney[20], V.A. Khoze[21], S. Kolya[13], N. Konstantinidis[10], H. Kowalski[22], H.E. Larsen[23], V. Lemaitre[7], S.-L. Liu[24], A. Lyapine[10], F.K. Loebinger[13], R. Marshall[13], A. D. Martin[21], J. Monk[10], I. Nasteva[13], P. Nemegeer[7], M. M. Obertino[3], R. Orava[25], V. O'Shea[9], S. Ovyn[7], A. Pal[8], S. Parker[20], J. Pater[13], A.-L. Perrot[26], T. Pierzchala[7], A. D. Pilkington[13], J. Pinfold[24], K. Piotrzkowski[7], W. Plano[13], A. Poblaguev[4], V. Popov[27], K. M. Potter[2], S. Rescia[28], F. Roncarolo[2], A. Rostovtsev[27], X. Rouby[7], M. Ruspa[3], M.G. Ryskin[21], A. Santoro[29], N. Schul[7], G. Sellers[2], A. Solano[23], S. Spivey[8], W.J. Stirling[21], D. Swoboda[26], M. Tasevsky[30], R. Thompson[13], T. Tsang[28], P. Van Mechelen[6], A. Vilela Pereira[23], S.J. Watts[13], M. R. M. Warren[10], G. Weiglein[21], T. Wengler[13], S.N. White[28], B. Winter[11], Y. Yao[24], D. Zaborov[27], A. Zampieri[12], M. Zeller[4], A. Zhokin[6,27]*

FP420 R&D Collaboration

JINST **4** (2009) T10001

High **P**recision **S**pectrometers: Motivation

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



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 ≈ 2 GeV → direct limits on Higgs width
- Possibility of detecting H → $b\bar{b}$ mode

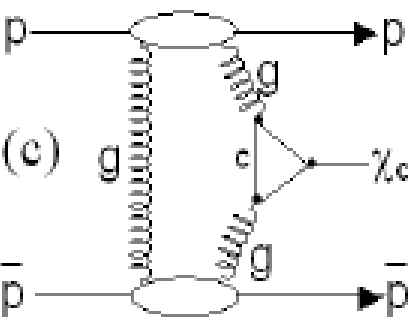
Detection of SM Higgs boson requires (very) large luminosity ($\sigma_{obs} \approx 0.1–0.2$ fb) and challenging timing detectors to keep backgrounds low (S/B≈1:2); in case of BSM physics HPS could provide discovery channels for Higgs bosons

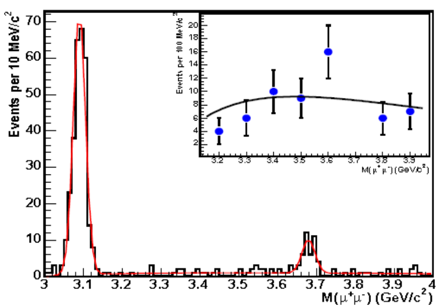
In addition, HPS offers access to 'guaranteed' and unique studies like electroweak physics in two-photon interactions, or new QCD phenomena in exclusive production, for example.

Observation of Exclusive Charmonium Production and $\gamma\gamma \rightarrow \mu+\mu-$ in pp Collisions at √s = 1.96 TeV

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

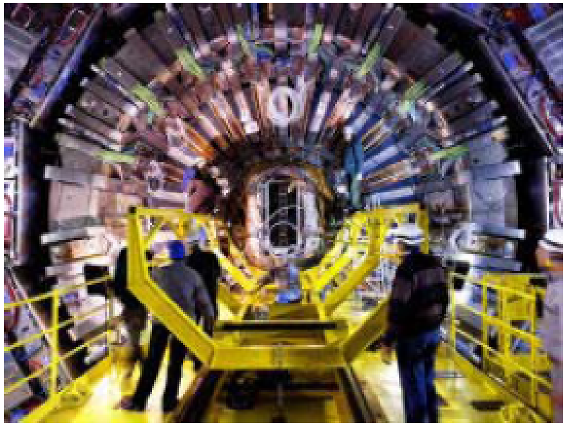
24 June 2009





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.

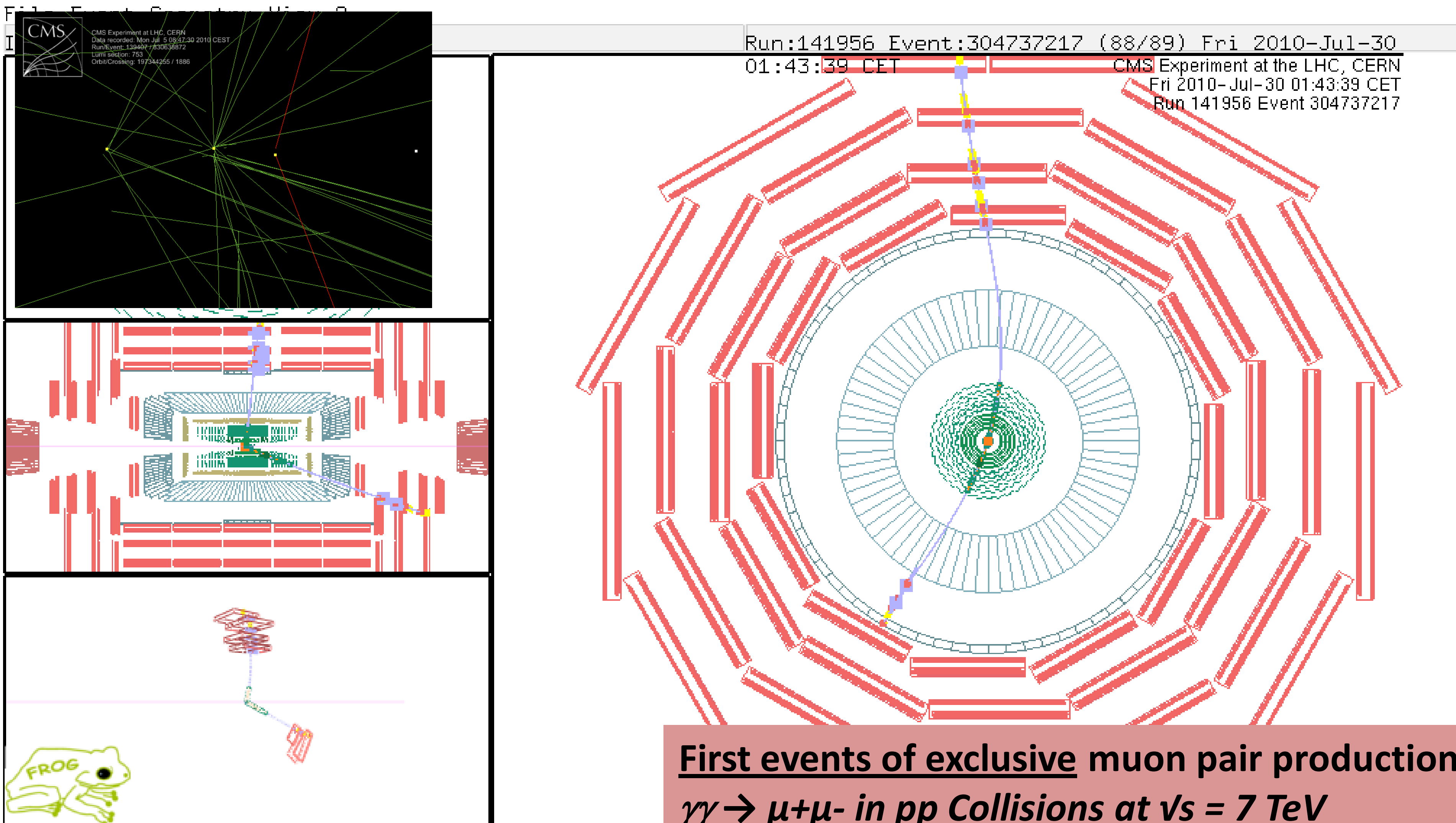


CERN

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).

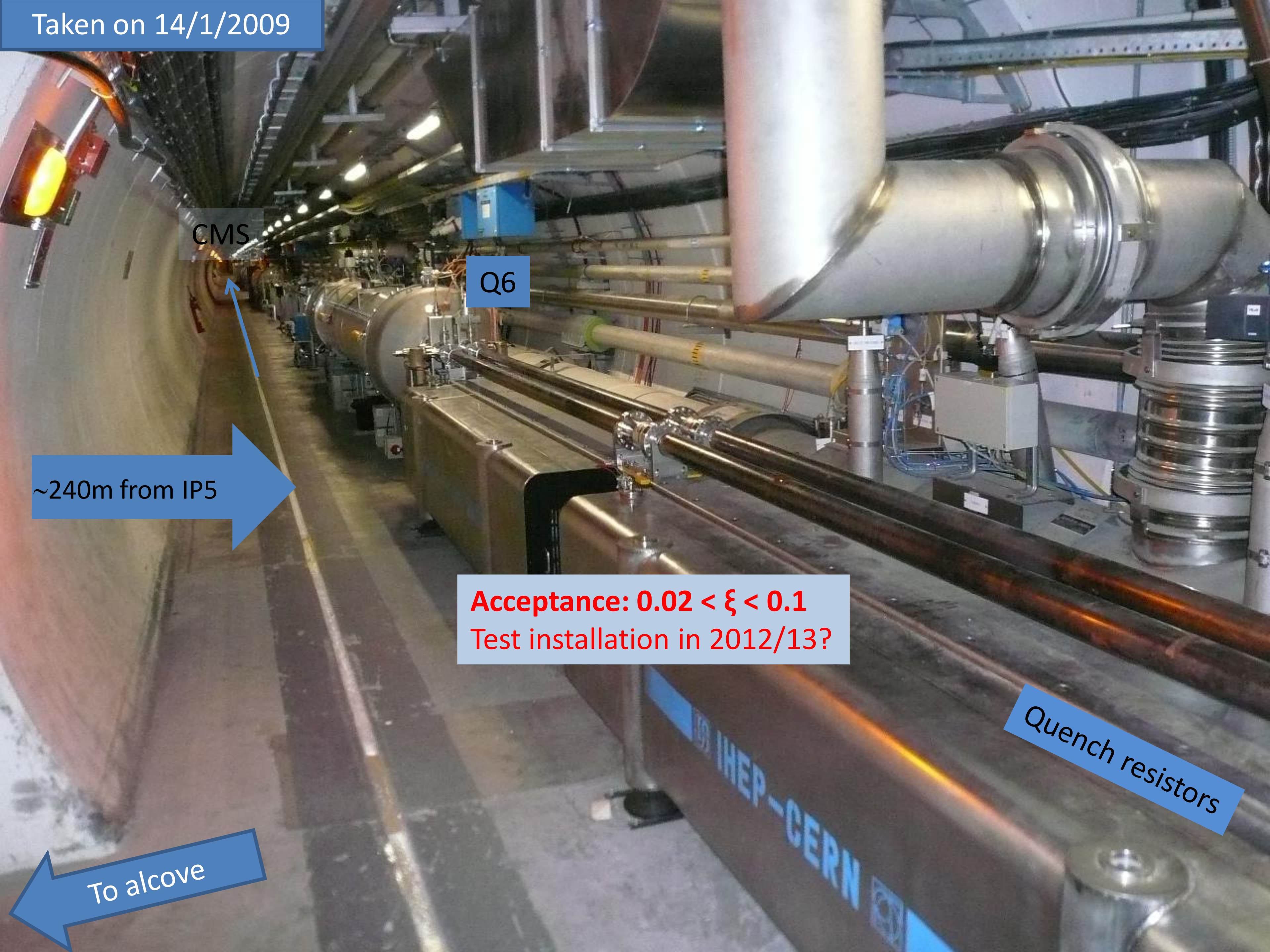
A proton is always surrounded by a swarm of ghostly virtual photons and gluons associated with the fields of the electromagnetic and strong nuclear forces. Researchers have predicted that when two protons (or a proton and an antiproton) fly past one another at close range, within

From CMS and LHC already in 2010…



<u>First events of exclusive</u> muon pair production

γγ→ μ+μ- in pp Collisions at √s = 7 TeV

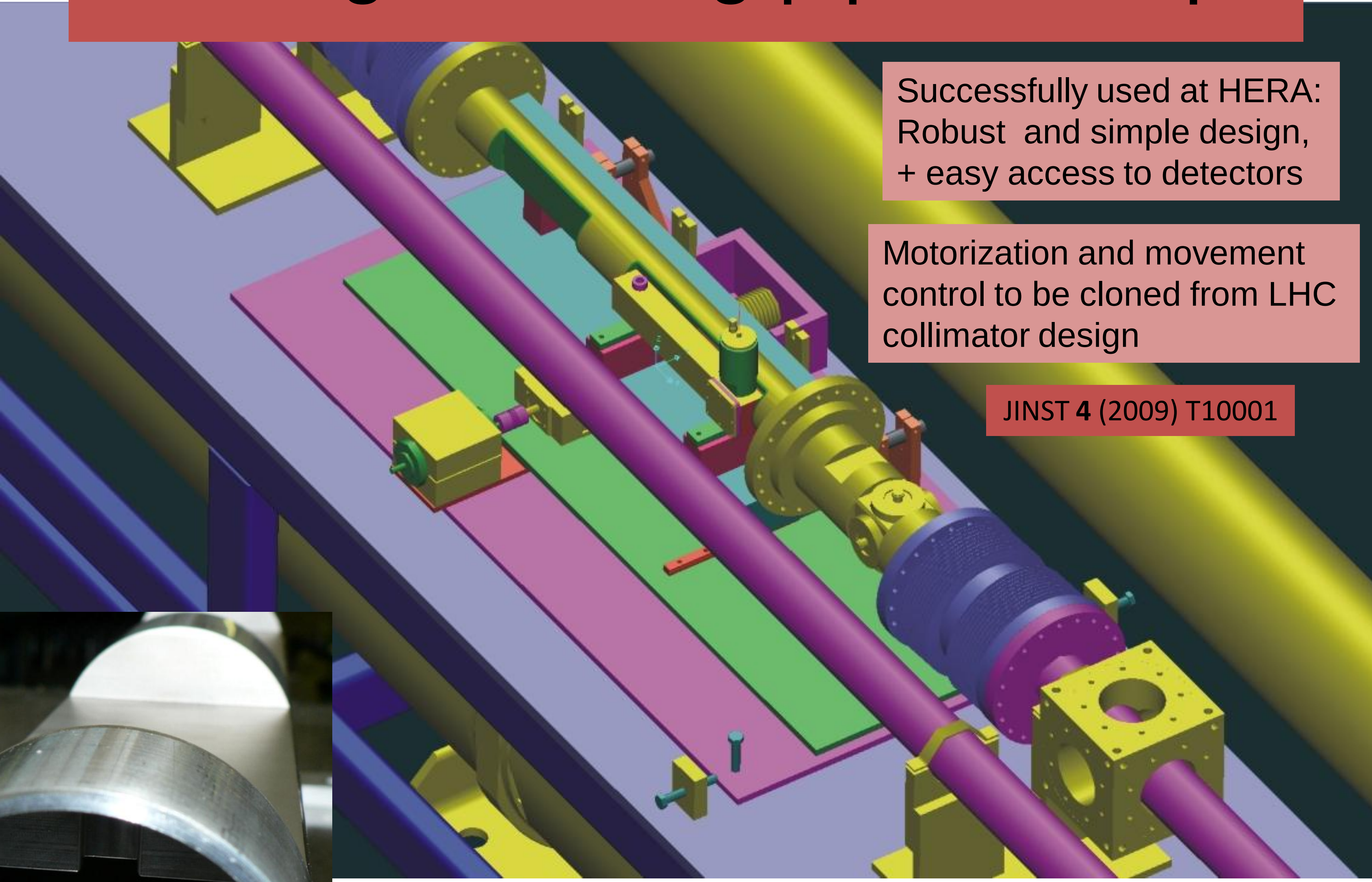

Taken on 14/1/2009
CMS
Q6
~240m from IP5
Acceptance: 0.02 < ξ < 0.1
Test installation in 2012/13?
Quench resistors
To alcove
IHEP-CERN

Moving Hamburg pipe concept

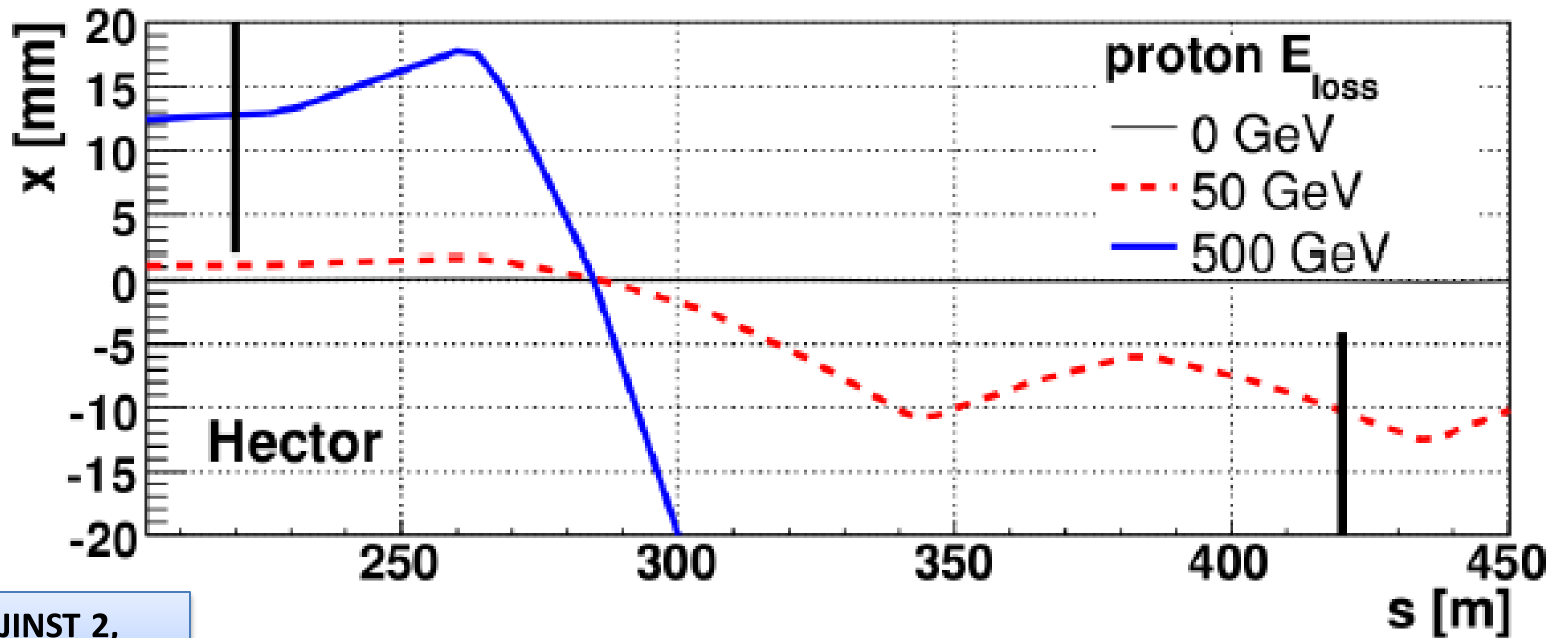
Successfully used at HERA:
Robust and simple design,
+ easy access to detectors

Motorization and movement control to be cloned from LHC collimator design

JINST **4** (2009) T10001



Forward proton trajectories @ LHC



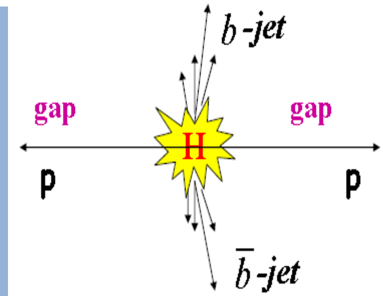
HECTOR: **JINST 2, P09005 (2007)**

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!

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)!



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

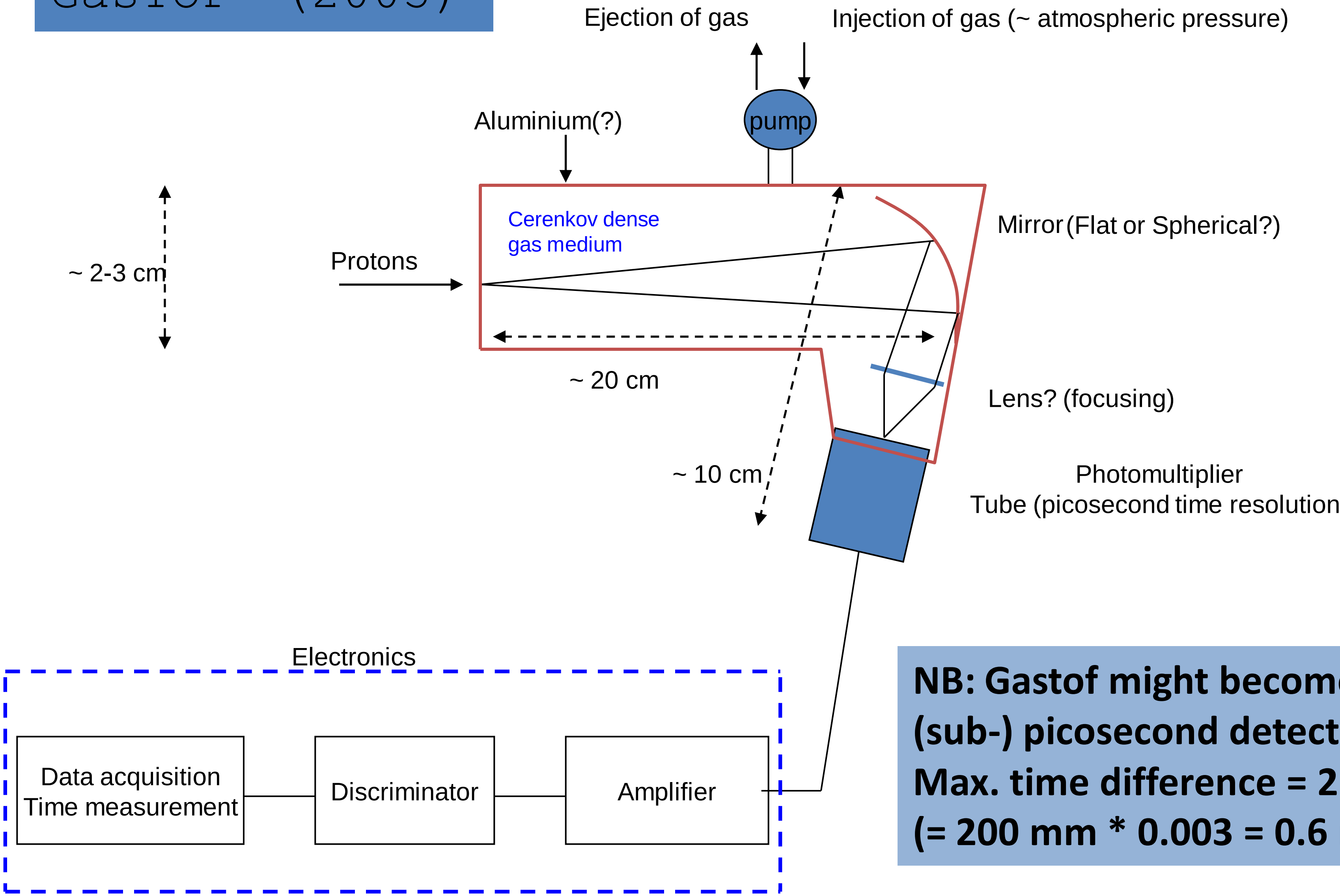
Proposed fast (& small ~10 cm^2) timing detectors: Čerenkov radiators + fastest MCP-PMTs

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

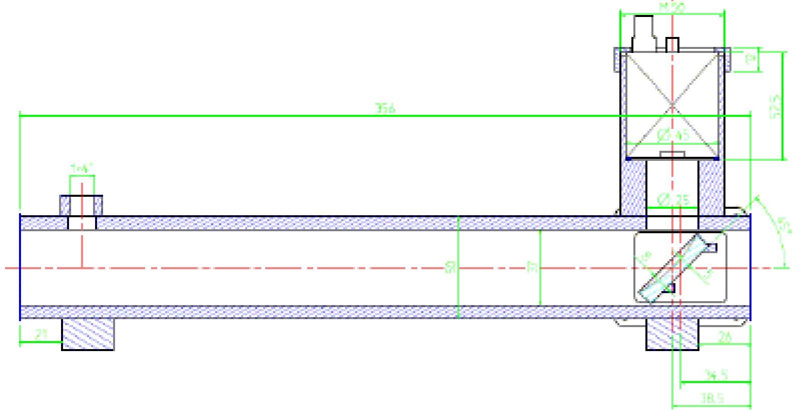
Quartic: Quartz based Čerenkov with fine segmentation – multi-hit capability

GasToF™ (2005)



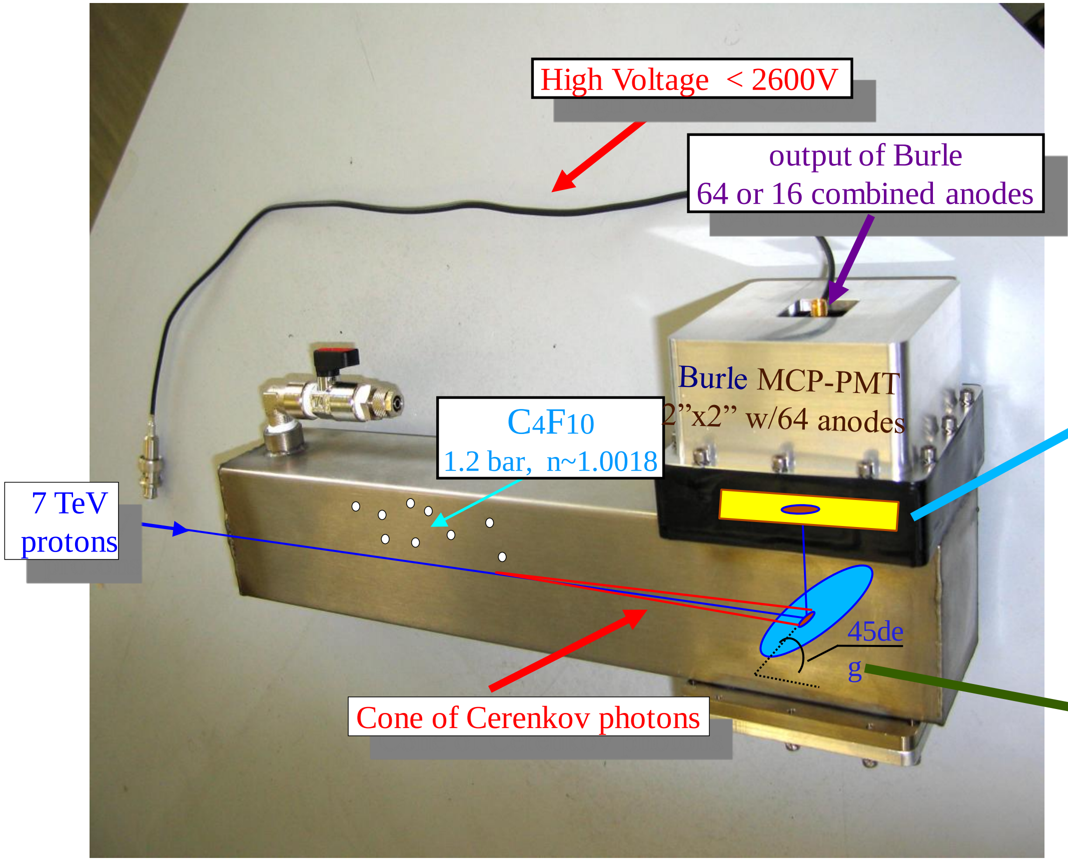
NB: Gastof might become (sub-) picosecond detector!
Max. time difference = 2*L*Δn (= 200 mm * 0.003 = 0.6 mm !)

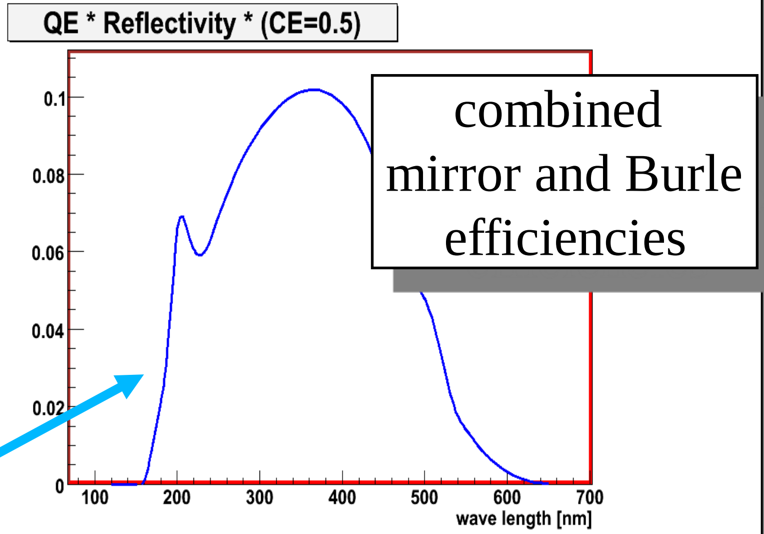
GasToF Concept

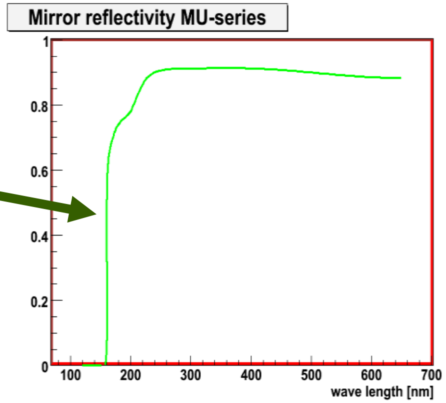


- Intrinsically very fast
- Light detector – can be used with(in) tracking
- Simple (small chromacity) – modeling with ray tracing
- Robust and radiation hard

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

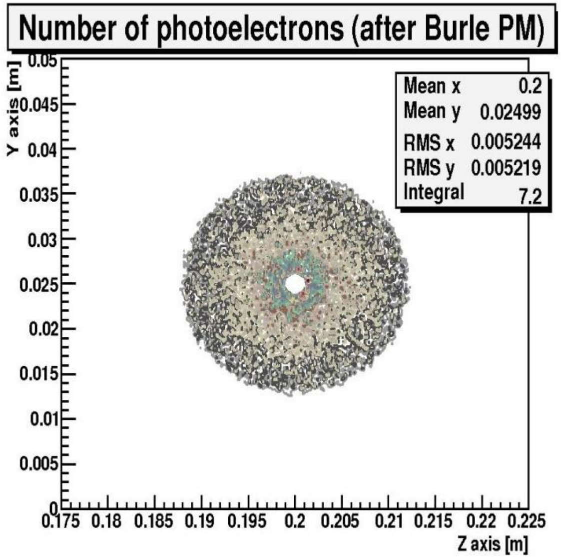


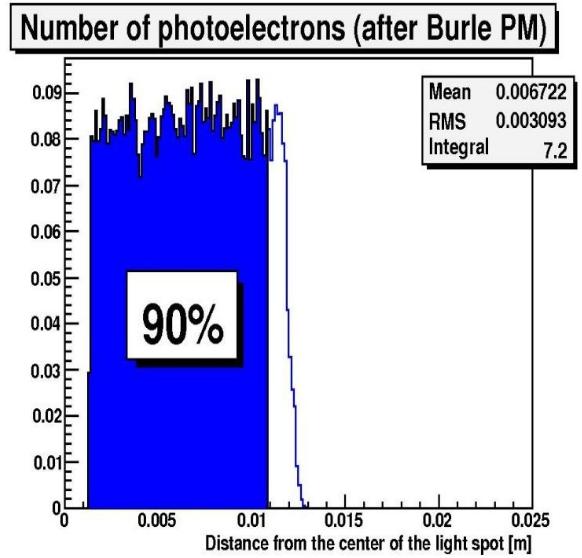


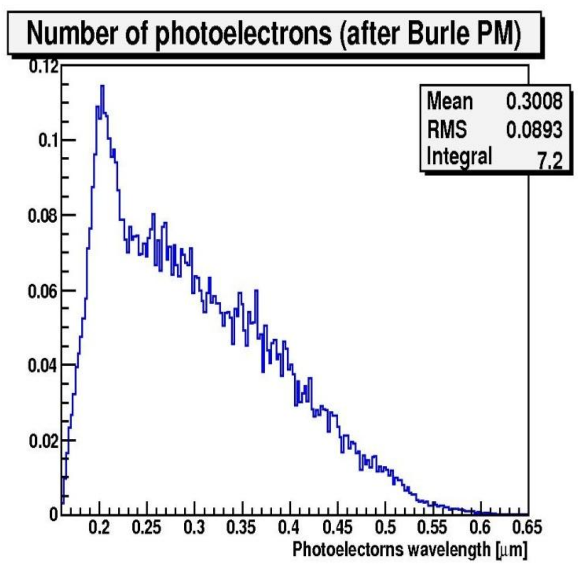


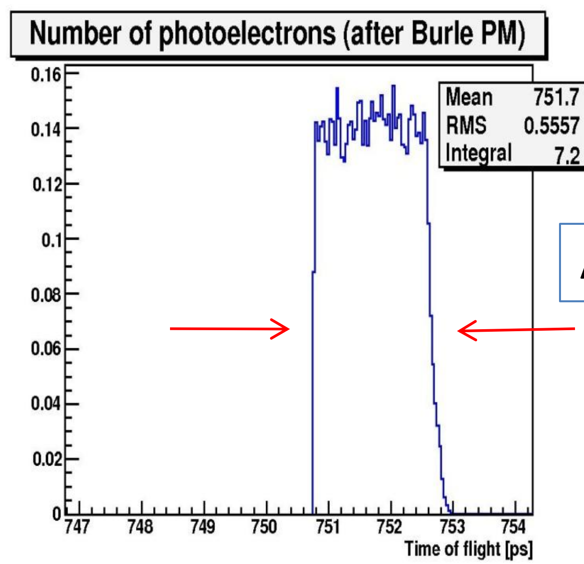
Our 'workhorse': very robust with timing resolution of ~30 ps (due to TTS) → L. Bonnet *et al.* Acta Phys. Pol. B38 (2007) 447; FP420 Collab., JINST 4 (2009) T10001

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









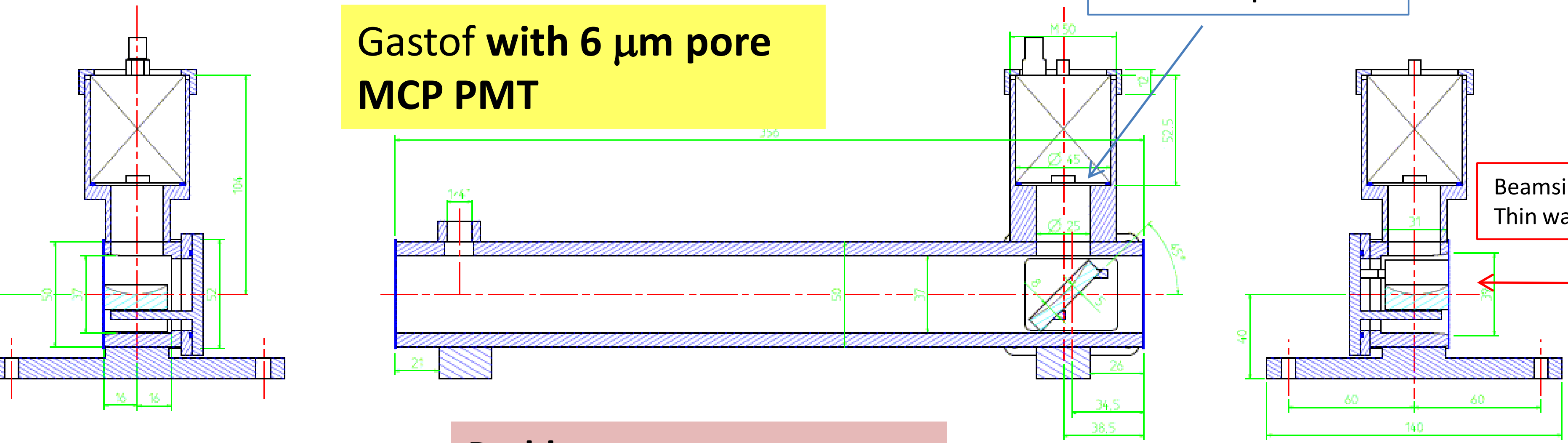
All in 2ps !!

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

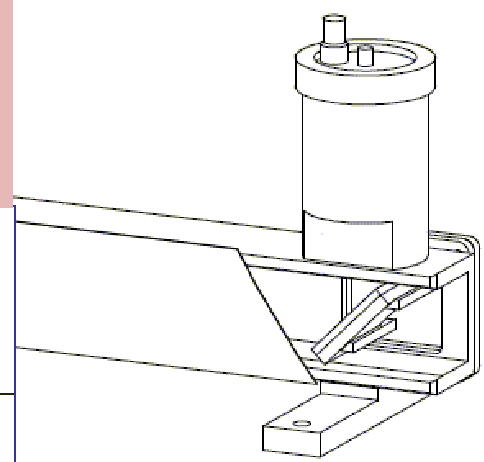
Gastof **with 6 μm pore MCP PMT**

Gas leak problem

Beamside: Thin wall



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

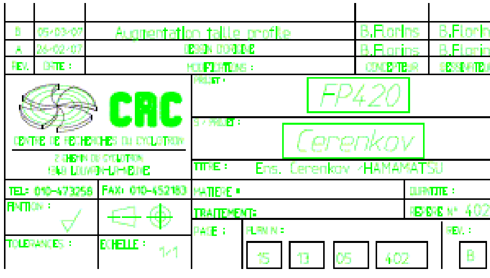


HAMAMATSU

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

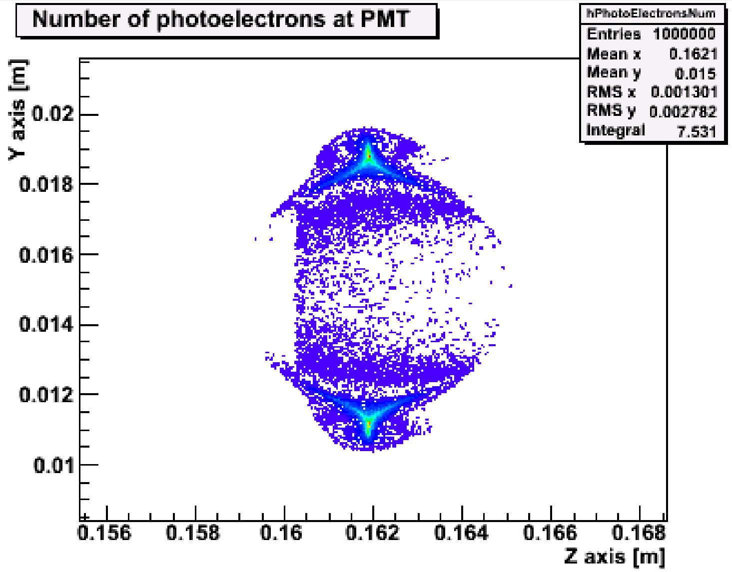
Compact MCP-PMT Series Featuring
Variety of Spectral Response with Fast Time Response

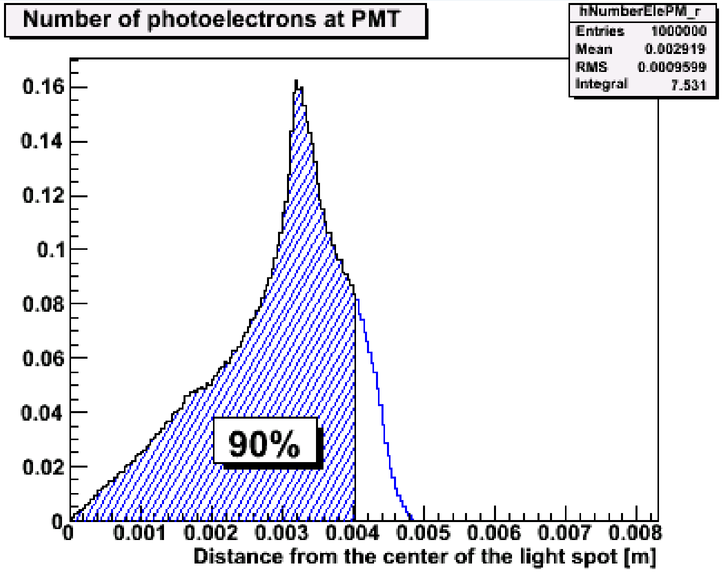
FEATURES
- High Speed
  Rise Time: 150ps
  T.T.S. (Transit Time Spread)[1]: ≦ 25ps(FWHM)
- Low Noise
- Compact Profile
  Useful Photocathode: 11mm diameter
  (Overall length: 70.2mm Outer diameter: 45.0mm)

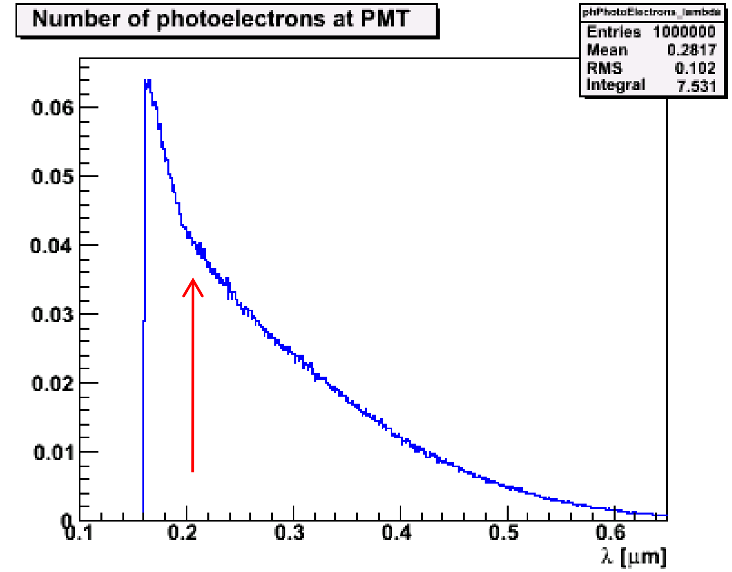


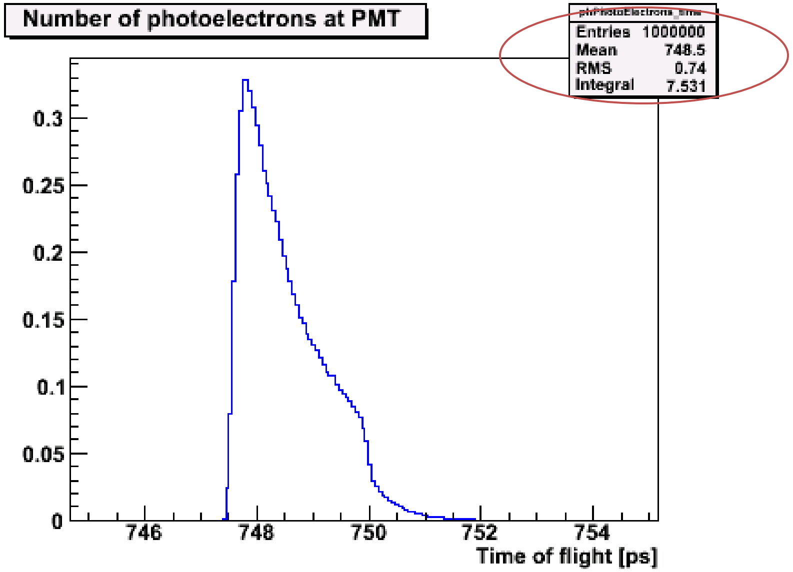
Short GasToF (20cm), reflective beam-wall, R3809U-58 PMT, protons on axis:

Nicolas Schul



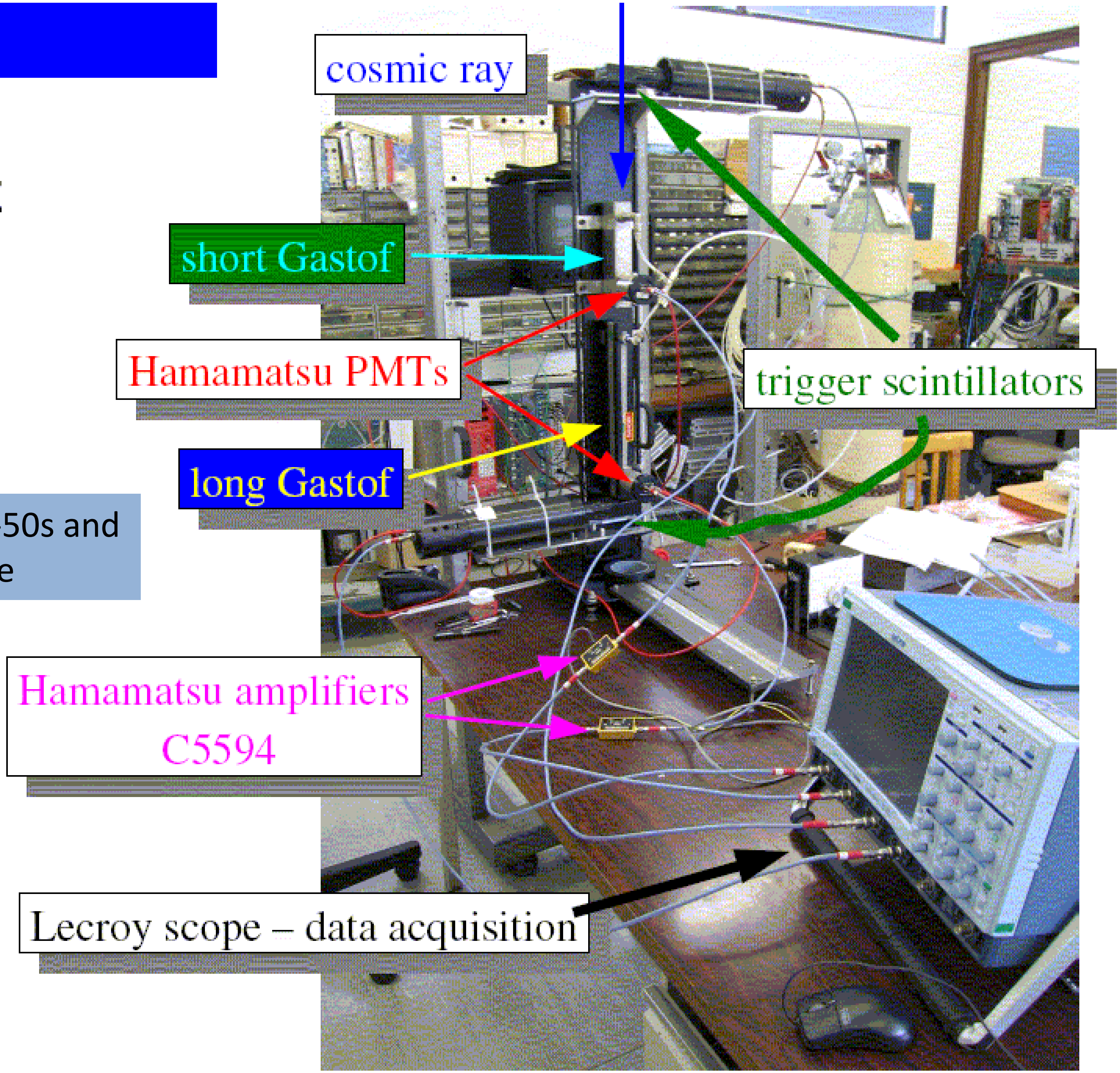






Tomek Pierzchala

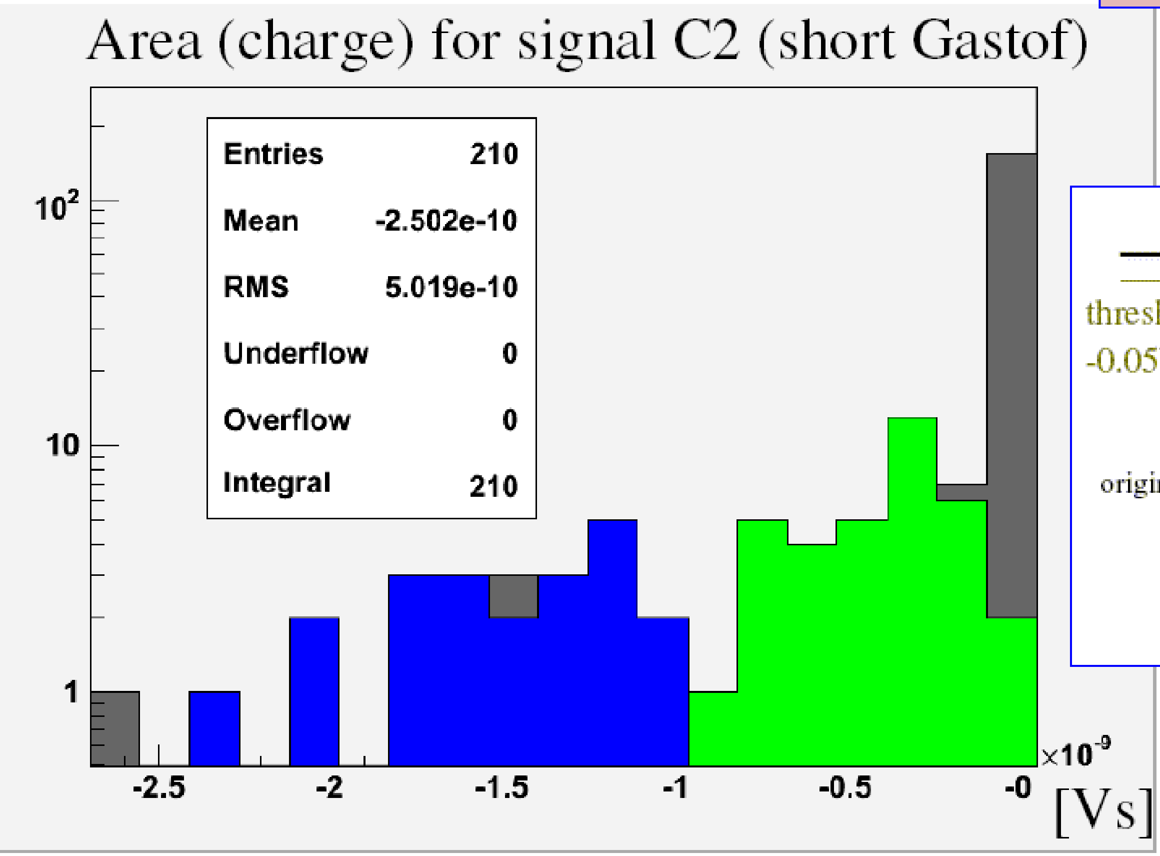
Cosmic rays test stand

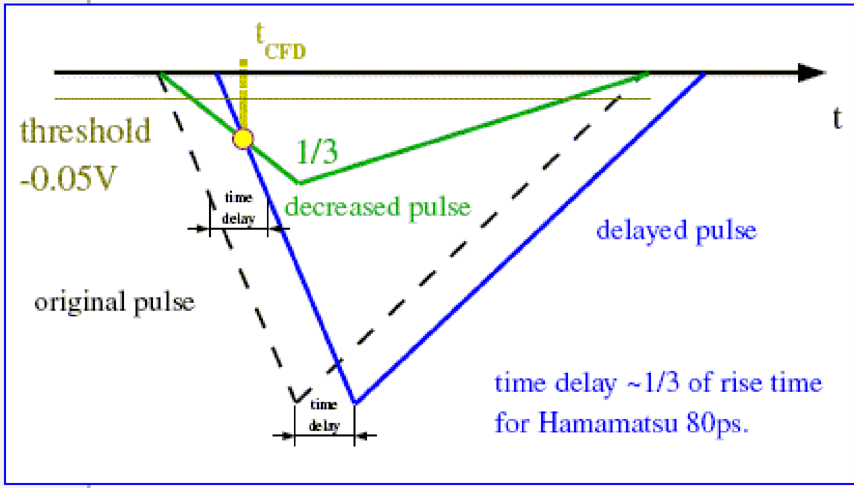


Tests using R3809U-50s and 3 GHz, 20 Gs/s scope

Charge distributions for the cosmic ray events

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



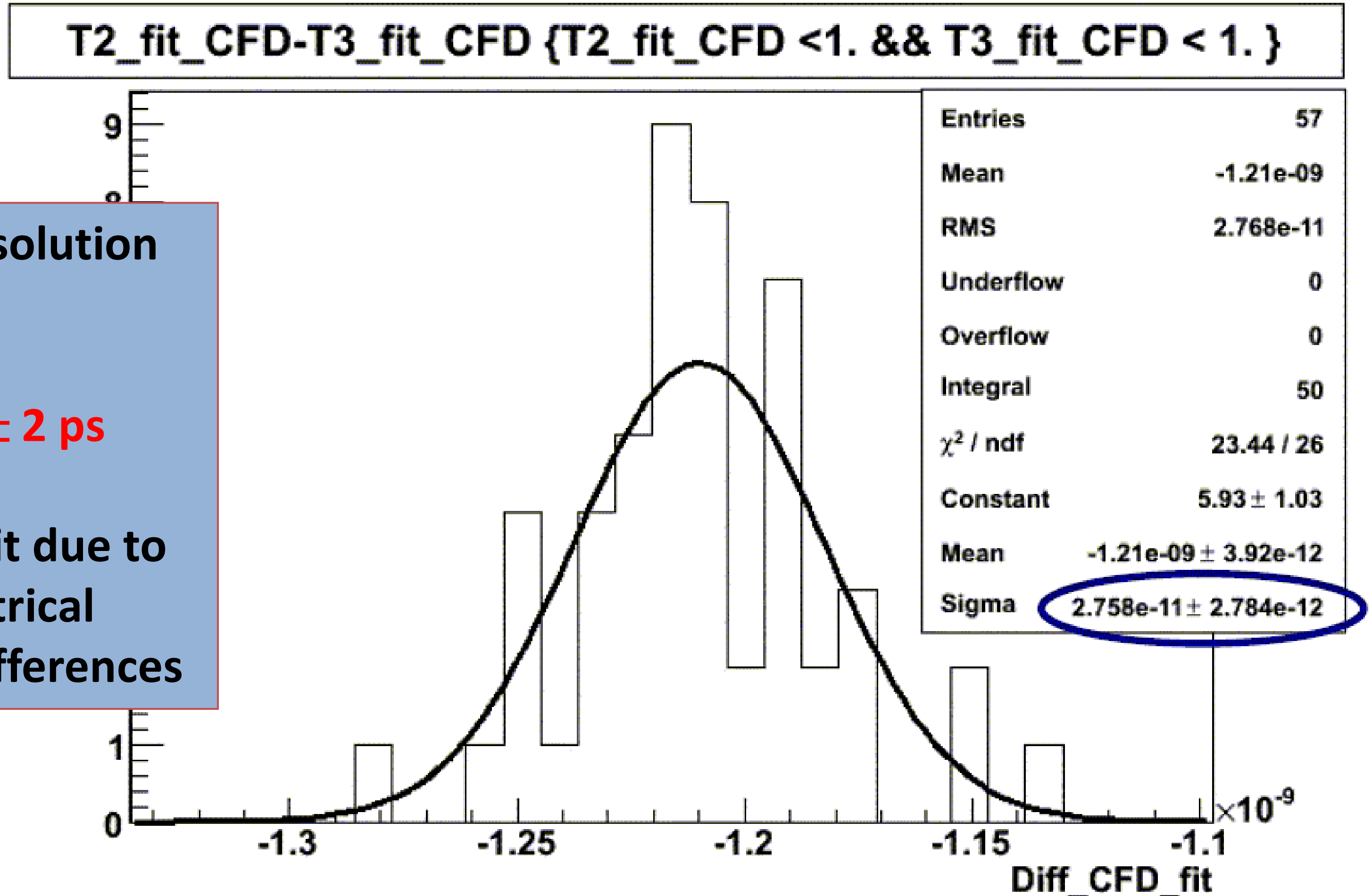


Run offline CFD algorithms (Tomek Pierzchala)

1 pe, 2 pe, …

Tomek Pierzchala

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

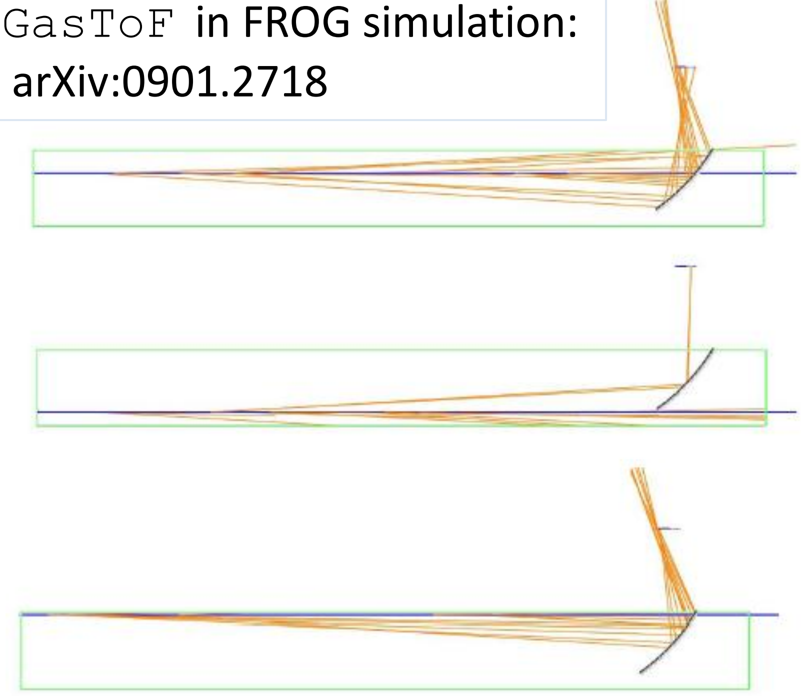


Derived GasToF resolution (for ~1 pe):

< 28 ps/$\sqrt{2}$ = 19.5 ± 2 ps

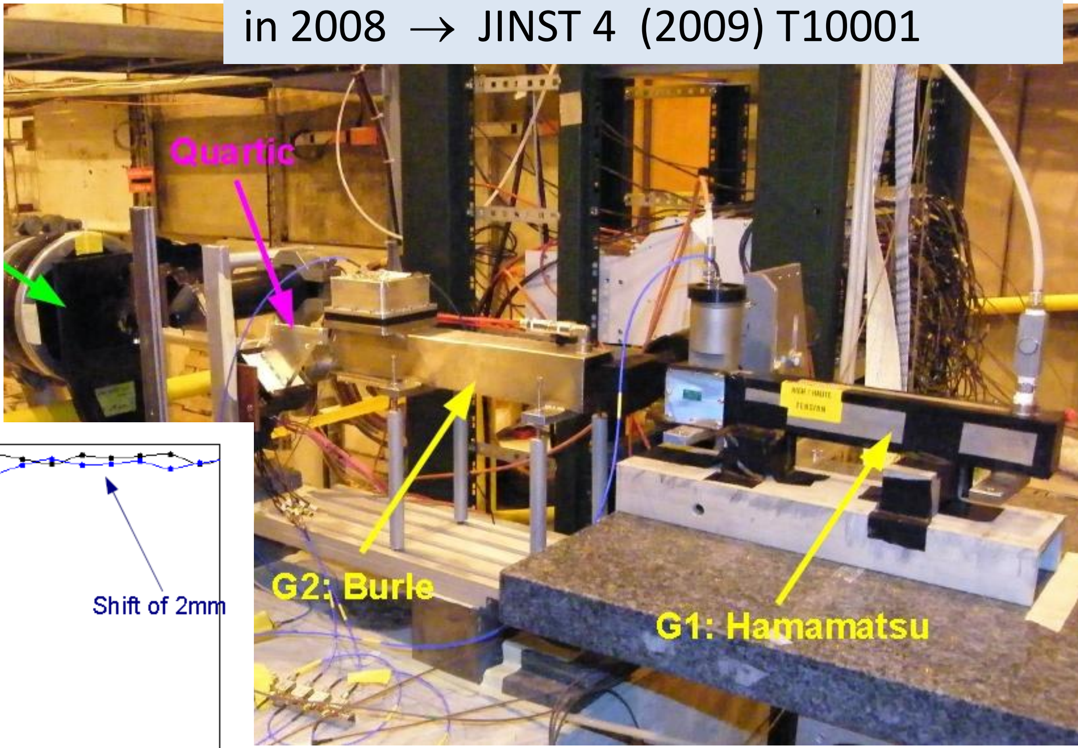
NB: Just upper limit due to significant 'geometrical spread' of time differences

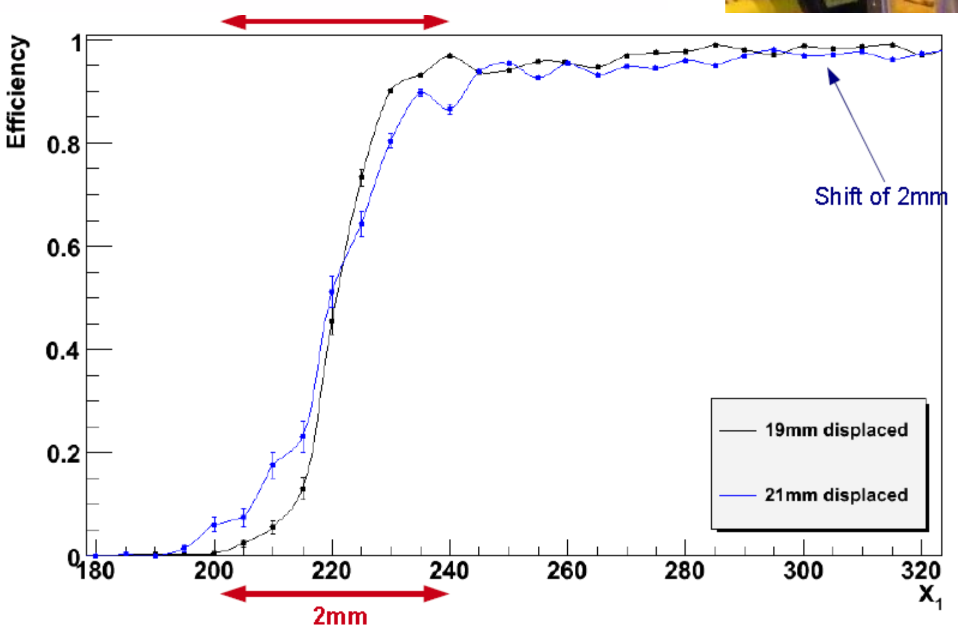
GasToF in FROG simulation: arXiv:0901.2718



N. Schul

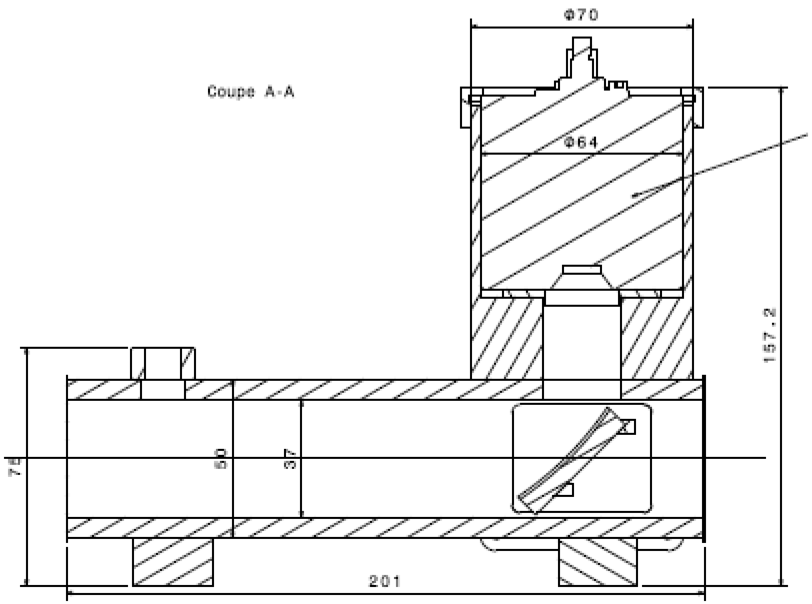
Two GasToF detectors at CERN test beam in 2008 → JINST 4 (2009) T10001





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

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 μm pore MCP-PMTs…

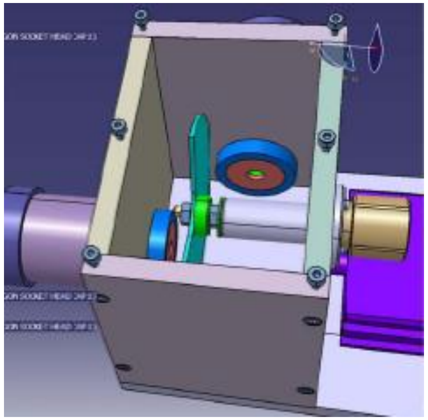
…so fast that had to upgrade to yet faster scope…

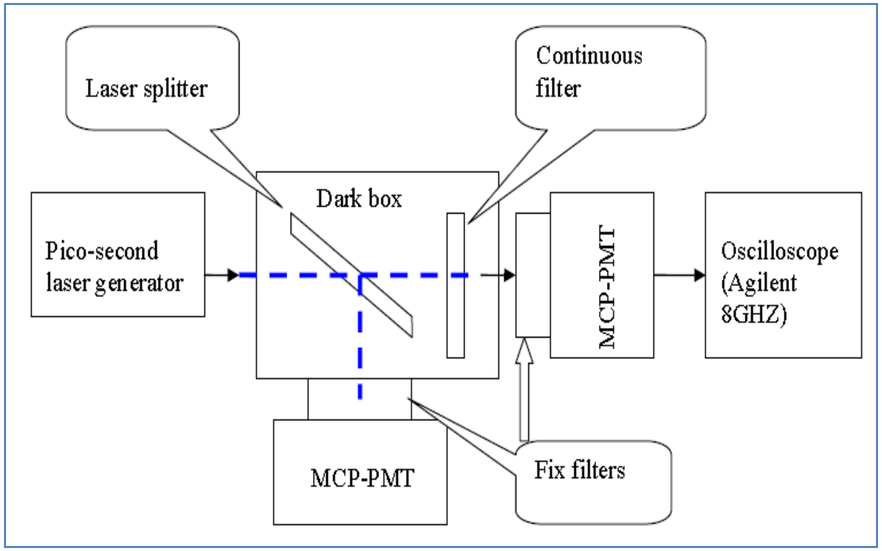
Dedicated picosecond laser test setup was developed to characterize fastest MCP-PMTs from Photek and Hamamatsu – using Agilent scope with 8 GHz BW and 40 GSamples/s

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

FWHM

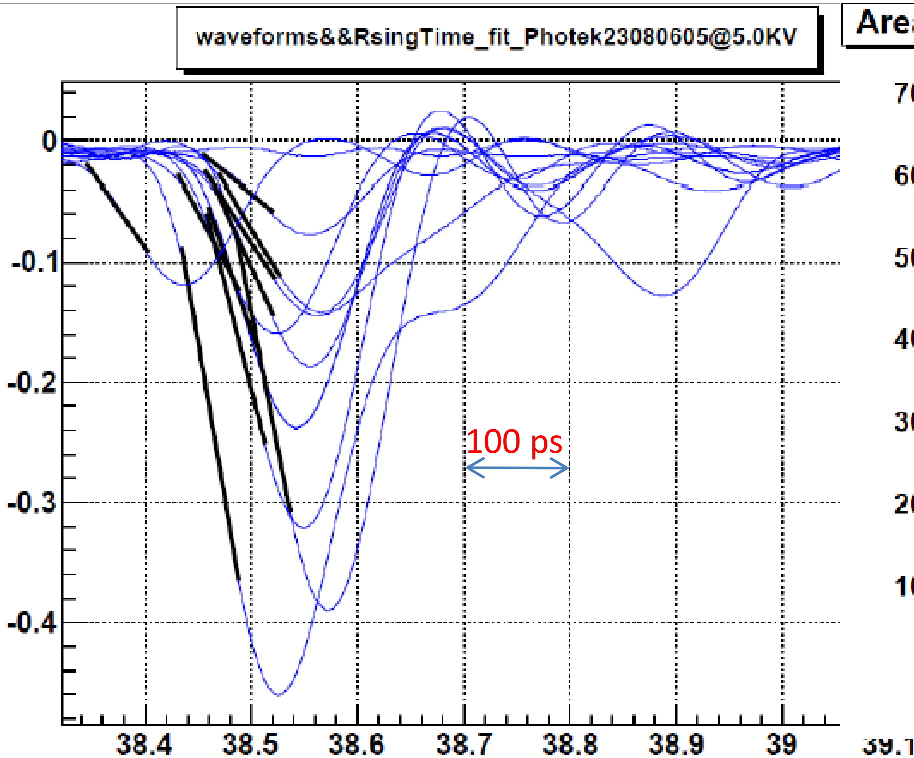
PiLas 408 nm



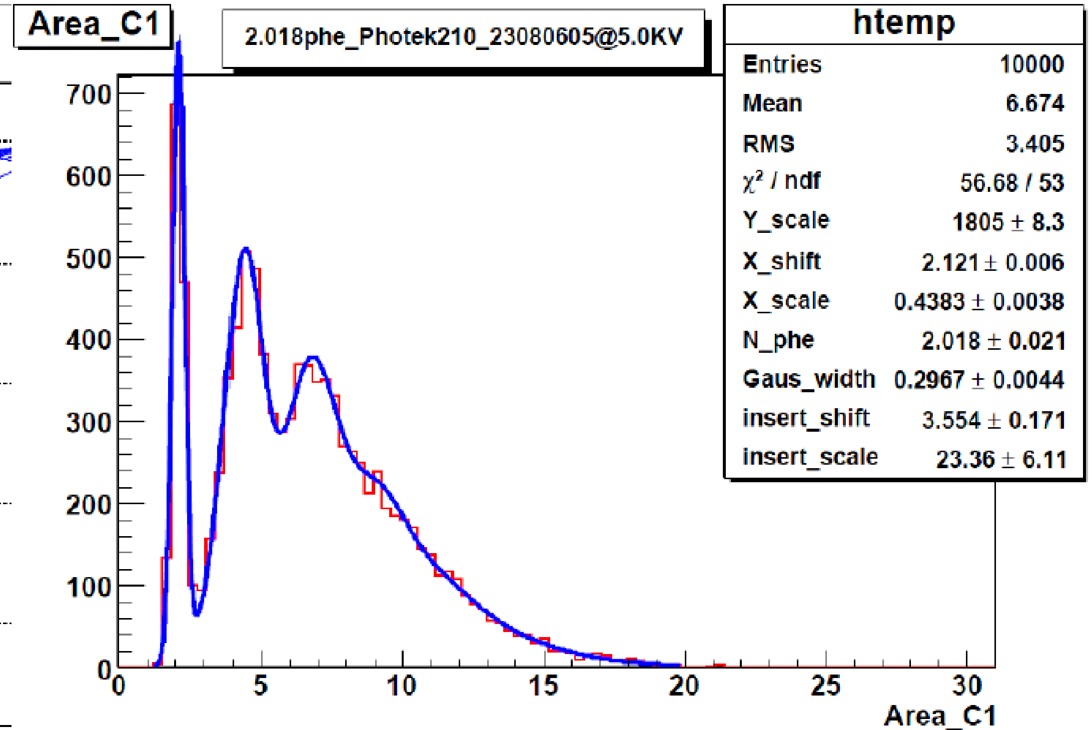


PiLas laser test setup runs up to 1 MHz repetition rate at 408 nm and using 8 GHz Agilent scope with 40 GSa/s

J. Liao



Photek23090605_2.5phe

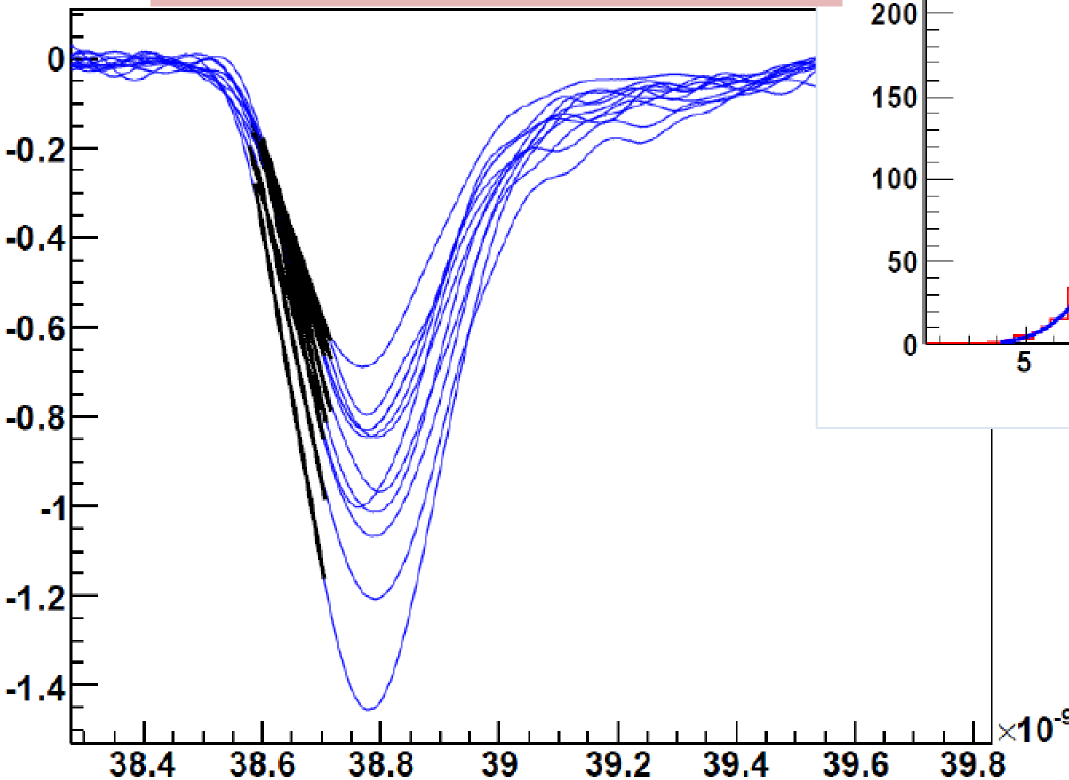


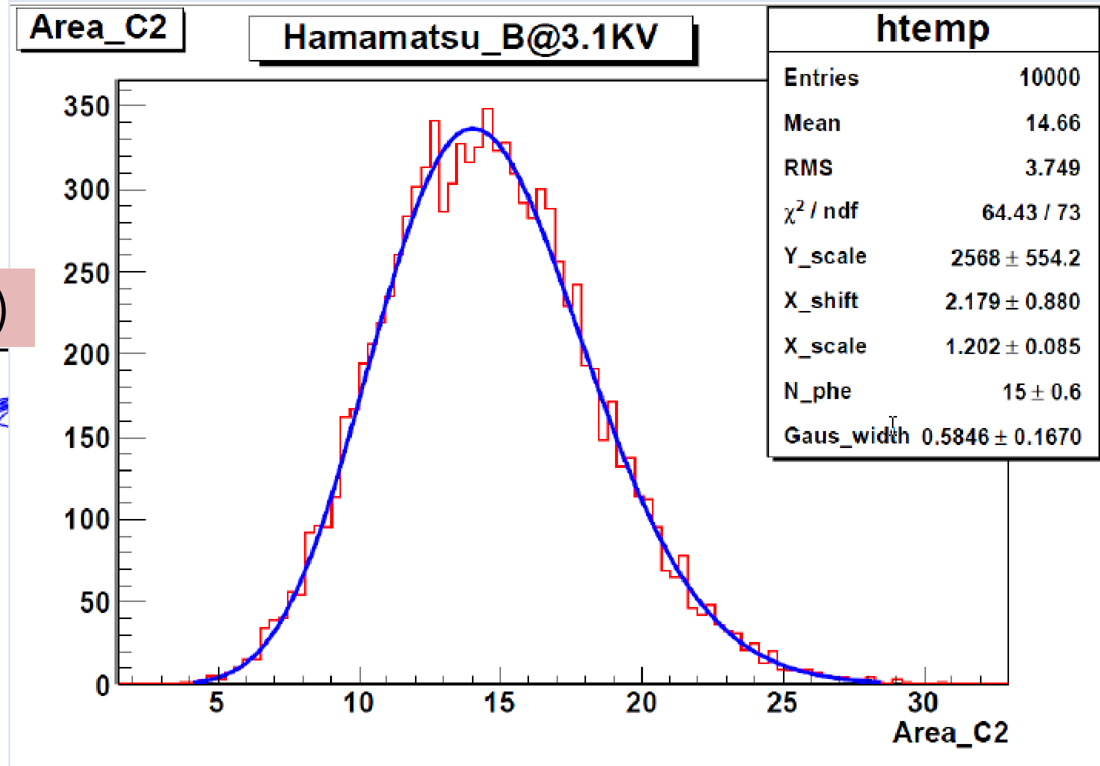
Impressive rise time (10→90%) measured: 80 ps for PHOTEK 3 μm pore **PMT210** (and 150 ps for R 3809U-50)

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 (mostly charge)
→ Input to MC simulations

GasToF Challenge

High rate/lifetime issues – two scenarios/setups:

HPS in 2014 (15?)

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

Use a couple of short GasToFs ?

HPS in > 2016?

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)

GasToF single anode final prototypes

• Make short detectors to keep light signal low, and make several measurements in a row (for example 3 x 10 cm detector)?

• Make final GasToF single anode prototypes for HPK and Photek MCP-PMTs: use MgF_2 windows + side mirrors

• Use photocathodes only sensitive in deep UV ('solar blind') – will test soon Photek PMT210 with new telluride PCs

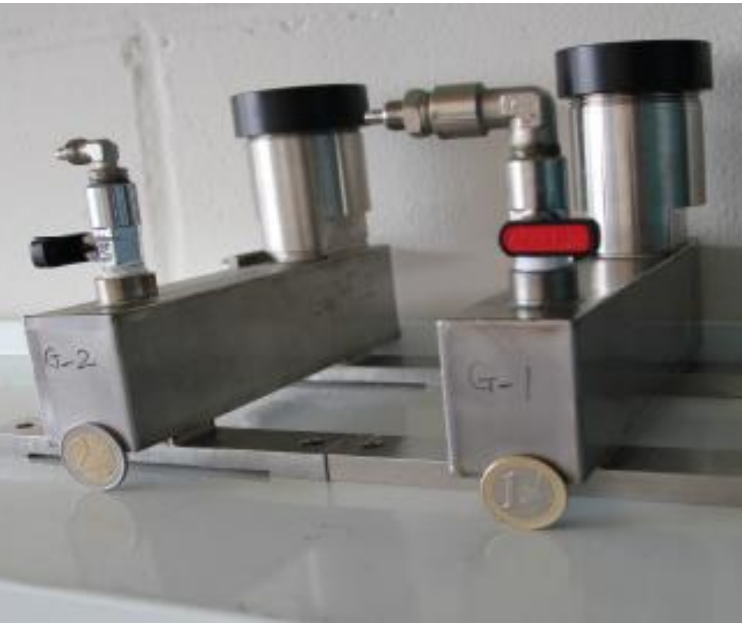
• (If possible use MCP-PMTs with thin foil as ion barrier to increase their lifetime – NB: QE loss is not an issue…)

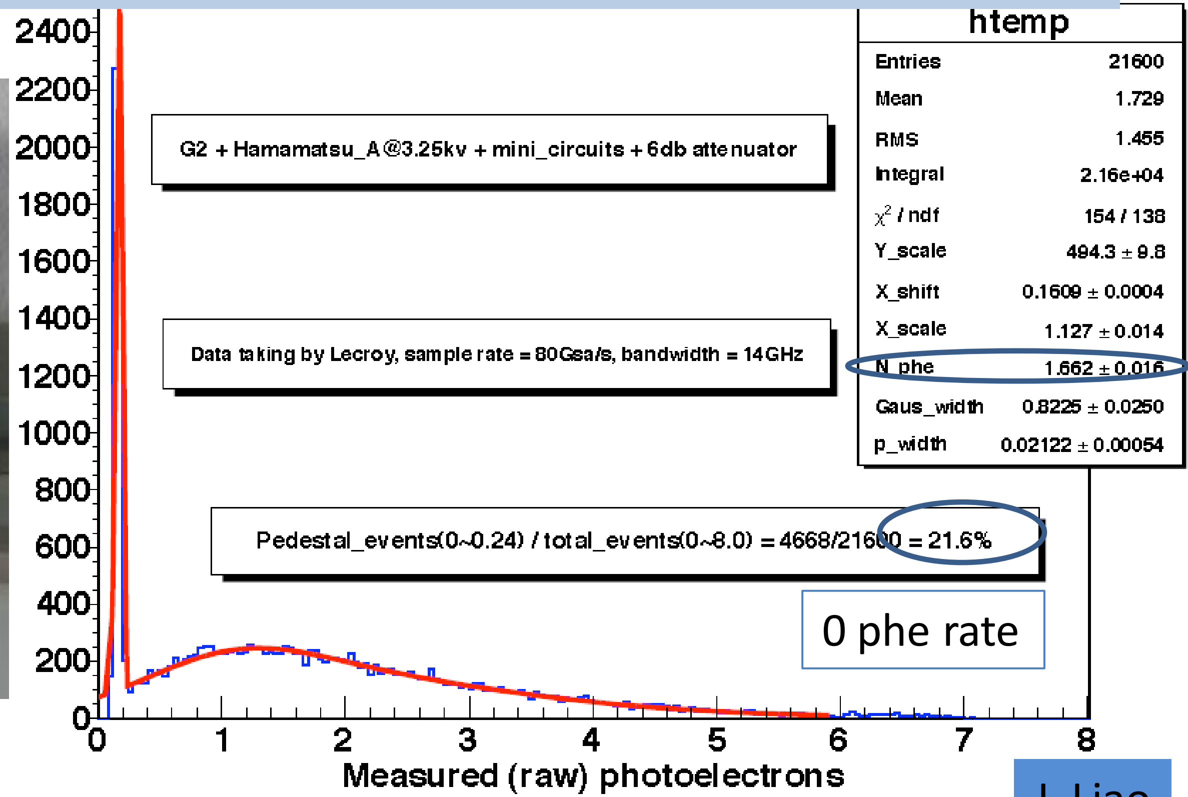
• Go to test beams to verify performance

… at the moment only with present prototypes:

GasToF at CERN test beam

- Two short GasToF prototypes with HPK tubes and readout with 40 (80) GSa/s scope (thanks to UTA and AFP!) at CERN test beam in Aug'10
- (Quartz windows were added to seal gas volume)
- Expected (low) signals are observed (would increase by ~2 for final design)

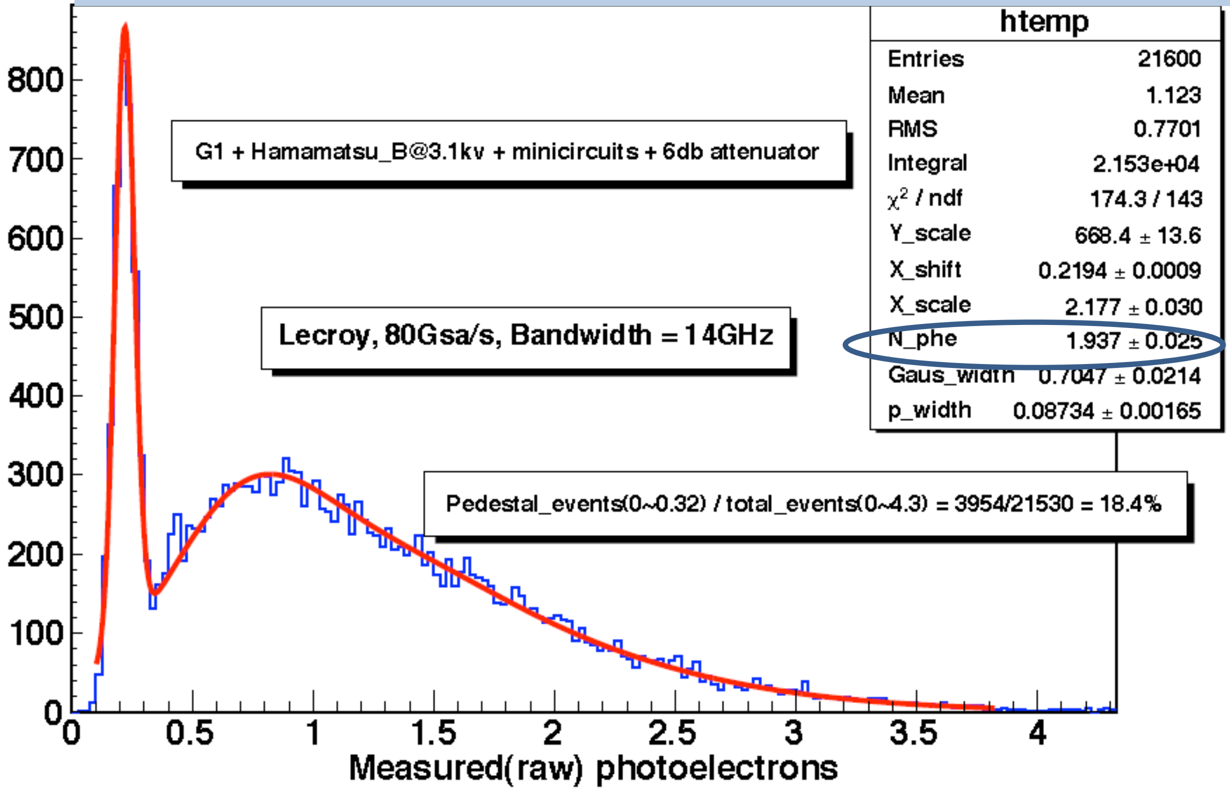




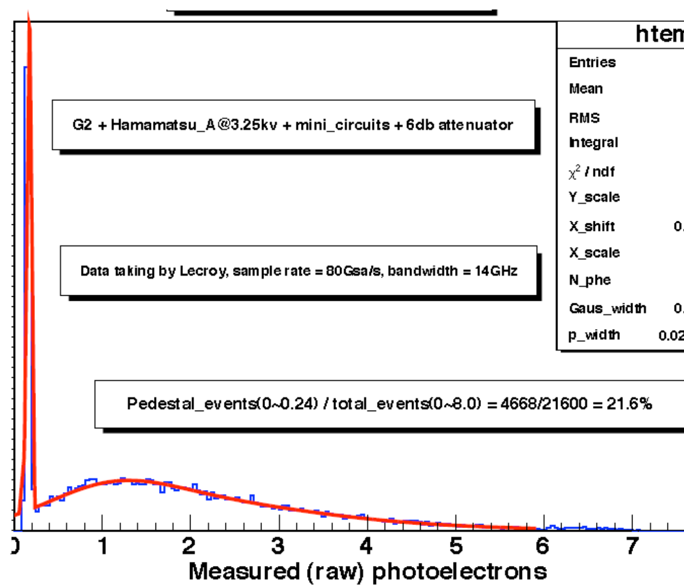
J. Liao

GasToF at CERN test beam

- Two short GasToF prototypes with HPK tubes at 3.1 and 3.25 kV, this corresponds to gains of about 4.10^5
- Use fast amplifiers and 6 dB attenuators (should simulate well long cables)
- Expected (low) signals are observed (would increase by ~2 for final design)

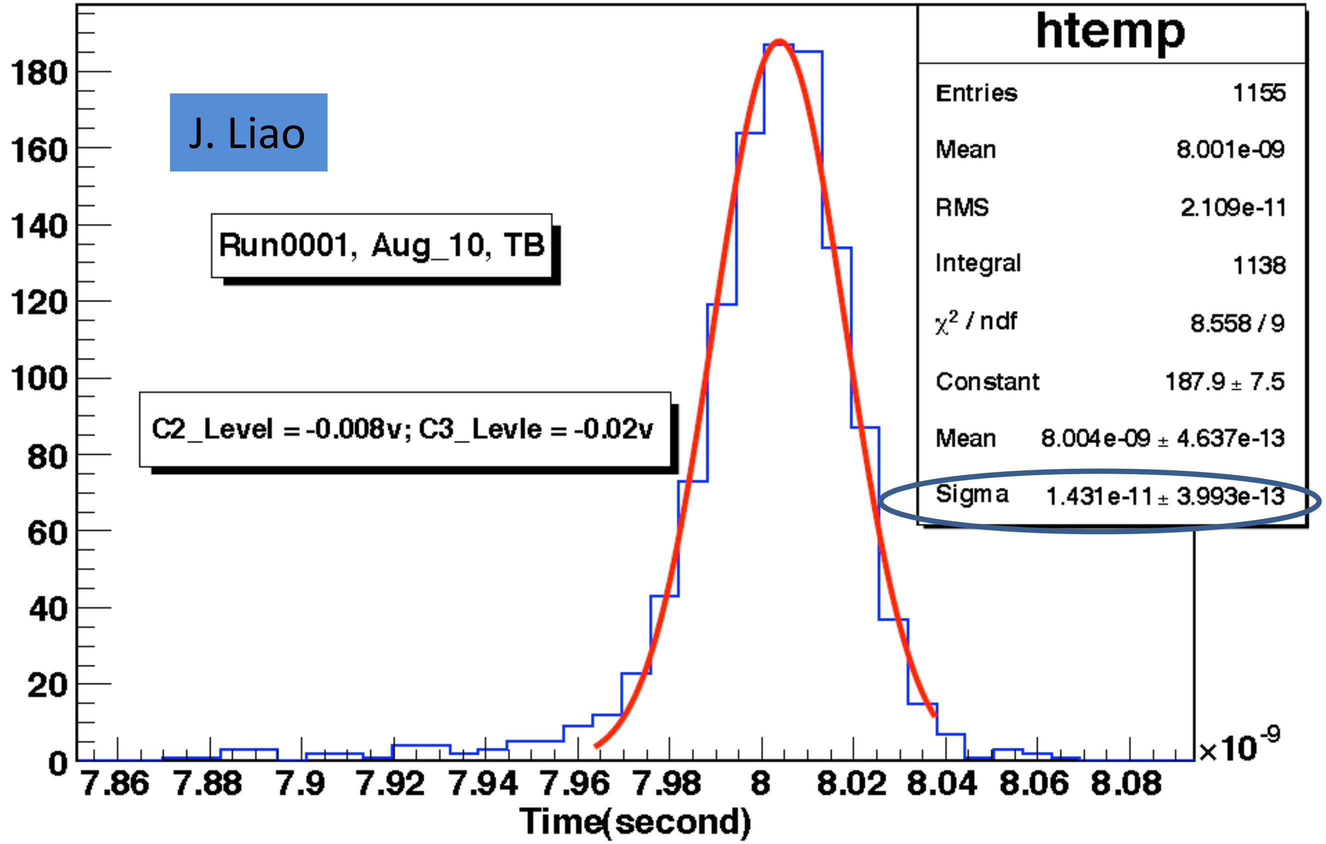


J. Liao



GasToF at CERN test beam

- preliminary results on time difference between two GasToF detectors:



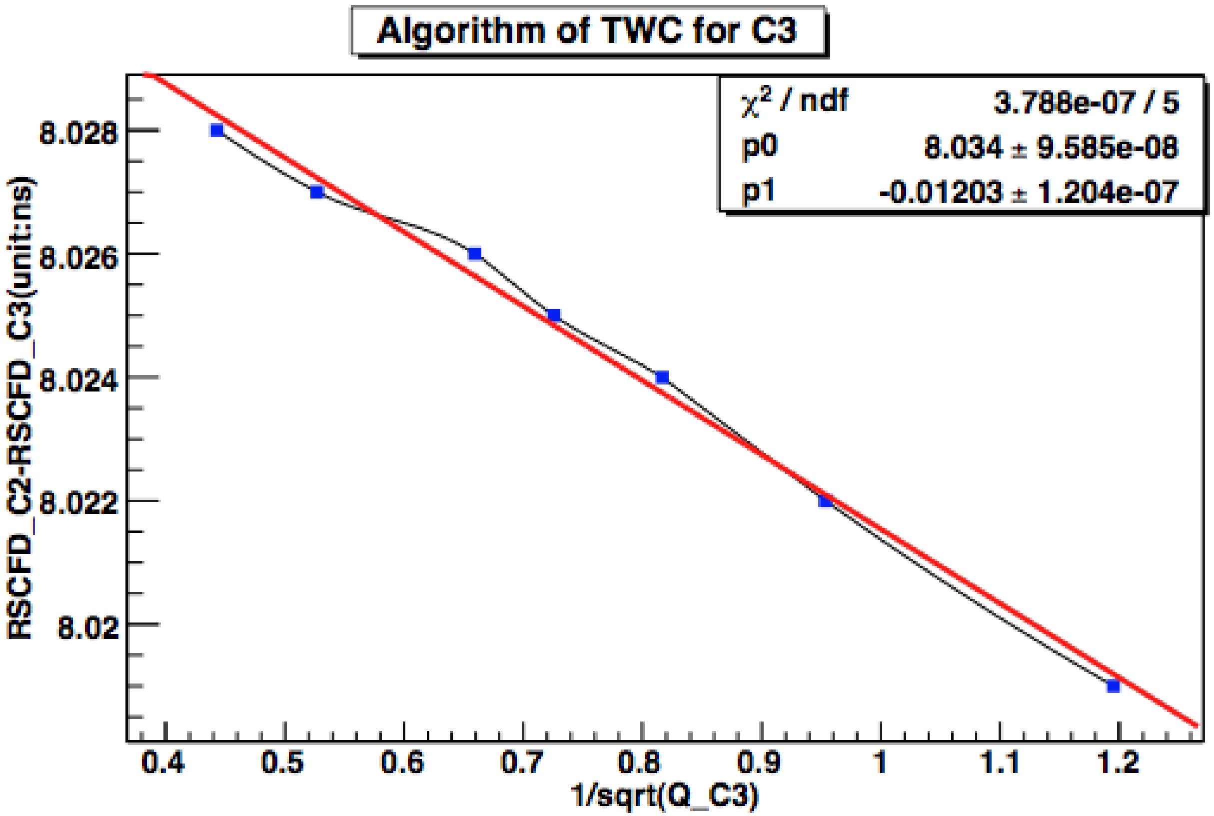
10 ps detector resolution measured for signals > 3 phe
Should still improve for better signal discrimination
(need to watch tails too)

… and more results in preparation, including GasToF with Photek data from CERN test beam in September'10…

GasToF at CERN test beam

- To get ultimate timing results Time-Walk-Corrections were applied offline (on top of CFD, or fixed threshold, algorithms) – measure GasToF 1 vs 2 time difference as a function of the one or the other signal size:

J. Liao



Obtained ~ 5 ps corrections to CFD scaling like $1/\sqrt{N_{phe}}$

Final results in preparation

GasToF: Outlook

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

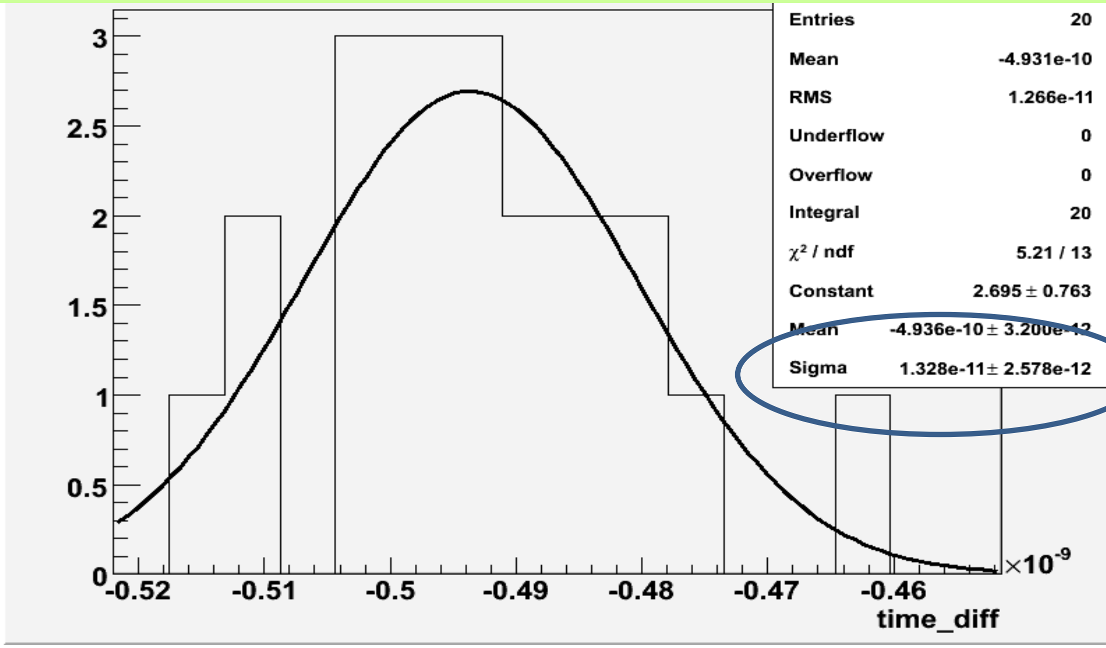
• Addressing in detail high rate/lifetime issues
(NB: MCP-PMT radiation hardness already tested)

• For single anode GasToF a 2ps resolution DAQ system is under study - will use long distance (over ~260 m) analog transmission (Heliax cables with 3.7 dB/100m attenuation at 1 GHz + PCI card from Becker&Hickl: SPC-150, with maximal signal rate of 4 MHz)

• Very exciting, long-term development program is crystallizing: Continue R&D toward 1 ps ToF detectors (streak tubes?)

Extra slides

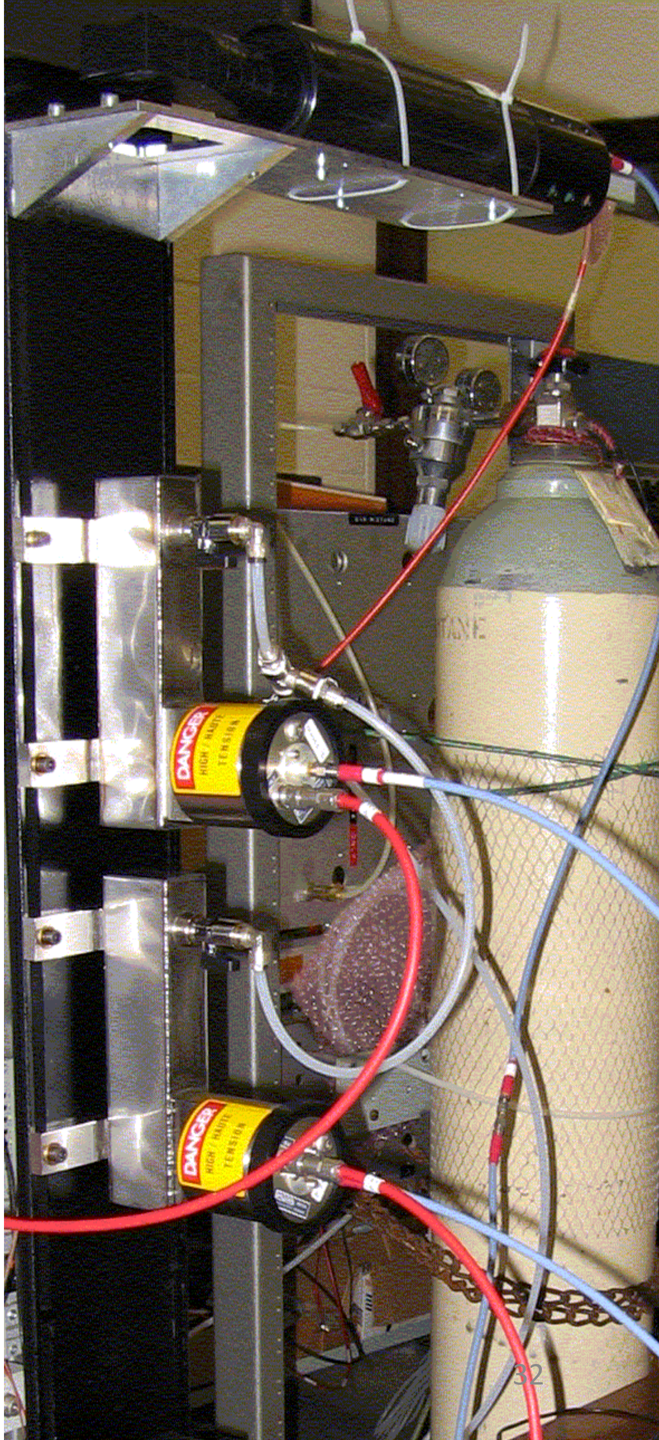
Cosmic rays results for PHOTEK two 3 μm pore MCP PMTS:



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

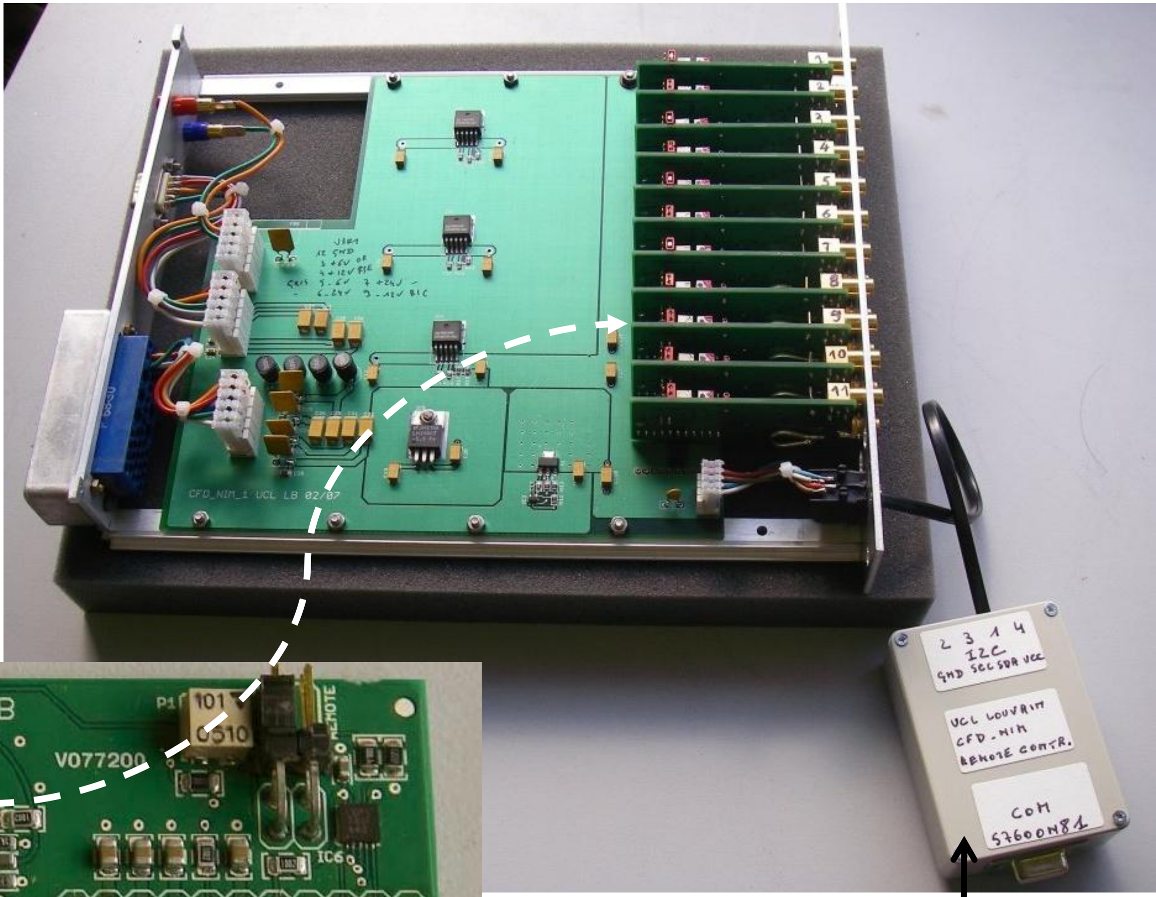


Fast Constant Fraction Discriminator

L. Bonnet (UCLouvain)

Development of LCFD

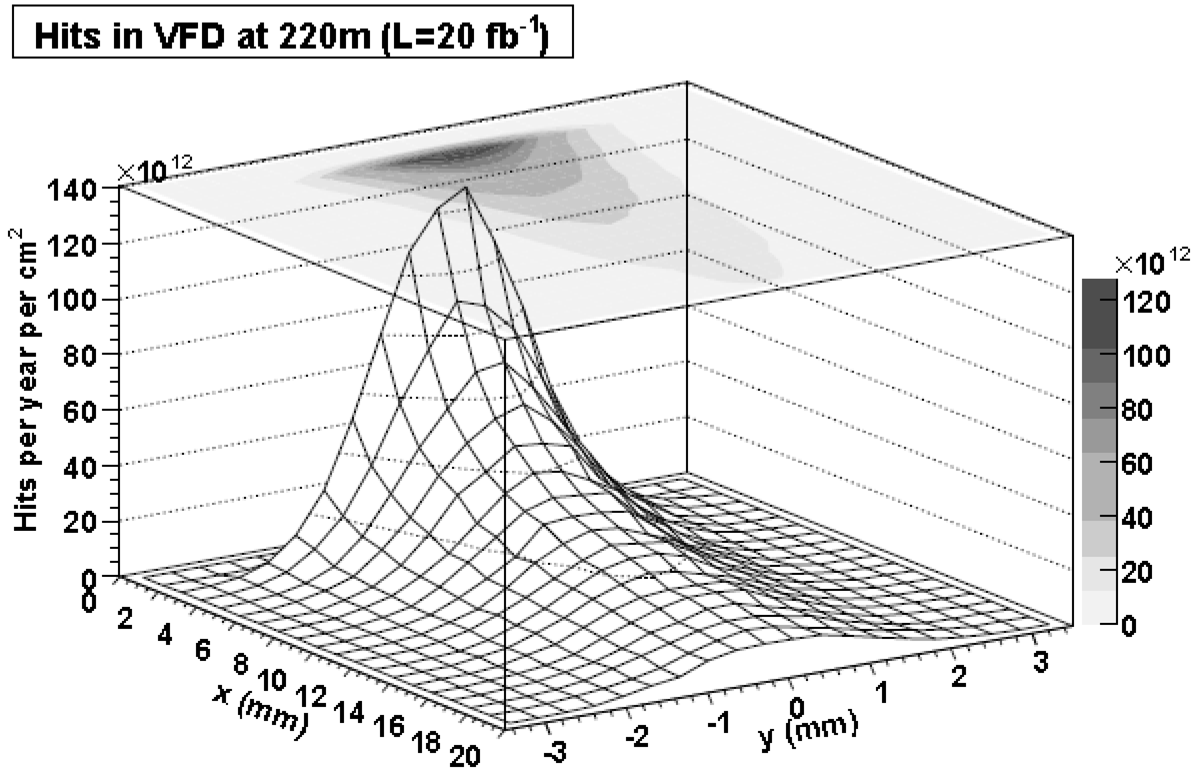
- 12 channel NIM units
- mini-module approach tuned to PMT rise time (HPK/Photek vs Photonis)
- Good performance: < 10 ps resolution for 4 or more phe's (A. Brandt)

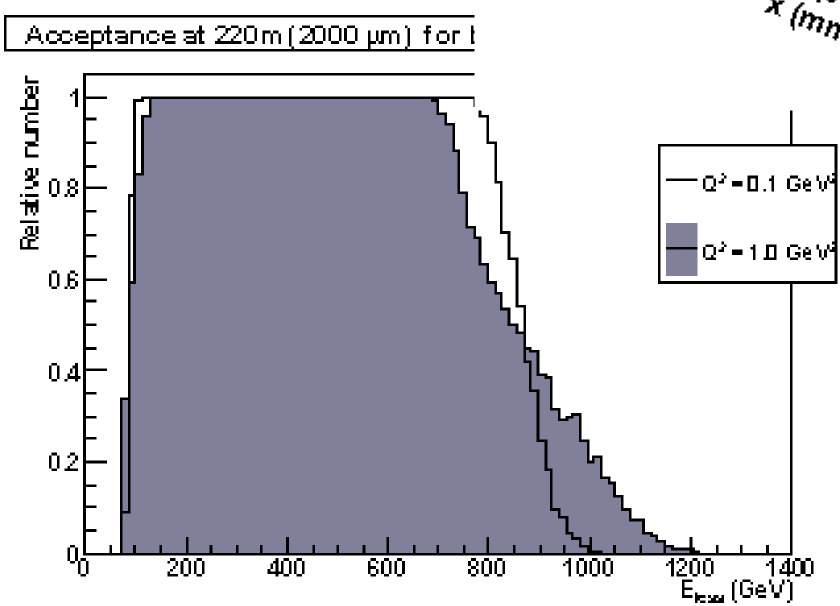


Remote control for threshold

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

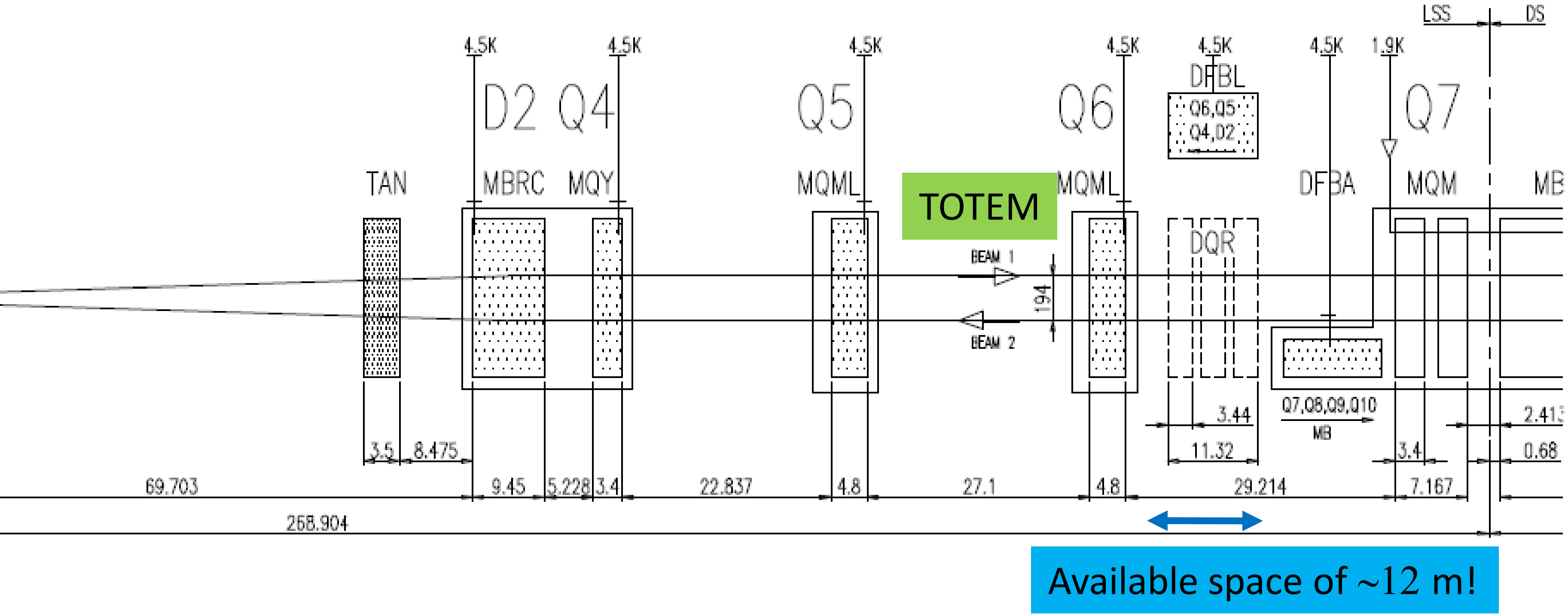
HECTOR: **JINST 2, P09005 (2007)**





Similar proton lateral distributions to HPS420

LHC beam-line close to 240 m

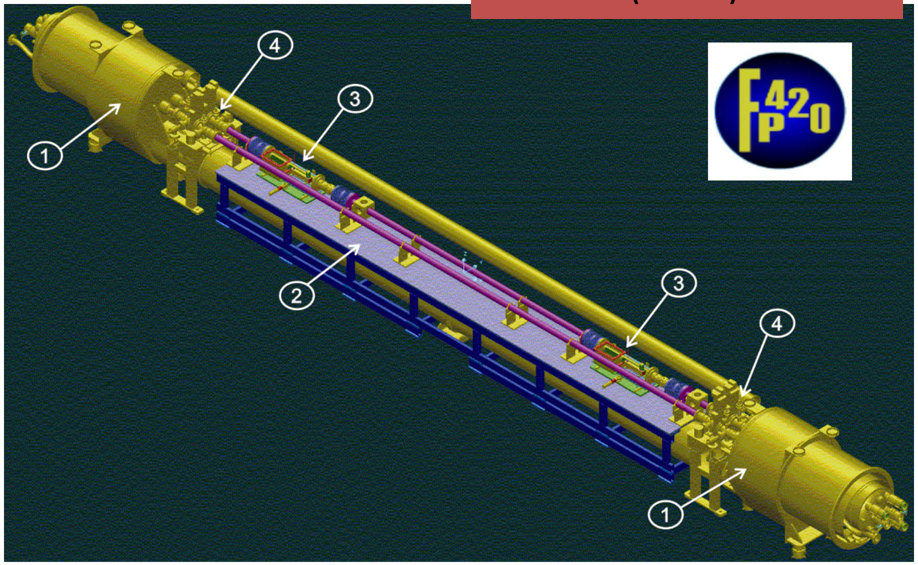


From Detlef:

- 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

Forward proton detectors @ (high ℒ) LHC

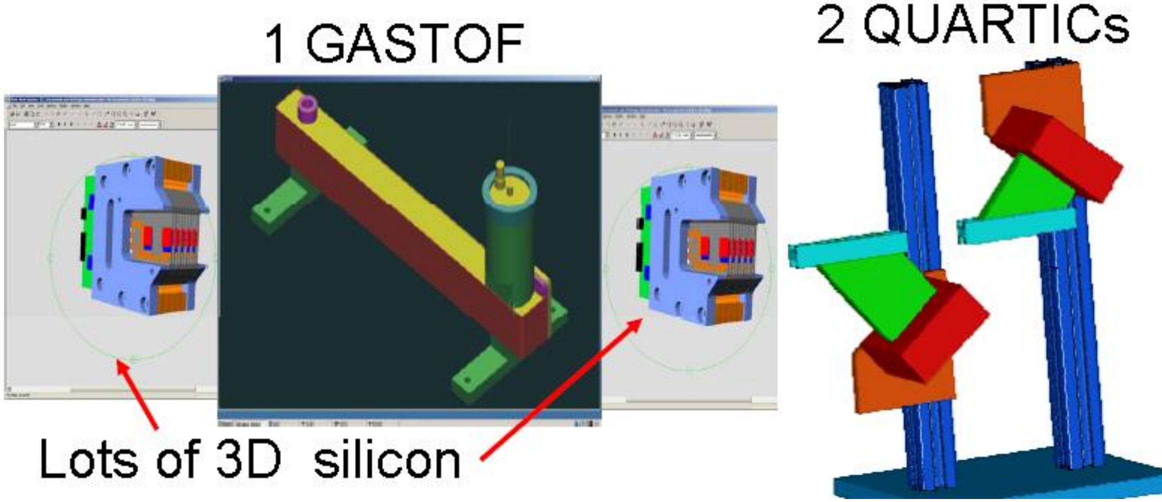
JINST **4** (2009) T10001



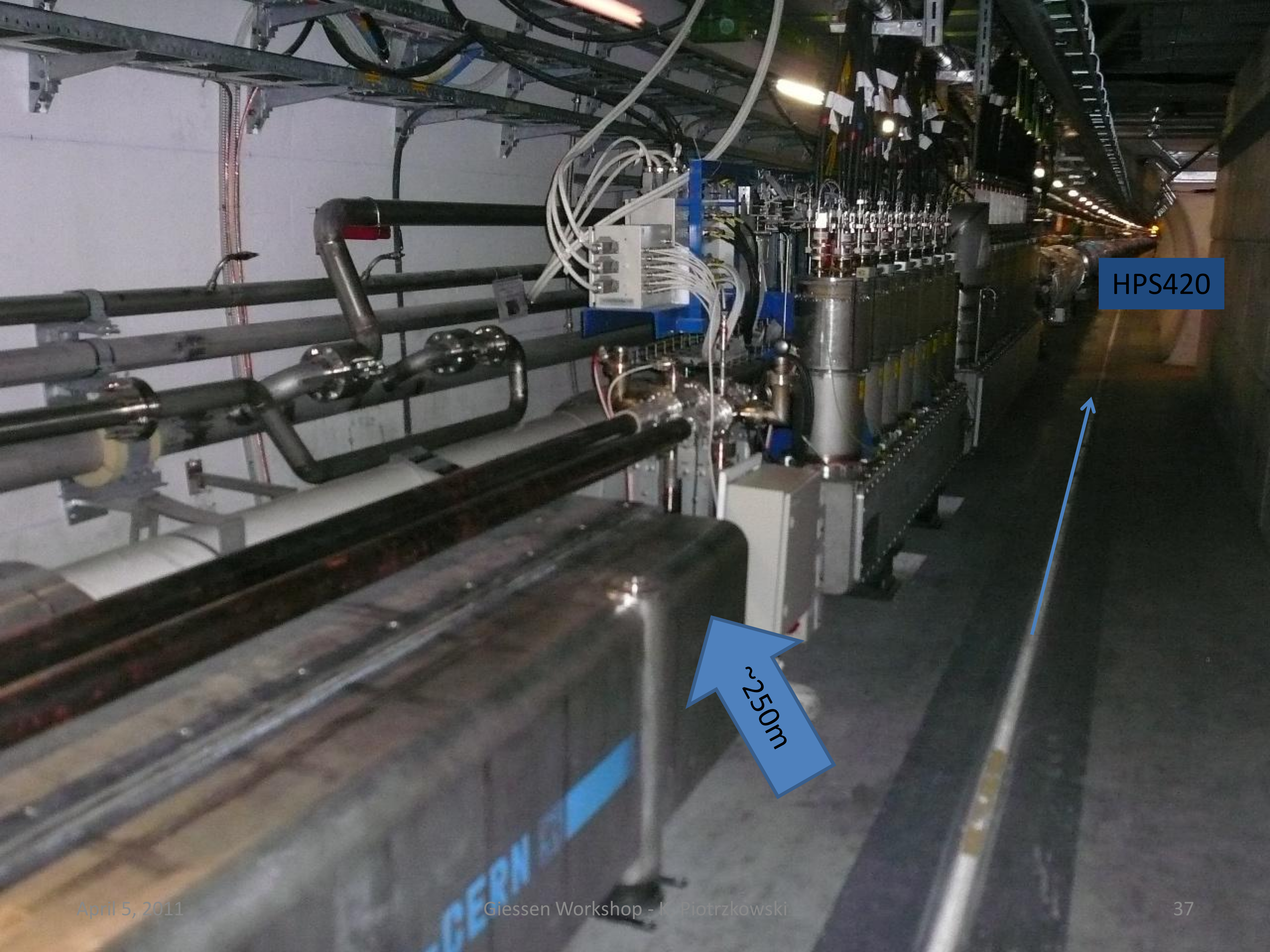
- Installation of Si detectors in cryogenic region of LHC, i.e. cryostat redesign needed
- Strict space limitations rule out Roman Pot technology, use movable beam-pipe instead
- Radiation hardness required of Si is comparable to those at SLHC, use novel 3-D Silicon technology
- To control pile-up background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

Acceptance in fractional energy loss (at nominal LHC β^* = 0.5 m):

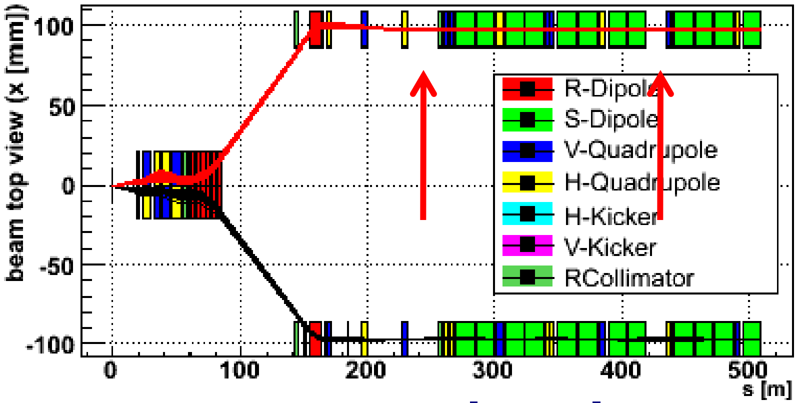
$0.002 < \xi < 0.02$



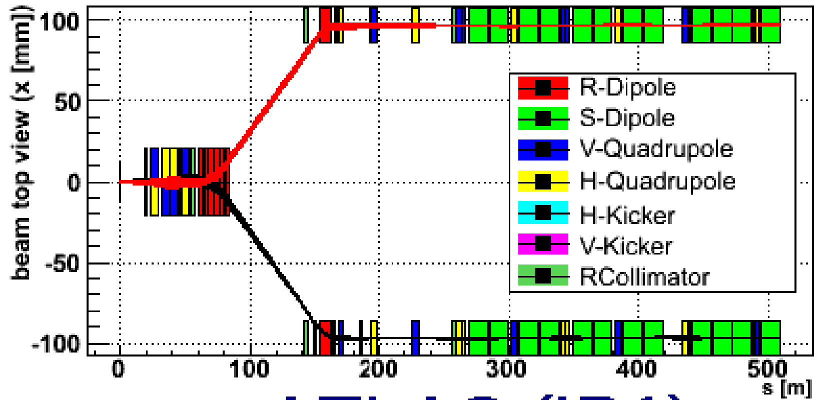
Two detector stations per arm (4 in total): each station contains tracking and timing detectors


HPS420
~250m
CERN

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

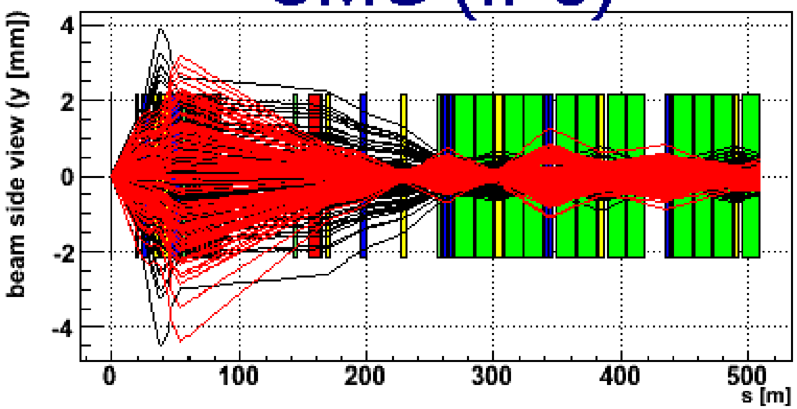


top

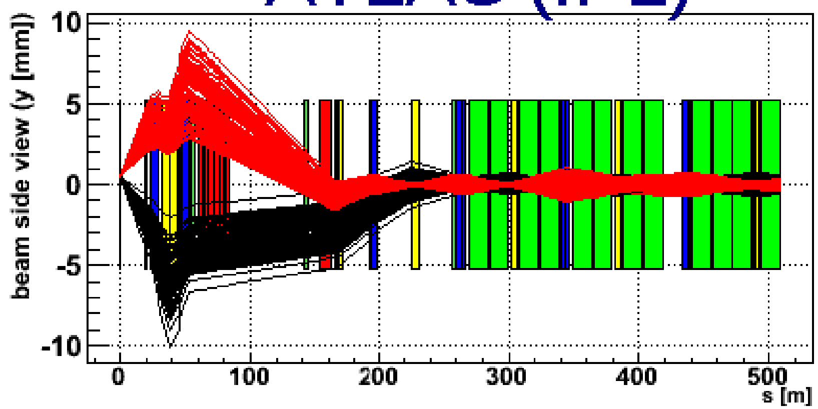


CMS (IP5)

ATLAS (IP1)



side

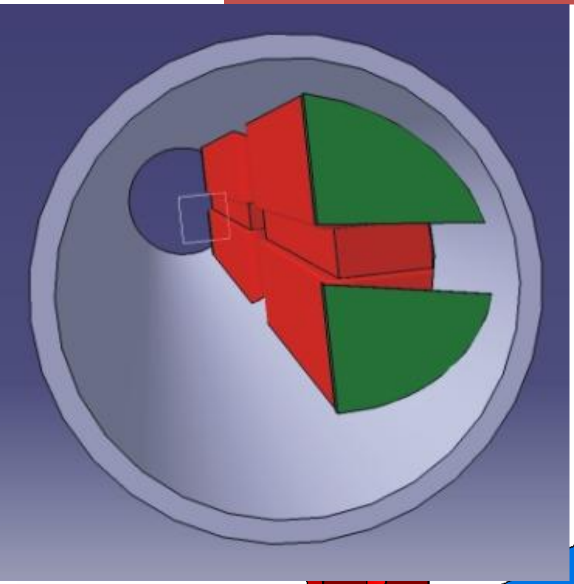


Horizontal crossing plane

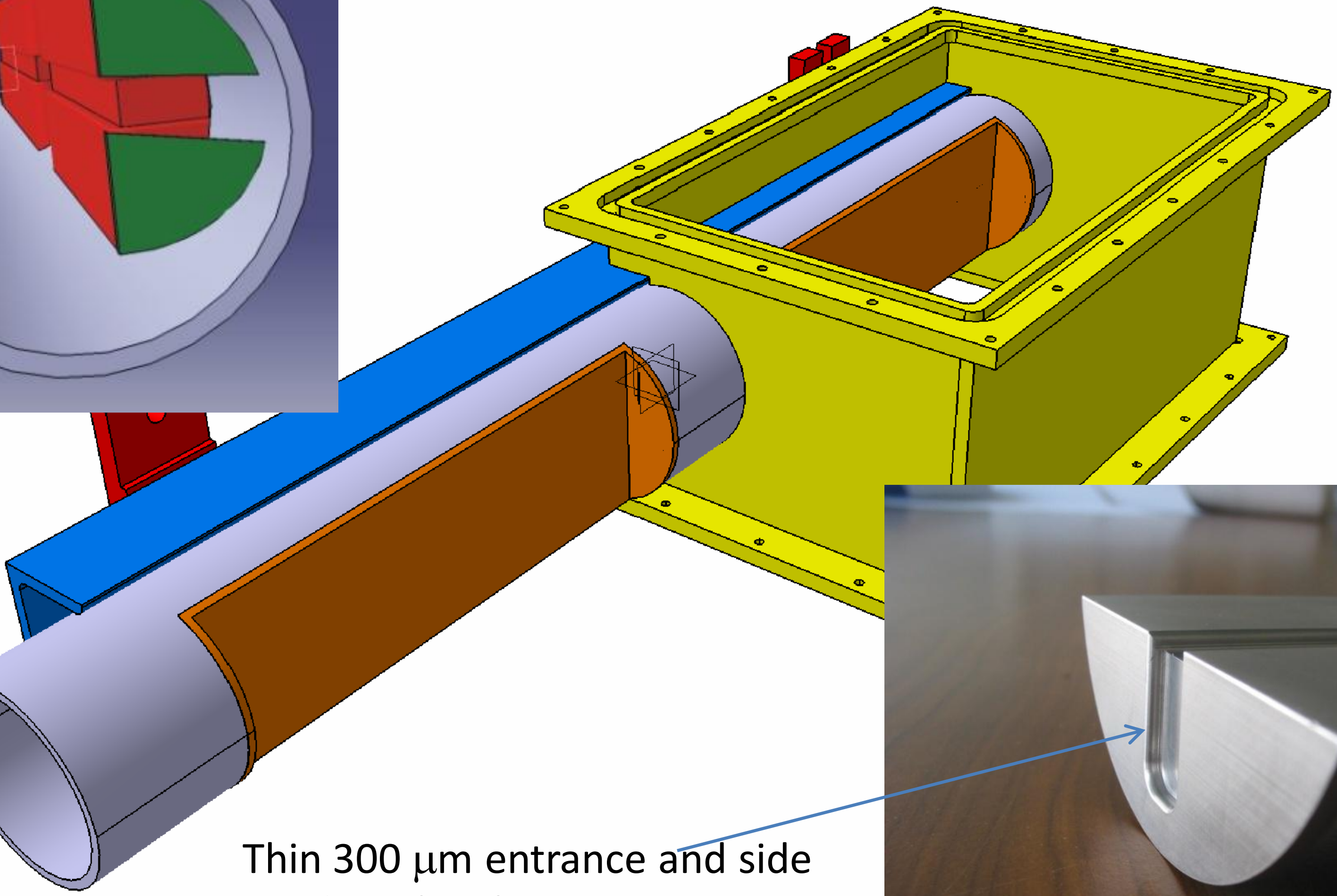
Vertical crossing plane

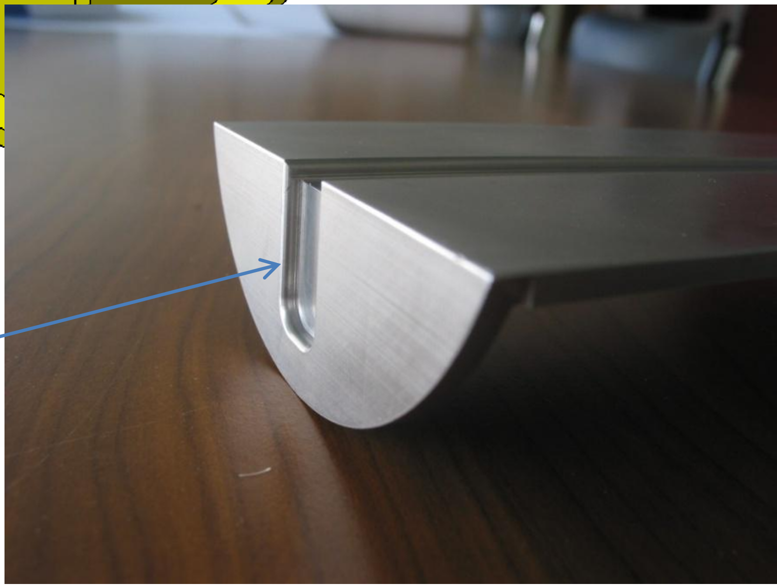
HECTOR: **JINST 2, P09005 (2007)**
For nominal low-β LHC optics

Moving pipe: Detector ‘pockets’



Prepared for beam tests:

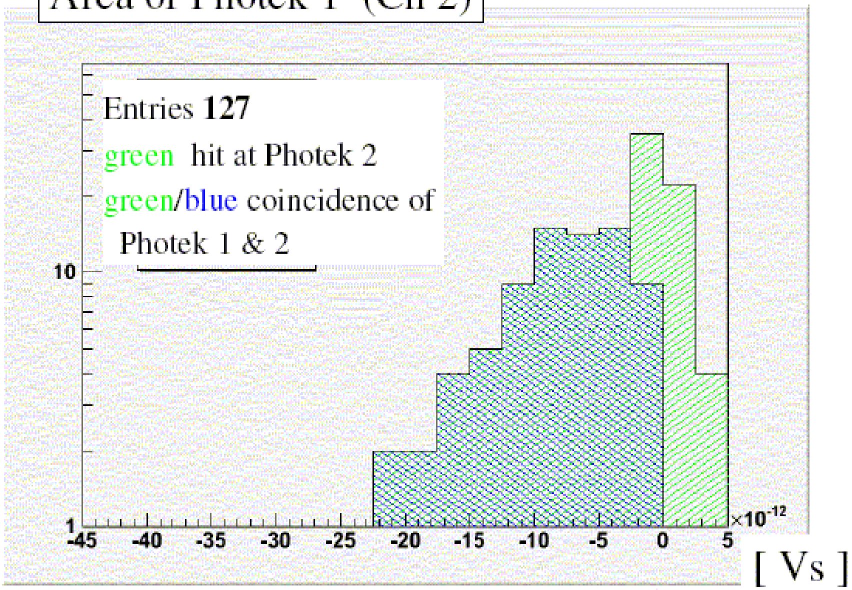




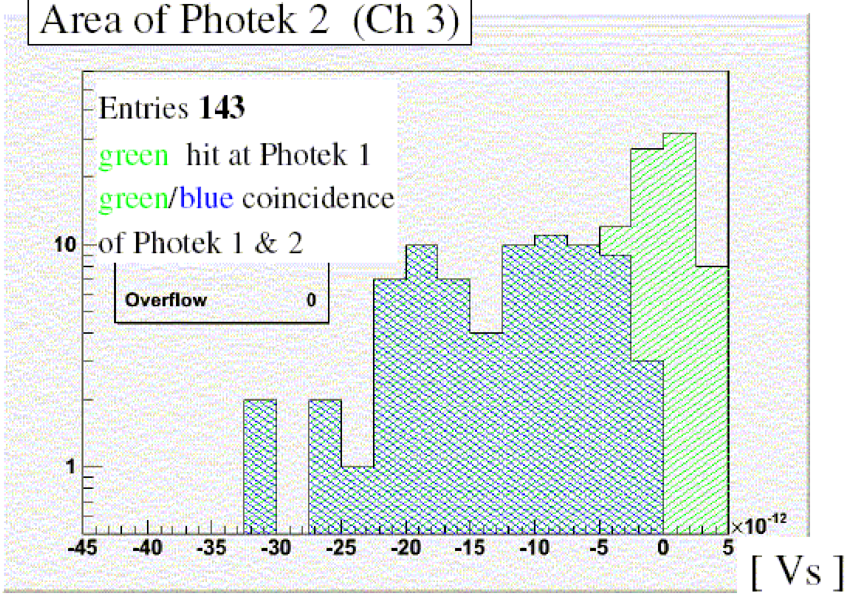
Thin 300 μm entrance and side windows by electro-erosion

Tomek Pierzchala

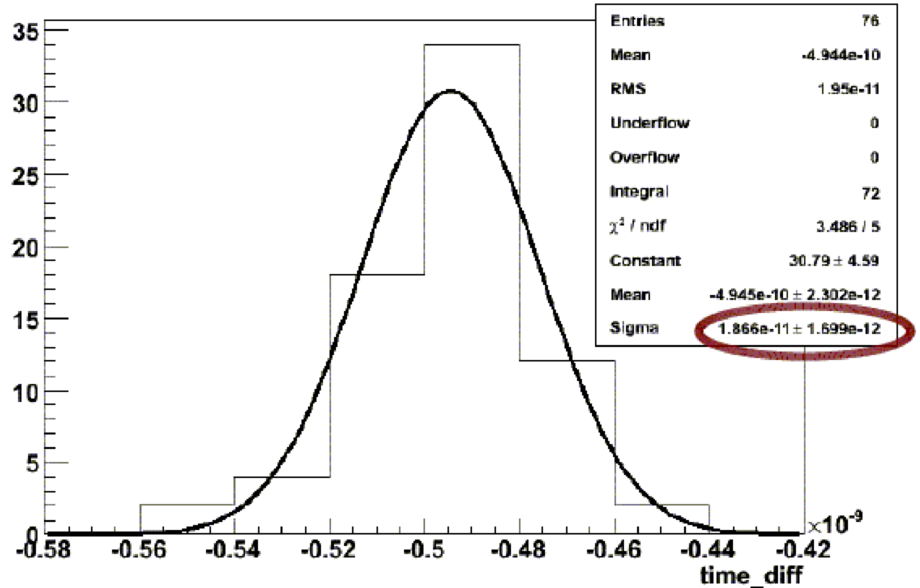
Area of Photek 1 (Ch 2)



Area of Photek 2 (Ch 3)



T2_fit_CFD - T3_fit_CFD {T2_fit_CFD<1 && T3_fit_CFD<1}



we measured an uncertainty of time difference:

18.0 ps ± 1.6 ps

and

18.7 ps ± 1.7 ps

both are consistent

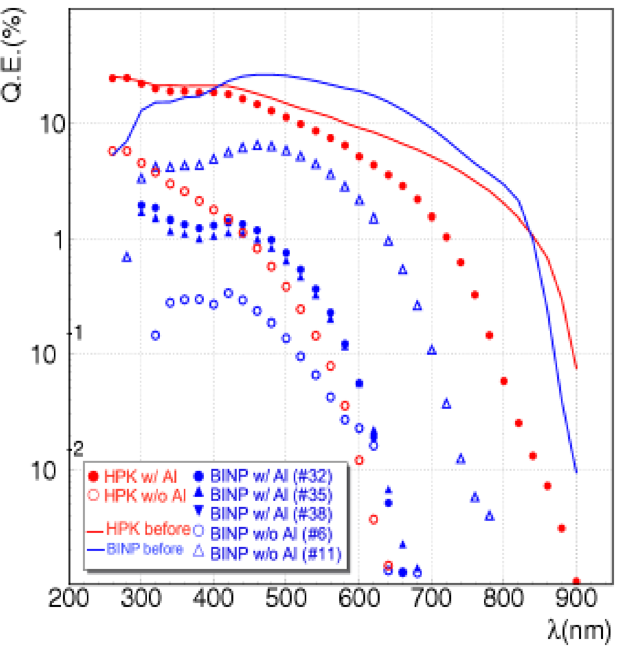
taking worst result and assuming to detectors have the same jitter, we have a Gastof jitter:

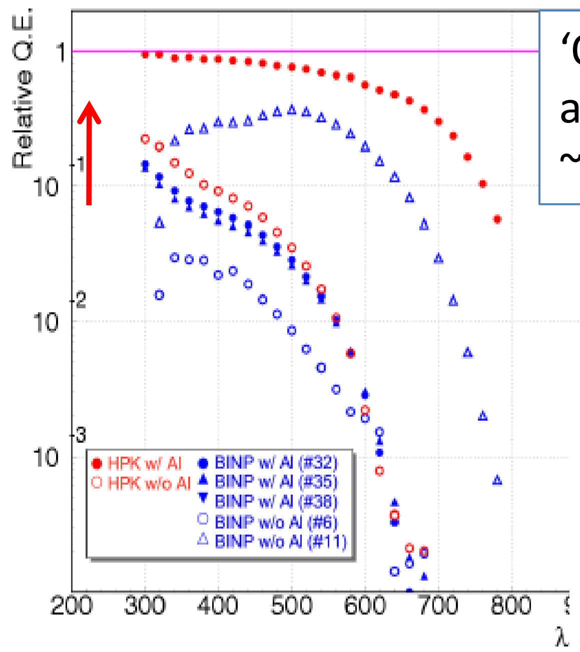
< **13.2 ps ± 1.2 ps**

HPS proposal: Adding HPS240 detectors

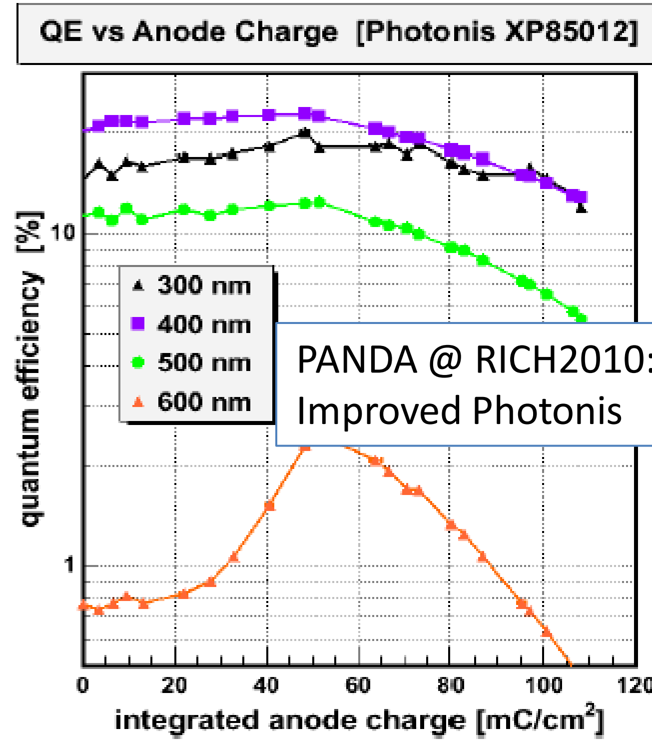
- Tagging at 420m and 240(220)m is complementary – together $\sim 0.2\text{–}10\%$ energy loss range is covered !
- This leads to significantly higher tagged cross sections
- Both 220 and 240 m locations are 'warm&free' – just bare beam-pipes
- At IP5, locations at 220 m are occupied by TOTEM -> go 240m (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

GasToF: MCP-PMT lifetime issue





'Old' Nagoya results for accumulated charge of ~3.5C/cm²



PANDA @ RICH2010: Improved Photonis

Strong outcome from past/present measurements:
QE is much less affected for UV photons

Optimize GasToF design so 'working point' is kept around 200 nm!