*Fast Timing detectors for Forward Protons at the LHC**

* LHC = Large Hadron Collider at CERN

Mike Albrow, Fermilab

Need for ~ 10 ps timing: **HPS** = High Precision Spectrometer
AFP = ATLAS Forward Protons

$p + p \rightarrow p + H + p$, $p + W^+W^- + p$, etc…

How to get 10 ps timing: **QUARTIC**s (Gas, Fused Silica) + MCP-PMTs
Q-bars + SiPMs (Silicon Photomultipliers)

Beam tests at Fermilab

Longer term (m^2): **Forward Discs, Central Barrel ?**

Fast Timing applications at the LHC*

* LHC = Large Hadron Collider at CERN

From speed and momentum to mass : particle identification

Finding collision point in spacetime, i.e. time as well as space.

Matching particles to that collision point (even at same space position)

Selection of some rare events even with ~ 25 collisions in 500 ps X

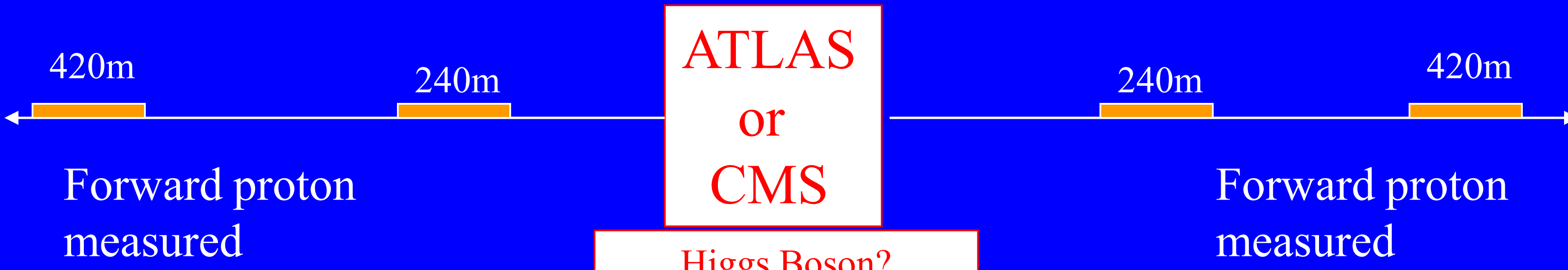
Detectors: QUARTIC = QUARtz TIming Cherenkov
with Microchannel plate PMTs or with SiPMs

Goals : $\sigma \sim 10$ ps, edgeless, rad-hard ($\sim 10^{15}/cm^2$), readout/25-50 ns

FP420 = Forward Protons at z = +/- 420m at LHC (Joint R&D project)

→ AFP = ATLAS Forward Protons

→ HPS = High Precision Spectrometers (CMS)



Higgs Boson?
W+ W- pair
seen in central detector

Can measure mass, width, spin, CP of Higgs

Problem: Cross section small, need high luminosity, $L \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$

$\langle n_{inel} \rangle \sim 25$ collisions/X

Pile-up: p, p, H candidate from different collisions

Time difference between p's → z(collision) IFF same collision

$$\Delta z(\text{pp, TOF}) = \frac{1}{\sqrt{2}c}\Delta t(p-p) = 2.1\text{mm}/10\text{ps}$$

cf σ(z-vertex) ~ 60 mm

Timing detectors for AFP/HPS, requirements:

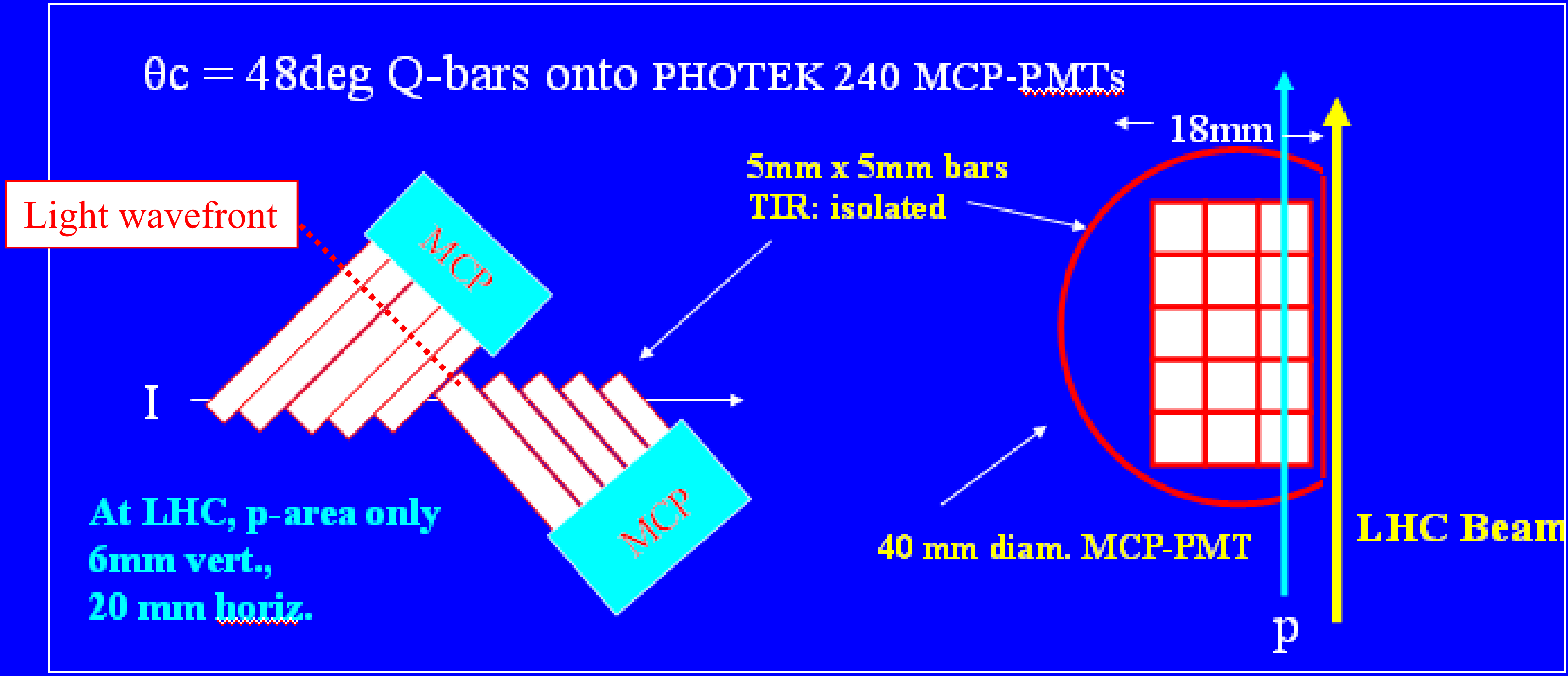
Area only ~ 8 mm x 20 mm
Edgeless (<~ 100 μm, one edge)
Rad hard, ~ 10^{15} p/cm^2 (? depending fluxes, replacement time)
Readout (pipelined) compatible with LHC Ops (50 ns / 25 ns)
1 ns every 25/50 ns is occupied, σ(collisions) ~ 150 ps/bunch
Ability to time 2 (tracked) protons in same bunch an advantage

Solutions being developed:

Cherenkov light (prompt, unlike scintillation) in gas (GASTOF)
or fused silica (artificial quartz, Q) bars.
Light detected with fast microchannel plate photomultipliers (MCP-PMT)
or silicon photomultipliers SiPMs

An edgeless design: QUARTIC = QUARtz TIming Cherenkov

Principle of QUARTIC: Cherenkov light in quartz at θ ~ 48°
Incline Q-bars at 48° & normal to PMT
Light from all bars arrives simultaneously at PMT window
Can have bars to individual pads (Photonis), or single anode (Photek)
Cross-talk, sharing does not matter. Can be "edgeless" (thin foil)

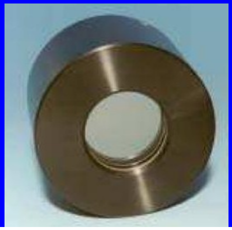


T979: High-Resolution Timing Detectors in Fermi MTest

R&D program, ~ 2 x 1 week/year

10 ps = 3 mm   0.13 s = around the world

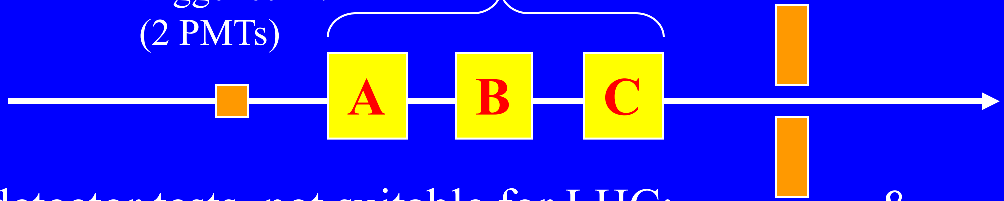
Basic setup (in dark shielded box with feedthroughs)



PHOTEK 240
2 MCP, 40mm Φ

2mm x 2mm
trigger scint.
(2 PMTs)

Detectors under test

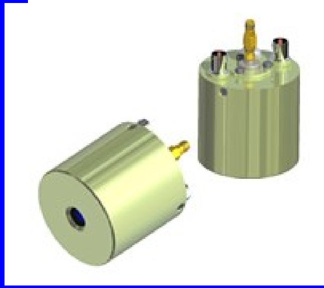


VETO with hole
trigger scint.
(2 PMTs)

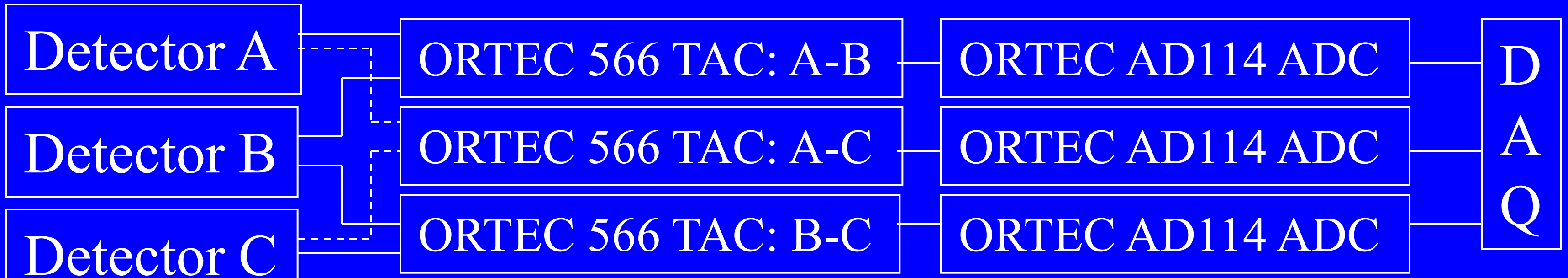
120 GeV/c p

& one run 8 GeV/c π + p

PHOTEK 210
2 MCP, 10mm Φ
Tx Jon Howarth



Electronics for detector tests, not suitable for LHC:



A-B-C in-line results: Cherenkov light in PMT windows

ADC distributions: cut out tails and stragglers (~ 10%)

T1 = tA – tB

T2 = tA – tC

T3 = tB – tC

========

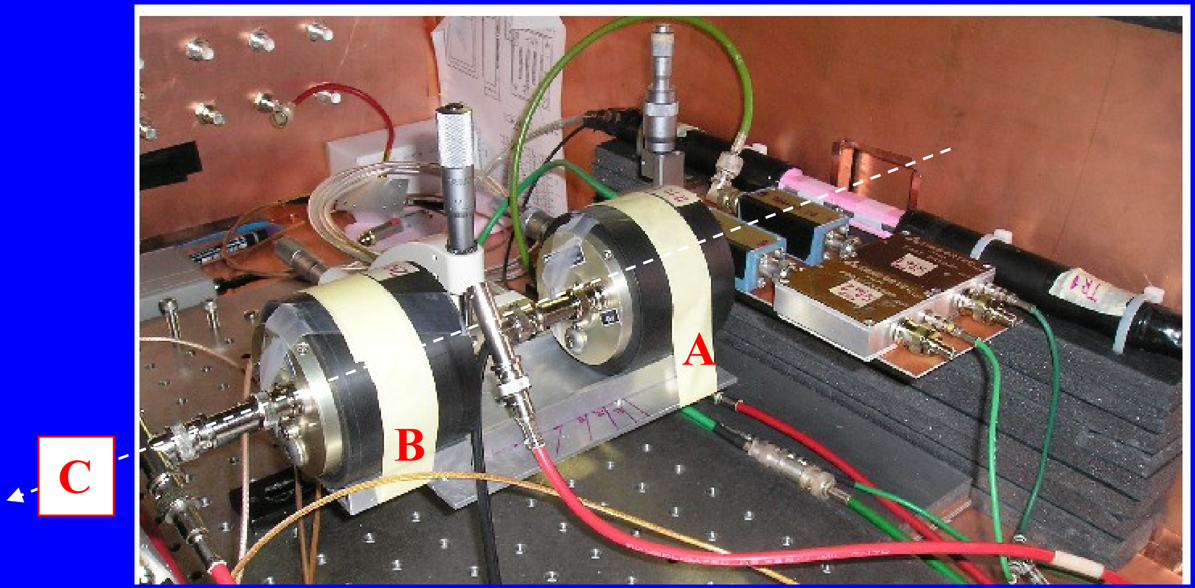
Check Ti(PH A,B)

Make slewing corrections

Unfold:

$$\sigma_A = \frac{1}{\sqrt{2}}\sqrt{T_1^2 + T_2^2 - T_3^2}$$

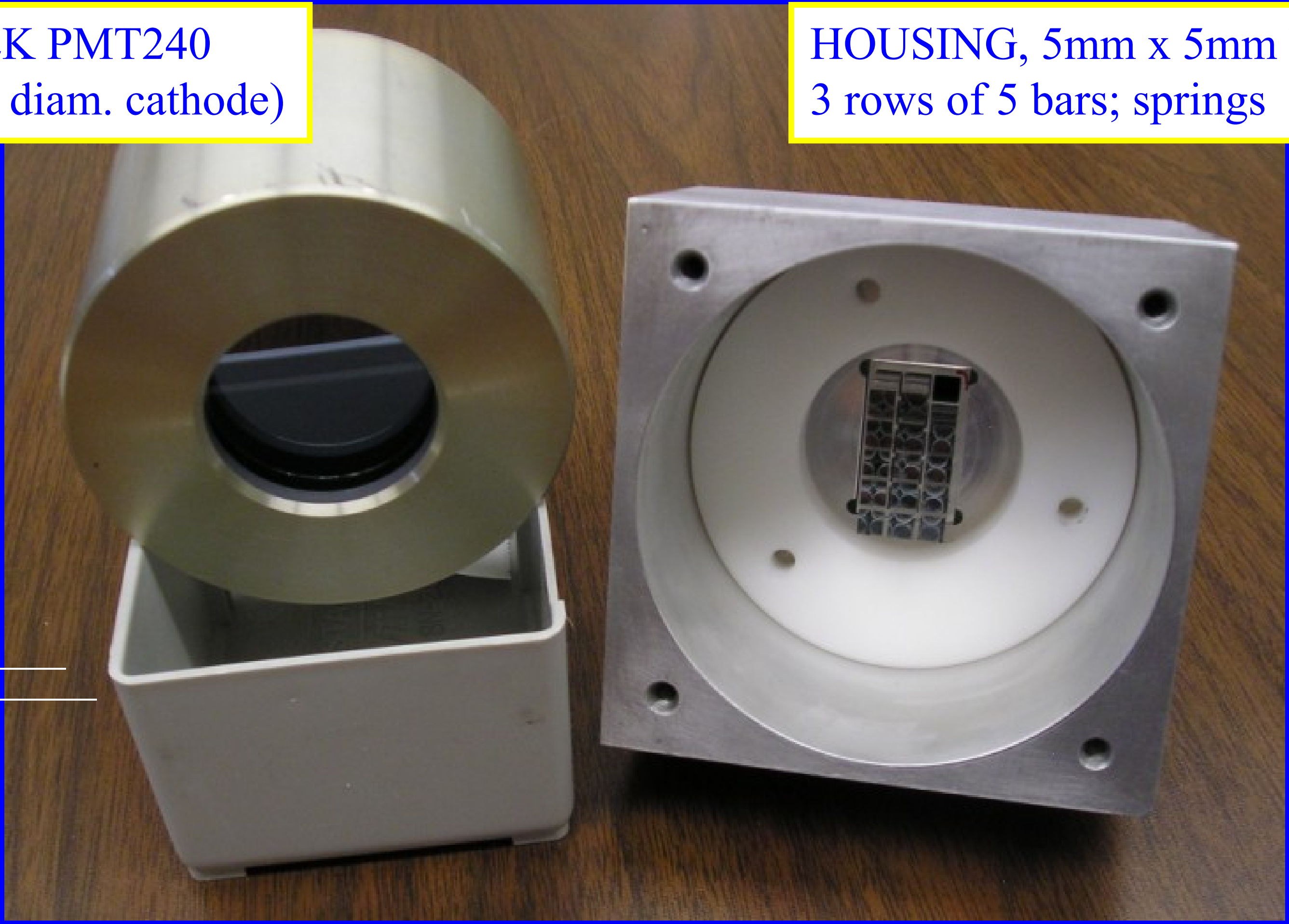
etc.



PMT-1 (Photek-210, 4.7 kV)=12.0 ps
PMT-2 (Photek-210, 4.6 kV)=12.0 ps
PMT-3 (Photek-240, 4.2 kV)=7.7 ps

Cherenkov light in PMT windows

Single Channel multi-bar QUARTIC-1 Detector



This version of QUARTIC: all bars on single 40 mm photocathode (nice isochronous design, $\Delta t <\sim 2$ ps over 40 mm surface)

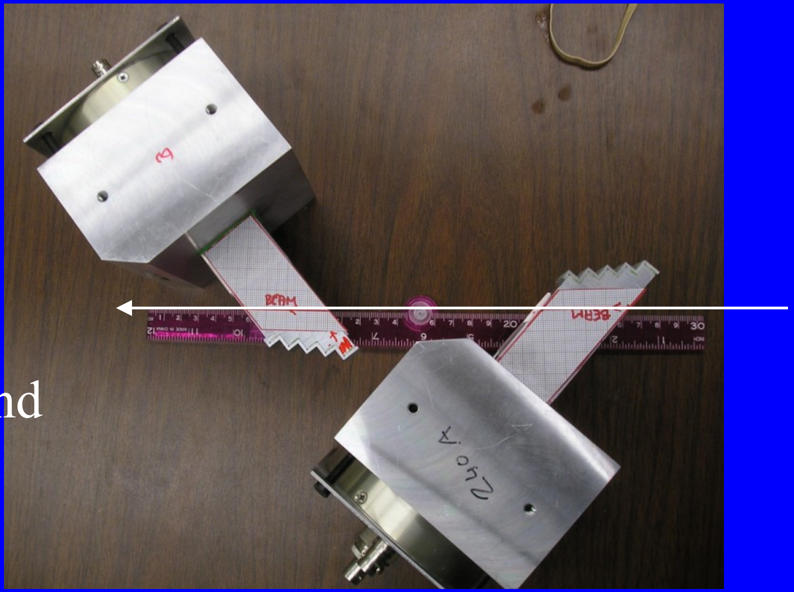
QUARTIC-1

Same side: t(A) - t(B) independent of x.
(but dx only 2 mm, ~ 15 ps)

Opposite side: t(A) + t(B) independent of x
t(A) - t(B) ~ 7.5 ps/mm (dx).

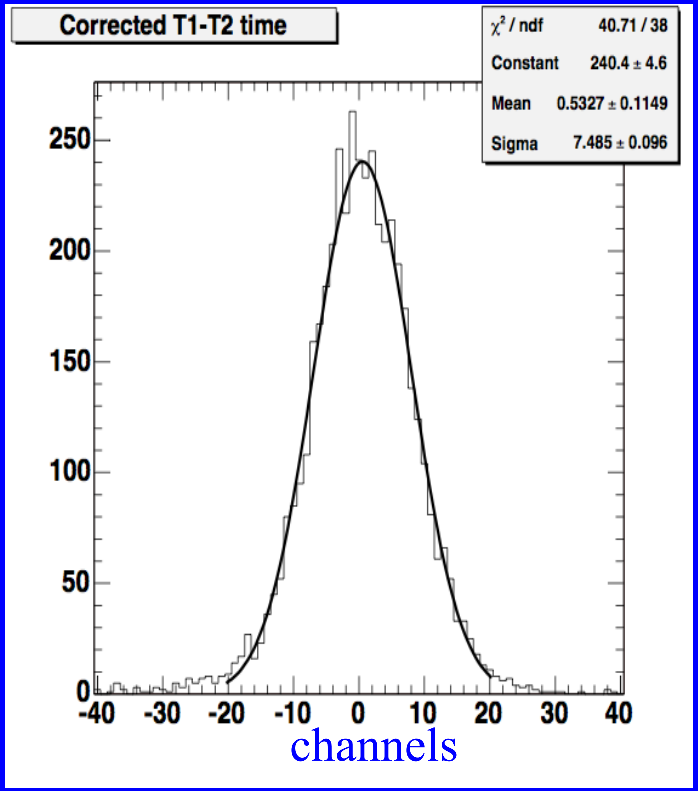
Tracking can show correlation and show this.

Double-Quartic: we give resolution for this and each one separately.



Some Results:

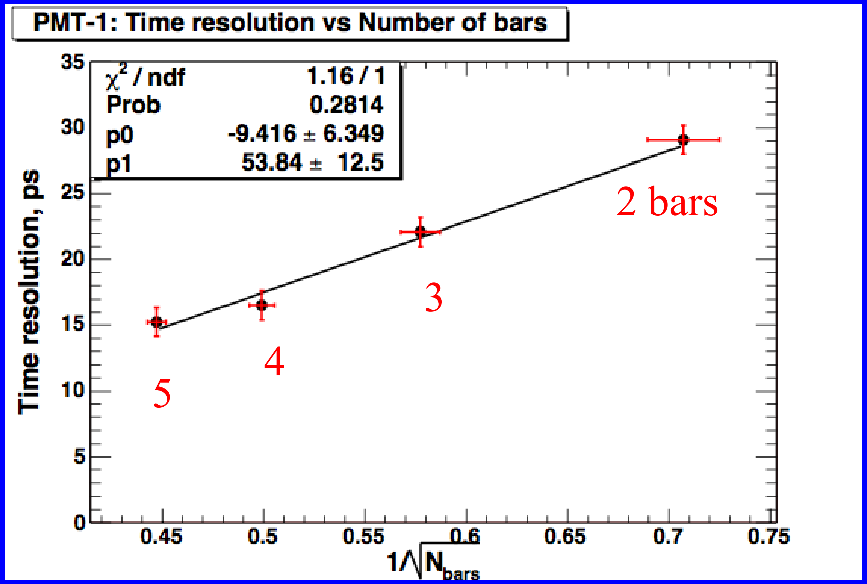
Remove tails of PH distributions
(correlated, probably interactions).
Apply time-slewing correction
(CFD needs residual PH correction)
Fit t(1) – t(2) to Gaussians (good fits):

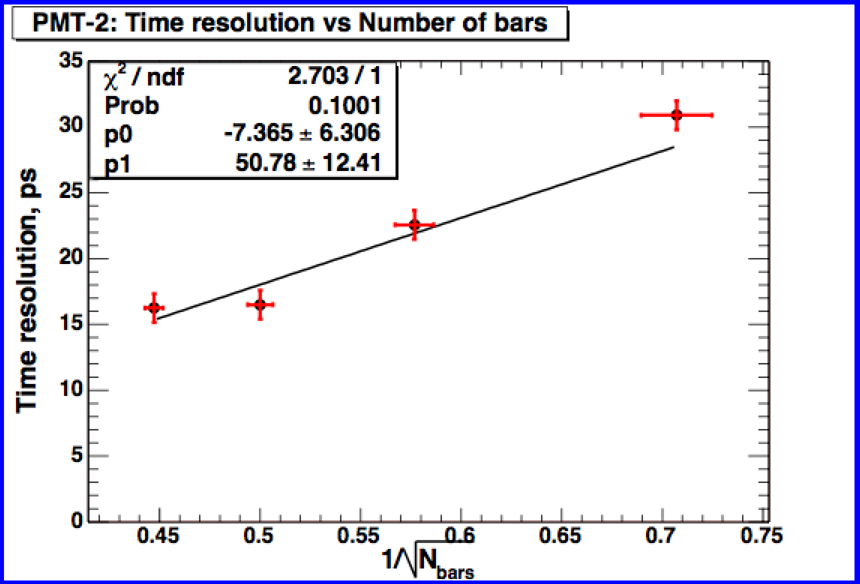


A=15.5 ps B=16.3 ps quadrature combination σ = 11.2 ps
Beam at nominal x and 10 mm closer to PMT

OS T1 = A-B, cf SS … is it wider (should be + ~ 15ps in quad)
Can get [A+B] resolution using event-by-event formula

Resolution vs Nbars





$\sigma(\Delta t) = 1 / \sqrt{N(\text{bars})}$

→Bars contribute about equally
→Two detectors the same

p.e. ~ 20-25 (5 bars)

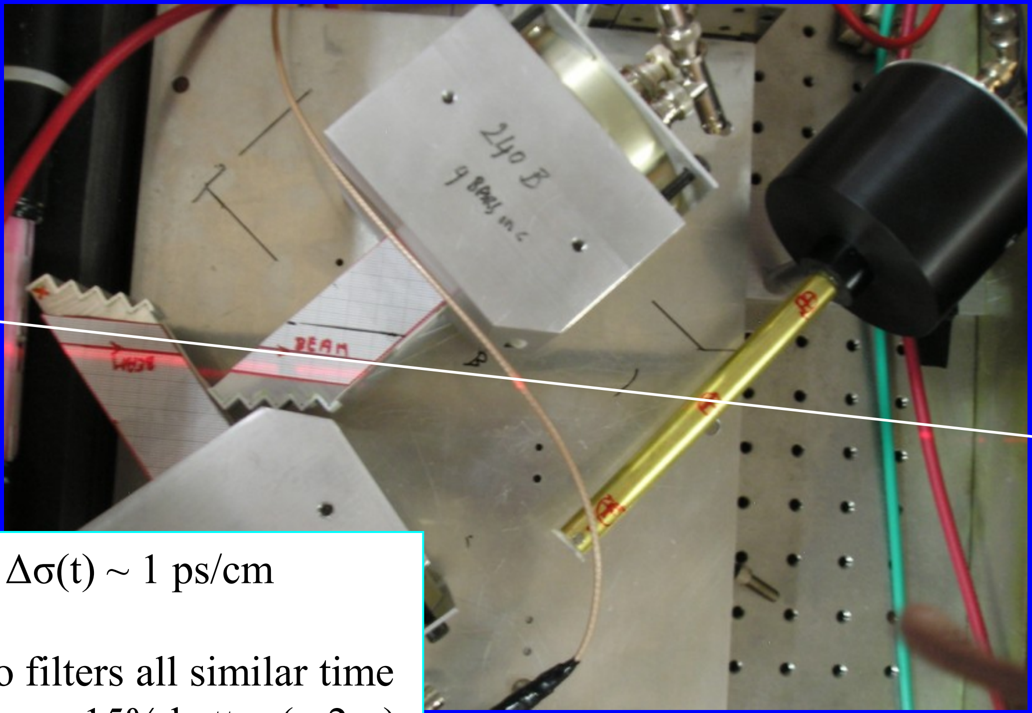
Further studies: enable tests of simulations and optimizing designs.

Dependence on bar length: (longer is better … further from beams.
but chromatic dispersion (more intense blue light slower than red) begins to hurt.

Measure: $\Delta\sigma(t) \sim 1$ ps/cm

Effect of reducing light spectrum with red-pass and blue-pass filters.

Long 150mm bar : PH, N(pe) , $\sigma(t)$ for 3 positions along bar.



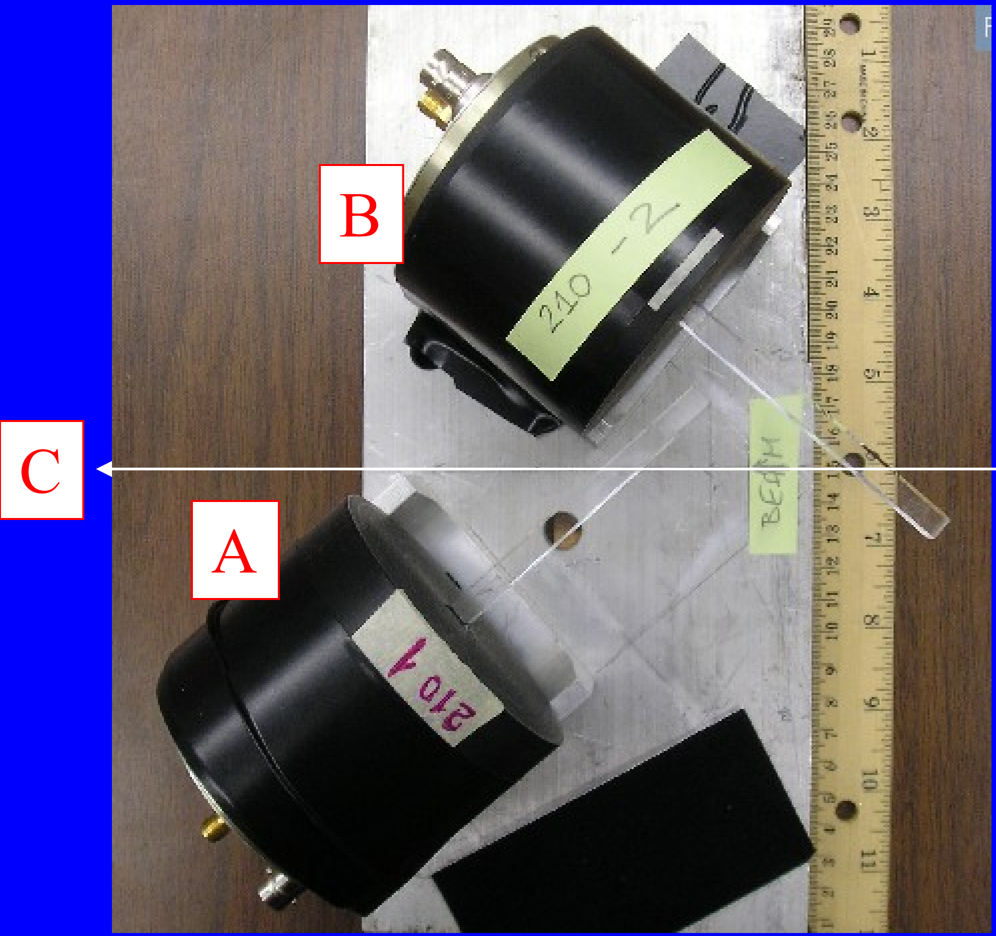
BEAM

Bar length traversed by light: $\Delta\sigma(t) \sim 1$ ps/cm

Red pass and blue pass and no filters all similar time resolution (less light), blue pass ~ 15% better (~ 2 σ)

Double Q-bar

Quartz (fused silica) bars 6mm x 6mm x 90mm → PHOTEK 210
Mounted at Cherenkov angle $\theta_c \sim 48^o$ on opposite sides.
dz = 6 mm/sin(48) = 8.1 mm. Some light direct to PMT, ~1/2 TIR to PMT
Black "sock" over bars just to avoid light sharing



Unfold:
σ(A) = 22.3 ps
σ(B) = 30.5 ps

Includes electronics (~3 ps)
and 2 mm beam width smear (A,B)
Δt = 2 mm x (10 ps/2 mm)

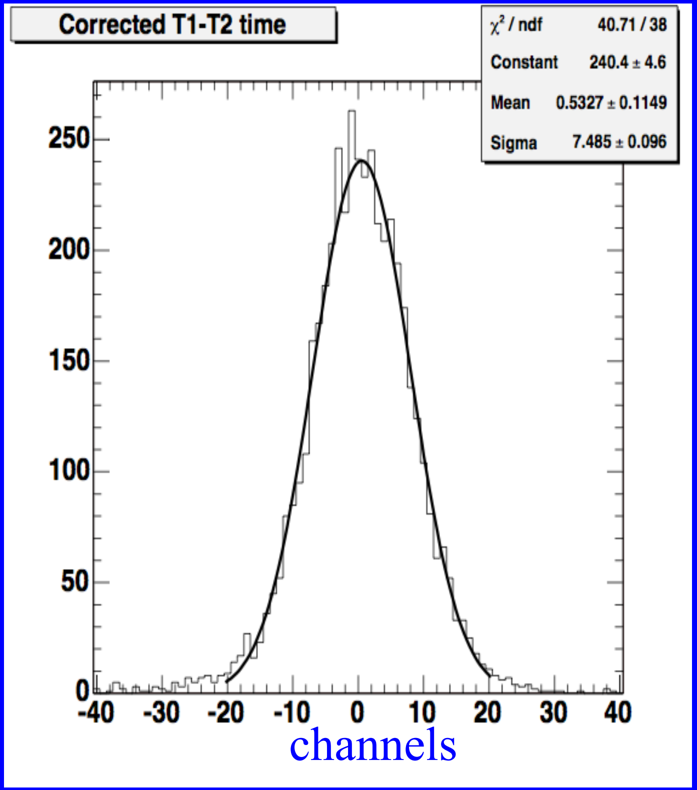
$$\sigma_A \approx \sqrt{22.3^2 - 3^2 - 10^2} = 19.7 \text{ ps}$$

$$\sigma_B \approx \sqrt{30.5^2 - 3^2 - 10^2} = 28.7 \text{ ps}$$

Combining [AB] removes beam spread (later, tracking)

Some Results:

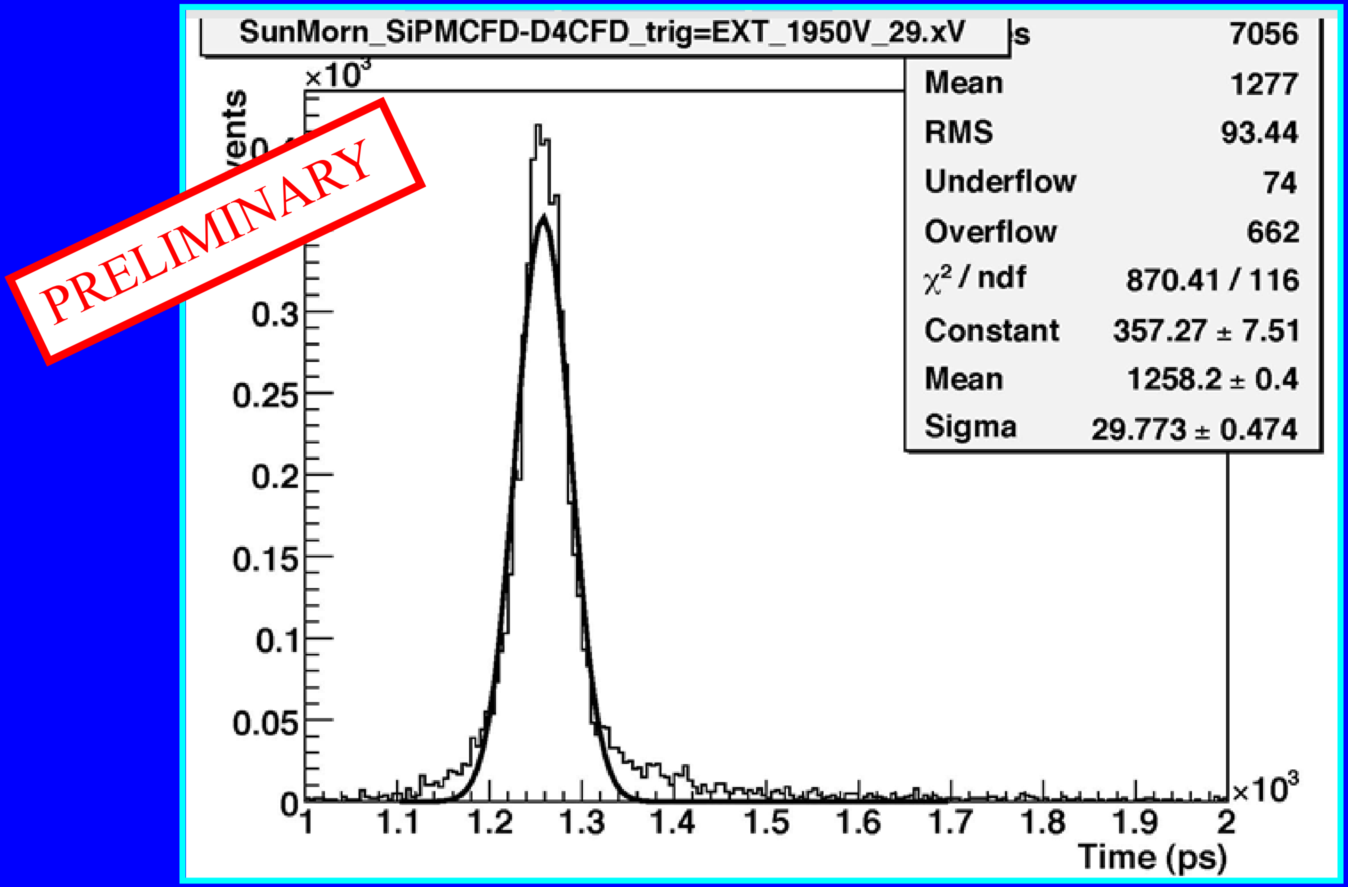
Remove tails of PH distributions
(correlated, probably interactions).
Apply time-slewing correction
(CFD needs residual PH correction)
Fit t(1) – t(2) to Gaussians (good fits):



A=15.5 ps B=16.3 ps :
in quadrature combination 11.2 ps
Beam at nominal x and 10 mm closer to PMT

Are we there yet? (11.2 = 10) No, because:
1) Electronics not LHC/25ns compatible
2) Lifetime of MCP-PMTs may be an issue
3) Bars need to be longer, further from beam.
4) No multi-hit capability yet.

Time difference distribution between Q-bar 4 and SiPM:
σ = 29.8 ps → ~ 20 ps for one Q-bar and 15 ps for Q-SiPM
Expect ~ 10 ps for an 8-bar Quartic or 4 Q-SiPMs (T.B.D.)



SiPMs : A Ronzhin et al. (FNAL)

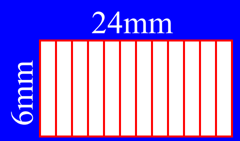
SiPMs (+ quartz radiator window)

Small pads : x,y

Many layers in line ?

Say ~ 20 ps, then 4 layers (+ +)

→~ 10 ps



Possible strips 6mm x 2mm (e.g.)

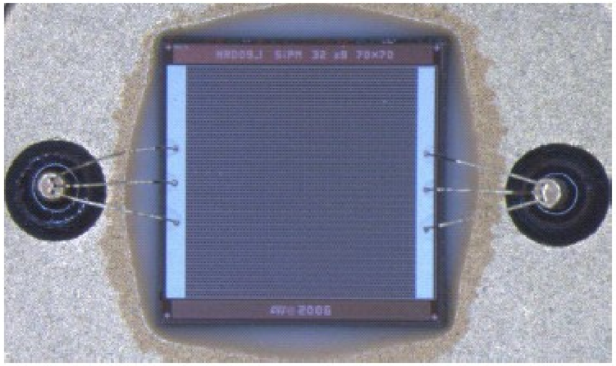


Fig 1. Optical microscopy image of the large area SiPM investigated in the paper. The device has a total area 3.5x3.5 mm^2, 4900 microcells and a geometrical fill factor of 36%.

Each SiPM 2mm x 2mm or 3mm x 3mm

We tested with different thicknesses of quartz radiator.

GEANT simulations (Moriah Tobin, student) concur

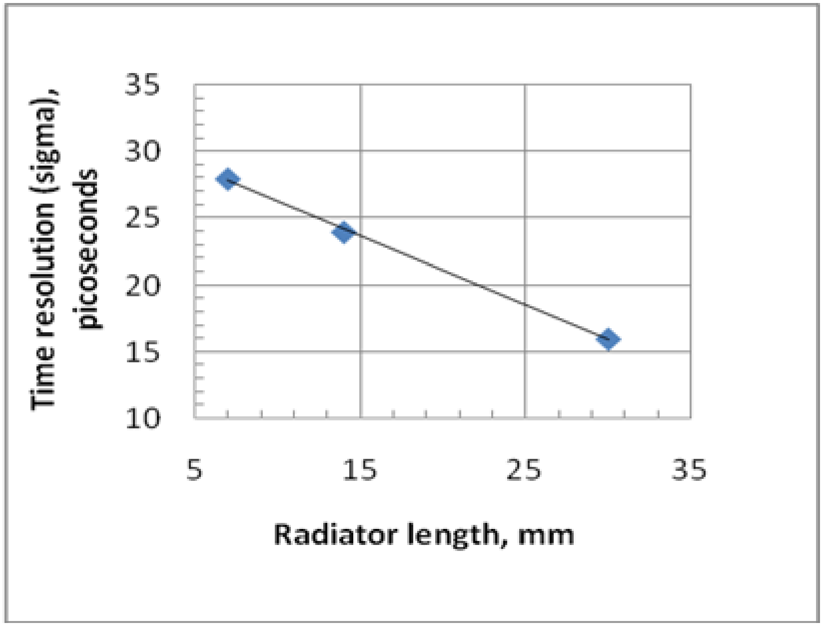
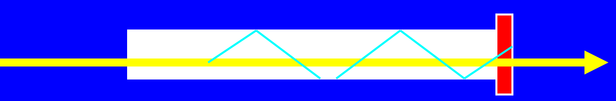


Fig. 25. Dependence of the measured time resolution of the MPPC
the Cherenkov radiator (3x3 mm^2 of cross section). The data are n



p

For parallel to axis particles all Ch. light is T.I.R → back. Front light lags, but helps (bigger pulse)

Not corrected for electonics (3.1 ps) and PMT240 (7.7 ps) …
unfolded **14.4 ps with 30 mm Q**.

Nice features of SiPM:

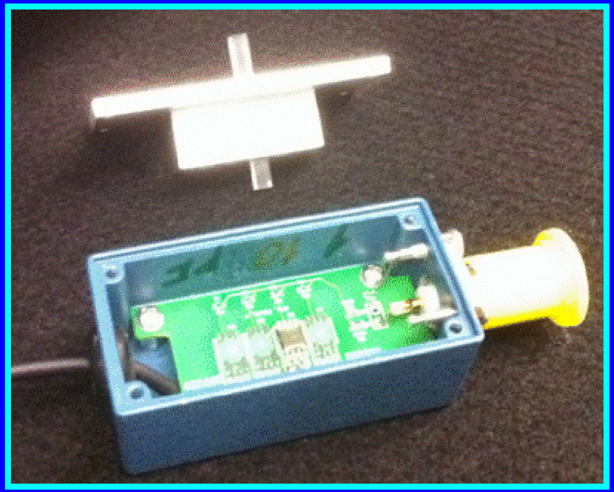
Having many measurements – "timetrack" – robust – self calibrating
Resolution and offsets of each detector monitored by data.
(In QUARTIC design, argument for multipad Photonis)

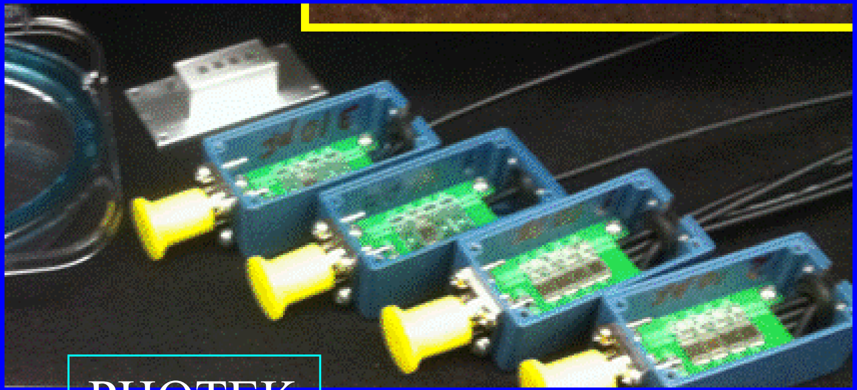
Demands on electronics less: σ = 25 ns/ channel HPTDC can be used.
Cheap: < $100 each (just detector) = $16K for 160 devices.
Can be quickly exchanged ("cartouche", if mechanics designed)
Can be extended with extra layers if z-slot large to improve measurement.
Low voltage (~ 30-40V) gives gain ~ 10^6 and single p.e. resolution.

ALICE uses for ToF, CMS getting 10,000's for HOuter.
HPTDC adequate, but next version may get to ~ 10 ps
DRS4 waveform digitizer looks good (DRS4 ← → CMS DAQ ?)

Quartz bar + SiPM arrays (A.Ronzhin, S.Los)

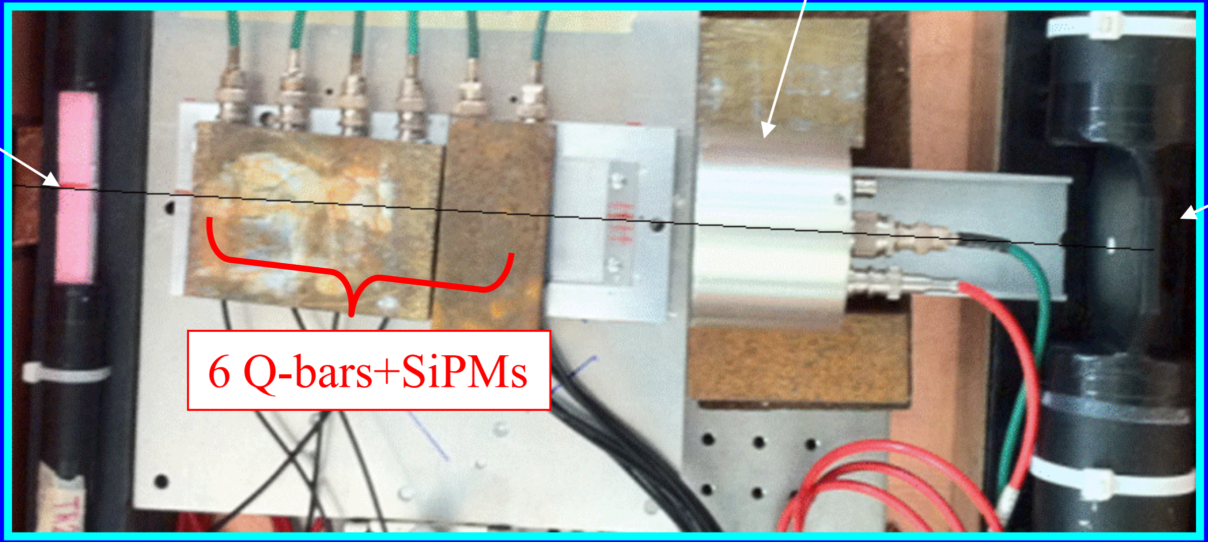
STM (Catania, Italy) **[thanks]** 3.5 x 3.5 mm^2, 4900 cells, 50x50 μm





PHOTEK
PMT240

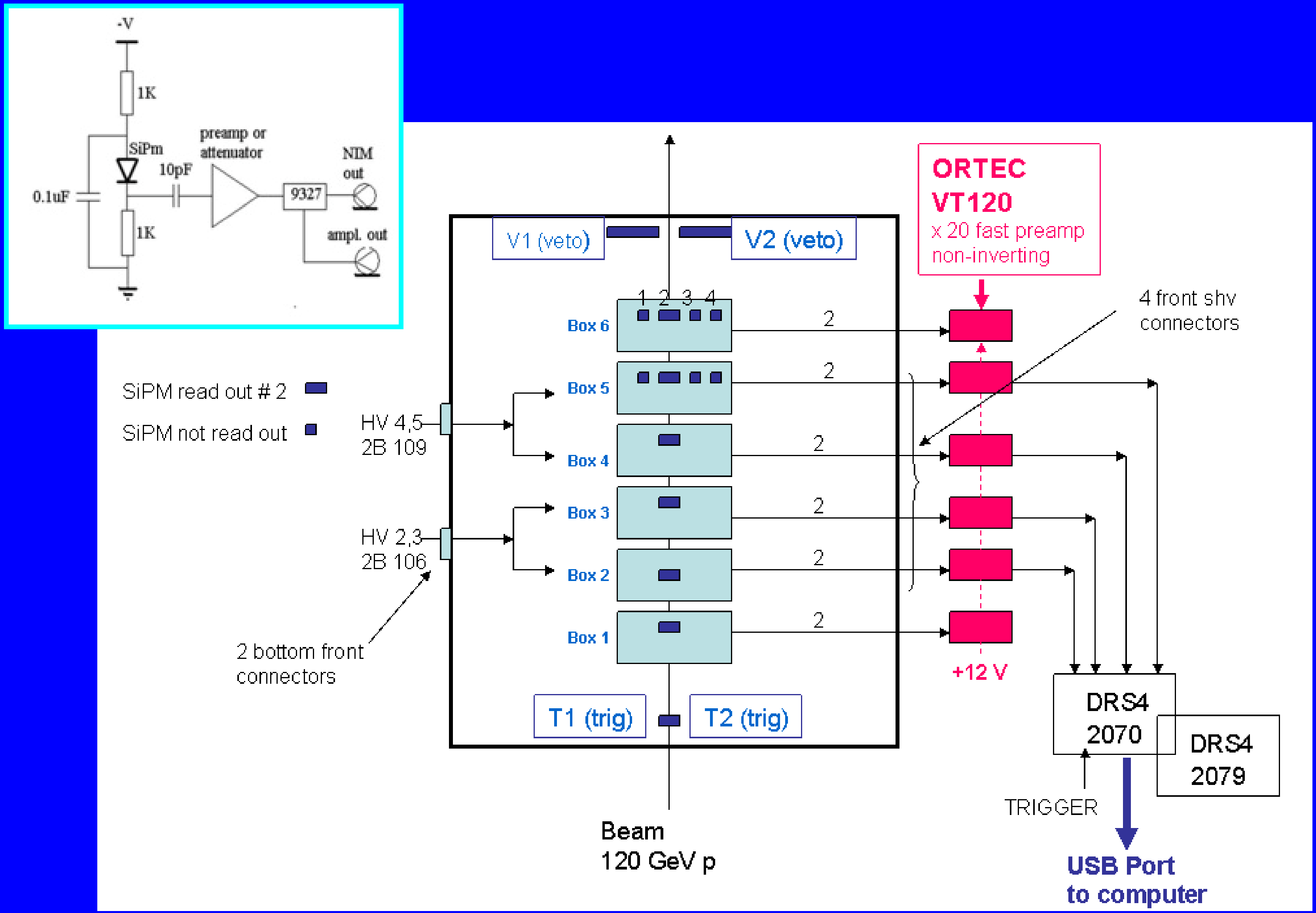
2mm x 2mm
trigger counter



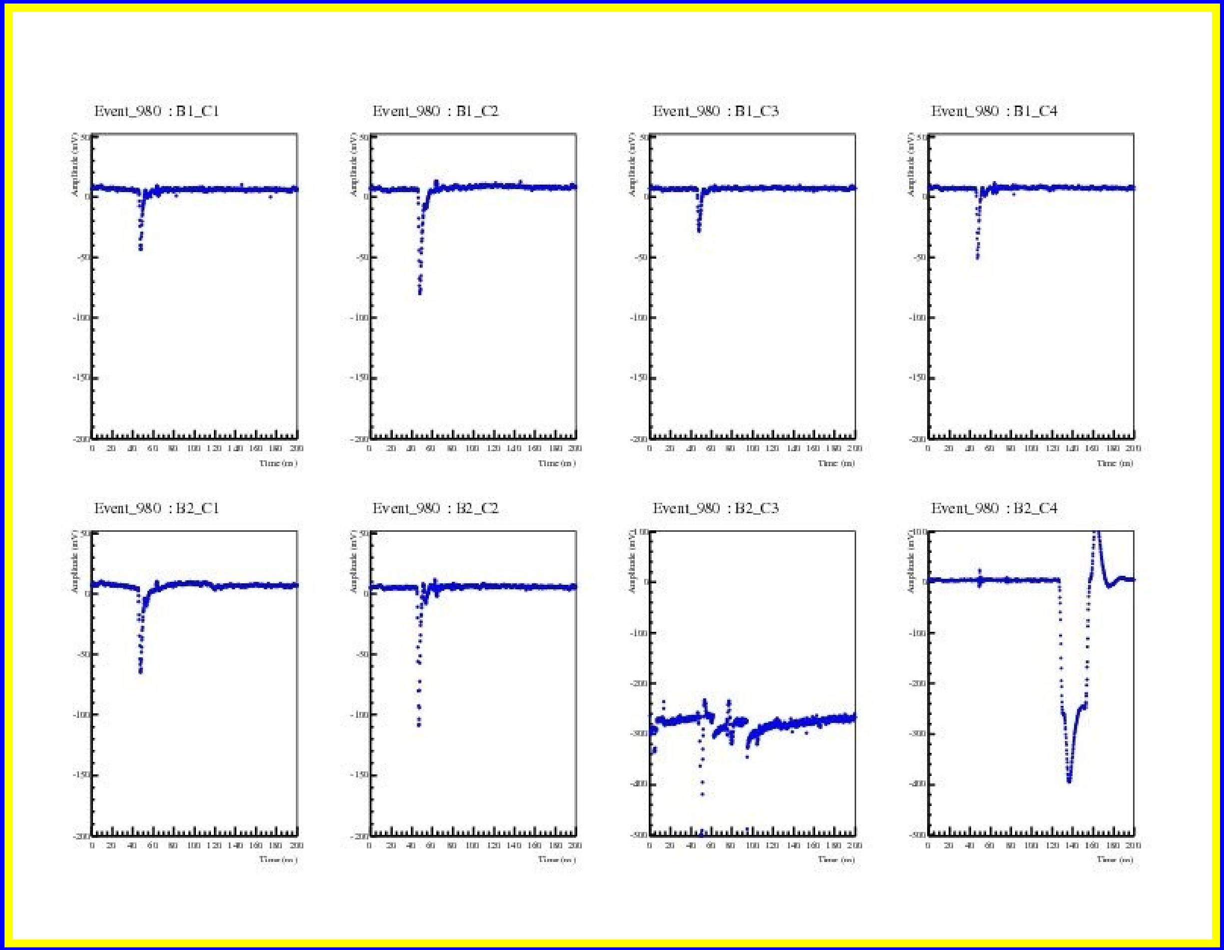
Veto counter
with hole

BEAM

Test beam arrangement for Q+SiPMs



One event, p through 6 Q+SiPMs → DRS4 "scope-guts" (200 ps/sampling). Fit 10% - 90% & extrapolate → 0 is fine.



Photek PMT240 ref.

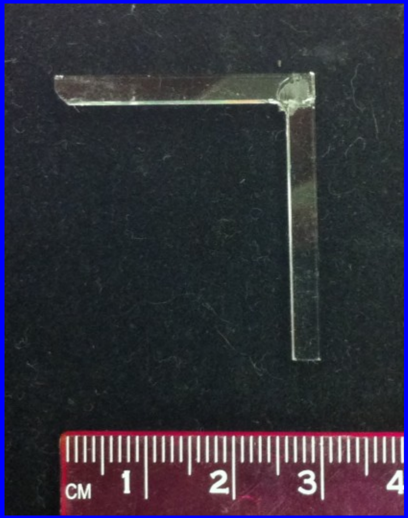
Trigger counter.

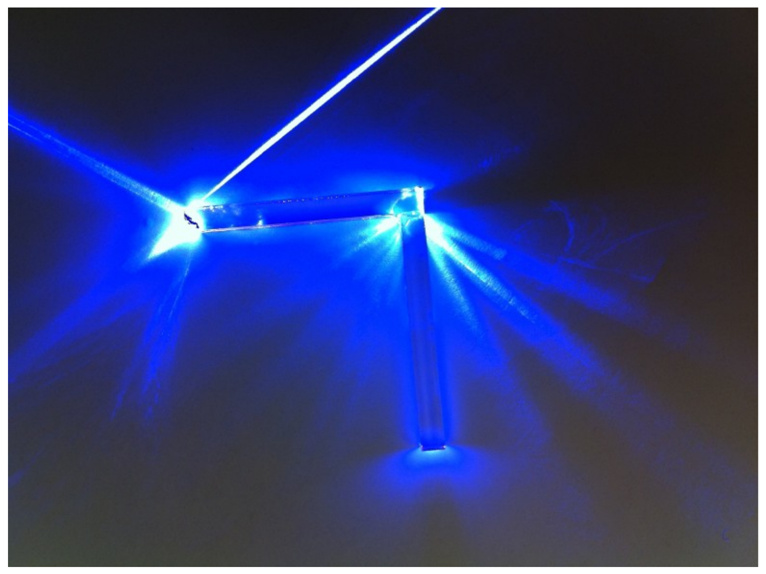
QUARTIC 48° bars + MCP-MPT:
2 give 11 ps but: MCP lifetime issue, multiple measurements

QUARTIC 0° bars + SiPM in line: Radiation damage to SiPM

QUARTIC 48° bars + SiPM: Tests recent, but as bars individually read out, 48° not necessary … smaller angle → more light.

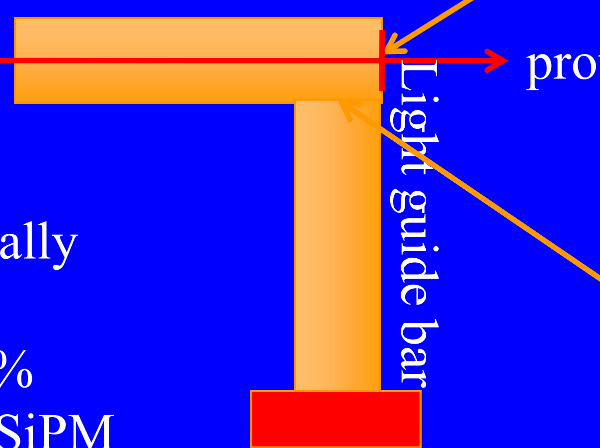
New solution: L-Qbars + SiPM: 68% collected, SiPMs away from beam





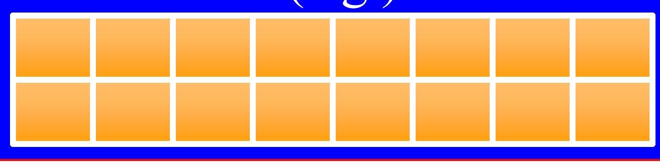
The Q-L-SiPM configuration
"Lbar QUARTIC"

May 17th 2011



All Cherenkov light is totally Internally reflected along radiator bar and about 66% goes along light guide to SiPM

Front view : 2mm x 2mm (e.g.)

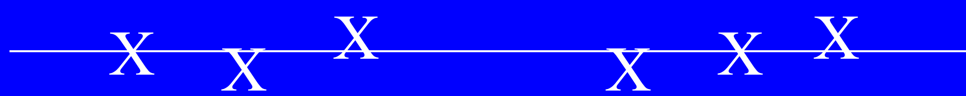


Hodoscope of 3mm x 3mm or 2mm x 2mm independent elements
Can repeat N times in depth for sqrt{N} improvement (timetrack)

For FP420: Notion of "TIMETRACKS"

Particle tracking in space: Many measurements and fit a track.
$1/\sqrt{N}$ improvement

Typical HEP ToF: measure once, $t_1 - t_2$
FP420 application: Have space behind tracking for several timing detectors. Small (6mm x 20mm) and can afford many.


(Could have drawn at 45deg!)

HPS Baseline: GASTOF + 2 QUARTICS
R&D continues: SiPM arrays
Combinations allowed:
(Cf CDF Tracking: Si strips + drift chamber + muon dc)

If large areas (many m^2) with ~ cm^2 pads, σ <~ 20 ps and thin

(Goal of ANL-Chicago-FNAL , Frisch inter alia group)

Two additional pile-up rejection possibilities for HPS

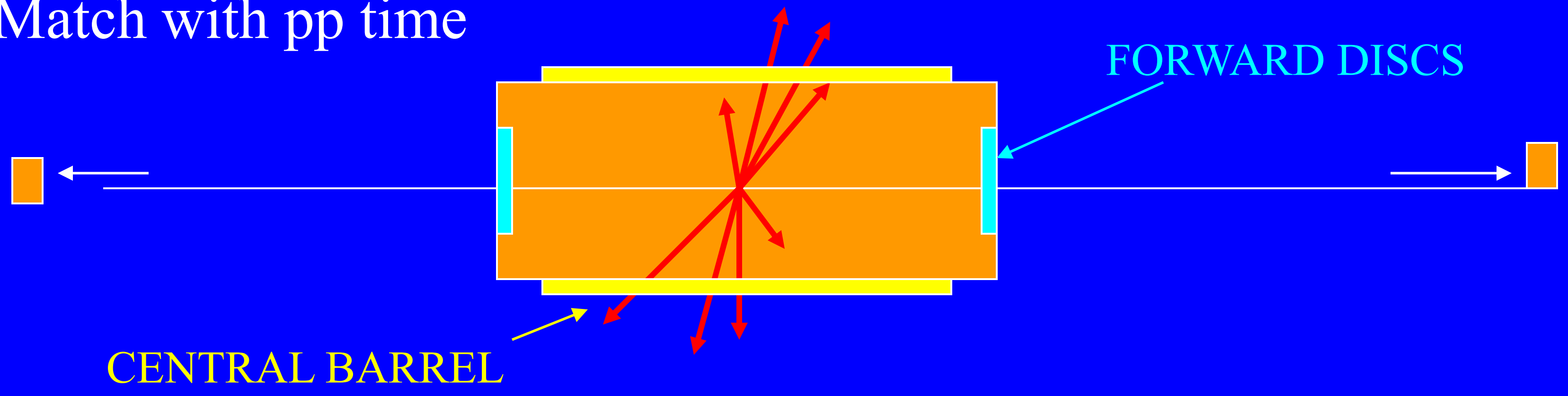
** Forward discs covering HF calorimeters, large $|\eta|$, ~ 1m^2
e.g. 10^4 pixels of 1 cm^2, timing all tracks that hit it.
Reconstruct collision time of those events.

They are pile-up background : NO tracks from exclusive H go forward

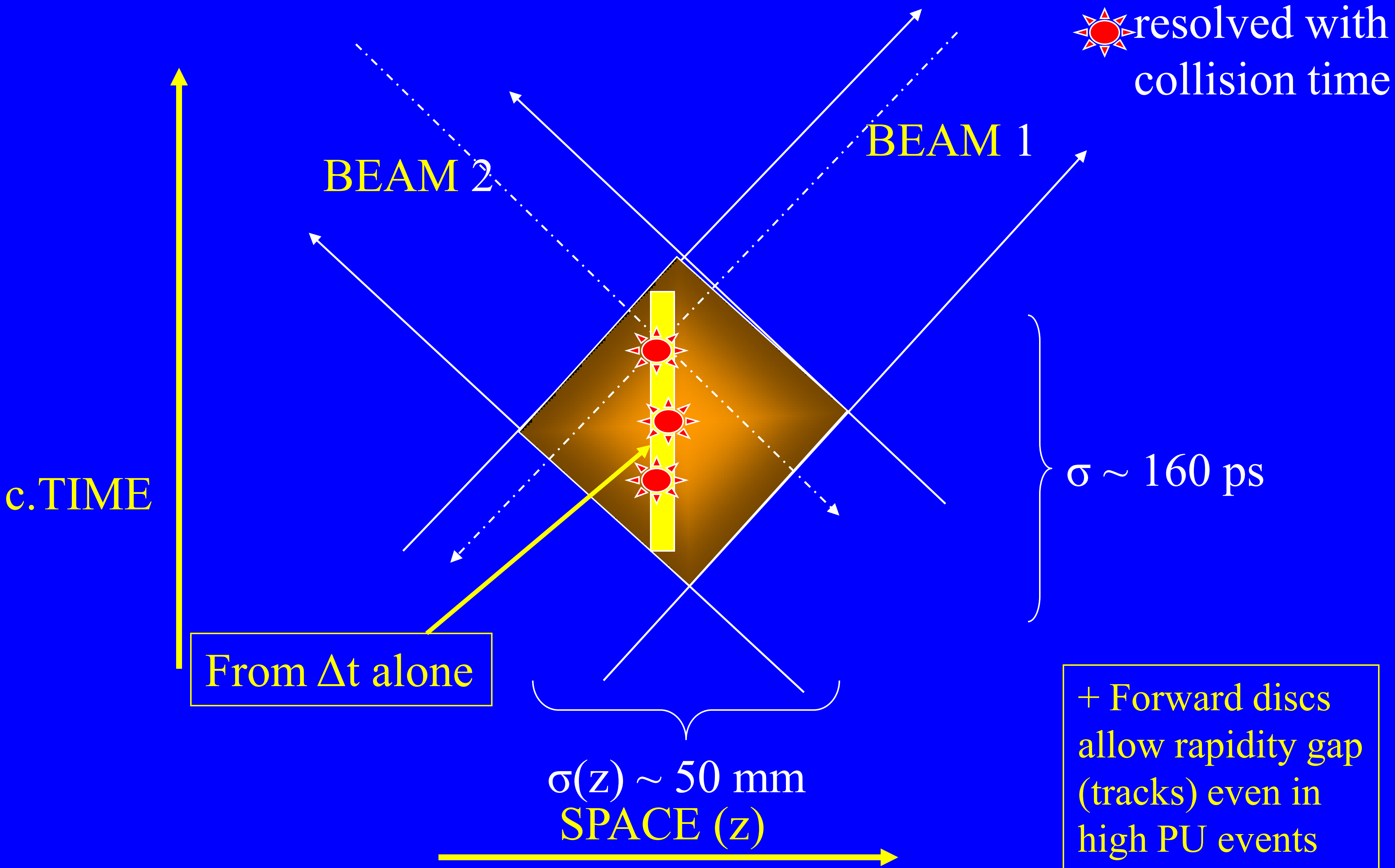
Central barrel (much larger)

Reconstruct collision time of dijet candidates

Match with pp time

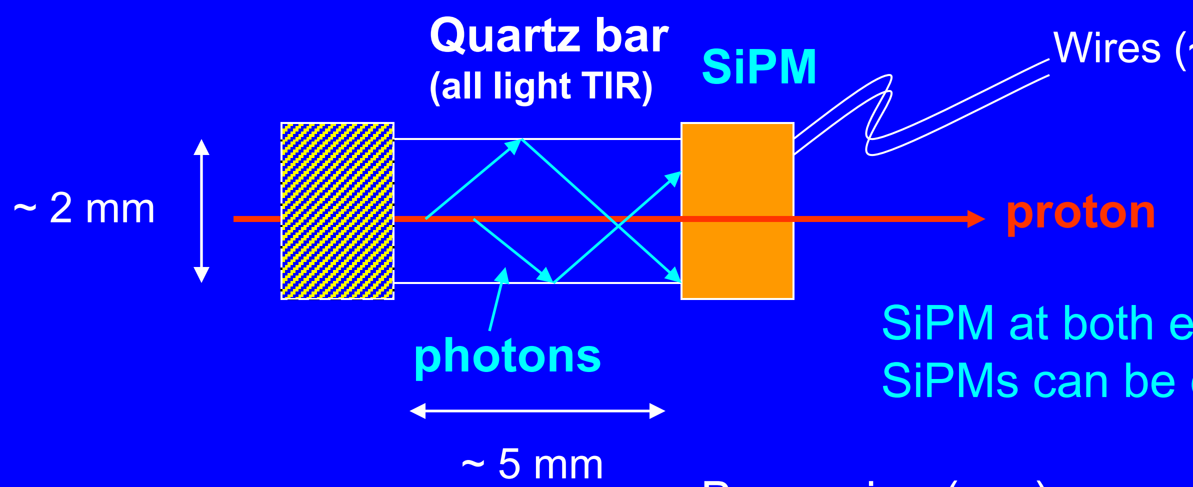


Three timing techniques each give a good factor in rejecting PU



+ Forward discs allow rapidity gap (tracks) even in high PU events

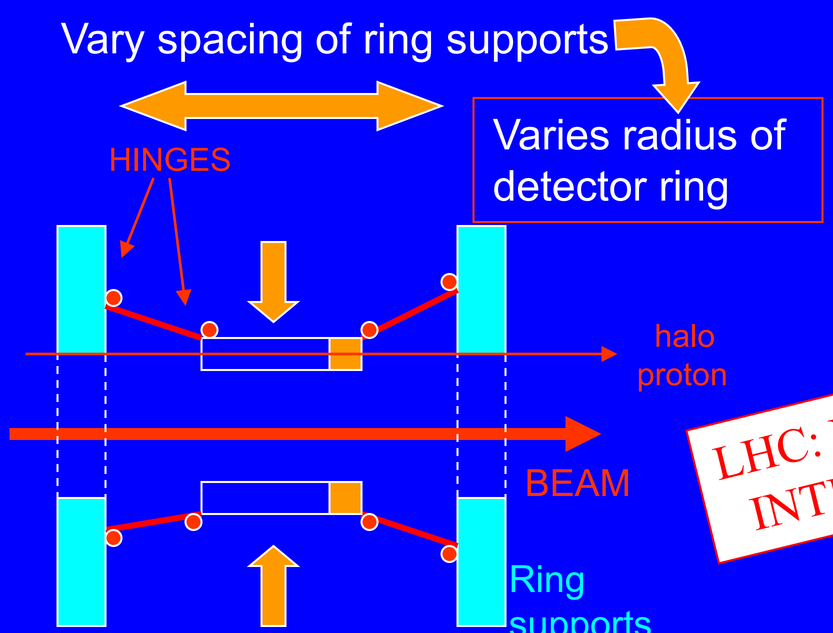
Qbar-SiPM as LHC (e.g.) beam halo monitors with good timing: f(R,φ,t)

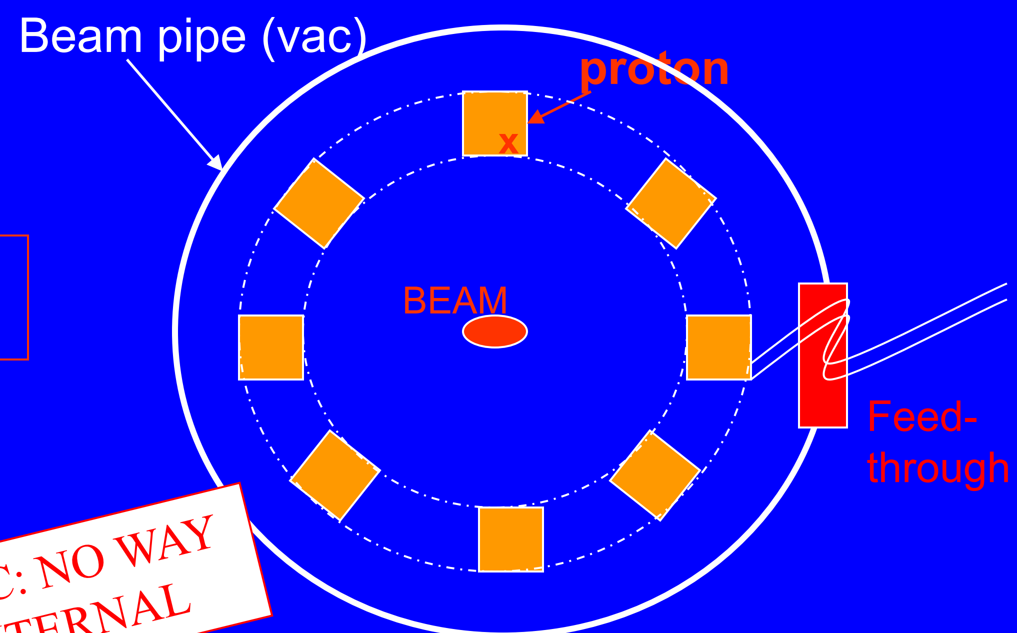


Doing studies with LHC instrumenation

SiPM at both ends if two opposite beams
SiPMs can be external (reflection)

Possible support scheme::





LHC: NO WAY INTERNAL

Transverse view

Detector ring may have x-y position control

May rotate to cross-calibrate detectors

Summary

Many HEP applications of fast timing ~ 10 ps (better is better)
In AFP/HPS projects at LHC it is:

Essential for p's (small area), have solutions:
Cherenkov Q-bars or gas or aerogel + MCP-PMT or SiPMs
Tested, some R&D issues to complete

Large area detectors can also give further pile-up rejection

Plenty of ideas to work with.

THANK YOU