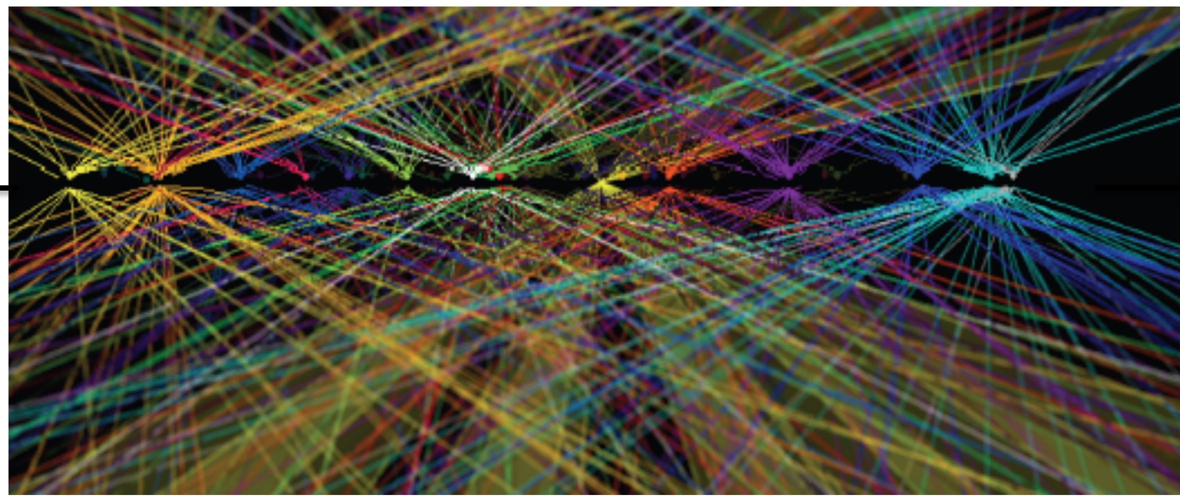
Fast Timing Detectors for the CMS-TOTEM Precision Proton Spectrometer CT-PPS

Michael Albrow (Fermi National Accelerator Laboratory, USA)

Fast Timing Workshop, Prague June 2015

~ 5 cm

p ← ~ 210 m



~ 210 m → p

$$p + p \rightarrow p + X + p$$

~ 30 – 40 interactions / bunch crossing … how to match protons to X ?

Kinematics (4p-conservation), Event characteristics, **TIMING of protons**

MAIN PHYSICS goals: Both protons measured, M_X(min) ~ 300 GeV

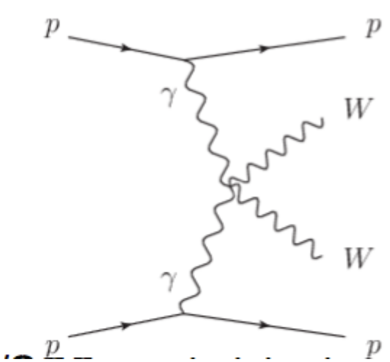
QCD

Exclusive dijets, M(JJ) to ~ 800 GeV. Pure gluon-jets, small (≈ 1 %) component of b-bbar dijets (need double tag). Test of **$J_z = 0$** rule. q-qbar dijets forbidden for massless quarks at t = 0.
Test of pQCD mechanisms of exclusive production, "superhard" pomeron.
Optimizing b-tagging … one b-jet means other jet is b-bar jet.
Measure exclusive bJ-bJ spectrum (important for later – H?)
[b-jet and homage to Bjorken!]

EWK

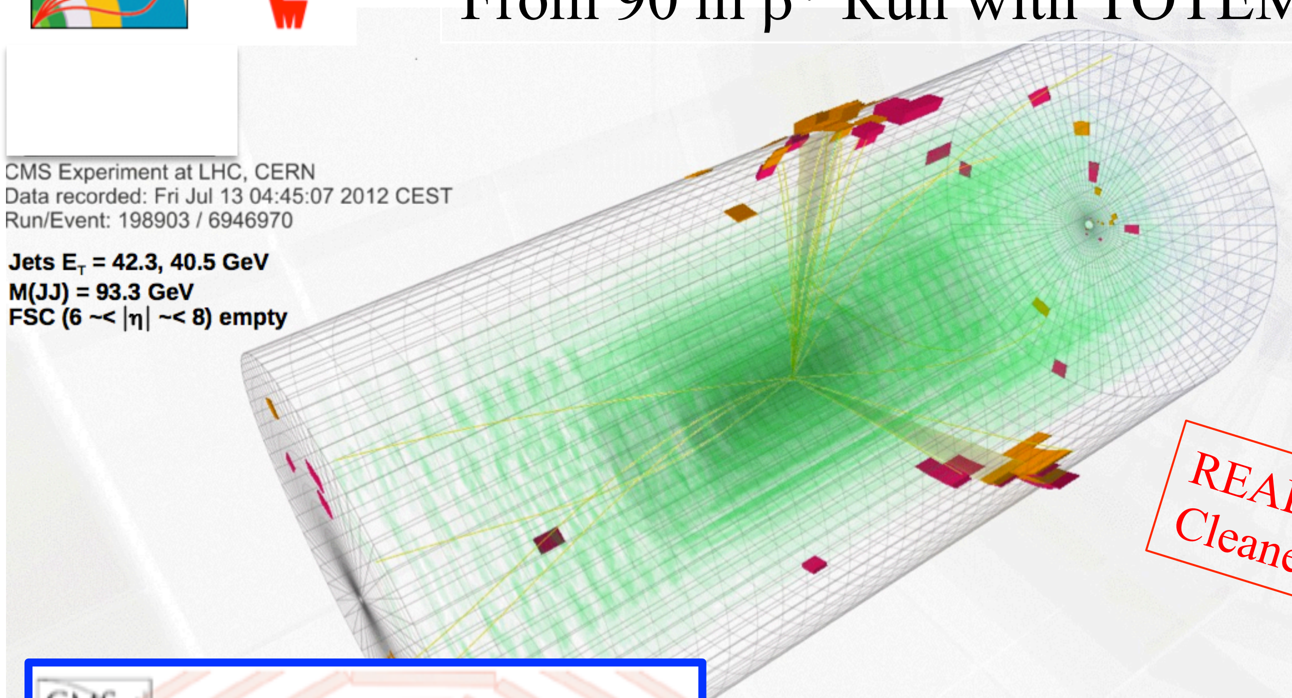
Measure $\gamma\gamma \rightarrow W^+W^-$. Anomalies in WW final state interactions (but transverse, so H should not appear in $\gamma\gamma$ channel). Triple, quartic gauge boson couplings: Most sensitive searches (>> LEP)

& a new window for potential surprises

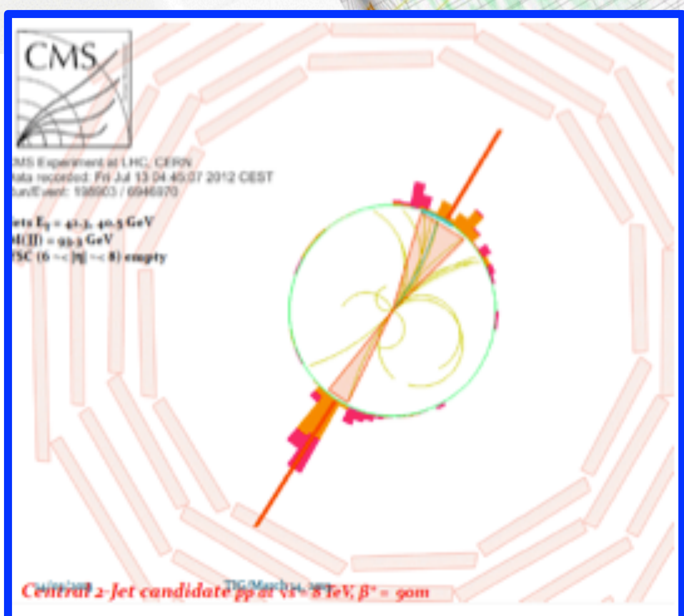


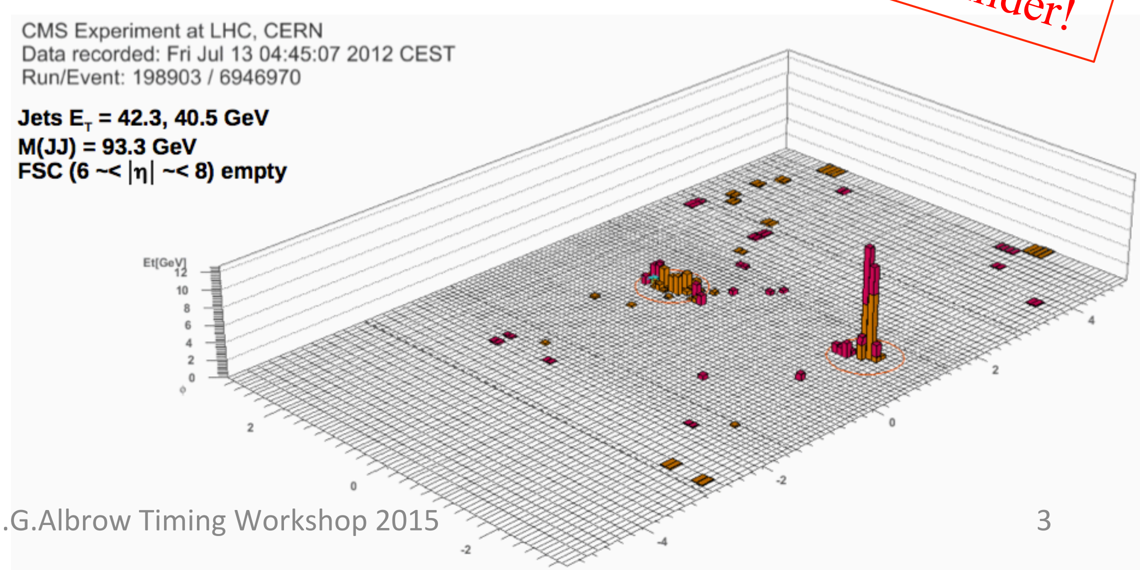
Very clean (exclusive candidate) jet events

From 90 m β* Run with TOTEM: p + JJ + p

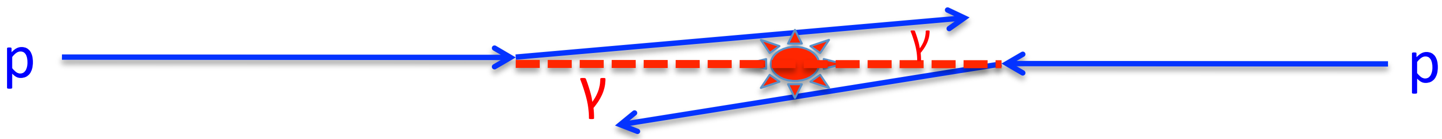


REAL CMS+TOTEM EVENTS!
Cleanest dijets in a hadron collider!

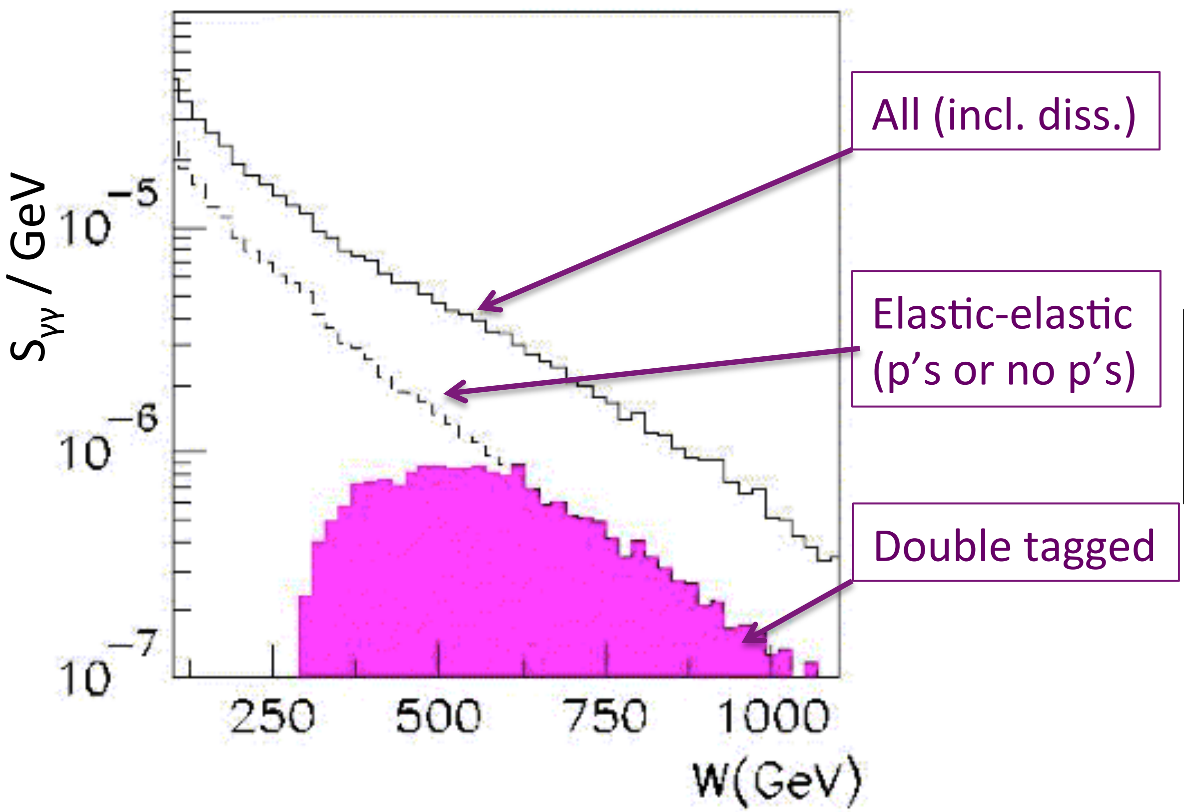




LHC is a Photon-Photon Collider



Coulomb field is long range
Protons can pass at a few fm
& emerge with small p_T
(intact or dissociated)



$W_{\gamma\gamma}$ = centre-of-mass energy of $\gamma\gamma$ collisions ... hundreds of GeV. >> LEP

UNIQUE until ILC/CLIC

Tagged photon-photon luminosity spectrum
example: 2 mm from beams at 14 TeV
From K.Piotrzkowski, Phys.Rev D63 (2001) 071502

STATUS of CT-PPS

Project to **add to CMS precision tracking and timing detectors at $z = \pm 204 - 215$ m with TOTEM** in new Roman pots, capable of operating at **high luminosity** (normal running) to study $p + p \longrightarrow p + X + p$ events.
Collaboration of CMS and TOTEM.

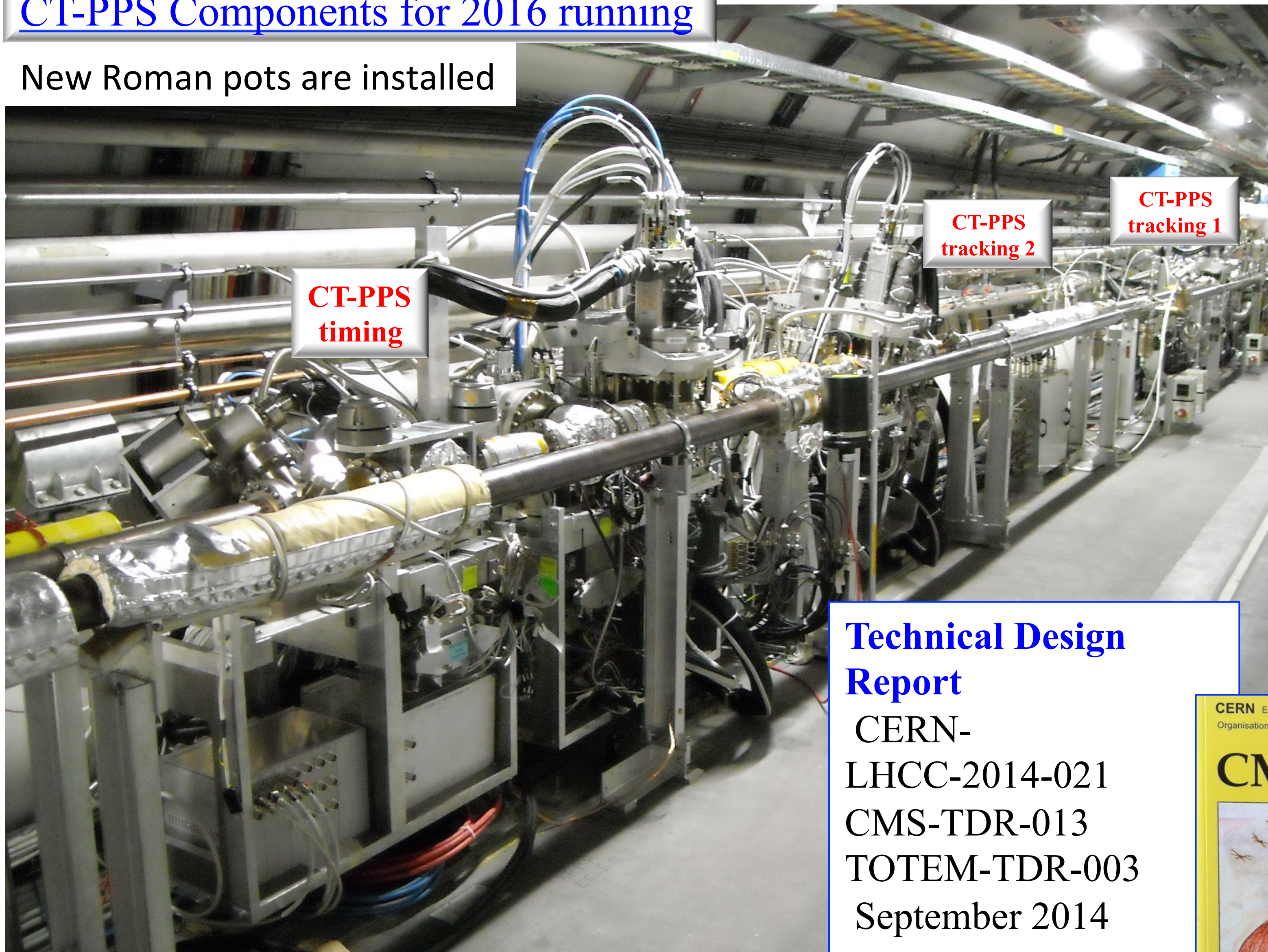
CT-PPS project is **approved** by both CMS and TOTEM managements and by the LHCC and Research Board.

2015 : Construction, and beam tests: Roman pot operation at high luminosity.
January 2016 : Installation of detectors at 204-215m in both directions
2016 : commissioning and first physics data

2016-2017: Physics : $M(X) > \sim 300$ GeV … WW, Jets etc.
Aim for **100 fb^{-1}** data before 2018(?) shutdown

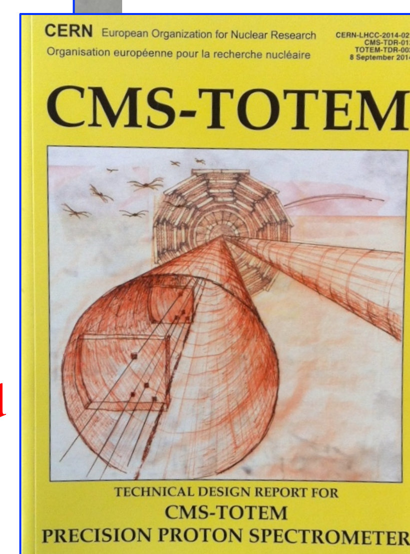
CT-PPS Components for 2016 running

New Roman pots are installed

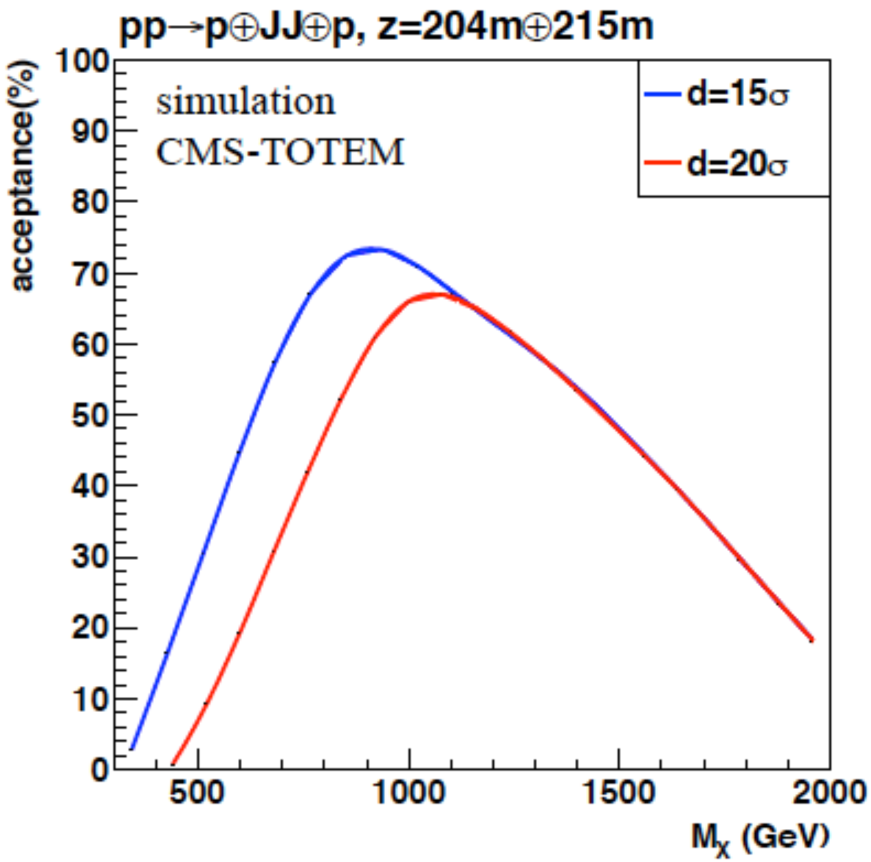


Technical Design Report
CERN-LHCC-2014-021
CMS-TDR-013
TOTEM-TDR-003
September 2014

Now have LHCC and Research Board approval



Mass acceptance for two arm events



Want 2 – 3 mm from beam center!

Good for
W^+W^- and Jet + Jet (+ Jet) and
BSMH(400-800)

Closer to beams gains low mass acceptance

Acceptance is very similar for W^+W^- (Smaller |t| because γγ)

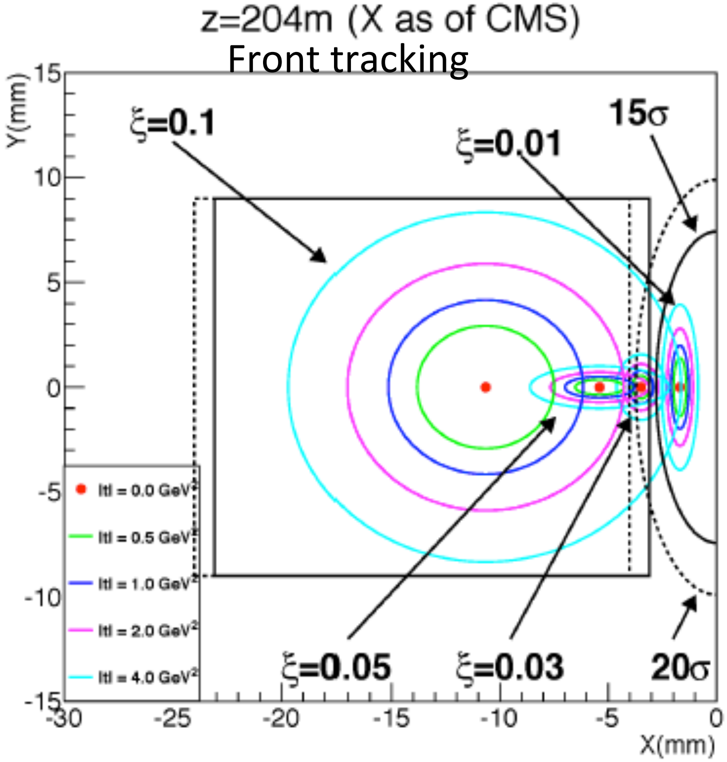
Is acceptance possible for **p + H(125 GeV) + p**? Need z = ± 420m detectors – FP420 project 2005 ++ meetings. Not proposed to CMS at this time.

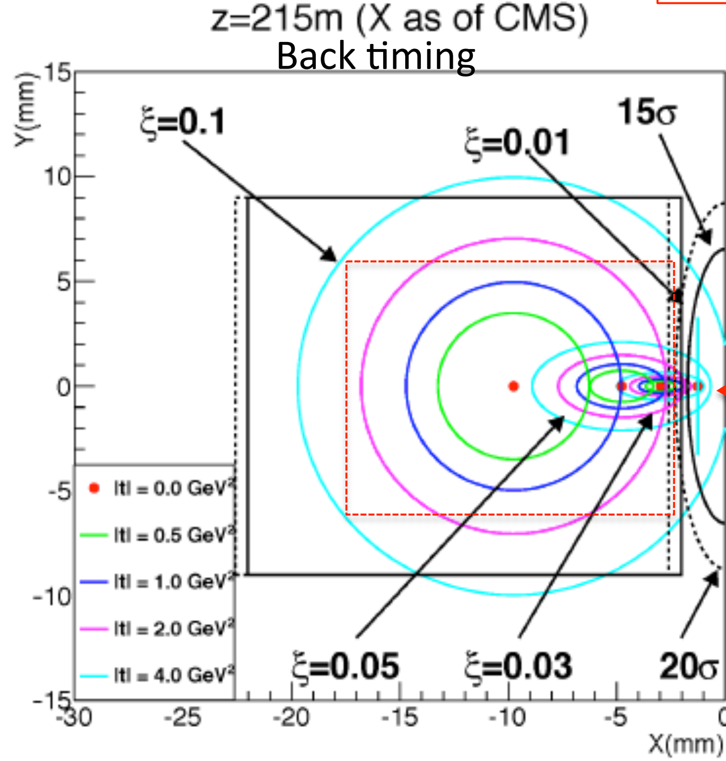
Where are wanted protons in the detectors at 204 m, 215 m ?

Transverse view ("proton's view")

$t \sim -p_T^2$ and $\xi = 1 - p_z/p_{beam}$

$\beta^* = 0.55$ m



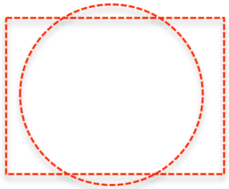


γ-emission, small-t

p has y ~ 0

Timing detector design 15mm x 12mm

Circle is $\xi = 0.1$, $t = -2$ GeV^2



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 ~ 30-40 collisions in 150 ps X

Detectors: QUARTIC = QUARtz TIming Cherenkov
Quartz bars with SiPM photodetection (baseline) or MCP-PMT later?

Goals : $\sigma \sim 10$ ps, edgeless, rad-hard ($\sim 10^{15}/cm^2$), readout every 25 ns
Area only ~ 15mm x 15mm
with x-y segmentation for multi-hit capability

TIMING is essential for PU rejection.

$z(pp, ToF) = c.\ \Delta t(pp)/\sqrt{2} = 2.1$ mm / 10 ps

$\sigma(t) = 20$ ps → $\sigma(z) = 4.2$ mm IFF from same interaction

Two protons are 440 m apart: good reference time "clock"

As well as high time precision proton detectors

Without the development of good timing detectors the project could not have been proposed.

Requirements:

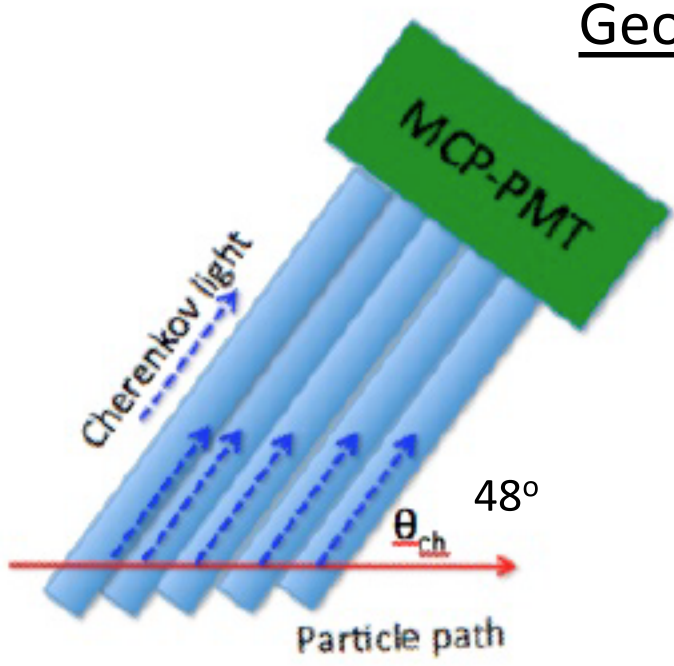
1) Excellent time resolution ($\sigma(t) \sim 20$ ps → 10 ps)
2) Edgeless on beam side ($\Delta x \sim 200$ μm)
3) Radiation hard close to beam ($\sim 10^{15}$ p/cm^{2})
4) Fast readout (25 ns crossings) --- & trigger signal
5) Segmentation (multi-hit capability)

Solution developed: Quartz bars for Cherenkov light with Silicon PMs (SiPMs)

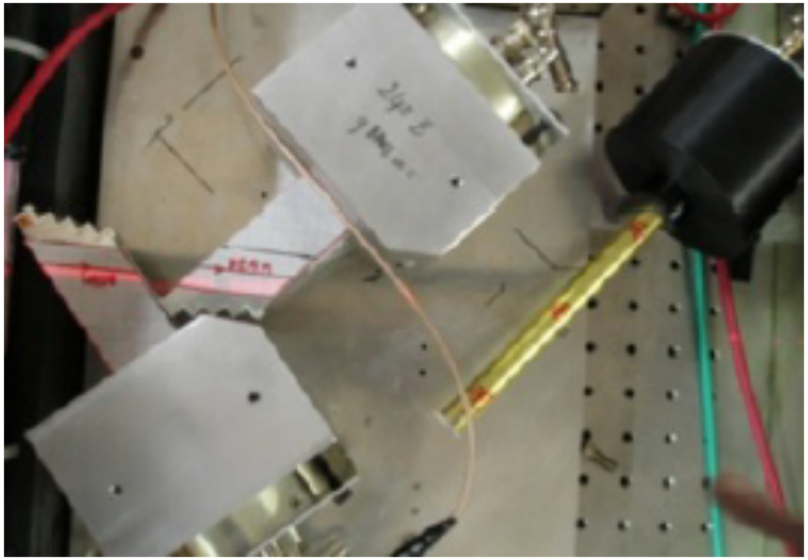
QUARtz **TI**ming **C**herenkov = QUARTIC

QUARTIC: see
M.G.Albrow et al.,2012 J.Inst **7** P10027

Geometry 1: angled bar QUARTIC

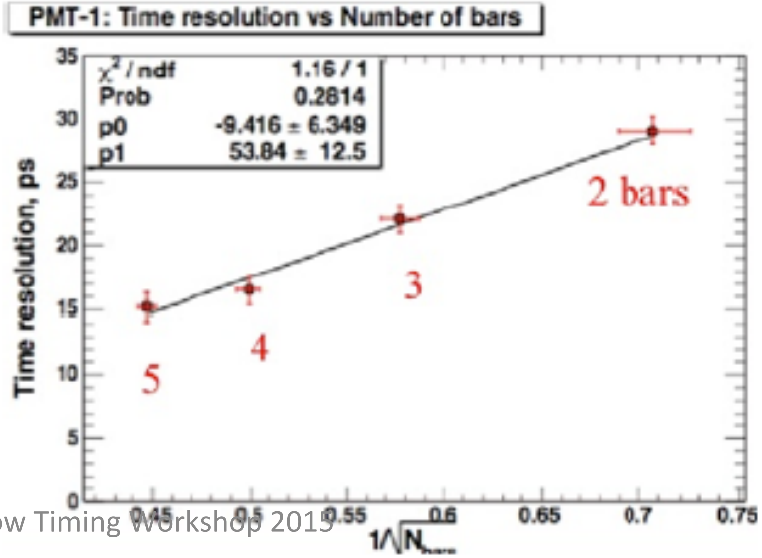


Angled Multi-bar QUARTIC



Set-up in Fermilab, with PMT240 (2 MCPs, 40mm diam)
> 20K$ each! Not segmented.

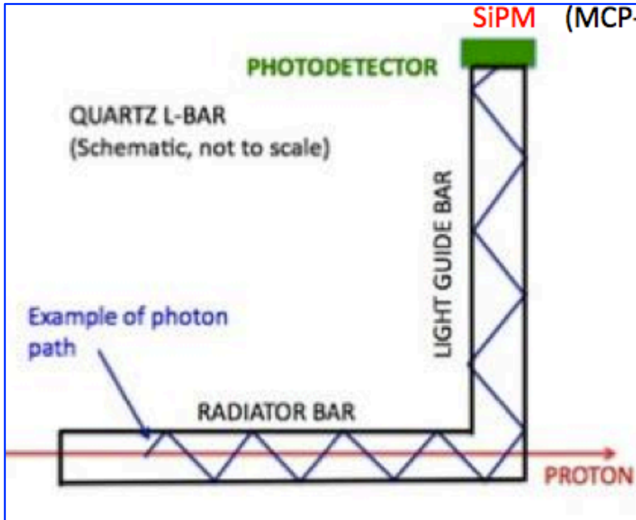
Resolution vs # bars:
2 modules → 10 ps



Need segmented anode.
MCP-PMT Lifetime limit, now "solved"
This geometry pursued by ATLAS
AFP project with improvements.

Changed to a different Cherenkov geometry : L-bar

If particles are very parallel to a bar (R) axis (and they are) all the Cherenkov light is totally internally reflected (TIR) to the back.
If refractive index n > 1.414 (√2) ~ 60% reflected up bar at 90° (LG) – no mirrors!



L-BAR QUARTIC: LBQ

Principle: All Cherenkov light is totally internally reflected to back of radiator bar. ~ 2/3 goes up light guide bar promptly, rest folllows.

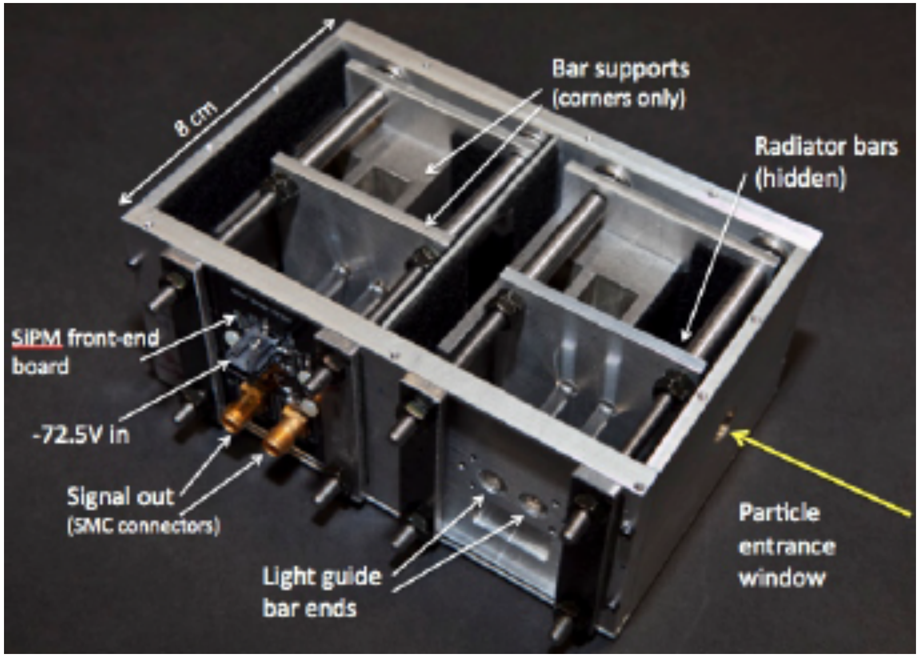
Total Internal Reflection:
Bars separated by fine wire (100 um)

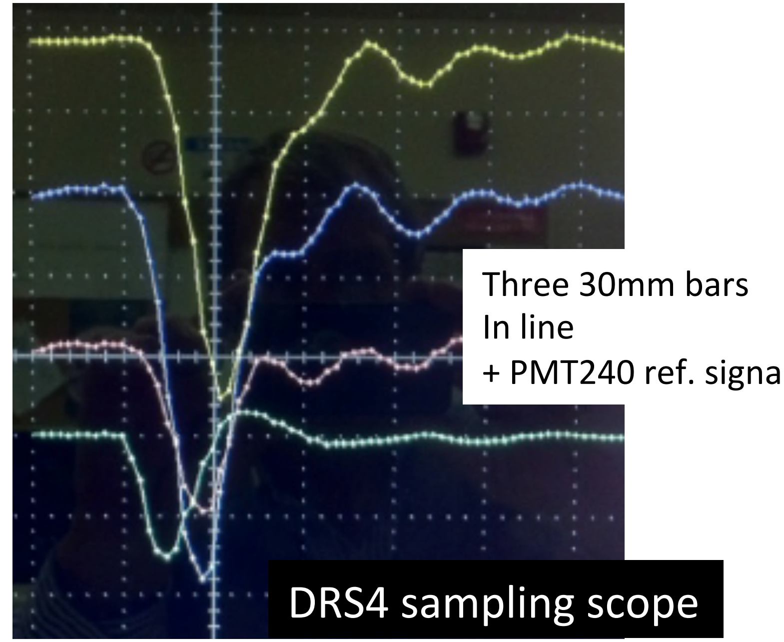
In 3D space its more complicated, but it still works! GEANT simulations.
Light Guide bars positions photodetectors away from the high radiation beam proximity.

One can make a close-packed array of such bars (x,y matrix) separated to maintain TIR.
I use just 2 ~ 1 mm^2 separating foils (wire option tricky)

Array of SiPMs can be spaced out. Could be replaced by long-life MCP-PMT (better timing)

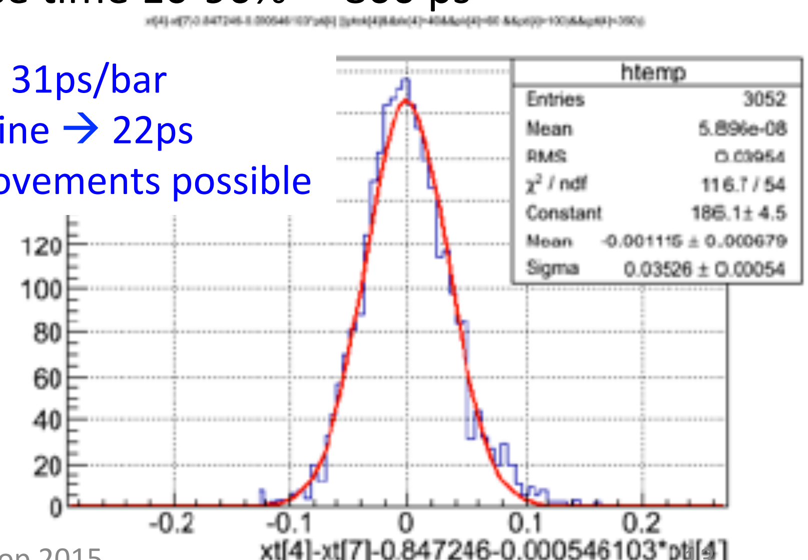
Prototype for beam tests (2 in line- 4 bars)





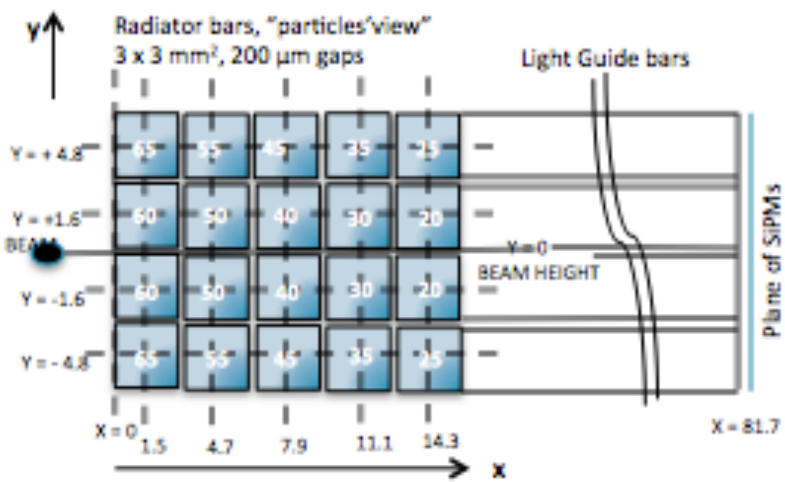
Scope traces, 1 event. 2ns/div, 20mV/div
Rise time 10-90% ~ 800 ps

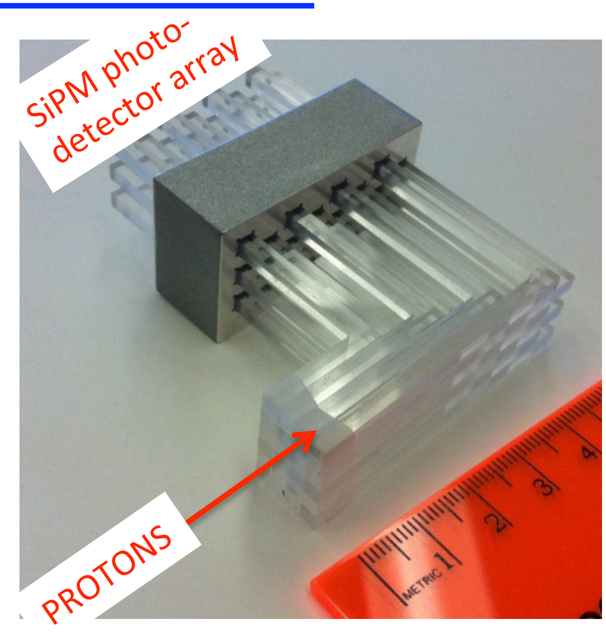
σ(t) = 31ps/bar
2-in-line → 22ps
Improvements possible

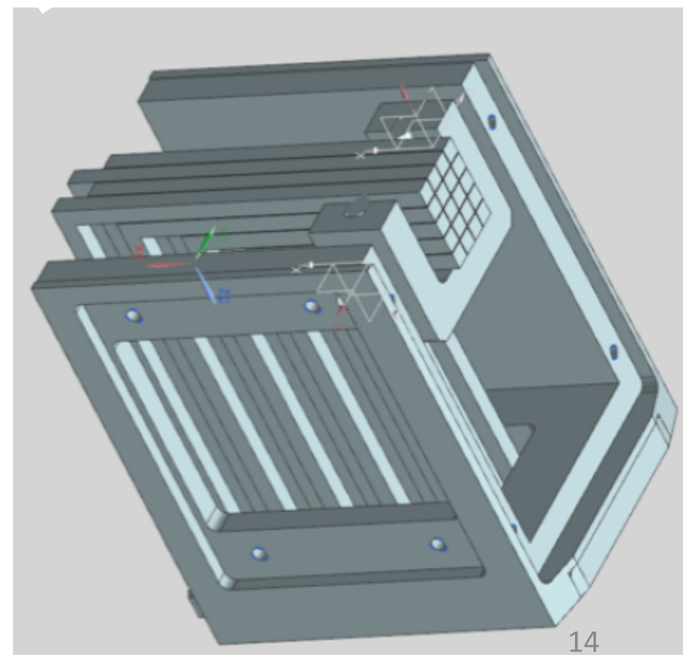


QUARTICs chosen as baseline timing detector for CT-PPS

- Cherenkov light in quartz bars
  - n=1.475, θ=47.3°, at 350 nm.
  - ρ=2.20 g·cm^{-3}, λ_I = 44.5 cm.
- Quartic module:
  - 4x5=20 3x3 mm^2 bar elements
  - 100 µm small Al pads separating the bars
  - active area is 12.6 mm x 15.8 mm

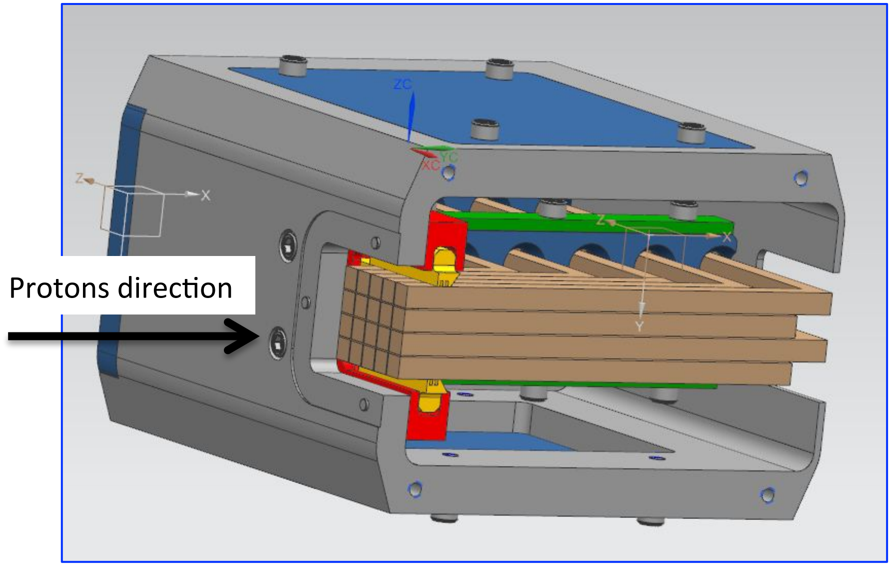






Further developments for 2015:
L-bars + long life multi-anode MCP-PMTs
Finer segmentation. Materials (e.g. sapphire)

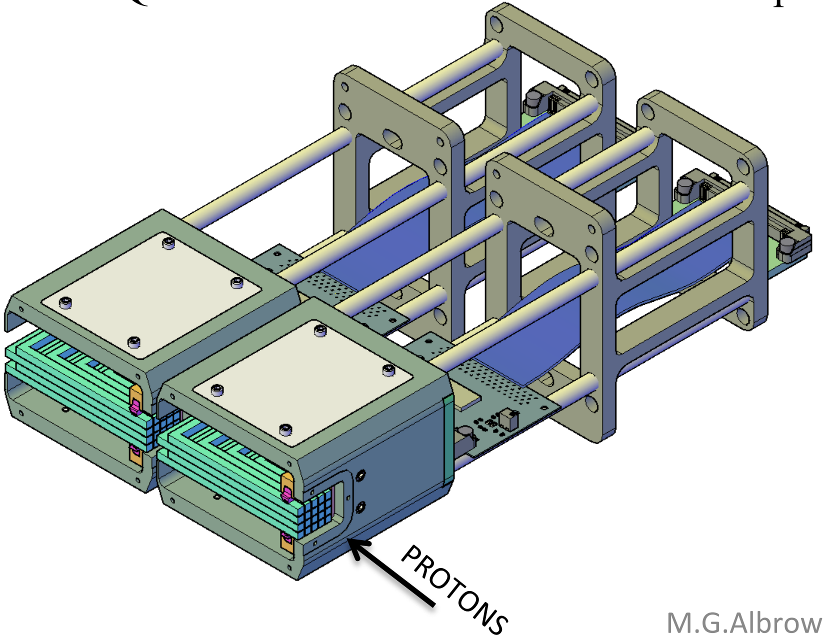
QUARTIC (QUARtz TIming Cherenkov) baseline for timing



Active 0.4 mm from *inside* beam pipe.
Two modules in one Roman pot.

View from bottom of pot.
4 x 5 array of 3mm x 3mm quartz L-bars (shown in brown)
Hidden: Front end board with SiPM array

Double QUARTIC module inside one Roman pot



Borated polyethylene block w/holes for LG bars between two precision bar-positioning plates.
Inside black anodised for stray light absorption.
200 μm wires between bars and bottom of pot

Status : Prototype made
Beam tests next week at Fermilab
Two or more in August at CERN with DAQ.
Four ready for January installation in tunnel.

Beam Tests at Fermilab June 2015 : goals

Sorry not to have results to show yet, workshop is two weeks too early!

For 120 GeV protons (β = 1) measure pulse **waveforms → pulse height and time resolution**
For 10 quartz bars (different lengths) and 10 sapphire bars (ditto).

Measure **cross-talk between bars** … signal ideally should be contained in one bar.
Check **uniformity** over 3 x 3 mm^2 area (using MWPC tracking) and through 100 μm spaces.
Measure signals with beam crossing **light guide bars** (3mm) … can be included?
Measure **angular dependence** over a few degrees from bar axis

Replace SiPM array with a multi-anode (8x8 6mm x 6mm anodes) Burle-Photonis **MCP-PMT**
… test 4 quartz bars and 4 sapphire bars.

Compare all results with GEANT simulations.

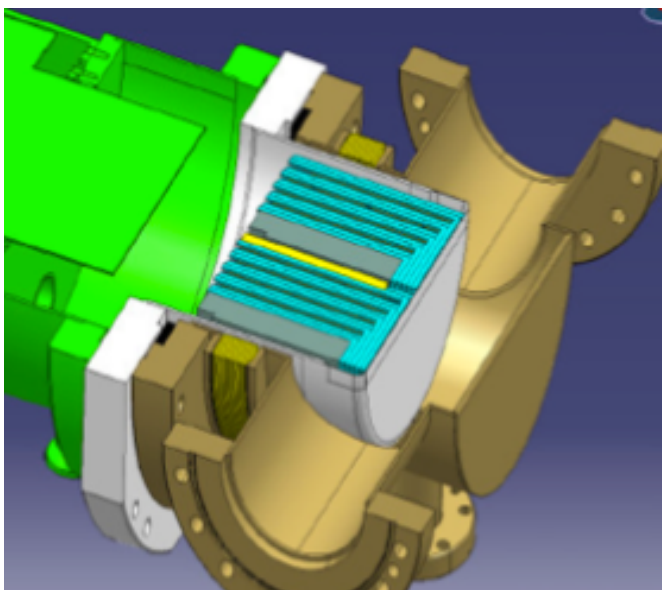
This "prototype" module should be real #1
Main concern is optical cross-talk, method of spacing bars by 100 μm with ~mm^2 Al pads
If it is a problem, is there an opaque surface covering that has very high reflectivity?
(Have ~ 50 internal surface reflections in some bars)

Roman pots

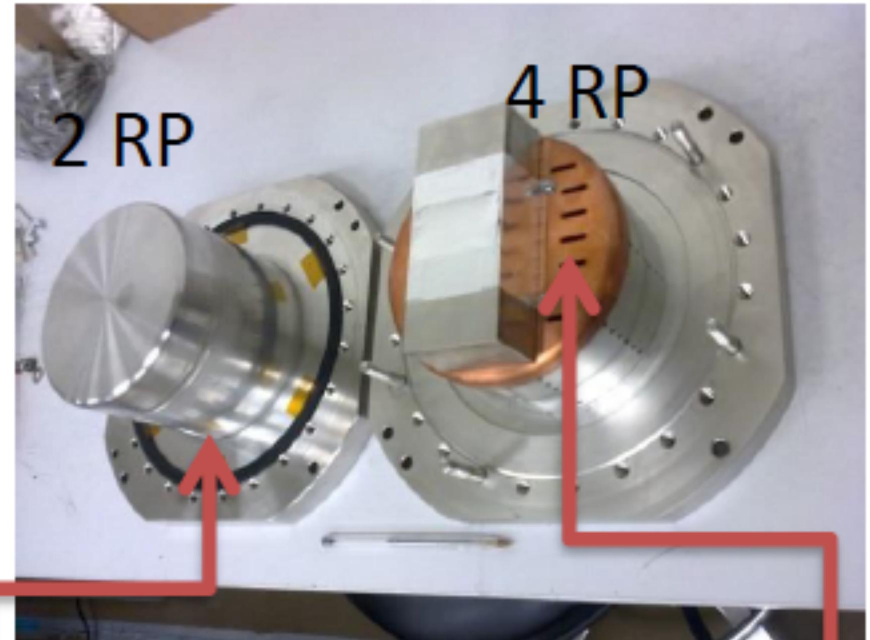
(named for CERN-Rome expt. at ISR (1971))

Previous TOTEM Roman pots could not be used with high beam currents: Impedance mismatch affects beams.

New cylindrical design ameliorates that. Should operate with normal high-L operation … as planned for CT-PPS



Cherenkov bars (timing) shown in blue



New cylindrical Roman Pot & RF shield for box Roman Pot

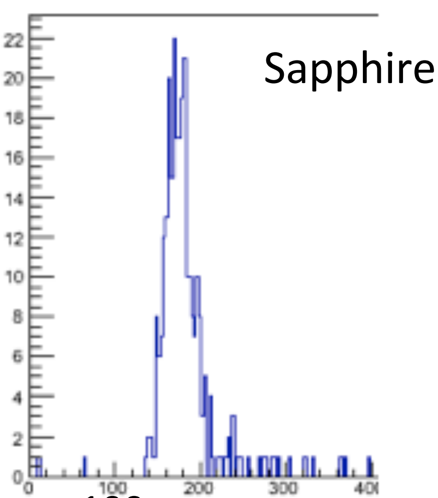
New pots (in horizontal plane) are installed.
Insertion tests to do this year.
How close can we go (3mm?)
Effect on stable beam, backgrounds generated, heat generated …

Quartz bars (default) or sapphire?

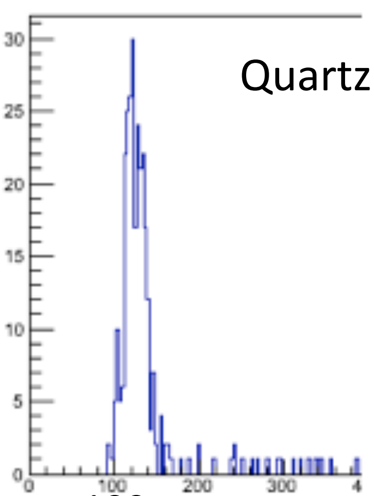
Blue favours sapphire : red favors quartz

Sapphire has higher refractive index, about 1.89 – 1.77 for λ = 200nm – 600nm (cf ~ 1.48 for Q)
So more Cherenkov photons / cm,
but θ_{Ch} higher so more reflections/cm (radiator) and longer light path in radiator.
But with L-bar geometry fewer reflections/cm of light guide and shorter light path.
Higher chromatic dispersion increases spread in light collection time

GEANT simulations of optics (Vladimir Samoylenko, IHEP)
Radiator bar = 40mm, Light Guide bar = 80 mm, realistic other assumptions



100



100

Number of photoelectrons

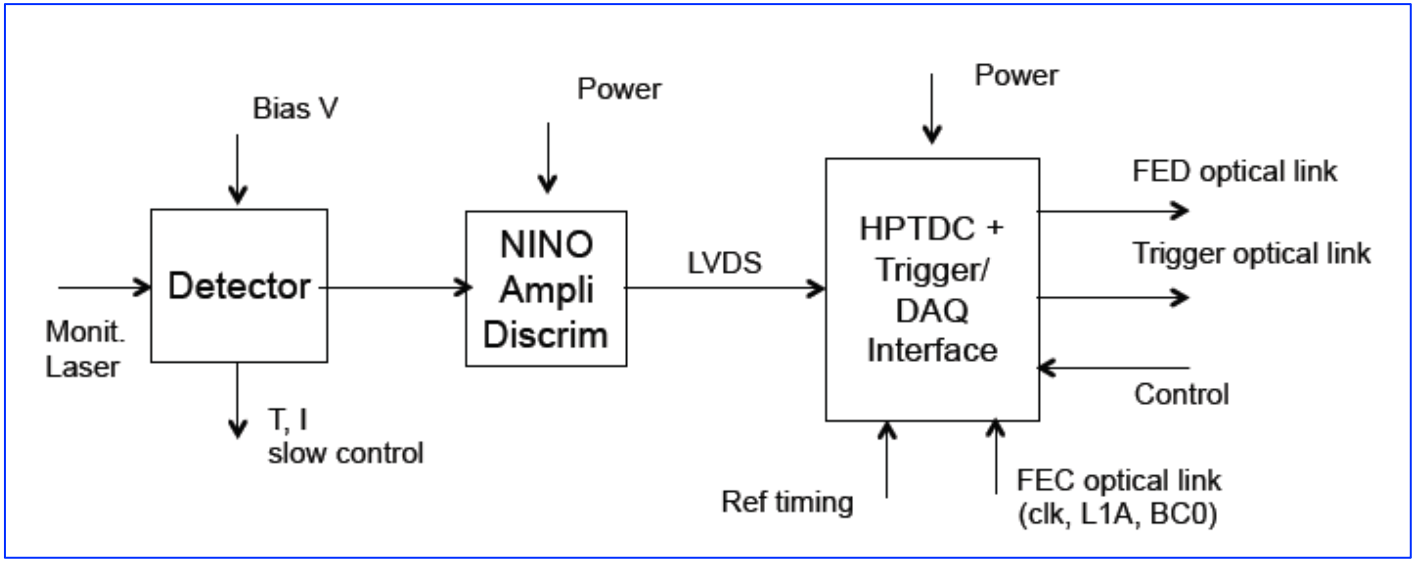
Time resolution for 1st 20 p.e.'s
Is 10 ps (S) cf 13 ps (Q) before electronics.

Other considerations:
Sapphire (clear, looks like quartz) cheaper!
Harder material and easier to machine.
But nuclear interaction shorter so more ints.

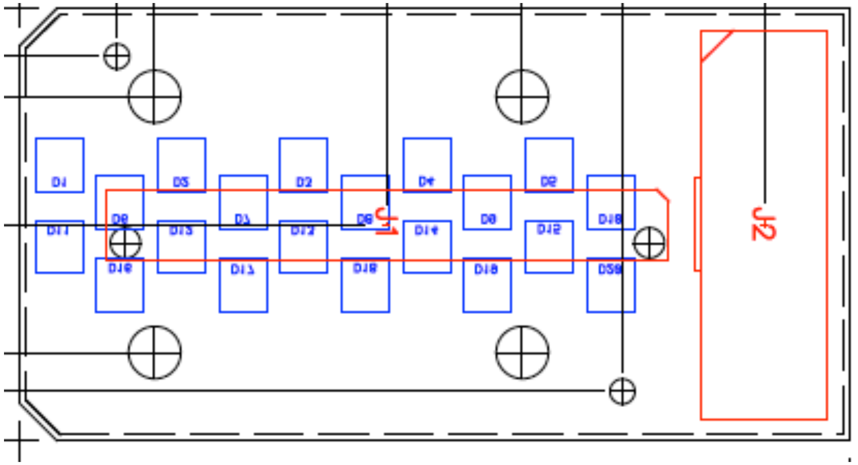
Will make direct comparison in beam.

TIMING Readout

Schematic

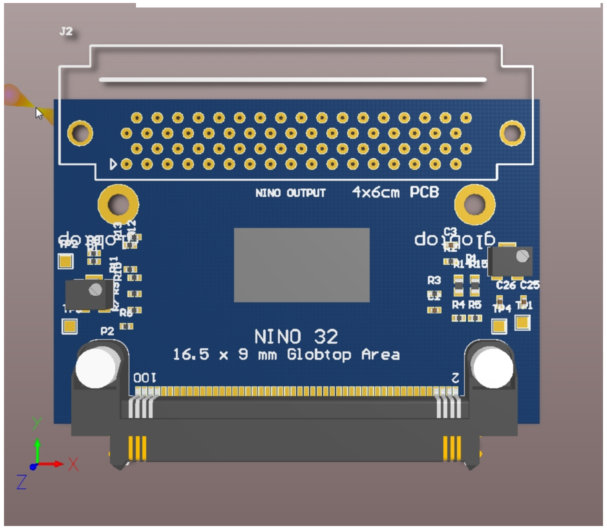


20 channel SiPM Mounting Front End Board



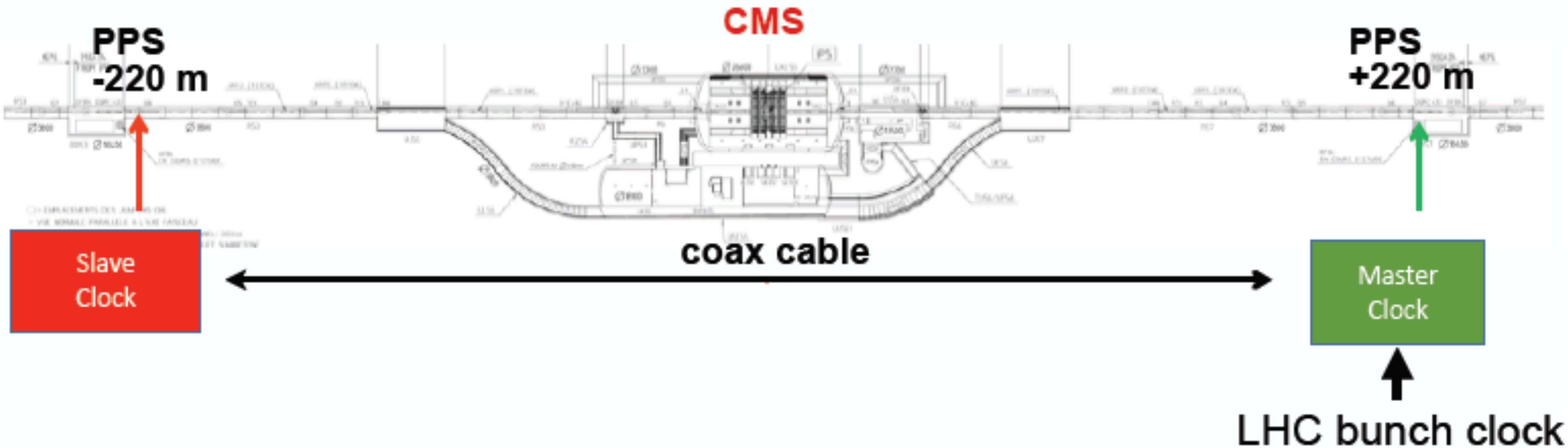
LV, Leakage current, temp and pressure monitors

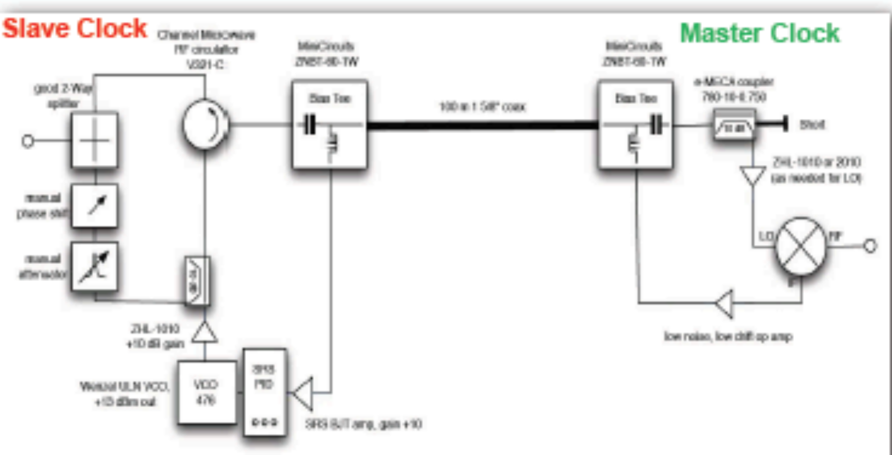
NINO board
Fast amlipfier-discriminator



Reference Timing System using RF Cable

Need Δt = tL – tR for z(interaction). Synchronized clocks (few ps) at L and R stations





- RF cable with feedback to keep clocks at each end in sync.
  - Based on system used at SLAC for LCLS experiment. 2 timing systems have been deployed and have operated continuously without a single failure for a combined time of seven years. LCLS experiments typically last 10 months out of the year
- LHC bunch clock is input into master.
- Output of master and slave will be input to TDCs

Another system based on optical fibers is being implemented. “Belt and braces”

Plans and Schedule

During 2015: Roman pots for timing detectors are installed at 220 m
Insertion tests will be done with end-of store beams:
How close can they go without generating background or effects on beam?
Establish *modus operandi*

One 20 channel Quartic "prototype" is made, ready for beam tests:

1) Proton beam at Fermilab June 17-23 with DRS4 (5 GHz scope) readout
2) Have two ready for beam tests August 4^{th} at CERN with NINO amplidiscr + HPTDC readout
3) Have all four (2+2) to CERN for Sept/Oct beam tests
4) Plan to install 2 + 2 in LHC in January 2016
5) Commissioning in LHC (weeks?) end-of-fill studies
6) Then aim for 100 fb-1 physics before LS2

Summary

The addition of small high precision tracking and timing detectors to CMS together with the TOTEM Collaboration, CT-PPS opens up a new field of physics:

p + X + p with both p's and X all measured, at high lumi ($\mu \sim 30$, depends on X)

Fast timing essential to suppress pile-up background at high luminosity.
Scattered protons measured with precision 3D-silicon pixel detectors → momentum
6 tracking layers in Roman pots 10 m apart → ~ 1 μrad on angle.
Behind is a Roman pot with two QUARTICs for timing, $\sigma(t)$ = 20 ps initially
A second Roman pot is allocated for other eventual timing detectors (high granularity?)

Suitable detectors are planned for installation in new (now installed) R.pots in January

Aim for physics in 2016, run to LS2 and possibly beyond.

Thank You

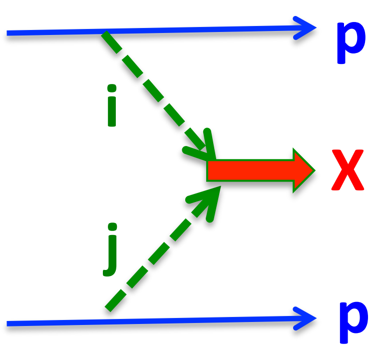
CT-PPS as addition to CMS

"Exclusive" reactions have the form: $p + p \longrightarrow p + X + p$

where X is a fully measured state in the central region, the p are leading ($x_F > \sim 0.9$) and no other particles are produced (rapidity gaps Δy exceeding about 4 units)

Allows the LHC to be used as a "tagged" photon-photon collider $\sqrt{s}(\gamma\gamma) >> \text{LEP}$
... and as a "tagged" gluon-gluon collider (with spectator gluon)

...enabling an extension of the CMS and TOTEM physics programs into a new regime
..... both **QCD** and **EWK** physics



The 4-momentum transfer in the t-channel is small, typically < about 1 GeV^2, so $\theta(p) \approx 1/7000$ & p's go down pipe. With this kinematics only γ and IP exchanges are allowed:
i + j = γ + γ,   γ + P or   P + P
where **P = pomeron** is a strongly interacting color singlet, at leading order a pair of gluons [gg]. **QCD, needs study!**

Other types of timing detector being developed:

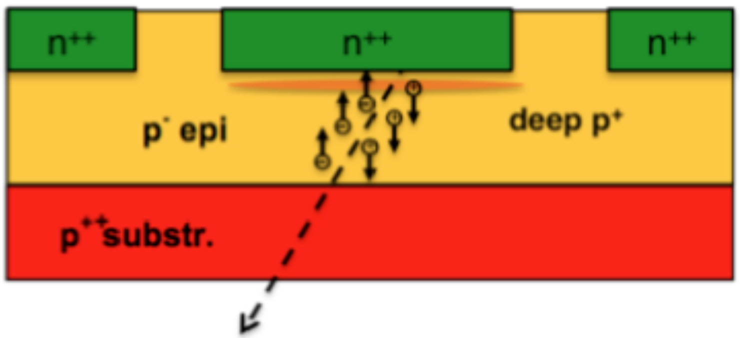
Improved granularity near beam.

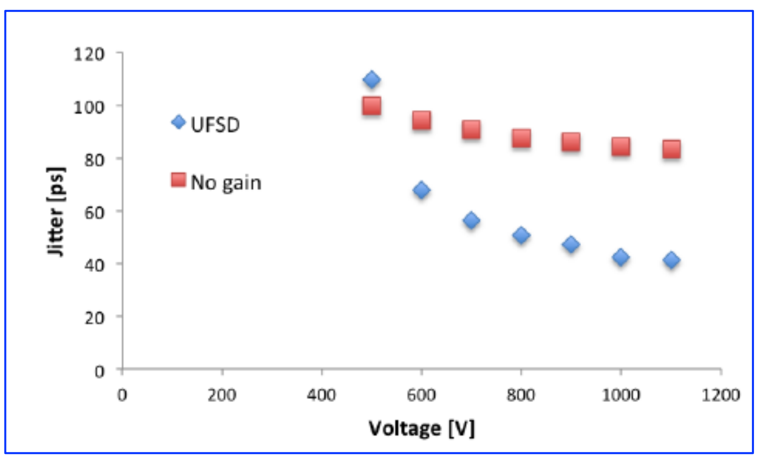
Solid state detectors, silicon or diamond, worse time resolution (today) but many thin detectors can be in a stack for √N improvement … "timetrack"

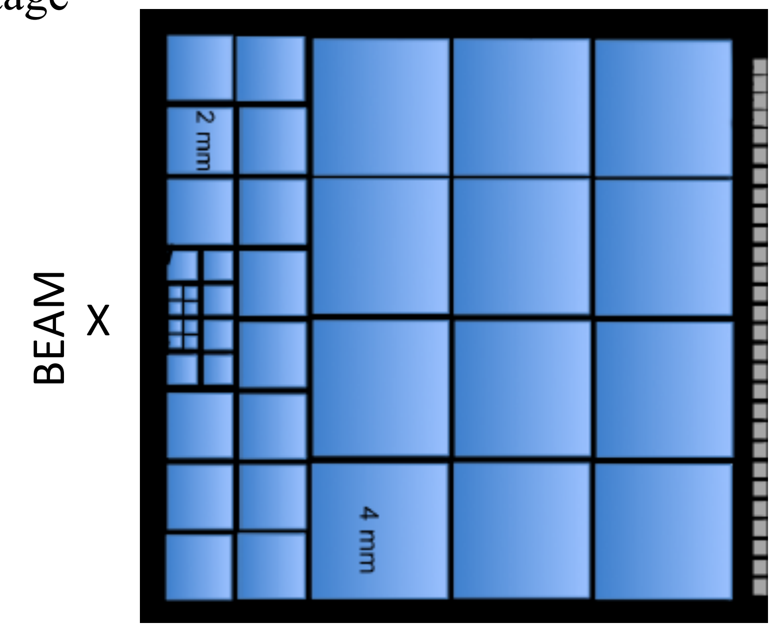
Example:

Low Gain Avalanche Diode (LGAD) High Voltage

→ Ultra-Fast Silicon Detectors (UFSD)







Not baseline, but space in pot upstream of Quartics could be used

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

(Developments for CMS calorimeter upgrade)

Two additional pile-up rejection possibilities for PPS

** Forward discs covering HF calorimeters, large $|\eta|$, ~ $1 m^2$
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 : Tracks from X are central

Central barrel (much larger)
Reconstruct collision time of dijet candidates
Match with pp time