Small angle detectors for study diffractive processes with CMS

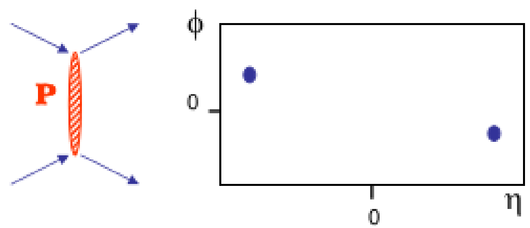
V.Samoylenko (IHEP, Protvino)
On behalf FSC + PPS

Forward Shower Counters (FSC): extending the CMS η-coverage.

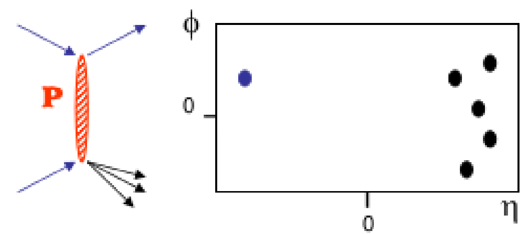
- CMS, as most collider detectors, has excellent hermeticity at low η
- In the forward direction the CMS coverage is extended with different additional detectors: HF + Castor + ZDC (+ TOTEM)
- There may be gaps in the coverage of the forward region (high η)
- The Forward Shower Counters (FSC) system is made of scintillators installed near the LHC beam pipe at 59, 85 and 114 m from IP5, on both sides of CMS
- These counters detect showers produced by very forward hadrons hitting the beam pipe and surrounding materials.

Forward Physics
Diffractive Processes at LHC

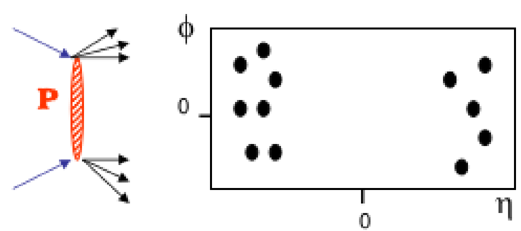
(see Sercan Sen's review talks)



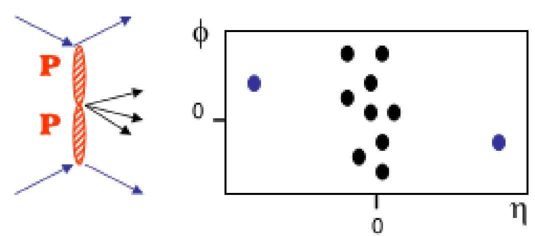
Elastic Scattering (ES)



Single Diffraction (SD)

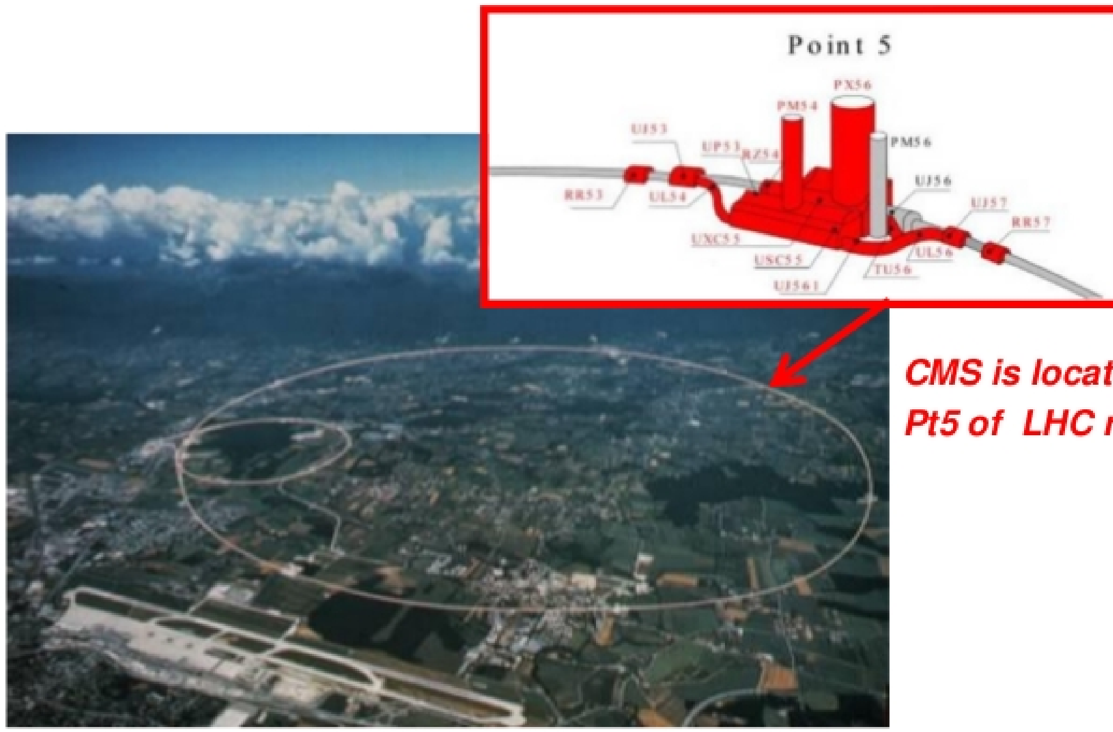


Double Diffraction (DD)



Central Diffraction (CD)

LHC and CMS Apparatus at Pt5



CMS is located at Pt5 of LHC ring.

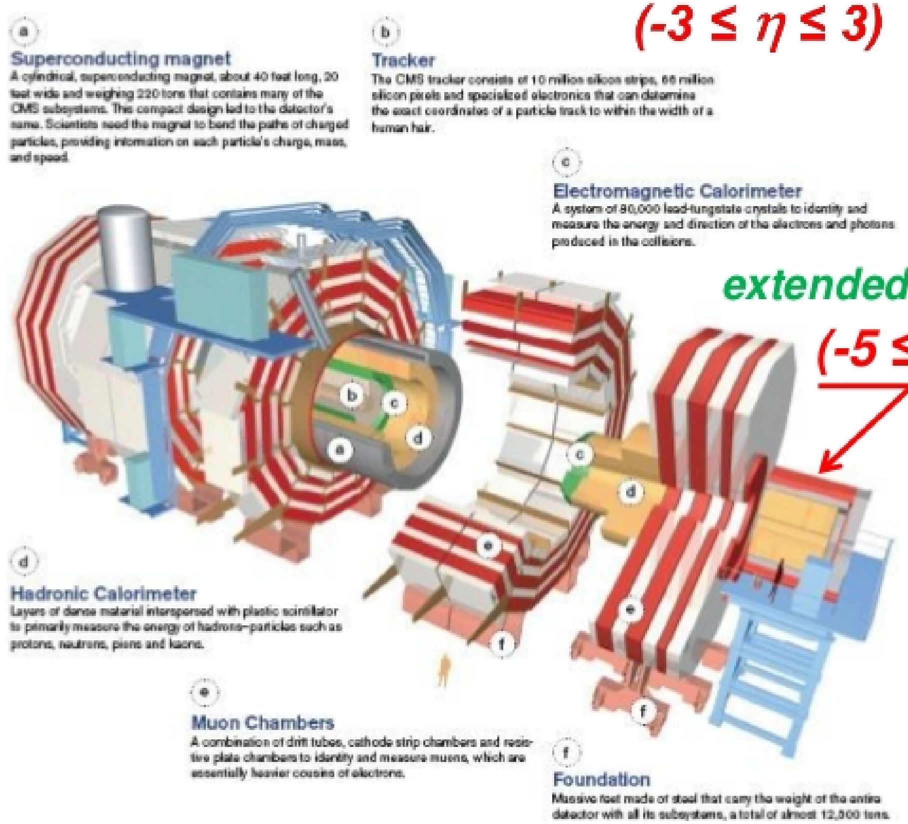
The CMS apparatus

has hermetic η coverage

$(-3 \leq \eta \leq 3)$

extended by HF to

$(-5 \leq \eta \leq 5)$



Diffraction at Pt5

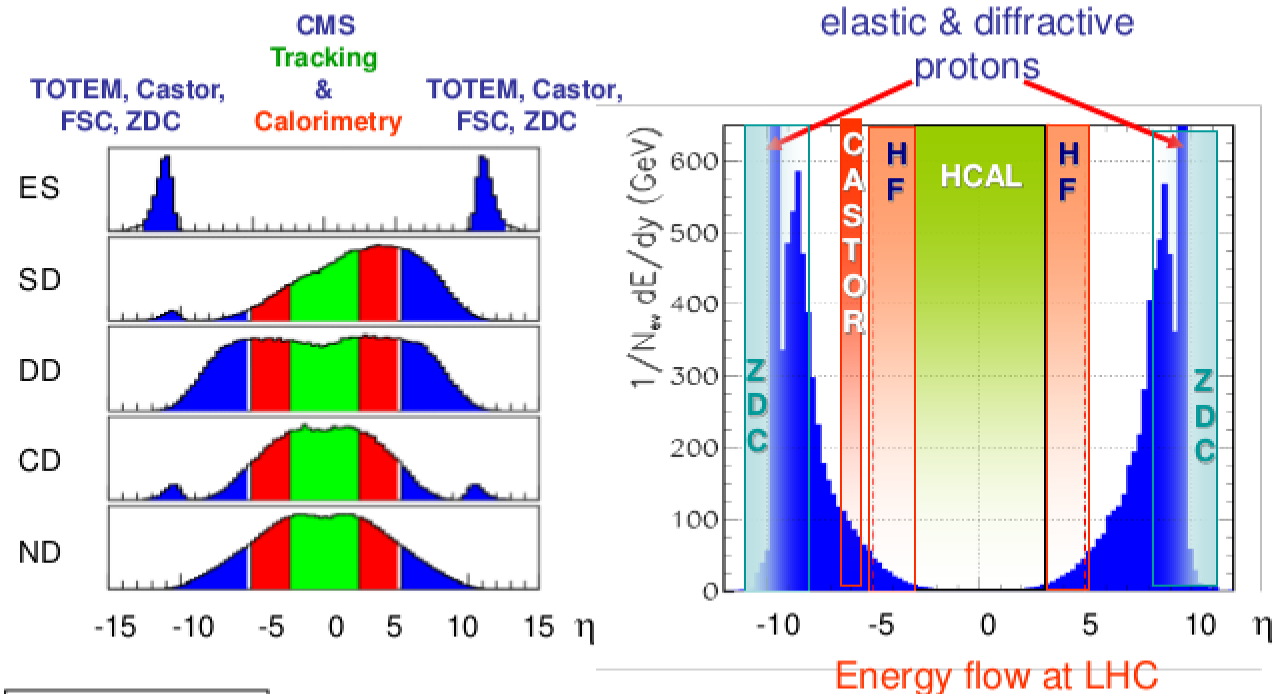


figure adapted from Risto Orava (Diffraction 2006)

A very large η-coverage, but…

Towards Full Acceptance

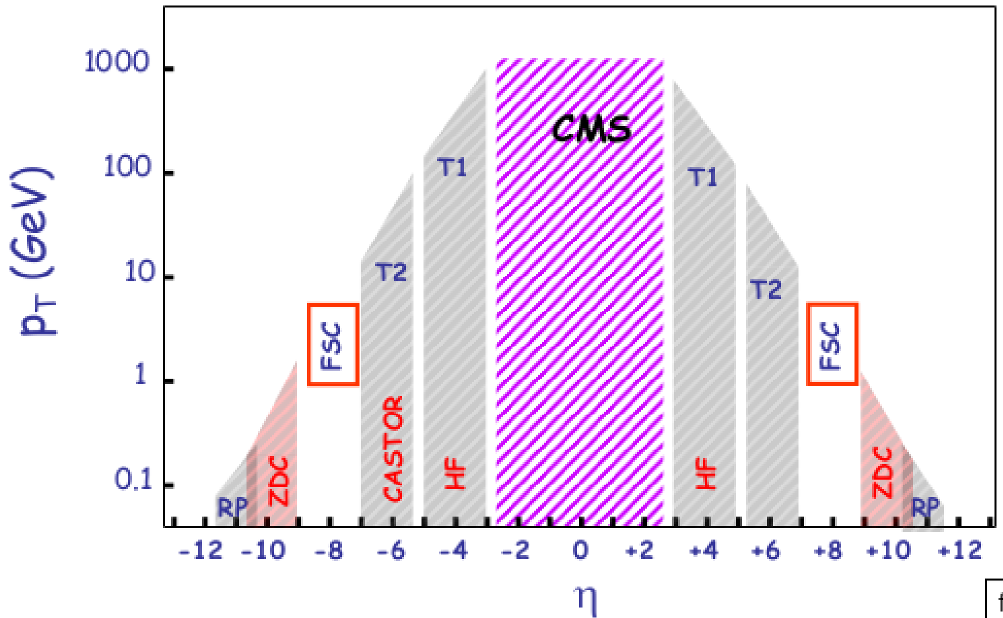


figure adapted from Risto Orava (Diffraction 2006)

FSC covers a gap in η between the forward calorimeters (HF, CASTOR) and the very forward (ZDC, TOTEM RP)

FSC Team

CMS FSC Team:

Fermilab: M.G.Albrow, S. Popescu, Y. Guo, N. Mokhov, I. Rakhno
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U. Kansas: O. Grachov, P.Kenny, M. Murray, Q. Wang, C. Bruner, Z.Tu

Other Institutions:

U. Durham: V. Khoze +…
U. Helsinki: J. Lamsa, R. Orava +…
U. Messina: A. Lamberto, G.F. Rappazzo

In collaboration with **CMS FSQ:**

Conveners: D. d'Enterria, J. Hollar, A. Vilela

FSC Documentation

- FSC on the CMS twiki page:
  - https://twiki.cern.ch/twiki/bin/viewauth/CMS/FSCWikiHome
- FSC Risk Analysis:
  - S. Lusin, Risk Analysis of the FSC Counters at CMS (14 June 2011)
- FSC integrated into LHC database:
  - ECR approved: LHC-X5FC-EC-0001 v.0.1

Papers and Notes:

[1] M.G.Albrow *et al.*, Forward Physics with Rapidity Gaps at the LHC, JINST **4** P10001 (2009)

[2] R.Orava, Detecting Diffraction at the LHC, AIP Conf. Proc. 1105, 91 (2009

[3] A. J. Bell *et al.*, Physics and Beam Monitoring with Forward Shower Counters (FSC) in CMS, CMS NOTE -2010/015 (19 July 2010)

[4] M.G.Albrow *et al.*, The CMS Forward Shower Counters Detector: Design and Installation, CMS IN - 2012/001 (21 January 2012)

[5] CMS DP-2013/006 -- Central high-p_T jet production during low pile-up, high β^* run at $\sqrt{s}$ = 8 TeV

[6] CMS DP-2013/004 -- CMS-TOTEM event display: high-p_T jets with two leading protons

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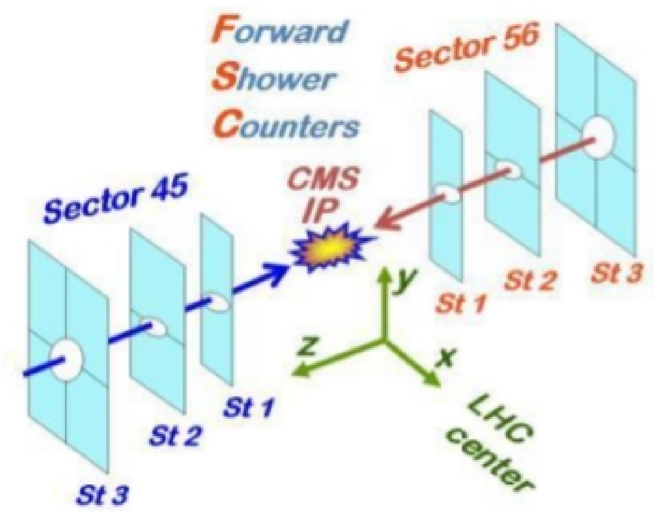
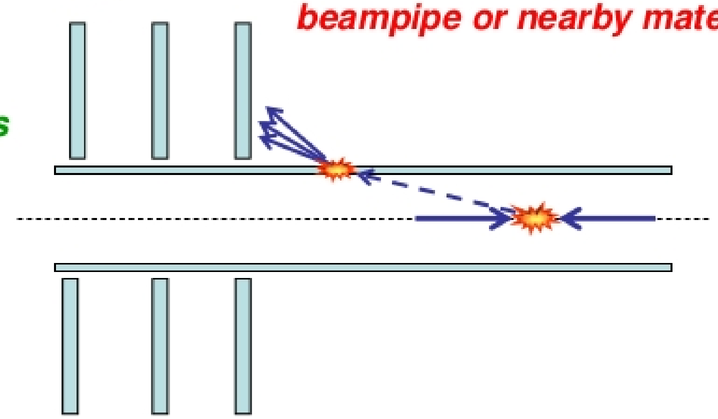
FSC Setup



- Scintillator paddles
  ~25cm x 25cm wide
  with one PMT each,
- 8 per side, symmetric to IP5
- See showers produced by particles from collisions in beampipe or nearby material

Forward Shower Counters cover a rapidity region:

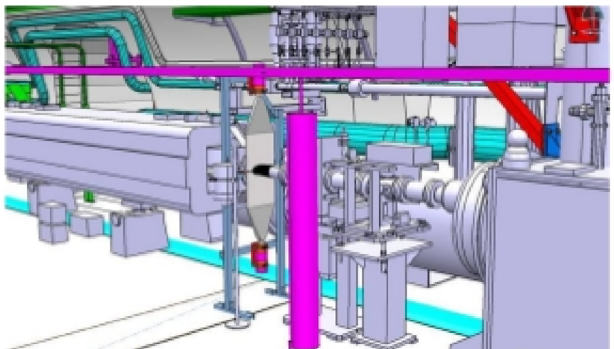
~ $6 < |\eta| < 8$



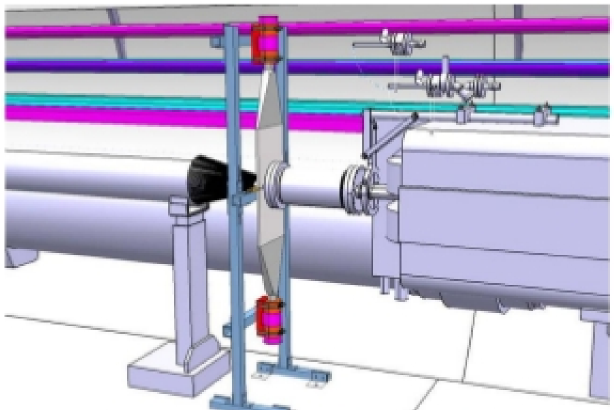
FSC Tasks

- ***Physics**, mainly diffractive*
  - *Detecting rapidity gaps in diffractive events*
  - *Measure low mass diffraction and double pomeron exchange*
  - *Heavy Ion runs*
- ***Beam monitoring***
  - *Beam halo of incoming and outgoing beams*
  - *Comparison with forward flux simulations (MARS, Fluka)*
  - *VdM scans*

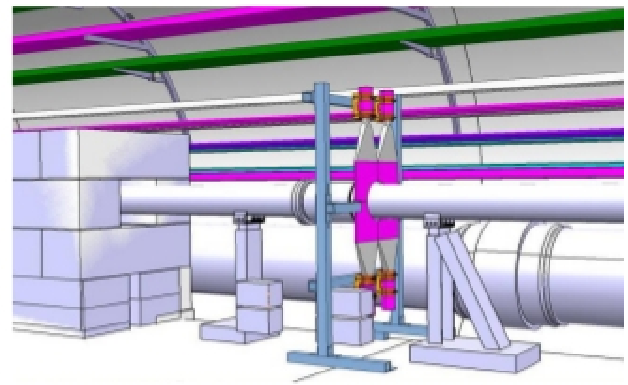
FSC Locations



Station 1, front of D1 (59m from IP5)

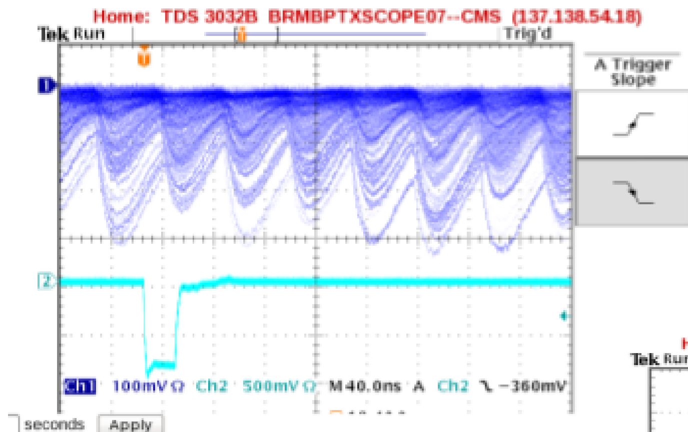


Station 2, D1 end (85m from IP5)

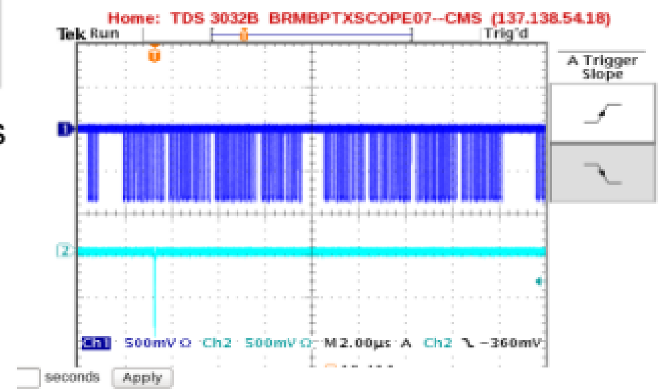


Station 3, 114m from IP5
(26m before ZDC/TAN)

FSC Signals with Collisions

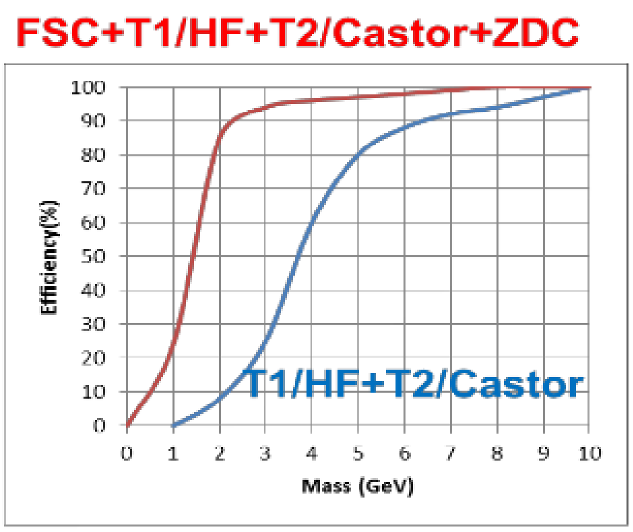


Signals from PMT; time scale 40ns



Signals through Discriminators; time scale 2µs

FSC "efficiency"



SD events at lowβ*

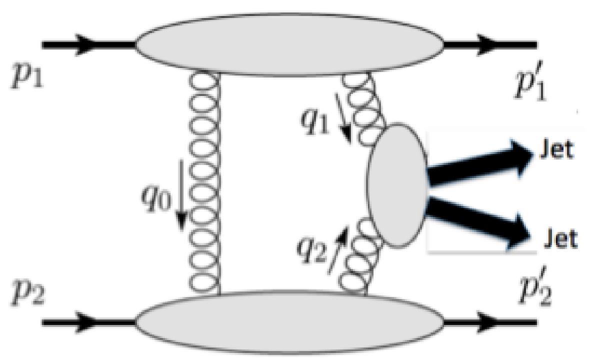
- Efficiency >90% for lower mass region, ~100% for region >10 GeV (approx 25% of SD below 10 GeV!)
- Forward systems from reactions like CID would have ~ efficiency.
- High efficiency for exclusive diffractive baryon-resonance production: $p\,p \rightarrow p\,N^*(1400)$, where $N^* \rightarrow p\,\pi^o$, $n\,\pi^+$, $\Delta^{++}\pi^-$. ..

[R. Orava, ECT-Trento, 6Jan2010]

- The detection efficiencies for single diffractive events simulated by PYTHIA6.2 as a function of η or of the diffractive mass.
- At least five charged particles ("hits") in any of the forward shower counters, or at least one track in the η region covered by T1/HF or T2/CASTOR, or a minimum energy deposit in the ZDC. . .

Results from Low PU Runs

- *Data collected during **low PU (β* = 90 m) pp at 8 TeV** runs in July 2012, with CMS and TOTEM operating with **common triggers**, show events consistent with central production of high-pT jets accompanied by two leading protons.*
- *FSC detectors, covering the very forward pseudo-rapidity $6 < |\eta| < 8$, were **required to be empty**.*
- *The leading protons were detected as tracks in the TOTEM Roman Pot (RP) stations around the CMS interaction point.*
- *Preliminary results shown in:*
- ***CMS DP -2013/004:** CMS-TOTEM events: high-pT jets with two leading protons*
- ***CMS DP -2013/006:** Central high-pT jet production during low pile-up, β* = 90m, 8 TeV pp run*



Conclusions and Outlook

- *FSC is a relatively simple system*
- *Principle (detecting secondary showers) works well*
  - *both for pp and HI*
  - *2012 -2013 data being analyzed*
- *Valuable for low PU runs in association with*
  - *TOTEM*
  - *CMS central + HF+CASTOR+ZDC*
- *During LS1:*
  - *maintenance and consolidation*
  - *planning new station in front of TAN/ZDC*

From FSC to presice measurment of diffraction proton:

HPS (High Presicion Spectrometer)

PPS (Proton Presicion Spectrometer)

Already in 2000 need for fast timing was recognised:

Searching for the Higgs Boson at Hadron Colliders using the Missing Mass Method

Michael G. Albrow,[1] Andrey Rostovtsev[2]

arXiv:hep-ph/0009336v1 28 Sep 2000

With multiple interactions in a bunch crossing a background could come from two single diffractive collisions, one producing the p and the other the $\bar{p}$. One way of reducing this is to require longitudinal momentum balance. However "pile-up" can be reduced by one to two orders of magnitude by backing up the silicon detectors in the pots by counters with excellent timing resolution. A conventional fast detector would be a quartz (for radiation hardness) block producing Cerenkov light viewed by a fast photomultiplier. One can achieve 30 ps timing resolution on the p and $\bar{p}$, much better than the ($\approx$ 1 ns) spread between random concidences. There are ideas [22] for Fast Timing Cerenkov Detectors (*FTCD*) using microchannel plates which might achieve a resolution of a few ps. The sum of the p and $\bar{p}$ times is a constant for genuine coincidences, and their difference Δt is a measure of z_{vtx} at the level of 1 cm (for $\Delta t = 30$ ps).

(apart from event time spread!)

Tevatron!

Courtesy M.Albrow

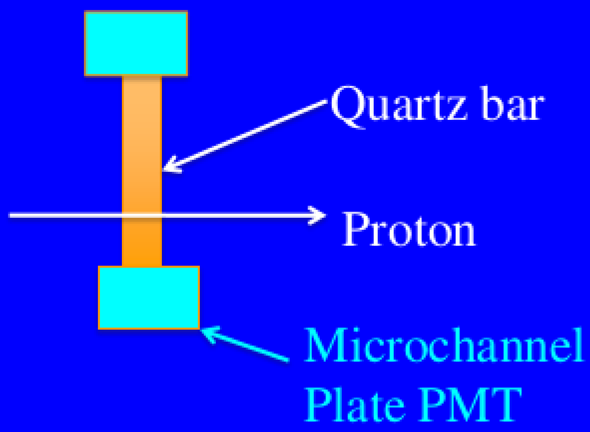
Fast Timing detectors: QUARTIC

Precision Proton Spectrometer (PPS) development

Michael Albrow, Fermilab

with mainly:
Anatoly Ronzhin, Sergey Los, Erik Ramberg, Heejong Kim,
Vladimir Samoylenko, A. Zatserklyaniy

Pile-up reduction by timing



Original concept (2000)
~ 30 ps expected
σ_z(interactions) ~ 25 cm
PU (μ) ~ 10

[pXp] ... good ones
[p][Xp] + [pX][p]
[p][X][p]
} 2 uncorrelated protons -- PU
[pp][X] ... was "good" but wrong X

Algebra:
Time difference = Δt
z(pp) = 0.5 c Δt
If time resolution = $\sigma(t)$ = 10ps
$\sigma(\Delta t) = \sqrt{2}\,\sigma(t)$ = 14.1 ps
$\sigma(z(pp))$ = 0.5 c 14.1 ps = 2.1mm

σ_z(interactions) ~ 50 mm == 150 ps

10 ps: not a fundamental limit but achievable goal
Spread in p-path differences <~ 2 ps.

- Courtesy M.Albrow

Requirements on timing detectors for HPS

1) Excellent time resolution ($\sigma(t) \sim 10$ ps)
2) Edgeless on beam side ($\Delta x <\sim 200\ \mu m$)
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)

Two detectors developed: **Quartz Cherenkov Counters for Fast Timing: QUARTIC** MGA et al., 2012 JINST 7 P10027

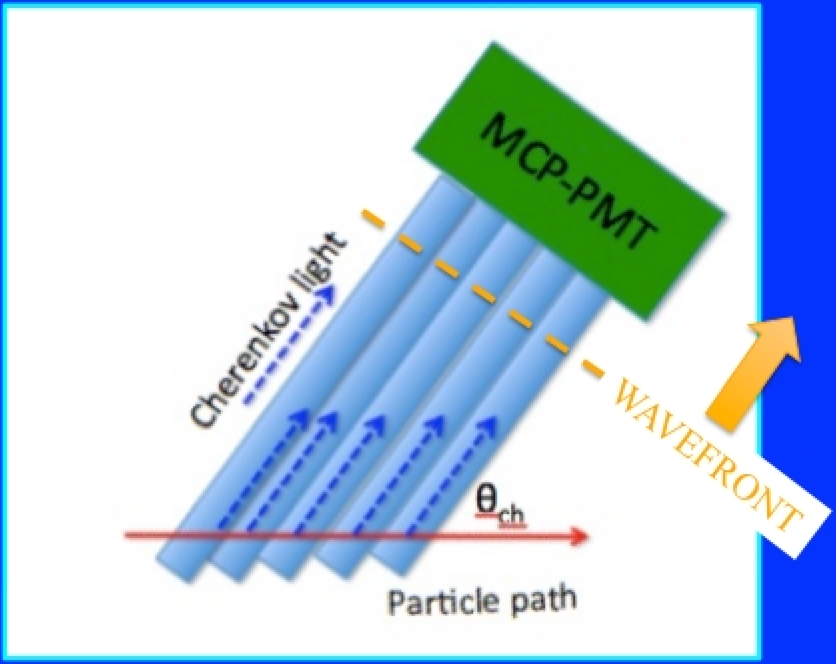
Cherenkov detectors with quartz radiators:
Angled-bar QUARTIC and L-bar QUARTIC
Light detected by MCP-PMTs or Silicon PMs (SiPMs)

MCP-PMTs: Faster and better Q.E. but lifetime issues

SiPMs: Small, cheap, but slower and radiation issues

Angled multi-bar QUARTIC. Multi-anode or single anode

Developments with AFP, Andrew Brandt et al. This is AFP baseline



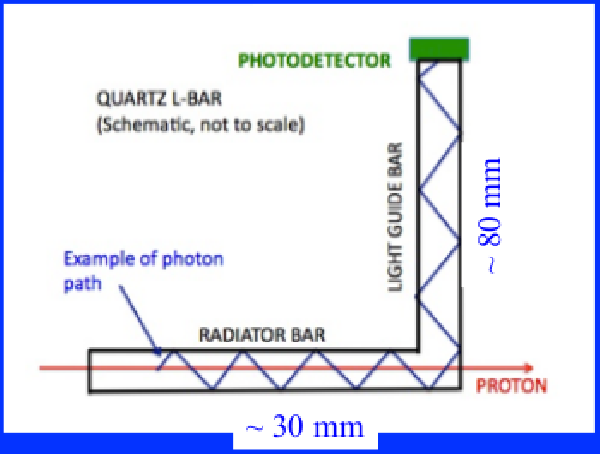
Cherenkov light cone $\theta_{ch} = 48^o$, 360^o in Φ

Direct light propagates as wavefront – isochronous

Light emitted at “wrong” Φ ... longer path or exiting

L-bar QUARTIC principle

All Cherenkov light is totally internally reflected along radiator bar and about 66% goes promptly along light guide to SiPM or segmented MCP-PMT.
No light "leaks out".



Conditions:

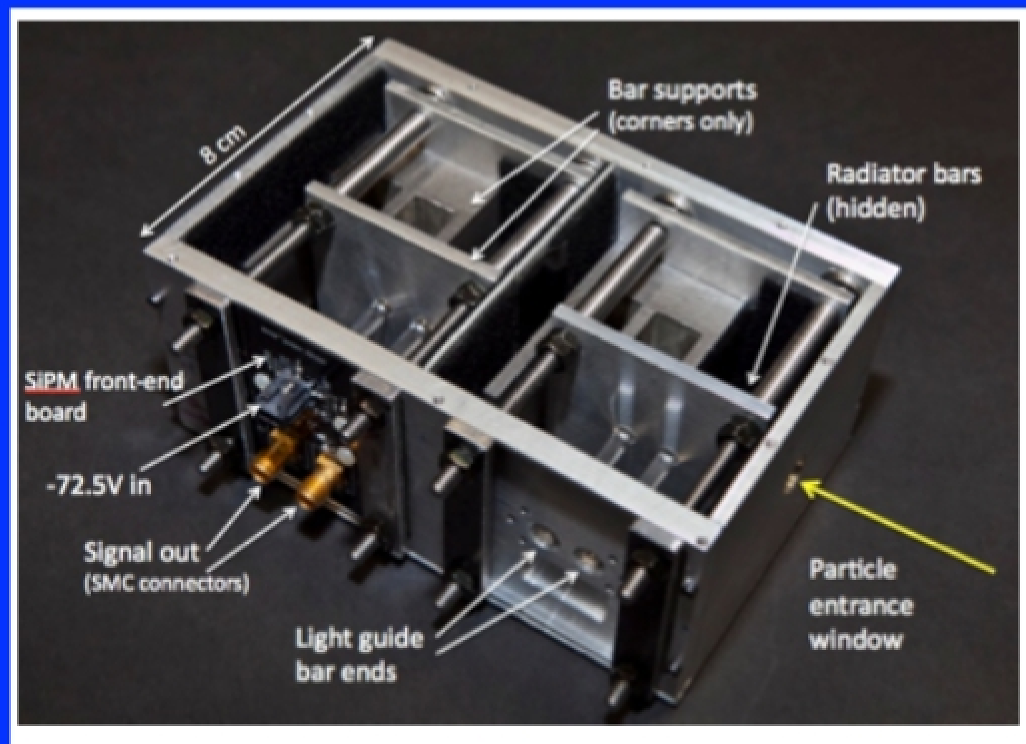
1) protons are parallel to radiator
2) n (refractive index) > √2
   so TIR maintained in LG-bar

Radiator close to beam while photo-detector remote (and may be shielded)

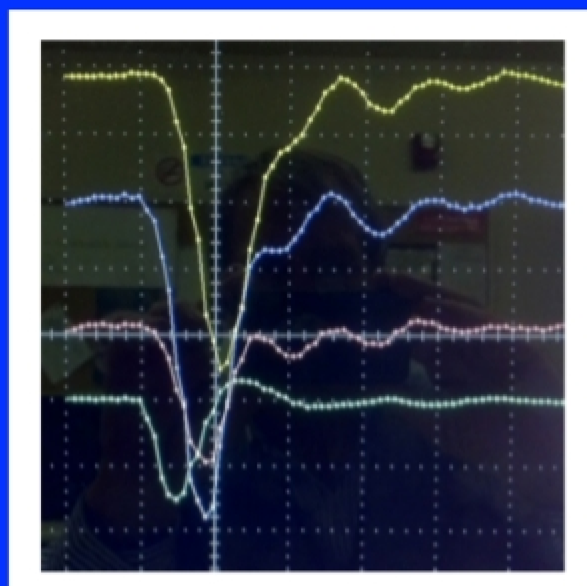
NO MIRRORS

Hodoscope of 3mm x 3mm independent elements
Repeat N times in depth for sqrt{N} improvement (timetrack)
Finer segmentation eg 2x2 mm^2 possible in principle

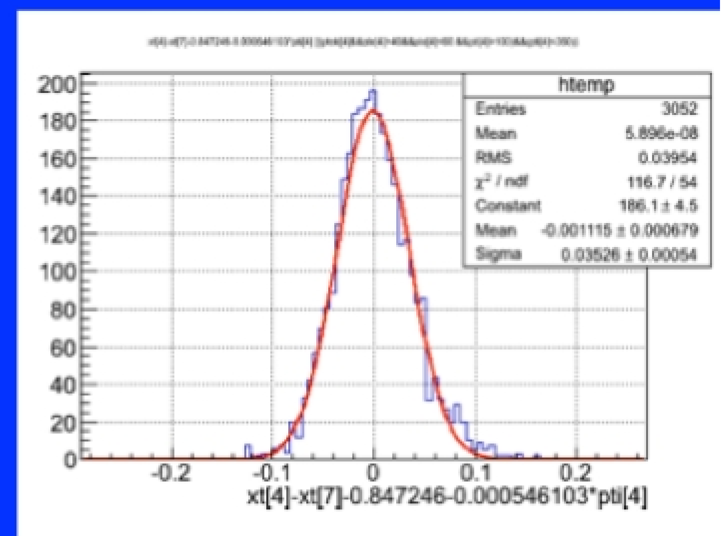
Test beam modules made: Four in-line radiators, 3 cm and 4 cm



Typical event (120 GeV proton) in 3 radiator bars
and (bottom) PMT240 in line. 200ps/sample, DRS4 scope
Signal rise times ~ 800 ps



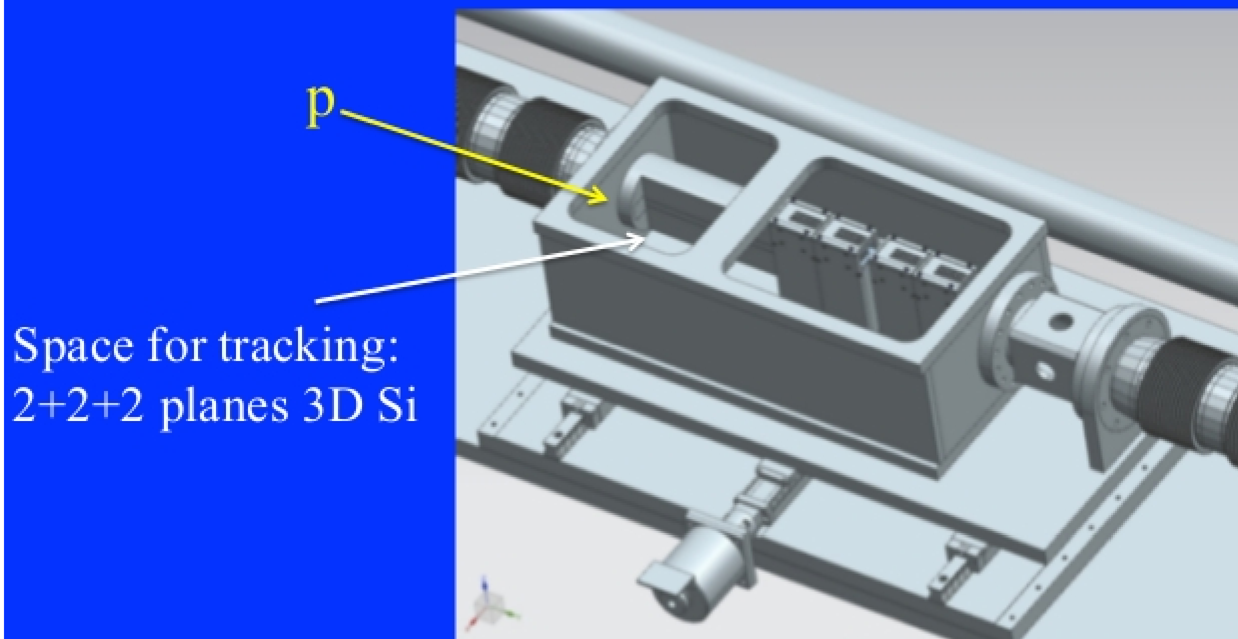
Δt (30mm bar – PMT240)



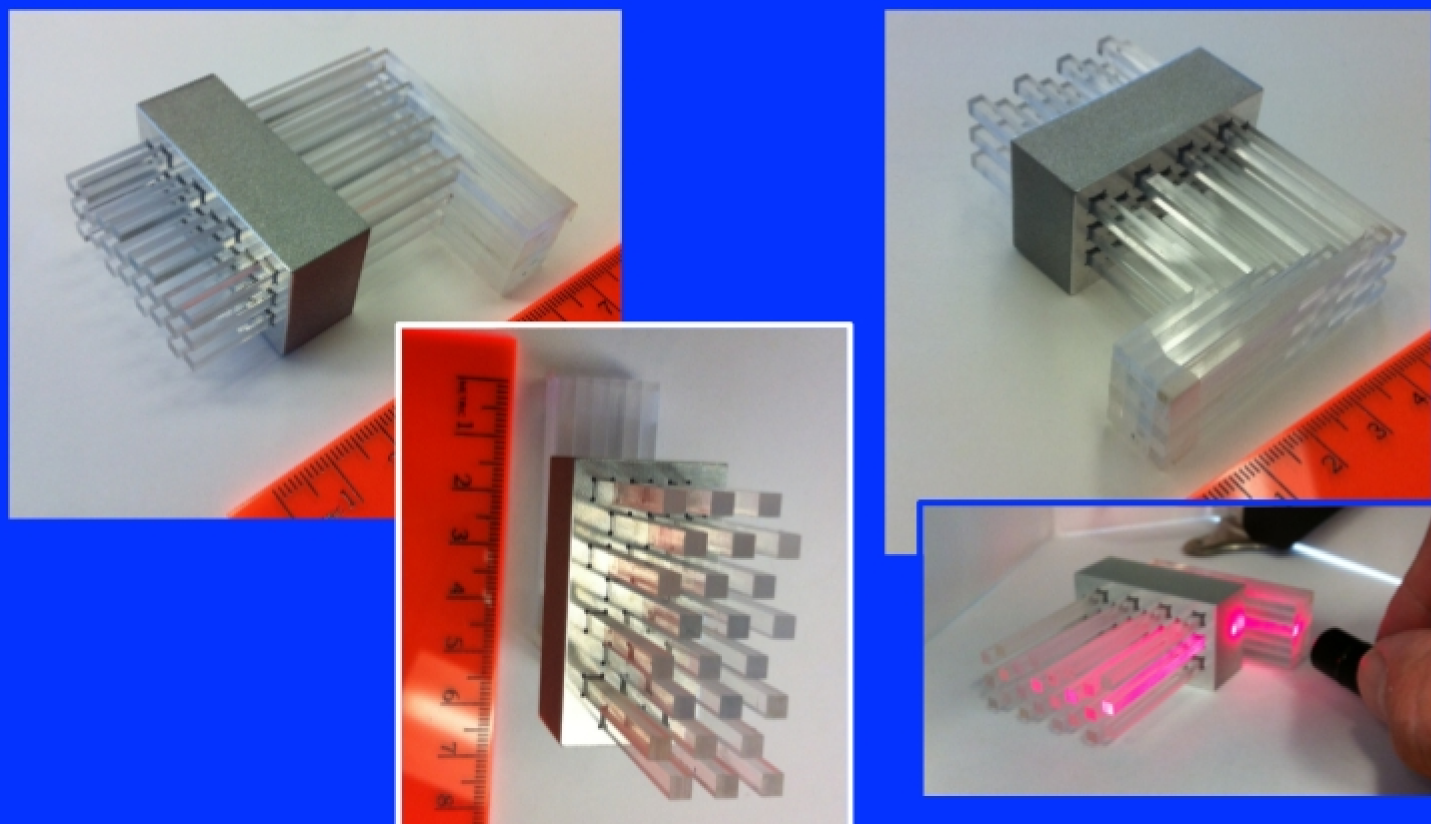
σ(t) = 31 ps for 30 mm bar
Four-in-line → 15 ps

Expected improvements: sapphire bars (+30%) & faster SiPMs (50%?)

Arrangement of four QUARTIC modules with moving beam pipe



Test assembly (with plexiglas bars)
100 μm spacing between adjacent bars.
Precision block is a “jig”, removed after front of array glued



Developments

We have the design achieving requirements, but $\sigma(t)$ = 15 ps. Good, but any improvement is useful

Before full production, & in parallel with Module #1 assembly and testing, study of two possible improvements:

Radiator bar material:

Sapphire Al_2O_3 replacing quartz? Higher $n(\lambda) = 1.75 - 1.80$

> More Cherenkov light /cm but more chromatic dispersion, absorption, surface quality etc to be studied. GEANT (v. preliminary)

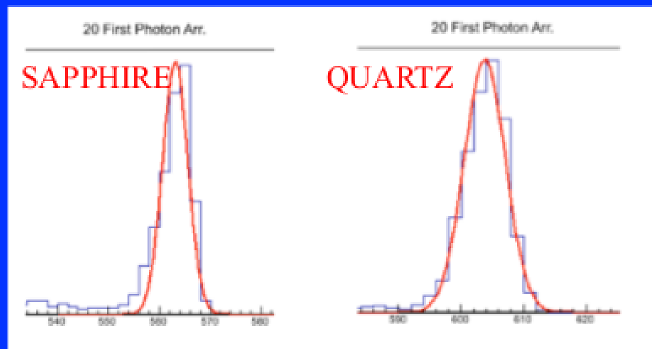


Fig.4 The time distribution for first 20 photoelectrons from Sapphire(left) and quartz(right).

SiPMs: faster (better single photon time resolution SPTR) are made.

Big markets, e.g. ToF-PET so rapid developments

Summary

Precision timing of protons ($t_L - t_R$) essential for PPS

Requirements are challenging but we have solutions:

Angled-bar QUARTIC with MCP-PMT
L-bar QUARTIC with SiPM array or MCP-PMT

Four-in-line L-bar is HPS baseline. ~ Meets requirements but:

1) so far 30 ps/√4 = 15 ps. Improvements expected: faster SiPMs, better radiator (sapphire?), or custom multianode MCP-PMT.
2) Radiation "soft", can shield n's. Can replace > 1/year.