Plans for the Upgrade of the CMS Barrel Electromagnetic Calorimeter

2017 Meeting of

The American Physical Society Division of Particles and Fields

Objectives of the upgrade

1. **Compensate for radiation damage to the avalanche photodiode detectors (APDs) and to the 61,200 barrel $PbWO_4$ crystal calorimetry elements**

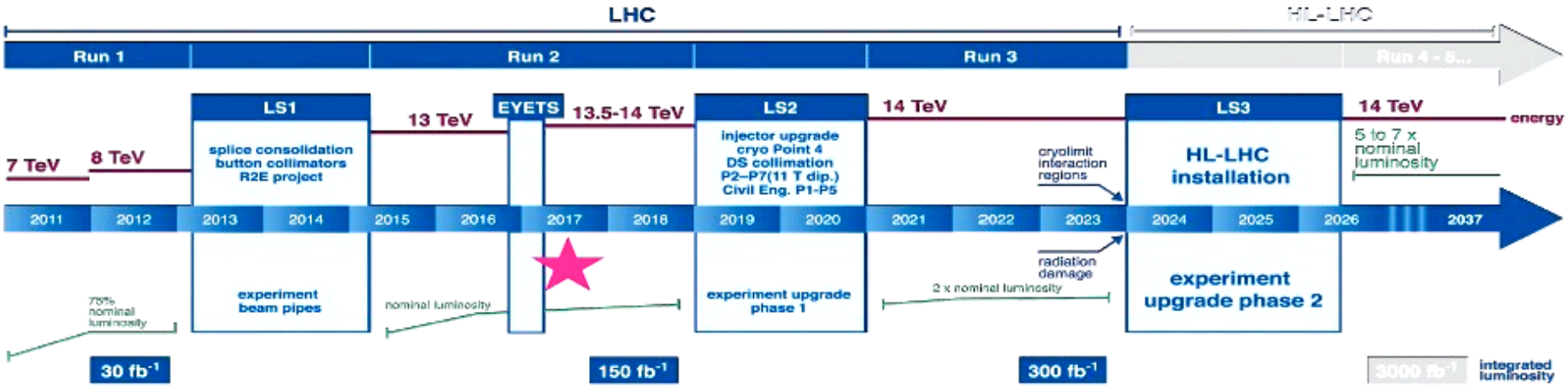
2. **Lower the noise of the front-end electronics**

3. **Allow use of direct APD signal by using a trans-impedance amplifier to reduce false signals ("spikes") by signal shape discrimination**

4. **Improve the timing resolution of the $PbWO_4$ elements to deal with much higher pileup (~200 interactions per bunch crossing)**

5. **Allow single crystal trigger primitives transmission for all 61,200 $PbWO_4$ barrel calorimetry elements to the Level 1 trigger with latency (12.5μs)**

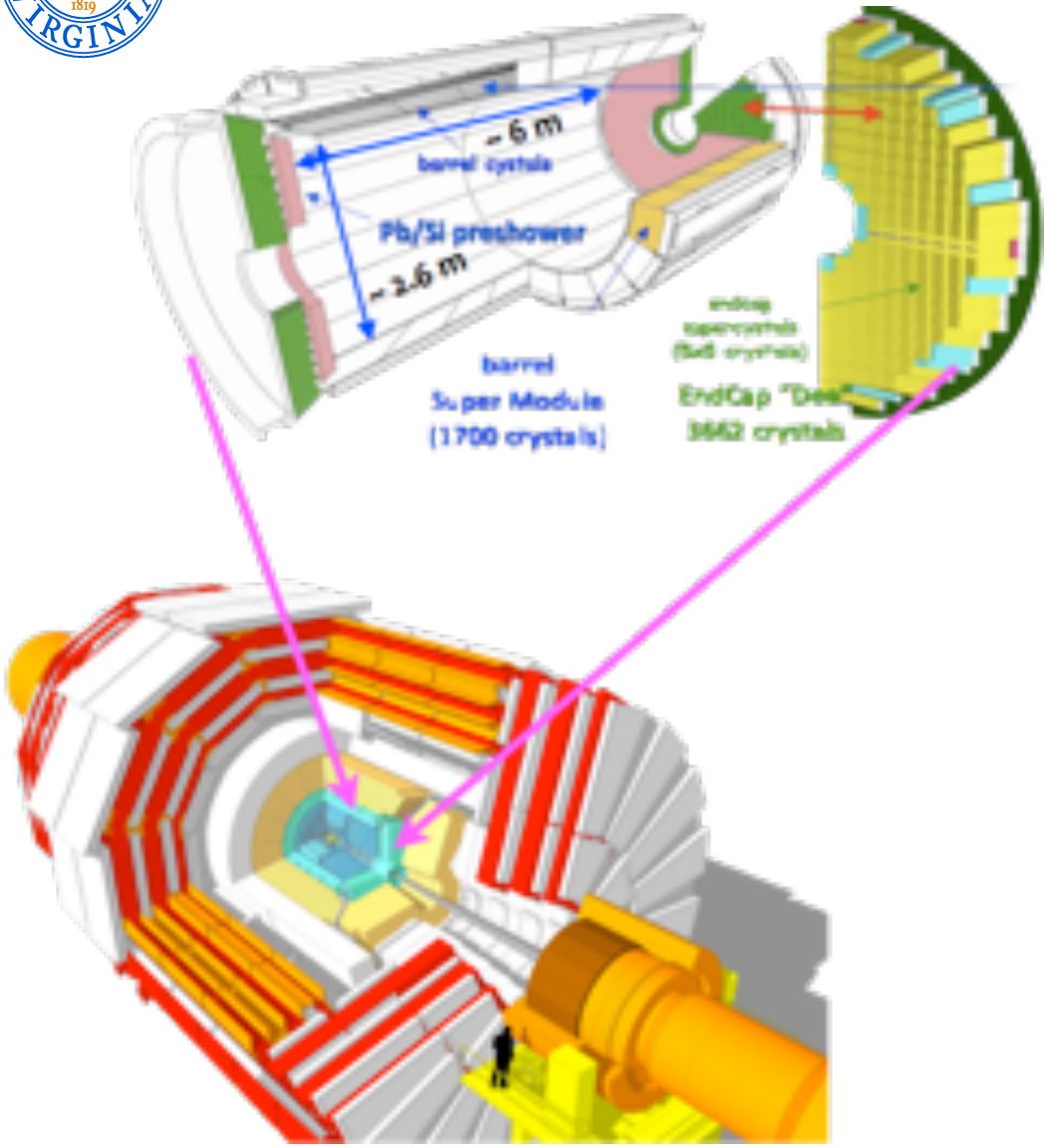
The Schedule for the HL-LHC



	DESIGN	CURRENT STATE	UPGRADED
E_{beam} (TeV)	7	6.5	7
L_{inst} (cm^{-2} s^{-1})	10^{34}	(1.0-1.4)x10^{34}	5x10^{34}
L_{int} (fb^{-1}) 10 years operation	300	40 per year	3000
β* (cm)	50	40	15
PILEUP (PU)	20	37	120-200

- Higher instantaneous and annual integrated luminosity
- Much higher levels of overlapping events: pile-up (PU)
- Radiation levels will be 6x higher than for LHC

The CMS Electromagnetic Detector
Talk will focus on Barrel Upgrade



CMS EM Calorimeter Barrel |eta|<1.48

36 “supermodules”
with 1700 $PbWO_4$ crystals each
avalanche photodiode sensors

Energy resolution

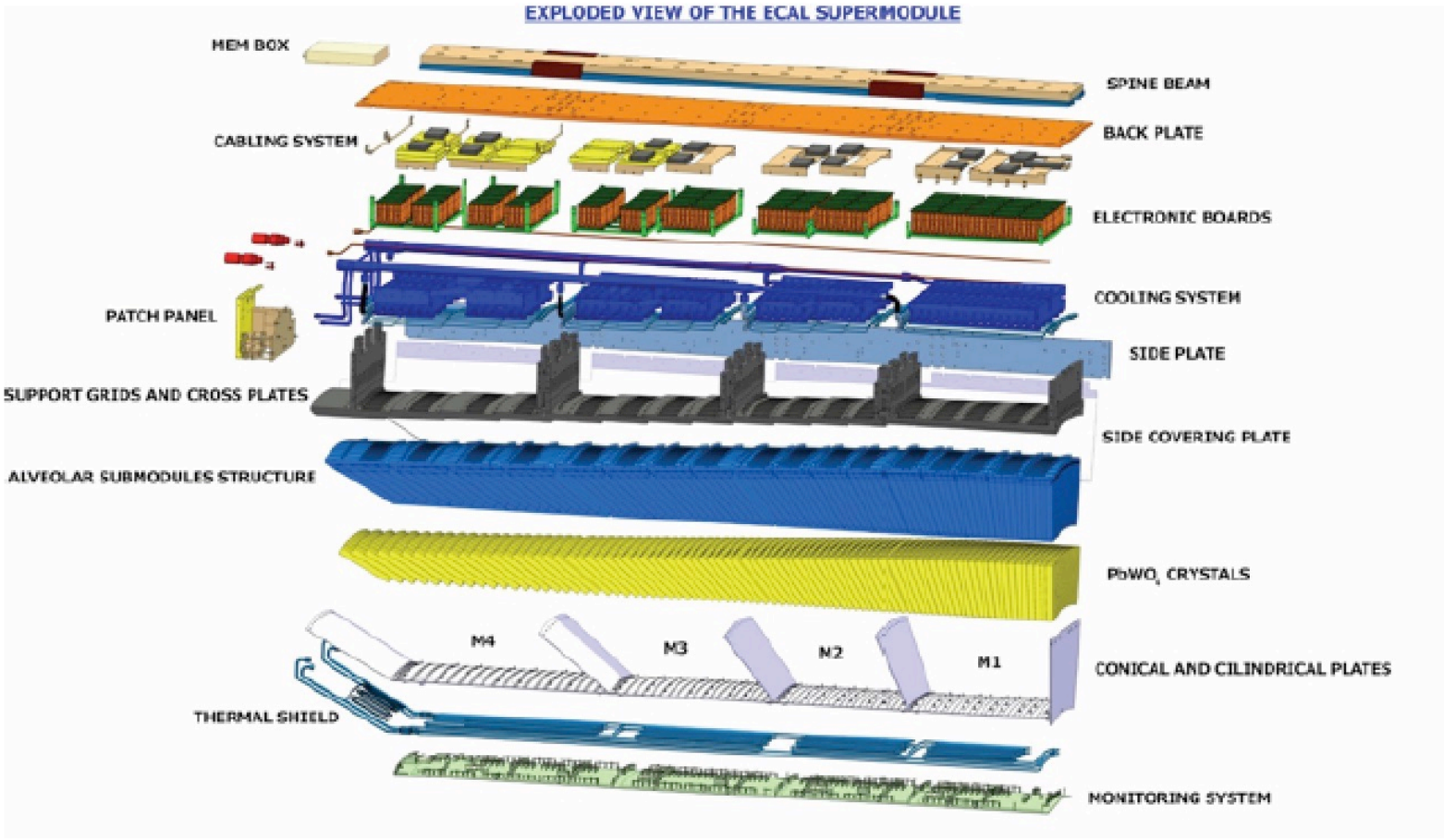
$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

- A: stochastic term
- B: noise term
- C: constant term

Performance of the EM barrel
1-3% photon energy resolution

ECAL Supermodule

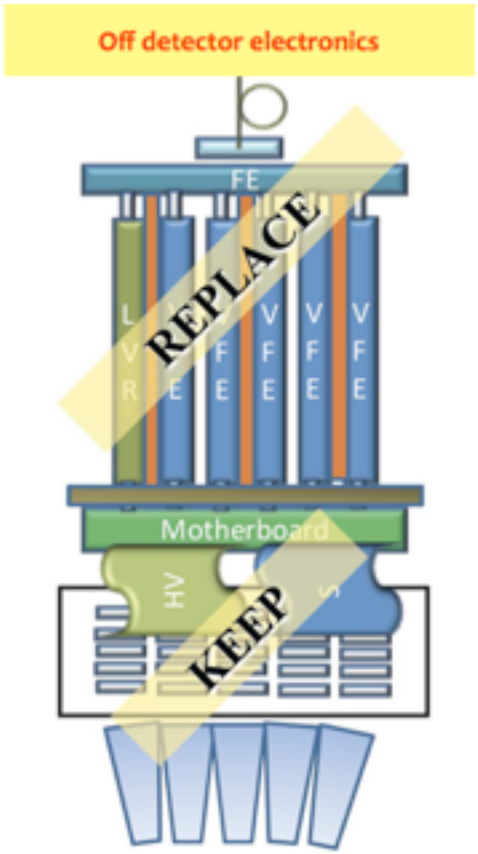
36 such module supporting the $PbWO_4$ crystals arranged azimuthally around the beam pipe



The complexity of the ECAL barrel supermodules makes extraction and disassembly prohibitive and prevents changes to the APDs and $PbWO_4$ elements

On-Detector Barrel Electronics Upgrade

Constraint: The $PbWO_4$ detectors and the APDs cannot be changed



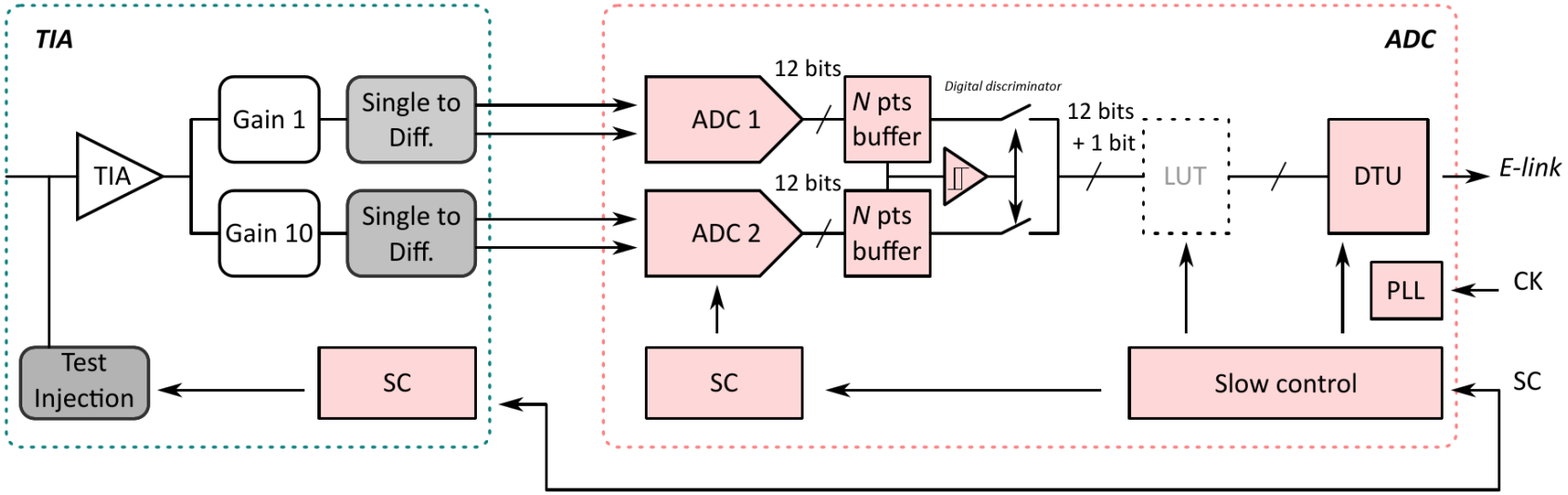
Trigger tower configuration
25 $PbWO_5$ crystals

The driver of the barrel EM calorimeter upgrade Is the desire from the **increase in trigger latency From 4 μs to 12.5 μs and a level 1 trigger rate increase from 100 kHz to 750 kHz**

Upgrade of the transmission rate of the data transfer from the front end electronics to the L1 trigger to allow transmission of all 61,200 $PbWO_4$ crystal signals

Use a **trans-impedance amplifier** to make available the fast APD signals for "spike" rejection by time profile of $PbWO_4$ signals.
Improve and Replace **the Low Voltage Regulators** (LVR)
Improve and Replace **the Very Front End ADC** cards (VFE)
Improve and Replace **the Front End Data transmissions** card (FE)
Use faster **optical fiber links (9.6 Gb/s)** to increase capacity
Increase sampling frequency to 160 MHz to improve timing eliminate spikes

Schematic of Frontend Electronics

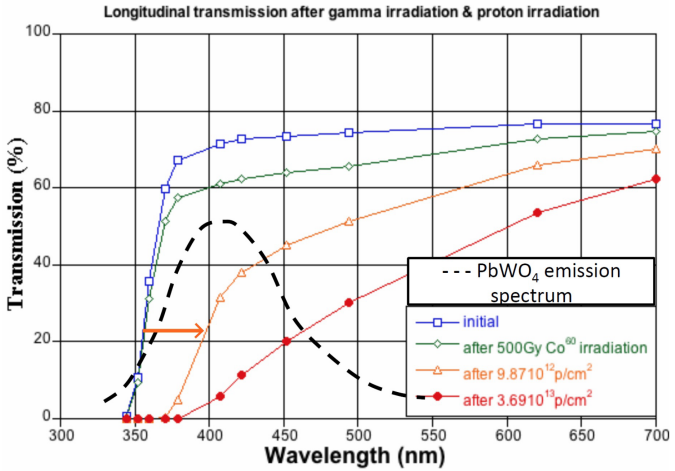


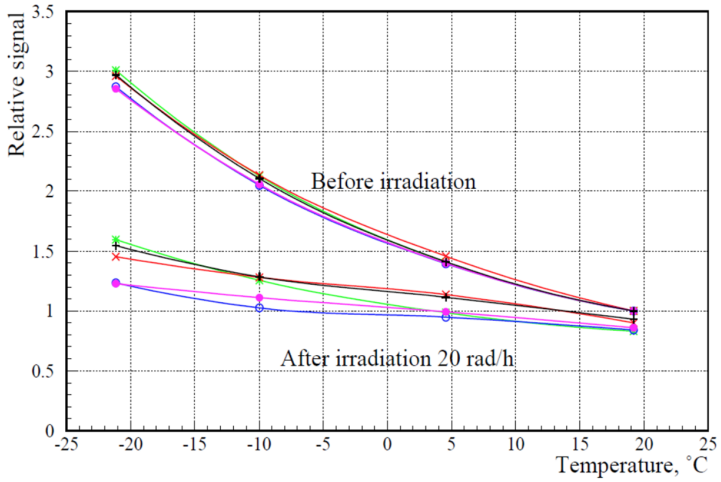
Trans-impedance amplifier/two gains/12 bit ADCs/fast optical inks/12.5 µs latency

Problem 1a
The Radiation Damage Effects on $PbWO_4$

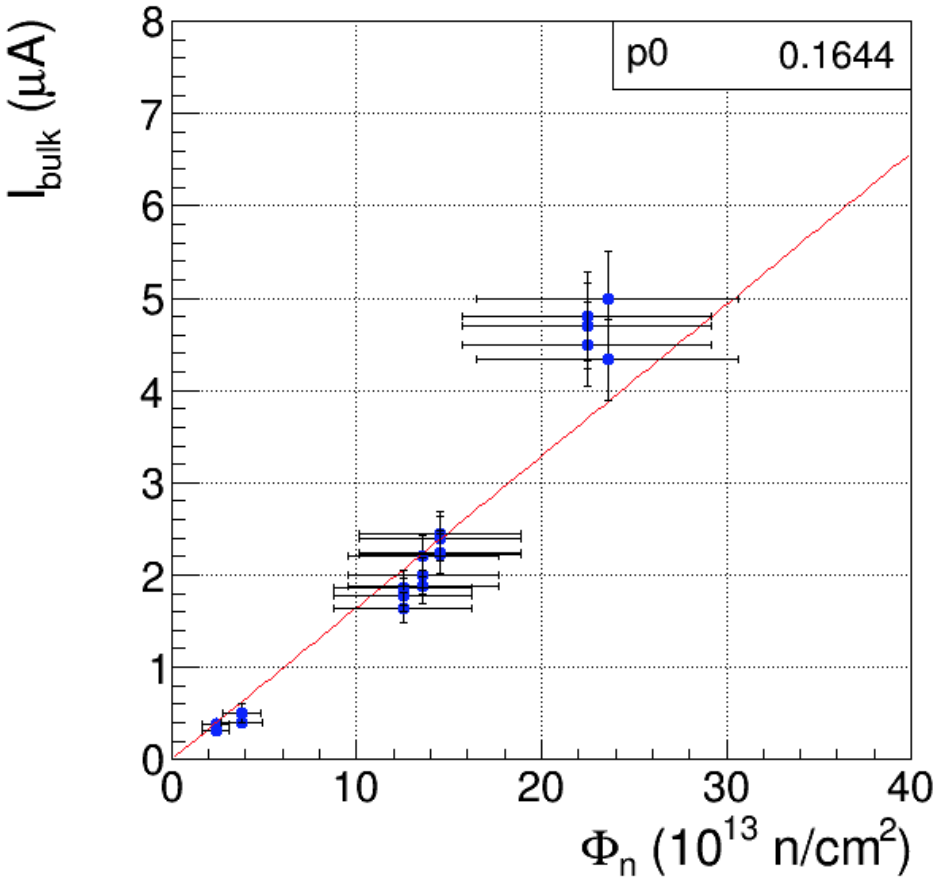
Effect of HL-LHC Increased Dose on $PbWO_4$ to decrease light yield
Partially Compensated by $PbWO_4$ operating temperature decrease (18^0 to 9^0 C)

	LHC design	HL-LHC prediction
Luminosity [$cm^{-2}s^{-1}$]	1×10^{34}	5×10^{34}
Int. Luminosity [fb^{-1}]	500	3000
γ dose rate (EB $\lvert\eta\rvert = 1.0$)	0.2	1.0
[Gy/h] (EE $\lvert\eta\rvert = 2.6$)	6	30
hadron fluence (EB $\lvert\eta\rvert = 1.0$)	12×10^{11}	7.6×10^{12}
[particle/cm²] (EE $\lvert\eta\rvert = 2.6$)	3×10^{13}	2.0×10^{14}



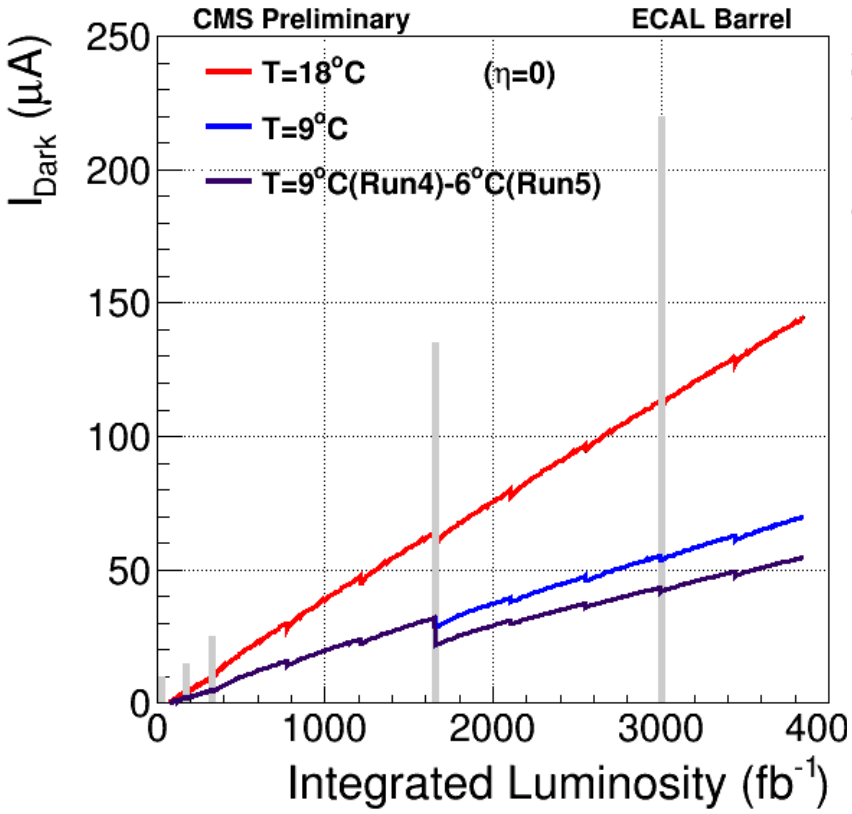


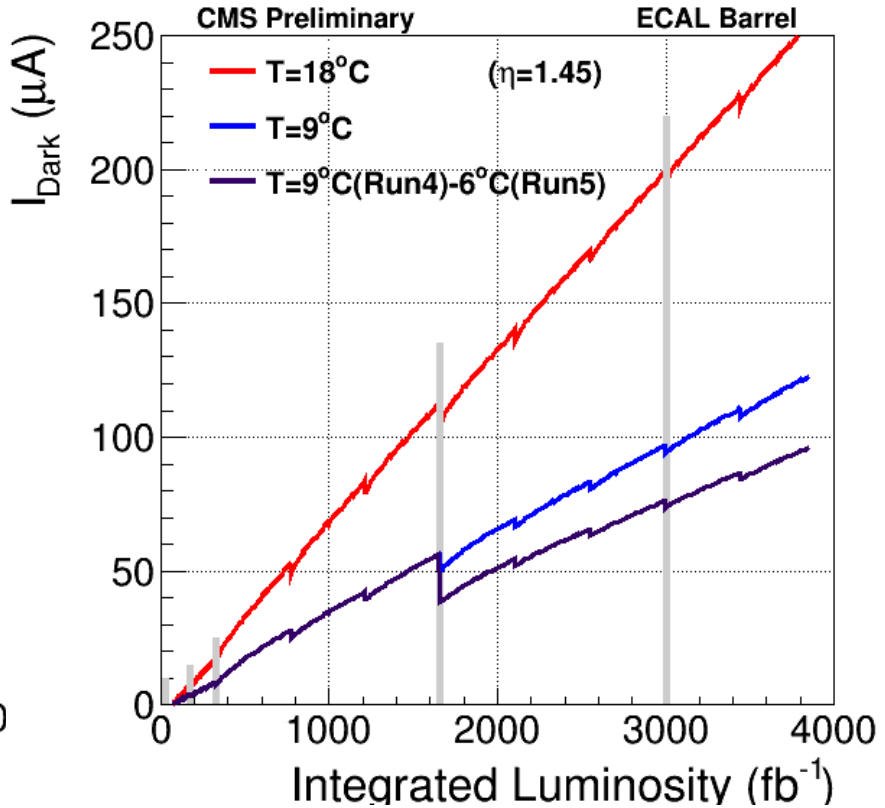
Problem 1b Radiation Effects on APDs



Measured APD Dark Current Increase with integrated hadron dose

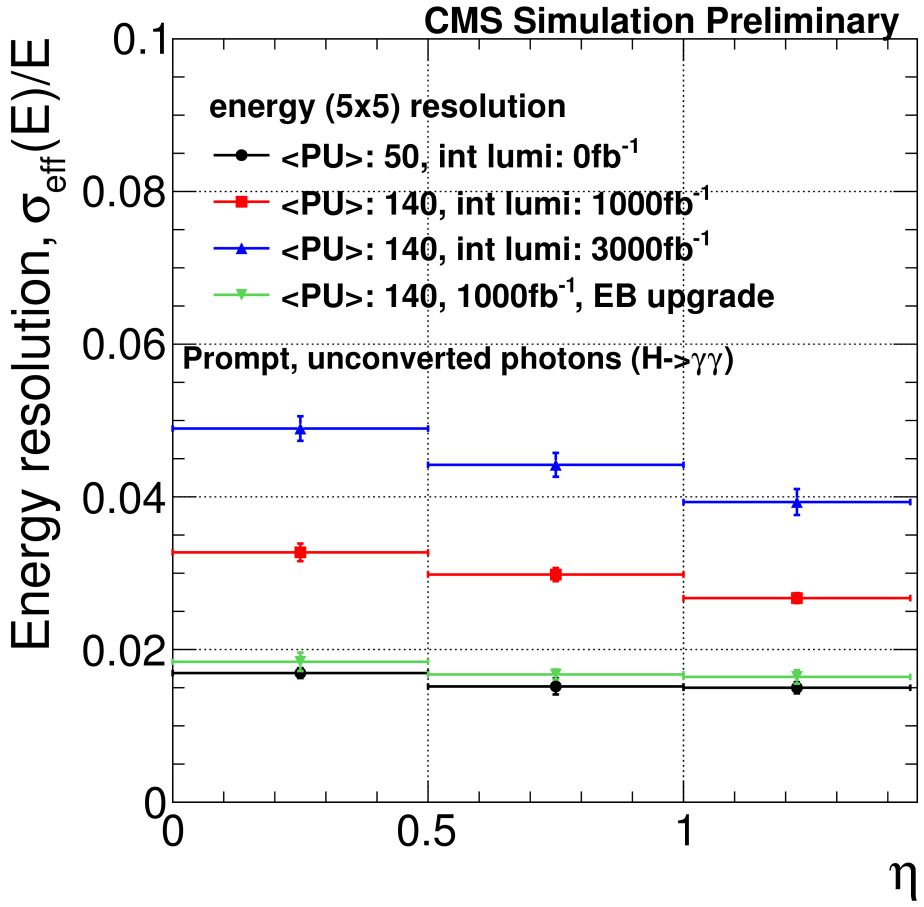
Extrapolated APD Radiation Damage Dark Currents with different operating temperatures





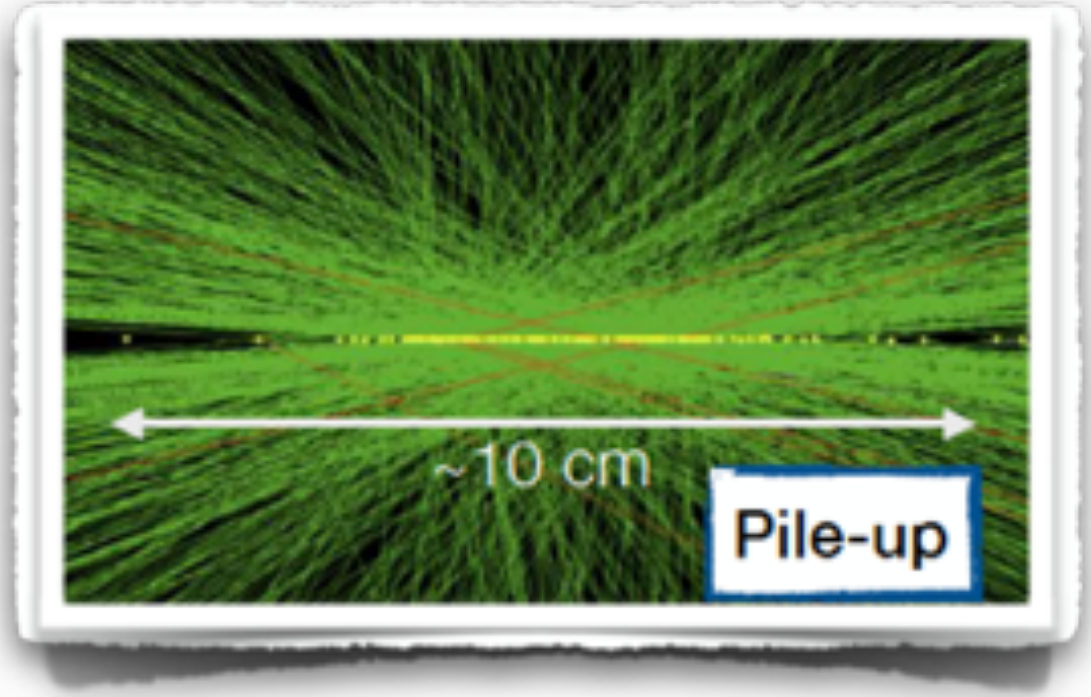
(Partially mitigated by operation at lower temperature 9° C)

Energy Resolution for Higgs gammas Different Integrated Hadron Fluxes vs. Eta (with and without EB Upgrade at 1000 fb^{-1})



Both rad damage and pileup included

Problem 2
Massive Pileup
(200 overlapping in-time events)



1. Leads to a high rate of "spikes" (false signals from hadrons passing through the APD acceleration region) proportional to pileup rate.
2. Pileup of true signals from 200 overlapping interactions per bunch crossing.

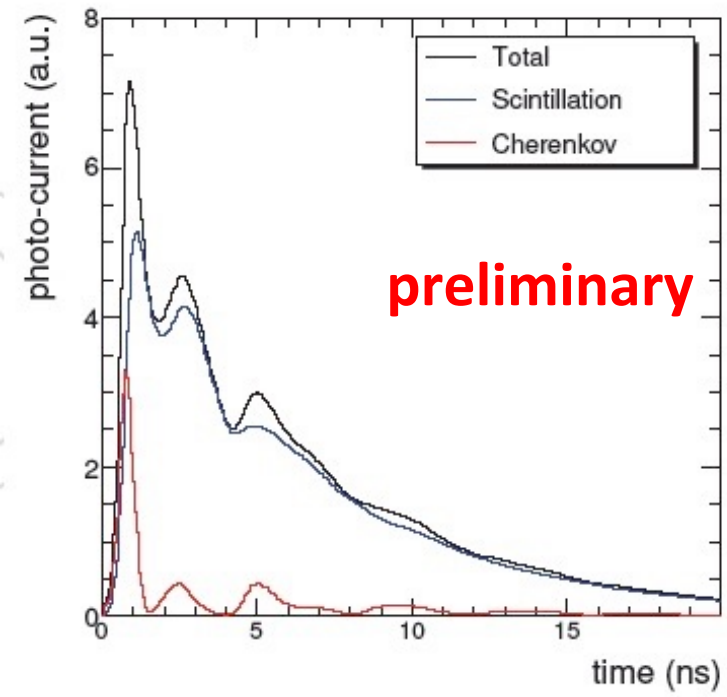
Can we find a way to mitigate these problems?

Mitigation of "Spikes" by

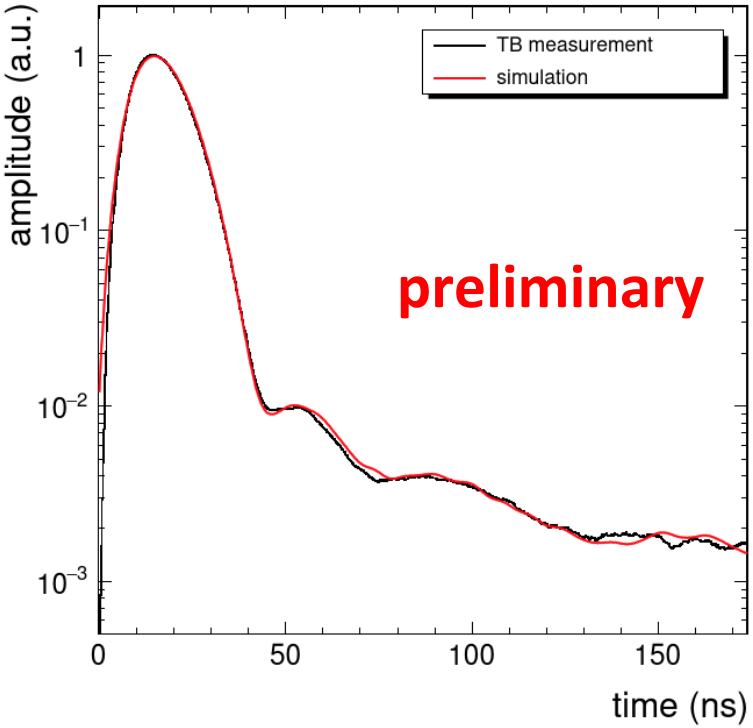
1. Discriminating on shape difference wrt true signals
2. Use of the "Swiss cross" discriminant of shower shapes in trigger towers

Reduction of pileup of true signals by 30 ps timing

$PbWO_4$ Signals Time Profile
Scintillation plus Cerenkov

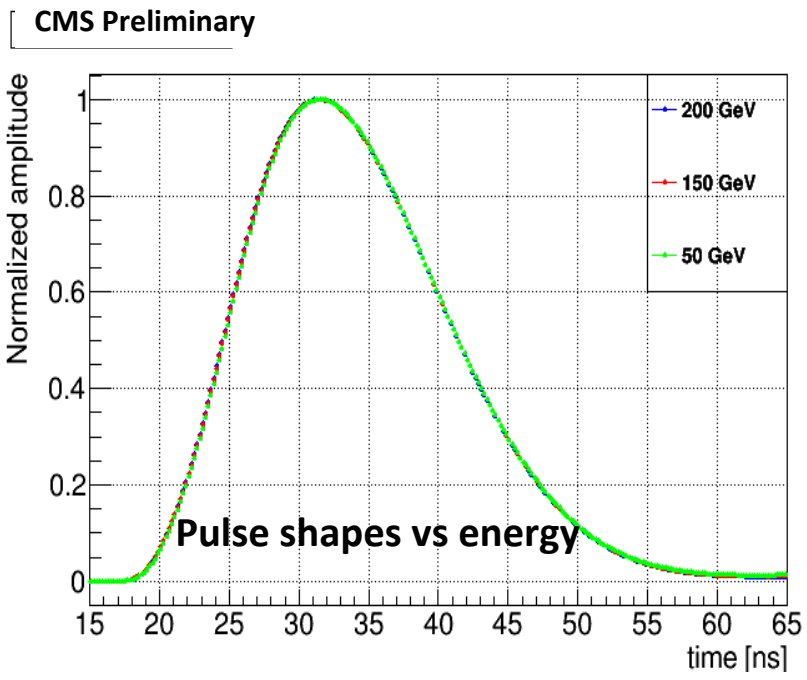


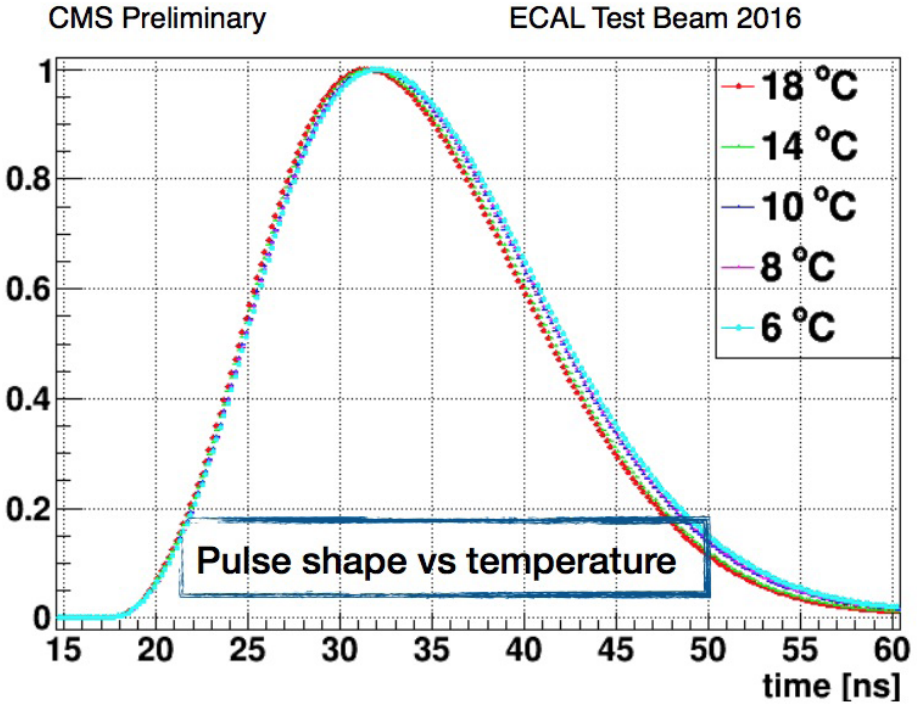
Simulation of components of the pulse shape from EM shower with APD and trans-impedance amplifier (TIA) before digitization



Comparison of actual test beam signals to simulations using a TIA

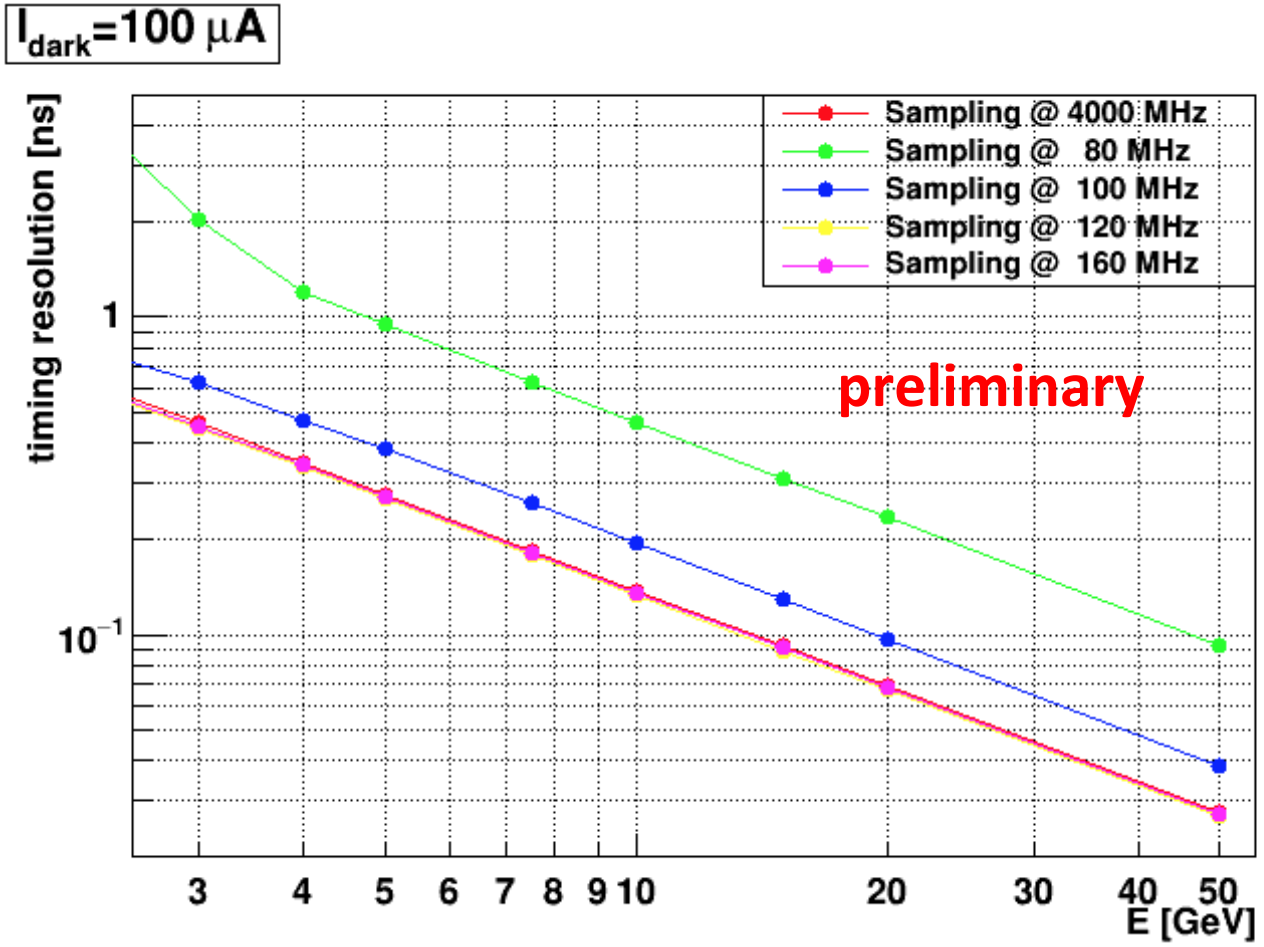
Stability of Phase I Pulse shapes With Energy/Temperature





Phase I front end with TIA

Requirement of 160 MHz sampling rate for EM barrel calorimeter time resolution of < 30 ps

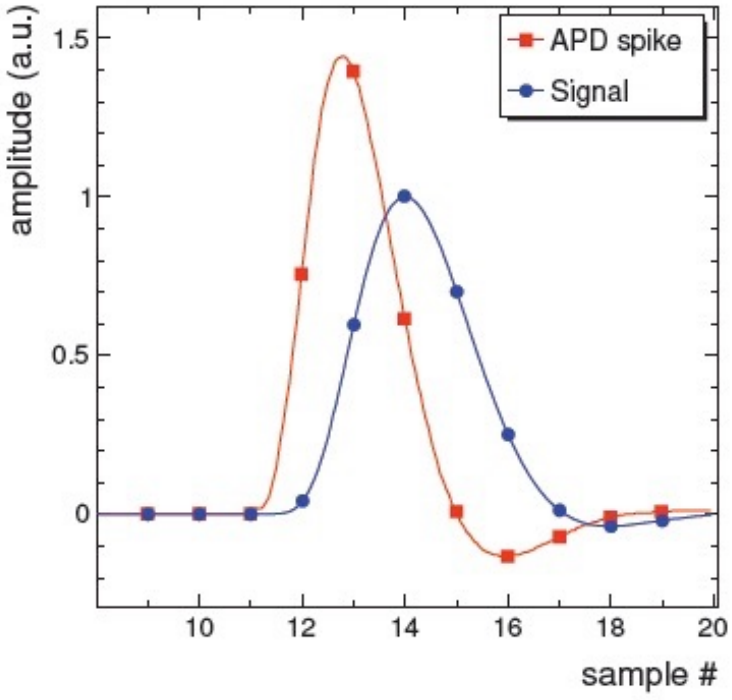


160 MHz required for < 30 ps timing resolution in EM calorimeter

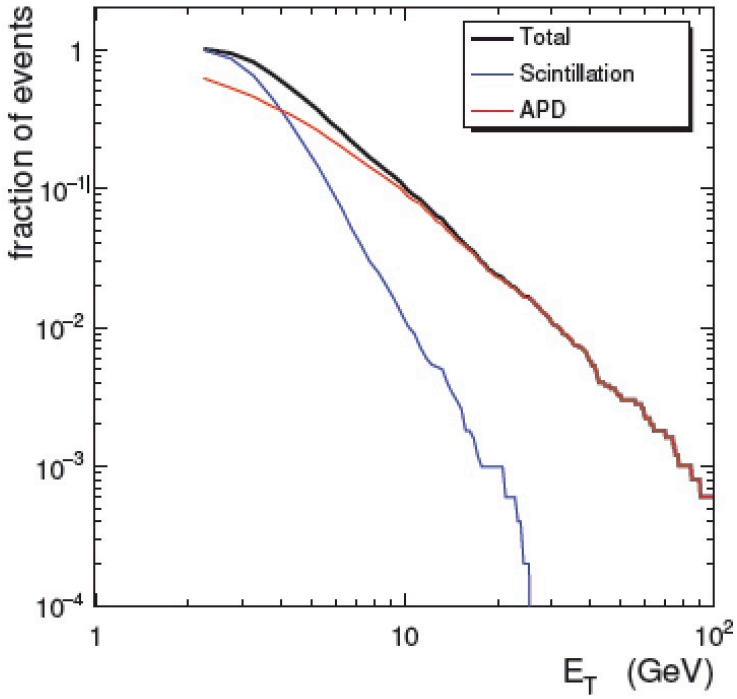
Spike Frequency Fraction vs True Signal Rate.

False signal Spike rate is proportional to PU

preliminary



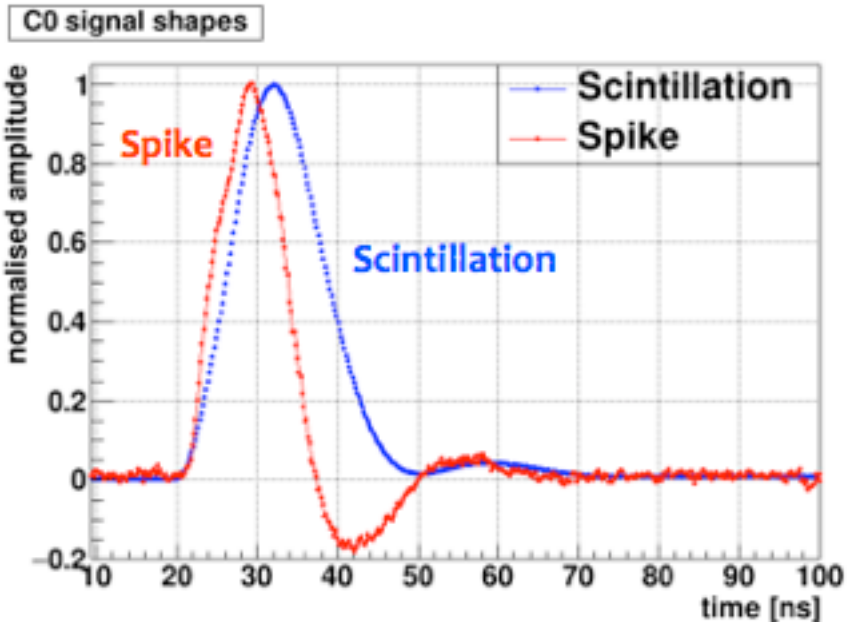
Spike vs true signal rate shape

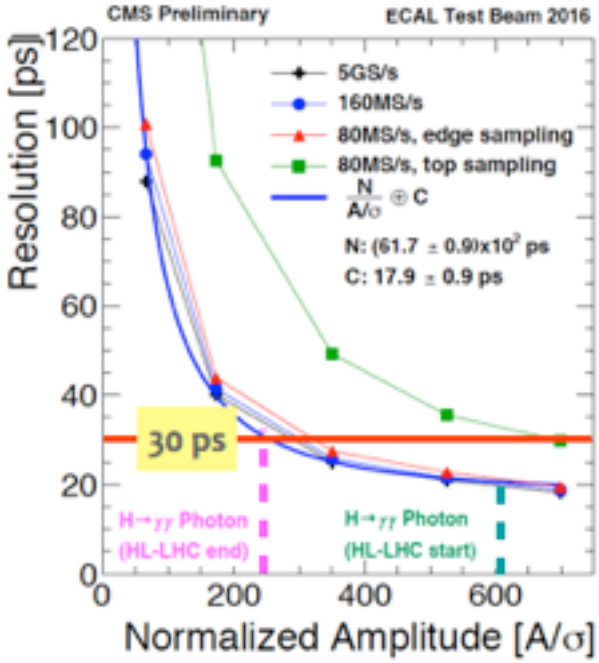


Fraction of events due to "spikes" as opposed to true signals as a function of energy

Spike Discrimination and Pulse Timing

preliminary





Spikes have different shapes from scintillation signals and can be rejected at an early stage by shape discrimination.

30 ps timing of signals in the Higgs photon energy regime with 5 MHz sampling to allow better vertex resolution for photons to reduce Pileup.

Results of Improved VFE and FE

- Trans-impedance amplifier allows direct look at APD analog signal allowing possibility of early spike rejection on pulse shape.
- VFE changes to decreased shaping time (20 ns) plus increased digitization rate (160 MHz) to reduce out-of-time pileup contamination, spikes, and electronics noise by 30 ps timing.
- FE card becomes pipeline, moving all 61,200 $PbWO_4$ signals off-detector for more complete processing.
- Off-detector electronics will be upgraded to accommodate required higher data transfer rates.
- Single crystal signals transmitted to offline Level 1 trigger will allow arbitrary latency and offline primitive usage in the trigger leading to improved spike rejection and higher trigger rates.

Summary of Phase II EM Barrel Upgrades

The barrel electromagnetic calorimeter will sustain some radiation damage somewhat **mitigated by operation at 9° C** but, unlike the endcap electromagnetic calorimeter survive to 3000 fb^{-1} and will not have to be replaced.

APDs will survive but will be noisier but this **will also mitigated by operation at 9^0 C**

No physical changes will be attempted for the $PbWO_4$ and the APDs

Replacement of the on-detector electronics to

Allow for increase trigger rate from 100 kHz to 750 kHz
Allow increase in latency for L1 trigger from 5 to 12.5 μs
Improve spike rejection by single crystal info transmitted to L1 and by access to APD fast pulse shapes.
Achieve 30 ps timing to allow good vertex determination and PU mitigation by 5 MHz sampling.