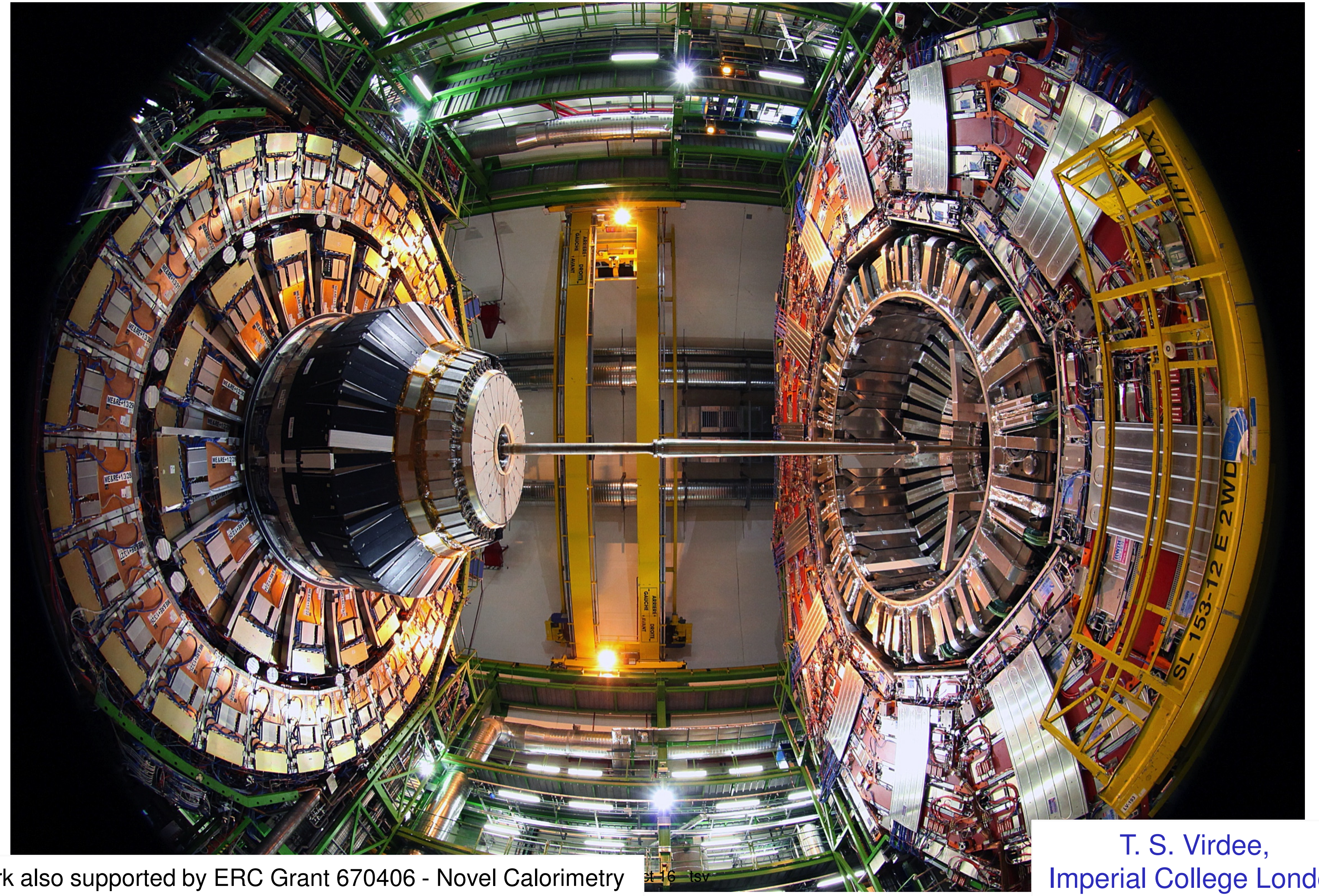
A Novel Calorimeter for HL-LHC and Beyond

CMS Endcap High Granularity Calorimeter for Phase II

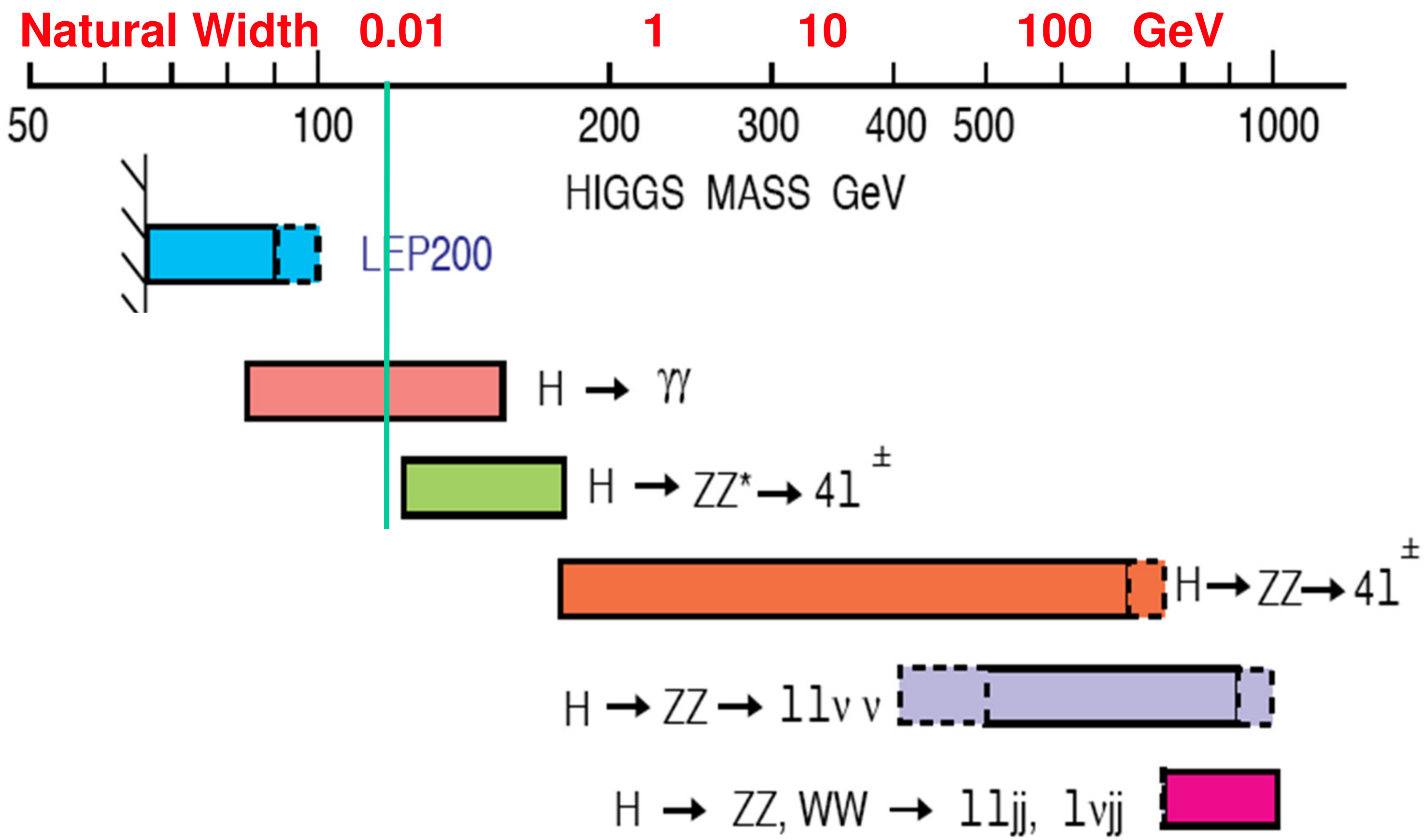


Work also supported by ERC Grant 670406 - Novel Calorimetry

T. S. Virdee,
Imperial College London

Imperial College London

Physics Drives Detector Design: e.g. the Higgs boson



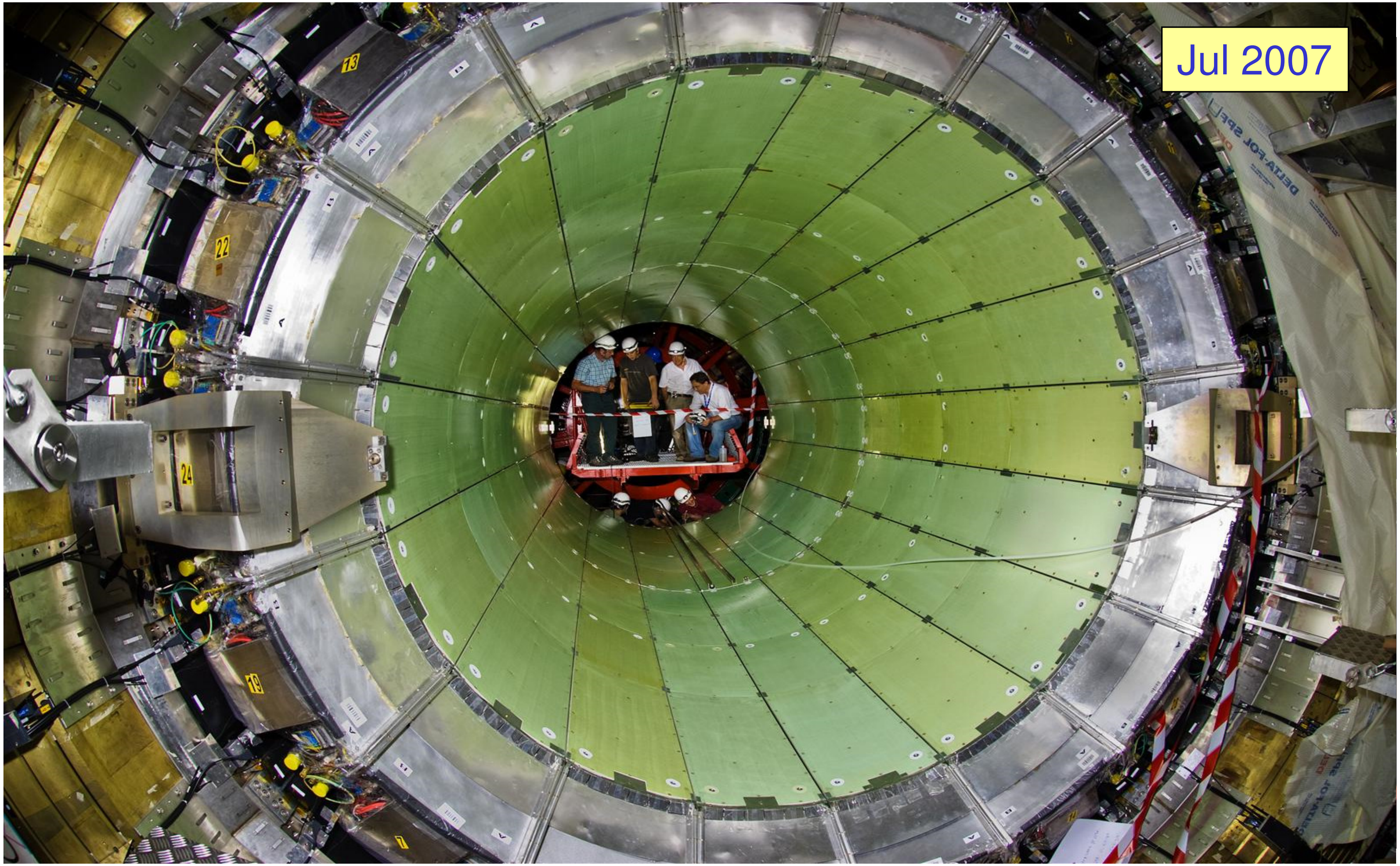
Theory does not predict m_H

The favourable decay modes change with mass

Transparency from the 90's

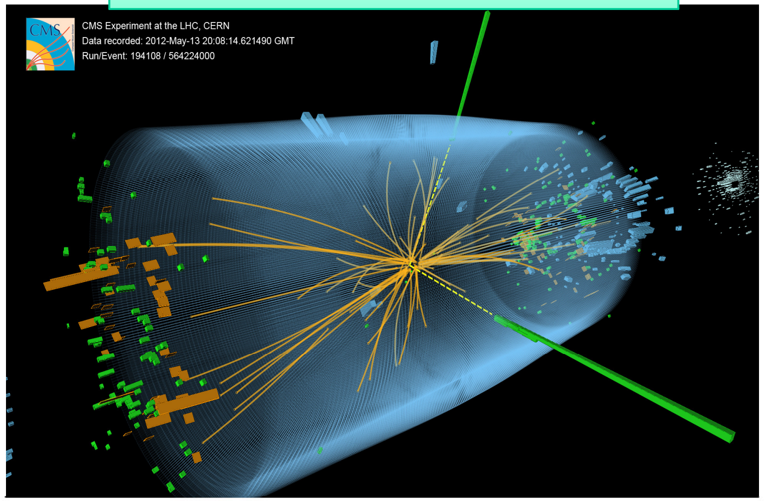
Instrument Quality and Capability Matters

Discovery of the Higgs Boson

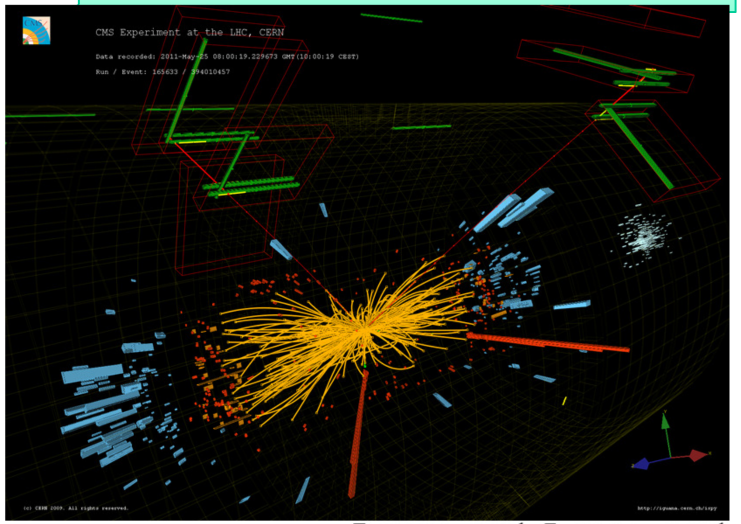


The Higgs boson in CMS

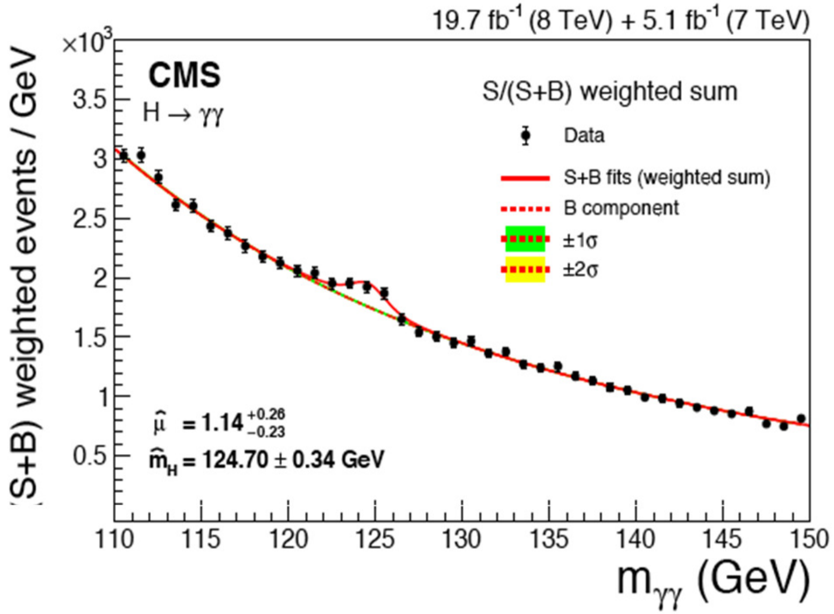
CMS: H→γγ Channel

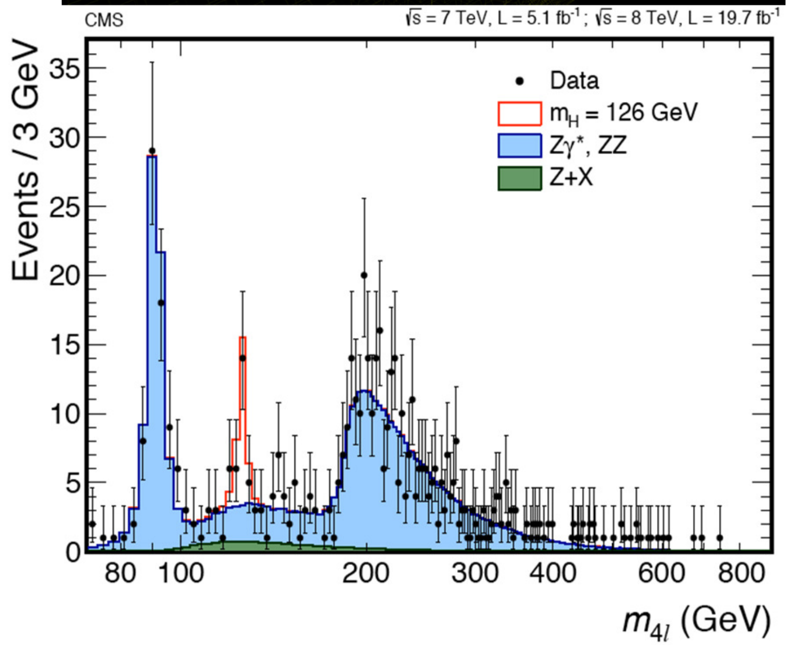


CMS: H→Z→4*l* Channel



2013

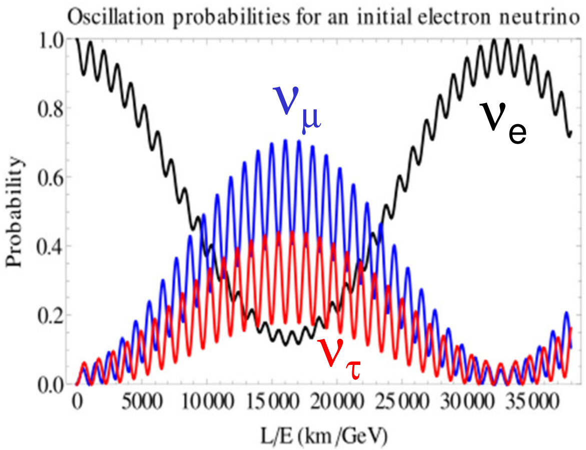




Moving Forward

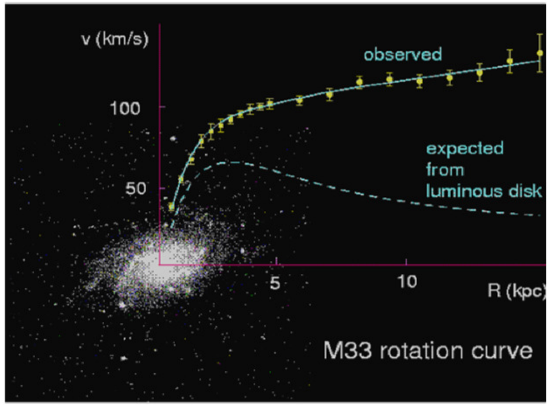
Ample observational evidence for physics Beyond the SM

Neutrino mass (oscillations)

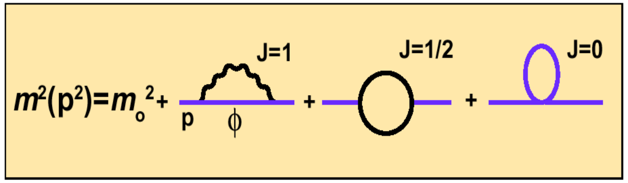


2015

Dark Matter



The lightness of the Higgs boson?



Matter-antimatter asymmetry

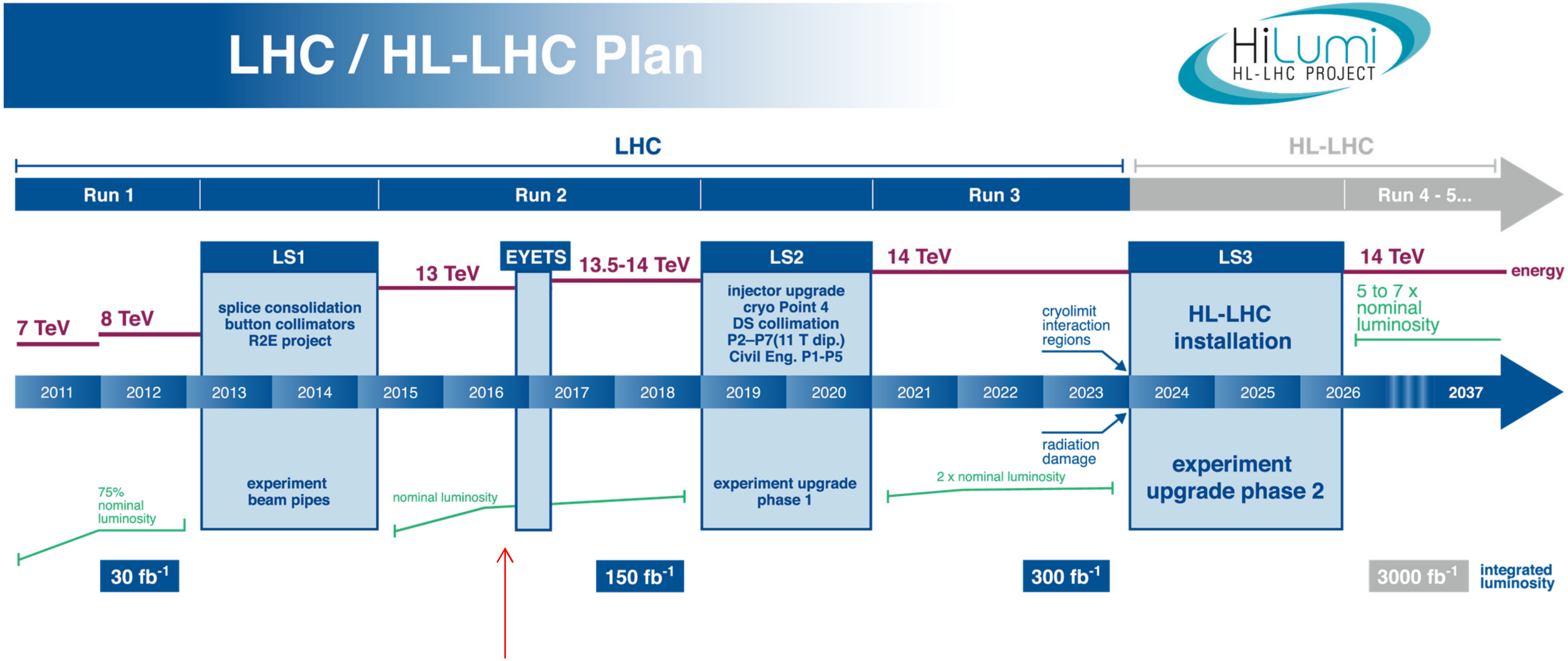
How did it arise?

Imperial College London

What makes it worthwhile to run longer an HEP experiment ?

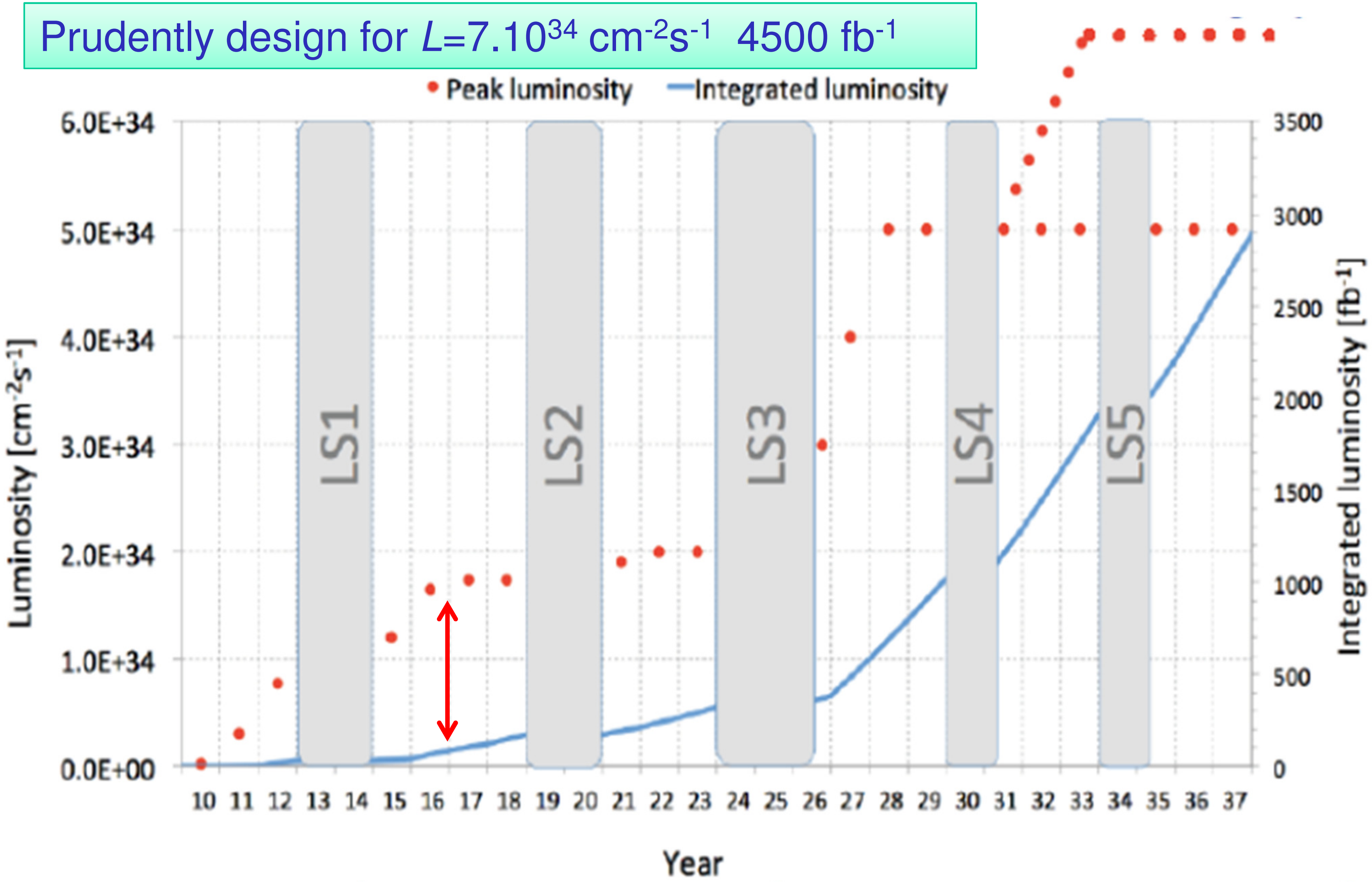
1. Higher centre-of-mass energy
2. Higher integrated luminosity
3. Qualitatively better detectors

LHC roadmap to achieve full potential



Hi-Lumi LHC to achieve full potential

Prudently design for L=7.10^{34} cm^{-2}s^{-1} 4500 fb^{-1}



30 fb^{-1} 300 fb^{-1} 3000 fb^{-1}

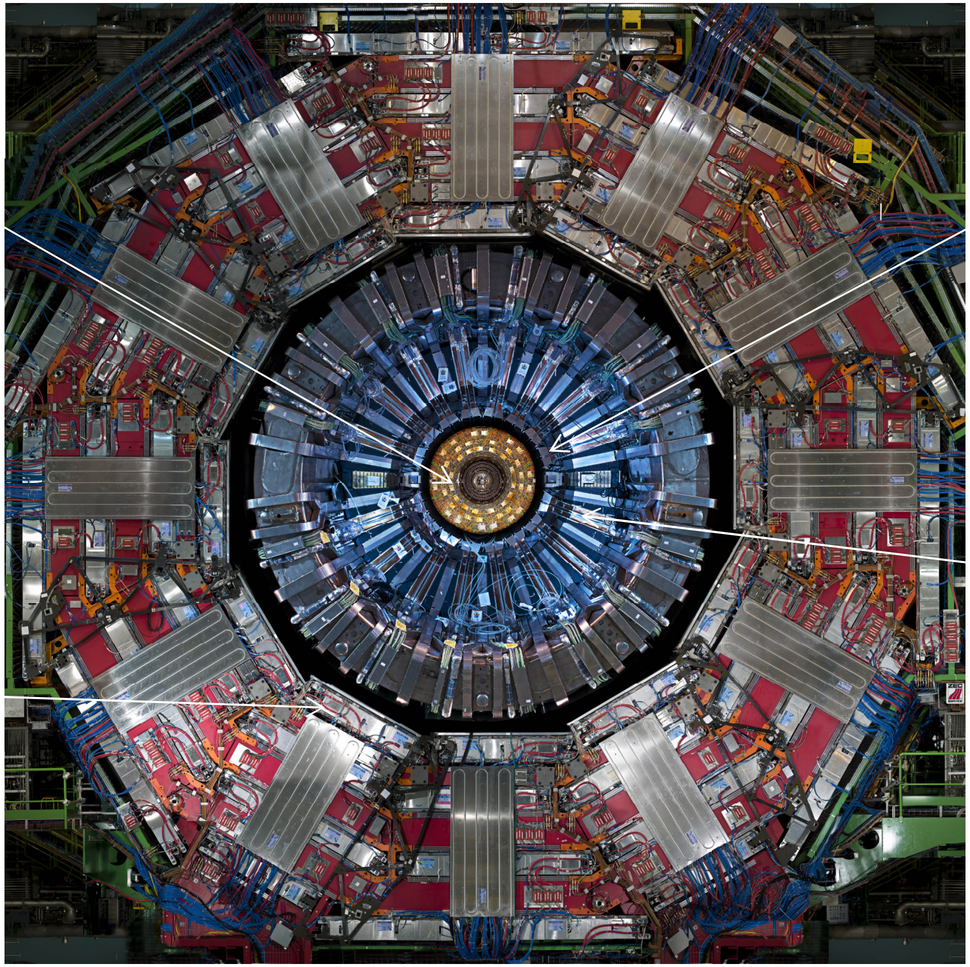
Imperial College London

The Current CMS Detector!

Silicon Tracker

Gas ionization chambers

3000 scientists from 40 countries



Originally designed for 500 fb^{-1}

Scintillating Crystals

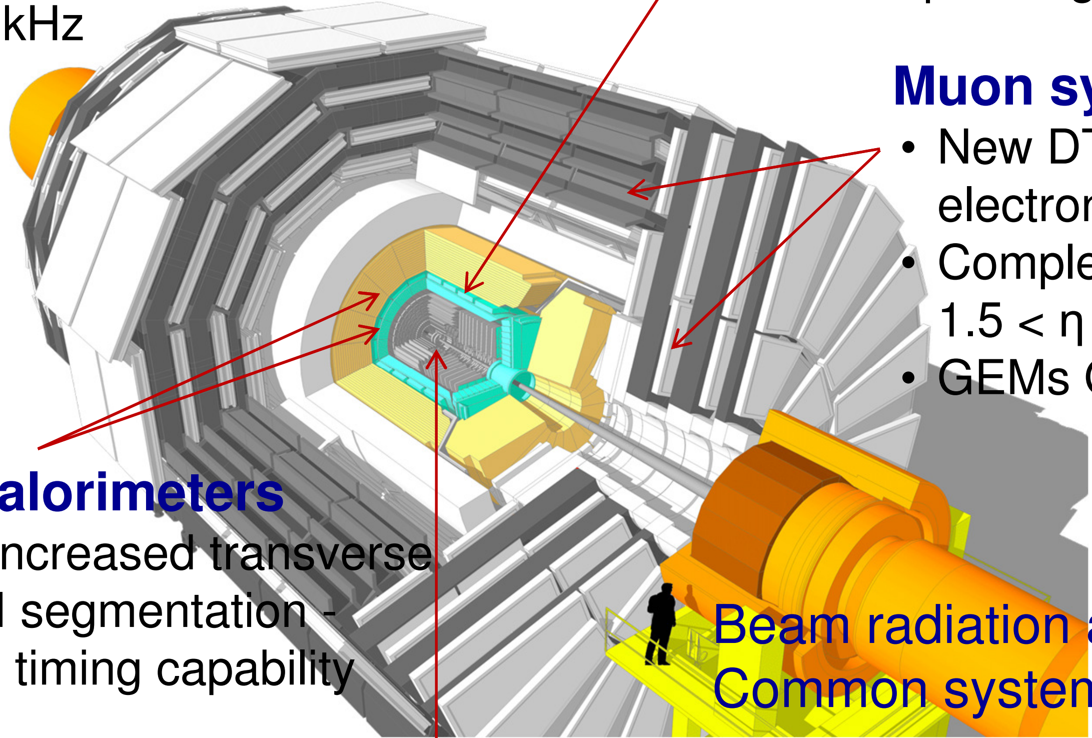
Brass plastic scintillator

CMS “Reference” Upgrades for Phase II (TP)

Trigger/HLT/DAQ
- Track information in Trigger (hardware)
- Trigger latency 12.5 μs - output rate 750 kHz
- HLT output 7.5 kHz

Barrel EM calorimeter
- New FE/BE electronics
- Lower operating temperature (8°C)

Muon systems
- New DT & CSC FE/BE electronics
- Complete RPC coverage $1.5 < \eta < 2.4$
- GEMs GE1/1, GE2/1, ME0



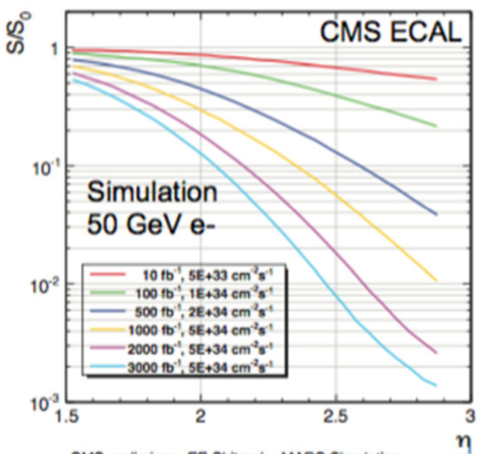
New Endcap Calorimeters
- Rad. tolerant - increased transverse and longitudinal segmentation - intrinsic precise timing capability

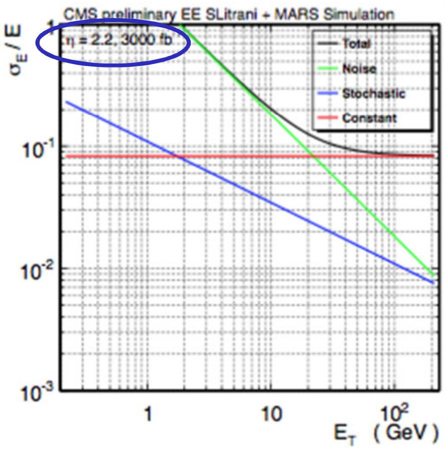
Beam radiation and luminosity
Common systems &infrastructure

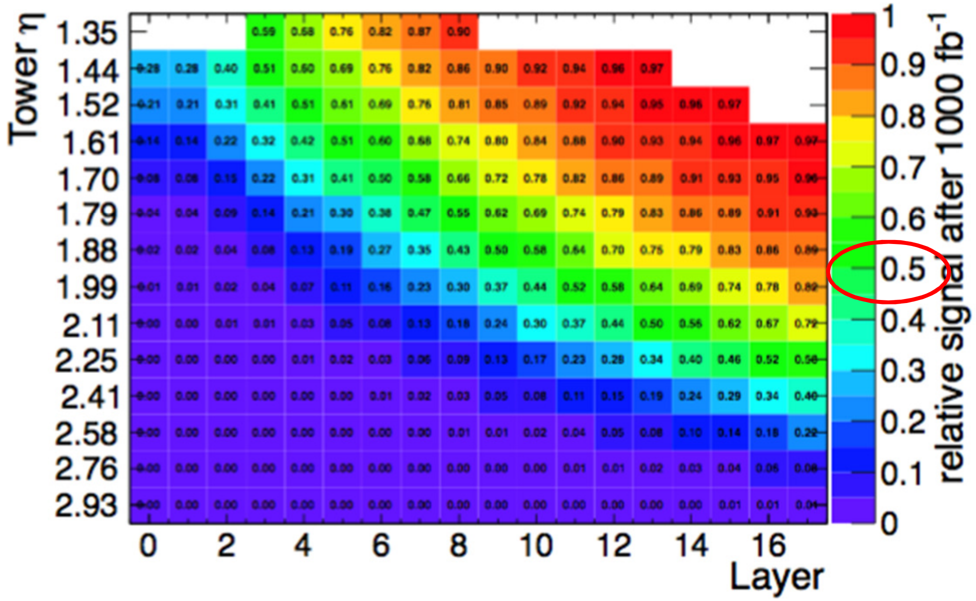
New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout ($p_T \geq 2$ GeV) in Outer Tracker for Trigger
- Extended coverage to $\eta \simeq 3.8$

$PbWO_4$ Endcap ECAL will need Replacing

The replacement of CMS Endcap calorimeters is required due to radiation-induced effects [see CMS TP: LHCC-2015-10, p 72-82]







Expected relative signal after 1000 fb-1 for the existing Hadronic Endcap Calorimeter

Relative response (top) and expected energy resolution (bottom) of the existing Endcap Electromagnetic Calorimeter after 3000 fb^{-1}. The resolution is O(10%) at the end of HL-LHC

Endcap HCAL due to radiation damage of plastic scintillator

$PbWO_4$ crystals due to radiation damage by hadrons

CMS’ Endcap Calorimetry needs replacing

Start by considering the endcap region as a blank canvas

and ask

After the discovery of the Higgs boson
what are the physics priorities for the endcaps?

Imperial College London

Reminder: Physics Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

✓ **2. Clarify the e-w symmetry breaking sector**

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, M_Z ~ 100,000 MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found all is not completely well with SM alone: next question is "Why is (Higgs) mass so low"?

*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV)**

5. Search for new physics at the TeV scale

SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

Imperial College London

Looking Ahead to Phase 1 and Phase 2 (HL-LHC)

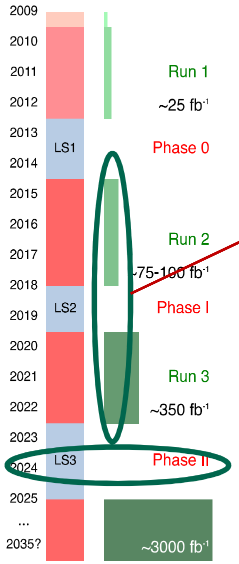
Topmost Priority – exploitation of the full potential of the LHC

High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

Conduct detailed studies of the properties of the found Higgs boson.

How much does it contribute to restoring unitarity in VBF (closure test of SM), exotic decays, rare decays (e.g. $H \rightarrow \mu\mu$)

LHC → HL-LHC - a Higgs factory! 100M produced with $3ab^{-1}$



$L(fb^{-1})$	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

Couplings Precision ~ 2-10%, H self coupling ~30% (needs study)

- **Search for new physics: resonances, supersymmetry, exotica, yet unknown.** If new physics found in Phase 1, associated particle(s) will be heavy. Then conduct detailed studies in HL-LHC
- **Look for deviations from the standard model – precision SM measurements** (e.g. tens of millions of top pairs produced/yr).

Physics Case at HL-LHC

Physics Drivers for the Design of Endcap Calorimeter Upgrade

Some Examples:

1. Physics with isolated objects (e, γ, μ, τ ..) **as today (→low thresholds)**
2. Physics with VBF/VBS tags
3. Physics using boosted objects (jet substructure in boosted W, Z, tops)
4. QCD studies of quark v/s gluon jets

ALL at 140-200 events pileup

Some Challenges

Trigger (especially L1) e.g. VBF jets without placing any requirement on the on the rest of the event,
Vertex ID, PU jet ID/rejection, timing, pileup suppression, ..

- Take Example 2 and look in some detail:
  - VBF H($\tau\tau$), H(inv, e.g. DM), Dark Matter, SUSY production (may be the only way to discover at LHC moderately heavy charginos /neutralinos)
  - VBS: closure test of SM, “bread and butter” SM physics

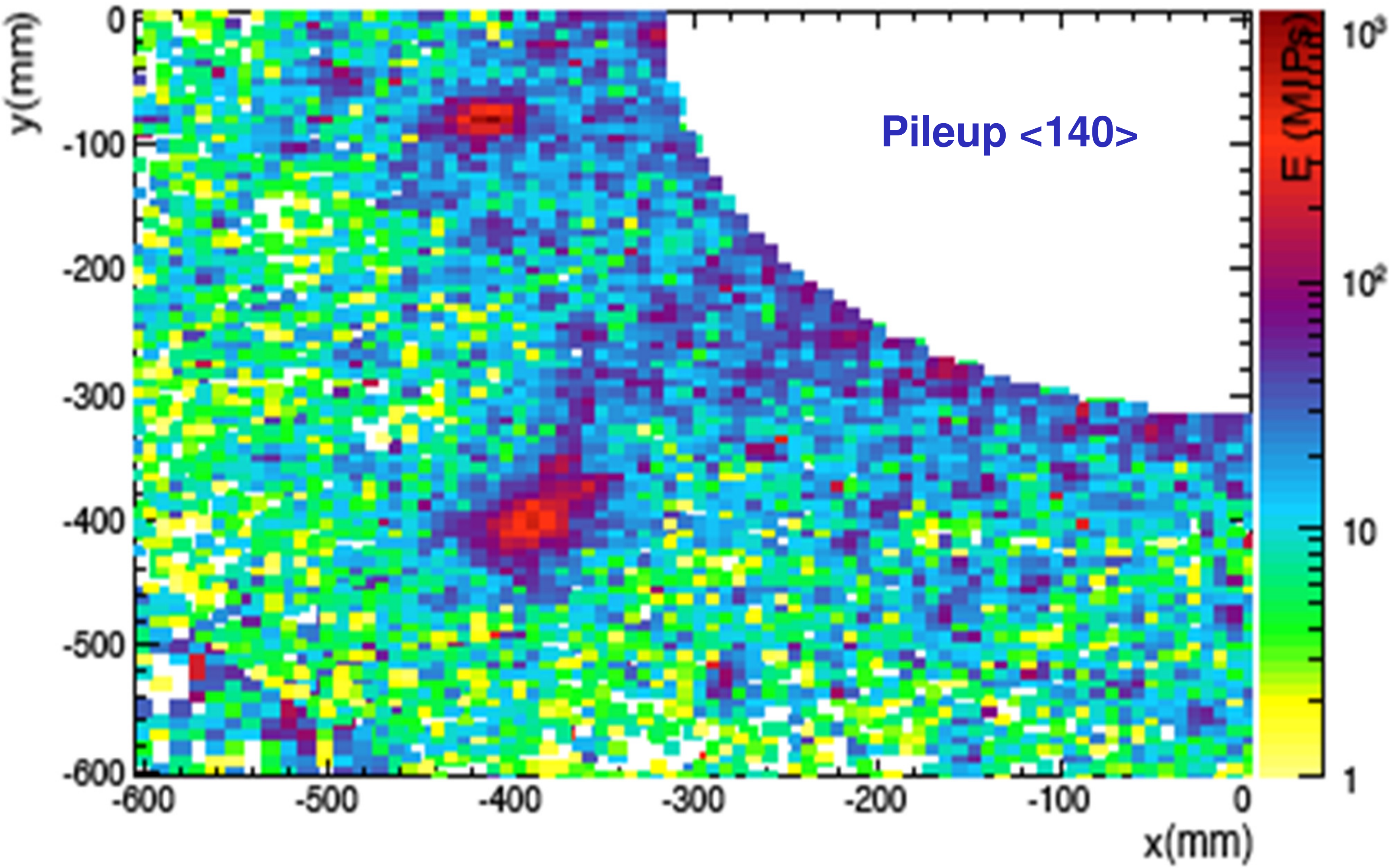
Imperial College London

Looking closely at a VBF Jet (VBF H$\rightarrow\gamma\gamma$)

VBFH evt 5 characteristics

vtx	pId	pdg	status	E (GeV)	pT (GeV)	η	ϕ	xFF	yFF
5	3	25	3	267.234	62.6023	2.00296	1.36729	176.108	853.37
6	1	22	3	176.836	21.8914	2.77842	-2.9555	-388.644	-73.1711
5	1	1	3	717.497	117.849	2.4927	-2.35589	-373.128	-373.353
60	4	321	1	7.29636	1.25235	2.44572	1.83431	-144.198	534.494
60	10	-211	1	1.78182	0.462846	2.02064	-1.83334	-222.04	-826.214
60	12	-211	1	11.7788	1.69217	2.62817	-2.51502	-372.791	-269.858
60	17	-211	1	247.168	40.4587	2.49616	-2.34136	-366.375	-377.406
92	1	-321	1	4.30936	1.00983	2.12334	-1.78458	-163.255	-751.959
138	1	-211	1	2.32255	0.588201	2.0482	1.23511	273.902	785.074
139	1	-211	1	2.23853	0.474176	2.23174	-3.08816	-687.496	-36.7692
140	1	-321	1	5.55465	0.560226	2.98066	-0.105339	320.857	-33.9245
142	1	-211	1	1.65867	0.336068	2.27555	-0.812546	452.696	-477.968
144	1	211	1	19.5236	2.40514	2.78332	-2.8646	-378.524	-107.614
146	1	-321	1	15.5038	2.39386	2.5548	-2.83058	-471.88	-151.683
148	1	211	1	252.986	41.7544	2.4878	-2.32486	-363.165	-386.666
229	1	130	1	3.76919	0.928466	2.06963	-2.57243	-685.065	-438.296
269	1	22	1	0.756801	0.129004	2.45506	2.9175	-534.673	121.86
271	2	22	1	1.38013	0.248237	2.4005	0.25498	560.887	146.197
272	2	22	1	1.94457	0.454496	2.13281	-2.78818	-714.922	-263.736
273	1	310	1	47.4983	7.83109	2.48882	-2.30261	-354.104	-394.243
274	1	22	1	17.8013	2.73597	2.55998	-2.38144	-357.343	-339.741
274	2	22	1	19.7095	3.03037	2.5596	-2.33456	-341.159	-356.25
275	1	22	1	68.3848	11.2397	2.49203	-2.35071	-371.44	-375.539
275	2	22	1	10.3692	1.6526	2.52322	-2.34794	-358.873	-364.848

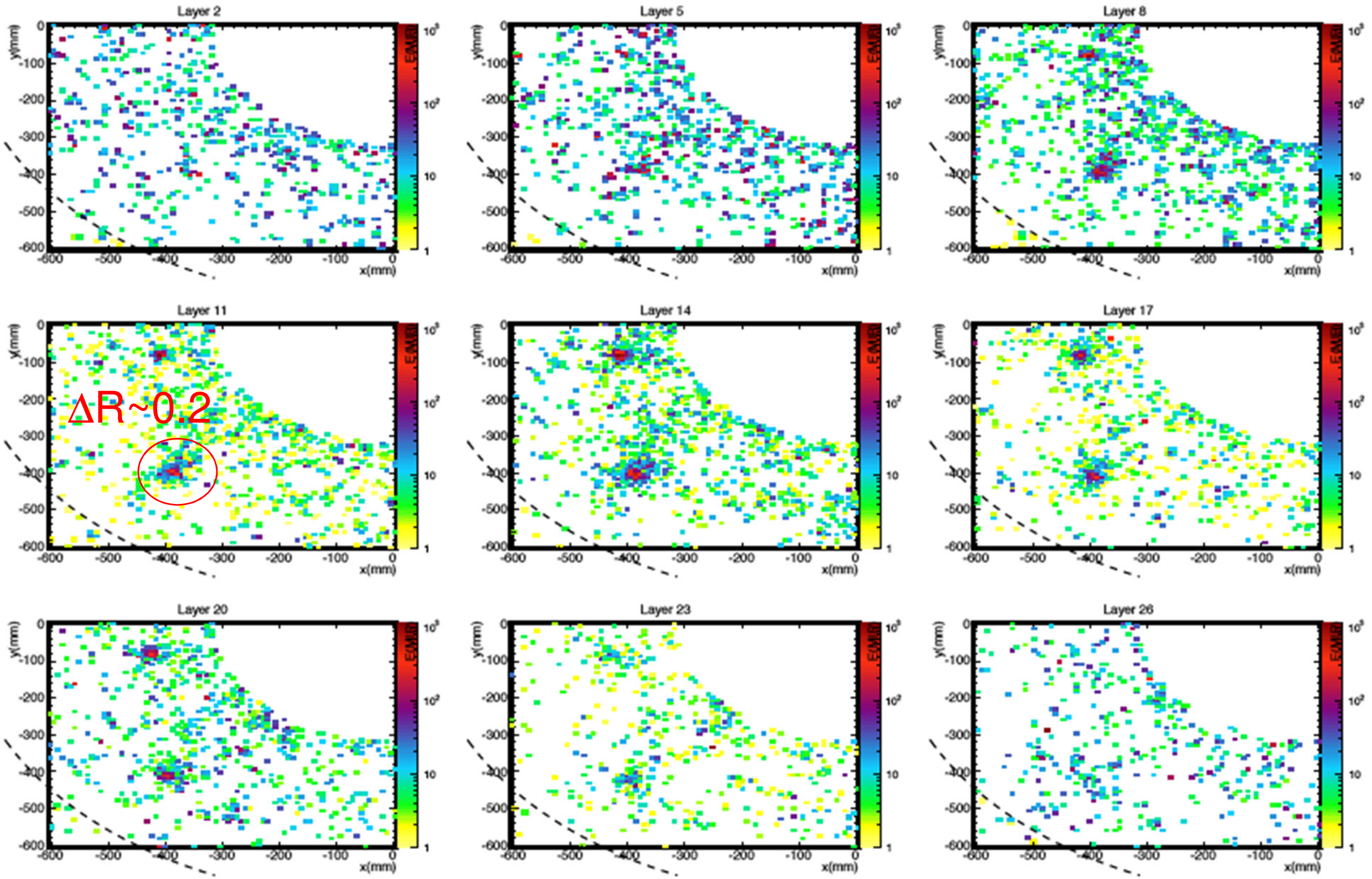
Event Display of VBF Jets (VBF H→γγ)



Imperial College London

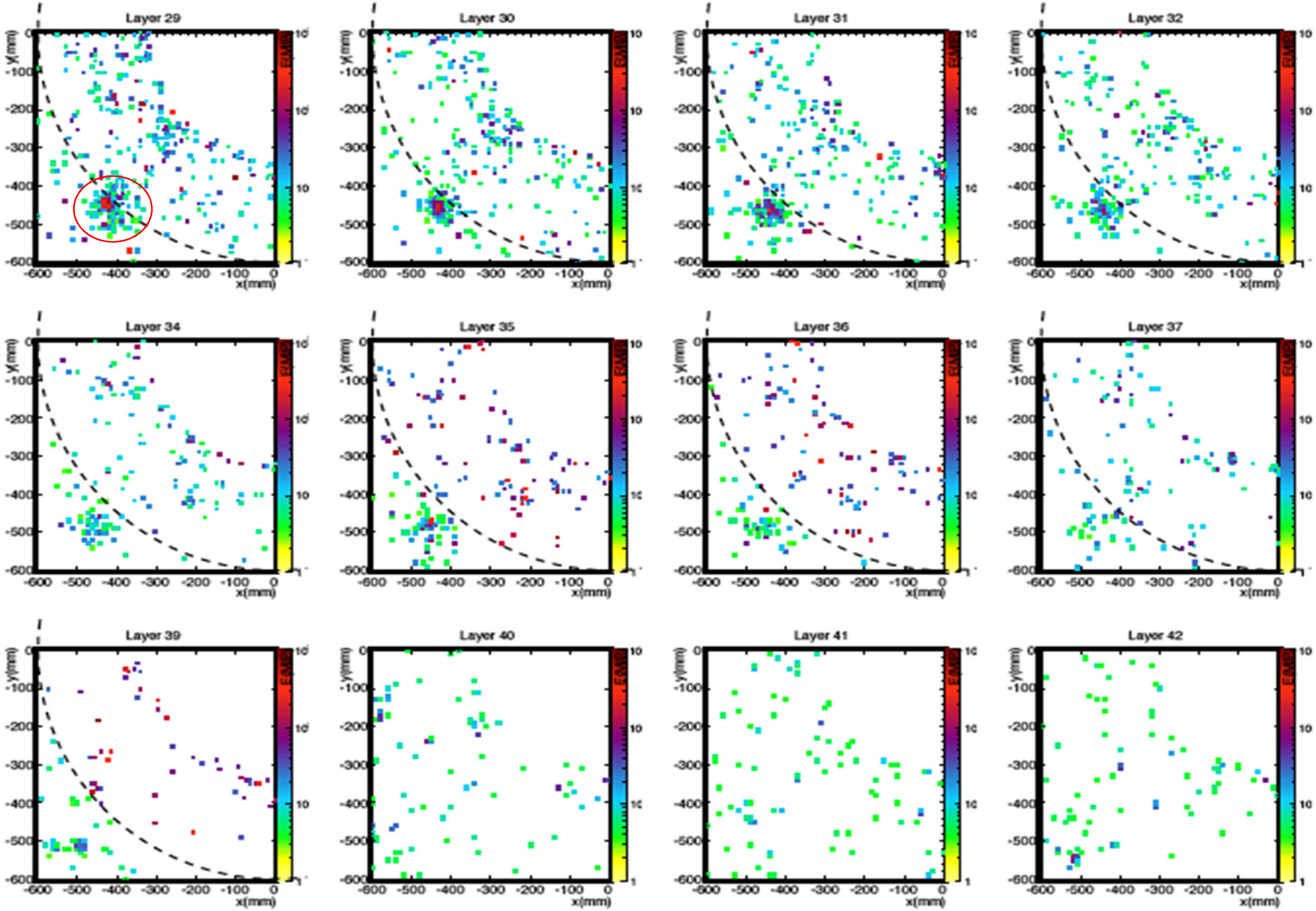
Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through ECAL section



Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through Si- HCAL section



How to proceed?

Look for a proven and adequately radiation hard active material
allowing a dense, good energy resolution
combined e.m./hadronic calorimeter, with a small R_M,
good two-shower separation (em and hadronic),
with high lateral and longitudinal granularity

Explore use of a silicon based sampling calorimeter
(absorber material – W, Pb, Steel)

Choice of Silicon for Endcap (EC) Calorimetry

Recent advances in silicon detectors, in electronics and data transmission suggest the possibility of their use in high granularity electromagnetic and hadronic calorimetry at the LHC.

The obvious questions that arise when considering such a silicon sampling calorimeter are:

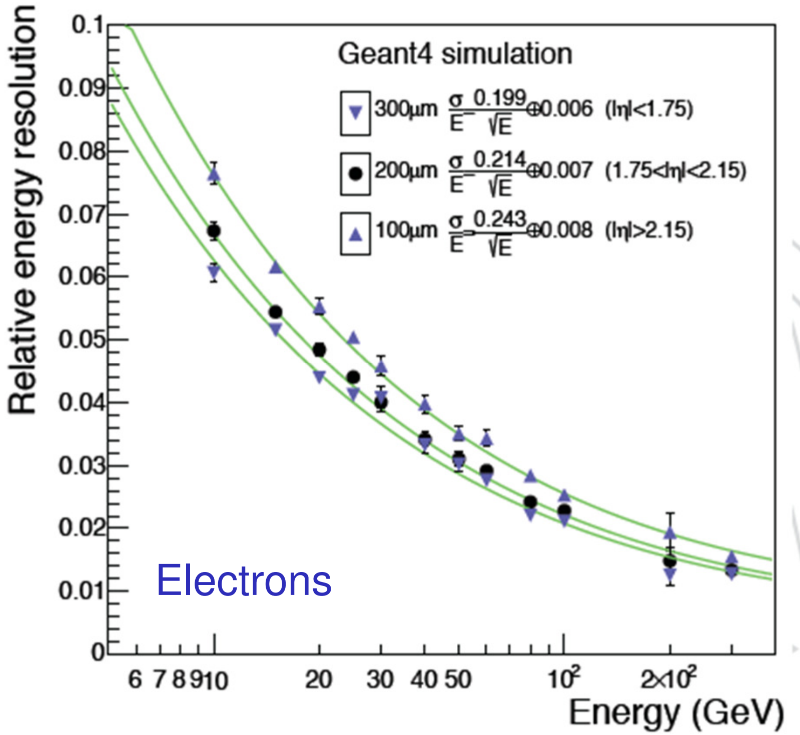
- **Cost of Si sensors (and overall cost)**
  - Cost basis has been established through a price enquiry from a reputable vendor (EC uses much simpler design than for strip trackers)
- **Radiation tolerance of sensors and electronics**
  - effects understood and reproducible from a wide range of tests carried out for the Hi-Lumi pixels detectors (similar radiation levels)
- **Level-1 trigger when using very high granularity**
  - a new challenge (but already can be faced with current technology)
- **Engineering challenge**
  - integration, construction, assembly, thermal management, connectivity/services,….

All of the above benefits from synergies with the Tracker and previous work (e.g. RD50, RD51, CMS and ATLAS Tracker R&D, CALICE)

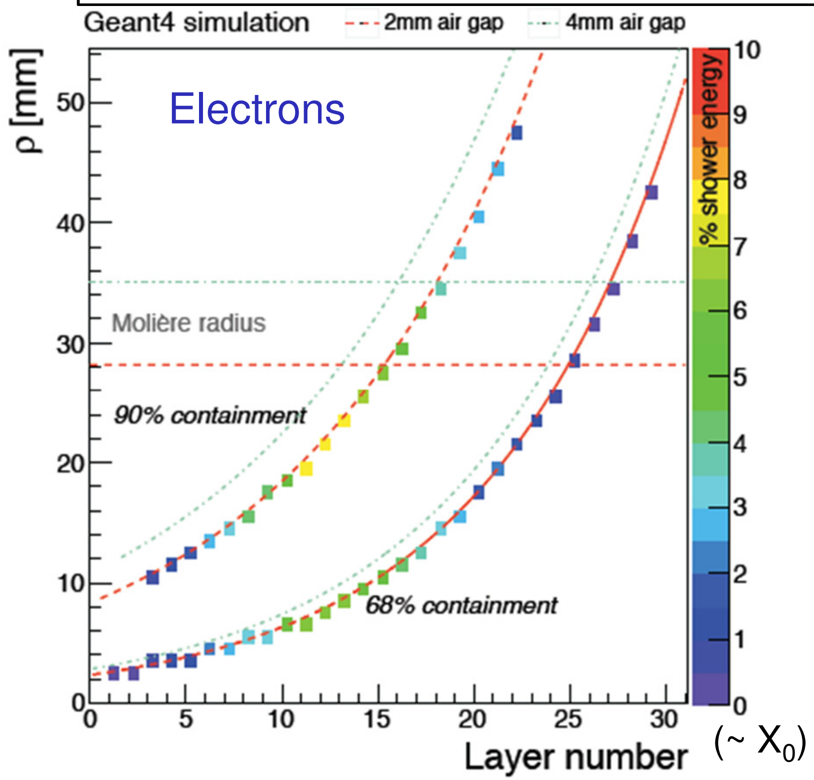
Performance studies in standalone setup

Simulation benchmarked against published CALICE test-beam results

Energy Resolution v/s Si thickness



em shower energy containment



In the endcap even at moderate p_T, E is high
Stochastic Term ~ 20-25% acceptable
Target small constant term (< 1%)

em showers very narrow in first $10X_0$ or so will aid pileup rejection, and allow good two-particle separation for the PFlow approach

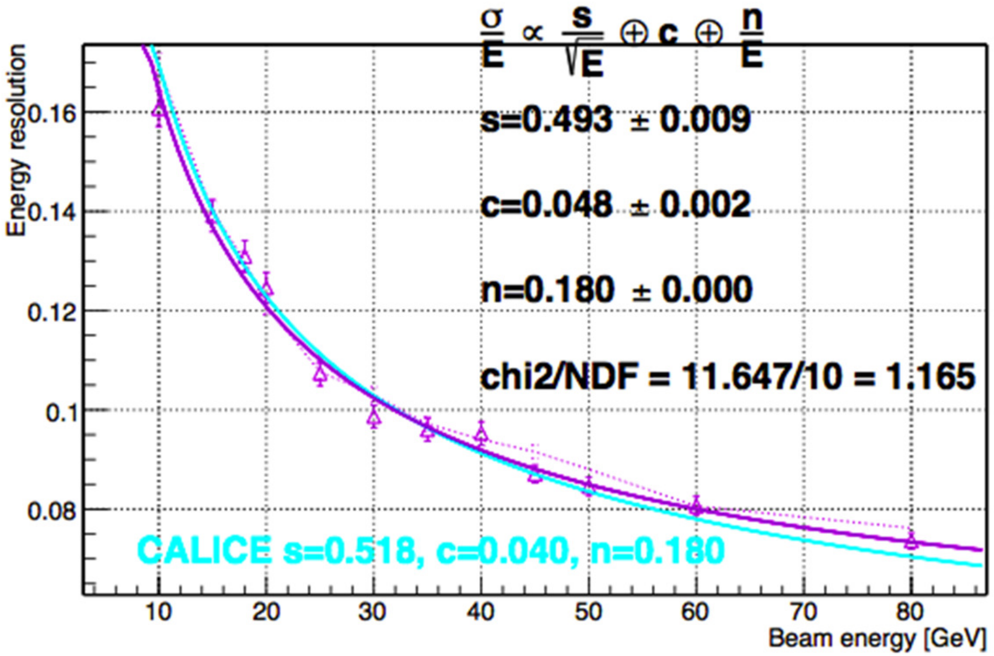
Good shower angular resolution possible: σ_θ~4mrad, at |η|=1.5, and PU140 (σ_Z~3cm)

Performance studies in standalone setup

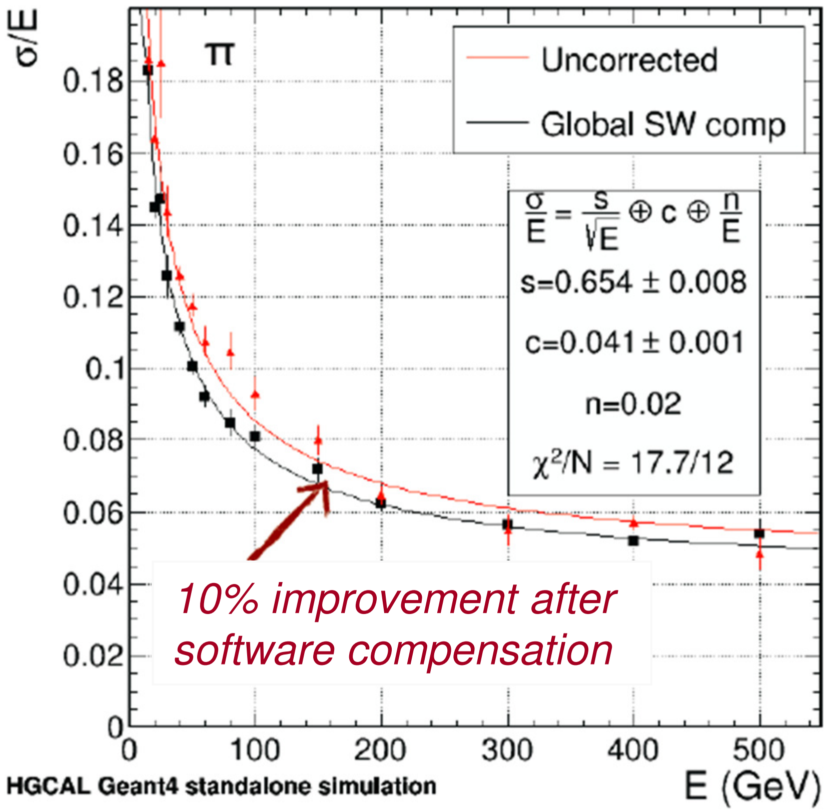
Our simulation benchmarked against published CALICE test-beam results

Pions

Energy Resolution: CALICE



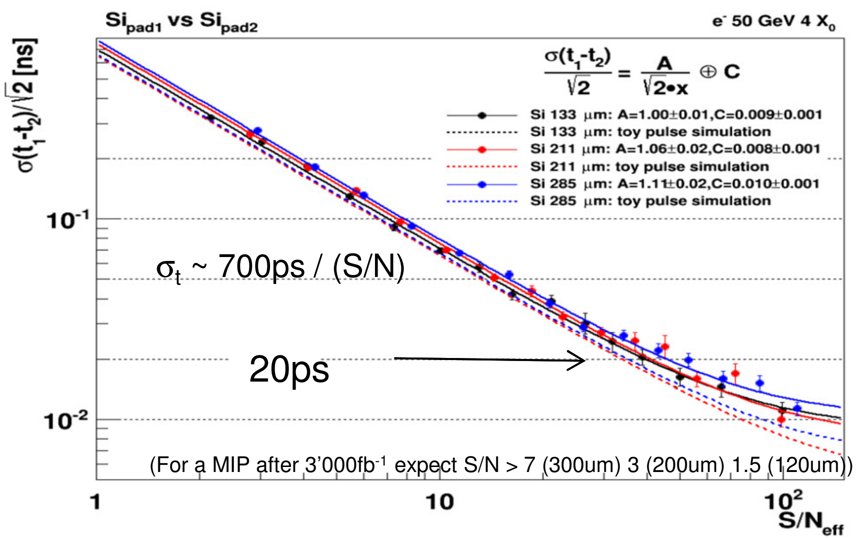
Energy Resolution: EC



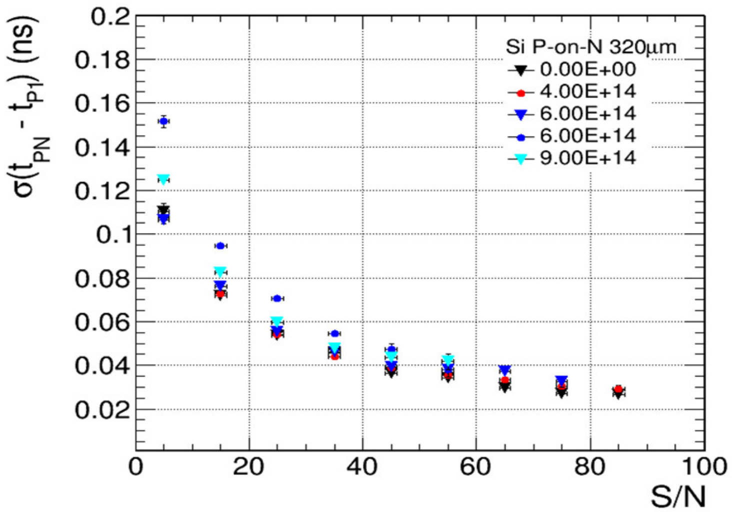
Si: Intrinsic Timing Precision

Precision timing helps in checking the compatibility of different showers originating from the vertex of interest - particularly useful for H->γγ

Tests in beam have shown that for large enough signals in a Si cell, an intrinsic timing better than 20ps can be obtained for both non-irradiated and irradiated sensors. This opens the possibility of measuring precise timing for em. (and large energy hadron) deposits and showers.



σ_t ~ 20ps for ~ 5 (300um) –> 20 (120um) MIPs

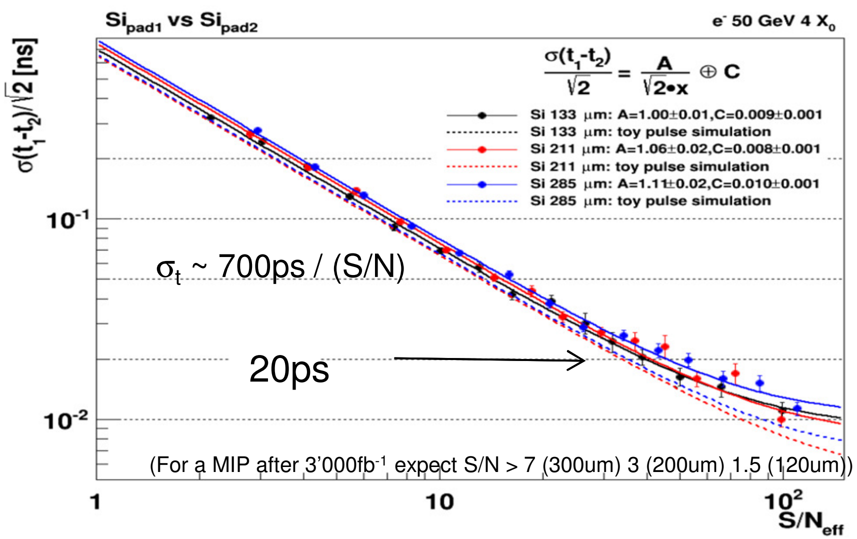


Irradiated diodes show very similar performance to non-irradiated ones

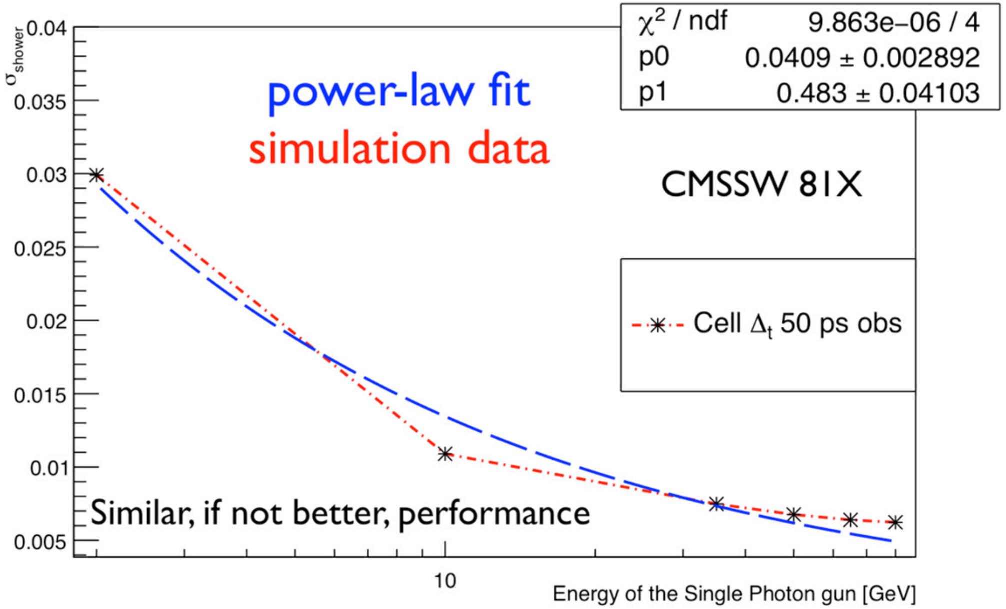
Si: Intrinsic Timing Precision

Precision timing helps in checking the compatibility of different showers originating from the vertex of interest - particularly useful for H->$\gamma\gamma$

Tests in beam have shown that for large enough signals in a Si cell, an intrinsic timing better than 20ps can be obtained for both non-irradiated and irradiated sensors. This opens the possibility of measuring precise timing for em. (and large energy hadron) deposits and showers.



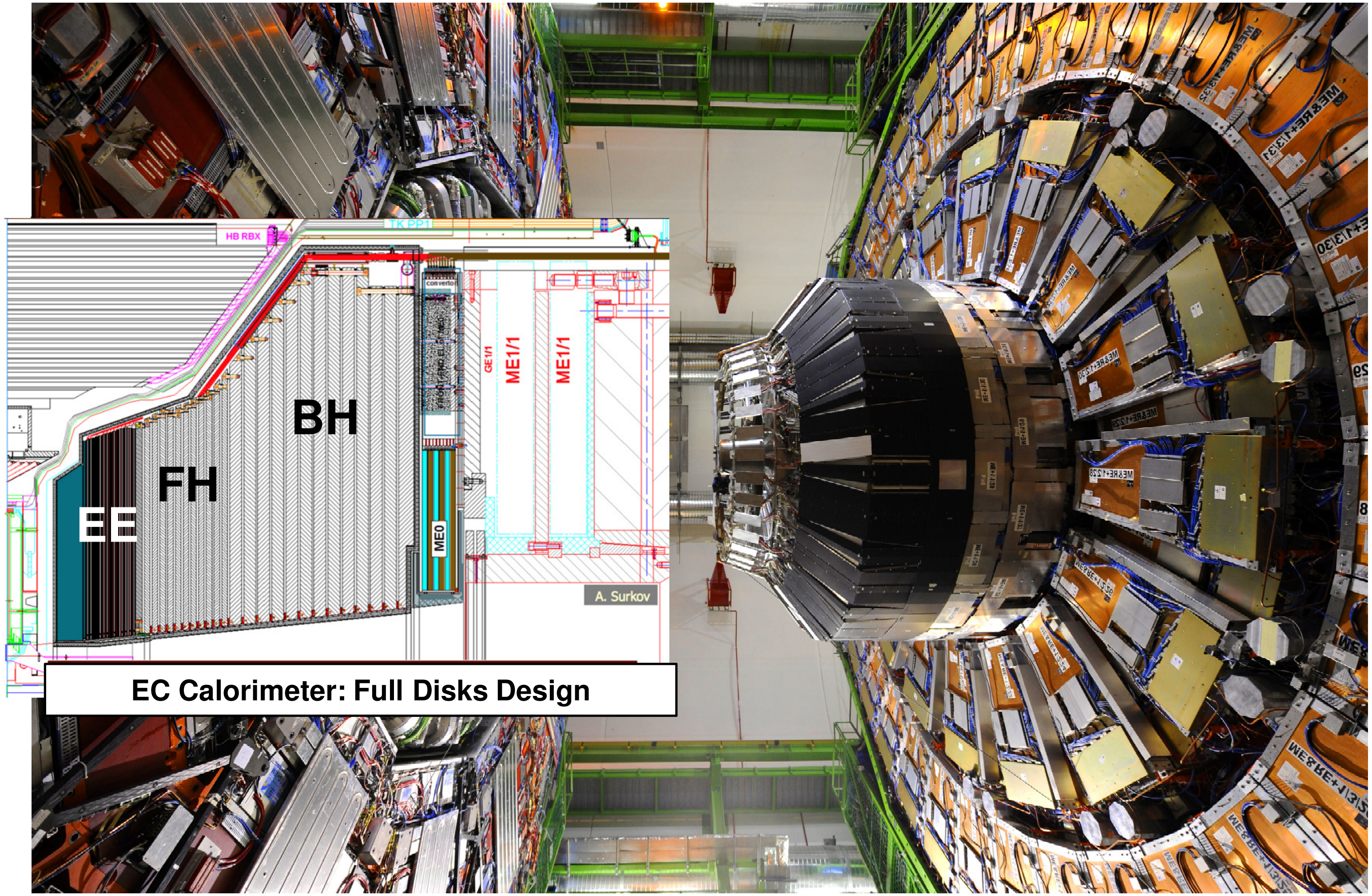
$\sigma_t \sim$ 20ps for ~ 5 (300um) –> 20 (120um) MIPs



Target: keep clock jitter, systematics etc. <20ps

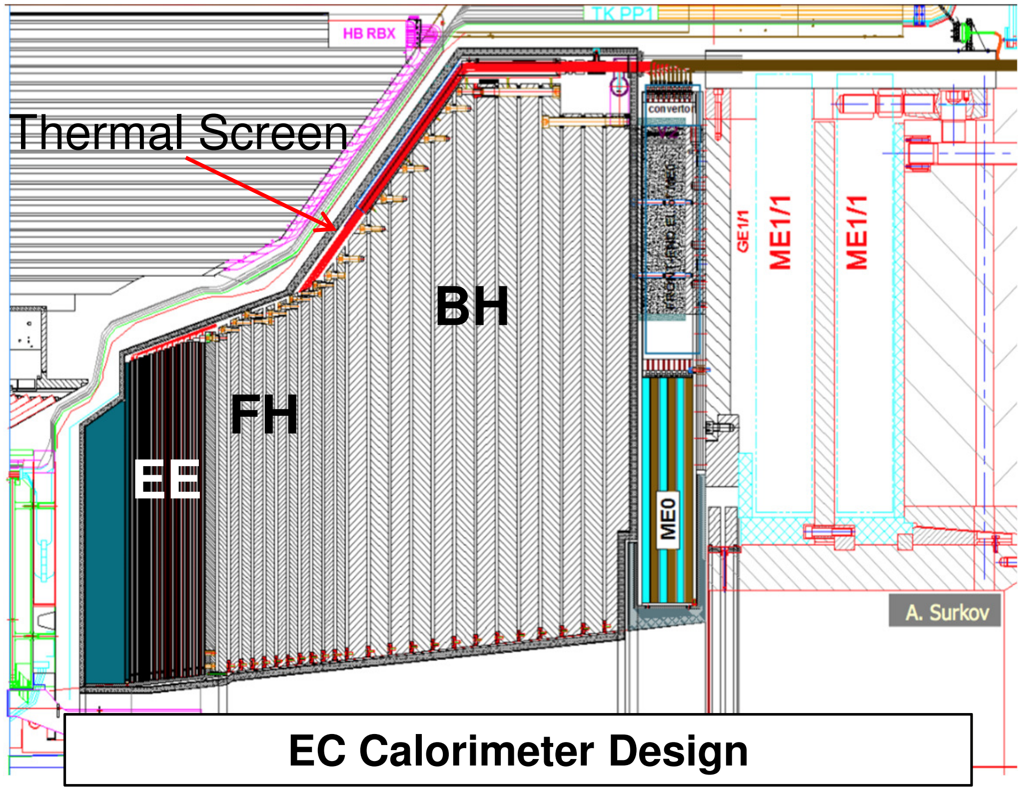
Imperial College London

What Needs Replacing?



EC Calorimeter: Full Disks Design

Calorimeter Design



EC Calorimeter Design

Construction:
- *Hexagonal Si-sensors built into modules.*
- *Modules with a W/Cu backing plate and PCB readout board.*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes integrated into absorber structures at integration site (CERN)*

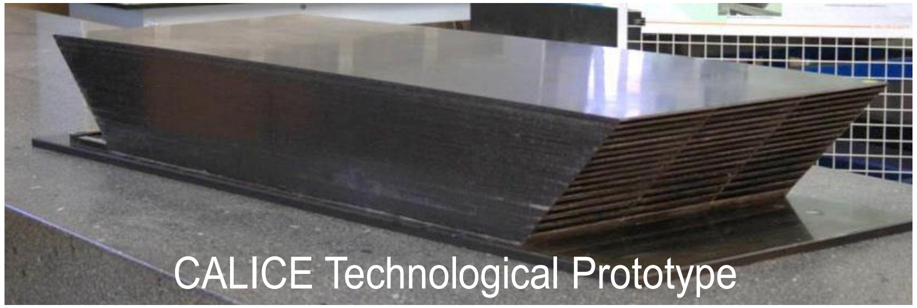
Key parameters:
- *593 m^2 of silicon*
- *6M ch, 0.5 or 1 cm^2 cell-size*
- *21,660 modules (8" or 2x6" sensors)*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*

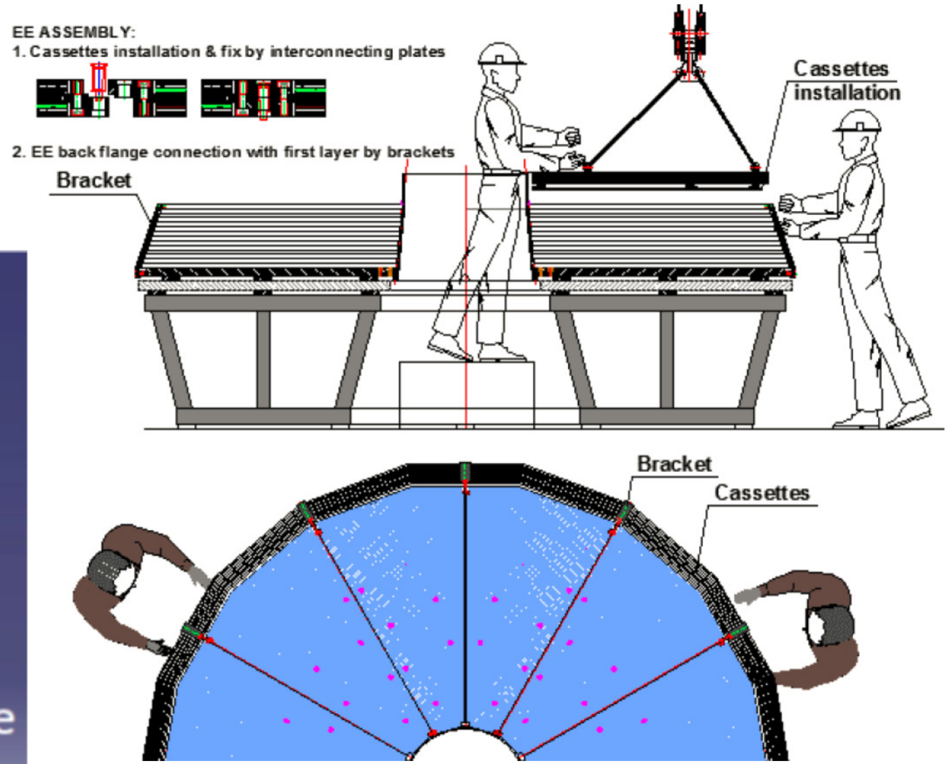
System Divided into three separate parts:

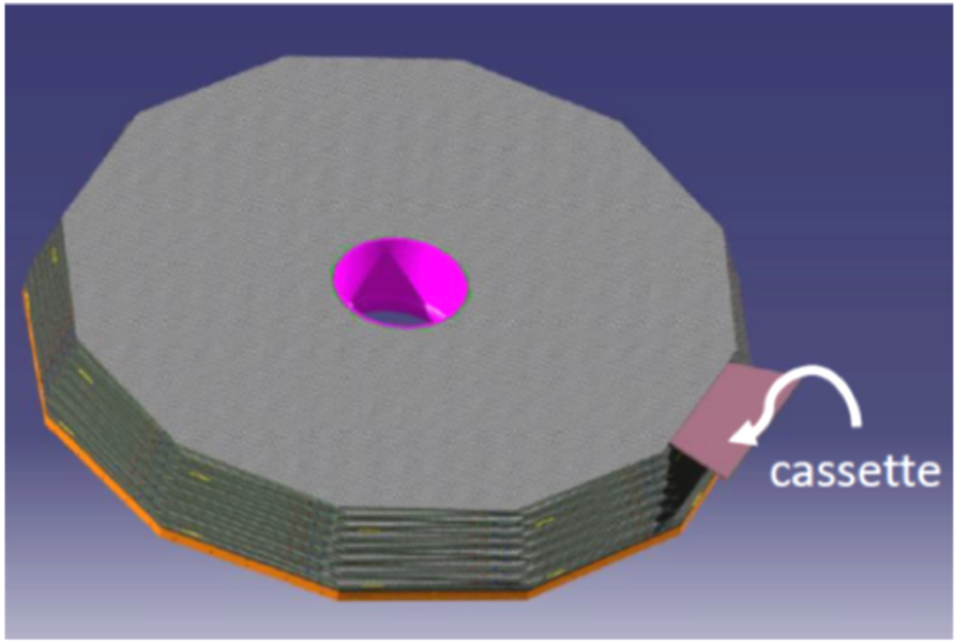
EE – Silicon with tungsten/Pb absorber – 28 sampling layers – 25 X_o + ~1.3 λ
FH – Silicon with SS absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with SS absorber – 12 layers – 5.5 λ

EE and FH are maintained at – 30^{o}C. BH is at room temperature (under review).

Decide on EE Structure by end-2016







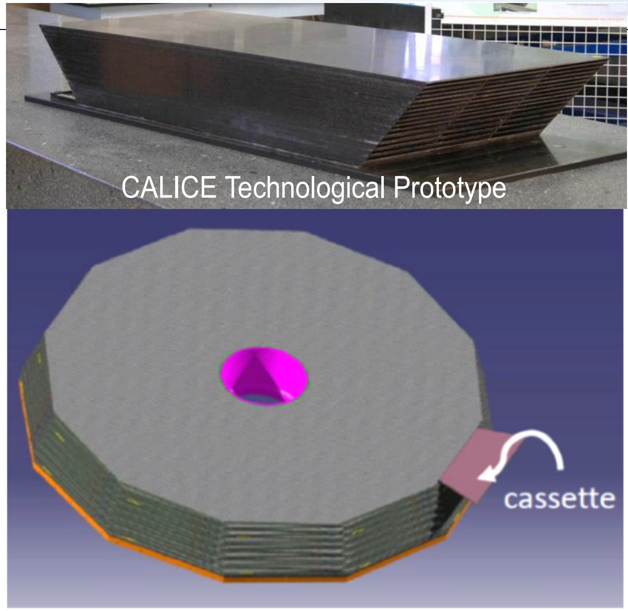
Alveolar Disk

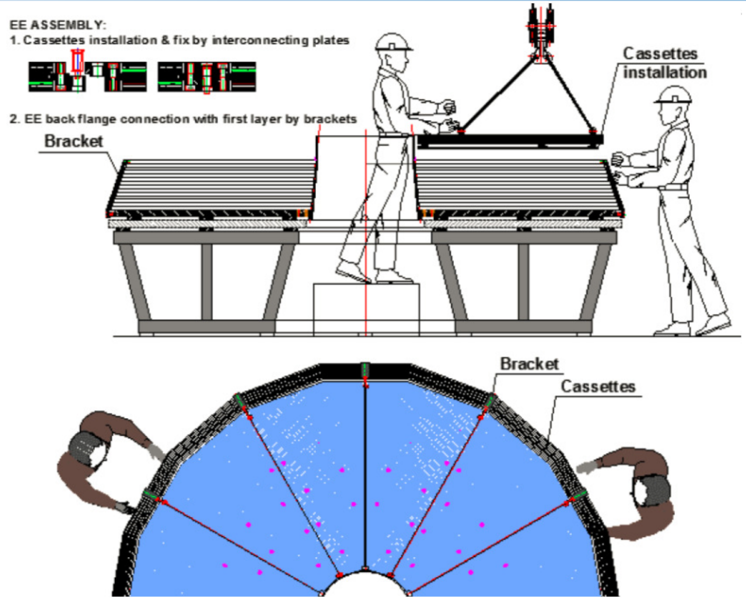
Cassettes inserted into "drawers"

Disk & Spacer

Cassettes part of structure

Decide on EE Structure by end-2016





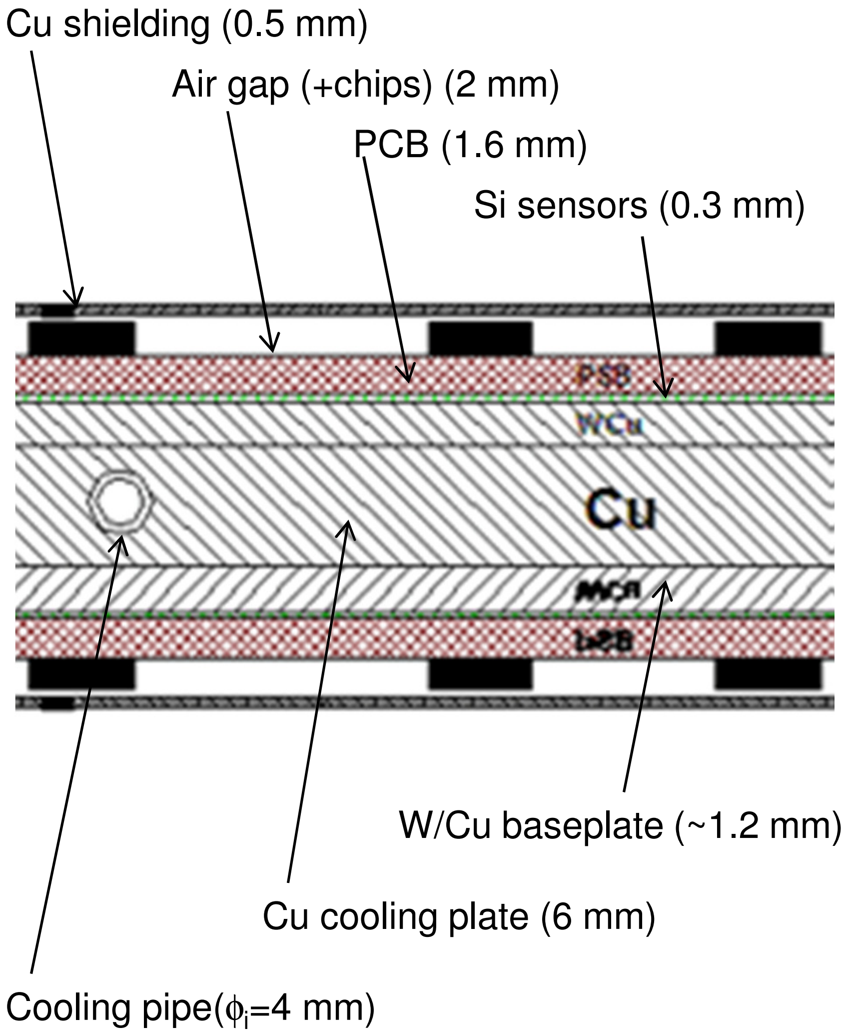
Alveolar Disk
Cassettes inserted into "drawers"

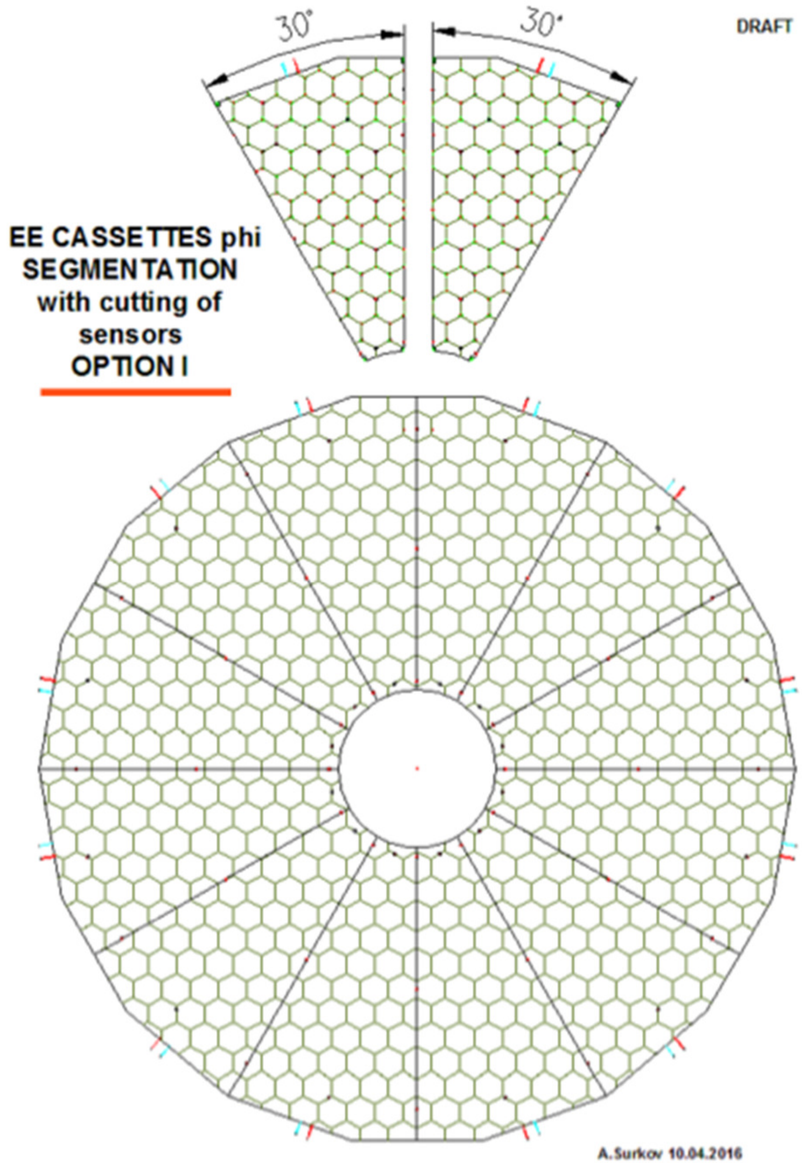
Disk & Spacer
Cassettes part of structure

Criteria for comparison of designs (decide by end-2016)

- *Assembly and installation*: ease, reliability, cost and time; ability to detect and repair problems during assembly and installation; connection of services; central vs. distributed subassembly construction, …
- *Risk, reliability, maintainability*
- *Physics*: cracks, impact of cone, low- & high-η coverage, density,..
- *Mechanical behaviour*: under assembly, operational, transient conditions

Cassette Design





Thermal Mockups and Tests

Keeping sensors at low T is essential to mitigate radiation effects

- Limit the leakage current (self heating $\propto$ I_{leak}, noise $\propto$ □ I_{leak})
- avoid reverse annealing

Cu cooling plate (part of absorber structure) in close contact with sensor module

Baseline is evaporative CO_2 cooling at T ≤ -30°C

Cassettes FEA

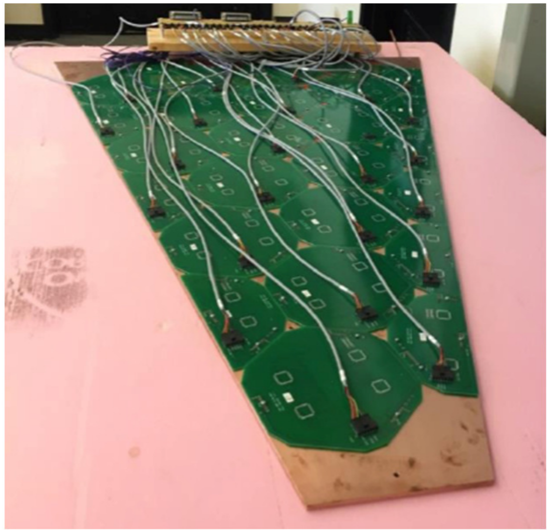
Goal: ΔT ~ 1-2 K

6mm Cu plate 1 pipe – uniform heat load

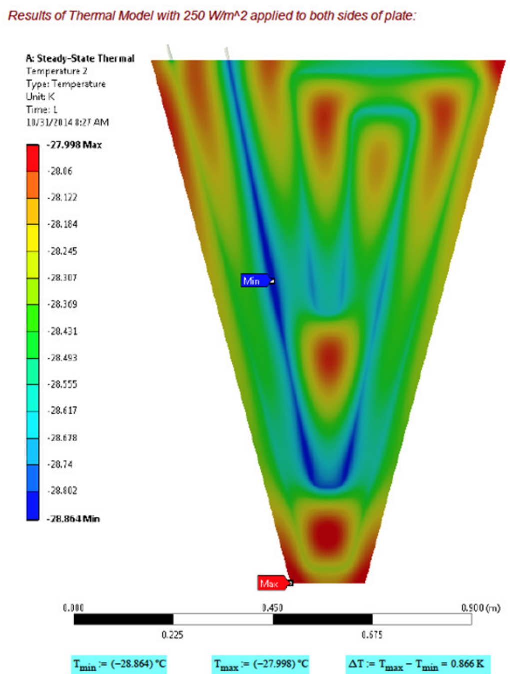
ΔT ~ 0.9K (over the cassette)

Cooling Tube: OD-4.8mm, ID-3.2mm, Length - 5.9 m, mass flow: 2.0 gm/sec, T_{max} -28.00C, T_{min} -28-86C.

Results Summary (post-calibration)	Full heat load, 0.3 bar	Full heat load, 0.2 bar
Min. temp. (°C)	-30.3	-30.2
Max. temp. (°C)	-29.2	-29.0
Temp. spread (°C)	1.1	1.2
Mean (°C)	-29.8	-29.7
Standard dev. (°C)	0.225	0.226

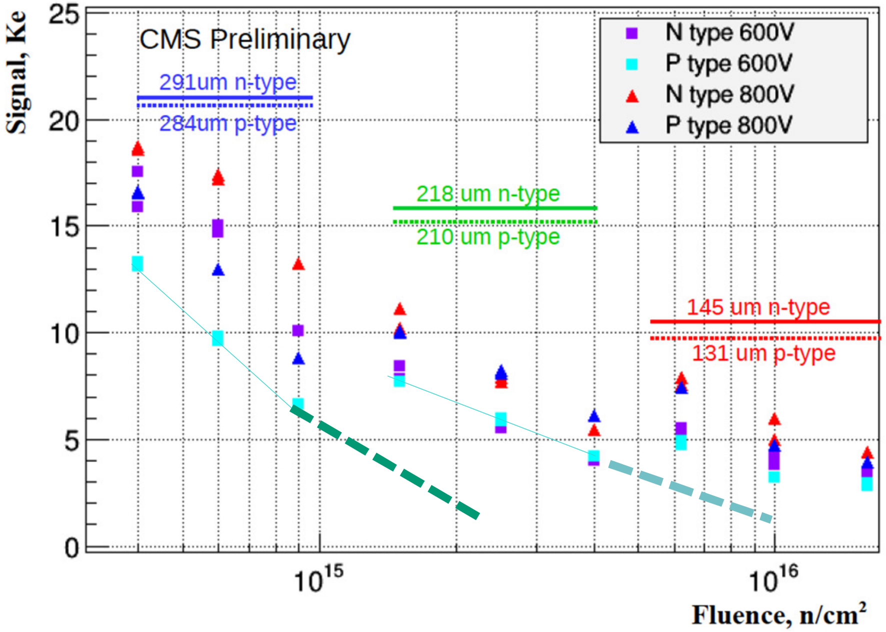


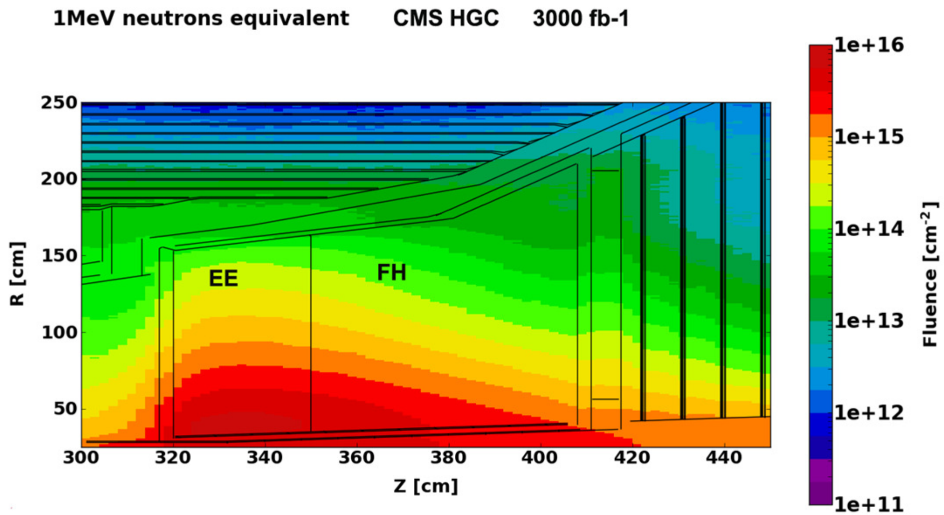
Mockup with heaters uniform load 360 W/m² Temperature spread within 1.2° C



Si Sensors Radiation Tolerance

Complemented charged hadron irradiation with neutron irradiation



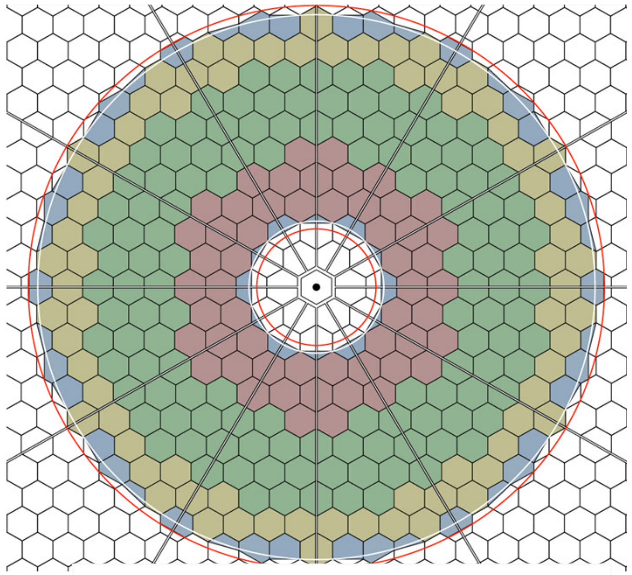


Thickness of Si sensors should be reduced in high fluence regions:

$I_{leak} \propto$ Volume . Φ decreases

Collected Charge improves at high Φ

Requires reduction in cell size to maintain moderate capacitance.



One EE layer

Tile using ϕ=8” sensors

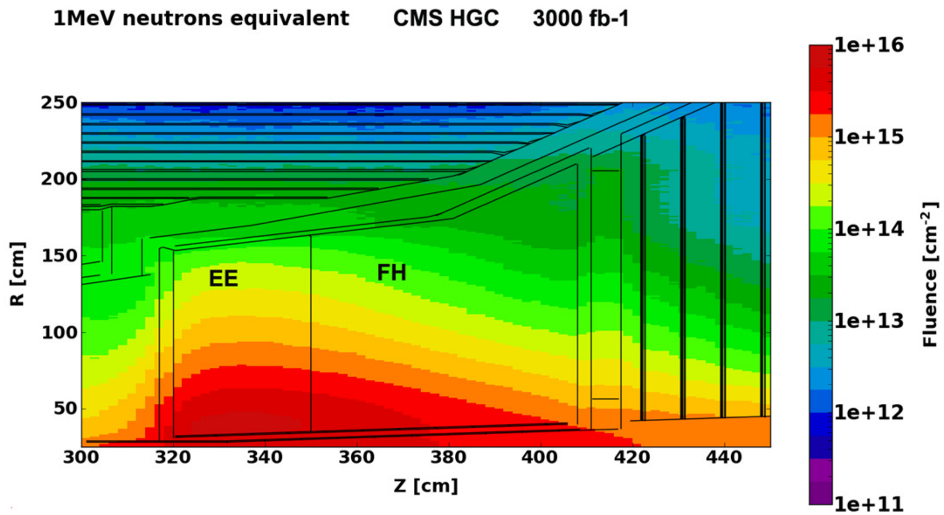
Si Sensors Radiation Tolerance

Sensors of three (active) thicknesses 100 µm, 200 µm, 300 µm (deep diffusion process or physical wafer thickness)

2 different designs: 256 and 512 channels

Cell sizes ~ 1 cm^2, ~ 0.5 cm^2 (limit cell capacitance to about 60 pF)

Total area of silicon ~ 600 m^2

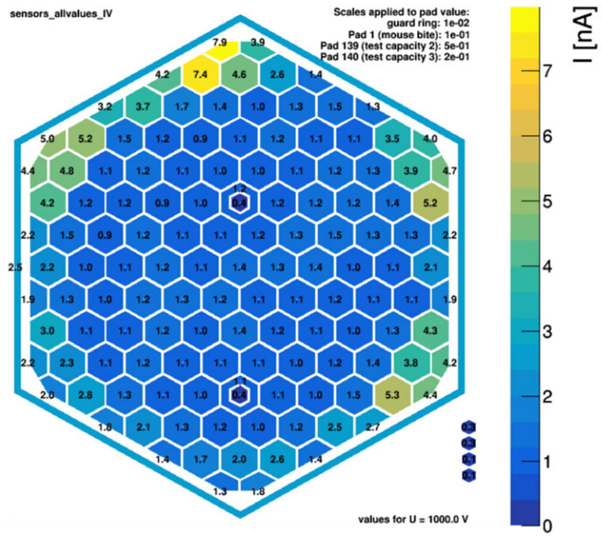


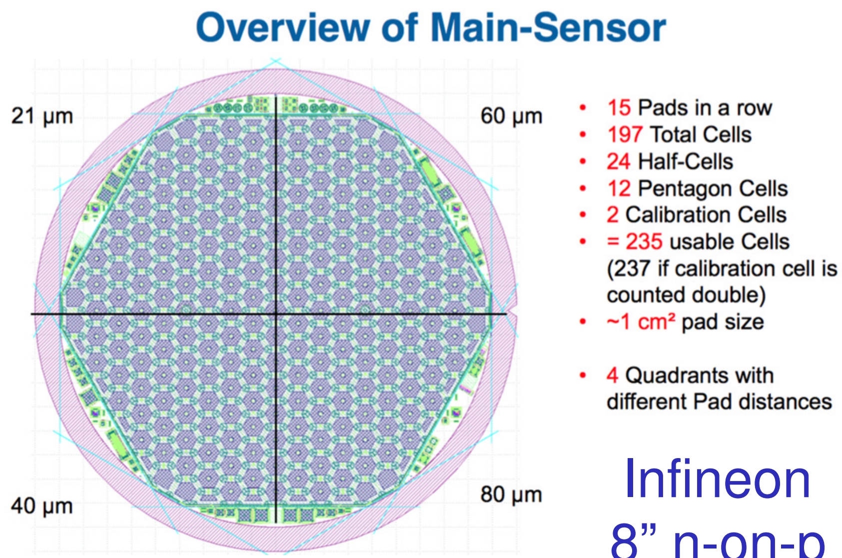
Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7

Silicon Sensors

- **Sensors Procurement: Status**
- **HPK 182** 6" p-on-n 128- and 256-channel sensors, 300/200/100um – **delivery completed**. 256-channel sensors include concept of "remote" pad contact to allow large area component placement on module PCB. **Very good quality.**
- **Infineon** 8" n-on-p 256 channel sensors – **fabrication started**
- **HPK** 8" n-on-p 256 channel sensors (using stepper) – **fabrication started**
- **HPK To order** 6" n-on-p to complete full-size sensors irradiation studies
- **Novati received** half hexagonal sensors off 8" wafers.

HPK 6" p-on-n 128 channel sensors
I_{leak} @ 1000V: average for 15 sensors

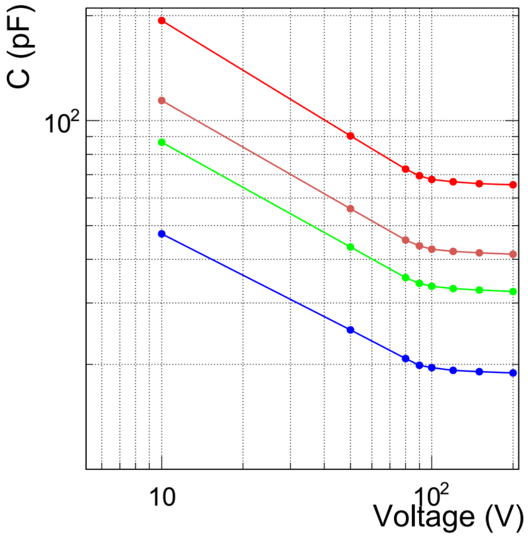


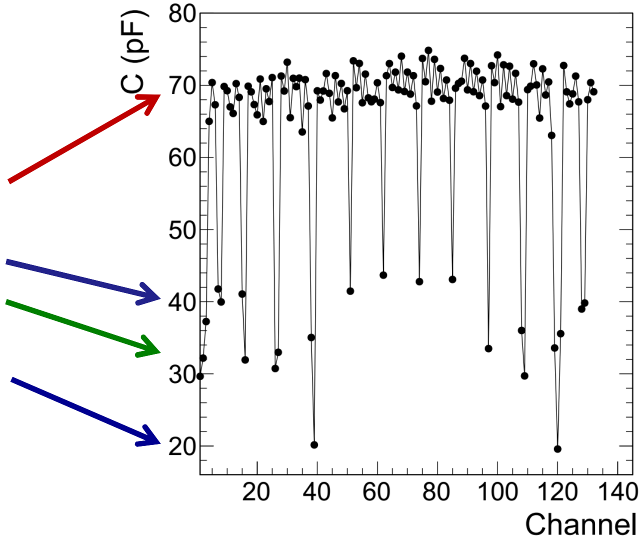


Infineon
8" n-on-p

Imperial College London

HPK Silicon Sensors



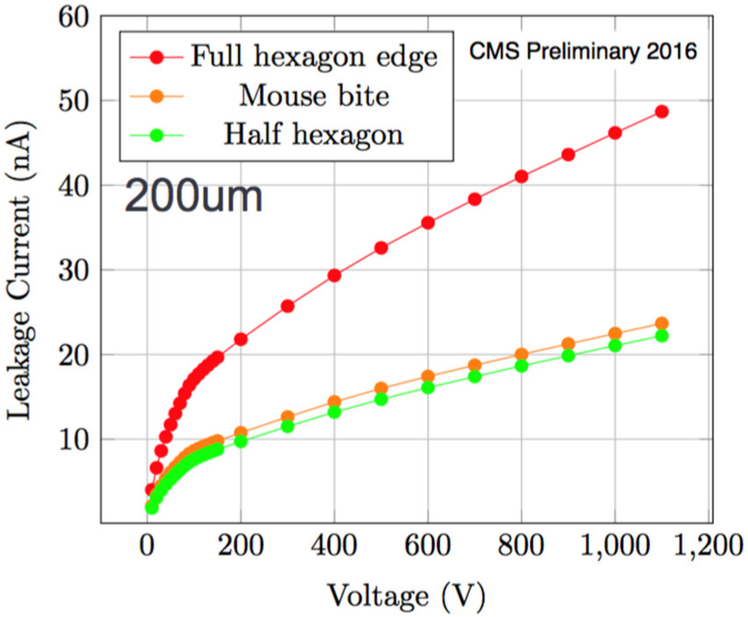


Full Hexagon pads

For an example sensor

Partial Hexagon pads

Calibration pads



Imperial College London

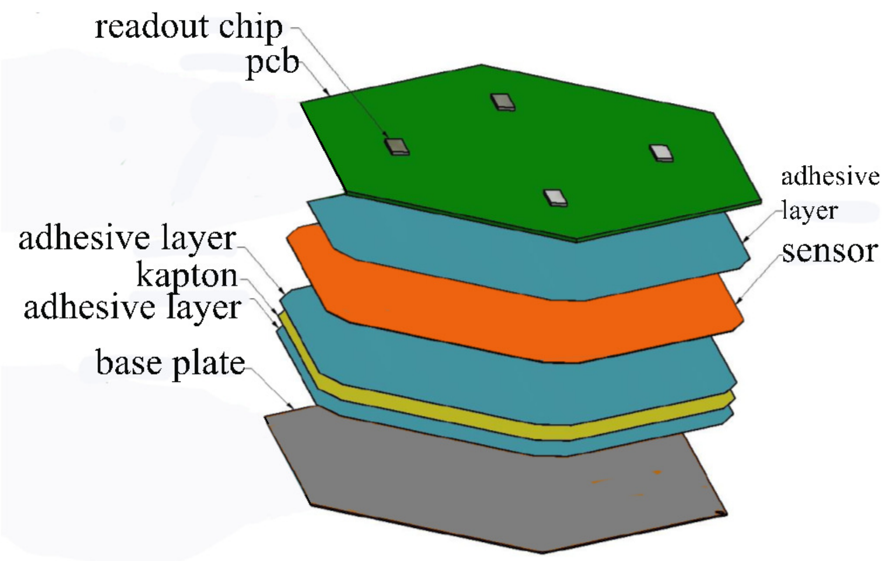
Si Sensor development

Meeting at Infineon Villach site (Austria) on October 2015

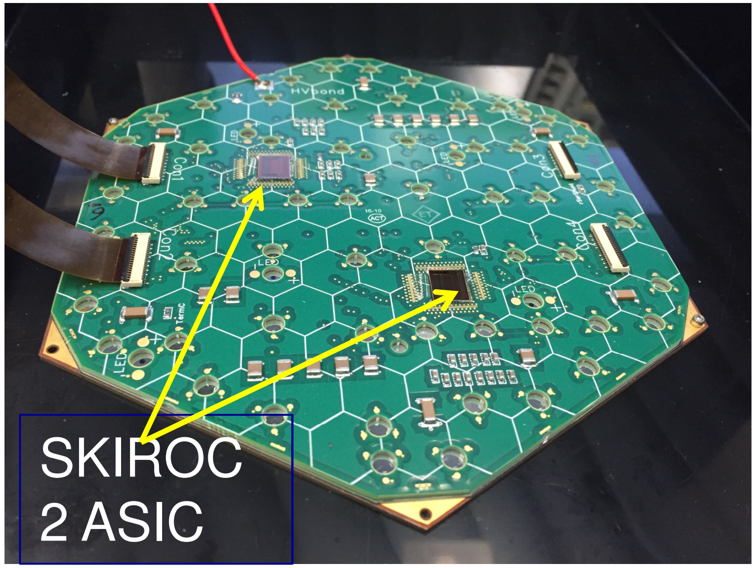
High level attendance from Infineon included CEO & CTO of Infineon Villach as well as senior management representative from Infineon headquarters in Munich

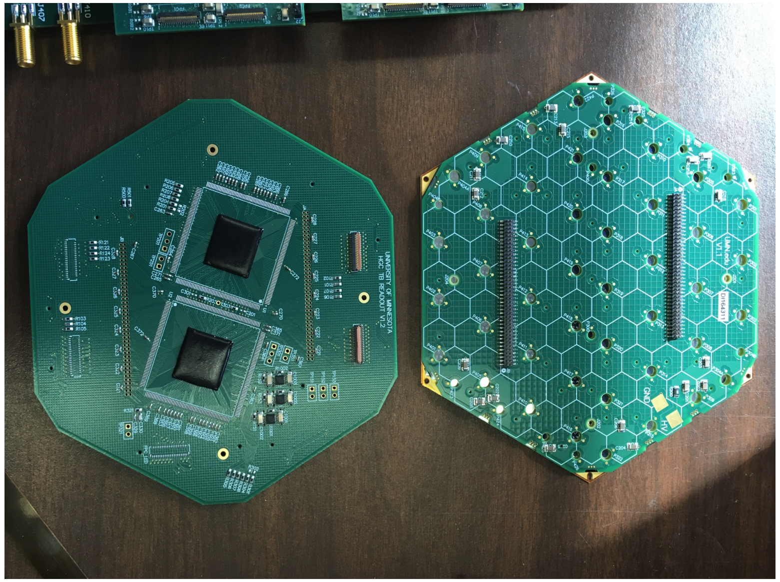
8” endcap n-on-p sensors will be delivered soon

Silicon Modules



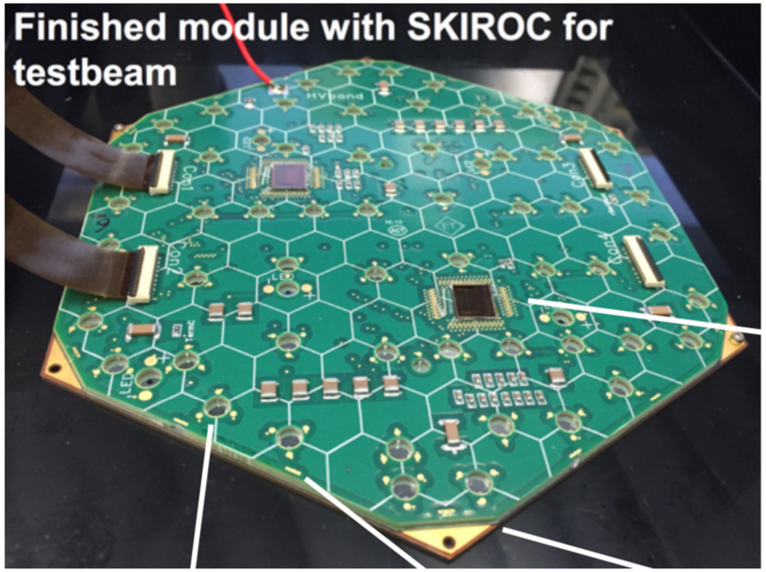
Single-layer PCB module with W/Cu plate and 128 channels readout



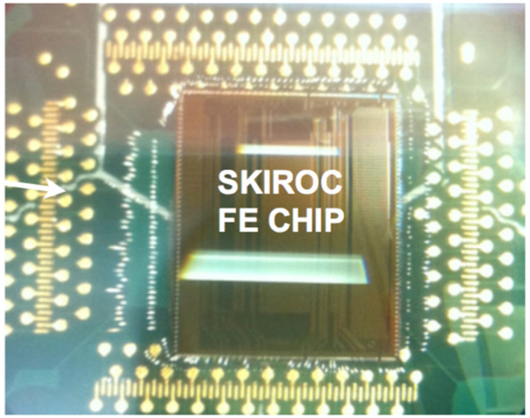


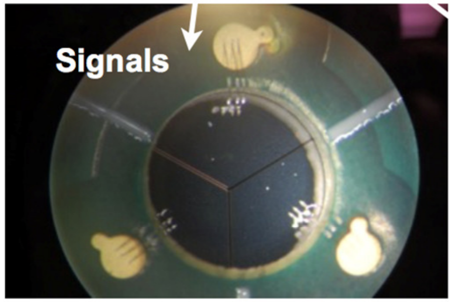
Variant: double layer PCB module – one passive board glued to the sensor and 2nd board with SKIROC2 ASIC.
Used in 2016 test beam campaign

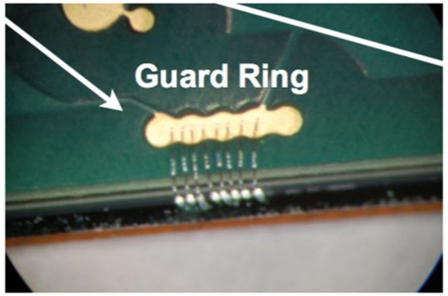
Silicon Modules

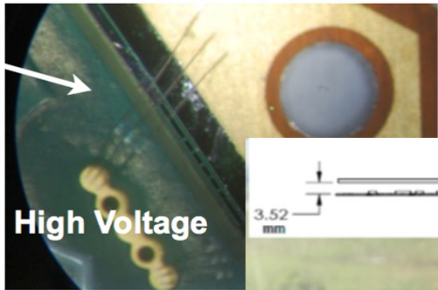


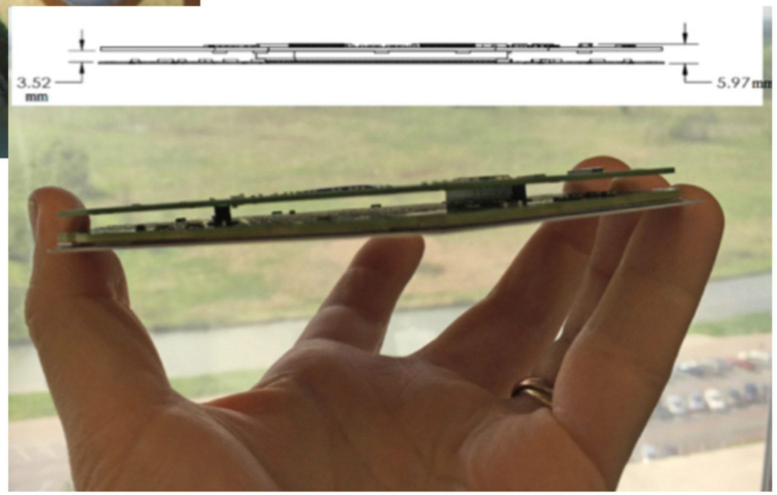
- ~ 700 wire bonds on a single module!











Front-end Electronics: Specifications

Major challenge is large dynamic range @ low power and low noise (radiation hardness to 150 Mrads, 10^{16} n_{eq}/cm^2)

Front-End Chip Requirements

Noise ~ 2'000e$^-$ (capability to see a mip after 3000 fb^{-1})

Including Sensor I_{leak} noise (end of HL-LHC I_{leak}^{max} ~ 10 uA)

Shaping Time 10 ~ 20ns

Dynamic range ~ 0.4-10pC*

~ 3'000MIP in 300um Silicon

Power budget ~ 10mW / channel

On-detector electronics ~ Σ100kW for ~ 6M channels

Precision timing

50ps for cells with $Q_{deposited}$ > 60fC (~20ps per shower)

System on chip (digitization, processing), high speed readout (>Gb/s), large buffers to accommodate 12.5μs latency of L1 trigger

* Dynamic range of 10 pC (3000 mips @ 300um, 4500 mips @ 200 um, 9000 mips @ 100 um) roughly constant in E_T. Increased energy compensates for smaller Si thickness

Front-end Electronics: Design

Baseline: Charge + Time over Threshold (ToT)

Charge readout 0-100 fC 10 bits ADC

Time Over Threshold 0.1 -10 pC, 12 bits TDC

(Variants with bi-gain also studied as backup)

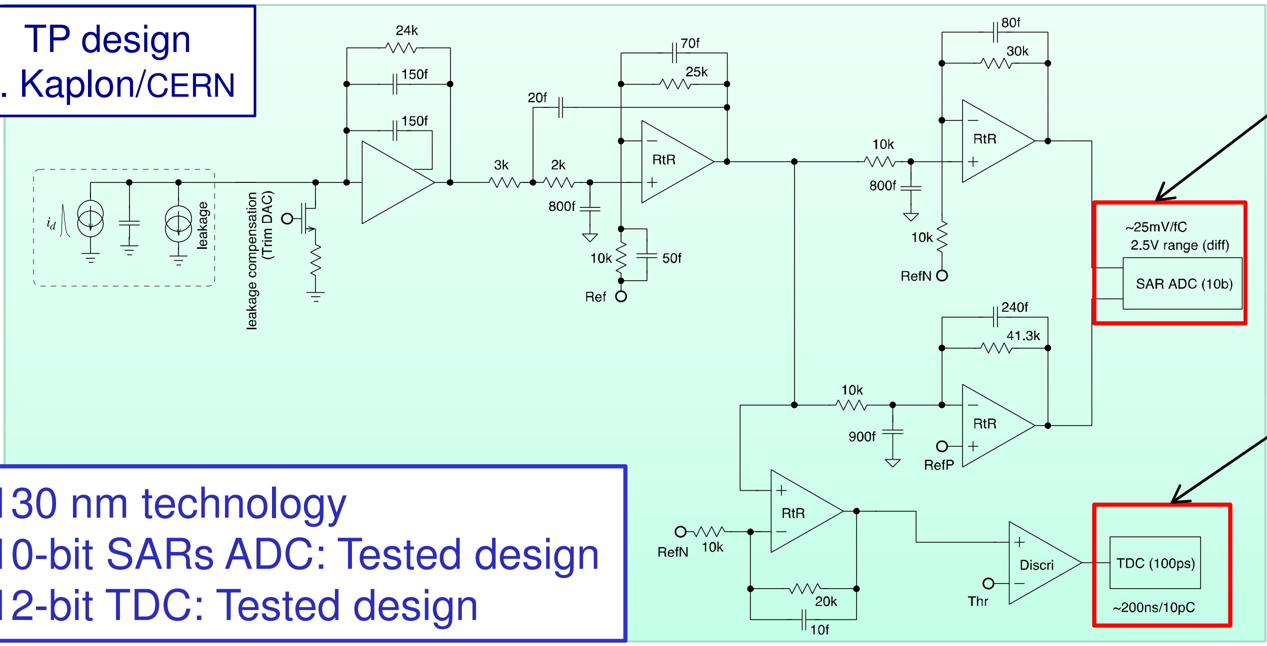
130nm TSMC technology

Known radiation hardness up to required dose

Higher voltage rail than 65nm (good for analogue)

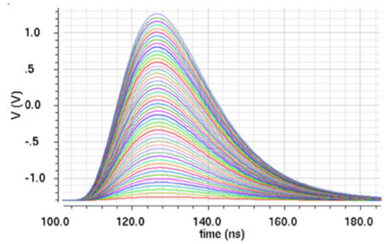
Some basic blocks available

TP design
J. Kaplon/CERN

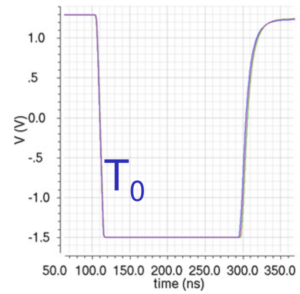


130 nm technology
10-bit SARs ADC: Tested design
12-bit TDC: Tested design

SARs ADC (<100fC)

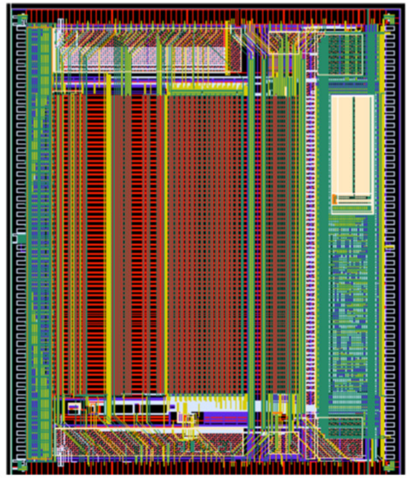


ToT σ_{T0}~ 50ps



Front-end Electronics: Strategy

1) Existing CALICE chip modified to include most of the required functionalities: SKIROC2 -> **SKIROC2-CMS** 0.35 µm AMS (non radhard)



Use in 2017 Test beams

faster shaper 25ns instead of 200 ns

sampling @ 40 MHz, depth 300 ns

ToT, TDC for ToA, 20 ps binning, 50 ps jitter

Received **late June, under full test**

(good preliminary results)

2) Submit Test Vehicles in 130 nm

TV1 ***received*** **mid-September: analogue architecture, baseline + variants (good preliminary results)**

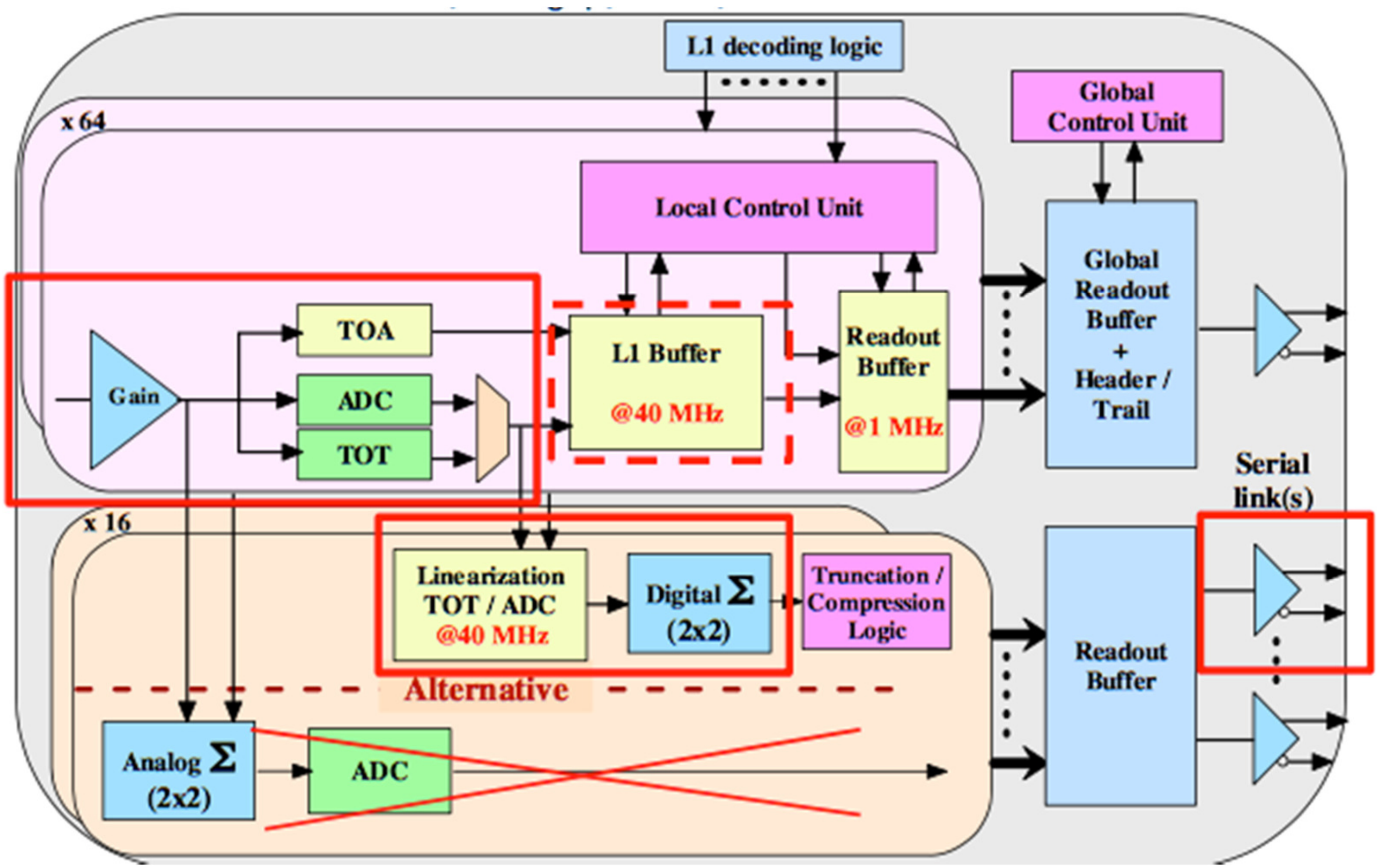
TV2 to be submitted before end 2016: 8 channels, full analogue channel (ADC+ToT+ Trigger sums)

3) Submit first “complete” ASIC June 2017

(some digital functionalities may still be incomplete)

4) Two further iterations foreseen in the overall planning

Front-end Electronics Block and TV2



The blocks in *red rectangles* will be included in TV2

Full analogue channel (preamp, shaper, comparator, input DAC (leakage current compensation)

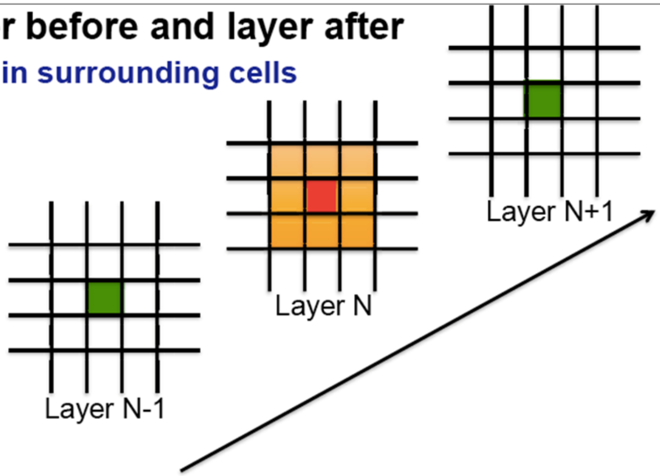
ADC, TDC

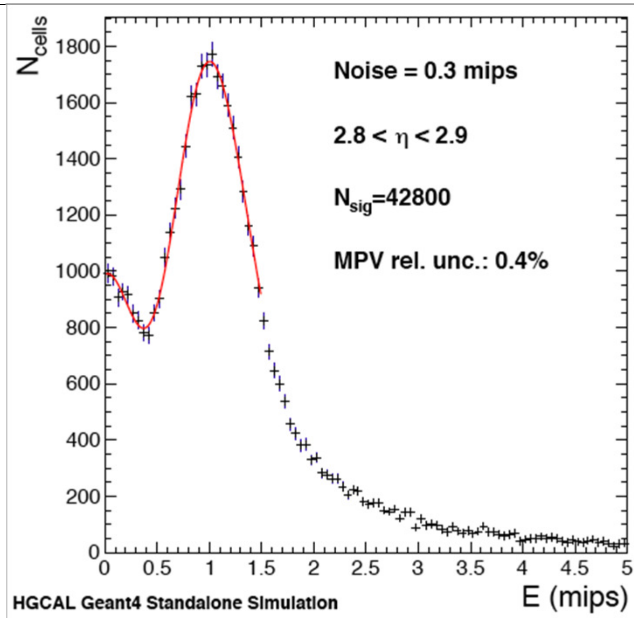
Digital sum for trigger path (linearization ToT @ 40 MHz, Digital sum (2x2 cells),..

Common services (LVDS, PLL, DLL,…)

Mip Inter-calibration of each cell

- **Require signal in layer before and layer after**
  - **Also require no signal in surrounding cells**





- **This can be used on any event read out (i.e. full L-1 rate)**
  - **We envisage using it in HLT farm on all/any L-1 accepted events**
- **Tested in minimum-bias pileup, $\langle N_{PU} \rangle$=140**

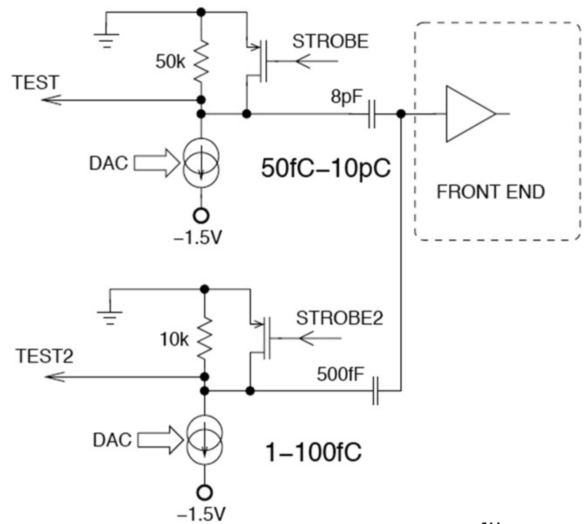
Targeting 0.5% contribution to constant term -> 3% inter-cell calibration

mip tracking

e.g. ±1 layer MIP tracking
Need ≈ 1.5M events (even possible in HLT farm) to reach 3% precision with noise = 0.4 MIP, <NPU> = 140

Special small area pads for large S/N

Charge calibration circuit
2 overlapping ranges



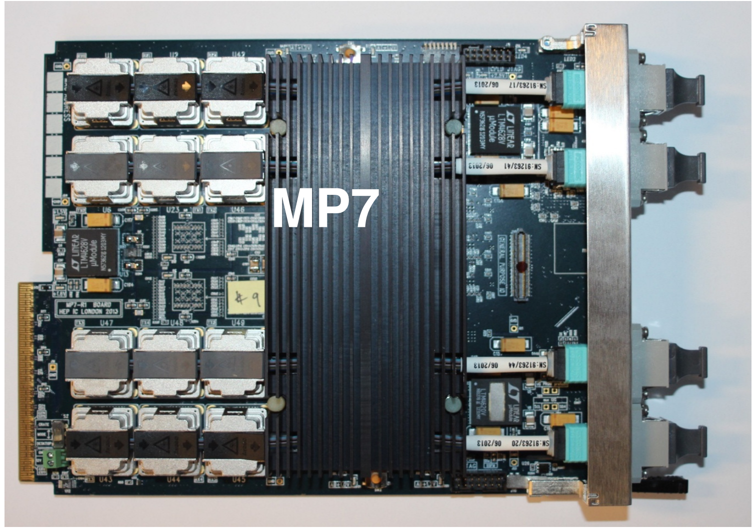
Level-1 Trigger: TP Design

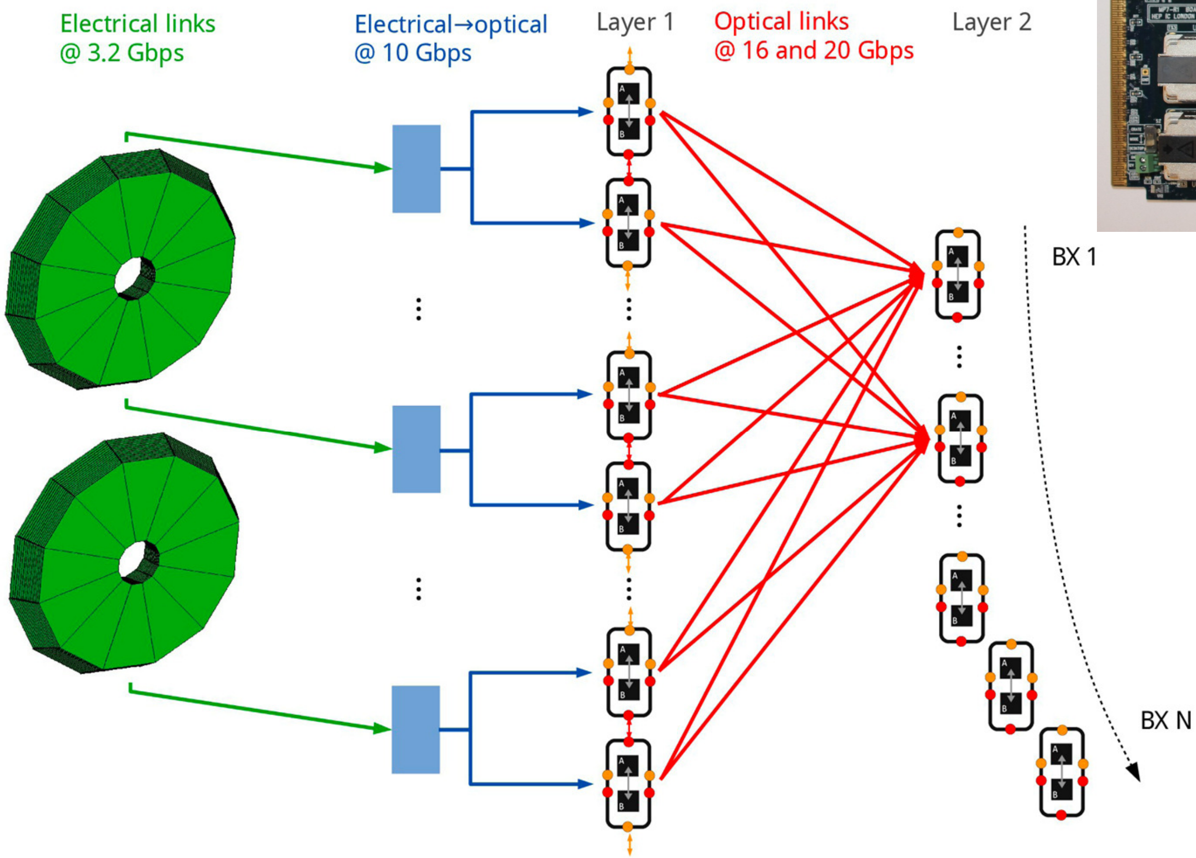
- The design of the following trigger architecture is based on existing or near-existing technology
  - ↳ FPGAs with similar capabilities as next generation Xilinx Virtex Ultrascale
  - ↳ 10 Gbps links (lpGBT) will be used for the transfer of data between the detector and the trigger system (mild radiation area)
  - ↳ 20 Gbps will be available for communication between off-detector trigger modules (no radiation)

- The architecture is similar to the Phase-1 Stage-2 calorimeter trigger architecture
  - ↳ Two processing layers
    - – The first one with a regional view of the detector
    - – The second one with a global view of the detector
  - ↳ Time multiplexing to concentrate data in the second layer

Level-1 Trigger

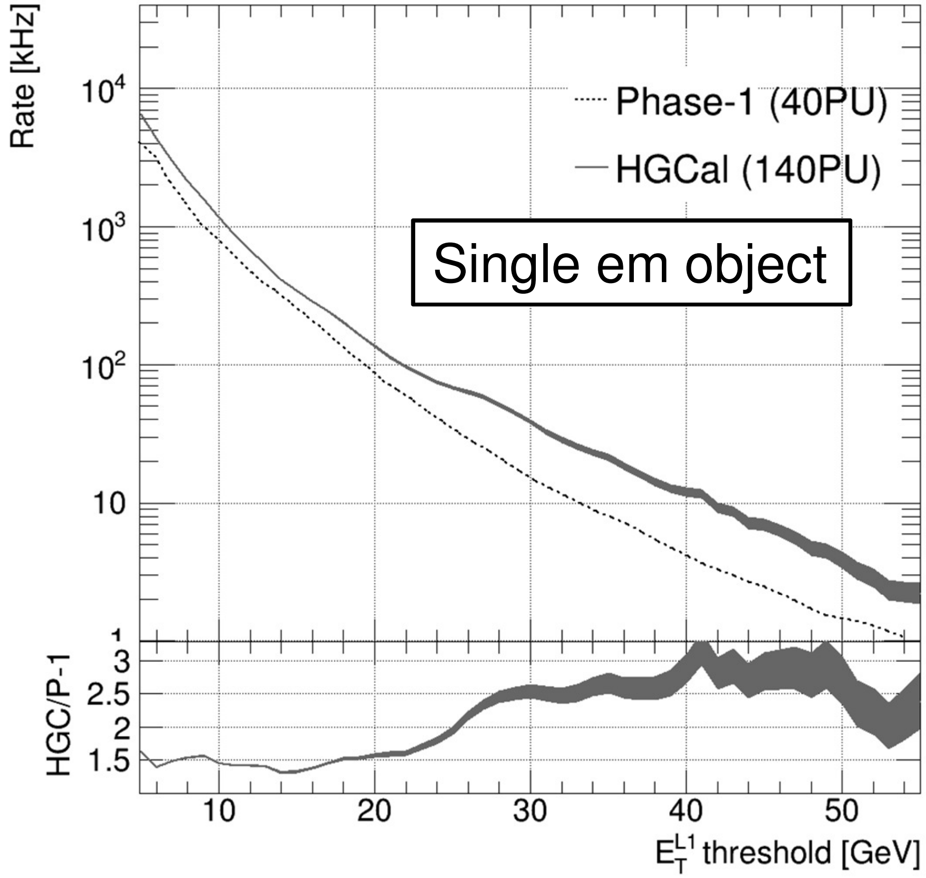
Group 4 cells to get a trigger cell
Simple data compression
Full resolution data
Each module produces up to 6 Gb/s

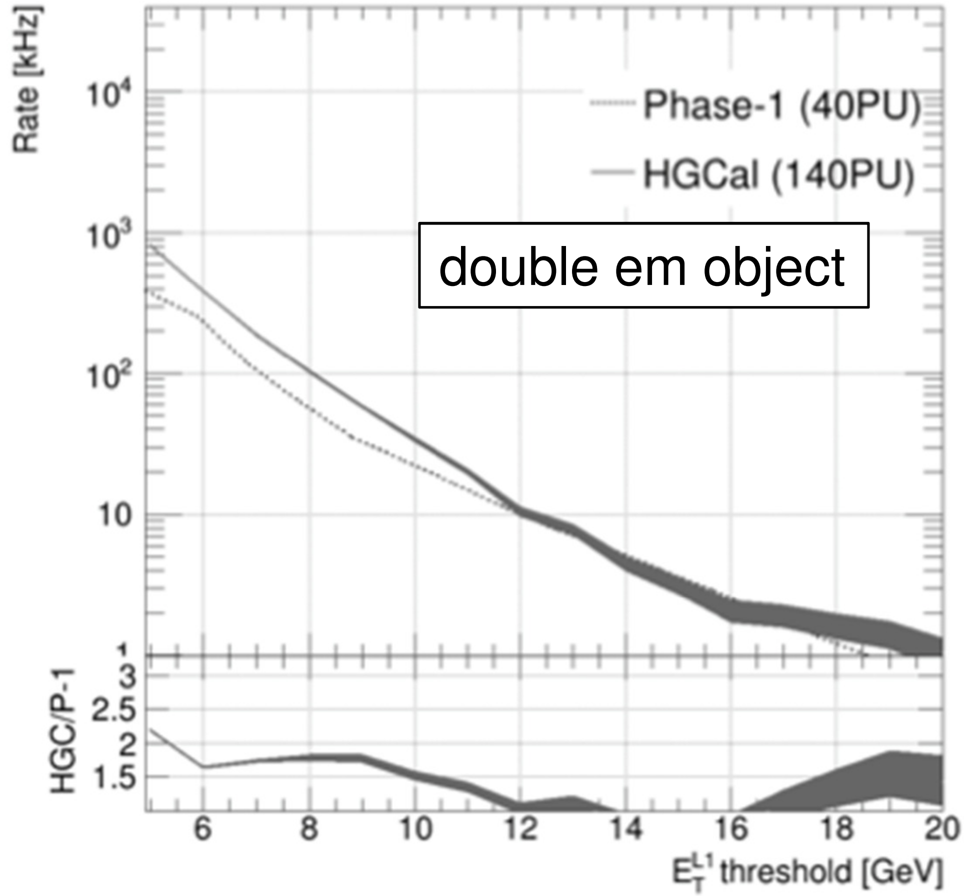




Performance: Level-1 Trigger

The longitudinal information enables good pileup mitigation
For an increase in luminosity by a factor 3.5 (compared to Phase 1), the background trigger rate increases by a factor 1.5-2.5 (in 20-30GeV region), with similar signal efficiency (close to 100%)



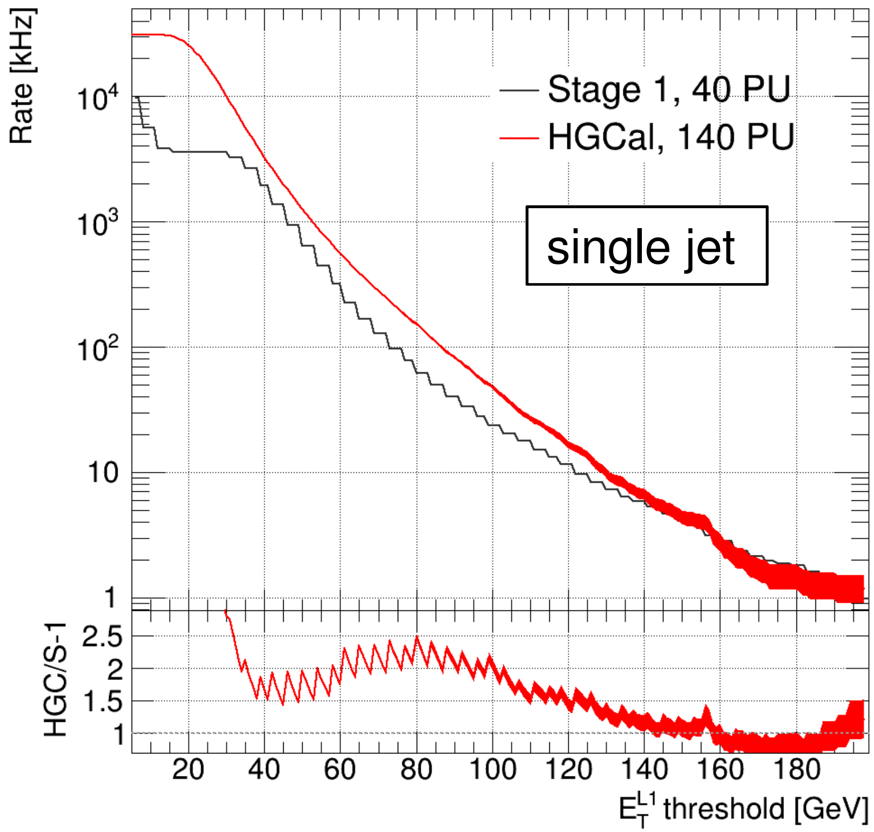


Imperial College London

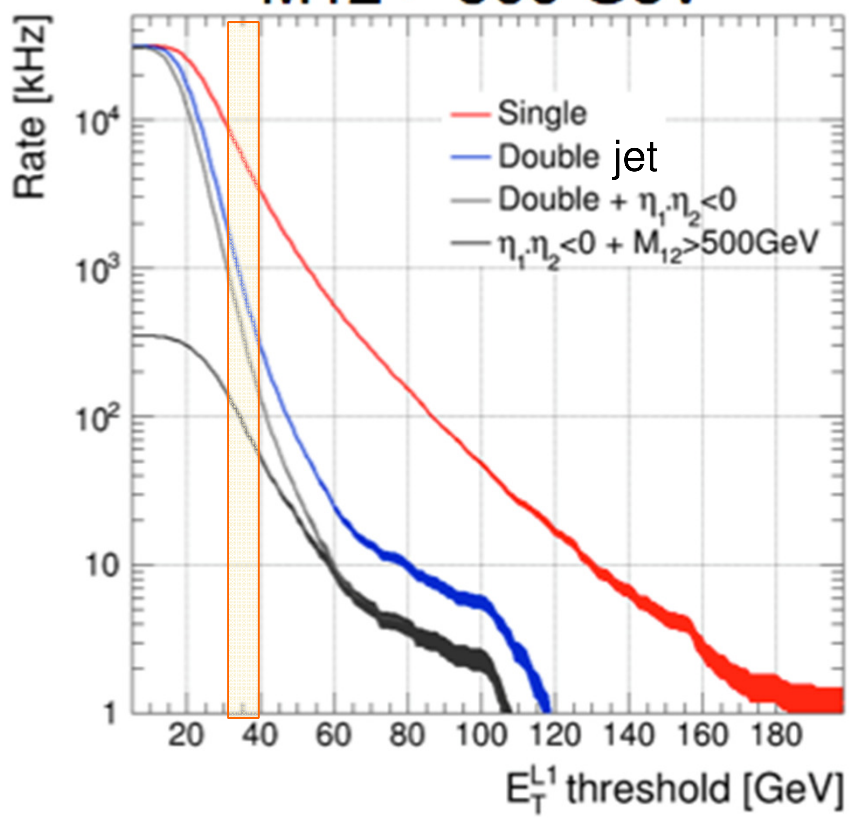
Performance: Level-1 Trigger

Jet-Trigger Endcap region

Considerable power lies in the selection of events with difficult signatures e.g. selection at L1 of VBF topologies without any requirement in the central region.



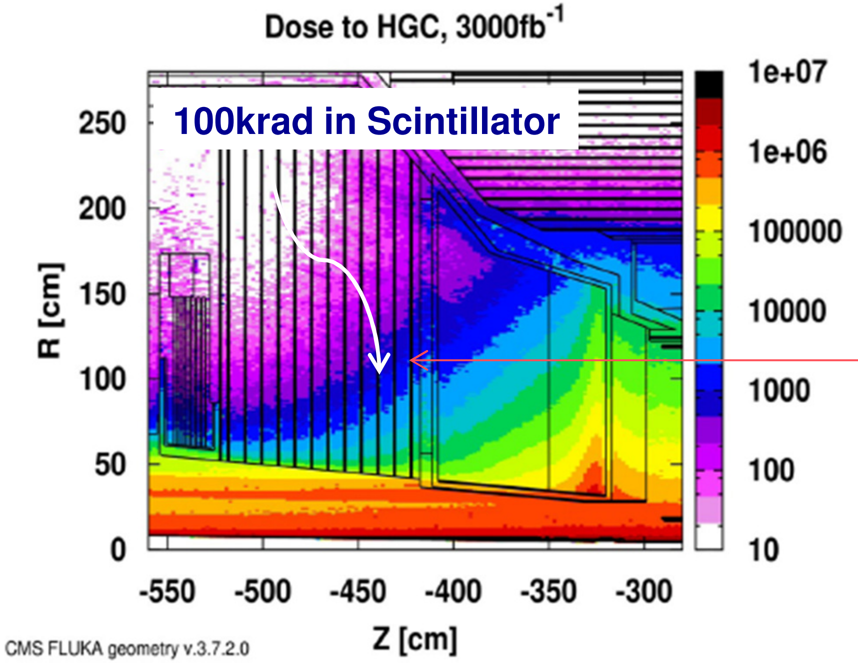
M12 > 500 GeV

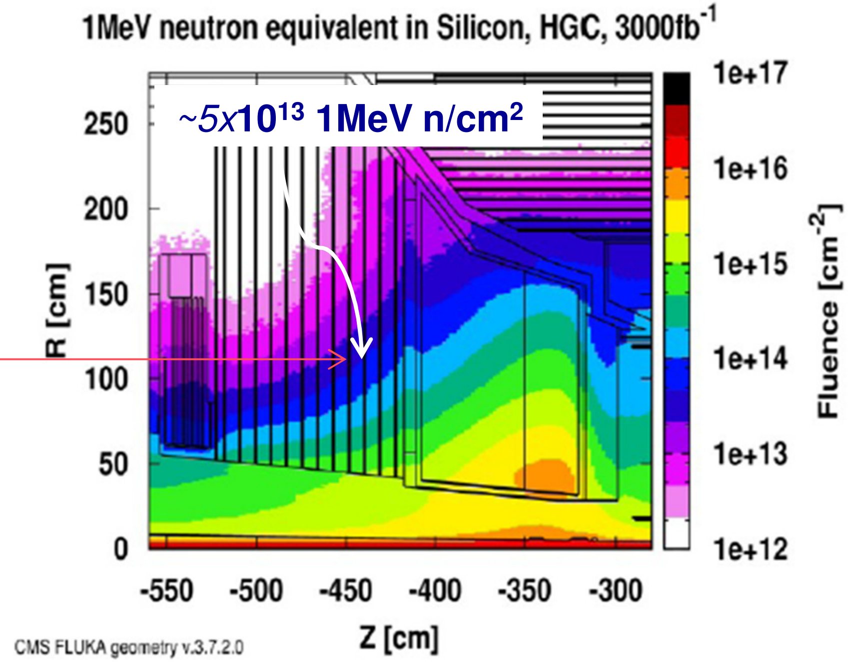


Imperial College London

Active Material for Backing Calorimeter (BH)

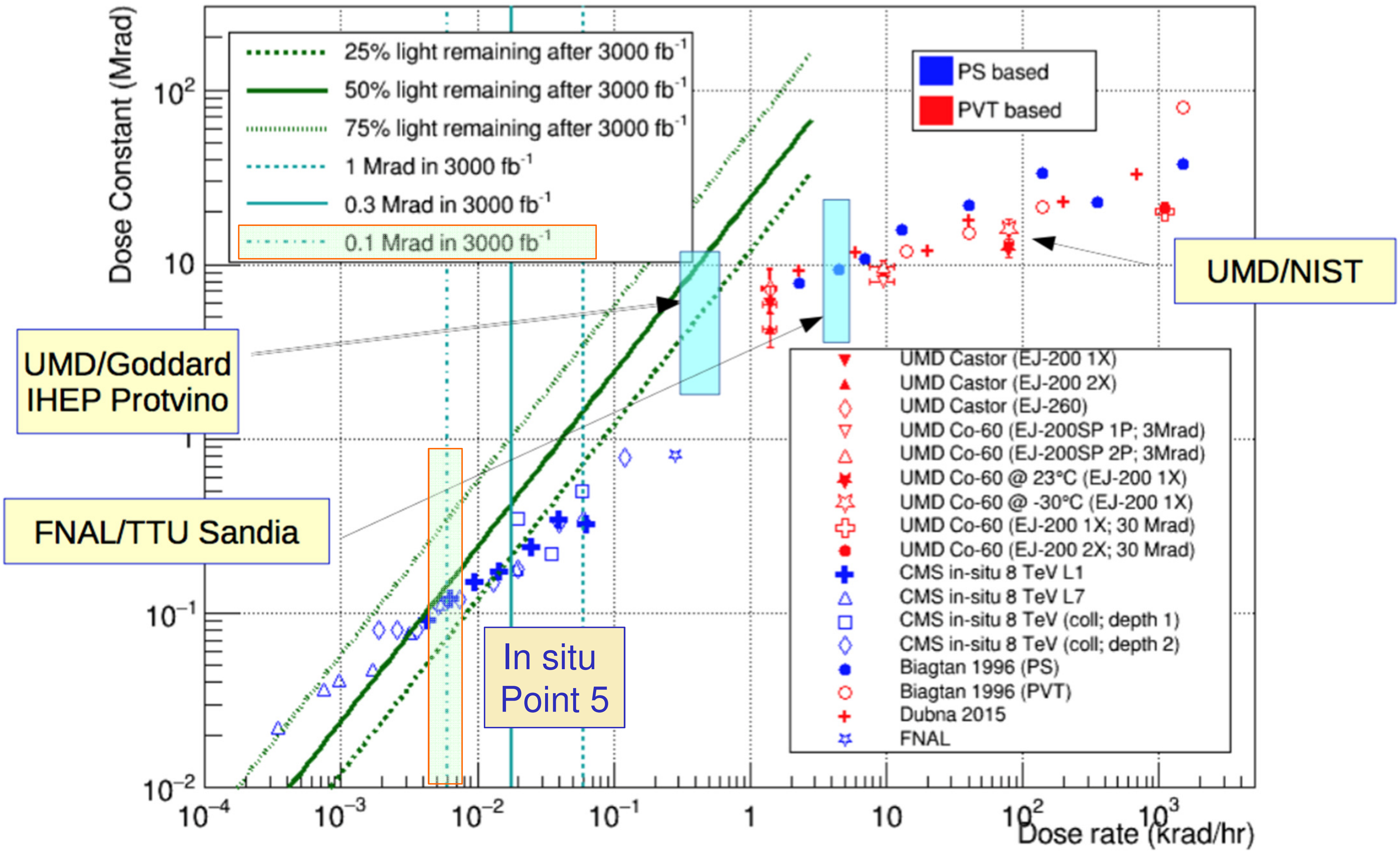
Despite being "protected" by EE+FH, the TID in BH reaches several MRads in the inner parts (high |η|).





- Aim to use a material that will not require replacement during HL-LHC lifetime
- Currently used scintillator would lose too much light in high |η| region (however, could be considered if dose kept <100krad).
- Large dose rate effects : Dose Constant D (defined by $S/S_0 = e^{-\text{Integrated Dose}/D}$) has a strong dependence on dose rate: smaller dose rates damage more.

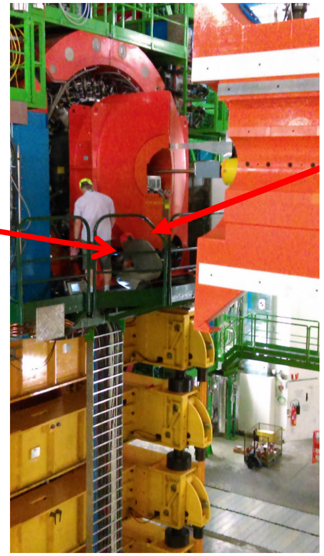
Measurements: Dose constant v/s dose rate plastic scintillators



Choosing the Active Material for BH

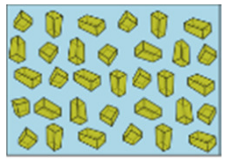
Select more rad hard plastic scintillator

- Several campaigns of irradiation, with as-realistic-as-possible dose rates including irradiations in situ (CMS CASTOR table)
- Includes some irradiations at low T (-30^{o}C)
- Favoured candidate: green scintillator (e.g. over-doped EJ260) with orange WLS



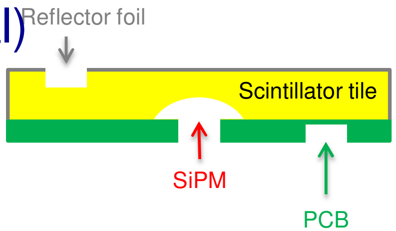
Use other material in the highest radiation region ?

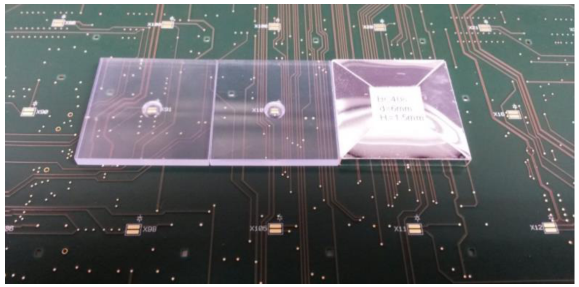
- Silicon? Only 10% increase of total Si area. **Requires cold endcap**
- Crystal-composite (e.g. YAG) material coupled to quartz plate?



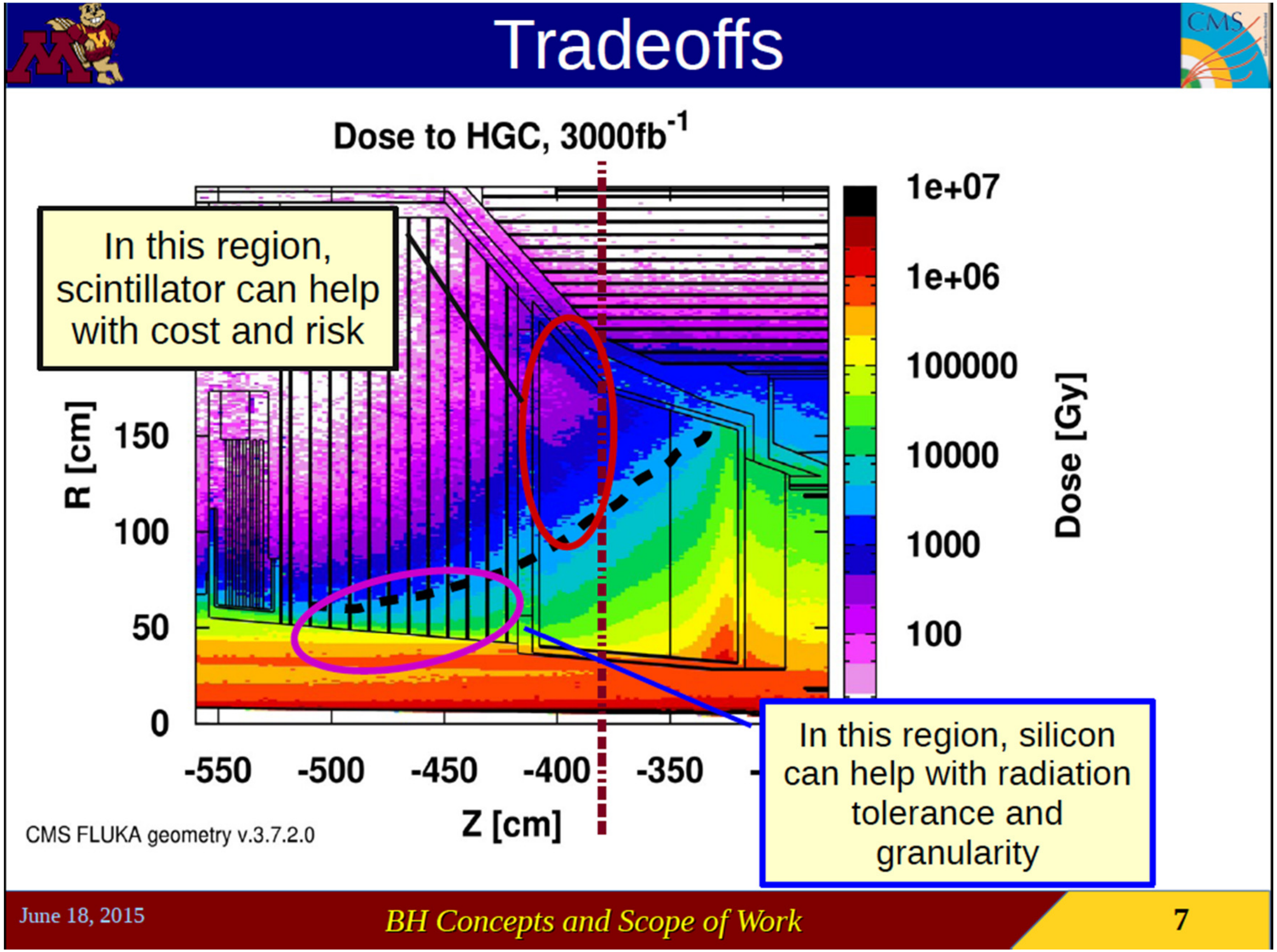
If BH is cold, an attractive possibility is to mix Si sensors with SiPMs-on-tile (scintillator)

- Alowing finer granularity (if beneficial)
- No complicated WLS/clear fibres
- Extensively studied by CALICE

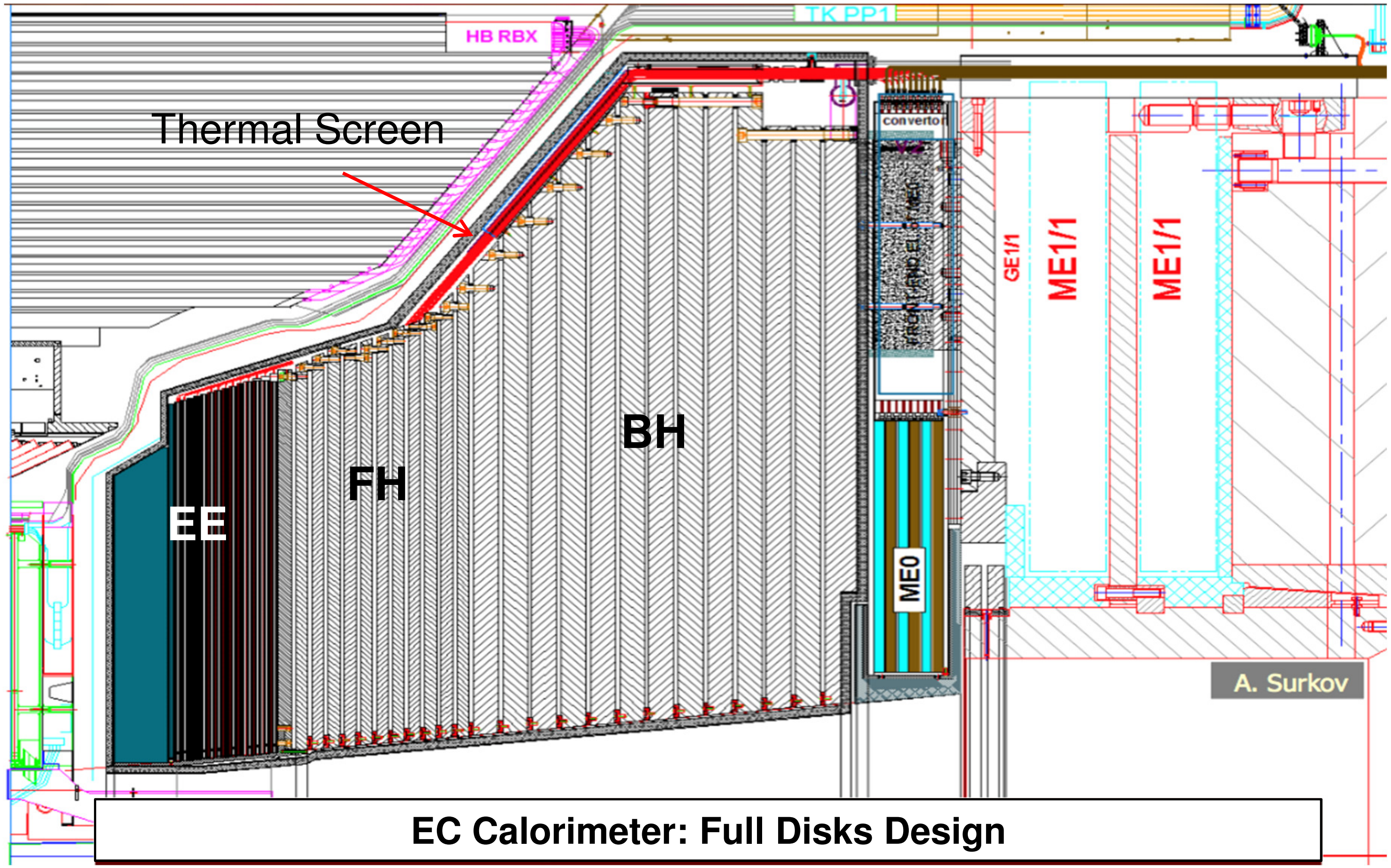




All cold Endcap



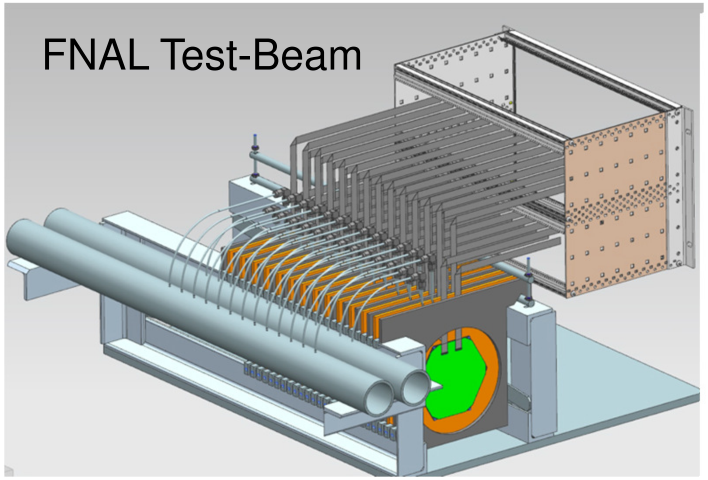
All cold Endcap



EC Calorimeter: Full Disks Design

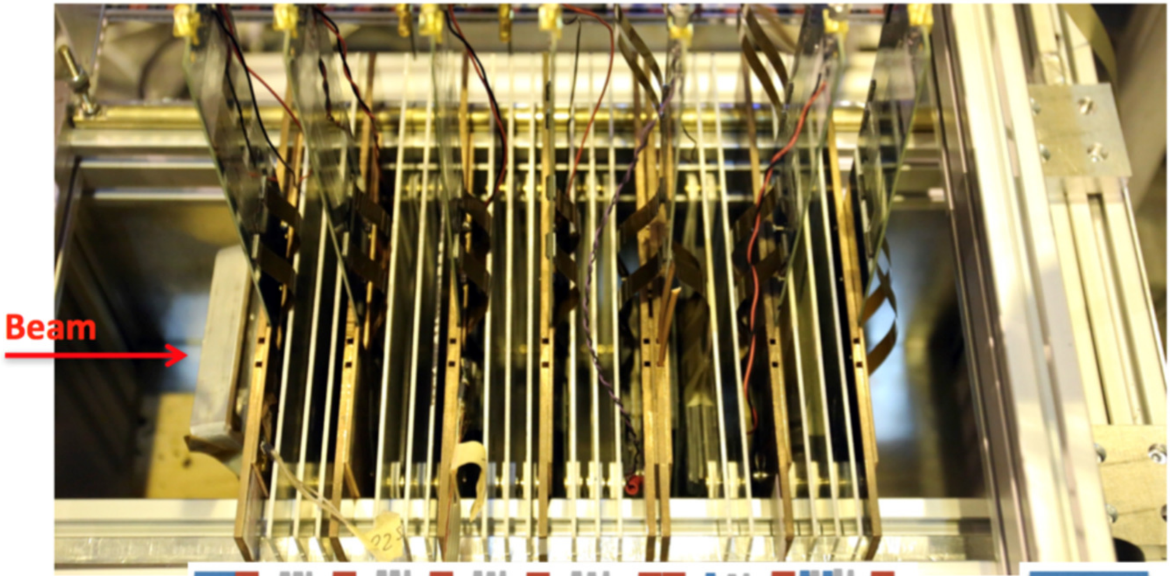
Test Beam Campaigns

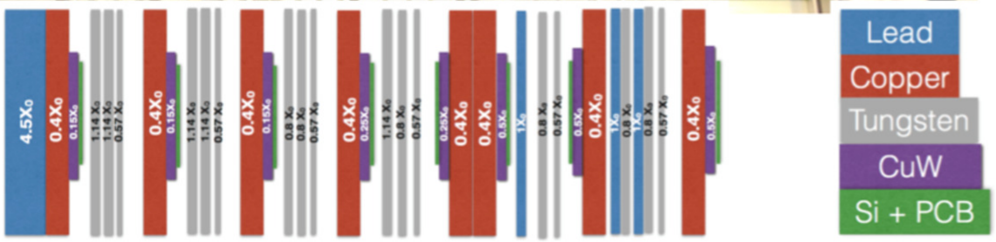
“Hanging File” Calorimeter design



2016

Setup at CERN



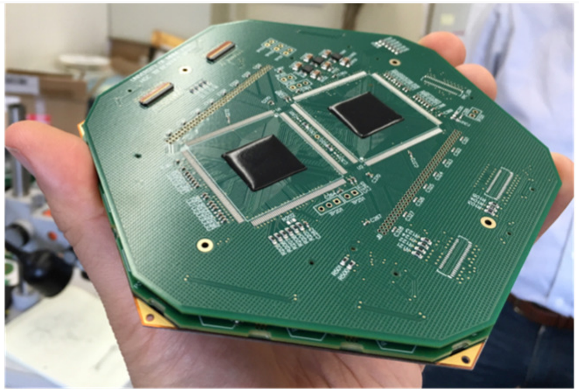


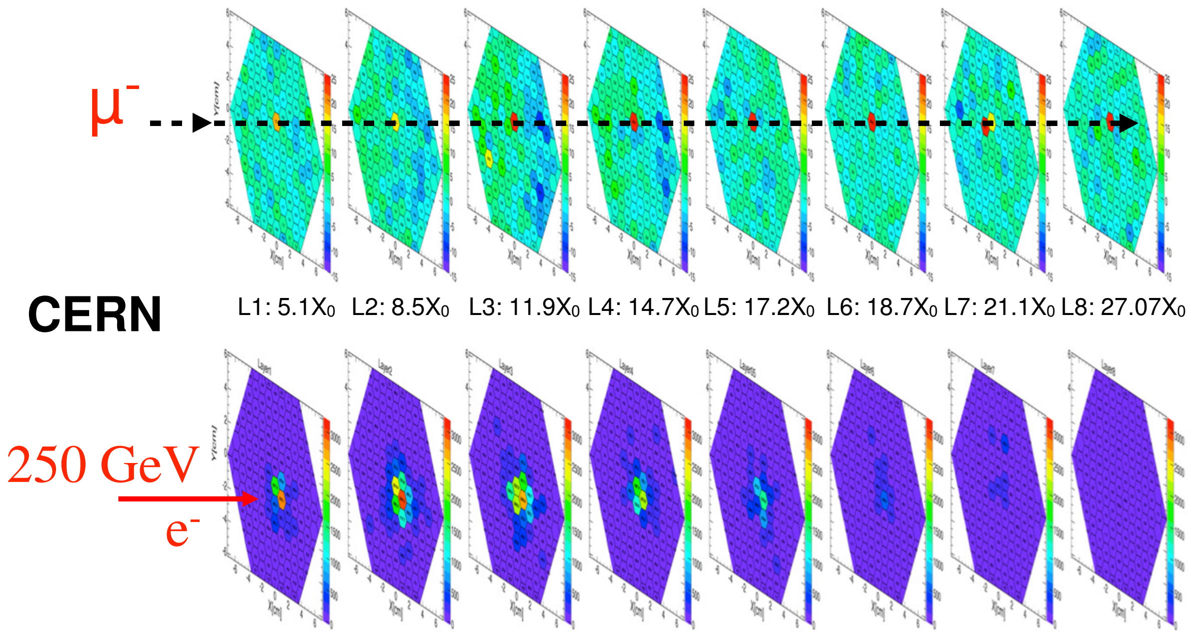
2017: Test a 28-layer EE + 12-layer FH + “BH” using SKIROC2_CMS

(for BH exploring use of a 36x36 cm^2 CALICE SiPM-on-tile prototype)

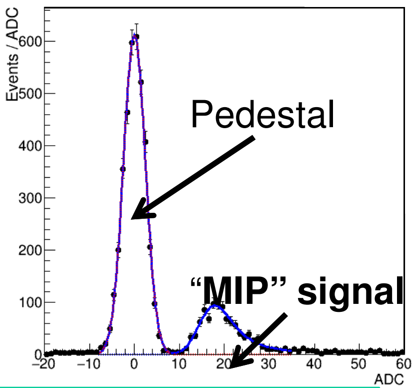
Beam-tests of EC prototypes at FNAL & CERN have validated the basic design

Working hexagonal silicon modules with through-hole wire bonds

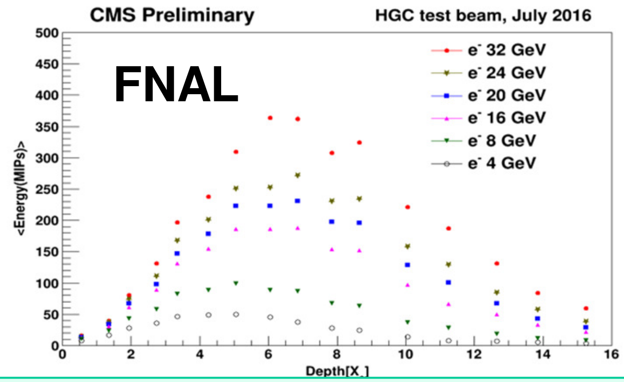




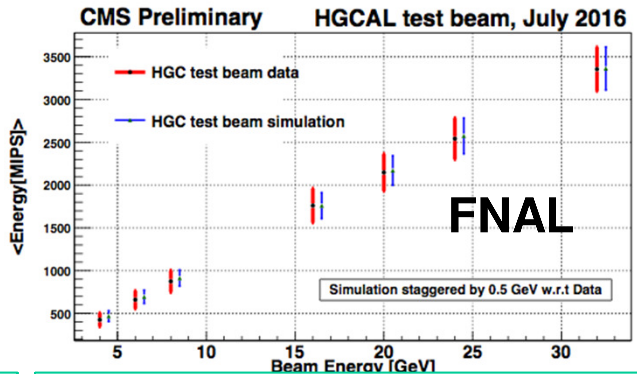
Clear signals seen in systems
16 layers (**FNAL**) & 8 layers (**CERN**)



S/N for single π^+ ~7.4



Longitudinal e^- **shower profile** in 16 layers



Good **agreement** between data & MC

Presented at several conferences in 2016; full analyses ongoing

Performance Studies

Simulation and Performance group has two (related) but distinct tasks:

1) **To develop simulation and reconstruction within the CMS software framework** capable of demonstrating both adequate performance, and the potential and promise of HGCAL for the TDR
2) **2) To provide simulation results** to assist in design choices, and, where appropriate, provide illustrations and justifications for use in the TDR

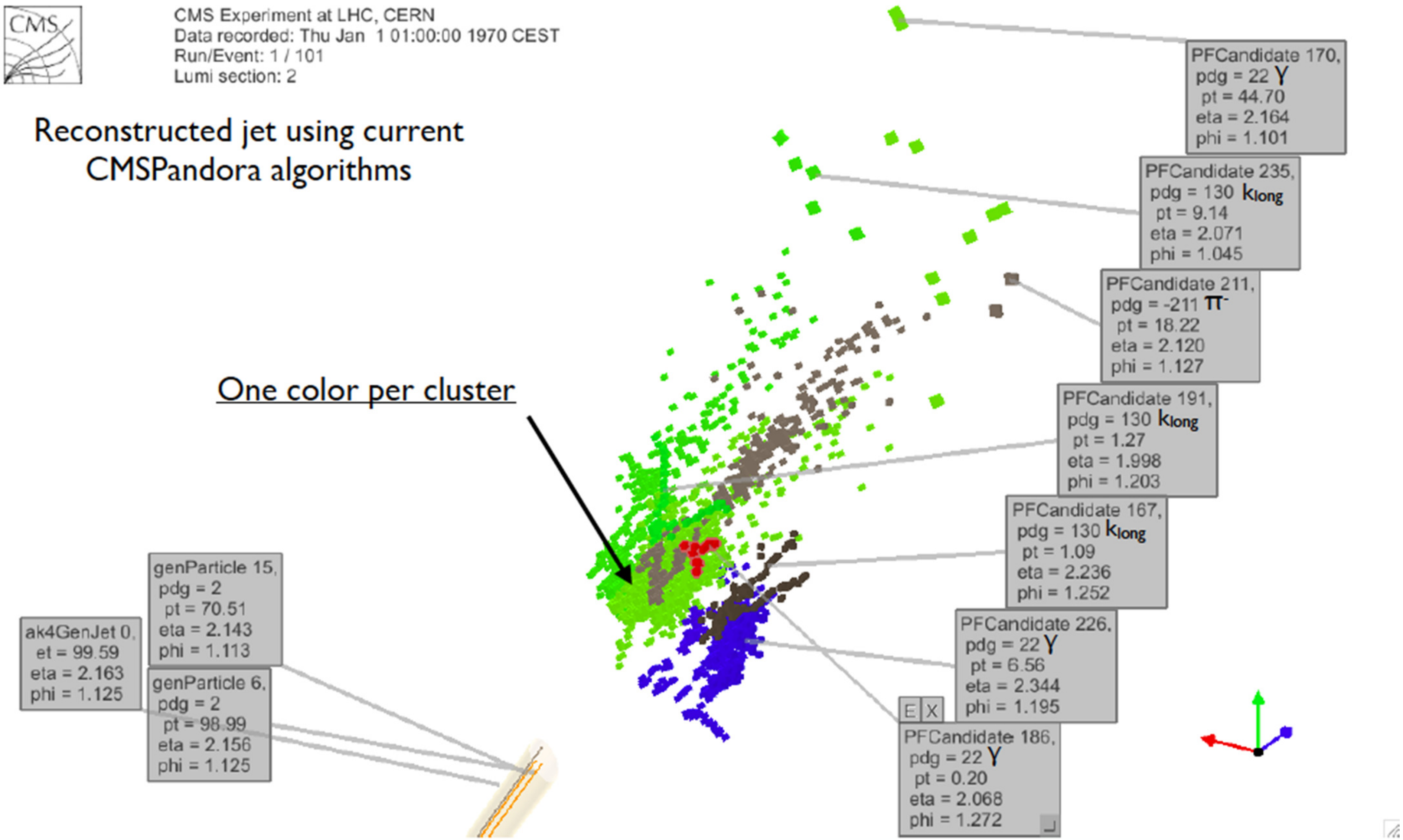
Major Milestones before the TDR submission (Nov 2017)

1	Jun 2016	Baseline clustering selected
2	Sep 2016	Particle flow candidates defined
3	**Dec 2016**	**Simulation geometry frozen for TDR**
4	**Dec 2016**	**Physics objects available**
5	**Mar 2017**	**Software ready for TDR sample production**
6	**Jun 2017**	**TDR reconstruction available**

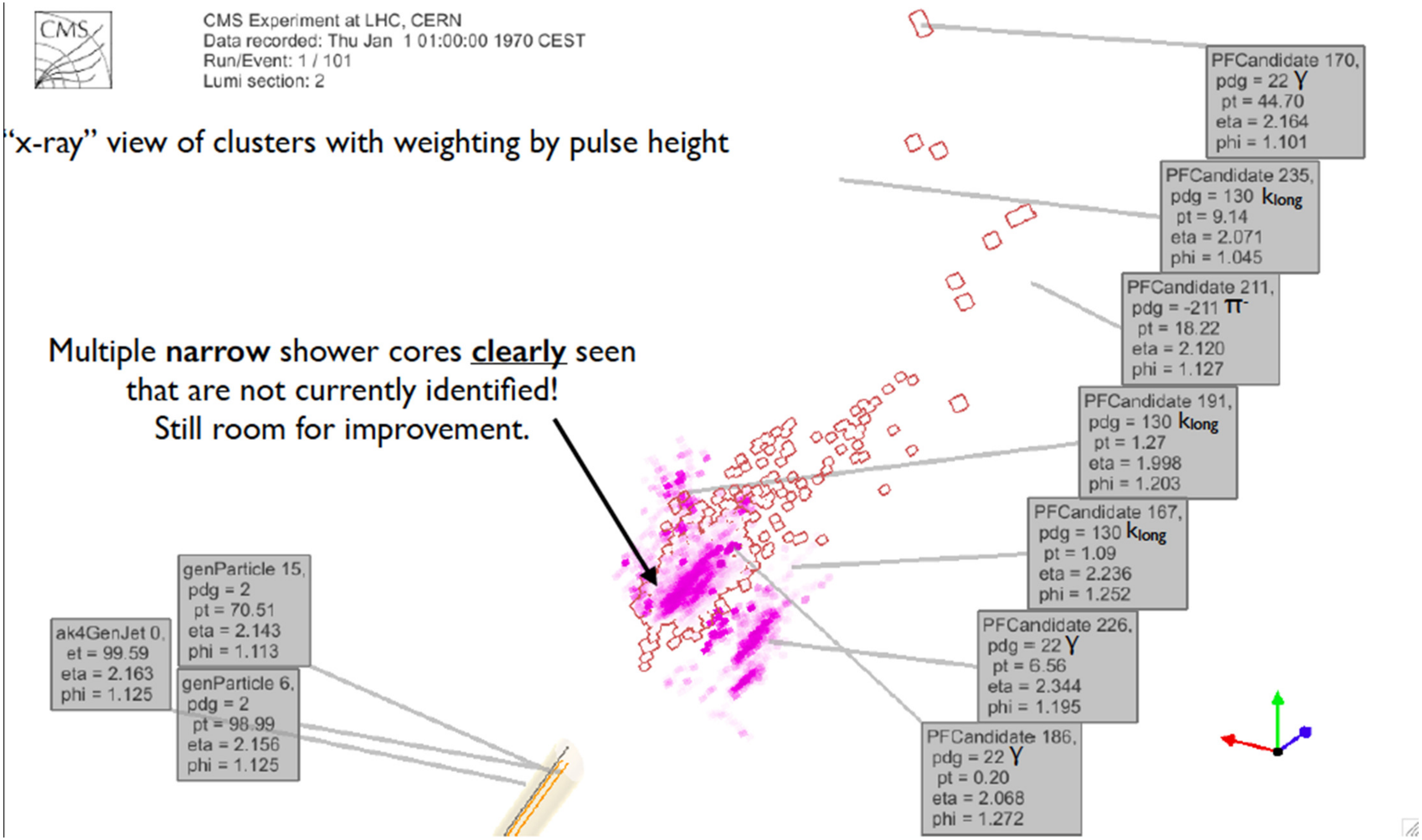
High Level milestones in **bold**

Imperial College London

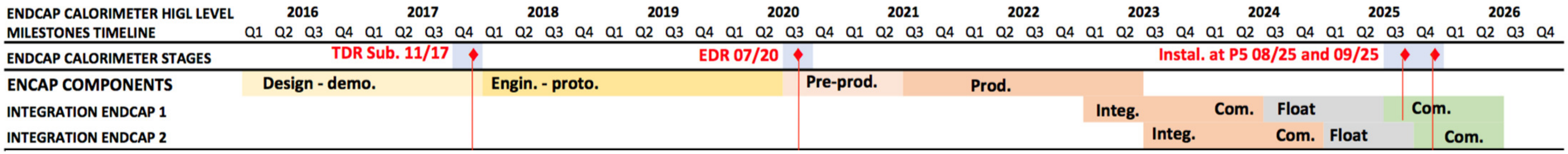
Event Display: VBF Jets



Event Display: VBF Jets

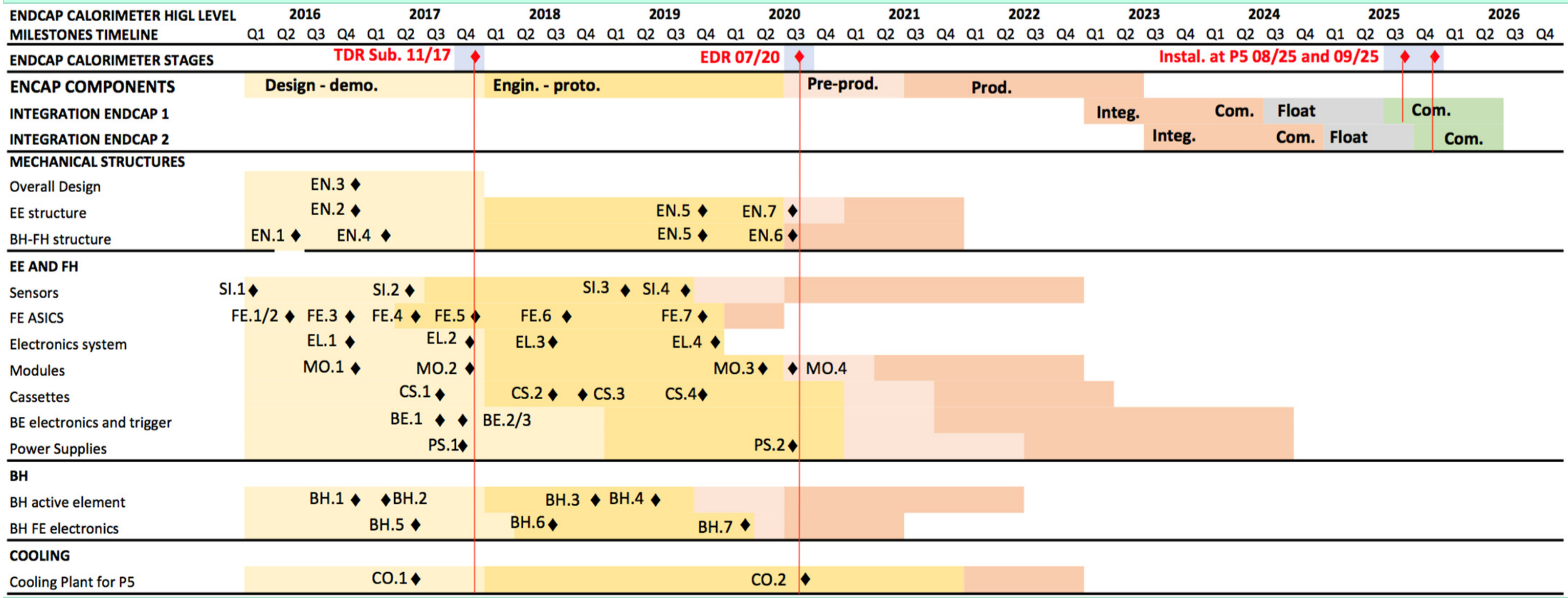


Project Progress, Milestones and Schedule



Project Progress, Milestones and Schedule

Examining TP design from a view of simplicity, cost-effective technical solutions, and physics performance.



e.g. Principal Milestones in 2016

✓ Jun 2016 EC.EN.1: SS absorber chosen for FH and BH

- **Dec 2016**

EC.EN.3: Decision on cold volume: silicon section only or full calorimeter

EC.EN.2: Select EE mechanics structure

EC.EL.1: Define preliminary architecture for LV, links and on-module components

Summary I

The physics program in the HL_LHC phase will have a different emphasis now that we have found a Higgs boson

Requiring precision and finesse across the broadest possible range of signatures

Jets, especially VBF jets, tau-jets, boosted jets (jet substructure) etc. will play an important role as well as traditional channels involving photons, electrons and muons such as $H \rightarrow \gamma\gamma$ and $H \rightarrow 4$ electrons

CMS is designing and prototyping an integrated sampling em and hadronic endcap calorimeter primarily based on Si sensors

Extensive R&D in the past 20 years for Trackers and Pixels have led to the development of cost-effective Si sensors that can sustain high radiation levels.

Potentially allows a "5D" reconstruction of showers/jets (E, x, y, z, t) – will help mitigate effect of pileup.

High resolution timing appears naturally in the f.e. design.

Electronics in 130/65 nm technology allows for low noise, low power consumption readout f.e. electronics (10-15 mW/ch), for large dynamic range

Synergy with developments for Trackers and Linear Collider detectors that plan to use Si calorimetry for their ECALs (e.g. CALICE).

Summary II

Silicon-based calorimetry will be a powerful upgrade of CMS endcap calorimetry. The technology chosen should be able to tolerate up to 4500 fb^{-1} whilst retaining almost full performance throughout.

The challenges ahead lie in engineering (and prototyping). Construction will be launched after all final components/system are in hand and tested. EDR scheduled for mid-2020. Schedule has >1 year of contingency before first HL-LHC beams (2026).

High granularity calorimetry has an excellent potential and offers improvement of physics performance at the HL-LHC.