Overview of Particle Physics Detector R&D

Phil Allport

- Introduction
- Collider and Fixed Target
  - Hadron Collider Detectors
  - Lepton Collider Experiments
  - Lepton-hadron Colliders
  - Fixed Target
- Accelerator and Reactor Neutrinos
  - Far Detector
  - Near Detector
  - Reactor
- Non-accelerator and Low Energy Searches for Rare Processes
  - Dark Matter
  - Neutrino-less Double β-decay
  - Low Energy (includes: g-2, n-EDM, e-EDM, anti-hydrogen, …)
- Astro-particle Experiments
  - Charged Cosmic Rays
  - UHE Gamma-rays
  - UUHE Neutrinos
  - Solar, Atmospheric and Supernova Neutrinos
- Status of ECFA Detector Panel Survey
- Conclusions

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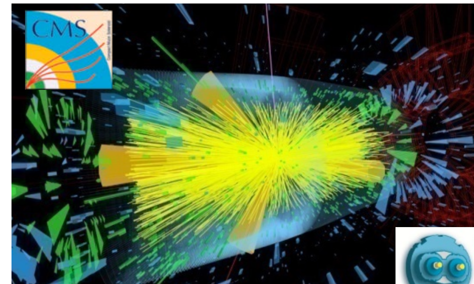
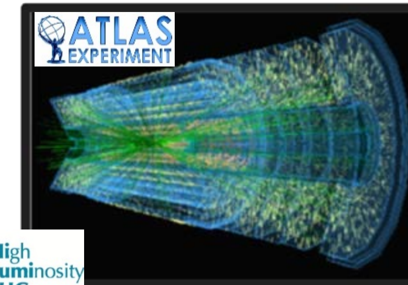
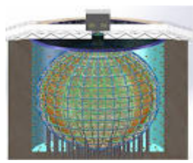
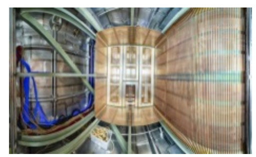
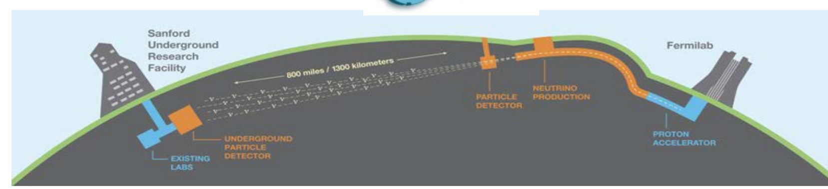




- **Accelerator and Reactor Neutrinos**
  - **Far Detector**
  - **Near Detector**
  - Reactor







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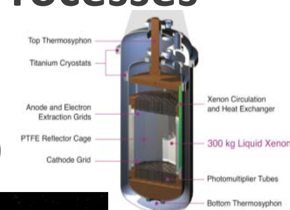

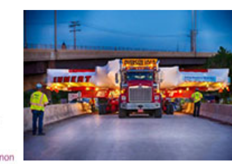

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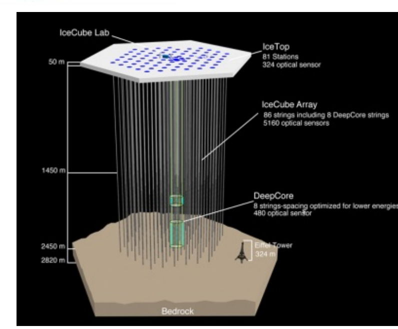


- **Status of ECFA Detector Panel Survey**
- **Conclusions**

Introduction

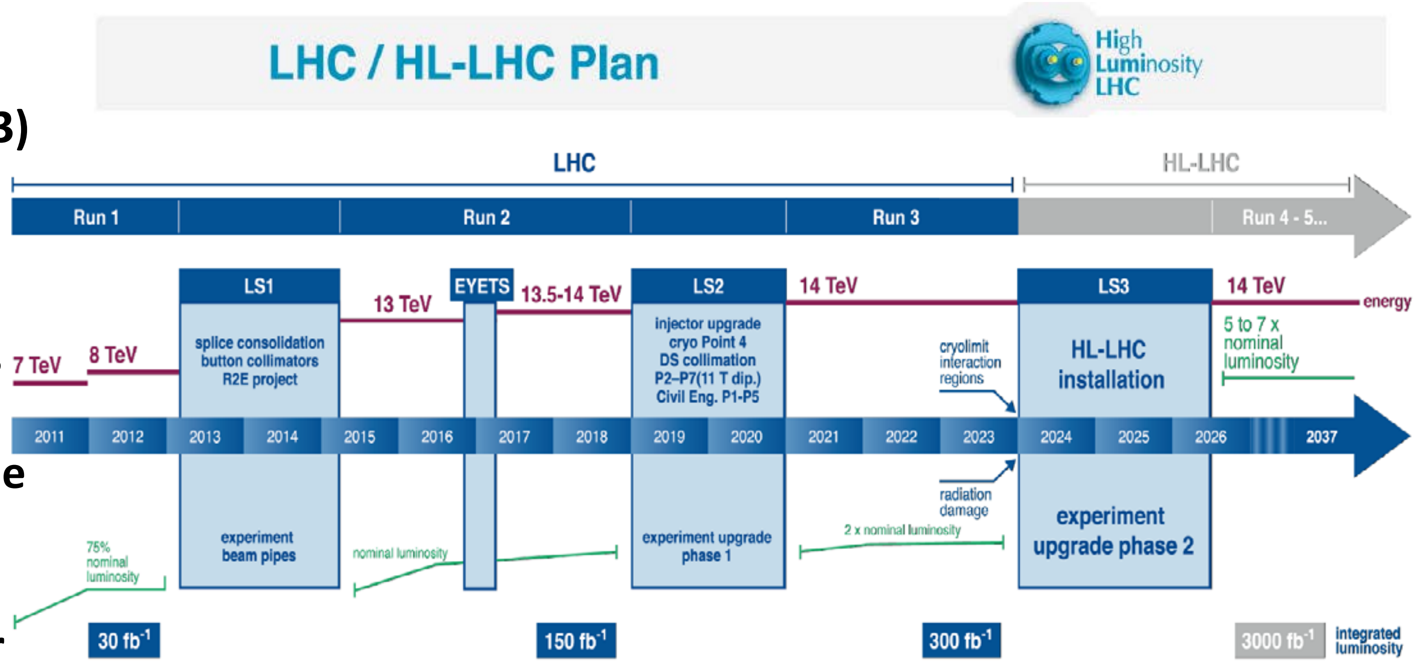
CERN Council has by virtue of the **Convention for the Establishment of a European Organization for Nuclear Research** responsibility for defining the strategic orientation of European particle physics and not just those relating to activities at CERN (see https://council.web.cern.ch/en/content/european-strategy-particle-physics)

The first "European Strategy for Particle Physics" was adopted by CERN Council on 14/7/06. The strategy was prepared by a Strategy Group consisting of eight members drawn from ECFA and the SPC, two co-chairmen, and a scientific secretary. This group took contributions from the community and at an Open Symposium held in Orsay 30/1/06 to 1/2/06.

A Strategy Update was developed following the Open Symposium in Krakow on 10/9/12 to 12/9/12 and published by the European Strategy Group following its Update of Strategy meeting in Erice on 21/1/13 to 26/1/13. It was adopted following a "European Strategy Session" of CERN Council held on 28/5/13 in Brussels.

The next Update is expected to be published in 2020 with significant material developed in 2018 to provide inputs to meetings of the preparatory groups for the European Strategy during 2019.

Hadron Colliders: the HL-LHC Programme



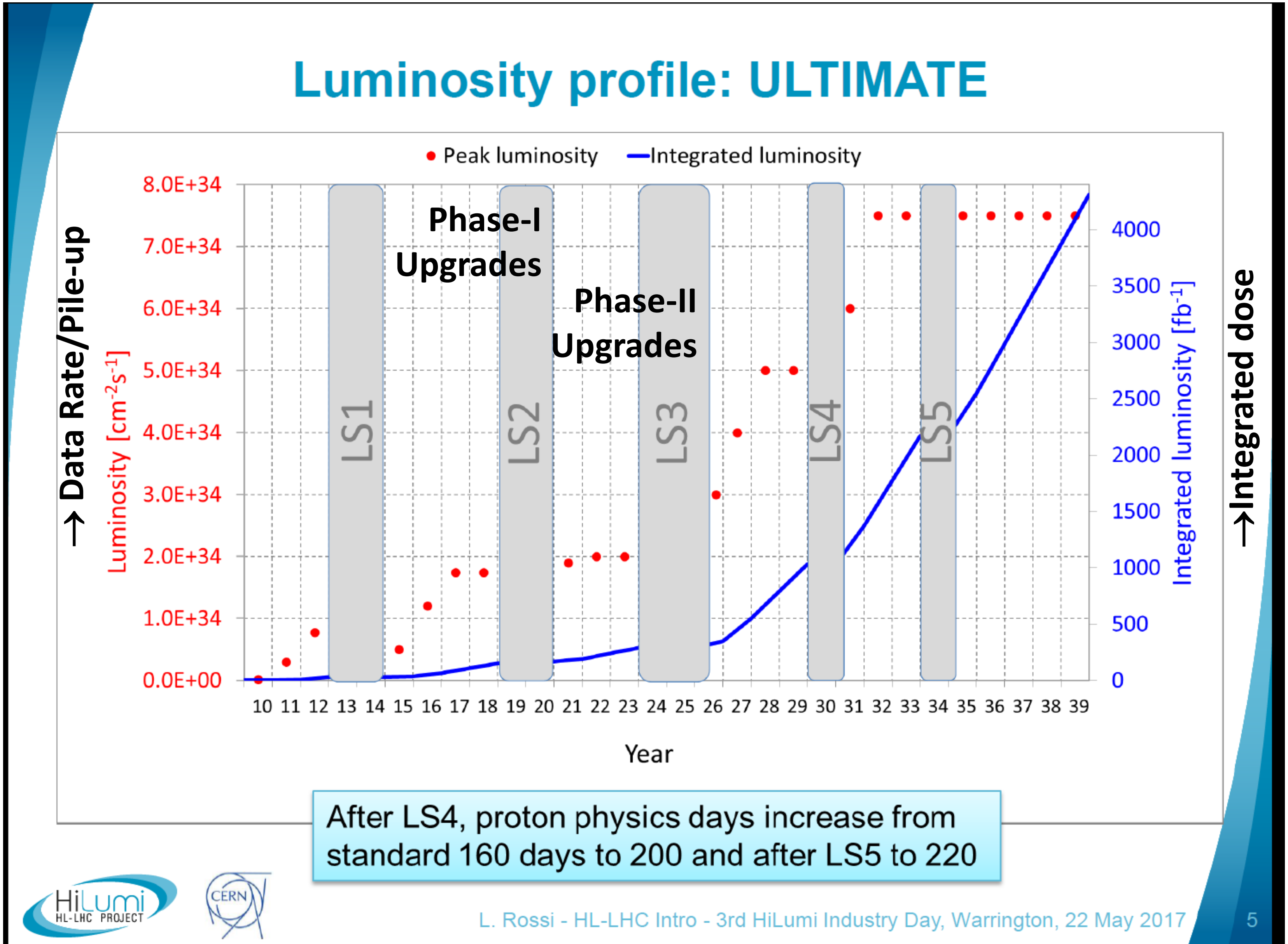
CERN Council (May 2013)
"The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme."

"Europe's top priority should be the exploitation of the full potential of the LHC, including the <u>high-luminosity upgrade of the machine and detectors</u> with a view to collecting ten times more data than in the initial design, by around 2030"

HEPAP in the US (May 2014) decided: "*The <u>HL-LHC</u> is strongly supported and is the first high-priority large-category project in our recommended program*"

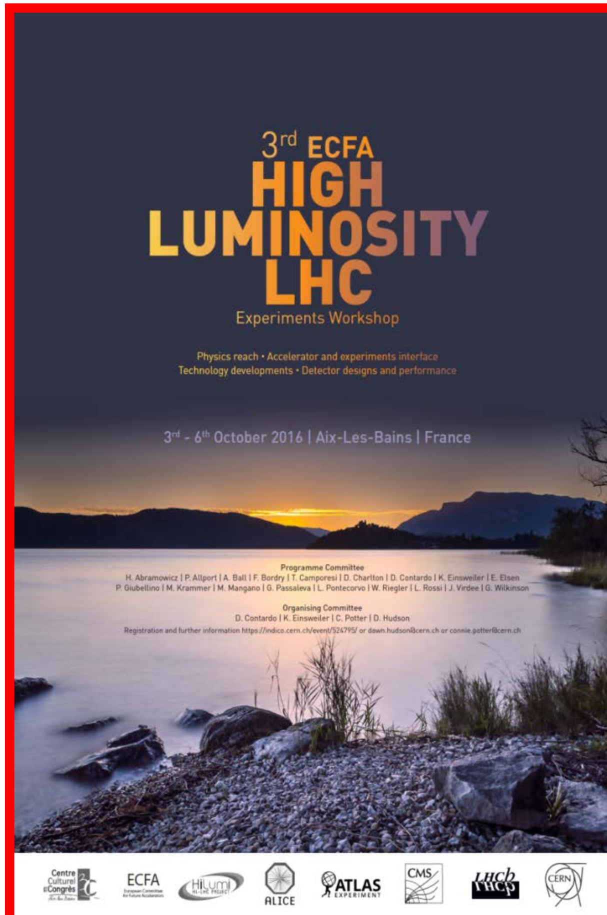
CERN Council (June 2016) Formal approval of the High Luminosity LHC project, HL-LHC

Detector Upgrades for the HL-LHC Programme



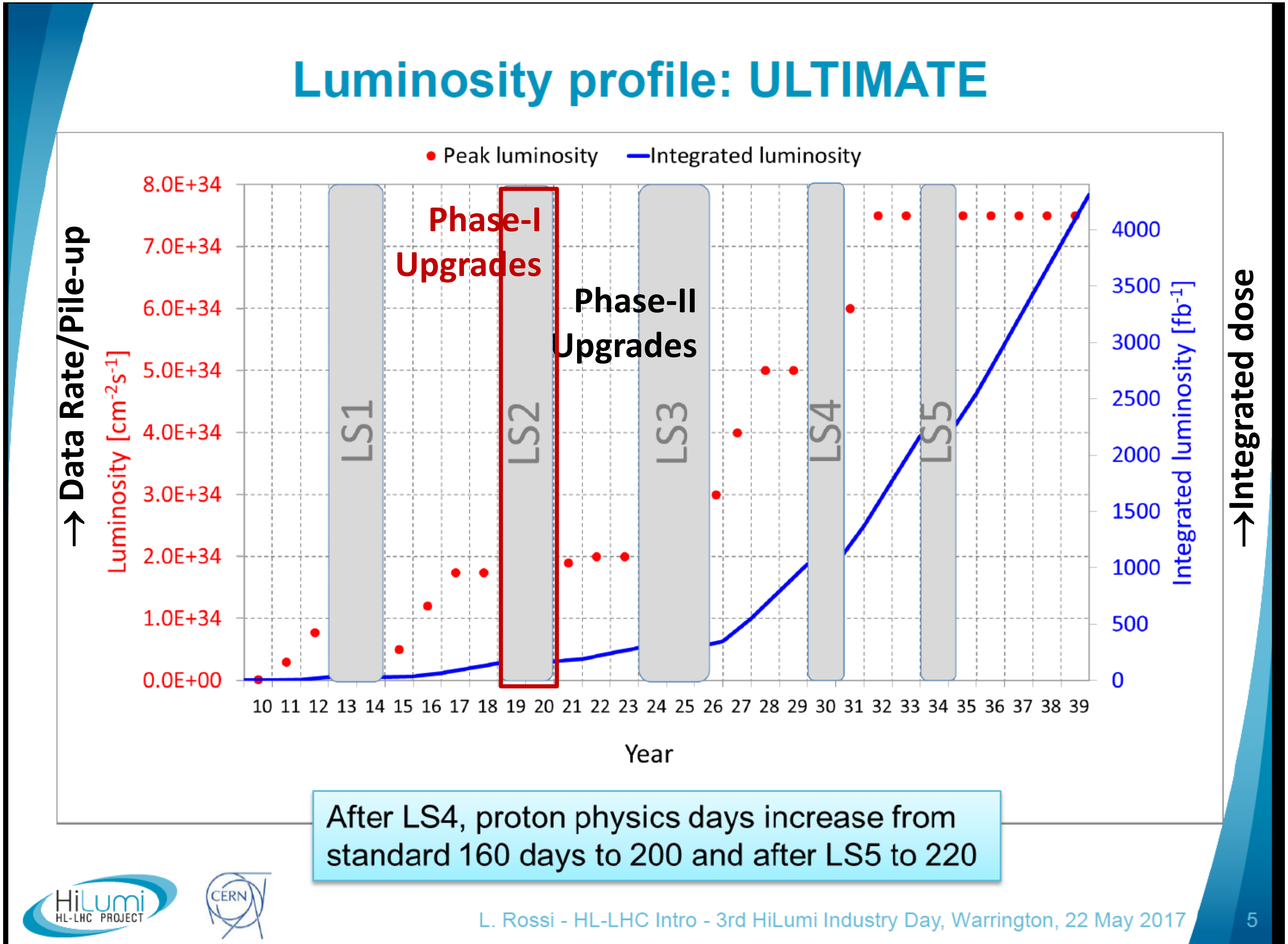
Detector Upgrades for the HL-LHC Programme

https://indico.cern.ch/category/4863/

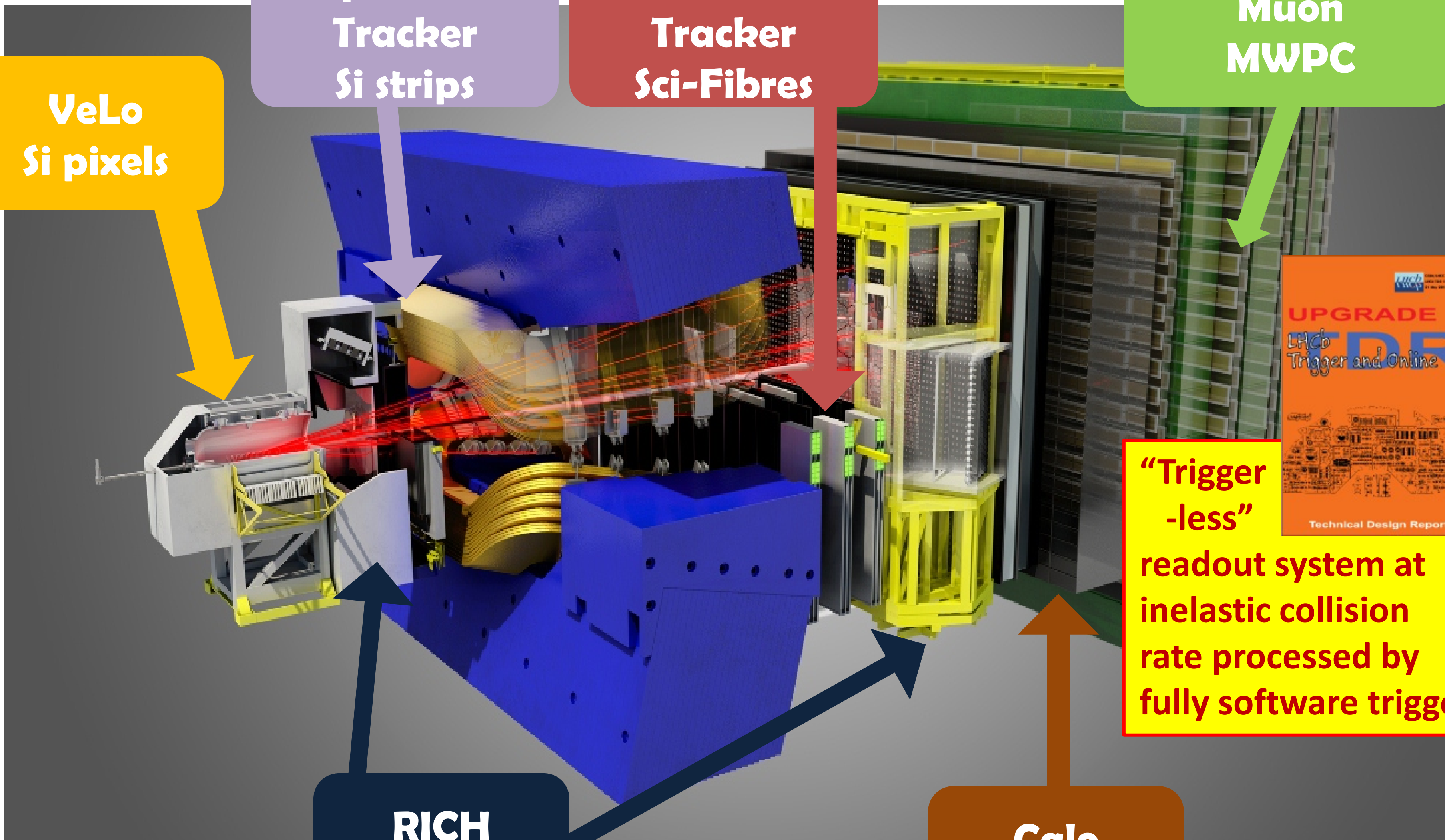


https://indico.cern.ch/event/524795/

Detector Upgrades for the HL-LHC Programme

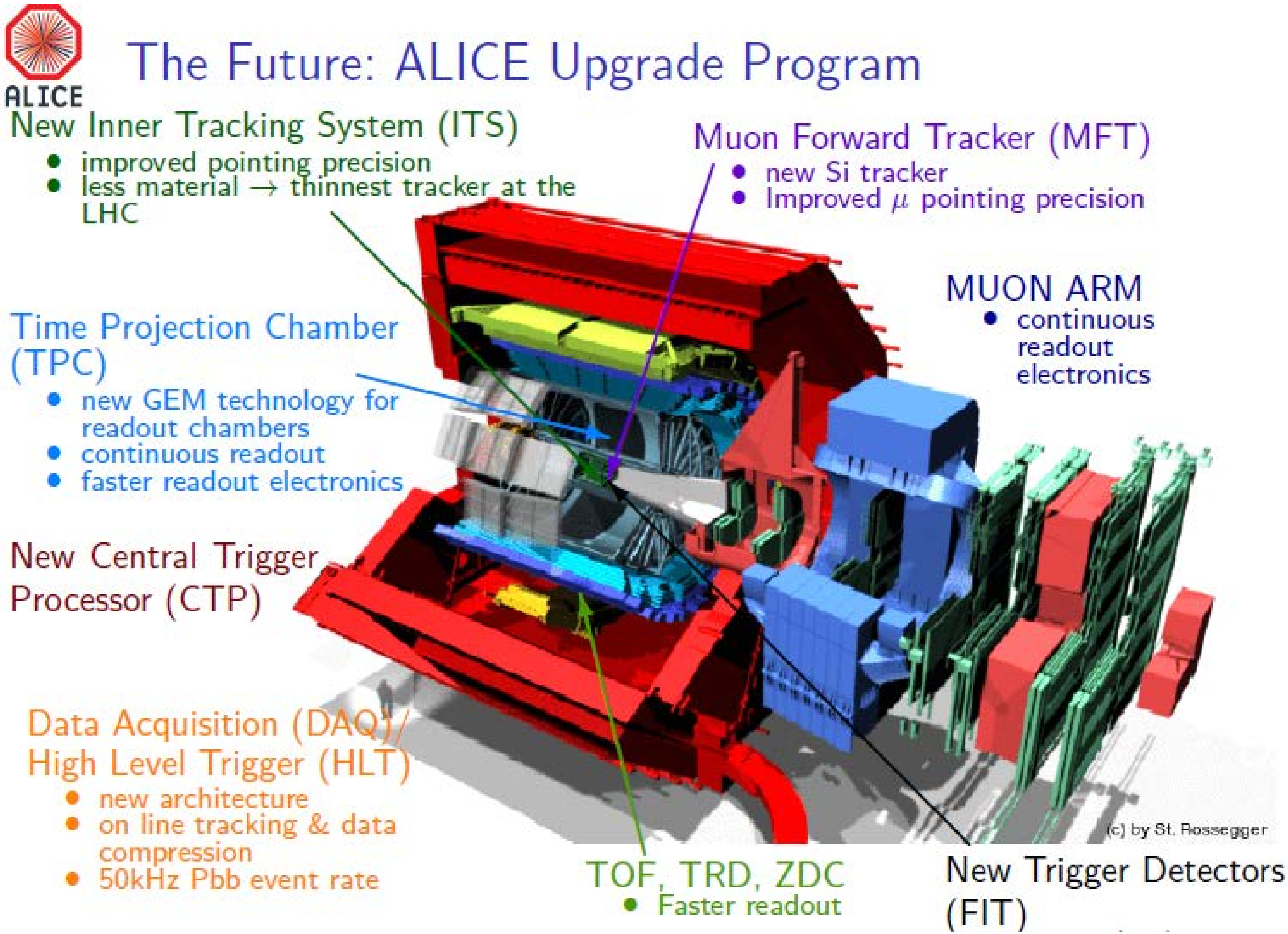


LHCb: Phase-I Upgrades



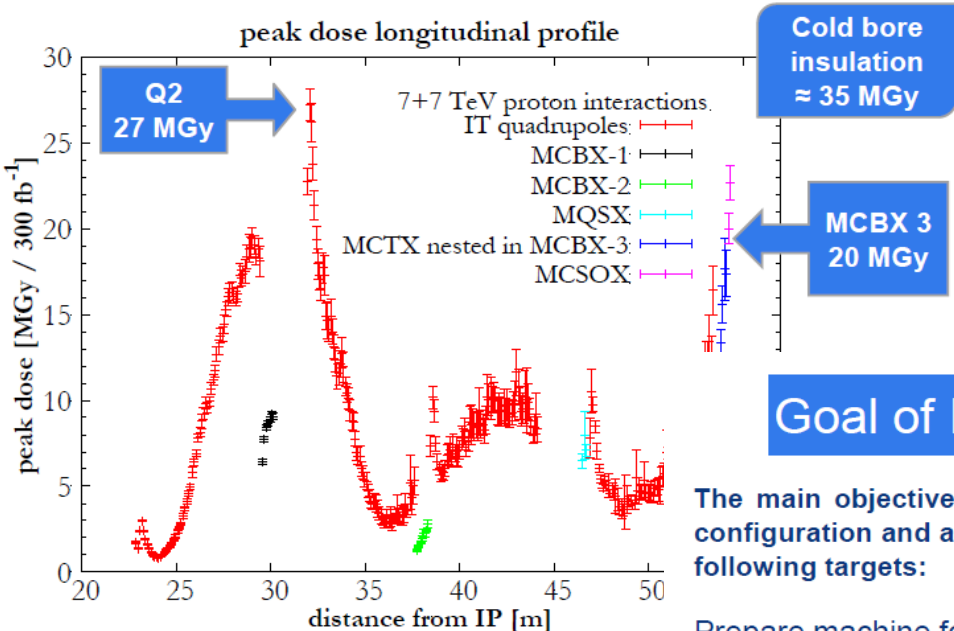
"Trigger-less" readout system at inelastic collision rate processed by fully software trigger

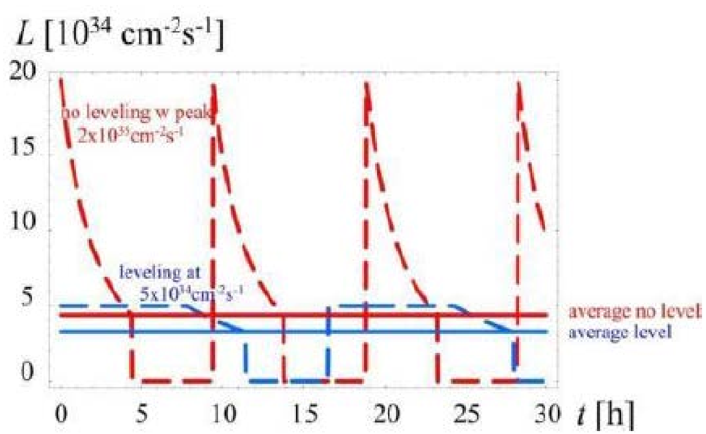
ALICE: Phase-I Upgrades

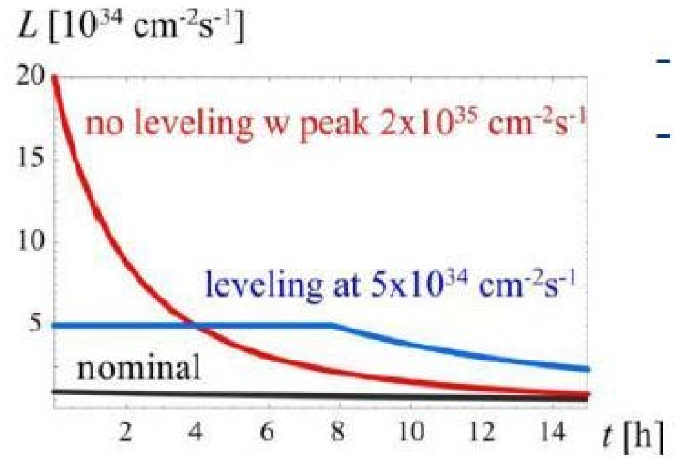


Overview of HL-LHC Programme

Radiation damage to triplet magnets at 300 fb-1







Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation **beyond 2025 and up to 2035-37**

Devise beam parameters and operation scenarios for:

#enabling a total integrated luminosity of **3000 fb^{-1}**

#implying an integrated luminosity of **250-300 fb^{-1} per year**,

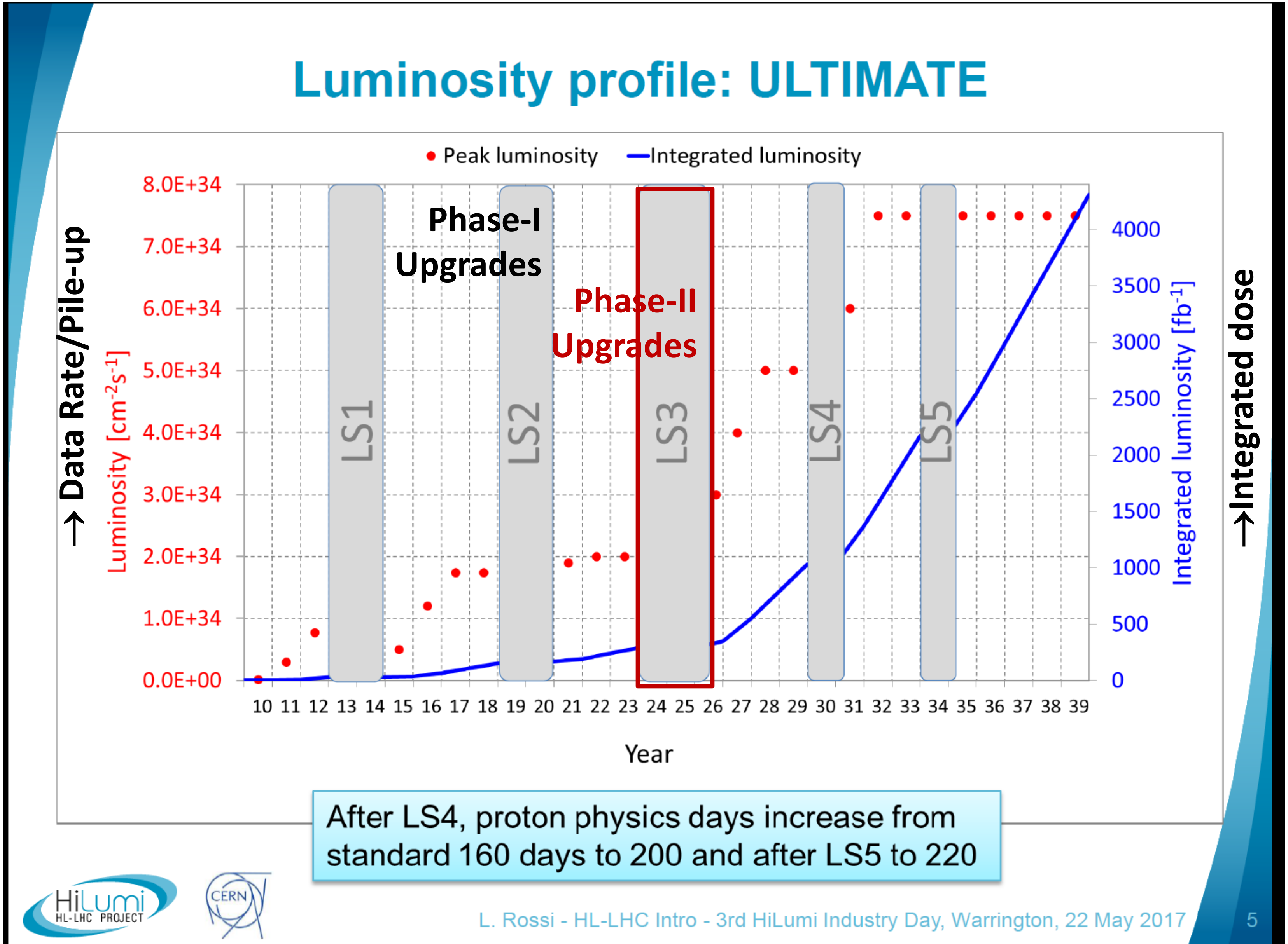
#design for μ ~ **140 (~ 200)** (➔ peak luminosity of **5 (7) 10^{34} cm^{-2} s^{-1}**)
pile-up density (<1.3 events/mm)

#design equipment for 'ultimate' performance of **7.5 10^{34} cm^{-2} s^{-1}** and **4000 fb^{-1}**

=> Ten times the luminosity reach of first 10 years of LHC operation

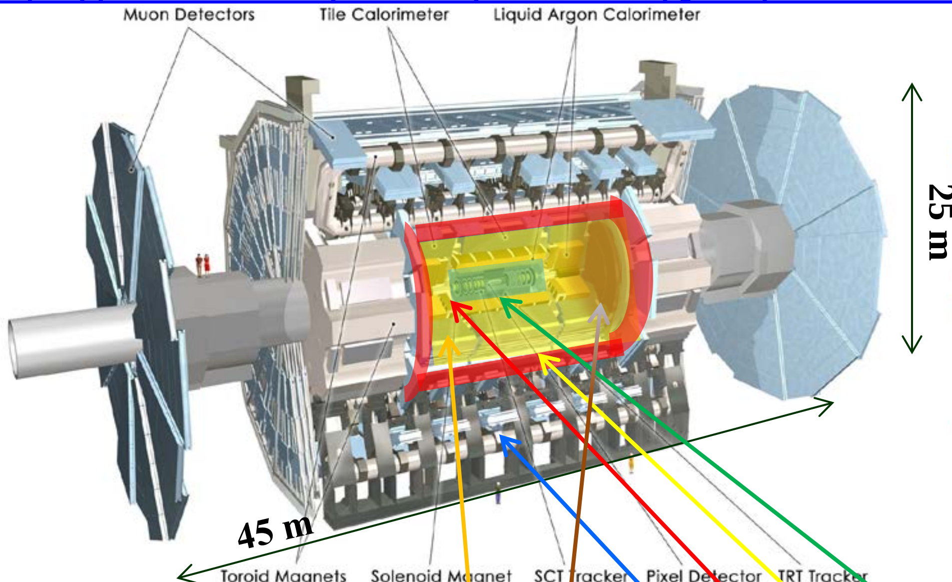
LHC accelerator overviw
Frédérick Bordry
3rd ECFA High-luminosity LHC experiments workshop
3rd October 2016 – Aix-les-Bains

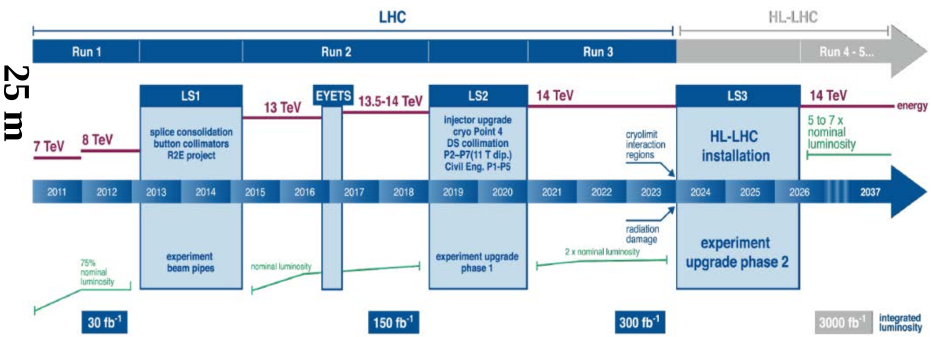
Detector Upgrades for the HL-LHC Programme



ATLAS: Phase-II Upgrades

[https://cds.cern.ch/record/2055248/**files**/LHCC-G-166.pdf](https://cds.cern.ch/record/2055248/files/LHCC-G-166.pdf)





Phase-1 Upgrade	Phase-2 Upgrade
L = 2e34 (μ~60) int L = 200 fb^{-1}	L = 7.5e34 (μ~200) Int L = 4000 fb^{-1}
• New Muon Small Wheel (NSW) • Fast Track Trigger (FTK) • TDAQ Phase-1 • LAr Calorimeter Electronics • ATLAS Forward Protons (AFP)	• All new Tracking Inner Detector (ITk-Strip/Pixel) • Calorimeter Electronics Upgrade • Forward Timing Detector • Muon System Upgrade • TDAQ Phase-2

CMS: Phase-II Upgrades

http://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf?version=4

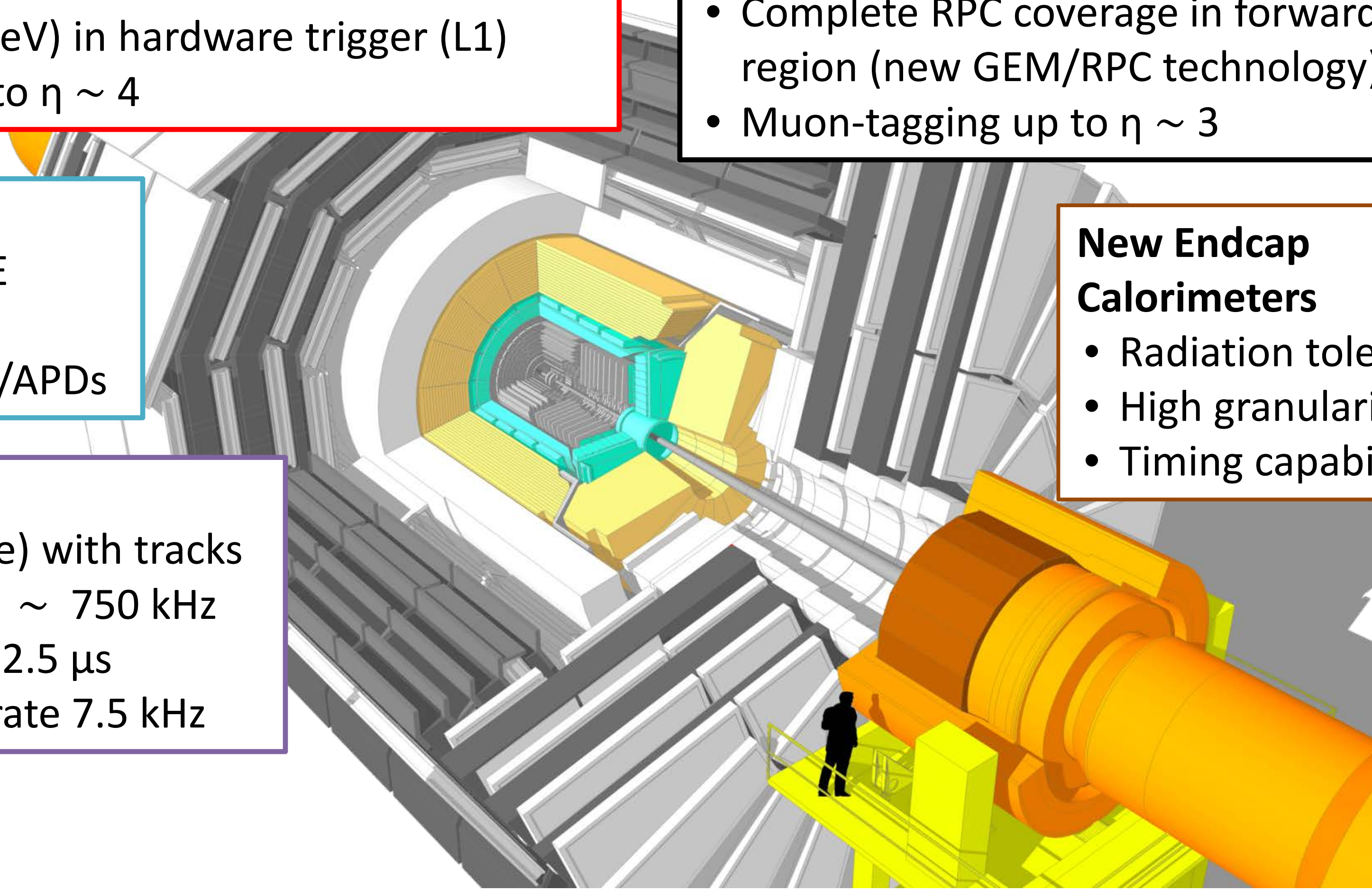
New Tracker
- Radiation tolerant - high granularity - less material
- Tracks (P_T>2GeV) in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT and CSC FE/BE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Muon-tagging up to η ~ 3

Barrel ECAL
- Replace FE/BE electronics
- Cool detector/APDs

New Endcap Calorimeters
- Radiation tolerant
- High granularity
- Timing capability

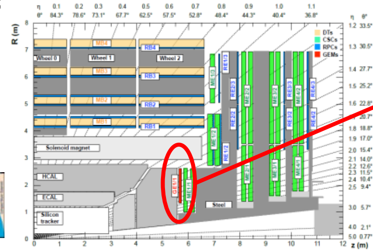
Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 µs
- HLT output rate 7.5 kHz

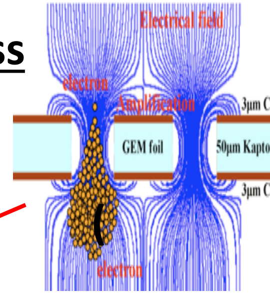


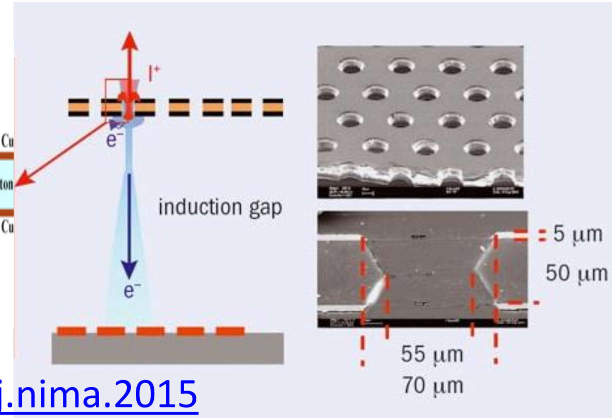
Large Area High Rate Gas Detectors (>10^4Hz/cm^2)

Major R&D activities on micro-pattern gaseous detectors for LHC large volume tracking (eg muon systems)

- **<u>Increase rate capabilities and radiation hardness</u>**
- **Improved resolution (online trigger and offline analyses)**
- **Improved timing precision background rejection)**







Fabio Sauli
doi:10.1016/j.nima.2015

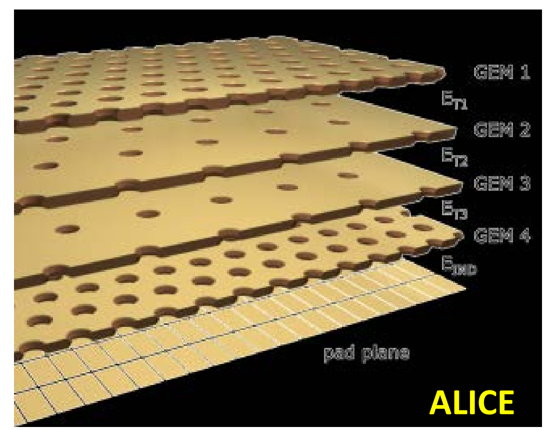
Technologies

- **Straws (NA62) and drift tubes (ATLAS)**
- **Gas Electron Multiplier (CMS, ALICE TPC R/O and current LHCb)**

RD51: common micro-pattern gas detector R&D

Cylindrical GEM
KLOE-2 and for **BESIII**

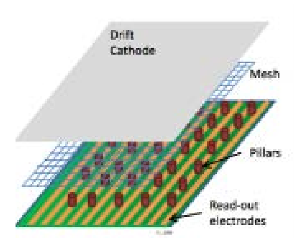
ALICE TPC Read-out



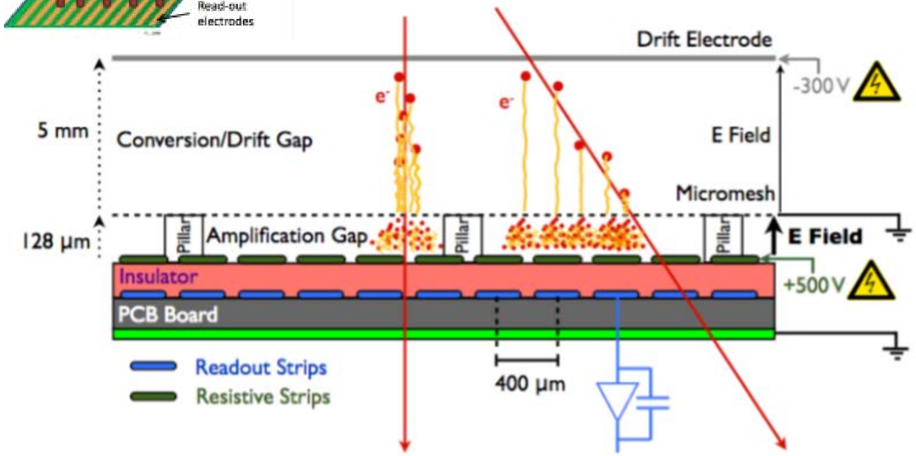
4 layer GEM stack to target Ion backflow < 1% given continuous readout at 50kHz

Large Area High Rate Gas Detectors ($>10^4 Hz/cm^2$)

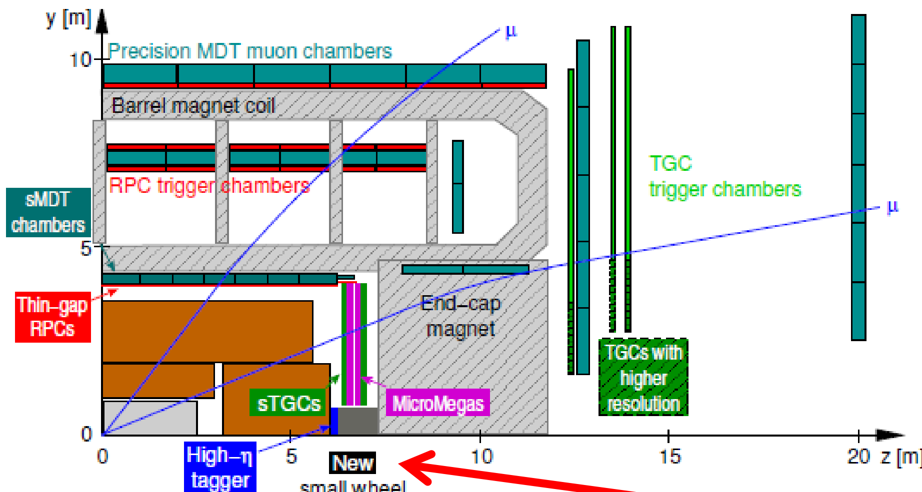
- **MicroMegas and Thin Gap Chambers (TGCs): ATLAS "New Small Wheels"**



MicroMegas Principle



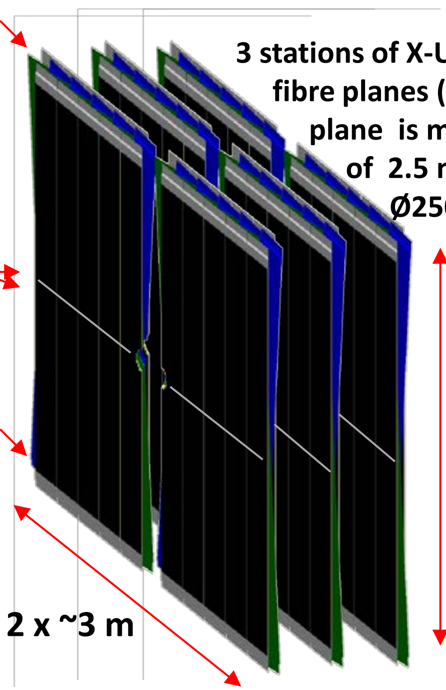
- **Many challenges including the development of commercial large-scale production capabilities (ATLAS NSW Forward Muons: $2*1200m^2$ and 2.4M channels)**

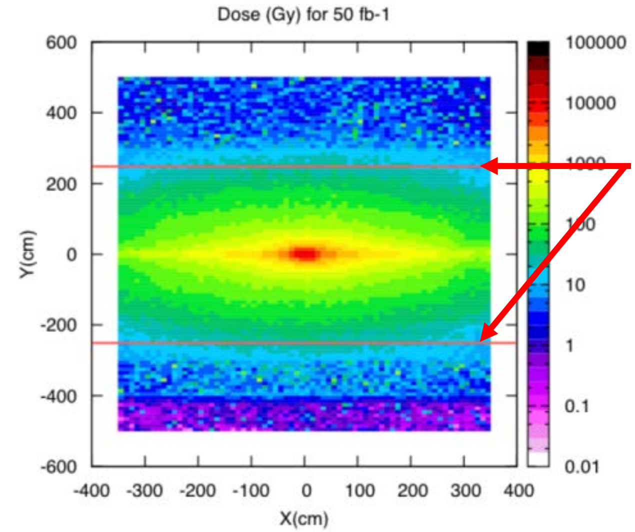


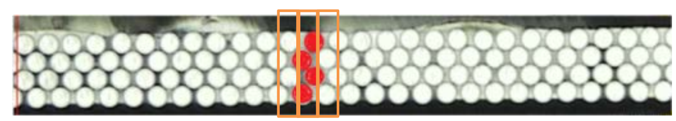
- **Resistive Plate Chambers (RPCs) - low resistivity glass for rate capability, multi-gap precision timing (ALICE/ATLAS/CMS)**

Scintillating Fibre Tracking

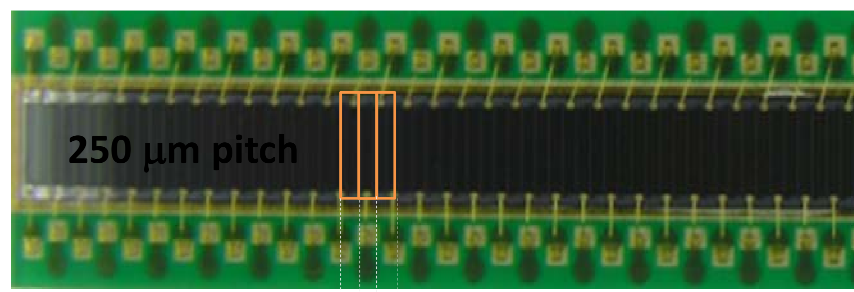
Large scale SciFi tracker for LHCb







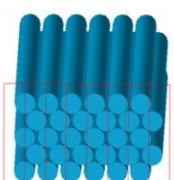
4 layer proto mat



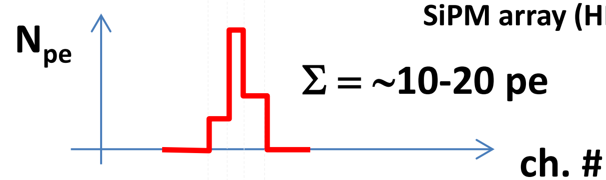
SiPM array (HPK)

Challenges

- Large size – high precision
- O(10,000 km) of fibres
- Operation of SiPM at -40°C

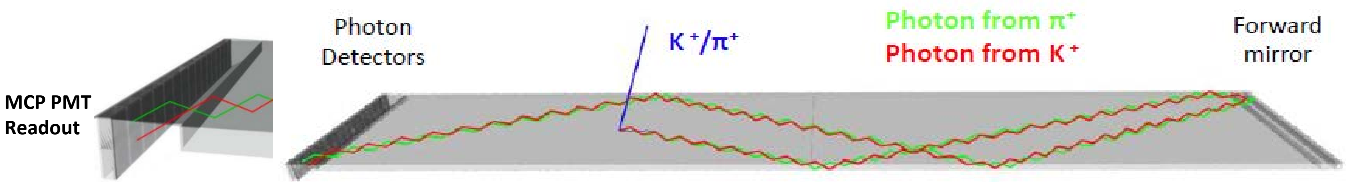


3 million (SCSF-78MJ TDR baseline) scintillating fibres with up to 30kGy non-uniform exposure (CERN/LHCC 2014-001)

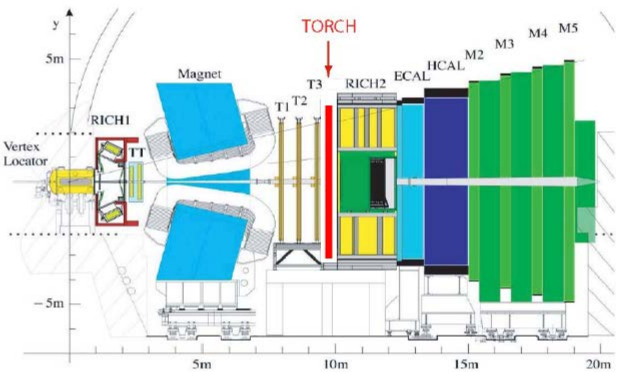


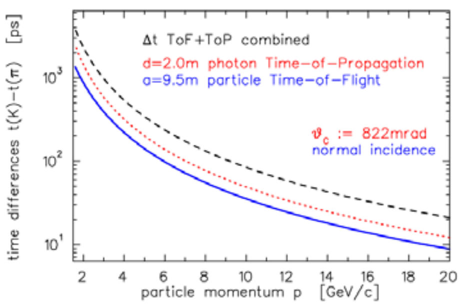
Timing Detectors (c=30cm/ns; 1/c= 33ps/cm)

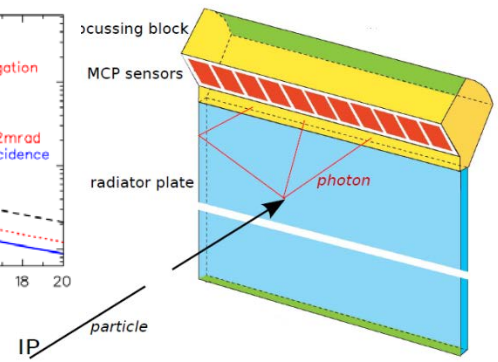
- **Many applications call for precision timing for particle ID (incl Time of Flight)**
  - ***eg* BELLE-II TOP (Time of Propagation) σ = 35ps: 2.5m x 0.45m x 2cm Quartz bars**

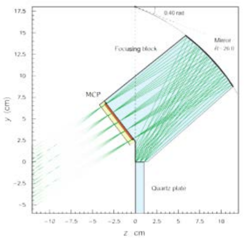


  - ***eg* LHCb TORCH** (Time Of internally Reflected CHerenkov light) **15ps ToF (30 pe/track)**

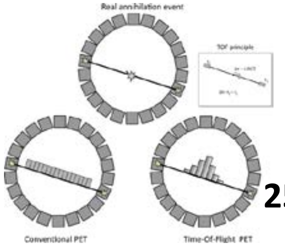






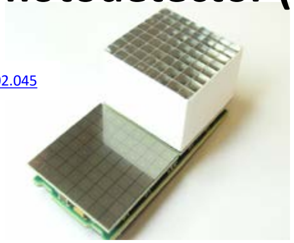


- **PET Scanner technologies: ToF fast scintillator and photodetector (eg LYSO+SiPM)**



25ps time bins

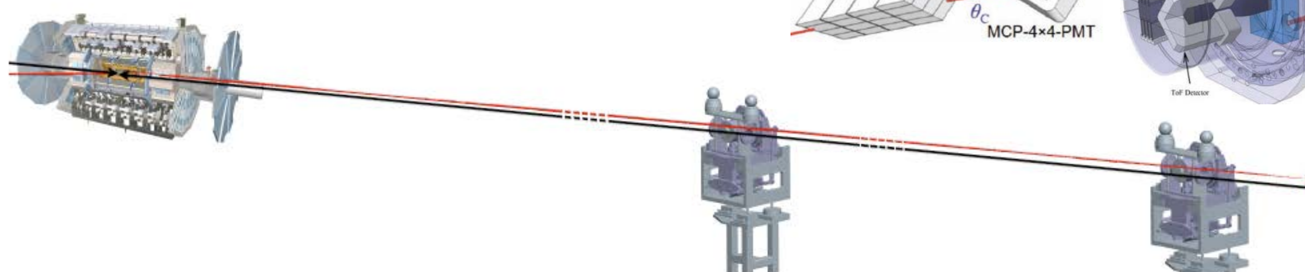
https://doi.org/10.1016/j.nima.2017.02.045

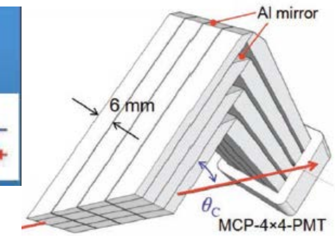


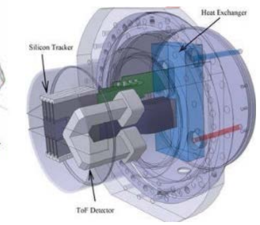
Also CMS Barrel Timing Layer (30ps pile-up mitigation)

Timing Detectors (c=30cm/ns; 1/c= 33ps/cm)

- **Charged particle detection with quartz/scintillator plus fast photodetectors *eg* ATLAS Forward Physics, or direct detection also possible with fast gas or semiconductor detectors**







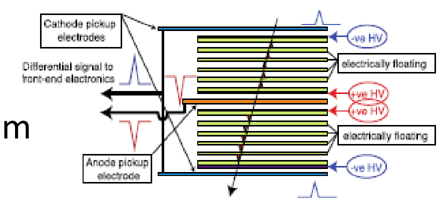
ATLAS AFP: <15ps James Pinfold (https://indico.cern.ch/event/466934/contributions/2591363/)

ALiCE ToF

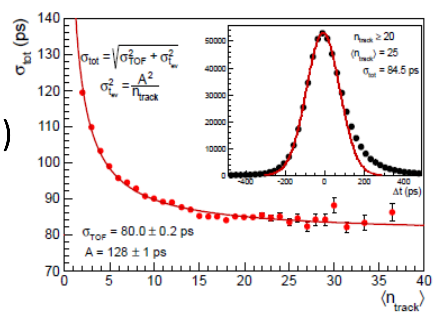
140 m² of Multigap RPCs at 3.7 m from the IP

- Rate capability ~100 Hz/cm² (glass resistivity)
- **Fast readout electronics**
- Leading edge disc. with time-over-thresh correction (NINO)

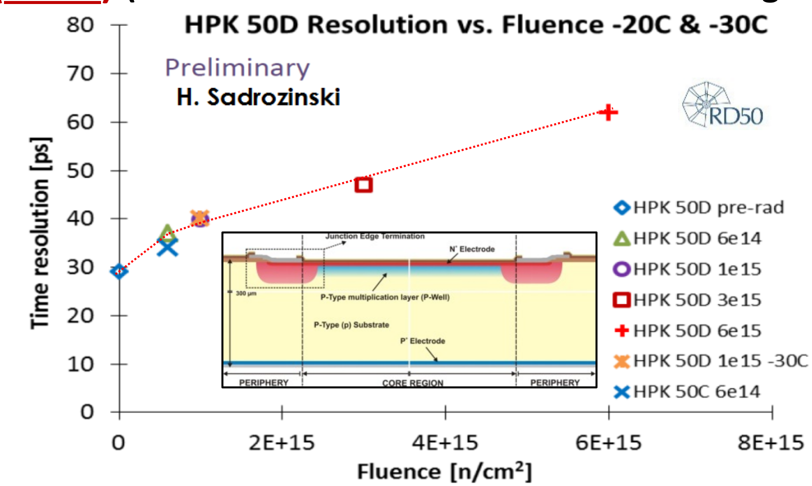
- **Single particle resolution *in situ*: down to 80 ps**



2014 JINST 9 C10019



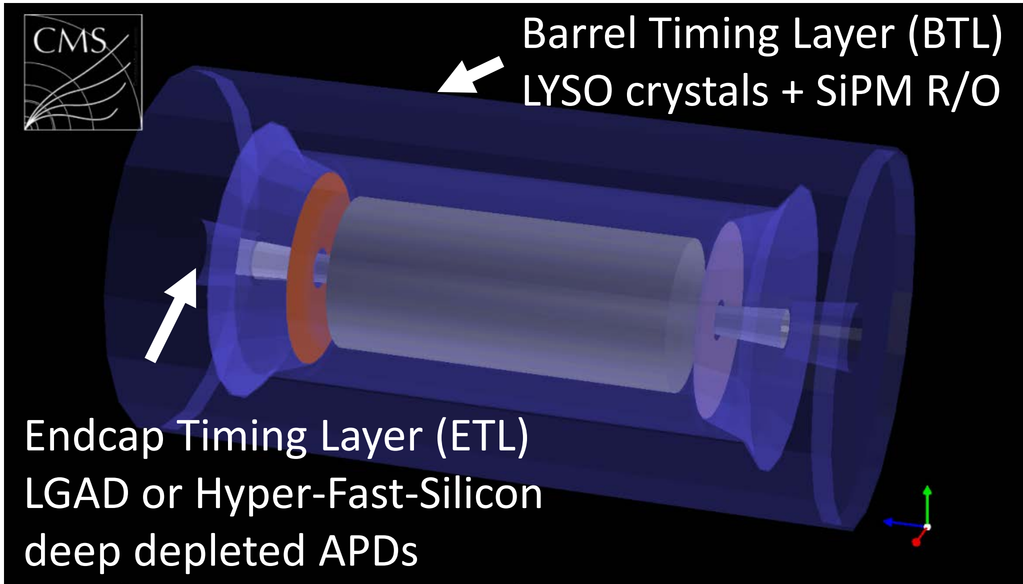
RD50, ATLAS, CMS: Low Gain Avalanche Detectors (LGAD) (need to watch radiation issues - work ongoing)

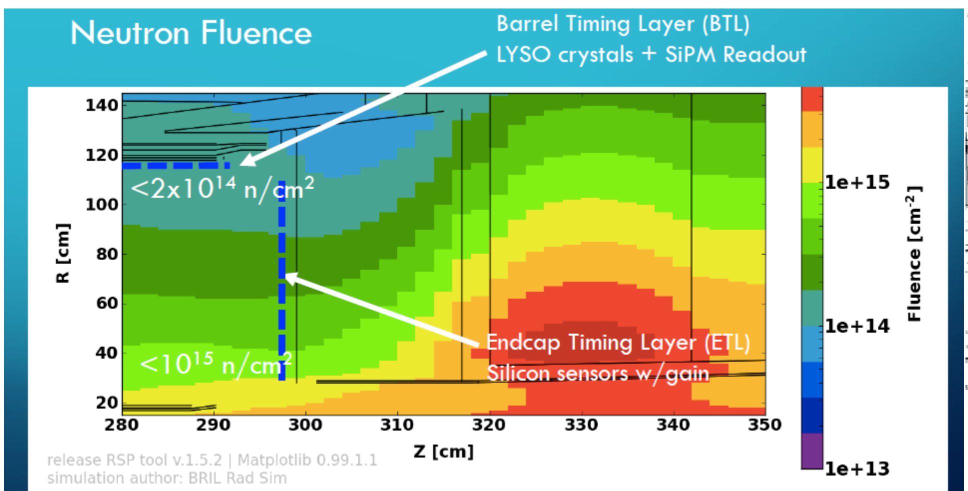


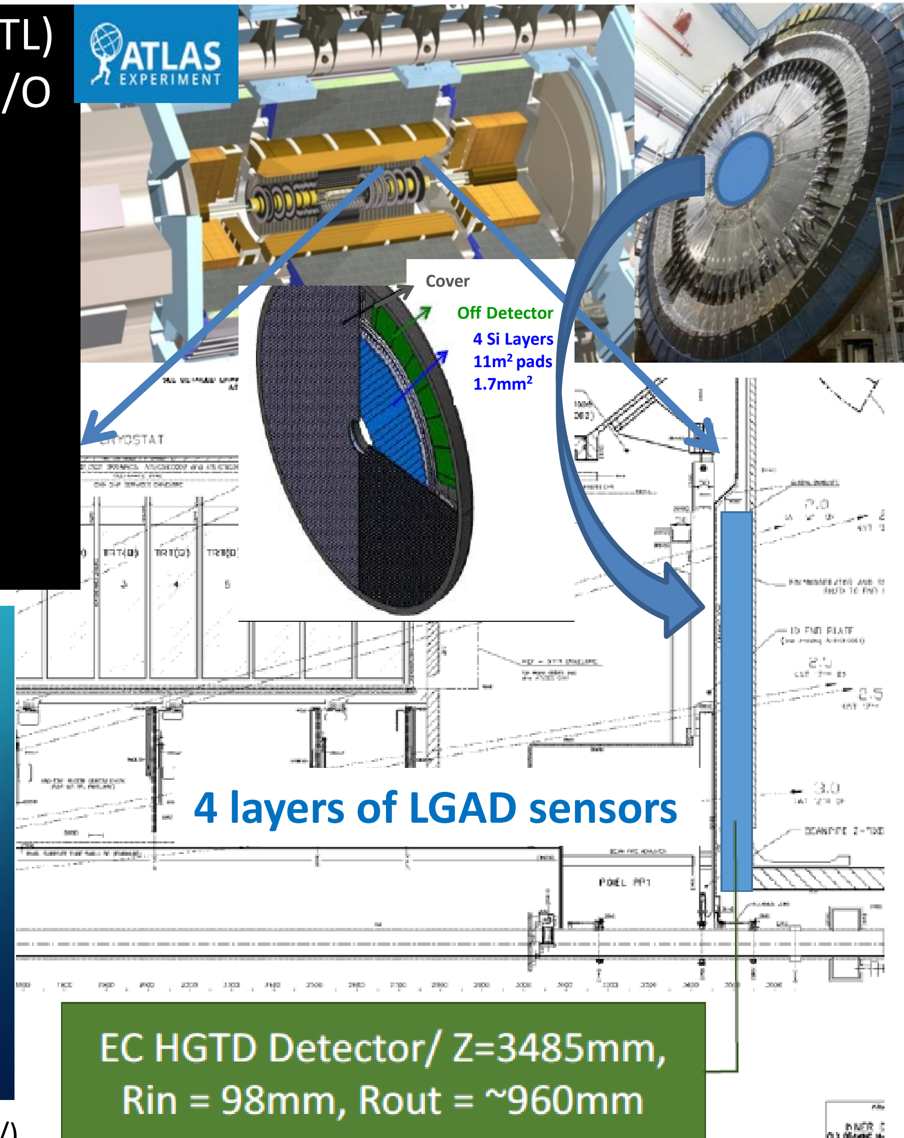
HL-LHC Timing Detectors

(Beamspot: σ_z ~ 9 cm; σ_t ~ 0.2ns
200 pile-up: 2017-03-16_HLLHC-TC.pdf)

Use timing to help identify tracks with correct vertices

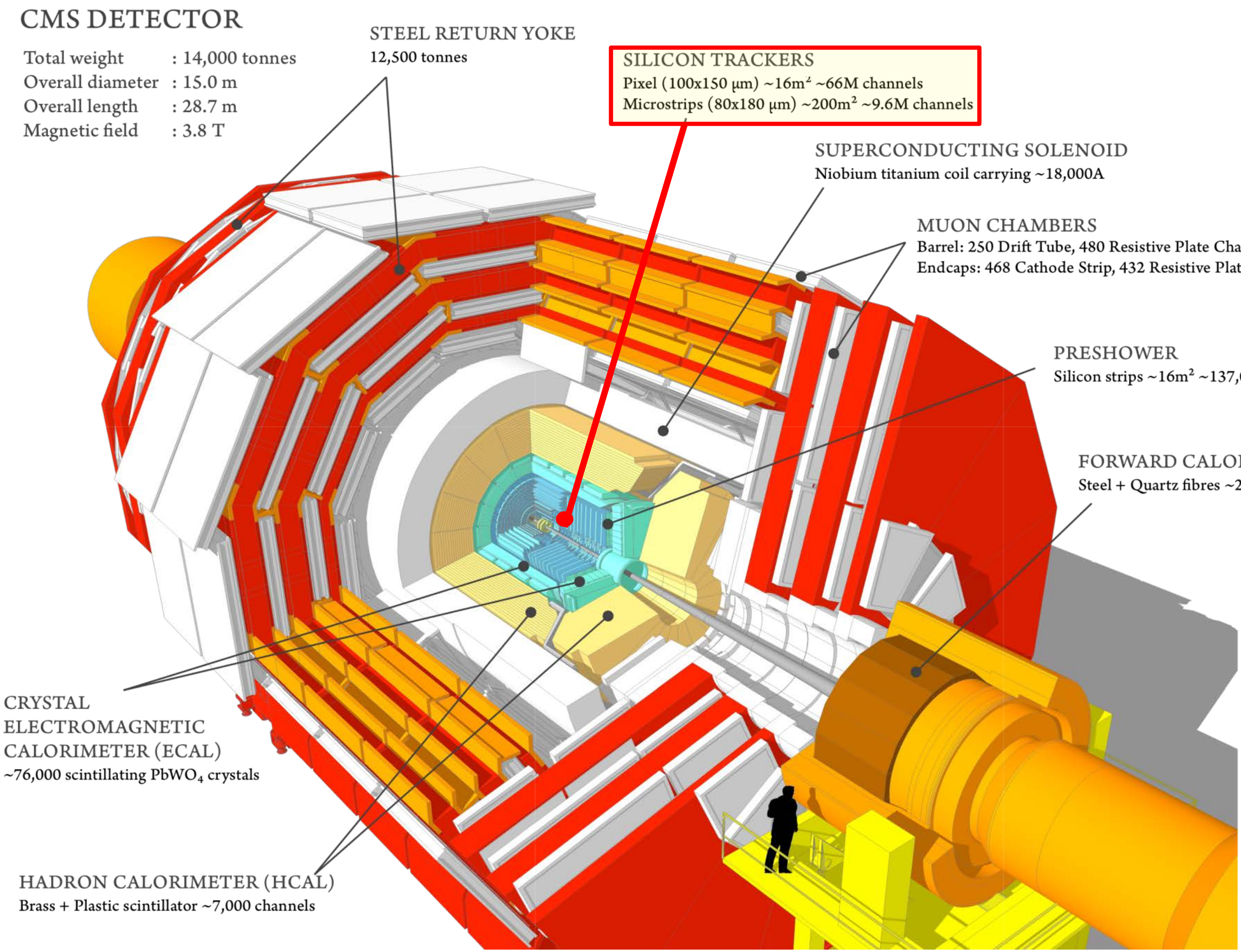






(Lectures by Christopher Tully at https://indico.cern.ch/event/633343/)

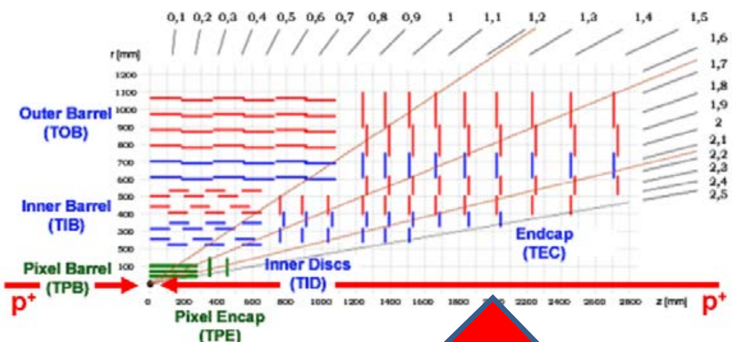
CMS Tracker Upgrade



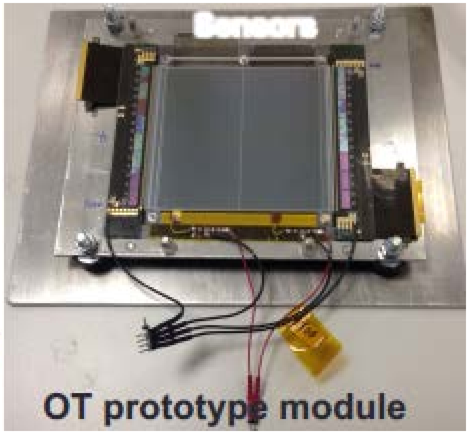
CMS Tracker Upgrade

Outer trackers need radiation hardness of current n-in-n pixel sensors at fraction of the cost

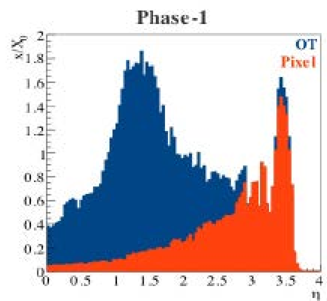
→ **ATLAS/CMS: n-in-p strip technology**



Many large area sensors produced for both ATLAS and CMS

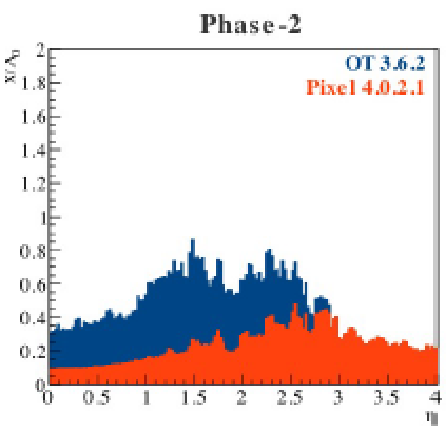


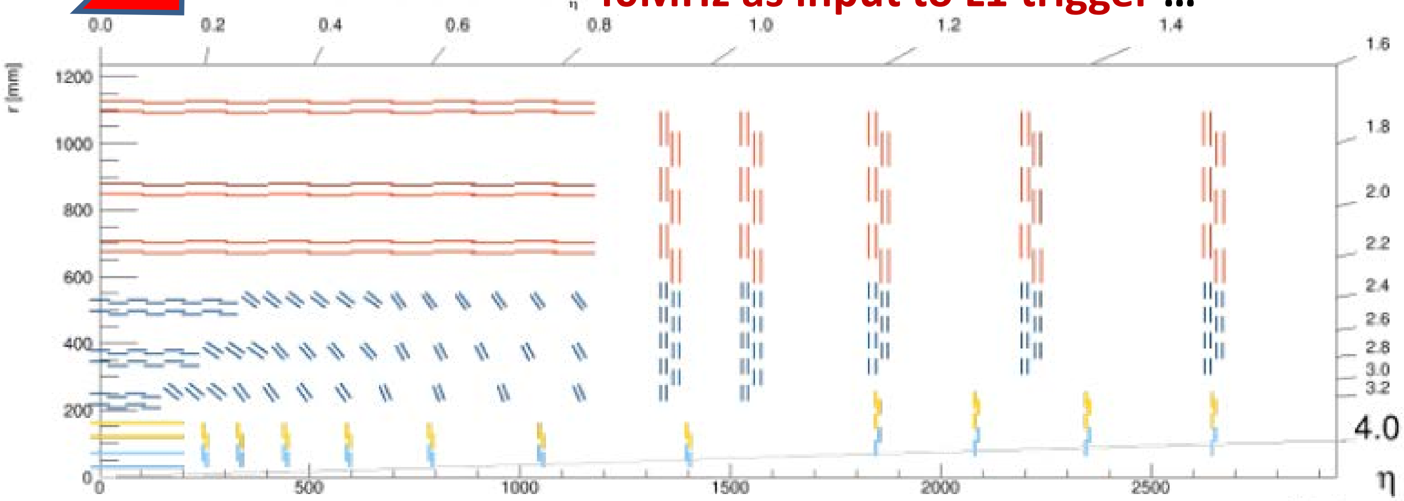
Interest in larger (8") wafers particularly for forward regions (and HGCAL)



Greatly reduced material in tracking volume

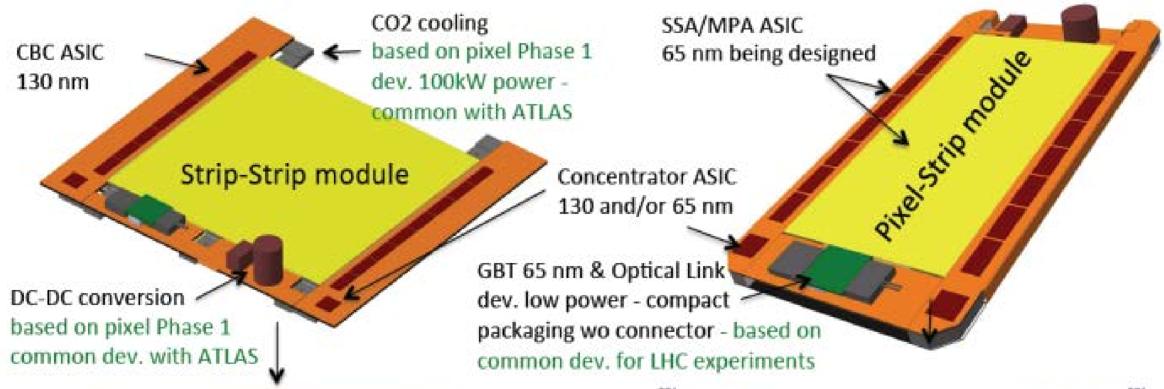
In CMS design driven by requirement to identify all tracks with P_T>2GeV at 40MHz as input to L1 trigger …

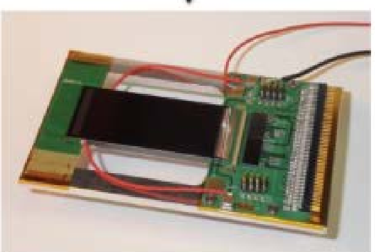


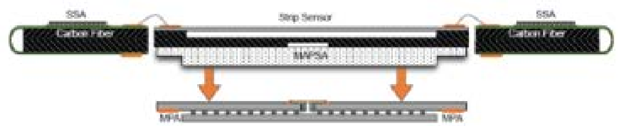


CMS Tracker Upgrade

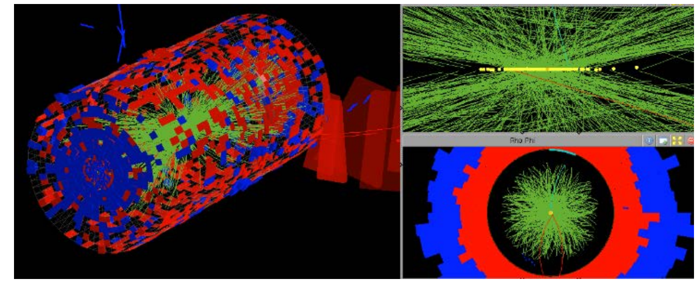
Paired layers with short strips (outer radii) and long pixels plus short strips (inner radii)

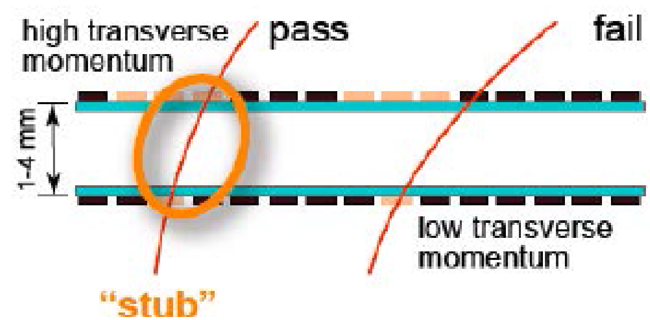






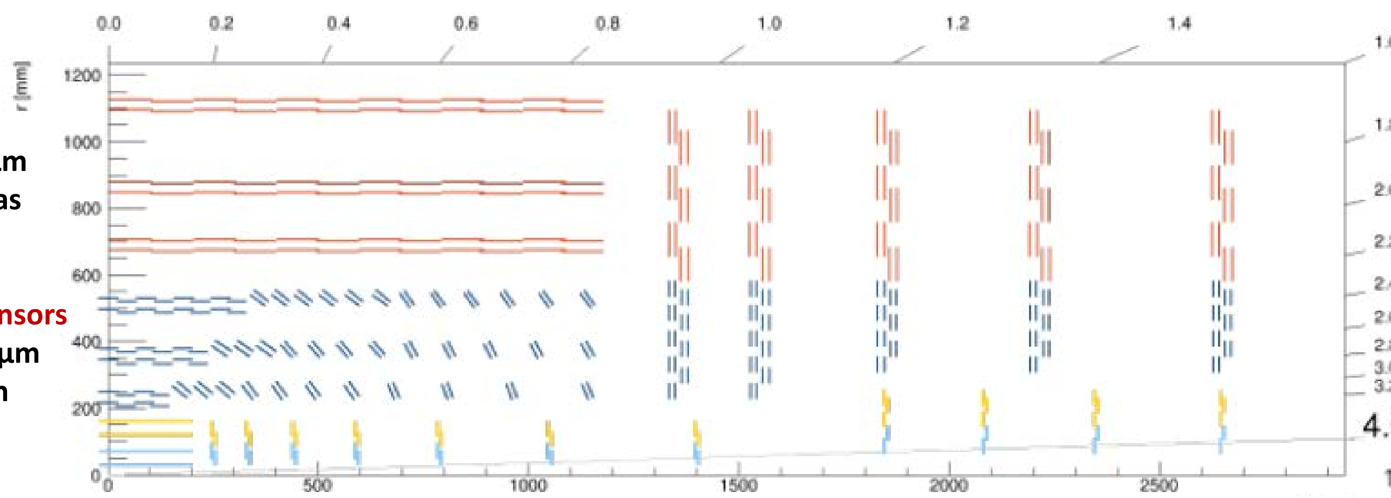
Flex hybrid - Flip-Chip assembly - possibly TSV for inter-chip connection





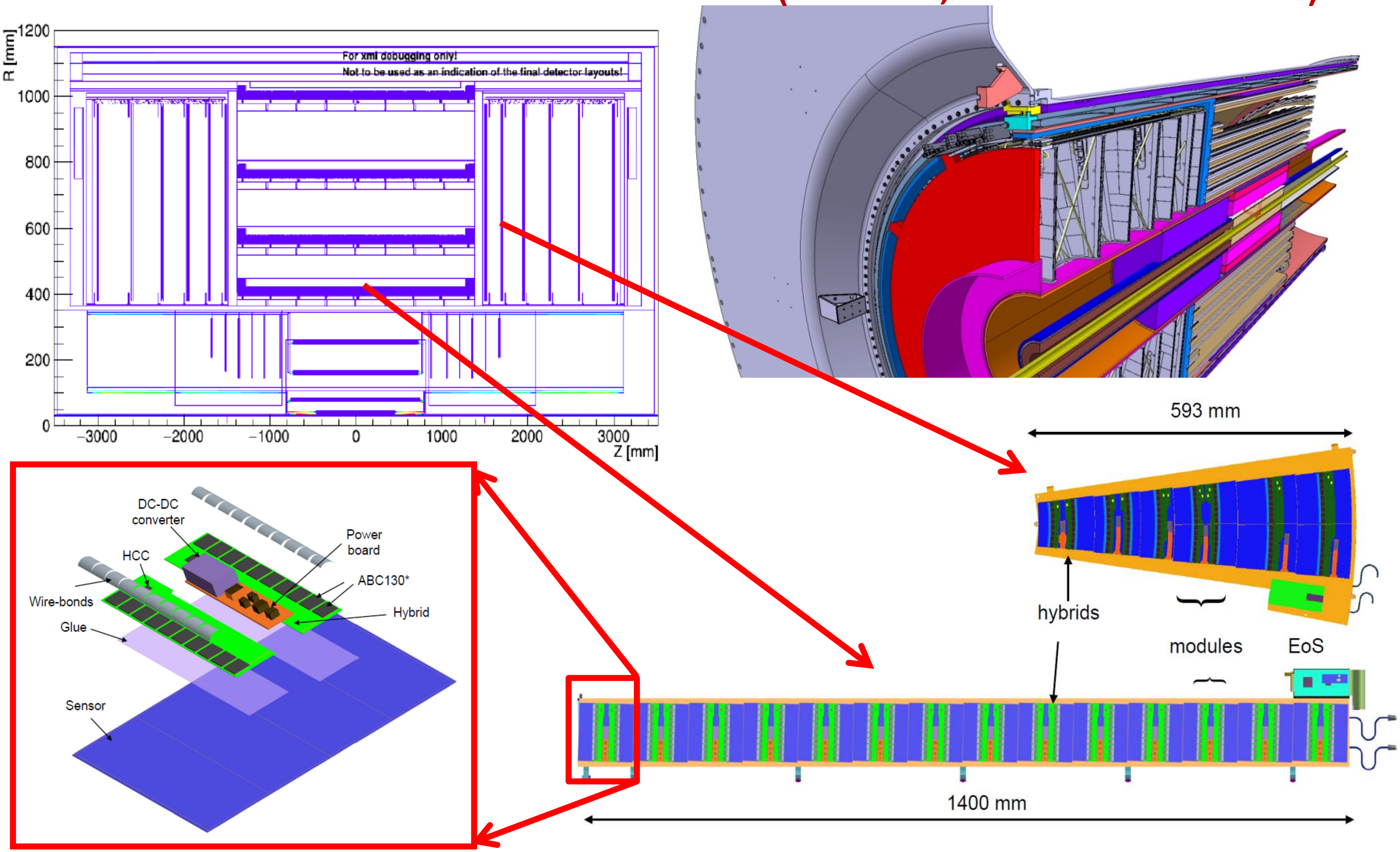
5cm x 10cm silicon strip sensors
- strips: length 2.5cm, pitch 100µm
- AC coupled with poly-silicon bias resistors

5cm x 10cm silicon macro-pixel sensors
- strips: length 1.5mm, pitch 100µm
- DC coupled with punch-through biasing



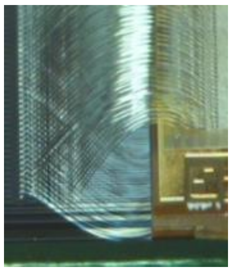
ATLAS Tracker Upgrade (ITk)

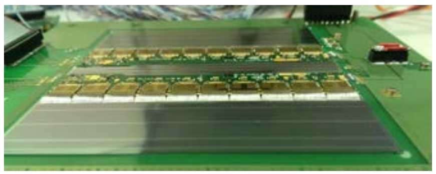
New All Silicon Inner Detector (200m^2, ~10^{10} channels)



ATLAS Tracker Upgrade (ITk)

Single-sided modules sandwiched around low mass structures

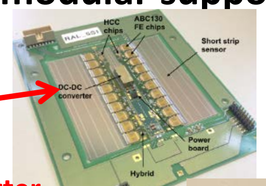




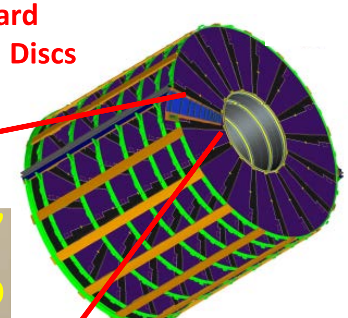
256 Channel ASICs (4 row wire bonding) in 130nm CMOS with L0/L1 functionality

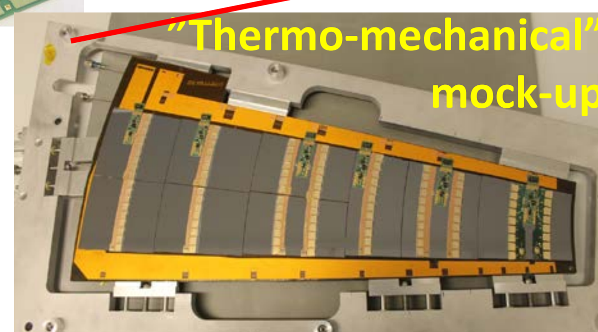
Powering (DC/DC strip, Serial pixel), HV multiplexing, CO_2 embedded cooling, low mass modular supports & services

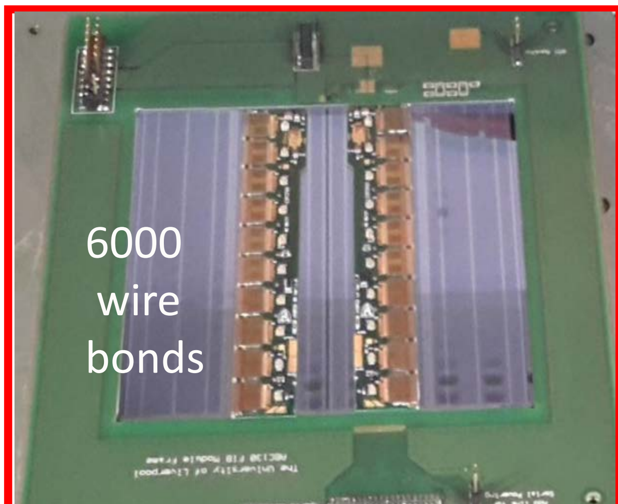
Module with on-board DC-DC converter

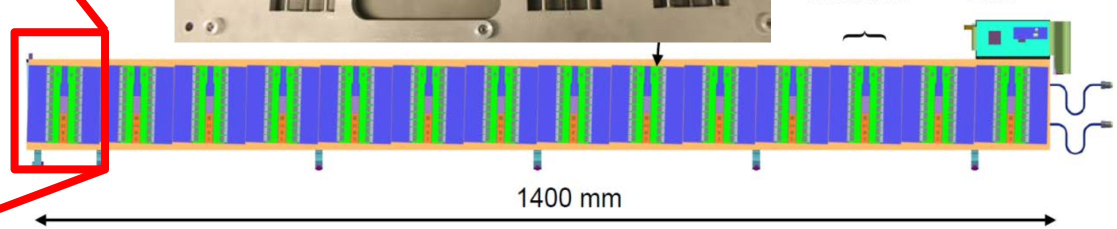


ATLAS Forward Wedges and Discs





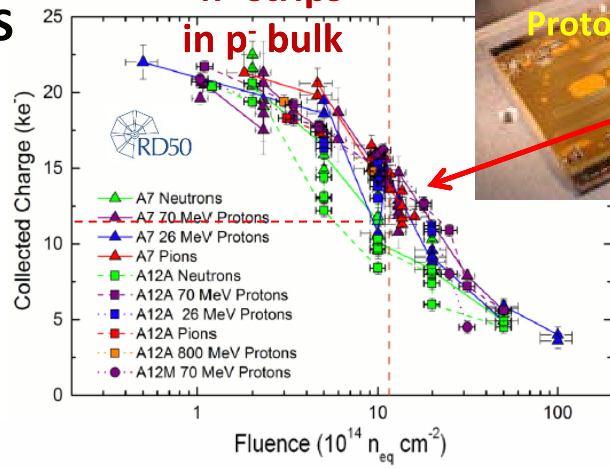


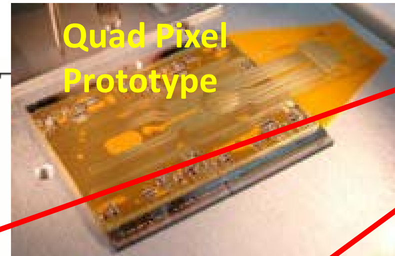


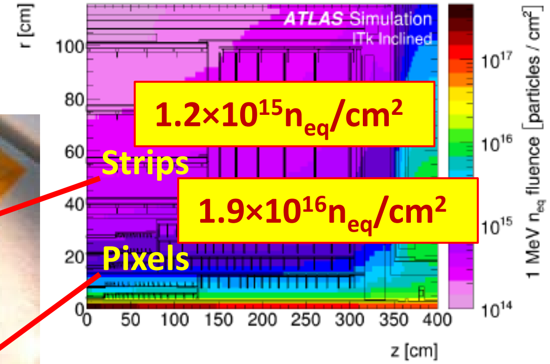
HL-LHC Radiation Hardness

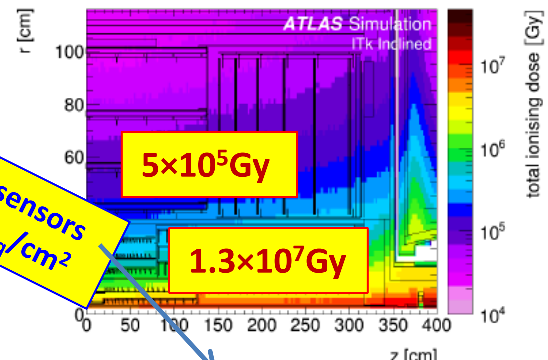
- Hybrid silicon detectors (pixels strips) efficient even at HL-LHC doses

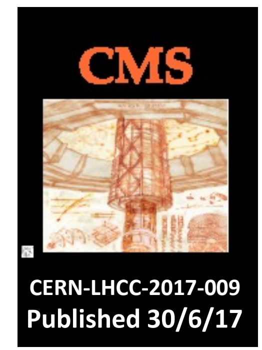
RD50
ATLAS
CMS
LHCb



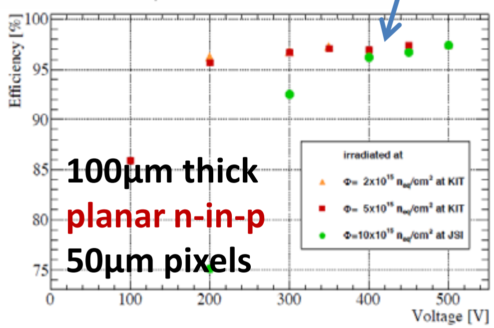


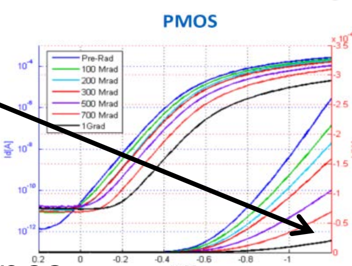


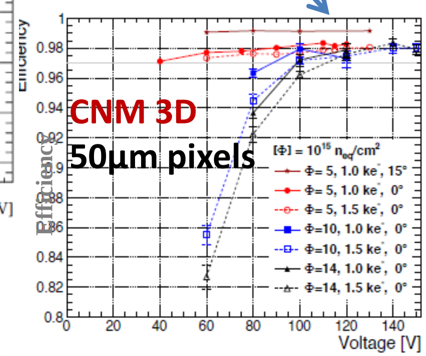


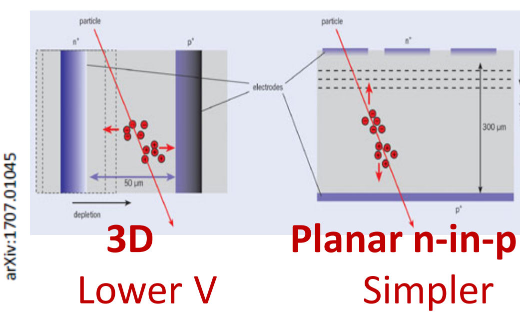


- For pixel layers: **microelectronics** (65nm CMOS - **RD53**) can start to see significant deterioration at **1Grad (=10^7Gy)** particularly in PMOS transistors with further temperature, bias and manufacturer dependence







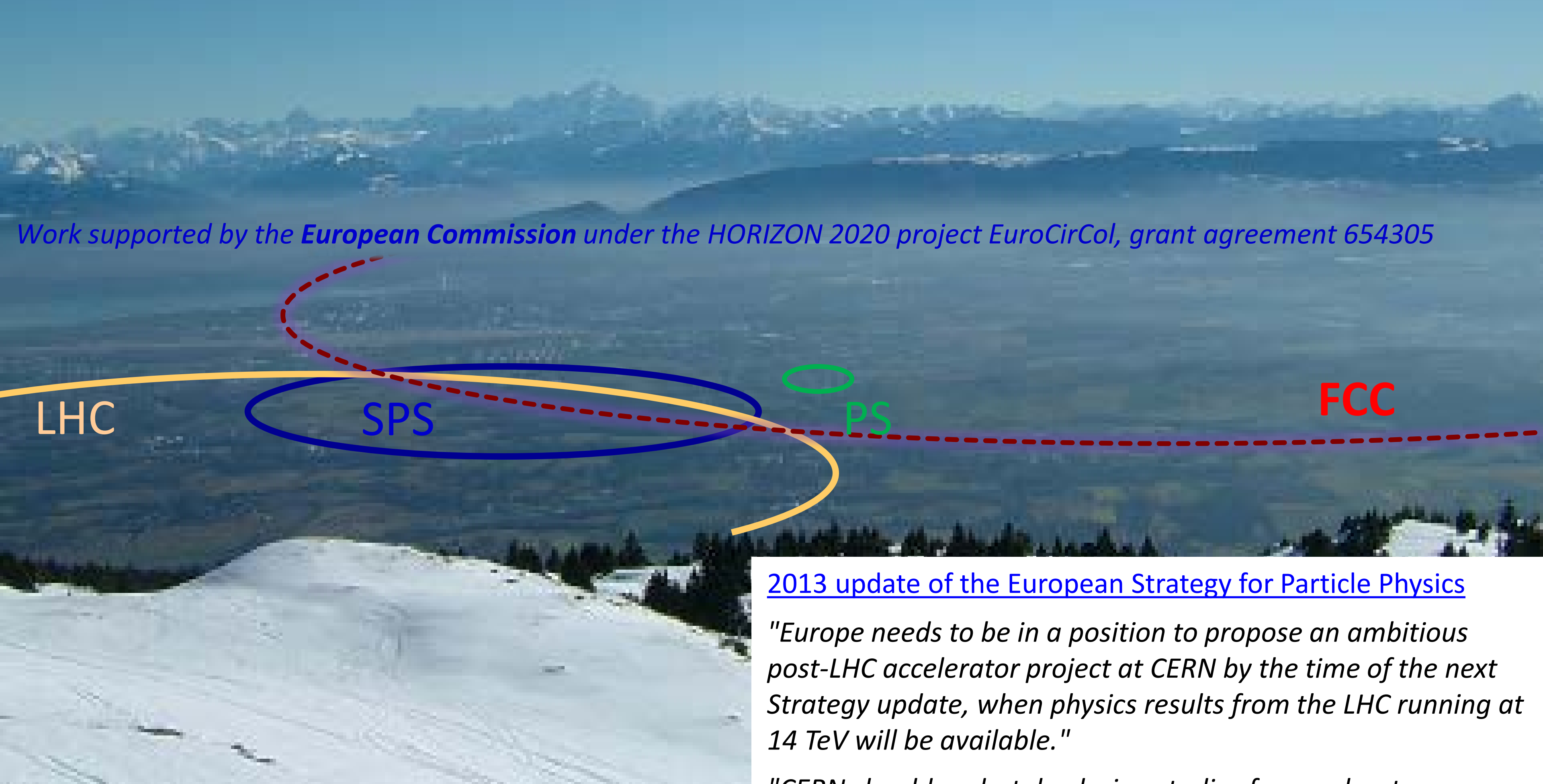


https://indico.cern.ch/event/468486/
Federico Faccio

→ **Also need rad-hard data links with up to ~40 hits/cm² each 25ns**

Future Circular Collider

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*



[2013 update of the European Strategy for Particle Physics](http://cern.ch/fcc)

"Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available."

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."

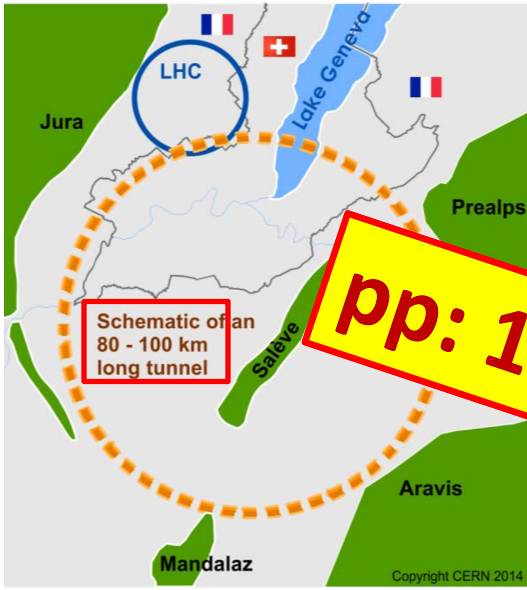
FCC hh ee he

EuroCirCol

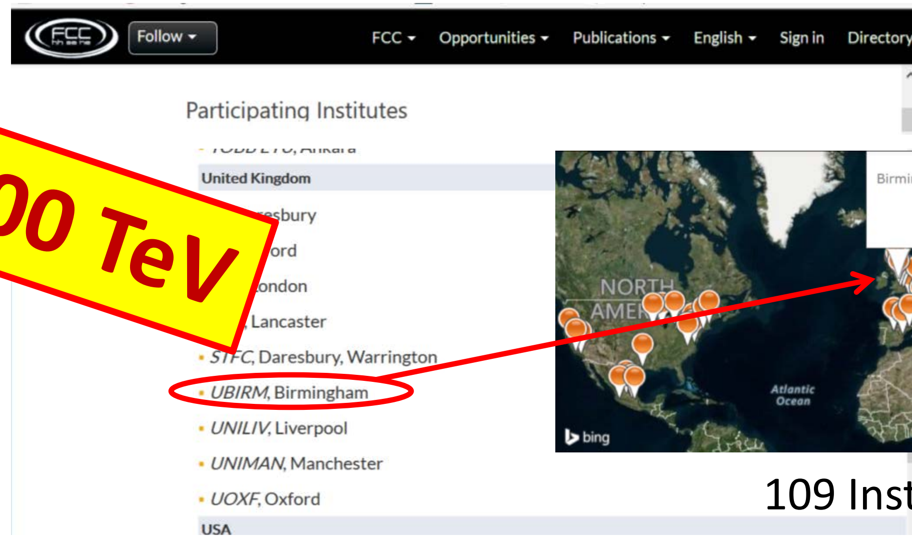
http://cern.ch/fcc

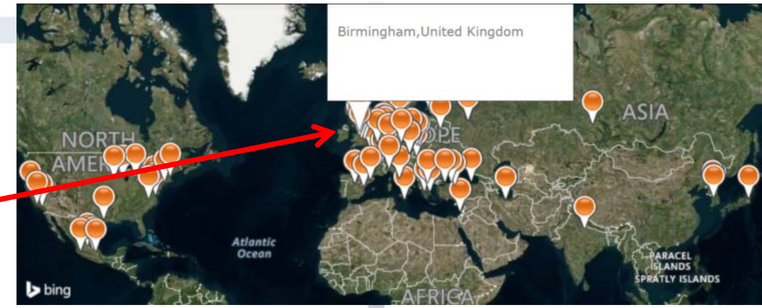
FCC Programme

hh: pp and AA
e^+e^-: Higgs factory
eh: ep/eA options

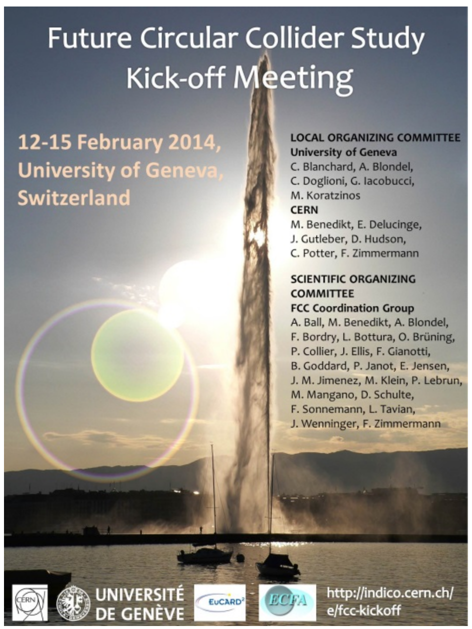


pp: 100 TeV





109 Institutes



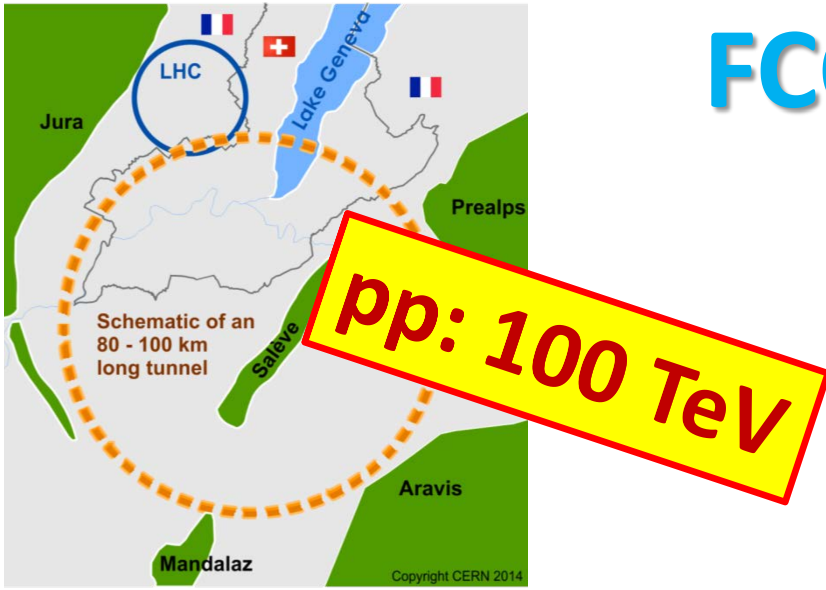
341 participants

468 participants

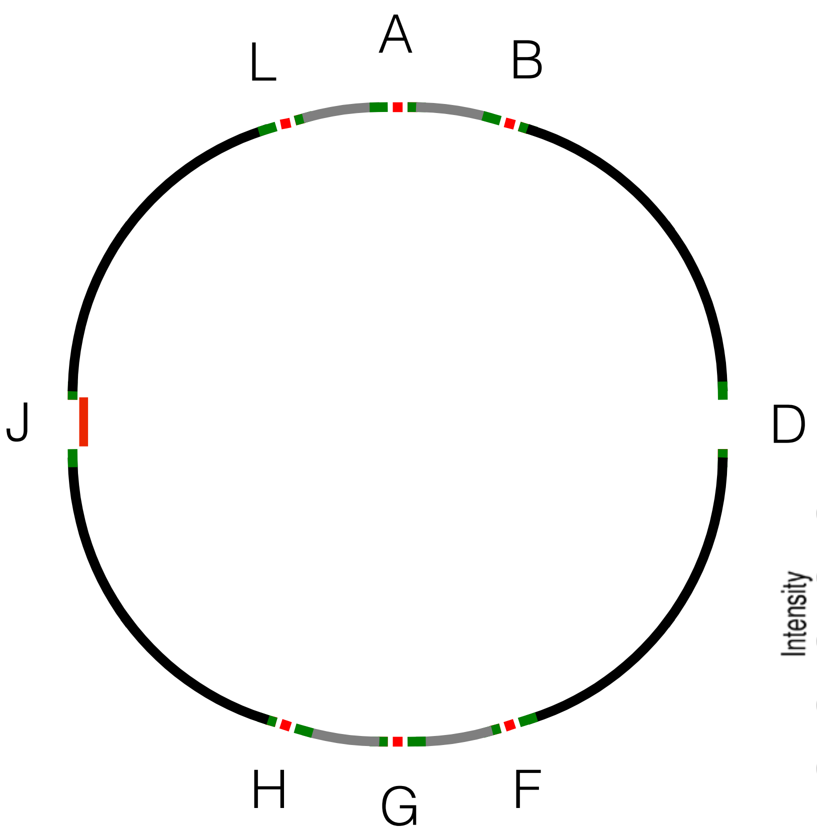
534 participants

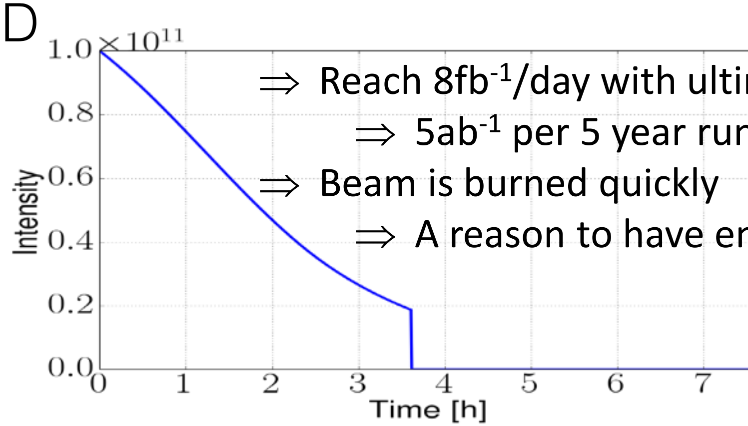
April 9-13 2018:
FCC week Amsterdam

FCC-hh Parameters



	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4





⇒ Reach $8fb^{-1}$/day with ultimate for 25ns spacing

⇒ $5ab^{-1}$ per 5 year run

⇒ Beam is burned quickly

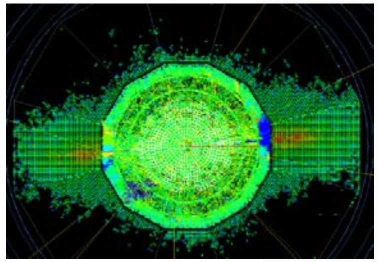
⇒ A reason to have enough charge stored

FCC-hh Detector Concept

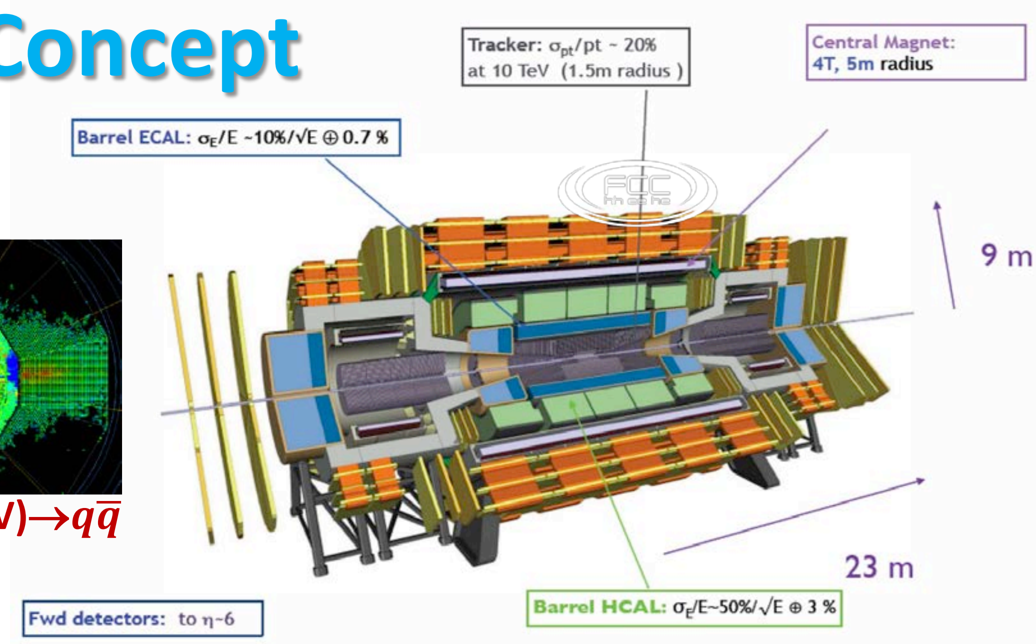
Baseline for Conceptual Design Review
https://fccw2017.web.cern.ch/

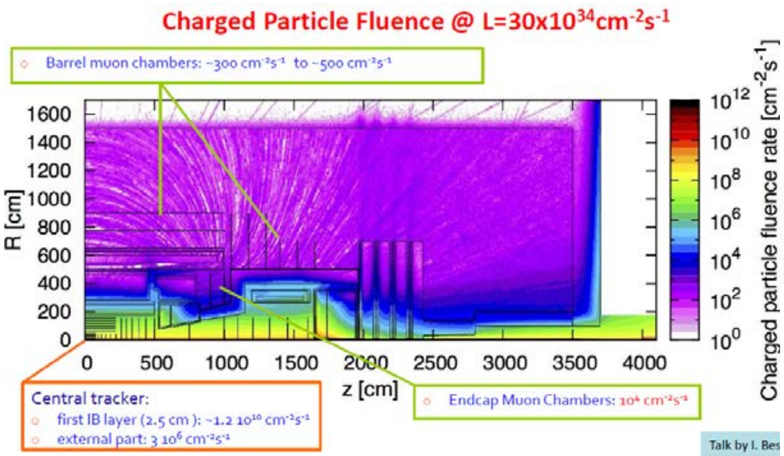
- 4T 10m solenoid
- Forward solenoids
- **Silicon** tracker
- Barrel ECAL **LAr/Si-W**
- Barrel HCAL Fe/**Sci**
- Endcap HCAL/ECAL **LAr**
- Forward HCAL/ECAL **LAr**

Other options explored

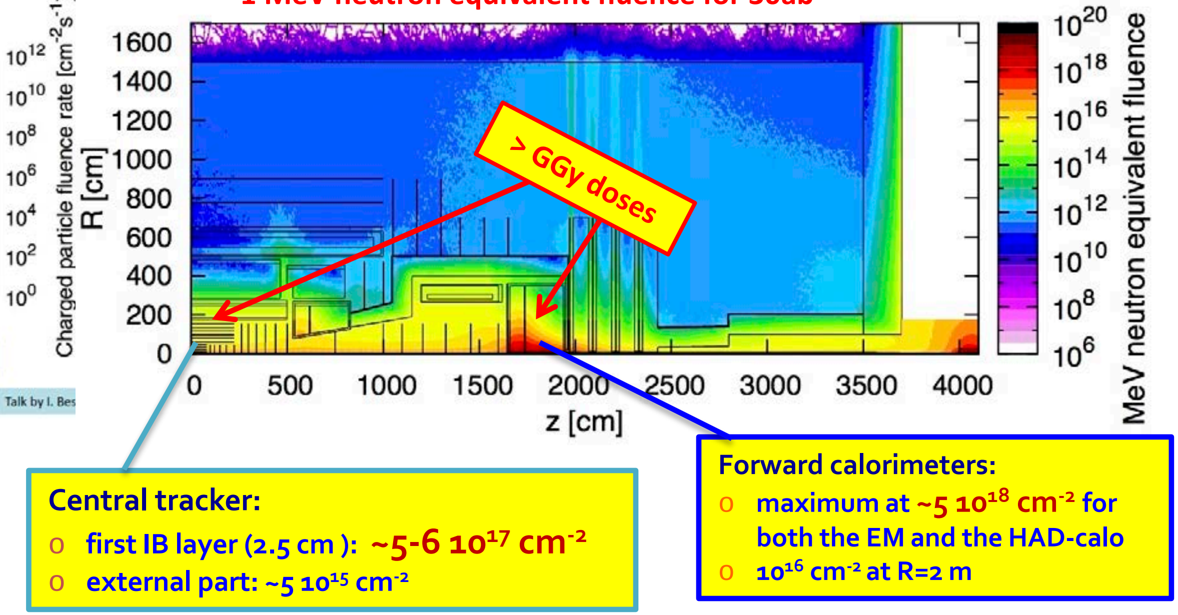


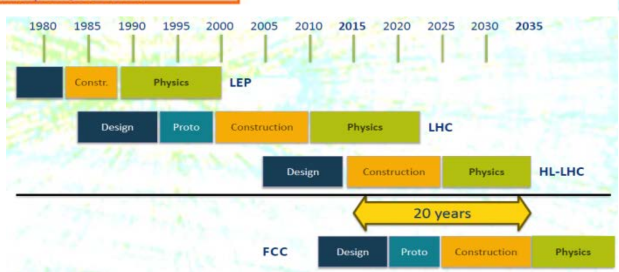
$Z'(40\text{TeV}) \rightarrow q\bar{q}$





1 MeV neutron equivalent fluence for $30ab^{-1}$





- 20 year R&D lead-times (concept → large arrays)

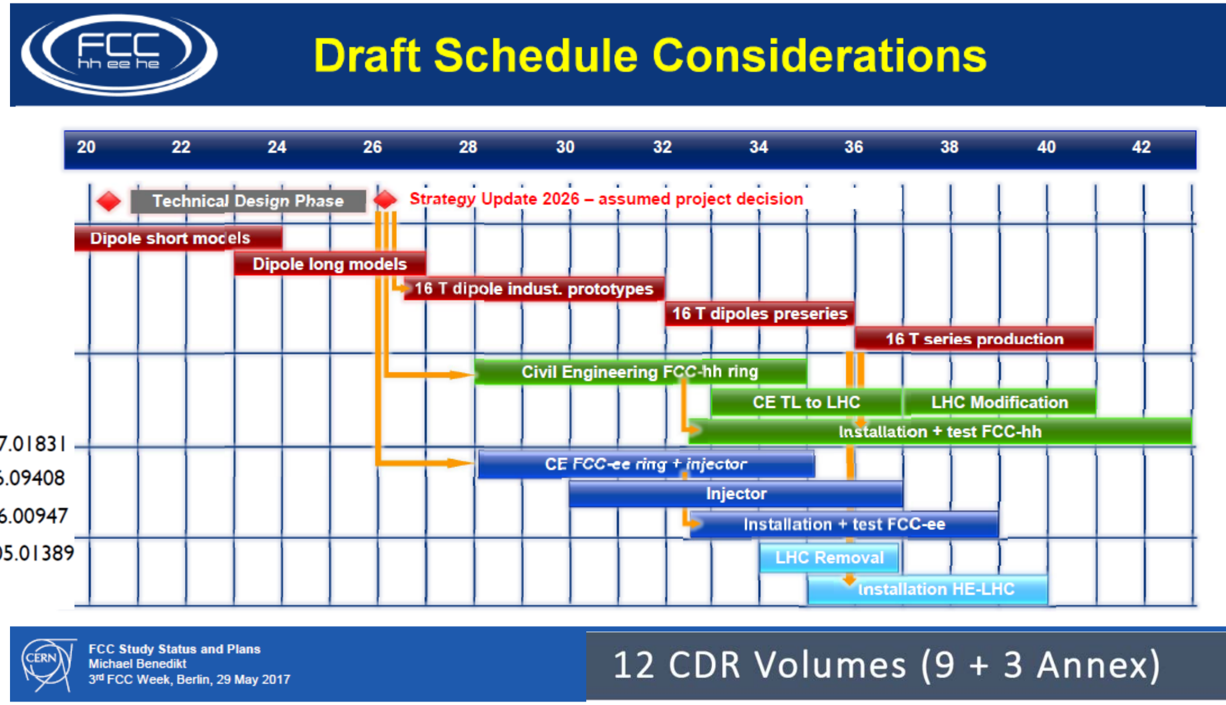
FCC Planning and Status

- Fastest "*technically feasible*" schedule
- Very/hopelessly optimistic schedule; scenario with no cash-flow limitations
- Not even consistent with HL-LHC schedule, but shows what could be achieved
- Physics and performance simulations prepared for Rome FCC Week

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages) arXiv:1607.01831
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages) arXiv:1606.09408
- **Volume 3: beyond the Standard Model phenomena** (189 pages) arXiv:1606.00947
- **Volume 4: physics with heavy ions** (56 pages) arXiv:1605.01389
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)



12 CDR Volumes (9 + 3 Annex)

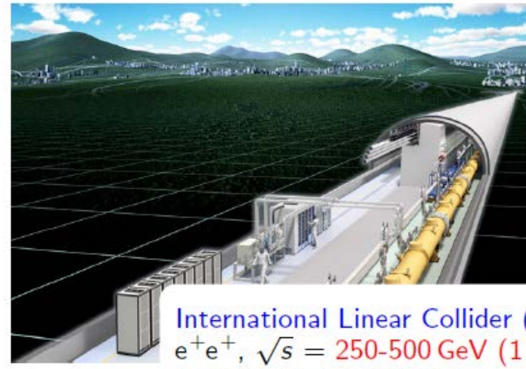
- Full Conceptual Design Review (CDR) driven by **European Strategy update in 2020**
- FCC-hh summary volume (100-200 pages) as well as the extensive FCC-hh comprehensive CDR volume "Experiment and Detectors" (>1000 pages)
- November 22nd 2018: Publication

Energy Frontier e^+e^- Facilities

2013 update of the European Strategy for Particle Physics

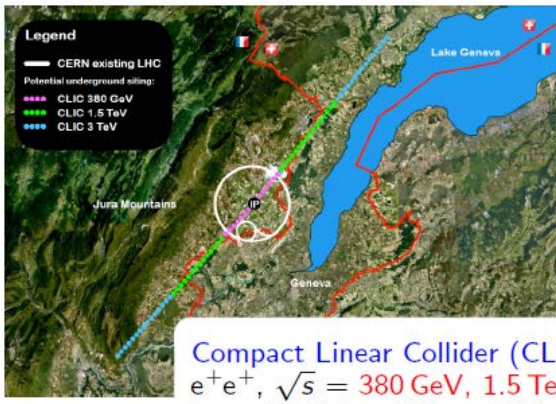
"There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded …. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation"

Circular Electron Positron Collider (CEPC)
e^+e^-, $\sqrt{s}$ = 240-250 GeV; SPPC pp,
Circumference: 54-100 km

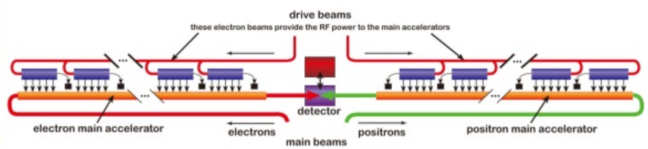


Future Circular Collider (FCC)
e^+e^-, $\sqrt{s}$ = 90-350 GeV;
pp, $\sqrt{s}$:~100 TeV
Circumference: 90-100 km

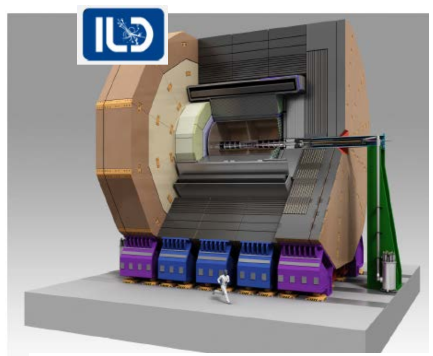
International Linear Collider (ILC)
e^+e^+, $\sqrt{s}$ = 250-500 GeV (1 TeV)
Length: 31 km (50 km)

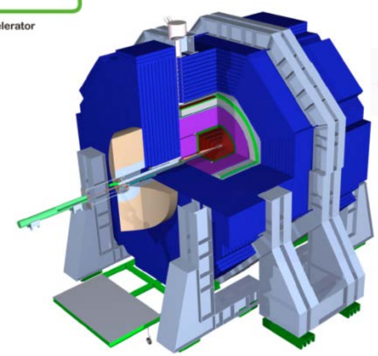


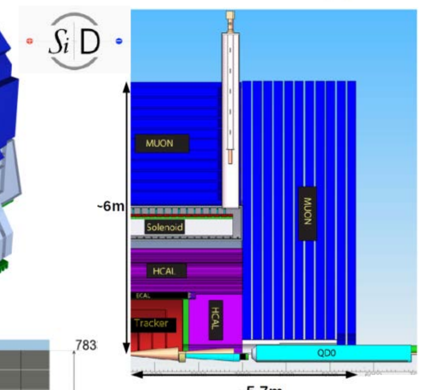
Compact Linear Collider

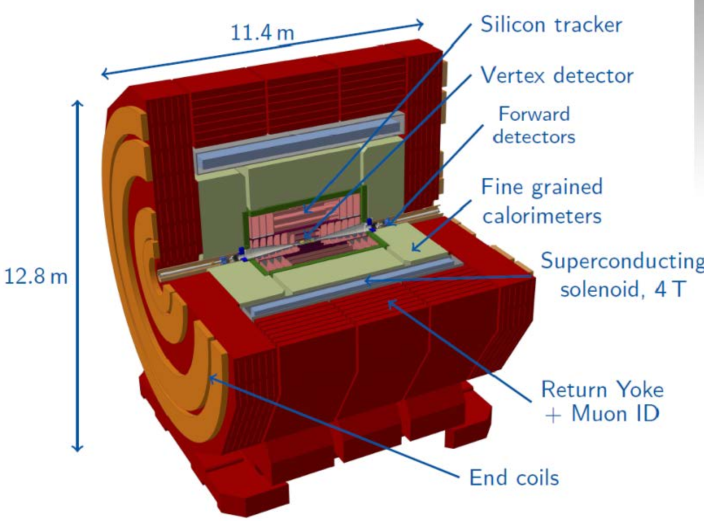


Compact Linear Collider (CLIC)
e^+e^+, $\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km

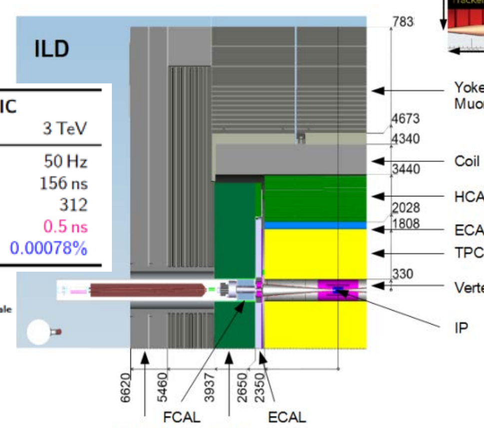


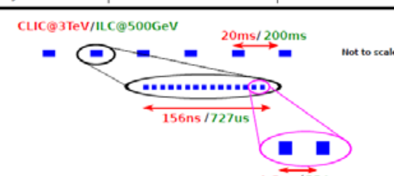






Property	ILC		CLIC	
$\sqrt{s}$	500 GeV	1 TeV	380 GeV	3 TeV
Repetition rate	5 Hz	4 Hz	50 Hz	50 Hz
Train duration	727 µs	897 µs	178 ns	156 ns
BX / train	1312	2450	356	312
Bunch separation	554 ns	366 ns	0.5 ns	0.5 ns
Duty cycle	0.36%	0.36%	0.00089%	0.00078%





ILC/CLIC Inspired Pixel Technologies

(See Vertex 2016 https://indico.cern.ch/event/452781/sessions/208678/#20160930)

- Demands of ultra-low mass, highest resolution, low power and fast time-stamp
- A wide range of technologies with many years of development:
  - DEPFET (see also BELLE-II)
  - FinePixel CCD
  - Thin Planar sensor or HV-CMOS Hybrid (C3PD)+CLICpix
  - Monolithic CMOS
    - Vertical integration with TSVs (FNAL 3D)
    - Chronopix
    - SoI for Fine Space and Time (SOFIST)
    - Monolithic Active Pixel Sensors (MAPS)
      - MIMOSA (developments since 2000 for ILC)

        → STAR Heavy Flavour Tracker (doi: 10.1016/j.phpro.2015.05.067)

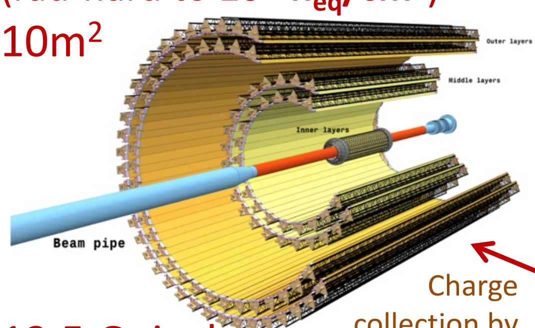
  → ALPIDE for ALICE Inner Tracker System Upgrade (ALICE-TDR-017)

  → Depleted MAPS (DMAPS): (large fill factor + deep-depletion or low fill factor = low C)

VERTEX 2016:
J Goldstein
A G Besson

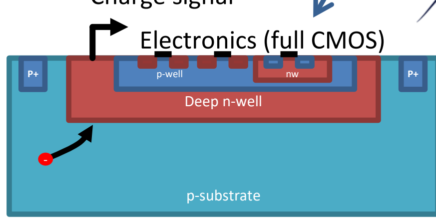
Spatial resolution: highly granular sensor:
$\sigma_{R\phi}$ ~ 3 μm (pitch ~ 20 μm)
multiple scattering : very low material budget:
$O(0.1\%X_0/\text{layer})$
Single bunch time resolution
→ 1st layer: ~ 5 part/cm²/BX → few % occupancy
Power dissipation ↔ preferably gas cooling
→ <130μW/mm² (Power cycling, ~3% duty cycle)

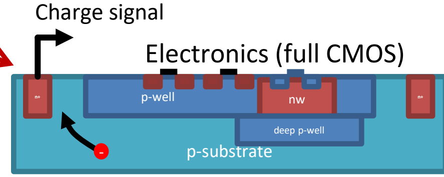
ALICE ITS (<30μs resolution)
(rad-hard to $10^{13} n_{eq}/cm^2$)
10m²



12.5 Gpixel

Charge collection by drift and diffusion

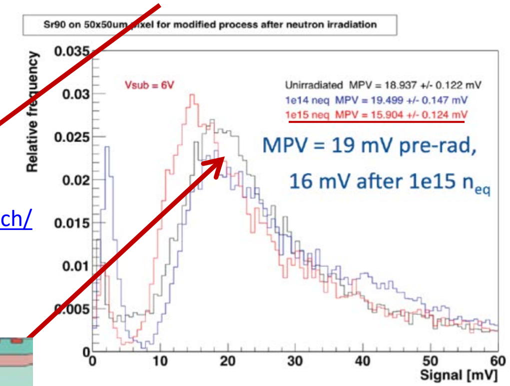




ATLAS

N. Wermes

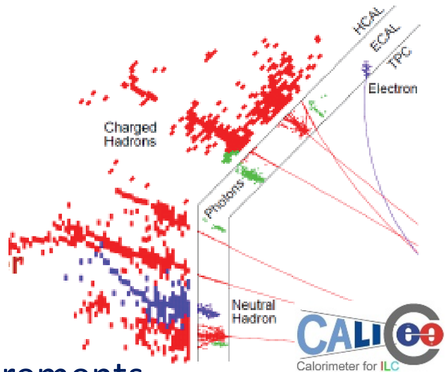
https://fccw2017.web.cern.ch/

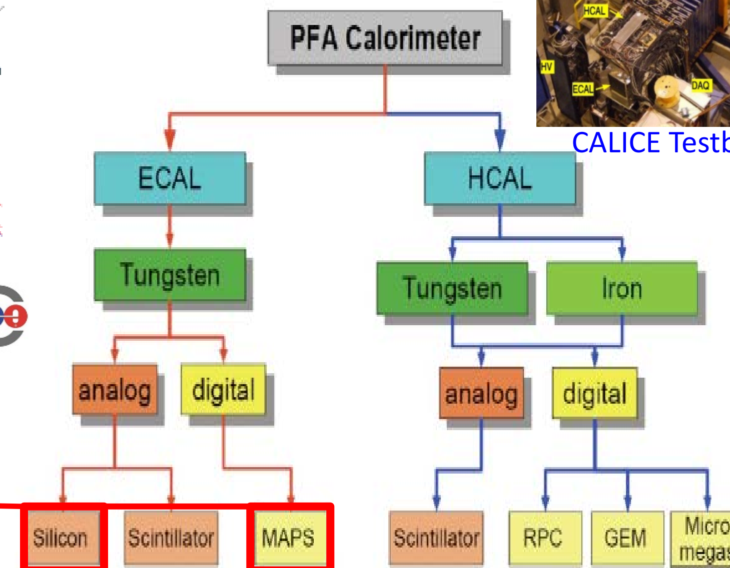


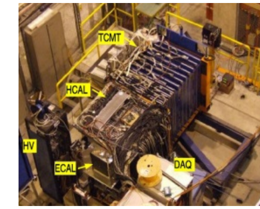
Both DMAPS approaches
Rad-hard to $>10^{15} n_{eq}/cm^2$

Calorimetry and Particle Flow

- **CALICE** (Calorimeter for *ILC*)
  - Fundamental concept:
    - Particle flow
    - Associate energy deposits with charged particles
    - → Drives granularity requirements
    - Allows "tracking" of neutrals





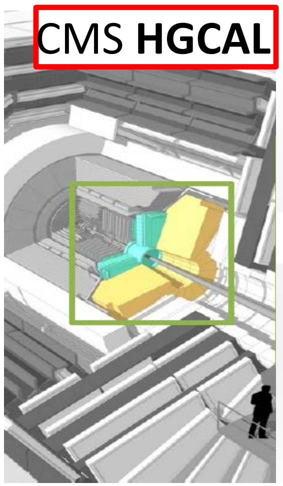


CALICE Testbeam

- ALICE **FoCAL**
  - Tungsten-Silicon sampling EM Calorimeter

FCC-hh?

- CMS **HGCAL**



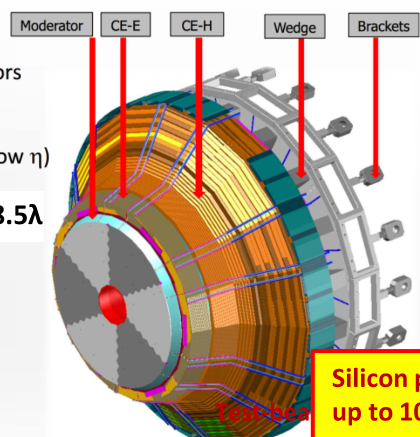
Main characteristics:

EC-E - 28 active layers, silicon sensors
EC-H - 24 active layers
8 silicon sensor
16 silicon (high η) + scint (low η)

ECAL: 25 X_0, ~1.3λ; HCAL: 8.5λ

EC-E total weight =18.5t
EC-H Absorbers material:
St.Steel, weight = 170t
Front Shielding weight = 0.8t

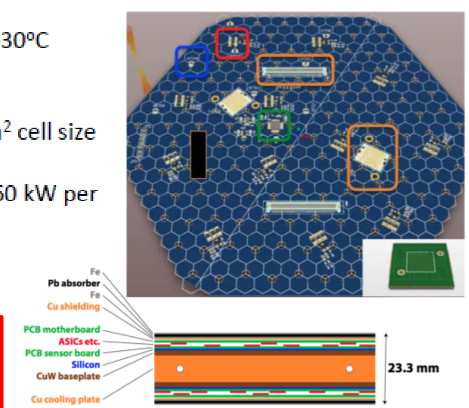
Total weight of Endcap = 253t



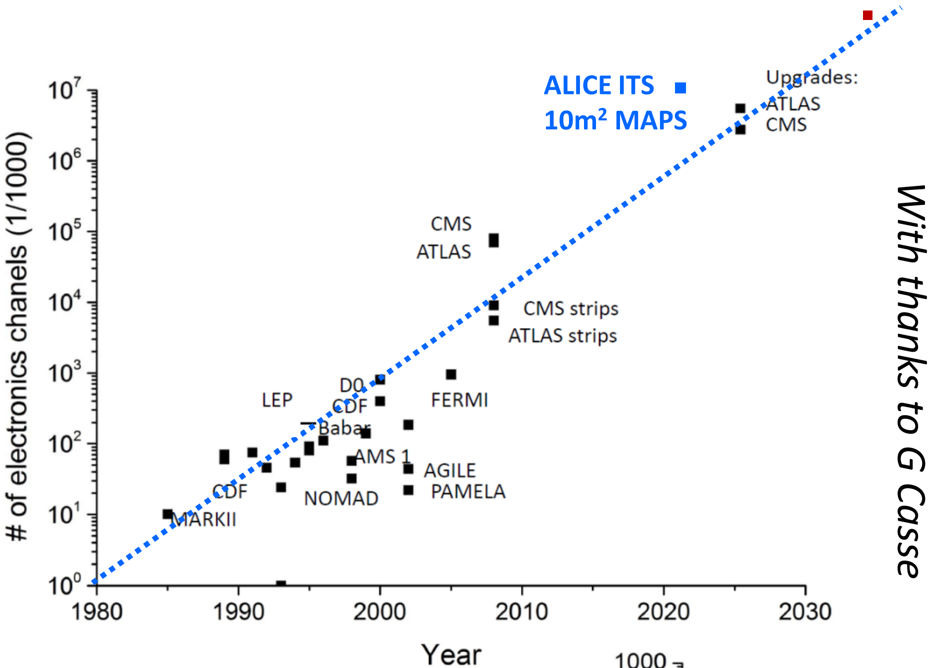
Key Parameters:

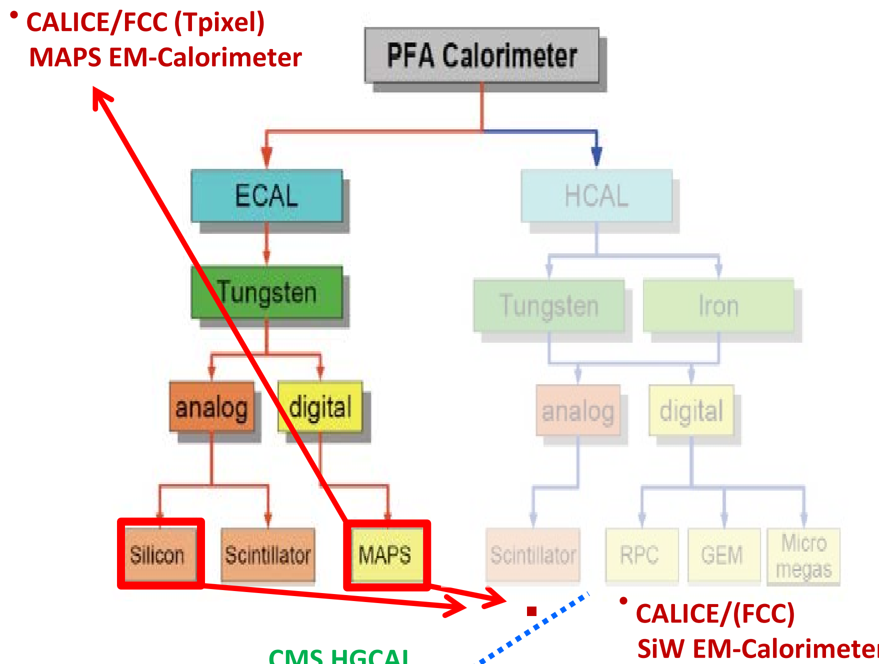
- EC covers 1.5 < η < 3.0
- Full system maintained at -30ºC
- ~600m² of silicon sensors
- ~500m² of scintillators
- 6M si channels, 0.5 or 1 cm² cell size
- ~22000 si modules
- Power at end of HL-LHC: ~60 kW per endcap

Silicon pads to withstand doses up to 10^{16}n/cm² and several MGy

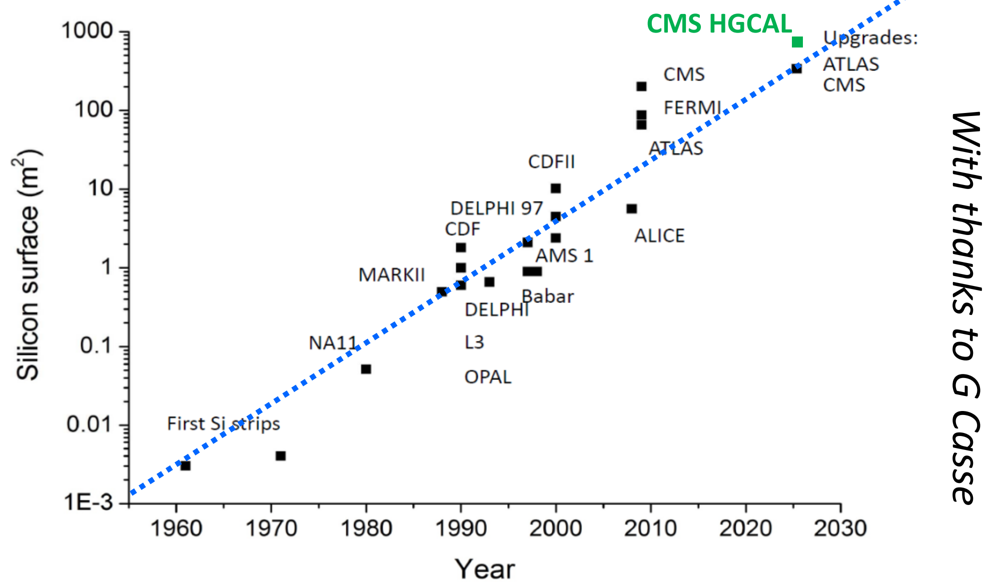


Silicon Based Detector Evolution

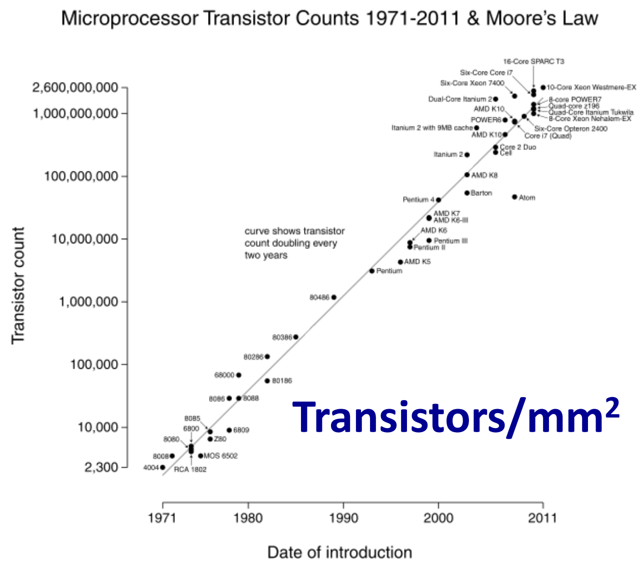


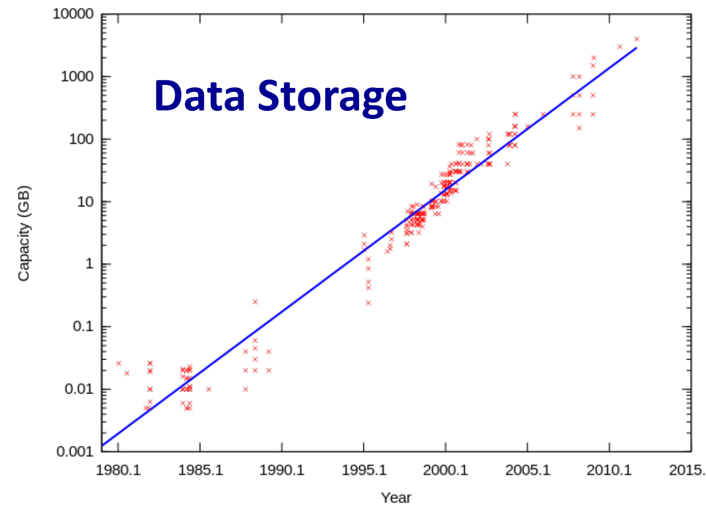


Need detector costs to scale with Moore's law.
For sensors, more likely with fully commercial processes such as CMOS Imaging Sensors (MAPS) as used in mobile phones, cameras etc.
(Need « $/cm²)

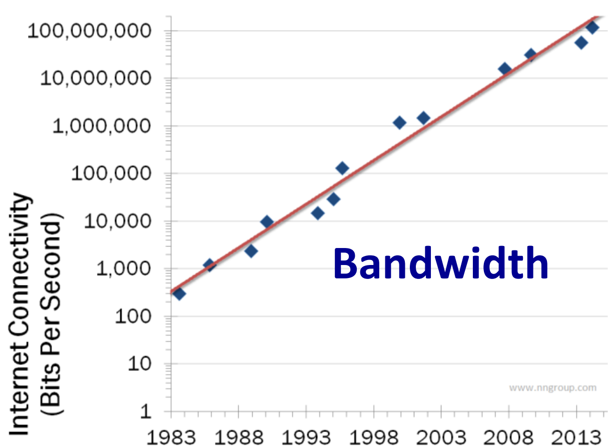


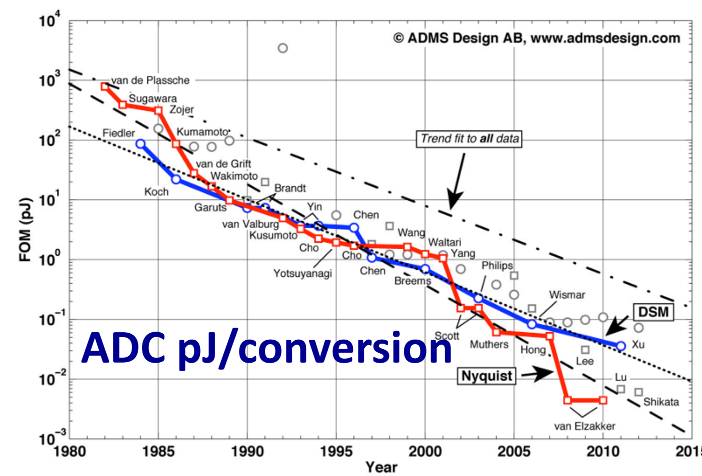
Microelectronics/Computing Evolution





With thanks to W Riegler





All these figures showed doubling times of < 2 years up to now. Some scalings will stop, but different improvements conceivable. Can still hope for major detector improvements and enhanced TDAQ plus computing capabilities. However, storage and CPU costs not expected to continue to scale this fast.

Accelerator and Reactor Neutrinos

https://en.wikipedia.org/wiki/List_of_neutrino_experiments gives over 50 experiments (but this list does include neutrinoless ββ decay and neutrino observatories)

Abbreviation	Full name	Sensitivity[a]	Type	Induced reaction	Type of reaction[b]	Detector	Type of detector	Threshold energy	Location	Operation	Home page
UNO	Underground Nucleon decay and neutrino Observatory	S, ATM, GSN, RSN	ν_e, ν_μ, ν_τ	$\nu_e + e^- \to \nu_e + e^-$	ES	Water (440 kt H_2O)	Cherenkov		Henderson Mine, Colorado	*future*	[50] (http://ale.physics.sunysb.edu/uno/)
T2K	Tokai to Kamioka	AC	ν_e, ν_μ $\bar{\nu}_e, \bar{\nu}_\mu$	$\nu_e + n \to e^- + p\ (+\pi, +X)$ $\nu_\mu + n \to \mu^- + p\ (+\pi, +X)$ $\bar{\nu}_e + p \to e^+ + n\ (+\pi, +X)$ $\bar{\nu}_\mu + p \to \mu^+ + n\ (+\pi, +X)$	CC (NC)	Water (H_2O)	Cherenkov	200 MeV	Tokai, Japan Kamioka, Japan	2011-	[49] (http://t2k-experiment.org)
SuperNEMO	SuperNEMO	BB	ν_e	$^{100}Se \to {}^{100}Kr + 2e^-$ $^{150}Nd \to {}^{150}Sm + 2e^-$	BB	Tracker + calorimeter	He+Ar wire chamber, plastic scintillators	150 keV	Modane Underground Laboratory, Fréjus Road Tunnel, France	2017-	[48] (http://nemo.in2p3.fr/nemow3/)
Super-K	Super-Kamiokande	S, ATM, GSN	ν_e, ν_μ, ν_τ	$\nu_e + e^- \to \nu_e + e^-$ $\nu_e + n \to e^- + p$ $\bar{\nu}_e + p \to e^+ + n$	ES CC CC	Water (H_2O)	Cherenkov	200 MeV	Kamioka, Japan	1996–	[46] (http://neutrino.phys.washington.edu/~superk/) [47] (http://www-sk.icrr.u-tokyo.ac.jp/sk/index_e.html)
STEREO	Short baseline Oscillation Search with LS Detector	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \to e^+ + n$	CC	liquid organic scintillator loaded with Gd	Scintillation	≈2 MeV	Grenoble, France	2013-	
SoLid	Short baseline Oscillation Search with Lithium-6 Detector	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \to e^+ + n$	CC	plastic and anorganic scintillator	Scintillation	≈2 MeV	Mol, Belgium	2015-	
SNO+	SNO with liquid scintillator	S,LS,R,T, SN,LSN	ν_e	$\nu_x + e^- \to \nu_x + e^-$ $\bar{\nu}_e + p \to e^+ + n$	ES, BB	linear alkylbenzene (LAB) + PPO	Scintillation	≈≲1MeV	Creighton Mine, Ontario	2014–	[45] (http://www.sno.phy.queensu.ca/)
SNO	Sudbury Neutrino Observatory	S, ATM, GSN	ν_e, ν_μ, ν_τ	$\nu_e + {}^2D \to 2p + e^-$ $\nu_x + {}^2D \to \nu_x + n + p$ $\nu_e + e^- \to \nu_e + e^-$	CC NC ES	Heavy water (1 kt D_2O)	Cherenkov	3.5 MeV	Creighton Mine, Ontario	1999–2006	[44] (http://www.sno.phy.queensu.ca/)
SciBooNE	SciBar (Scintillator Bar) Booster Neutrino Experiment	AC	ν_μ	$\nu_\mu + {}^{12}C \to \mu^- + X$	CC, NC	Plastic (CH,10 ton)	Scintillation	≈100 keV	Illinois, United States	2007–2008	[43] (http://www-sciboone.fnal.gov)
SAGE	Soviet–American Gallium Experiment	LS	ν_e	$\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$	CC	$GaCl_3$	Radiochemical	233.2 keV	Baksan Valley, Russia	1990–2006	[42] (http://ewi.npl.washington.edu/SAGE/sage.html)
RENO	Reactor Experiment for Neutrino Oscillation	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \to e^+ + n$	CC	Gd-doped LOS	Scintillation	1.8 MeV	South Korea	2011–	
OPERA	Oscillation Project with Emulsion-tRacking Apparatus	AC	ν_τ	ν_τ+nucleus $\to \tau^-$+X	CC	Lead/Emulsion	Nuclear Emulsion	≈1.0 GeV	LNGS (Italy) and CERN	2008–	[41] (http://operaweb.lngs.infn.it/)
NOvA	NuMI Off-Axis ν_e Appearance	AC	ν_e, ν_μ	ν_e+nucleus $\to e^-$+X	CC	Liquid scintillator	Scintillation	≈0.1 GeV	Illinois and Minnesota, United States	2011–	[40] (http://www-nova.fnal.gov)
NEVOD	Cherenkov water detector NEVOD	ATM, CR	ν_μ	$\nu_\mu + n \to \mu^- + p$ $\bar{\nu}_\mu + p \to \mu^+ + n$	CC	Water (H_2O)	Cherenkov	≈2 GeV	Moscow, Russia	1993–	[39] (http://www.nevod.mephi.ru/English/index.htm)
NEMO-3	Neutrino Ettore Majorana Observatory	BB	ν_e	$^{100}Mo \to {}^{100}Ru + 2e^-$ $^{100}Se \to {}^{100}Kr + 2e^-$	BB	Tracker + calorimeter	He+Ar wire chamber, plastic scintillators	150 keV	Modane Underground Laboratory, Fréjus Road Tunnel, France	2003–2011	[36] (http://nemo.in2p3.fr/nemow3/)
NEMO Telescope	NEutrino Mediterranean Observatory								Mediterranean Sea, Italy	2007–	[38] (http://nemoweb.lns.infn.it)
MOON	Molybdenum Observatory Of Neutrinos	LS, LSN	ν_e	$\nu_e + {}^{100}Mo \to {}^{100}Tc + e^-$	CC	^{100}Mo (1 kt) + MoF6 (gas)	Scintillation	168 keV	Washington, United States		[37] (http://ewi.npl.washington.edu/moon/)
MINOS+	Upgraded electronics for MINOS	AC, ATM	ν_e, ν_μ,	ν_μ+nucleus $\to \mu^-$+X	CC, NC	Solid scintillator	Scintillation	≈0.5 GeV	Illinois and Minnesota, United States	2013–	[35] (http://www-numi.fnal.gov/MinosPlus/minosPlus.html)
MINOS	Main Injector Neutrino Oscillation Search	AC, ATM	ν_e, ν_μ	ν_μ+nucleus $\to \mu^-$+X	CC, NC	Solid scintillator	Scintillation	≈0.5 GeV	Illinois and Minnesota, United States	2005–2012	[34] (http://www-numi.fnal.gov)
MiniBooNE	Mini Booster Neutrino Experiment	AC	ν_e, ν_μ	$\nu_e + {}^{12}C \to e^- + X$	CC	Mineral oil (1000 t)	Cherenkov	≈100 keV	Illinois, United States	2002–	[33] (http://www-boone.fnal.gov)
MINERvA	Main Injector ExpeRiment for ν-A	AC	ν_μ	many	CC, NC	Solid scintillator, targets of Liquid helium, Carbon, Water, Iron, Lead	Scintillation	≈0.5 GeV	Illinois, United States	2009–	[32] (http://minerva.fnal.gov/)
MicroBooNE		AC, SN	ν_e, ν_μ		ES, NC, CC	Liquid Argon	TPC	few MeV	Illinois, United States	2014-	[31] (http://www-microboone.fnal.gov/)
Majorana Demonstrator	The Majorana Demonstrator	BB	$\bar{\nu}_e$	$^{76}Ge \to {}^{76}As + e^- + e^-$	BB	HPGe	Semiconductor	2039 keV	Homestake Mine, South Dakota	*construction start* 2012	[30] (http://majorana.npl.washington.edu/)
LENS	Low Energy Neutrino Spectroscopy	LS	ν_e	$\nu_e + {}^{115}In \to {}^{115}Sn + \nu_e + 2\gamma$	CC	In-doped LOS	Scintillation	120 keV			[28] (http://www.phys.vt.edu/~lens/) [29] (http://lens.in2p3.fr/)
LBNE/DUNE	Long-Baseline Neutrino Experiment / Deep Underground Neutrino Experiment								Homestake Mine (South Dakota)	*future*	[27] (http://lbne.fnal.gov/)
LAGUNA	Large Apparatus studying Grand									*future*	[26] (http://www.laguna-science.eu/)

Abbreviation	Full name	Sensitivity[a]	Type	Induced reaction	Type of reaction[b]	Detector	Type of detector	Threshold energy	Location	Operation	Home page
	Unification and Neutrino Astrophysics										
KM3NeT	KM3 Neutrino Telescope	S, ATM, CR, SN, AGN, PUL	ν_μ, ν_e, ν_τ			Sea water (≈5 km^3)	Cherenkov		Mediterranean Sea	[25] (http://www.km3net.org)	
KamLAND	Kamioka Liquid Scintillator Antineutrino Detector	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \to e^+ + n$	CC	LOS	Scintillation	1.8 MeV	Kamioka, Japan	2002–	[24] (http://www.awa.tohoku.ac.jp/KamLAND/)
Kamiokande	Kamioka Nucleon Decay Experiment	S, ATM	ν_e	$\nu + e^- \to \nu + e^-$	ES	Water (H_2O)	Cherenkov	7.5 MeV	Kamioka, Japan	1986–1995	[23] (http://www-sk.icrr.u-tokyo.ac.jp/doc/kam/index.html)
JUNO	Jiangmen Underground Neutrino Observatory	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \to e^+ + n$	CC	LAB (LOS) + PPO + Bis-MSB	Scintillation		Kaiping, China	2014– (construction)	[22] (http://english.ihep.cas.cn/rs/fs/juno0815/)
India-based Neutrino Observatory	Iron Calorimeter Detector @ India-based Neutrino Observatory	ATM	ν_μ	ν_μ+Fe→μ^-+X	CC (dominant), NC	Magnetised iron (50 kton)	RPC active detector elements	≈0.6 GeV	Theni, Tamil Nadu, India	2012– (lab construction); 2018– (detector operation)	[21] (http://www.ino.tifr.res.in/ino/)
IceCube	IceCube Neutrino Detector	ATM, CR, AGN, ?	ν_e, ν_μ, ν_τ	$\nu + N \to \nu$ + Cascade , $\nu + N \to$ Charged lepton + Cascade	CC, NC	Water ice (1 km^3)	Cherenkov	≈10 GeV	South Pole, Antarctica	2006–	[20] (http://icecube.wisc.edu/)
ICARUS	Imaging Cosmic And Rare Underground Signal	S, ATM, GSN	ν_e, ν_μ, ν_τ	$\nu + e^- \to \nu + e^-$	ES	Liquid Ar	Cherenkov	5.9 MeV	Gran Sasso, Italy	2010–	[19] (http://icarus.lngs.infn.it)
HOMESTAKE–IODINE	Homestake iodine experiment	S	ν_e	$\nu + e^- \to \nu + e^-$ $\nu_e + {}^{127}I \to {}^{127}Xe + e^-$	ES CC	NaI in water	Radiochemical	789 keV	Homestake Mine, South Dakota	*future*	[18] (http://www-spires.dur.ac.uk/cgi-bin/spiface/find/experiments/www2?rawcmd=fin+expt+homestake)
HOMESTAKE–CHLORINE	Homestake chlorine experiment	S	ν_e	$^{37}Cl + \nu_e \to {}^{37}Ar^* + e^-$ $^{37}Ar^* \to {}^{37}Cl + e^+ + \nu_e$	CC	C_2Cl_4 (615 t)	Radiochemical	814 keV	Homestake Mine, South Dakota	1967–1998	[17] (http://www-spires.dur.ac.uk/cgi-bin/spiface/find/experiments/www2?rawcmd=fin+expt+homestake)
HERON	Helium Roton Observation of Neutrinos	LS	ν_e (mainly)	$\nu_e + e^- \to \nu_e + e^-$	NC	Superfluid He	Rotational excitation	1 MeV		*future*	[16] (http://www.physics.brown.edu/physics/researchpages/cme/heron/LTD_home.html)
HALO	Helium And Lead Observatory	SN	ν_e, ν_x	$\nu_e + {}^{208}Pb \to e^- + {}^{208}Bi^*$ $\nu + {}^{208}Pb \to \nu + {}^{208}Pb^*$	CC, NC	Lead (79 t) and ^3He	High-Z	≈10 MeV	Creighton Mine, Ontario	2012–	[15] (https://www.snolab.ca/halo/)
GNO	Gallium Neutrino Observatory	LS	ν_e	$\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$	CC	$GaCl_3$ (30 t)	Radiochemical	233.2 keV	Gran Sasso, Italy	May 1998–Jan 2002	[14] (http://www.lngs.infn.it/lngs_infn/contents/lngs_en/research/experiments_scientific_info/experiments/past/gno/)
GERDA	The GERmanium Detector Array	BB	$\bar{\nu}_e$	$^{76}Ge \to {}^{76}As + e^- + e^-$	BB	HPGe	Semiconductor		Gran Sasso, Italy		[13] (http://www.mpi-hd.mpg.de/gerda/)
GALLEX	GALLium EXperiment	LS	ν_e	$\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$	CC	$GaCl_3$ (30 t)	Radiochemical	233.2 keV	Gran Sasso, Italy	1991–1997	[12] (http://www.mpi-hd.mpg.de/nuastro/gallex.html)
EXO-200	Enriched Xenon Observatory			$^{134}Xe \to {}^{134}Ba + e^- + e^-$ $^{136}Xe \to {}^{136}Ba + e^- + e^-$	BB	Liquid Xenon			WIPP, New Mexico	2009-	[11] (http://www-project.slac.stanford.edu/exo/)
Double Chooz	Double Chooz Reactor Neutrino Experiment	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \to e^+ + n$	CC	Gd-doped LOS	Scintillation	1.8 MeV	Chooz, France	2011–	[10] (http://doublechooz.in2p3.fr/)
Daya Bay	Daya Bay Reactor Neutrino Experiment	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \to e^+ + n$	CC	Gd-doped LAB (LOS)	Scintillation	1.8 MeV	Daya Bay, China	2011–	[9] (http://dayawane.ihep.ac.cn/)
COBRA	Cadmium zinc telluride 0-neutrino double-Beta Research Apparatus			$^{64}Zn + e^- \to {}^{64}Ni + e^-$ $^{70}Zn \to {}^{70}Ge + e^- + e^-$ $^{106}Cd \to {}^{106}Pd + e^+ + e^+$ $^{108}Cd + e^- + e^- \to {}^{108}Pd$ $^{114}Cd \to {}^{114}Sn + e^- + e^-$ $^{116}Cd \to {}^{116}Sn + e^- + e^-$ $^{120}Te + e^- \to {}^{120}Sn + e^+$ $^{128}Te \to {}^{128}Xe + e^- + e^-$ $^{130}Te \to {}^{130}Xe + e^- + e^-$	BB	Cadmium zinc telluride			Gran Sasso, Italy	2007–	[8] (http://www.cobra-experiment.org/)
CLEAN	Cryogenic Low-Energy Astrophysics with Neon	LS, SN, WIMP	ν_e	$\nu_x + e^- \to \nu_x + e^-$ $\nu_e + {}^{20}Ne \to \nu_e + {}^{20}Ne$	ES ES	Liquid Ne (10 t)	Scintillation			*future*	[7] (http://mckinseygroup.physics.yale.edu/publications/CLEAN.pdf)
BOREXINO	BORon EXperiment	LS	ν_e	$\nu_x + e^- \to \nu_x + e^-$	ES	LOS shielded by water	Scintillation	250–665 keV	Gran Sasso, Italy	May 2007–	[5] (http://www.ge.infn.it/borexino/) [6] (http://borex.lngs.infn.it/)
BDUNT (NT-200+)	Baikal Deep Underwater Neutrino Telescope	S, ATM, LS, AGN, PUL	ν_e, ν_μ, ν_τ		CC, NC	Water (H_2O)	Cherenkov	≈10 GeV	Lake Baikal, Russia	1993–	[4] (http://baikalweb.jinr.ru/)
ARIANNA	Antarctic Ross Ice-Shelf ANtenna Neutrino Array	S, CR, AGN, ?	ν_e, ν_μ, ν_τ						Ross Ice Shelf, Antarctica	future	[3] (http://arianna.ps.uci.edu)
ANTARES	Astronomy with a Neutrino Telescope and Abyss Environmental RESearch	ATM, CR, AGN, PUL	ν_e, ν_μ, ν_τ						Mediterranean Sea, France	2006–	[2] (http://antares.in2p3.fr/index.html)
ANNIE	Accelerator Neutrino Neutron Interaction Experiment								SciBooNE Hall, Illinois, United States	*future*	[1] (http://annie.uchicago.edu/doku.php)

Accelerator and Reactor Neutrinos

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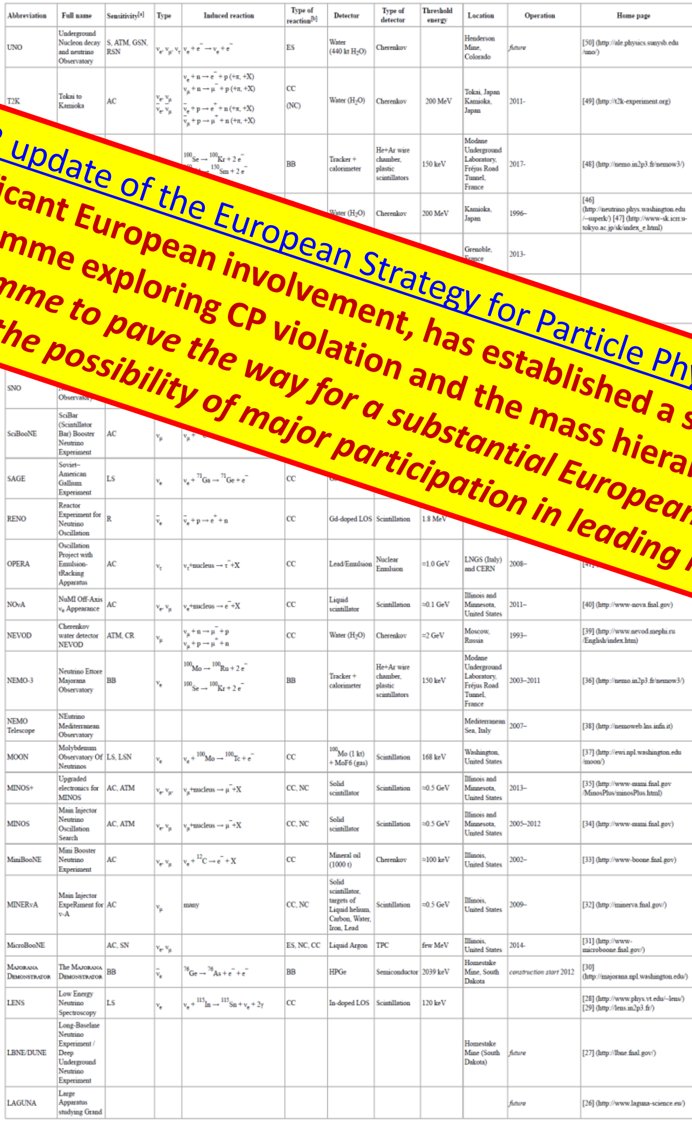
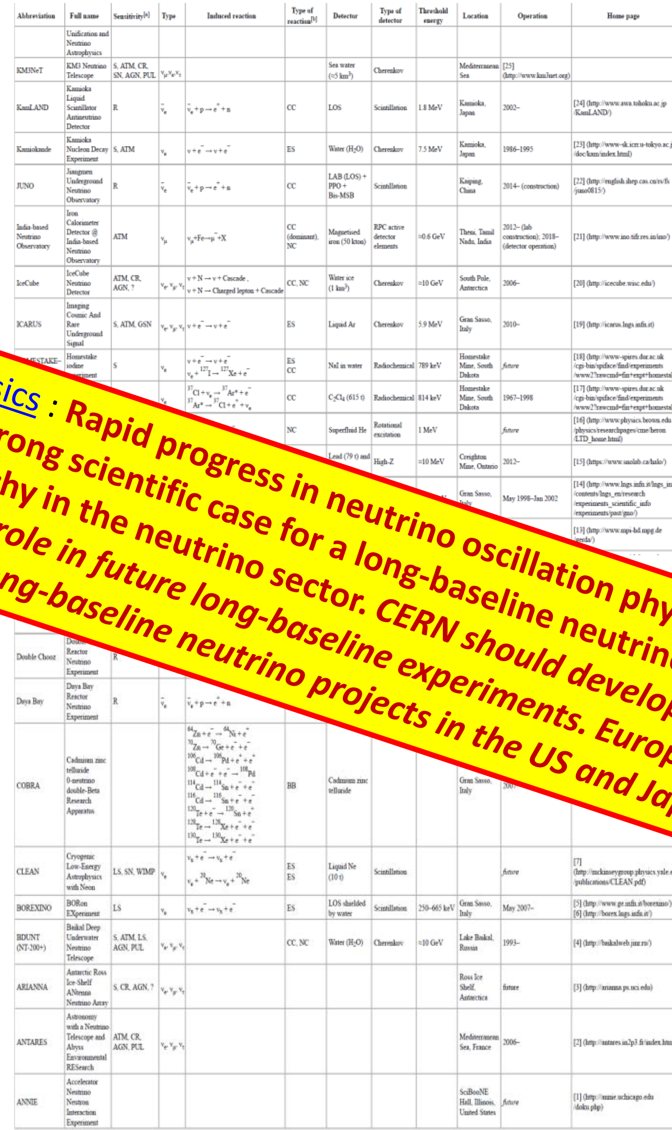
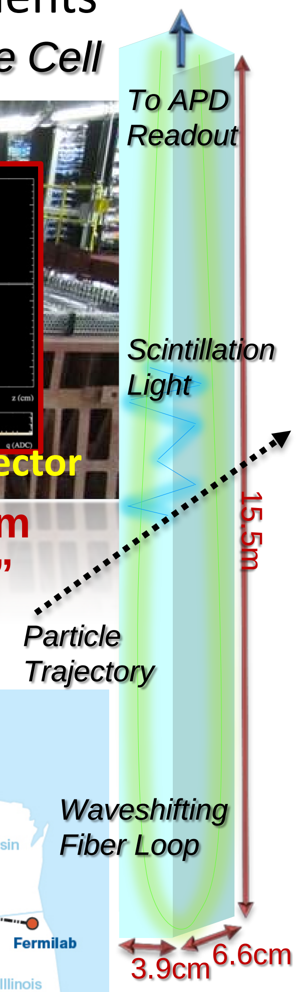


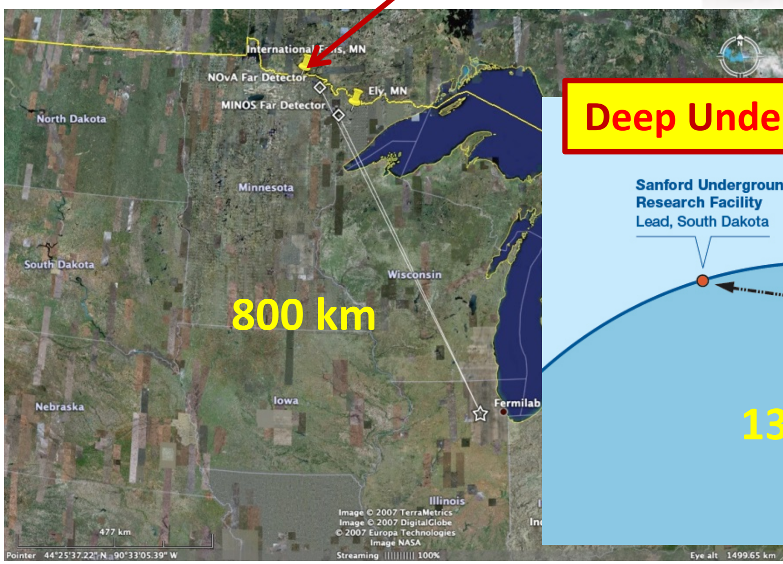


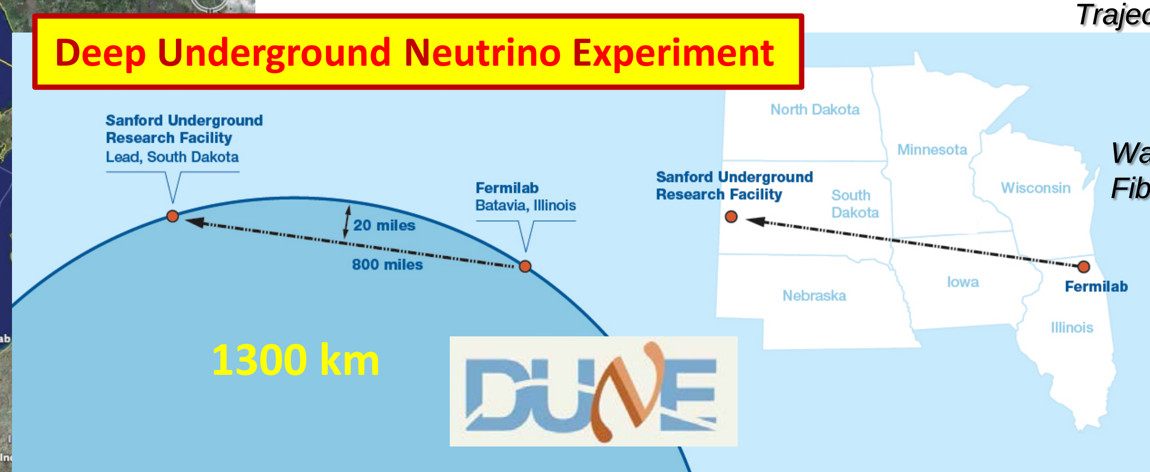
[2013 update of the European Strategy for Particle Physics](#) : Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

Long Baseline Neutrino Detectors

- The issue of scale associated with current and future neutrino experiments introduces a very different set of challenges:





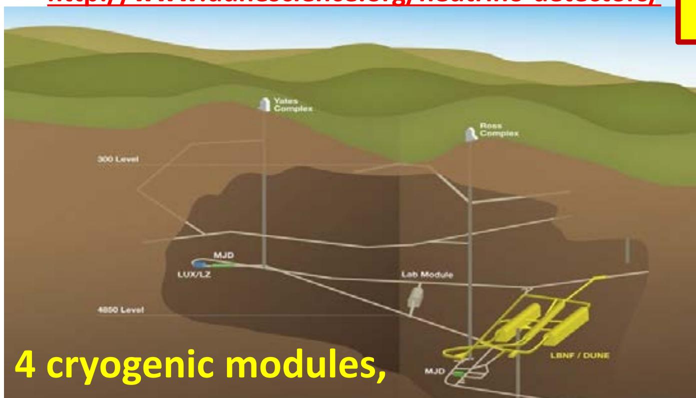


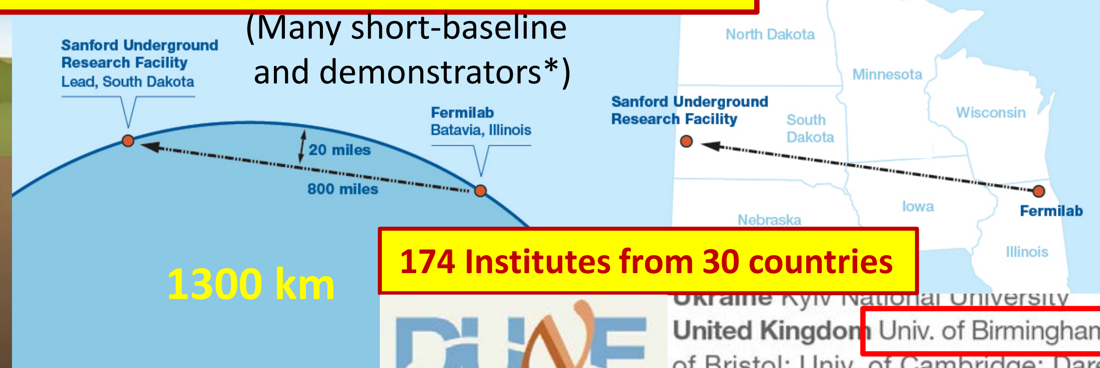
Long Baseline Neutrino Detectors

http://www.dunescience.org/neutrino-detectors/

Deep Underground Neutrino Experiment

(Many short-baseline and demonstrators*)



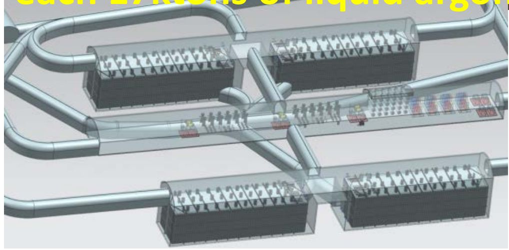


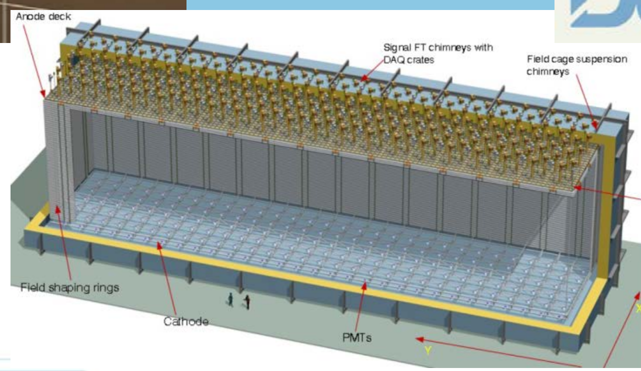
1300 km

174 Institutes from 30 countries

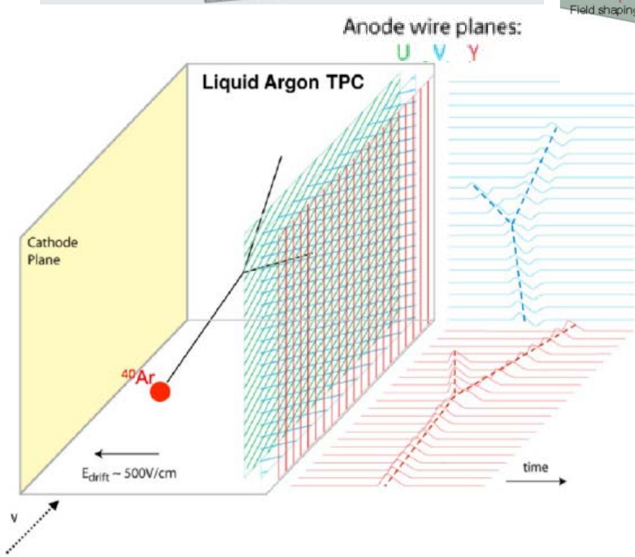
United Kingdom Univ. of Birmingham; Univ. of Bristol; Univ. of Cambridge; Daresbury Laboratory; Univ. of Durham; Imperial

4 cryogenic modules, each 17ktons of liquid argon





- 2 technologies for far detector
  - Single phase TPC
  - Dual phase TPC
- high resolution tracking, calorimetry, PID via dE/dx

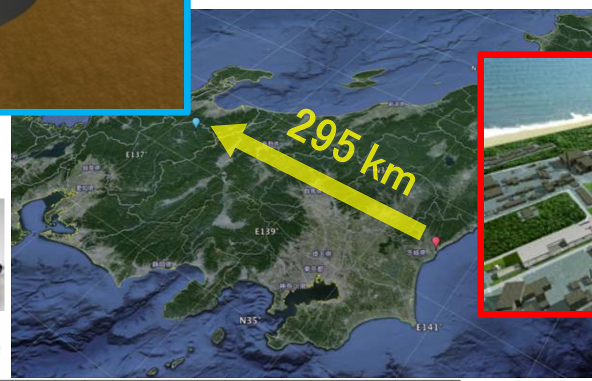


- Single phase TPC cathode planes biased to -180kV
- LAr scintillates at 128nm → drift time t_0
- Dual phase:
  - vertical drift and multiplication in gaseous phase improves signal/noise with reduced number of R/O channels
  - vertical drift over 12m requires ~600kV

→ Many challenges of scale for both detector concepts

Long Baseline Neutrino Detectors

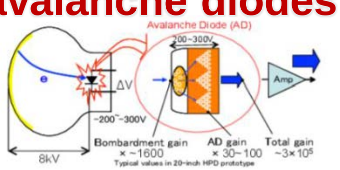
- Tank : 60 m tall × 78 m diameter
- 260 kton ultrapure water
  190 kton fiducial mass : 10 × Super-K
- Innermost main volume viewed by
  40,000 of new 50cm photo-sensors
- Improved photon sensitivity: 2×Super-K
- Second tank as upgrade path (6 yr later)

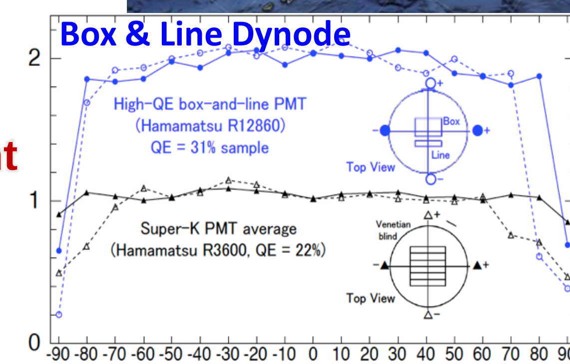


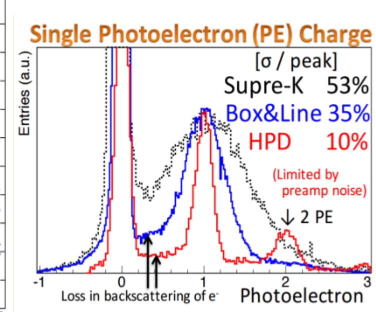
J-PARC
Accelerator Complex

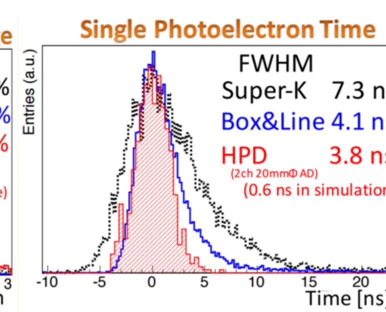
- New 50 cm PMT completed
  - ×2 single photon efficiency
  - ×2 timing resolution
  - ×2 hydrostatic pressure tolerance
  - (all w.r.t. Super-K PMT)

- Hybrid-Photo-Detector (HPD): R&D development with avalanche diodes



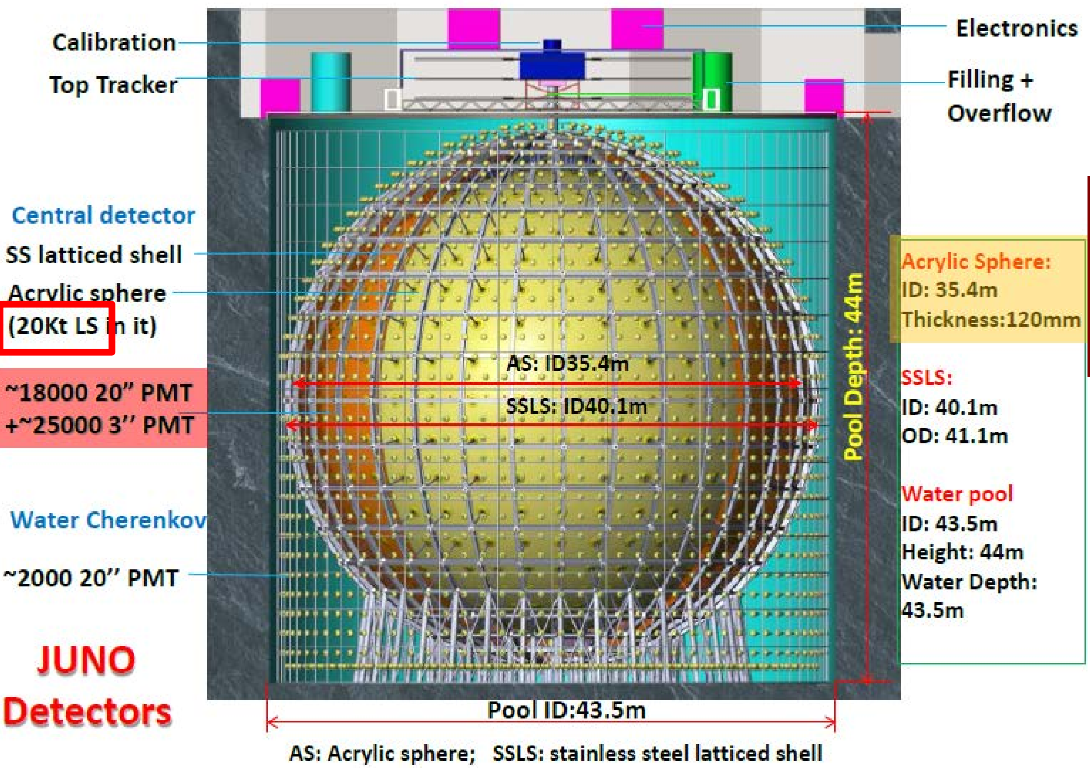






Reactor Neutrino Detectors

Liangjian Wen TIPP, Beijing, 2017



Daya Bay Liquid Scintillator pilot plant

Linear alkyl benzene (LAB) as solvent
2,5-diphenyloxazole (PPO) as fluor
p-bis-(o-methylstyryl)-benzene (bis-MSB) as wavelength shifter

$^{14}C/^{12}C \sim 2.7 \times 10^{-18}$

^{238}U (Bi-Po 214) $< 9.7 \times 10^{-19}$ g/g (95% CL)

^{232}Th (Bi-Po 212) $< 1.2 \times 10^{-18}$ g/g (95% CL)

^{40}K no evidence (TBD)

$^{39}Ar << {}^{85}Kr$

Technologies to achieve required radio-purity: Al_2O_3 column, distillation, gas striping, water extraction

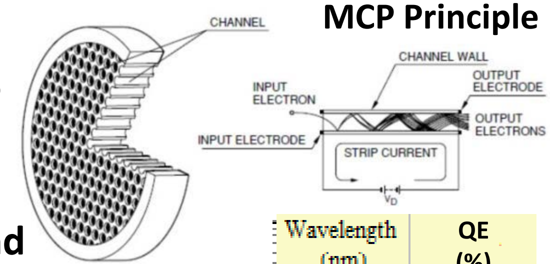
Levels achieved at Borexino: N. Rossi (Neutrino2016)

Neutrino Experiment Photodetectors

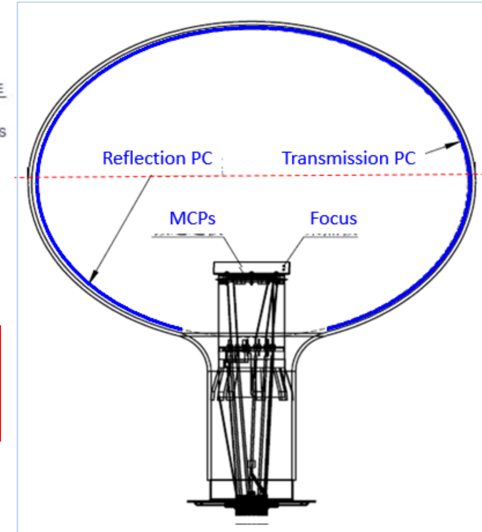
20" Micro-Channel Plate PMT for JUNO
- **Higher QE: transmissive photocathode at top plus reflective photocathode at bottom**
- **Less shadowing effect**
- **Easier production: less manual operations and steps**

Liangjian Wen TIPP, Beijing, 2017

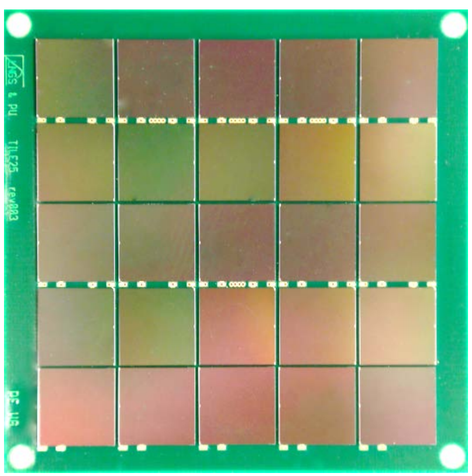
MCP Principle



Wavelength (nm)	QE (%)
390	26.32155
400	26.18978
410	26.058
420	25.4807
430	24.47675
440	23.4516
450	22.37645



Large area (24 cm^2) single-channel, SiPM-based cryogenic (77K) photodetector with single photon sensitivity (https://arxiv.org/abs/1706.04220v2)
- **Single photon counting with signal to noise >13**
- **Dark rate lower than 4 mHz/mm^2**
- **SiPM photon detection efficiency**



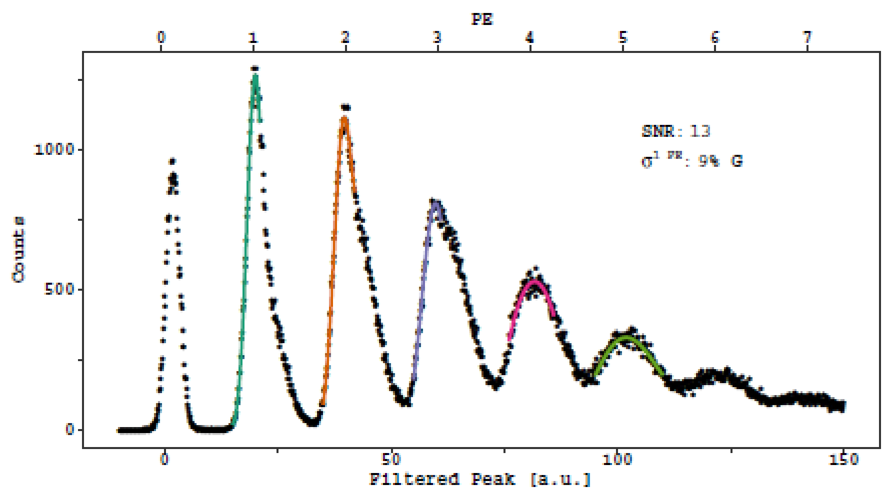


Fig. 11. Photoelectron spectrum of the full 24 cm^2 detector calculated using a matched filter. The solid lines represent a gaussian fit to the photoelectron peaks.

Non-accelerator and Low Energy Searches for Rare Processes

Facilities

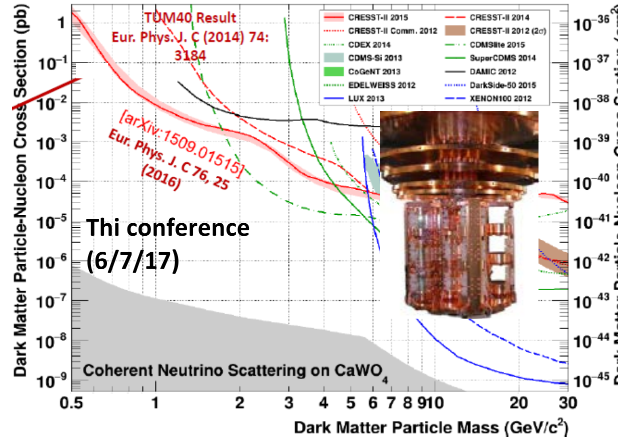
- Underground laboratories for Dark Matter searches
- Underground laboratories for neutrino-less double β decay
- No and low energy accelerator ultra-rare processes (eg g-2,COMET, Mu3e, edm, …)

Some Key Techniques

- Tracking semiconductor detectors
- Gaseous tracking detectors
- Scintillating Fibres
- Sampling Calorimeter
- Homogenous Calorimetry
- Superconducting Detectors
- Liquid Noble gas
- Liquid Scintillator

Underground Experiments for Dark Matter

- Huge variety of DM experiments with small and rare signals as ionisation, scintillation light, phonons or various combinations thereof.
- Need extreme control of background sources (radiopurity) coupled with high sensitivity and discrimination of signal from residual backgrounds.



CRESST $CaWO_4$ crystals (10mK)

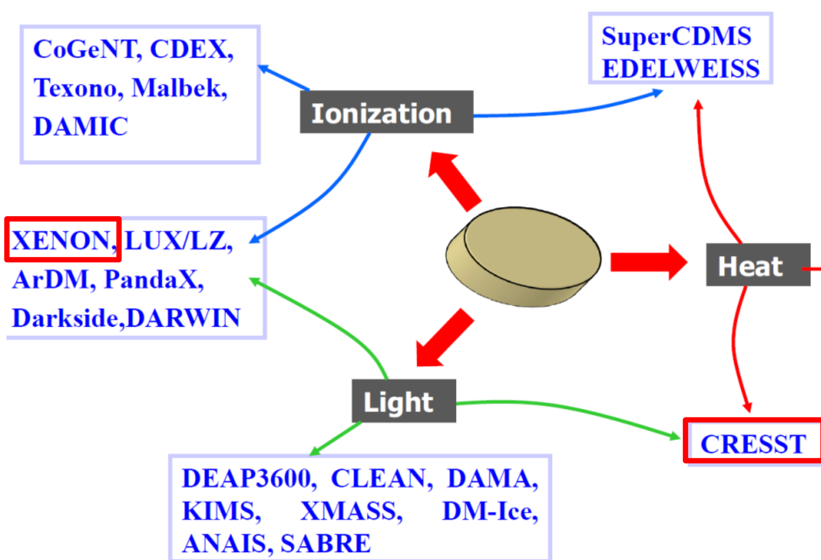
largest LXe TPC ever built
- cylinder: 96 × 97 cm
- active LXe target: 2.0t (3.2t total)
- 248 PMTs (Hamamatsu R11410-21)

World leading bkg level: 0.2×10^{-3} evt/day/kg/keV

Detection metods: Crystals (NaI, Ge, Si), Cryogenic Detectors, Liquid Noble Gases

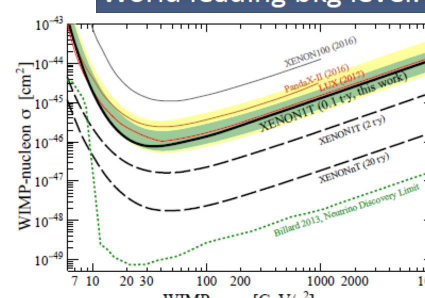
Manfred Lindner

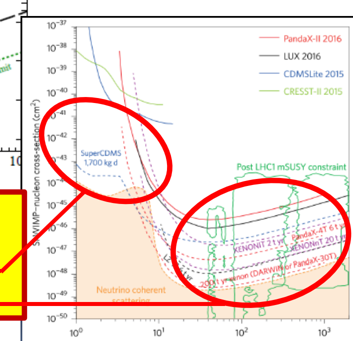
Max-Planck-Institut für Kernphysik Heidelberg



Tracking:
DRIFT, DMTPC
MIMAC
NEWAGE

Superheated Liquids:
COUPP — PICO
PICASSO
SIMPLE

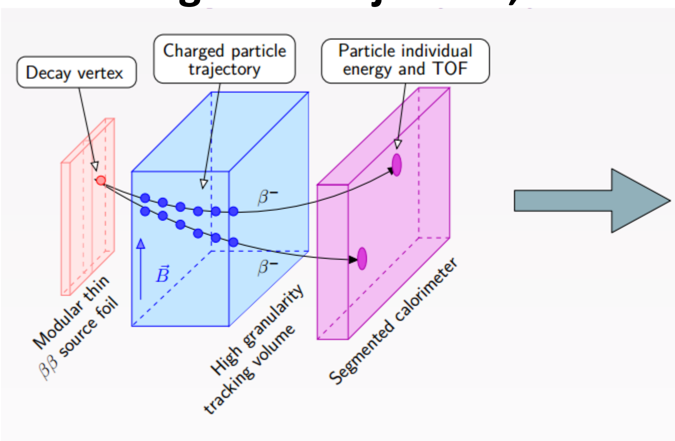


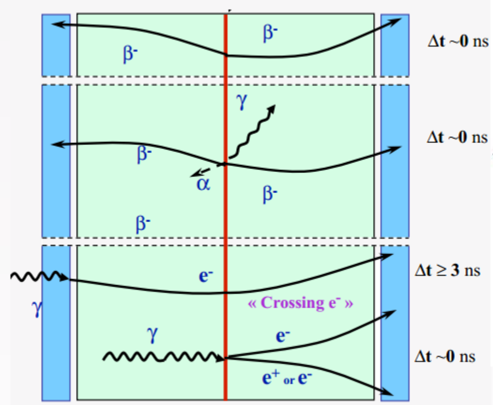


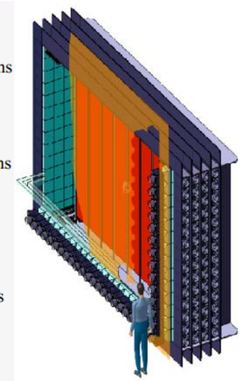
In next 5 years expect further huge progress at both low mass and high mass range

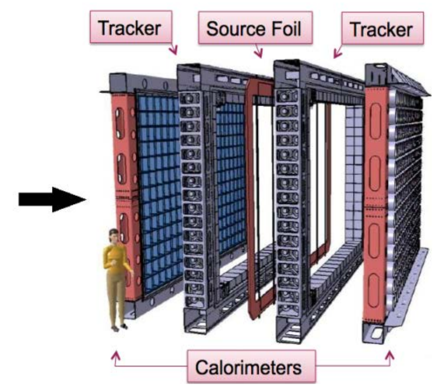
Underground Experiments for 0ν2β

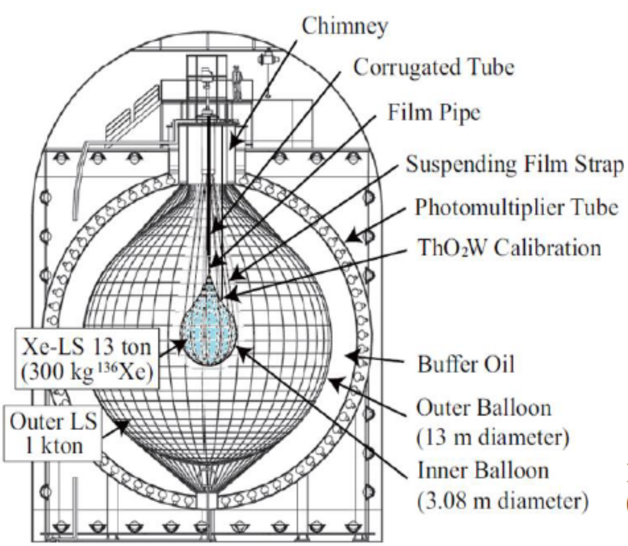
- **Many techniques also for neutrinoless double-beta decay involving many different techniques (SuperNEMO, EXO, CUPID, Majorana, KamLAND-Zen, NEXT, GERDA, SNO+, LEGEND, CUORE, AXEL, PANDAX, … but all with a requirement of high radio-purity, background rejection, extreme detector resolution and isotope enrichment**











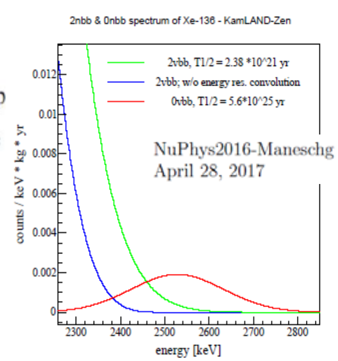
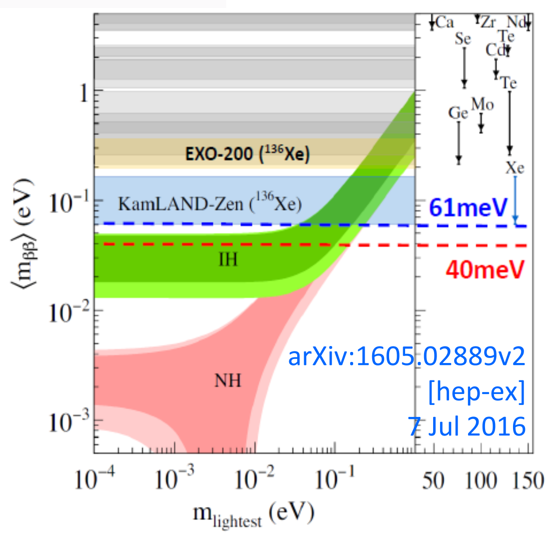


Figure 1: KamLAND-Zen: $2\nu\beta\beta$ vs. $0\nu\beta\beta$ for present $T^{0\nu}_{1/2}(^{136}\text{Xe})$.



- **Need better energy resolution to measure $T^{0\nu}_{1/2}$ »10^{26} yr.**
  - **GERDA, CUORE, NEXT, EXO, SNO+, CUPID, LEGEND, …**

Astro-particle Detectors

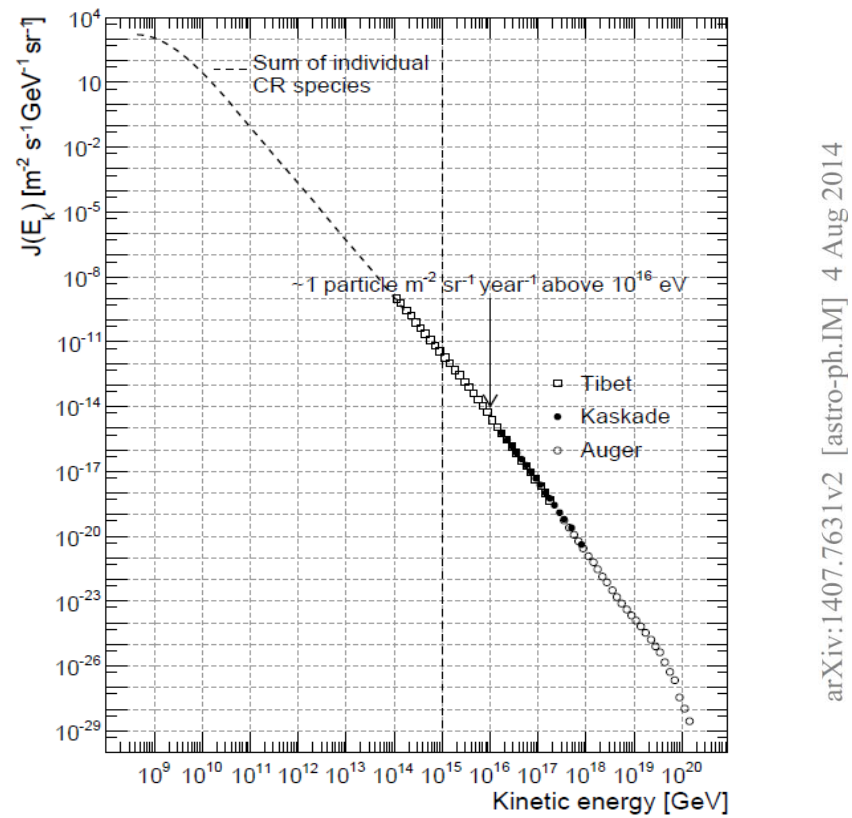
Huge Topic (35 space based, 23 balloon and 57 ground based experiments listed at https://www.mpi-hd.mpg.de/hfm/CosmicRay/CosmicRaySites.html)

Facilities

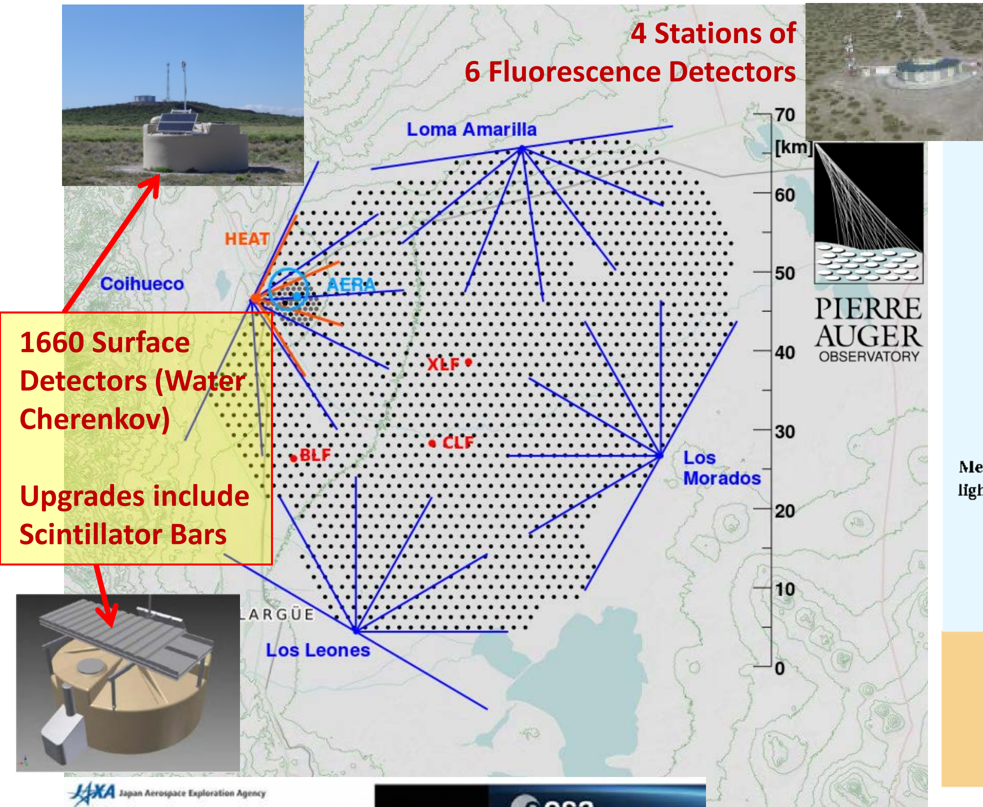
- **Charged Cosmic Rays (eg Pierre Auger, …)**
- **Ultra High Energy Gamma-rays (eg CTA, …)**
- **Ultra and Ultra^2 High Energy Neutrinos (eg IceCube, …)**
- **Solar, Atmospheric and Supernova Neutrinos (eg Long Baseline and Reactor experiments, SNO+, INO, …)**

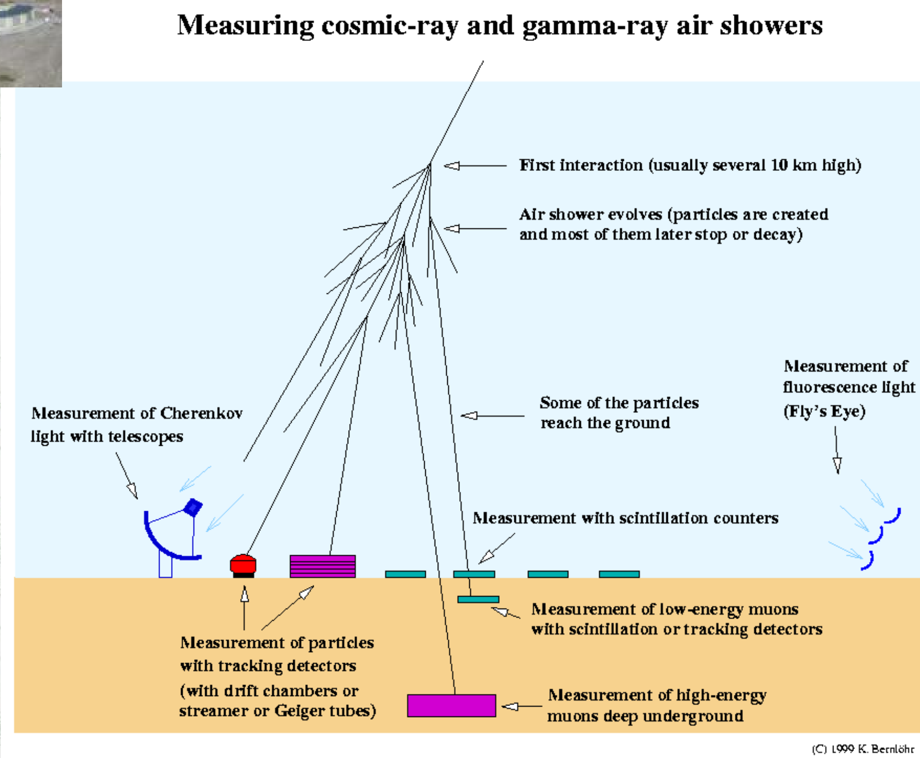
Some Key Techniques

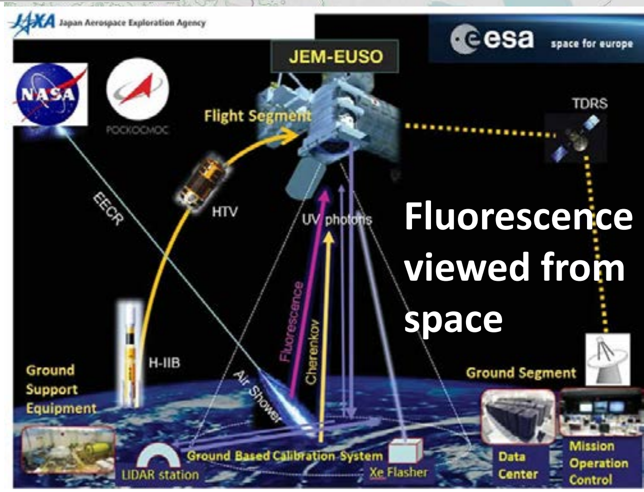
- **Tracking detectors**
- **Sampling Calorimeter**
- **Liquid Noble gas**
- **Liquid Scintillator**
- **Air/Water/Ice/rock**
- **Cherenkov and Fluorescence**
- **Large scale engineering**

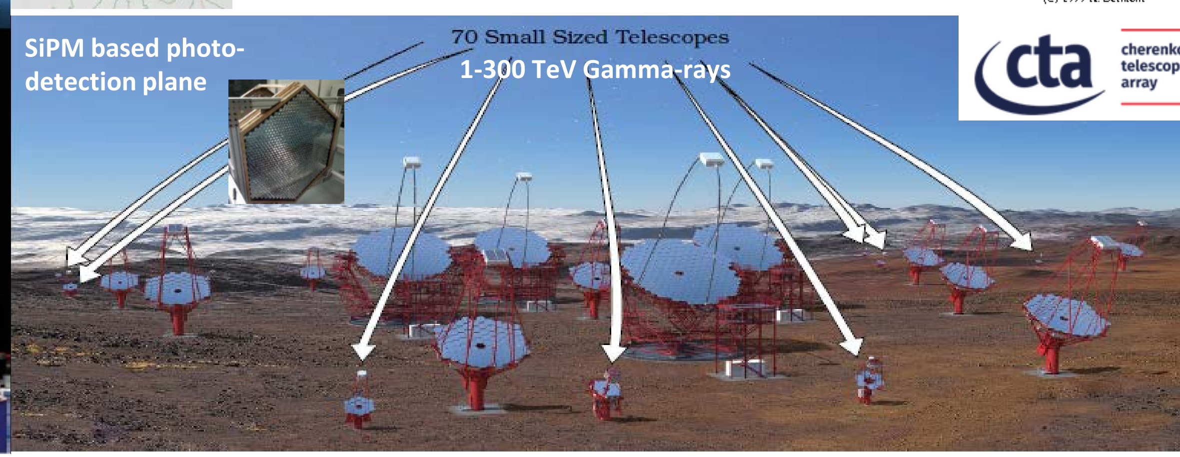


Detectors for Cosmic Rays and UHE Gammas



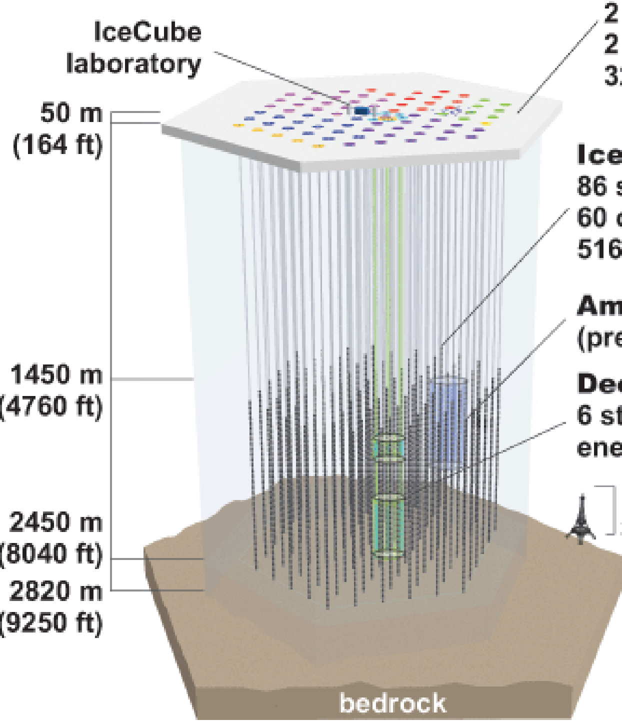






Ultra High Energy Neutrinos

Southern Hemisphere:



IceTop
80 stations, each with
2 IceTop Cerenkov detector tanks
2 optical sensors per tank
320 optical sensors

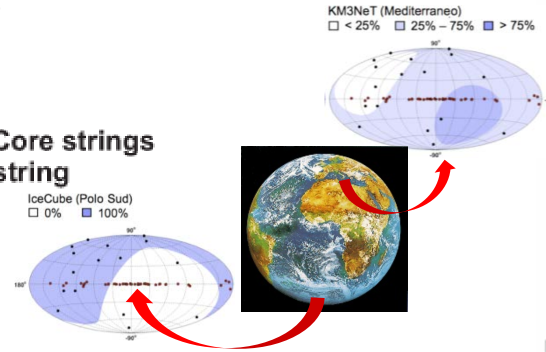
IceCube array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors

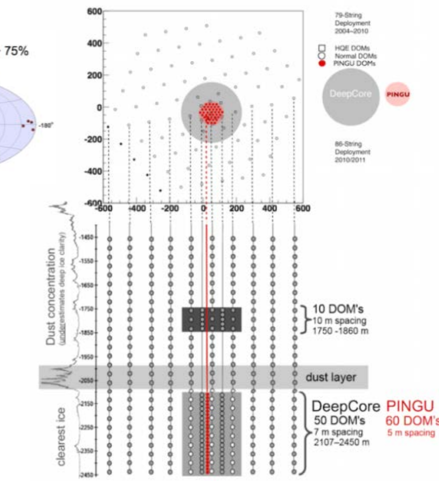
Amanda II array
(precurser to IceCube)

DeepCore
6 strings-spacing optimized for lower energies, 360 optical sensors

Eiffel Tower
324 m (1063 ft)

Northern Hemisphere:
KM3NeT collaboration megaton-scale neutrino detectors 2500m depth in Mediterranean.



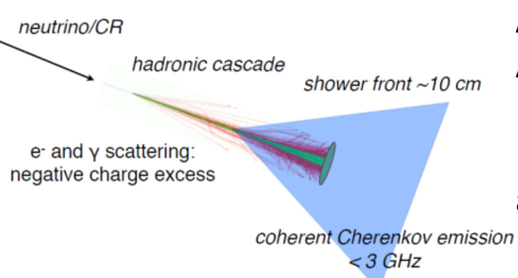


PINGU will deploy 40 new strings at the center of IceCube.

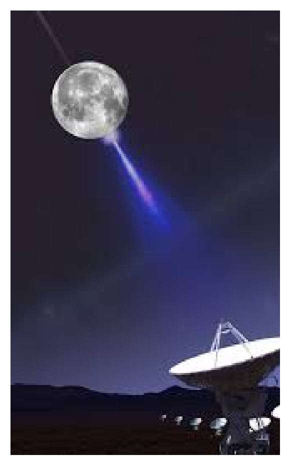
Precision IceCube Next Generation Upgrade

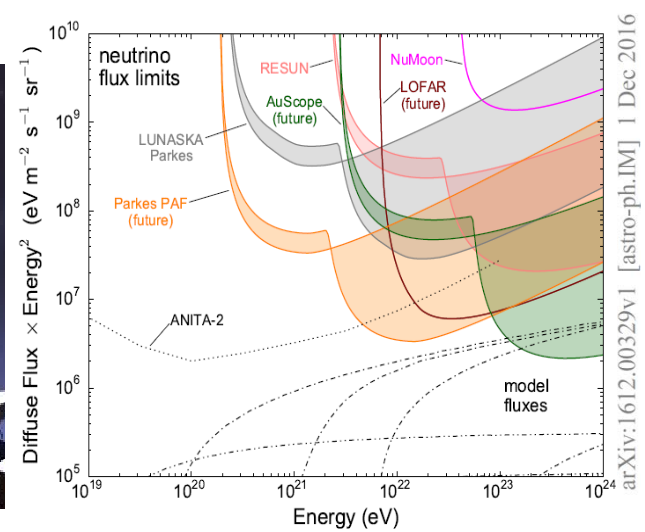
Energy threshold of a few GeV, able to distinguish between the normal and inverted mass hierarchy at 3σ significance with ~3.5 years of data

Askaryan effect



ARA/ARIANNA (array in ice)
ANITA (Antarctica from balloon)
LOFAR/NuMoon/AUScope
LUNASKA Parkes (the Moon as an U^2HE neutrino detector)



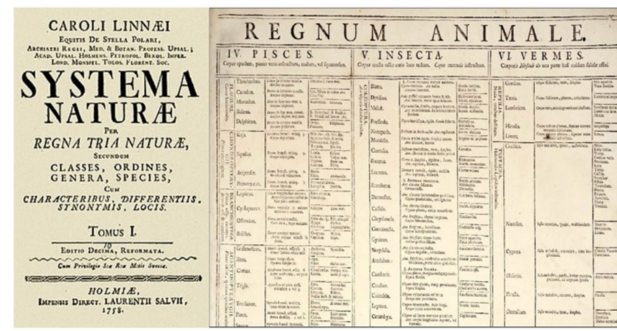


European Committee for Future Accelerators (ECFA) Detectors Panel Survey

- Only a fraction of different experiments and techniques covered
- List of facilities is one way of grouping the different styles of experiments
- Another possibility is a taxonomy of technologies:

a. Pixel sensors (silicon: hybrid, monolithic)
b. Inner tracking (silicon)
c. Inner tracking and muon tracking (gas: MPGD, wires, TPC, straws and drift tubes)
d. Scintillating fibre tracking
e. Sampling calorimetry (scintillators)
f. Sampling calorimetry (liquid noble gases)
g. Sampling calorimetry (high granularity particle flow)
h. Homogenous calorimetry (crystals, plastics)
i. Fast timing detectors (semiconductor, crystal/scintillator, gas)
j. Detectors exploiting superconductivity
k. Particle Identification (Cherenkov plus efficient single photon detection)
l. Large volume liquid noble gas for track and energy reconstruction
m. Large volume liquid scintillators for timing and energy reconstruction
n. Air/Water/Ice/Rock Cherenkov and fluorescence detection (light, sound, Askaryan effect)
o. Custom microelectronics and other front-end electronics
p. Data links and optoelectronics
q. Mechanics, large-scale engineering, cooling and services
r. Trigger, data acquisition and computing

…. everything I've forgotten



1. Collider and Fixed Target

List of key technology challenges in the context of different facilities

Technique	1.1 (hadron collider)	1.2 (lepton collider)	1.3 (lepton-hadron)	1.4 (fixed target)	Comment
1.a (Si) Vertexing (& Lumi/FP)	Rad-hard (pp) Low mass (AA) Data rate (pp)	Low mass Fine pitch Time stamp	Fine pitch Low mass	Fast R/O Fine pitch Radiation	Monolithic devices incorporate electronics. Time structure dictates on-detector R/O.
1.b Inner track (Si)	Area/cost Radiation (pp)	Low mass Area/Cost	Area/cost	Radiation	Can be few $10^{15}n_{eq}/cm^2$ radiation levels
1.c Track gas (inlc muons)	Area/cost Hit rate, aging	Volume (TPC)	Area/cost Hit rate	Hit rate	Industrialisation of gas micro-pattern detectors
1.d Sci Fibre	Radiation incl photodetectors			Efficiency	Photodetector radiation hardness
1.e Scint Calo	Radiation Granularity	Granularity EM Resolution	Granularity EM Resolution	EM Resolution	Timing for ToF or pile-up mitigation
1.f Calo L-noble	Charge collection time	EM Resolution	EM Resolution	EM Resolution Speed	Rate capabilities
1.g HG-Calo	Area/cost Resolution	Area/cost	Area/cost EM Resolution	EM Resolution	Particle Flow Analysis (EM Resolution?)
1.h Calo homogenous	Radiation Granularity	EM Resolution Granularity	EM Resolution Granularity	EM Resolution Granularity	Timing for ToF or pile-up mitigation
1.i Fast Timing (Si, gas, scintillator)	Radiation, Speed, Rate Area/cost	Time stampArea/cost	Area/cost	Speed Sensitivity	Primary vertexing. Time of Flight for lower momenta PID
1.k Particle ID RICH	Volume Area/cost	Volume Area/cost	Volume Area/cost	Volume Area/cost	Efficiency for single photo-detection
1.o FE Electronics & Interconnect	Radiation Cost/channel # Power	Channel #, Power, fine-pitch	Cost/channel #, Power	Speed/ data volumes	Prototyping costs for deep-sub-micron engineering runs
1.p Data links (incl opto-electronics)	Radiation Cost/channel # Low mass	Channel # Low mass	Channel # Low mass	Speed/ data volumes	How to exploit commercial developments?
1.q Mech, cool, services	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Large-scale magnet systems
1.r TDAQ + Computing	Cost, Speed Commercial Solutions	Cost Channel #	Cost, Speed Commercial Solutions	Speed/ data volumes	Is Moore's Law safe forever?

1. Collider and Fixed Target

Aspects of some areas are the topics of dedicated international R&D programmes

Technique	1.1 (hadron collider)	1.2 (lepton collider)	1.3 (lepton-hadron)	1.4 (fixed target)	Comment
1.a (Si) Vertexing (& Lumi/FP)	Rad-hard (pp) Low mass (AA) Data rate (pp)	Low mass Fine pitch Time stamp	Fine pitch Low mass	Fast R/O Fine pitch Radiation	Monolithic devices incorporate electronics. Time structure dictates on-detector R/O.
1.b Inner track (Si)	Area/cost Radiation (pp)	Low mass Area/Cost	Area/cost	Radiation	Can be few $10^{15} n_{eq}/cm^2$ radiation levels
1.c Track gas (inlc muons)	Area/cost Hit rate, aging	Volume (TPC)	Area/cost Hit rate	Hit rate	Industrialisation of gas micro-pattern detectors
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1.e Scint Calo	Radiation Granularity	Granularity EM Resolution	Granularity EM Resolution	EM Resolution	Timing for ToF or pile-up mitigation
1.f Calo L-noble	Charge collection time	EM Resolution	EM Resolution	EM Resolution Speed	Rate capabilities
1.g HG-Calo	Area/cost Resolution	Area/cost	Area/cost EM Resolution	EM Resolution	Particle Flow Analysis (EM Resolution?)
1.h Calo homogenous	Radiation Granularity	EM Resolution Granularity	EM Resolution Granularity	EM Resolution Granularity	Timing for ToF or pile-up mitigation
1.i Fast Timing (Si, gas, scintillator)	Radiation, Speed, Rate Area/cost	Time stampArea/cost	Area/cost	Speed Sensitivity	Primary vertexing. Time of Flight for lower momenta PID
1.k Particle ID RICH	Volume Area/cost	Volume Area/cost	Volume Area/cost	Volume Area/cost	Efficiency for single photo-detection
1.o FE Electronics & Interconnect	Radiation Cost/channel # Power	Channel #, Power, fine-pitch	Cost/channel #, Power	Speed/ data volumes	Prototyping costs for deep-sub-micron engineering runs
1.p Data links (incl opto-electronics)	Radiation Cost/channel # Low mass	Channel # Low mass	Channel # Low mass	Speed/ data volumes	How to exploit commercial developments?
1.q Mech, cool, services	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Large-scale magnet systems
1.r TDAQ + Computing	Cost, Speed Commercial Solutions	Cost Channel #	Cost, Speed Commercial Solutions	Speed/ data volumes	Is Moore's Law safe forever?

1. Collider and Fixed Target

Aspects of some areas are the topics of dedicated international R&D programmes

Technique	1.1 (hadron collider)	1.2 (lepton collider)	1.3 (lepton-hadron)	1.4 (fixed target)	Comment
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1.b Inner track (Si)	Area/cost Radiation (pp)	Low mass Area/Cost	Area/cost	Radiation	Can be few $10^{15}n_{eq}/cm^2$ radiation levels
1.c Track gas	Area/cost	Volume (TPC)	Area/cost	Hit rate	Industrialisation of gas micro-
1.q Mech, cool, services	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Low mass, reliable, stable	Large-scale magnet systems
1.r TDAQ + Computing	Cost, Speed Commercial Solutions	Cost Channel #	Cost, Speed Commercial Solutions	Speed/ data volumes	Is Moore's Law safe forever?

AIDA-2020: 1.1.a, 1.2.a, 1.1.b, 1.1c, 1.2c,1.1g, 1.1.i, 1.1.n, 1.2.n, 1.1.p, 1.2.p, 1.1.q, 1.2.q
CALICE: 1.2.g
Crystal Clear Collaboration: 1.1.e, 1.2.e, 1.3.e, 1.4.e, 1.2.h, 1.3.h, 1.4.h
ILC/CLIC FCAL Collaboration: 1.2.g
ILC TPC Collaboration: 1.2c
RD42: 1.1.a, 1.2.a, 1.1.i, 1.2.i
RD50: 1.1.a, 1.2.a, 1.1.b, 1.4.b, 1.1.i
RD51: 1.1.c, 1.2.c, 1.4.c, 1.2i, 1.4i, 1.2.i, 1.4.i
RD52: 1.2.e
RD53: 1.1.n, 1.2.n
Versatile Link Project: 1.1.o

Apologies to other collaborations I am not aware of particularly outside Europe

1. Collider and Fixed Target

Aspects of some areas are the topics of dedicated international R&D programmes

Technique	1.1 (hadron collider)	1.2 (lepton collider)	1.3 (lepton-hadron)	1.4 (fixed target)	Comment
1.a (Si) Vertexing (& Lumi/FP)	Rad-hard (pp) Low mass (AA) Data rate (pp)	Low mass Fine pitch Time stamp	Fine pitch Low mass	Fast R/O Fine pitch Radiation	Monolithic devices incorporate electronics. Time structure dictates on-detector R/O.
1.b Inner track (Si)	Area/cost Radiation (pp)	Low mass Area/Cost	Area/cost	Radiation	Can be few $10^{15} n_{eq}/cm^2$ radiation levels
1.c Track gas	Area/cost	Volume (TPC)	Area/cost	Hit rate	Industrialisation of gas micro
cool, services	stable	stable	reliable, stable	reliable, stable	
1.r TDAQ + Computing	Cost, Speed Commercial Solutions	Cost Channel #	Cost, Speed Commercial Solutions	Speed/ data volumes	Is Moore's Law safe forever?

AIDA-2020: http://aida2020.web.cern.ch/activities
CALICE: https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome
Crystal Clear Collaboration: https://crystalclear.web.cern.ch/crystalclear/
ILC/CLIC FCAL Collaboration: http://fcal.desy.de/
ILC TPC Collaboration: https://www.lctpc.org/
RD42 (diamond): http://rd42.web.cern.ch/rd42/*
RD50 (rad-hard silicon): https://www.cern.ch/rd50/*
RD51 (micro-pattern gas detectors): http://rd51-public.web.cern.ch/rd51-public/*
RD52 (dual readout calorimetry): http://cds.cern.ch/record/2255826/files/*
RD53 (rad-hard electronics): https://rd53.web.cern.ch/RD53/
VL Project: https://espace.cern.ch/project-Versatile-Link-Plus/SitePages/Home.aspx
** See LHCC 10/5/17 presentations at https://indico.cern.ch/event/632309/*

Apologies to other collaborations I am not aware of particularly outside Europe

2. Accelerator and Reactor Neutrinos

List of key technology challenges in the context of different facilities

	2.1 Long Baseline	2.2 Short Baseline	2.3 Reactor/source
2.c Gas detectors	Amplification	High pressure	
2.e,h Solid scintillator (sampling and homogeneous)	Photodetector costs Material costs Large scale engineering	Energy threshold Noise, Timing Granularity	Energy and spatial resolution. Low noise. Calibration. Shielding.
2.l,q Liquid scintillator and associated engineering	Photodetector sensitive area and cost, Radio-purity, Large scale engineering	Photo-detector QE Mechanics Shielding	Photo-detector QE Radio-purity, Gd doping, flux modelling
2.m,q Liquid noble gas and associated engineering	Purification Very high voltage Large scale cryogenics	In cryostat low noise CMOS, space charge, FE range	Coherent neutrino-nucleus scattering?
2.n,q Water Cherenkov and associated engineering	Photodetector timing, efficiency and costs Large scale engineering	Separation of pile-up events (same bunch), Gd-doping	Gd-doping. Radon. Shielding.
2.r DAQ & Computing	Reliability, buffering, dynamic range, data volume	Reliability, data volume	Reliability

AIDA 2020 WP8: Large scale cryogenic liquid detectors

Far fewer areas coordinated by dedicated international R&D programmes

3. Non-accelerator and Low Energy Searches for Rare Processes

List of key technology challenges in the context of different facilities

	3.1 Dark Matter	3.2 Rare neutrino	3.3 Other rare decay
3.a,b,d Tracker	Ultra-radio-purity Optical as well as electrical read-out	Radio-purity Very low material. Isotope enrichment	Thin, fine granularity. Single etch GEM foils, High rate, fast timing, complex field
3.e,h,j Calorimetry	Ultra-radio-purity, Ultra-low noise, (mK), Energy resolution	Radio-purity Ultra-low noise Energy resolution	High rate, fast timing, energy resolution at low energies, radiation
3.d Liquid noble gas	Ultra-radio-purity Ultra-low noise and high efficiency photodetectors	Radio-purity Ultra-low noise and high efficiency photodetectors	Energy resolution Background rates
3.e Liquid scintillator	Ultra-radio-purity Ultra-low noise and high efficiency photodetectors	Radio-purity Ultra-low noise and high efficiency photodetectors	Energy resolution Background rates
3.r DAQ & Computing			Event rates

List of key technology challenges in the context of different facilities

	3.1 Dark Matter	3.2 Rare neutrino	3.3 Other rare decay
3.a,b,d Tracker	Ultra-radio-purity Optical as well as electrical read-out	Radio-purity Very low material. Isotope enrichment	Thin, fine granularity. Single etch GEM foils, High rate, fast timing, complex field
3.e,h,j Calorimetry	Ultra-radio-purity, Ultra-low noise, (mK), Energy resolution	Radio-purity Ultra-low noise Energy resolution	High rate, fast timing, energy resolution at low energies, radiation
3.d Liquid noble gas	Ultra-radio-purity Ultra-low noise and high efficiency photodetectors	Radio-purity Ultra-low noise and high efficiency photodetectors	Energy resolution Background rates
3.e Liquid scintillator	Ultra-radio-purity Ultra-low noise and high efficiency photodetectors	Radio-purity Ultra-low noise and high efficiency photodetectors	Energy resolution Background rates
3.r DAQ & Computing			Event rates

4. Astro-particle Detectors

Not aware on either topic of any areas coordinated by dedicated international R&D programmes

Conclusions

- Vast range of techniques and detection scales… *from microns to the Moon* (or arguably Earth/Sun/galactic centre for neutrinos/WIMPS/axions, …)
  - One exciting area of recent development is in 4D detectors (precision spatial resolution coupled with accurate timing) with many applications (such as mitigating the effects of pile-up in hadron colliders by associating tracks to vertices in both space and time)
  - Monolithic Active Pixel Sensors offer the potential of exploiting the huge commercial market in CMOS Imaging Sensors and now there are process variants which are also radiation hard
  - Large format micro-pattern gas detectors now being manufactured on industrial scales and also being produced as cylindrical structures
  - Liquid noble gas based detectors are opening up many new opportunities for precision tracking and calorimetry within huge volume detectors
  - Many experiments benefit from the steady improvements in scintillator and photodetector technologies often driven by collaboration with major industrial suppliers
  - Huge progress also in online data handling (trigger and data acquisition), computing and offline tools (not covered here due to limitations of time)
- Note that typical R&D timescales are a decade from proof-of-principle to first demonstrator or small-scale implementation and a further decade to large-scale detector realisation
- In many areas, cross-experiment R&D collaborations exist which both foster cooperation and diminish duplication and help share developments costs (which can be challenging)
  - Still some gaps in R&D areas which may benefit from further such organisations
  - Great potential to link more closely with other sciences and application areas

References and Conferences

1. FCC Week (https://fccw2017.web.cern.ch/) 29/5/17
2. Technology and Instrumentation in Particle Physics, TIPP (http://tipp2017.ihep.ac.cn/) 22/5/17
3. LHCC Open Session (https://indico.cern.ch/event/632309/) 11/5/17
   (Links to RD42, RD50, RD51, RD52 and RD53 along with other international R&D collaborations on slide 7)
4. AIDA 2020 Annual Meeting (https://indico.cern.ch/event/590645/) 4/4/17
5. CALICE 2017 (https://agenda.linearcollider.org/event/7454/) 22/3/17
6. Neutrino Telescopes (https://agenda.infn.it/confLogin.py?confId=11857) 13/3/17
7. IEEE NSS MIC (http://2016.nss-mic.org/) 29/10/16
8. ECFA HL-LHC Workshop (https://indico.cern.ch/event/524795/) 3/10/16
9. Vertex 2016 (https://indico.cern.ch/event/452781/overview) 25/9/16
10. Neutrino 2016 (http://neutrino2016.iopconfs.org/home) 4/7/16
11. ECFA Linear Collider Workshop (https://agenda.linearcollider.org/event/7014/) 30/5/16
12. CALOR 2016 (https://indico.cern.ch/event/472938/page/6018-calor-2016) 15/5/16
13. FCC Week (http://fccw2016.web.cern.ch/fccw2016/) 11/4/16
14. Common ATLAS CMS Electronics, ACES (https://indico.cern.ch/event/468486/) 7/3/16
15. ILC (https://www.linearcollider.org/P-D/ILC-detector-concepts)
16. CLIC (http://clicdp.web.cern.ch/)
17. LBNF (http://lbnf.fnal.gov/)
18. EPS (https://indico.cern.ch/event/466934/)

ANY QUESTIONS

Even More Challenging: FCC-hh

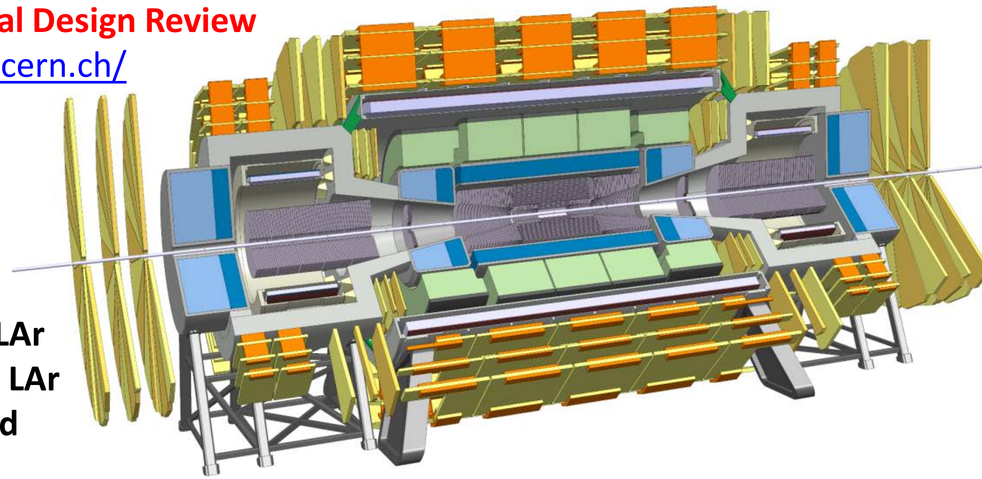
(And many other specific challenges for FCC-ee and FCC-eh)

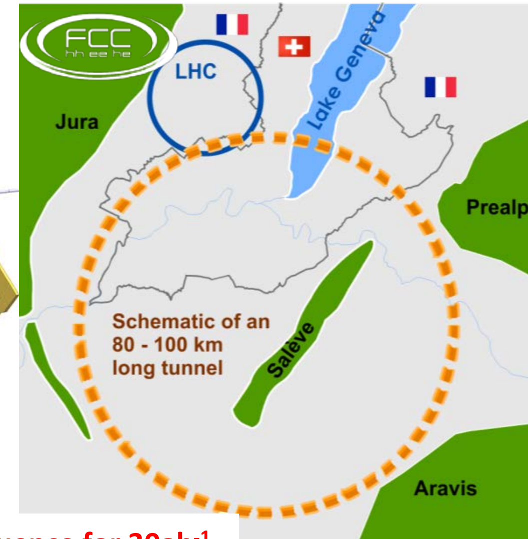
Baseline for Conceptual Design Review

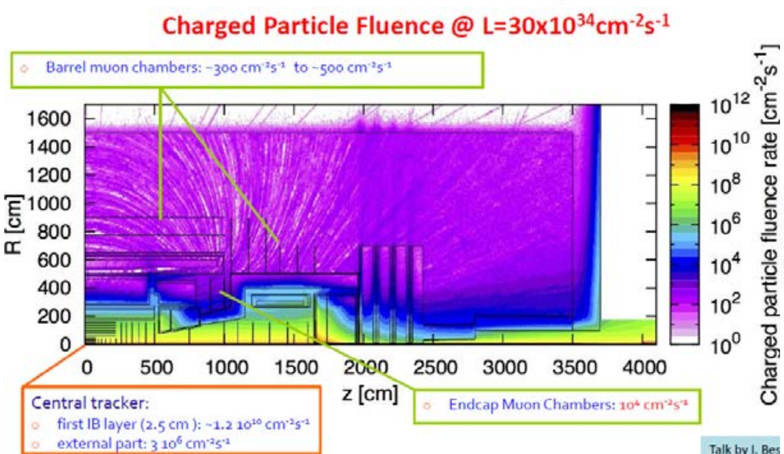
https://fccw2017.web.cern.ch/

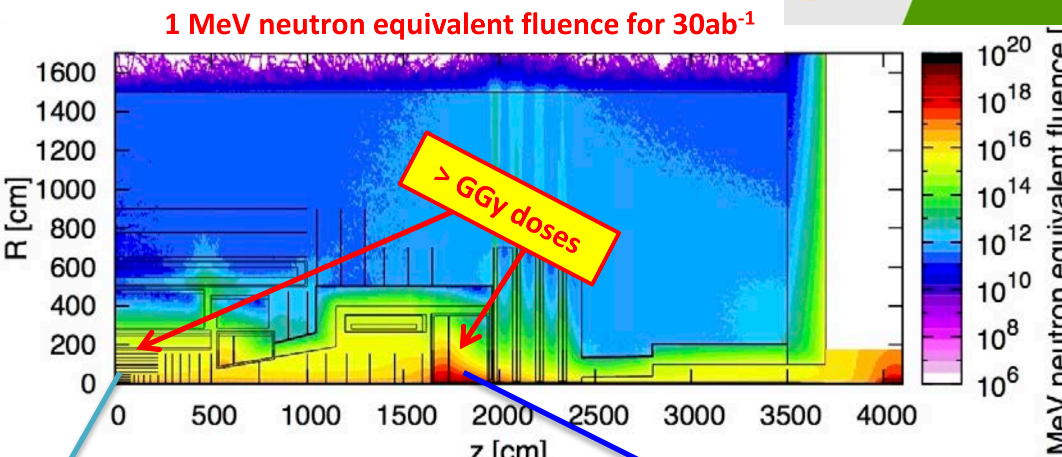
- 4T 10m solenoid
- Forward solenoids
- **Silicon** tracker
- Barrel ECAL **LAr**
- Barrel HCAL Fe/**Sci**
- Endcap HCAL/ECAL **LAr**
- Forward HCAL/ECAL **LAr**

Other options explored









Central tracker:

- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Forward calorimeters:

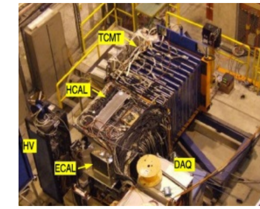
- maximum at ~5 10^{18} cm^{-2} for both the EM and the HAD-calo
- 10^{16} cm^{-2} at R=2 m

- Schedule prepared **European Strategy Update 2020**

Calorimetry and Particle Flow

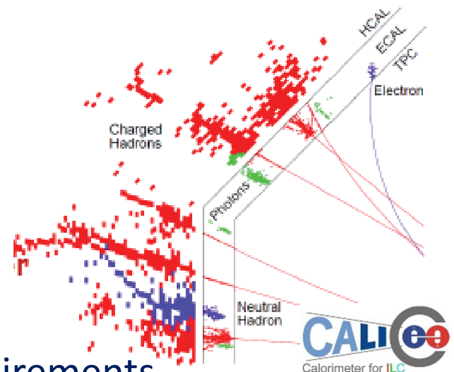
- **RD52 Dual REAd-out Method**
  - FCC-ee?

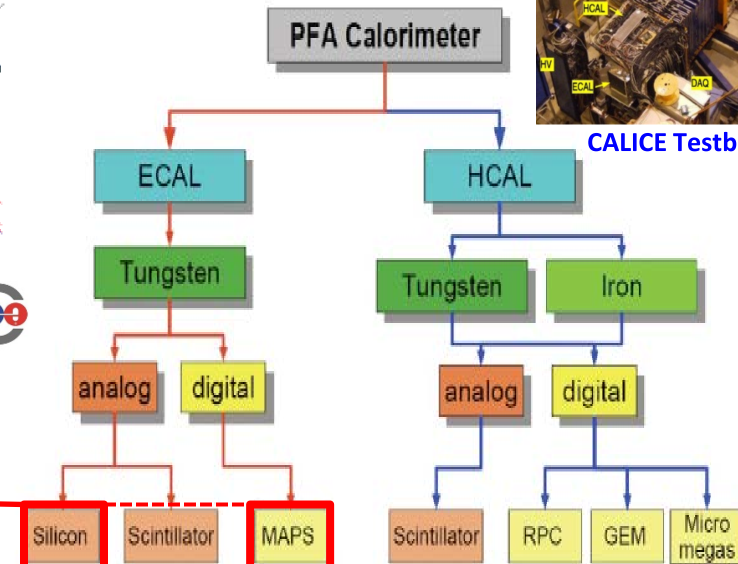
Simultaneous measurement, during shower development, of:
- **Scintillation light (dE/dx charged particles)**
- **Cherenkov light (EM part of the shower)**



CALICE Testbeam

- **CALICE** (Calorimeter for *ILC*)
  - Fundamental concept:
    - Particle flow
    - Associate energy deposits with charged particles
    - → Drives granularity requirements
    - Allows "tracking" of neutrals

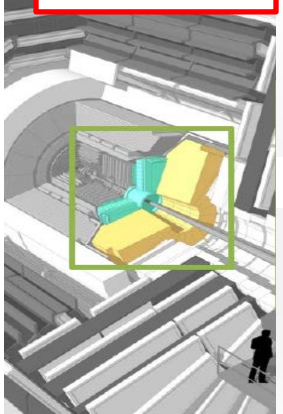




- ALICE **FoCAL**
  - Tungsten-Silicon sampling EM Calorimeter

FCC-hh?

- CMS **HGCAL**



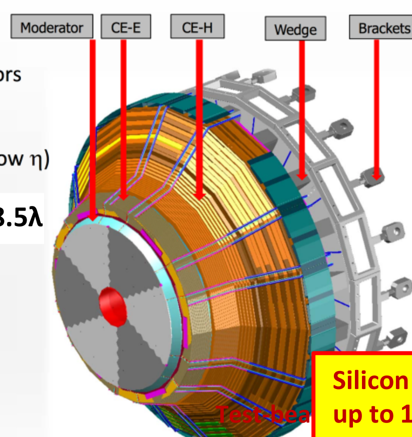
Main characteristics:

EC-E - 28 active layers, silicon sensors
EC-H - 24 active layers
8 silicon sensor
16 silicon (high η) + scint (low η)

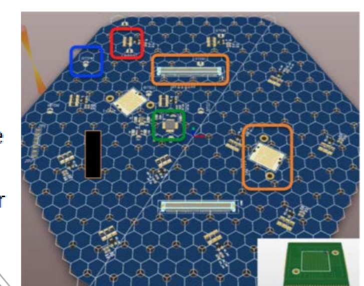
ECAL: 25 X_0, ~1.3λ; HCAL: 8.5λ

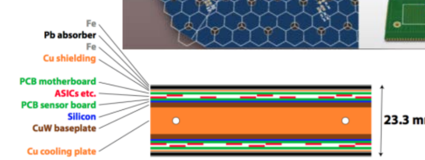
EC-E total weight =18.5t
EC-H Absorbers material:
St.Steel, weight = 170t
Front Shielding weight = 0.8t

Total weight of Endcap = 253t



Key Parameters:
- EC covers 1.5 < η < 3.0
- Full system maintained at -30ºC
- ~600m² of silicon sensors
- ~500m² of scintillators
- 6M si channels, 0.5 or 1 cm² cell size
- ~22000 si modules
- Power at end of HL-LHC: ~60 kW per endcap



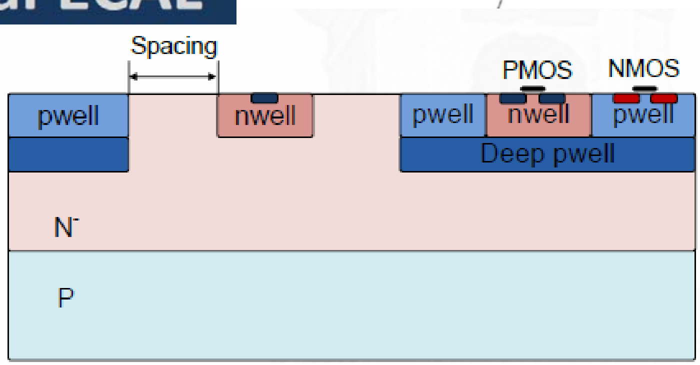


Silicon pads to withstand doses up to 10^{16}n/cm² and several MGy

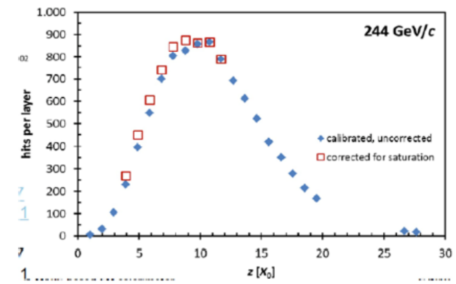
Interesting digital ECAL option using CMOS MAPS

Summary of 7 Parallel Sessions at Berlin by Martin Aleksa on behalf of the FCC-hh Experiments WG

Digital ECAL



- Can achieve the ultra high granularity with the use of CMOS Monolithic Active Pixel Sensors
- Thin sensitive region, usually 12-25um
- Thin substrates, low material budget
- Low noise
- Readout on the sensor so no need for separate chip
- Developments in HV/HR CMOS to deplete the sensor improve charge collection speed and radiation hardness



Number of hits per layer defines necessary granularity

Generally the more active layers the better the resolution (speaking about 30 – 50 layers)
Absorber material: Pb and W equivalent in terms of resolution, but lead shows better linearity (wider shower)

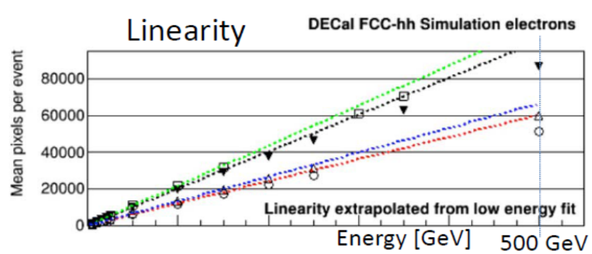
https://indico.cern.ch/event/556692/contributions/2487578/

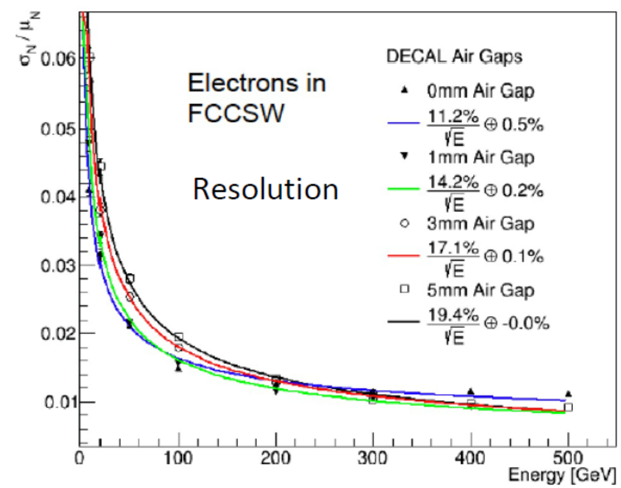
Reconfigurable summing **hits over threshold**

DECAL chip being prototyped RAL/Bham

Designed to support both EM calorimetry and outer tracking (ST/N002911/1)

- Optimal granularity: pixel pitch ~50µm
- Sensor thickness ~18µm
- With realistic geometry (1mm air gap for read-out, cooling, power) achieving 14% / Sqrt(E) at η = 0.
- Linearity is of concern (more than one particle per pixel)





- Radiation Hardness
  - Forward region of FCC-hh detectors Si not an option
  - Depleted CMOS currently under development (HV/HR) with results to 10^{15} n_{eq}/cm^2 and beyond presented recently by other groups so feasible for Barrel region
- Cost
  - Cost of CMOS imaging sensors needs to decrease to make affordable but over 20 years this is expected to fall dramatically.
  - A cost of 30 cents / cm² would mean an ECAL of ~$30M.
  - Much more compact ECAL would also reduce costs of other systems

T. Price