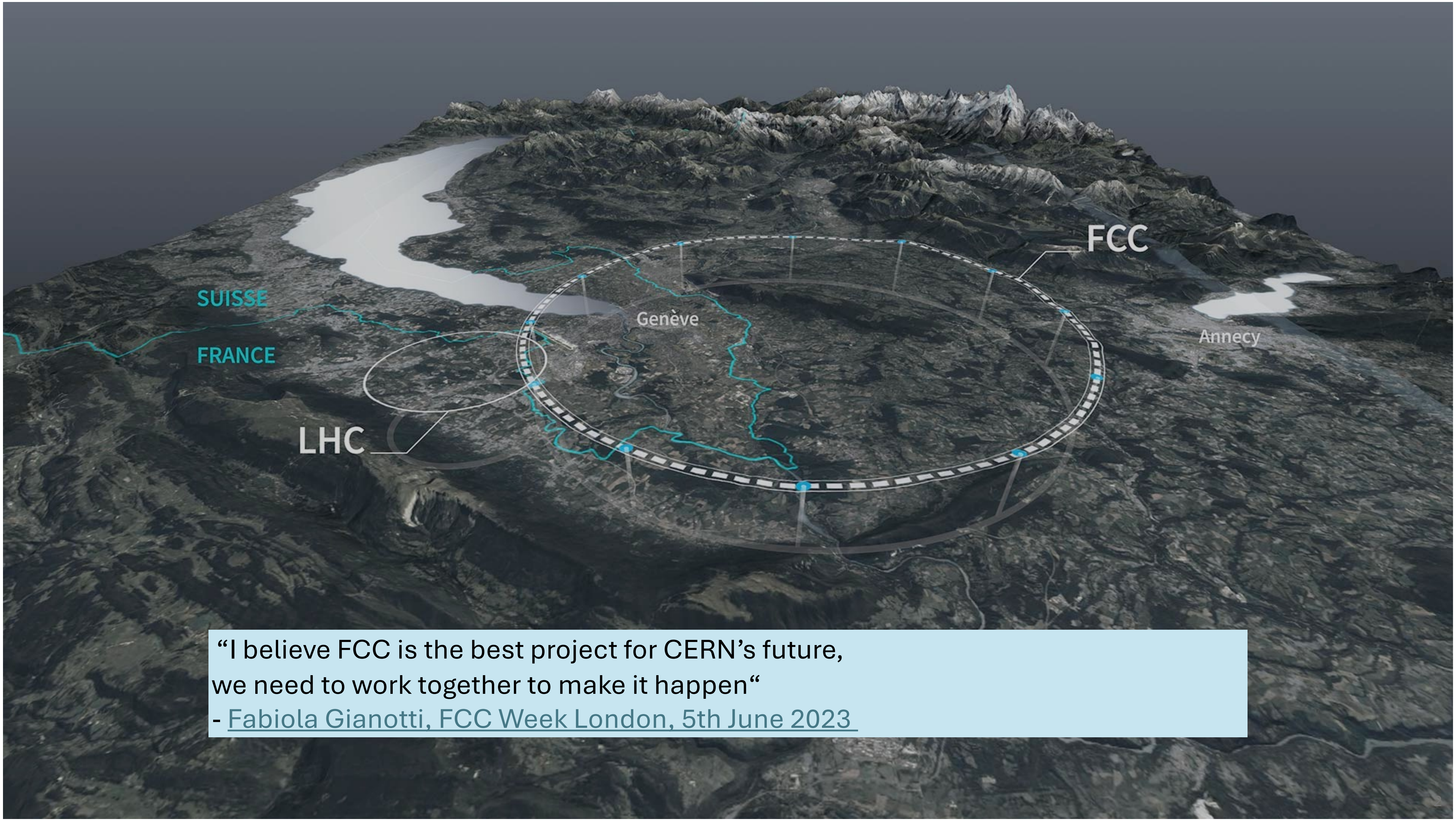
Experimental perspective for future colliders

(Taking FCC as an example)

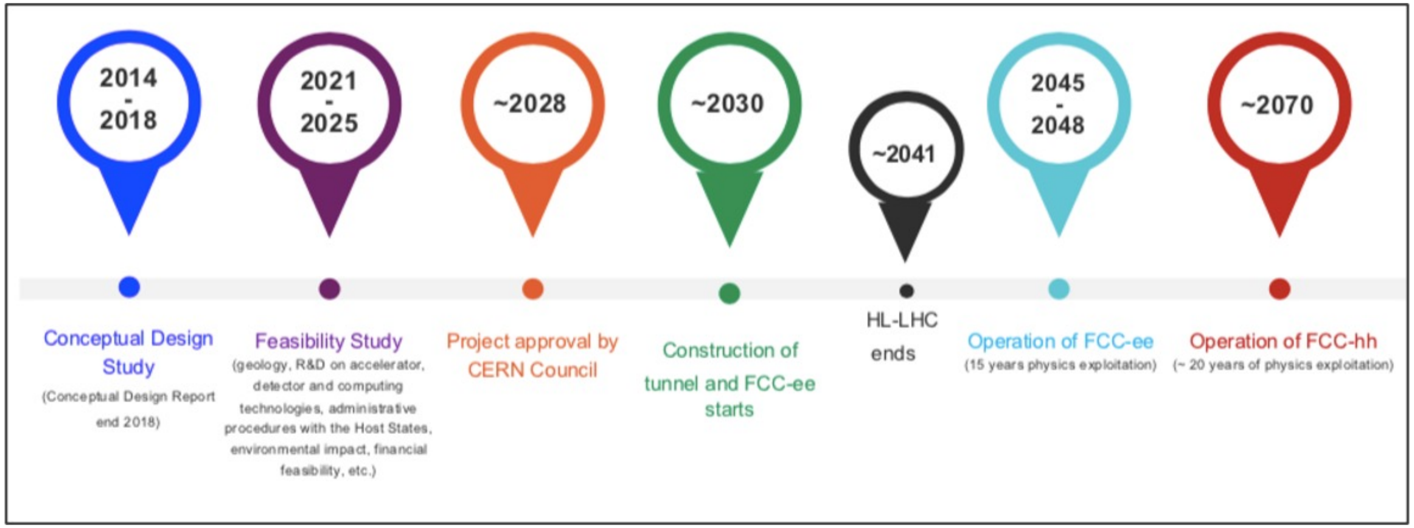
M. Cobal, UniUD & INFN, 20 Sept 2024

Thanks to: P. Azzi, G. Gaudio, P. Jenni, I. Vivarelli,



"I believe FCC is the best project for CERN's future,
we need to work together to make it happen"
- Fabiola Gianotti, FCC Week London, 5th June 2023

The Timeline



- FCC-ee **technology is mature** → construction in parallel to HL-LHC operation
- Physics a few years after the HL-LHC (2045-2048)
- Continuity of HEP guaranteed & only facility commensurate to size of community

Two-stage approach: first FCC-ee, then FCC-hh

- Allows to spread the cost of the (more expensive) FCC-hh over more years
- 20 years of R&D work towards affordable magnets
- Optimization of overall investment by **reusing civil engineering and large part of the technical infrastructure**
- Allows CERN and Europe to keep the **leadership** in the field for the next 60-70 years

A little bit of propaganda

Optimal energy range for SM particles

Sharpen and challenge our knowledge of already existing physics

LEP1 statistics in a few minutes

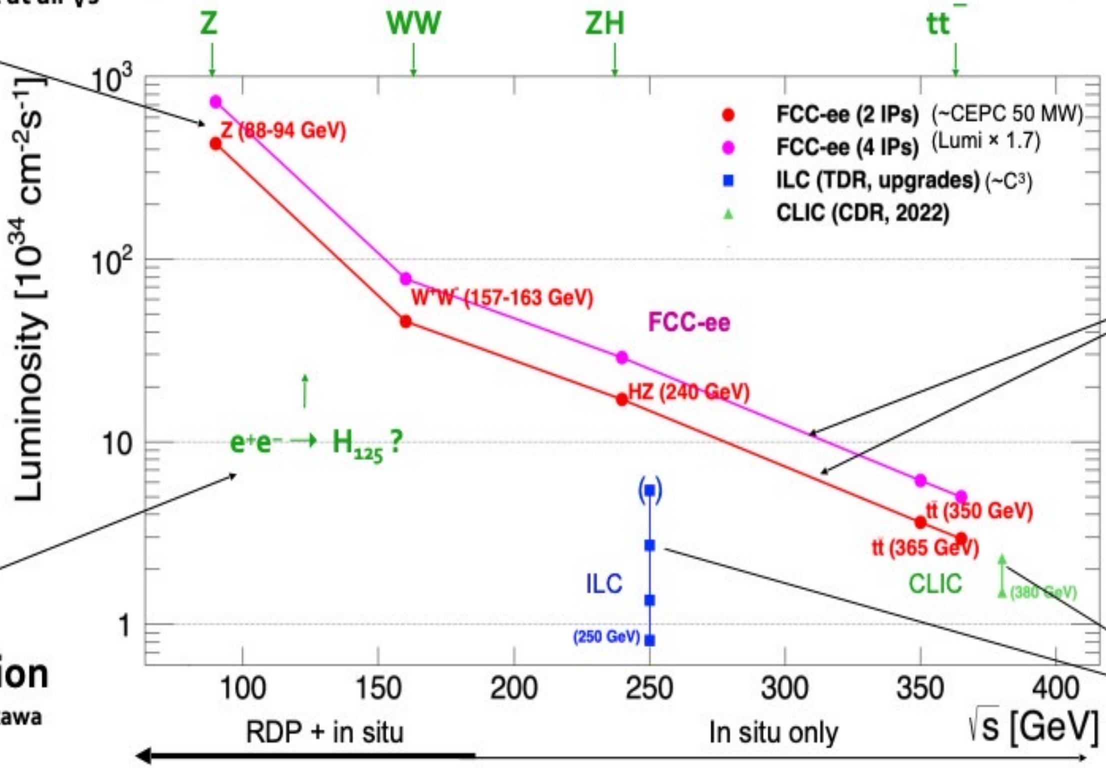
Detector calibration/alignment at all √s

Highest luminosities

Less running time for a given physics outcome

Better physics outcome for a given running time

Increase discovery potential



Serve up to 4 interaction points

Net overall gain in MW/ab⁻¹ or CO_2-eq/ab⁻¹

Essential redundancy for precision measurements

May satisfy all detector requirements

Increase discovery potential

Enhance the community (FCC/CERN clients)

√s Monochromatisation

Unique opportunity for electron Yukawa

Motivates the competition

Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination

Both with resonant depolarisation (RDP) and with collision events in up to four detectors

Essential for precision measurements

The physics we can do

Detector hermeticity, flexibility

Tracking resolution (tagging), vertexing (flavour), jet resolution

Precision SM

- $m_Z, \Gamma_Z, N_\nu, R_l, A_{FB}, m_W, \Gamma_W$
- α_s (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

BSM direct searches

Axion-like particles, dark photons, Heavy Neutral Leptons, LLPs

Higgs

Higgs physics

Higgs width, Higgs to invisible, couplings (including self-couplings)

Particle ID, detector resolution, systematics, stability

EW factory (Z,WW)

FCC-ee

Top

Top physics

m_{top}, Γ_{top}, EW top couplings

Flavour Physics

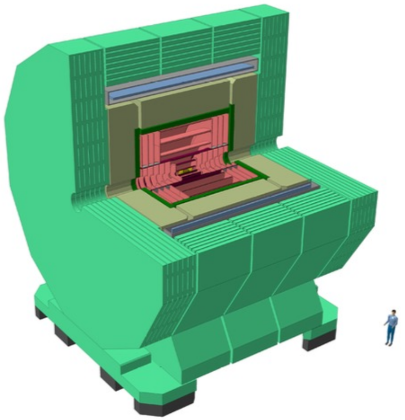
- 10^{11}: τ-based EW observables, lepton universality
- 10^{12} $b\bar{b}/c\bar{c}$ pairs: flavour observables, flavour anomalies, CKM, CP, etc.

Vertexing, Particle ID (tracking,calo)

Preliminary detectors

CLIC-like Detector (CLD)

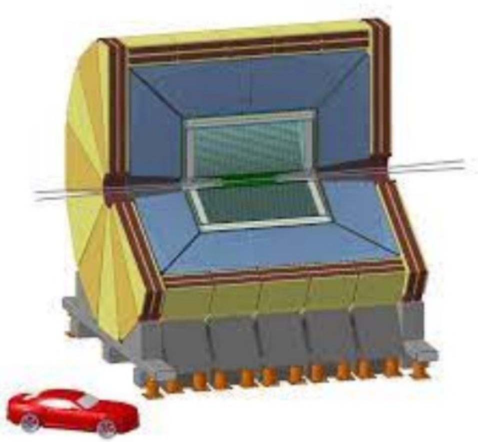
- Full silicon vertex-detector + tracker
- 3D high-granularity calorimeter
- Solenoid outside calorimeter



- Sci-steel high-granularity HAD Calo
- RPC-based Muon detector

Innovative Detector for an Electron-Positron Accelerator (IDEA)

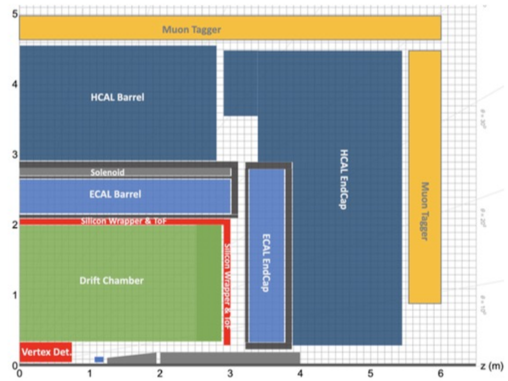
- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter (solenoid inside)



Total length. 11–13m
Height. 10–12m

Noble Liquid (ALLEGRO)

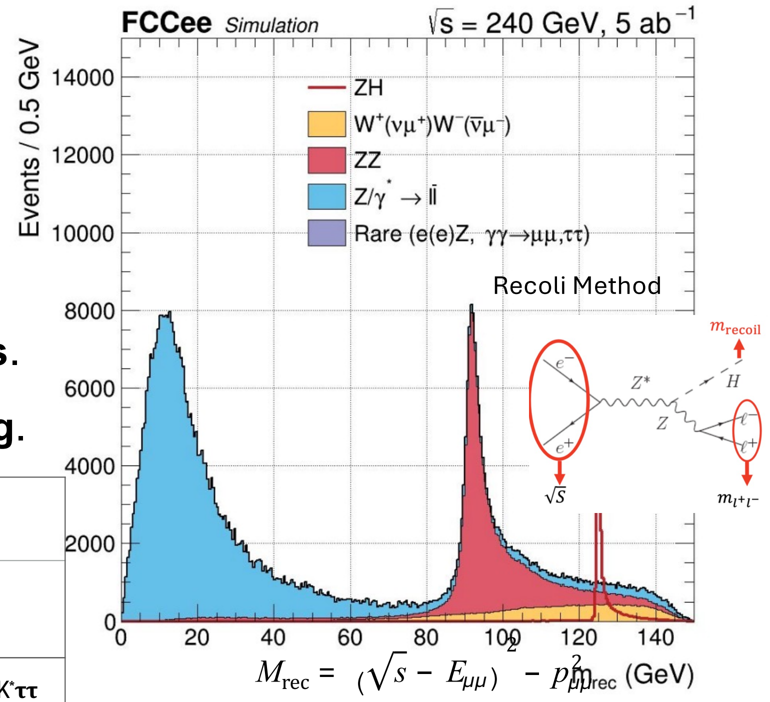
- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal



With 4IP, opportunity to have detector optimised for specific processes

Benchmarks for detectors

- **Higgs boson tagging** and **BR into invisibles** sets requirements on:
  - Material in the tracking volume.
  - Magnetic field (and thickness of solenoid).
- Higgs BR sets requirements on e, γ, jet energy and angular **resolutions**.
- Tagging $H \to b\bar{b}$, $c\bar{c}$ ($s\bar{s}$?) sets requirements **on tracking and vertexing**.



	Critical detector	Requirement	Comments
$ZH \to \ell^+\ell^- X$	Tracker	$\frac{\sigma(p_T)}{p_T^2} \sim \frac{0.1\,\%}{p_T} \oplus 2 \cdot 10^{-5}$	But also precision EW flavour, BSM
$H \to b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu\mathrm{m}]$	Additional case study: B→K*ττ
$H \to gg, q\bar{q}, VV$	ECAL, HCAL	$\frac{\sigma(E_{jet})}{E_{jet}} \sim 4\,\%$ (at $E_{jet} \sim 50$ GeV)	Also BSM and missing energy reconstruction
$H \to \gamma\gamma$	ECAL	$\frac{\sigma(E_\gamma)}{E_\gamma} \sim \frac{10-15\,\%}{\sqrt{E_\gamma}}$	But flavour physics may need better EM energy resolution

Benchmark physics channels for Higgs/Top/EW factories discussed in 2401.07564 will improve detector requirements by spring 2025

- Spoiler: "Higgs factory" requirements are not the most stringent
- …and in general requirements grow as more and more physics is explored.

SM/BSM in Flavour/Tau physics (Tera-Z run)

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	600	170

~10 times Belle's stat

Boost at the Z!

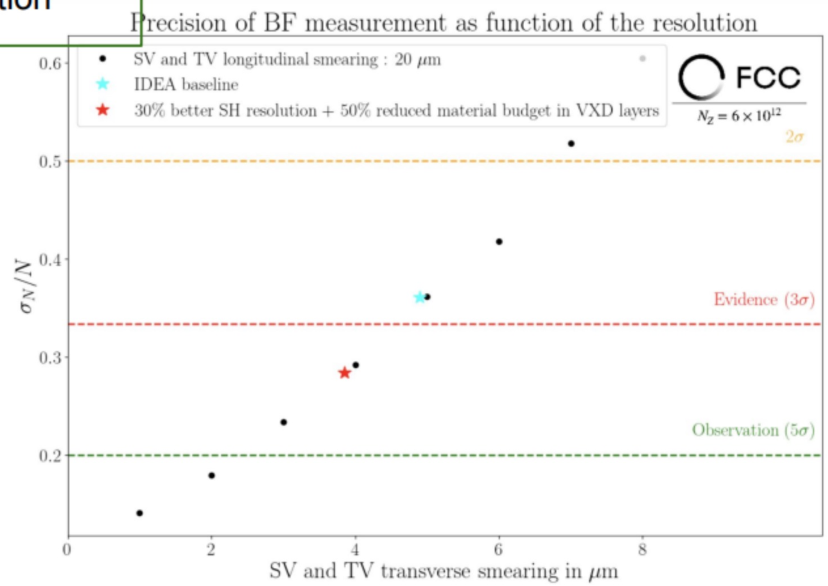
Lots of BSM searches/signatures
(rare decays, LFV/LFU tests)

- **Enormous statistics**
  10^{12} $b\bar{b}$, $c\bar{c}$, 2x10^{11} $\tau\tau$ events

- Clean environment
- Favourable kinematics -> boost
- Excellent vertexing/tracking/PID

5σ observation with **2 μm** vertex resolution

$B^0 \rightarrow K^{*0}\tau\tau$

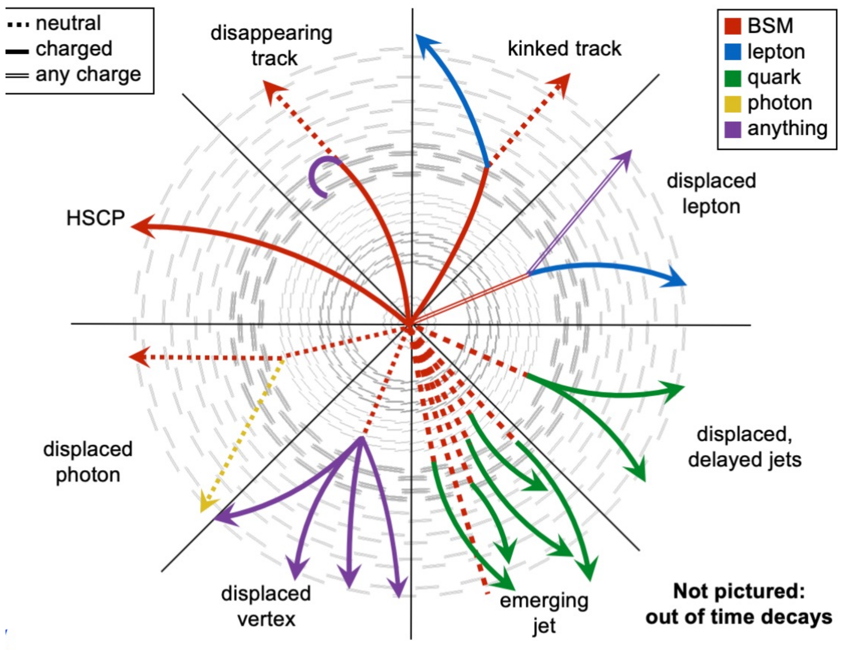


Direct search for Feebly Interacting Particles

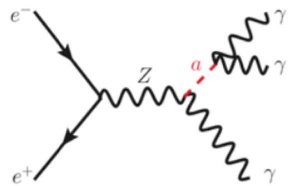
Intensity frontier at Tera-Z offers the opportunity to directly observe new feebly interacting particles in a very clean environment

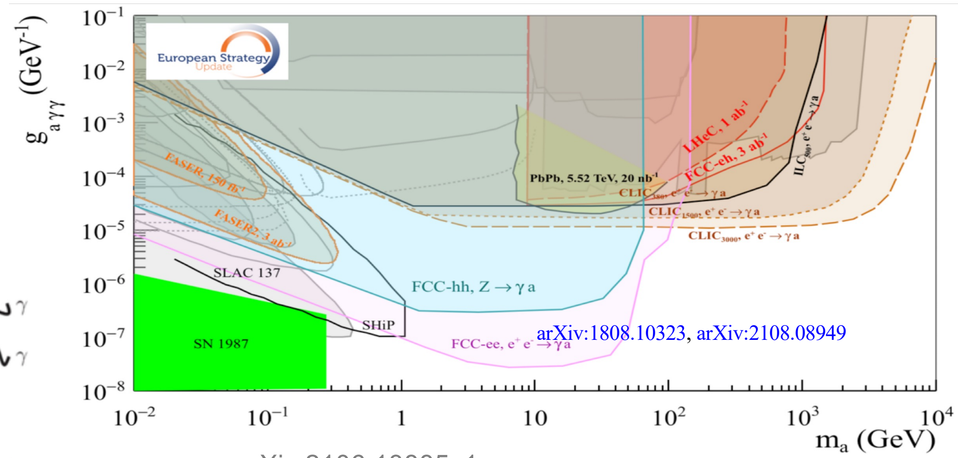
Signatures driven by search for unusual final states

Novel detector requirement to fully exploit possibilities



Axion-like Particles (ALPs) are pseudo-scalars in models with spontaneously broken global symmetries. Very weakly coupled to the dark sector





arXiv:2106.13885v1

- ALPS might be long-lived when couplings and mass are small
  - Final states with at least 1 photon (or more) can set requirements on the electromagnetic calorimeter energy resolution and granularity

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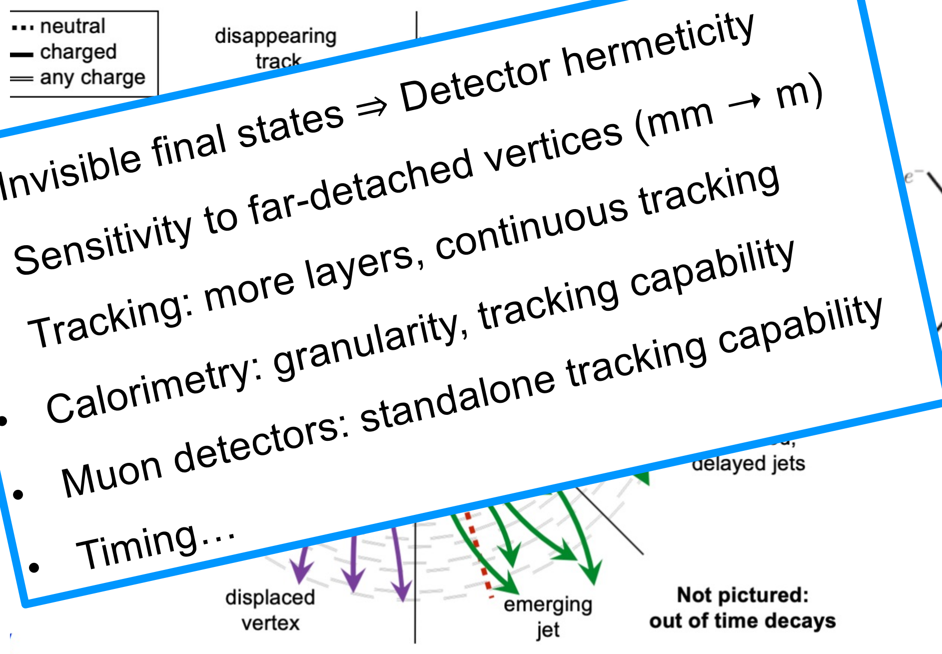
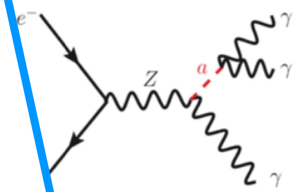


- Invisible final states ⇒ Detector hermeticity
- Sensitivity to far-detached vertices (mm → m)
- Tracking: more layers, continuous tracking
- Calorimetry: granularity, tracking capability
- Muon detectors: standalone tracking capability
- Timing…



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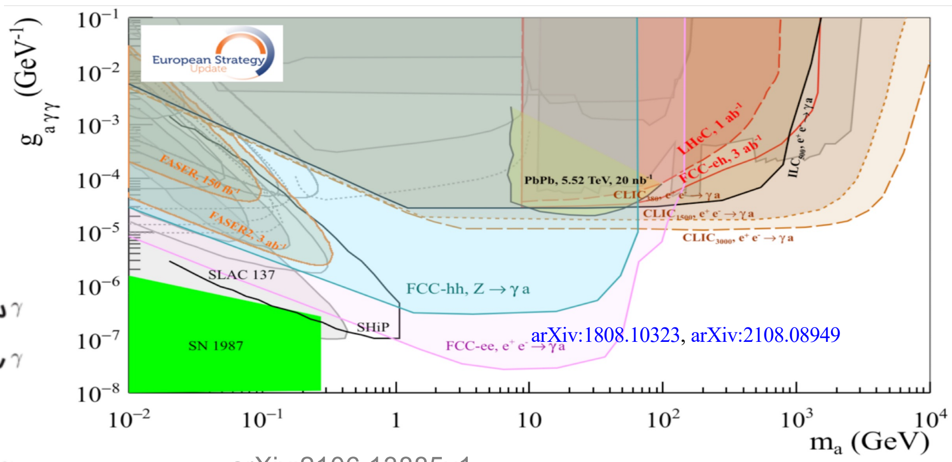

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Vertex detectors

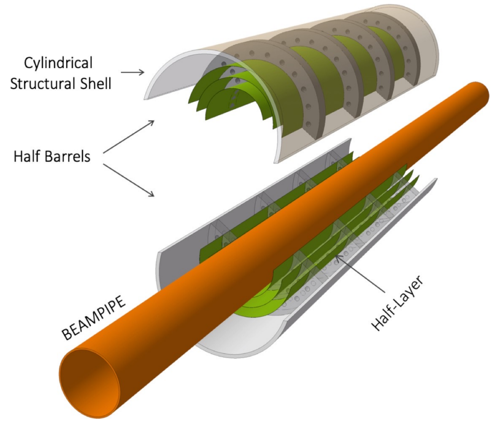
General requirements

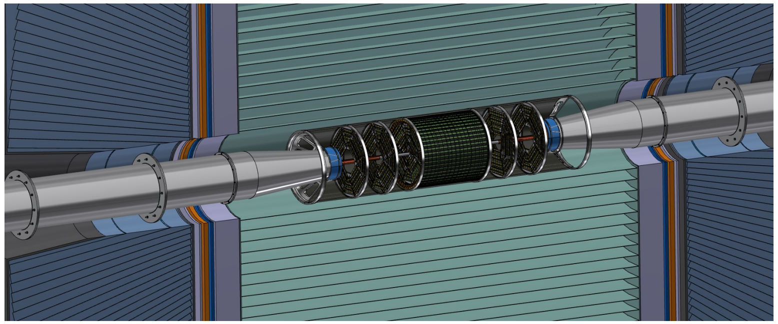
Flavour physics and tagging requires 3-5 μm→ pixel size ~20 μm.
Small material budget (0.1% of X_0/layer) → Thickness ~ 50 mm.
Low power consumption (especially inner layers) → 10-30 mW/cm2.

Solution: CMOS MAPS

- High spacial resolution and small material (integrated circuitery)
- In a number of LHC experiment upgrades (ALICE ITS, ATLAS ITK, etc.)
- No need for bump-bonding: allow smaller pixel size
- Affordable overall

Bent silicon sensors (ALICE ITS3 R&D)





The IDEA design

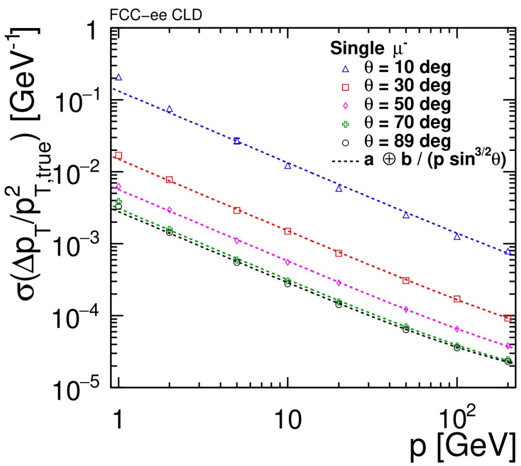
All-silicon tracking - the CLD approach

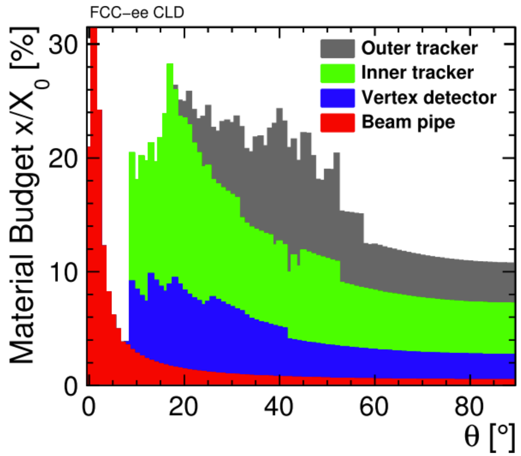
VTX:

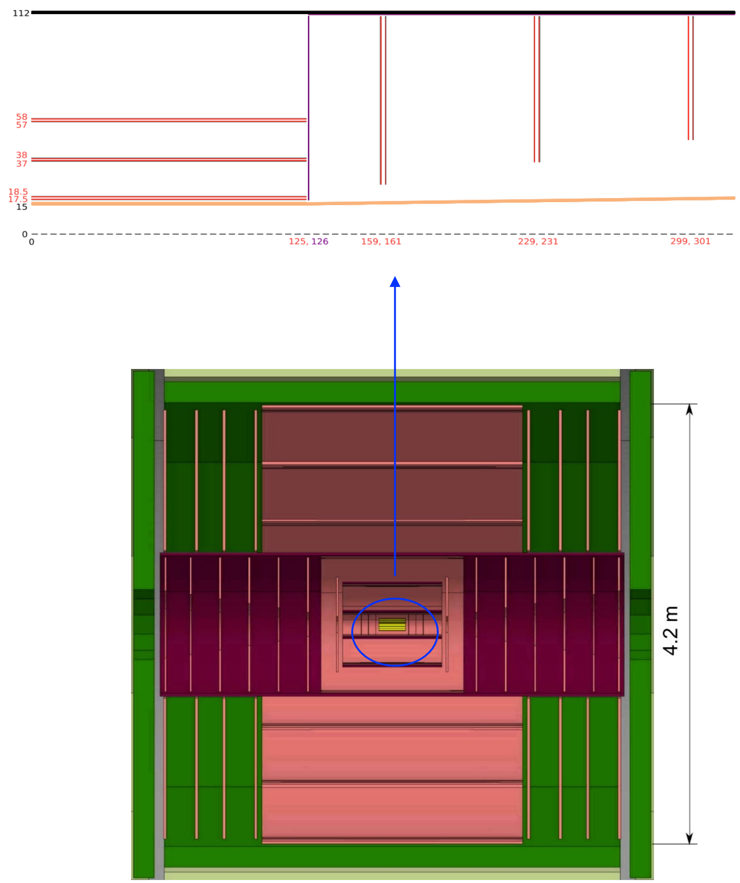
- Pixel size 25x25 μm² - 50 μm sensor thickness to have 3 μm resolution.
- Material and cooling benchmarked on ALICE ITS (LS2) upgrade design.
- Power dissipation: 40 mW/cm² - water cooled.

ID:

- Single point resolution 7x90 μm² - 5x5 μm² in 1st layer.
- Inner tracker: Barrel 3 layers, end-cap 7 discs.
- Outer tracker: Barrel 3 layers, end-cap 4 discs.



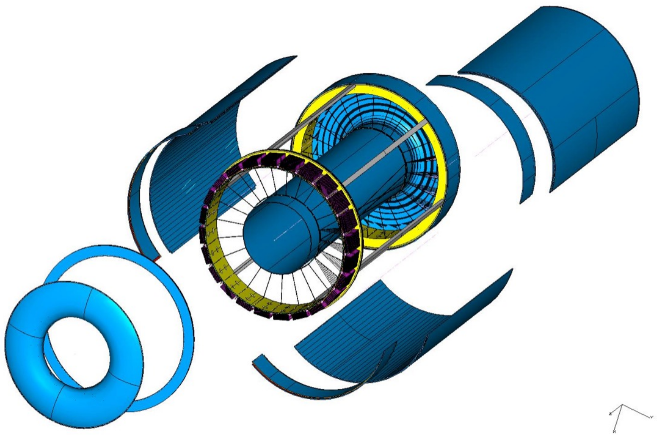


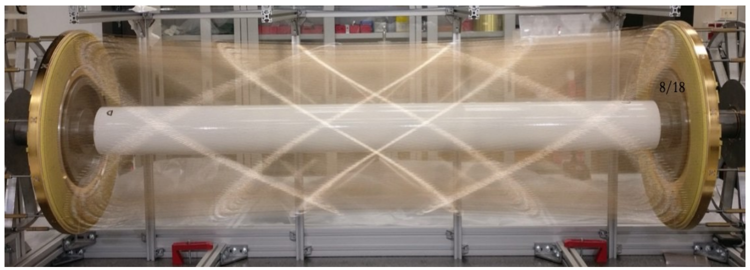


Light-weight tracking

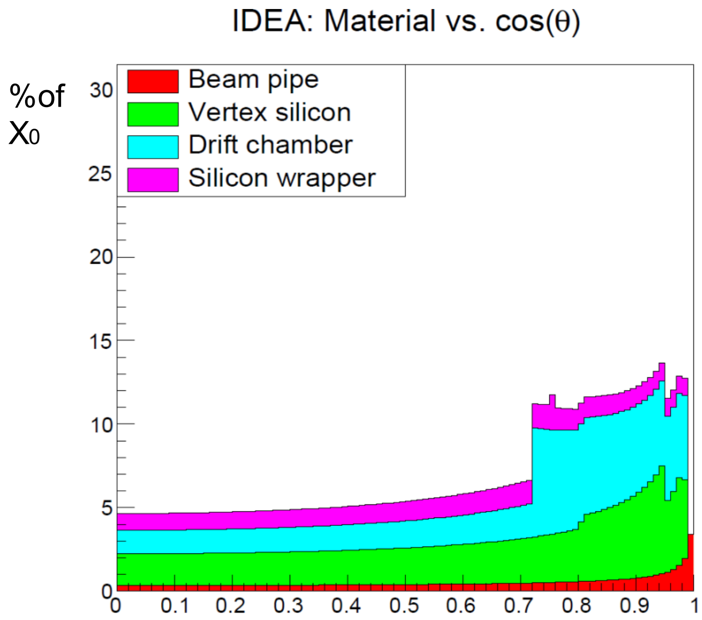
ALLEGRO: VTX similar to CLD

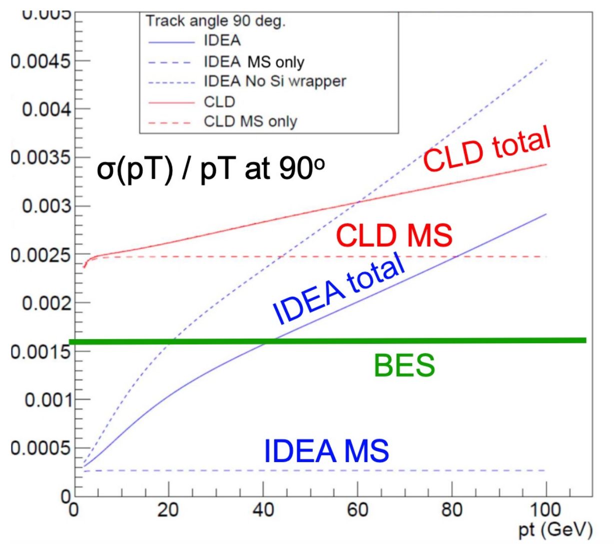
- Tracking with **drift chamber**
  (As in IDEA - similar in concept to MEG II chamber).
- Minimise multiple scattering, with **only 2%** X_0 in front of calorimeter.
- Drift time O(300 ns).
- Cluster counting (12.5 cm^{-1} clusters) **improves spacial resolution and dE/dx measurement.**
- Single point precision (with cluster counting) better than ~100 μm.
  Many points on each track.





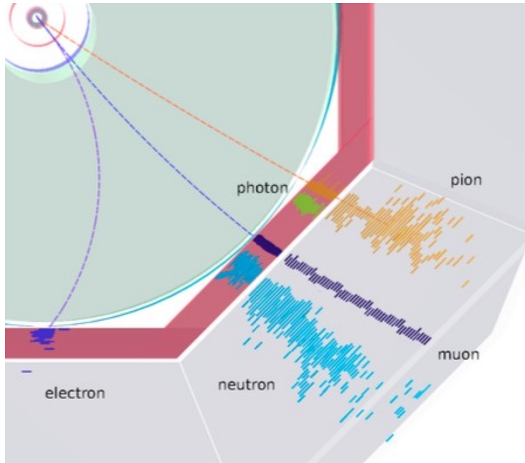
(MEG II chamber)





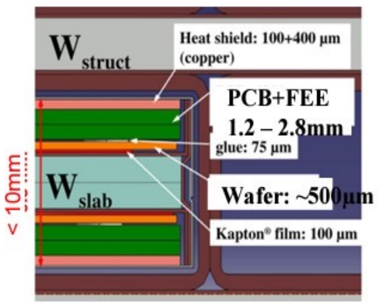
Particle-flow oriented calorimeters

- Basic idea: for charged particles, measure their contribution to jets by using tracker rather than calorimeter.
- Requirements: High granularity - compactness (small Moliere radius).
- Drawbacks: confusion term (when the calorimeter subtraction goes wrong - produces tails in jet energy distributions).



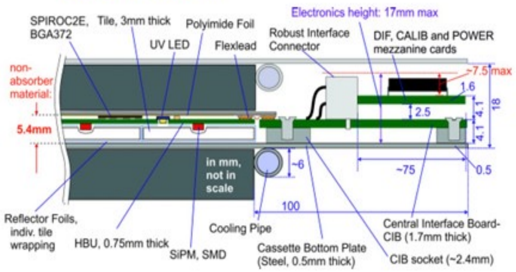
Challenges:
- Cooling despite challenging environment (no power pulsing possible)
- Timing for particle flow?
- AI-boosted particle flow?

SiW ECAL



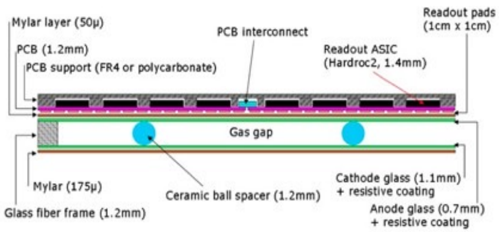
Active area: silicon PiN Diodes
Typical segmentation: 0.5x0.5 cm²

Analogue Scintillator HCAL and ECAL



Scintillator tiles/strips + SiPM
Typical segmentation: 3x3cm²

Semi Digital HCAL



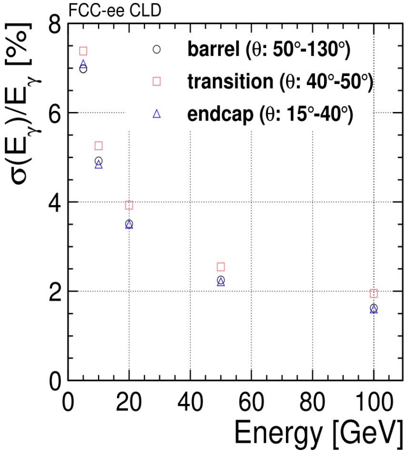
Gas RPCs
Typical segmentation: 1x1cm²

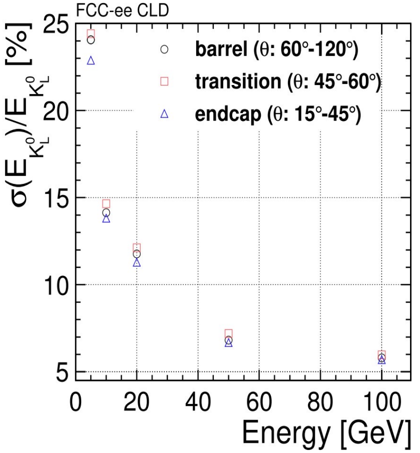
Calorimeters (CLD)

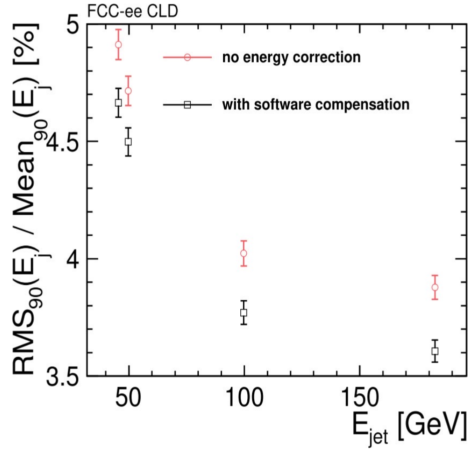
- Goal: calorimeter **optimised for particle flow** (emphasis on **granularity** rather than **quality of the energy measurement**)

- **ECAL** (CDR numbers):
  - Cell size 5x5 mm^2 with Si-W.
  - 40 layers - 5.05 mm thickness each.
  - Total 20 cm, 22 X0, ~ 1 λI.

  No power pulsing - cooling is an issue - part of the optimisation proce
- **HCAL**:
  - Cell size 30x30 mm^2 scintillator-steel. 44 layers - 26.5 thickness each.
  - Total 117 cm, 5.5 λI.







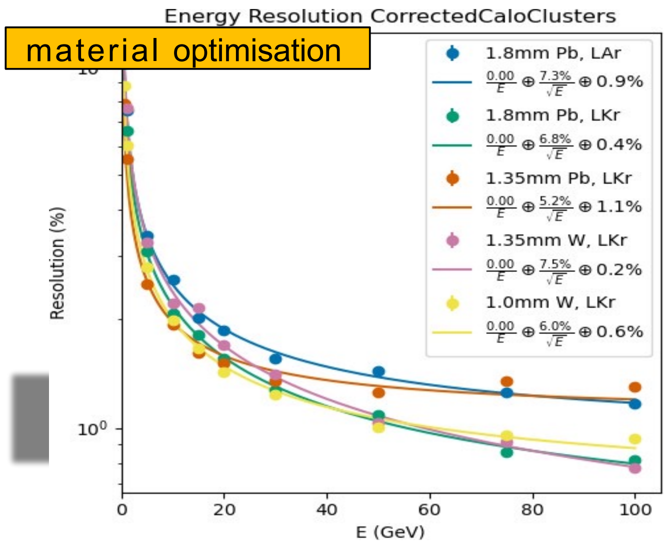
Calorimeters (ALLEGRO)

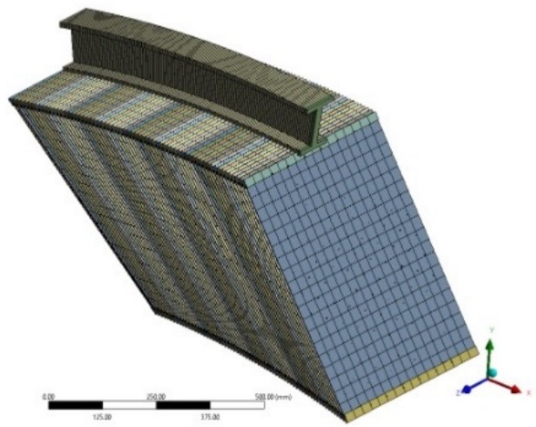
EM Calorimeter:

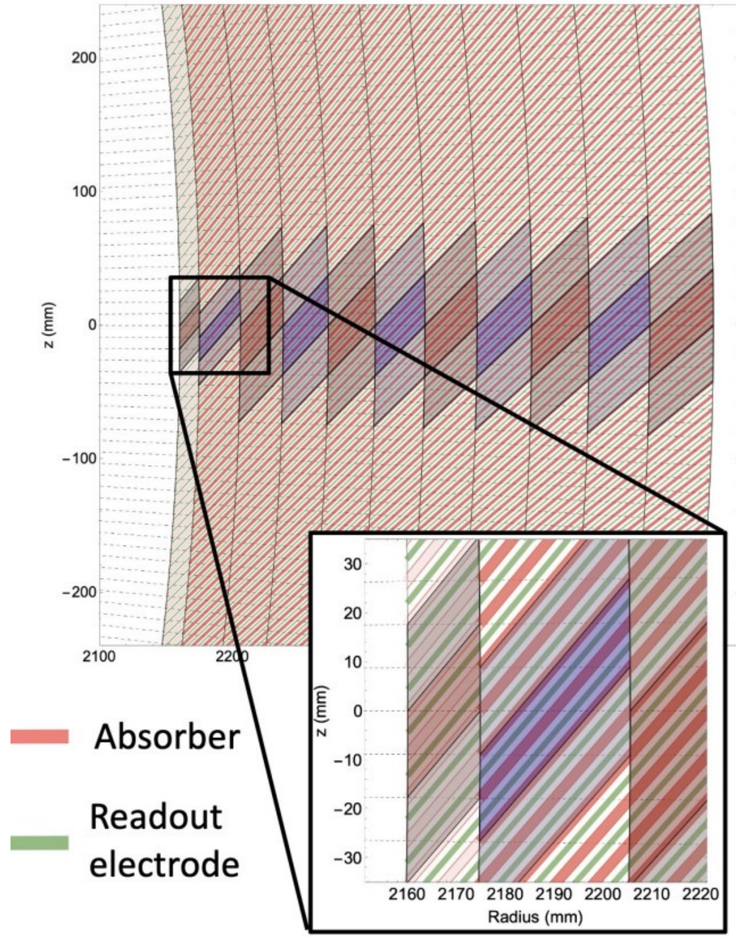
- Noble liquid calorimeters: good energy resolution, long-term stability, easy to calibrate.
  - Ideas to **achieve high granularity** targeting particle flow.
- Solution heavily inspired to ATLAS: LAr + copper - but different geometry.

Hadronic section with an increased granularity scintillator tile + steel (a la TileCal).

material optimisation







Dual-Read out Calorimeters (IDEA)

- 2m / 7 λ_{int}
- Measure simultaneously:

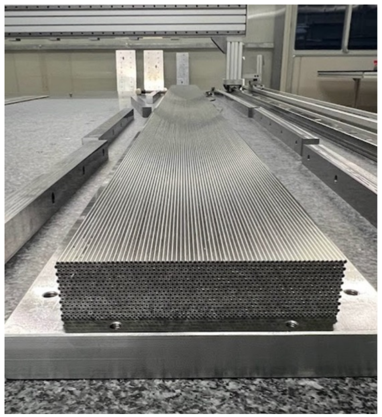
Scintillation signal (S)
Cherenkov signal (C)

- Calibrate both signals with e-
- Unfold event-by-event f_{em} to obtain corrected energy

$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

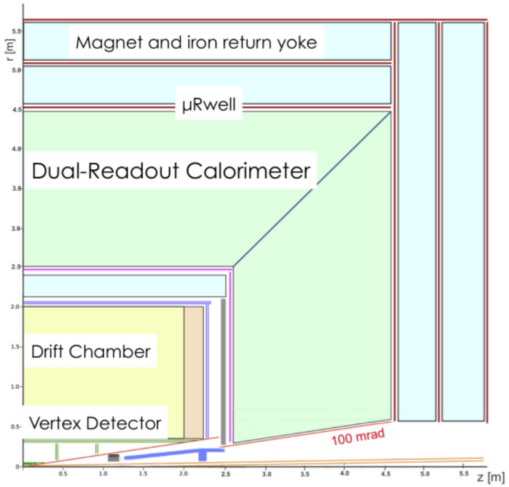
$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

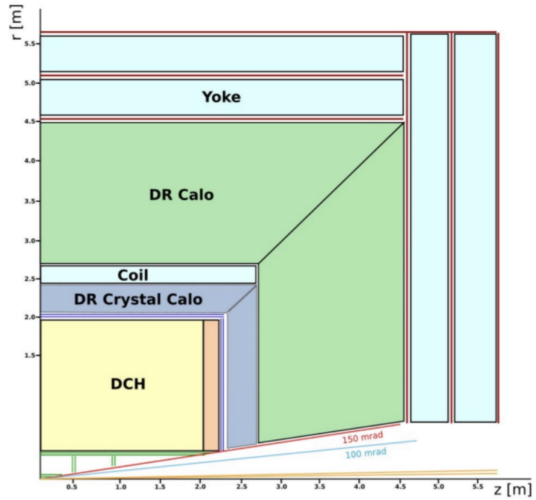
$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with: } \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$



Currently 2 options under study:

- Longitudinal unsegmented dual-readout fibre calorimeter (combined EM+HAD)
- Dual-readout crystal (EM calo) + dual-readout fibre calorimeter (HAD calo)

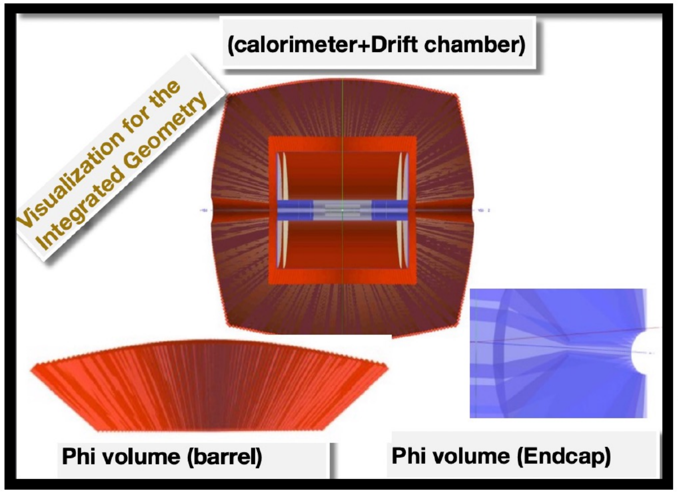




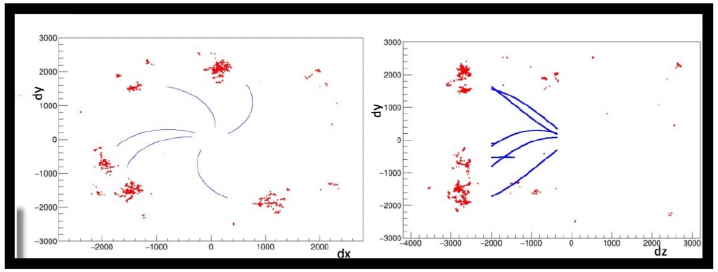
Not only detectors construction

- Plenty of activities to take care of, starting from the idea of an experiment to its realization, commissioning, and exploitation

Detector simulation
Test beam campaigns
Detector performance studies
Physics simulation
Data acquision
Triggers
Data storage and distribution
Analysis software …..



FASTSIM Delphes IDEA card used for performance studies FCCSW
Very sophisticated compared to default.
Latest additions: Vertexing, LLP, PID, dN/dx, dE/dx



FULLSIM: standalone GEANT4 description
- **Fully integrated geometry**
- **Output hits and reco tracks converted to EDM4HEP**
- **Ready for PFlow development and other reconstruction frameworks/algorithms (ACTS, Pandora etc) in FCCSW**

Latest and next steps

- **703 pages**: 7 chapters (cost and financial feasibility is a separate document) + refs.
  - Placement scenario (75 pages)
  - Civil engineering (50 pages)
  - Implementation with the host states (45 pages)
  - Technical infrastructure (110 pages)
  - FCC-ee collider design and performance (170 pages)
  - FCC-hh accelerator (60 pages)
  - (Cost and financial feasibility)
  - Physics and experiments (110 pages)
  - References (70 pages)
- **Executive summary**: 44 pages
- Reviewed by
  - Scientific Advisory Committee and Cost Review Panel on Oct. 16-18
  - Scientific Policy Committee and Financial Committee on Nov. 21-22
  - CERN Council Feb. 2


Future Circular Collider
Midterm Report

February 2024

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, T. Watson, F. Zimmermann

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The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

296 authors
16 editors

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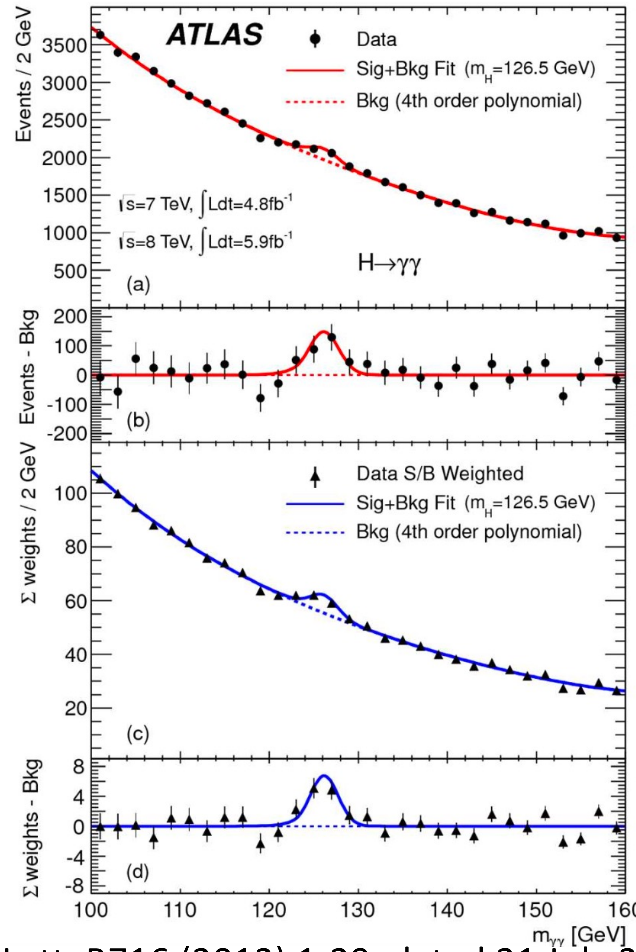
Too much time without data

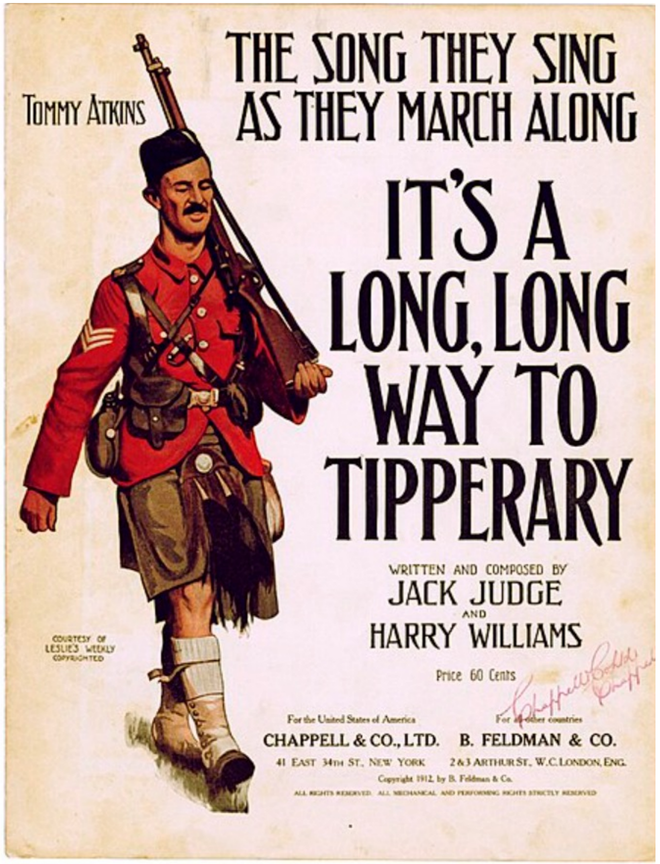
The past: what the world saw..

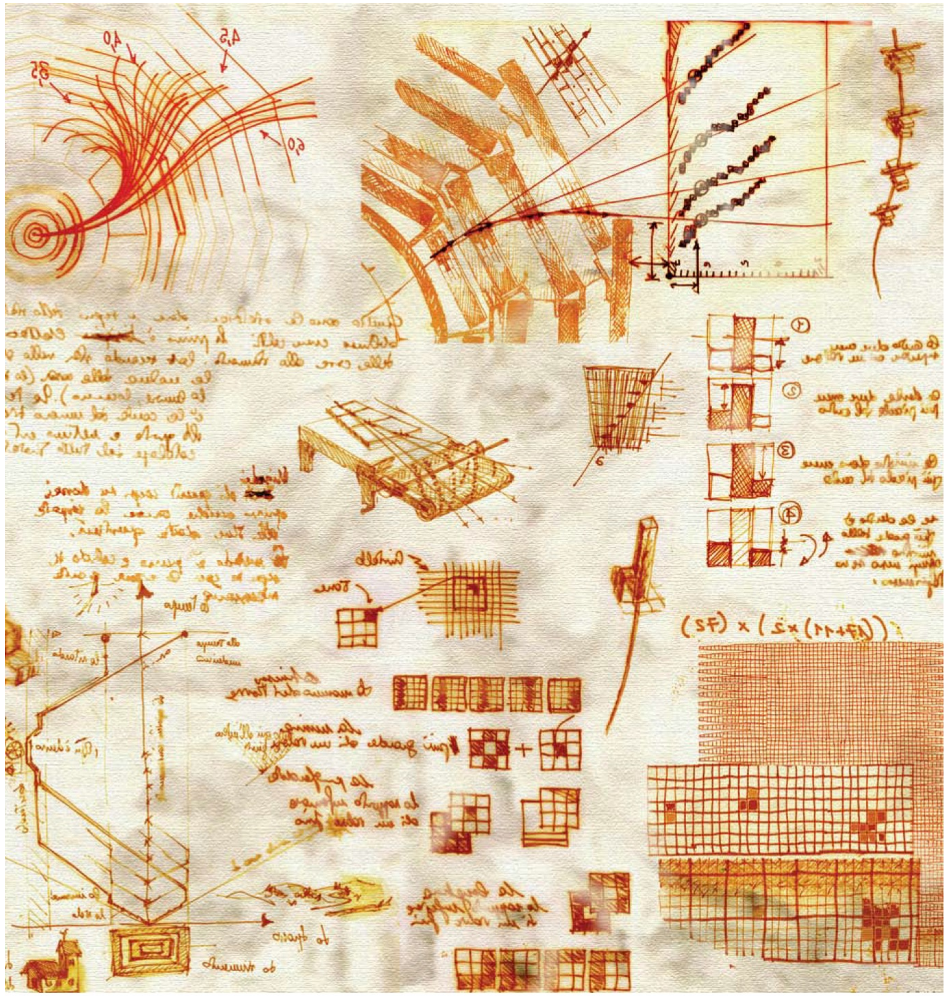


Phys. Lett. B716 (2012) 1-29, dated 31 July 2012

..And how did we get there

By Sergio Cittolin





How the LHC came to be

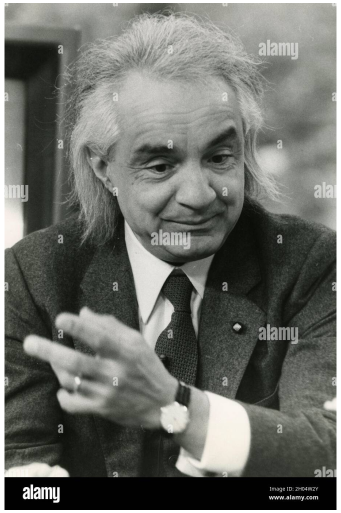
Some very early key dates

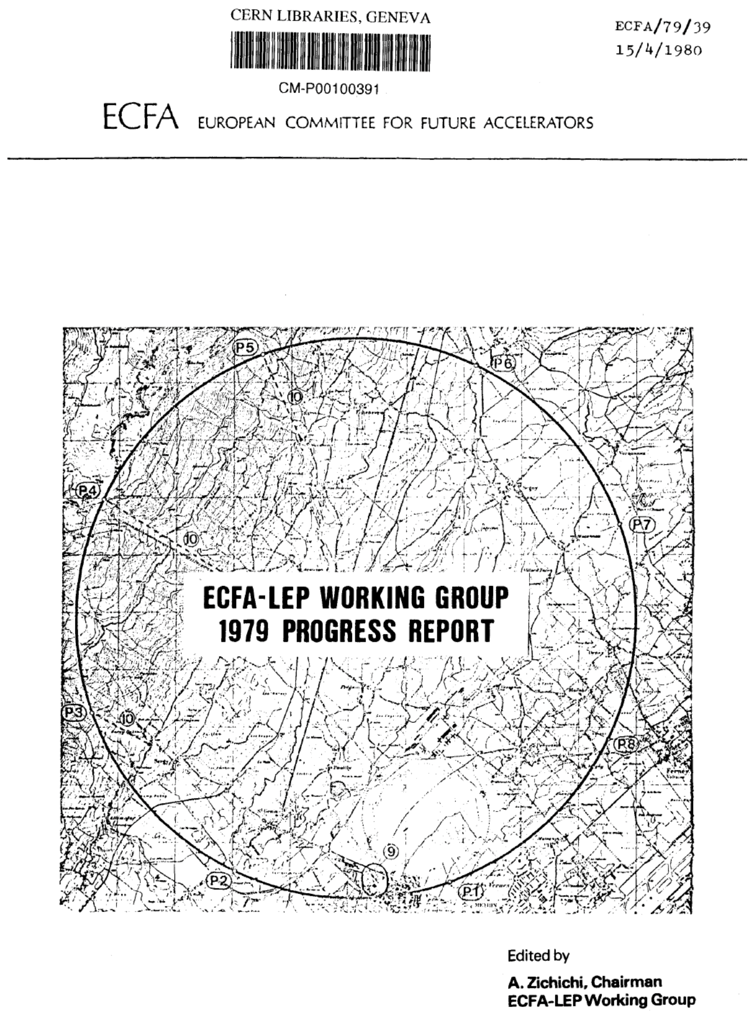
1977 The community talked about the LEP project, and it was already mentioned that **a new tunnel could also house a hadron collider in the far future**

1979: LEP White Book:

ECFA-LEP Working Group chaired by A Zichichi

'Tunnel with 27 km circumference and a diameter of 5 m, with a view to the **replacement of LEP at the end of its activities by a proton-proton Collider using cryogenic magnets**'





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CM-P00100391

ECFA/79/39
15/4/1980

ECFA EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

ECFA-LEP WORKING GROUP
1979 PROGRESS REPORT

Edited by

A. Zichichi, Chairman
ECFA-LEP Working Group

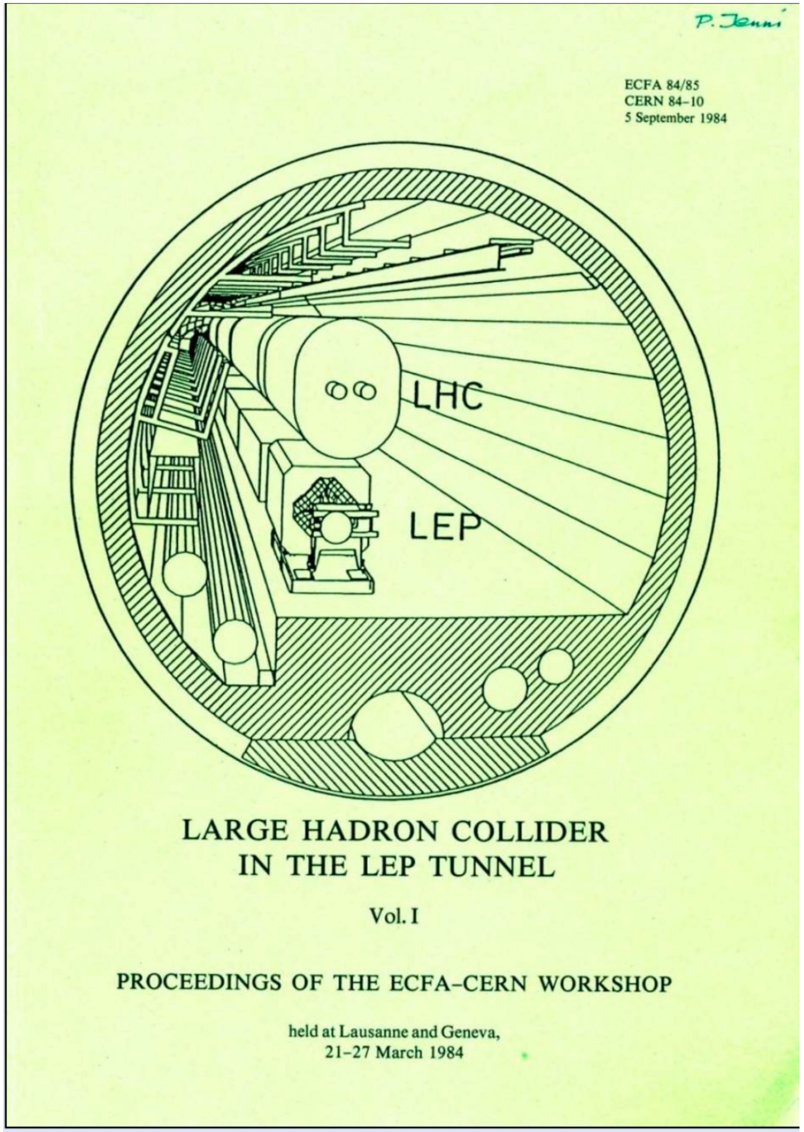
1984: CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

Giorgio Brianti,
leading the LHC studies until 1993

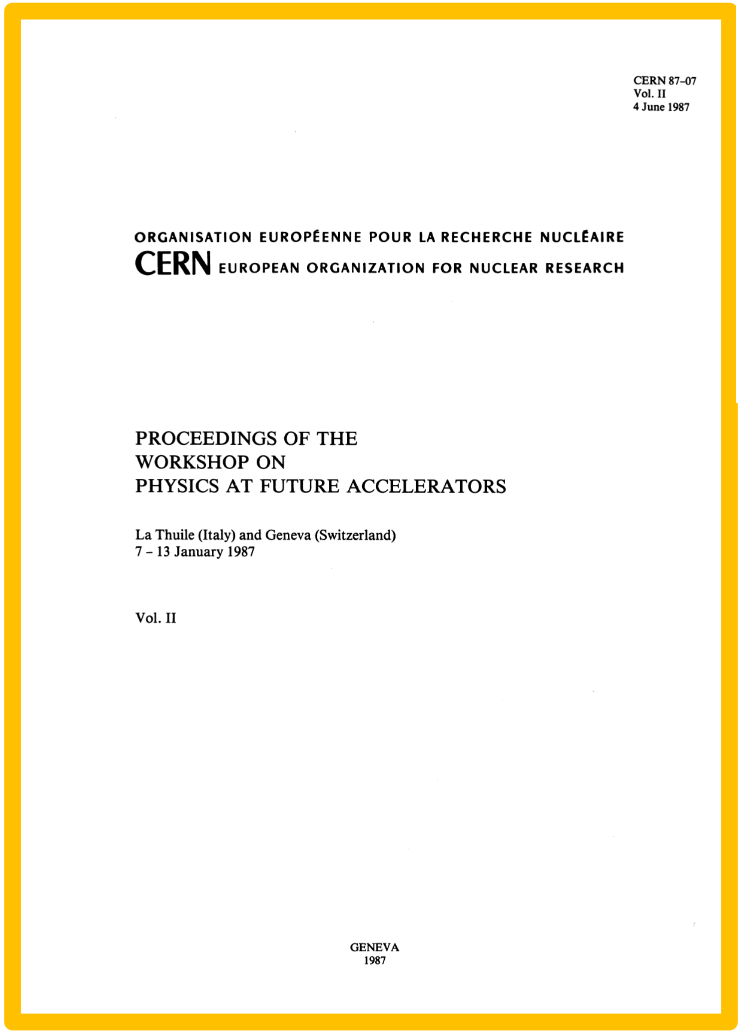
1986: LAA **R&D on new detector technologies for TeV colliders** started,

1987 La Thuile Workshop

Many LHC members were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee



Carlo Rubbia's Committee



CERN 87-07
Vol. II
4 June 1987

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROCEEDINGS OF THE
WORKSHOP ON
PHYSICS AT FUTURE ACCELERATORS

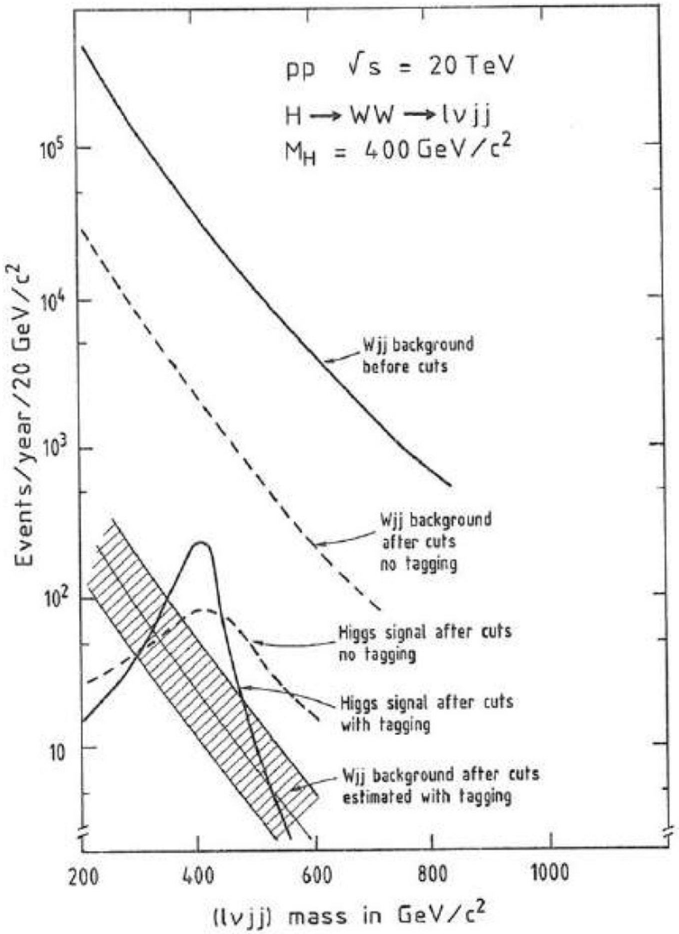
La Thuile (Italy) and Geneva (Switzerland)
7 – 13 January 1987

Vol. II

GENEVA
1987

Collider parameters

Machine		$\sqrt{s}$ (TeV)	L ($cm^{-2}s^{-1}$)
LHC	pp	16	$10^{33} \rightarrow 10^{34}$
LHC	ep	1.3	10^{32}
LHC	ep	1.8	10^{31}
CLIC	e^+e^-	2	$10^{33} \rightarrow 10^{34}$

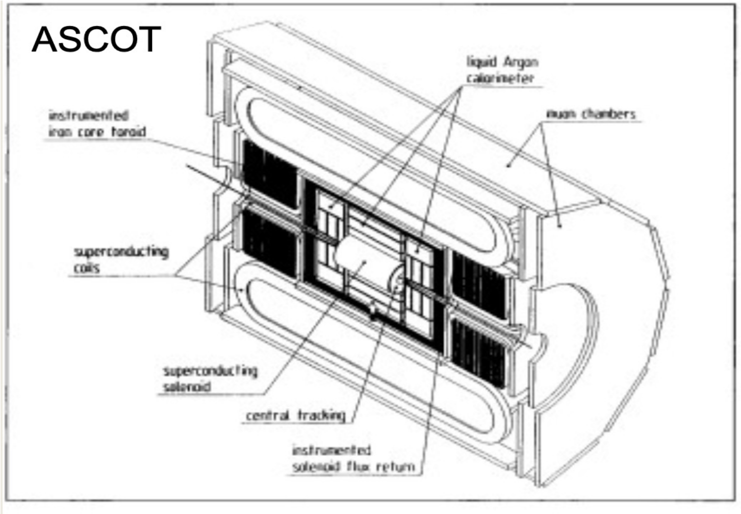


1989 ECFA Study Week in Barcelona for LHC instrumentation
(forming of first proto-Collaborations)

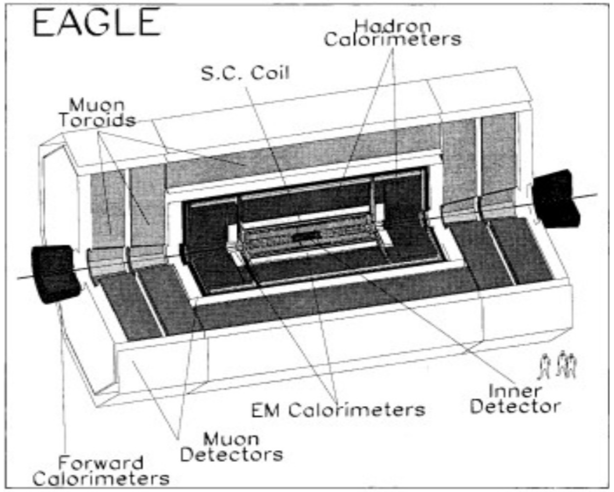
1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)
(First serious R&D results)

1992 CERN – ECFA meeting ‘Towards the LHC Experimental Programme’
in Evian

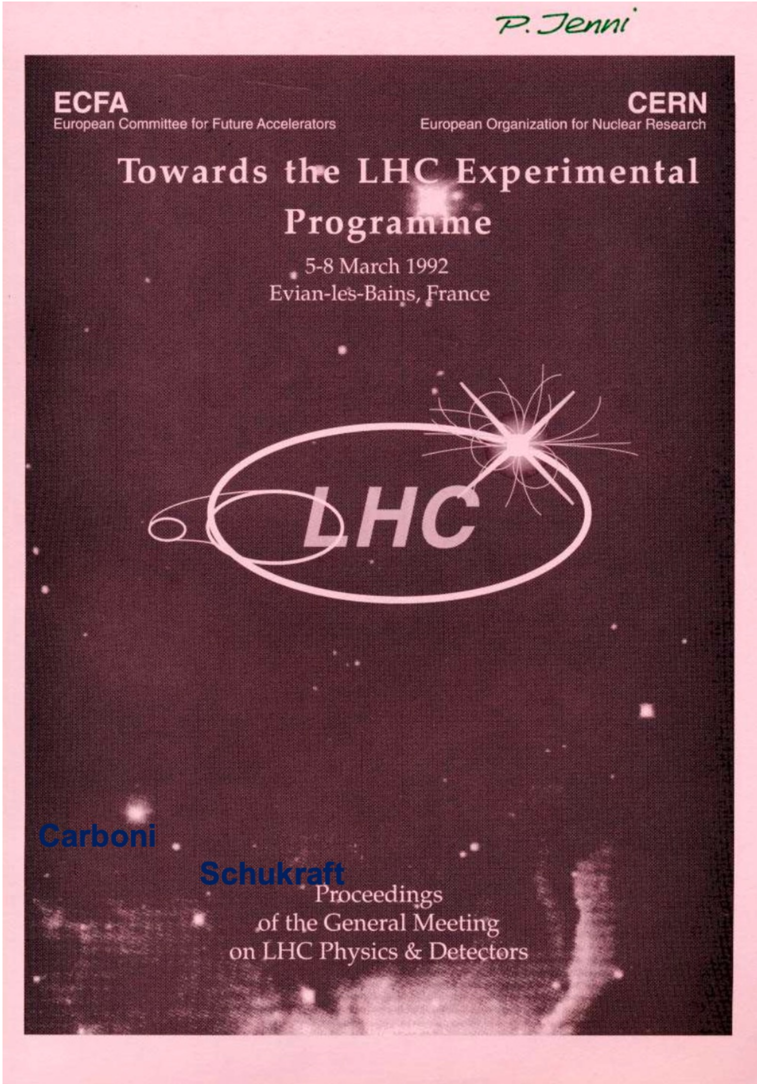
Four general purpose experiments: (ASCOT, CMS, EAGLE, and L3+1)



ASCOT: superconducting air-core barrel and warm iron end-cap toroids



EAGLE: warm iron barrel and end-cap toroids



ASCOT/EAGLE merging

1992

In September: Decision on the name taken in vote at the Collaboration Board based on many names suggested by Collaboration members

1st October 1992
ATLAS LoI submitted to the LHCC
'Official birth of the ATLAS Collaboration'

ATLAS
Collaboration

Alberta, Alma Ata, NIKHEF Amsterdam, LAPP Annecy, Athens, NTU Athens, UA Barcelona, Bern, Birmingham, Bratislava, Cambridge, CERN, Clermont-Ferrand, NBI Copenhagen, Cosenza, INP Cracow, IPNT Cracow, Debrecen, Dortmund, JINR Dubna, Edinburgh, Florence, Frascati, Freiburg, Geneva, Glasgow, ISN Grenoble, Technion Haifa, Hamburg, Heidelberg, SEFT Helsinki, Innsbruck, Jena, Kobe, Kosice, Lancaster, Lisbon, Liverpool, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Melbourne, Milano, Montreal, ITEP Moscow, Lebedev Moscow, MEPhI Moscow, MSU Moscow, Munich, MPI Munich, Nijmegen, LAL Orsay, Oslo, Oxford, Paris VI and VII, Pavia, Pisa, Prague, IHEP Protvino, COPPE Rio de Janeiro, Rome I and II, Rutherford Appleton Laboratory, DAPNIA Saclay, CST Saratov, Sheffield, Siegen, LITMO St. Petersburg, NPI St. Petersburg, Stockholm, MSI Stockholm, Ansto Sydney, Tel-Aviv, Tokyo, Uppsala, Valencia, UBC Vancouver, Victoria, Vienna, Warsaw, Weizmann Rehovot, Wuppertal

(88 Institutions with about 850 authors on LoI)

Spokespersons: F. Dydak and P. Jenni

On the LHC machine side..

1993 proposal of LHC with commissioning in 2002

Minister Boris Saltykov and DG Carlo Rubbia signing an updated Cooperation Agreement Russia and CERN (28 June 1993)

1994 to have any chance at all of approval, the idea of a staged construction was worked out by the then new CERN DG Chris Llewellyn-Smith

LHC approval

The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including the experiments

1996

December Council approved finally the single-stage 14 TeV LHC for completion in 2005

Signature of the Japan-CERN agreement on 1st June 1995

(K Yosano – Japanese Minister, H Curien – Council President, C Llewellyn-Smith – CERN DG, with the famous Daruma doll)

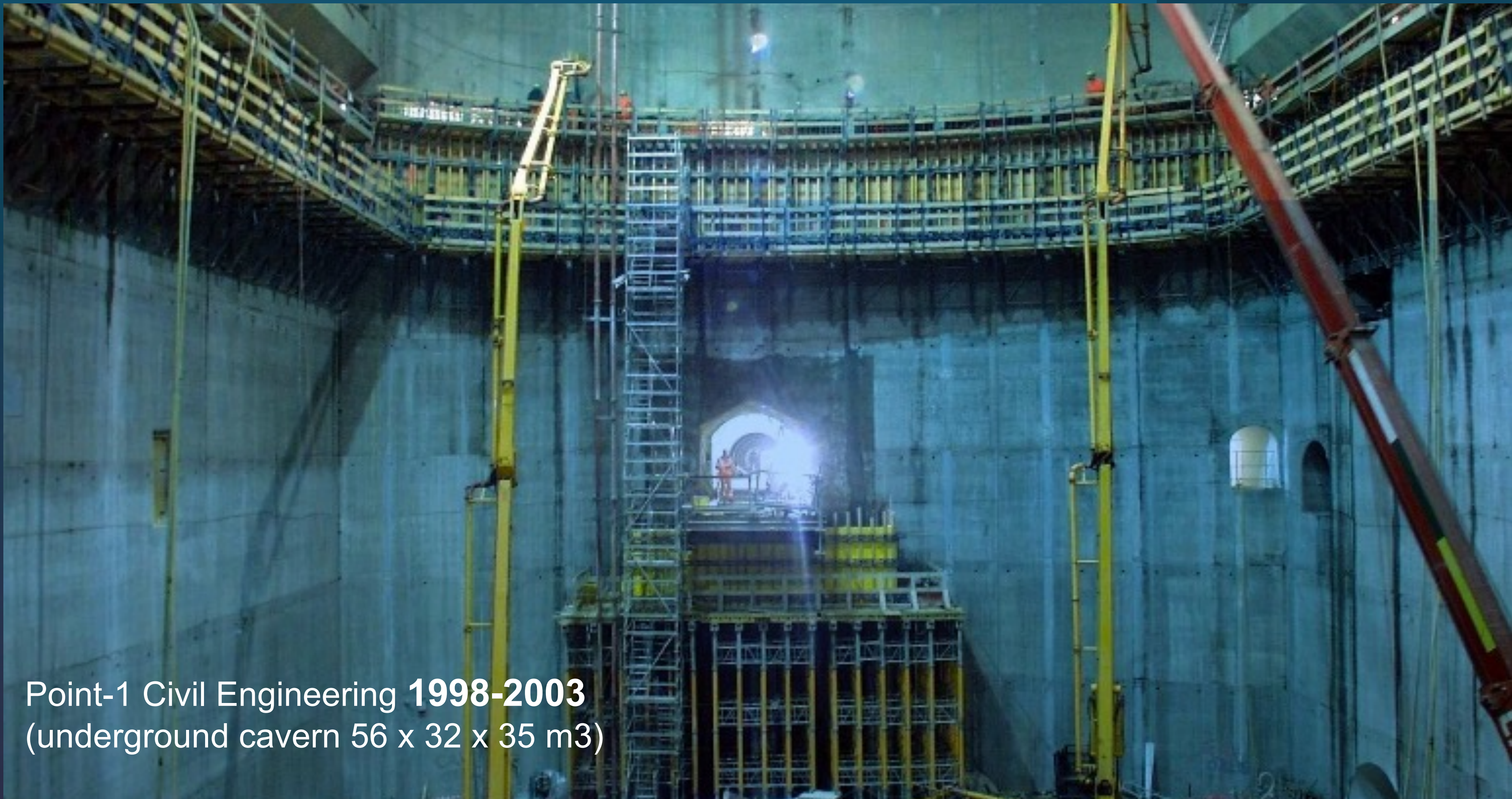
Atlas approval

1995: ATLAS presents to the LHCC the 1° Technical Proposal
(2 years of work)

Formal construction approval given with approval of first TDRs (**1997**)

TDR	Pages	Titles	Date
1	178	*Calorimeter Performance*	1996-12-15
2	606	*Liquid Argon Calorimeter*	1996-12-15
3	330	*Tile Calorimeter*	1996-12-15
4	256	*Inner Detector Vol 1*	1997-04-30
5	898	*Inner Detector Vol 2*	1997-04-30
6	101	*Magnet System*	1997-04-30
7	208	*Barrel Toroid*	1997-04-30
8	282	*End-Cap Tc*	
9	85	*Central Sol*	
10	513	*Muon Spec*	
11	317	*Pixel Detector*	1998-05-31
12	500	*First-Level Trigger*	1998-06-30
13	598	*Technical Coordination*	1999-01-31
14	458	*Detector and Physics Performance Vol 1*	1999-05-25
15	506	*Detector and Physics Performance Vol 2*	1999-05-25
16	370	*High-Level Trigger Data Acquisition and Controls*	2003-06-30
17	234	*Computing*	2005-03-18
Total	**6440**	**pages**	

ATLAS invited then to work out Technical Design Reports for the sub-systems


Point-1 Civil Engineering **1998-2003**
(underground cavern 56 x 32 x 35 m3)

The Tile Calorimeter Module Construction

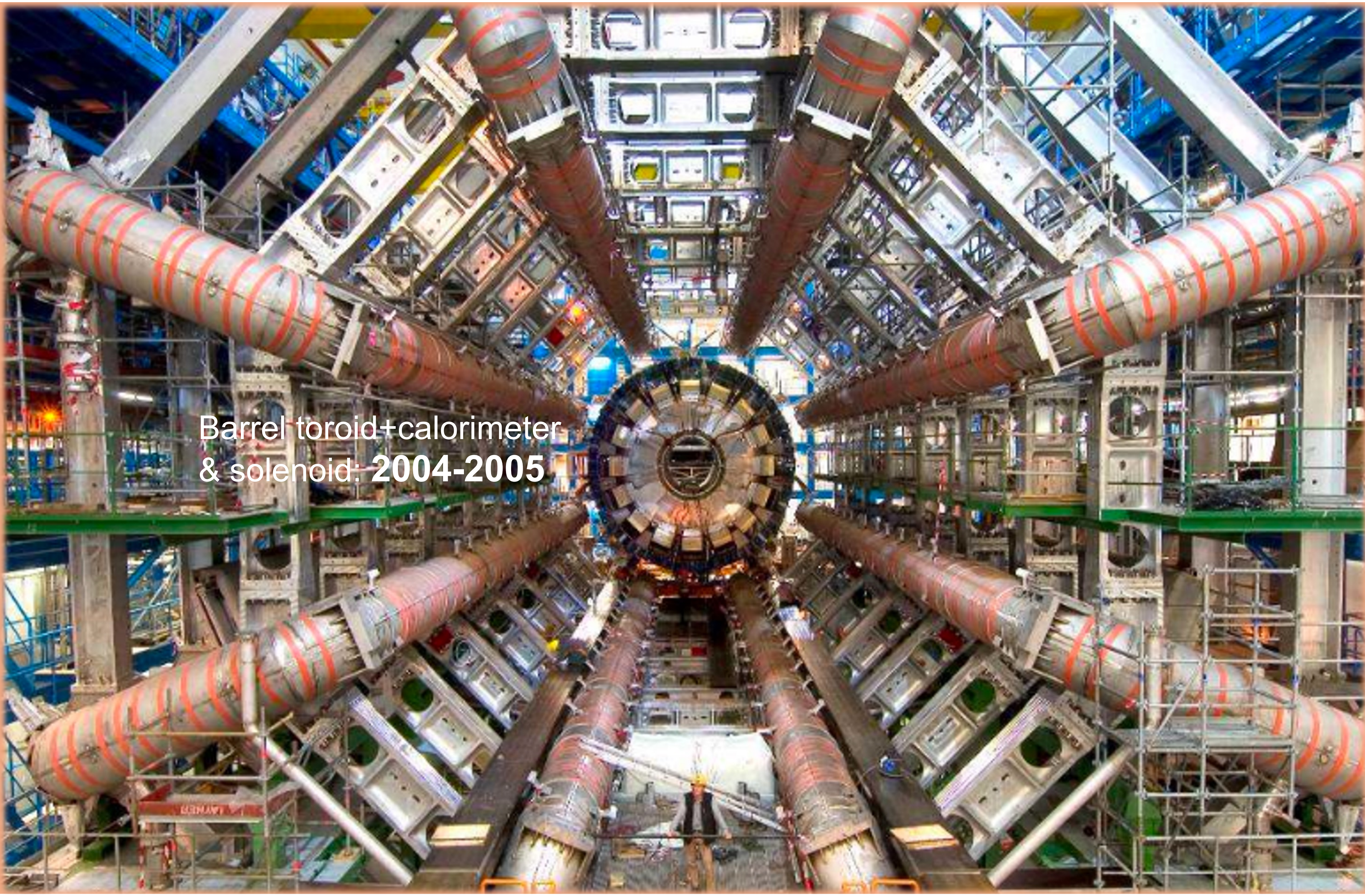
Optics

- Scintillating tiles
- Wrapping + masking
- Fibers + bundle polishing

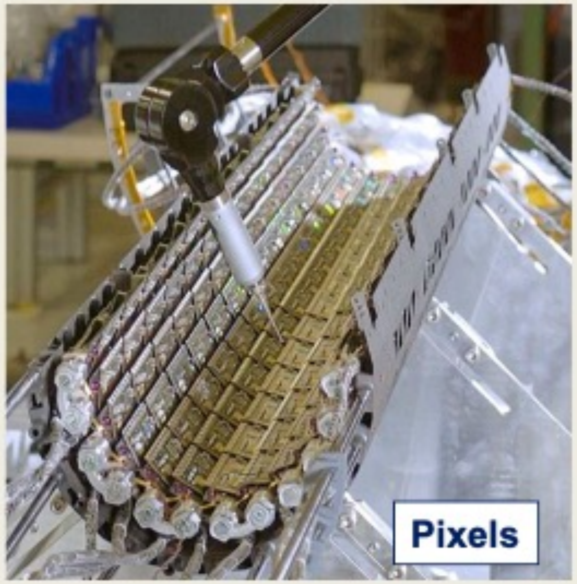
Electronics

- PMTs + HV
- FE electronics
- Cs calibration system
- Detector Control system

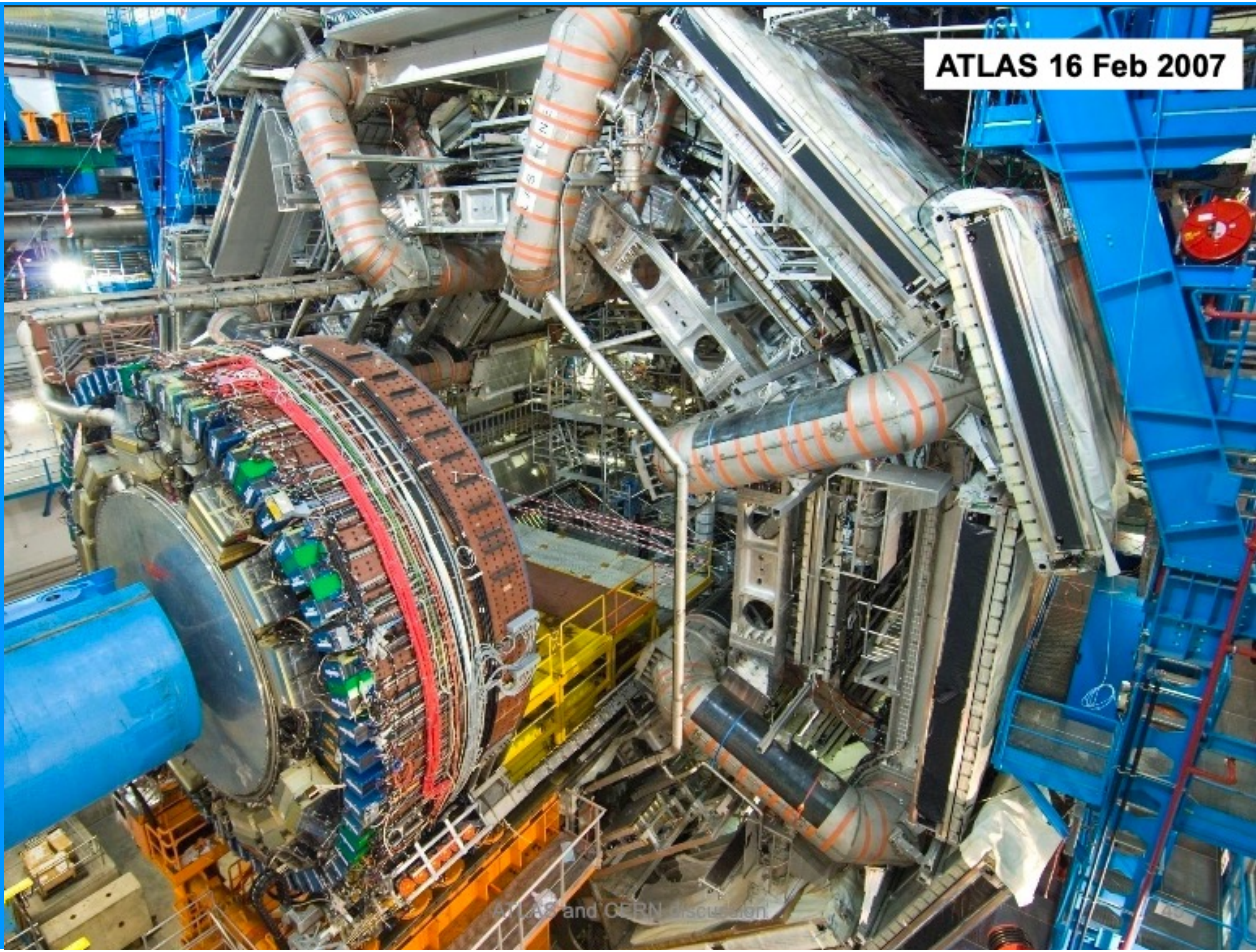

HWX 159
November 2003


Barrel toroid+calorimeter
& solenoid: 2004-2005

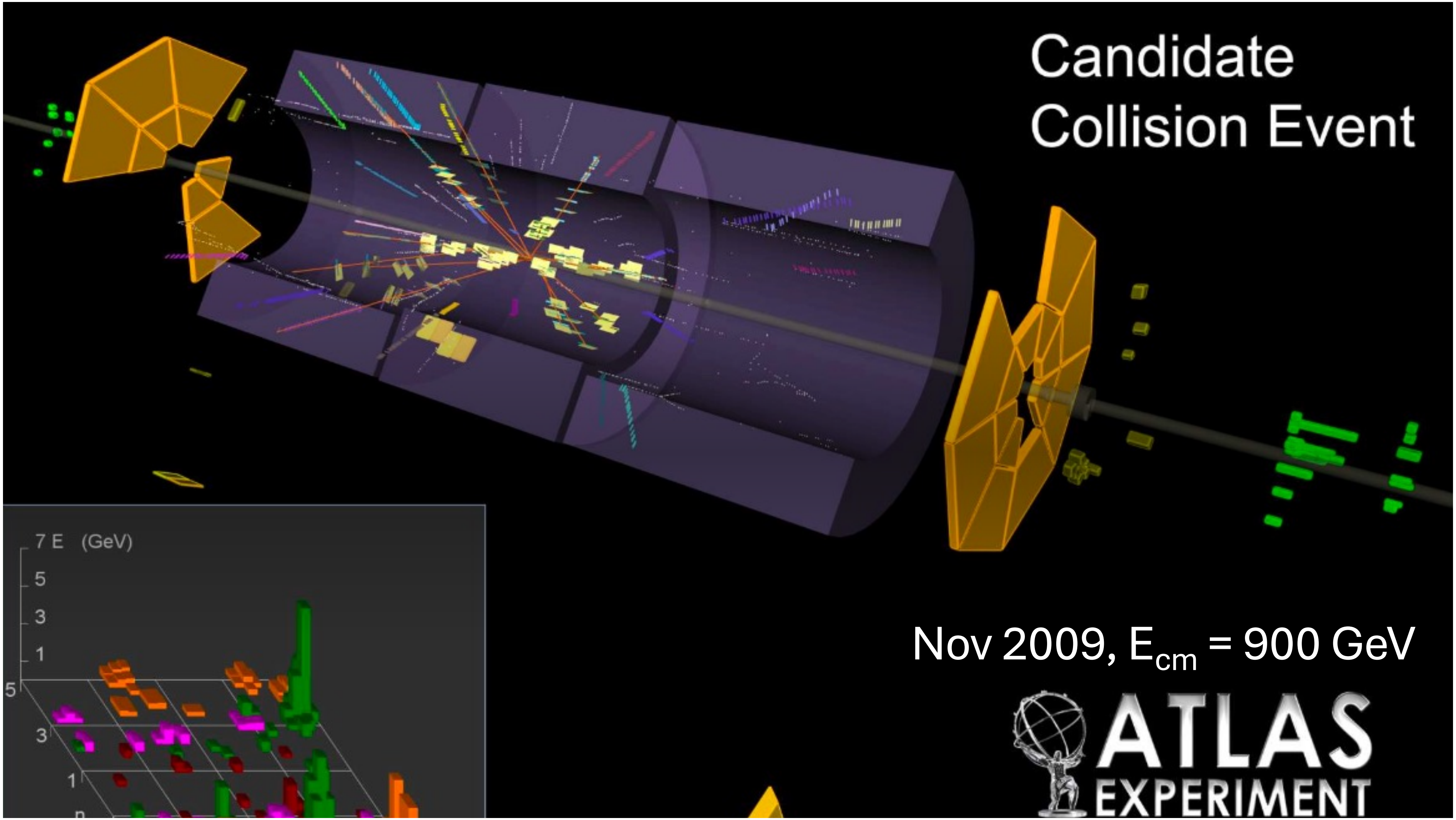
Snapshots from the Inner Detector construction years (2001 – 2007)



End-Cap Toroid A on its way to Point-1 (29 May 2007)


ATLAS 16 Feb 2007


LHC incident
Interconnections of two magnets
One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine (required a 15 months repair period)


Candidate
Collision Event
Nov 2009, E_{cm} = 900 GeV
ATLAS
EXPERIMENT
7 E (GeV)
5
3
1
5
3
1

2010: First 7 TeV collisions in ATLAS

You will not «wait» 20 or 40 years for FCC-ee and FCC-hh.
You will be overwhelmed by all the work needed to make them happen!

I will be too old when FCC will start

Ta’anit 23a

Thanks to all those who planted the carob trees I’ve found.

- One day, he was walking along the road when he saw a certain man planting a carob tree. Ḥoni said to him: This tree, after how many years will it bear fruit?
- The man said to him: It will not produce fruit until seventy years have passed. Ḥoni said to him: Is it obvious to you that you will live seventy years, that you expect to benefit from this tree?
- He said to him: That man himself found a world full of carob trees. Just as my ancestors planted for me, I too am planting for my descendants.

Conclusions

- We don't have anymore the Standard Model lighthouse while sailing in the ocean of attempts to understand our Universe.
- Particle physics requires now big machines, huge investments and long time (decades) to give results
- Still, there is a lot to be understood and we need to pave the way, staying flexible

Where to meet very soon

https://w3.lnf.infn.it/event/workshop-on-highlumi-lhc-and-hadron-colliders/

INFN-LNF

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https://agenda.infn.it/event/37960/

« Tutti gli Eventi

Workshop on HighLumi-LHC and Hadron Colliders

1 Ottobre @ 8:00 - 4 Ottobre @ 20:00

The **Workshop on HighLumi-LHC and Hadron Colliders** will be held in the Bruno Touschek Auditorium (Bldg. 36, access from LNF **secondary entrance** in Via E. Fermi, 60 – see map).

https://agenda.infn.it/event/37960/