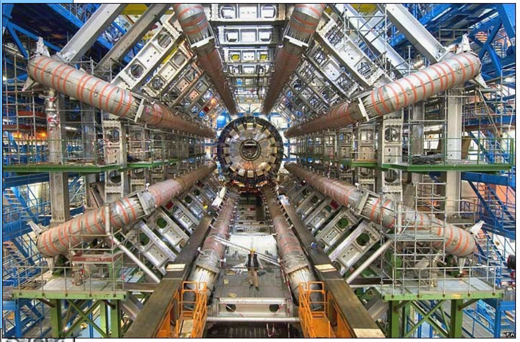
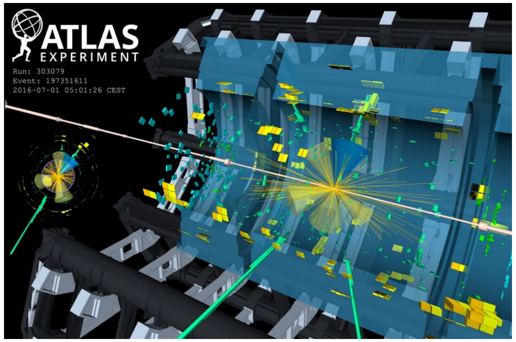
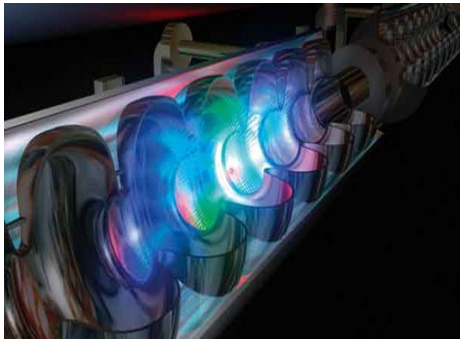
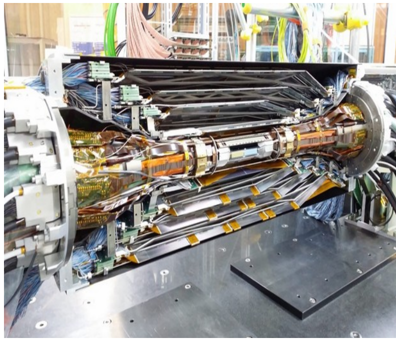
The next collider at the energy frontier: from accelerator and detector technology to the scientific programme

Marcel Vos, IFIC (UV/CSIC) Valencia









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Abstract

These two lectures discuss the future of high-energy physics. We will review the some past successes and the technology that enabled these discoveries.

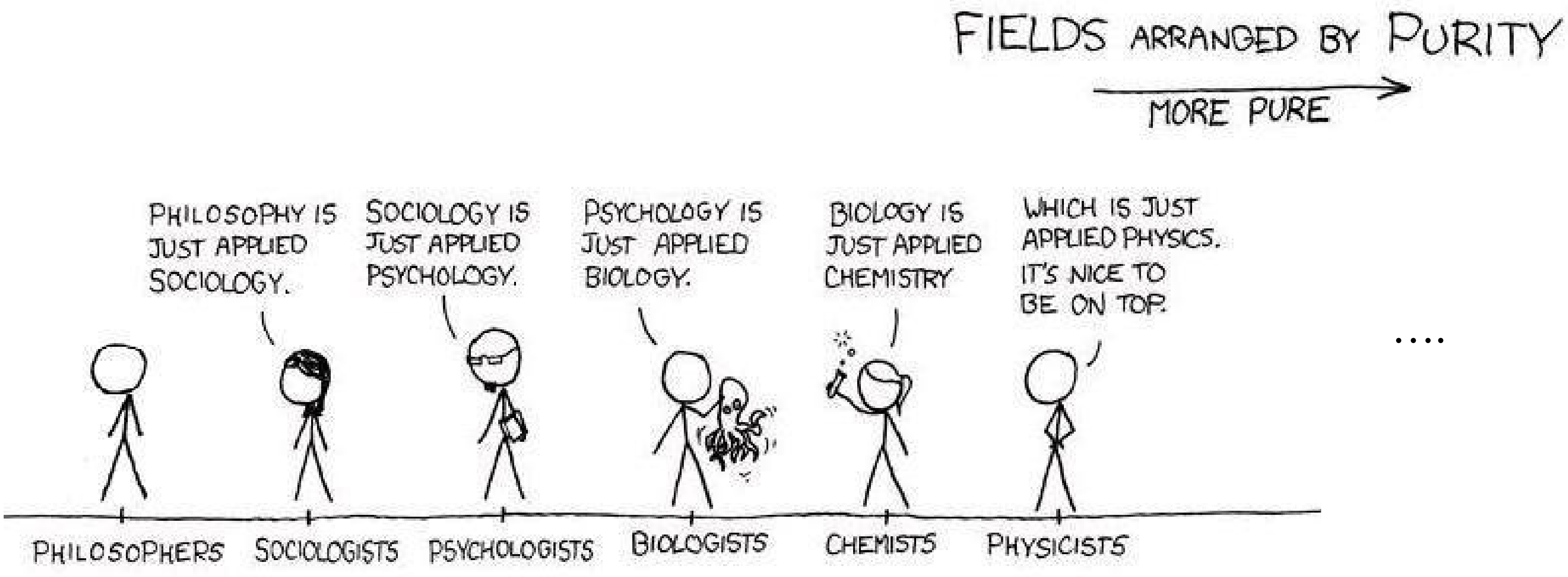
Lecture 1:
- introduction & a brief history of colliders
- the basis for success: accelerator & detector technology

Lecture 2:
- high-energy physics: what's next?
- future collider projects: from Higgs factory to discovery machine
- outlook: innovative accelerator technology

The aim of this lecture is to provide you with the elements to form an opinion on the future of fundamental physics

Effective theories

“The aim of particle physics is to understand what everything is made of, and how everything sticks together. By everything I mean me and you, the Earth, the Sun, the 100 billion suns in our galaxy and the 100 billion galaxies in the observable universe. Absolutely everything." - Brian Cox



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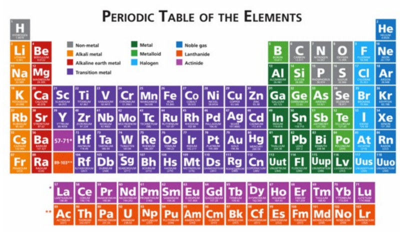
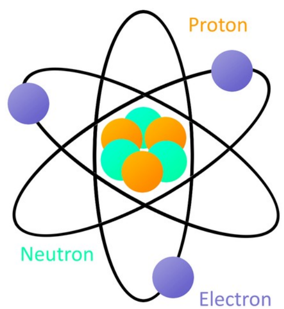
Mission statement

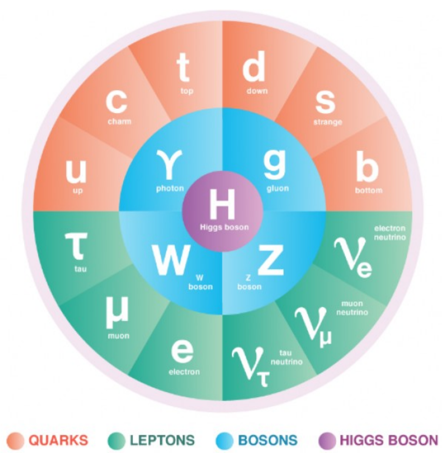


Biology, psychology, economy

Chemistry – Mendeleev 1869

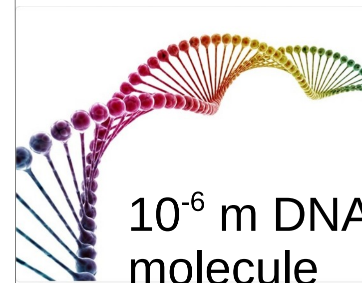


Atomic physics – Rutherford/Bohr 1913

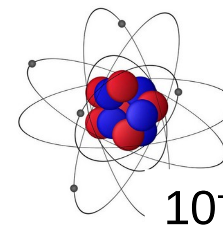


Particle physics – 2012

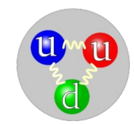
New physics?



10^{-6} m DNA molecule



10^{-10} m atom



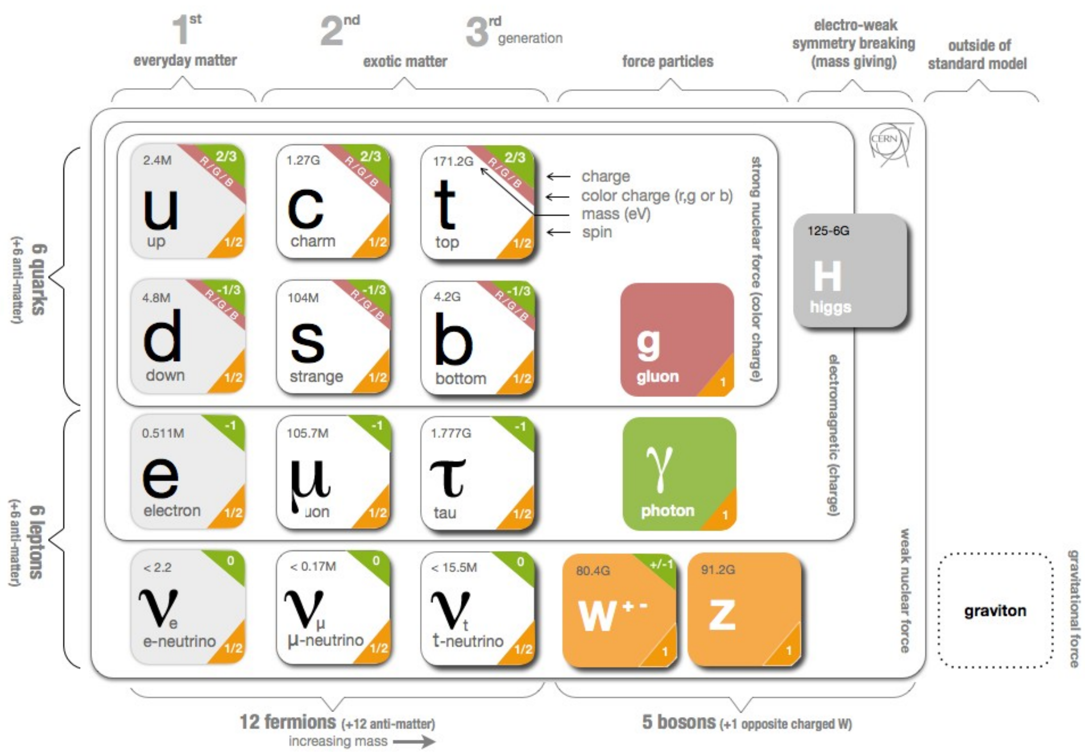
Nucleus 10^{-15} m

e^- dipole mom. $d/e < 10^{-30}$ m

Planck length 10^{-35} m

The Standard Model

The complexity of the world reduced to a minimal(?) set of ingredients
The SM constituents of matter: 6 quarks, 6 leptons (+anti-particles)
Forces are carried by “gauge” bosons; the Higgs field



The goal of fundamental science: discover the theory that lies beyond the Standard Model

We are quite certain that this picture is essentially correct,
but we are equally certain it’s not the end of the story
(SM = successful effective theory; SM ≠ Theory of Everything)

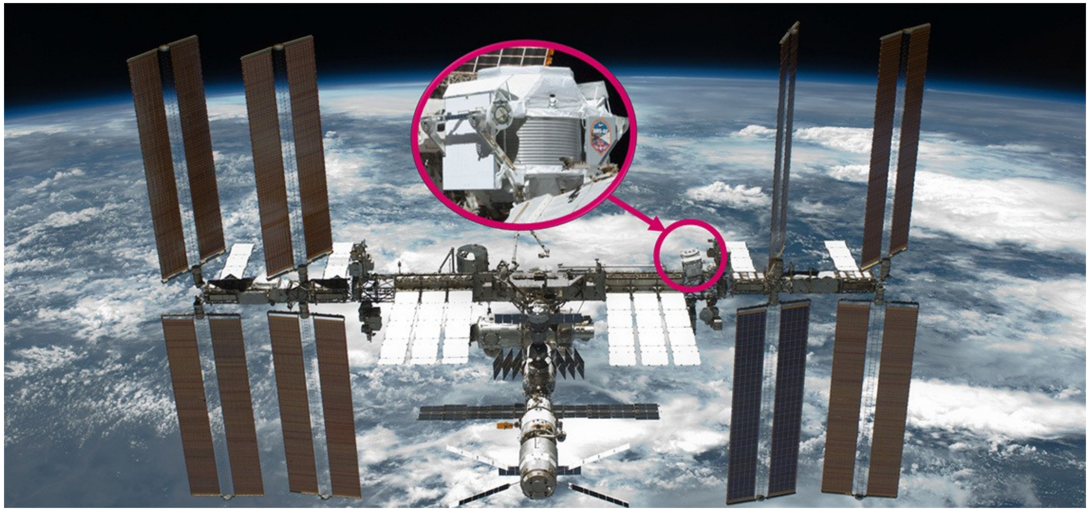
Colliders

A brief history of colliders

From cosmic rays …

Hess balloon experiment

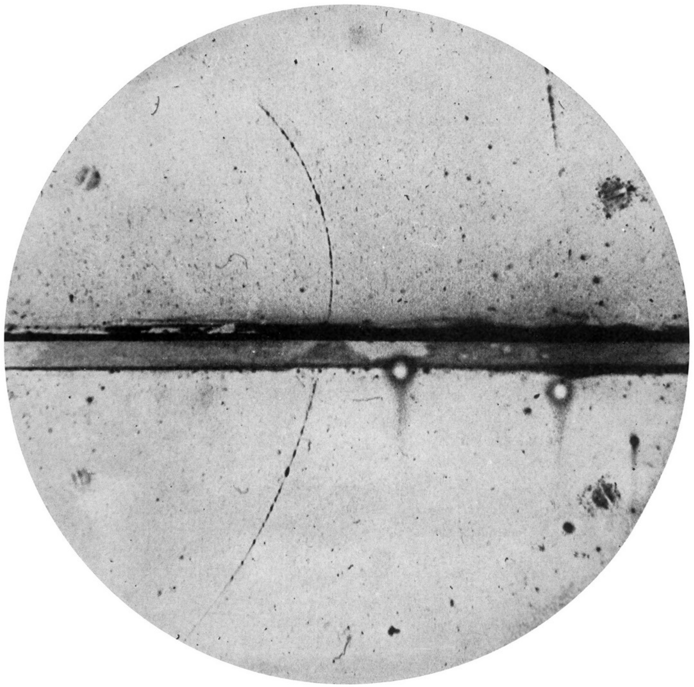
Jungfraujoch observatory

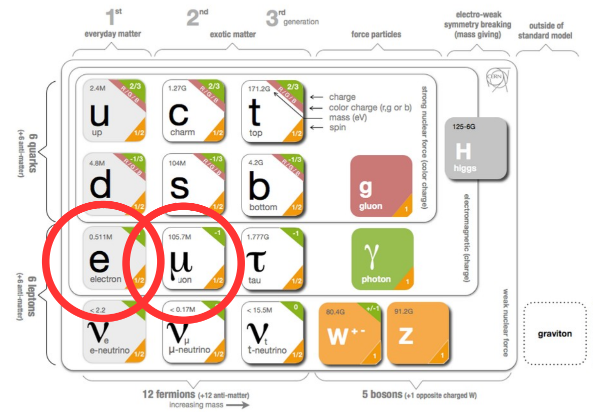


AMS experiment on the Int’l space station

Cosmic rays had served particle physics well (and continue to do so)

Anti-particles and muons

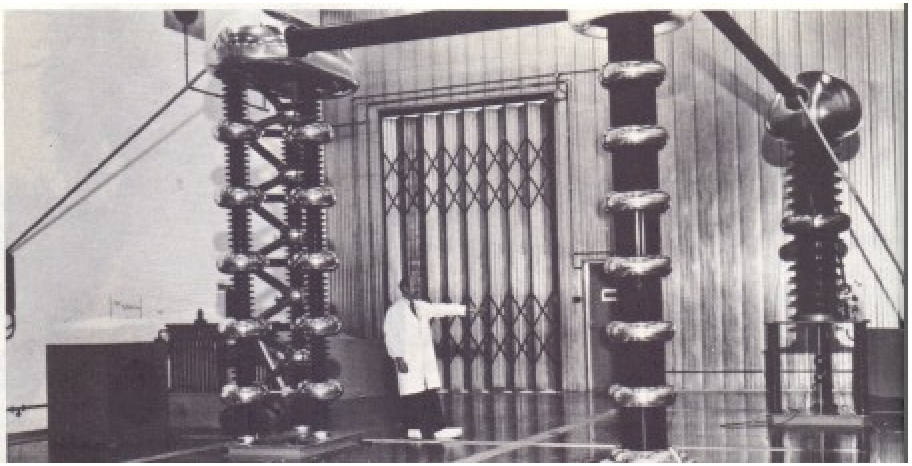




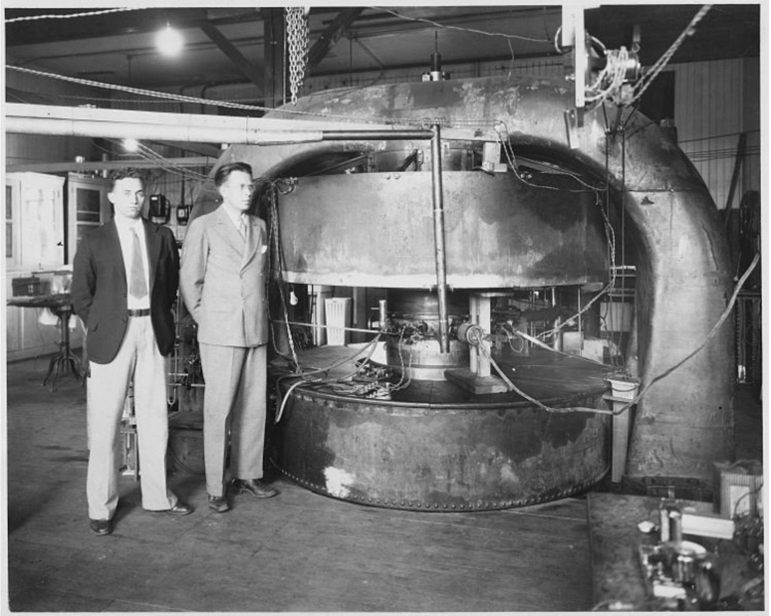
The positron (anti-matter!) was discovered in cosmic ray experiments in 1932

Surprise! Four years later, the same group discovered something nobody had ordered; the muon (and the second generation)

The birth of accelators …



Cockroft and Walton and van de Graaff developed powerful electrostatic accelerators ('30s)



Berkeley and Livingston in front of their cyclotron ('30s)

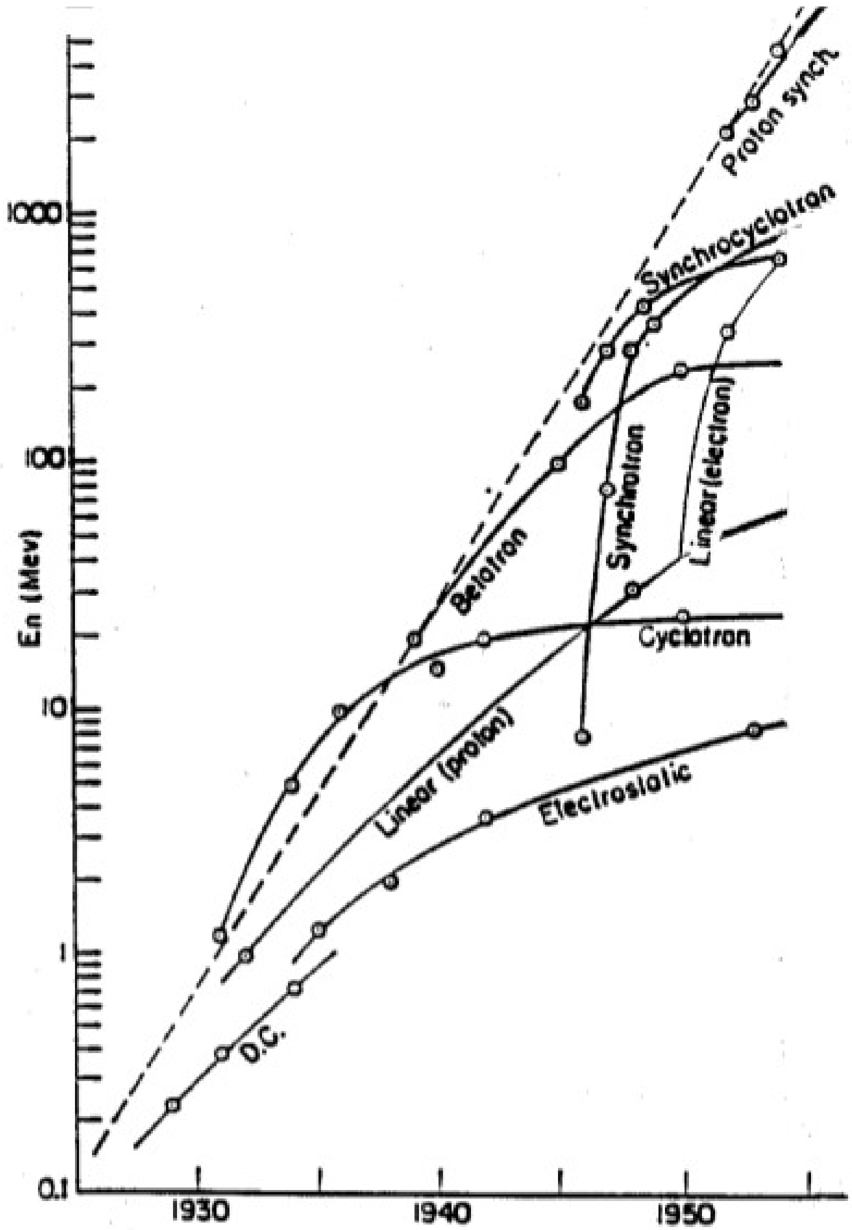
The '30s saw the rapid development of accelerator technology.

And their evolution..

The Livingston plot:

The ‘30s, ‘40s and ‘50s saw a rapid succession of different machine designs: D.C and electro-static accelerators were replaced at the “energy frontier” by cyclotrons, then betatrons, sychrocyclotrons…

Together, these techniques fueled exponential progress, with a factor 10 in energy every six years



to colliders …

The quantity that matters is "center-of-mass" energy

In fixed-target experiments:

$$E_{CM} \propto \sqrt{E_{beam}}$$

With colliding beams:

$$E_{CM} \propto E_{beam}$$

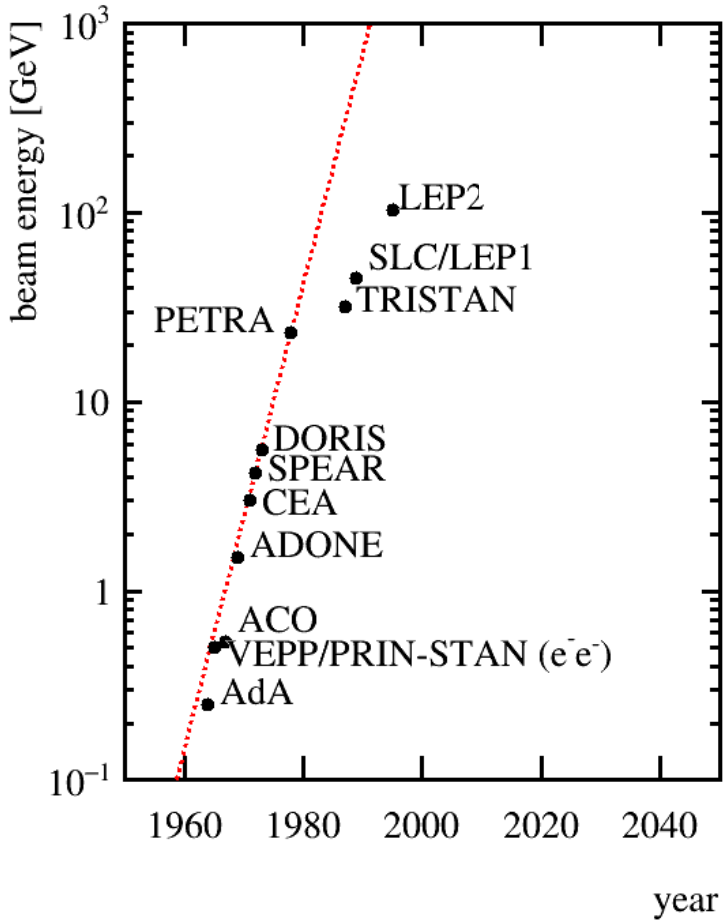
The key realization:
colliding beams of particles and anti-particles

Touschek and he Frascati group in front of ADA ('50s)

Pioneered by Wideroe and Touschek (ADA in Frascati!)
Biographical accounts from U. Amaldi and G. Pancheri

Colliders

After WWII colliders fueled progress in particle physics.



The ‘60 and ‘70s marked the golden days of e^+e^- colliders.

Two further decades of exponential progress!

Major discoveries at SPEAR and PETRA

TRISTAN, SLC and LEP

Circular colliders and synchrotron radiation

Synchrotron radiation limits acceleration:

$$(\Delta E)_{sync} \propto \frac{E^4/m^4}{L}$$

Energy loss per turn as a function of beam energy E, particle mass m and circumference L

Energy must be restored (RF power) and removed from magnets (cooling power)

Solutions:

- large rings (note that ΔE is only inversely proportional to L, but see tomorrow)
- linear colliders (SLC, but must accelerate in one go, but see tomorrow)
- accelerate more massive particles
  (proton energy loss is 10^{13} times smaller than for electrons)
- accelerate more massive *elementary* particles
  (see muon collider tomorrow)

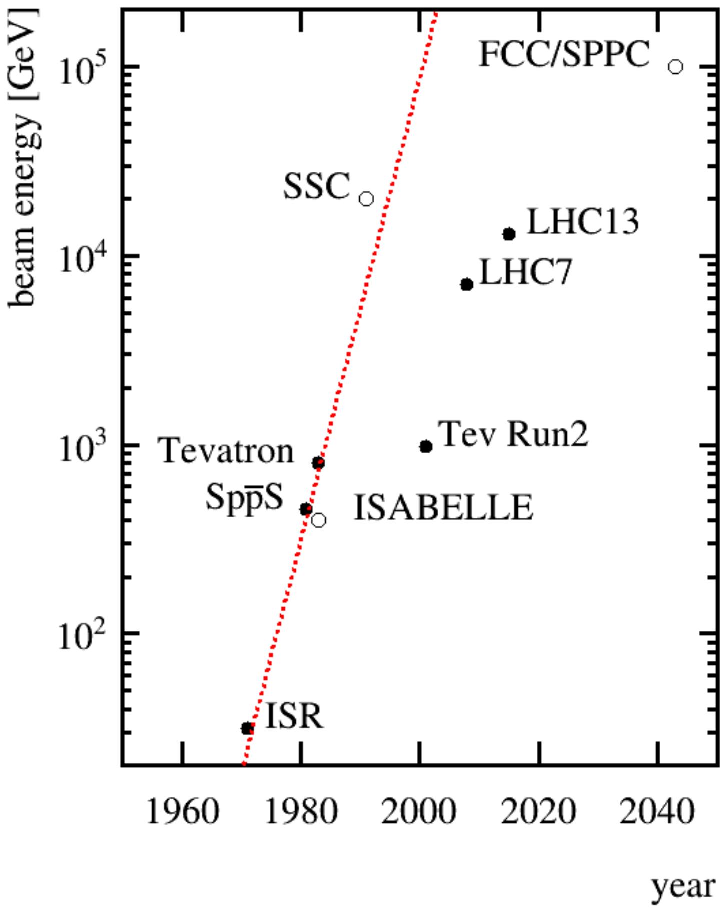
Colliders

Since the ‘80s proton colliders rule!

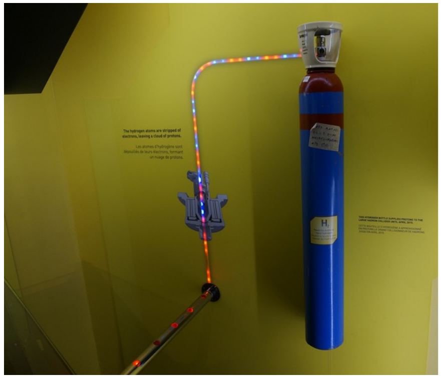
ISR was the key to unlock
the next generation of colliders
(but otherwise not so remarkable)

$Sp\bar{p}S$ (W/Z ‘84),
Tevatron (top ‘95)
and LHC (Higgs 2012)

US cancelled ISABELLE and SSC

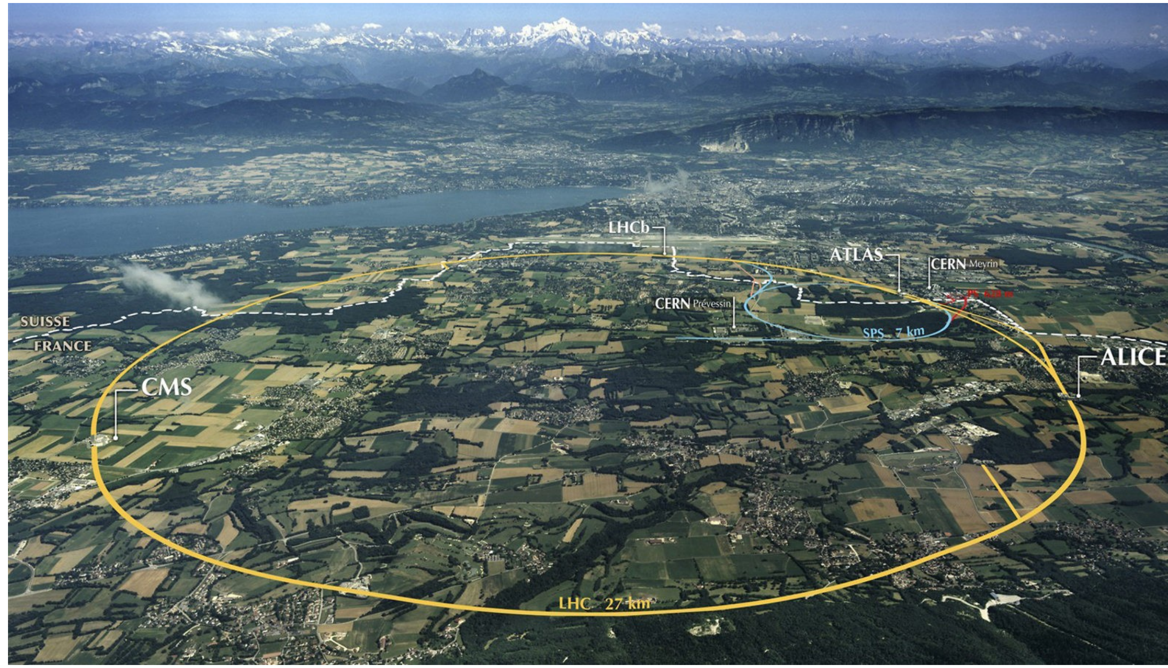


... the Large Hadron Collider

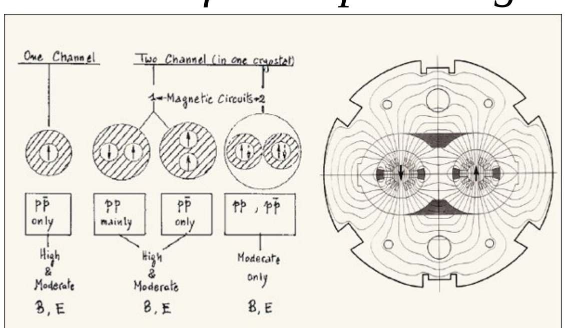


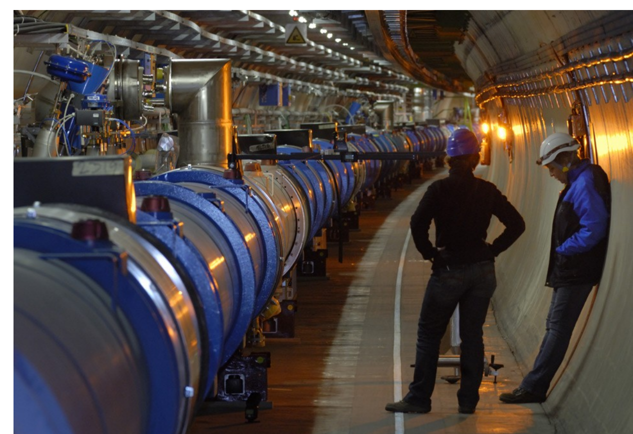
Some protons...

A 27 km long tunnel...



Thousands of 8 T dipole magnets...





The LHC – big science

Big questions require a big effort!

Big machine: 27 km circumference, experiments the size of small cathedrals

Big time lines: first LHC workshop 1984, first data 2010, HL-LHC until 2040

Big investment: the LHC cost several billion euros

Big collaboration: experiments with ~ 3000 authors!

Fortunately, big efforts lead to big rewards!

… discoveries 1960-2022

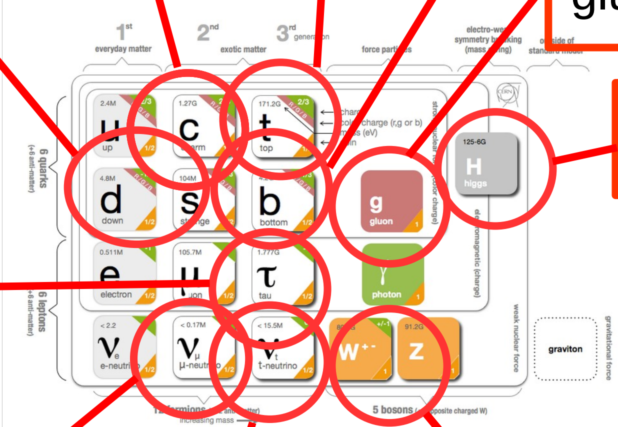
top Tevatron 1995

charm BNL/SLAC 1974

bottom FNAL 1977

Quarks, SLAC 1968

gluon DESY HERA 1975



Higgs CERN LHC 2012

τ, SLAC SPEAR, 1975

ν_μ, BNL, 1962

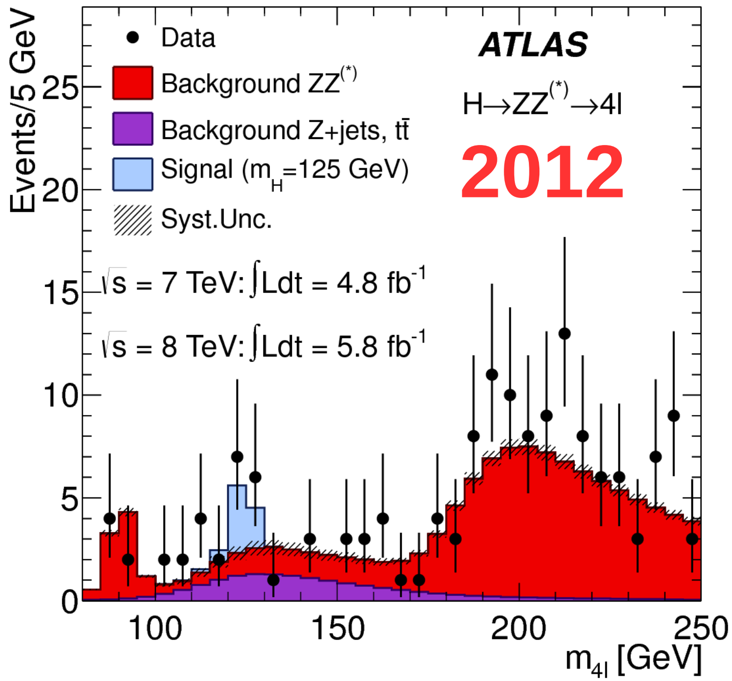
W/Z CERN Sp$\bar{p}$S 1984

ν_τ, FNAL, 2000

Colliders

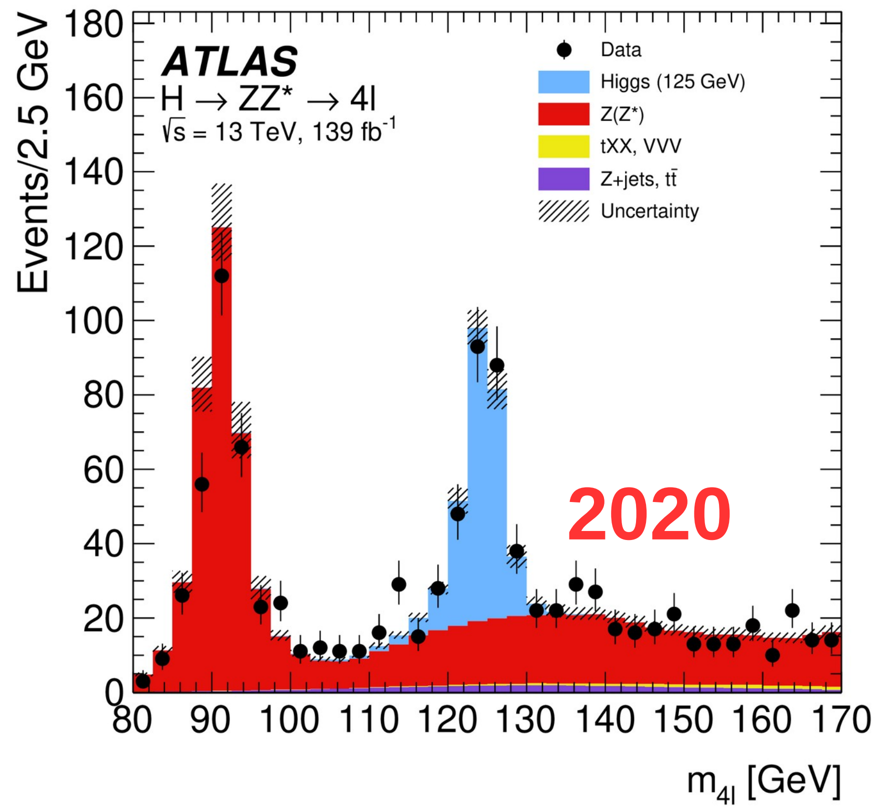
Beyond discovery

The Higgs boson – from run 1 to run 2



LHC run 2 delivered 140 fb^{-1}

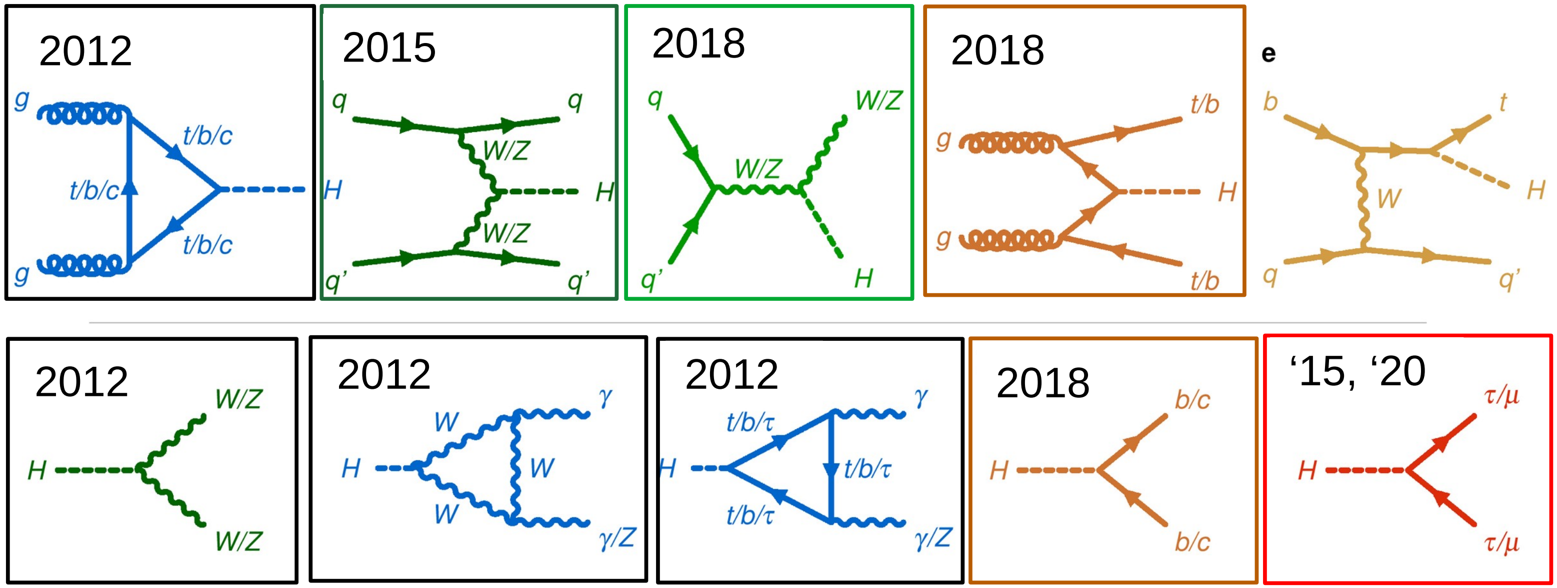
(cf. the Higgs boson was discovered with a bit over 10 fb^{-1} and the Tevatron delivered 10 fb^{-1} over the lifetime of the machine)



The signal in the “discovery channels” has grown very robust

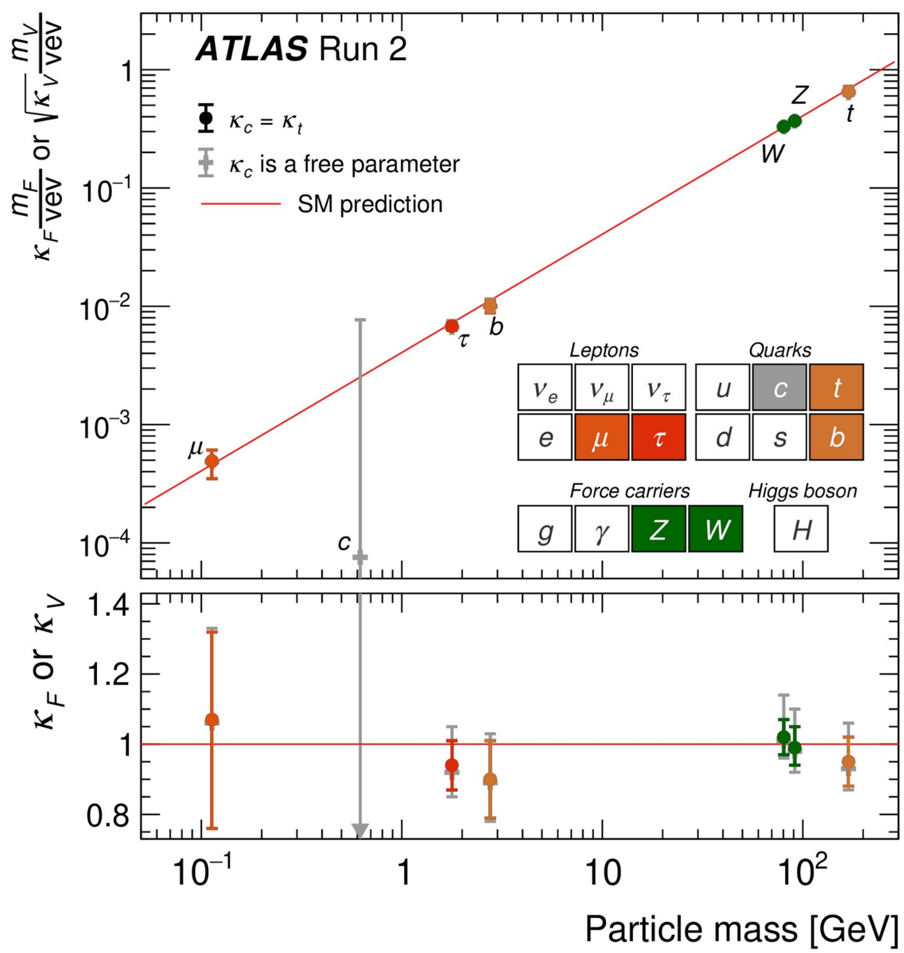
Higgs boson news

The particle discovered in 2012 is definitely A Higgs boson. If it is THE Higgs boson, it MUST behave exactly as predicted by theory.



2012: one out of four production mechanisms, two decay modes
2015: Vector-boson-fusion, H → ττ (fermions!)
2018: Associated ttH production, H → bb decay
2020: evidence H → μμ (2nd gen.) Missing: charm, tH production

Higgs boson summary



Fabiola Giannotti: we got very lucky (many couplings accessible at the LHC)

John Ellis: it looks and quacks like a Higgs boson (all measurements so far compatible with simplest Higgs particle)

ATLAS & CMS:
Nature articles with review of measurements so far, arXiv:2207.00043/92

See also: Salam, Wang, Zanderighi, https://arxiv.org/abs/2207.00478

Colliders

Initial discovery followed by multiple “minor discoveries” of Higgs processes. Slowly turning into precision characterization

Colliders are “discovery machines”, but also allow for precise study of new particles’ interactions and properties

Keys: controlled production, calculability of SM predictions, advanced detectors and analysis techniques

Compare: dark matter, observed through its gravitational impact since the ‘30s, but still very much in the dark.

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Colliders

Accelerator technology (basic intro only)

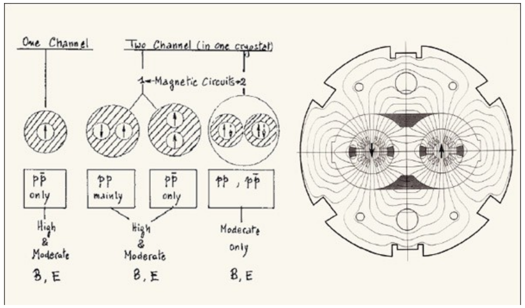
Magnets

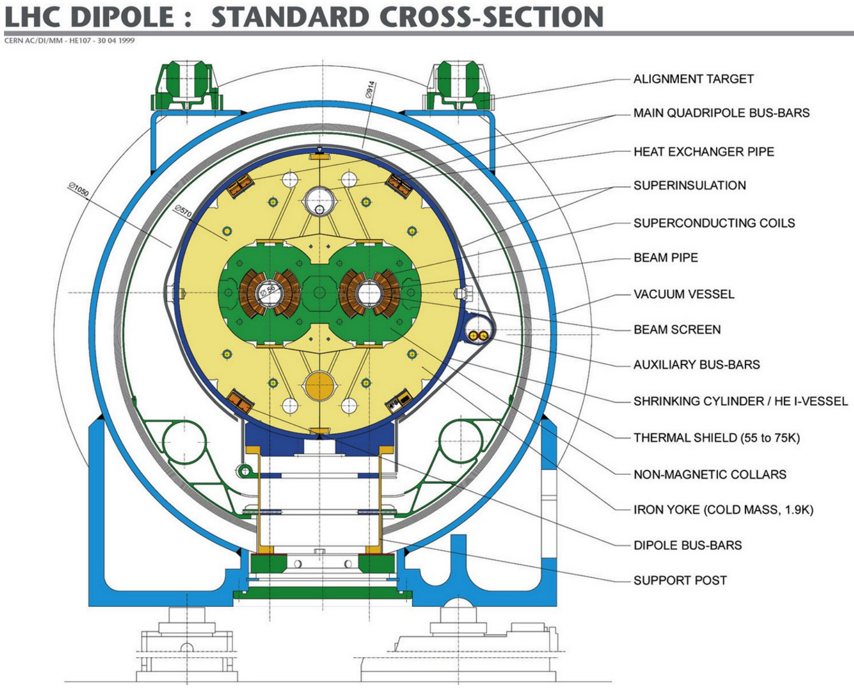
Circular colliders accelerate the beam in many passes through the same cavity

In pp colliders the limiting factor is the B-field that steers the beams around the orbit

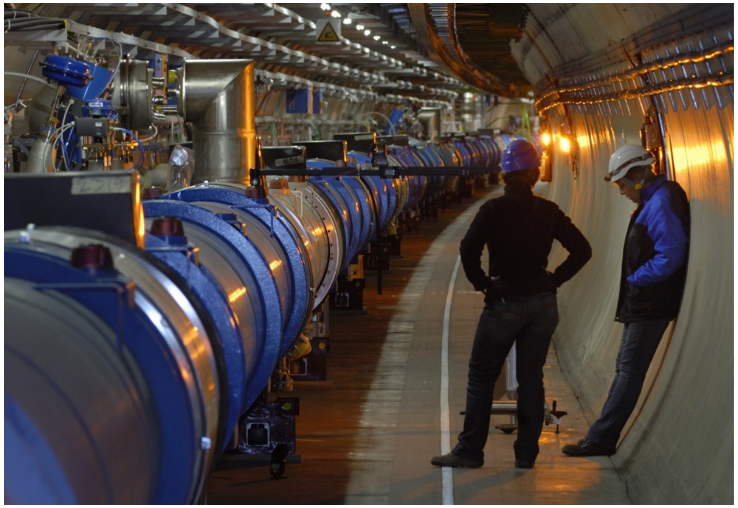
SppS had Tevatron pioneered (4T) super-conducting magnets

LHC was built with 8T dual-aperture dipole magnets





LHC construction



From a single working prototype magnet to a fully industrialized production takes years

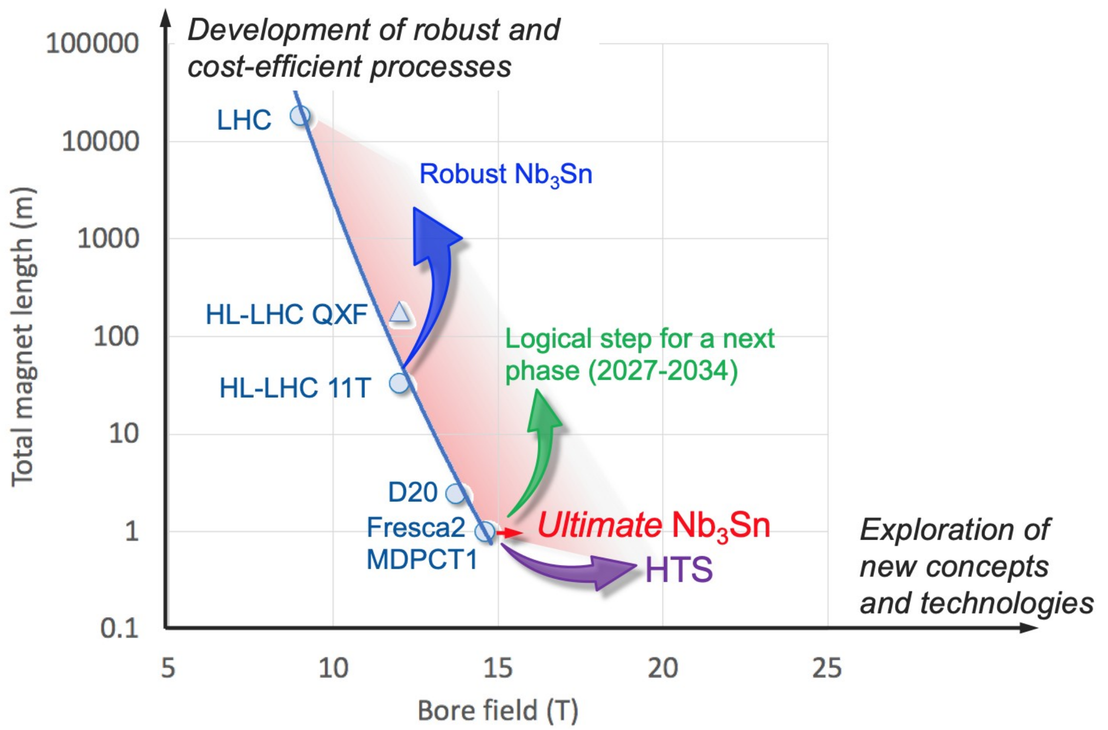
One small failure in 1000s of components can have large consequences (damage due to faulty connection in LHC after startup in 2008)

Magnets: progress

The key challenge: large-scale, large-field magnets

16T field is the target for the future FCC project

High Temperature Superconductor potentially a more cost-effective solution



RF Cavities

The accelerating structure in any modern collider

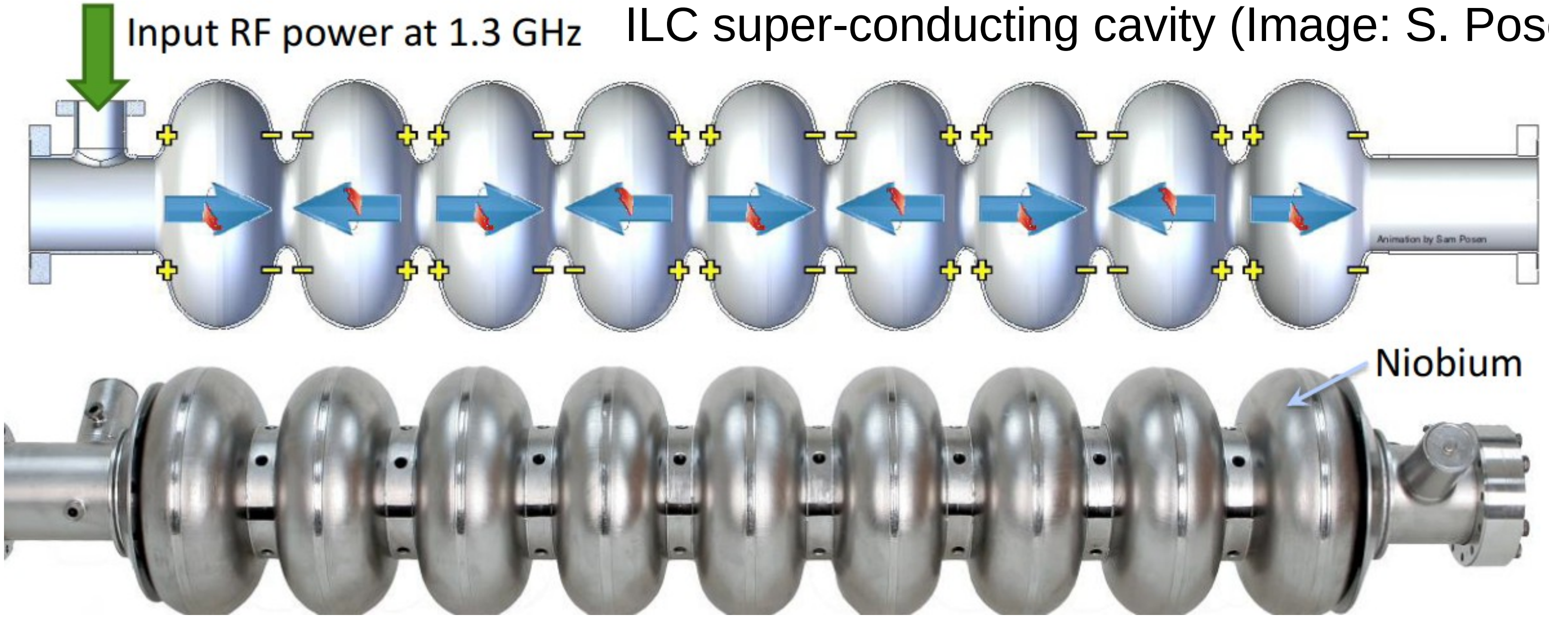
Set up a standing RF wave in Ghz frequency range in periodic metal structure

Particles that arrive “in sync” will be attracted and accelerated

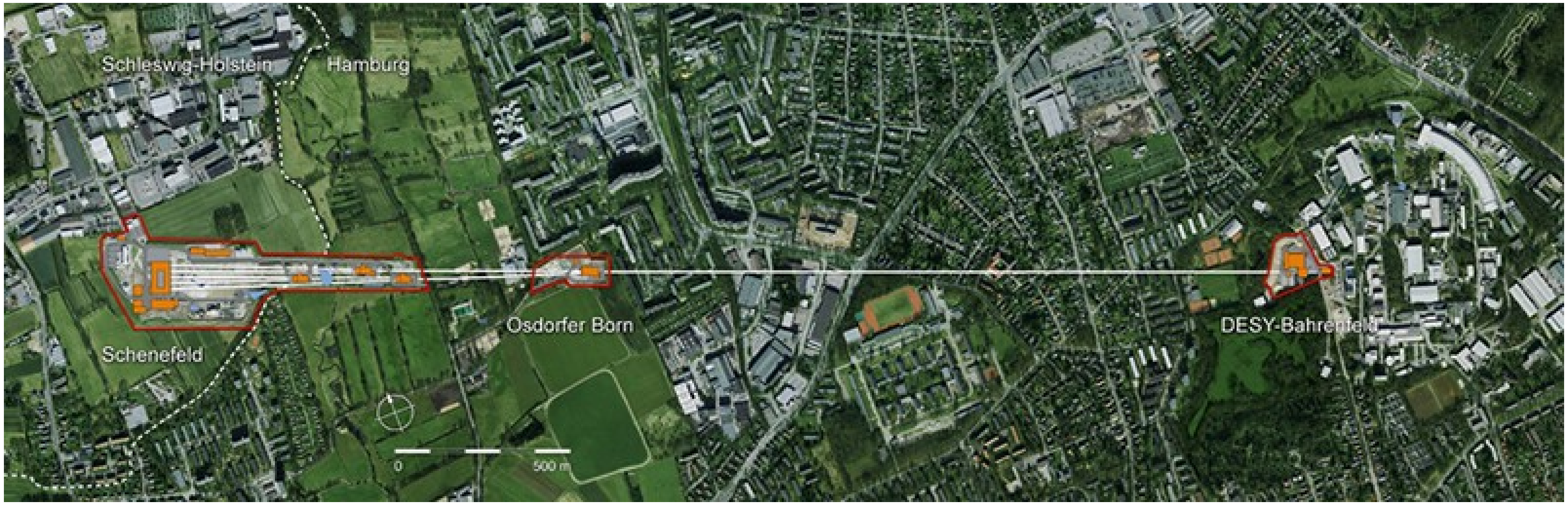
Linear colliders rely on a long series of cavities, circular colliders are multiple-pass

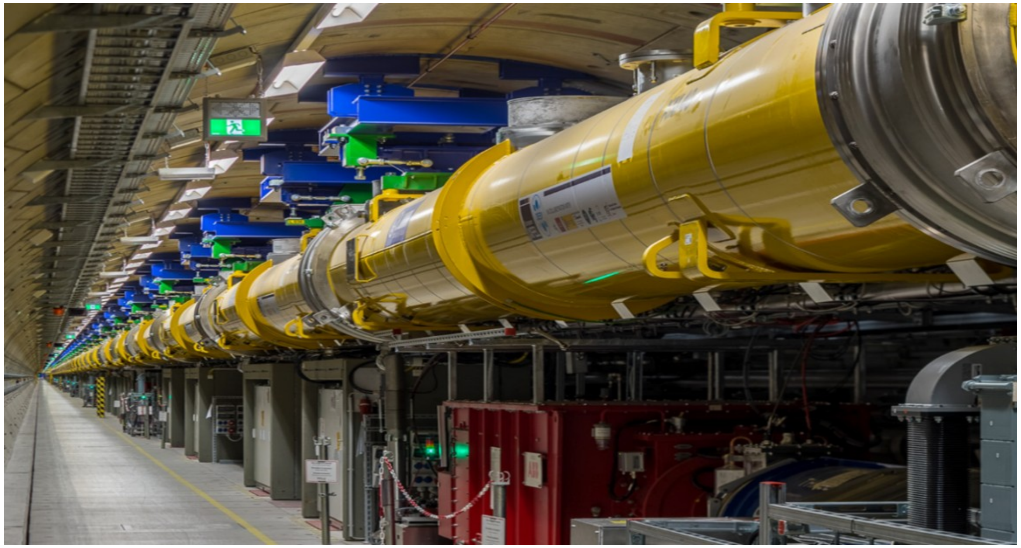
RF power provided by a klystron (or drive-beam in case of CLIC)

ILC super-conducting cavity (Image: S. Posen)



European XFEL





European XFEL at DESY Hamburg is a 19.5 GeV linear accelerator that is used to generate energetic X-ray beams for “photon science”

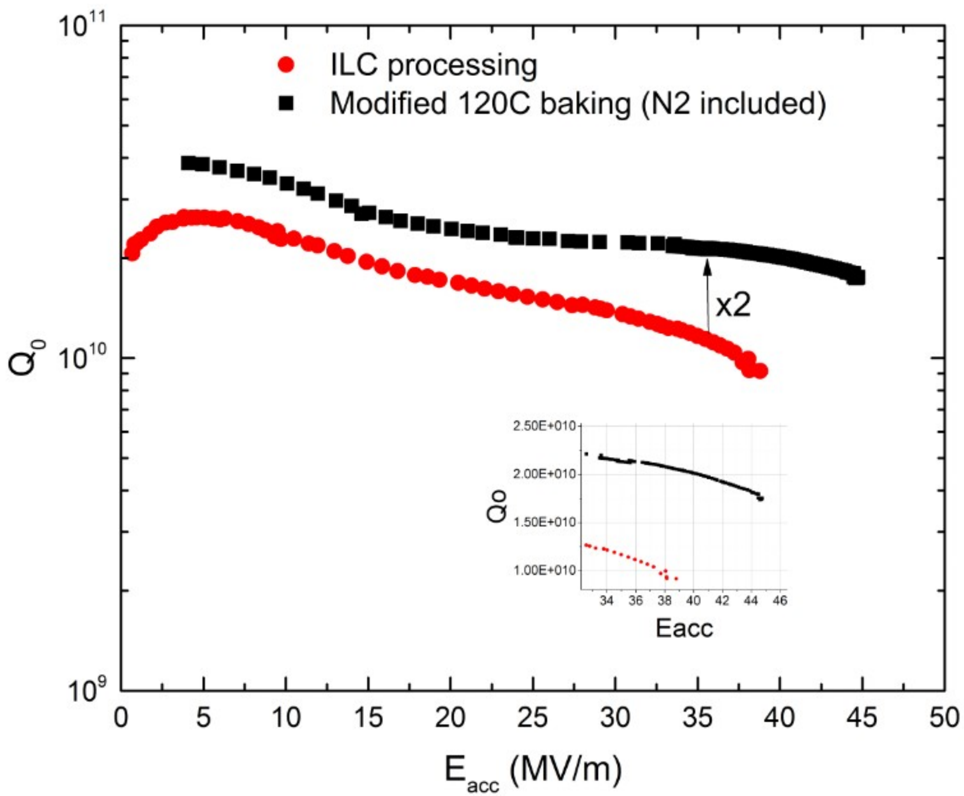
Based on TESLA/ILC cavities

RF Cavities: progress

Figure of merit: accelerating gradient in MV/m, quality factor Q0*

Super-conducting Niobium cavities: up to 45 MV/m (XFEL avg. ~ 22 MV/m)

Limiting factor: electromagnetic discharges. Key to high E_{acc} → surface treatment



*Q0 quality factor that is inversely proportional to the surface resistance and power dissipation in the cavity walls

Higher Q_0 = less power, less cooling, less cost

N infusion improves Eacc vs. Q0
A. Grasselino et al., Fermilab

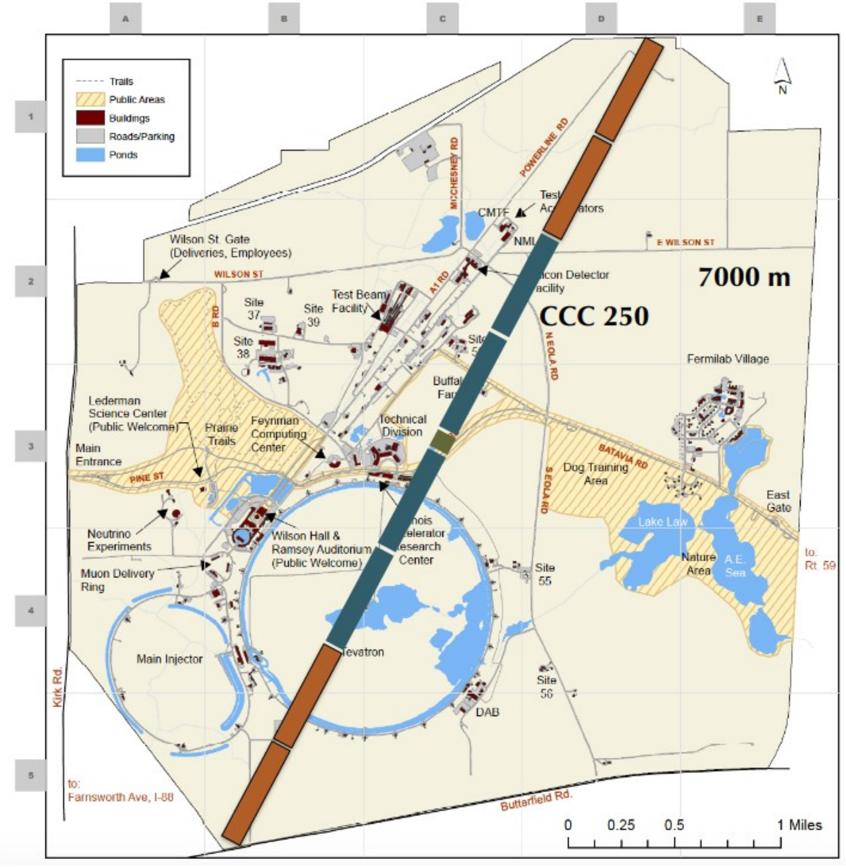
RF Cavities: progress

Copper normal-conducting “warm” cavities reach up to 100 MV/m (CLIC)

And “cool copper” cavities at 77K up to 150 MV/m (C3)

Higher gradient = more compact facility

Note: applications of advanced cavities in compact accelerators for Free-Electron-Lasers (XFEL, SwissFEL) and in medical applications (proton-therapy)



Final focus

The luminosity of the machine depends crucially on beam current and beam size:

$$L = \frac{k N_1 N_2 f}{4 \pi \sigma_x \sigma_y}$$

Where k = number of bunches (several 1000 for LHC), N1, N2 are the bunch population (10^{11} protons), σ_x, σ_y are the beam size (16 μm)

Smaller, higher-current beams are better, but require tight control over emittance

Nano-beams and crab-crossing achieved in Belle 2 and test facilities

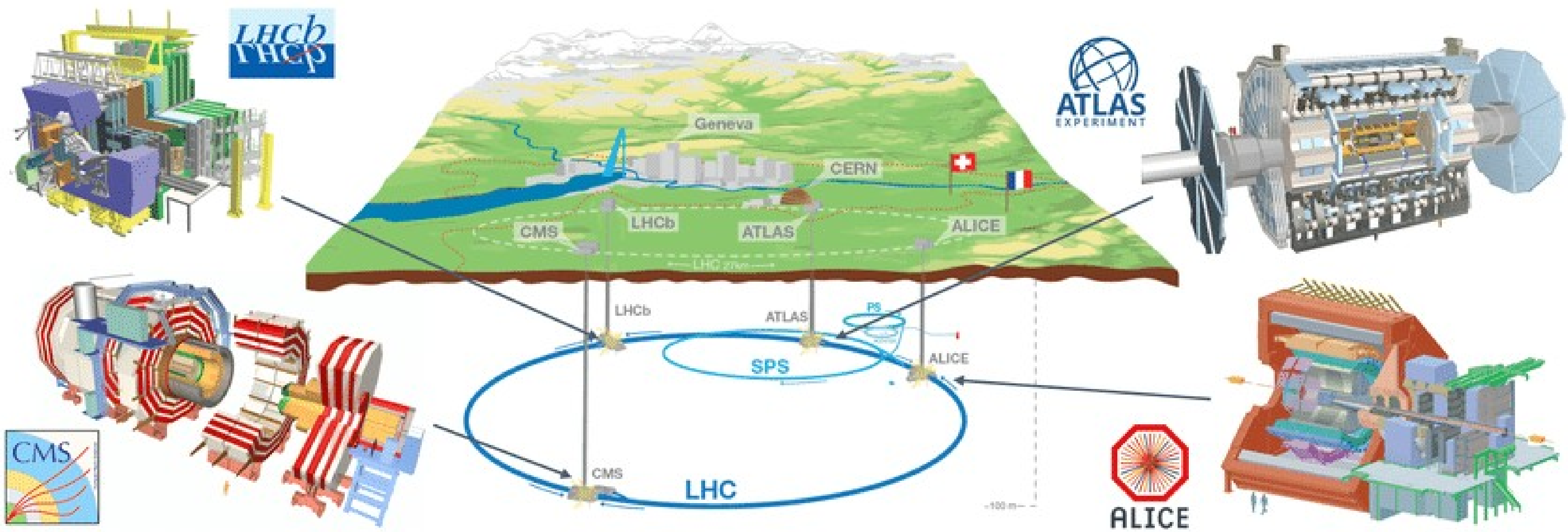
Image: ATF test facility at KEK

Colliders

Detector technology

The LHC experiments

The LHC provides proton beams with an energy of 6.5 TeV
(cf. previous world record by the Tevatron: 0.98 TeV)

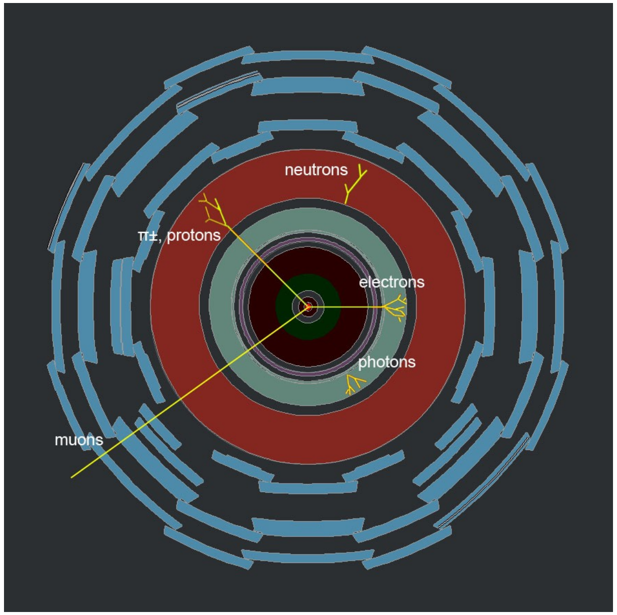


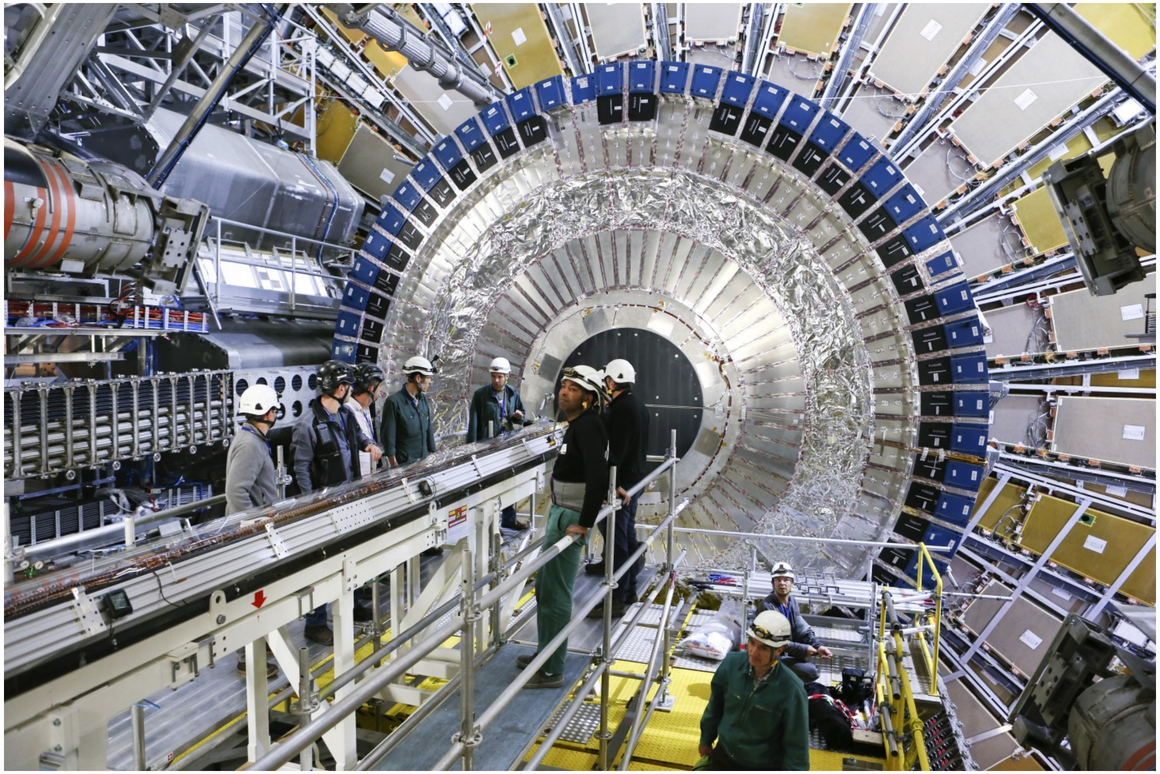
Beams cross and collide at 4 interaction points, equipped with experiments that register the products of the collisions

The LHC experiments

The experiments consist of a number of subsystems – a charged particle tracker, a calorimeter system, muon chambers

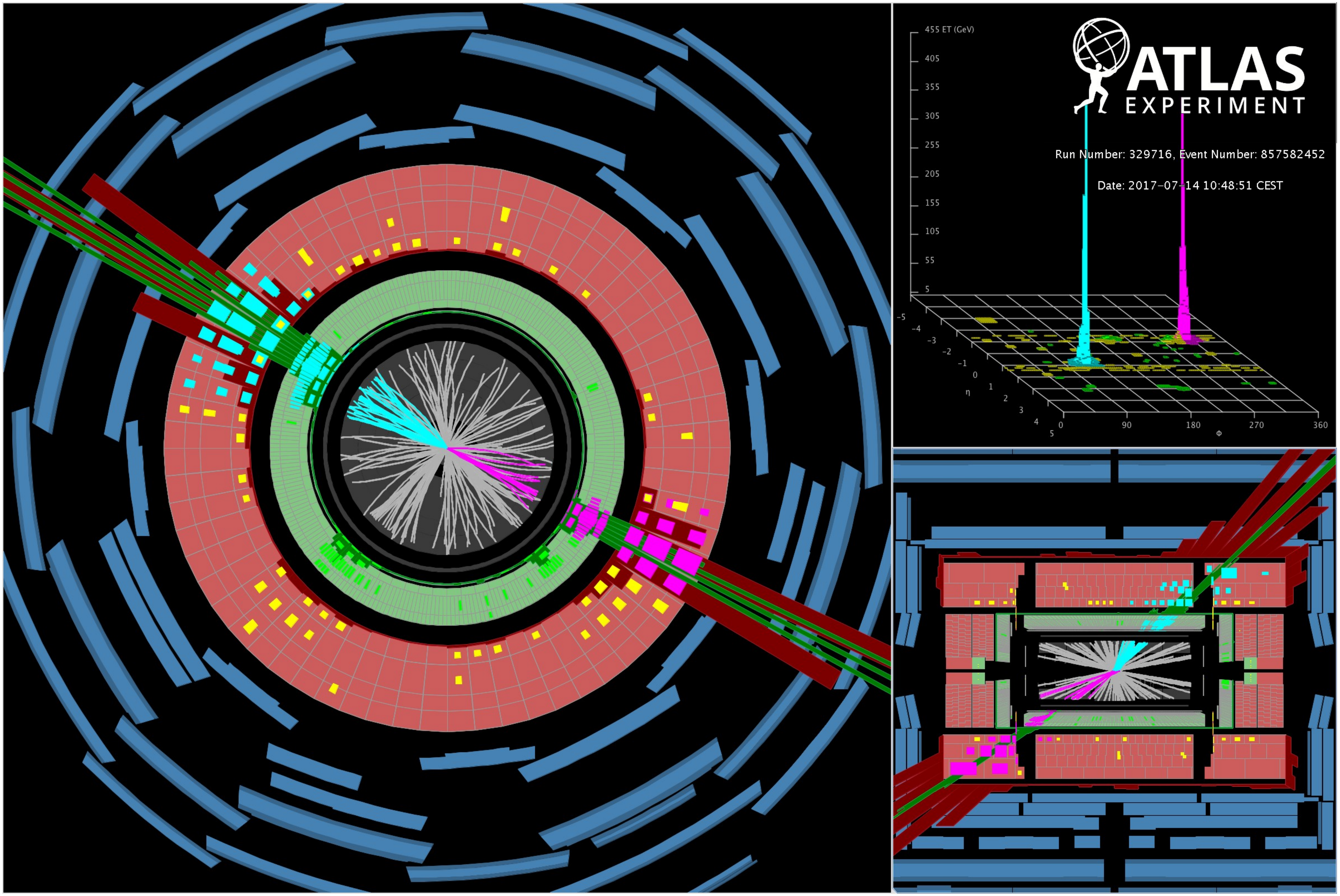
Each particle leaves a specific signature...





Piecing together all detected particles we can infer what happened in the proton collision

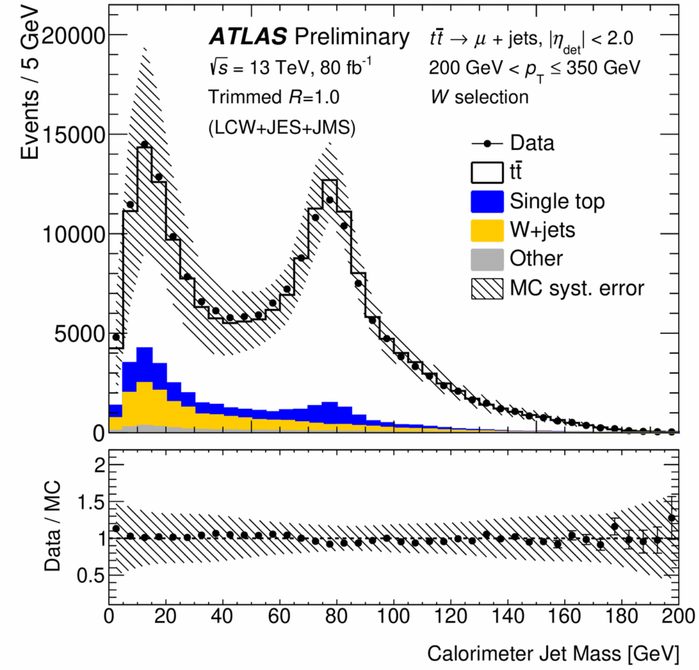
Jets

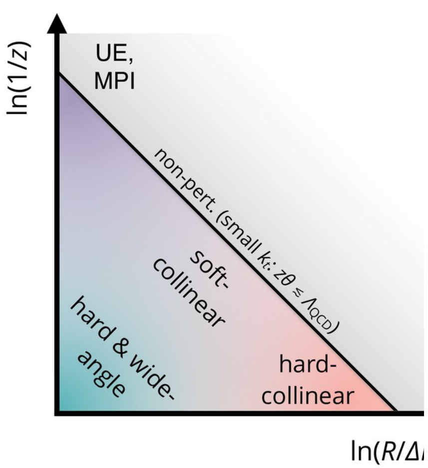

ATLAS
EXPERIMENT
Run Number: 329716, Event Number: 857582452
Date: 2017-07-14 10:48:51 CEST
455 ET (GeV)
405
355
305
255
205
155
105
55
5
η
φ
0
90
180
270
360

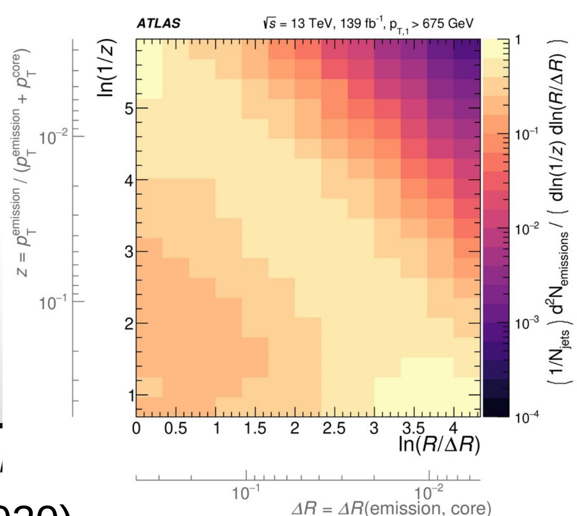
A look inside jets

The sub-structure of jets is accessible thanks to more granular detectors

Jet mass and substructure reveals the origin of (large-radius) jets: the boosted W-peak clearly stands out







ATLAS, PRL 124 (2020)

The Lund jet plane provides an image of the jet that separates hard splittings (matrix element), soft and collinear radiation (parton shower) and non-perturbative effects (hadronization model)

Colliders

Detector technology for the next collider

Detector requirements: e+e-

From key requirements from physics:

- **p_t resolution** (total ZH x-section)

  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$

  ≈ CMS / 40

- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)

  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$

  ≈ CMS / 4

- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%

  ≈ ATLAS / 2

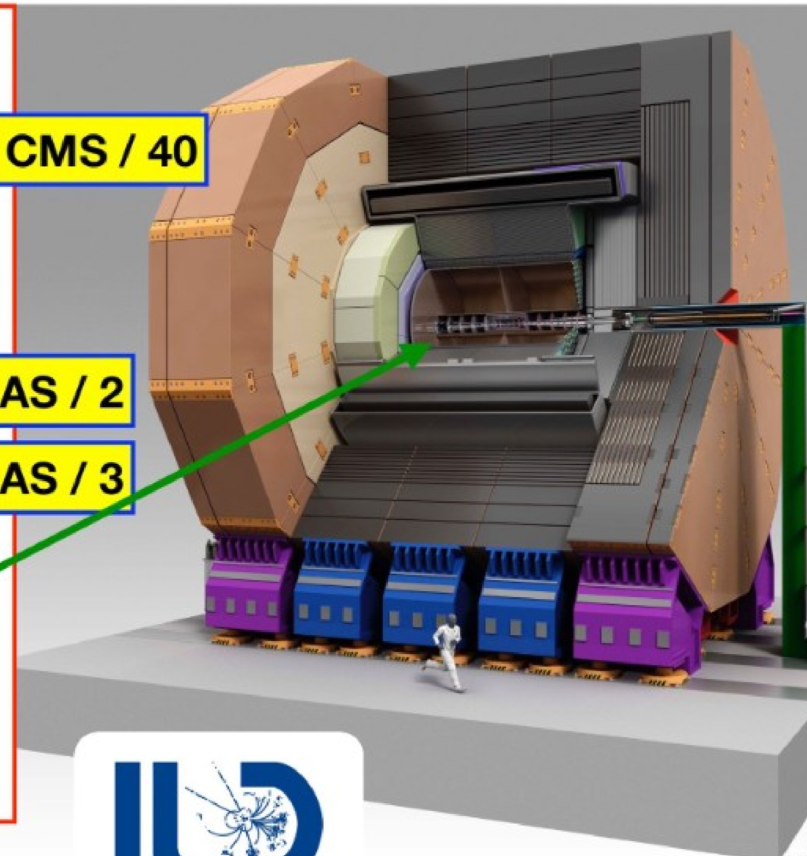
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad

  ≈ ATLAS / 3

To key features of the **detector**:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow

~x1000 more r/o cells than LHC exps.
~x10-100 more than HL-LHC exps.



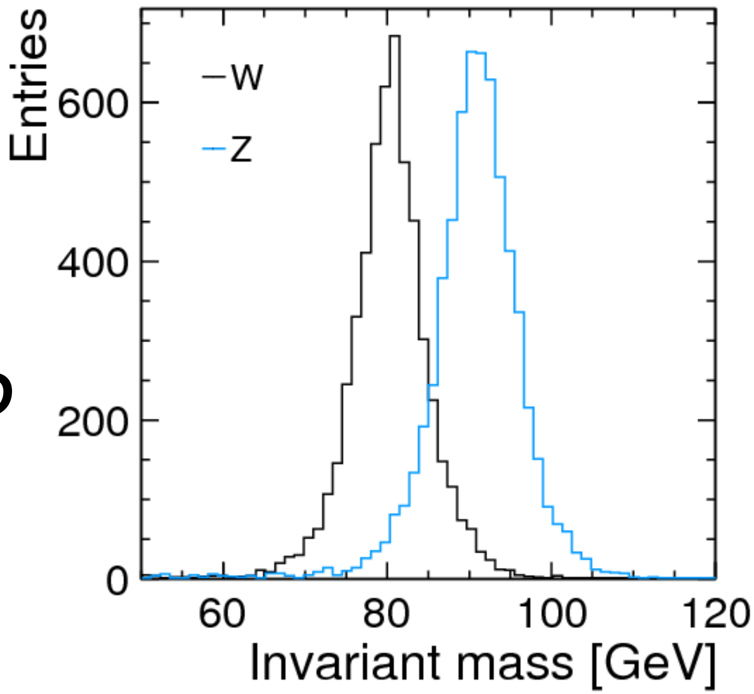
Borrowed from J. List

A. Irles, ILCX2021

Hadronic final states

Hadronic final states are key for the precision e^+e^- programme

- Higgs production, arXiv:1509.02853
- Gauge boson pair production
- Top quark production, arXiv:1604.0122



Lepton colliders offer a lot of QCD

- Controlled and calculable initial state
- Reference samples of q/g/b/W/Z/H/t jets
- Jets "without the junk" (MPI, UE, pile-up)

Jet reconstruction is important

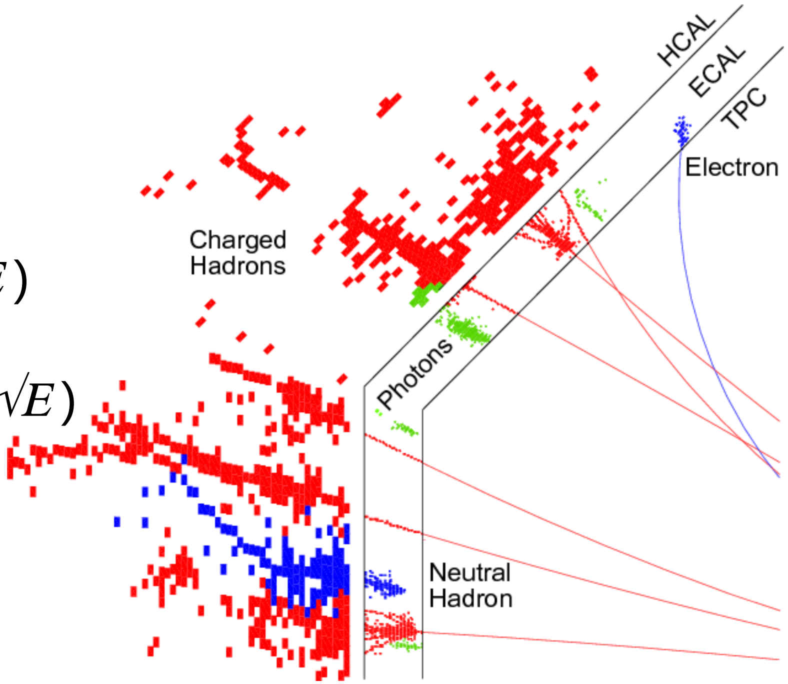
Performance goal: distinguish hadronic W and Z decays

Jet response

Particle flow offers the ultimate jet energy resolution

Combine information from all sub-systems, use the best measurement available for each category of particles:

- charged particles
  (>60%, tracker, DpT/pT ~)
- photons/electrons
  (~25%, EM Calo, ΔE/E ~10-20%//$\sqrt{E}$)
- neutral hadrons
  (~10%, had. Calo. ΔE/E ~40-100%//$\sqrt{E}$)



Theoretical limit $\Delta E/E = 19\%/\sqrt{E}$ *(for perfect track-cluster association)*

Jet response

Full-simulation studies show Pflow limitations, in particular at high energy

Overlapping calorimeter clusters
can be hard to associate to tracks

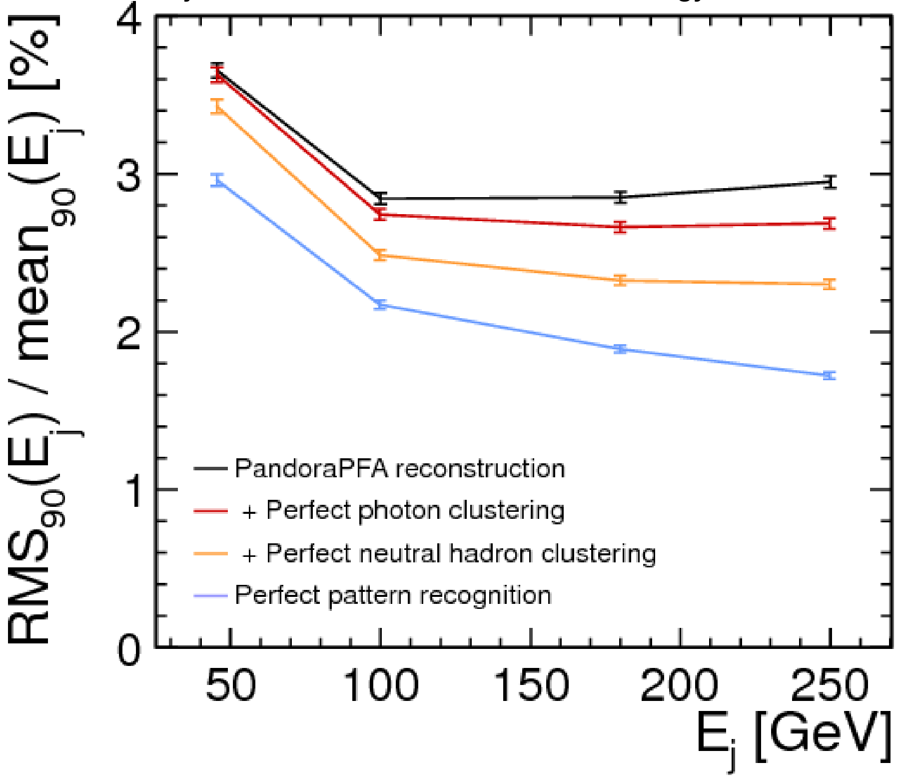
Lateral "width" of calorimeter showers

EM showers:
Moliere radius ~1cm in SiW stack

Hadronic showers:
Int. length ~10 cm in W, 17 cm in Fe

Highly segmented stack, both lateral
(< shower width) and longitudinal
(tens of samples)

ILD: Di-jet events, energy resolution for
"jets" inferred from total visible energy



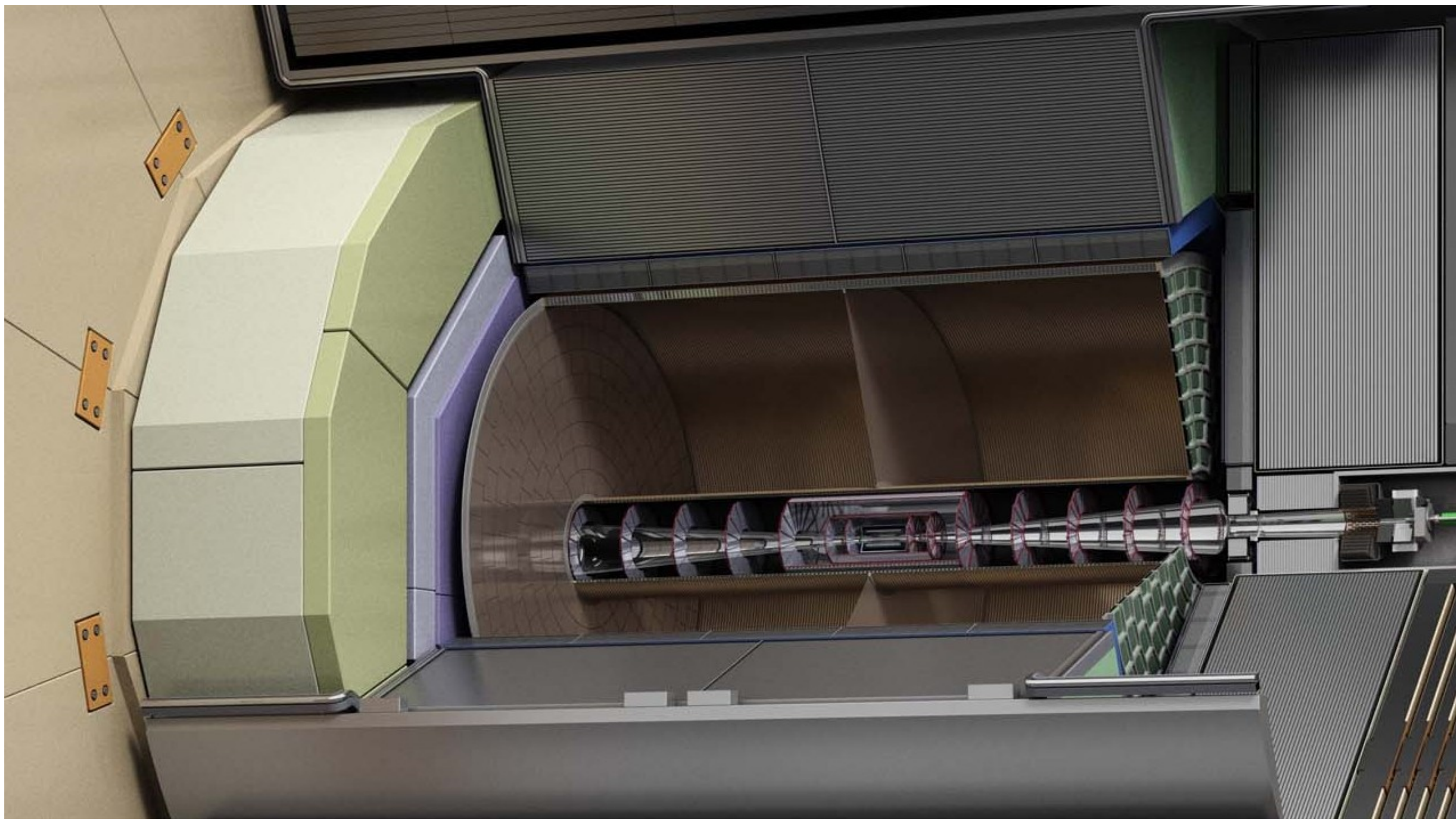
Often, jet clustering limits resolution in complex multi-jet topologies
see e.g. CLIC di-Higgs production at 3 TeV, arXiv:1607.05039)

Detector concepts

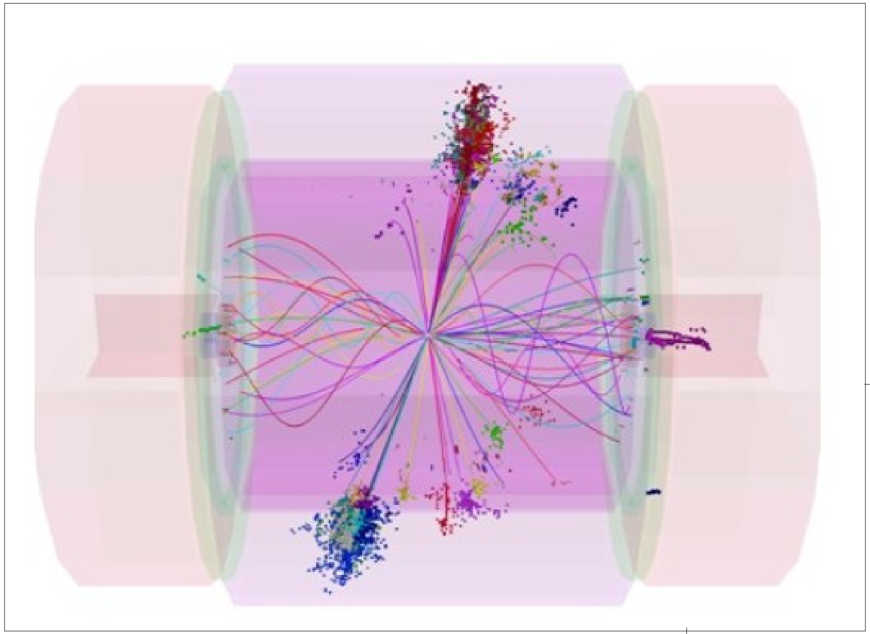
The detector concepts for a future e+e- collider (ILD, SiD, CLIC, FCC) are optimized for particle flow

- granular calorimeter - 4-5 Tesla solenoid - low-mass tracking and vertexing

Image: ILD For details:
ILC TDR, arXiv:1306.6329

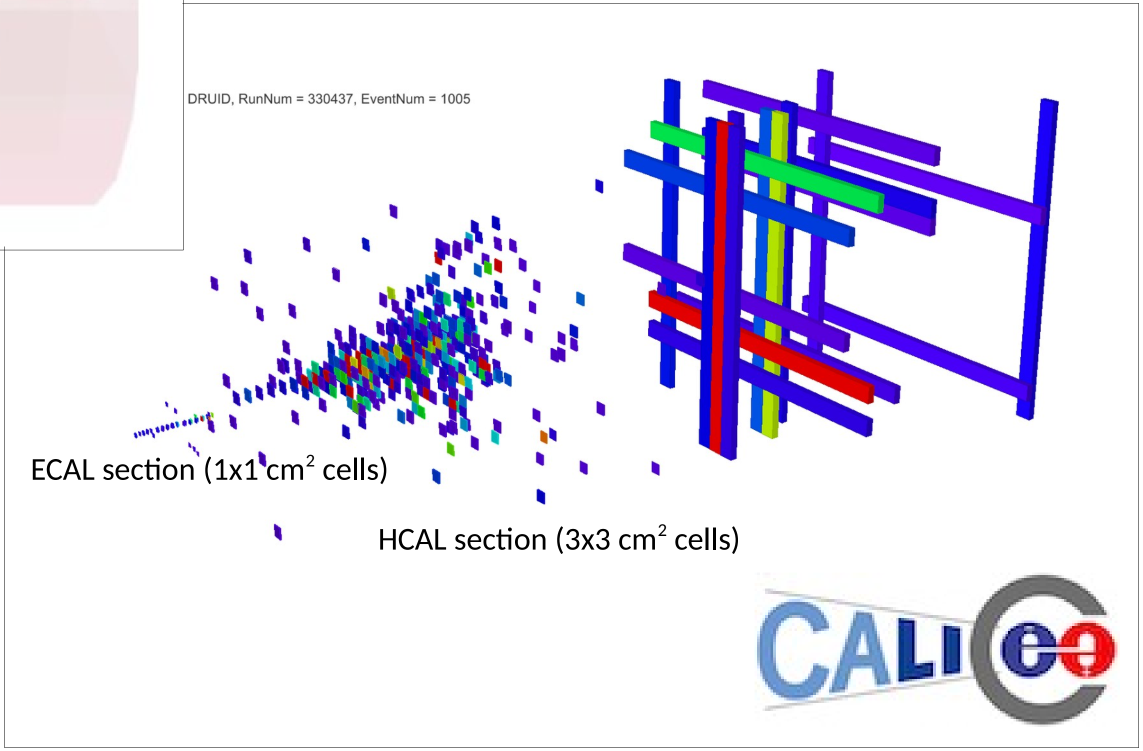


Monte Carlo simulation



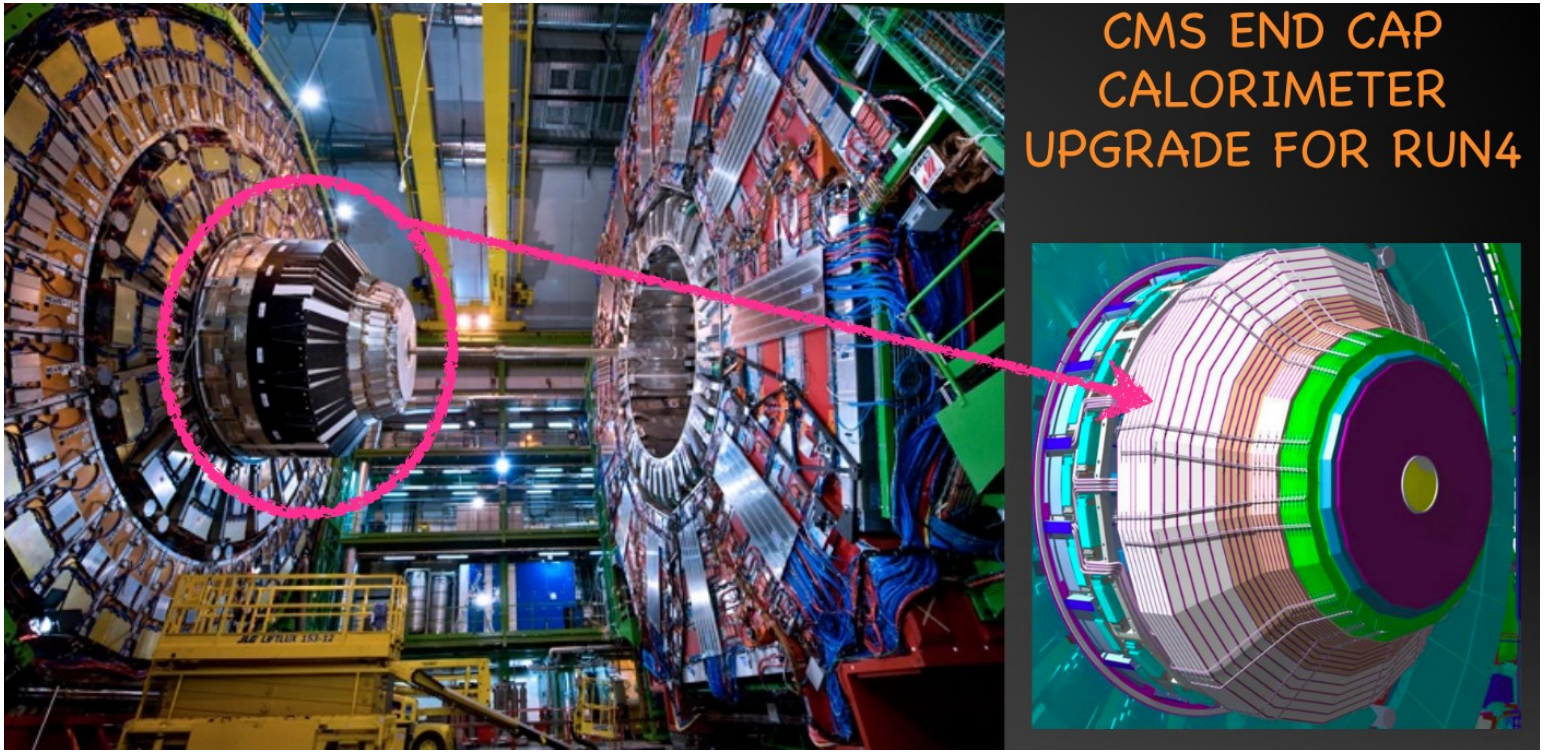
Not Science Fiction: extensive design and Monte Carlo studies.

40 GeV π^+ in test beam



Not Science Fiction:
1 m^3 prototype beam test
Complete engineering and production chain for CMS HGCAL

Granular calorimetry: proof-of-principle



CMS HGCal, a complete Si+absorber sampling calorimeter prototype,
Solidly establishes the ultra-granular “CALICE-style” calorimeters as the baseline for ILC (both ILD and SiD)
see D. Bhowmik, LCWS21, link to talk

Calorimetry

Highly granular calorimeter system:

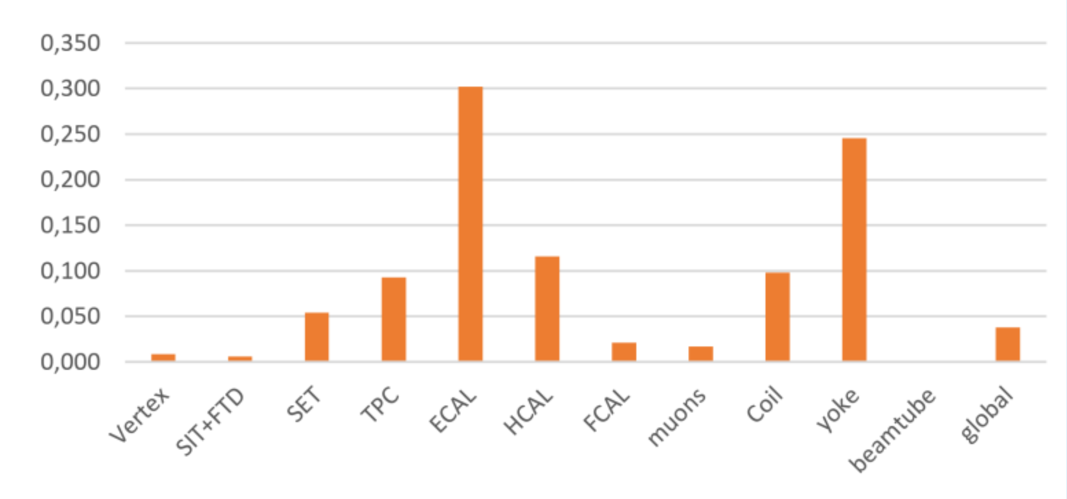
- CALICE has developed highly granular solutions for ECAL & HCAL
- Keep the stack compact and uniform (thin PCBs, minimal dead material)
- CMOS pixels may be a cost-effective alternative for pads?

Key challenge is the sheer scale, channel count and cost

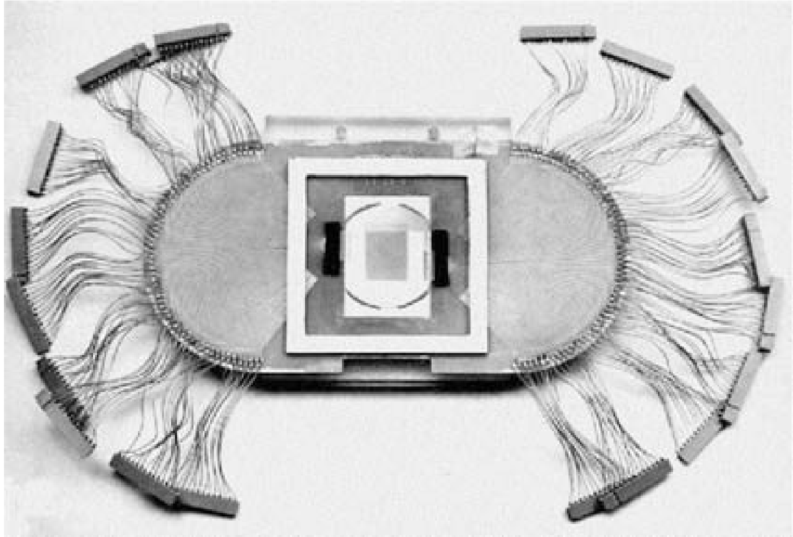
- Cost reduction R&D
- Ensure multiple vendors
- Automatization
- Industrialization

And only as a last resort:

- negotiate size & granularity



Silicon tracking



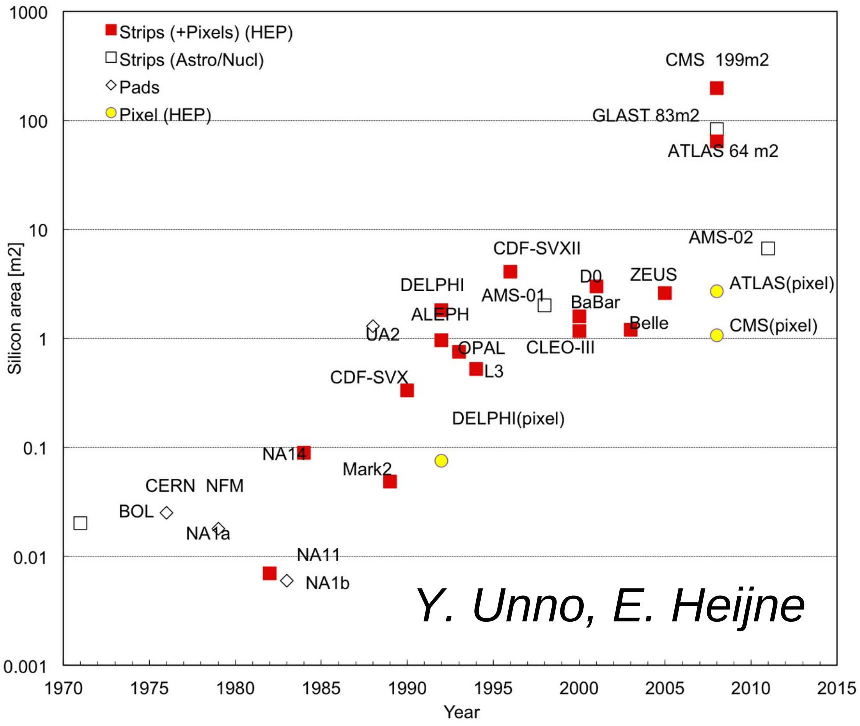
NIM217 (1983):

1200 diode strips on a 2” wafer

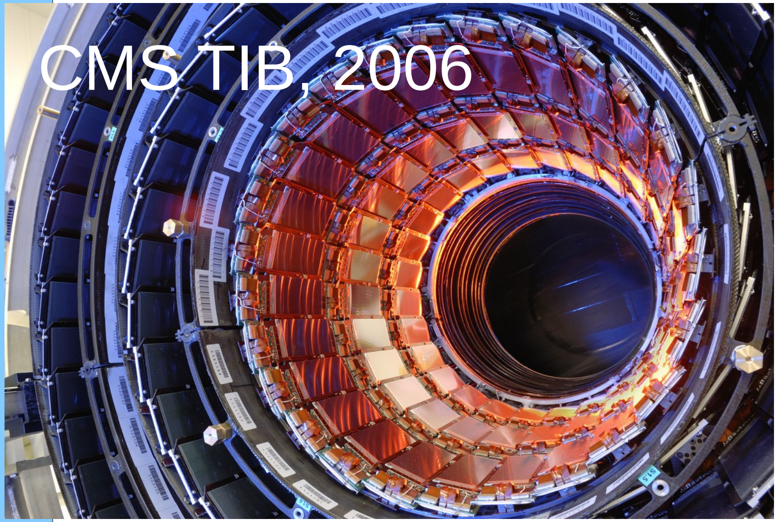
Very bulky support and ancillary systems

2022

Silicon sensors now dominate tracking and vertexing with large O(100 m^2) systems



Silicon tracking for LHC run 1,2,3



Still pretty much the same planar process
Industrial scale: 2” wafers → 8”
Segmentation: pixels 100 x 100 μm^2
Micro-electronics: compact FE/interconnect

So, what's next?

Silicon 4D tracking

Timing detectors open up 4D tracking

Low Gain Avalanche Detectors (LGADs)

LGAD TECHNOLOGY

- Segmentation of the multiplication.
- Electron collection
- Single side process

iLGAD TECHNOLOGY (iLG1)

- Multiplication extended over the electrode.
- Hole collection
- Complex double side process

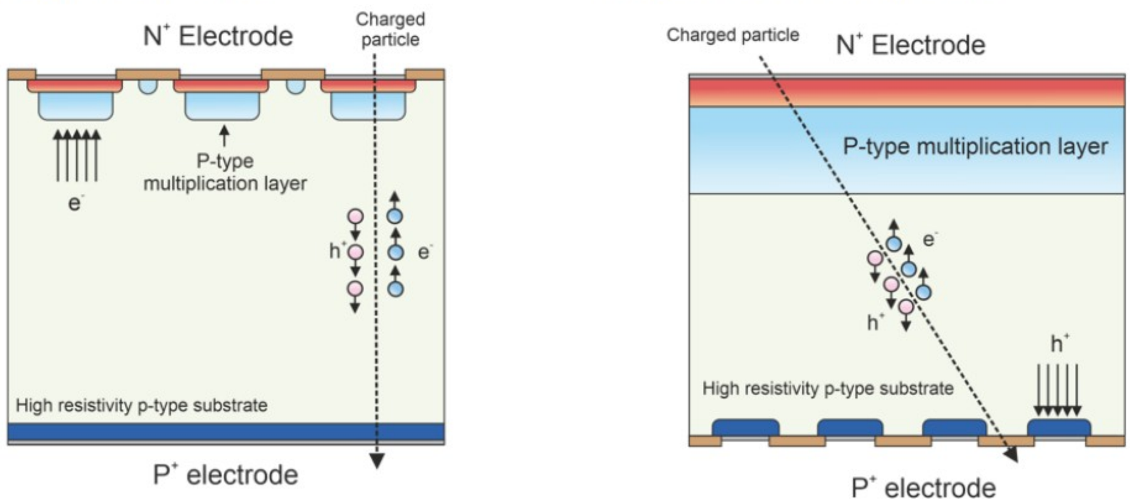


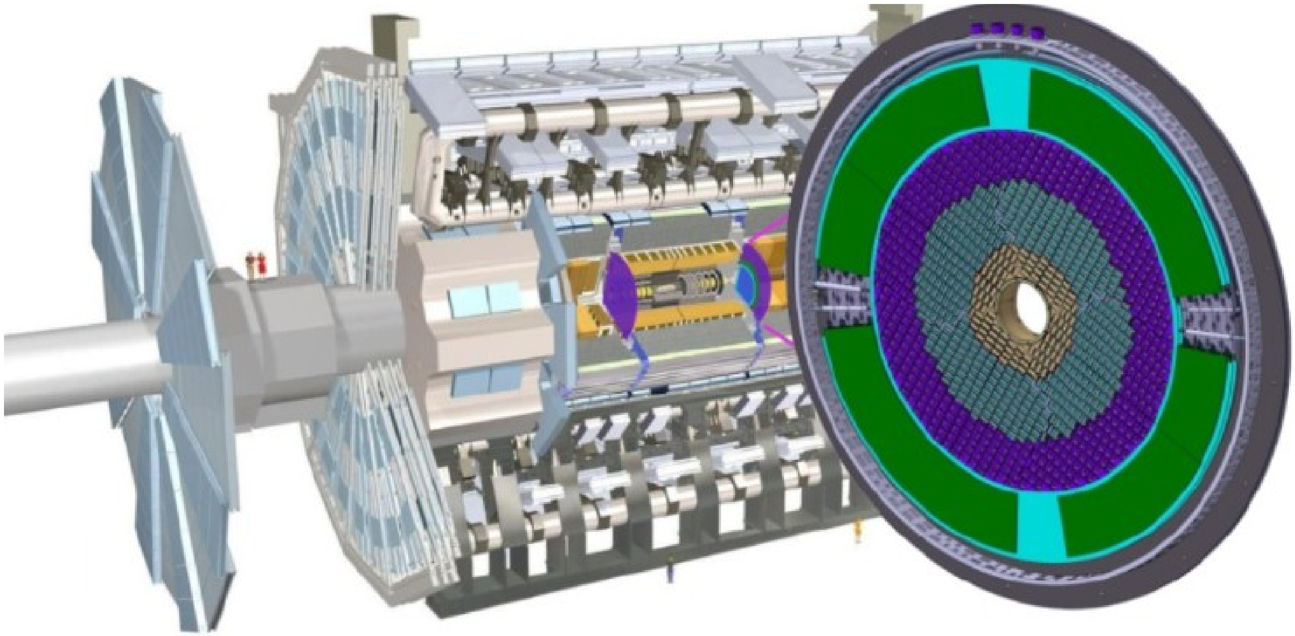
Image from A. Doblas

But, also, RICH for PID, time information from SiPMs in calorimeter

LGADs: progress

2011: LGAD Technology, P. Fernandez NIM A658 (2011), G. Pellegrini NIMA 765
2013: Promise 20 ps time resolution, Turin/CNM/UCSC, arXiv:1312.1080
Then, things started to move really fast!!

Today: Construction, ATLAS and CMS include several m^2 in upgrades



See Xin Shi, LCWS21, link to talk

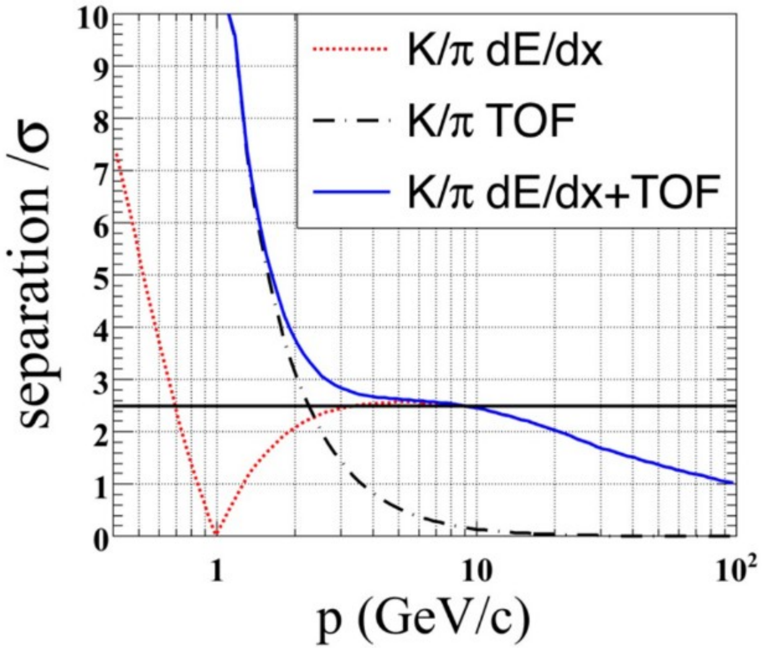
Timing in e+e- colliders

What is the role of time information in the ILC experiments?

Use PID from TOF, bring VXD closer to IP, reduce confusion in PFA?

Does it increase the power budget?

Should we revise the cooling strategy?



Silicon tracking for e+e- colliders

Precision tracking & vertexing requires further integration

Less radiation, less dense environment, less power
→ Better performance

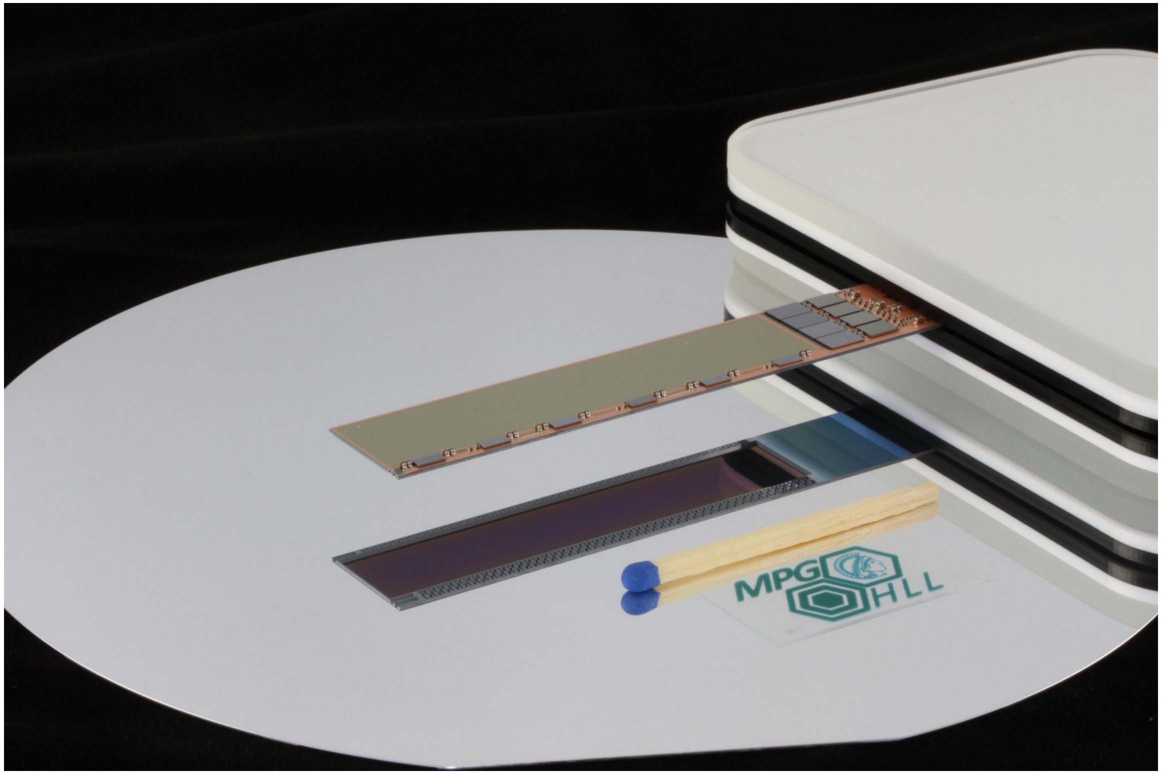
Sensor is still pretty much the same high-R silicon

But: thinned to 50-75 μm

read-out electronics:
on the silicon

Power & signal lines:
on the silicon

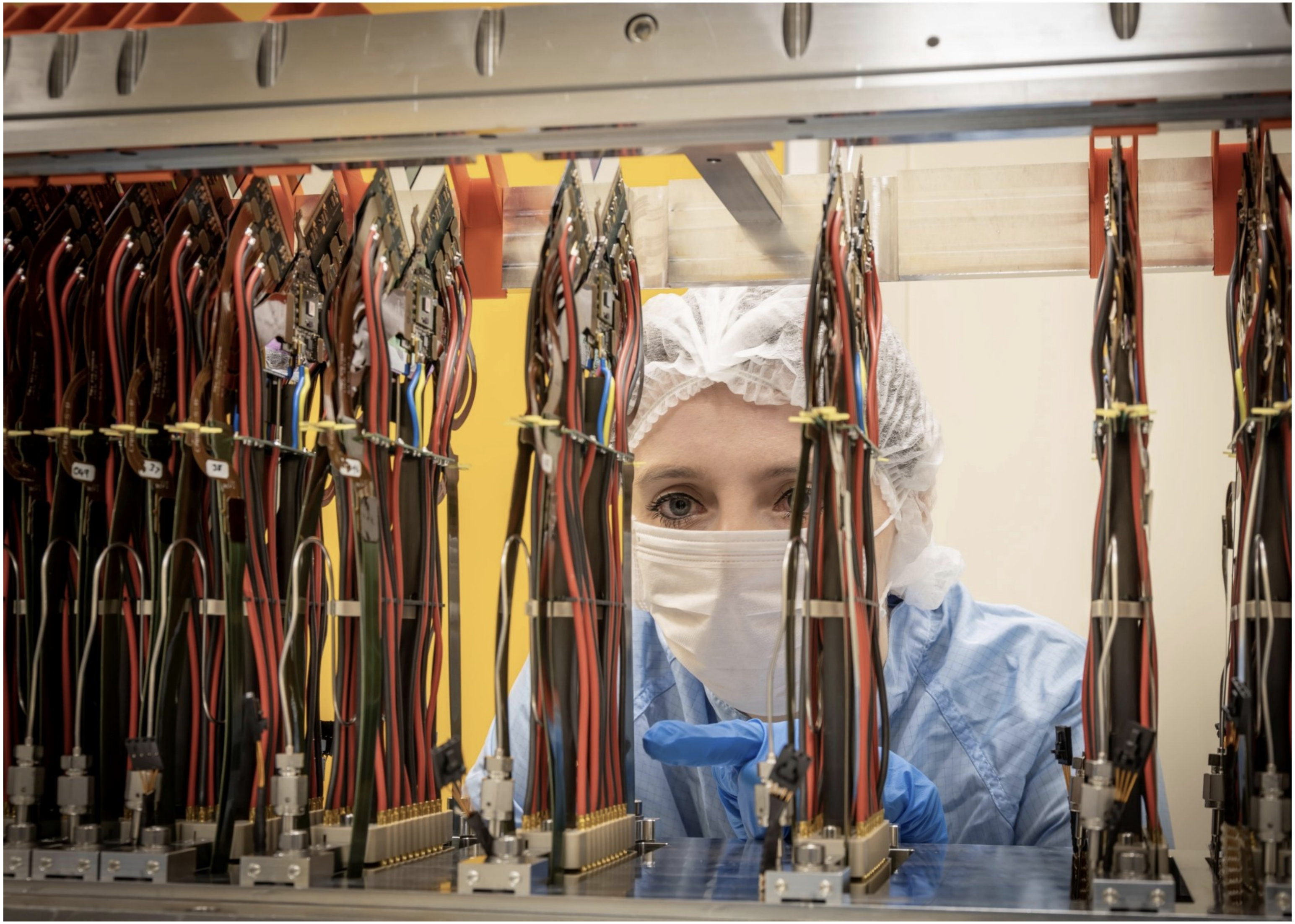
Support structure:
= the silicon



DEPFET pixel sensor for Belle 2

LHCb VELO

Micro-channel cooling: arXiv:2112.12763

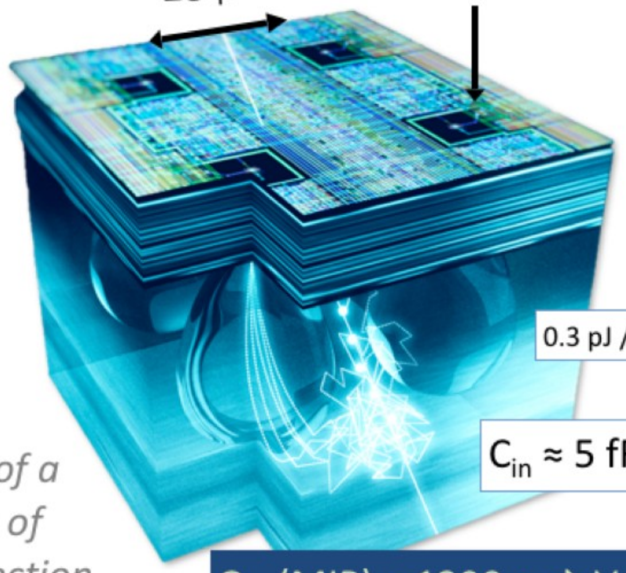


Several groups/collaborations have developed CMOS sensors for e+e- vertex detectors and tracking systems

Fully monolithic sensor

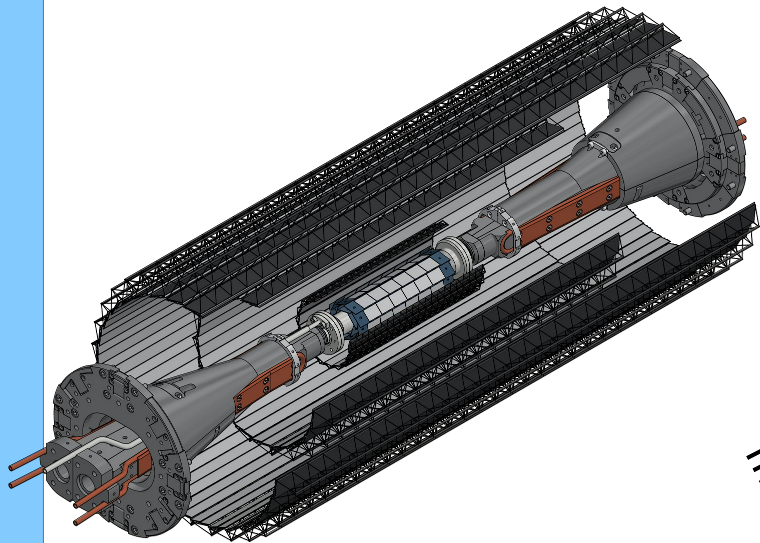
Today's CMOS sensors *(MIMOSA, ALPIDE, MonoPix,...)* can meet e+e- requirements.

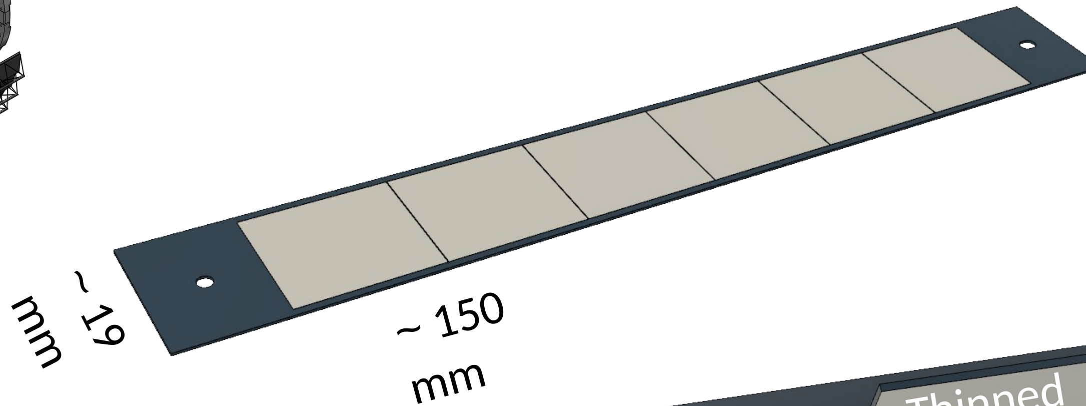
I will focus on engineering & integration in the following

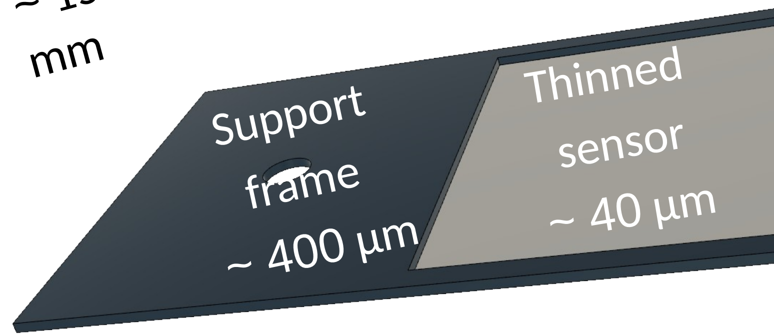


Artistic view of a SEM picture of ALPIDE cross section
Not to scale

Silicon tracking for e+e- colliders

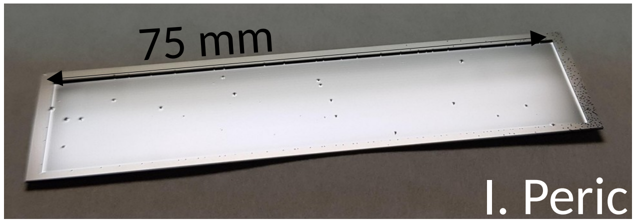






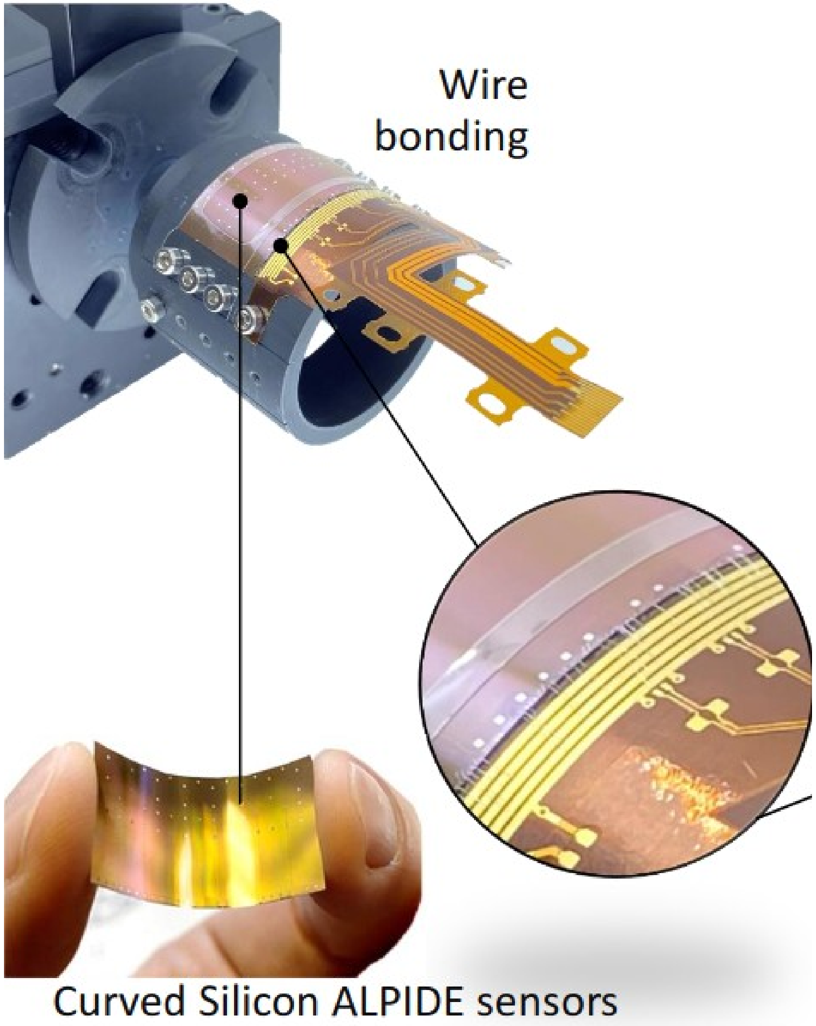
Belle 2 VXD upgrade (~2026) is foreseen with OBELIX (TJ-monopix) CMOS sensors

Adapt the all-silicon ladder concept



Promising steps towards all-CMOS ladder by I. Peric/IZM HV35DEMO.

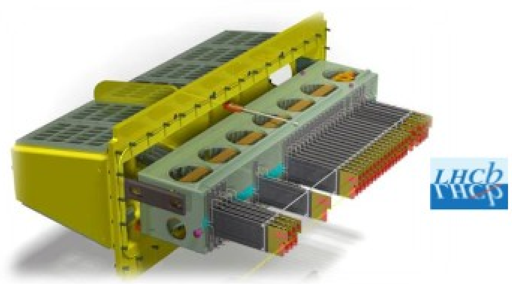
Silicon tracking for e+e- colliders

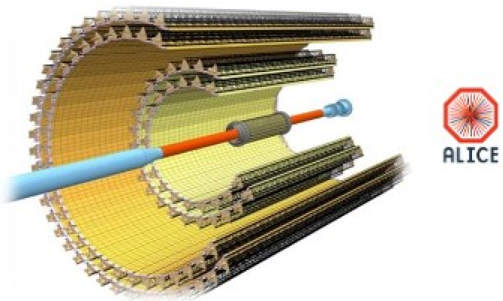


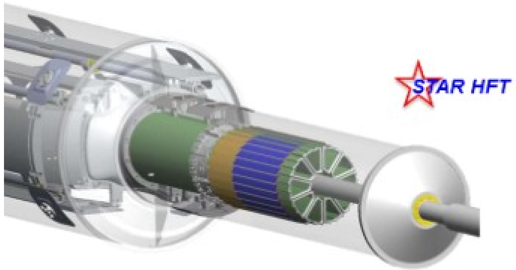
The Mu3e experiment and ALICE have aggressive plans to reduce detector material (Kapton support structures, bent sensors)

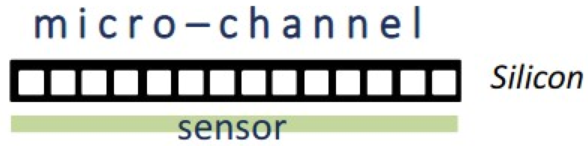
Mechanics and cooling

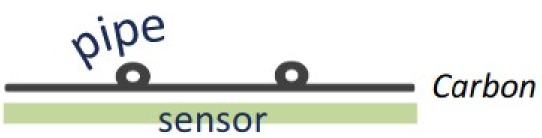
Image from Corrado Gargiulo







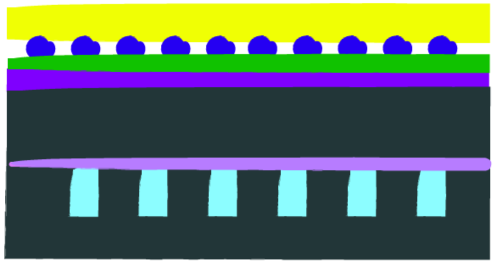




Also: new refrigerants (Krypton, super-critical CO_2)

Micro-channel cooling

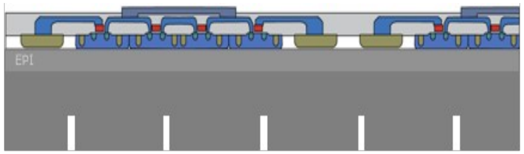
Active cold plates
used by NA62 GTK and LHCb VELO
See P. Collins at ILCX2021



Integrated micro-channel
used by NA62 GTK and LHCb VELO
See P. Collins at ILCX2021

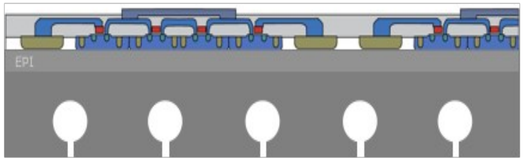
Integrated micro-channel cooling

(i.e. R. van Erp et al., Nature 585, 211–216 (2020))



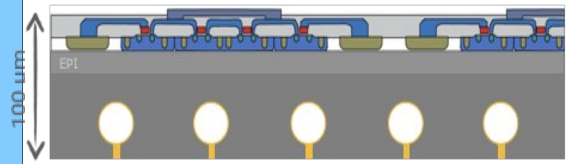
DRIE of small trenches (anisotropic)

A pattern of small trenches (3 x 10 μm) is etched on the backside of the pixel detector



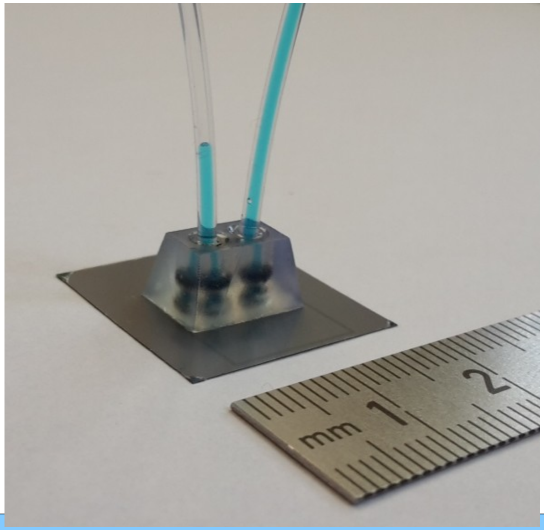
XeF_2 etching of microchannels (isotropic)

Microchannels are etched isotropically with XeF2.



Filling of trenches (e.g. PECVD, Parylene)

A thin film of parylene (5 μm) seals the microchannels. It is finally cured by a thermal cycle.



M. Boscardin et al., NIM A, 2013
L. Andricek et al., JINST 11 (2016) P06018
C. Lipp, MSc Thesis, EPFL, 2017
I. Berdalovic et al., JINST 13 (2018) C01023

Working MALTA CMOS sensor with integrated μ-channels

From A. Mapelli (CERN+EPFL)

THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators Detector R&D Roadmap Process Group

European Strategy Update

ECFA European Committee for Future Accelerators

Contents

We ought, in every instance, to submit our reasoning to the test of experiment, and never to search for truth but by the natural road of experiment and observation.

Antoine Lavoisier
Traité élémentaire de chimie, 1789

More information:

https://europeanstrategy.cern
https://indico.cern.ch/e/ECFADetectorRDRoadmap
https://ecfa.web.cern.ch/

ISBN 978-92-9083-614-8 (online)
ISBN 978-92-9083-615-5 (paperback)

European Strategy Update

ECFA European Committee for Future Accelerators

2021

AIDA innova

Blue-sky and long-term R&D is poorly funded

AIDA innova provides EU-funded forum for detector R&D,

Pool resources across all experiments and future collider concepts

Use near-future experiments as stepping stones

Connect to developments beyond HEP

Summary

High-energy collisions are a key tool to advance knowledge of the constituents of matter and their interactions at the most fundamental level

The tremendous progress in fundamental physics in the last century is fueled by exponential improvements in accelerator technology

The LHC program has opened the TeV regime and delivered a long series of discoveries of previously unobserved processes, with or without Higgs boson
Much more to come in the the next two decades with run 3 and the HL-LHC

The key technologies behind the collider programme are high-field magnets, powerful and efficient RF cavities, advanced beam focussing.

Experiments require the most advanced detector technology. Examples of highly successful detector R&D: ultra-granular calorimeters and silicon detectors.

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Biography

Marcel Vos is an experimental physicist at the particle physics institute IFIC (UVEG/CSIC) in Valencia, Spain He is active in the ATLAS experiment at the LHC and in the ILC and CLIC projects for a linear electron-positron collider. His work focuses on jets and the top quark, and on Silicon detectors for charged-particle detection. Dutch by birth and education (U. Utrecht, U. Twente), he is a staff member of the Spanish research council CSIC

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