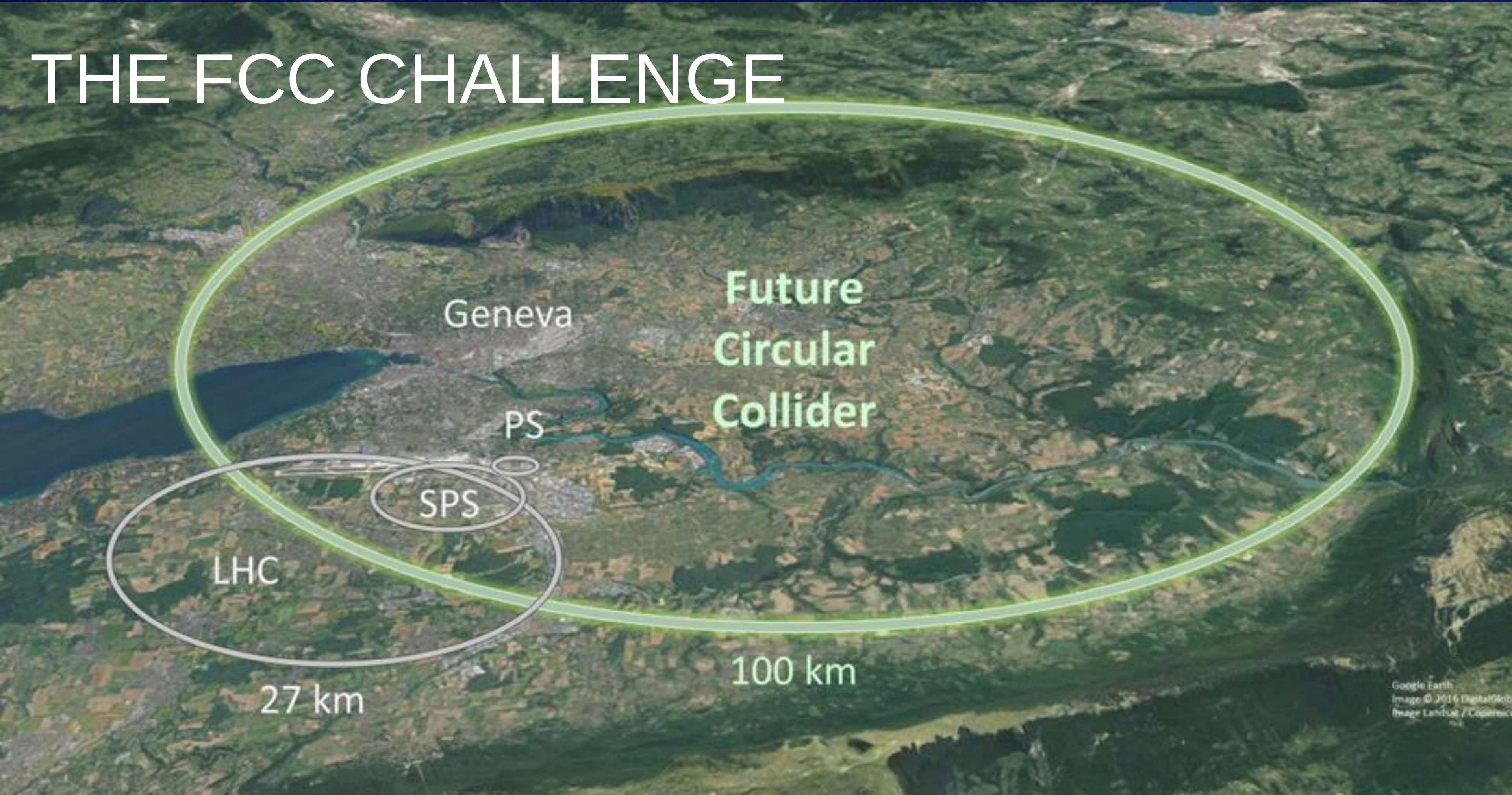
THE DETECTOR CHALLENGE

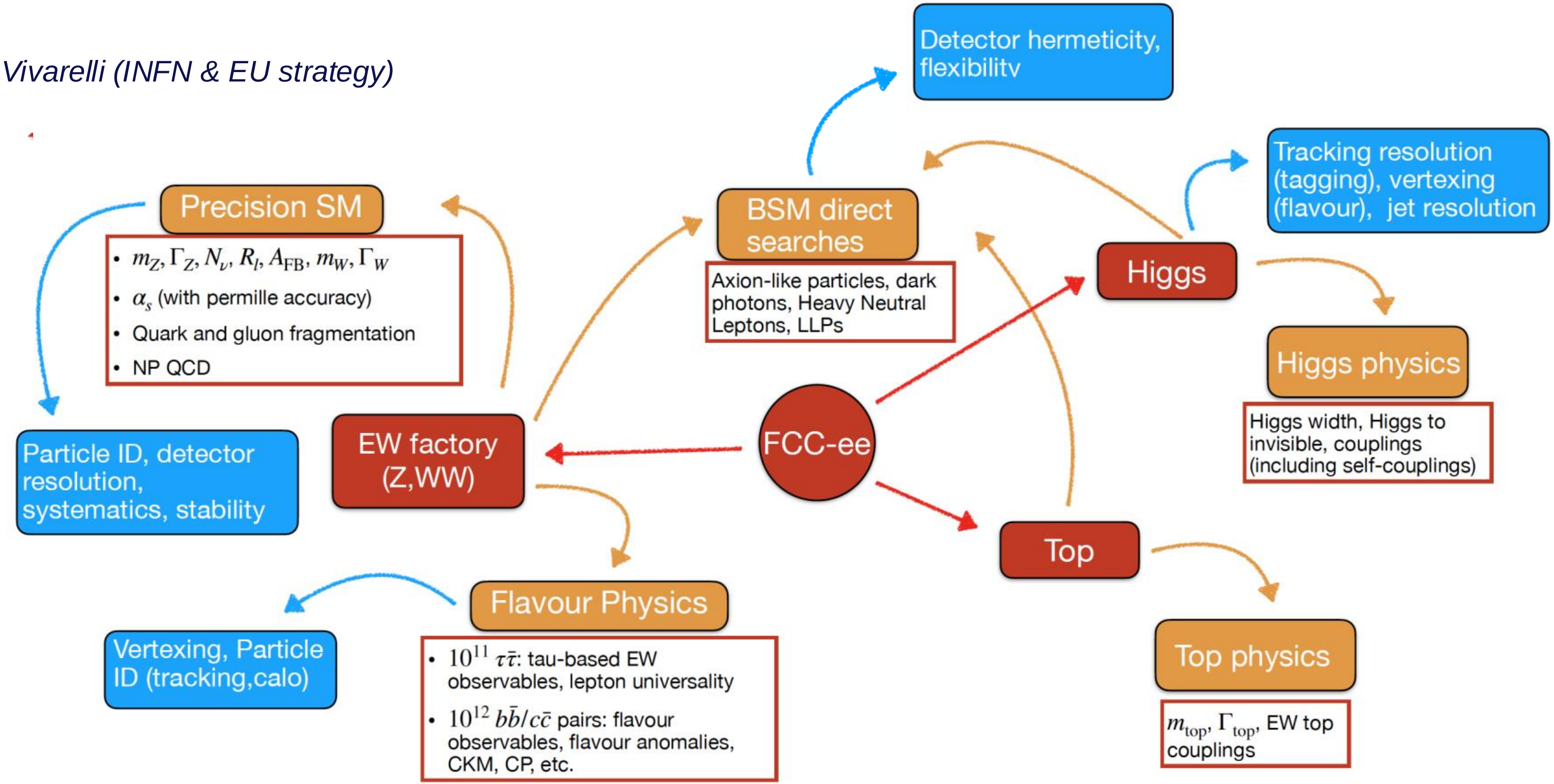
Gabriella Gaudio
INFN Pavia

THE FCC CHALLENGE



The Physics you want – The Detector you need

I. Vivarelli (INFN & EU strategy)



The physics case drivers

Higgs boson tagging and **BR into invisibles** sets requirements on:

- Tracking performance
  - Material in the tracking volume.
  - Magnetic field (and thickness of solenoid).

Higgs boson BR sets requirements on **e, γ and jet energy and angular resolutions**.

- Tagging sets requirements **on tracking and vertexing**.

…and in general requirements grow as more and more physics is explored.

Focus topics for the ECFA study on Higgs / Top / EW factories

Juan Alcaraz Maestre[1], Juliette Alimena[2], John Alison[3], Patrizia Azzi[4], Paolo Azzurri[5], Emanuele Bagnaschi[6,7], Timothy Barklow[8], Matthew J. Basso[9], Josh Bendavid[10], Martin Beneke[11], Eli Ben-Haim[12], Mikael Berggren[2], Jorge de Blas[13], Marzia Bordone[6], Ivanka Bozovic[14], Valentina Cairo[6], Nuno Filipe Castro[15], Marina Cobal[16], Paula Collins[6], Mogens Dam[17], Valerio Dao[6], Matteo Defranchis[6], Ansgar Denner[18], Stefan Dittmaier[19], Gauthier Durieux[20], Ulrich Einhaus[2], Mary-Cruz Fouz[1], Roberto Franceschini[21], Ayres Freitas[22], Frank Gaede[2], Gerardo Ganis[6], Pablo Goldenzweig[23], Ricardo Gonçalo[24,25], Rebeca Gonzalez Suarez[26], Loukas Gouskos[27], Alexander Grohsjean[28], Jan Hajer[29], Chris Hays[30], Sven Heinemeyer[31], André Hoang[32], Adrián Irles[33], Abideh Jafari[2], Karl Jakobs[19], Daniel Jeans[34], Jernej F. Kamenik[35], Matthew Kenzie[36], Wolfgang Kilian[37], Markus Klute[23], Patrick Koppenburg[38], Sandra Kortner[39], Karsten Köneke[19], Marcin Kucharczyk[40], Christos Leonidopoulos[41], Cheng Li[42], Zoltan Ligeti[43], Jenny List[2], Fabio Maltoni[20], Elisa Manoni[44], Giovanni Marchiori[45], David Marzocca[46], Andreas B. Meyer[2], Ken Mimasu[48], Tristan Miralles[47], Victor Miralles[49], Abdollah Mohammadi[50], Stéphane Monteil[51], Gudrid Moortgat-Pick[28], Zohreh Najafabadi[52], María Teresa Núñez Pardo de Vera[2], Fabrizio Palla[5], Michael E. Peskin[8], Fulvio Piccinini[53], Laura Pintucci[54], Wiesław Płaczek[55], Simon Plätzer[56,32], Roman Pöschl[57], Tania Robens[58], Aidan Robson[59], Philipp Roloff[6], Nikolaos Rompotis[60], Andrej Saibel[33], André Sailer[6], Roberto Salerno[61], Matthias Schott[62], Reinhard Schwienhorst[63], Felix Sefkow[2], Michele Selvaggi[6], Frank Siegert[64], Frank Simon[23], Andrzej Siodmok[55], Torbjörn Sjöstrand[65], Kirill Skovpen[66], Maciej Skrzypek[40], Yotam Soreq[67], Raimund Ströhmer[18], Taikan Suehara[68], Junping Tian[68], Emma Torro Pastor[33], Maria Ubiali[36], Luiz Vale Silva[33], Caterina Vernieri[8], Alessandro Vicini[69] Marcel Vos[33], Aidan R. Wiederhold[70], Sarah Louise Williams[36], Graham Wilson[71], Aleksander Filip Zarnecki[72], Dirk Zerwas[73,57]

Abstract

In order to stimulate new engagement and trigger some concrete studies in areas where further work would be beneficial towards fully understanding the physics potential of an e^+e^- Higgs / Top / Electroweak factory, we propose to define a set of focus topics. The general reasoning and the proposed topics are described in this document.

arXiv:2401.07564v3 [hep-ph] 18 Jan 2024

Benchmark physics channels
=>
update on detector requirements
https://arxiv.org/abs/2401.07564

The physics case drivers

	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	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu m]$	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

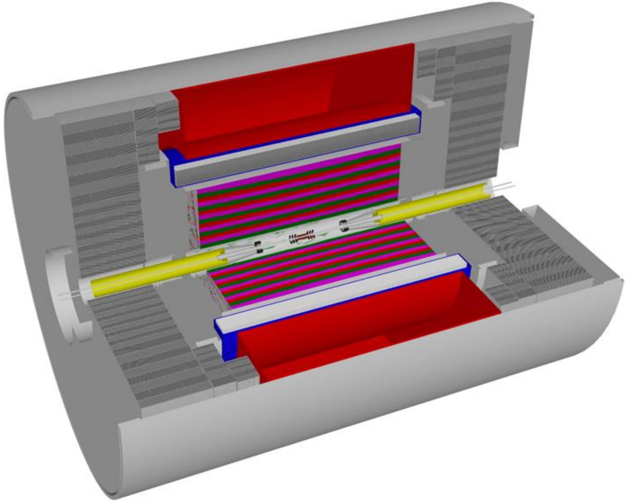
The physics case drivers

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

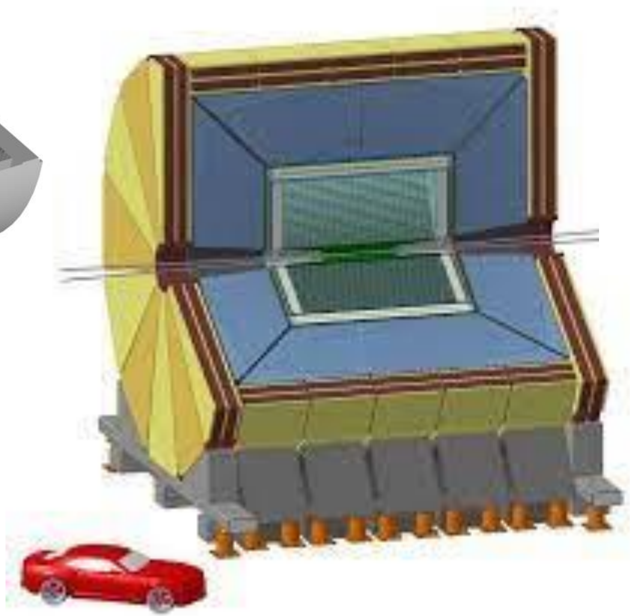
one problem – several solutions with different pros and cons

The Detector Concepts

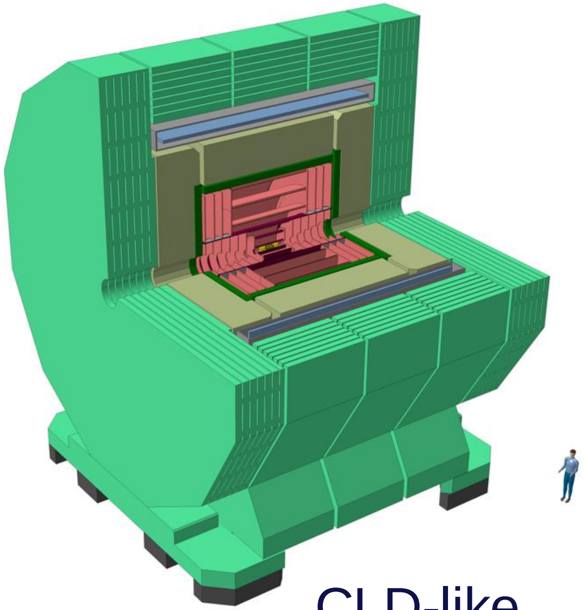
From detector R&D to integrated experiment views



ALLEGRO



IDEA



CLD-like

a 4th is needed

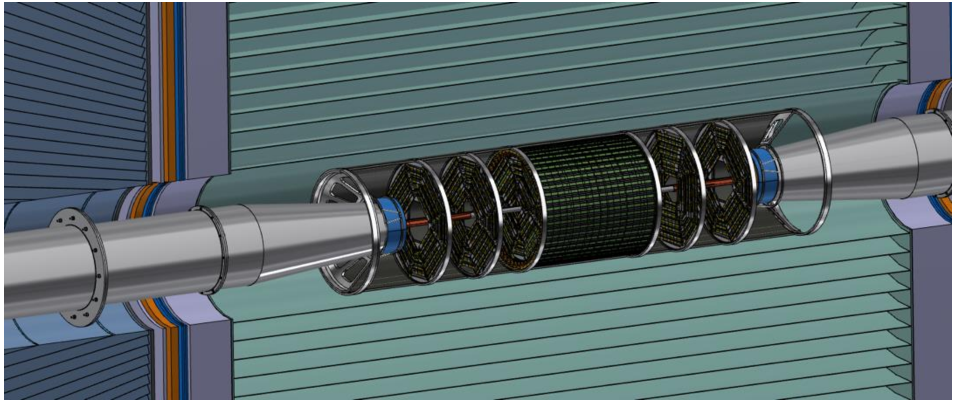
The physics case drivers

	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	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu m]$	Additional case study: $B \to K^* \tau\tau$
$H \to gg, q\bar{q}, VV$	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

one problem – several solutions with different pros and cons

Vertex technologies

Keywords:
- High spatial resolution (~ 3-5 μm)
- Lightweight (0.1% of X_0/layer)
- Low power consumption to cope with a 400 MHz/cm^2 estimated rate (10-30 mW/cm^2)



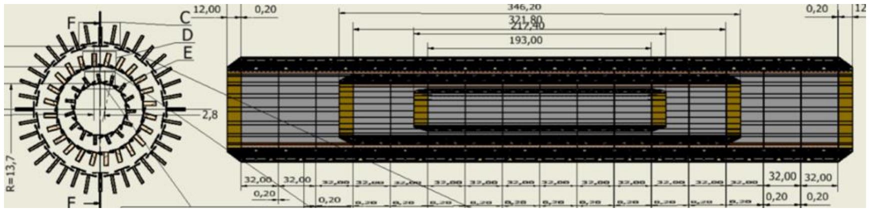
Efforts ongoing at different levels
- Technology selection
  - DMAPS: Depleted Monolithic Active Pixel Detectors
  - Curved MAPS
  - LGAD for timing information in the wrapper
- Vertex mechanical integration in the MDI (Machine Detector Interface)

Vertex technologies

DMAPS

ARCADIA based:
- Lfoundry 110 nm process
- *50 µm thick*
- Power density 30 mW/cm^2
- **100 MHz/cm^2**

ATLASPIX3 based
- TSI 180 nm process
- *50 µm thick*
- Power density 150 mW/cm^2
- **Up to 1.28 Gb/s downlink**

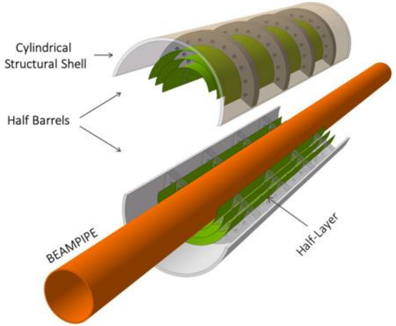


Curved and stitched MAPS

Proposed layout using an ALICE ITS3 inspired design (~0.05%X/X_0 material budget per layer)
- ALICE smaller radius will be 18 mm

(beam pipe 16 mm)
- To demonstrate bent MAPS 13.7 mm radius works electrically – mechanically is OK

Active pixels <95% of covered area (chip service zones)
- Which impact has on physics?

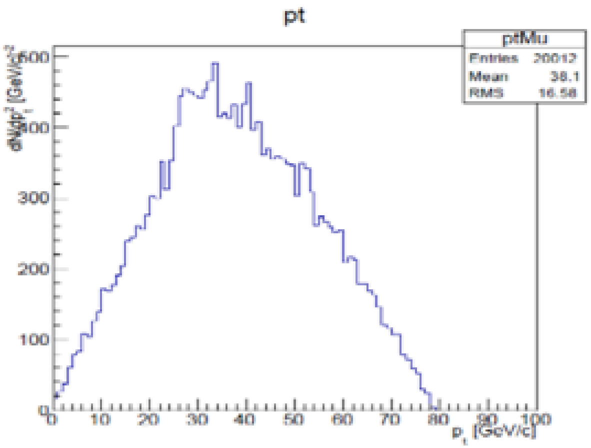


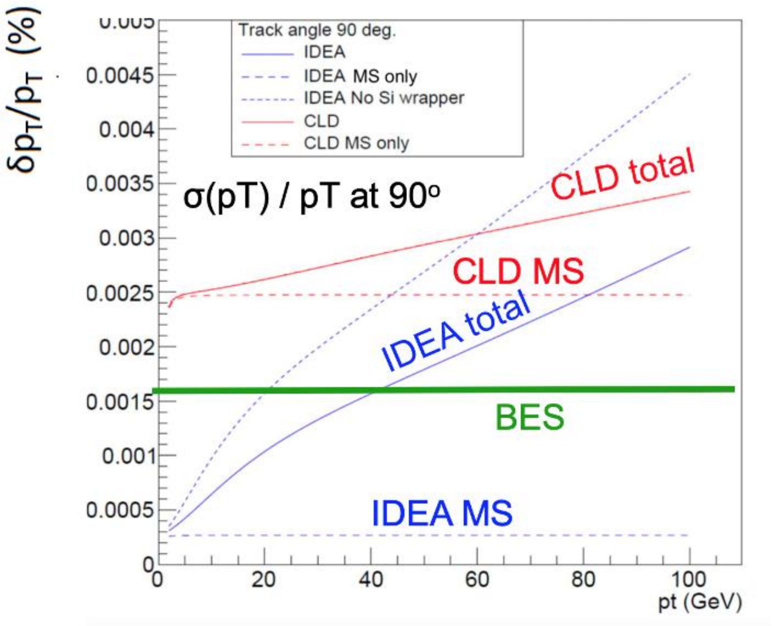
The physics case drivers

	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	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} [\mu\text{m}]$	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

one problem – several solutions with different pros and cons

Momentum resolution





Ideally: σ(p) / p ≈ rel. BES

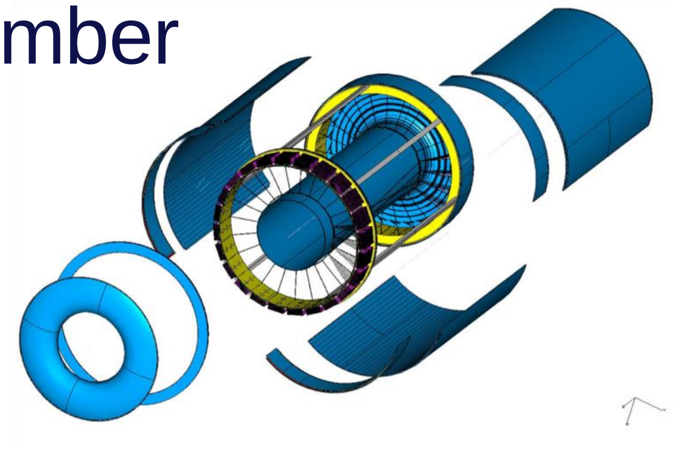
BES inherent to the machine.
~ 0.16% @ 240 GeV
(~ 0.13% @ the Z pole)

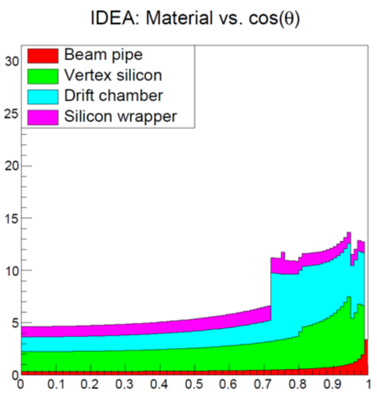
Muons in ZH events have rather small p_T
Transparency more relevant than asymptotic resolution

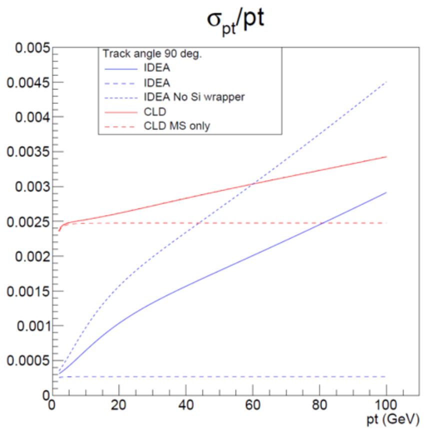
Extremely transparent Drift Chamber

Challenges

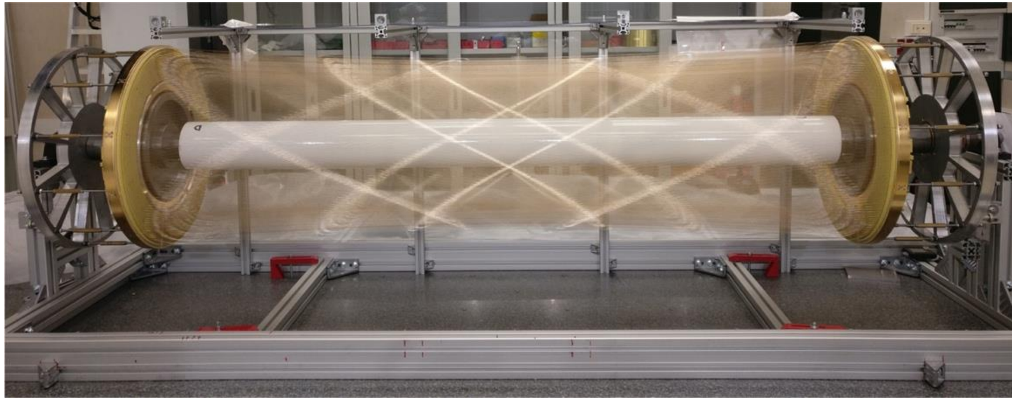
- Total thickness: 1.6% of X_0 at 90°
- Max drift time: 350 ns
- Single point precision σ_{xy} ~ 100 μm (many points in the same track) ; σ_z < 1 mm







Based on MEG2 experience

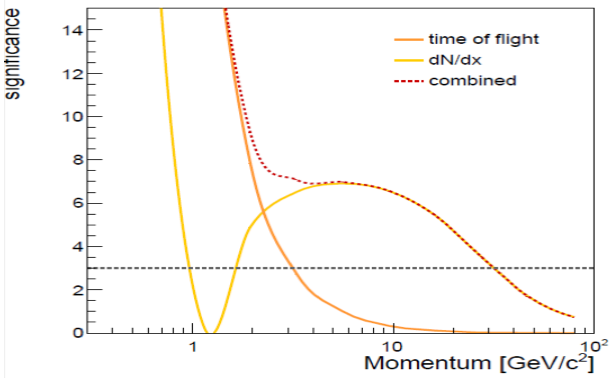


Drift Chambers

Open challenges

Complete mapping of dN/dx data in all relevant background regions

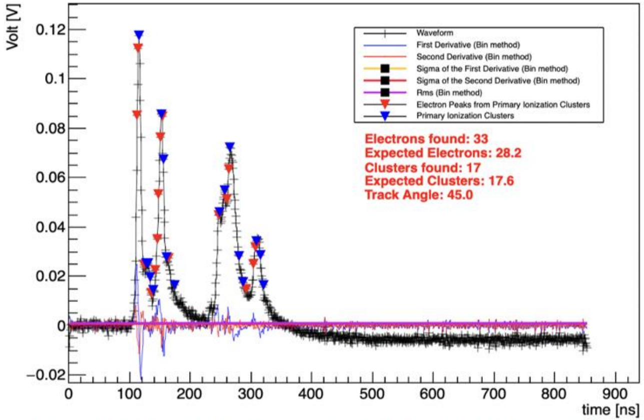
- Understand details of cluster counting performance



Build large mechanical prototype

- Inner radius R_{in} = 35 cm, outer radius R_{out} = 200 cm
- Mechanical deformation of the spokes (wire support) due to mechanical tension on wires

Develop on-detector cluster counting electronics

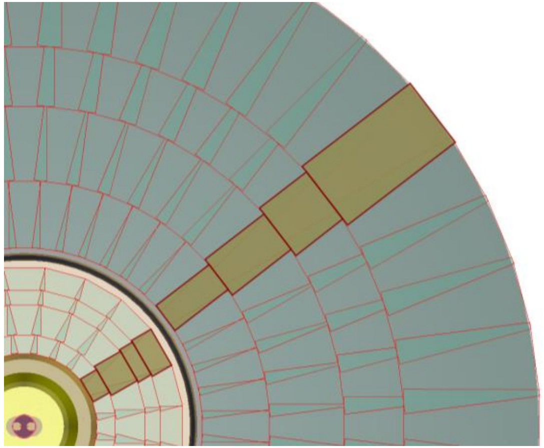


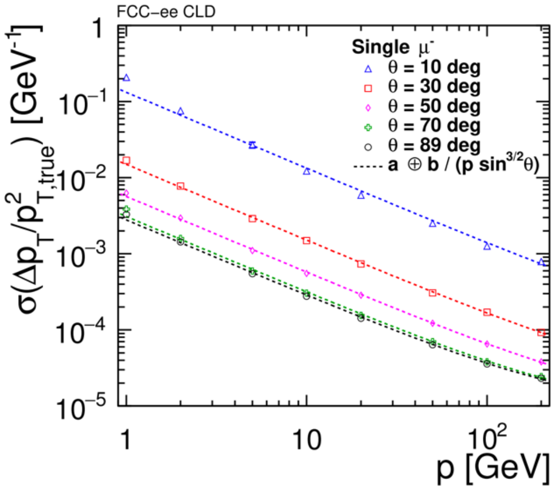
Sense Wire Diameter 10 um – Cell Size 1.0 cm – Track Angle 45° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV

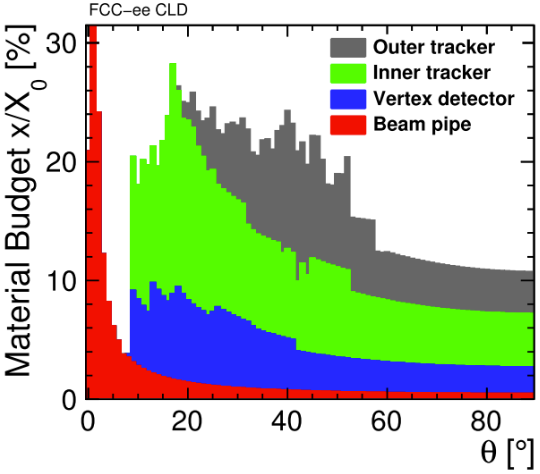
All-Silicon Tracker

Excellent working example: CMS all-SI

Optimized for high-resolution, Particle Flow approach







The physics case drivers

	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	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu m]$	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

one problem – several solutions with different pros and cons

Calorimeter performance

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

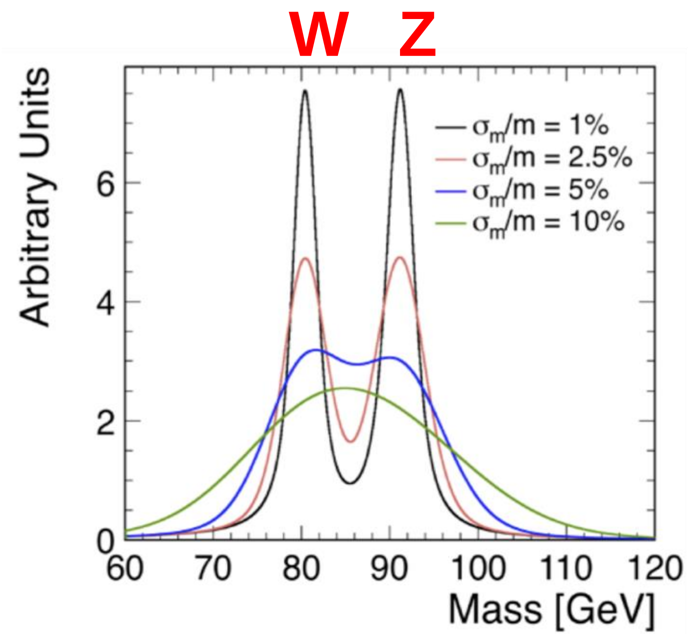
Jet final state will be dominant at FCC-ee
- higher BR
- clean environment

Disantangling W and Z peak
e.g. Separation of ννH from WW fusion and HZ

EM resolution

e+e- →HZ physics constraints
H→ $\gamma\gamma$ ➔ ECAL resolution
As good as possible – at least $20\%/\sqrt{E}$ + 1%

for HF physics **$3\%/\sqrt{E}$** is required



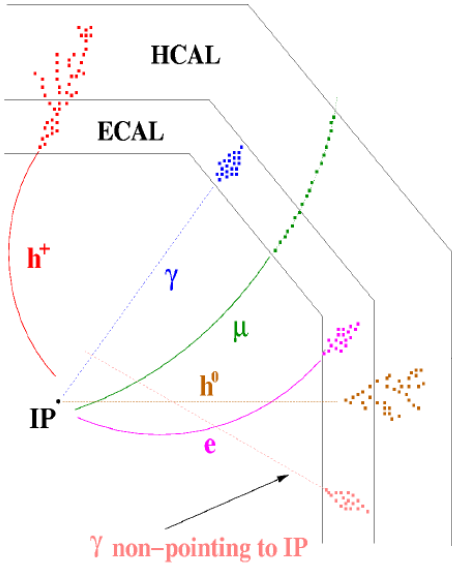
At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution comparable to Γ_W and Γ_Z

Particle-Flow calorimeter

Jet energy measurement by measurement of individual particles
Maximal exploitation of precise tracking measurement

Measure charged particles contribution to jets by **using tracker rather than calorimeter**.
• Requirements: High granularity - compactness (small Moliere radius) – high magnetic field.
• Drawbacks: confusion term (possible error in subtracting charged contribution)

Jet composition:
charged hadrons ~70%→**tracker** $\sigma(p_T)/p_T \sim 1\%$
photons ~20%→**ECAL** $\sigma(E)/E < 20\%/\sqrt{E}$
neutral hadrons ~10%→**HCAL** $\sigma(E)/E < 60\%/\sqrt{E}$

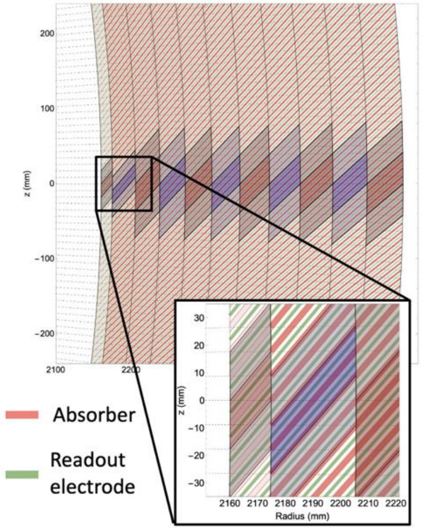


Liquified Noble Gas Calorimeter

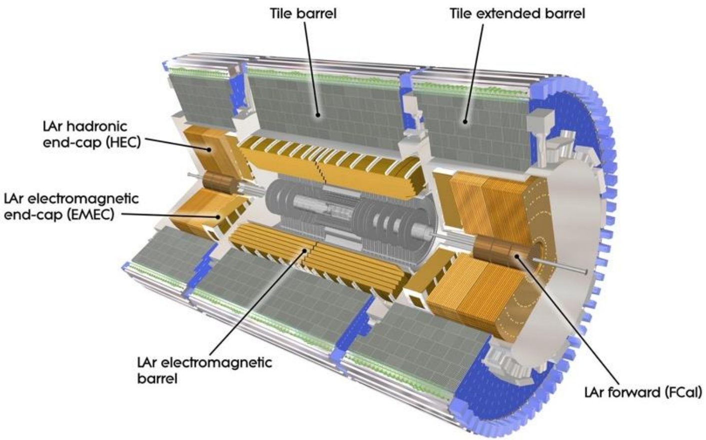
EM Calorimeter:

• 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
- different geometry.



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



Dual-readout calorimeter(s)

Measure simultaneously:

- Scintillation signal (S)
- Cherenkov signal (C)

Calibrate both signals with e$^-$

Unfold event-by-event f_{em} to obtain corrected energy

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

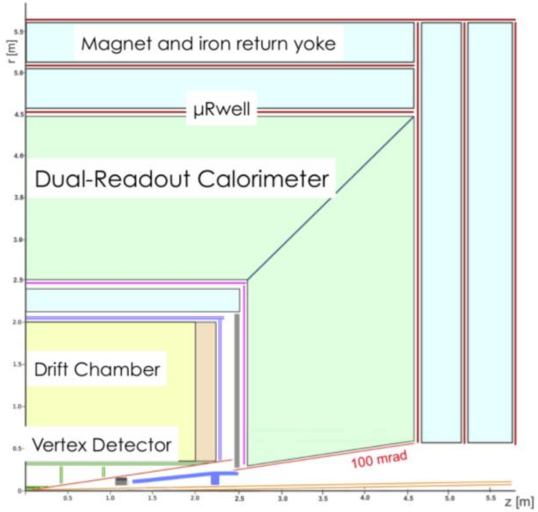
$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

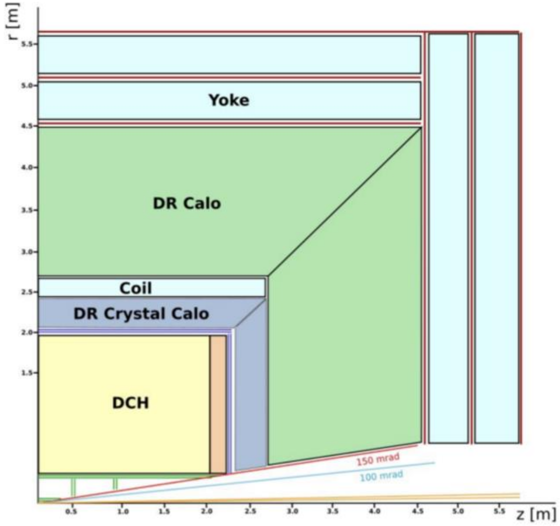
$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

Natively High-Resolution Calorimeter
High-granularity for PF-friendly approach

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)





Muon detectors

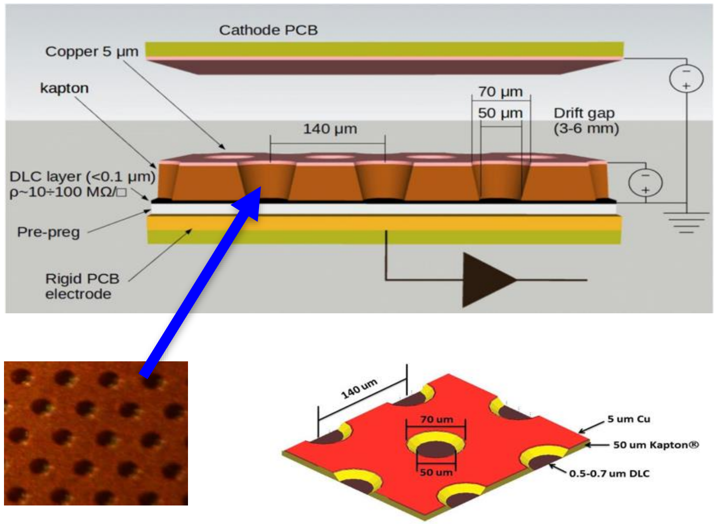
RPC traditional approach

Requirements on muon detector not strict
Using known technology widely spread in HEP

MPGD innovative approach

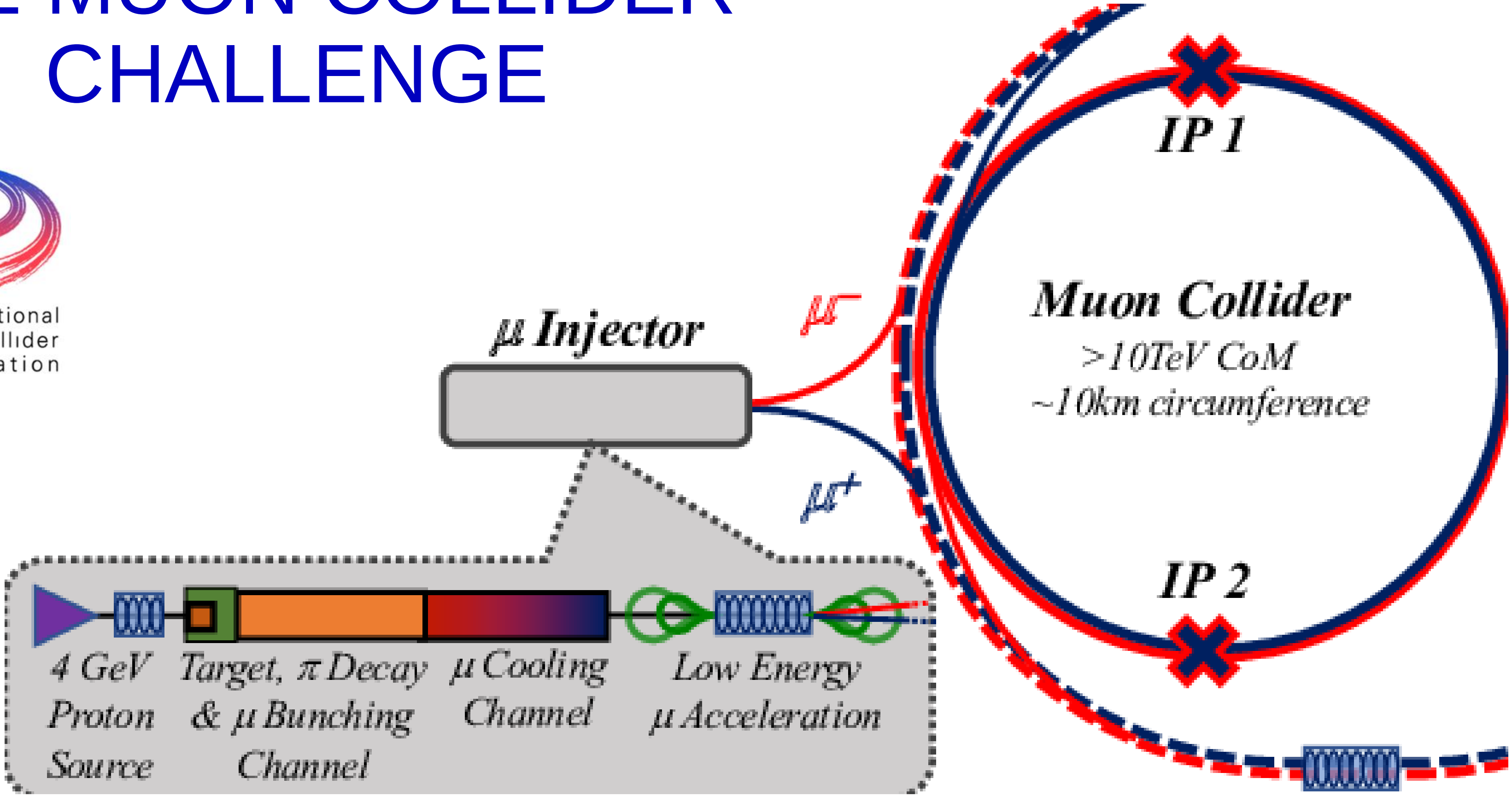
μ-Rwell proposal

- Good spatial resolution
- Good rate capability



THE MUON COLLIDER CHALLENGE

International MUON Collider Collaboration



M. Casarasa (INFN & EU strategy)

Detector challenge

The requirements for the detector specifications from physics are similar to those of other multi-TeV machines

but

Beam Induced Background is dominant source of background

hadronic calorimeter

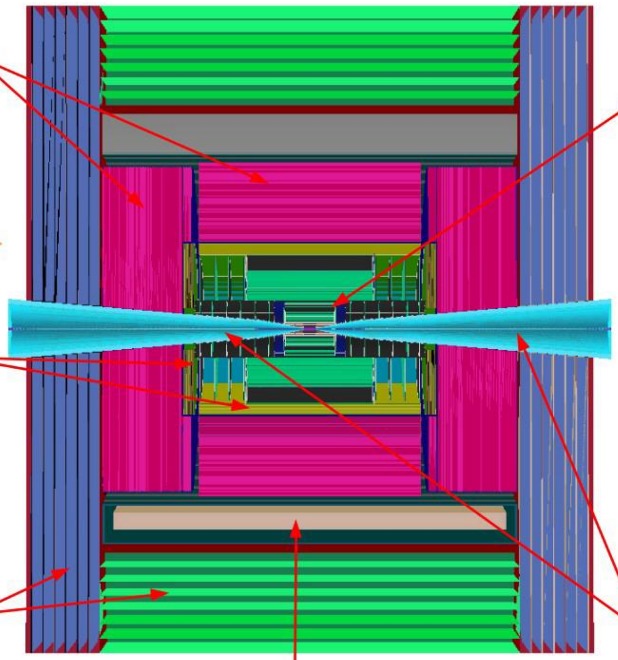
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

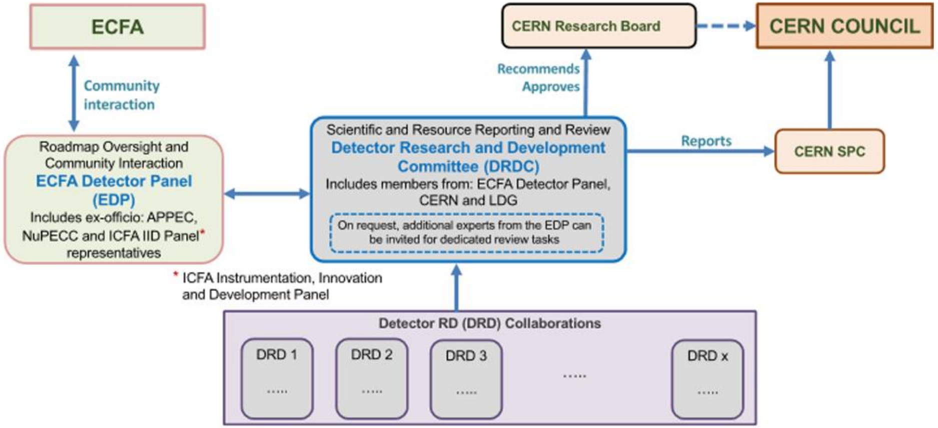
- Tungsten cones + borated polyethylene cladding.

It’s not all about detector construction

Bringing an experiment to live is much more

Detector simulation and performance study
Physics benchmark studies
Data model
Data Acquisition
...

ECFA Detector R&D Roadmap



INFN strategically placed in many of the key R&Ds.

There is for sure a DRDx activity in your institute.
Join the effort!

When it's going to happen?

Is this far away? Nope!

Brief History of LHC experiments

Learning from experience

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**

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

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

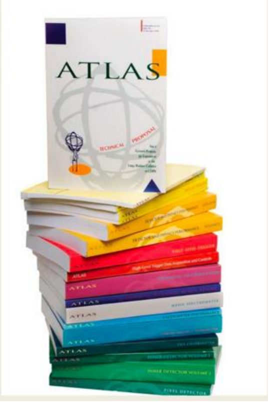
1990 Large Hadron Collider Workshop Aachen (CERN - ECFA) (First serious R&D results)

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

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

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

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

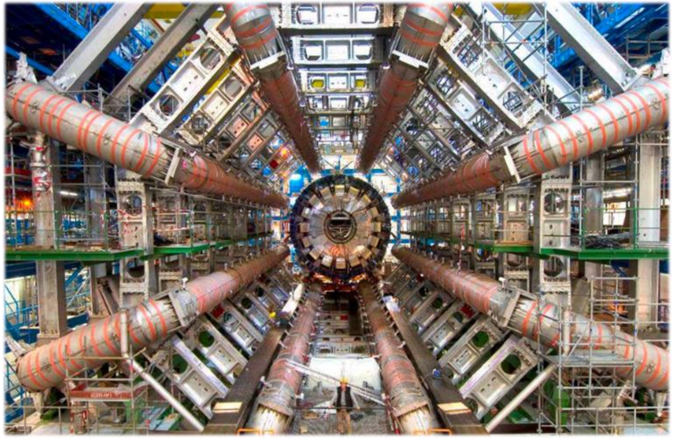


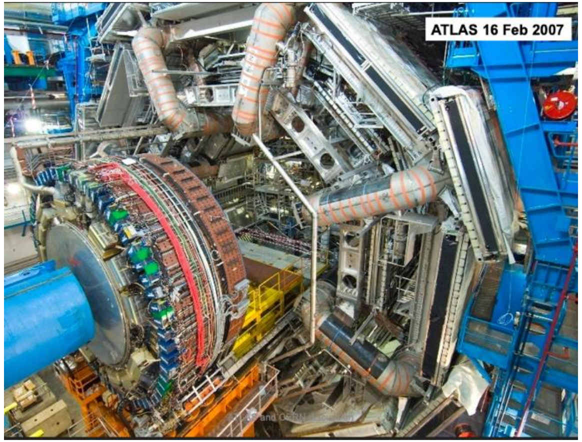
1996

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

“~~Rome~~ Experiment wasn't built in a day”

Atlas example





1998-2003:
Point-1 Civil Engineering
Underground cavern 56 x 32 x 35m^3

Barrel toroid+calorimeter & solenoid: 2004-2005

ATLAS installation of all the detectors

“~~Rome~~ Experiment wasn't built in a day”

Atlas (MDT) example

1998: testing prototypes on beam

1999-2004: detector mass production & commissioning

2006: detector installation in ATLAS

... and then there was the Physics

09.2008: False start: the LHC incident
11.2009: the first collisions @ 900 GeV
03.2010: First 7 TeV collision 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!

Enjoy it!