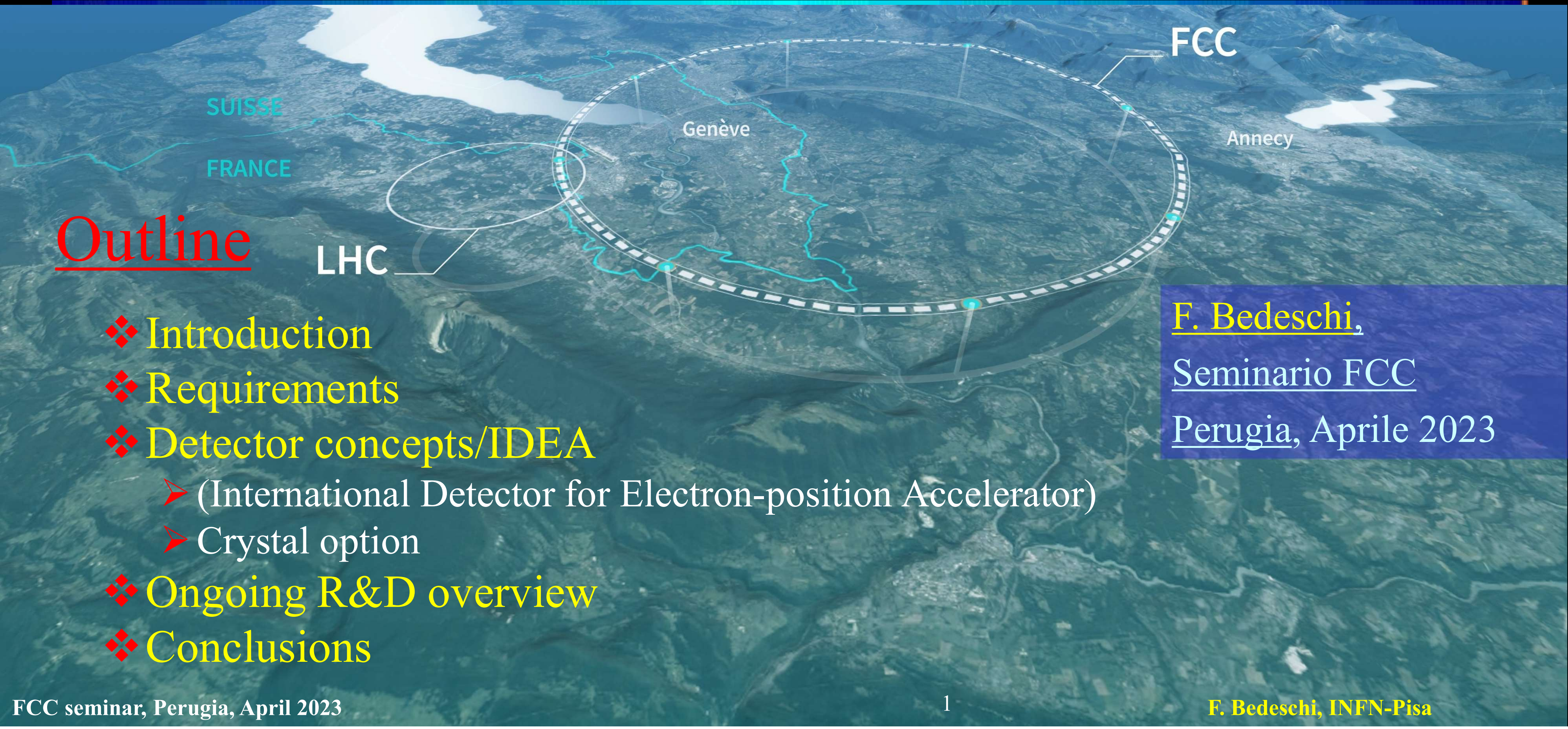
FCC-ee detectors



Outline

- Introduction
- Requirements
- Detector concepts/IDEA
  - (International Detector for Electron-position Accelerator)
  - Crystal option
- Ongoing R&D overview
- Conclusions

F. Bedeschi,
Seminario FCC
Perugia, Aprile 2023

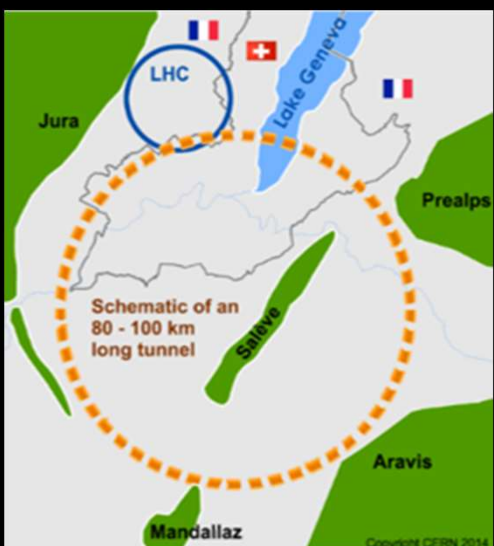
European Strategy for Particle Physics

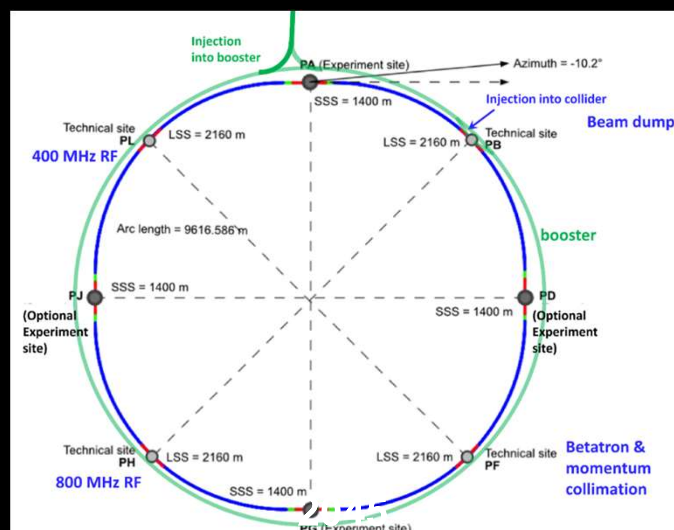
- Recommendations of the 2020 update of the European Strategy for Particle Physics (ESPP):
  - Full exploitation of the high-luminosity LHC upgrade
  - **An electron-positron Higgs factory is the highest-priority next collider**. **For the longer term**, the European particle physics community has the ambition to **operate a proton-proton collider at the highest achievable energy**.
  - Europe, together with its international partners**, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage**.

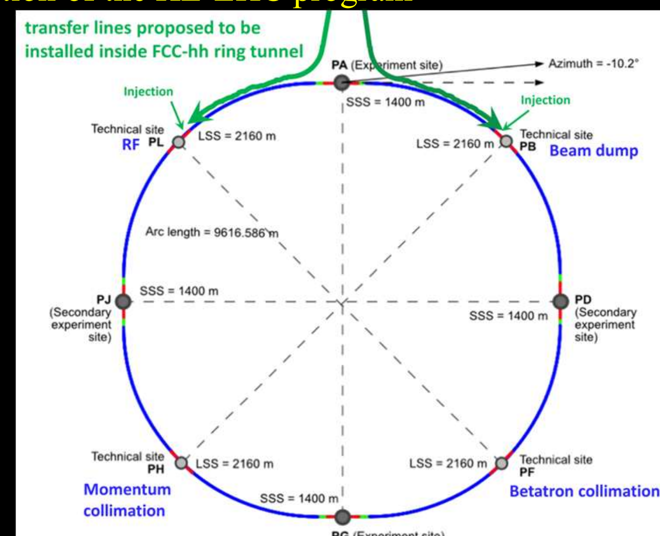
- **FCC Feasibility Study** is one of the main recommendations of the 2020 update of the European Strategy for Particle Physics

FCC integrated program

- Comprehensive long-term program maximizing physics opportunities
  - stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
  - stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
    - complementary physics
    - common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
    - FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program







2020 - 2040 | 2045 - 2060 | 2065 - 2090

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FCC Feasibility Study

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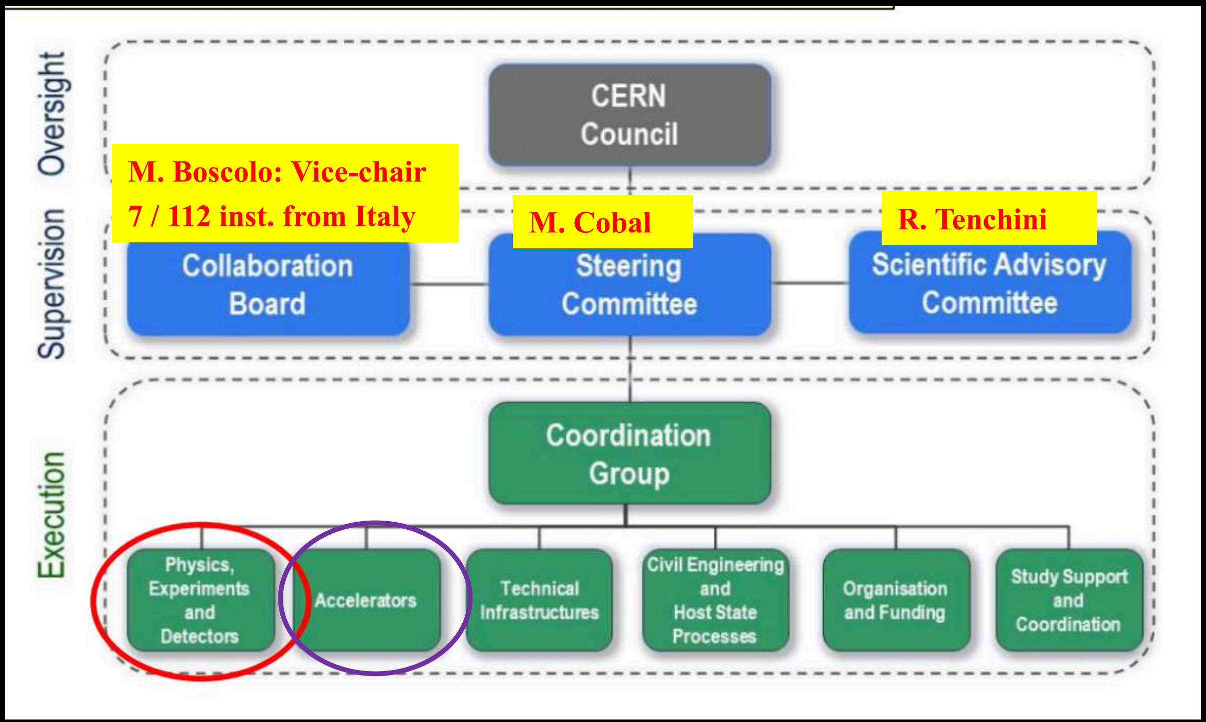
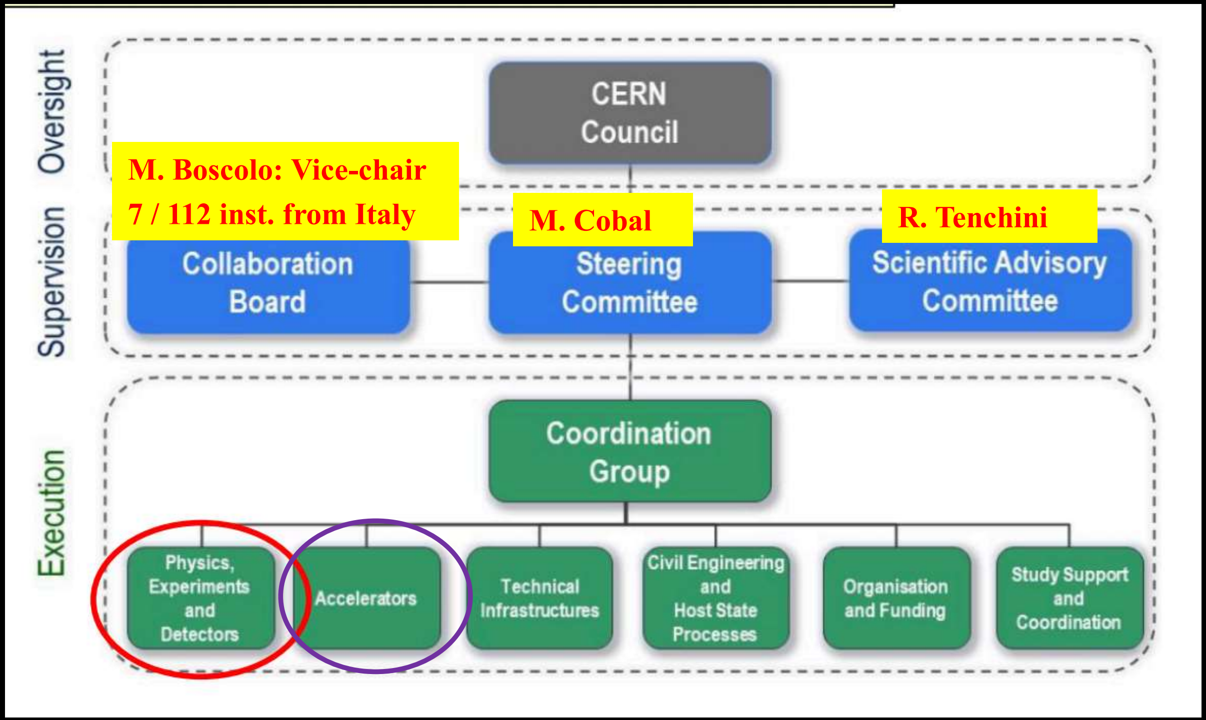


FCC Feasibility Study

- ❖ FCC Feasibility Study approved by CERN Council June '21
  - Organization: CERN/3566/Rev;
  - Deliverables: CERN/ 3588): Consolidation of the physics case and detector concepts for both colliders.



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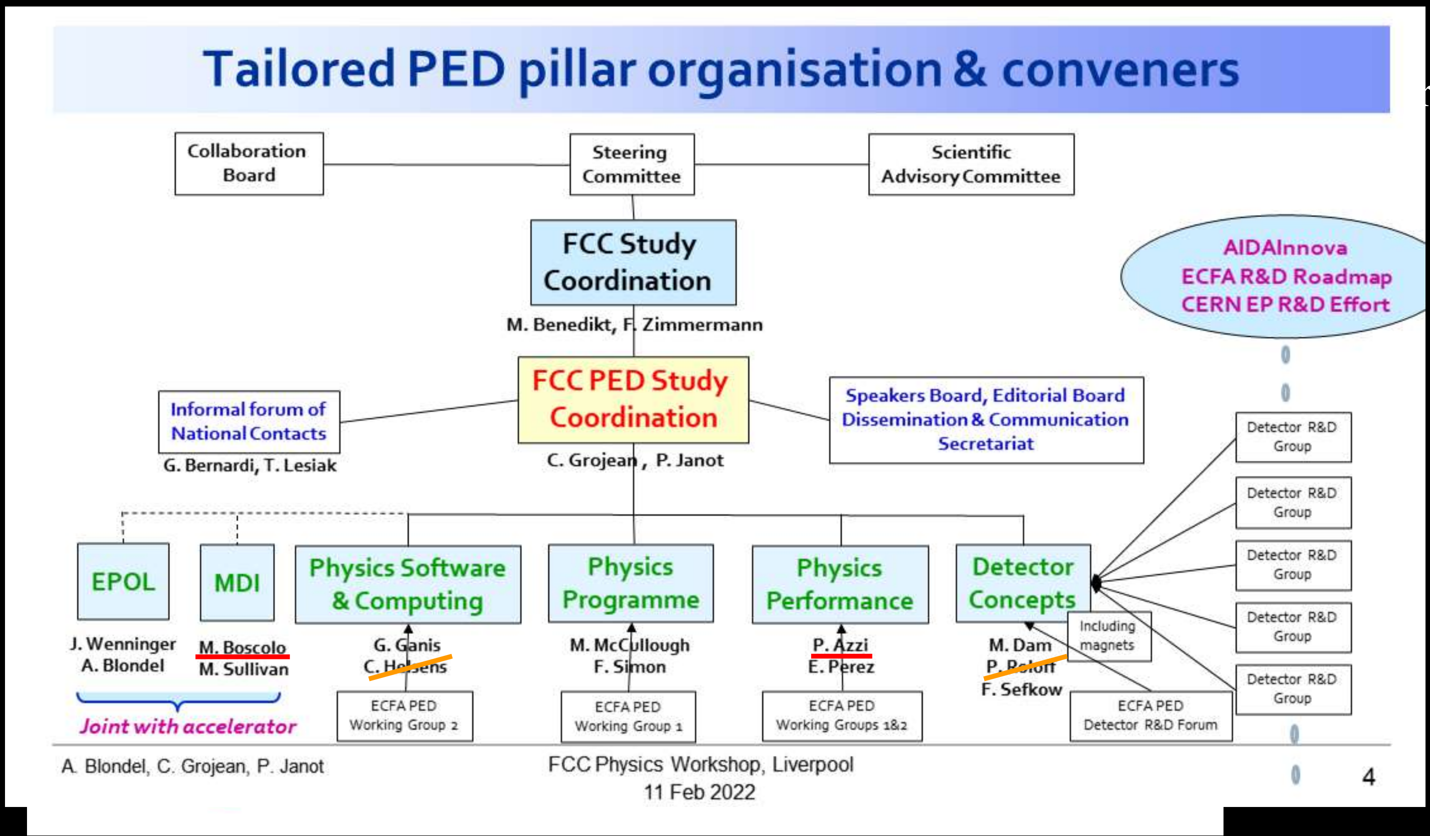

concepts for both colliders.

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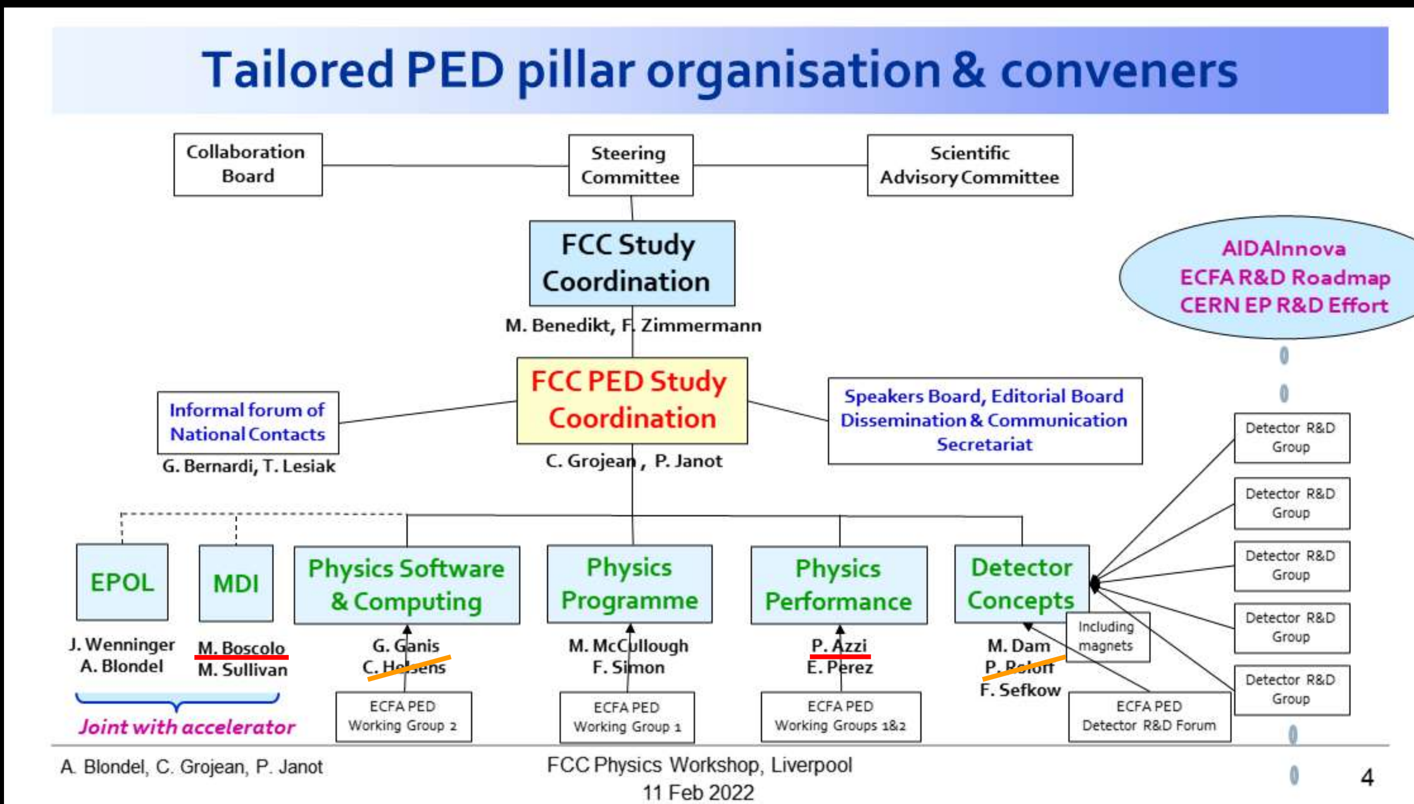


End 2023:

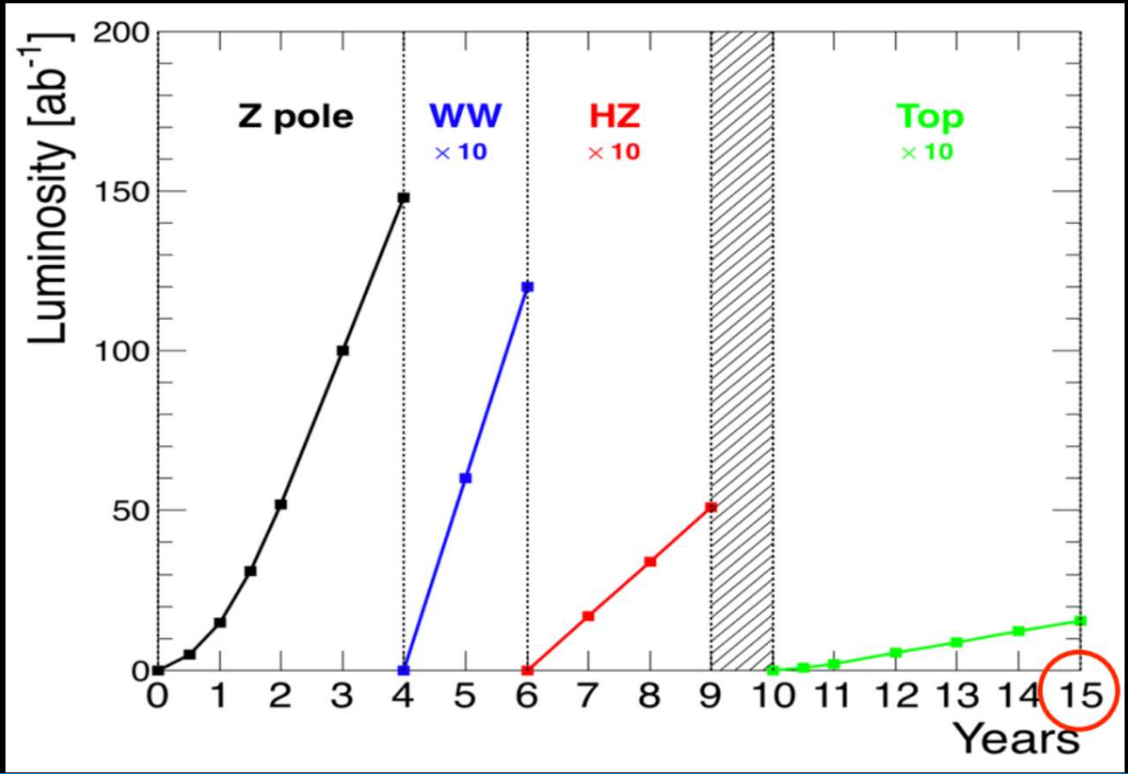
- mid-term report
- 1st cost review
- (tunnel +FCCee

End 2025:

- final report
- 2nd cost review
- (tunnel +FCCee

FCCee physics summary

- Higgs factory
  - 10^6 e+e- → HZ
- EW & Top factory
  - $3x10^{12}$ e+e- → Z
  - 10^8 e+e- → W+W- ;
  - 10^6 e+e- → tt
- Flavor factory
  - $5x10^{12}$ e+e- → bb, cc
  - 10^{11} e+e- → **τ+τ-**
- Potential discovery of NP
  - LLP's, ALPs, RH ν's, …



Physics plan still under discussion – Order may change

FCCee physics summary

13 December 2022

Optimal energy range for SM particles

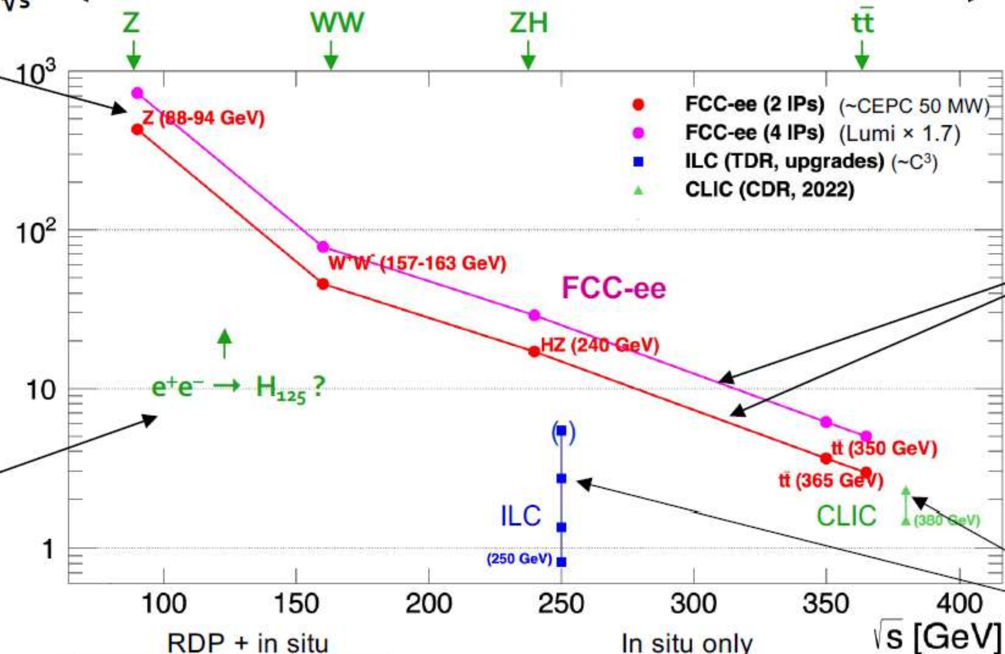
Sharpen and challenge our knowledge of already existing physics

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 CO2-eq/ab⁻¹
Essential redundancy for precision measurements
May satisfy all detector requirements
Increase discovery potential
Enhance the community (FCC/CERN clients)

Motivates the competition

Luminosity is the name of the game

√s Monochromatisation

Unique opportunity for electron Yukawa

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

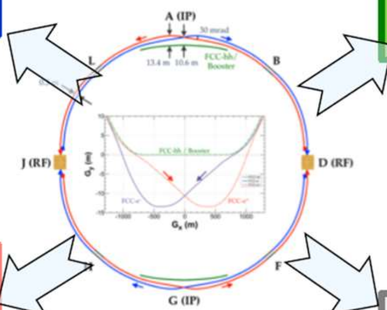
Detector requirements

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

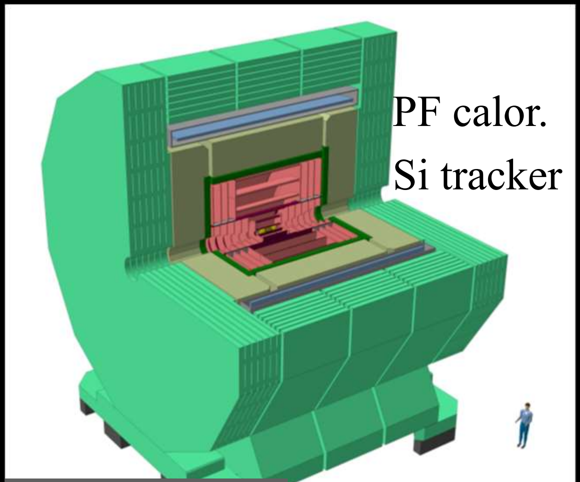
Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

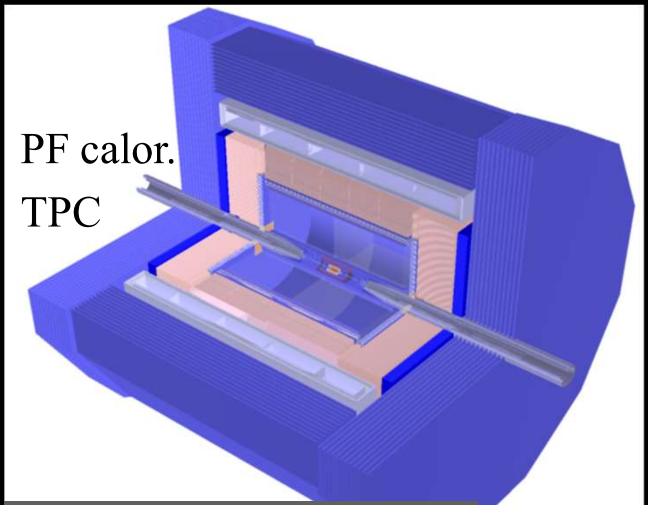
❖ M. Dam, ECFA Det. R&D Roadmap, 2021, https://indico.cern.ch/event/994685/

Early detector concepts

- Early studies for the FCCee (and CEPC) CDR's based on minor modifications of CLIC (or ILC) detectors
  - Exploit existing simulation software
  - Not optimized for FCCee



CLD concept



CEPC baseline concept

Differences with ILC/CLIC

- Luminosity is much higher!
  - Non-negligible machine backgrounds
    - Fast detector integrates less background in each readout

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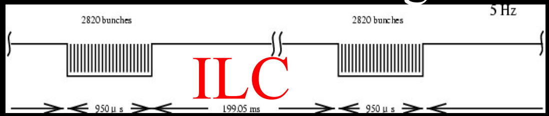
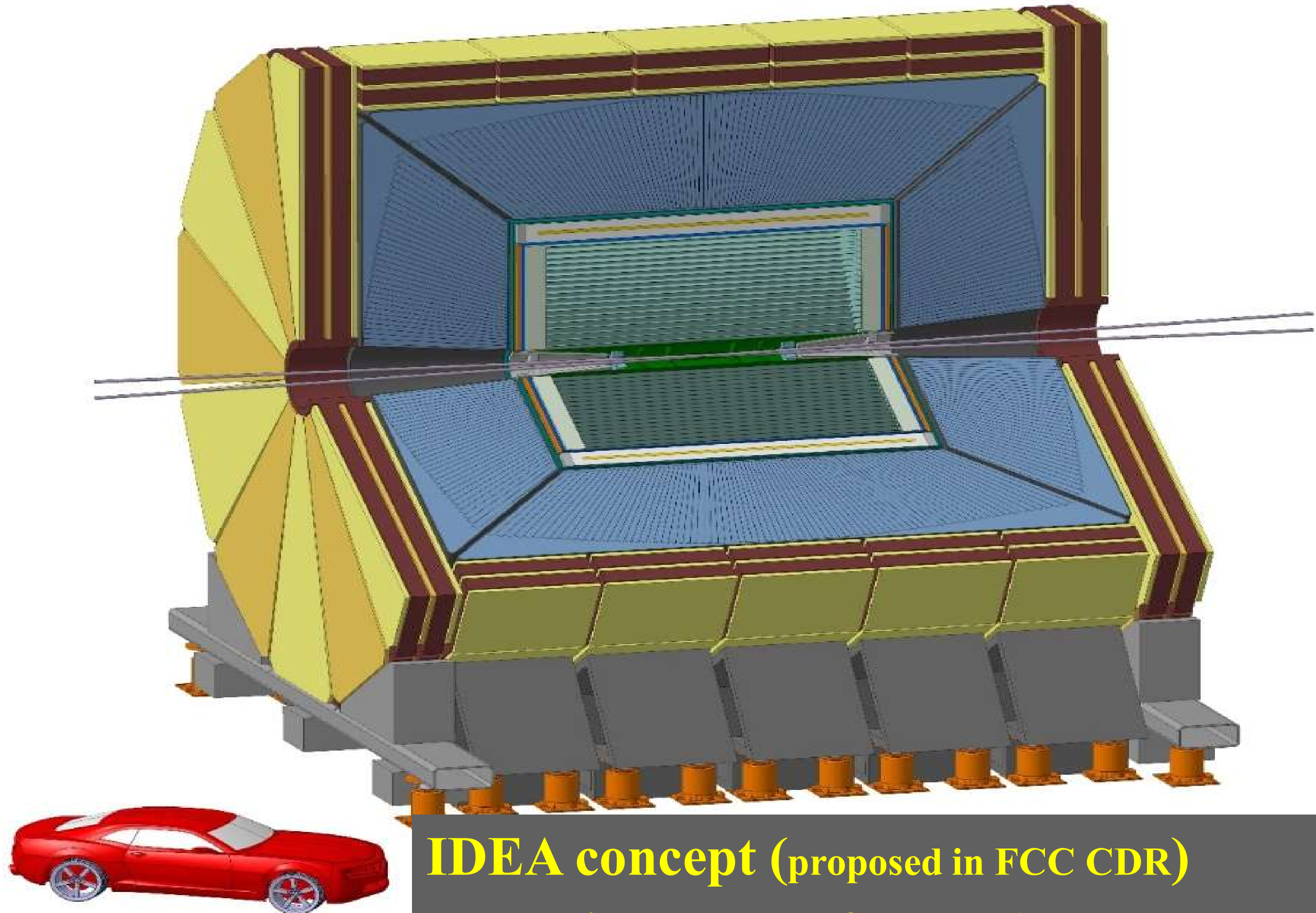
- Beam time structure:



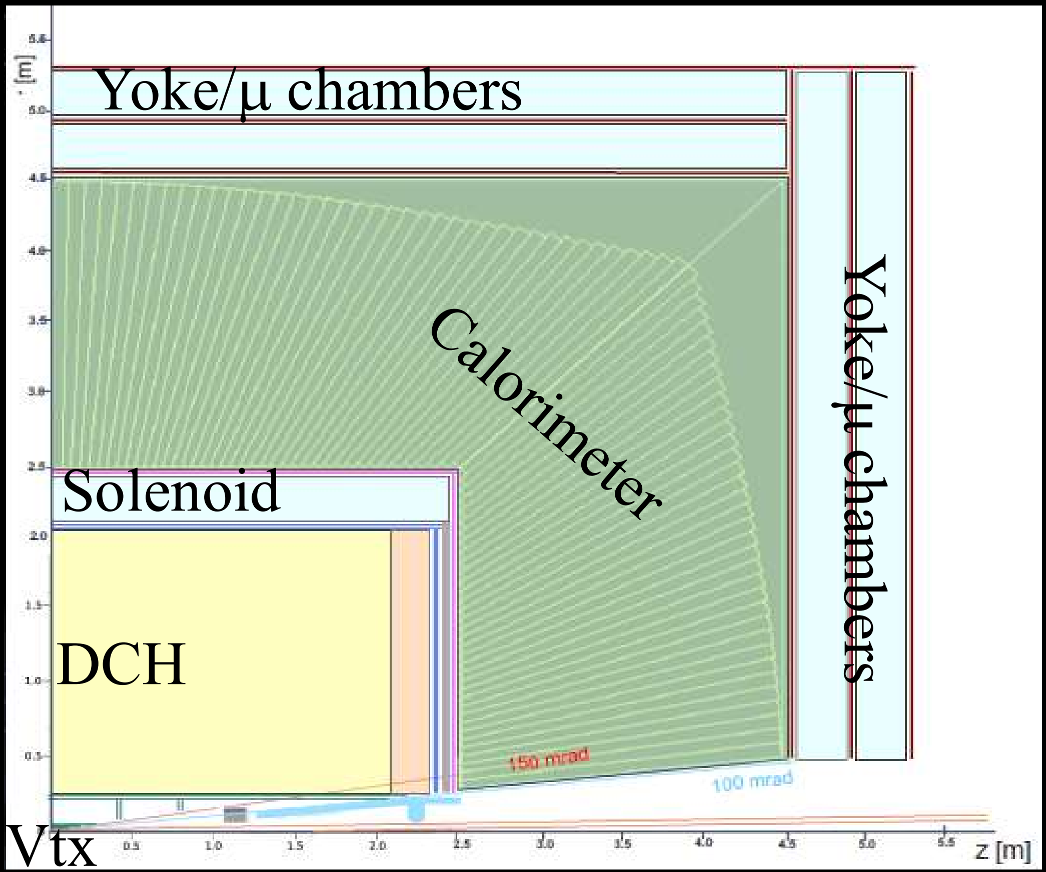
  - Short bunch spacing (~ 20 ns Z, ~ 1 μs H, ~ 3 μs $t\bar{t}$)
  - No large time gap
    - Cooling issues for PF calorimeter and vertex detector
    - TPC ion backflow



IDEA concept (proposed in FCC CDR)

Innovative Detector for e+e- Accelerator

IDEA details



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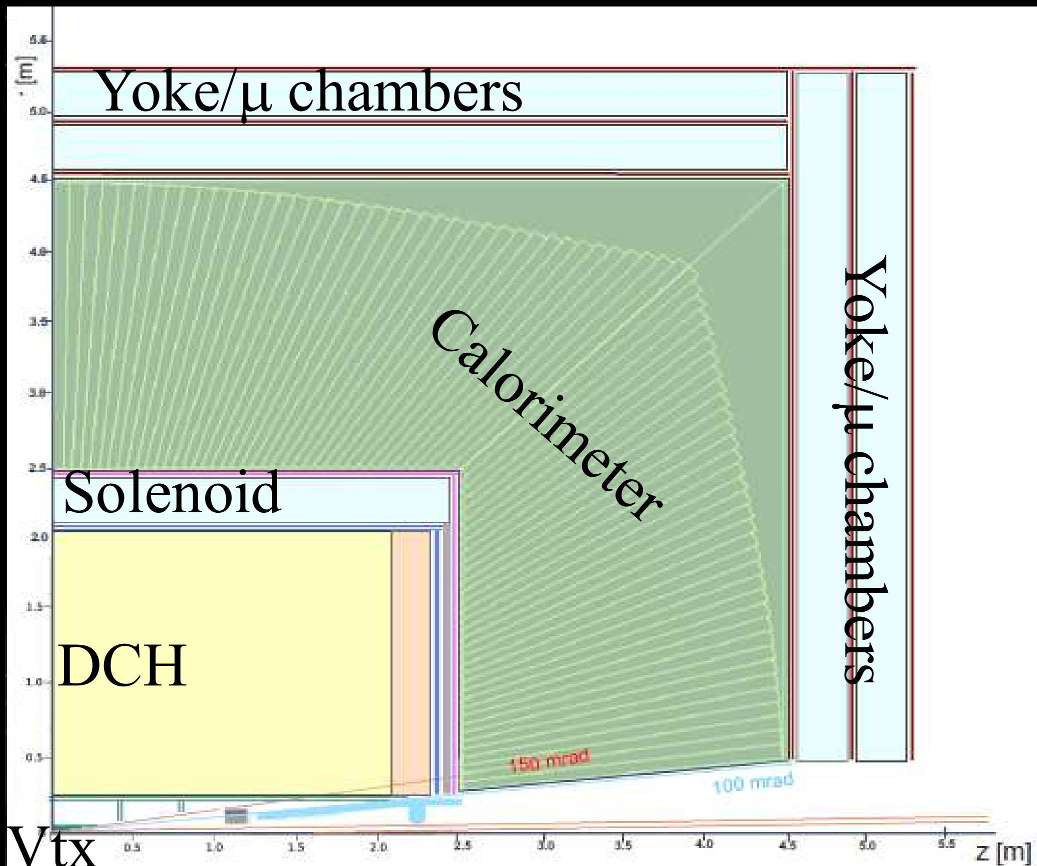

Small magnet
⬇
Small yoke

IDEA details

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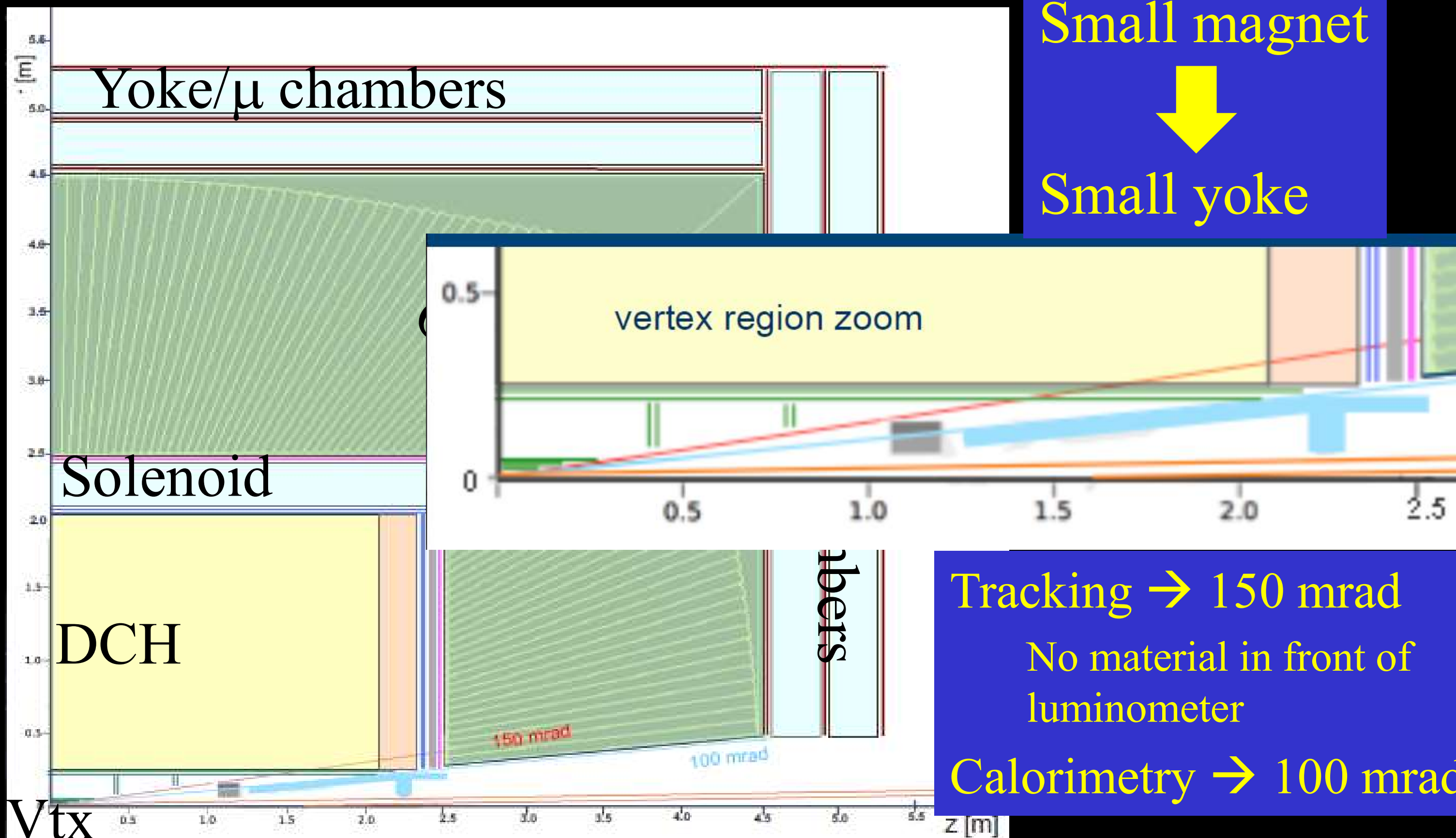


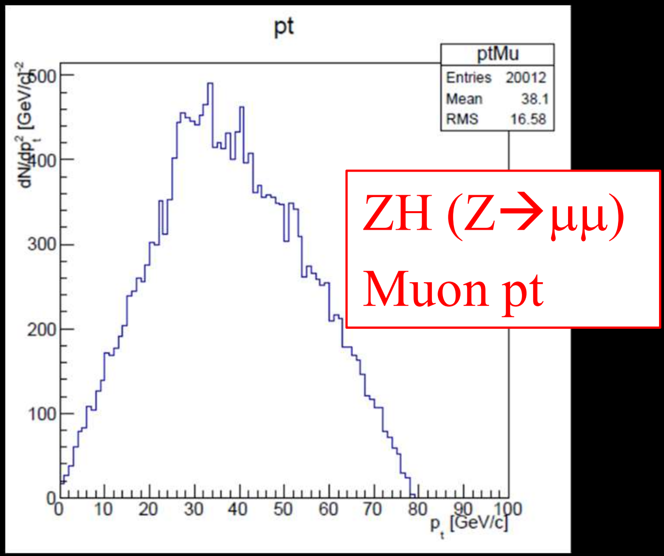
Tracking → 150 mrad

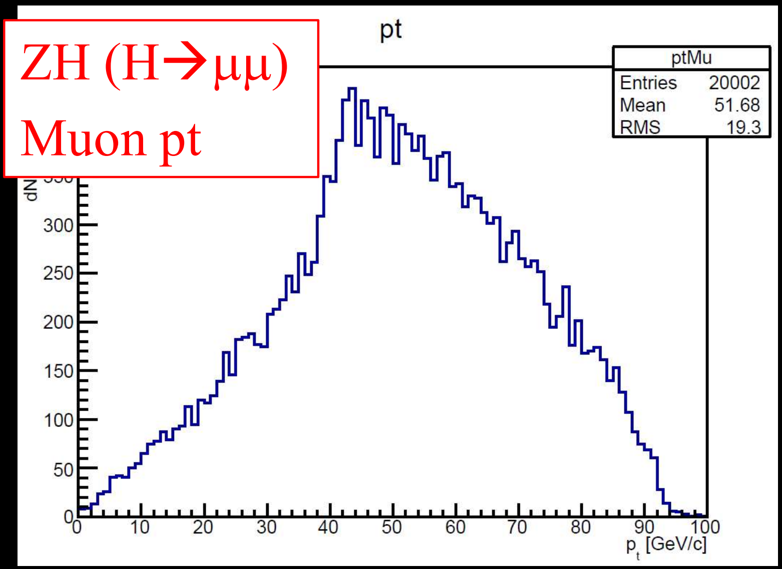
- No material in front of luminometer

Calorimetry → 100 mrad

Momentum measurement

❖ Z or H decay muons in ZH events have rather small p_t





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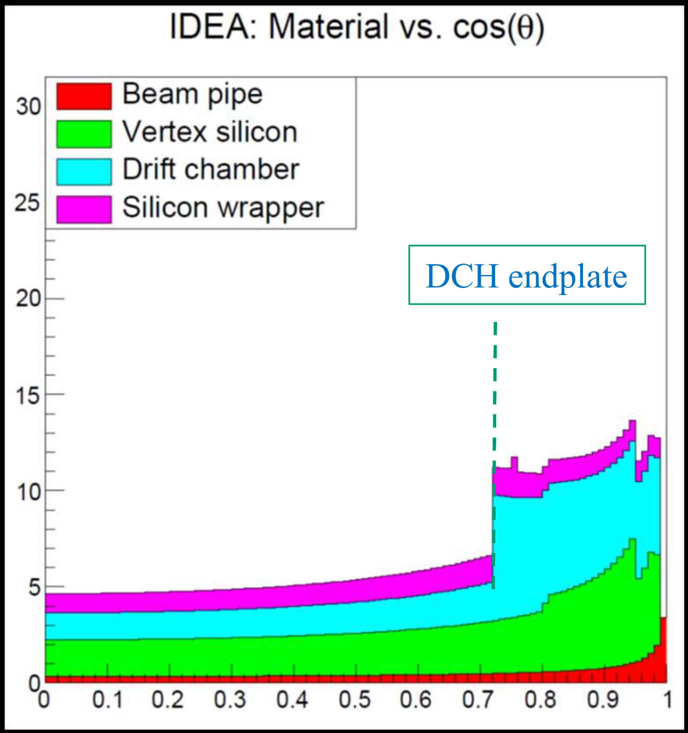

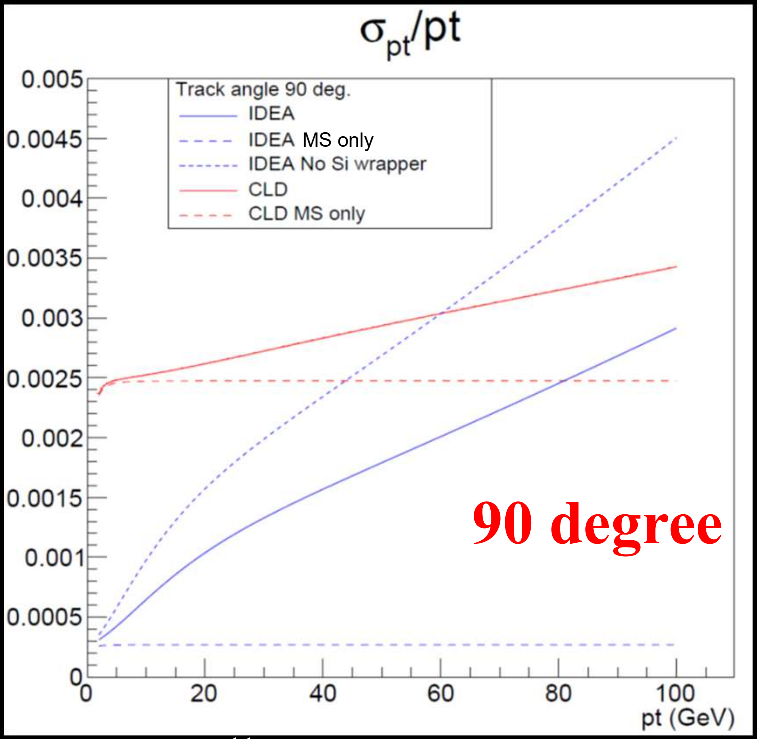

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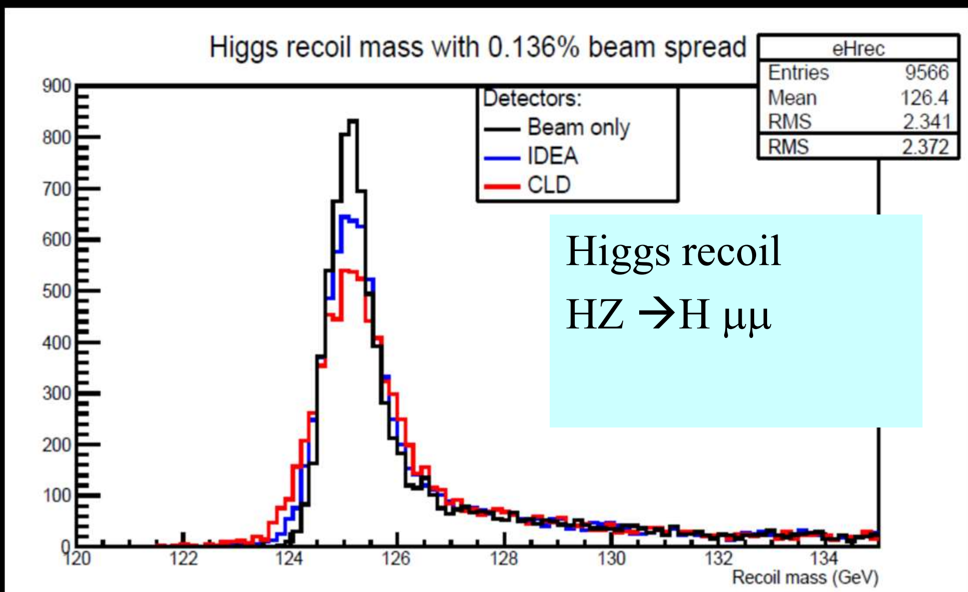
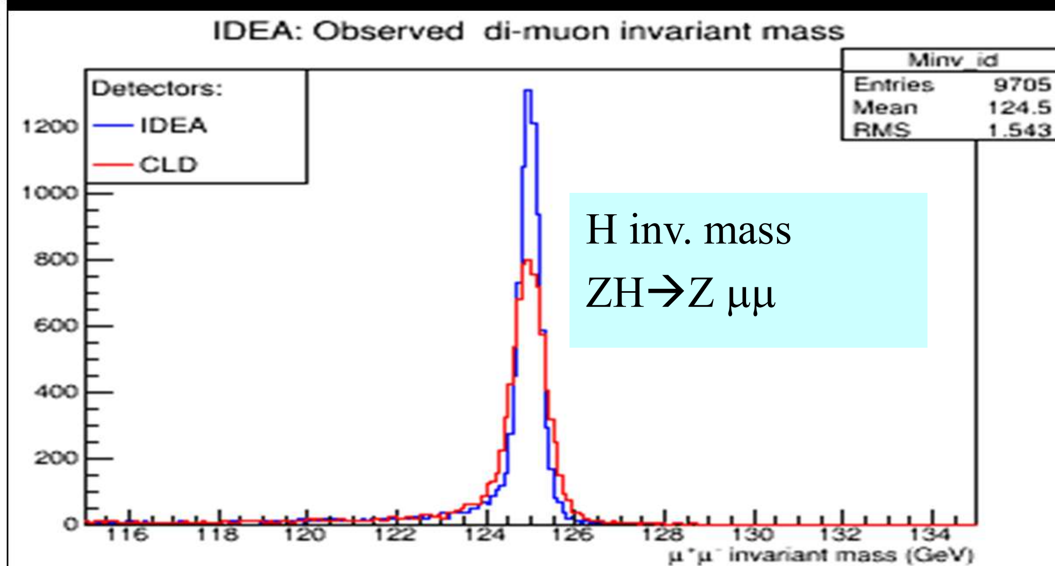
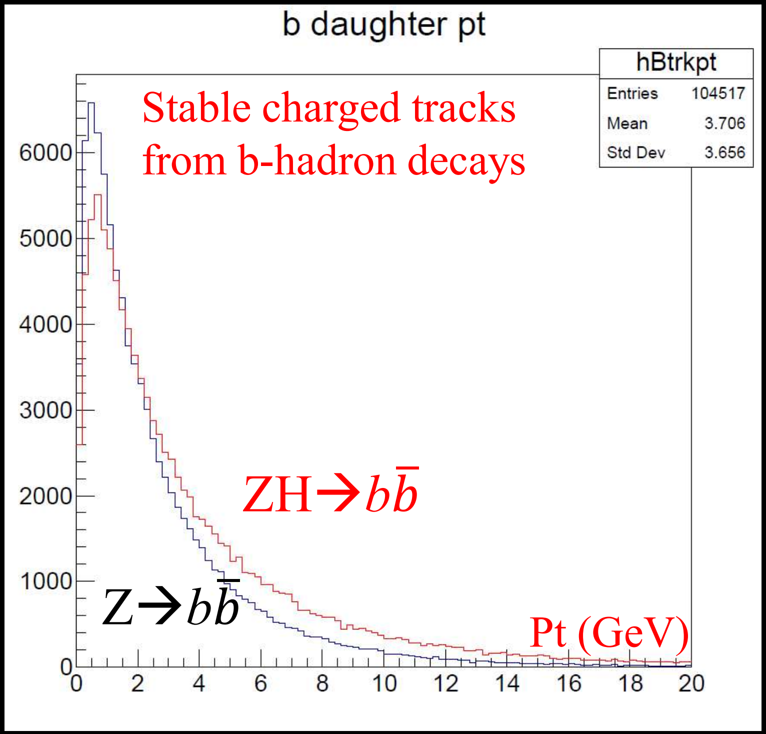
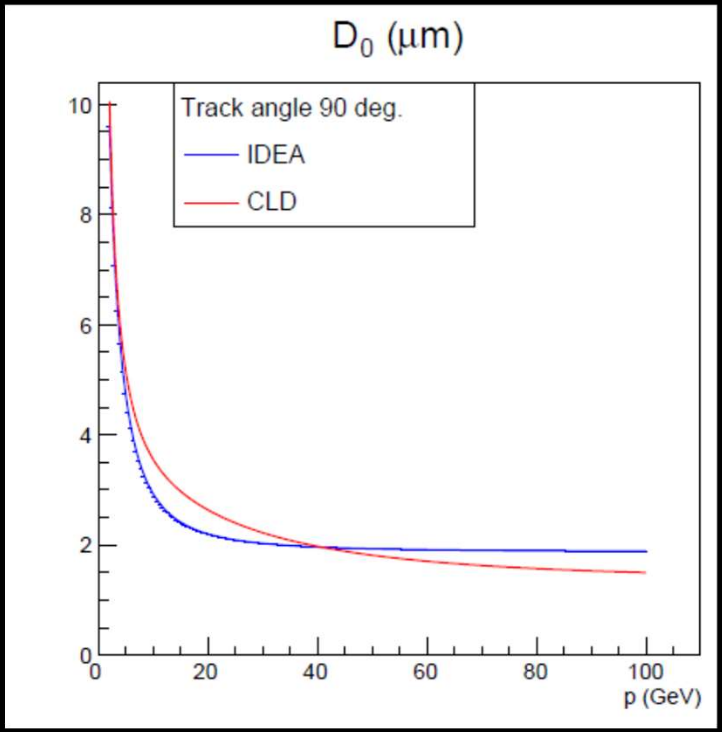




Vertex resolution

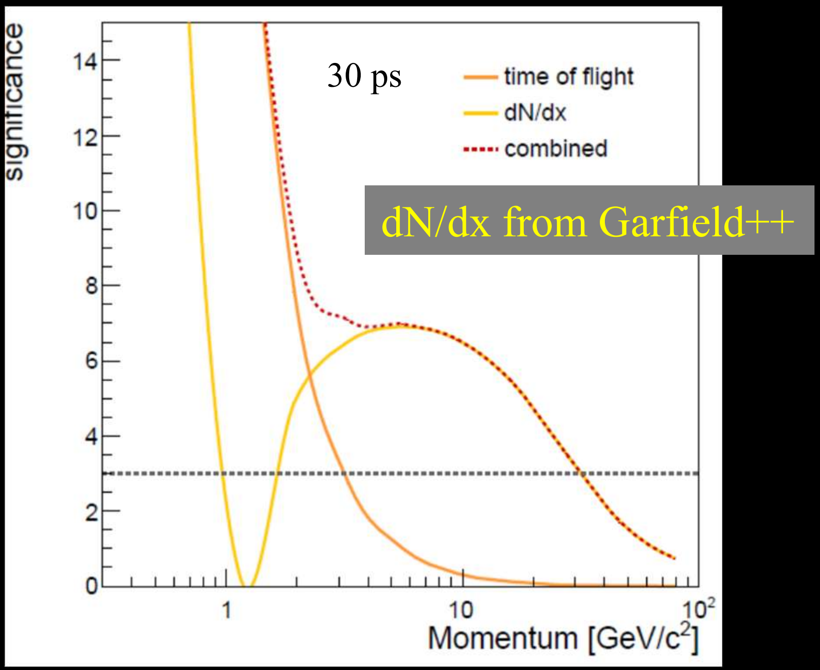
- Transparency again very important
  - Tracks from secondary and tertiary HF decays have few GeV





PID

- Expect > 3σ K/π separation from cluster counting in Drift Chamber up to ~ 30 GeV



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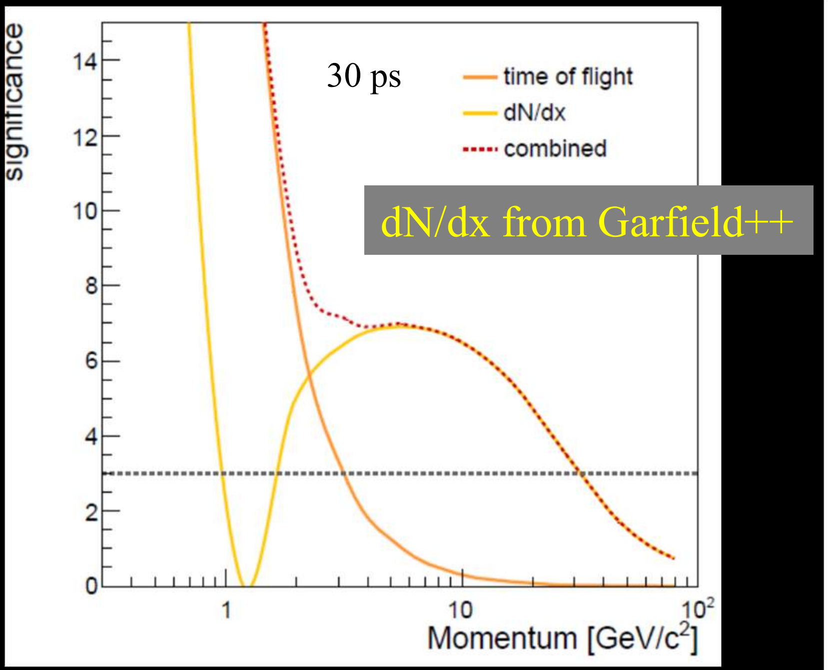
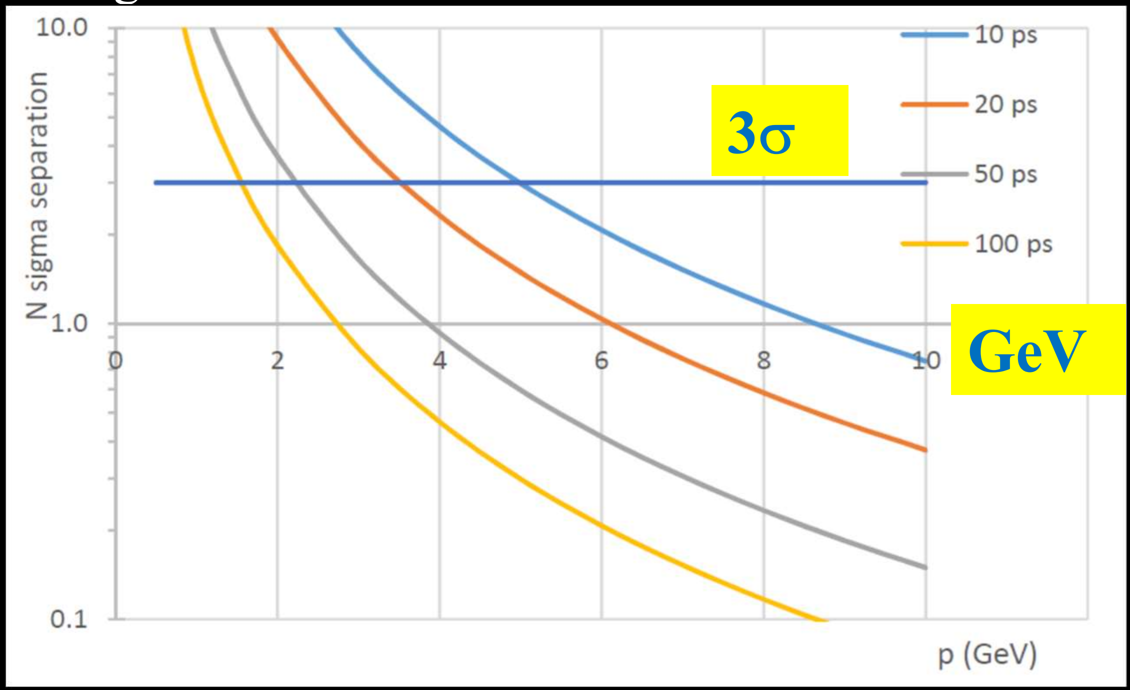
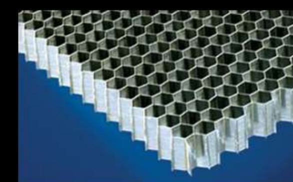
  - ToF at 50-100 ps resolution covers region ~ 1 GeV



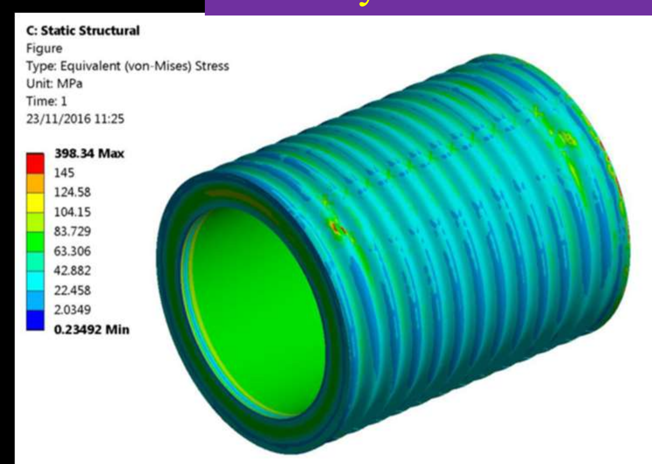


Solenoid

- Ultra light 2 T solenoid:
  - Radial envelope 30 cm
  - Single layer self-supporting winding (20 kA)
    - Cold mass: $X_0 = 0.46$, $\lambda = 0.09$
  - Vacuum vessel (25 mm Al): $X_0 = 0.28$
    - Can improve with new technology
      - Corrugated plate: $X_0 = 0.11$
      - Honeycomb: $X_0 = 0.04$
- Exploring MgB_2 conductor
  - Lighter cold mass



Courtesy of H. TenKate



Calorimeter

❖ Design guidelines:

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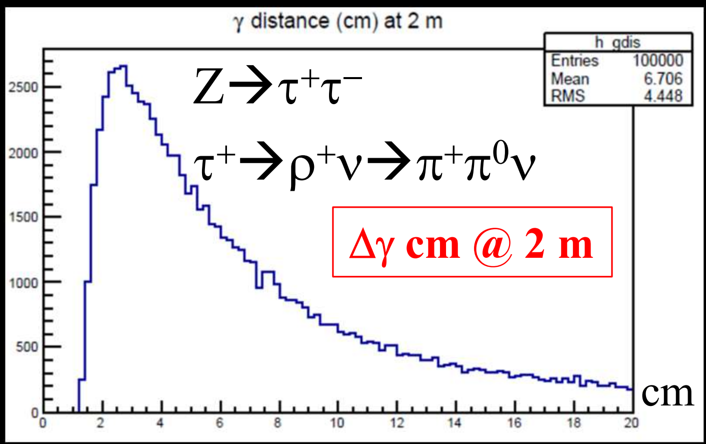

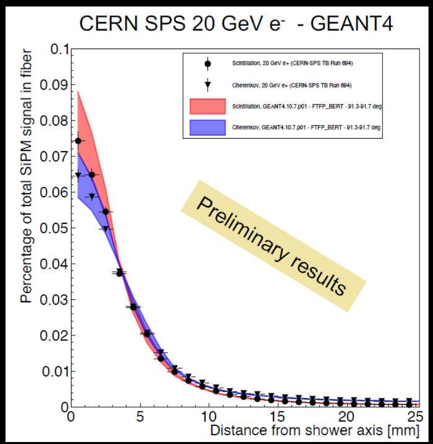

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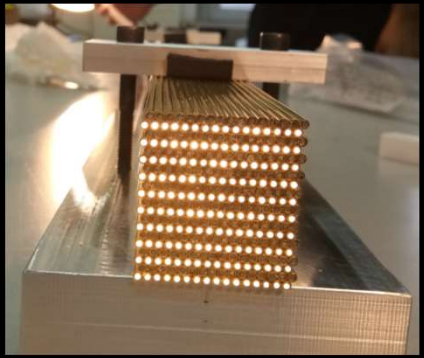

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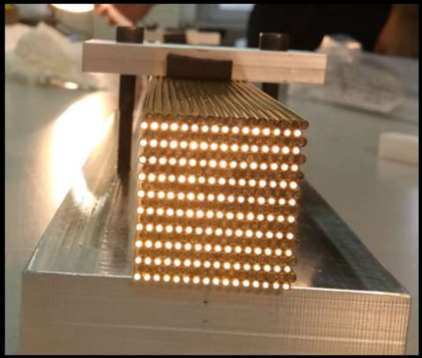
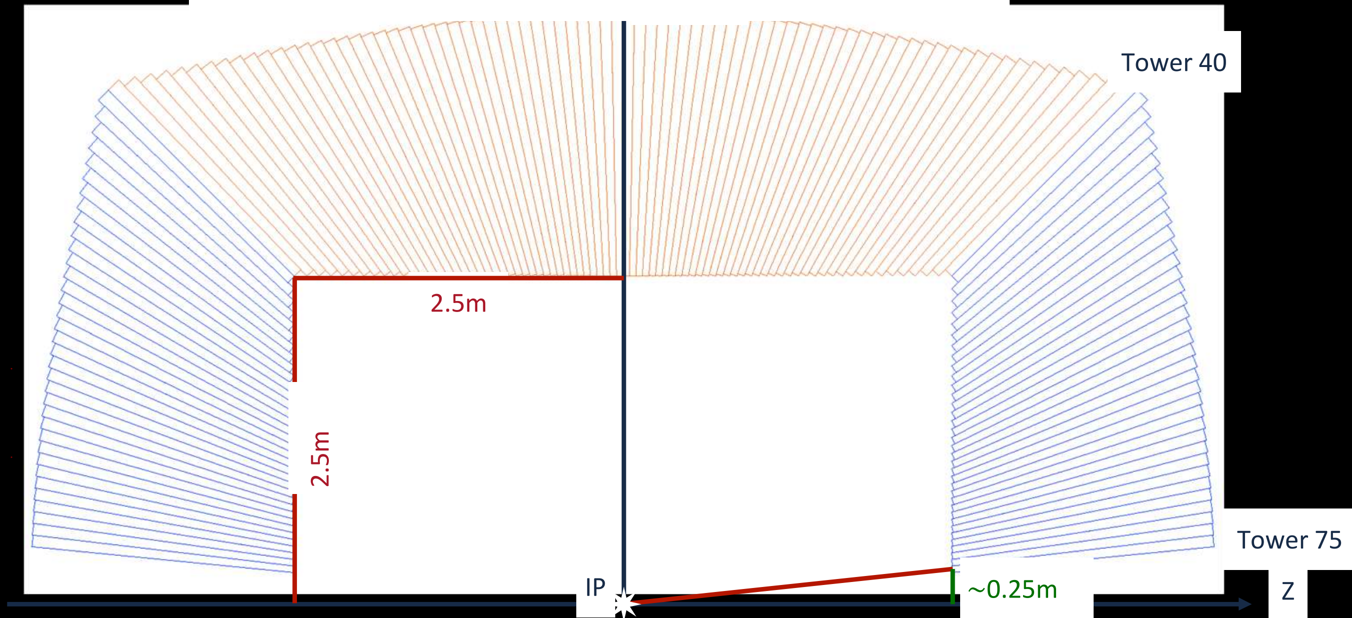


- Dual Readout fiber calorimeter satisfies these requirements
  - Possible extension with crystal EM gives outstanding performance

Calorimeter simulation

- 4π detector in GEANT4 tuned to RD52 test beam data

Tower segmentation: $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
Number of towers in barrel: 40 x 2 x 36 = 2880
Number of towers per endcap: 35 x 36 = 1260
Theta coverage up to ~0.100 rad



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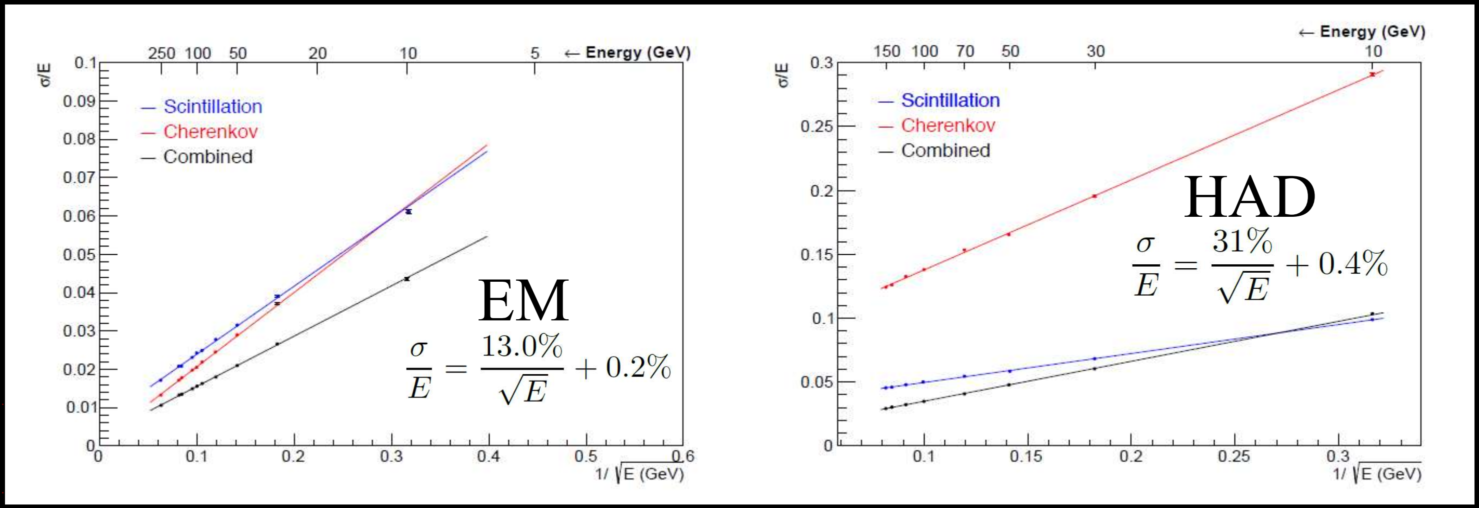

Calorimeter simulation

- 4π detector in GEANT4 tuned to RD52 test beam data
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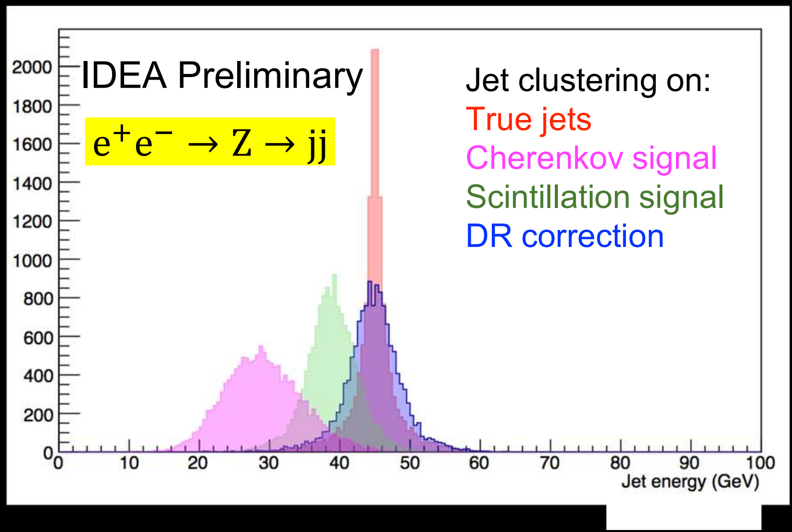
  - Gaussian resolution



Calorimeter simulation

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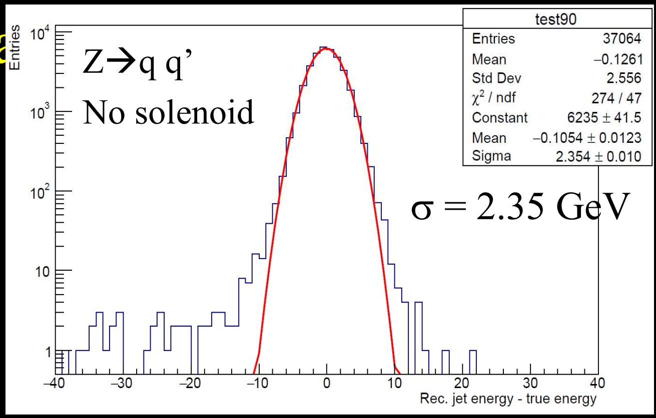
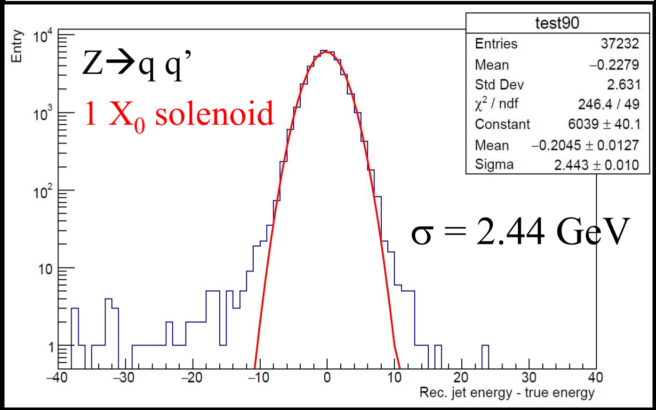
  - Small effect from solenoid material





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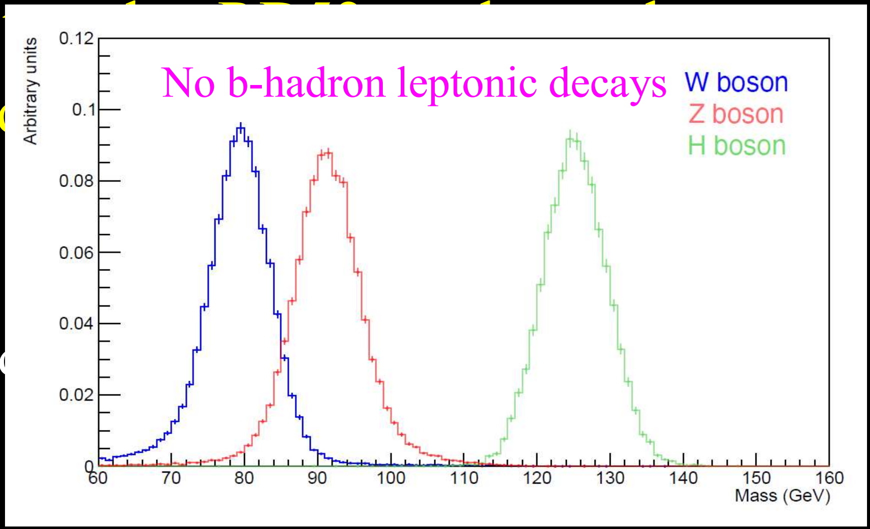
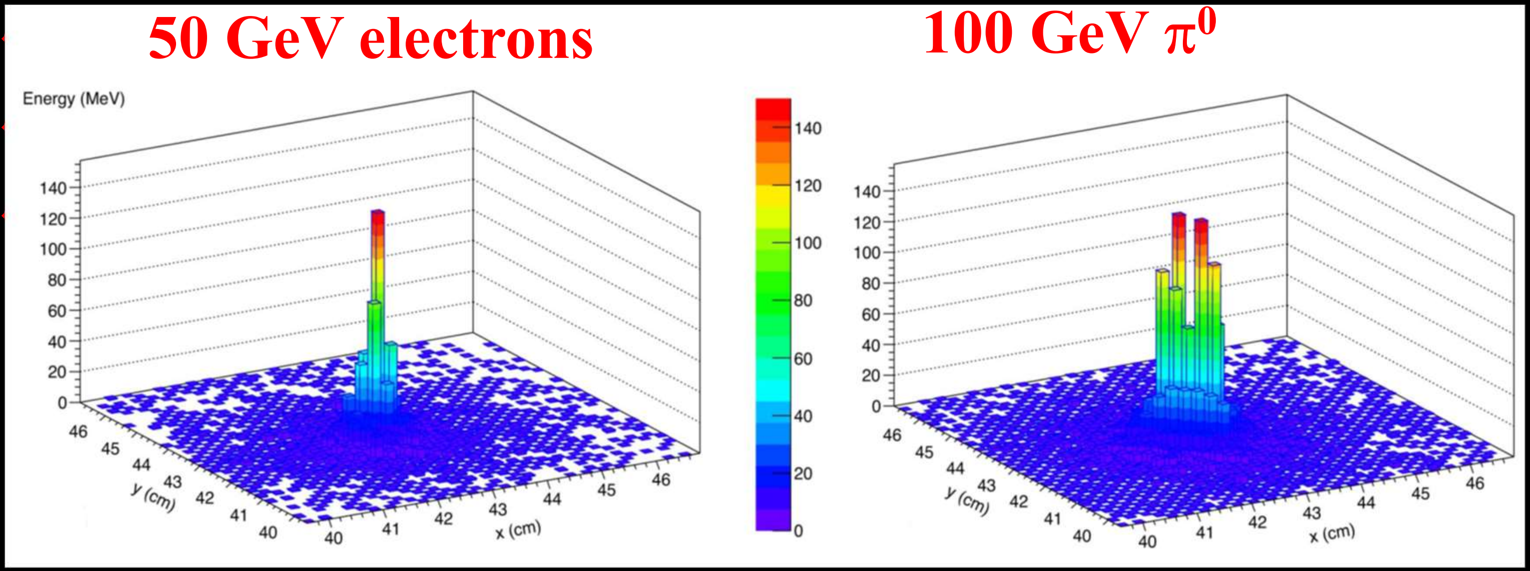


- Adequate separation of W/Z/H

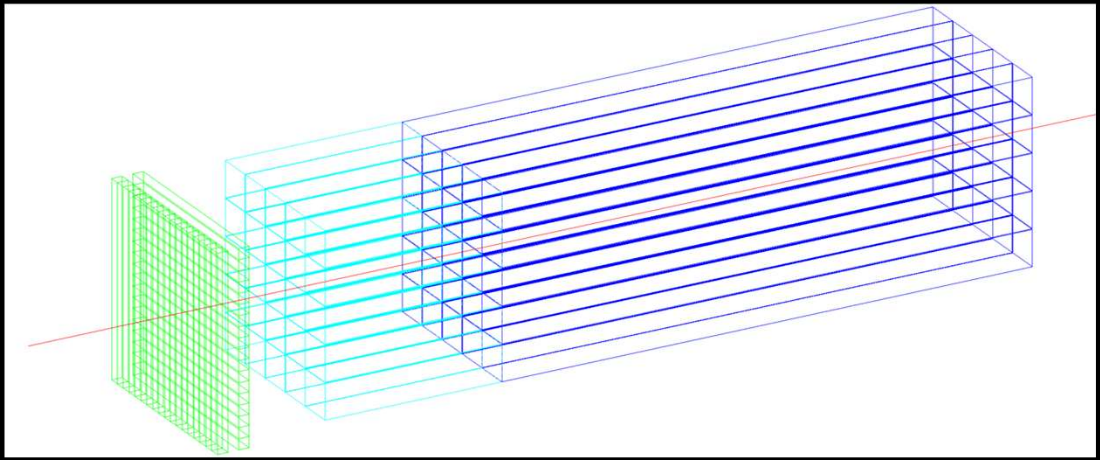
Calorimeter simulation



- ❖ Adequate separation of W/Z/H
- ❖ Event displays

Crystal option

- ~20 cm $PbWO_4$
- $\sigma_{EM} \approx 3\%/\sqrt{E}$
- DR w. filters
- Timing layer
  - LYSO 20-30 ps



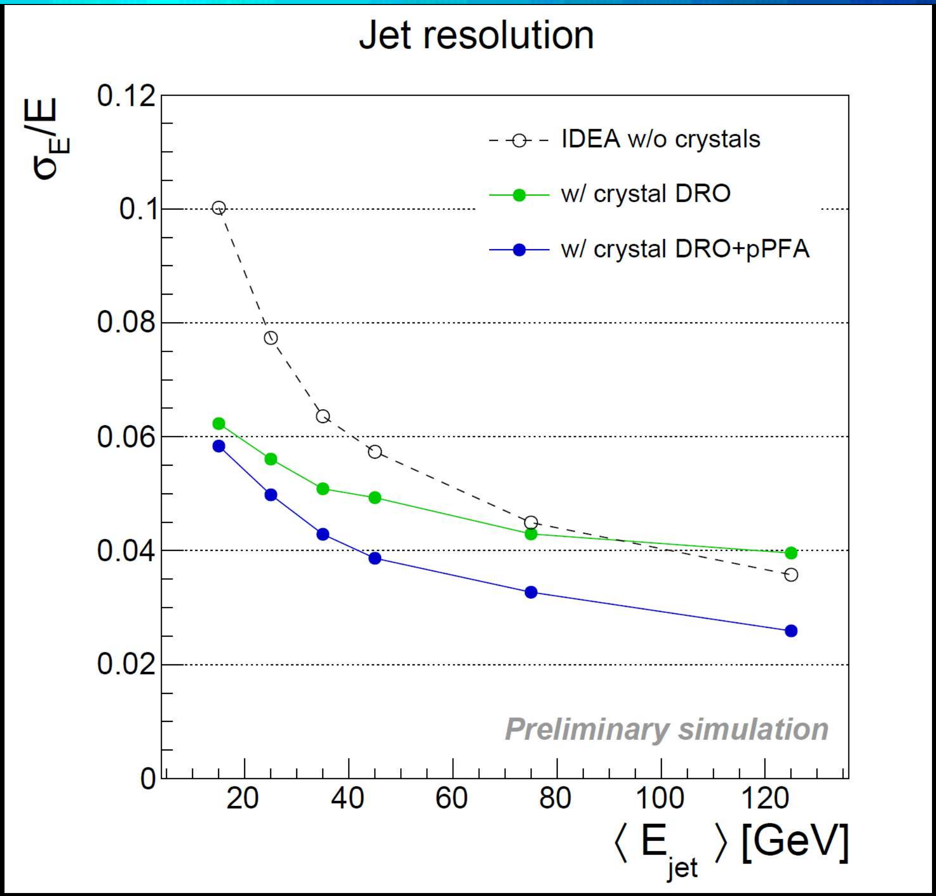
1x1x5cm^3 PbWO

1x1x15cm^3 PbWO

- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4X_0)
  - rear segment for core shower
  - (15 cm ~16.3X_0)
  - 10x10x200 mm^3 of crystal
  - 5x5 mm^2 SiPMs (10-15 um)

Crystal option

- ~20 cm $PbWO_4$
- $\sigma_{EM} \approx 3\%/\sqrt{E}$
- DR w. filters
- Timing layer
  - LYSO 20-30 ps
- PF for jets



INFN RD_FCC detector work

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  - Tracking detectors
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    - Vertex detector/MDI mechanical structure and cooling – Collaboration with CERN
    - Silicon wrapper: AtlasPix3 – International collaboration, Resistive LGADs
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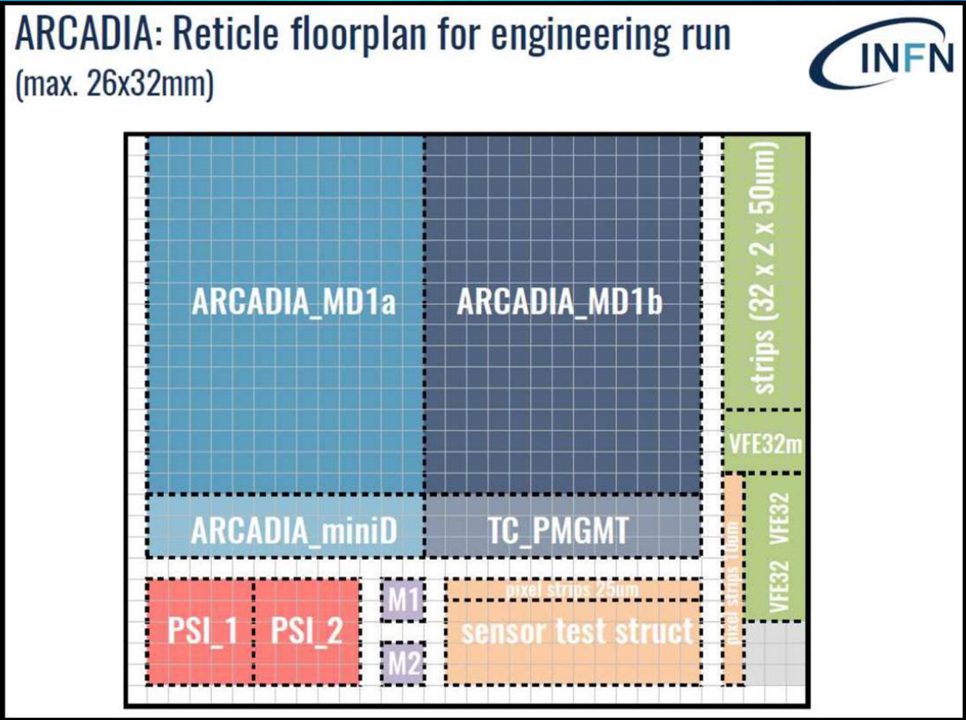
    - Muon chambers: μRwell technology – synergy with LHCb/CLAS12 upgrades
  - Calorimeter
    - New mechanical & electronics solutions – Digital SiPMs
    - Full containment fiber prototype/ Crystal EM - International collaboration

ARCADIA (contacts: M. Rolo, M. Caccia)

- CMOS DMAPS:
  - 110 µm CMOS CIS
  - 25 x 25 µm pixels
  - Thickness 50-500 µm
    - Current sample 200 µm
  - Fast full depletion charge collection
  - Low power data driven architecture (<20 mW/cm^2)
  - Scalable to reticle-size
    - Side buttable



Call CSN5 & collaboration with IHEP, PSI

Included in AidaInnova

DRD3 CMOS in progress

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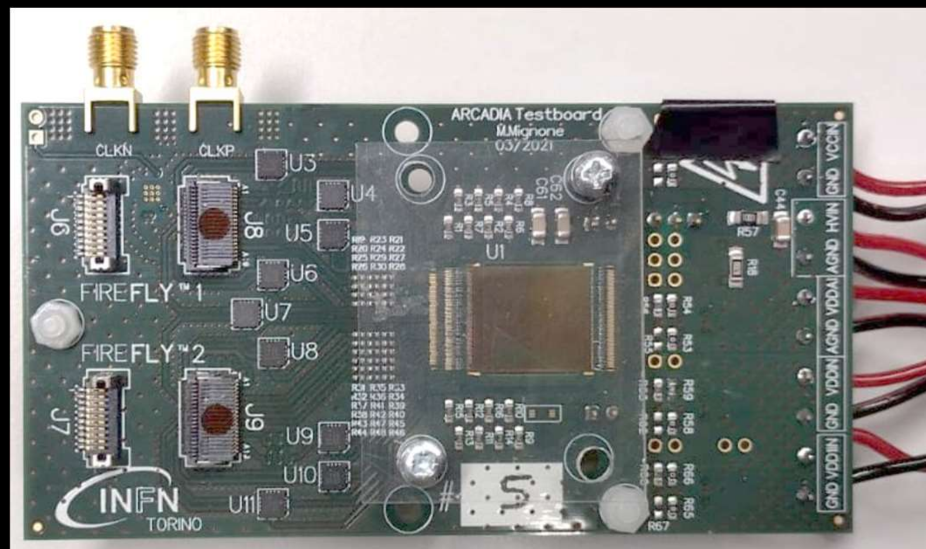
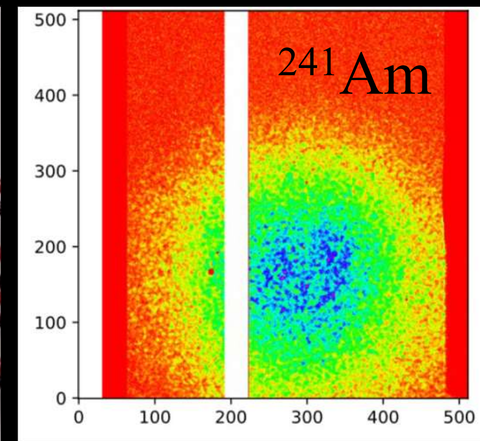
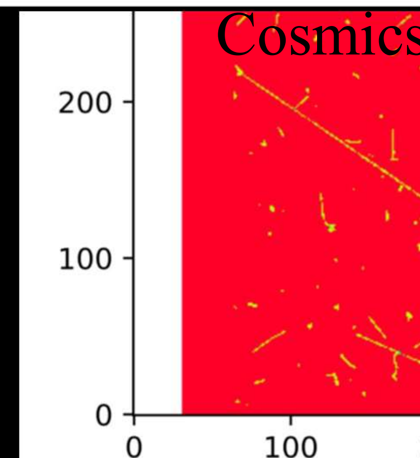
- 512x512 proto tested
  - Updated version for TB







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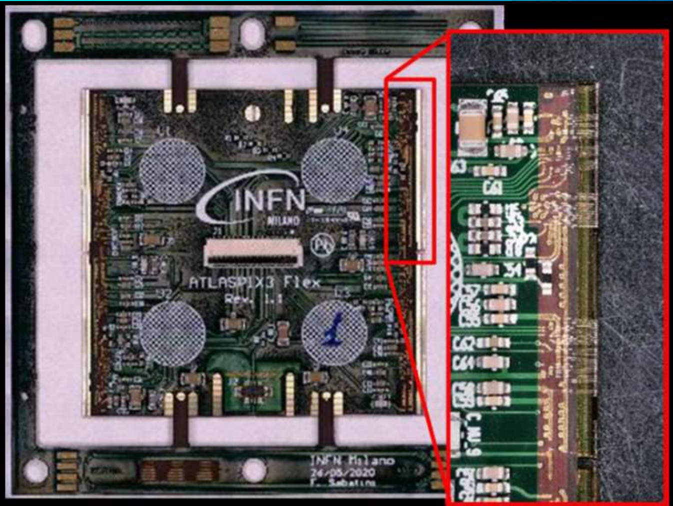
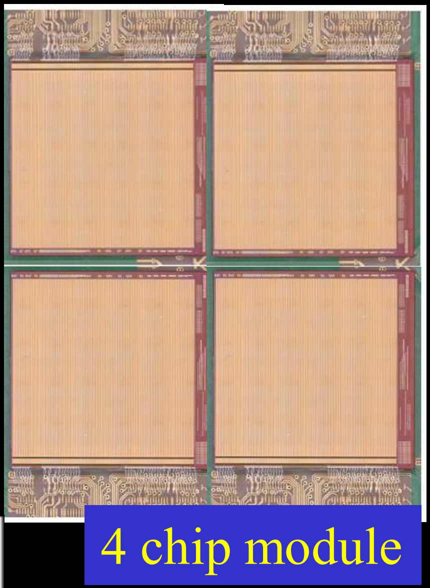
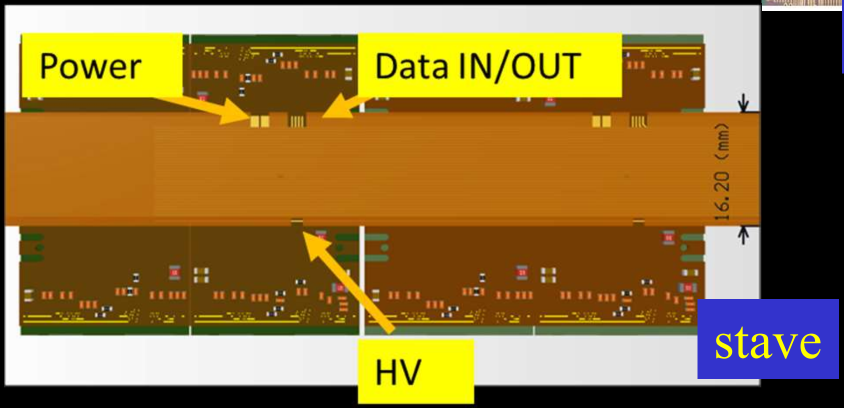
DRD3 CMOS in progress

AtlasPix3 (Contact: A. Andeazza)

- Based on ATLASPIX3 R&D
  - 50 x 150 µm2
  - Up to 1.28 Gb/s downlink
  - TSI 180 nm process
  - 132 columns of 372 pixels
- Active (total) length (r-phi x z)
  - 18.6 (21) mm x 19.8 (20.2) mm
- Module is made of 2x2 chips
- Power budget not established







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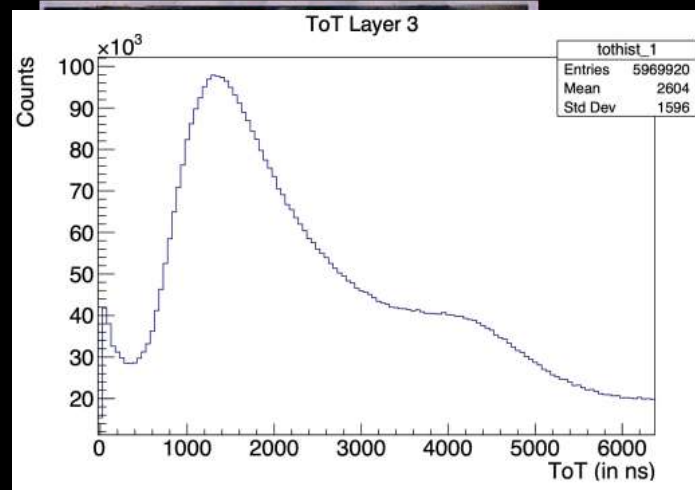
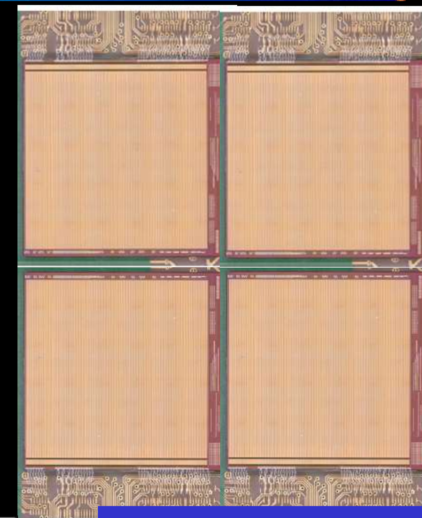
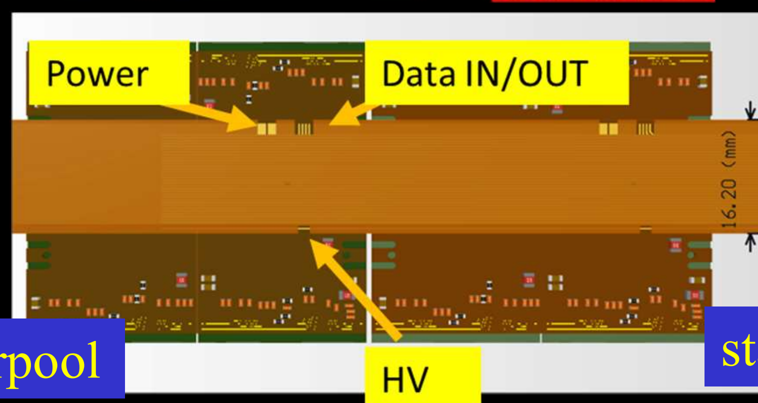
Collaborazione: INFN, IHEP, KIT, Liverpool





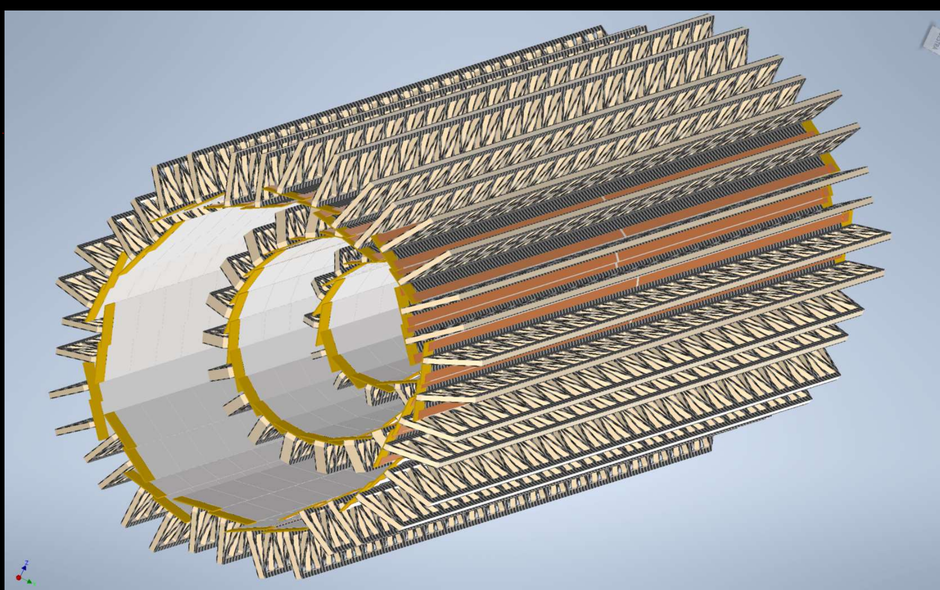
4 chip module

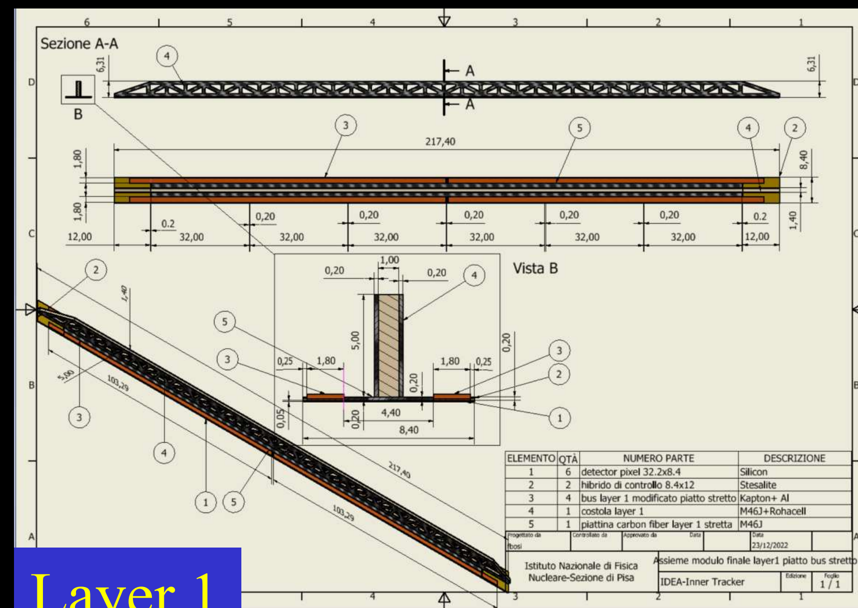


stave

Mechanical integration
(Contacts: F. Palla, M. Boscolo)

- Vertex design based on:
  - ARCADIA inner 3 layers
    - Air cooled





Layer 1

Mechanical integration
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- Vertex design based on:
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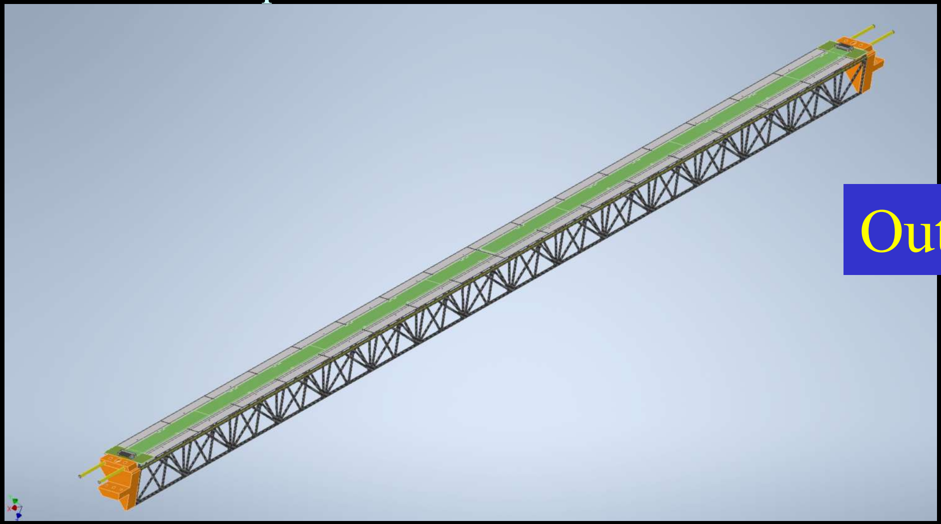
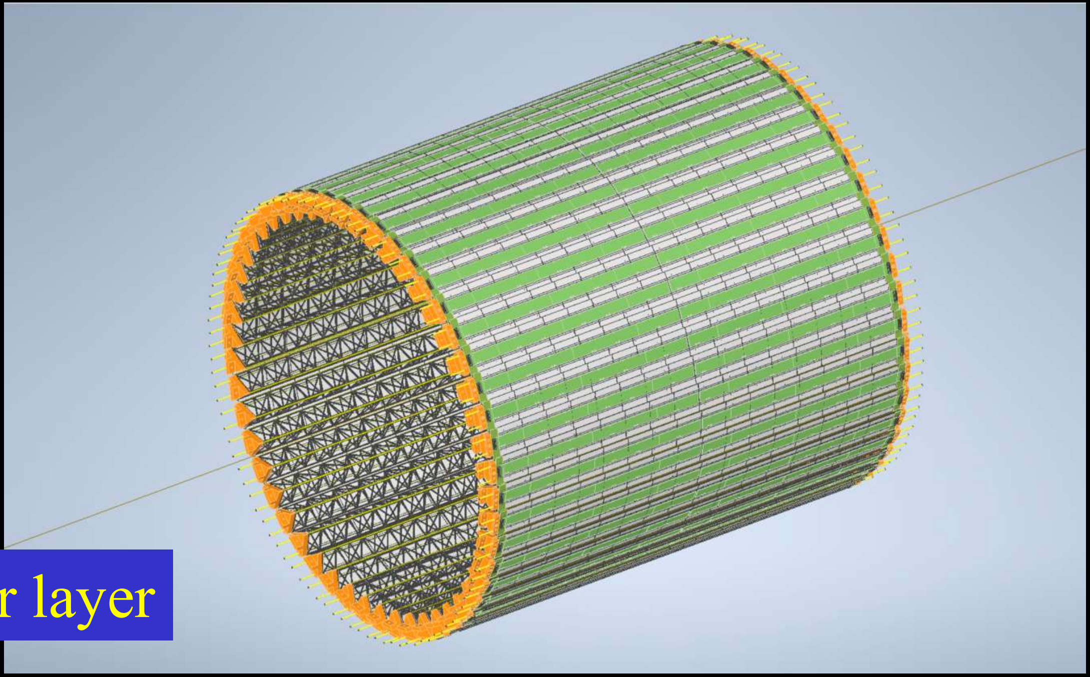
  - AtlasPix3 outer 2 layers
    - Liquid cooled





Outer layer

Mechanical integration
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- Vertex design based on:
  - ARCADIA inner 3 layers
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- Full view with support cylinder
  - Supported by:
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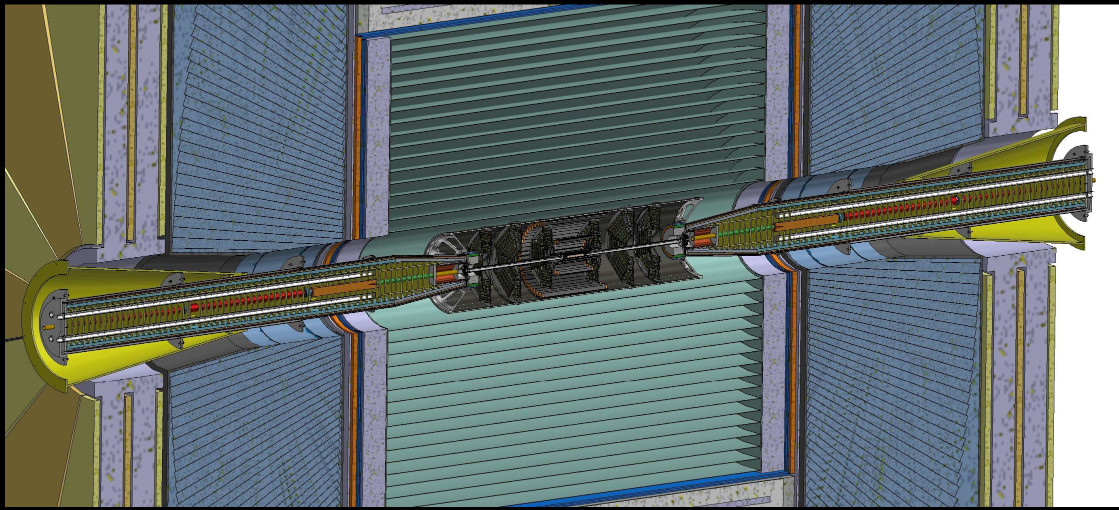

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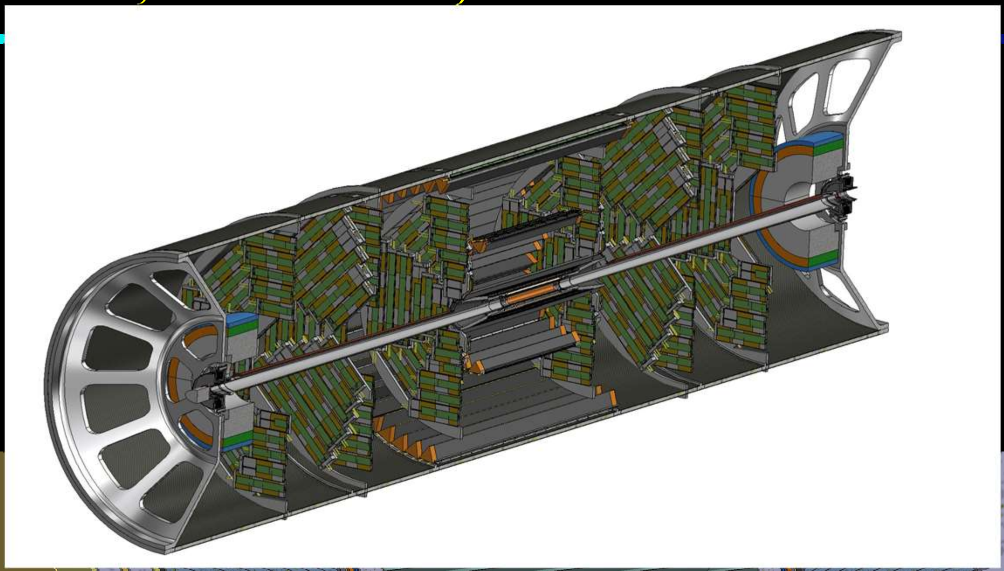
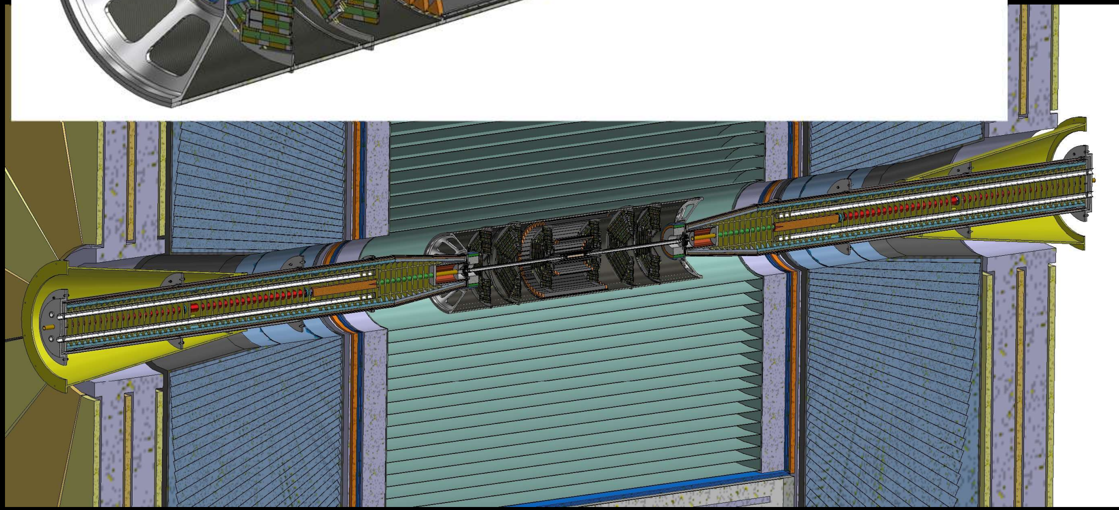
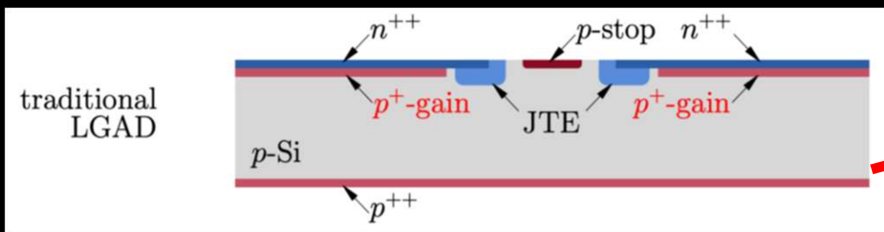
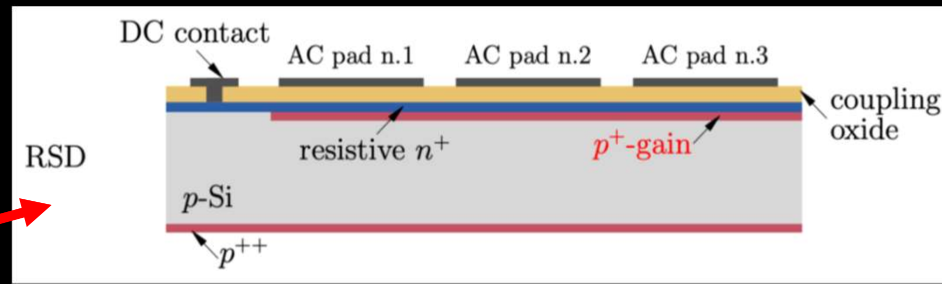


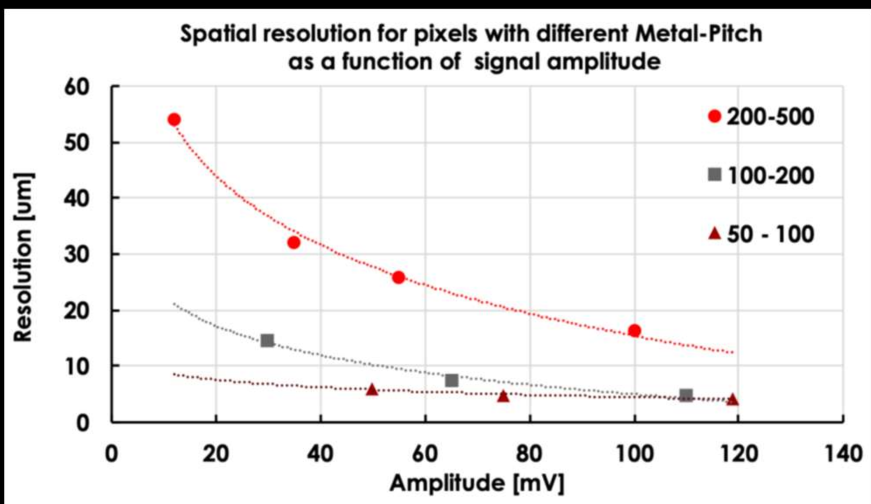


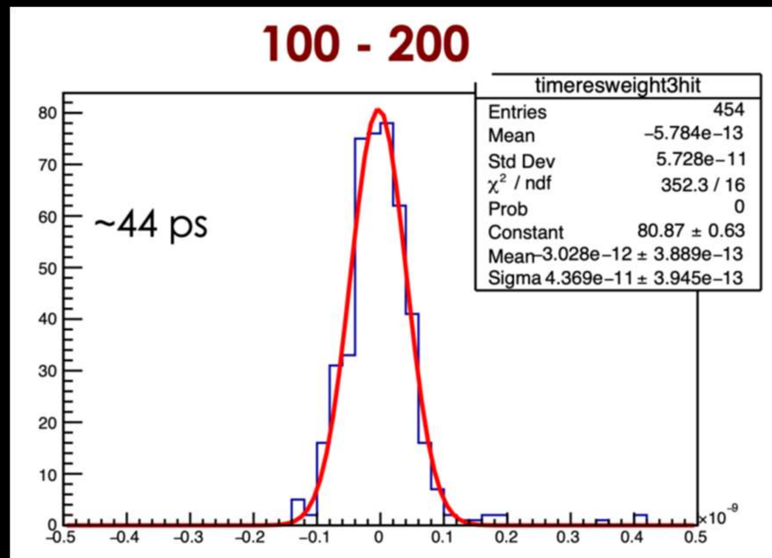
Resistive LGAD (Contact: E. Robutti)

- Recent new activity with INFN-GE/(TO)
  - Match time and position resolution



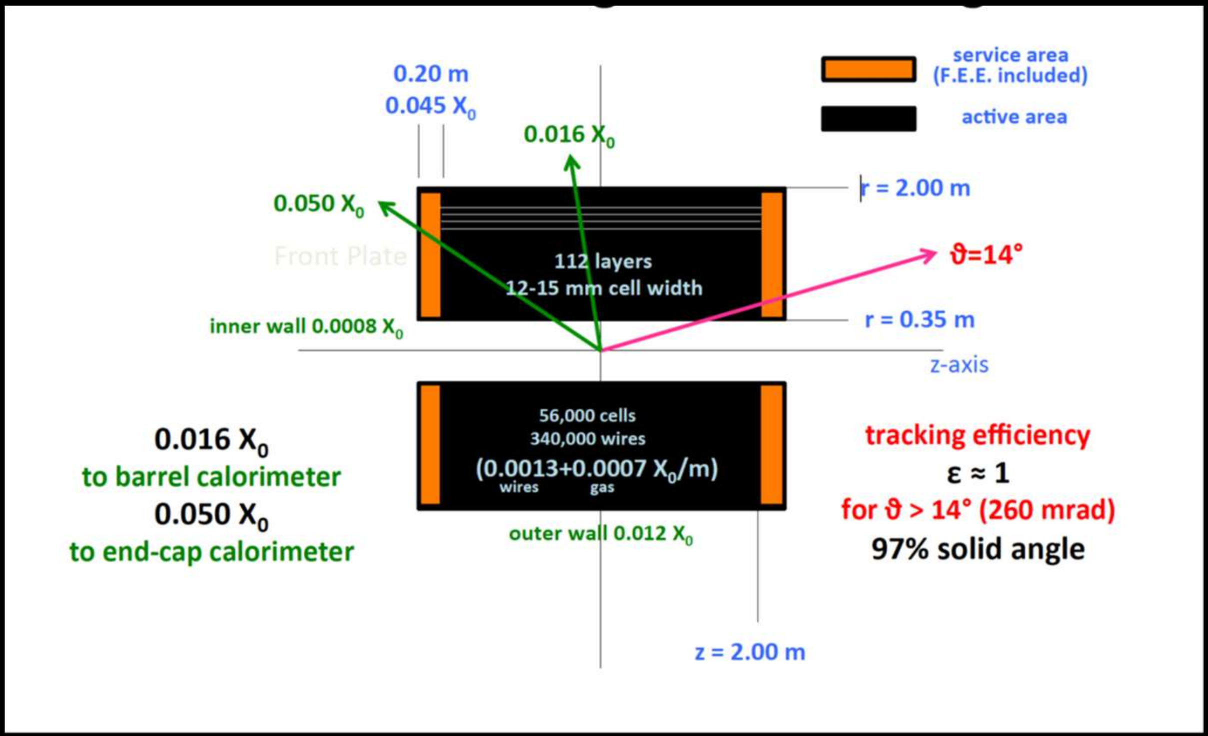


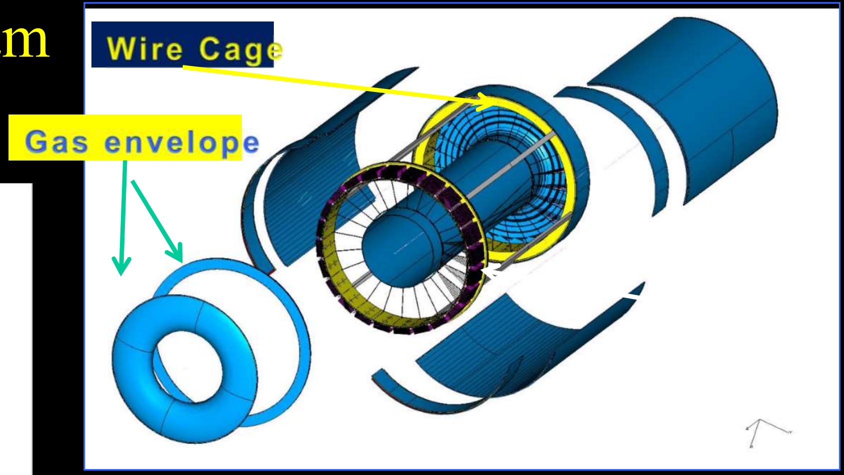


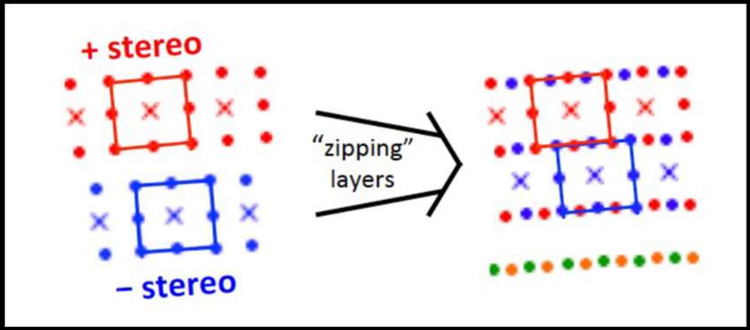


Drift chamber (Contact: F. Grancagnolo)

- 90% He/ 10% C_4H_{10} – All stereo – $\sigma \sim 100\ \mu m$
- Small cells, max drift time ~ 400 ns







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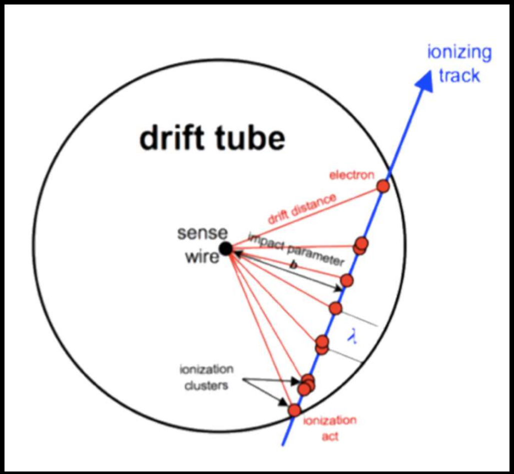
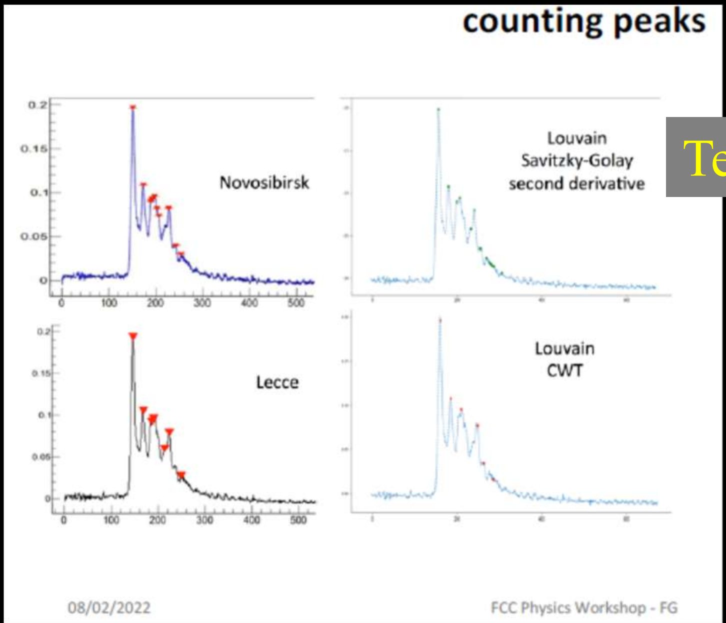
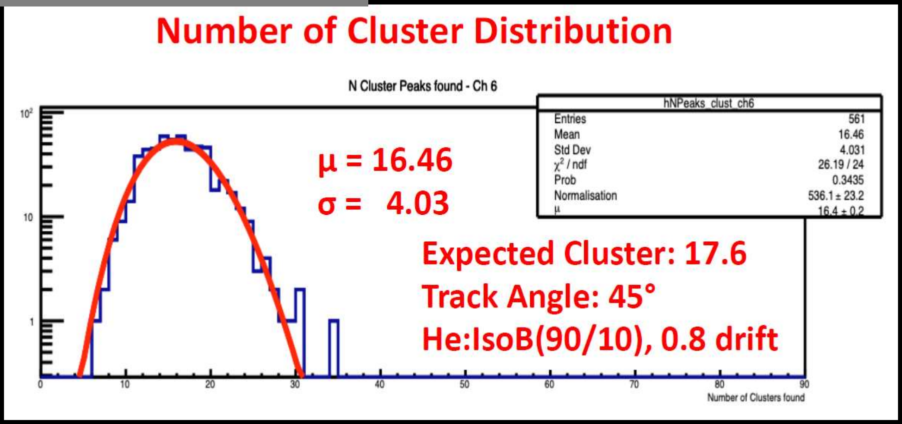
Cluster counting

- Cluster counting x2 better than dE/dx
  - Poisson vs . Landau → no large tails
- Sample signal few GHz → on detector electronics R&D





Test beam data 2022



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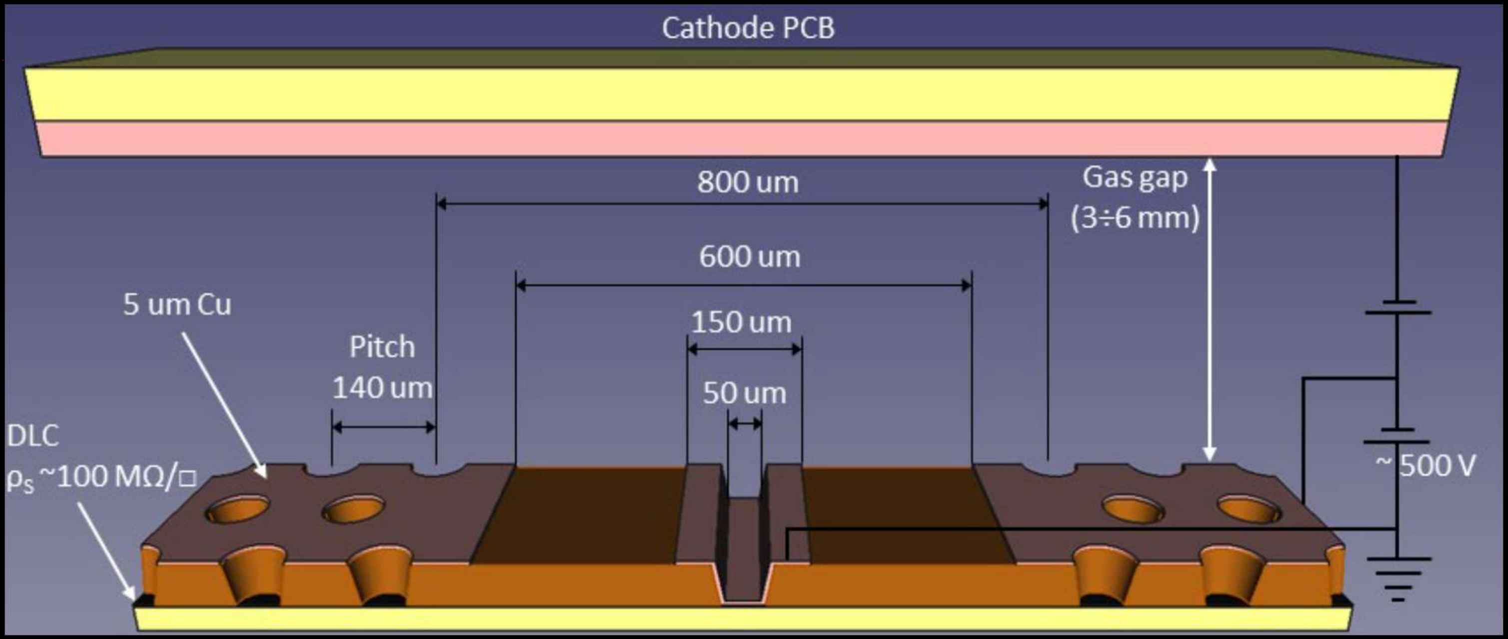

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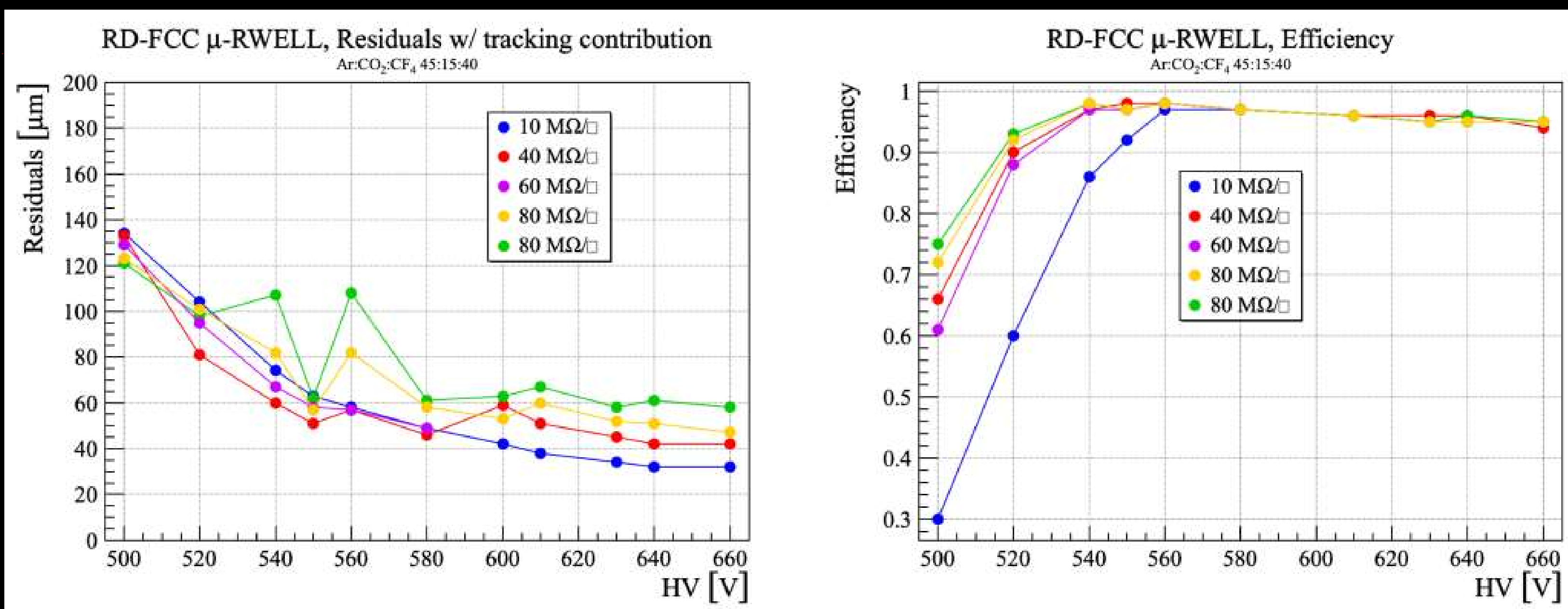

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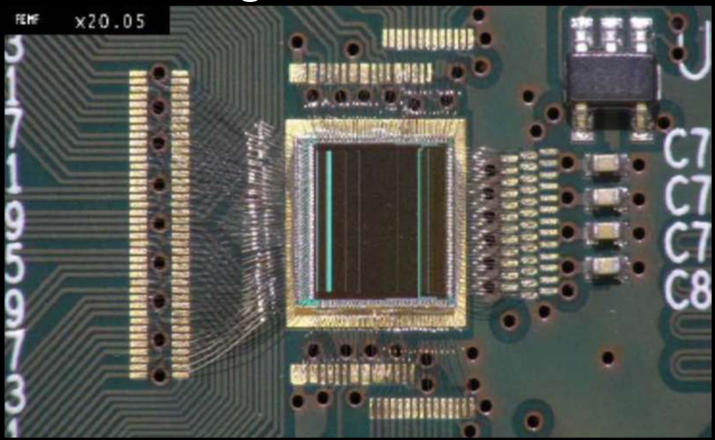
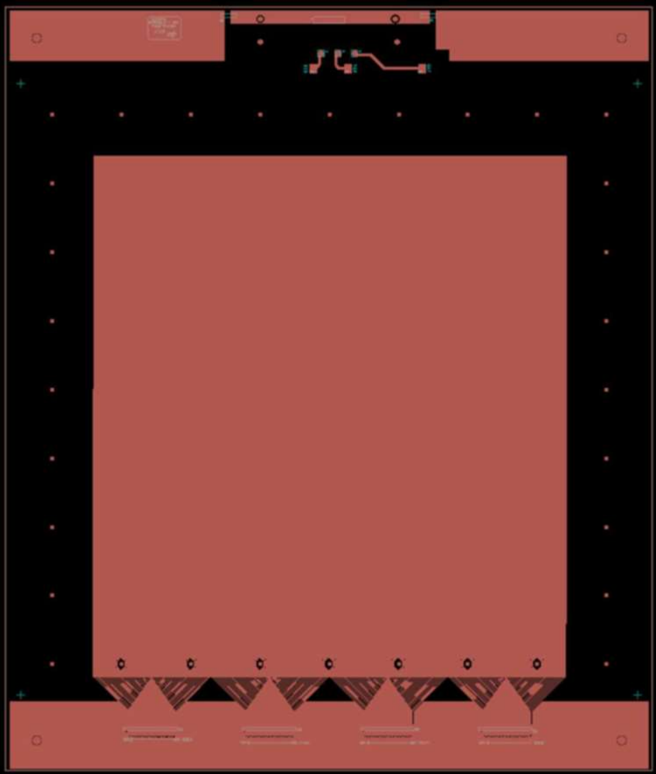
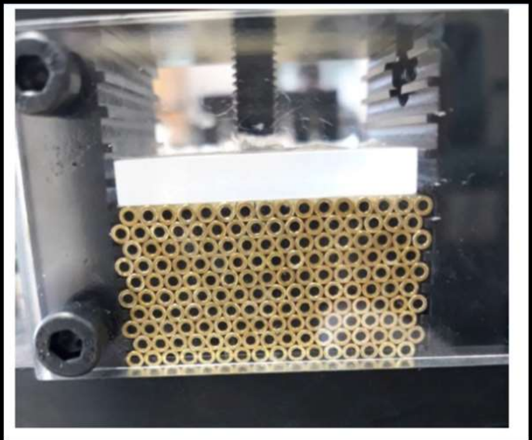
- Several satisfactory test beams
- Next:
  - Study 2D readout and new integrated electronics (TIGER)
  - Build large 50x50 cm chambers

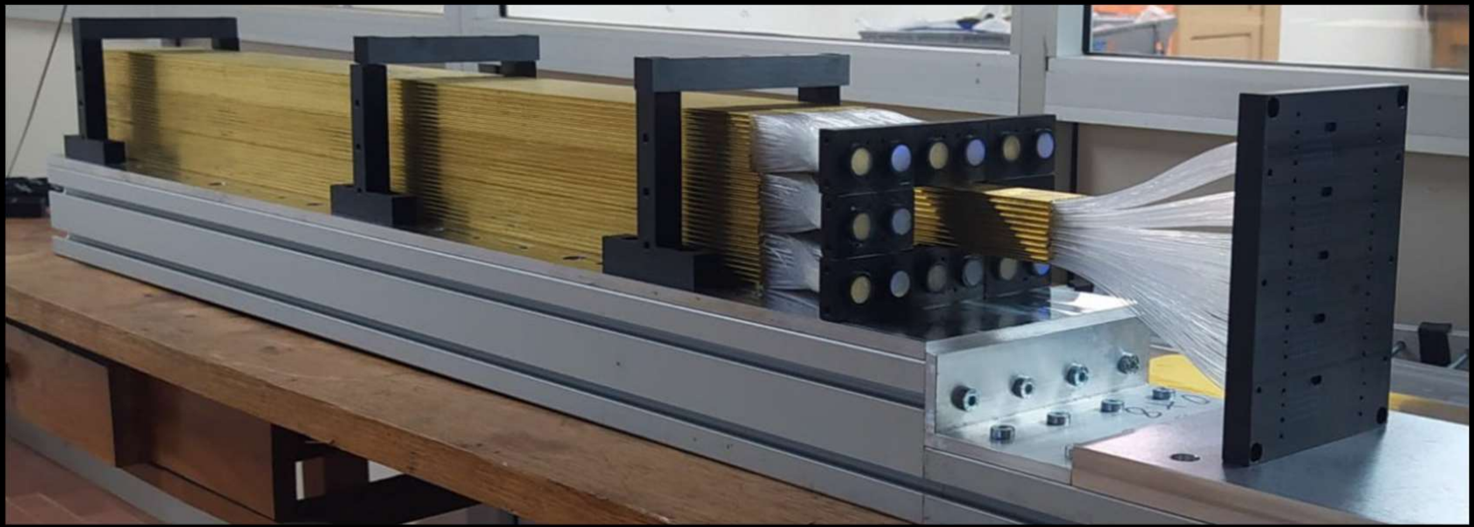




DR calorimeter (Contacts: R. Ferrari)

- International collaboration:
  - TTU (USA), Sussex (UK), several universities (Korea – 2 M$/5 yr), Chile
  - Princeton, Maryland (USA), CERN for crystal extension
- EM prototype built and tested on beams (DESY/CERN)





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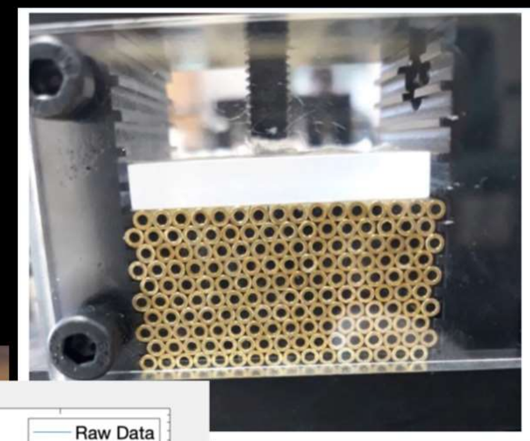

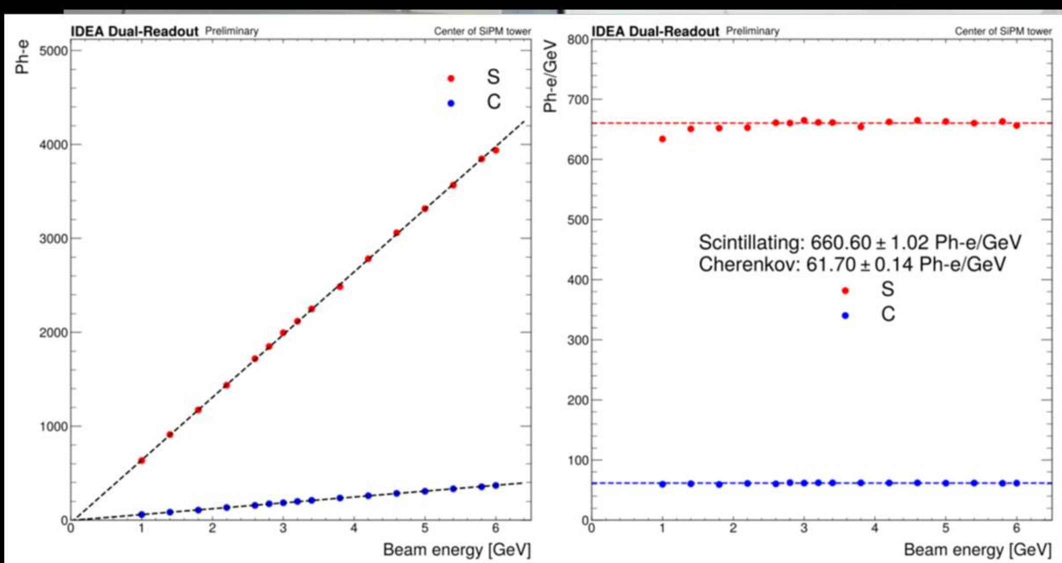

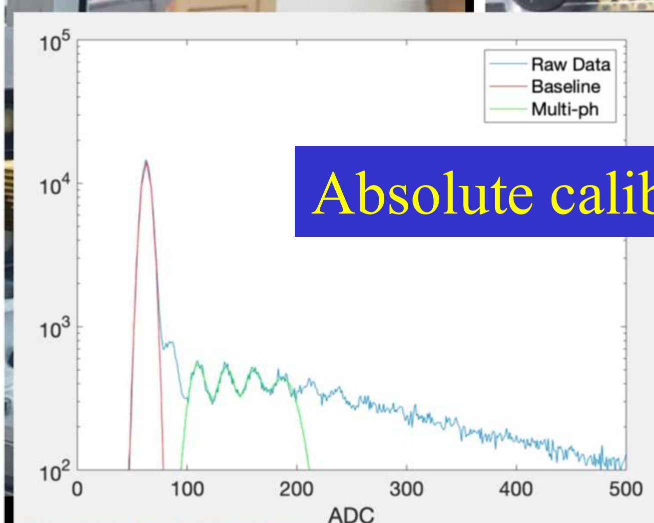

Absolute calibration in ph.e

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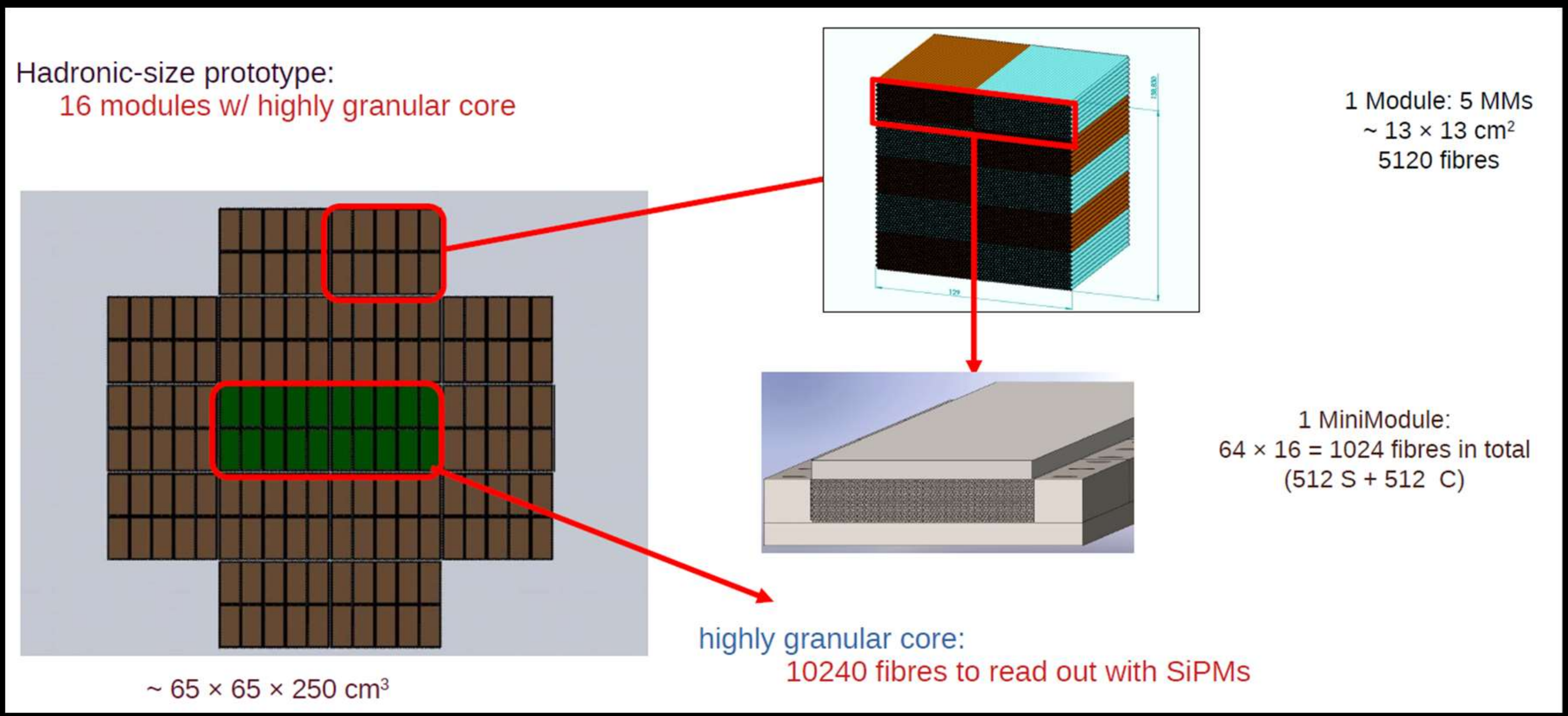

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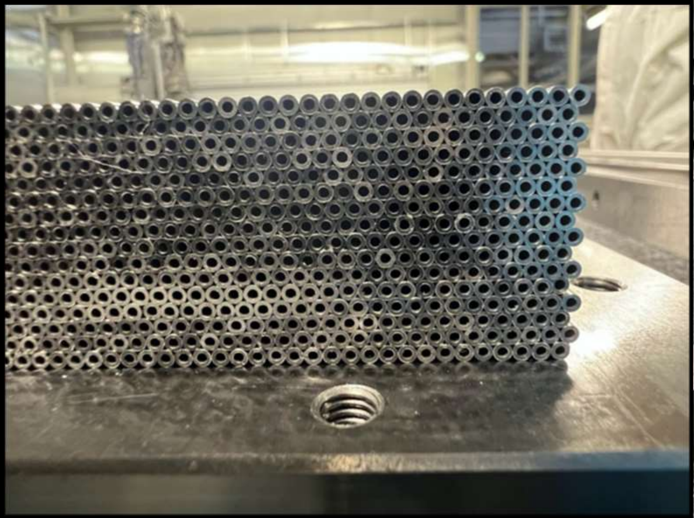

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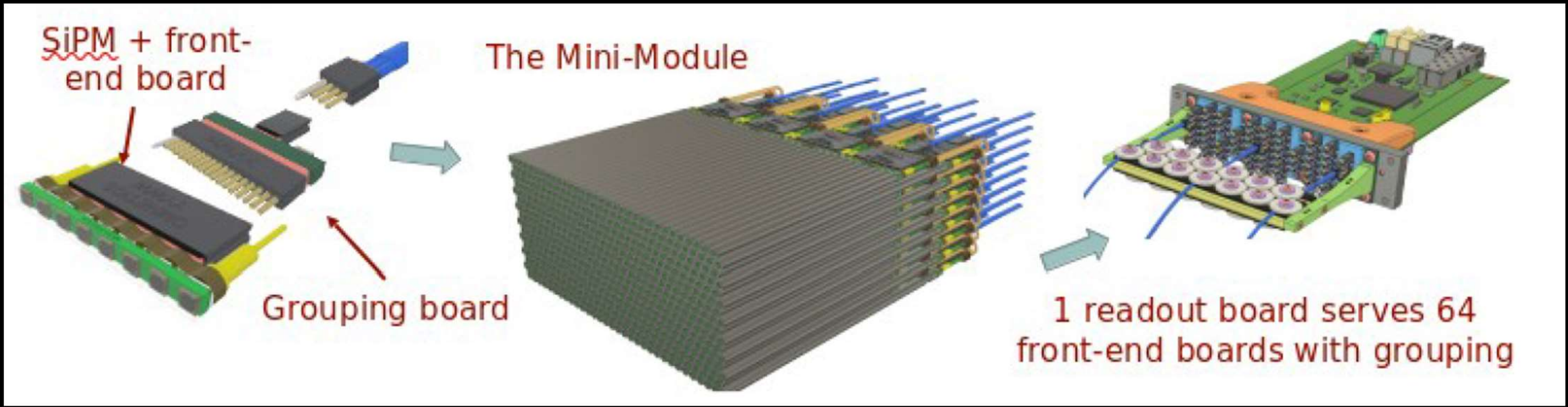
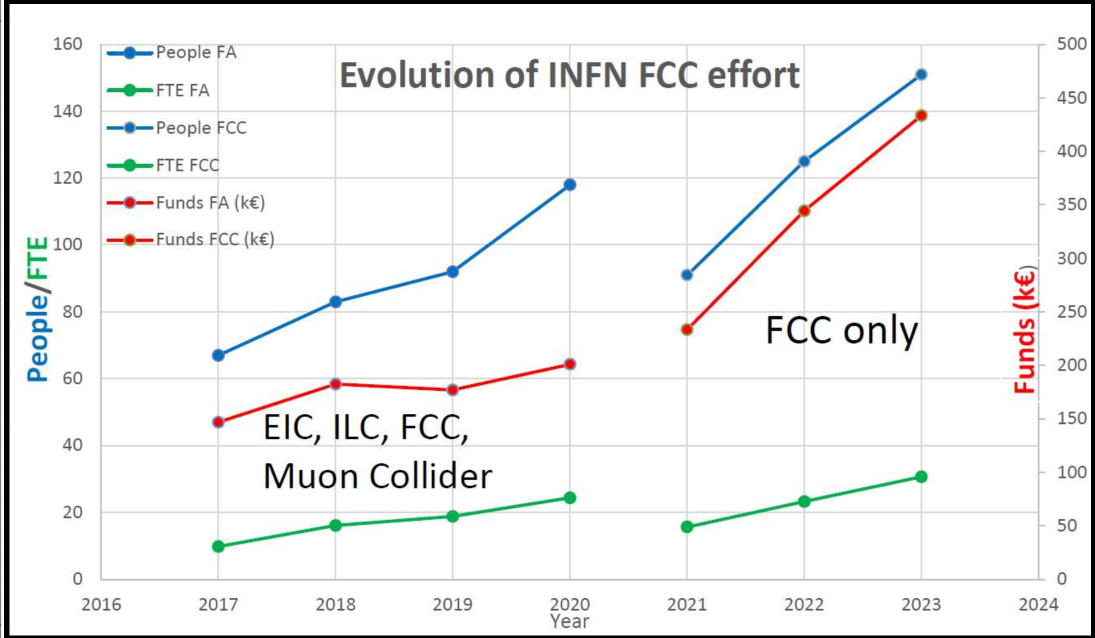


FCC @ INFN

❖ INFN FCC Work Packages

- **WP1: Physics and software**
  - **All 19 INFN sections**
- **WP2: Accelerator**
  - **GE, LNF, LNL, MI**
- **WP3: Silicon Detectors**
  - **GE, MI, PI, TO**
- **WP4: Drift Chamber**
  - **BA, LE**
- **WP5: MPGD muon**
  - **BO, FE, LNF**
- **WP6: DR calorimetry**
  - **BO, MI, MIB, NA, PI, PV, RM1, RM3**

Sezione	Total FTE	Scientists
BA	2.40	11
BO	3.40	16
CT	1.80	4
FE	1.50	7
FI	0.15	2
GE	0.75	8
LE	1.10	6
LNF	4.85	15
LNL	0.10	1
MI	3.45	7
MIB	0.10	1
NA	1.00	9
PD	1.25	9
PI	2.10	21
PV	4.10	12
RM1	0.30	2
RM3	0.90	5
TO	0.90	10
UD	0.55	5
Totali	30.70	151



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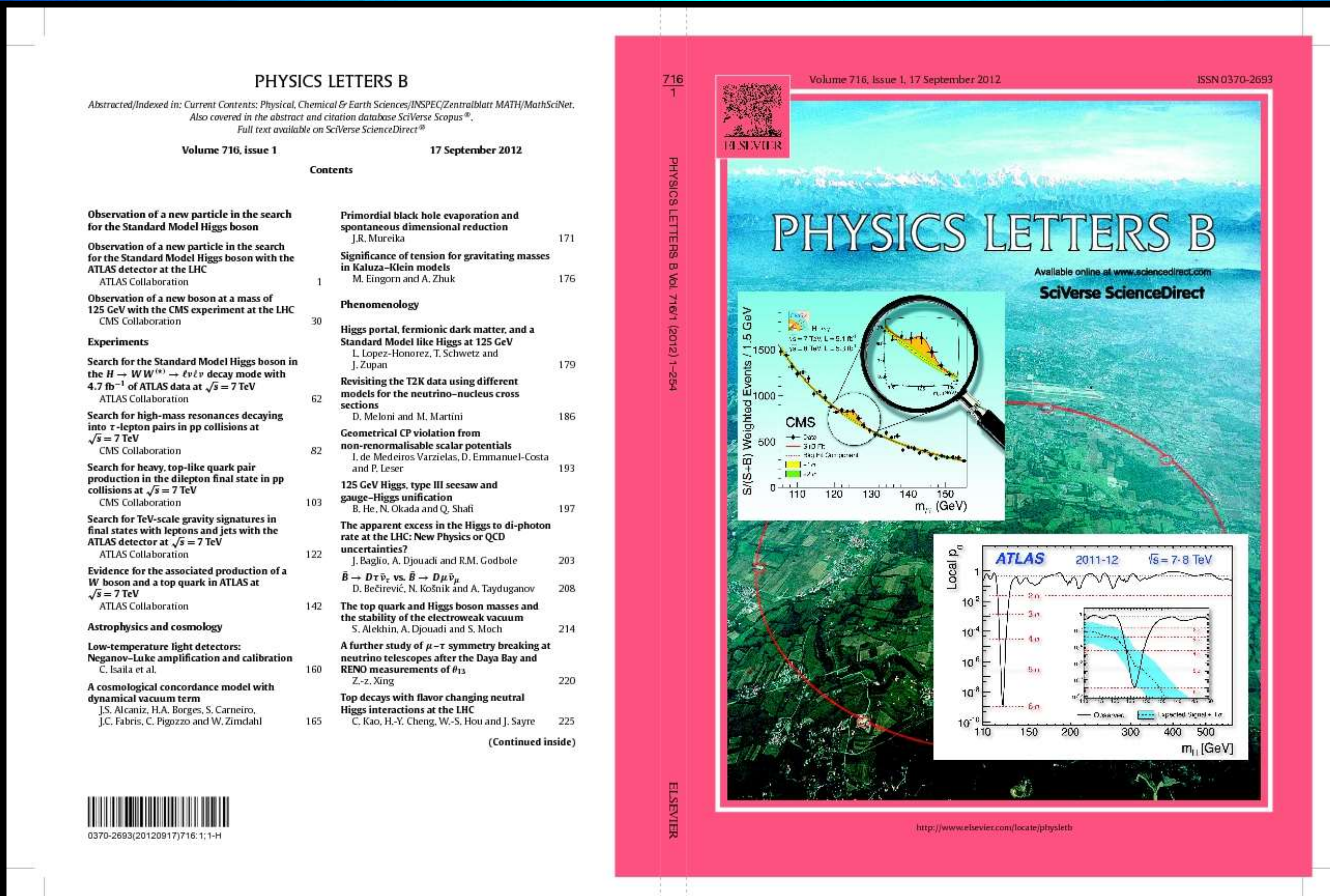
- All R&D activities still very open to new collaborators
- Need more people to carry on these exciting/demanding programs

Backup slides

It all started with the Higgs boson …



PHYSICS LETTERS B

Abstracted/Indexed in: Current Contents: Physical, Chemical & Earth Sciences/INSPEC/Zentralblatt MATH/MathSciNet.
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Volume 716, issue 1 **17 September 2012**

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0370-2693(20120917)716:1;1-H

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Frascati Phys. Ser. 60 (2015) pp. 1-291
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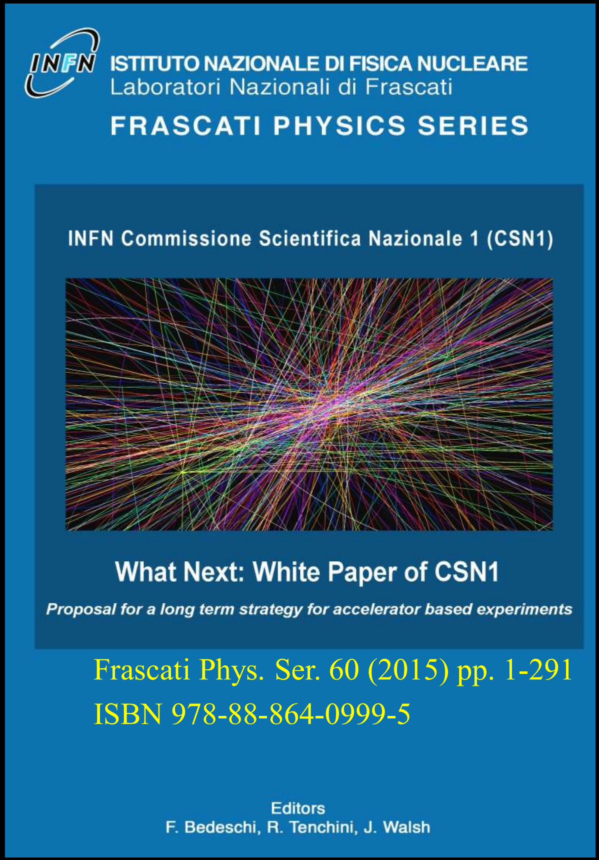

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FUTURE CIRCULAR COLLIDER

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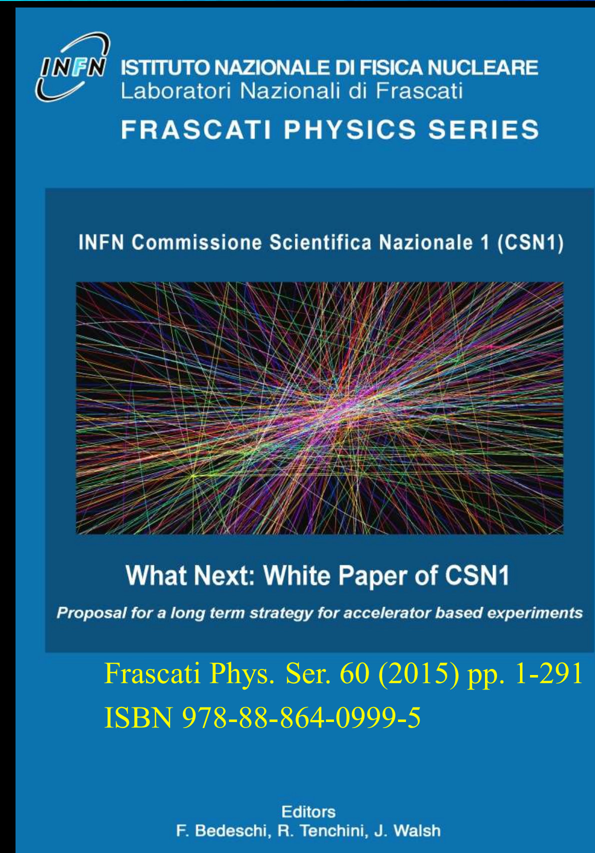

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CSN1 White Paper 2015

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  - In the absence of new physics observations at LHC …, it will be crucial …. a detailed examination of the electroweak sector, in particular precision measurements of the recently discovered Higgs boson; this could be achieved with a new electron-positron machine, possibly complemented at a later stage by a very high-energy hadron collider …

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CSN1 White Paper 2015

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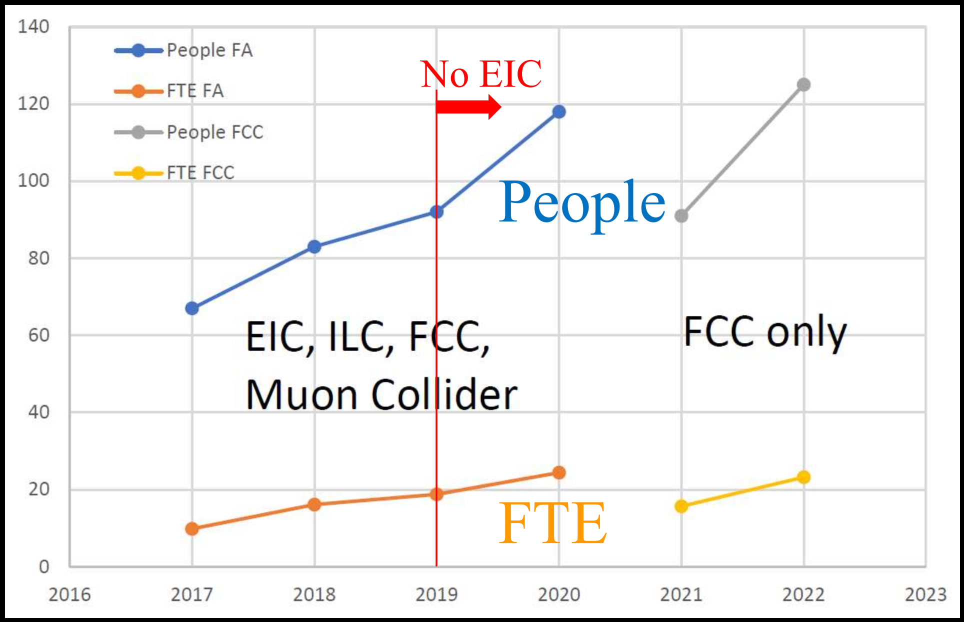
  - CSN1 supports INFN participation in studies and R&D related to the future colliders. **Our community must be part of the planning of the future.**

INFN organization

- Fall 2016: line of research on future accelerators created in CSN1
  - Interest keeps growing over the years



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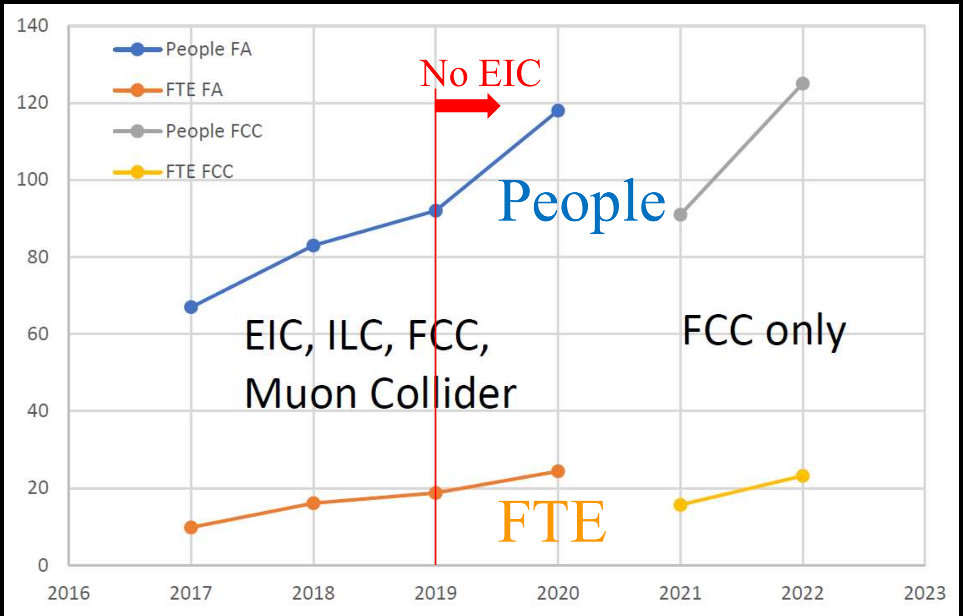

- More resources
  - CSN5 grants
    - ARCADIA
    - Hidra2
  - EU grants:
    - EuroCirCol
    - FCC-IS
    - Attract
    - AidaInnova
    - EuroLabs
    - Cremlin+, FEST

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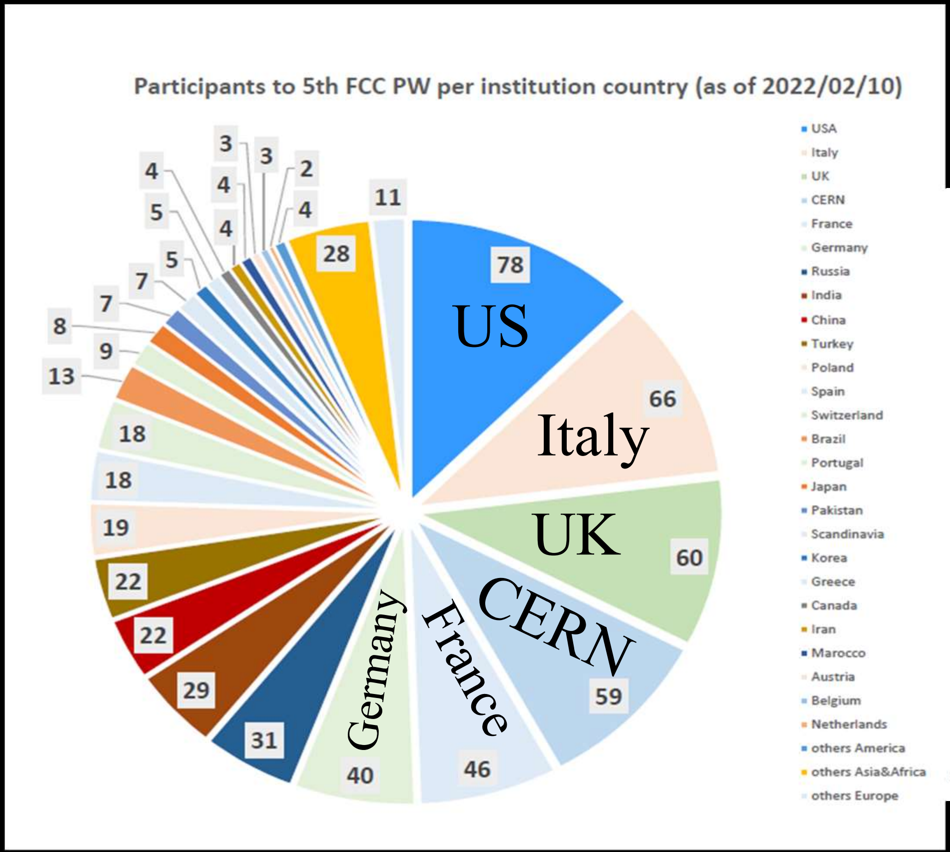

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Detector requirements

❖ Constraints from physics (some similar to LC)

Physics process		Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
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$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

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FUTURE CIRCULAR COLLIDER

Detector requirements

INFN Istituto Nazionale di Fisica Nucleare

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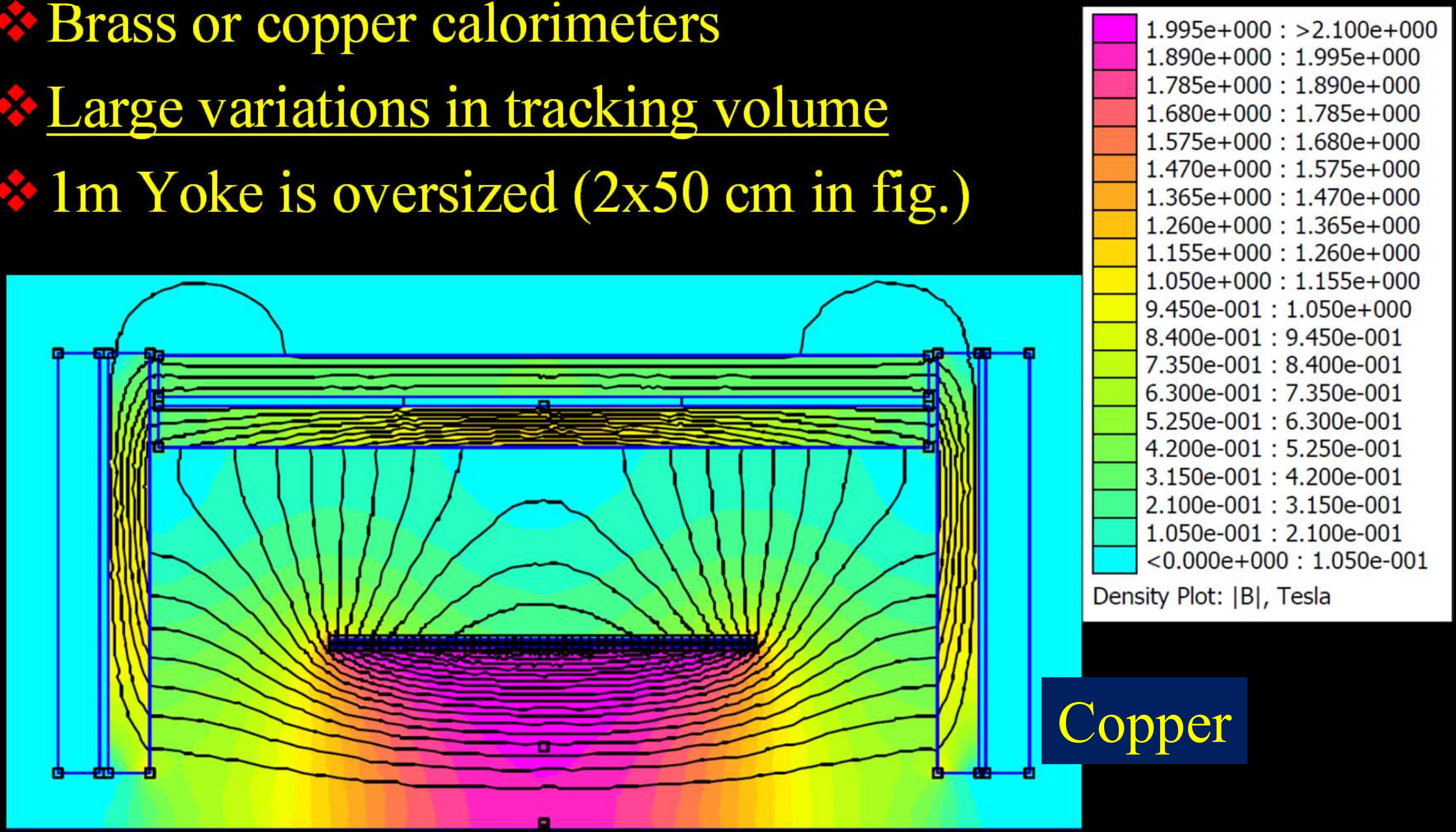
➢ Addditional constraints

- Excellent acceptance and luminosity control
- PID & π^0 ID for HF/τ physics
- Low B field to avoid emittance blow up
- Power pulsing not allowed

} Not present at LC

Simulation results: field map

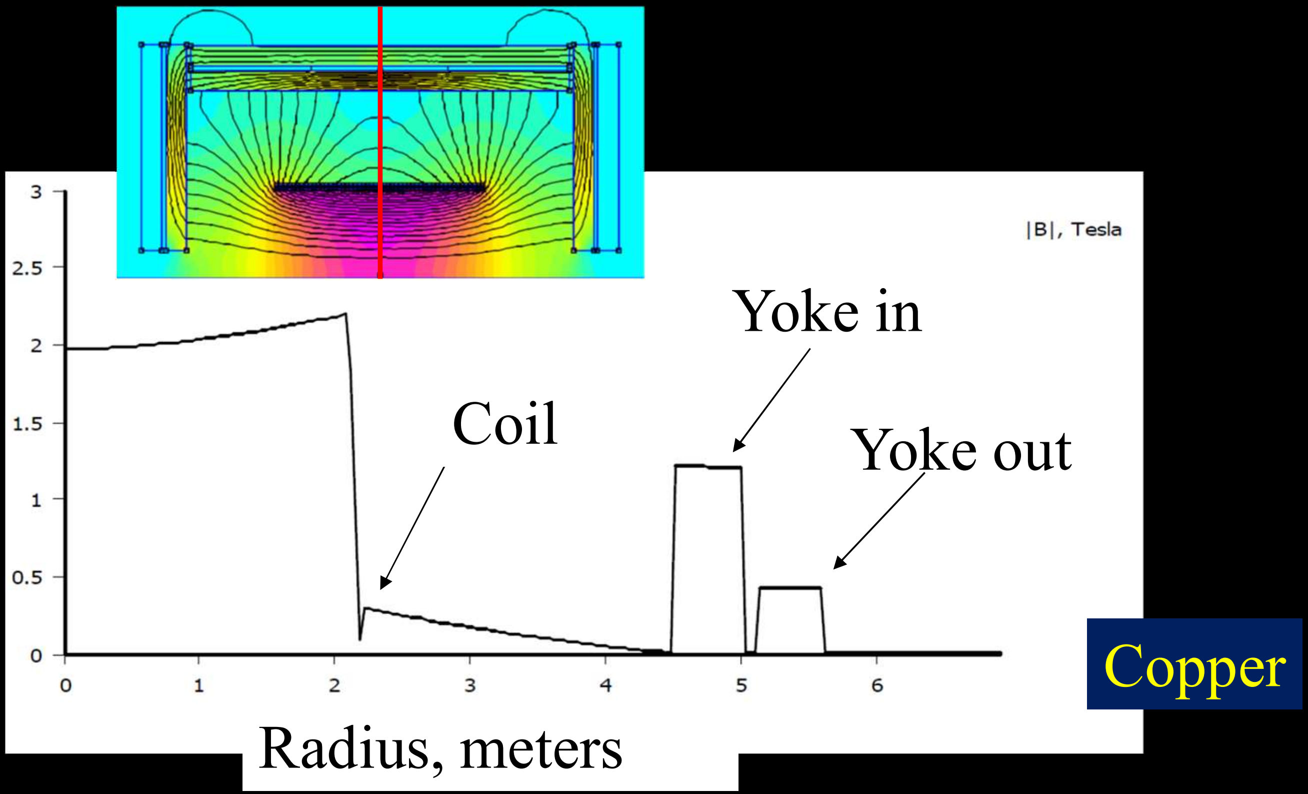
- Brass or copper calorimeters
- Large variations in tracking volume
- 1m Yoke is oversized (2x50 cm in fig.)



Copper

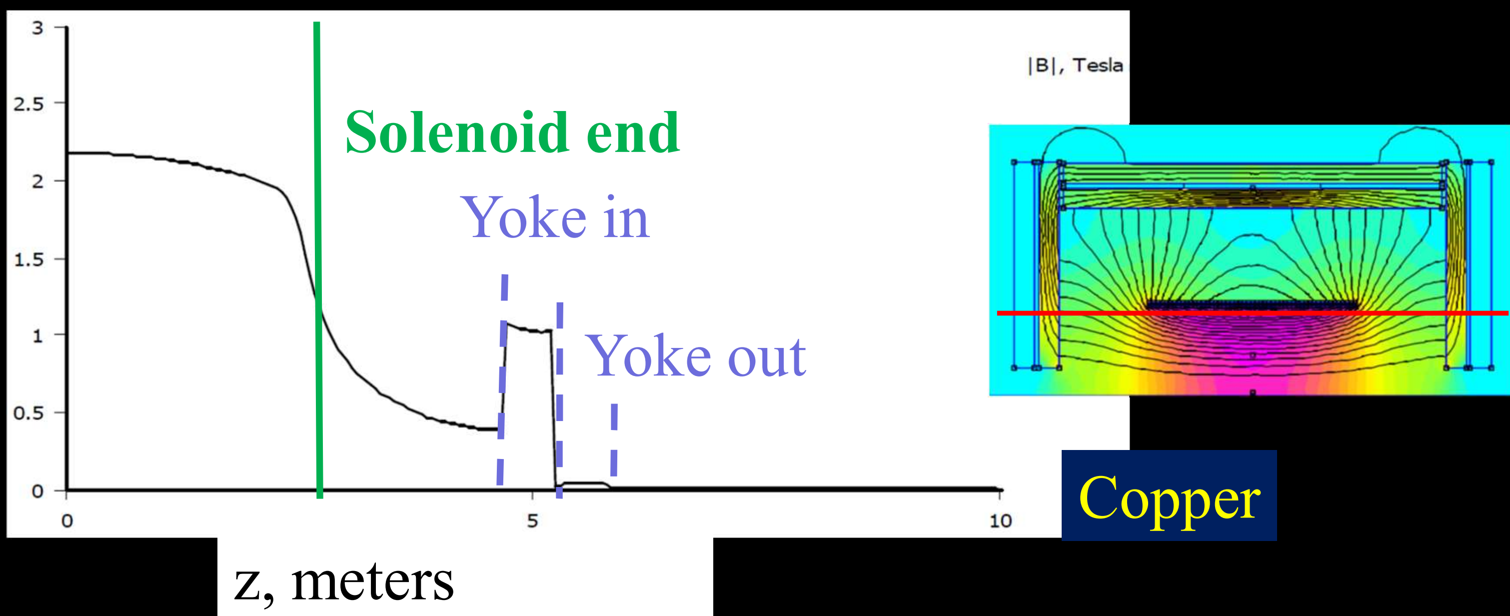
Simulation results: projections (R)

❖ Radial field variation: interaction vertex till after yoke



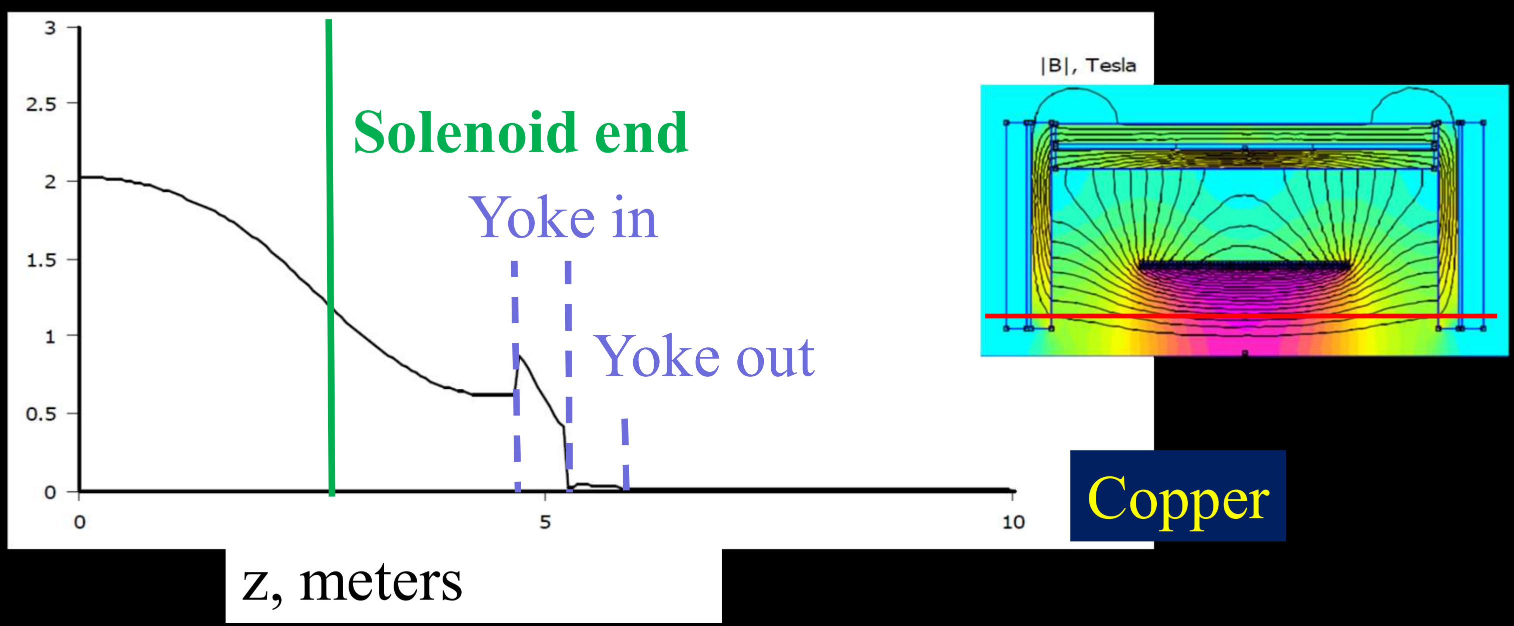
Simulation results: proj. (R = 2.0 m)

❖ Longitudinal field projection @ R = 2.0 m



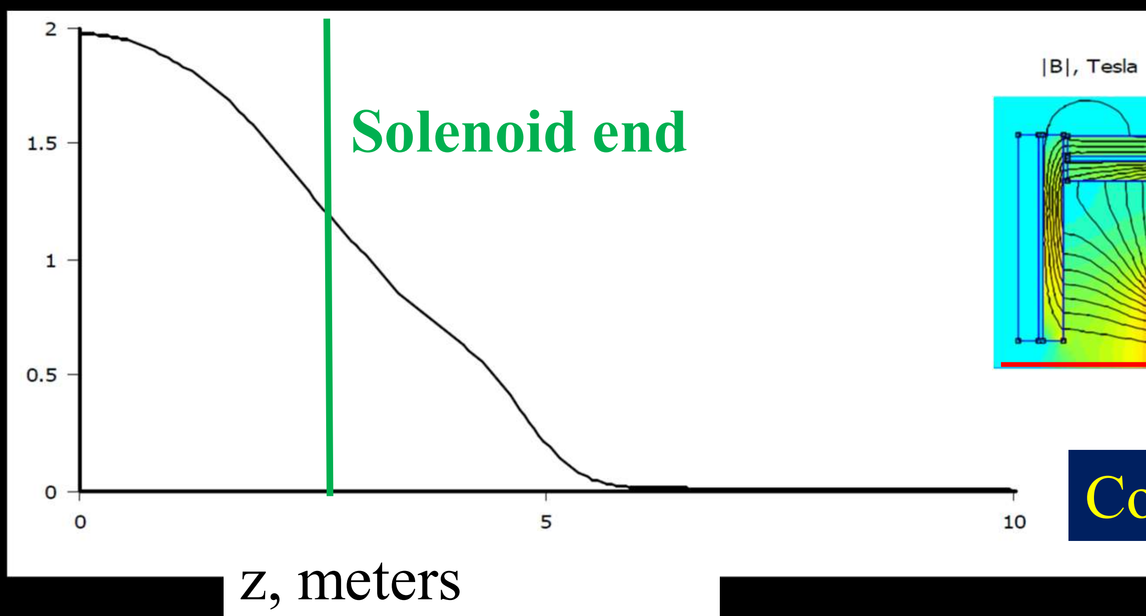
Simulation results: proj. (R = 1.0 m)

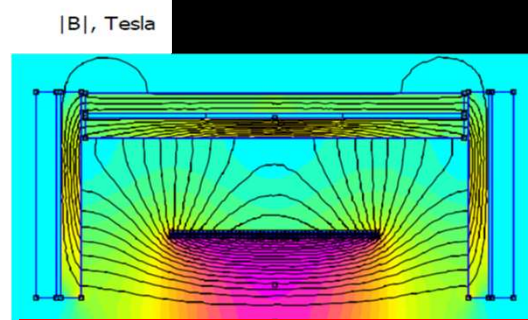
- Longitudinal field projection @ R=1.0 m



Simulation results: proj. (R = 0.1 m)

❖ Longitudinal field projection @ R=10 cm

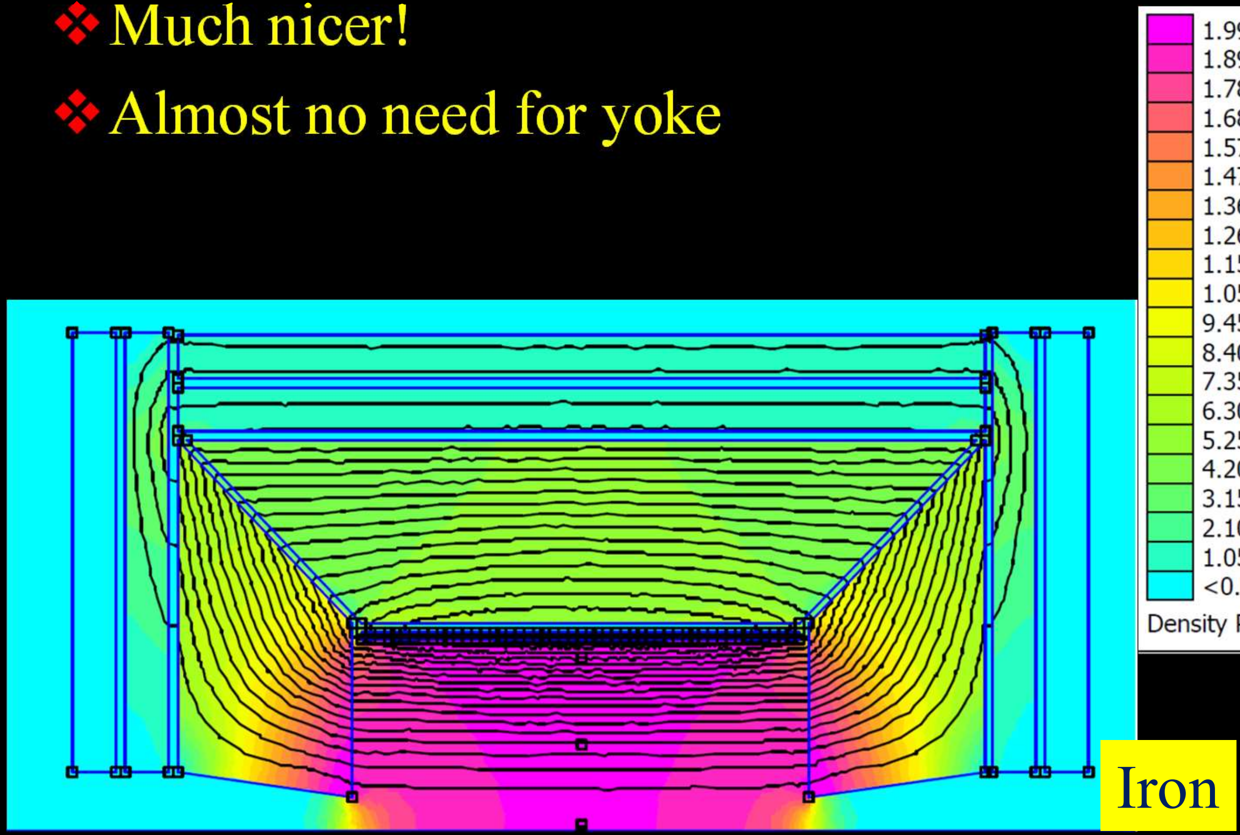




Copper

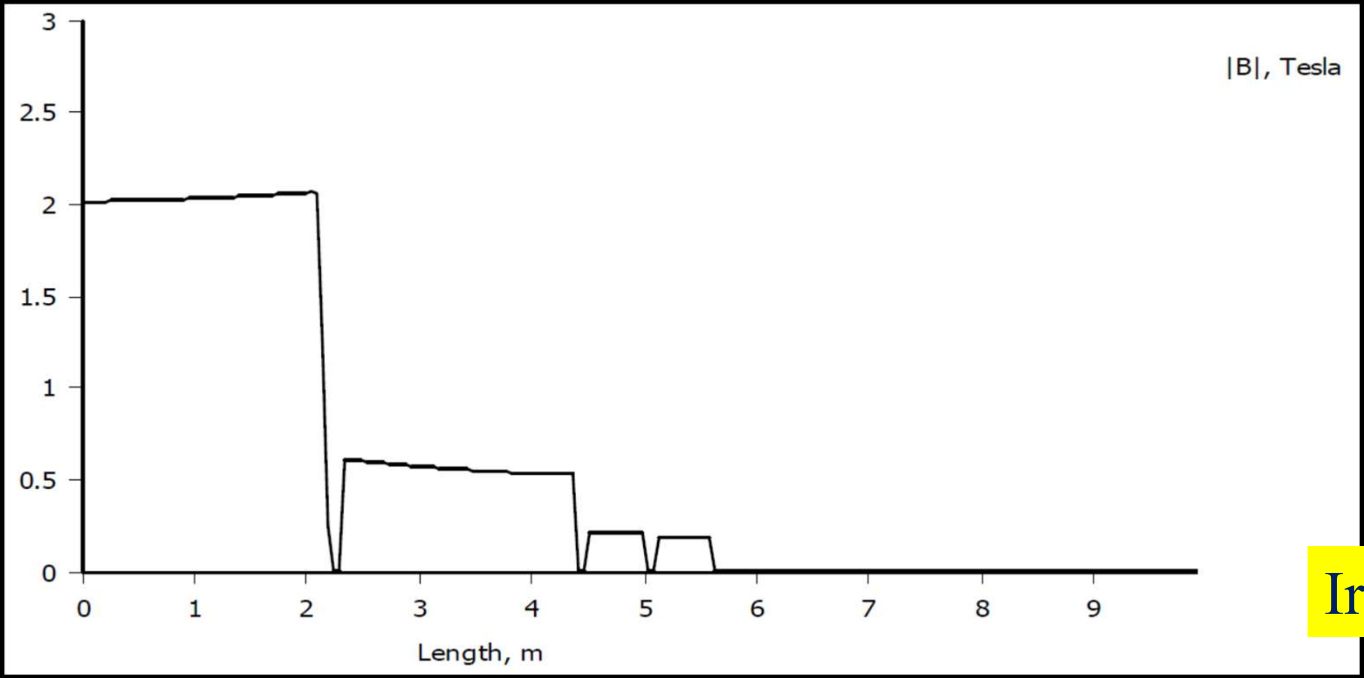
Iron calorimeter

- Much nicer!
- Almost no need for yoke



Iron calorimeter

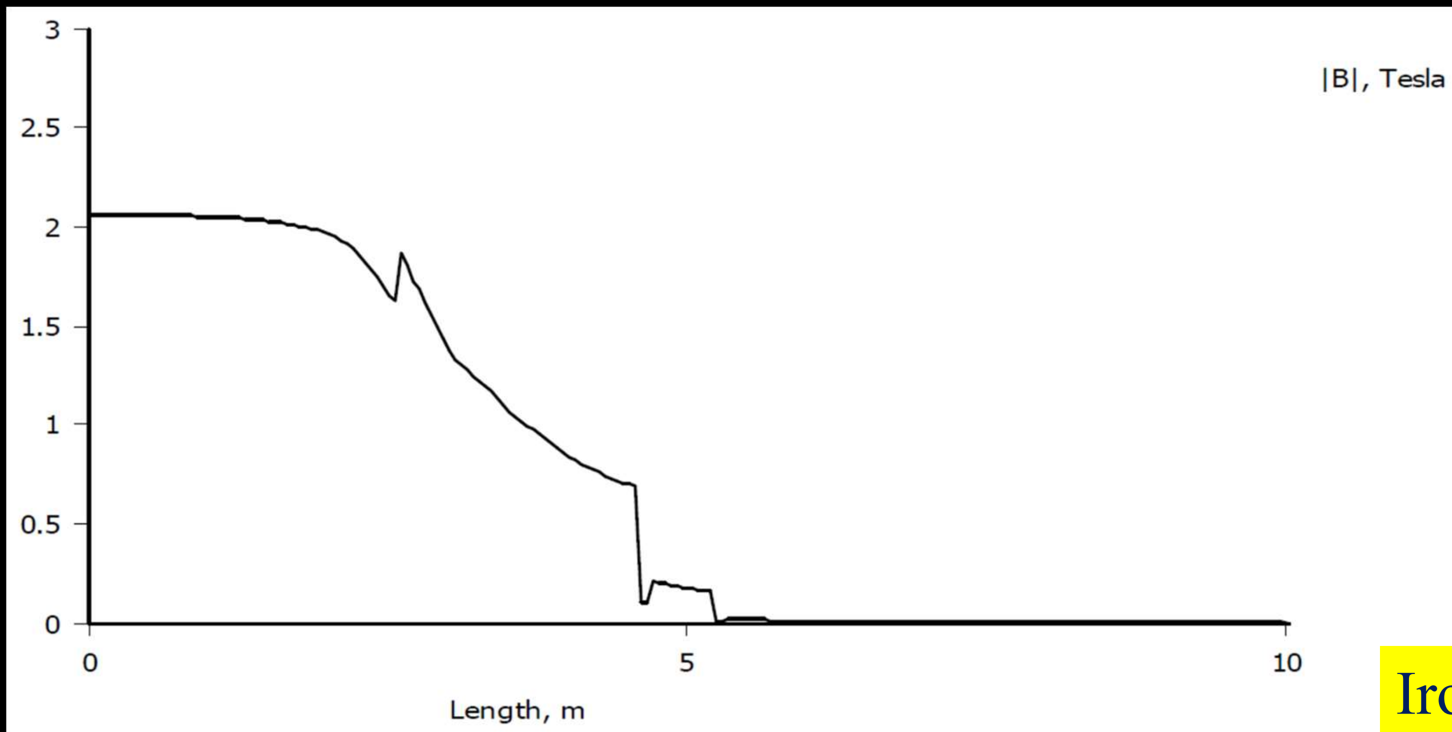
❖ B vs R from interaction point



Iron

Iron calorimeter

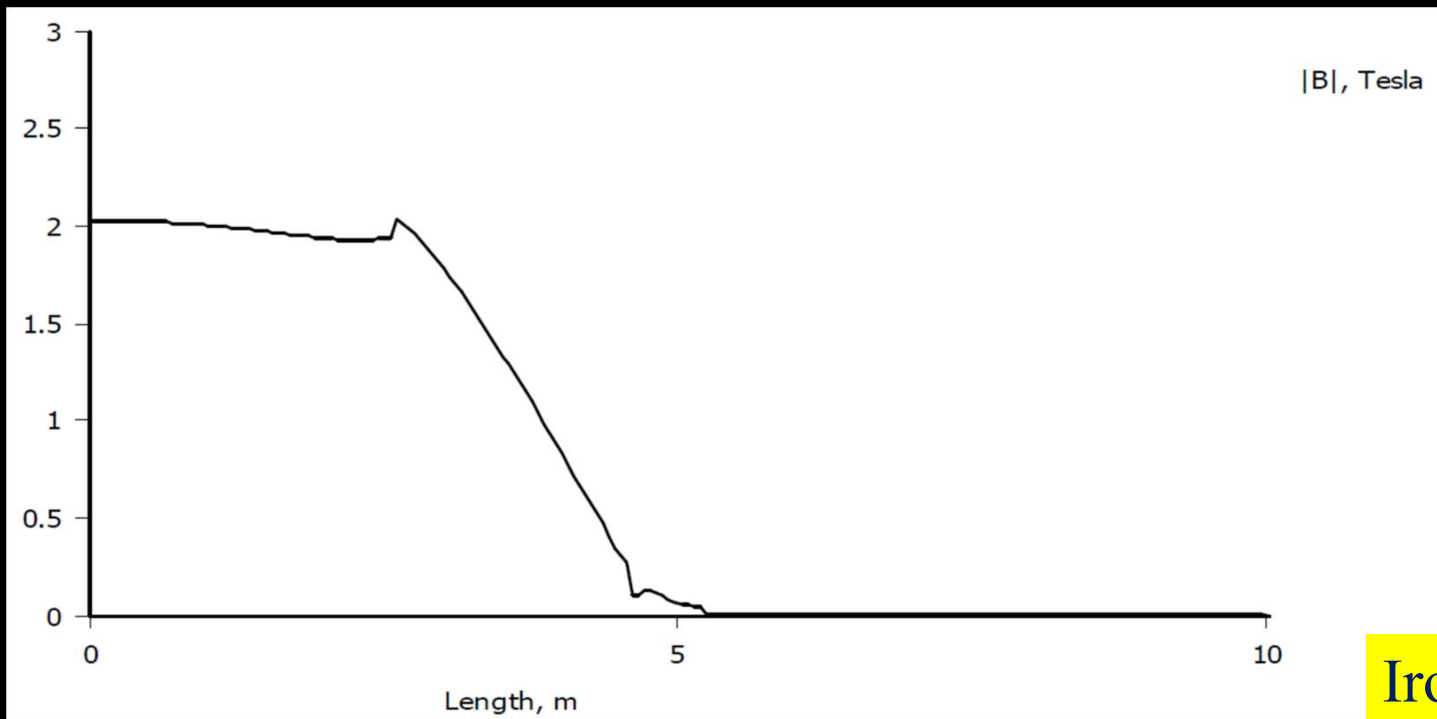
❖ R = 2 m – B vs z



Iron

Iron calorimeter

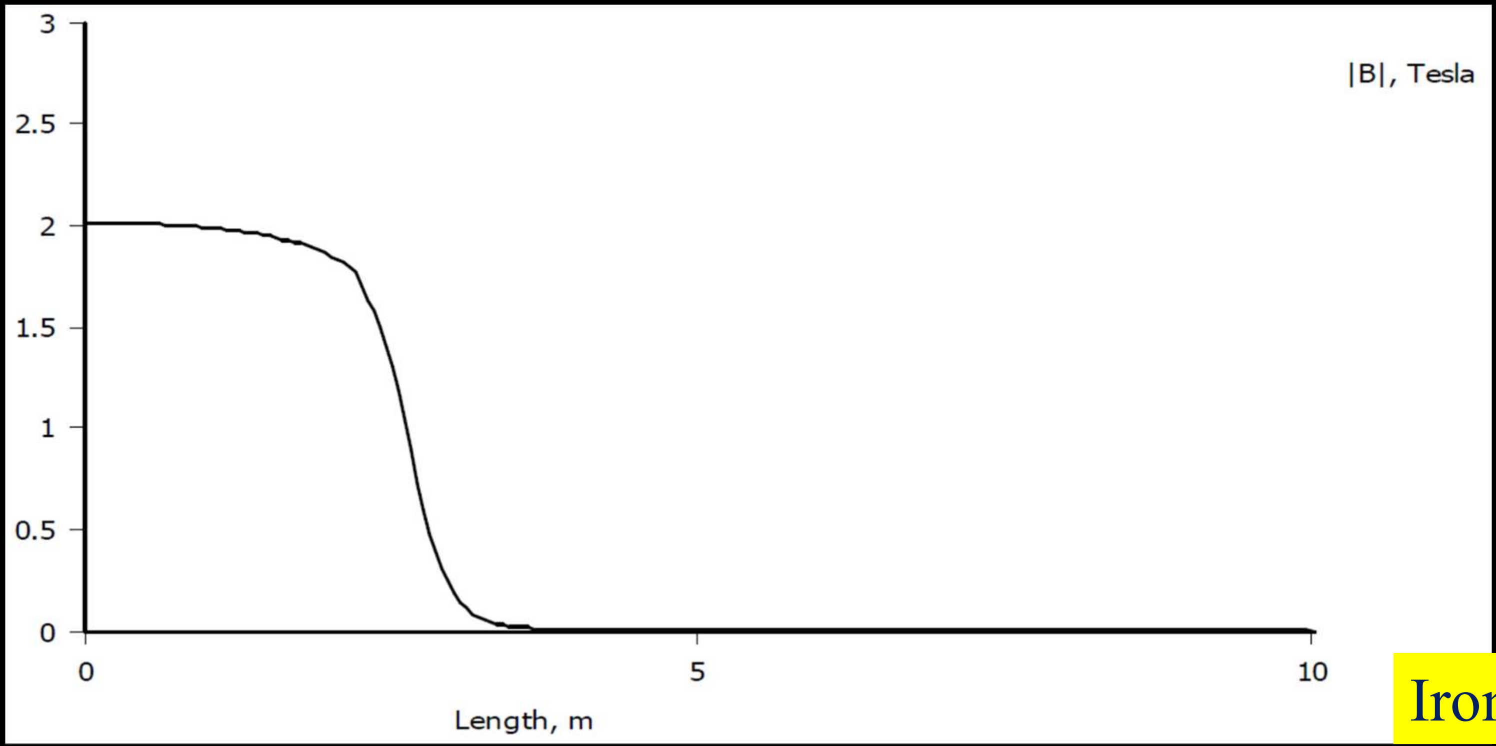
❖ R = 1 m – B vs z



Iron

Iron calorimeter

❖ R = 10 cm – B vs z



Iron