Future large circular colliders

14 May 2024

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INFN Bologna

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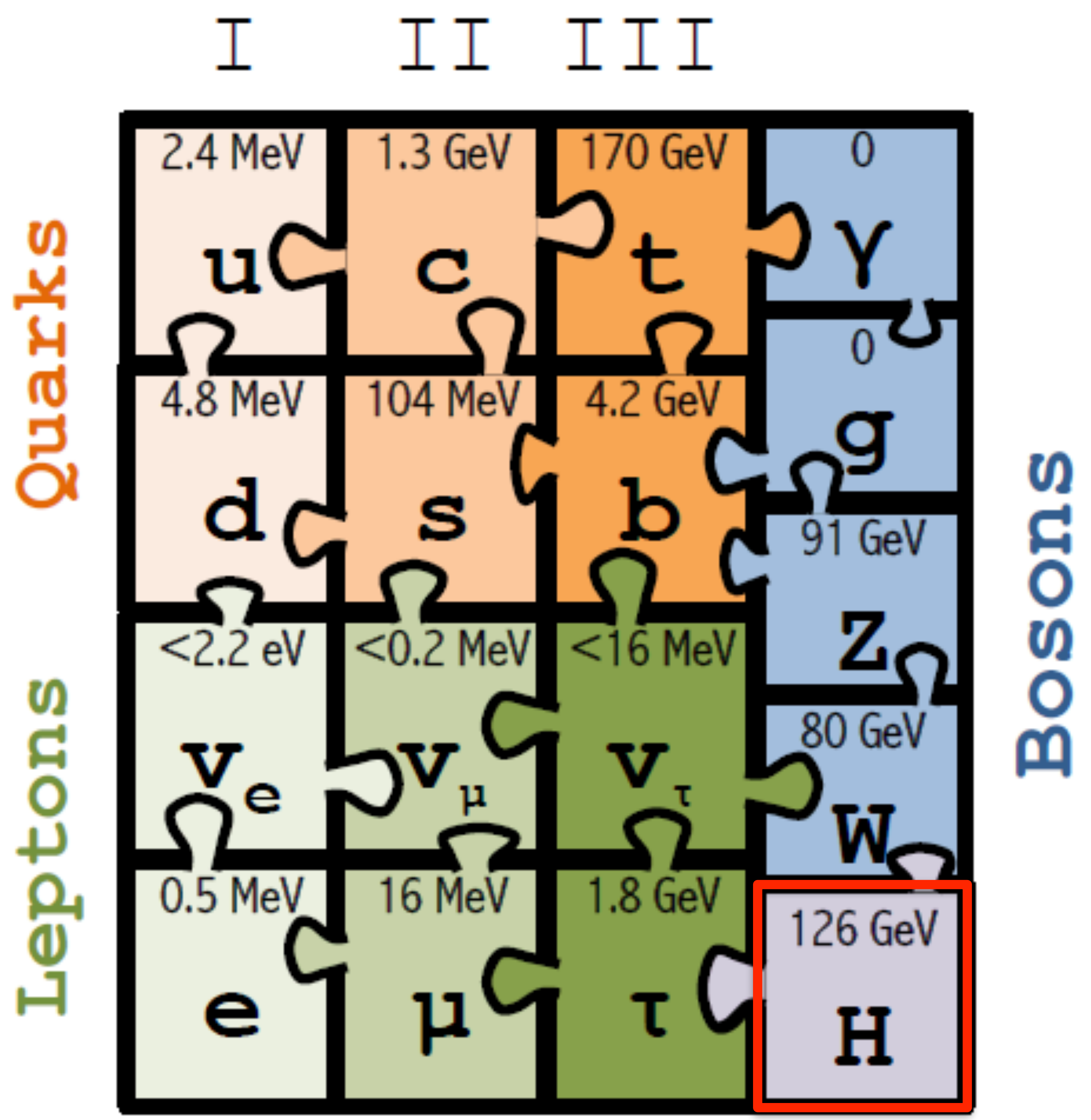
Outline

- **The physics landscape**
- **Why we need a new collider**
- **FCC-ee and CEPC**
- **Circular colliders vs. Linear colliders**
- **Physics performances**
- **Detector requirements**
- **A detector concept for an electron circular collider: IDEA**
- **Conclusions**

Disclaimer

To prepare these slides I used content from many friends and colleagues, whom I wholeheartedly wish to thank. Any mistake or misinterpretation is entirely my fault!

The Physics Landscape



P. Janot

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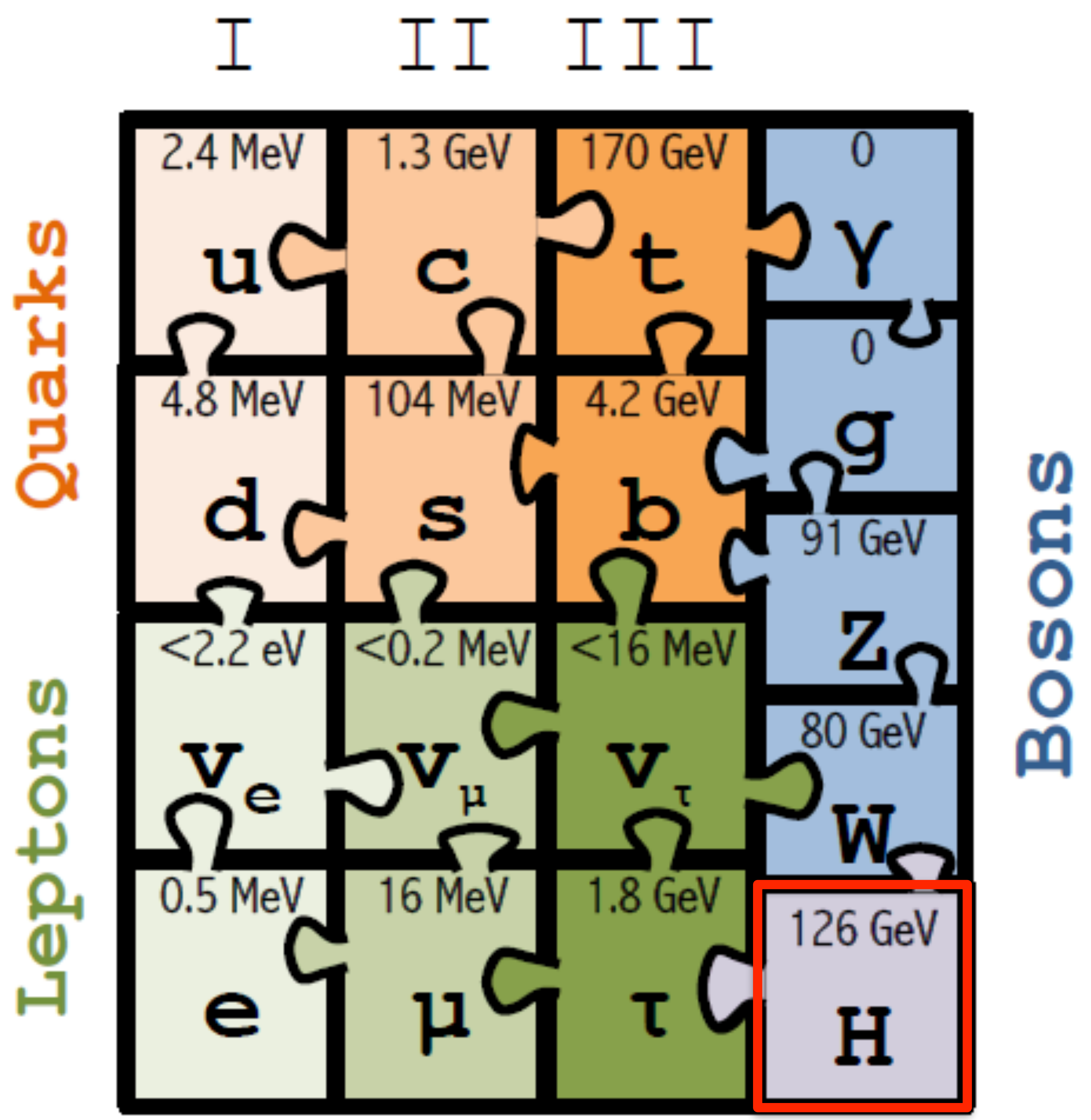

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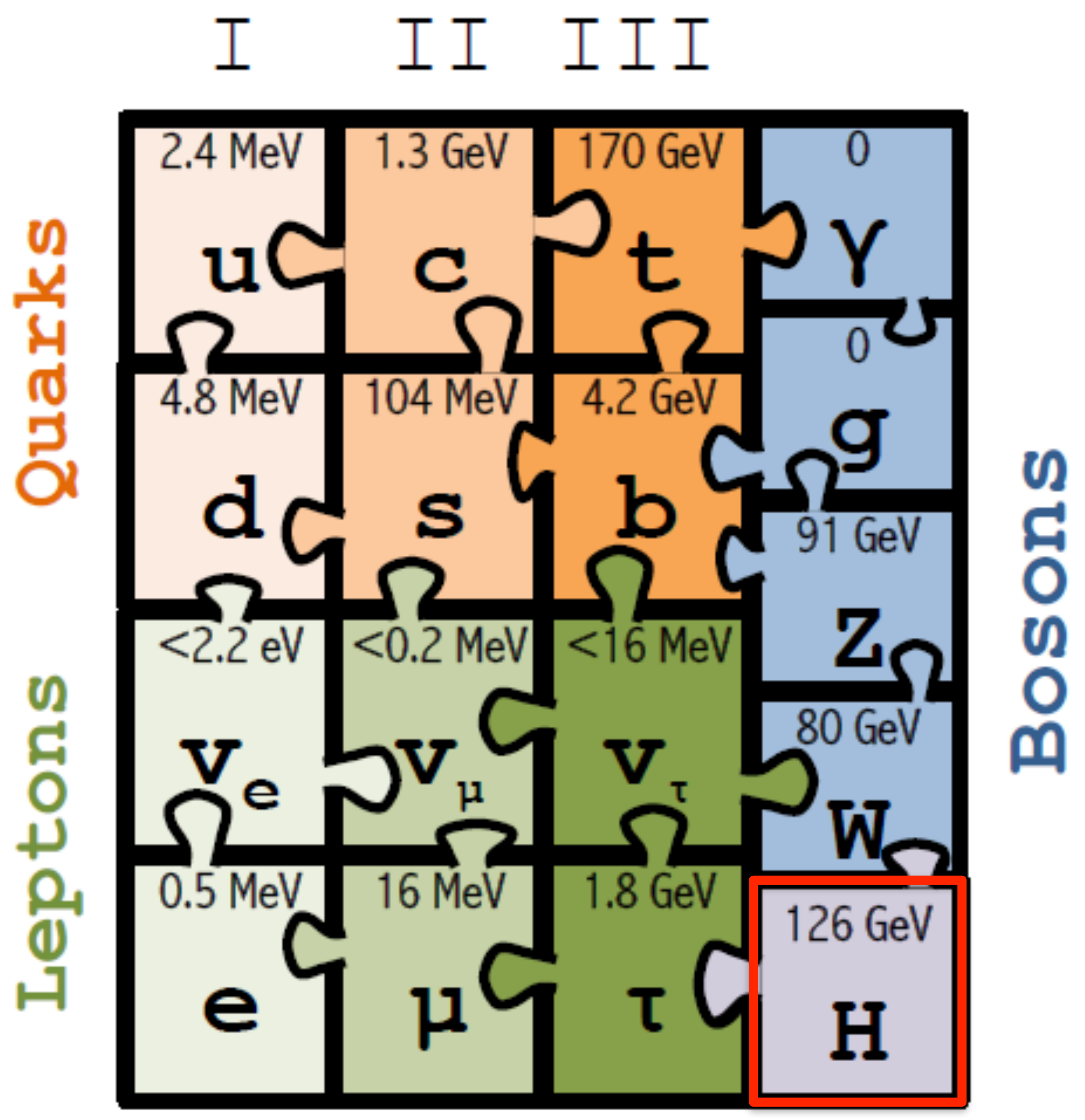

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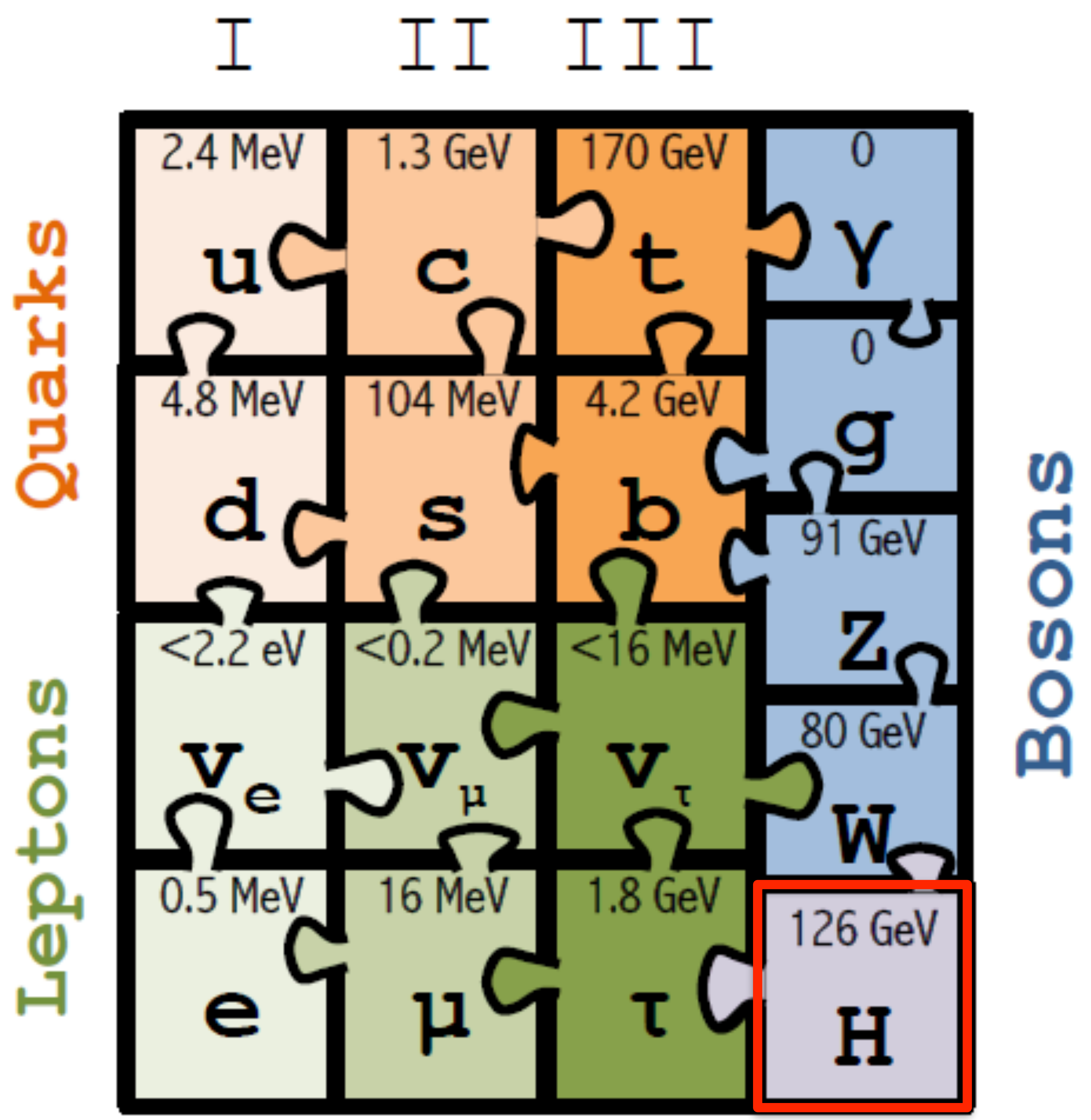

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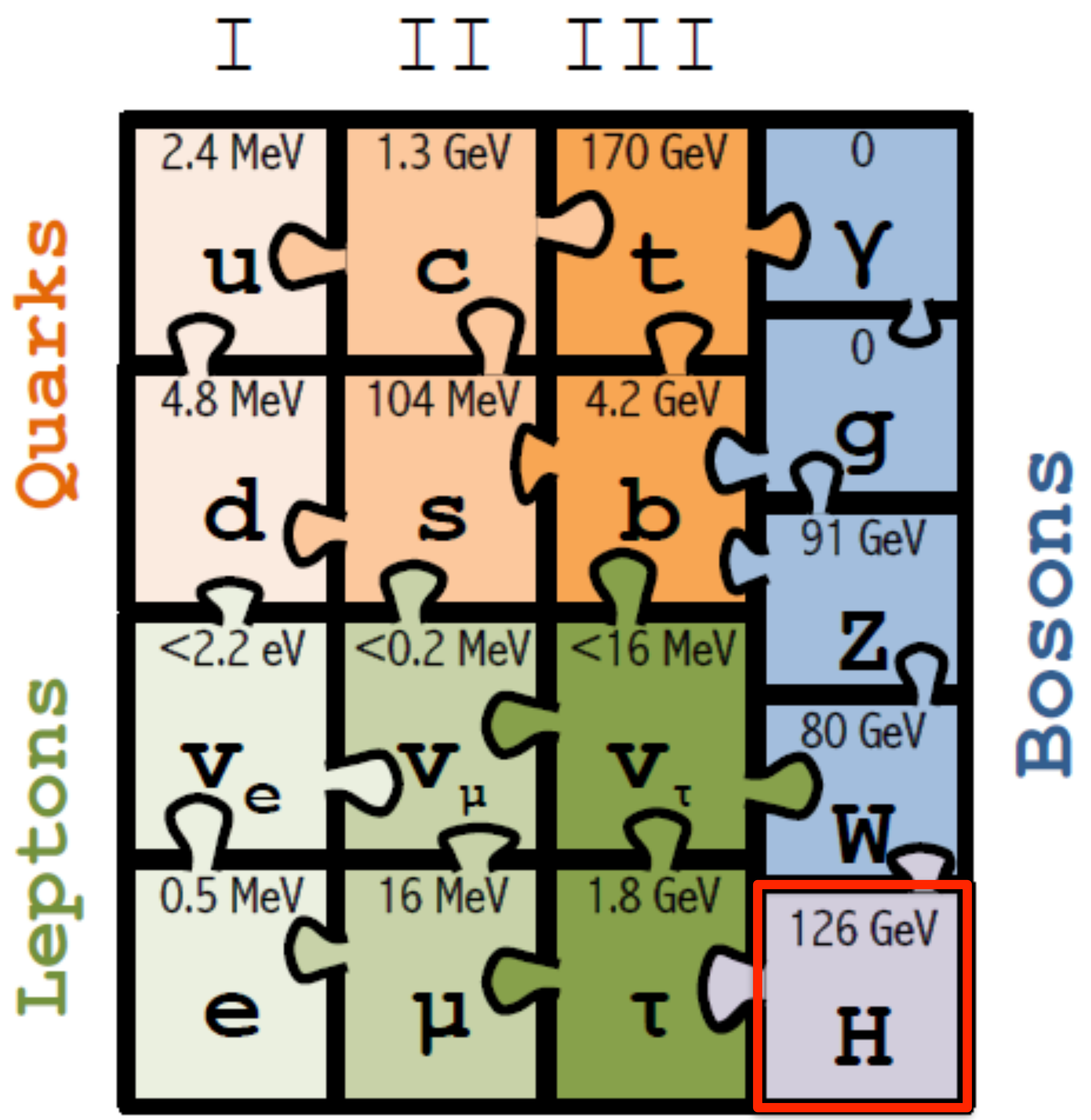

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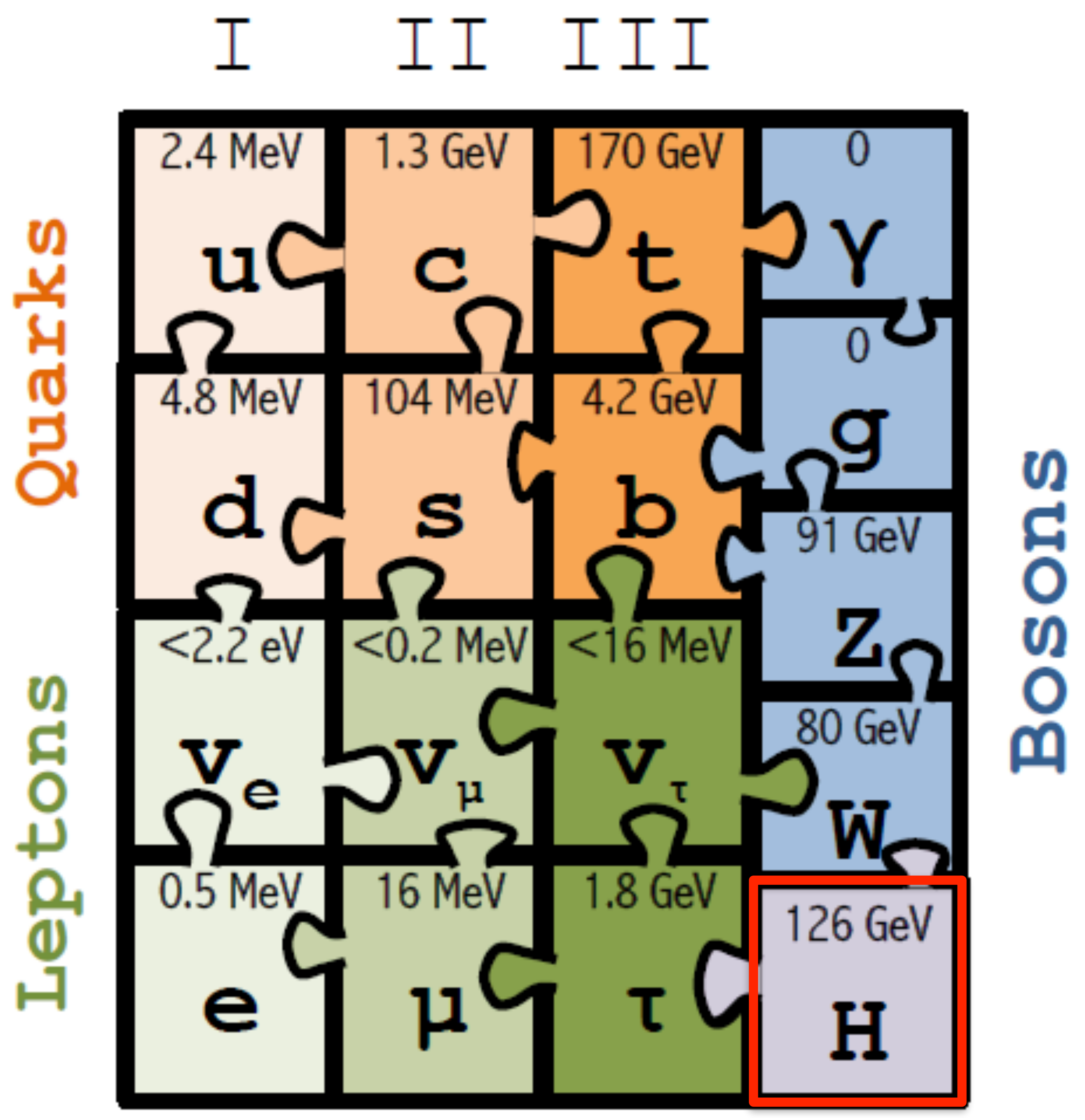

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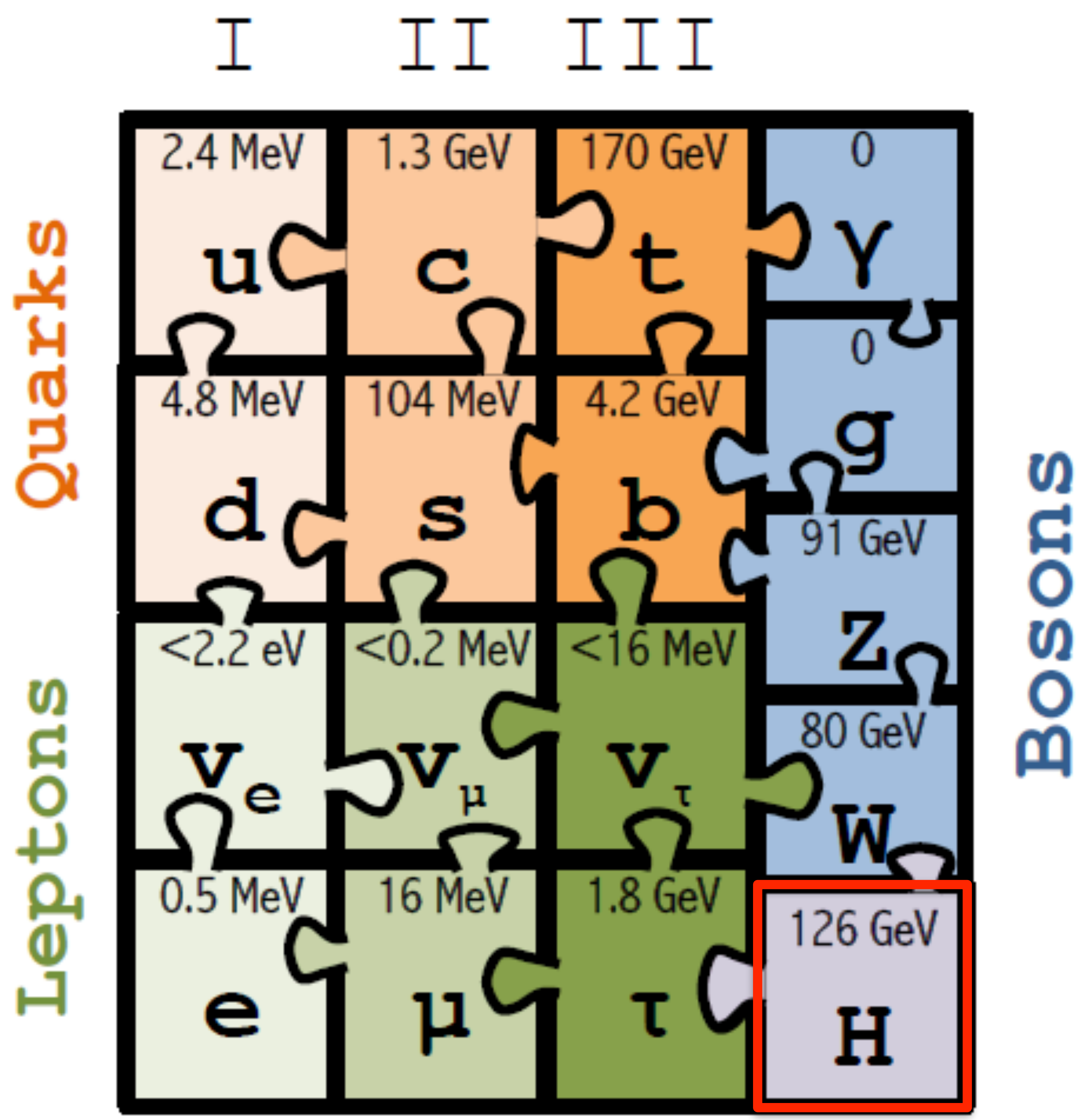

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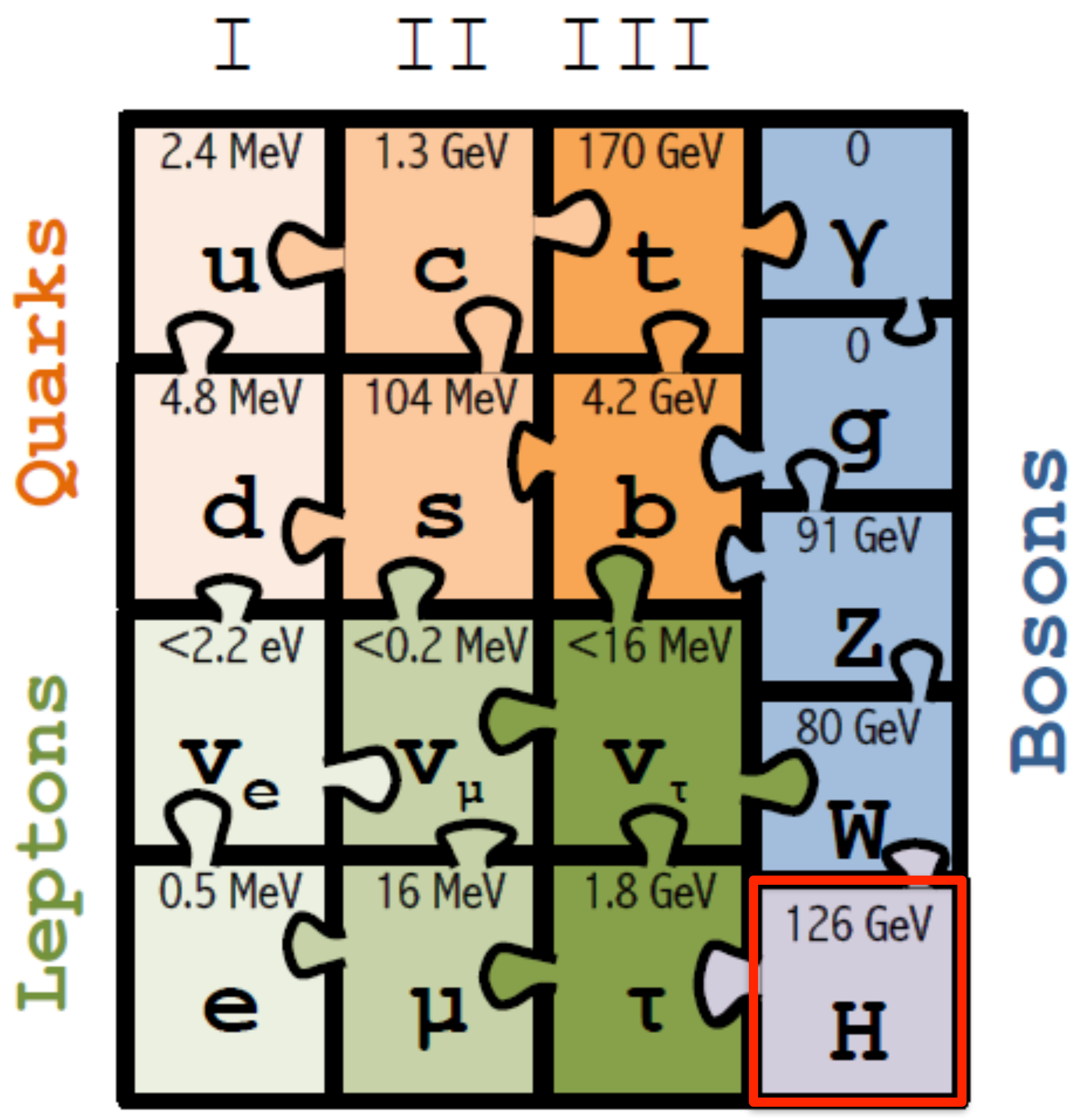

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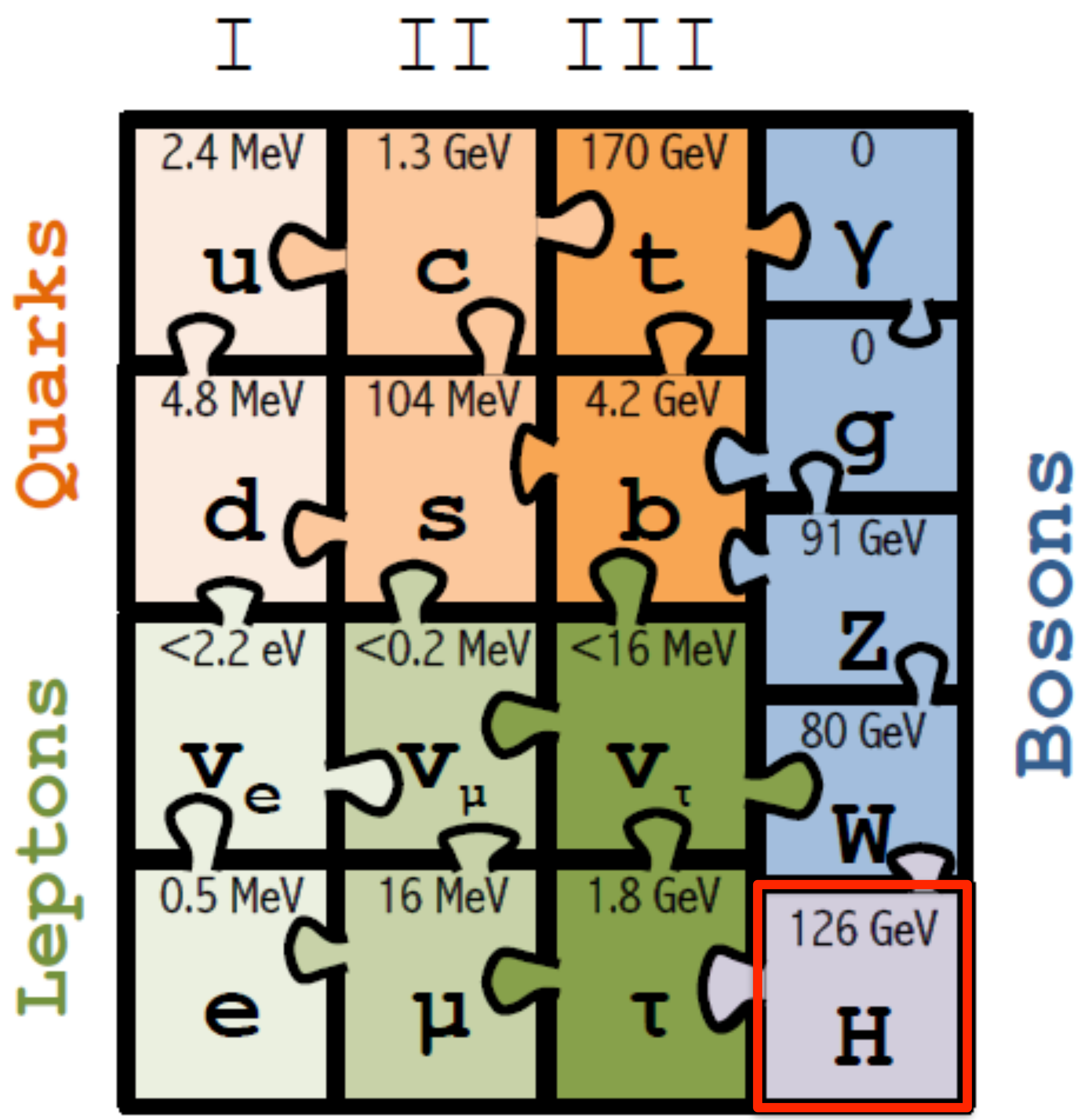

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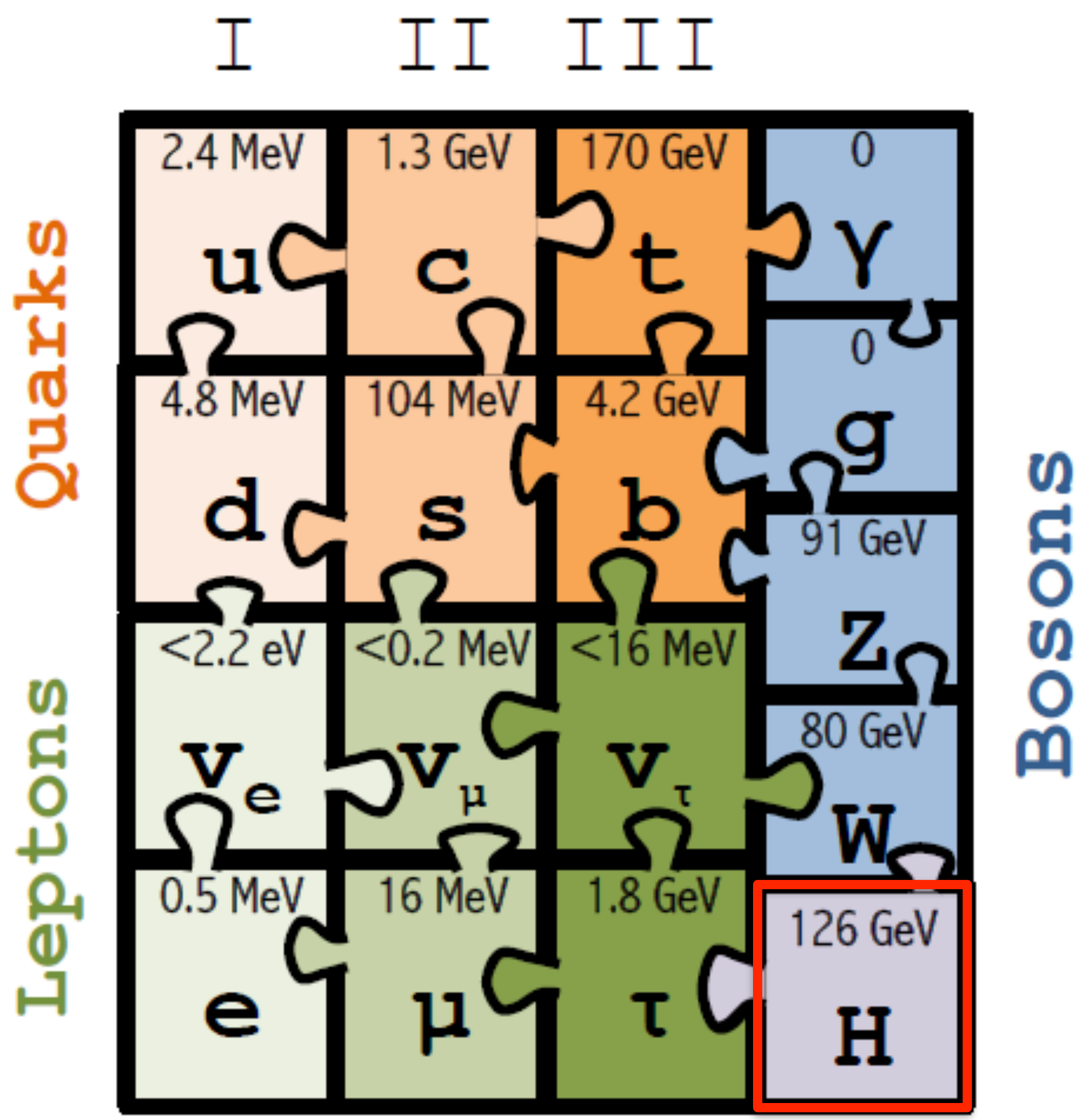

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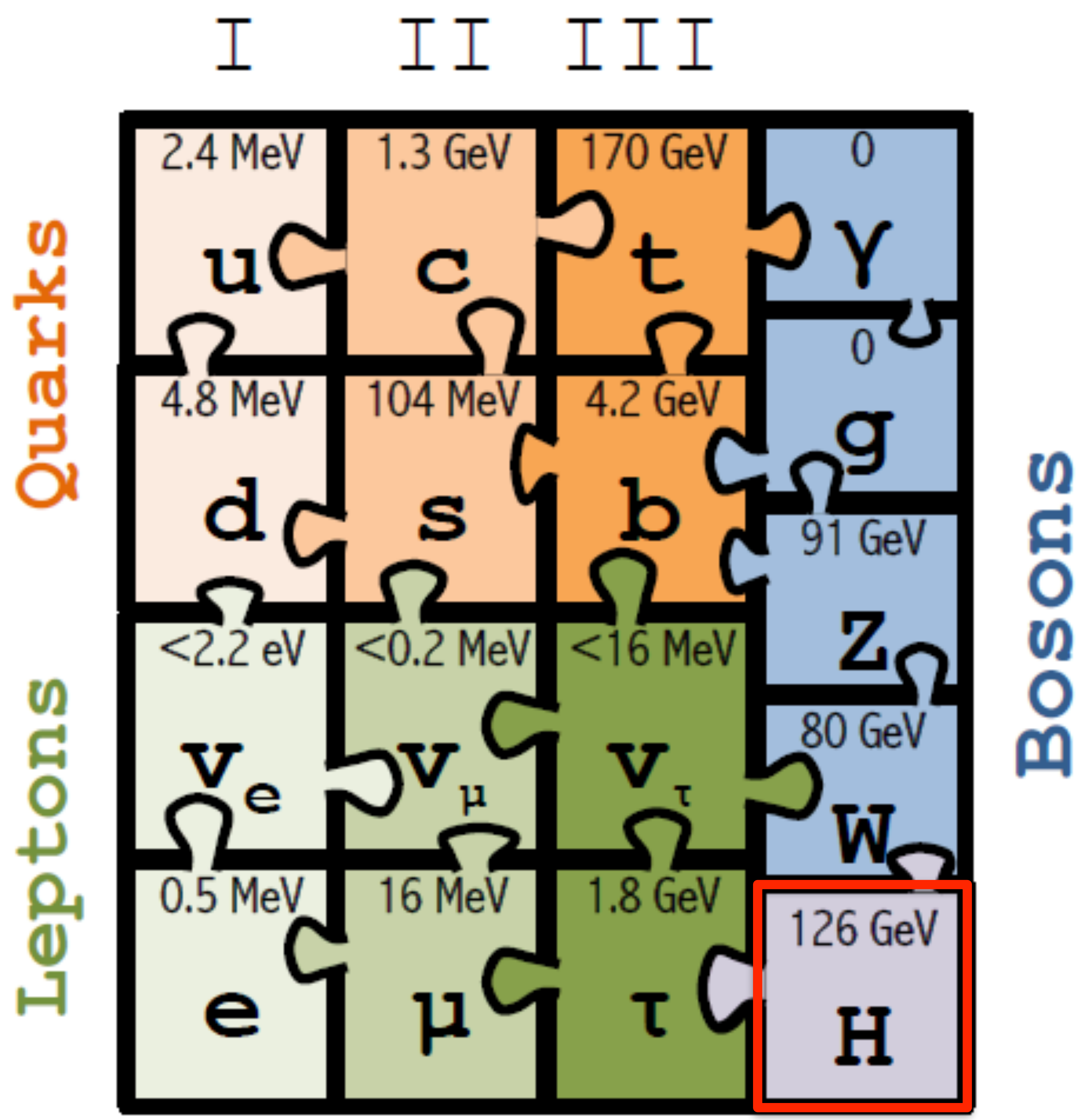

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- Hierarchy problem
- etc.

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The LHC legacy

- **Standard Model (SM) confirmed to high accuracy up to energies of several TeV**
  (thanks to a firm control of exp. & th. syst. uncertainties, the LHC became a precision machine)

- **Higgs boson discovered** at the mass predicted* by LEP precision EW measurements

  *within the Standard Model

- **Absence of new physics**
  - TeV-scale Naturalness might not explain DM/baryogenesis
  - Traditional New Physics models are under siege
  - New approaches: relaxion, Nnaturalness, clockwork…
  - Cosmology might settle the vacuum of the SM

We need a broad, versatile and ambitious programme that
1. sharpens our knowledge of already discovered physics
2. pushes the frontiers of the unknown at high and low scales

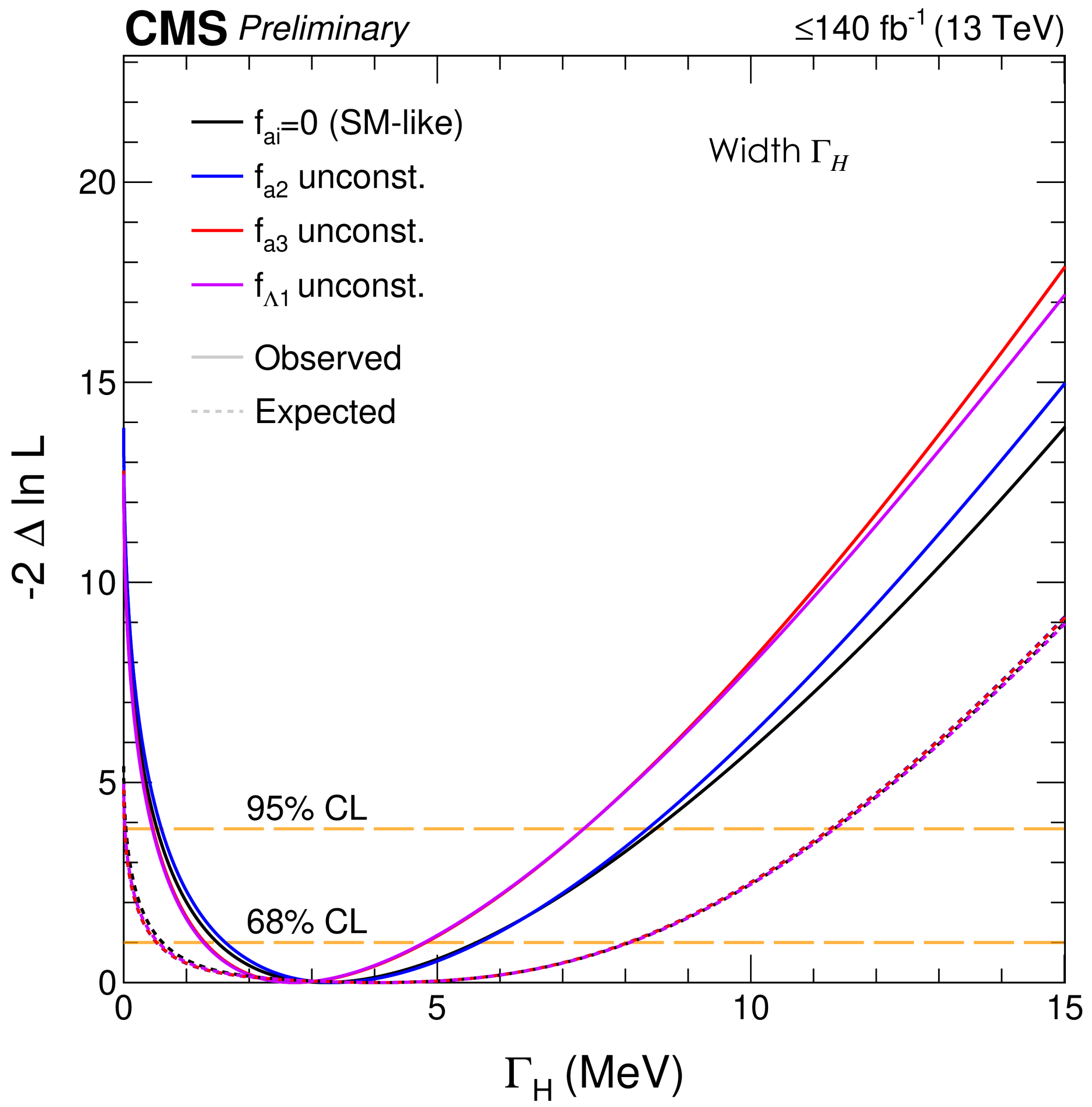
— together FCC-ee & FCC-hh combine these 2 aspects —

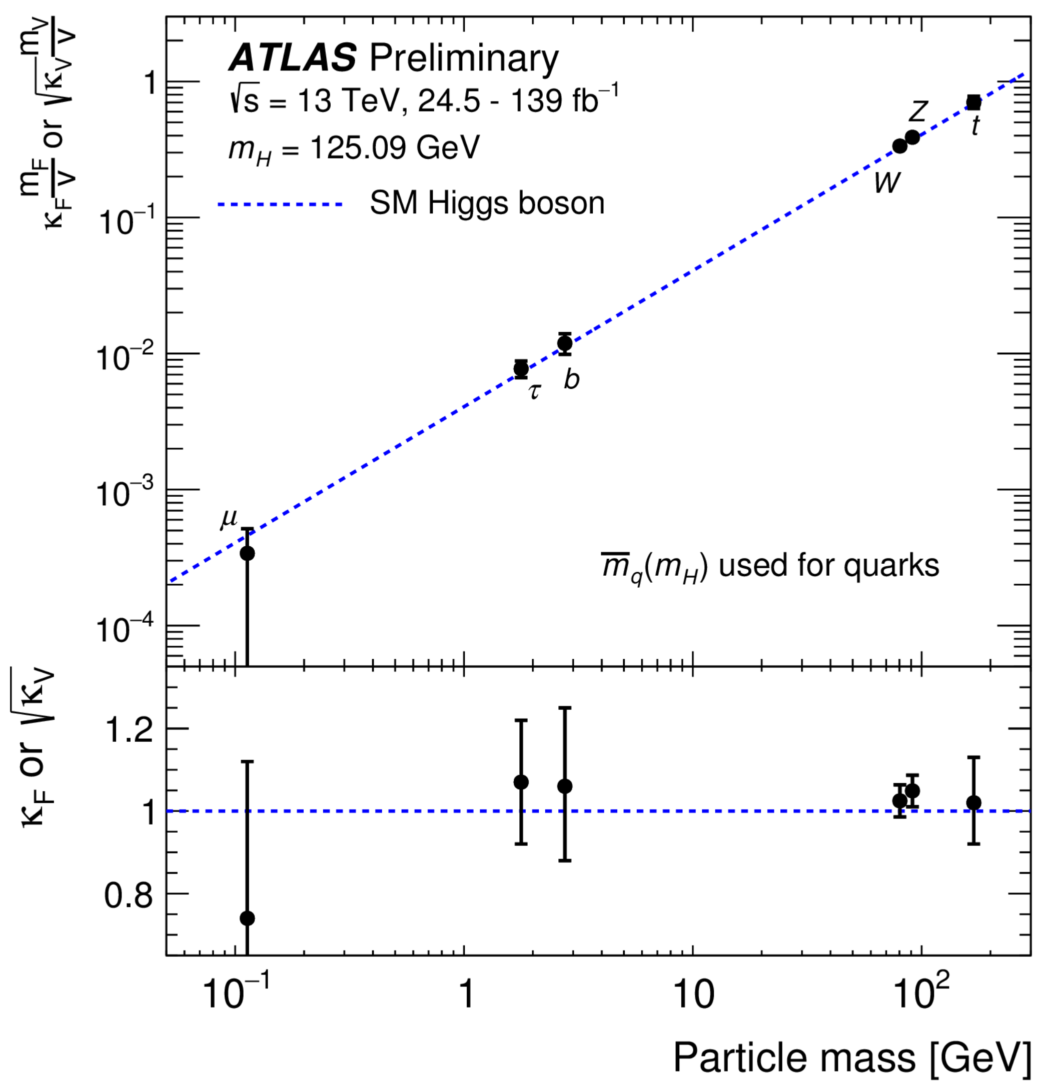
more PRECISION and more ENERGY, for more SENSITIVITY to New Physics

C. Grojean

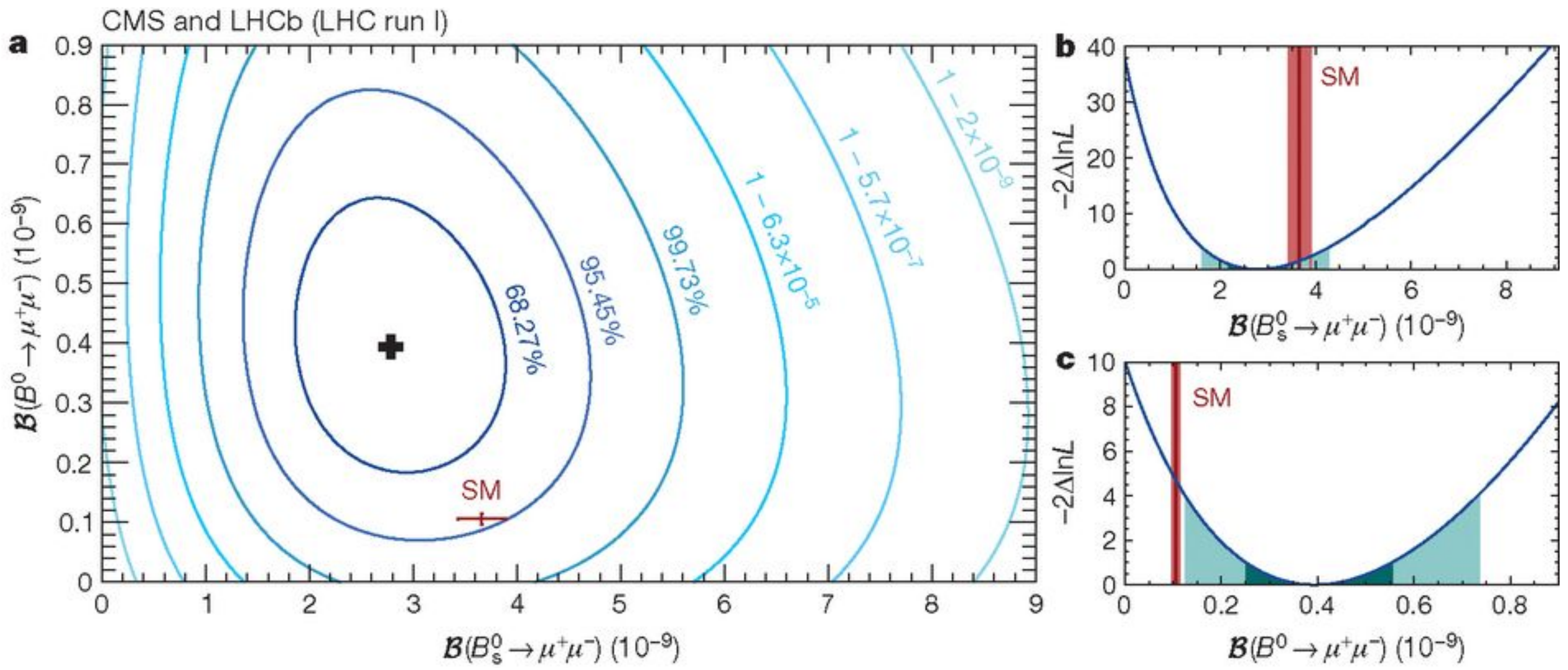
Where do we stand…

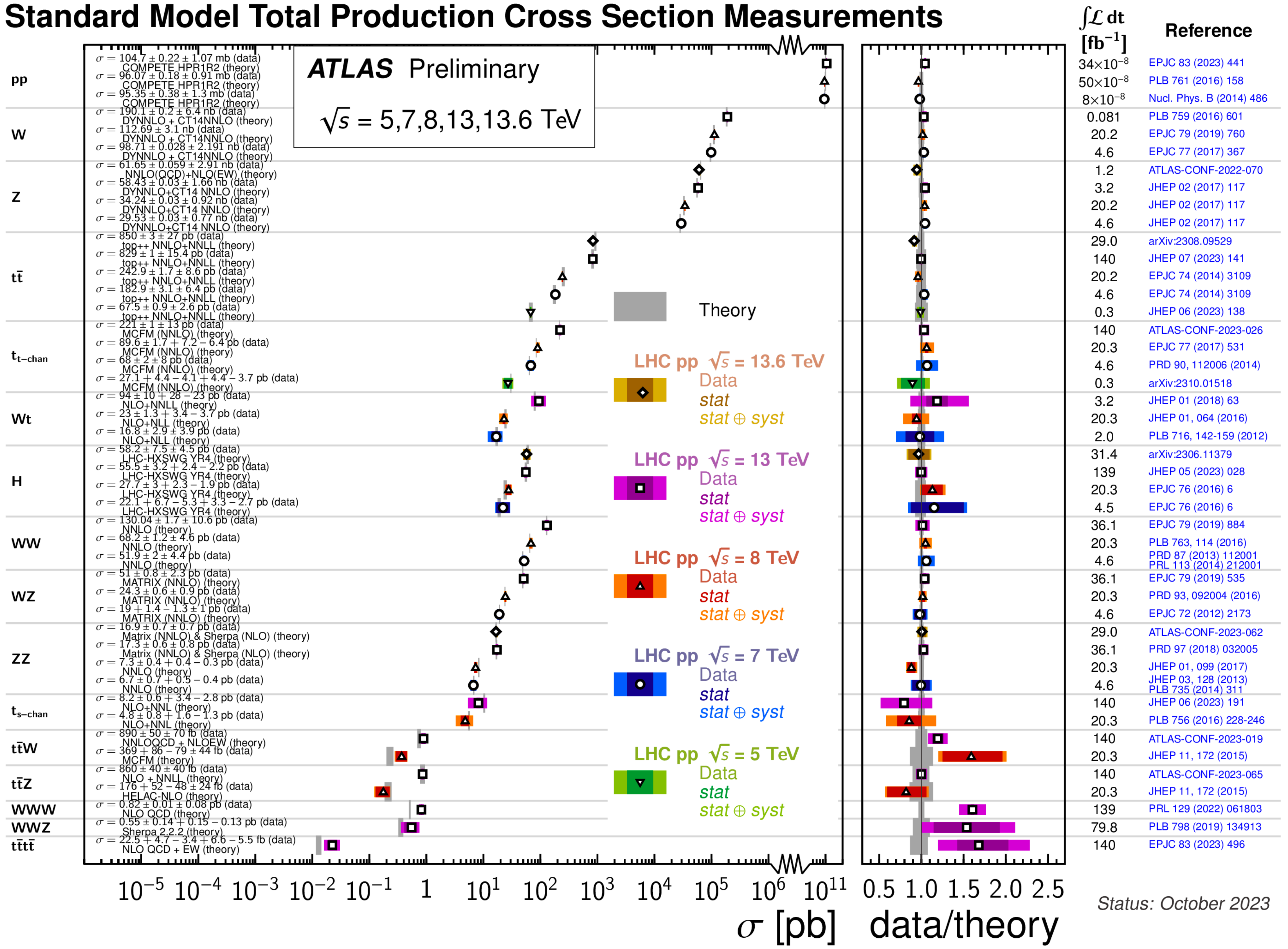
- The take-home message from the LHC so far: **this universe is very SM-like.**





No significant deviation from SM with 140 fb^{-1} of pp collisions (not promising for BSM at HL-LHC)





I. Vivarelli

Where do we go from here?

We are in an interesting situation

- No experimental hint to the origin of these observed phenomena
- No clear theoretical hint to indicate the best direction to go

We have no clear energy scale for new physics
We don't know its coupling strength to the SM particles

- **Next facility must be versatile**
  - With a reach as broad as possible

More Sensitivity, more Precision, more ENERGY

- A high precision, high intensity lepton collider, later followed by a high energy hadron collider offers the **best** solution

P. Janot

Precision as a discovery tool

Many historical examples

- Uranus anomalous trajectory ⇢ Neptune
- Mercury perihelion ⇢ General Relativity
- Z/W interactions to quarks and leptons ⇢ Higgs boson
- …

Sometimes, these discoveries were expected based on theoretical arguments
(e.g. Rayleigh-Jeans UV catastrophe for QM, unitarity breakdown for the Higgs)
but precision gave valuable additional clues.
In any case, experimentalists shouldn't lean too heavily on theorist priors/prejudices
(remember discovery of CP violation).
At times when we don't have a precise theoretical guidance that we need powerful experimental tools to make progress.

The FCC project offers unprecedented opportunities on many different fronts.
No LHC/SSC-like **no-lose theorem** but a **promise** of making significant steps forward in our understanding of the fundamental laws of Nature.

The Standard Model structure has seemingly "accidental" aspects (e.g. B, L number conservations) that should be probed to form a deeper understanding of Nature.

C. Grojean

The FCC Feasibility Study

"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."

— CERN council approved the Strategy and CERN management implemented it —

FCC Feasibility Study (FS) started in 2021 and will be completed in 2025.

Mid-term review in 2023.

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The physics we need

INFN Istituto Nazionale di Fisica Nucleare

Precision SM

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

BSM direct searches

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

Higgs physics

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

Flavour Physics

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

Top physics

$m_{\rm top}$, $\Gamma_{\rm top}$, EW top couplings

C. Grojean

The physics we need

EW factory (Z,WW)

Precision SM

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Top

Top physics

m_{top}, Γ_{top}, EW top couplings

C. Grojean

the Higgs requires more precision

(HL)-LHC will make remarkable progress.
But it won't be enough.
A new collider is needed!

The knowledge of the values of the **Higgs couplings** is essential to understand the deep structure of matter/Universe:

$m_W, m_Z \leftrightarrow$ Higgs couplings ✓

lifetime of stars
(why $t_{Sun} \sim t_{life\ evolution}$?)

$m_e, m_u, m_d \leftrightarrow$ Higgs couplings ?

size of atoms   nuclei stability

EWSB @ $t \sim 10^{-10}$s $\leftrightarrow$? Higgs self-coupling(s)
Higgs(es) potential

matter/anti-matter $\leftrightarrow$? CPV in Higgs sector

FCC integrated program

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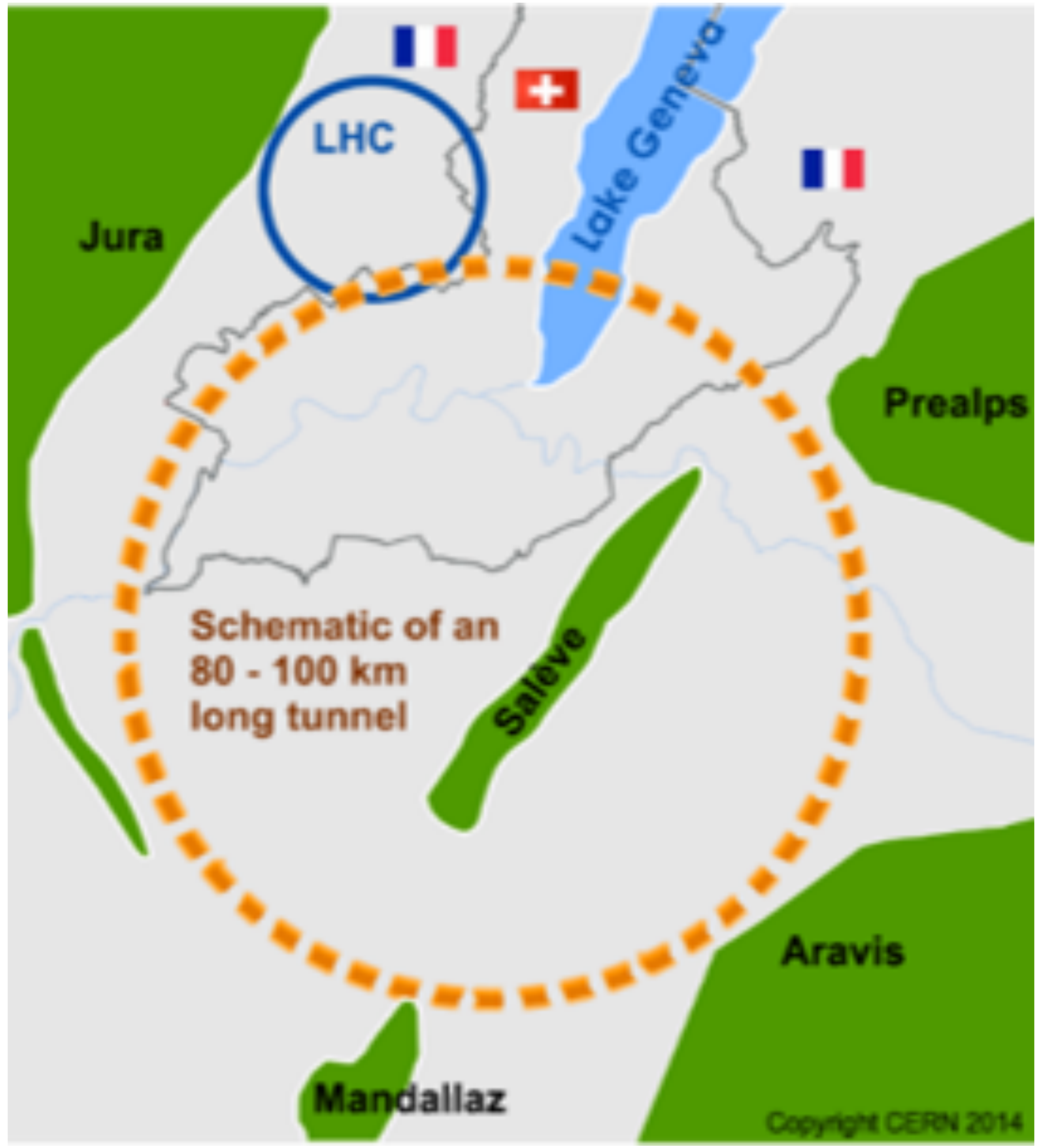
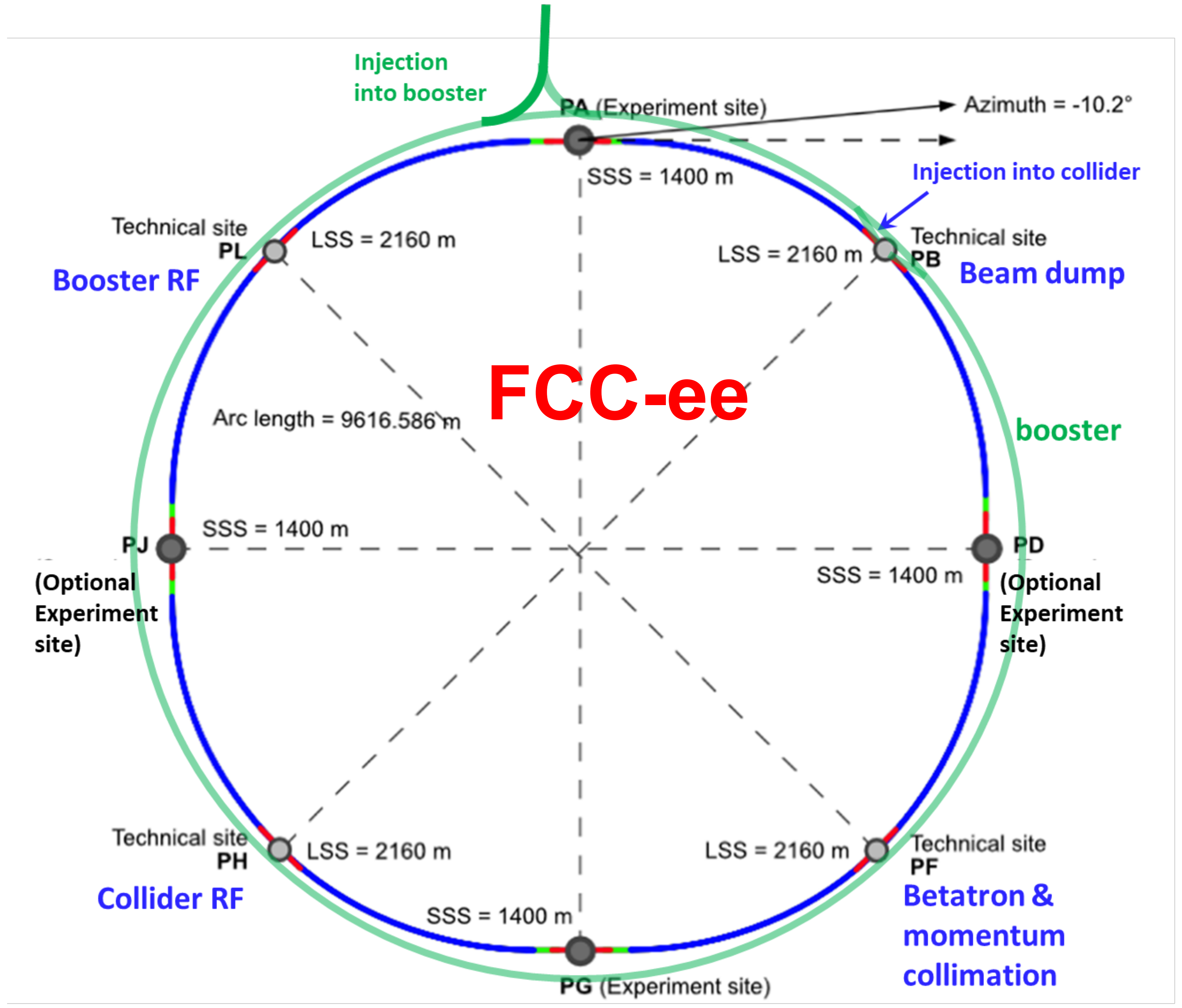
comprehensive long-term program maximizing physics opportunities

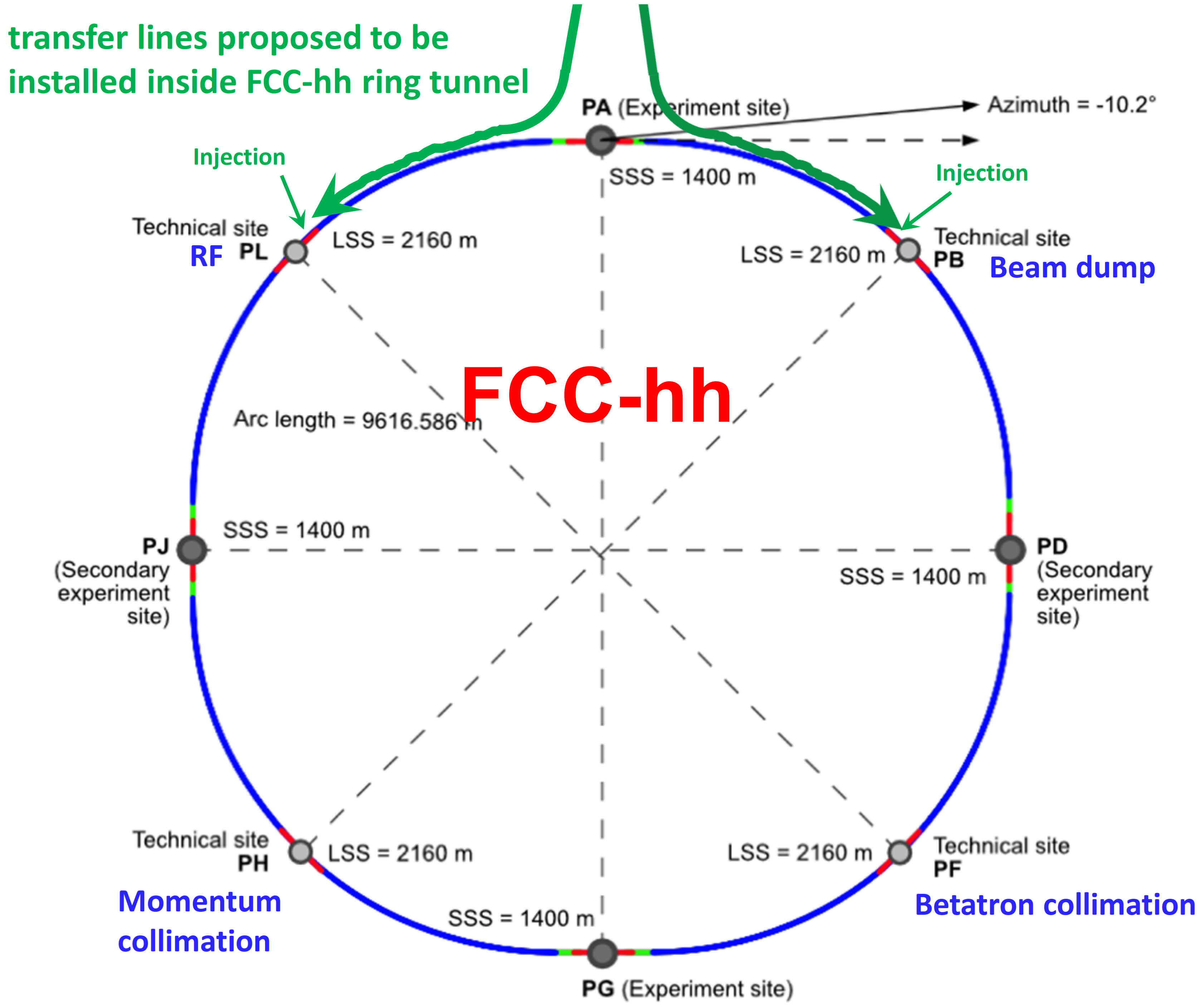
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at the highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



2020 - 2040



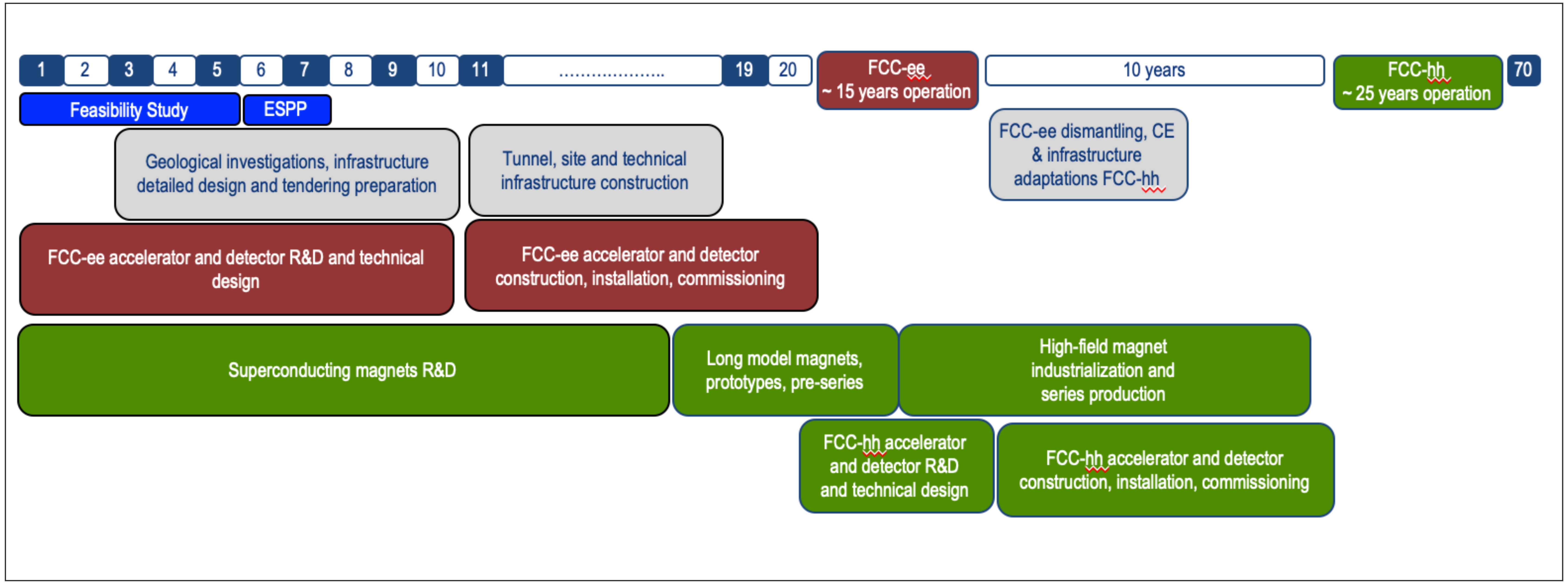
2045 - 2063



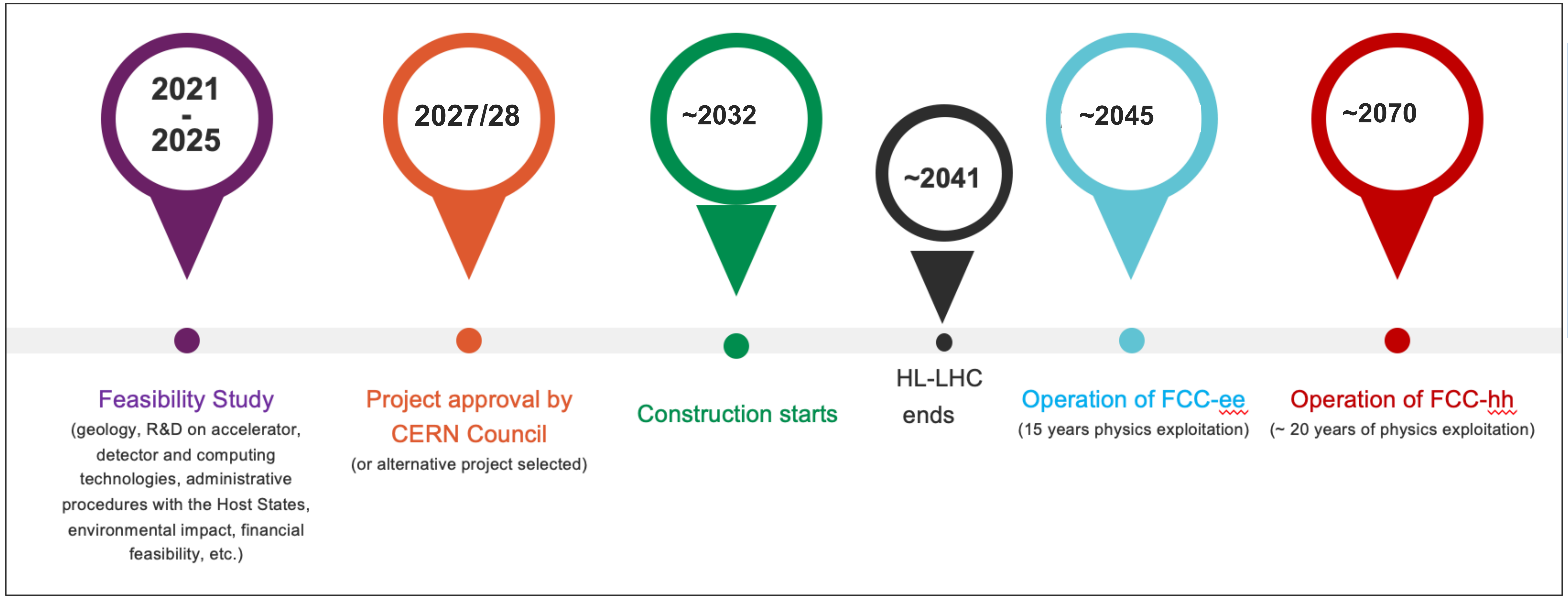
2070 - 2095

M.Benedikt

FCC integrated timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018



Ambitious schedule taking into account:

- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041
- **project preparatory phase with adequate resources immediately after Feasibility Study**

M. Benedikt

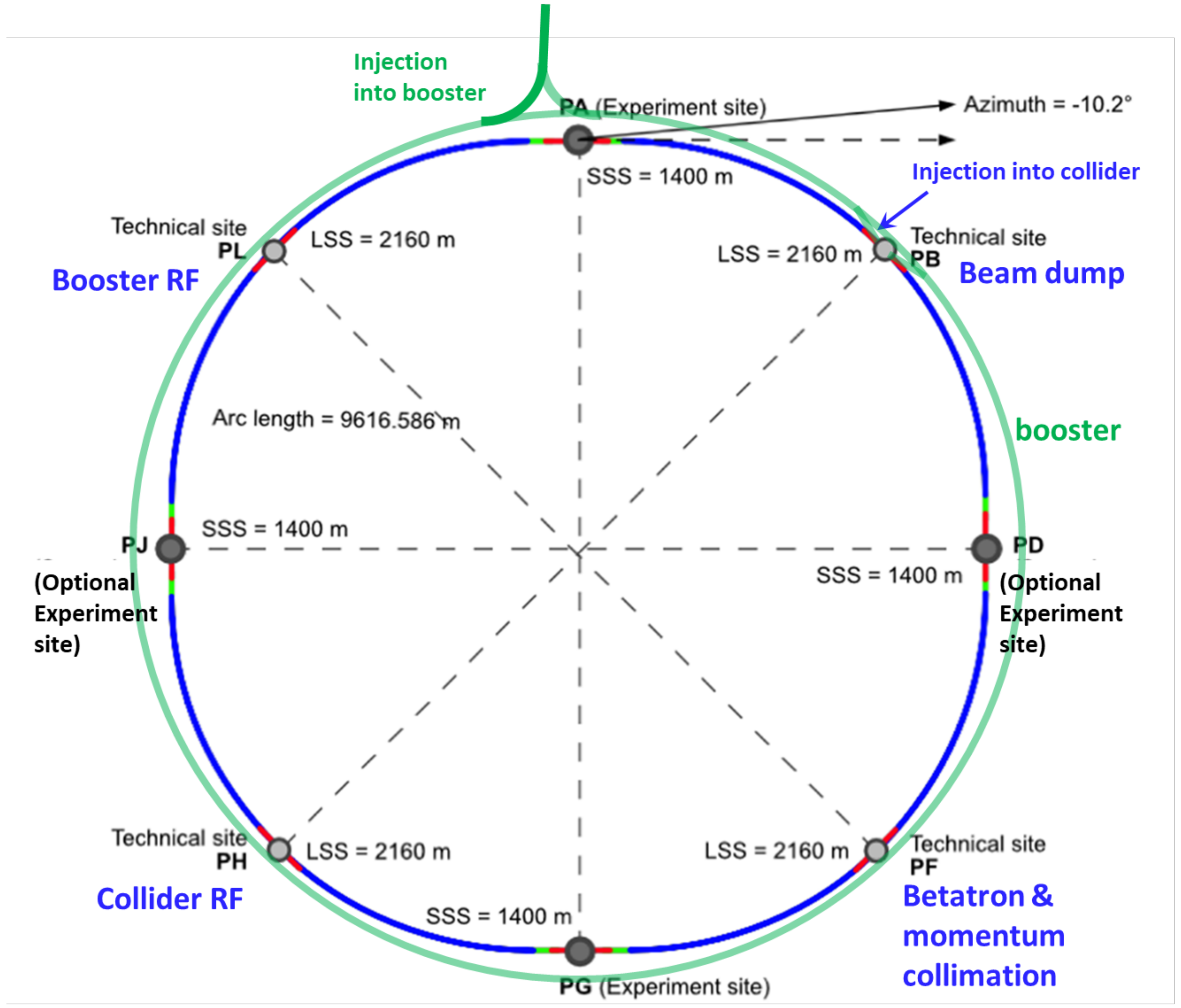
FCC placement

V. Mertens,
J. Gutleber

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce-compensate” principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement



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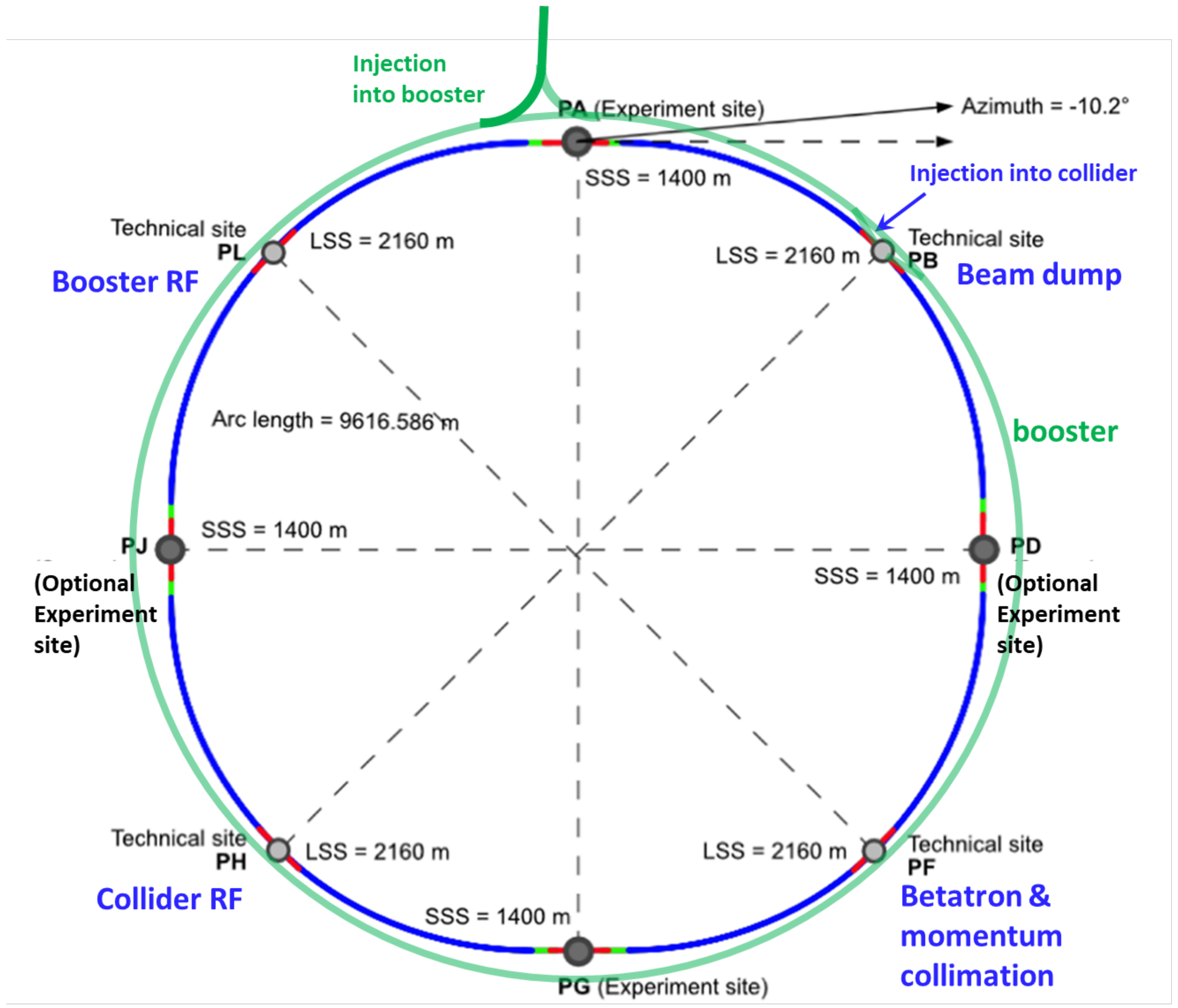

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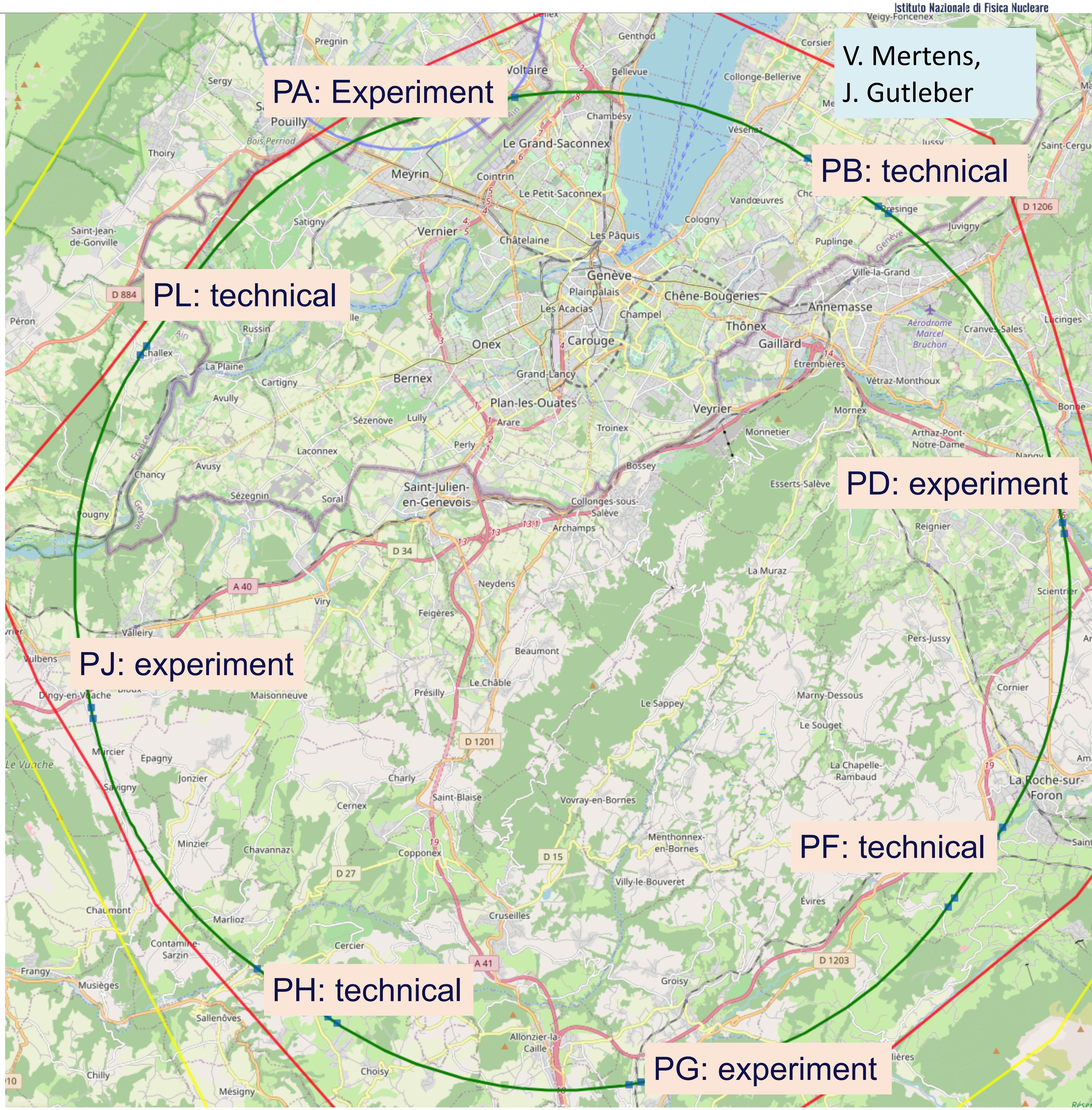

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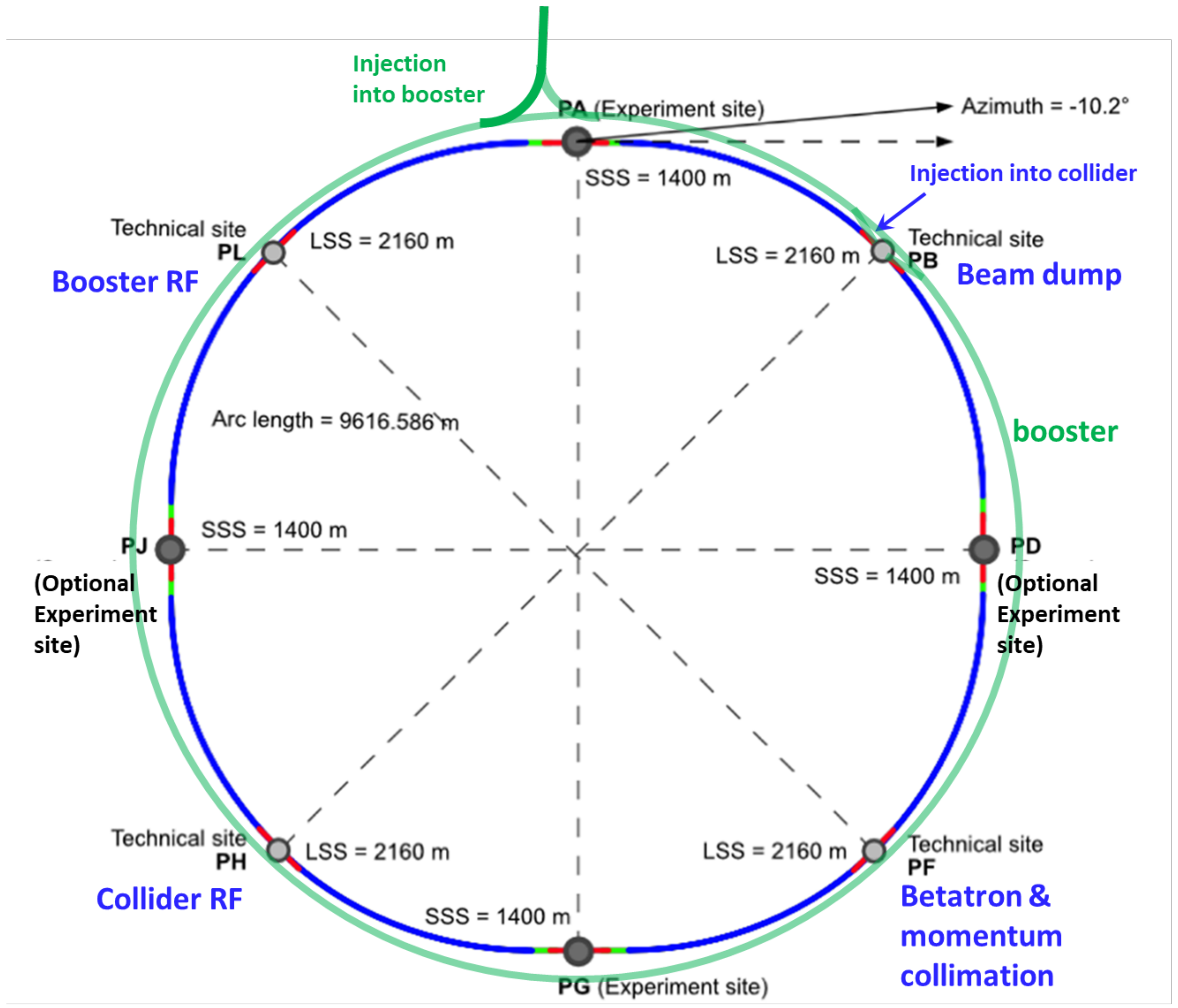

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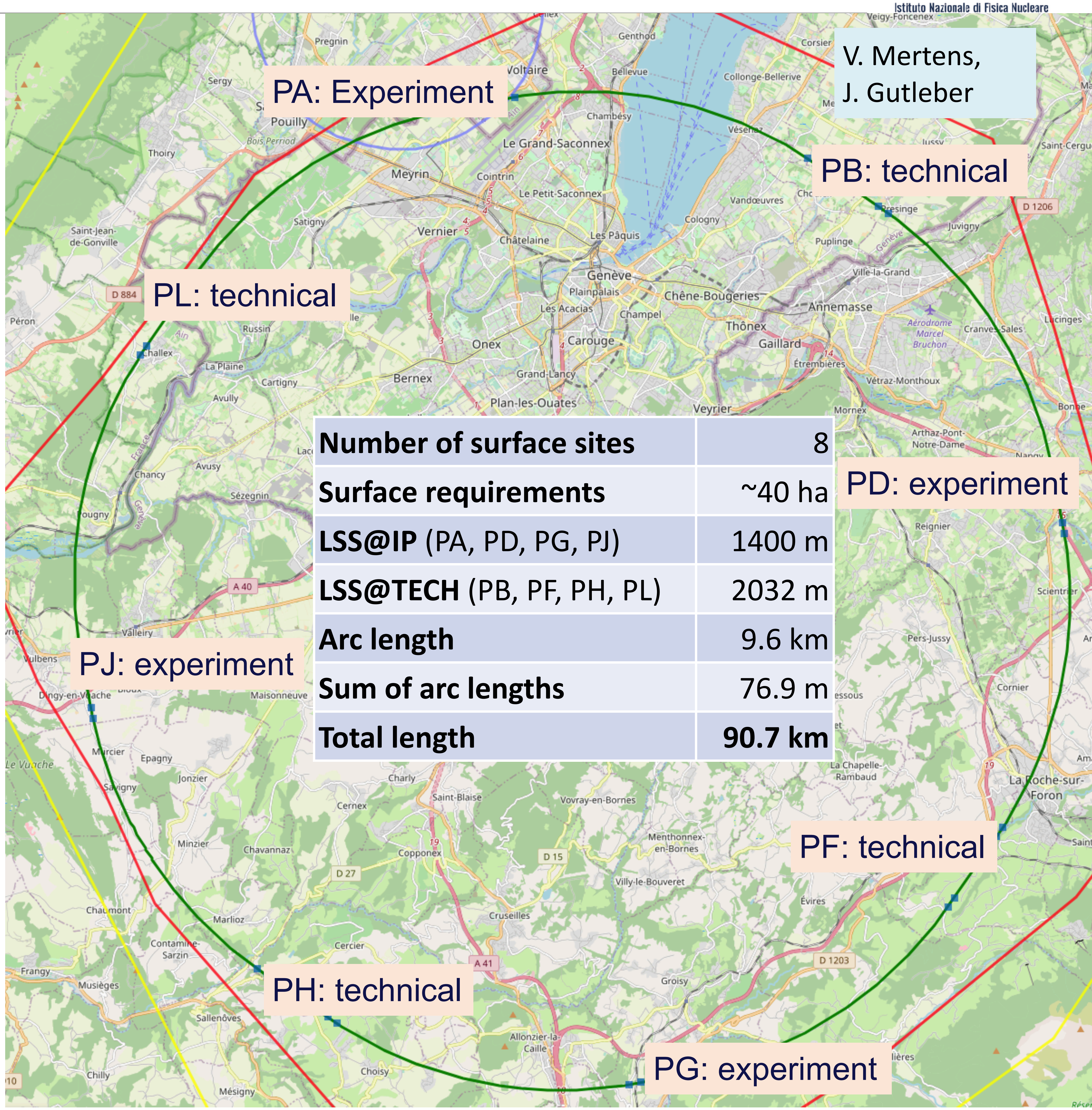

Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

OpenSky laboratory: demonstrate molasse reuse

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GOAL: demonstrate the feasibility to transform Molasse (excavated material) into fertile soil.

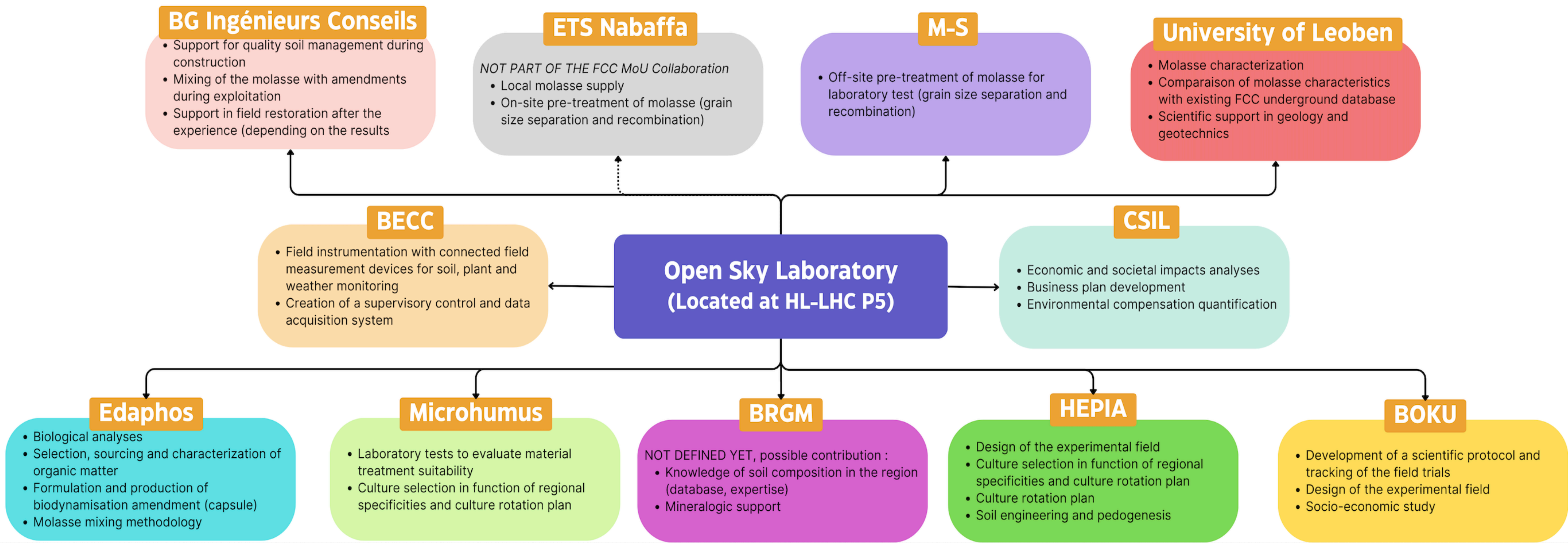
- **Project launched in January 2024**
- **10000 m² near LHC P5 in Cessy, France.**

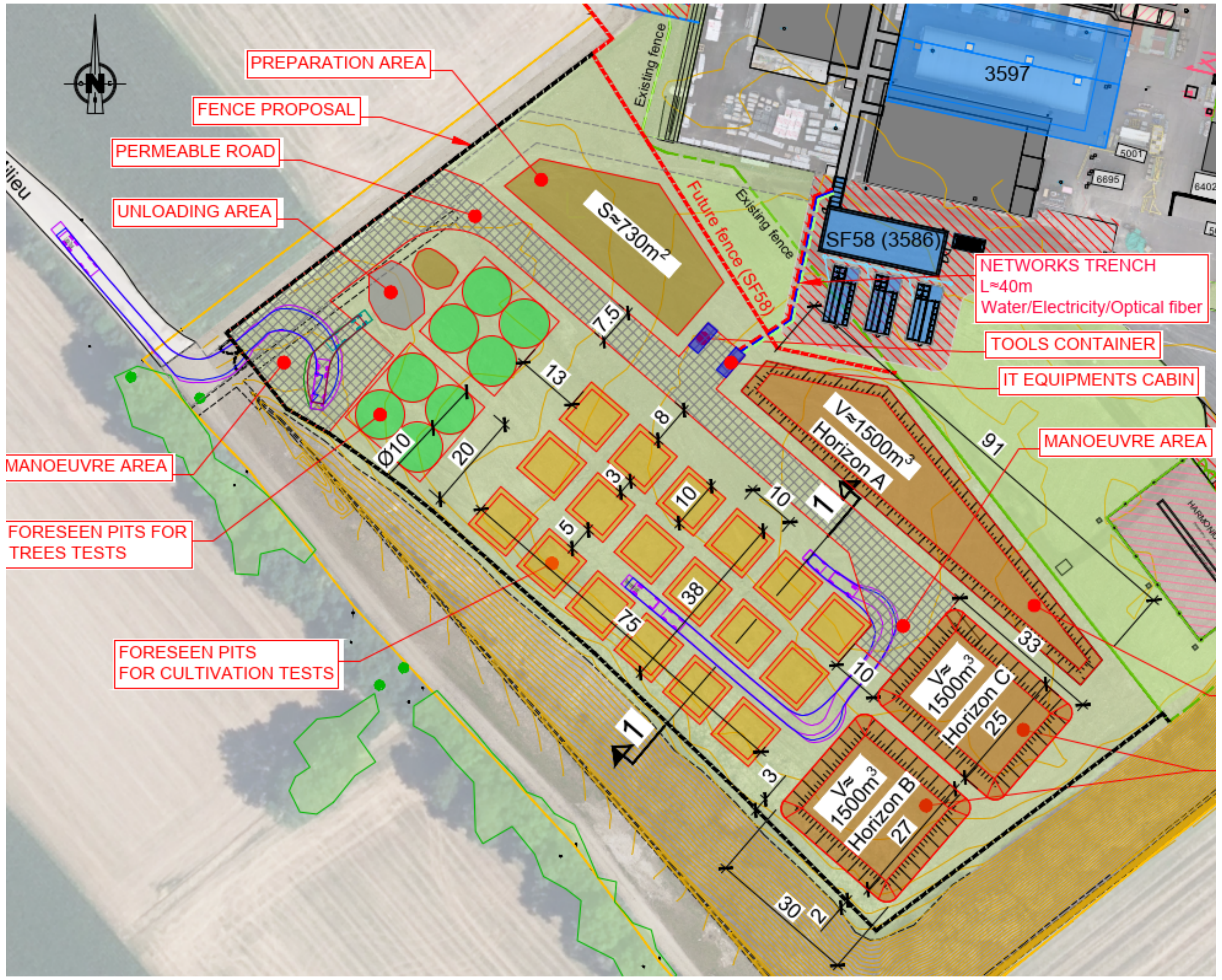
Project phases:

1) Laboratory tests to **identify** the **most suitable mix** of molasse and amendments.

2) **Field tests** in a **controlled environment** (plants selected in function of regional specificities and possible soil reuse cases)

International collaboration with partners from academia and industry specialised in agronomy, soil paedogenesis, phytoremediation





Status - March 2024:

- **Project approved at CERN level**
- **Collaboration agreements being signed**
- **Definition of the laboratory and field tests**

M. Benedikt

FCC Tunnel

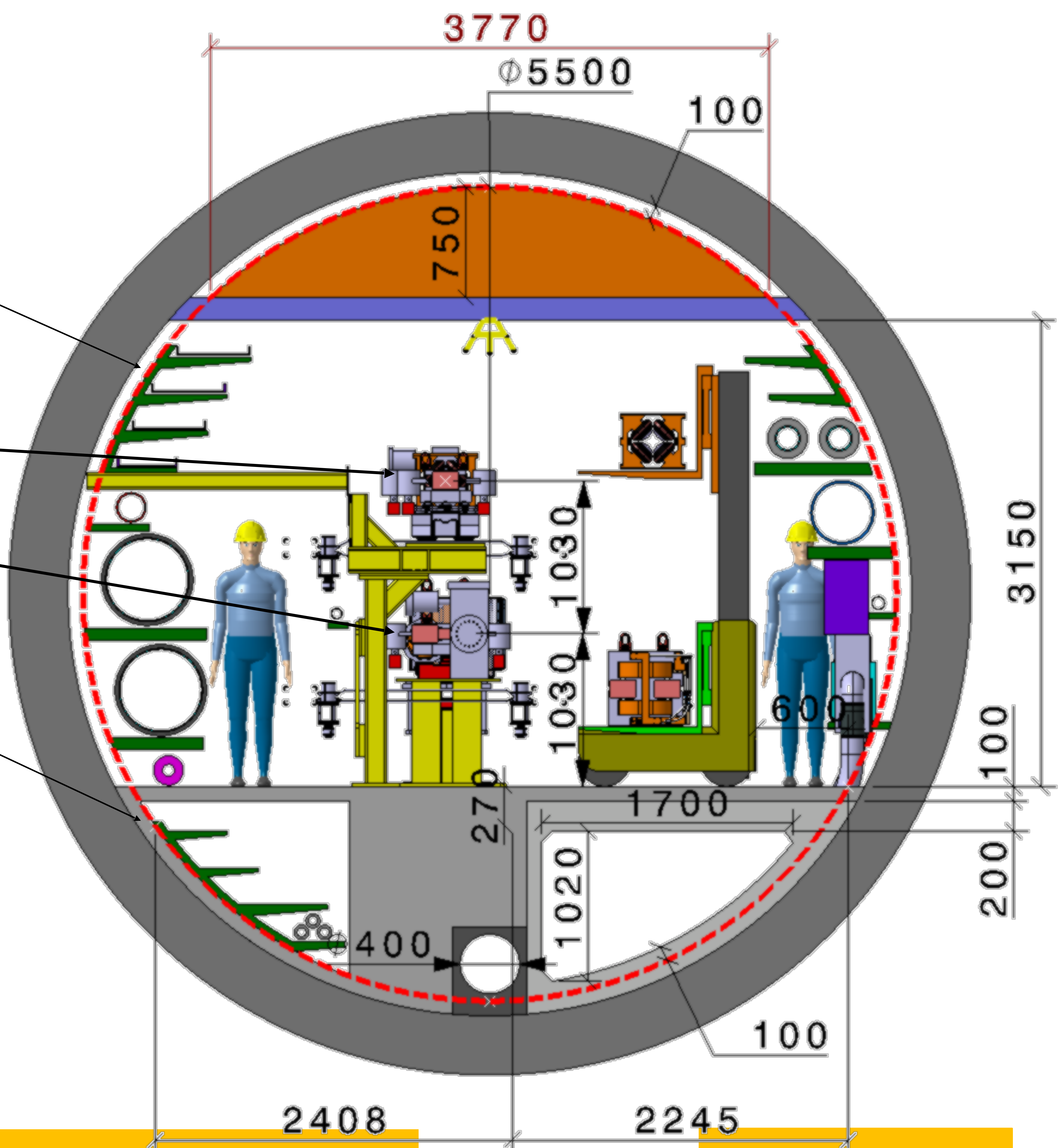
FCC-ee

Cable trays:
Fibre optic
LV distribution
Control cables

Booster ring

Collider ring

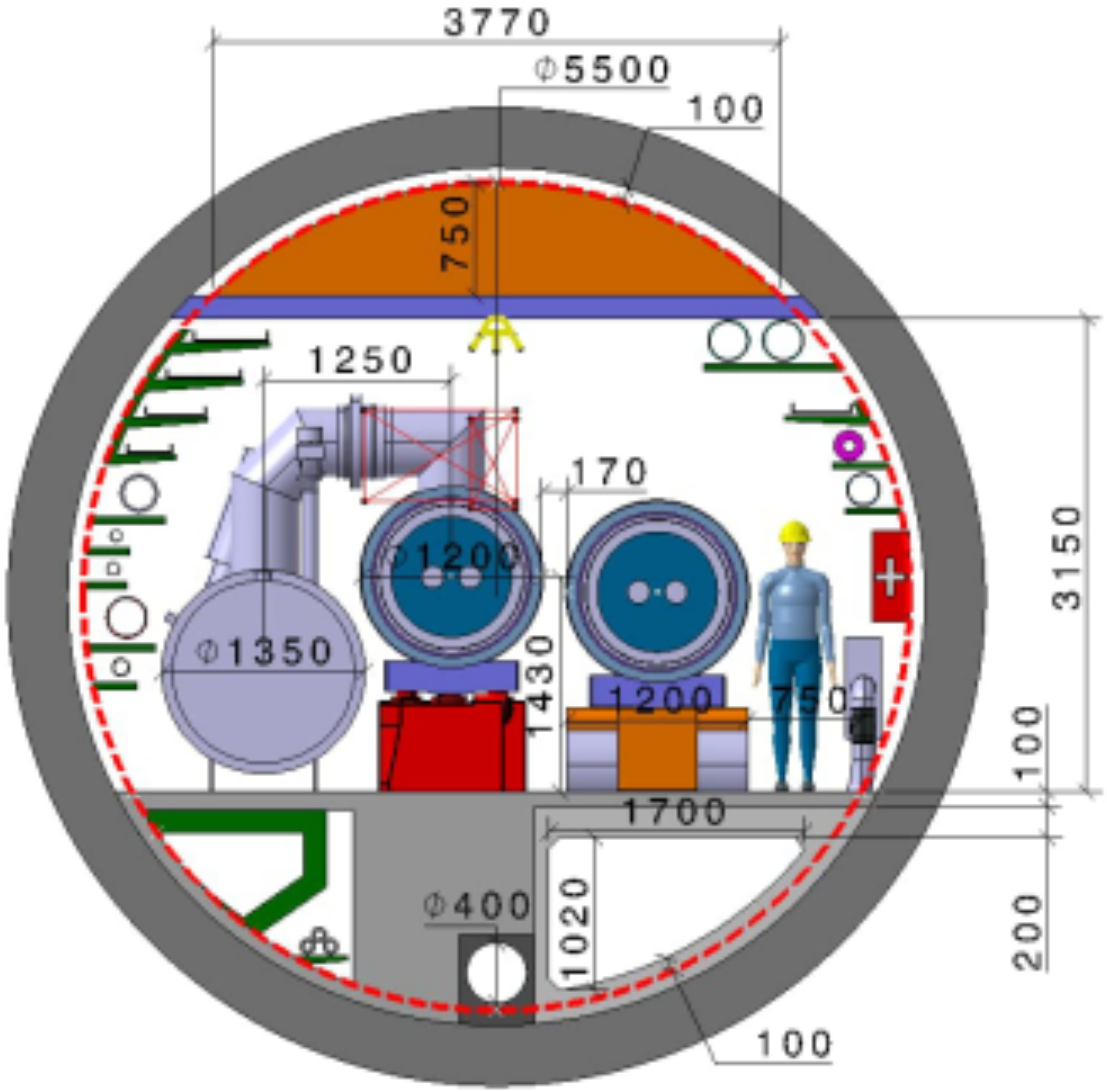
DC cable trays
HV cable



Main ring below of booster ring
Main ring and booster ring 1.03 m apart

Collider Center

FCC-hh



Collider Center

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FCC-ee main parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

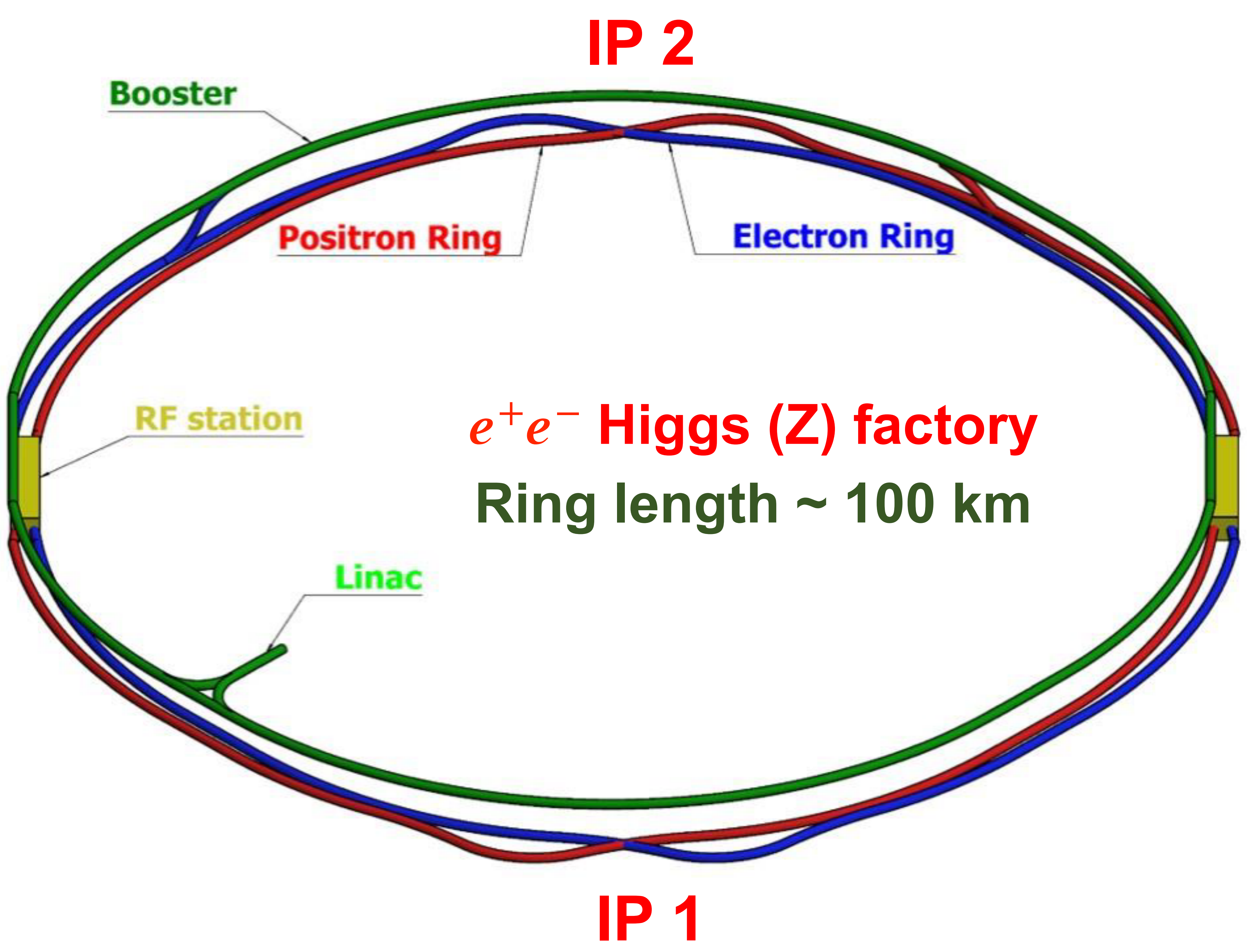
- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

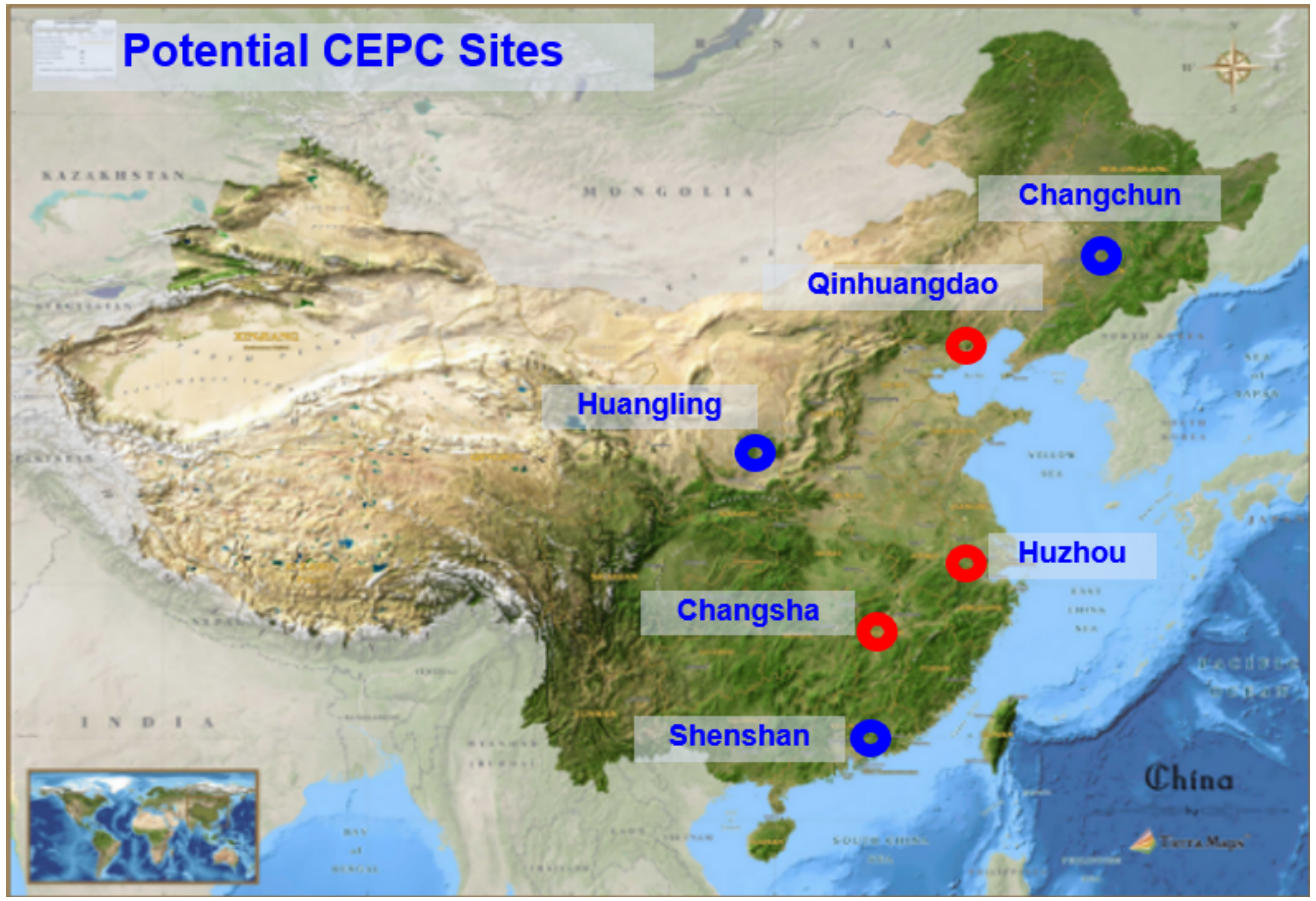
Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

Circular Electron Positron Collider (CEPC)

- CEPC is an e^+e^- Higgs factory producing Higgs / W / Z bosons and top quarks, aims at discovering new physics beyond the Standard Model
- Proposed in September 2012 right after the Higgs discovery
- Upgrade: Super pp Collider (SppC) of $\sqrt{s}$ ~ 100 TeV in the future.

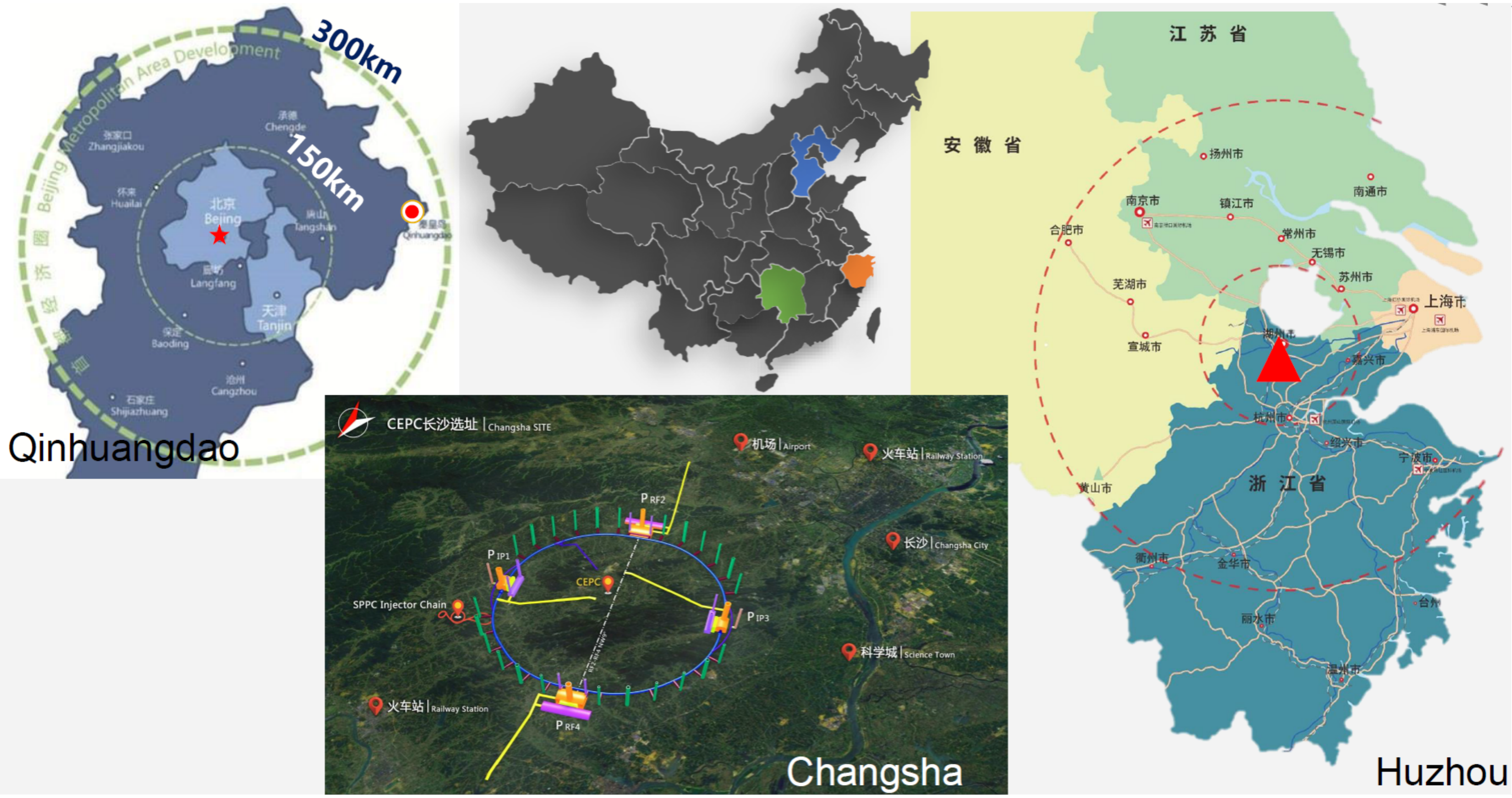


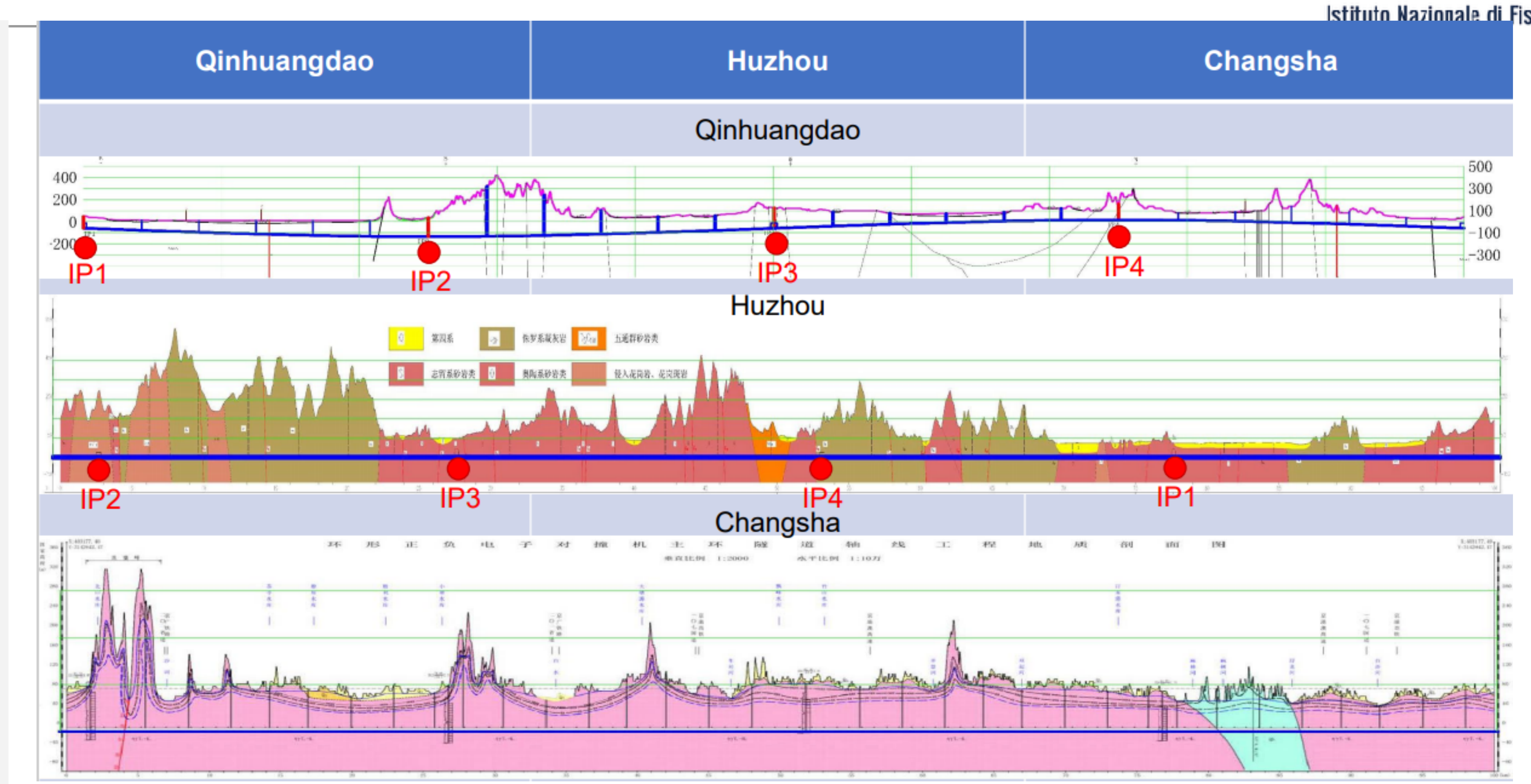


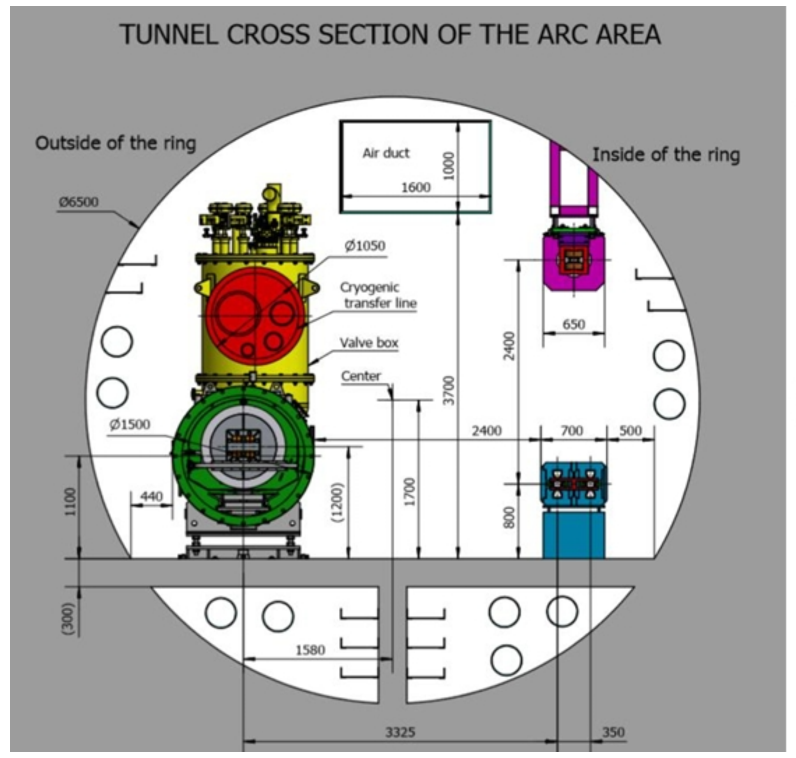
http://cepc.ihep.ac.cn

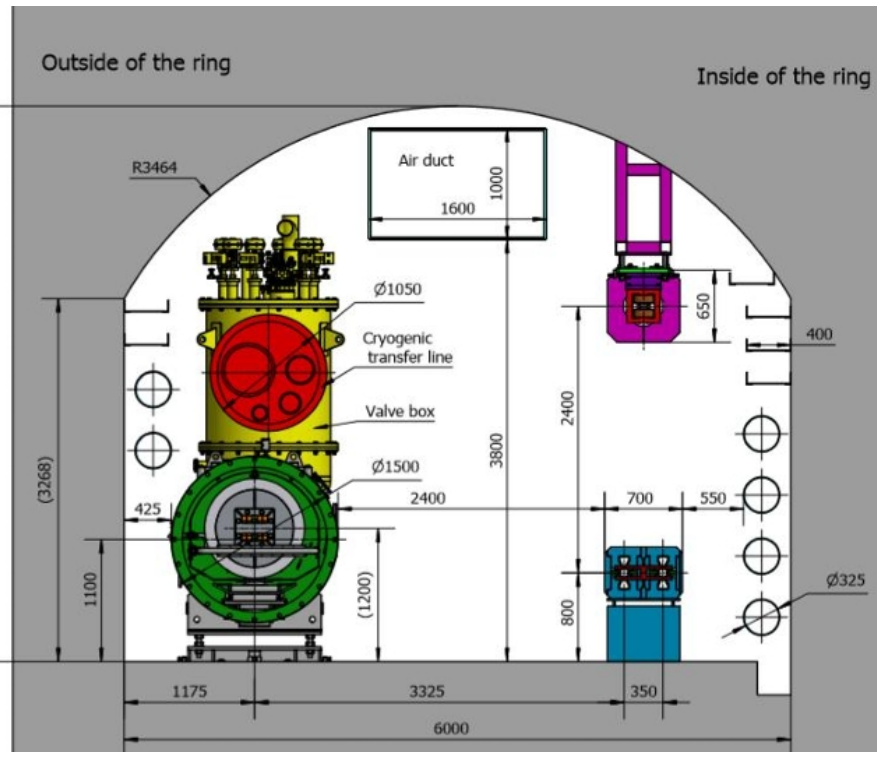
H. Yang

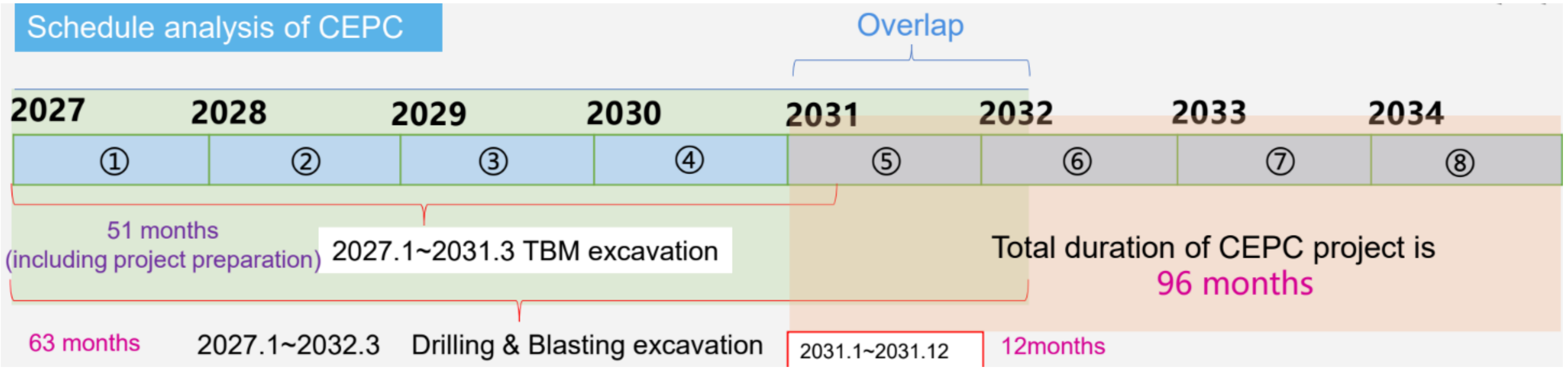
CEPC site selection











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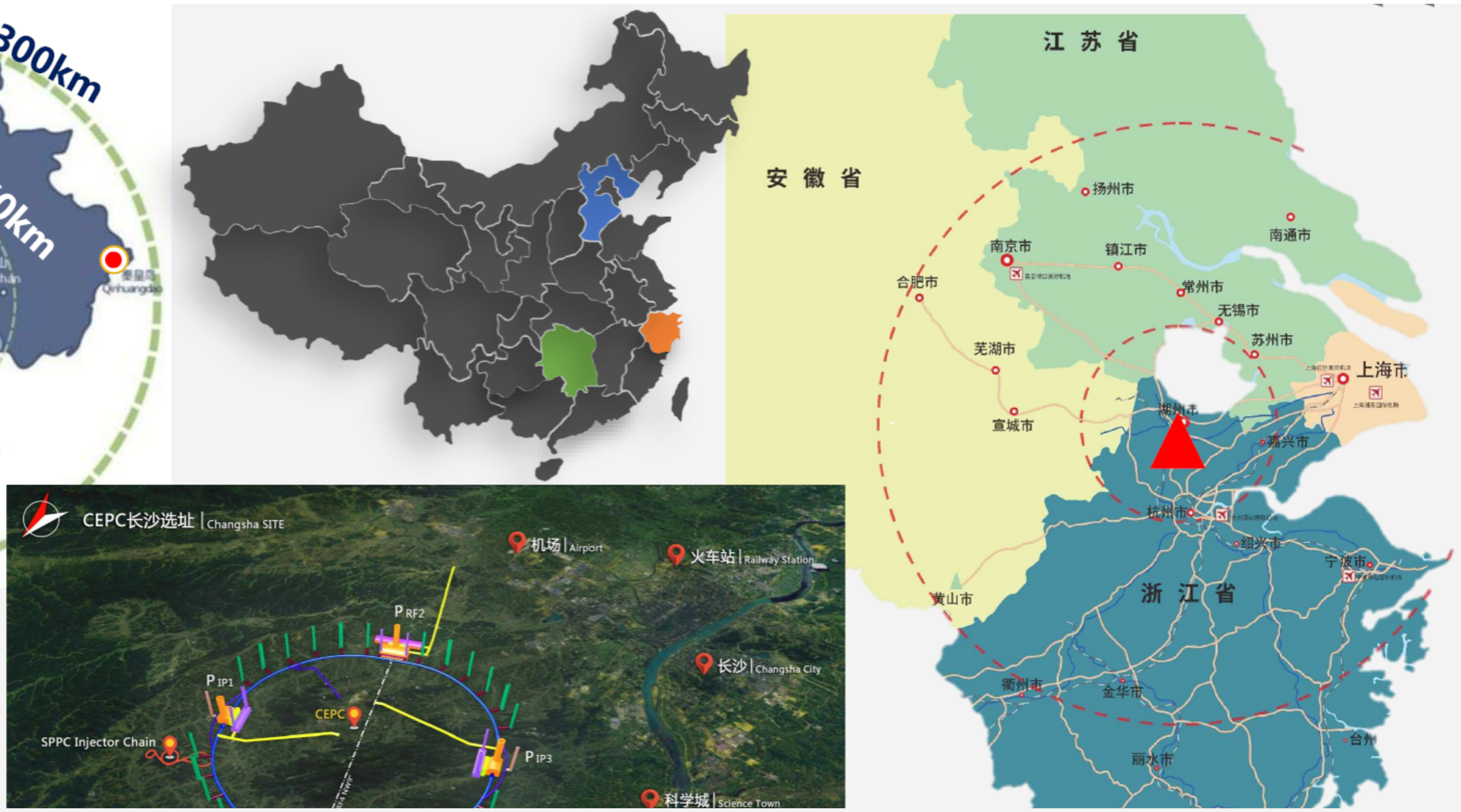
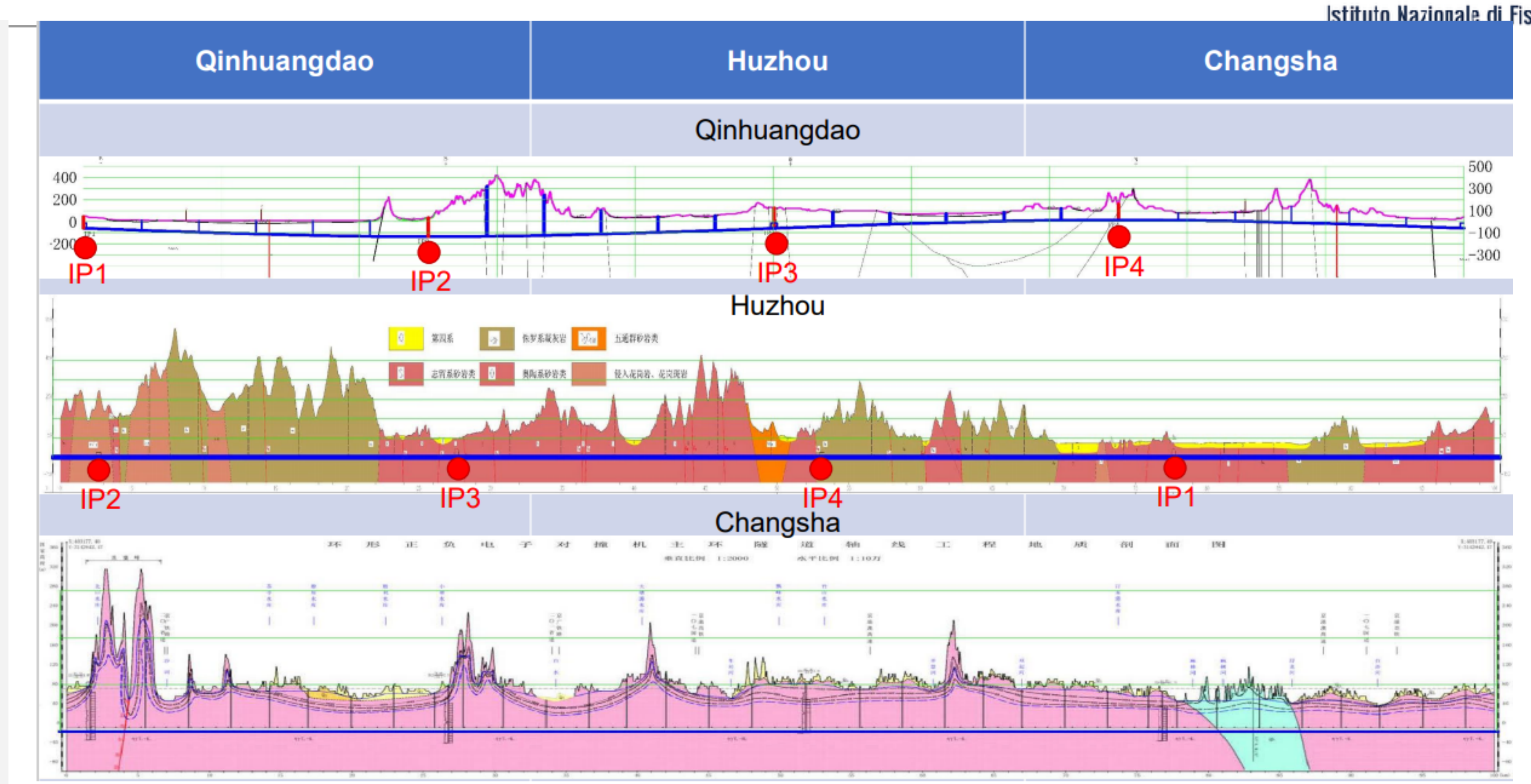


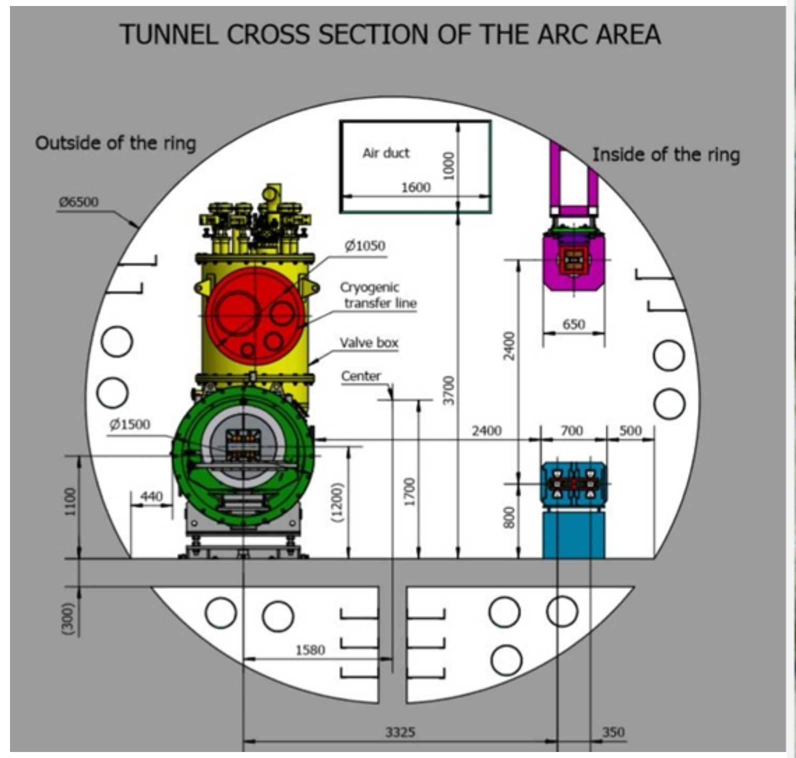


Huzhou

中国电建 POWERCHINA 中国电建集团华东勘测设计研究院有限公司 HUADONG ENGINEERING CORPORATION LIMITED

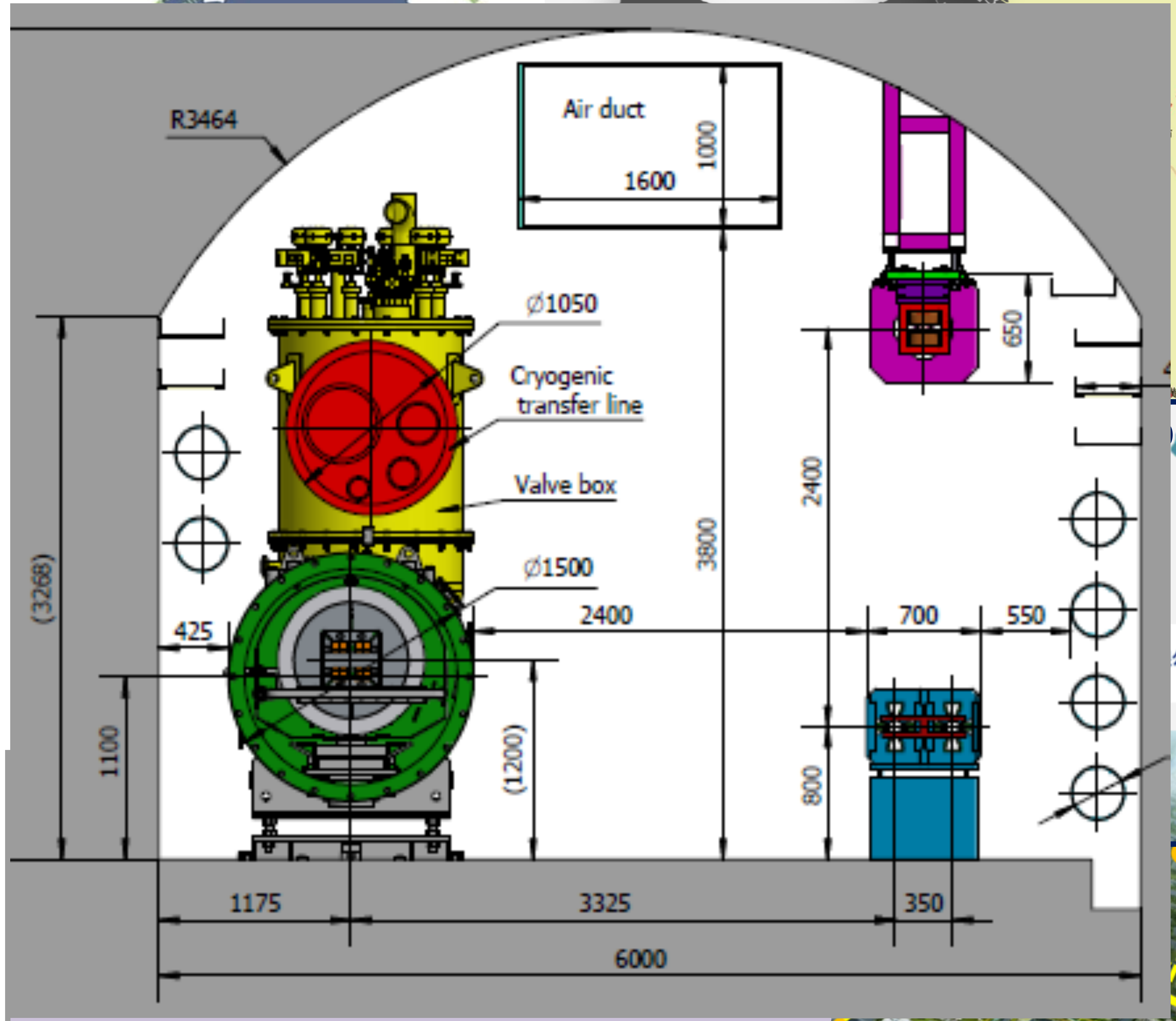
Changsha

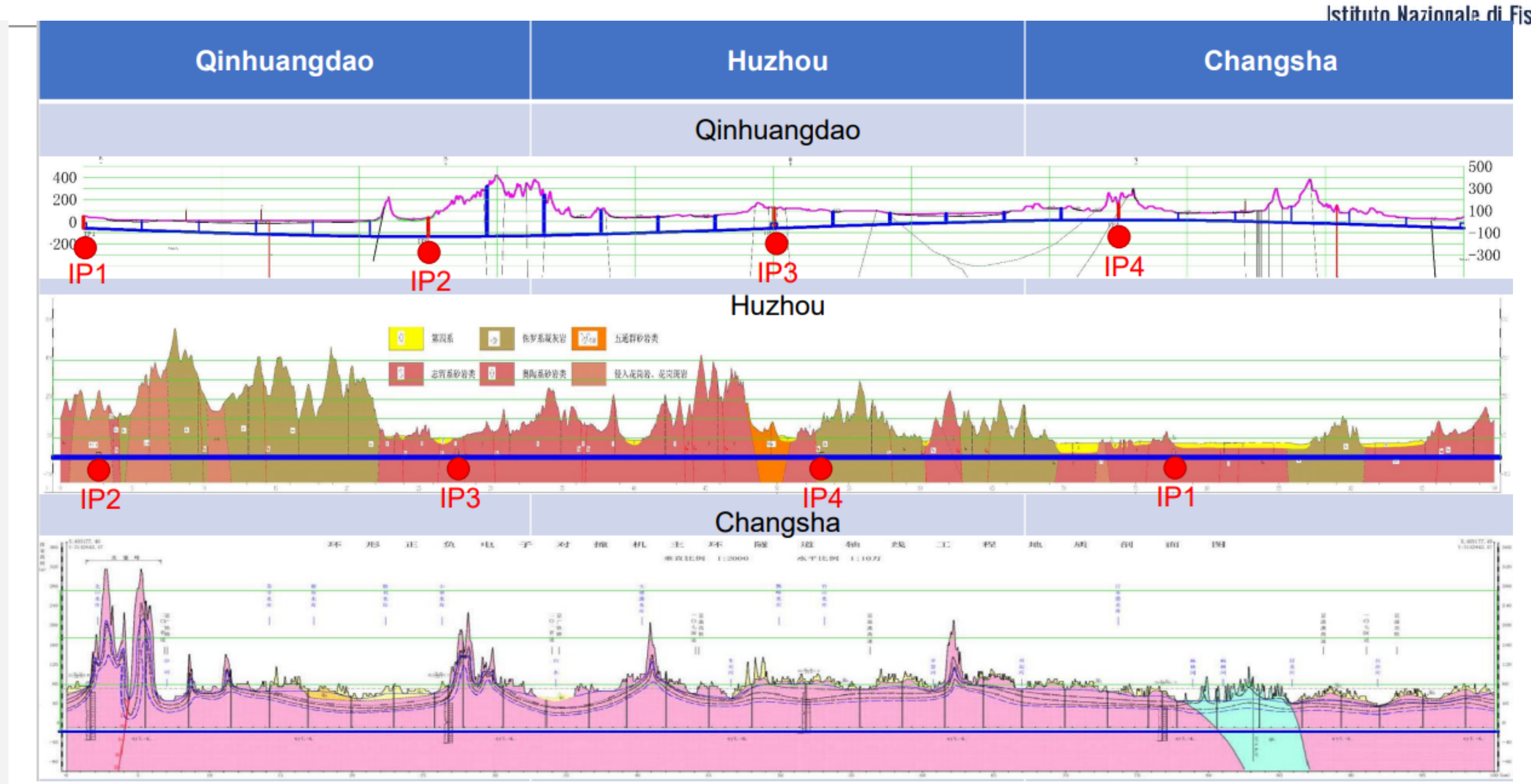
中国电建 POWERCHINA 中南勘测设计研究院有限公司 ZHONGNAN ENGINEERING CORPORATION LIMITED



H. Yang

CEPC site selection





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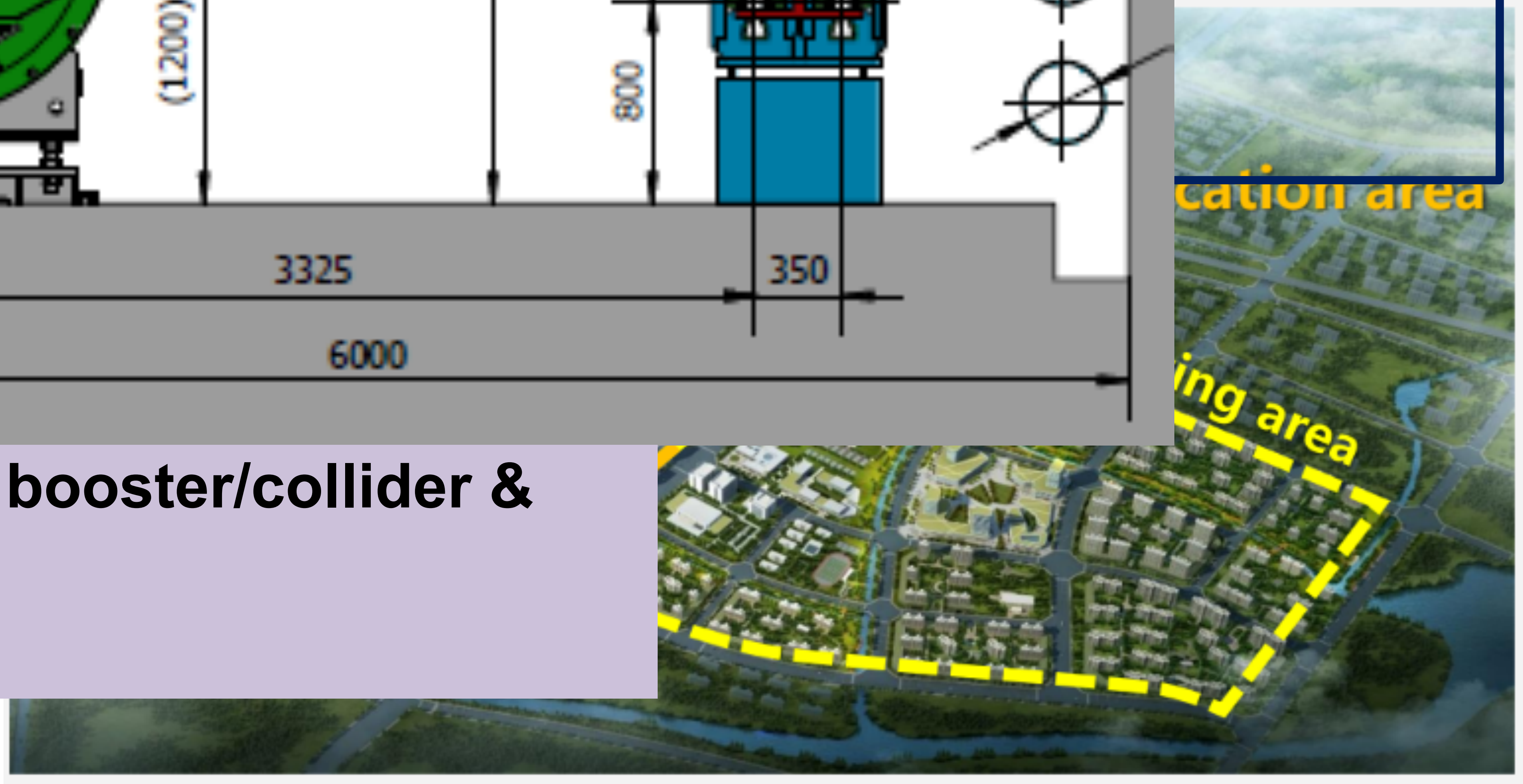


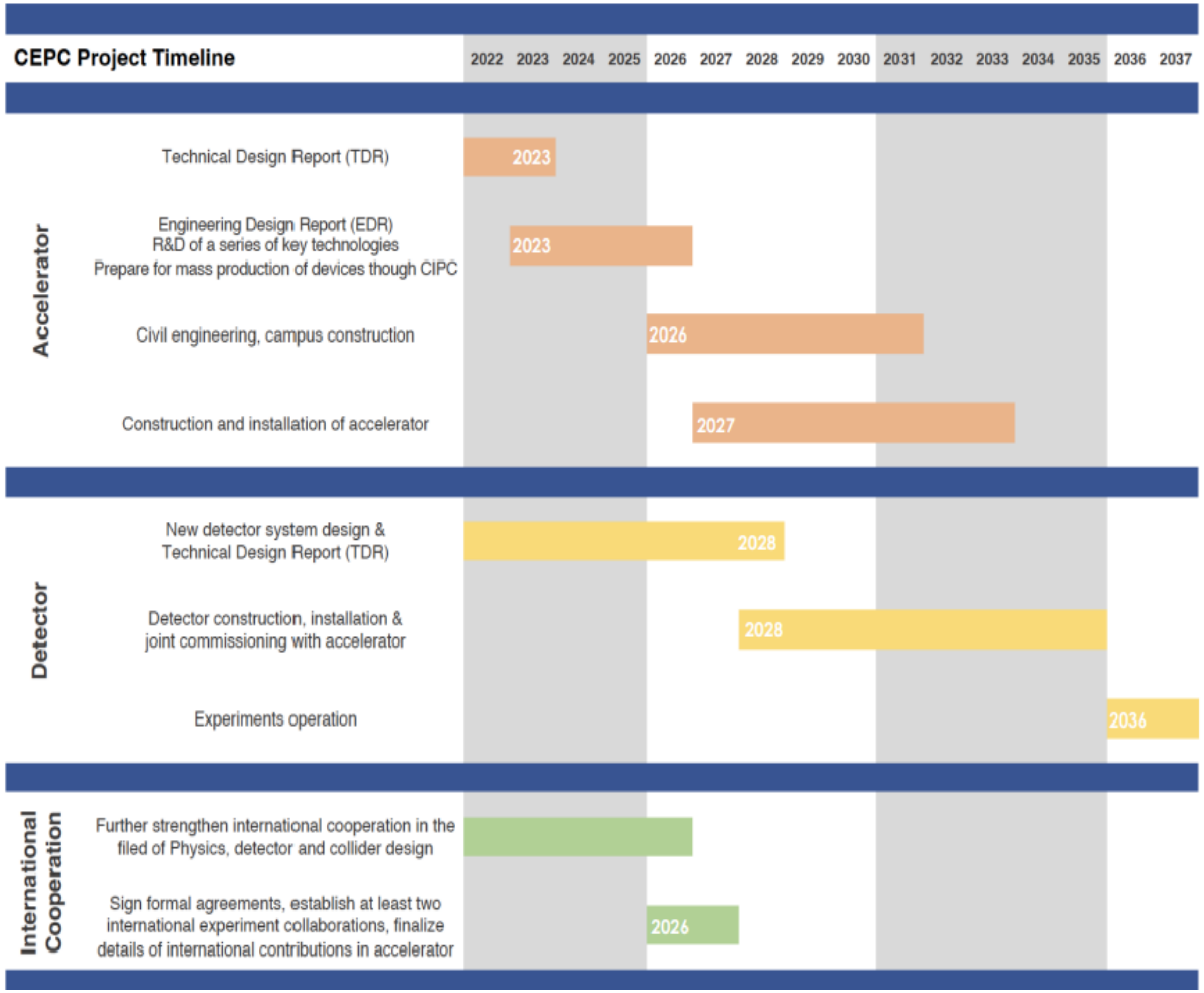
Common tunnel for booster/collider & SppC

CEPC Planning and Schedule

2012.9	2015.3	2018.11	2023.12	2025.6	2027	15th five year plan (2026-2030)
proposed	Pre-CDR	CDR	Acc. TDR	Det. TDR	EDR	Start of construction

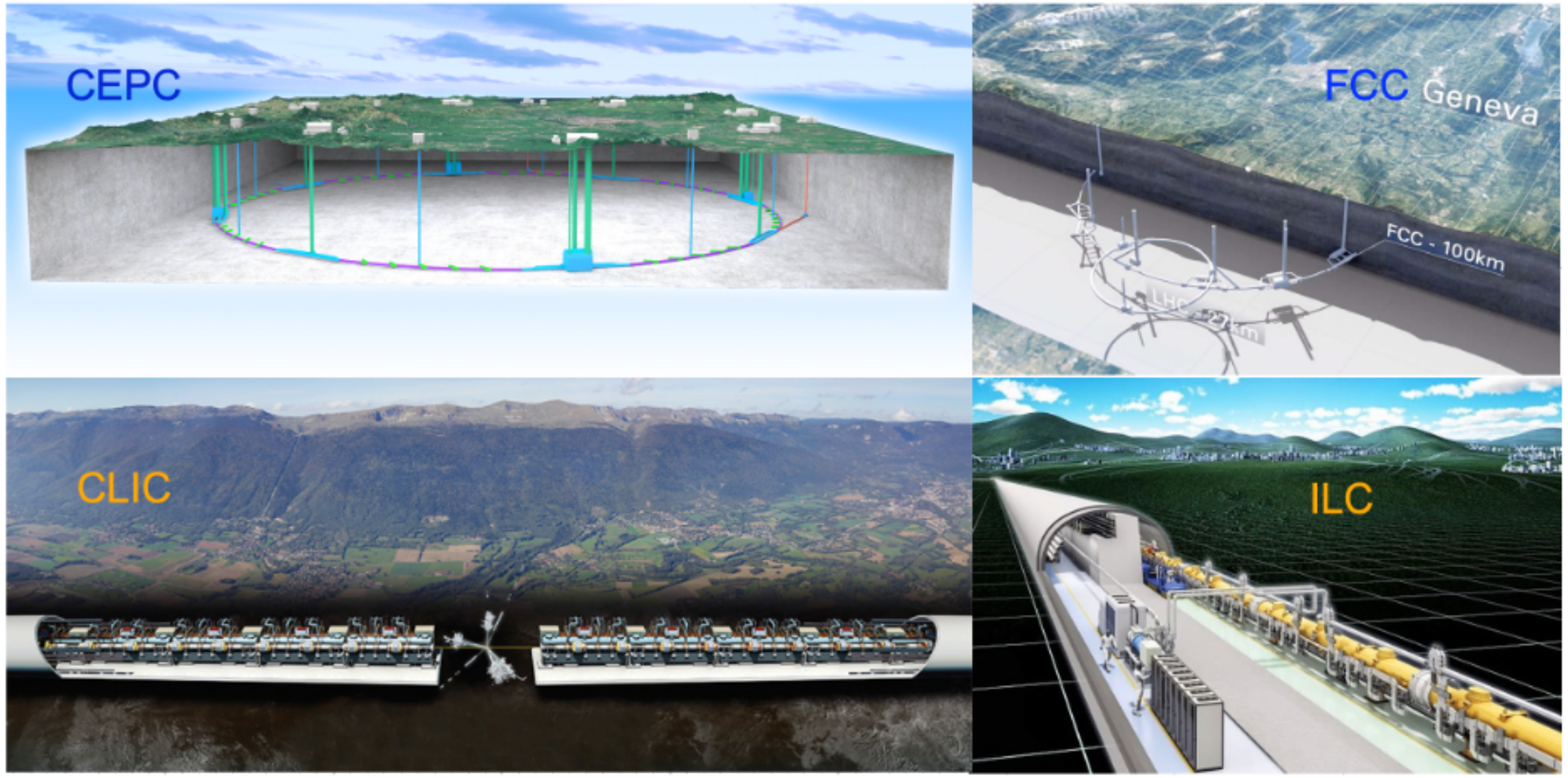
CEPC EDR Phase: 2024-2027

- ➢ **CEPC Accelerator EDR** starts with 35 WGs in 2024, to be completed in **2027**
- ➢ **CEPC Reference Detector TDR** will be released by June, **2025**
- ➢ **CEPC proposal** will be submitted to Chinese government for approval in **2025**
- ➢ **Upon approval**, establish at least two international experiment collaborations
- ➢ **CEPC construction starts** during the 15th five year plan (2026-2030, e.g. **2027**)
- ➢ **CEPC construction complete** around **2035**, at the end of the 16th five year plan

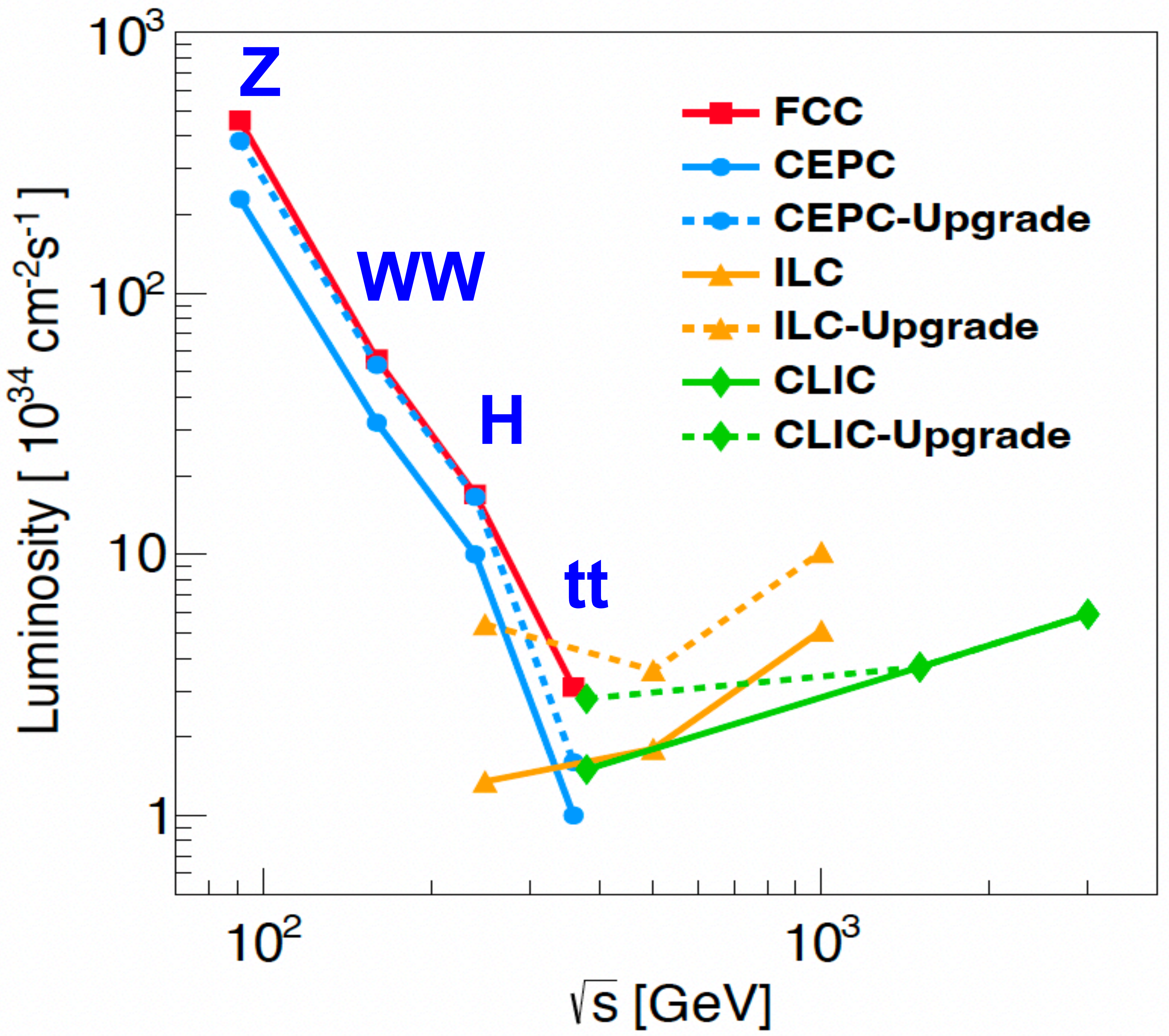


H. Yang

Comparison of Higgs factories: Circular vs. Linear



CEPC Accelerator white paper for Snowmass21, arXiv:2203.09451



CEPC has strong advantages among mature e^+e^- Higgs factories (design report delivered)

Versus FCC-ee

- Earlier data: collisions expected in 2030s (vs. ~ 2040s)
- Large tunnel cross section (ee & pp coexistence)
- Lower construction cost

Versus Linear Colliders

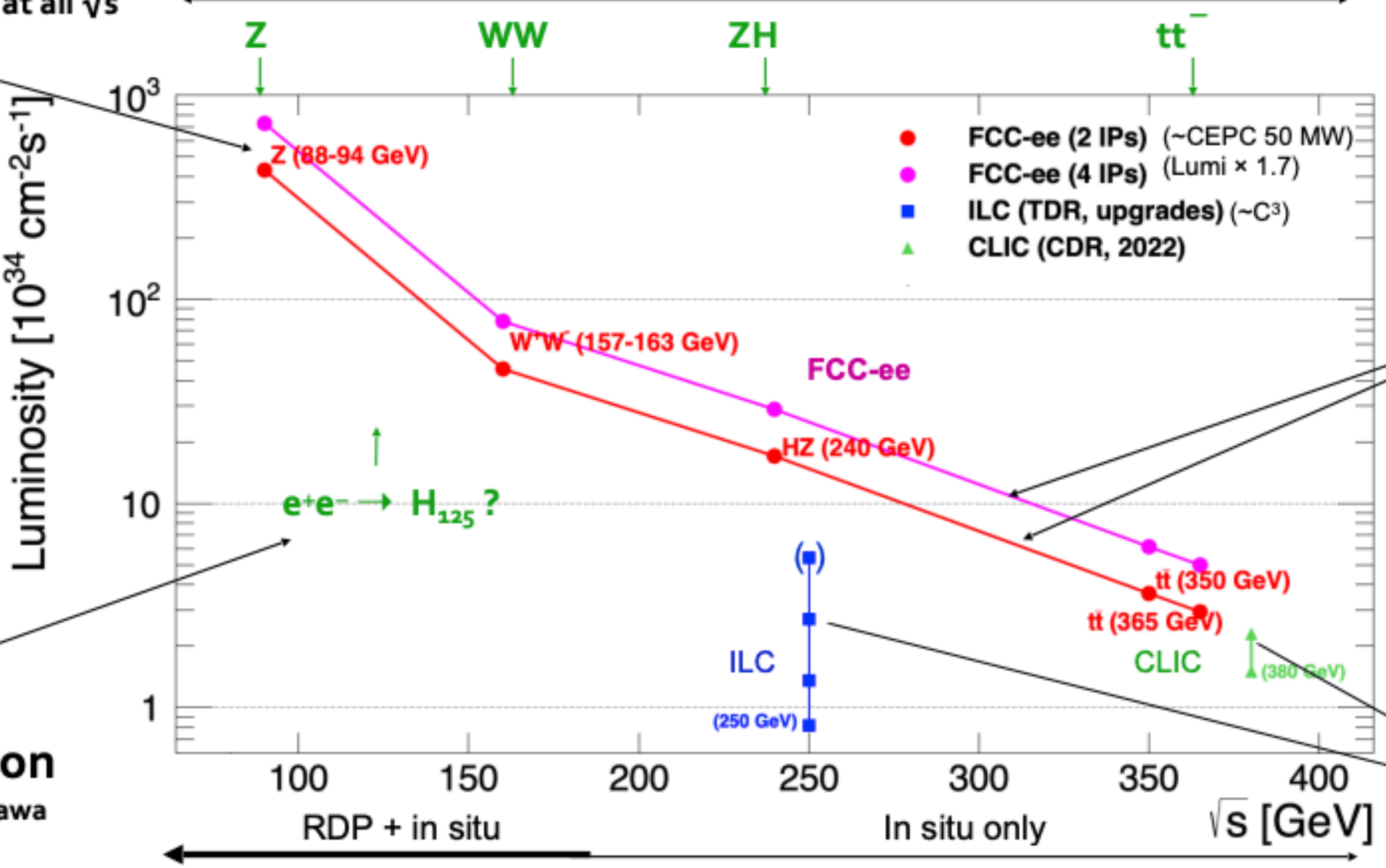
- Higher luminosity / precision for Higgs & Z
- Potential upgrade for pp collider

Why circular is better than linear...

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



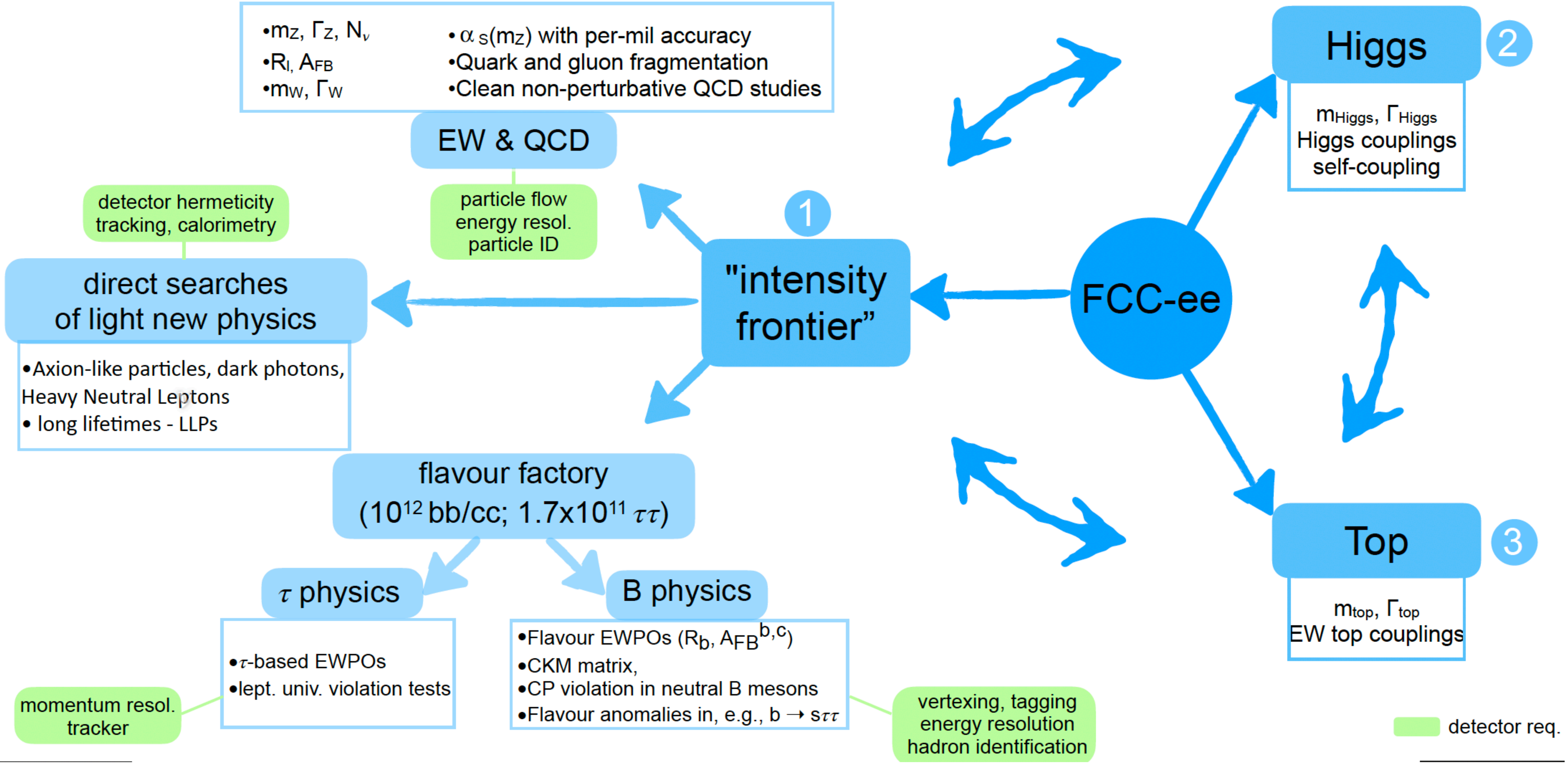
Serve up to 4 interaction points
Net overall gain in MW/ab⁻¹ or CO2-eq/ab⁻¹
Essential redundancy for precision measurements
May satisfy all detector requirements
Increase discovery potential
Enhance the community (FCC/CERN clients)

√s Monochromatisation
Unique opportunity for electron Yukawa

Motivates the competition
Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination
Both with resonant depolarisation (RDP) and with collision events in up to four detectors
Essential for precision measurements

FCC-ee Physics programme



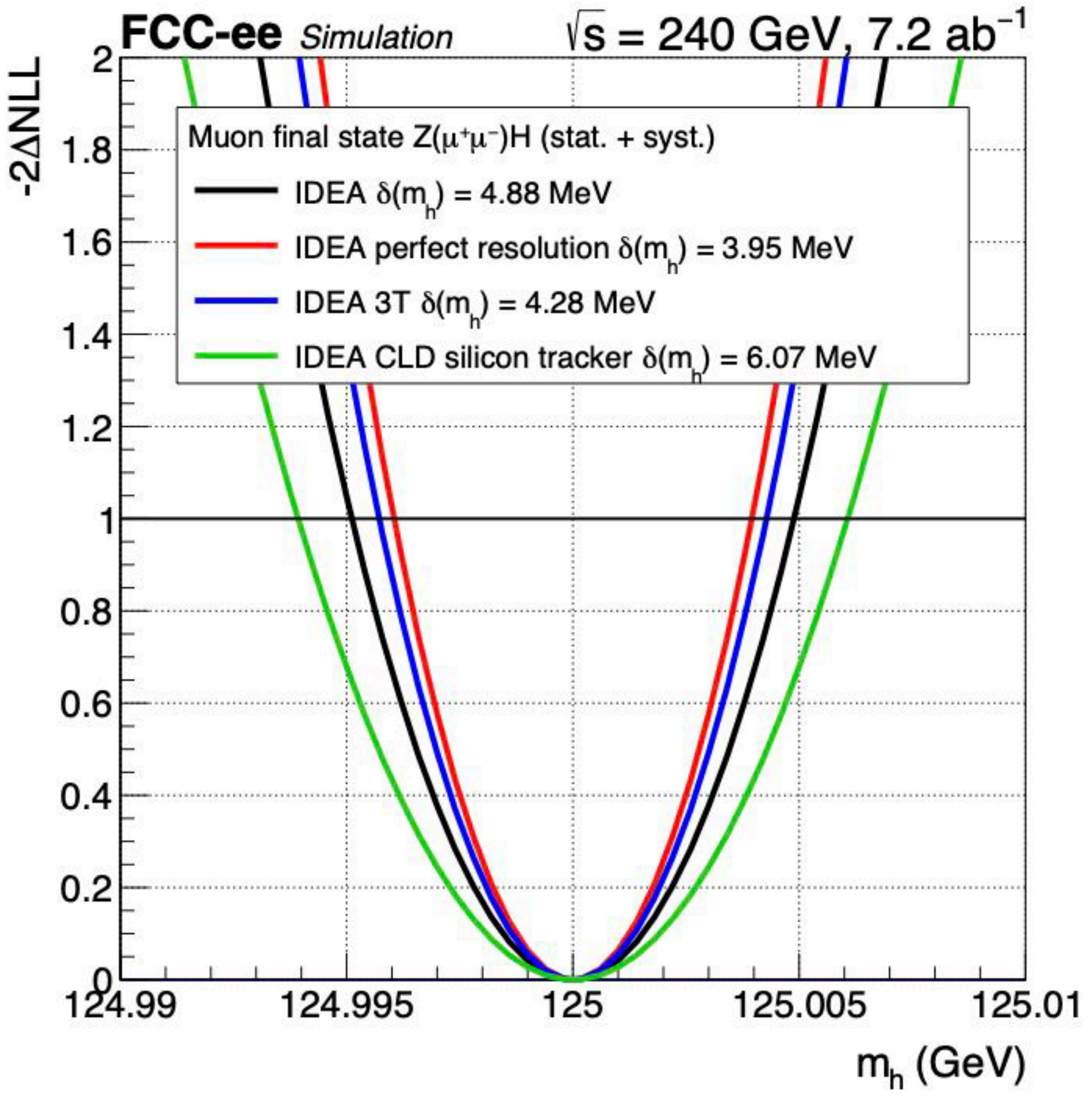
C. Grojean

EW observables at the Z

$5\times10^{12}\ e^+e^- \rightarrow Z$

From data collected in a lineshape energy scan:

- **Z mass** (key for jump in precision for ewk fits)
- **Z width** (jump in sensitivity to ewk rad corr)
- **R_l** = hadronic/leptonic width ($\alpha_s(m_Z^2)$, lepton couplings)
- **peak cross section** (invisible width, N_ν)
- **$A_{FB}(\mu\mu)$** ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings)

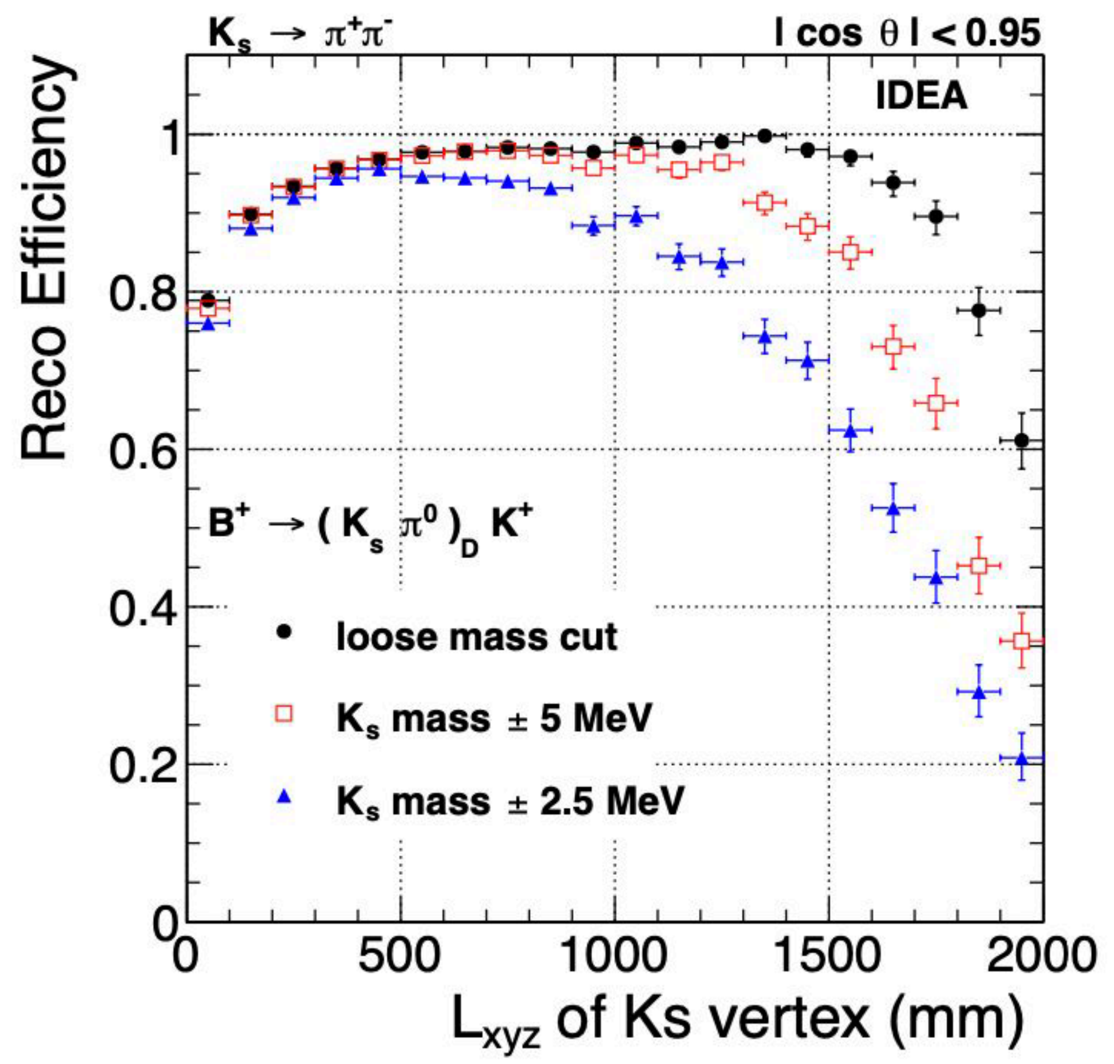


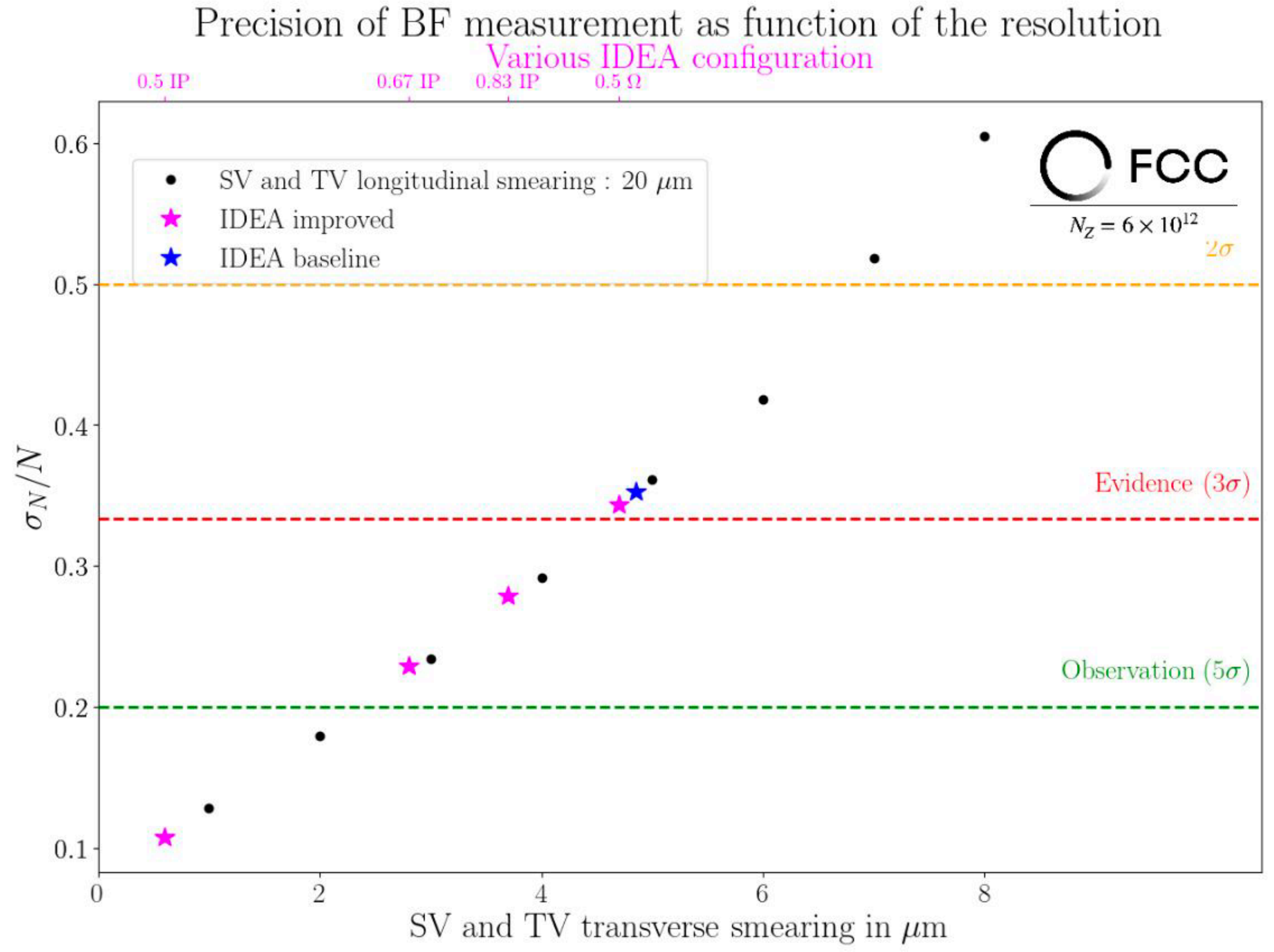
R. Tenchini, P. Azzi

Flavour potential

10^{12} bb/cc, 1.7×10^{11} $\tau\tau$

- **R_b, R_c, A_{FB}(bb), A_{FB}(cc)** (quark couplings)
- **CKM matrix**
- **CP violation in neutral B mesons**
- **Flavour anomalies**
- **Tau polarization** ($\sin^2\theta_{eff}$, lepton couplings, $\alpha_{QED}(m_Z^2)$)
- much more...





R. Tenchini, P. Azzi

EW observables at W^+W^-

10^8 $e^+e^- \to$ WW

From data collected around and above the WW threshold:

- **W mass** (key for jump in precision for ewk fits)
- **W width** (first precise direct measurement)
- $\mathbf{R^W = \Gamma_{had}/\Gamma_{lept}}$ ($\alpha_s(m_Z^2)$)
- Γ_e , Γ_μ , Γ_τ (precise universality test)
- direct **CKM** measurements (with jet-flavor tagging)
- **Triple** and **Quartic Gauge couplings** (jump in precision, especially for charged couplings)

R. Tenchini

FUTURE CIRCULAR COLLIDER

EW precision measurements at FCC-ee

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	$<$ 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

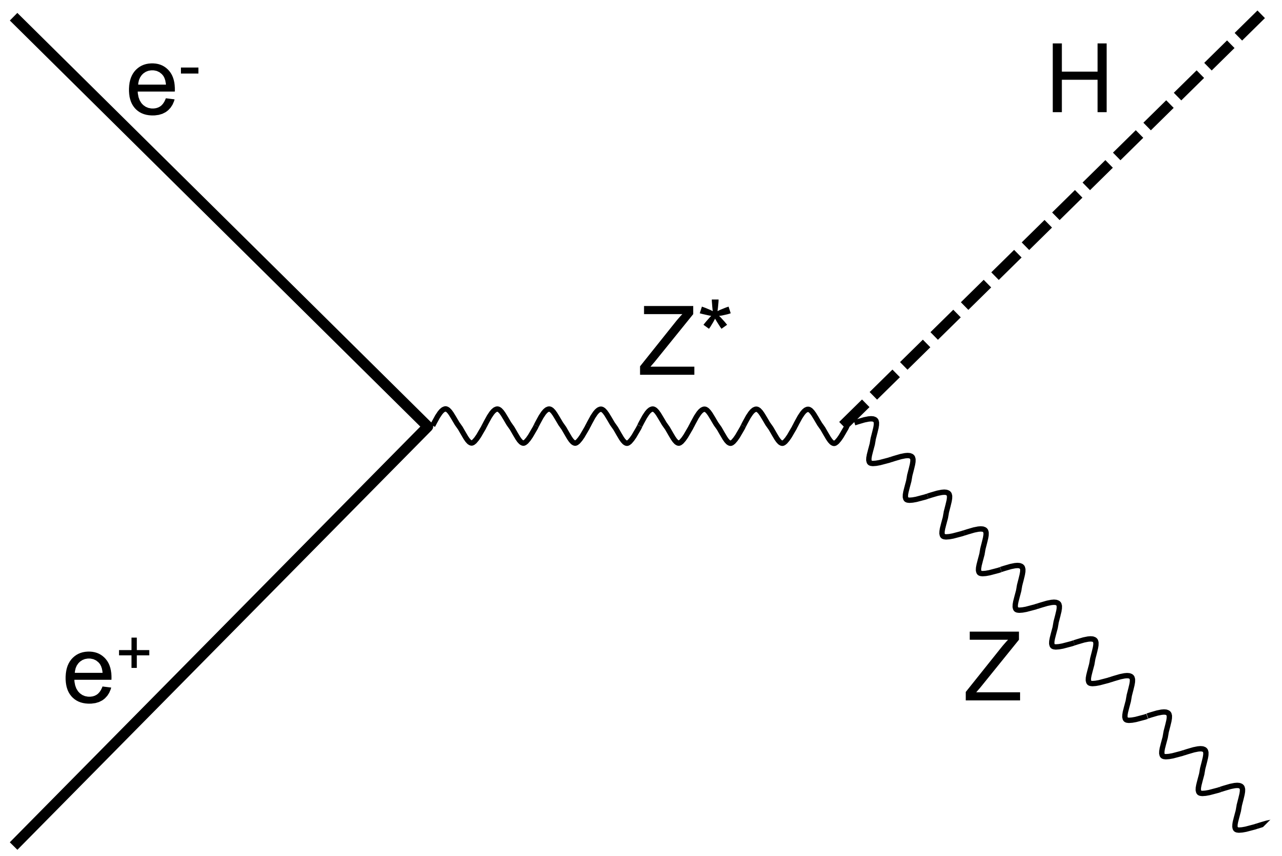
Improvement of **10-50** times compared to LEP

Higgs production at an e+e- collider

"Higgsstrahlung" process close to threshold

Production cross section has a maximum at near threshold ~200 fb

$10^{34}/cm^2/s$ ➔ 20'000 HZ events per year

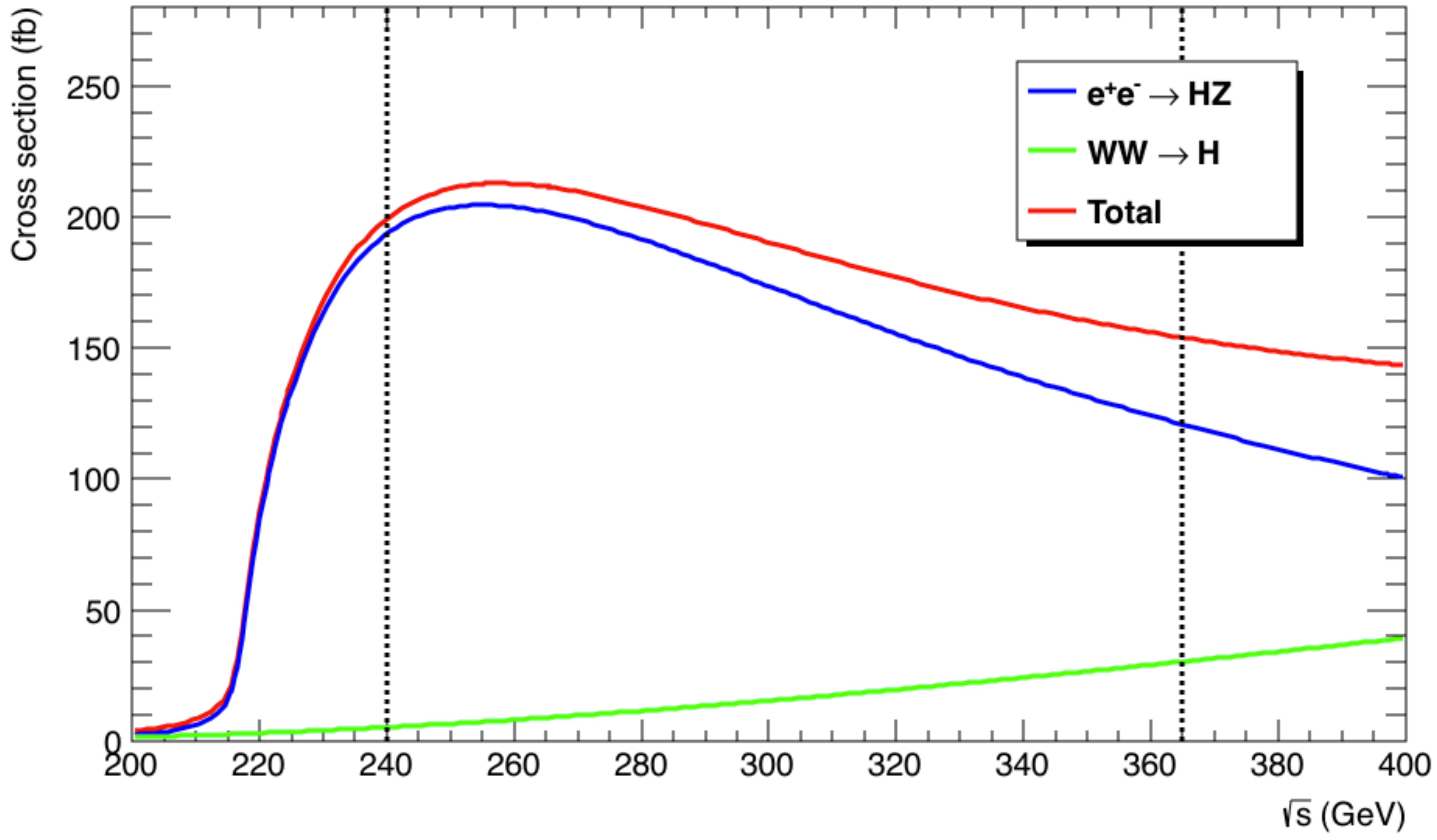


Z – tagging of Higgs events

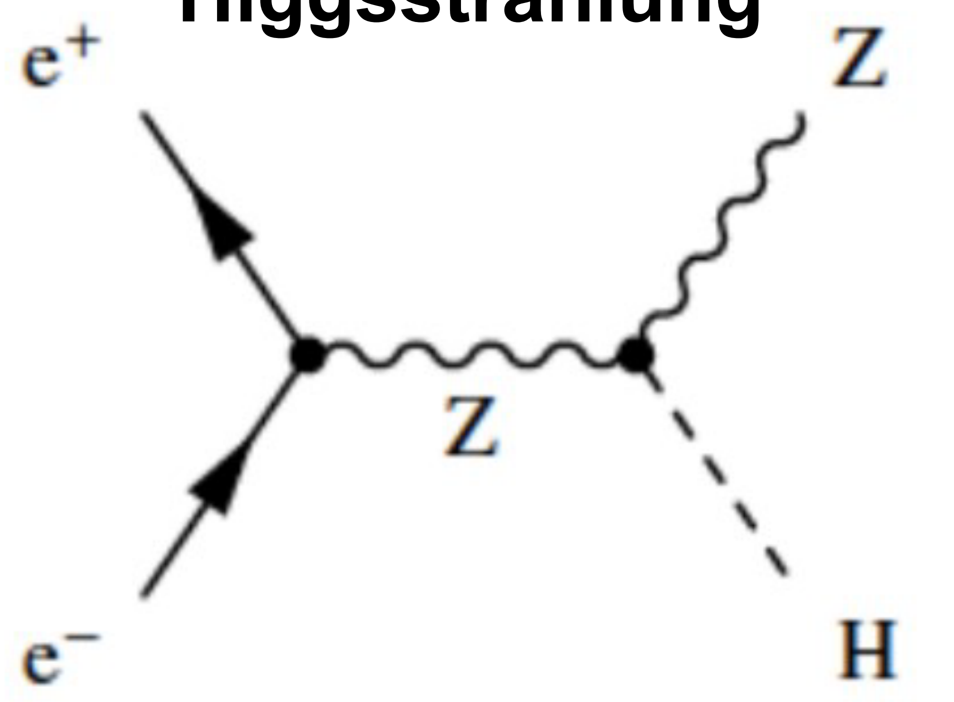
For a Higgs of 125 GeV, a centre of mass energy of 240-250 GeV is optimal
➔ kinematical constraint near threshold for high precision in mass, width, selection purity

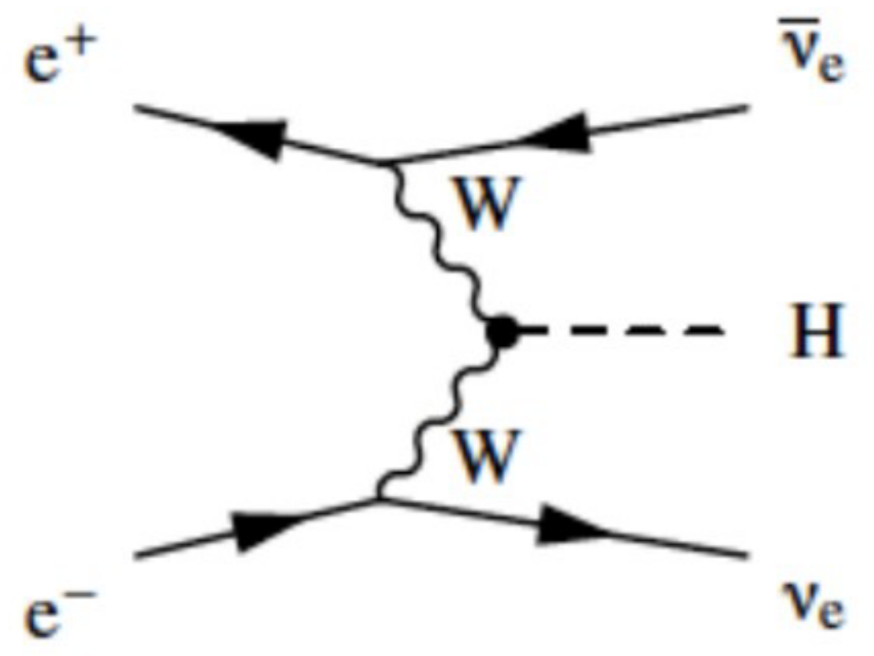
Higgs production at FCC-ee

FCC-ee
7.2 ab^{-1}@240 GeV
~2.7 ab^{-1}@365 GeV

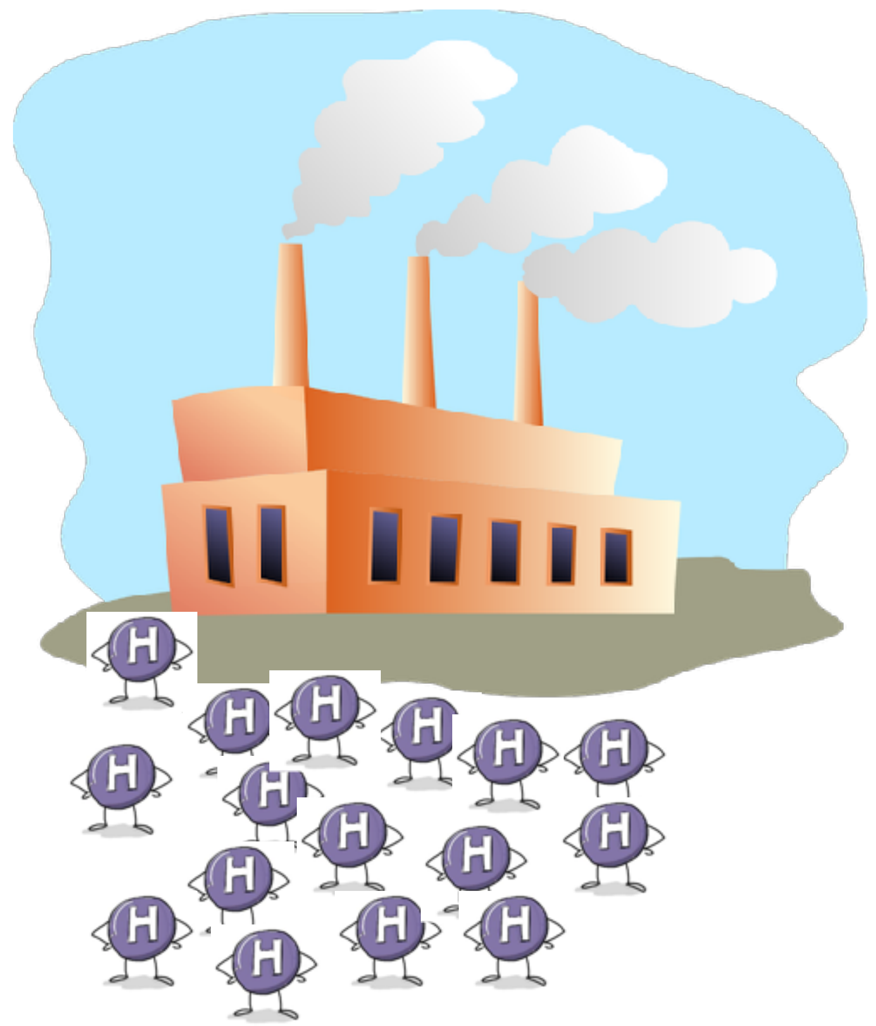


Higgsstrahlung





WW fusion



Higgs Factory!

	FCC-ee 240 GeV	FCC-ee 365 GeV
Total Integrated Luminosity (ab^{-1})	7.2	2.7
# Higgs bosons from $e^+e^- \rightarrow HZ$	1500000	330000
# Higgs bosons from fusion process	45000	80000

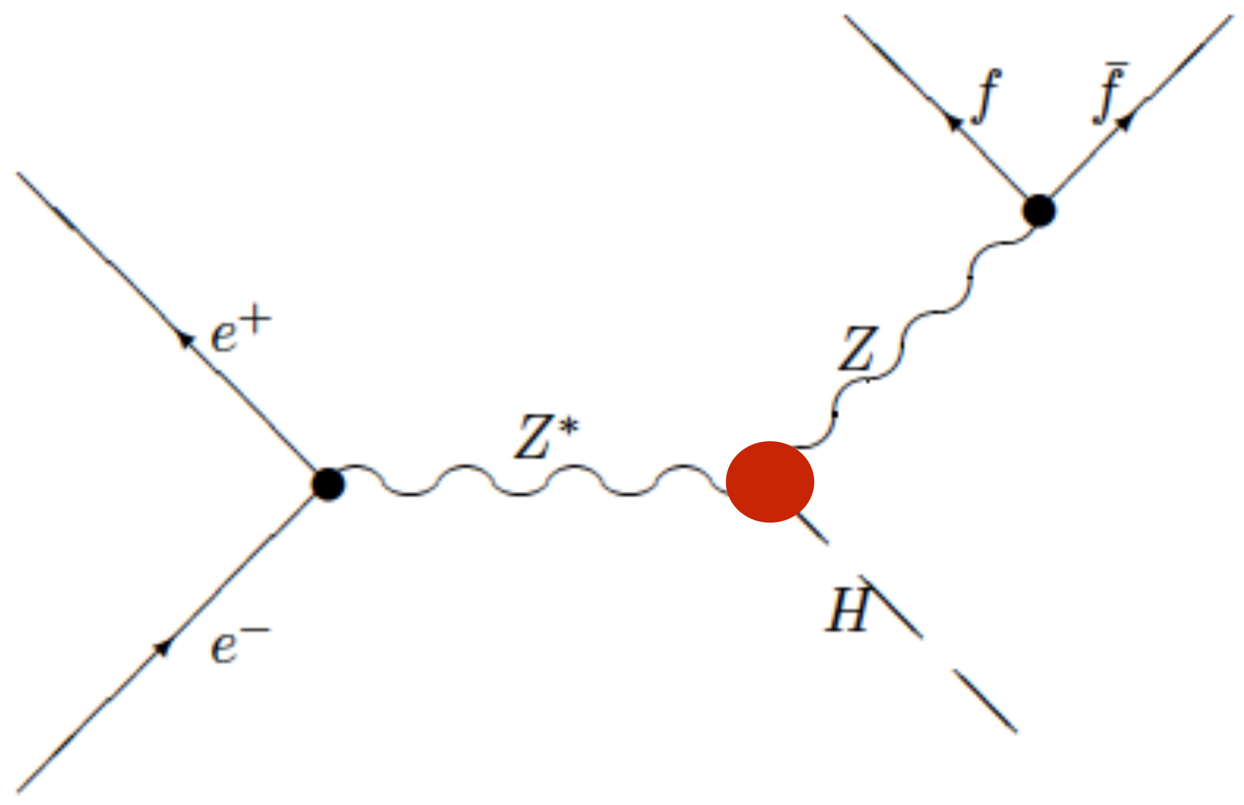
Higgs couplings to Z

➡ **Recoil method provides a unique opportunity for a decay-mode independent measurement of the HZ coupling**

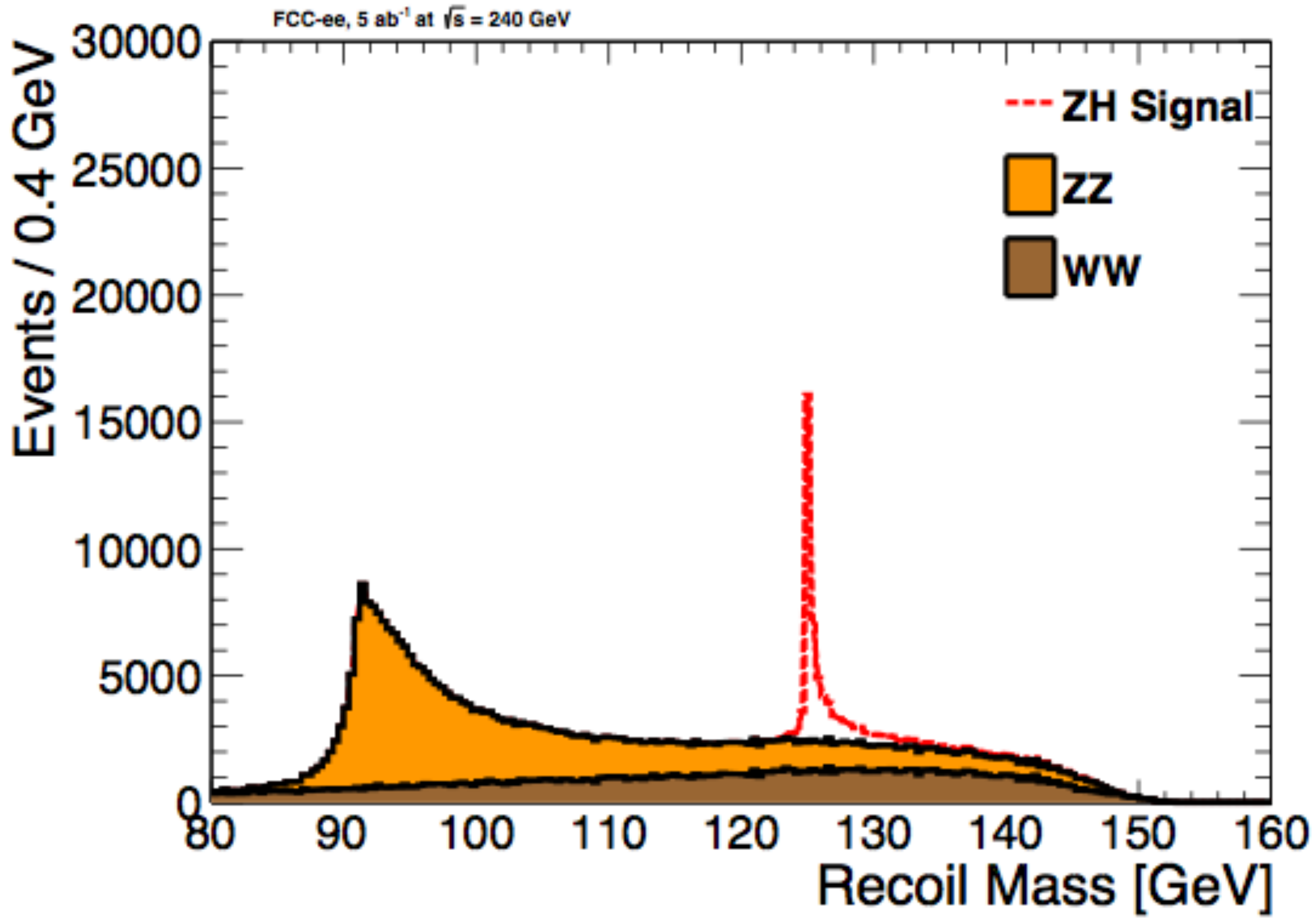
- Higgs events are tagged with the Z boson decays, independently of Higgs decay mode, $m_{recoil} = m_H$
- Expected precision **0.7%** on the ZH cross section
- Using only leptonic Z decays and only a measurement at 240 GeV so far

$$\boxed{\sigma(\mathrm{ee} \to \mathrm{ZH}) \propto \mathrm{g}^2_{\mathrm{HZ}}}$$

Higgs-strahlung



$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



Higgs @ FCC-ee

- Absolute normalisation of couplings (by recoil method)
- Measurement of width (from ZH>ZZZ* and WW>H)
- $\delta\Gamma_H \sim 1\%, \delta m_H \sim 3\,\mathrm{MeV}$ (resp. 25%, 30 MeV @ HL-LHC)
- Model-independent coupling determination and improvement factor up to 10 compared to LHC
- (Indirect) sensitivity to new physics up to 70 TeV (for maximally strongly coupled models)

$$(\delta\kappa_X = v^2/f^2 \quad \& \quad m_{\mathrm{NP}} = g_{\mathrm{NP}} f)$$

— Higgs programme needs Z-pole —

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

C. Grojean

FCC-hh main parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly
more time for high-field magnet R&D
aiming at highest possible energies

Formidable challenges:

- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

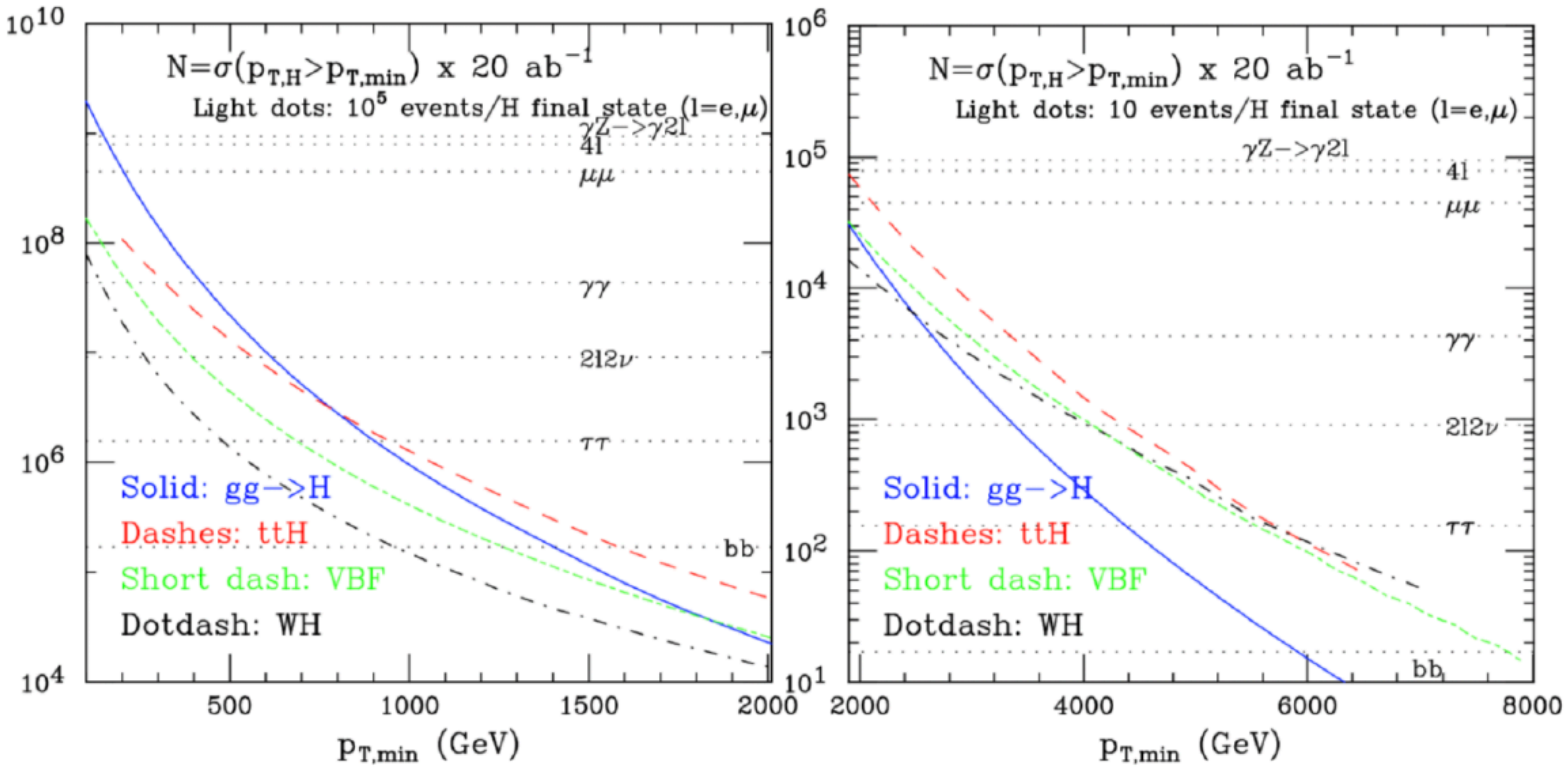
- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, Zγ, μμ)
- ❑ Final word about WIMP dark matter

F. Gianotti

Higgs @ FCC-hh

	ggH (N^{3}LO)	VBF (N^{2}LO)	WH (N^{2}LO)	ZH (N^{2}LO)	$t\bar{t}$H (N^{2}LO)	HH (NLO)
N100	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N100/N14	180	170	100	110	530	390

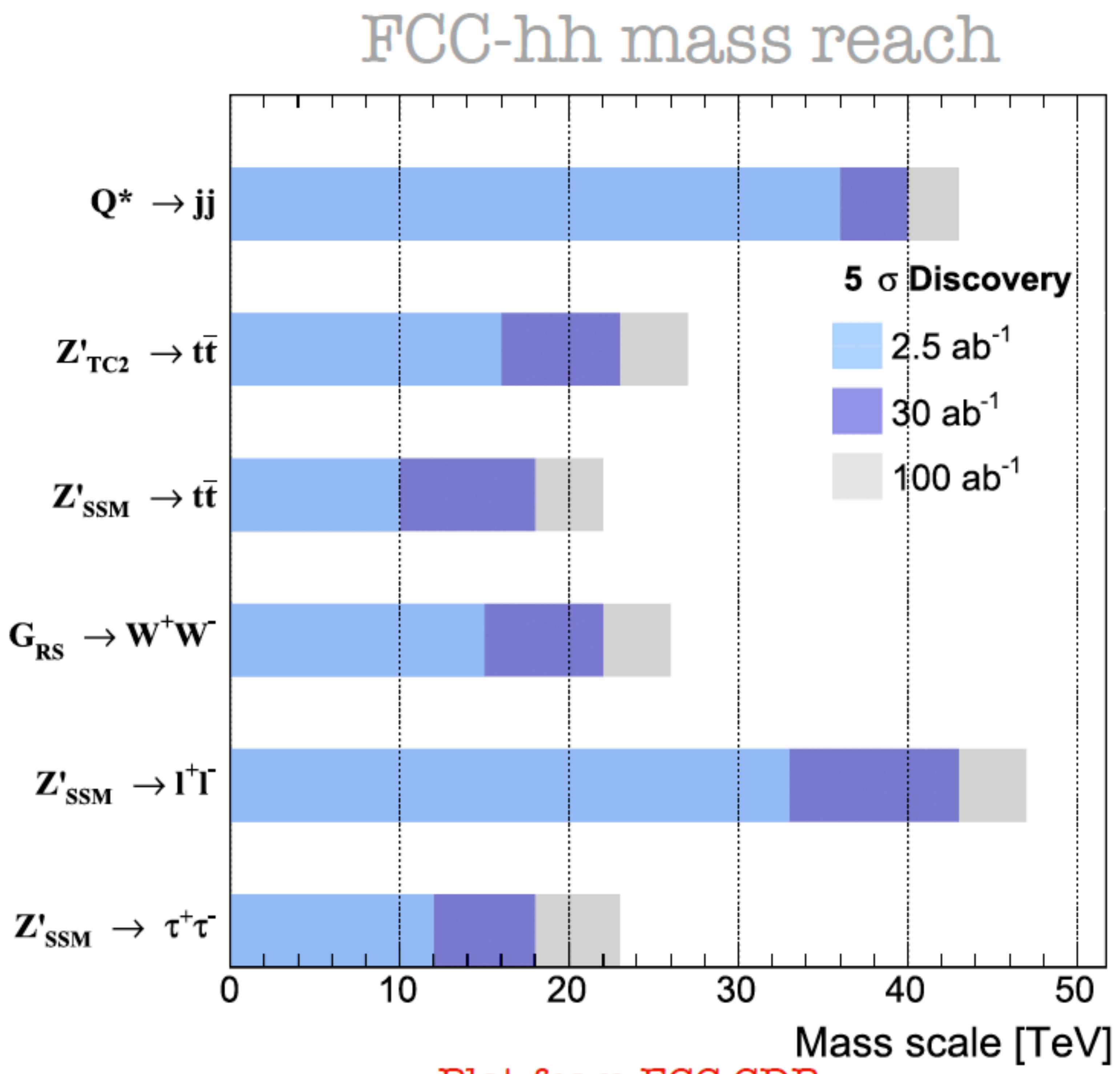
$$(\mathrm{N100} = \sigma_{100\,\mathrm{TeV}} \times 30\,\mathrm{ab}^{-1} \quad \& \quad \mathrm{N14} = \sigma_{14\,\mathrm{TeV}} \times 3\,\mathrm{ab}^{-1})$$



- Large rate (> 10^{10}H, > 10^7 HH)
  - unique sensitivity to rare decays
  - few % sensitivity to self-coupling
- Explore extreme phase space:
  - e.g. 10^6 H w/ pT>1 TeV
  - clean samples with high S/B
  - small systematics

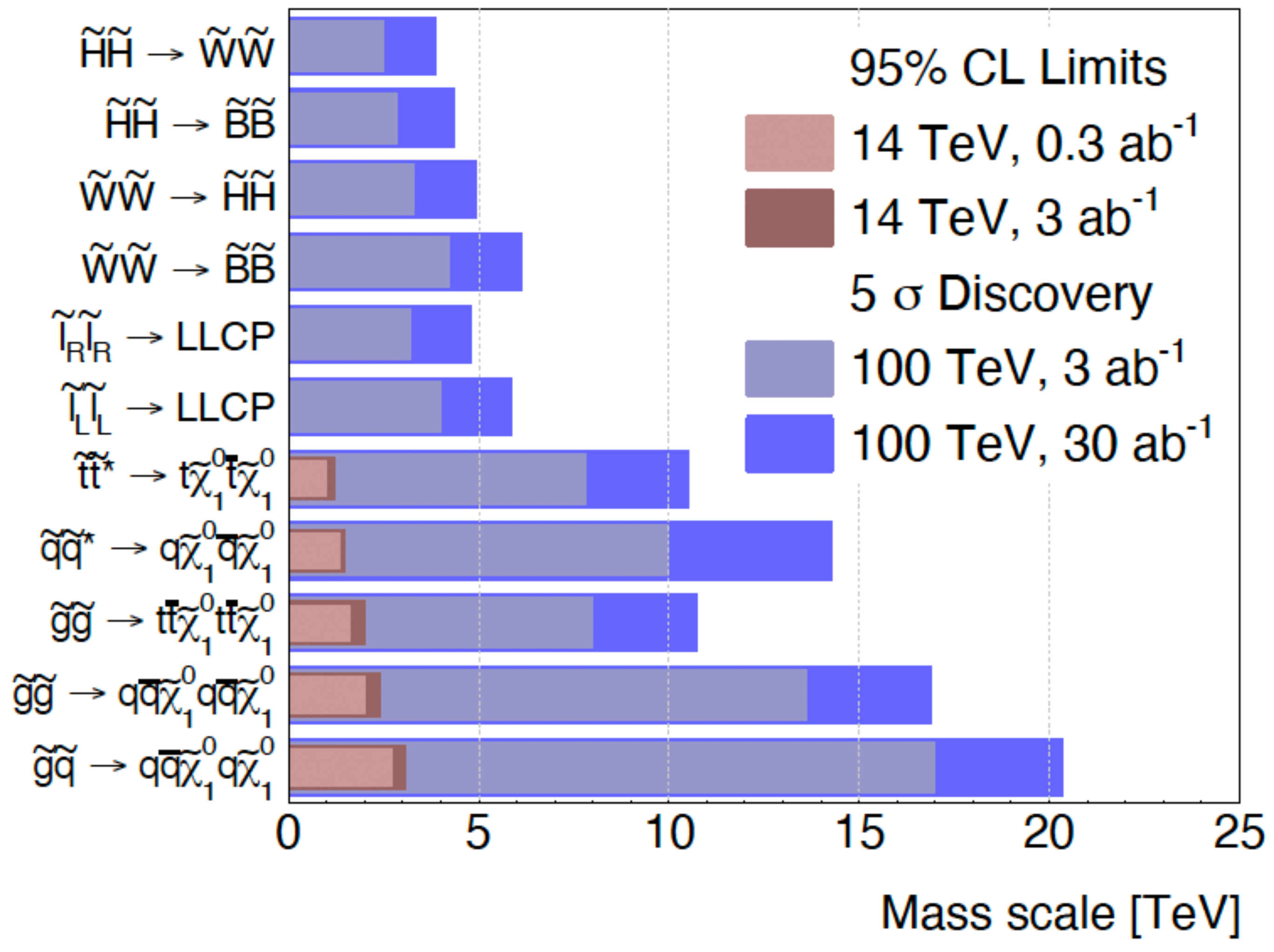
Physics at FCC-hh

- FCC-hh provides us the broadest exploration potential
  - Allows the direct exploration of new physics up 40 TeV
- An order of magnitude increase on SUSY limits compared to HL-LHC

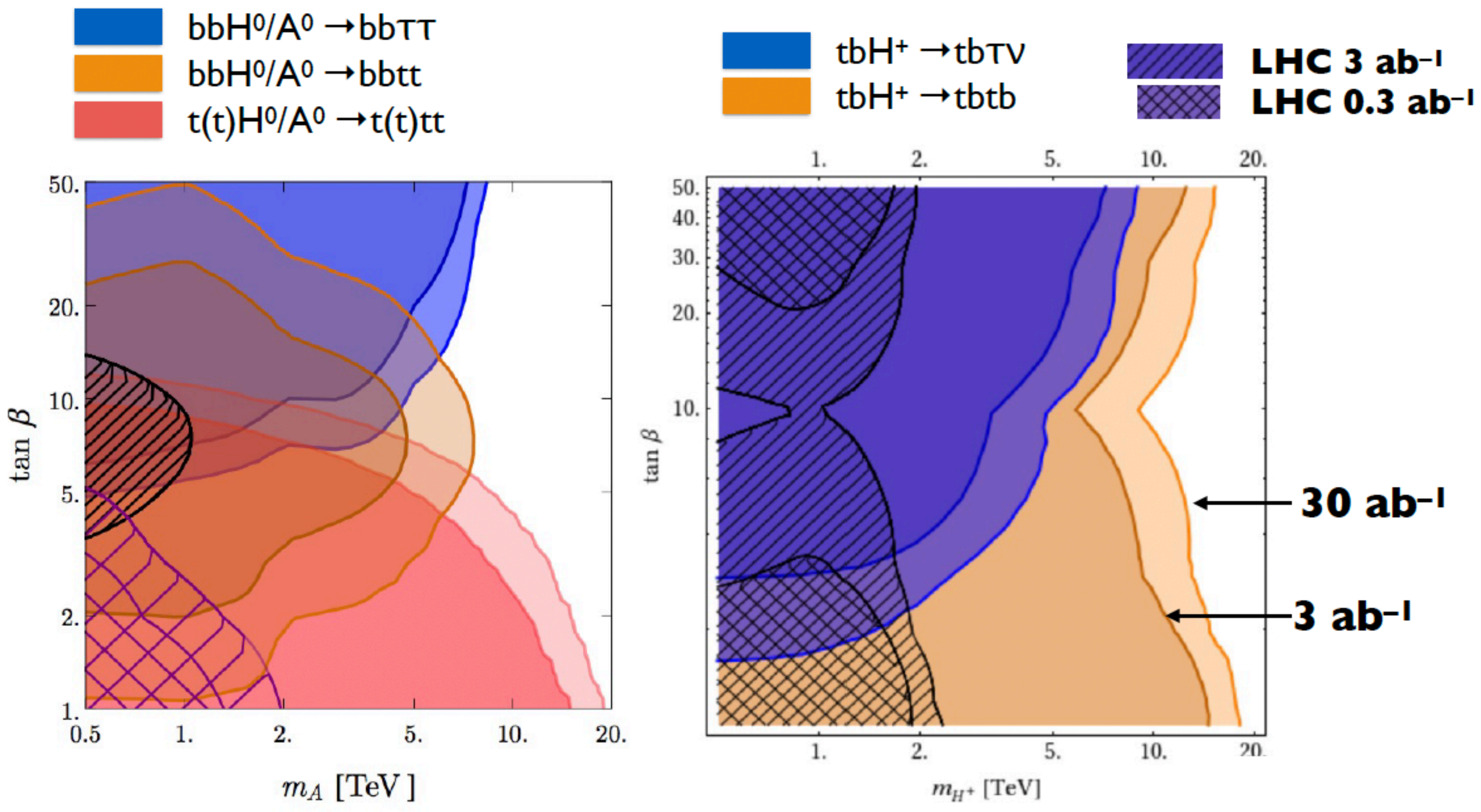


Plot from FCC CDR

SUSY



Plot from arXiv:1606.00947

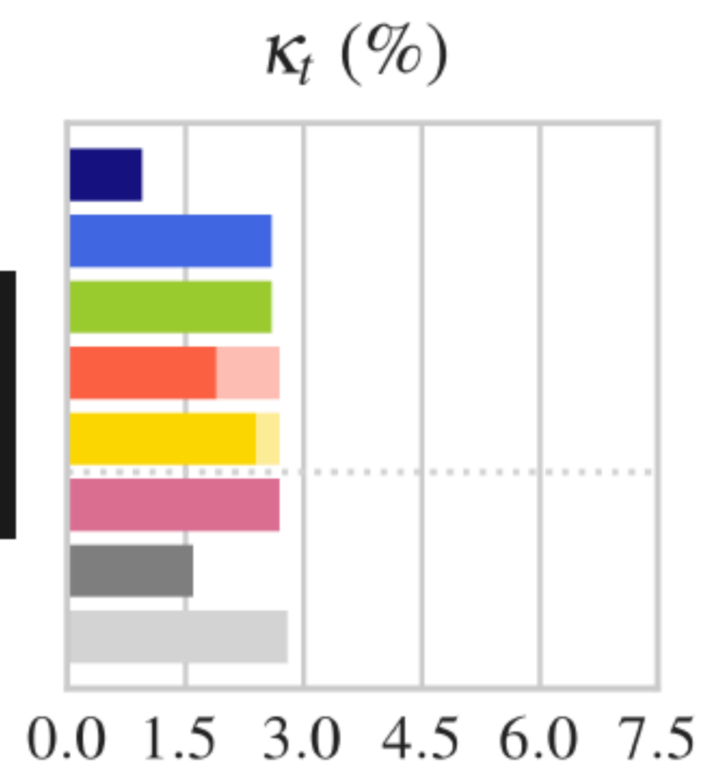


Plot from arXiv:1605.08744 and arXiv:1504.07617

Complementarity FCC-ee & FCC-hh

1 FCC-hh without ee could bound BR_{inv} but it could say nothing about $BR_{untagged}$ (FCC-ee needed for absolute normalisation of Higgs couplings)

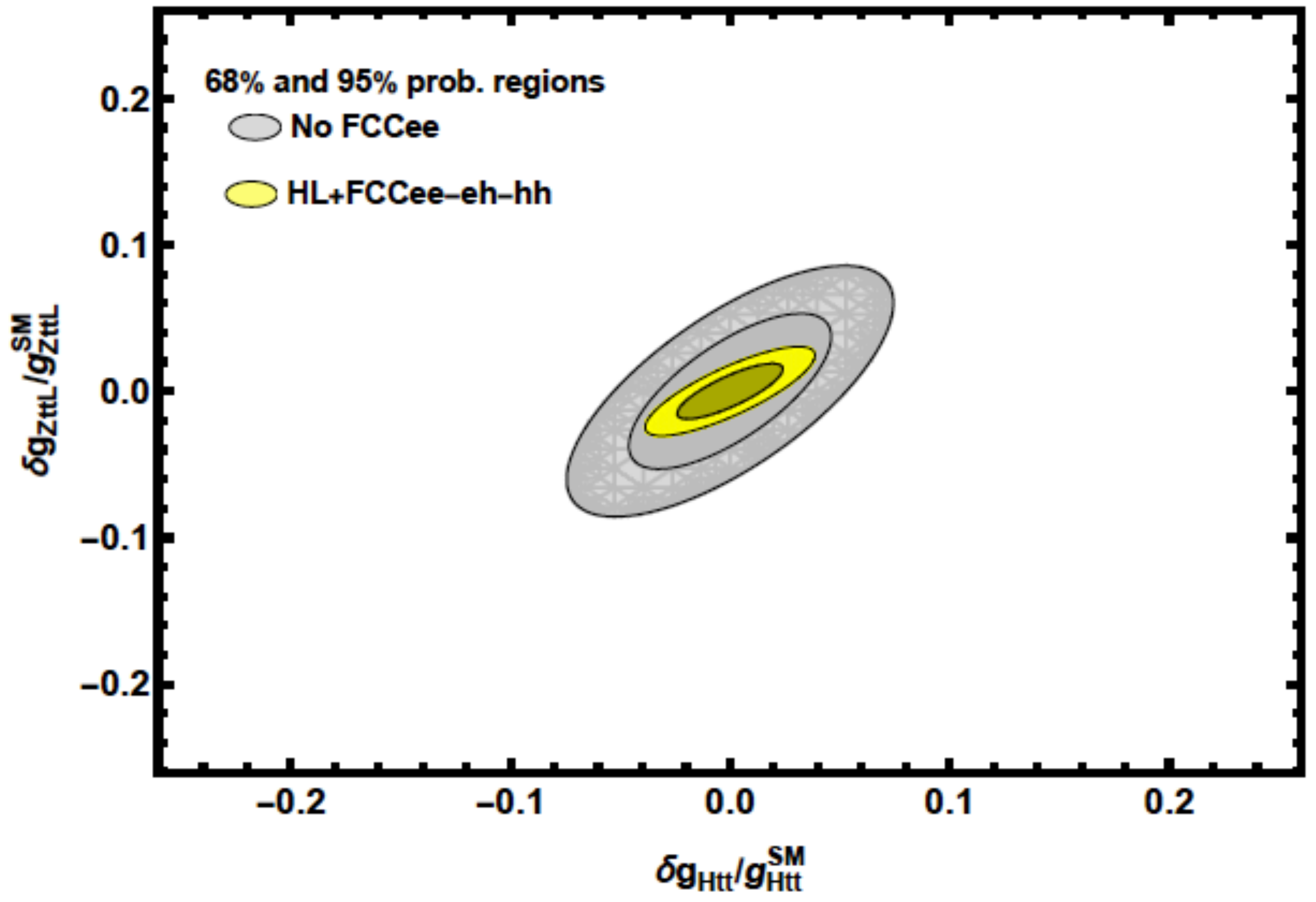
2 FCC-hh is determining top Yukawa through ratio tth/ttZ
So the extraction of top Yukawa heavily relies on the knowledge of ttZ from FCC-ee



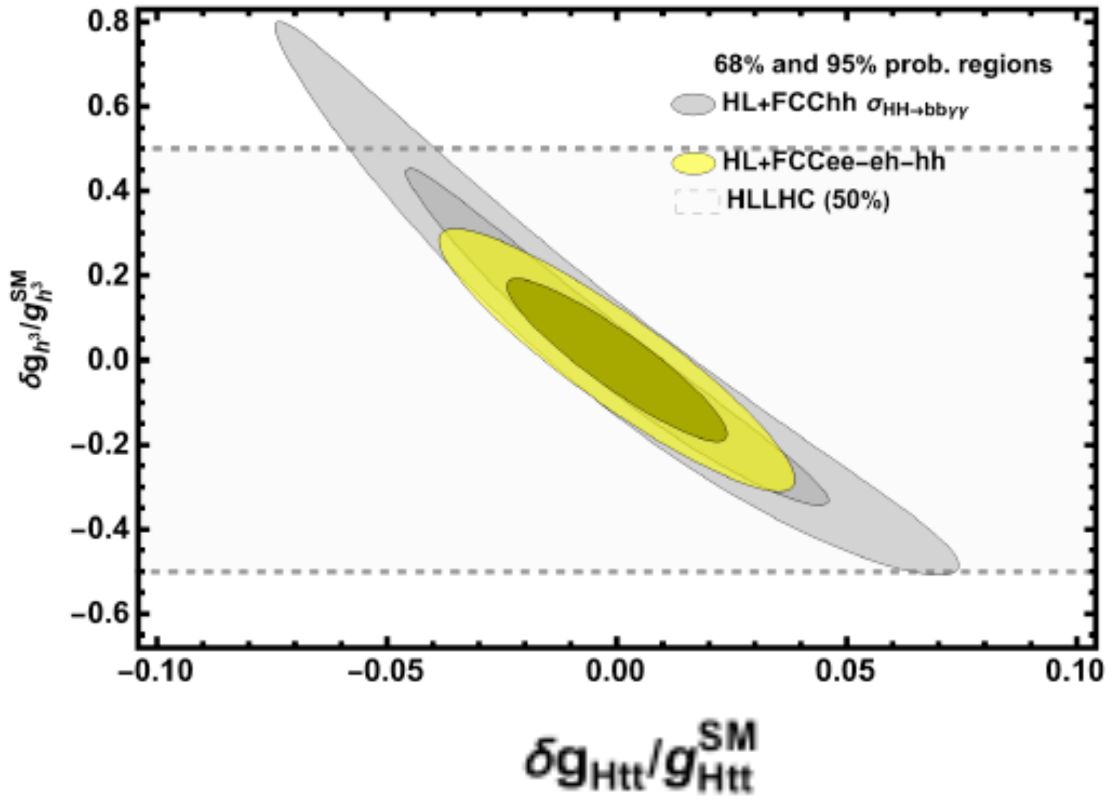
Mangano+ '15

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

(uncertainty drops in ratio)



3 Subsequently, the 1% sensitivity on tth is essential to determine h³ at O(5%) at FCC-hh



Plots from mid-term report

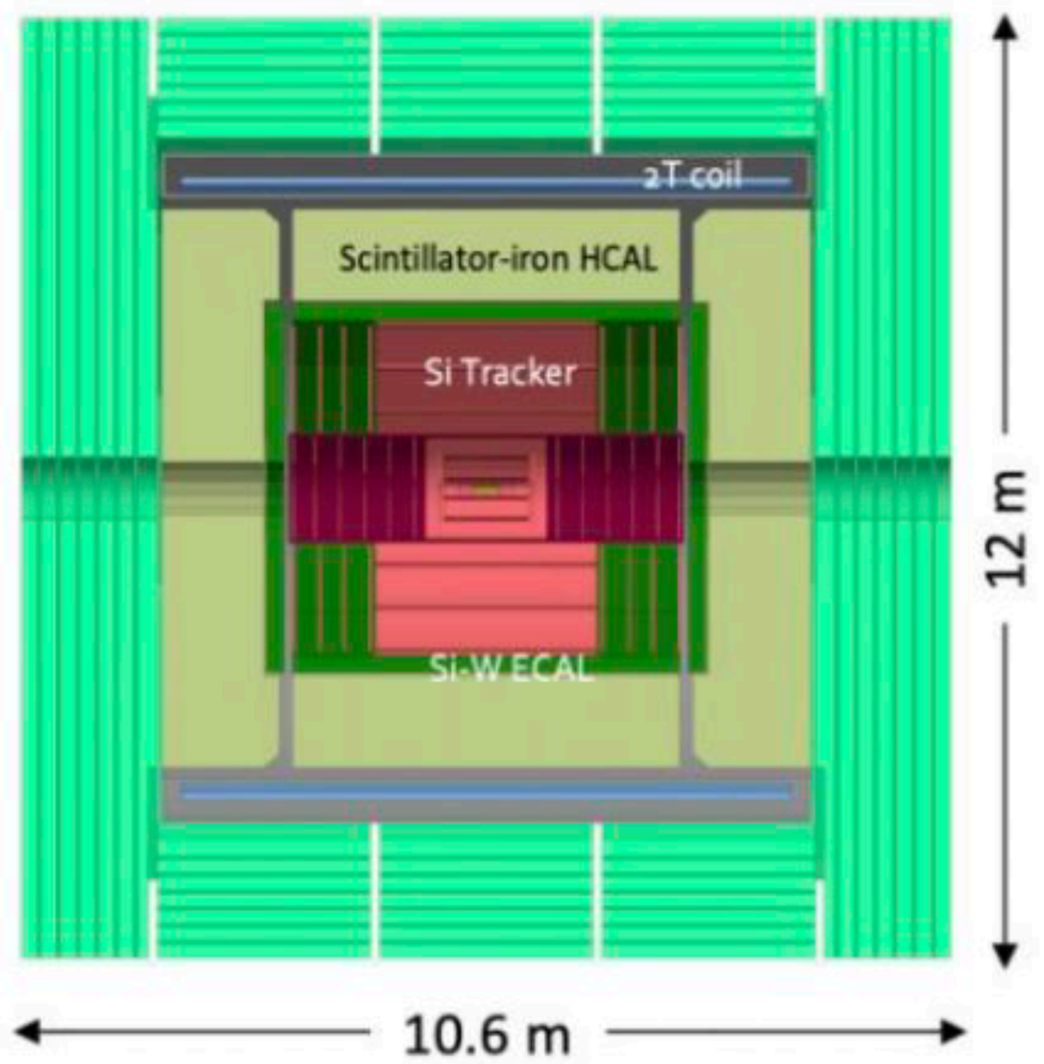
C. Grojean

The physics we need

C. Grojean, I. Vivarelli

Detector concepts fast overview

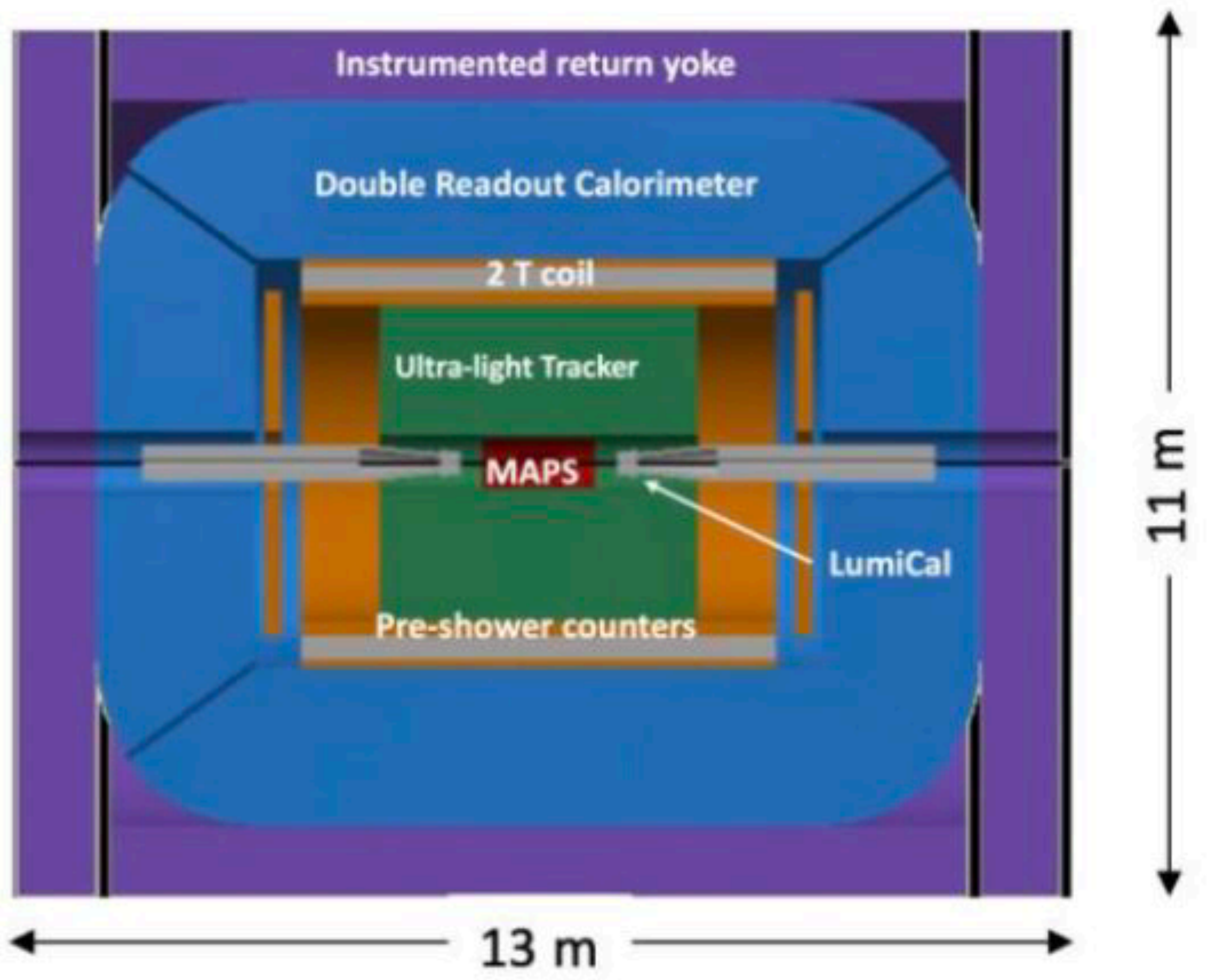
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

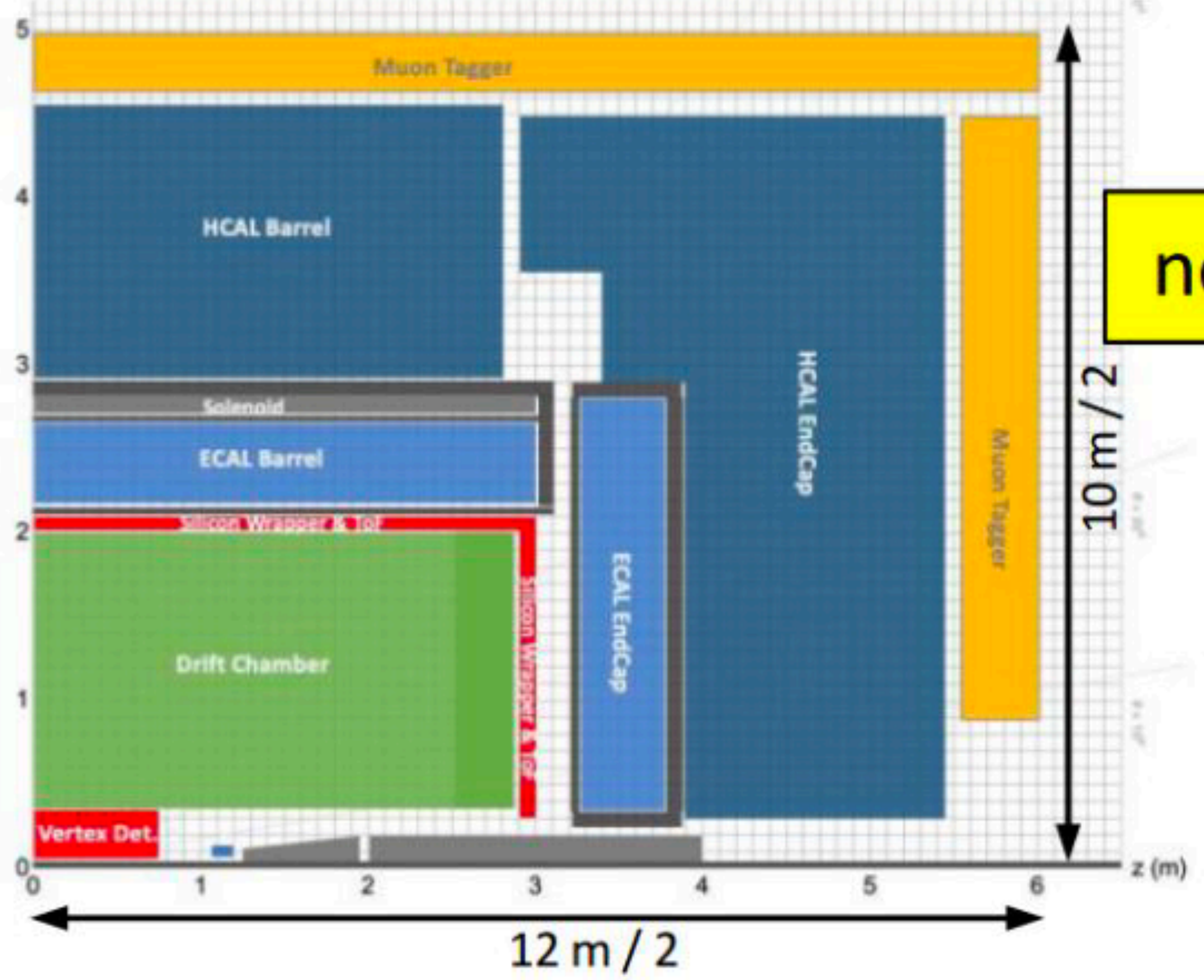
CDR

IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based



new

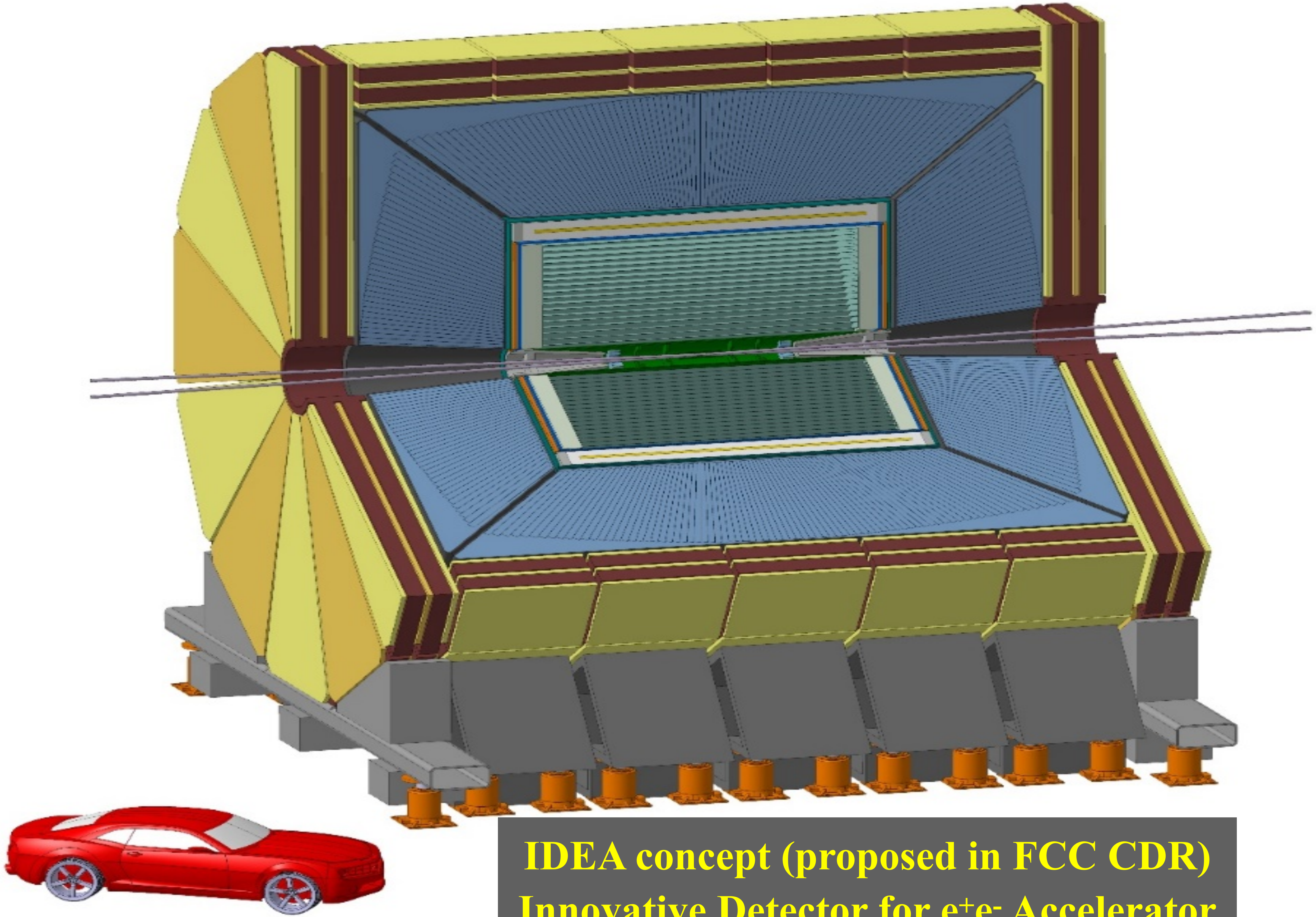
- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520 https://pos.sissa.it/390/

The IDEA detector concept

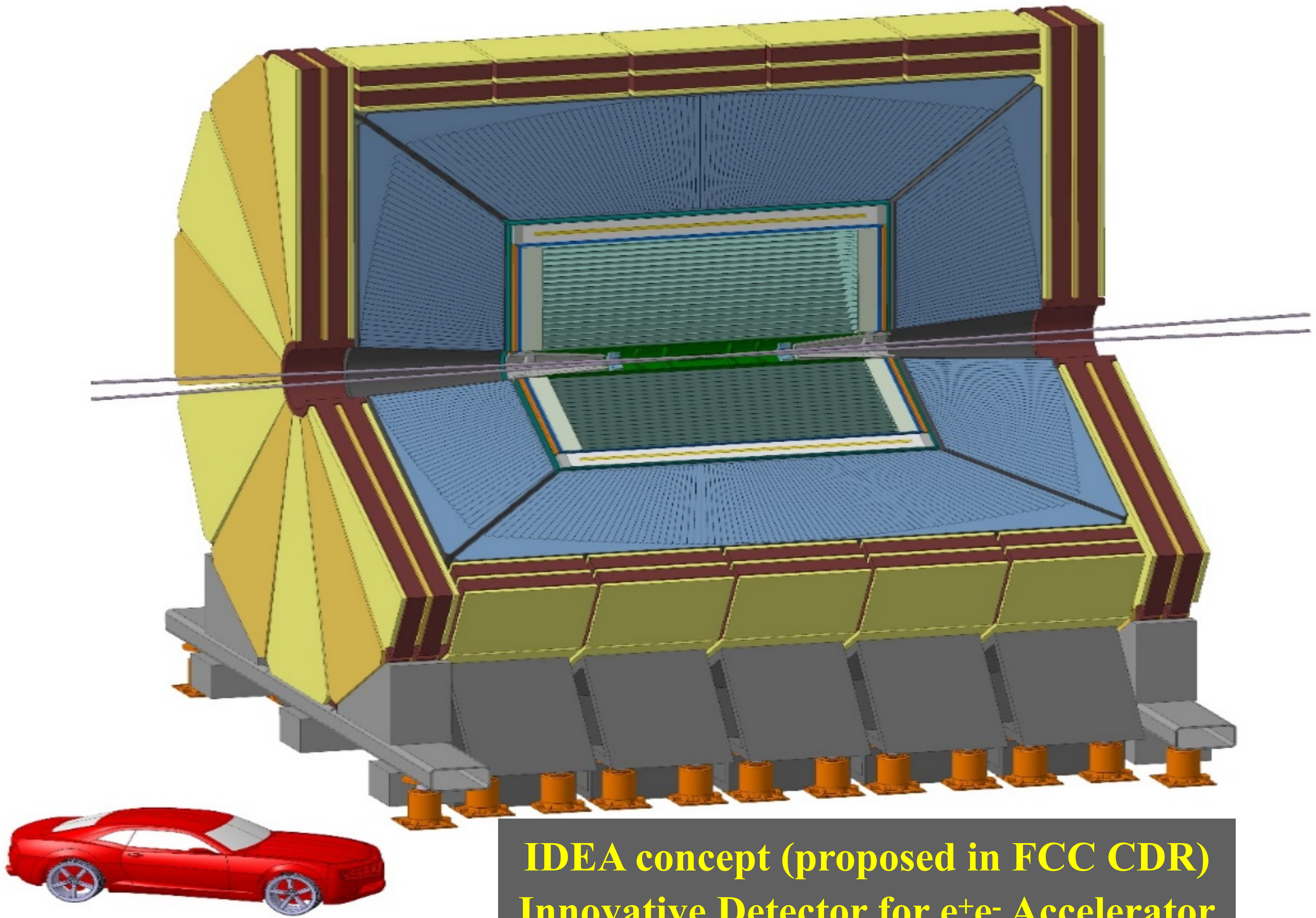
The IDEA detector concept



IDEA concept (proposed in FCC CDR)
Innovative Detector for e^+e^- Accelerator

The IDEA detector concept

- **New, innovative, possibly more cost-effective concept**



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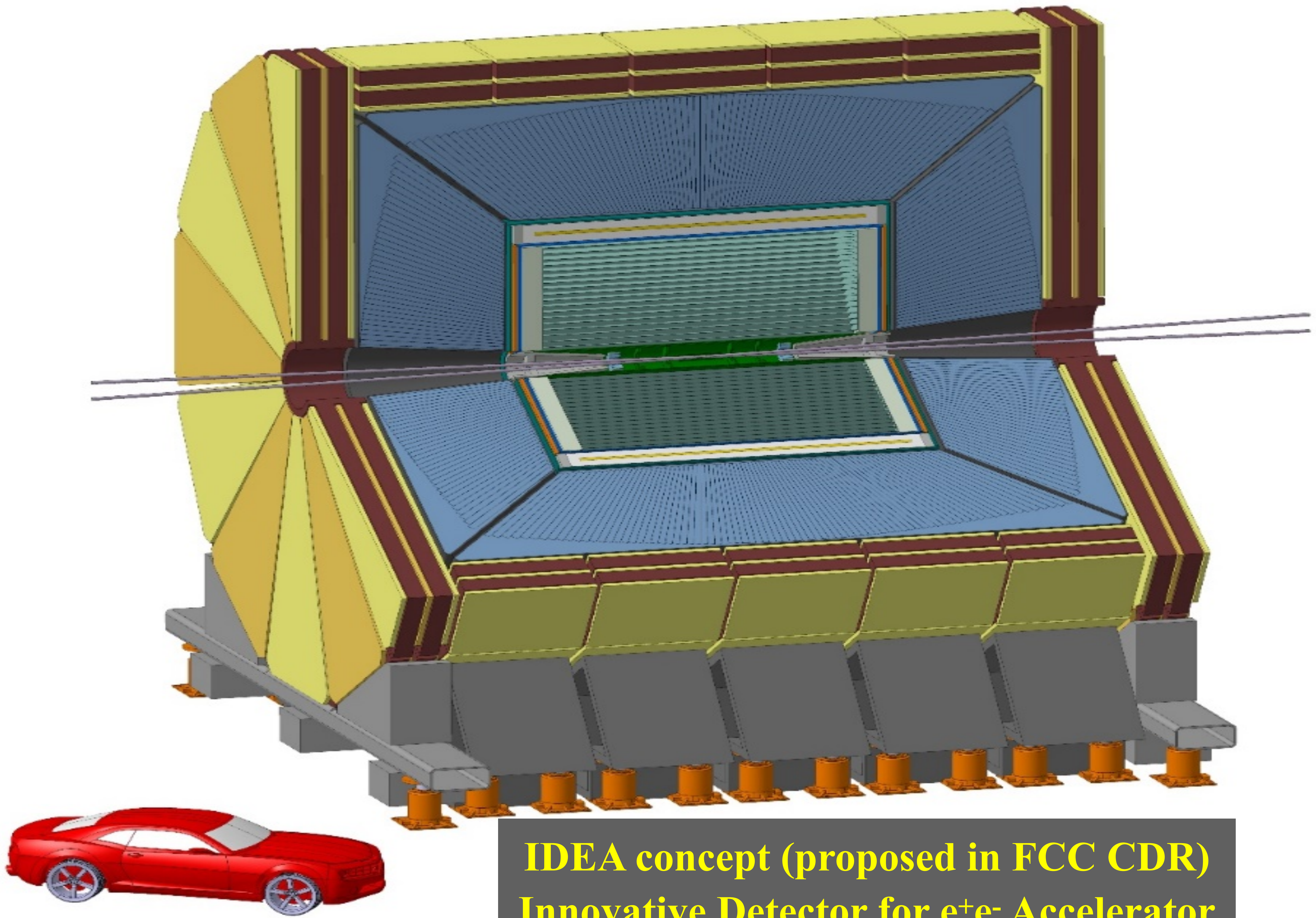

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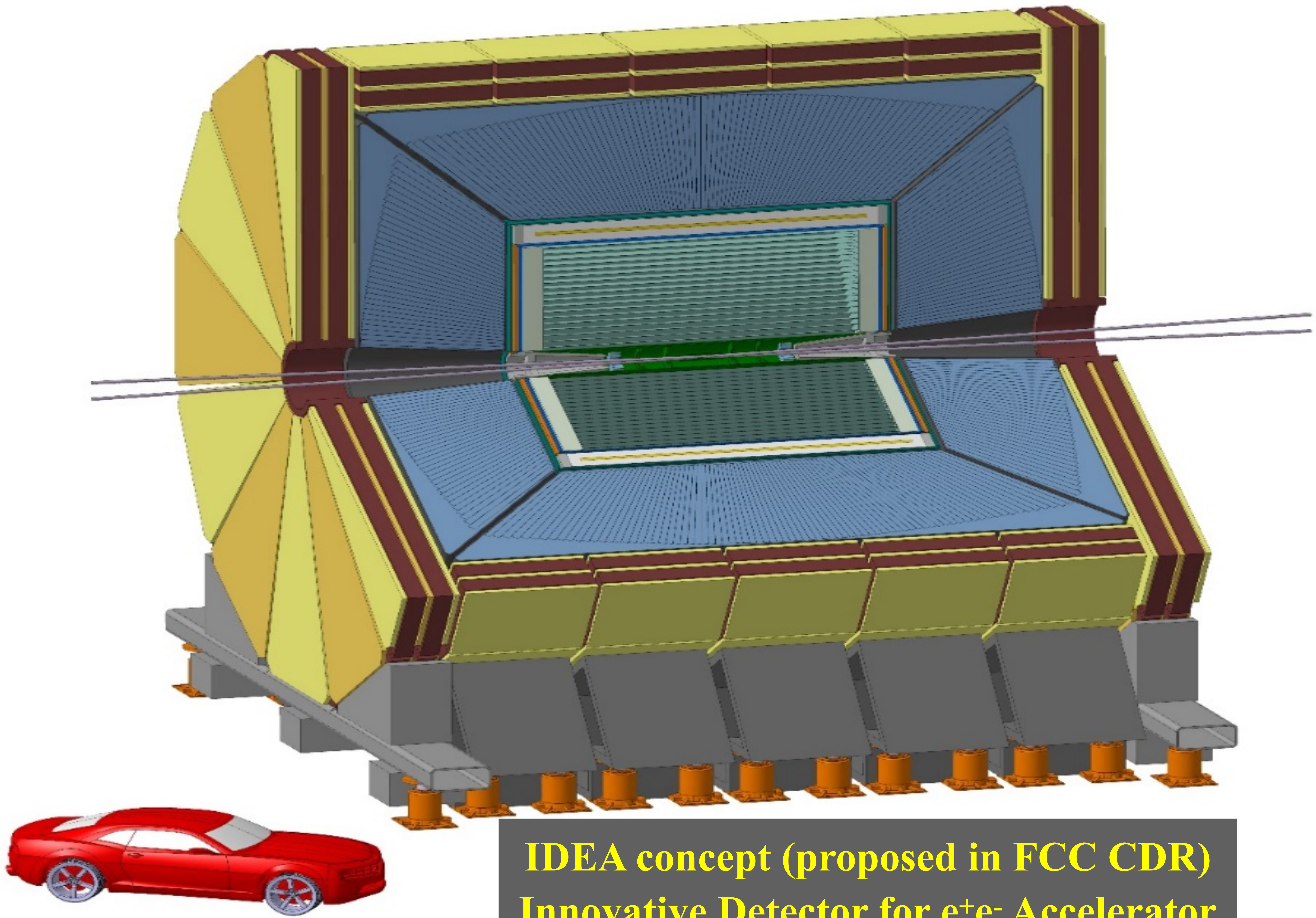

IDEA concept (proposed in FCC CDR)
Innovative Detector for e^+e^- Accelerator

- **New, innovative, possibly more cost-effective concept**
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  - Short-drift, ultra-light wire chamber

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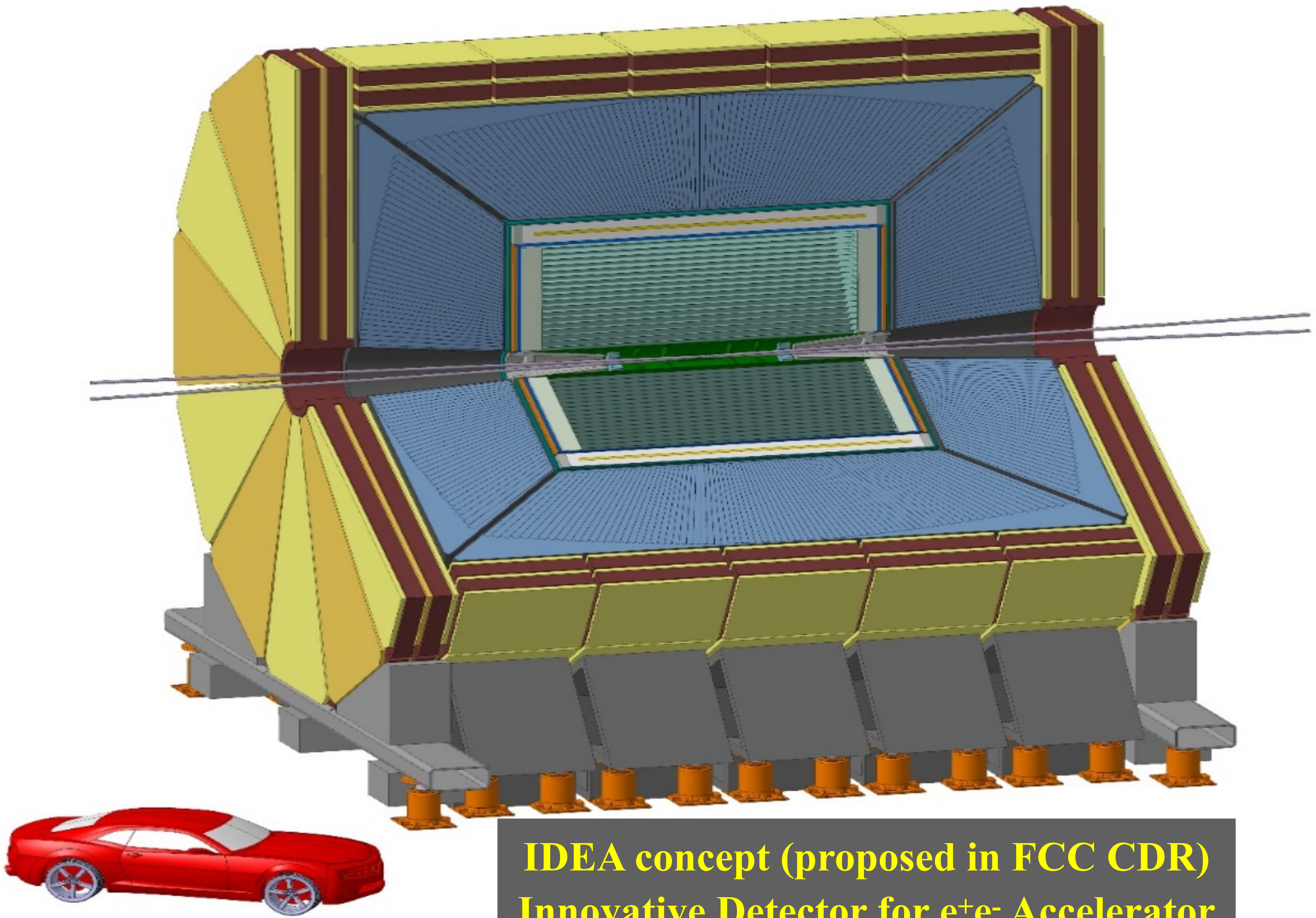

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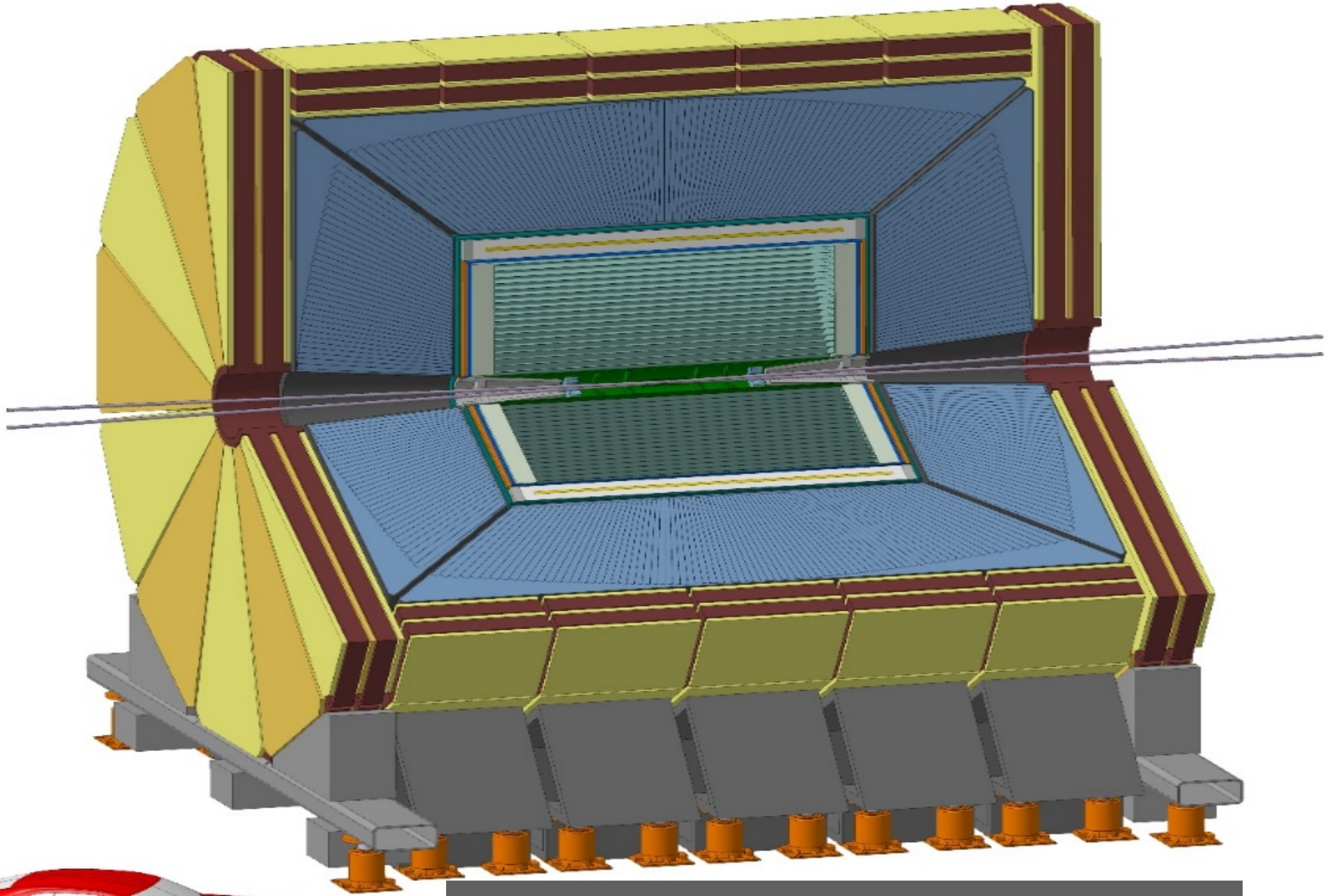

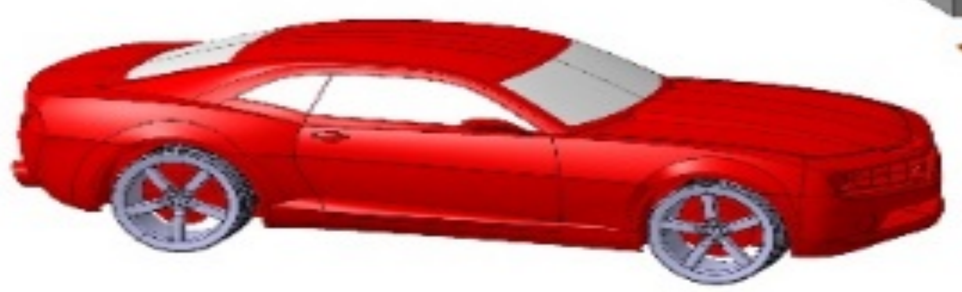

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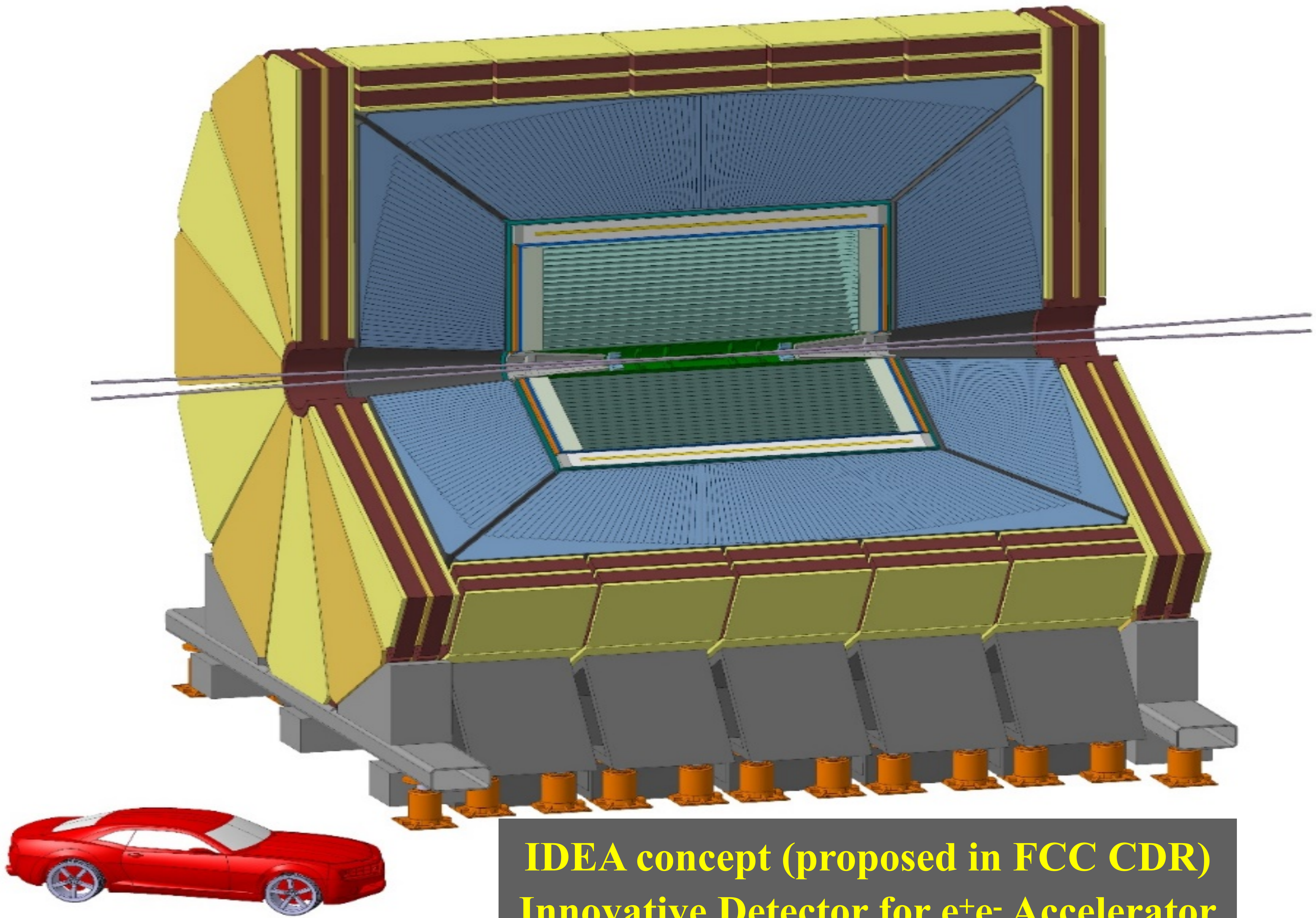

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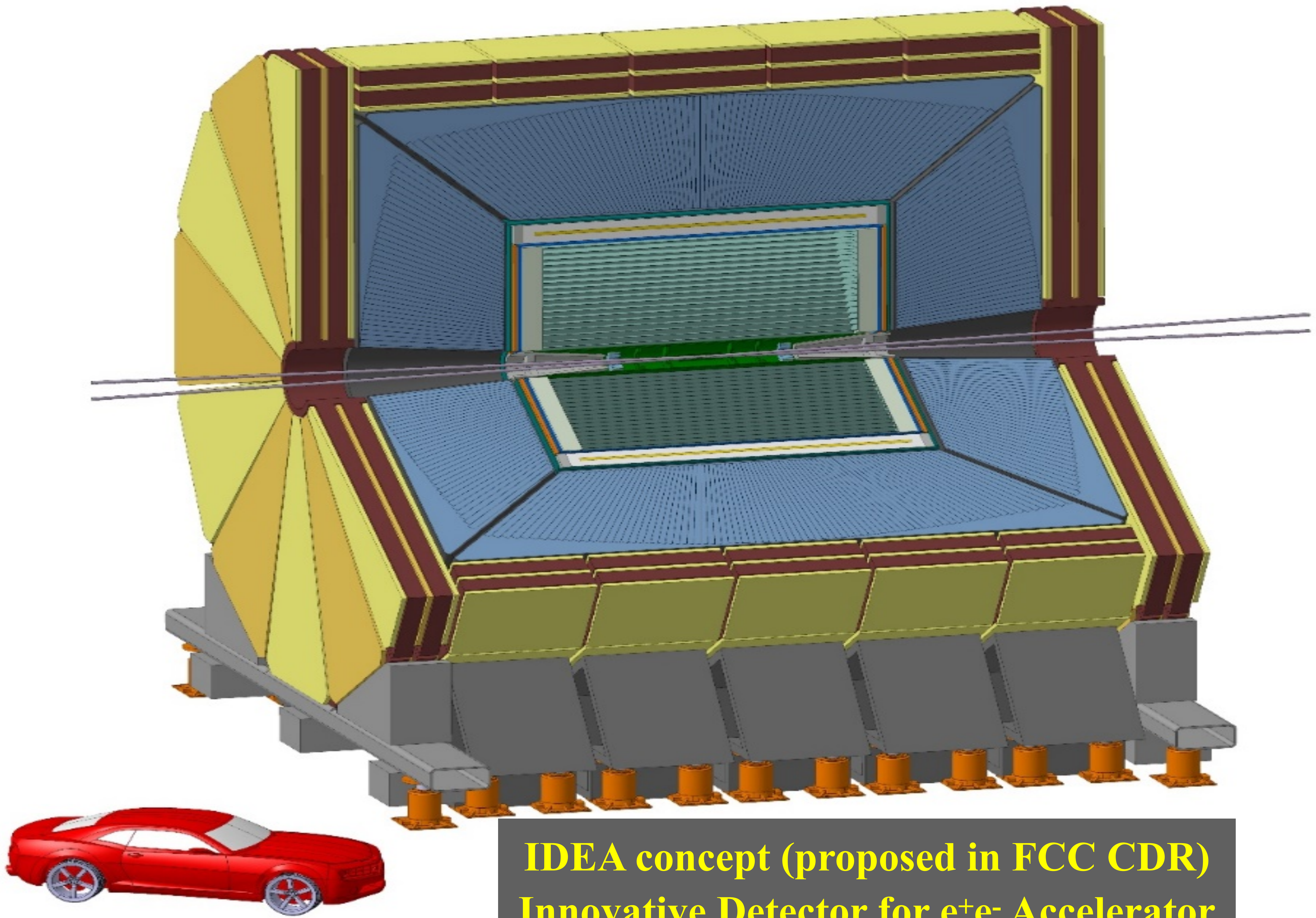

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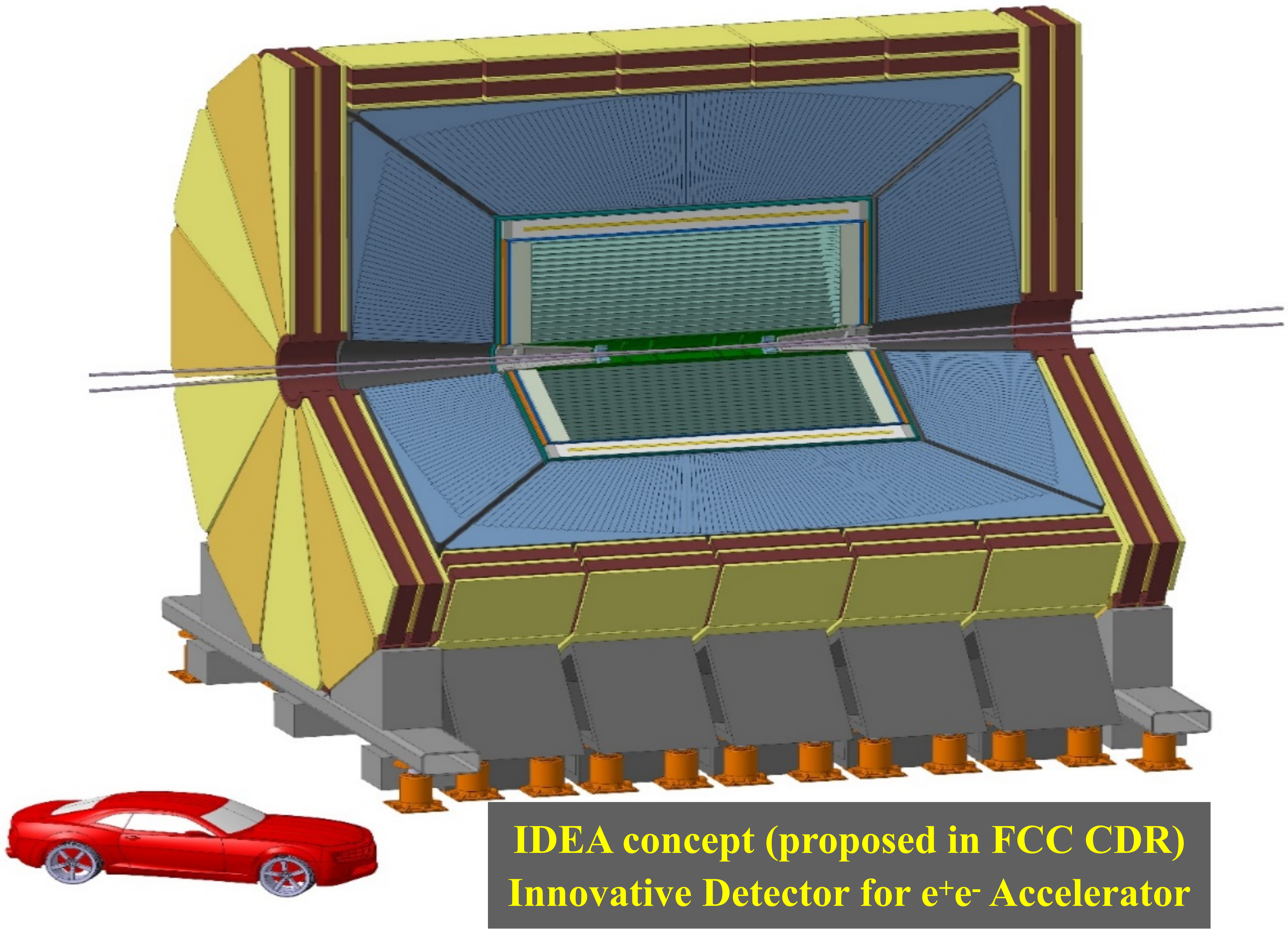

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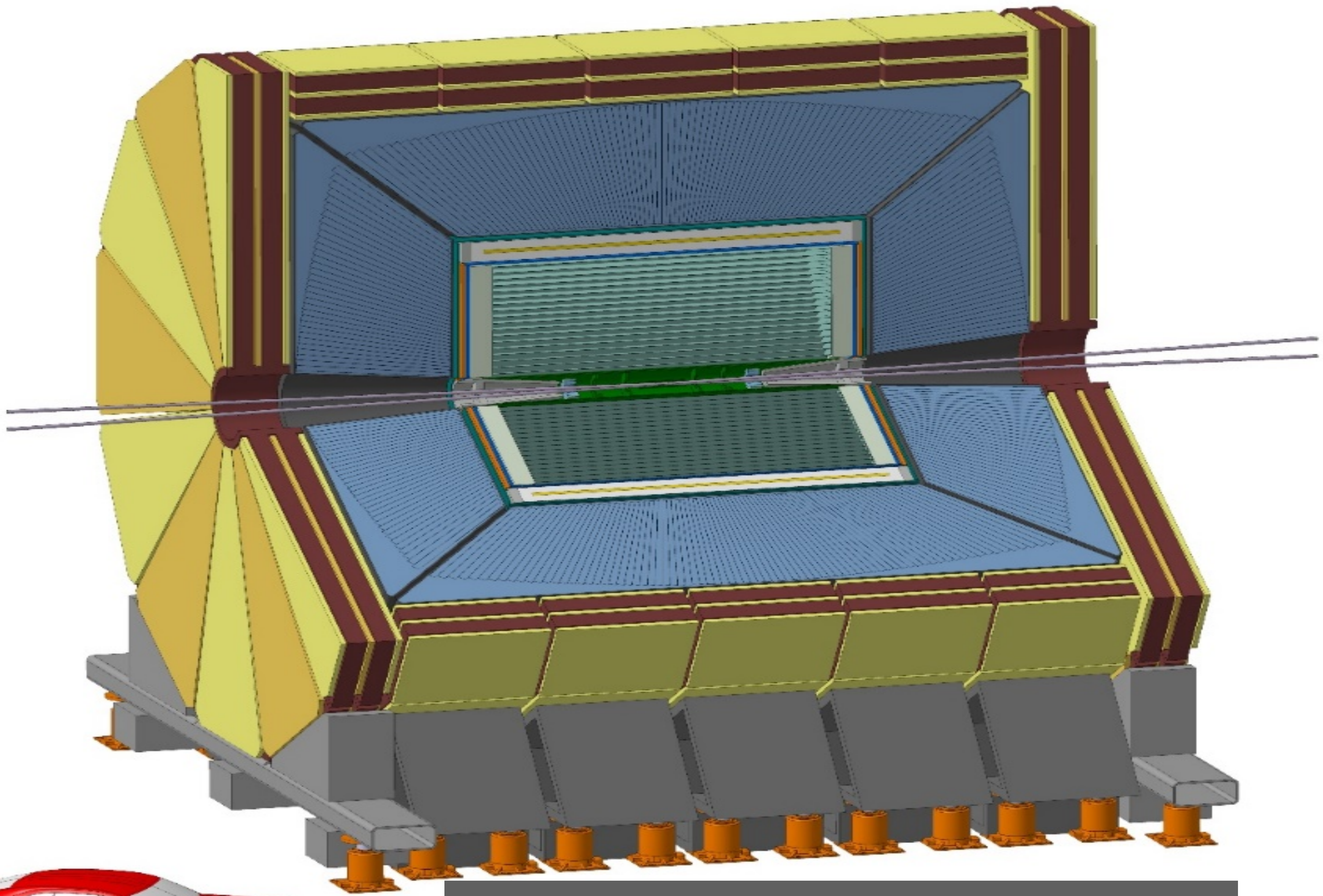
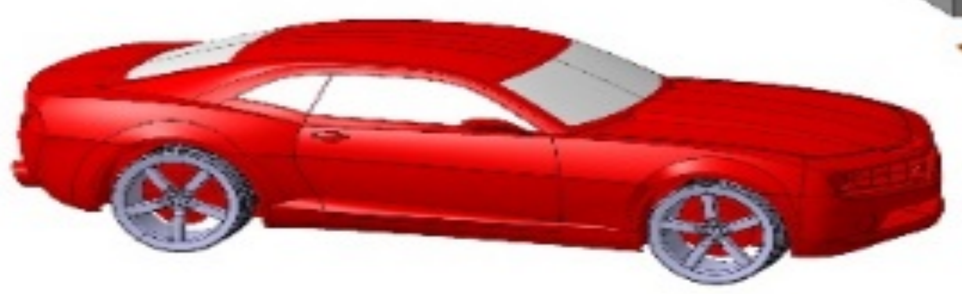
https://pos.sissa.it/390/

FUTURE CIRCULAR COLLIDER

The IDEA detector concept

INFN Istituto Nazionale di Fisica Nucleare





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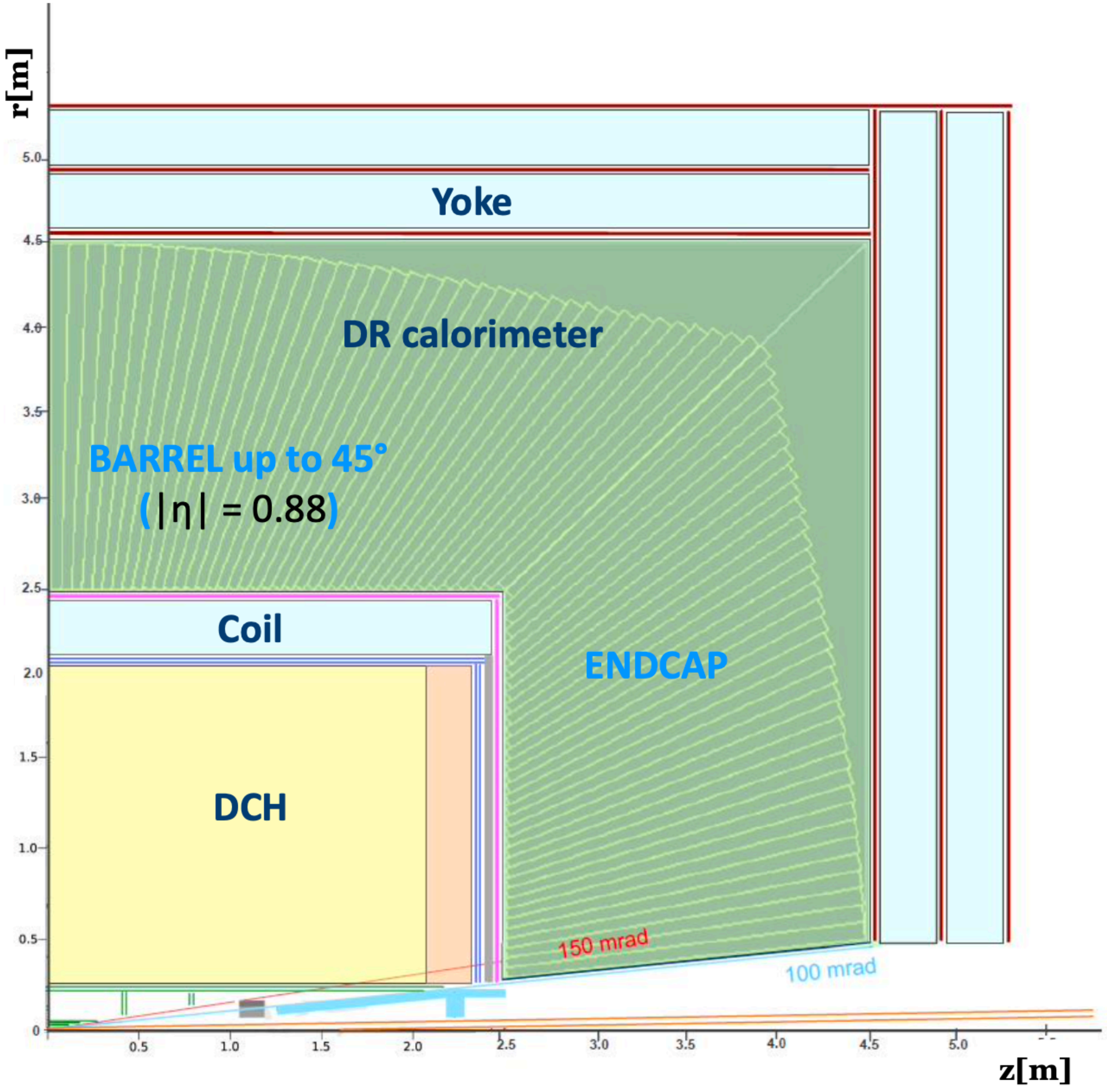
Acknowledgments
I need to thank many colleagues, in particular:
F. Bedeschi

IDEA detector layout

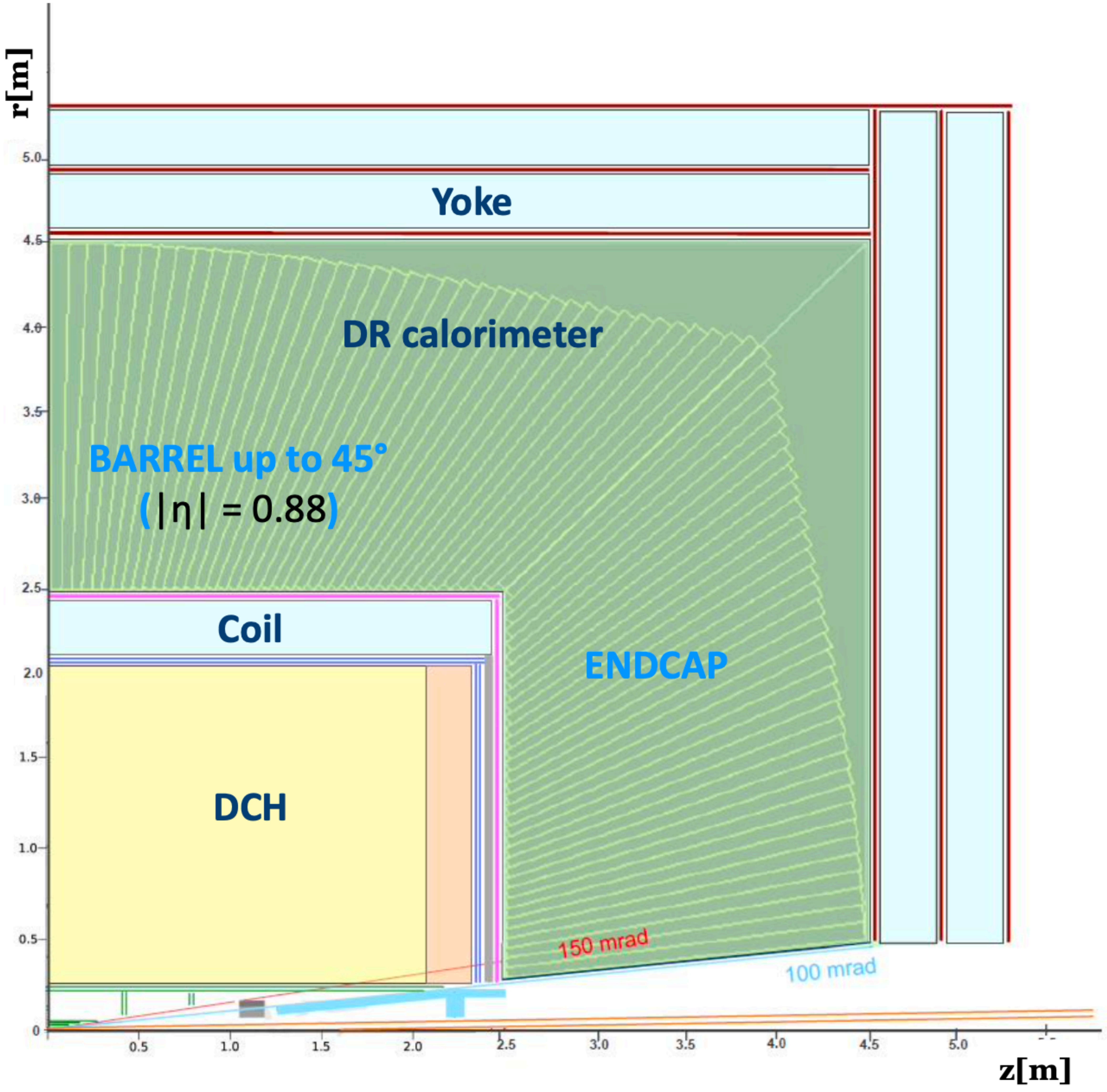


FUTURE CIRCULAR COLLIDER

IDEA detector layout

INFN Istituto Nazionale di Fisica Nucleare

Beam pipe: R~1.2 cm



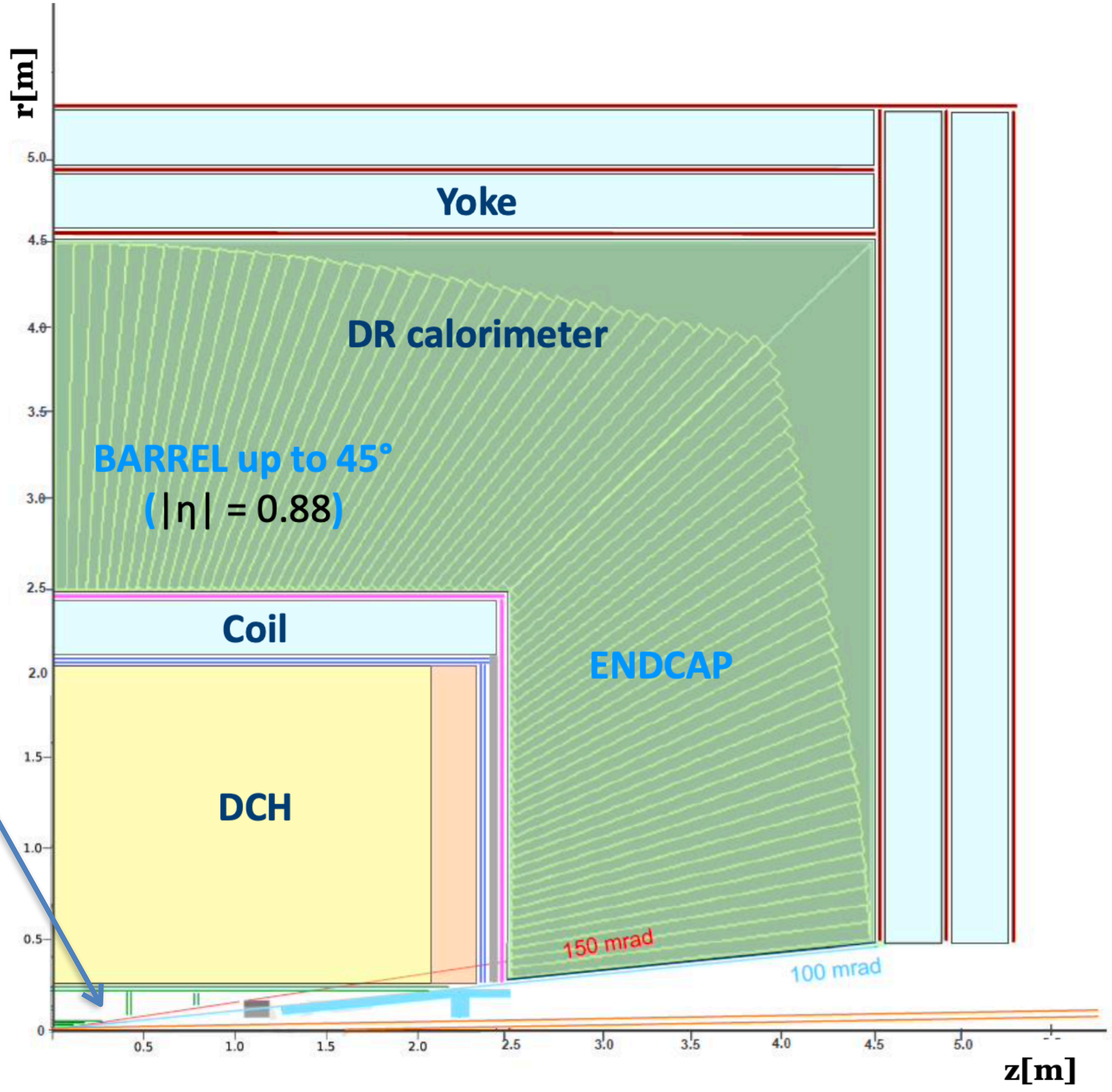
IDEA detector layout

Beam pipe: R~1.2 cm

Vertex:

5 MAPS layers

R = 1.37-31.5 cm



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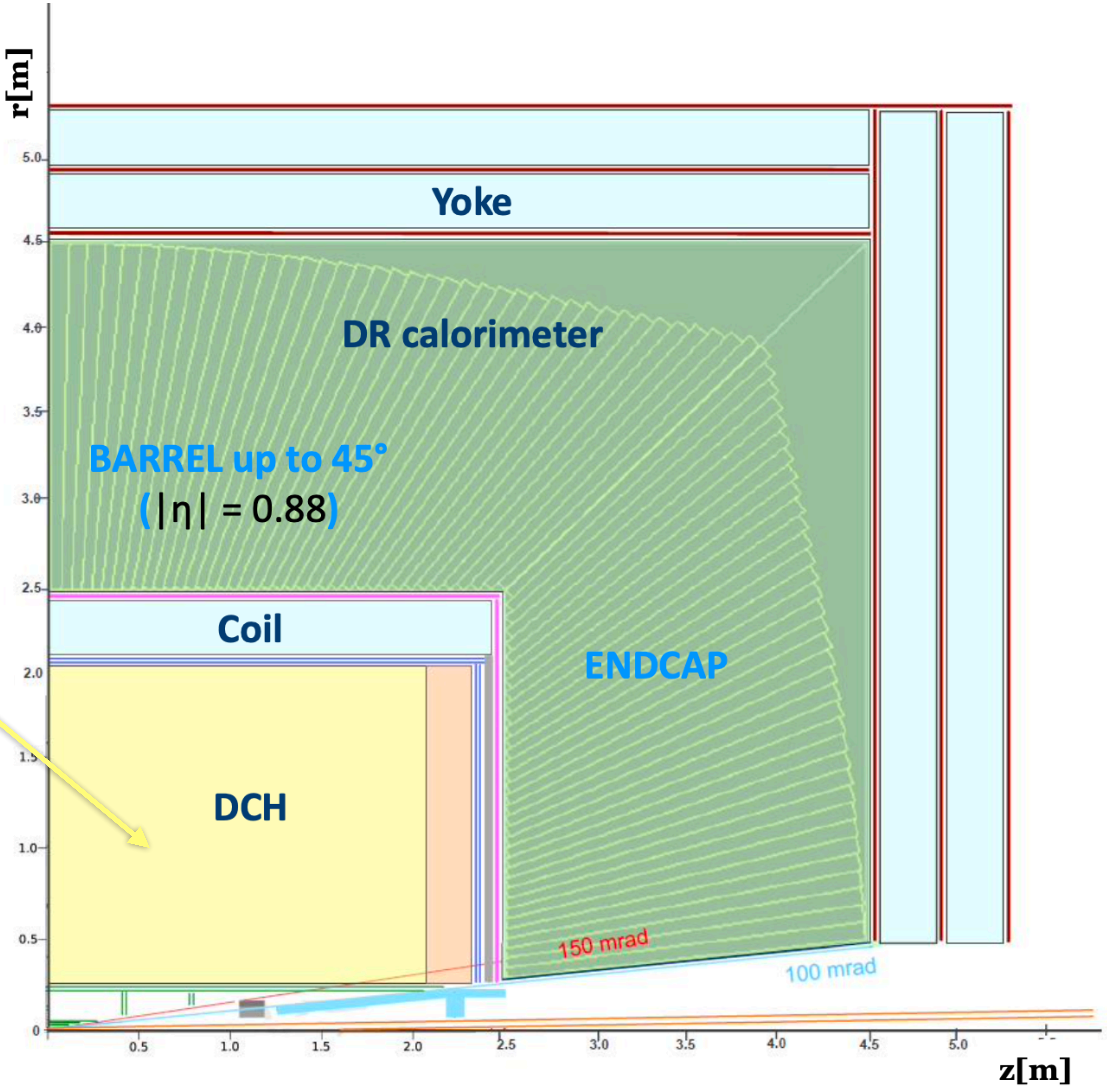
Drift Chamber: 112 layers

4 m long, R = 35-200 cm



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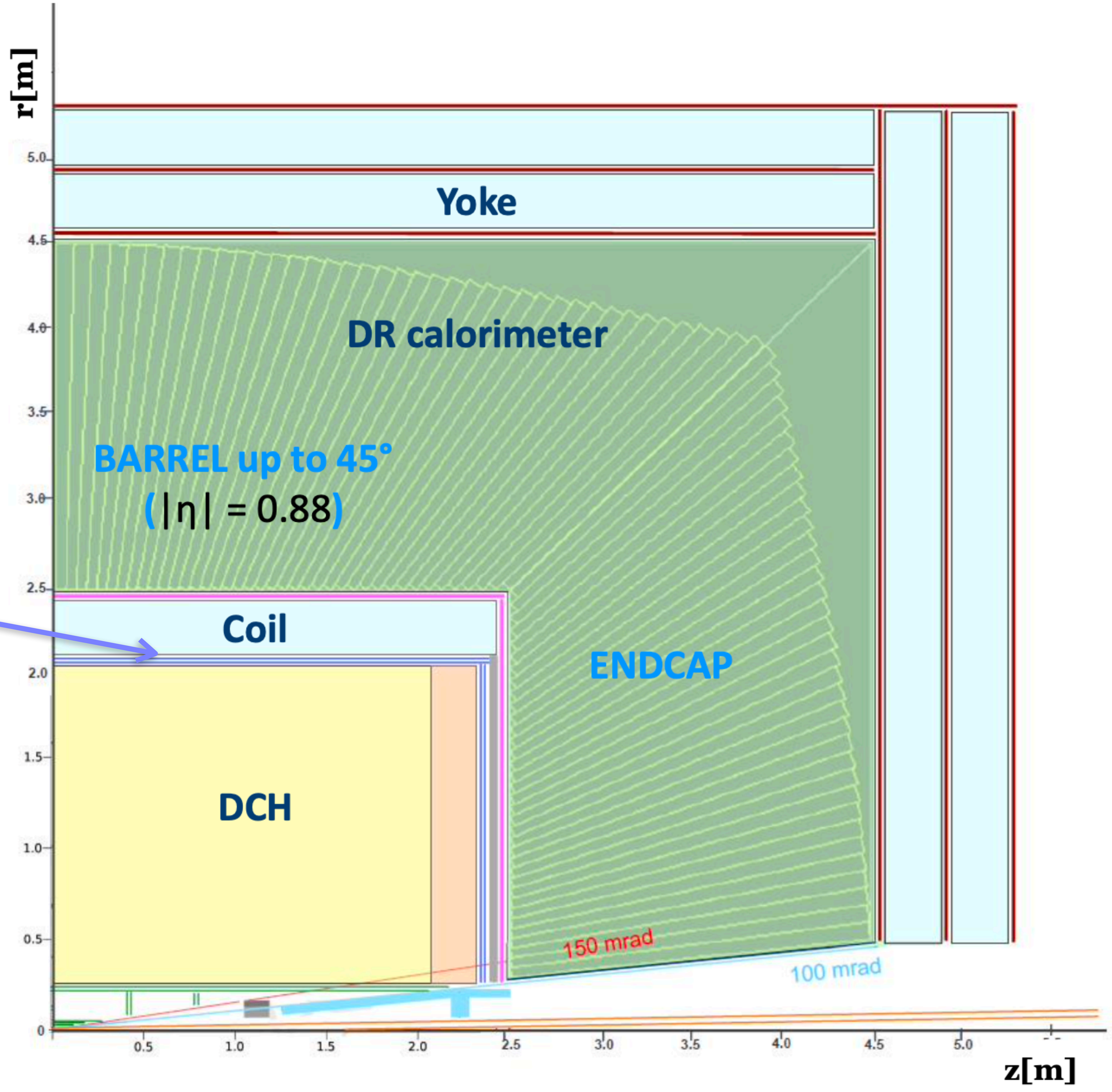
Si strips



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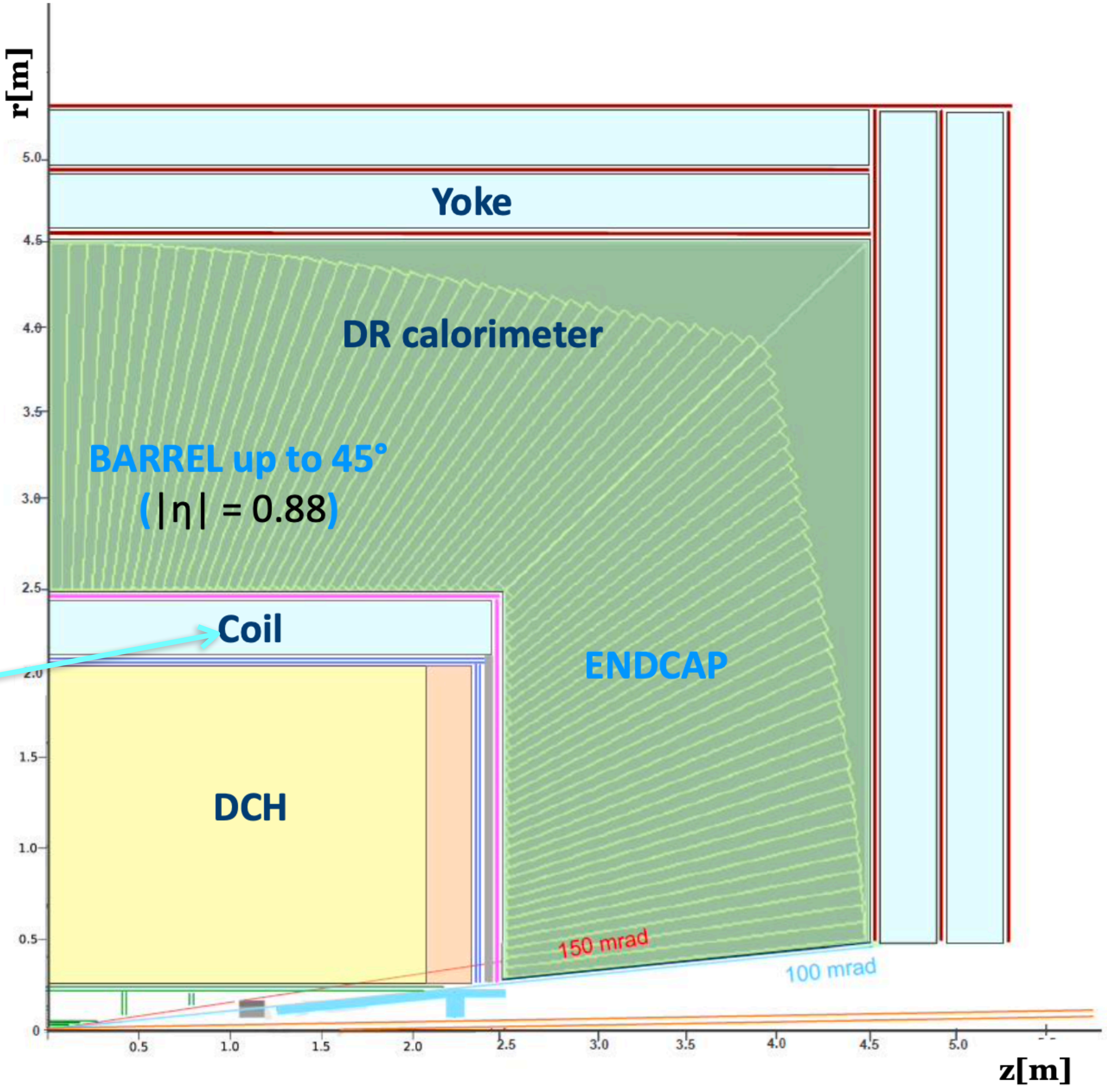
Superconducting solenoid coil:

2 T, R ~ 2.1-2.4 m

0.74 X_0, 0.16 λ @ 90°



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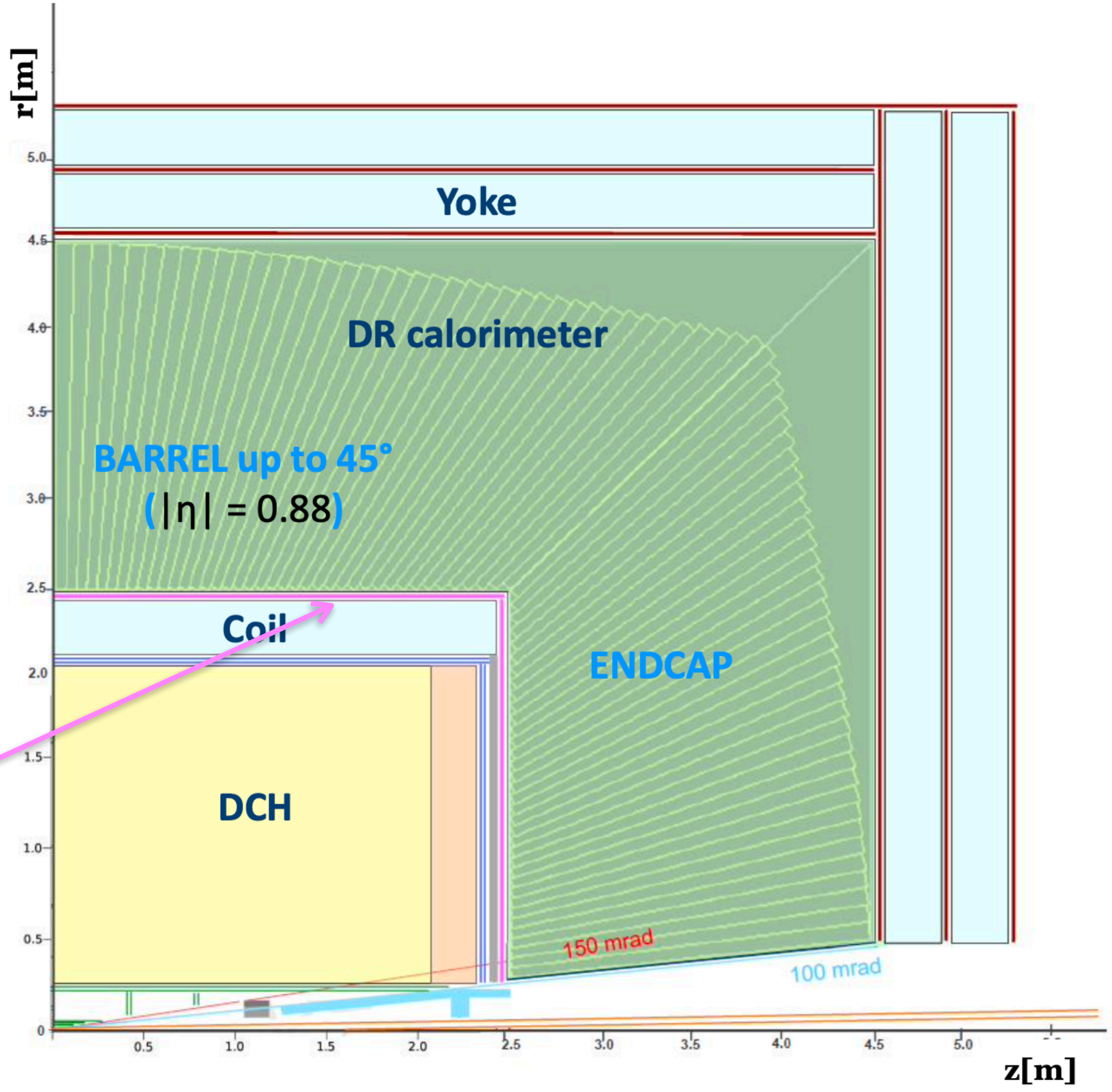

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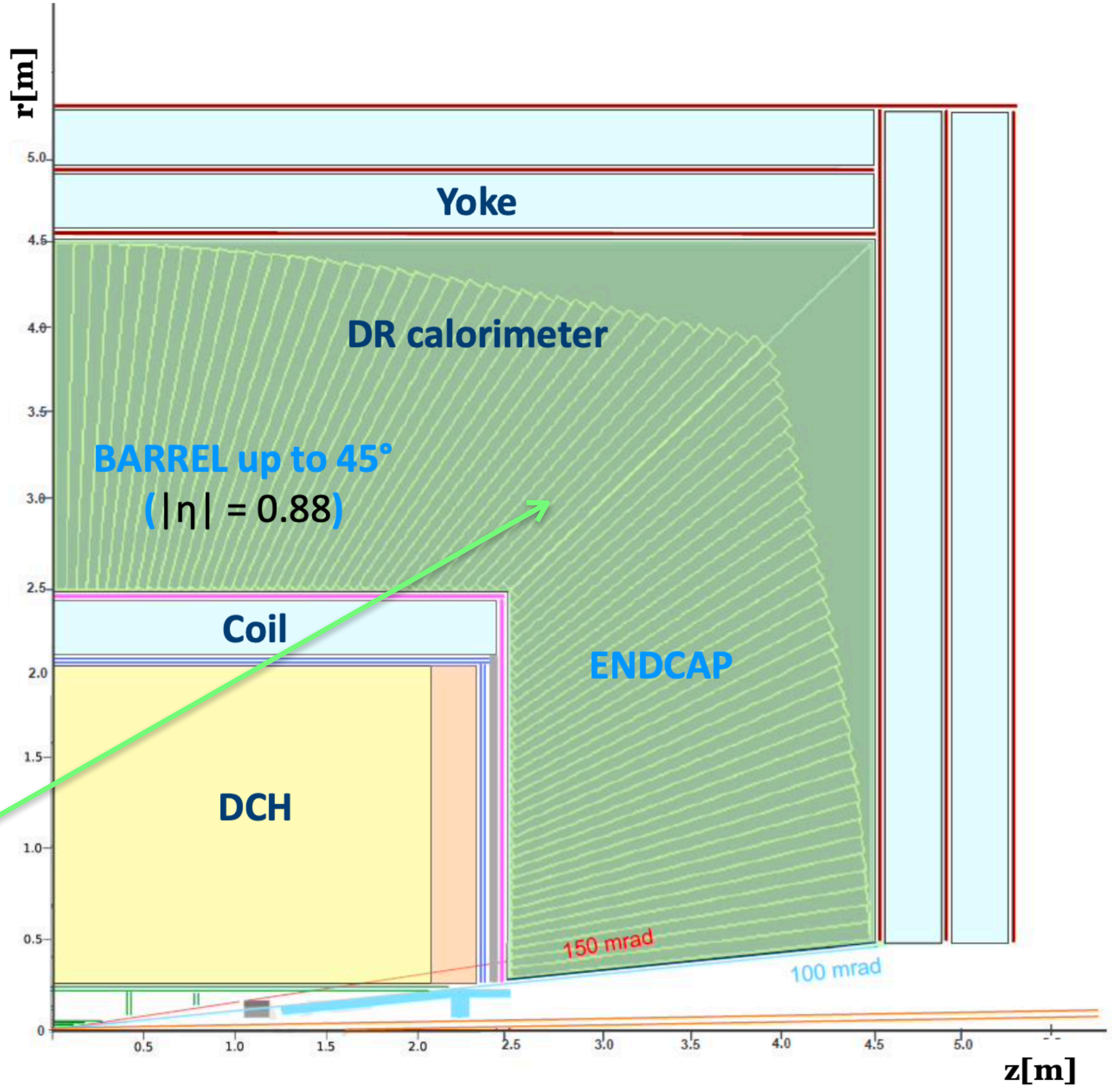
2m / 7 λ_{int}



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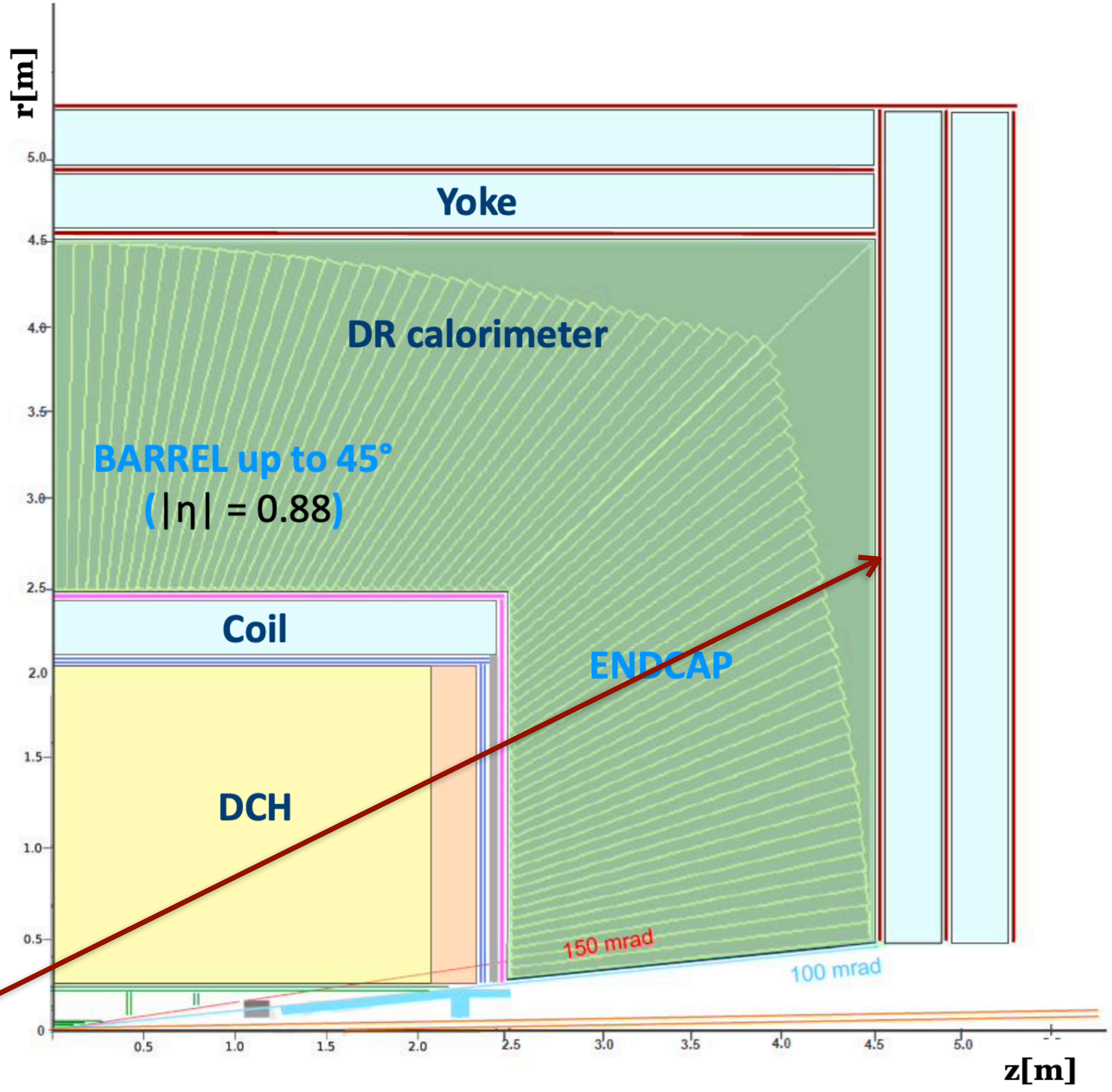
Yoke + Muon chambers



Vertex detector: IDEA

Mid-term review vertex detector overall layout

F. Palla

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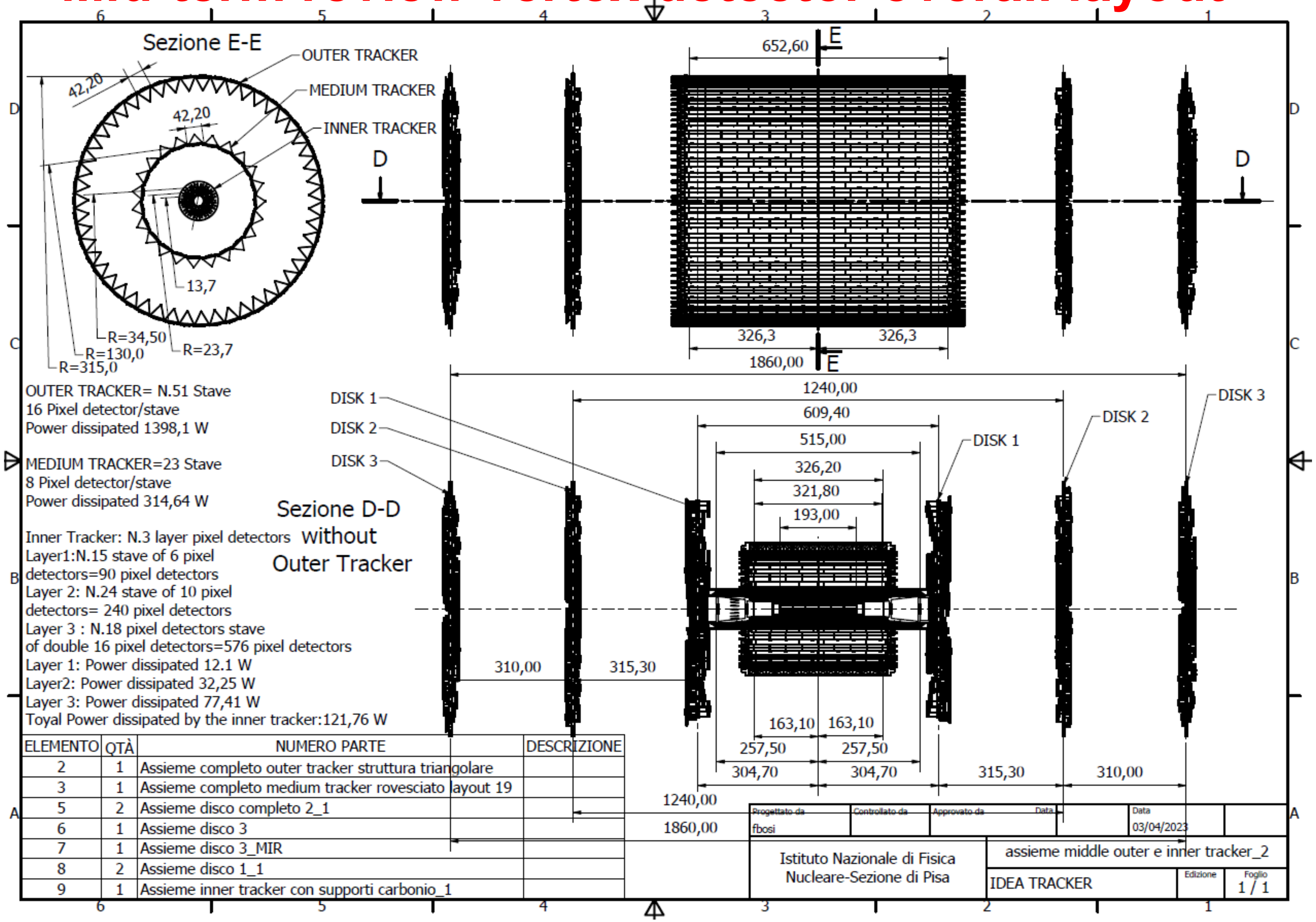
Mid-term review vertex detector overall layout

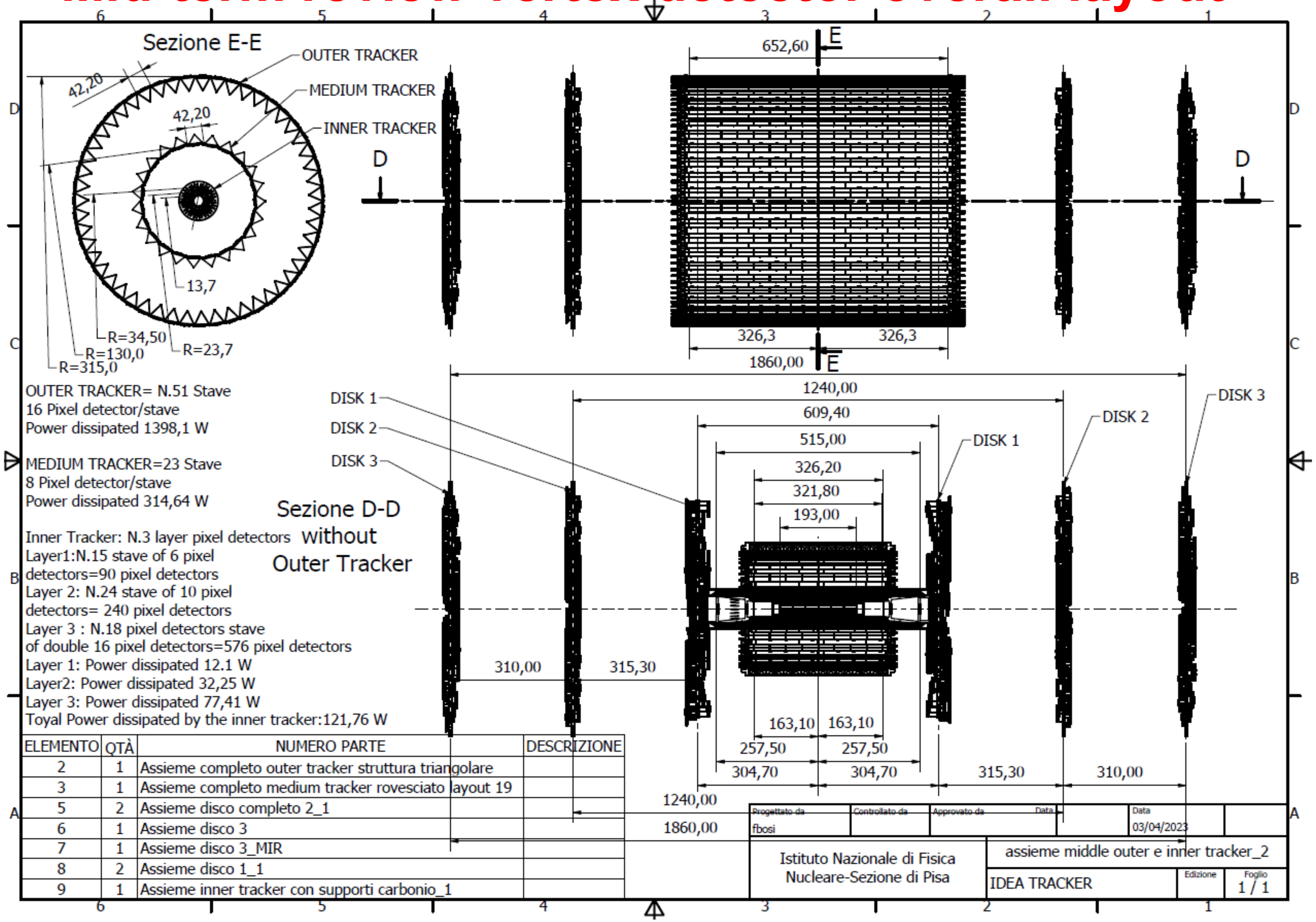


ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
2	1	Assieme completo outer tracker struttura triangolare	
3	1	Assieme completo medium tracker rovesciato layout 19	
5	2	Assieme disco completo 2_1	
6	1	Assieme disco 3	
7	1	Assieme disco 3_MIR	
8	2	Assieme disco 1_1	
9	1	Assieme inner tracker con supporti carbonio_1	

F. Palla

Vertex detector: IDEA

Mid-term review vertex detector overall layout



Inner Vertex detector:

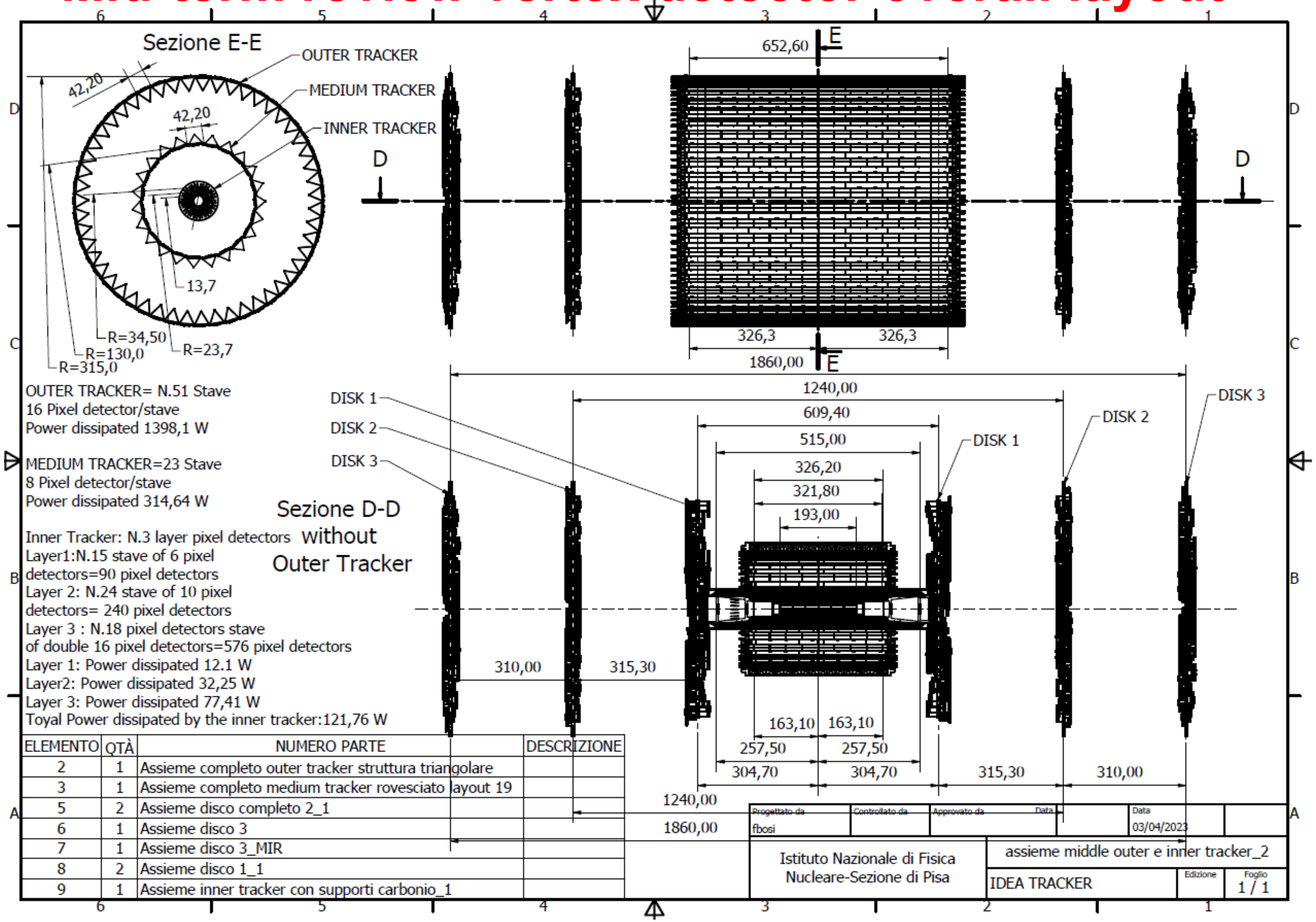
Modules of $25 \times 25\ \mu m^2$ pixel size

3 barrel layers at
- 13.7, 22.7 and 34.8 mm radius

F. Palla

Vertex detector: IDEA

Mid-term review vertex detector overall layout



Outer vertex tracker:

Modules of $50 \times 150\ \mu m^2$ pixel size

- Intermediate barrel at 13 cm radius (improved reconstruction for $p_T > 40$ MeV tracks)
- Outer barrel at 31.5 cm radius
- 3 disks per side

Inner Vertex detector:

Modules of $25 \times 25\ \mu m^2$ pixel size

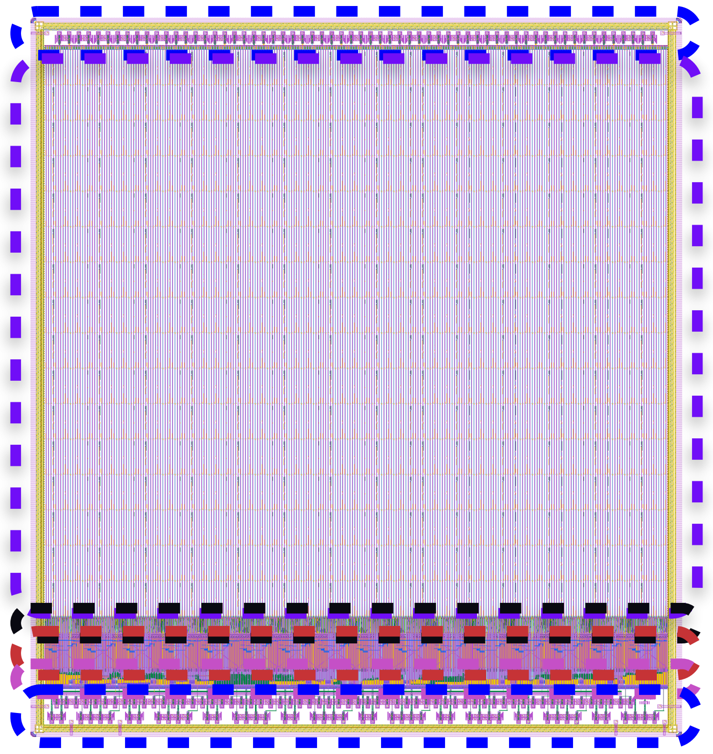
3 barrel layers at
- 13.7, 22.7 and 34.8 mm radius

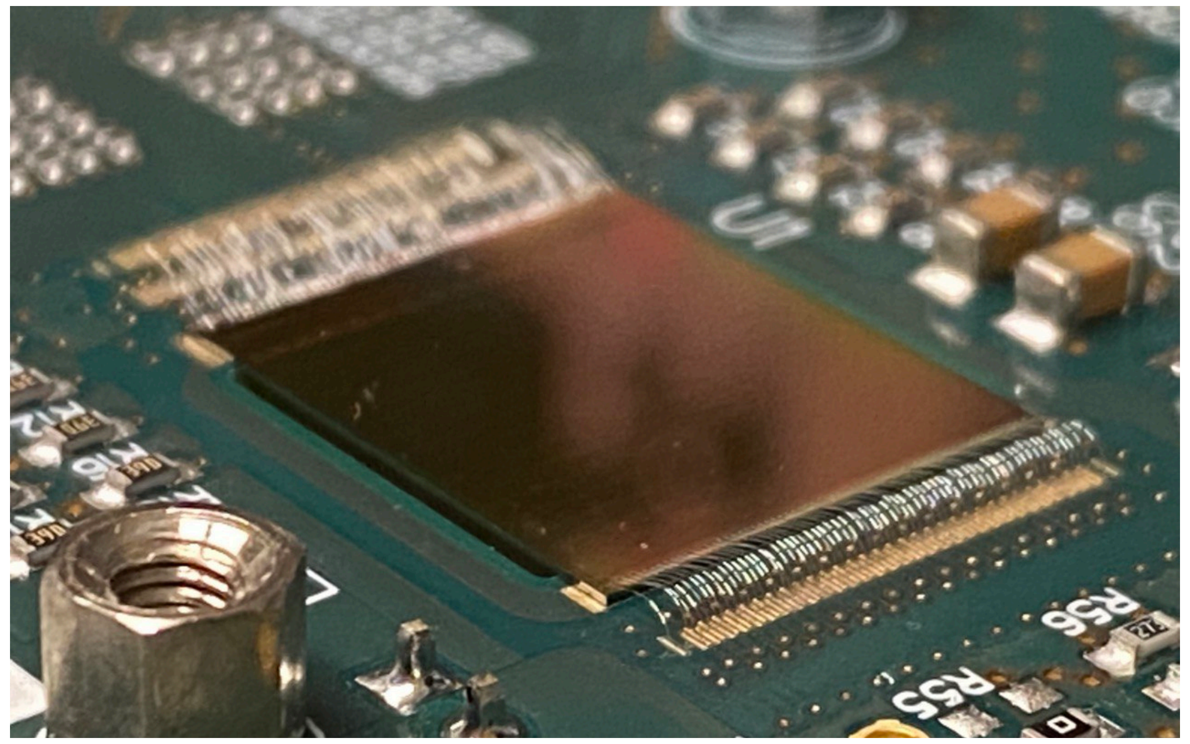
F. Palla

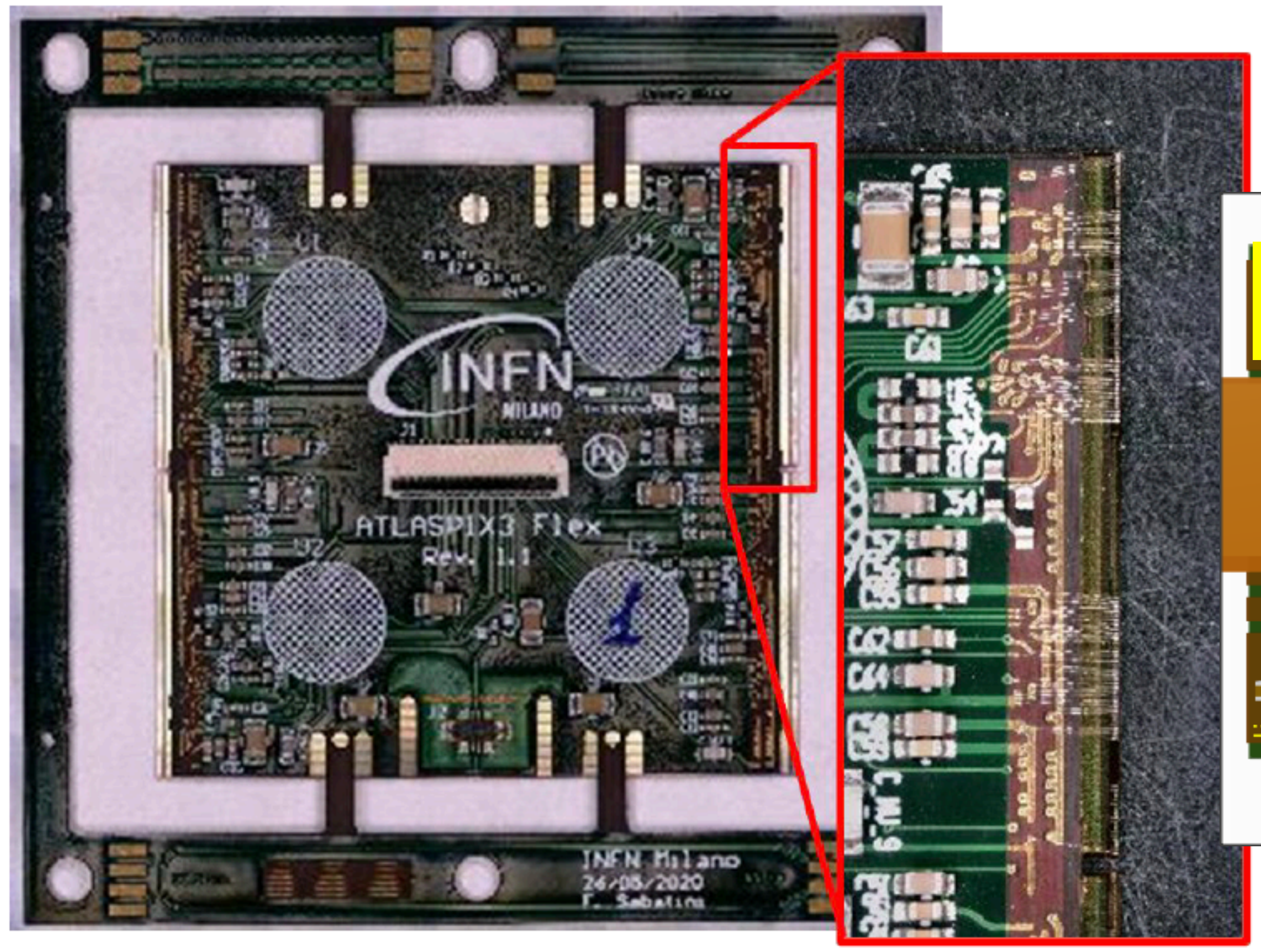
Vertex detector: IDEA

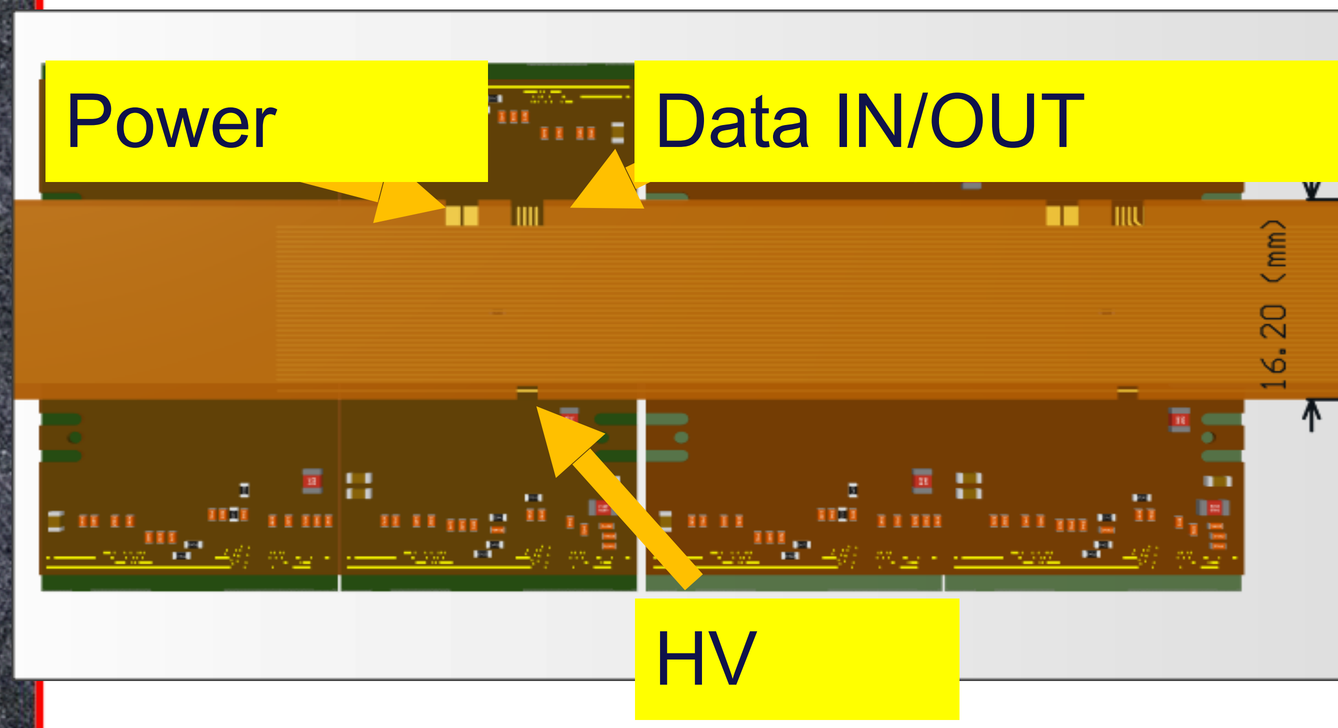
Depleted Monolithic Active Pixel Detectors

- **Inner Vertex (ARCADIA based):**
  - Lfoundry 110 nm process
  - *50 µm thick*
  - Dimensions: $8.4 \times 32\ mm^2$
  - Power density 30 mW/cm²
  - **100 MHz/cm²**
- **Outer Vertex and disks (ATLASPIX3 based)**
  - TSI 180 nm process
  - *50 µm thick*
  - Module dimensions: $42.2 \times 40.6\ mm^2$
  - Power density 170 mW/cm²
  - **Up to 1.28 Gb/s downlink**







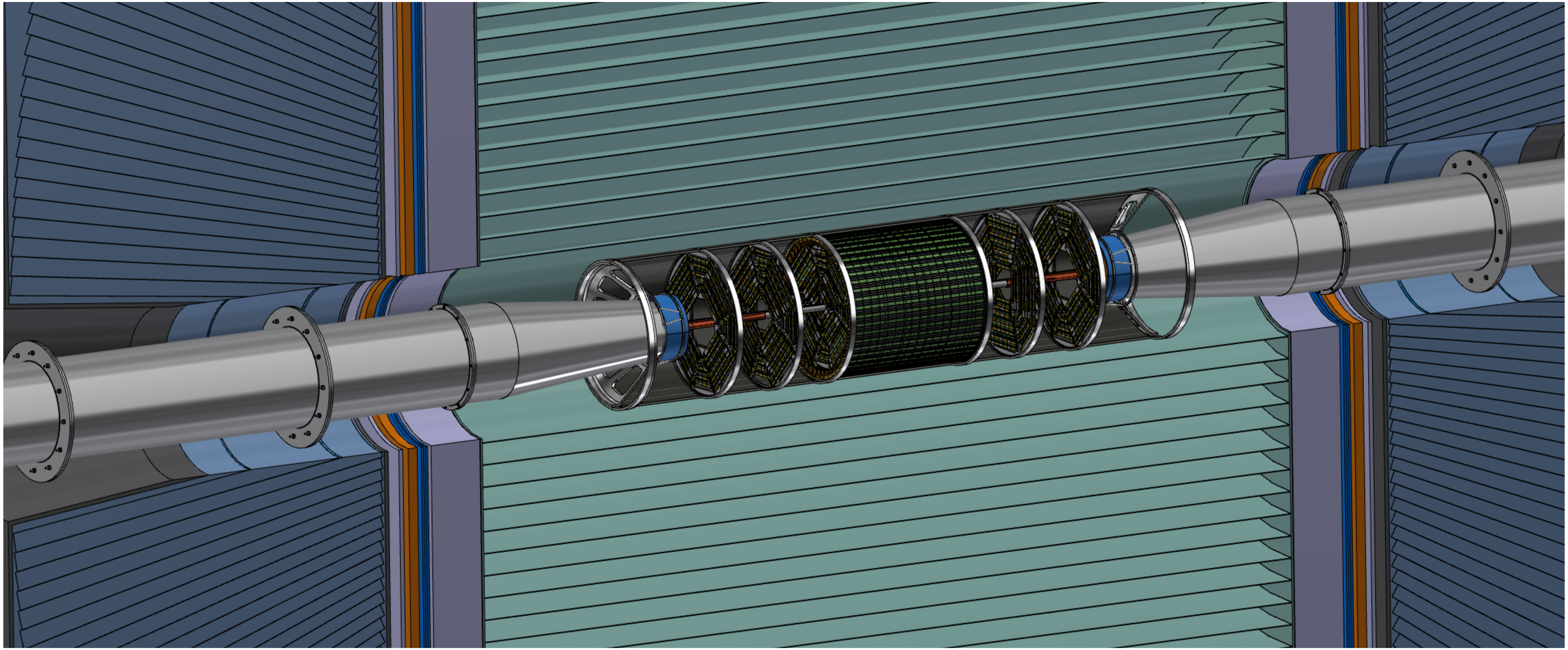


See talk by F. Palla for more details on the vertex tracker

F. Palla

Vertex detector: IDEA

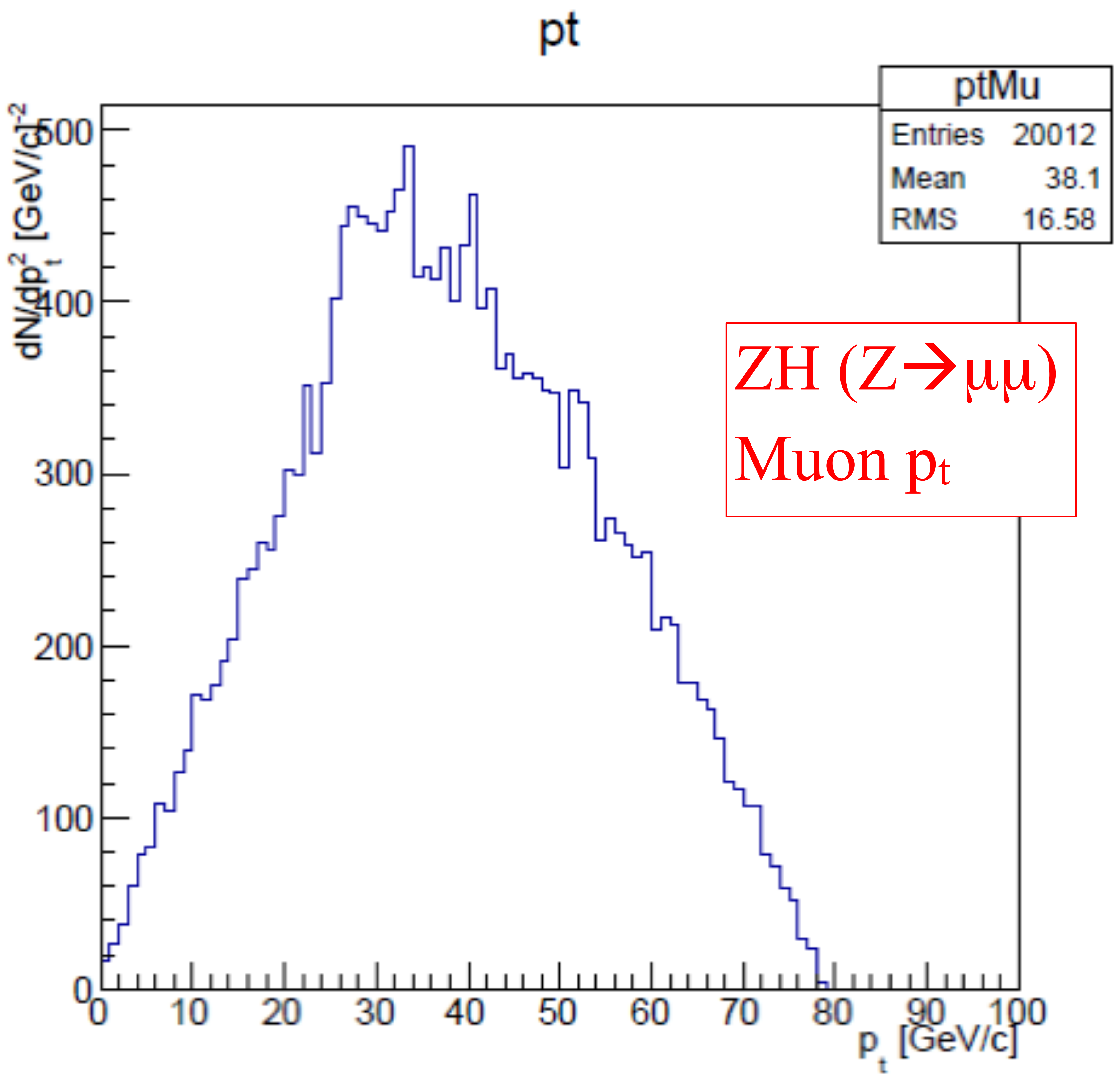
General integration

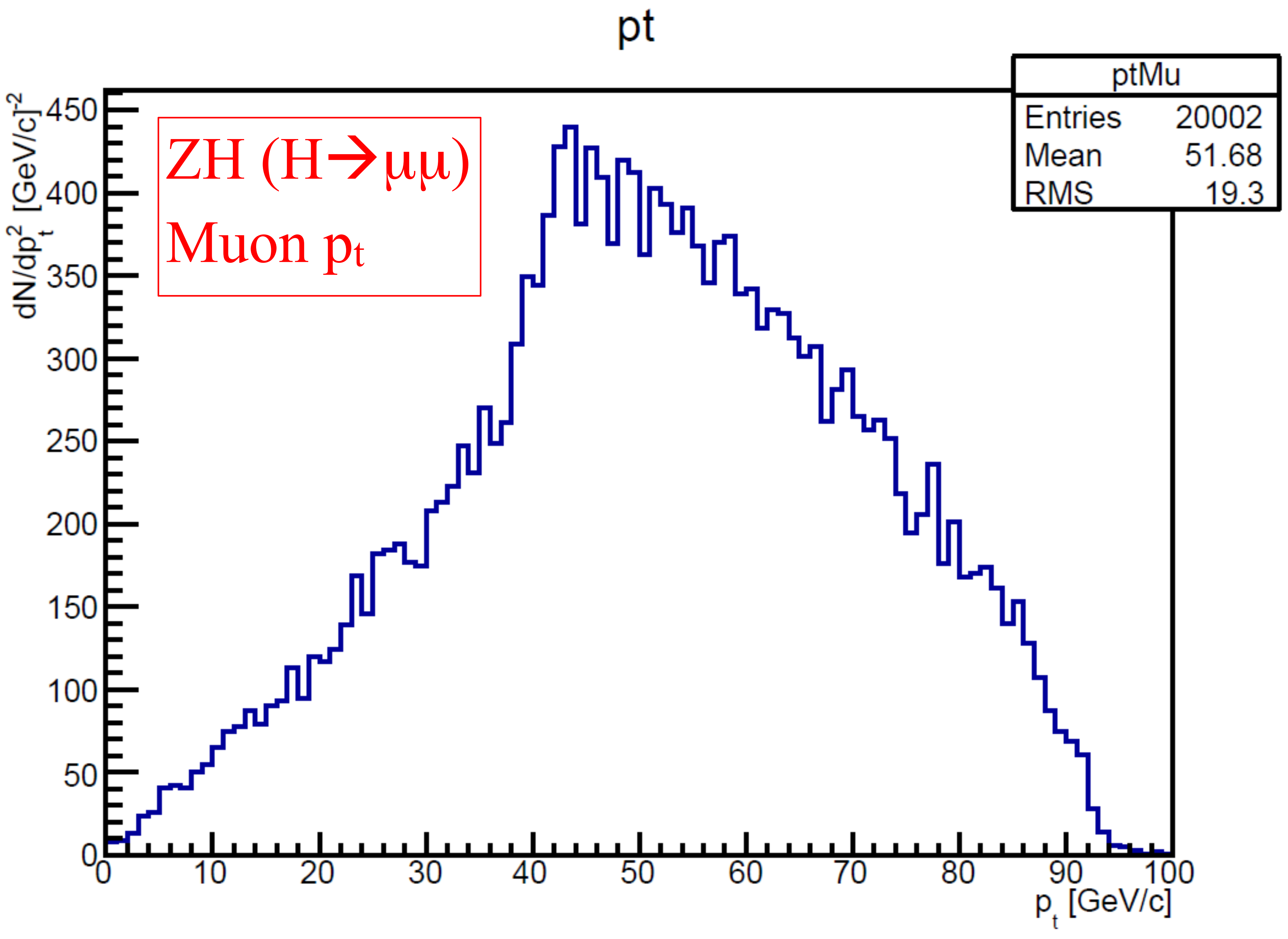


F. Palla

FUTURE CIRCULAR COLLIDER

Momentum measurement





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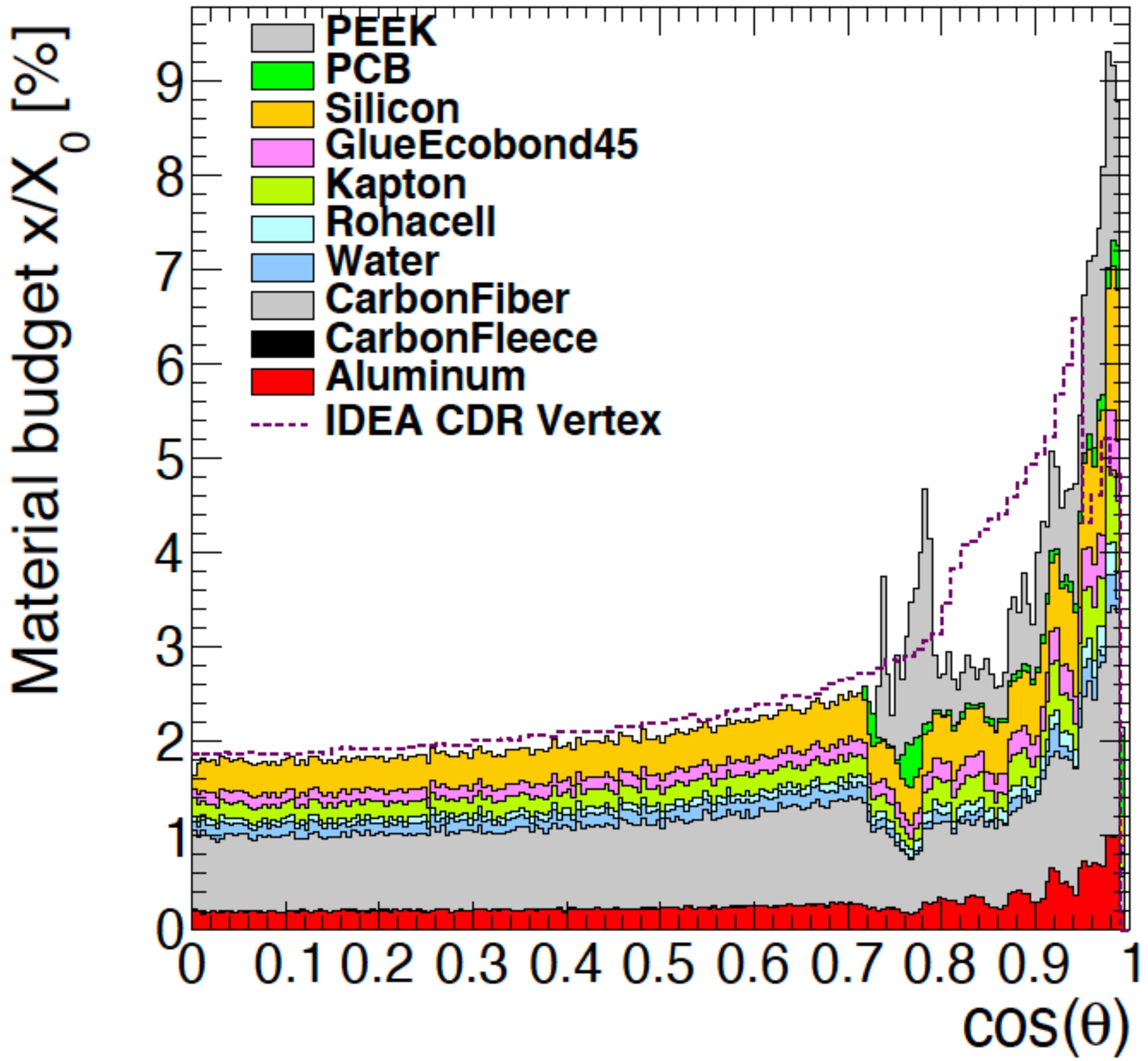
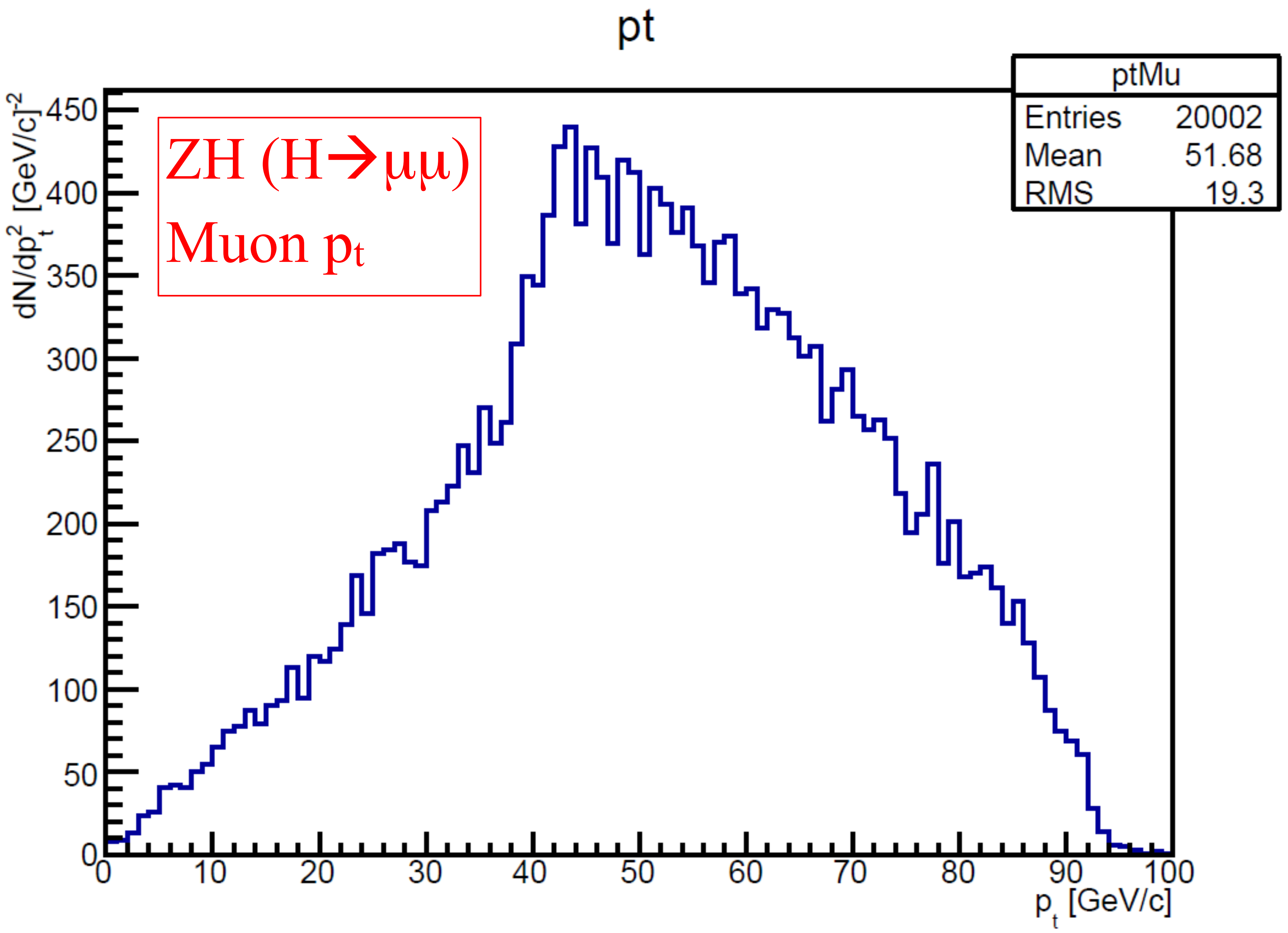
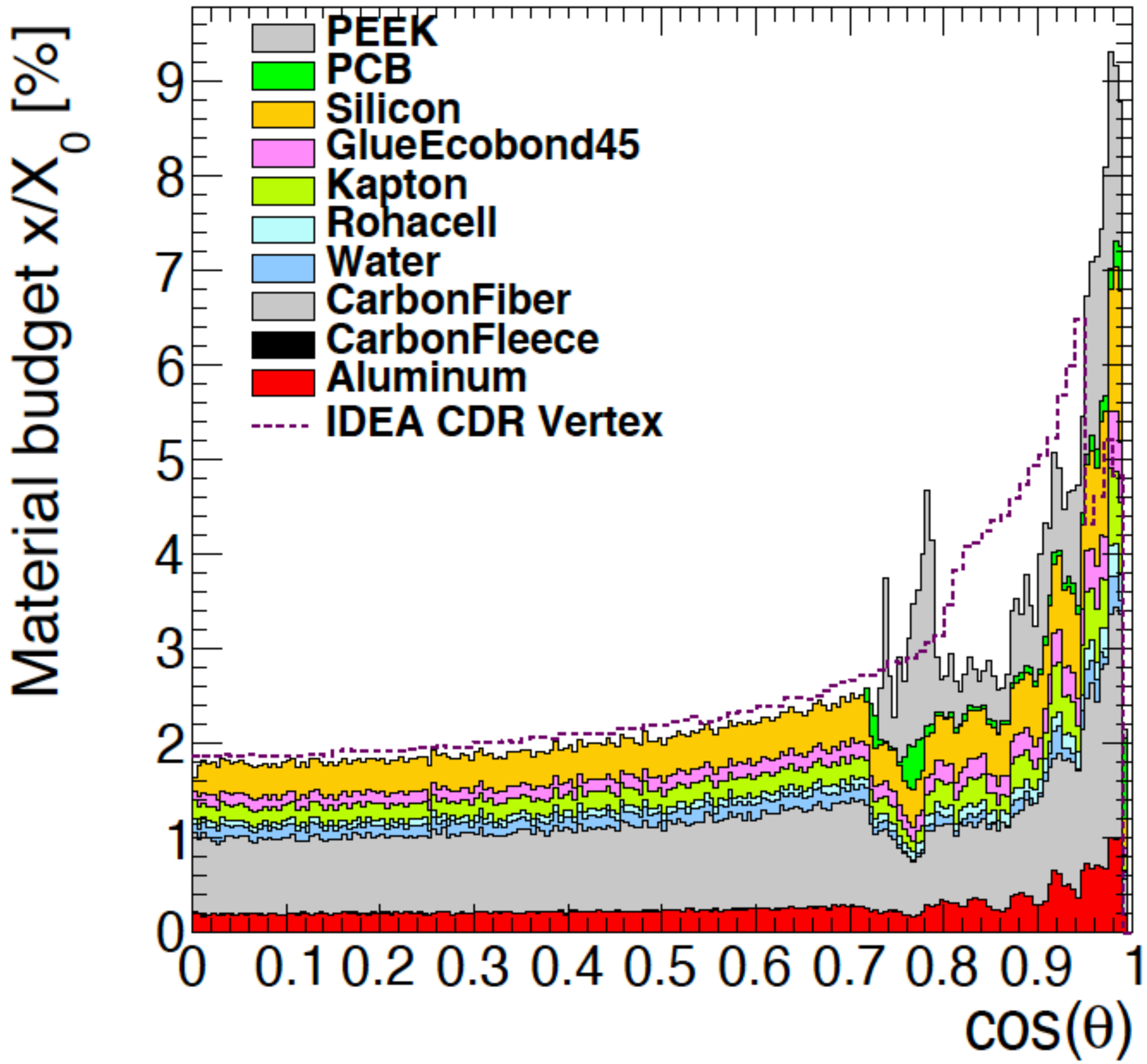


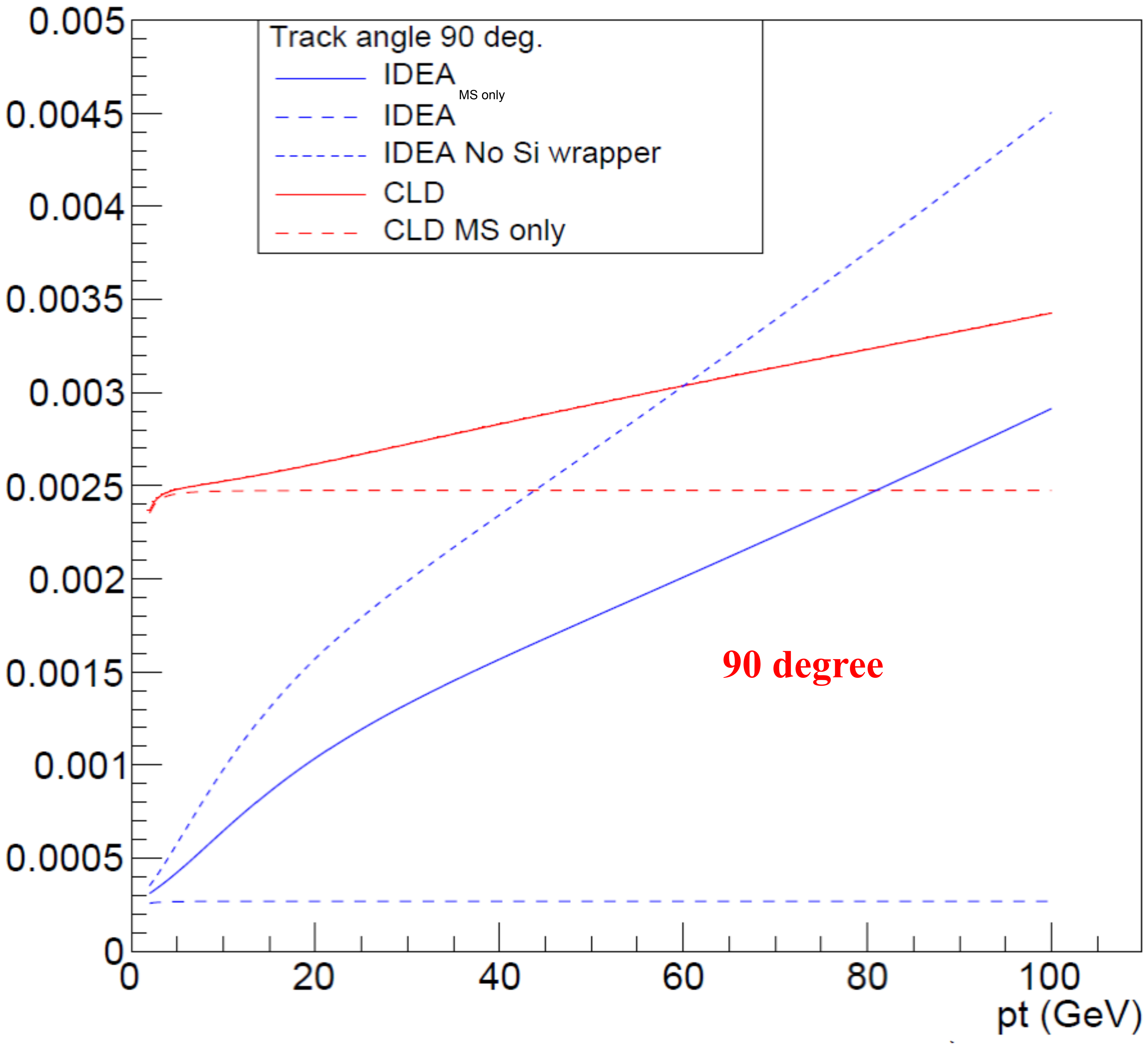


Momentum measurement

- Z or H decay muons in ZH events have rather low p_t
  - Transparency more important than asymptotic resolution

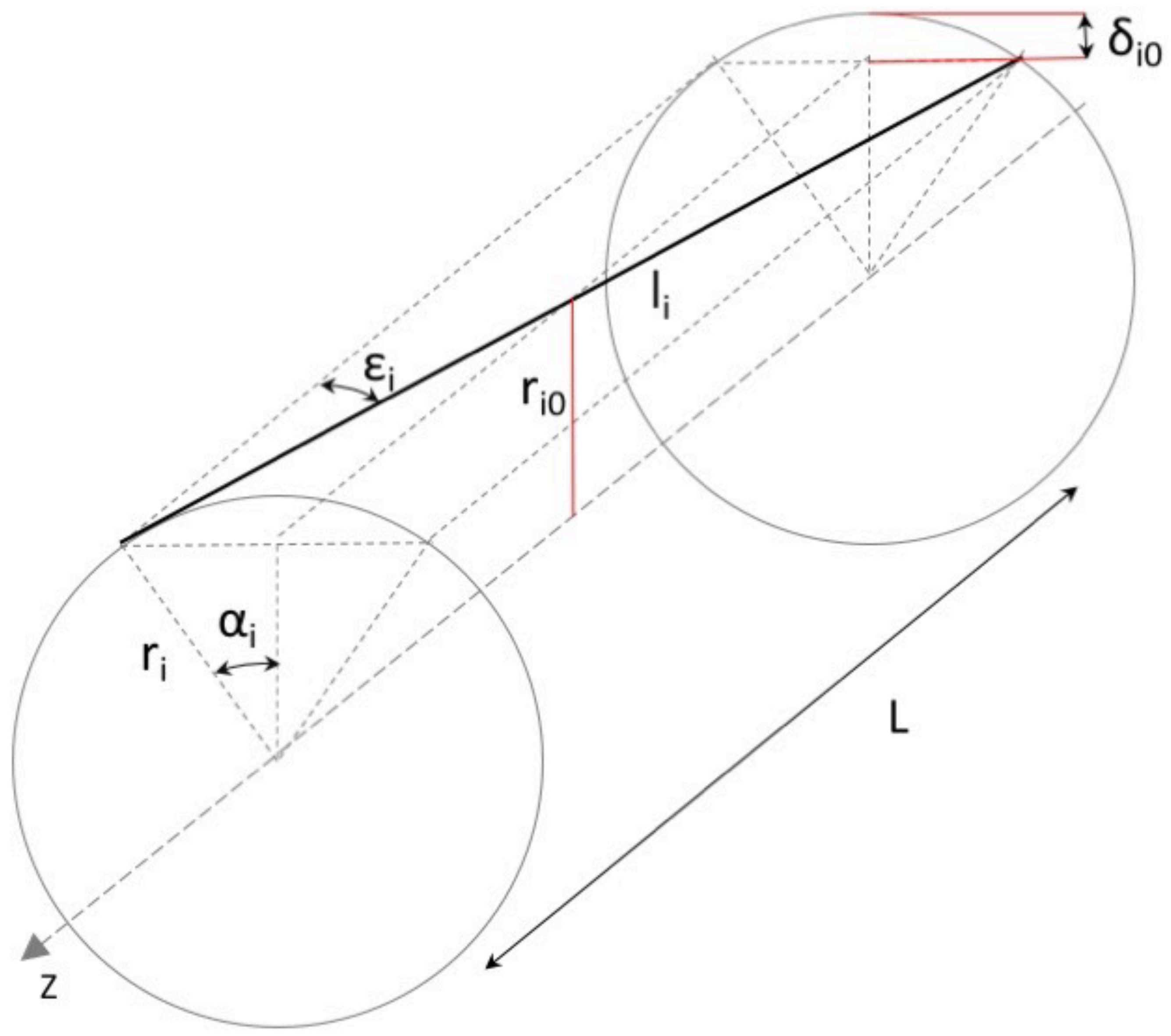


σ_{pt}/pt

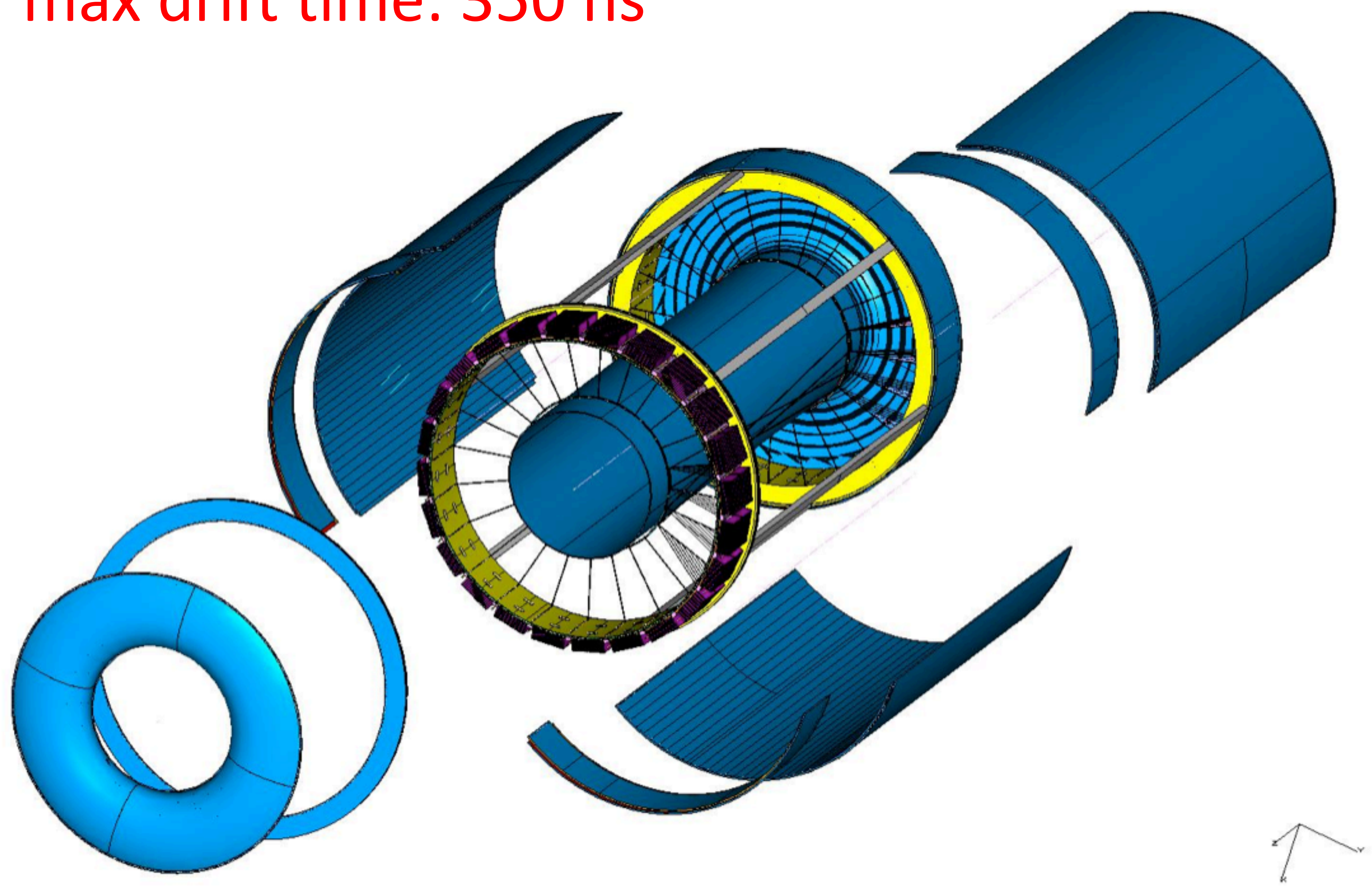


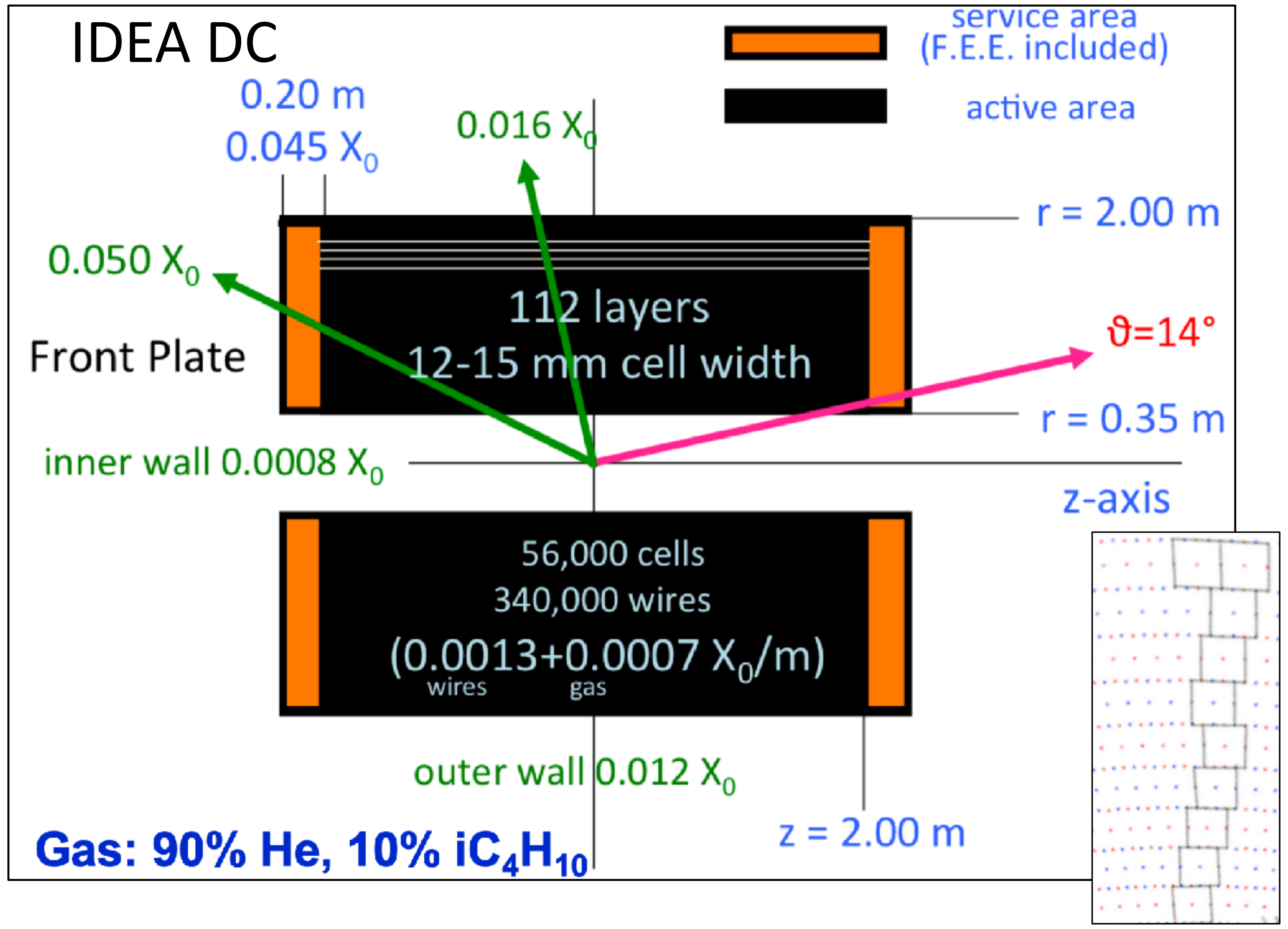
Drift chamber

- IDEA: Extremely transparent Drift Chamber
  - Gas: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90º
  - All stereo wires (56448 cells, 343968 wires)
    - Tungsten wires dominant contribution
  - 112 layers for each 15º azimuthal sector
  - max drift time: 350 ns



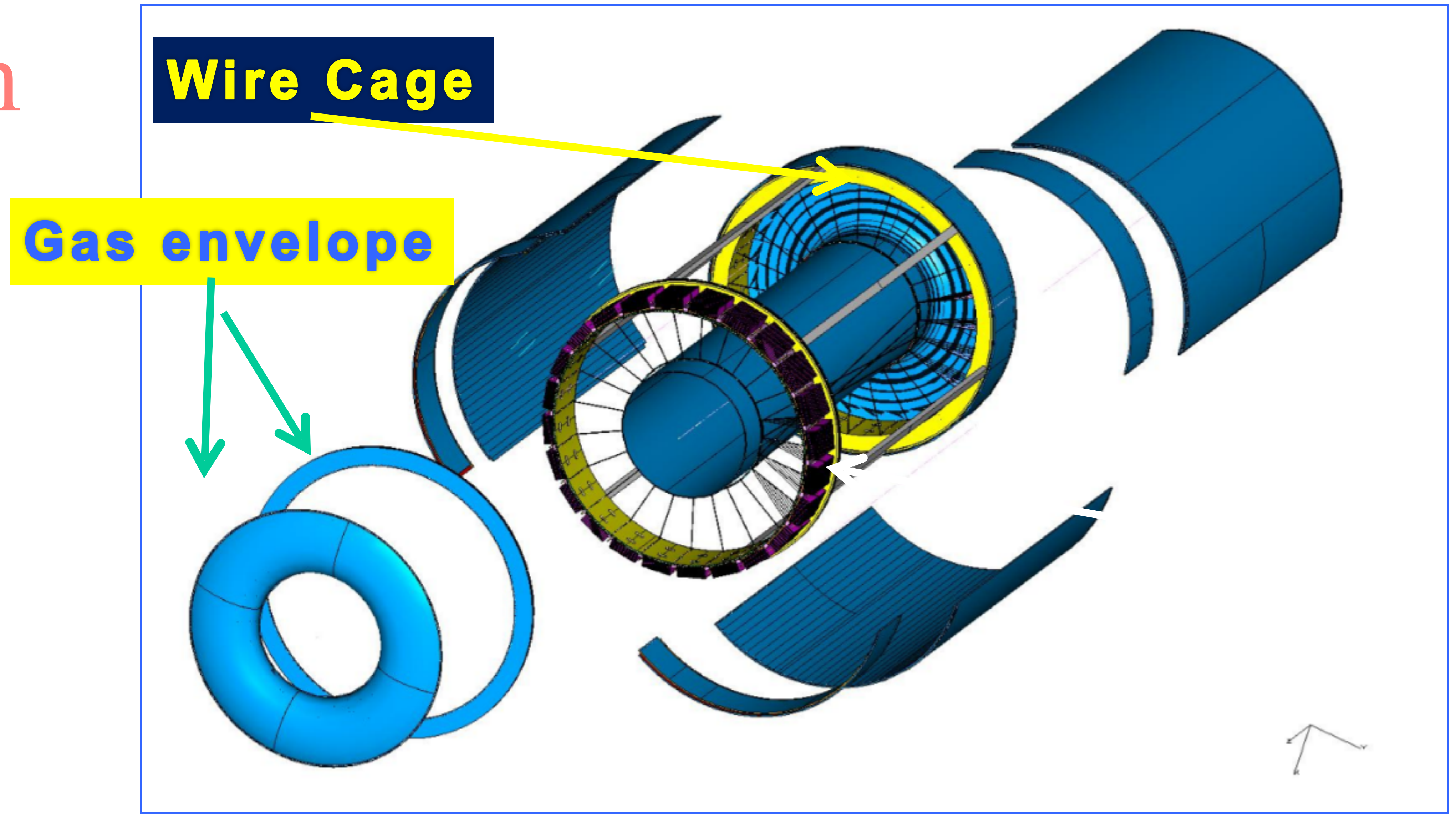
L = 4m

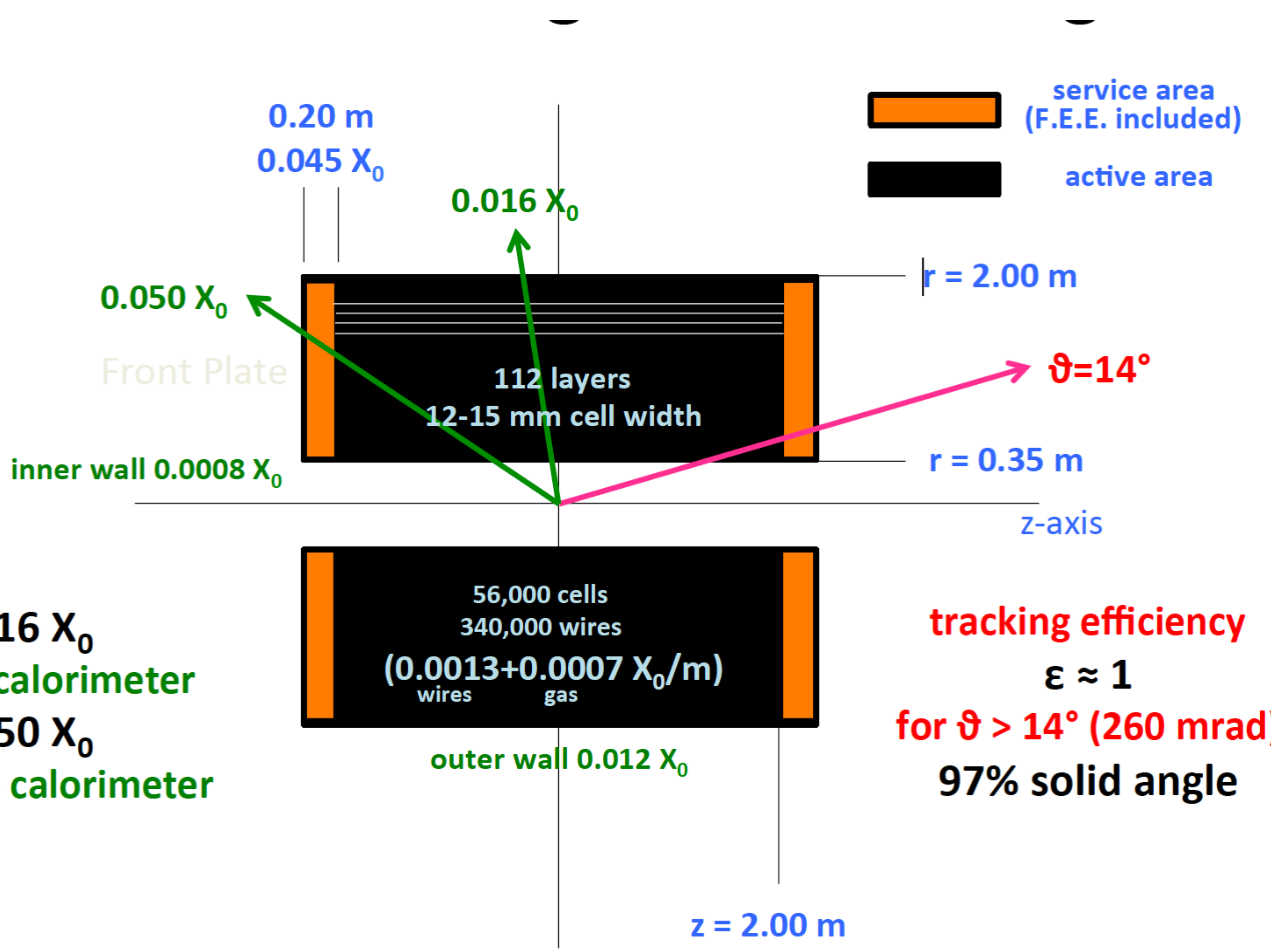




Drift chamber

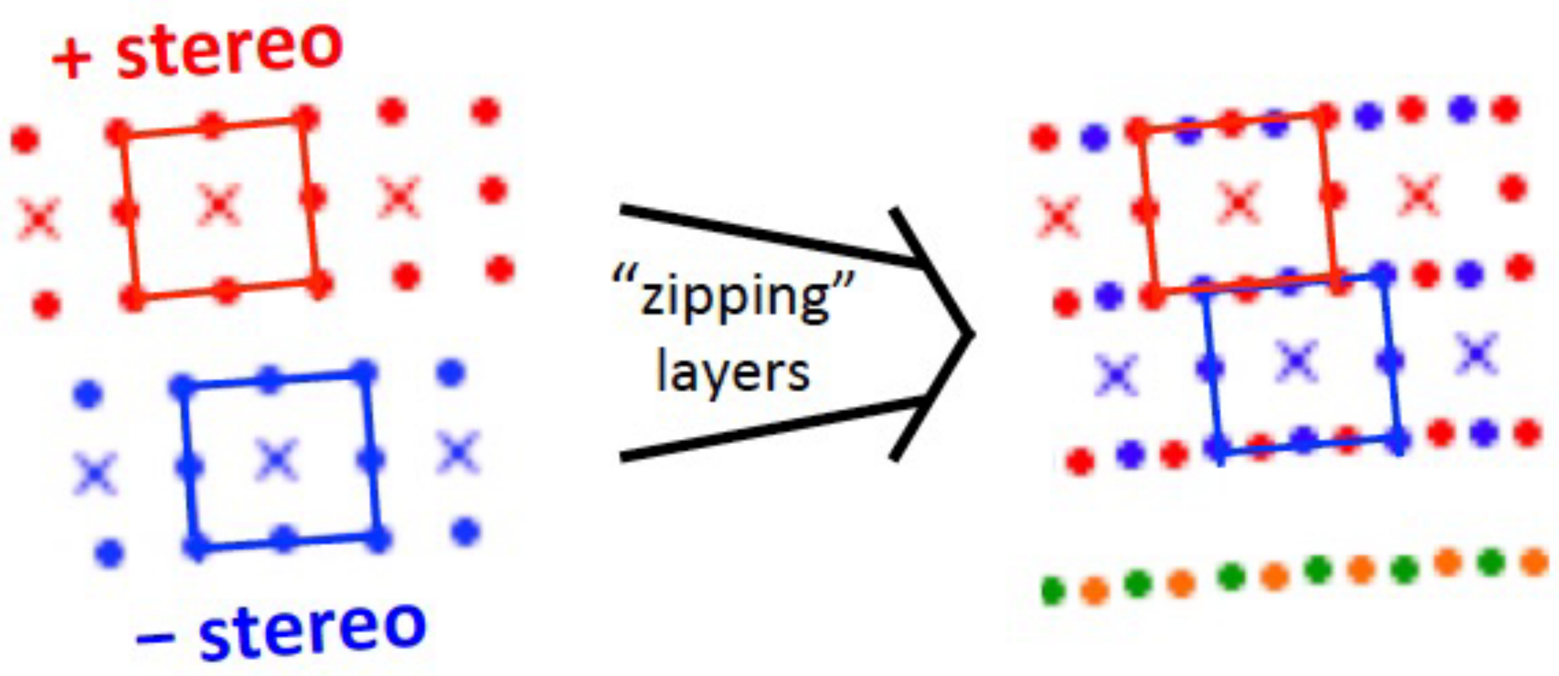
- 90% He - 10% C_4H_{10} – All stereo – $\sigma \sim 100\ \mu m$
- Small cells, max drift time ~ 350 ns





0.016 X_0
to barrel calorimeter
0.050 X_0
to end-cap calorimeter

tracking efficiency
$\varepsilon \approx 1$
for $\vartheta > 14°$ (260 mrad)
97% solid angle



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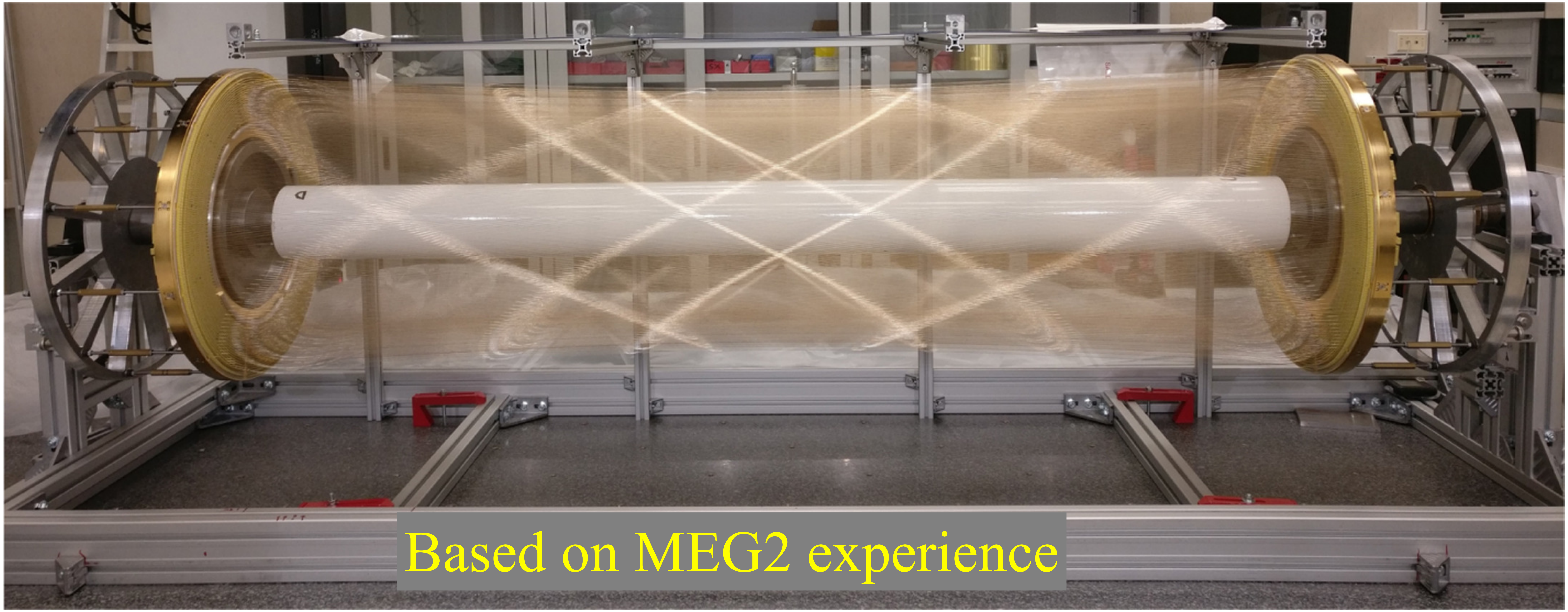
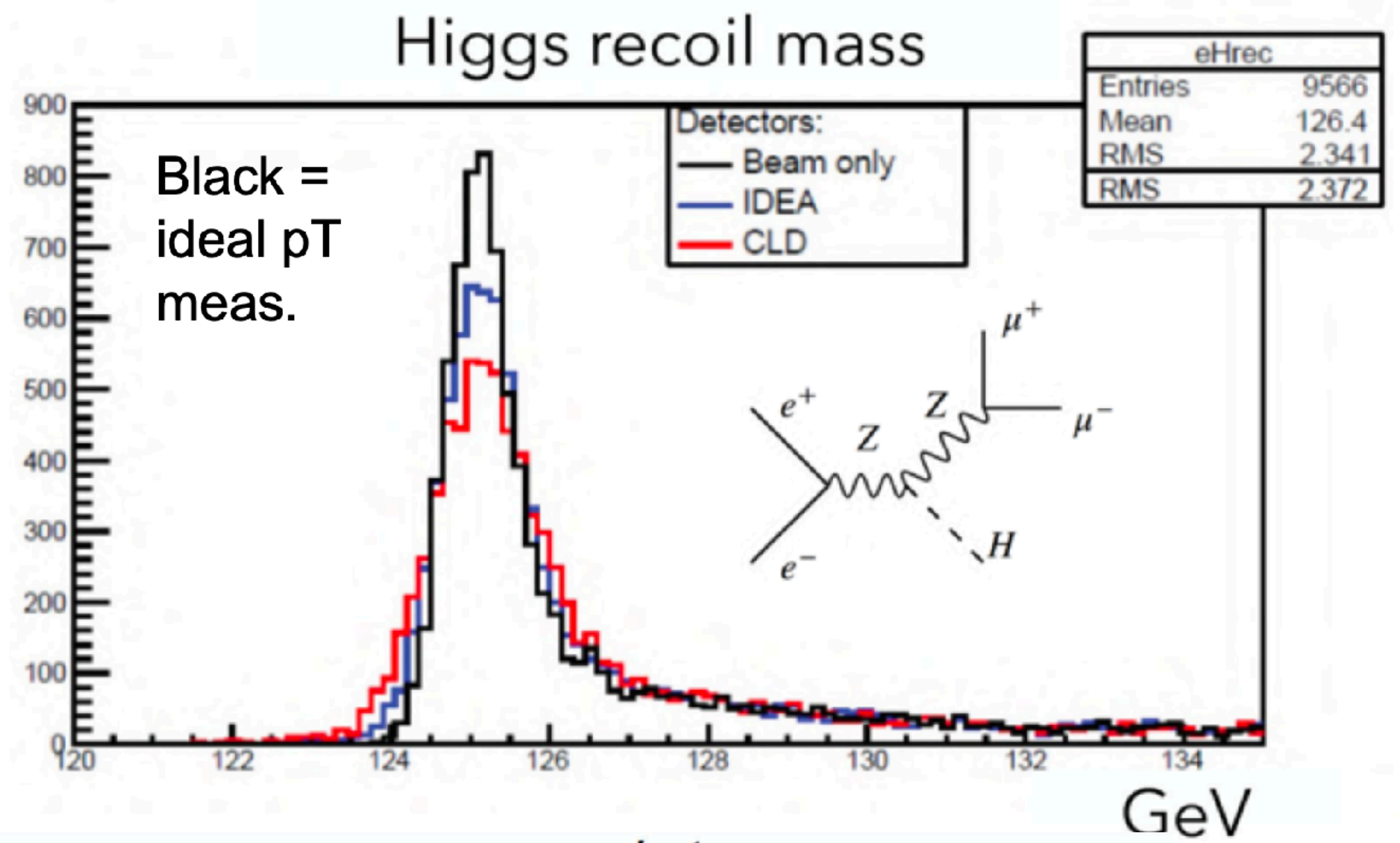
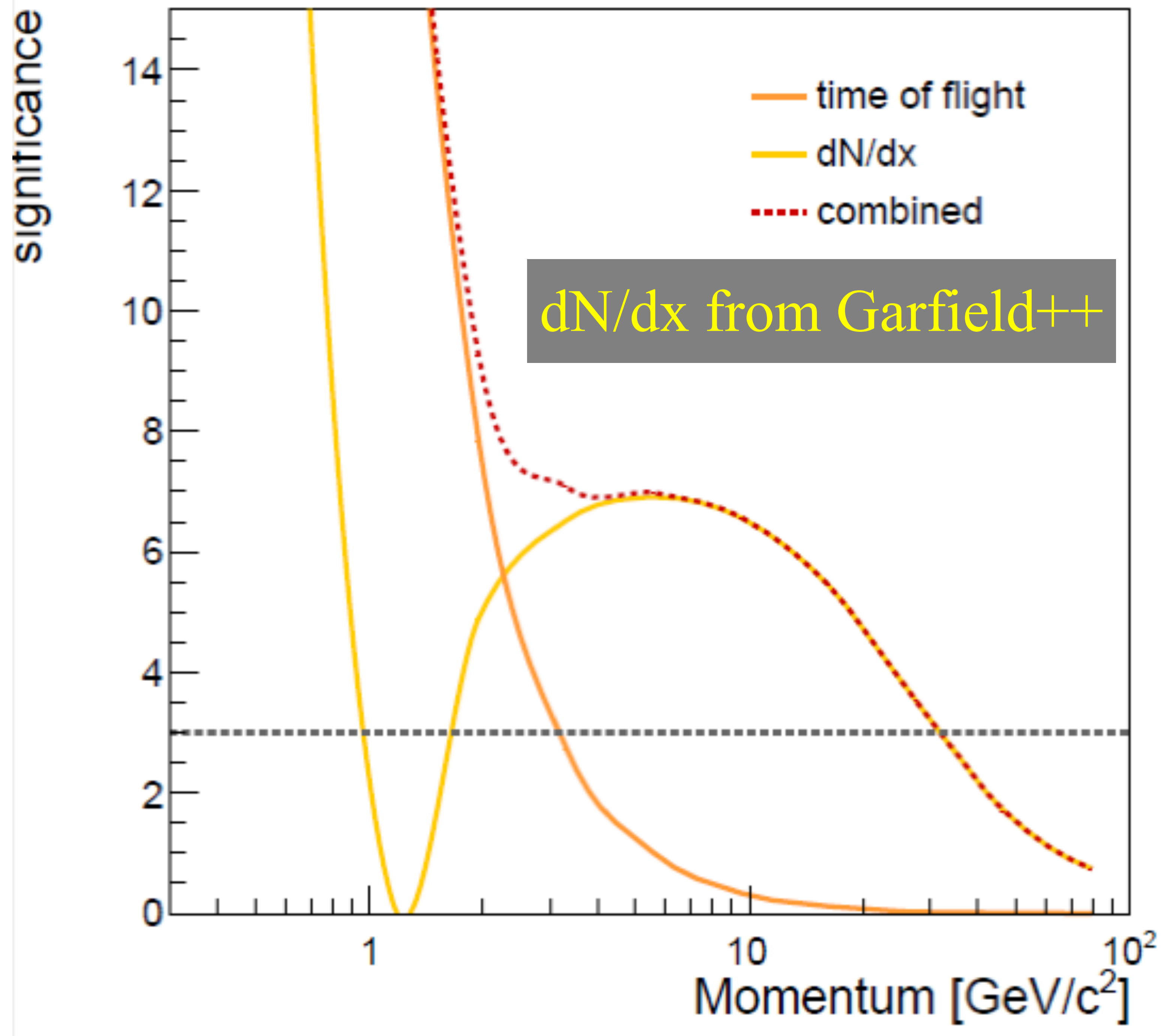


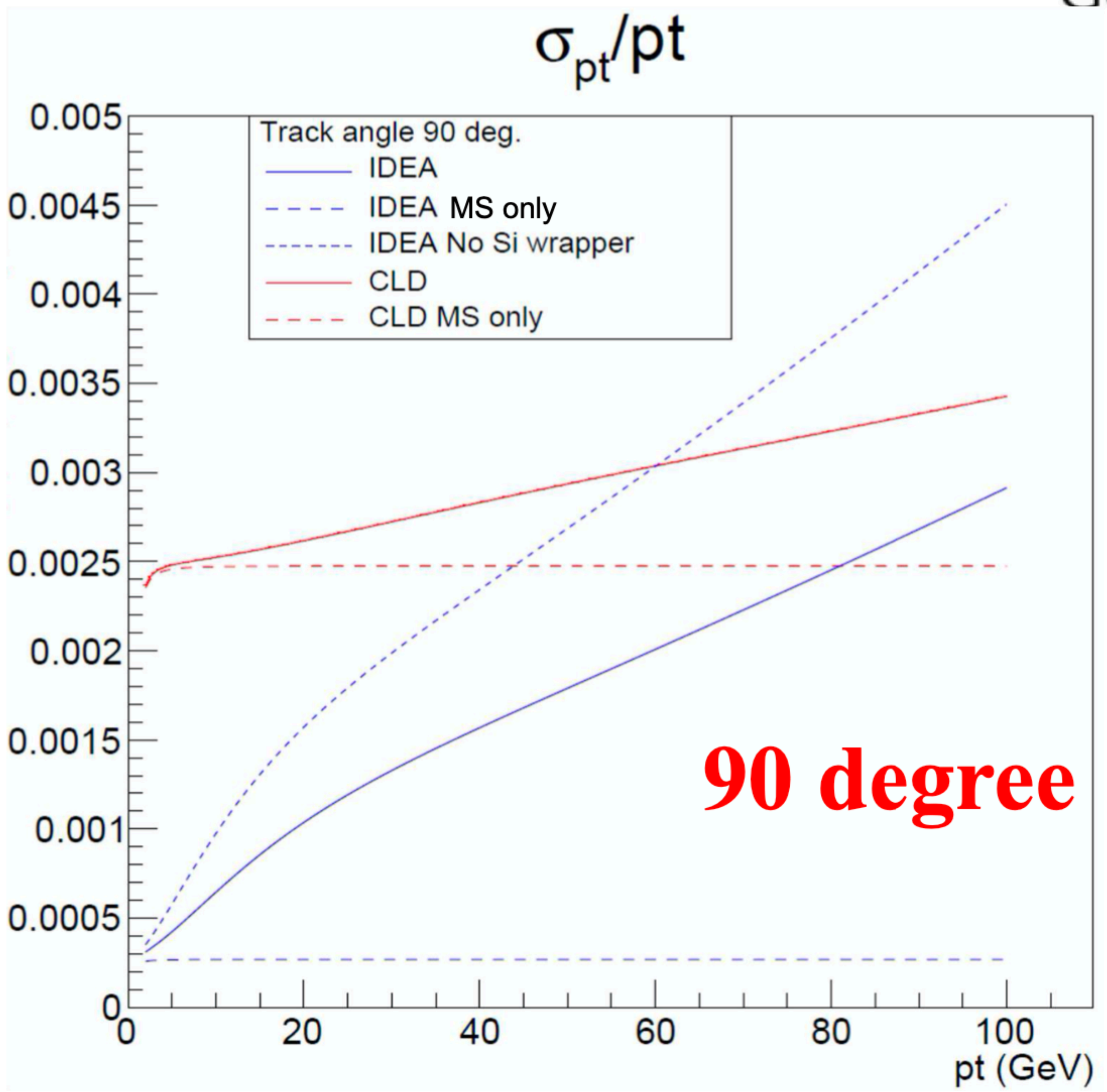
Based on MEG2 experience

Drift chamber

- In general, tracks have rather low momenta ($p_T \lesssim 50$ GeV)
  - Transparency more relevant than asymptotic resolution
- Drift chamber (gaseous tracker) advantages
  - Extremely transparent: minimal multiple scattering and secondary interactions
  - Continuous tracking: reconstruction of far-detached vertices (K^0_S, Λ, BSM, LLPs)
  - Outstanding Particle separation via dE/dx or cluster counting (dN/dx)
    - >3σ K/π separation up to ~35 GeV



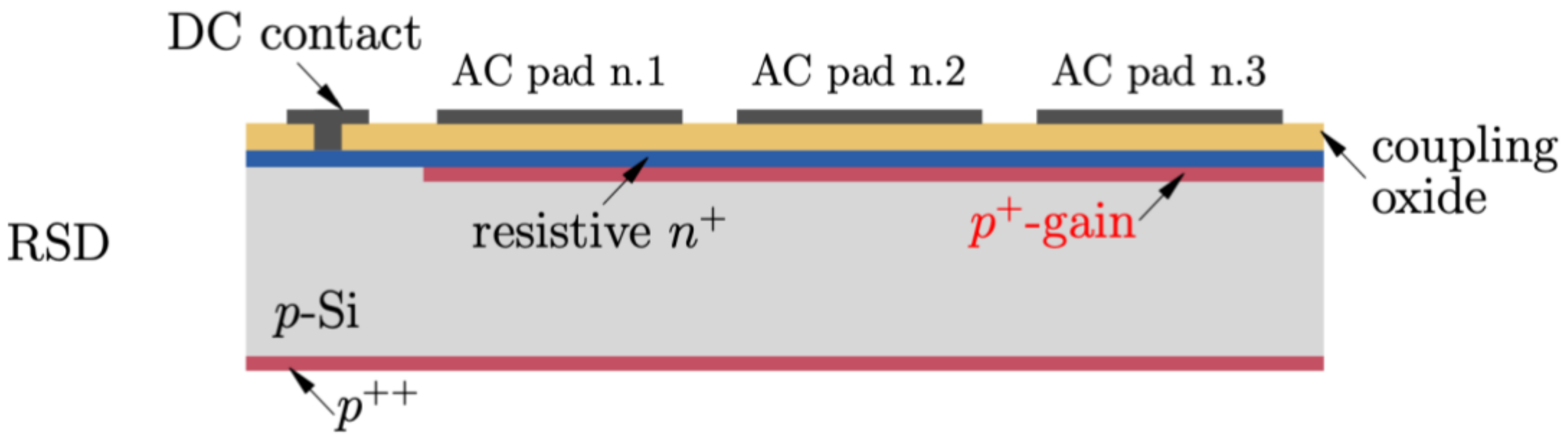


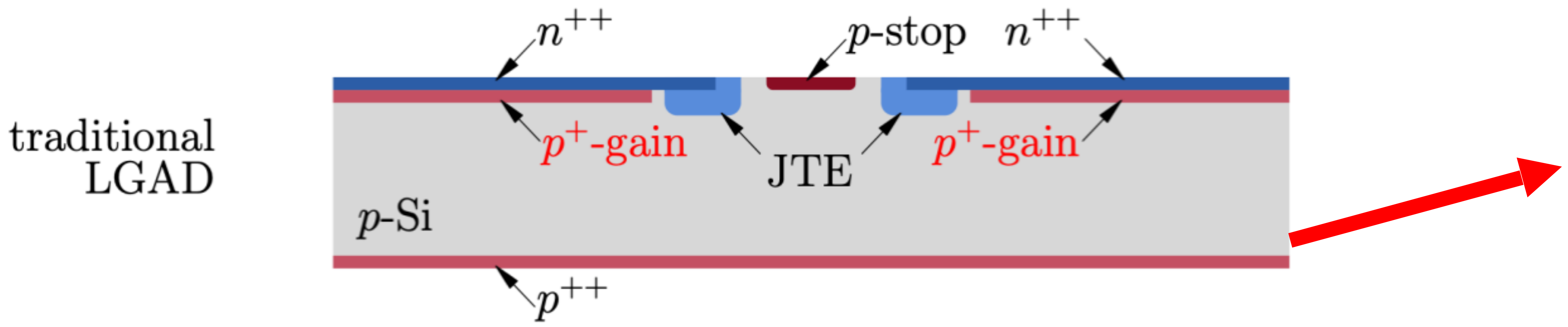


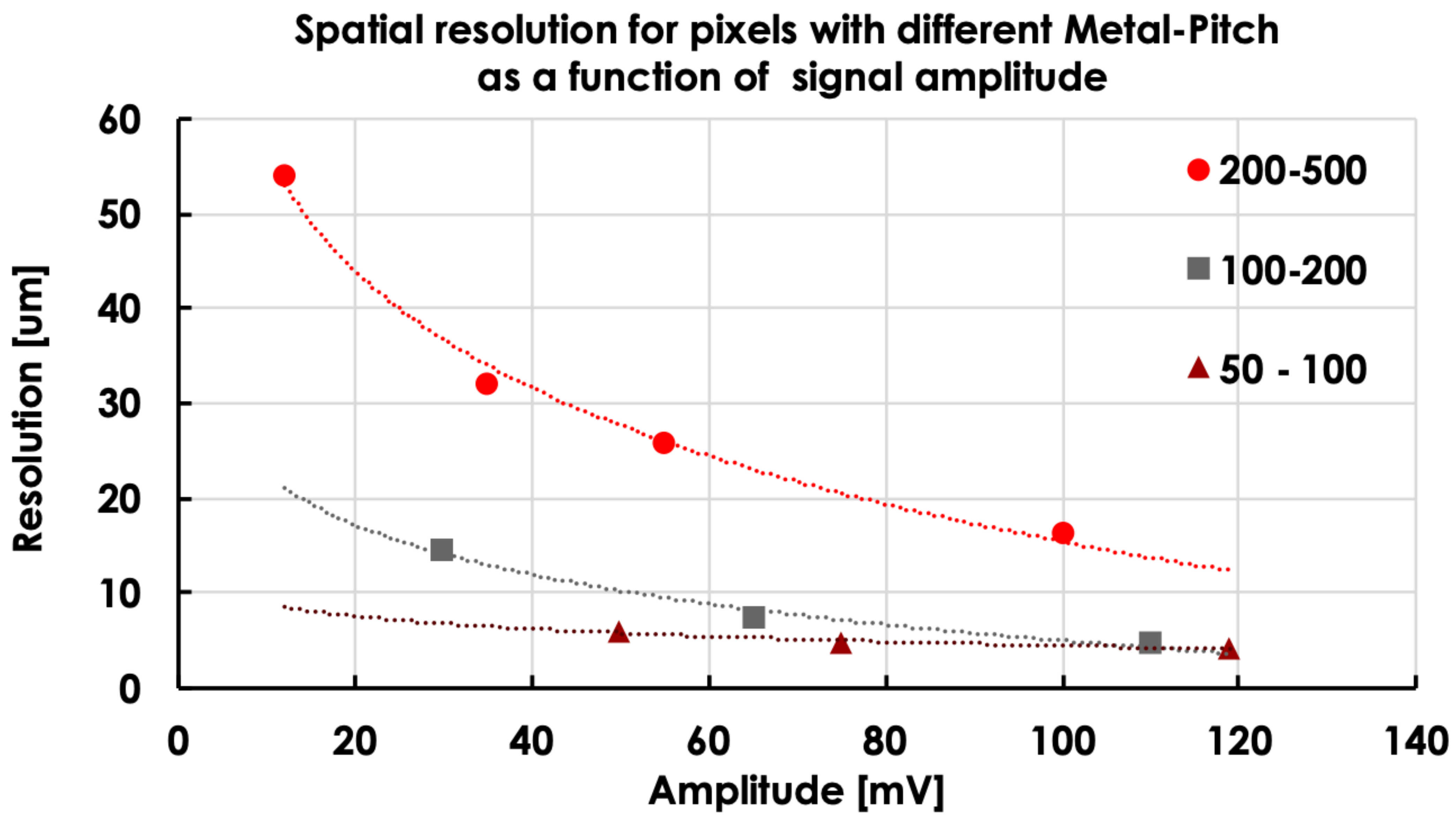
Resistive LGAD

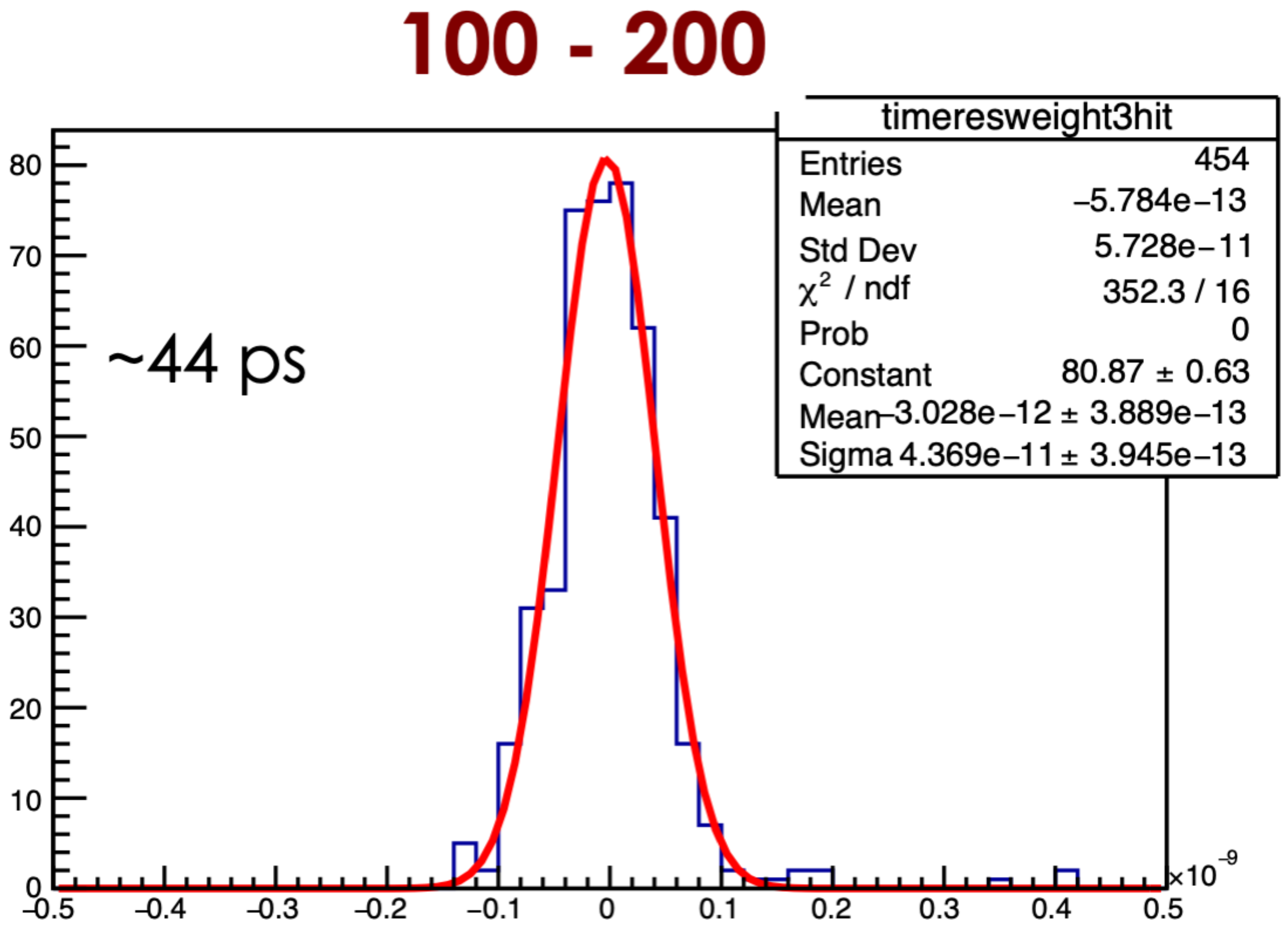
❖ Recent new activity with INFN-GE/(TO)

➢ Match time and position resolution









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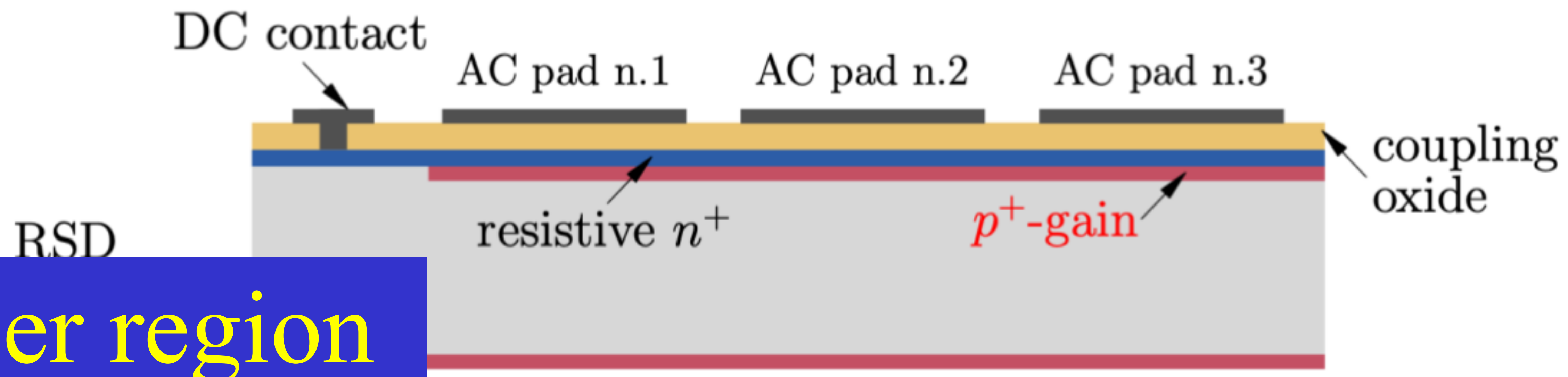
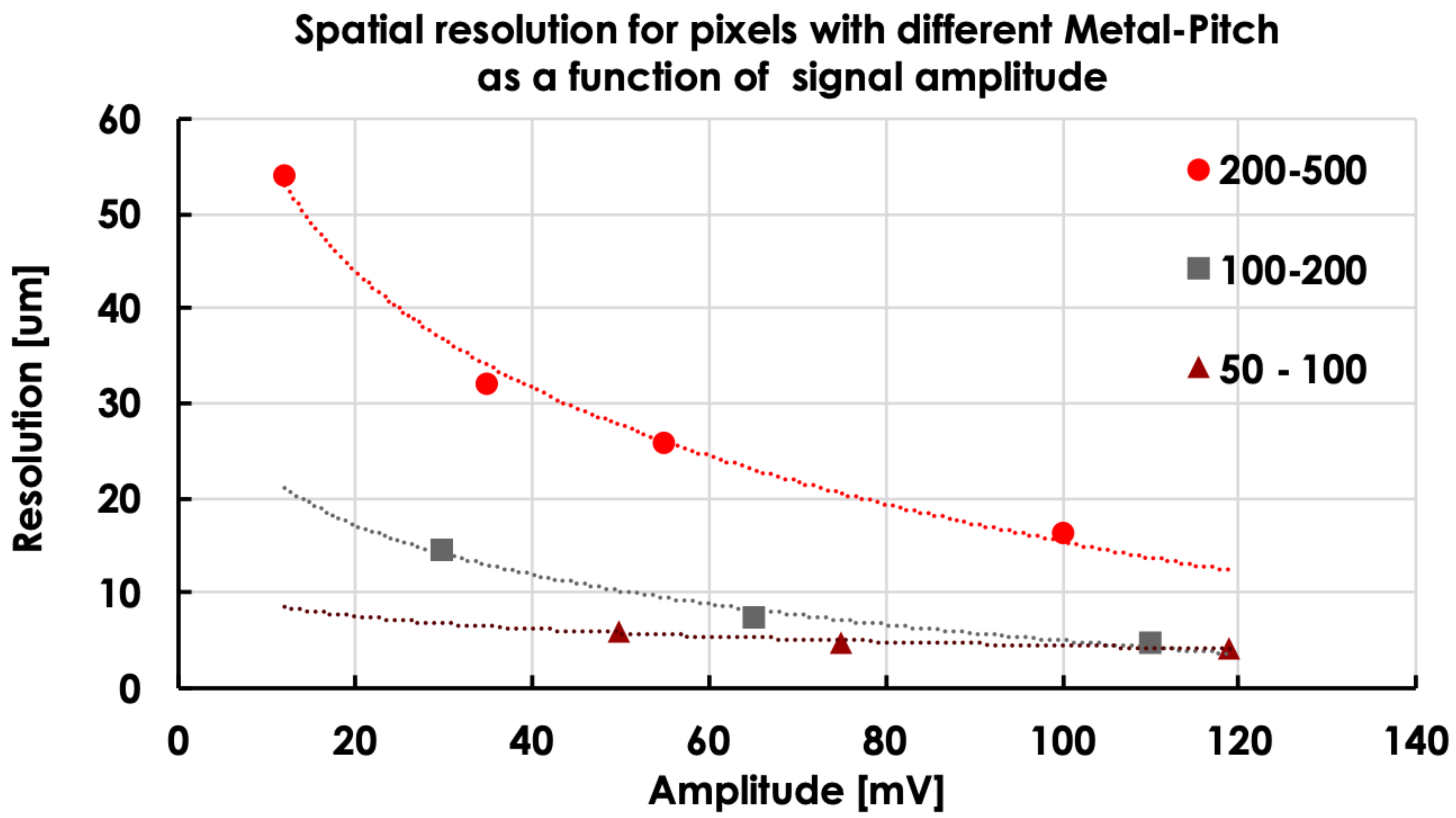
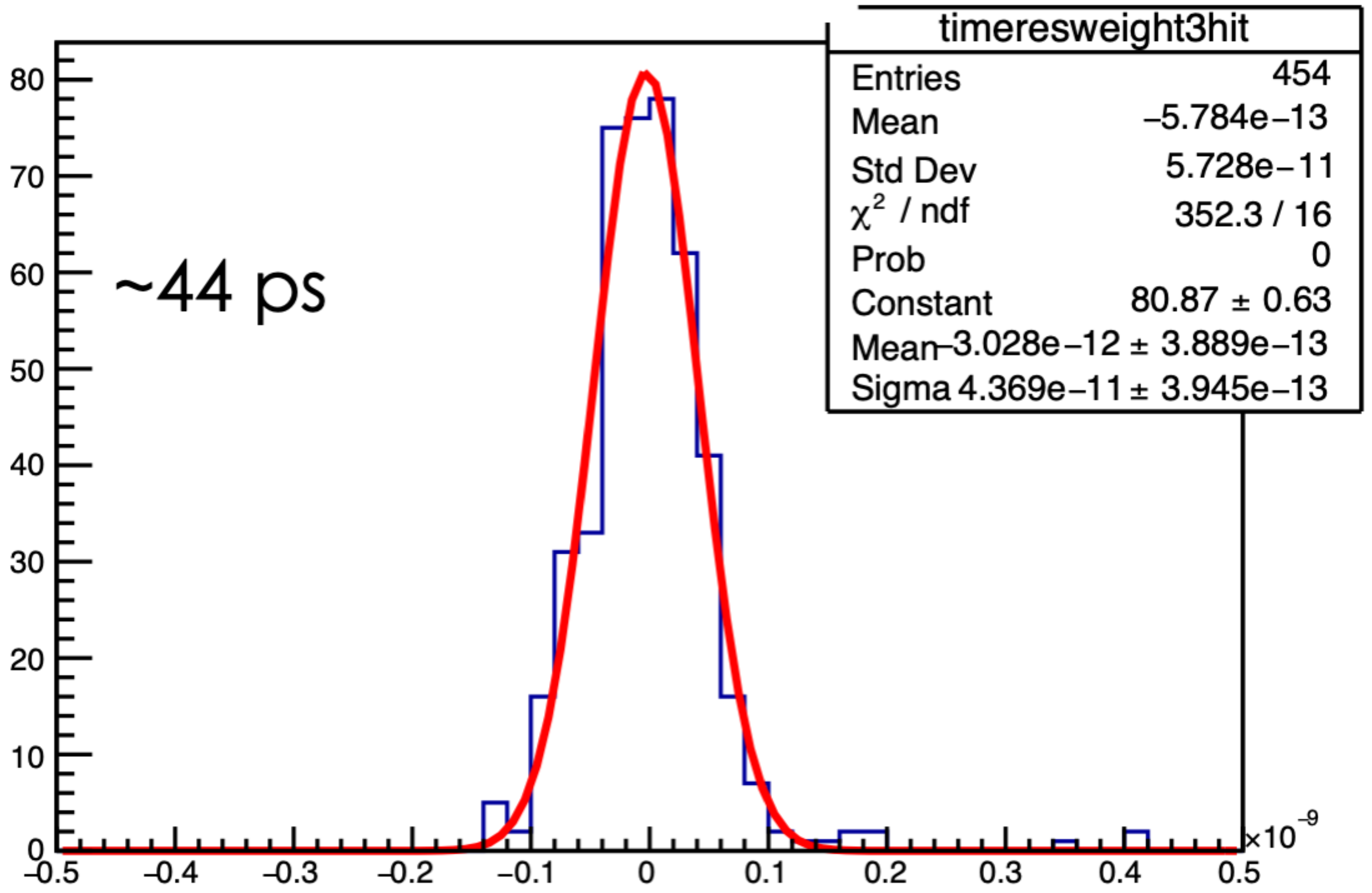


Very attractive option for timing in Si wrapper region
Cost reduction is major area of R&D
Some "fast" devices also prototyped by Arcadia group

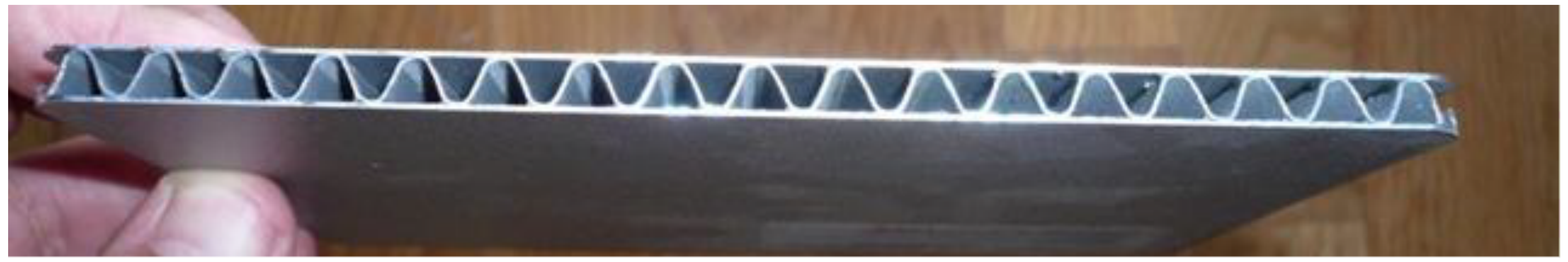


100 - 200

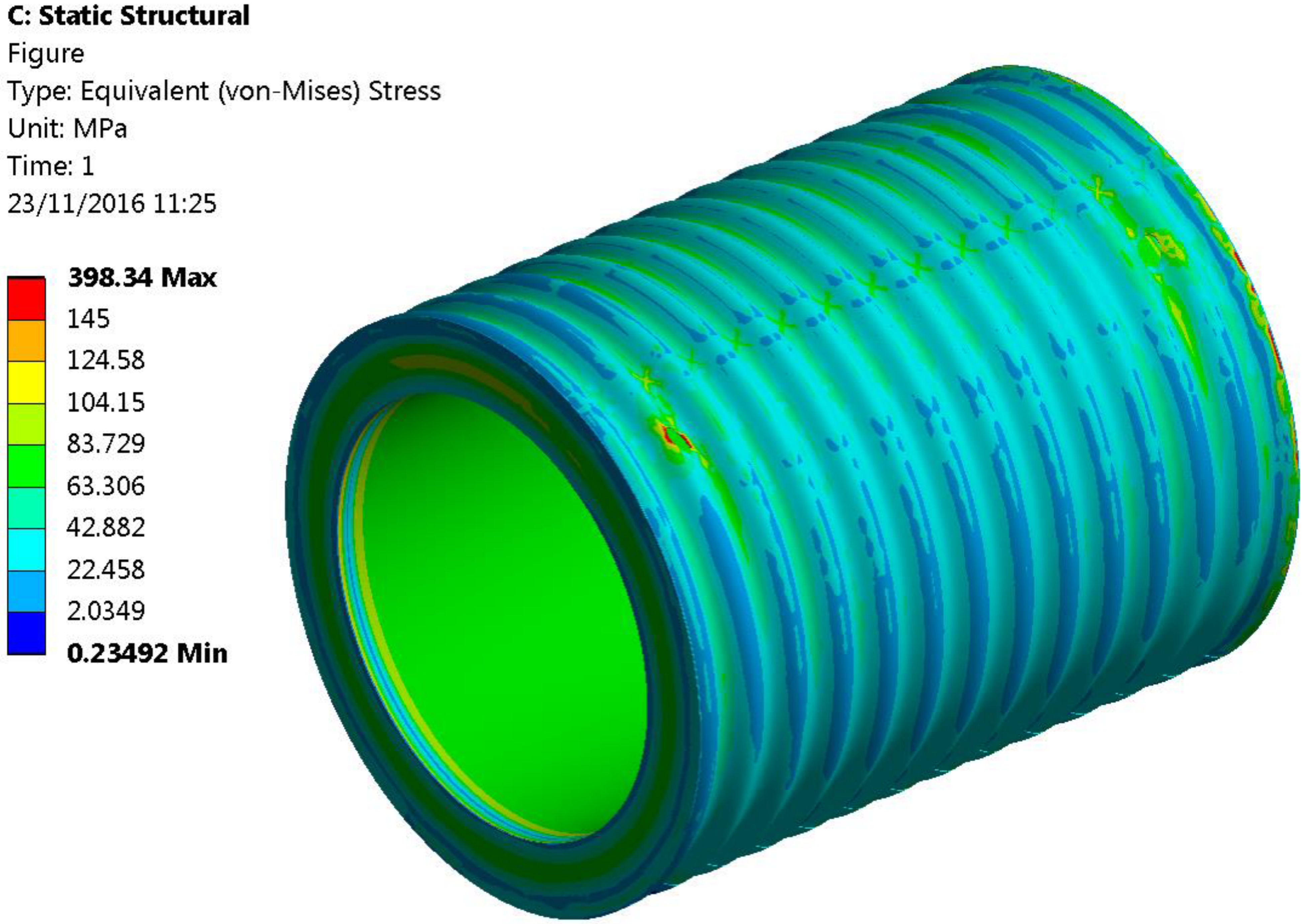


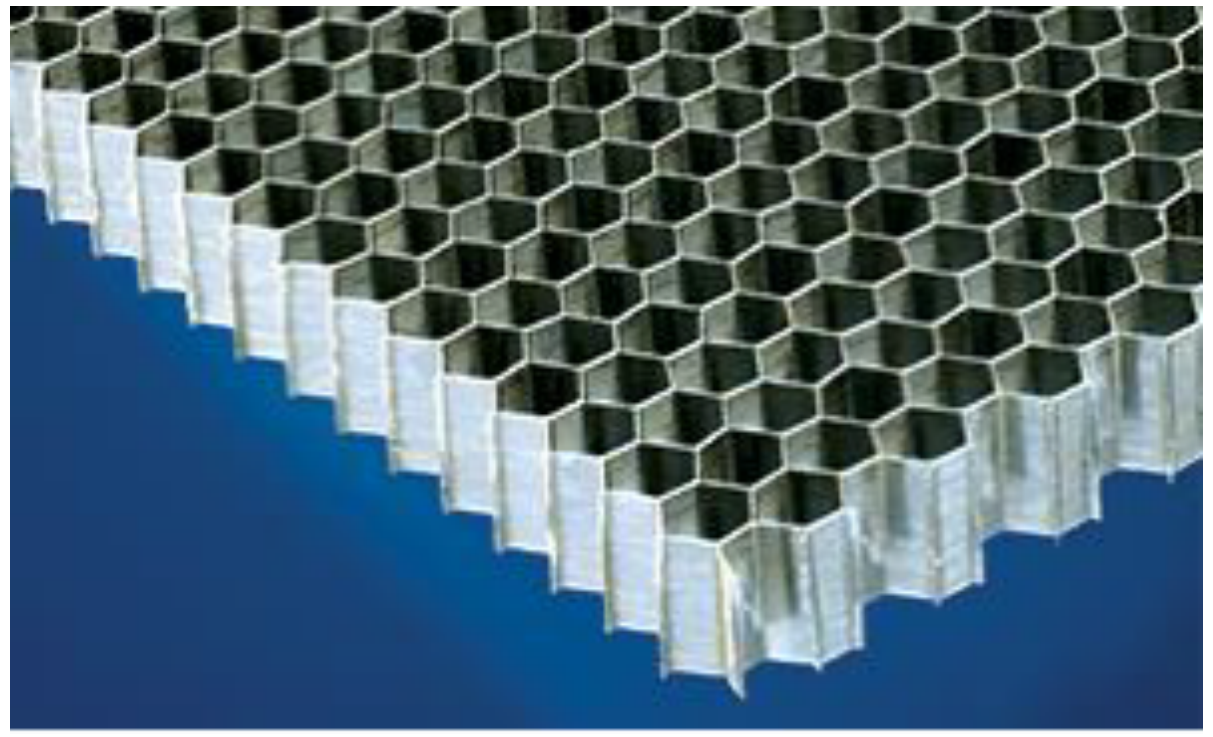
Superconducting solenoid

- 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: $X_0 = 0.04$



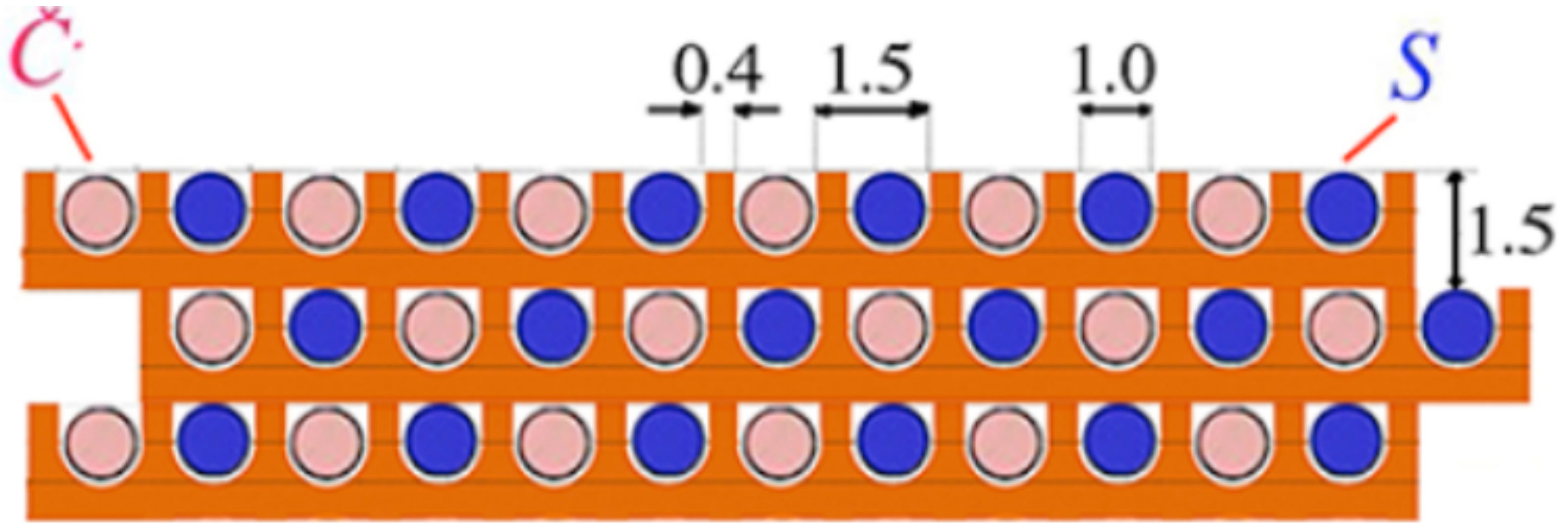
Courtesy of H. TenKate





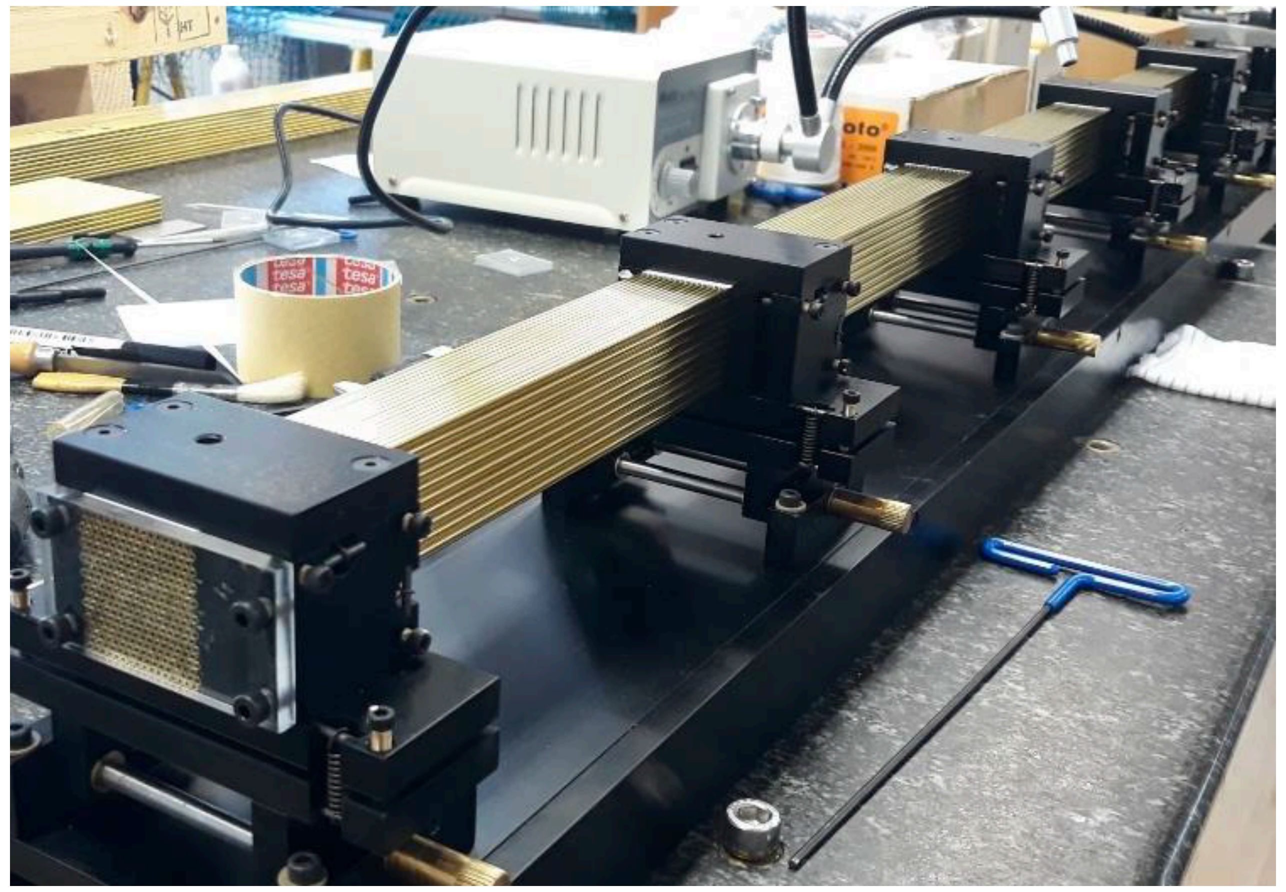
Interest from Genova (in synergy with DUNE) on alternative superconducting magnets like MgB_2

Dual Readout Calorimetry



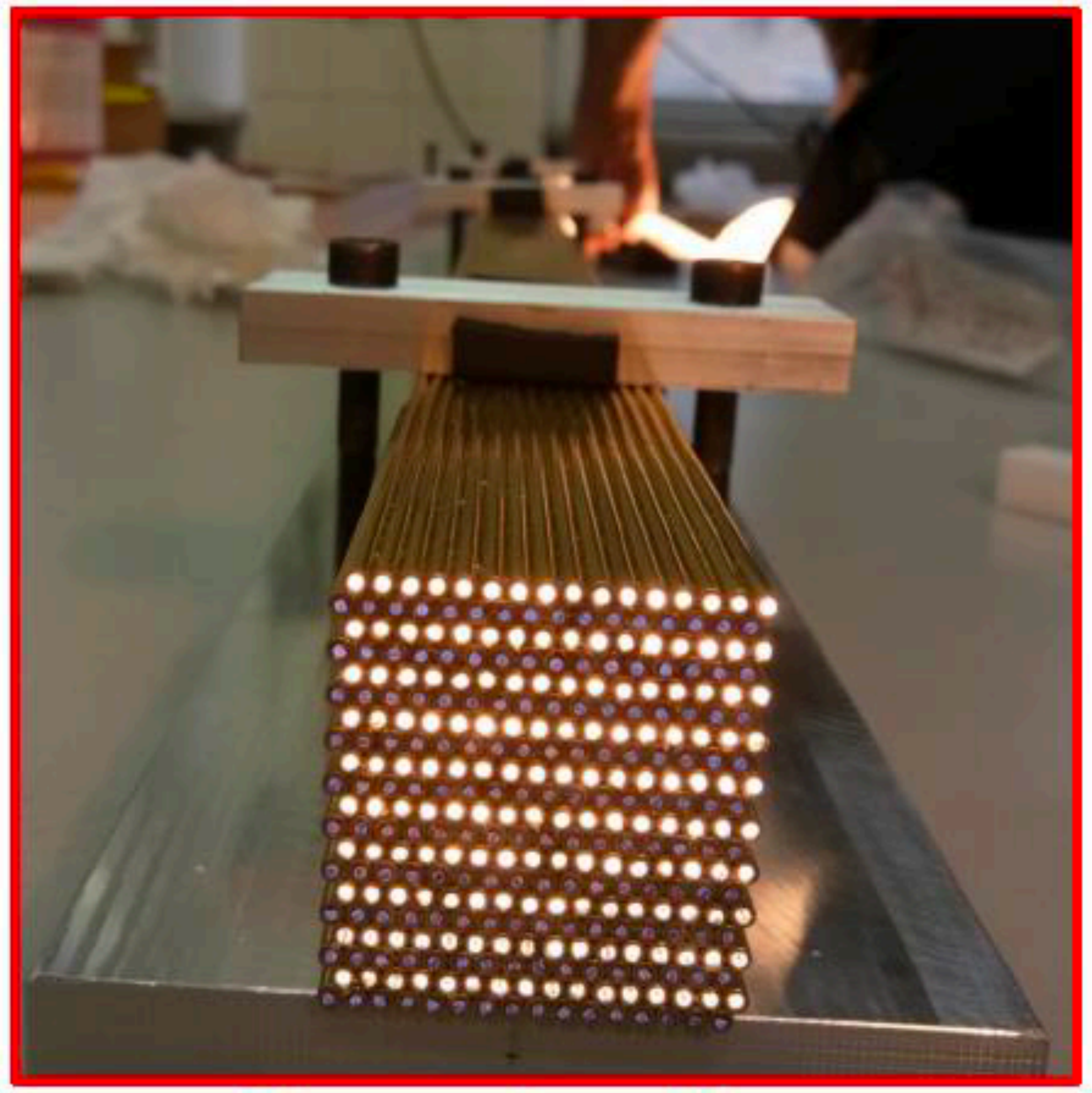
Alternate
Cherenkov fibers
Scintillating fibers

~2m long capillaries



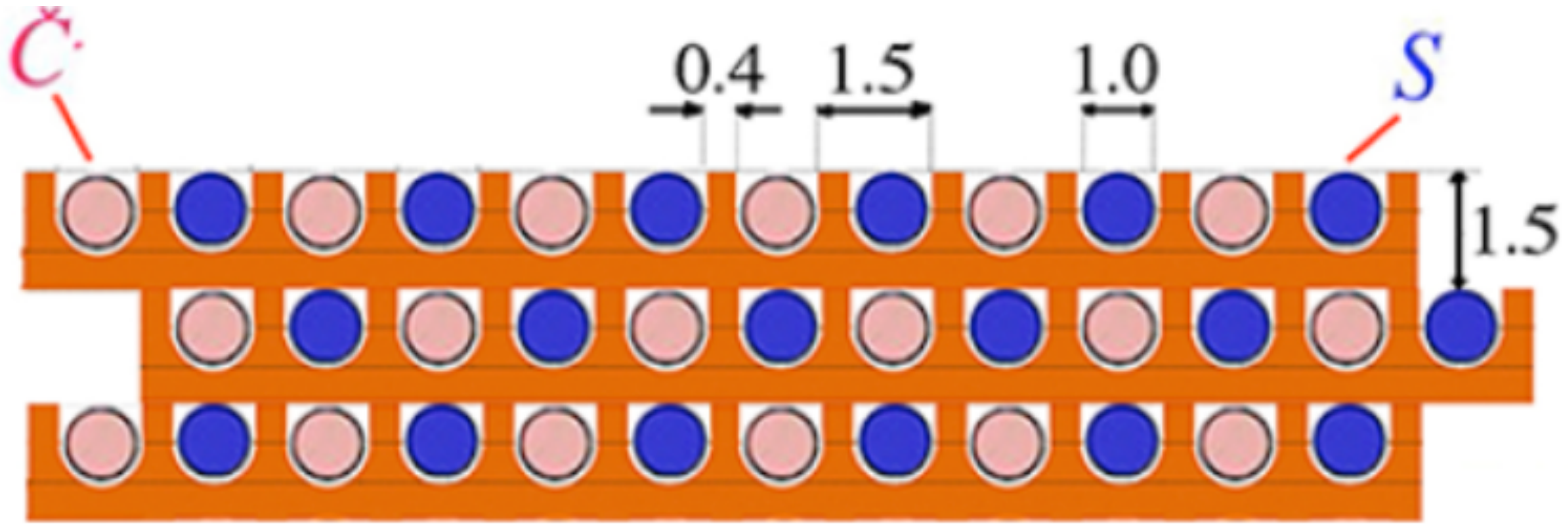
Newer DR calorimeter
(bucatini calorimeter)

Scintillation fibers



Cherenkov fibers

Dual Readout Calorimetry



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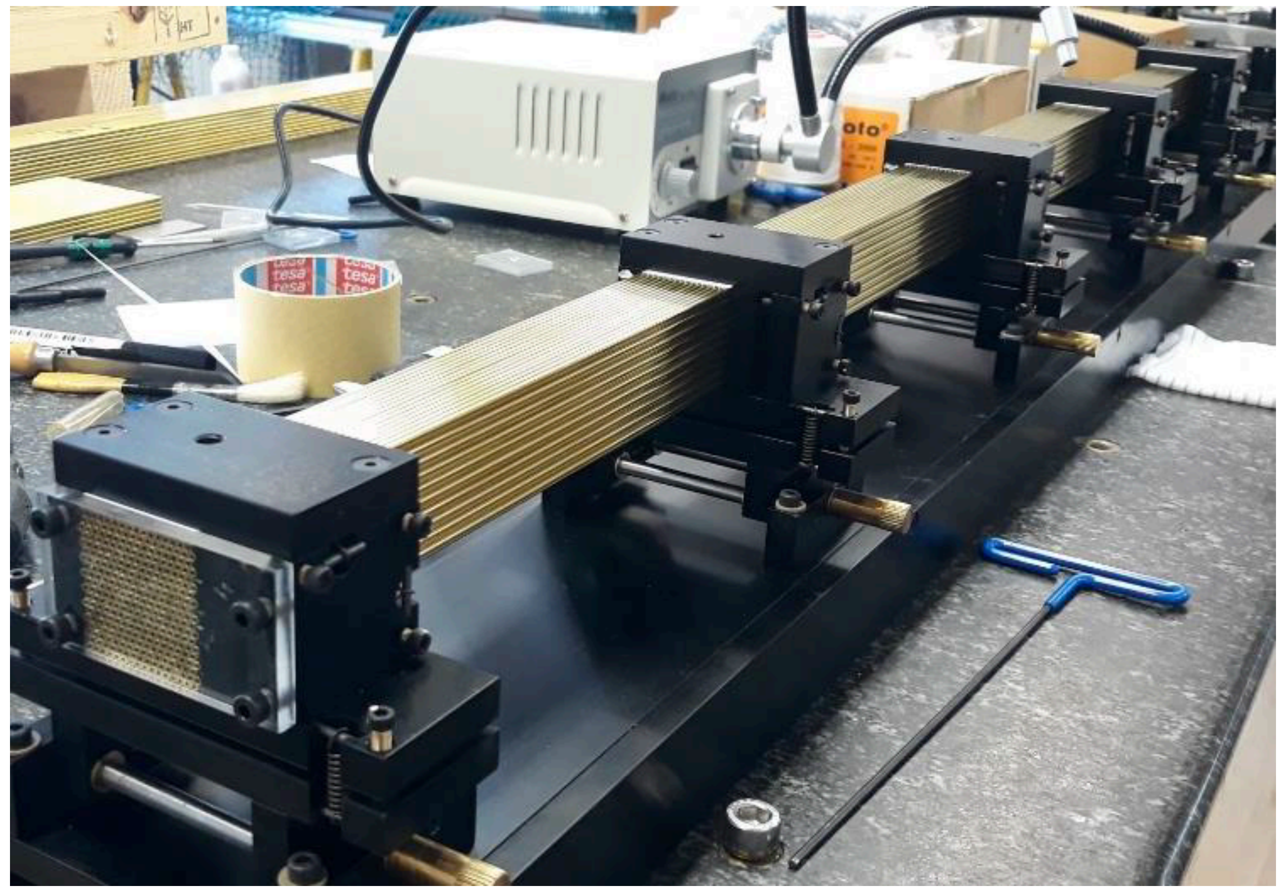

- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)

Newer DR calorimeter
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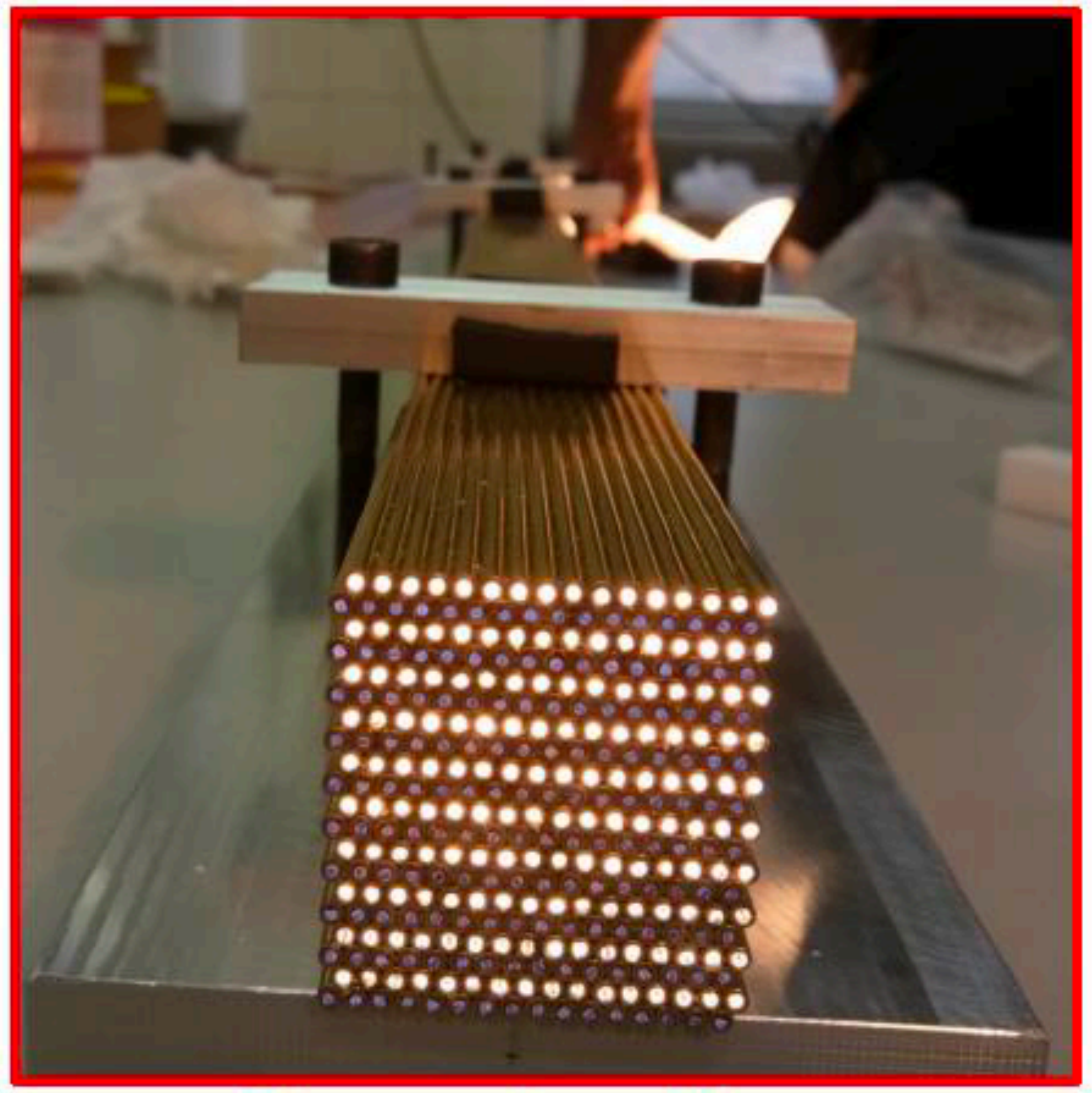
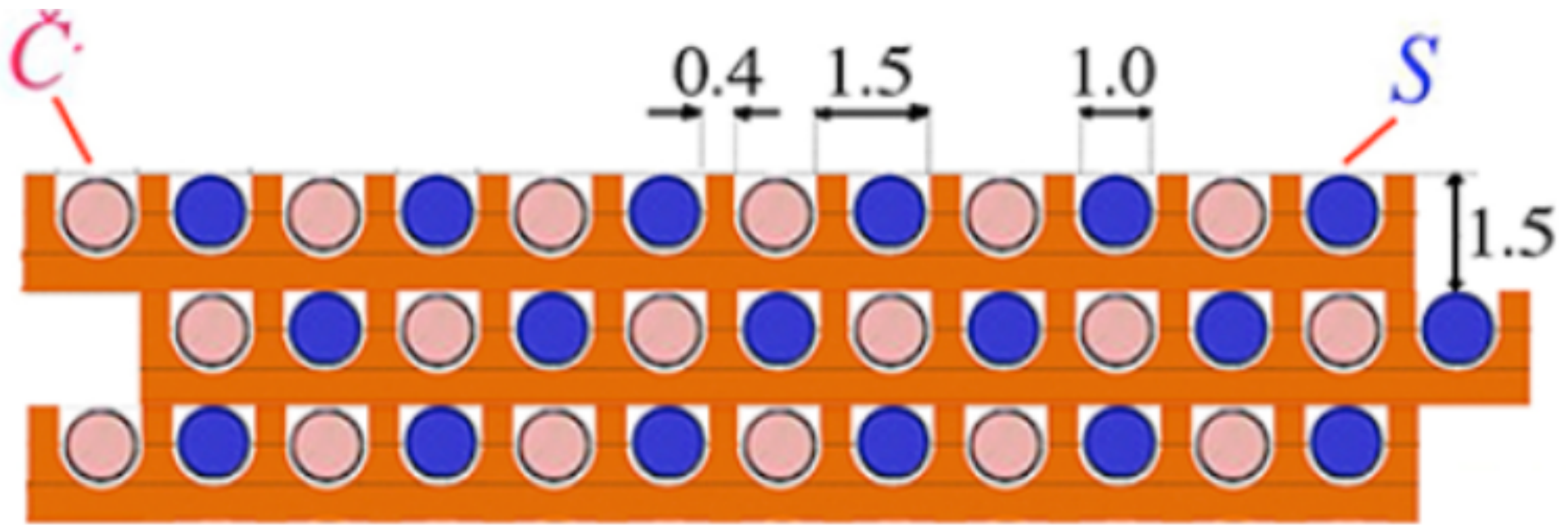
Scintillation fibers



Cherenkov fibers

Dual Readout Calorimetry



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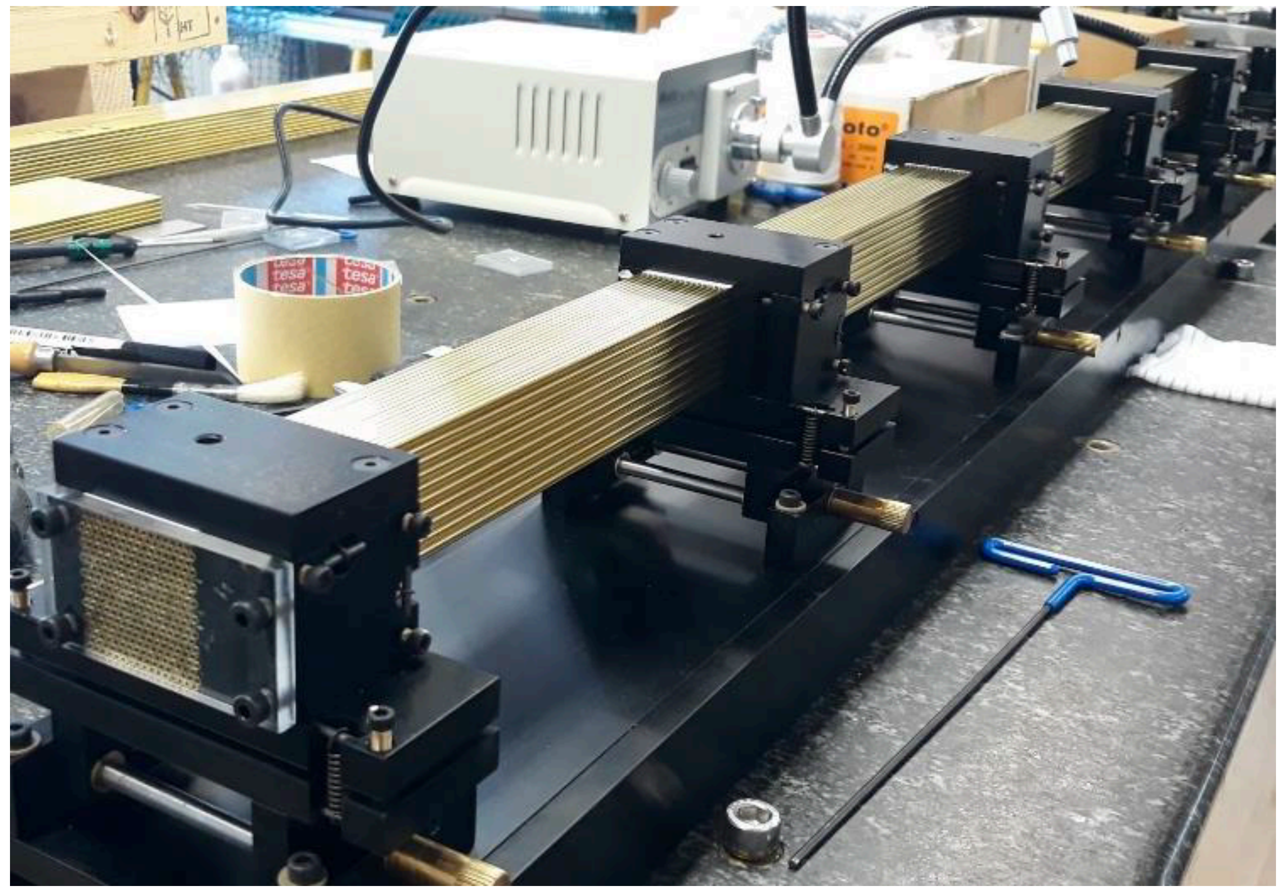
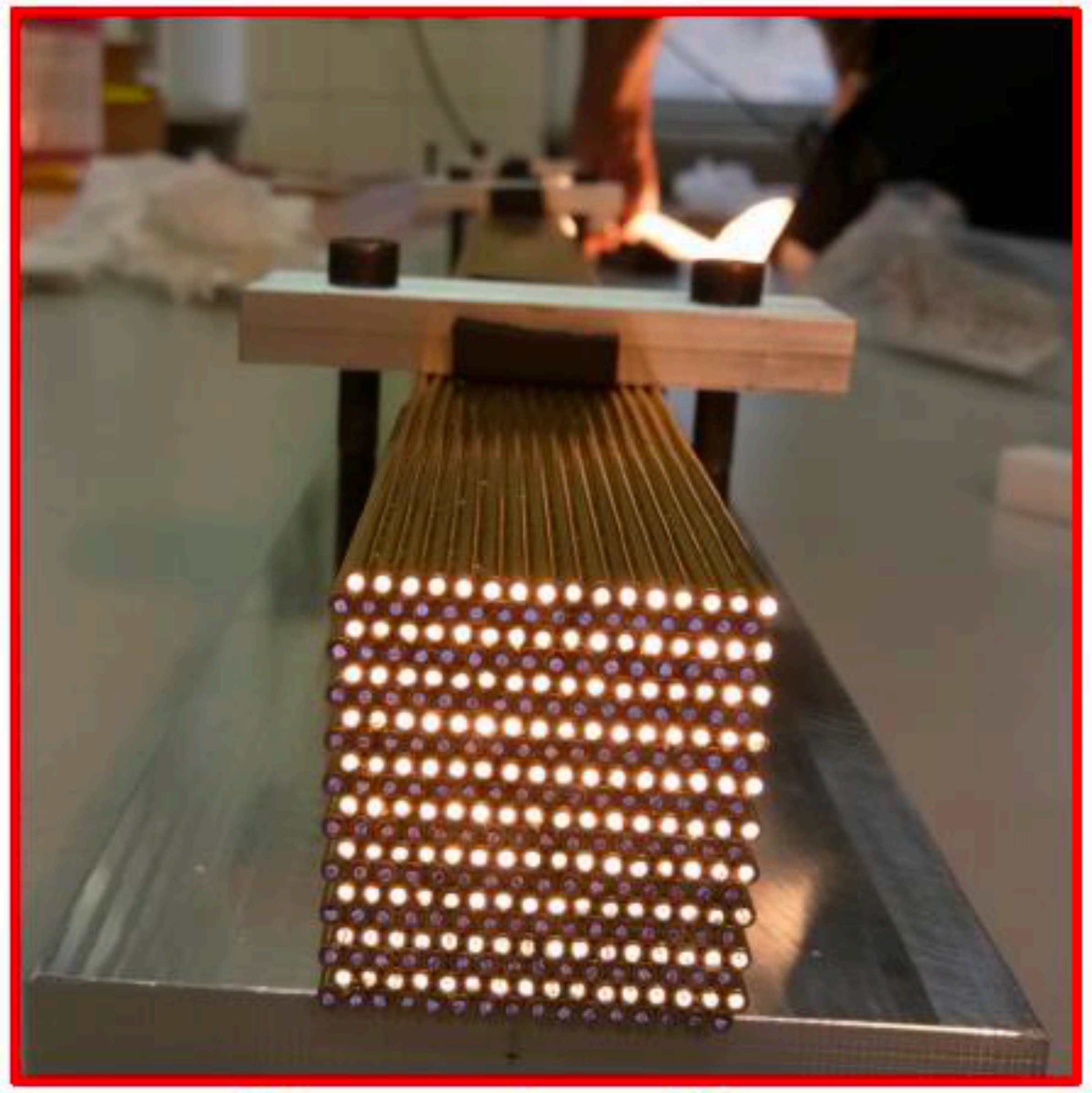
~2m long capillaries



- ❖ Measure simultaneously:
  - ➢ Scintillation signal (S)
  - ➢ Cherenkov signal (Q)
- ❖ Calibrate both signals with e-

Newer DR calorimeter
(bucatini calorimeter)

Scintillation fibers



Cherenkov fibers

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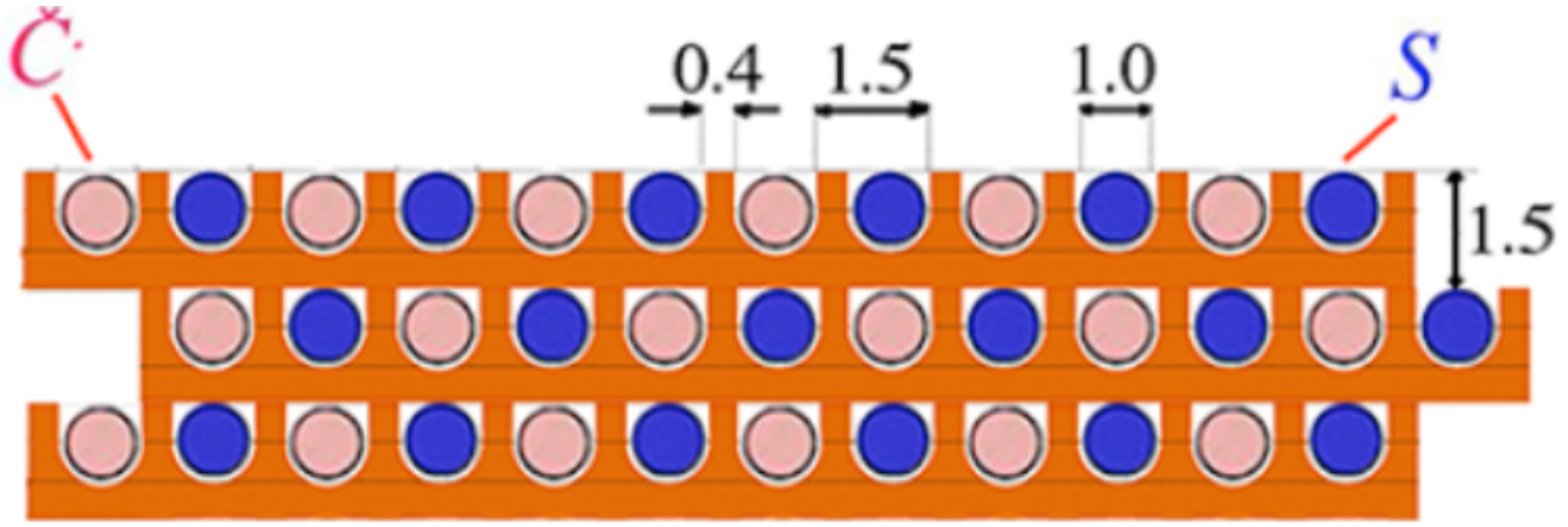

Alternate
Cherenkov fibers
Scintillating fibers

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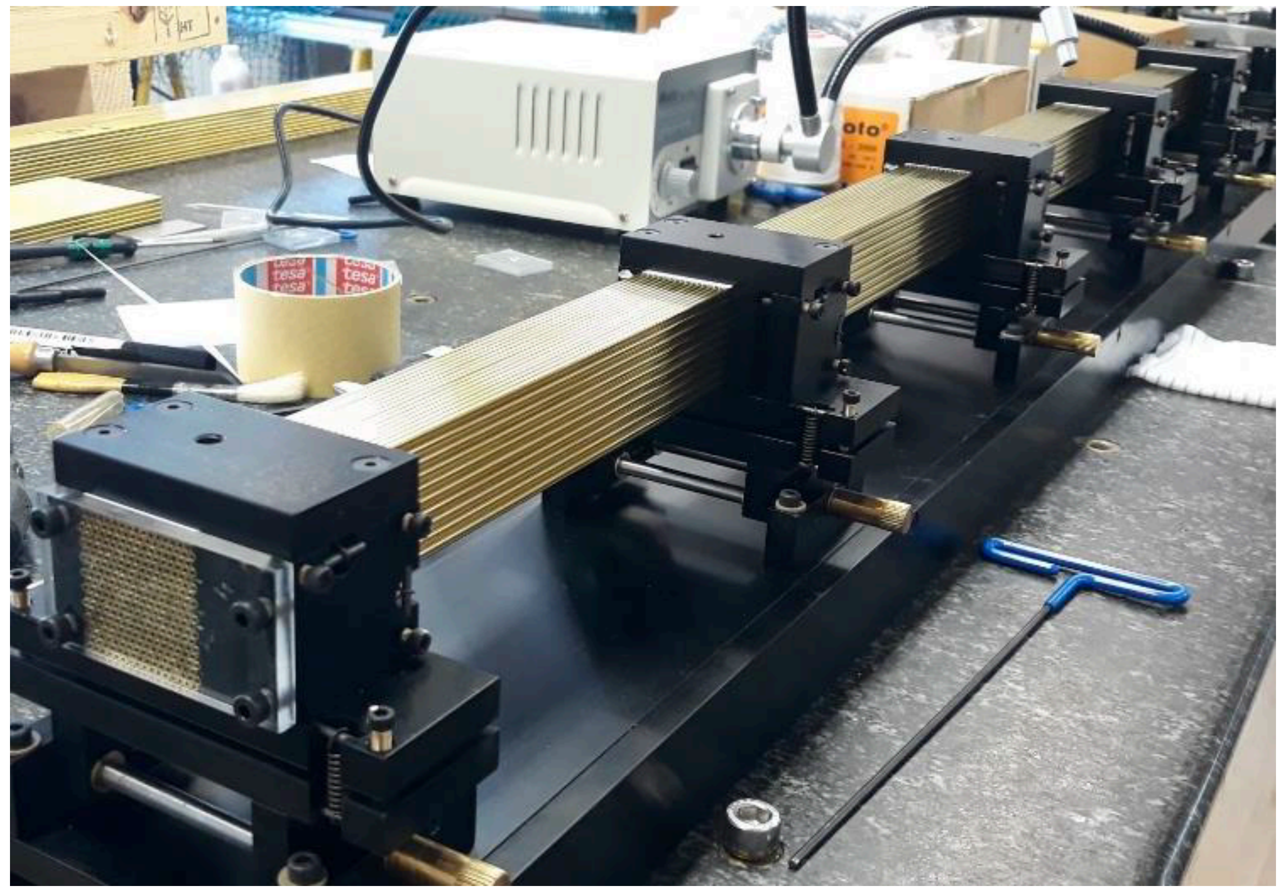

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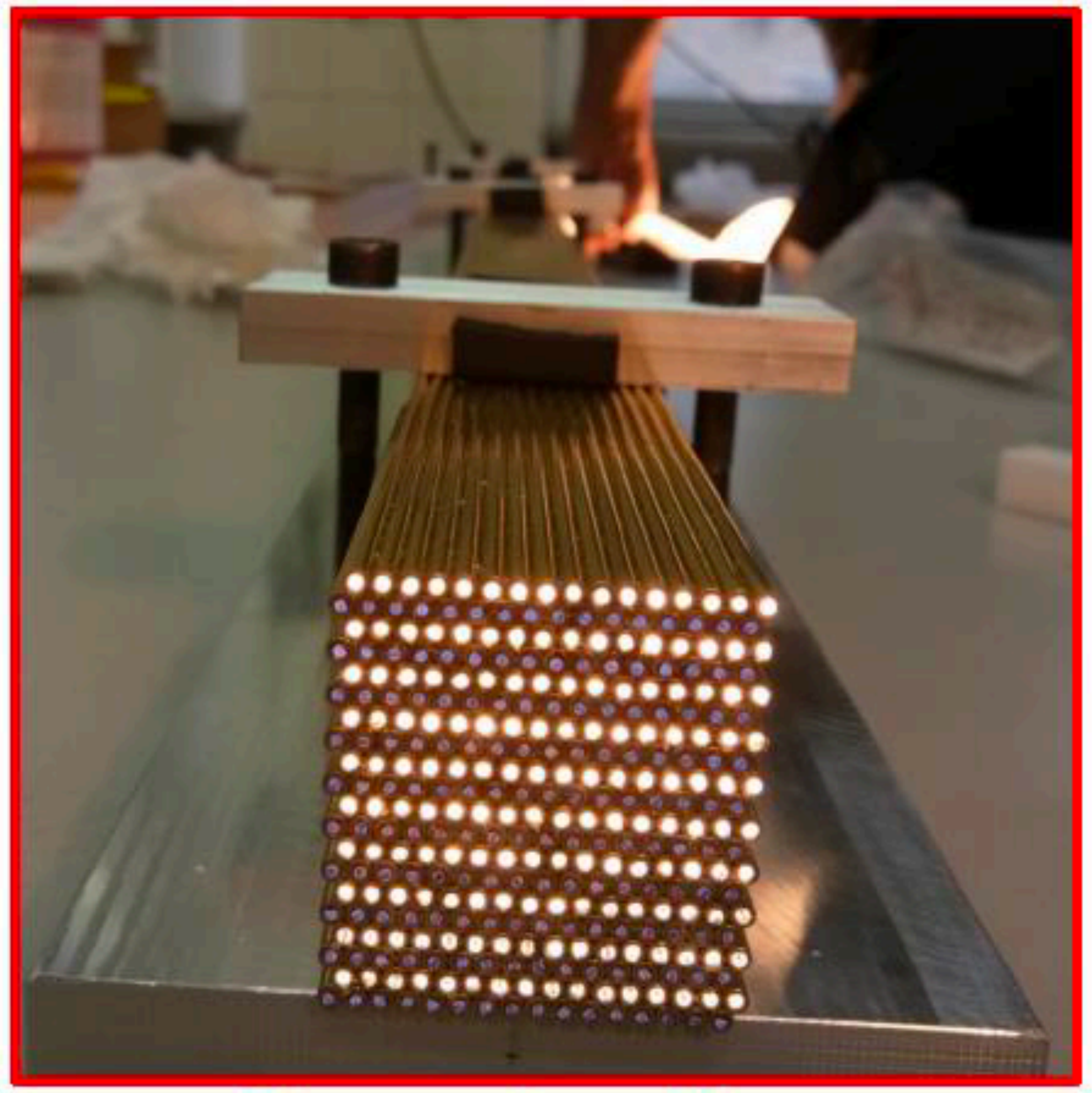
Newer DR calorimeter
(bucatini calorimeter)

Scintillation fibers



Cherenkov fibers

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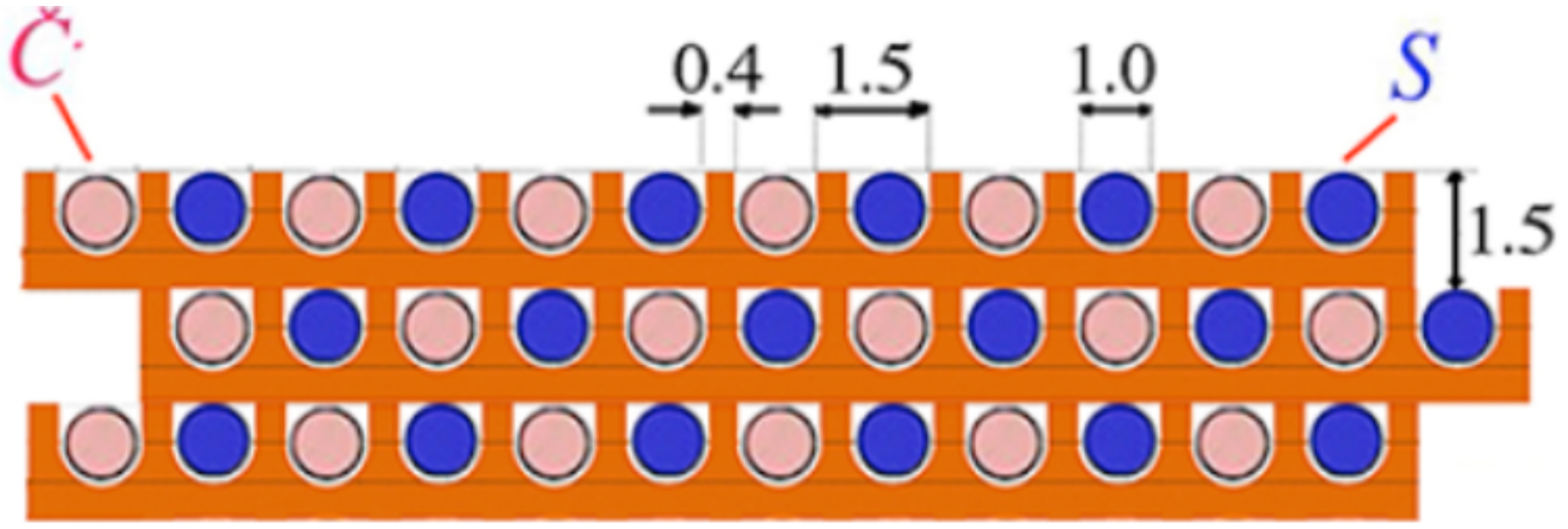

Alternate
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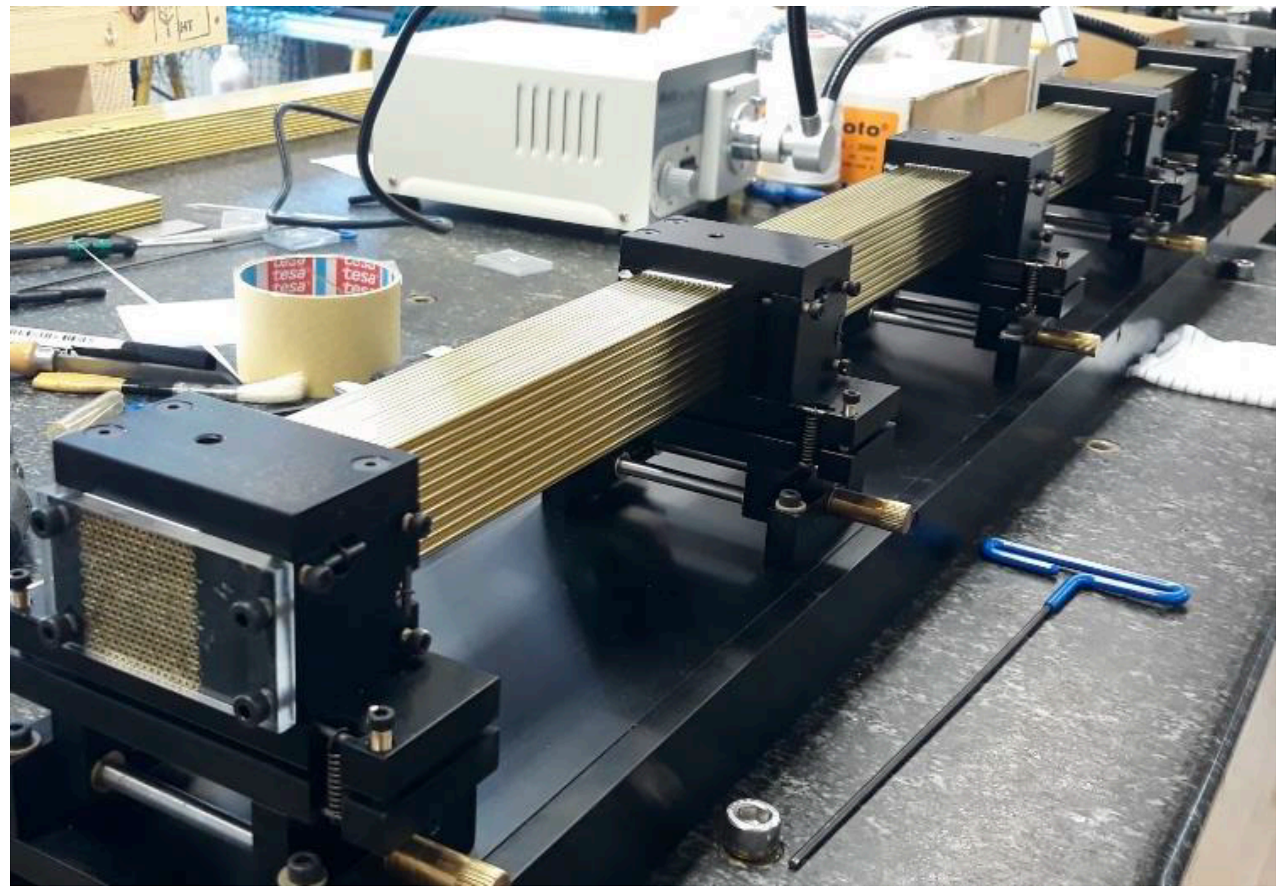

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- ❖ Unfold event by event f_{em} to obtain corrected energy

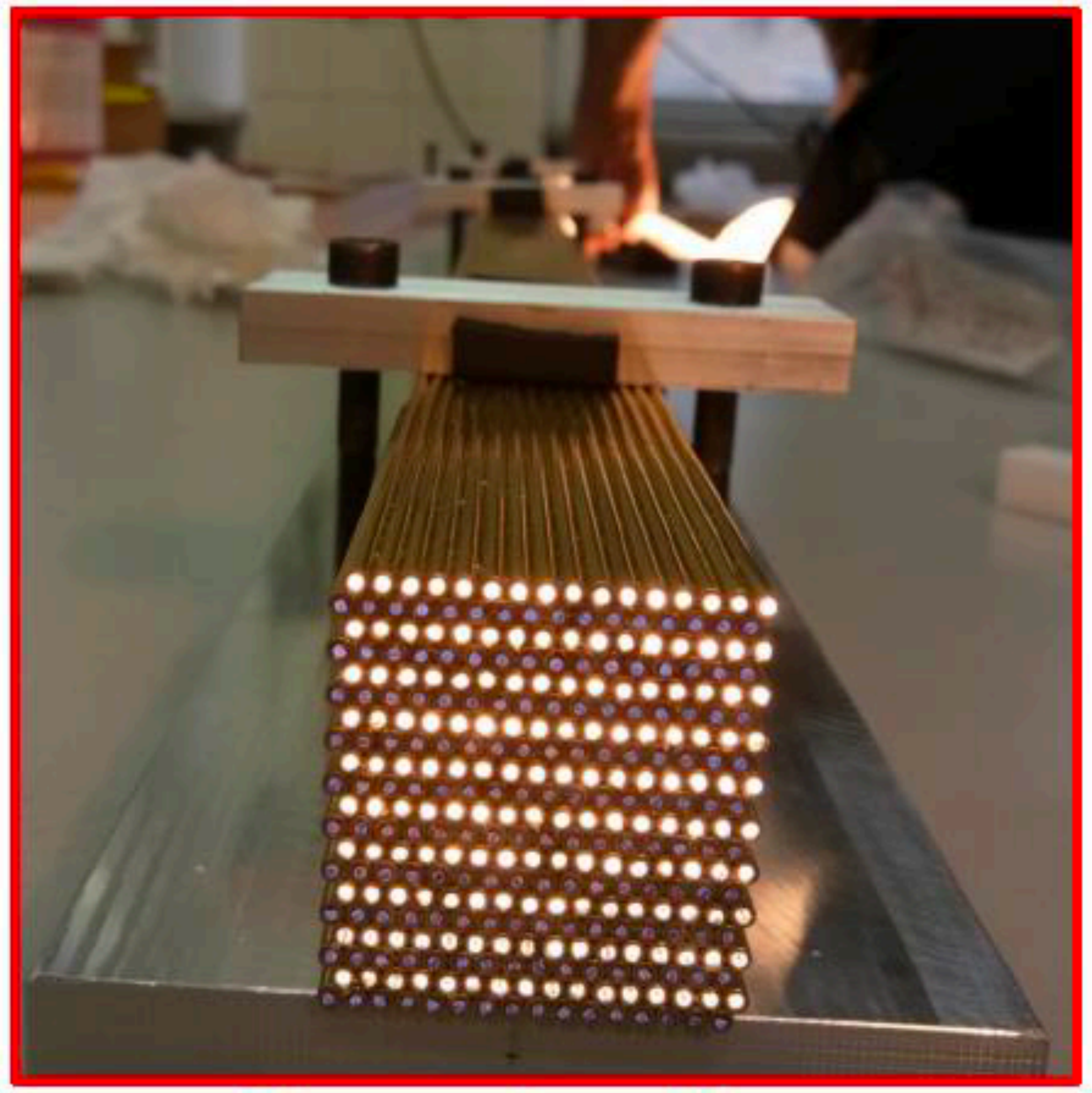
$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

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

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

Newer DR calorimeter
(bucatini calorimeter)

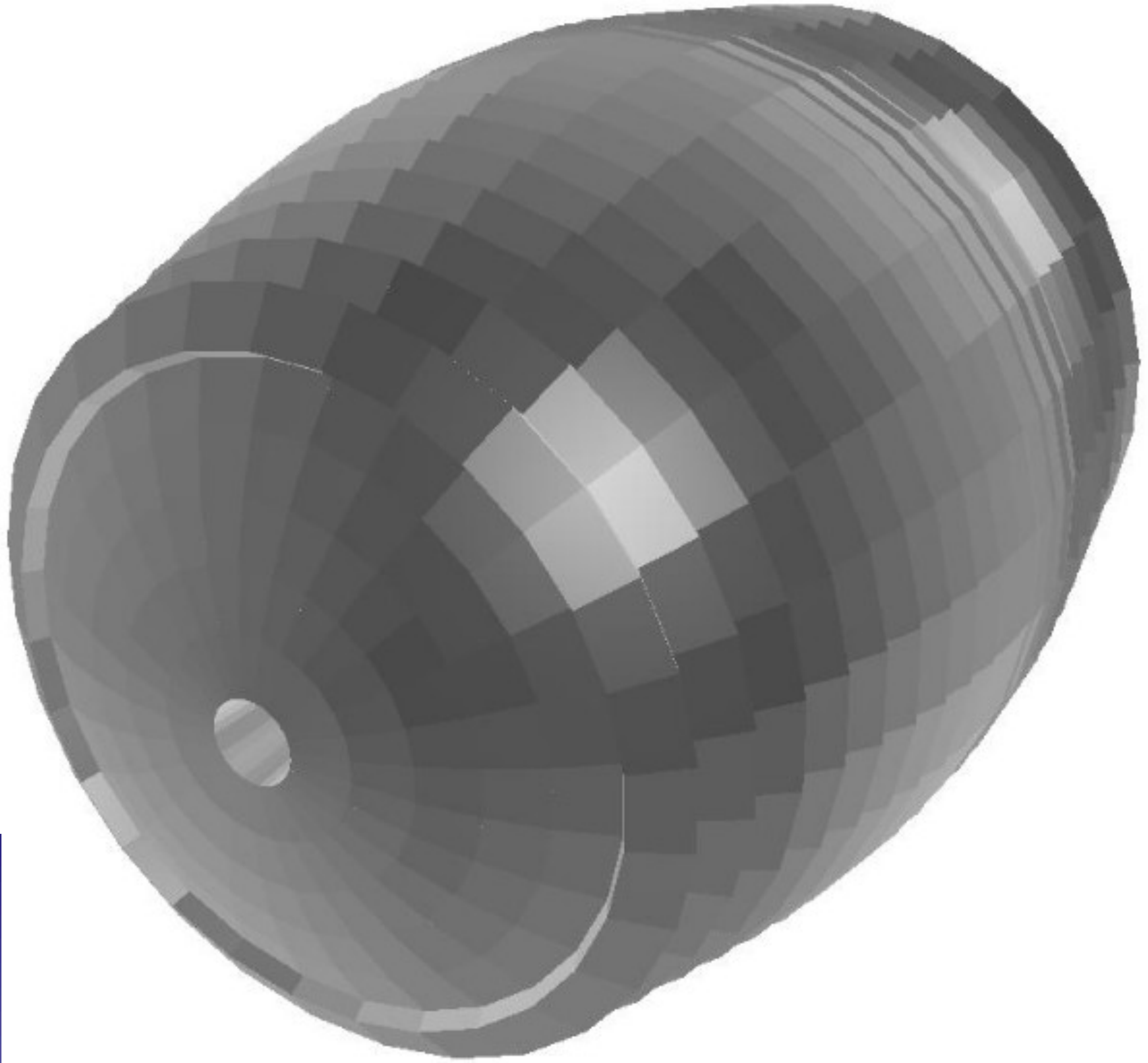
Scintillation fibers

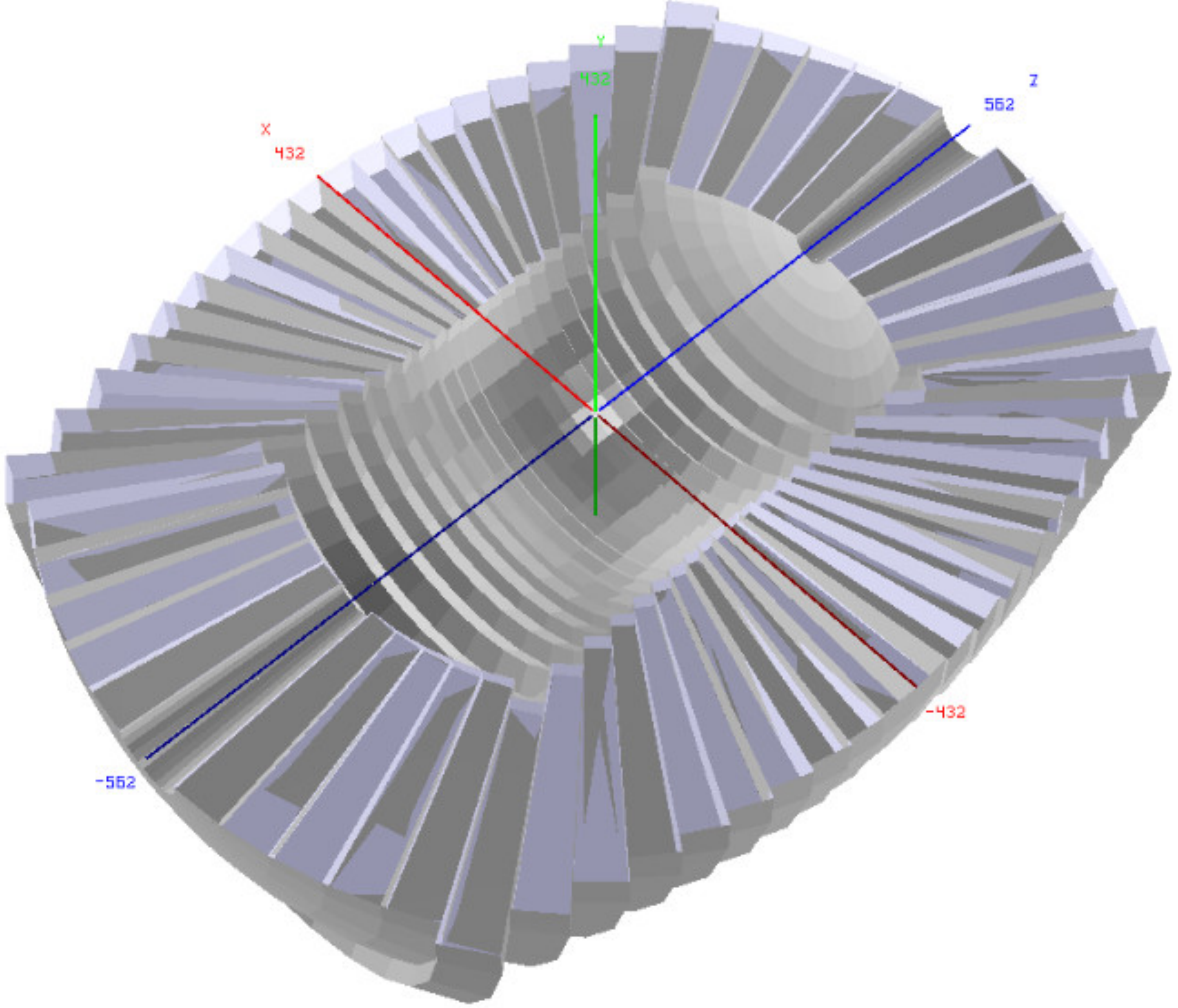


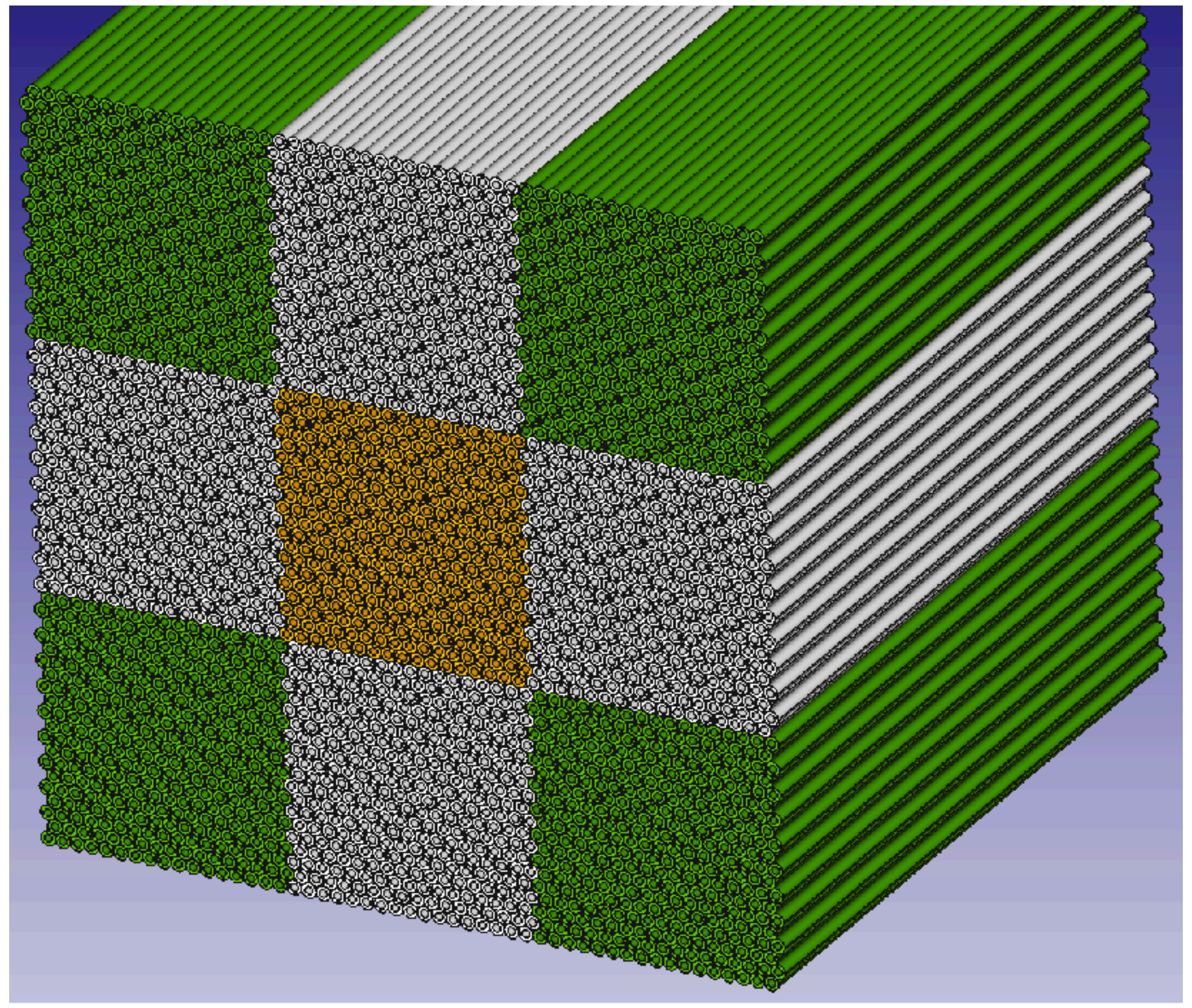
Cherenkov fibers

Dual Readout Calorimeter

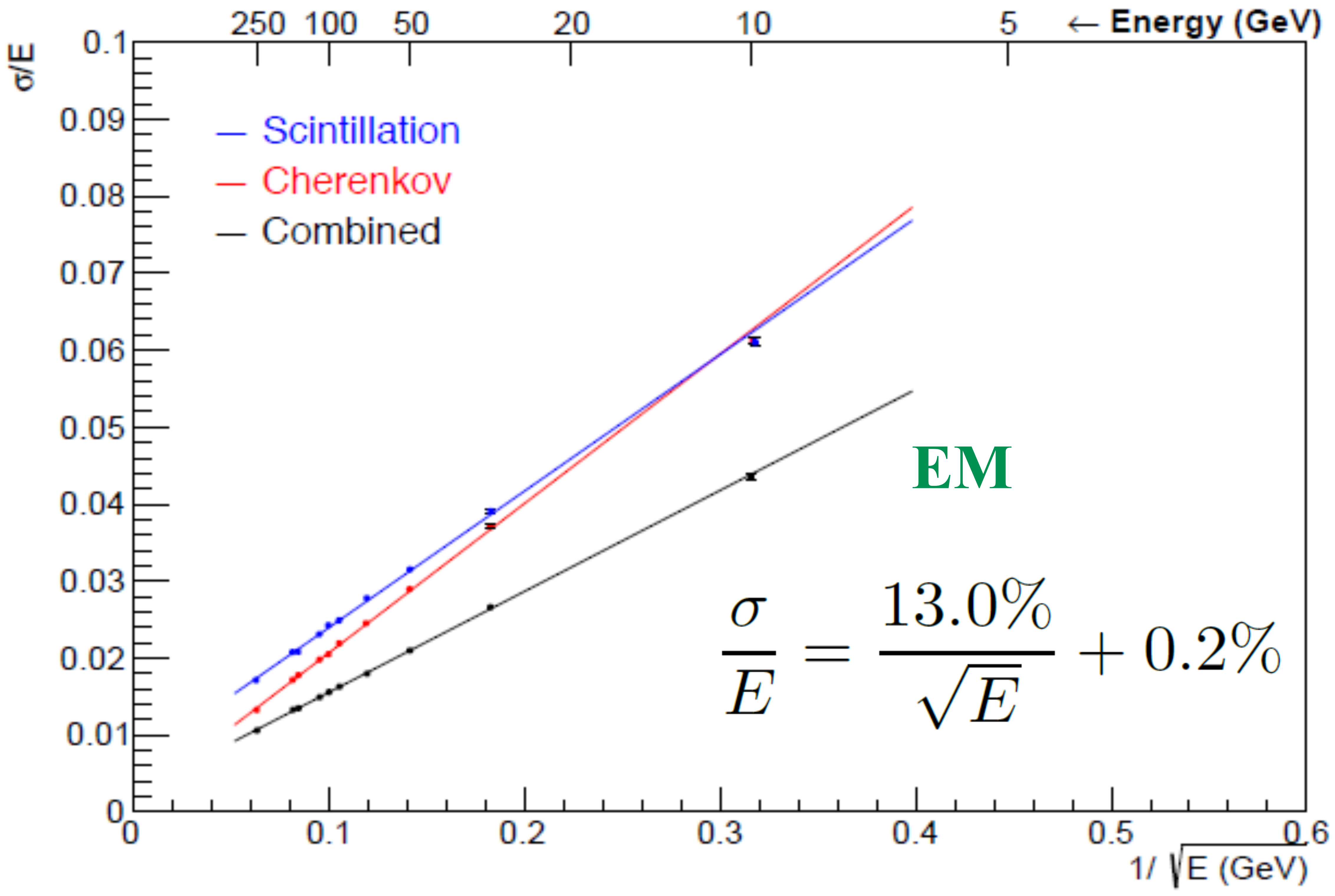
Full GEANT4 implementation of the DR calorimeter

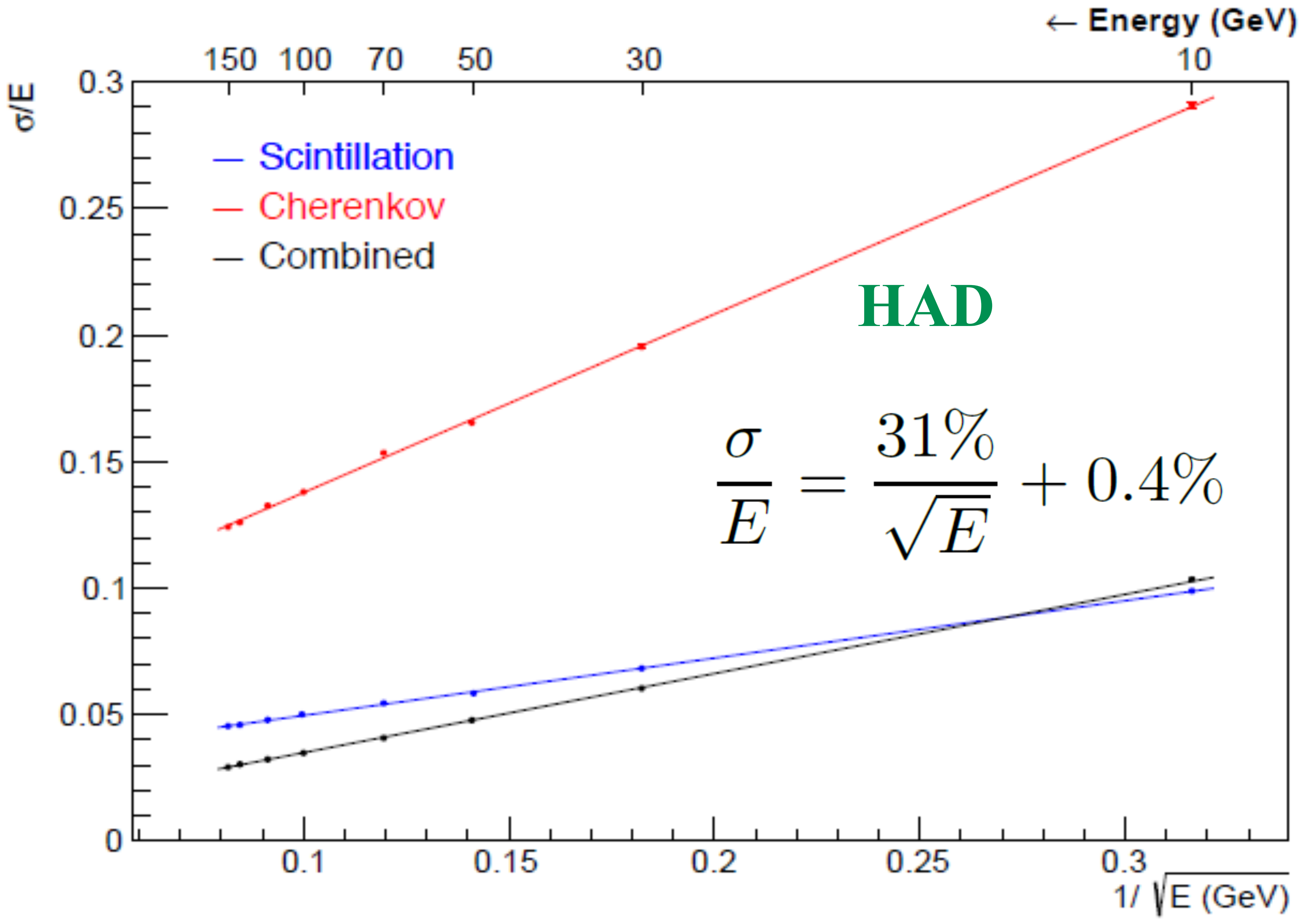






Dual Readout Calorimeter



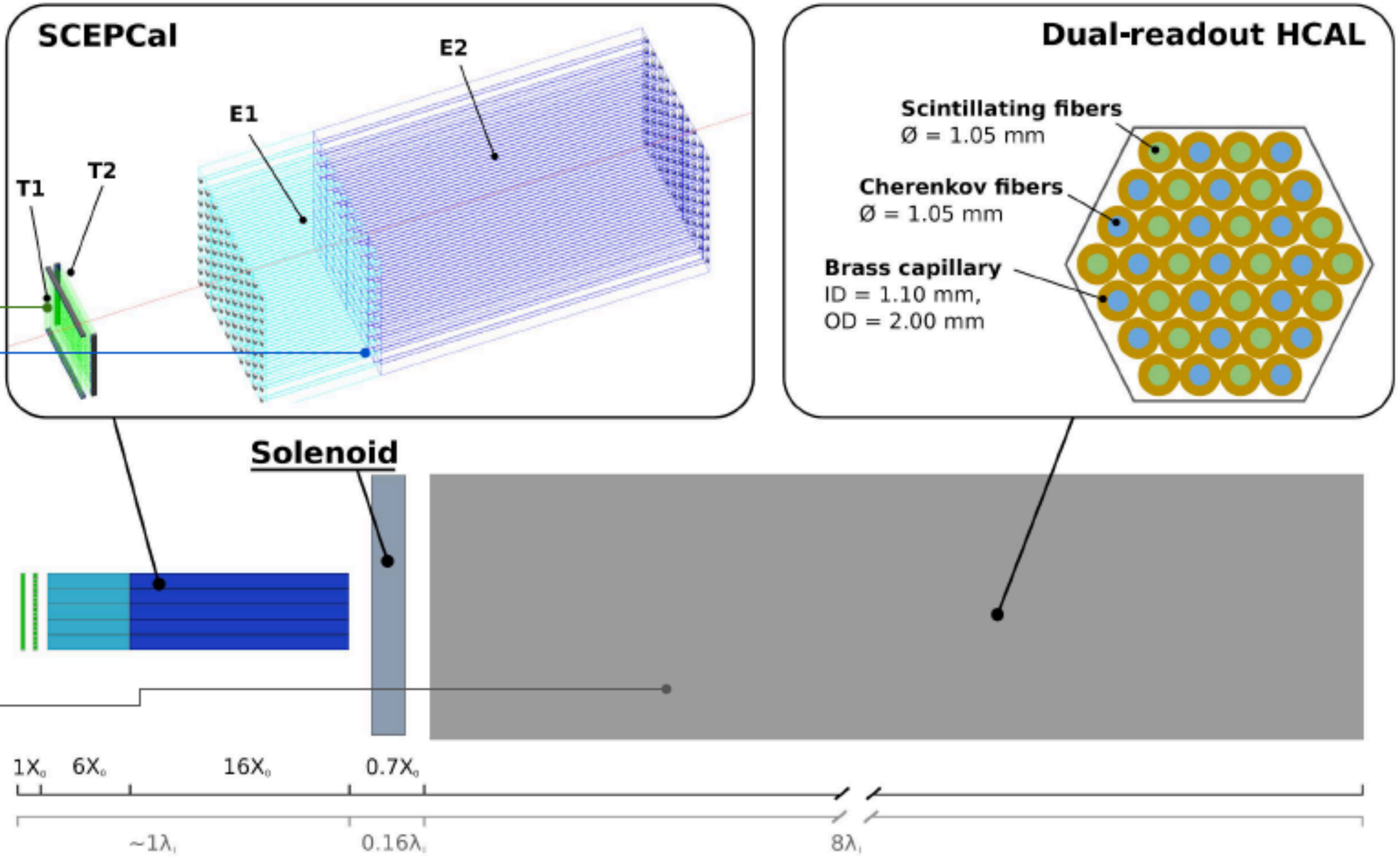


Crystal ECAL with DR calorimeter

Layout overview

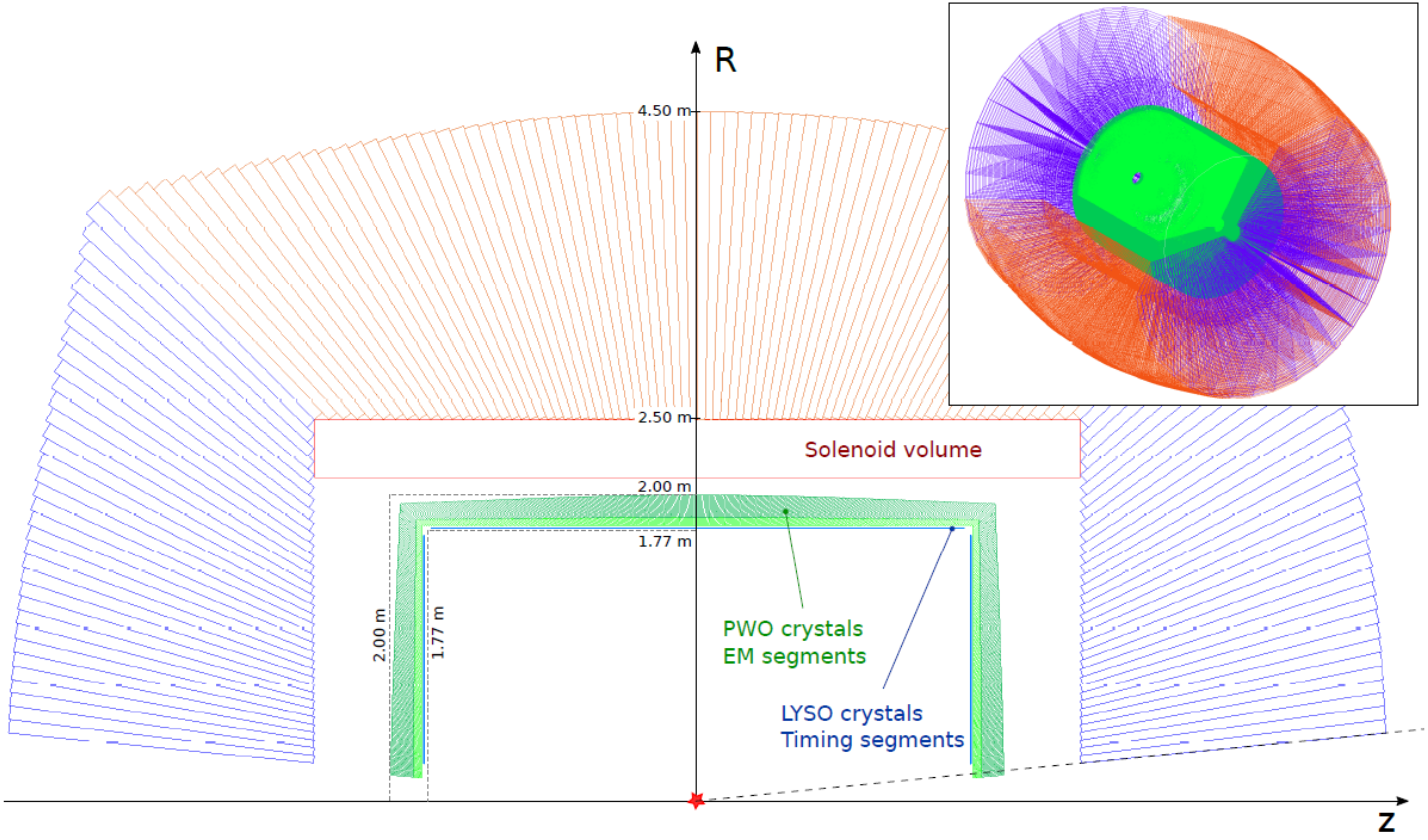
- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - $\sim 0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries

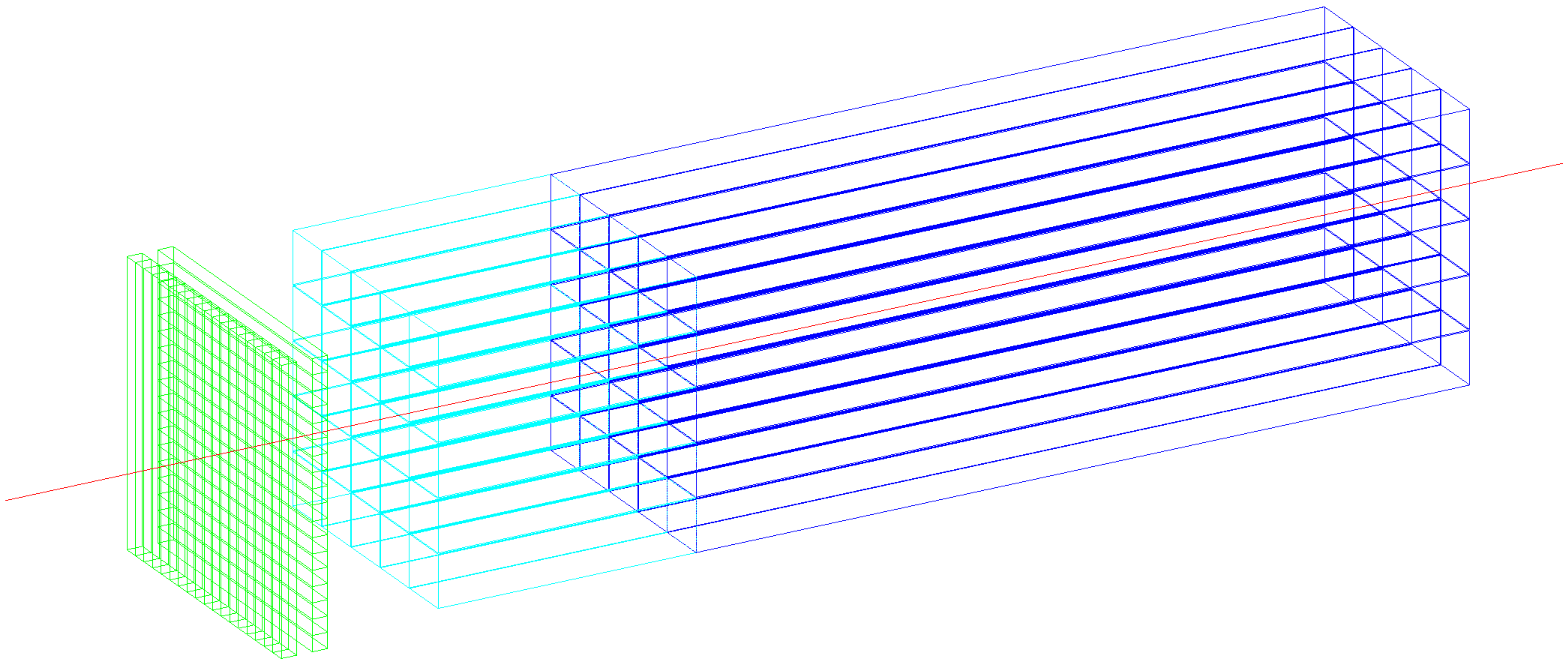


M. Lucchini

Crystal option



Crystal option

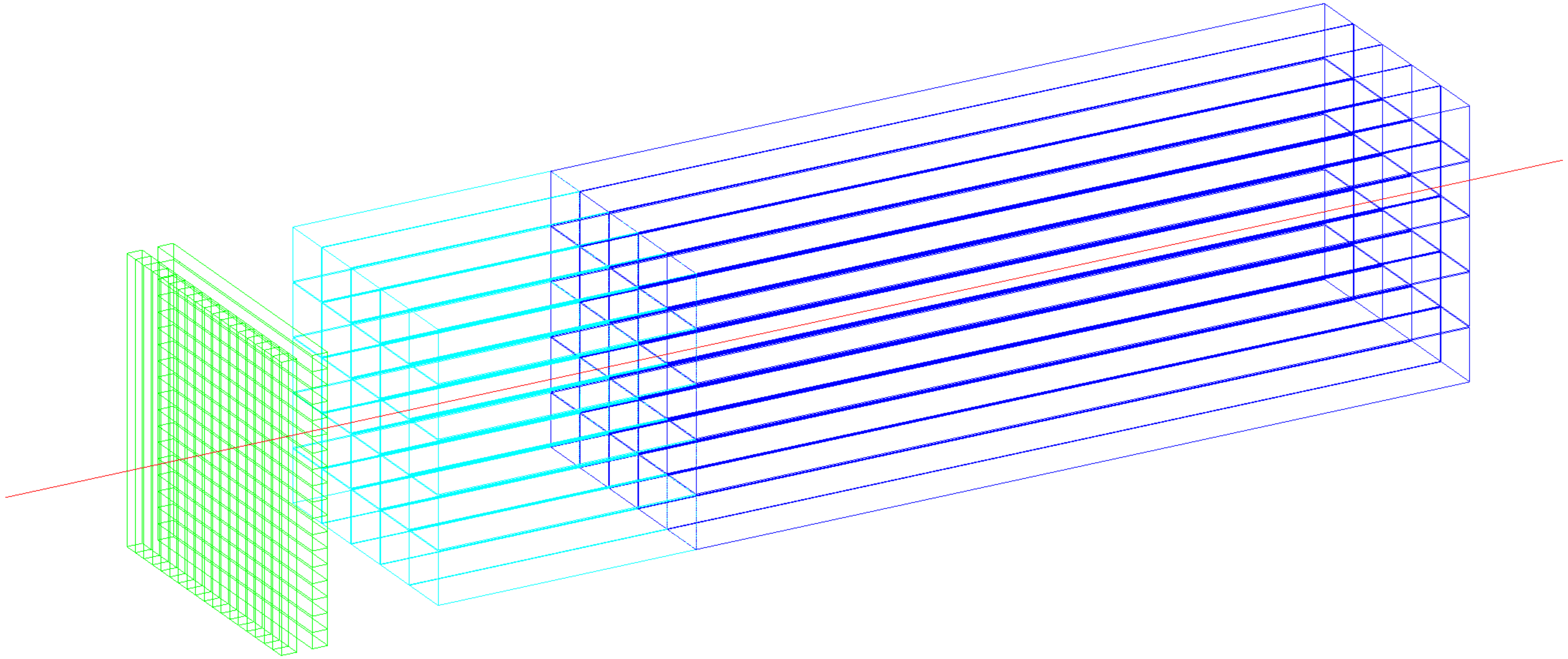


1x1x5 cm³
PbWO

1x1x15 cm³
PbWO

Crystal option

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



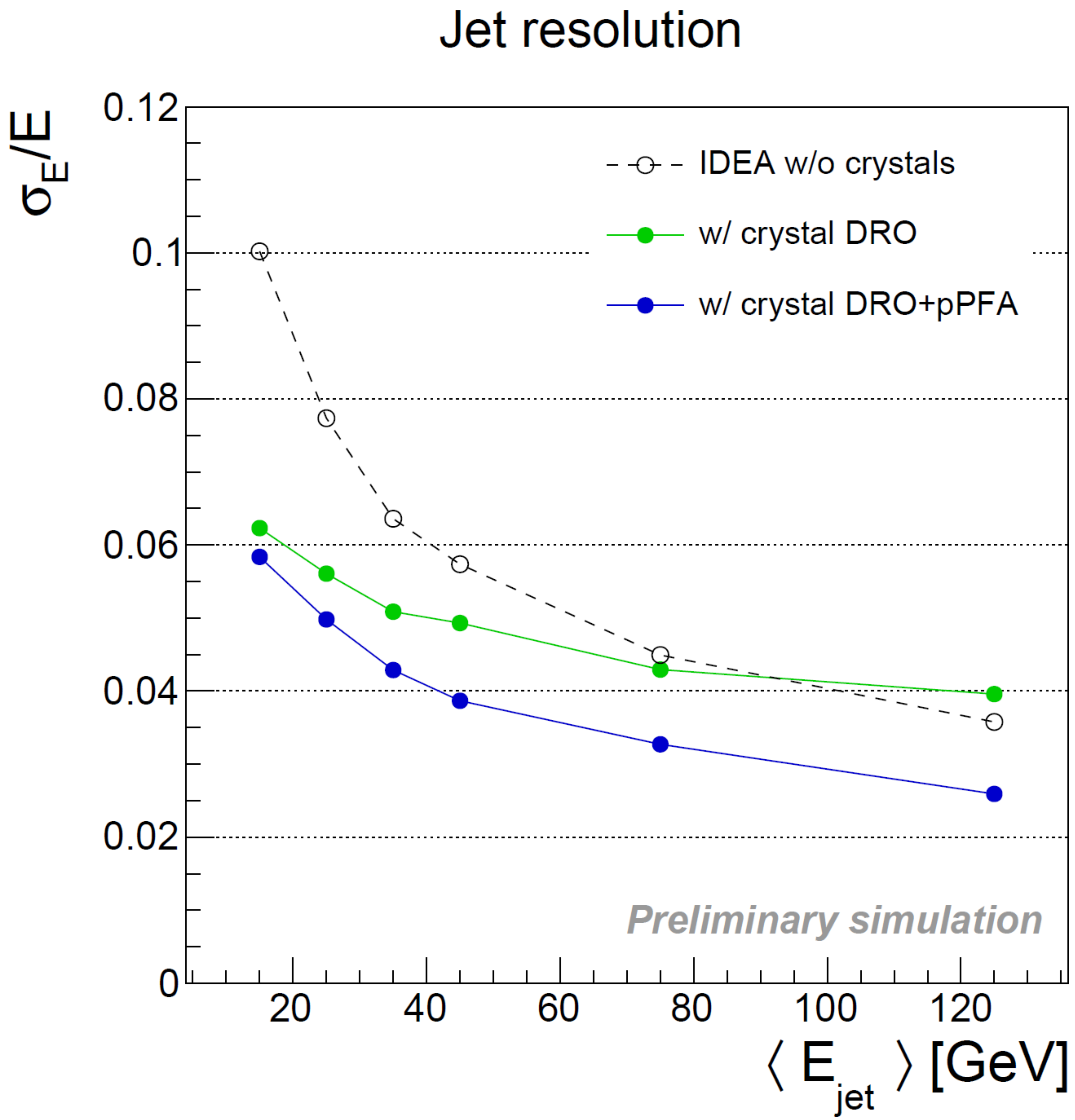
1x1x5 cm³ PbWO

1x1x15 cm³ PbWO

Crystal option

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

- PF for jets
  - **ECAL layer:**
    - PbWO crystals
    - front segment 5 cm (~5.4 X_0)
    - rear segment for core shower
    - (15 cm ~16.3 X_0)
    - 10x10x200 mm³ of crystal
    - 5x5 mm² SiPMs (10-15 um)



Preshower and muon detector

Preshower Detector

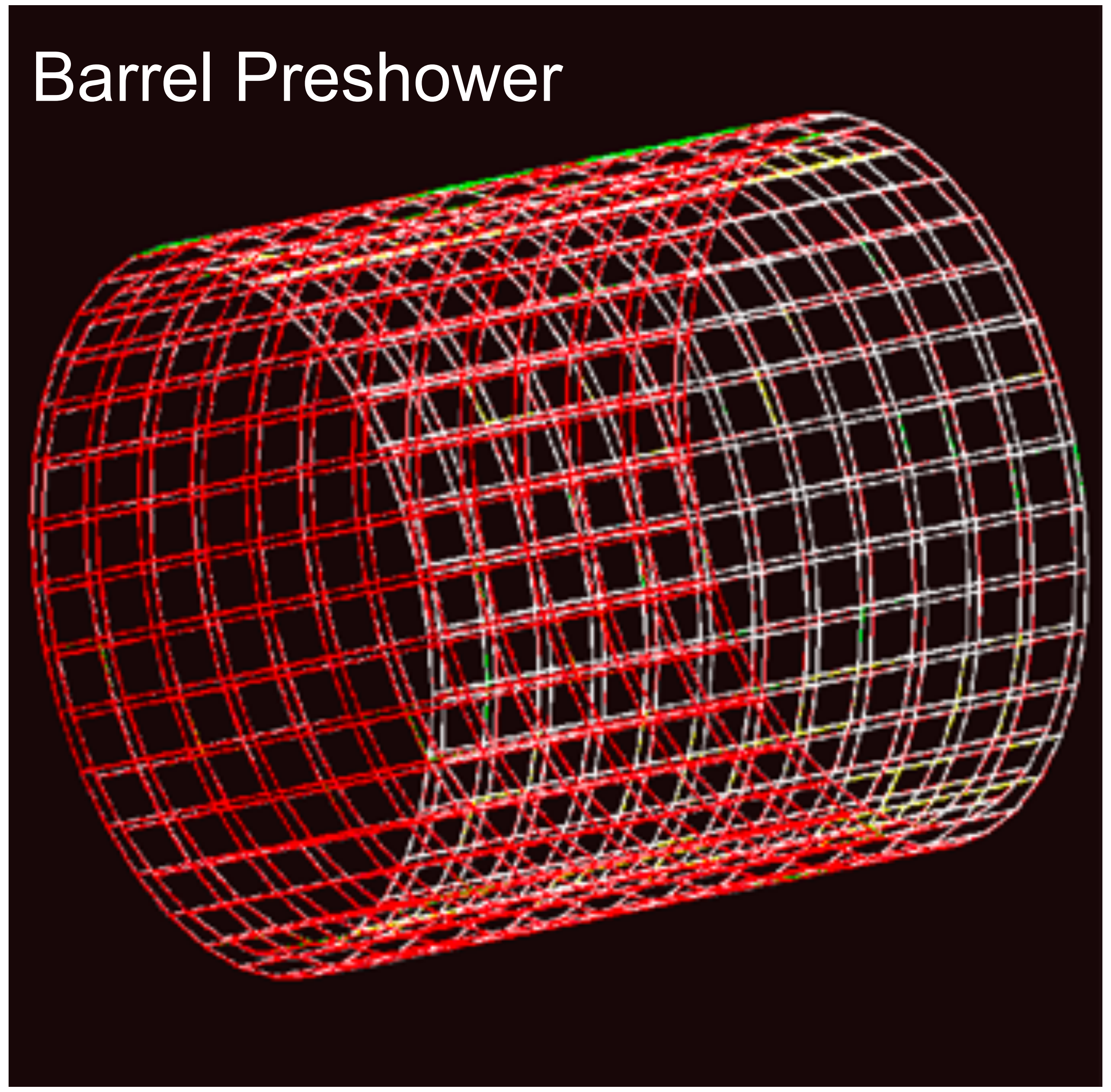
High resolution after the magnet
to improve $\pi^{\pm}/e^{\pm}$ and 2γ separation

Efficiency > 98%
Space Resolution < 100 μm
Mass production
Optimization of FEE channels/cost

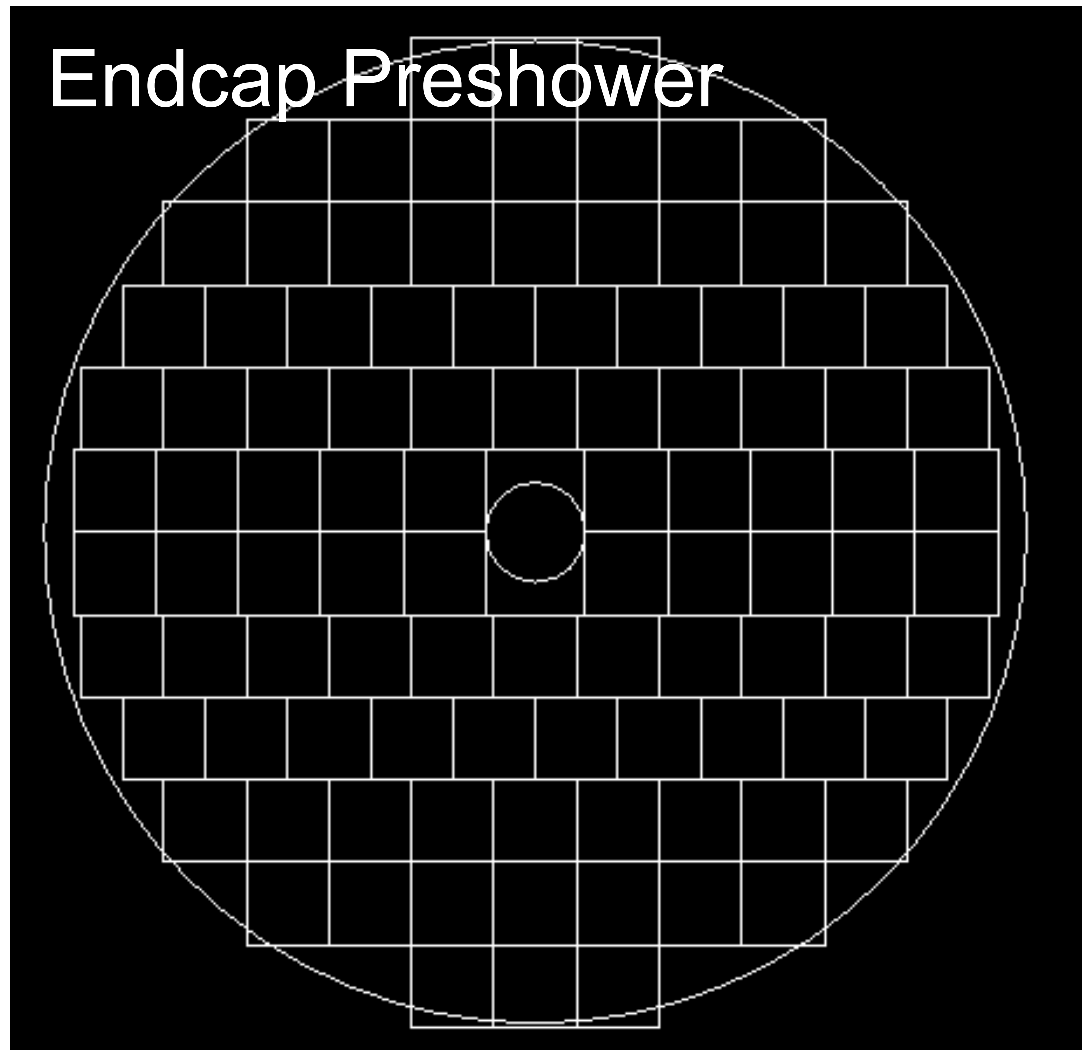
Muon Detector

Identify muons and search for LLPs

Efficiency > 98%
Space Resolution < 400 μm
Mass production
Optimization of FEE channels/cost



Similar design for
the Muon detector



Similar design for
the Muon detector

Detector technology: μ-RWELL

50x50 cm^2 2D tiles to
cover more than 1650 m^2

Preshower
pitch = 0.4 mm
FEE capacitance = 70 pF
1.3 million channels

Muon
pitch = 1.2 mm
FEE capacitance = 220 pF
5 million channels

μ-RWELL technology

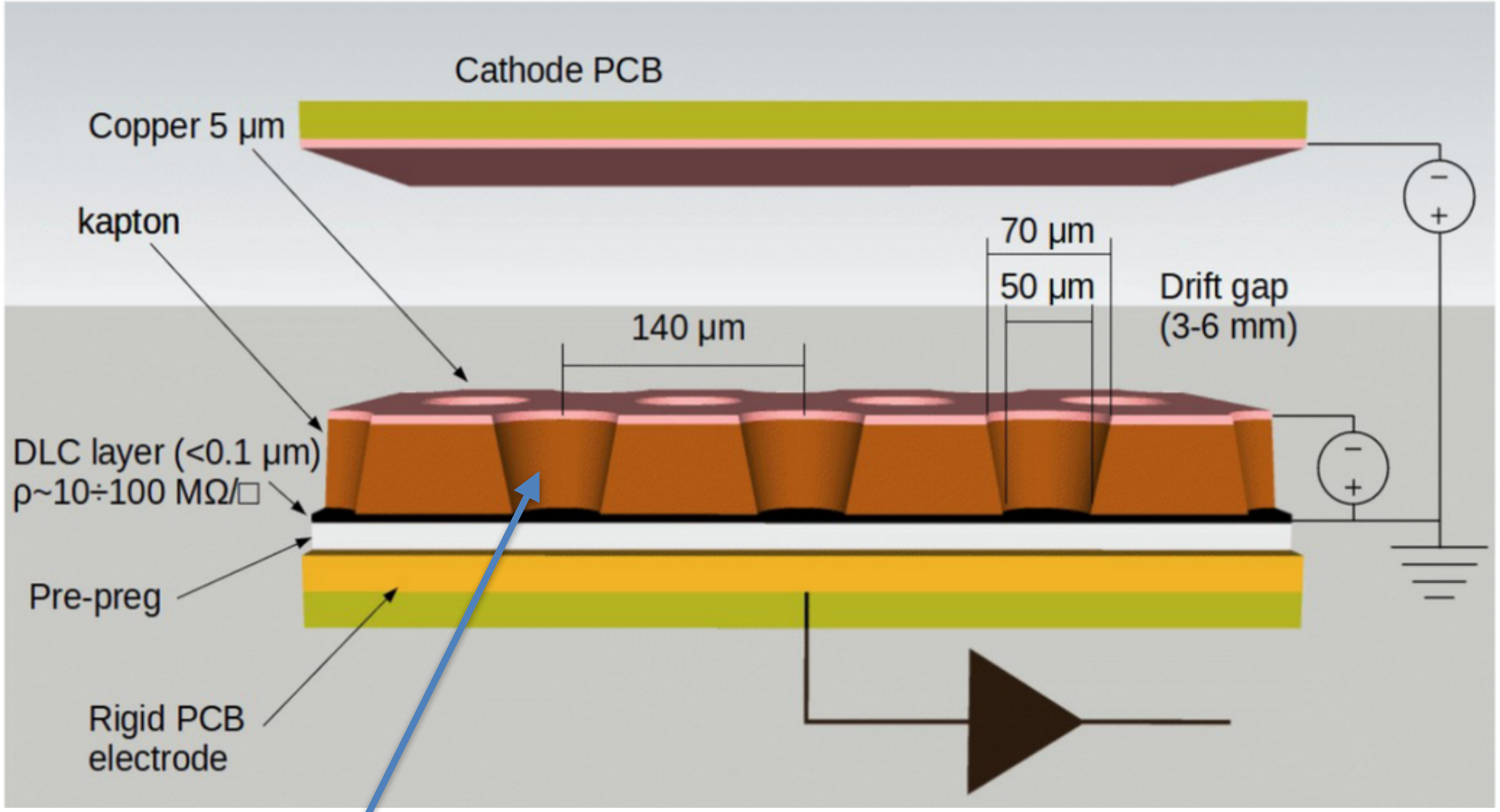
The μ-RWELL is composed of only two elements:

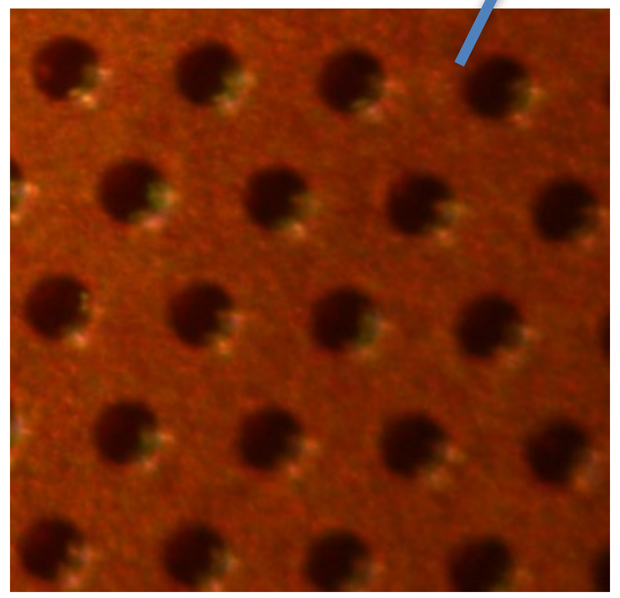
- μ-RWELL_PCB
- drift/cathode PCB defining the gas gap

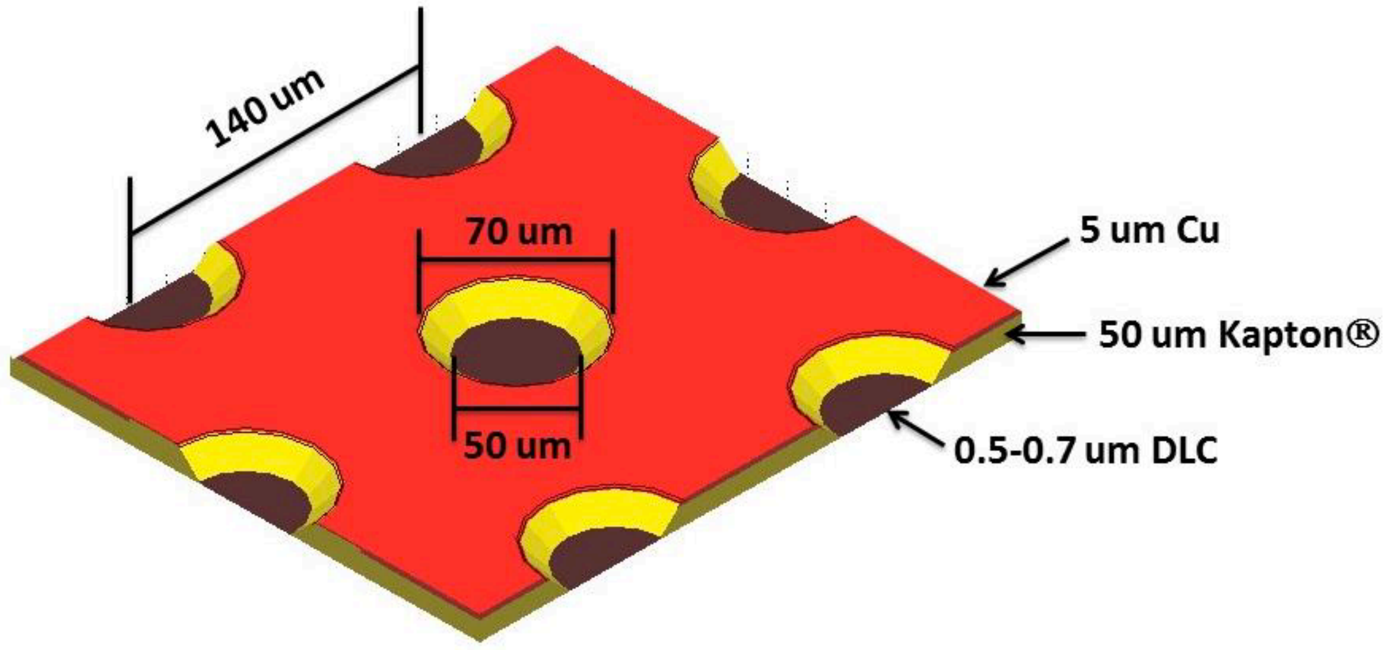
μ-RWELL_PCB = amplification-stage ⊕ resistive stage ⊕ readout PCB

μ-RWELL operation:

- A charged particle ionises the gas between the two detector elements
- Primary electrons drift towards the μ-RWELL_PCB (anode) where they are multiplied, while ions drift to the cathode
- The signal is induced capacitively, through the DLC layer, to the readout PCB
- HV is applied between the Anode and Cathode PCB electrodes
- HV is also applied to the copper layer on the top of the kapton foil, providing the amplification field

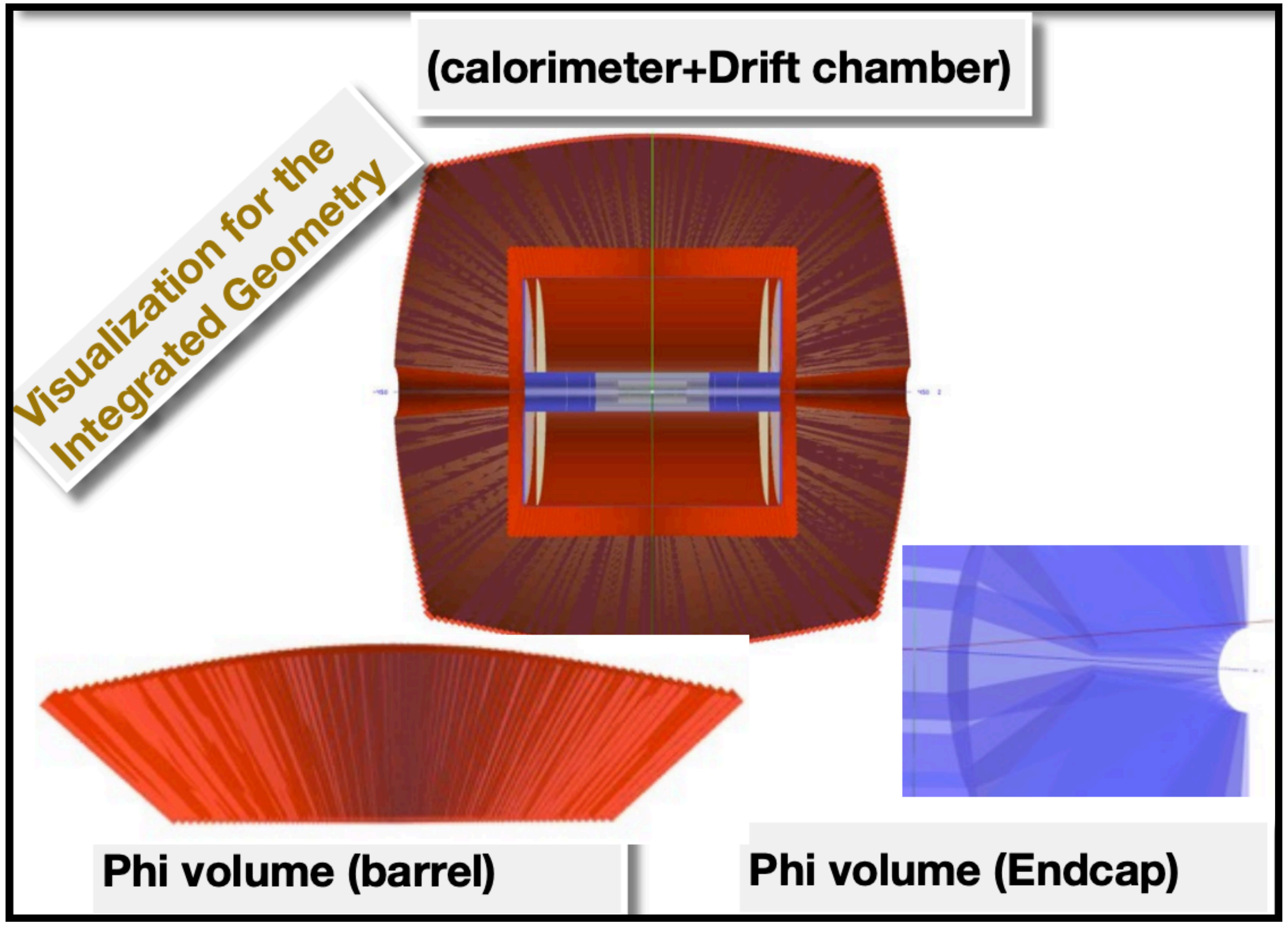






(*) G. Bencivenni et al., “The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD”, 2015_JINST_10_P02008)

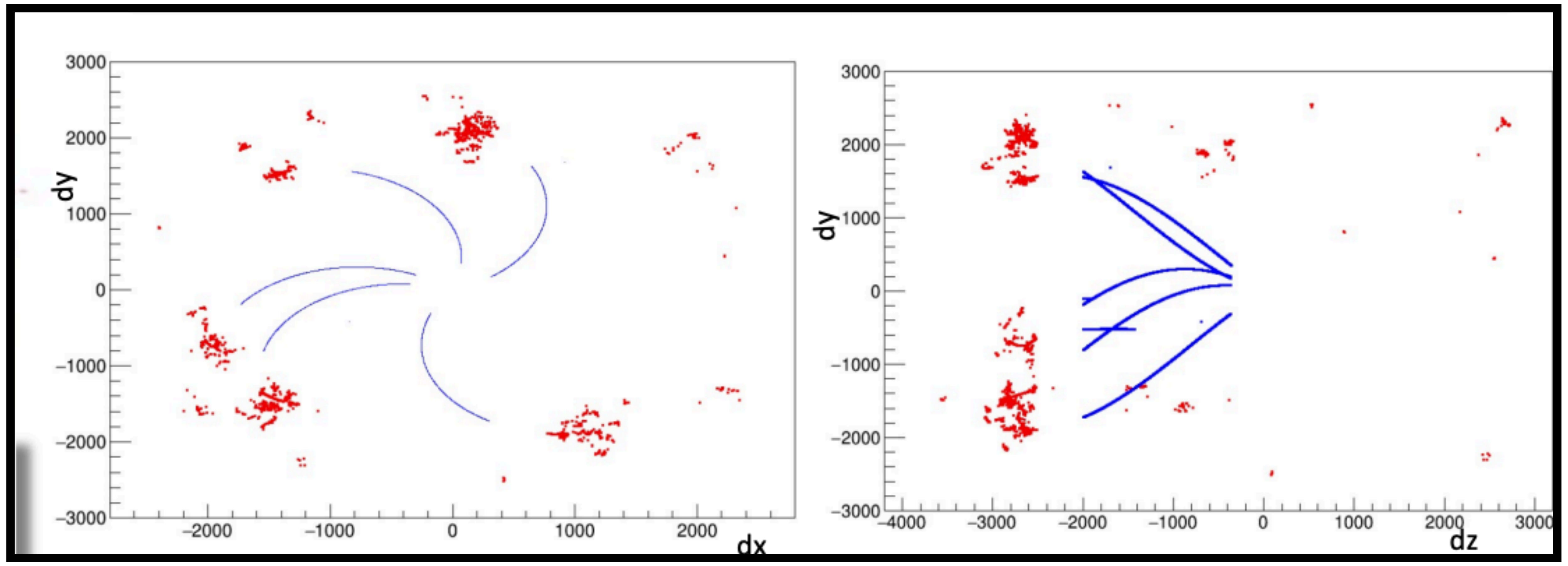
Status of Simulation of IDEA concept



FASTSIM Delphes IDEA card used for performance studies FCCSW

Very sophisticated compared to default.

Latest additions: Vertexing, LLP, PID, dN/dx, dE/dx

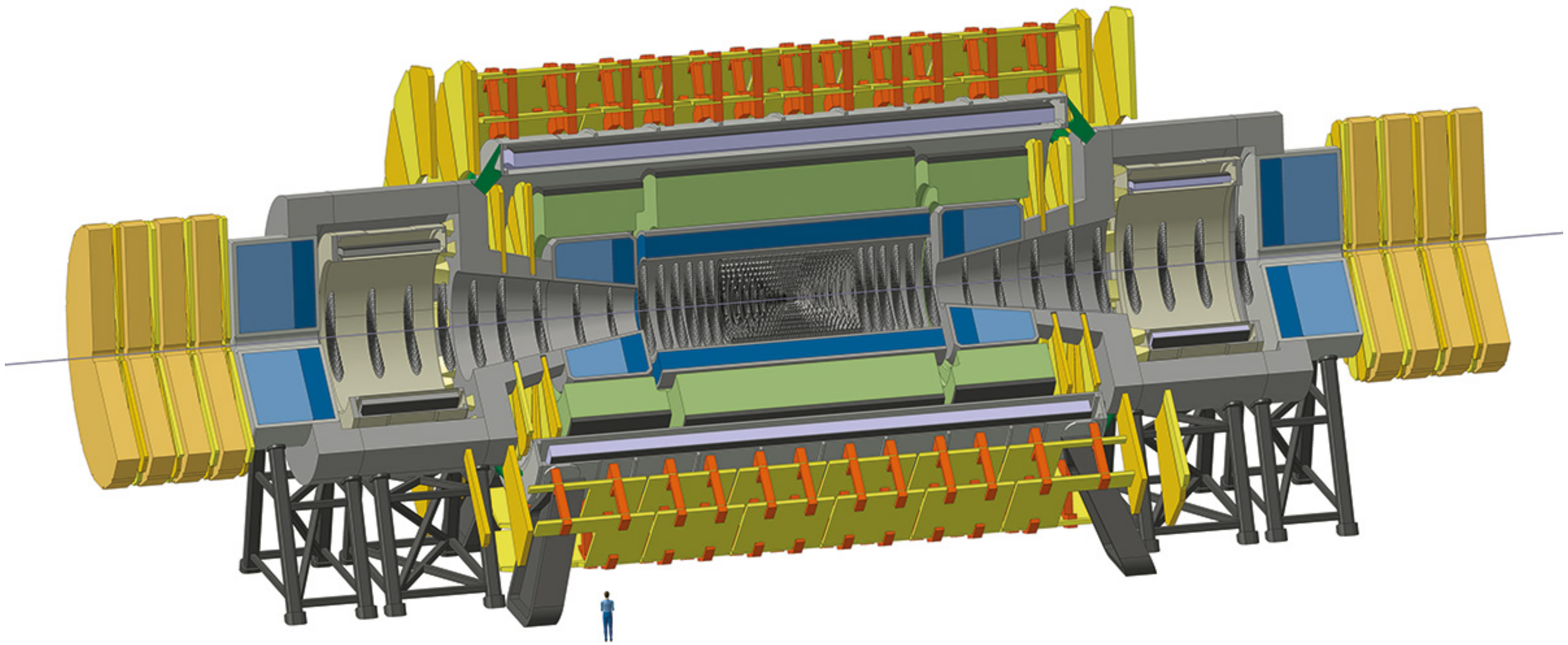


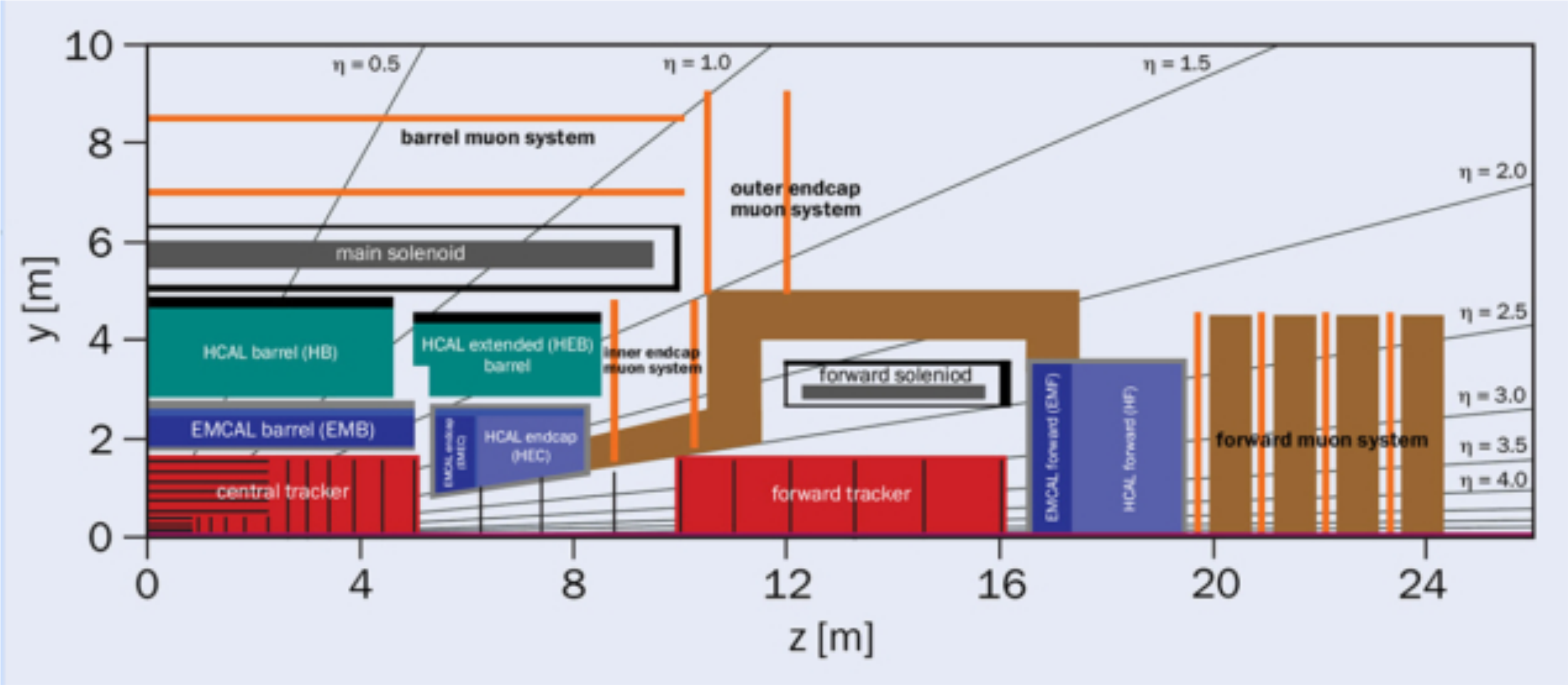
FULLSIM: standalone GEANT4 description

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

FCC-hh detector concept

- pp collisions at $\sqrt{s}$ > 100 TeV, luminosity up to 3 x 10^{35} cm^{-2} s^{-1} (up to 1000 pileup events)
- Central detector houses tracking, e.m. and hadron calorimetry inside a 4T solenoid with a free bore of 10 m diameter
- Forward parts are displaced by 10m from the interaction point, with two forward magnet coils
- The muon system is placed outside the magnet coils
- Overall length ~50m, diameter ~20m





→ No field return yoke for FCC-hh reference detector

Progress on international collaboration

Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science

The United States and CERN intend to:

- Enhance collaboration in future planning activities for large-scale, resource-intensive facilities with the goal of providing a sustainable and responsible pathway for the peaceful use of future accelerator technologies;
- Continue to collaborate in the feasibility study of the Future Circular Collider Higgs Factory (FCC-ee), the proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise and providing a clear pathway for future activities in open and trusted research environments; and
- Discuss potential collaboration on pilot projects on incorporating new analytics techniques and tools such as artificial intelligence (AI) into particle physics research at scale.

Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals.

26 April 2024

White House Office of Science and Technology Policy Principal Deputy U.S. Chief Technology Officer Deirdre Mulligan signed for the United States while Director-General Fabiola Gianotti signed for CERN.

Conclusions

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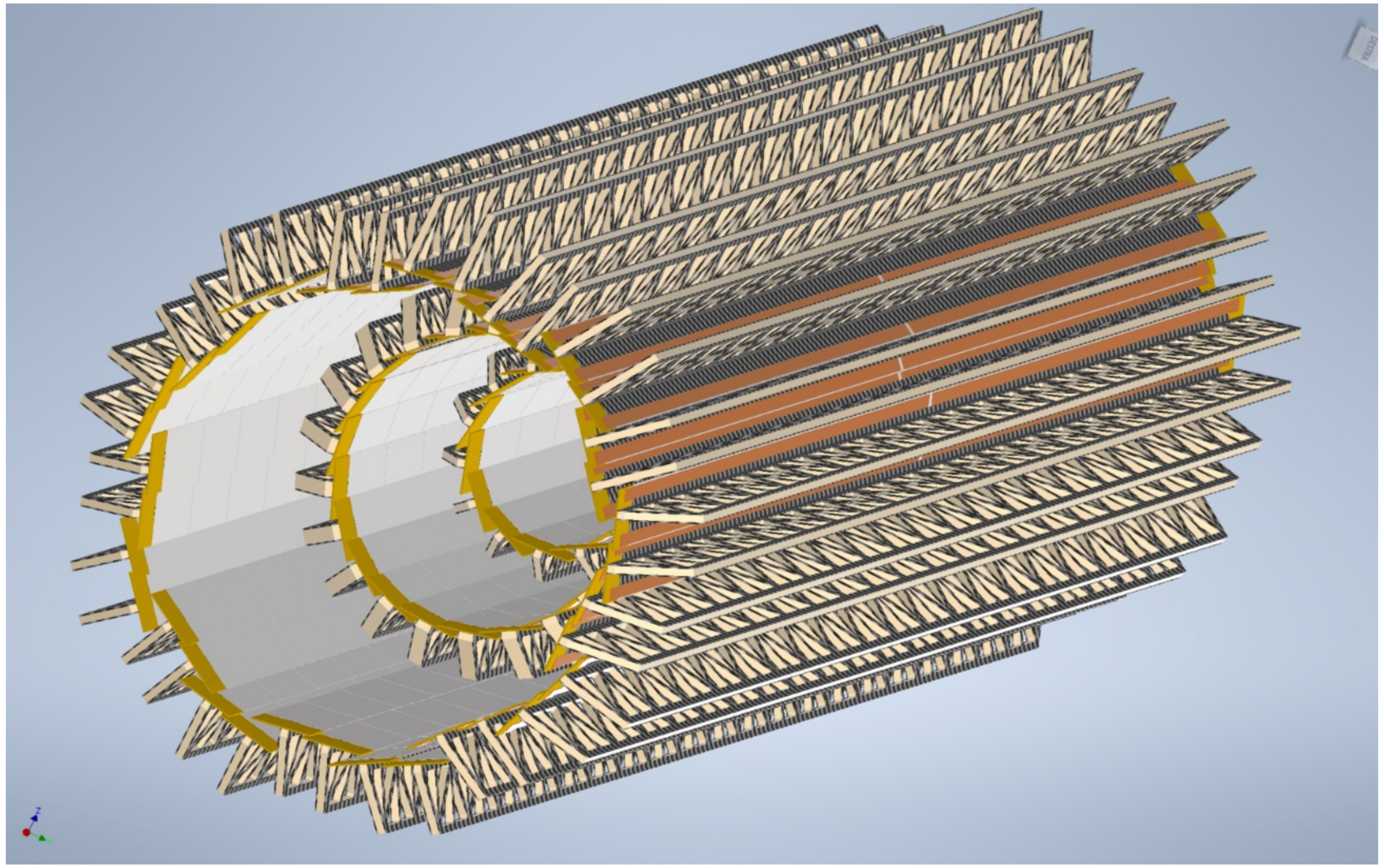
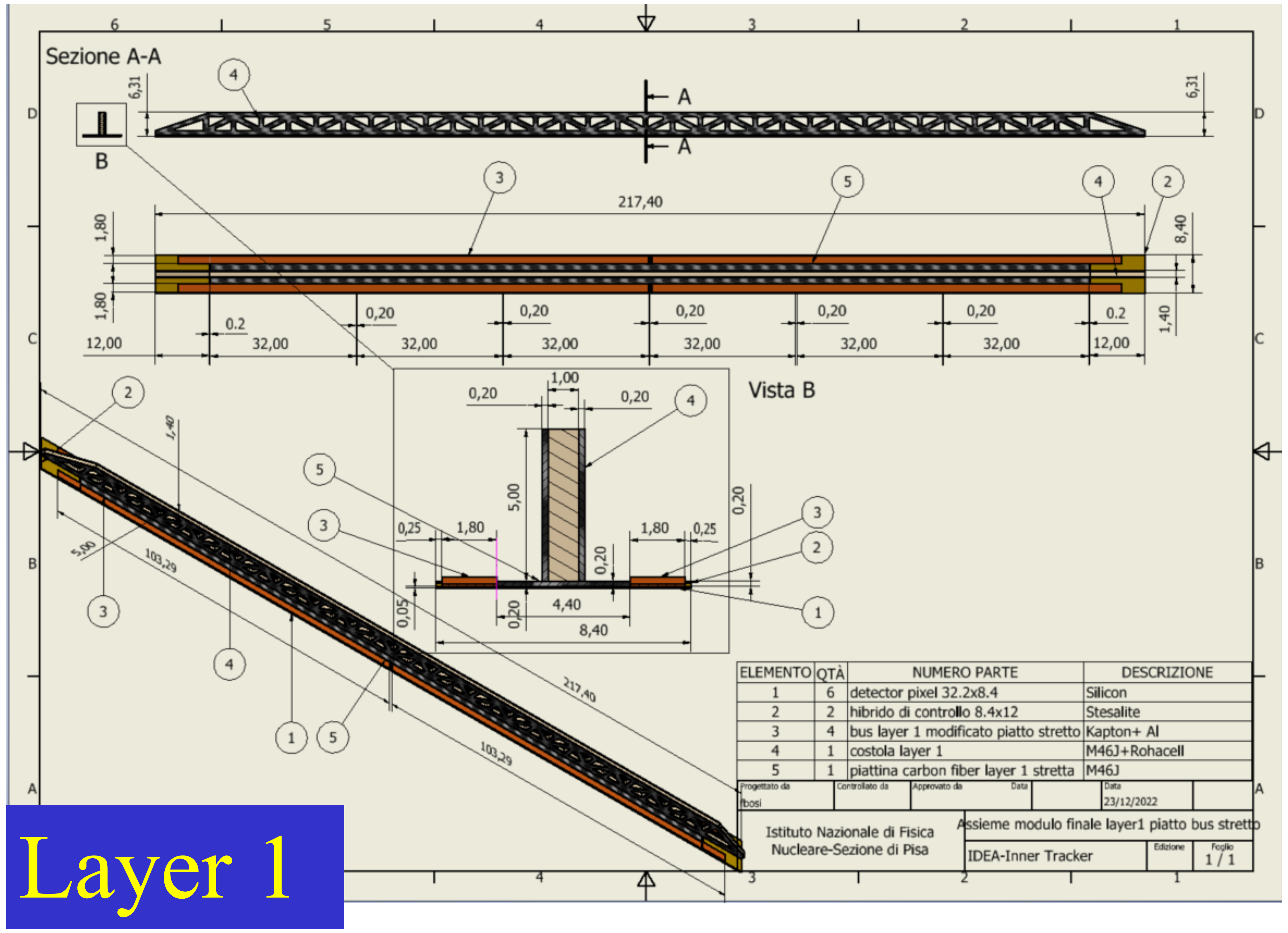
  - We are living in very interesting times, especially for our young collaborators
- **Lots of possibilities for German colleagues to join FCC-ee and IDEA and contribute to all these developments!!**

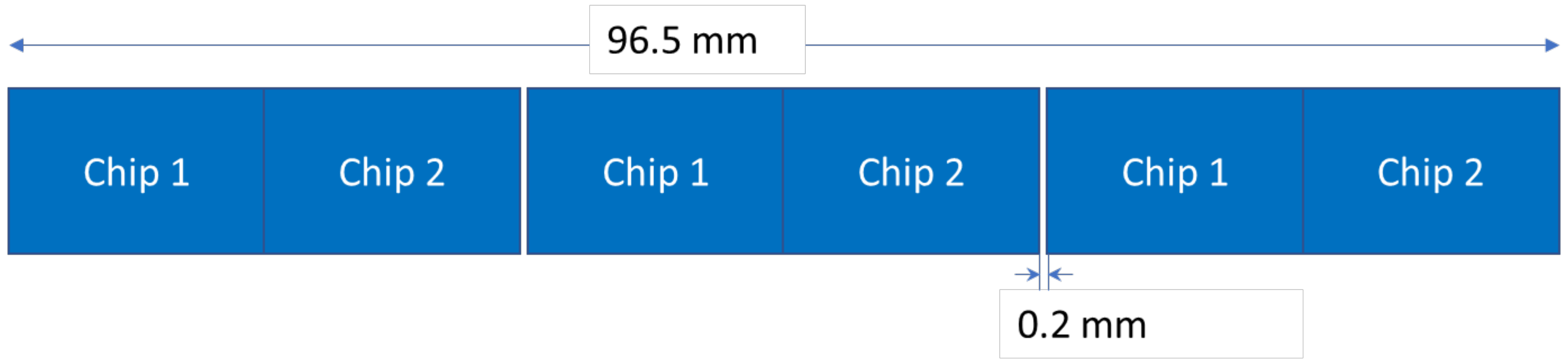
Backup

Vertex detector mechanical integration

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

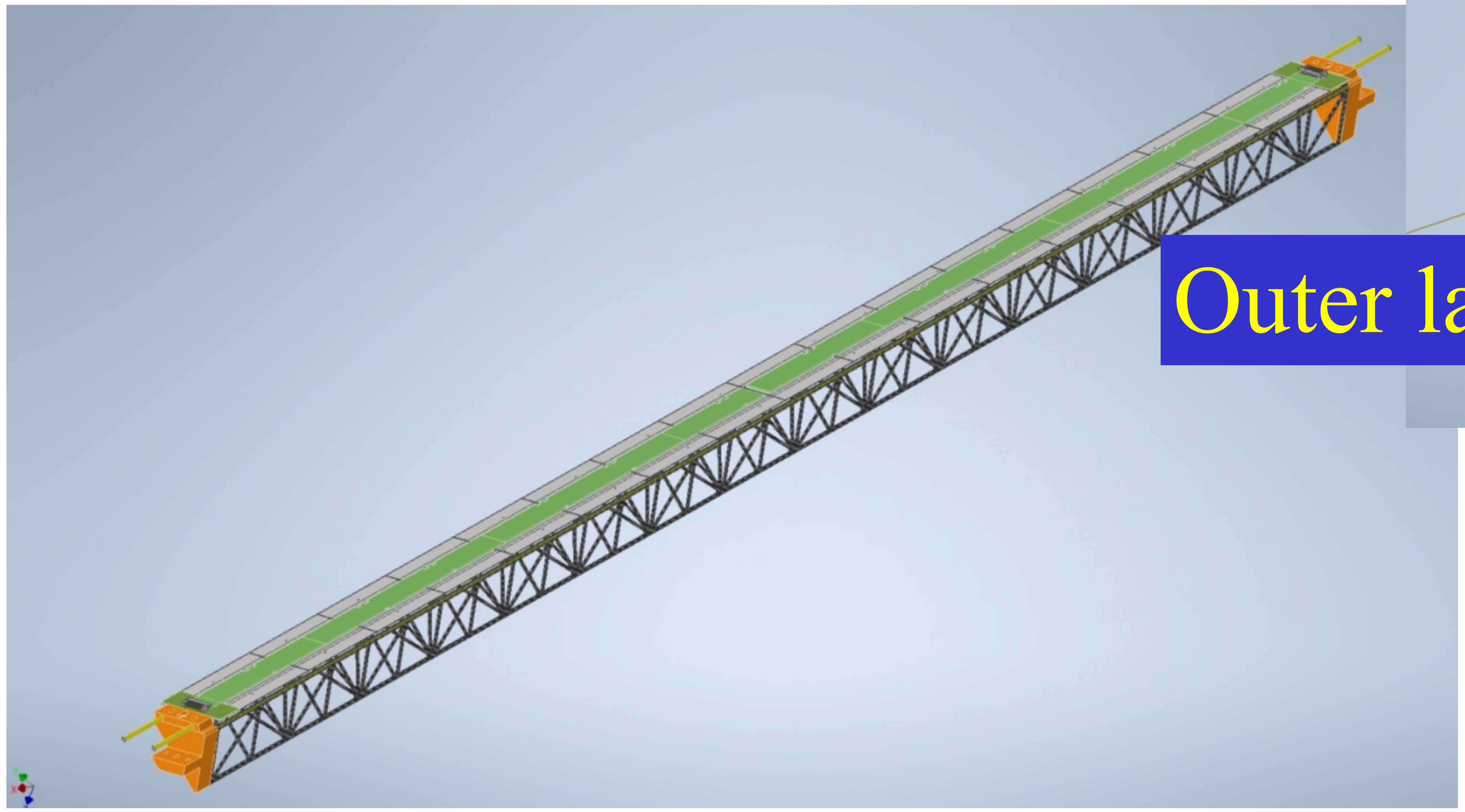


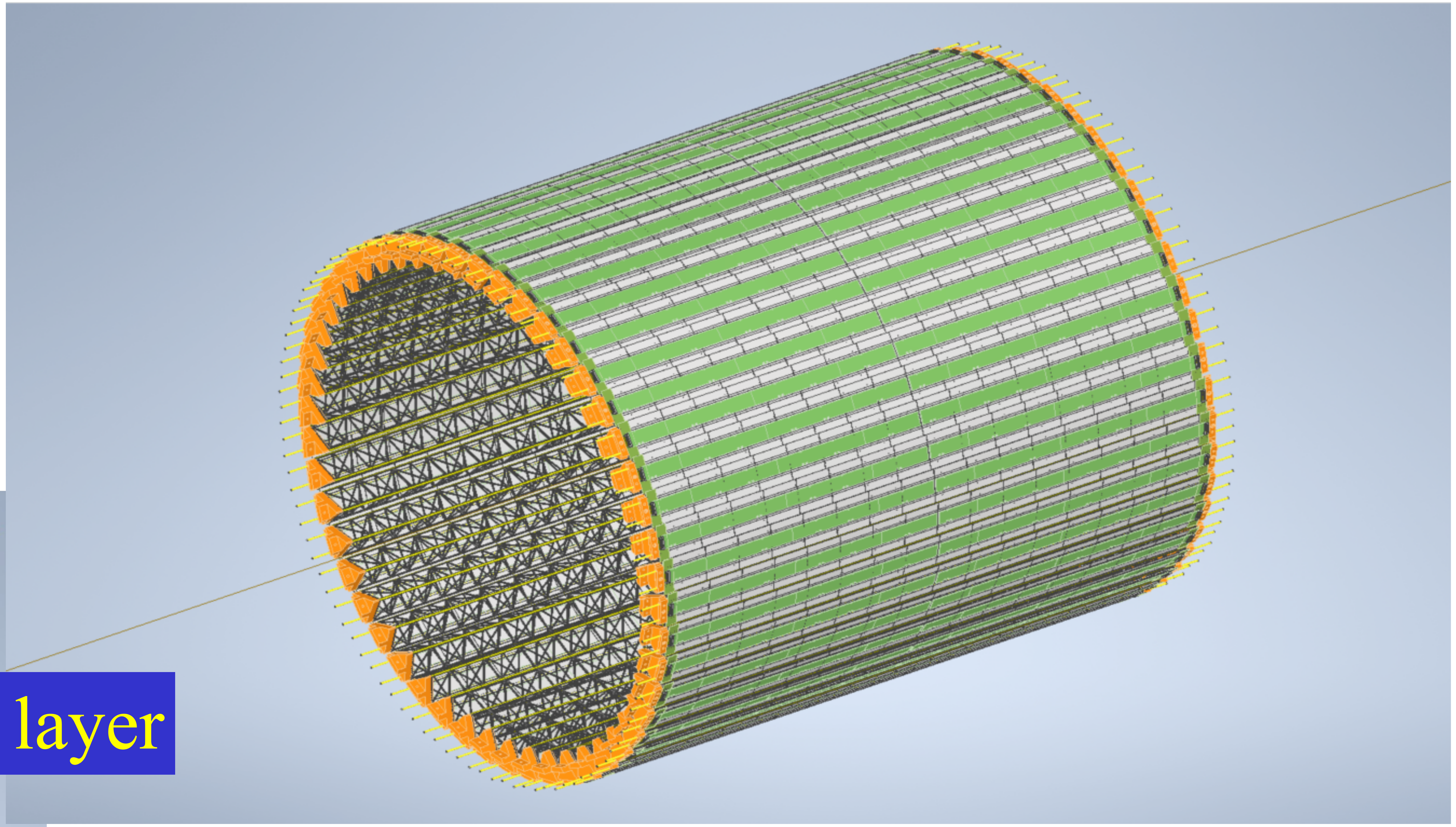




Vertex detector mechanical integration

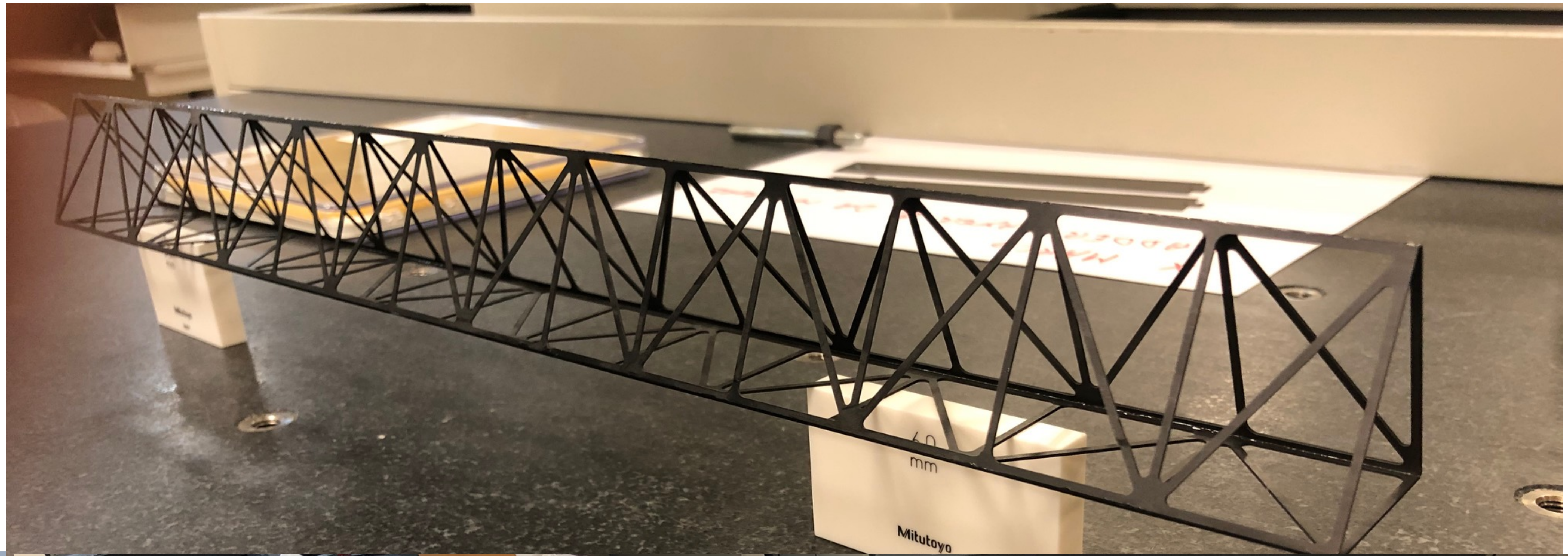
- Vertex design based on:
  - ARCADIA inner 3 layers
    - Air cooled
  - AtlasPix3 outer 2 layers/disks
    - Liquid cooled

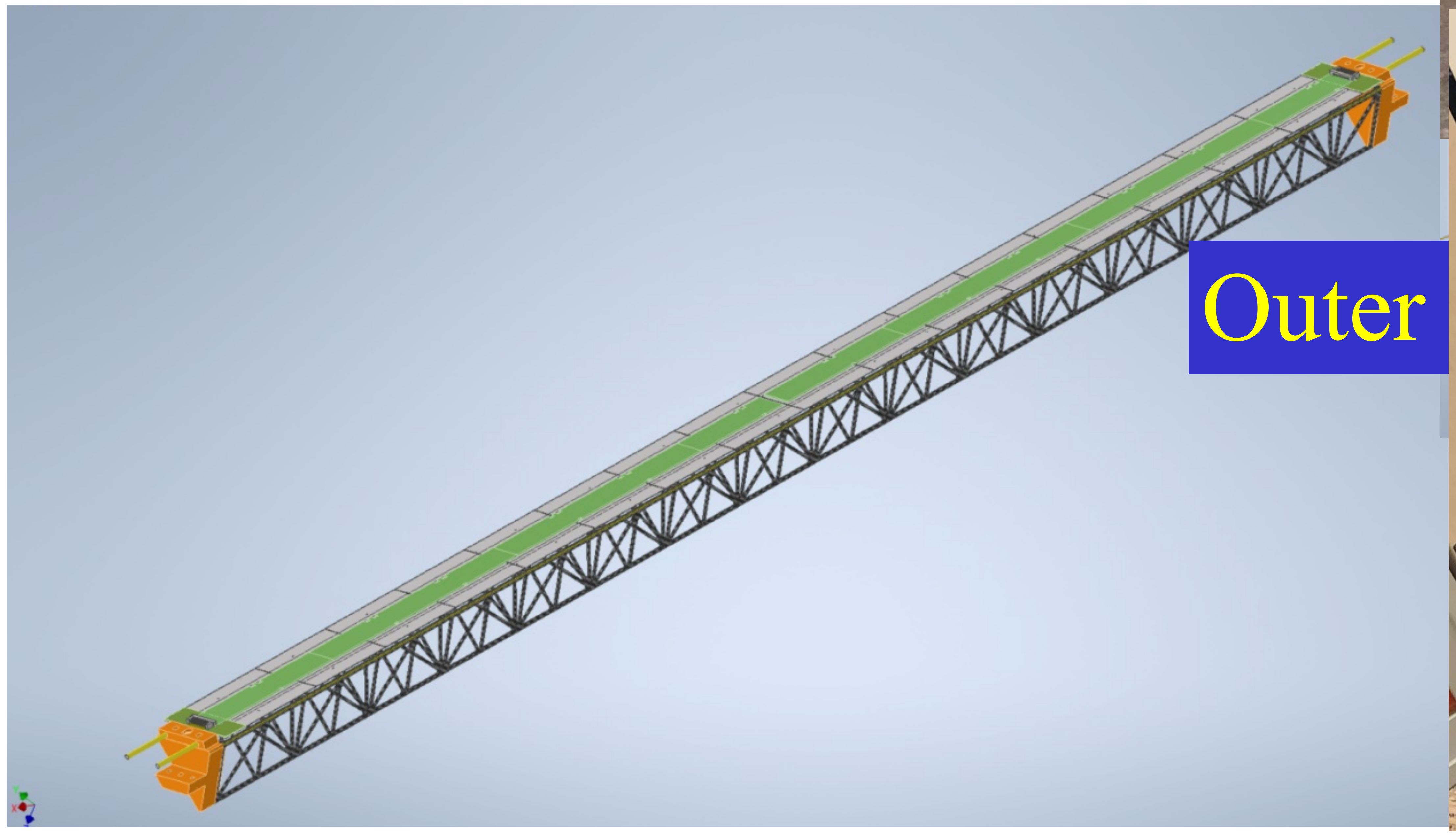




Vertex detector mechanical integration

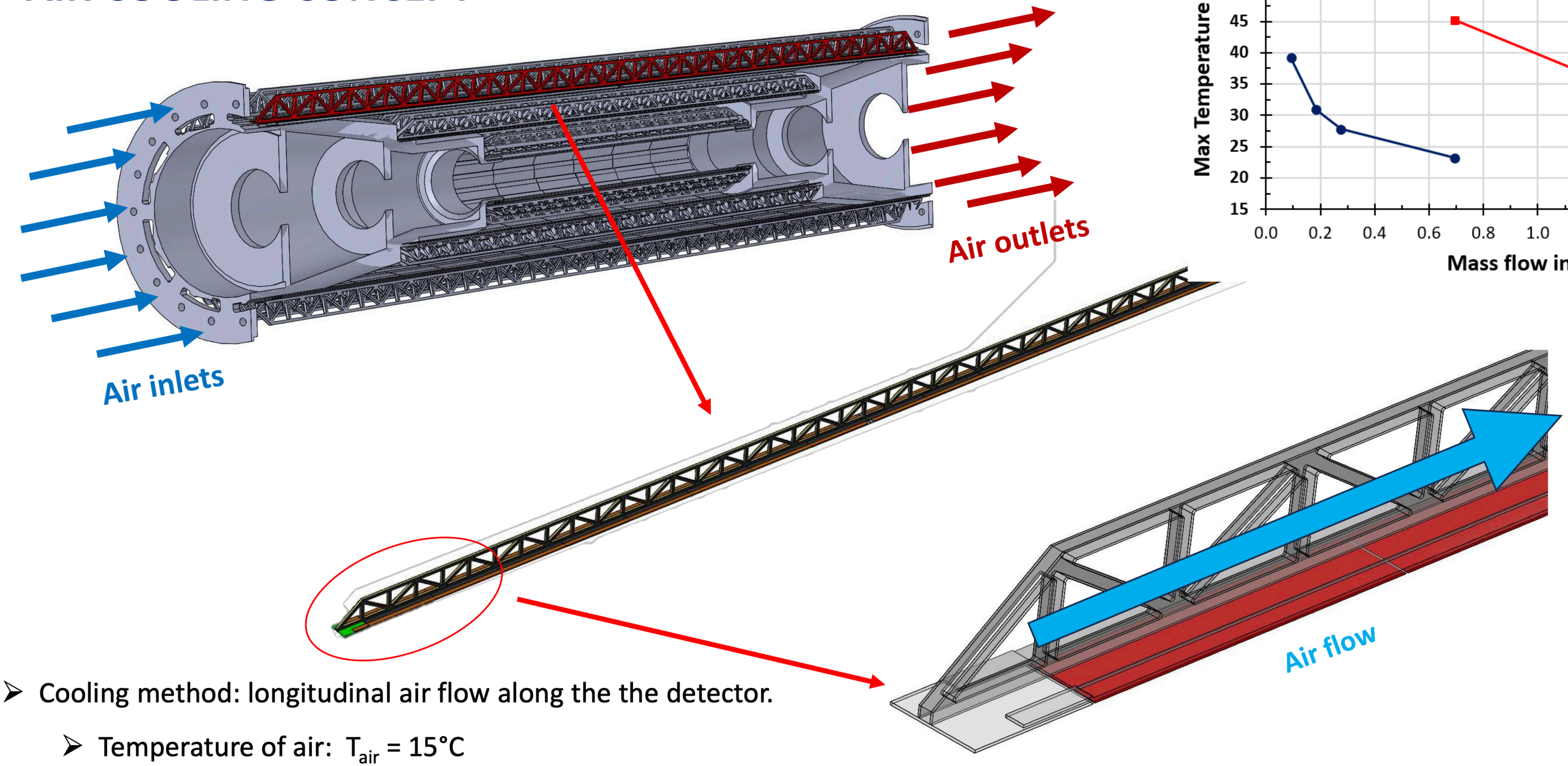
- Vertex design based on:
  - ARCADIA inner 3 layers
    - Air cooled
  - AtlasPix3 outer 2 layers/disks
    - Liquid cooled

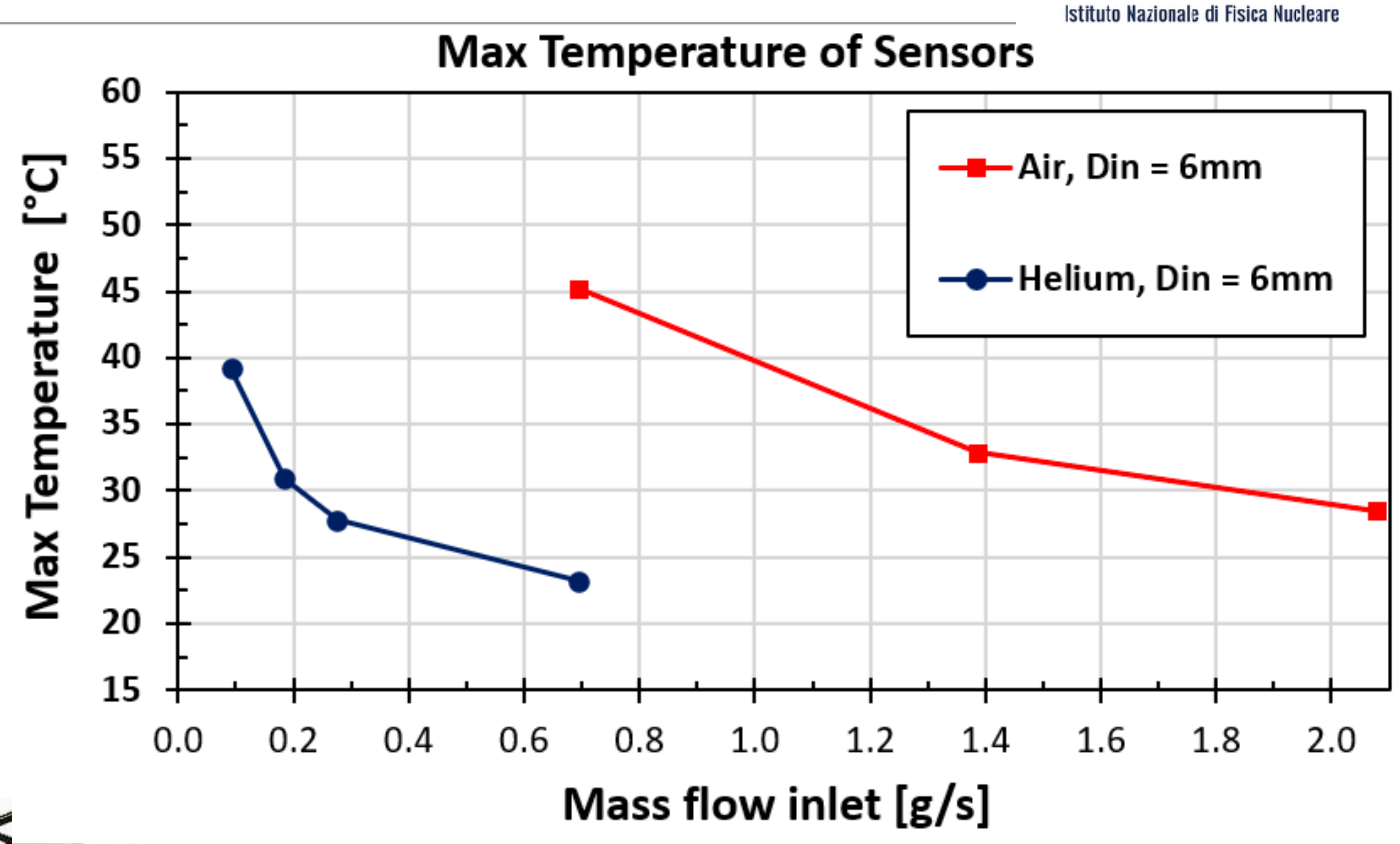




Vertex detector: IDEA

AIR COOLING CONCEPT

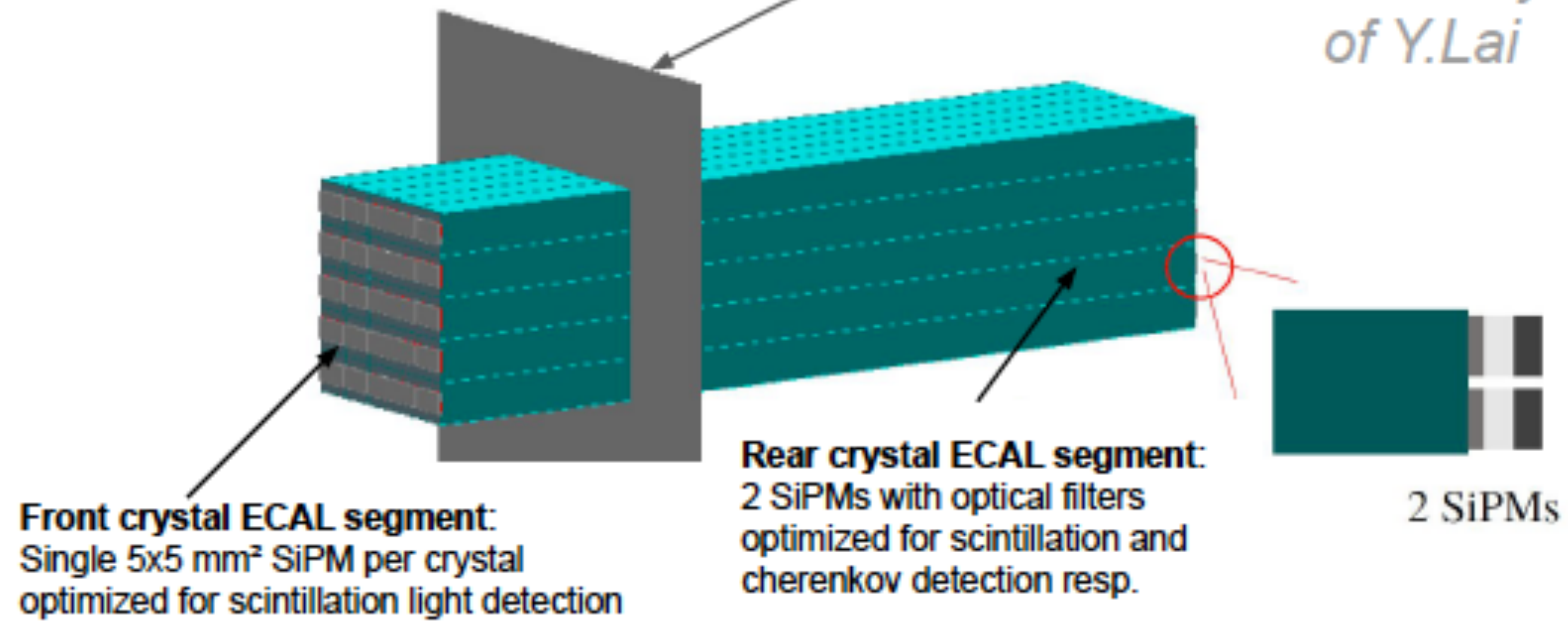




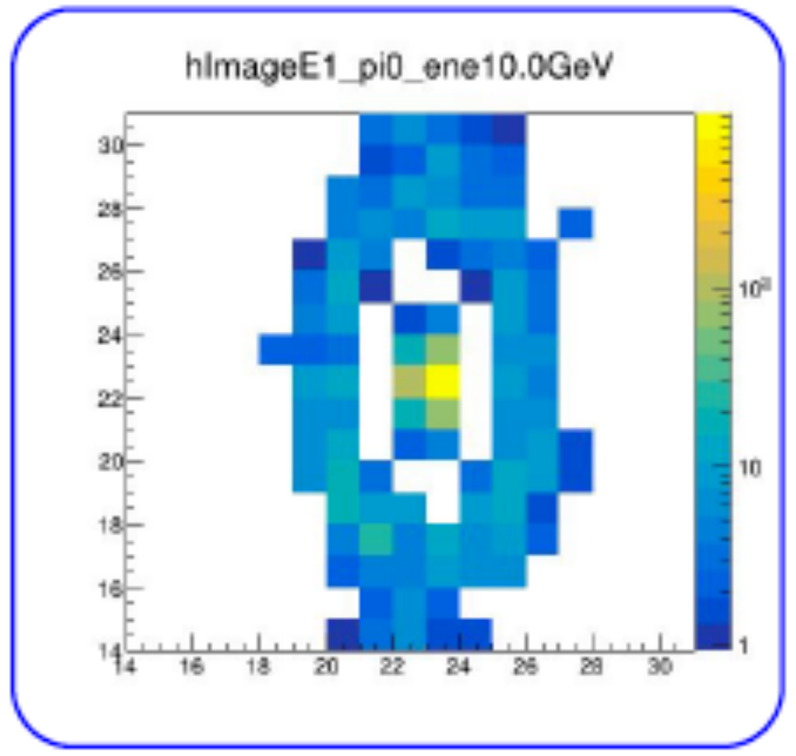
- Cooling method: longitudinal air flow along the the detector.
  - Temperature of air: T_{air} = 15°C

C. Turrioni

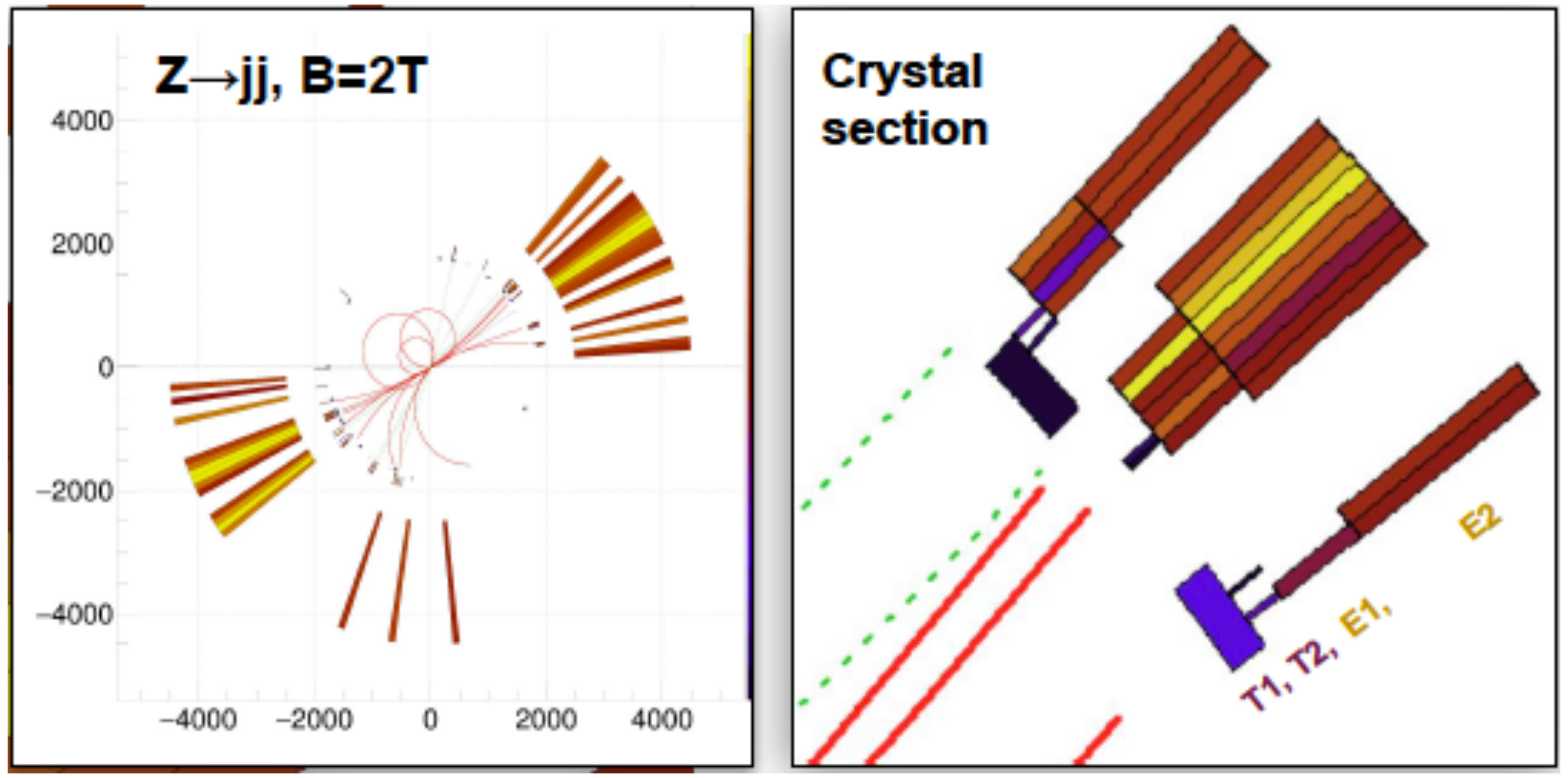
Crystal ECAL with DR calorimeter

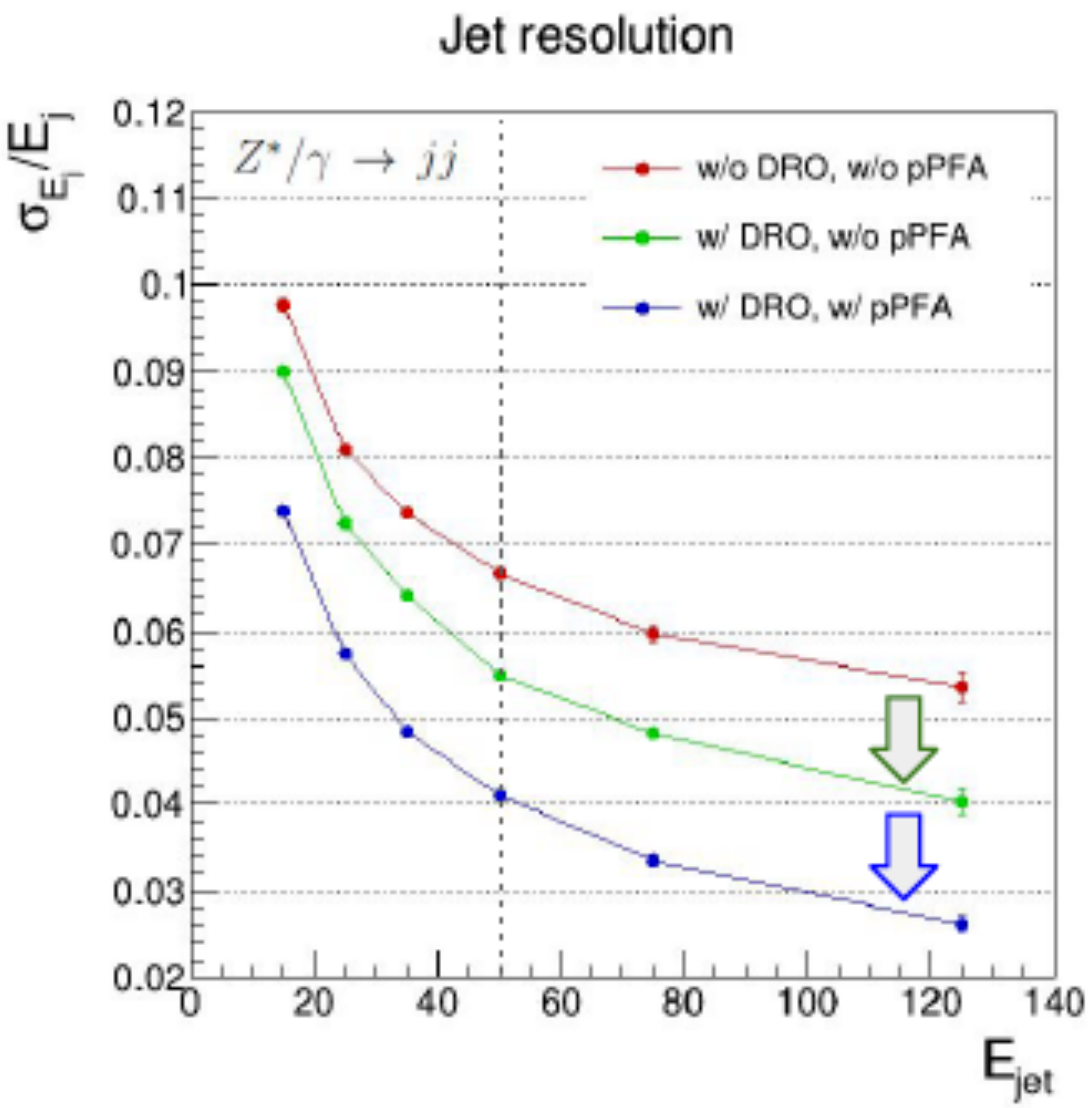


$\pi^0 \rightarrow \gamma\gamma$ events



Event display





crystals + IDEA w/o DRO

crystals + IDEA w/ DRO

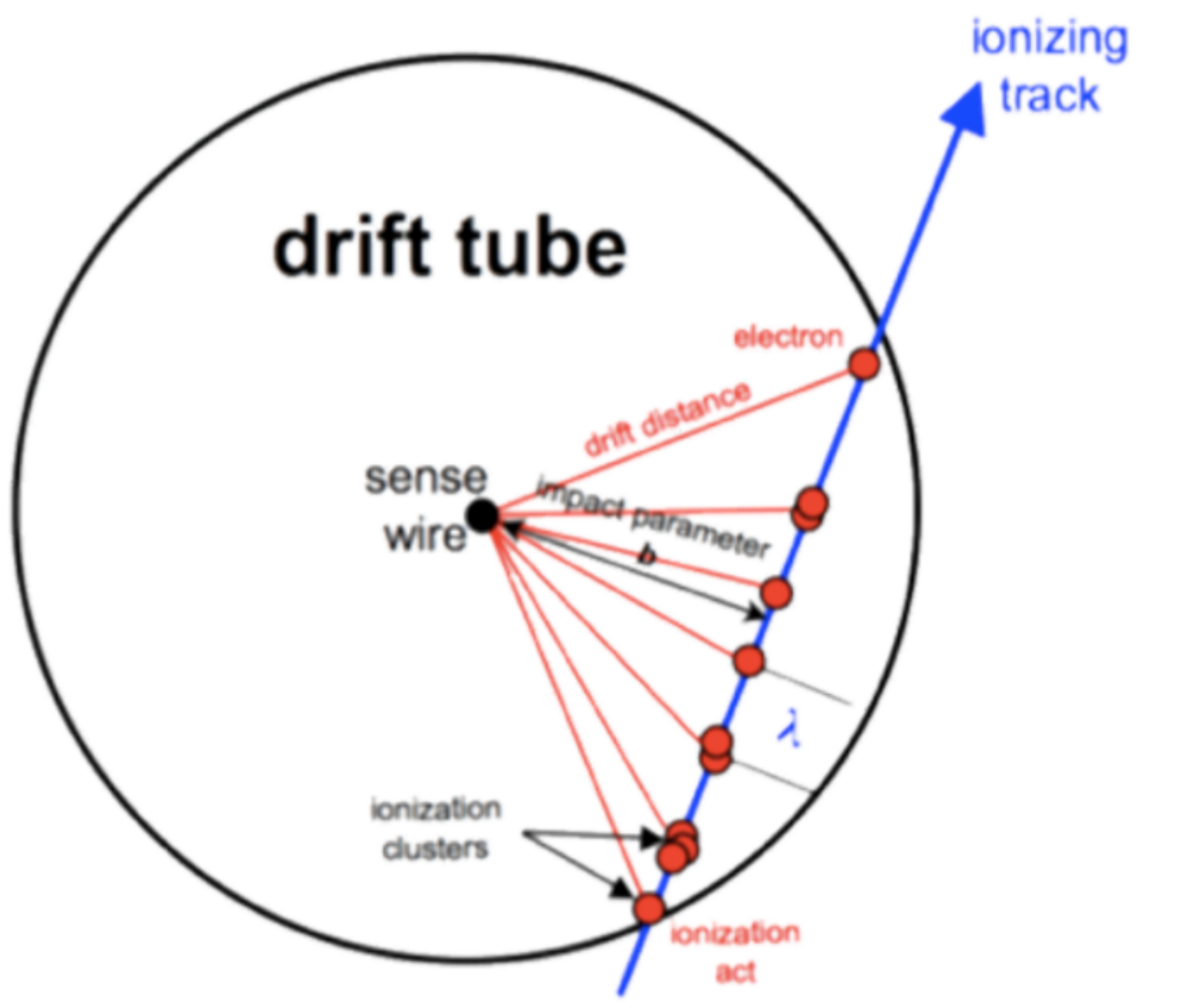
crystals + IDEA w/ DRO + pPFA

Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

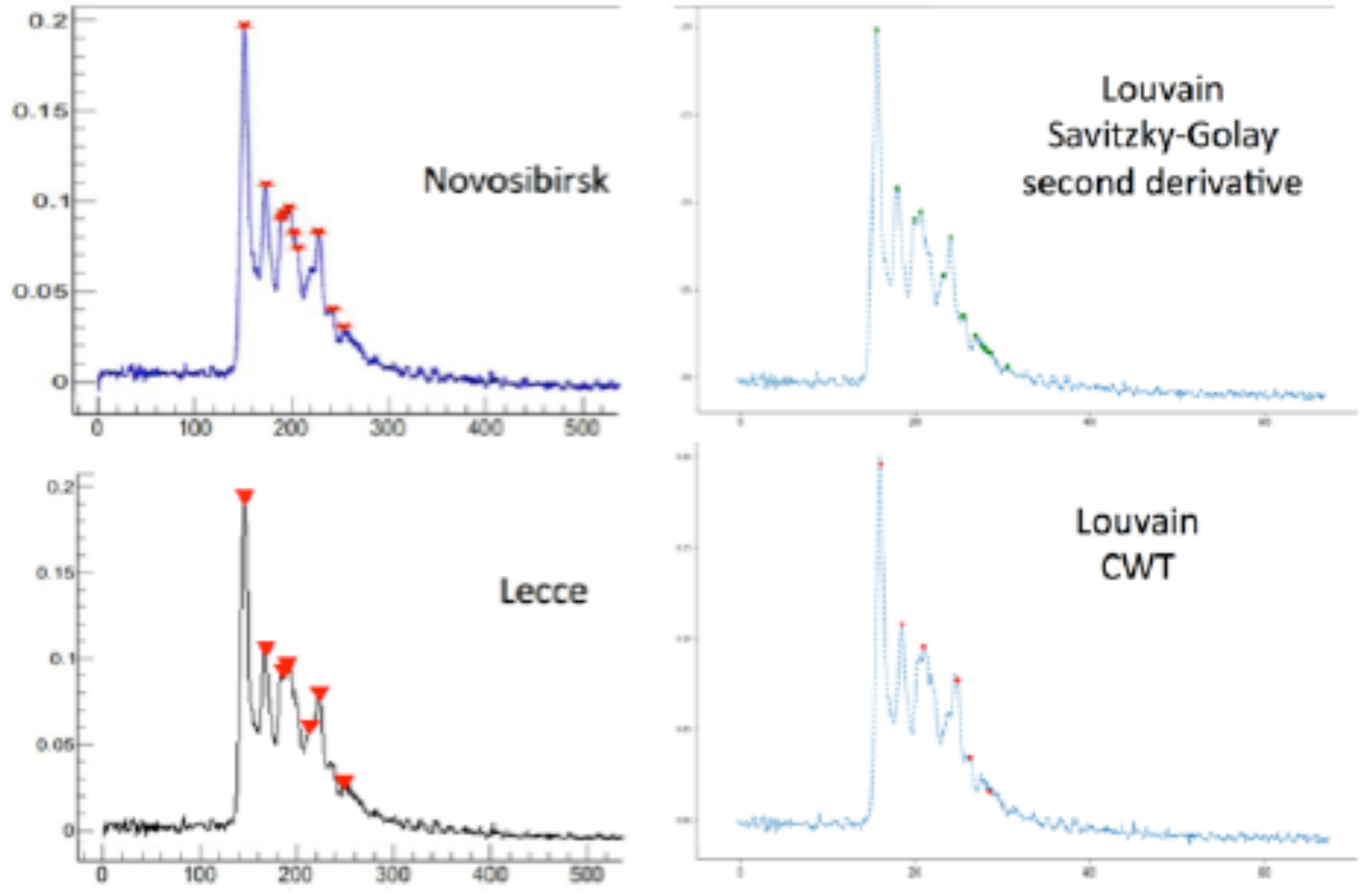
M. Lucchini

Cluster counting

- Cluster counting 2x better than dE/dx
  - Poisson vs . Landau → no large tails
- Sample signal few GHz → on detector electronics R&D



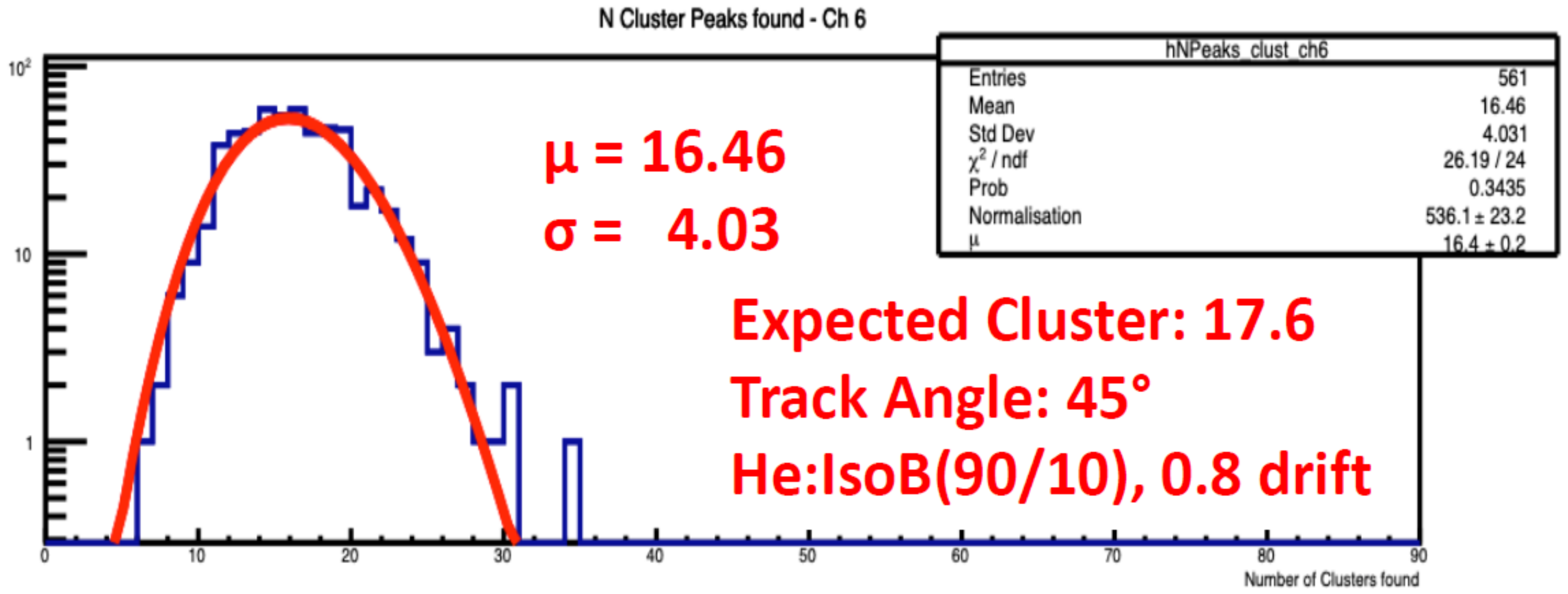
counting peaks



08/02/2022 FCC Physics Workshop - FG

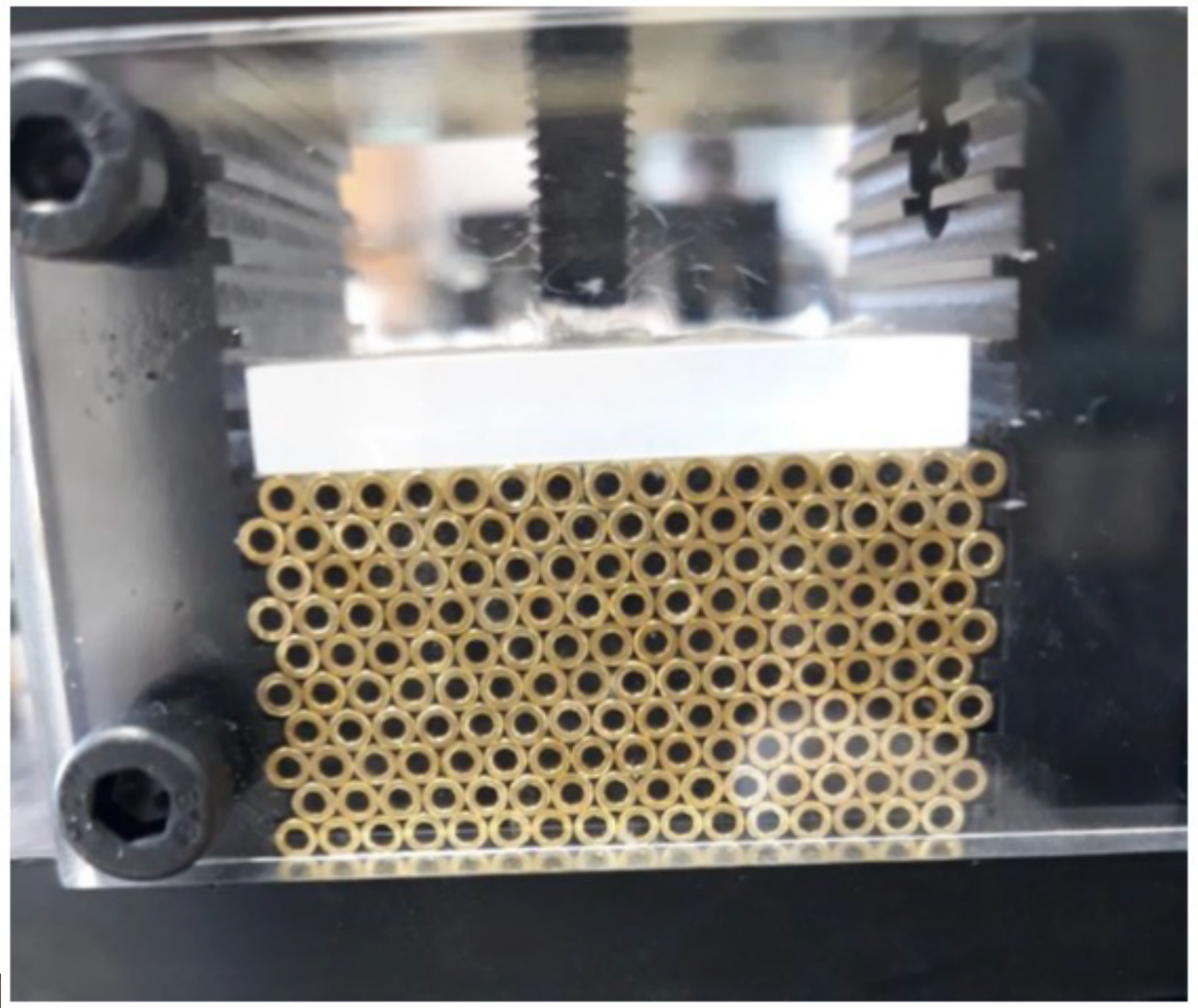
Test beam data 2022

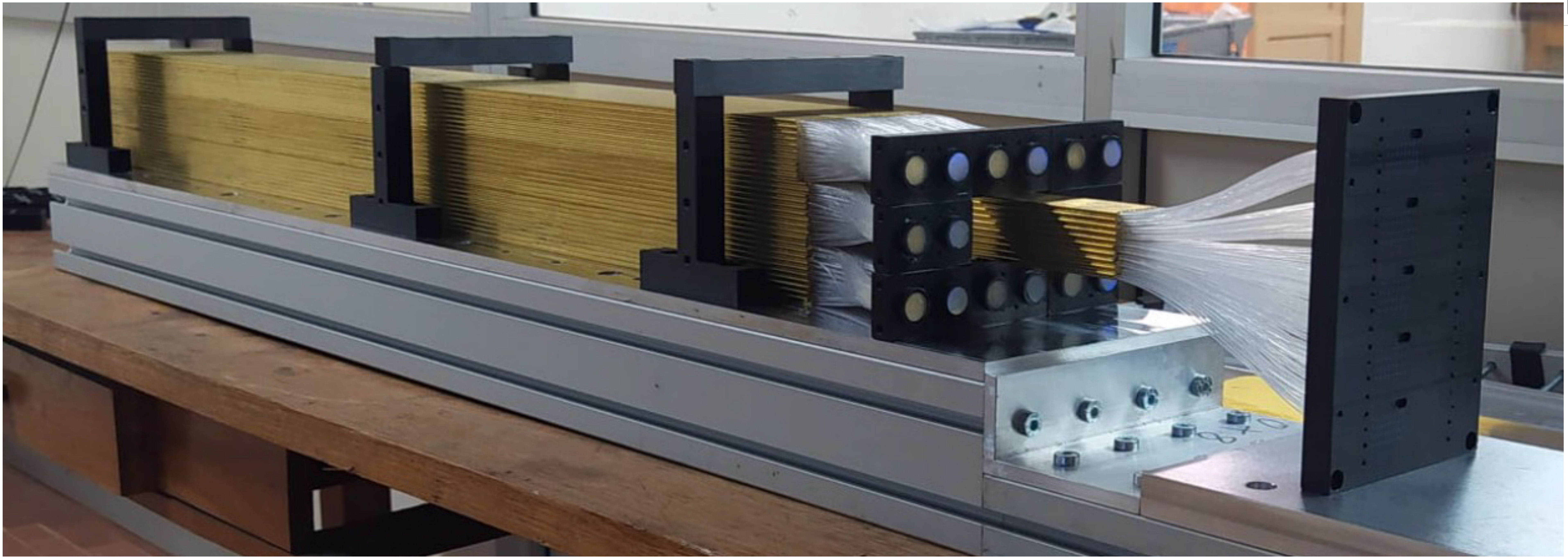
Number of Cluster Distribution



DR calorimeter

- 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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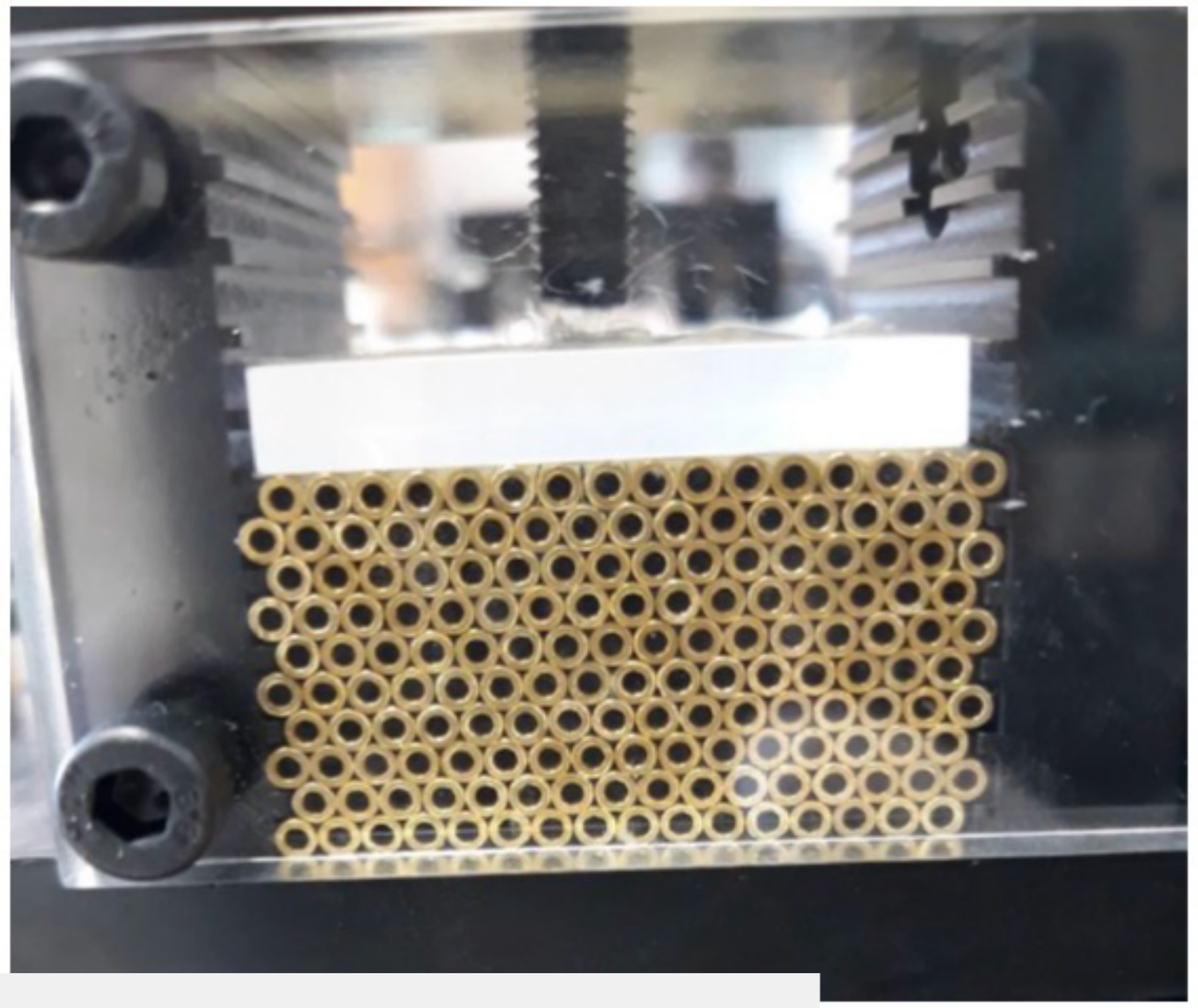
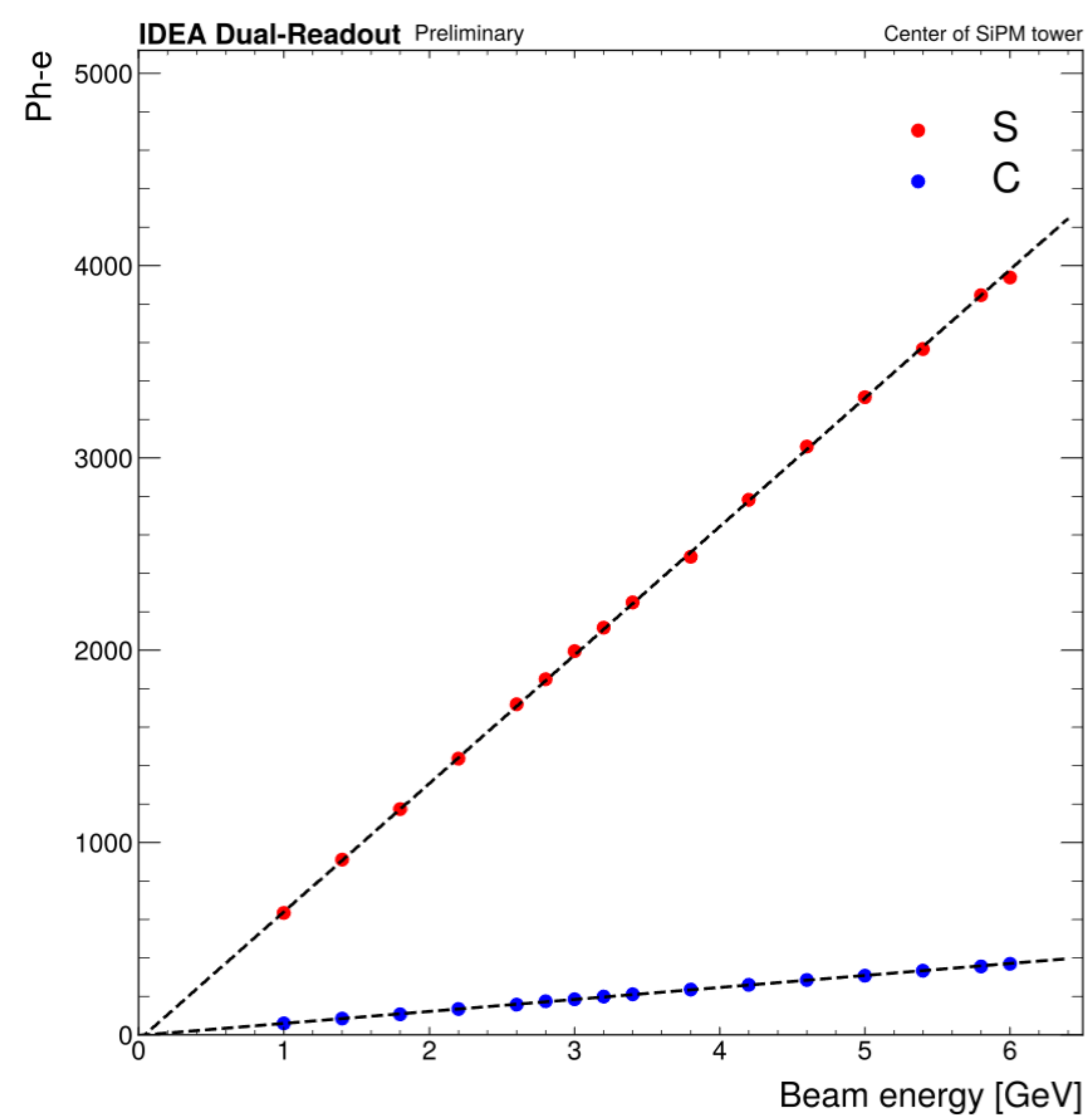
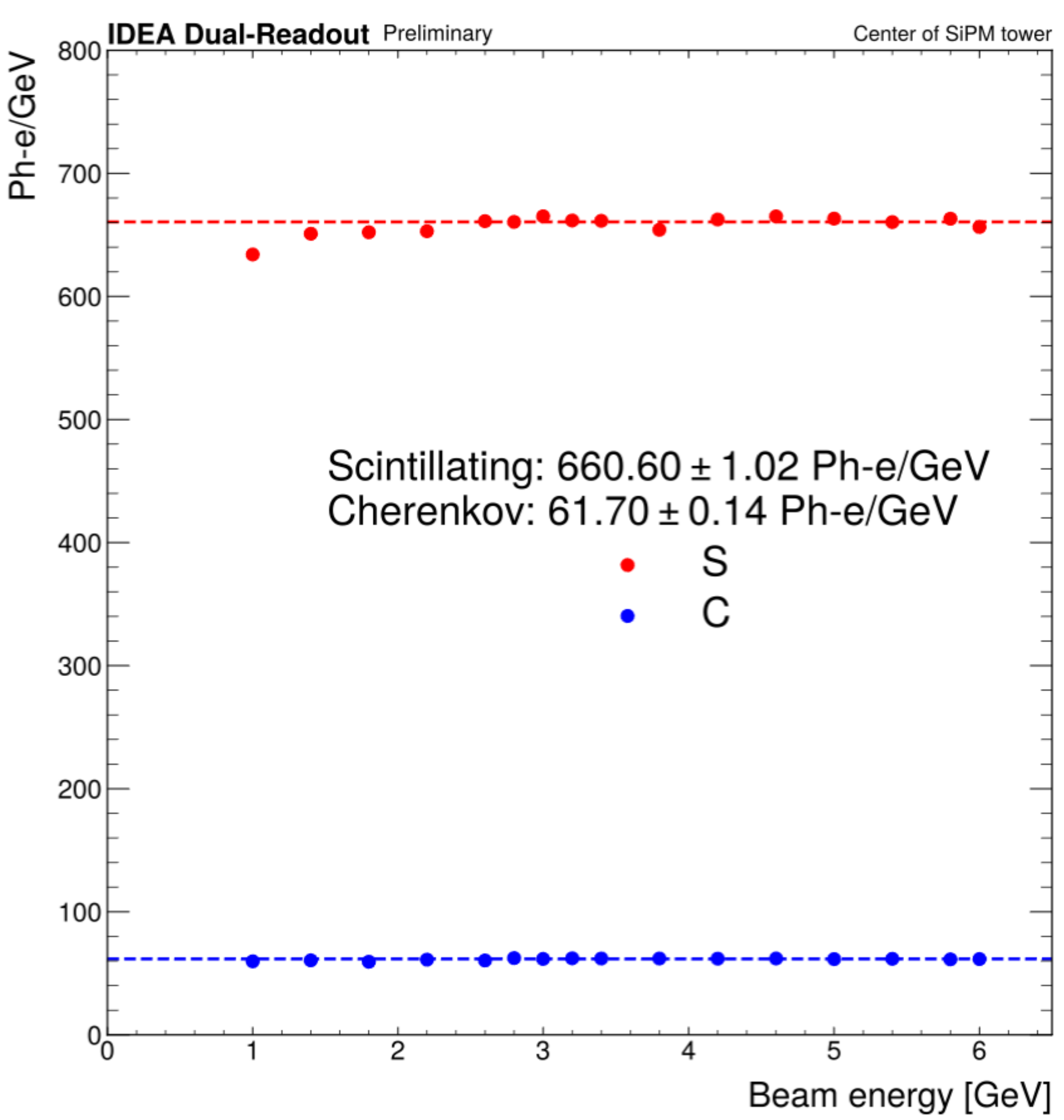
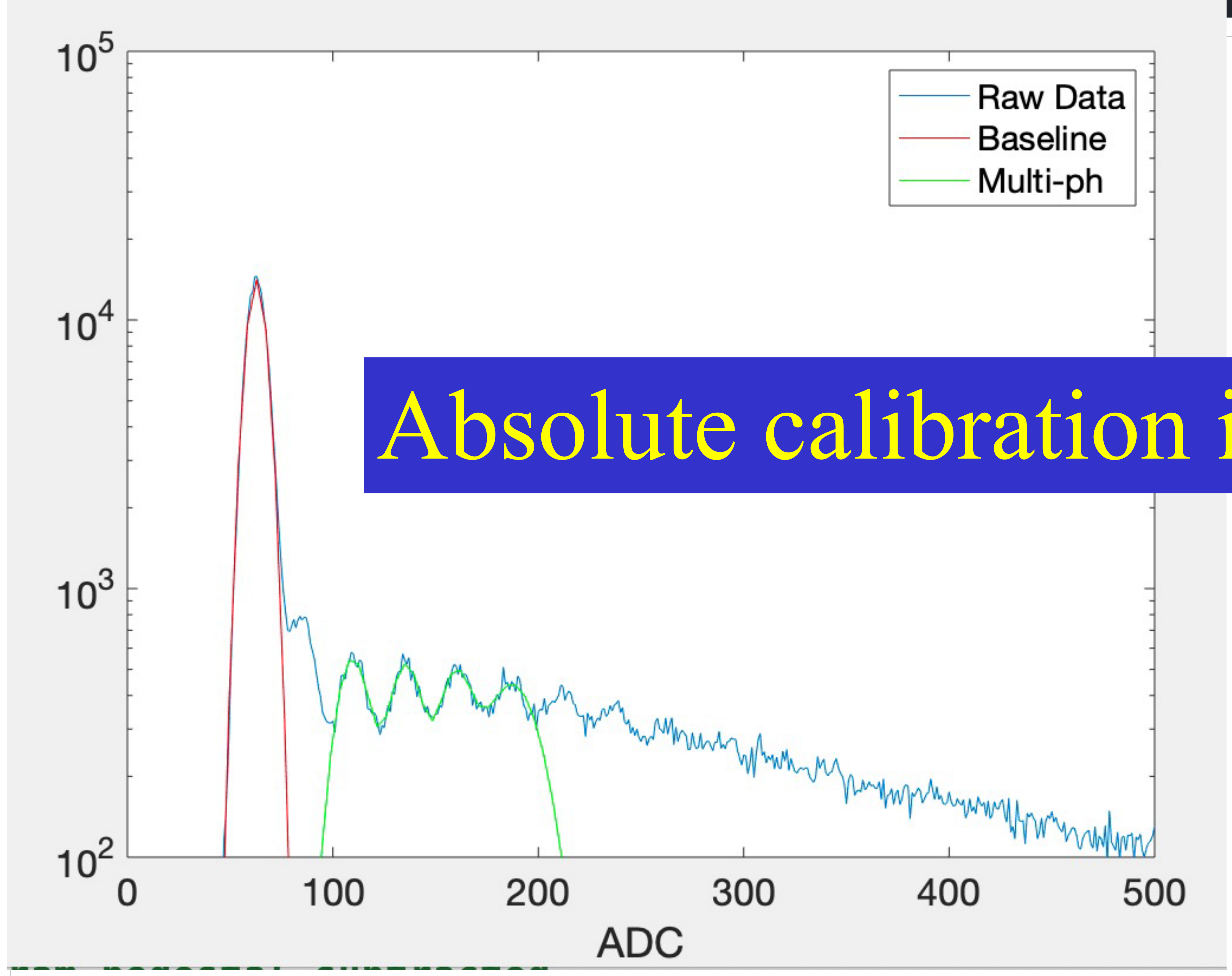








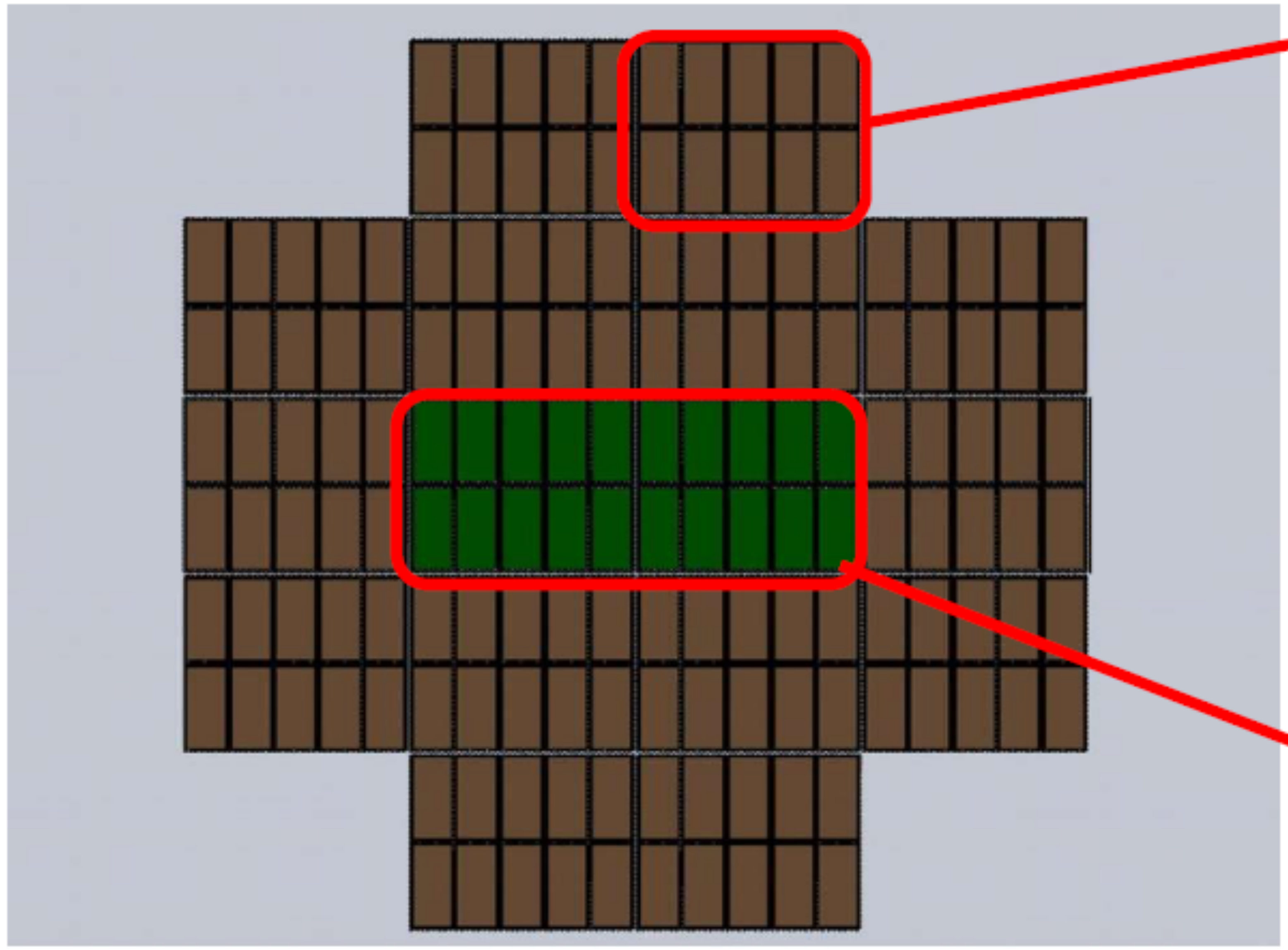
Absolute calibration in ph.e

DR calorimeter

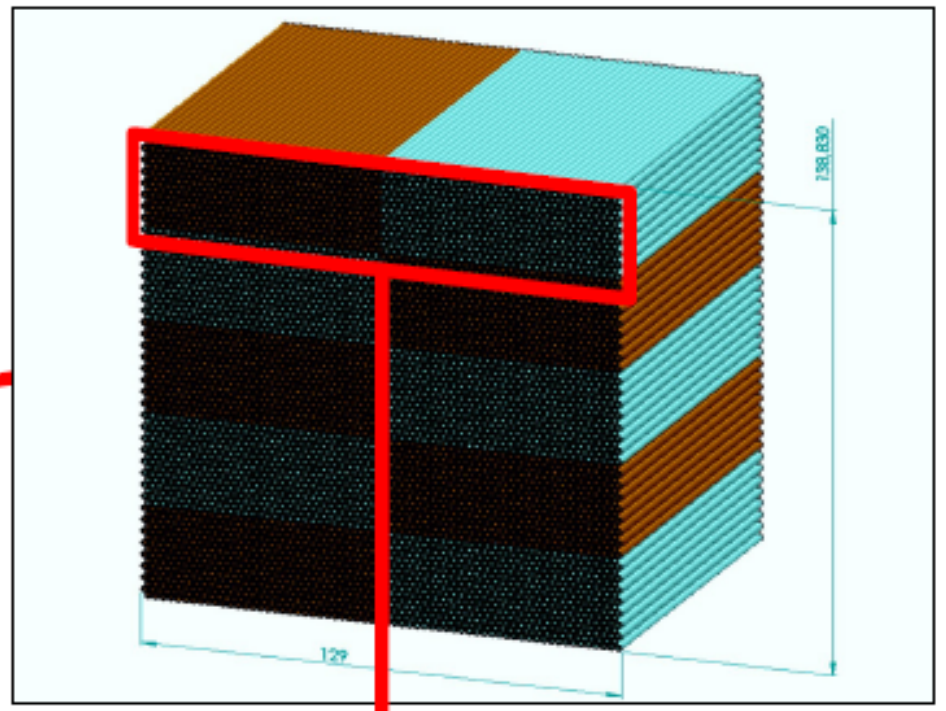
❖ Full containment hadronic prototype in progress

➢ Hidra2 call INFN CSN5

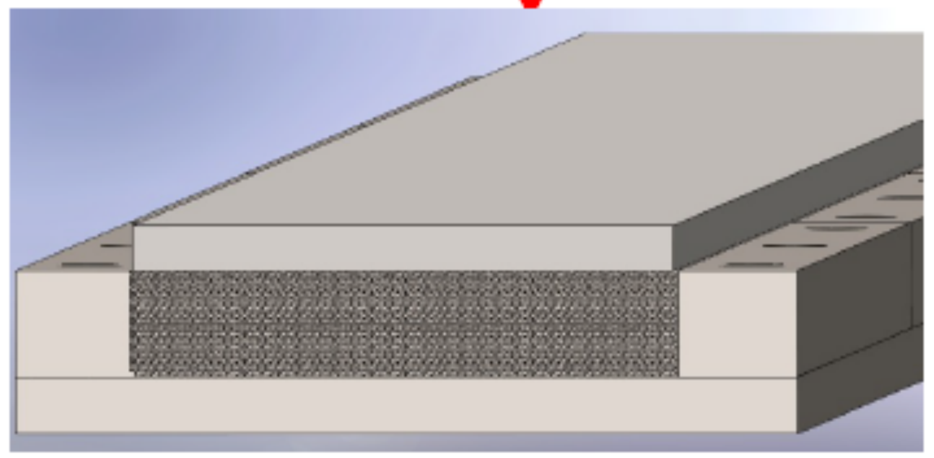
Hadronic-size prototype:
16 modules w/ highly granular core



~ 65 × 65 × 250 cm^3



1 Module: 5 MMs
~ 13 × 13 cm^2
5120 fibres

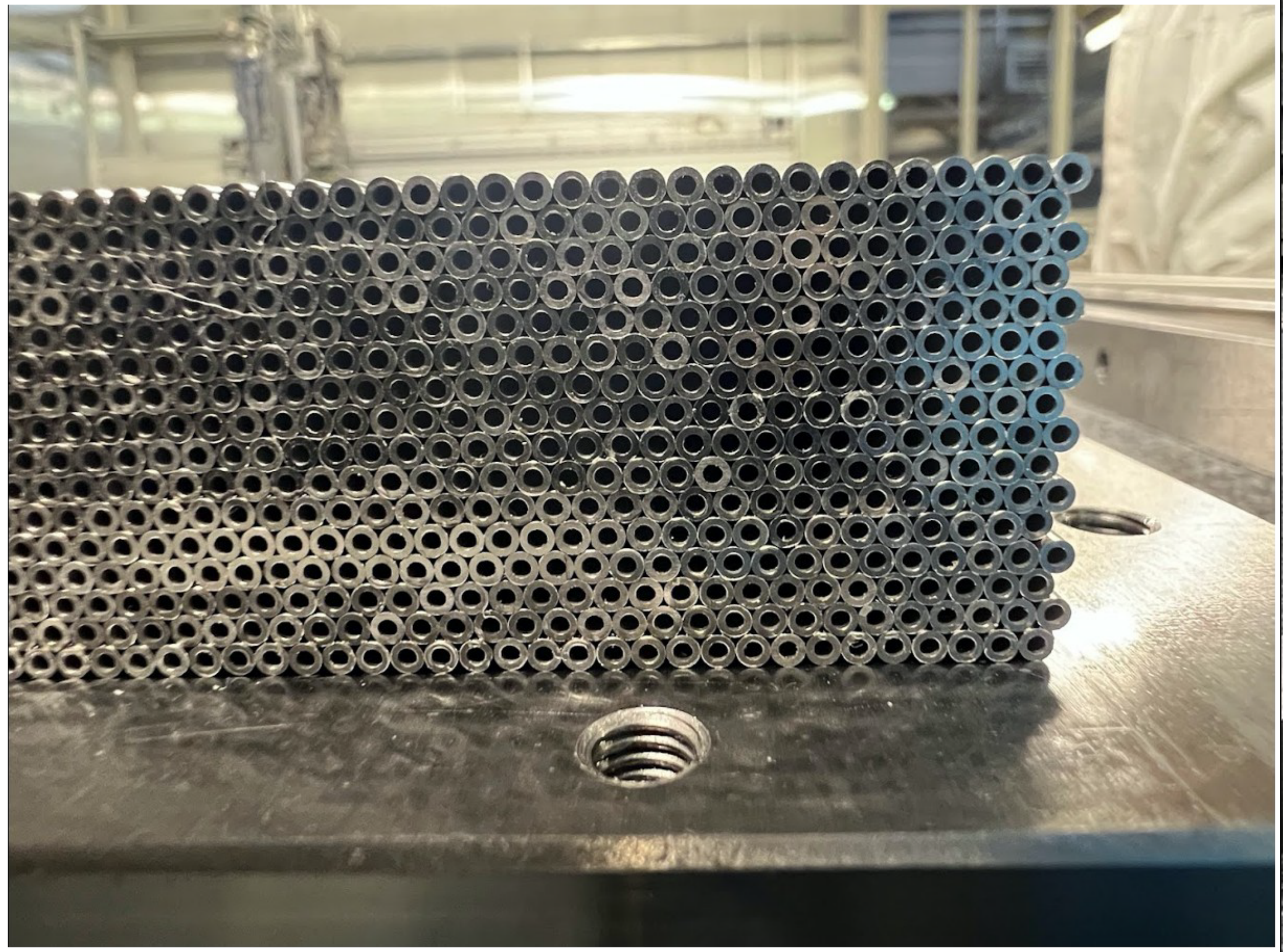


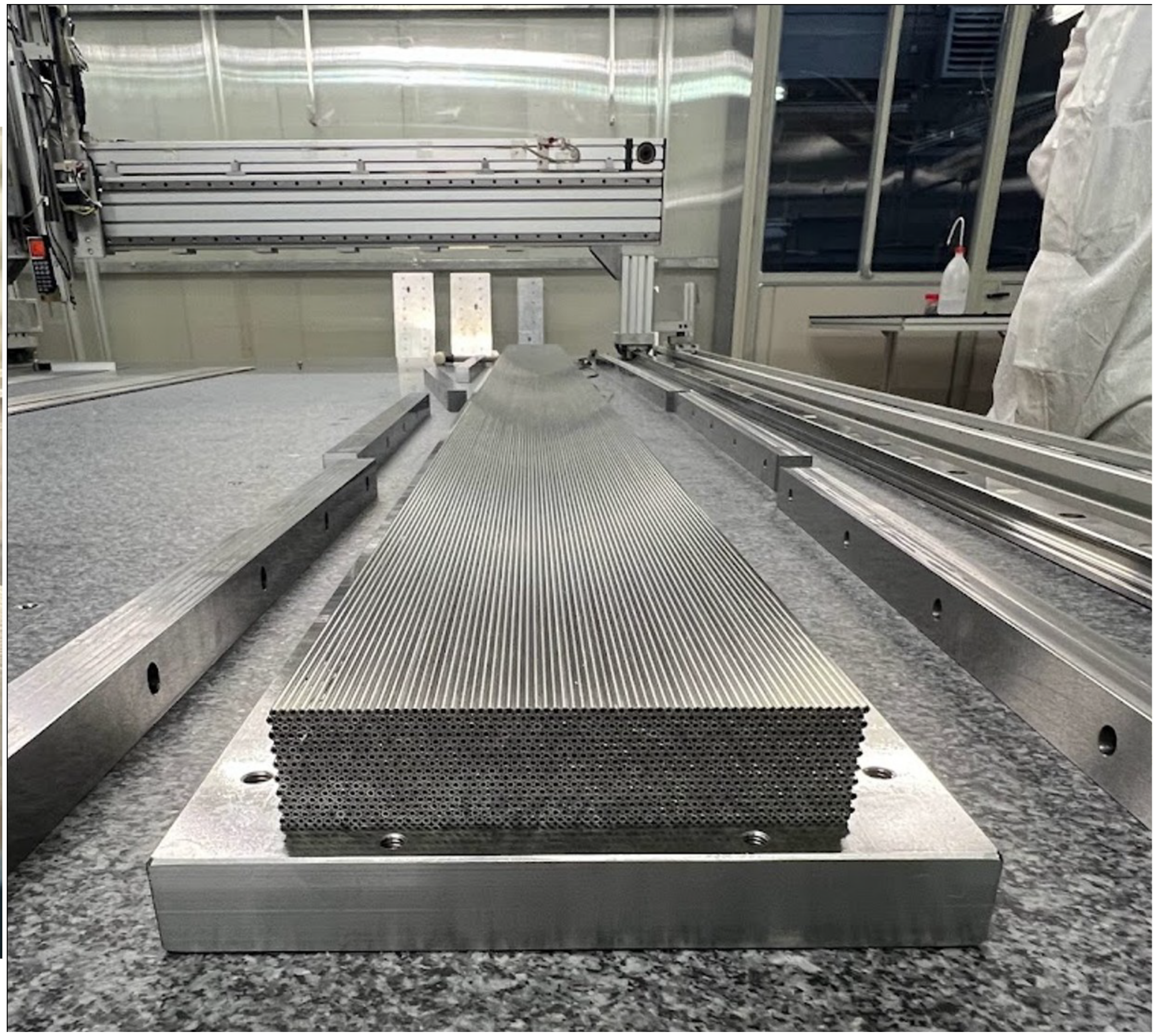
1 MiniModule:
64 × 16 = 1024 fibres in total
(512 S + 512 C)

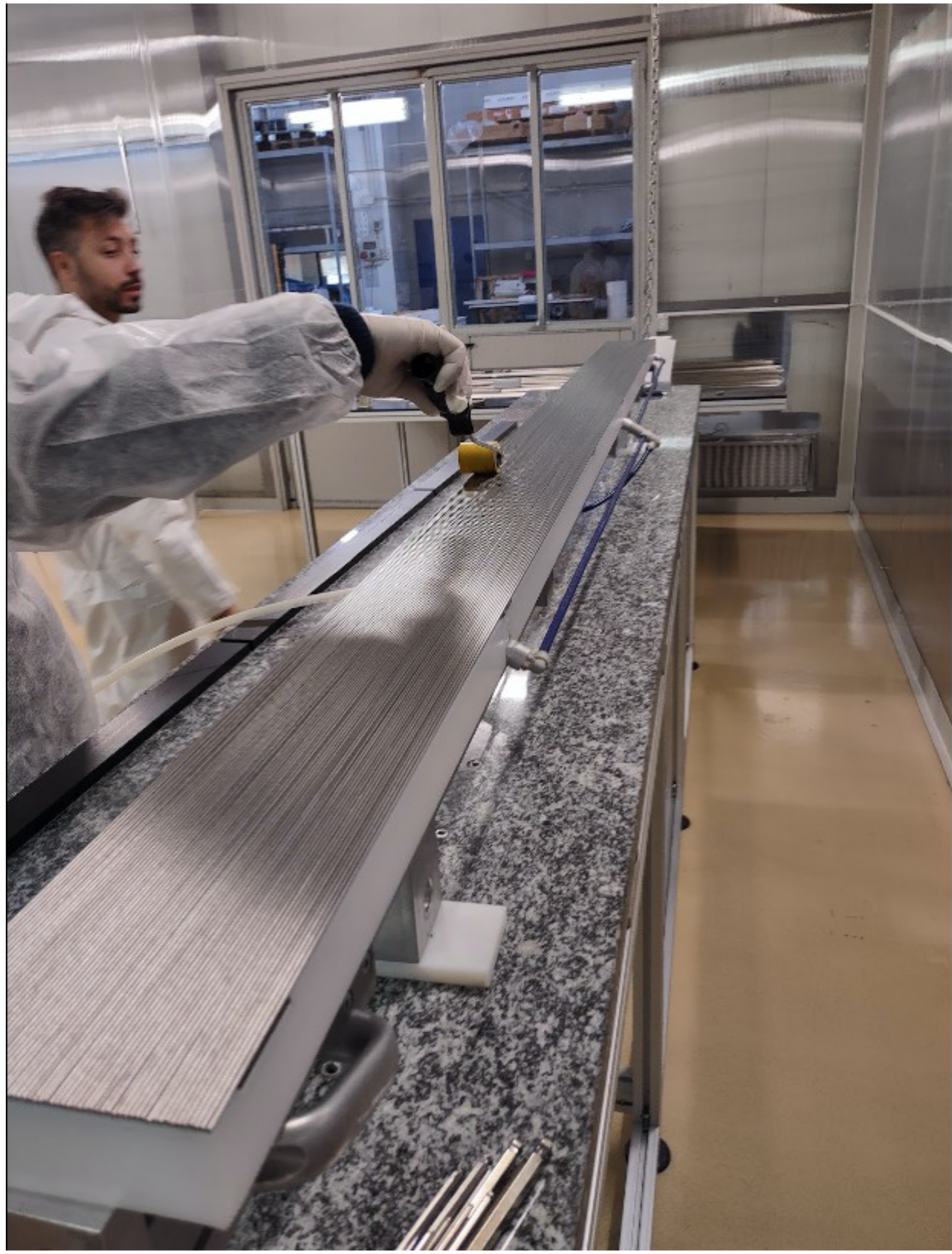
highly granular core:
10240 fibres to read out with SiPMs

DR calorimeter

- Full containment hadronic prototype in progress
  - Hidra2 call INFN CSN5







DR calorimeter

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