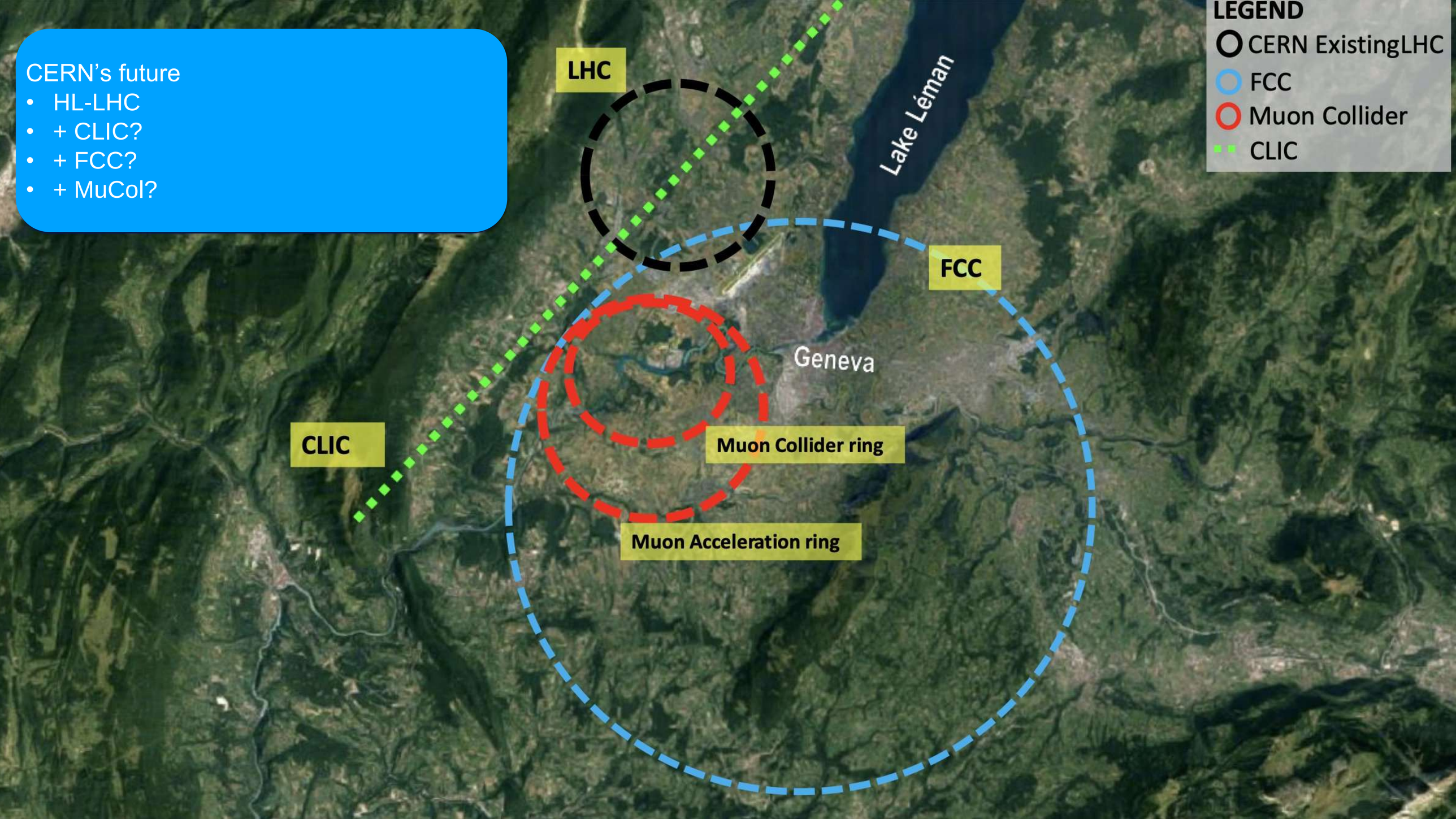
CERN's future
- HL-LHC
- + CLIC?
- + FCC?
- + MuCol?



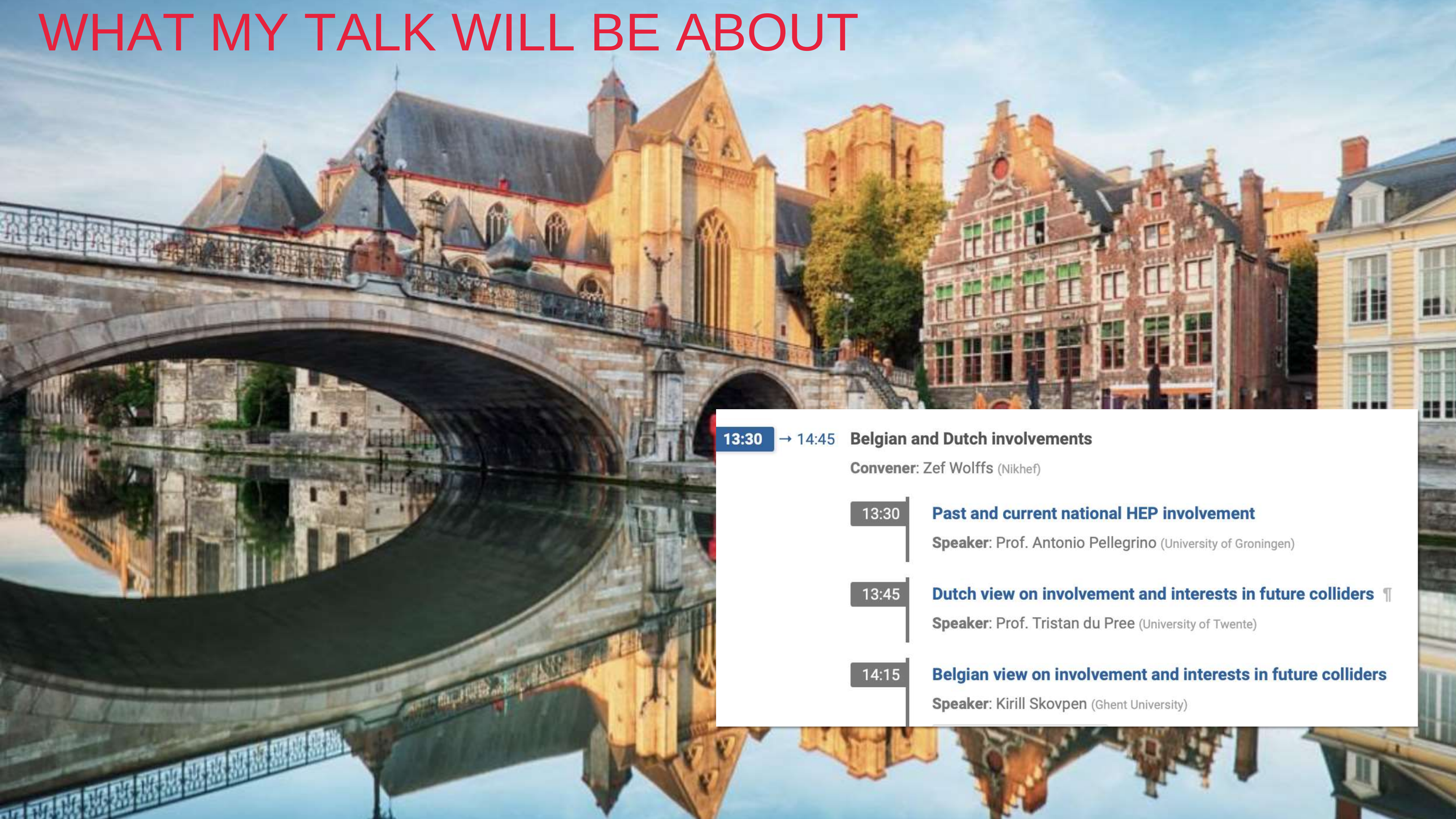
LINEAR OR CIRCULAR?

…preference for linear in Ghent?

LINEAR OR CIRCULAR?

No conclusive answer in Ghent either…

WHAT MY TALK WILL BE ABOUT



13:30 → 14:45 **Belgian and Dutch involvements**

Convener: Zef Wolffs (Nikhef)

13:30 **Past and current national HEP involvement**

Speaker: Prof. Antonio Pellegrino (University of Groningen)

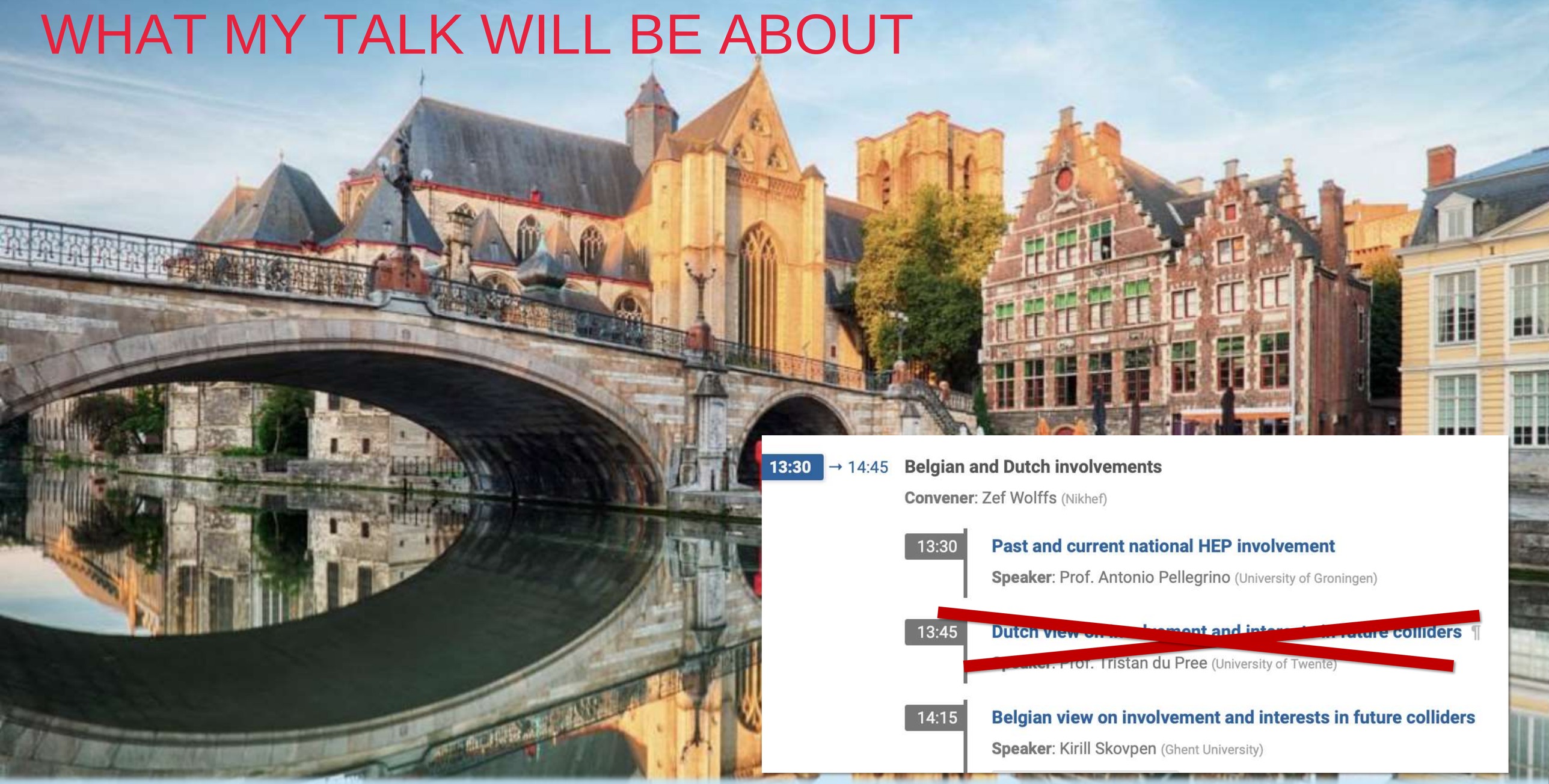
13:45 **Dutch view on involvement and interests in future colliders** ¶

Speaker: Prof. Tristan du Pree (University of Twente)

14:15 **Belgian view on involvement and interests in future colliders**

Speaker: Kirill Skovpen (Ghent University)

WHAT MY TALK WILL BE ABOUT



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~~Speaker: Prof. Tristan du Pree (University of Twente)~~

14:15 **Belgian view on involvement and interests in future colliders**

Speaker: Kirill Skovpen (Ghent University)

There is no “Dutch view” (yet) so I cannot speak on behalf of whole NL

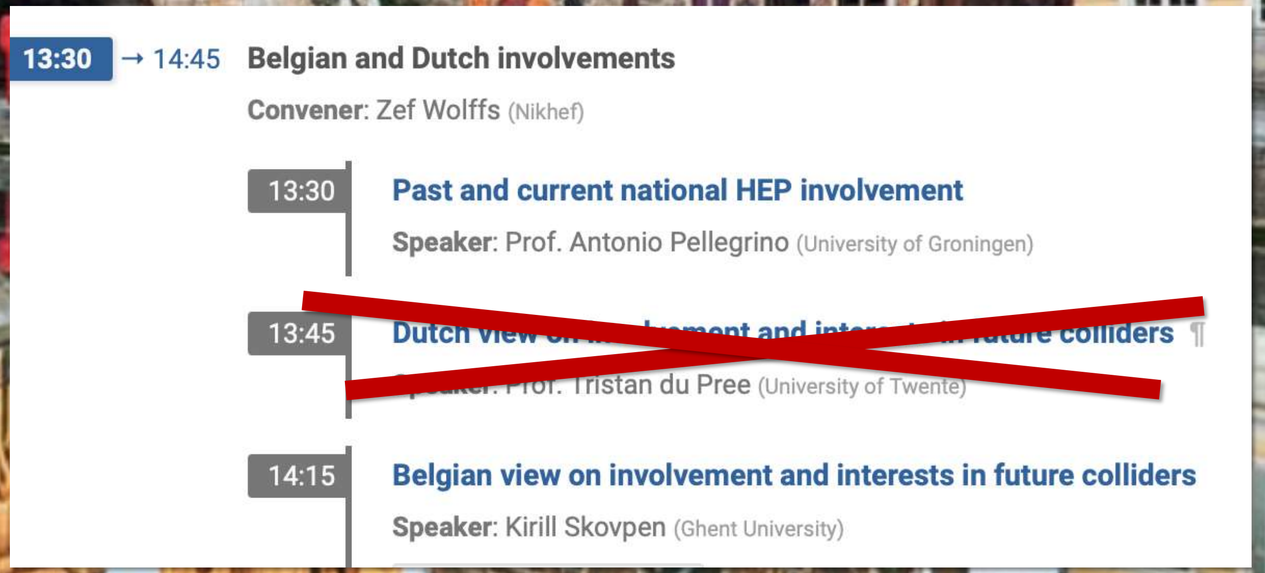
WHAT MY TALK WILL BE ABOUT

What **we are** doing

What **we should** be doing

~~What you should be doing~~

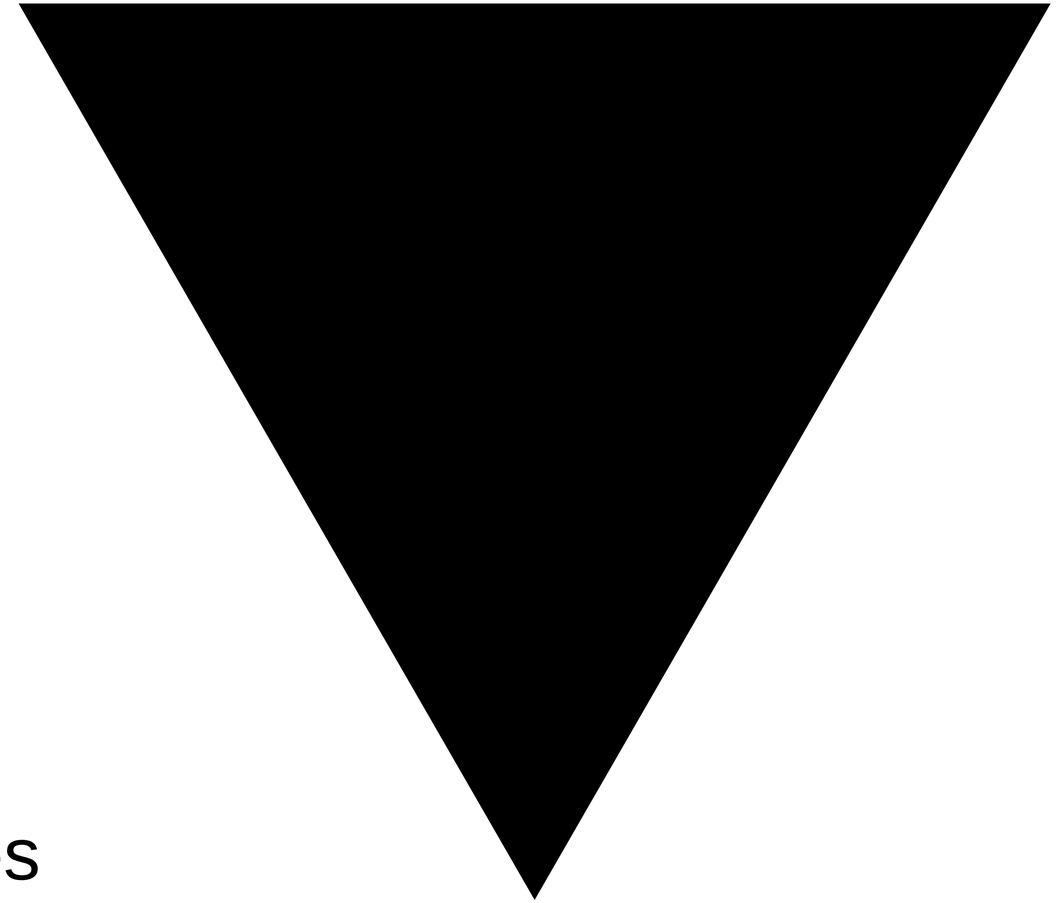
What **you could** be doing



MY PROFESSIONAL LIGHTCONE

2050

Retirement

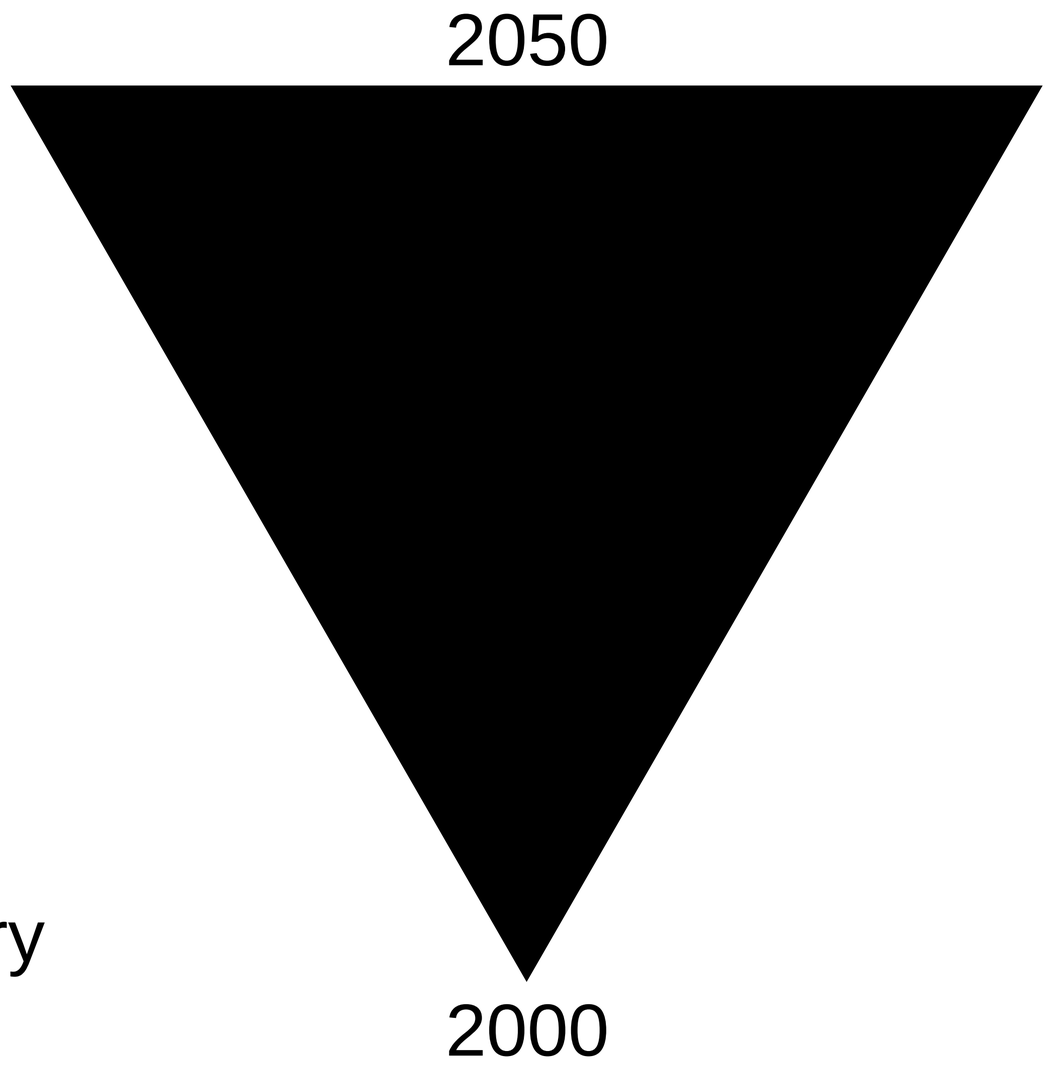


Start physics studies

2000

MY PROFESSIONAL LIGHTCONE

Retirement



2017++ ATLAS

2010-17 PD CMS

2006-10 PhD LHCb

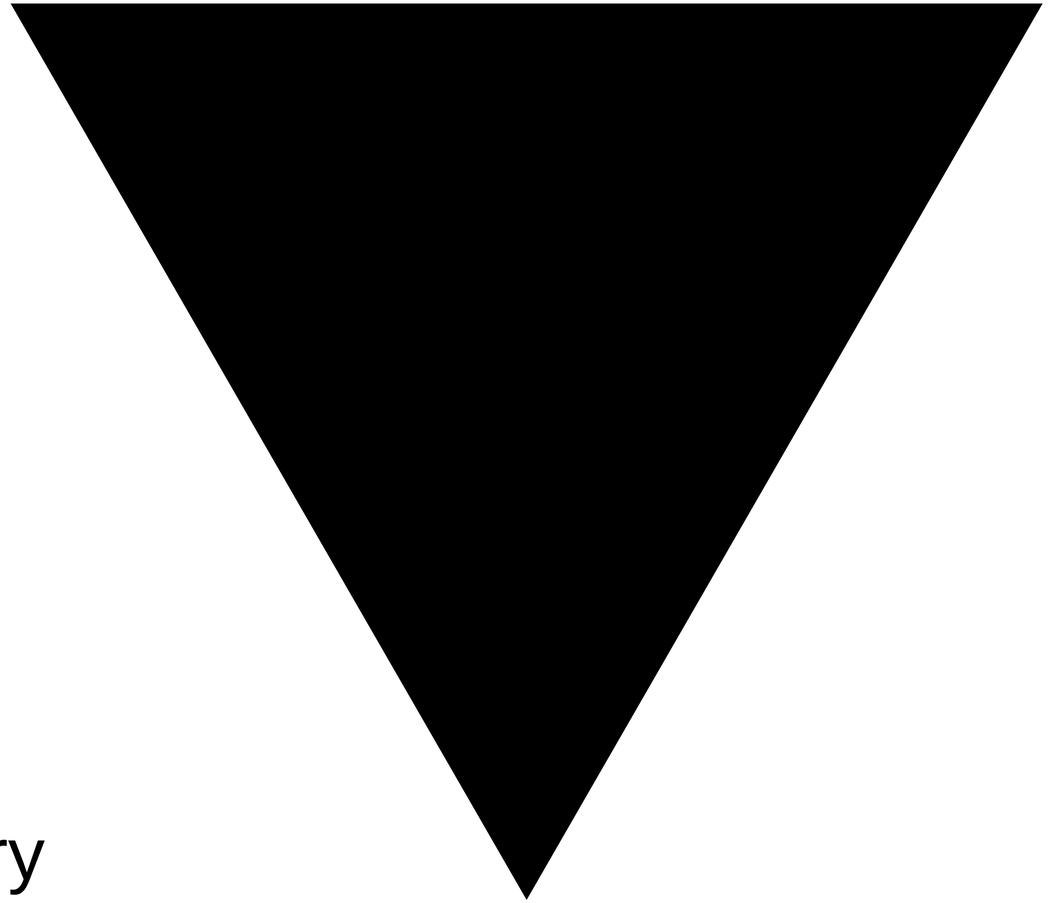
2000-05 MSc Theory

MY PROFESSIONAL LIGHTCONE

2050

Retirement

New collider?



2017++ ATLAS

2010-17 PD CMS

2006-10 PhD LHCb

2000-05 MSc Theory

2022 C^3

2020 MuCol

2017 FCC report

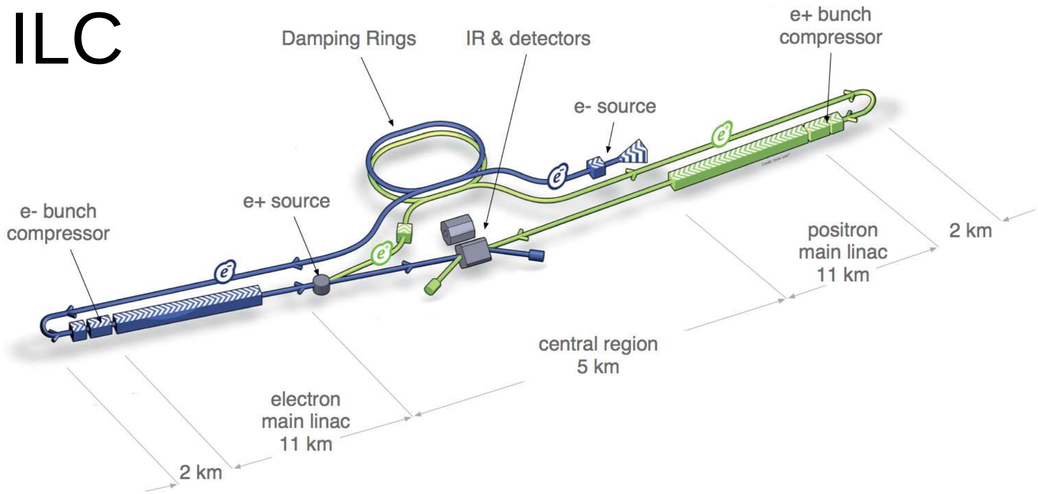
2013 ILC cand.site

2008 Start of the LHC

2000

MY ACTIVITIES (SO FAR)

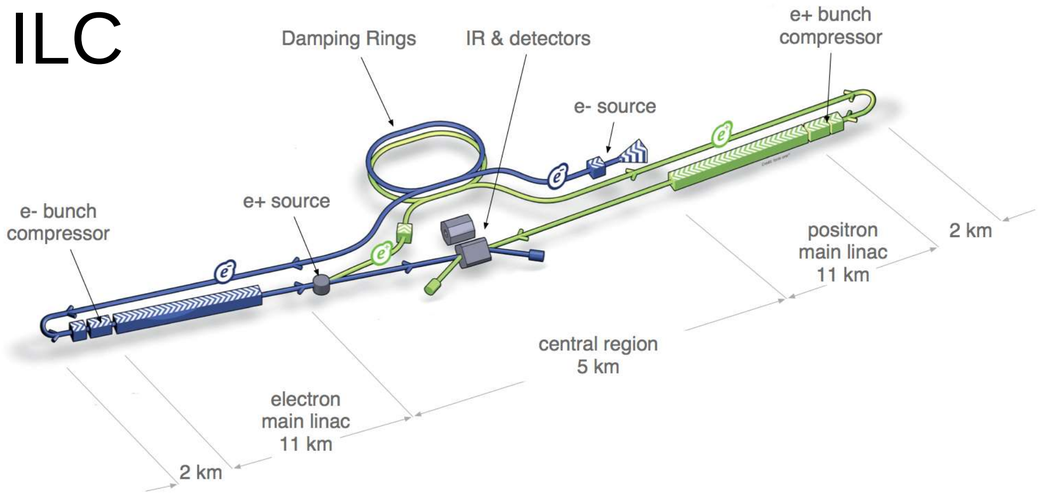
ILC



2013: ILC site visit

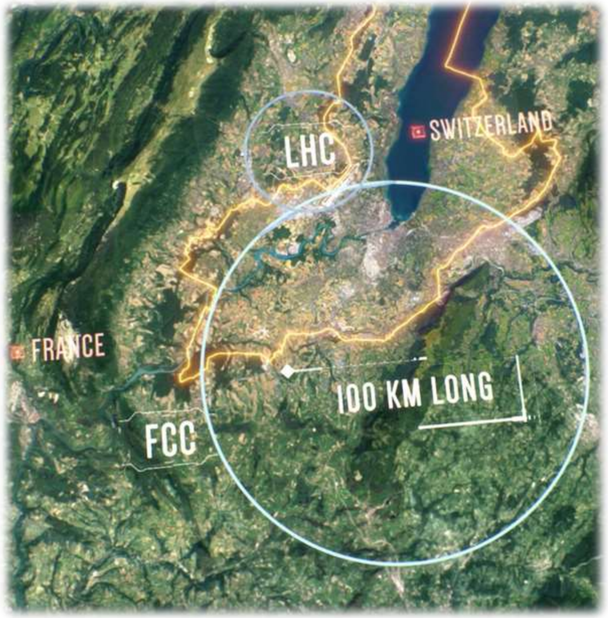
MY ACTIVITIES (SO FAR)

ILC



2013: ILC site visit

FCC

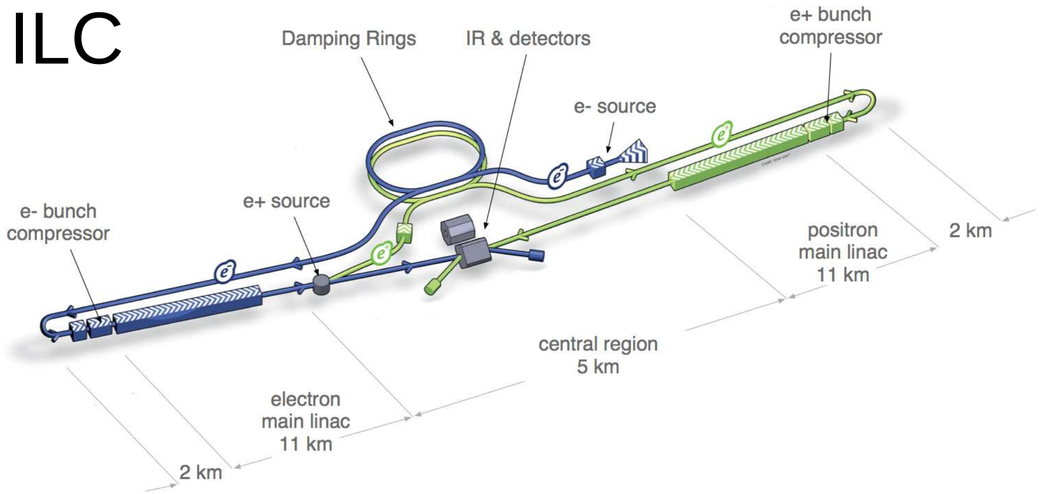


2017: Yellow report co-author

2021-23: FCC national contact

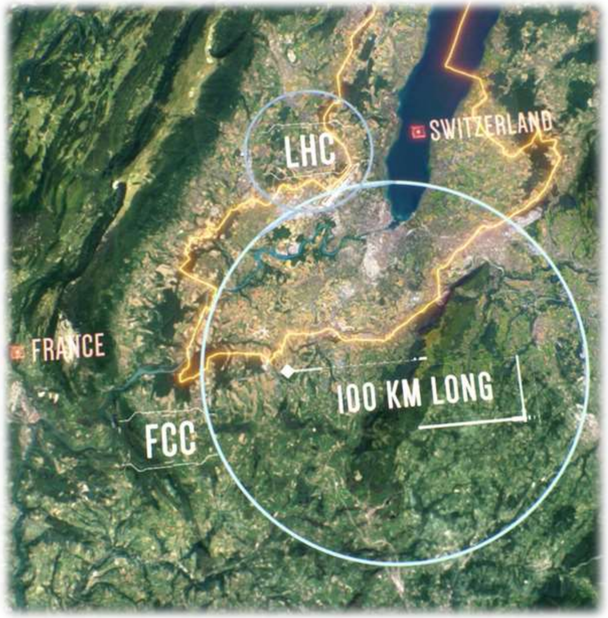
MY ACTIVITIES (SO FAR)

ILC



2013: ILC site visit

FCC



2017: Yellow report co-author

2021-23: FCC national contact

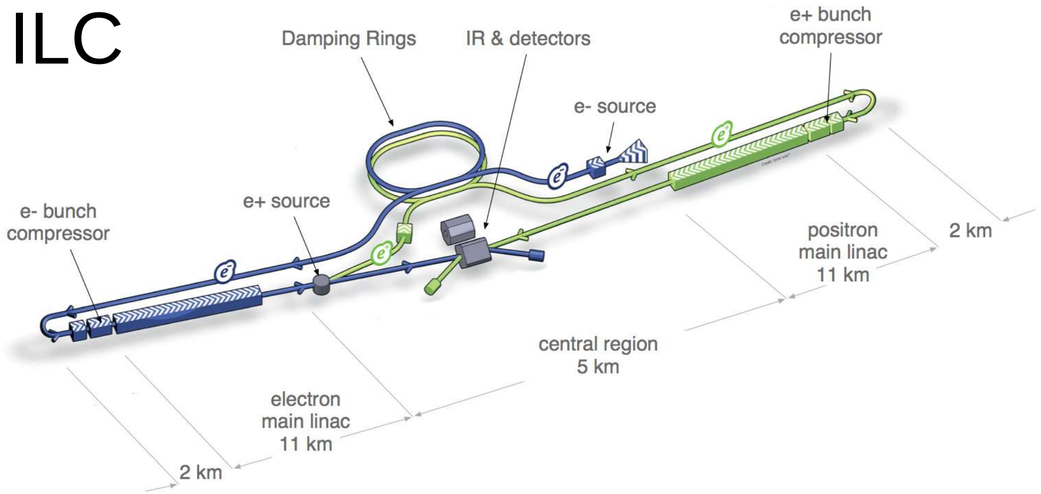
C^3

2022+: Accelerator alignment R&D

2024: European workshop organizer

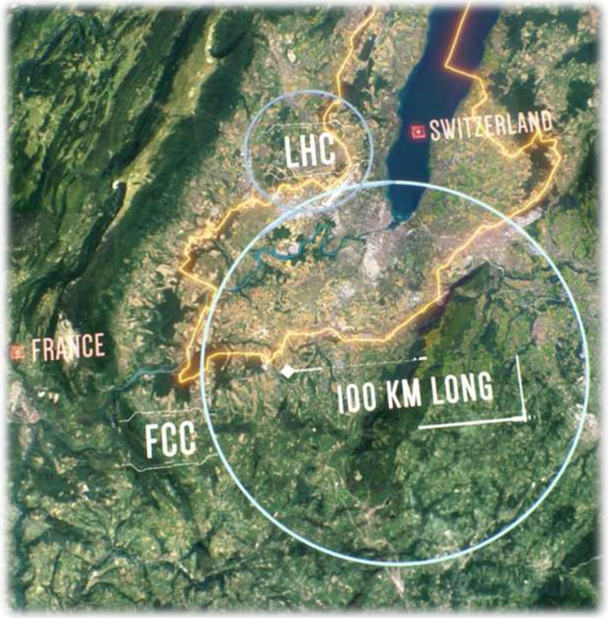
MY ACTIVITIES (SO FAR)

ILC



2013: ILC site visit

FCC



2017: Yellow report co-author

2021-23: FCC national contact

Muon Collider

2020+: Enthusiastic co-author

2024: NWO grant submission

C^3

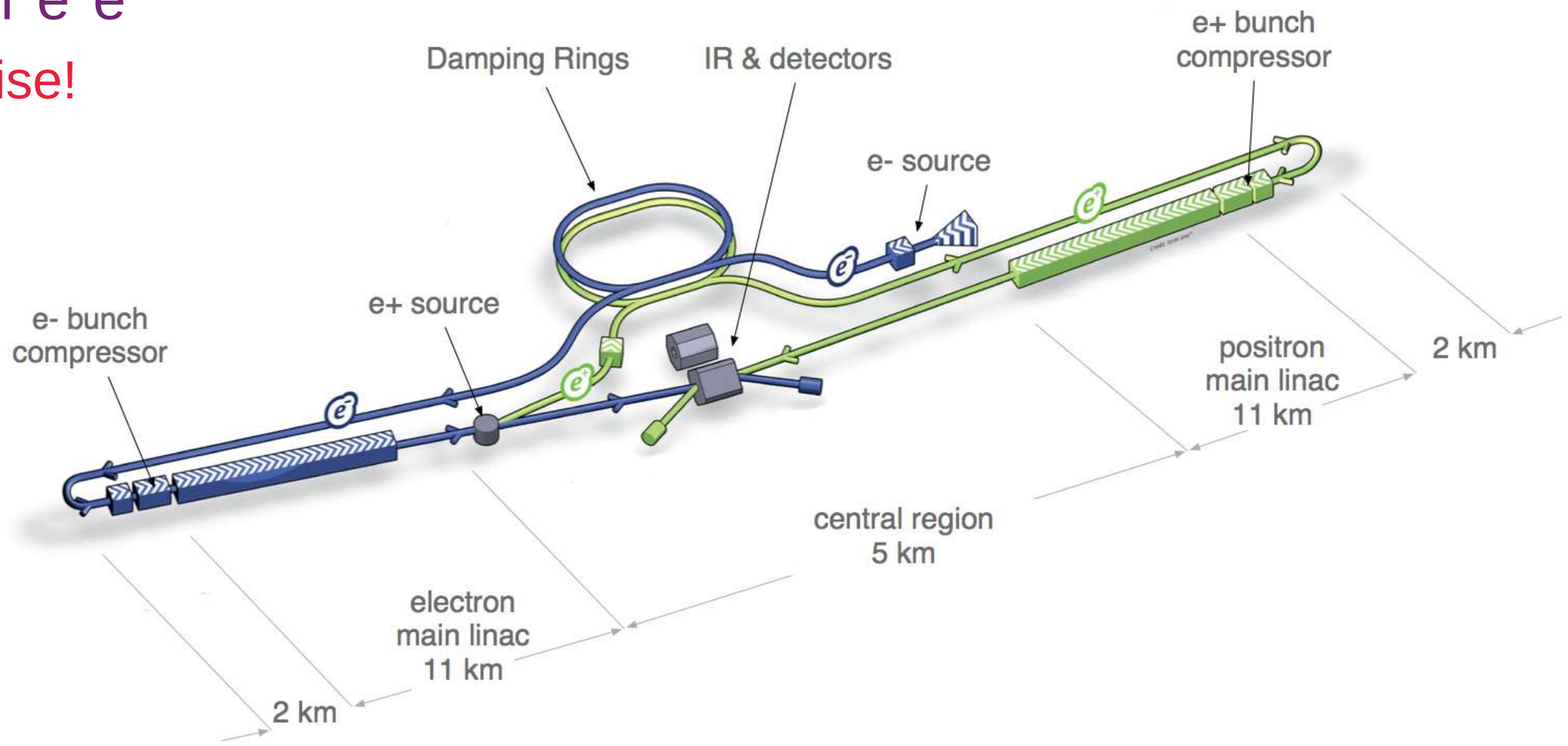
2022+: Accelerator alignment R&D

2024: European workshop organizer

ILC

Netherlands involvement

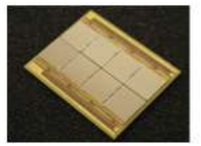
- Detector R&D for e^+e^-
  - Goal: ultra precise!



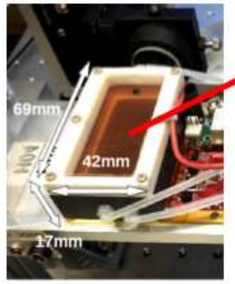
ILC

ILD: Detector R&D for e^+e^-

- Very low material budget
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)

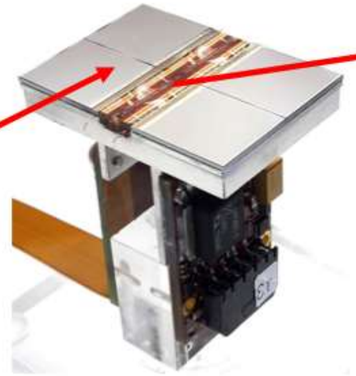


(Octopuce)



(TimePix1)

(2007-14)



TPX3 chip

2017

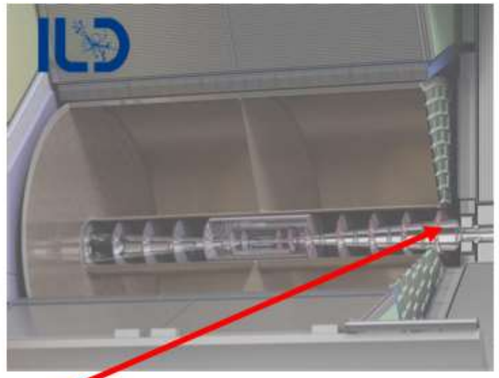
Quad

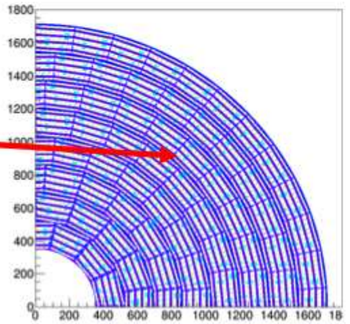
2018

Module

2019

Pixel TPC



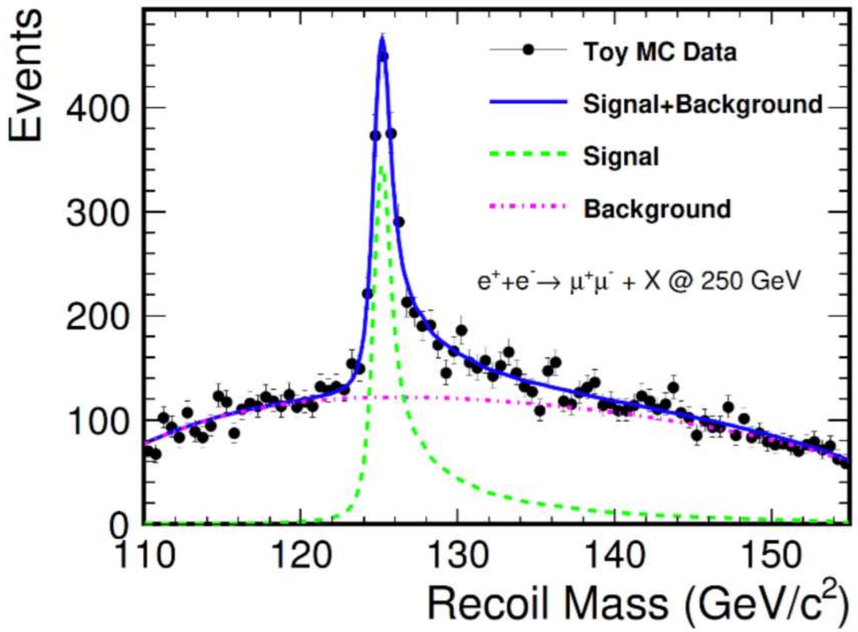


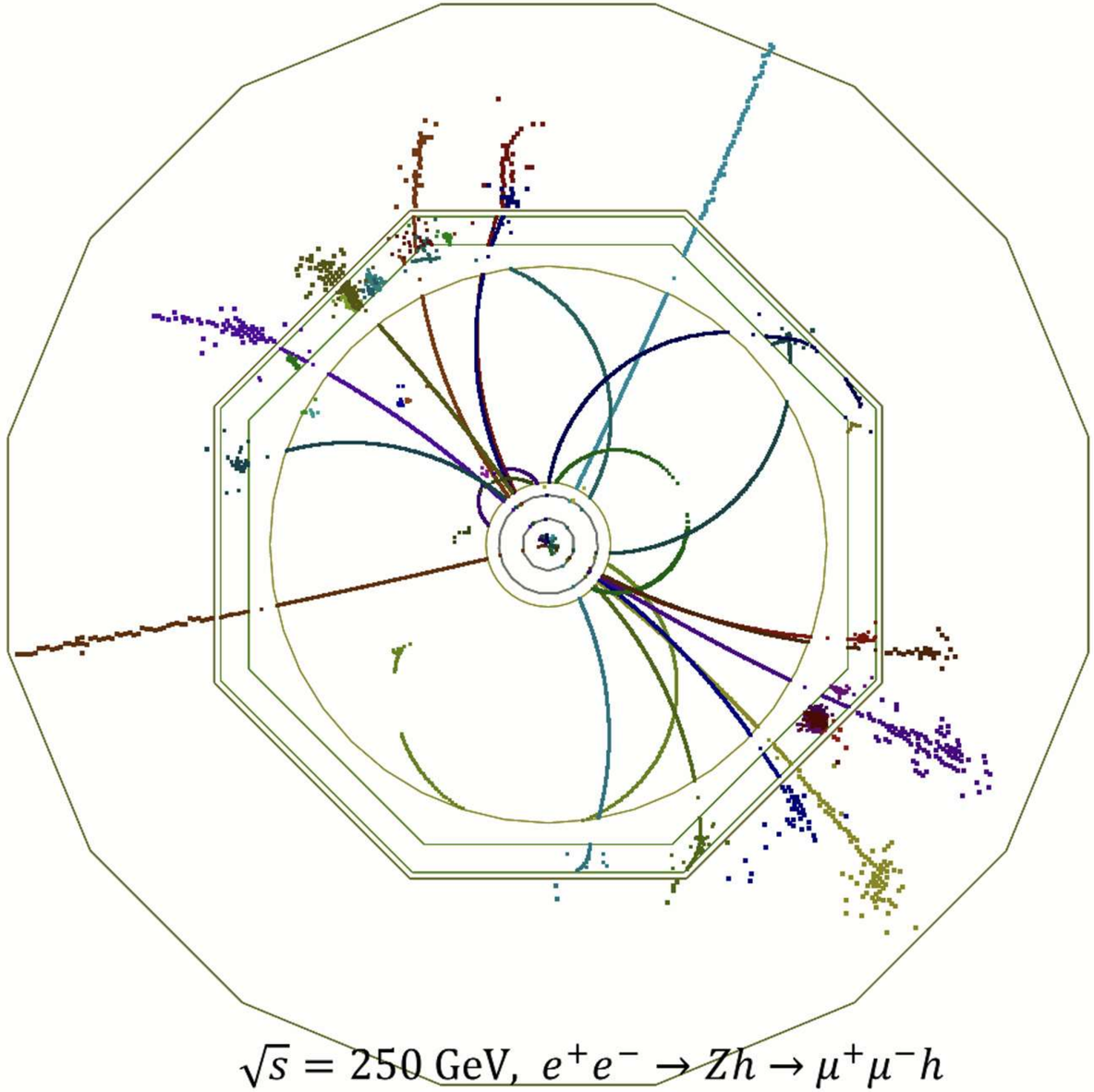
TPC plane

ILC PHYSICS

Precision at e^+e^-

- Order of magnitude in Higgs physics



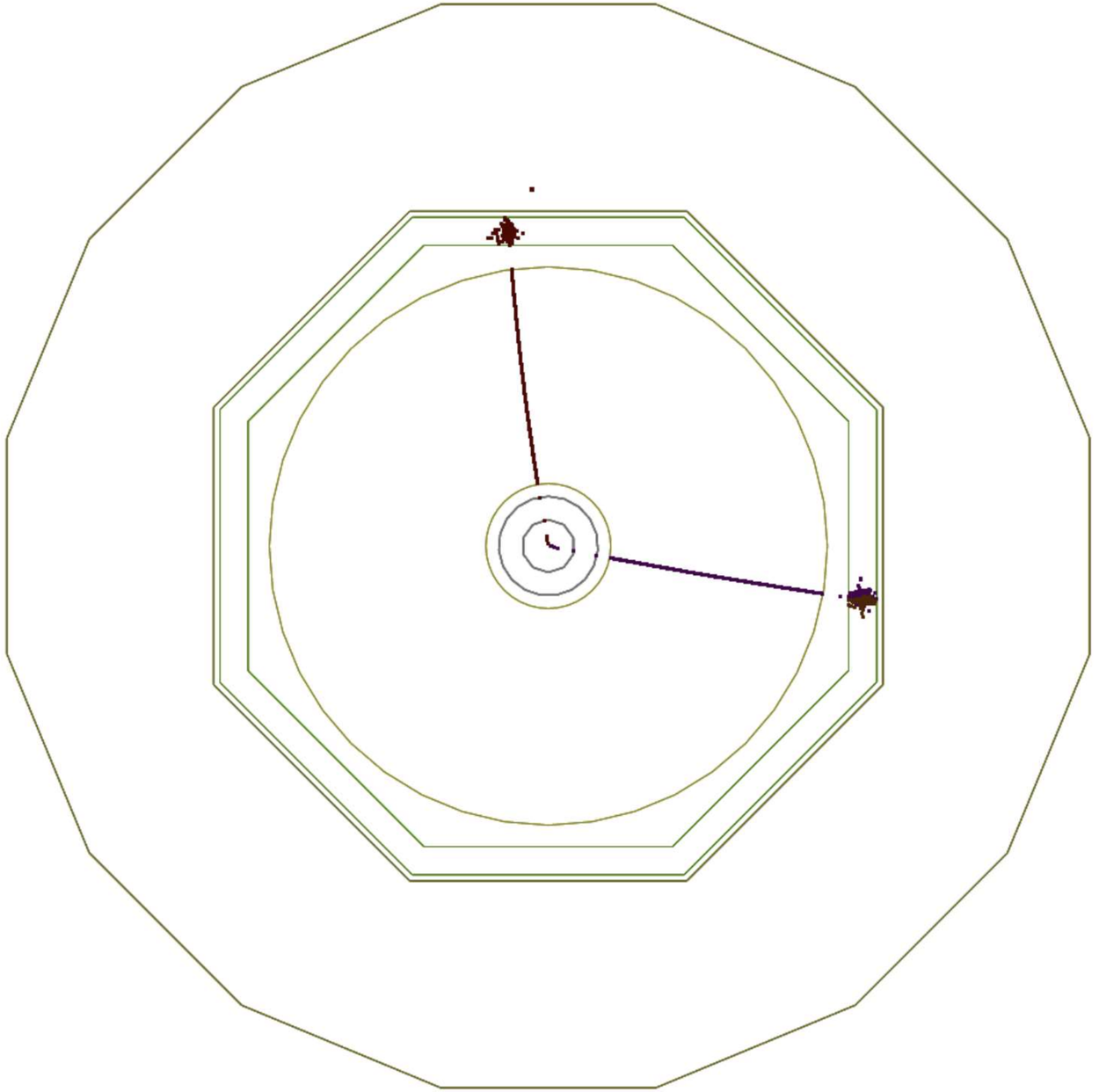


$\sqrt{s} = 250\ \mathrm{GeV},\ e^+e^- \to Zh \to \mu^+\mu^- h$

ILC PHYSICS

Precision phyics, but…

- *“Elk voordeel heb z’n nadeel”*
  - *J.Cruijff*



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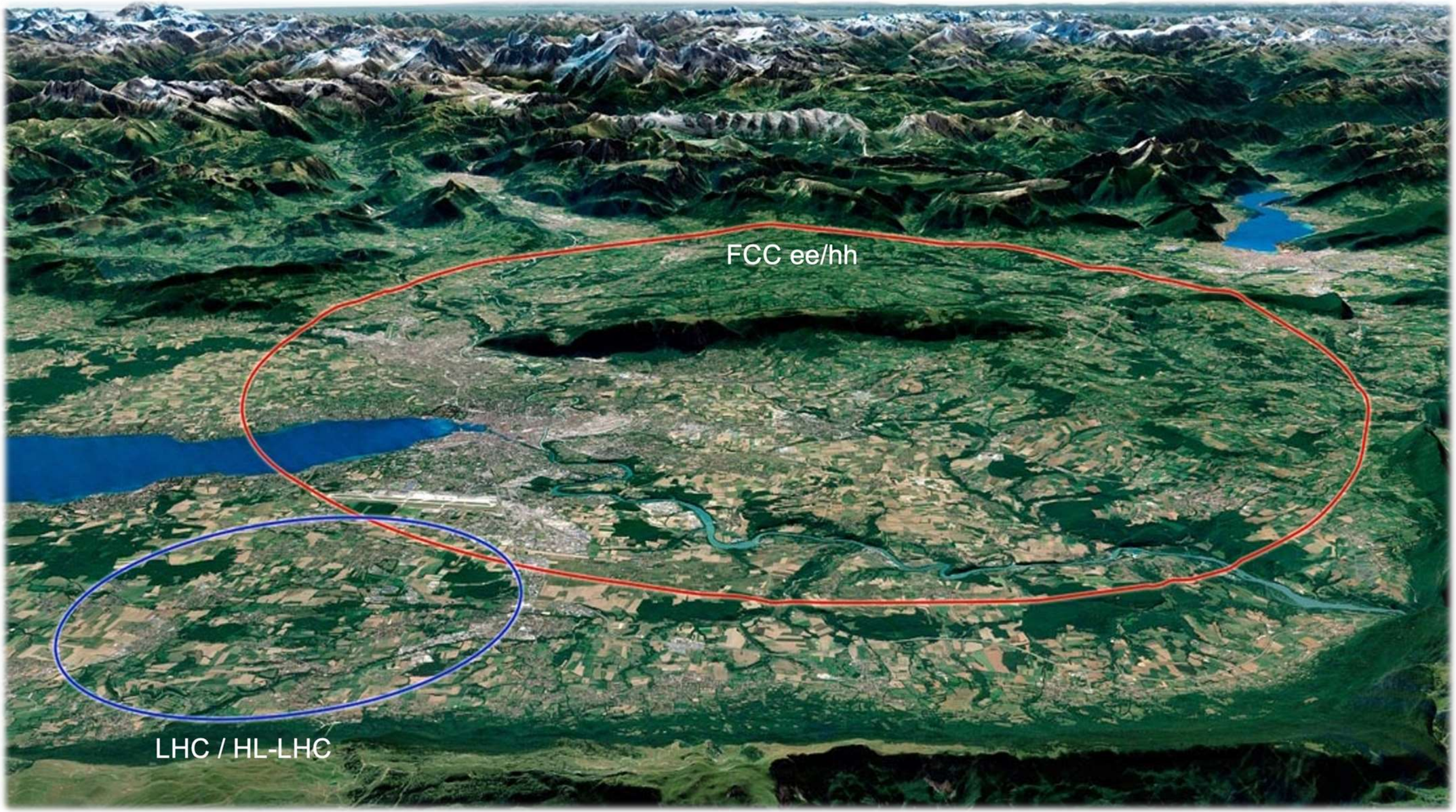


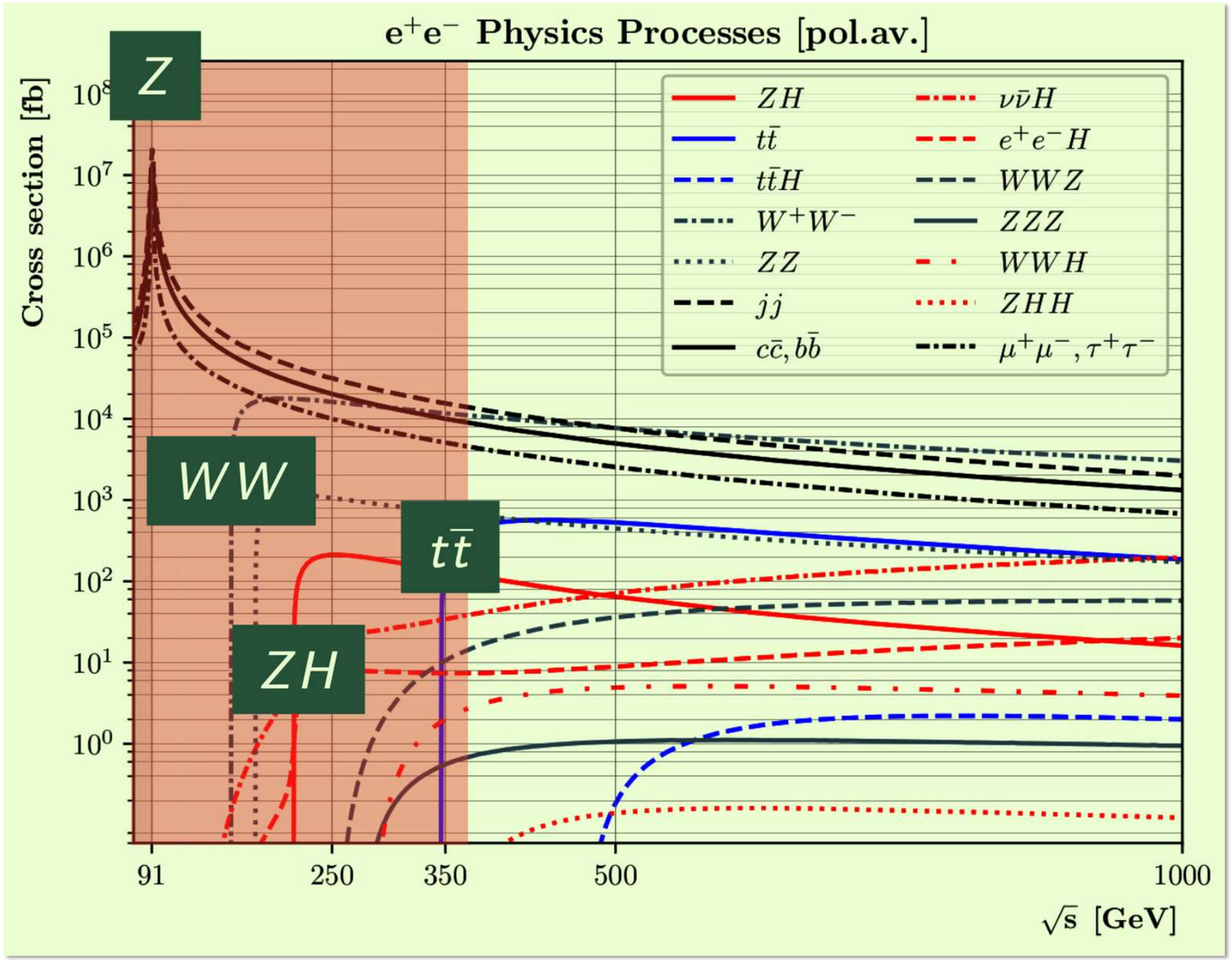
E+E- COLLIDERS

ECFA studies: e+e-

- Z, WW, ZH, tt
  - ‘Focus topics’

NL contact: Patrick Koppenburg

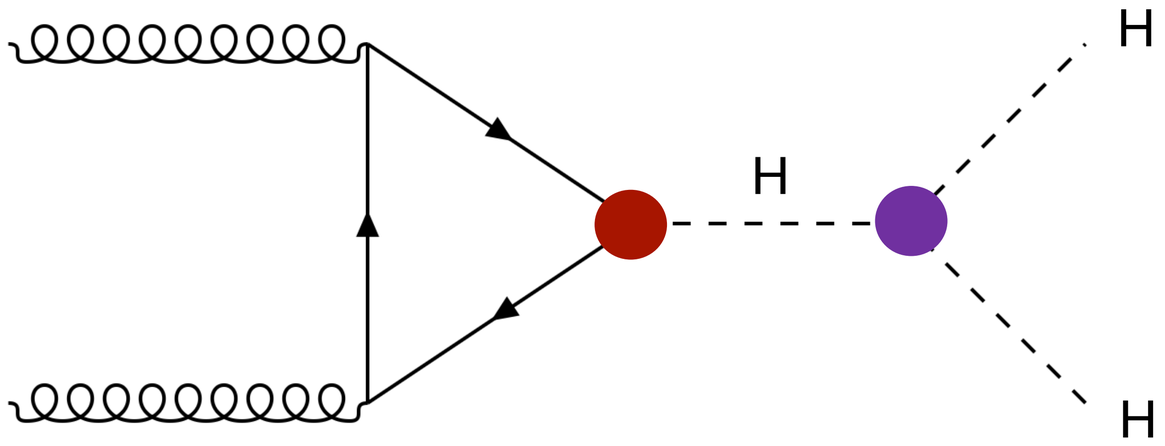
BE contact: Fabio Maltoni



FCC-EE

Global SMEFT analysis

- Higgs, top, electroweak
  - With LEP, LHC and FCC-ee

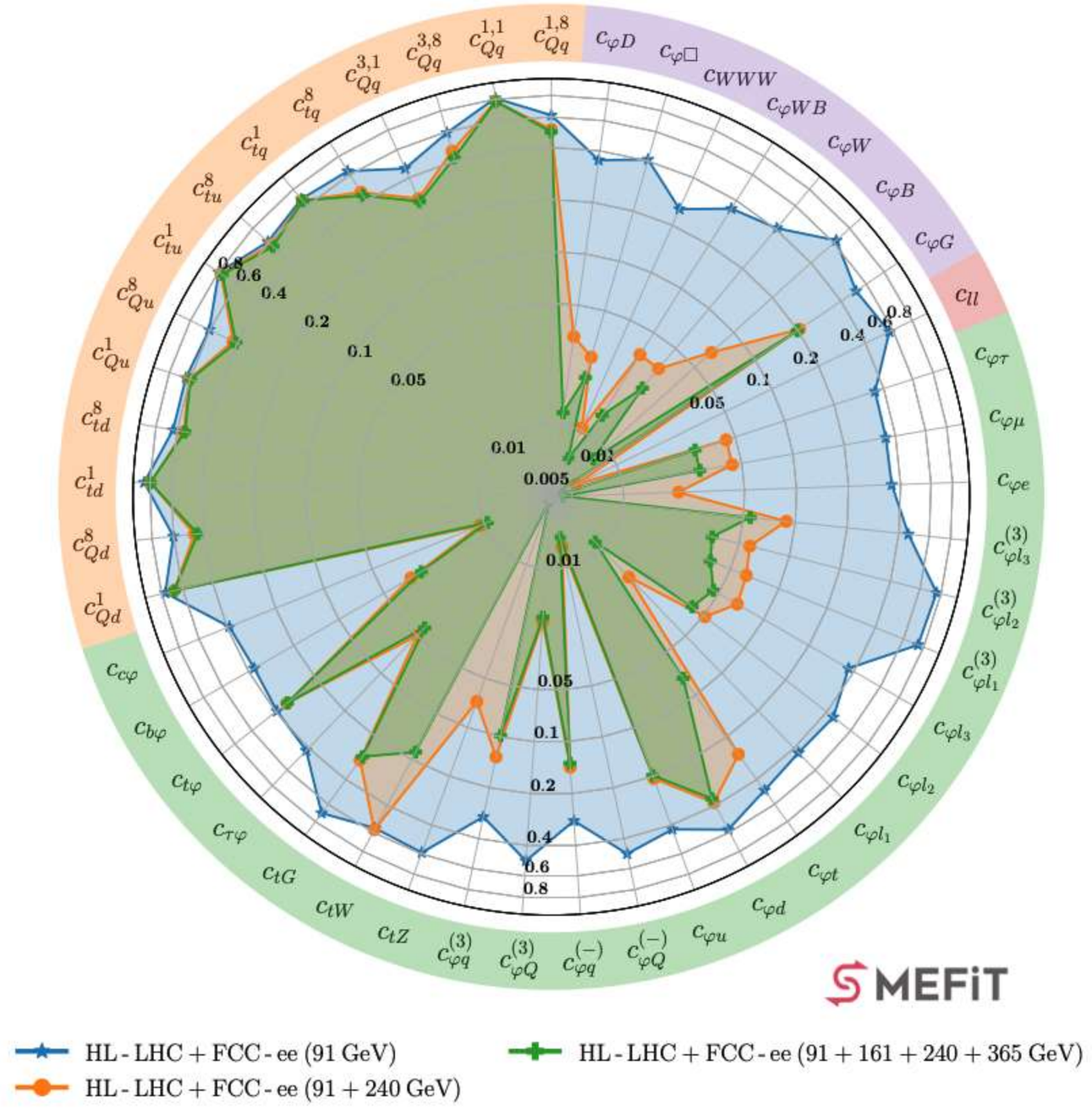


FCC-EE

Global SMEFT analysis

- Higgs, top, electroweak
  - With LEP, LHC and FCC-ee

J.Rojo et al, arXiv:2404.12809

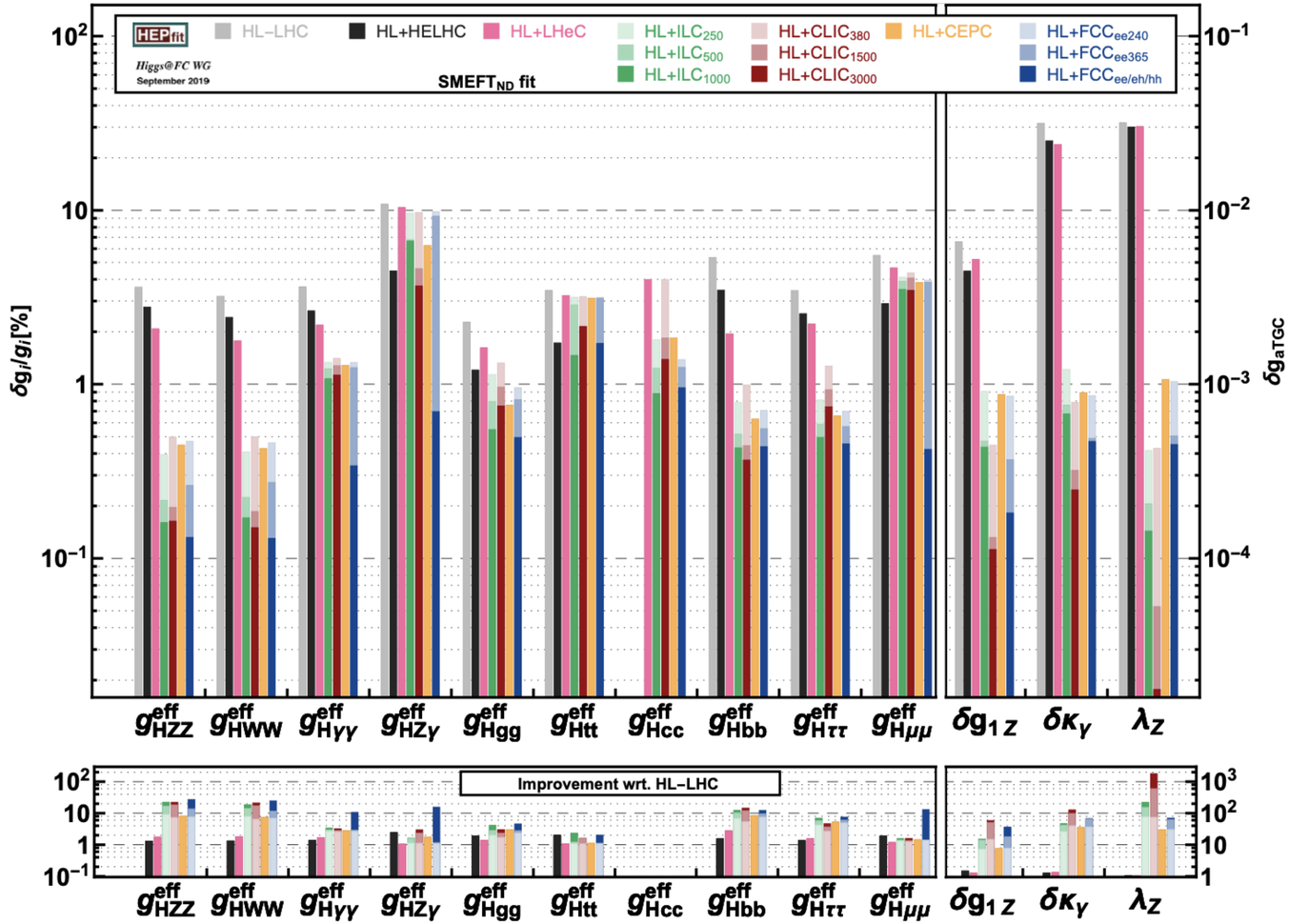


COMBINATIONS & COMPARISONS

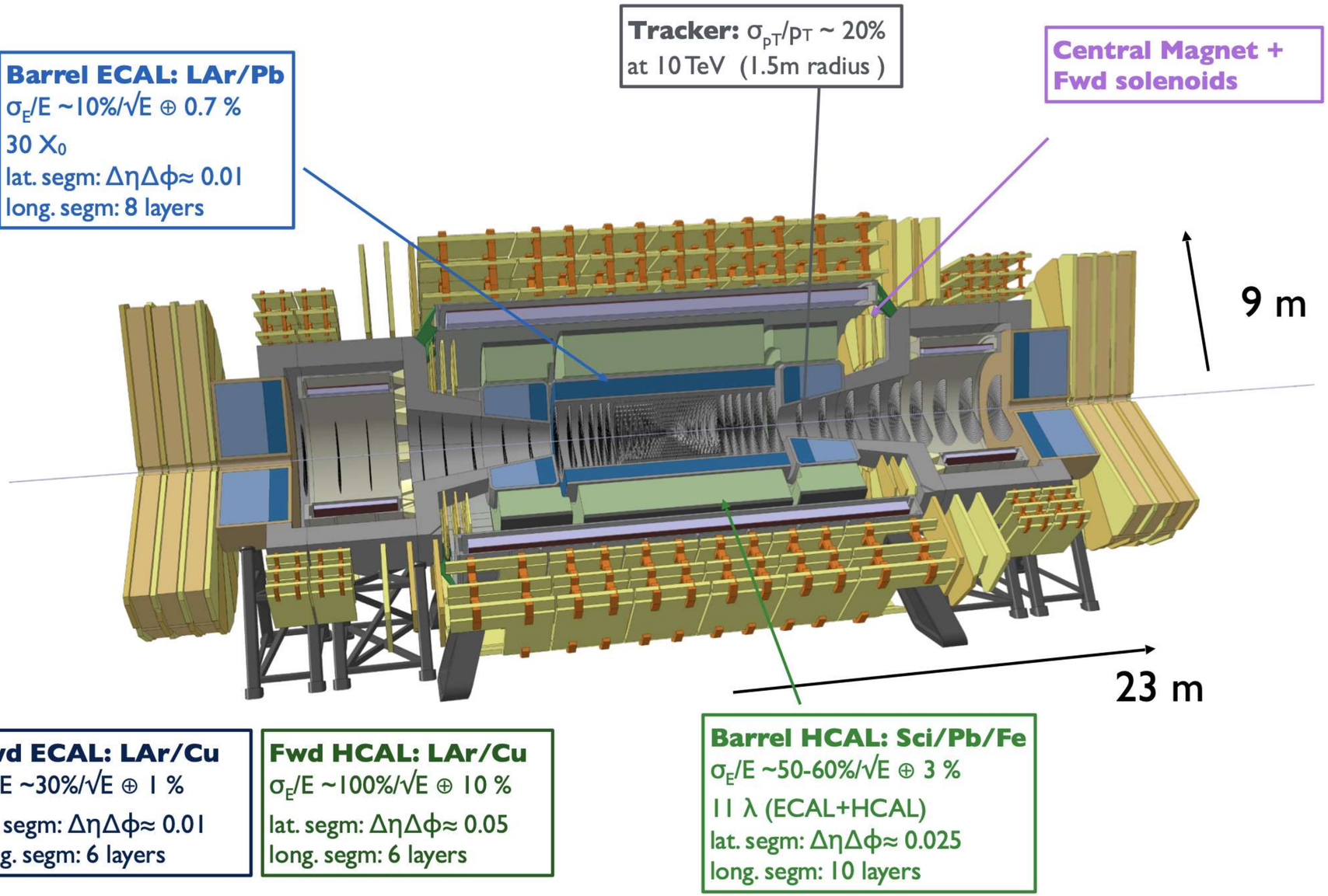
Higgs factories sensitivities

- Factor ~10 wrt HL-LHC
  - Overall similar performance!
    - Particulary Γ, $K_{W,Z}$, $K_{b,c}$

W.Verkerke, J.D'Hondt, F.Maltoni et al, arXiv:1905.03764



FCC-HH



M.Selvaggi et al

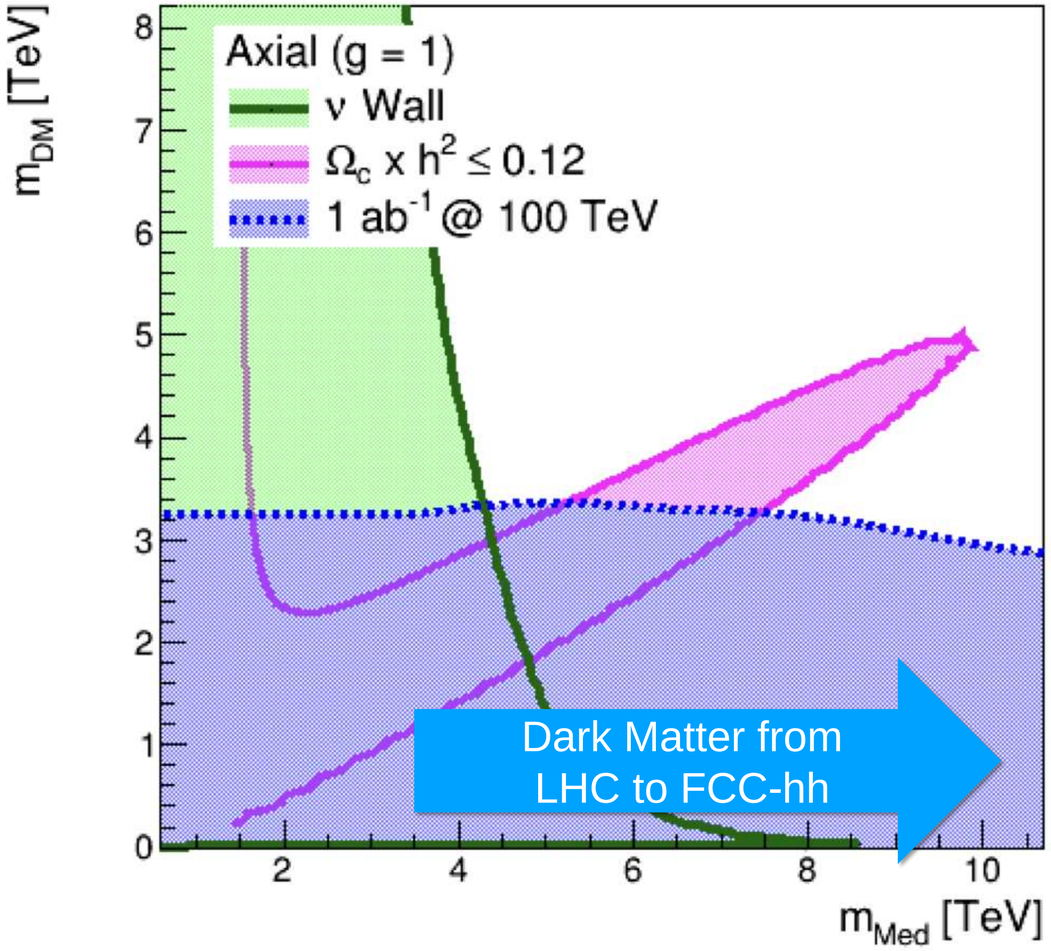
FCC-HH

FCC-hh: direct searches

- Scales LHC limits
  - BSM: factor 100/14~7

FCC yellow report, 2017

T.du Pree et al, arXiv: 1603.08525



FCC-HH

Ongoing studies for FCC-hh

- Accelerator magnets
  - University Twente
- Scenario studies
  - Mini-workshop
    3 Sep 2024

F.Zimmermann, 3 Sep 2024

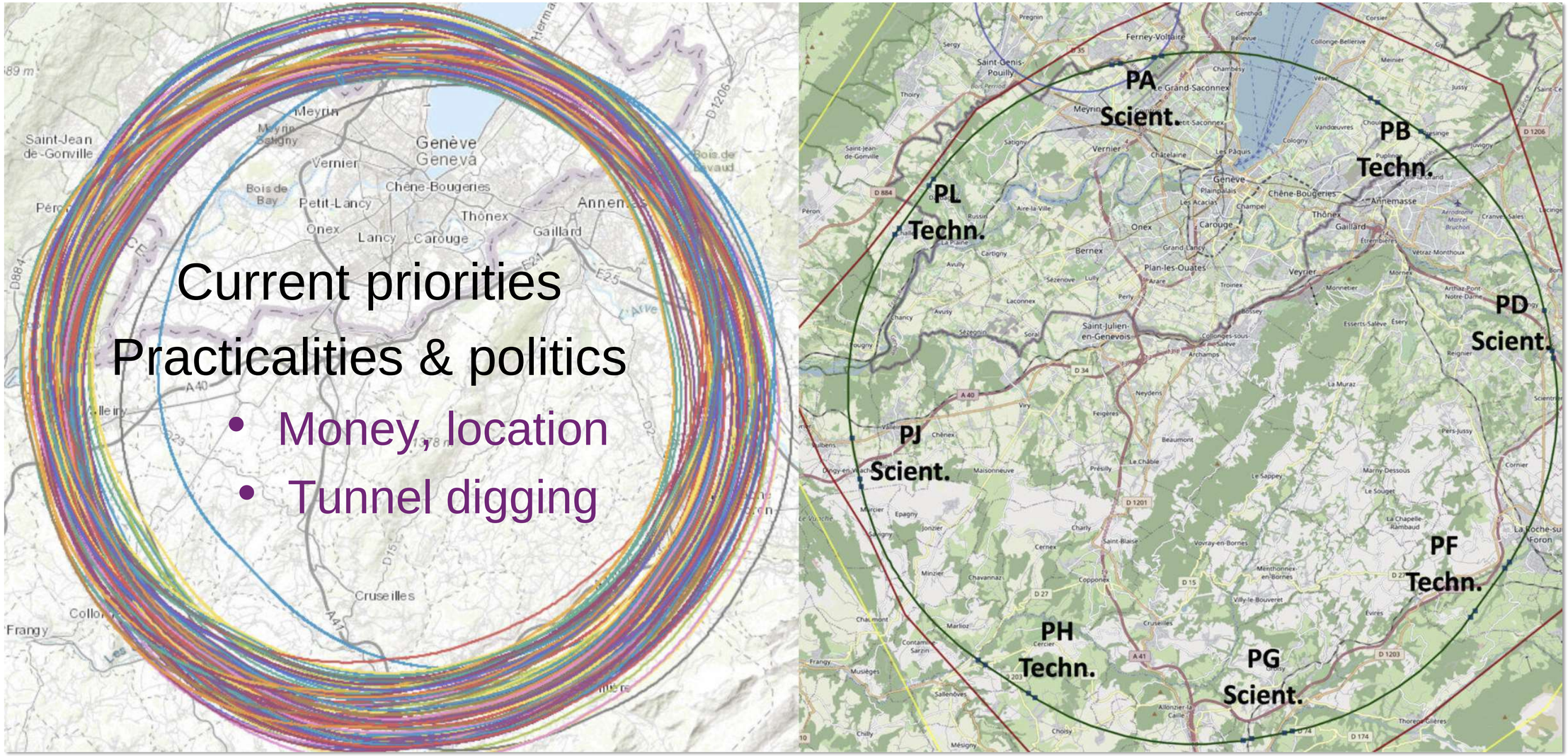
Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS

M.L.Mangano, 3 Sep 2024

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	0.9	1.0	0.8

➔ Study scenarios for different magnets

FCC


Current priorities
Practicalities & politics
• Money, location
• Tunnel digging
PA
Scient.
PB
Techn.
PL
Techn.
PD
Scient.
PJ
Scient.
PF
Techn.
PH
Techn.
PG
Scient.

C3

Alignment for C^3 accelerator

- With Nikhef engineer Harry v/d Graaf
  - Based on system used for ATLAS Muon
  - “RasNik”

H. v/d Graaf at Nikhef

C3

Alignment for C3 accelerator

- With engineer
  Harry v/d Graaf
  - “RasNik”

H. v/d Graaf, T.du Pree et al, arXiv:24xx.yyyy

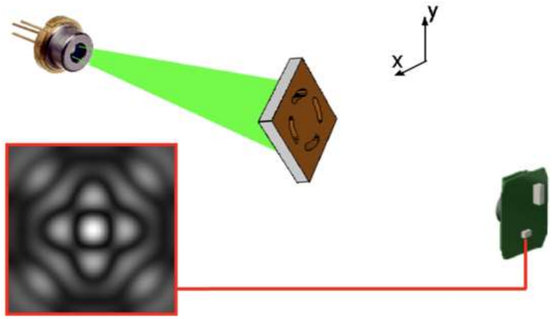


Figure 3. Principle of the RasDif system. The monochromatic waves, arriving at the zone plate, result in a diffraction pattern on the image sensor.

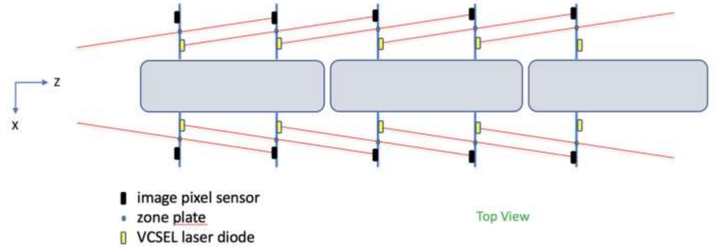


Figure 4. The ’leap frog’ multipoint alignment system: with the known alignment of any set of three adjacent chainplates, the alignment of all chainplates is known.

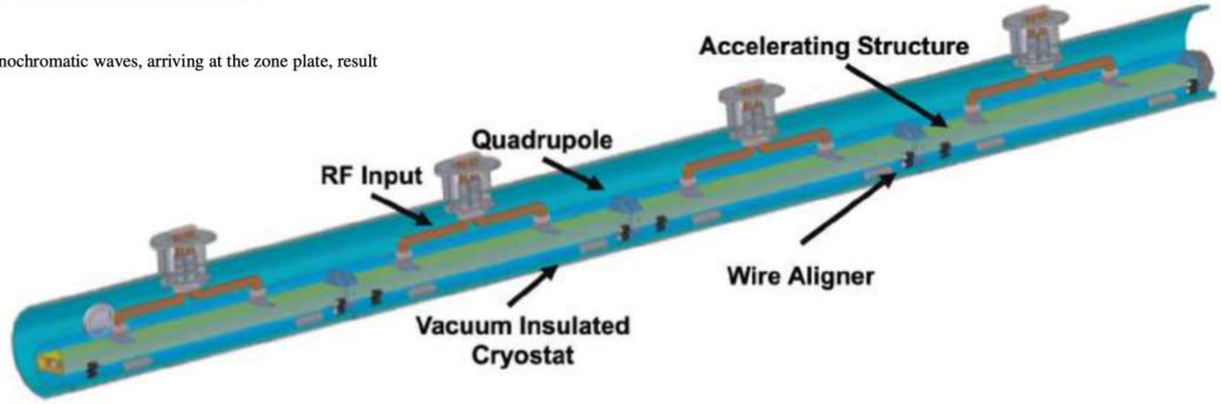


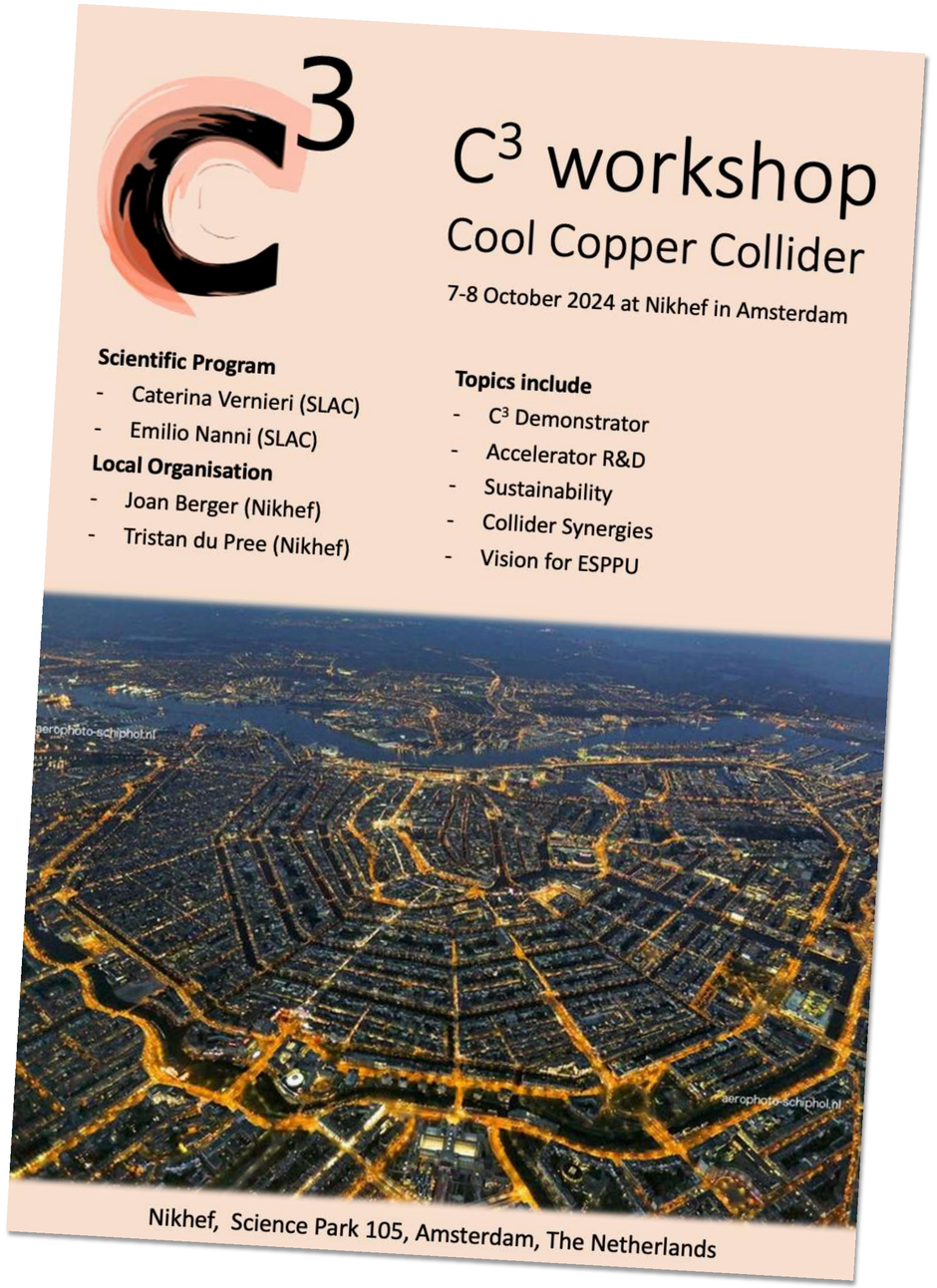
Figure 2. The 9 meter long CryoModule CM.

C3

Workshop in Amsterdam

- 7-8 October at Nikhef
  - You're welcome!

https://indico.slac.stanford.edu/event/9113/overview

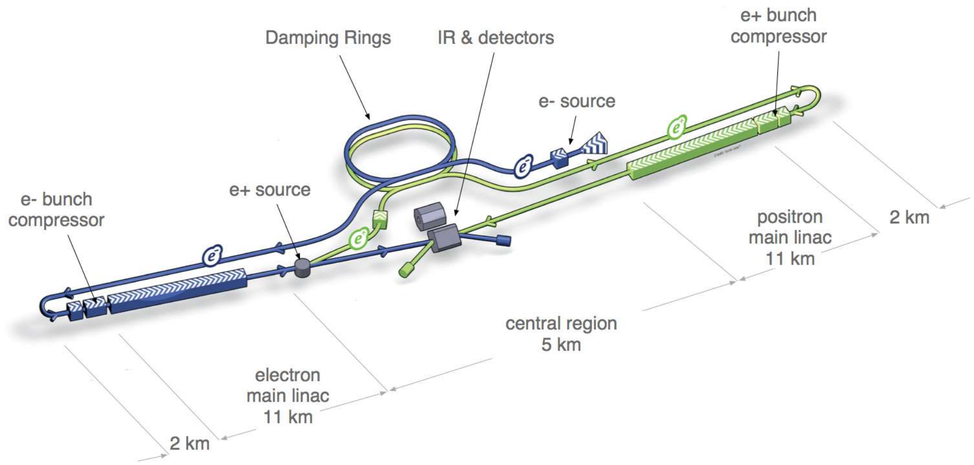


“LINEAR COLLIDER VISION”

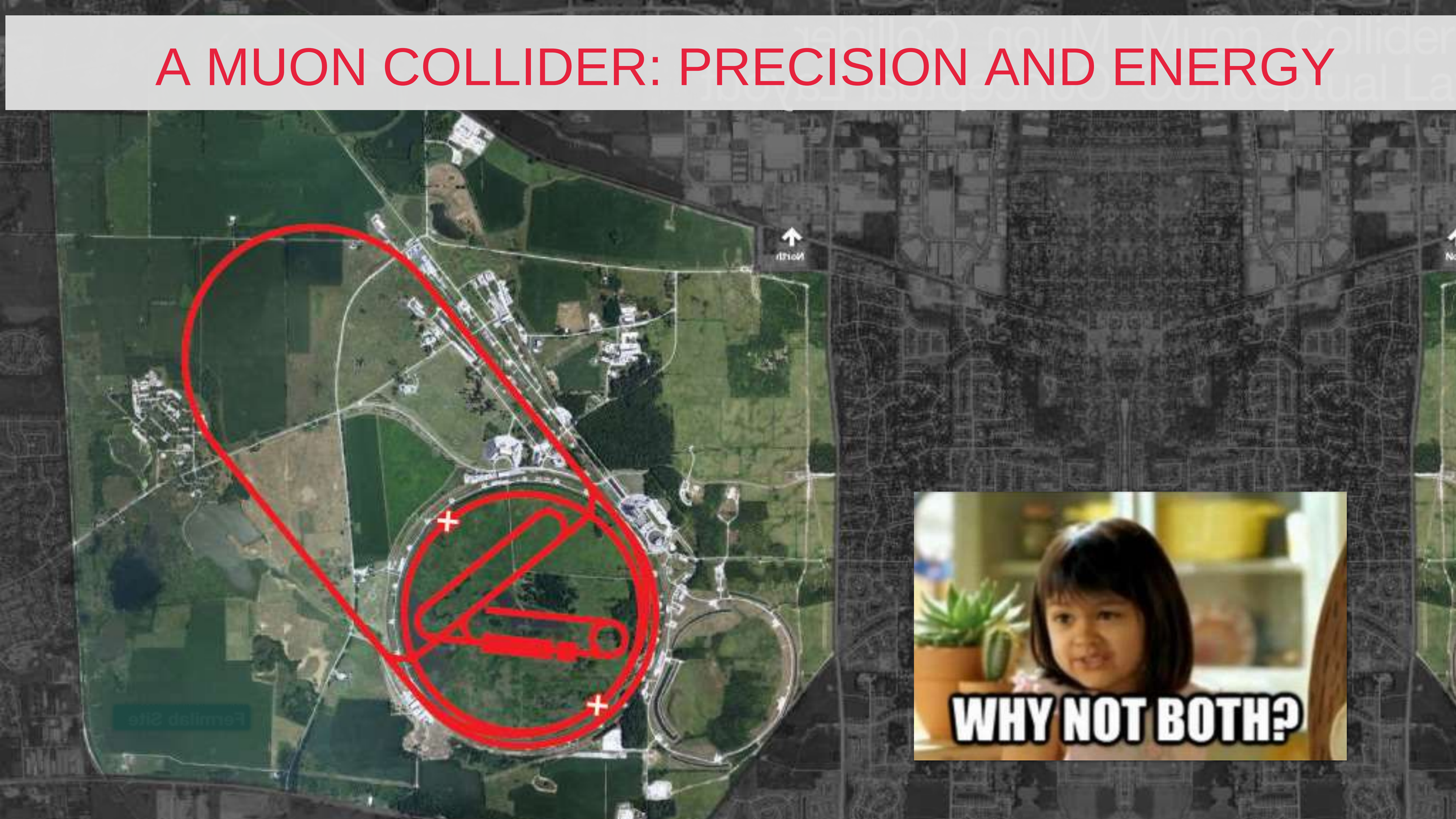
Possible scenario for ECFA

1) Start with ILC
   - Mature technology

2) Upgrade with new technology
   - CLIC ?
   - C^3 ?
   - Wakefield?



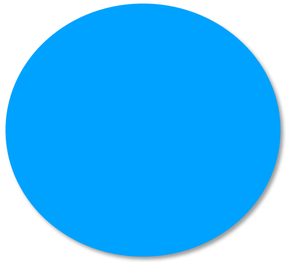
A MUON COLLIDER: PRECISION AND ENERGY



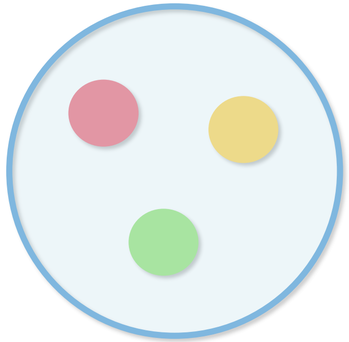
THE BEST OF BOTH WORLDS!

$\mu^+\mu^-$

m_e = 0.5 MeV



m_μ = 106 MeV



m_p = 938 MeV

✓ Precision physics

✓ And high energy

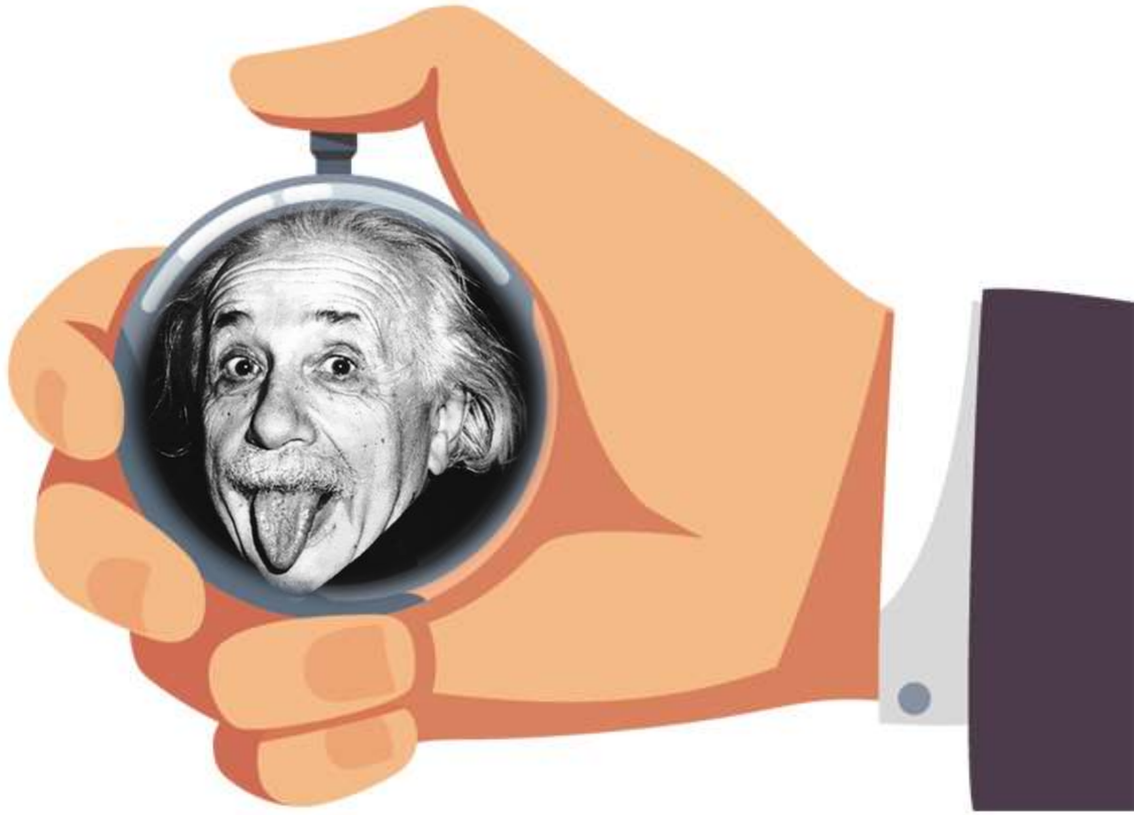
MAIN CHALLENGE

The main challenge:

- Finite lifetime
  - $\tau_\mu = 2\mu s$

Example: 5 TeV muon

- $\gamma = 50{,}000$
  - $\gamma\tau_\mu \sim 0.1s$
- $\gamma c\tau_\mu = 3 \times 10^7 m$
  - 1000 x LHC!

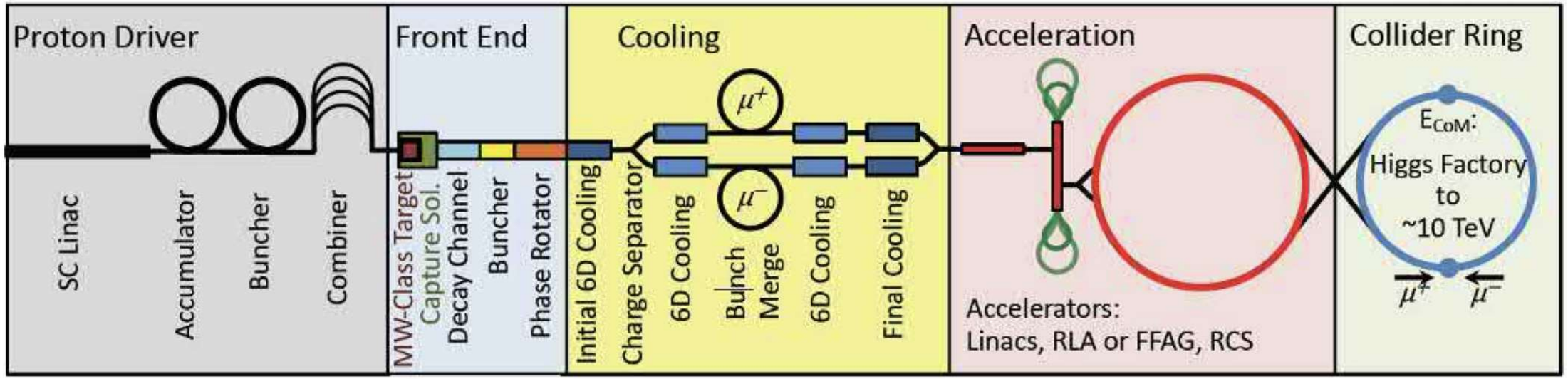


“Een echte muoncollider-fysicus kan niet zonder gamma”

MUON COLLIDER: SCHEME

In 0.1s

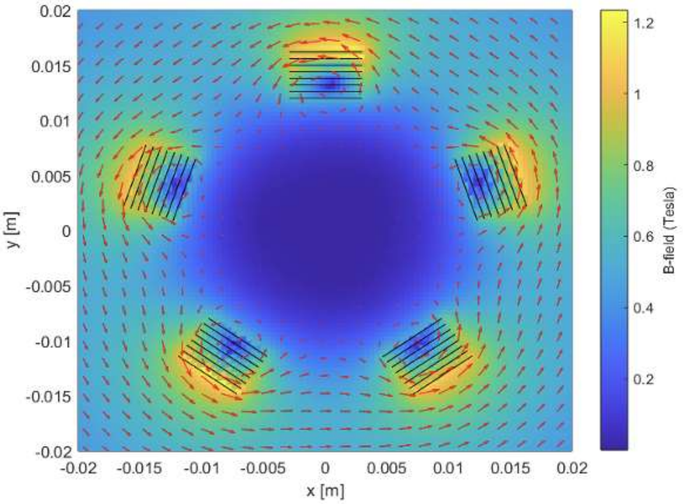
Approach: p → π → μ → cool → accelerate → collide



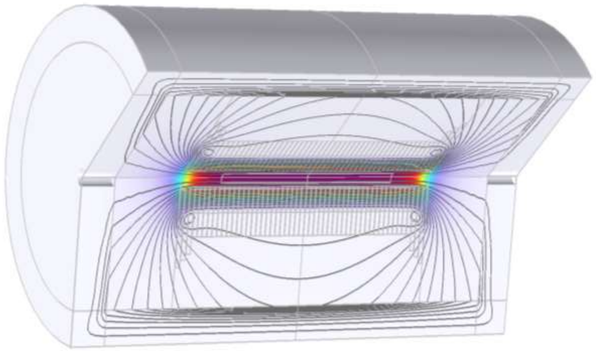
Various exciting challenges for accelerator technology

ACCELERATOR TECHNOLOGIES

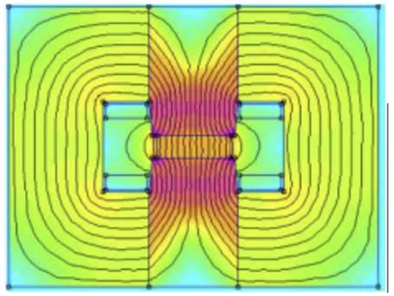
ReBCO cable magnetic field profile

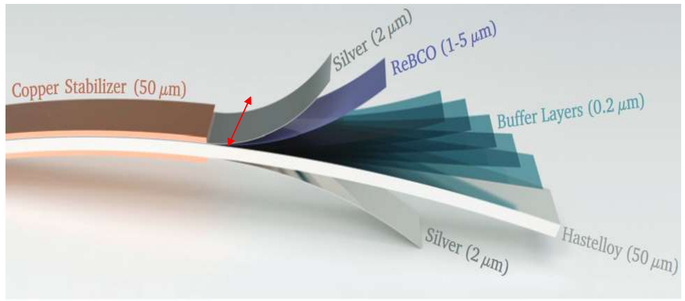


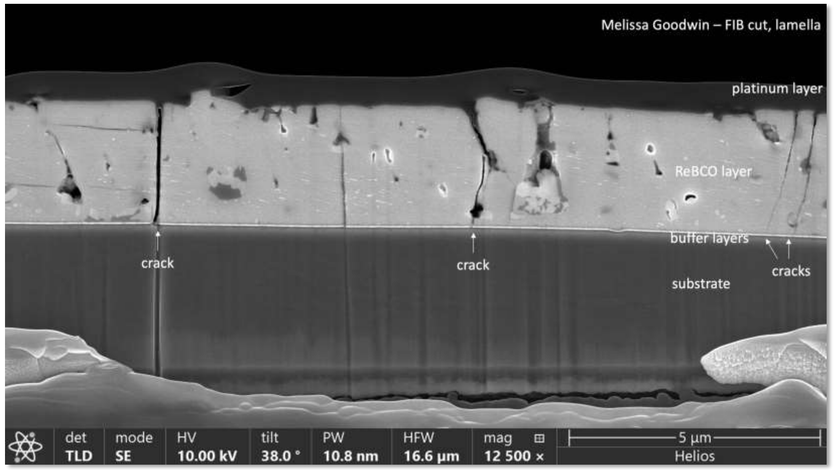
$B_{max} \approx 55$ T



H-type





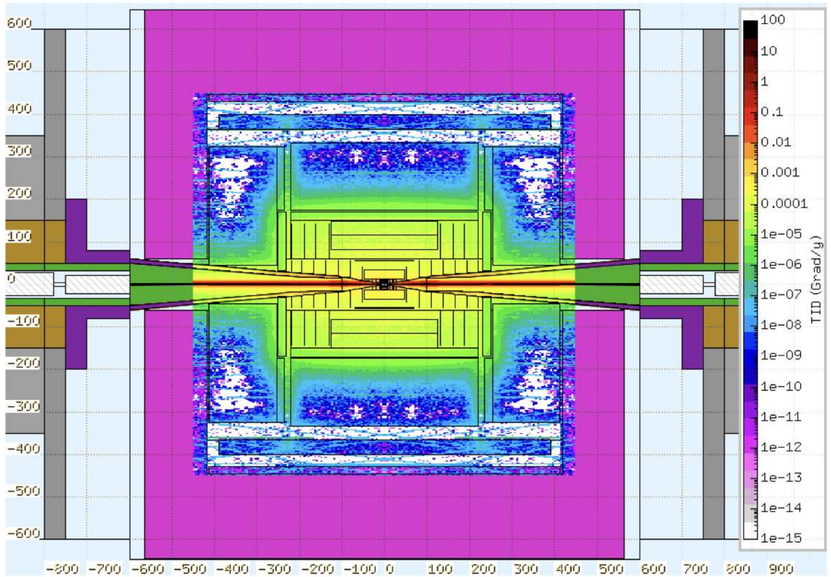


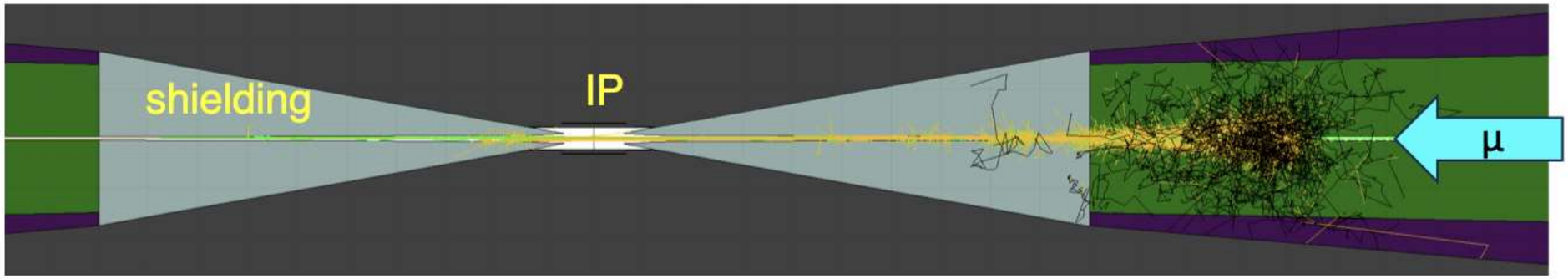
University of Twente

MUON COLLIDER: DETECTOR CHALLENGE

Beam Induced Background

- Muon decays
  - 5TeV: 10^5 muon decays/m
- Secondary products
  - In detector and in accelerator!





F. Collamati et al. 2021 JINST 16 P11009

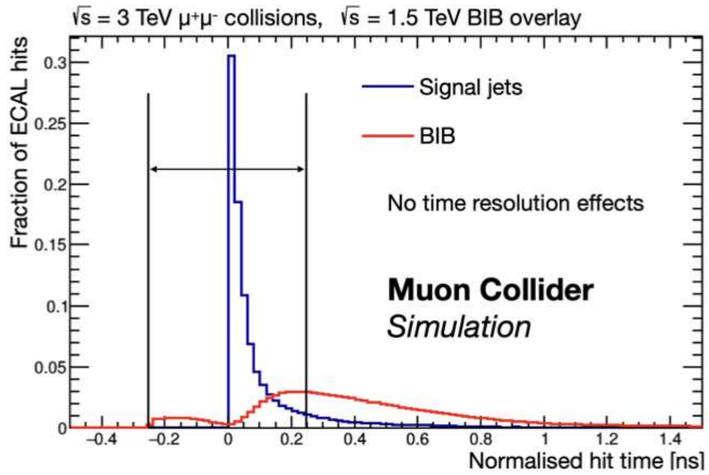
Single muon decay tracks

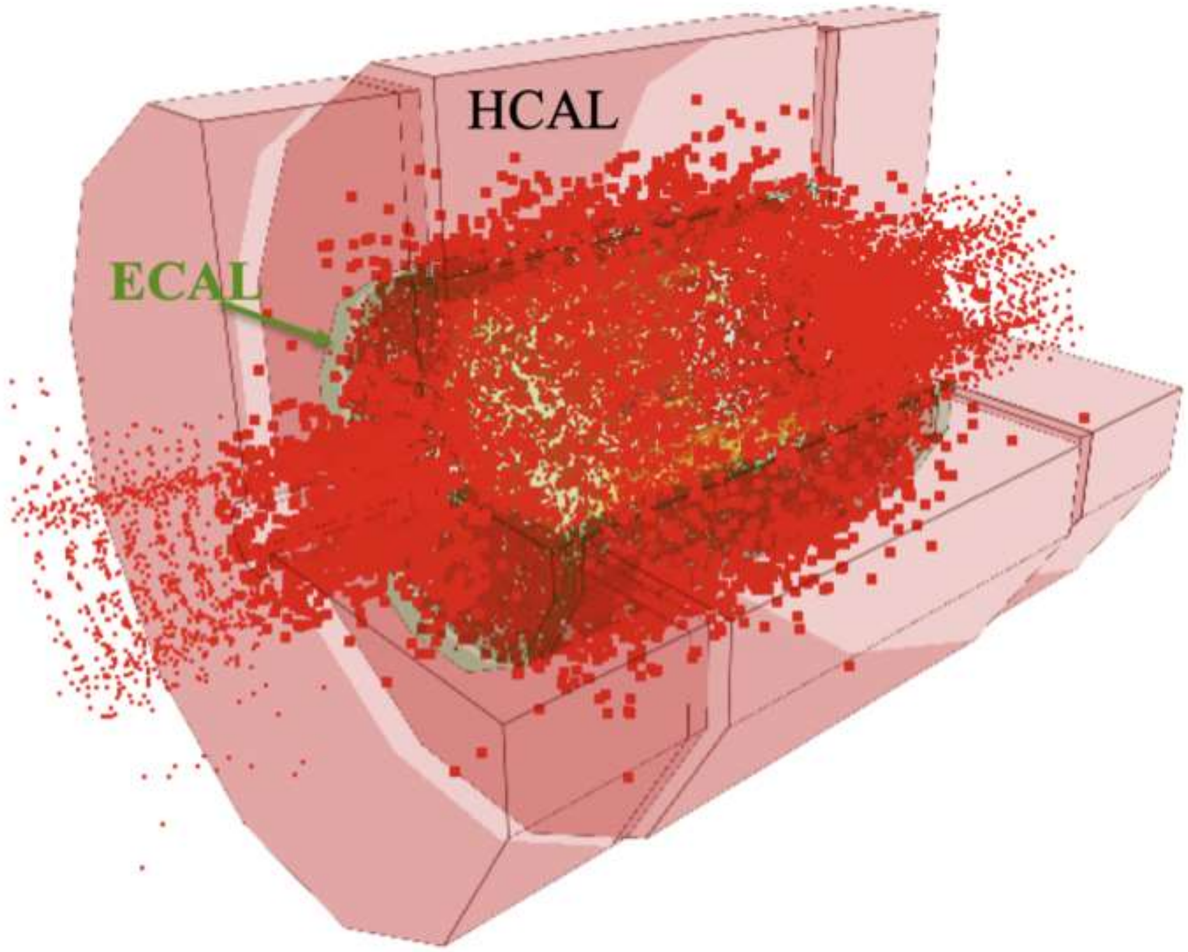
$N_{\mu}^{\pm} \sim 2x10^{12}$/bunch

MUON COLLIDER: DETECTOR TECHNOLOGY

Main challenge: ‘BIB’

- Detector designs ongoing
  - Trackers & calorimeters
  - Crucial solution: timing

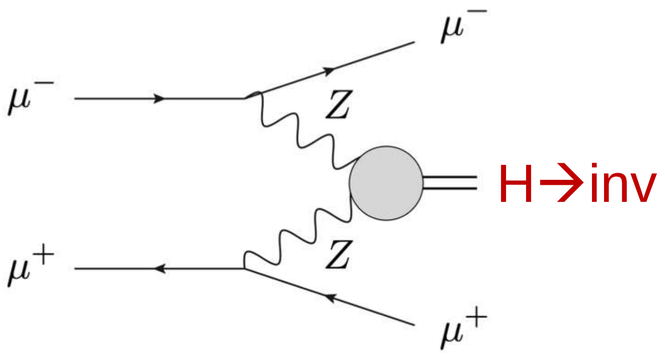




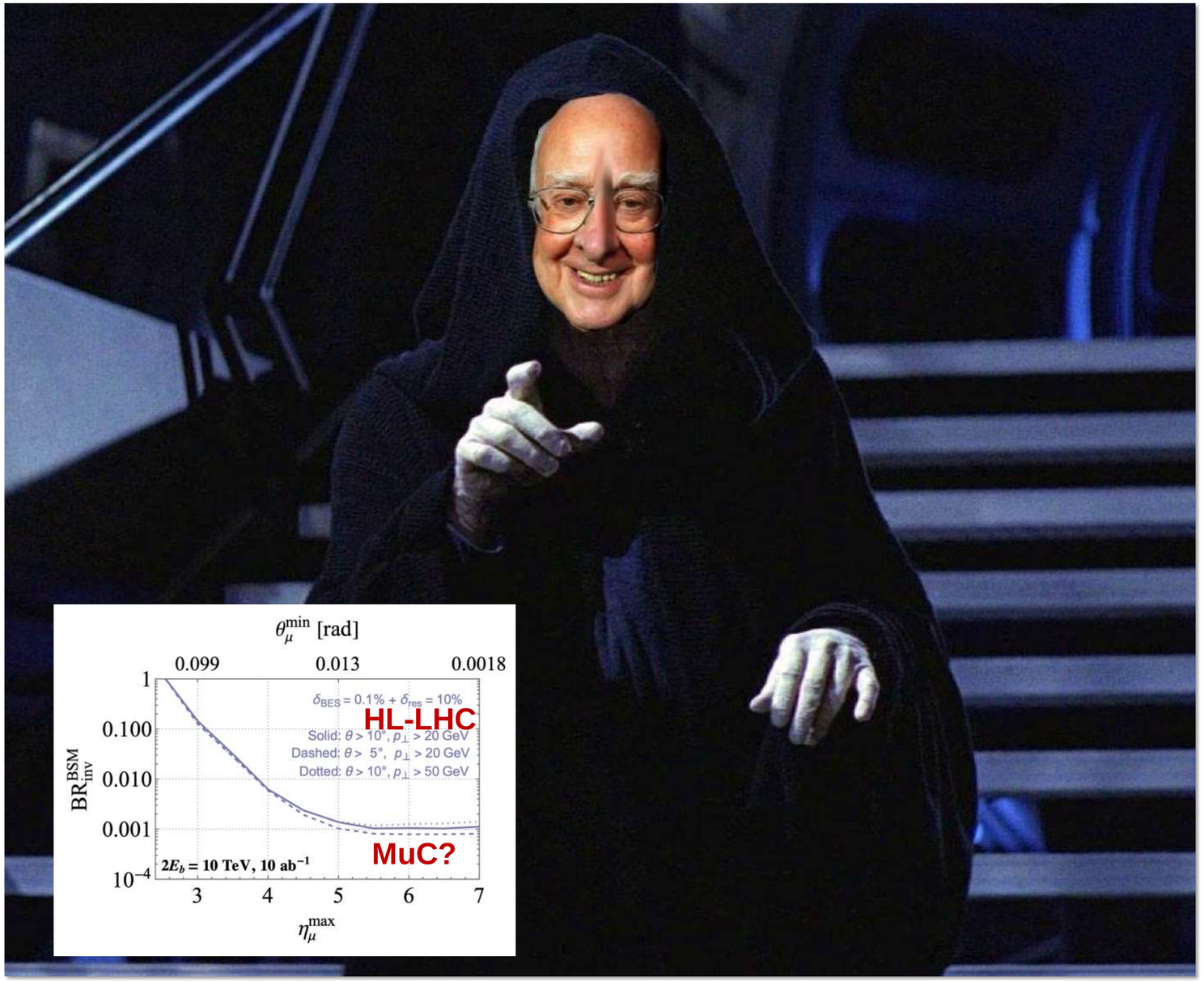
MUCOL PHYSICS

Ex: H→invisible

- Studies still needed
  - Higgs vs Dark Matter?



Important at future colliders

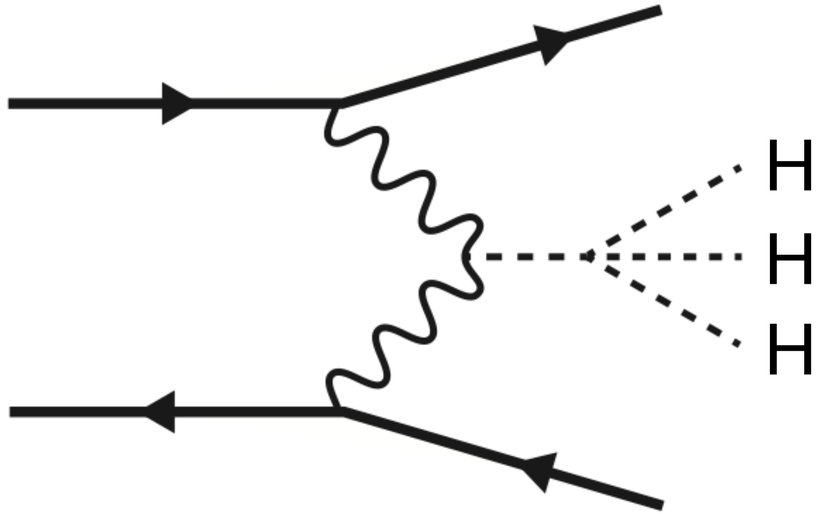


MUON COLLIDER

E.g. HHH at MuCol

- Backgrounds
- Simulation
  - Work needed for muon collider studies

$$V = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v}(1 + \delta\kappa_3) H^3 + \frac{m_H^2}{8v^2}(1 + \delta\kappa_4) H^4$$

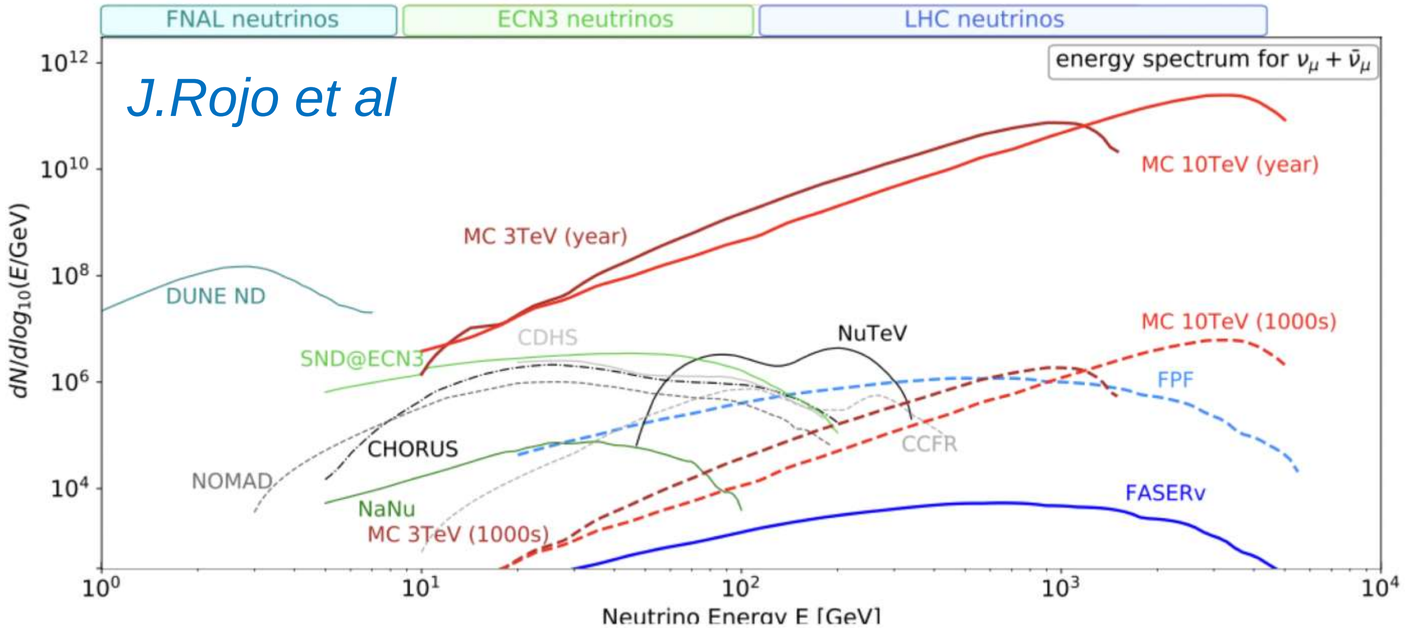


ATLAS publication in the works!

NEUTRINOS AS COLLIDER SPIN-OFFS

Muon collider as source for additional research

- Neutrino physics
  - Use flat sections
  - Short baseline



Neutrinos at muon collider

- https://inspirehep.net/literature/2808571

Faser-like at FCC-hh

- https://inspirehep.net/literature/2824738

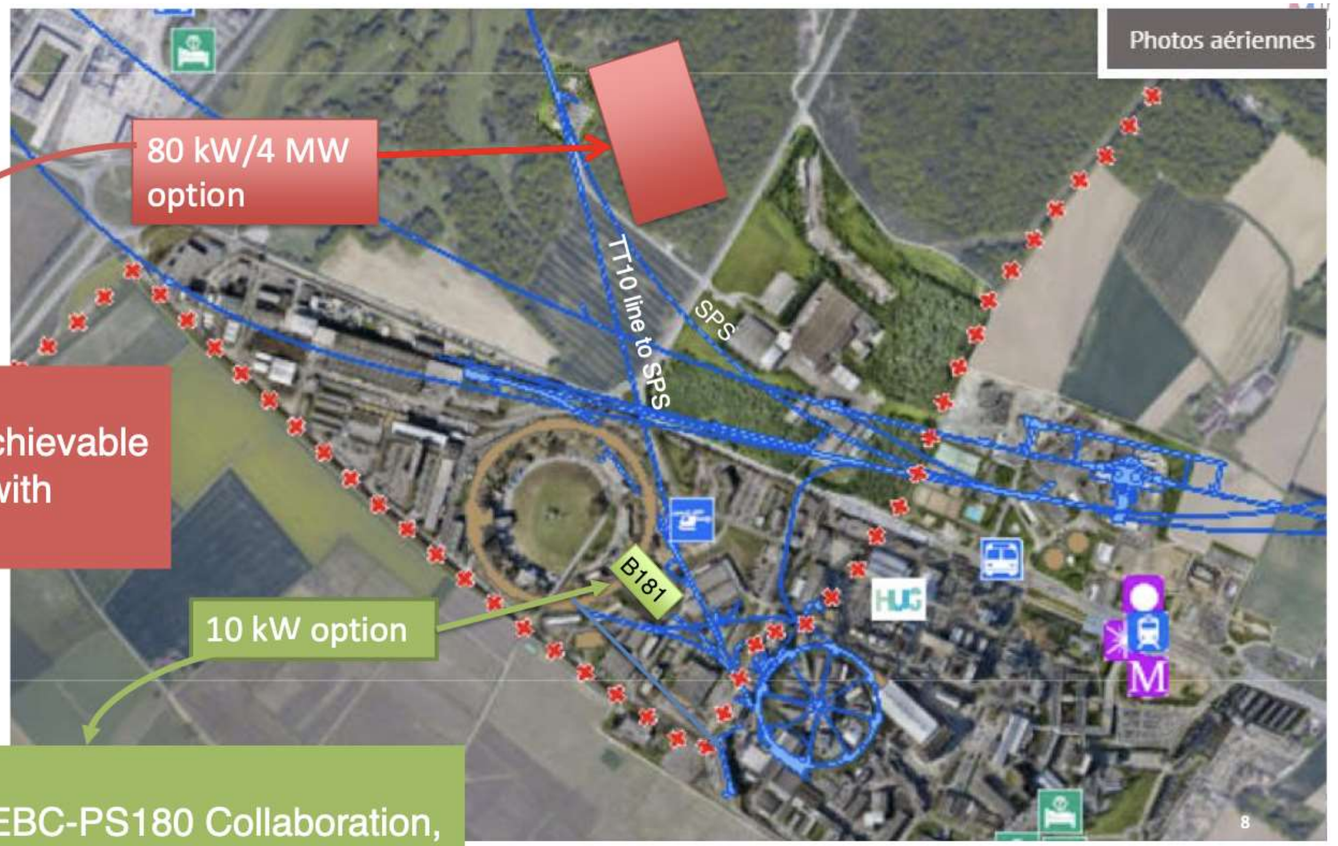
PLANS FOR A MUON COLLIDER DEMONSTRATOR

D.Lucchesi, for the IMCC – 17 Oct 2023 at CERN

At CERN site?

Both use maximum intensity per pulse ~10^{13} ppp (or more) in pulses of few ns at 20+ GeV.
Different repetition rate:

- 1 pulse/few second
- 1÷2 pulse/per minute



High power
O(80kW) on target easily achievable
No showstopper for 4 MW with beam at a depth of 40 m

Low power:
Reuse line of BEBC-PS180 Collaboration, decommissioned, extending it towards B181 (now magnet factory)

NIKHEF STATUS TOWARDS FUTURE COLLIDERS

ESUPP

- CERN Council
  - NL representation
- European strategy update
  - Voice your opinion!

At Nikhef

- Future collider activities
  - Clara, Patrick, Wouter
- Colloquia, topical lectures, etc

Future collider research

- ILC, C3, FCC, MuCol
  - Case-by-case basis

Actual science

- No clear structure (yet)
  - Research suggestions on next pages

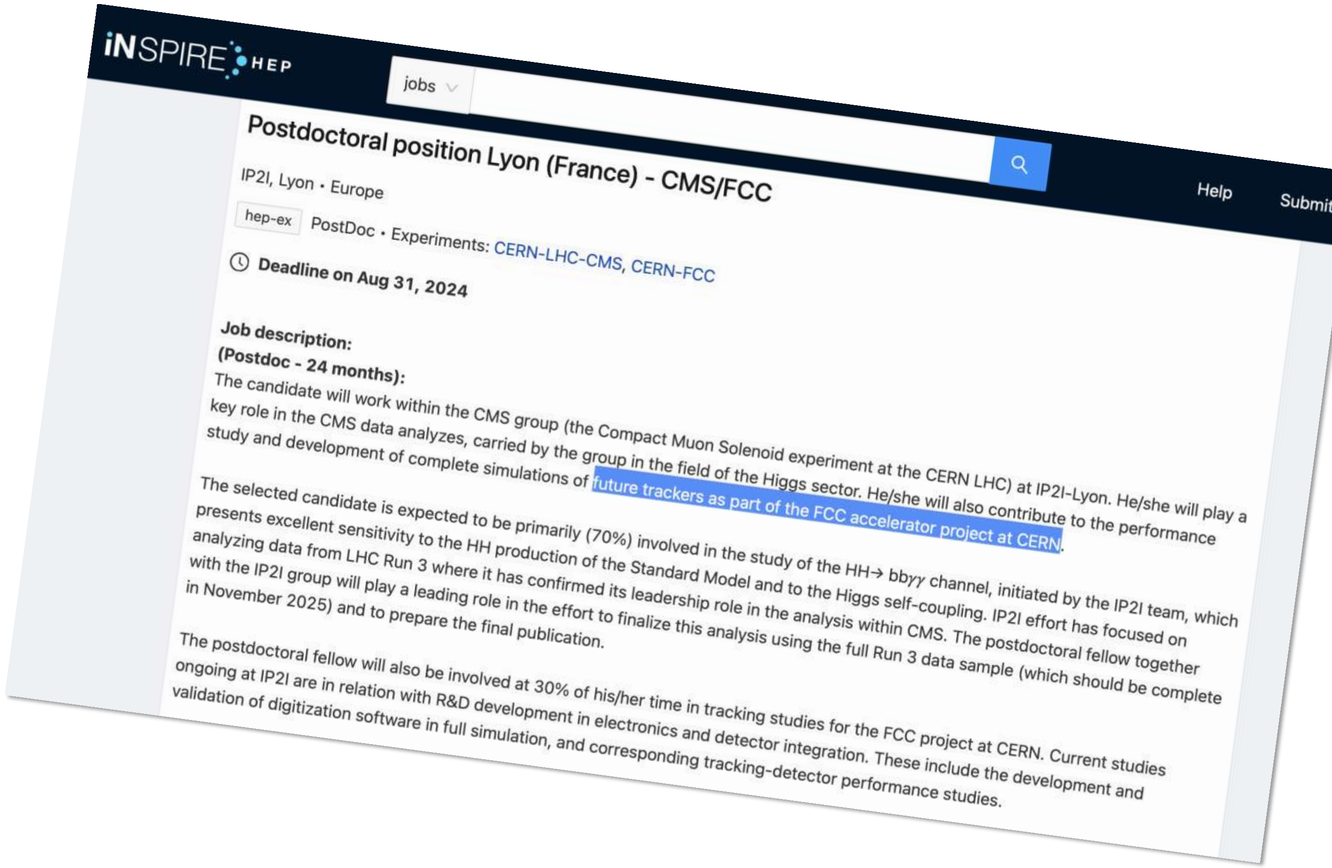
WHY YOU SHOULD GET INVOLVED

It’s exciting & interesting

- I hope ;-)

It’s important

- For CERN
- For the field
- For your next job
  - Postdoc / staff



SOME IDEAS

Higgs physics

- H→cc, H→ss, H→gg
  - c-/s-/g-tagging
- H→invisible
- ee→H
- HH and HHH
  - Boosted tagging

Other physics

- EWK, ttbar?
- B-physics at Z→bb?

My advice: do something
- New / exciting
- Low-hanging fruit
- Exploit ongoing activities

NB: The ‘right’ choice also depends on the stage of the project

SOME IDEAS

Higgs physics

- H→cc, H→ss, H→gg
  - c-/s-/g-tagging
- H→invisible
- ee→H
- HH and HHH

Other physics

- EWK, ttbar?
- B-physics at Z→bb?

Theory/combinations

- Higgs self-coupling
- SMEFT, NLO, jets
- BSM, Dark Matter

Technology

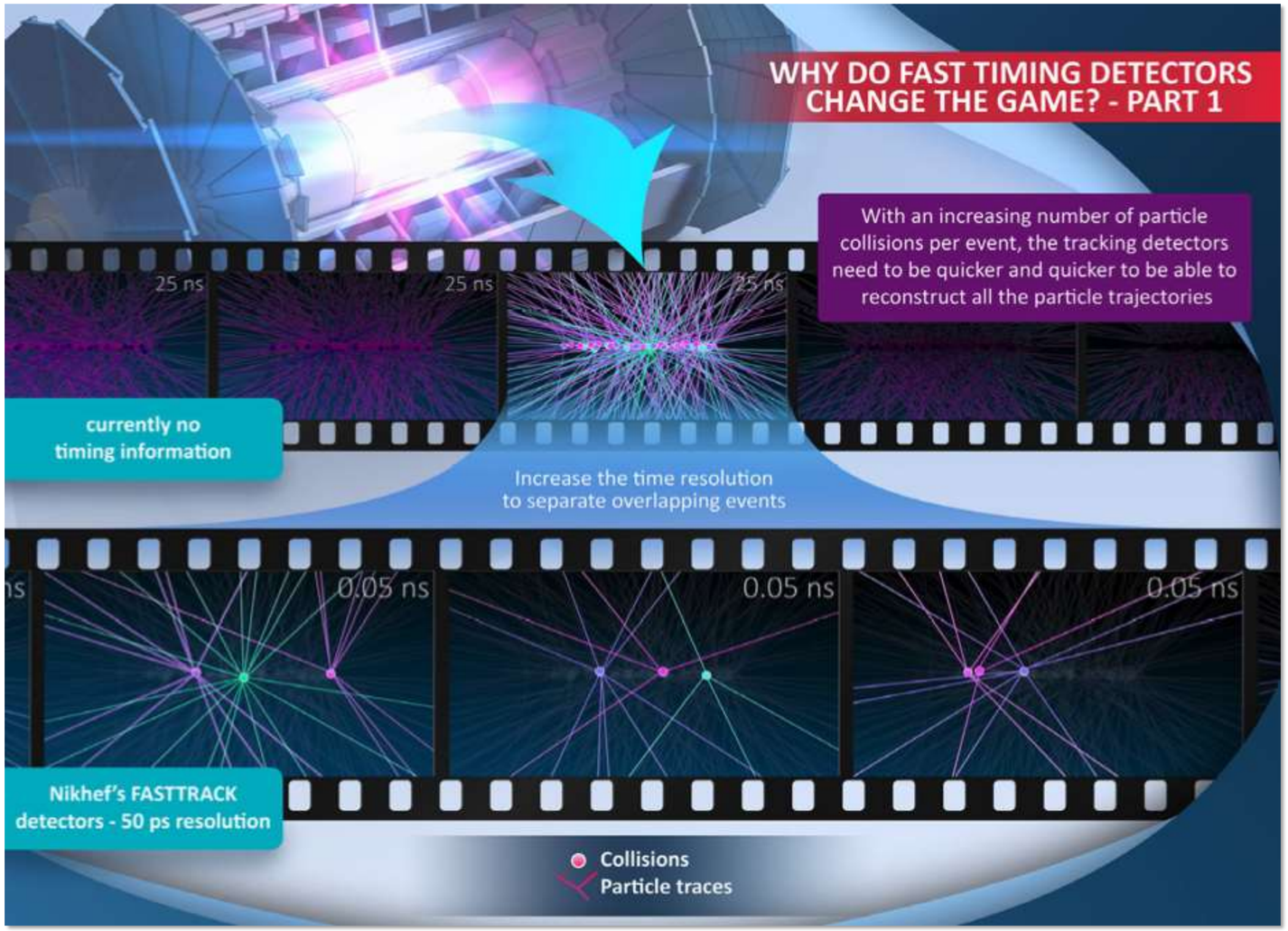
- Detector R&D – e.g. timing
- Reconstruction – e.g. calorimetry
- Accelerators, sustainability
- AOB, e.g. alignment

DETECTOR R&D

Nikhef: emphasis on “timing”

- In view of HL-LHC
  - Upgrades for Run-4+
- Also very relevant for future colliders
  - Out-of-time pileup
  - Beam-induced backgrounds

Nikhef grant proposal for HL-LHC detector upgrades



IT’S MORE THAN JUST PHYSICS!

Physics

+Society

+Money

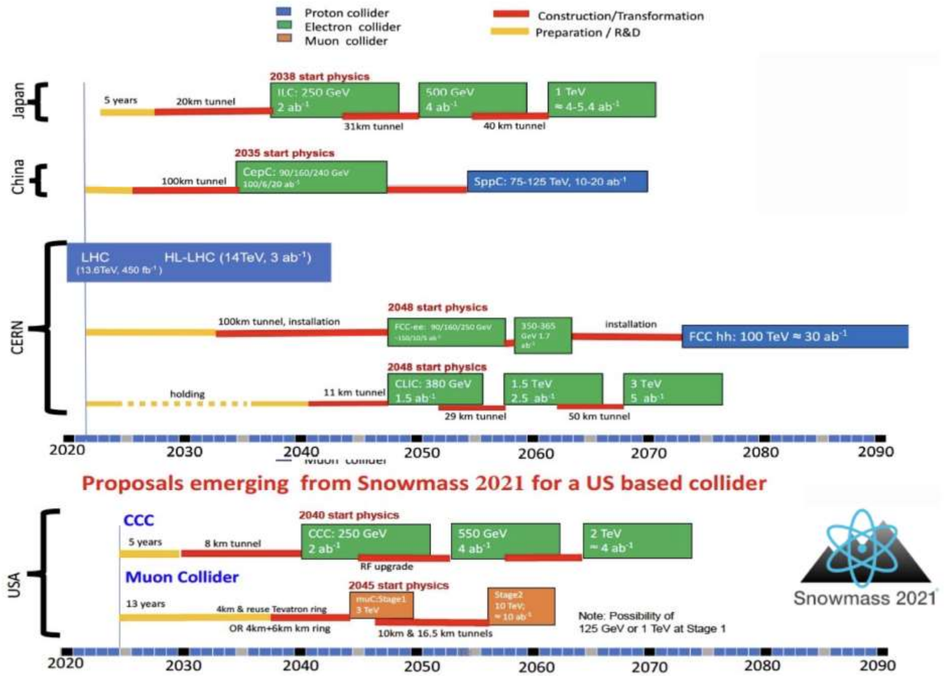
+Time

+R&D

+…

Project Cost (no esc., no cont.)	4	7	12	18	30	50
FCCee-0.24						
FCCee-0.37						
FNAL eeHF						
ILC-0.25						
ILC-0.5						
CLIC-0.38						
CCC-0.25						
CCC-0.55						
CERC-0.24						
CERC-0.6						
ReLiC-0.25						
ERLC-0.25						
MuColl-0.125						
XCC-0.125						

Figure 8. The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.



MY RECOMMENDATION TO YOU

It might be challenging to work on future colliders, since you already have to:

- Do your LHC analysis
- Work on reconstruction/software
- Detector upgrade & operation
- Maybe some HL-LHC projection
- And also some theory interpretation
  - Plus all the schools, courses, etc…

And then future colliders is at the end of the list…

- But I think you should try!

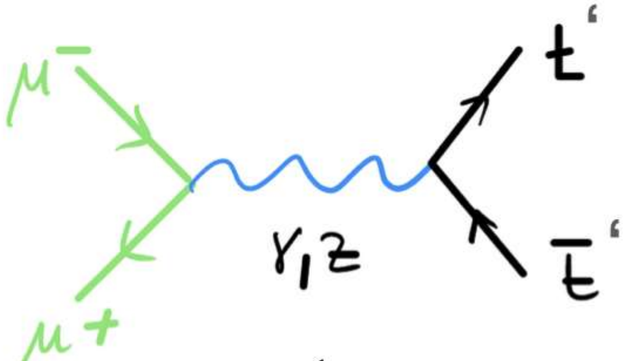
JOIN THE ADVENTURE TOWARDS THE NEXT ESUPP!

NPO2 with Diederik Jekel, 13 April 2022

4 July 2012

MUCOL PHYSICS

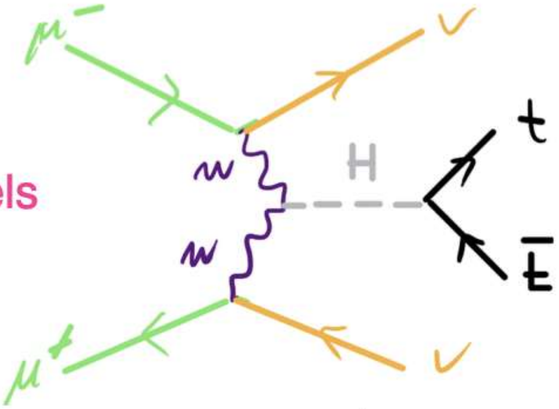
Multi-TeV collider: Higgs precision and Searches



$$\sigma \sim \frac{1}{s}$$

Energetic final states
(heavy particle or very boosted)

Different physics can be probed in the two channels

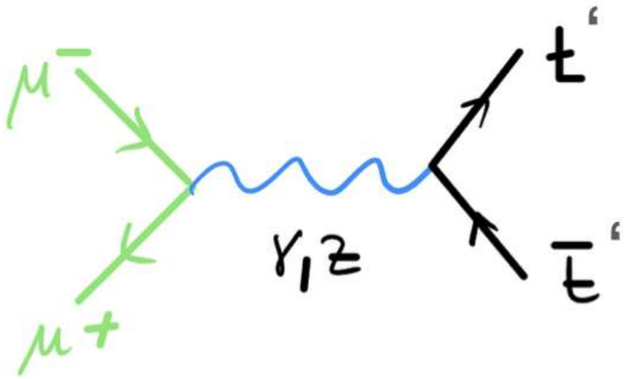


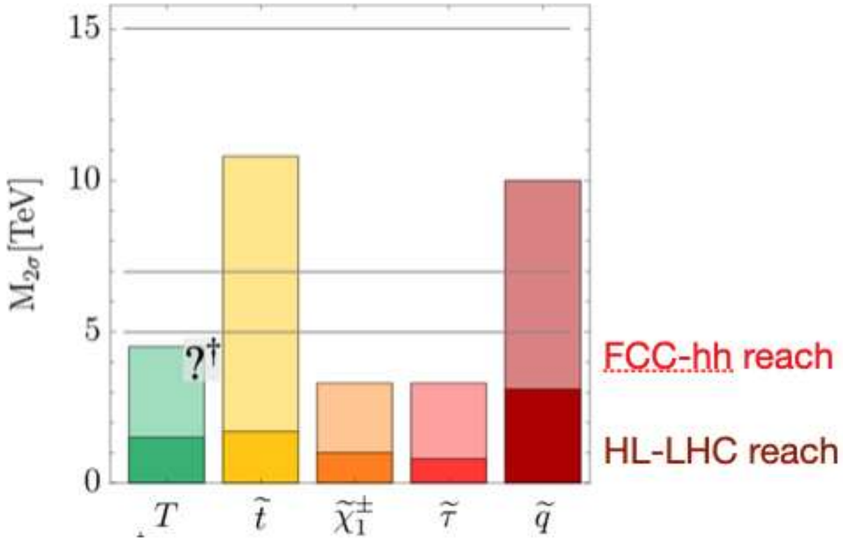
$$\sigma \sim \frac{1}{M^2} log^n \frac{s}{M}$$

Standard Model coupling measurements
Discovery light and weakly interacting particles

MUCOL PHYSICS

Multi-TeV collider: Higgs precision and Searches

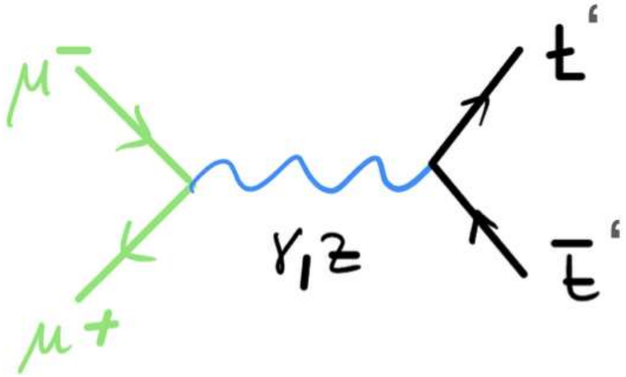


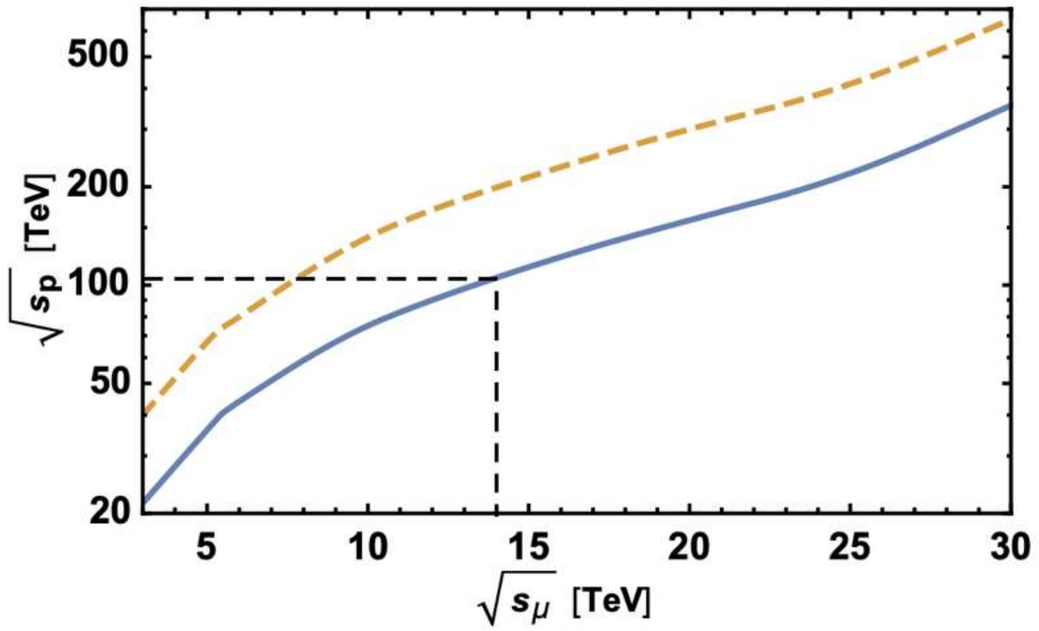


BSM direct reach in similar ballpark as FCC-hh!

MUCOL PHYSICS

Multi-TeV collider: Higgs precision and Searches



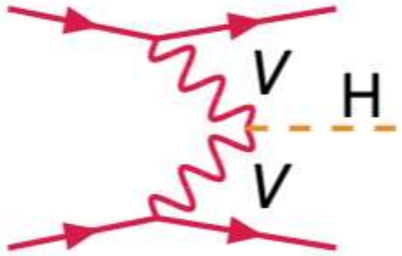


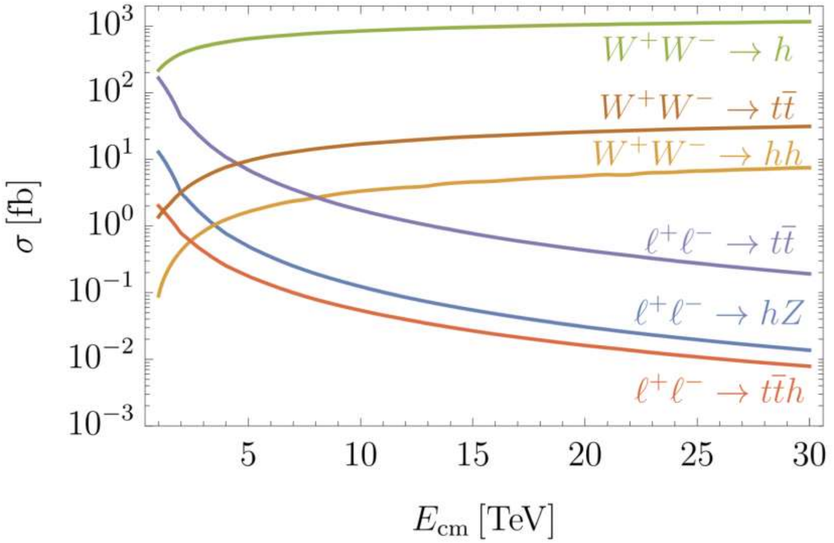
BSM direct reach in similar ballpark as FCC-hh!

MUCOL PHYSICS: HIGGS

VBF-H production increases with energy

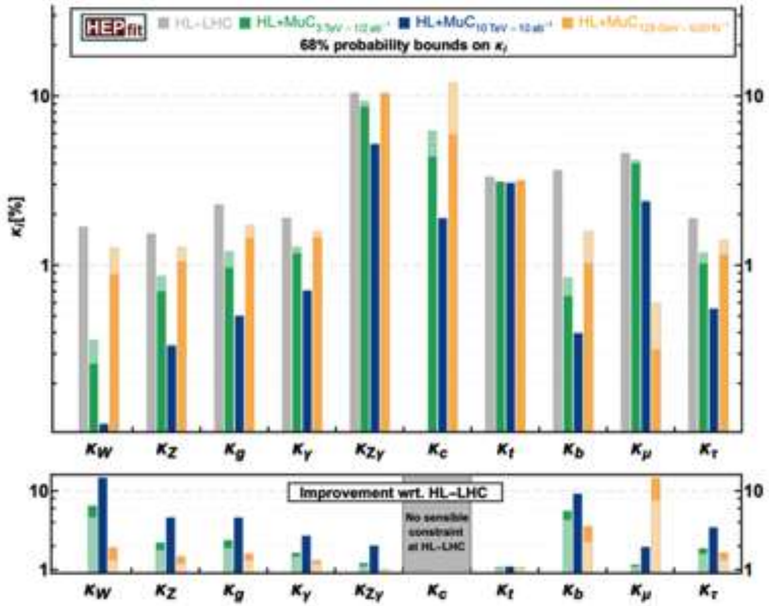
- 10/ab @ 10 TeV
  - 10,000,000 single-H





Sizable sensitivity improvement

- K_W, K_Z, K_g, K_c, K_b, K_μ, K_τ,…
  - Comparable to (other) Higgs factories!



HH @ MUCOL

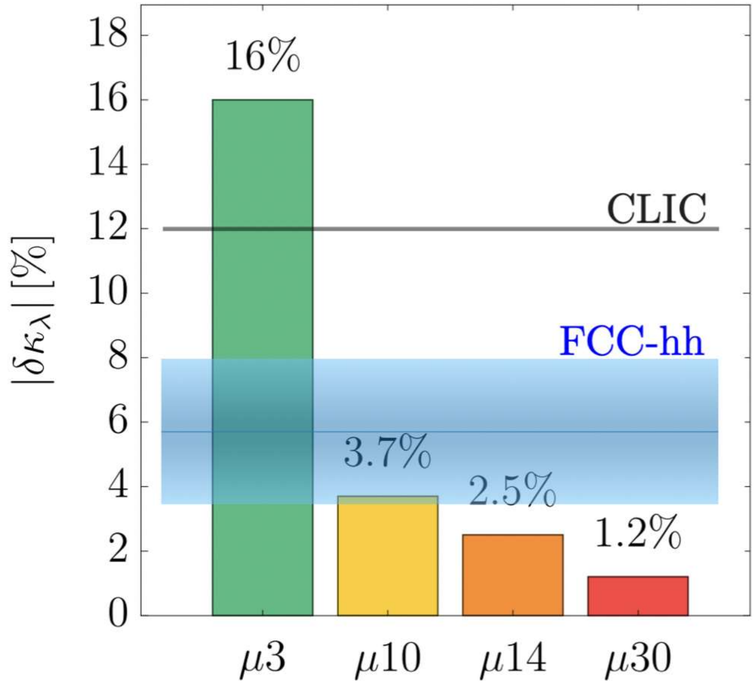
Self-coupling from HH

- 10/ab @ 10TeV
  - 30,000 VBF-HH

$$V = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v}(1+\delta\kappa_3) H^3 + \frac{m_H^2}{8v^2}(1+\delta\kappa_4) H^4$$

10TeV MuCol

- <5% uncertainty
  on the self-coupling
  - Similar to FCC-hh



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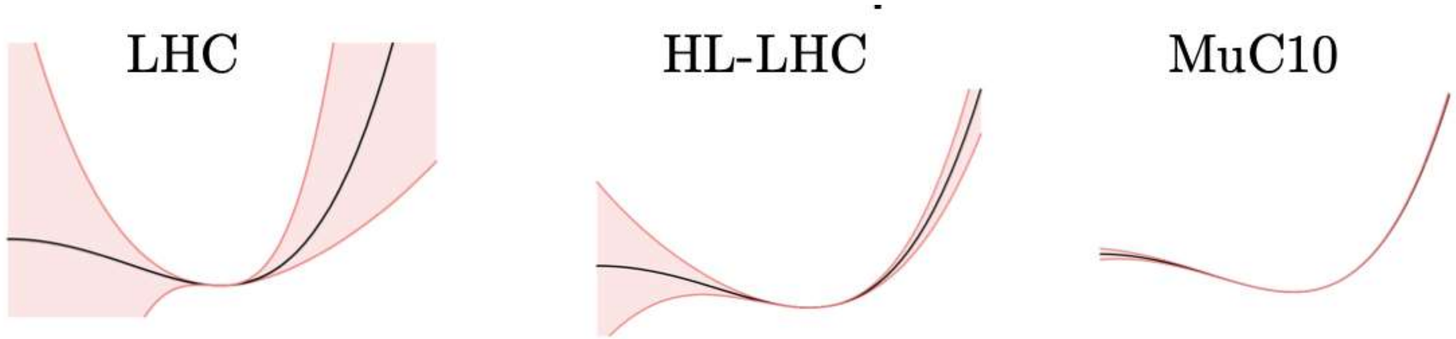


10TeV MuCol

- <5% uncertainty
  on the self-coupling
  - Constrain shape of Higgs potential

HH(H) @ MUCOL

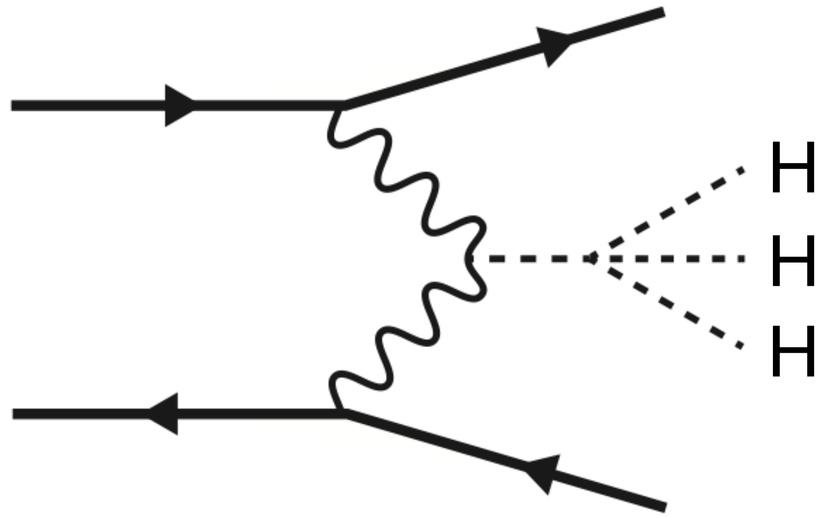
Self-coupling from HH(H)

- 10/ab @ 10TeV

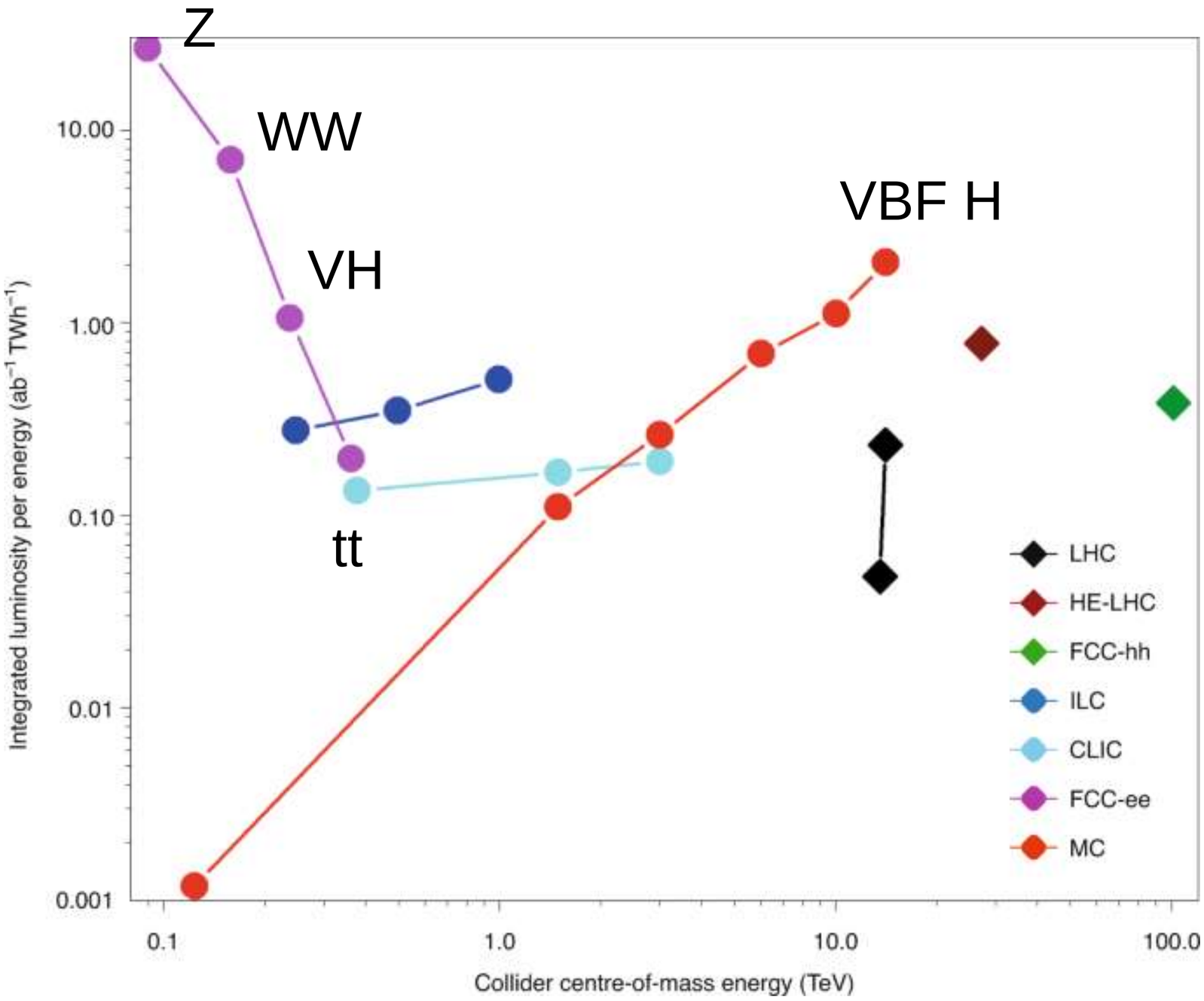
$$V = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v}(1+\delta\kappa_3) H^3 + \frac{m_H^2}{8v^2}(1+\delta\kappa_4) H^4$$

Constrain HH K_3 self-coupling

- Possibly even K_4
  - Unique HHH production

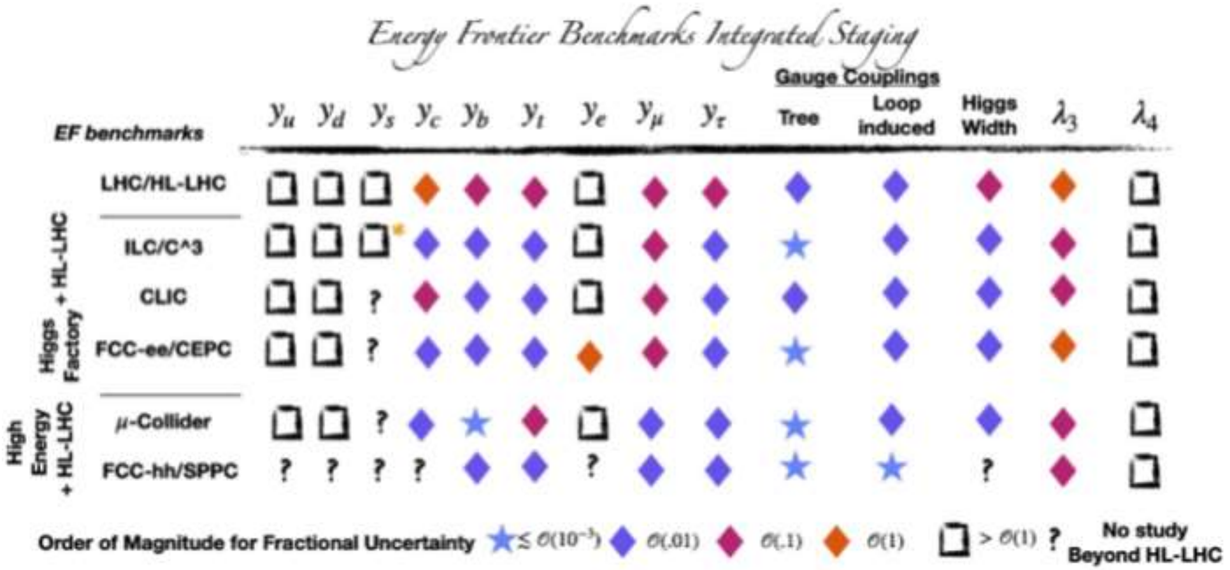


LUMI


Z
WW
VH
tt
VBF H
10.00
1.00
0.10
0.01
0.001
0.1
1.0
10.0
100.0
Integrated luminosity per energy (ab^{-1} TWh^{-1})
Collider centre-of-mass energy (TeV)
LHC
HE-LHC
FCC-hh
ILC
CLIC
FCC-ee
MC

HIGGS PHYSICS SENSITIVITIES SUMMARY

Similar reach in Higgs physics for different future accelerators



➔ The muon collider is a discovery machine and a precision machine!

MUCOL PHYSICS SUMMARY

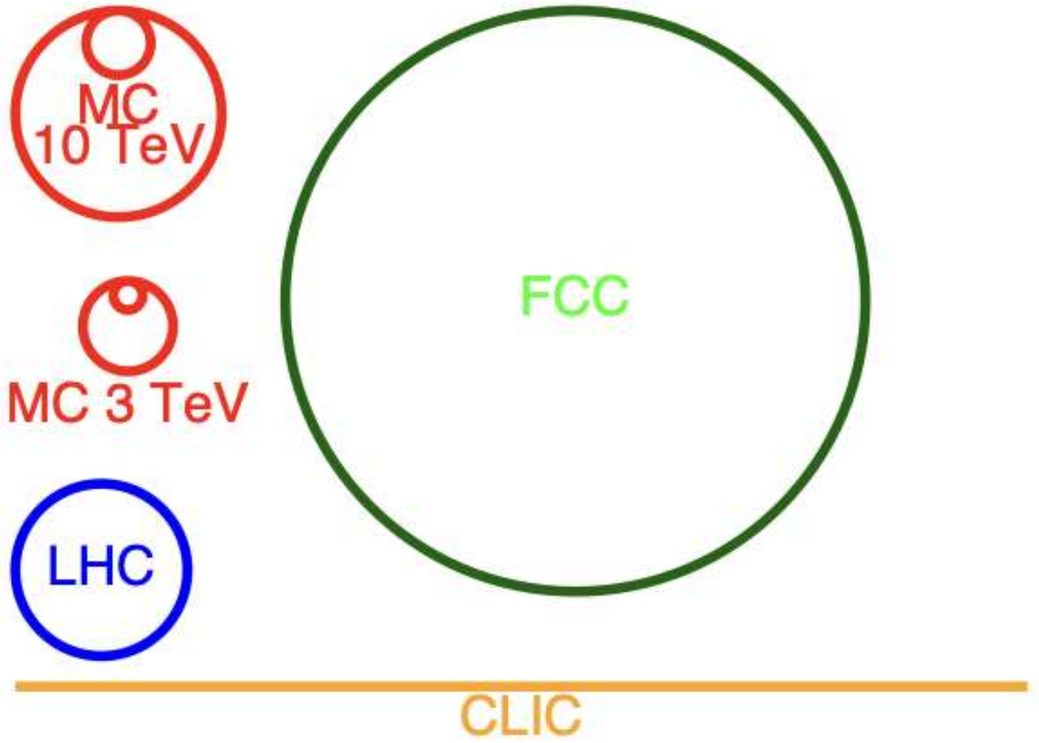
Main physics programme

- Higgs precision
- Higgs self-coupling
- New energy scale

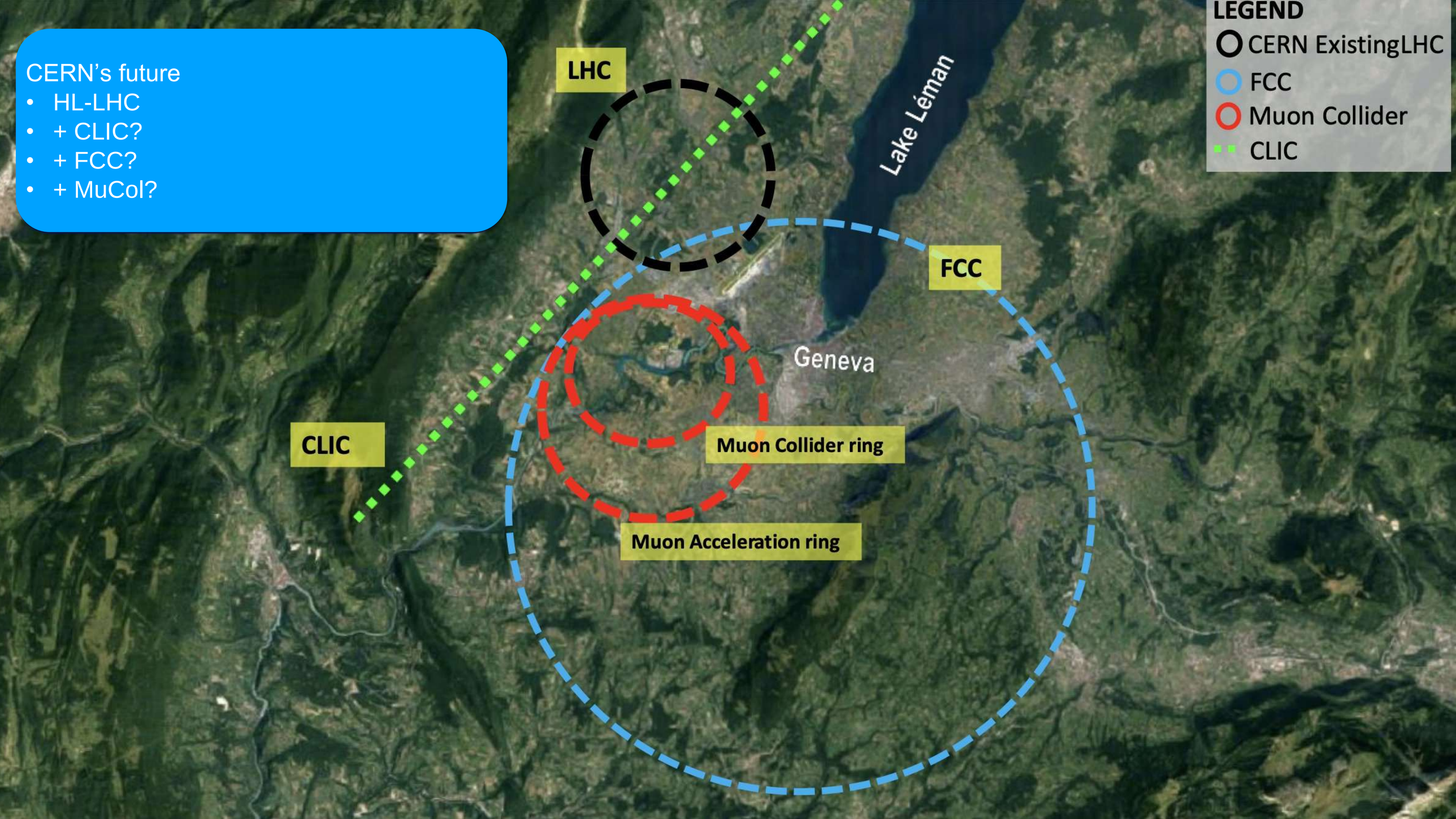
Additional possibilities

- Long-lived particles
- Neutrinos

And it’s compact!



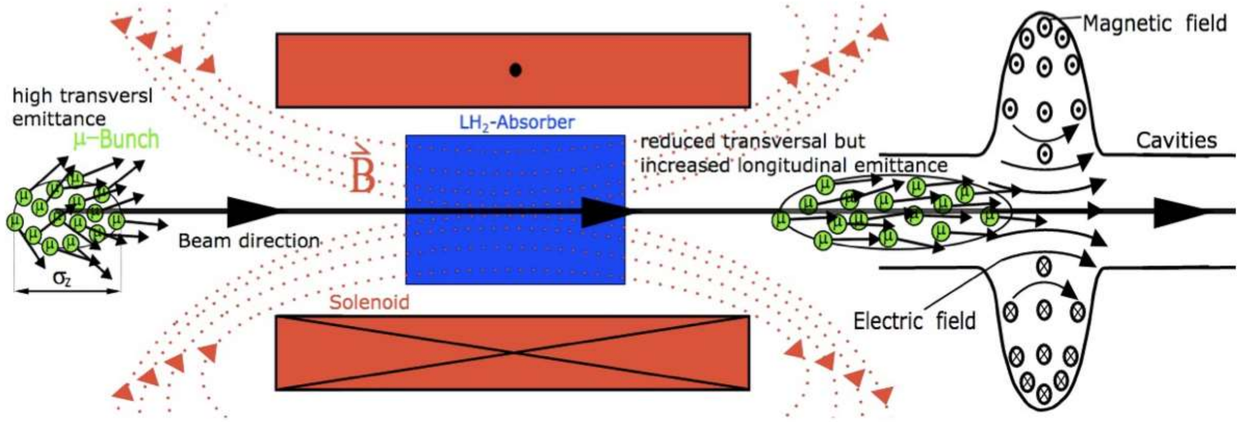
CERN's future
- HL-LHC
- + CLIC?
- + FCC?
- + MuCol?



COOLING

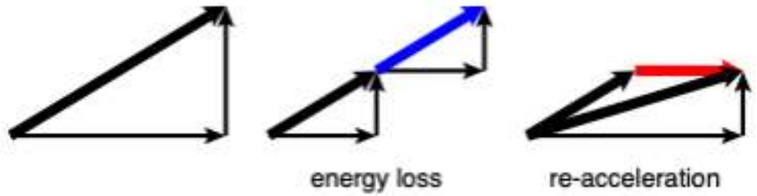
Main challenge

- ‘6D’ ionization cooling



Minimize energy loss:

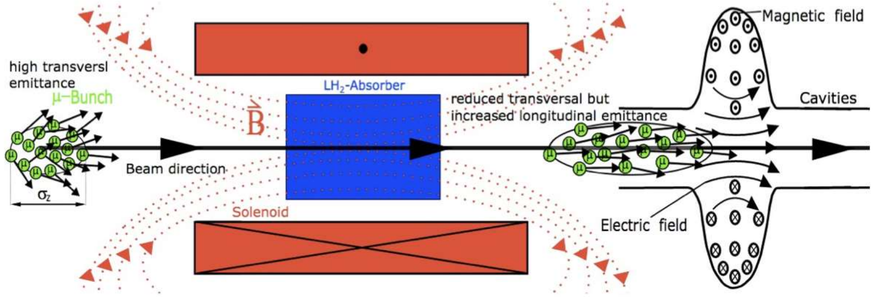
- Low-Z material → LH_2
  - In strong magnetic field



COOLING

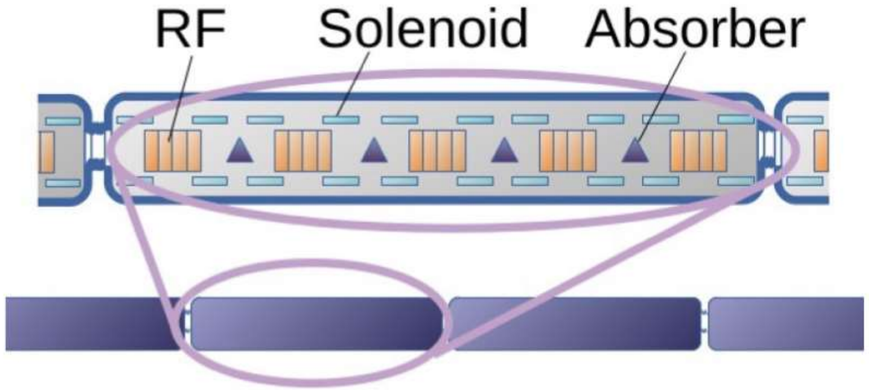
Main goal of demonstrator

- Prove cooling
  - Absorber + magnet + RF



Challenges

- Large bore solenoid
- High gradient RF
- Large intensity absorber
  - All together!



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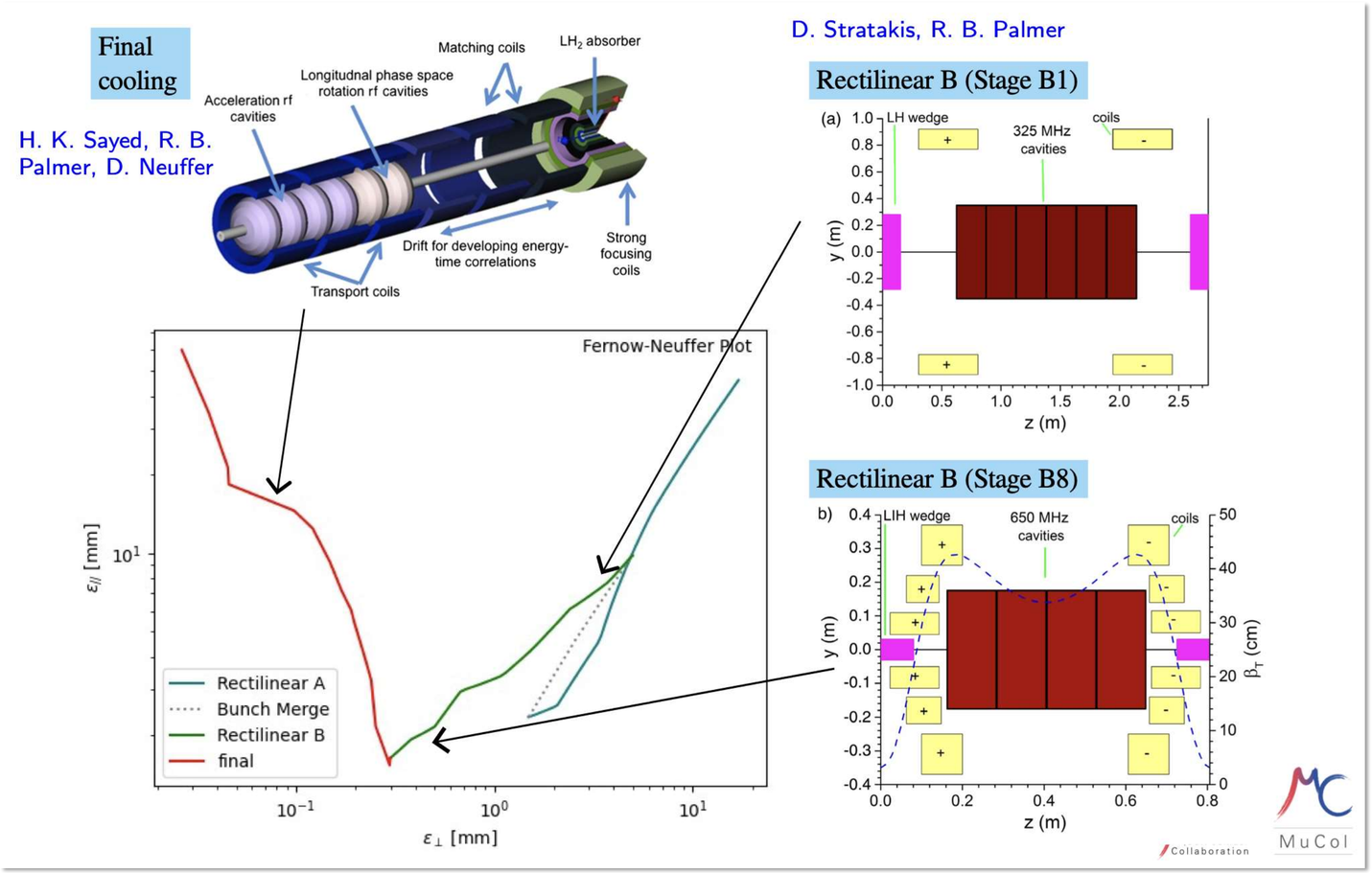
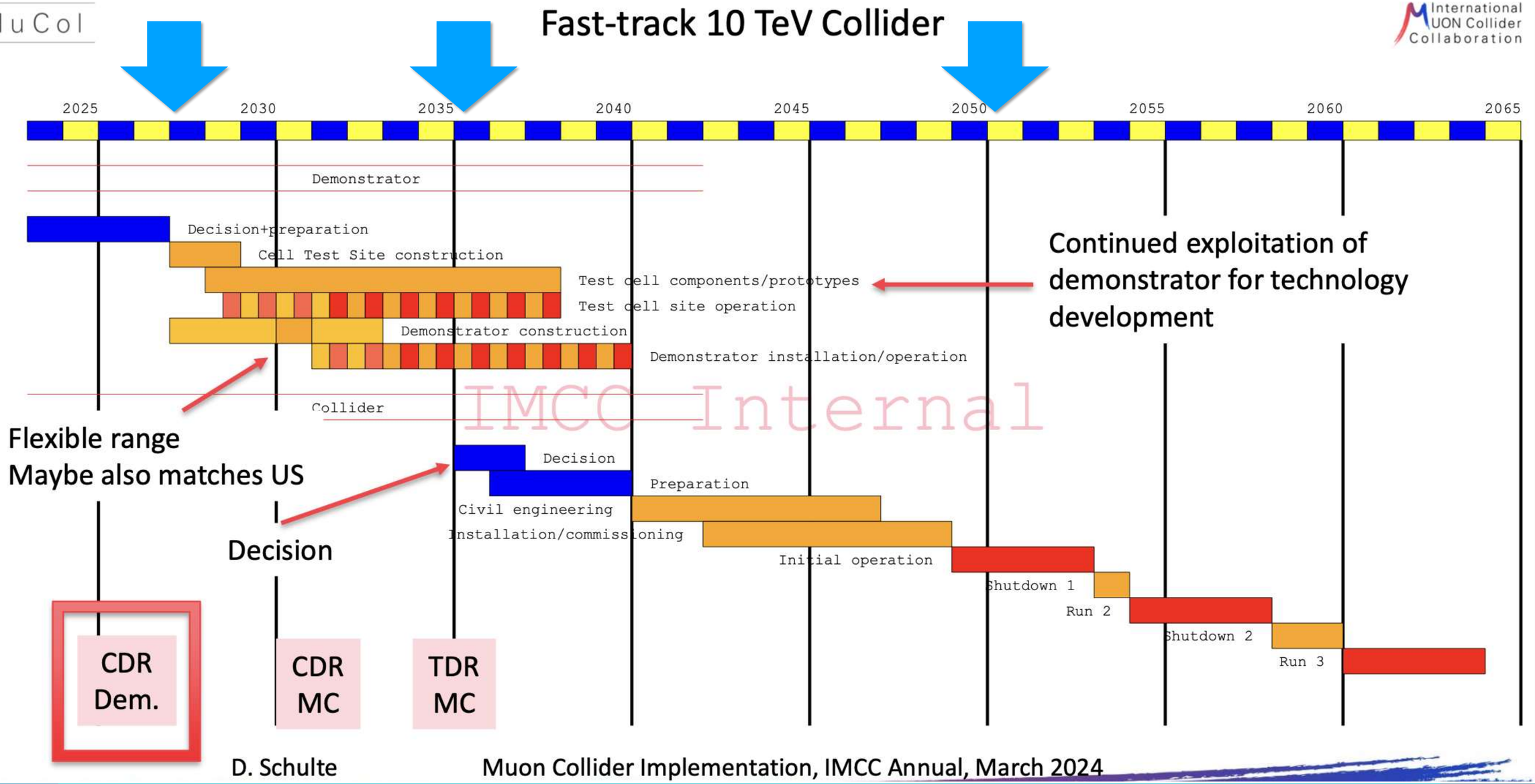


Example Timeline

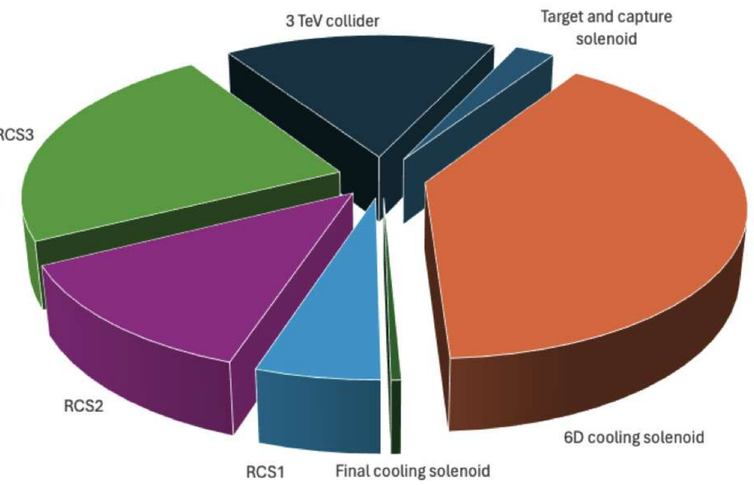


D. Schulte Muon Collider Implementation, IMCC Annual, March 2024

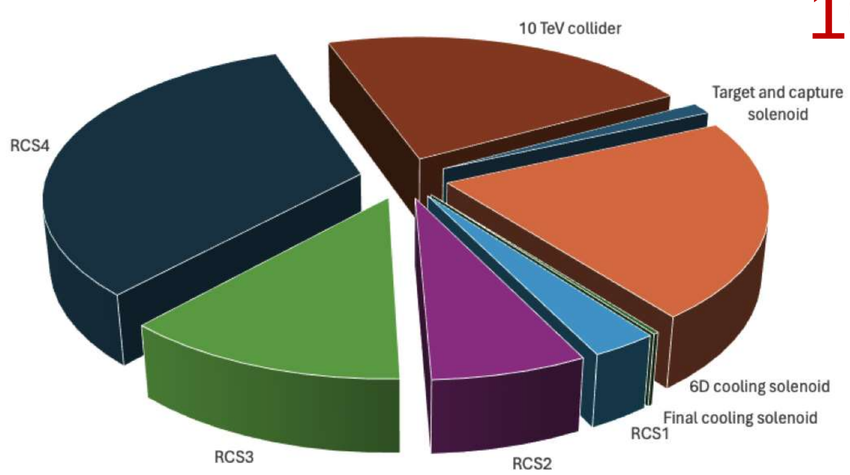
COSTS

Relative costs in MuCol project

3TeV



10TeV



Largest costs in 6D cooling and accelerator (RCS)

- Target, capture, final cooling only small fraction
  - Not dominated by (relatively) small collider

COSTS (1)

125-600 GeV

- Overall: 5-15B$
  - MuC on lower side of spectrum

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

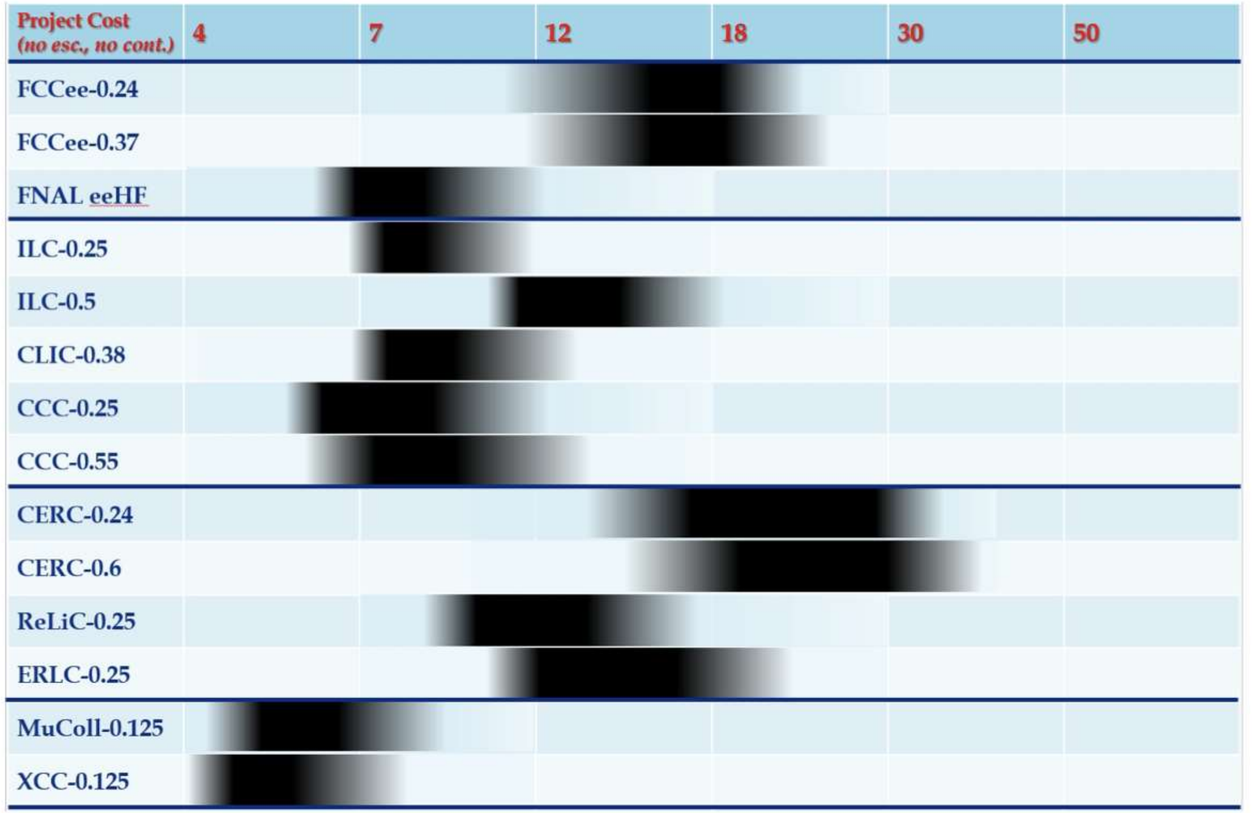


Figure 8. The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

COSTS (2)

1-10 TeV

- Overall: 10-30B$
  - MuC on lower side of spectrum

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

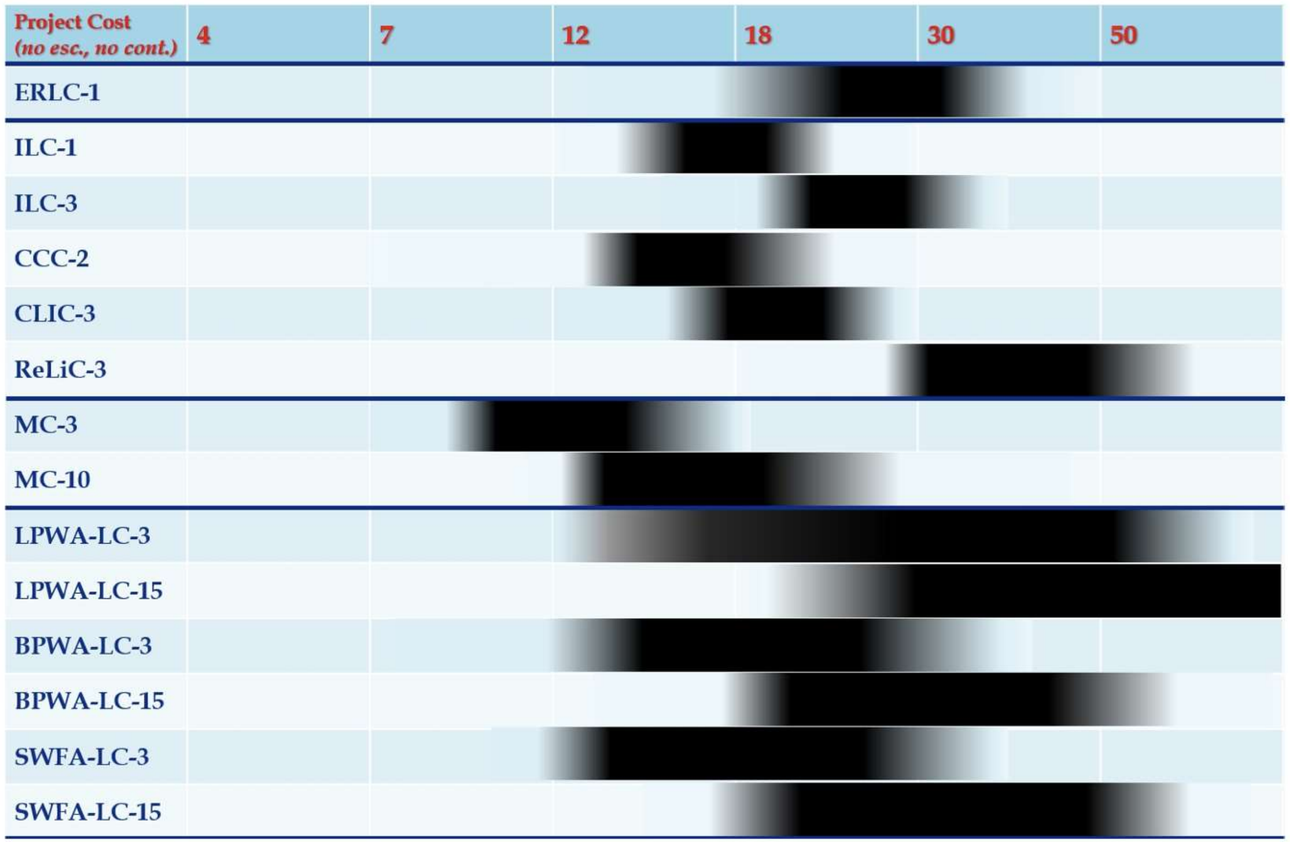


Figure 9. The ITF cost model for the multi-TeV lepton collider proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

COSTS (3)

Other projects

- FCC-hh >25B$

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

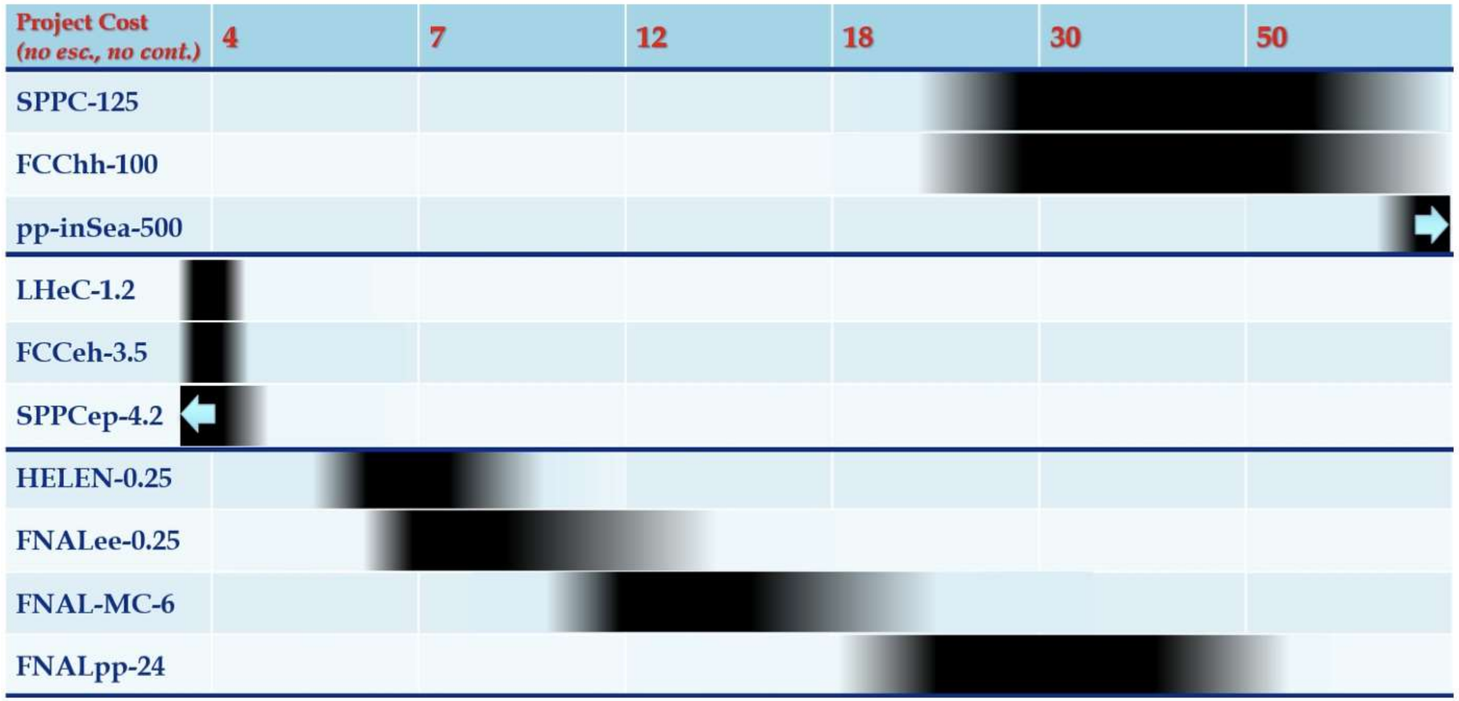
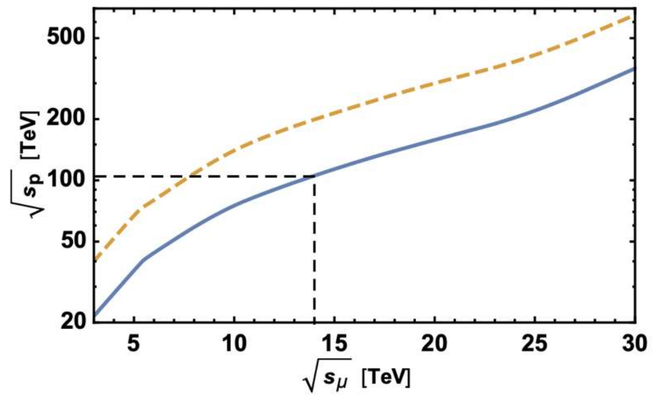


Figure 10. The ITF cost model for the energy frontier hadron collider, electron-proton colliders (incremental cost from hadron collider only) and for the proposed Fermilab site-filler colliders. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends are the cost estimate range for each machine. Right-arrow for the 500 TeV "Collider-in-the-Sea" indicates higher than 80 B$ cost. Left-arrow for the electron-proton "SPPC-CEPC" collider concept indicates smaller than 4 B$ cost.

MUON COLLIDER BENEFITS

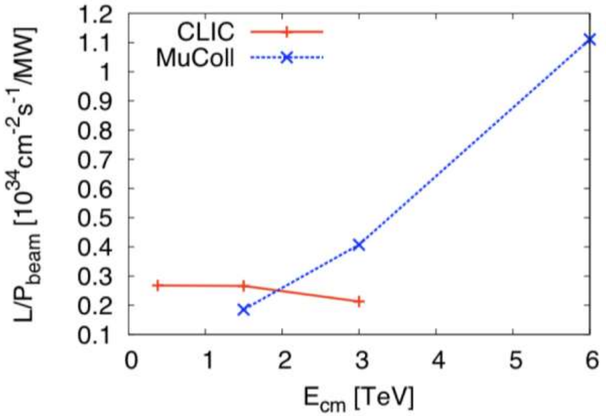
High energy

- Discovery machine
- Higgs self-coupling
  - Like FCC-hh



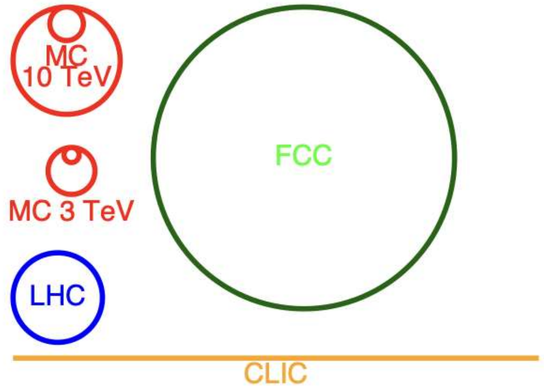
Precision physics

- Luminority frontier
- Higgs factory
  - Like FCC-ee



Compact & efficient

- √s=10 TeV: 10-30km
  - Like LHC



➢ And in the meantime we will do a lot of accelerator+detector R&D

MUON COLLIDER

Physics case of a muon collider is great

- But it might not even be the main criterium

Muon collider has many advantages

- Physics: Precision & Discovery
- Technology and Innovation
- Practicalities: Footprint & Cost
- Outreach: It’s New & Exciting!

Now: Let’s study physics, detector, accelerator


The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

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CERN's future
- HL-LHC
- + CLIC?
- + FCC?
- + MuCol?