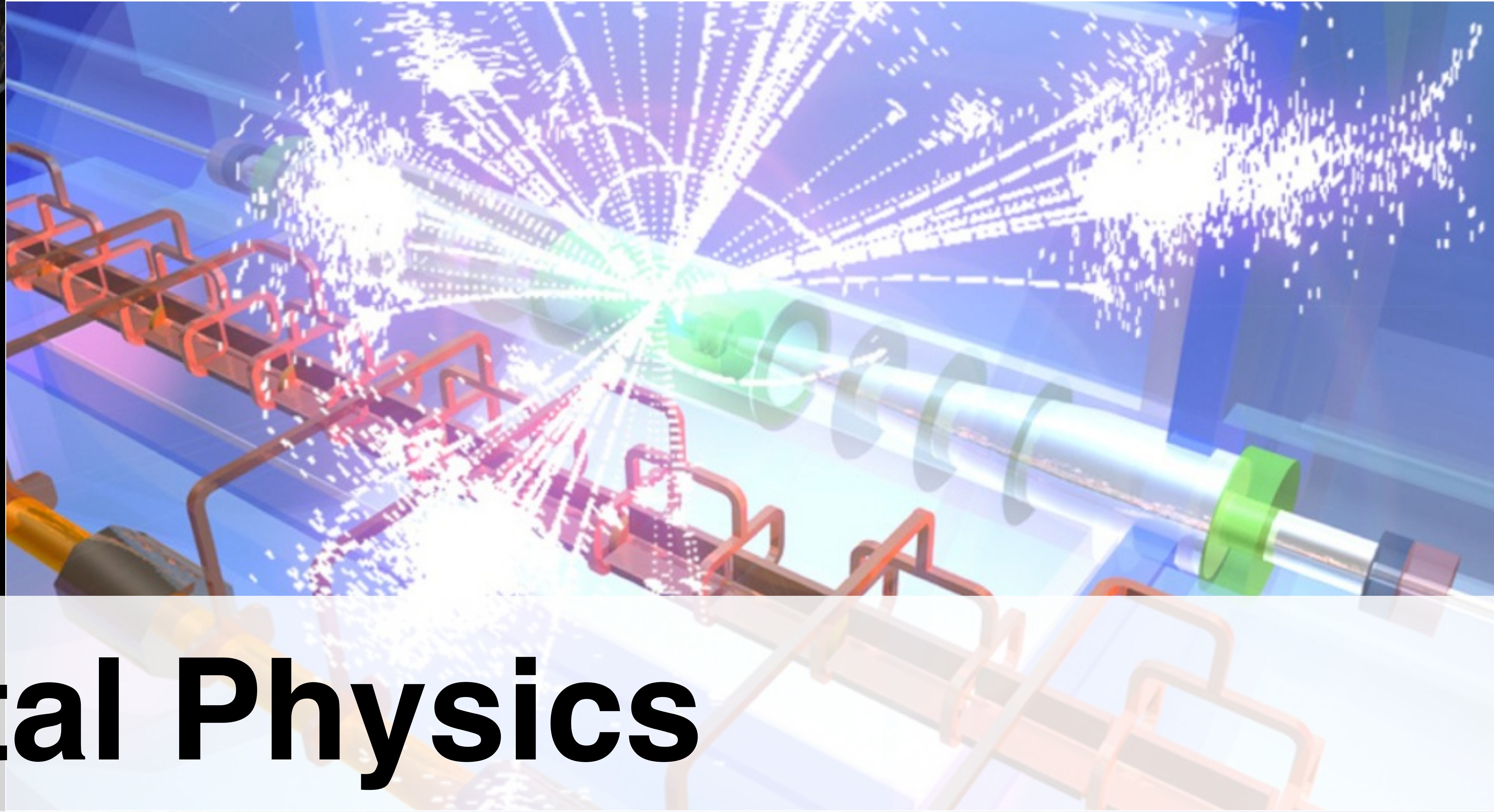


Experimental Physics at Lepton Colliders

Karlsruhe Institute of Technology

Frank Simon

@ Summer Student Lectures

CERN - July 2023

Institute for Data Processing and Electronics

Overview

A two-part story

- **Part 1:**
  - Scientific motivation
  - Future e^+e^- colliders in broad strokes
  - Detectors at future e^+e^- and $\mu^+\mu^-$ colliders
- Part 2:
  - Higgs physics
  - Electroweak precision
  - Top quark physics
  - Into the unknown

Disclaimer

I have taken material from many different presenters - impossible to list them all. I want to single out Mogens Dam, who gave excellent lectures on the same topic a few years ago, which I took as inspiration. An excellent resource reflecting the current state of this field is the Snowmass ’21 CSS Meeting in Seattle in July 2022: https://indico.fnal.gov/event/22303

The selection of material reflects my personal bias. I am not trying to “sell” a particular future facility - but use your own judgment to form you opinion!

Part I

Introduction

Where we are, how we got there

The Standard Model of Particle Physics

A Collider Success Story

Karlsruhe Institute of Technology

SPEAR / AGS 1974

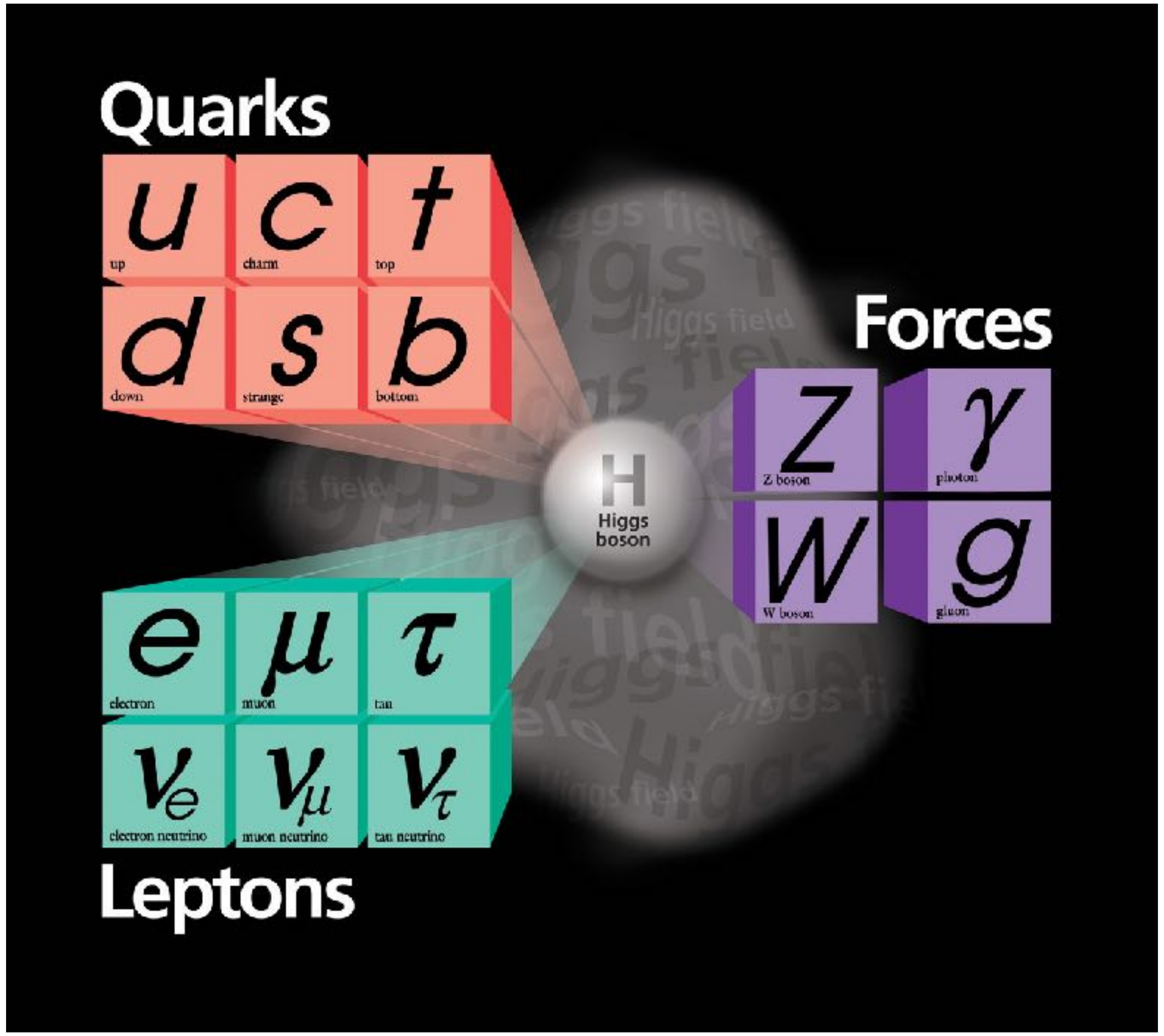
Fermilab 1977

Tevatron 1995

AGS 1962

SPEAR 1975

Fermilab 2000



PETRA 1979

SppS 1983

LHC 2012

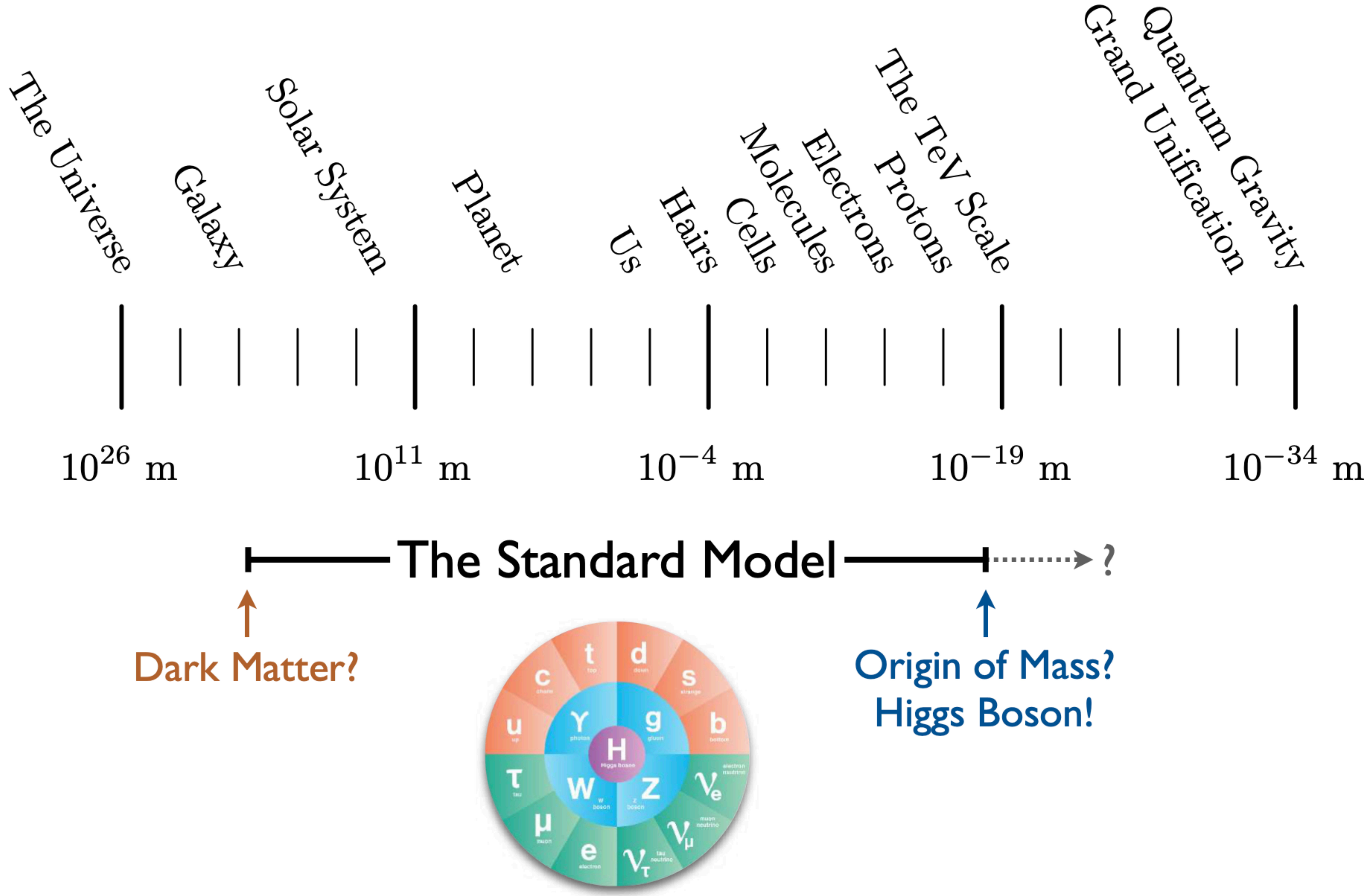
Contributions from

- e^+e^- colliders
- hadron colliders
- fixed target

- The result of generations of accelerators, and the interplay of experiment and theory
  Providing testable predictions

Understanding the Universe

Success and limits of the Standard Model



Jesse Thaler,
Snowmass CSS '22

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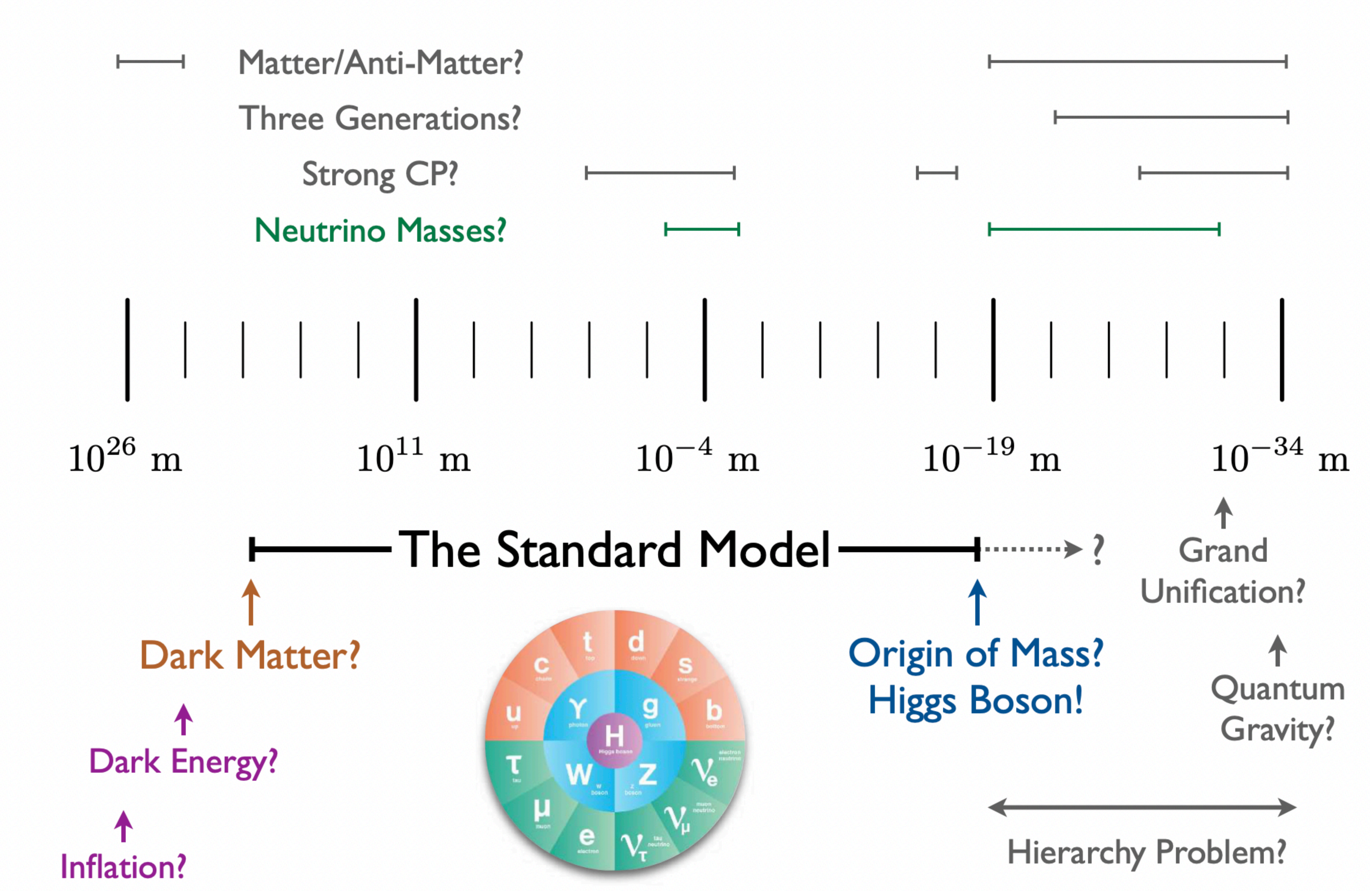
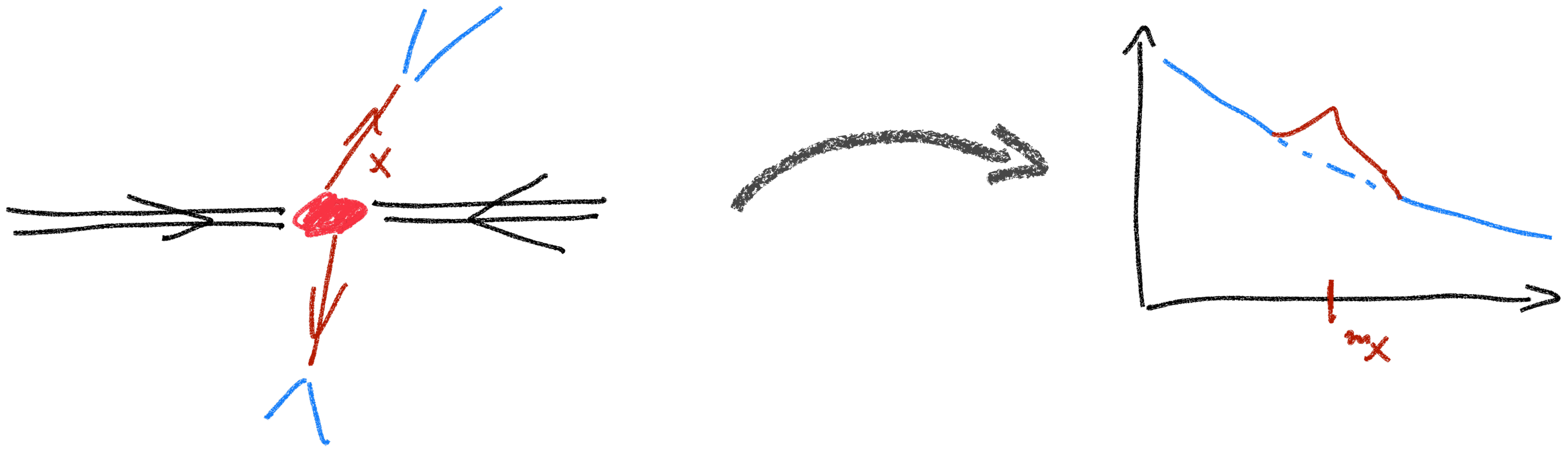


Jesse Thaler, Snowmass CSS '22

Strategies for Discovery in Particle Physics

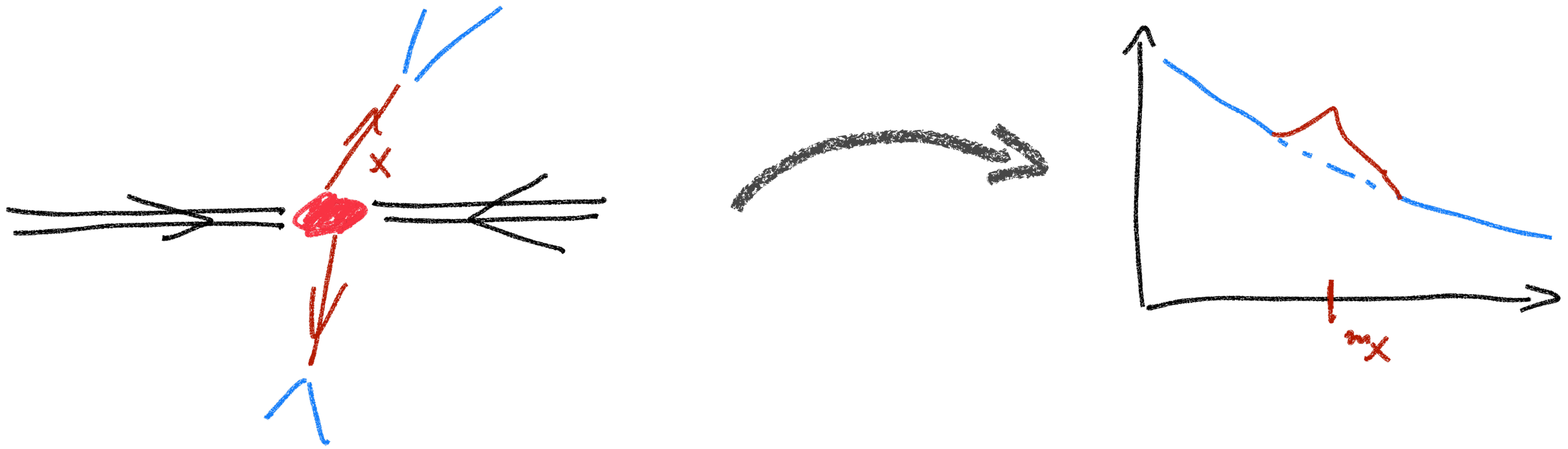
Direct and indirect



Direct observation of new particles: Requires sufficient energy for production

Strategies for Discovery in Particle Physics

Direct and indirect



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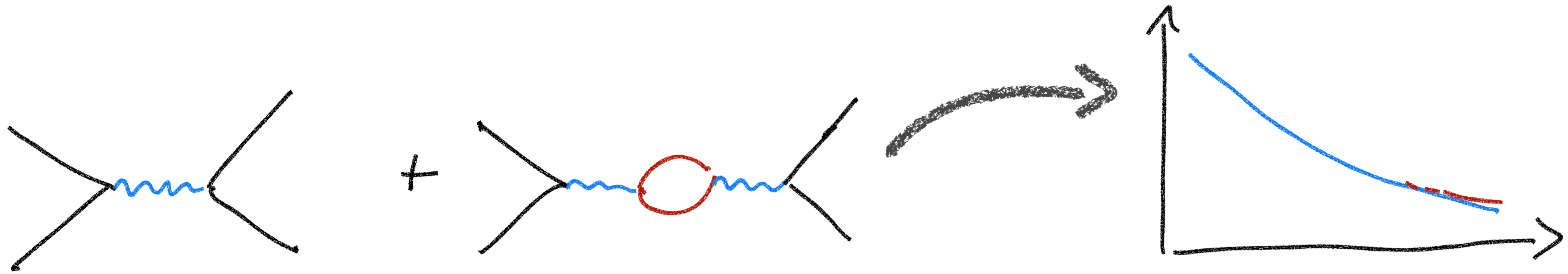


Indirect discovery: Deviations from expectation hinting at new phenomena at (much) higher energy scale

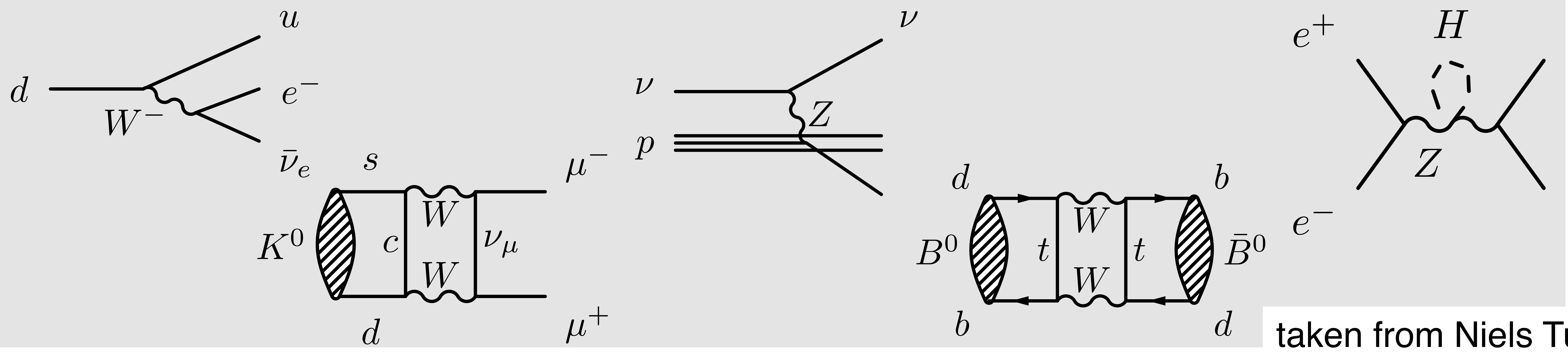
Precision Measurements

An established discovery strategy

Karlsruhe Institute of Technology

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Y	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?

with a well-founded theoretical model, precision measurements can be turned into discoveries - and precision measurements can guide the development of new models.



taken from Niels Turing, ICHEP 2018

Precision Measurements

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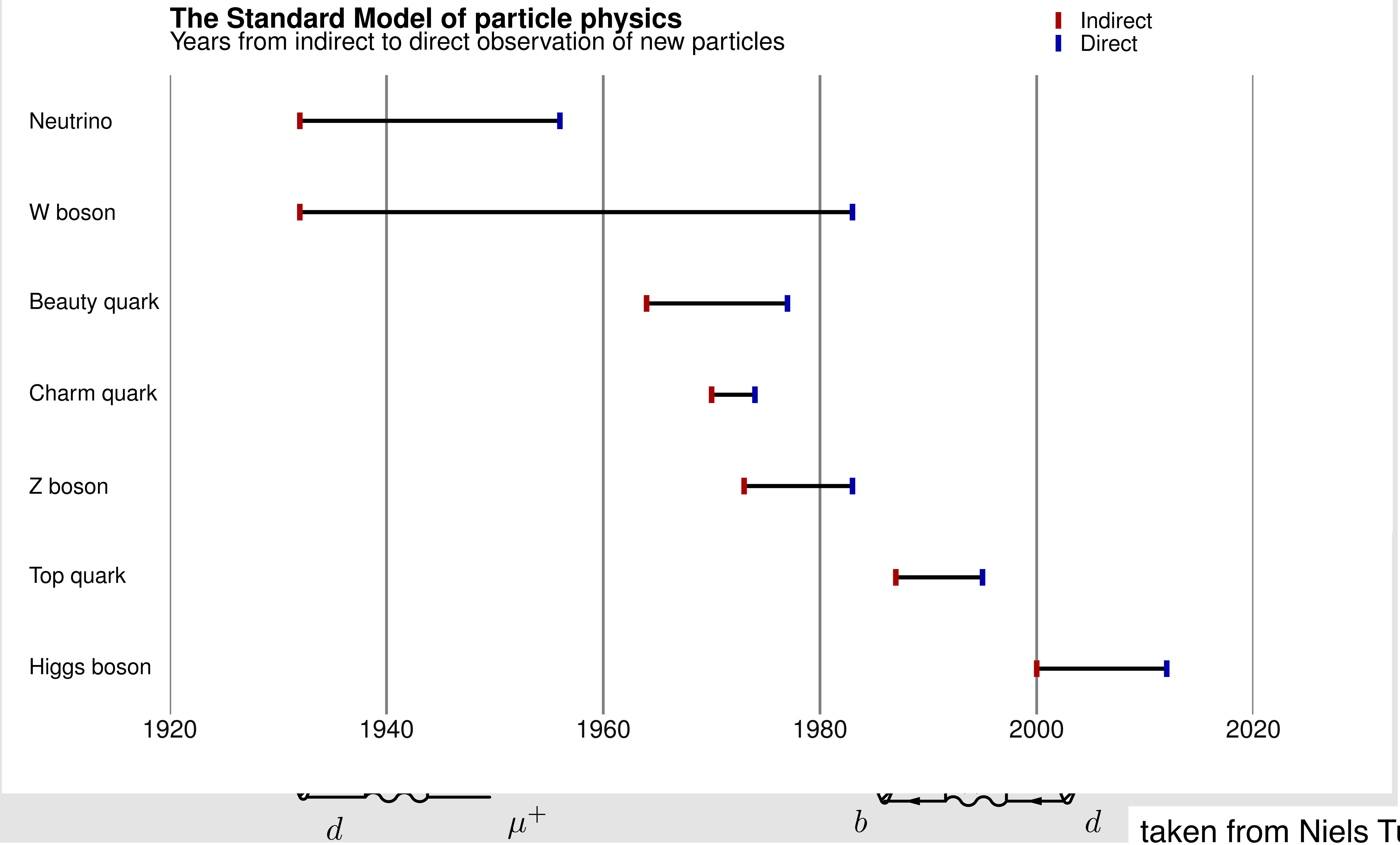


taken from Niels Turing, ICHEP 2018

with a well-founded theoretical model, precision measurements can be turned into discoveries - and precision measurements can guide the development of new models.

reaching higher scales: direct discoveries only follow with new generations of experiments

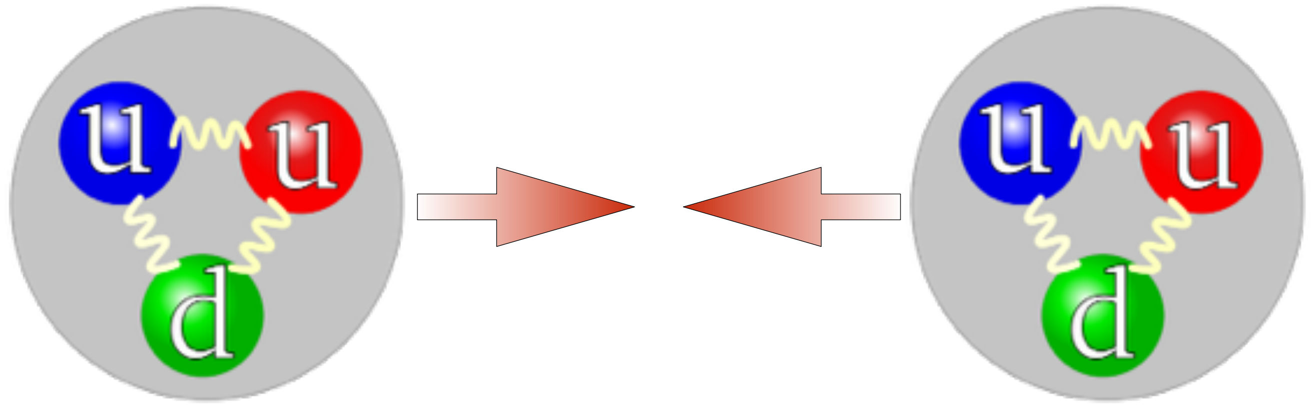
Why e^+e^- Colliders?

Electron and Proton Colliders

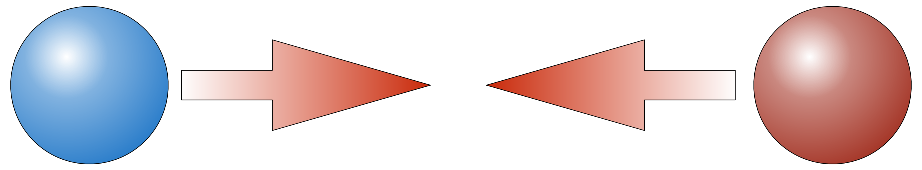
The main workhorses of HEP

- Colliders accelerate charged particles to high energy and bring them to collision - two main types so far:

proton-proton collider



electron-positron collider



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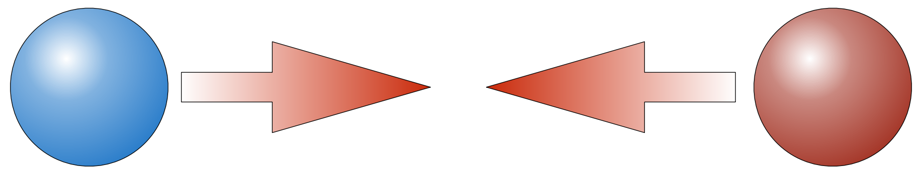

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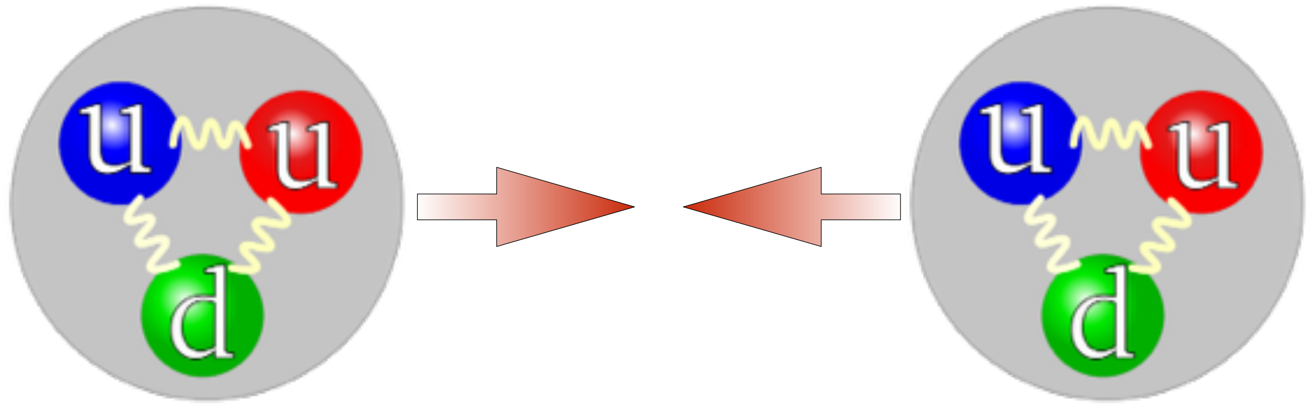

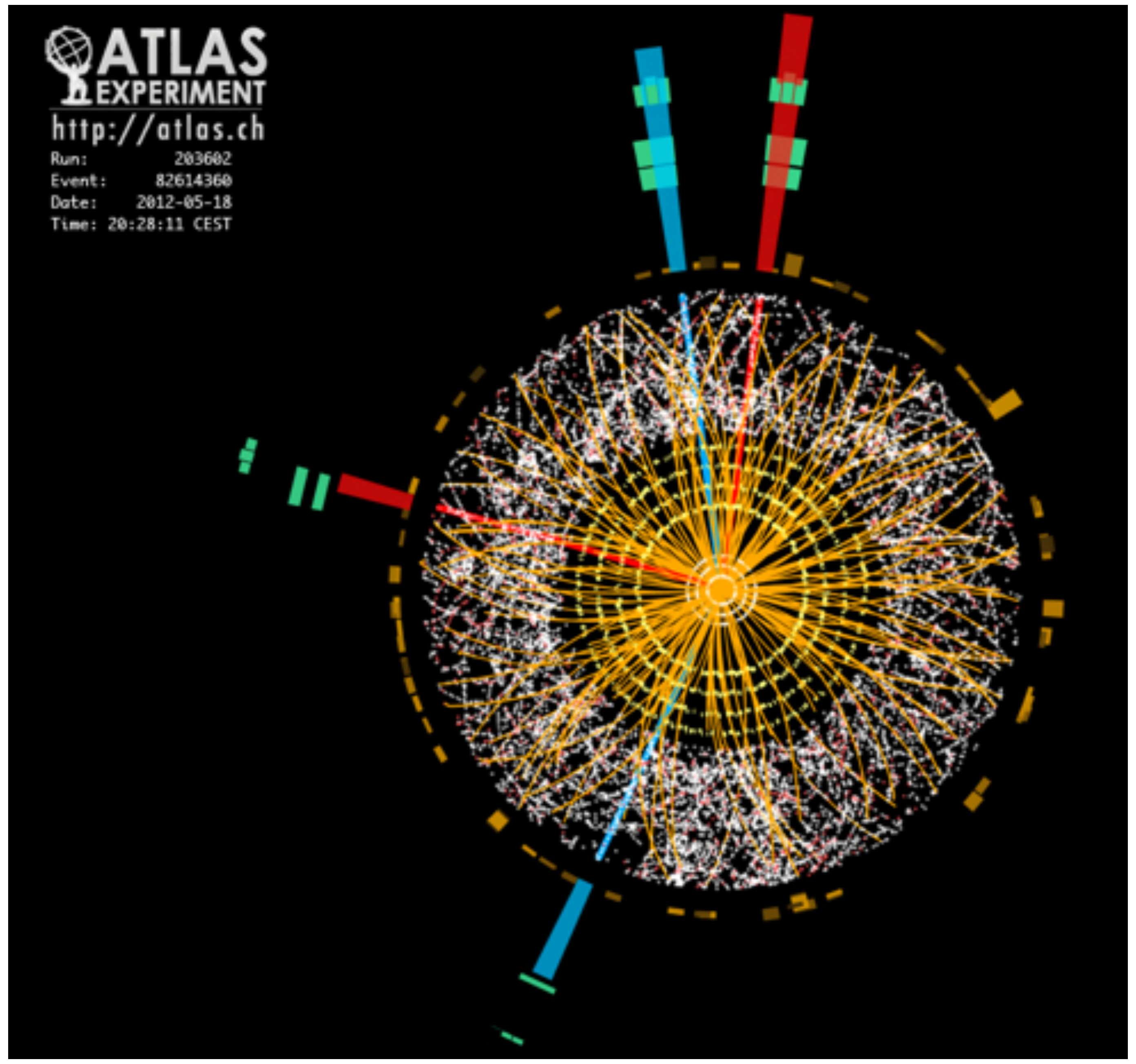

composite particles

dominated by strong interaction

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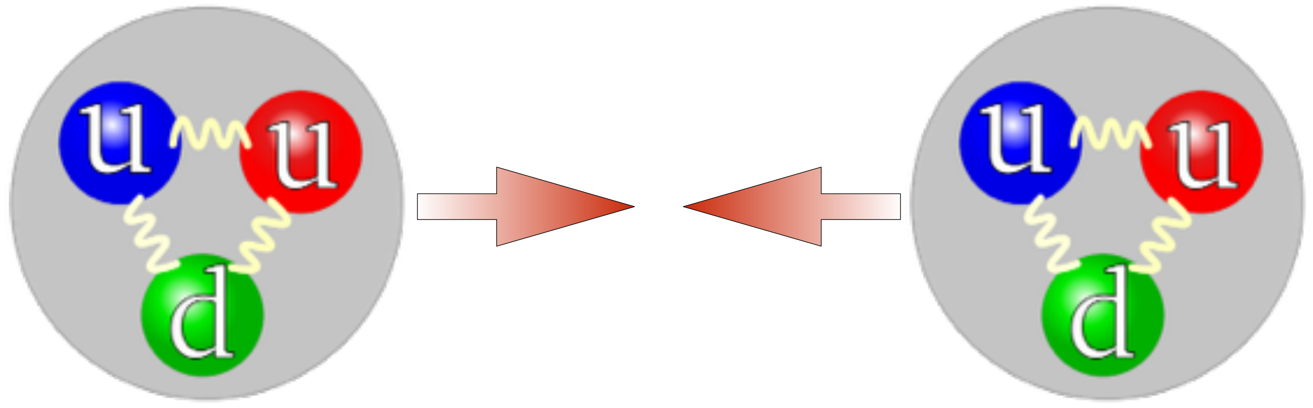

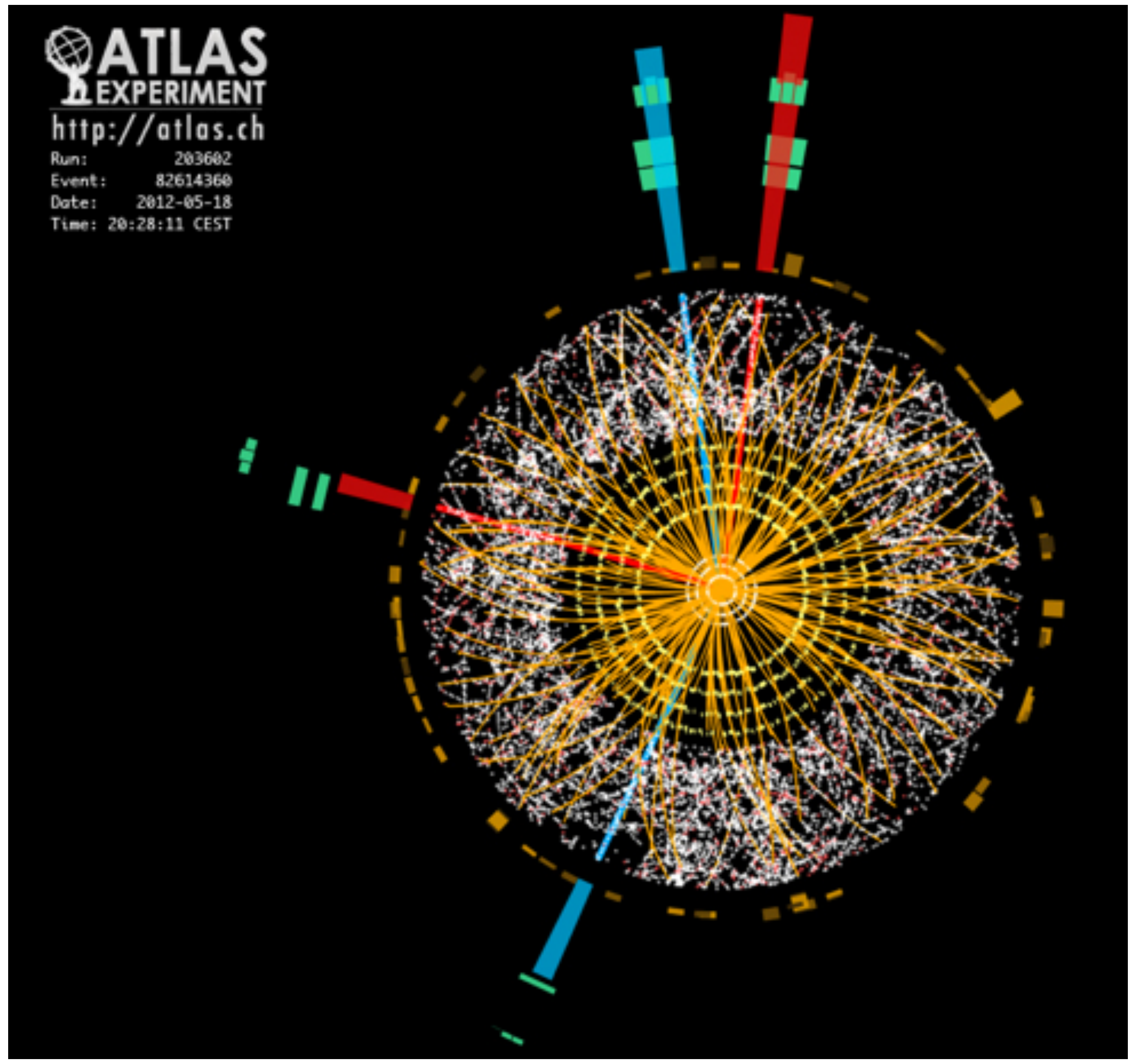

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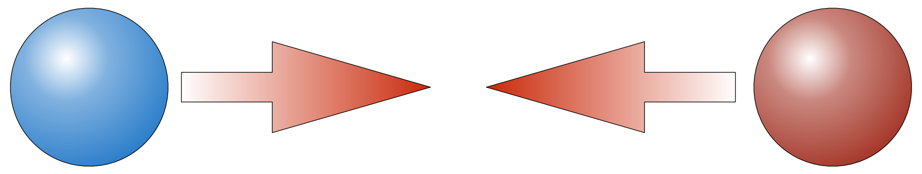
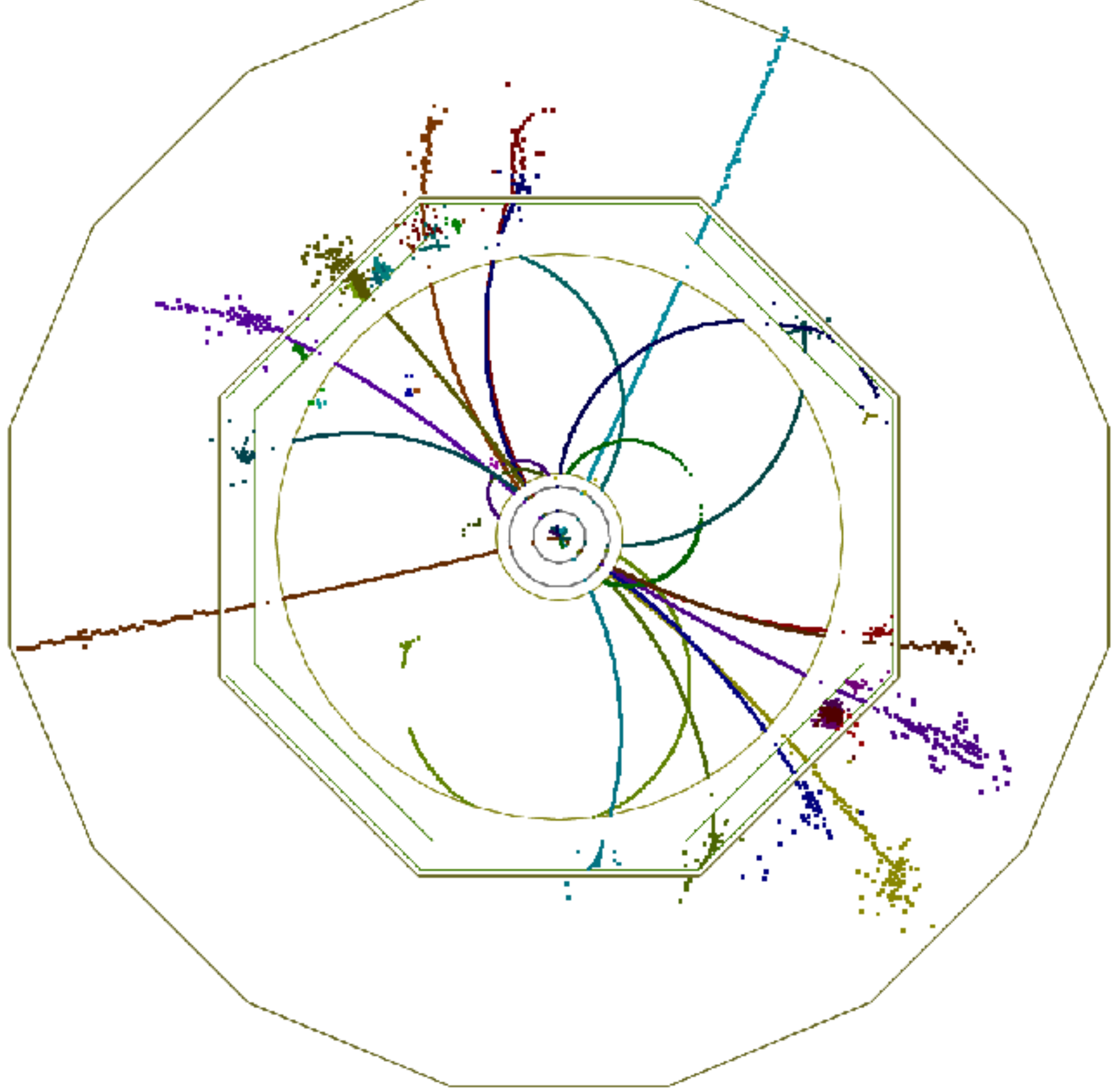


elementary particles



dominated by electroweak interaction

Electron and Proton Colliders

The main workhorses of HEP

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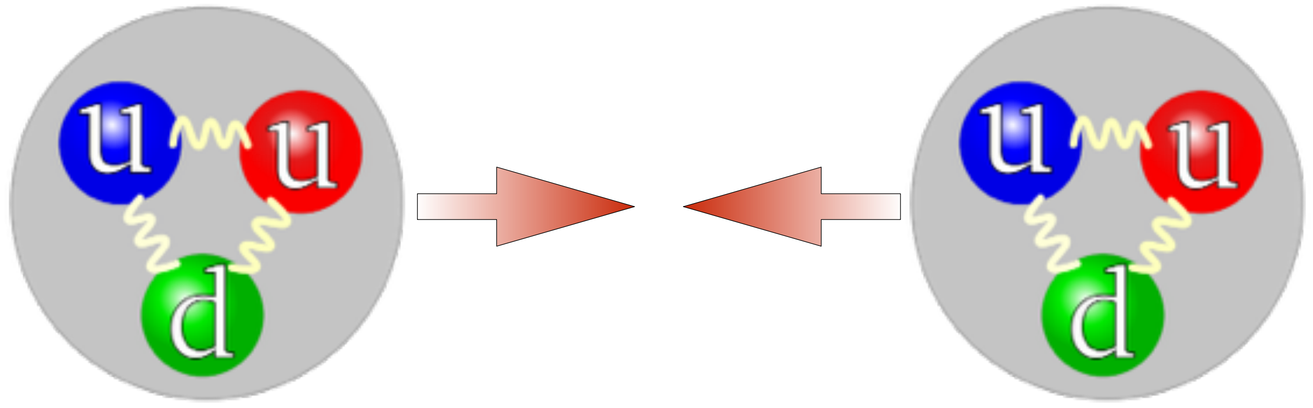
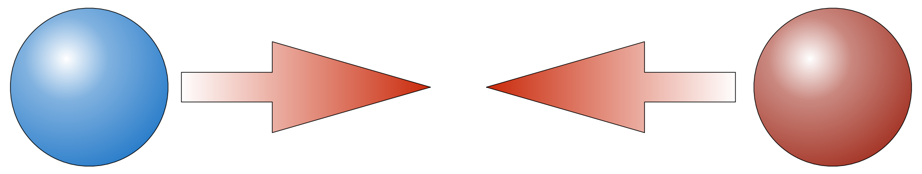
proton-proton collider

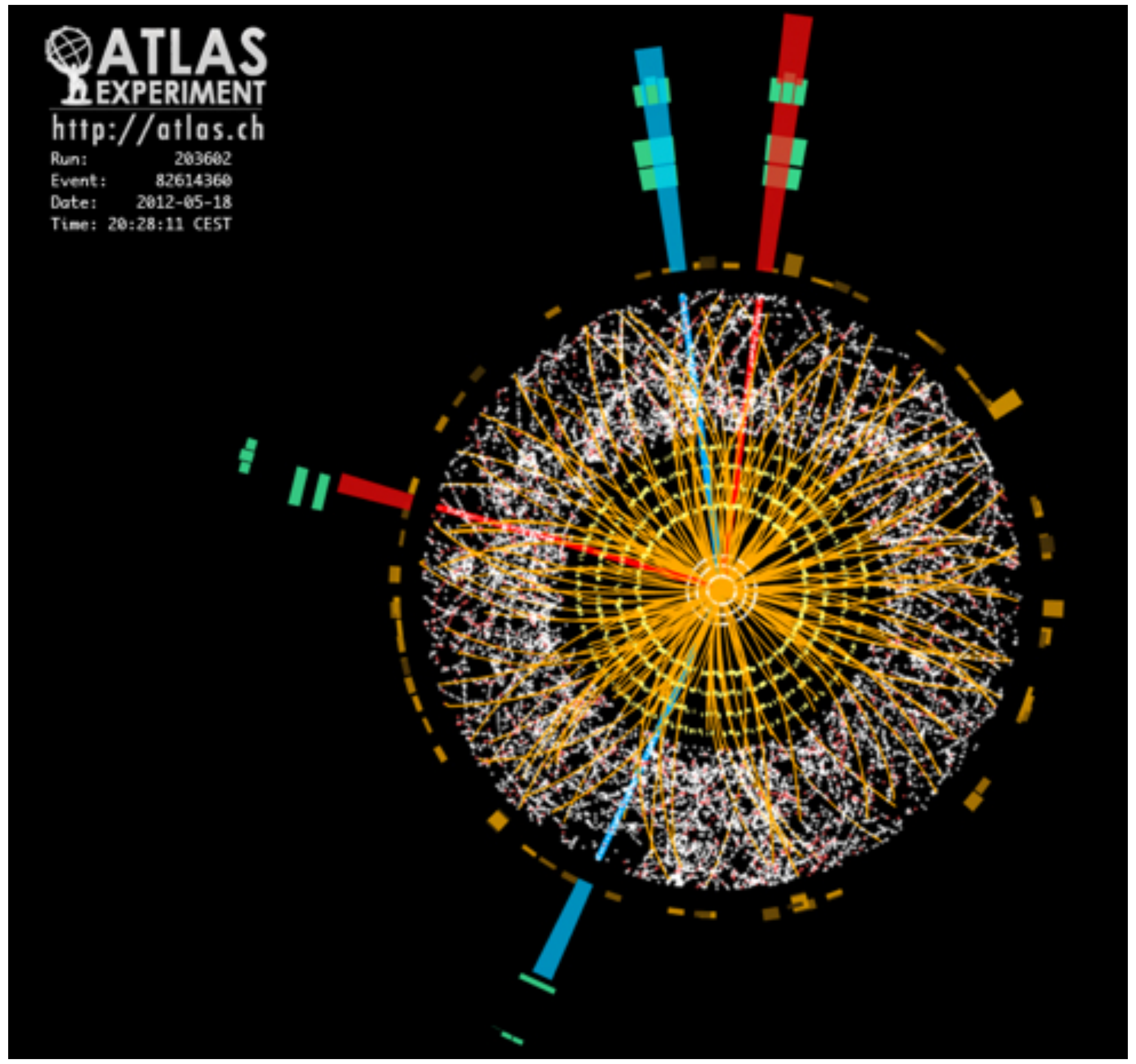


High complementarity of p+p and e^+e^- colliders

electron-positron collider



elementary particles



composite particles

dominated by strong interaction

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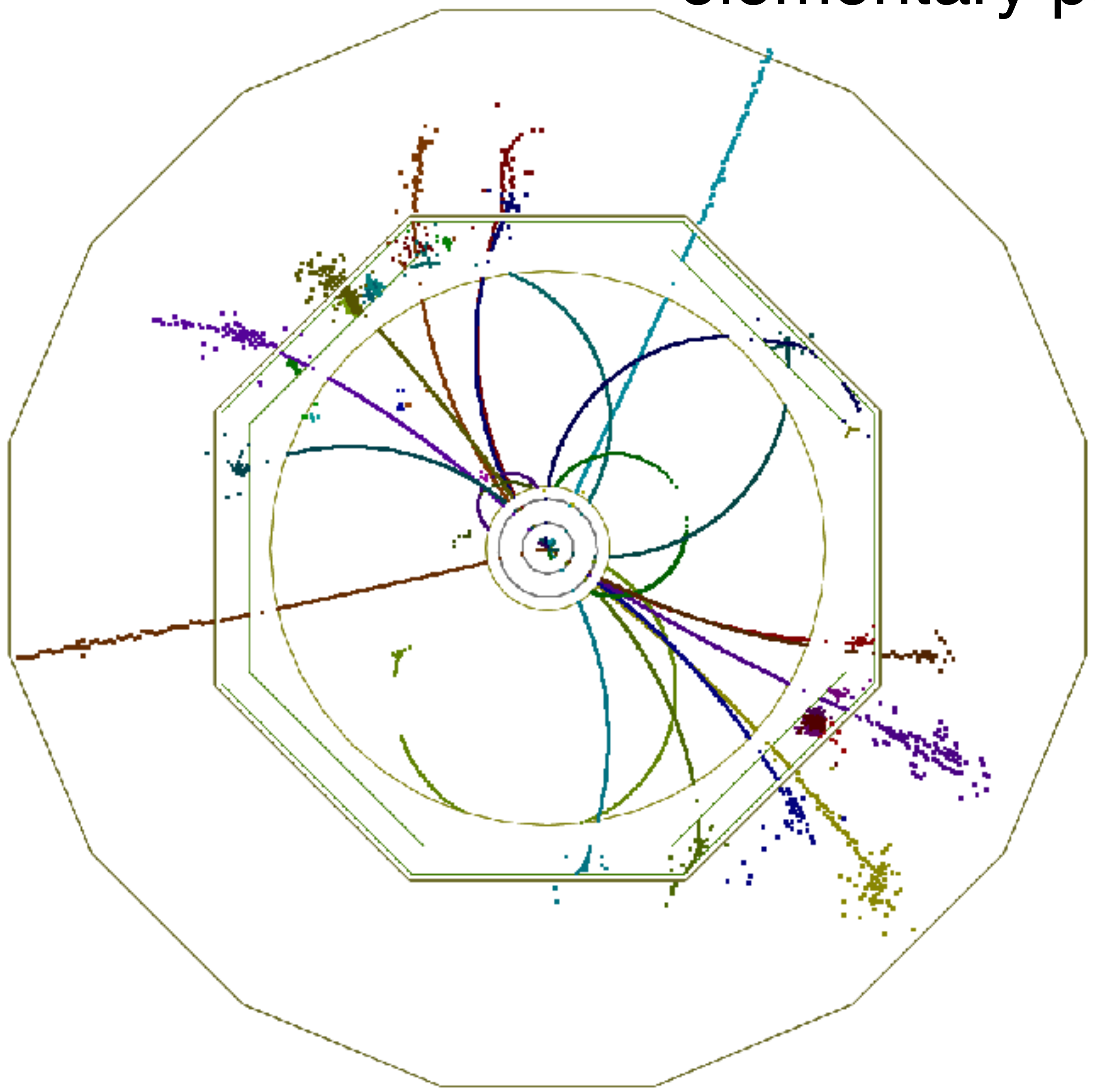
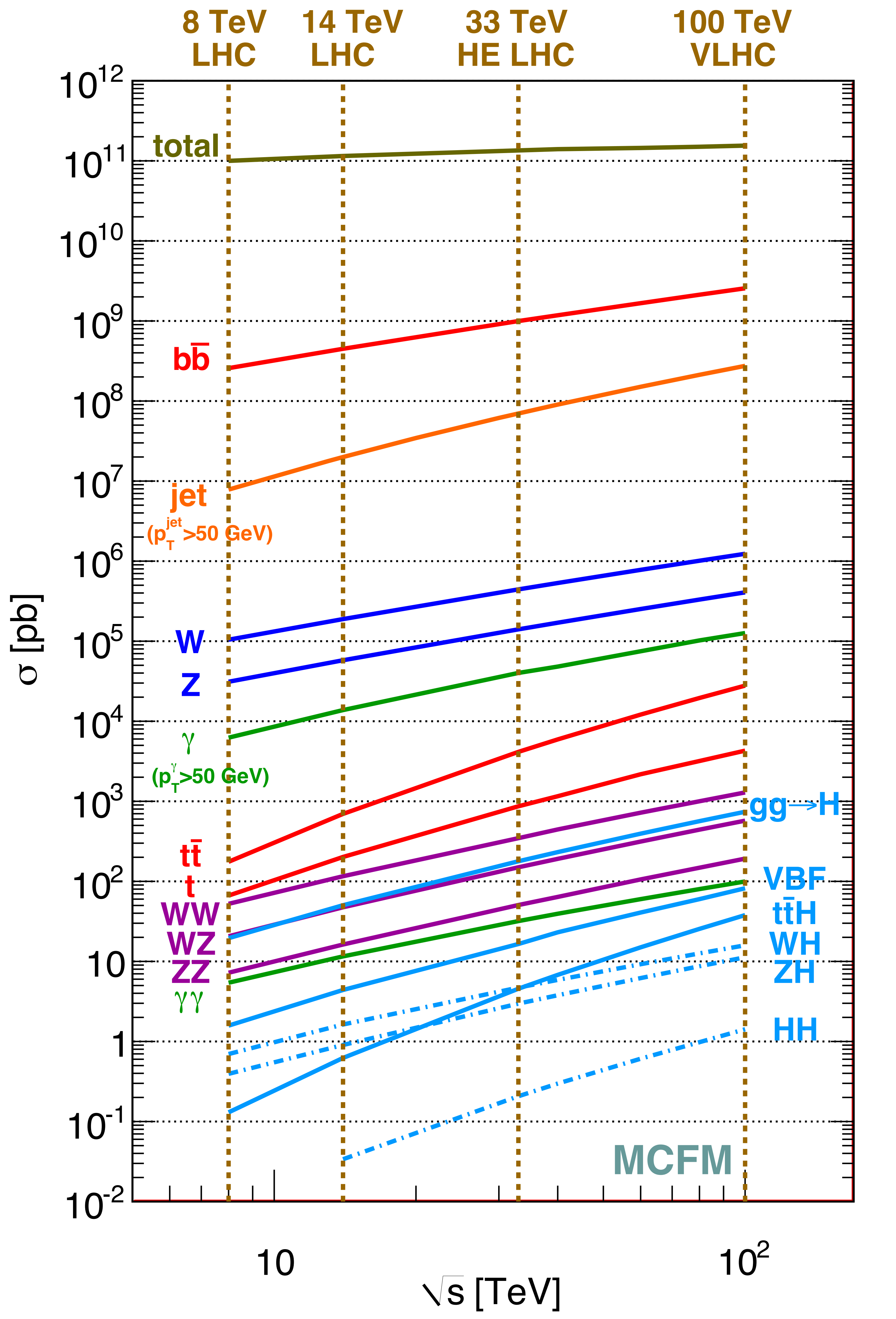


Electron & Proton Colliders

Higgs production as an example to illustrate differences



~ 9 orders of magnitude

Electron & Proton Colliders

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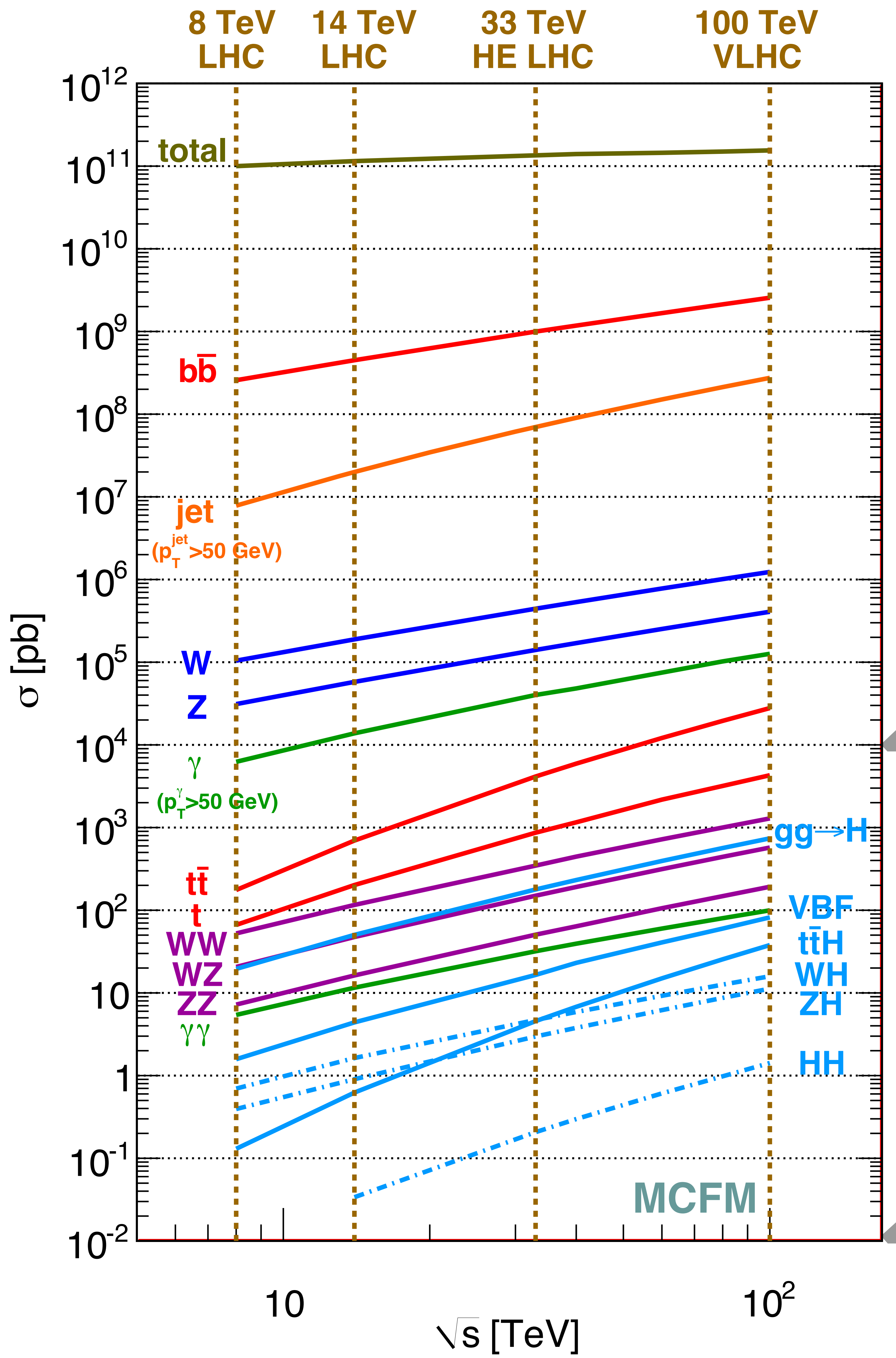

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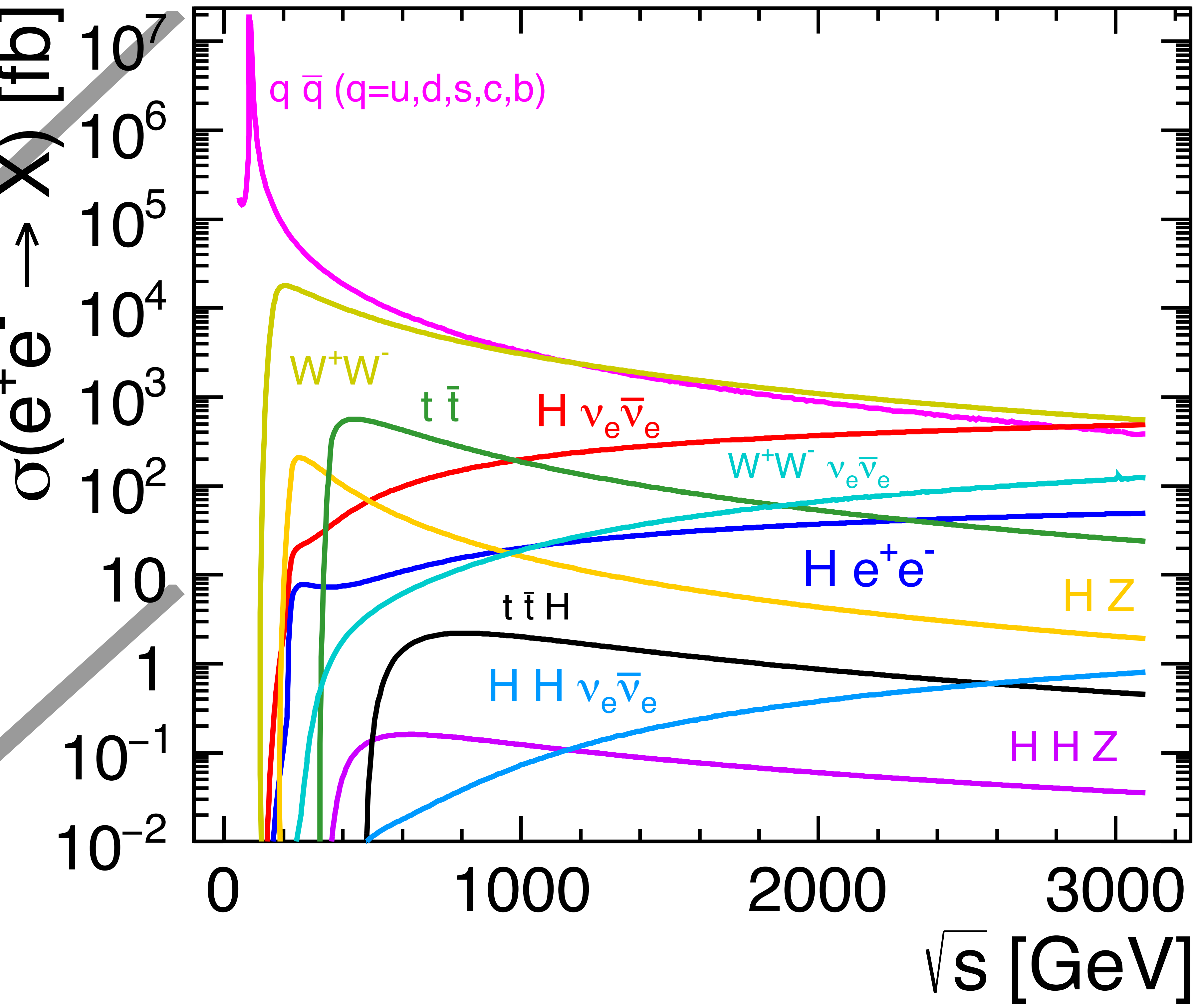

~ 2 orders of magnitude

Electron & Proton Colliders

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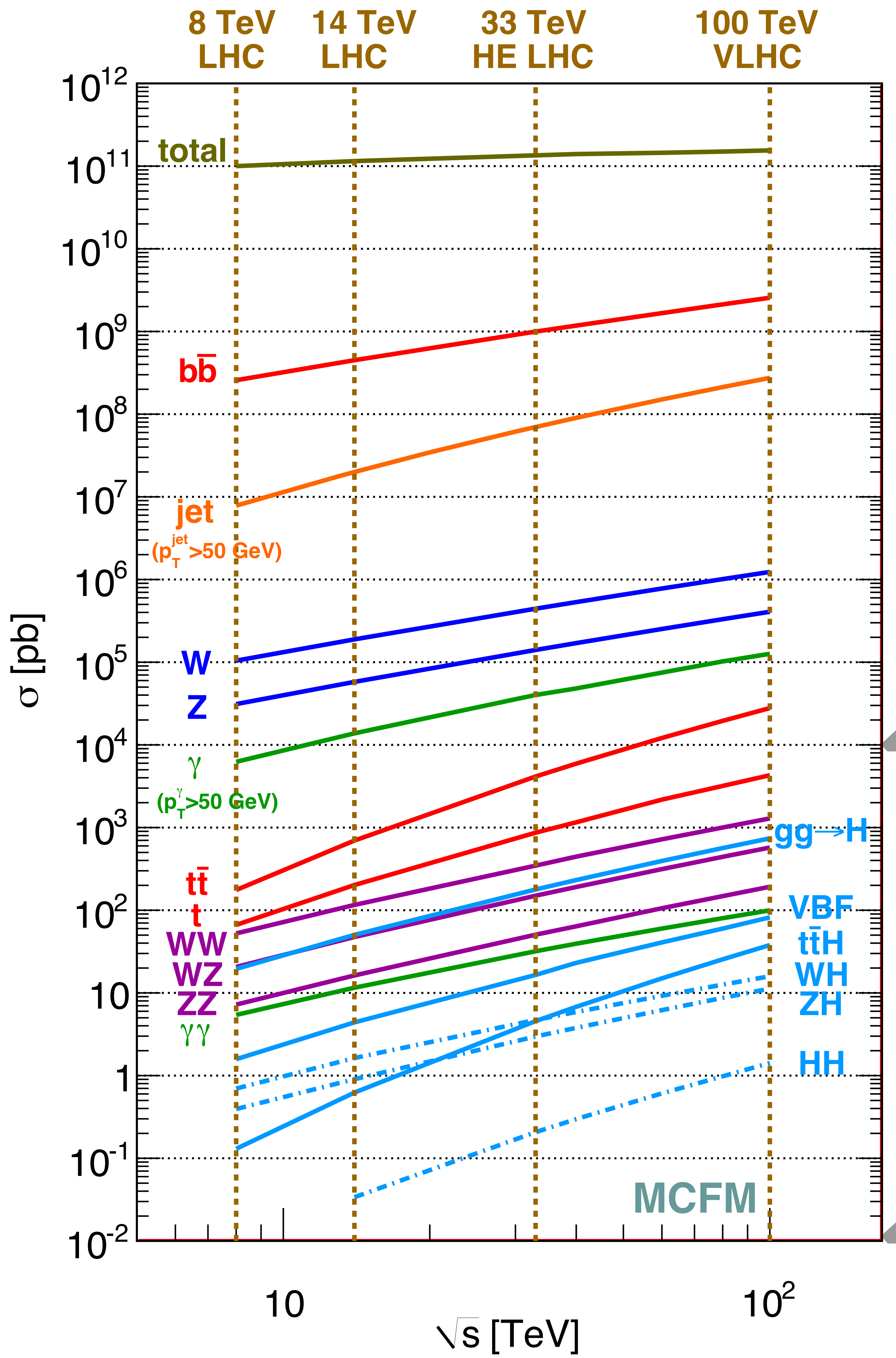

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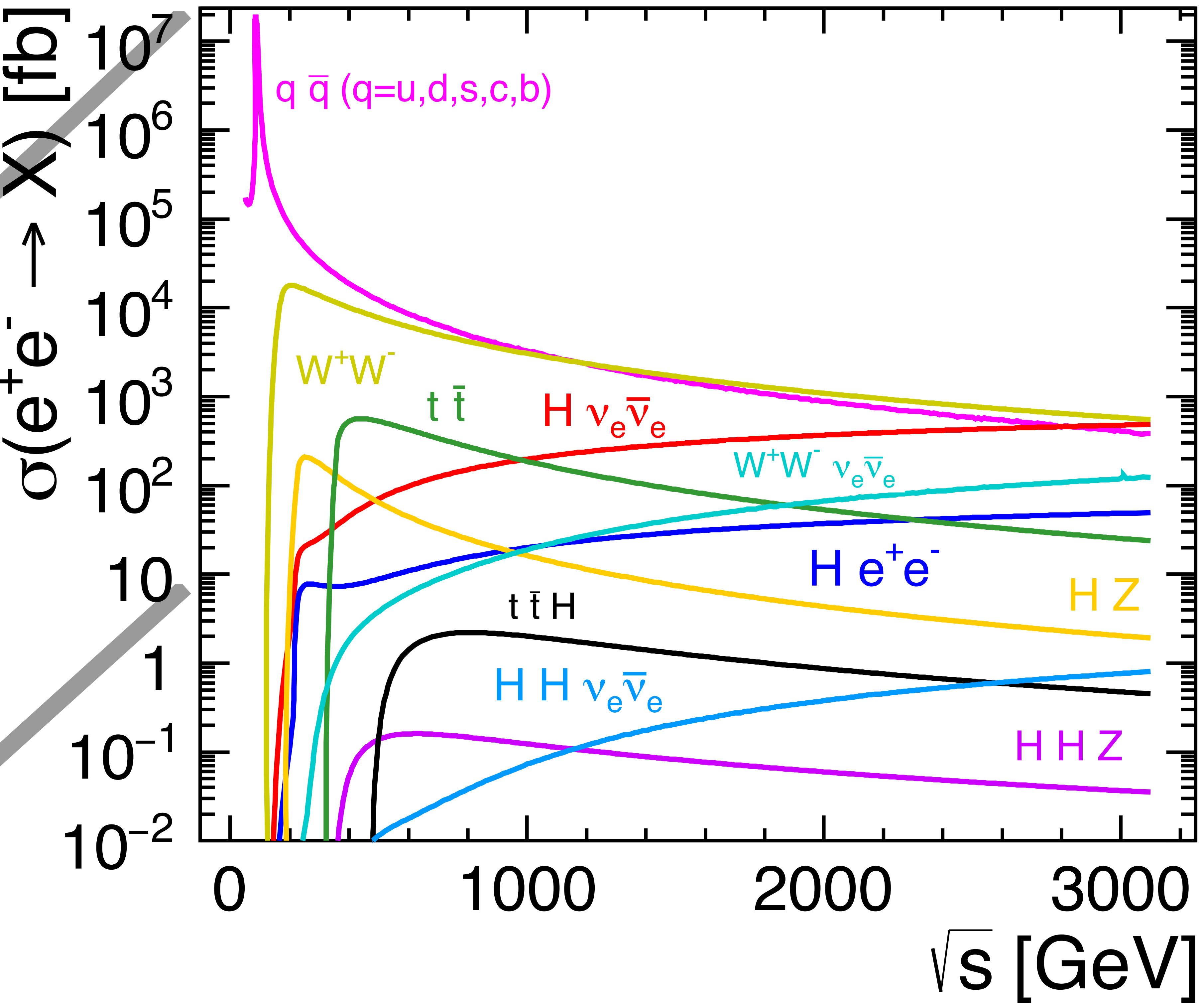


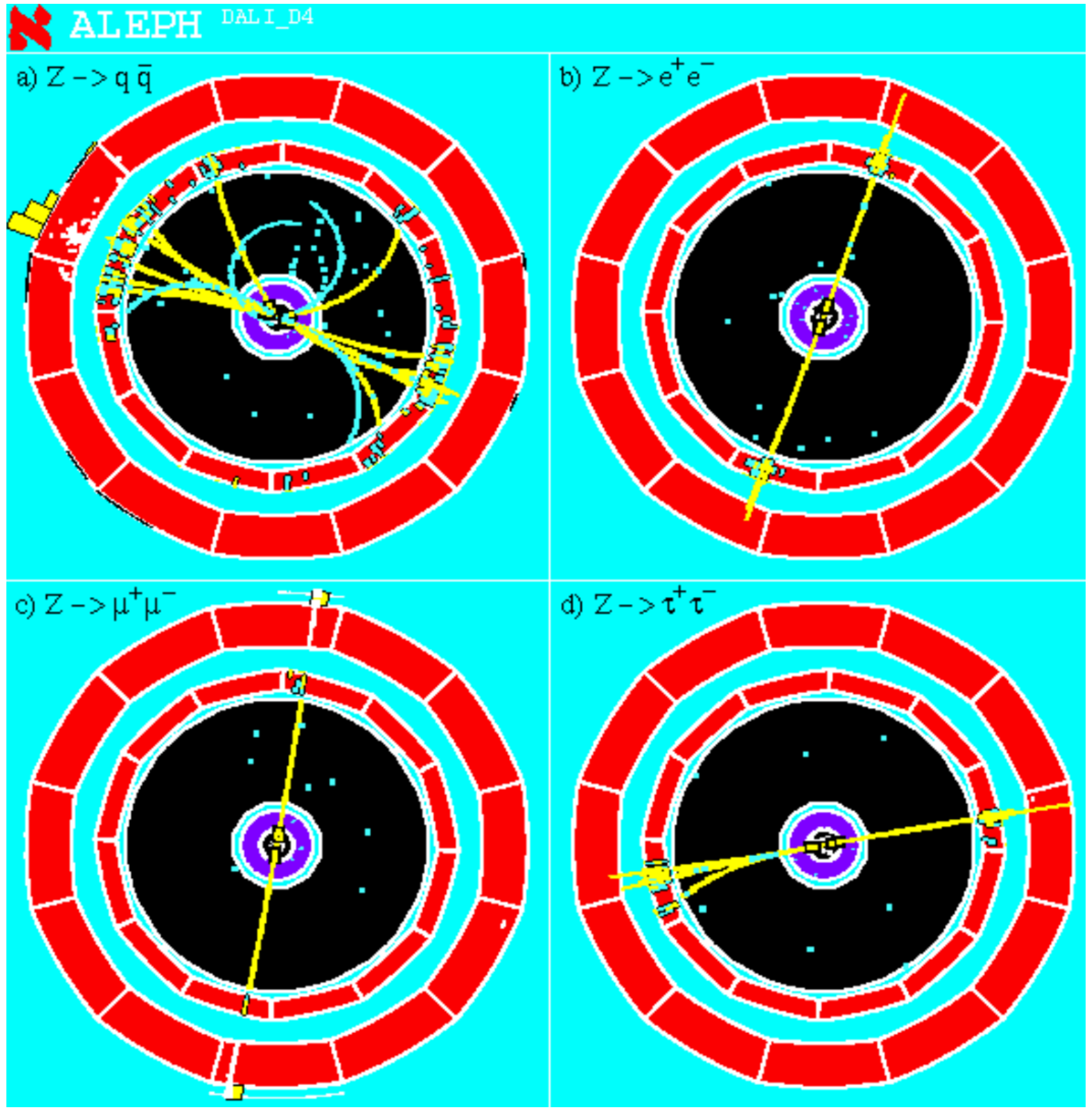
~ 2 orders of magnitude

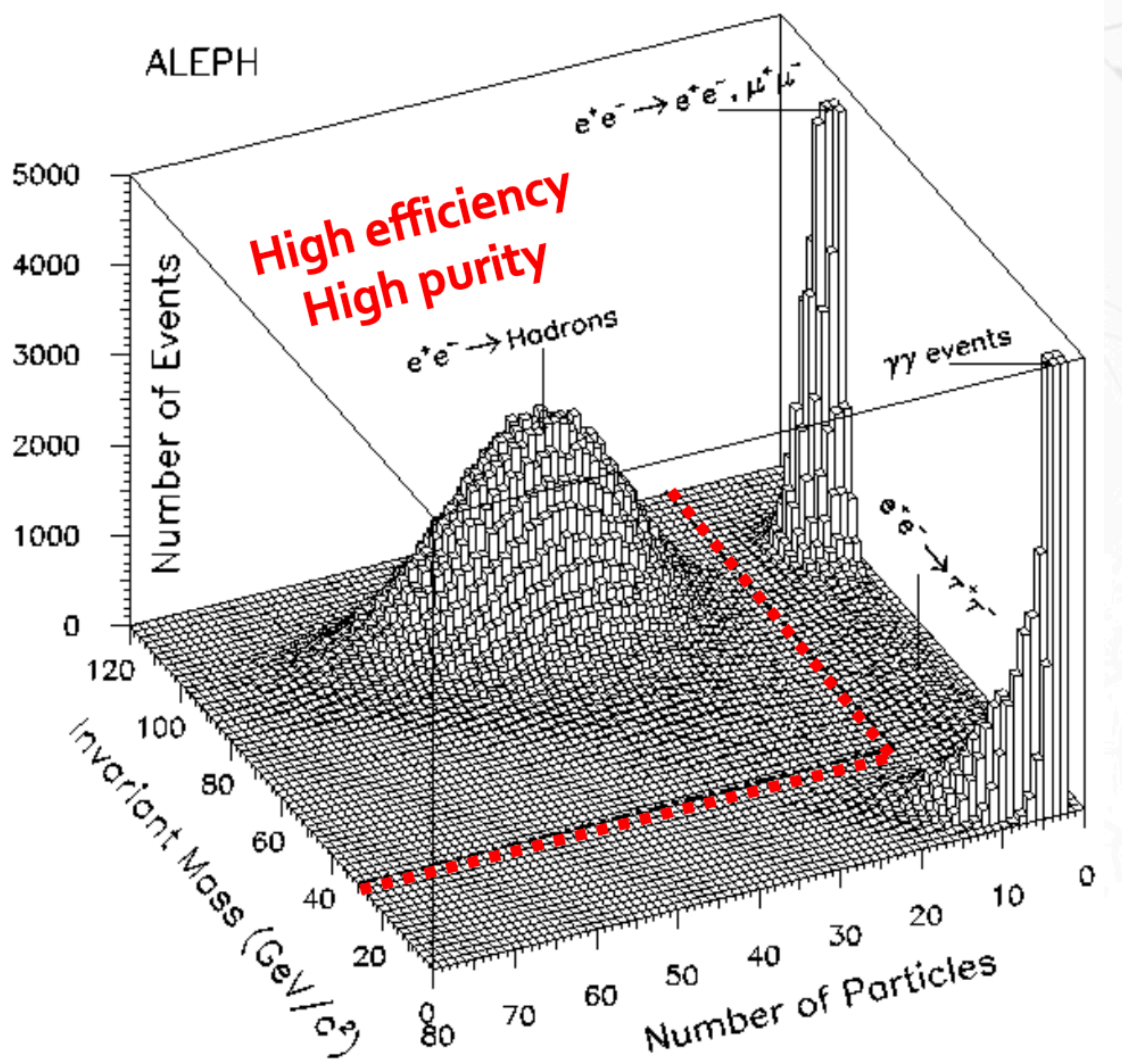
- Significantly higher signal yields in pp (2 - 3 orders of magnitude), but also ~ 9 orders of magnitude higher physics backgrounds

Experimental Conditions at e+e- Colliders

Looking back at LEP

- LEP - the first occupant of the tunnel we now know as the “LHC tunnel”: 1989 - 2000, 91 - 209 GeV
  - Fantastically clean events: No pile-up, no underlying events -> All you see is the physics!
  - Signal and physics background cross sections comparable: no trigger challenge!

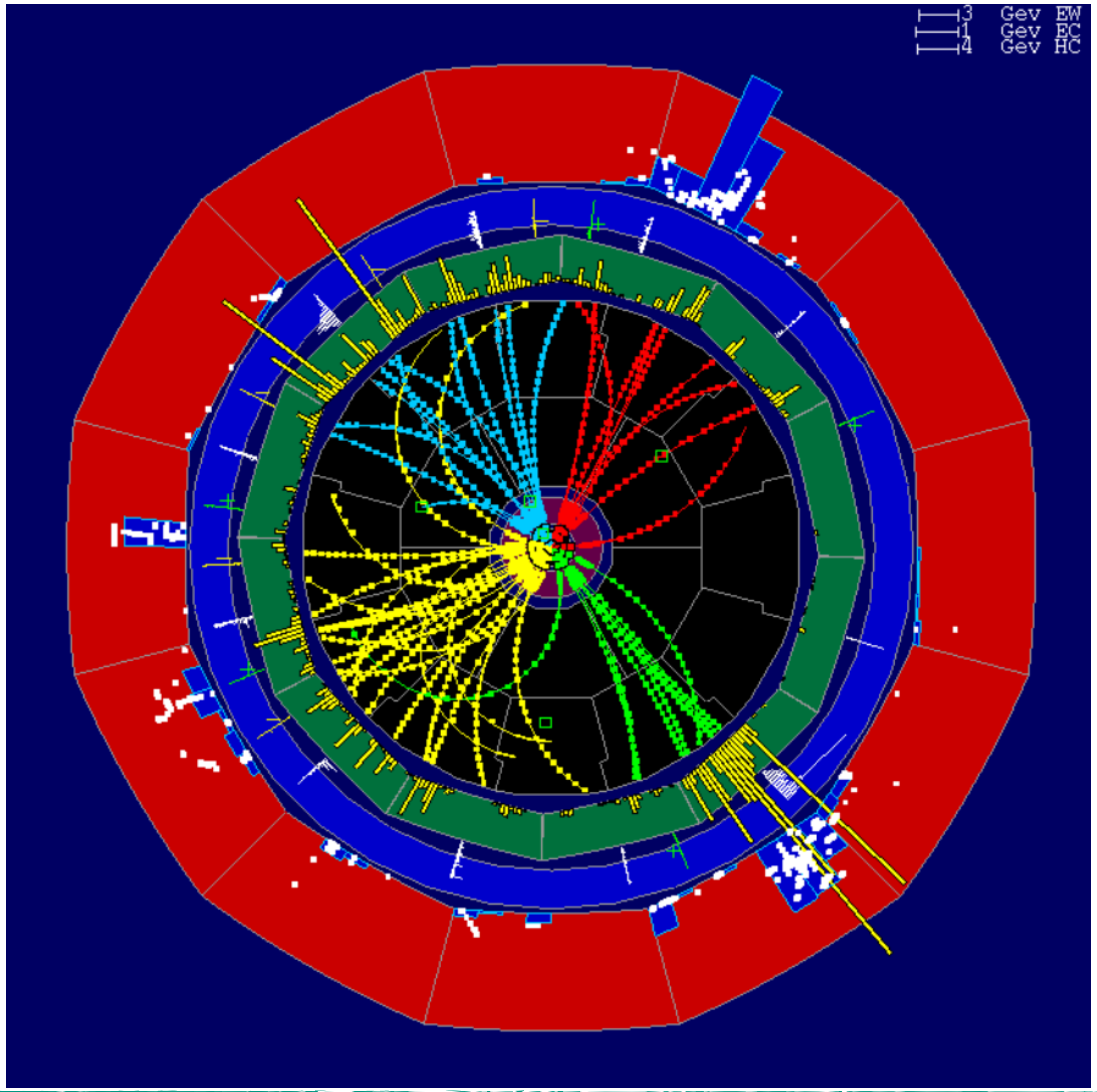




Experimental Conditions at e^+e^- Colliders

Looking back at LEP

- A key feature: Excellent knowledge of initial state, given by √s -> Energy conservation means the four-vector of the final state is known.
  - Can be exploited in event reconstruction - kinematic fitting, et. al., used to eliminate jet energy scale uncertainties in WW events, for example



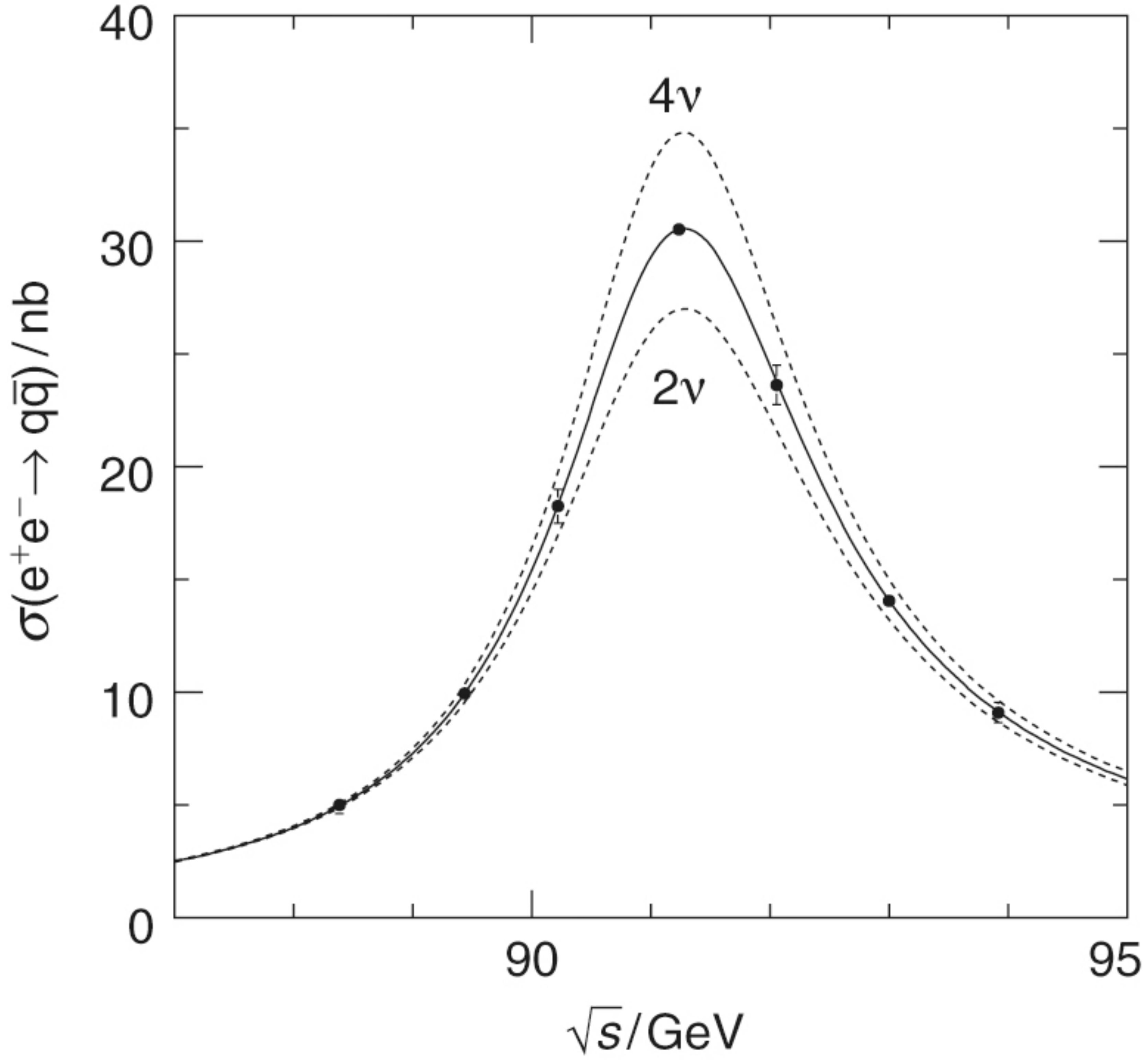
Here:

$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$

accurate measurements of the jet directions, together with event constraints provide precise jet energies and di-jet masses (W mass)

- An era of precision measurements - still dominating many parameters 25 years later…

A result directly after first LEP data: The number of light neutrinos



After 5 years at LEP1: per-mille level precision

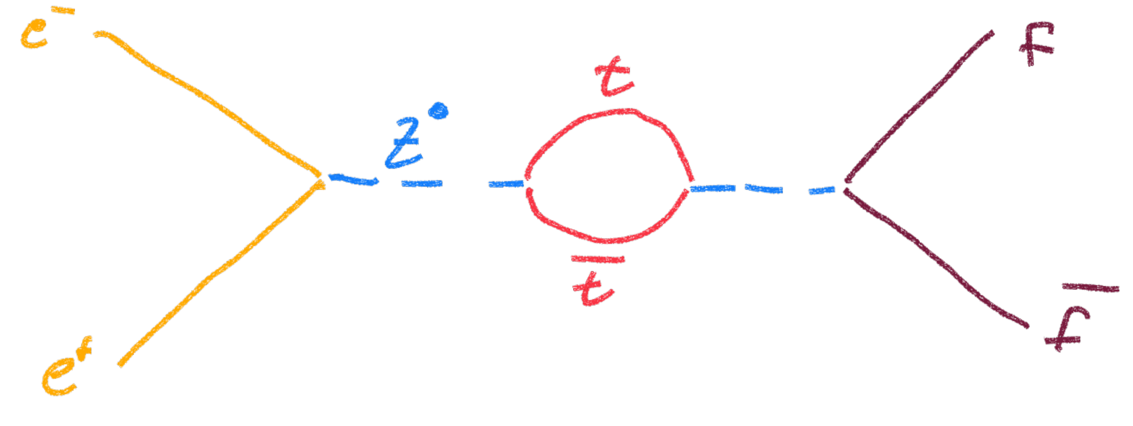
$N_\nu = 2.984 \pm 0.008$

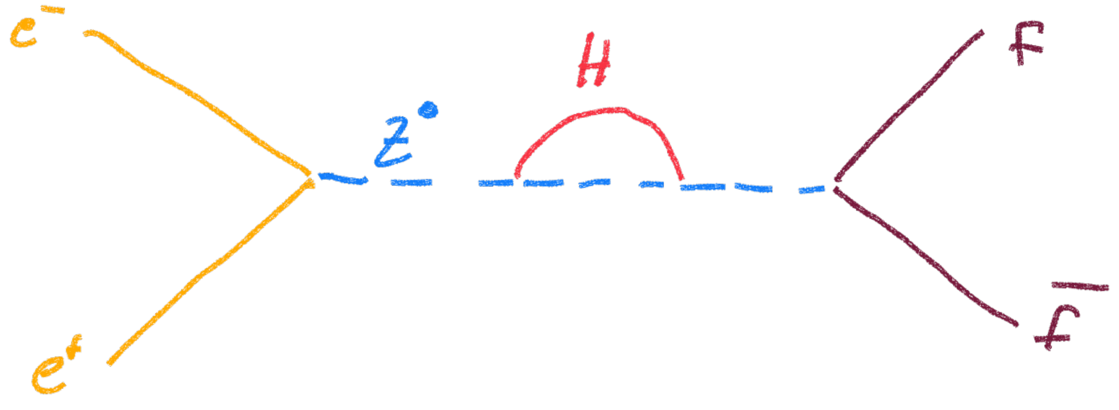
$\Gamma_Z = 2495.2 \pm 2.3$ MeV

$m_Z = 91187.5 \pm 2.1$ MeV

$\alpha_s = 0.1190 \pm 0.0025$

Precision measurements could predict the top and Higgs masses prior to discovery

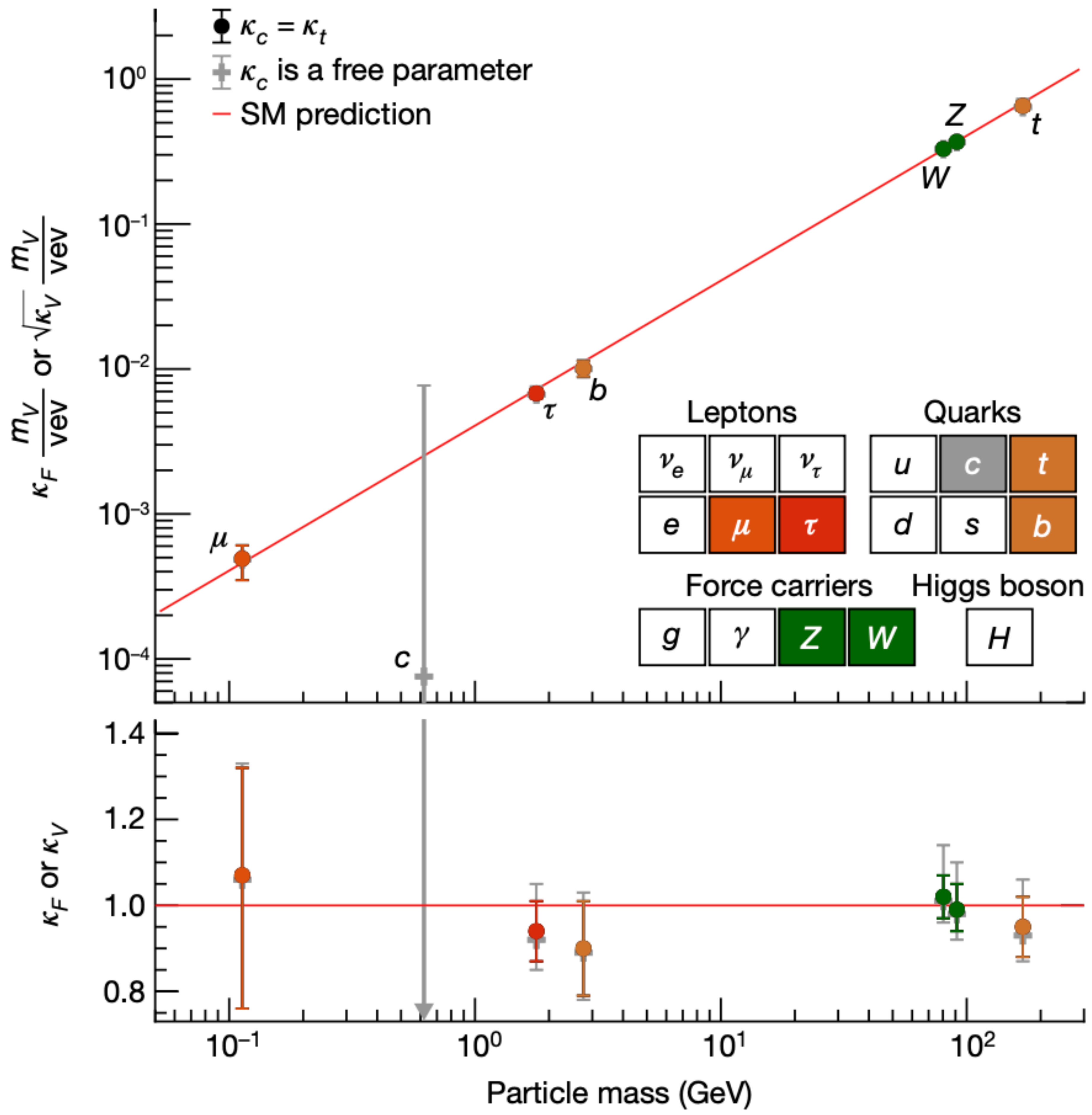




The Higgs @10

Where we are ~ today

- The coupling of many different particles to the Higgs have been observed - to date all agree with SM expectations



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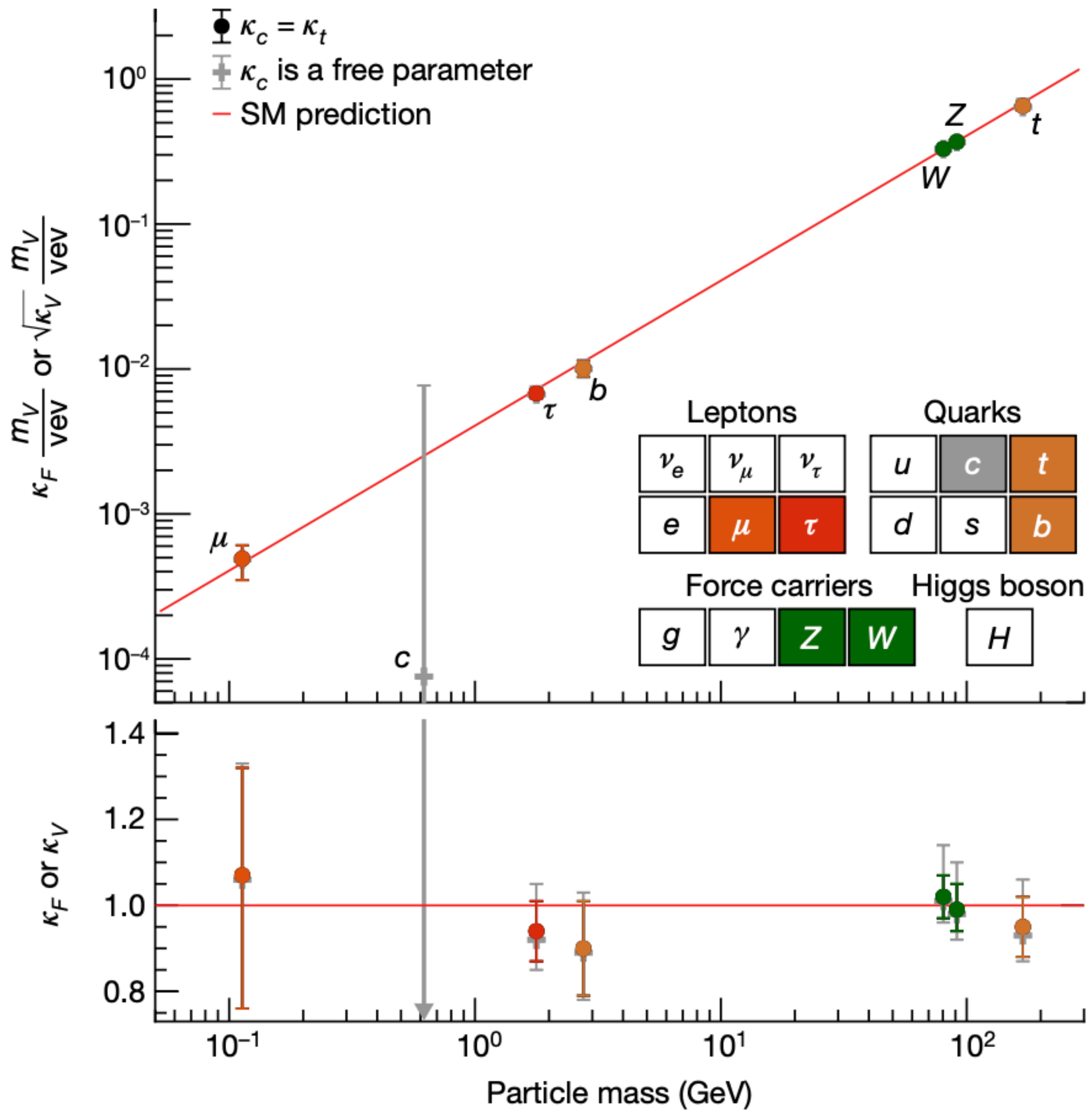
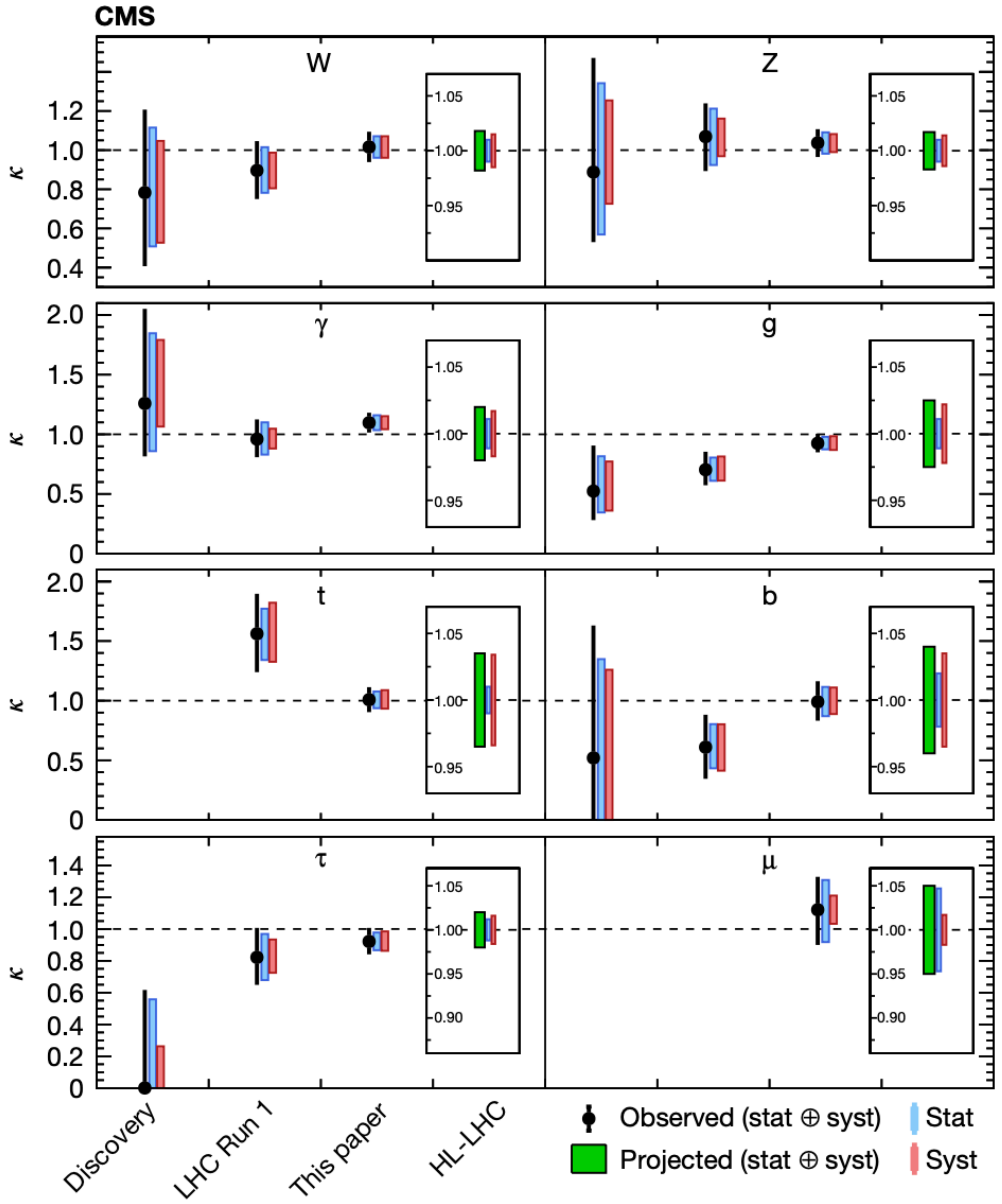


with HL-LHC data, the coupling modifiers will be measured to a few % precision



The Big Questions

What we know we don't know

- How can the Higgs boson be so light?
- What is the mechanism behind electroweak symmetry breaking?
- What is Dark Matter made out of?
- What drives inflation?
- Why is the universe made out of matter?
- What generates Neutrino masses?

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Karlsruhe Institute of Technology

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- Why is the universe made out of matter?
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...

The answers to these questions have to be *outside* of the Standard Model!

The Way Forward

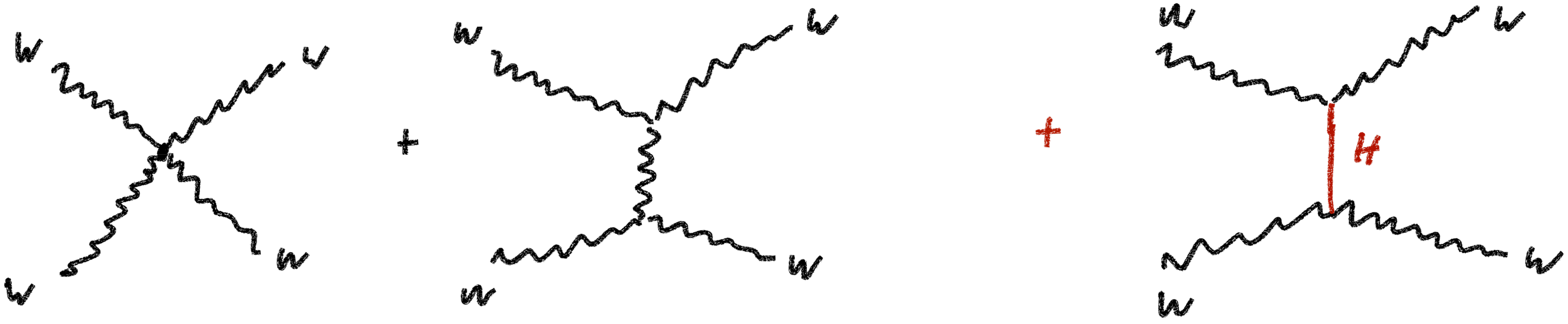
- What we do know:
  - The Higgs is connected to all particles we know - and is at the center of some of our questions
  - Most hints for new phenomena come from the electroweak + Higgs sector:
    Expect some new particles to be charged under electroweak interactions

- What we don't know:
  - The energy scale of new particles / phenomena

No Guarantees

The challenge of making the case for future colliders

- Before the start of LHC: The “no-lose theorem”



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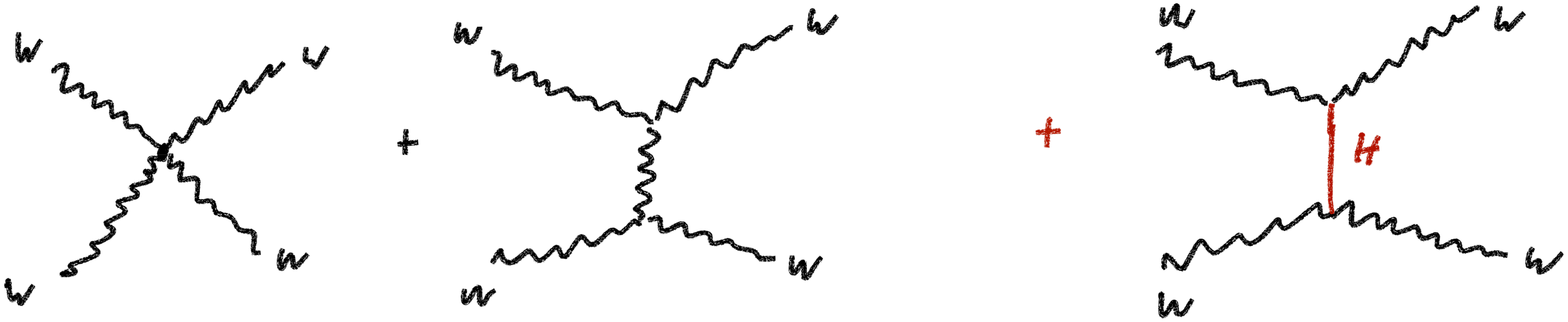

With the “completion” of the standard model:

No certainty - and no clear indication of the energy scale of new phenomena

Asking for Directions

Promising Areas for a New Precision Program

- Study with highest precision what has not yet been scrutinized in depth:
  The Higgs Boson, the top quark

- Revisit areas of previous precision exploits with a whole new level of scrutiny:
  The Z pole: Electroweak, QCD, flavour; the W boson

- Explore the unknown:
  Search for new phenomena at high energies,
  and with extreme luminosity / sensitivity at lower energies

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

The Higgs Boson

model-independent study
of all accessible couplings

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

Karlsruhe Institute of Technology

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

The Higgs Boson

model-independent study of all accessible couplings

Higgs-Electroweak-Top Factory Physics Menu

A new precision program

Karlsruhe Institute of Technology

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push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

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Flavour Physics

use extremely large data sets to explore, resolve and understand the puzzles in the flavour sector

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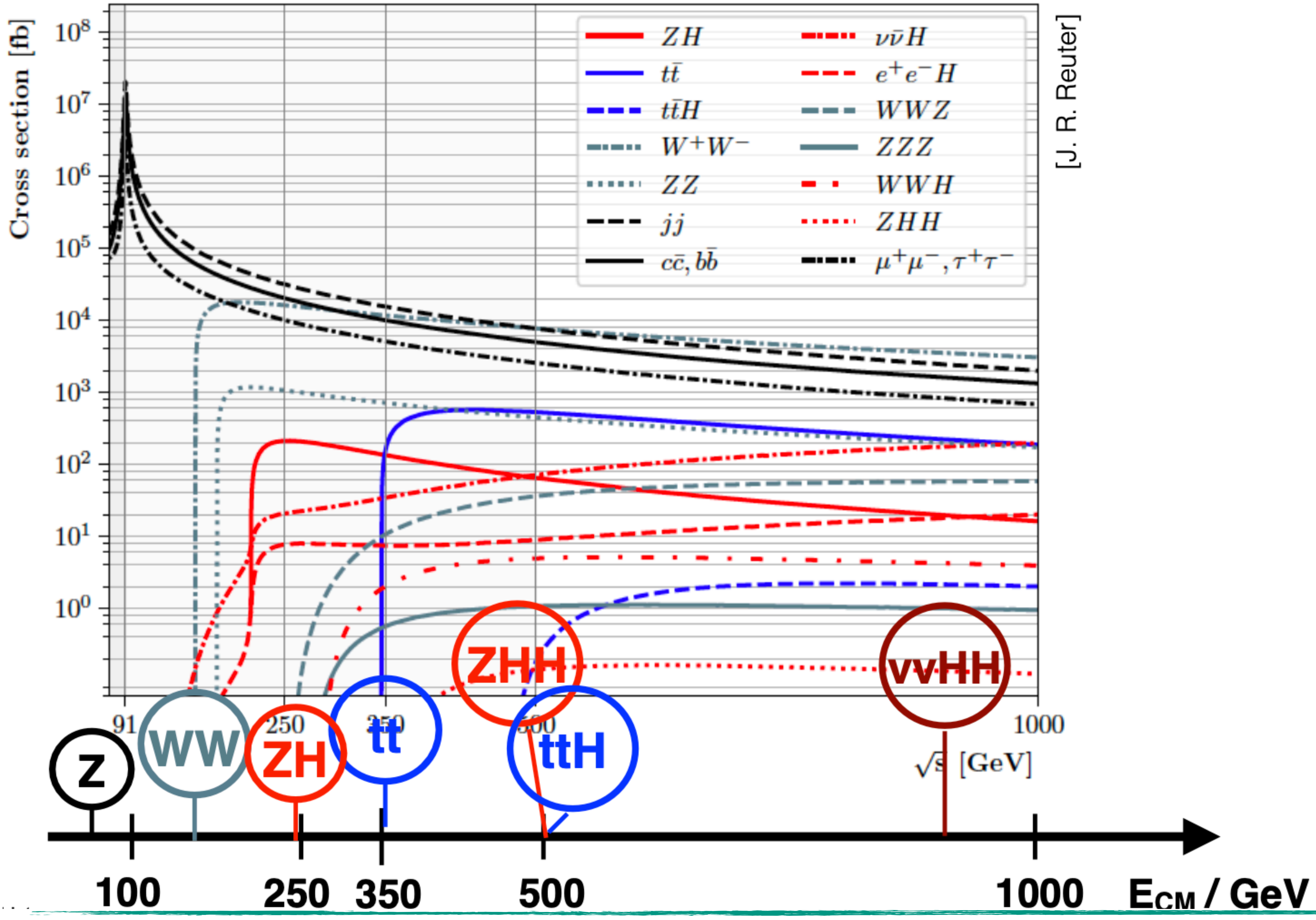
use extremely large data sets to explore, resolve and understand the puzzles in the flavour sector

New Particles

searches for weakly coupled new particles with high luminosity / high energy in a clean environment

Perspectives of Energy

Bringing together physics goals and collider energy



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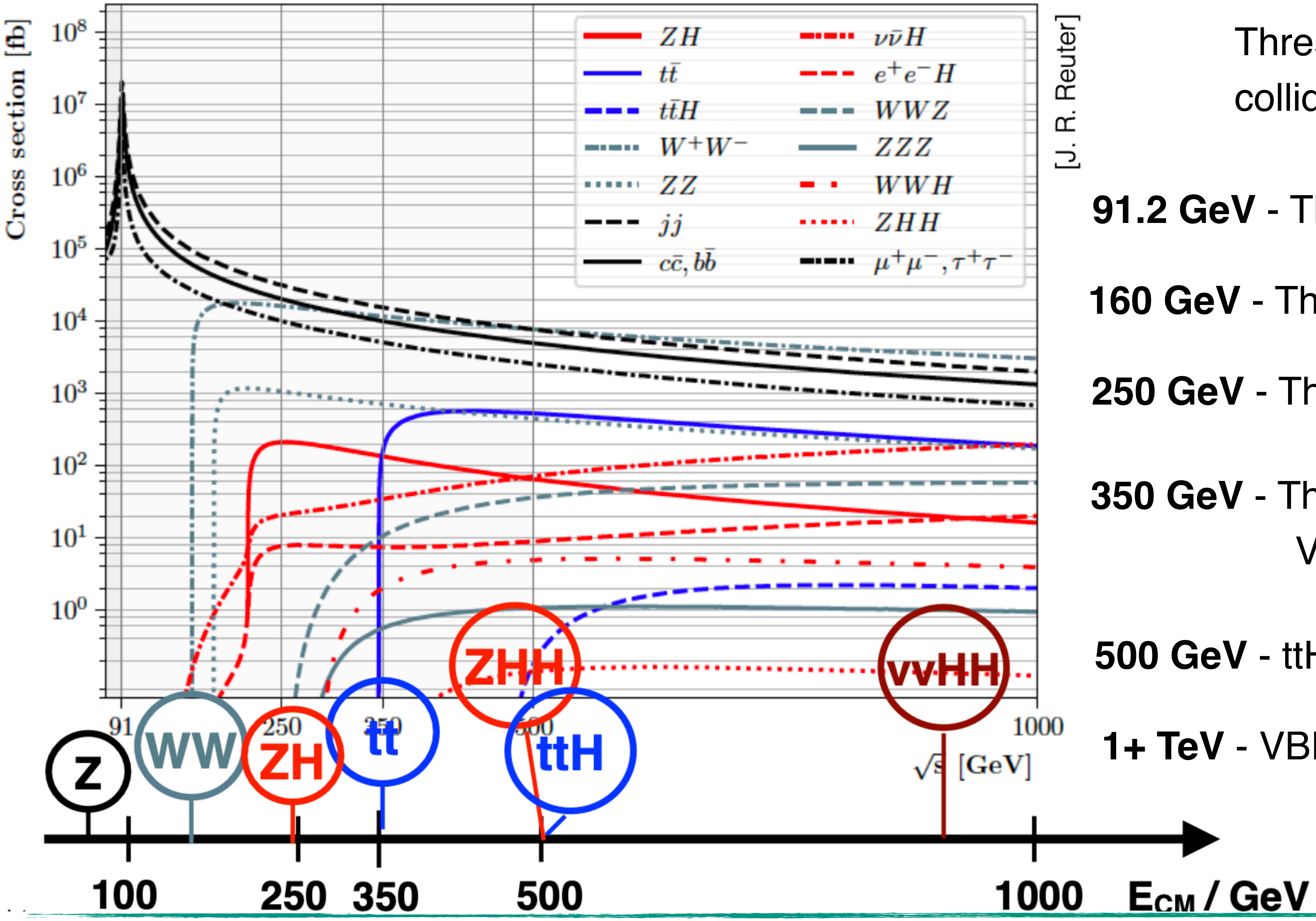


Thresholds and cross sections set collider energy targets:

91.2 GeV - The Z pole

160 GeV - The WW threshold

250 GeV - The ZH maximum

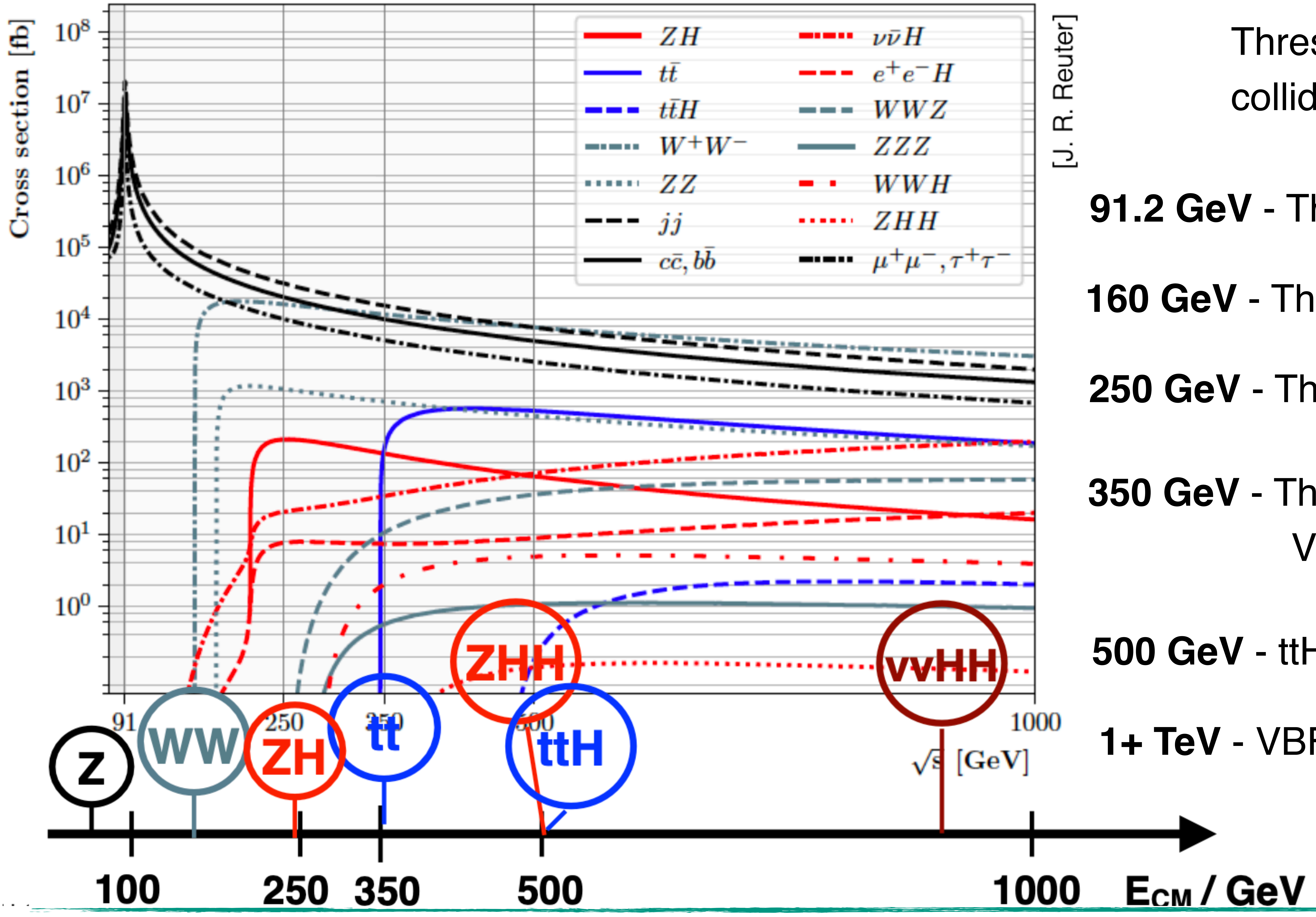
350 GeV - The top threshold,
VBF Higgs production

500 GeV - ttH, ZHH

1+ TeV - VBF double Higgs

Perspectives of Energy

Bringing together physics goals and collider energy



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Precision electroweak, Flavour, QCD, …

Higgs properties & couplings

Top properties, Top as probe

Direct top Yukawa Higgs selfcoupling

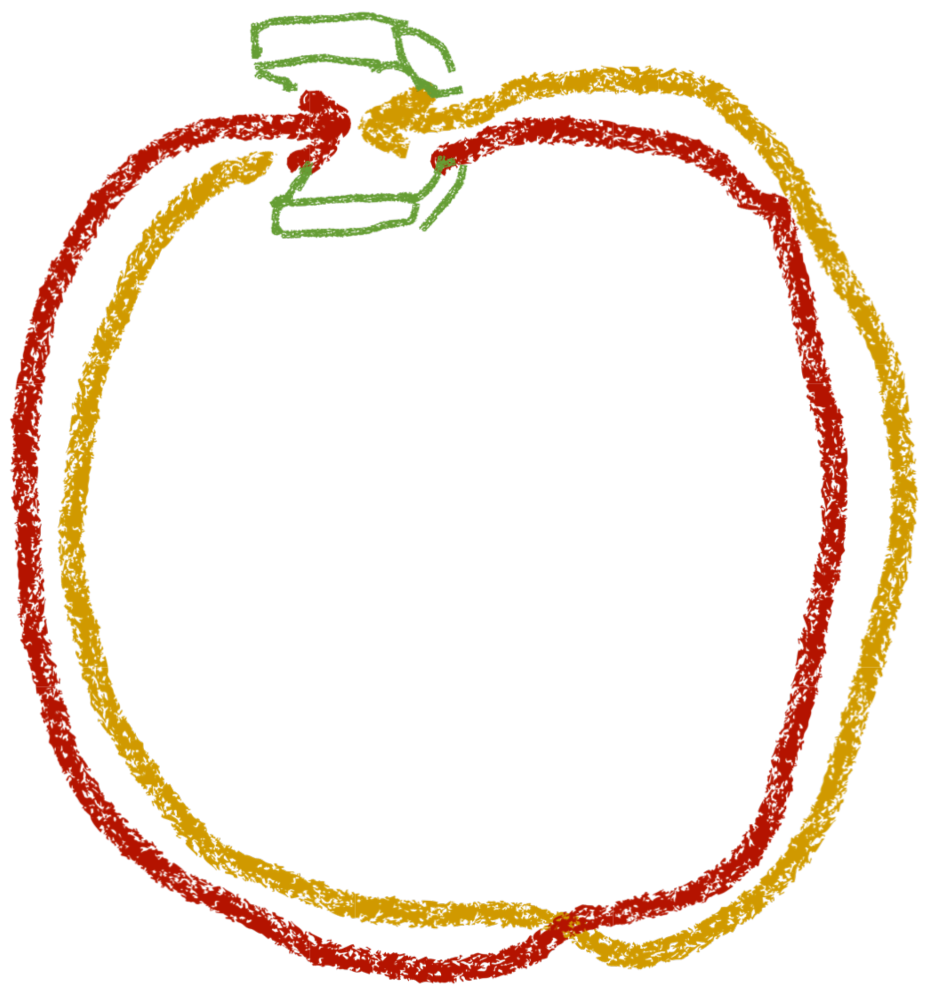
Search at the energy frontier

Collider Types

Circular and Linear

Circular Colliders:

Collision of two particle beams on circular orbits in opposite direction



Re-use of non-collided particles in future turns, acceleration can proceed over many revolutions. Need for bending magnets to keep particles on track.

Collider Types

Circular and Linear

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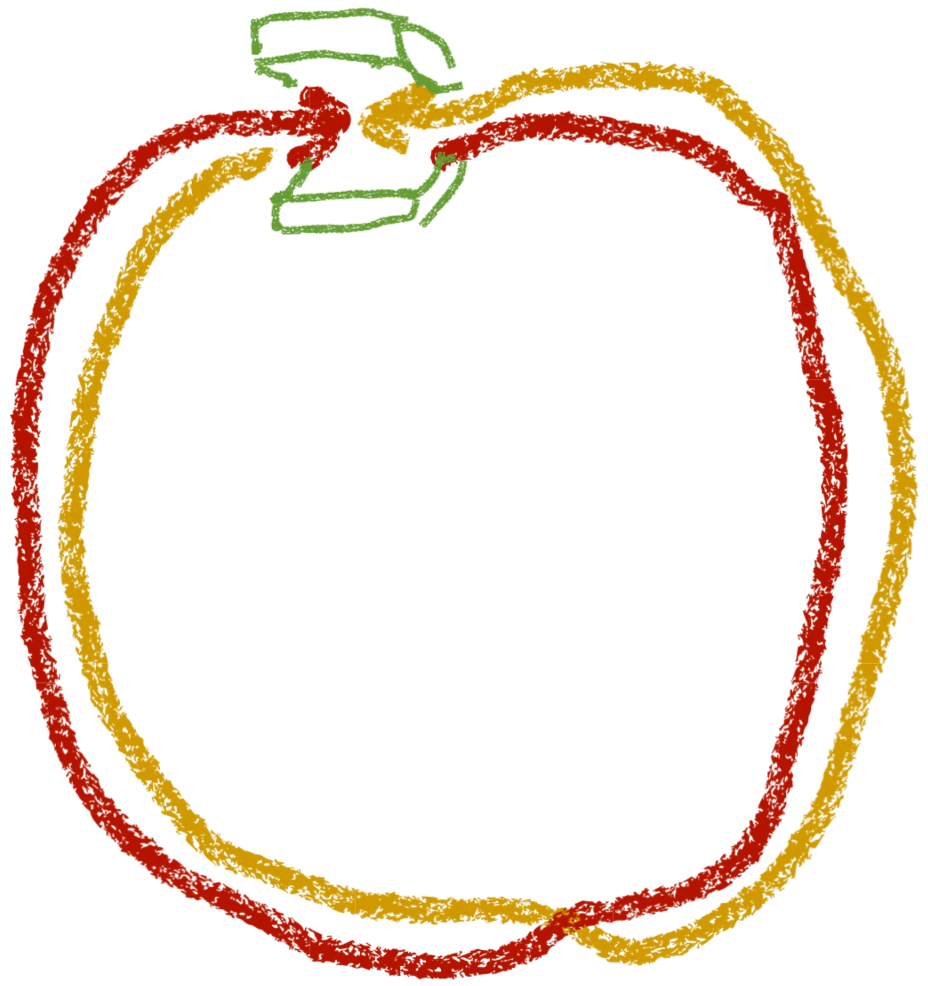

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Linear Colliders:

Collision of two particle beams from linear accelerators pointed at each other

Full acceleration in a "single shot", unused particles are lost. No need for magnets

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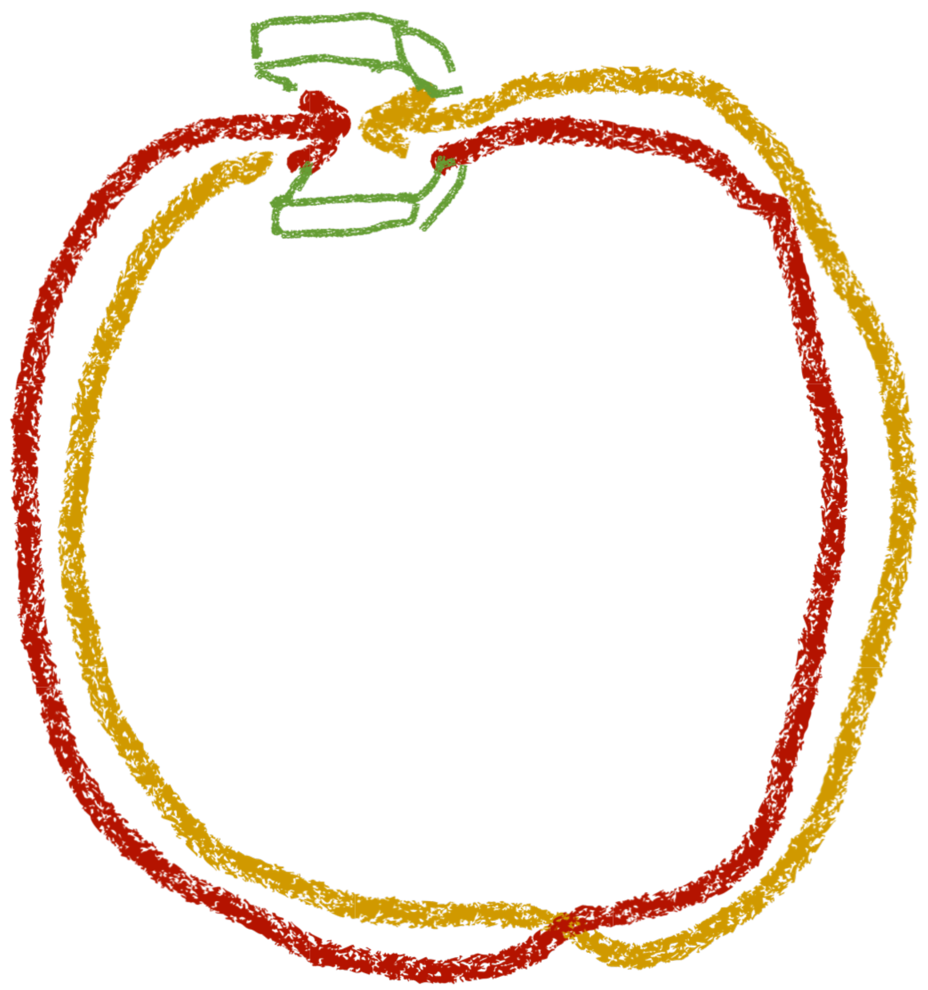

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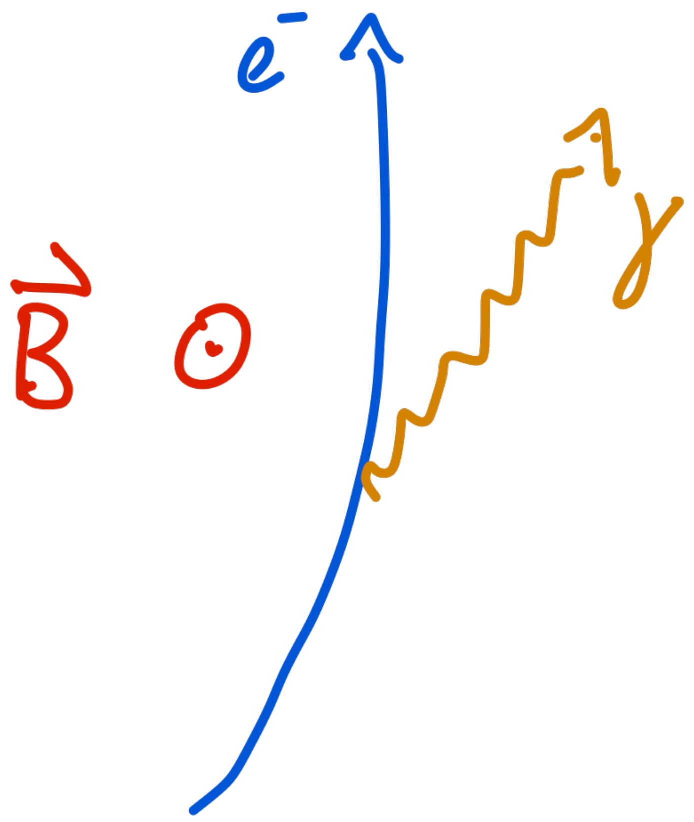


Linear Colliders:

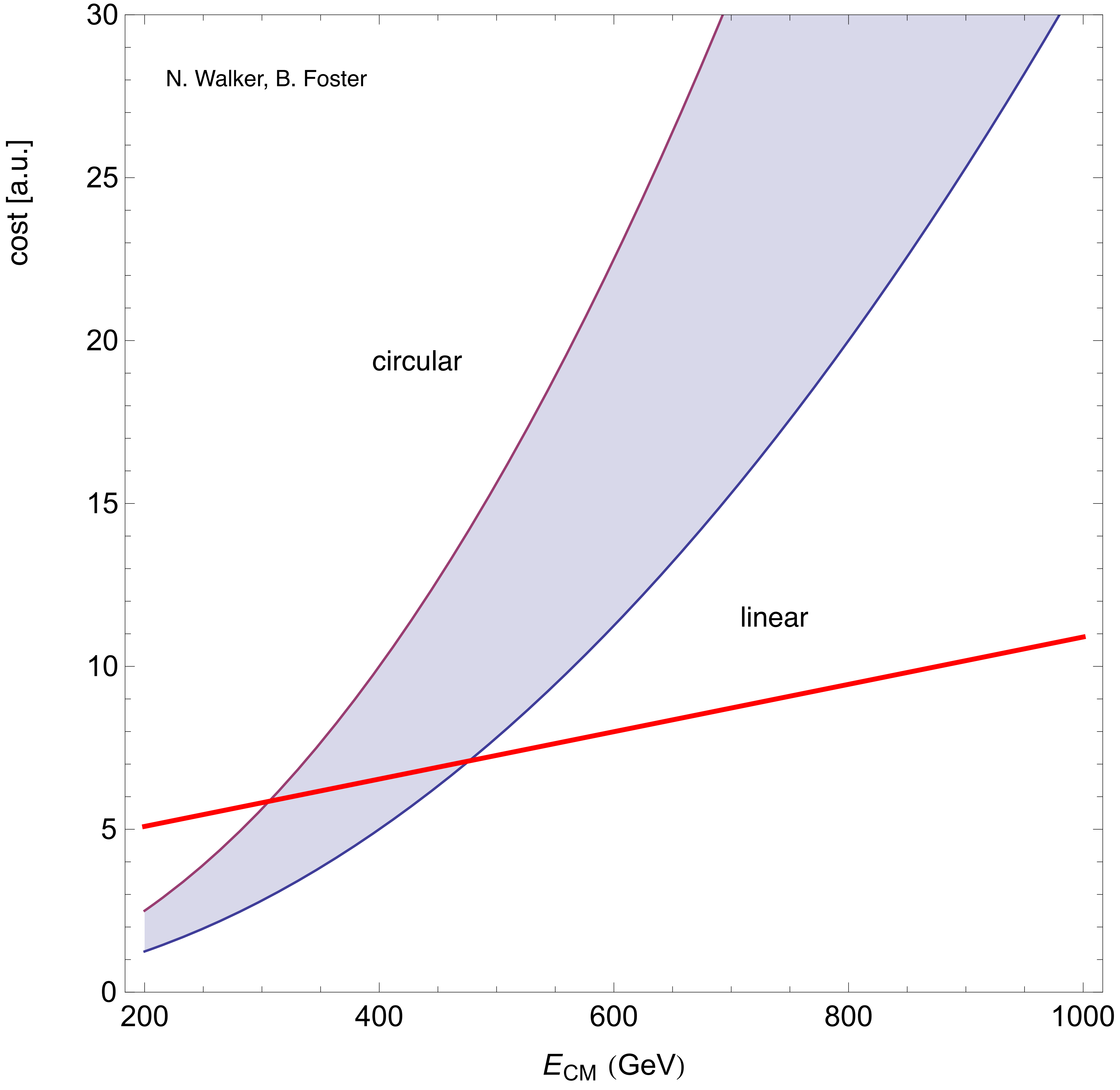
Collision of two particle beams from linear accelerators pointed at each other

Full acceleration in a "single shot", unused particles are lost. No need for magnets

Makes sense for light particles at high energy: Synchrotron radiation losses scale with E^4 and m^{-4} and r^{-2}

Circular vs Linear e+e-

Differences in luminosity and energy reach



- Circular colliders very efficient at low energies, at higher energies synchroton radiation becomes a key limiting factor:
  Power proportional to E^4/R^2 - Loss per turn ~ E^4/R

⇰ The scaling of the size of the facility with energy is very different:

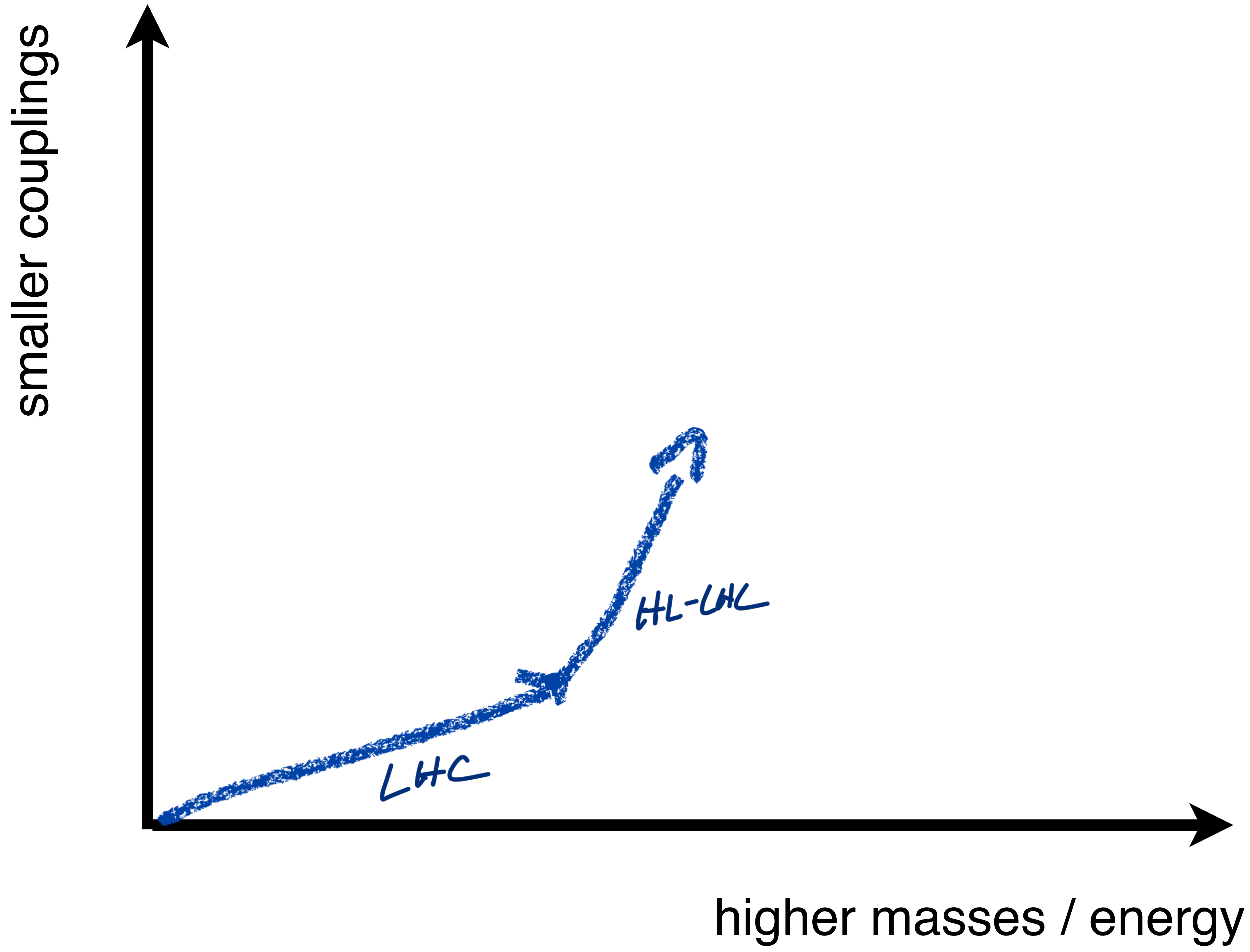
- Circular colliders have to grow at least with E^2
- Linear colliders grow with E - but inherently more complicated, with a large cost offset

Collider Options

Conceptual differences in physics reach

higher luminosity / statistics

=



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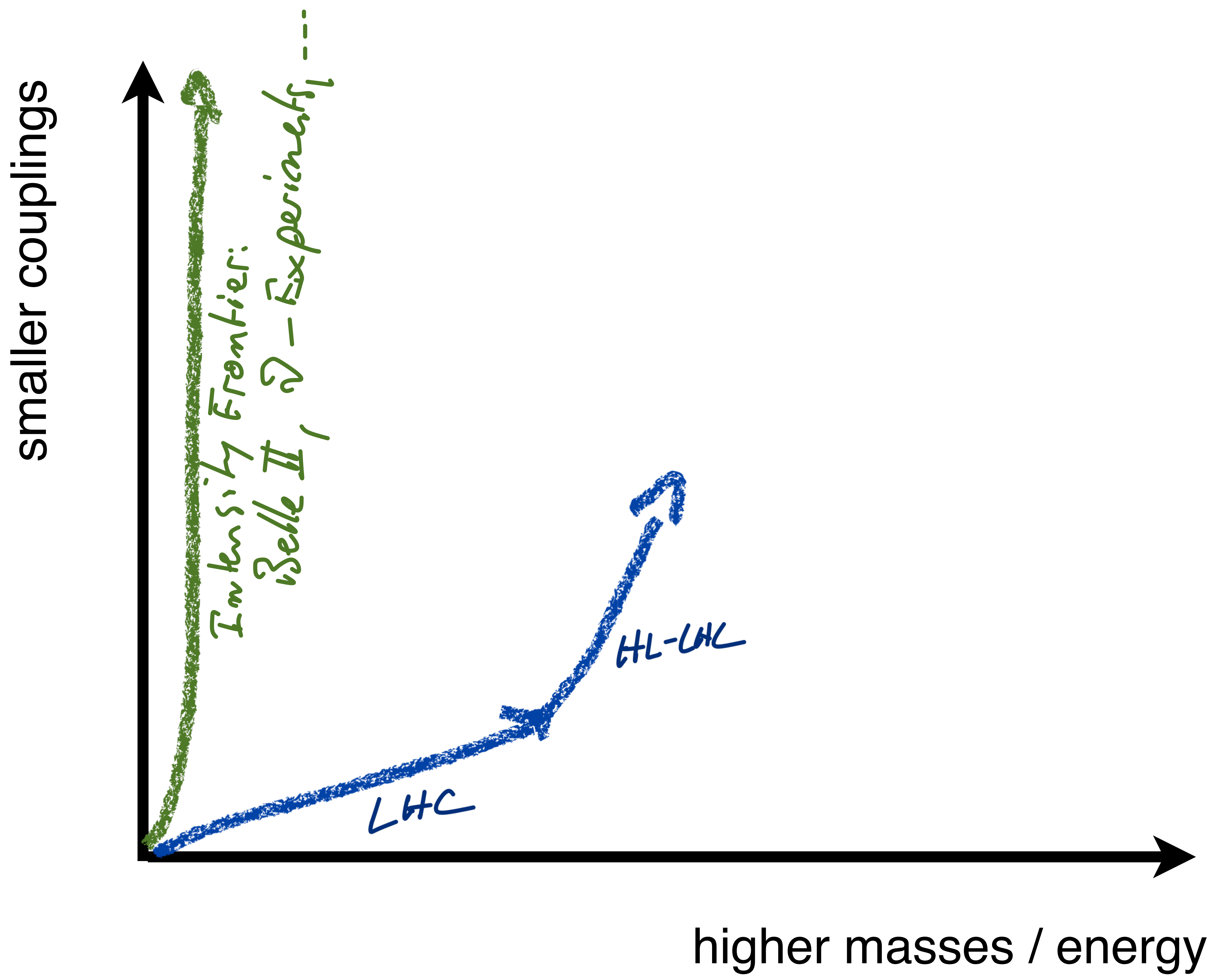

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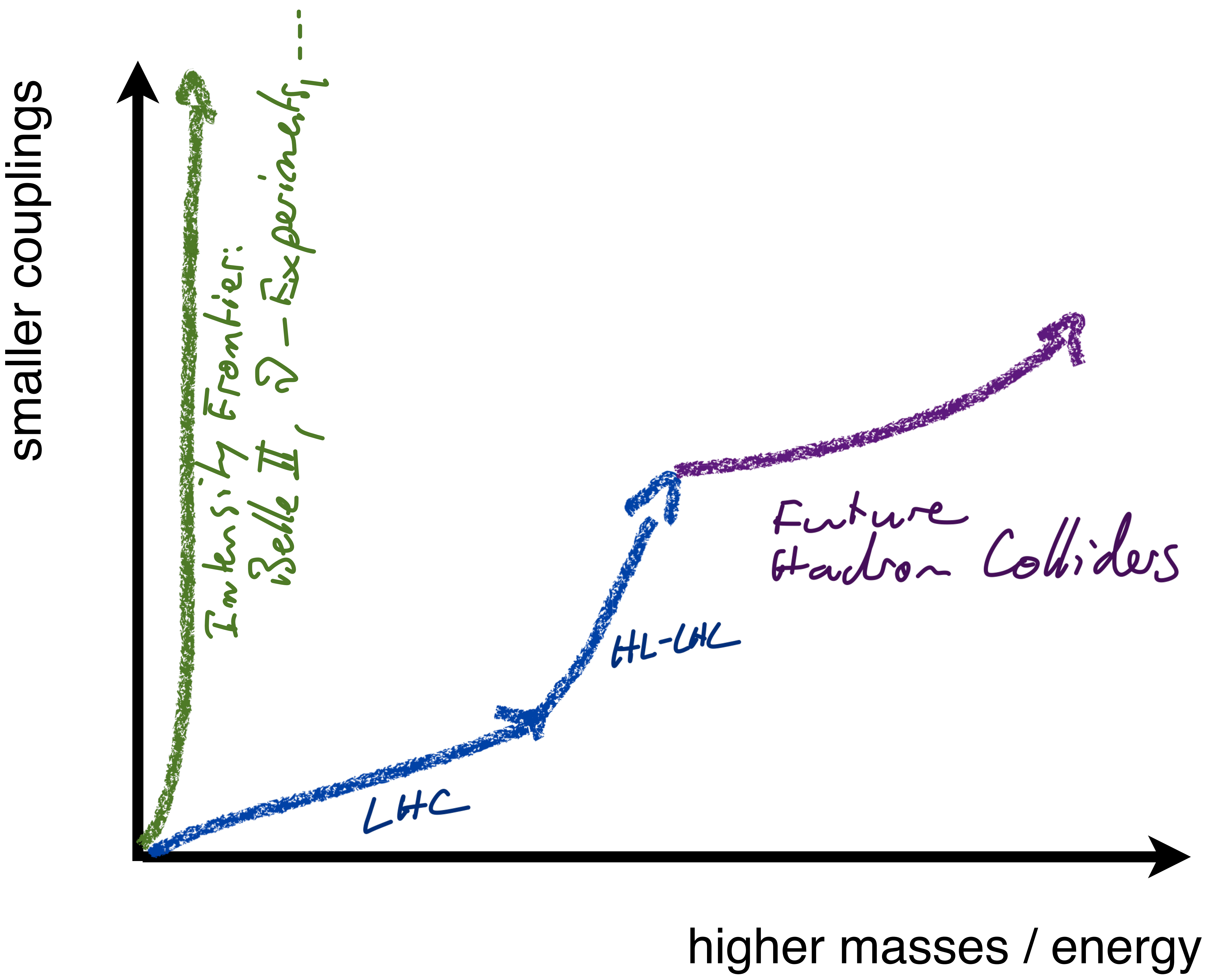

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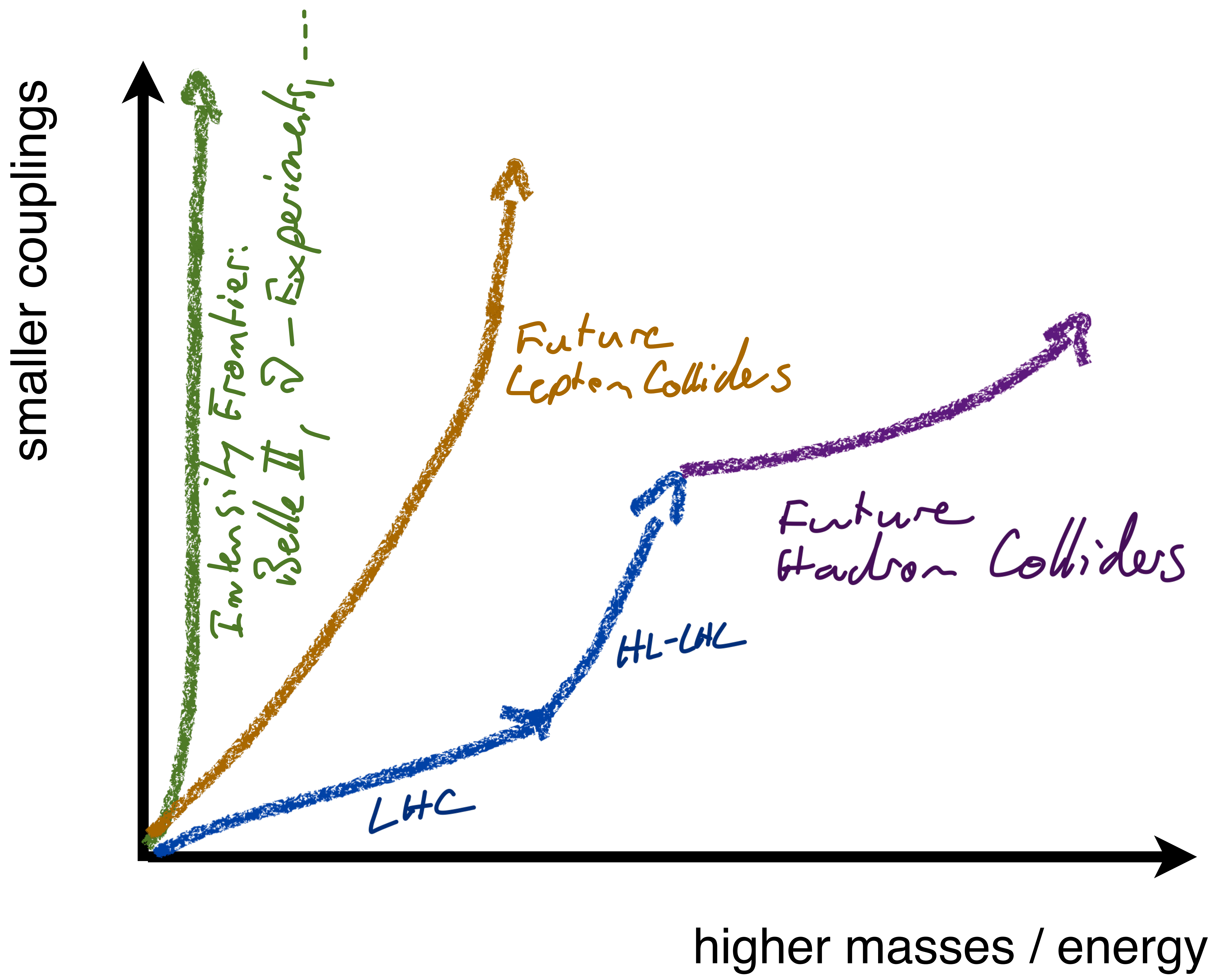

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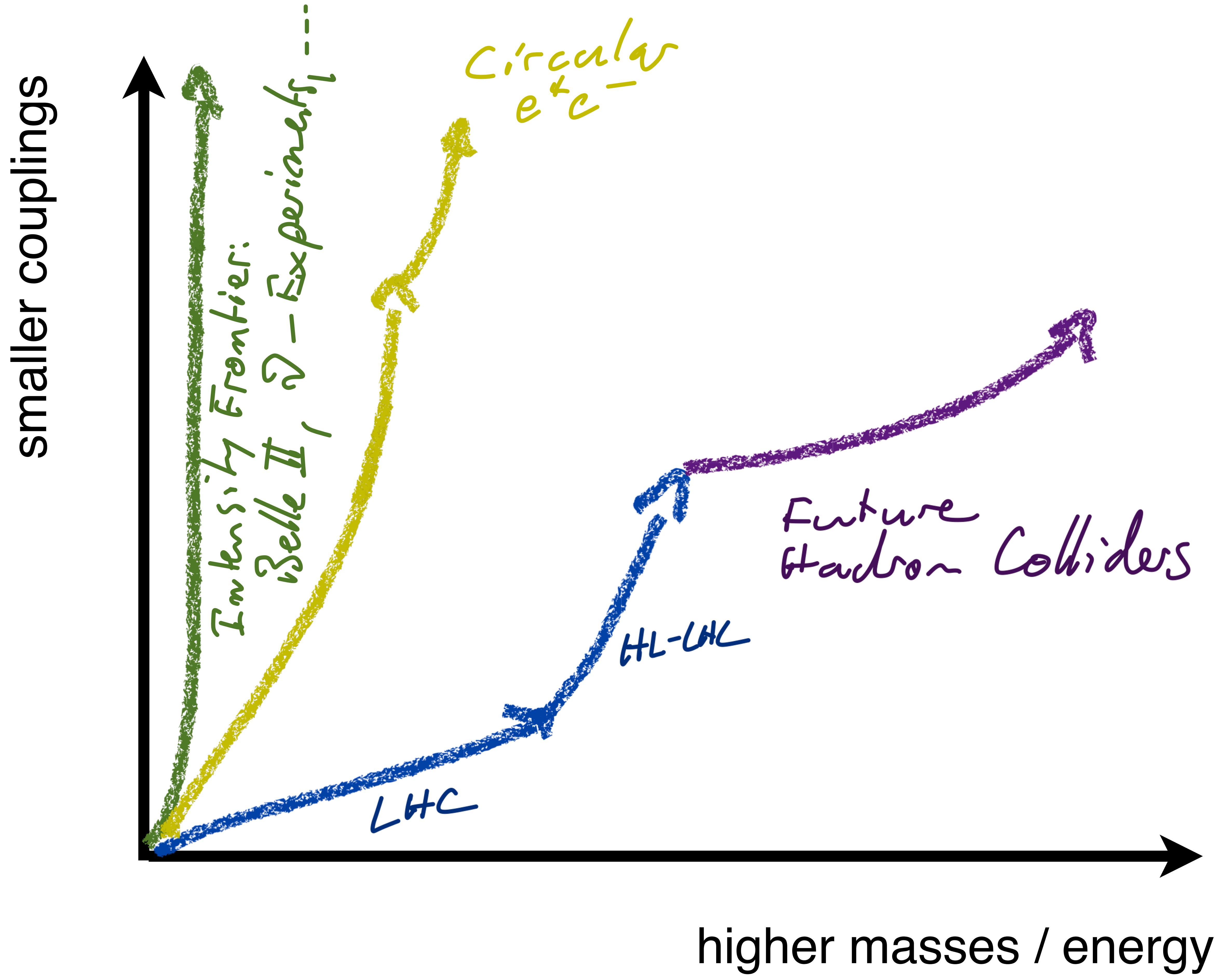

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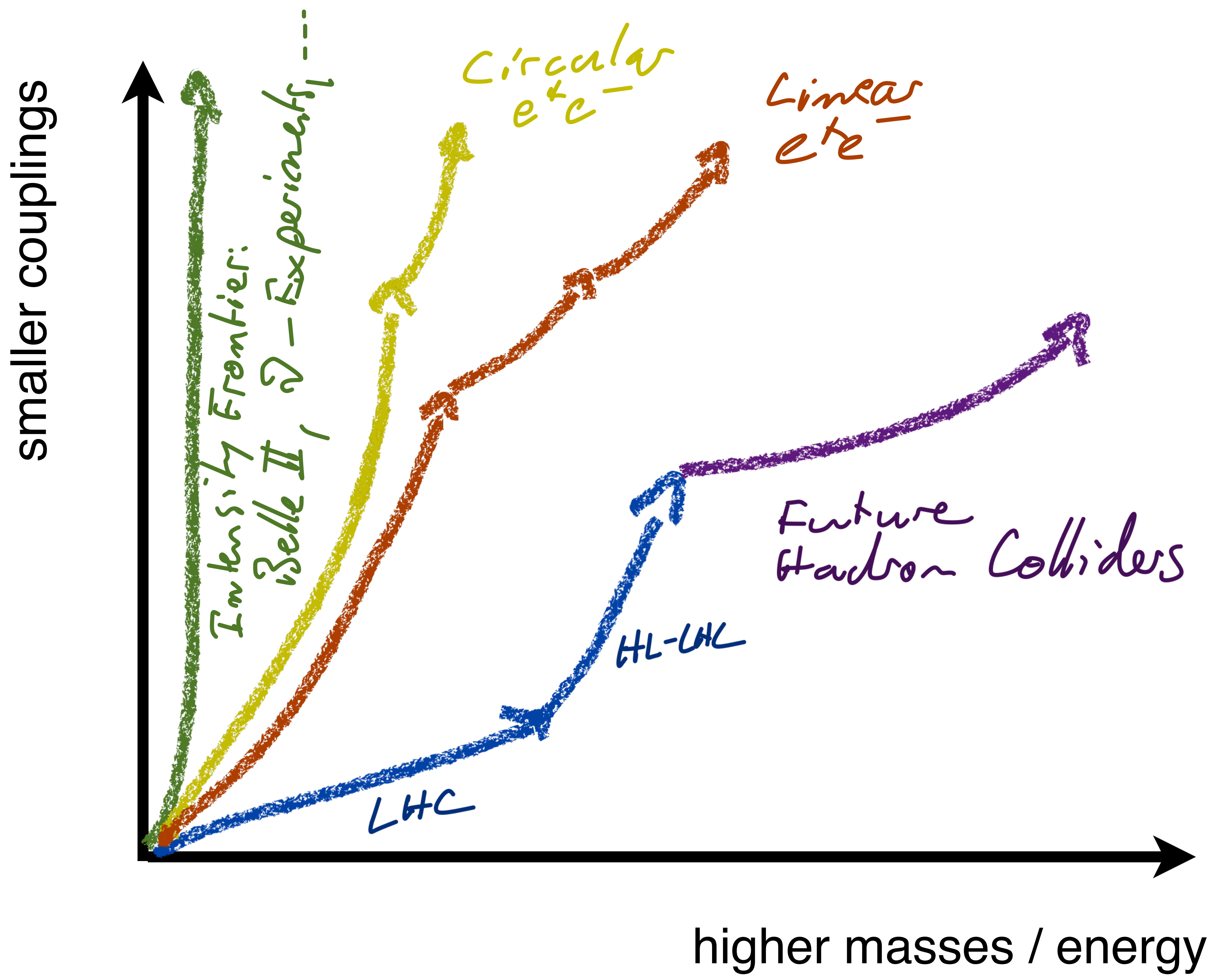
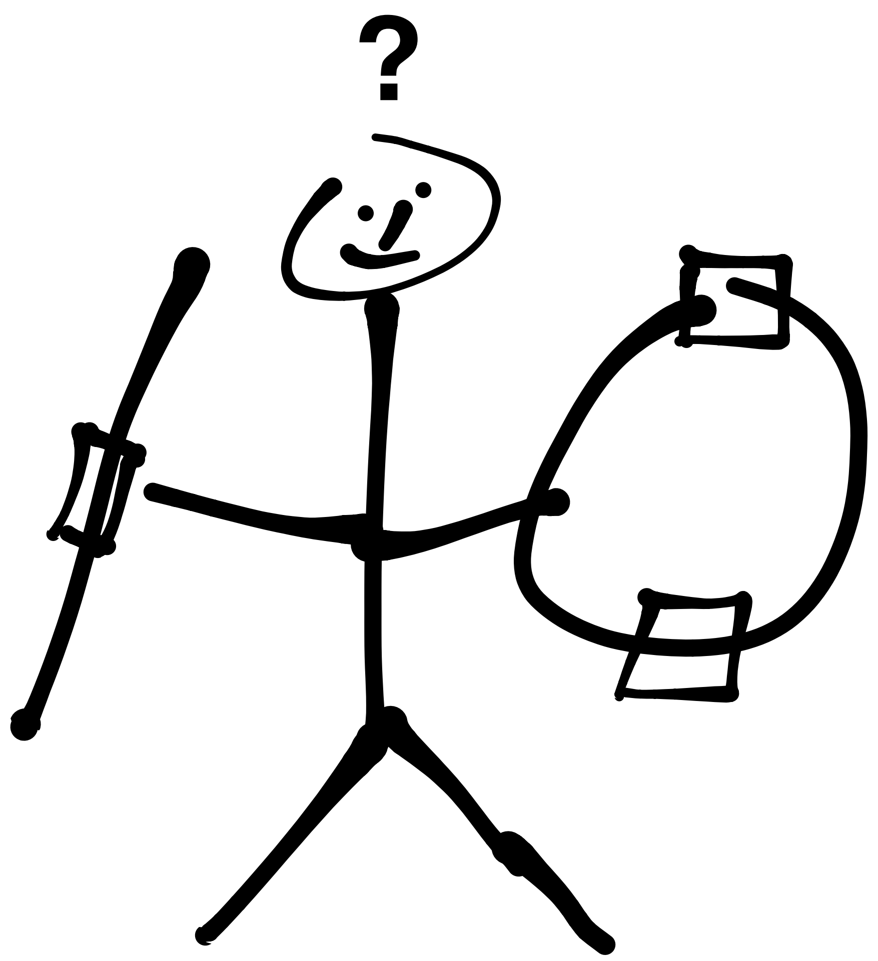


Evolving Collider Infrastructure

Maximising physics output, react to discoveries

- A general challenge: Colliders and the associated infrastructure are expensive - making long-term scientific exploitation mandatory
- It is basic research:
  Discoveries or new insights may call for changes in direction



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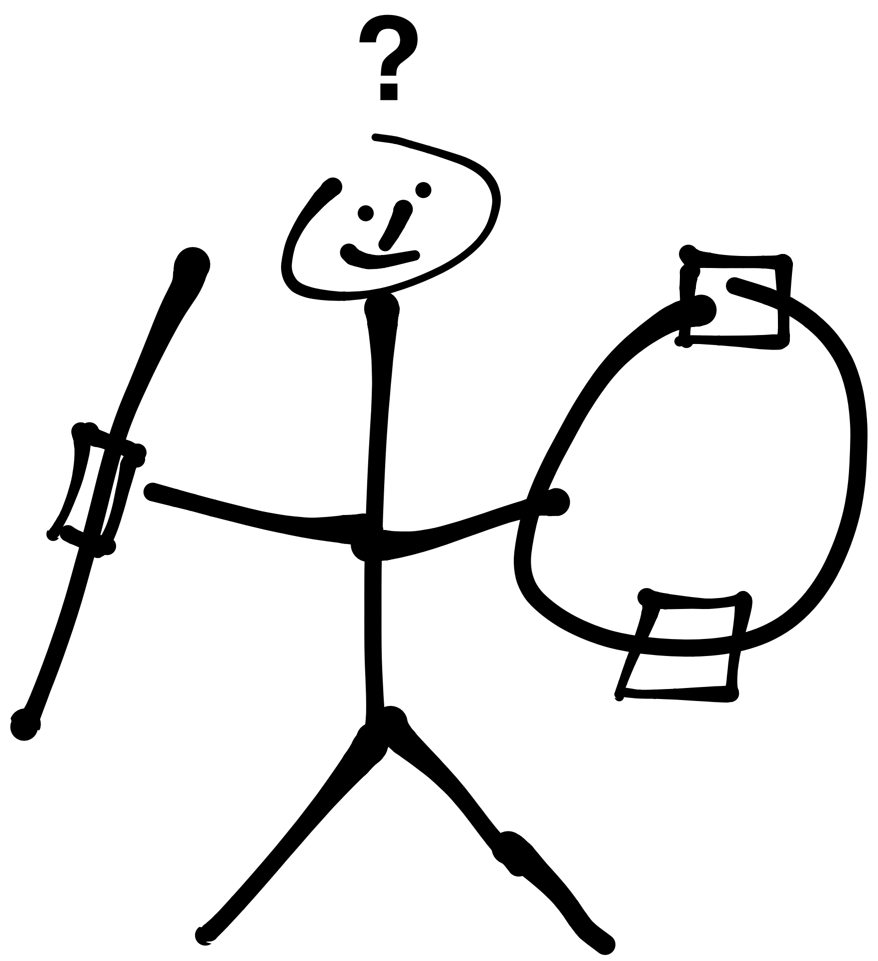

Evolution scenarios:

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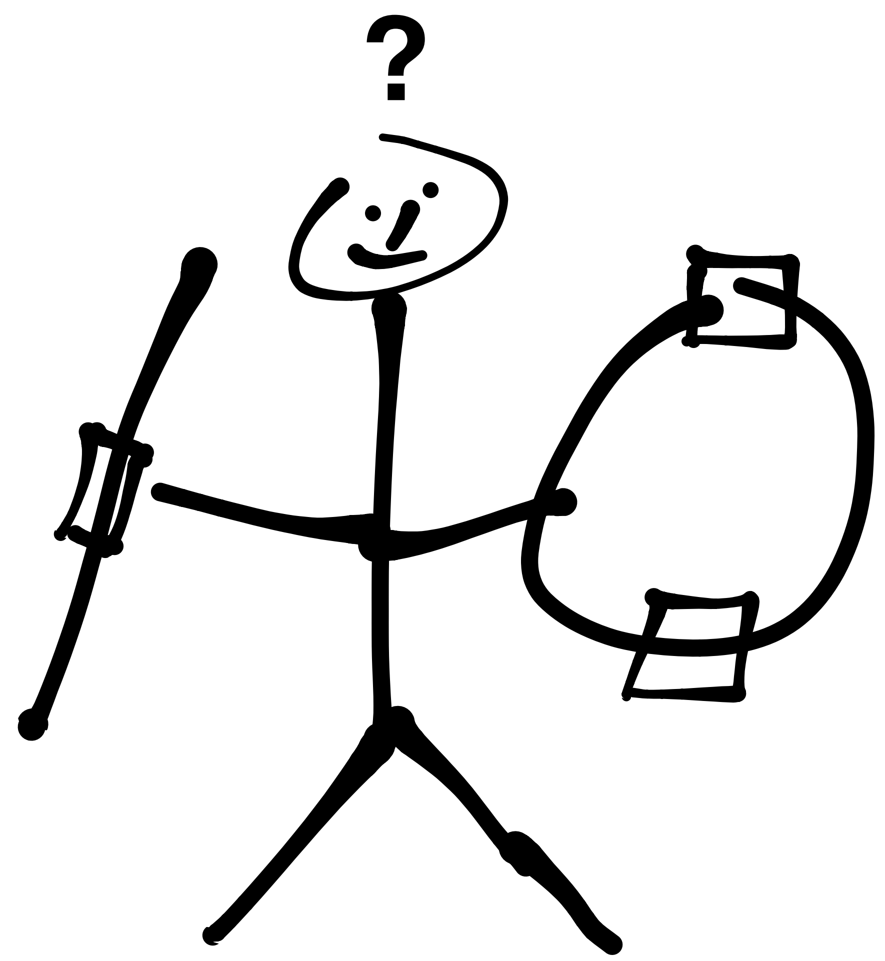

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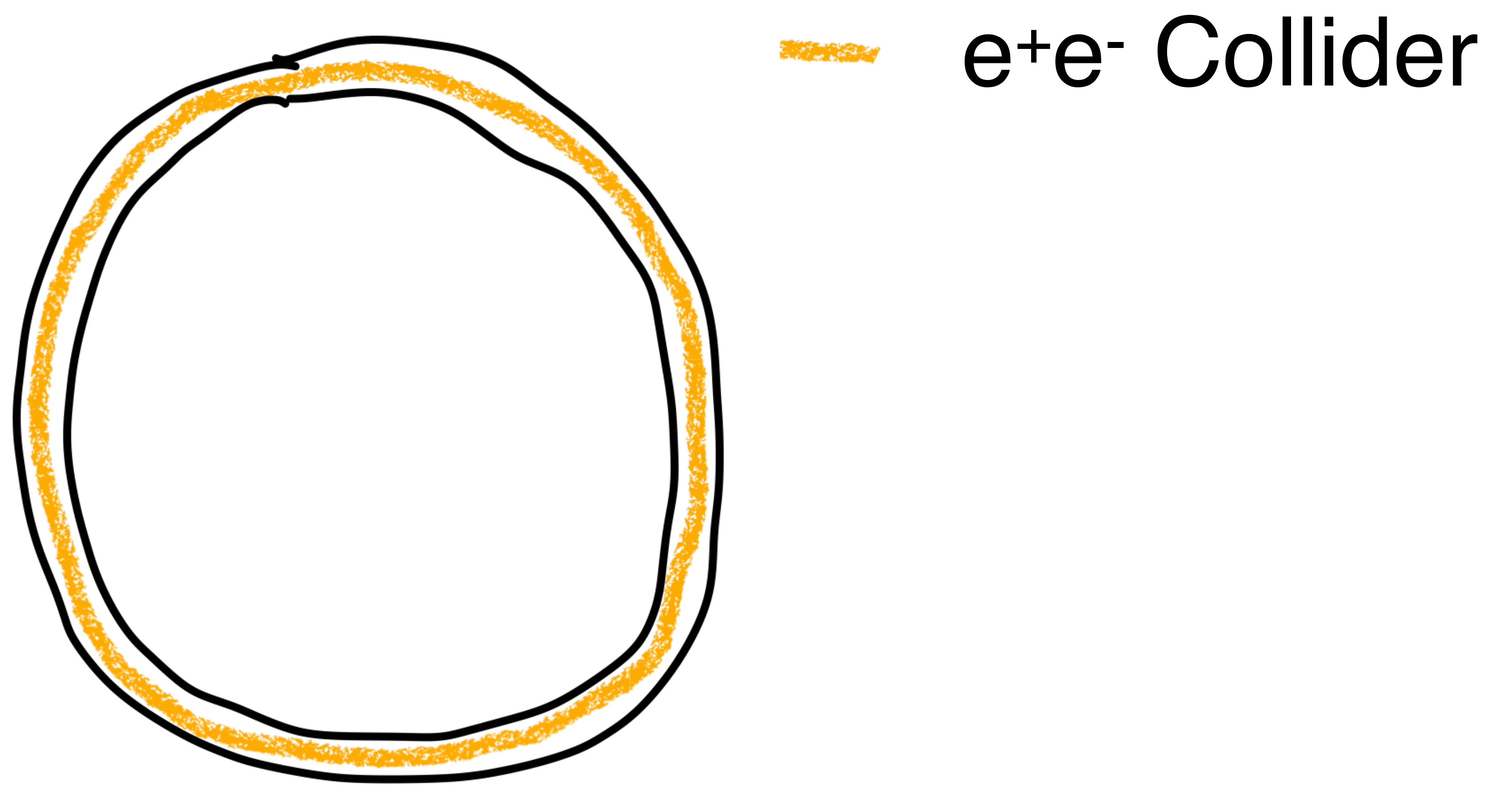

A big ring: Full length required on day one, then can be used for a lepton and a hadron collider sequentially

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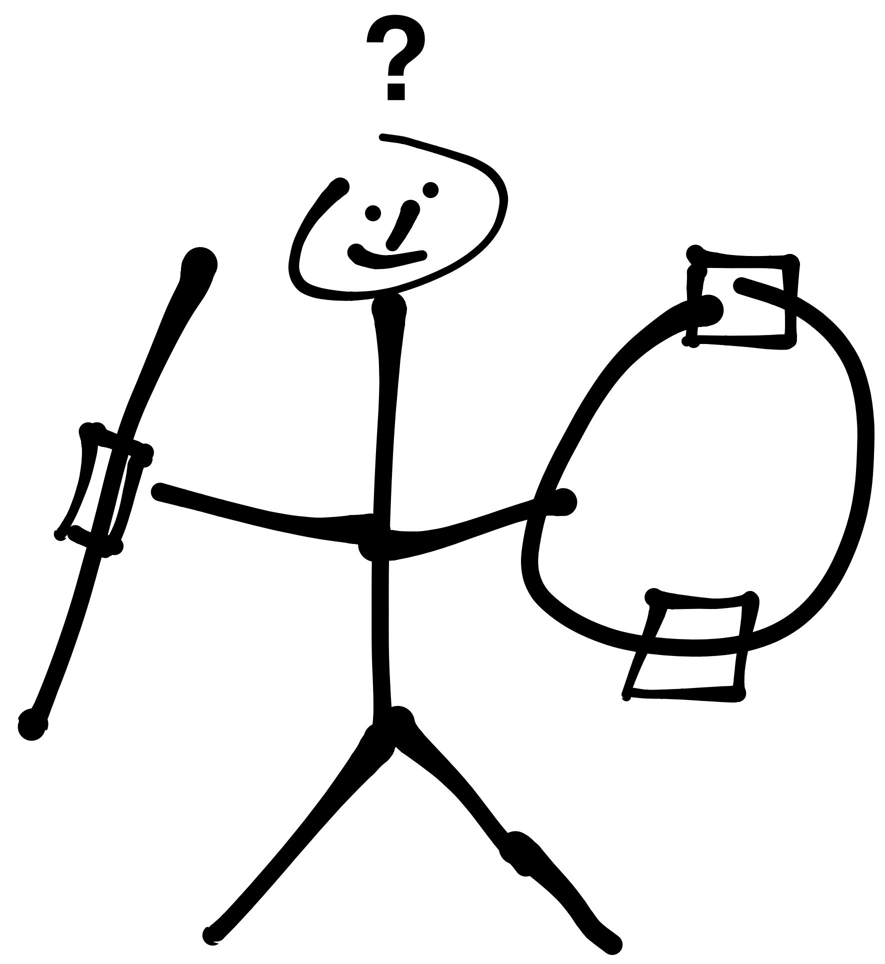

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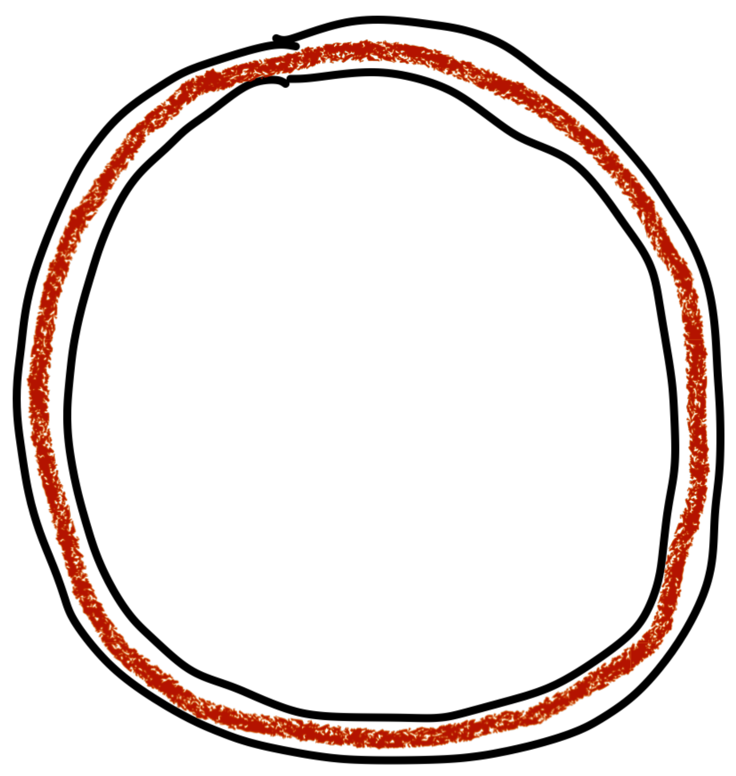

e^+e^- Collider

Hadron Collider

highest possible
energy:
100(+) TeV

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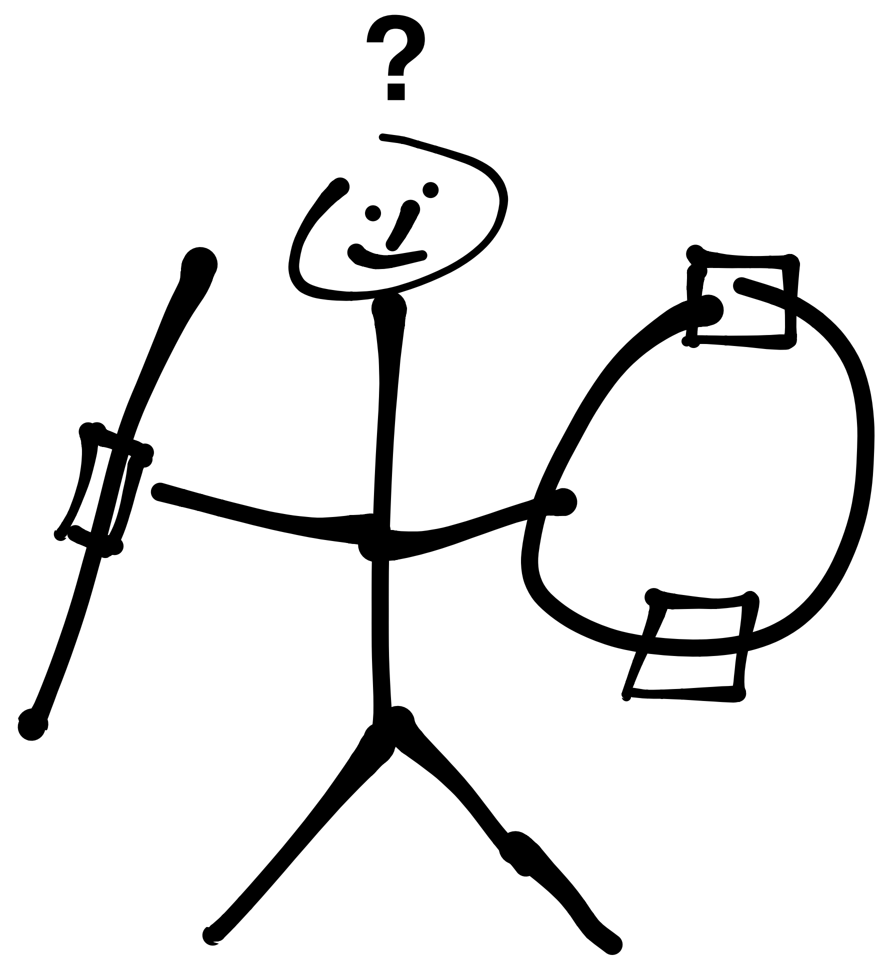

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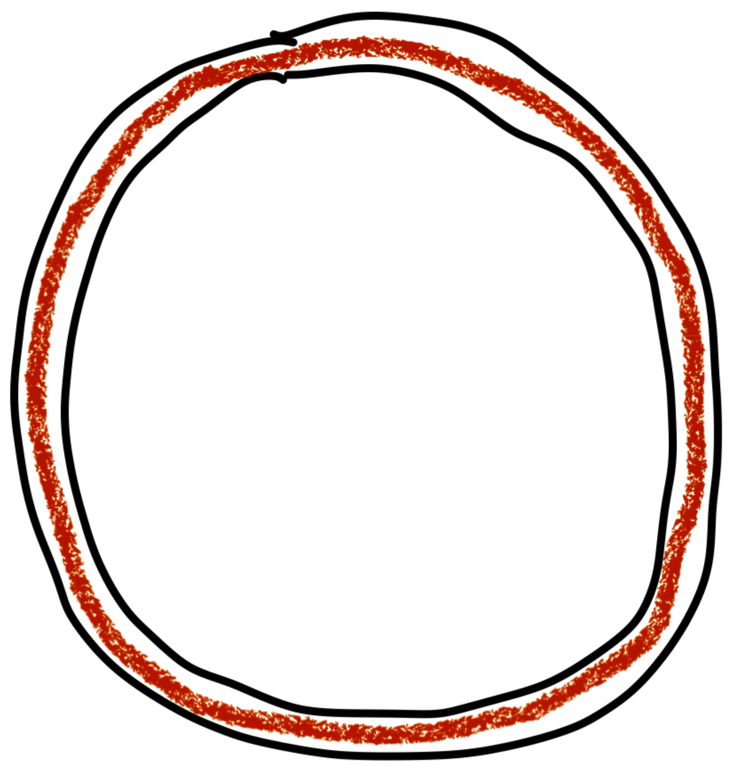

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e^+e^- Collider

A linear collider: Step-wise extension, lepton collisions at different energies in sequence

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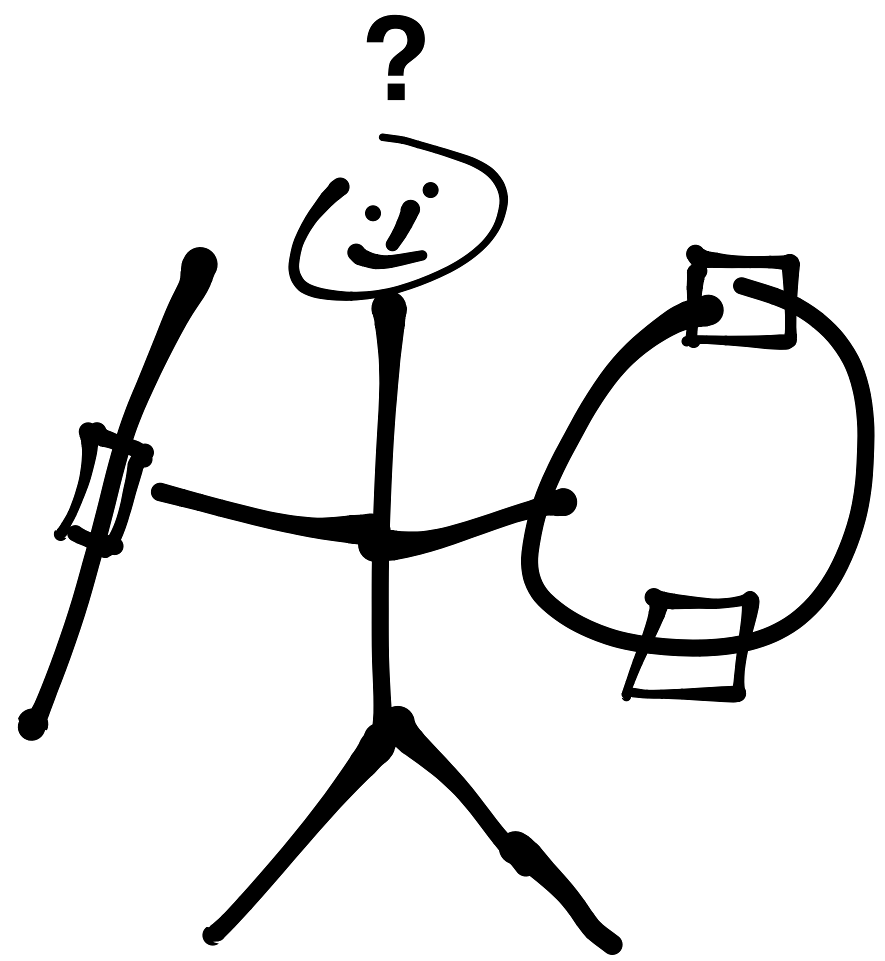

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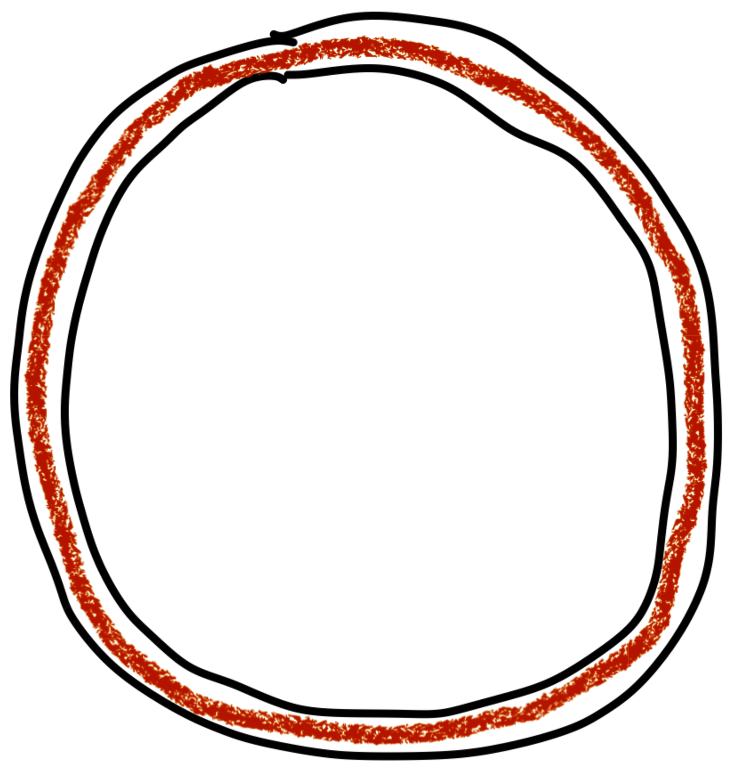

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longer tunnel: higher energy

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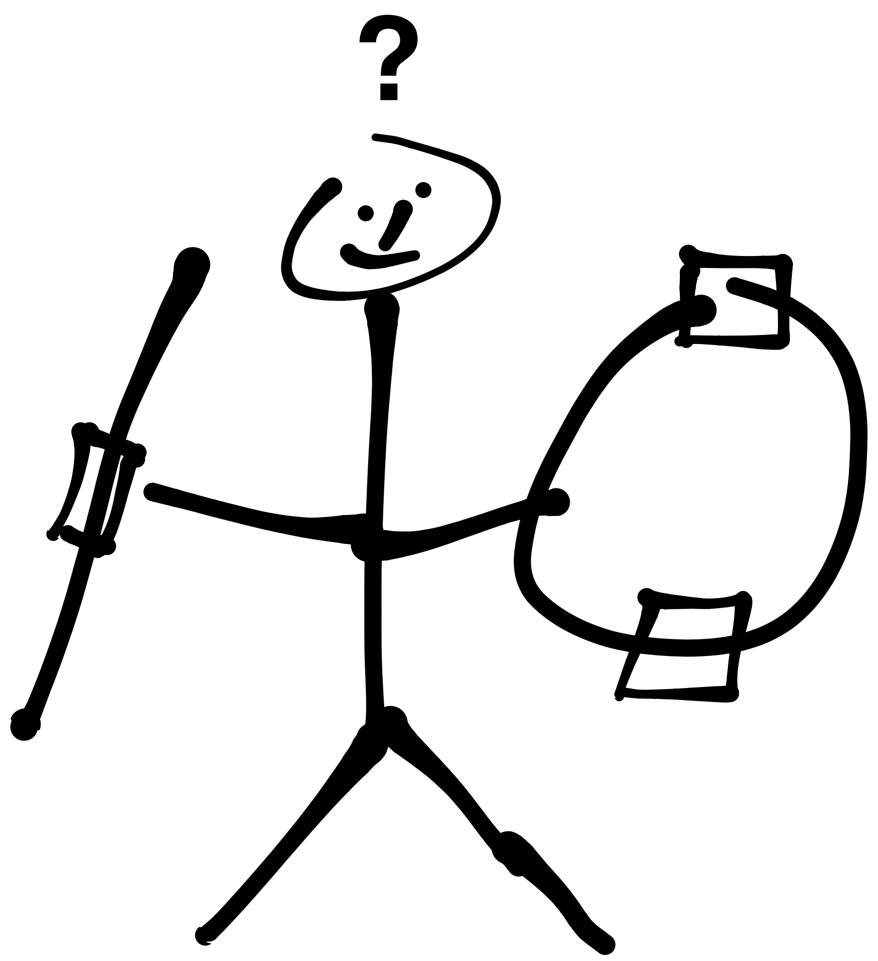

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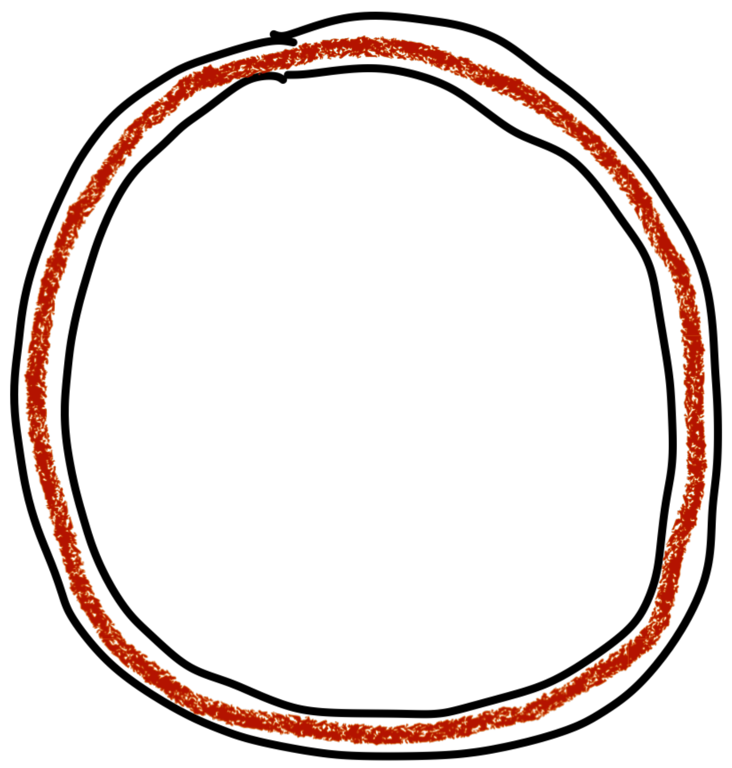

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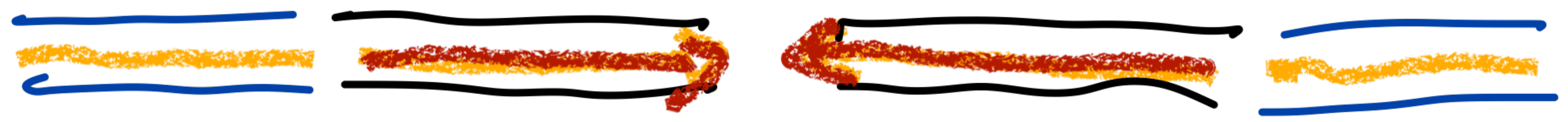

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longer tunnel: higher energy

new acceleration technology

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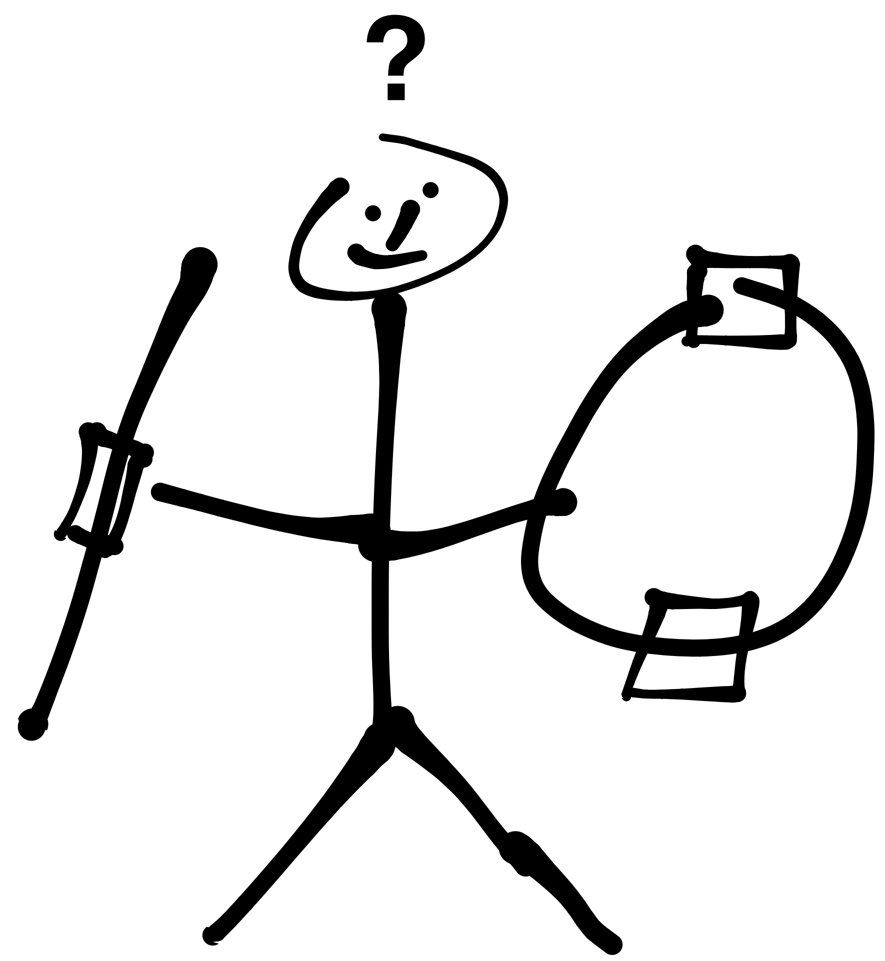
Evolving Collider Infrastructure

Maximising physics output, react to discoveries

Karlsruhe Institute of Technology



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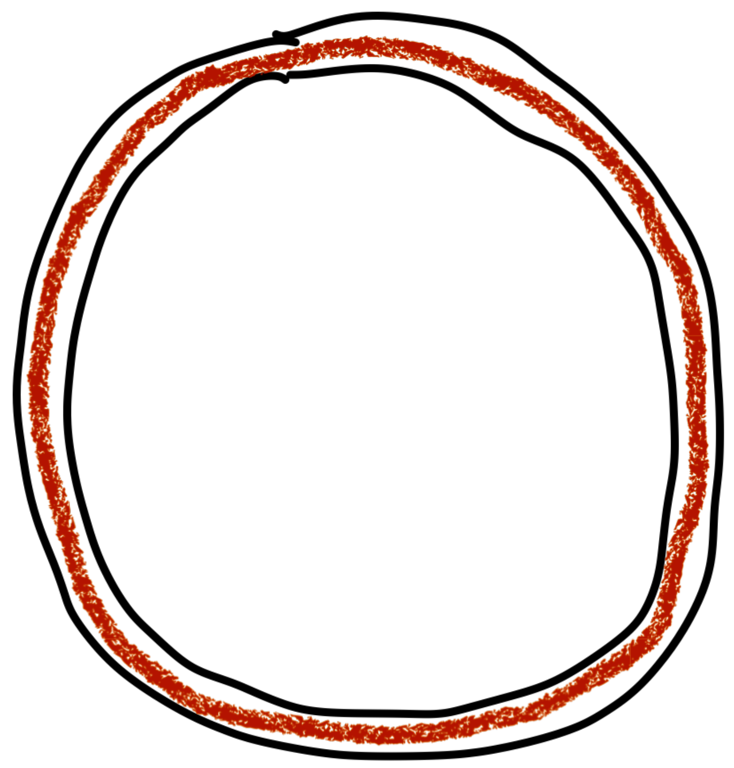

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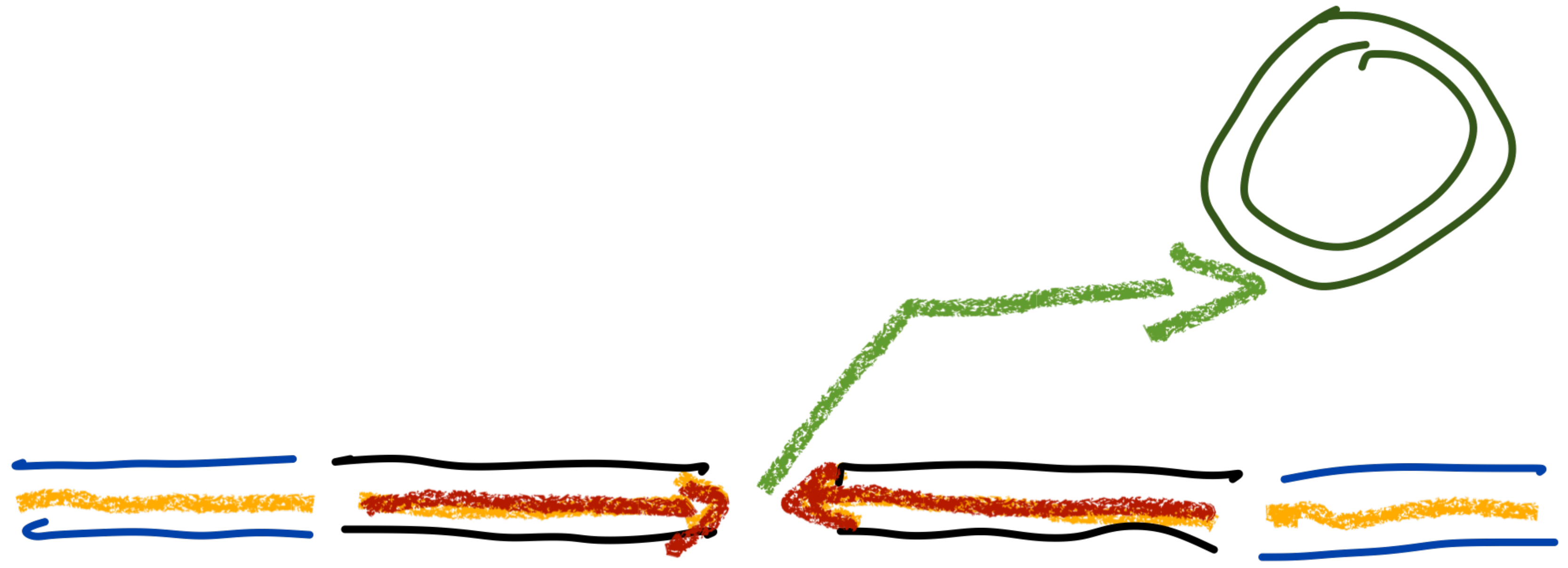

e^+e^- Collider

longer tunnel: higher energy

new acceleration technology

as source for other accelerators

A linear collider: Step-wise extension, lepton collisions at different energies in sequence

Energy Flexibility

A Linear Collider Story

Karlsruhe Institute of Technology

- Linear colliders provide a *staged* physics program - matched to the variety of center-of-mass energies relevant for a broad e^+e^- program

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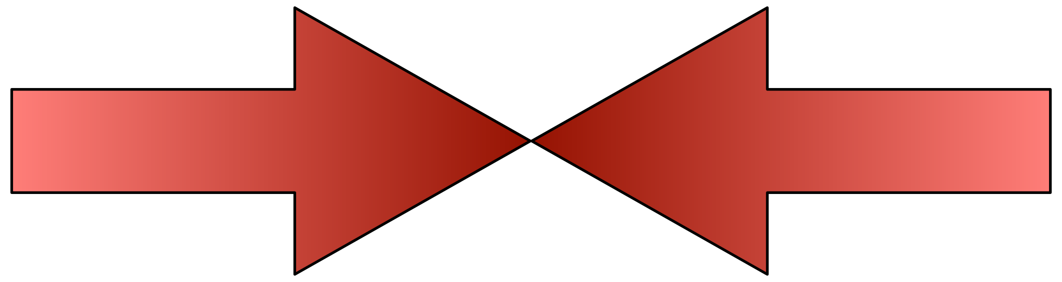

~ 250 GeV

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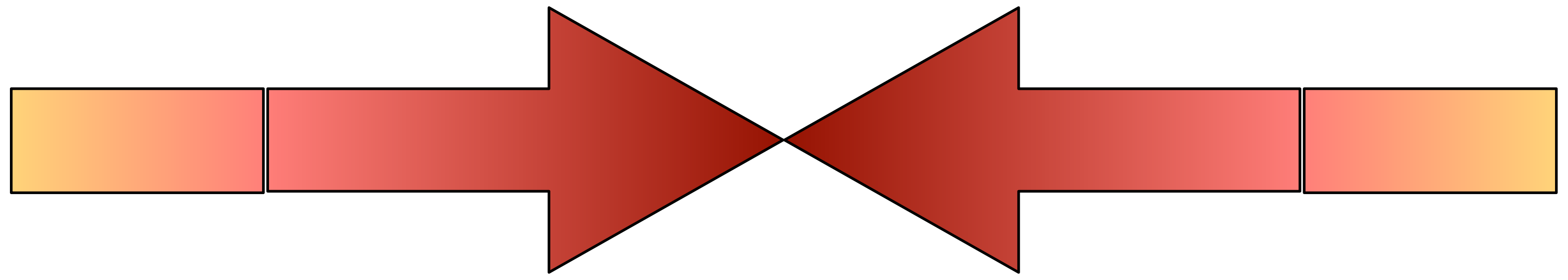

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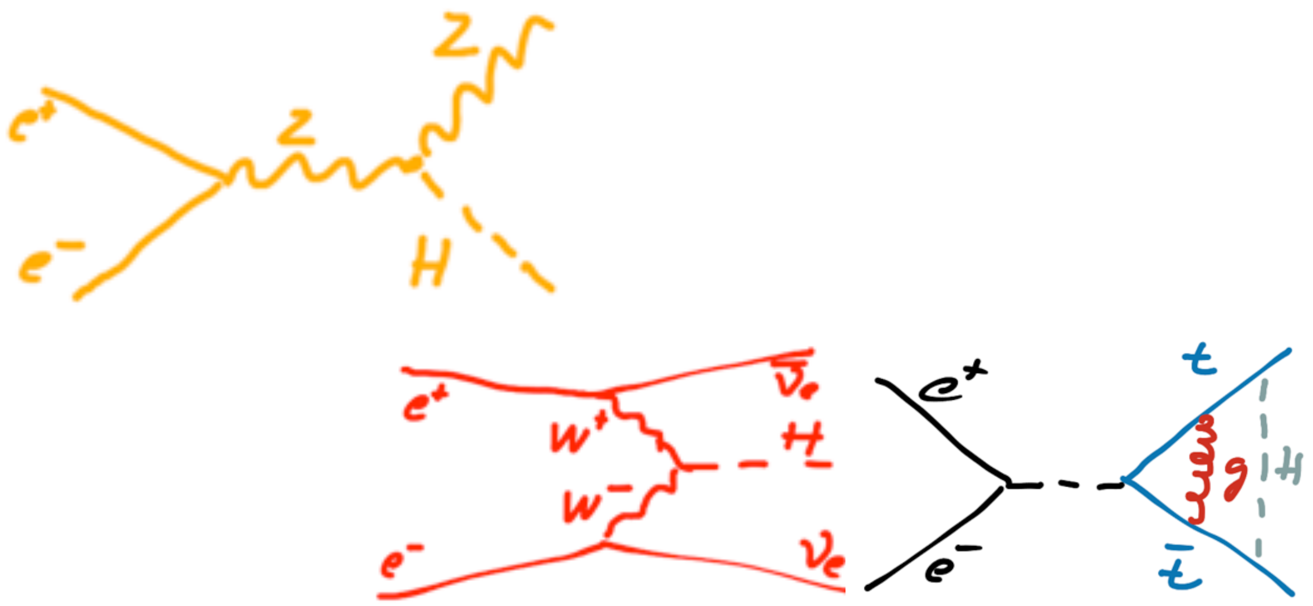
~ 350 - 380 GeV



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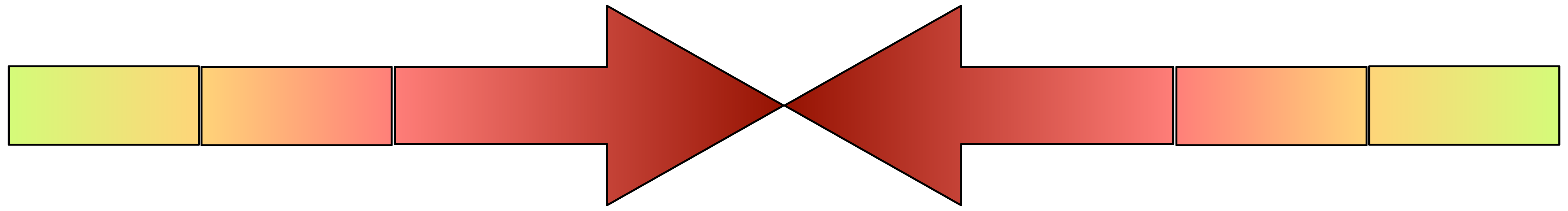

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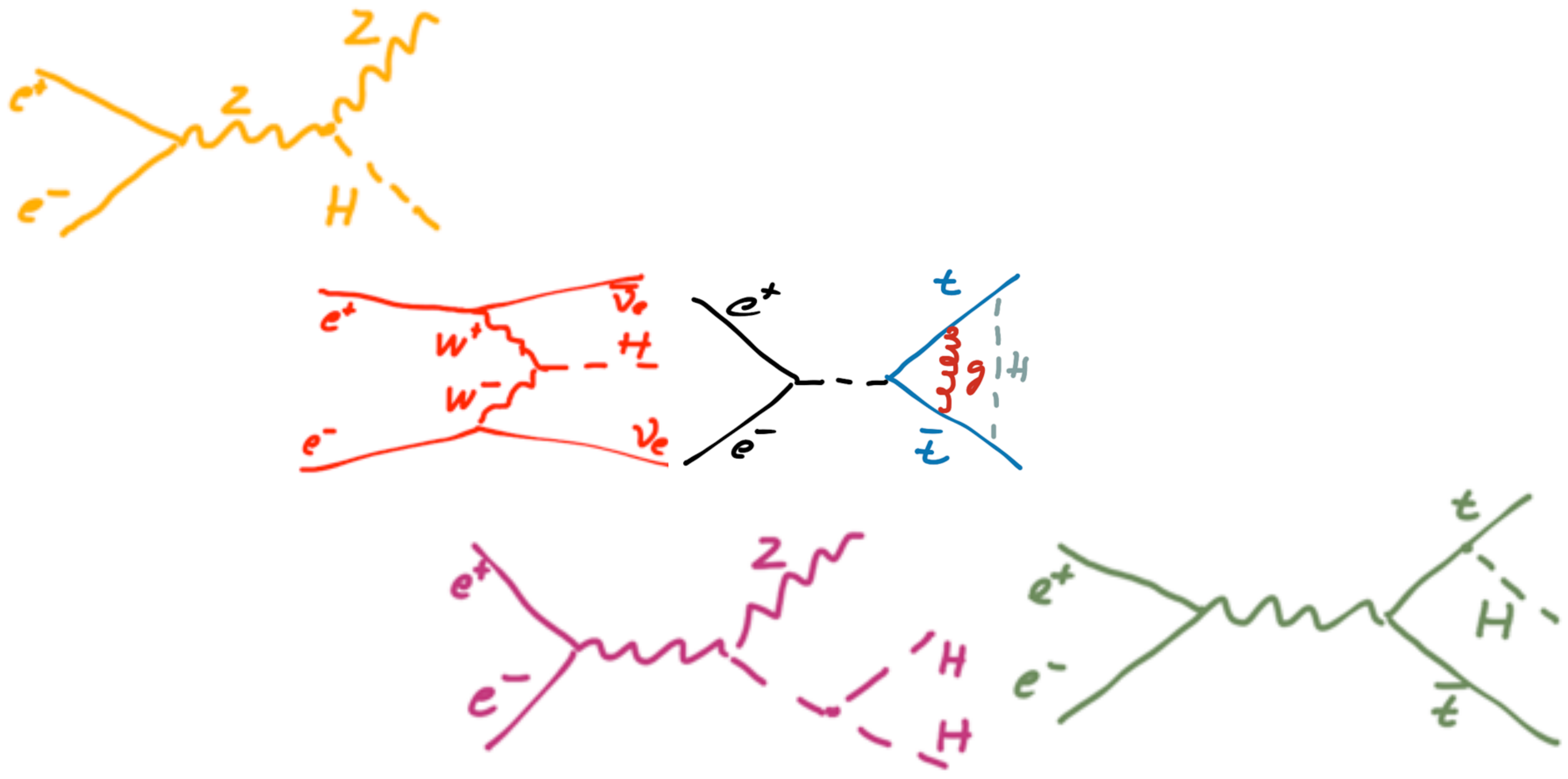

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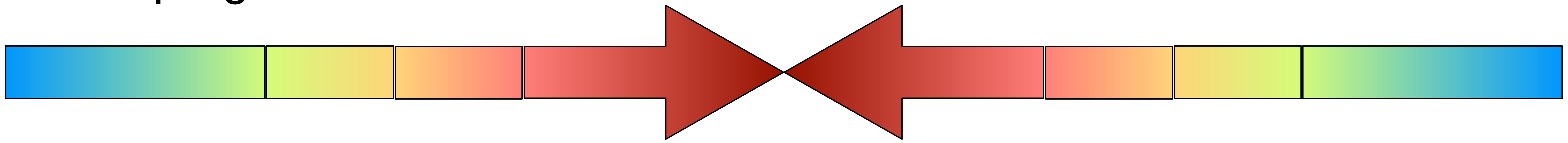

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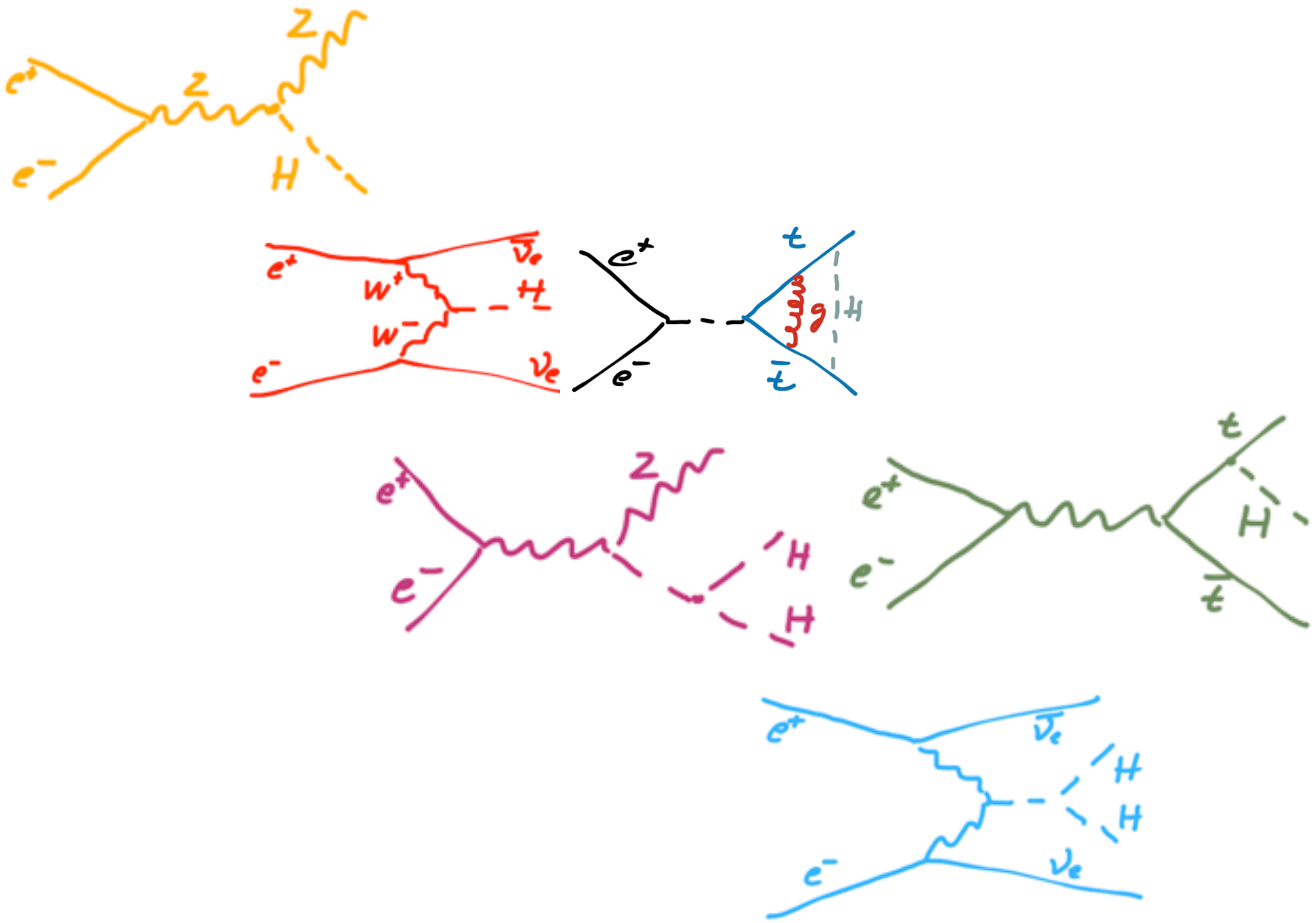

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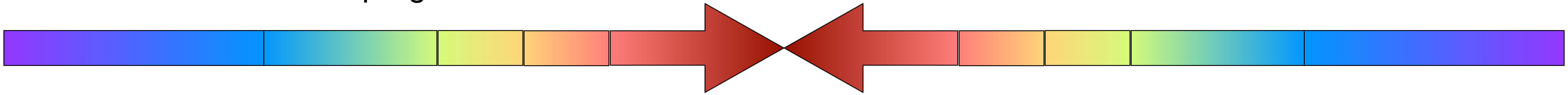

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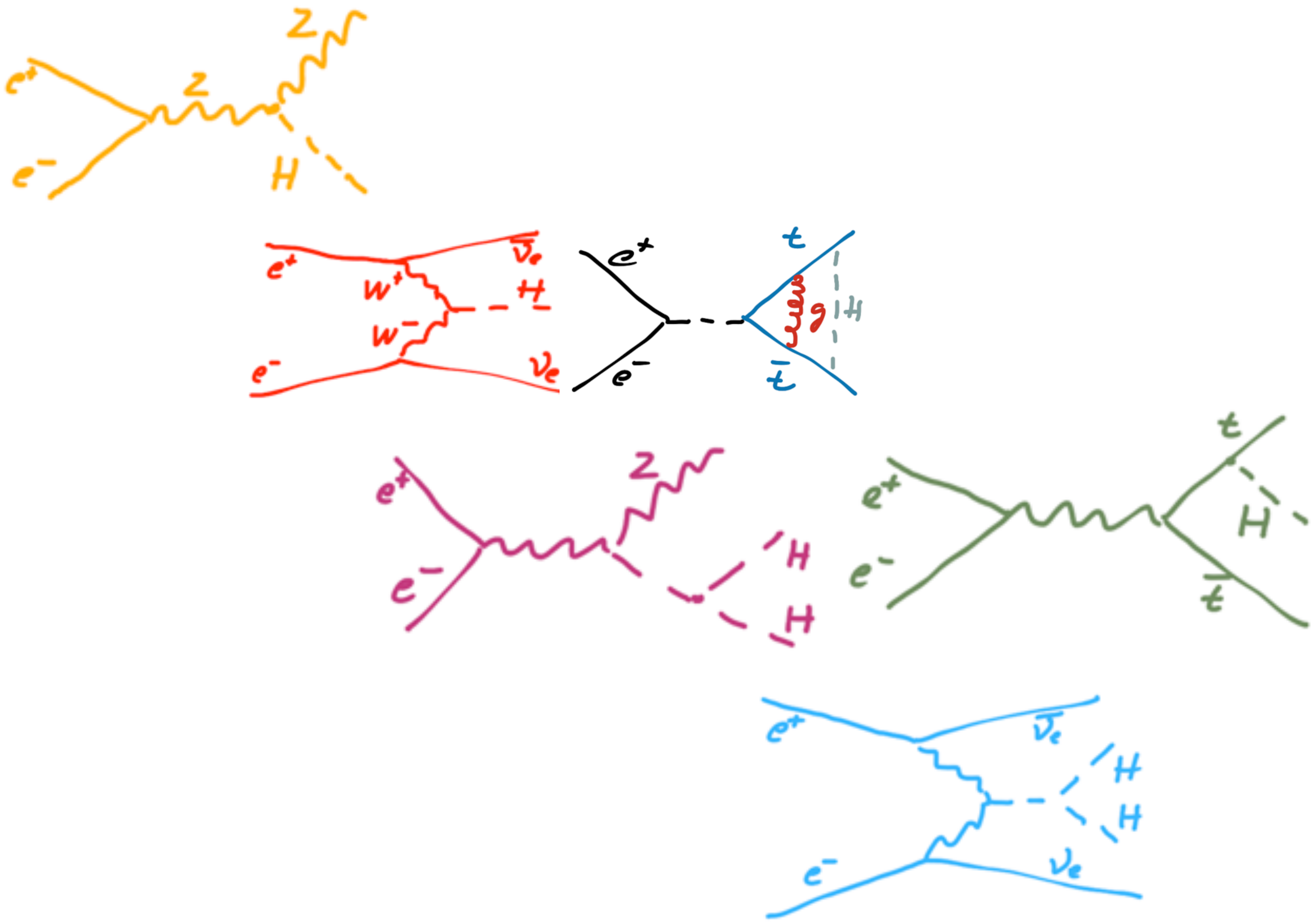

+ direct & indirect discovery potential increasing with energy

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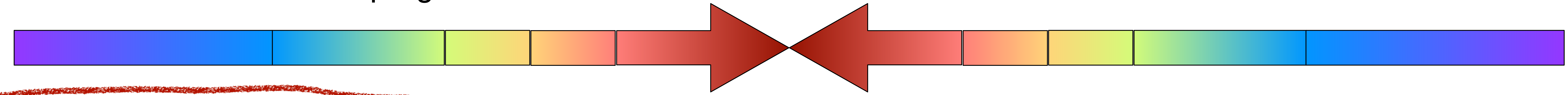

the “minimum” program to cover most aspects of Higgs and Top physics with high precision

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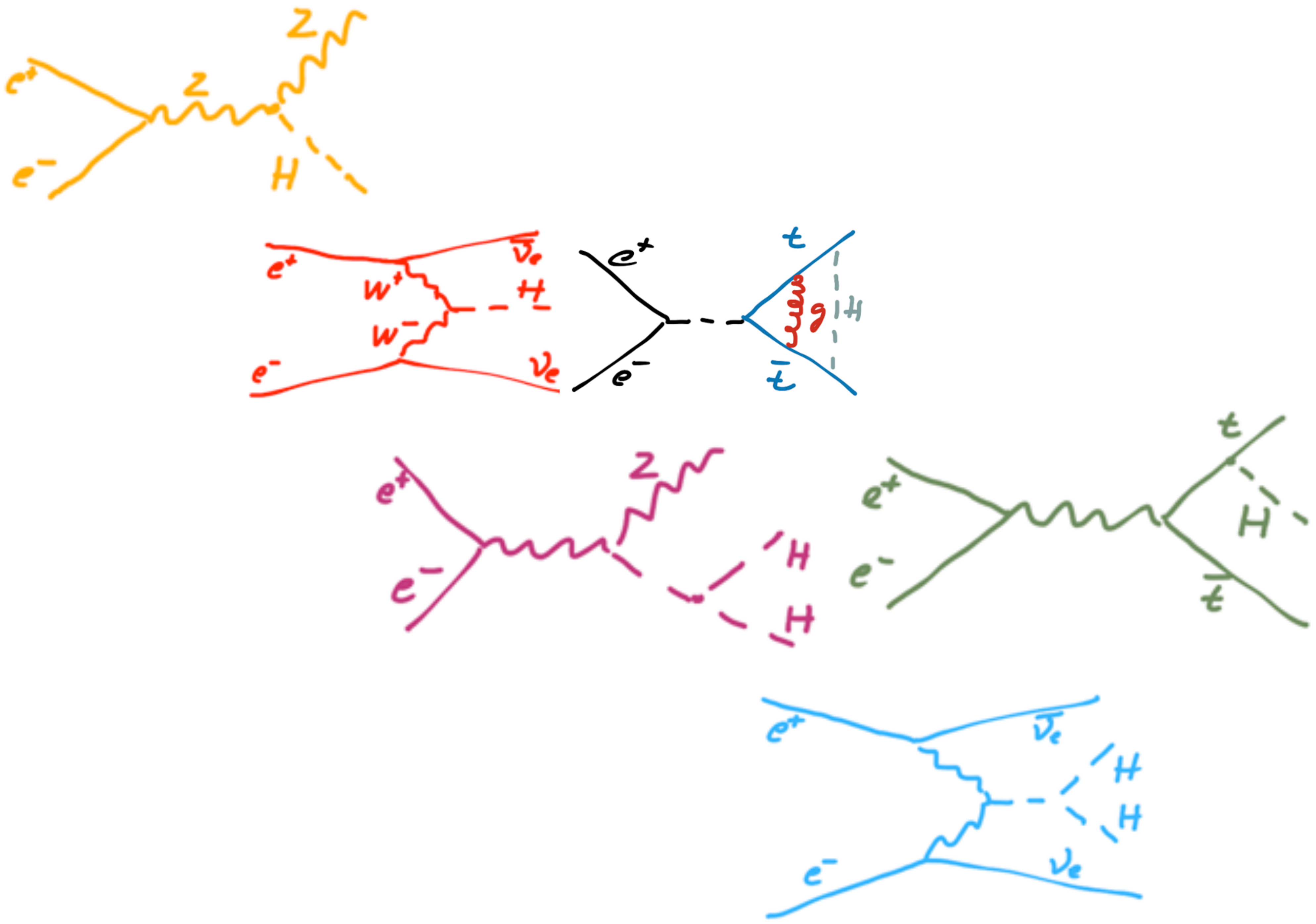

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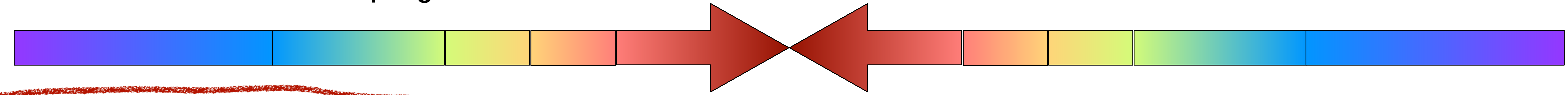

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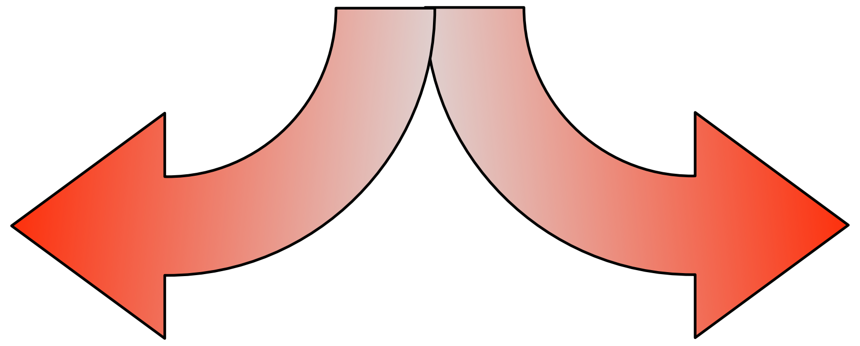
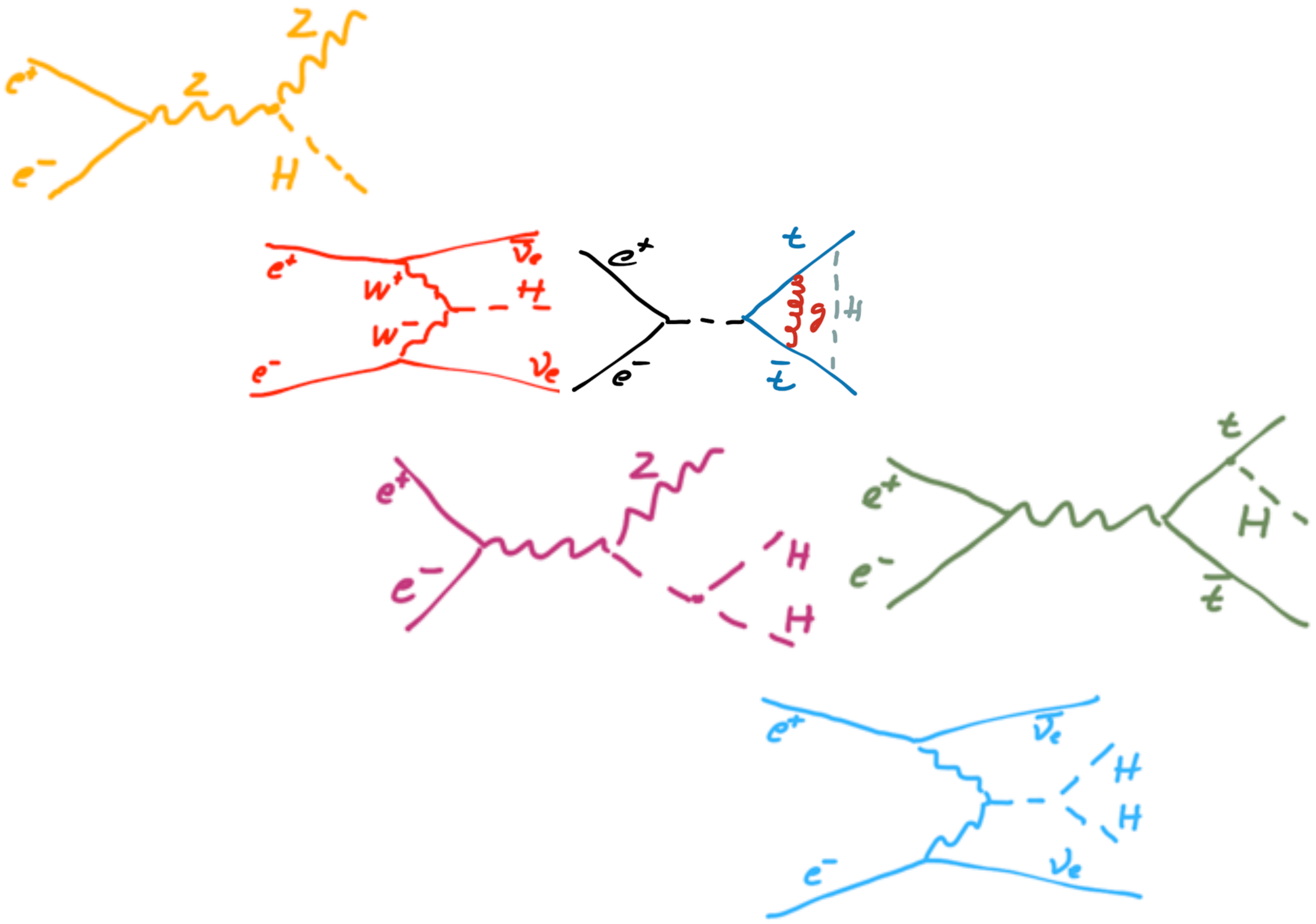




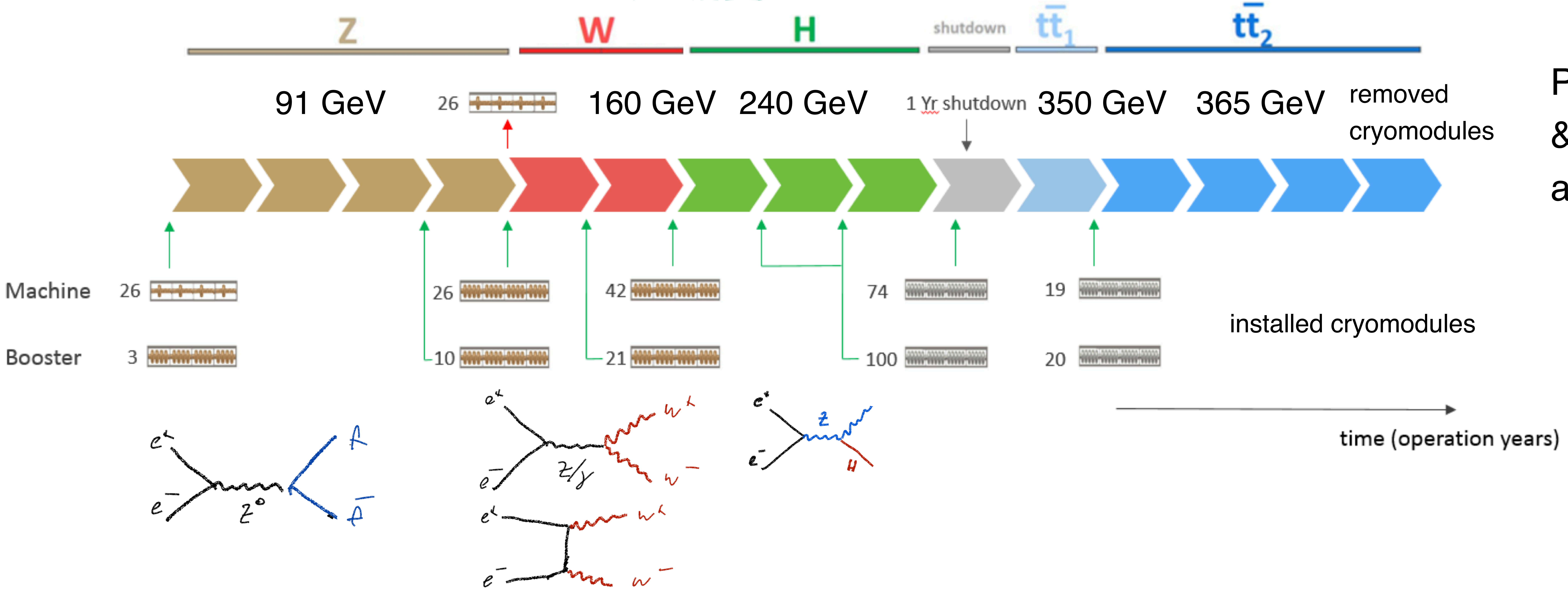
at each stage: Possibility to change focus / direction depending on results

total program ~ 25 years from first collisions

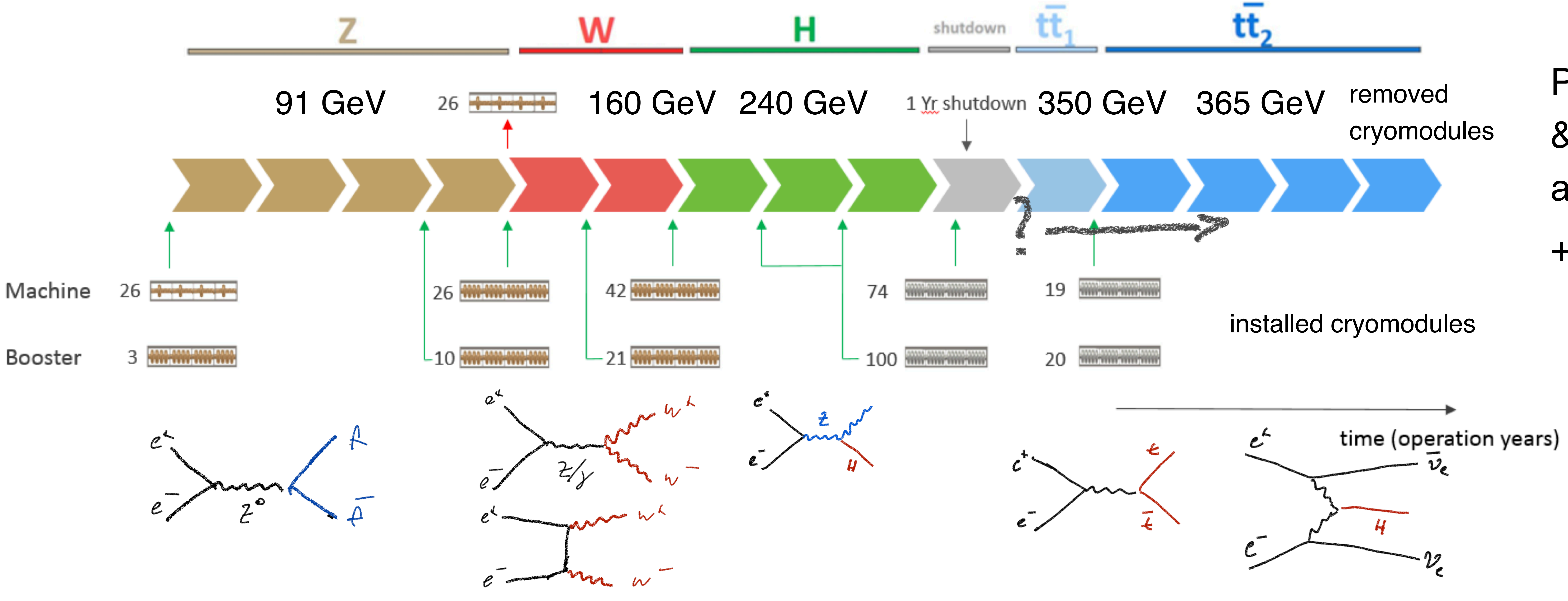
+ direct & indirect discovery potential increasing with energy

Electroweak Precision and Ultimate Energy Reach

A Circular Collider Story



Precision electroweak & Higgs program with an e^+e^- collider



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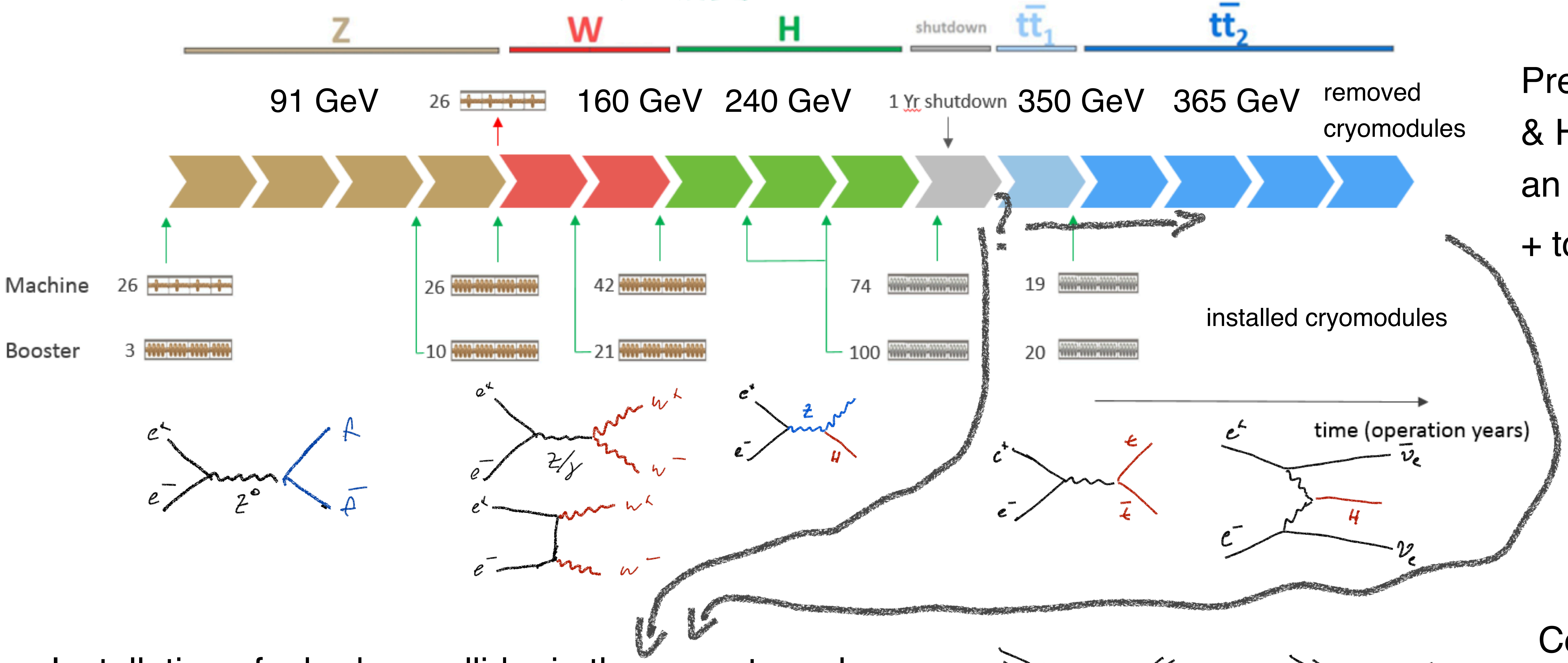

Precision electroweak & Higgs program with an e+e- collider

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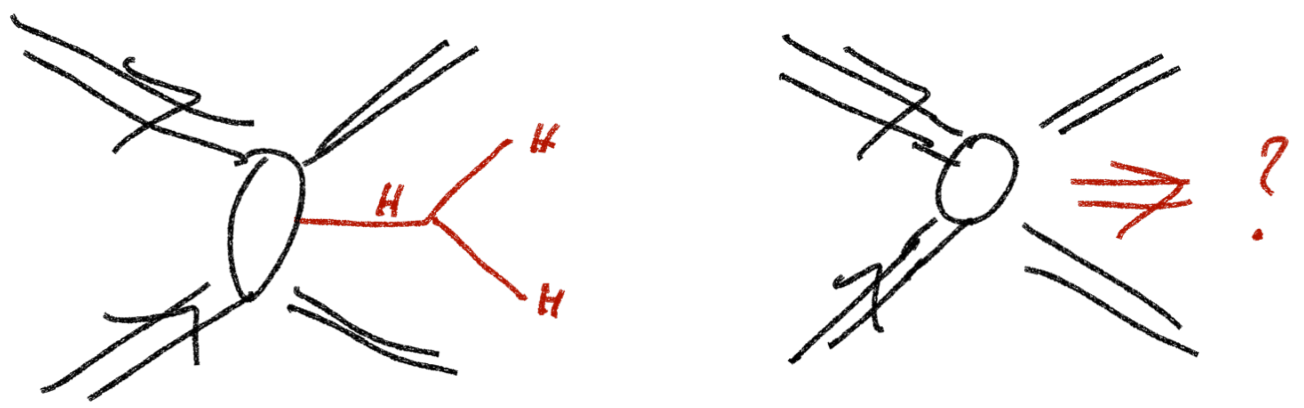
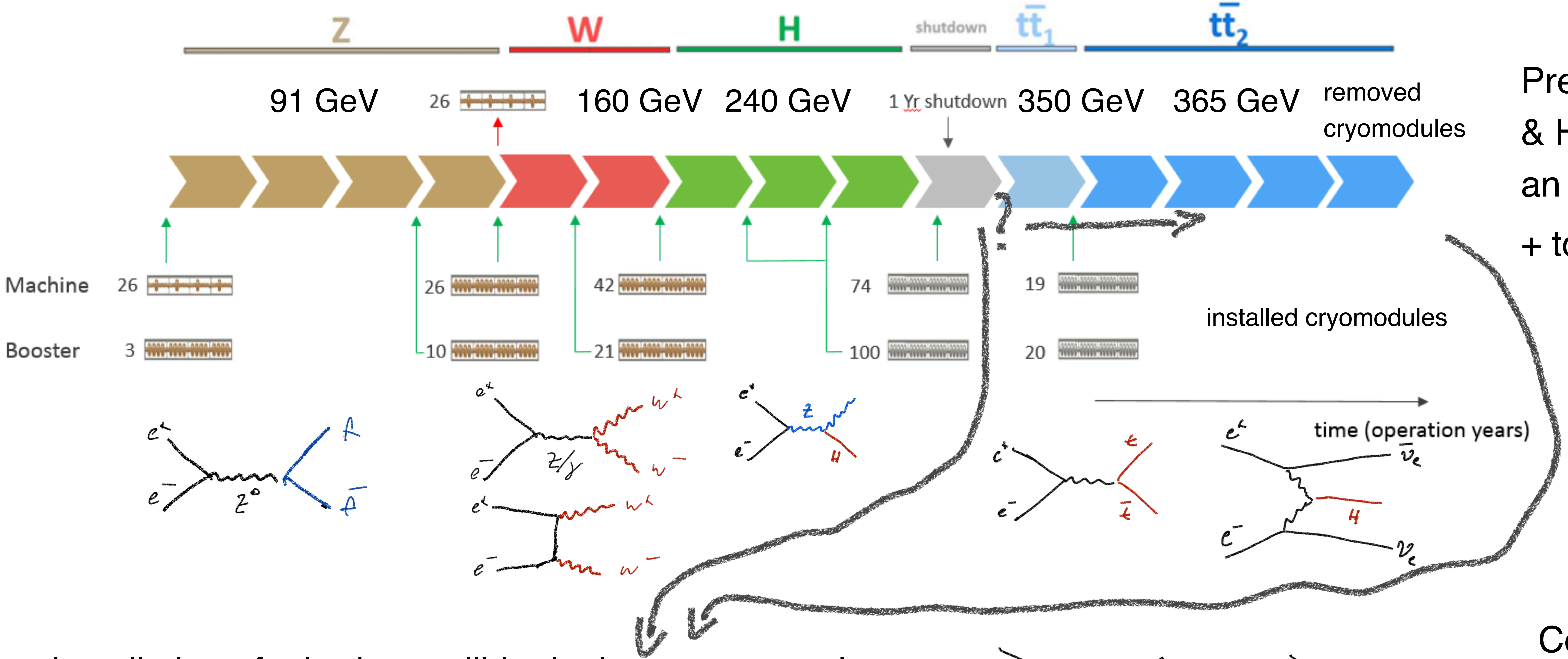
Installation of a hadron collider in the same tunnel (removal of lepton machine):
~10 year shutdown, then: **100(+) TeV** pp collisions



Completing the Higgs sector study, exploration of highest energy scales

Electroweak Precision and Ultimate Energy Reach

A Circular Collider Story



Precision electroweak & Higgs program with an e^+e^- collider

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Installation of a hadron collider in the same tunnel (removal of lepton machine):

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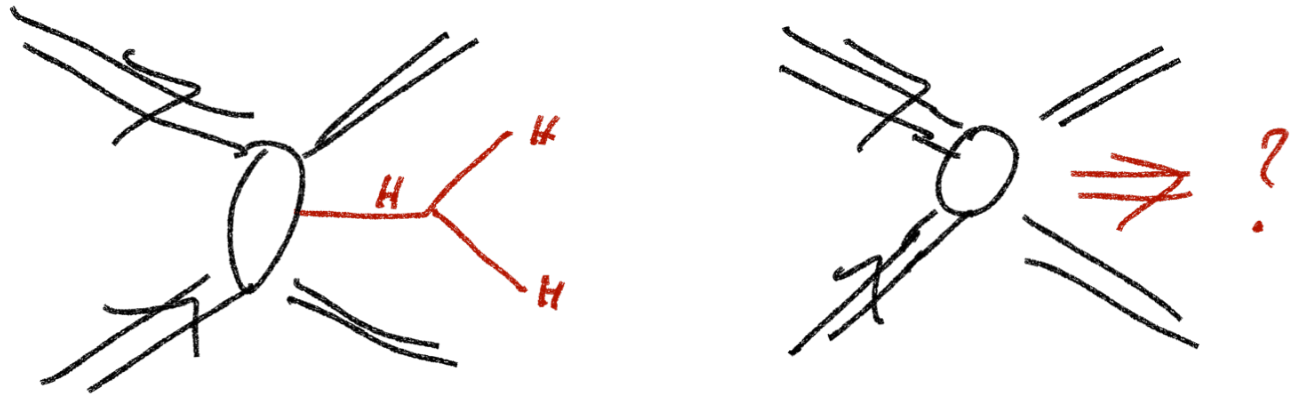
together: 50+ years from first e^+e^- collisions to completion of pp program



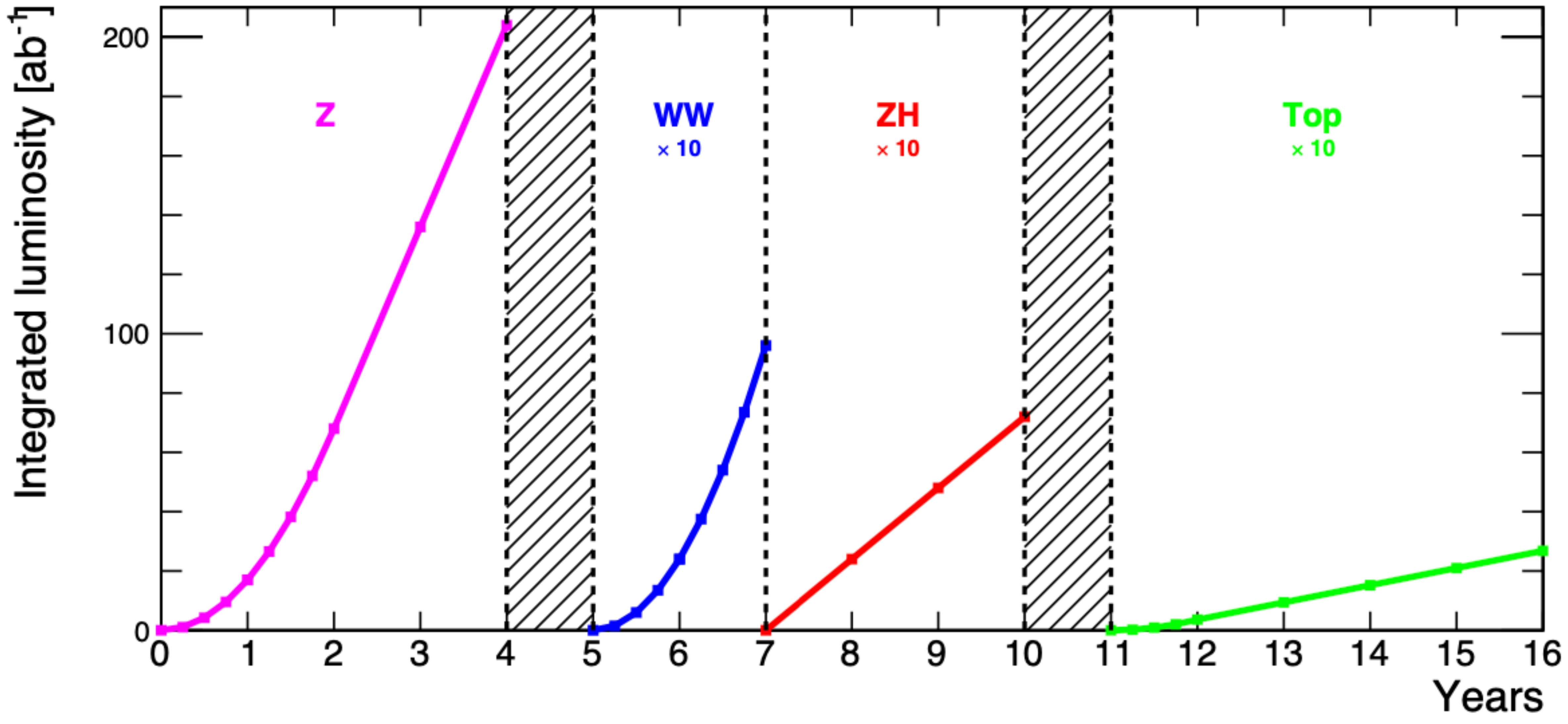
Completing the Higgs sector study, exploration of highest energy scales

Flexible Sequence for FCC-ee

Maximising physics output - and interest

- Energy sequence for FCC-ee under study

Default: ordered by energy



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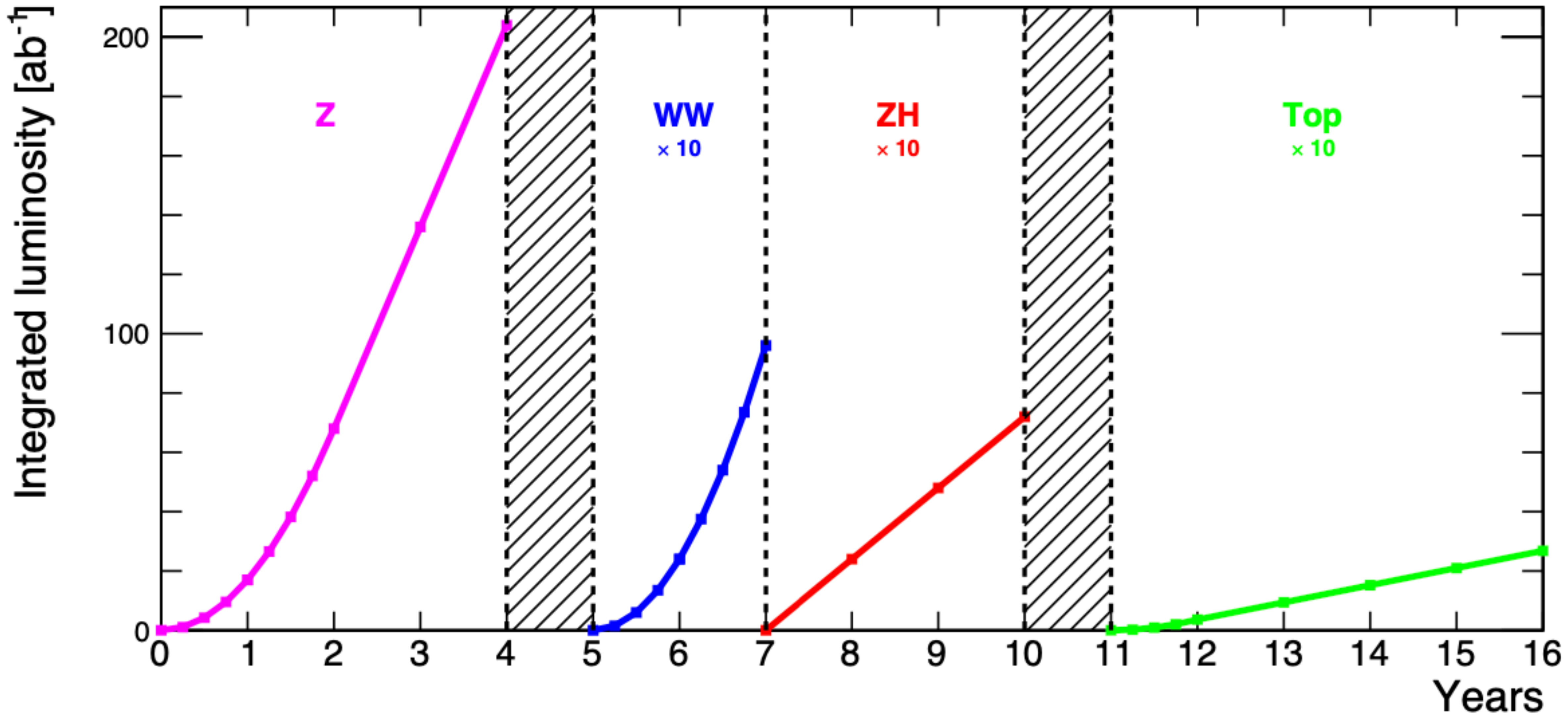
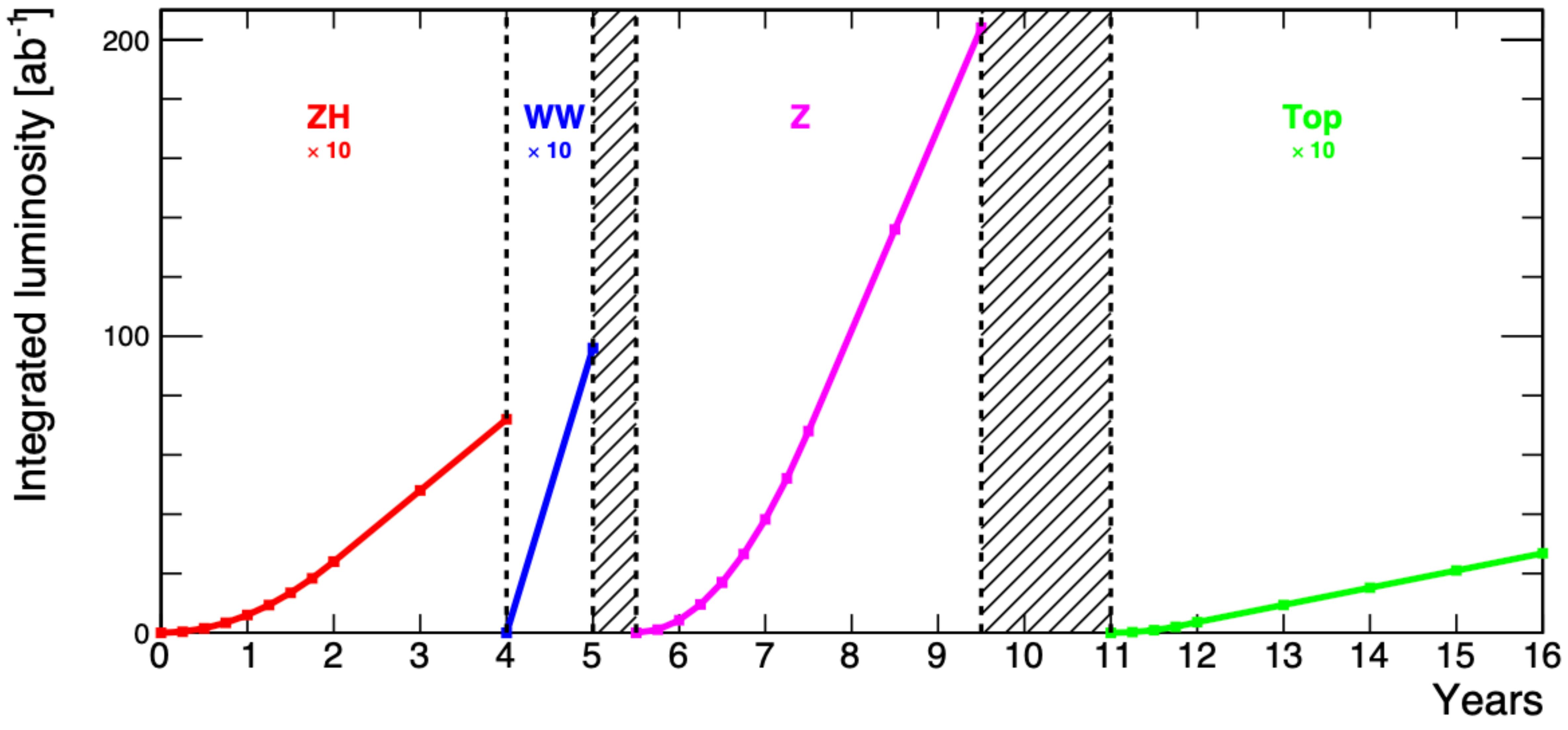


Higgs first:



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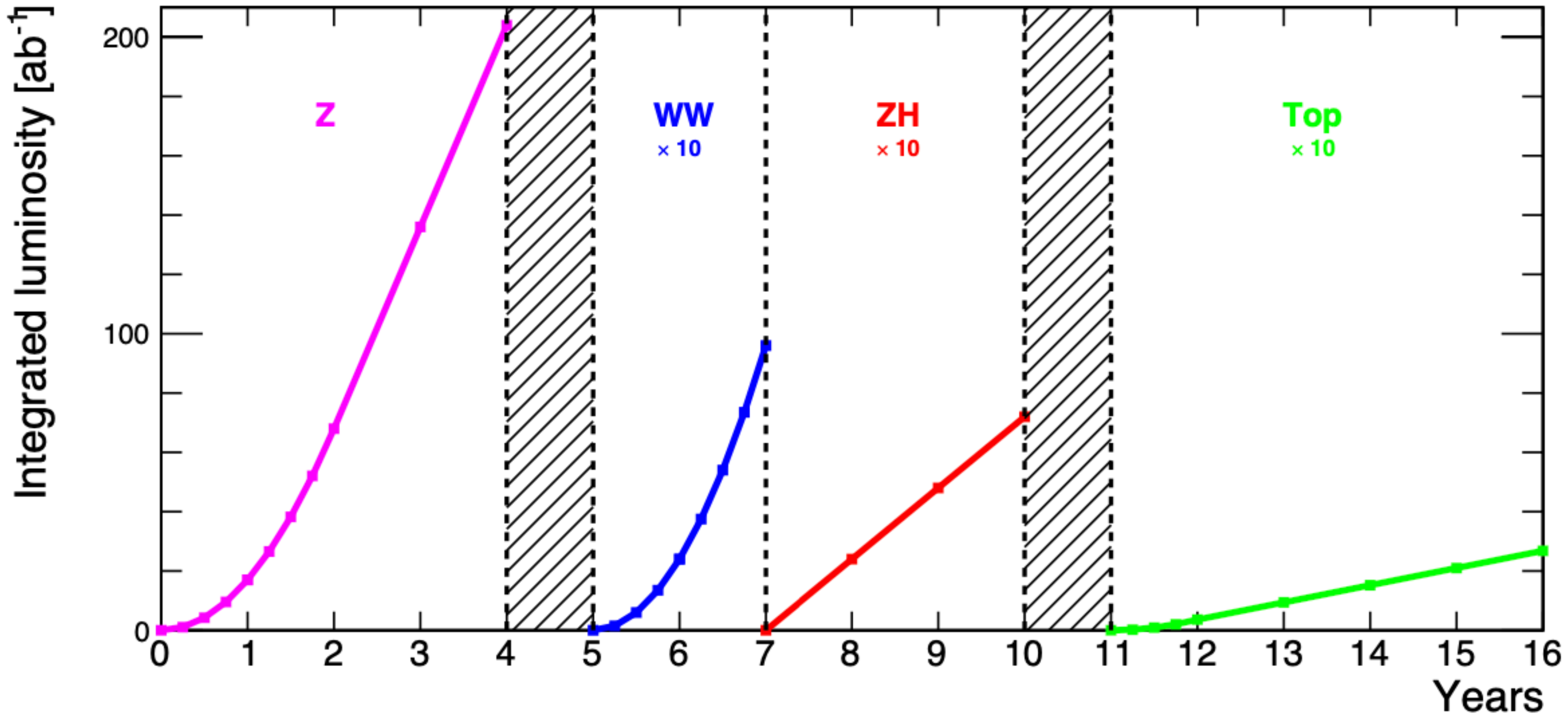

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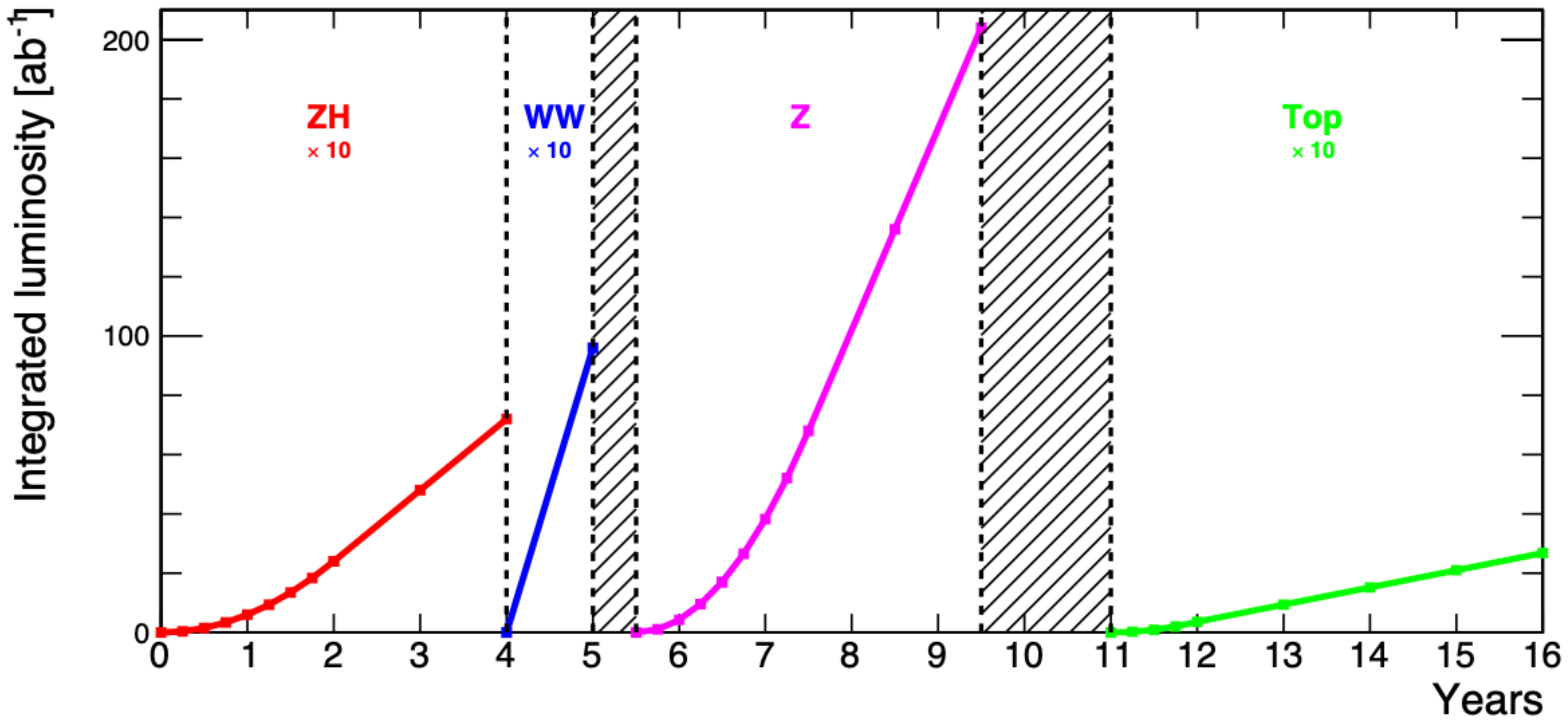
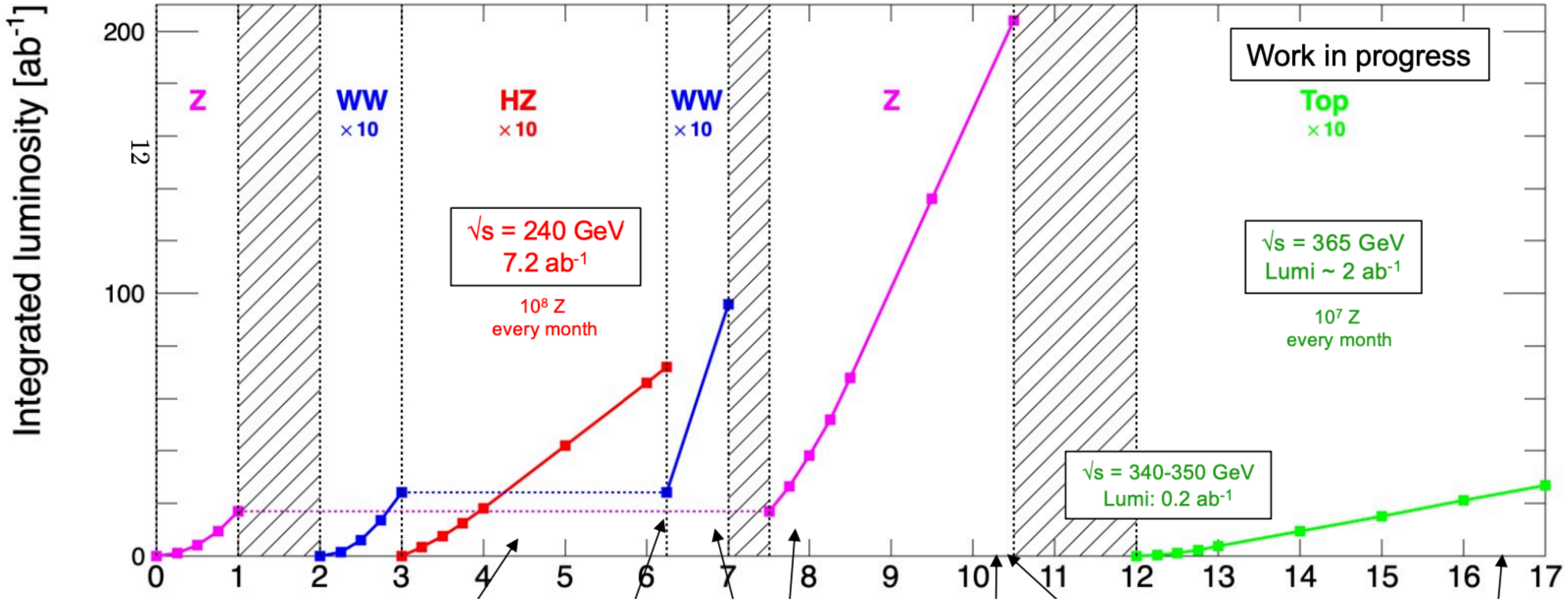


More speculative:

Interleaved energy stages:



Concrete Facilities

A selection of lepton colliders in backup

- See the lecture by Barbara Dalena

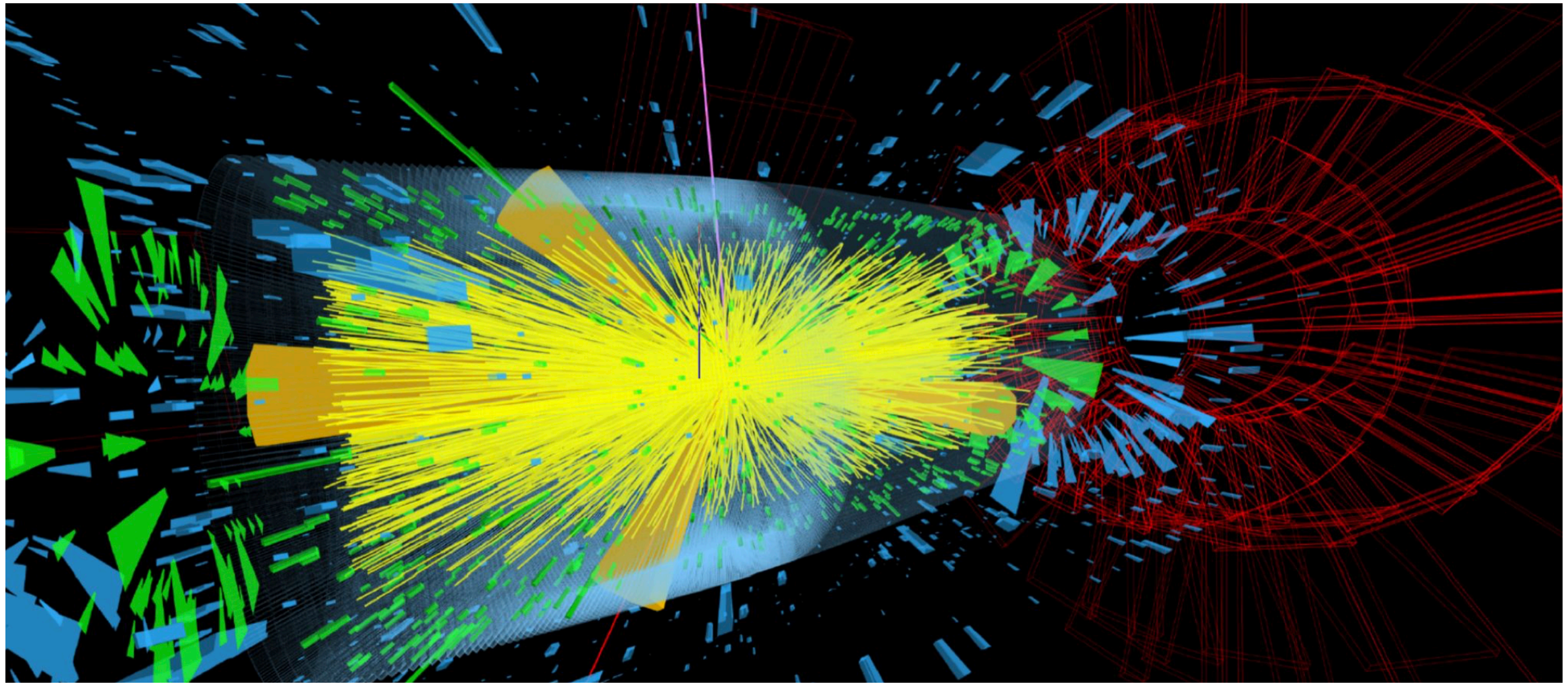
Detectors at Future Lepton Colliders

- Extensively developed for linear colliders (ILC, CLIC)
- Activities for FCC-ee now picking up, requiring some modifications

- Muon colliders the latest addition, challenges being understood, concepts emerging

General Detector Features

Aiming for precision, profiting from benign backgrounds



HL-LHC

from this…

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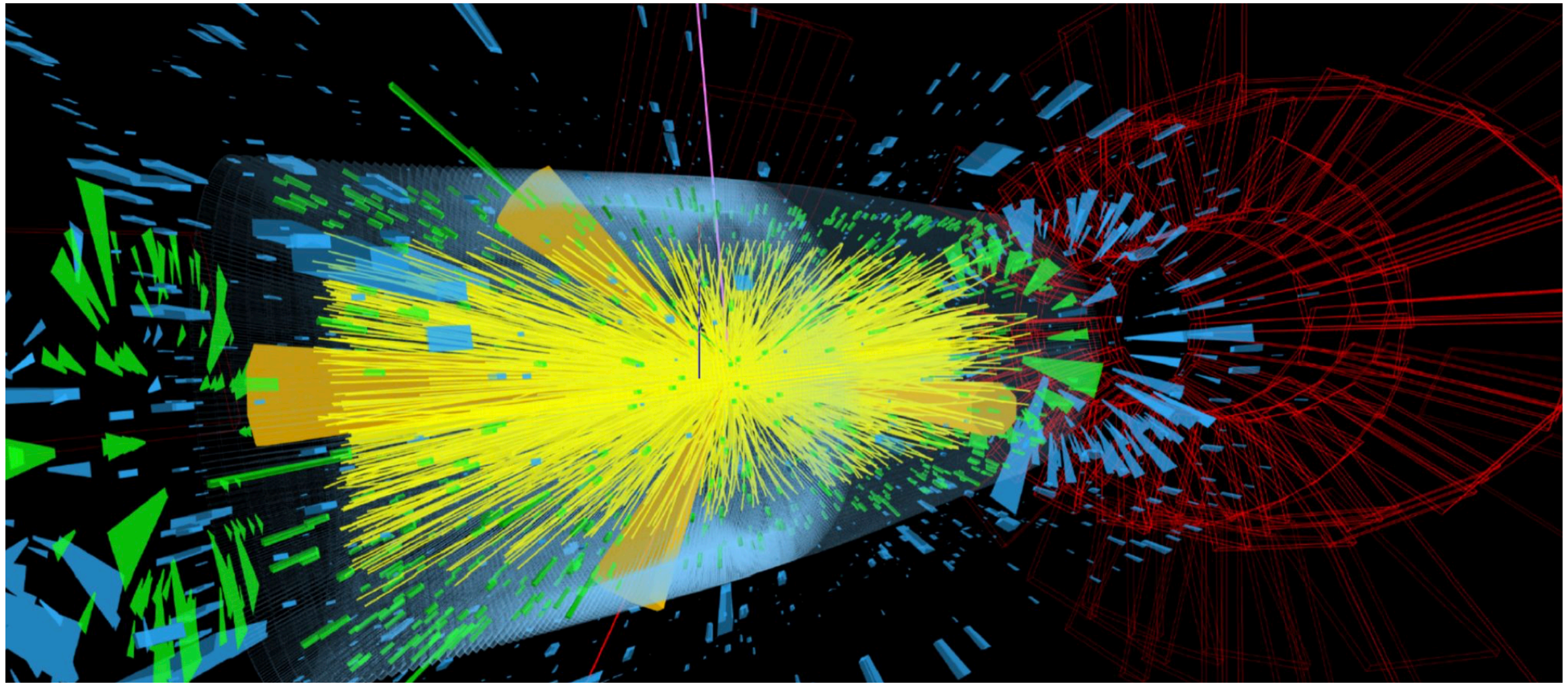

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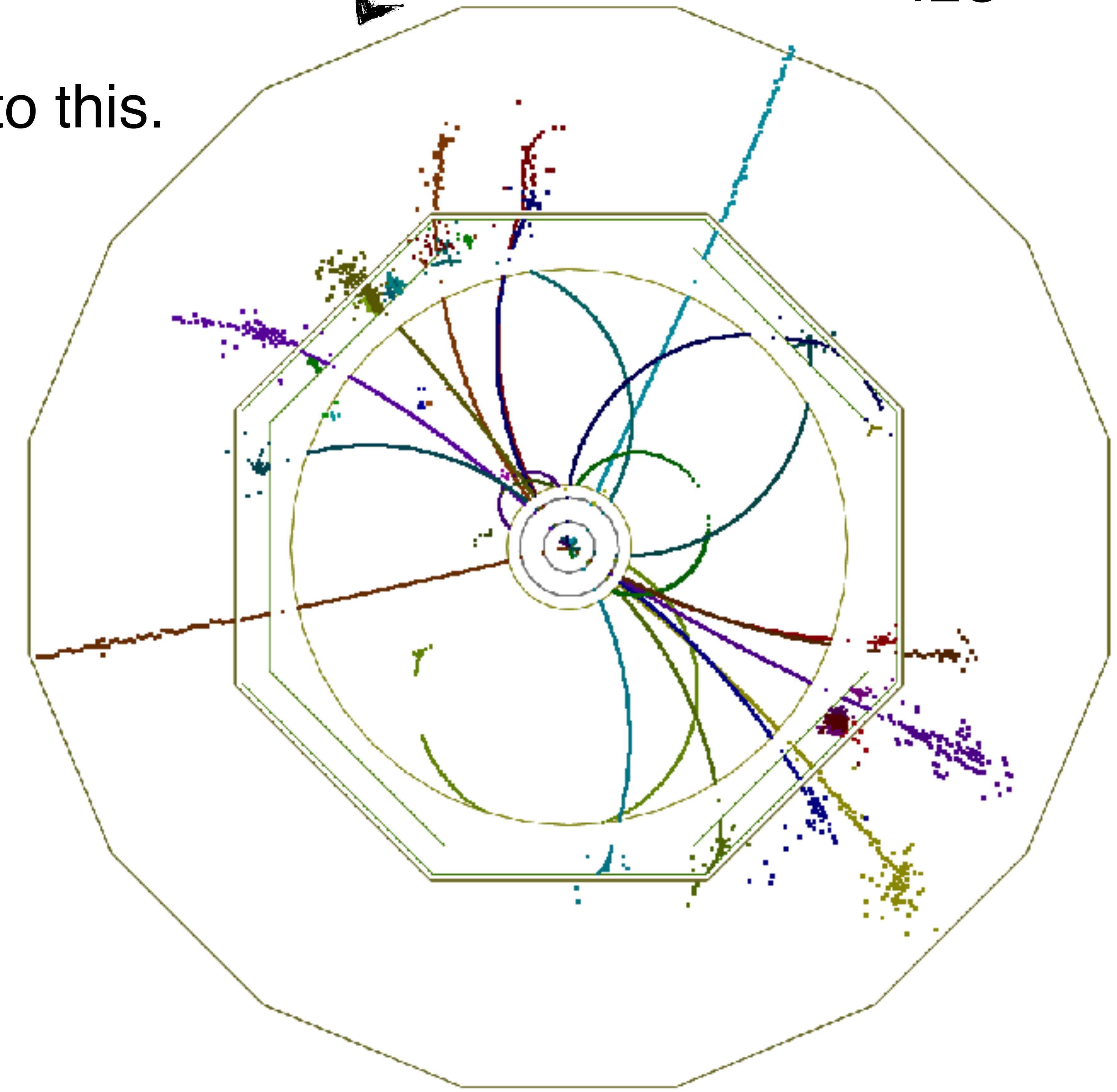
ILC



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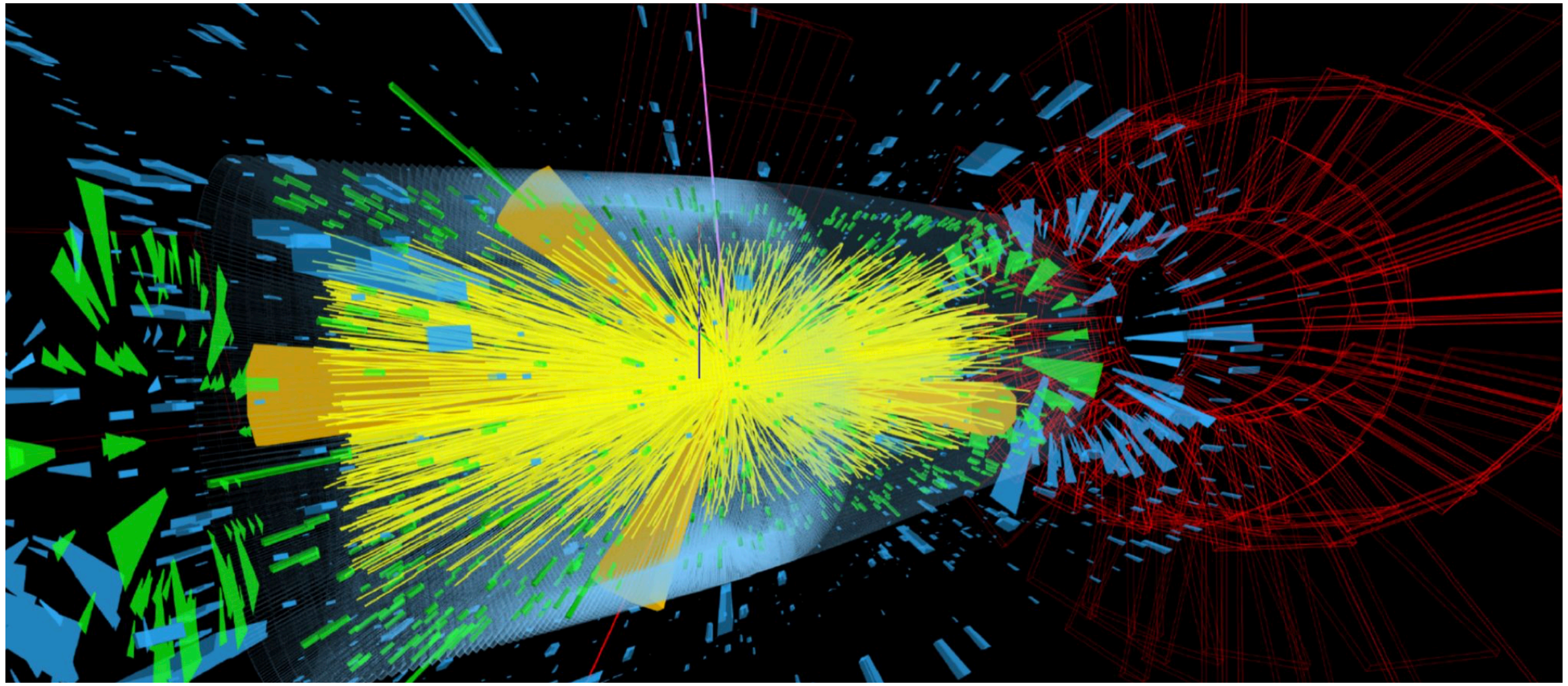

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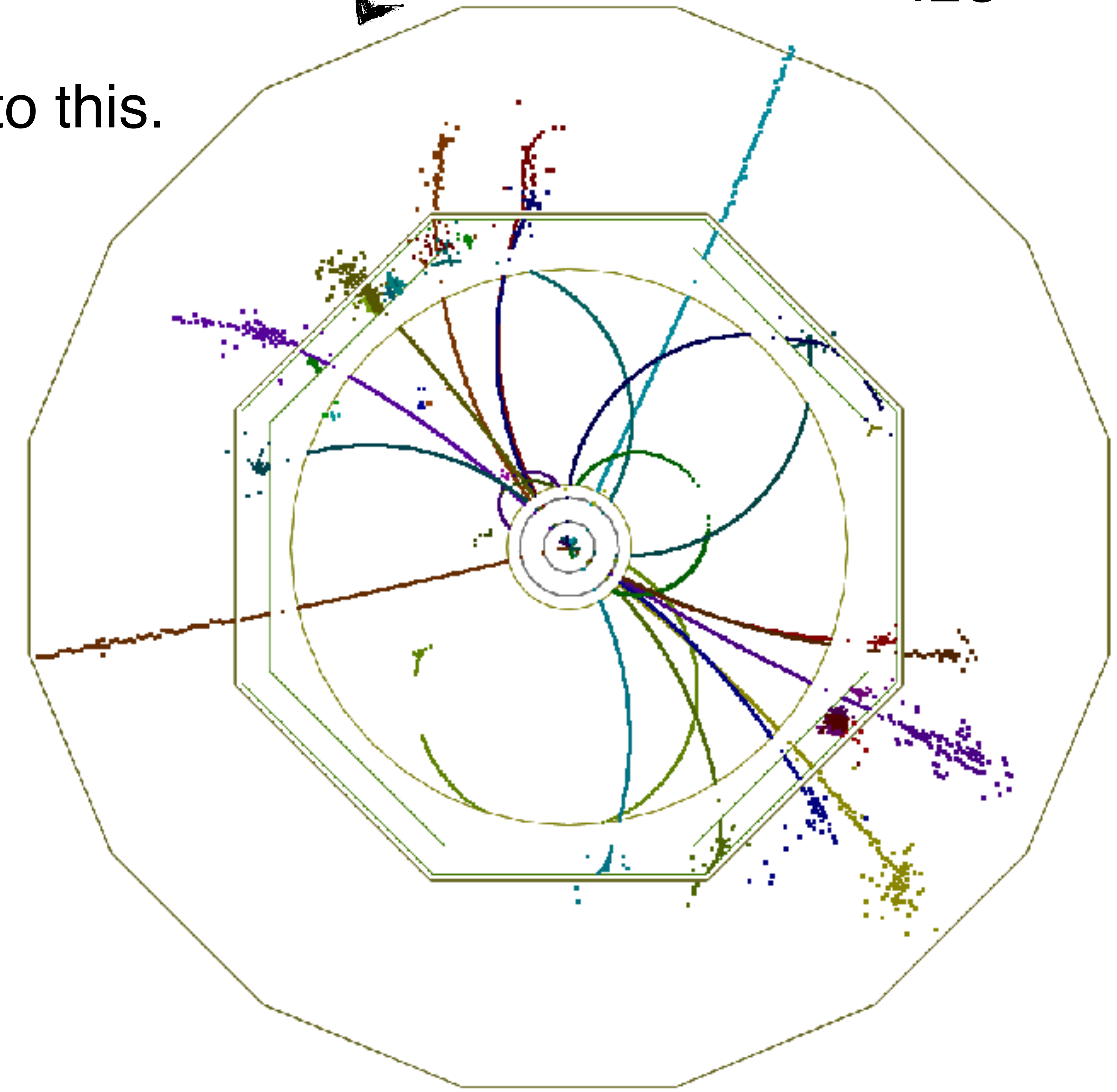


- Need detector systems that match the ambitious precision goals of lepton colliders: Resolution, calibration accuracy, stability…
- The main concern is not survival: (With very few exceptions) radiation tolerance requirements are very minor, occupancies and rates typically low

Detector Performance Goals - Tracking

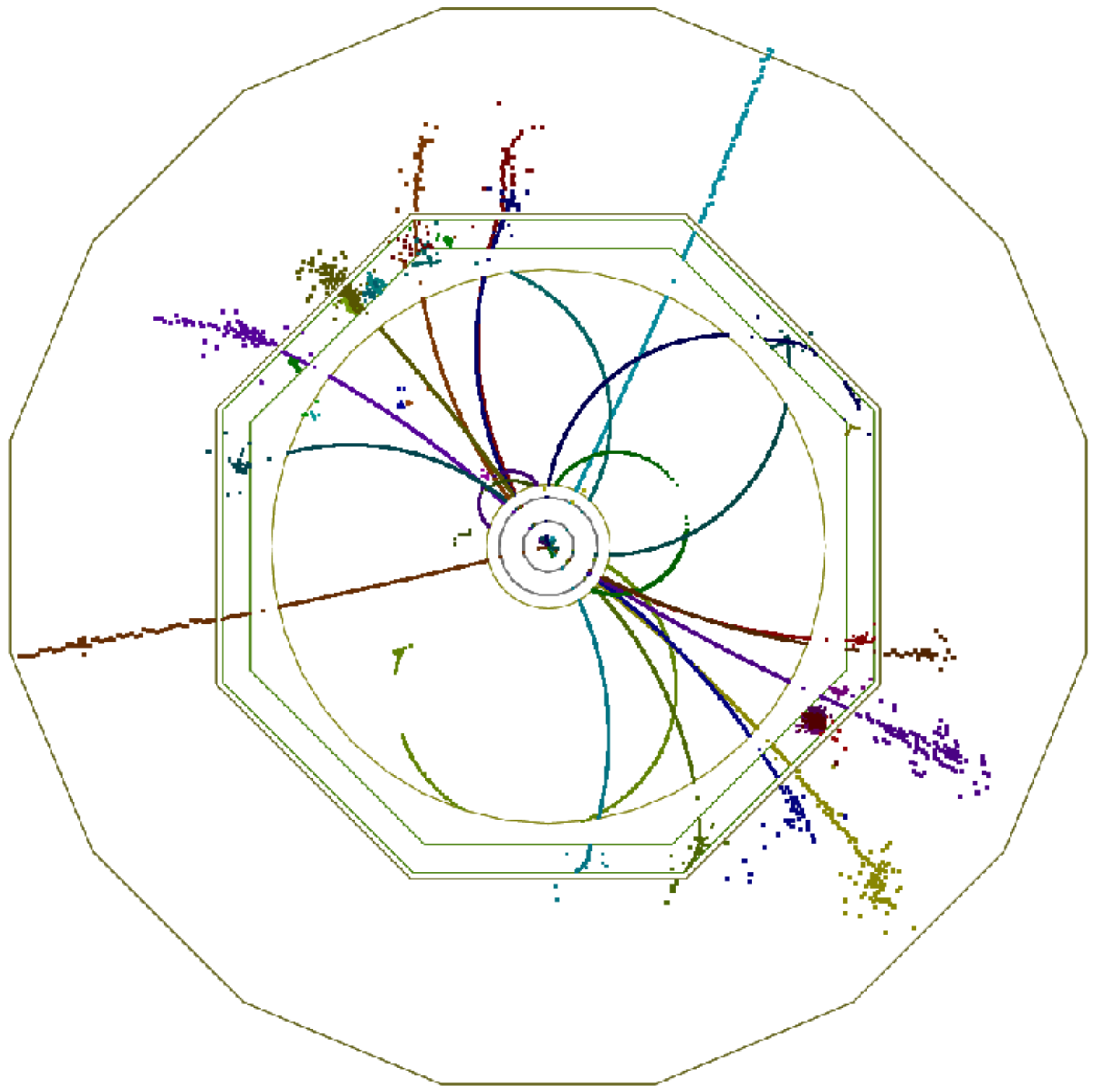
Motivated by key physics signatures

- ***Momentum resolution***

  Higgs recoil measurement, H -> $\mu\mu$,
  BSM decays with leptons

  $\sigma(p_T) / p_T^2 \sim 2 \times 10^{-5}$ / GeV

  precise and highly efficient tracking,
  extending to 100+ GeV



low mass, good resolution:
for Si tracker ~ 1-2% X_0 per layer, 7 μm point resolution

Detector Performance Goals - Tracking

Motivated by key physics signatures

- ***Momentum resolution***

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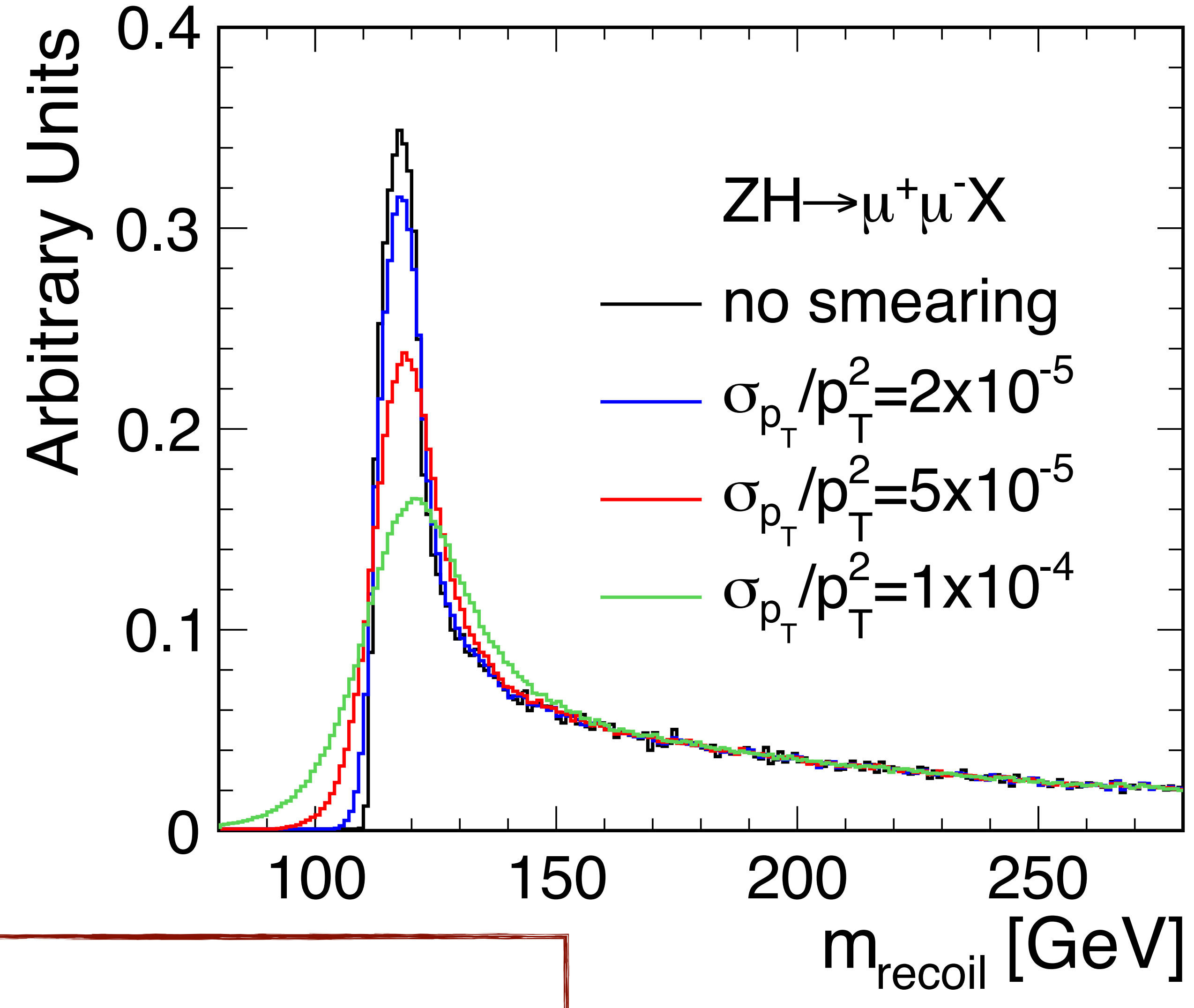

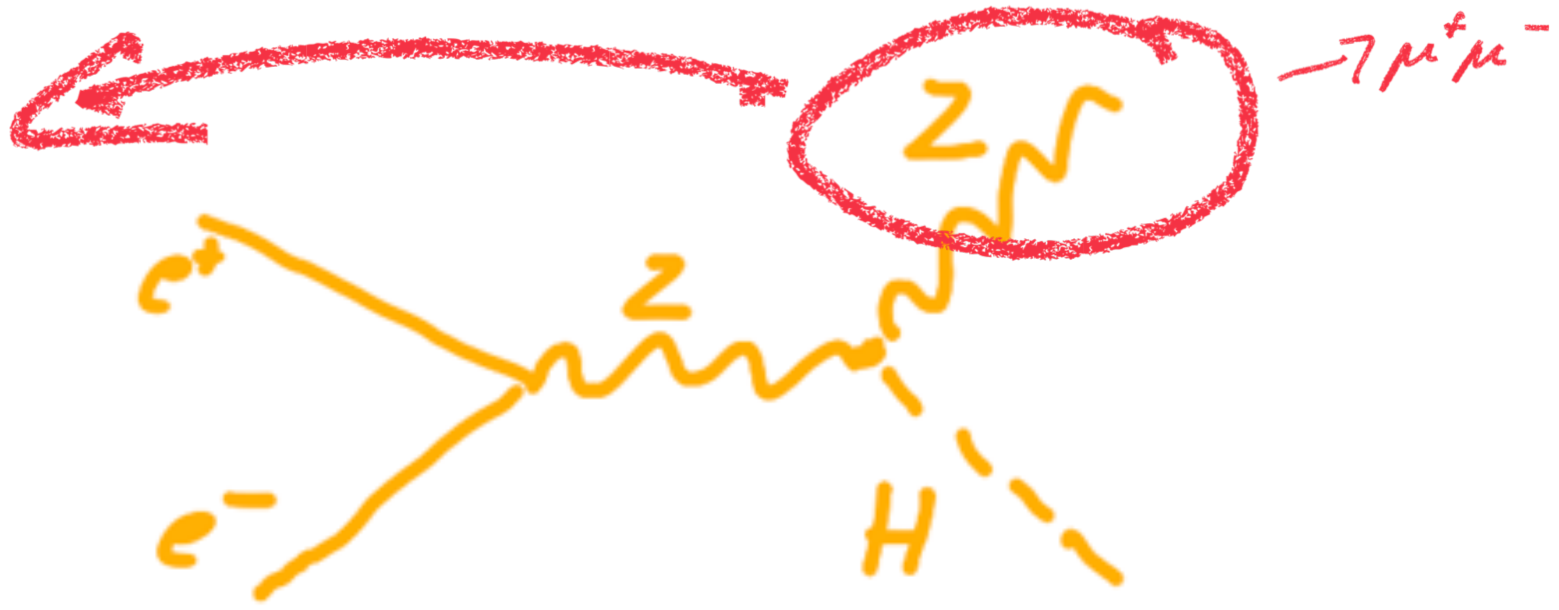

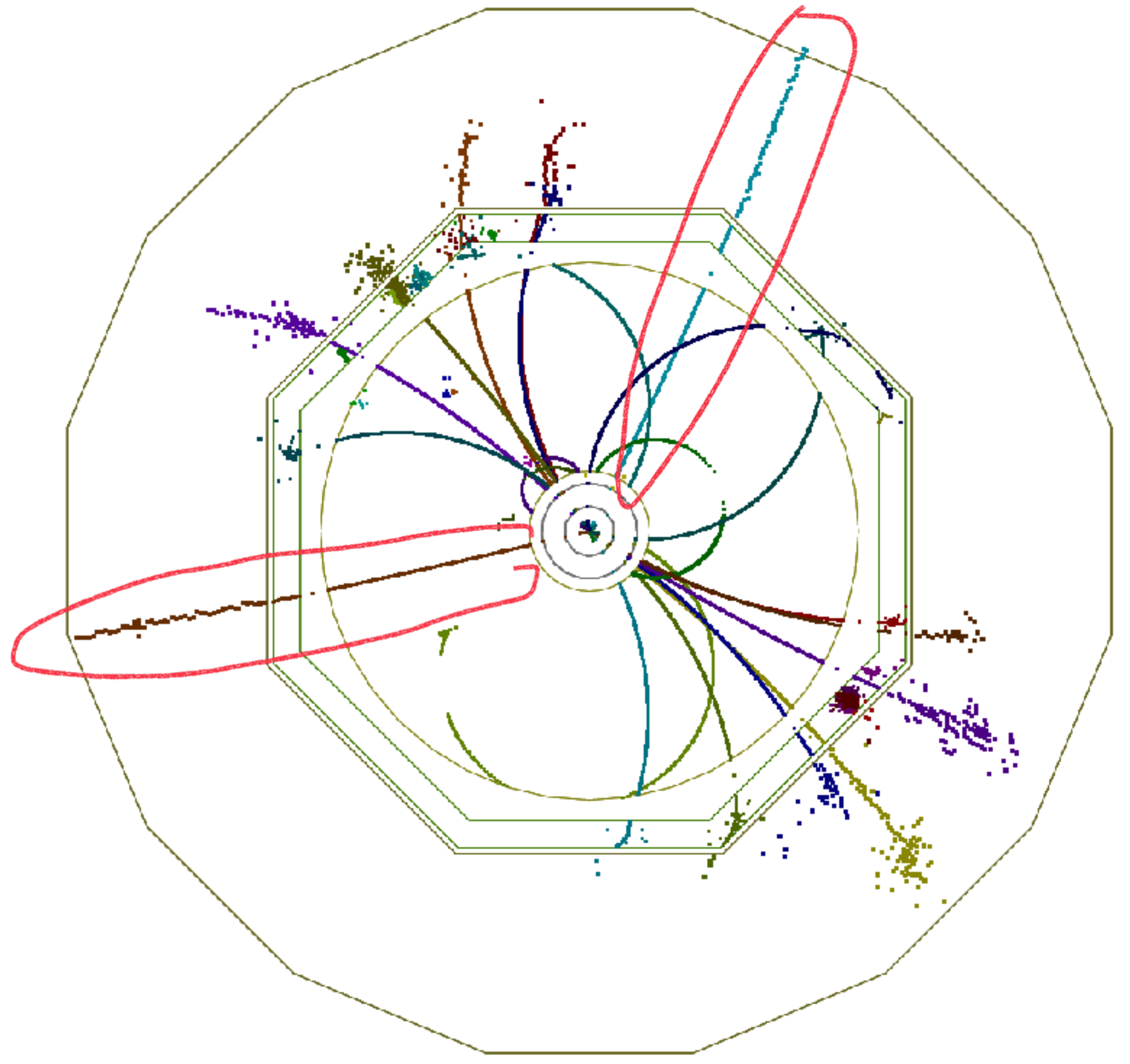

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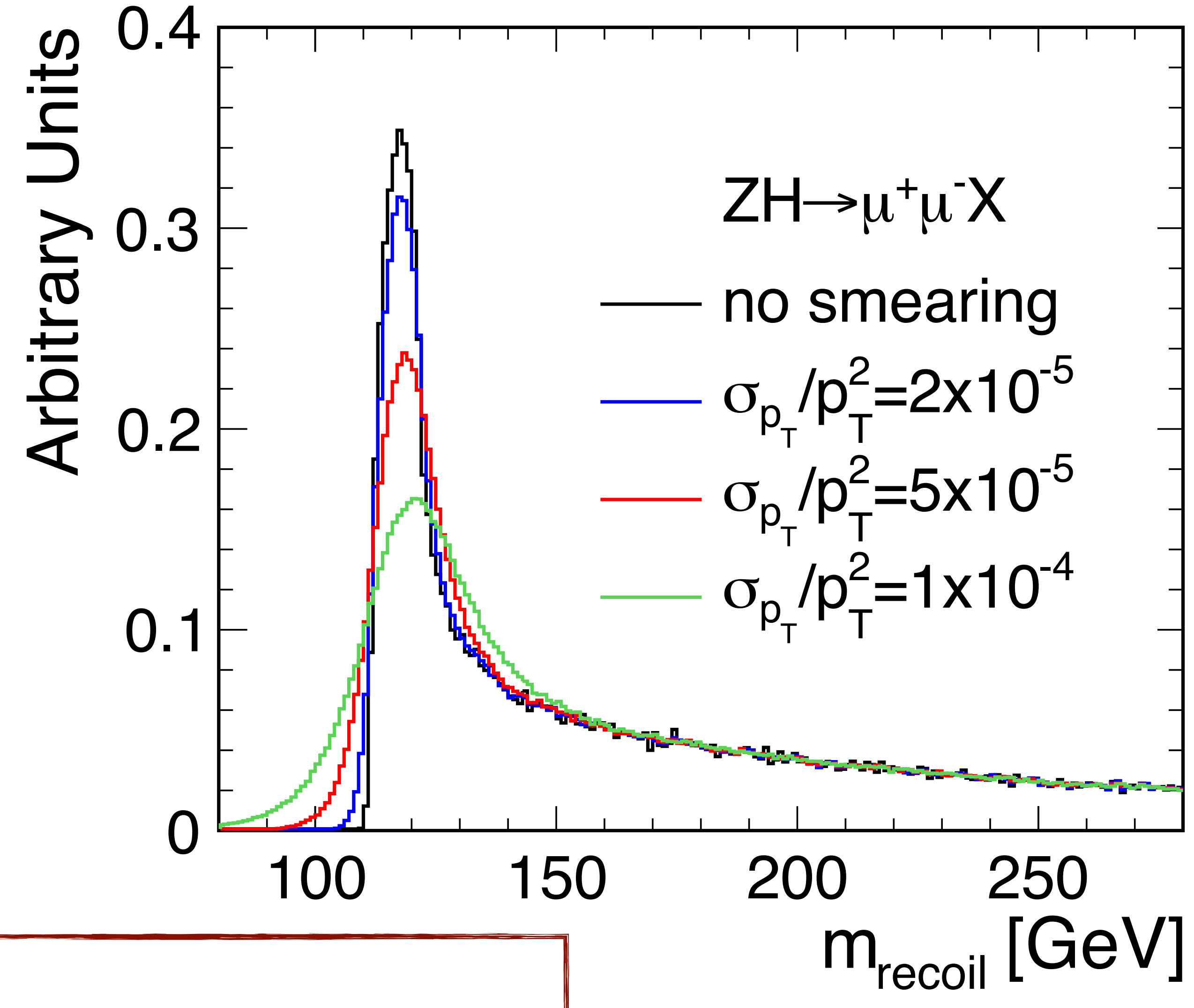

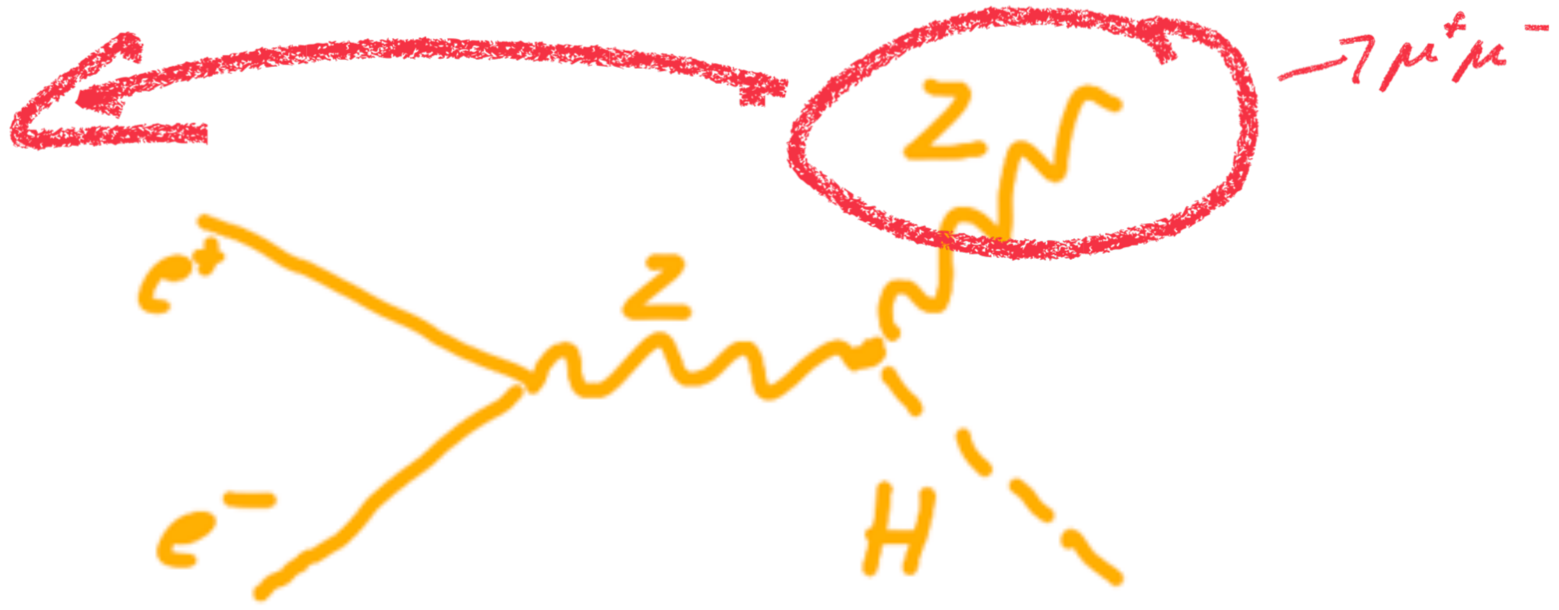

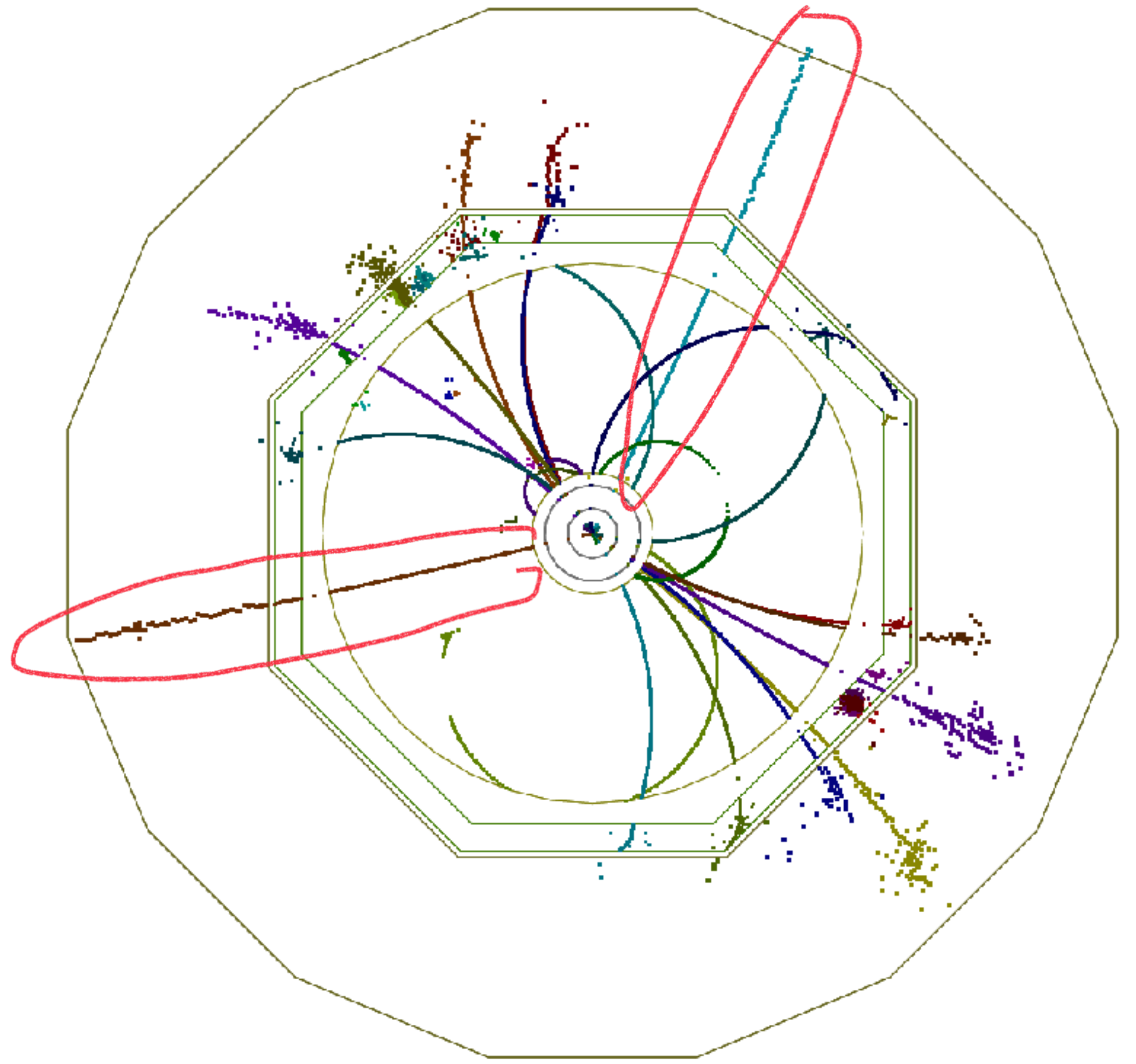

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- ***Impact parameter resolution,*** *vertex charge*

  Flavour tagging: b/c/light tagging in Higgs

$$\sigma(d_0) \sim [5 \oplus (10 - 15)/p\sin^{3/2}\theta]\ \mu m$$

single point resolution in vertex detector ~3 μm
< 0.2 X_0 per layer

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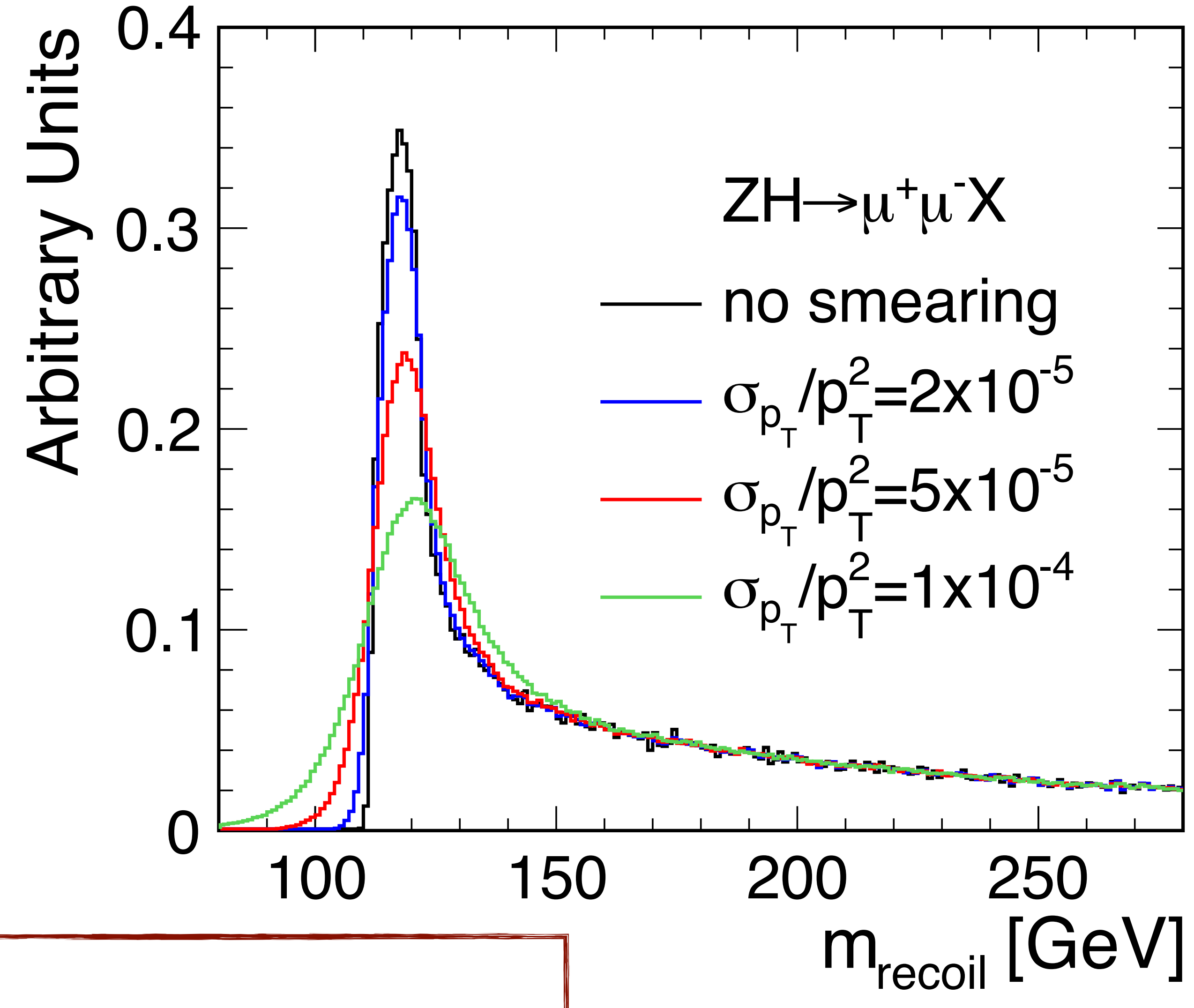

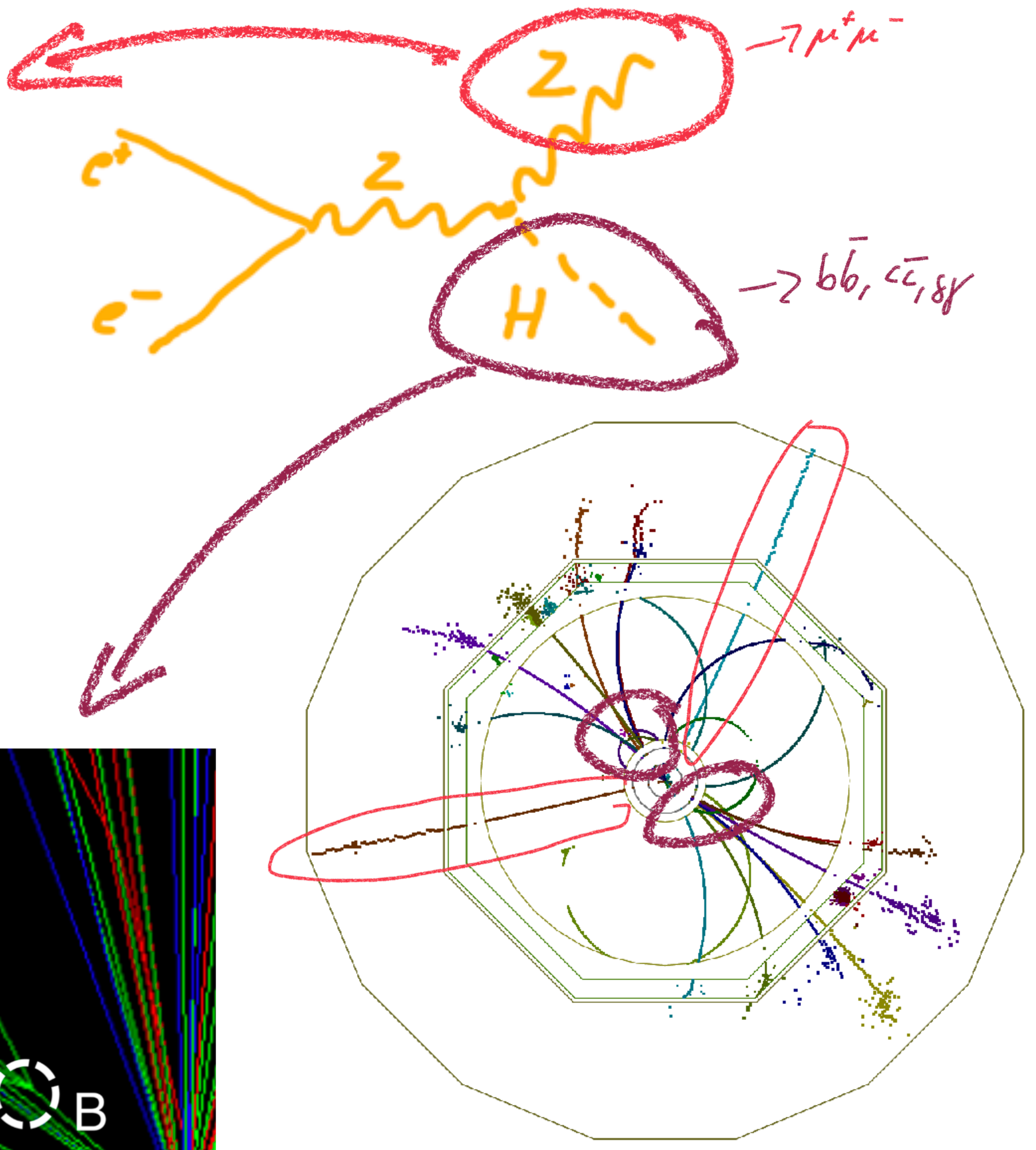

low mass, good resolution:
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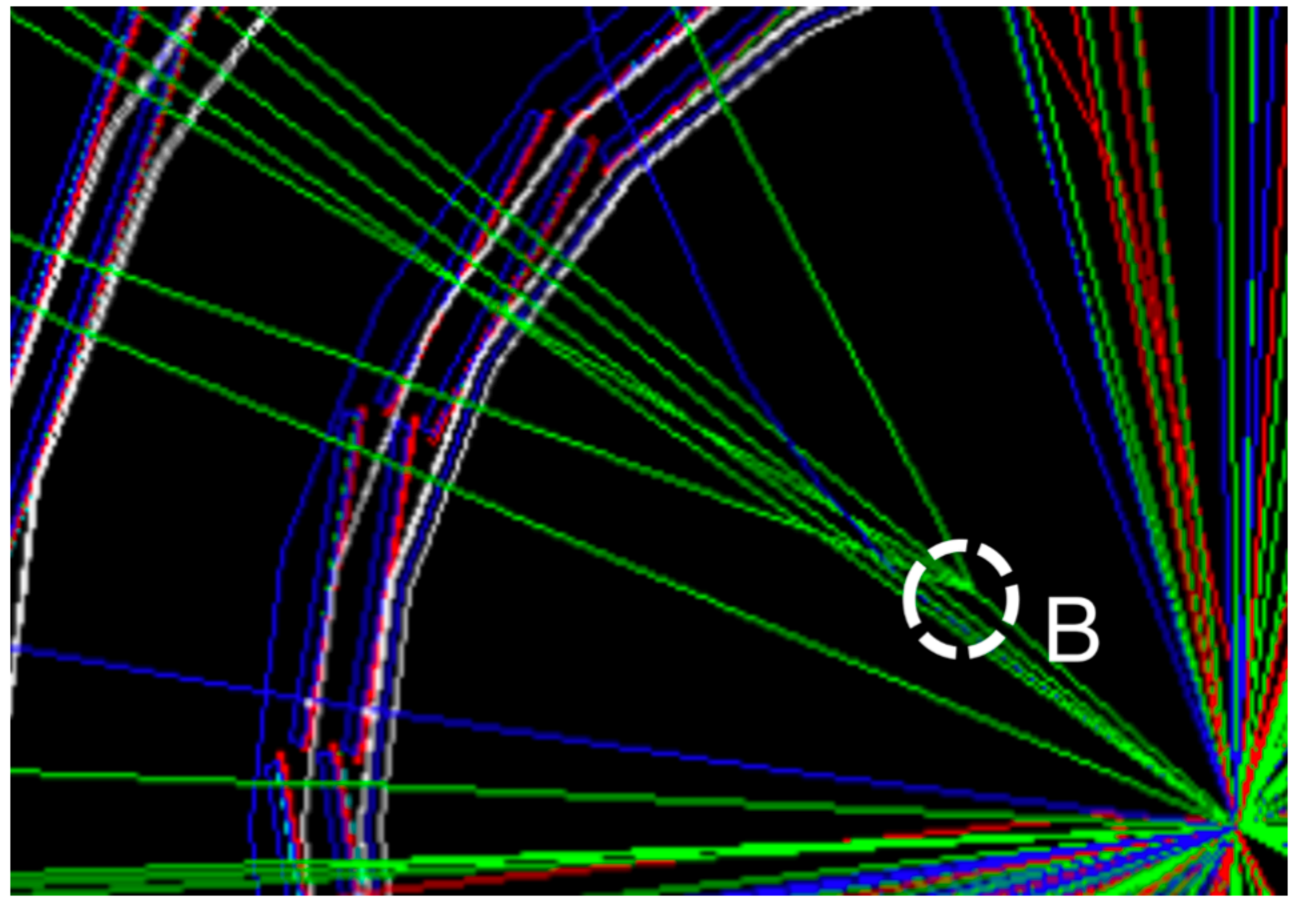

single point resolution in vertex detector ~3 *μ*m
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Detector Performance Goals - Jets, Photons, PID

Motivated by key physics signatures

- ***Jet energy resolution***

  Recoil measurements with hadronic Z decays, separation of W, Z, H bosons, …

  $\sigma(E_{jet}) / E_{jet}$ ~ 3% - 5% **for E_{jet} > 45 GeV**

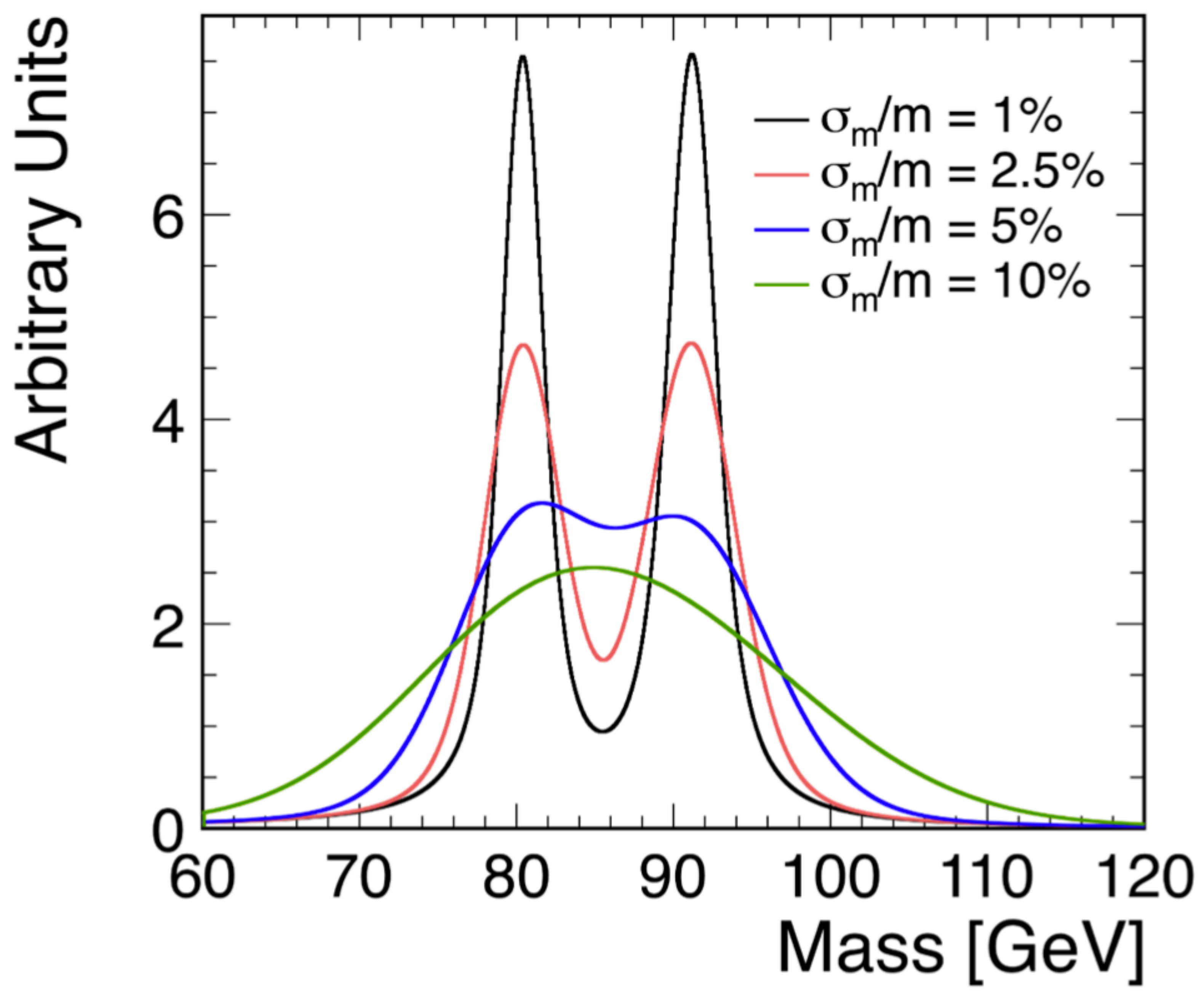
  reconstruction of complex multi-jet final states.

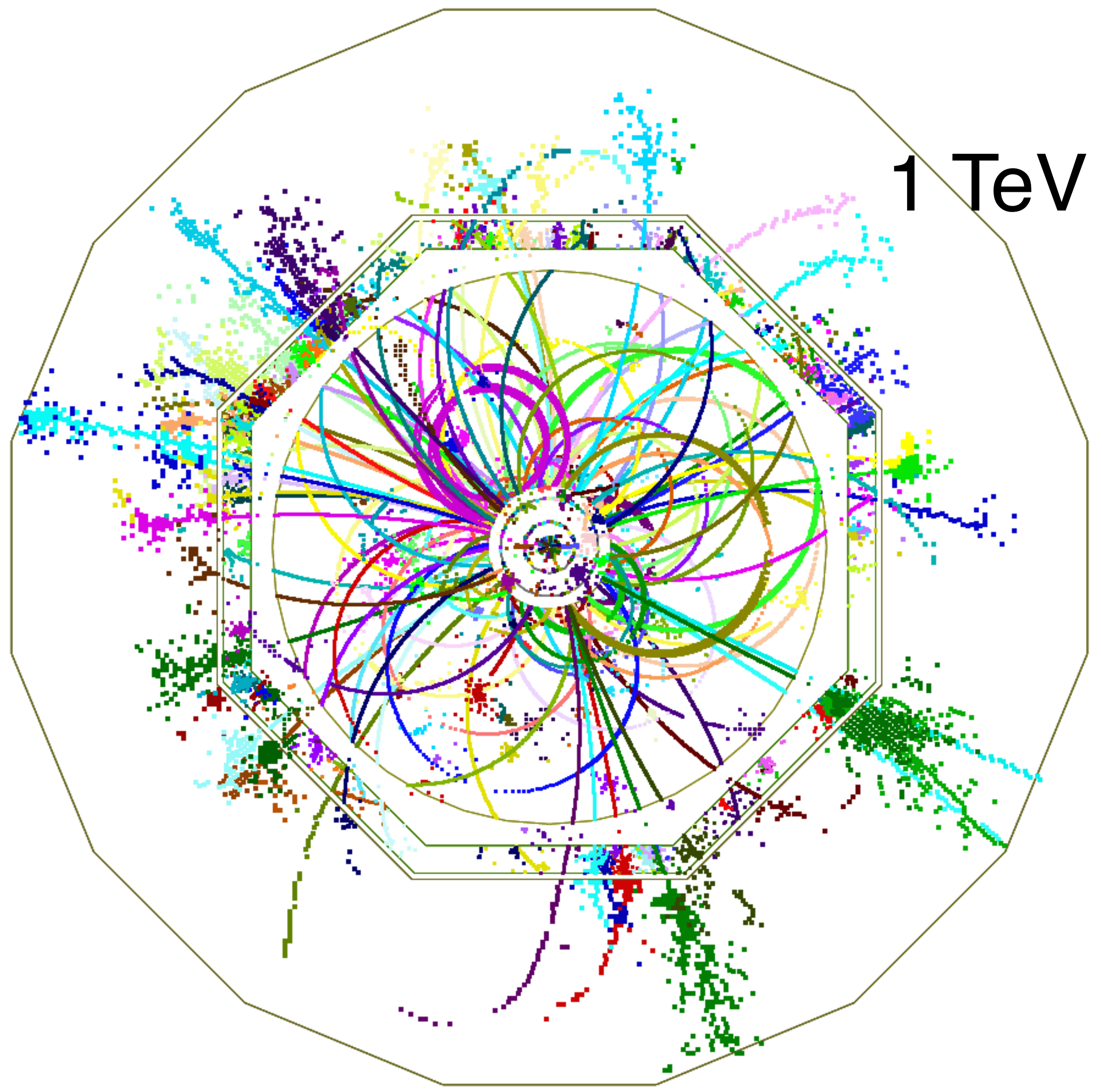
- ***Photons***

  Resolution not in the focus: ~ 15 - 20%/√E

  Worth another look ?

  Coverage to 100s of GeV important





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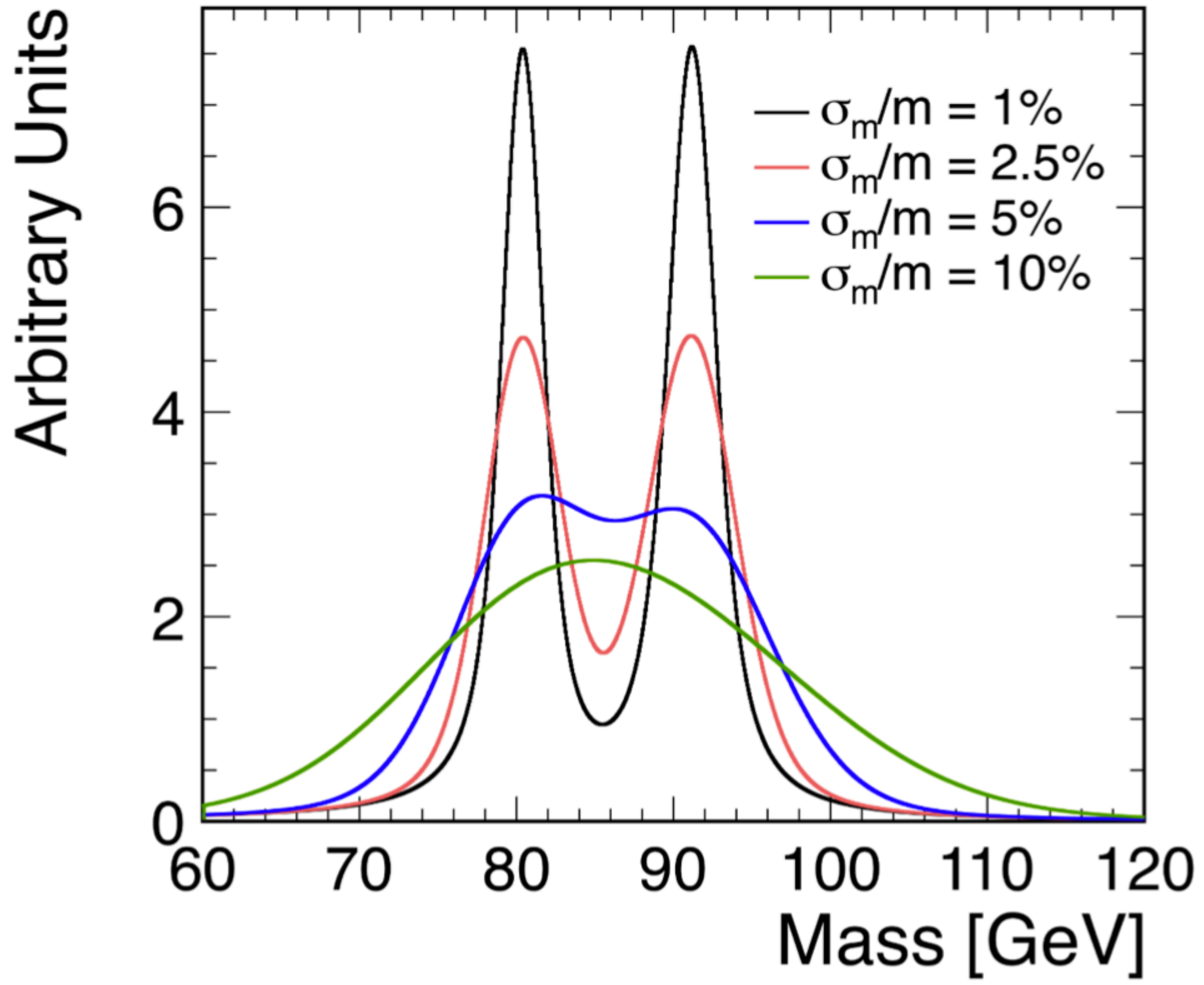
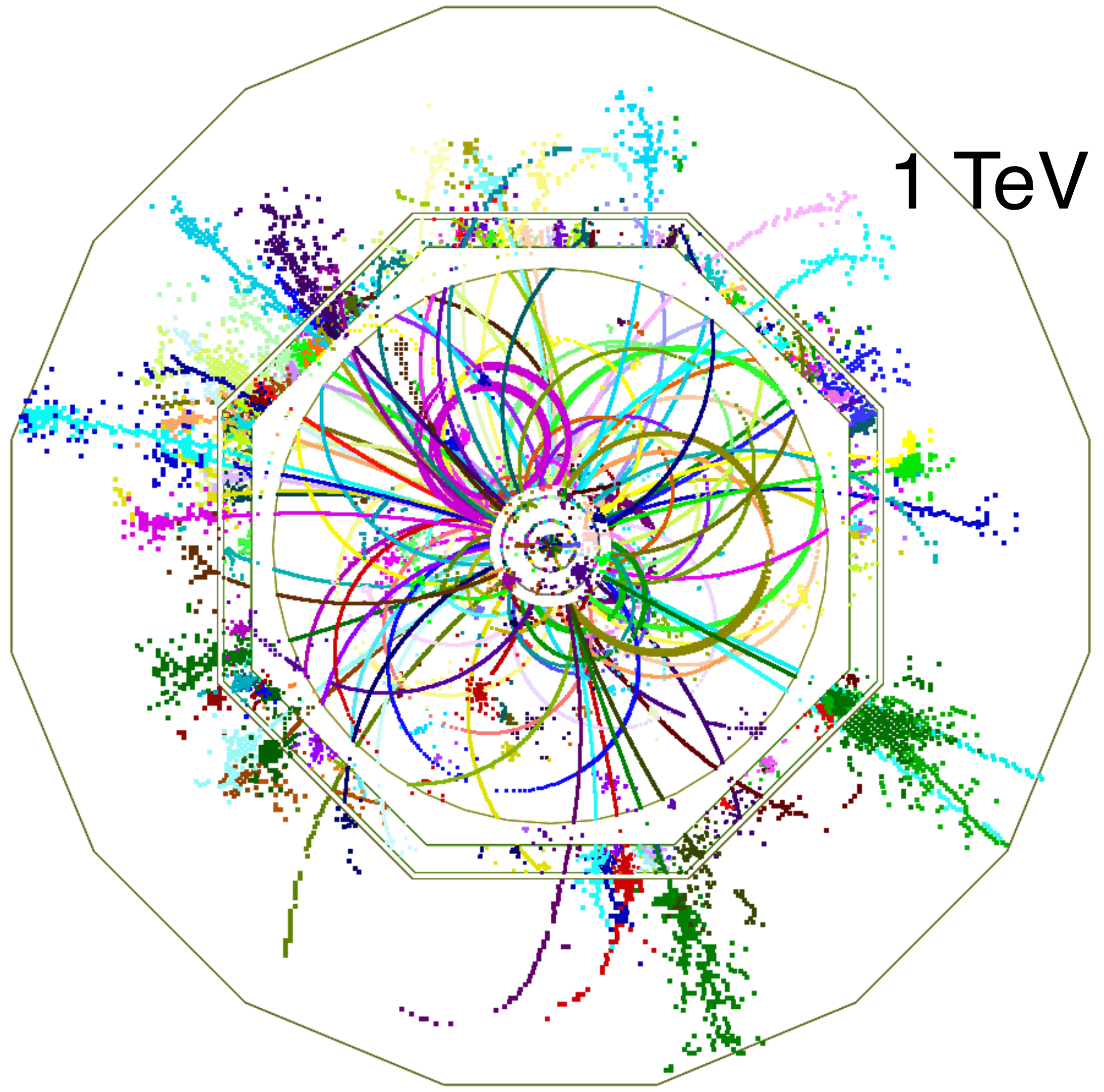
  Clean identification of e, μ up to highest energies

- PID of hadrons to improve tagging, jets,…





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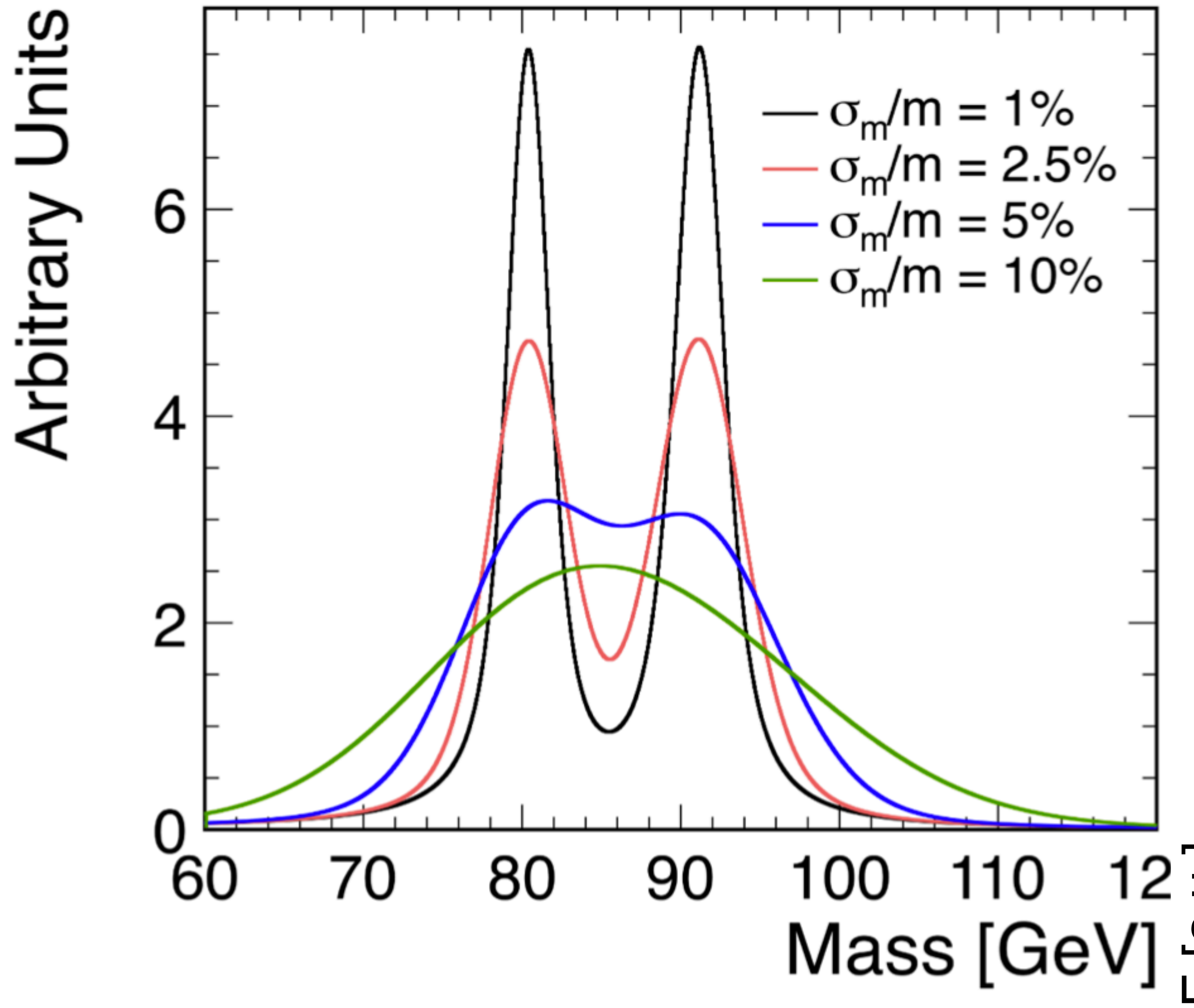
  Clean identification of e, μ up to highest energies

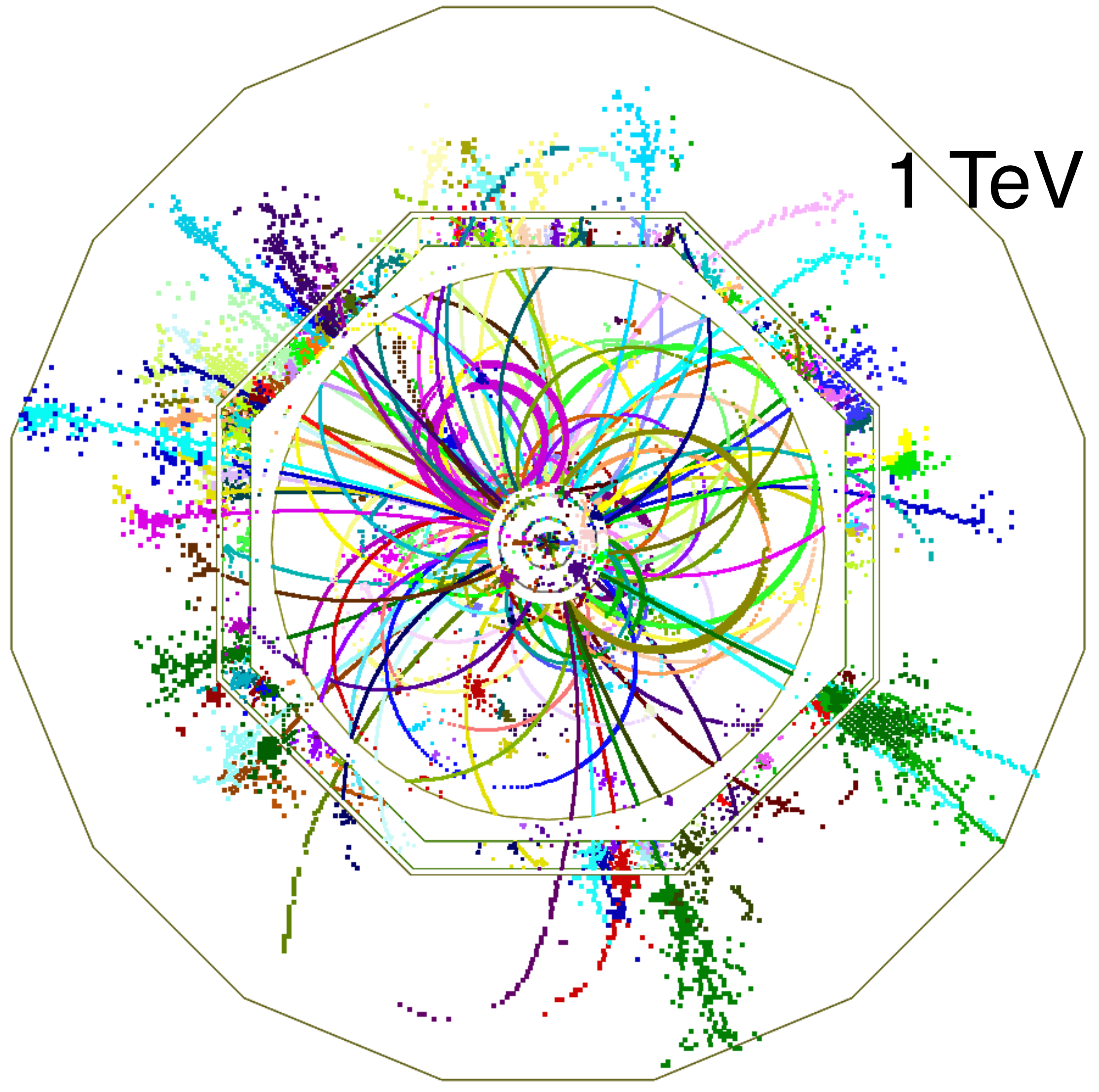
- PID of hadrons to improve tagging, jets,…

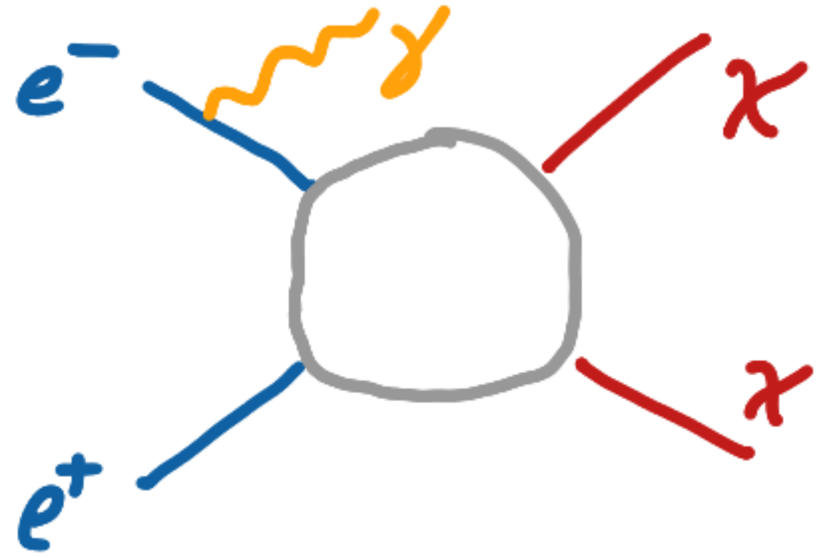
- ***Hermetic coverage***

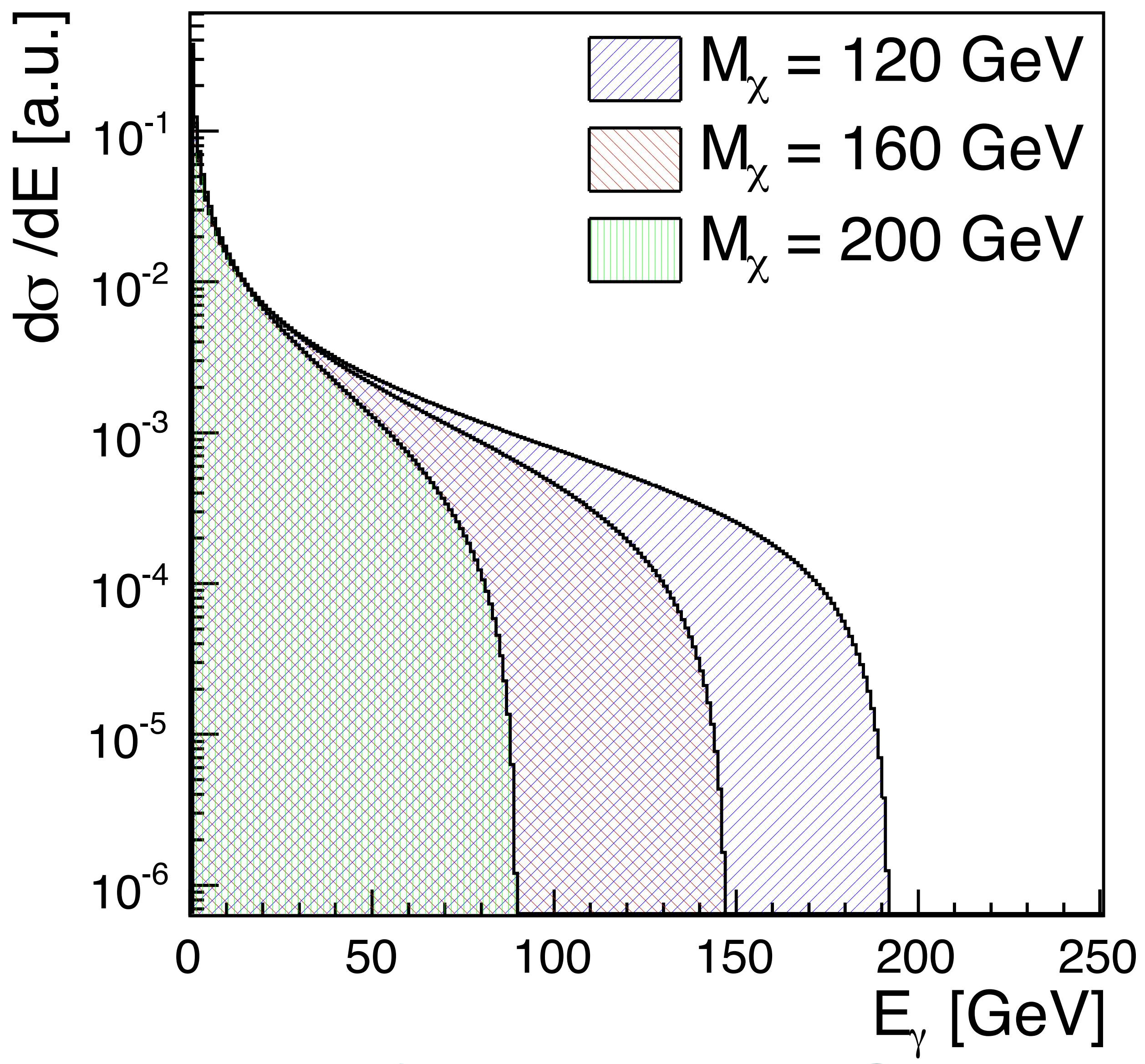
  Dark matter searches in mono-photon events, …

  N.B.: Achievable limits do not depend strongly on $\sigma(E_\gamma)$





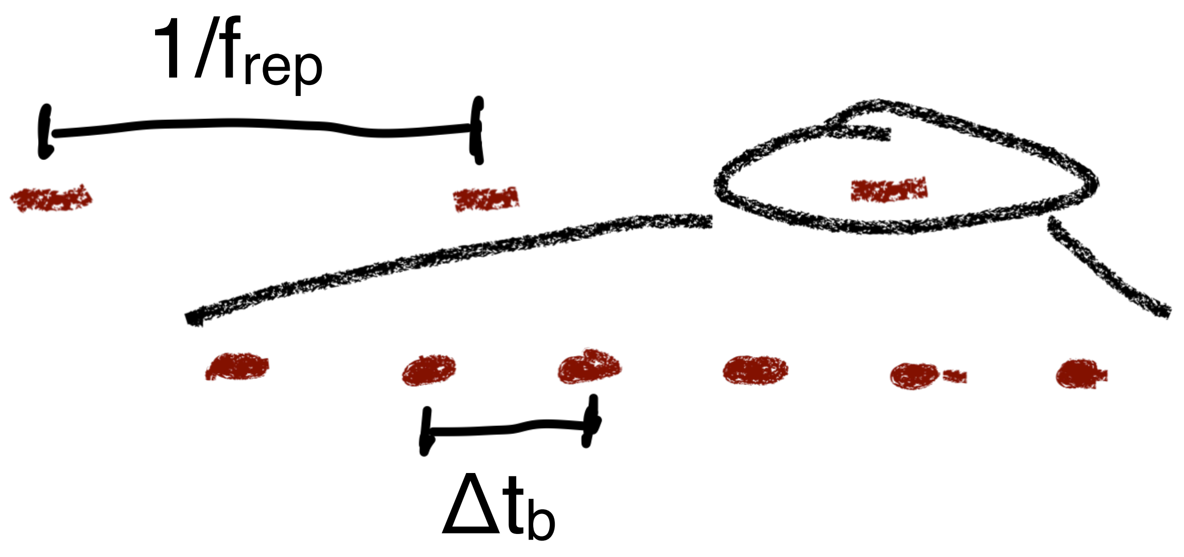




Linear Collider Conditions

… and the consequences for the detector design

- Linear Colliders operate in bunch trains:



  - at CLIC: $\mathbf{\Delta t_b = 0.5}$ **ns**; f_{rep} = 50 Hz
  - at ILC: Δt_b = 554 ns; f_{rep} = 5 Hz

⇨ Enables power pulsing of front-end electronics, resulting in dramatically reduced power consumption

- ⇨ Eliminates need for active cooling in many areas of the detectors: Reduced material, increased compactness

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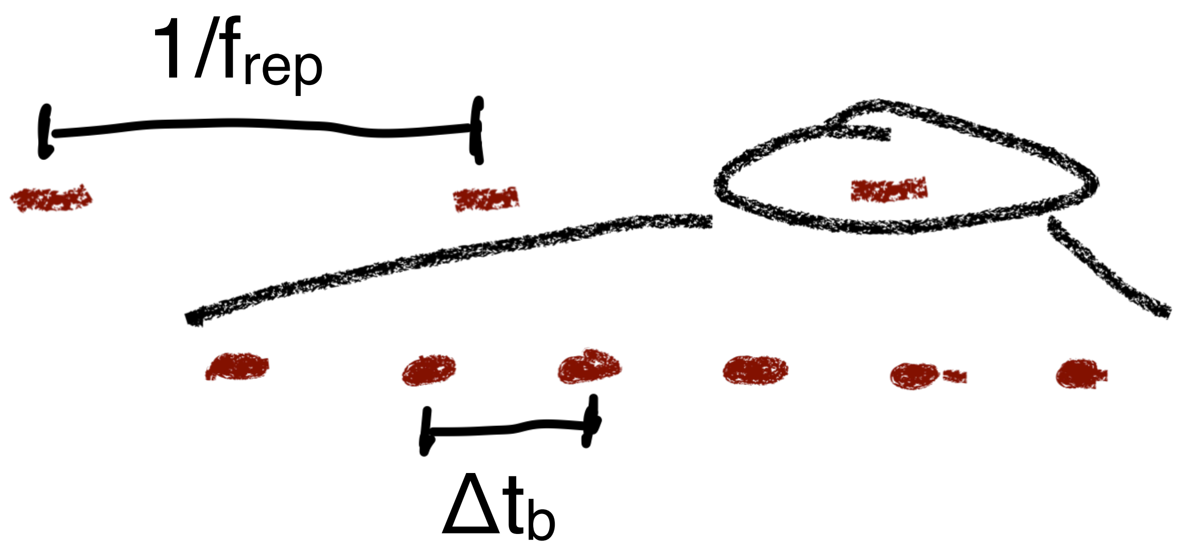

  - at CLIC: $\mathbf{\Delta t_b = 0.5}$ **ns**; f_{rep} = 50 Hz
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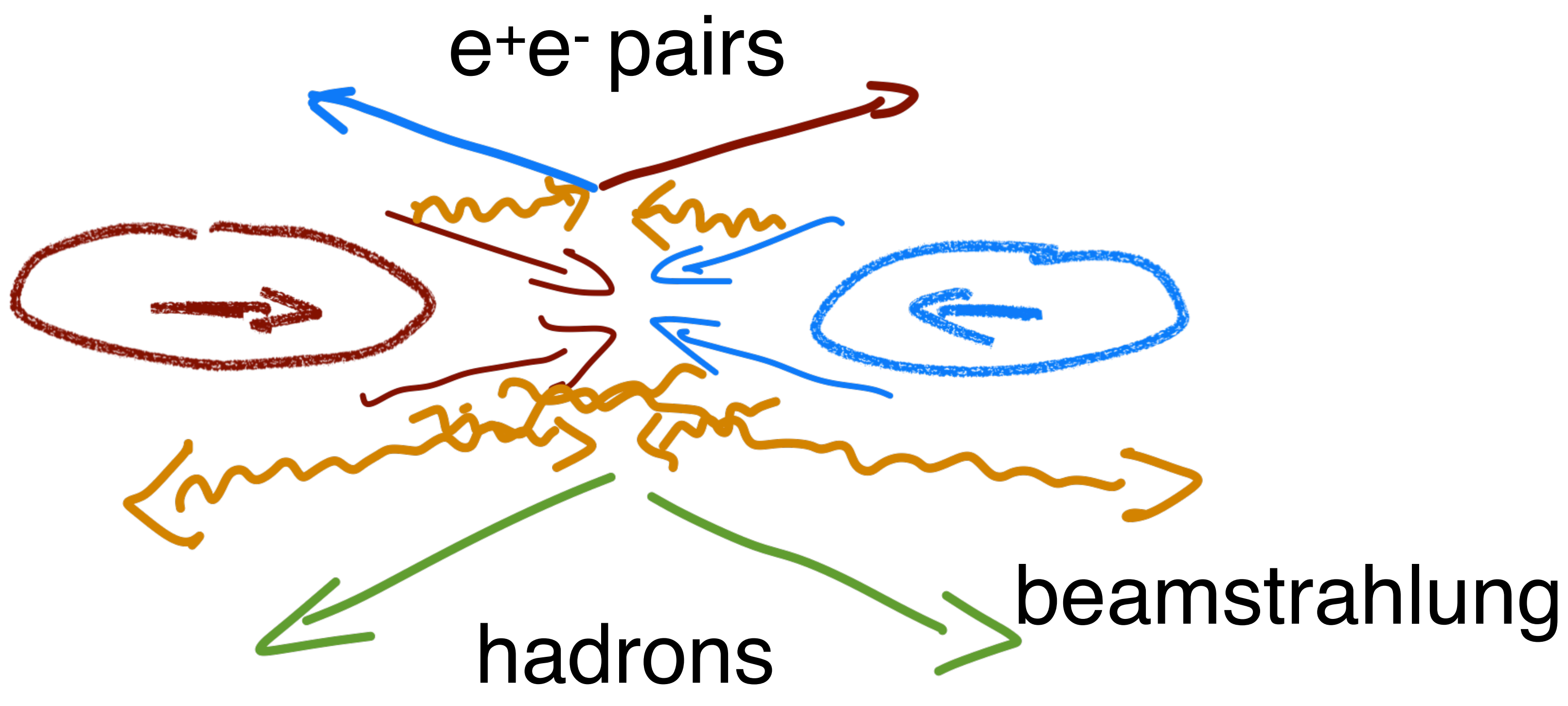
- … and require extreme focusing to achieve high luminosity



⇨ Enables power pulsing of front-end electronics, resulting in dramatically reduced power consumption

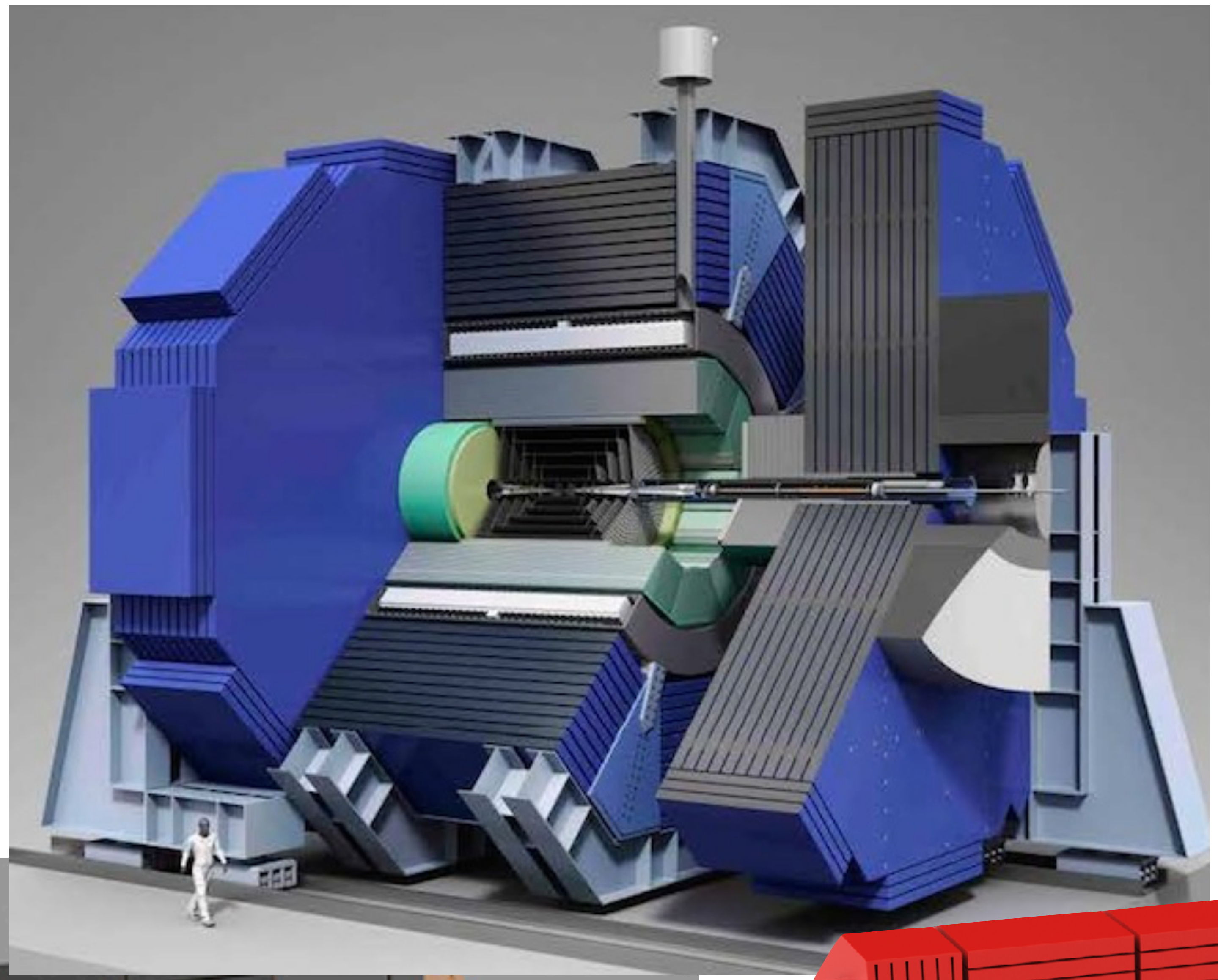
- ⇨ Eliminates need for active cooling in many areas of the detectors: Reduced material, increased compactness

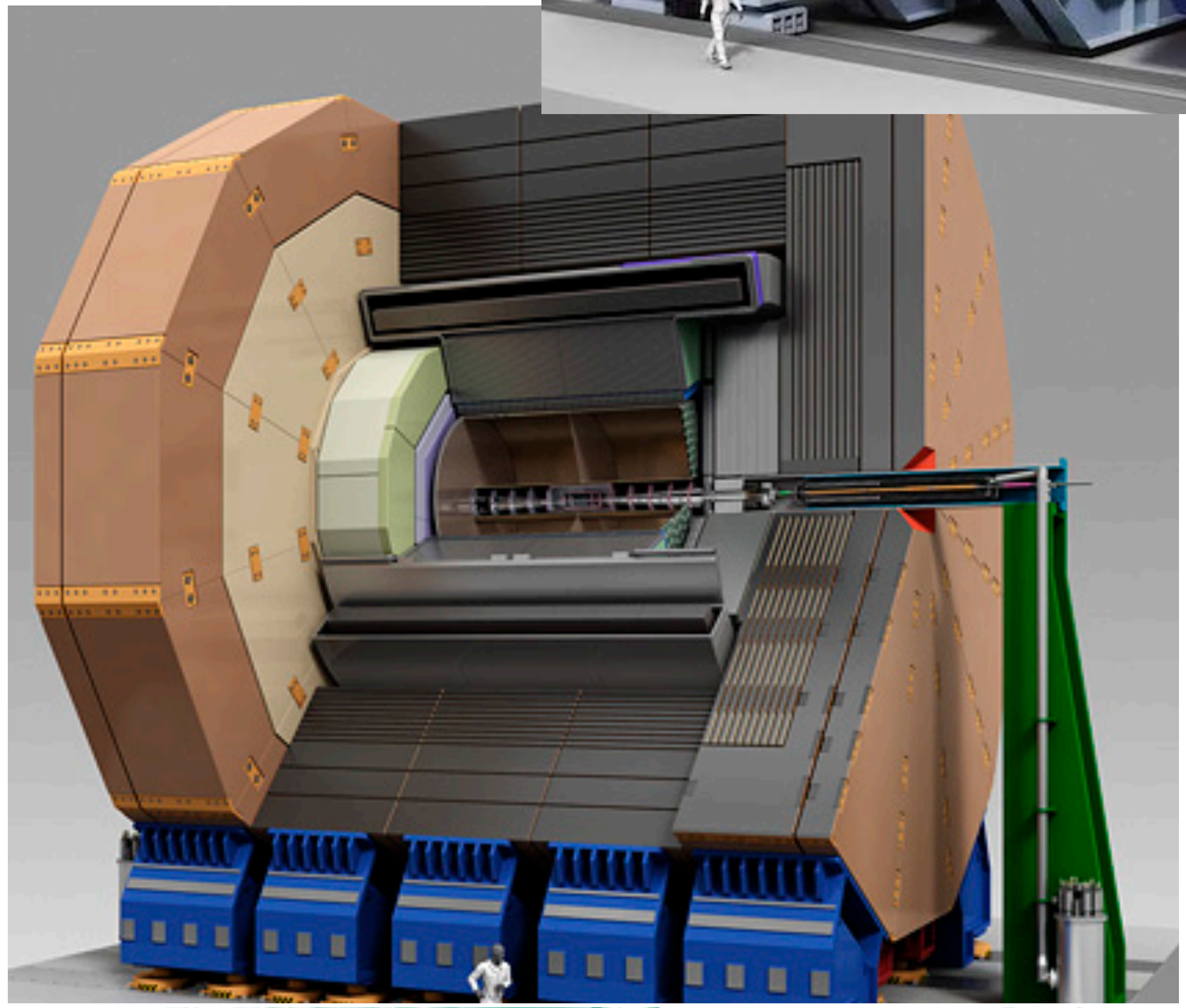
⇨ Significant beam-induced backgrounds

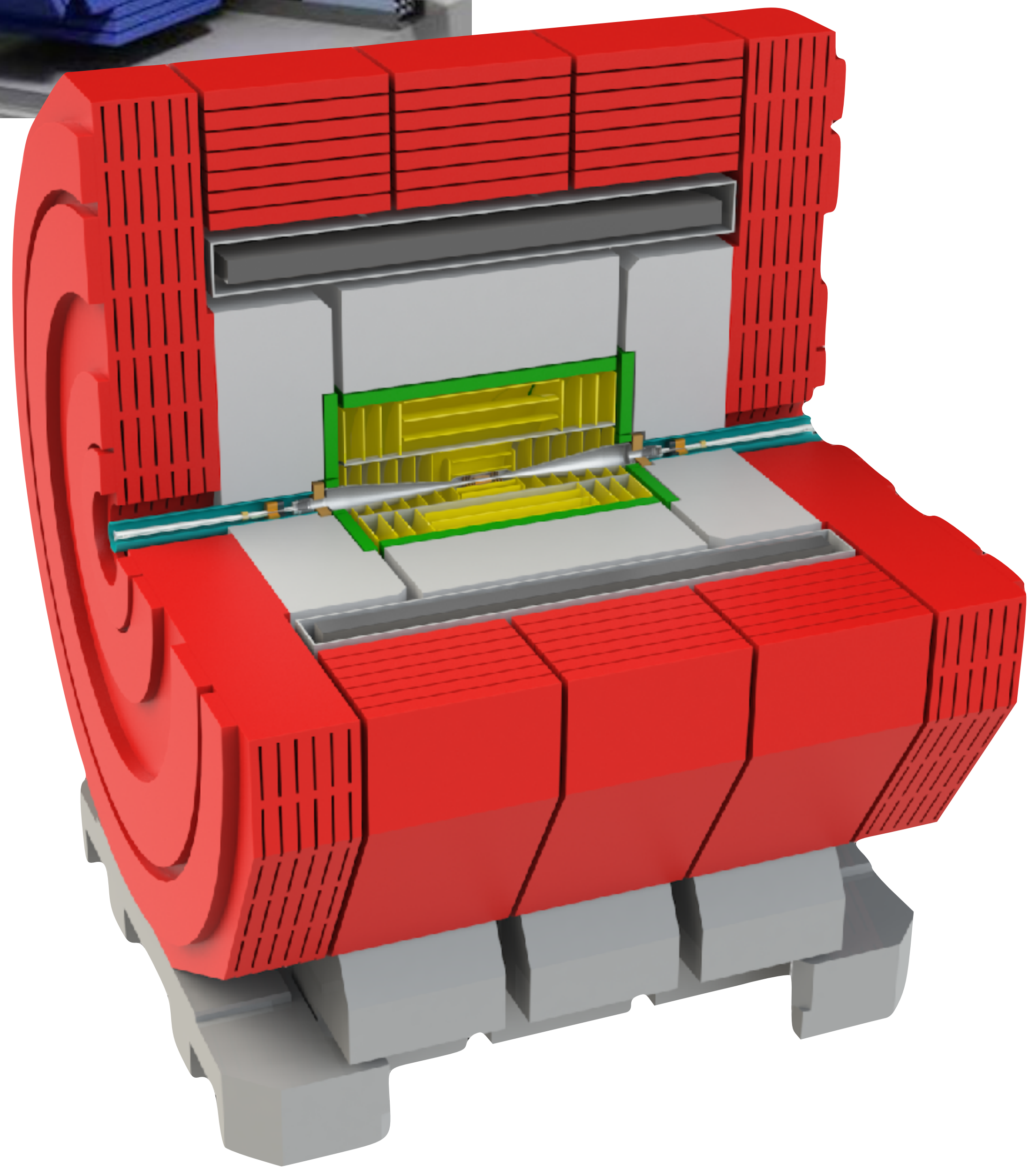
- ⇨ Constraints on beam pipe geometry, crossing angle and vertex detector radius
- ⇨ In-time pile-up of hadronic background: **sufficient granularity for topological rejection**
- ⇨ At CLIC: small Δt_b also results in out-of-time pile-up: **ns-level timing** in many detector systems

The Linear Collider Detector Design - Main Features

Focusing on general aspects







- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*

all: capable of dealing with beam background via timing, granularity, radiation hardness where needed

From linear to circular

Key differences with detector implications

- Energy: Focus on lower energy for FCCee - a maximum of 365 GeV
  - Reduced calorimeter depth
  - Less collimated jets - can potentially compromise on calorimeter compactness, granularity

- Need the beams to survive, and reach high luminosity
  - Limits on solenoidal field
    - Reduced momentum resolution at constant tracker size
    - Larger magnetic volume “affordable”: A path to recover momentum resolution

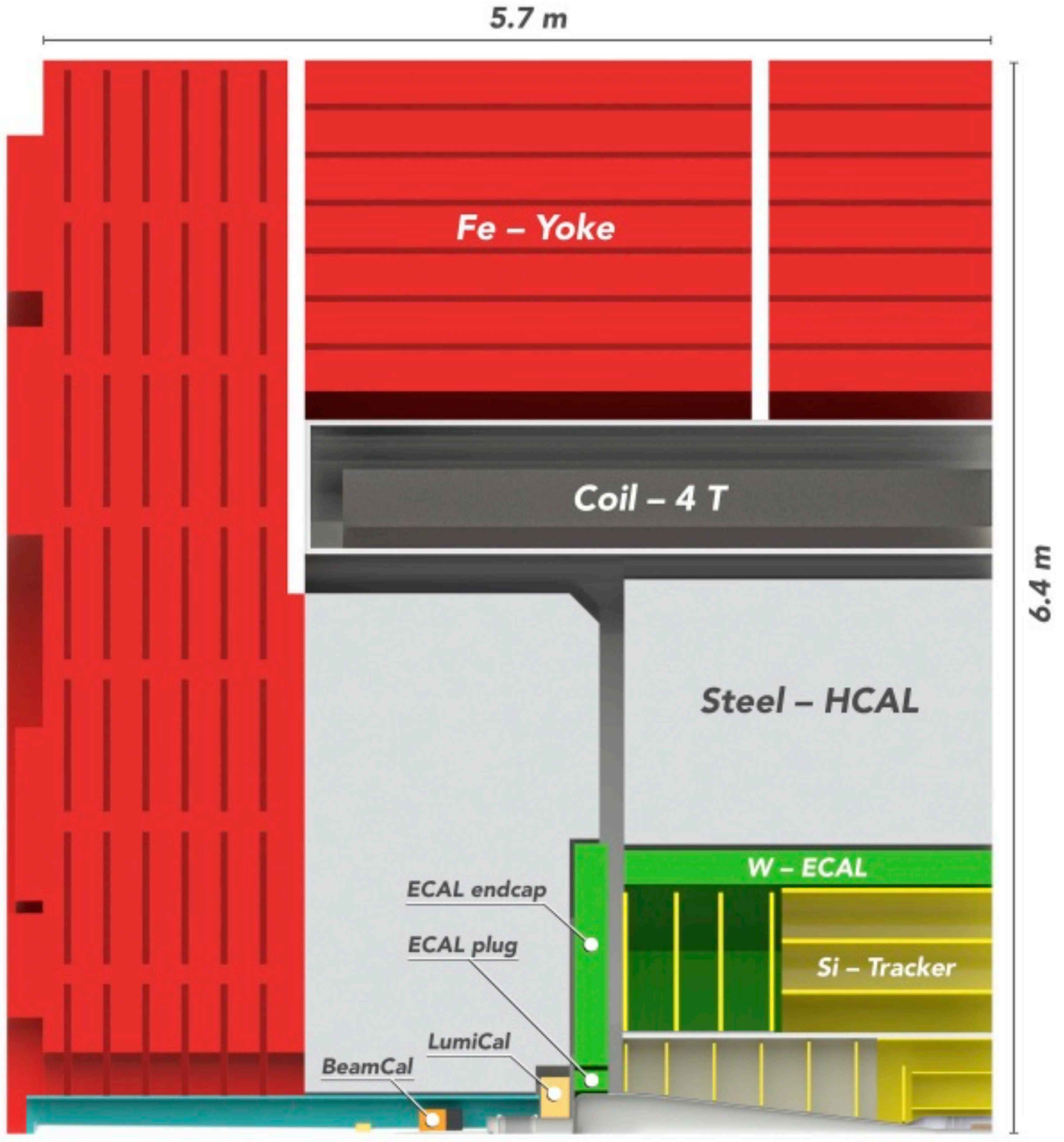
- No bunch train structure: DC operation of the detector readout
  - Active cooling (or compromises on granularity, speed) required in many areas of the detector: Increased material, less compact construction of calorimeters

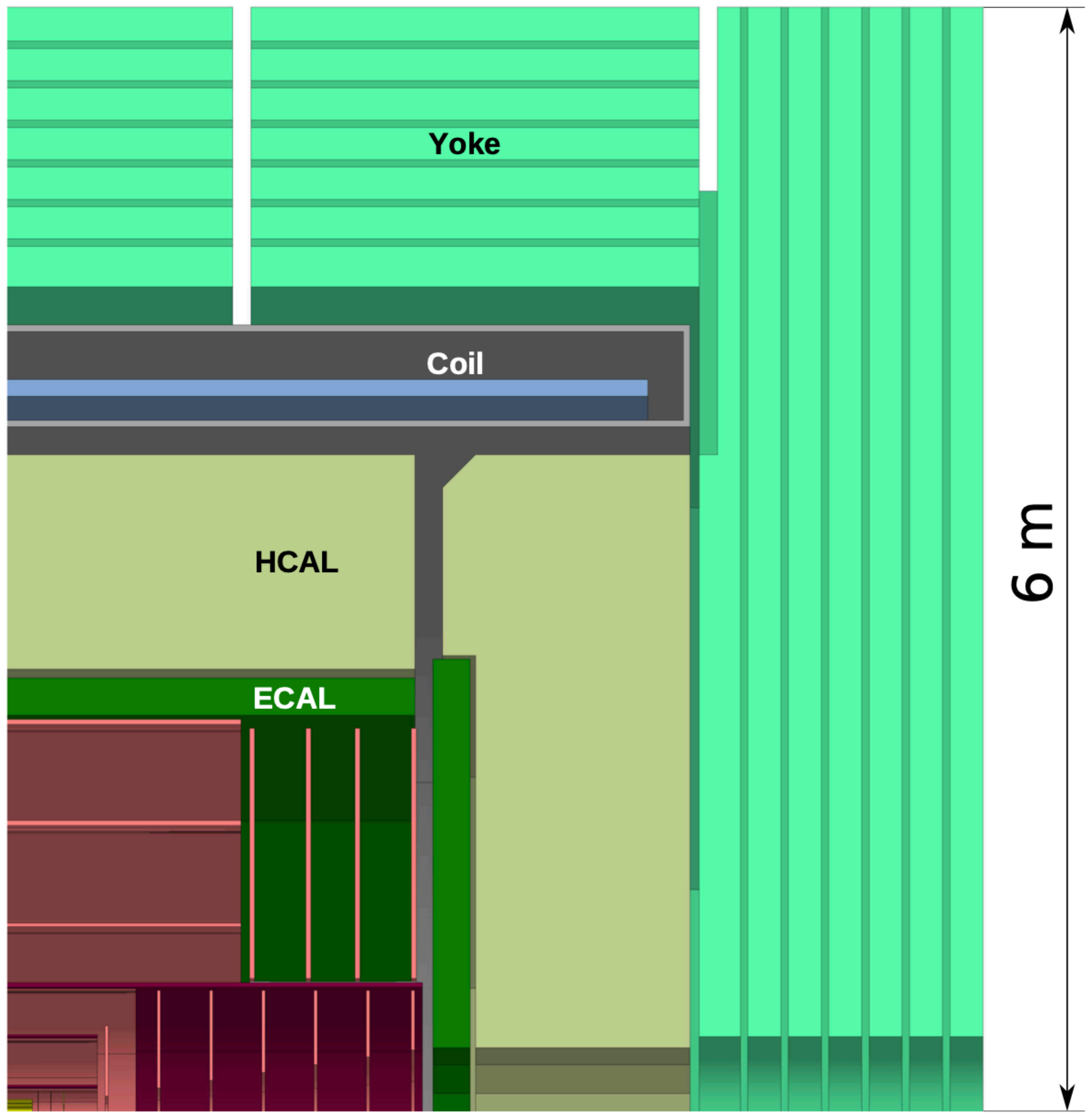
In addition: slightly different physics emphasis: Flavour at the Z pole in particular - which makes PID more important, adding additional detector requirements.

Linear to Circular: Illustrating Detector Changes

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD





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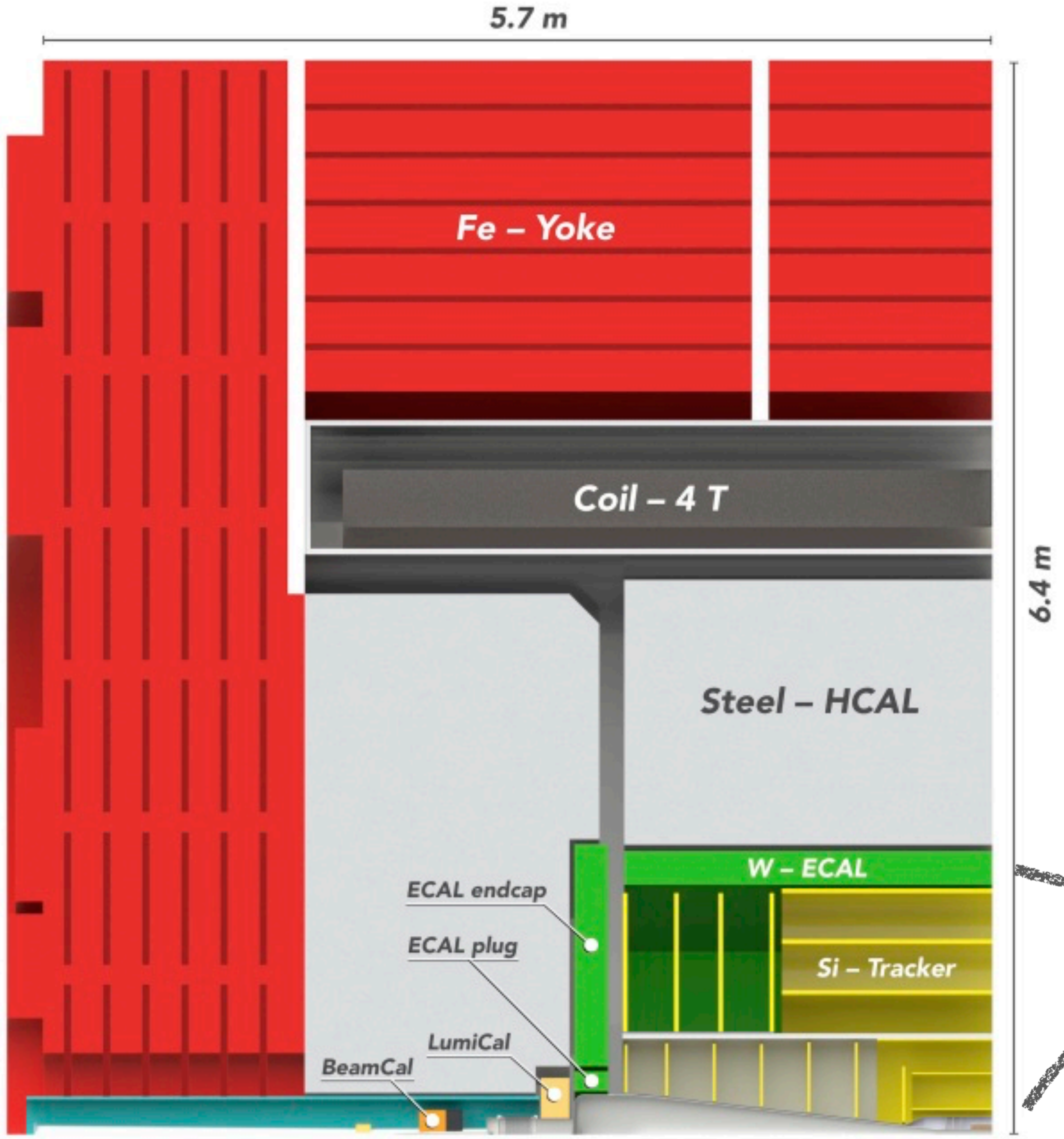
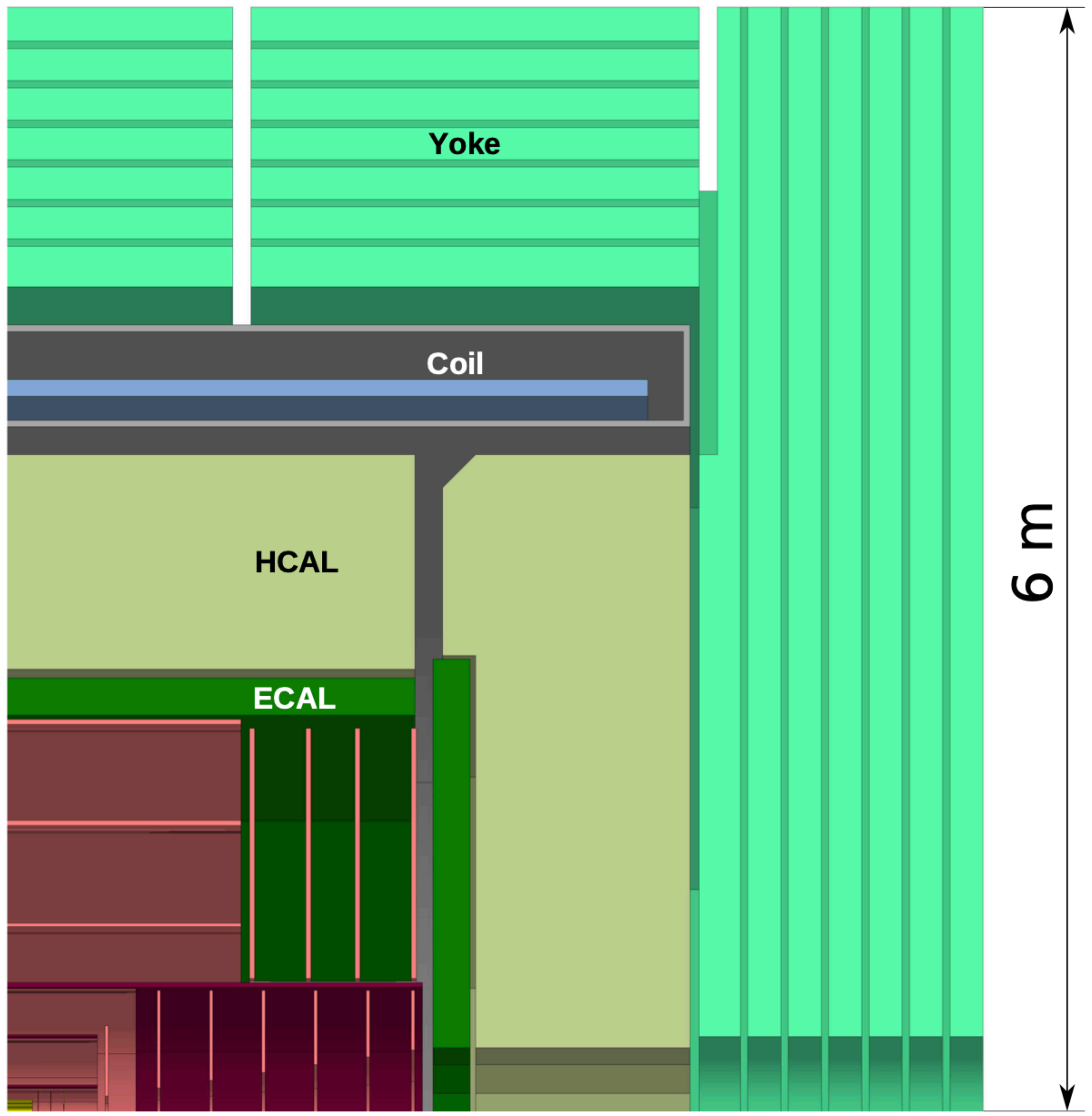


increase in tracker radius:
retain p resolution



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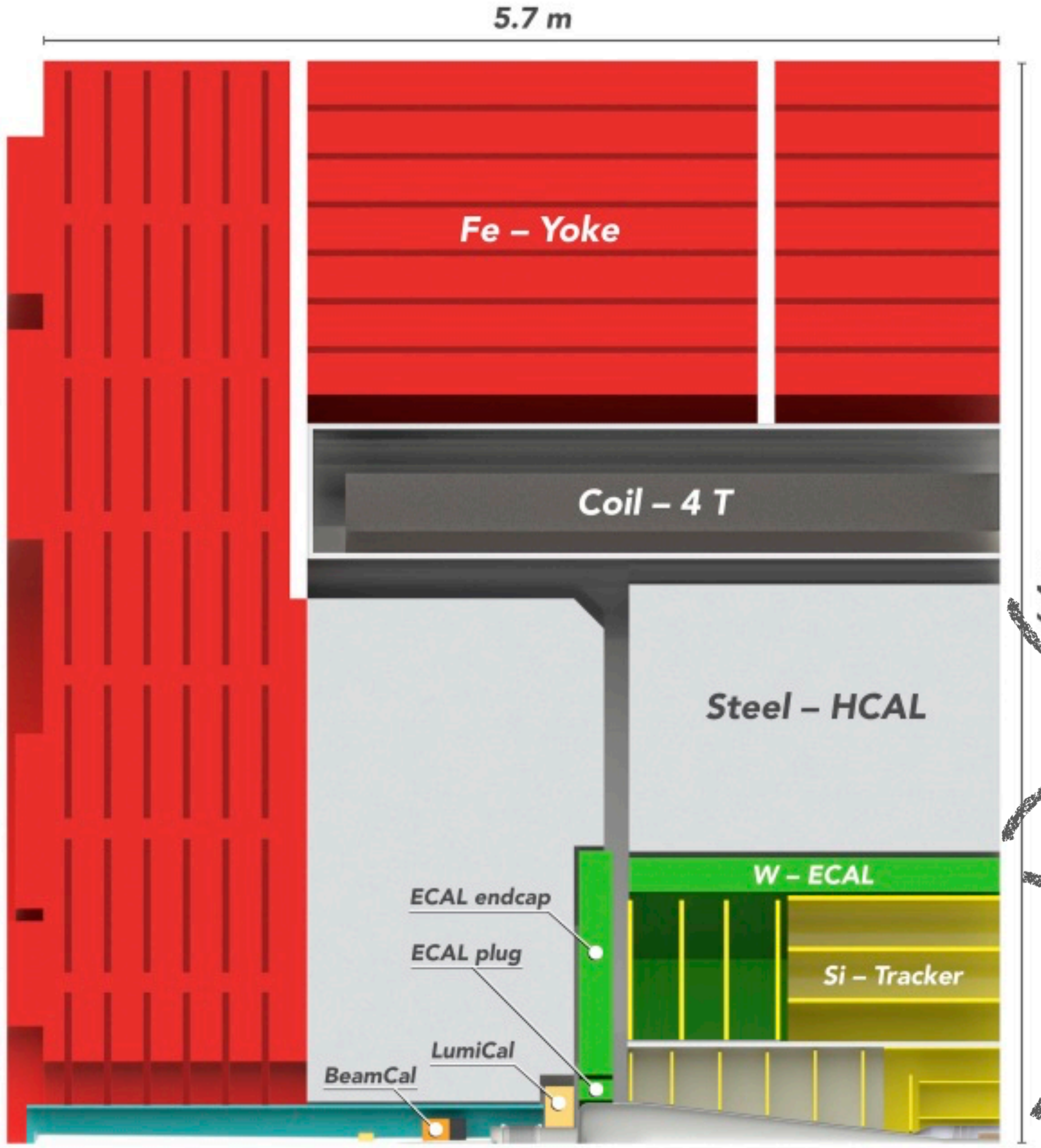
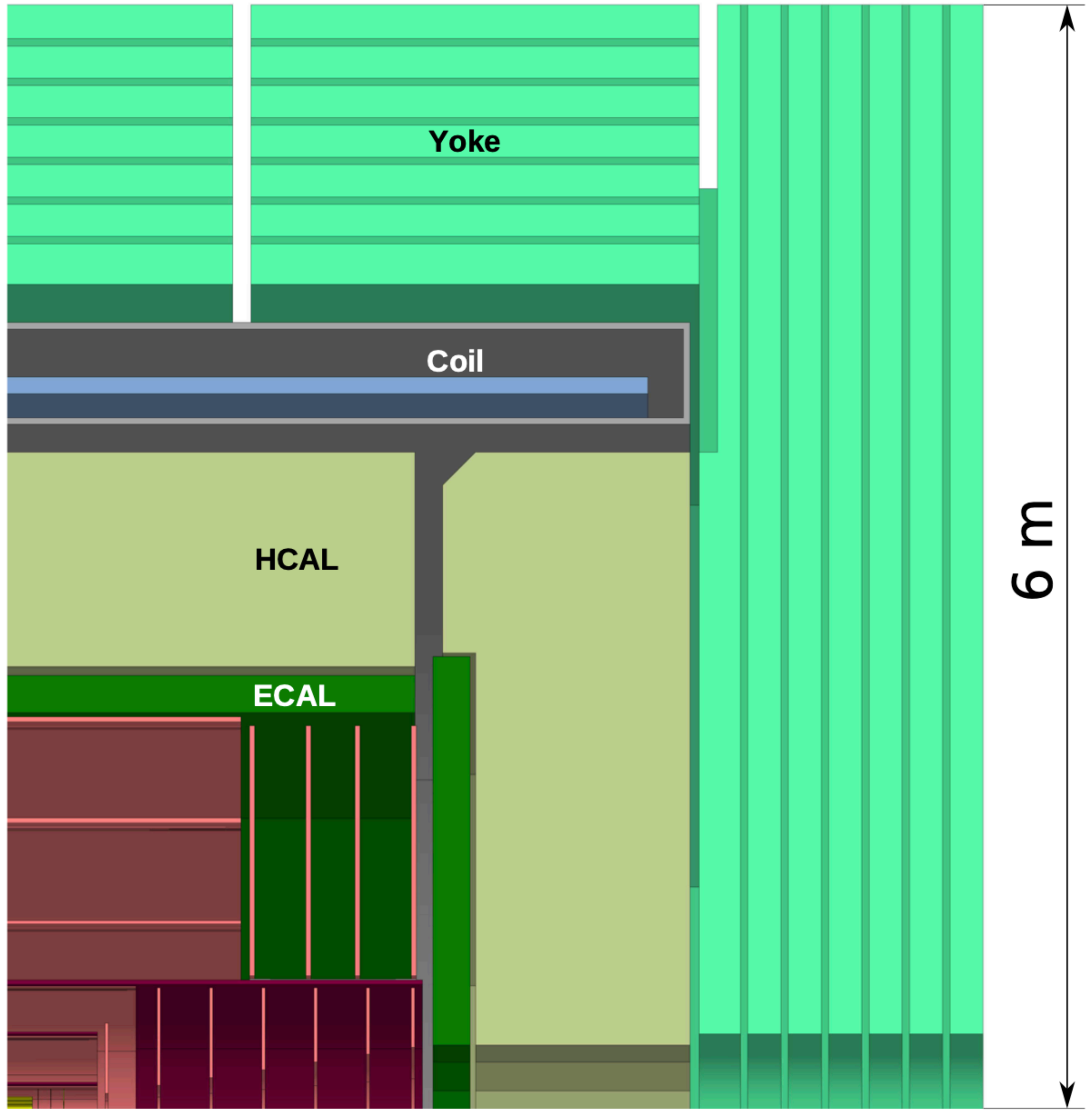


reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution



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Karlsruhe Institute of Technology

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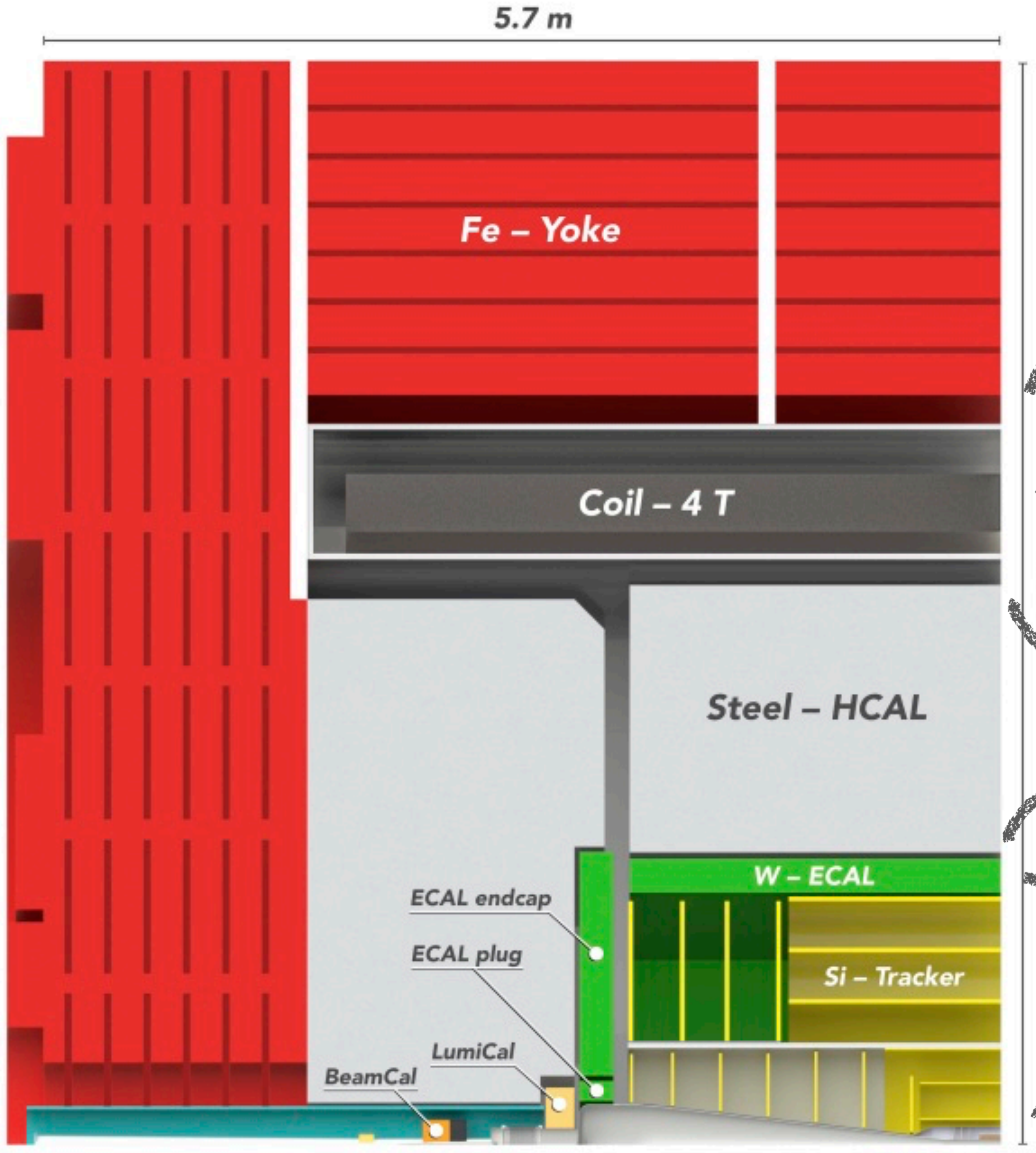
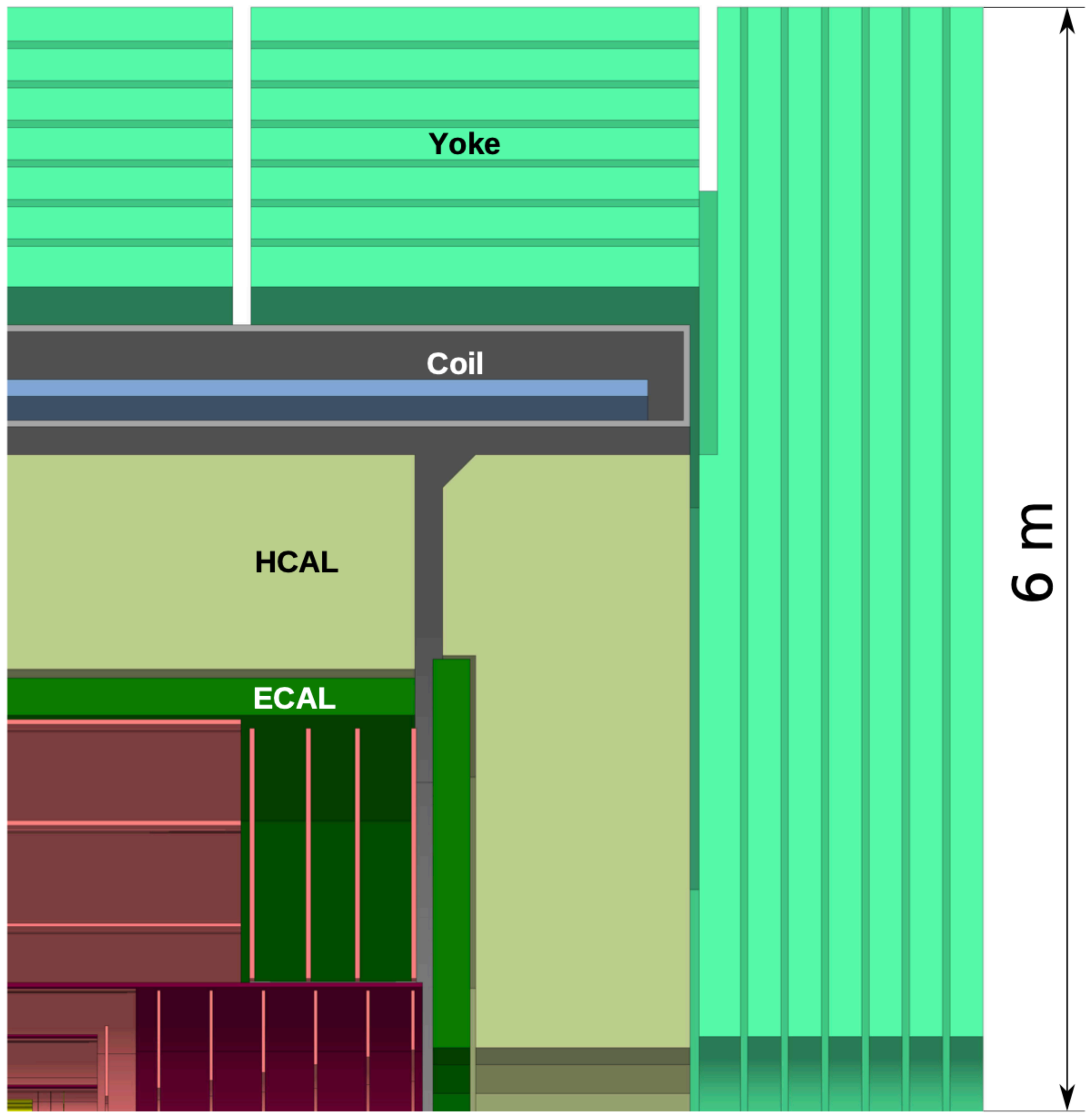


less steel: lower field allows reduced yoke thickness

lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

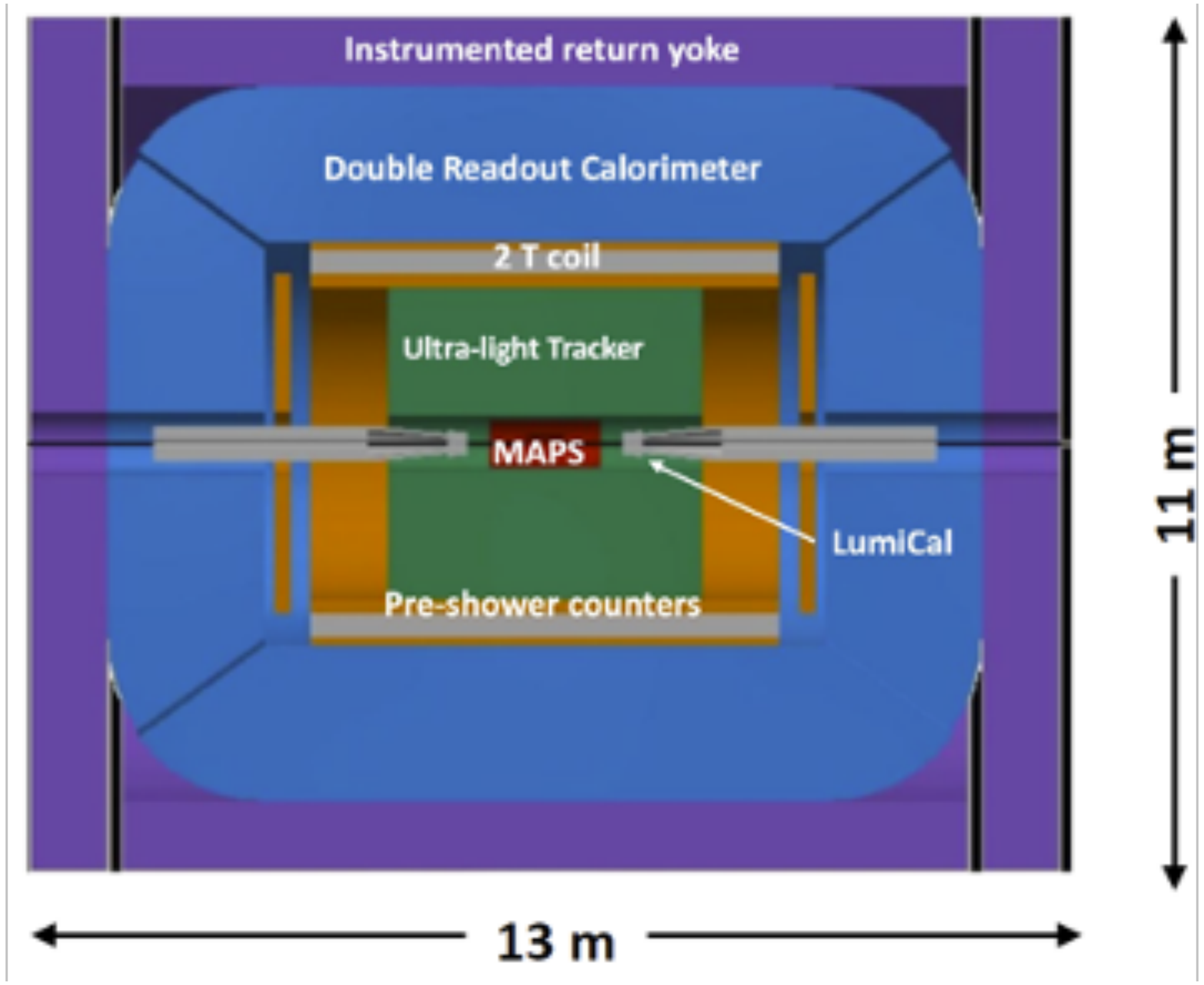
increase in tracker radius: retain p resolution



FCC-ee: Additional Concepts

Different calorimeter concepts, other track solutions

- Putting more emphasis on (low-energy) photons: Requires better resolution in the ECAL



IDEA: Based on dual readout calorimetry, low-mass drift chamber as main tracker

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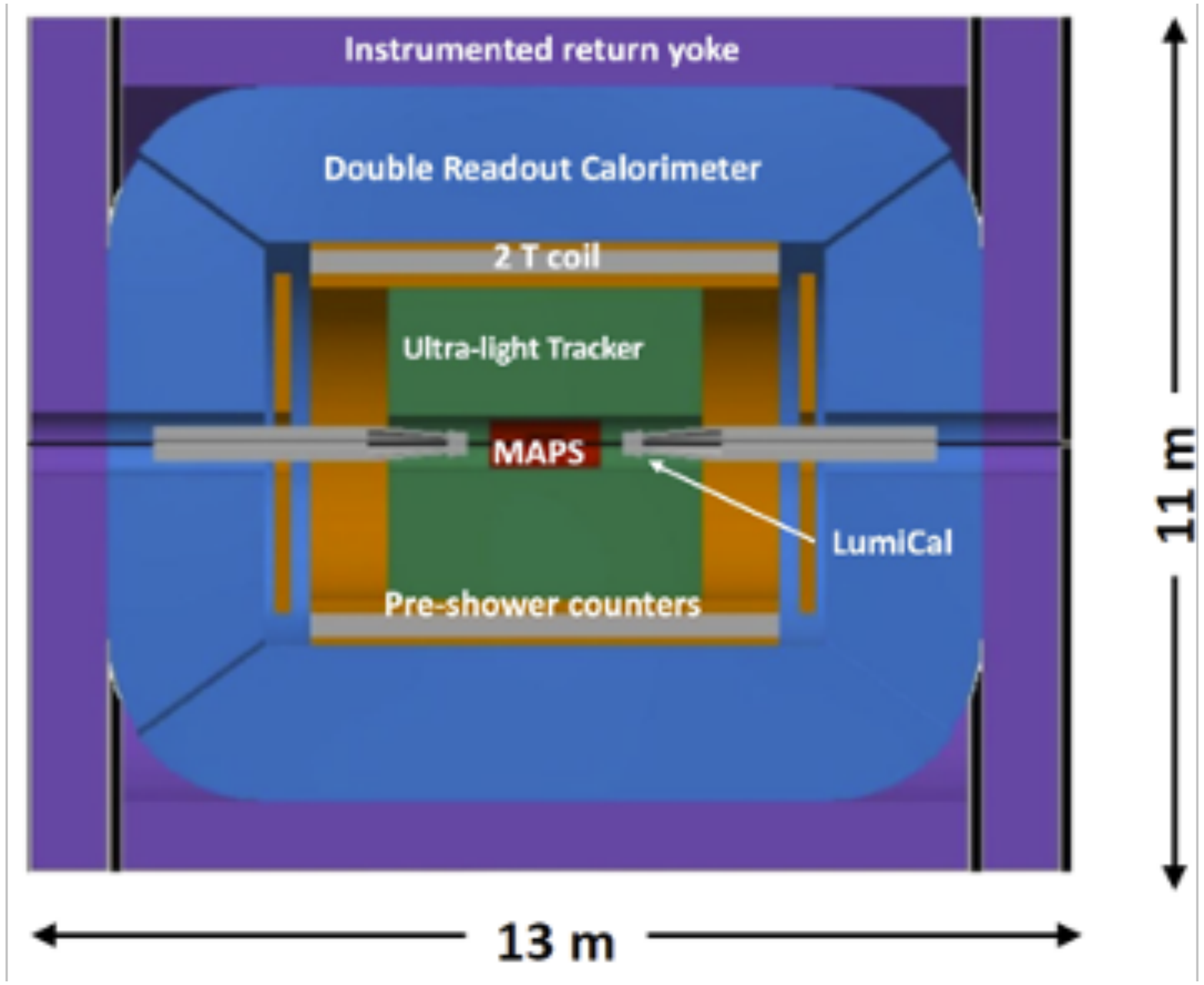

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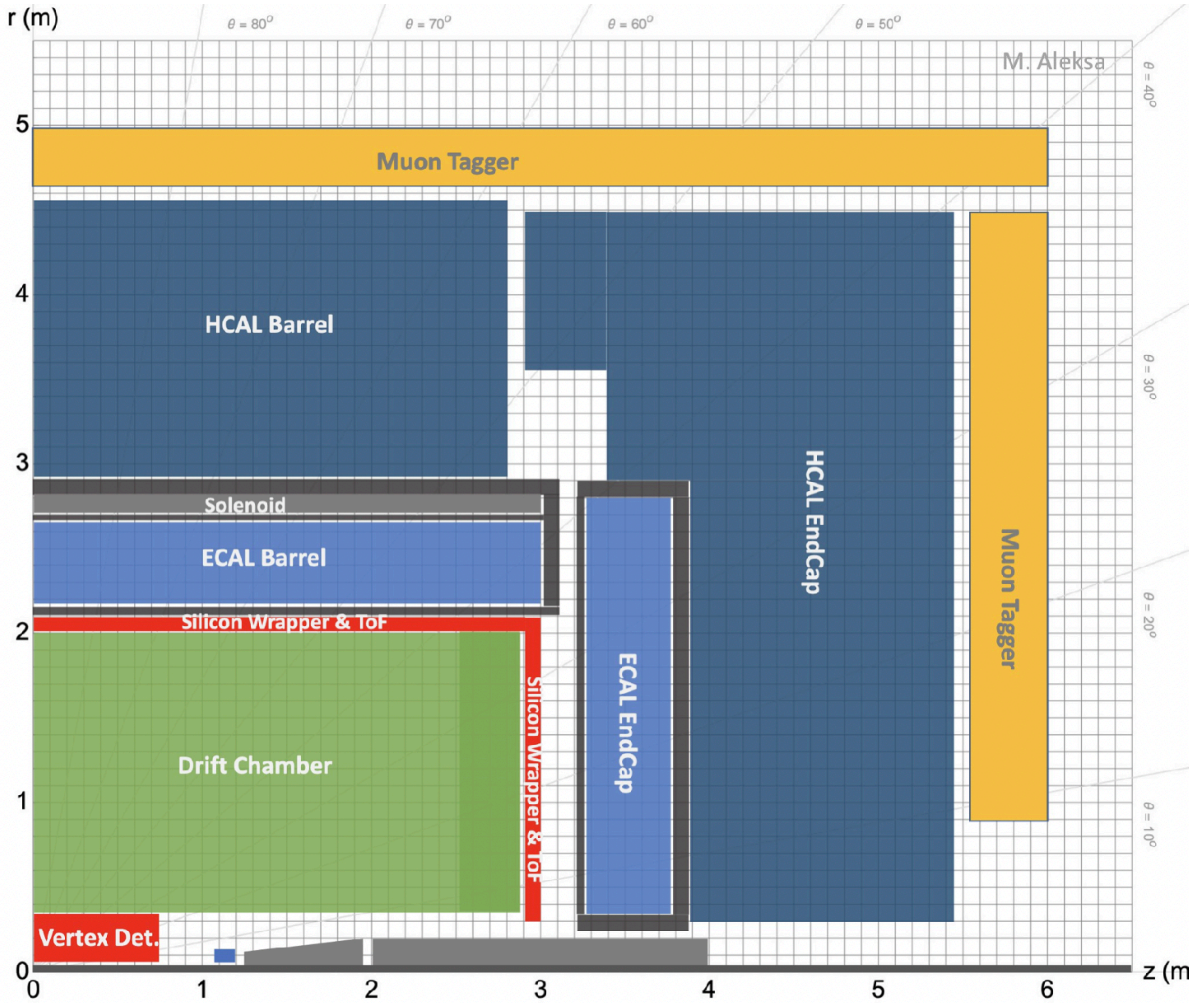

A liquid Ar ECAL: Ultimate stability. Combined with scintillator-based HCAL, different tracker options

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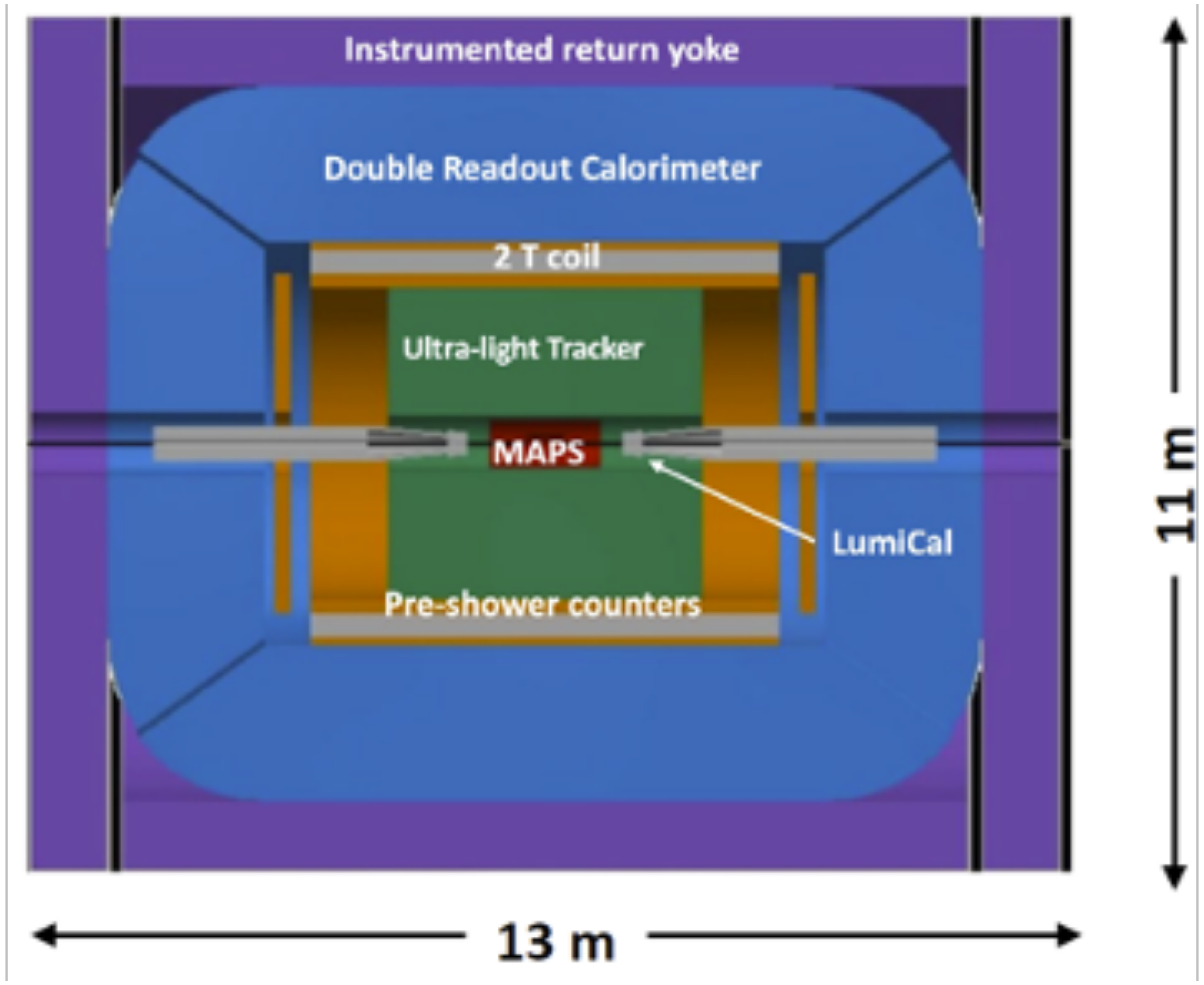


IDEA: Based on dual readout calorimetry, low-mass drift chamber as main tracker

A liquid Ar ECAL: Ultimate stability. Combined with scintillator-based HCAL, different tracker options

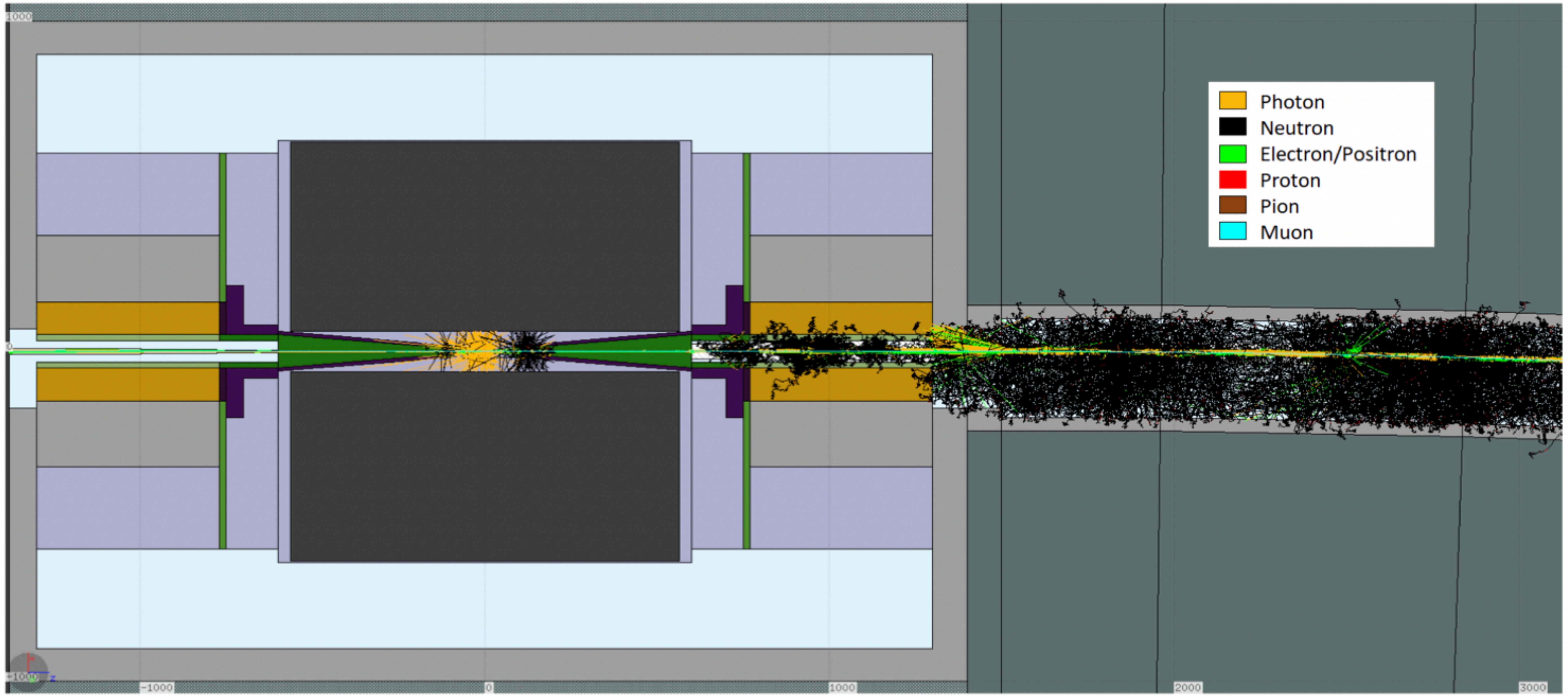
+ investigating detector concepts with added PID

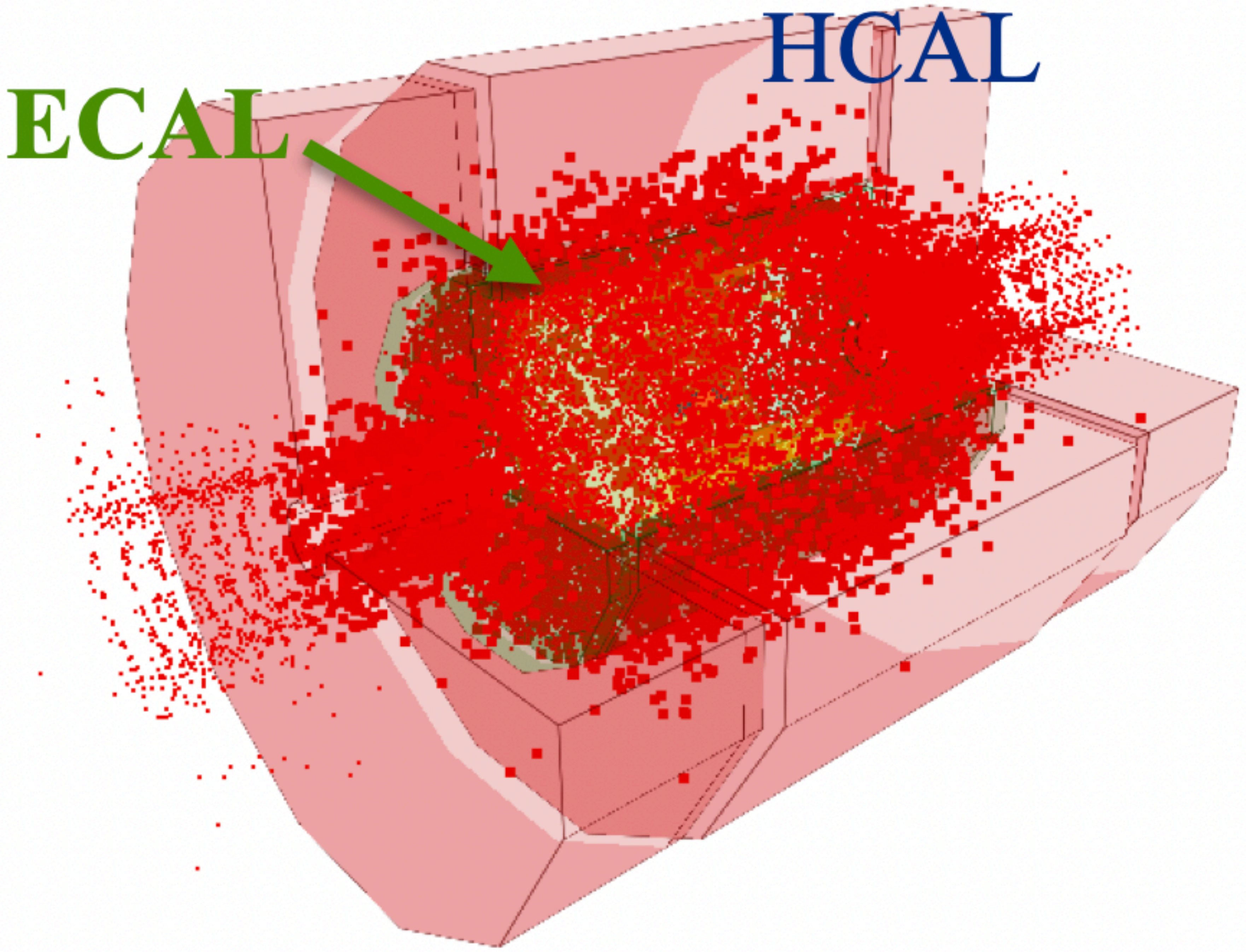
Detectors at Muon Colliders

The background challenge

- The constant decay μ -> eνν creates a very large beam-induced background (BIB): High-energy showers induced by electrons, creating a wide range of different background particles.
  - Radiation levels comparable to HL-LHC.

➯ The main challenge for experiments at muon colliders!

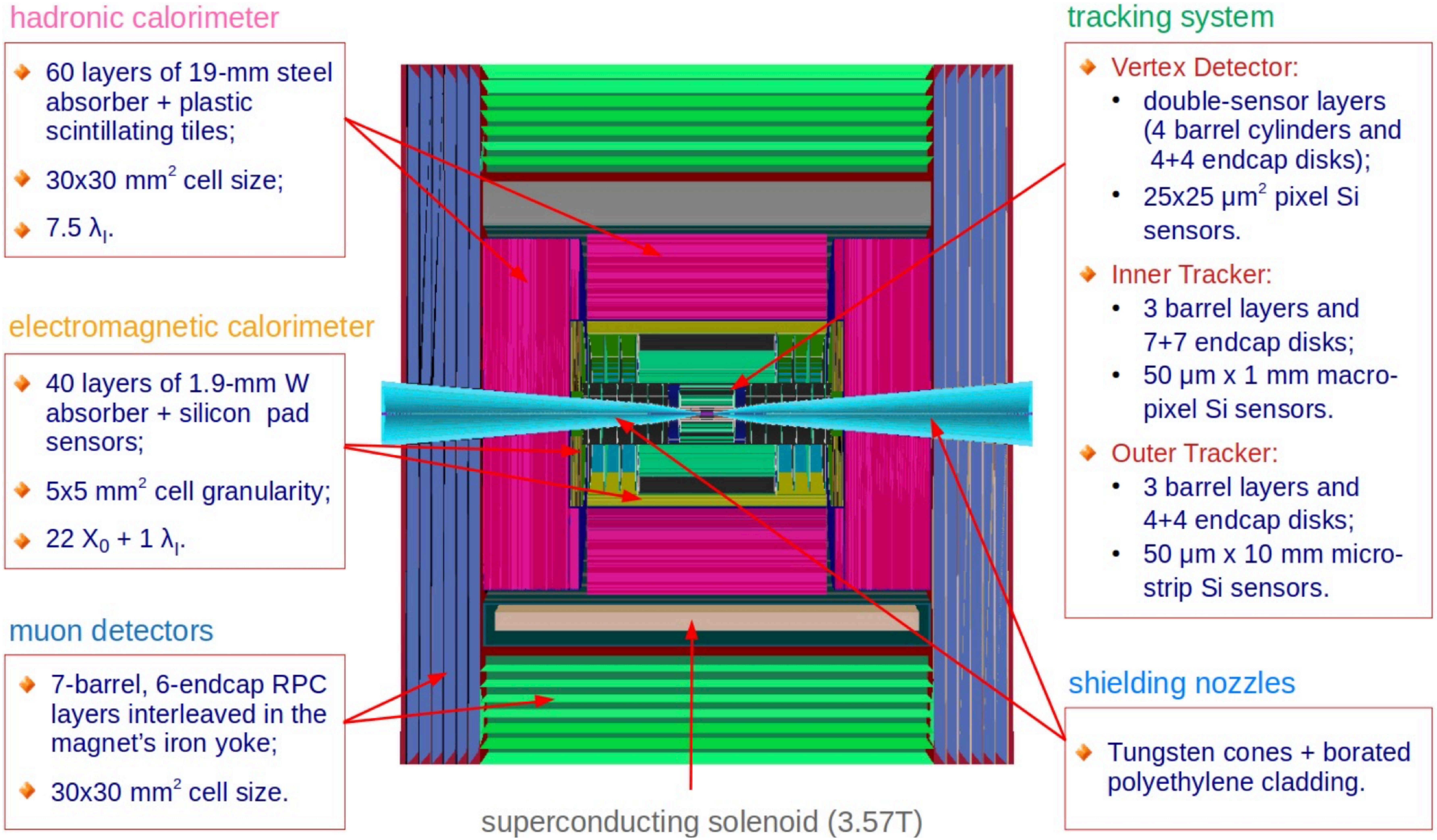




Detectors at Muon Colliders

First ideas

- A modified CLIC detector concept, adjusted for background conditions



~ 10 degree acceptance limitation in forward region due to tungsten nozzles

precise timing throughout detector important to reject BIB

Lecture 1 Wrap-up

Conclusions

Key Points Part 1

- Lepton and hadron colliders have been instrumental in firmly establishing the Standard Model. The next generation of experiments needs to show where it breaks.

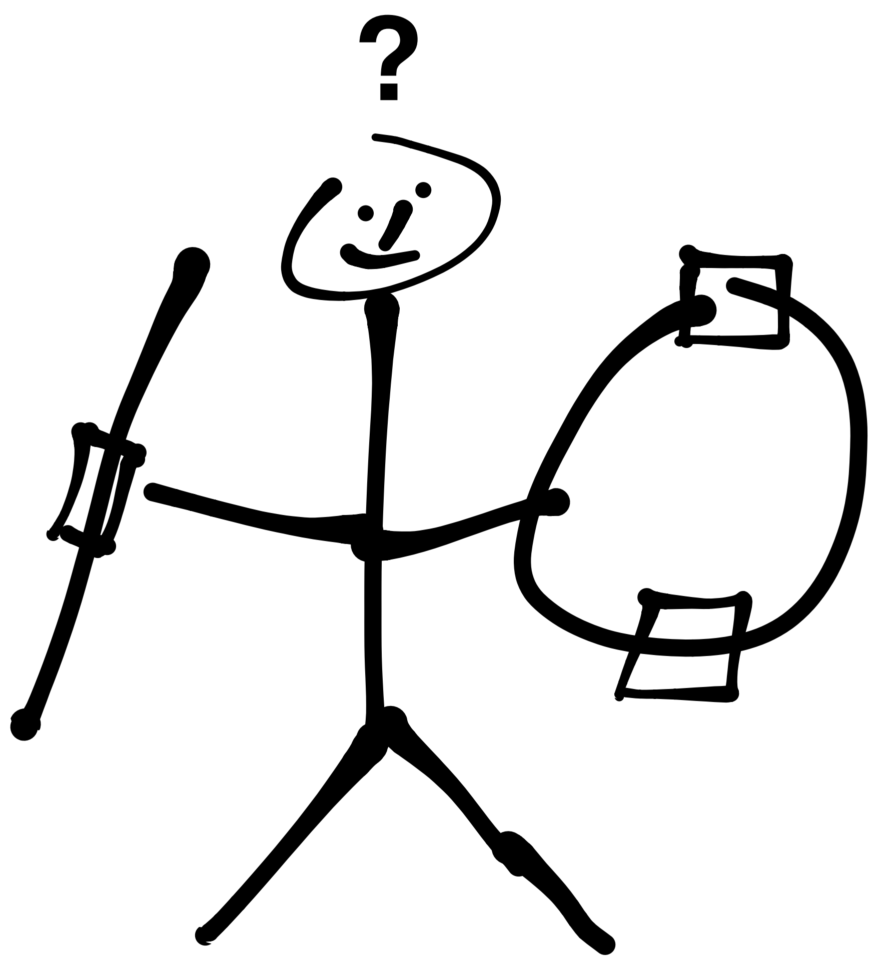
- Global agreement: a e^+e^- Higgs-Elektroweak-Top Factory as the next step:
  - A new era of precision measurements, profiting from benign background conditions, well-defined initial state, and low physics backgrounds.
  - Different possible realisations - linear or circular, each with specific strengths and weaknesses

- Well-established detector concepts tailored to physics goals and experimental conditions - but a lot of room for new ideas and further innovation!

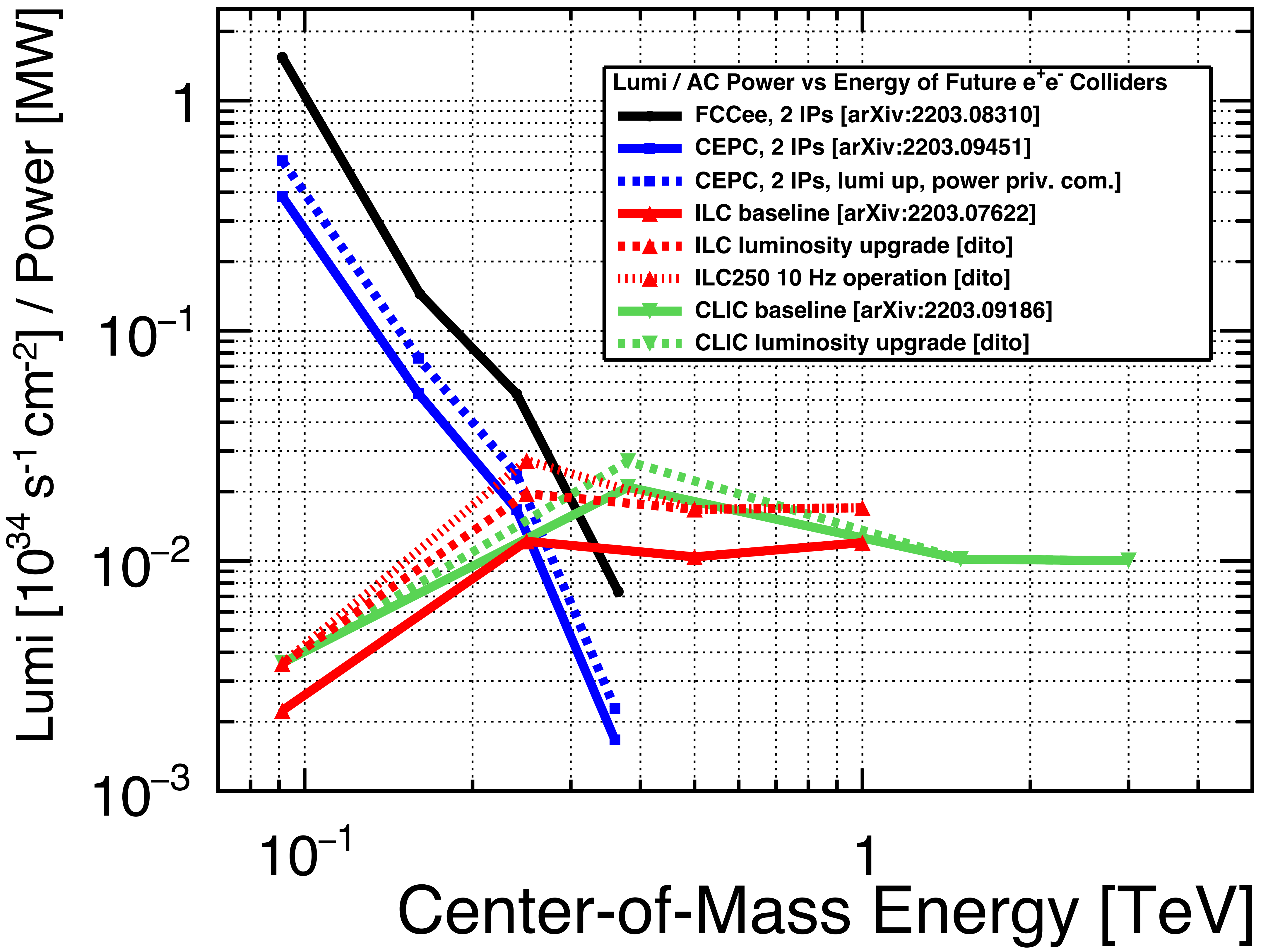
Perspectives: Physics Emphasis & Collider Geometry

In broad strokes

- e^+e^- collider geometry determines experimental focus beyond the core Higgsstrahlung program:



Circular:
extreme statistics at the Z pole and W threshold: precision electroweak



Linear:
reach to (multi-)TeV energy - double higgs production, high energy exploration

Extras Lecture 1

Concrete Facilities

A selection of lepton colliders

- Very quick panorama of the main facilities discussed since ~10+ years - for more details, and a discussion of a wider range of possibilities see the lecture by Barbara Dalena.

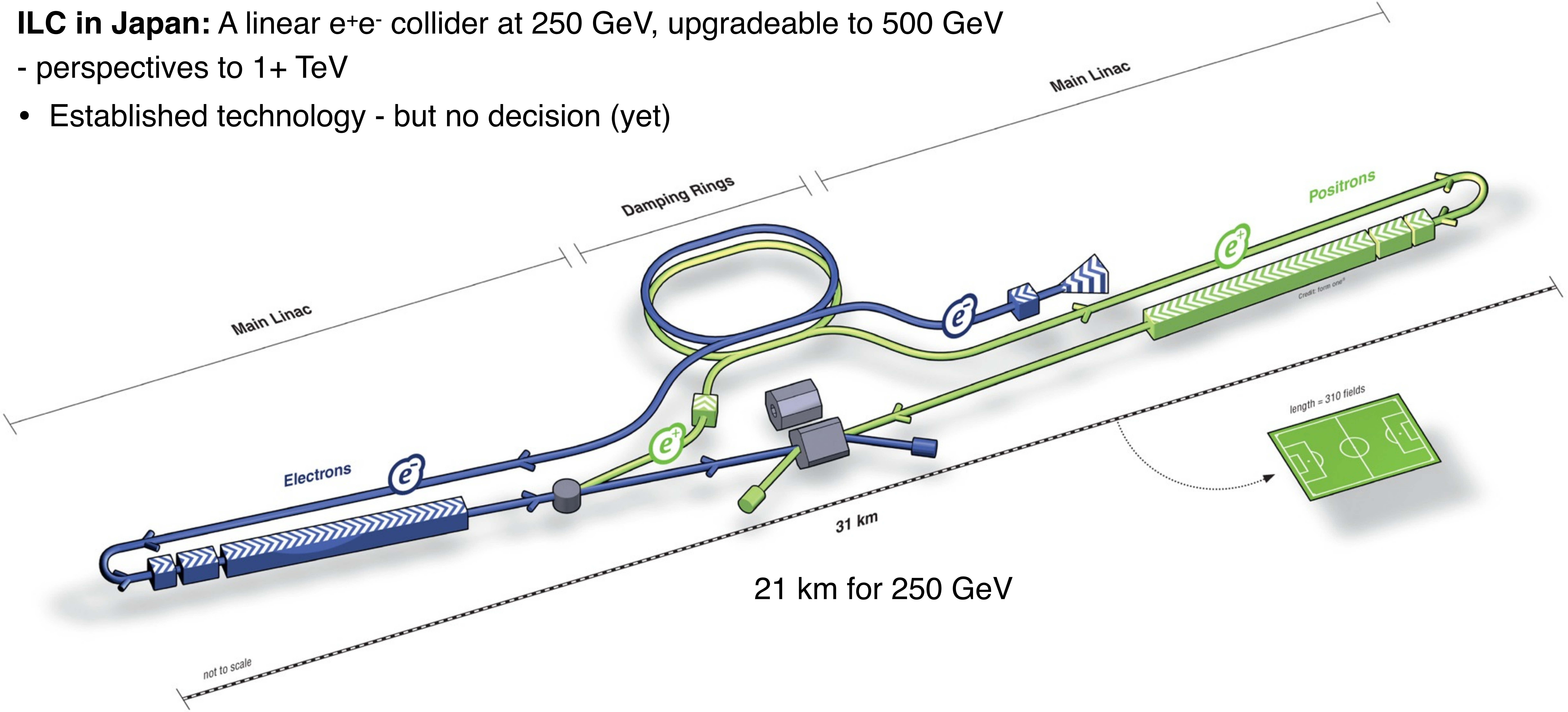
The International Linear Collider

e^+e^- Collider - Construction in Japan?

Karlsruhe Institute of Technology

ILC in Japan: A linear e^+e^- collider at 250 GeV, upgradeable to 500 GeV - perspectives to 1+ TeV

- Established technology - but no decision (yet)



21 km for 250 GeV

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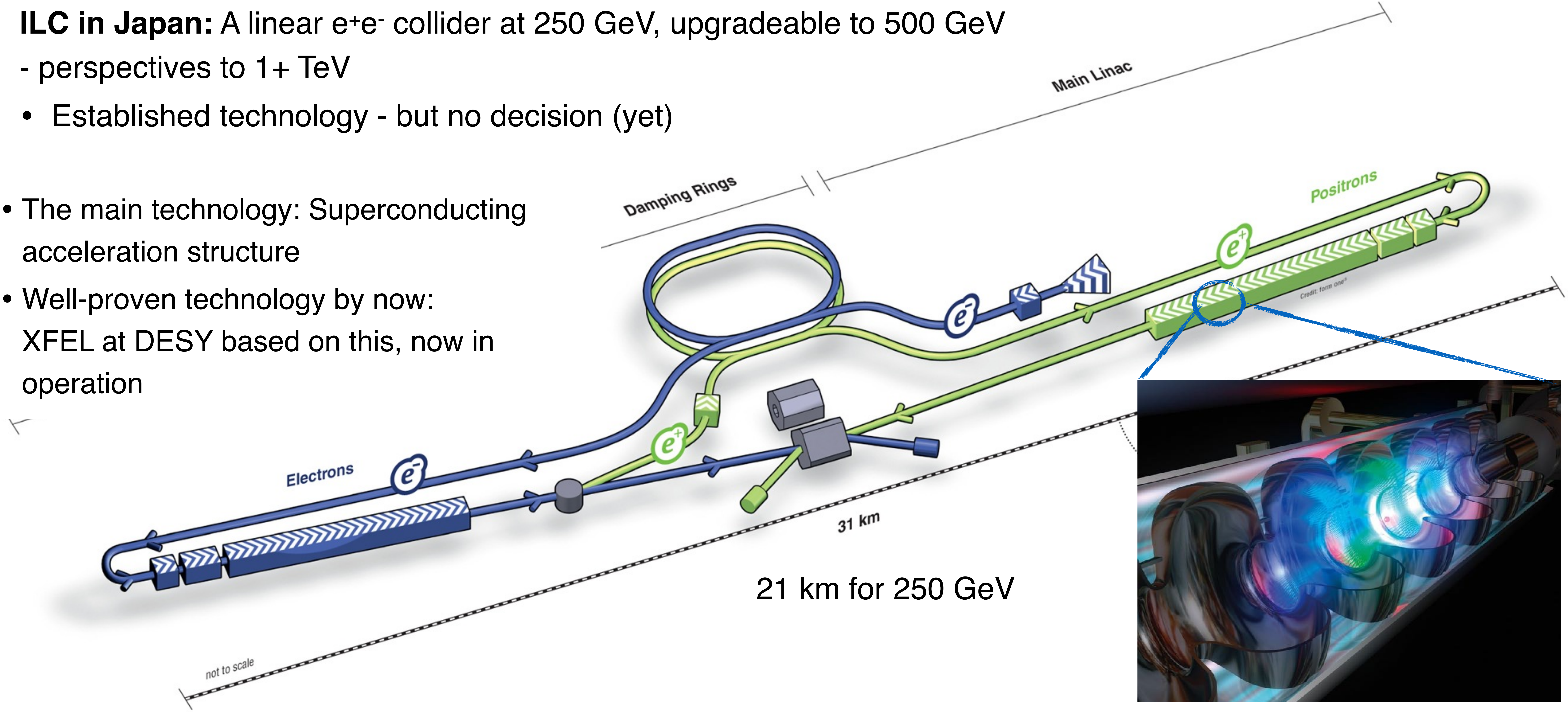
- Established technology - but no decision (yet)

- The main technology: Superconducting acceleration structure
- Well-proven technology by now: XFEL at DESY based on this, now in operation



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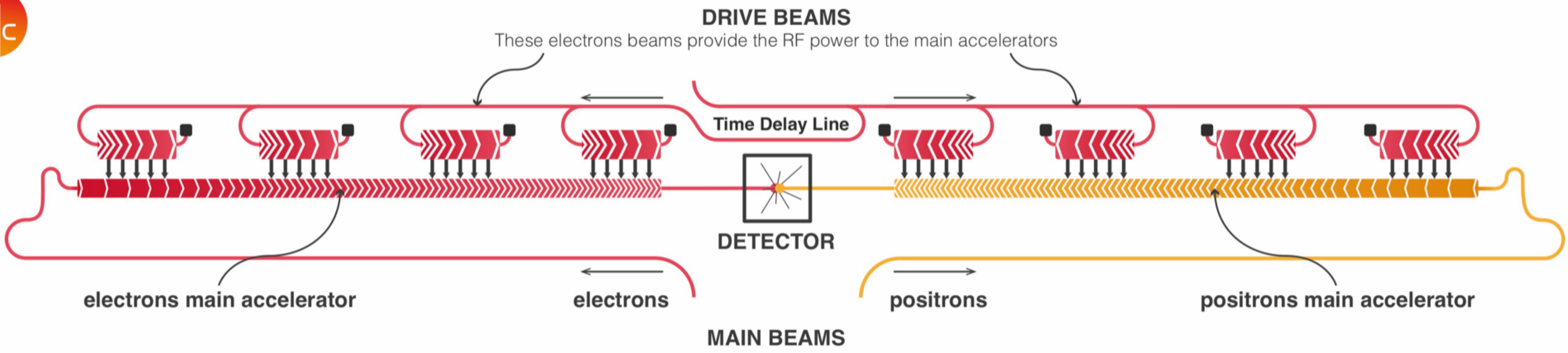
The Compact Linear Collider

e^+e^- Collider - a backup option at CERN

- CLIC at CERN: A linear e+e- Collider with 3 energy stages from 380 GeV to 3 TeV
  - Novel acceleration technology to reach high gradients in an energy-efficient manner



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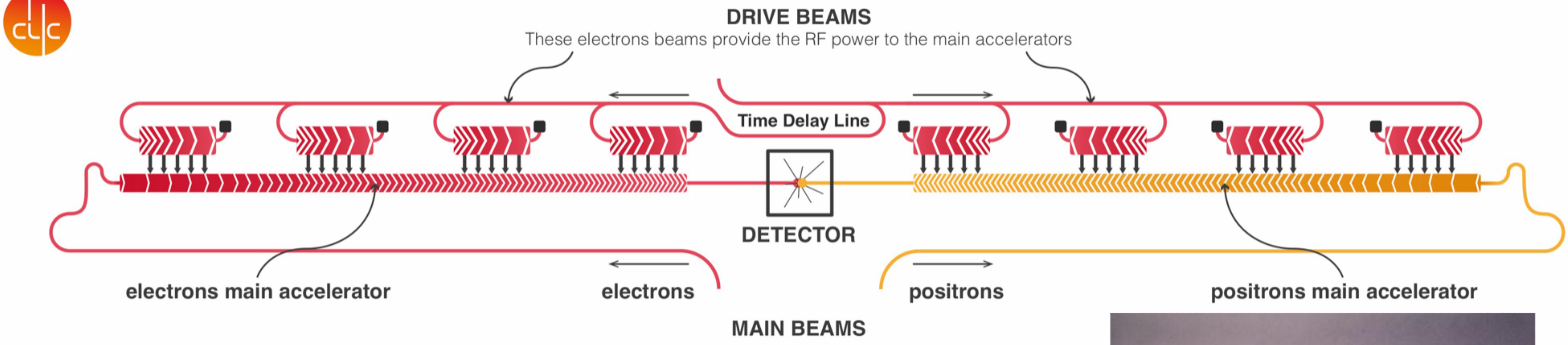
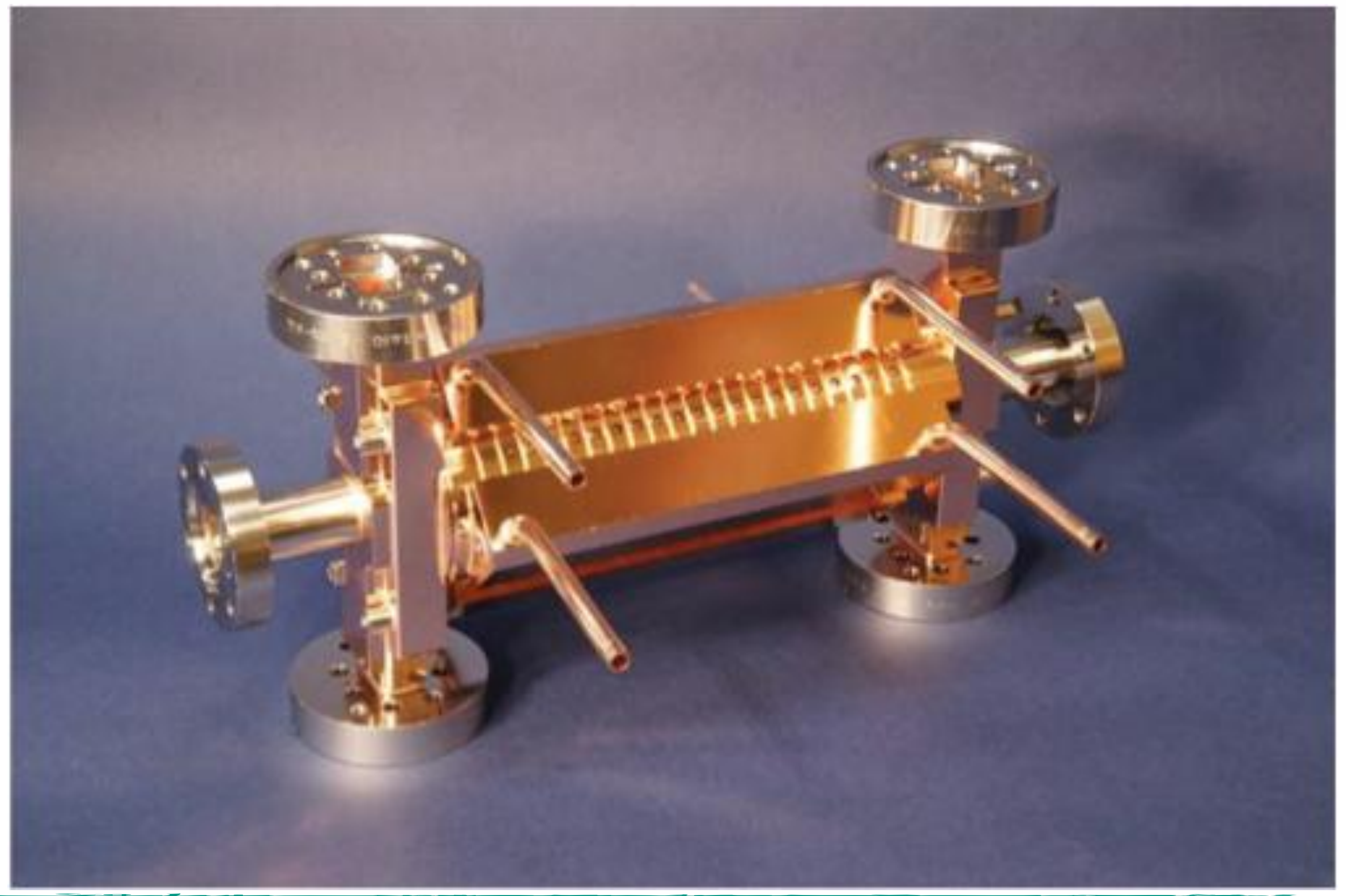


11 km for 380 GeV

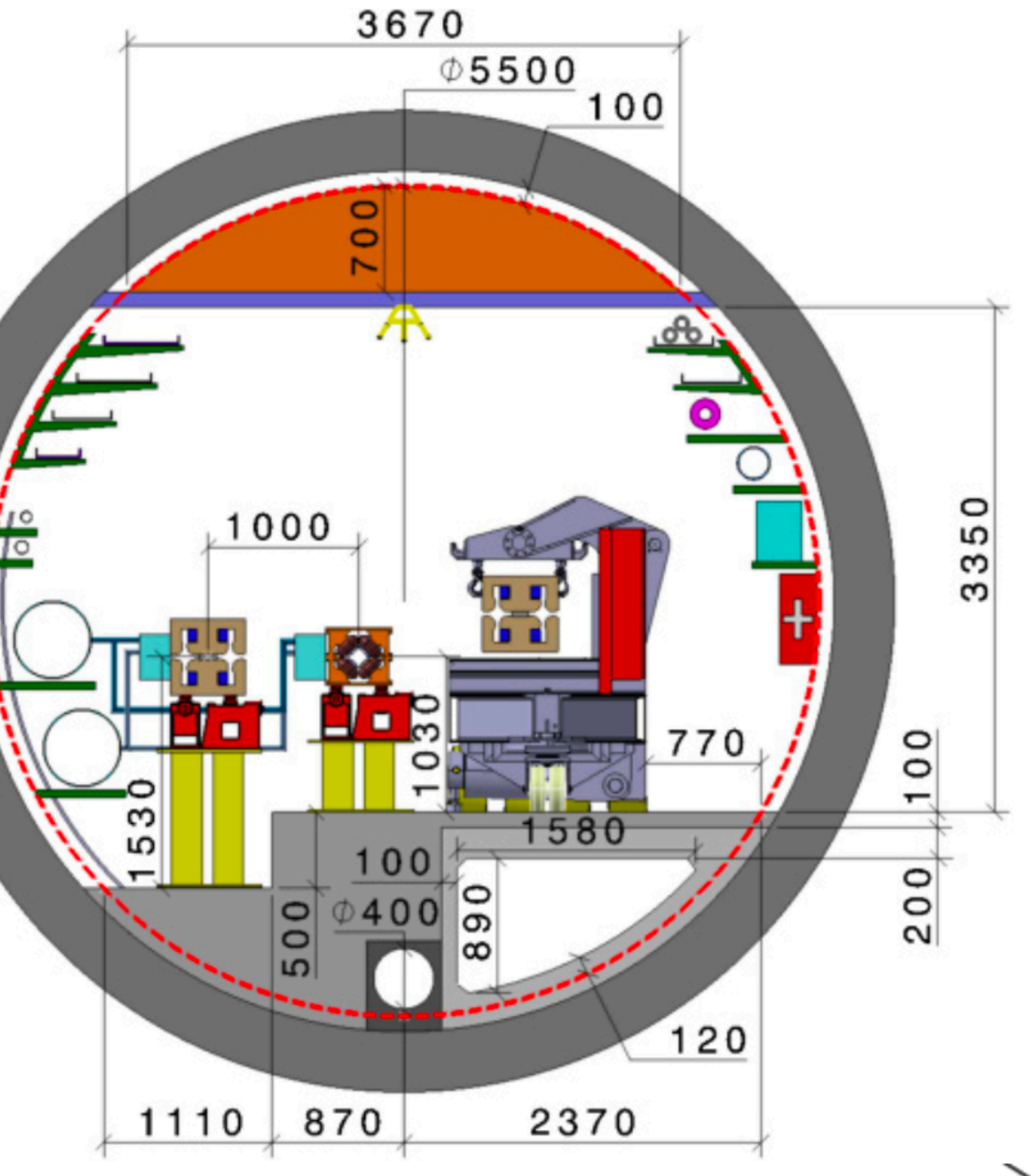
50 km for 3 TeV

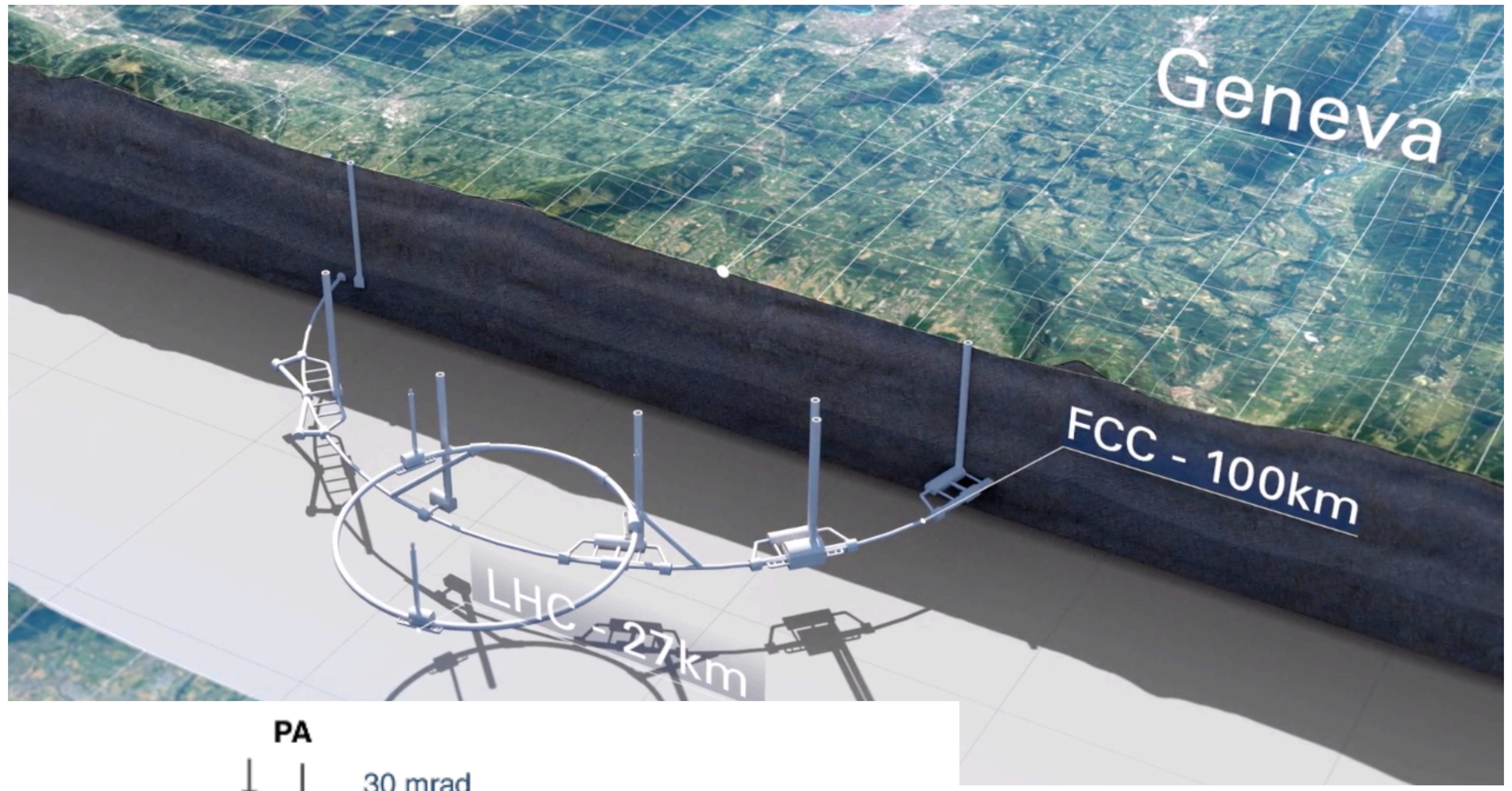
- The core technology: X-band two-beam acceleration
  - Working principle, individual components demonstrated, industrialization still missing



The Future Circular Collider FCC-ee

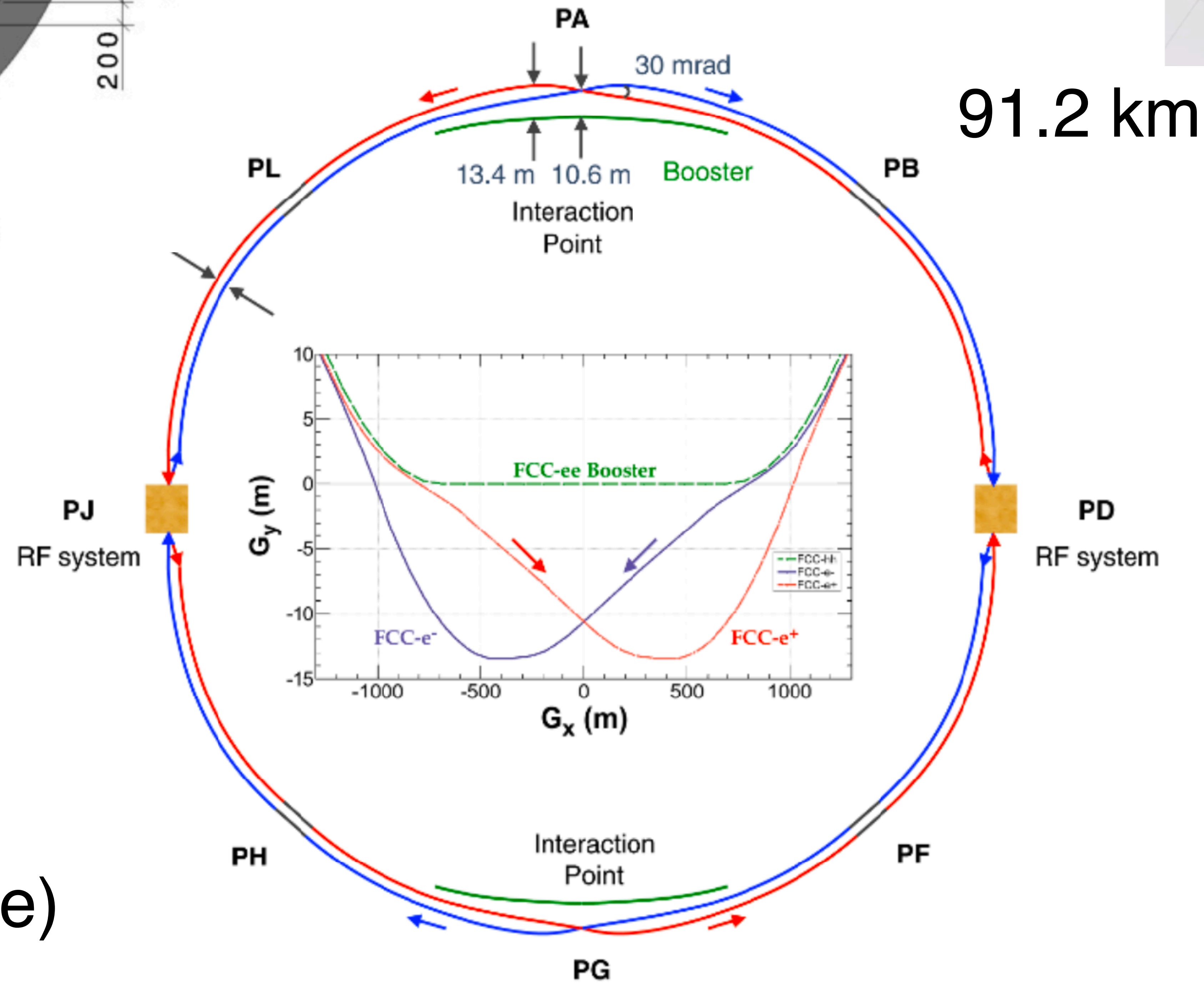
e^+e^- Collider - A possible future at CERN





- An electroweak, Higgs factory, running at 91 GeV, ~ 160 GeV, 240 GeV
  - Upgrade to the top: threshold around 350 GeV, and 365

91.2 km circumference



2 experiments

(up to 4 possible)

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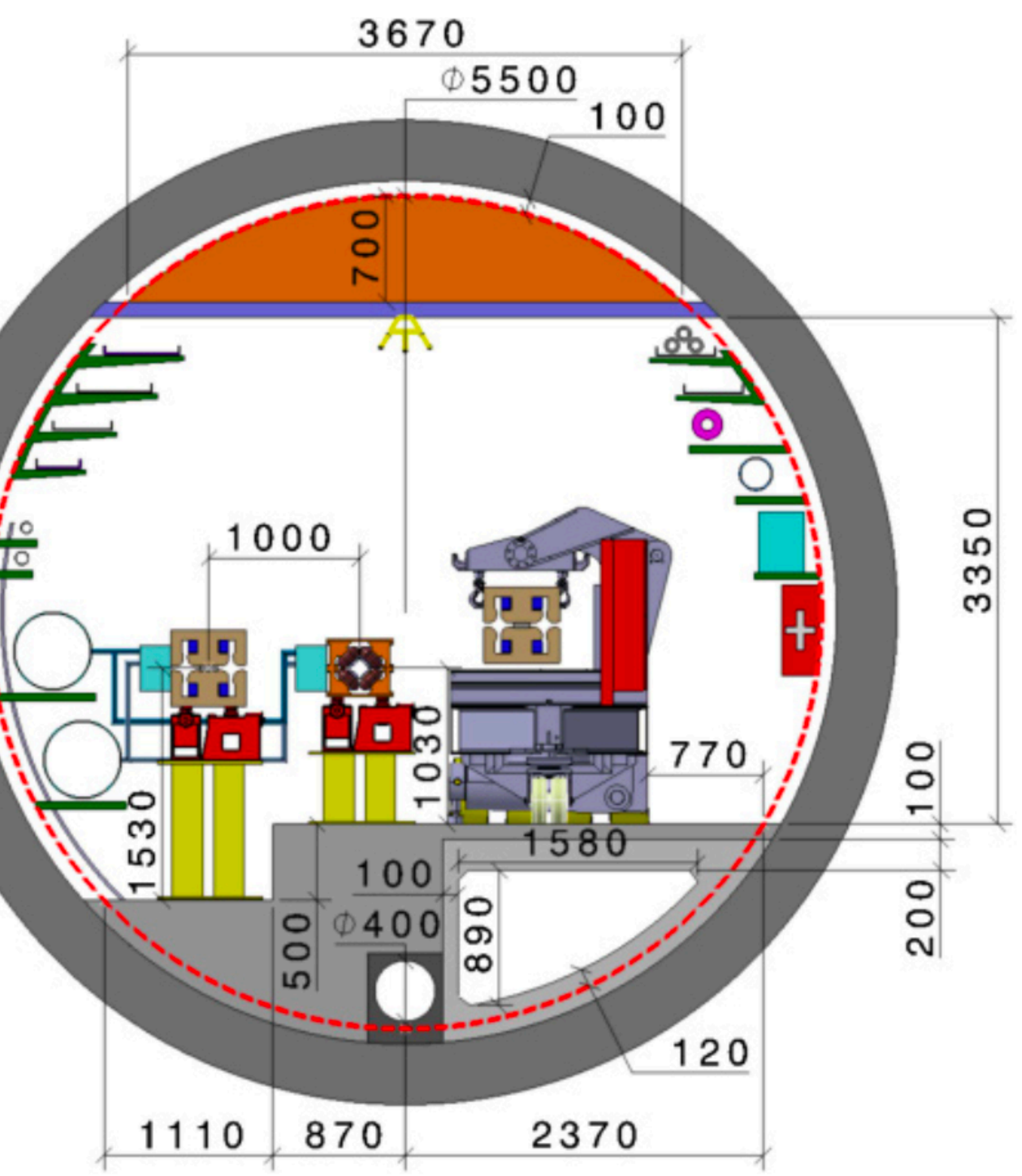
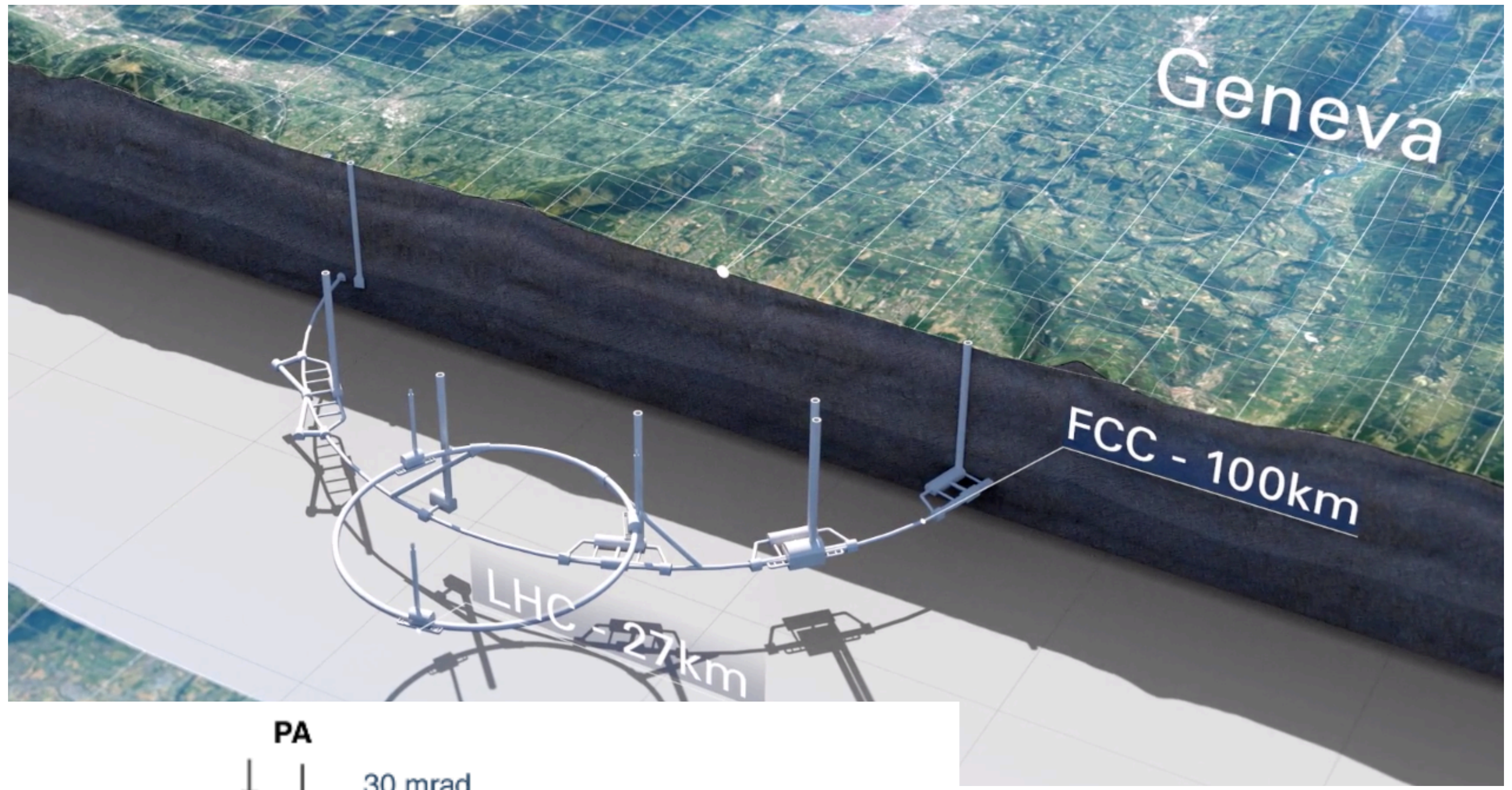
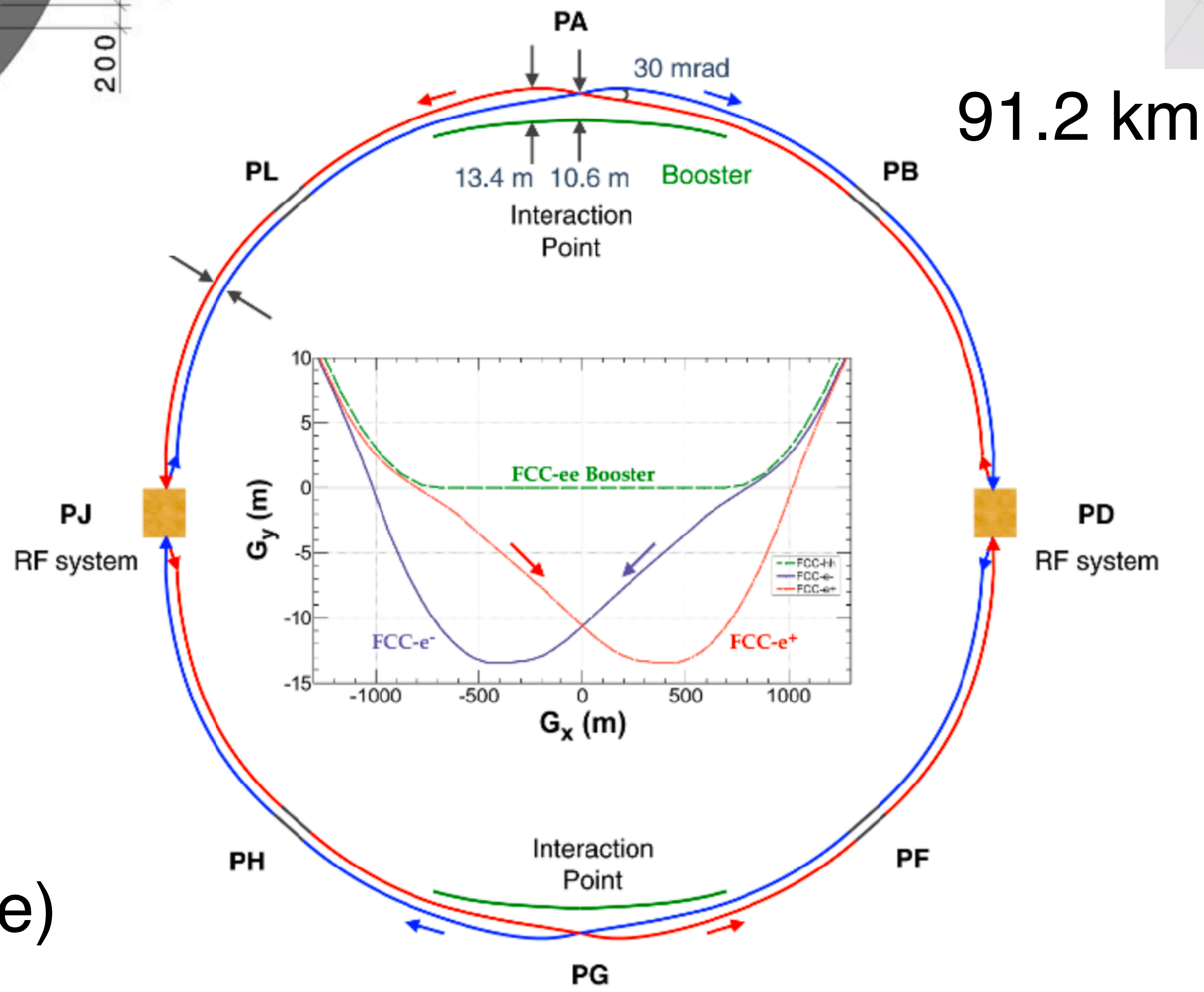




91.2 km circumference

- An electroweak, Higgs factory, running at 91 GeV, ~ 160 GeV, 240 GeV
  - Upgrade to the top: threshold around 350 GeV, and 365
- Main dipoles: 14 - 57 mT field - normal conducting
- Central: RF acceleration structures: Up to 11 GV total at 182.5 GeV, in both main rings and booster



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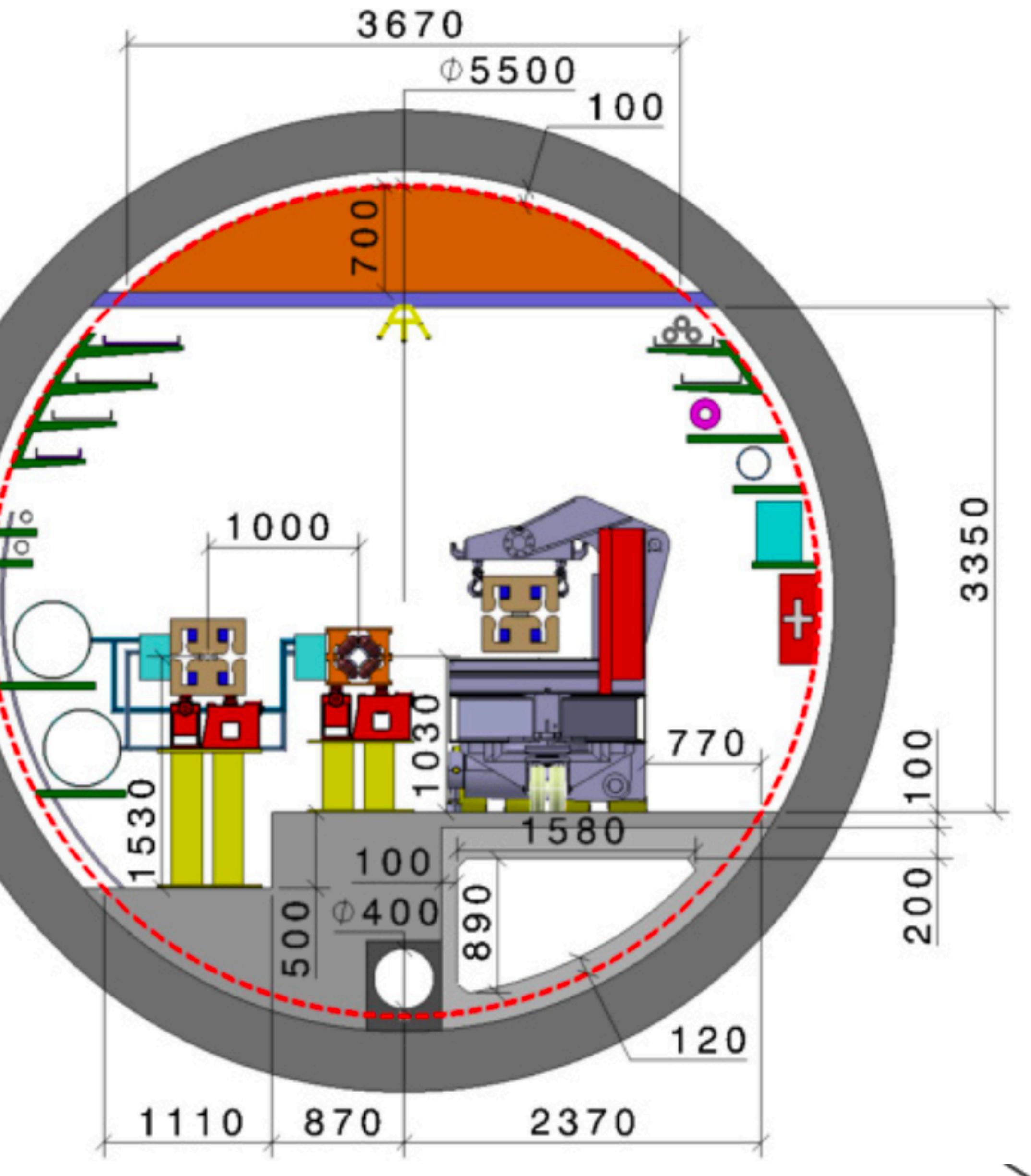

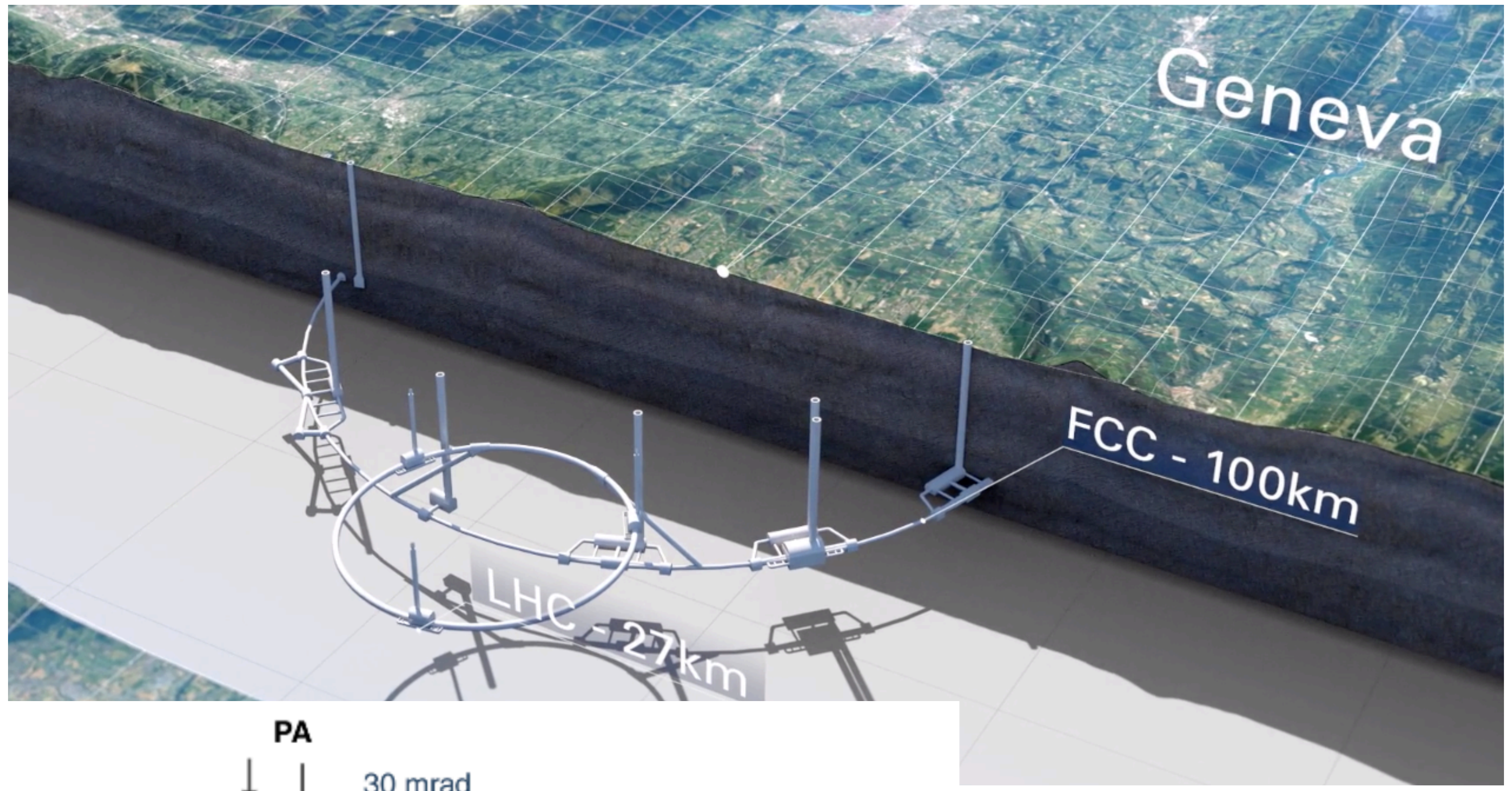

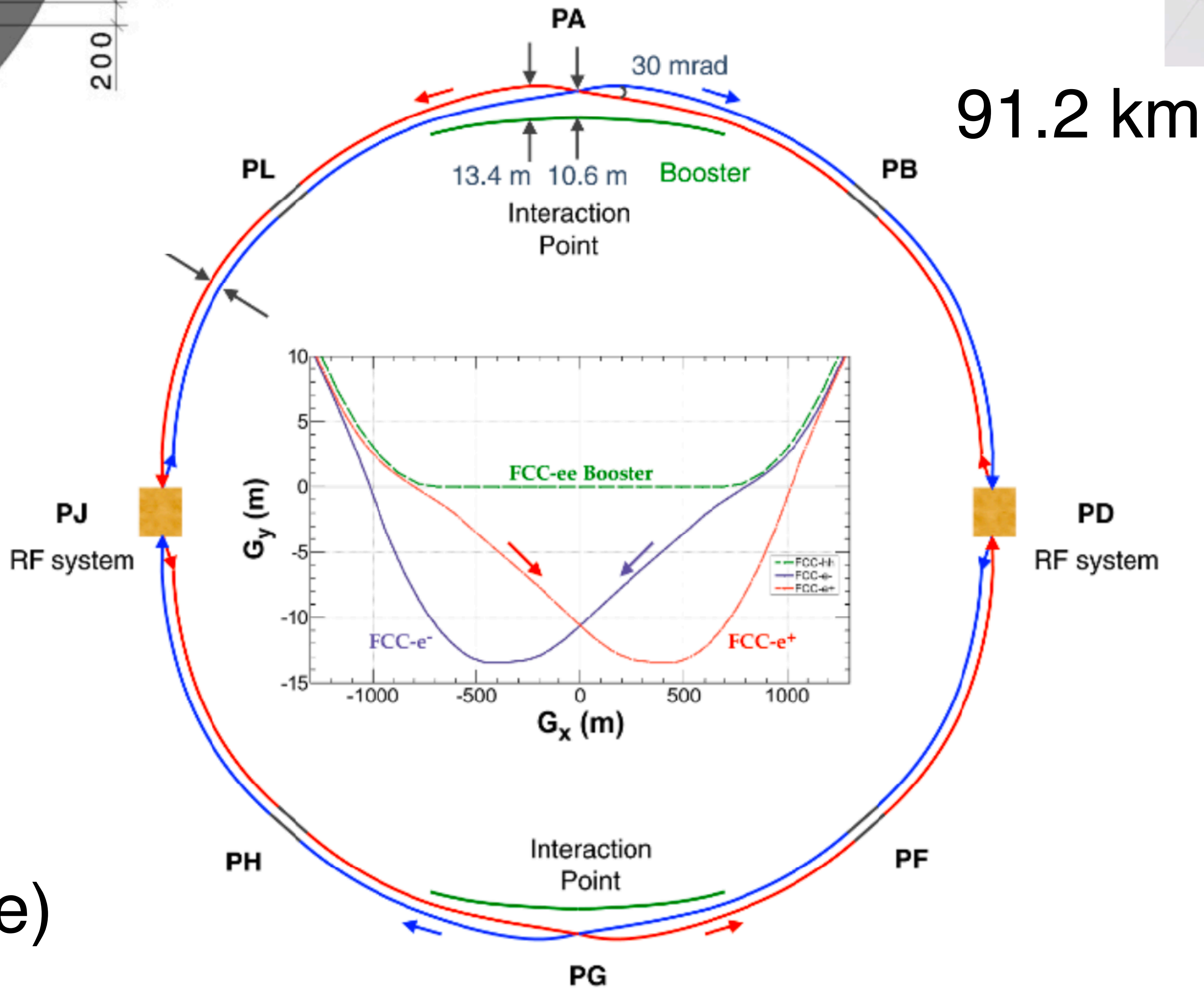

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A similar proposal in China: CEPC

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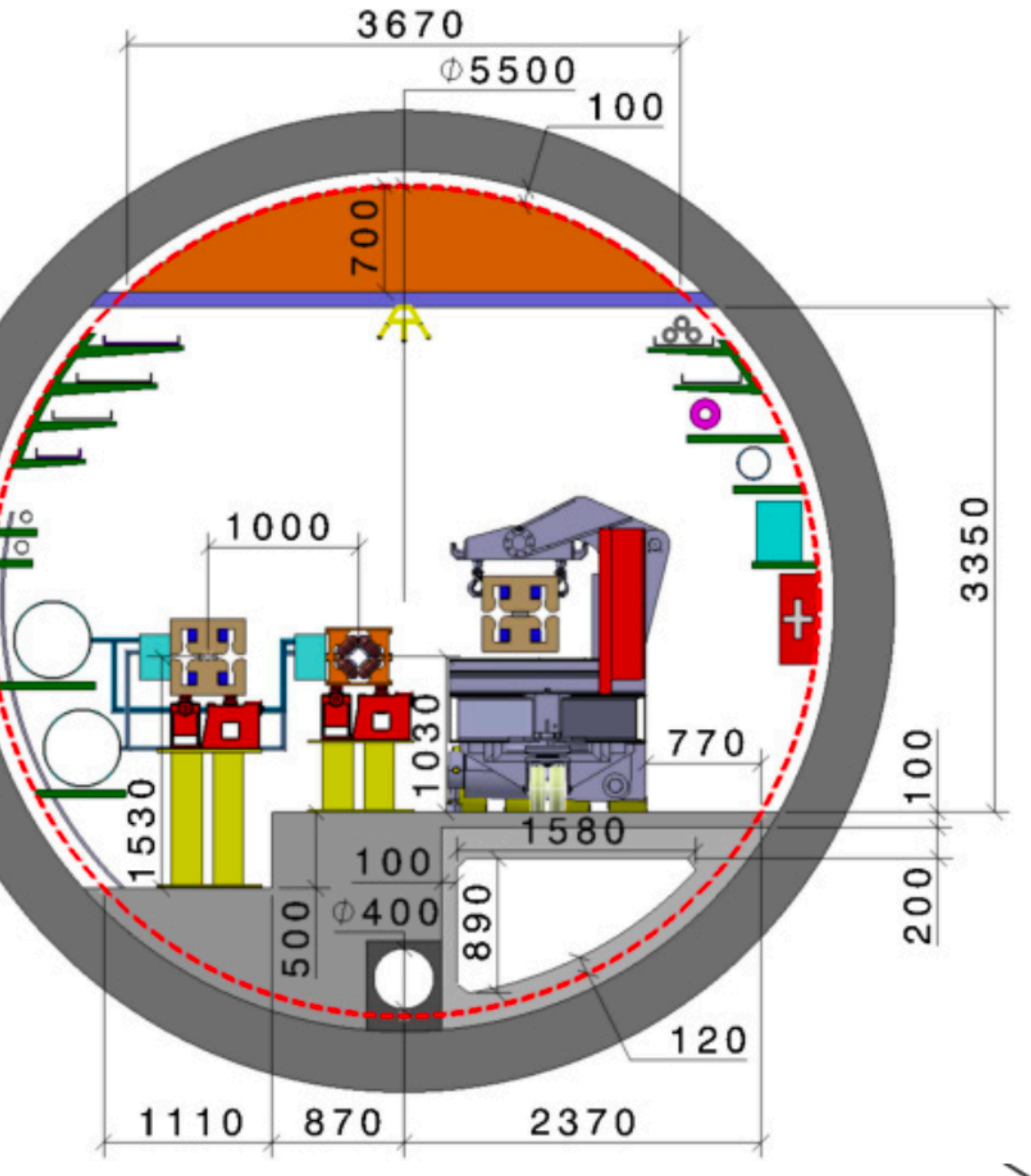

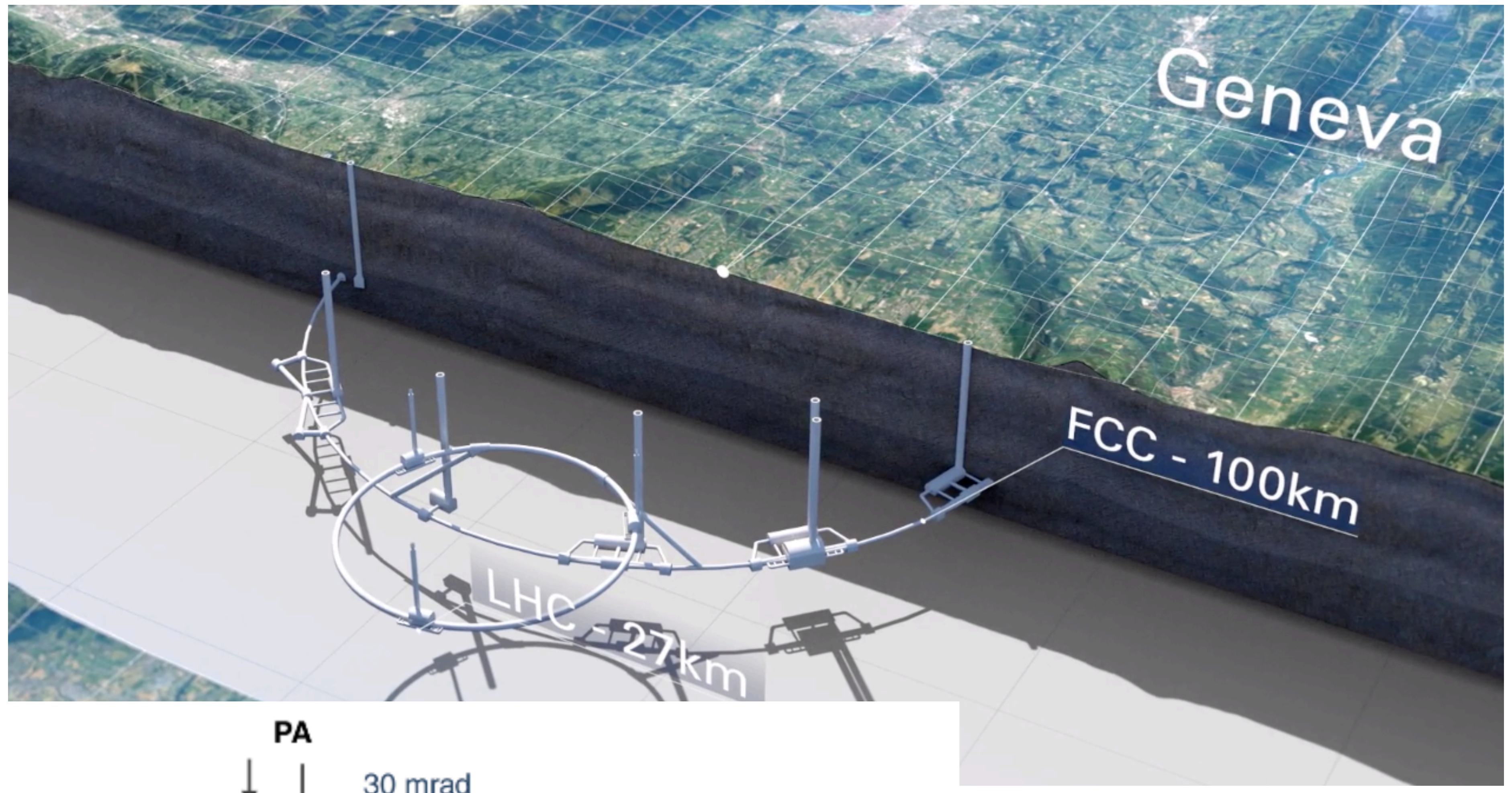

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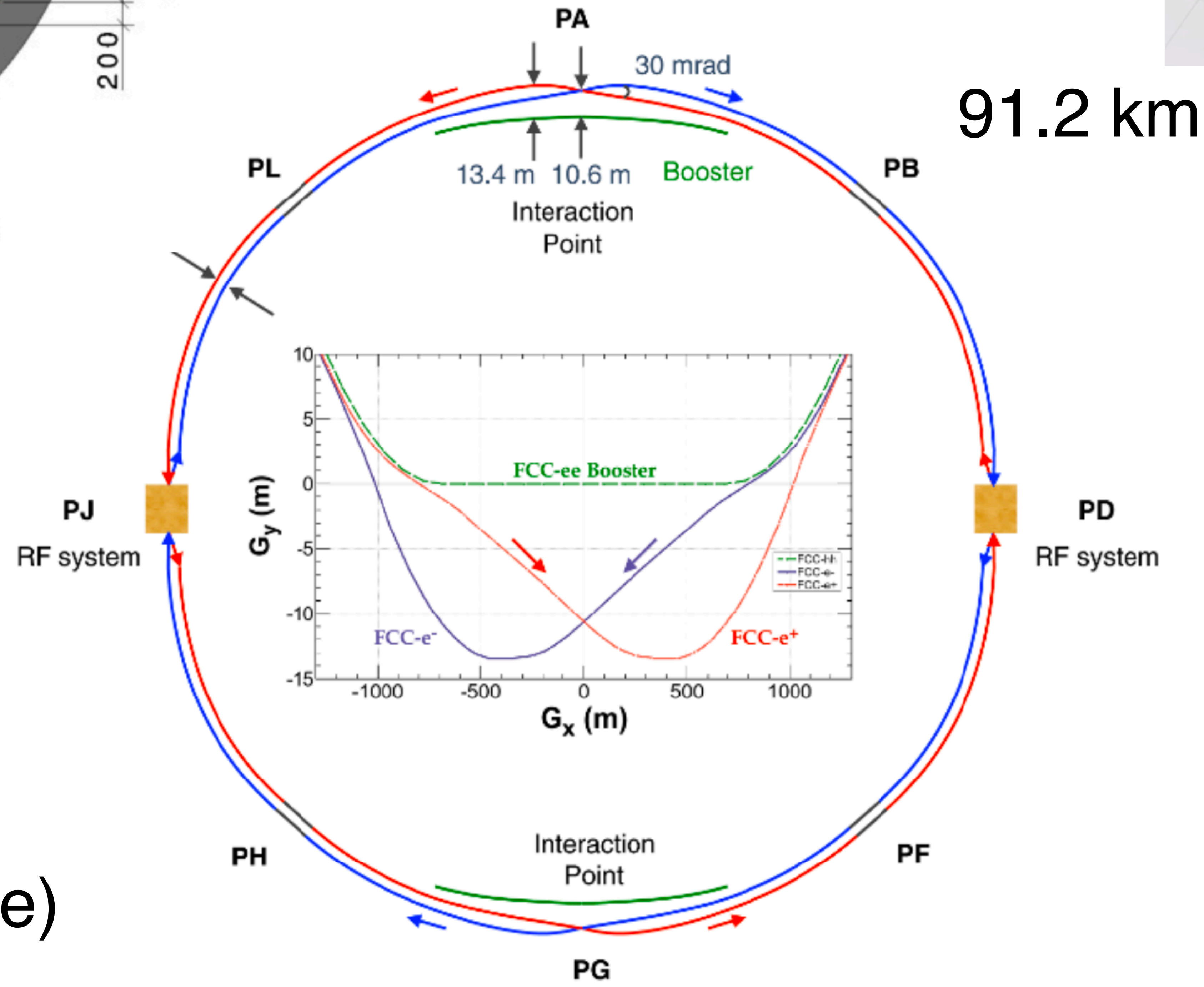

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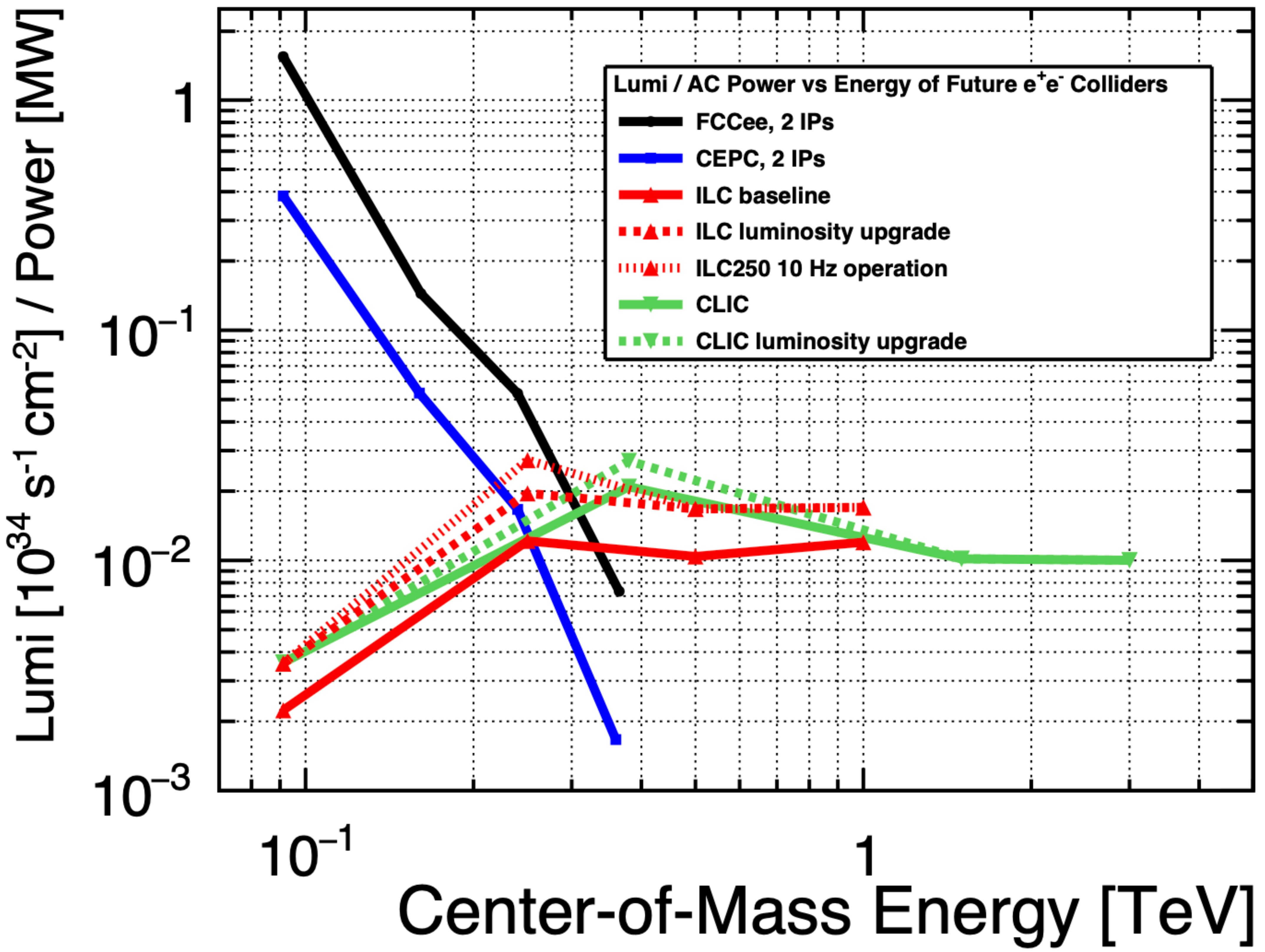
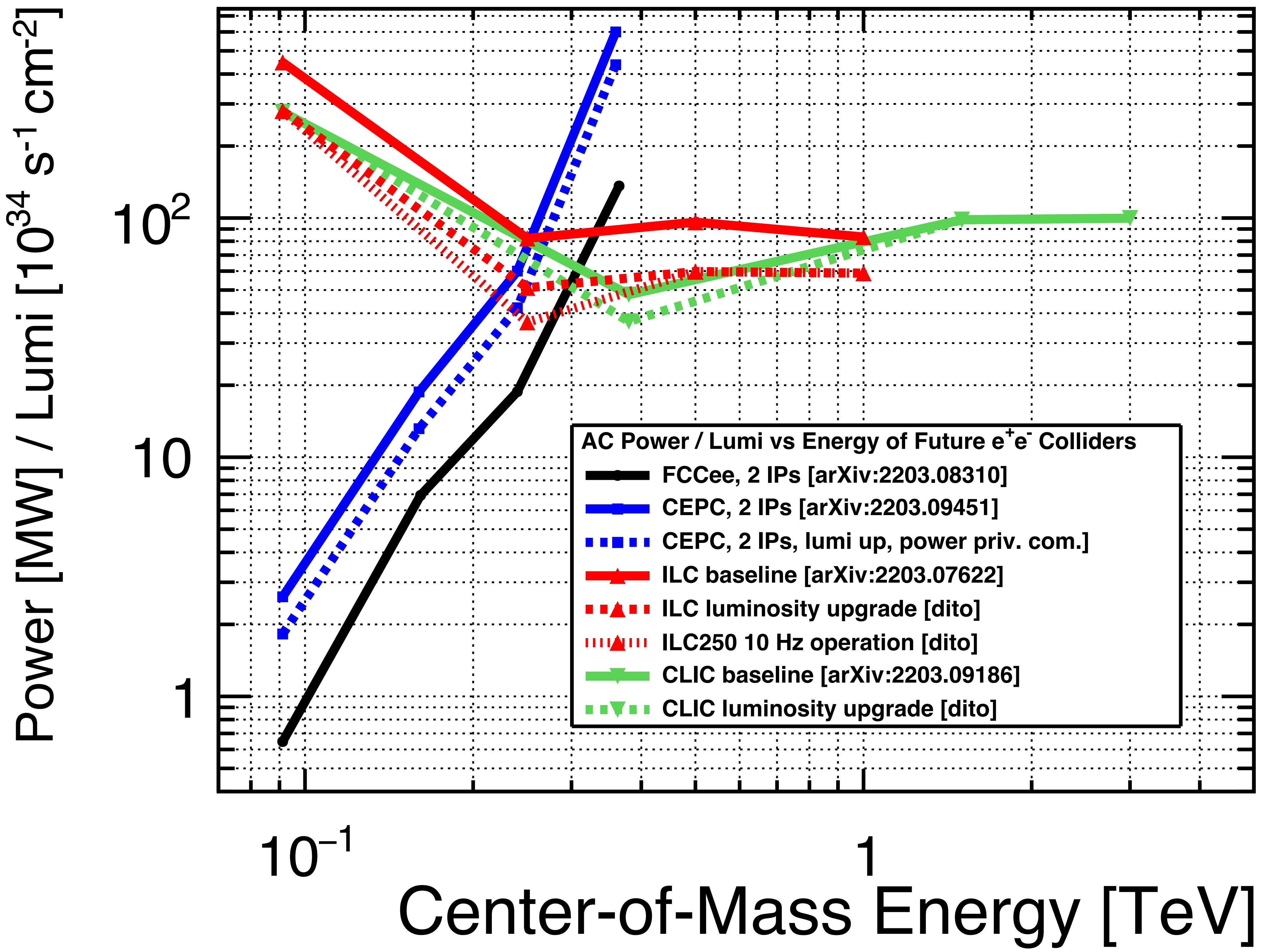
Long-term perspective:
a ~100 TeV Hadron Collider
FCC-hh / SppC

2 experiments
(up to 4 possible)





- General takeaway:
  - All options do well for Higgs around 250 GeV: Similar luminosity, similar power efficiency
  - Rings are unbeatable at low energies: The realm of electroweak precision measurements
  - Linear colliders unfold their full potential when going beyond the top threshold

Collision Energy Precision

A circular collider feature

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- In particular for electroweak precision measurements at the Z pole and the WW threshold the knowledge of the beam energy is a key systematic.
- Exploit the fact that the beams get transversely polarized over time - this effect drops with beam energy, was usable at LEP up to ~ 60 GeV, for FCC-ee expected to extend a bit further, up to WW threshold (< 90 GeV beam energy), measuring the beam energy via ***resonant depolarisation***.

Key ingredients:

Beam energy in a ring given by radius of particle orbit and dipole field:

$$E \sim p = eBR = \frac{e}{2\pi}BL$$

in real life B is not perfectly uniform, the orbit not a perfect circle:

$$E = \frac{e}{2\pi}\oint Bdl$$

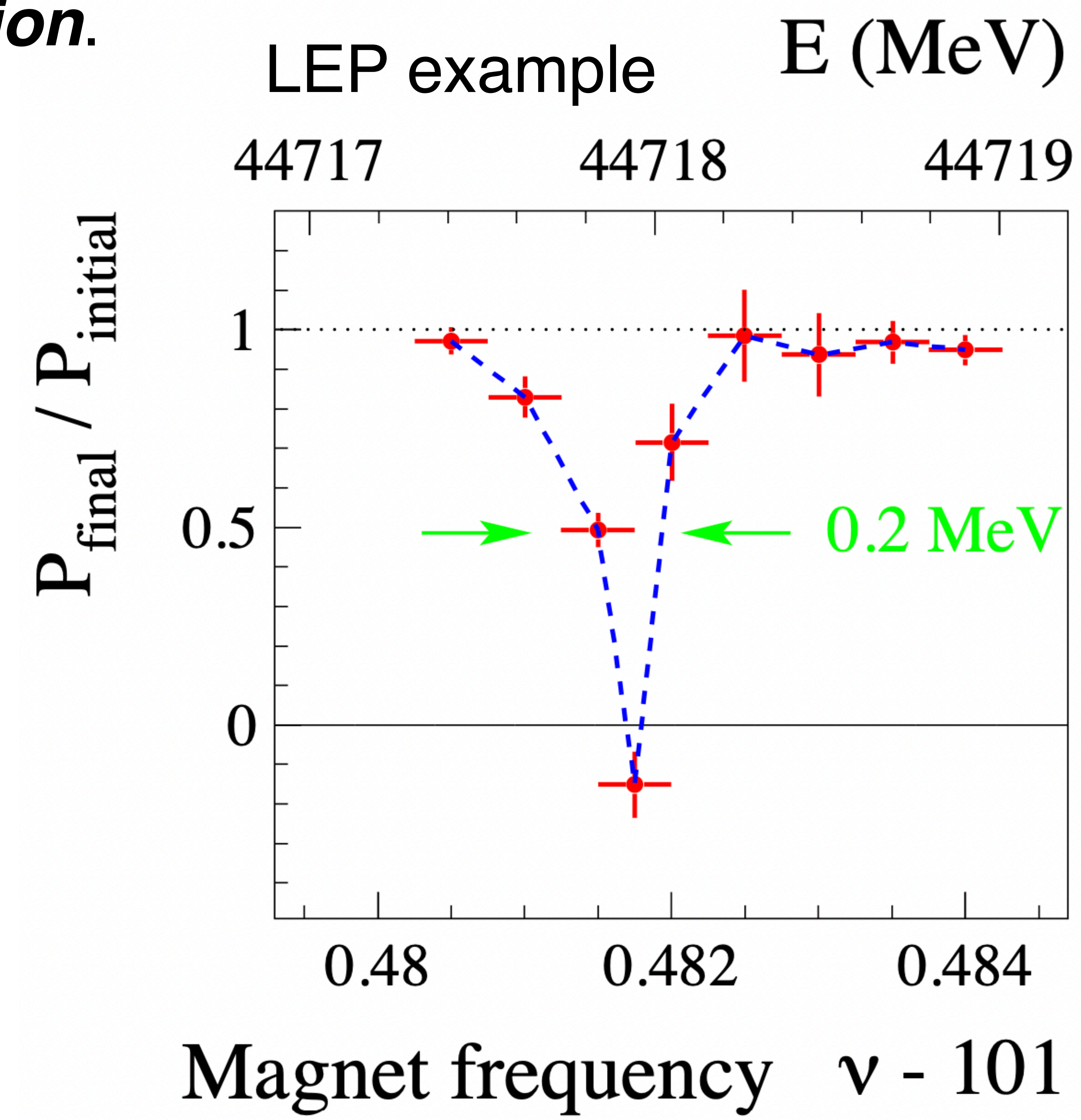
need to measure this!

Exploit transverse polarisation: spin precesses in B field!

Measure precession frequency (excitation with an RF magnet with different frequency, bringing polarisation to 0)

For FCC-ee: dedicated bunches to monitor beam energy

LEP example



Longitudinally Polarized Beams

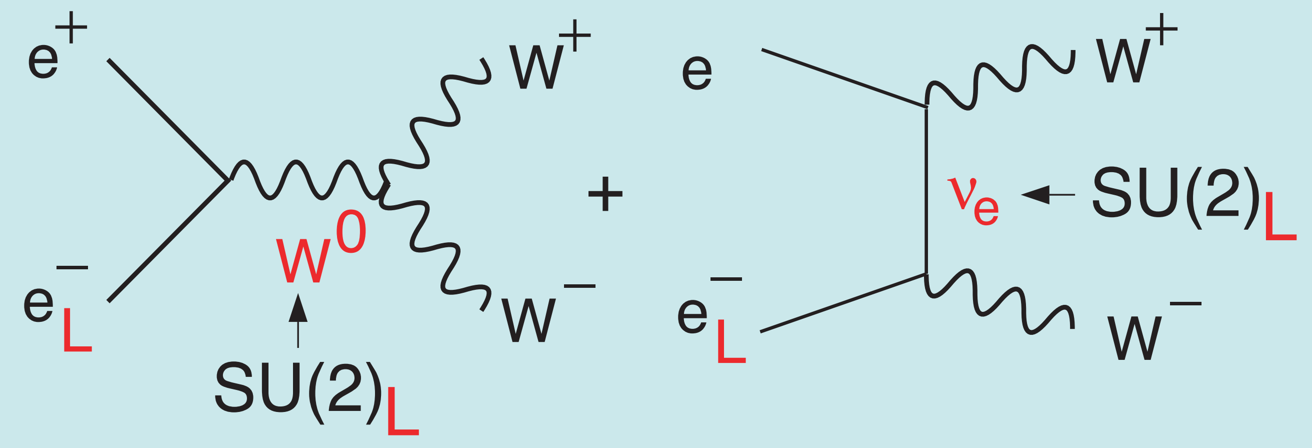
A Linear Collider Feature

- Longitudinal polarization can be preserved in a linear accelerator - enables the collision of polarized beams
- Requires polarized sources for electrons and positrons
  - High polarization for electrons routinely achievable - planning with 80%
  - 30% for positrons for ILC

Presents interesting physics possibilities:

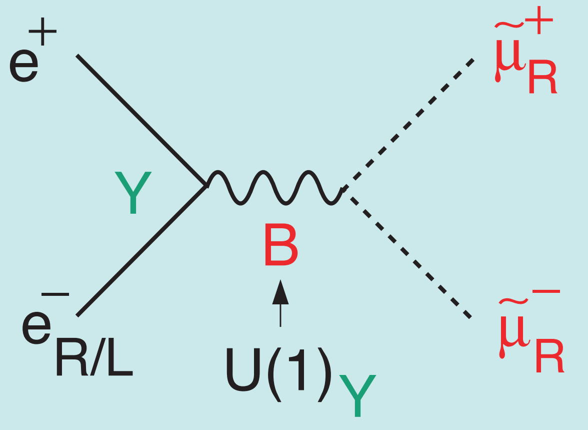
- Suppression of physics background
- Increase of signal cross sections
- Additional analyzing power for a wide range of electroweak processes

W^+W^-** **(Largest SM BG in SUSY searches)



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton Pair

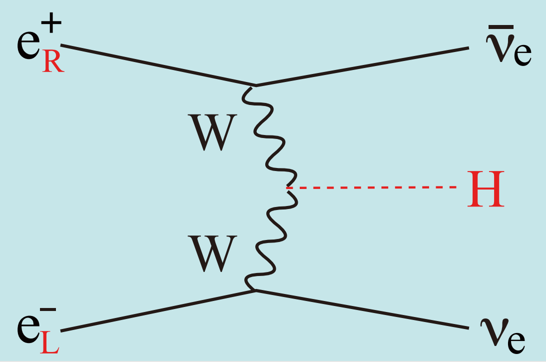


$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

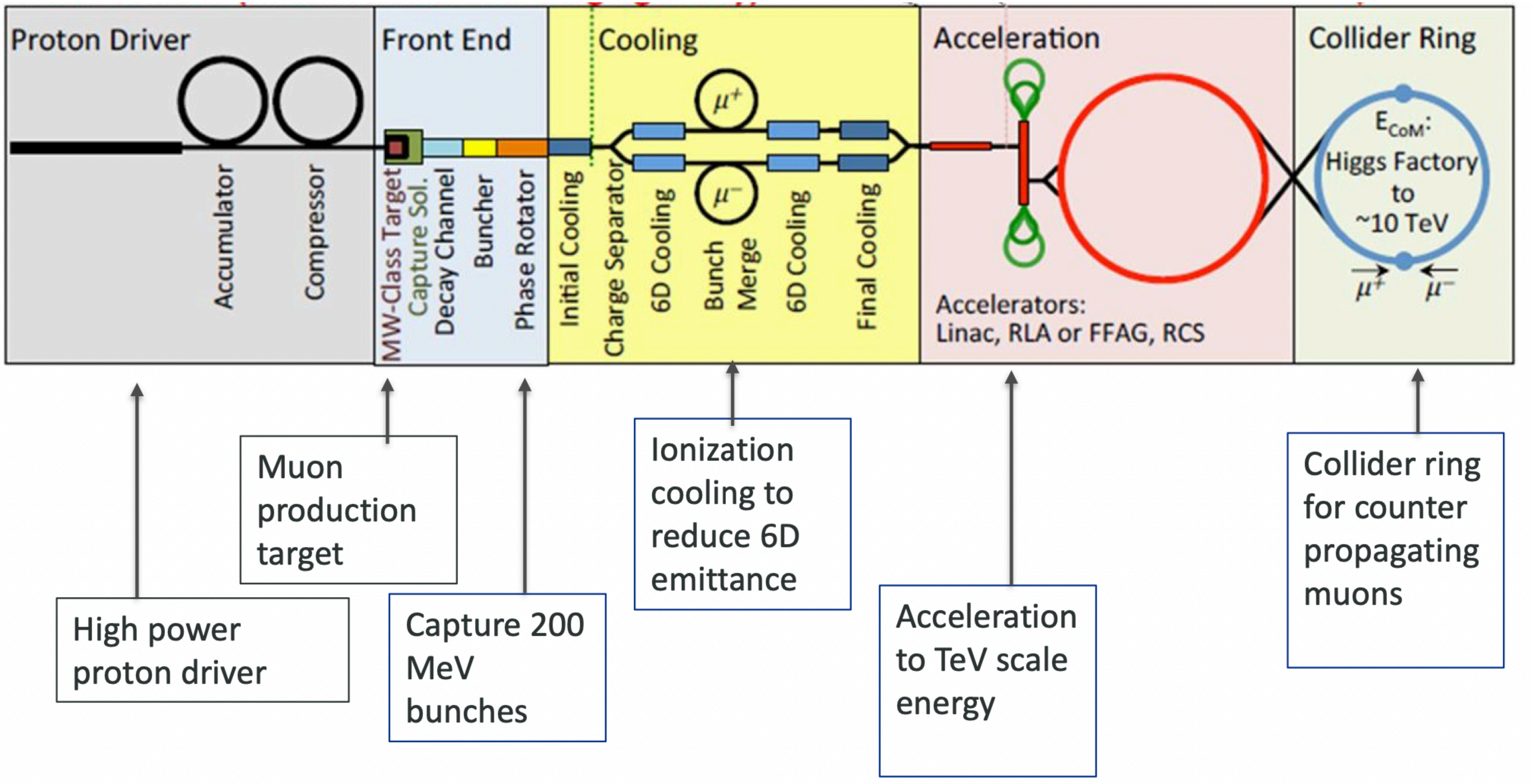
WW-fusion Higgs Prod.



	ILC
Pol (e^-)	-0.8
Pol (e^+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Muon Collider

A path to high energies with leptons



- Power efficient at high energies, key challenge the decay of muons.