XXXIII INTERNATIONAL SEMINAR OF NUCLEAR AND SUBNUCLEAR PHYSICS "FRANCESCO ROMANO" 2022

Physics @Future Colliders - 1

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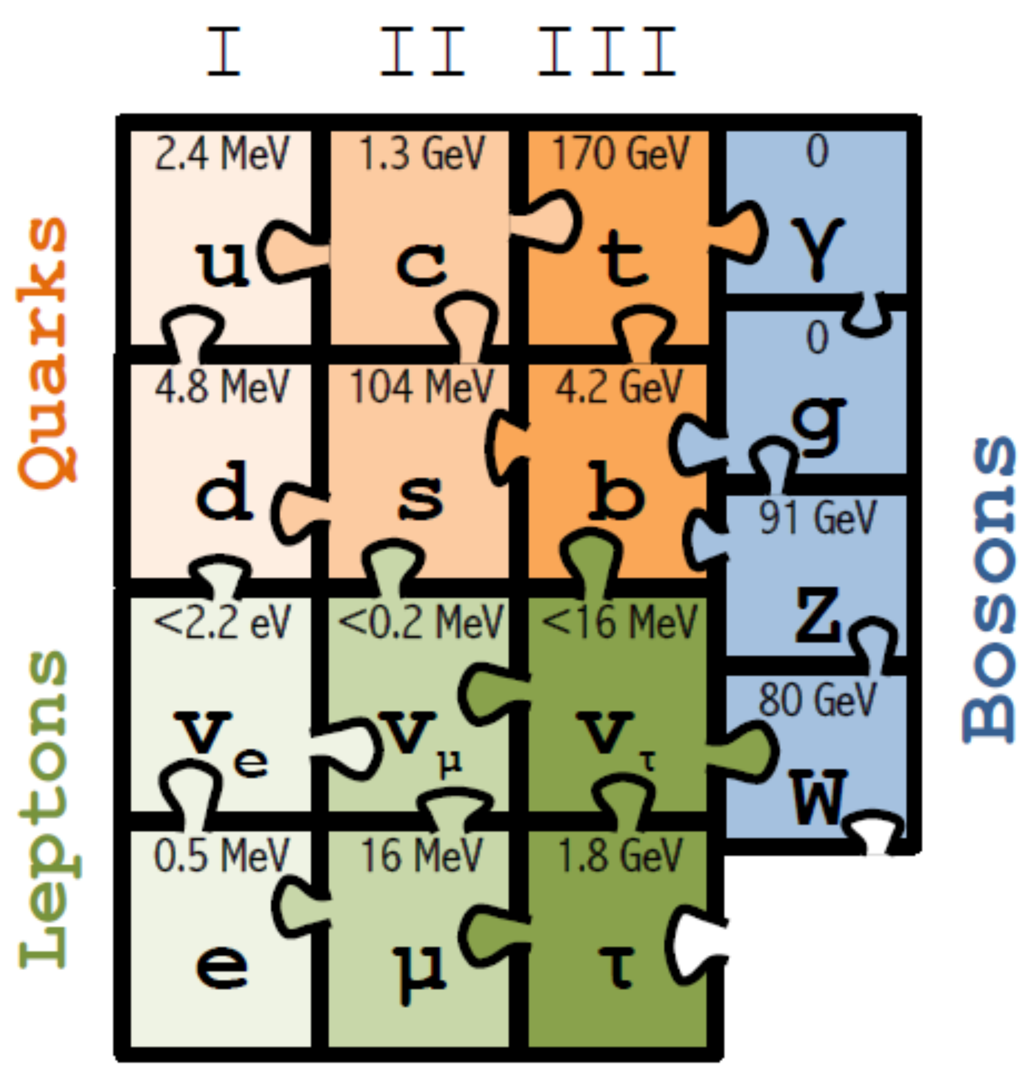
CONTENT OF LECTURES

- Today:
  - Introduction to future projects for lepton colliders on the market
  - Perspective on Higgs couplings measurements
- Tomorrow:
  - Running at the Z pole: EWPO, Flavour & BSM
  - High-energy opportunities: top Yukawa, Higgs self-coupling, BSM

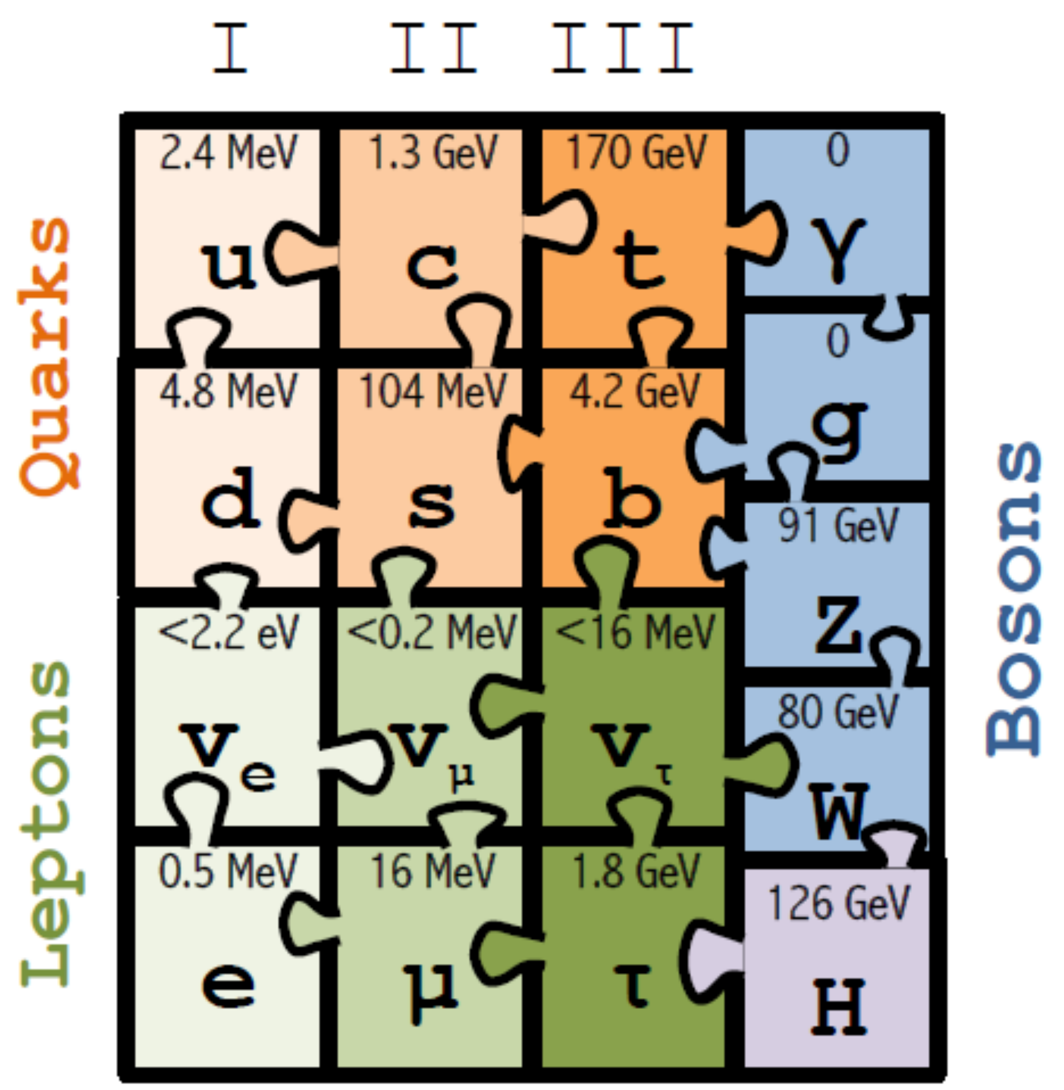
THE PHYSICS LANDSCAPE

- Particle Physics has arrived at an important moment of its History:

1989-1999:
Top mass predicted
(LEP mZ and ΓZ)
Top quark observed
at the right mass
(Tevatron, 1995)
Nobel Prize 1999
(t'Hooft & Veltman)



1997-2013:
Higgs mass cornered
(LEP EW + Tevatron mtop , mW)
Higgs boson observed
at the right mass
(LHC 2012)
Nobel Prize 2013
(Englert & Higgs)



  - It looks like the Standard Model is complete and consistent theory
  - It describes all observed collider phenomena – and actually all particle physics (except neutrino masses)
    - Was beautifully verified in a complementary manner at LEP, SLC, Tevatron, and LHC
    - EWPO radiative corrections predicted top and Higgs masses assuming SM and nothing else
  - With mH = 125 GeV, it can even be extrapolated to the Plank scale without the need of New Physics.
- Is it the *END* ?

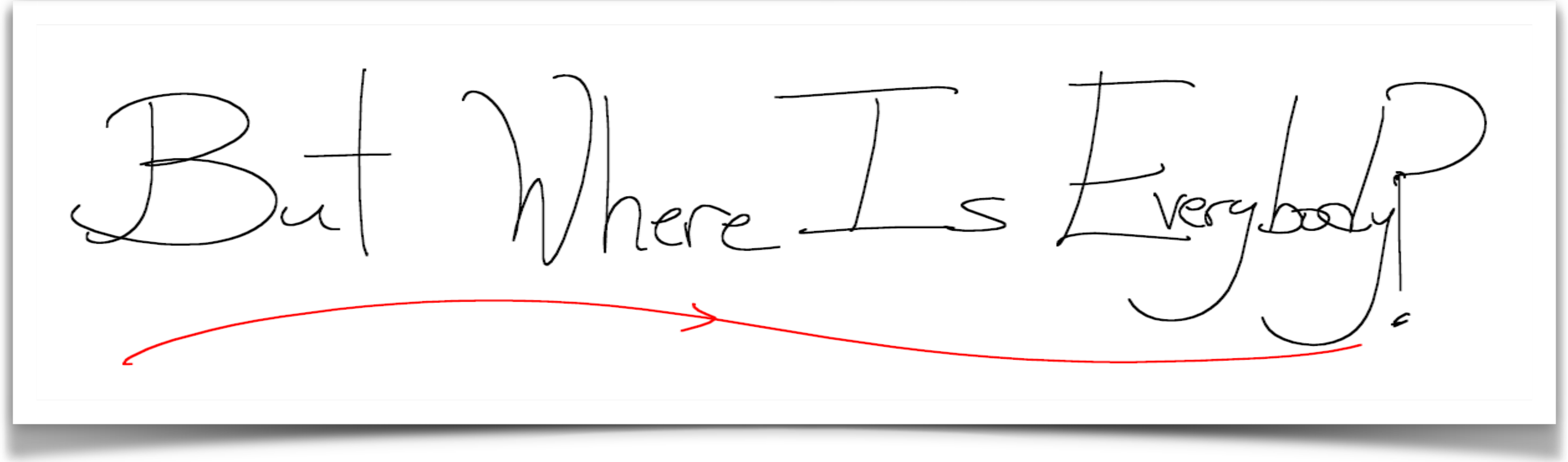
WHY NEW COLLIDER(S) / EXPERIMENTS?

- We need to extend mass & interaction reach for those phenomena that SM cannot explain:
  - Dark matter
    - SM particles constitute only 5% of the energy of the Universe
  - Baryon Asymmetry of the Universe
    - Where is anti-matter gone?
  - Neutrino Masses
    - Why so small? Dirac/Majorana? Heavier right-handed neutrinos? At what mass?

These facts require Particle Physics explanations

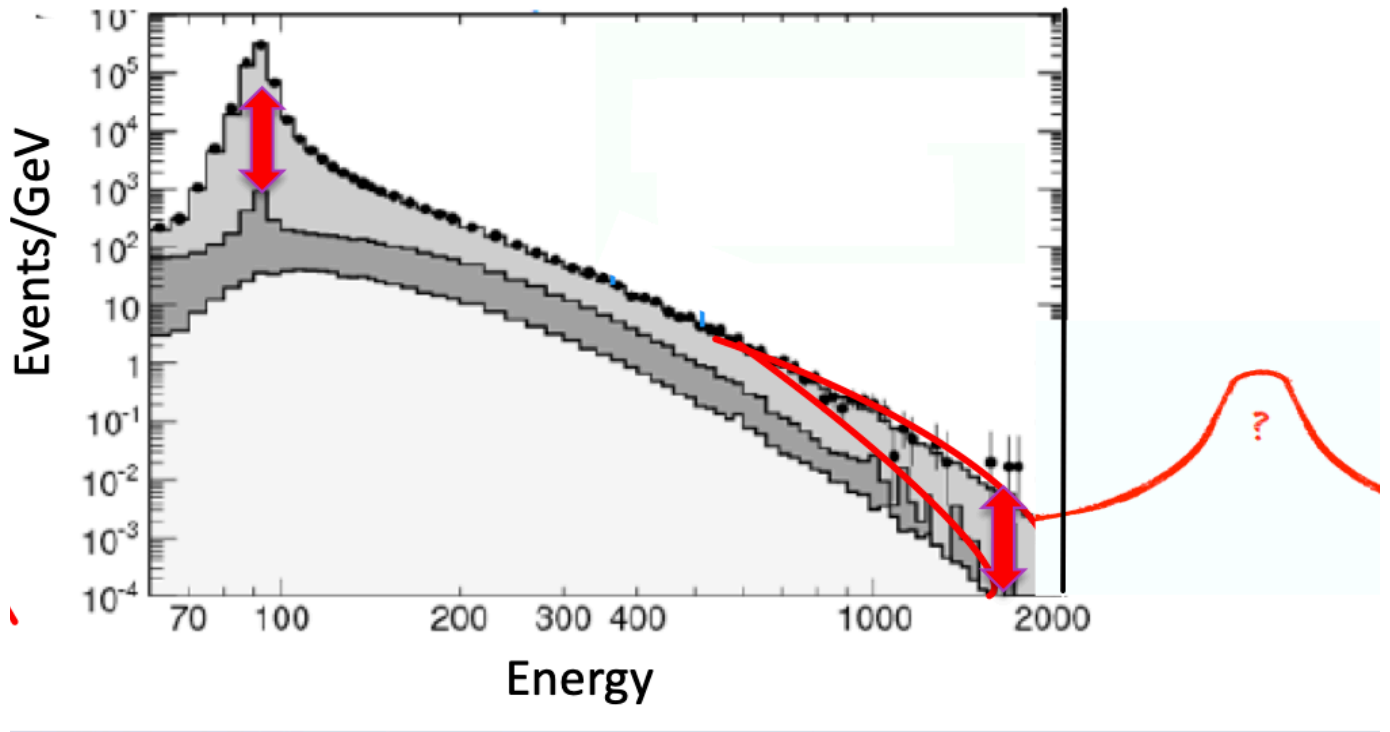
We must continue our quest, but HOW ?

WHICH WAY TO GO?



- Is new physics at larger masses ? Or at smaller couplings ? Or both ?
  - No experimental hints as to the origin of these observed (unexplained) phenomena
  - No theoretical hints that would point to one direction more than another
- Only way to find out: go look, following the historical approach:
  - Direct searches for new heavy particles ⇒ Need colliders with larger energies
  - Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles ⇒ Need colliders / measurements with unprecedented accuracy

WHICH TYPE OF COLLIDER?



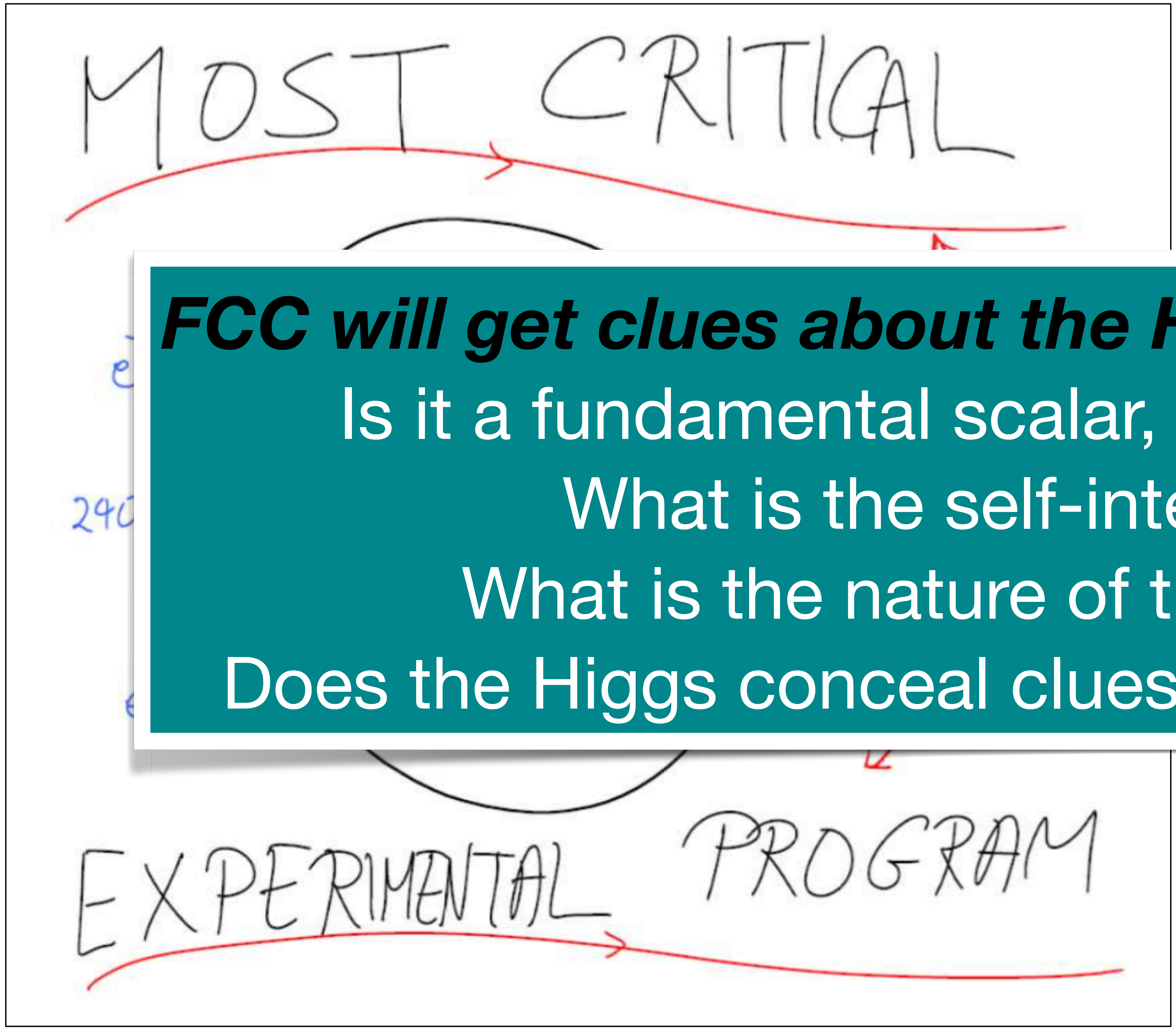
- Energy: direct access to new resonances
- Precision: indirect evidence of deviations at low and high energy.

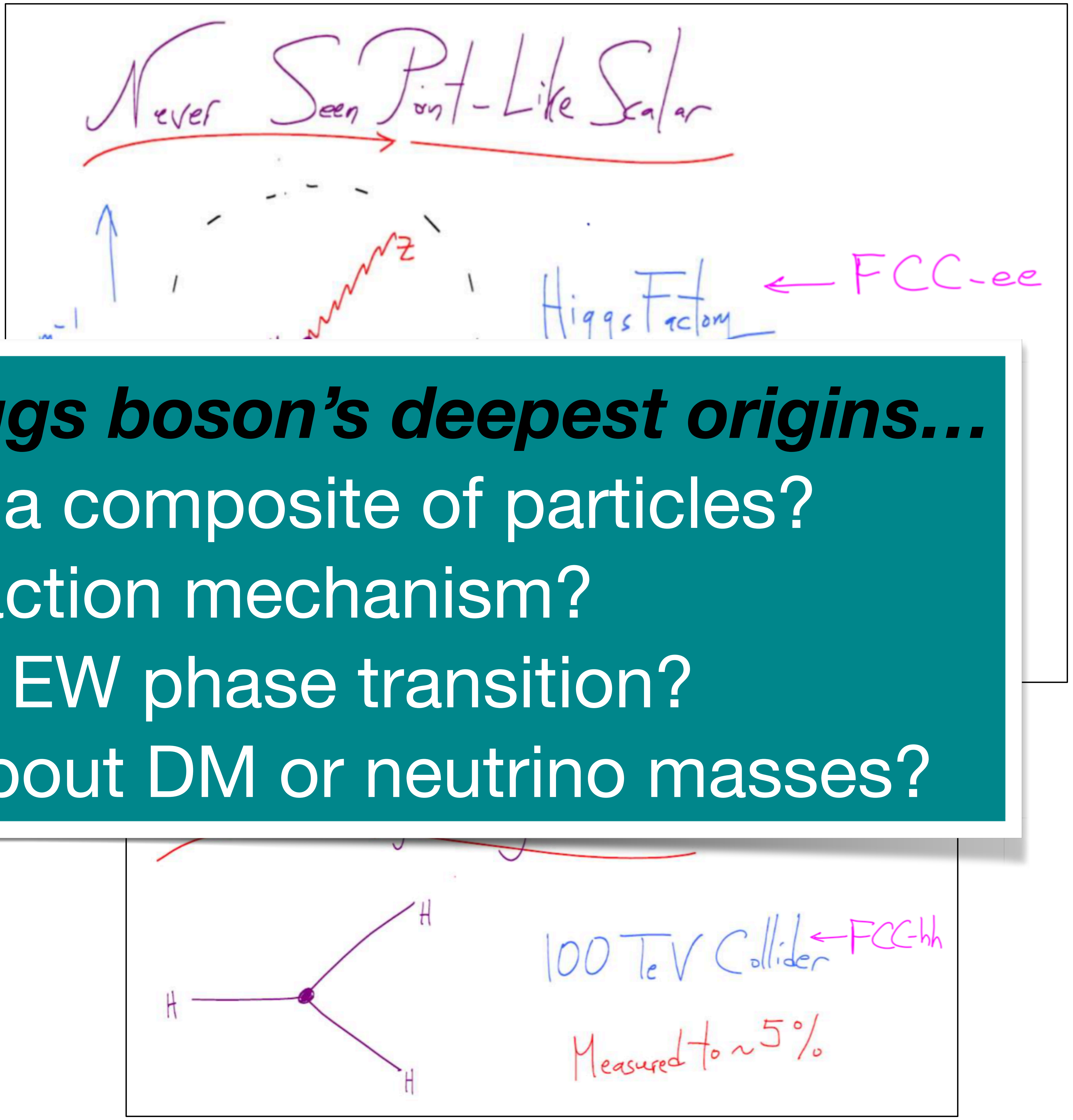
➤ The next facility must be versatile with a reach as broad and as powerful as possible – as there is no specific target

More SENSITIVITY, more PRECISION, more ENERGY

➤ Largest luminosity
➤ highest parton energy
➤ synergies and complementarities with other machines/projects

A CONCRETE TARGET: THE HIGGS BOSON





FCC will get clues about the Higgs boson's deepest origins…

Is it a fundamental scalar, or a composite of particles?

What is the self-interaction mechanism?

What is the nature of the EW phase transition?

Does the Higgs conceal clues about DM or neutrino masses?

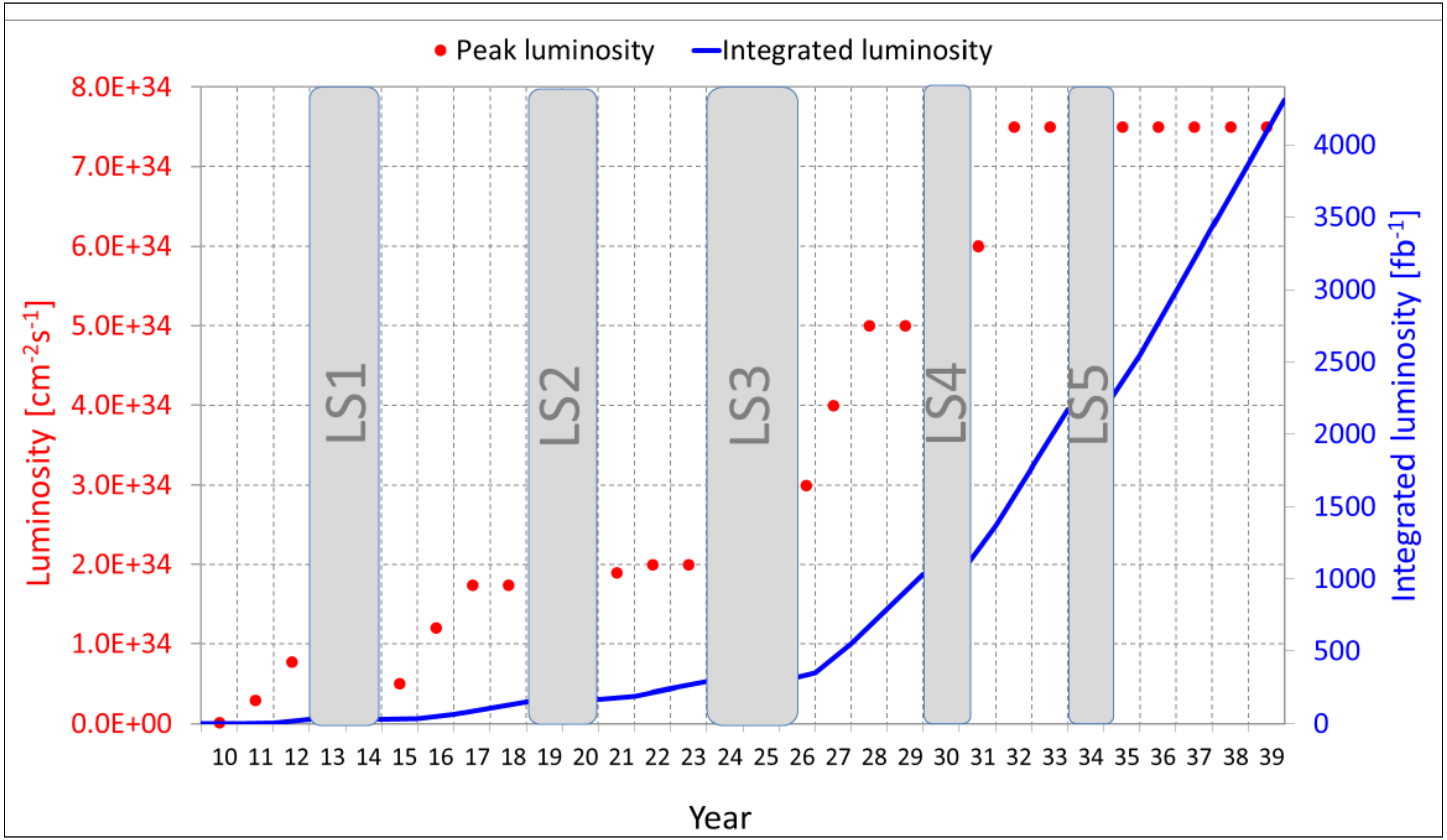
HISTORIC OVERVIEW OF IMPORTANT DISCOVERIES

Year	Discovery	Experiment	$\sqrt{s}$ [GeV]	Observation
1974	**c quark** (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \to J/\Psi)$ $J/\Psi \to \mu^+\mu^-$
1975	**τ lepton** (m=1.777 GeV)	e^+e^- ring (SPEAR/SLAC)	8	$e^+e^- \to \tau^+\tau^-$ $e^+\mu^-$ events
1977	**b quark** (m~4.5 GeV)	Fixed target (FNAL)	25	$\Upsilon \to \mu^+\mu^-$
1979	**gluon** (m = 0)	e^+e^- ring (PETRA/DESY)	30	$e^+e^- \to qqg$ Three-jet events
1983	**W, Z** (m ~ 80, 91 GeV)	pp ring (SPS/CERN)	900	$W \to \ell\nu$ $Z \to \ell^+\ell^-$
1989	**Three neutrino generations**	e^+e^- ring (LEP/CERN)	91	Z-boson lineshape *measurement*
1995	**t quark** (m=173 GeV)	pp ring (Tevatron/FNAL)	1960	Two semileptonic t-quark decays
2012	**Higgs boson** (m=125 GeV)	pp ring (LHC/CERN)	8000	$H \to \gamma\gamma$, $H \to Z^*Z \to 4\ell$

- *what do we see?*
- centre of mass energy increase
- moving from fixed target to colliders
- different type of particles colliding
- alternance of ee and pp machines

WHERE WE ARE HEADING

- The LHC is still pretty much in its childhood: factor 30 more luminosity to be collected with HL-LHC



HL-LHC PLAN (UPDATED SCHEDULE)

new interaction region layout and crab cavity

upgrade of injector chain to deliver brighter bunches

LHC

HL-LHC

Run 2:
Design $\mathcal{L} = 10^{34}/\mathrm{cm}^2/s$

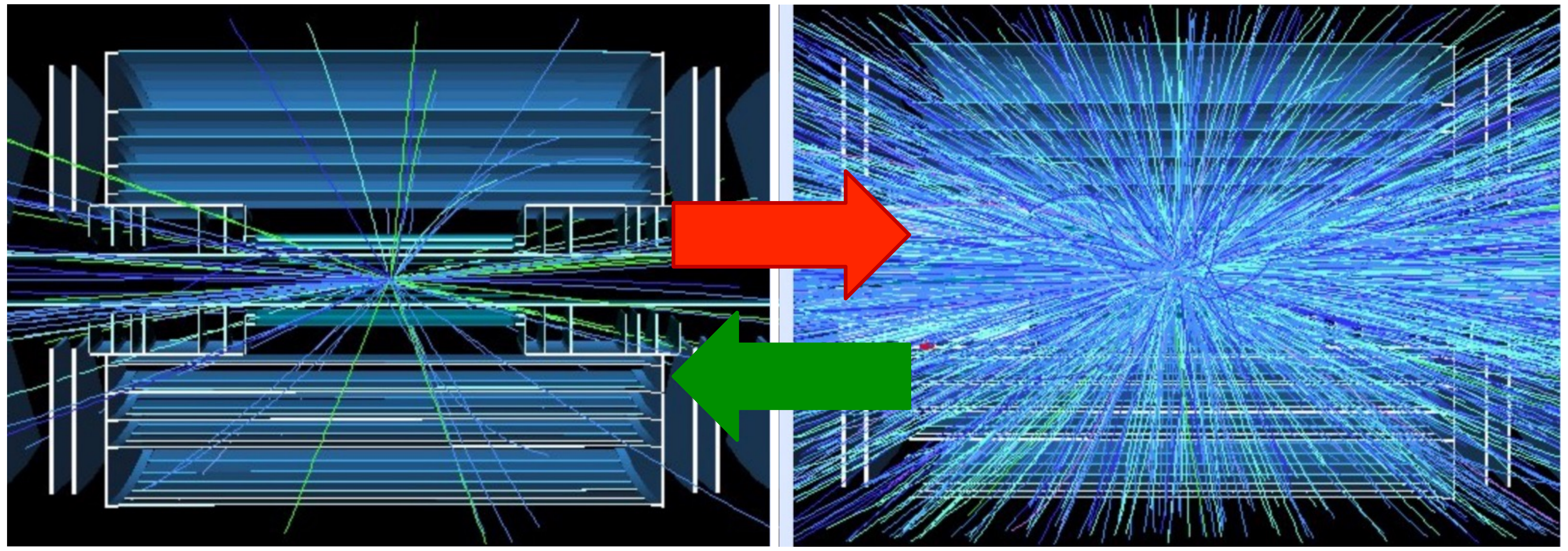
Run 3:
$\mathcal{L} = 2\times10^{34}/\mathrm{cm}^2/s$
for 300/fb

HL-LHC: Peak $\mathcal{L} = 2\times10^{35}/\mathrm{cm}^2/s$
level luminosity to
Nominal scenario: $\mathcal{L} = 5\times10^{34}/\mathrm{cm}^2/s$
for 3000/fb; Pile-up $<\mu>$ = 140
Ultimate Scenario: $\mathcal{L} = 7.5\times10^{34}/\mathrm{cm}^2/s$
for 4000/fb; Pile-up $<\mu>$ = 200
⇒25% increase in integrated lum.

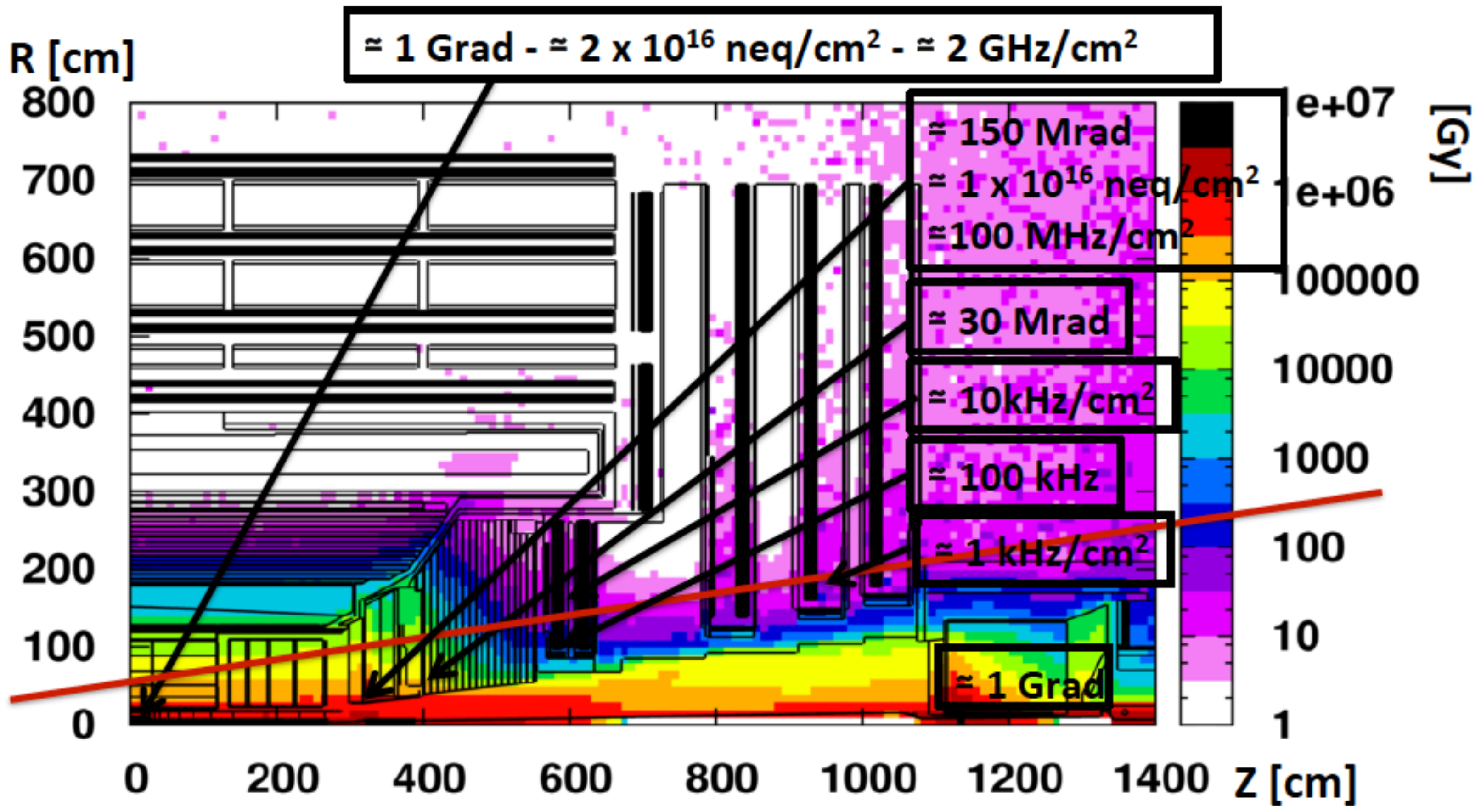
HL-LHC IS (ALREADY) A COMPLETELY NEW CHALLENGE

- High luminosity ➔ 200 soft pp interactions per crossing
  - Increased combinatorial complexity, rate of fake tracks, spurious energy in calorimeters, increased data volume to be read out in each event
- Detector elements and electronics are exposed to high radiation dose : requires new tracker, endcap calorimeters, forward muons, replacing readout systems
- We have demonstrated that the new detector will be able to explore the full physics potential of HL-LHC even in these conditions.

25 pileup 200 pileup



Expected HL-LHC results used as starting point for future machines performance!



Roughly reaching limits of current techniques in several systems

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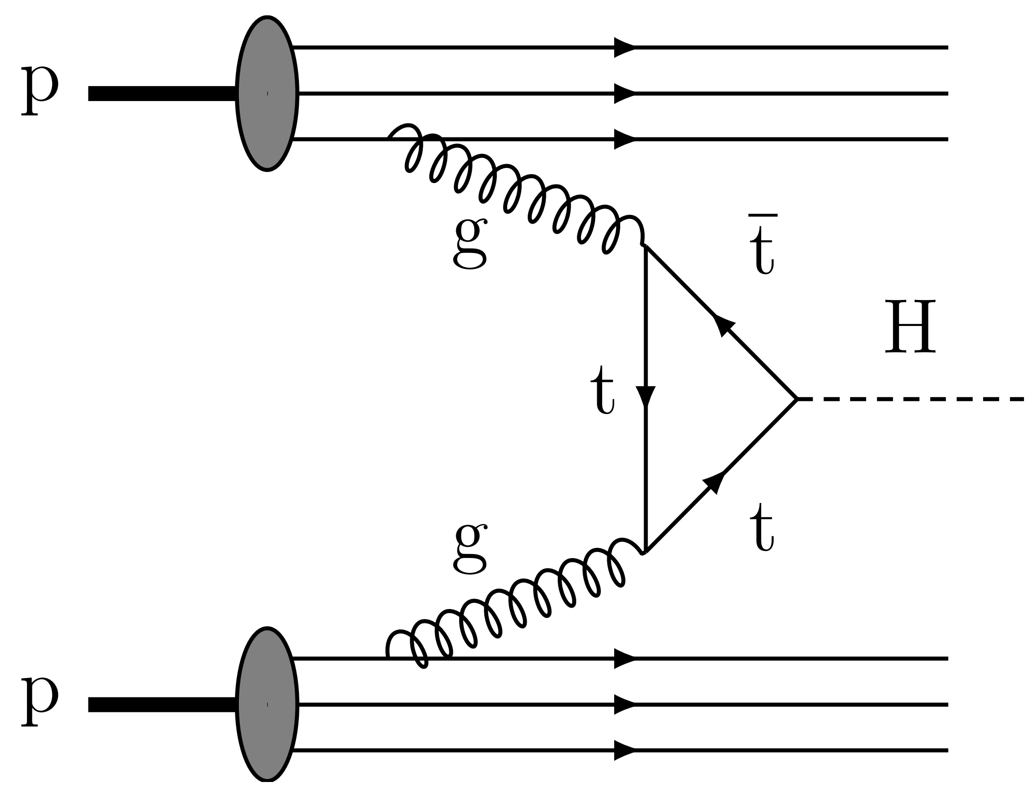
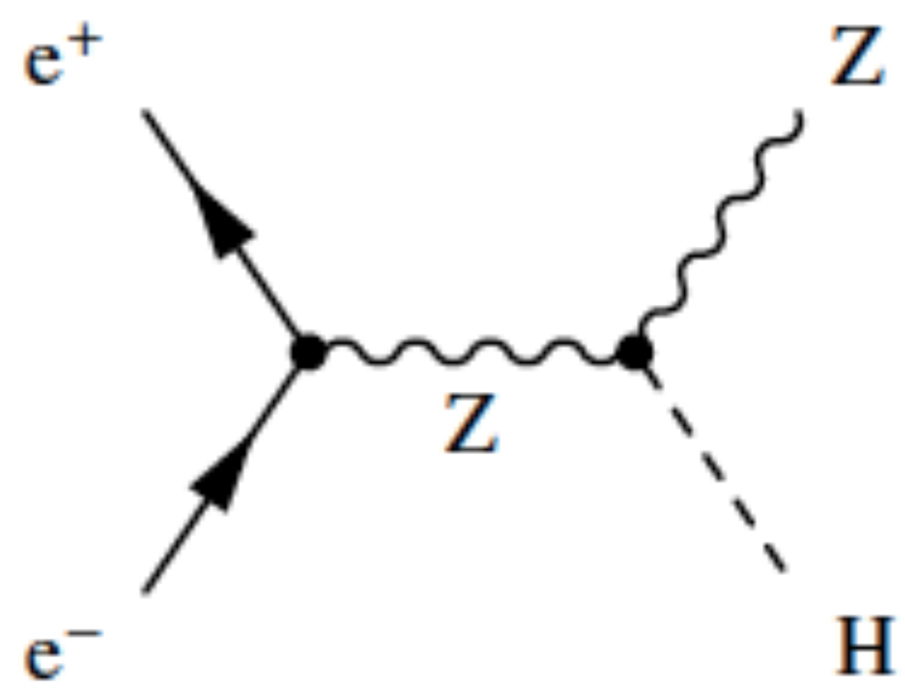
e^+e^- VS pp COLLISIONS - EVENT CHARACTERISTICS



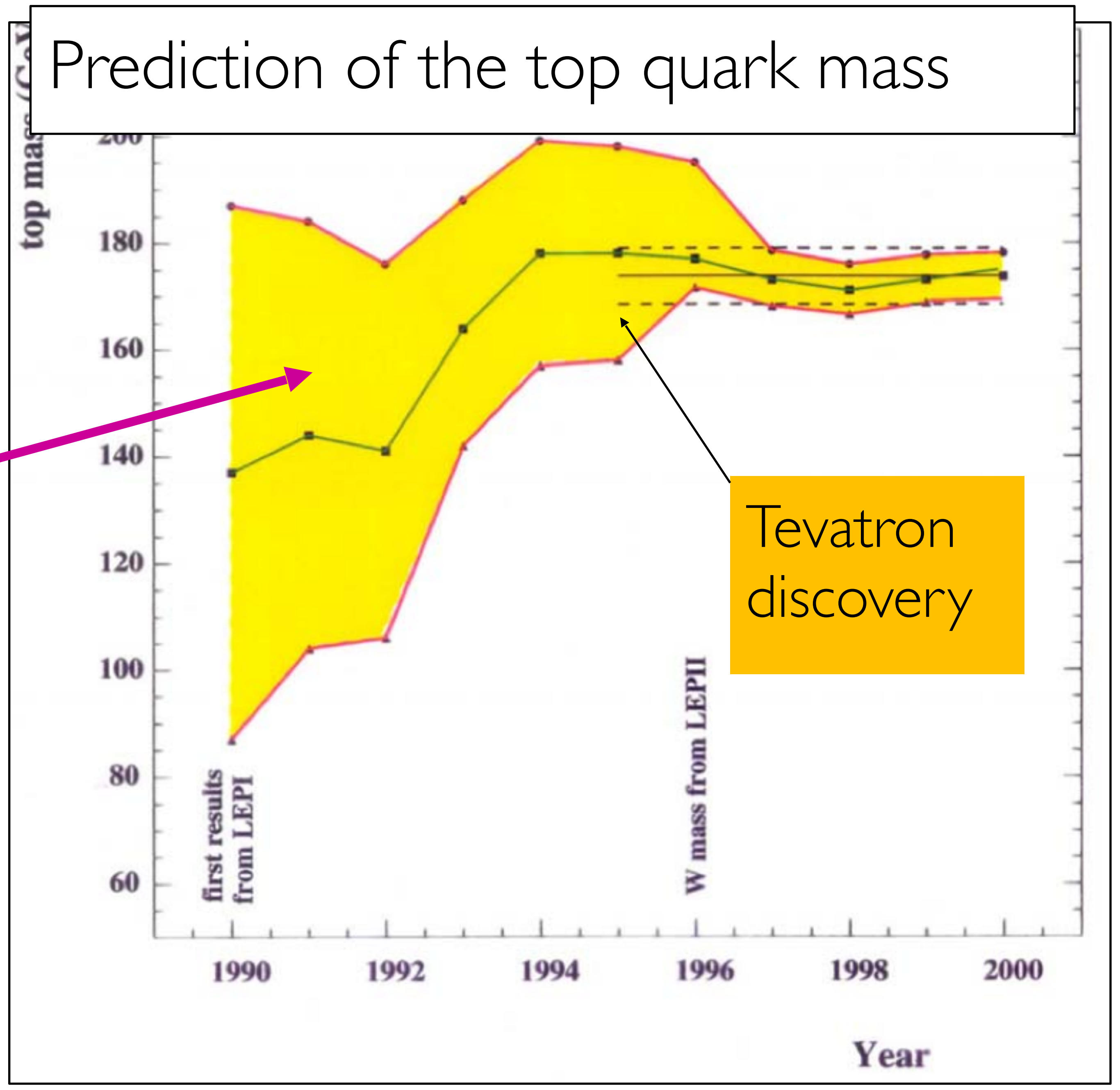


p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (E, **p**), polarisation → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Clean experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	- At lower energies (≲ 350 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.** - Higher energy (>1TeV) e^+e^- requires **linear** colliders

PRECISION FOR DISCOVERY

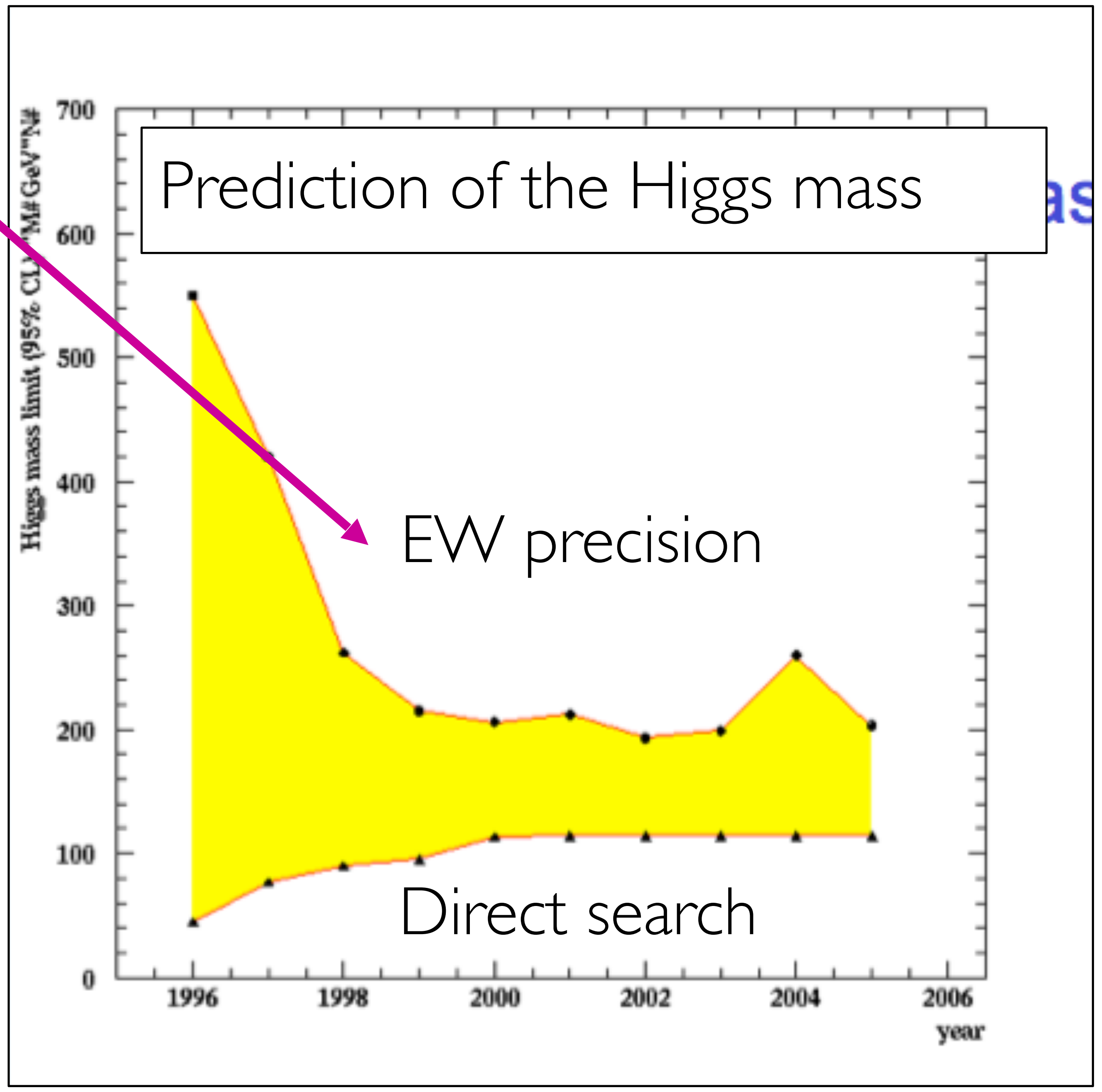
- Top quark
  - 1990-1994: Mass predicted from quantum loops
    - m_{top}(pred.) = 178.0 ± 10 GeV
  - 1995: Discovered at the Tevatron (DØ, CDF)
    - Today: m_{top}(obs.) = 173.23± 0.7 GeV

✓



- Higgs boson
  - 1996-2011: Mass predicted from quantum loops
    - m_{Higgs}(pred.) = 98 $^{+25}_{-21}$ GeV
  - 2012: Discovery at the LHC (ATLAS, CMS)
    - Today: m_{Higgs}(obs.) = 125.09 ± 0.24 GeV

✓



- Lesson:
  - Precision measurements interpreted via quantum loop corrections can give very strong constraints on particles at higher masses than what can be directly probed!

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

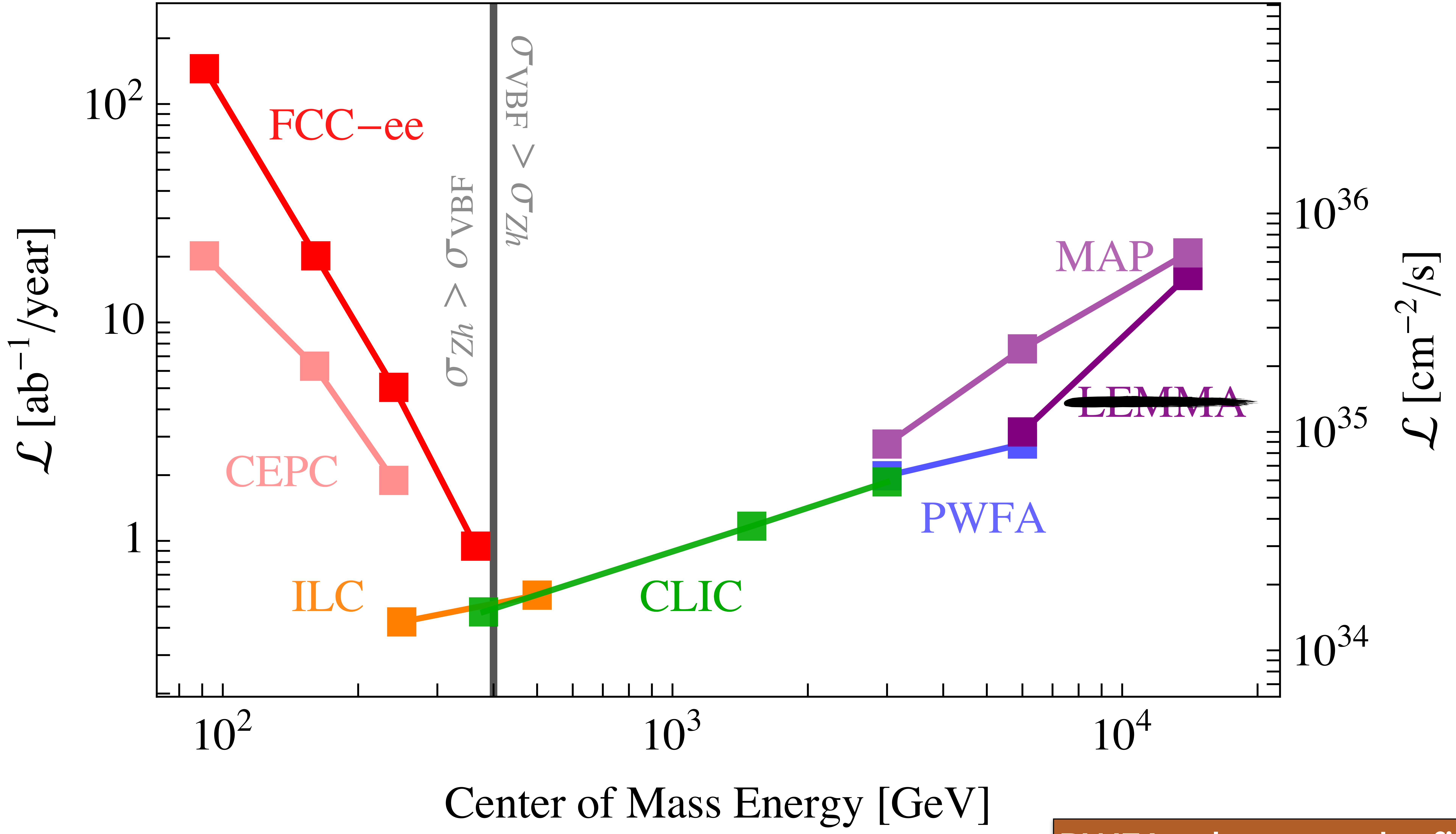
- $\sqrt{s}$ limited by synchroton radiation
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)

Linear

- easier to upgrade in energy
- easier to polarize beams
- large beamsthralung
- "greener": less power consumption

(New) **Which lepton?** Electrons or muons

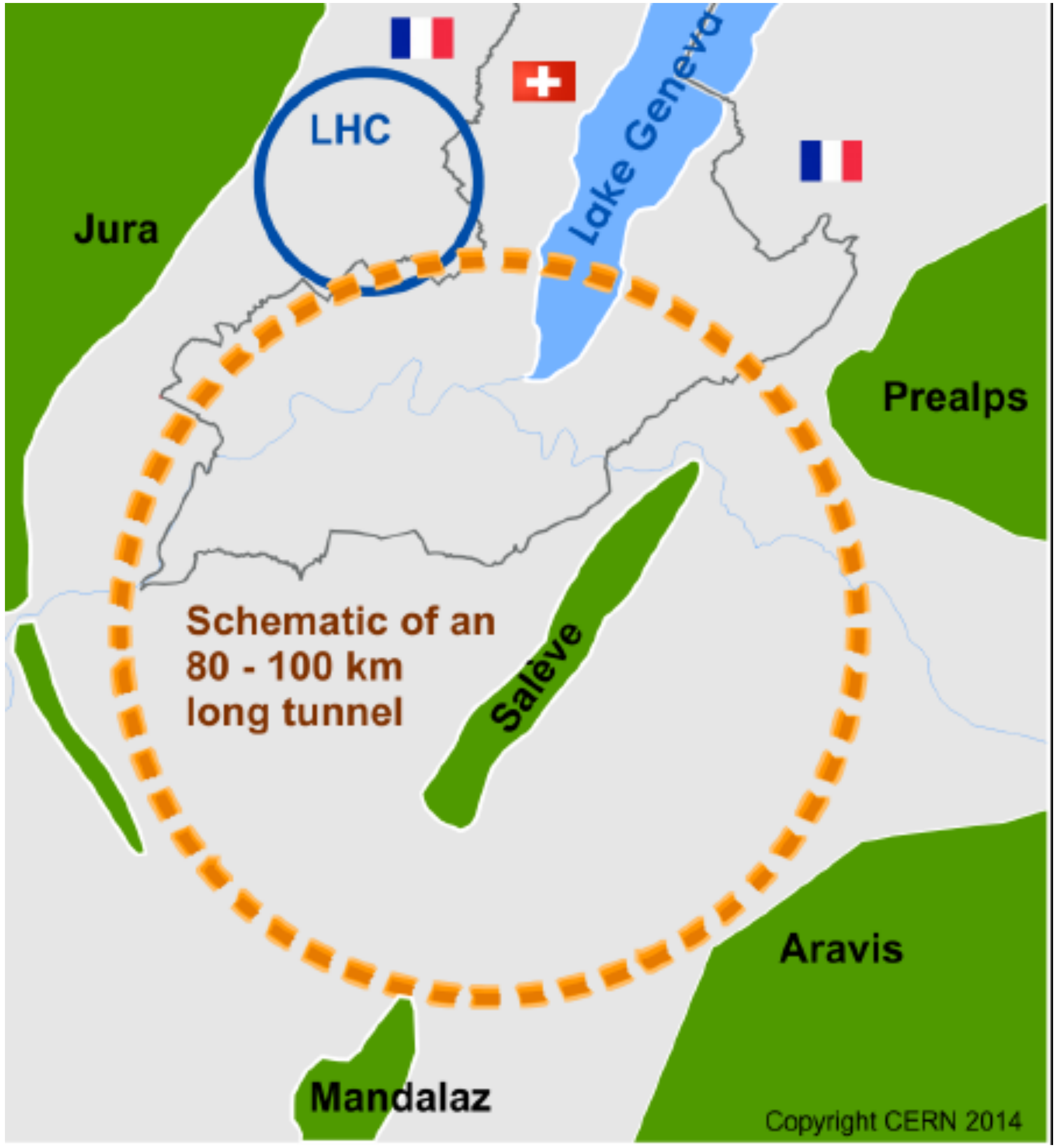
LEPTON COLLIDERS PROJECTS



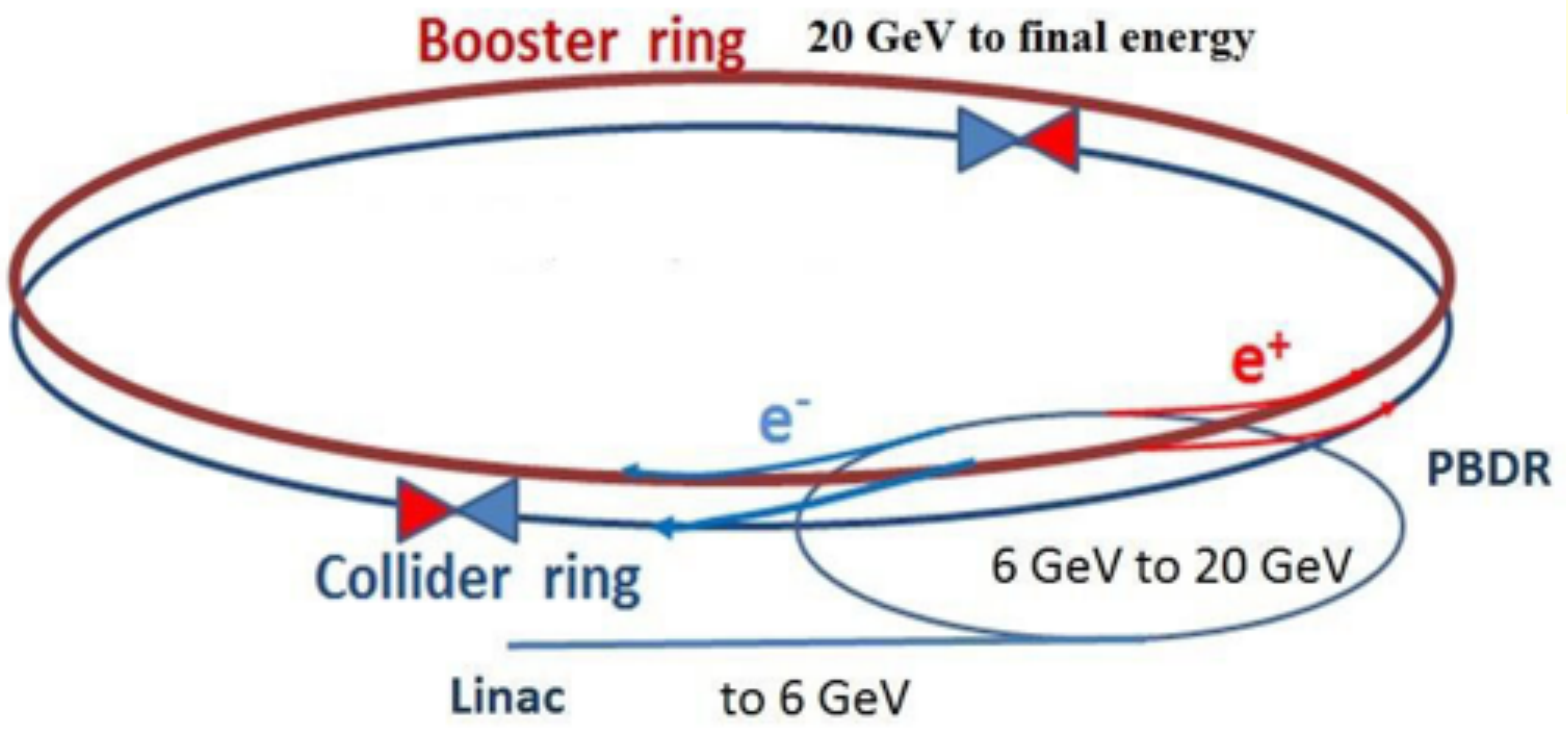
PWFA=plasma wake field Acc.

THE FCC INTEGRATED PROJECT

- Build a new 100 km tunnel in the Geneva region
- Ultimate goal: highest energy reach in pp collisions: 100 TeV
  - need time to develop the technology to get there
- First step: extreme precision circular e^+e^- collider (FCC-ee)
  - variable collision energy from 90-360 GeV (beyond top threshold)
- **As for the LEP+LHC, one tunnel for two complementary machines covering the largest phase space in the high energy frontier**
  - a complete physics program for the next 50 years



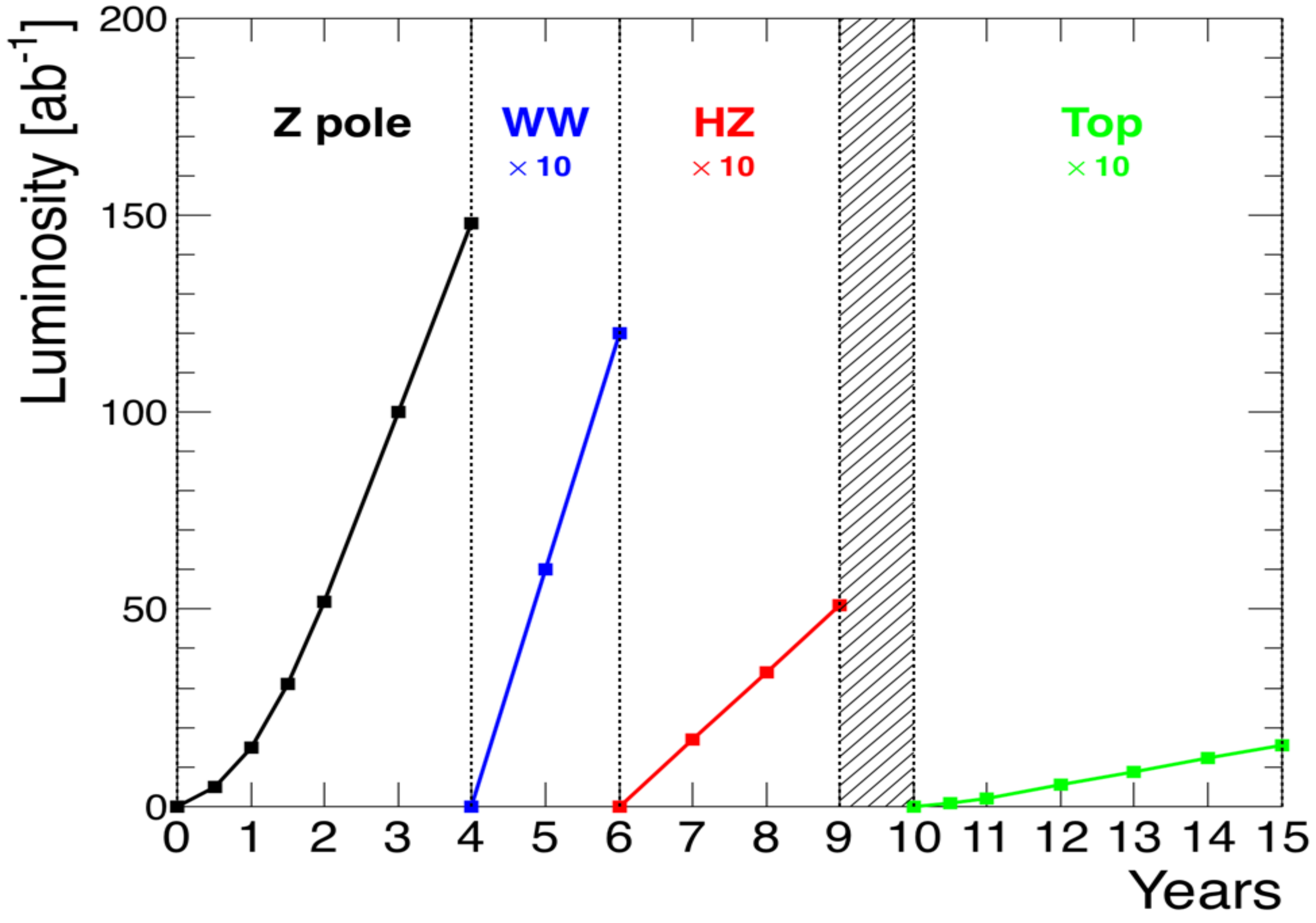
FCC-ee



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

First-phase machine in the **100-km tunnel** built to host eventually FCC-hh

Luminosity limited by SR
- top-up injection (once per minute)
- 50 MW power/beam
- 2 interaction points



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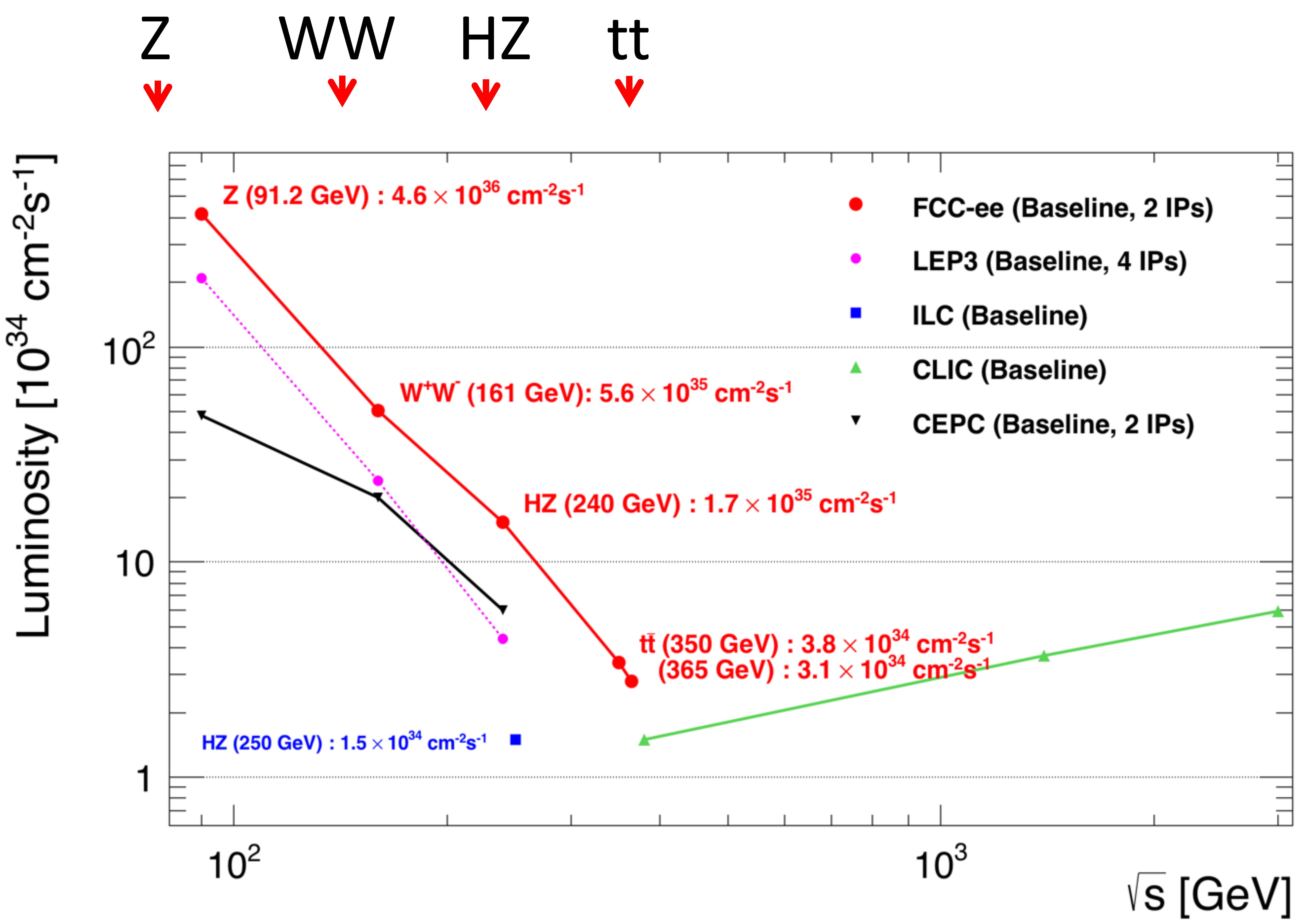
FCC-ee

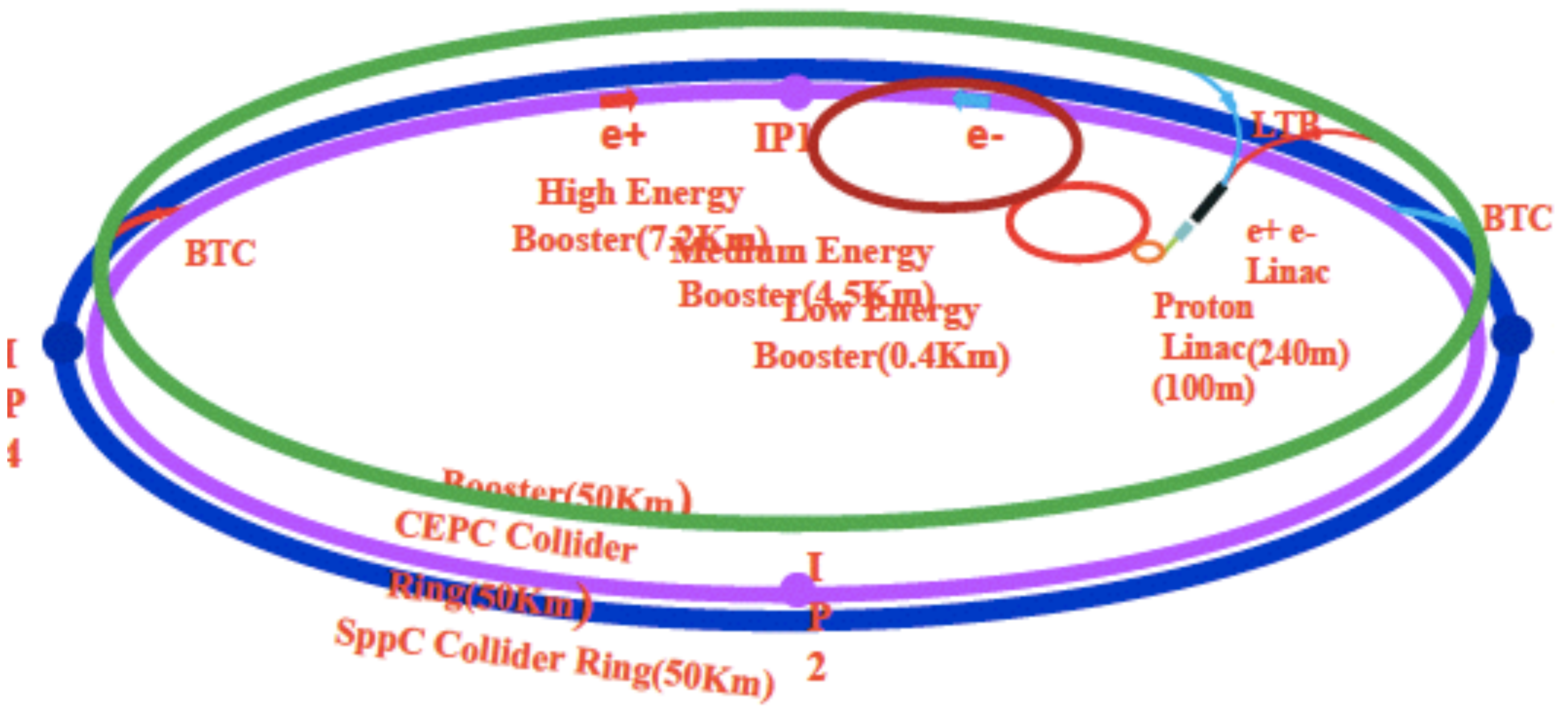


Event statistics :

				E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$ e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8 e+e- → WW**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6 e+e- → ZH**	**Never done**	1 MeV
$t\bar{t}$ threshold	**E_{cm} : 350 GeV**	**10^6 e+e- → $t\bar{t}$**	**Never done**	2 MeV

Great energy range for the heavy particles of the Standard Model.

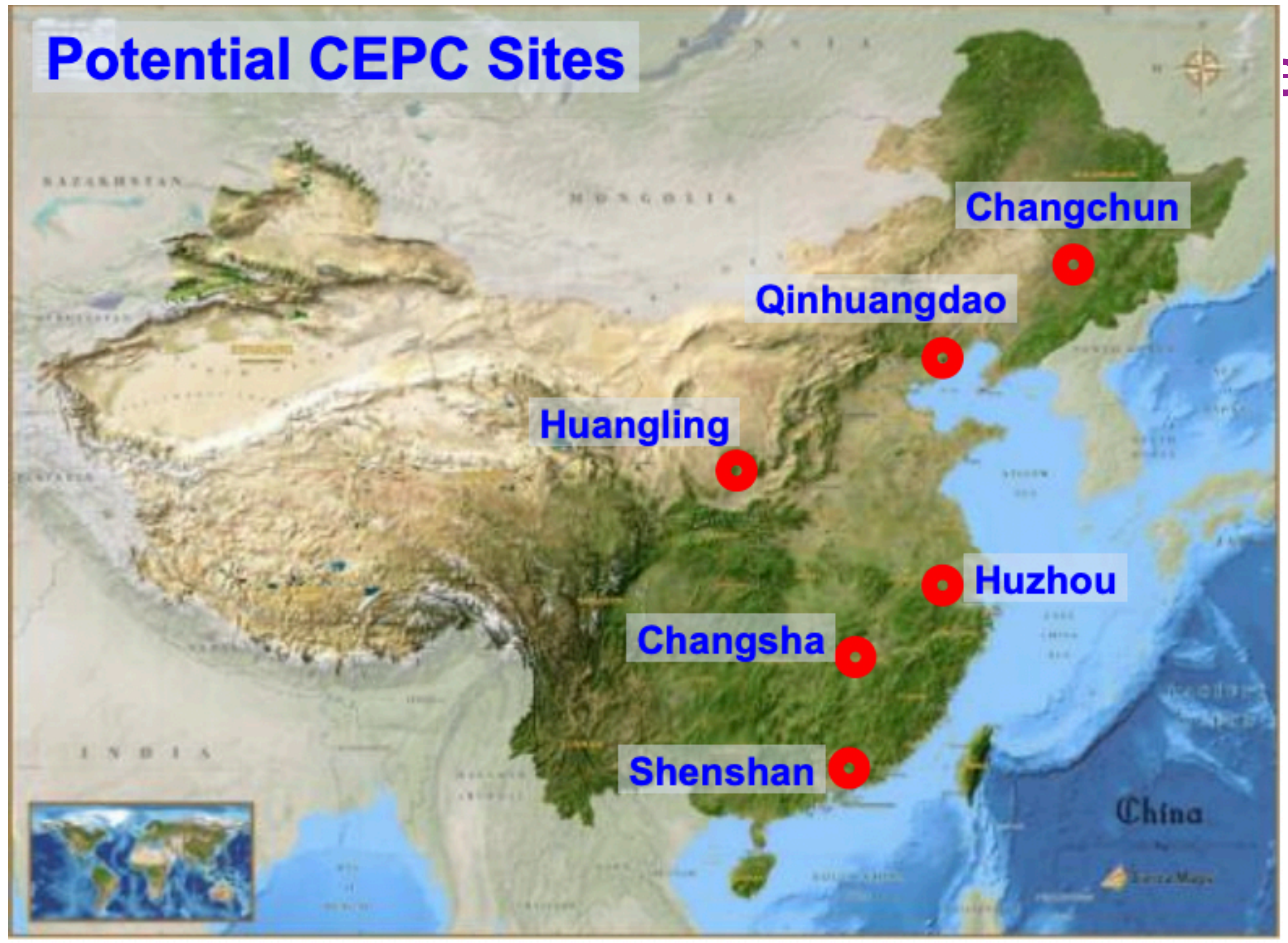
CEPC: Chinese e^+e^- Collider +SppC



Project similar to FCC-ee in China

- two colliding rings and a booster
- $\sqrt{s}$ = 90-240 GeV

  - Hosted in a 100-km tunnel which could eventually host a 70-TeV pp collider
  - several possible sites



eters)

Delayed to be approved now in 2026

Timeline

2013-2015	pre-s[illegible]ies
2016-2022	R&D Engineering Design
2022-2030	Construction
2030-2040	data taking

- Starts before the end of the HL-LHC
- possibly concurrent with the ILC

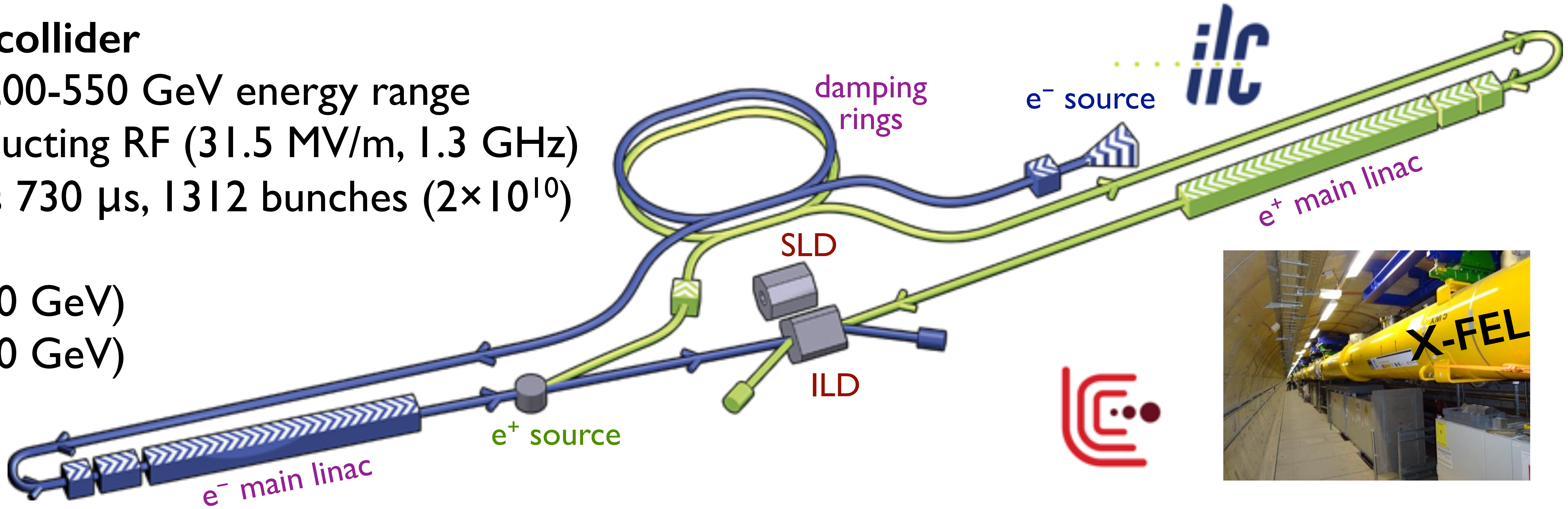
ILC: International Linear Collider

For a long time the only proposal on the market…then the Higgs came!

Linear e^+e^- collider

in the 200-550 GeV energy range

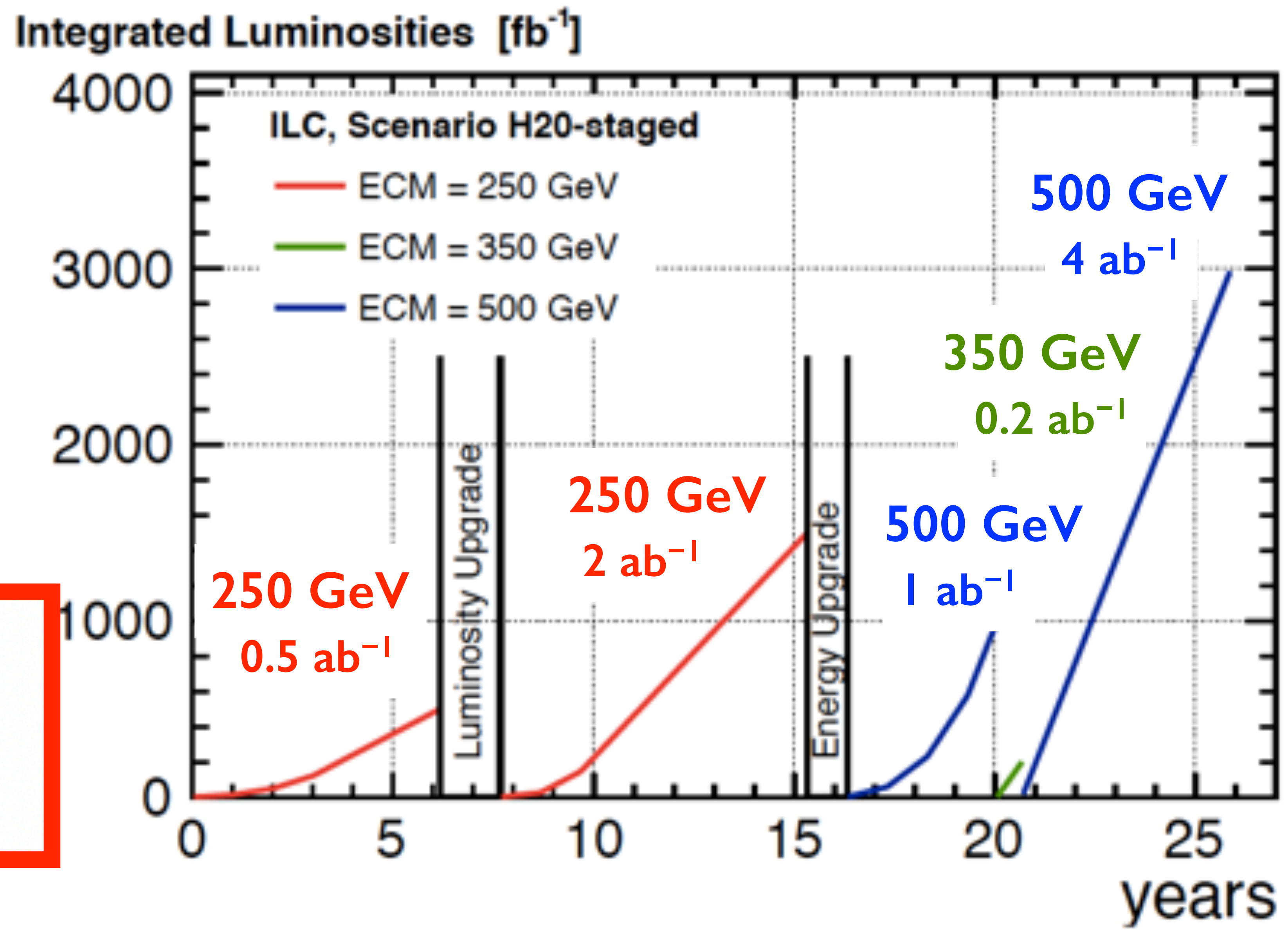
- super conducting RF (31.5 MV/m, 1.3 GHz)
- 5 Hz, trains 730 μs, 1312 bunches (2×10^{10})
- footprint:
  20 km (250 GeV)
  31 km (500 GeV)



Staging scenario

ILC TDR (2013)
ILC-250 Physics Case (2017)

- $\sqrt{s}$ = 250 GeV
- optimised luminosity: $\mathcal{L} = 1.5\times10^{34}$ cm^{-2}s^{-1}
- ±80% (±30%) e^- (e^+) beam polarisation
- (LR, RL, LL, RR) = (45%, 45%, 5%, 5%)



3. The panel recommends that the development work in the key technological issues for the next-generation accelerator should be carried out by further strengthening the international collaboration among institutes and laboratories, shelving the question of hosting the ILC.

Political situation not good for ILC

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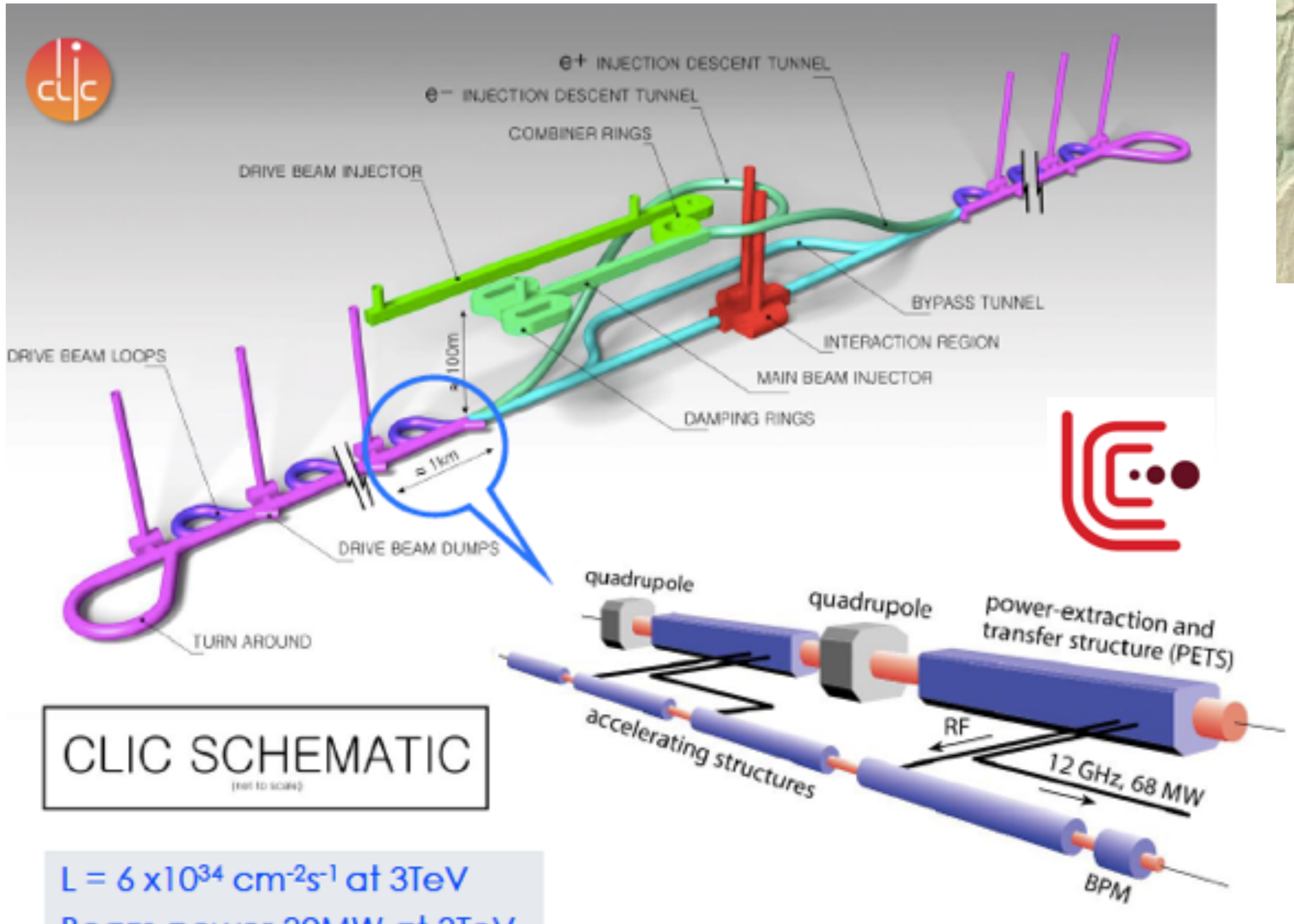
CLIC: Compact Linear Collider

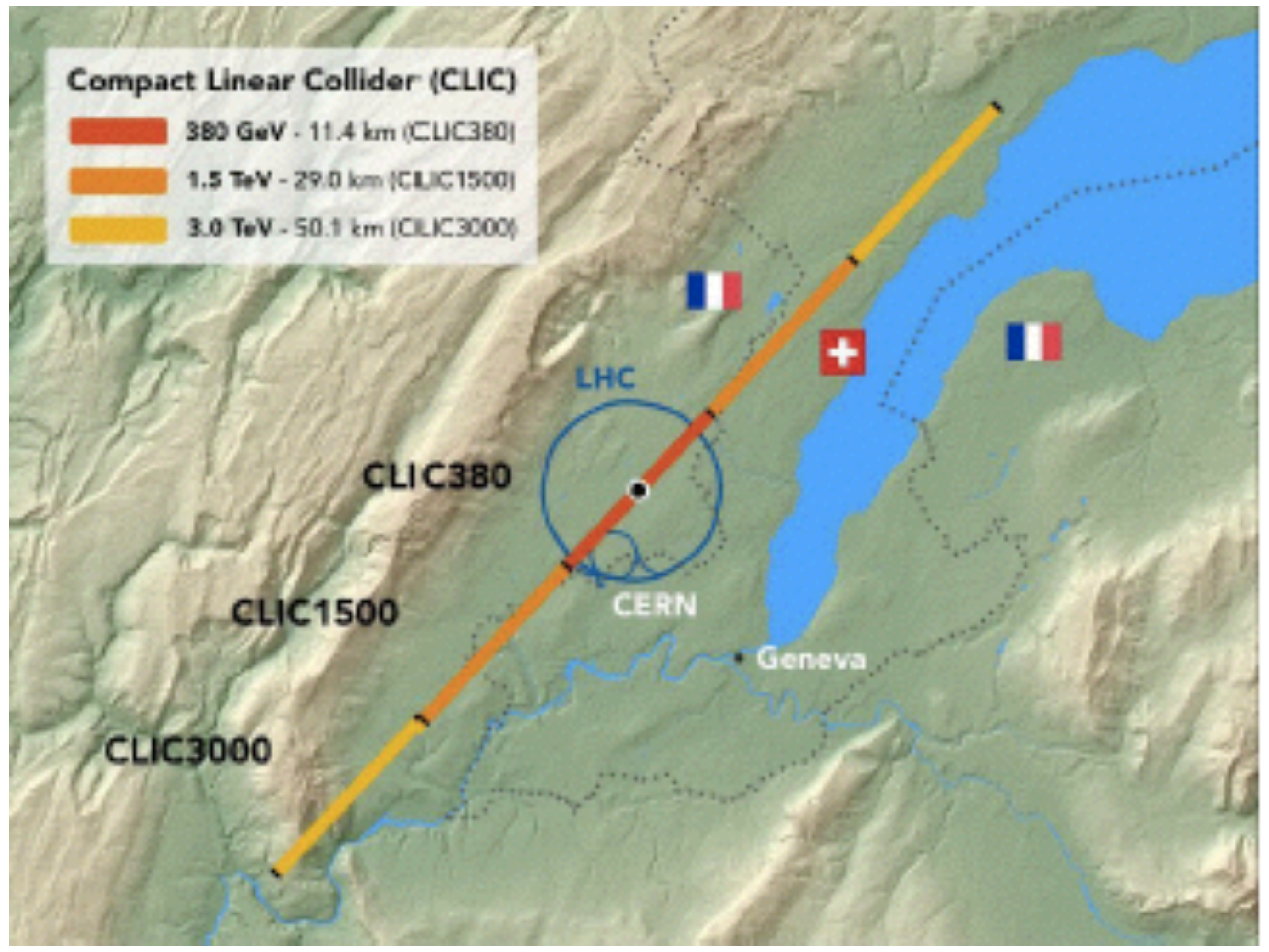
Linear e⁺e⁻ collider at CERN

in the up-to multi-TeV energy range

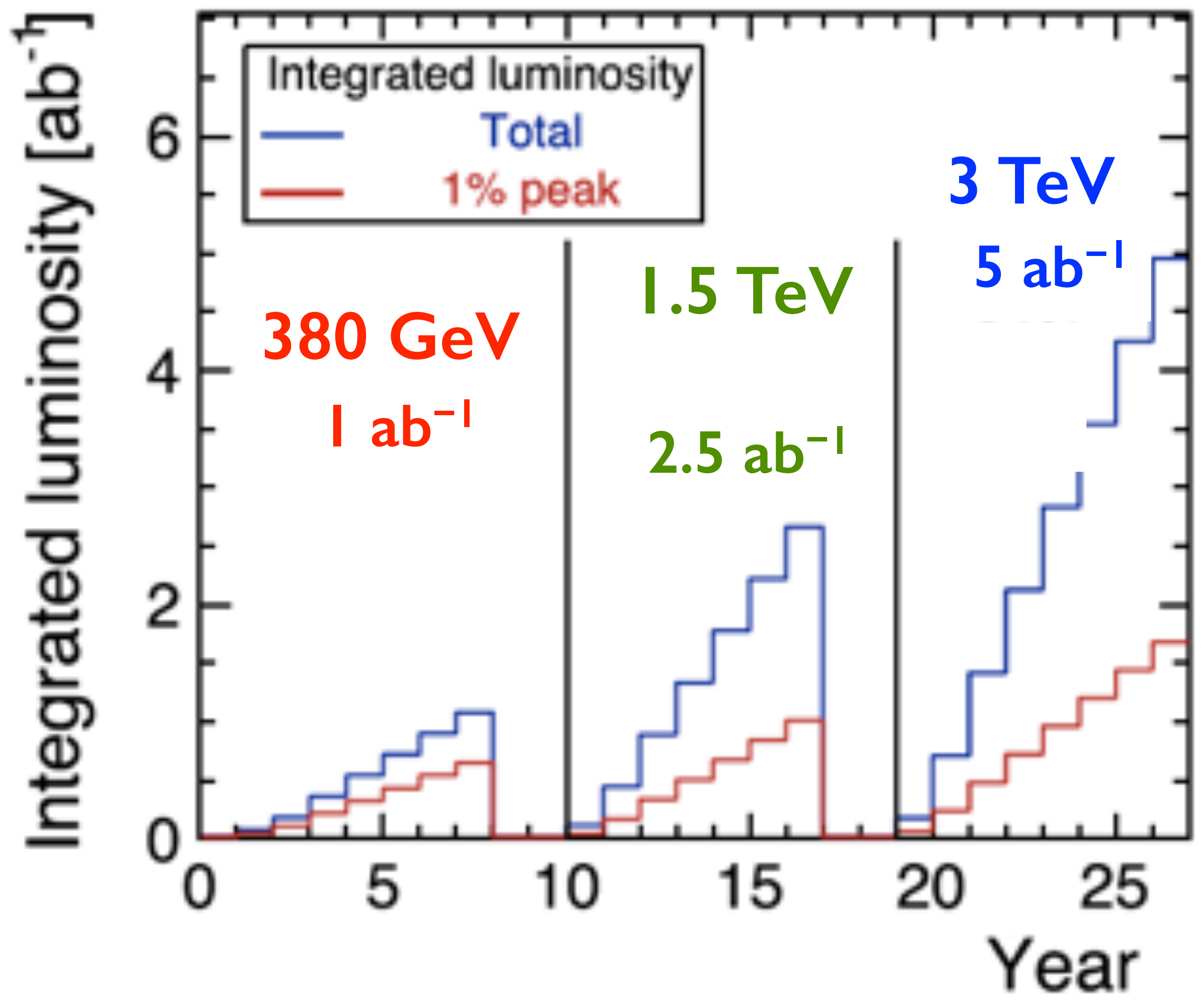
- normal conducting high-frequency RF (X-band, 12 GHz)
- e⁻ drive beam for RF power generation



$L = 6 \times 10^{34}\ cm^{-2}s^{-1}$ at 3TeV
Beam power 30MW at 3TeV



Scenario in 3 stages



Beam polarisation: (±80%, ∓80%)
LR / RL = 50% / 50%

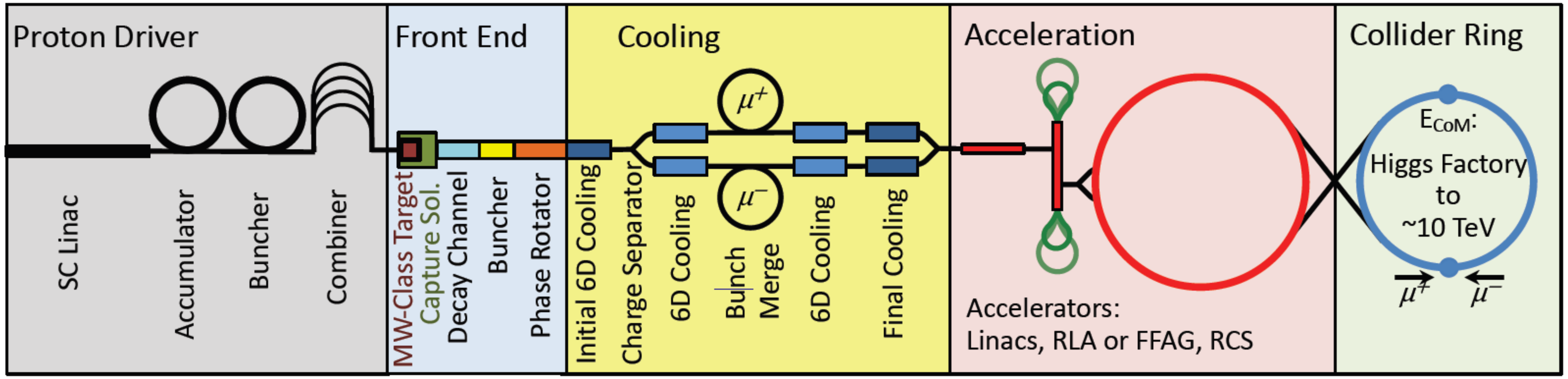
CERN/SPC/1114 (2018)

COLLIDING MUONS: ISSUES AND CHALLENGES

- Limited Lifetime: $2.2\mu s$ at rest
  - Race against death: fast generation, acceleration & collision before decay
  - Muons decay into the accelerator and detector:
    - Large backgrounds: physics feasibility needs to be assessed
    - Shielding of detector and facility (and surroundings) from irradiation
- Decays in neutrinos:
  - Ideal source of well defined electron and muons neutrino in equal quantities:
  - $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu \quad \mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$ "the neutrino factory concept"
  - Limitation in energy by neutrino radiation (hazard!)
- Generated as tertiary particles with large emittances
  - Powerful MW driver
  - Novel cooling method (10^6 reduction in emittance)

Need new ideas and technologies to overcome the accelerator and detector challenges

PROTON DRIVEN MUON COLLIDER CONCEPT (MAP)



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

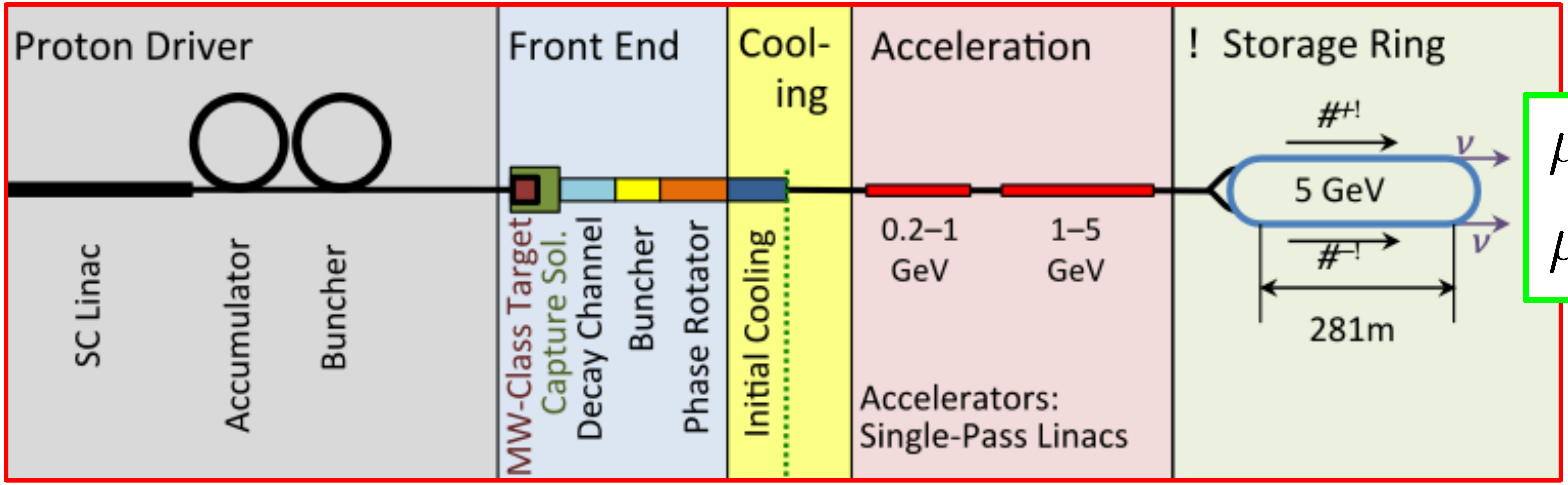
Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

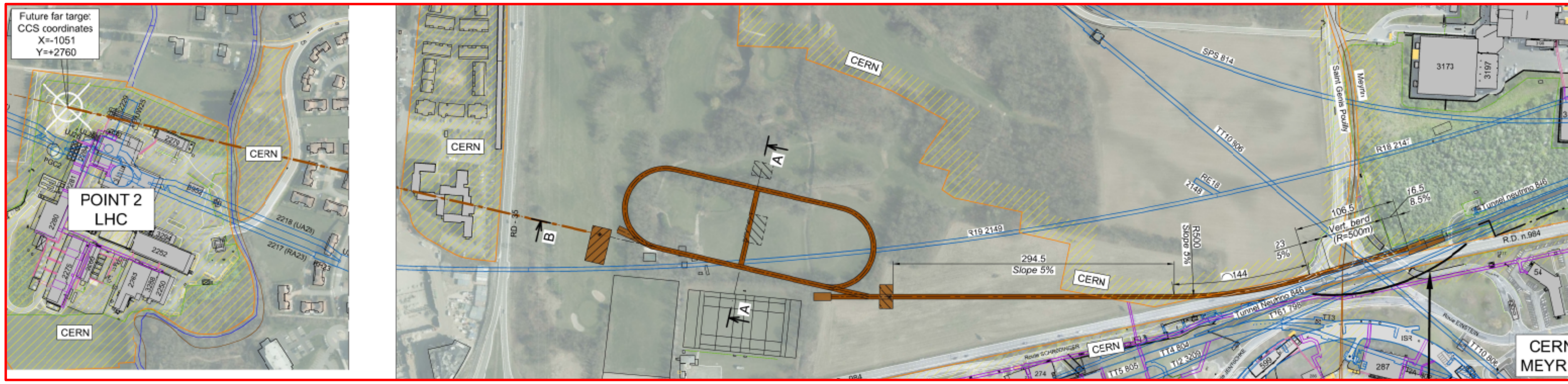
1980's concept
Still the baseline

- Muons generated at tertiary particles in pion decays created by an intense proton beam on a target.
- Needs cooling (5/6 orders of magnitude). Muon momenta ~few hundreds MeV
- Need large beam current for high luminosity: backgrounds and neutrino radiation issues for High energy.



$$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$
$$\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$$

- **Unique:**
  - Large, high-energy ν_e, ν_μ flux (equal number!)
    - Muon-beam cooling
- **Scientific objectives:**
  - %-level (ν_eN)cross sections
  - Sterile neutrino search



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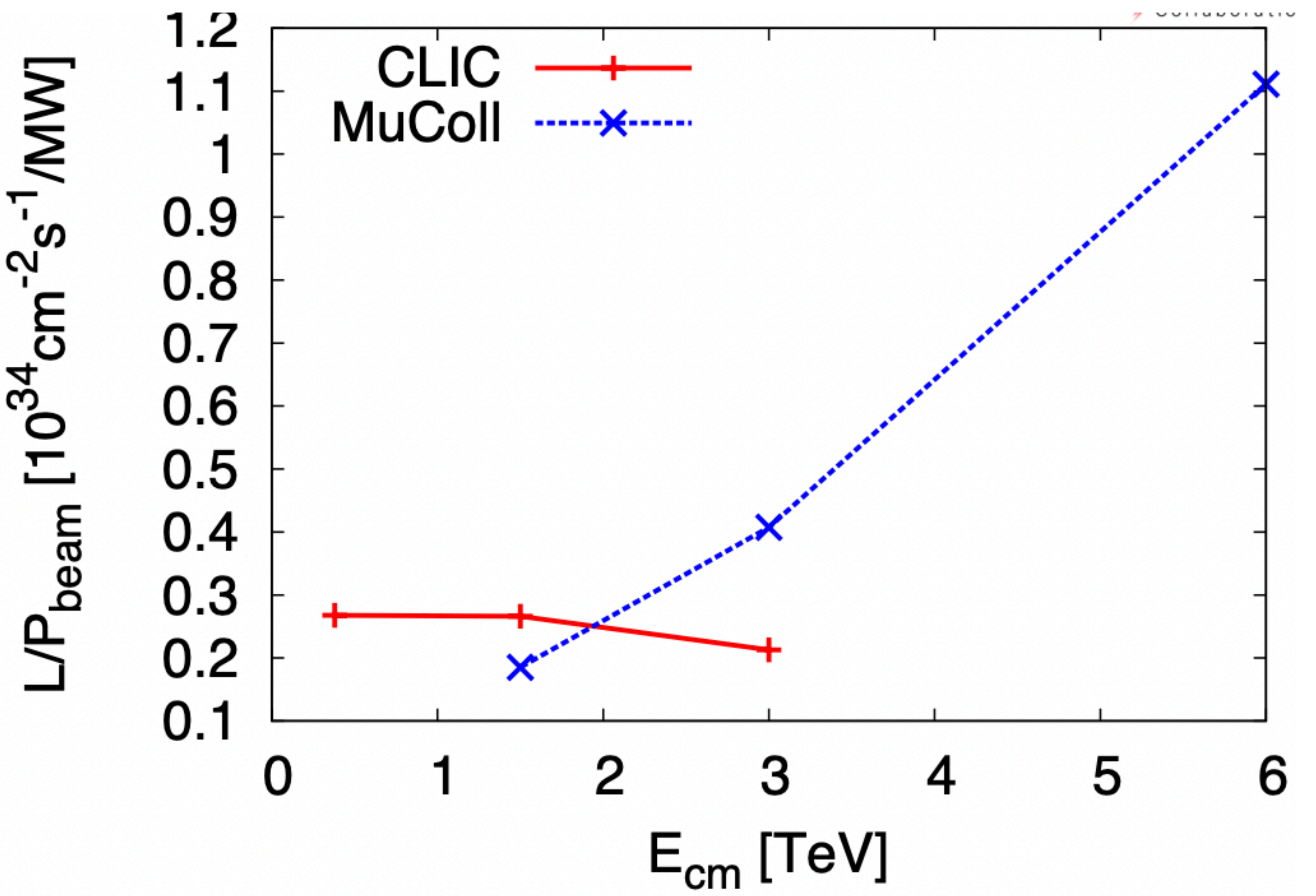
COMPARISON OF e^+e^- AND $\mu^+\mu^-$ COLLIDERS ENERGY REACH

In linear colliders, the luminosity per beam power is about constant
- have pushed technologies for decades

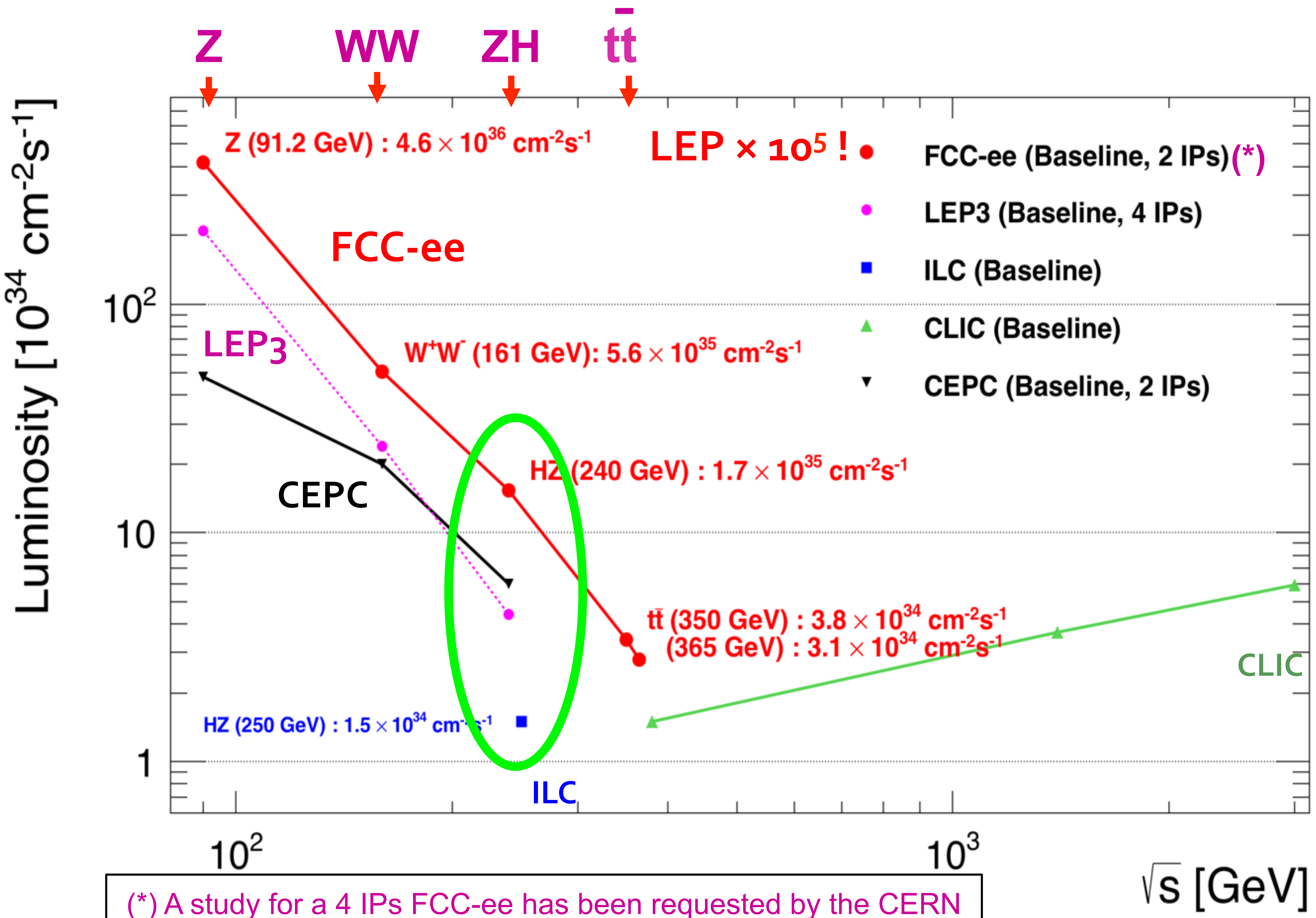
In muon collider, luminosity can increase linearly with energy



Muon collider can accelerate beams in several passes
⇒ efficient use of RF systems and power

Muon collider promising for **high energy**
Collaboration focuses on
- **10+ TeV** to reach well beyond other lepton colliders
- **3 TeV** as initial stage with technologies available in 20 years
- consider synergies (e.g. on-resonance higgs factory, neutrino facility)

COMPLEMENTARITY: LINEAR VS CIRCULAR



(*) A study for a 4 IPs FCC-ee has been requested by the CERN management and is foreseen to be conducted this year (2019)