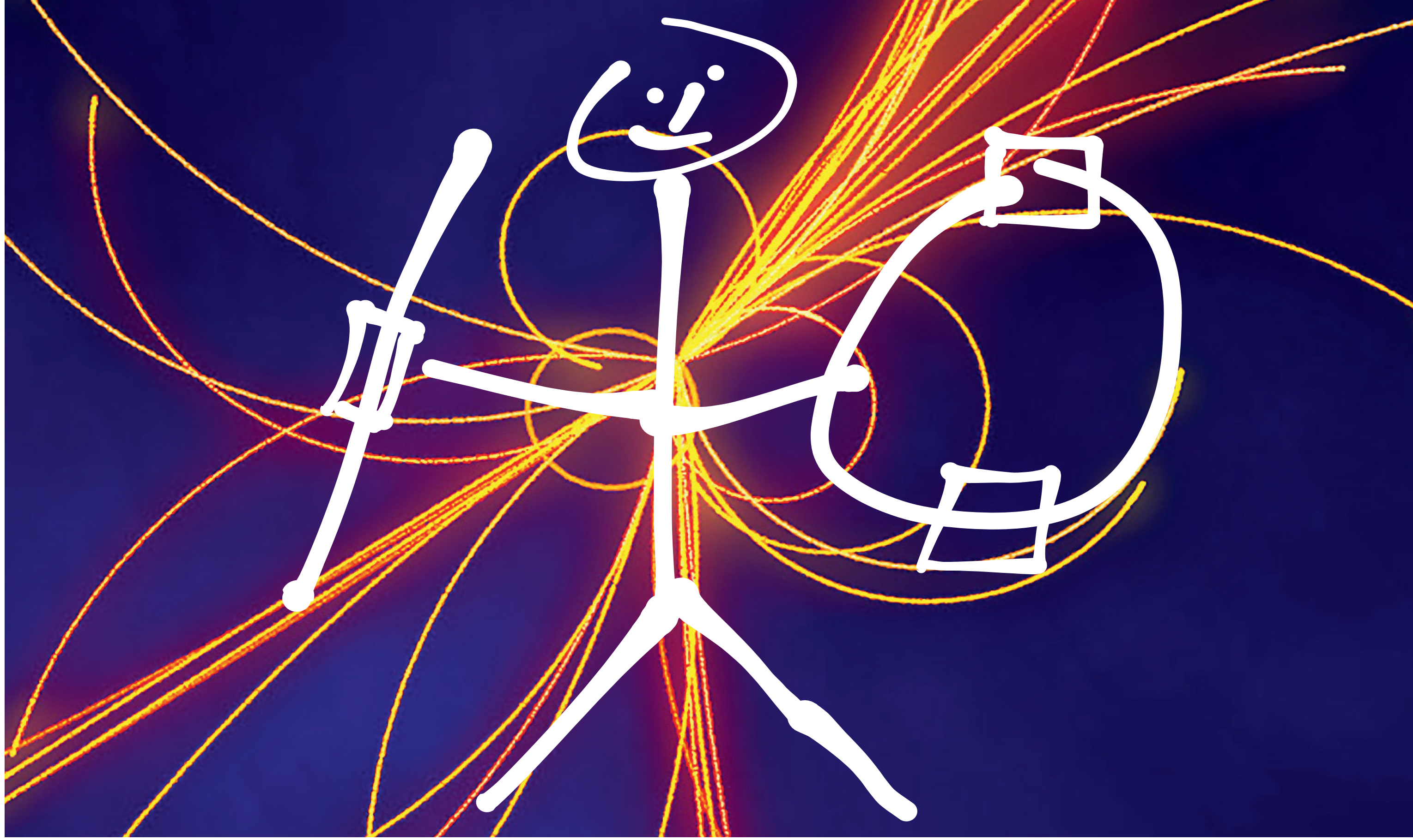
Status of e+e- Higgs Factory Projects

Physics, Technologies, Resources, Open Questions & Challenges



Jenny List (DESY)

2nd ECFA Workshop on HIggs / top / ew Factories
11-13 October 2023
Paestum

HELMHOLTZ

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

FTX

DESY.

Outline

Today's menu

- **Overview**
    - Higgs factories, physics, timelines, challenges
- **Selected Recent Developments**
    - SCRF, Klystrons, ITN
    - polarization, run plans
- **Sustainability**
    - construction & operation
- **Conclusions**

Many thanks to all who contributed material!
(with and without being asked ;)

Recent workshops

Much more going on than can possibly be covered in a 25' talk

- **Linear Collider Workshop 2023**
  - 15-19 May 2023, SLAC, US
  - https://indico.slac.stanford.edu/event/7467/
- **FCC Week 2023**
  - 5-9 June 2023, London, UK
  - https://indico.cern.ch/event/1202105/
- **CEPC Workshop 2023**
  - 3-6 July 2023, Edinburgh, UK
  - https://indico.ph.ed.ac.uk/event/259/
- **C3 Workshop**
  - 31 Aug - 1 Sep, U Cornell, US
  - https://indico.classe.cornell.edu/event/2283/

An e^+e^- Higgs factory is the highest-priority next collider

A clear message from EPPSU — and Snowmass

=> e+e- Higgs factory as highest priority next collider re-emphasized in the Snowmass process in the US (2022)

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

https://europeanstrategyupdate.web.cern.ch/welcome

3

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

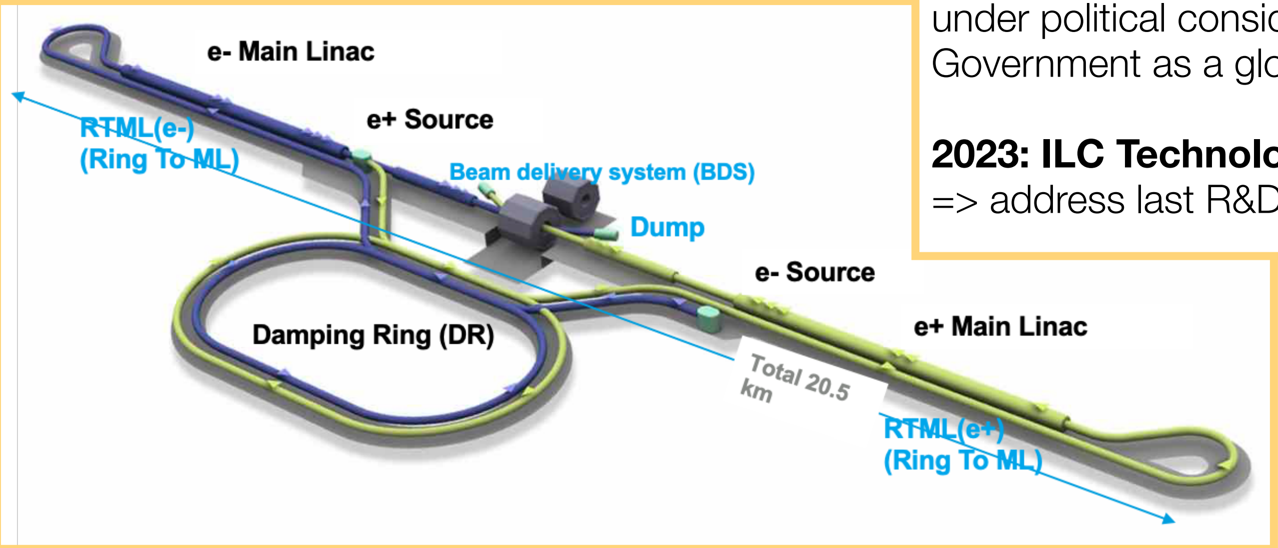
• *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*

• *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

The key contenders

Status overview



ILC: e+e- @ 90, 160**, 250,** 350**, 500 GeV, 1TeV**
TDR in **2012; 2017:** staged start at **250 GeV**
Superconducting RF

under political consideration by Japanese Government as a global project

2023: ILC Technology Network
=> address last R&D questions on accelerator

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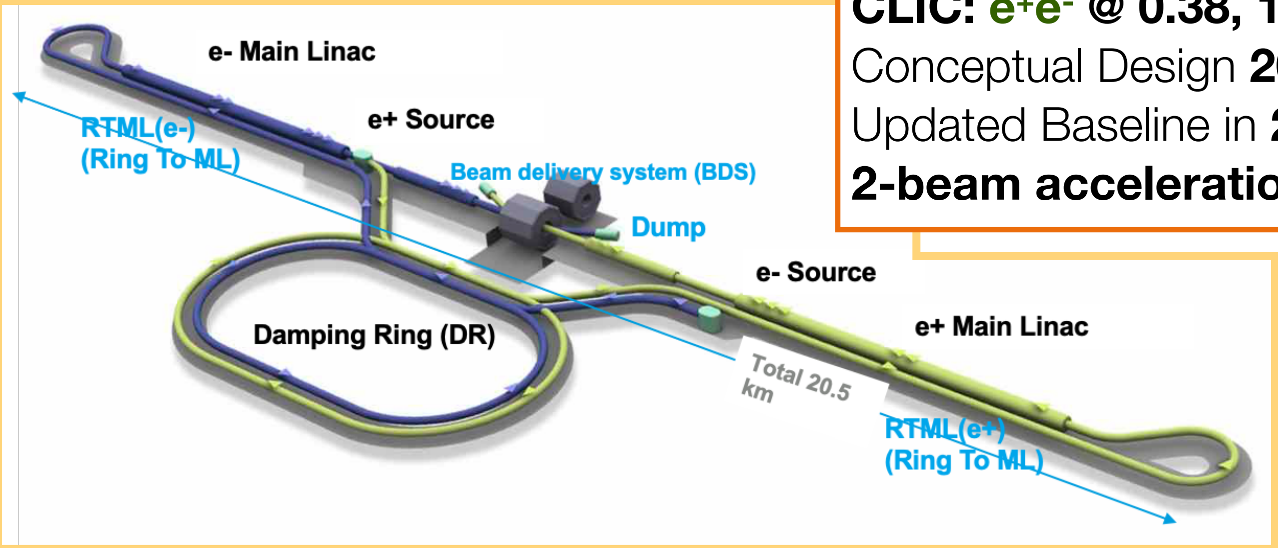
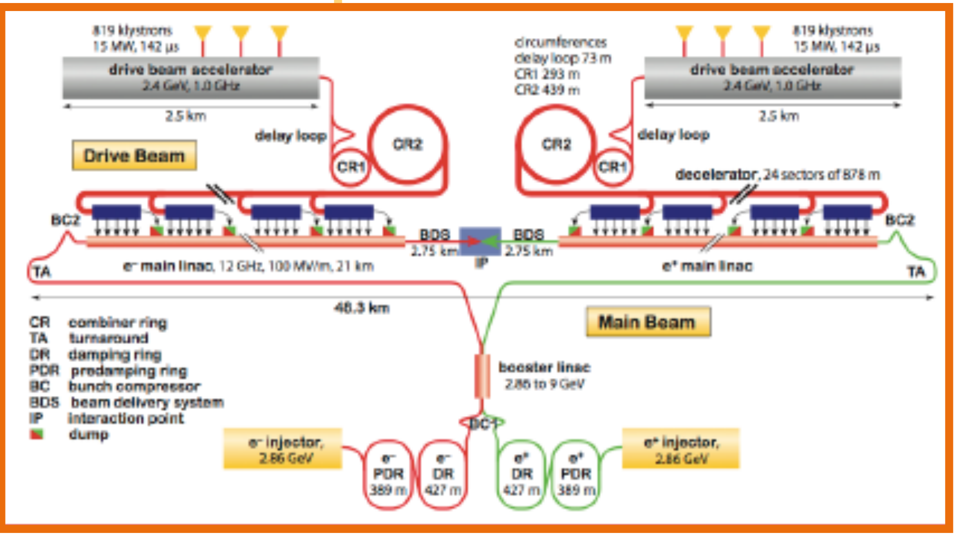


CLIC: e+e- @ 0.38, 1.4, 3 TeV
Conceptual Design **2013**
Updated Baseline in **2017**
2-beam acceleration



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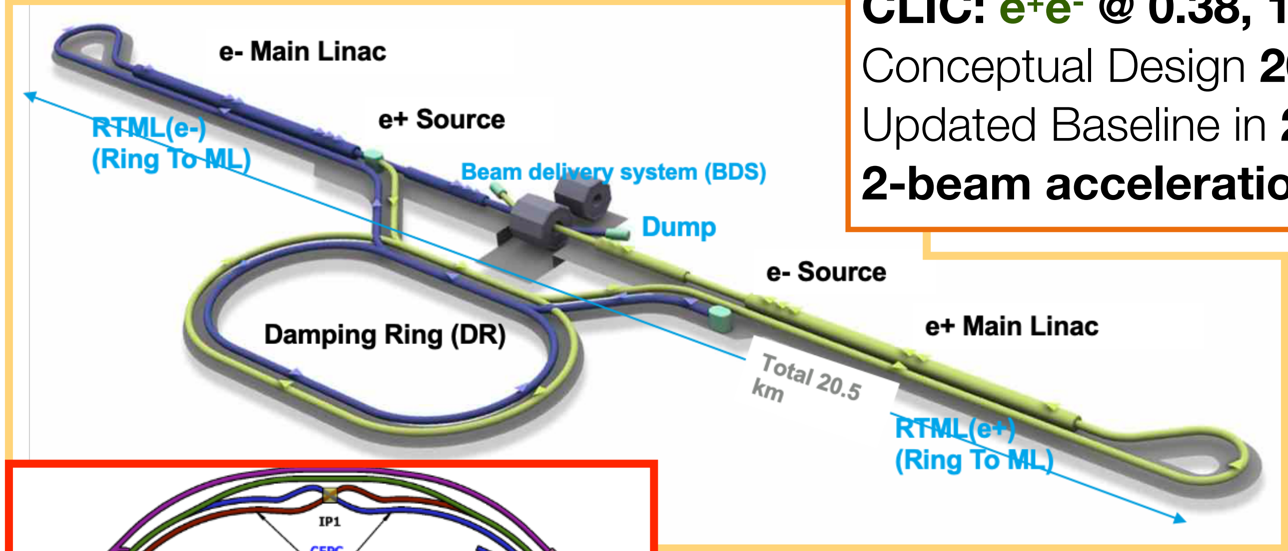

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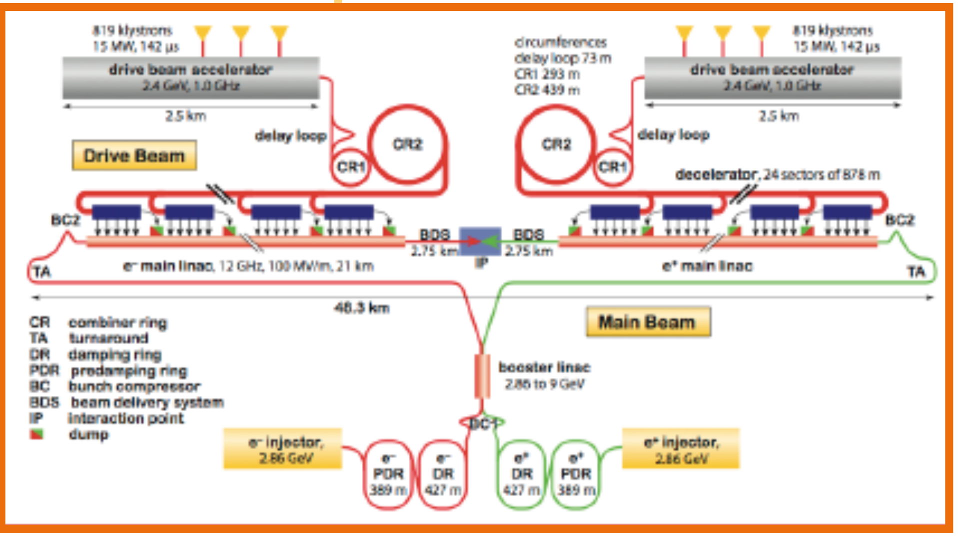

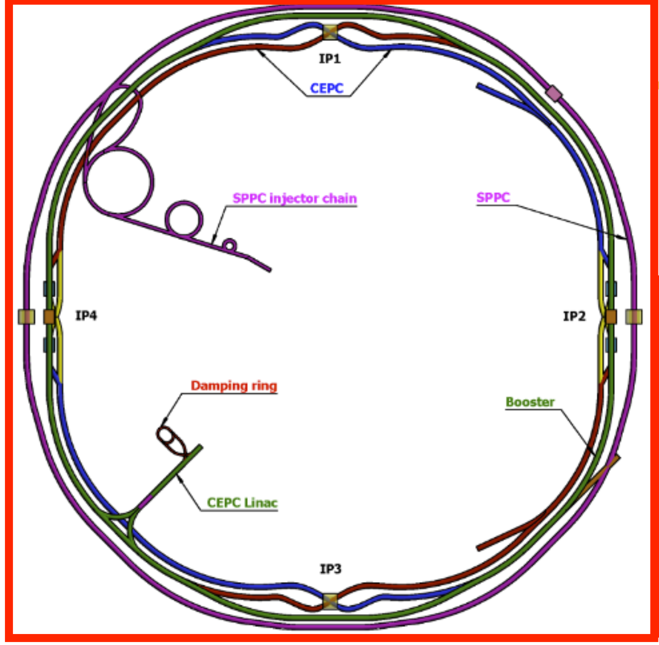

CEPC: e+e- @ 90-365 GeV

CDR published 2018
TDR in preparation, incl. cost review (Sep)
aiming for approval in next 5-year-plan (2025)
ranked 1st in HEP preselection

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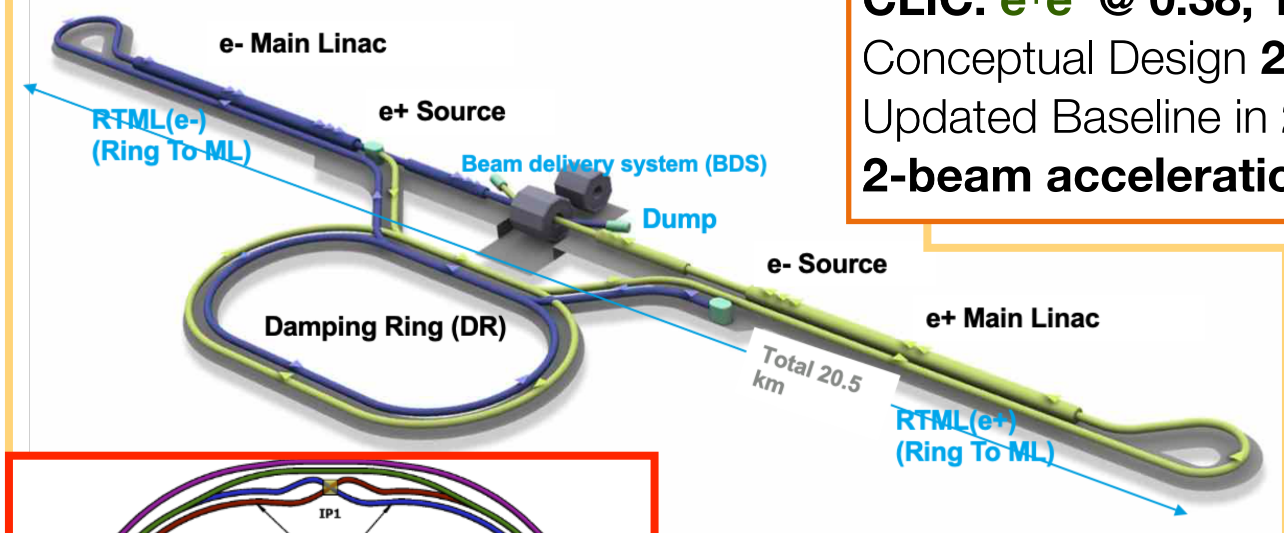

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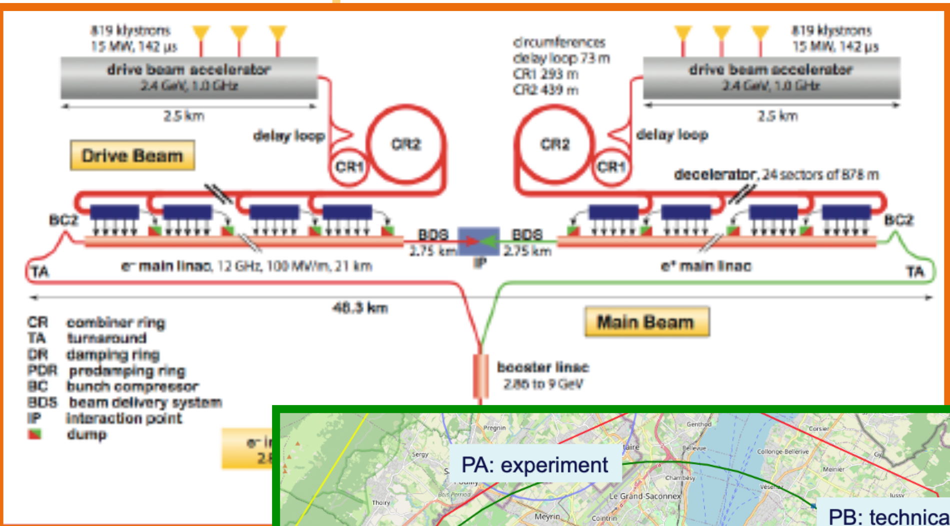

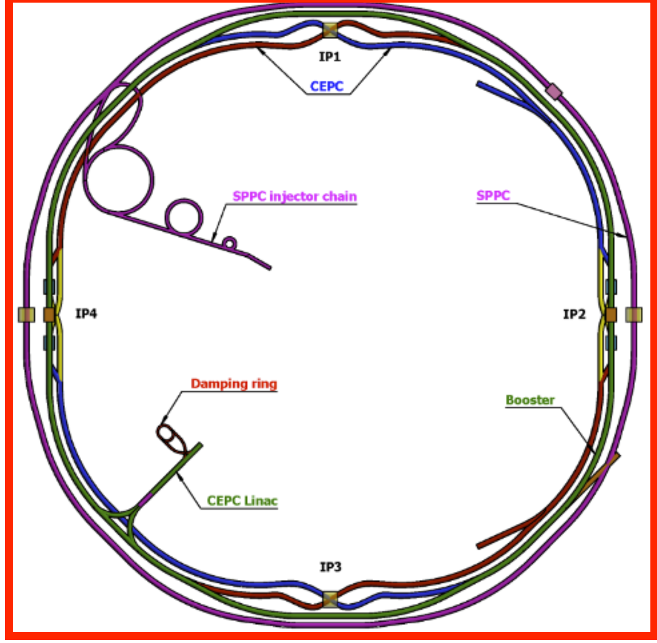

CEPC

CDR p

TDR i

aimin

ranke

FCC-ee e+e- @ 90-365 GeV
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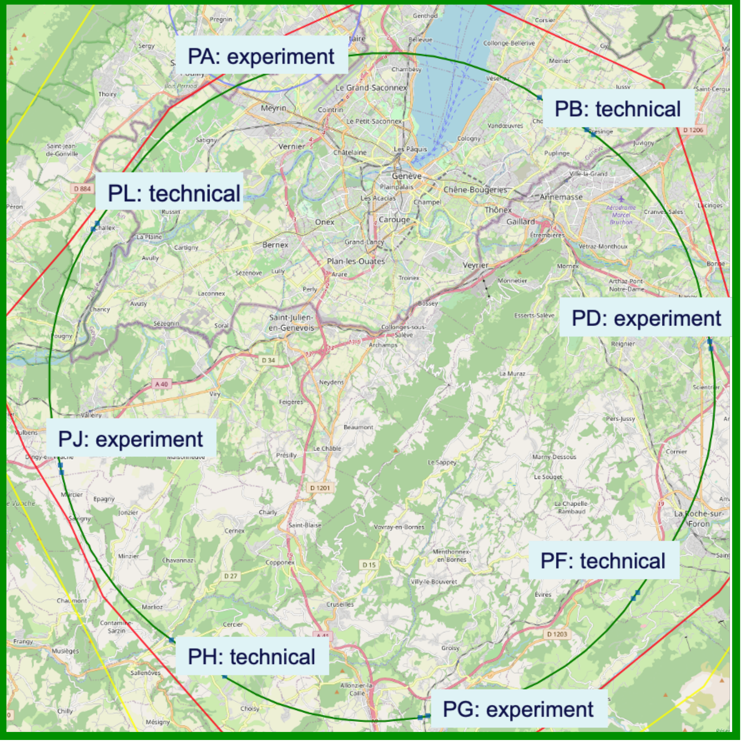
Since 2021: FCC Feasibility Study
(implementation scenario, environmental analysis, high-field magnets, ..)
=> demonstrate feasibility of FCC-ee by 2025

Special Council Session in Feb 2024



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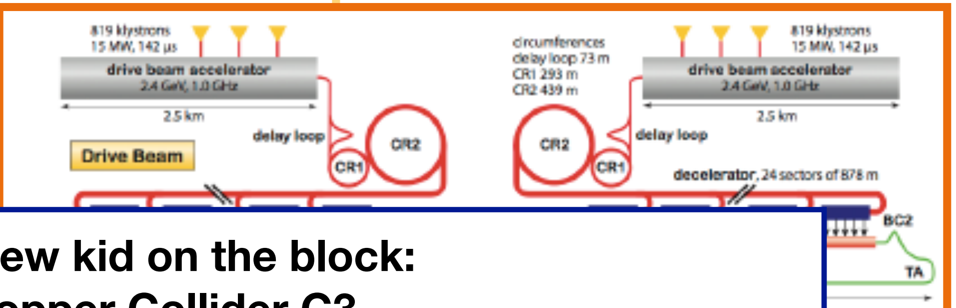
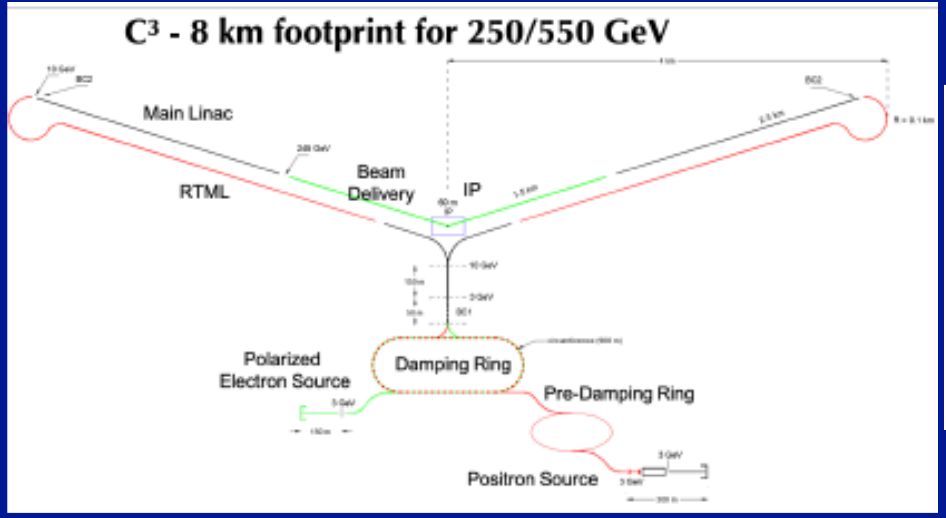
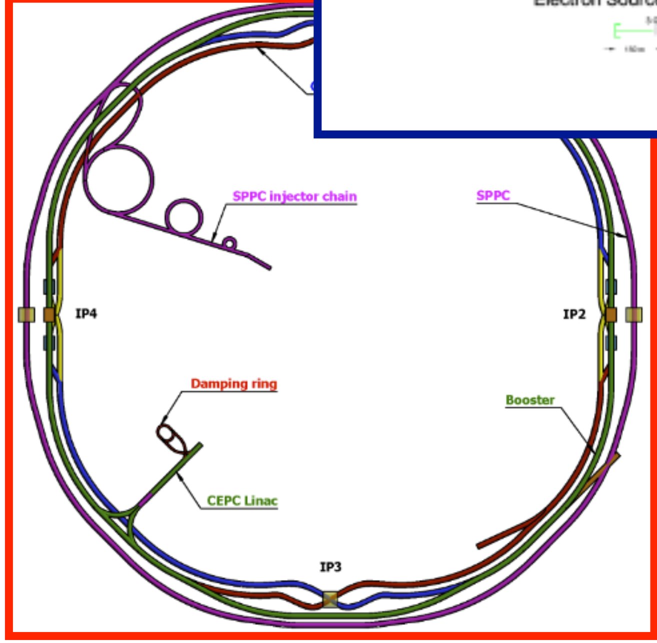




...and the new kid on the block:
the Cool Copper Collider C3,
first proposed 2018, arXiv:1807.10195

4km, time structure compatible with ILC detectors
hoping for support by P5 for 5-year R&D program



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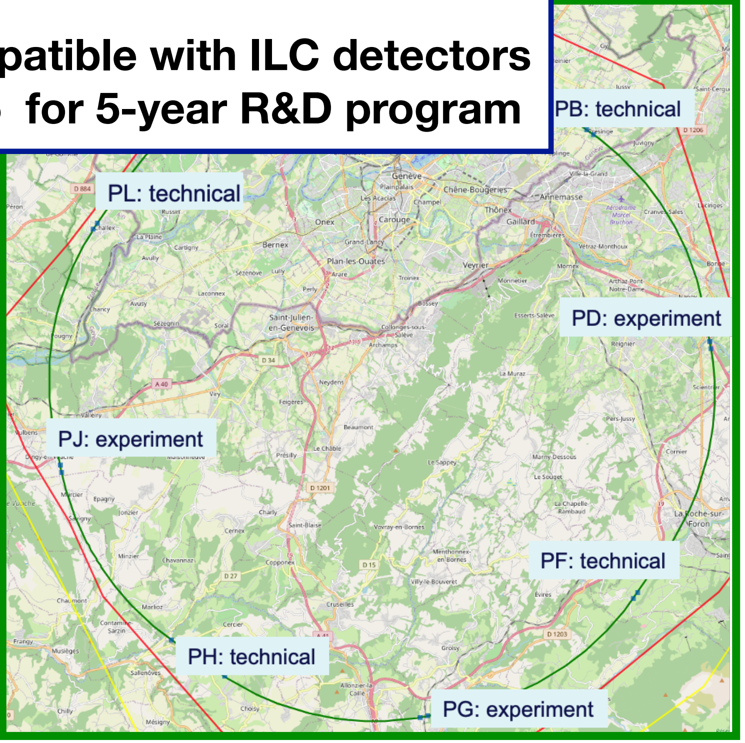

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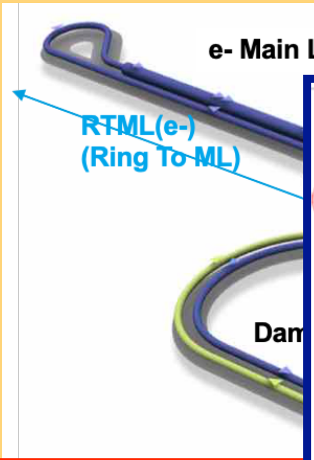

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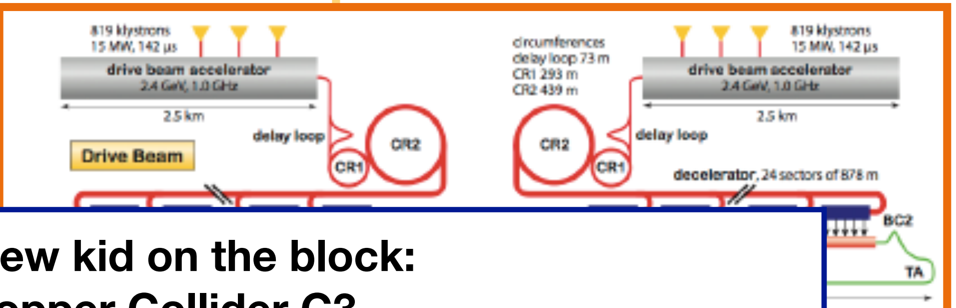

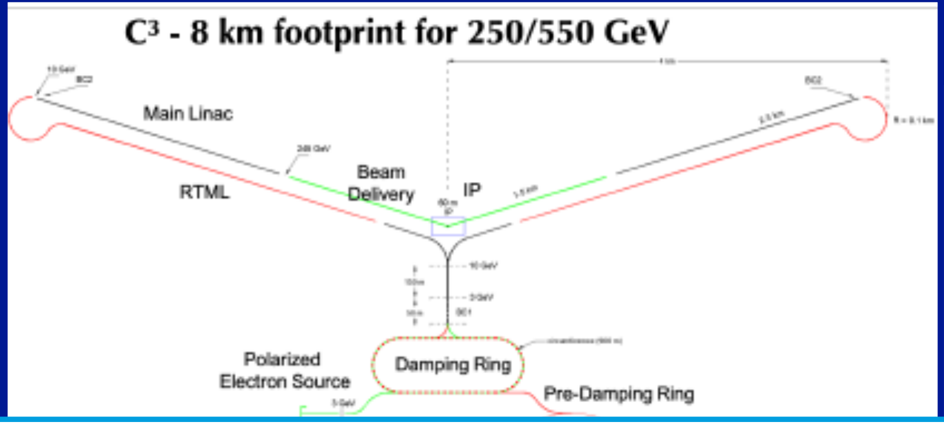

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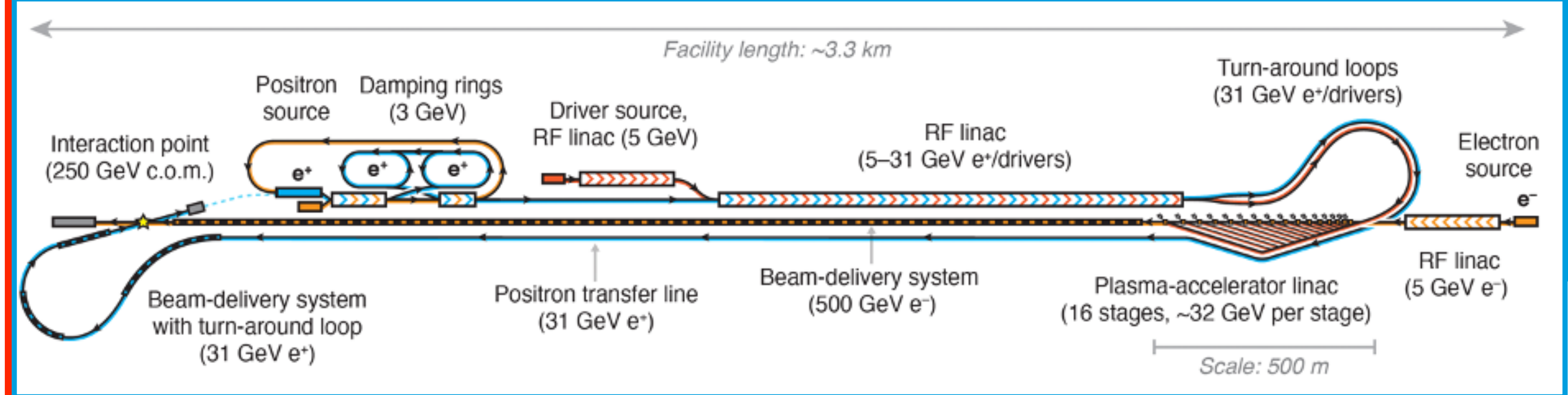
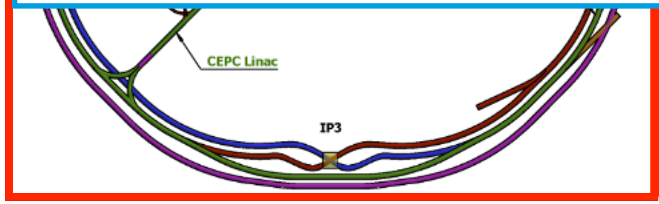


and an even newer proposal: Hybrid Asymmetric Linear Higgs Factory HALHF, arxiv:2303.10150

some first studies on detector / physics estimated ~10 years of R&D for PWFA part



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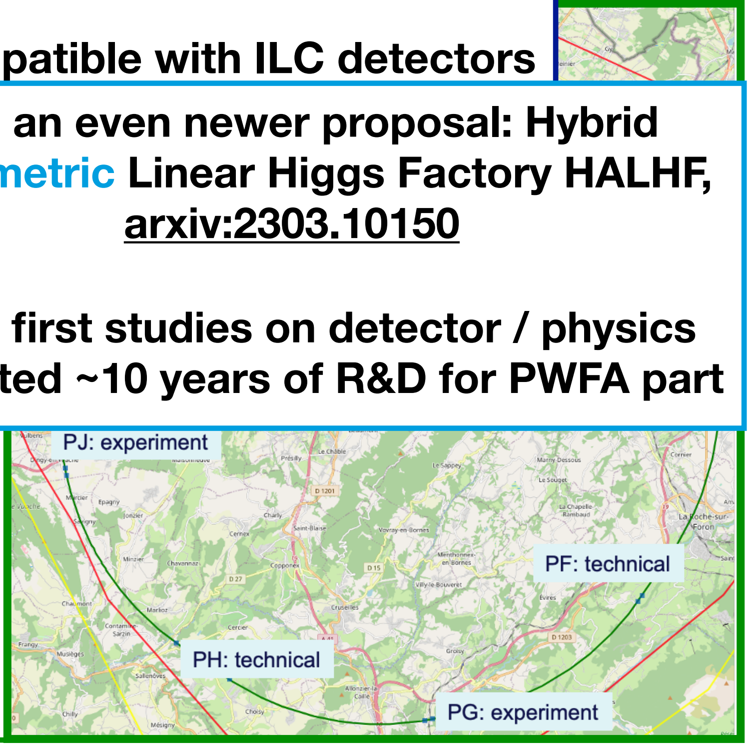

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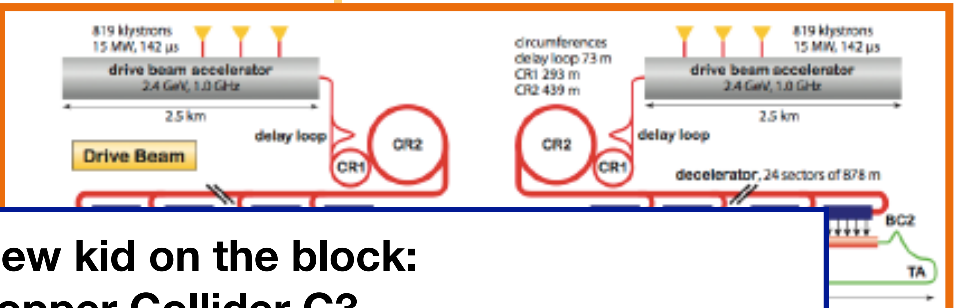

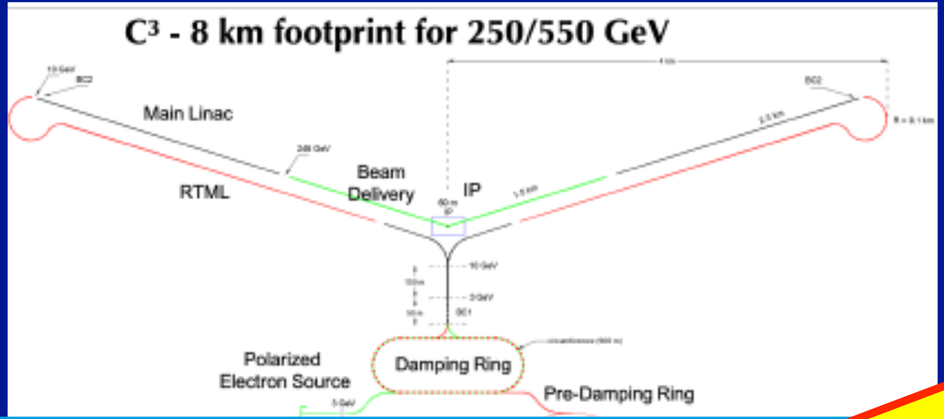

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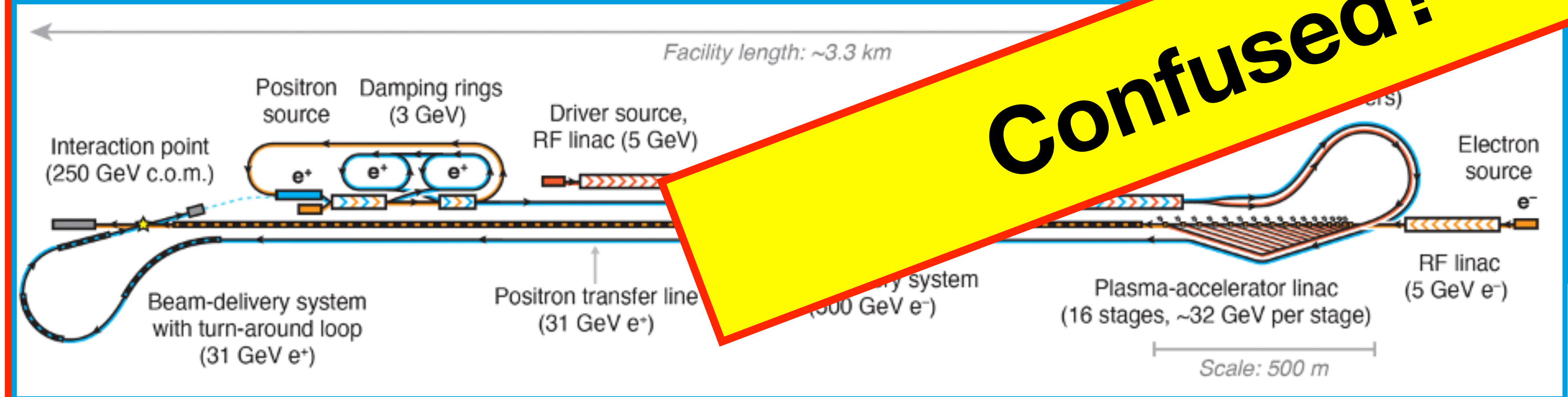
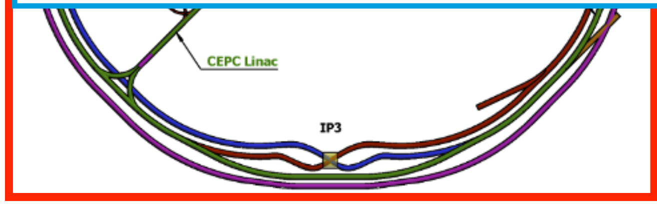


Confused?



TDR i...
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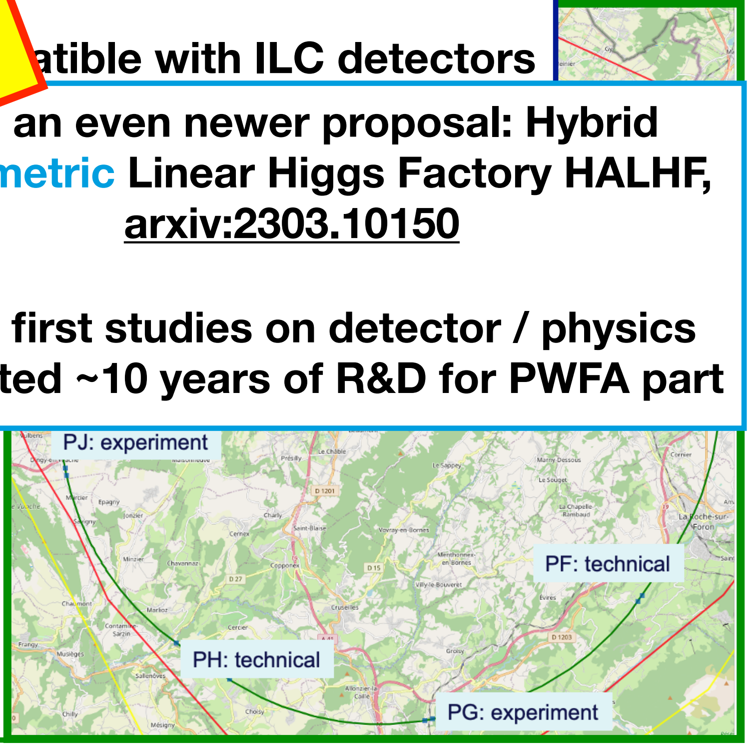
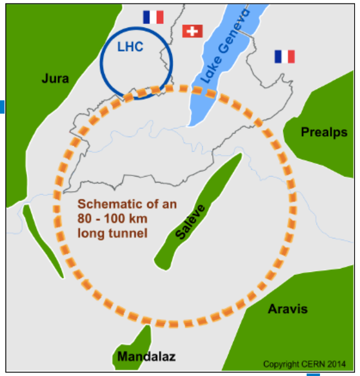


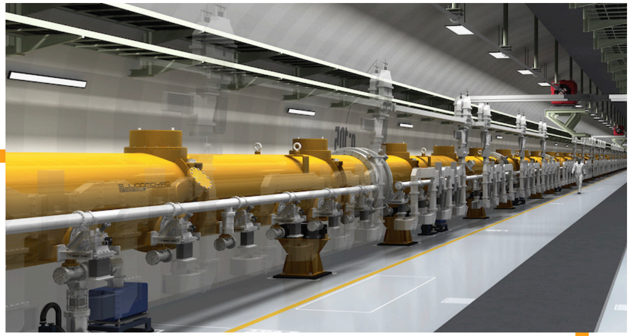
They fall into two classes

Each have their advantages



Circular e+e- Colliders

- FCCee, CEPC
- length 250 GeV: 90…100km
- high luminosity & power efficiency at **low energies**
- **multiple interaction regions**
- very clean: little beamstrahlung etc



Linear Colliders

- ILC, CLIC, C^3, …
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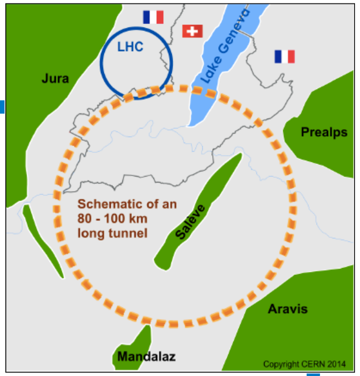

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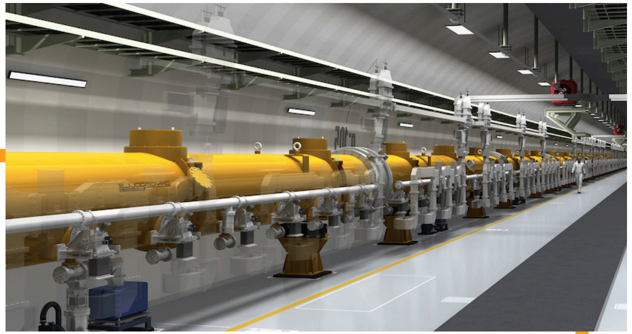
Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge



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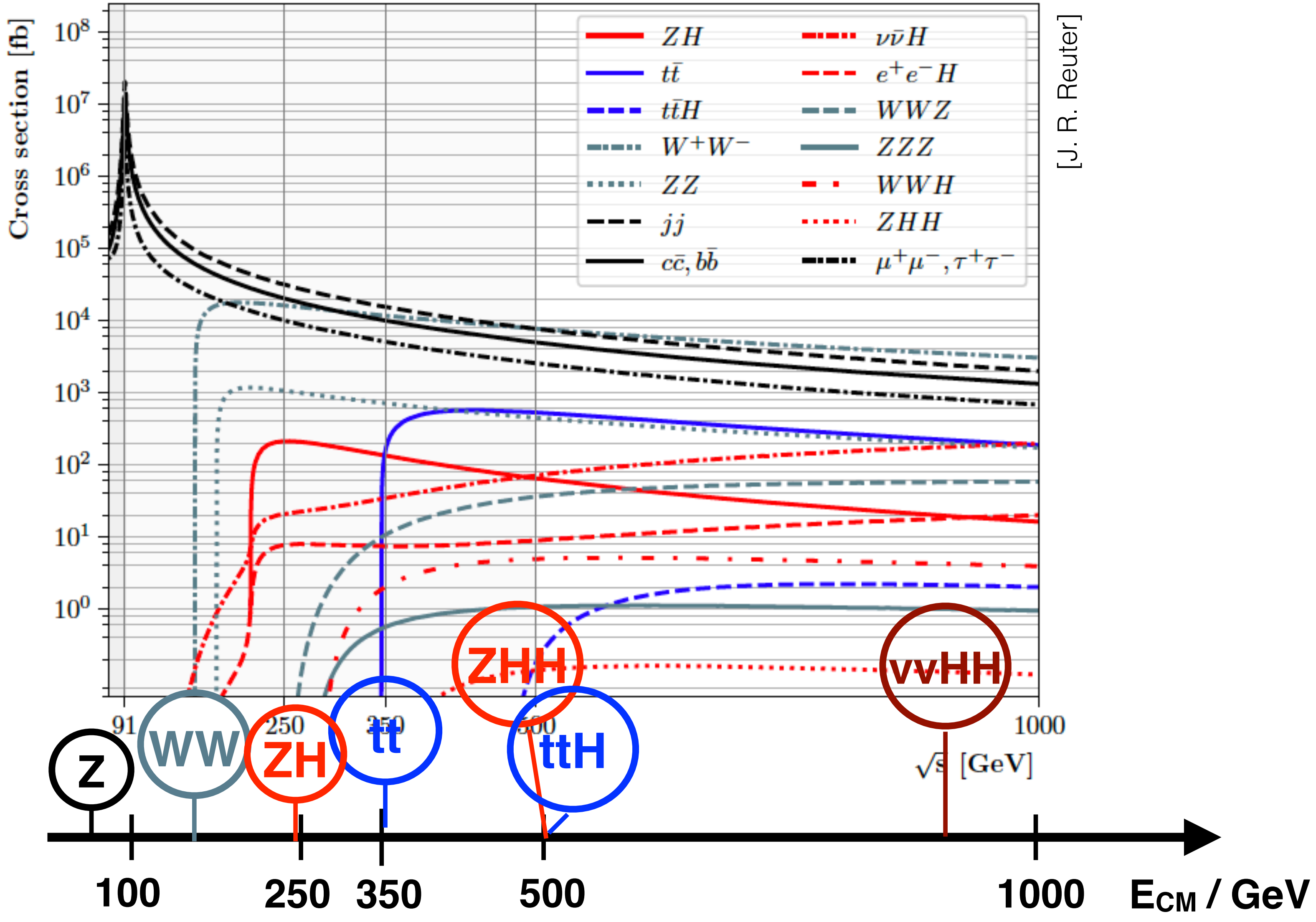
Long-term upgrades: energy extendability

- same technology: by increasing length
- **or by replacing accelerating structures with advanced technologies**
  - RF cavities with high gradient
  - plasma acceleration ?

The key physics at a Higgs Factory

Production rates vs collision energy



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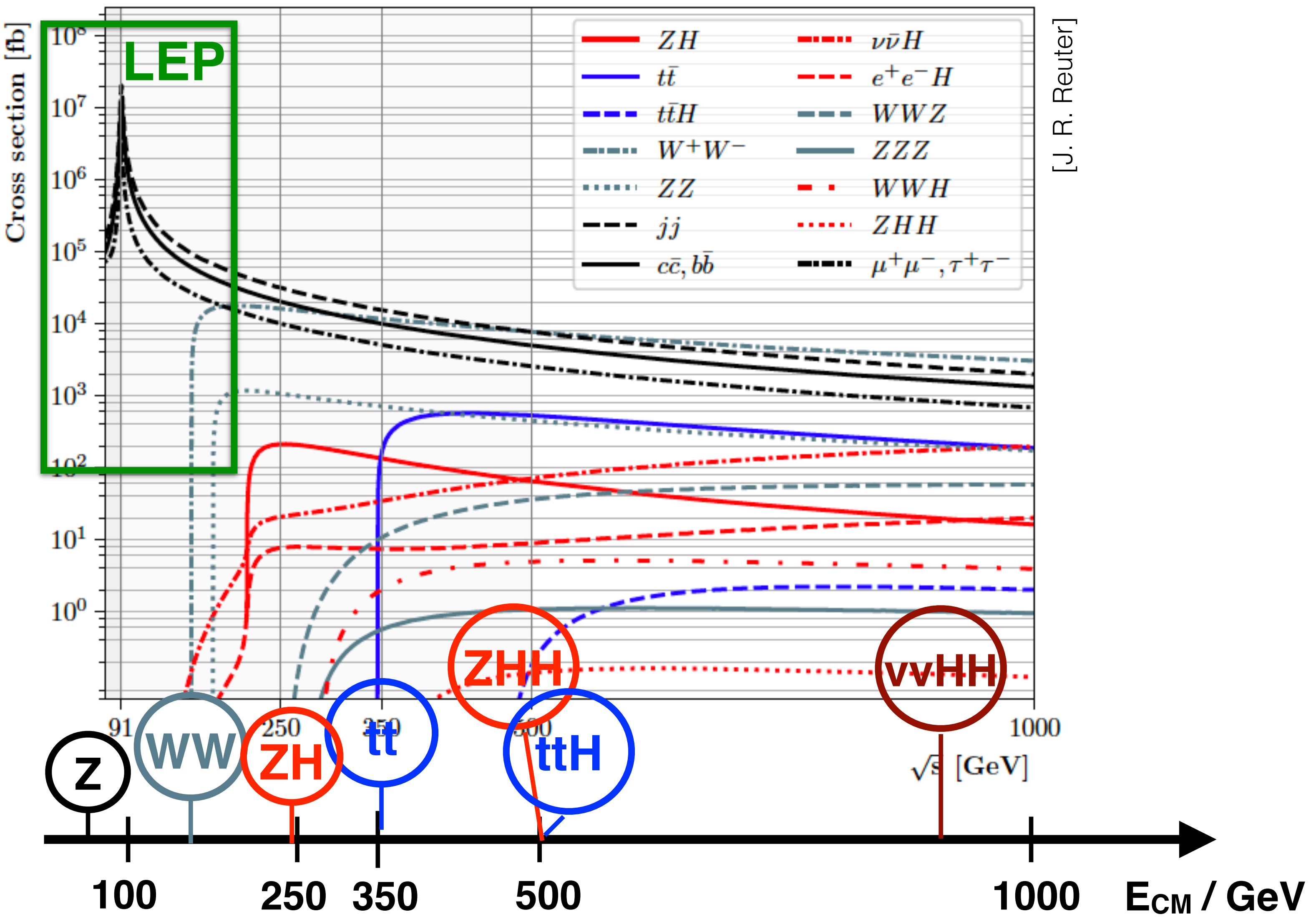

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Production rates vs collision energy

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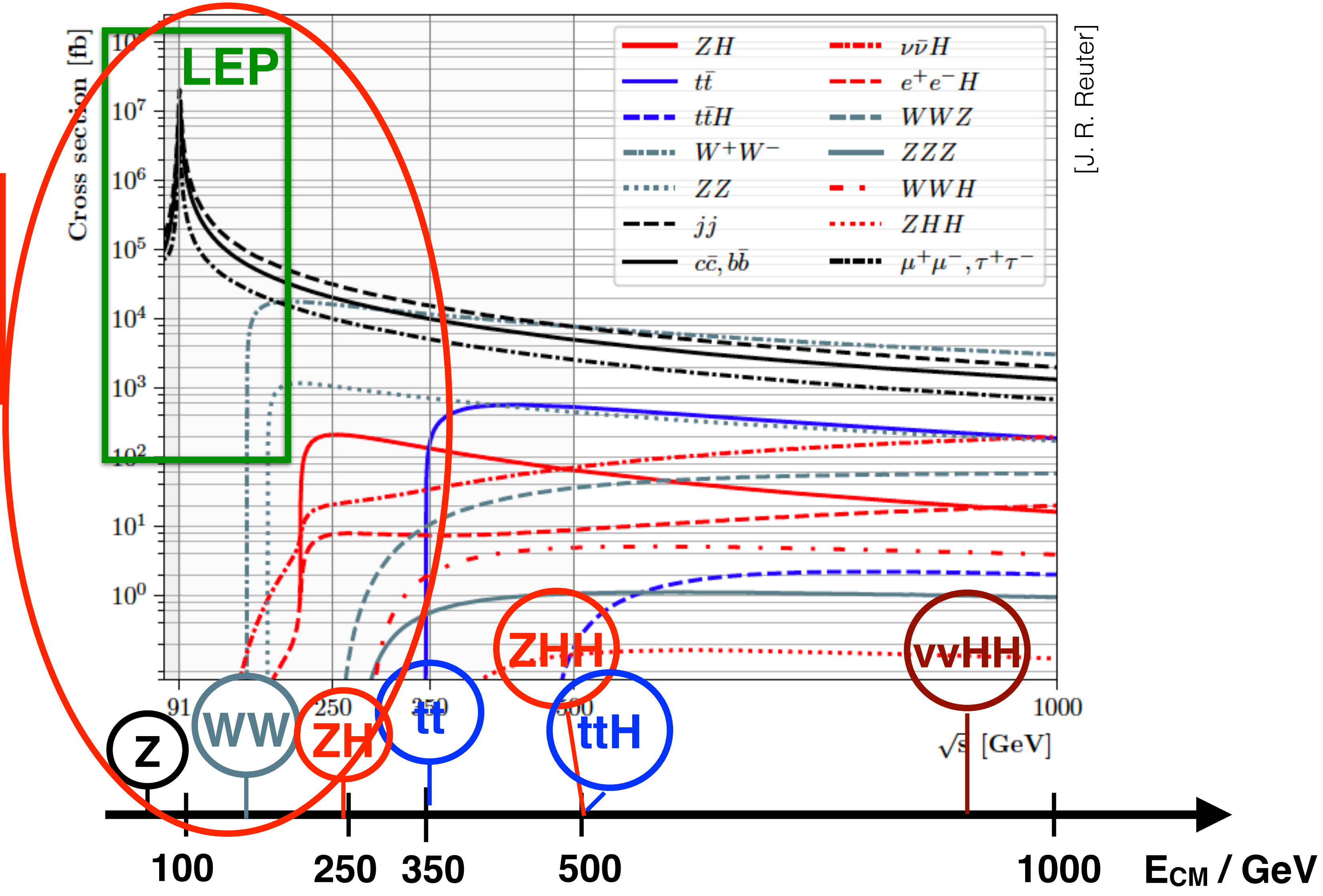

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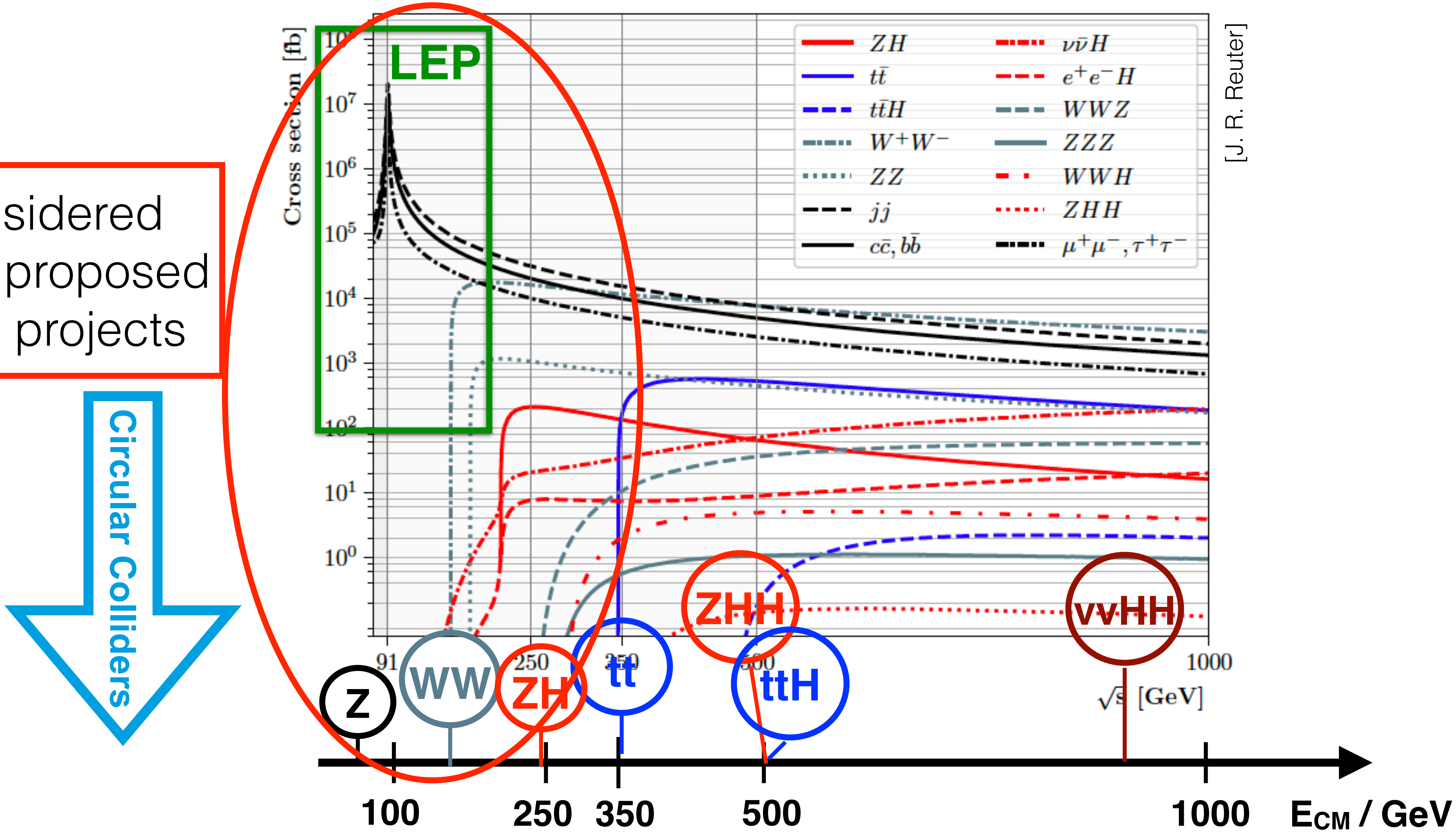

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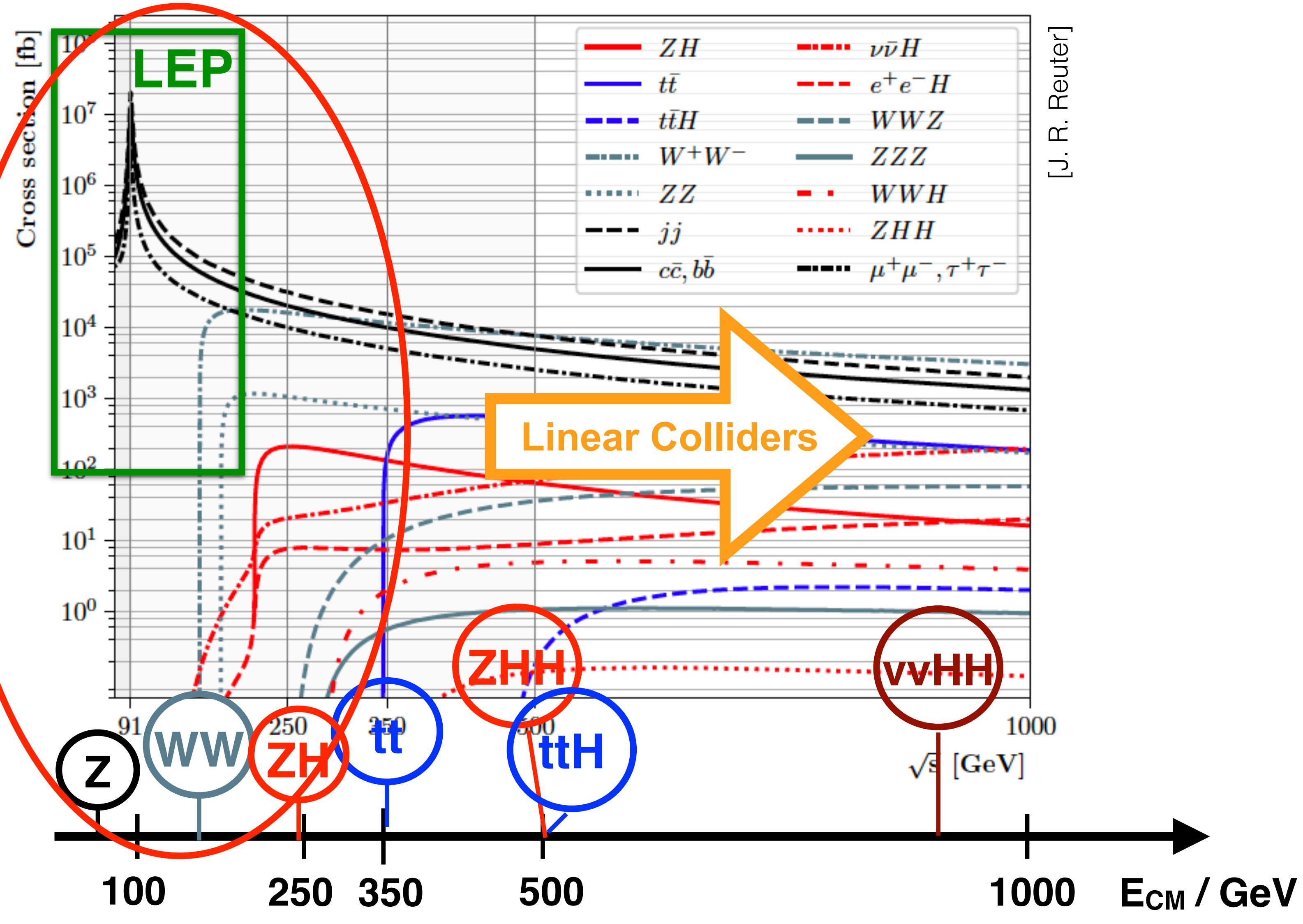

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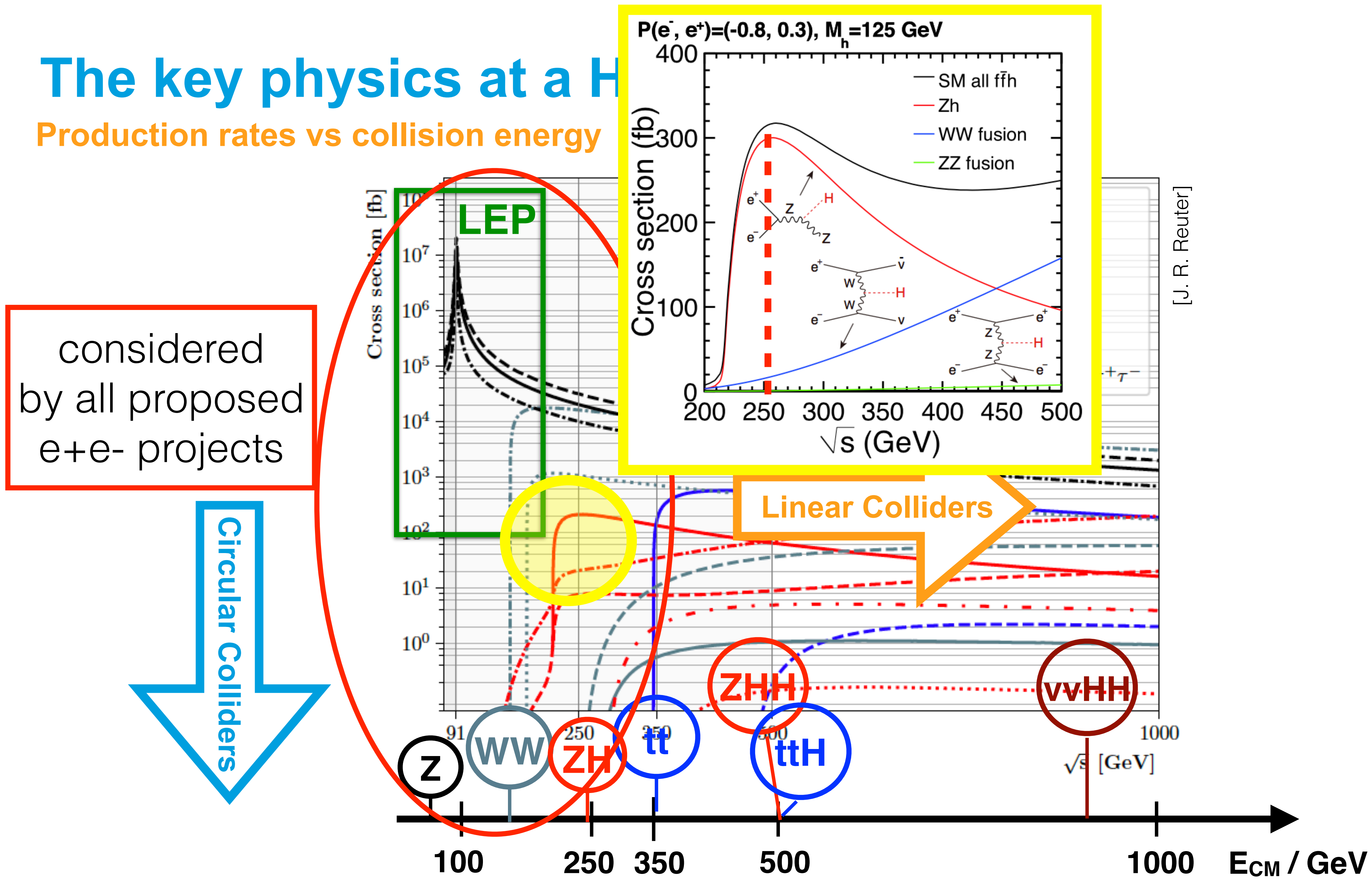

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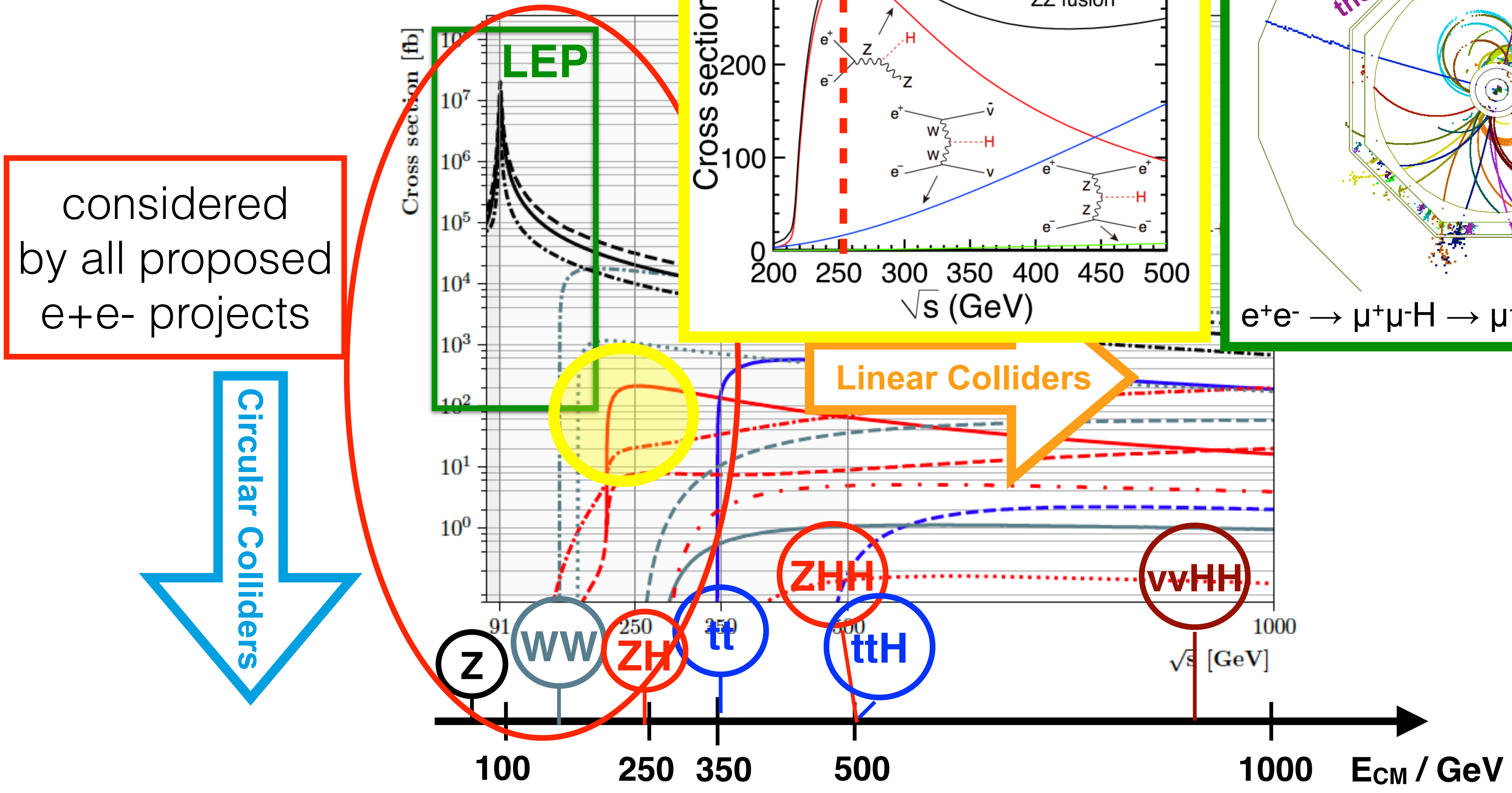

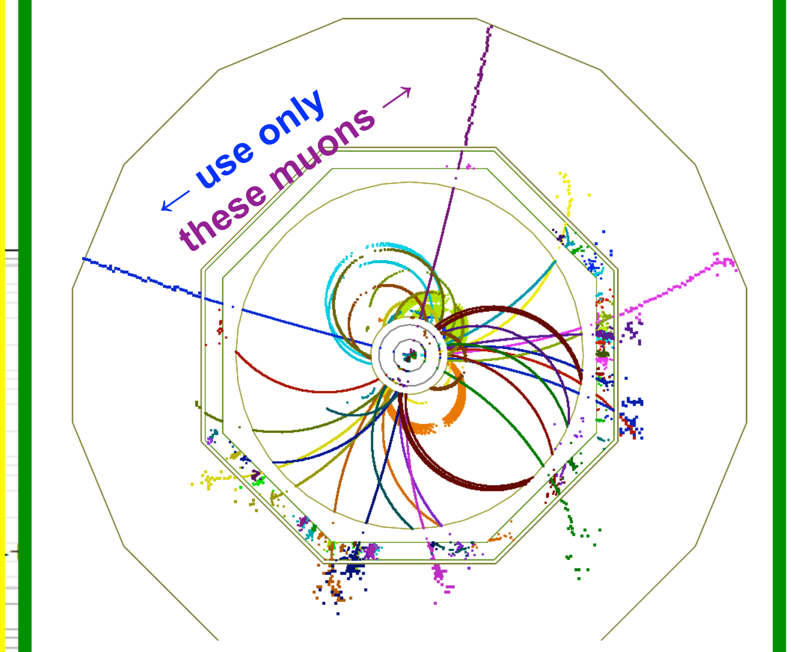

e+e- → μ+μ-H → μ+μ- bb in ILD

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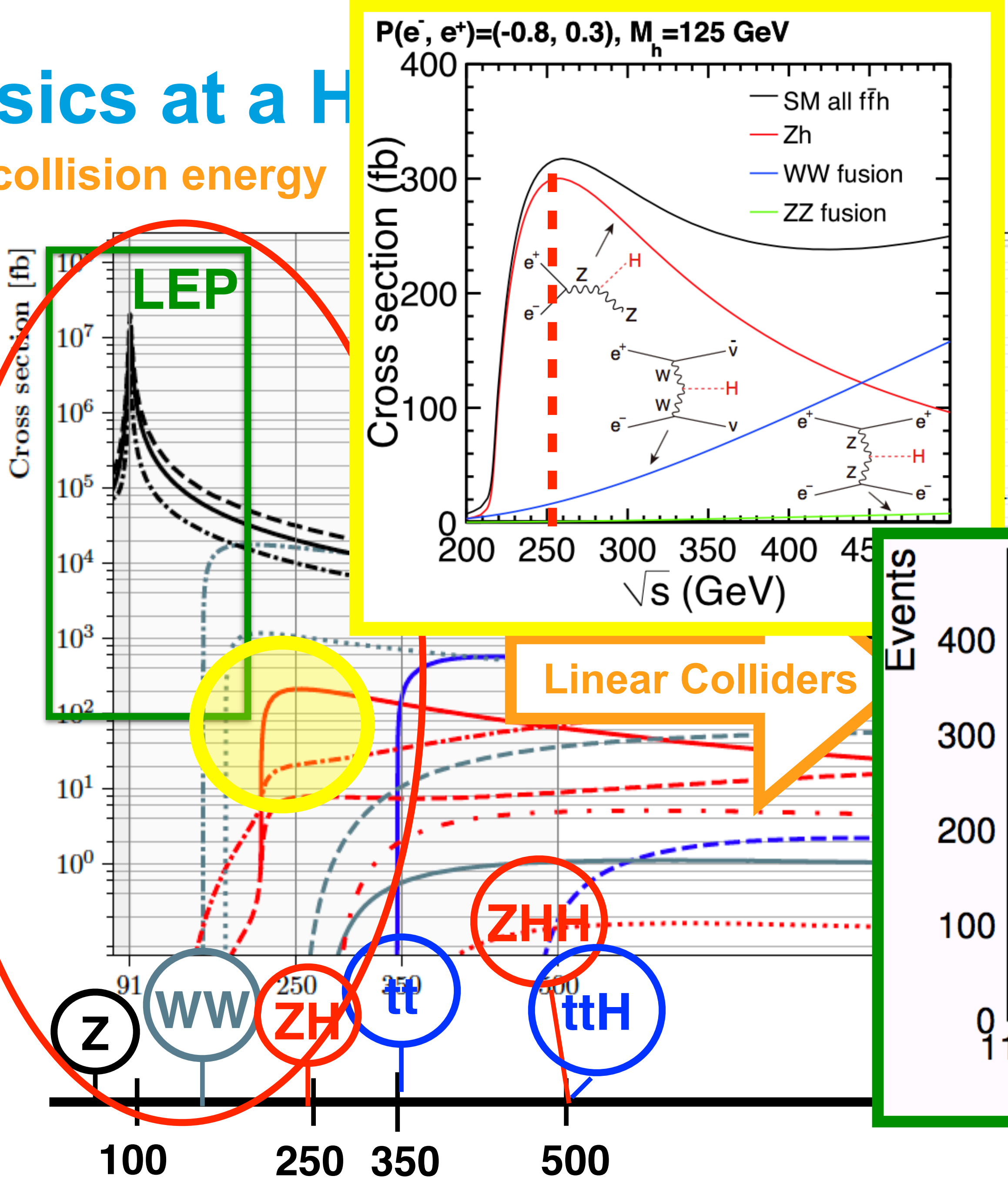

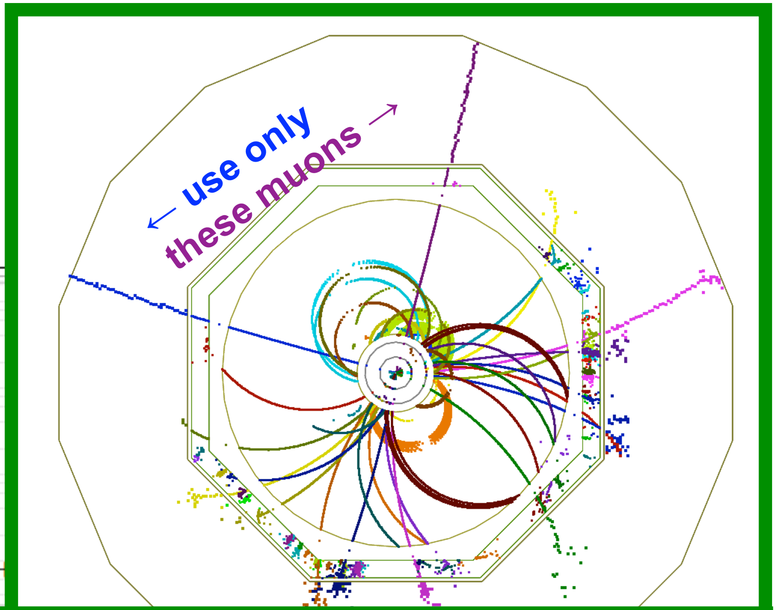

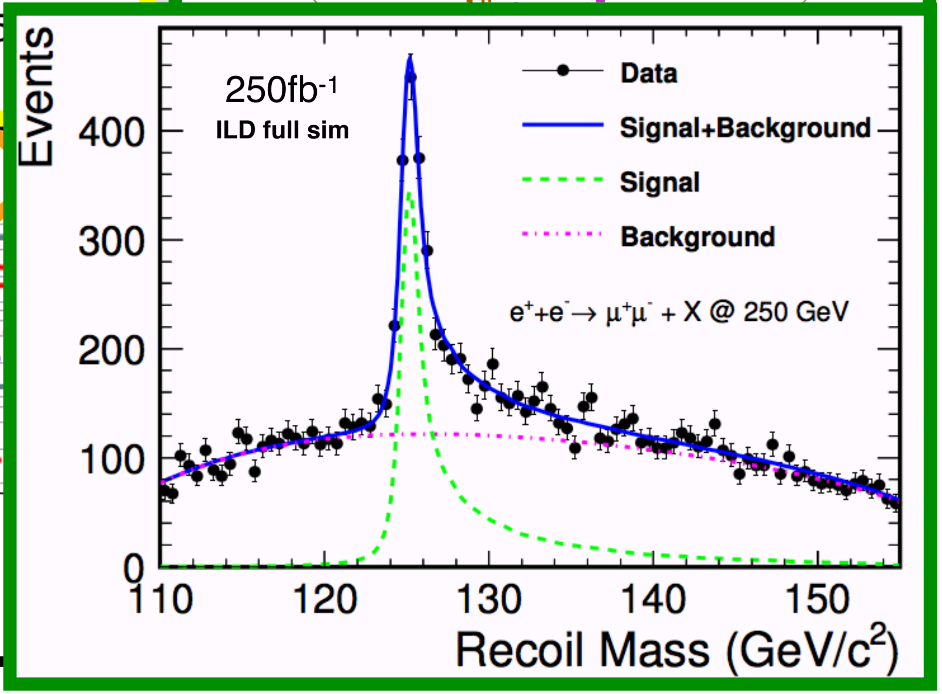

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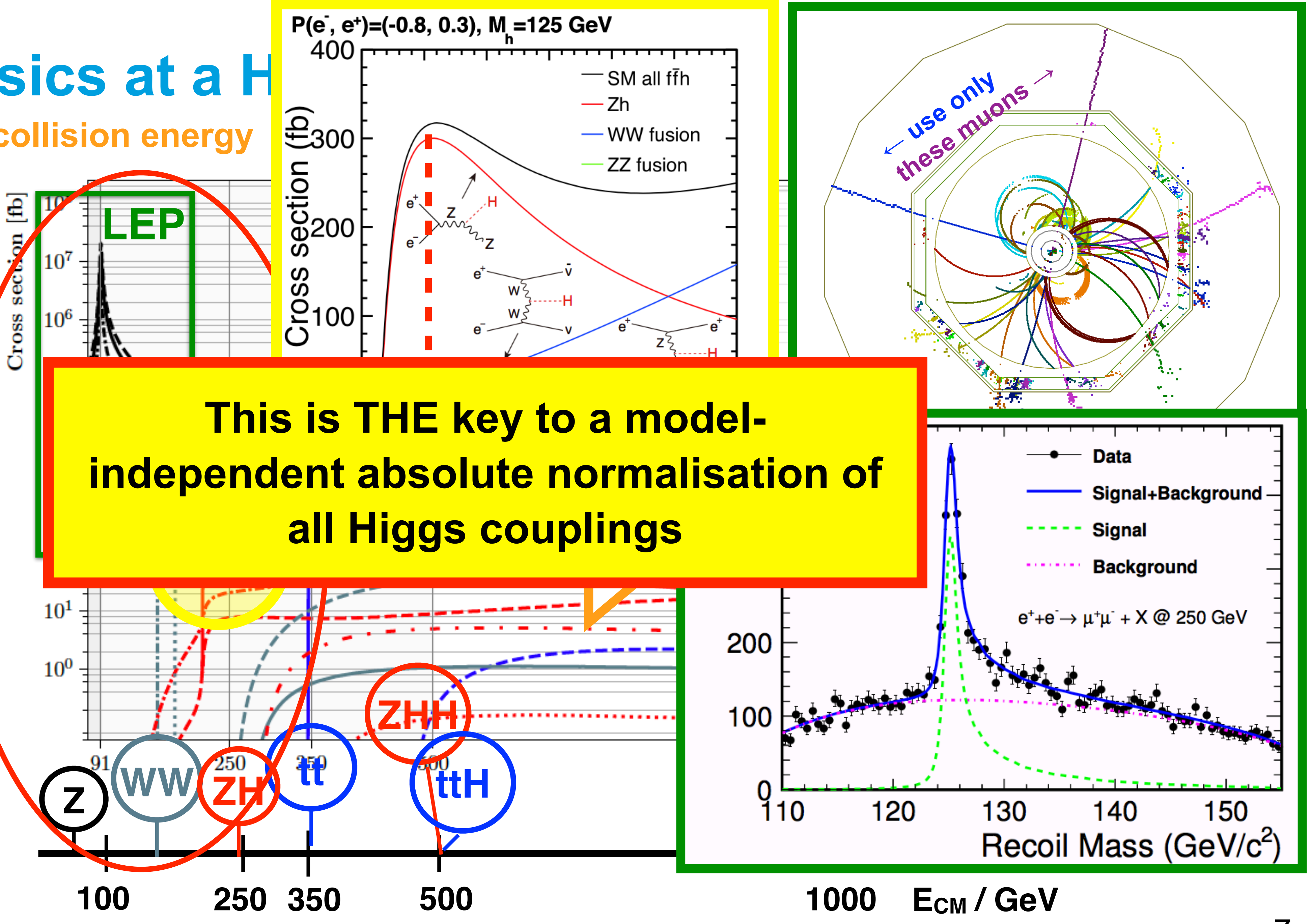
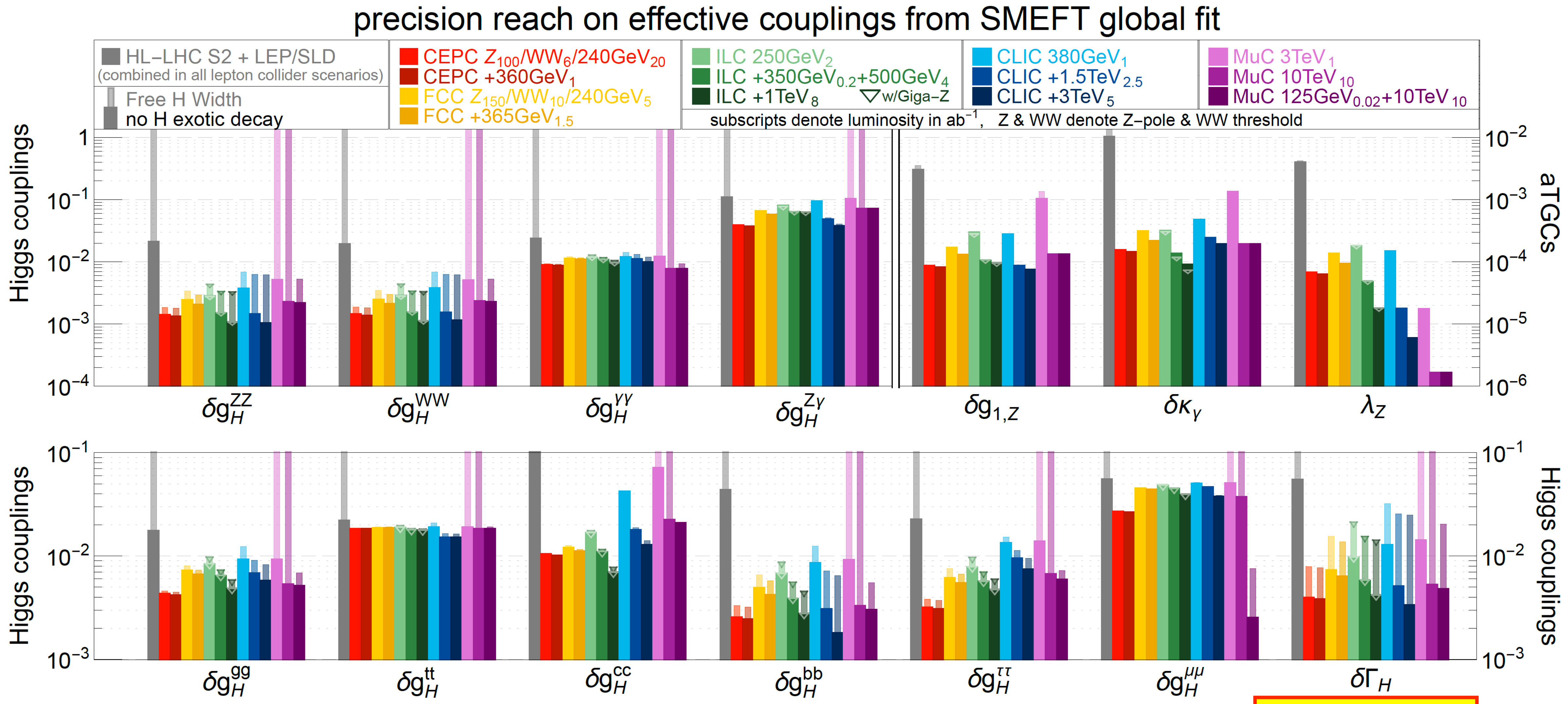


This is THE key to a model-independent absolute normalisation of all Higgs couplings

Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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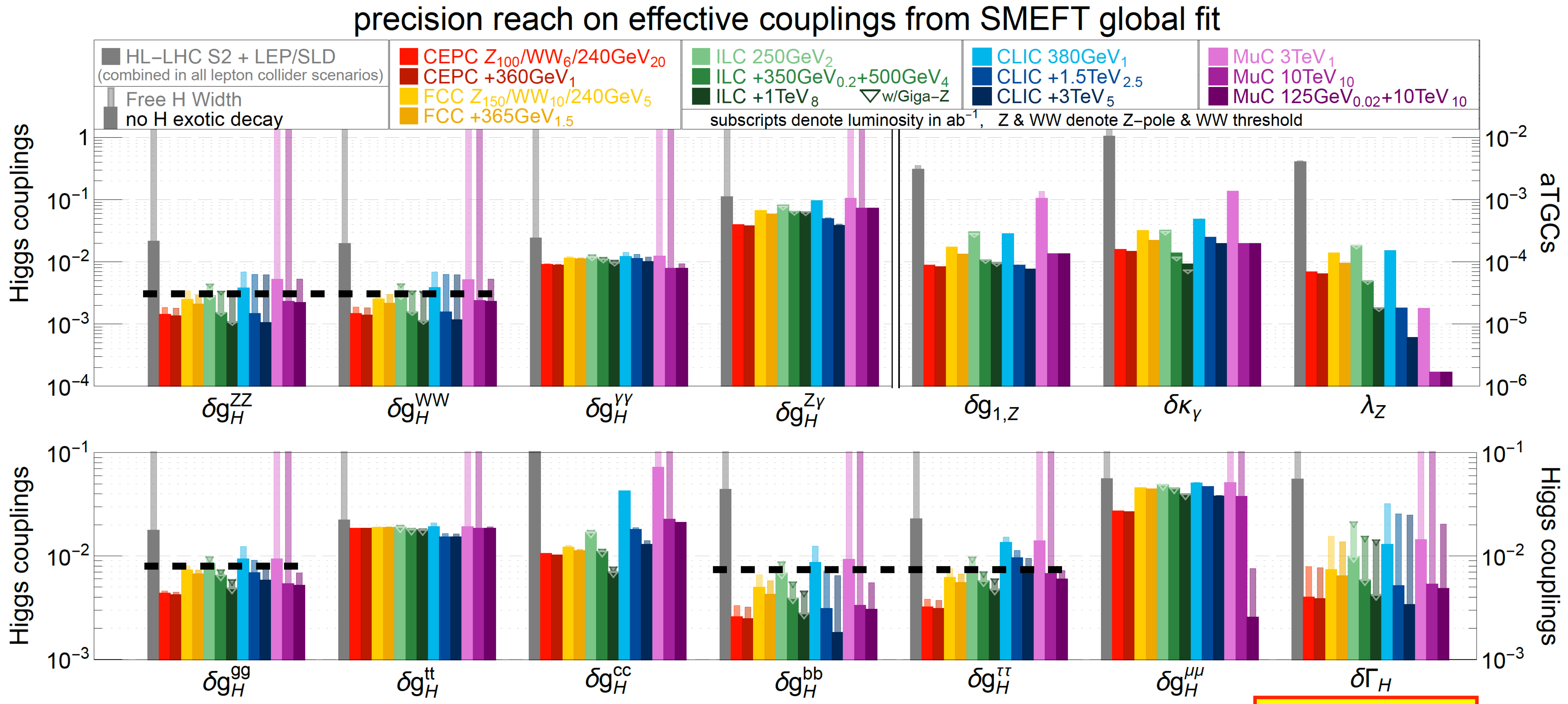

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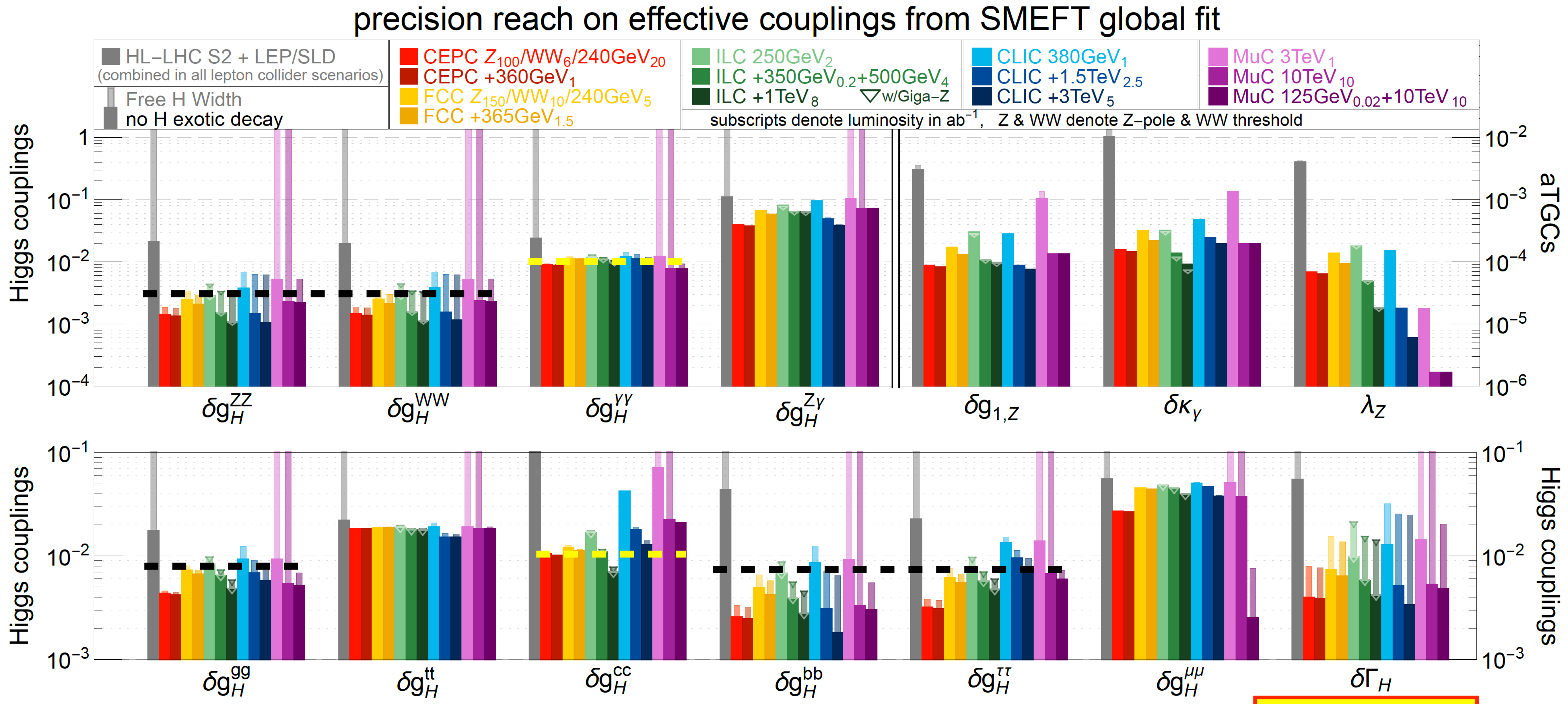

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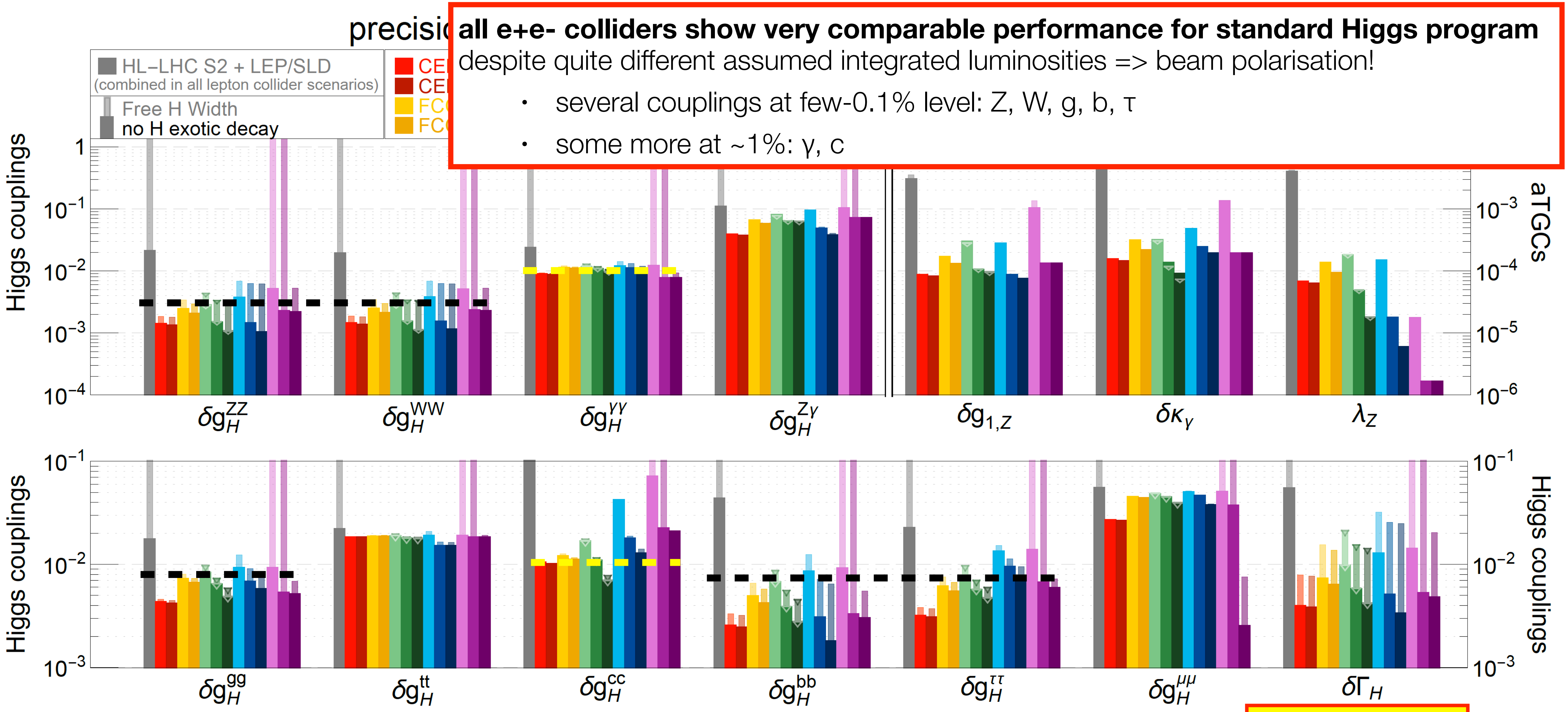

all e+e- colliders show very comparable performance for standard Higgs program

despite quite different assumed integrated luminosities => beam polarisation!

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

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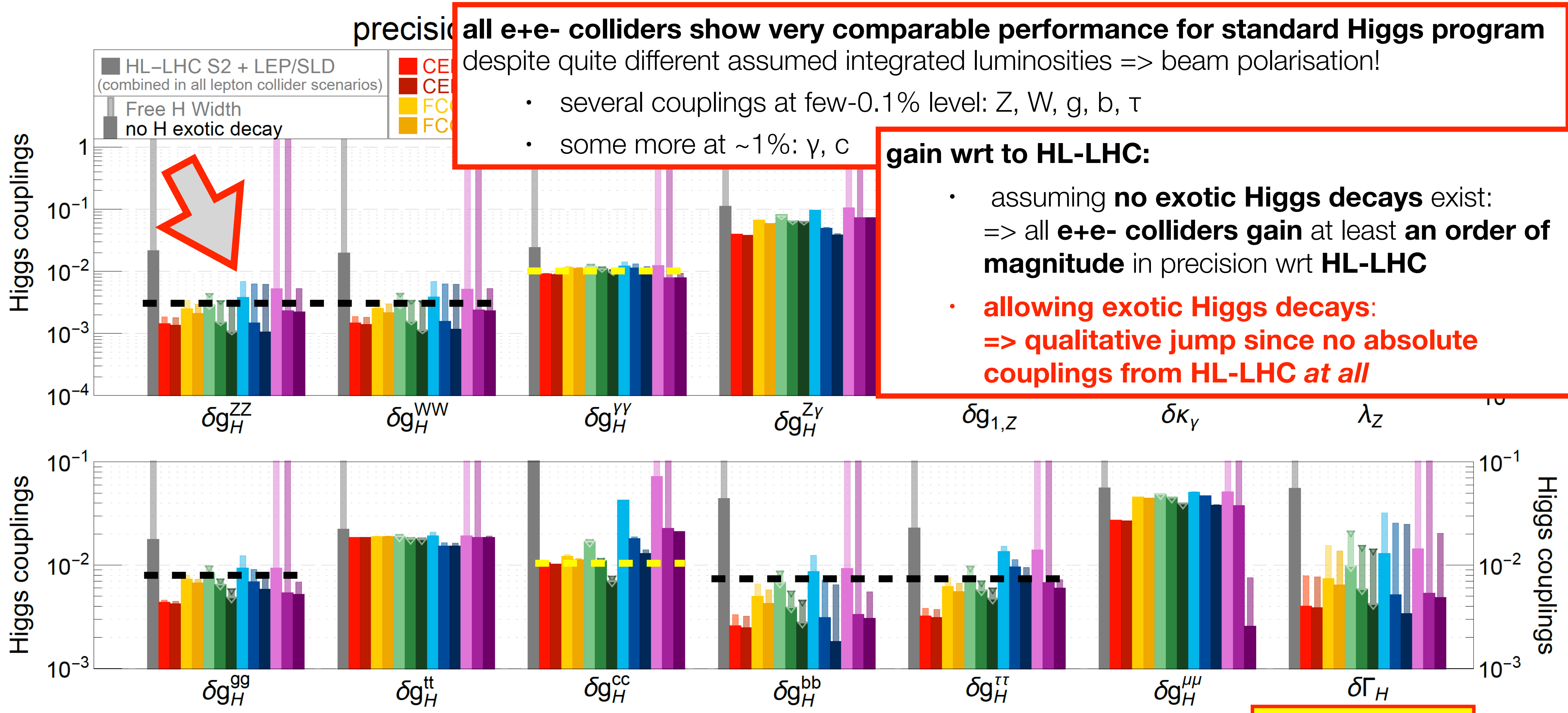

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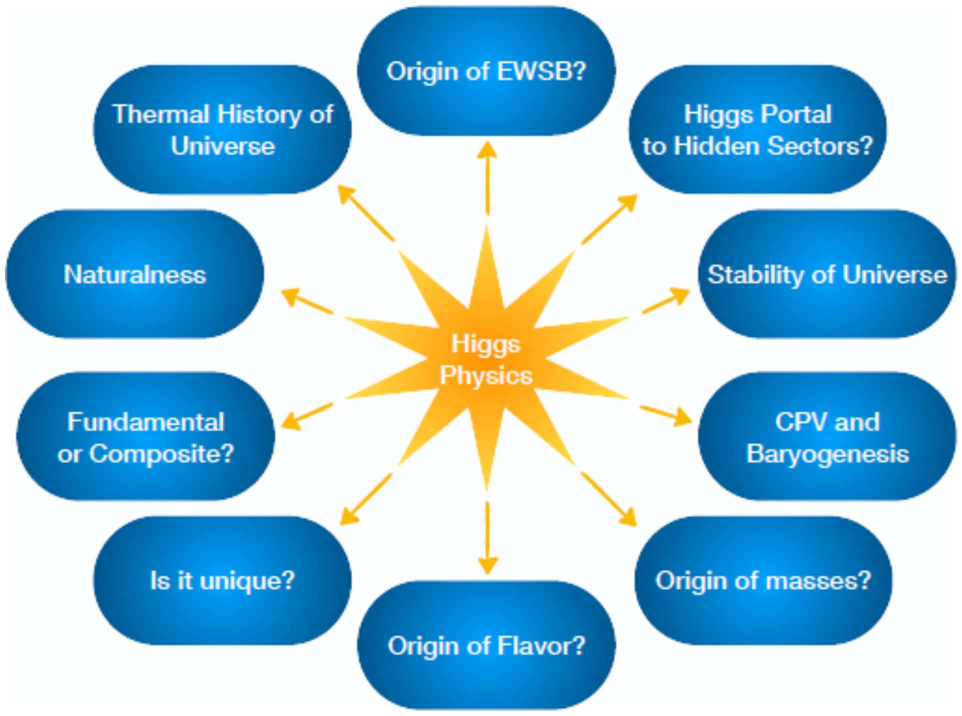
gain wrt to HL-LHC:

- assuming **no exotic Higgs decays** exist:
  => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays**:
  => qualitative jump since no absolute couplings from HL-LHC *at all*

arXiv:2206.08326

Why do we care about the length of these colored bars?!

The Higgs is connected to our fundamental questions about the universe



Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510

- **We need to understand this more quantitatively**
  - the interplay of precision measurements and direct searches
  - relation SMEFT <-> UV complete models
  - “inverse problem”, i.e. how do we figure out the underlying theory

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  - precision Z, W & top masses
    => essential for SM and BSM tests
  - precision W, Z and top couplings
    => essential for Higgs interpretation
  - direct BSM discovery potential complementary to LHC

Why do we care about the length of these colored bars?!

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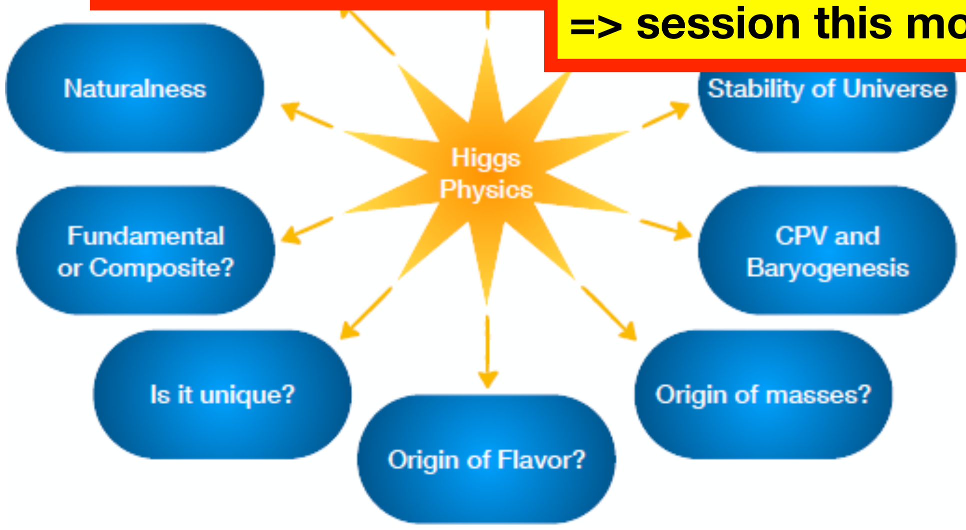
We need a much better way to explain this to policy makers and colleagues from other fields!

=> session this morning



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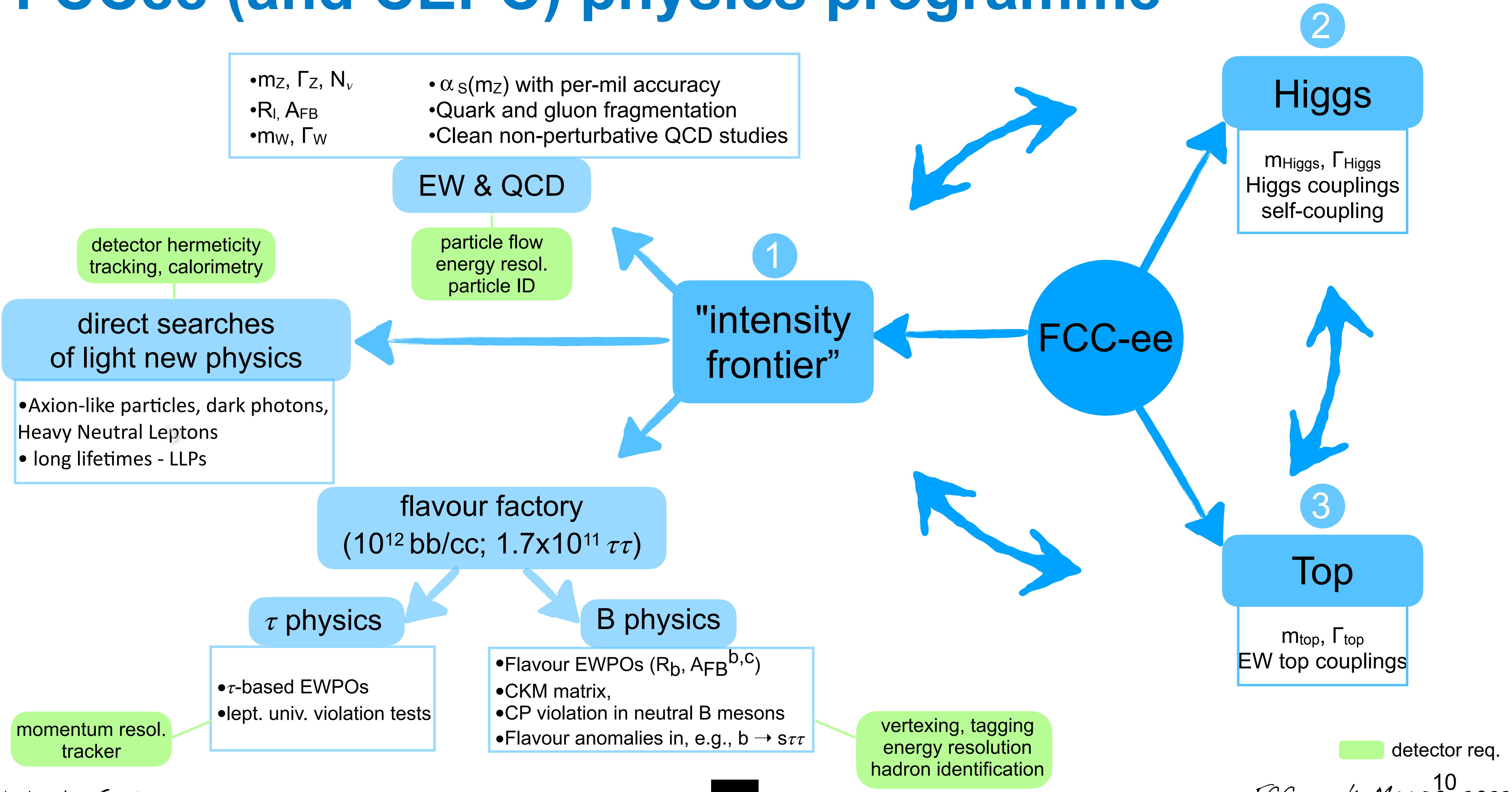
FCCee (and CEPC) physics programme



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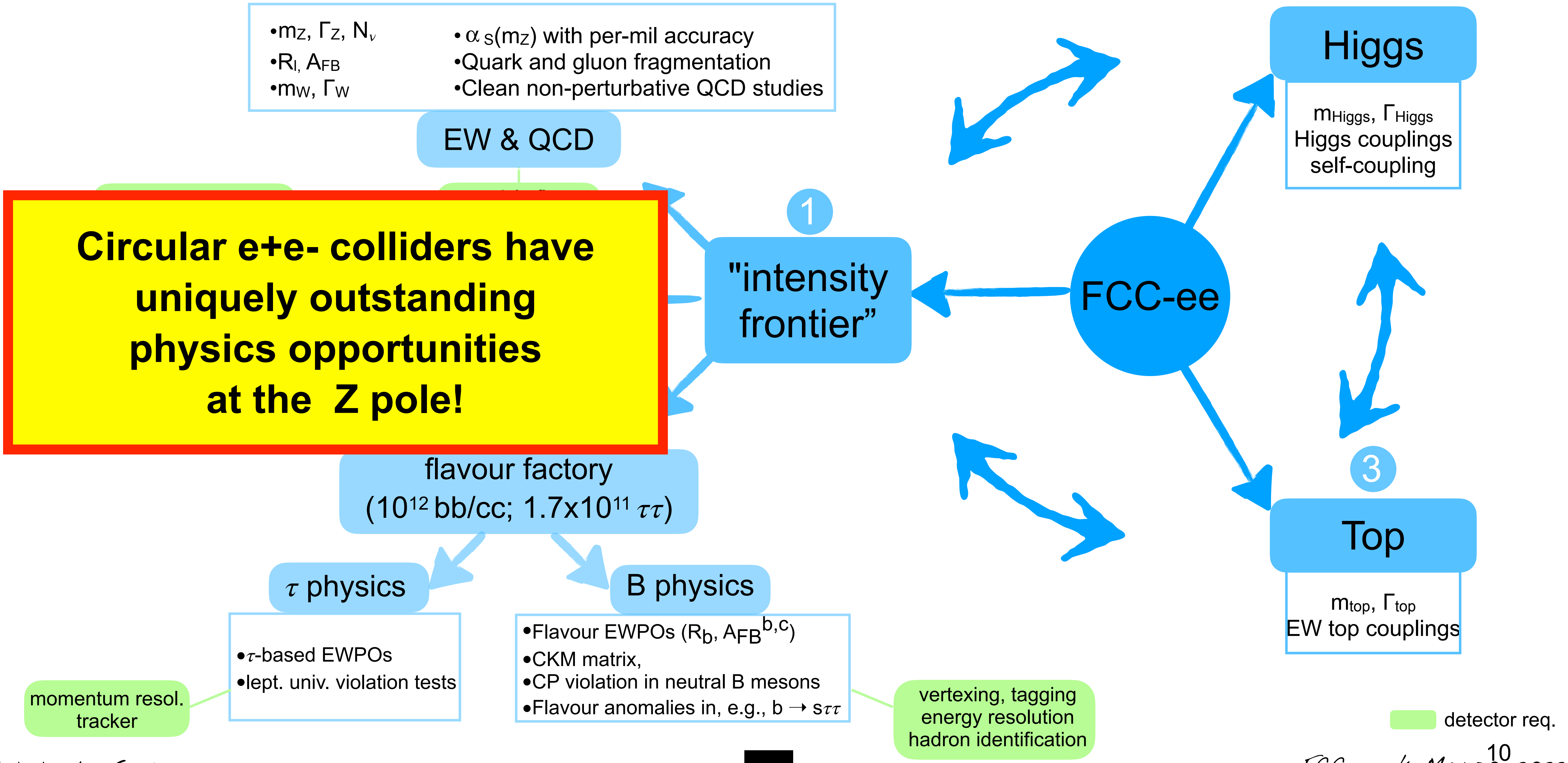
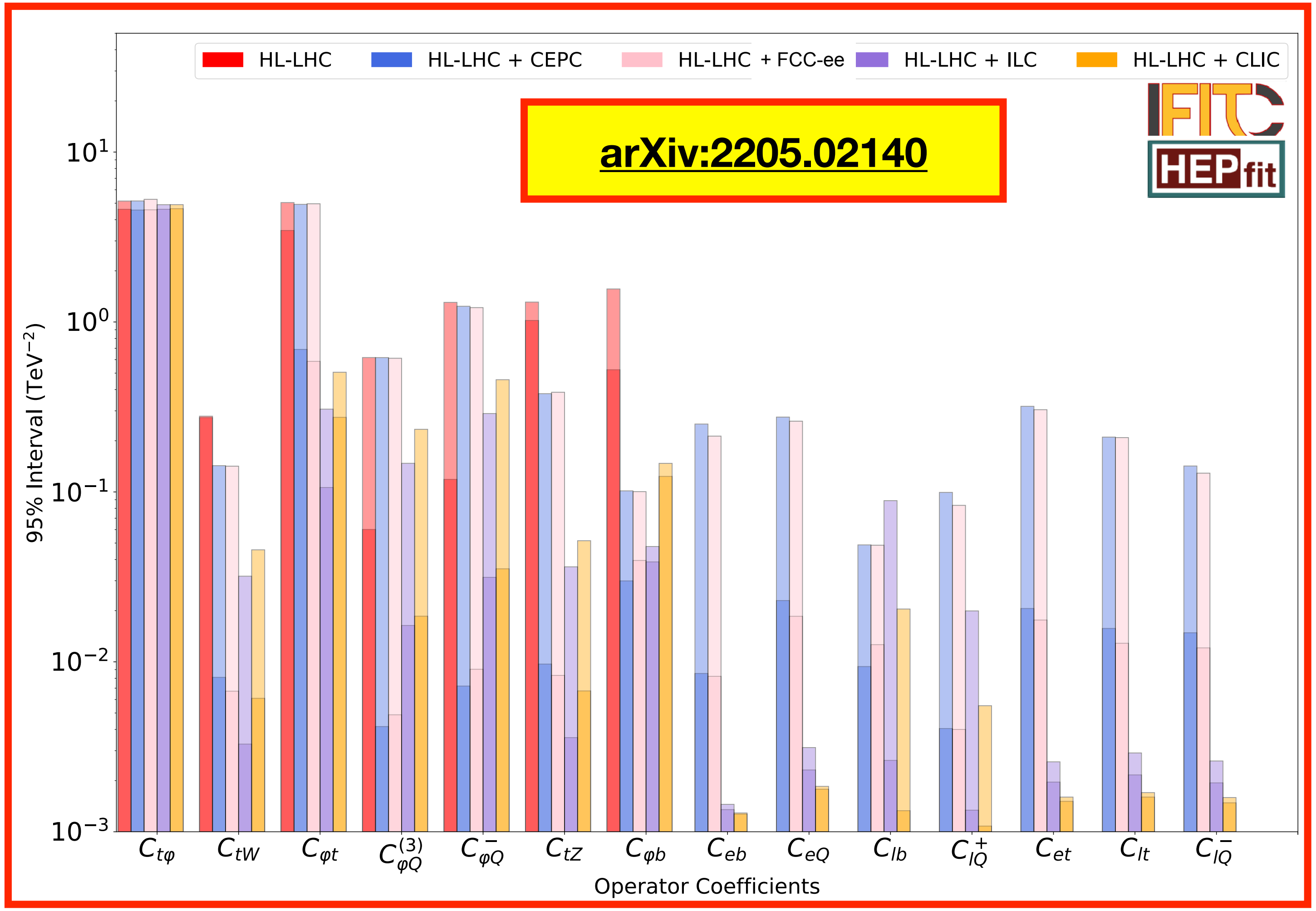


But also higher energies have some advantages…

Full top quark program, including EW couplings, Yukawa, CPV, di-Higgs production, direct BSM…

Example: SMEFT fit to top quark sector

- expected precision on Wilson coefficients for HL-LHC alone and combined with various e+e- proposals
- e+e- at high center-of-mass energy and with polarised beams lifts degeneracies between operators



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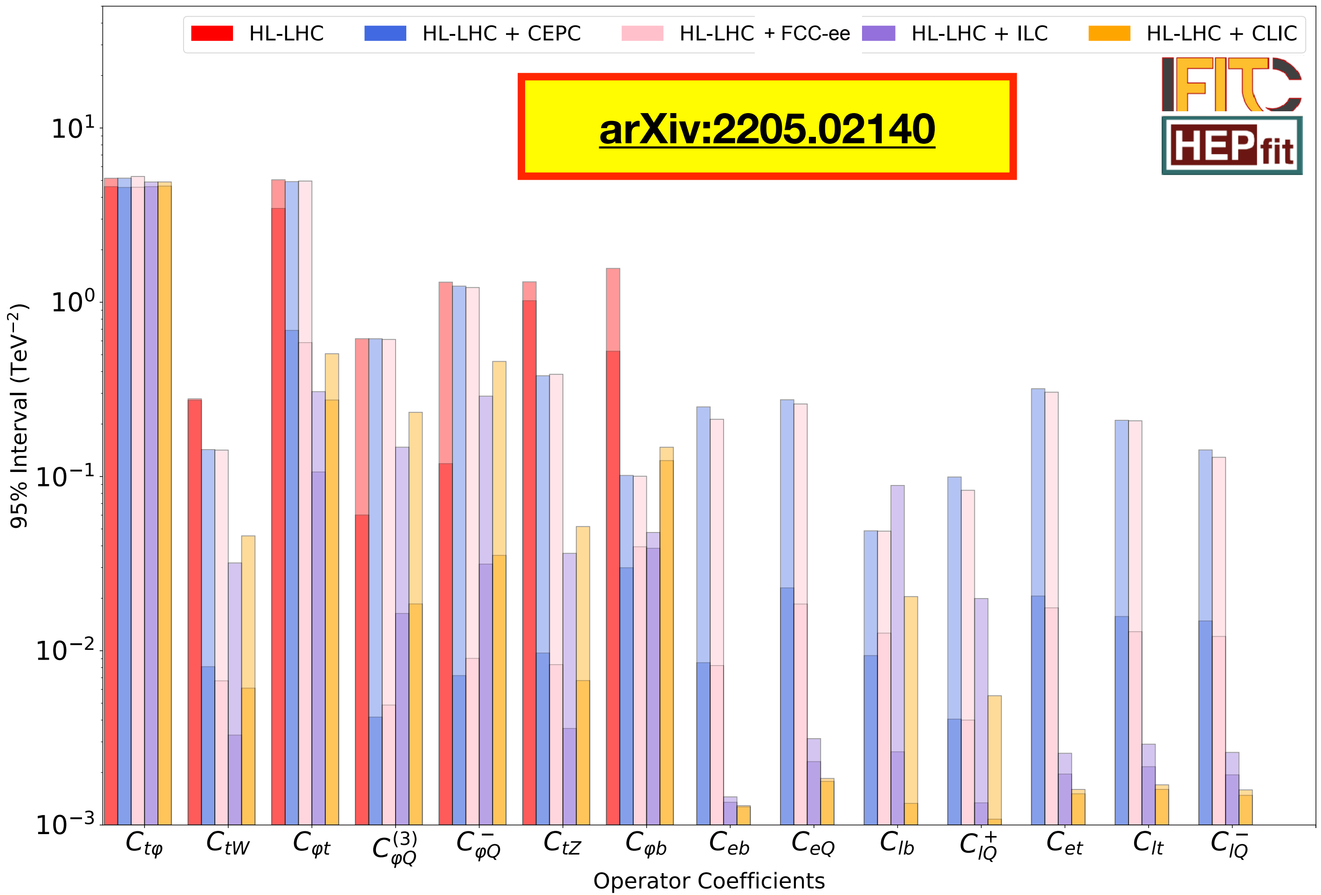
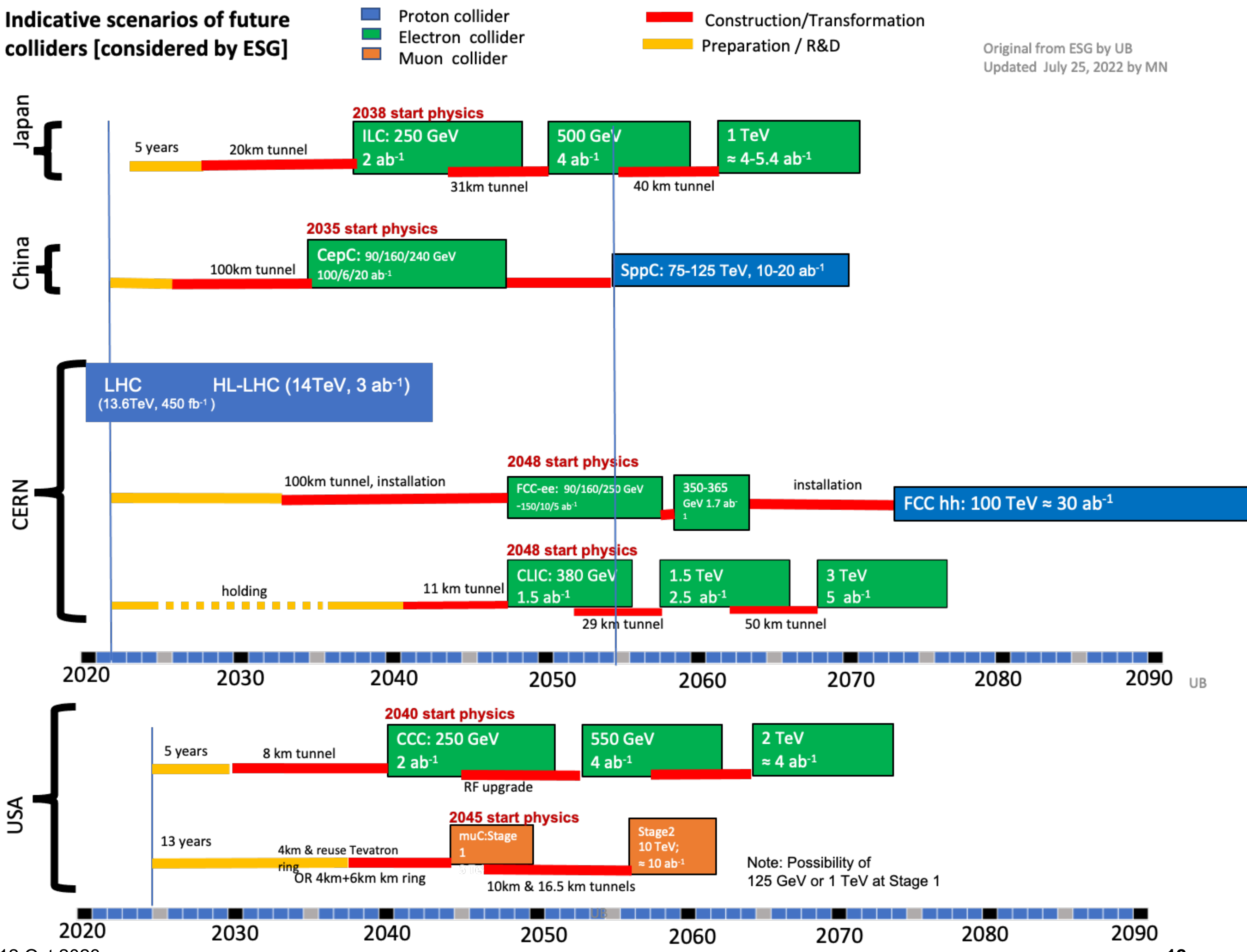
top-quark physics does not end at the ttbar threshold…



Timelines

As updated for Snowmass

- **Technologically-driven => start of physics in ~late 30ies**
- **Apart from CERN projects** due to coupling to completion of (HL-)LHC programme **=> ~late 40ies**
- **ILC and CEPC require political decisions very soon** to maintain timelines drawn here
- **If Higgs Factory is built elsewhere, CERN could go for FCC-hh directly (~2060)**



Snowmass Implementation Task Force

arXiv:2208.06030

Consistent assessment of readiness, risks, costs etc - not always identical to projects self-assessment

Proposal Name	c.m. energy [TeV]	Luminosity/IP $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Yrs. pre-project R&D	Yrs. to 1st physics
FCC-ee[1,2]	0.24	7.7 (28.9)	0-2	13-18
CEPC[1,2]	0.24	8.3 (16.6)	0-2	13-18
ILC[3]-0.25	0.25	2.7	0-2	$<$12
CLIC[3]-0.38	0.38	2.3	0-2	13-18
CCC[3]	0.25	1.3	3-5	13-18

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II	RF sys,. e+ src, arc & booster magnets				1
CEPC-0.24	II					1
ILC-0.25	I	pol. e+ src				1
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Lowest Technology Readiness Levels

- RF systems
- e+ source

=> let's take a closer look at relevant R&D!

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Recent Developments

Superconducting Radiofrequency Cavities (SCRF)

650 MHz & 1.3 GHz

synergetic between circular colliders (booster & collider rings) and linear colliders (damping rings & ILC Linac)

- higher quality factor Q0: less power => less operational costs
- simpler production => less construction cost
- higher gradient => shorter linac

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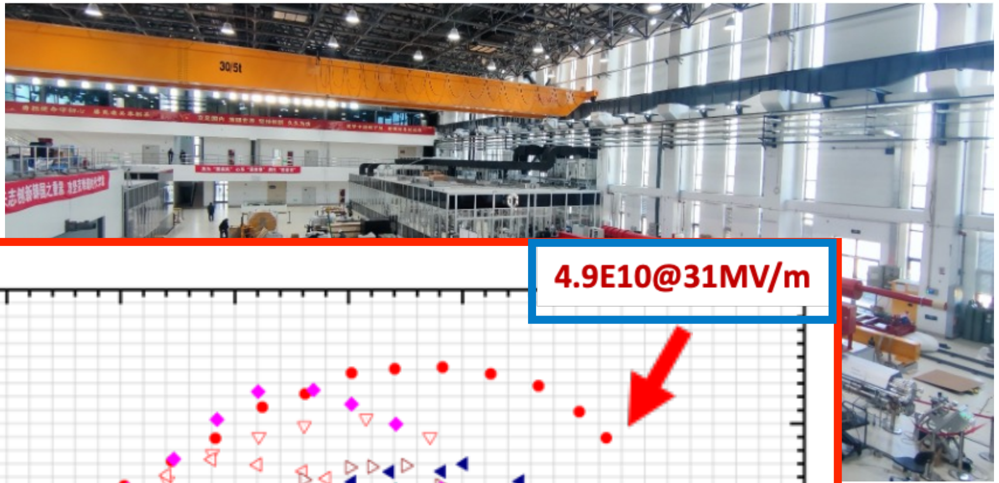
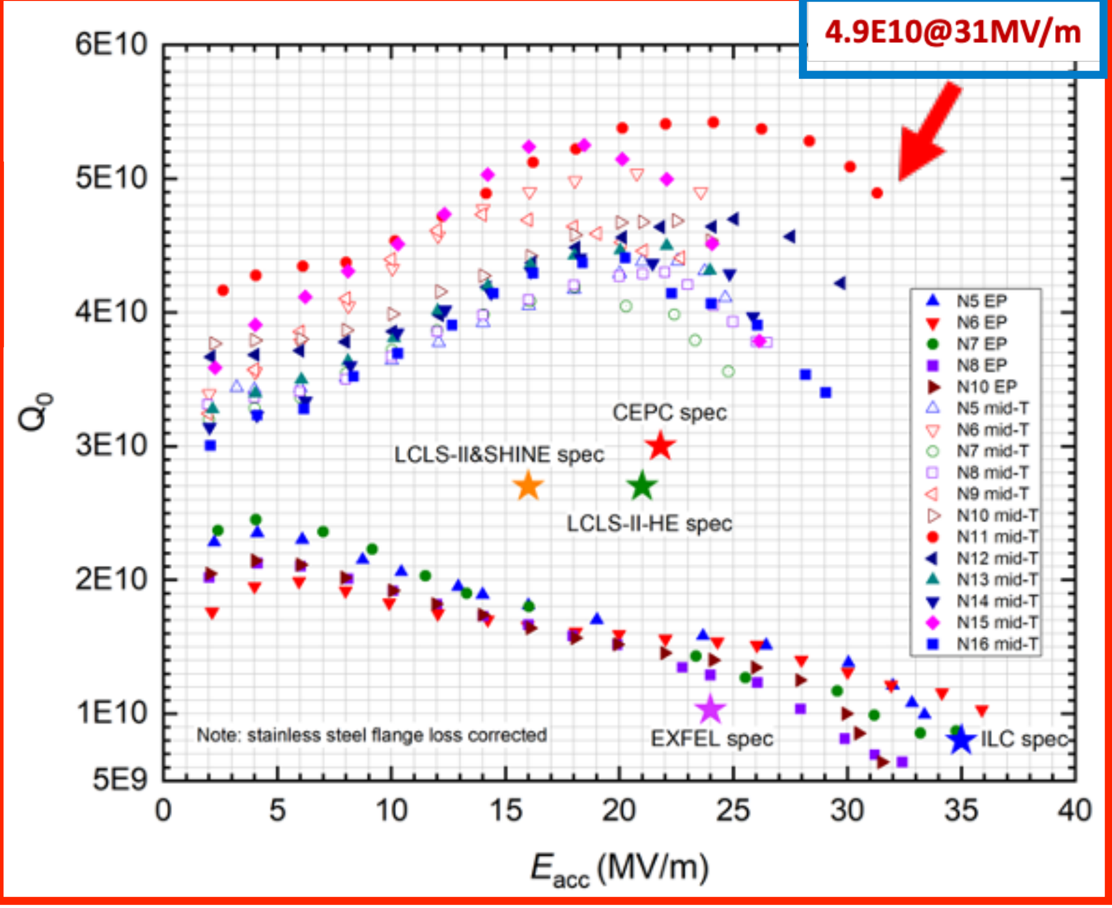
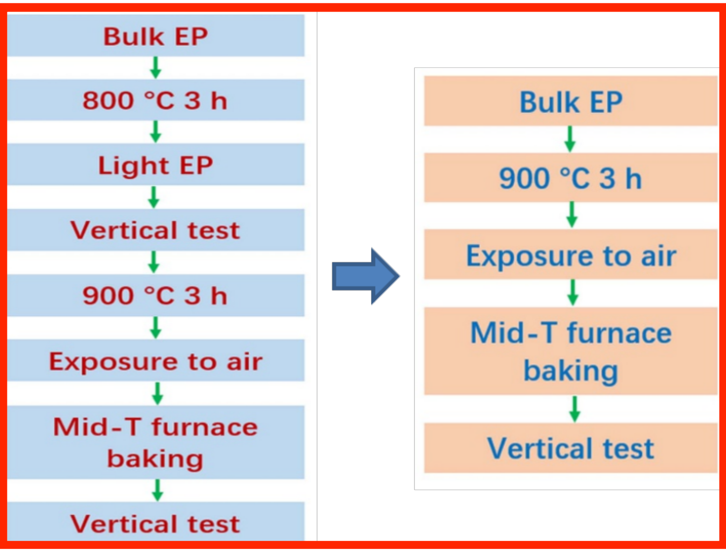


very interesting progress at IHEPs new SRF facility PAPS

- **impressive Q0 with simplified receipe**
- also working on higher gradients…





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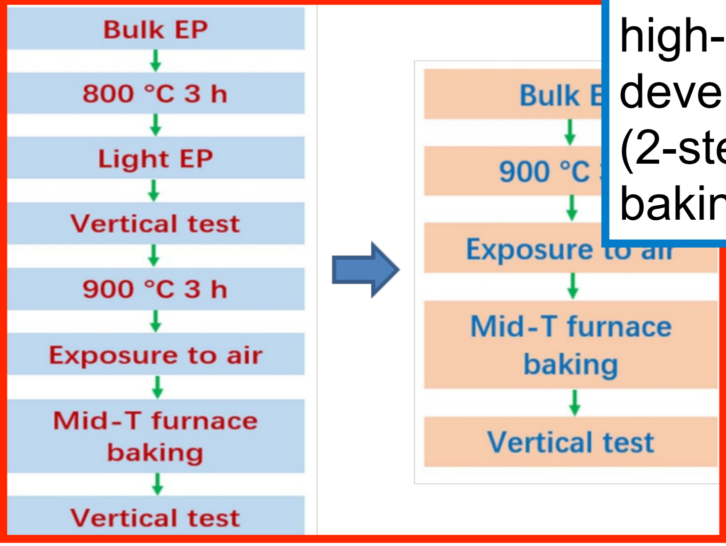
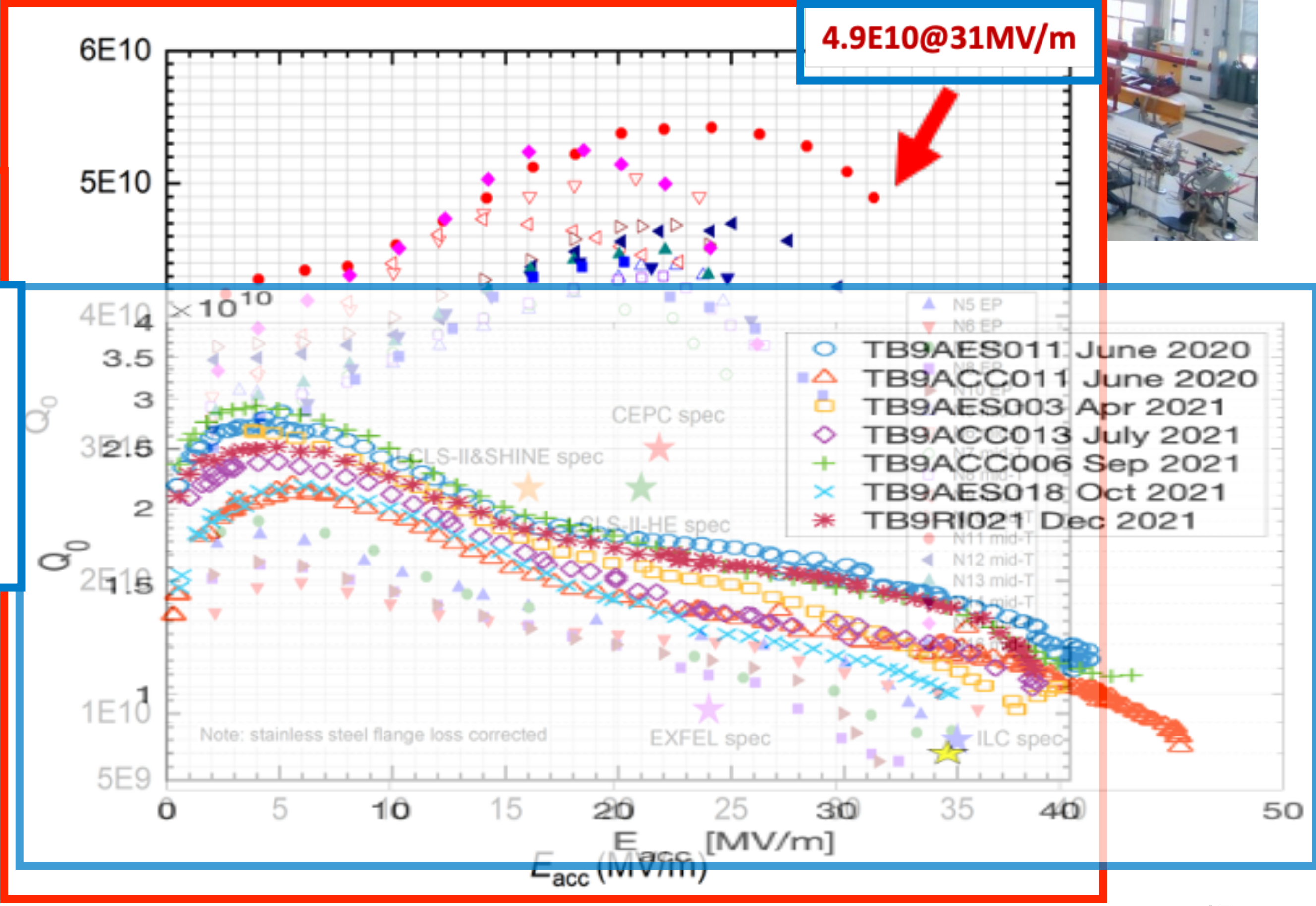


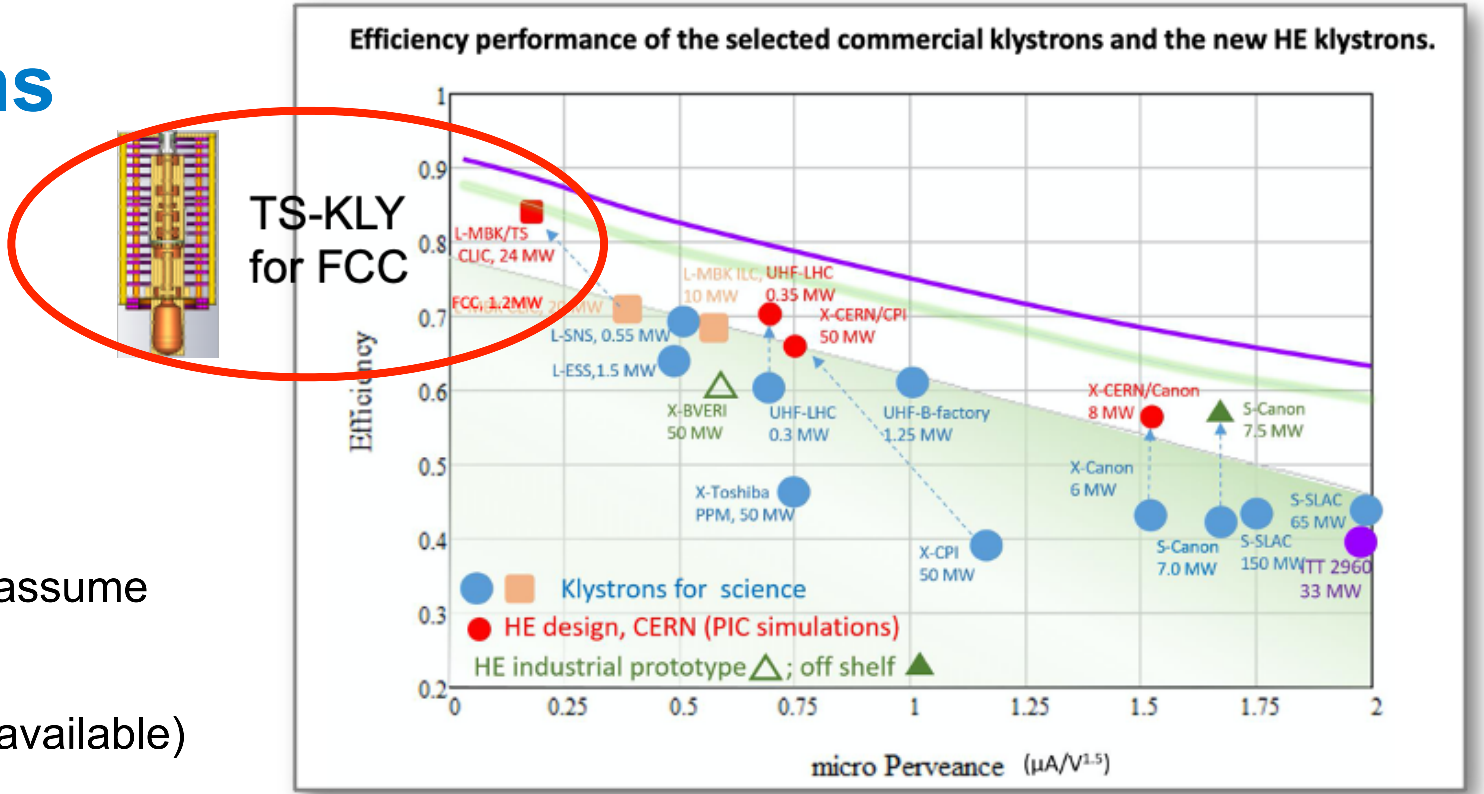
for comparison: high-gradient developments (2-step low-T baking, Fermilab)

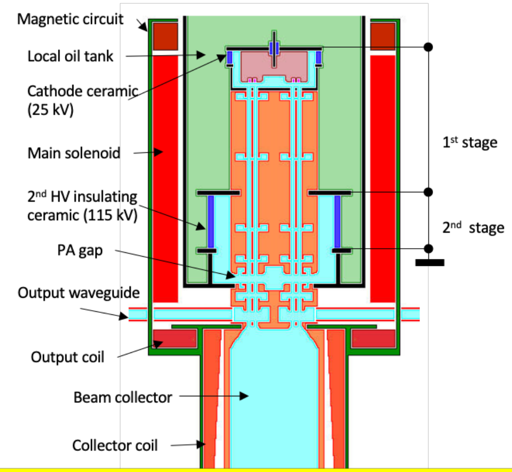


High-Efficiency Klystrons

Programmes at CERN and IHEP

- new design methods have pushed klystron efficiencies to 80% and beyond
- prototyped, efficiencies verified
- **substancial power & cost savings**
- FCCee, CEPC and CLIC power estimates assume these high-efficiency klystrons
- ILC estimates assume 65% (commerically available)





CLIC high-efficiency two-stage multi-beam klystron

J. Cai & I. Syratchev, IEEE Trans. El. Devices 67(2020)3362, doi:10.1109/ted.2020.3028348

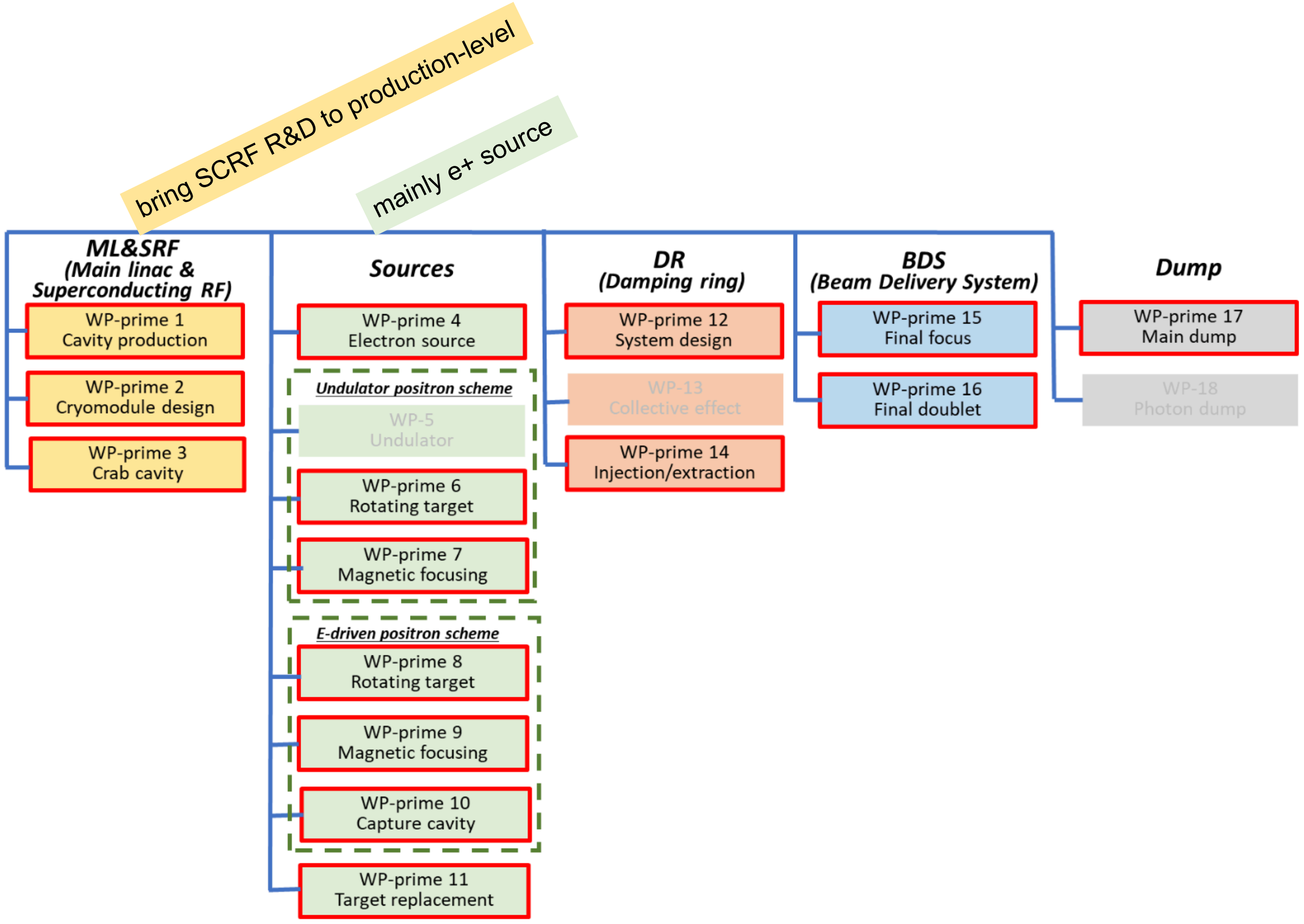
The klystron efficiency impact on the FCC^{ee} power consumption.
Example of the efficiency upgrade from existing 65% to 80%.

	Klystron eff.	Klystron eff.	Difference
DC input power	161.5MW	131.25MW	-30.25MW
Waste heat	56.5MW	26.25MW	-30.25MW
Annual consumption (5500 h)	888 GWh	721.9GWh	-166.1 GWh
Annual cost (50MCHF/MWh	44.5 MCHF	36.1 MCHF	-8.4 MCHF
Electricity installation dimensioned	161.5MW	131.25 MW	-20.6 %
CV installation dimensioned for	56.5 MW	26.25 MW	-53.54 %

The ILC Technology Network

and positron source R&D

- CERN and KEK recently signed an agreement as first members of the new ILC Technology Network
- CERN will act as a European hub facilitating money transfer to other institutes
- One of the **first** activities: WP7’ — magnetic focusing device for polarised positron source
  - new approach: pulsed solenoid
  - **detailed simulations show increase of e+ yield from 1.1 to ~1.8 e+ at damping ring per e- in undulator**
  - ITN: engineering design and prototype construction & tests of pulsed solenoid



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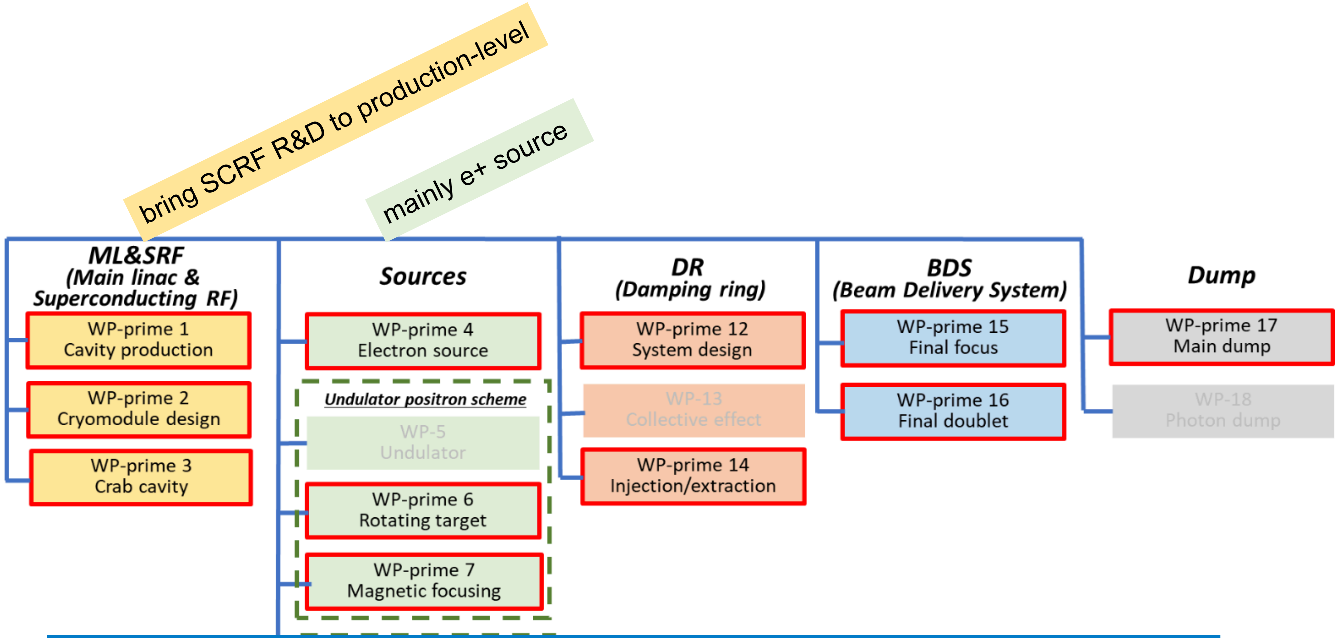

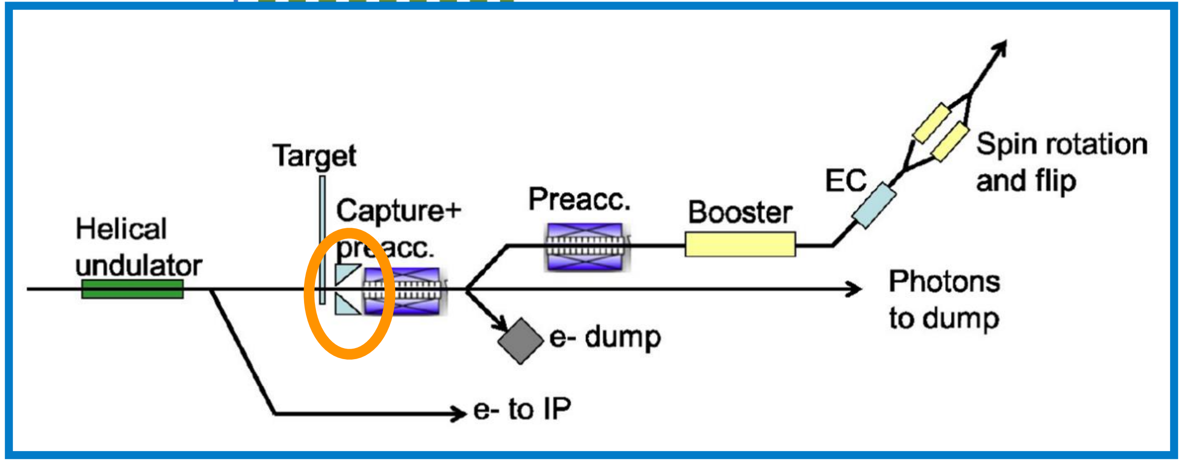

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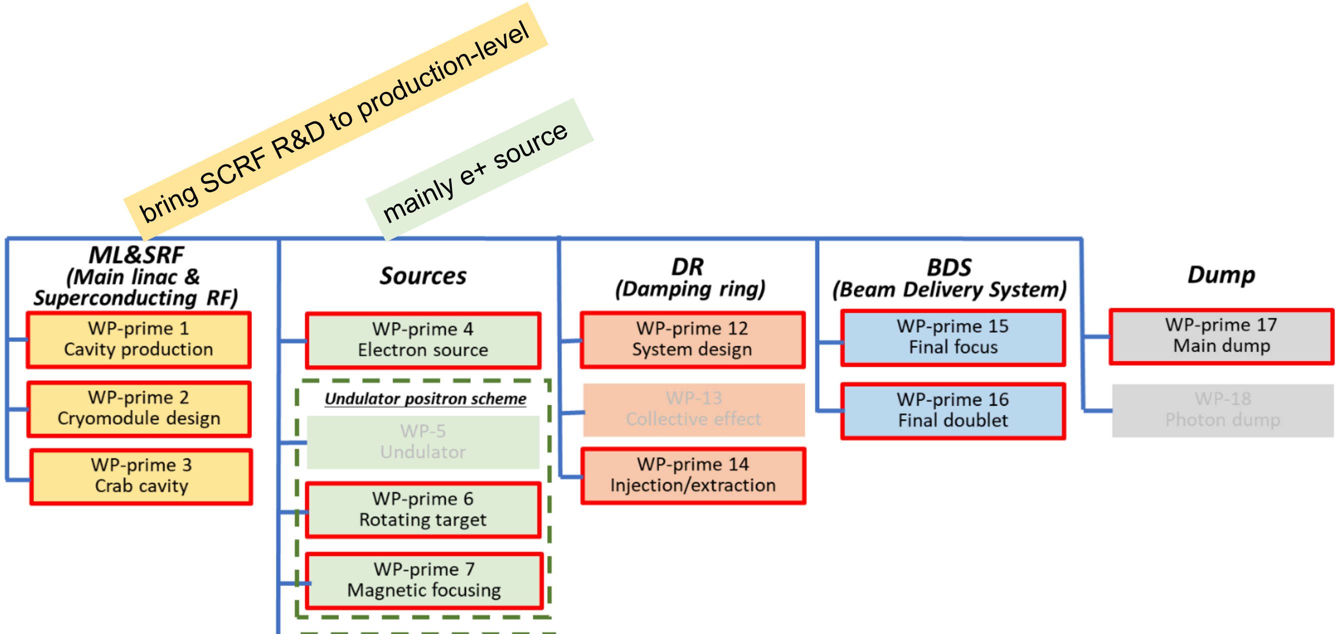
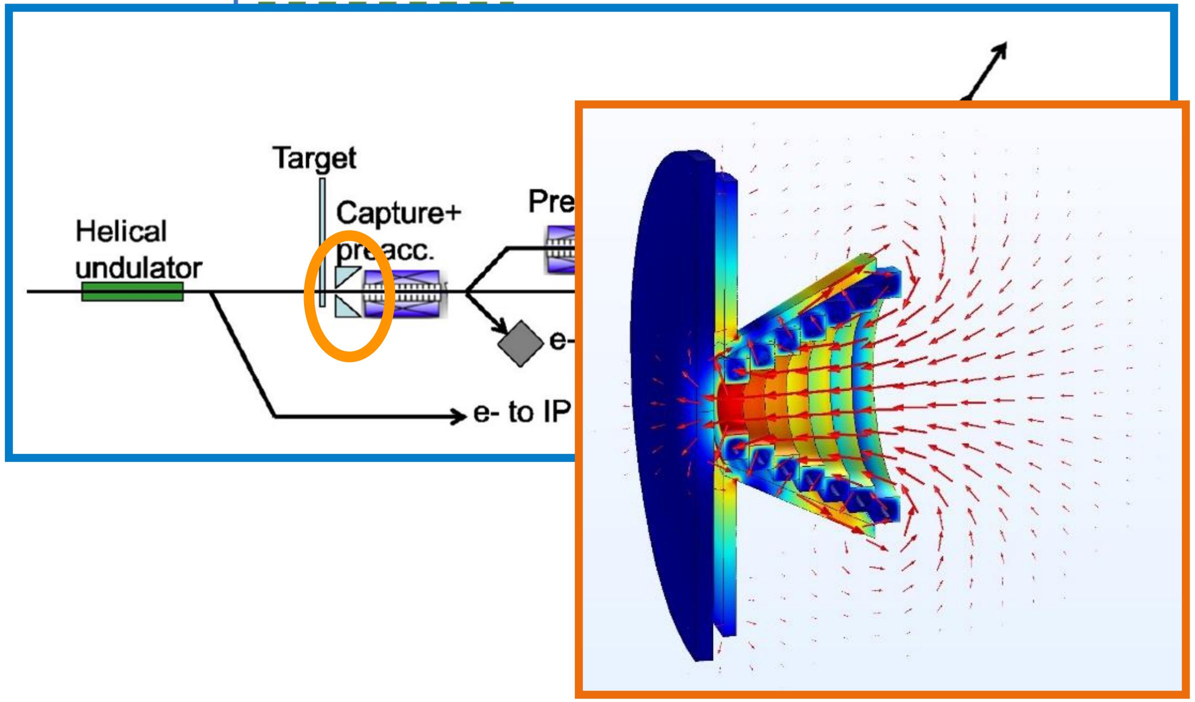
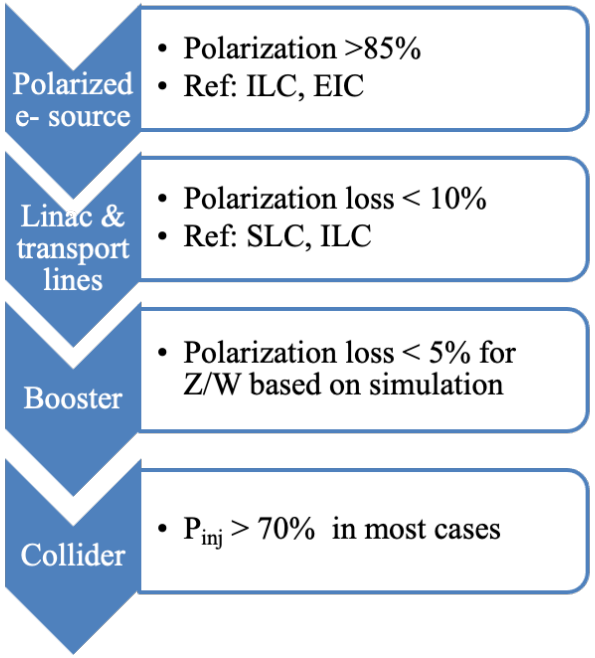




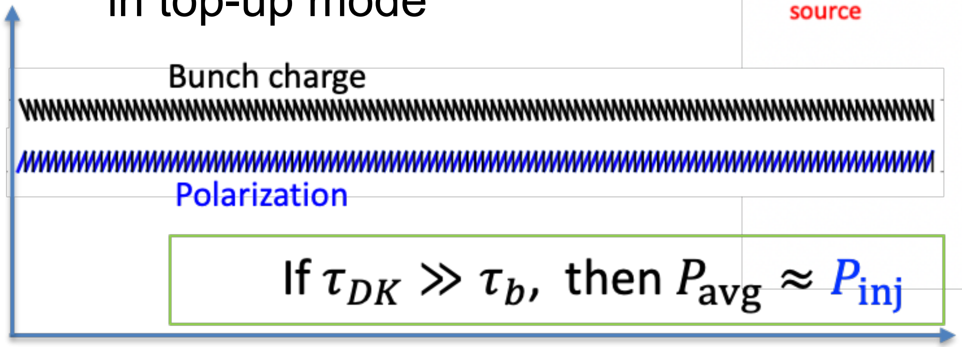
Polarization for CEPC

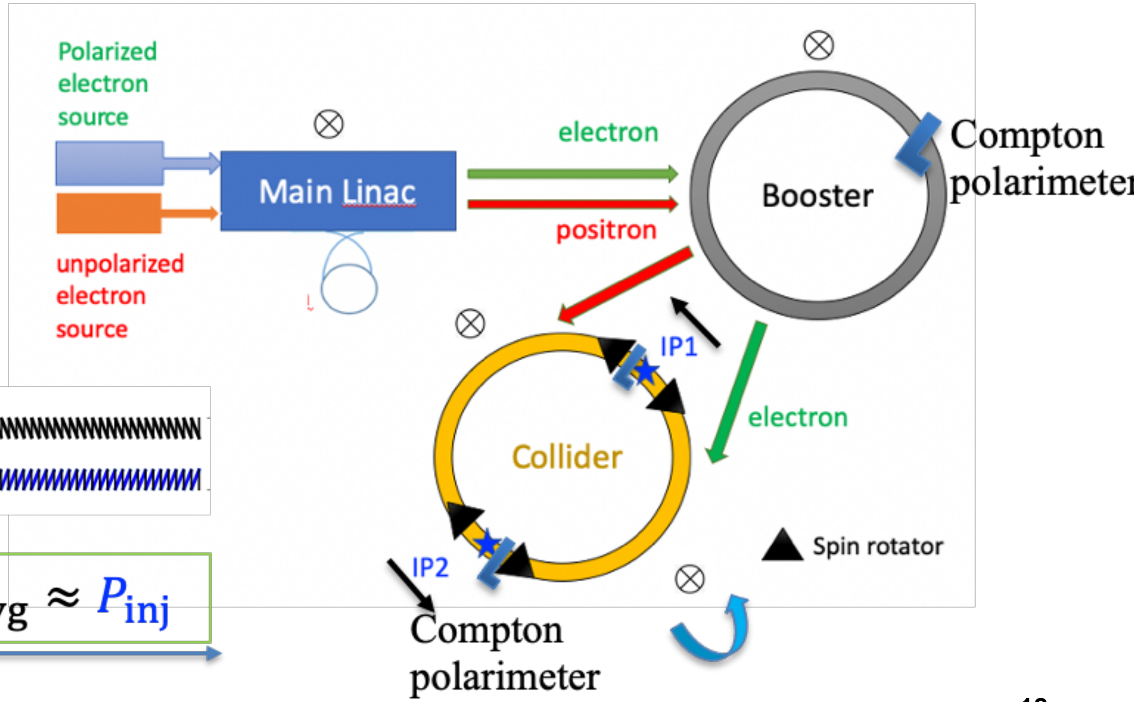
Longitudinal polarization for physics?

- so far CCs considered transverse polarisation of non-colliding pilot bunches for energy calibration
- **CEPC: simulations support average polarization > 50% for colliding bunches in Z and W runs**
- currently only e- , could use same scheme for e+ once a polarized e+ source meets specs
- next: integration of spin rotators and polarimeters into lattice



Colliding bunches in top-up mode



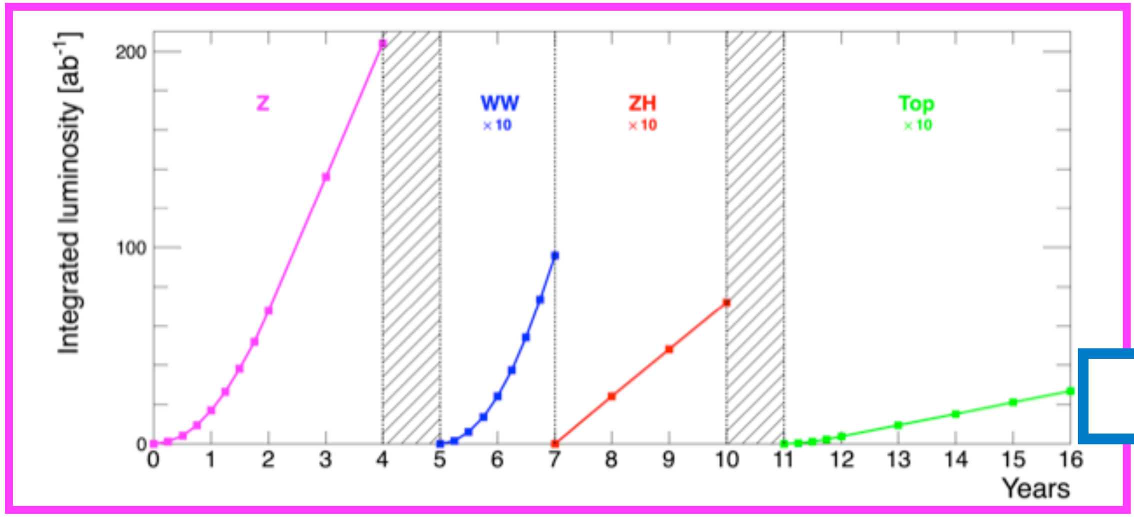


FCCee Run Plan

FCCee is re-discussing the time order of runs

- most “natural” from the accelerator point of view: start at Z pole, continuously increase energy
- however many people are impatient about the Higgs….
- **technically, start with Higgs run is feasible**
  - possibility for priorisation by community
  - **most important: stay flexible, i.e. able to react to findings from first data!**
- CEPC will start with Higgs run (then Z, WW, tt)

TeraZ needs different RF system than ZH and WW runs



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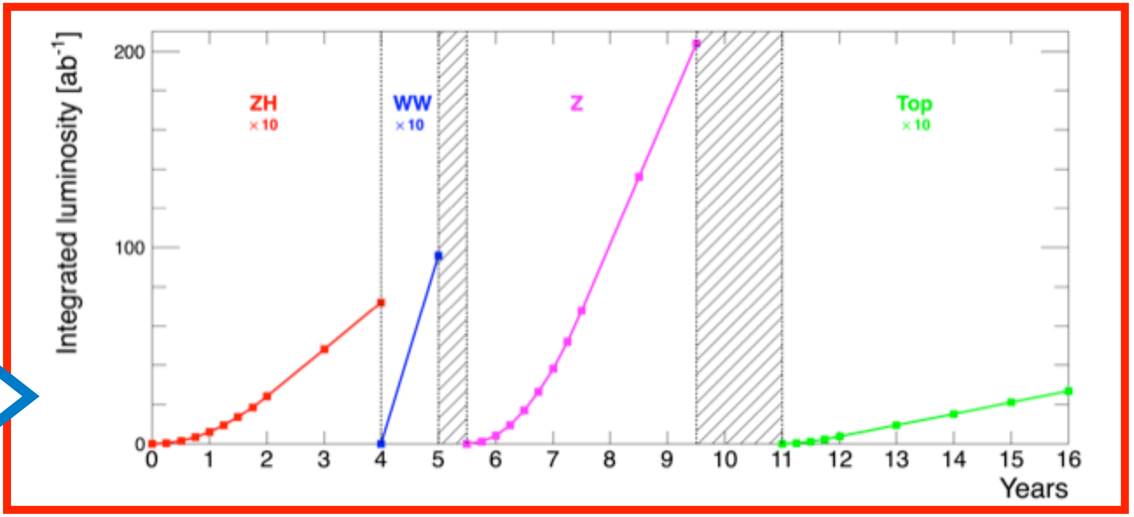
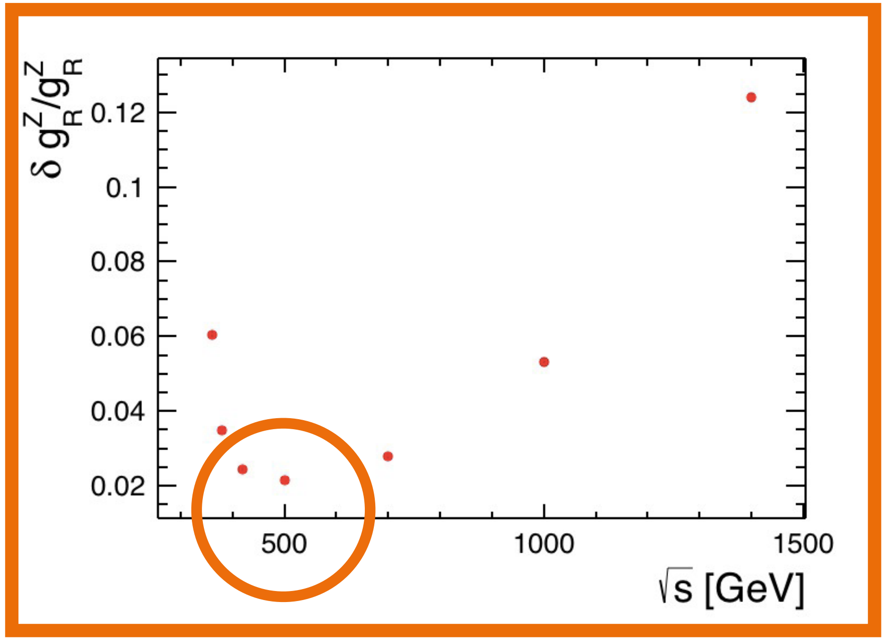


“2nd stage” energy for LCs

500…550…600 GeV?

- ECM ≈ 500 GeV is a sweet-spot for top couplings
- known ever since the Higgs discovery with mH ≈ 125 GeV: ECM=500 GeV “borderline” for ttH production
- **C3 decided for 550 GeV as baseline**
- ILC:
  - no official discussion, focus on getting 250 GeV approved
  - scientifically, it seems obvious that the 500 GeV choice needs to be re-assessed
- CLIC: completely different choice with 380 GeV and 1.4 TeV



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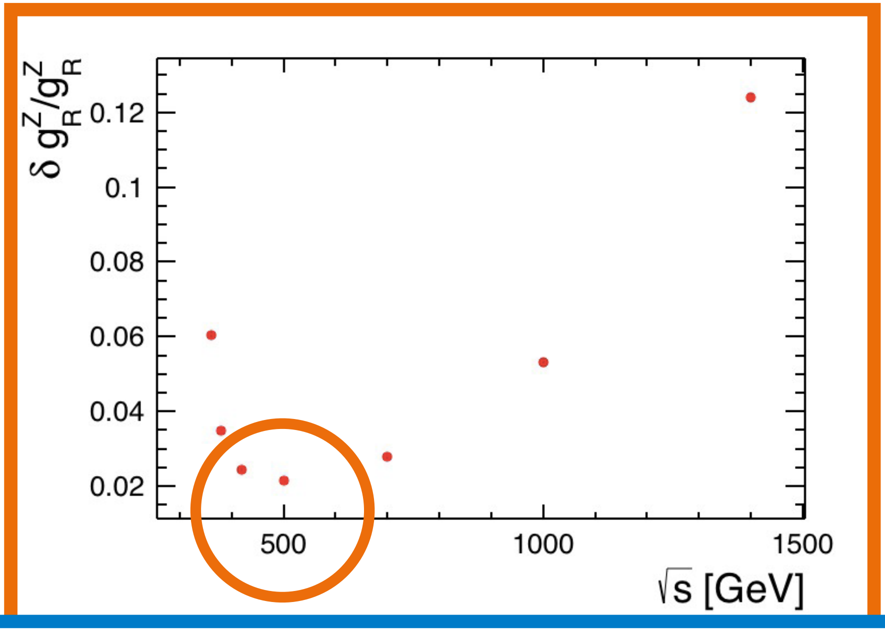

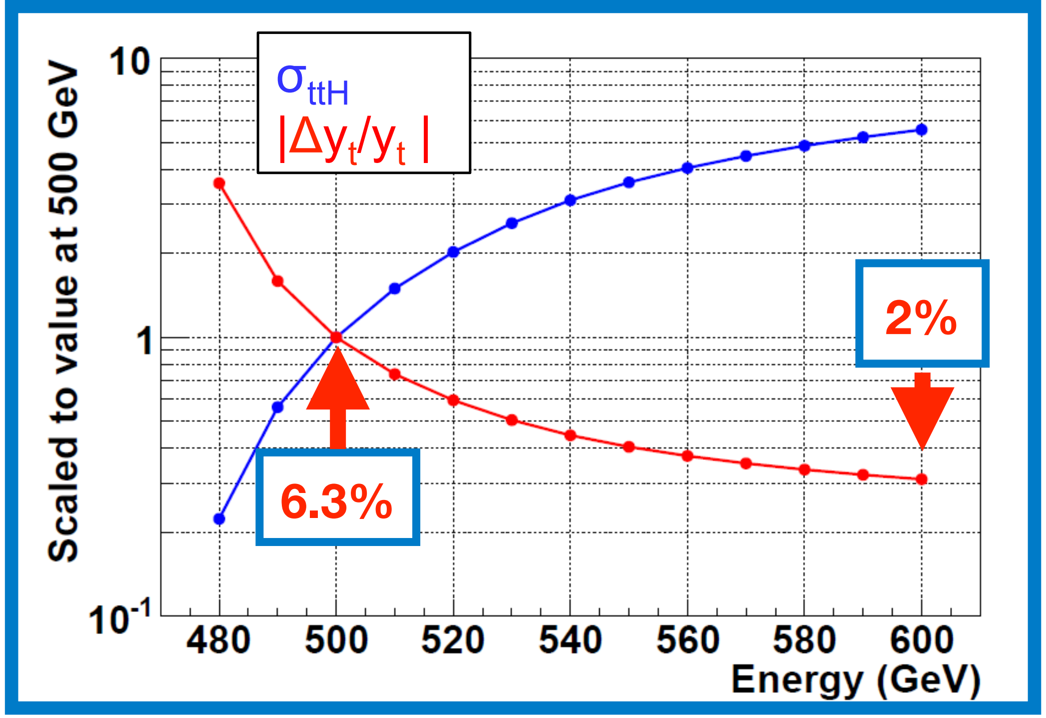

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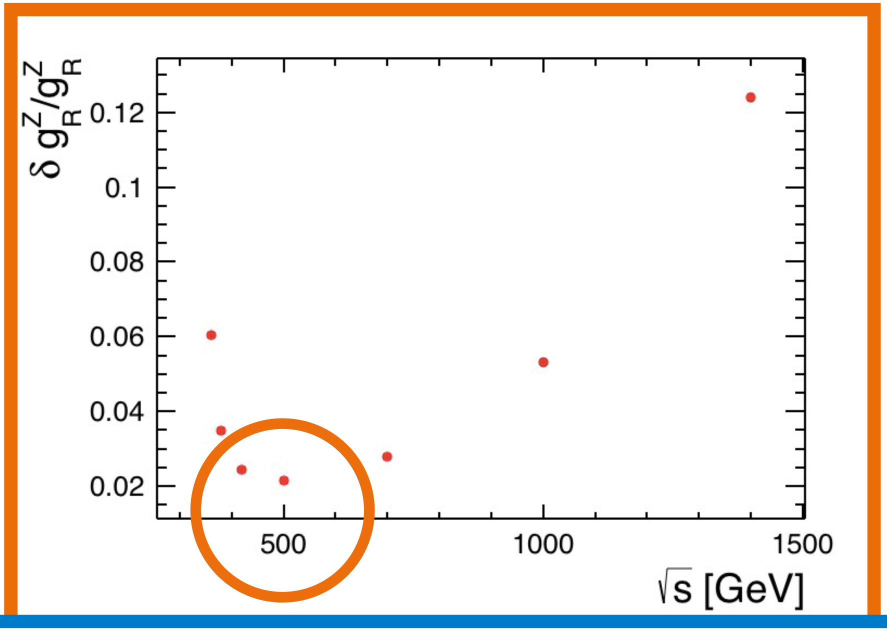

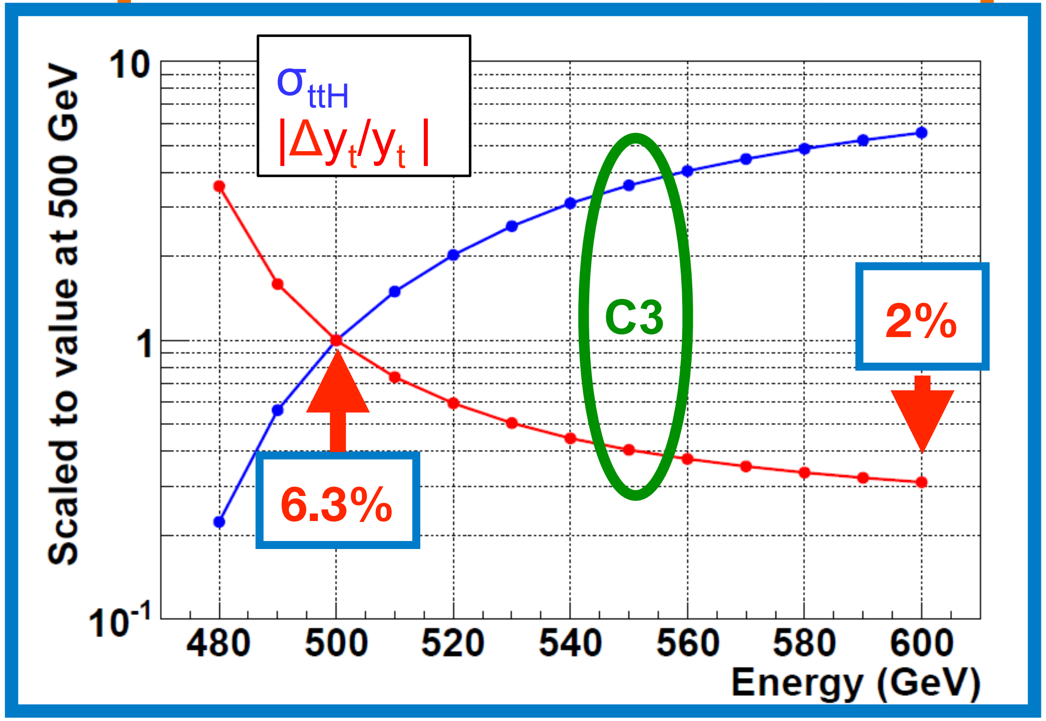

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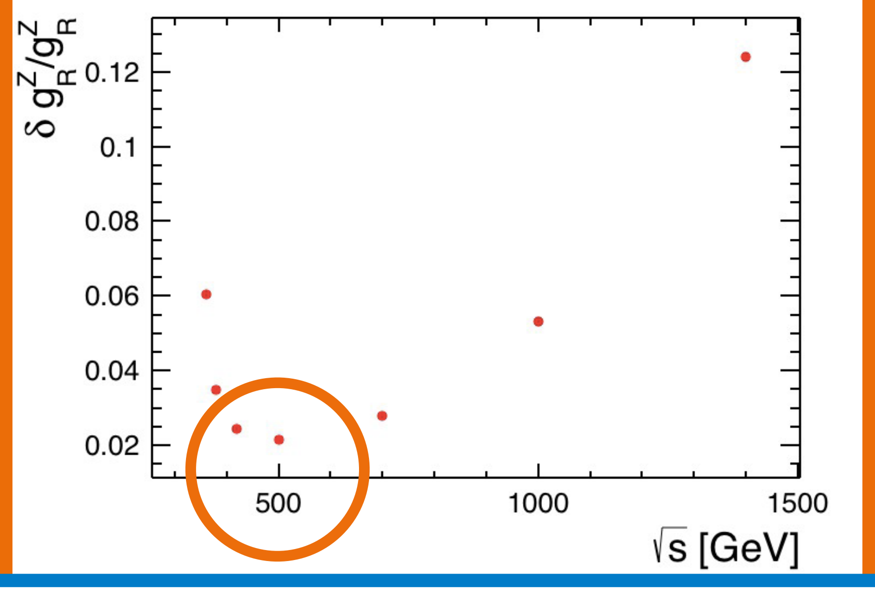
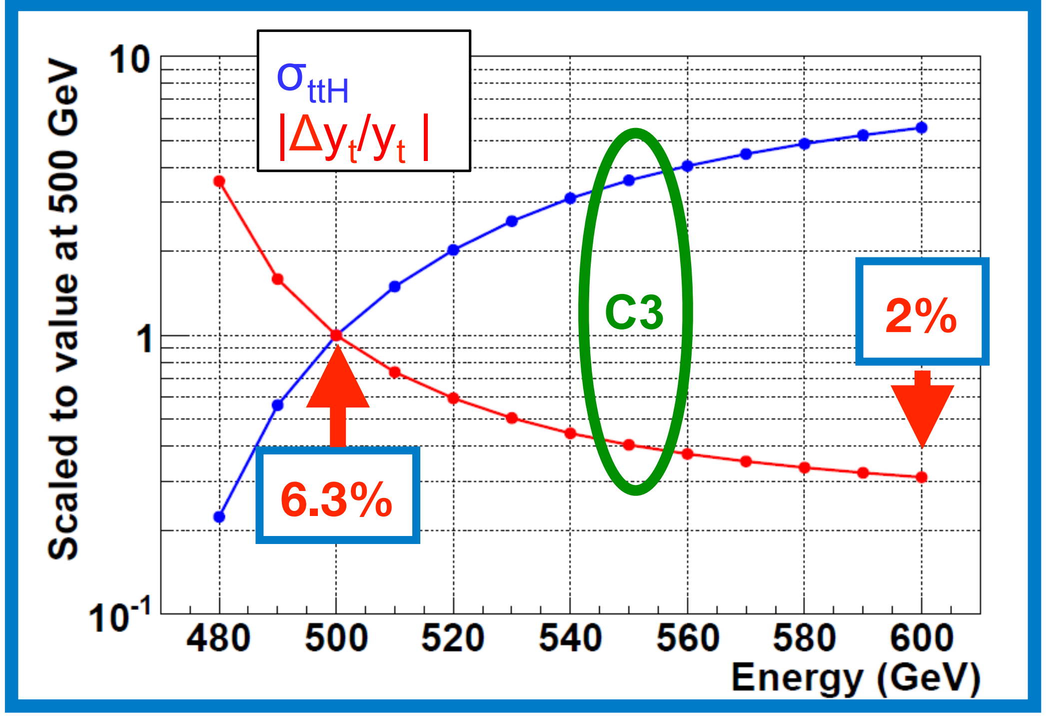
=> Is there a need to re-discuss the physics-optimized energy choices for LCs de-coupled from technology ?





Sustainability

Gro Harlem Brundlandt at WEF 1989

Cover of the "Brundtland Report" 1987

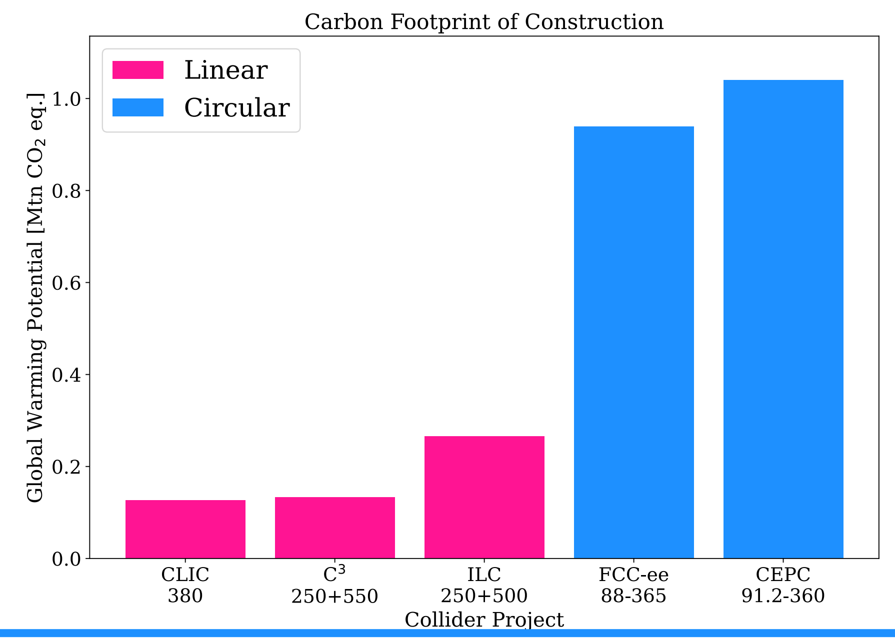
Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations. (WCED, 1987)

WCED (World Commission for Environment and Development) (1987) *Our Common Future*, Oxford University Press, Oxford.

Global Warming Potential

Study by C3

GWP of construction dominated by CO2 emission from the required concrete & steel
=> tunnel length (diameter, tunneling technique)



arXiv:2307.04084

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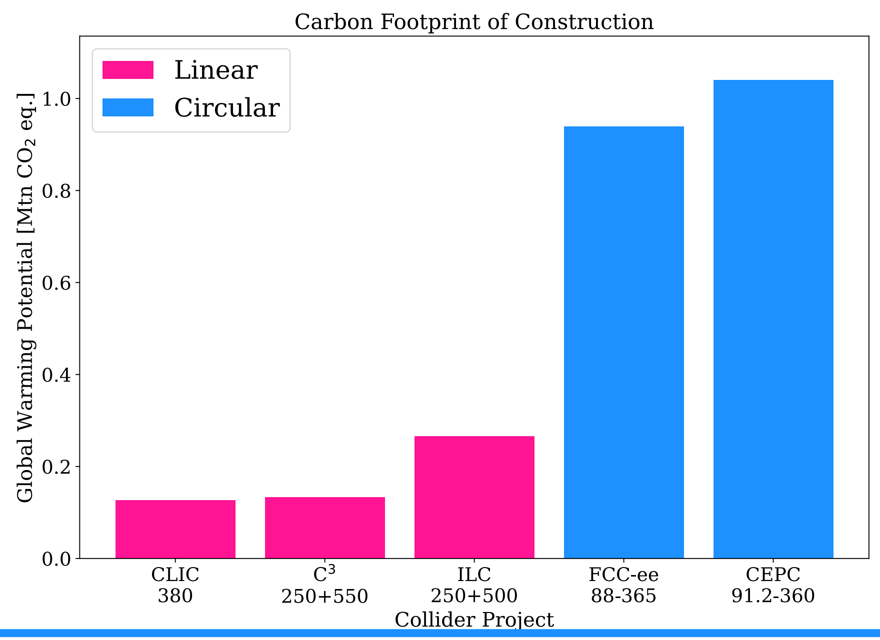
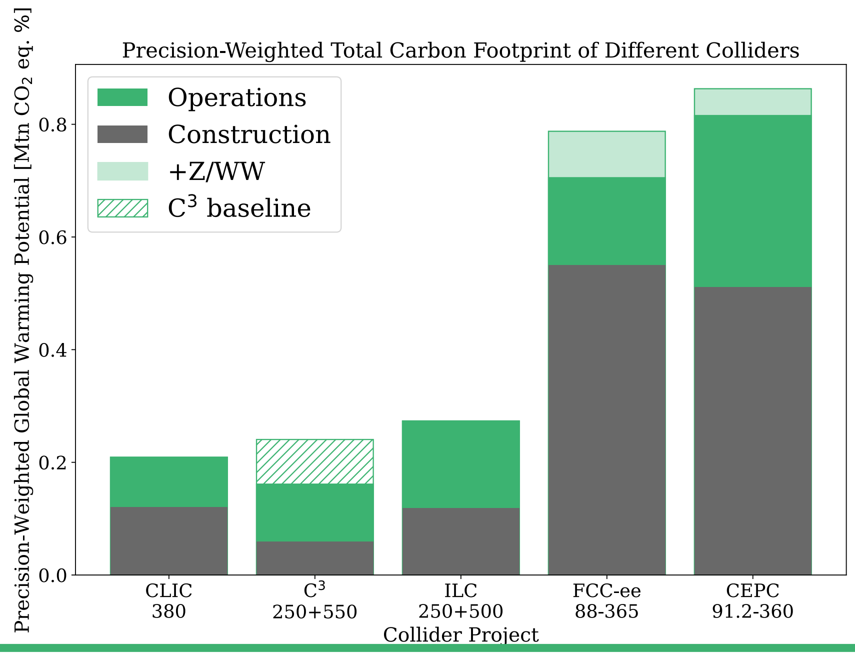




Adding operation GWP

(here weighted by improvement of Higgs couplings over HL-LHC, and with power mix predictions for CERN, US, Japan, China):

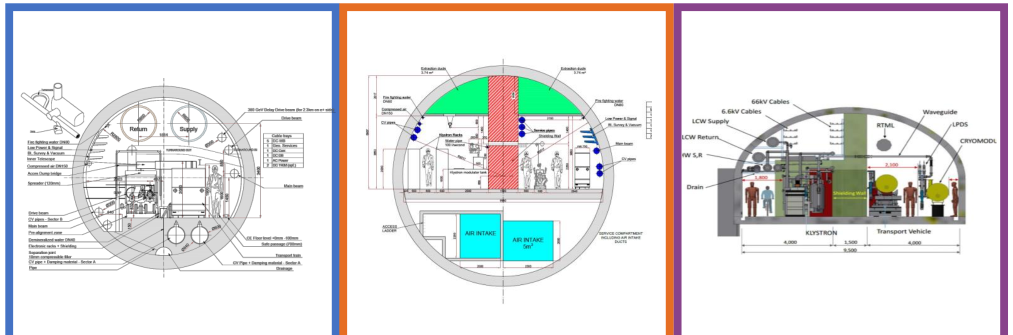
- **Operation dominates for LCs**
- **Construction dominates for CCs**

arXiv:2307.04084

GWP of tunnel construction

Study by CLIC and ILC

- **full life-cycle assessment according to ISO standards by consultancy company (ARUP)**
- **green house gas emission plus 13 more impact categorie**
- roughly confirms C3 estimates (prev. slide)



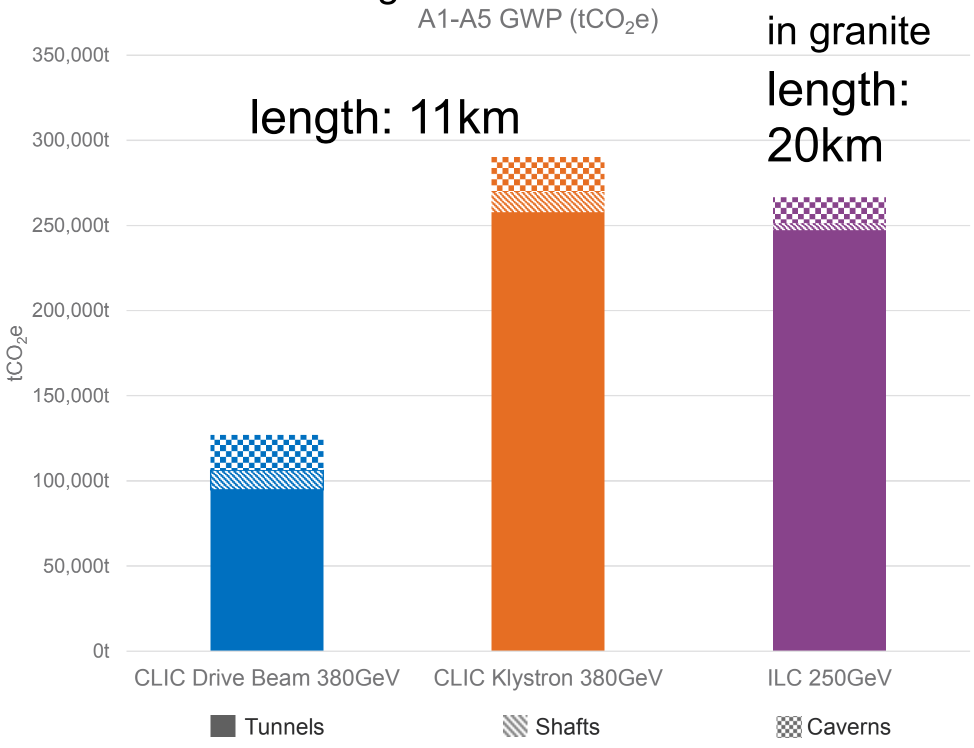
CLIC Drive beam, 5.6m dia.

CLIC Klystron, 10m dia.

ILC, 9.5m span

tunnel boring in molasse

drill&blast in granite



https://edms.cern.ch/document/2917948/1

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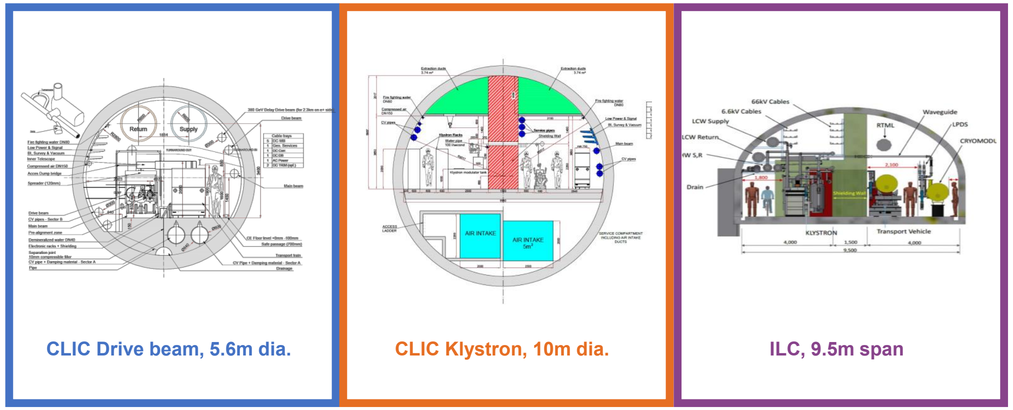
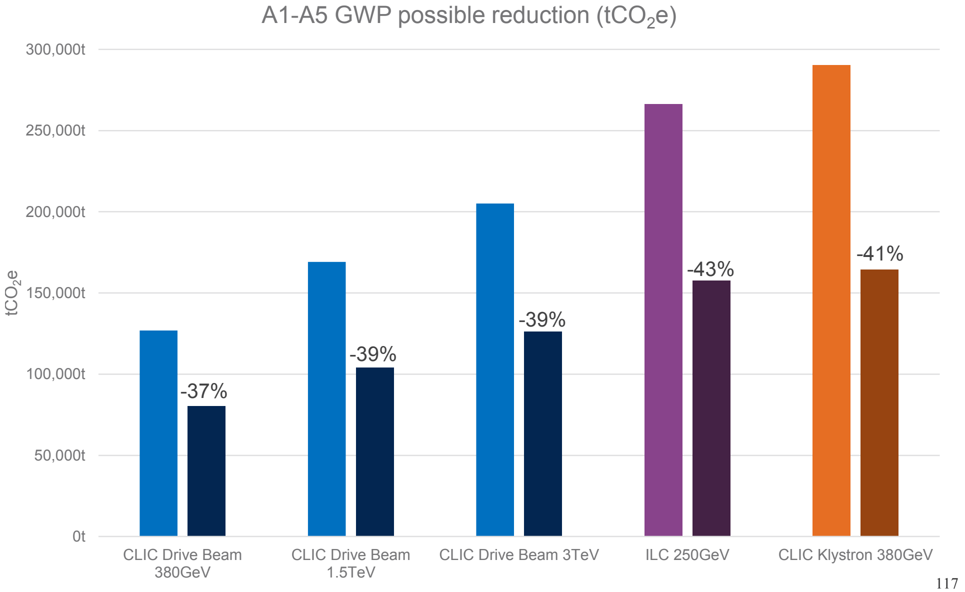
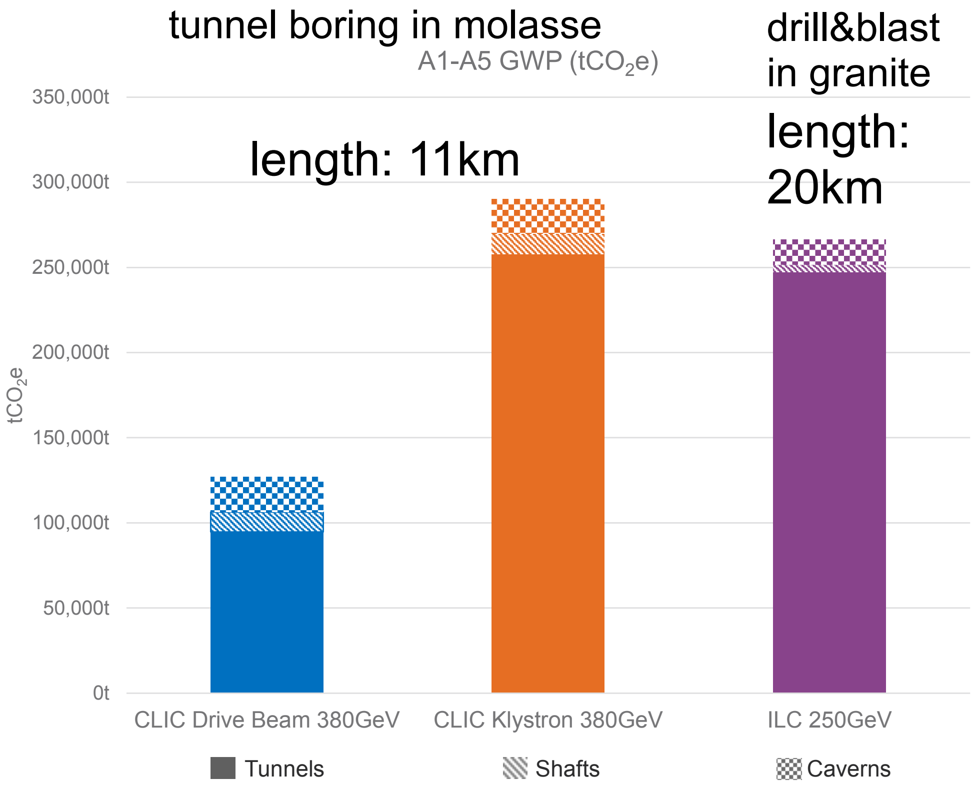
- **green house gas emission plus 13 more impact categorie**
- roughly confirms C3 estimates (prev. slide)
- **~40% of reduction potential by**
  - usage of low-CO2 materials (concrete, steel)
  - reduction of tunnel wall thickness





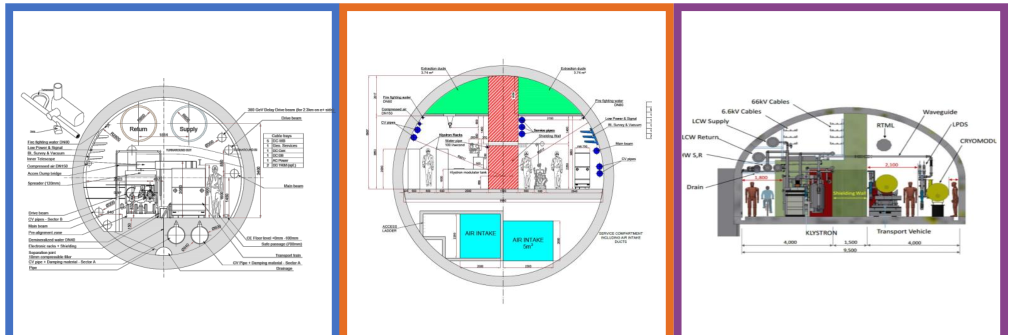


https://edms.cern.ch/document/2917948/1

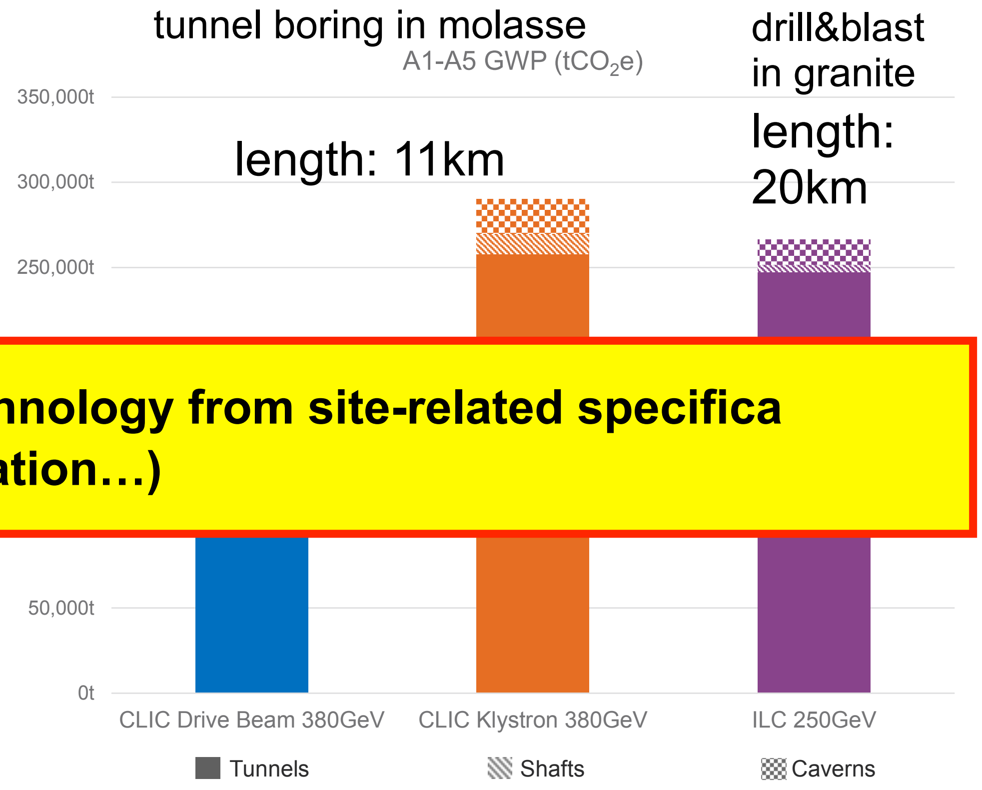
GWP of tunnel construction

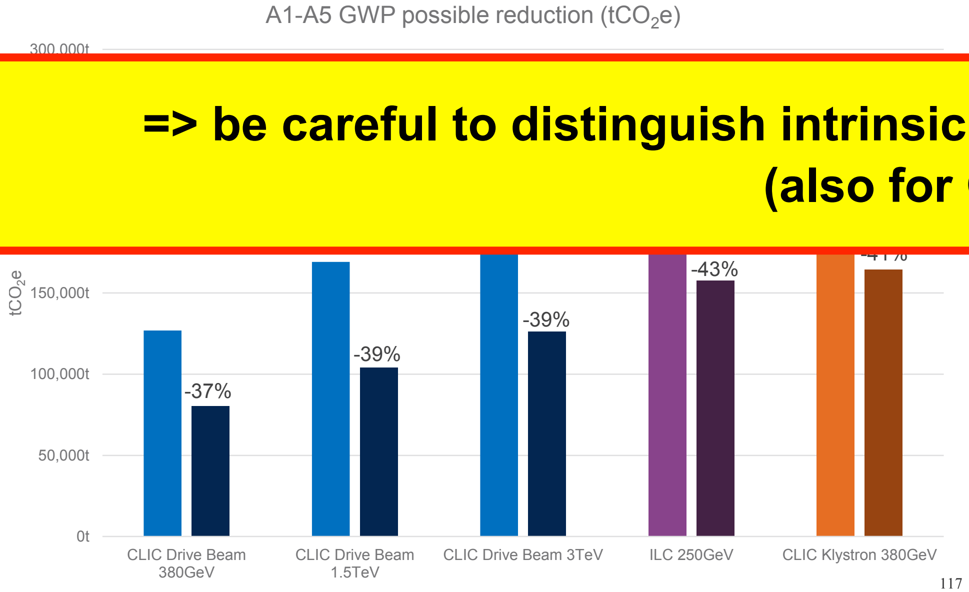
Study by CLIC and ILC

- **full life-cycle assessment according to ISO standards by consultancy company (ARUP)**
- **green house gas emission plus 13 more impact categorie**
- roughly confirms C3 estimates (prev. slide)
- **~40% of reduction potential by**
  - usage of low-CO2 materials (concrete, steel)
  - reduction of tunnel wall thickness



CLIC Drive beam, 5.6m dia. | CLIC Klystron, 10m dia. | ILC, 9.5m span





=> be careful to distinguish intrinsic needs of technology from site-related specifica (also for GWP of operation…)

https://edms.cern.ch/document/2917948/1

Sustainability: Objective Assessment of New Infrastructures

New Working Group of the European Lab Directors Group

- **goal:**
  - define to all new infrastructure proposals what they should quantify and report upon so that fair comparisons can be made between these proposals
  - e.g. key performance indicators, methodology, assumptions, …
- **membership:** designated experts from each of the foreseen collider projects (FCC, ILC, CLIC, Muon Collider, …??), ~10 or less
- **timeline:**
  - preliminary report to LDG by Spring 2024
  - final report by Summer 2024
    => enable new projects to carry out their sustainability assessments in a timescale compatible with the next European Strategy Update for PP (likely in 26/27).

c.f. presentation at Open Meeting of European Lab Directors Group, Frascati, 11th July 2023 https://agenda.infn.it/event/35700/contributions/205193/

Conclusions

Particle Physics View …

- **strong scientific consensus that an e+e- Higgs Factory is the highest-priority next collider**
  - a lot is going on in accelerator and detector R&D as well as physics studies
  - better communication needed: other scientists, politics, general public
  - …and also inside our field, in particular to the next generation!
- **open question: how to best complement the minimal Higgs Factory in e+e-?**
  - very strong Z pole program but limited in energy reach?
  - upgrades to higher energies but more modest Z program?
- **particle physics and society**
  - future large scale projects need to be sustainable
  - CO_2, but also financial, material and human resources
  - foster sustainable development worldwide
  - peaceful collaboration also across political differences

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  - peaceful collaboration also across political differences

Most importantly:
A Future Collider can only happen based on broad support within HEP community
=> get more people engaged and make it happen!

Thank you

Backup

Absolute Higgs Production Rate

Absolute normalisation of Higgs couplings & total decay width

- Higgs factory at 250 GeV: **e+e- → ZH**
- **can measure its total cross section: *the key*** to model-independent determination of **absolute** couplings
- measurable independently of Higgs decays modes via **recoil technique**
- only possible at e+e- collider due **to known momentum of colliding particle**
- **enables a plethora of further precision measurements**

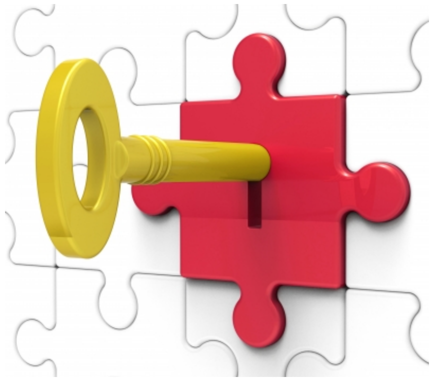
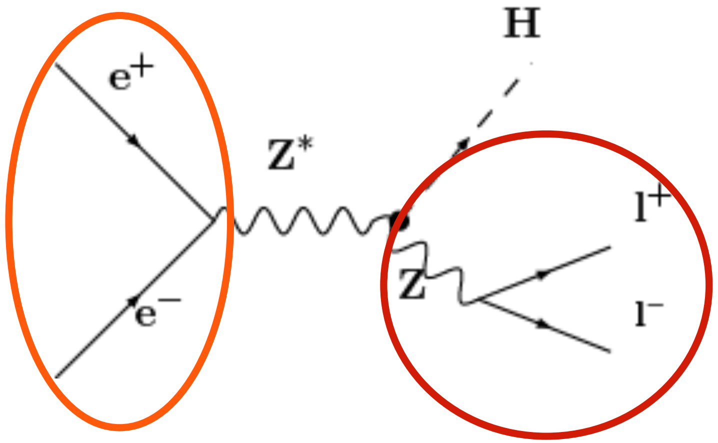
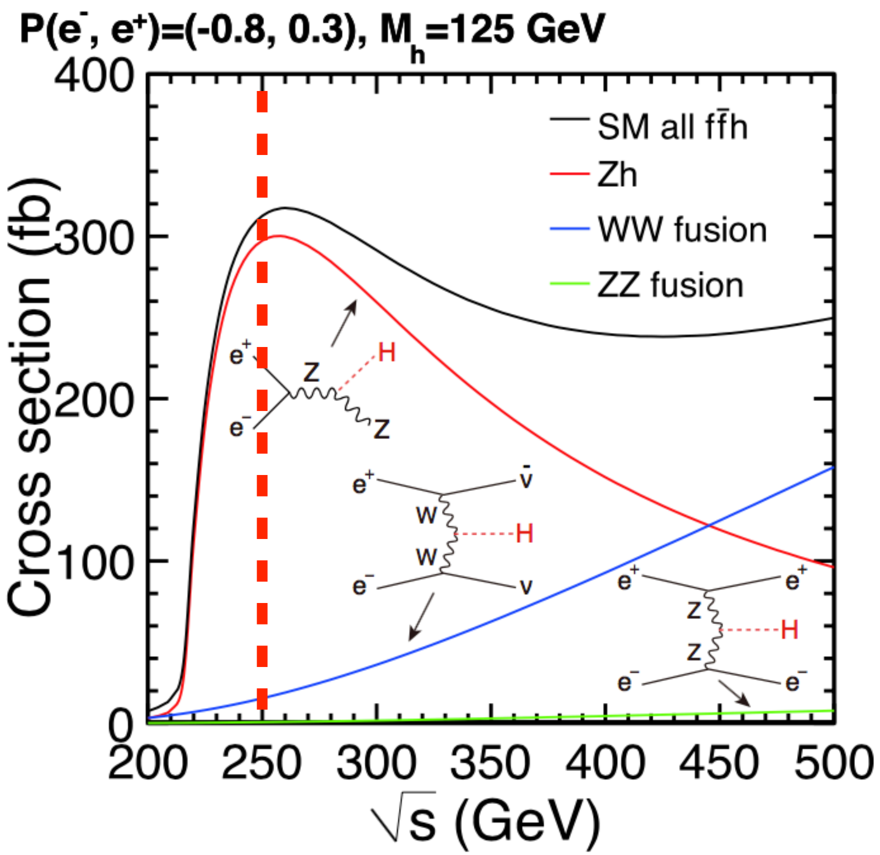


Image courtesy of Stuart Miles at FreeDigitalPhotos.net



$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$



Interlude: Chirality in Particle Physics

Just a quick reminder…

- Gauge group of weak x electromagnetic interaction: $SU(2)_L \times U(1)$
- L: left-handed, spin anti-|| momentum*
  R: right-handed, spin || momentum*

- **left-handed particles are fundamentally different from right-handed ones:**
  - only left-handed fermions (e^-) and right-handed anti-fermions (e^+) take part in the charged weak interaction, i.e. couple to the W bosons
  - there are (in the SM) no right-handed neutrinos
  - right-handed quarks and charged leptons are singlets under $SU(2)_L$
  - also couplings to the Z boson are different for left- and right-handed fermions

$$P = \frac{N_R - N_L}{N_R + N_L}$$

- **checking whether the differences between L and R are as predicted in the SM is a very sensitive test for new phenomena!**

* for massive particles, there is of course a difference between chirality and helicity, no time for this today, ask at the end in case of doubt!

Physics benefits of polarised beams

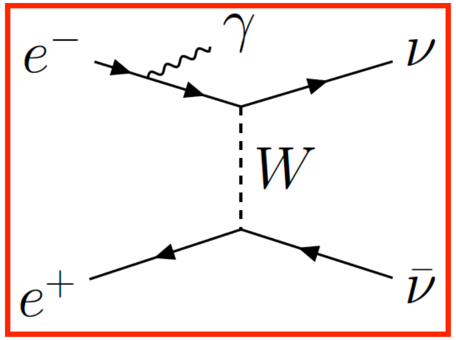
Much more than statistics!

General references on polarised e^+e^- physics:

- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

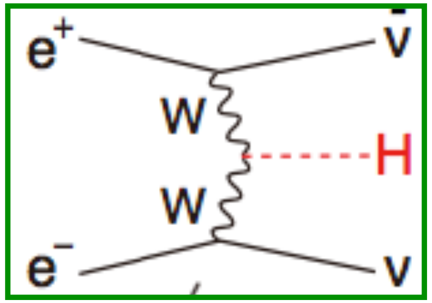
background suppression:

- $e^+e^- \to WW$ / $\nu_e \nu_e$ strongly P-dependent since t-channel only for $e^-_L e^+_R$



signal enhancement:

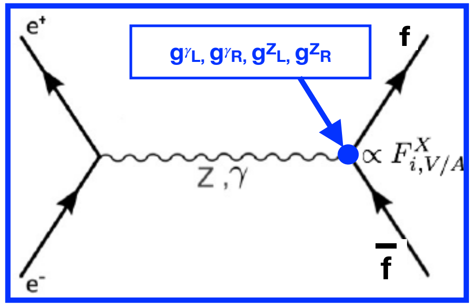
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions



- BSM:
chiral structure unknown, needs to be determined!

redundancy & control of systematics:

- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

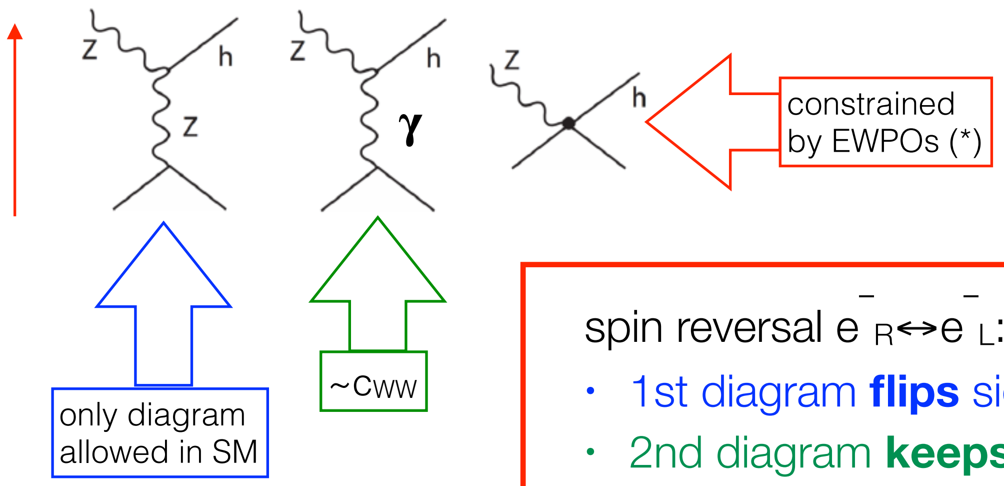
Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

- **THE key process** at a Higgs factory:

  Higgsstrahlung $e^+e^- \to Zh$

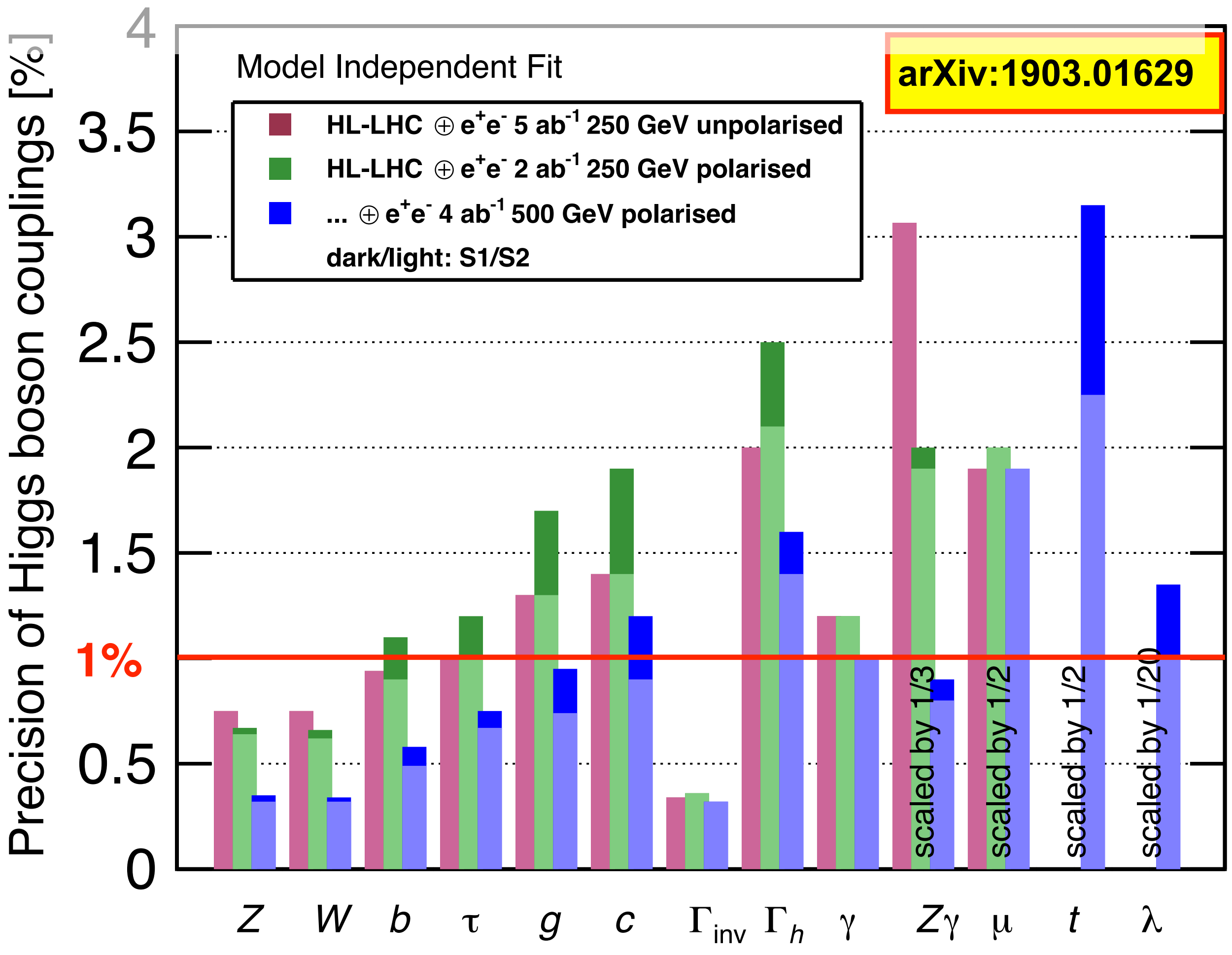
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



spin reversal $e^-_R \leftrightarrow e^-_L$:

- 1st diagram **flips** sign
- 2nd diagram **keeps** sign

⇒ **A_{LR} lifts degeneracy between operators!**



★ **2 ab⁻¹ polarised ≈ 5 ab⁻¹ unpolarised**

★ **that's why all e+e- Higgs factories perform so similar!**

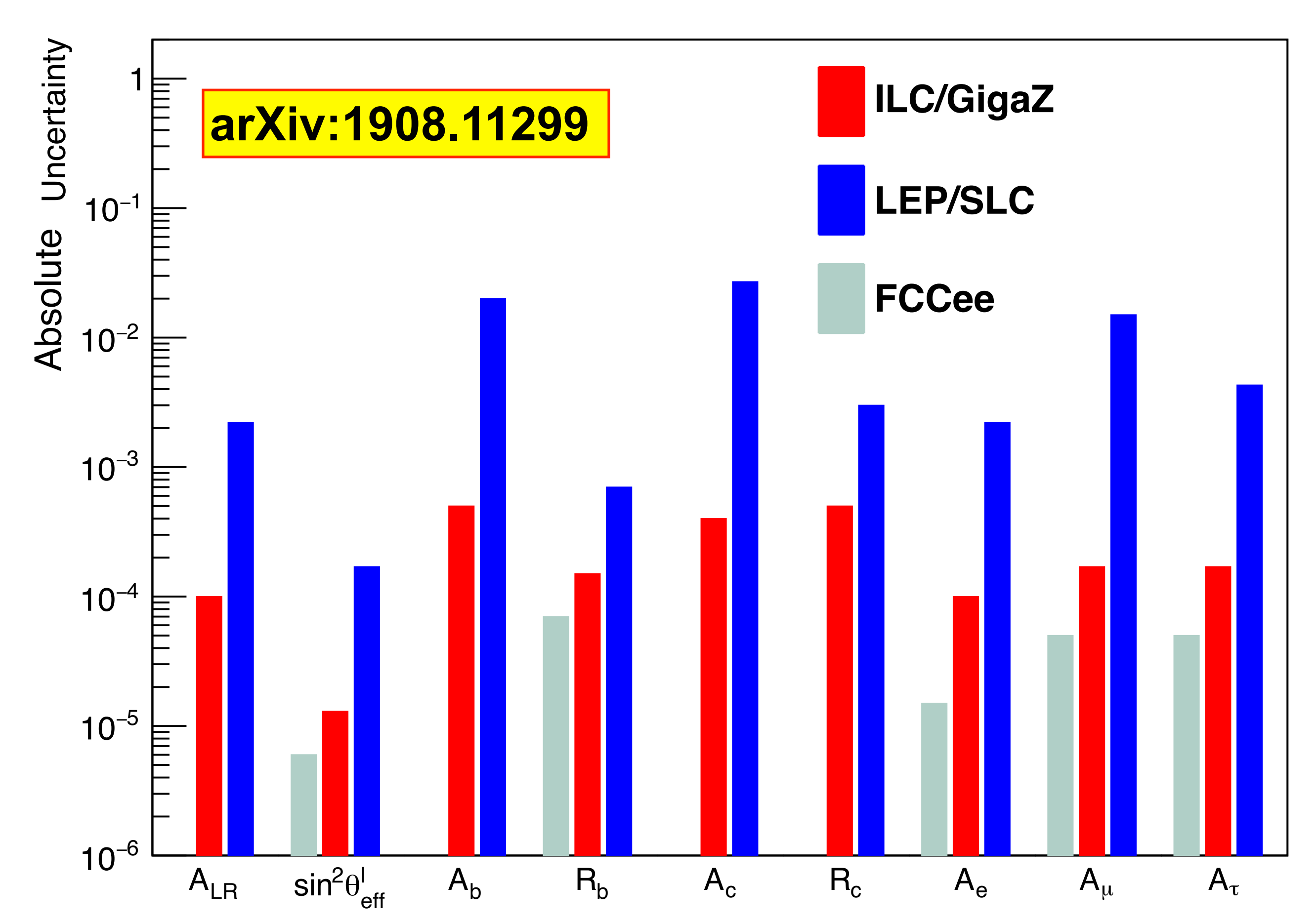
Polarisation & Electroweak Physics at the Z pole

LEP, ILC, FCCee

recent detailed studies by ILD@ILC:

- at least factor 10, often ~50 improvement over LEP/SLC
- note in particular:
  - **A_c nearly 100 x better** thanks to excellent charm / anti-charm tagging:
    - excellent vertex detector
    - tiny beam spot
    - Kaon-ID via dE/dx in ILD's TPC

polarised "GigaZ" typically only factor 2-3 less precise than FCCee's unpolarised *TeraZ*
=> polarisation buys
a factor of ~100 in luminosity



Note: not true for pure decay quantities!

Top Quark Operators

SMEFT

Relevant operators			
Coefficient	Operator	Coefficient	Operator
$C^1_{\varphi Q}$	$(\bar{Q}\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$	$C^3_{\varphi Q}$	$(\bar{Q}\tau^I\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi\right)$
$C_{\varphi t}$	$(\bar{t}\gamma^\mu t)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$	$C_{\varphi b}$	$(\bar{b}\gamma^\mu b)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$
$C_{t\varphi}$	$(\bar{Q}t)\left(\epsilon\varphi^*\ \varphi^\dagger\varphi\right)$	C_{tG}	$(\bar{t}\sigma^{\mu\nu}T^A t)\left(\epsilon\varphi^* G^A_{\mu\nu}\right)$
C_{tW}	$(\bar{Q}\tau^I\sigma^{\mu\nu}t)\left(\epsilon\varphi^* W^I_{\mu\nu}\right)$	C_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\left(\epsilon\varphi^* B_{\mu\nu}\right)$
$C^{1(ijkl)}_{qq}$	$(\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l)$	$C^{3(ijkl)}_{qq}$	$(\bar{q}_i\tau^I\gamma^\mu q_j)(\bar{q}_k\tau^I\gamma_\mu q_l)$
$C^{(ijkl)}_{uu}$	$(\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l)$	$C^{8(ijkl)}_{ud}$	$(\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l)$
$C^{8(ijkl)}_{qu}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l)$	$C^{8(ijkl)}_{qd}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l)$
C^1_{lQ}	$(\bar{Q}\gamma_\mu Q)\ (\bar{l}\gamma^\mu l)$	C^3_{lQ}	$(\bar{Q}\tau^I\gamma_\mu Q)\ (\bar{l}\tau^I\gamma^\mu l)$
C_{lt}	$(\bar{t}\gamma_\mu t)\ (\bar{l}\gamma^\mu l)$	C_{lb}	$(\bar{b}\gamma_\mu b)\ (\bar{l}\gamma^\mu l)$
C_{eQ}	$(\bar{Q}\gamma_\mu Q)\ (\bar{e}\gamma^\mu e)$	C_{et}	$(\bar{t}\gamma_\mu t)\ (\bar{e}\gamma^\mu e)$
C_{eb}	$(\bar{b}\gamma_\mu b)\ (\bar{e}\gamma^\mu e)$	–	–

Snowmass Implementation Task Force

arXiv:2208.06030

Consistent assessment of readiness, risks, costs etc - not always identical to projects self-assessment

Proposal Name	c.m. energy [TeV]	Luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	Yrs. pre-project R&D	Yrs. to 1st physics
FCC-ee[1,2]	0.24	7.7 (28.9)	0-2	13-18
CEPC[1,2]	0.24	8.3 (16.6)	0-2	13-18
ILC[3]-0.25	0.25	2.7	0-2	$<$12
CLIC[3]-0.38	0.38	2.3	0-2	13-18
CCC[3]	0.25	1.3	3-5	13-18

all rather similar in time for R&D and (technically needed) time to physics

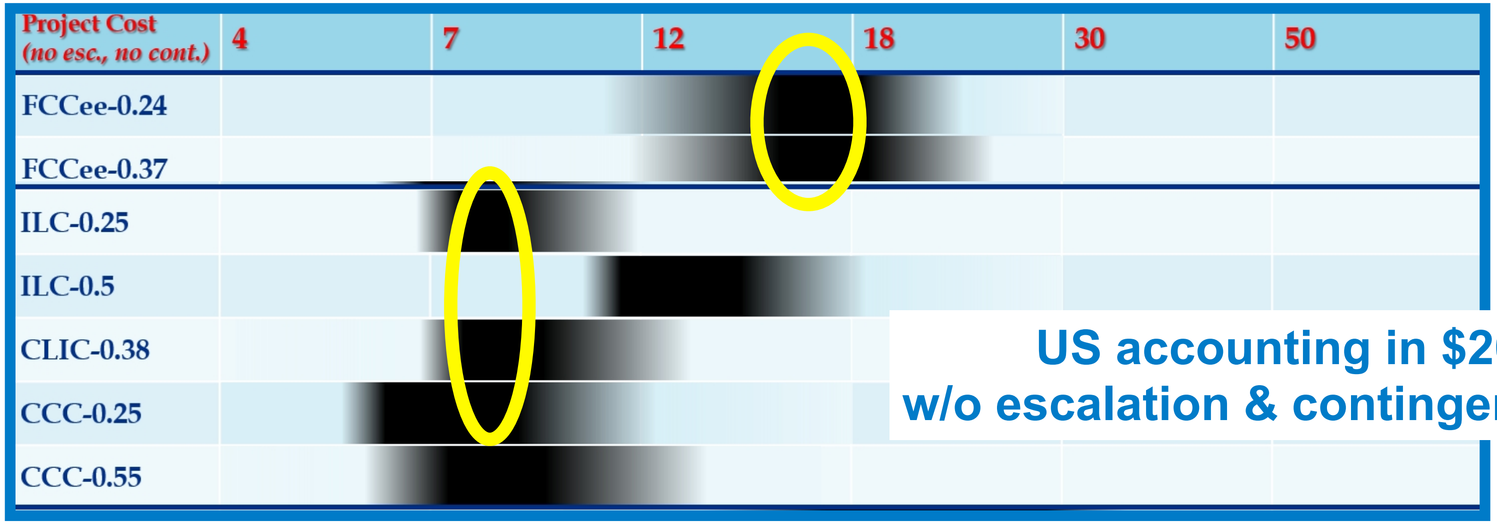
Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I

Circular colliders larger and more power hungry - but more lumi as well
CLIC more complex

Snowmass Implementation Task Force

arXiv:2208.06030

Consistent assessment of readiness, risks, costs etc - not always identical to projects self-assessment



Linear Higgs Factory ~7-8B$

Circular Higgs Factory ~15B$

Lowest Technology Readiness Levels

- RF systems
- e+ source

=> let's take a closer look at relevant R&D!

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II	RF sys,. e+ src, arc & booster magnets				1
CEPC-0.24	II					1
ILC-0.25	I	pol. e+ src				1
CCC-0.25	III	cryomodules, HOM detuning				2
CLIC-0.38	II	RF sys, 2-beam acc, emm. pres., spot size IP, stability				1

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