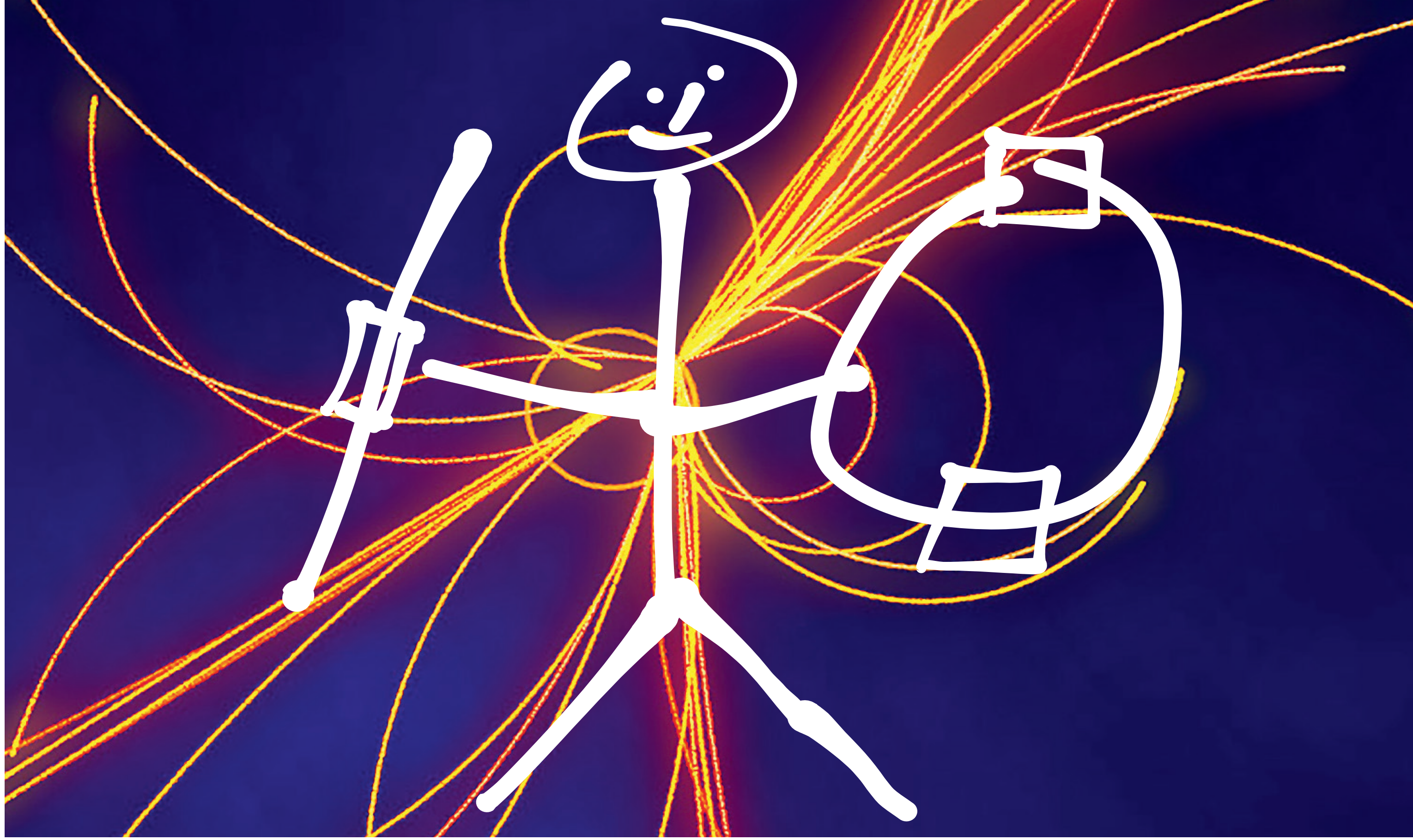
Overview of Linear Collider Projects

Physics, Technologies, Resources, Open Questions & Challenges



2024 European Edition of the International Workshop on the Circular Electron-Positron Collider

https://indico.in2p3.fr/e/cepc2024

Jenny List (DESY)
European CEPC Workshop
8-11 April 2024
Marseille

HELMHOLTZ

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Outline

Today's menu

- **Project Overview & Updates**
  - a tour across ILC, CLIC, C3 & HAL
- **Why a Linear Collider?**
  - physics, physics, physics…
- **Sustainability**
  - construction & operation
- **Instead of 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/
- **Special Workshops**
  - Cool Copper Collider 12 -13 Feb, SLAC, https://indico.slac.stanford.edu/event/8577
  - HALHF 4-5 April, Oslo, https://indico.cern.ch/event/1370201/

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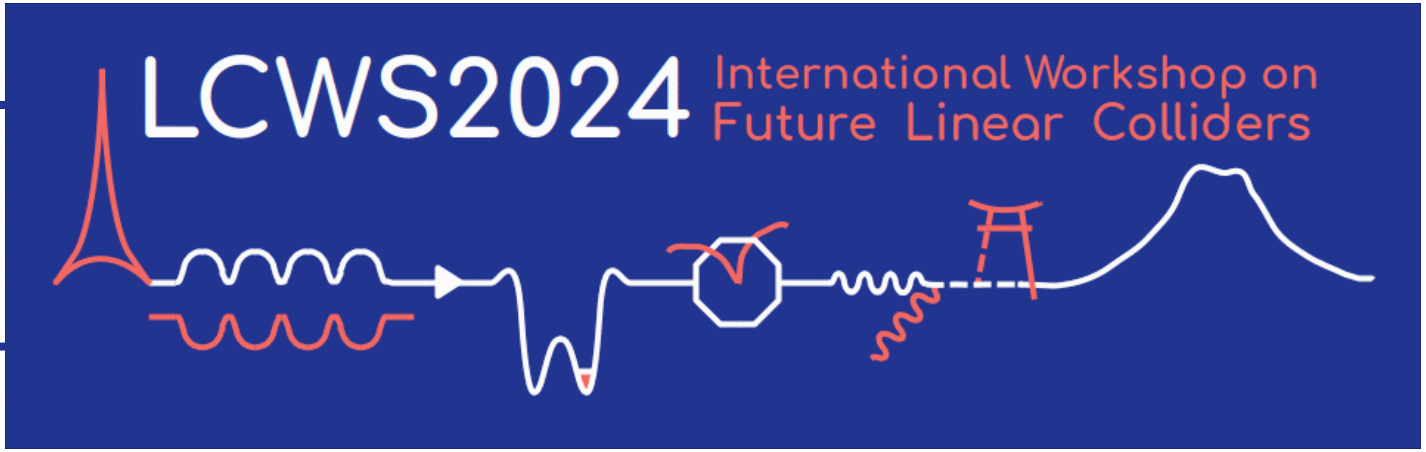
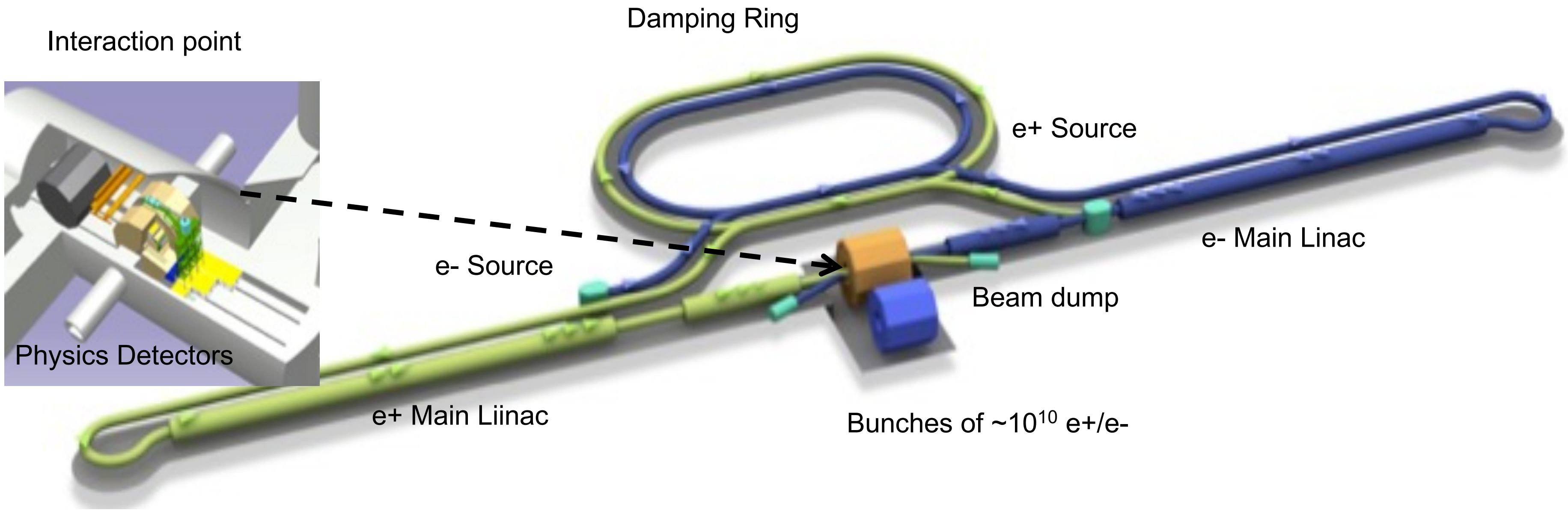
Upcoming:
LCWS 2024, July 8-11 in Tokyo
https://agenda.linearcollider.org/event/10134

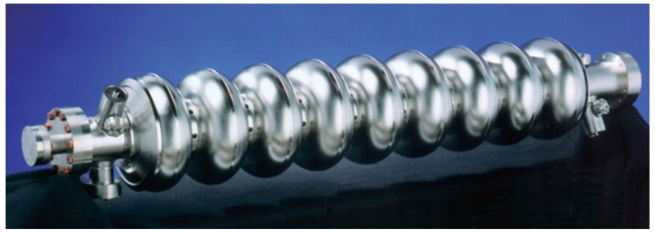


Project Overview & Updates

The ILC250 accelerator facility



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10 ^{10}



Parameters and plans for luminosity and energy upgrades are available, interesting and relevant SCRF R&D also for such upgrades (Snowmass input)

Key systems and challenges

The ILC is a very mature design, with a comprehensive TDR

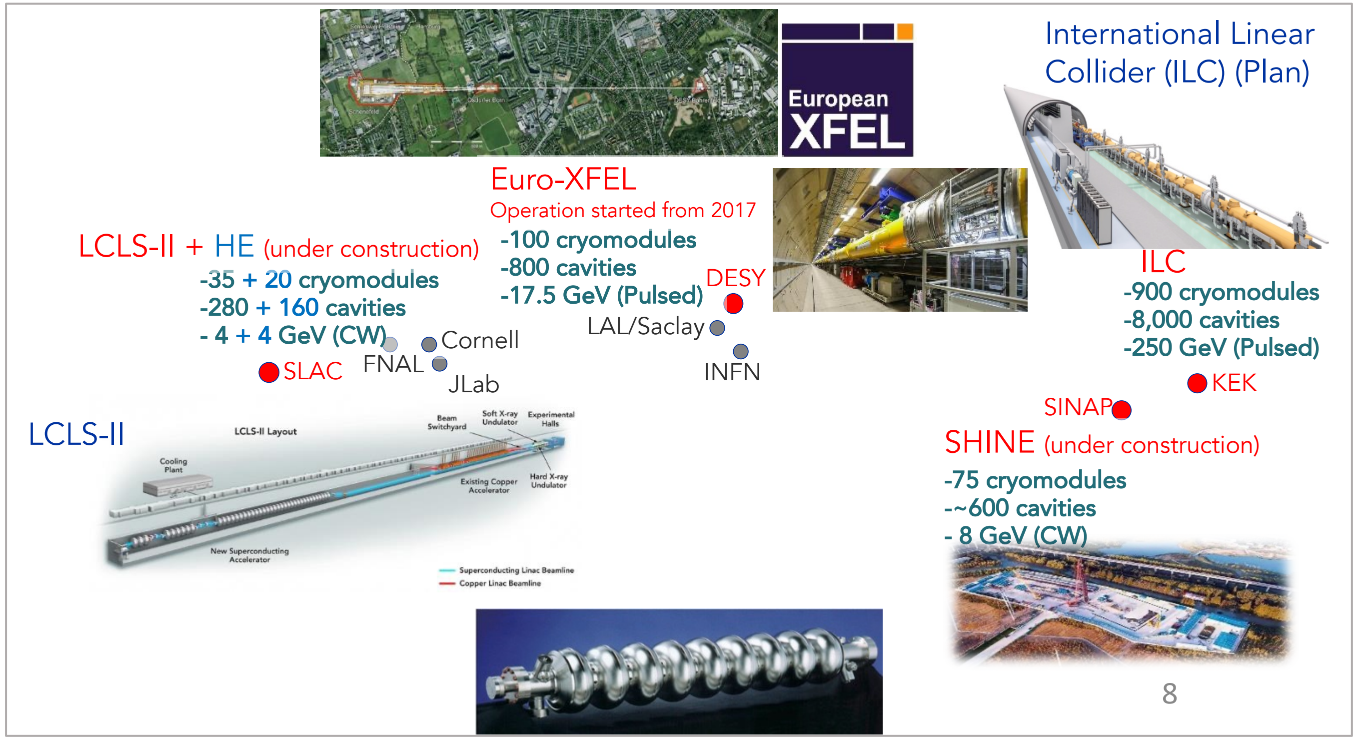
Next steps involve technical developments and industrial prototyping with final specs as needed for an Engineering Design and in preparation of pre-series and construction

- Creating particles — Sources
    - polarized elections/positrons
- High quality beam — Damping ring
    - low emittance beams
- Acceleration — Main linac
    - superconducting radio frequency (SRF)
- Collide them — Final focus
    - nano-meter beams
- Go to — Beam dumps

EU.XFEL:

Largest deployment of SCRF technology

- **100 cryomodules**
- **800 cavities**
- **17.5 GeV**
- **First beams 2016**



The ILC IDT organization – initiated at the ICFA meeting at SLAC February 2020

2020-21: The IDT – created by ICFA and hosted by KEK – was set up to move ILC towards construction. The worldwide structure of the WGs: https://linearcollider.org/team/
A set of key activities were identified in a Preparation Phase Programme.

2022-23: A subset of the technical activities of the full ILC preparation phase programme have been identified as critical (next slide). These are being addresses by a ~4 year programme called ITN – the ILC Technology Network. Moving forward with this work is being supported by the MEXT (ministry) providing crucial increased funding.

As of today: With funding from 1.4.2023 ITN is now starting. An agreement KEK and CERN and several European lab activities have been/are being set up. In the US the P5 process is ongoing, the hope is that ITN planning and interests can turn into important ITN involvements in due time.

The ITN

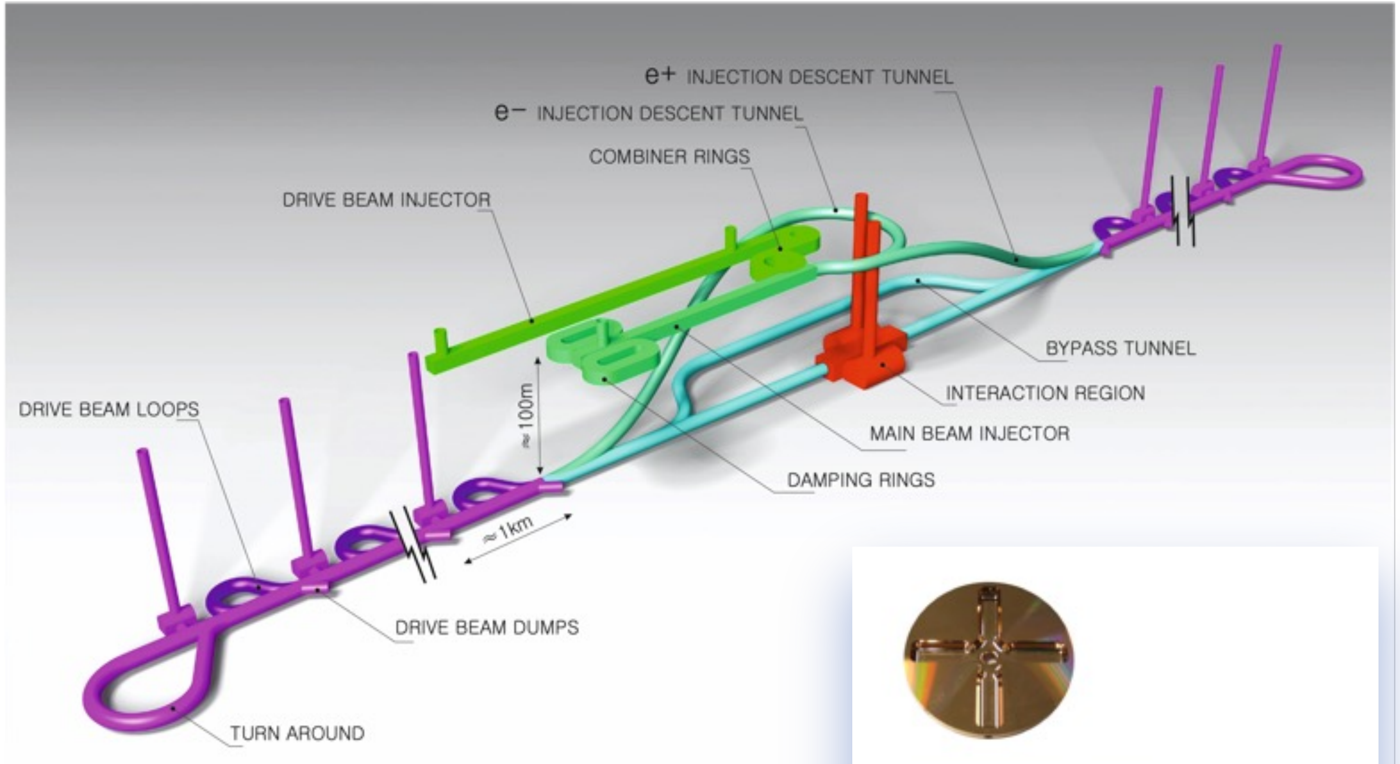
Promoting the technological development of the International Linear Collider:
Twenty-eight research institutes participated in the ITN Information Meeting

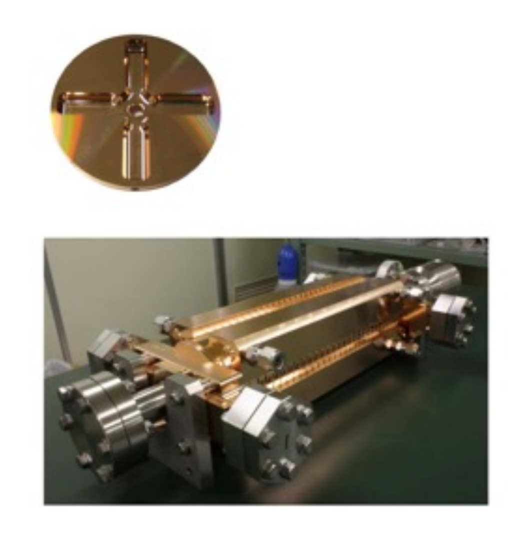
WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

Building the ITN activities:
- Planning in the IDT WG2 – significant interests and expertise already represented
- Information meeting at CERN 16-17.10 jointly organized by KEK and the IDT
- Interest matrix for the ITN work-packages, being consolidated
- The next step: Further technical discussion to define deliverables, followed by agreement who among the laboratories will deliver what

SRF	WPP	1	Cavity production	✓		✓	✓	✓			✓	✓	✓				✓	✓	✓		✓	✓		✓	✓	
	WPP	2	CM design	✓				✓				✓			✓	✓	✓	✓	✓			✓		✓	✓	
	WPP	3	Crab cavity			✓	✓							✓					✓			✓	✓		✓	✓
Sources	WPP	4	E-source			✓						✓							✓		✓			✓		
	WPP	6	Undulator target				✓												✓	✓			✓			
	WPP	7	Undulator focusing				✓												✓	✓			✓			
	WPP	8	E-driven target	✓		✓												✓	✓							
	WPP	9	E-driven focusing	✓														✓	✓							
	WPP	10	E-driven capture	✓															✓					✓		
	WPP	11	Target replacement	✓																						
Nano-beams	WPP	12	DR System design	✓	✓				✓	✓		✓							✓				✓	✓		
	WPP	14	DR Injection/extraction	✓					✓										✓				✓	✓		
	WPP	15	Final focus	✓			✓		✓		✓							✓			✓			✓		
	WPP	16	Final doublet	✓	✓													✓								
	WPP	17	Main dump	✓			✓					✓														

The Compact Linear Collider (CLIC)





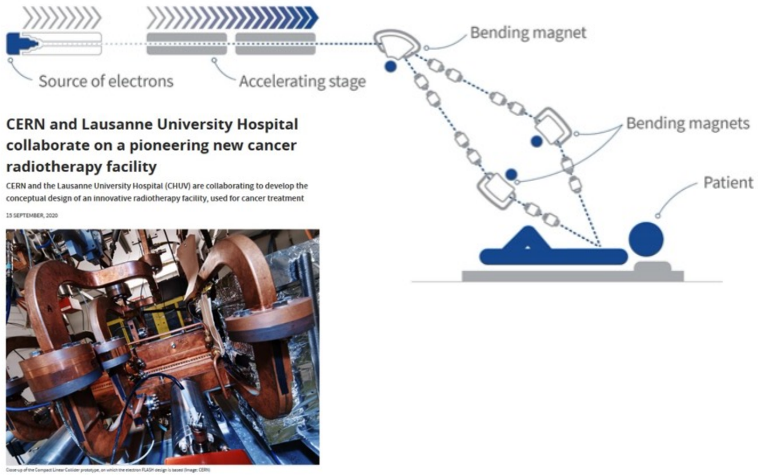
Accelerating structure prototype for CLIC: 12 GHz (L~25 cm), 100 MV/m

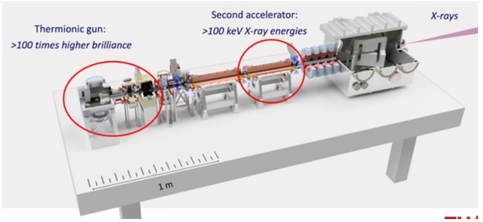
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

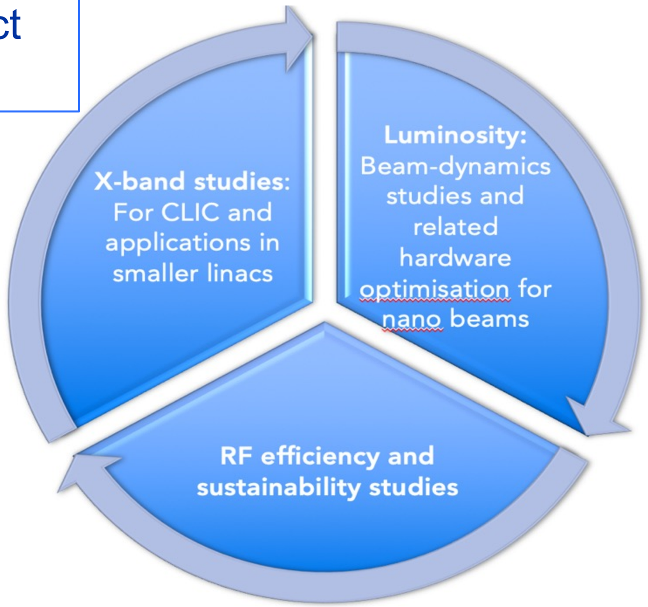
On-going CLIC studies towards next ESPP update

Project Readiness Report as a step toward a TDR
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

The X-band technology readiness for the 380 GeV CLIC initial phase - manufacturability and developments driven by use in small compact accelerators for industrial experience



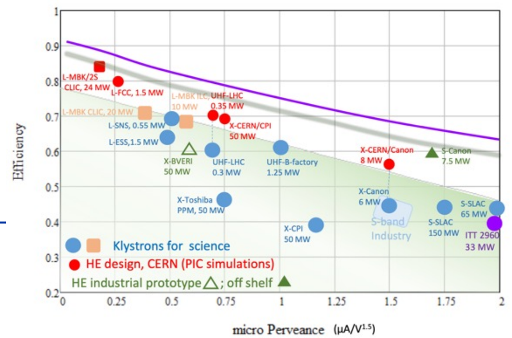




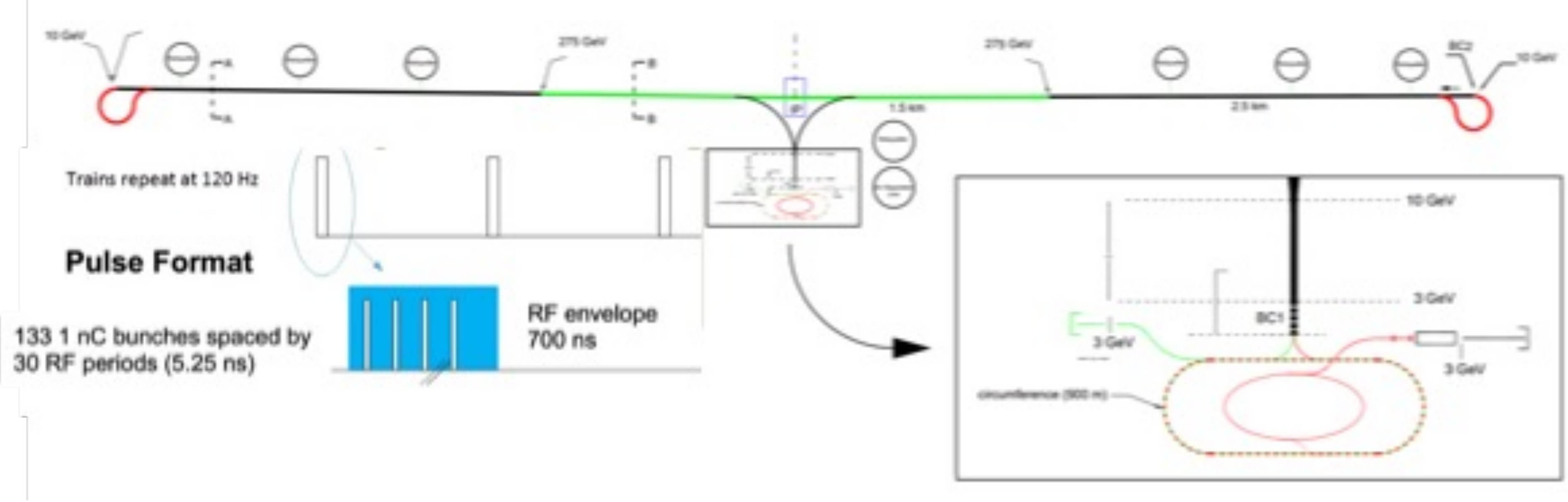
Optimizing the luminosity at 380 GeV at 2.3 x 10^{34} cm^{-2} s^{-1}– already implemented for Snowmass paper, further work to provide margins will continue (HW and SW)

Project summary for Snowmass:
https://arxiv.org/pdf/2203.09186.pdf

Improving the **power efficiency** for both the initial phase (already in Snowmass report) and at high energies, including more **general sustainability studies** (in many cases done together with ILC – see later)



C^3 Accelerator Complex



8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m
Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline

Snowmass paper: https://arxiv.org/pdf/2203.07646.pdf

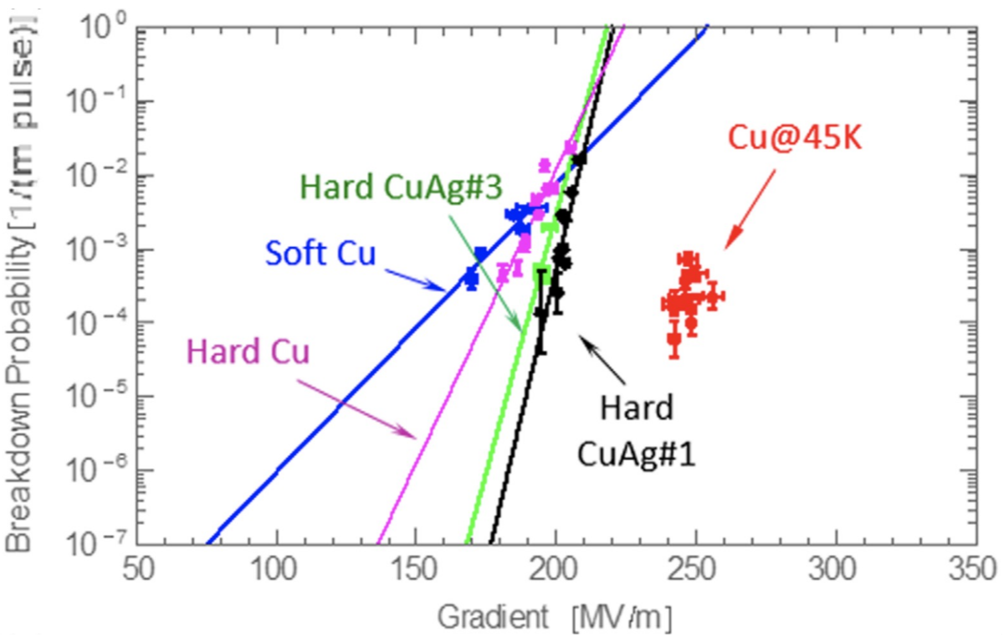
C^3 Parameters

Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

Cryo-Copper: Enabling High-Gradient Operation

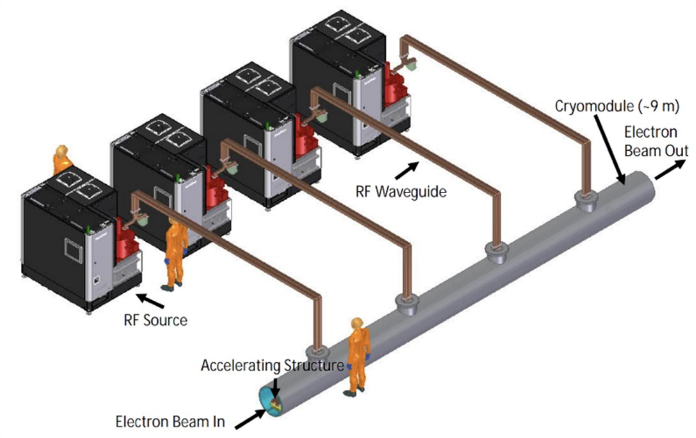
Cryogenic temperature (LN_2 at 80k) elevates gradient performance

- Increased material strength is key factor
- Increase electrical conductivity reduces pulsed heating in the material

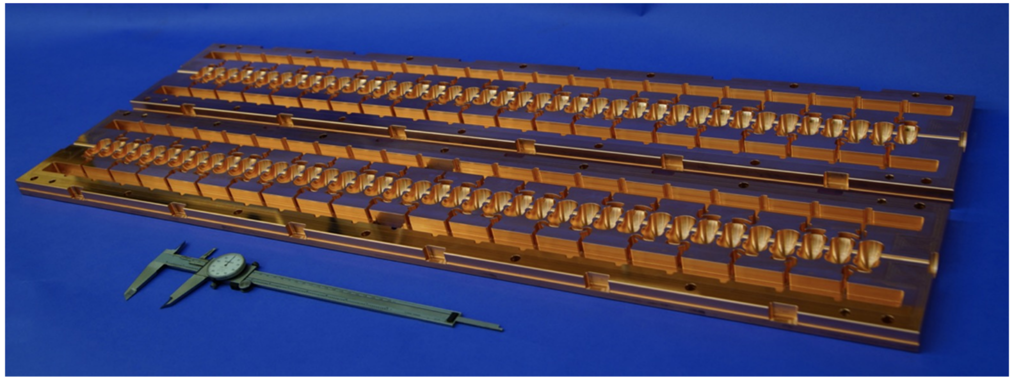


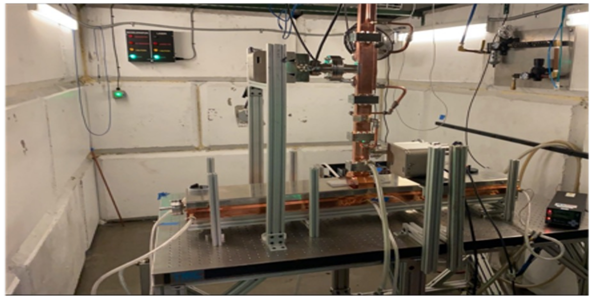
Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



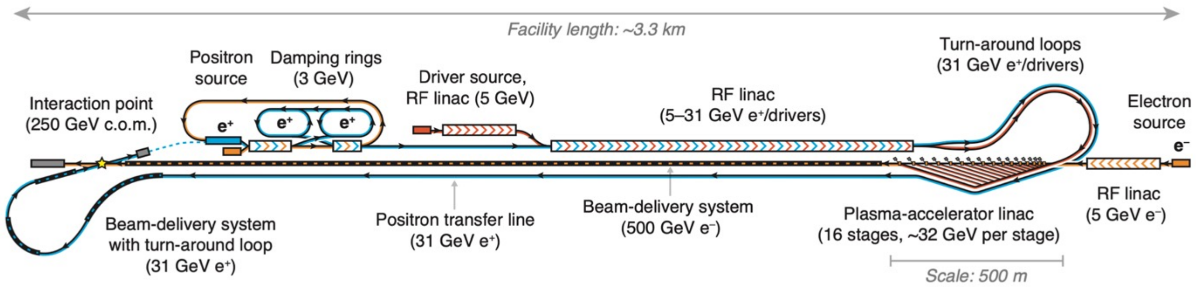
C^3 Prototype One Meter Structure





High power Test at Radiabeam

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

> Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**

  > Length dominated by e^- beam-delivery system

New concept, aiming for pre-CDR end 2024:

- 500 GeV for electrons with plasma acceleration
- 31 GeV positrons with RF based linac, used also to provide electron drivebeam for the plasma acceleration
- Reach 250 GeV collision energy, luminosity 10^{34}
- Paper: https://arxiv.org/pdf/2303.10150.pdf

Asymmetric technologies, energies and bunch charges

Small footprint, lower cost (half again?)

Several key plasma acc. challenges:
Multi-staging, emittances, energy spread, stabilities, spin polarisation preservation, efficiencies, rep rate, plasma cell cooling and more

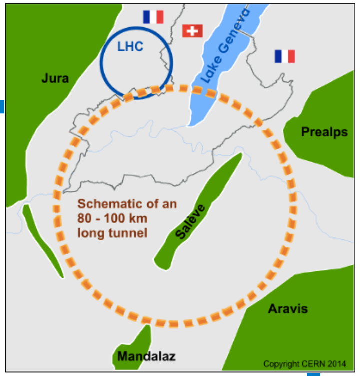
Conventional beam(s) challenges:
Positron production, damping rings, RF linac, beam delivery system

Experimental challenges with asymmetric beams

Why a linear collider?

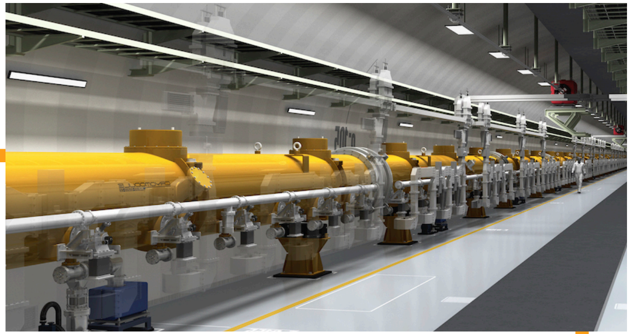
Circular or Linear Collider?

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, …
- length 250 GeV: 4…11…20 km
- high luminosity & power efficiency at **high energies**
- **longitudinally spin-polarised beam(s)**

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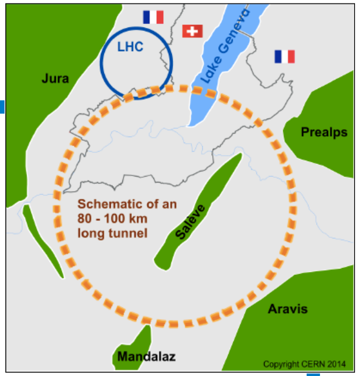

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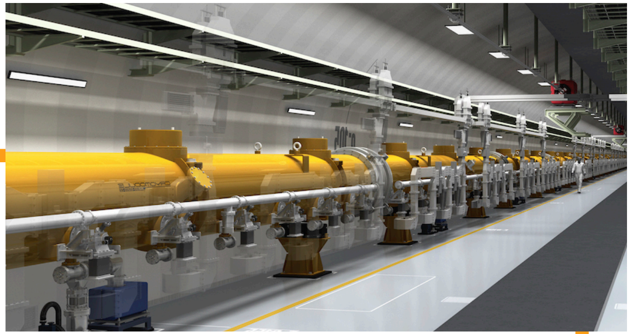
Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge



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- length 250 GeV: 4…11…20 km
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Long-term upgrades: energy extendability

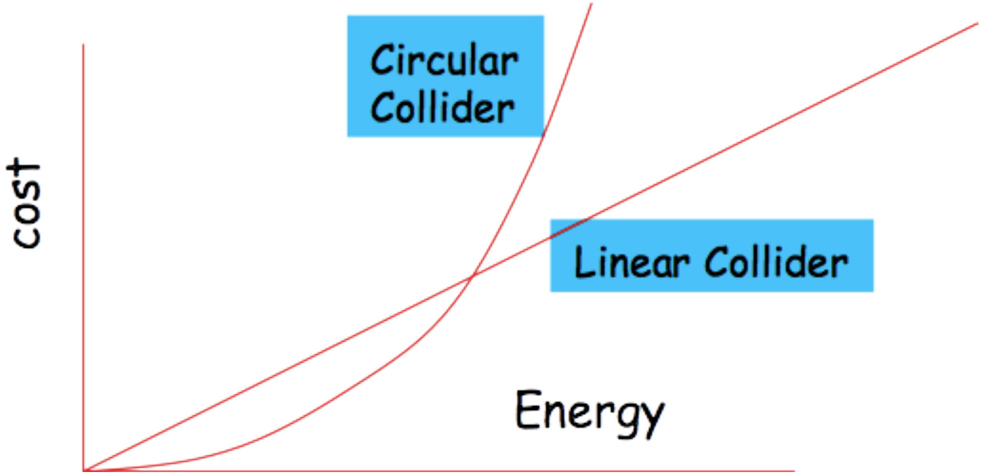
- same technology: by increasing length
- **or by replacing accelerating structures with advanced technologies**
  - RF cavities with high gradient
  - plasma acceleration ?

Luminosity vs Energy - a long debate…

Reminder: accelerated charges radiate

- **Synchrotron radiation ~ operation cost:**
  - **$\Delta E \sim (E^4 / m^4 R)$** per turn => 2 GeV at LEP2
- **Cost in high-energy limit:**
  - **circular :** \$\$ ~ a R + b **ΔE** ~ a R + b (**E^4 / m^4R**)

    optimize => $R \sim E^2$ => **\$\$ ~ E^2**
  - **linear :** \$\$ ~ **L**, with **L ~ E** => **\$\$ ~ E**



1978[1]

LIMITATIONS ON PERFORMANCE OF e^+e^- STORAGE RINGS AND LINEAR COLLIDING BEAM SYSTEMS AT HIGH ENERGY

J.-E. Augustin*, N. Dikanski†, Ya. Derbenev†, J. Rees‡, B. Richter‡, A. Skrinski†, M. Tigner**, and H. Wiedemann‡

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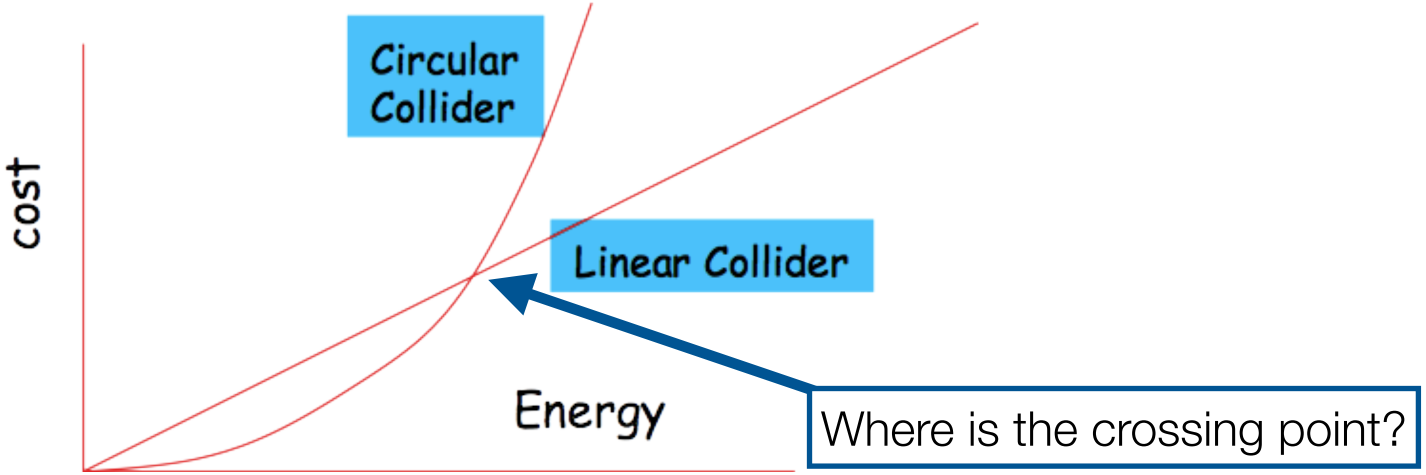

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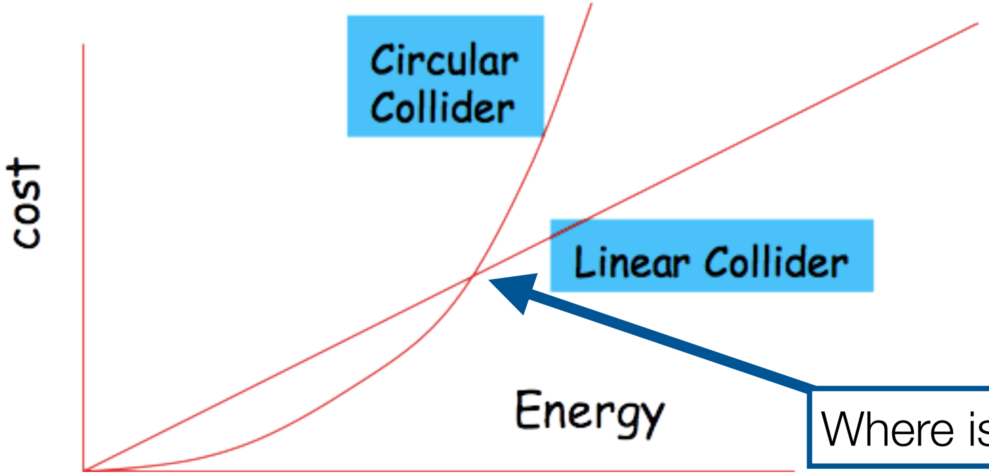

Where is the crossing point?

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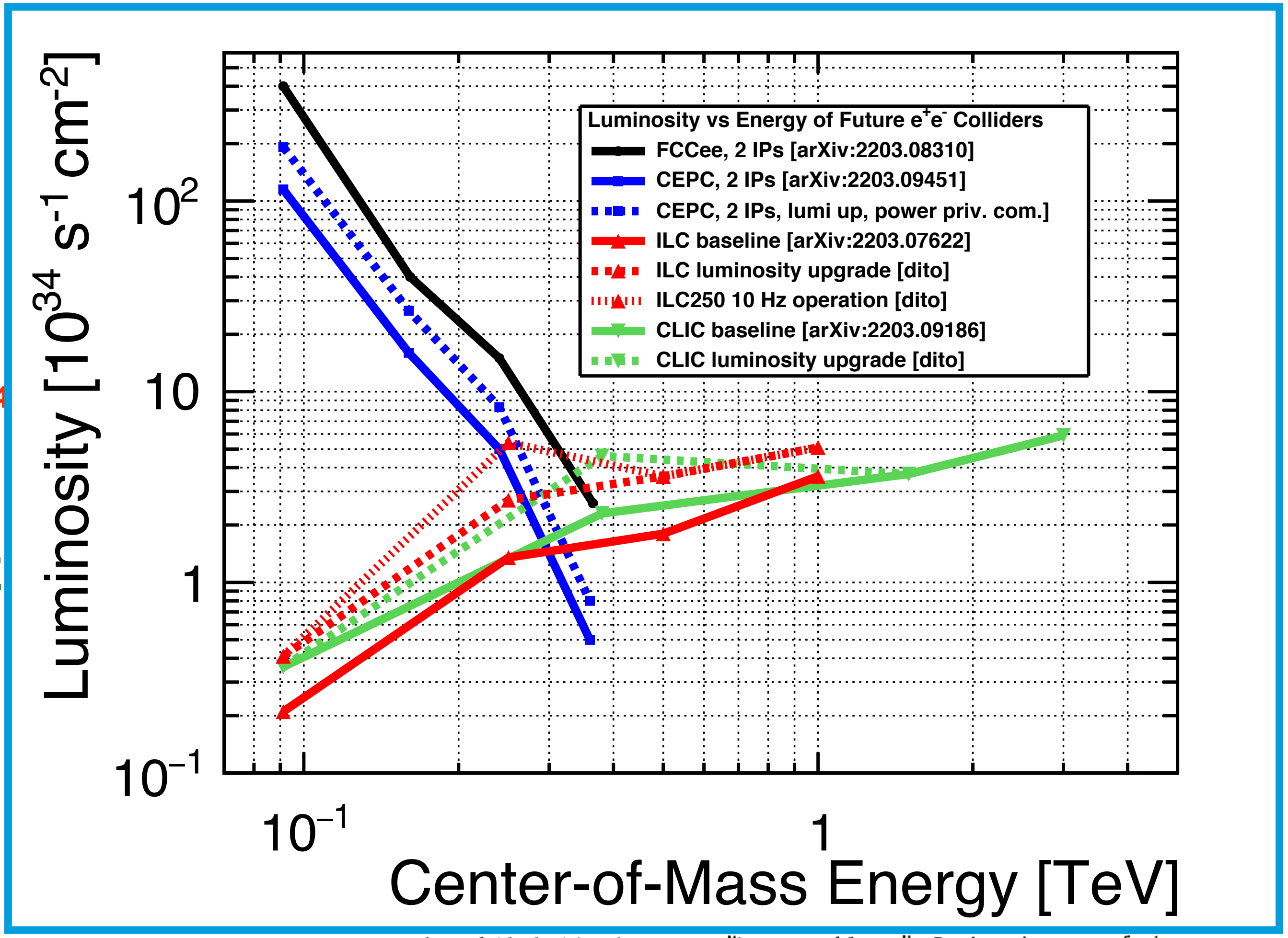

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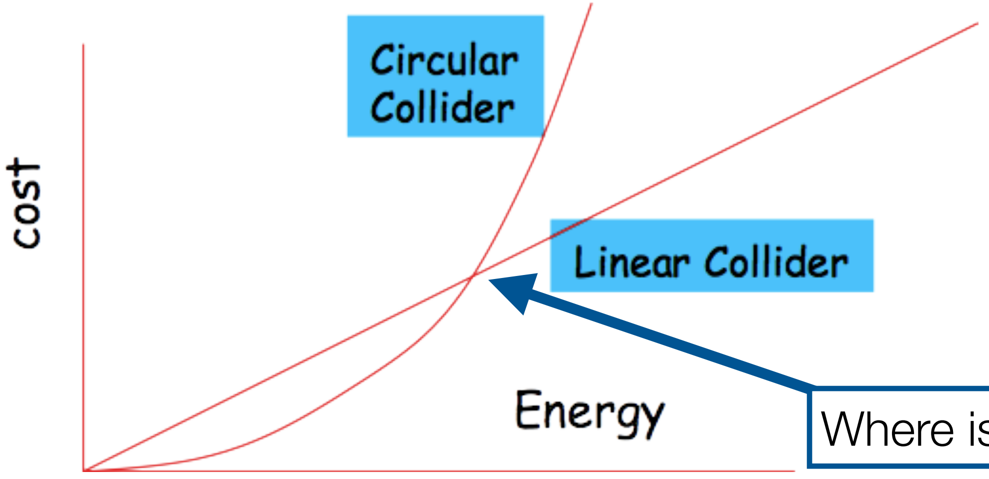

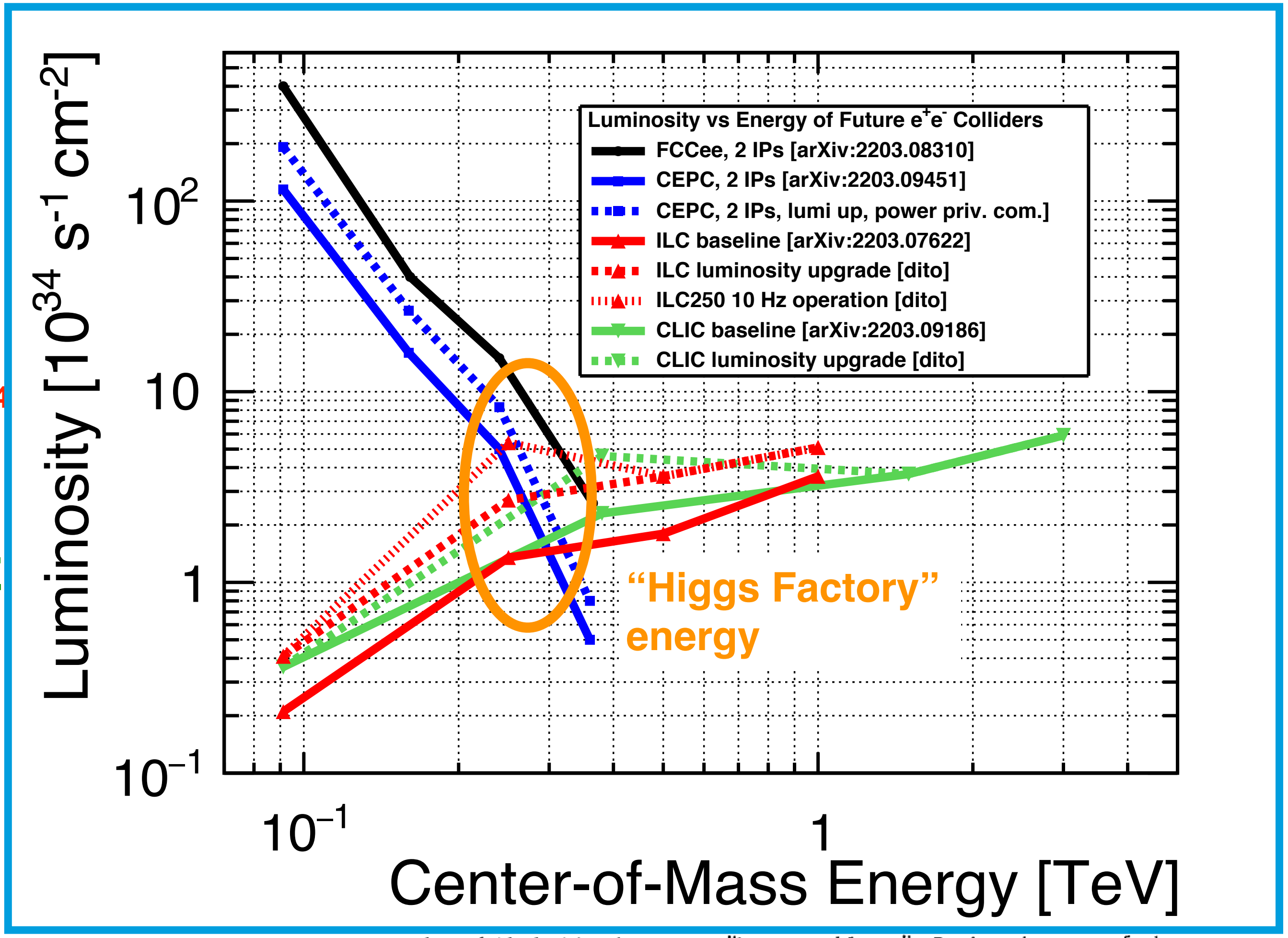

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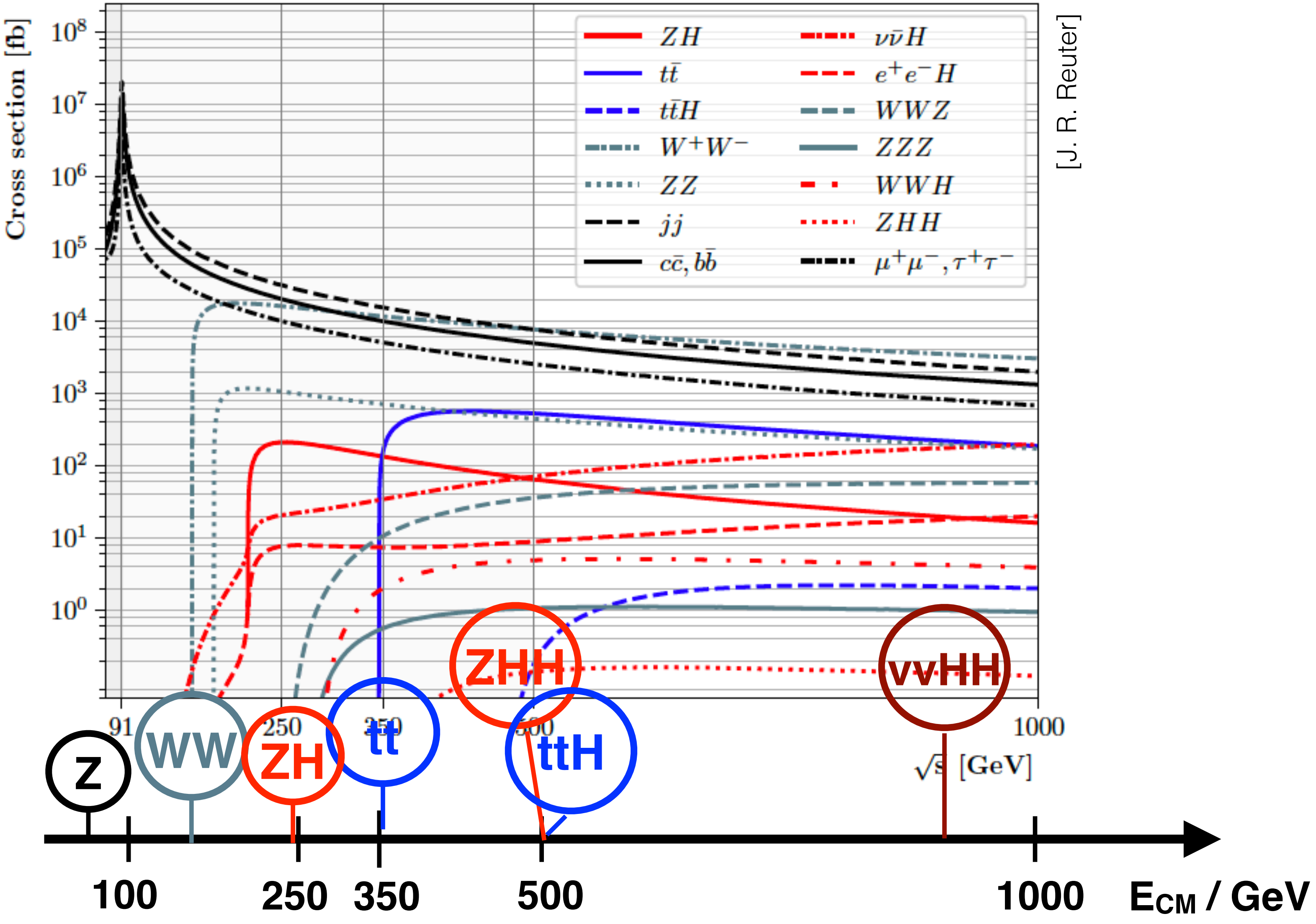
The key physics at a Higgs Factory

Production rates vs collision energy



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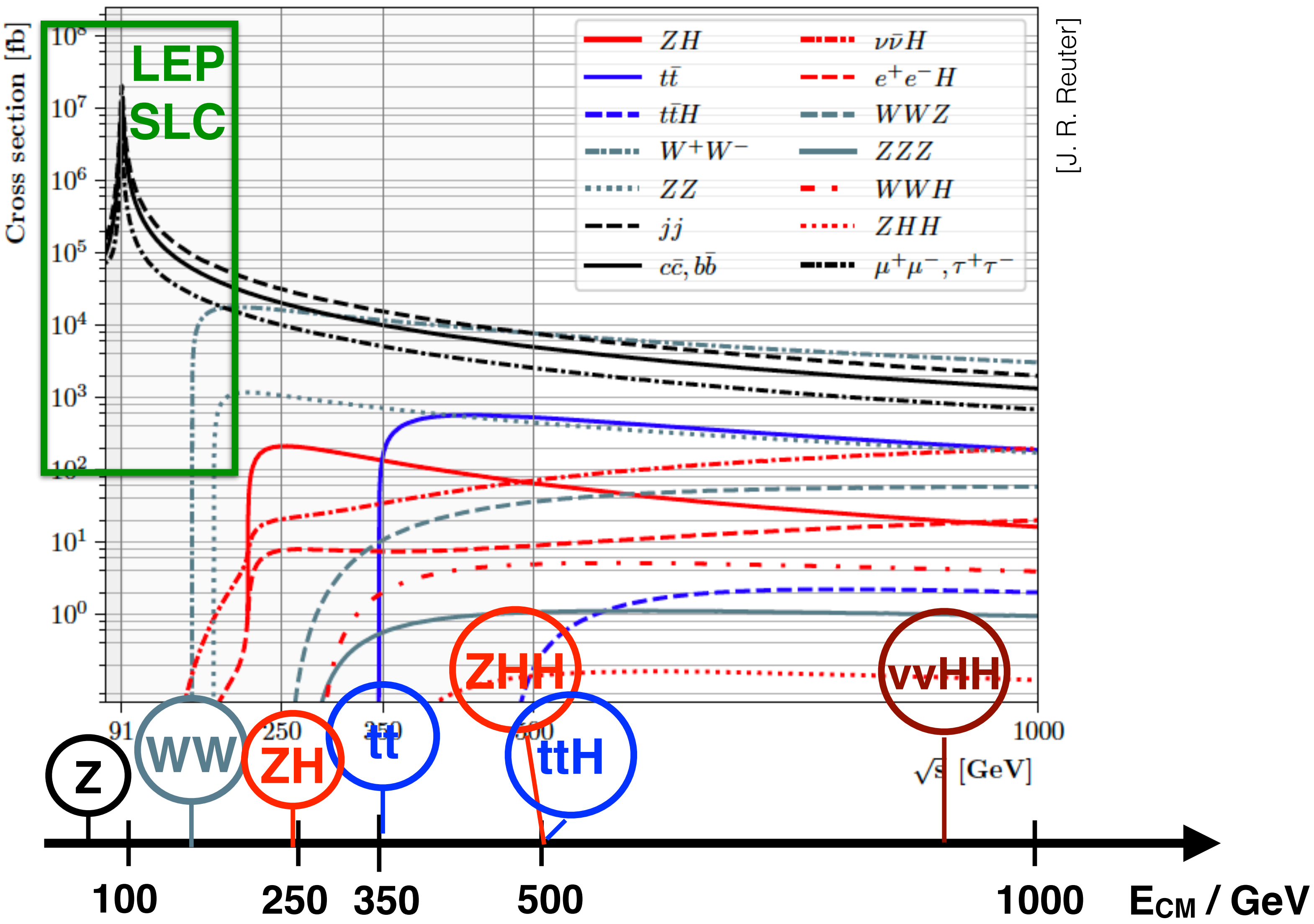

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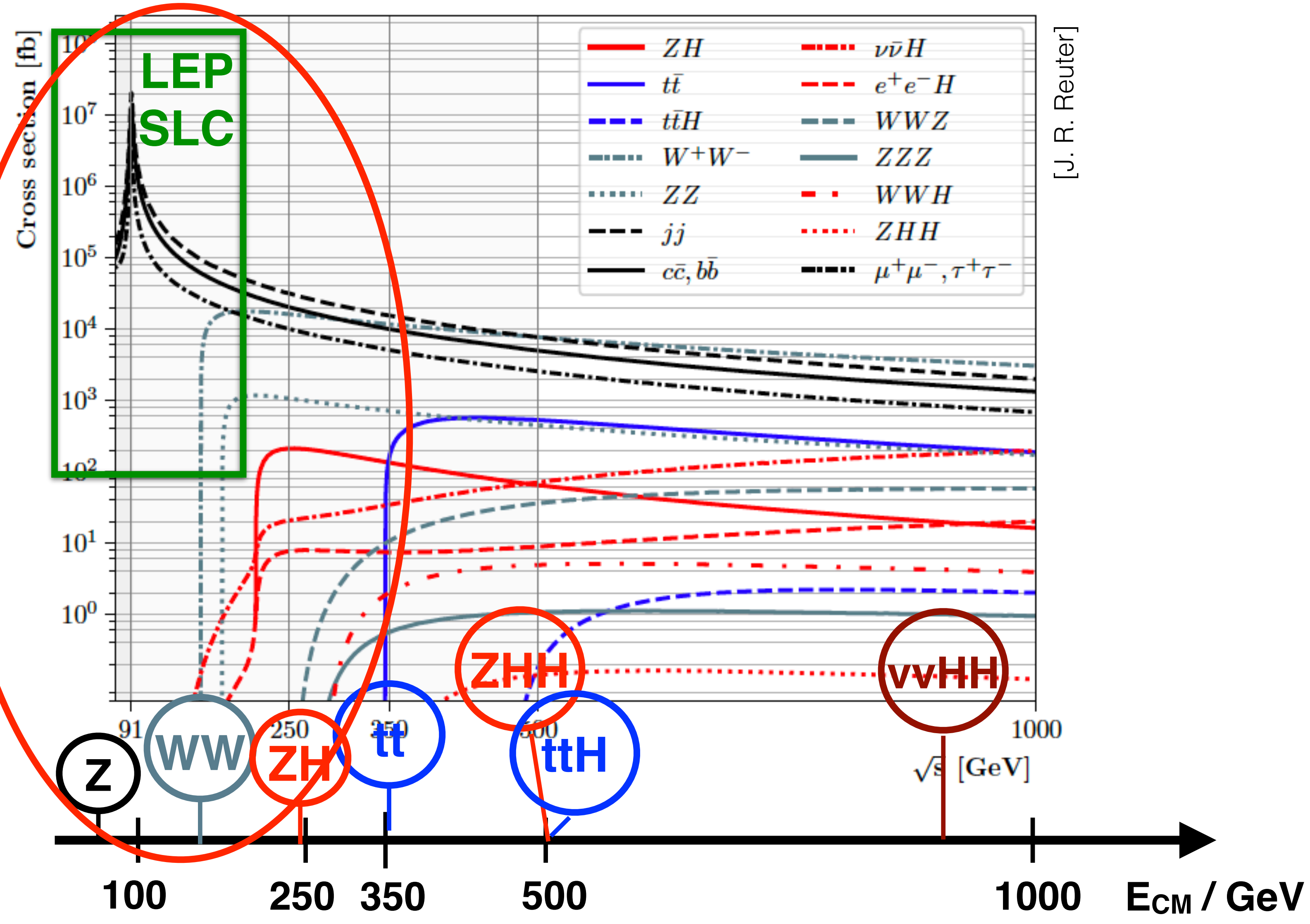
considered by all proposed e+e- projects



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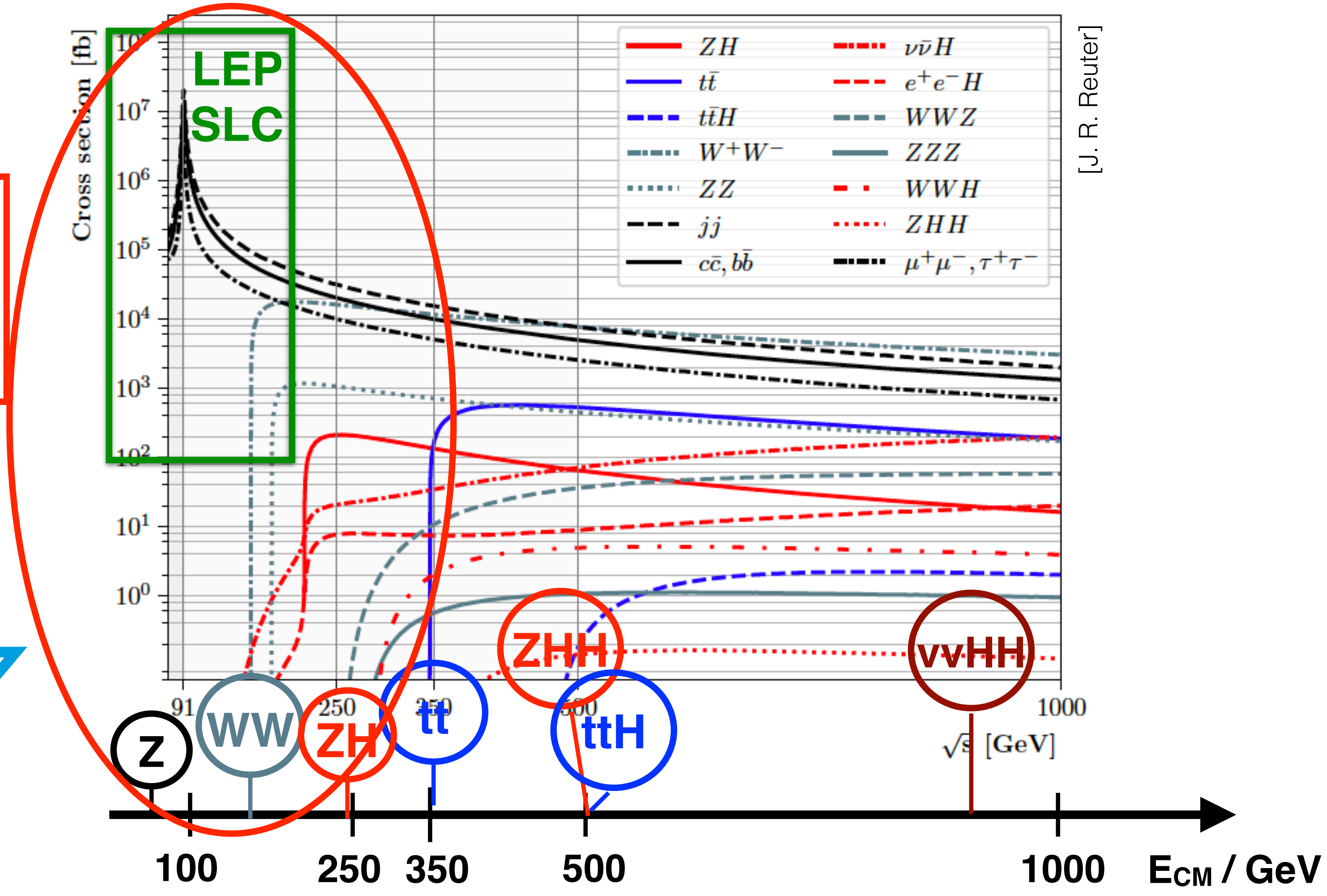
Circular Colliders



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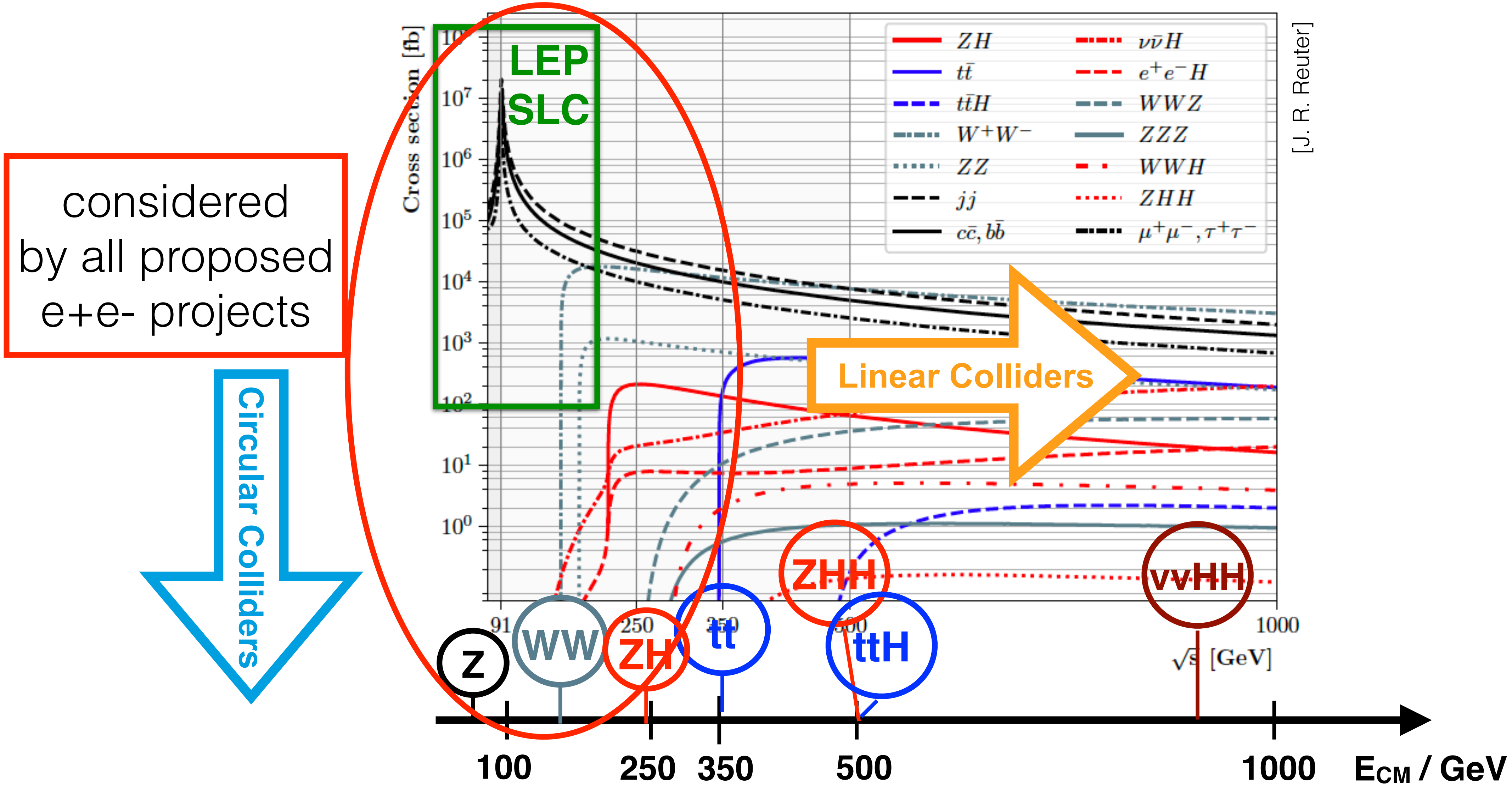
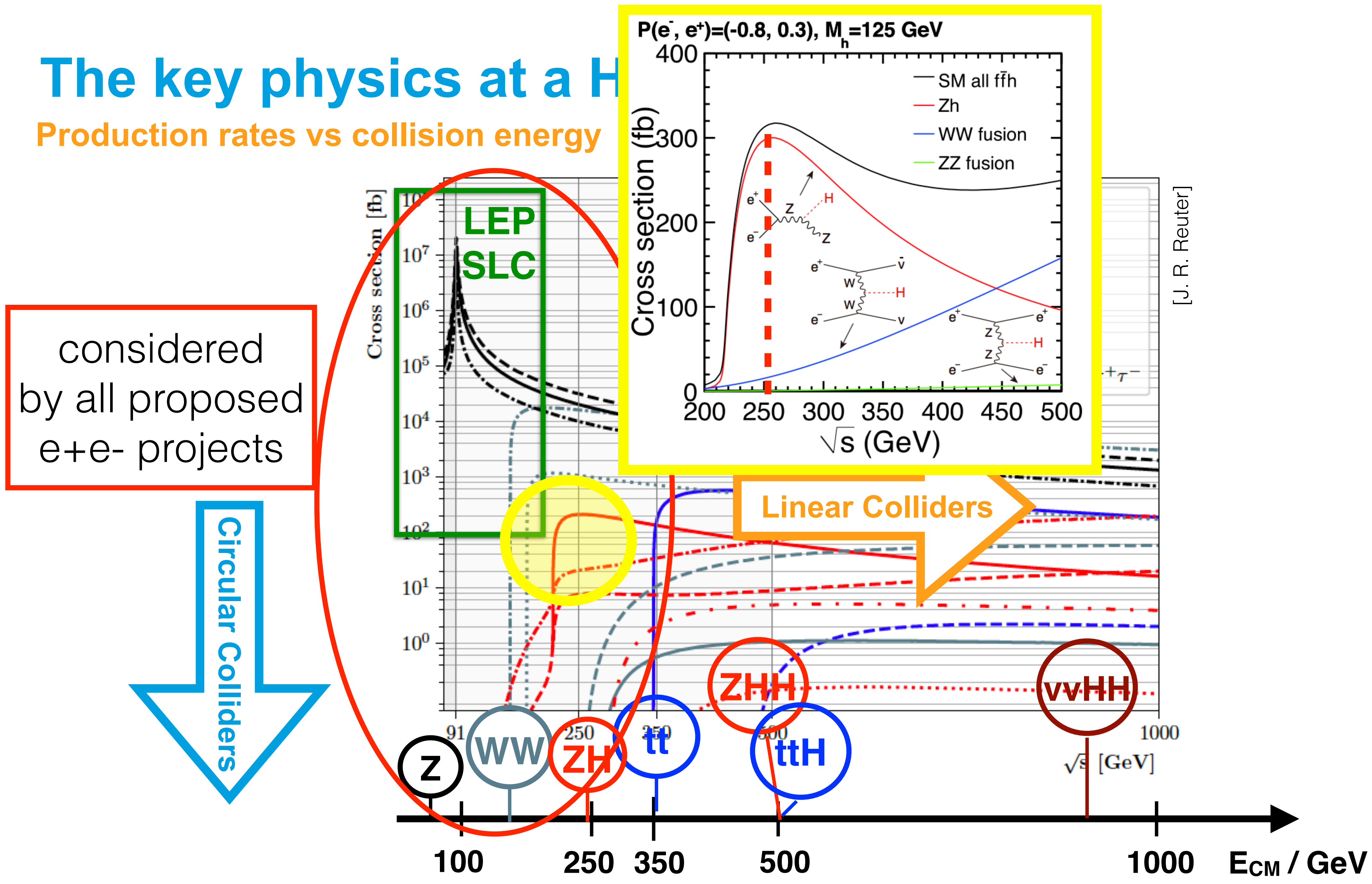


The key physics at a H

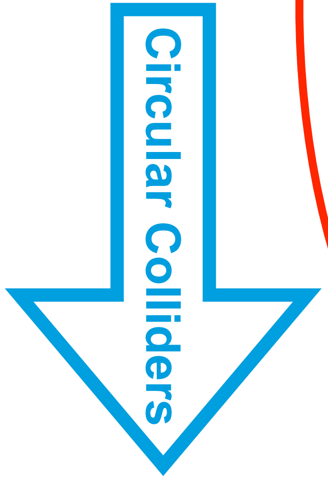
Production rates vs collision energy

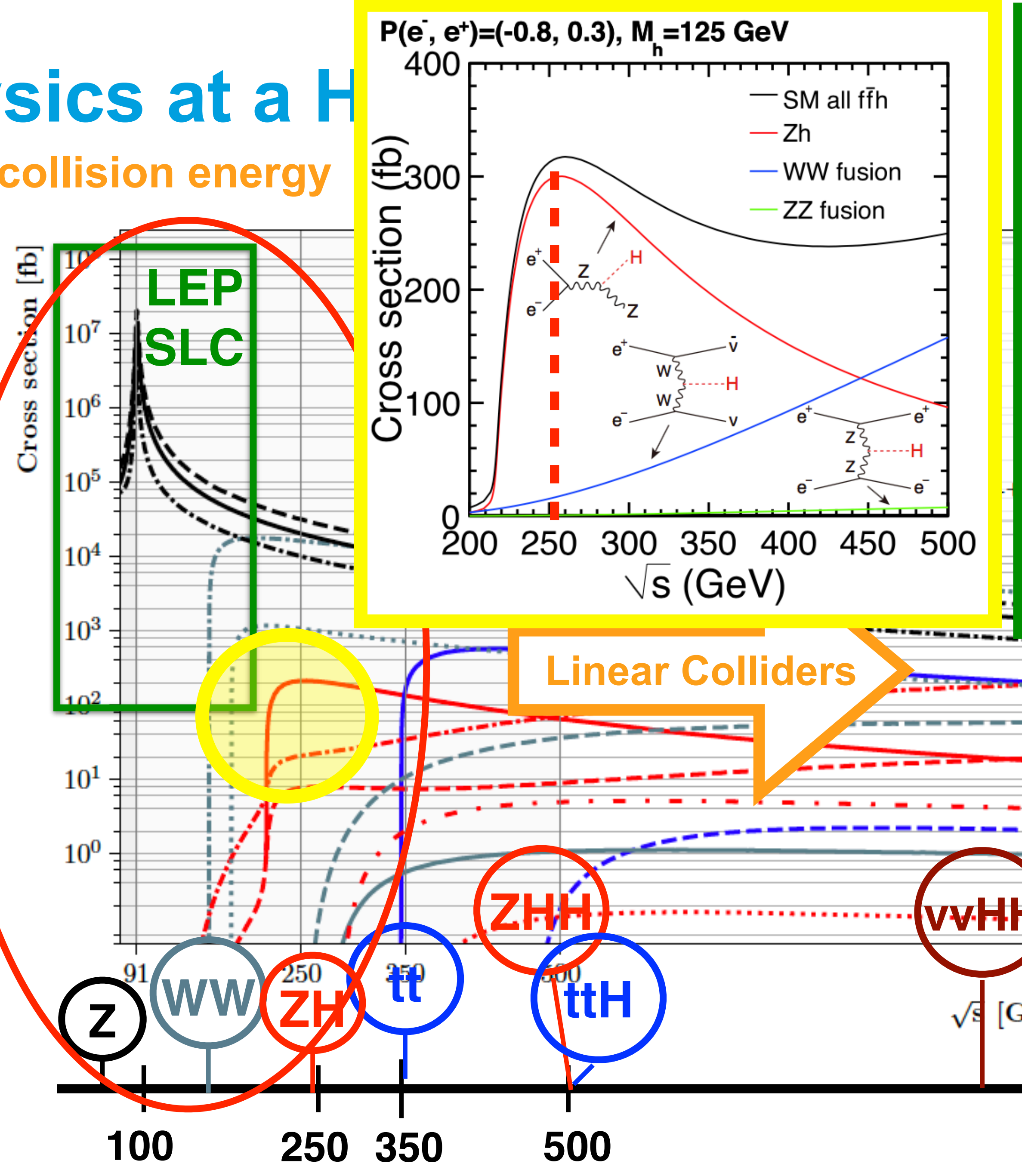


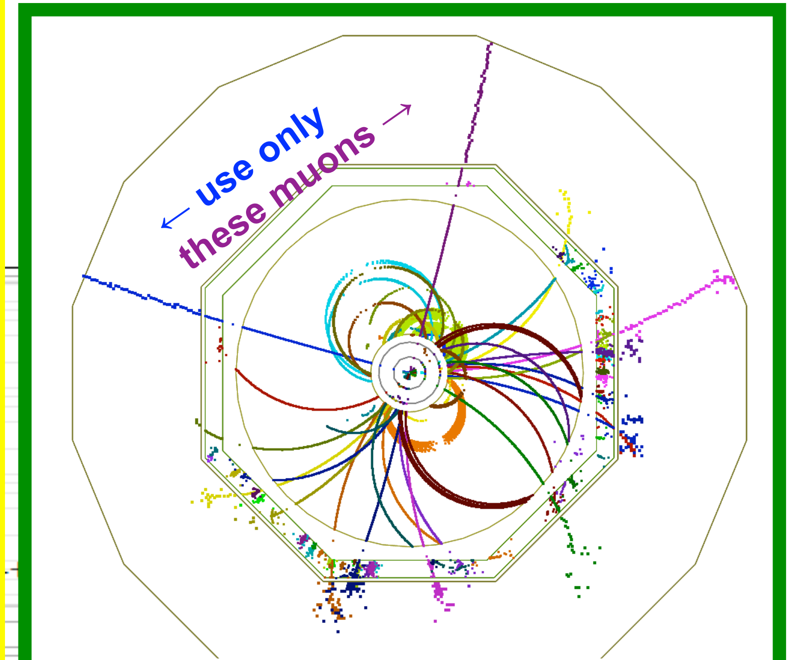
The key physics at a H

Production rates vs collision energy

considered by all proposed e+e- projects







$e^+e^- \rightarrow \mu^+\mu^- H \rightarrow \mu^+\mu^- bb$ in ILD

The key physics at a H

Production rates vs collision energy

considered
by all proposed
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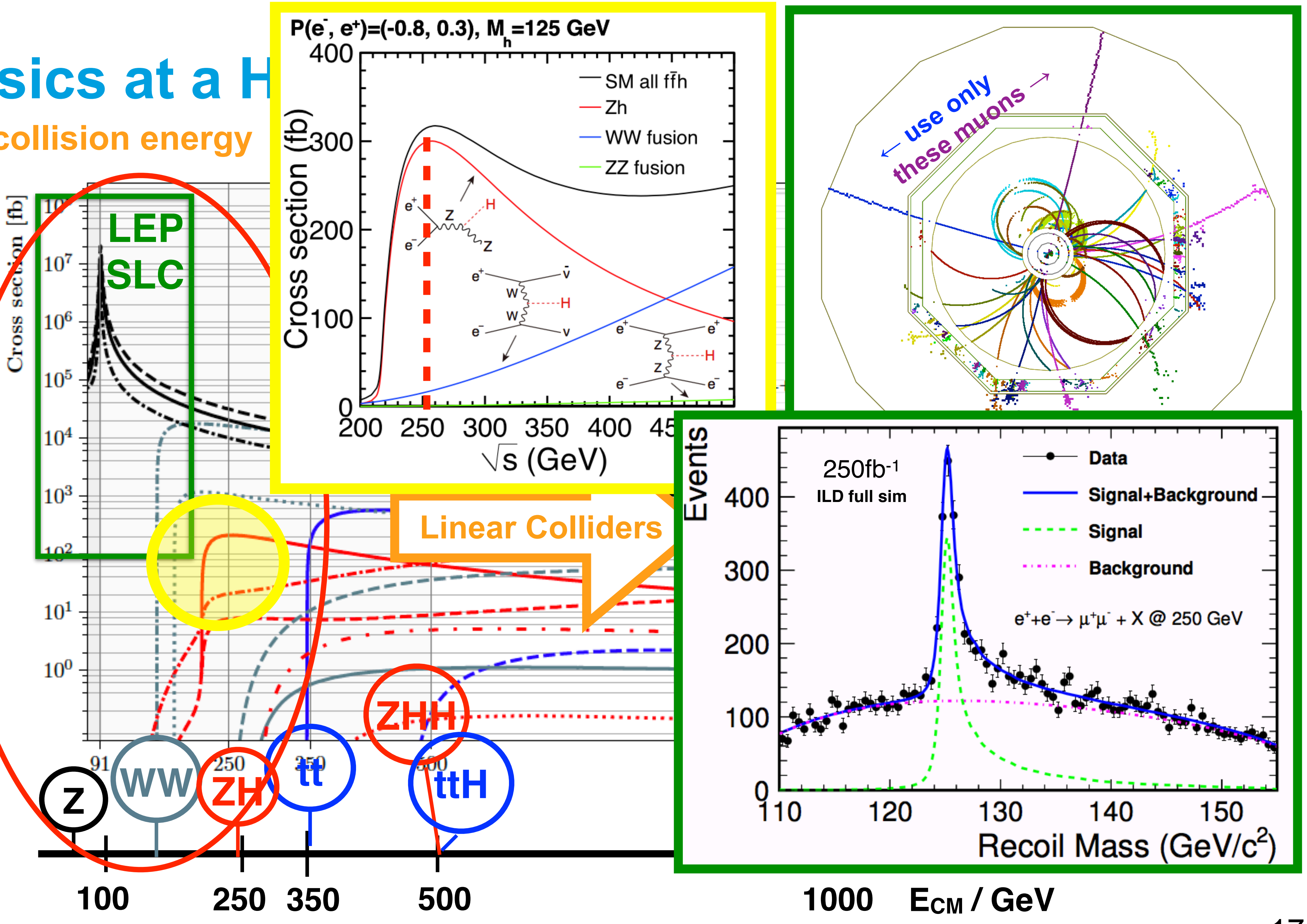
Circular Colliders



The key physics at a H...

Production rates vs collision energy

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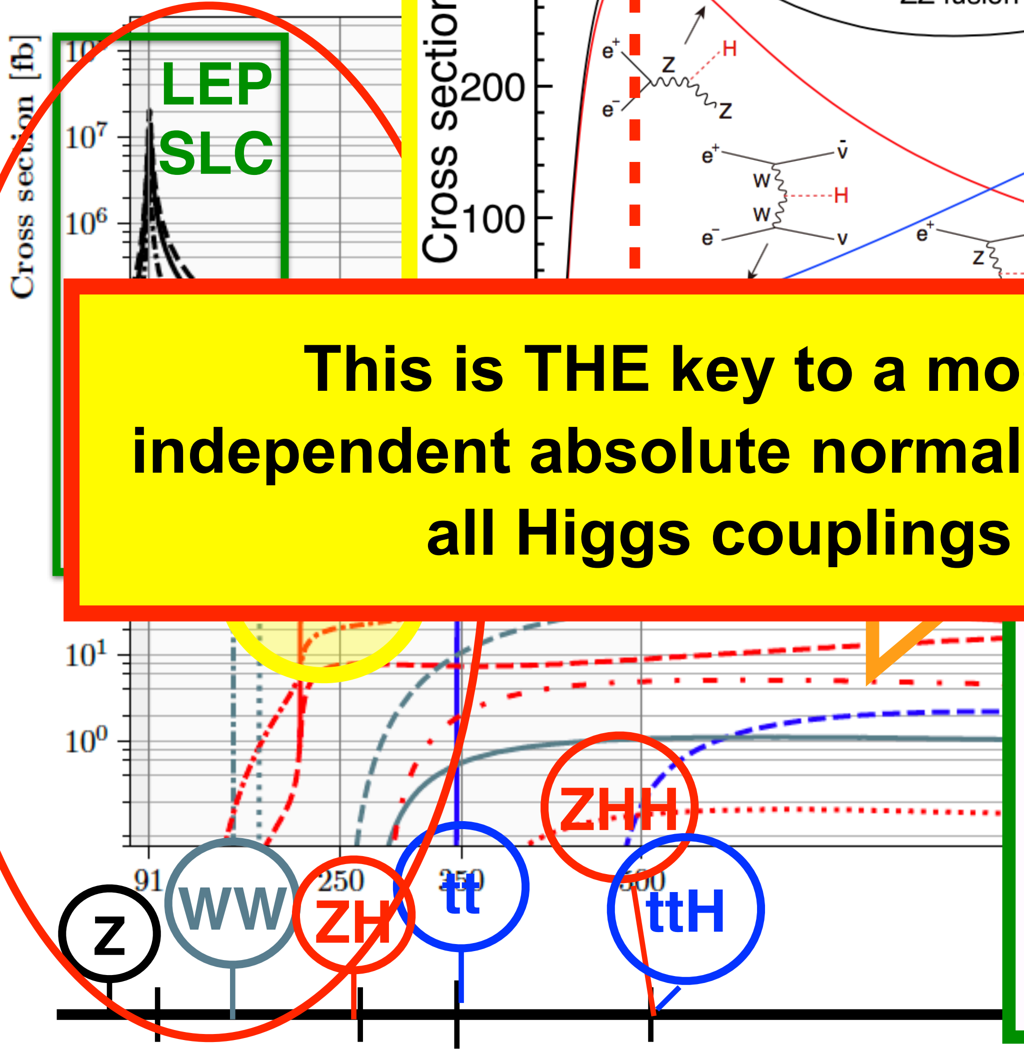
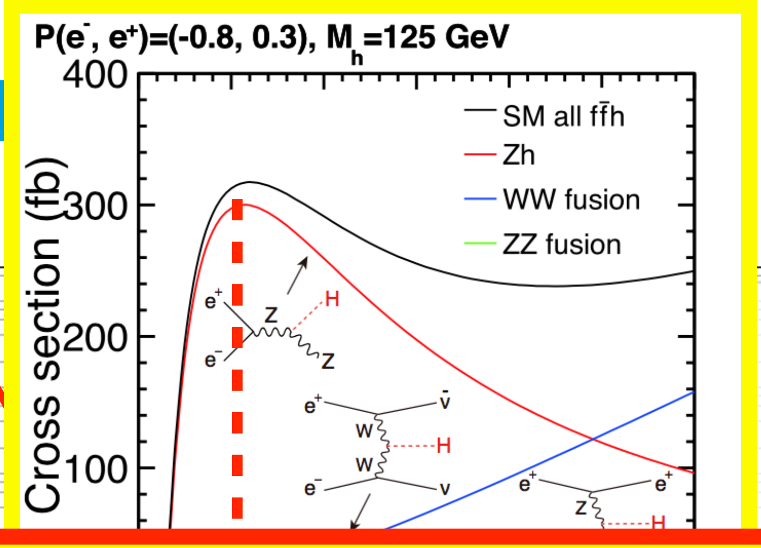
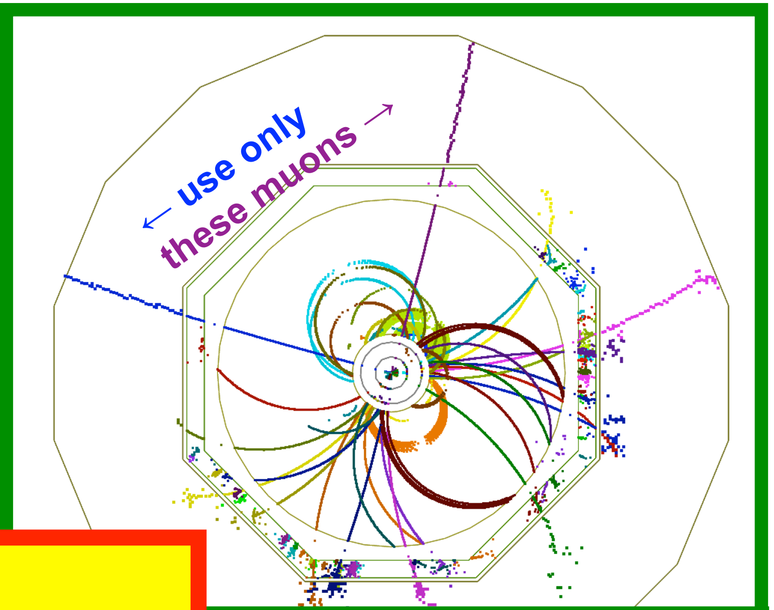
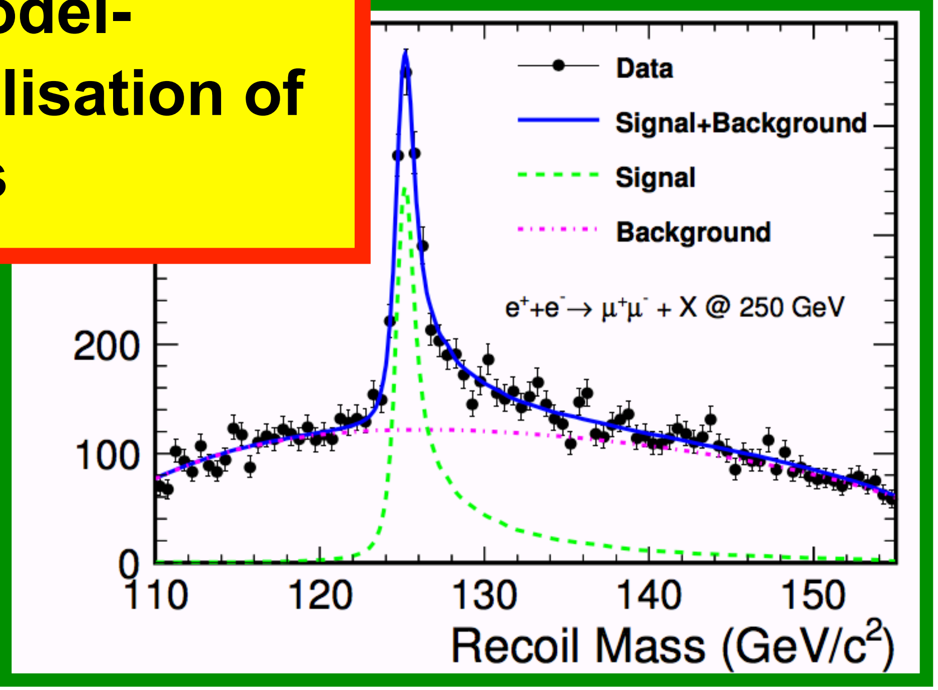






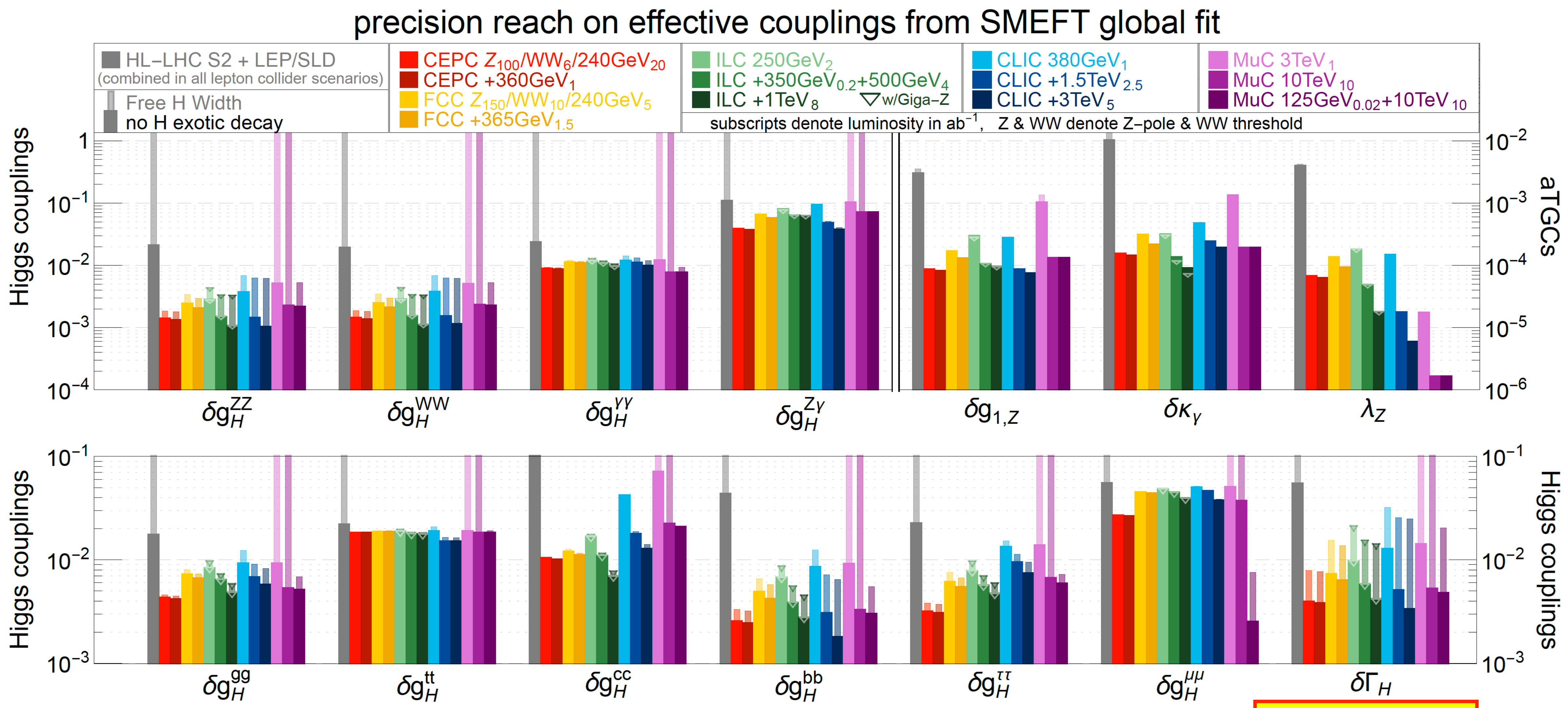


This is THE key to a model-independent absolute normalisation of all Higgs couplings

100 250 350 500 1000 E_{CM} / GeV

Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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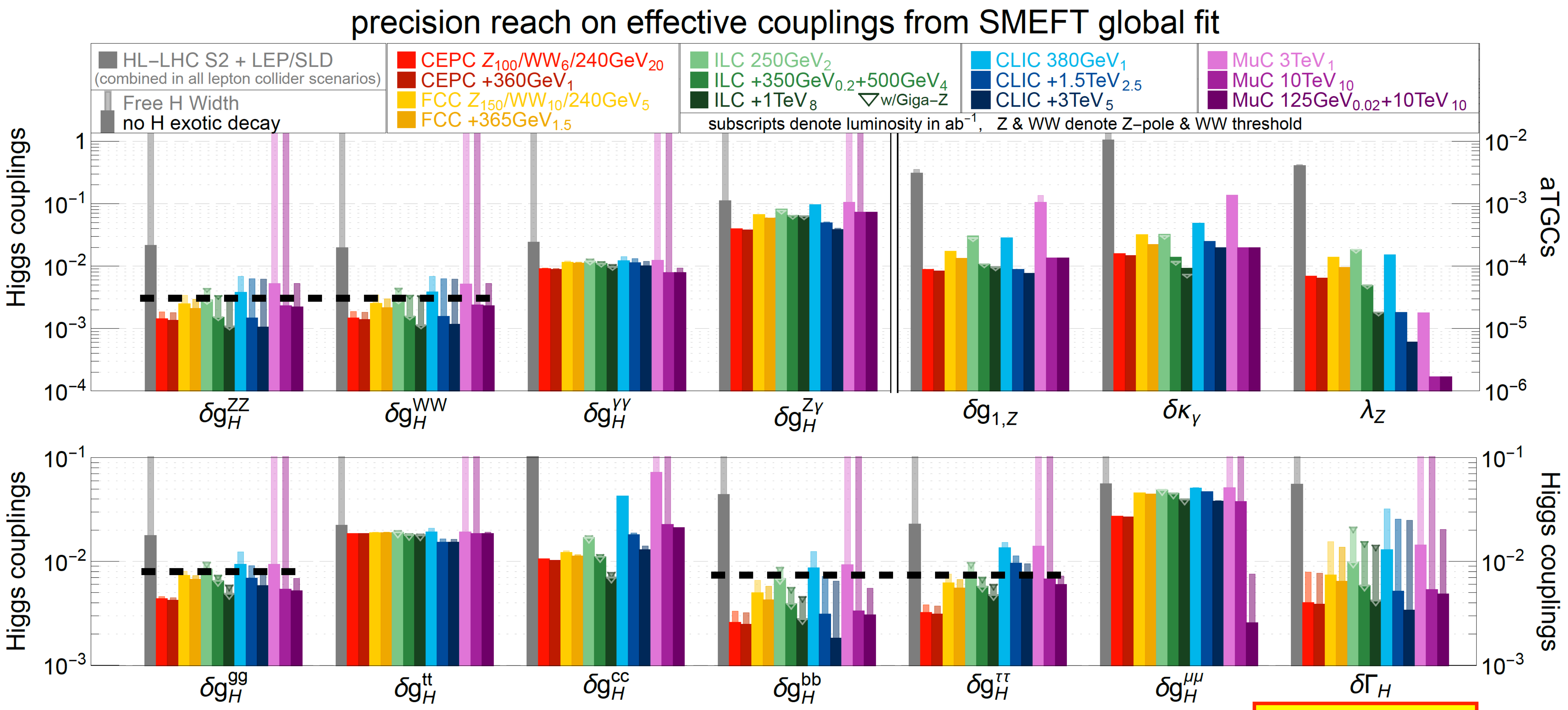

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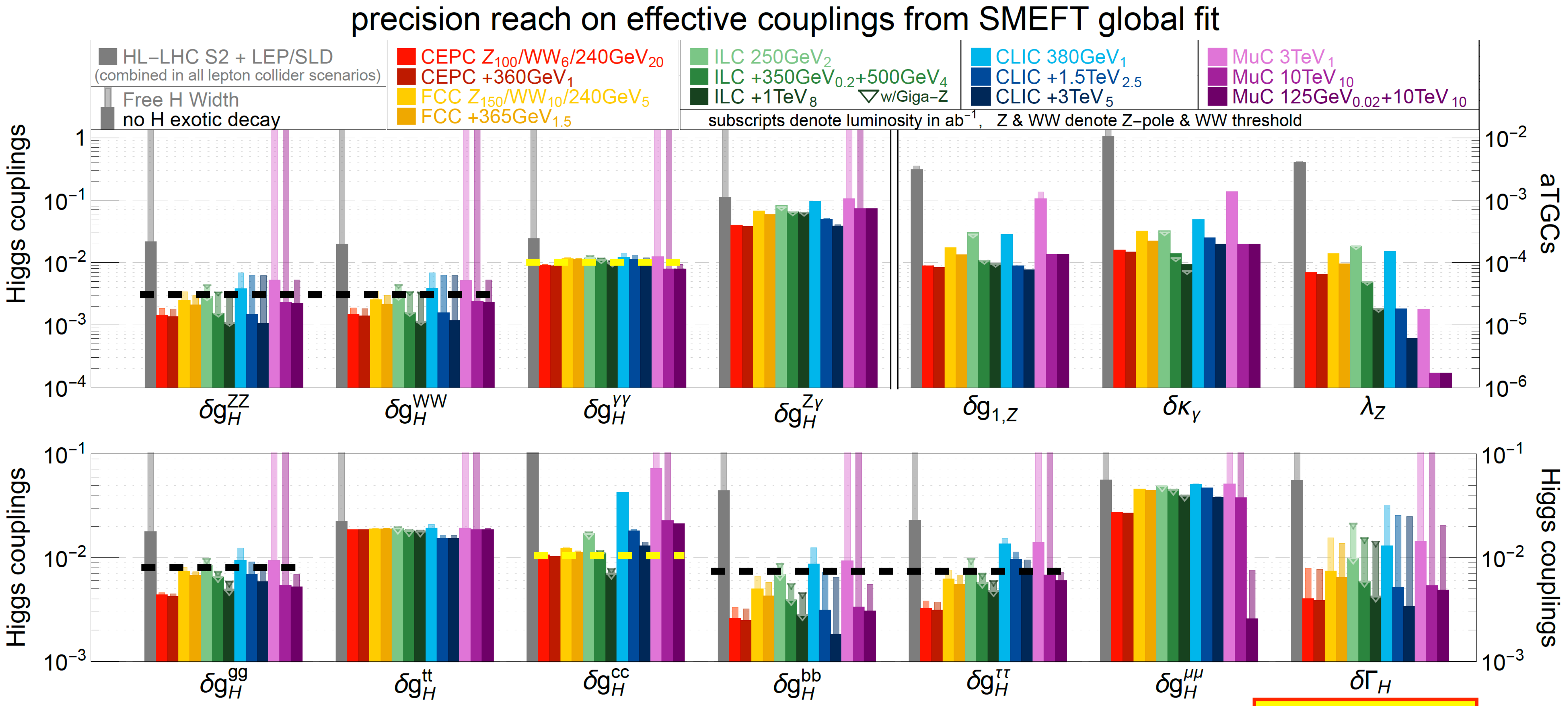

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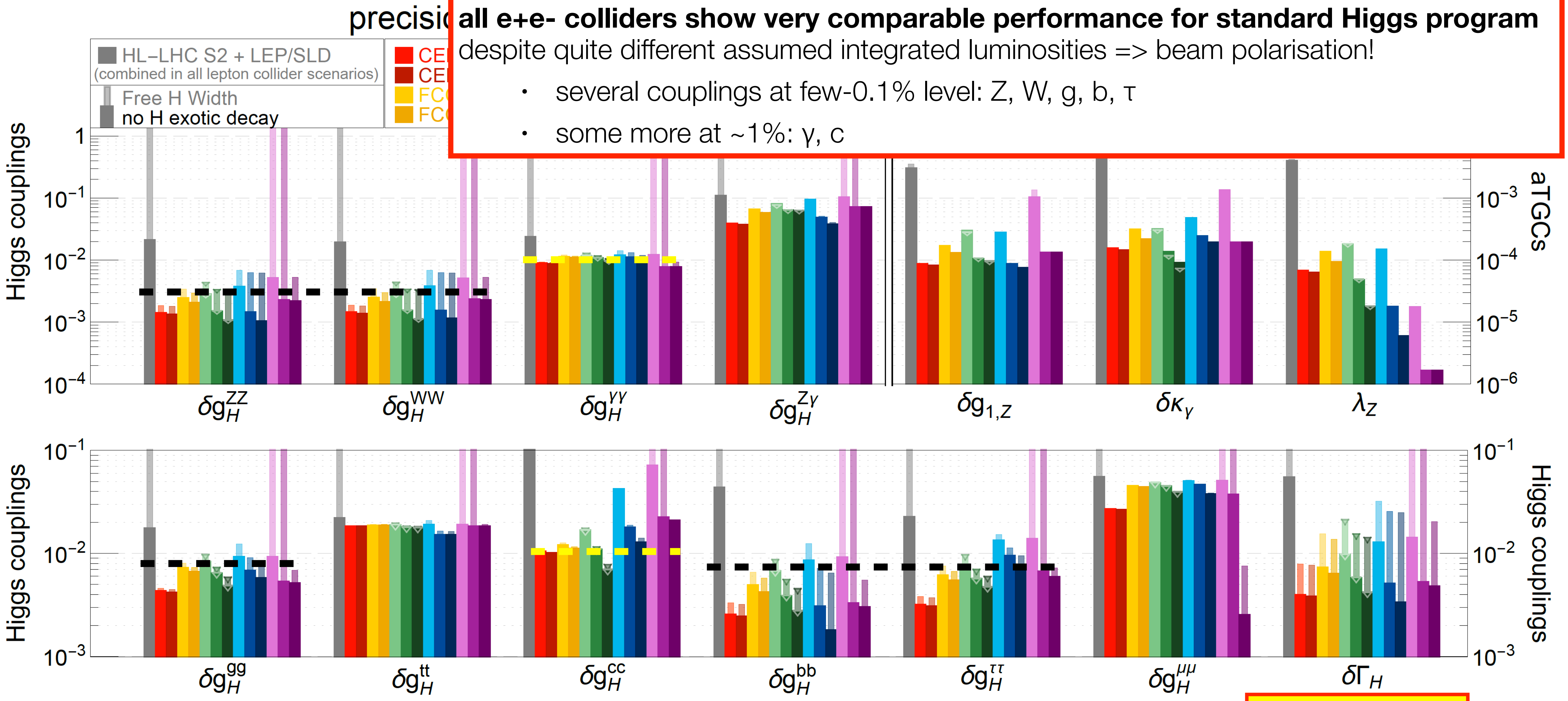
Rainbow-Manhattans

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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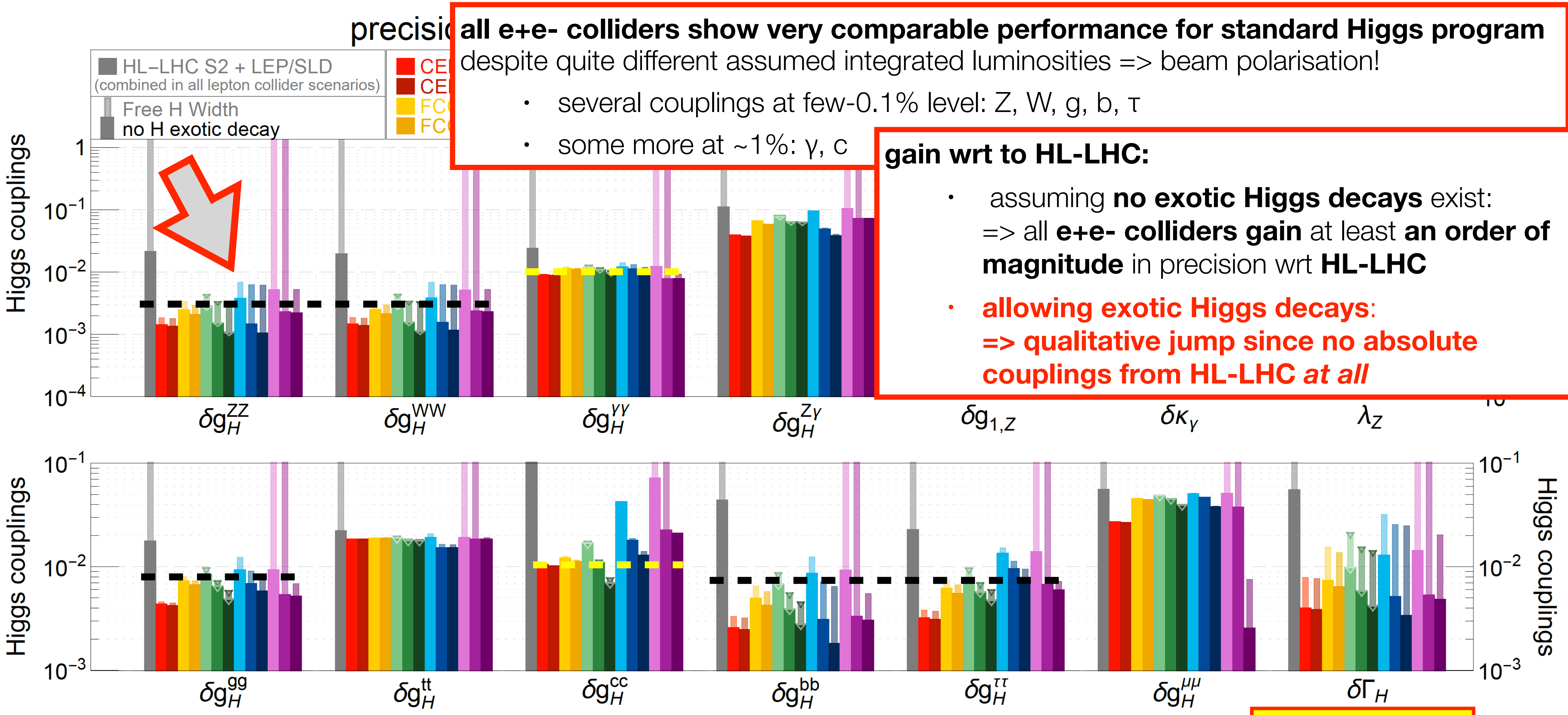

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- some more at ~1%: γ, c

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*

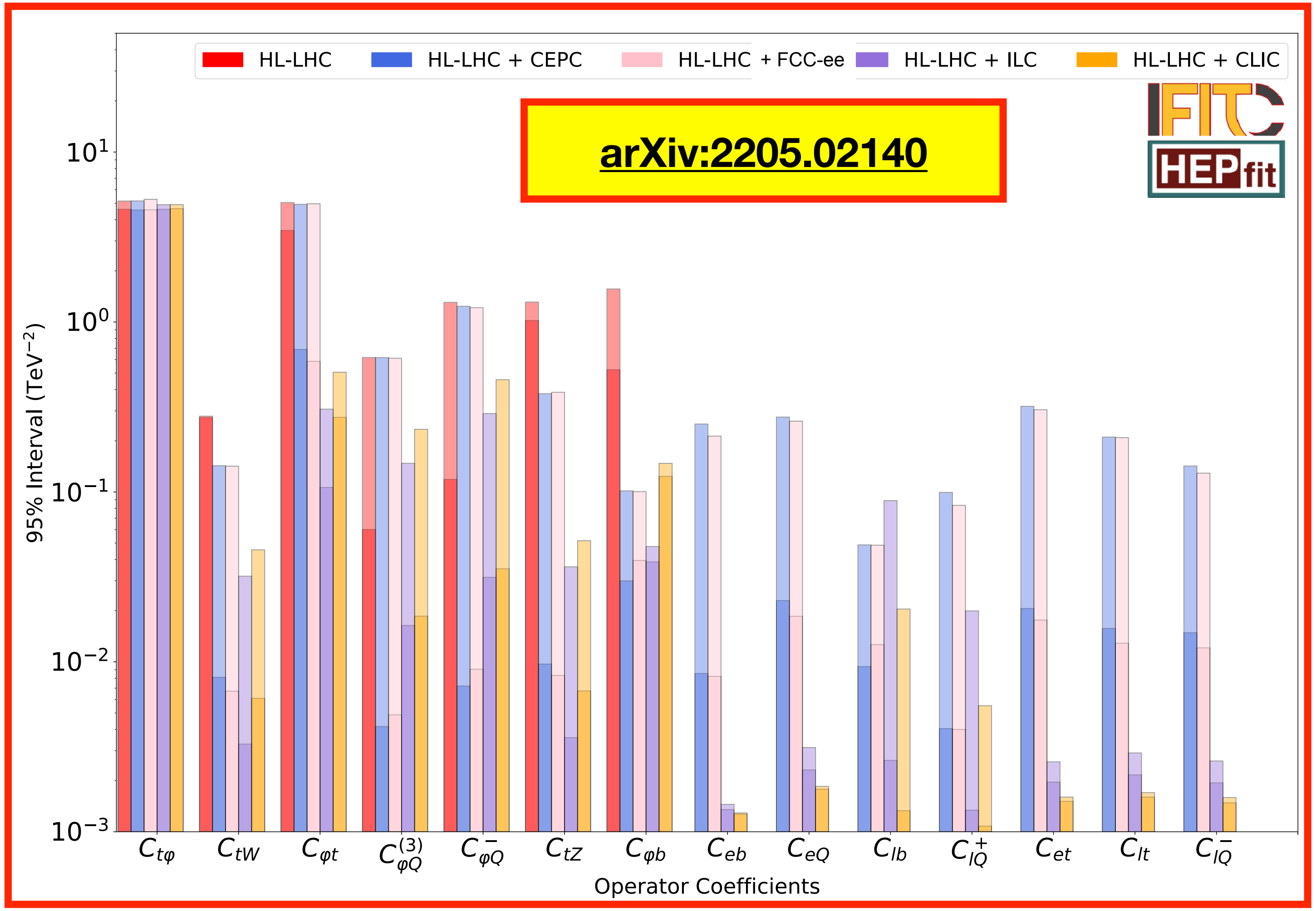
arXiv:2206.08326

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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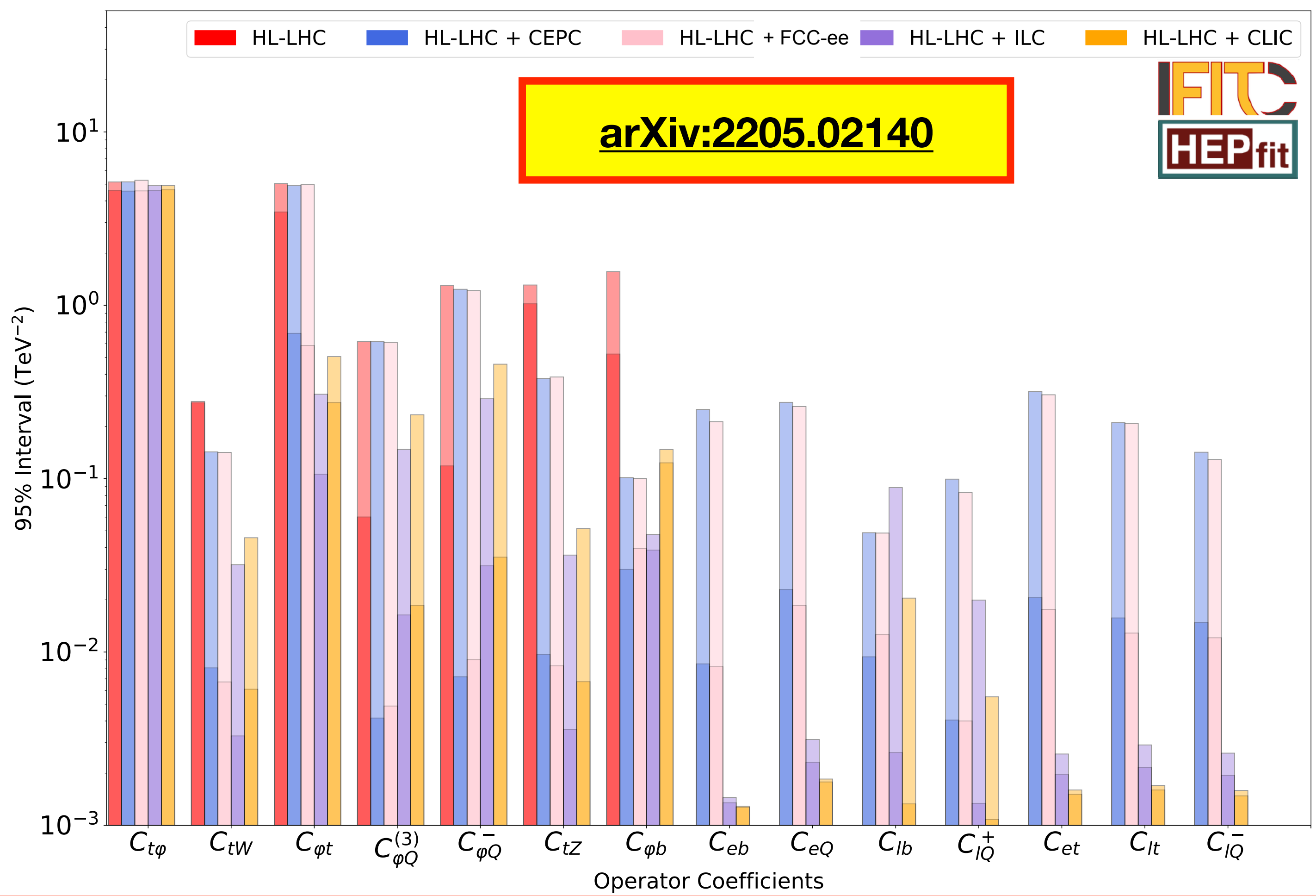
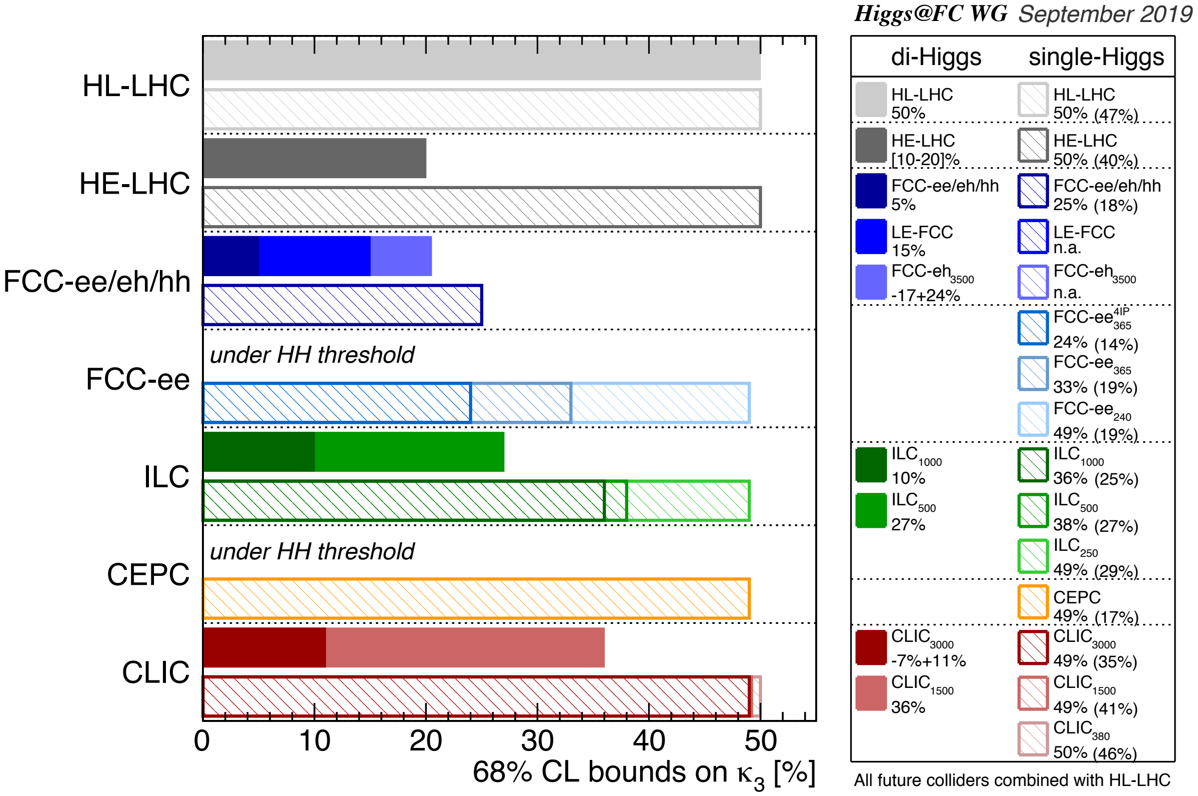


top-quark physics does not end at the ttbar threshold…

Higgs self-coupling

Electroweak Baryogenesis?



most detailed ILC ref: PhD Thesis C.Dürig
Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING!

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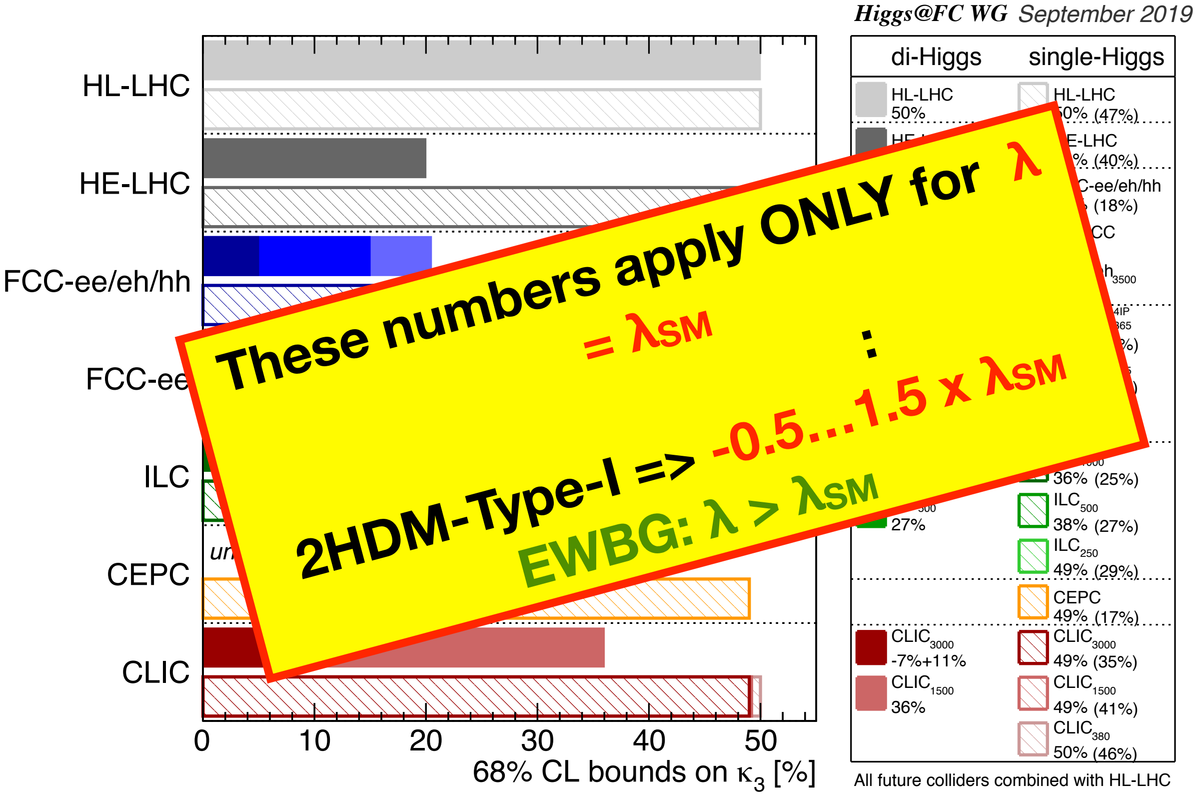

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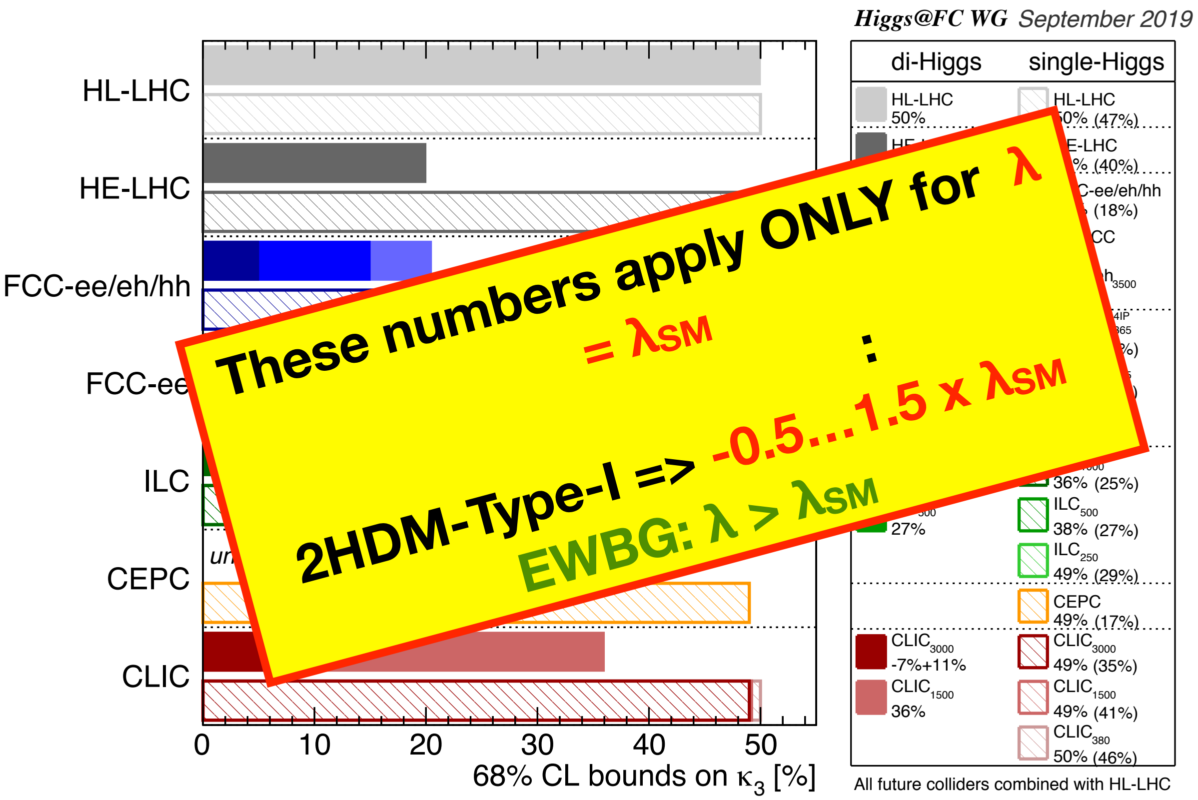

$\lambda > \lambda_{SM}$:

- **pp cross section drops**
- **ee cross section rises**

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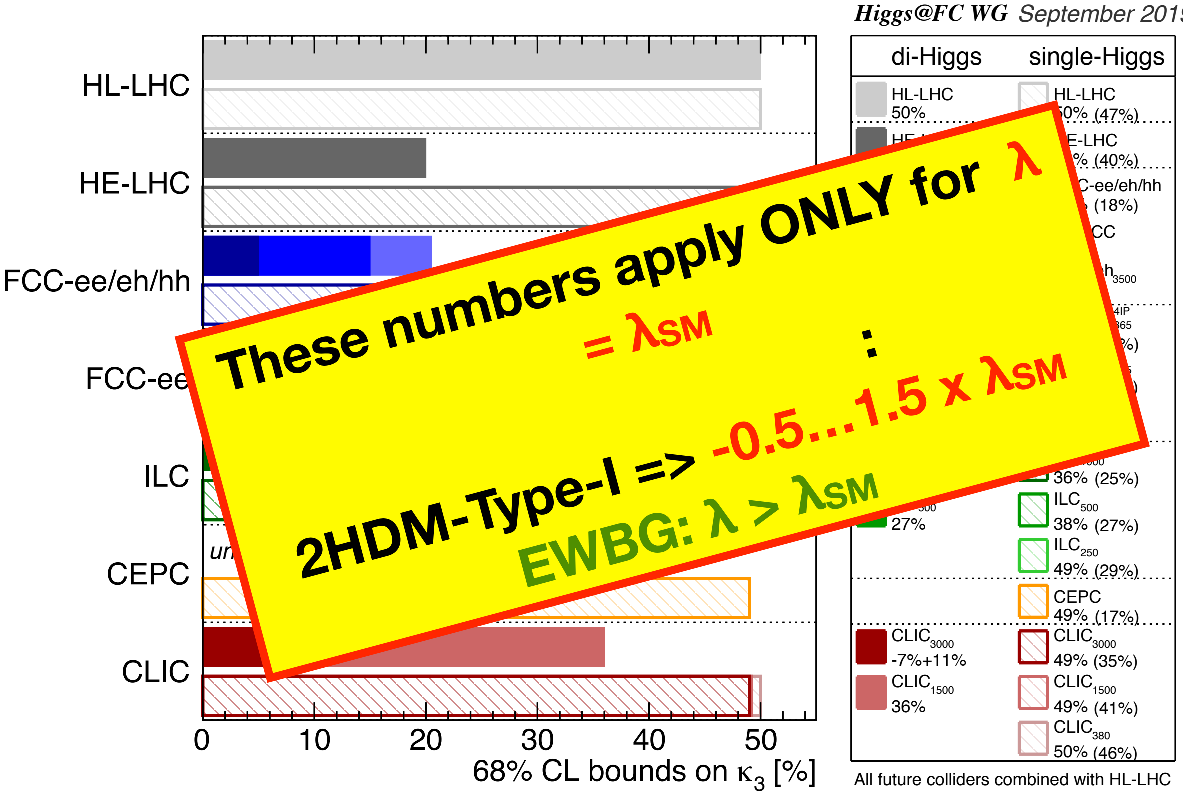

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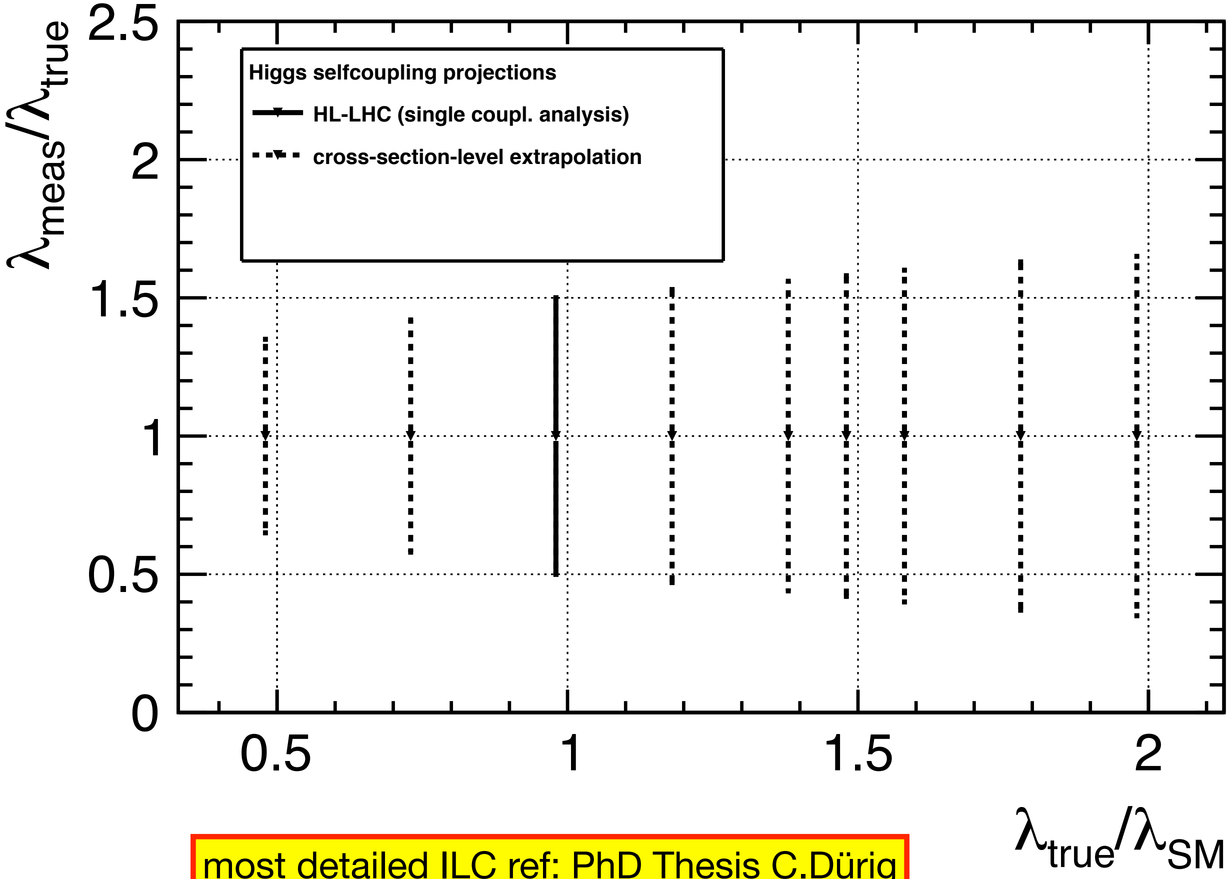
2HDM-Type-I => -0.5…1.5 x λ_{SM}

EWBG: $\lambda > \lambda_{SM}$



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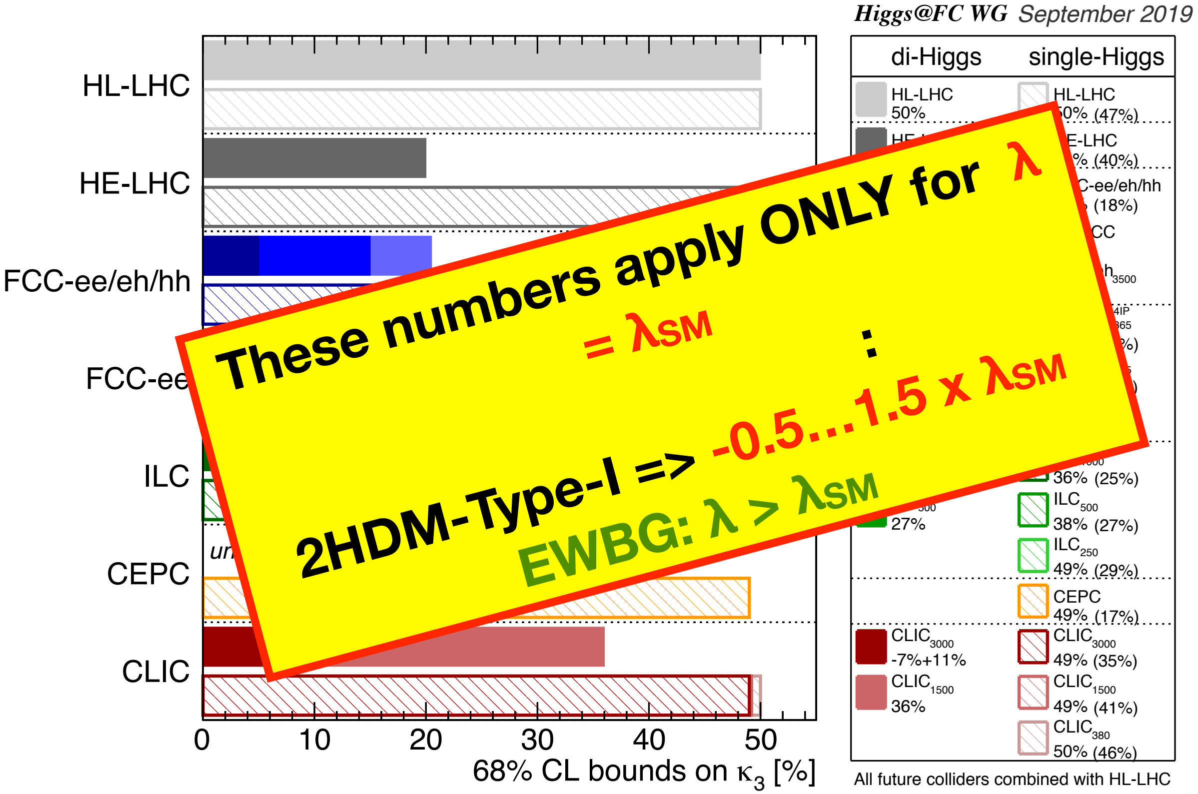

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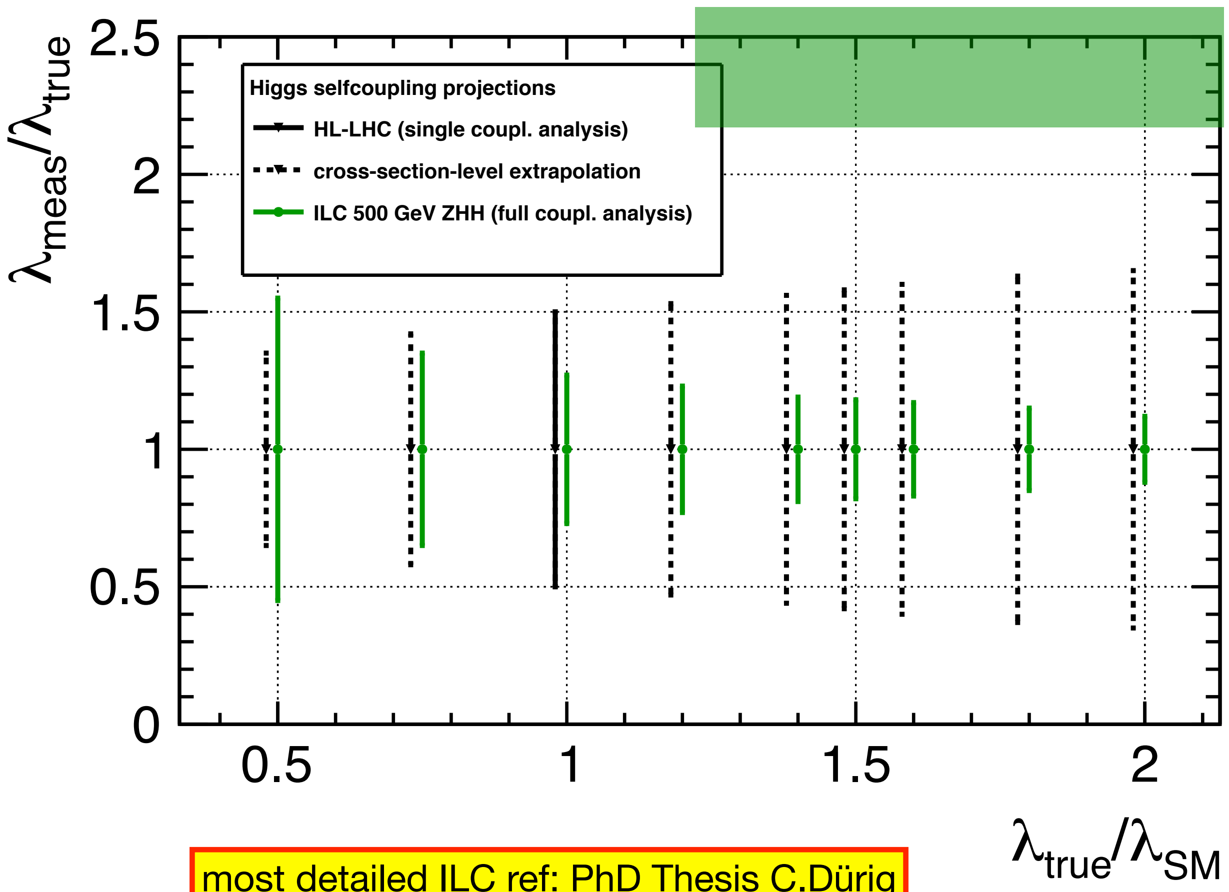
Region of interest for electroweak baryogenesis



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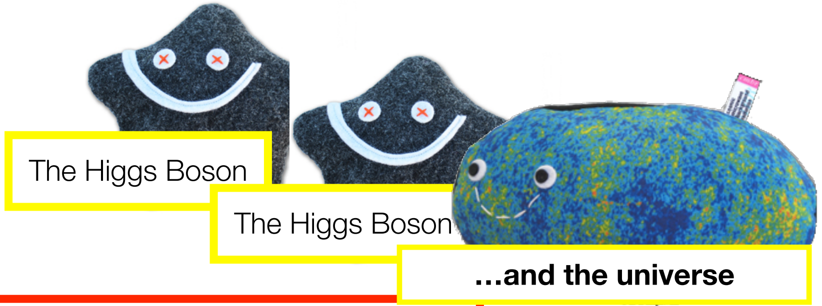

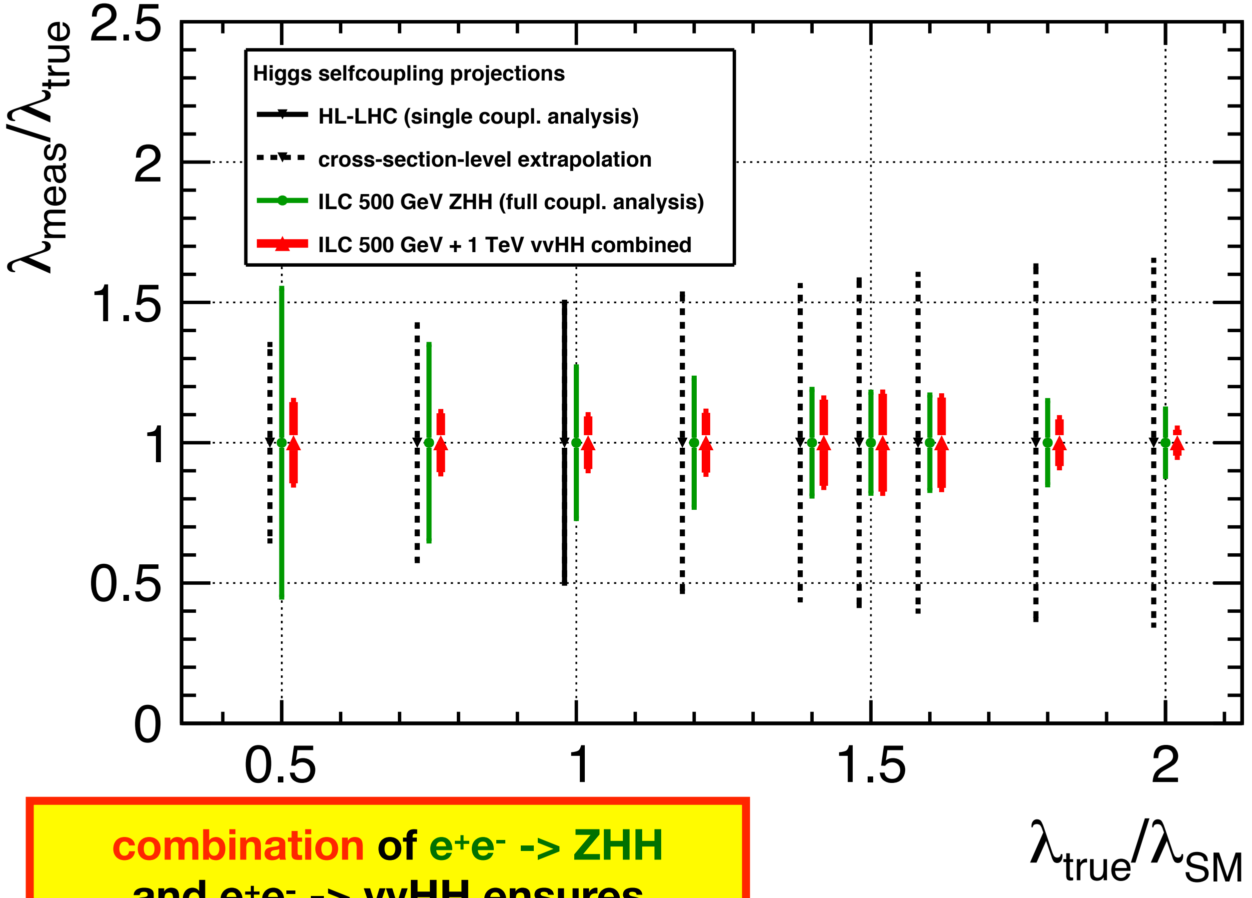

combination of e^+e^- -> ZHH and e^+e^- -> vvHH ensures at least 10-15% precision for all λ

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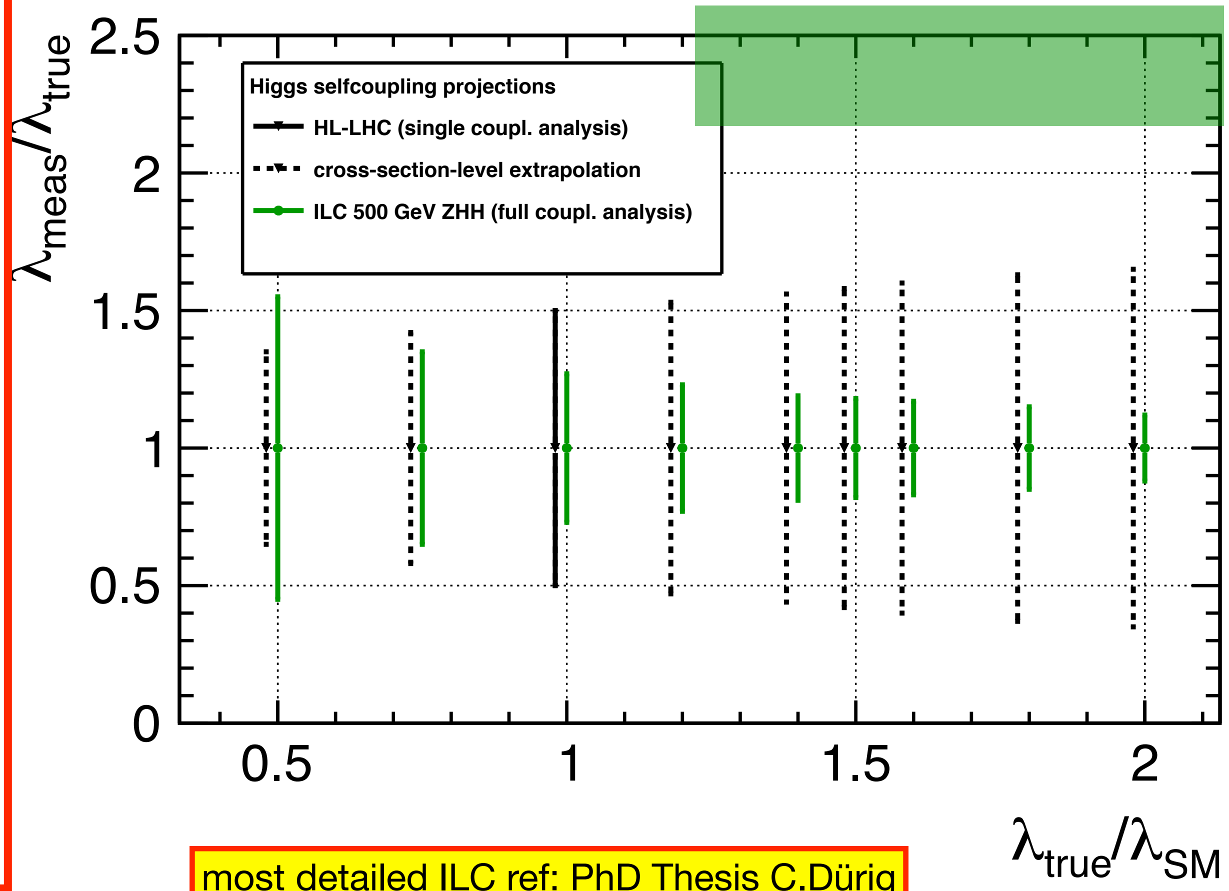

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UPDATE ONGOING!

BSM reach of ee → cc / bb

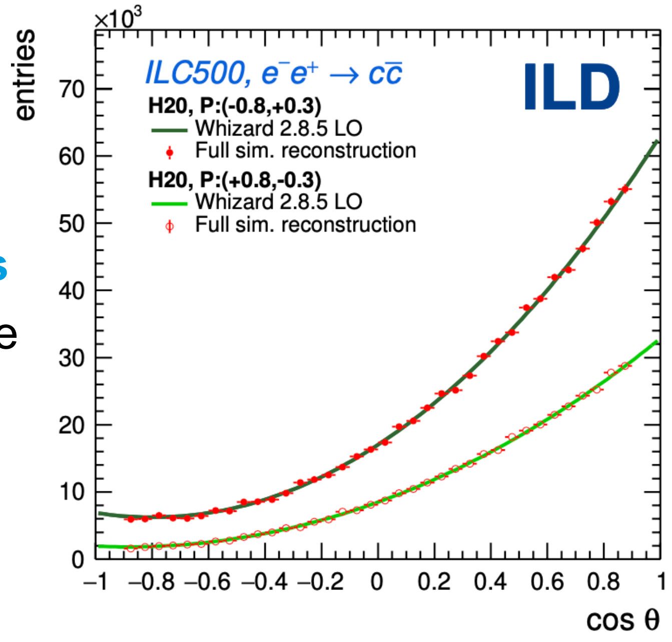
Forward-backward and left-right asymmetries above the Z pole

Study of ee → cc / bb

- full Geant4-based simulation of ILD [A.Irles et al, pub. in prep.]

BSM example: Gauge-Higgs Unification models

- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
- Z' as Kaluza-Klein excitations of γ, Z, Z_R
- various model point with $M_{Z'}$ = 7…20 TeV



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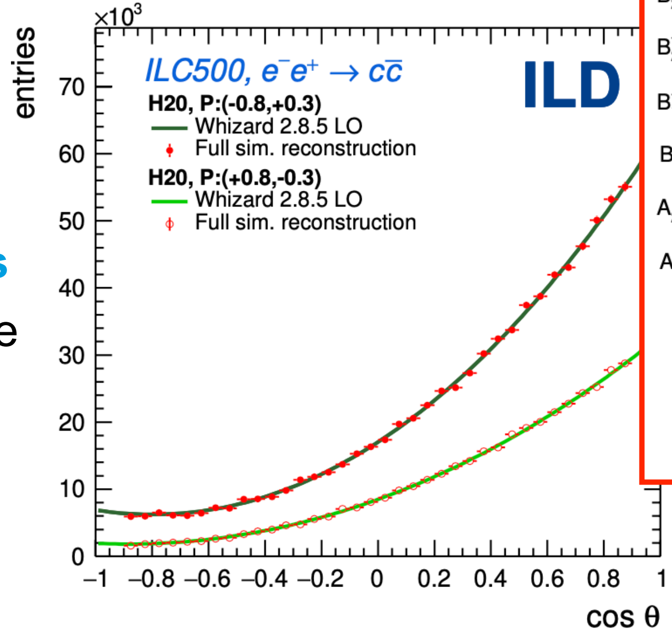

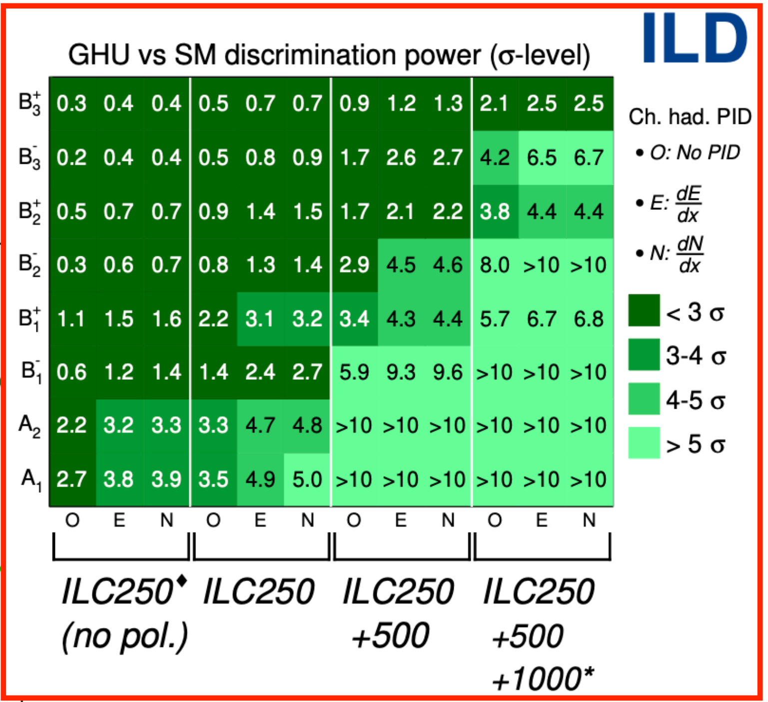

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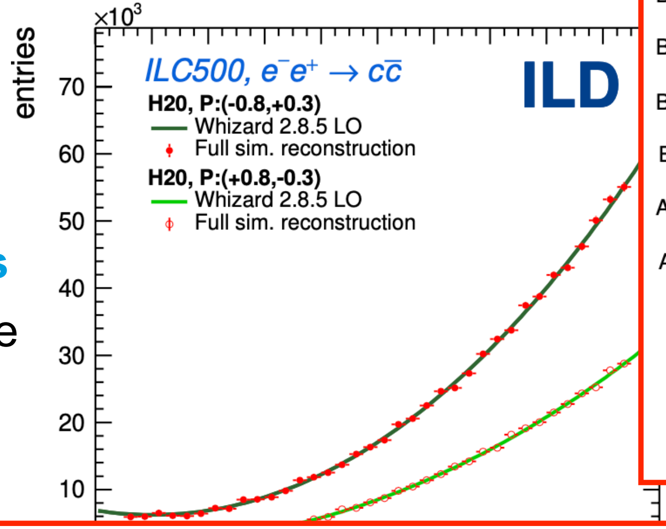

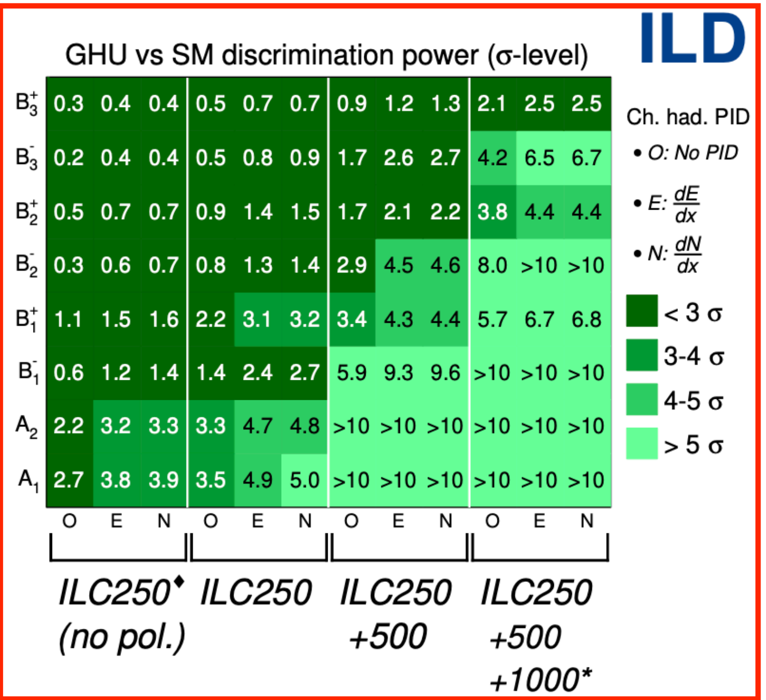

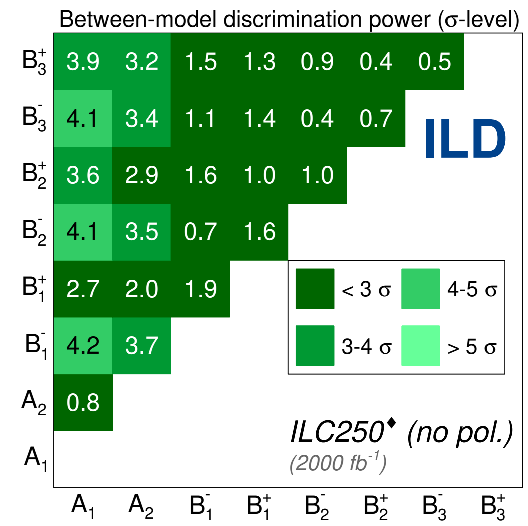

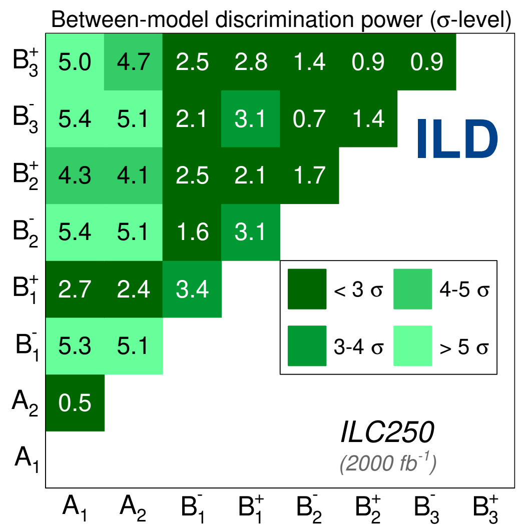

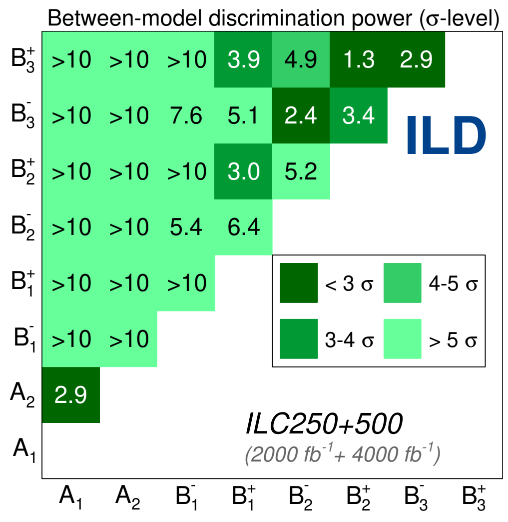

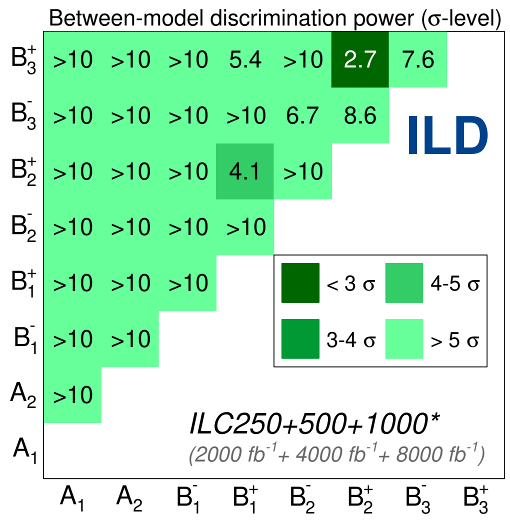

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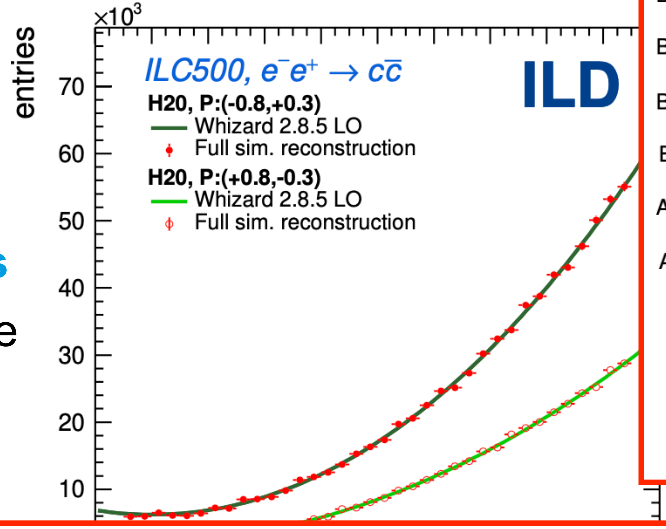

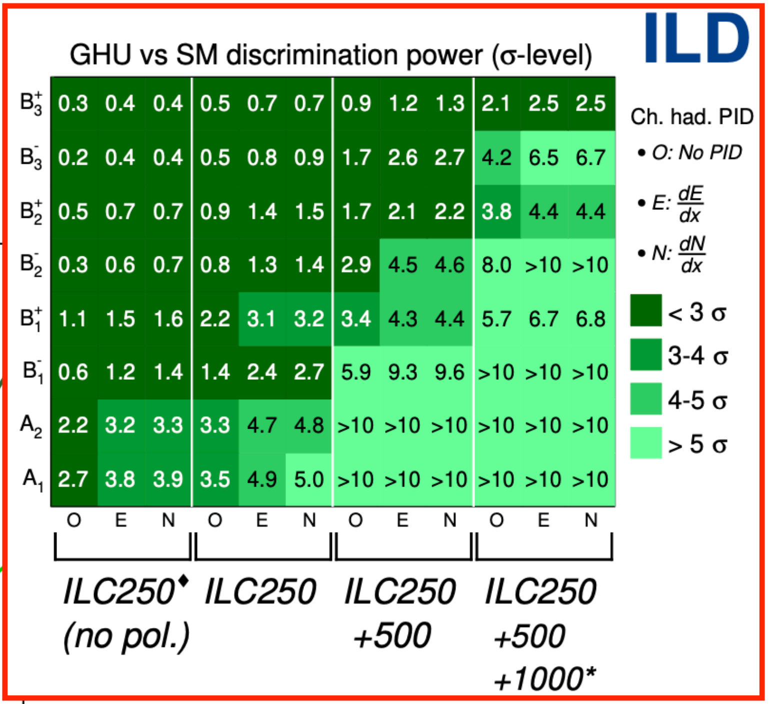

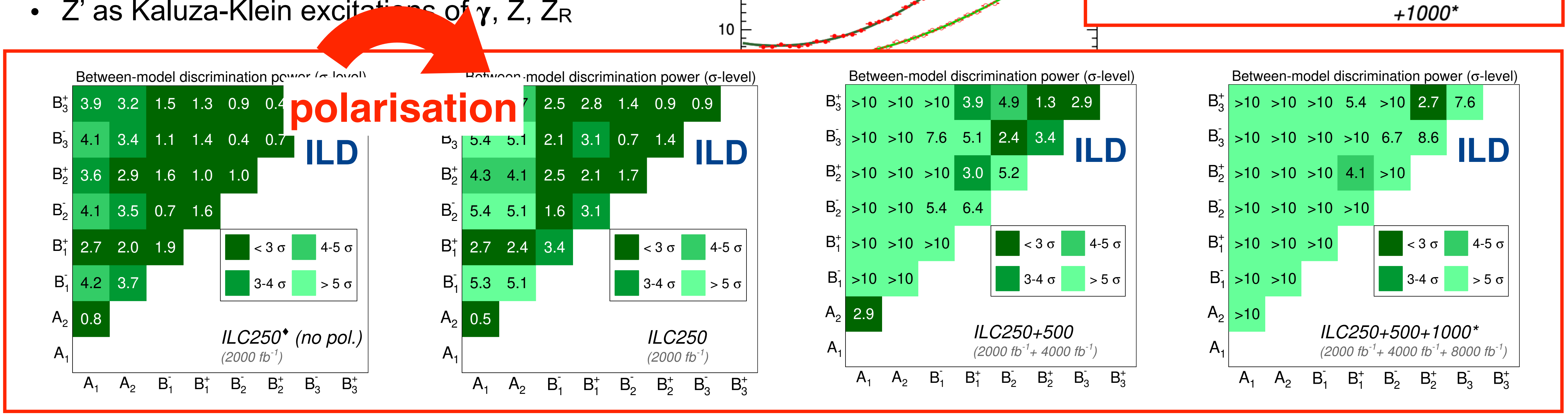

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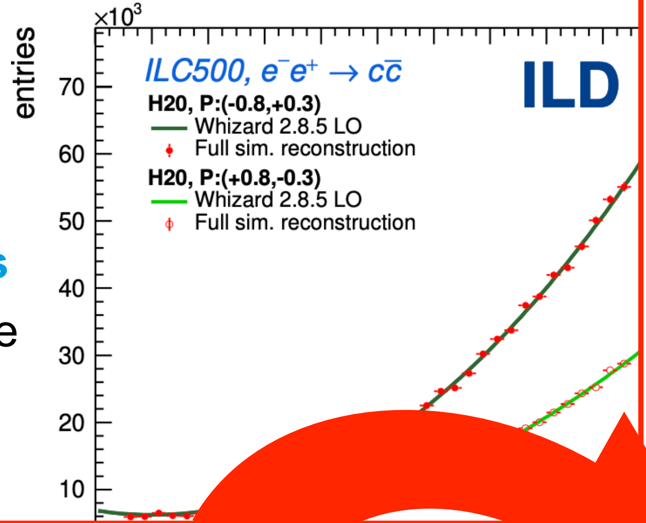
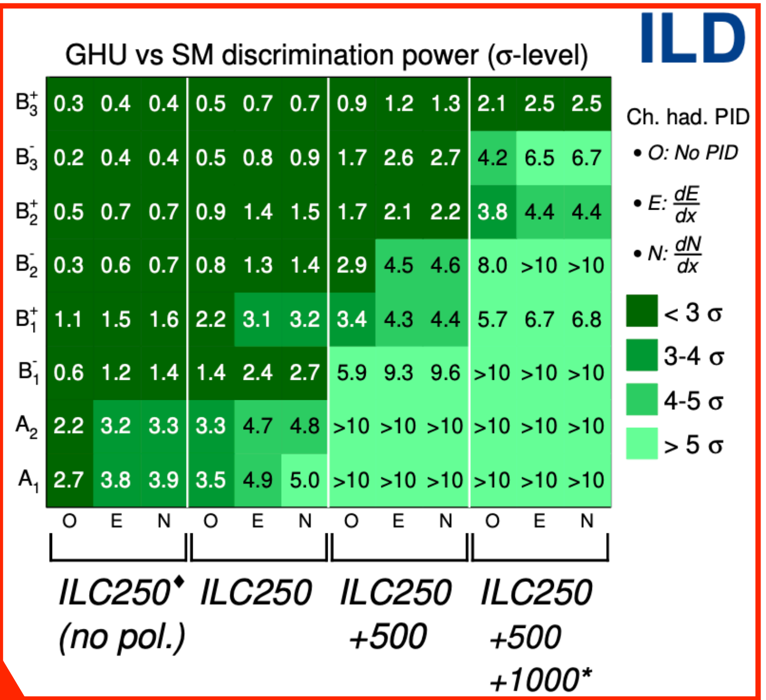
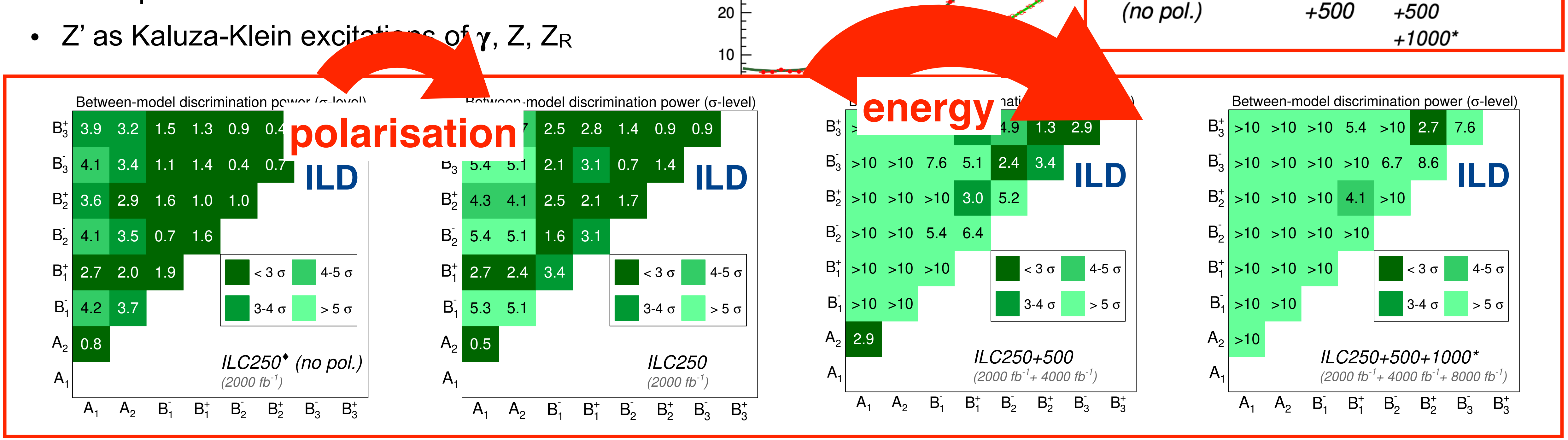


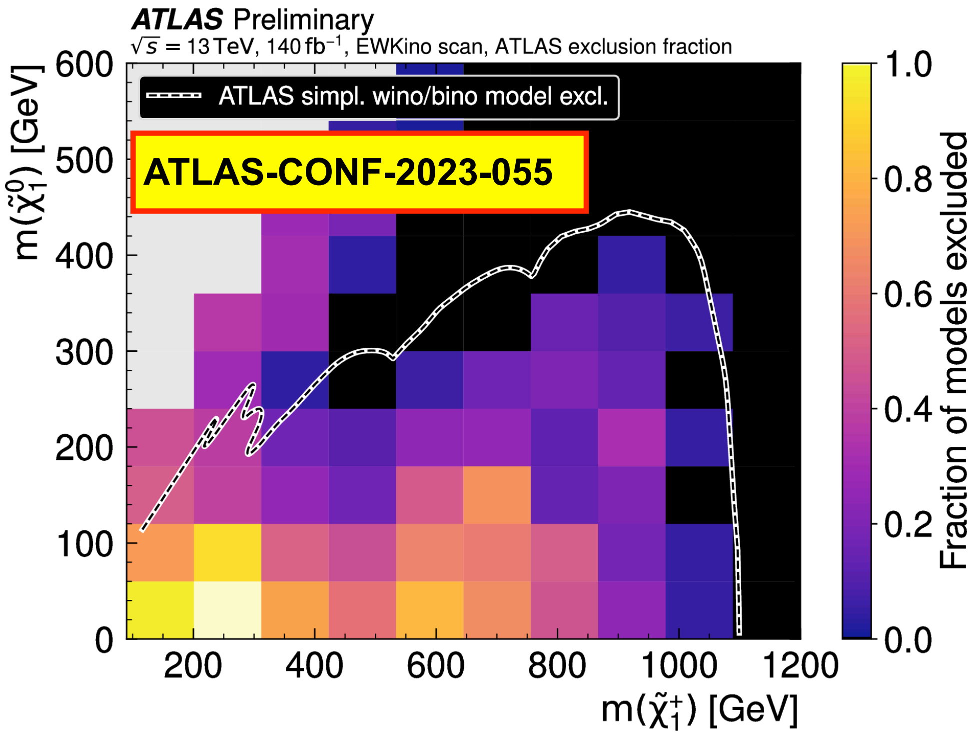




Light Higgsinos

Or: beware what LHC limits really mean!

- LHC does very well on probing some BSM phase space
- but beware that exclusion regions are extremely model-dependent, especially for electroweak new particles (eg charginos, staus, …)
- ILD study of full detector simulation for two benchmark points ★★ - motivated by leptogenesis & gravitino DM - and extrapolation to full plane
- conclusions:
  - loop-hole free discovery / exclusion potential up to ~ half E_{CM}
  - even in most challenging cases few % precision on masses, cross-sections etc
  - SUSY parameter determination, cross-check with cosmology



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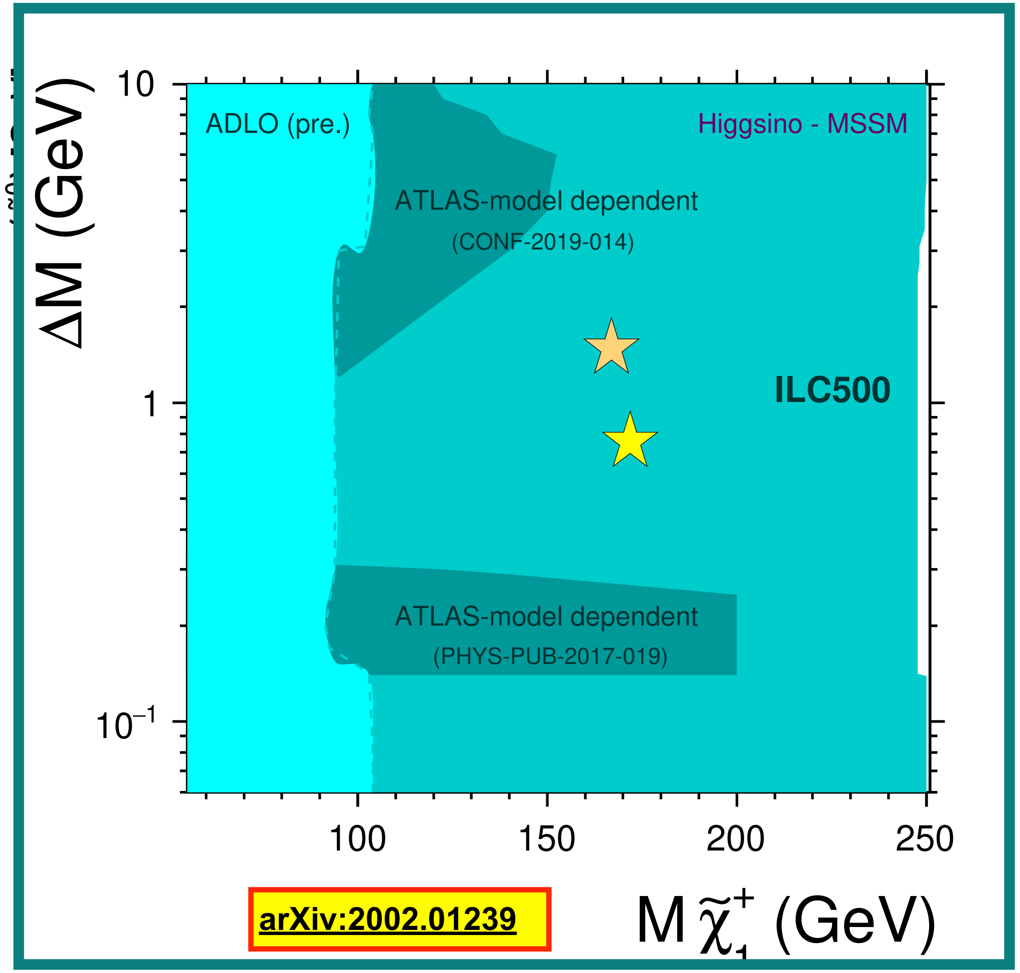

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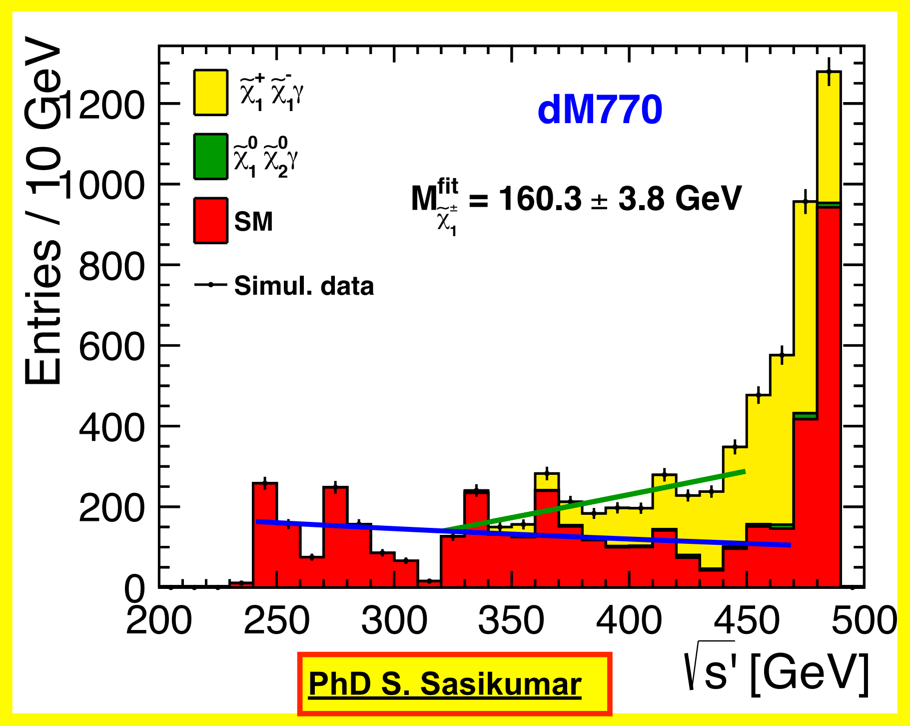

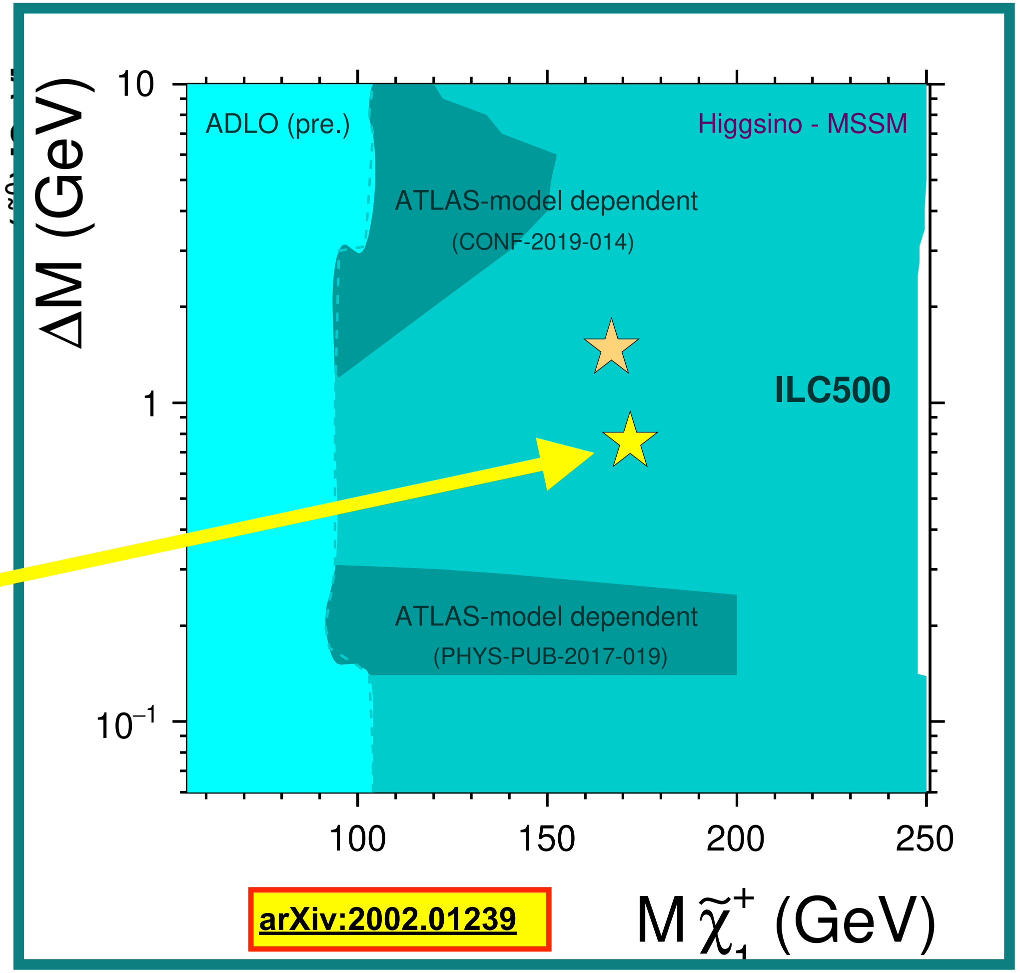

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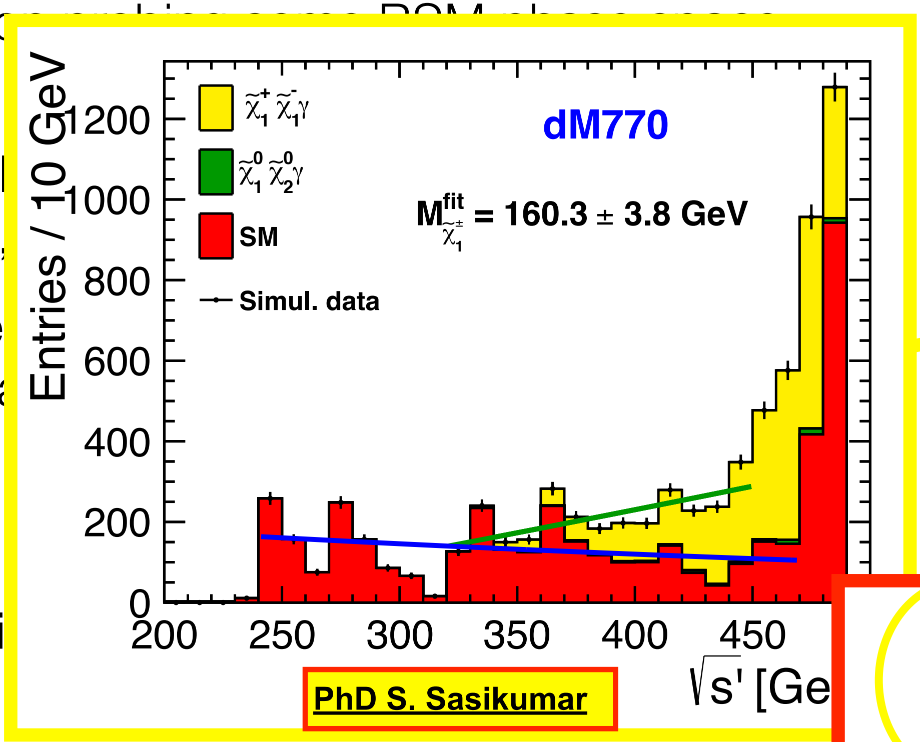

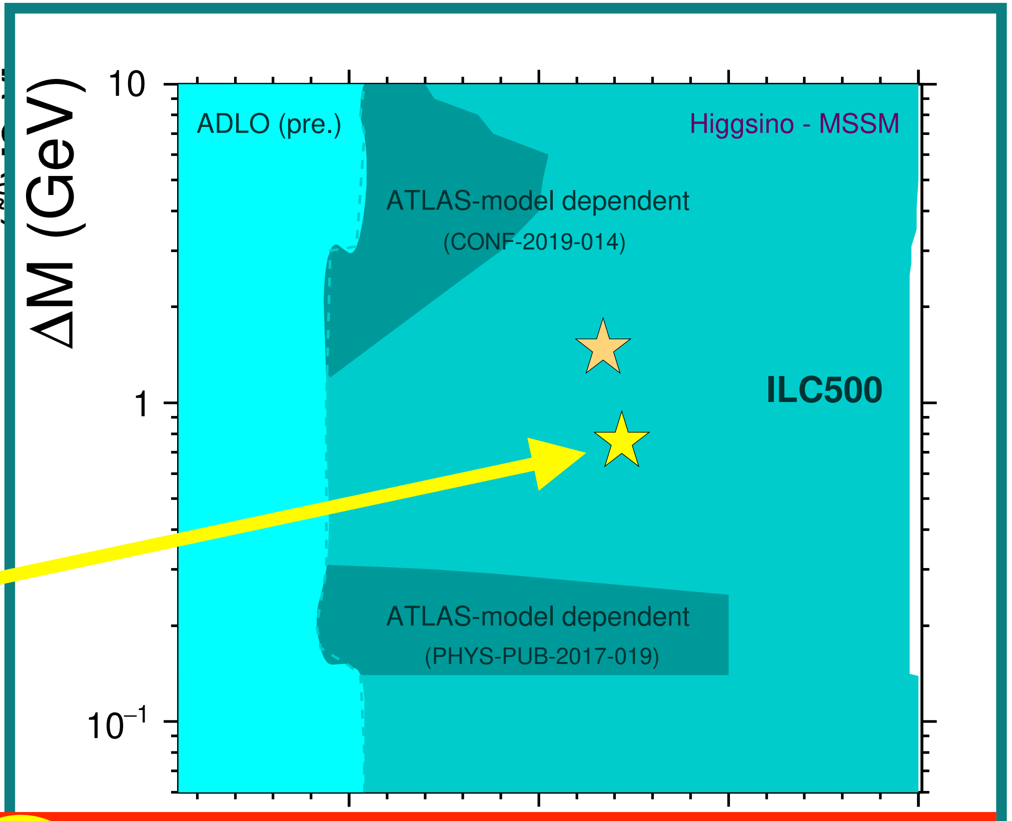

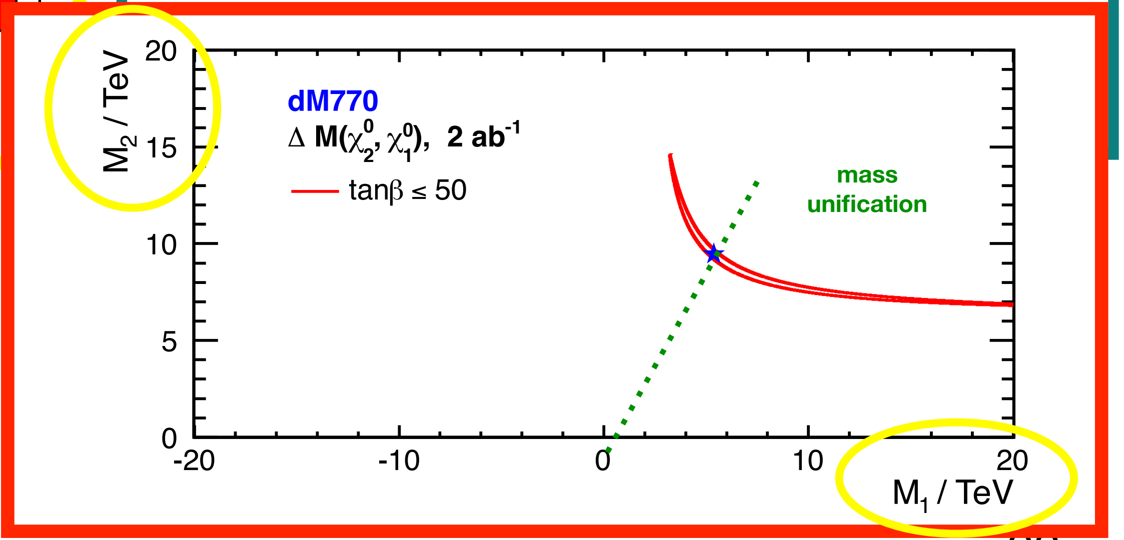

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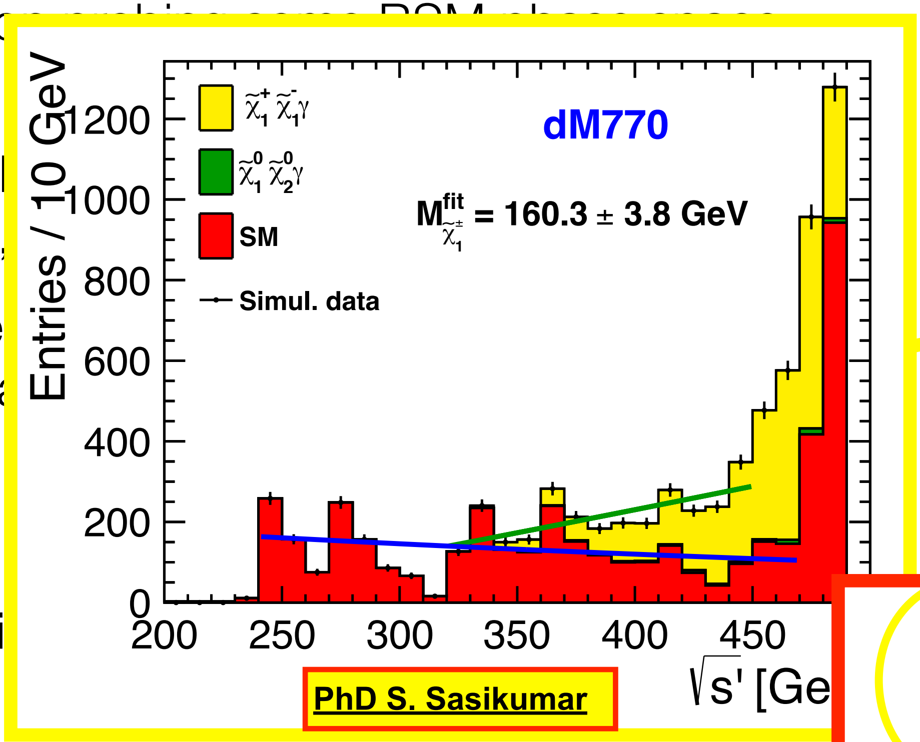
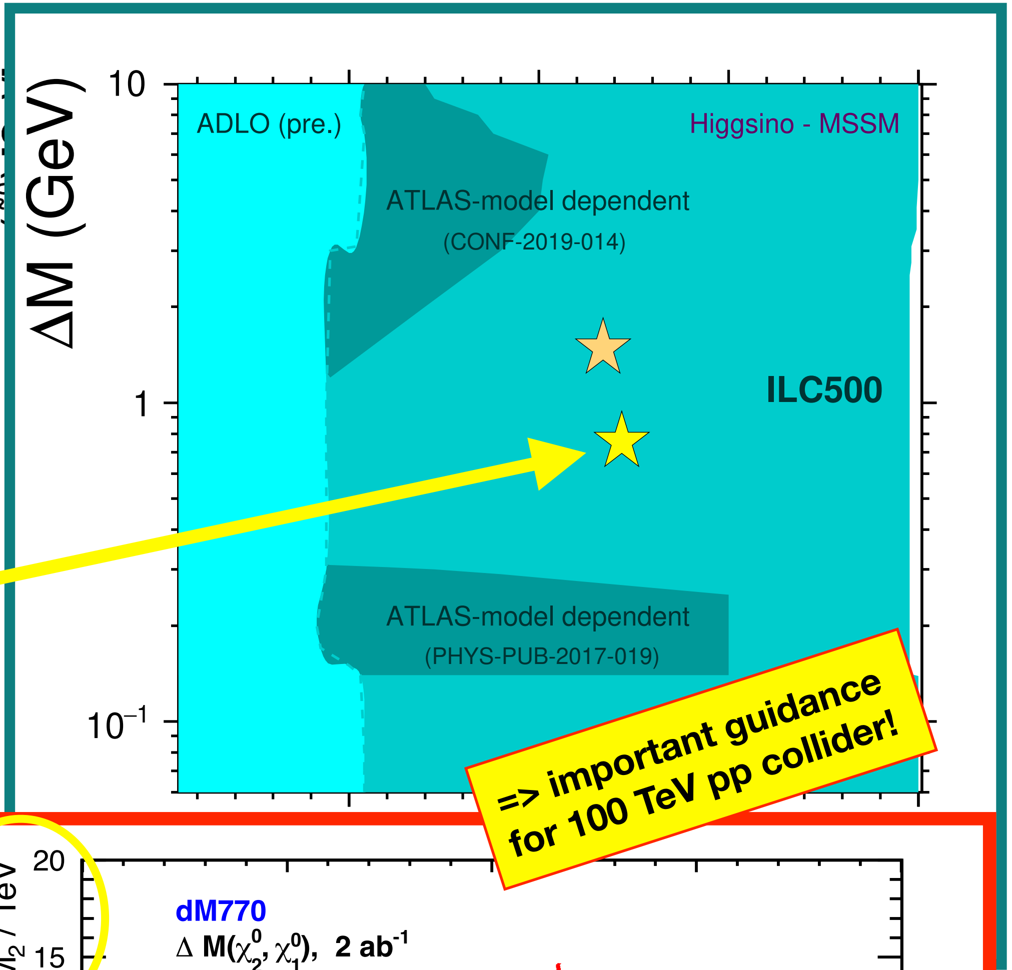
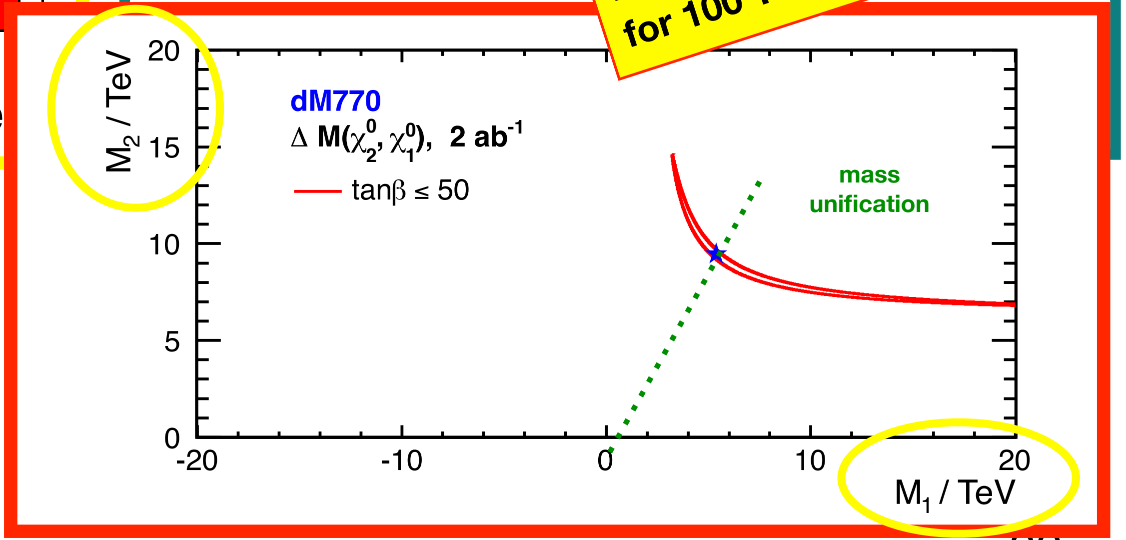




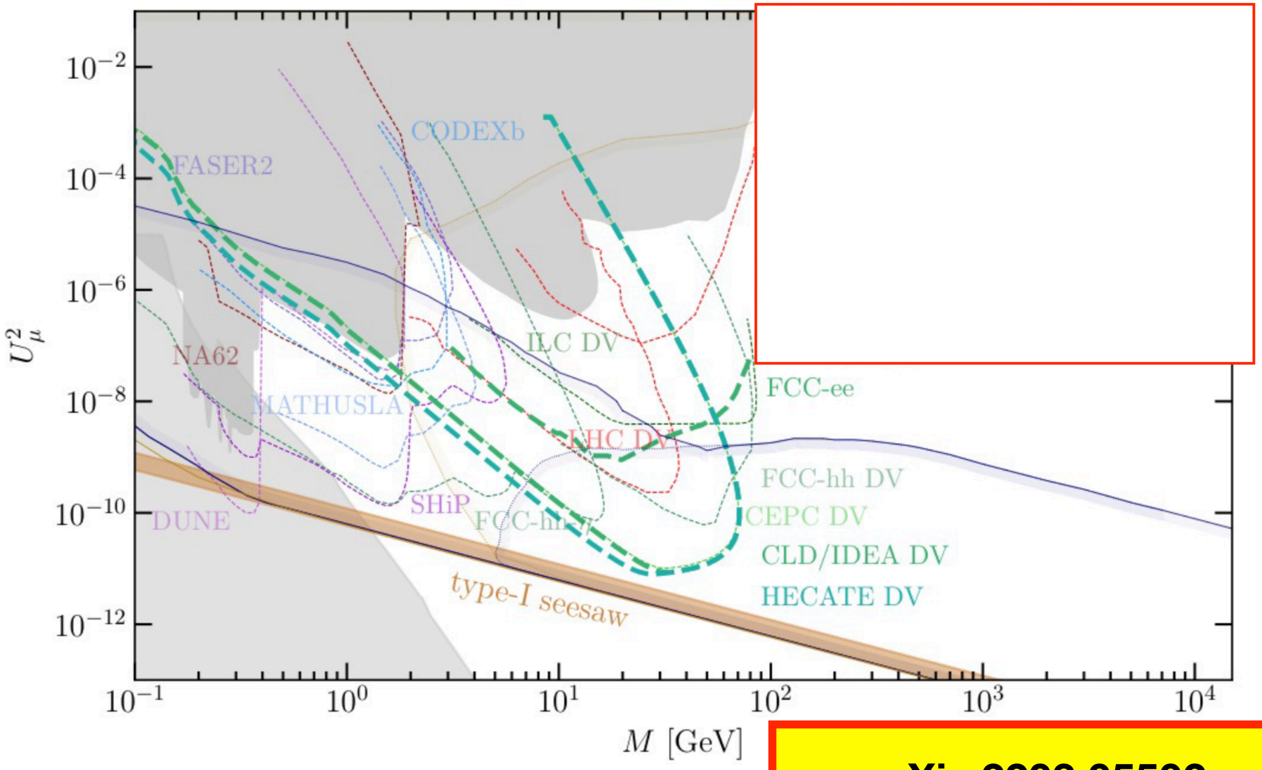
=> important guidance for 100 TeV pp collider!



Heavy Neutral Leptons

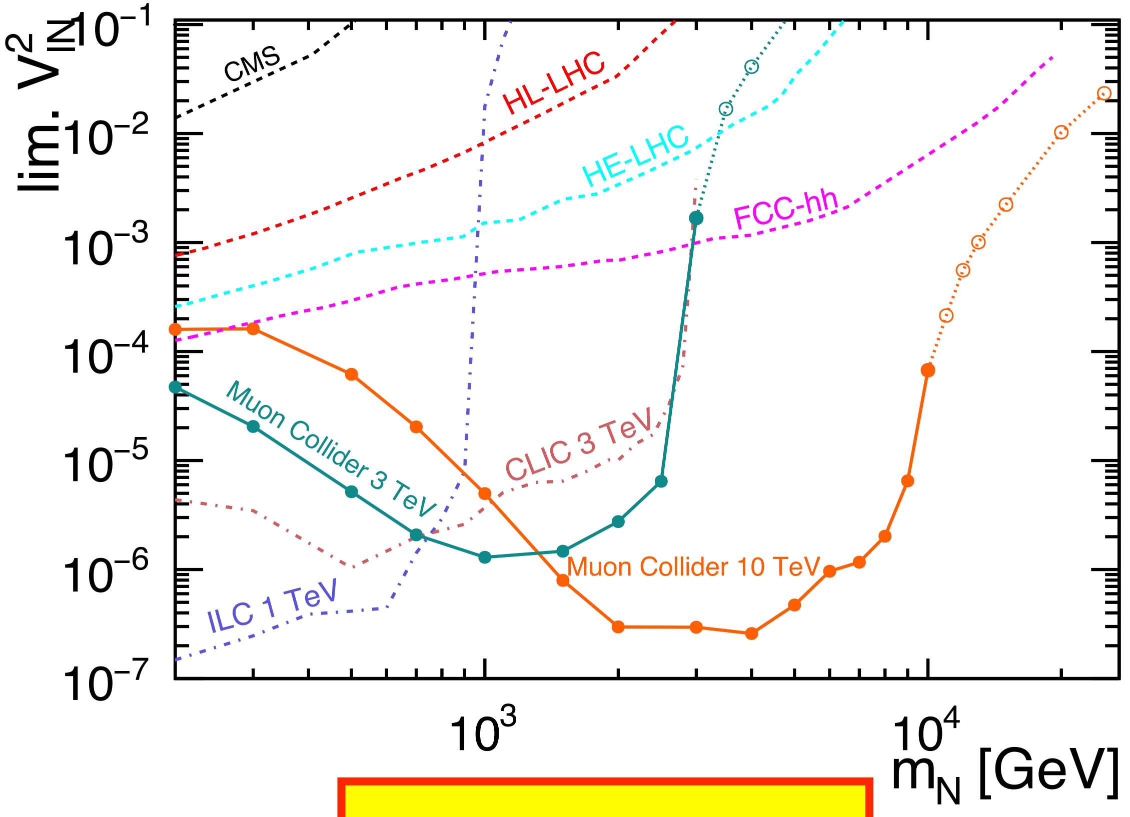
Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices…



arXiv:2203.05502

…and at high masses in prompt decays



arXiv:2301.02602

Sustainability

Gro Harlem Brundlandt at WEF 1989

Cover of the "Brundtland Report" 1987

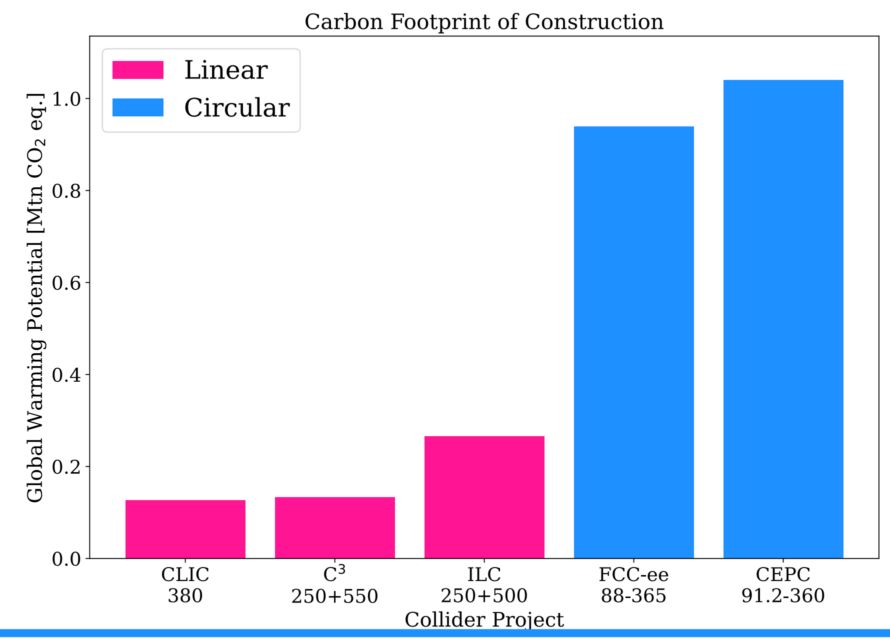
Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations. (WCED, 1987)

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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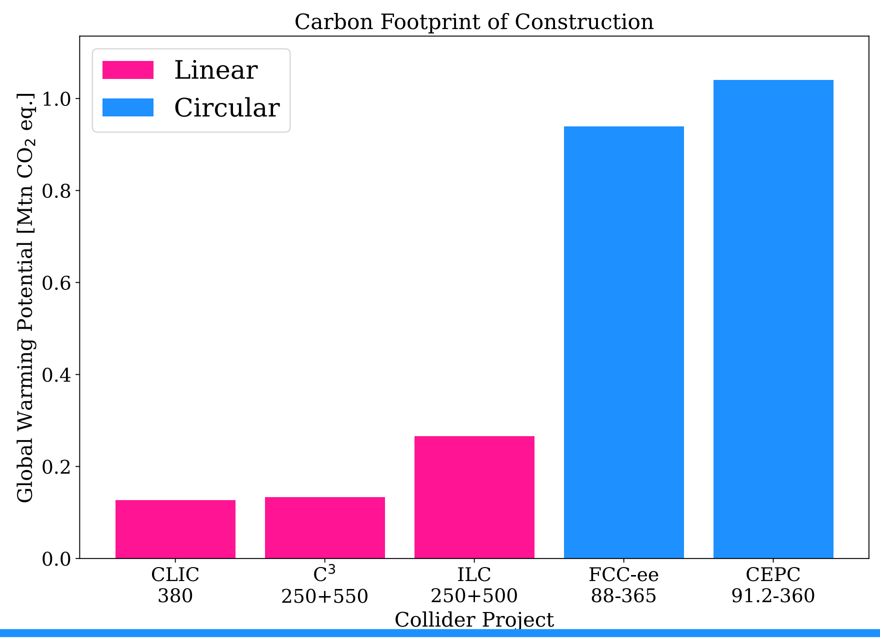
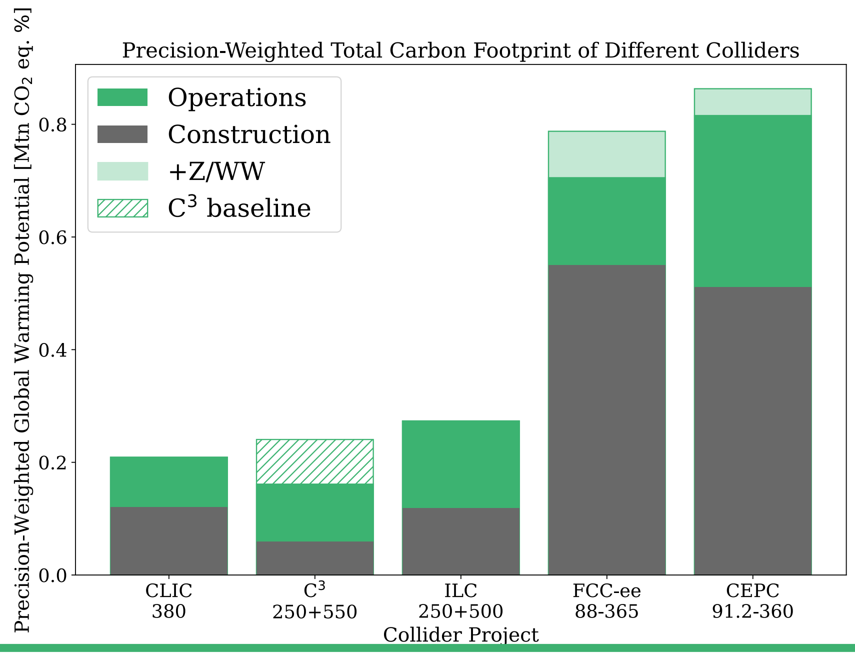




Adding operation GWP

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

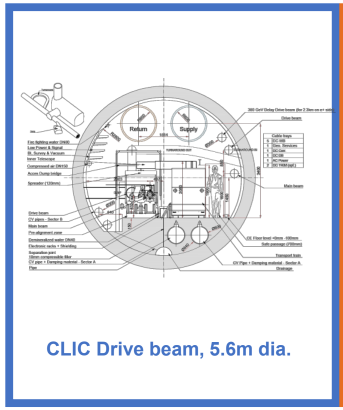
- **Operation dominates for LCs**
- **Construction dominates for CCs**

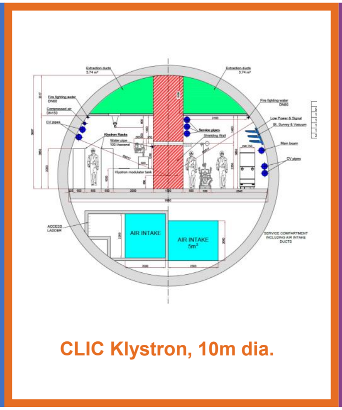
arXiv:2307.04084

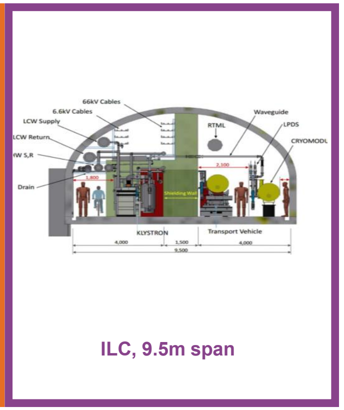
GWP of tunnel construction

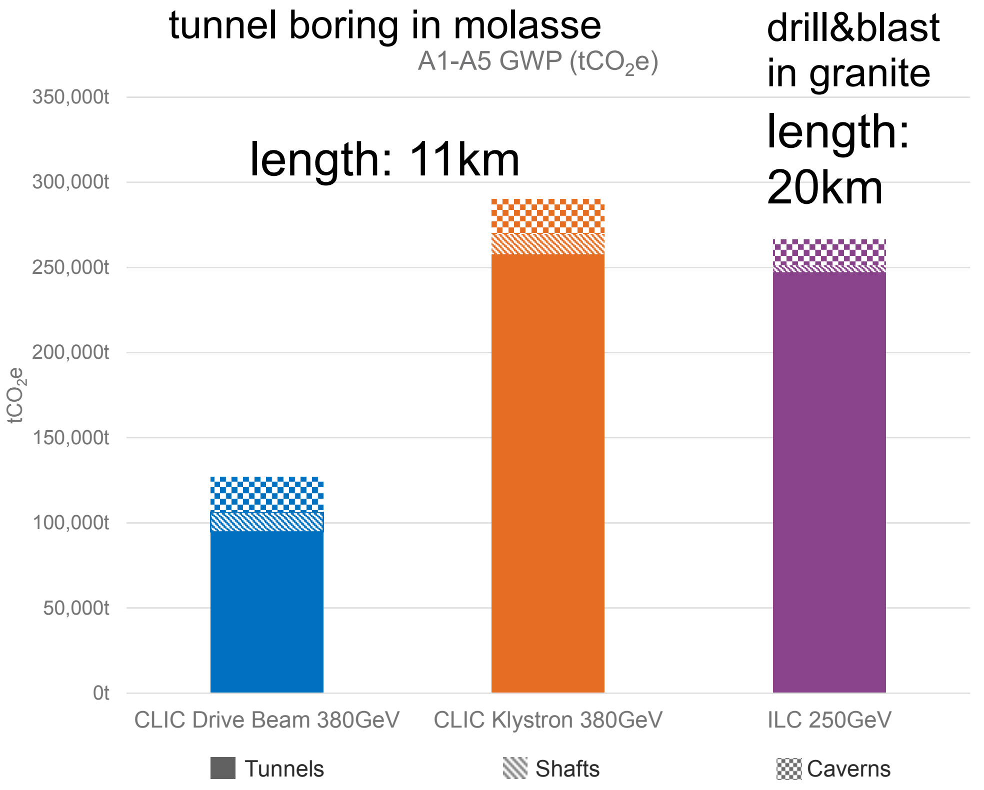
Study by CLIC and ILC

- **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)









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

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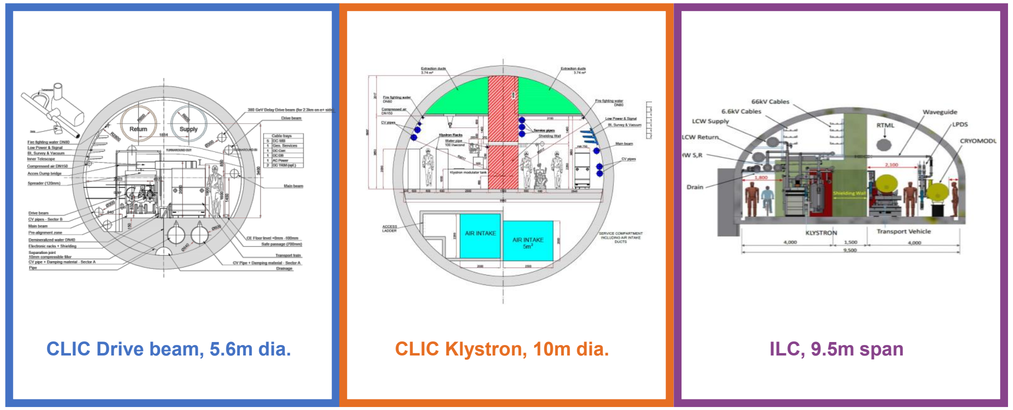
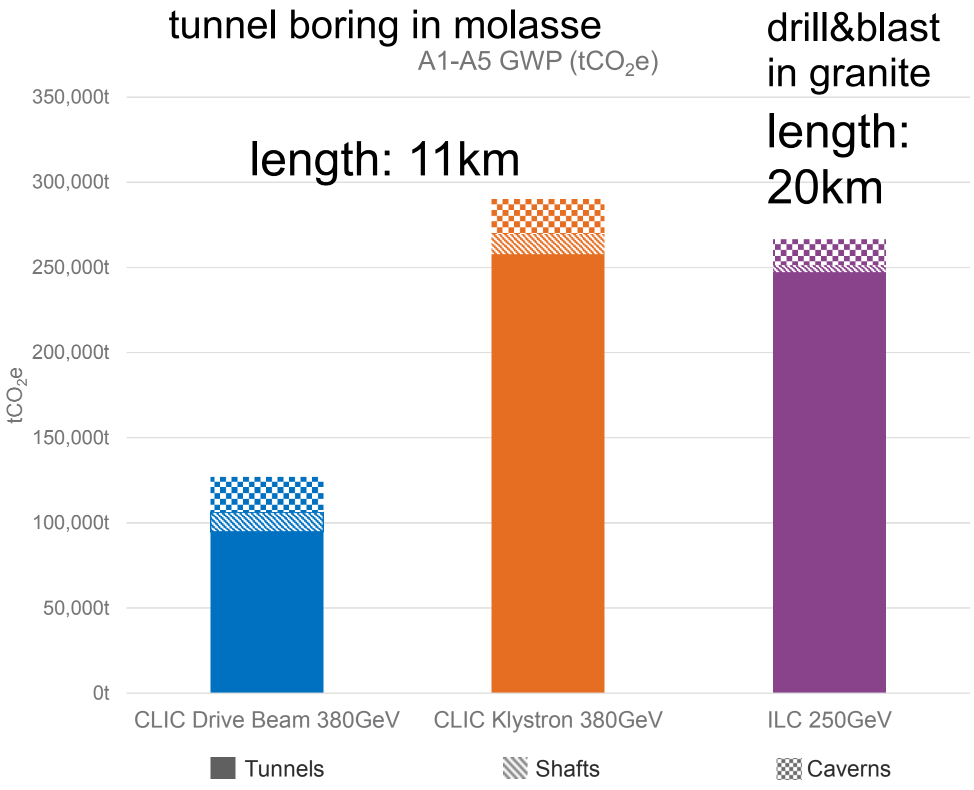
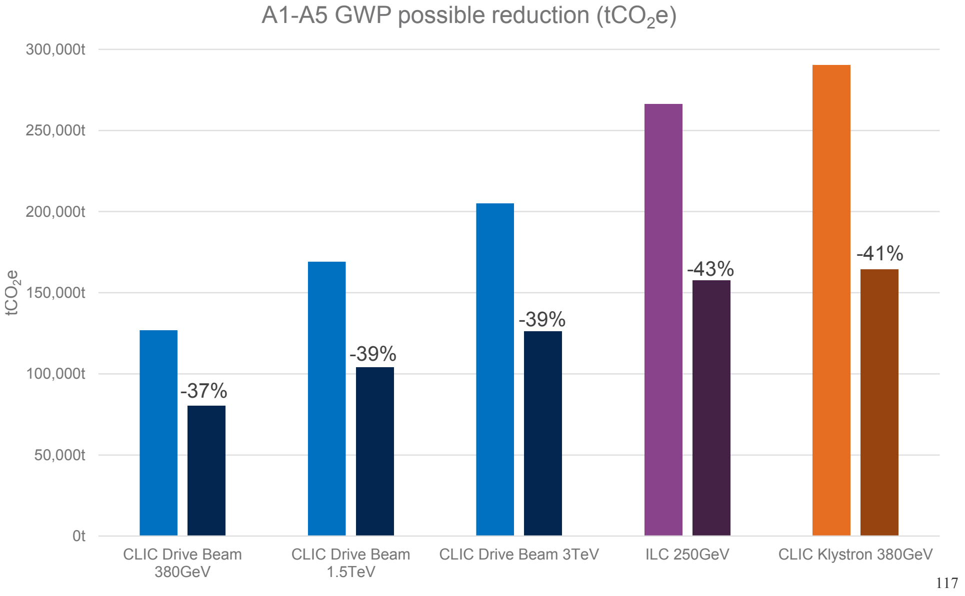
  - reduction of tunnel wall thickness







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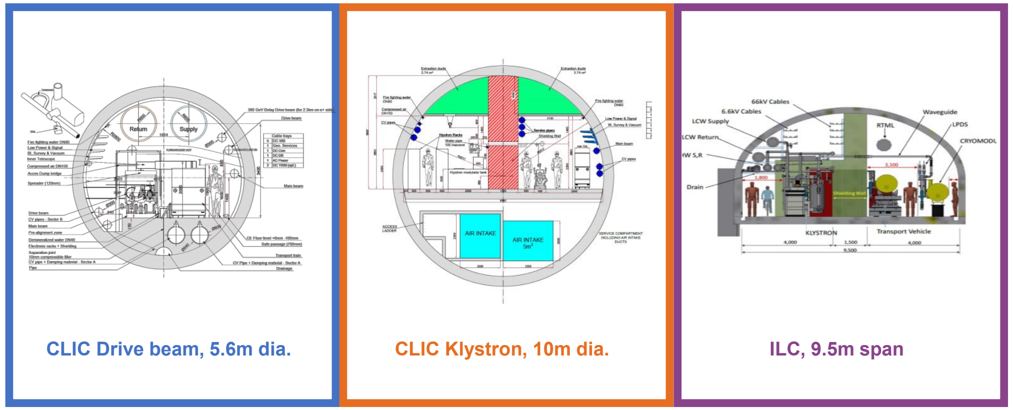
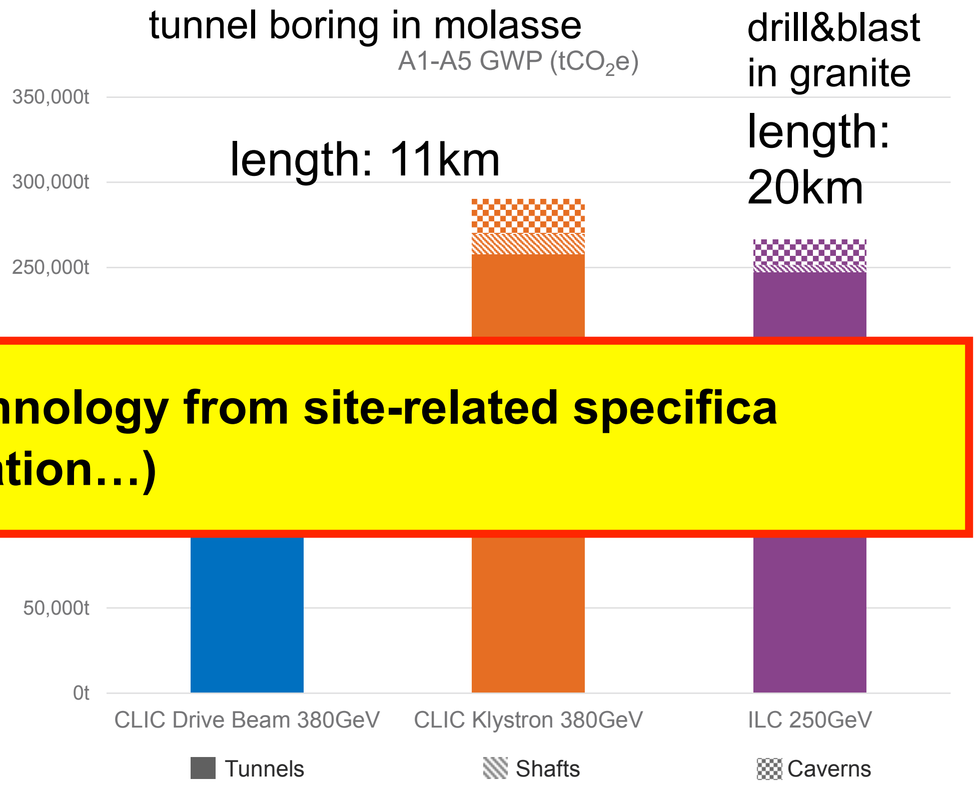
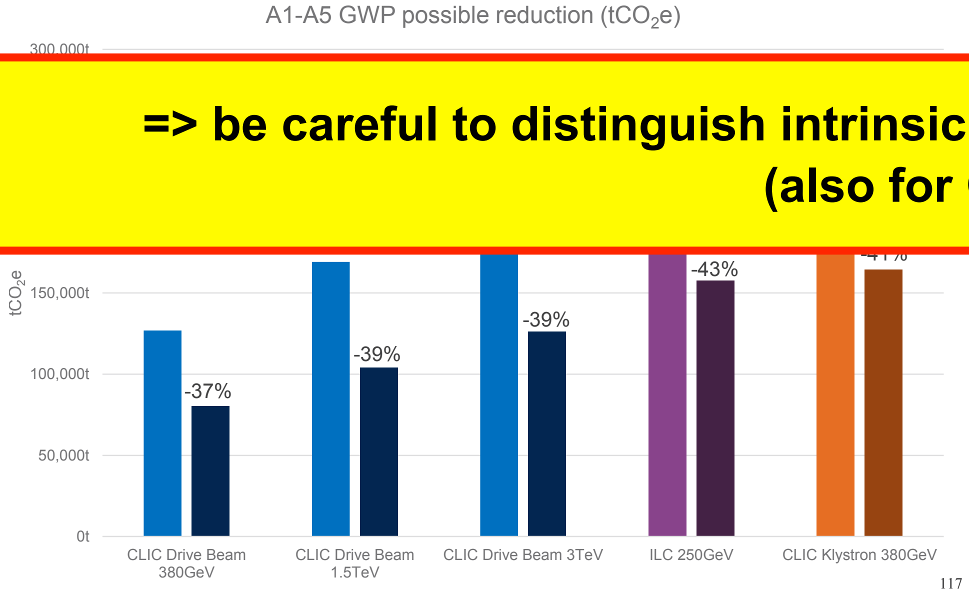






=> be careful to distinguish intrinsic needs of technology from site-related specifica (also for GWP of operation…)

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

Instead of a conclusion…

An adaptable e+e- LC facility for the world

A LC facility can be extended in length for higher energies, using the same or improved versions of the same technology, e.g. as suggested for ILC, CLIC, C3 and HALHF.

- It is also possible and realistic to change to more performant (usually higher gradient) technologies in an upgrade, e.g. from ILC to CLIC or C3, maybe even plasma
- Starting point for fast implementation: ILC has the most mature linac technology for large scale implementation, that is also well established in all regions and in industry - it is based on a 20-21km long and ~9-10m wide tunnel
- The physics at higher energies – Higgs sector and extended models with increased reach and precision, top in detail well above threshold, searches and hopefully new physics – will open for a very exciting long term e+e- programme
- Such a programme can run in parallel with future hadron and/or muon colliders that can be developed, optimised and implemented as their key technologies mature

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**

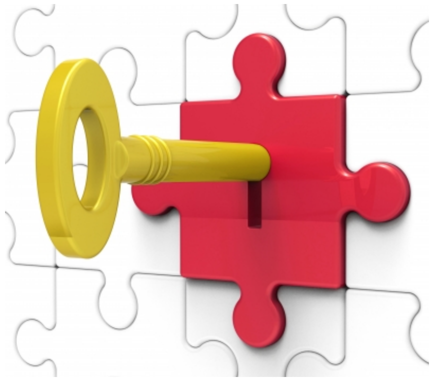
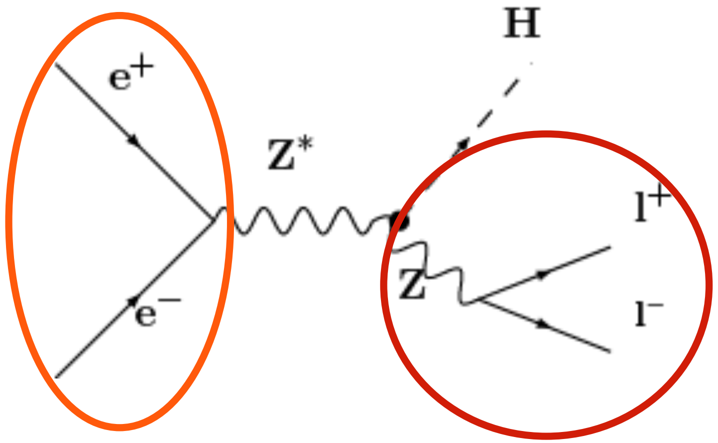
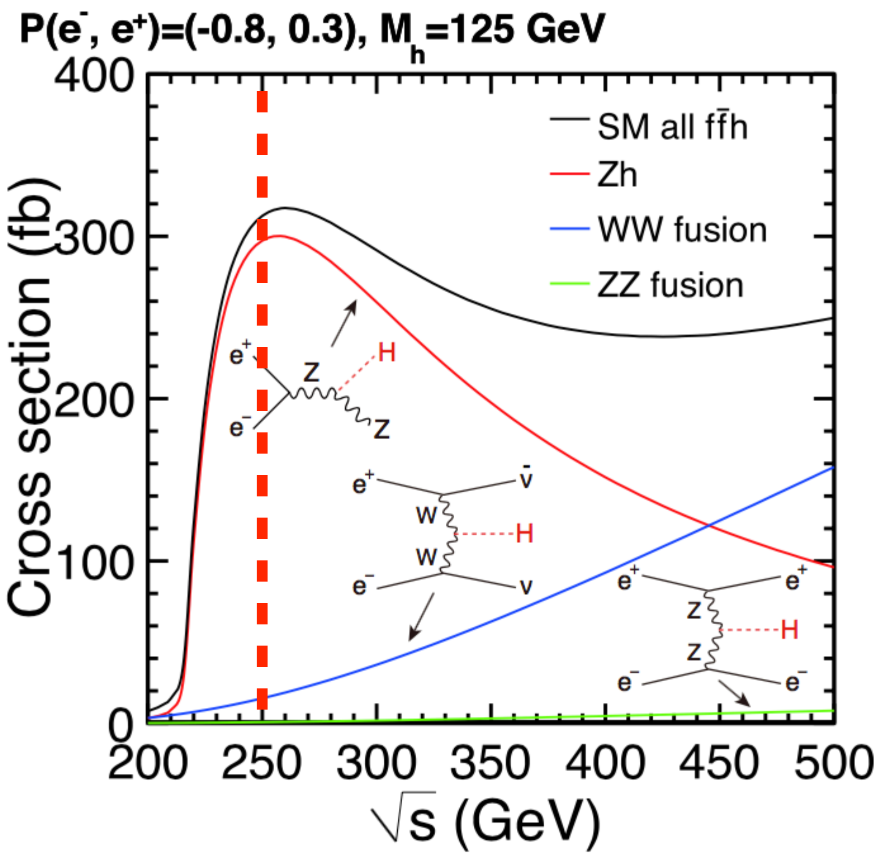


Image courtesy of Stuart Miles at FreeDigitalPhotos.net



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



Interlude: Chirality in Particle Physics

Just a quick reminder…

- Gauge group of weak x electromagnetic interaction: $SU(2)_L$ x 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!

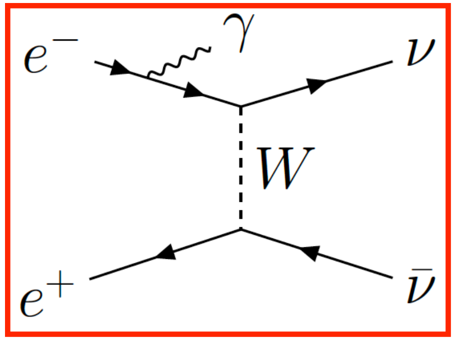
General references on polarised e^+e^- physics:

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

background suppression:

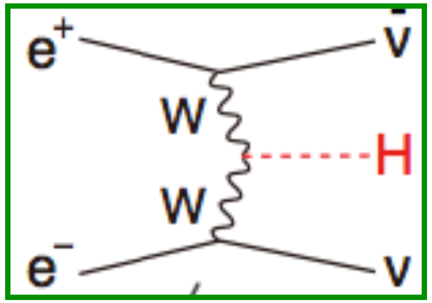
- $e^+e^- \rightarrow WW$ / $\nu_e \nu_e$ strongly P-dependent since t-channel only

  for $e^-_L e^+_R$



signal enhancement:

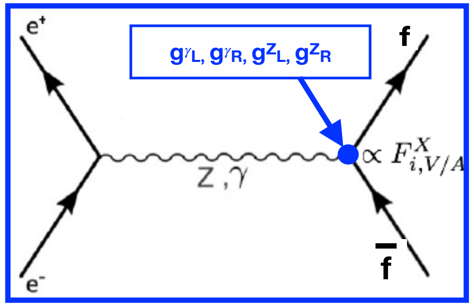
- Higgs production in WW fusion
- many BSM processes



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!

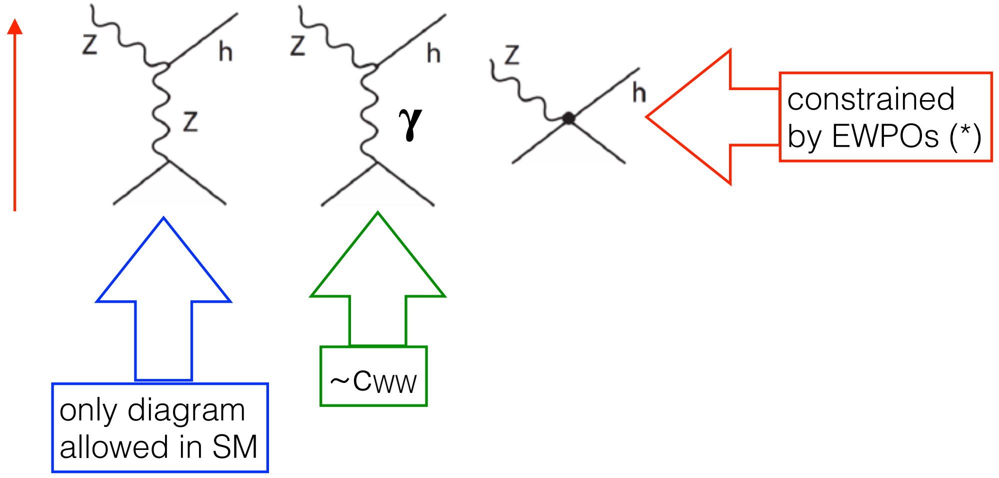
Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

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

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

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



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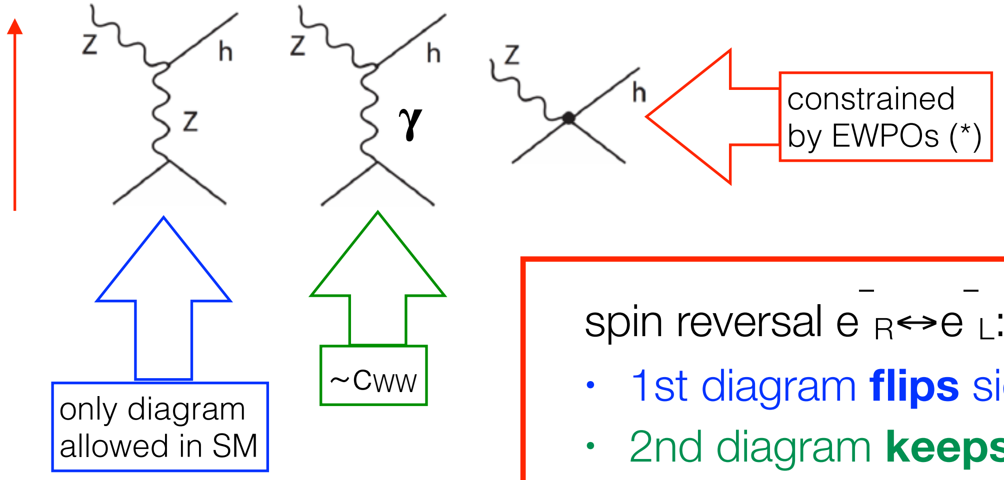

spin reversal $e^-_R \leftrightarrow e^-_L$:

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

⇒ A_{LR} lifts degeneracy between operators!

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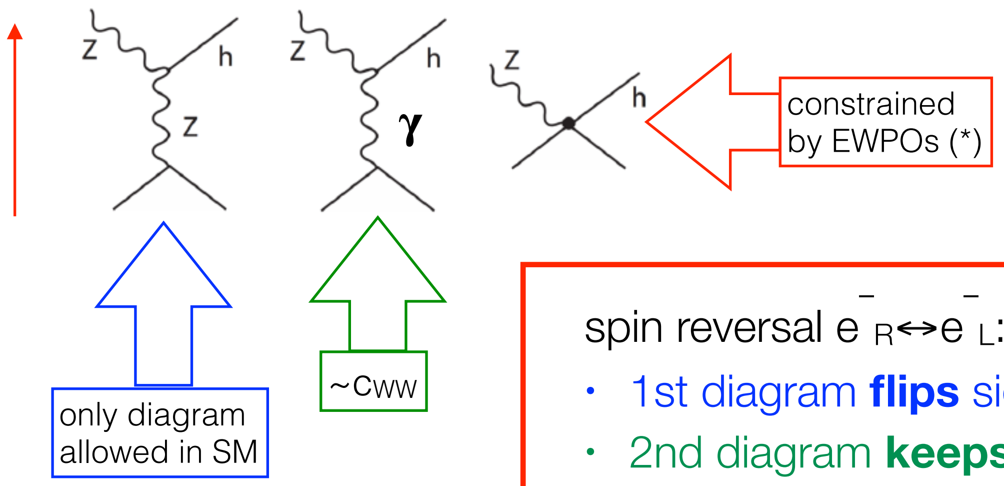

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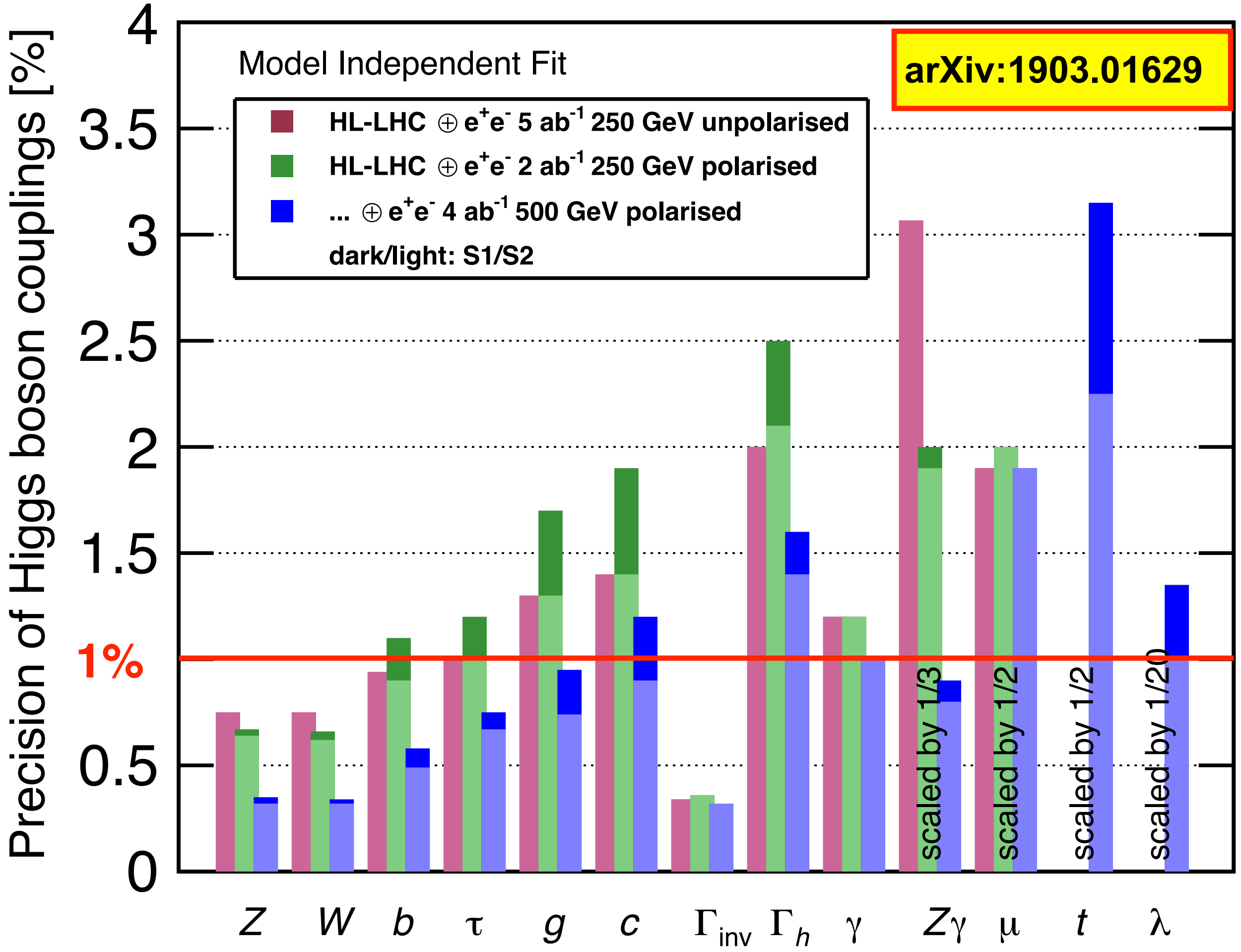

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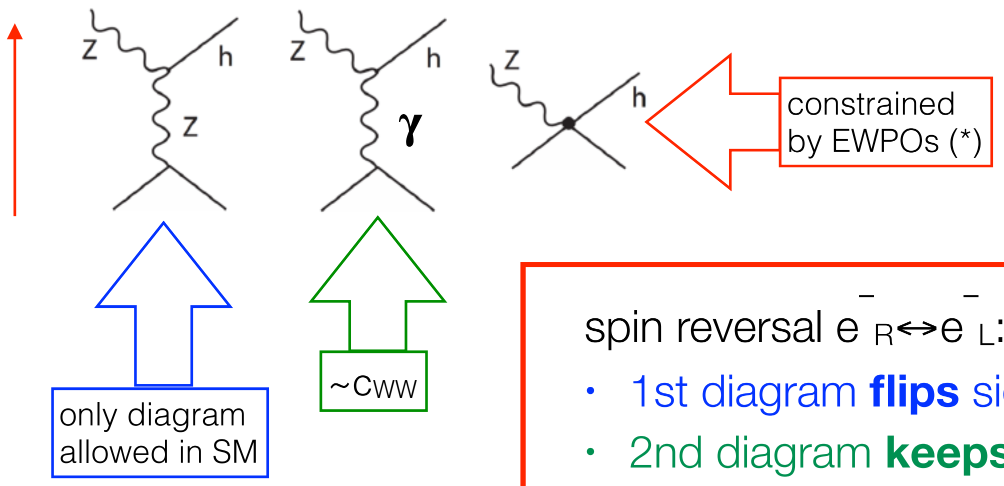

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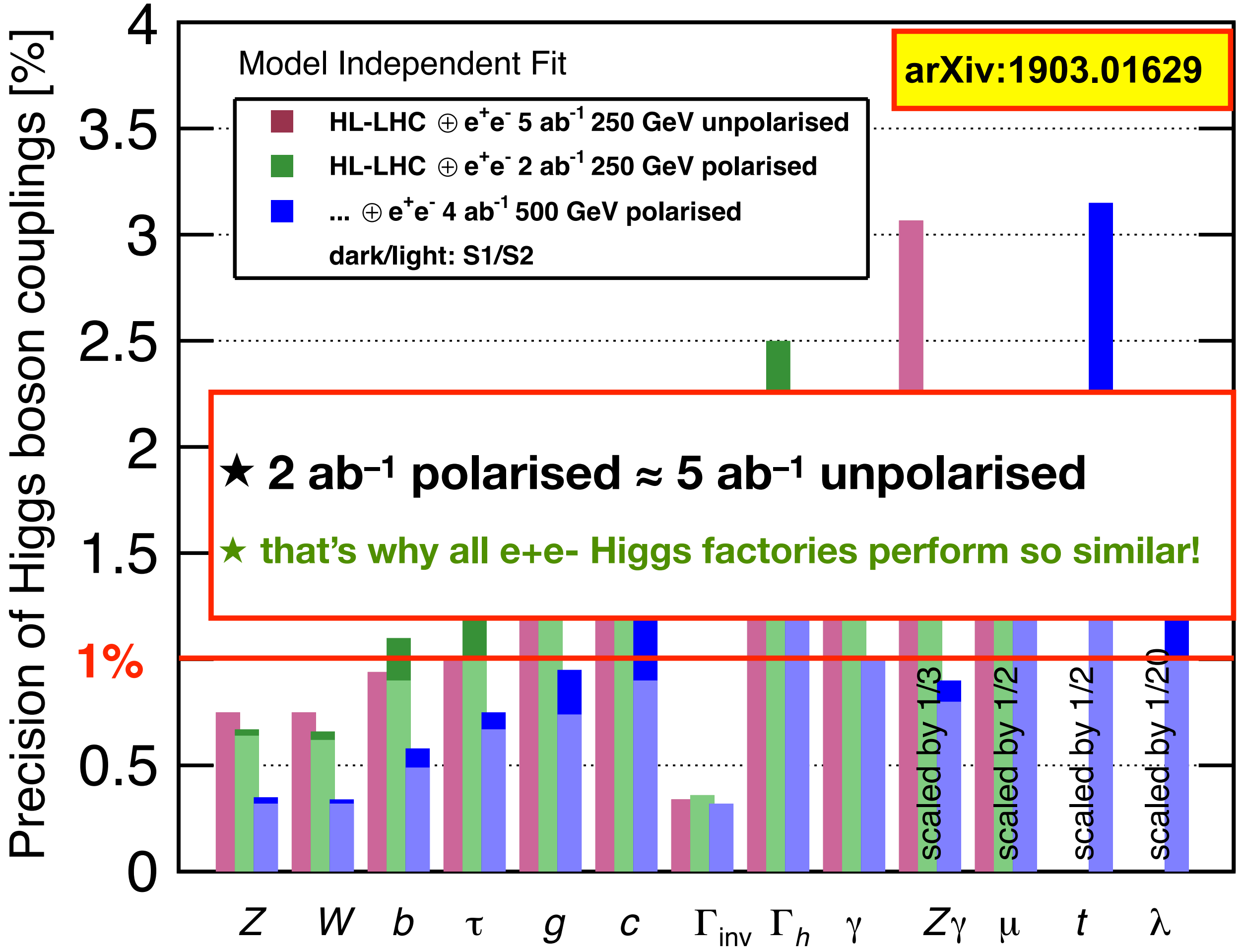


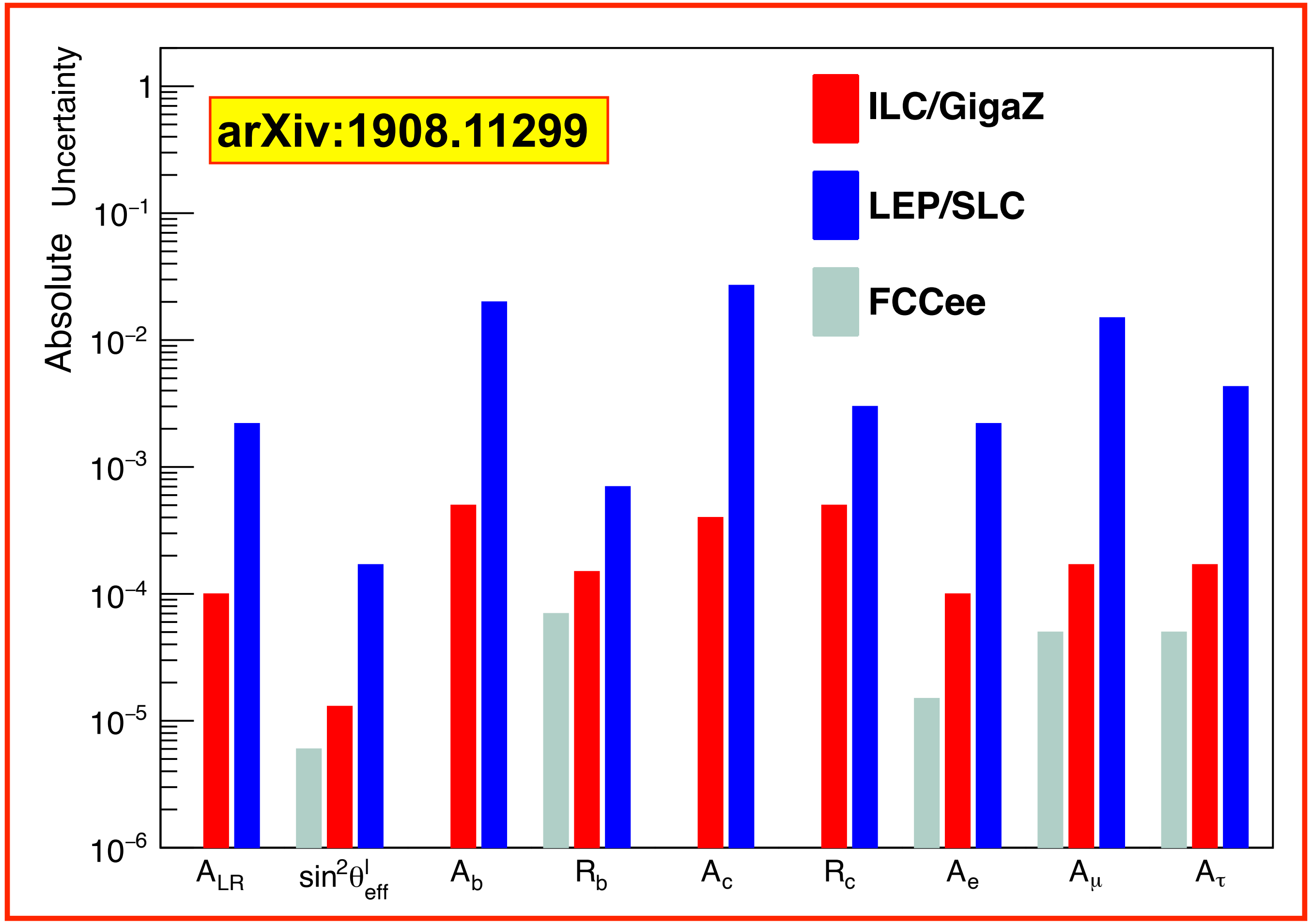
Polarisation & Electroweak Physics at the Z pole

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

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

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

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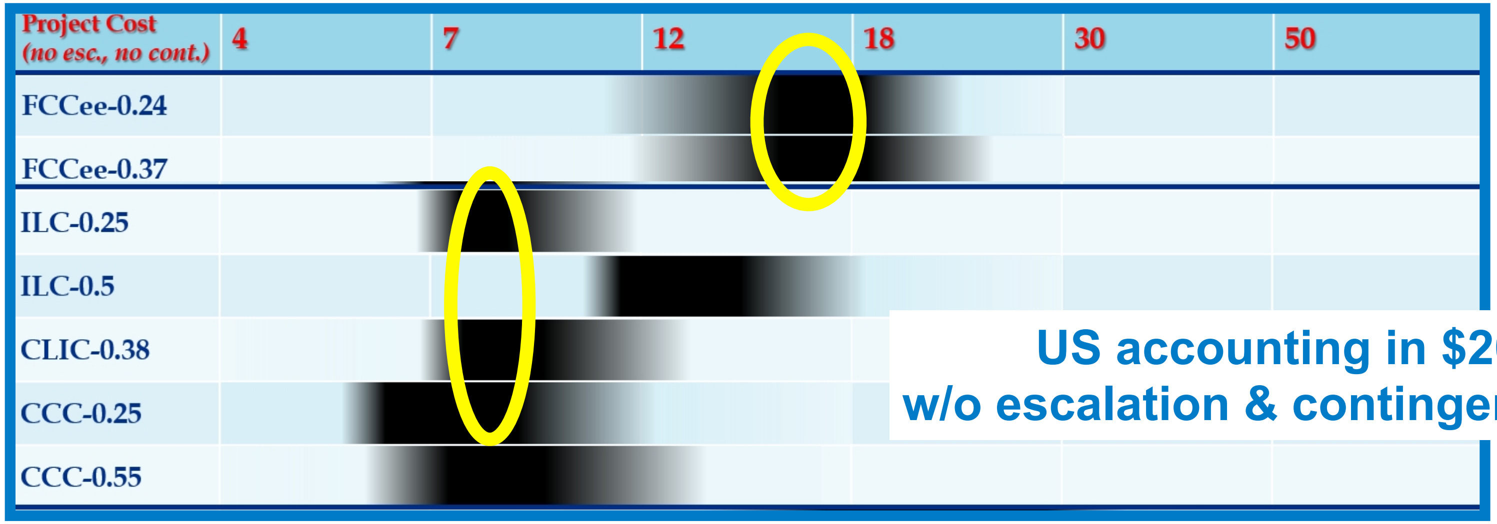

US accounting in $2021
w/o escalation & contingency

Linear Higgs Factory ~7-8B$

Circular Higgs Factory ~15B$

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

Lowest Technology Readiness Levels

- RF systems
- e+ source

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

Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Jenny List
FTX
jenny.list@desy.de