Straight to the Future: Physics Opportunities at Linear Colliders

J. List (DESY)

Colloquium, NIKHEF, April 19 2024

Outline

Today's menu

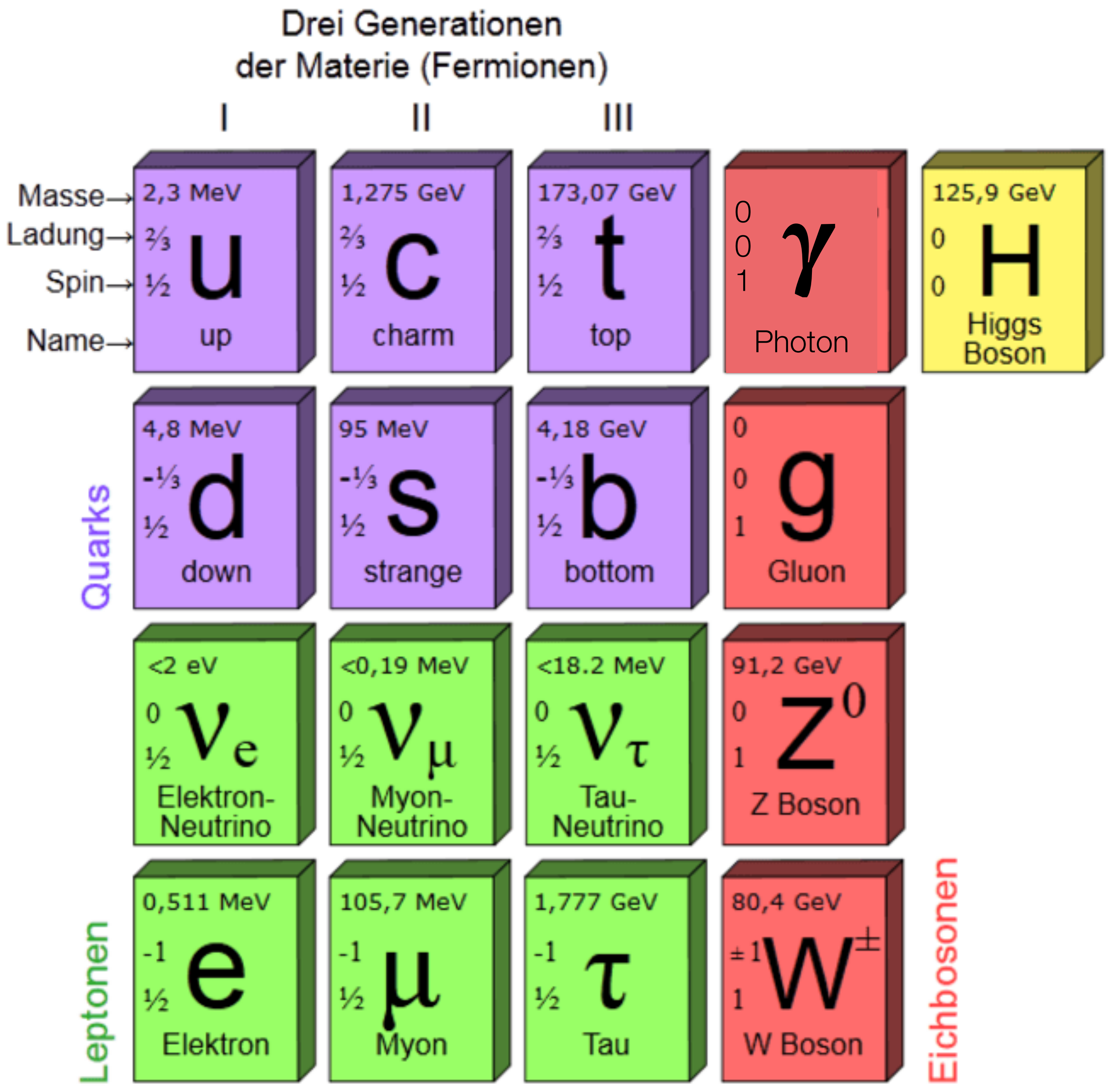
- **Introduction: The Higgs Physics and Higgs Factories**
- **The basic Higgs Factory program**
- **Beyond the minimal program - Energy & Polarisation**
- **Conclusions**

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

Introduction:
Higgs Physics &
Higgs Factories

The Higgs Boson and the Standard Model of Particle Physics

A discovery which is only the beginning …



The Standard Model of Particle Physics

- describes (nearly) all measurements down to the level of quantum fluctuations
- based on only a few fundamental ideas:
  - special relativity
  - quantum mechanics
  - invariance under local gauge transformations: $SU(3) \times SU(2)_L \times U(1)_Y$

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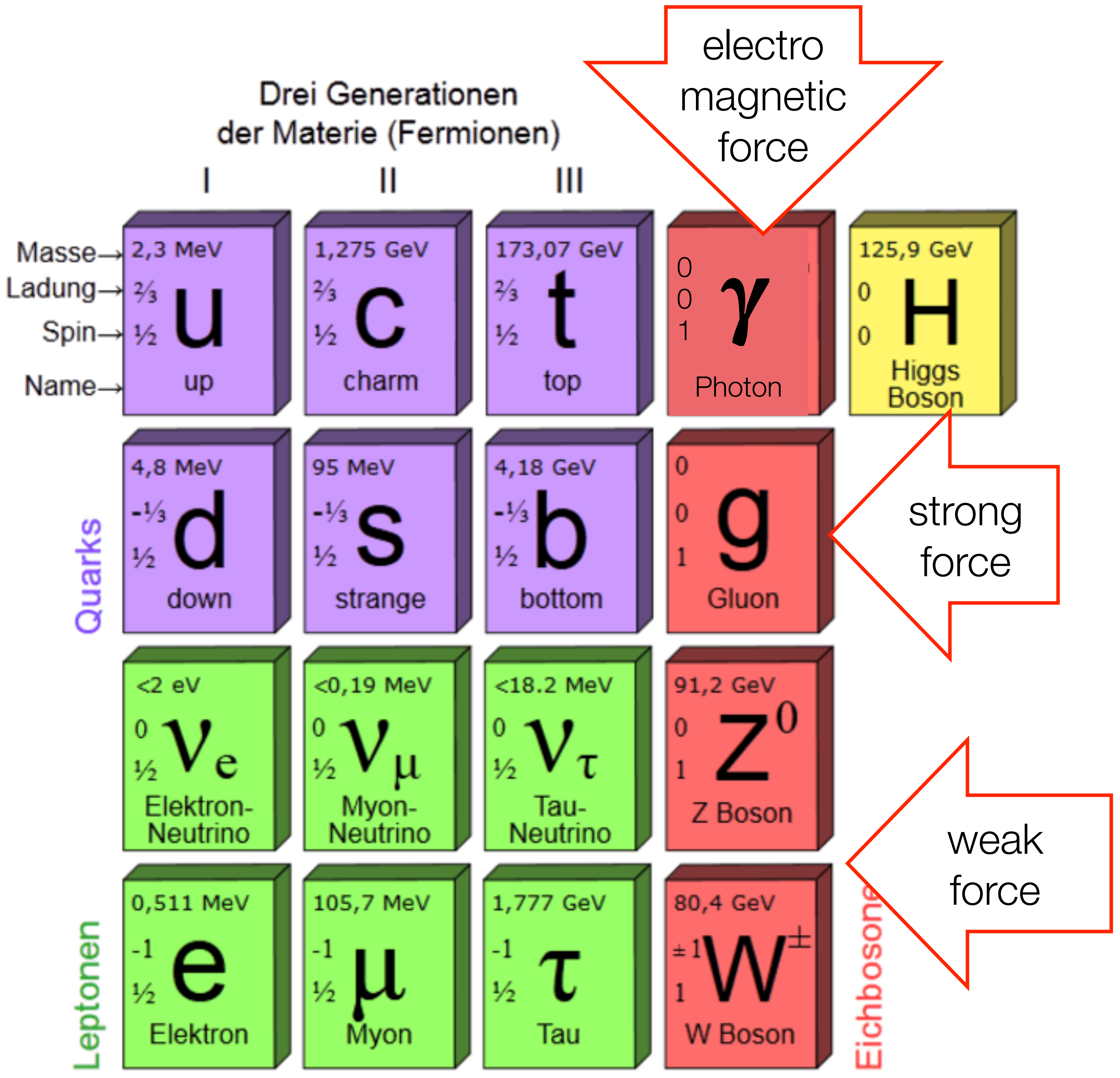

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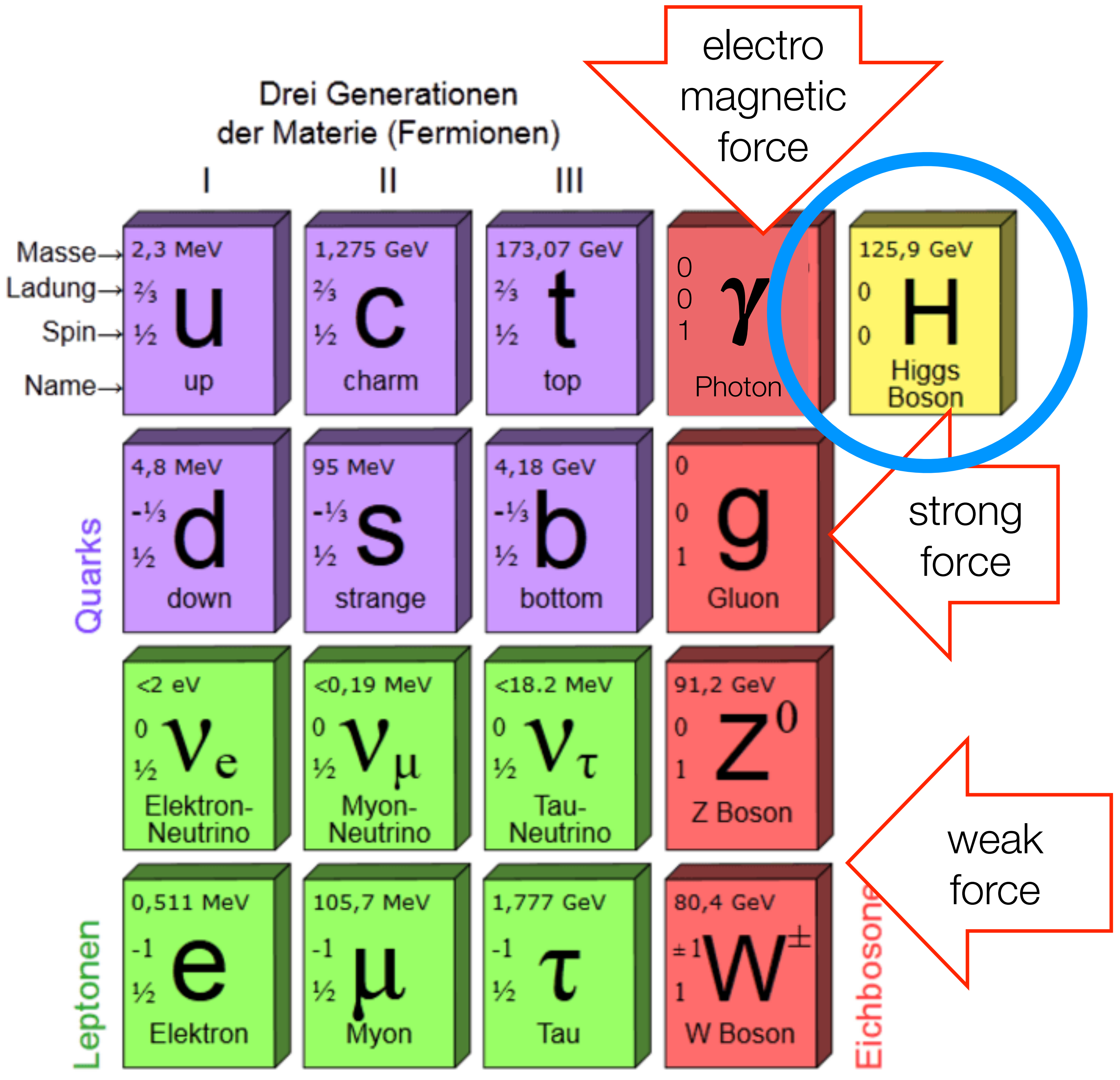

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2012: Discovery of a Higgs bosons at the LHC!

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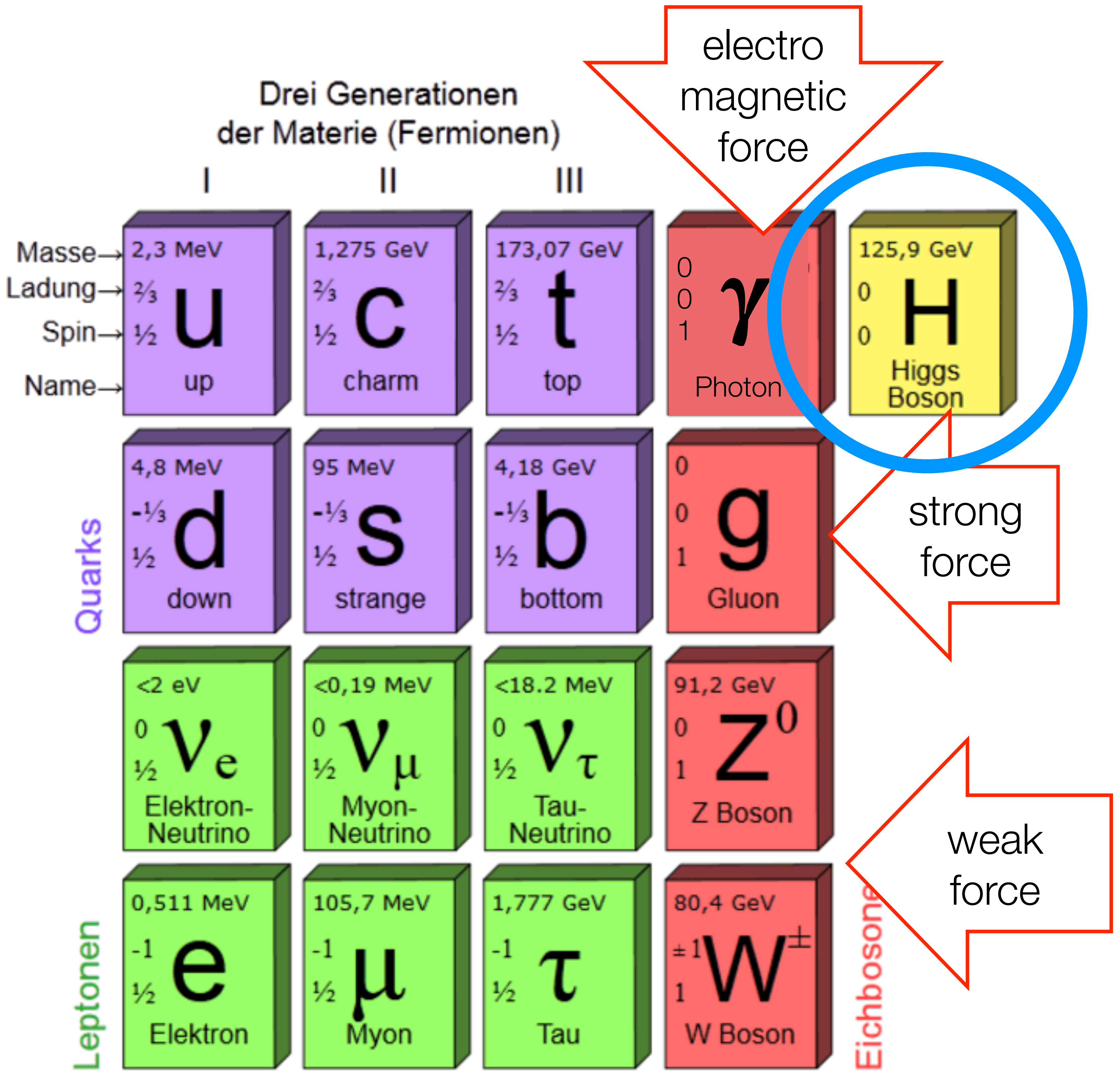

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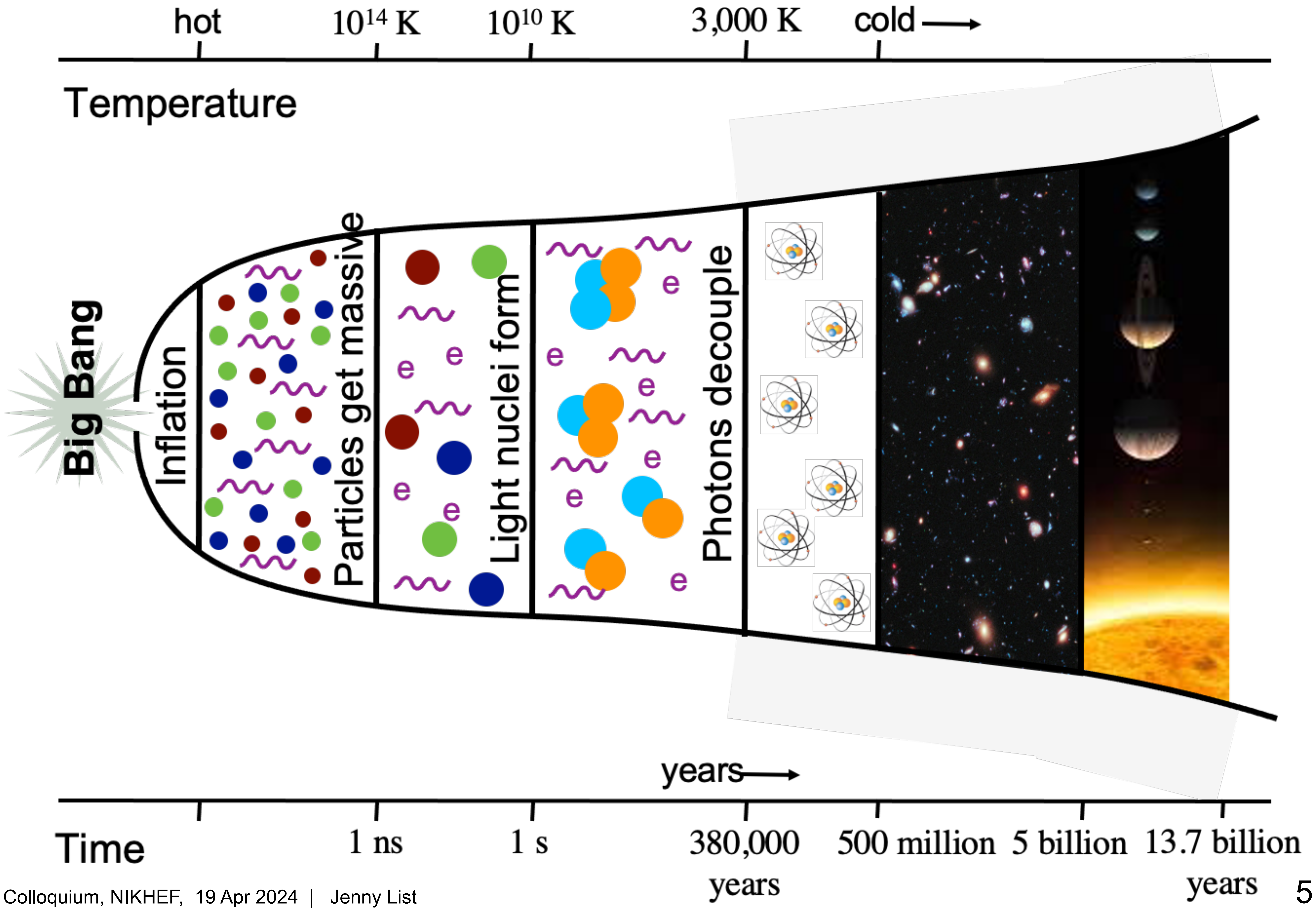
Are we done? — No! — The Higgs Boson is

1. **a mystery in itself: how can an elementary spin-0 particle exist and be so light?**
2. **intimately connected to cosmology => precision studies of the Higgs are a *new* messenger from the early universe!**

A new messenger from the early universe

The Higgs Boson



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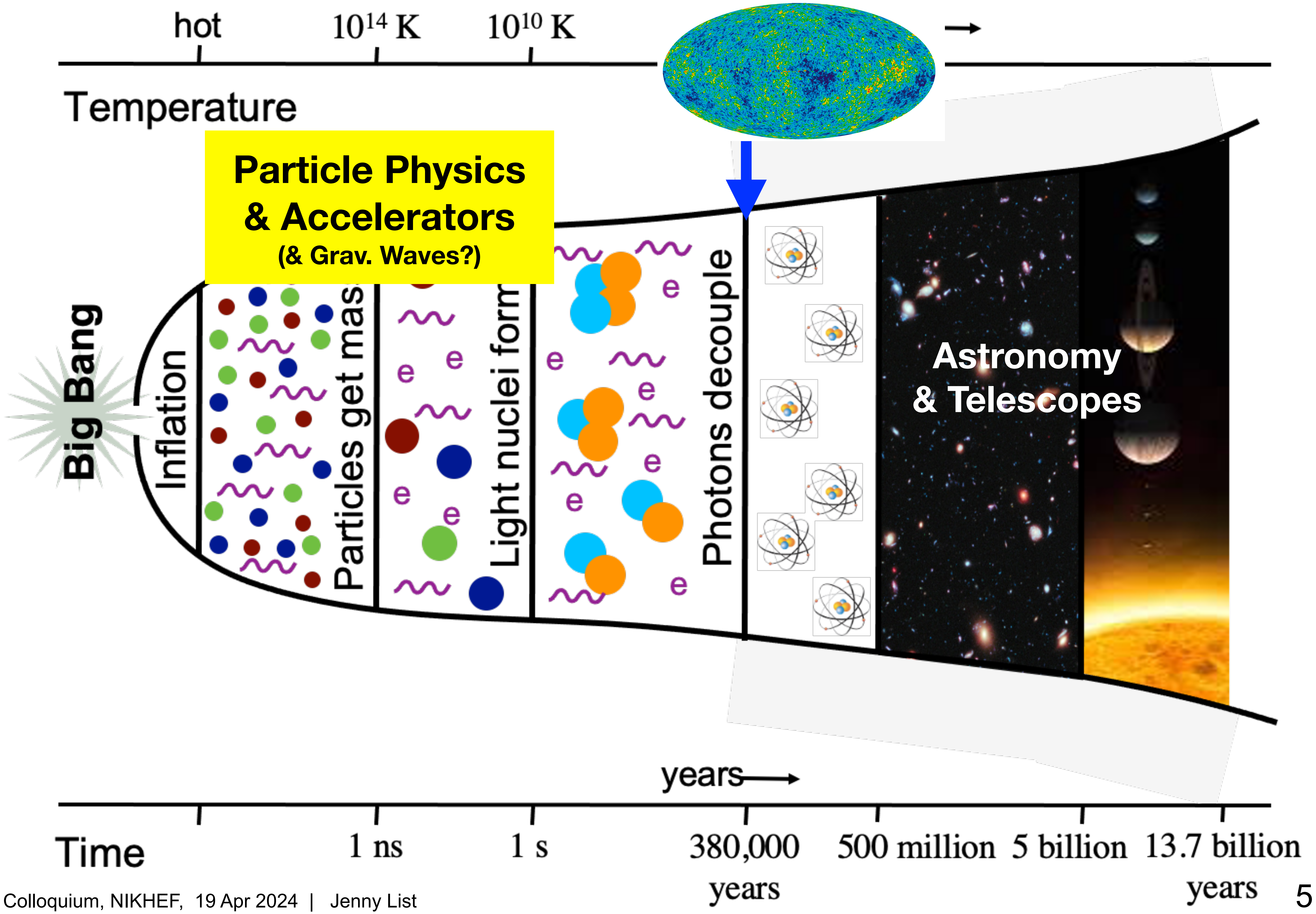

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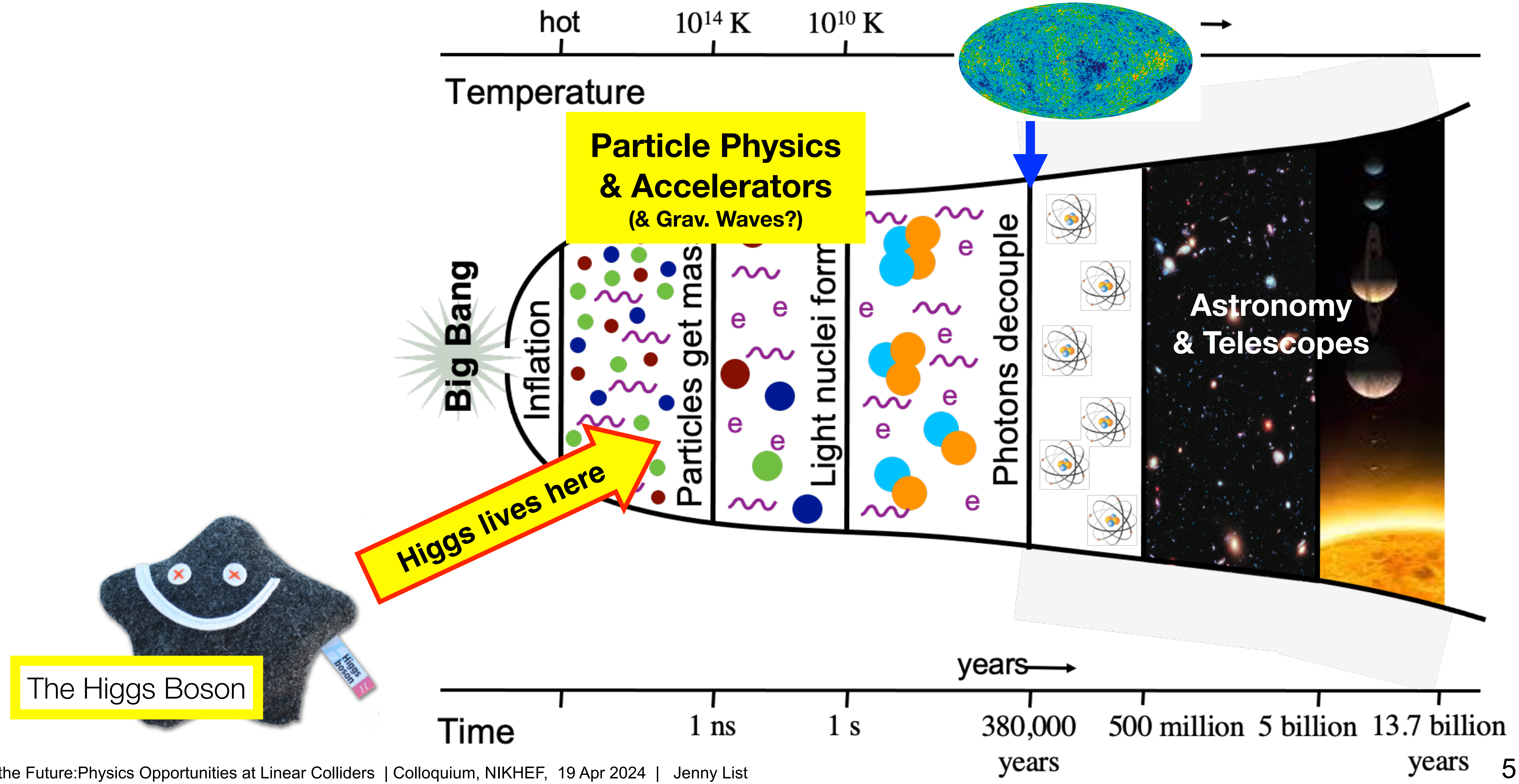

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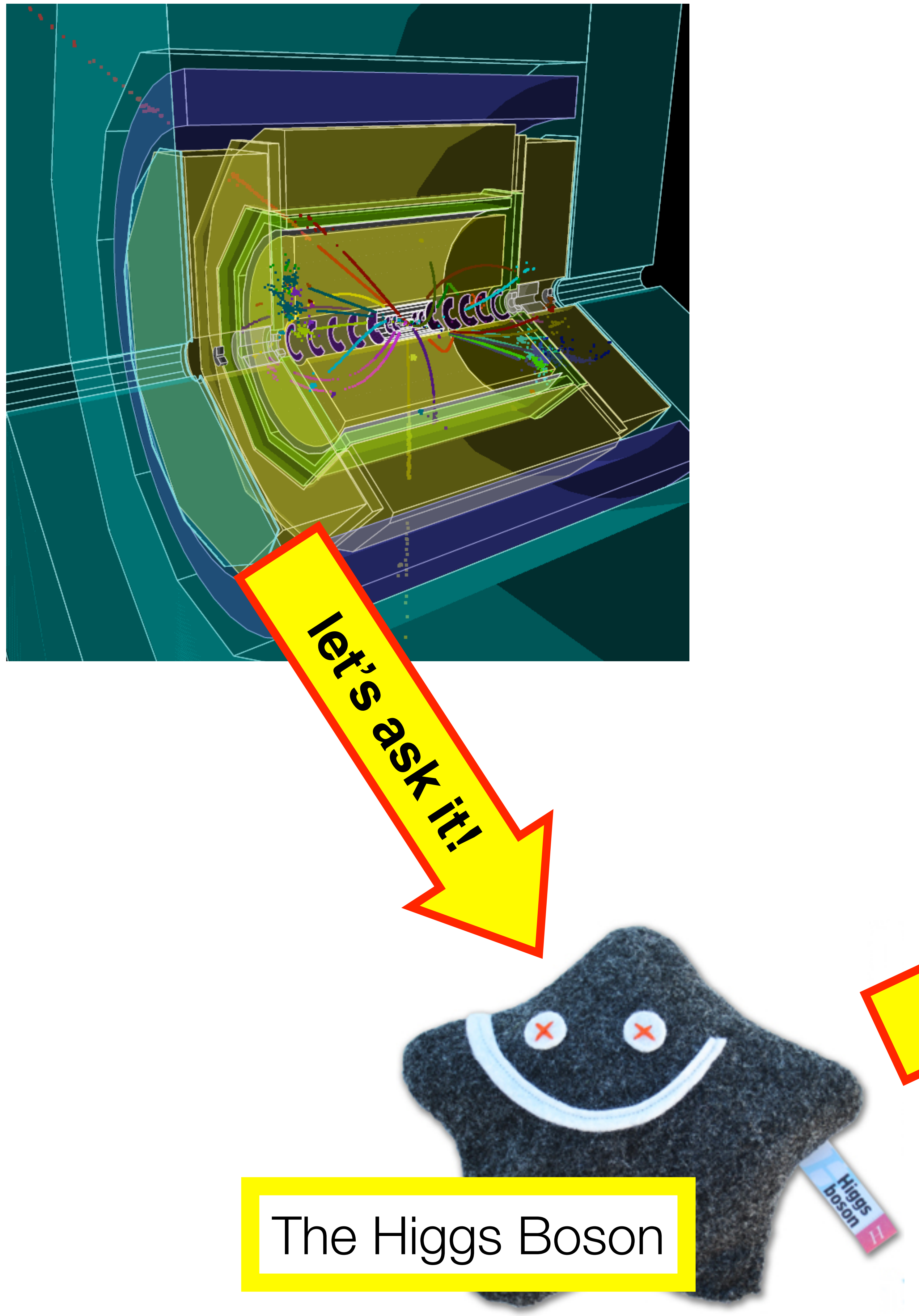
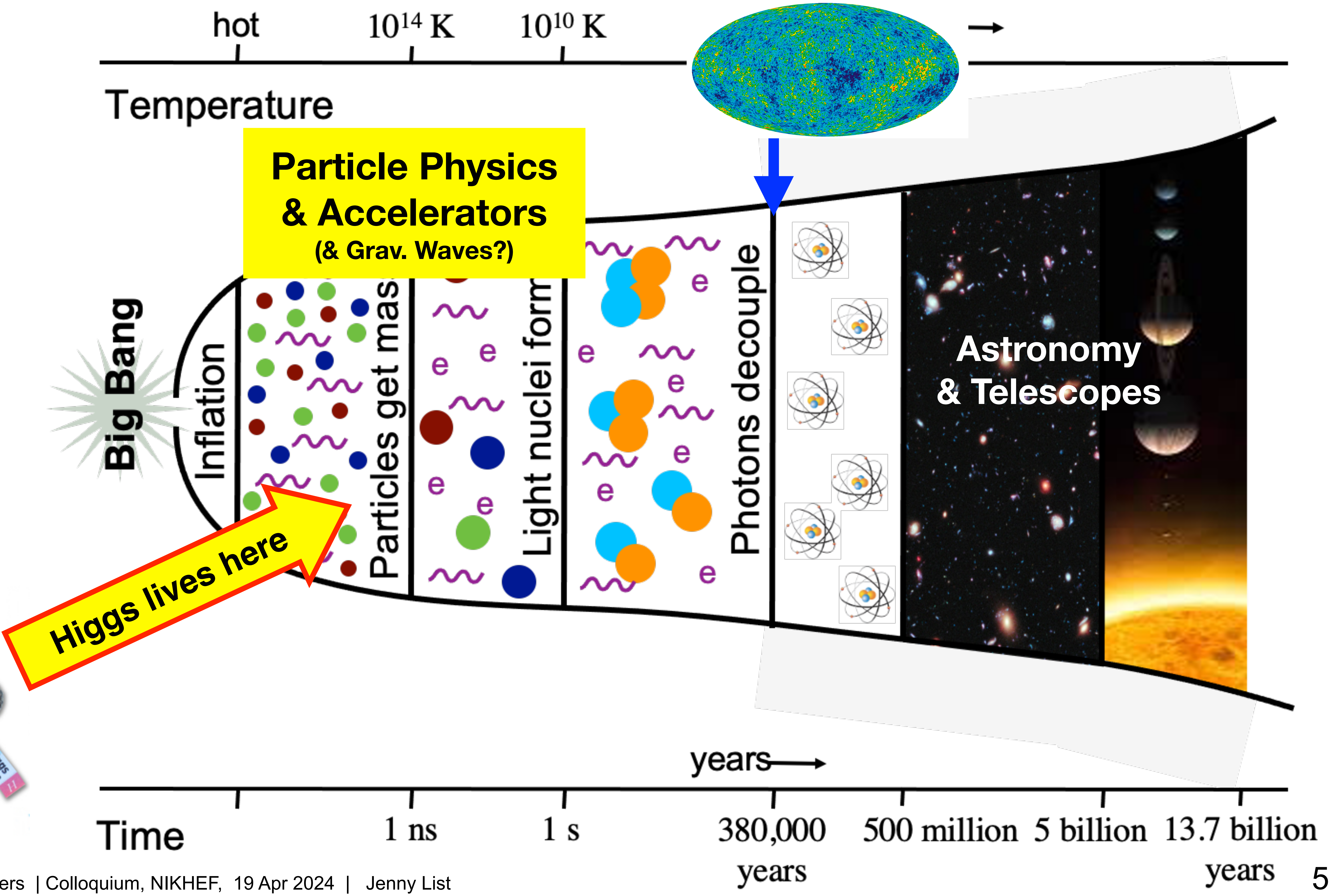
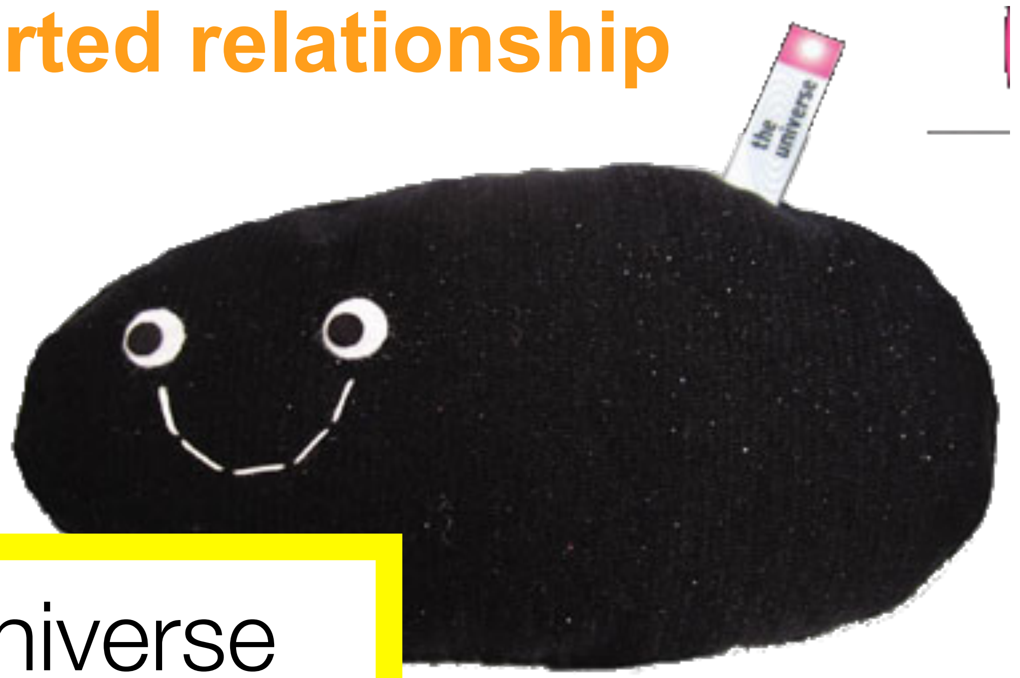




The Higgs Boson and the Universe

Exploration of an uncharted relationship



The Universe

The Higgs Boson

What we'd really like to know

- What is Dark Matter made out of?
- What drove cosmic inflation?
- What generates the mass pattern in quark and lepton sectors?
- What created the matter-antimatter asymmetry?
- What drove electroweak phase transition?
  - **and could it play a role in baryogenesis?**
- …

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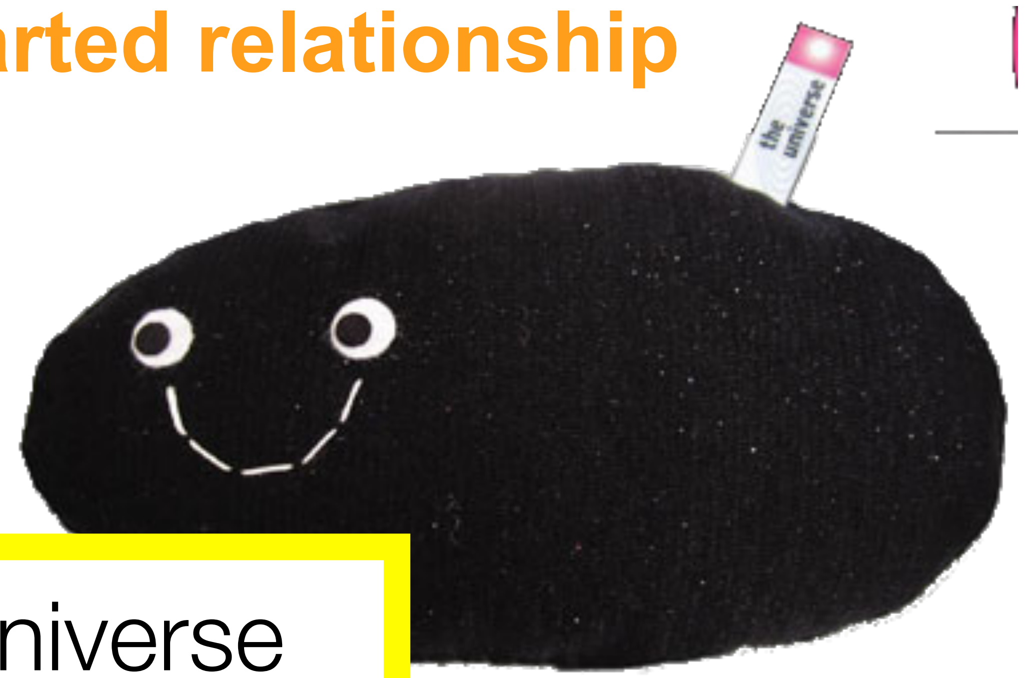

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Is the Higgs the portal to the Dark Sector?

- does the Higgs decays "invisibly", i.e. to dark sector particles?
- does the Higgs have siblings in the dark (or the visible) sector?

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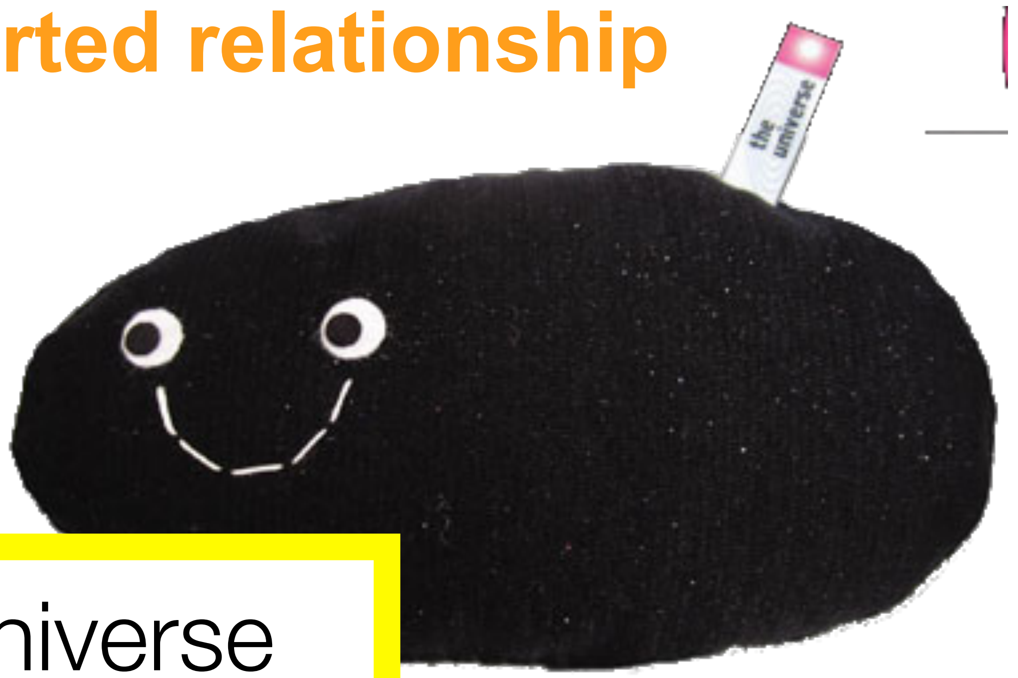

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Is the Higgs the portal to the Dark Sector?

- **The Higgs could be first "elementary" scalar we know -**
  - is it really elementary?
  - is it the inflaton?
  - even if not - it is the best "prototype" of a elementary scalar we have

=> study the Higgs properties precisely and look for siblings

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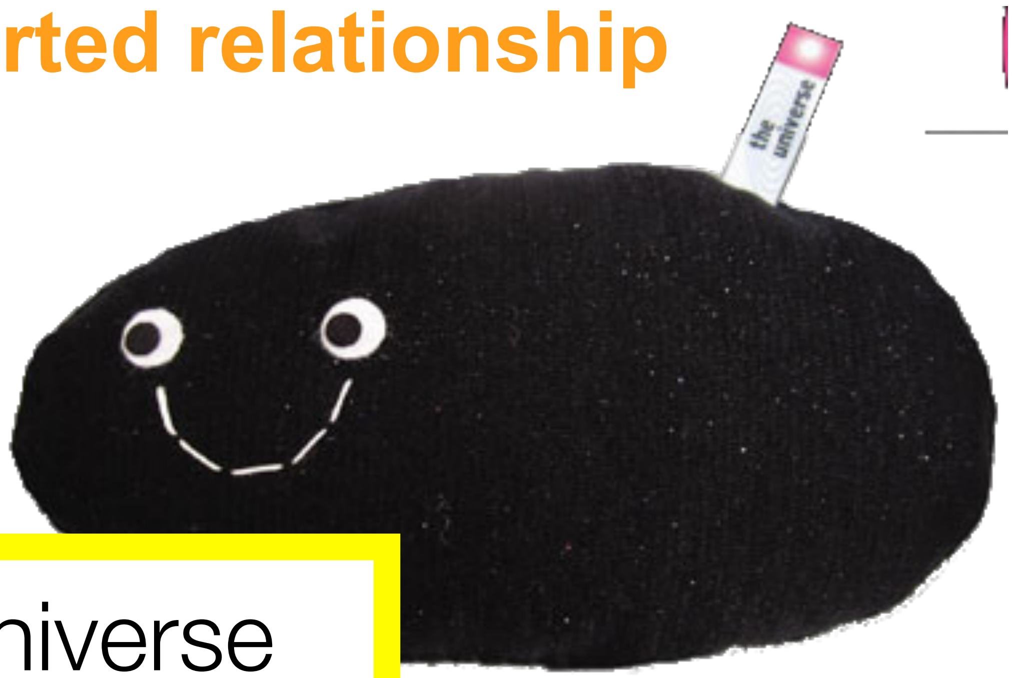

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Why is the Higgs-fermion interaction so different between the species?

- does the Higgs generate all the masses of all fermions?
- are the other Higgses involved - or other mass generation mechanisms?
- what is the Higgs' special relation to the top quark, making it so heavy?
- is there a connection to neutrino mass generation?

=> study Higgs and top - and search for possible siblings!

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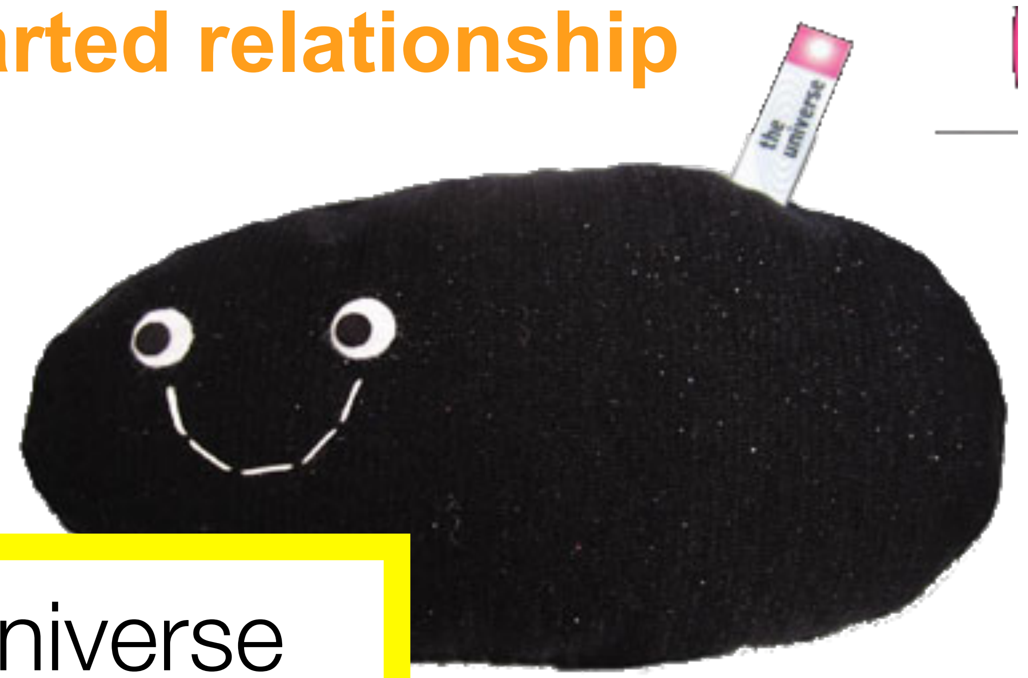

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Does the Higgs sector contain additional CP violation?

- in particular in couplings to fermions?
- or do its siblings have non-trivial CP properties?

=> small contributions -> need precise measurements!

The Higgs Boson and the Universe

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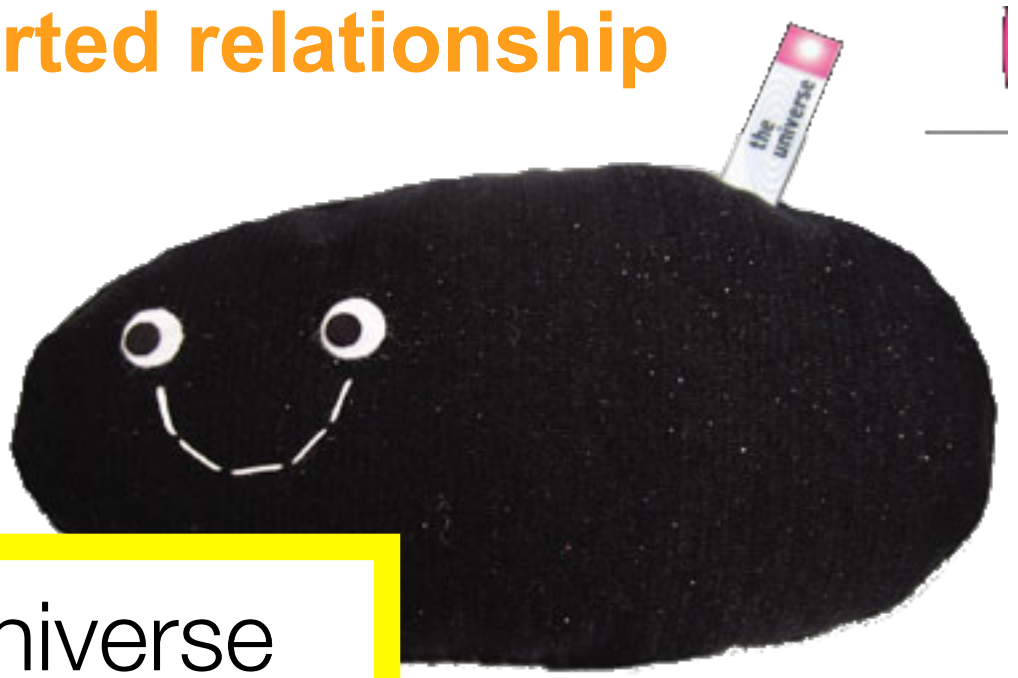

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What is the shape of the Higgs potential, and its evolution?

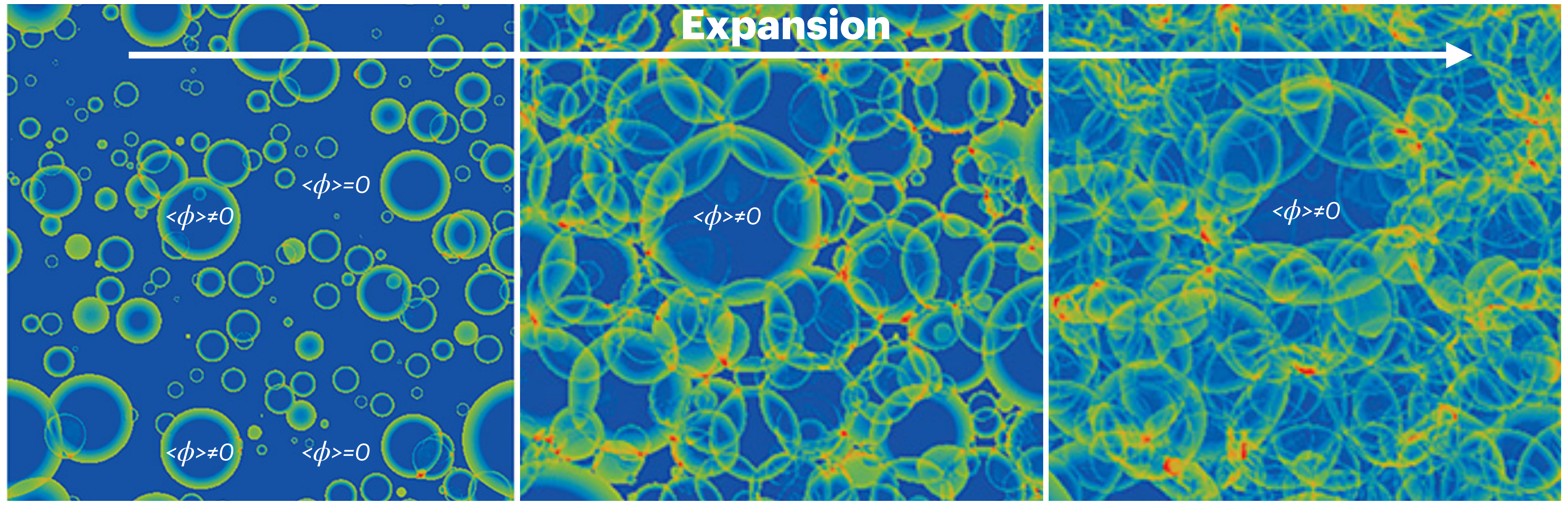
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

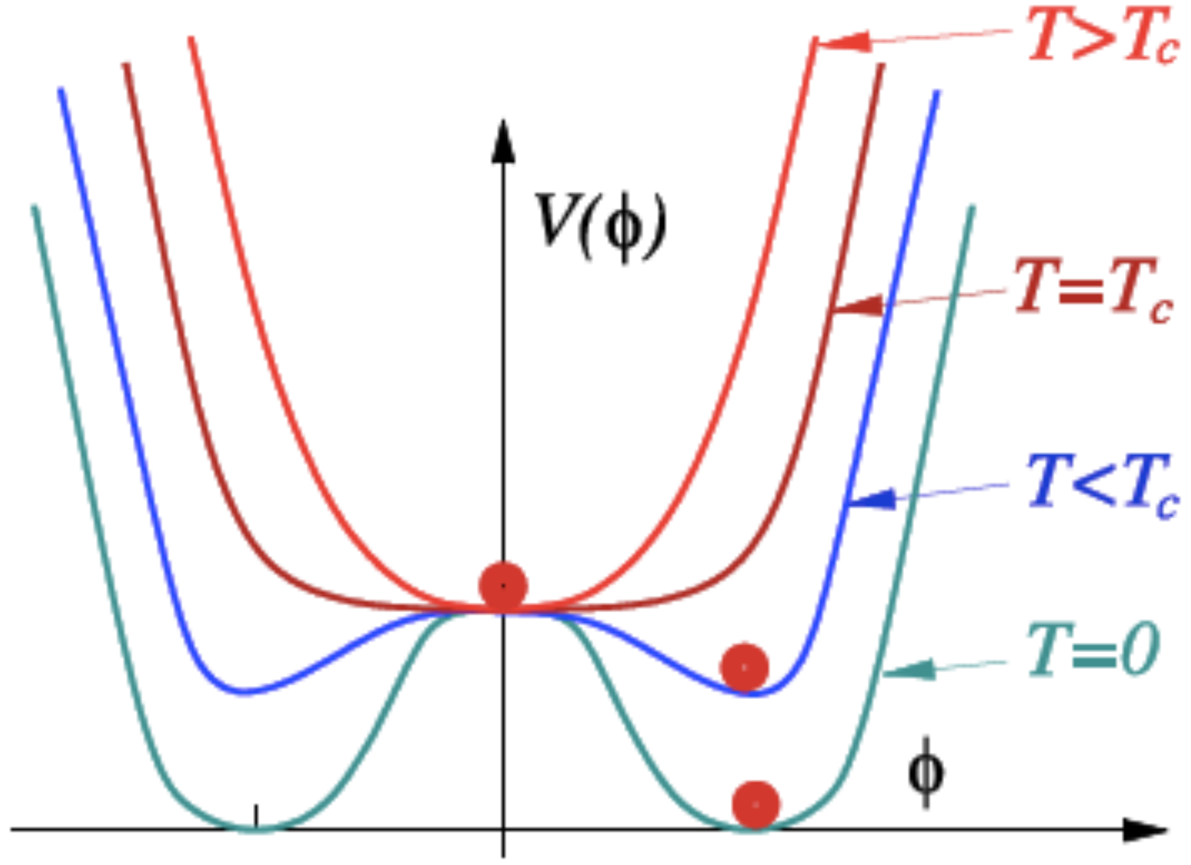
=> discover and study di-Higgs production

The Higgs potential, the Higgs self-coupling and Baryogenesis

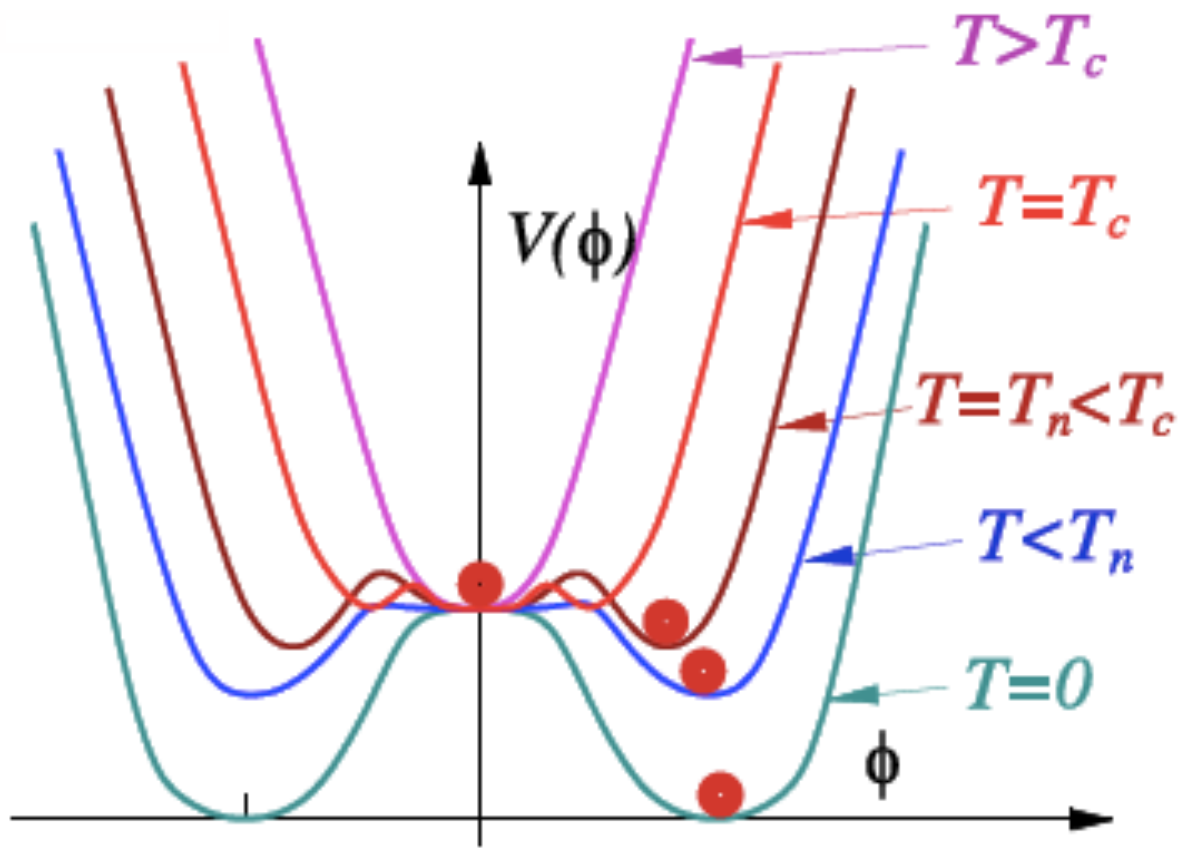
1st vs 2nd order phase transition

- origin of matter-antimatter asymmetry: universe must have been out of thermal equilibrium => 1.order phase transition
- **Electroweak phase transition?**





2nd order



1st order, requirement for EW baryogenesis

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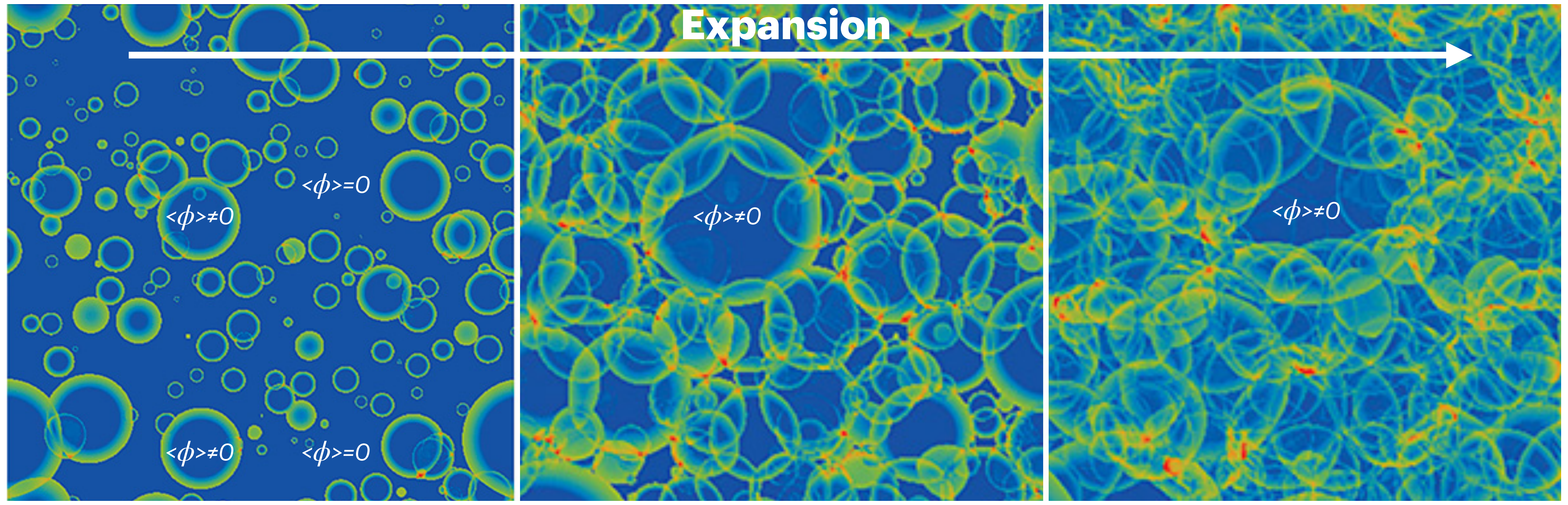

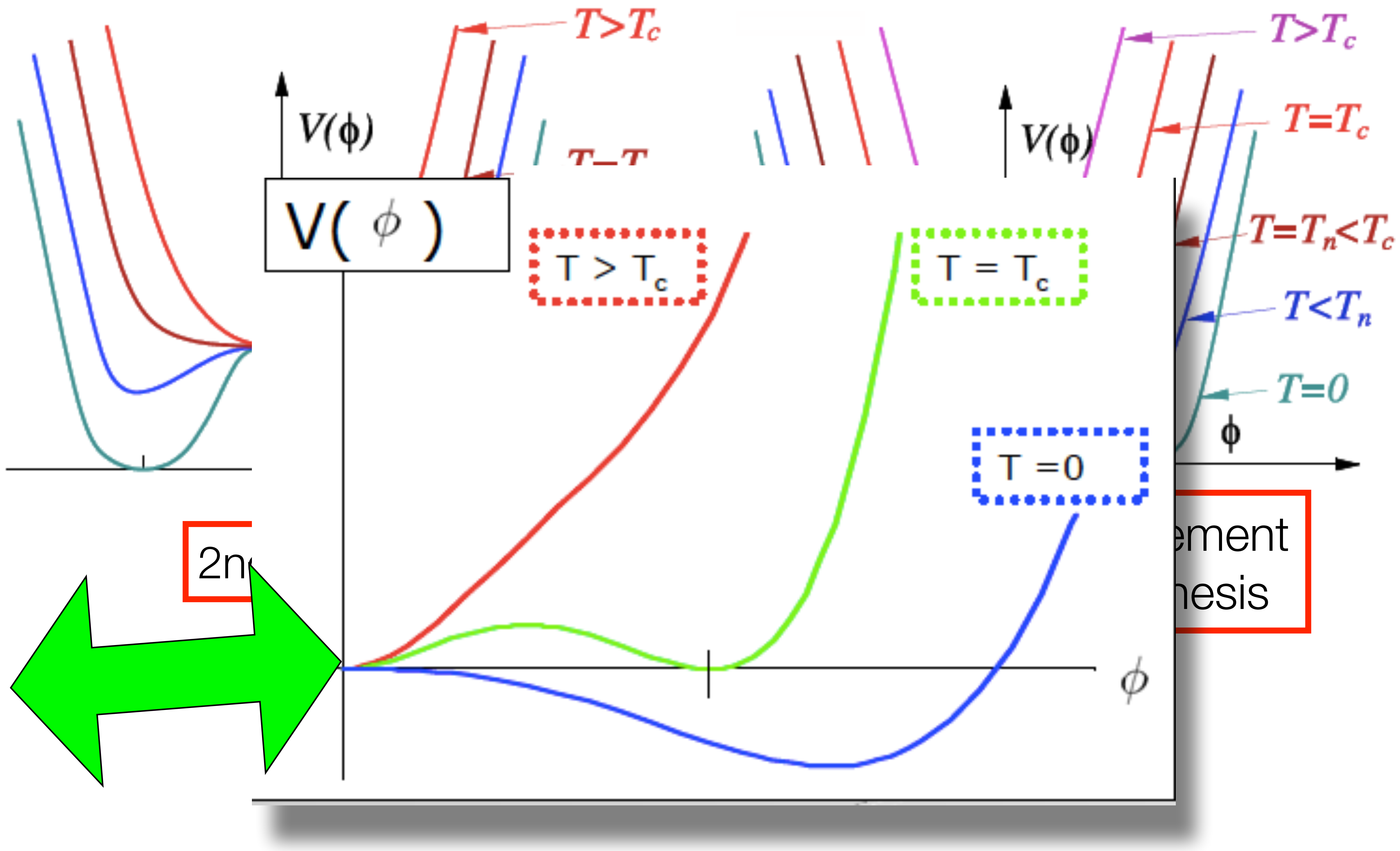

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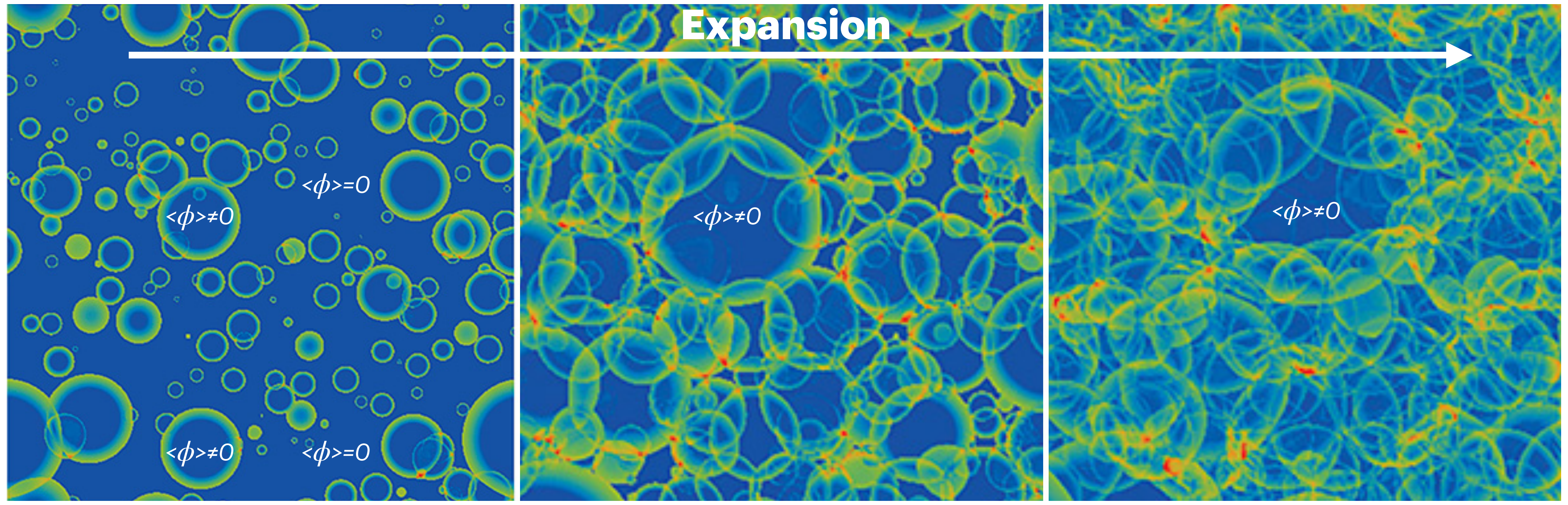

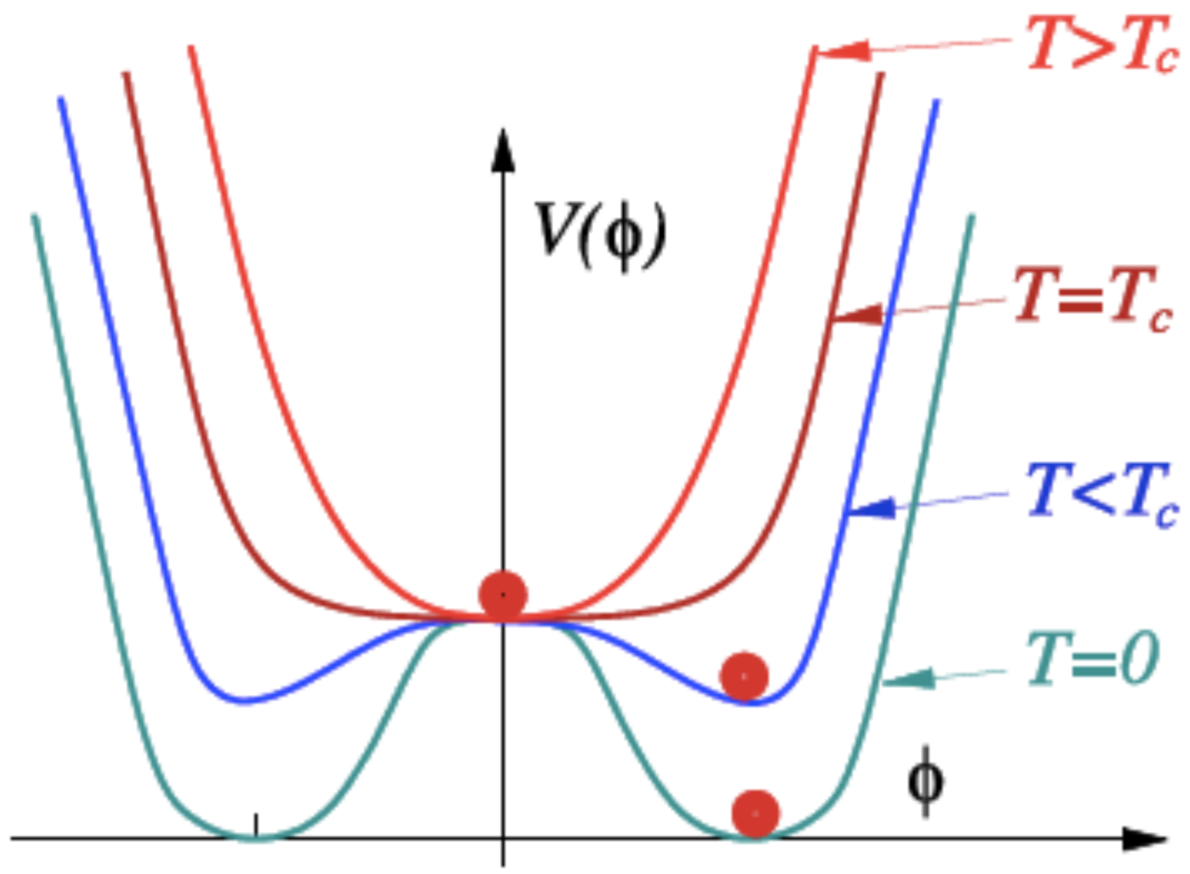

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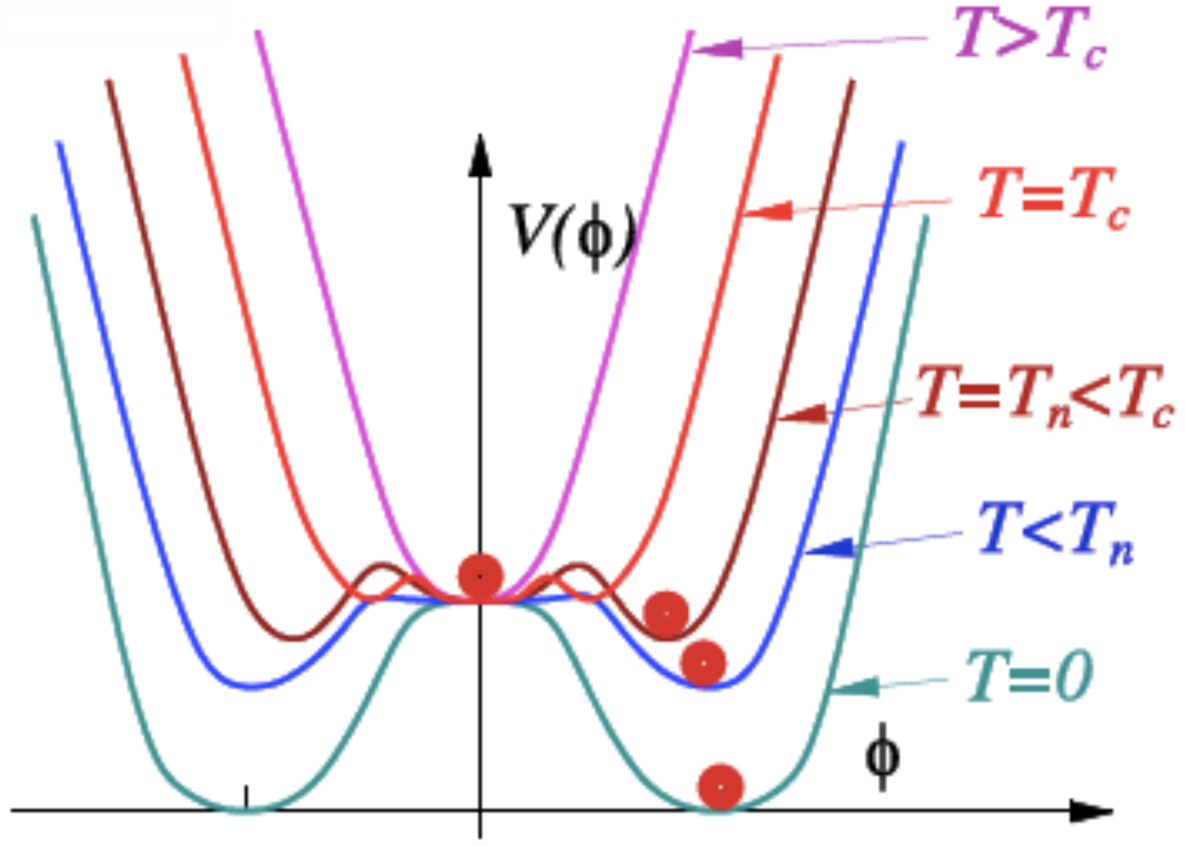

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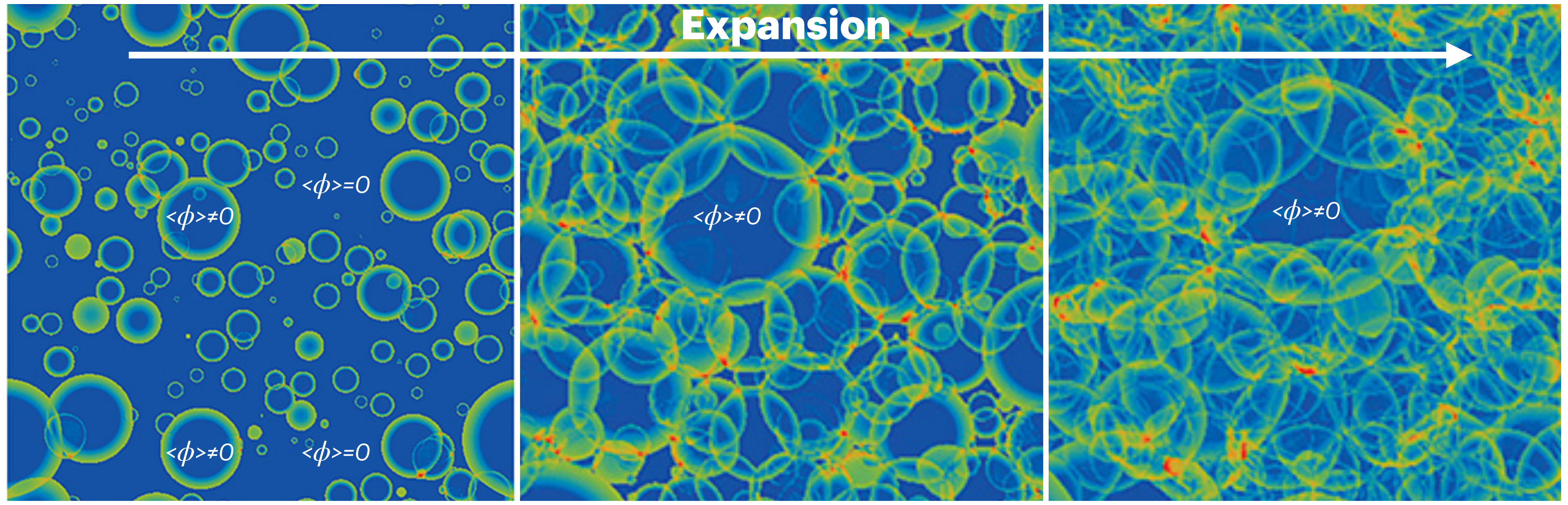

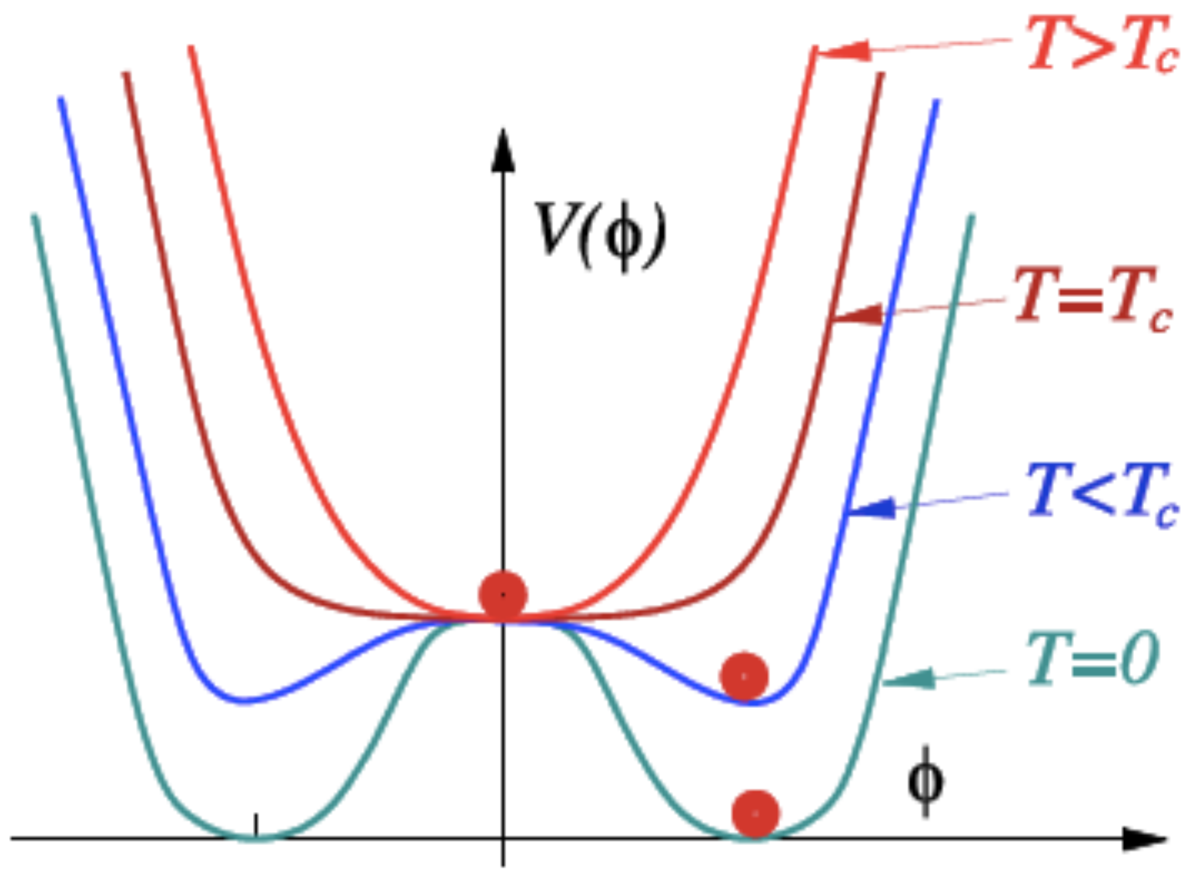

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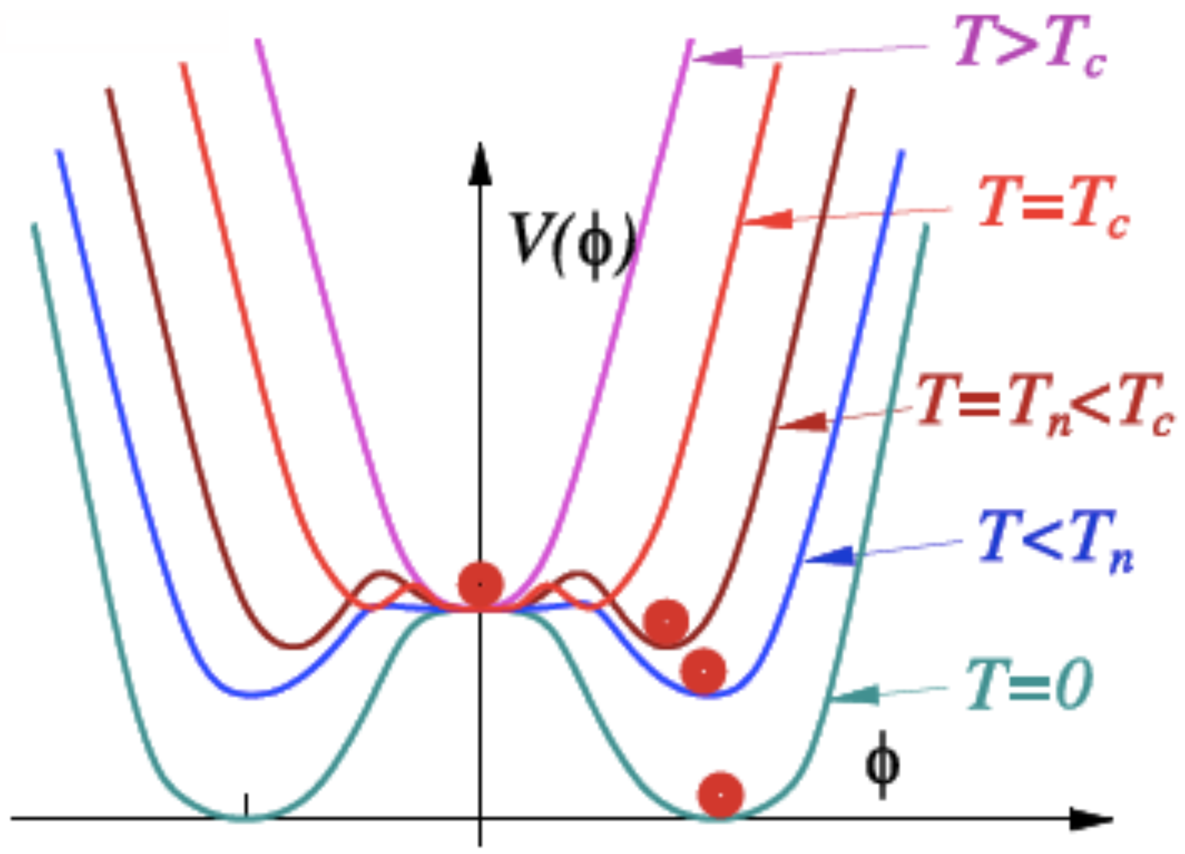

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- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
- electroweak baryogenesis possible in BSM scenarions with $\lambda > \lambda_{SM}$ (e.g. 2HDM, NMSSM, …)

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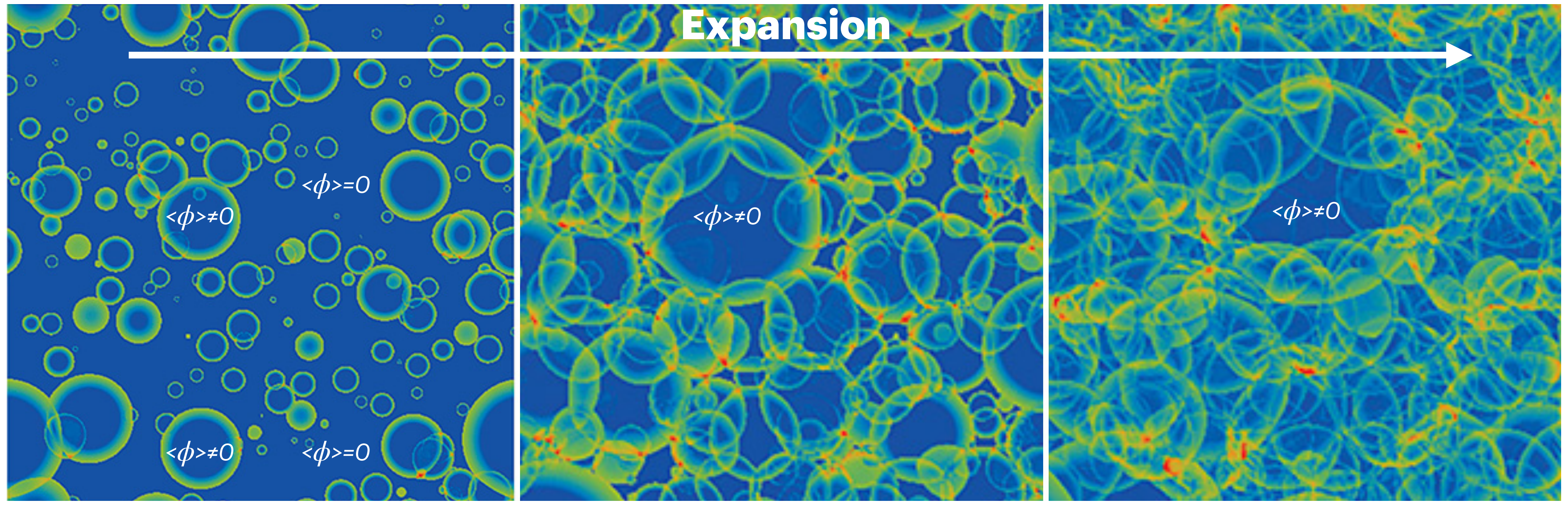

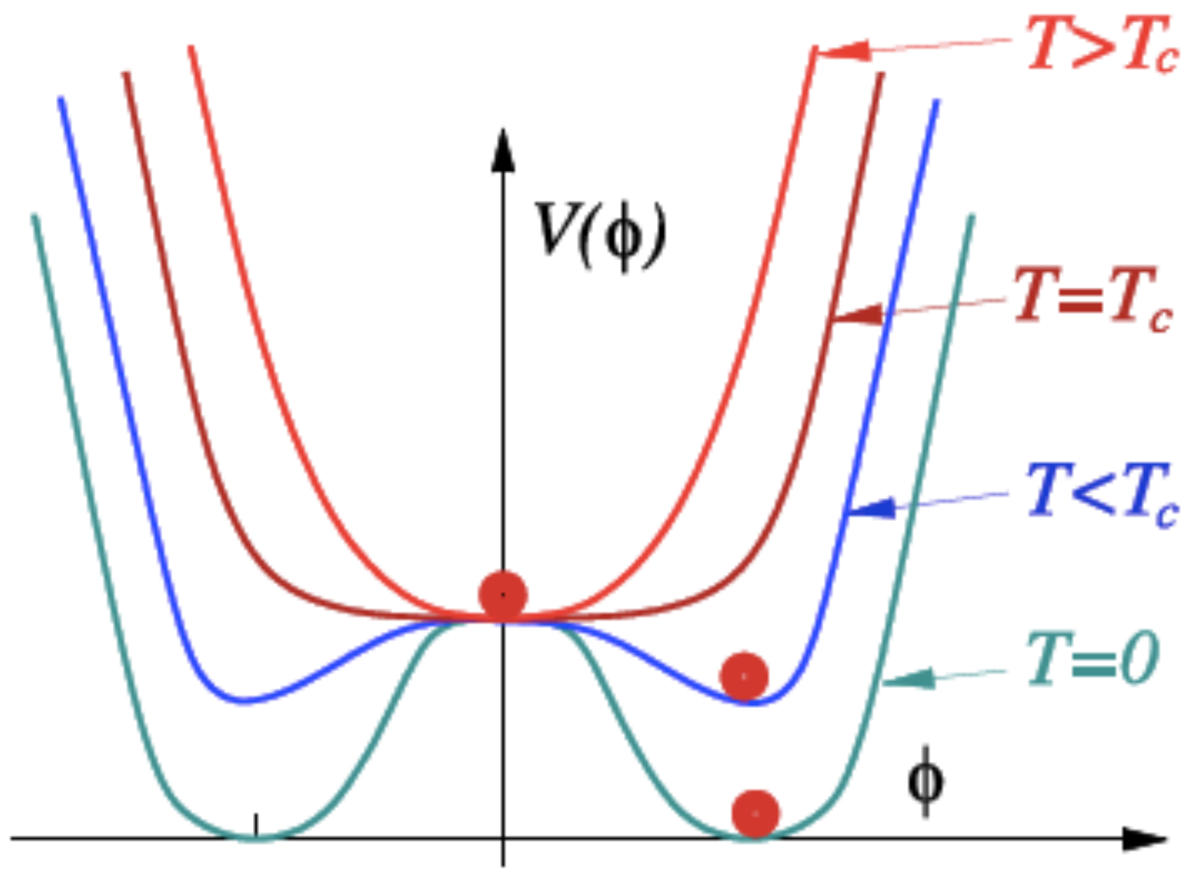

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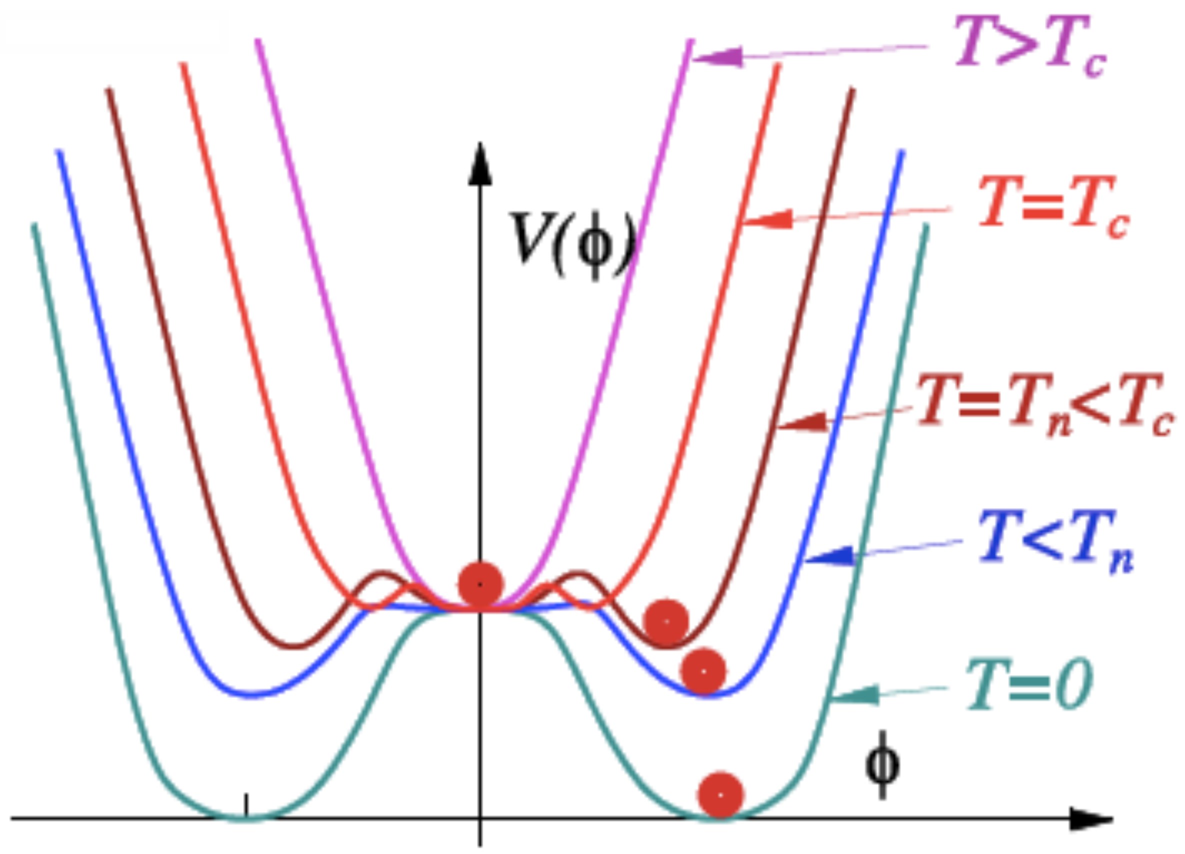

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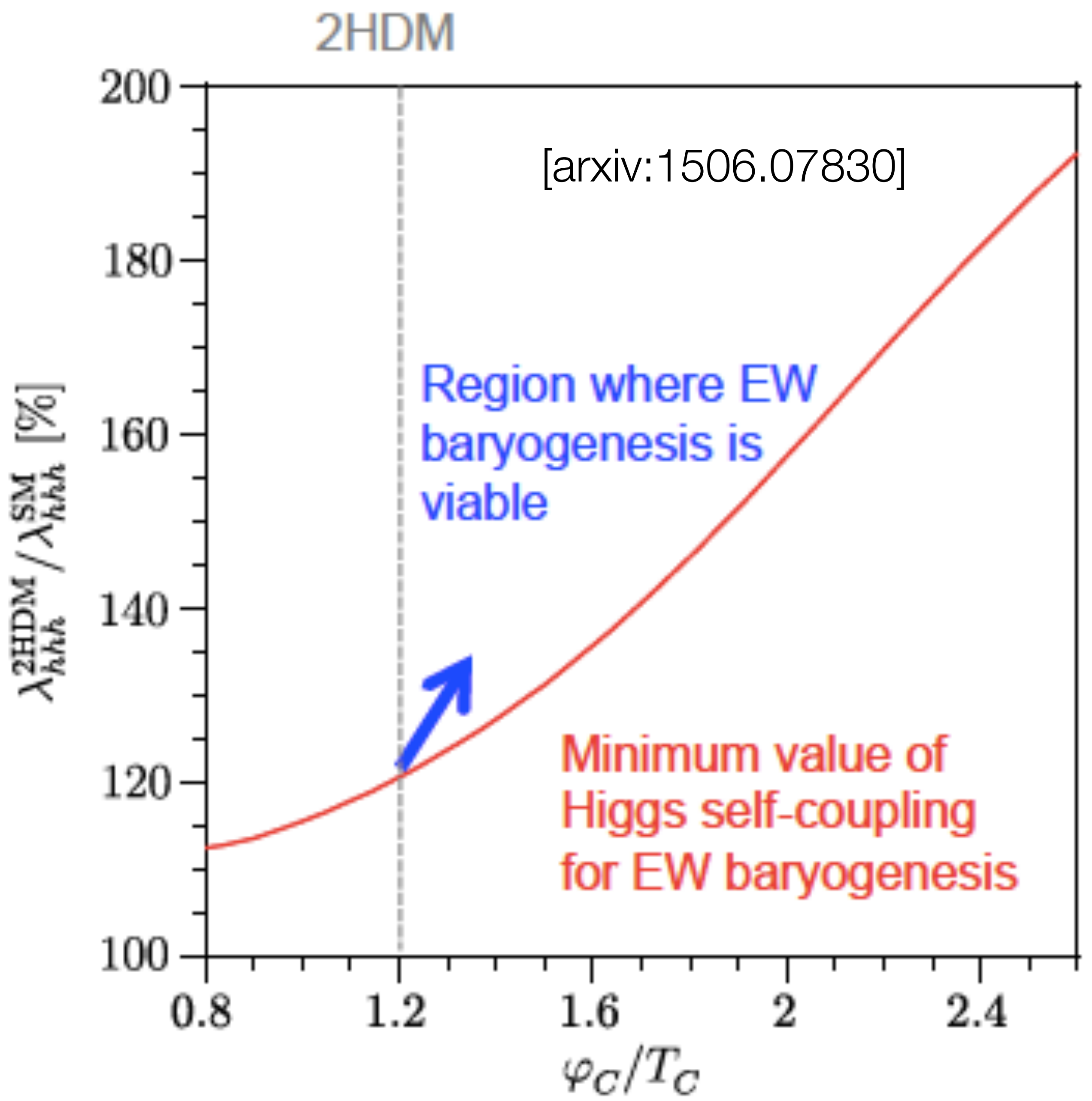

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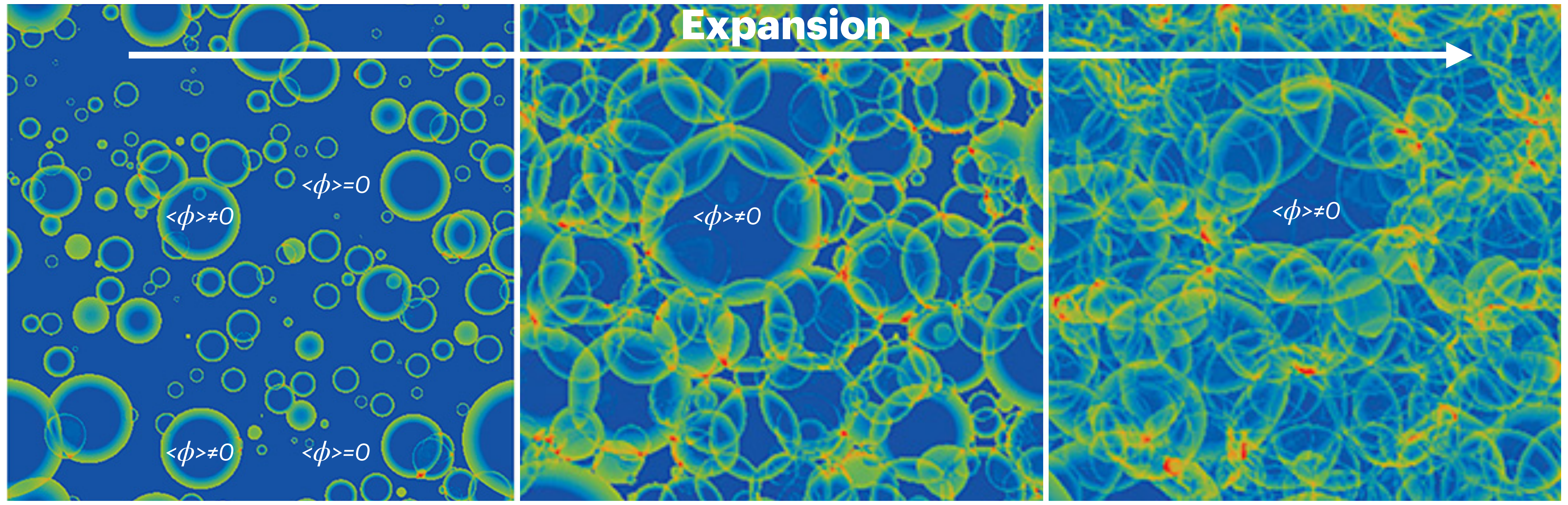

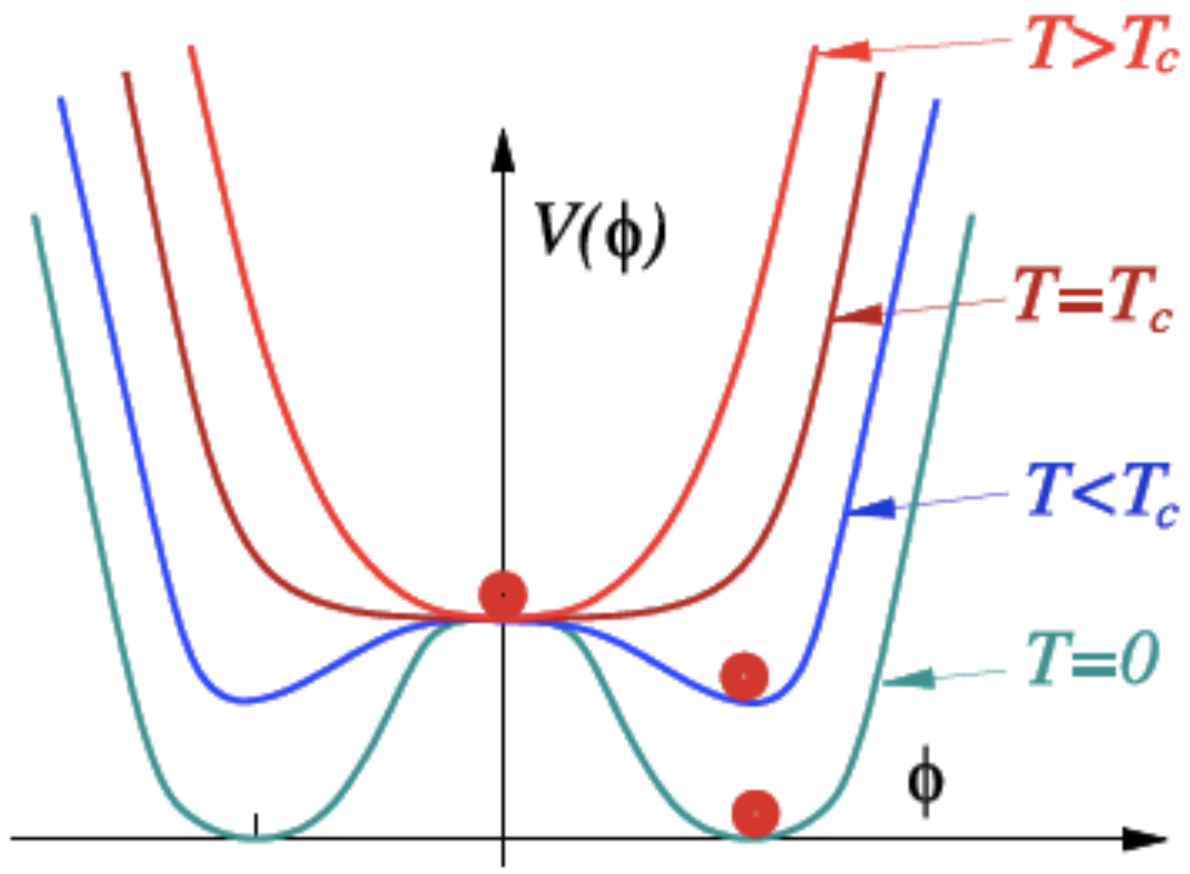

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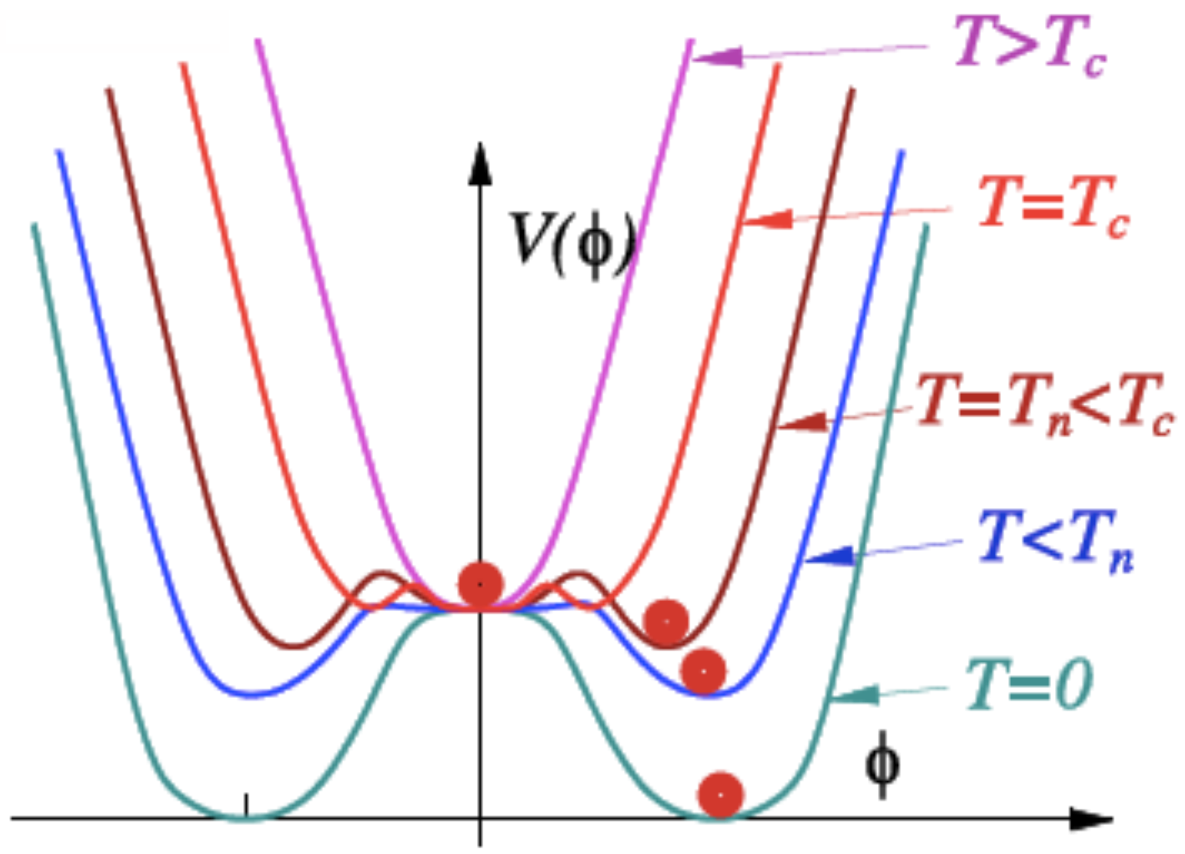

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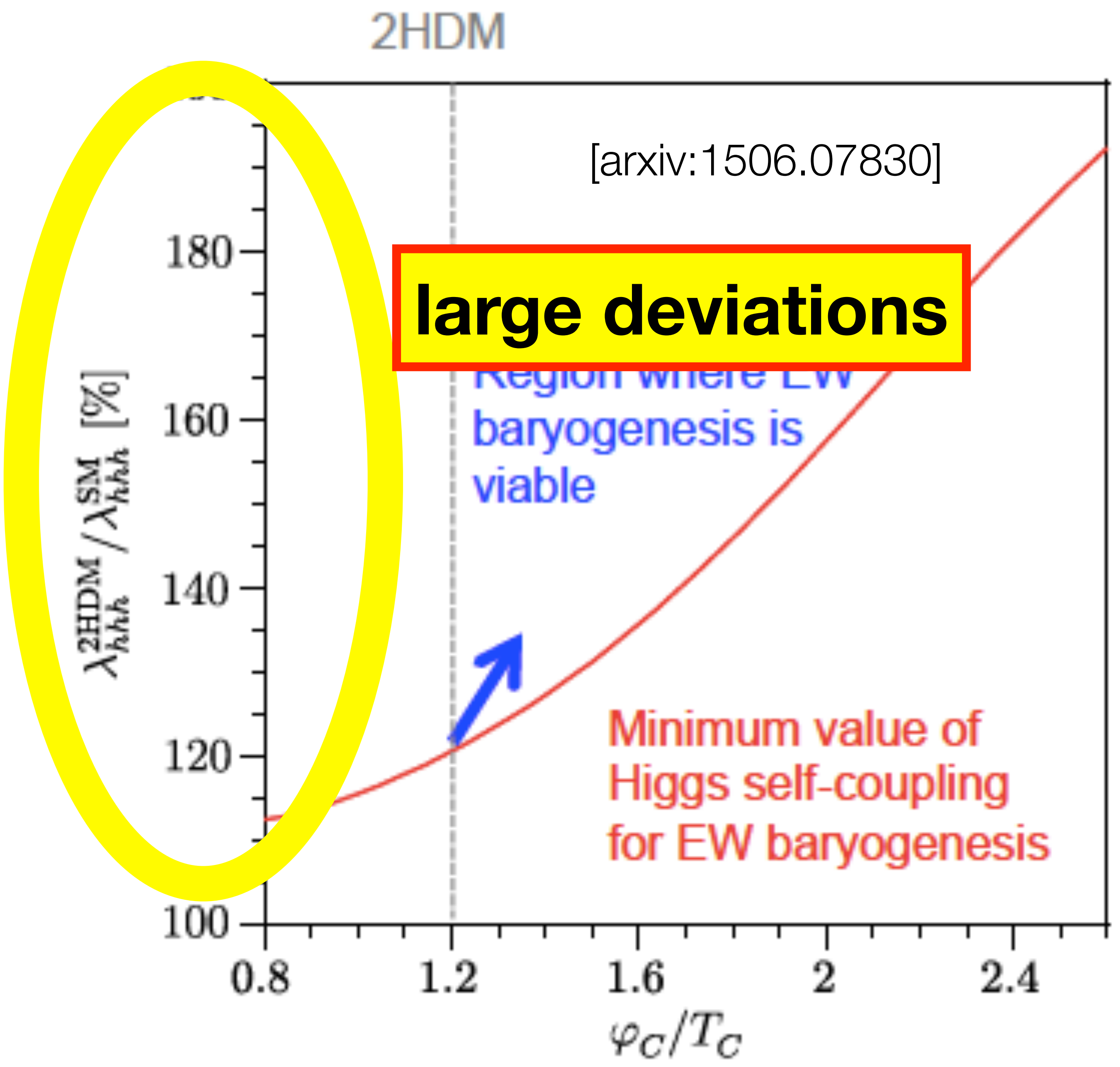

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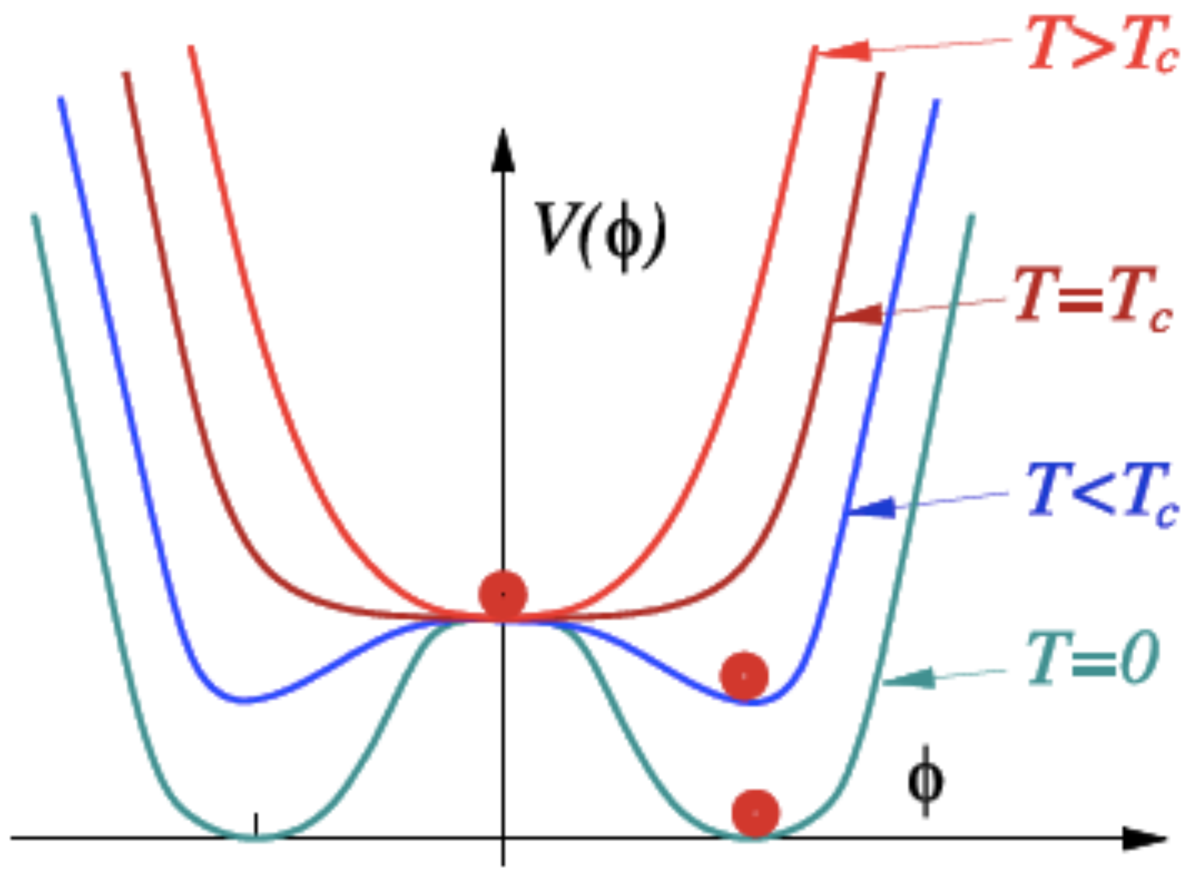

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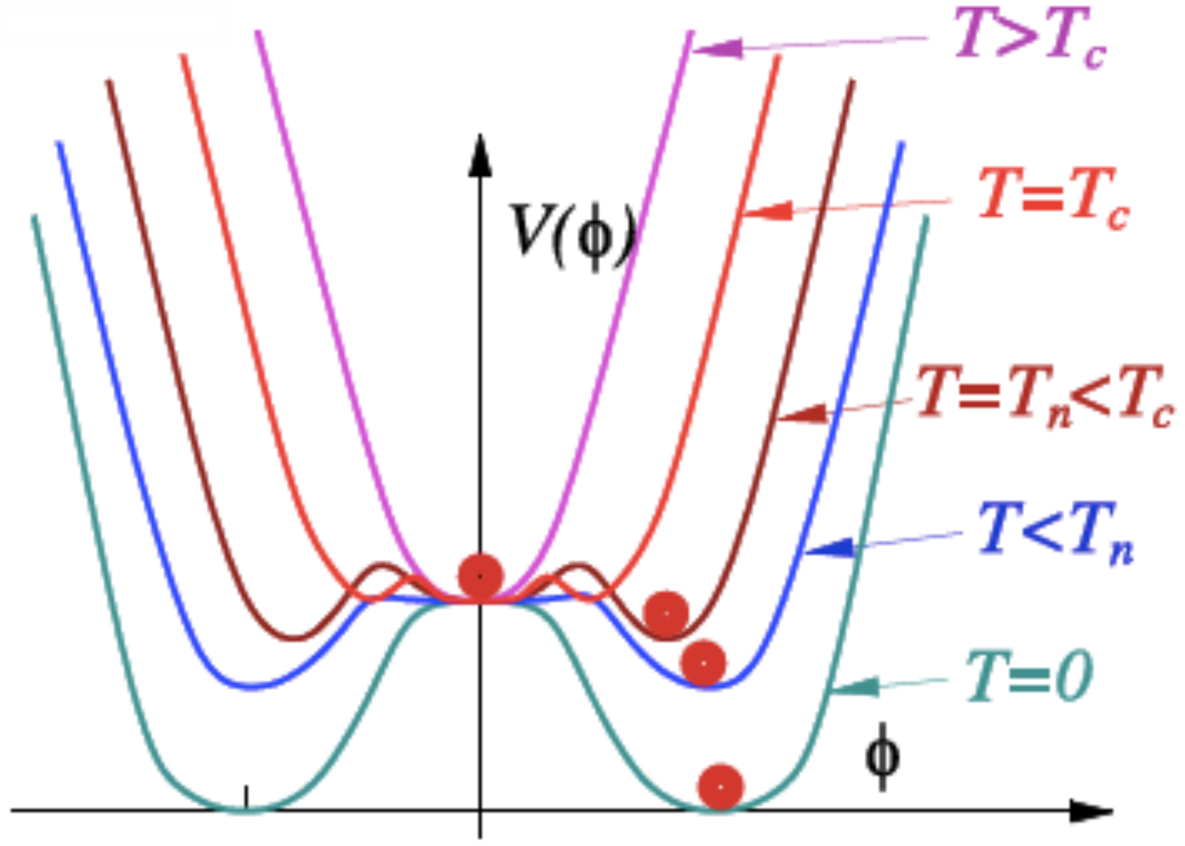

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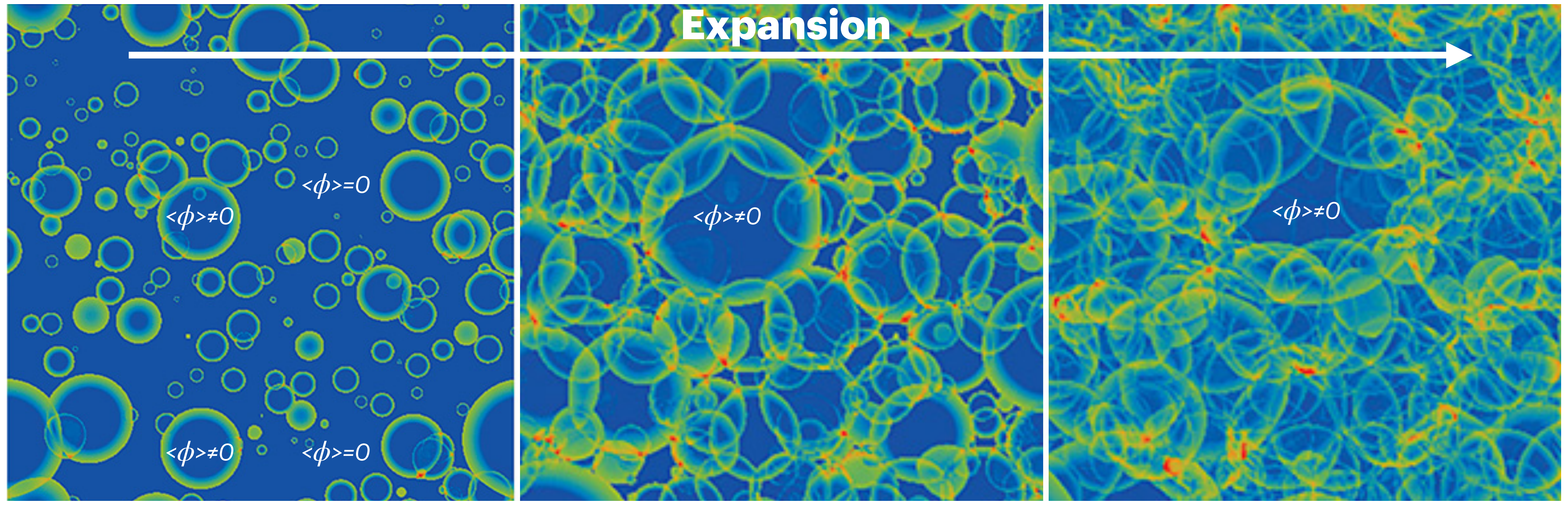

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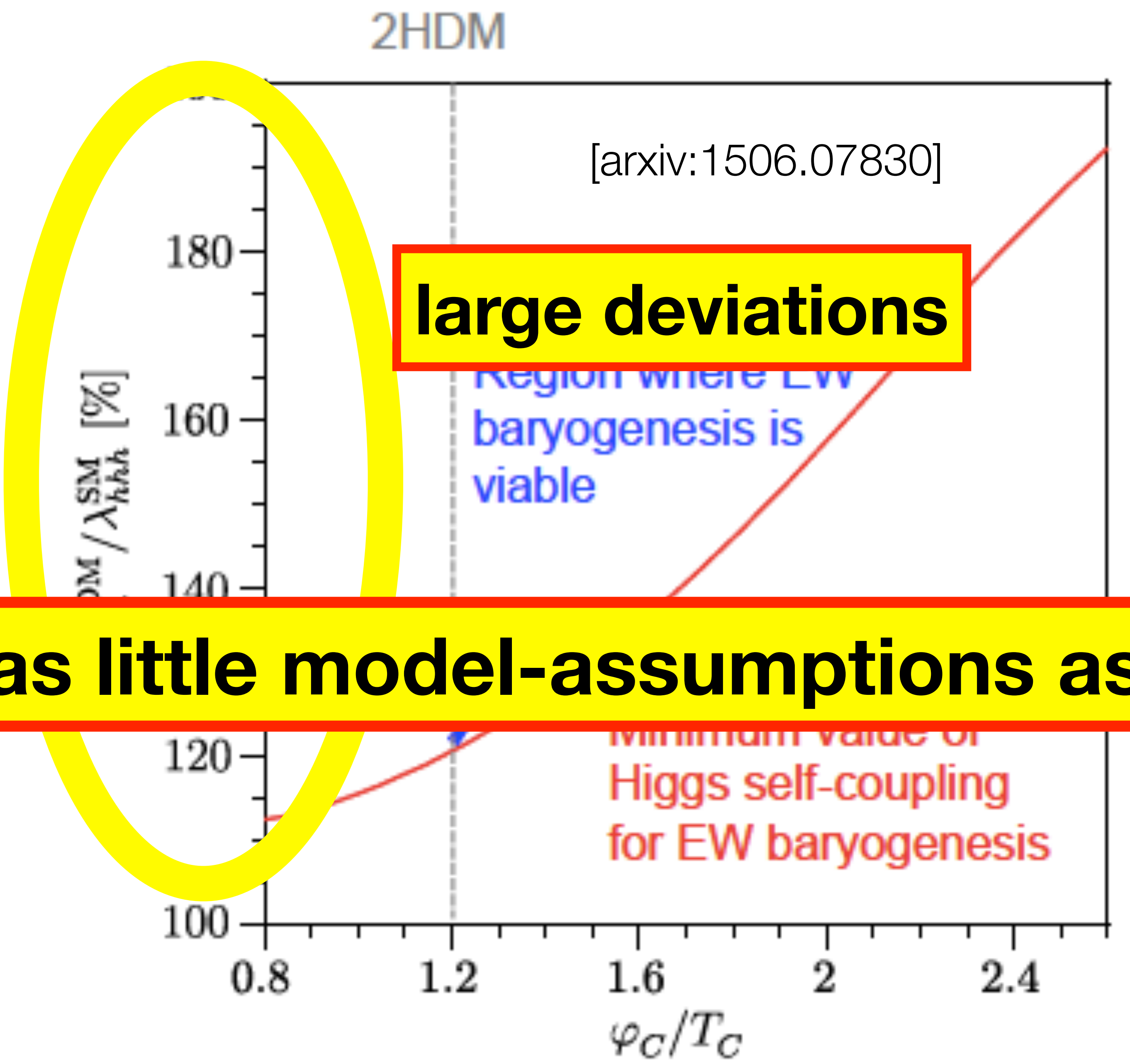

=> measure λ, with as little model-assumptions as possible!

The Higgs Boson Mission

Why we need a Higgs Factory

- **Find out as much as we can about the 125-GeV Higgs**
  - Basic properties:
    - **total production rate**, total width
    - decay rates to known particles
    - **invisible decays**
    - search for "exotic decays"
  - CP properties of couplings to gauge bosons and fermions
  - **self-coupling**
  - Is it the only one of its kind, or are there **other Higgs (or scalar) bosons**?
- **To interprete these Higgs measurements, also need**
  - top quark: mass, Yukawa & electroweak couplings, their CP properties…
  - Z / W bosons: masses, couplings to fermions, triple gauge couplings, incl CP…
- **Search for direct production of new particles - and determine their properties**
  - Dark Matter? **Dark Sector?**
  - Heavy neutrinos?
  - SUSY? **Higgsinos?**
  - The **UNEXPECTED** !

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=> e+e- Higgs factory identified as the highest priority next collider by
- European Strategy for Particle Physics (2020)
- The Snowmass process in the US (2022)

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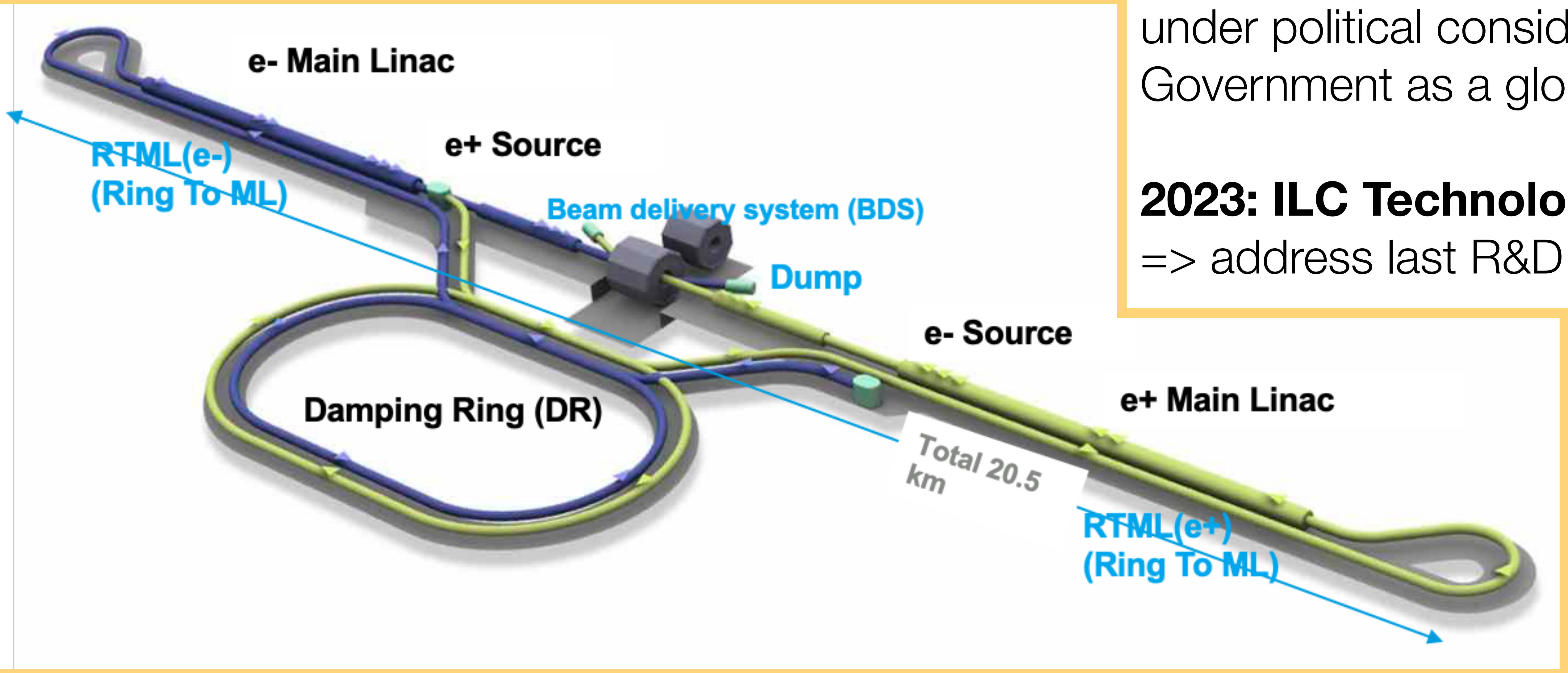
The key contenders

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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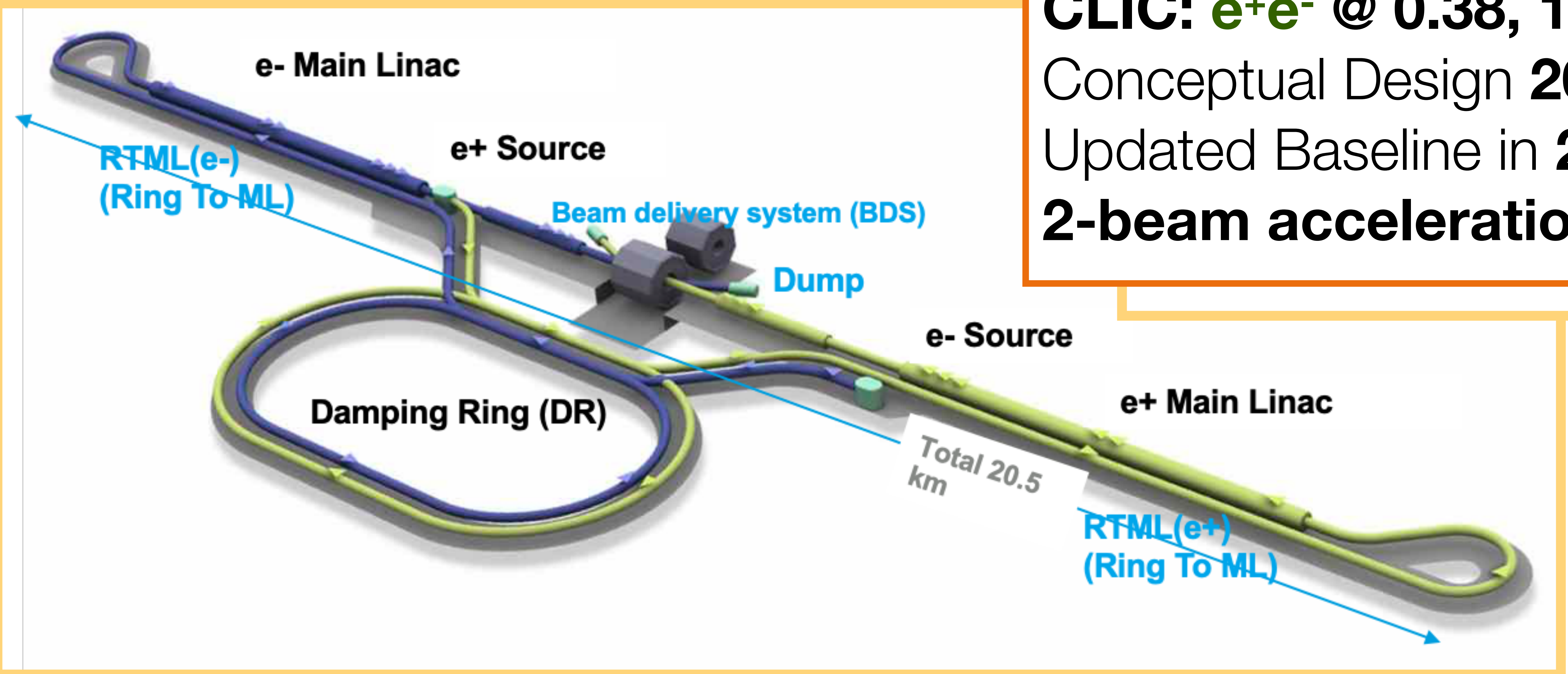
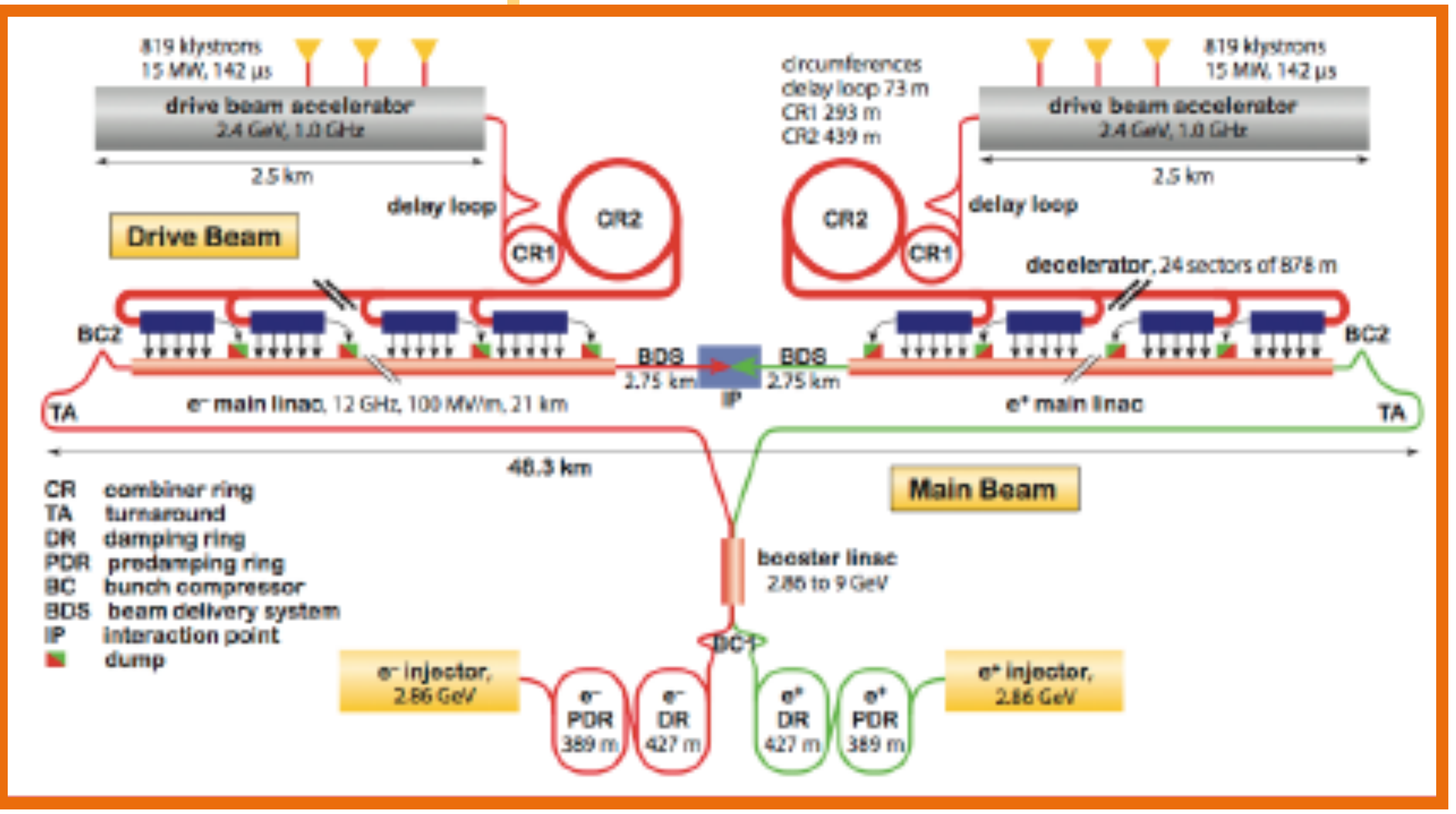


CLIC: e+e- @ 0.38, 1.4, 3 TeV
Conceptual Design **2013**
Updated Baseline in **2017**
2-beam acceleration



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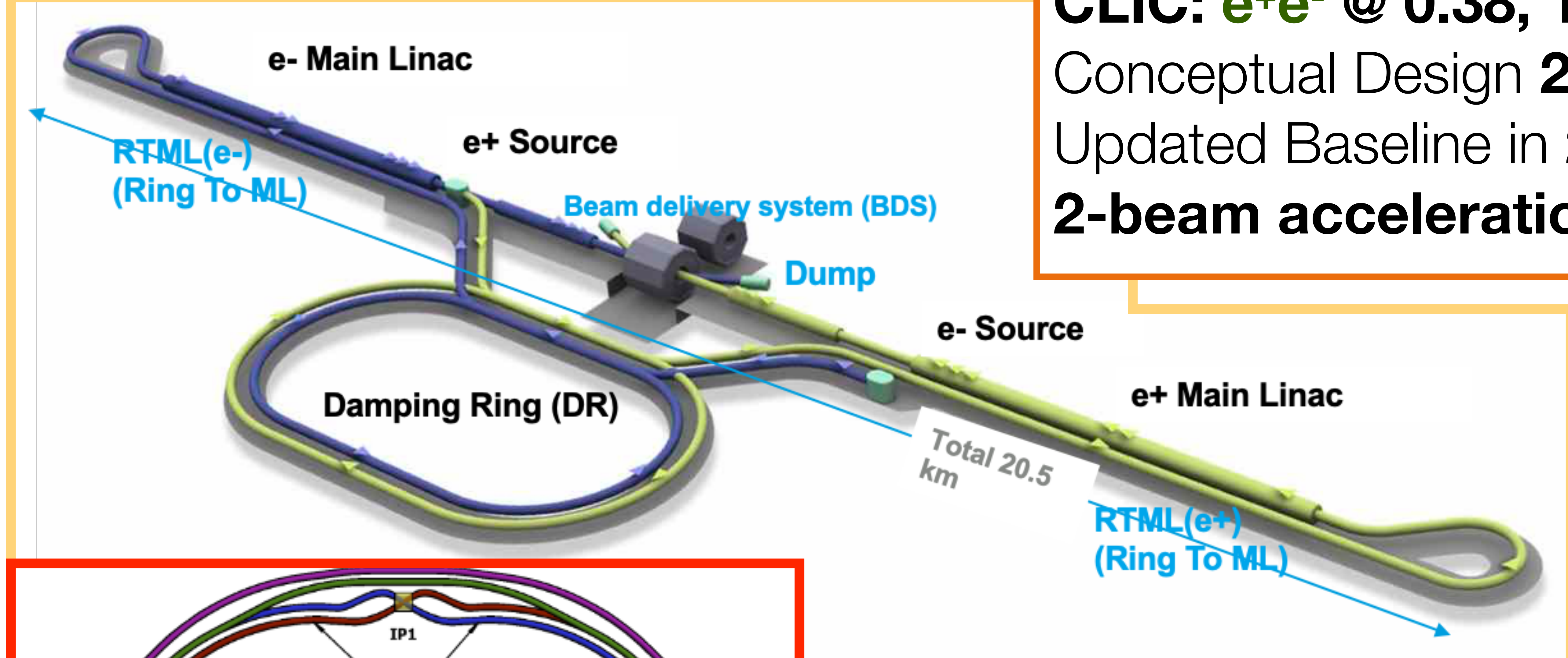

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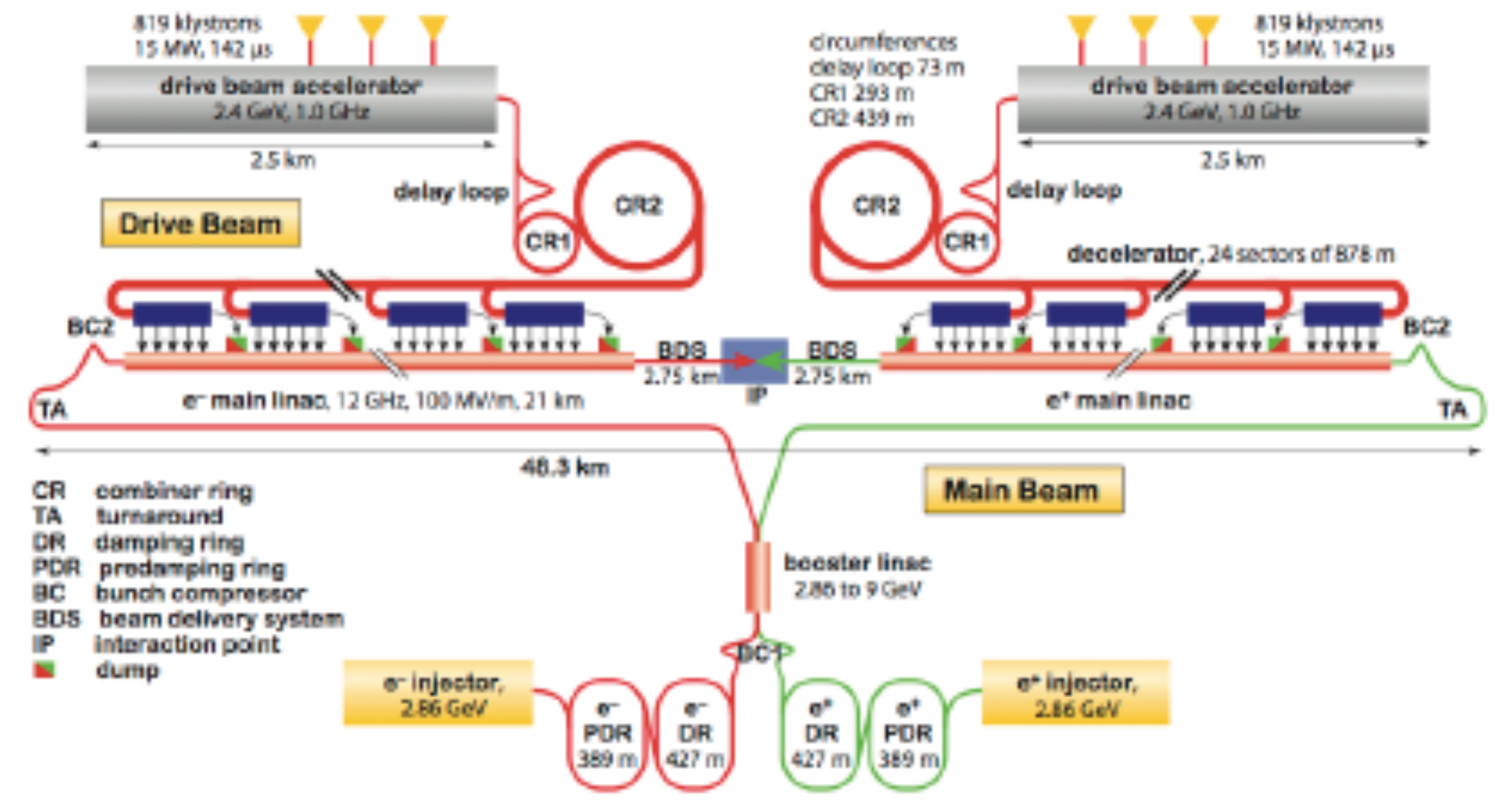

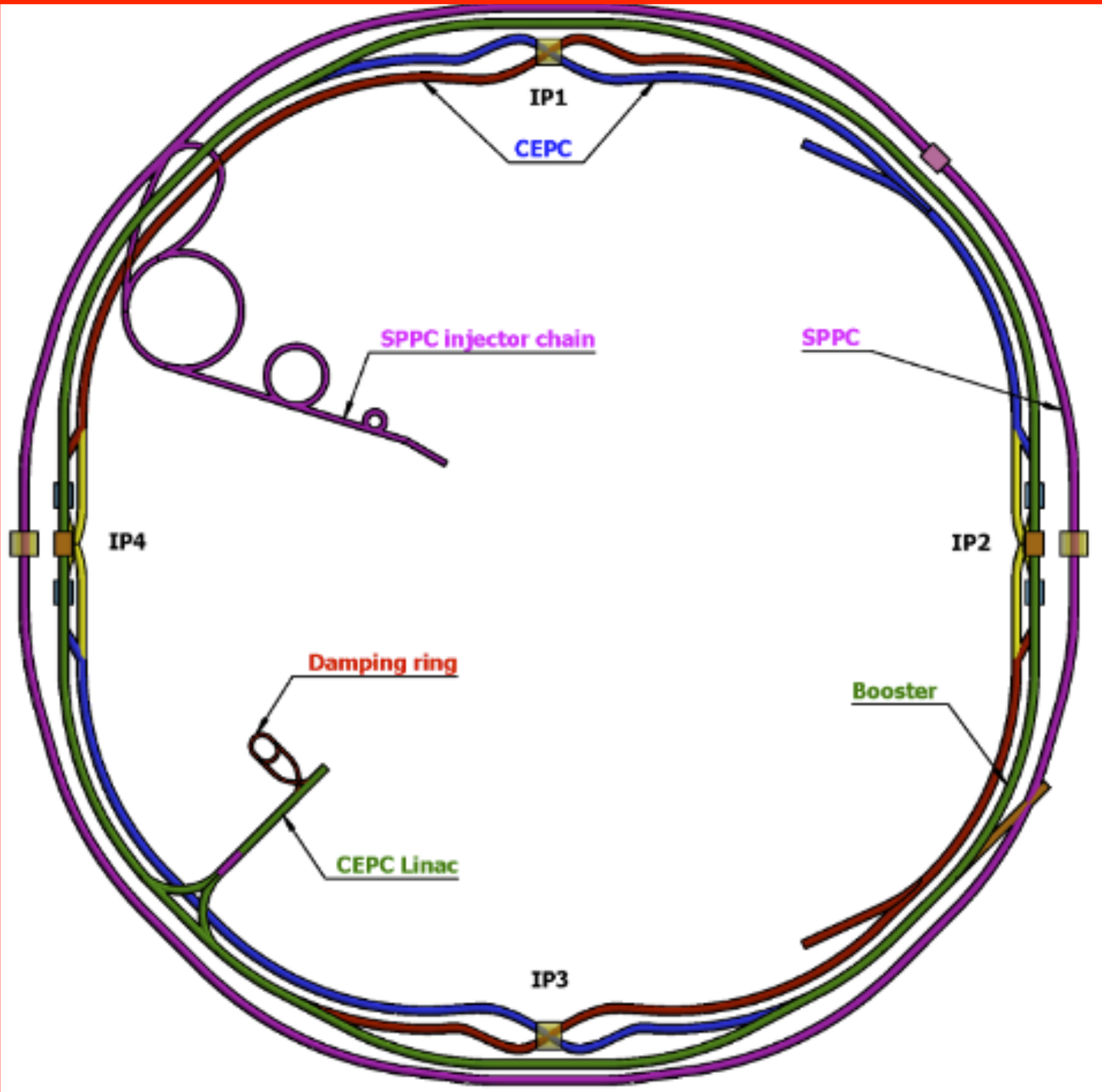

CEPC: e+e- @ 90-365 GeV

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

The key contenders

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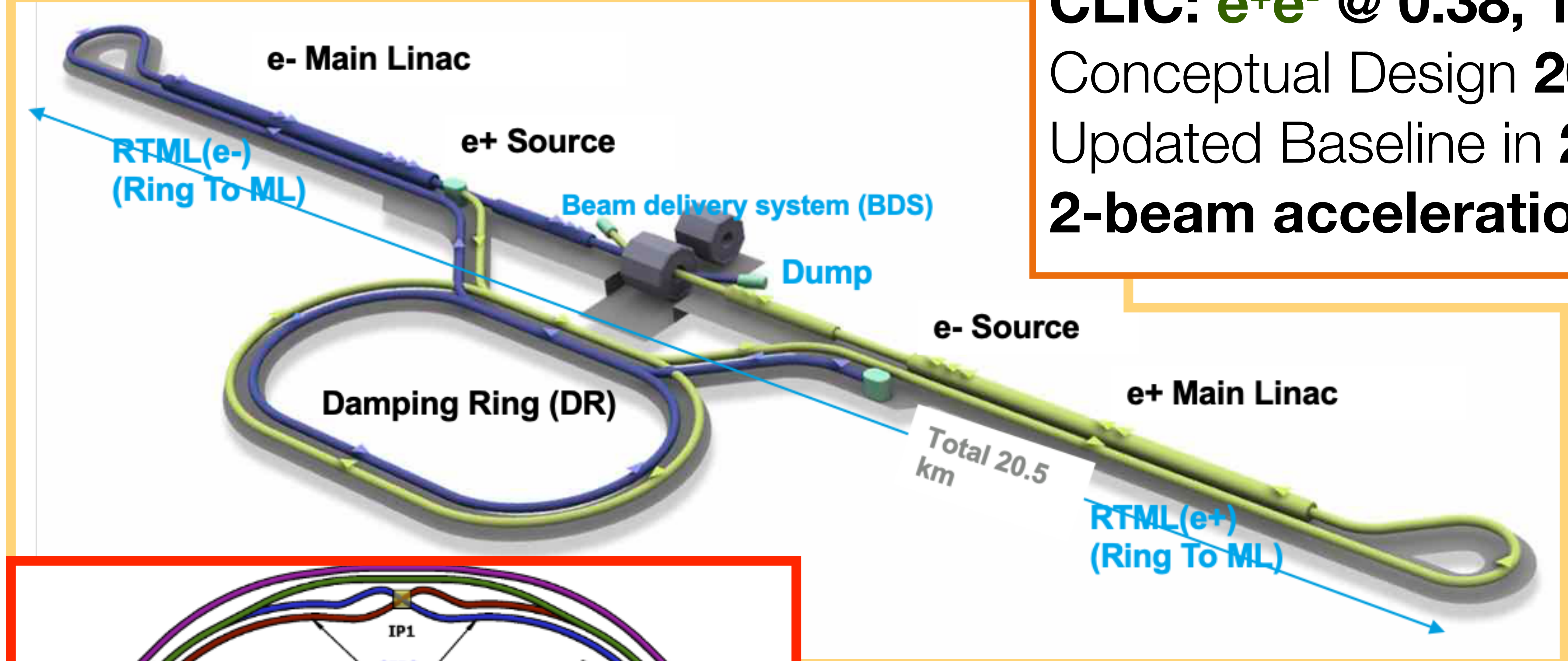

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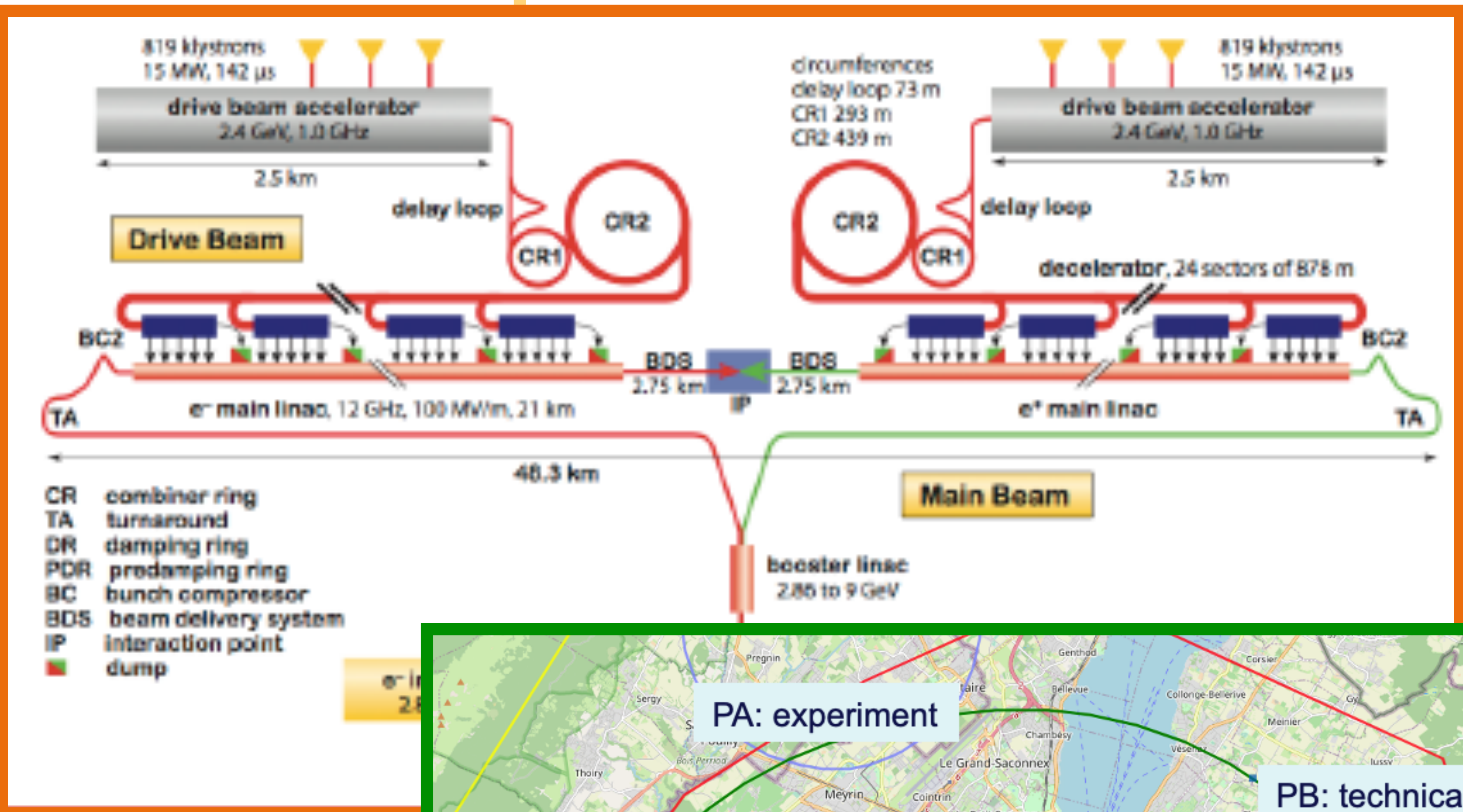

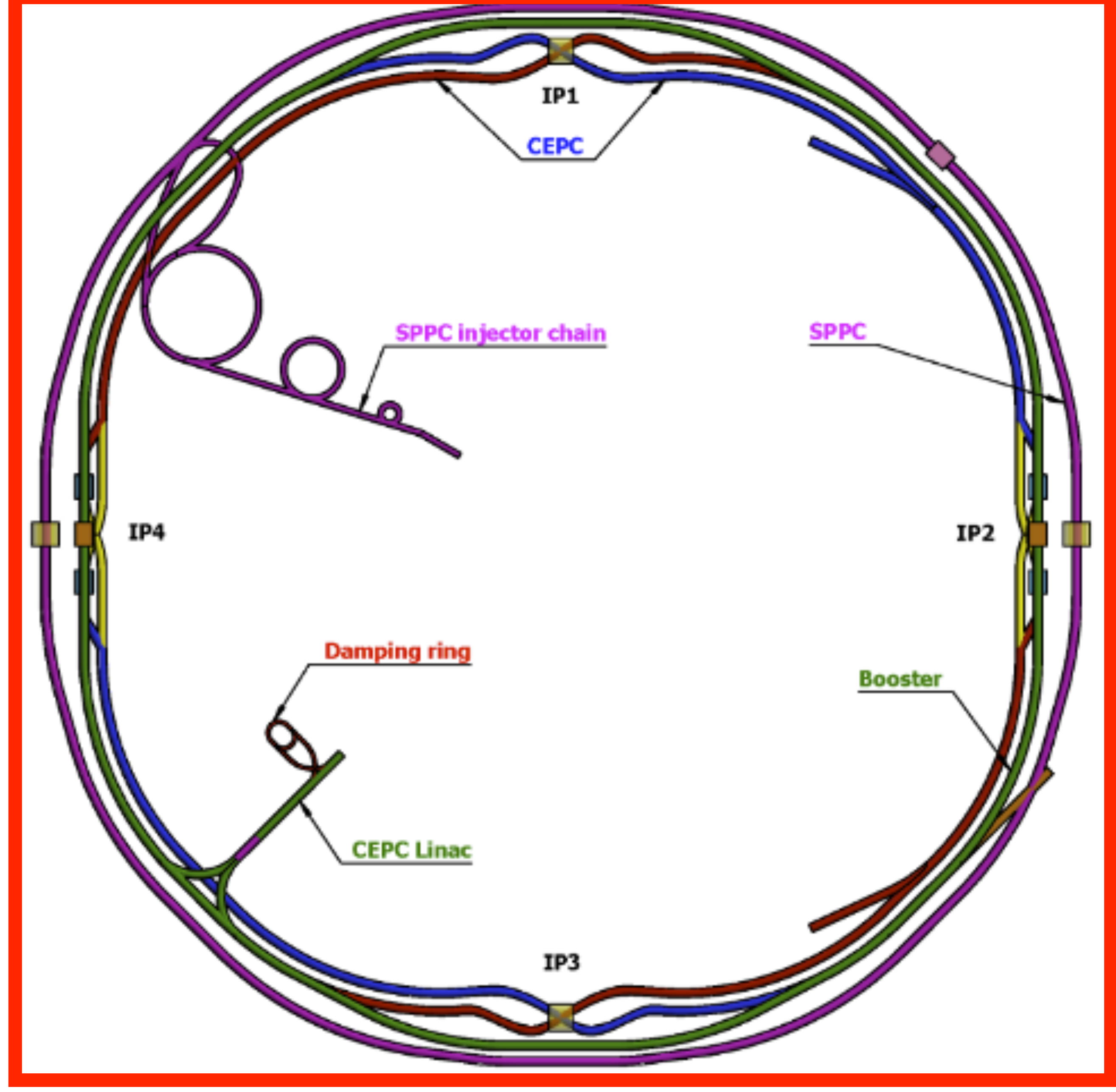

CEPC

CDR p
TDR i
aimin
ranke

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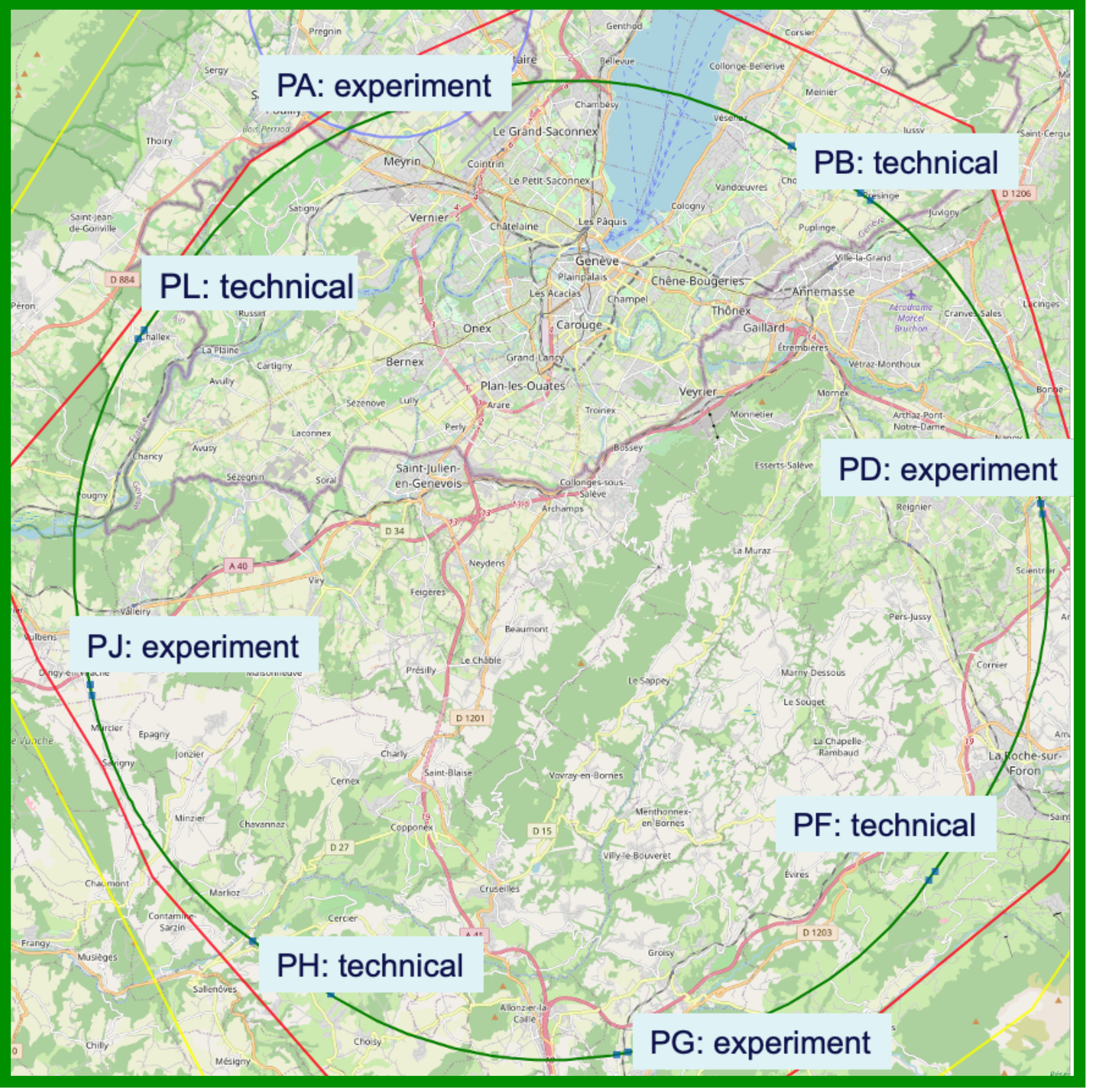
Since 2021: FCC Feasibility Study
(implementation scenario, environmental analysis, high-field magnets, ..)
=> demonstrate feasibility of FCC-ee by 2025

Special Council Session in Feb 2024



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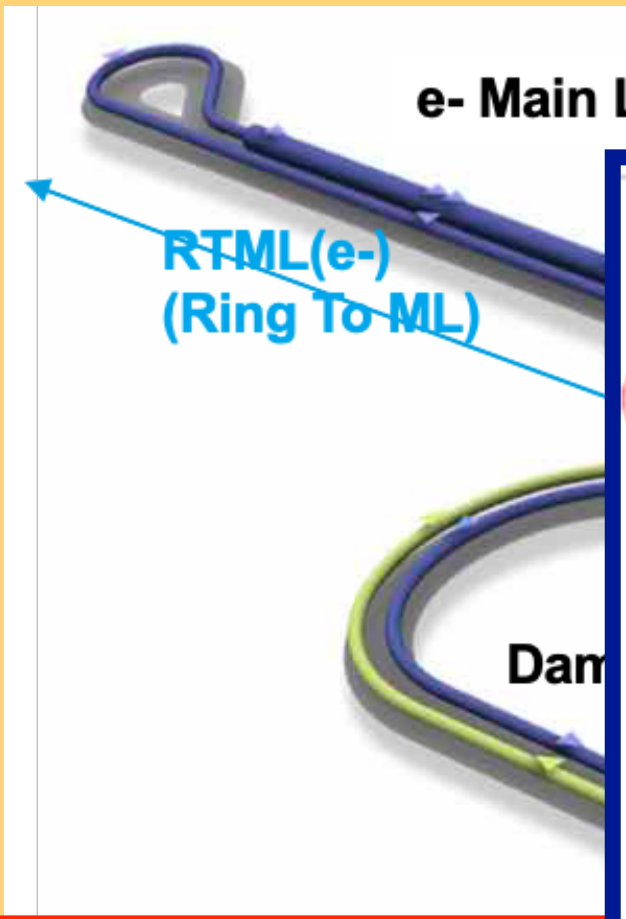

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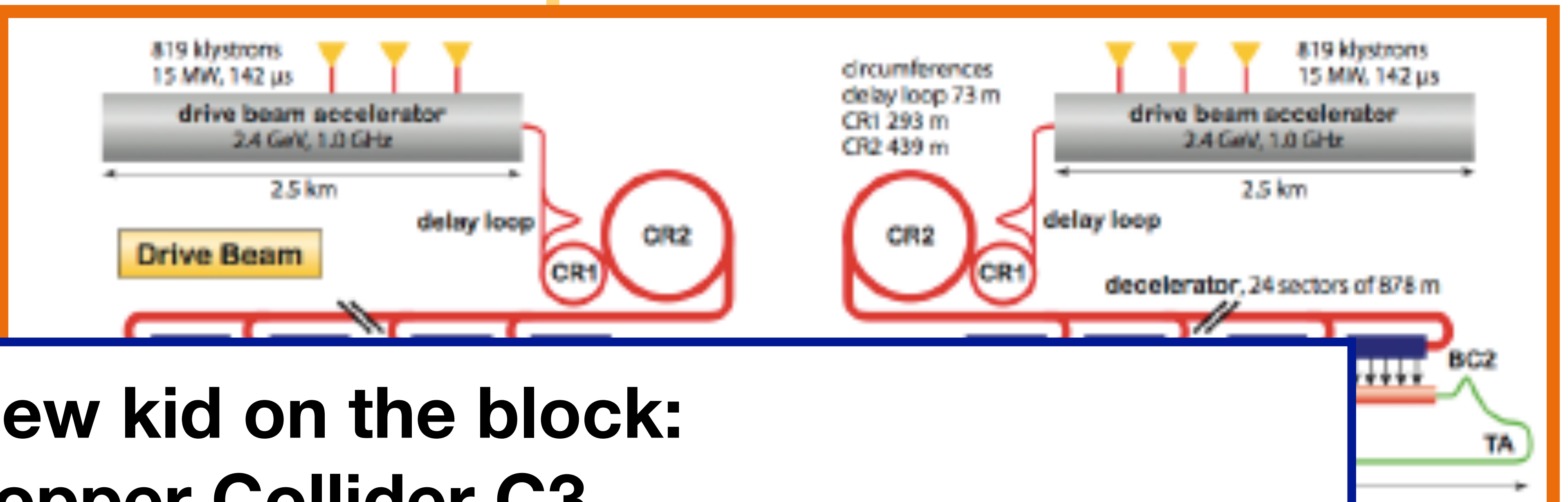
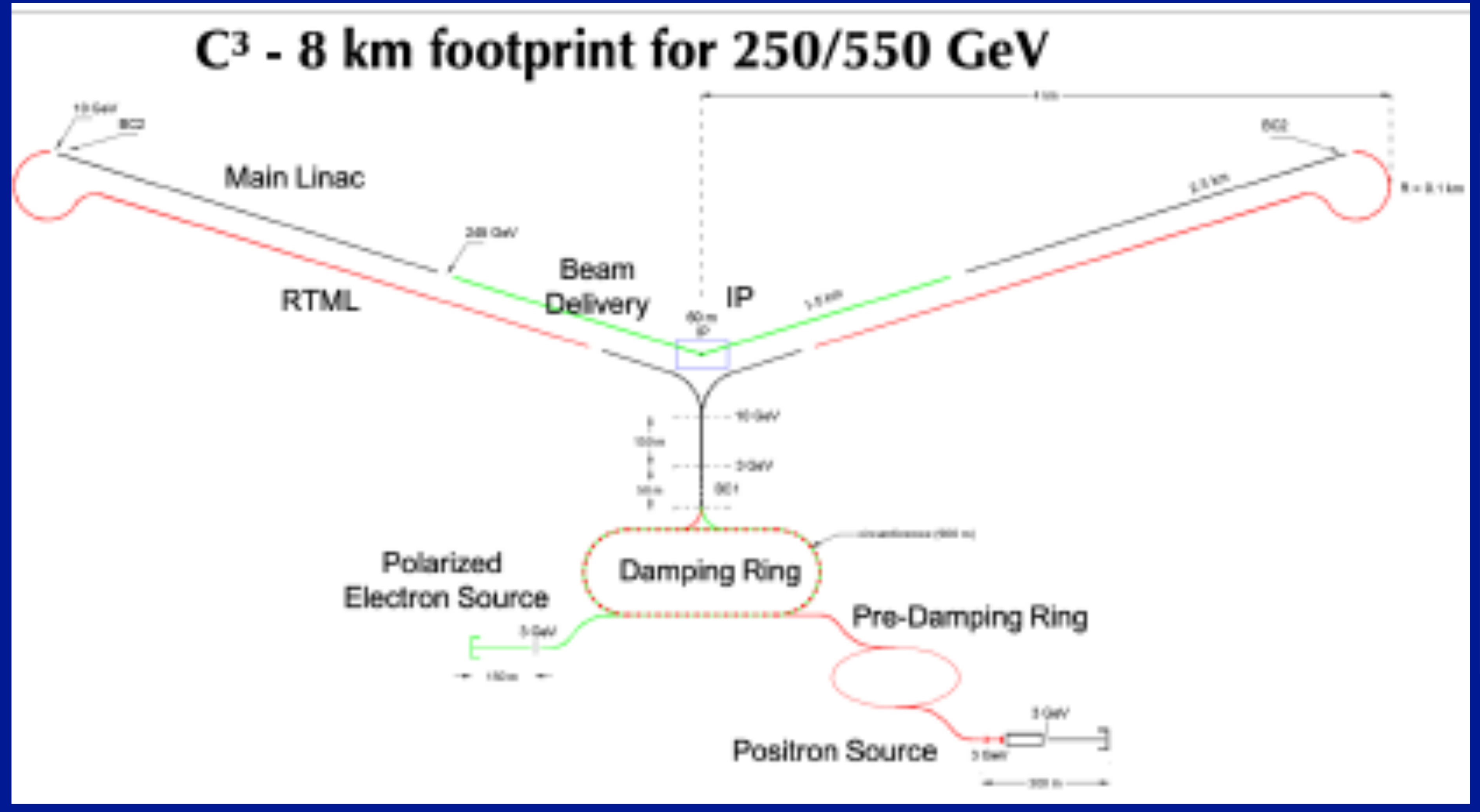
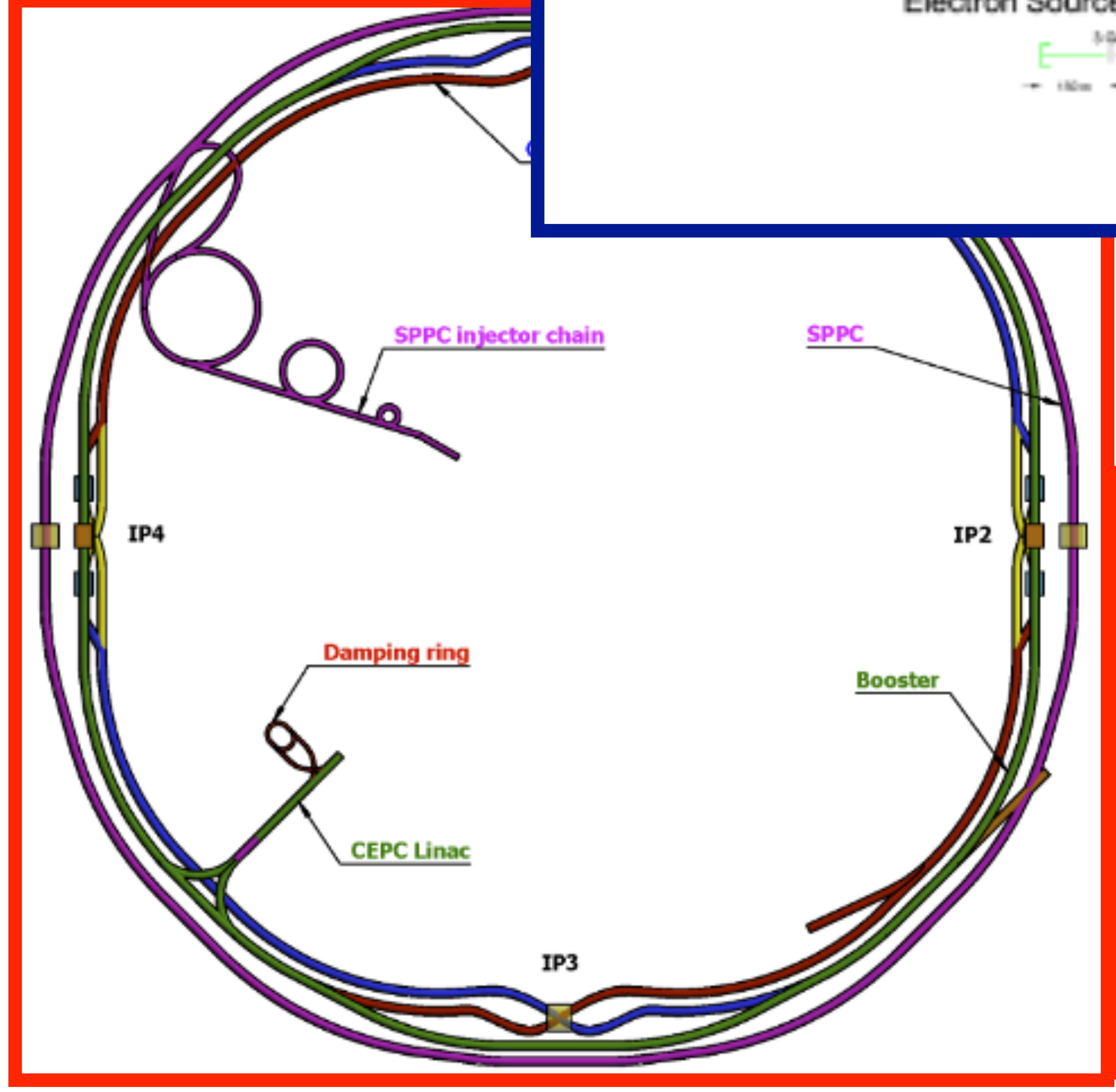




...and the new kid on the block:
the Cool Copper Collider C3,
first proposed 2018, arXiv:1807.10195

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



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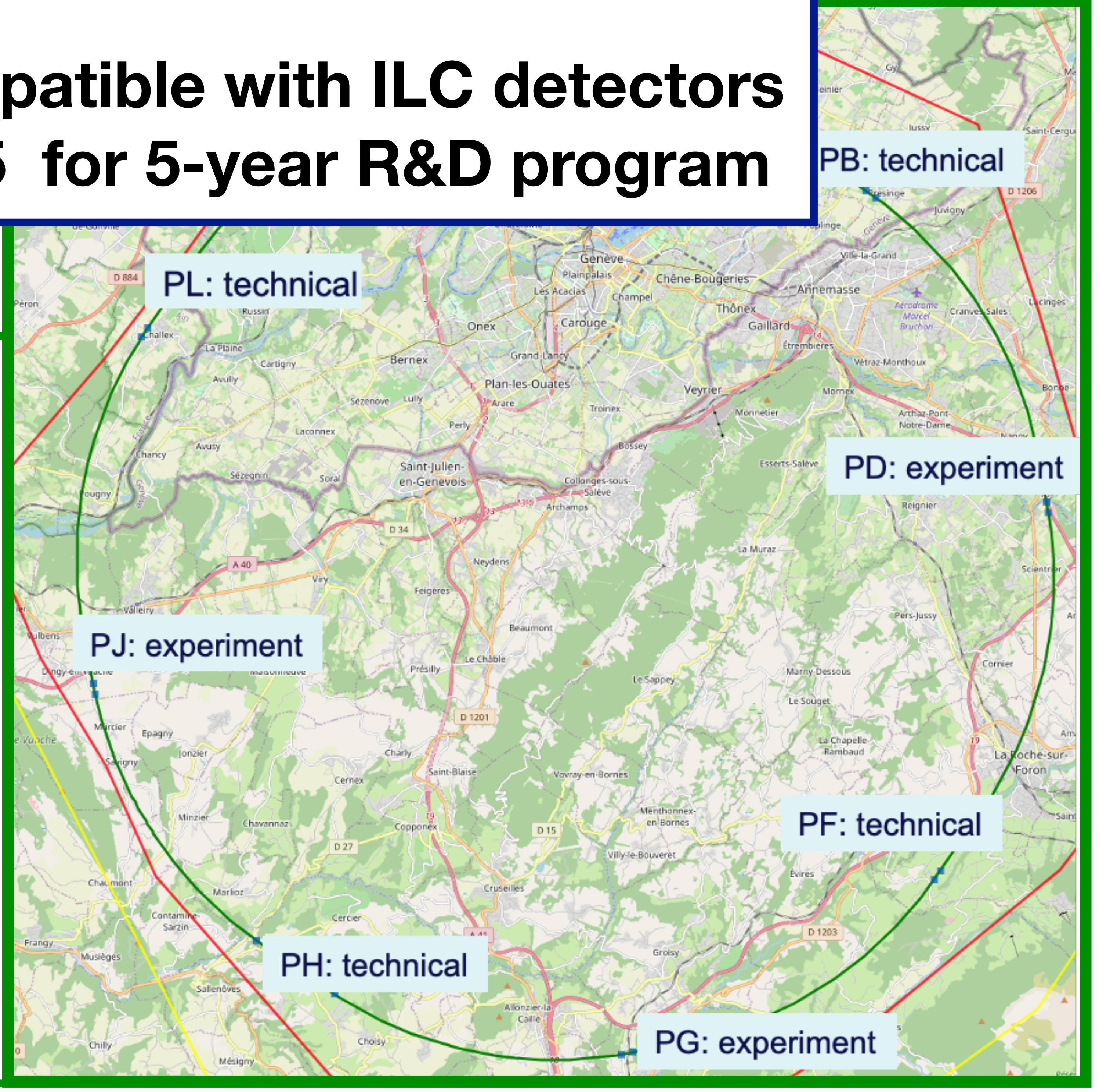

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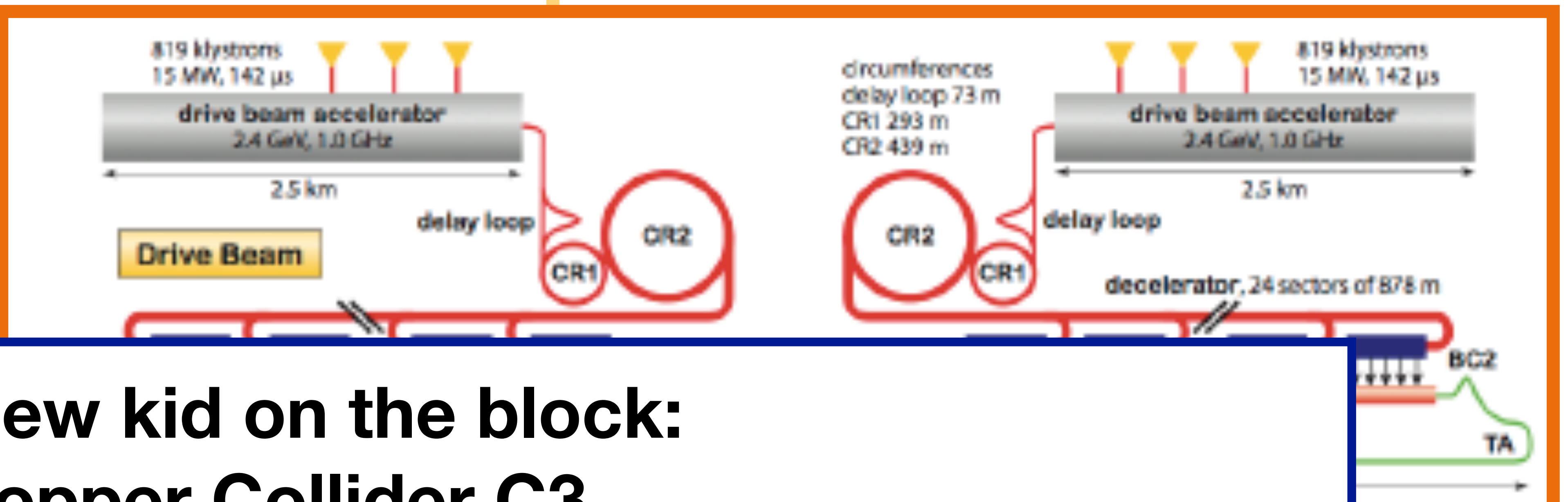

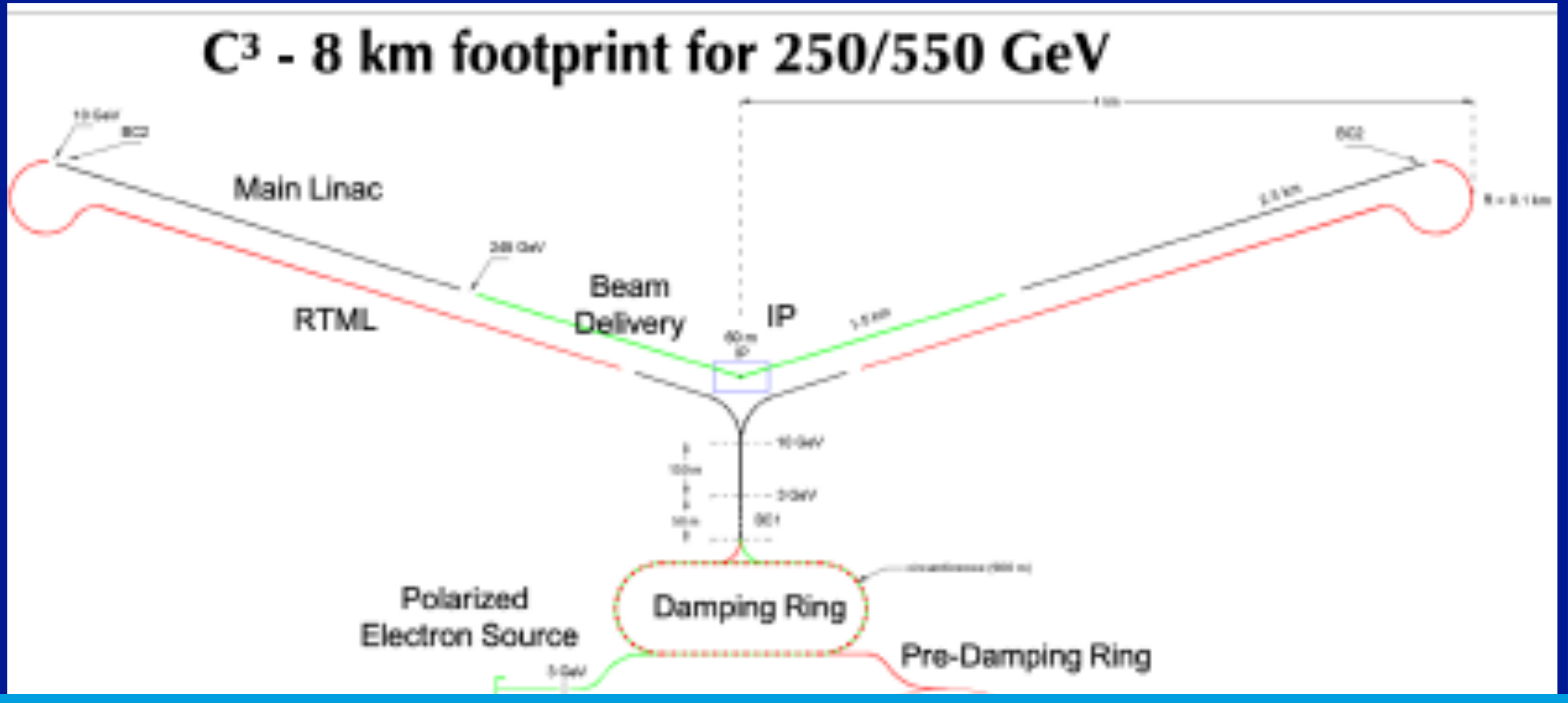

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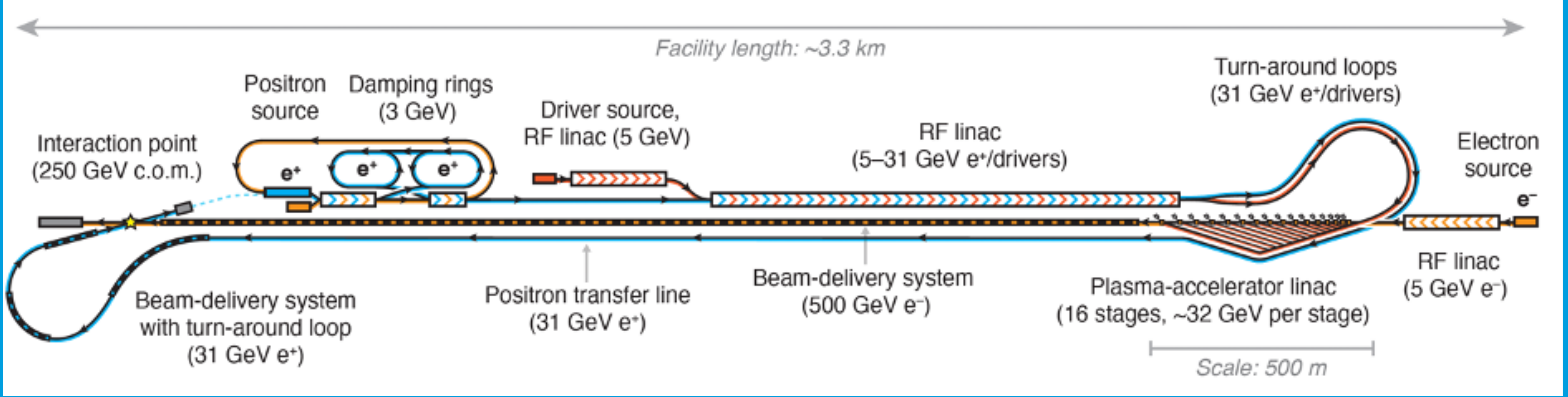

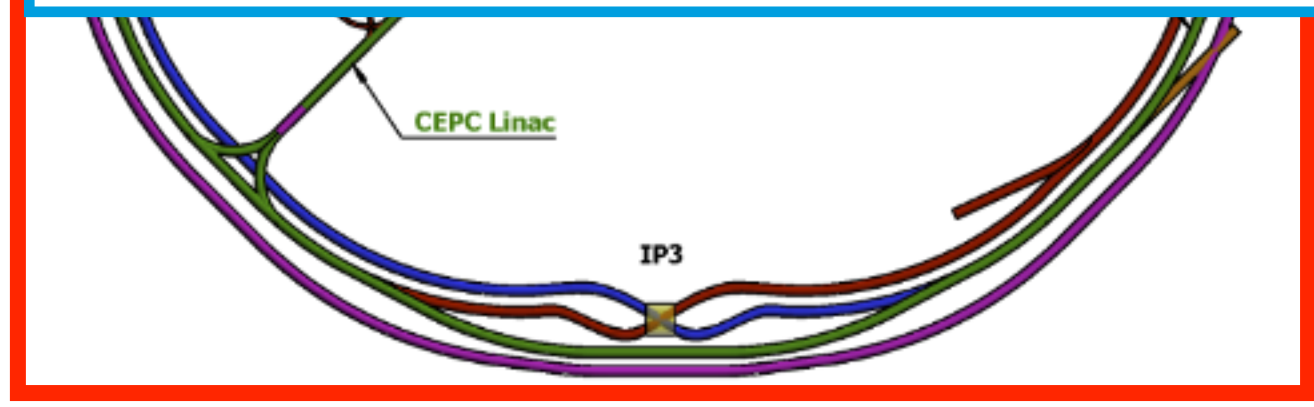

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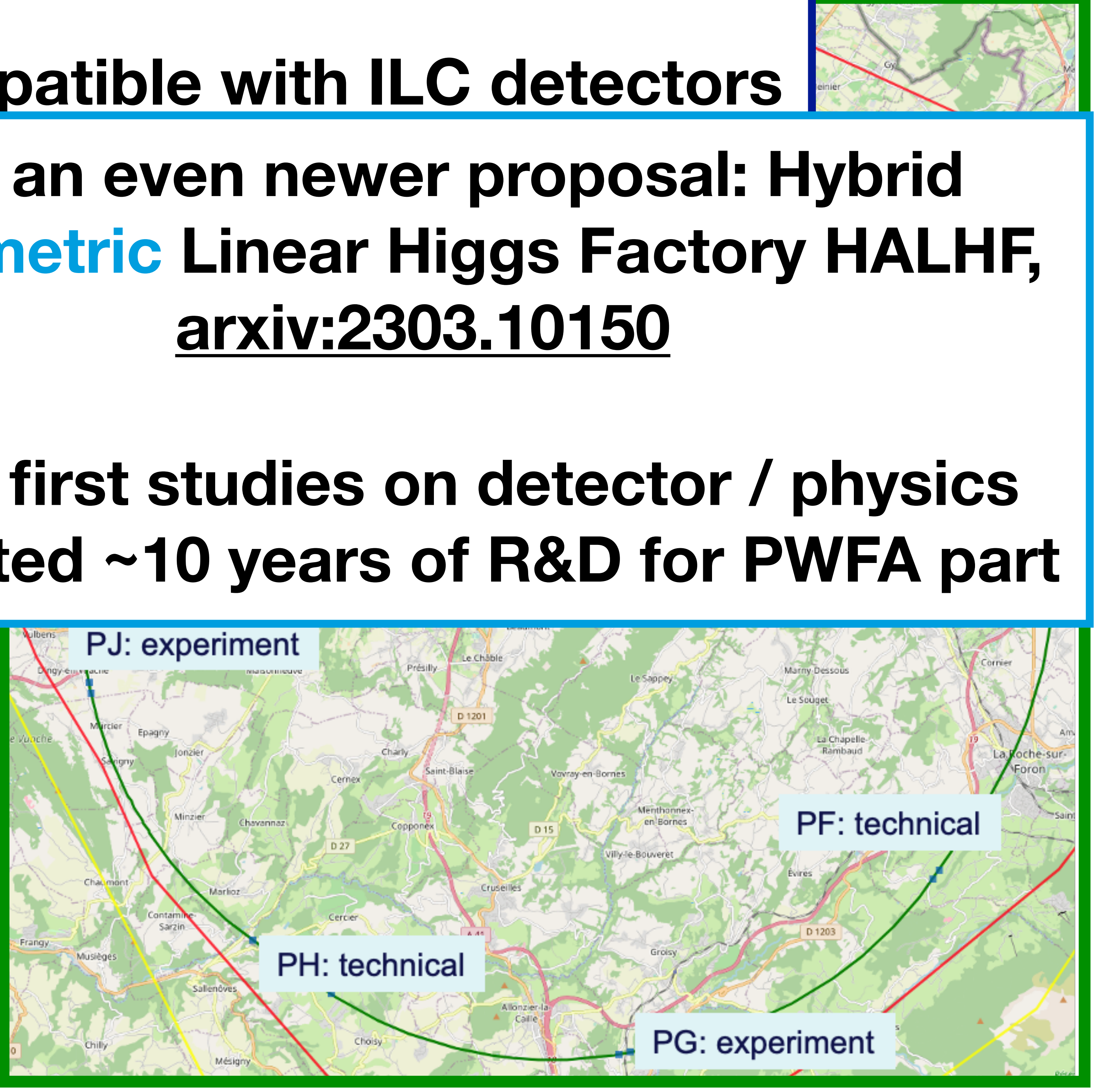

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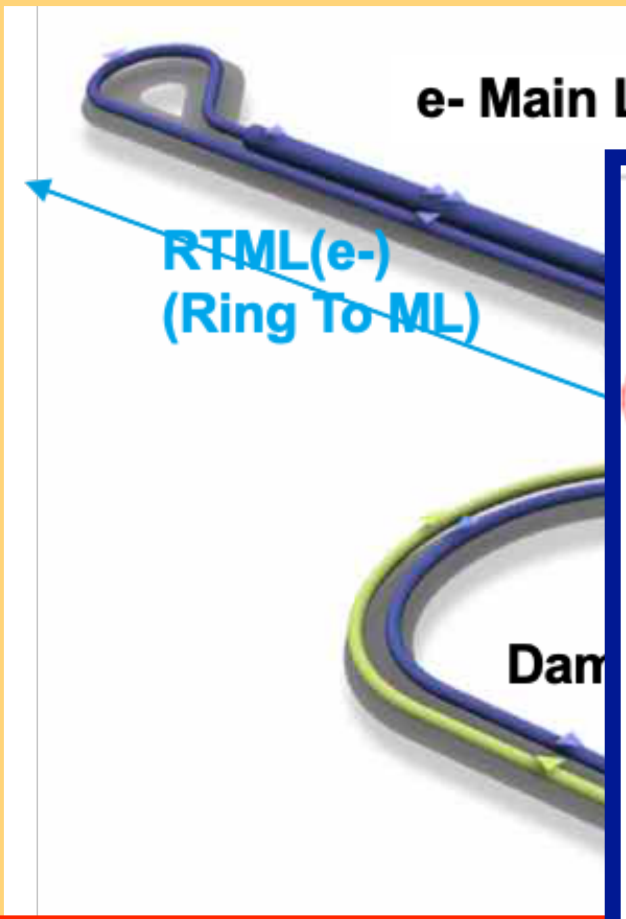

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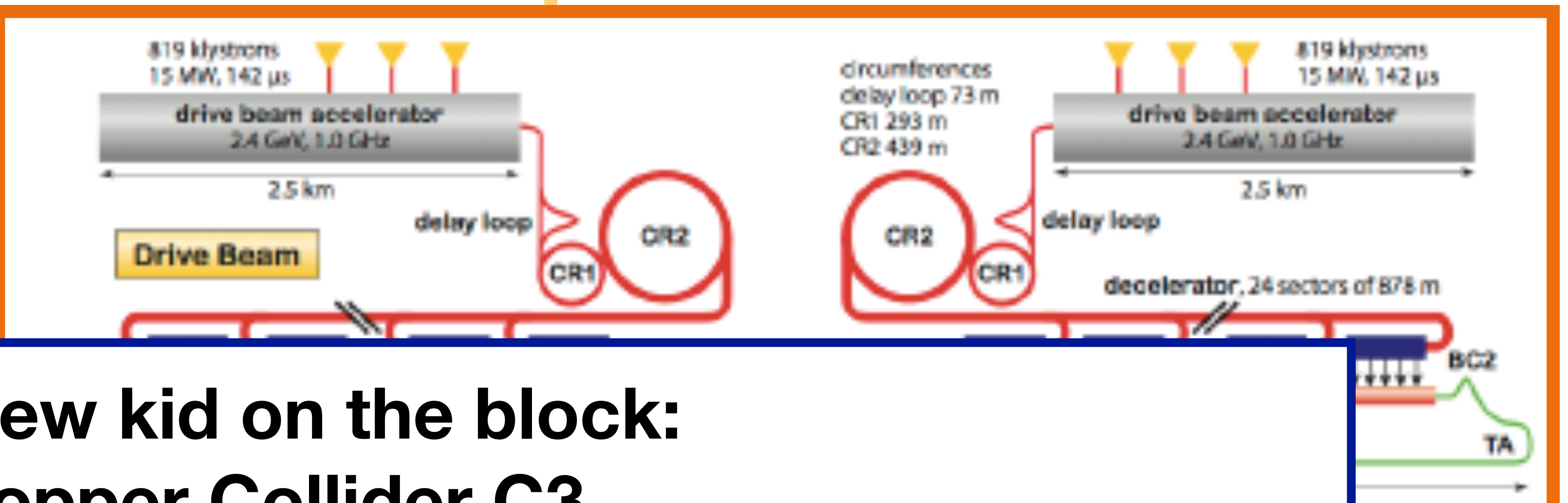

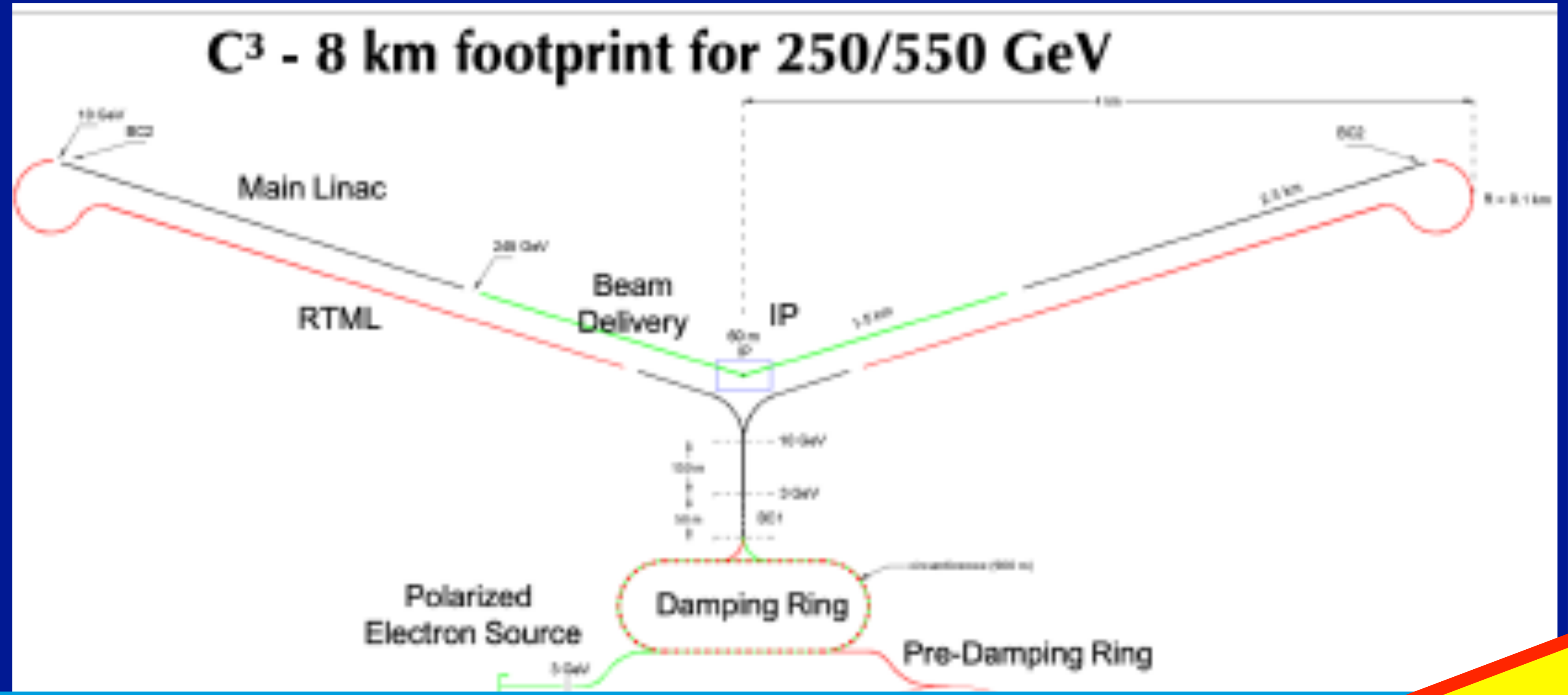

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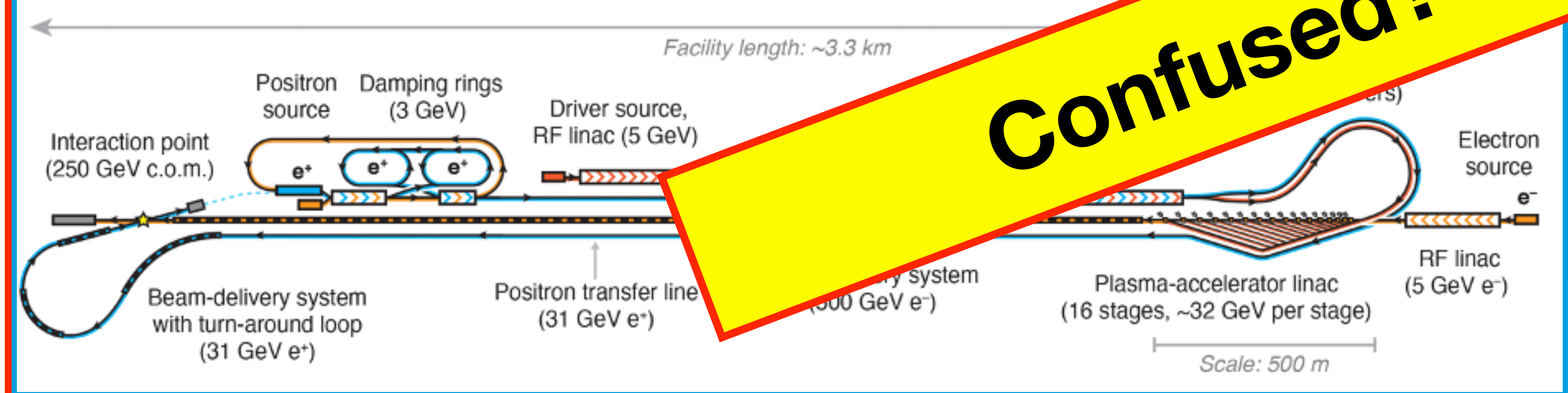
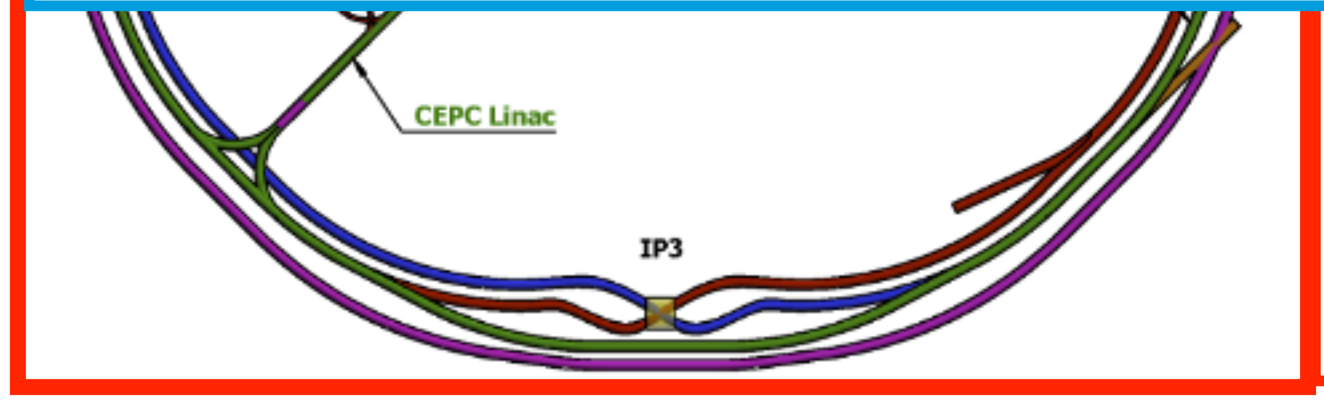


Confused?



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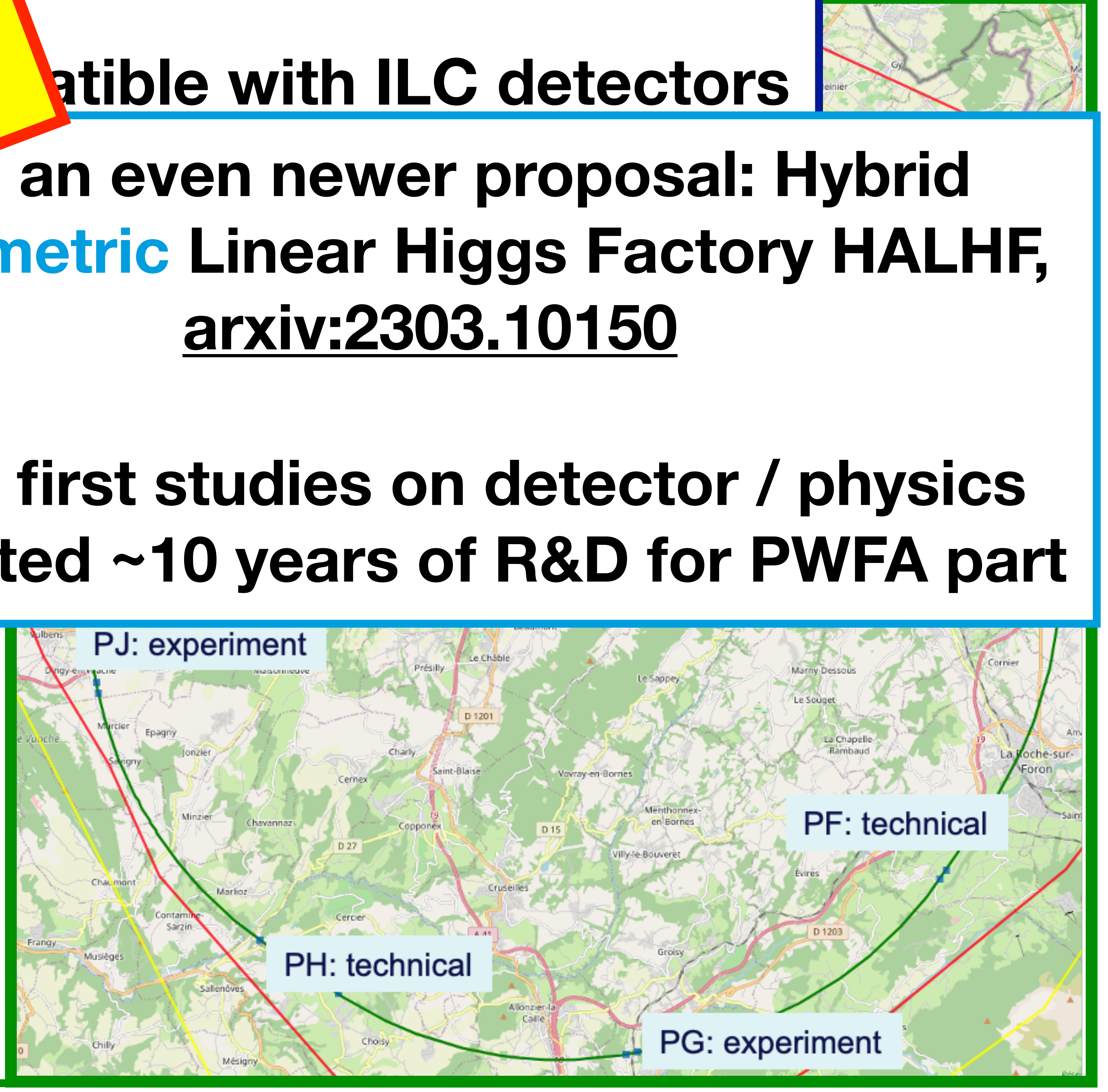
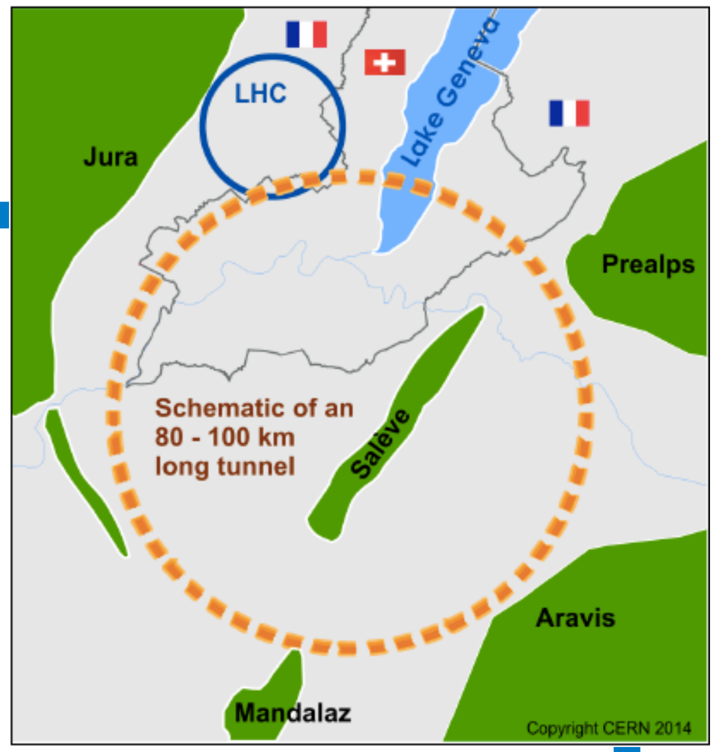


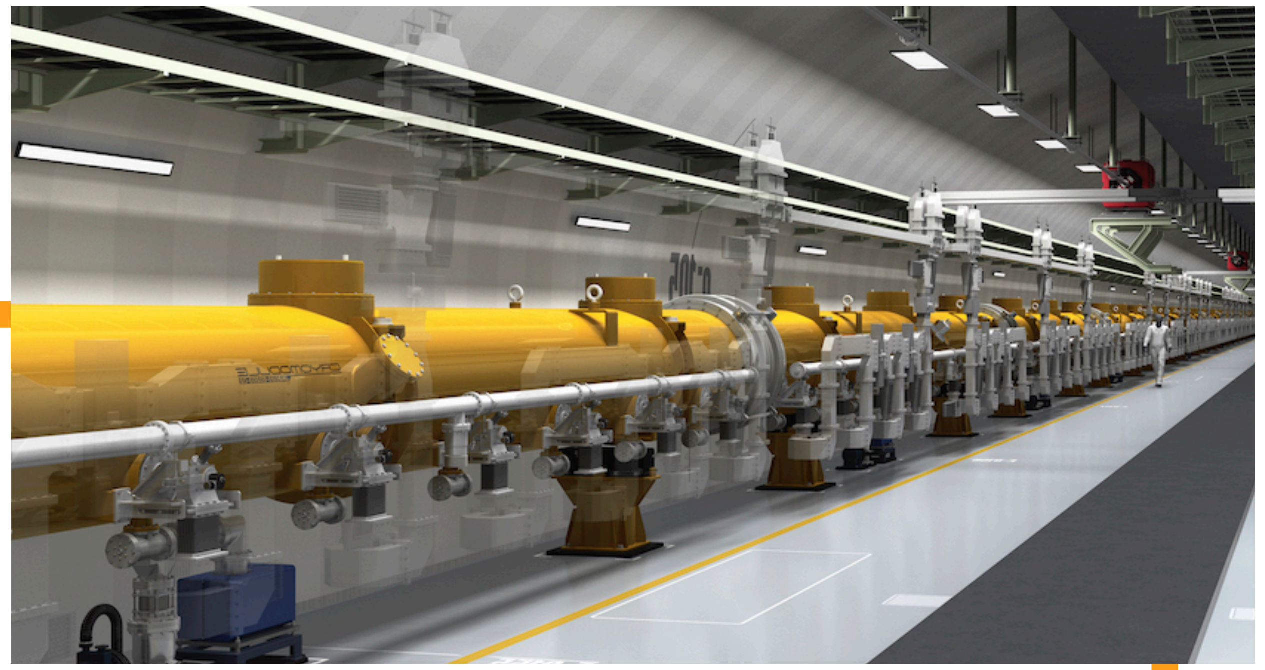
They fall into two classes

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

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- **longitudinally spin-polarised beam(s)**

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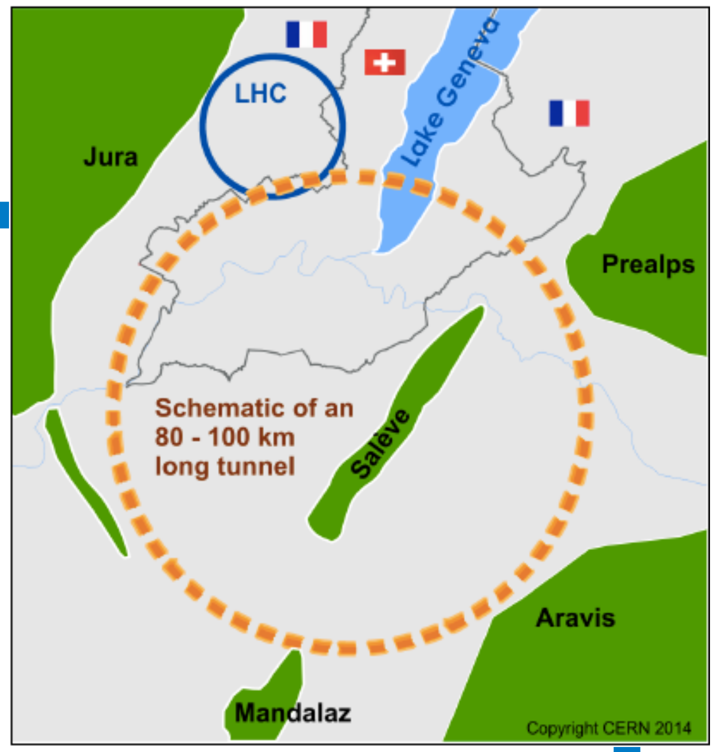

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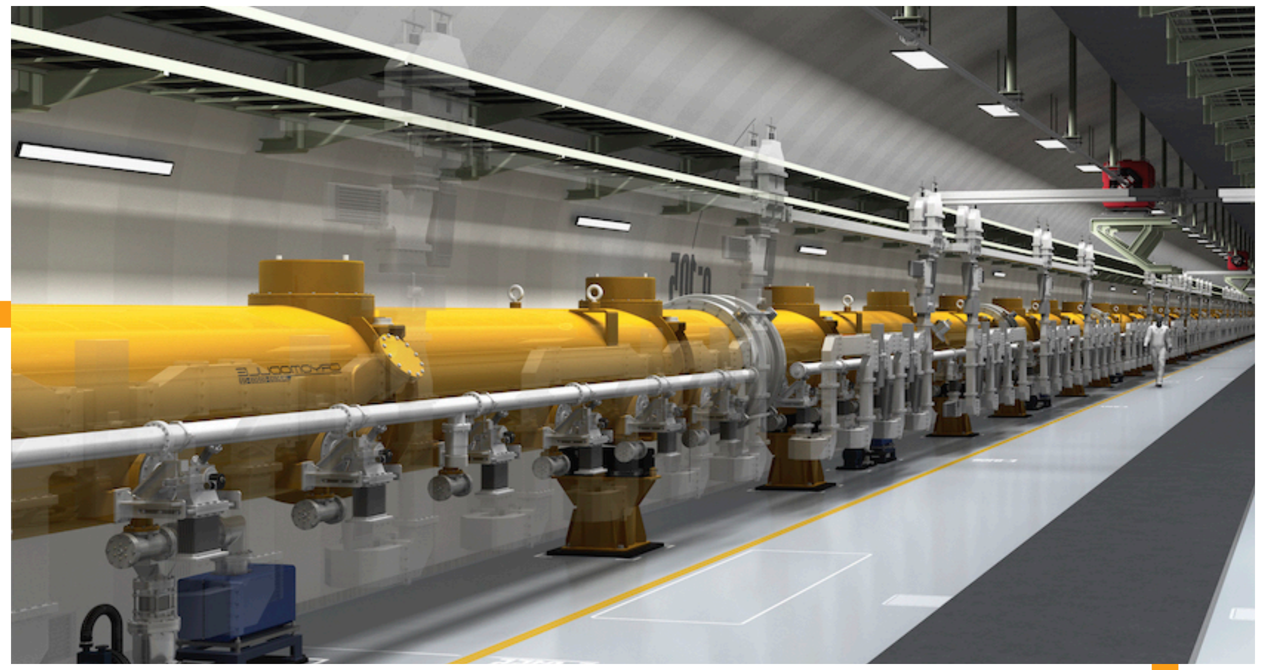
Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge



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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

1978[1)]

- **Synchrotron radiation ~ operation cost:**
  - **$\Delta E \sim (E^4 / m^4 R)$** per turn => 2 GeV at LEP2
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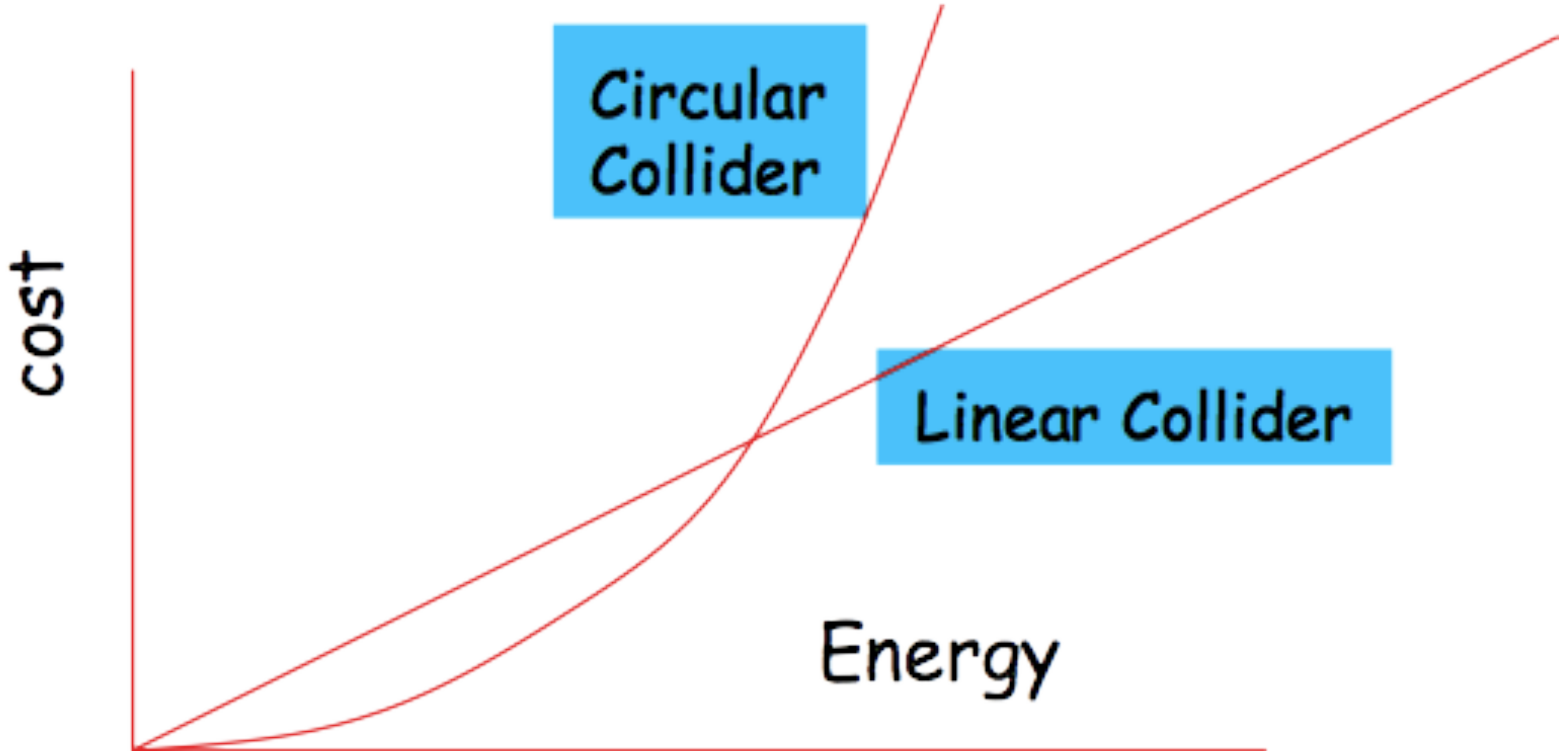

LIMITATIONS ON PERFORMANCE OF e^+e^- STORAGE RINGS AND

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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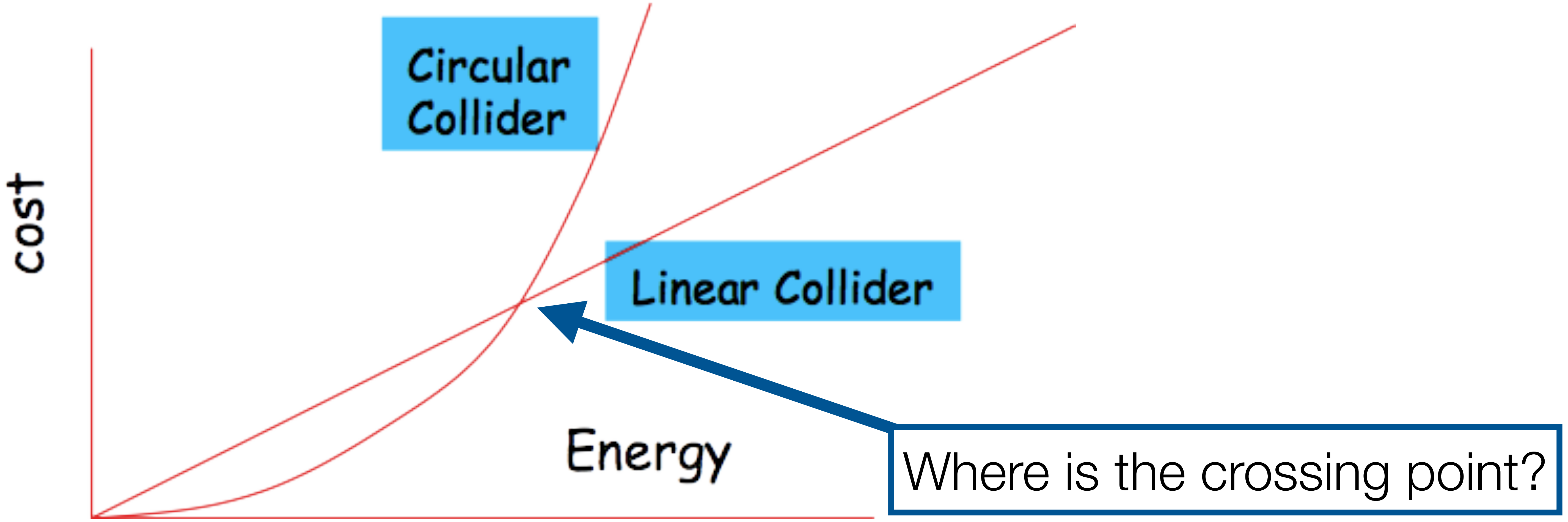

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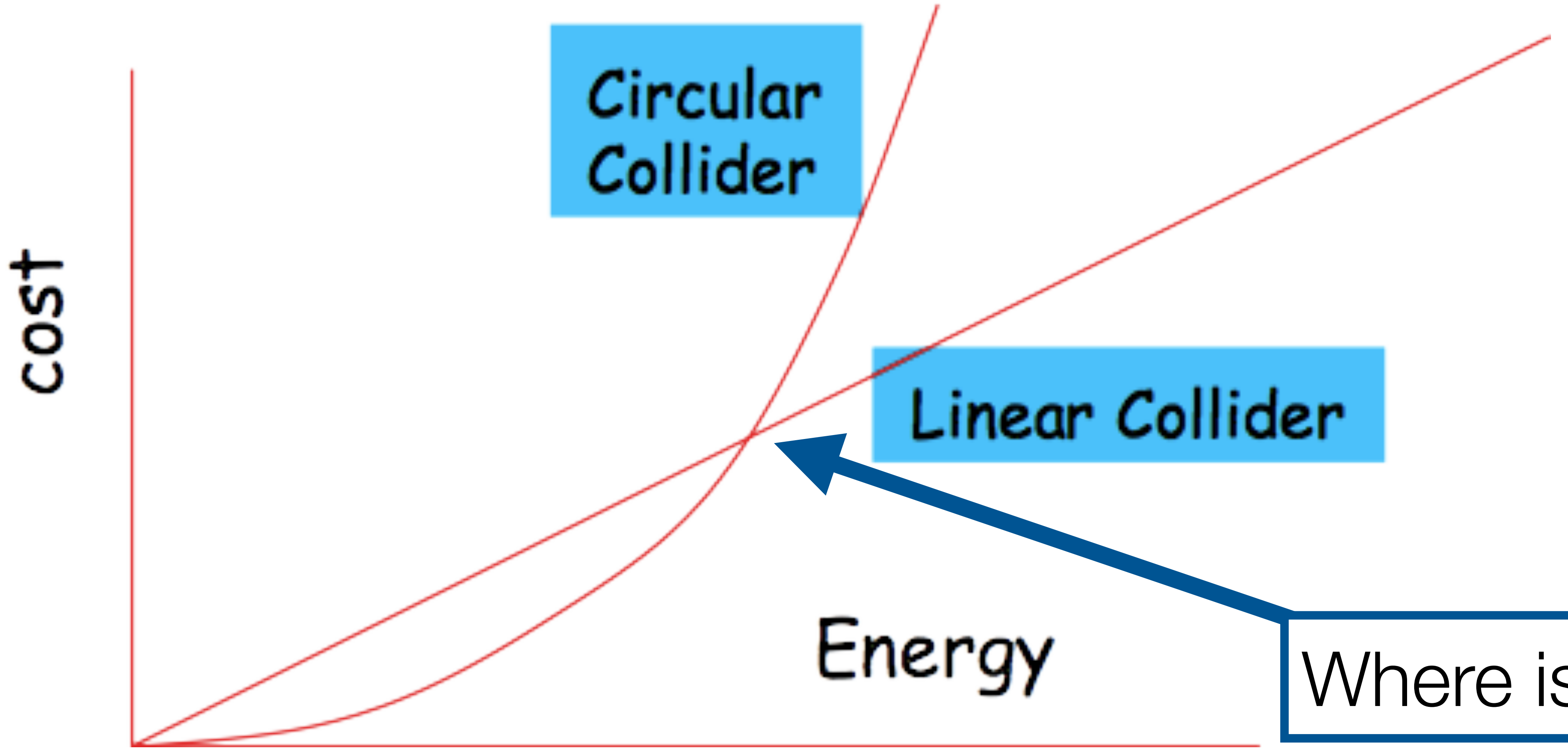
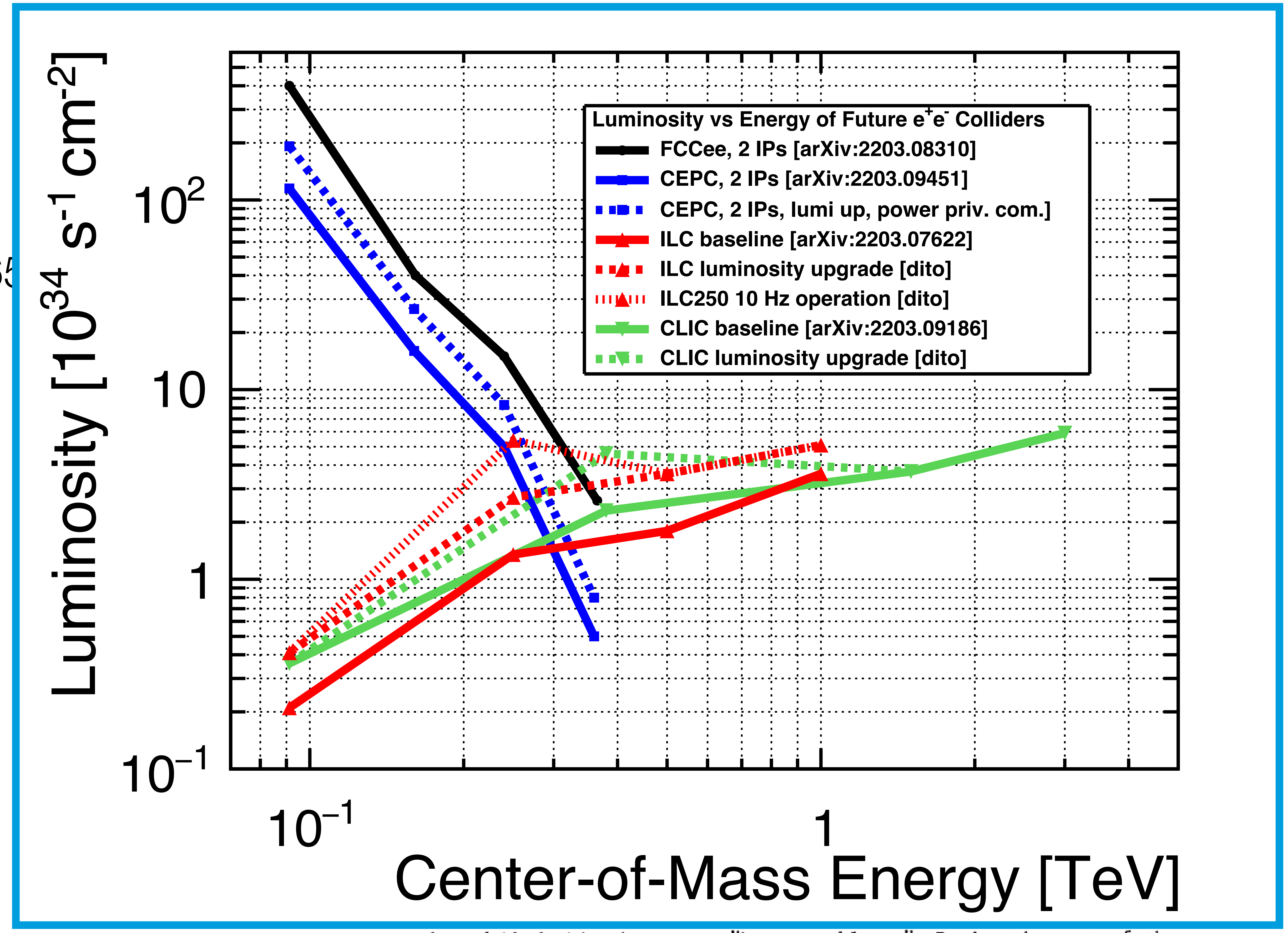


Where is the crossing point?



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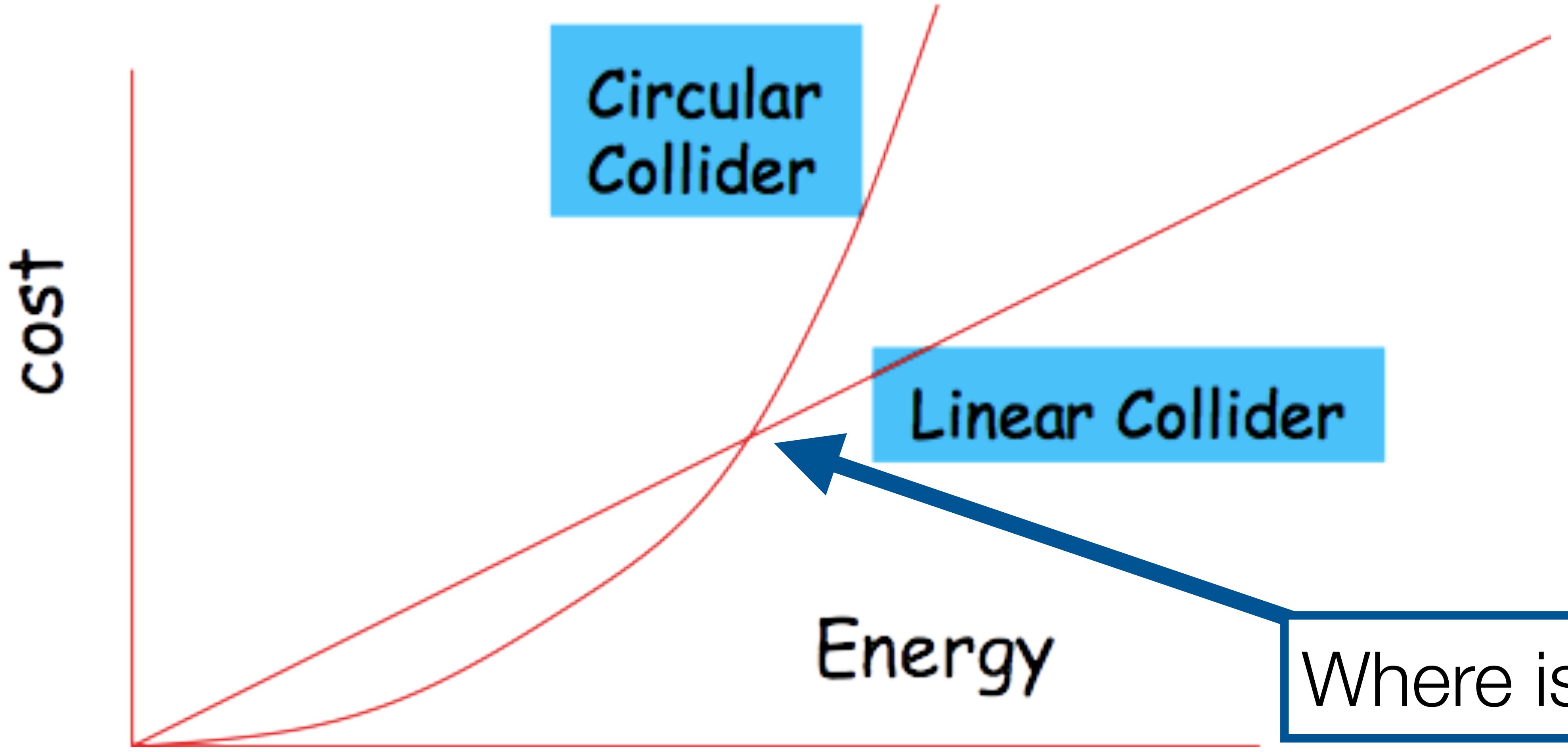

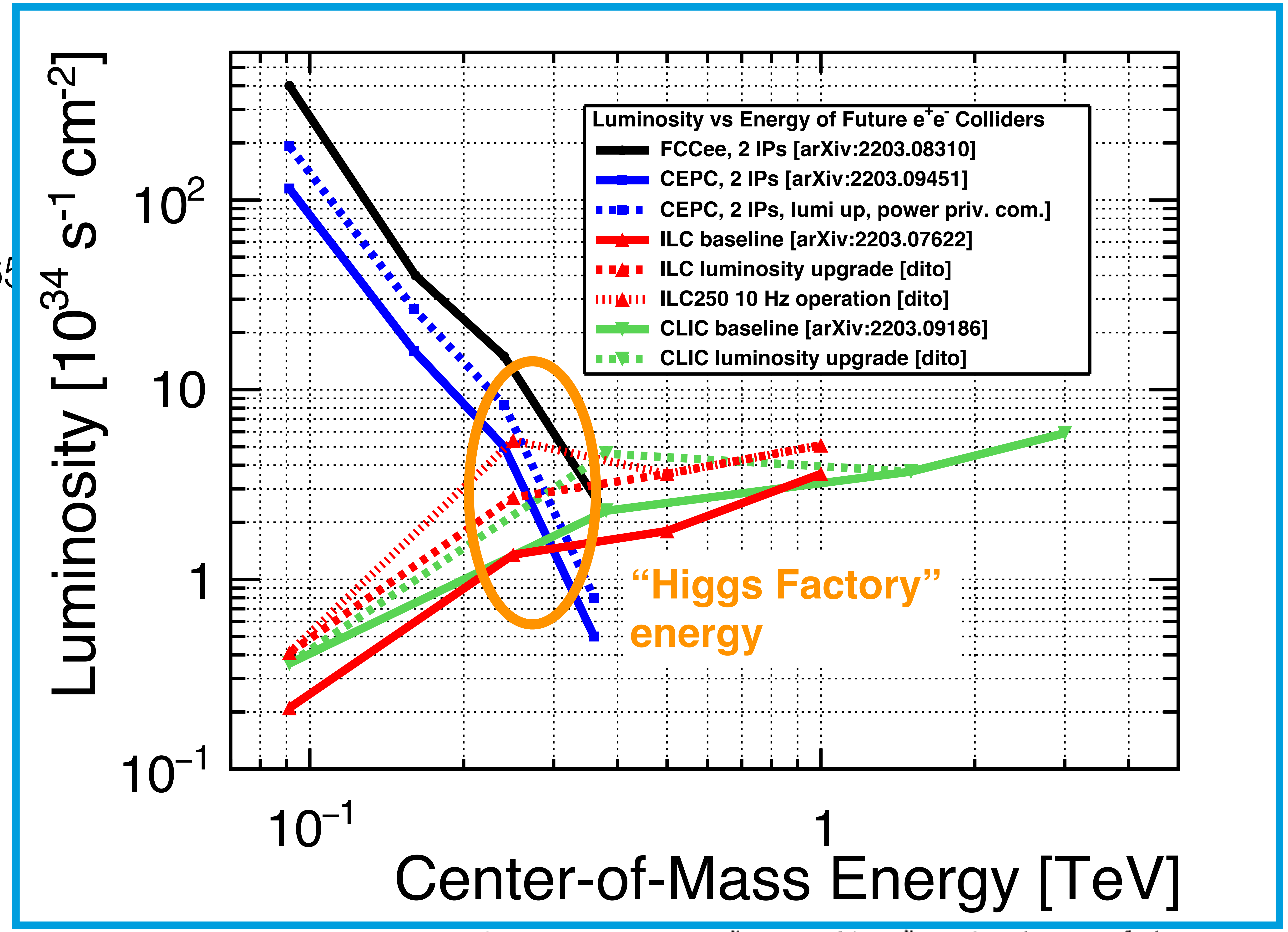

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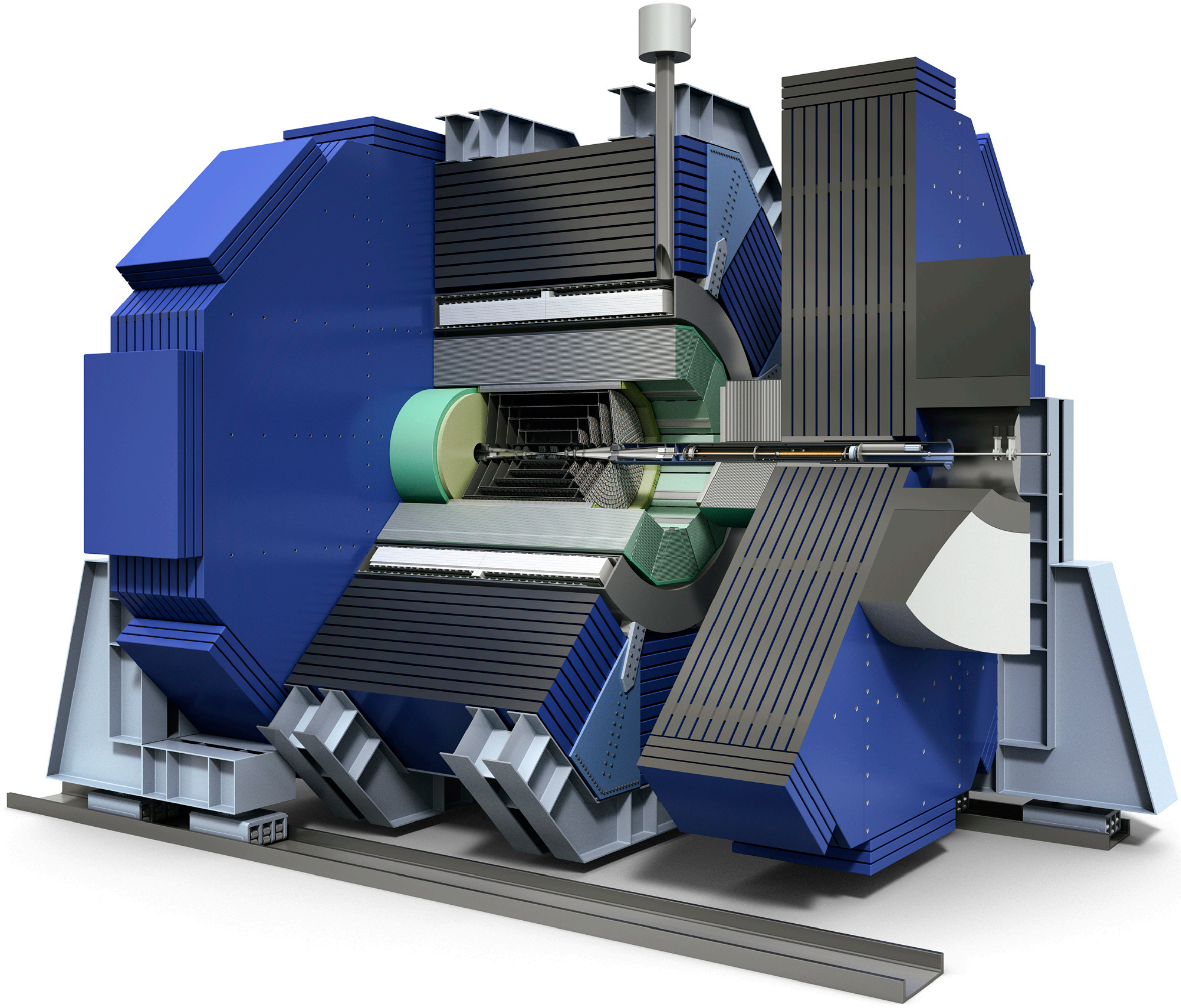
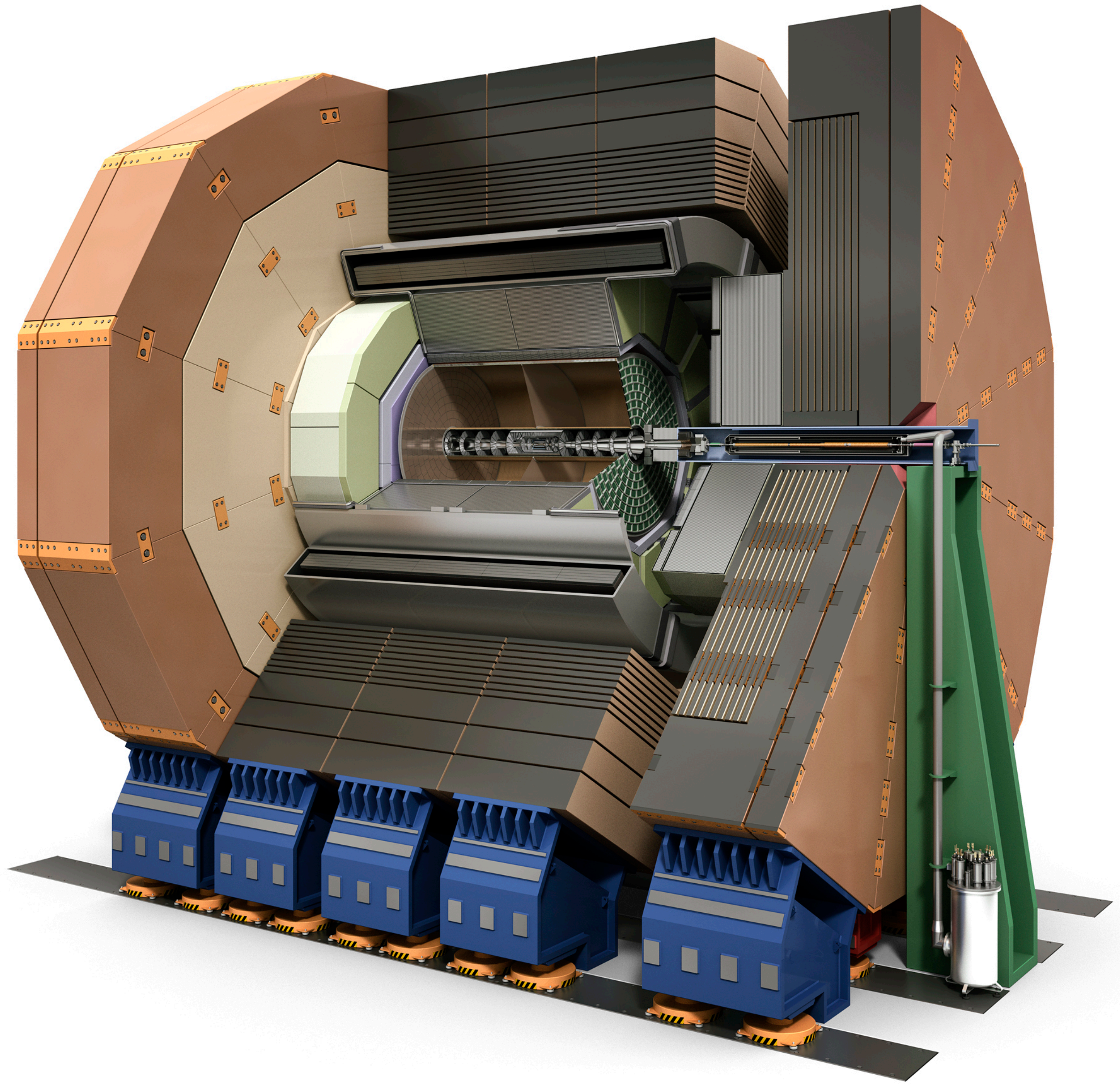
Higgs Factory Detector Concepts

for linear & circular





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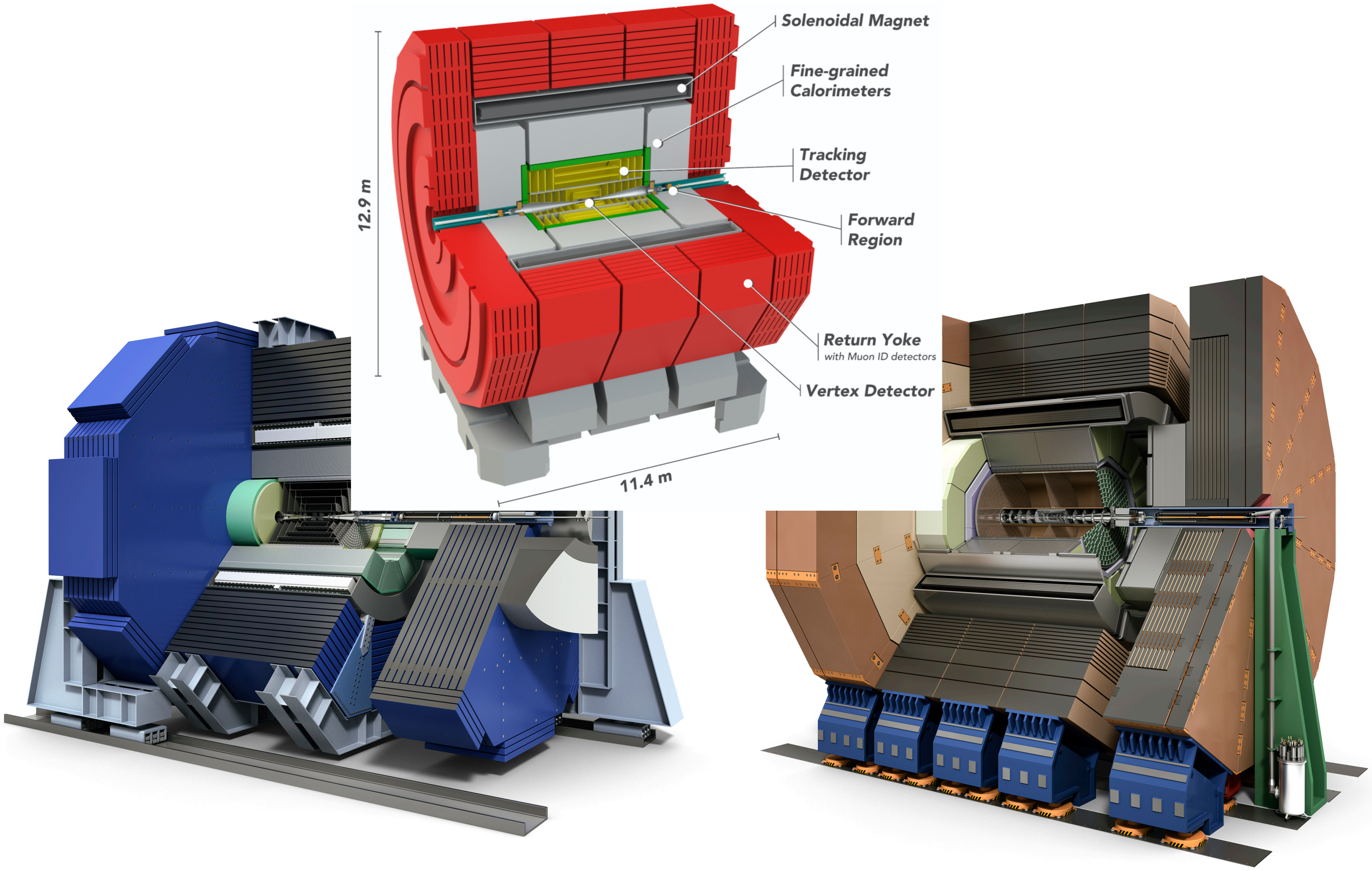

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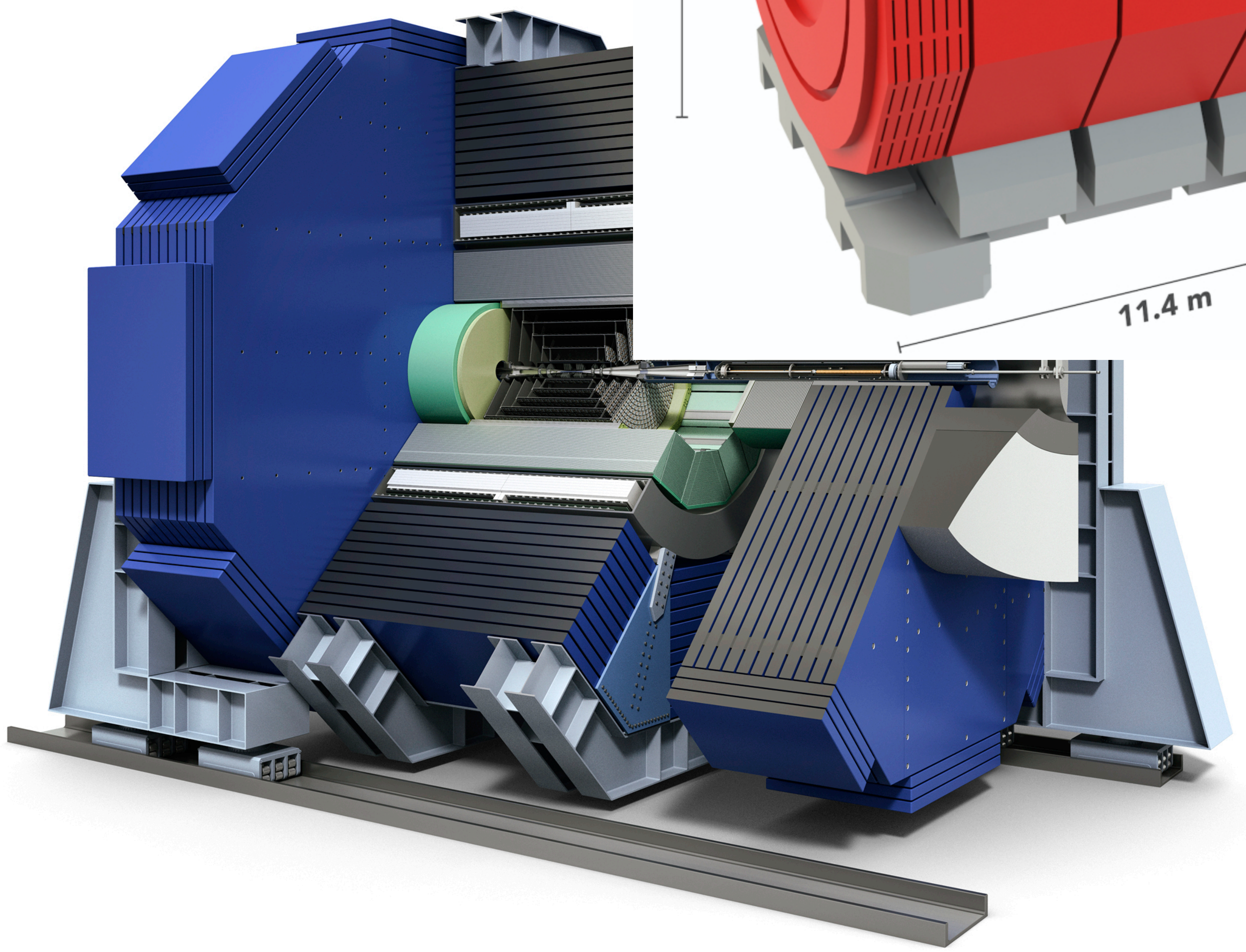

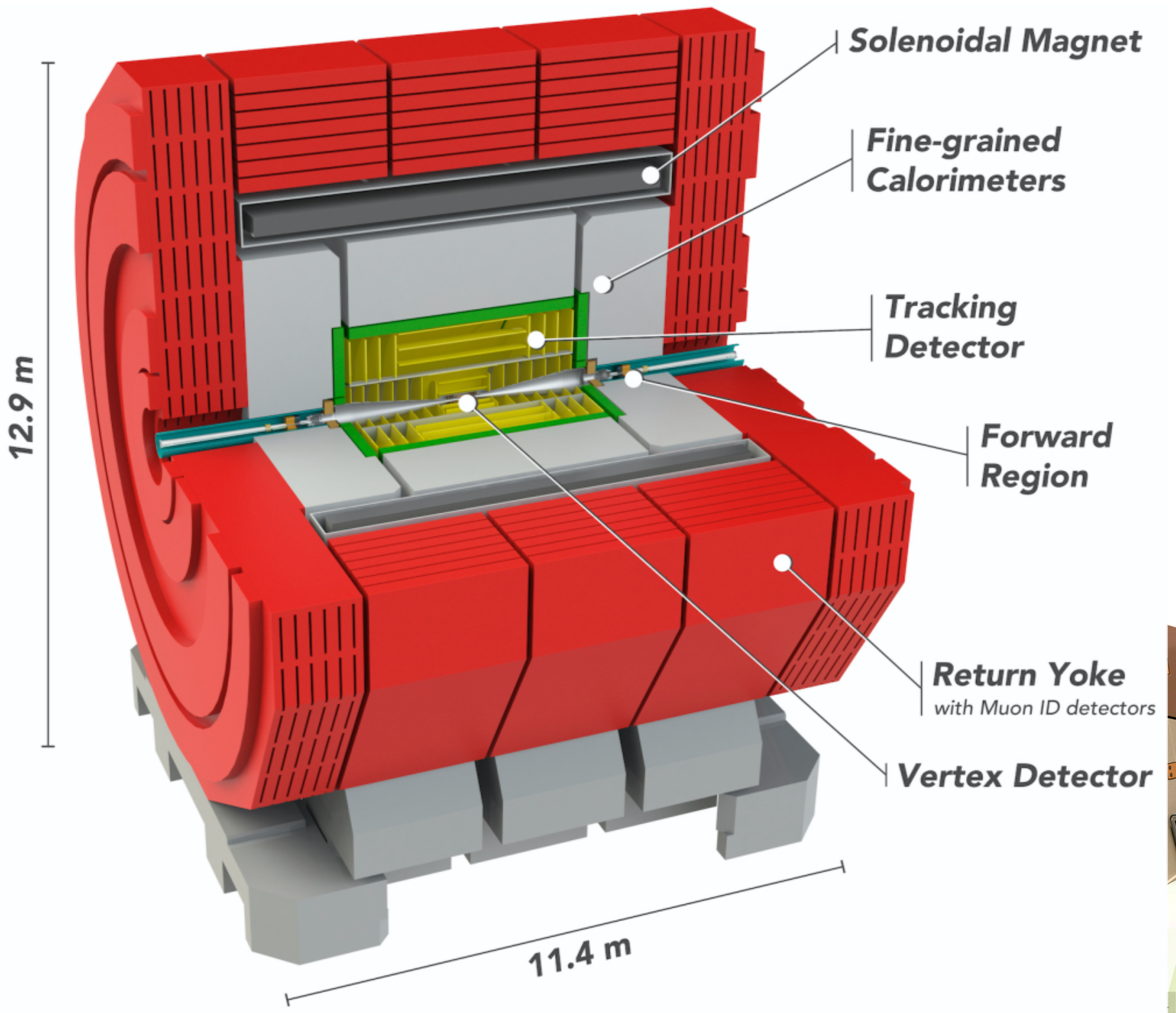

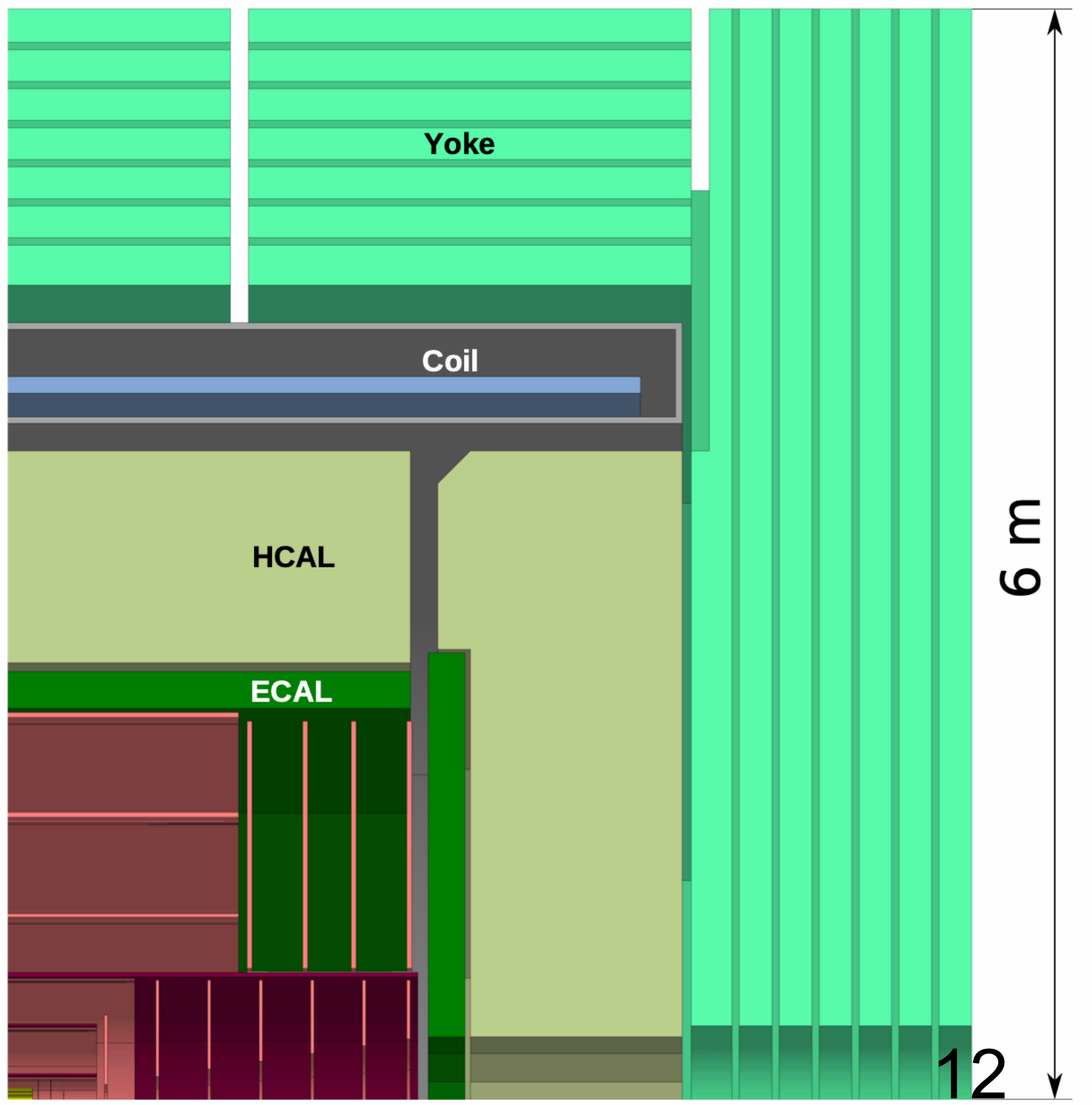

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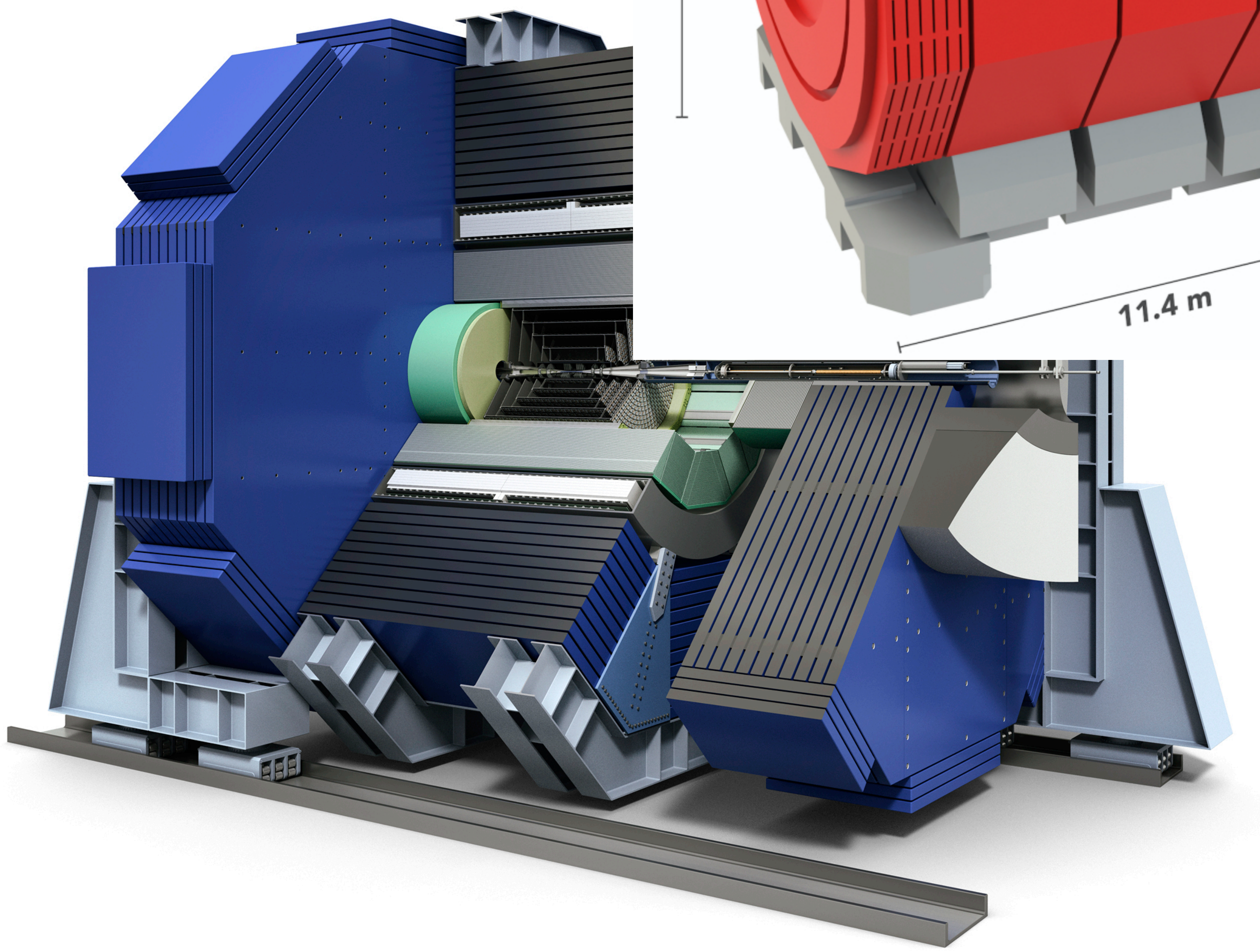

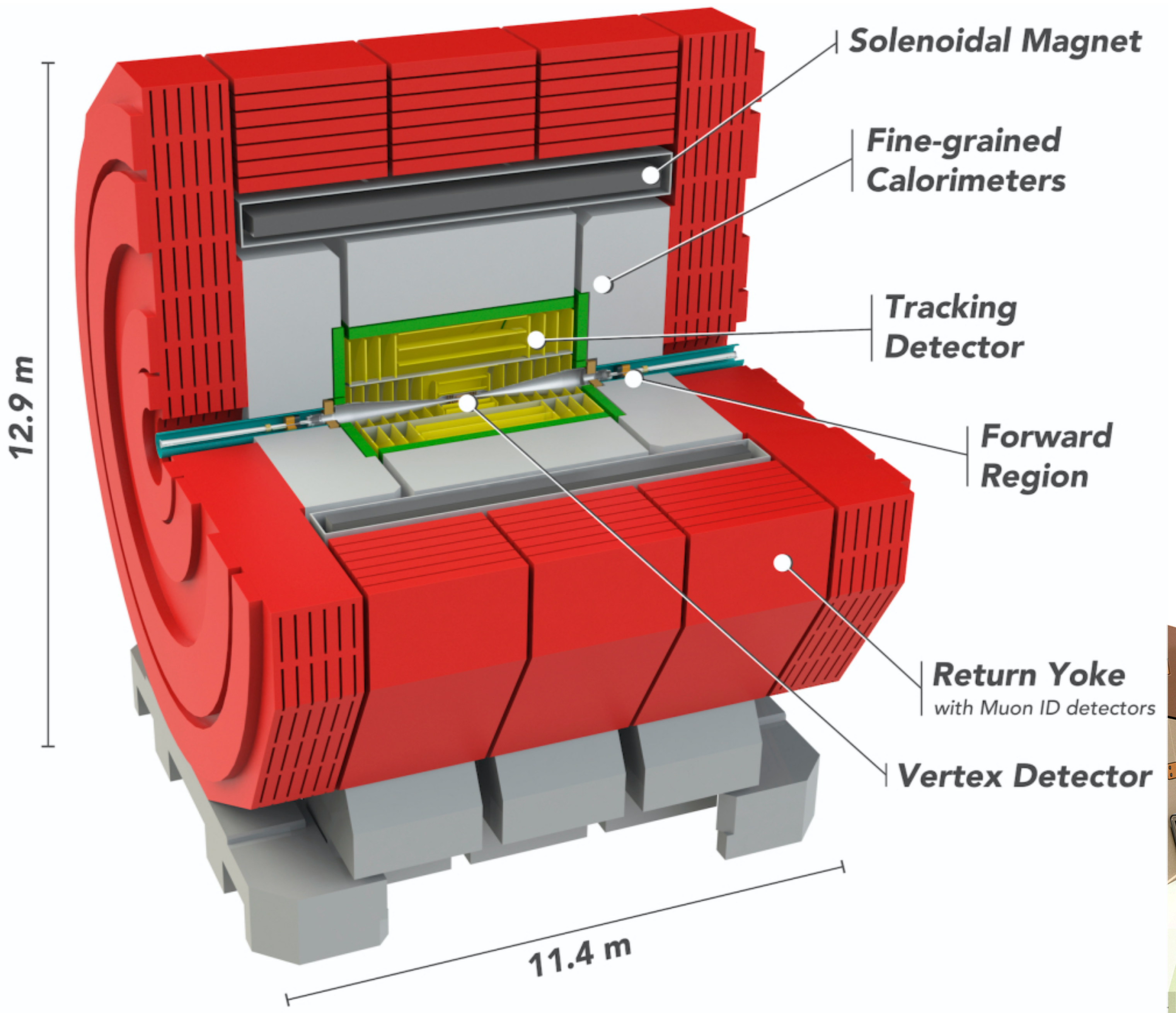

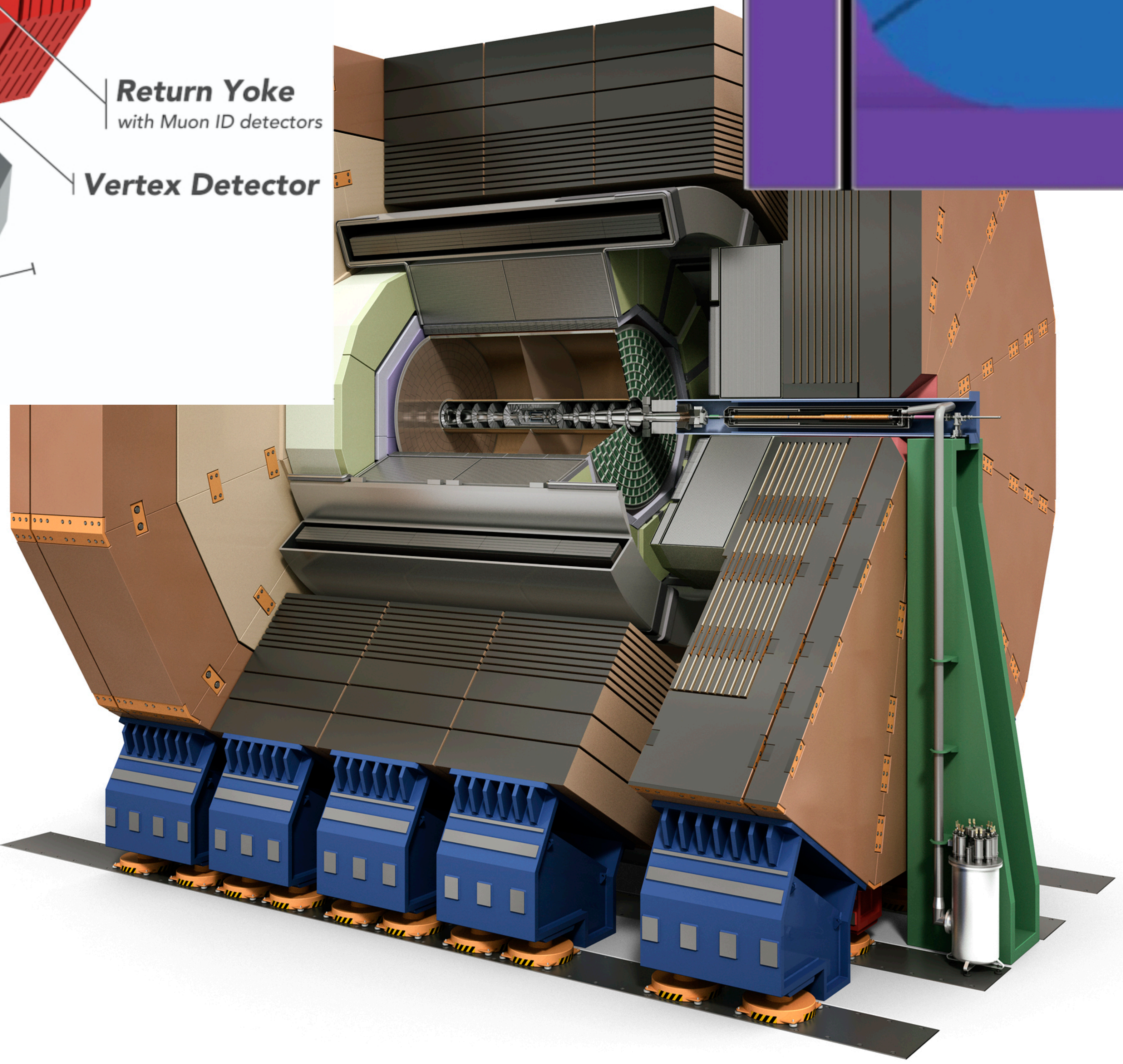

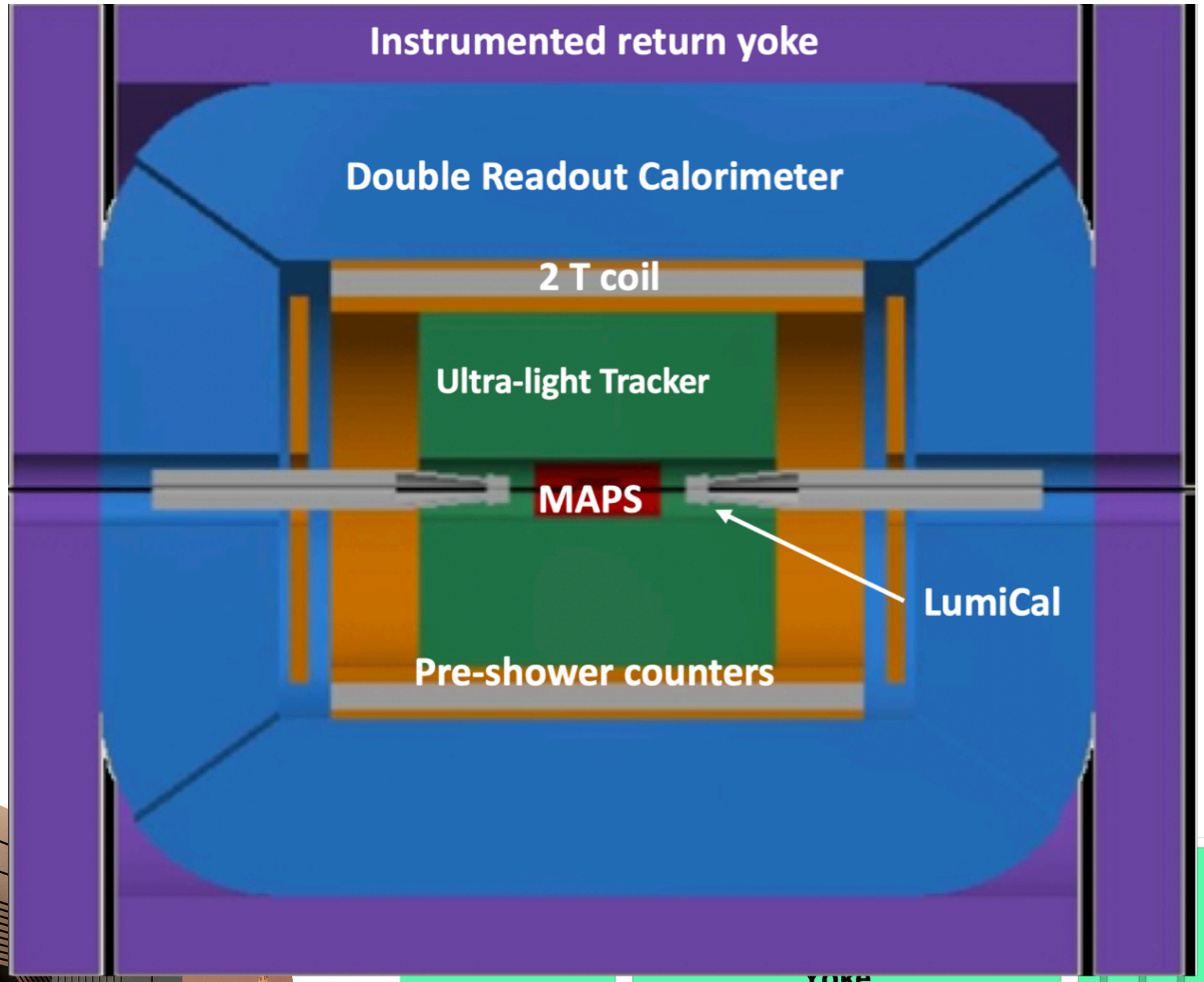

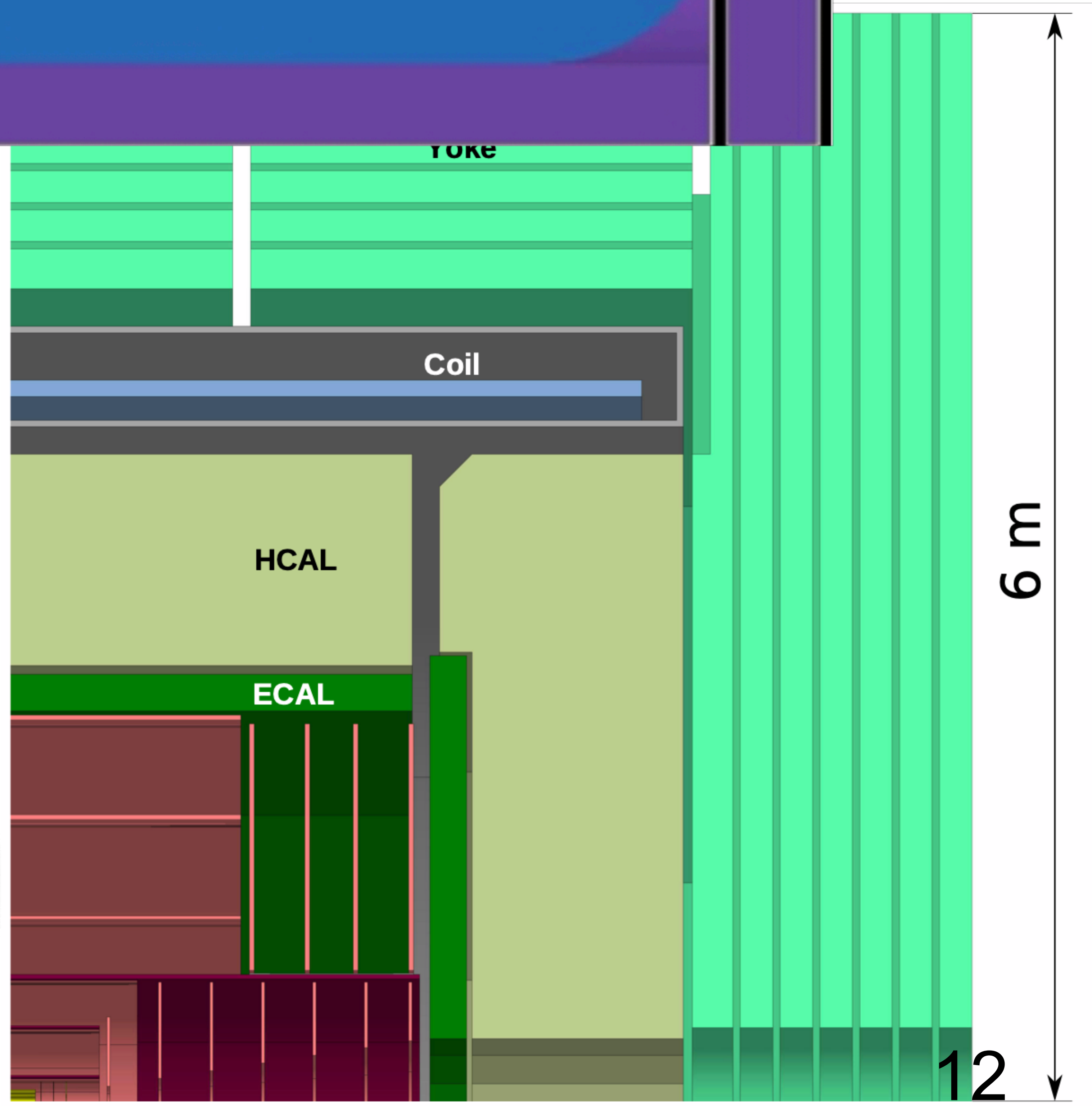

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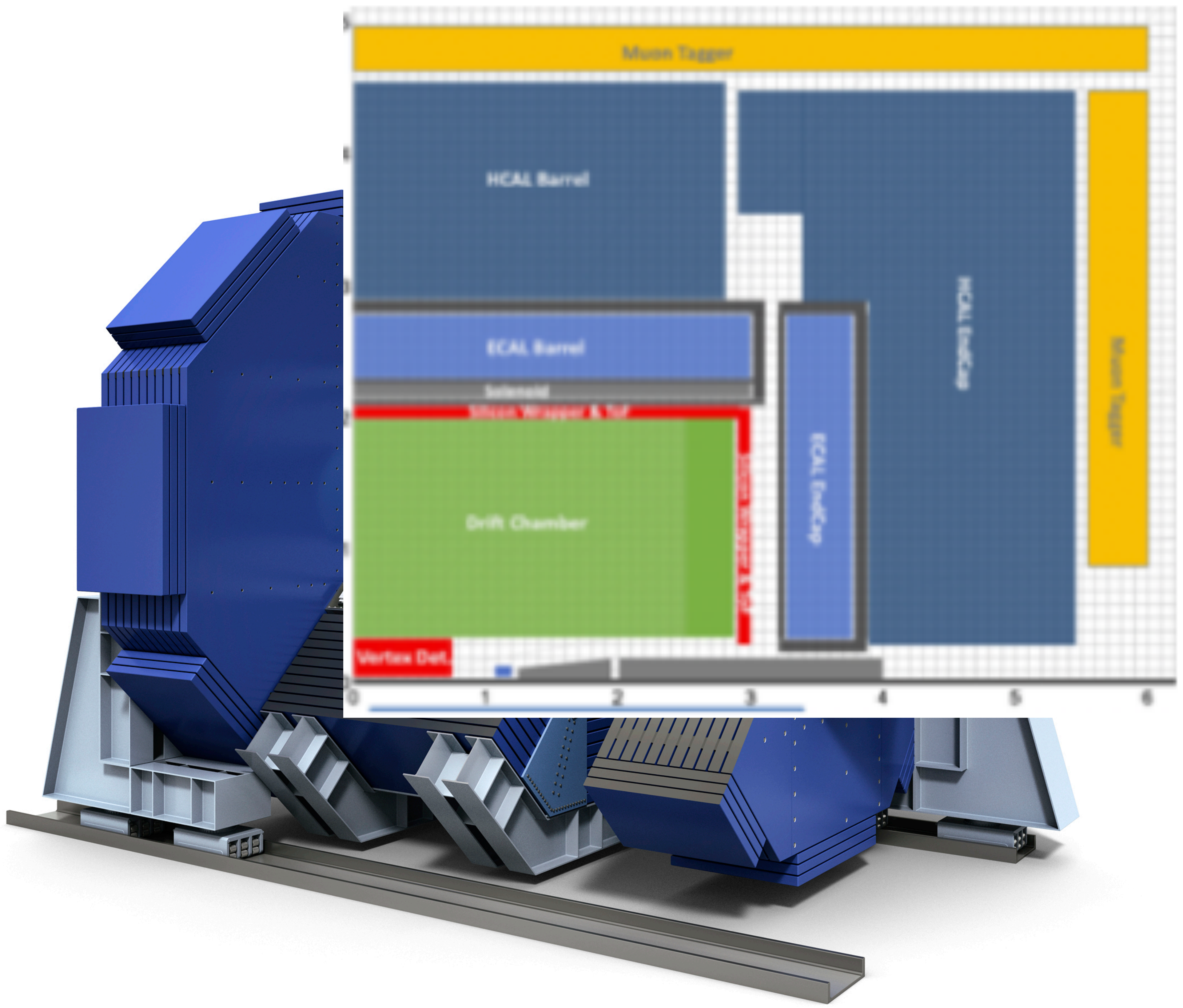

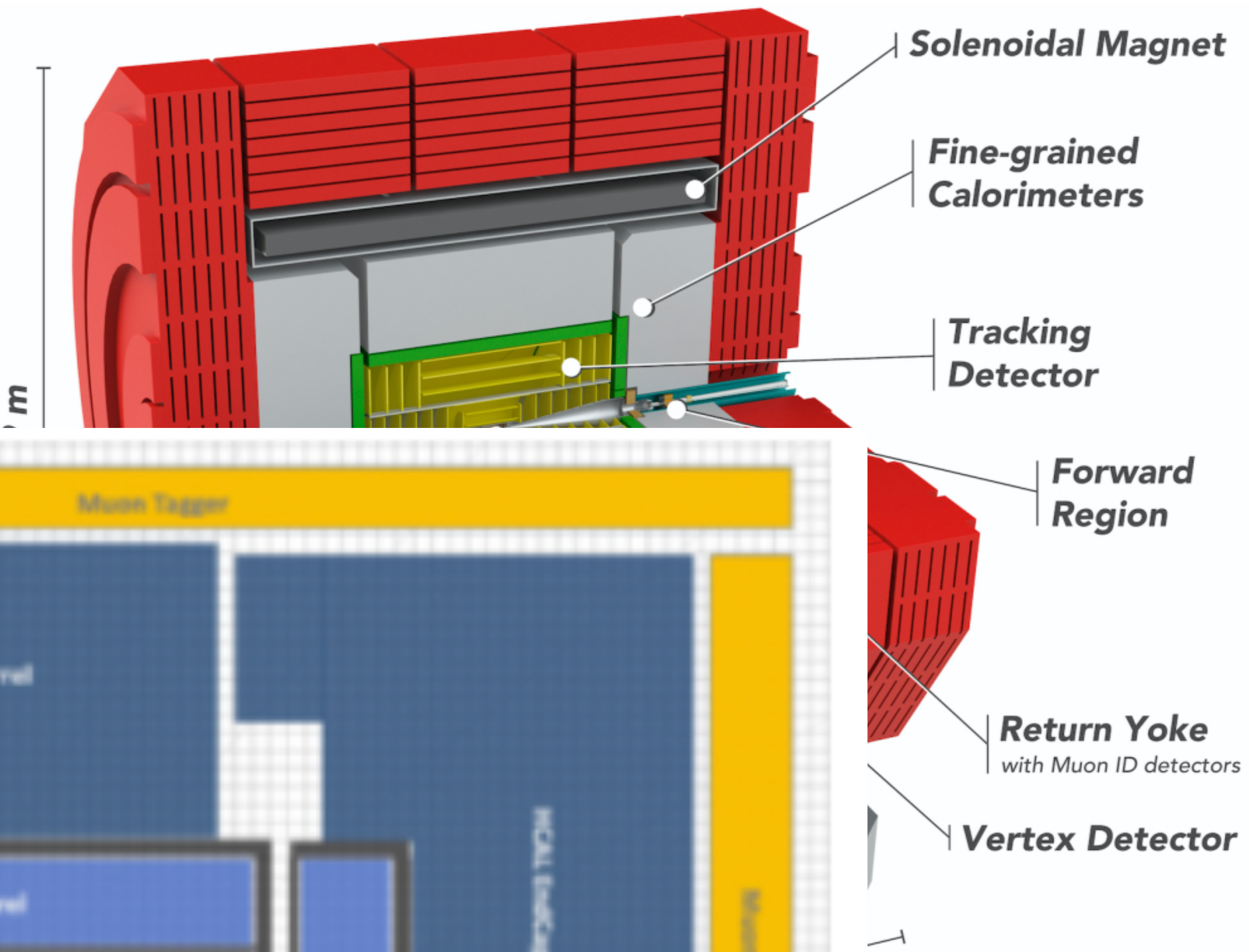

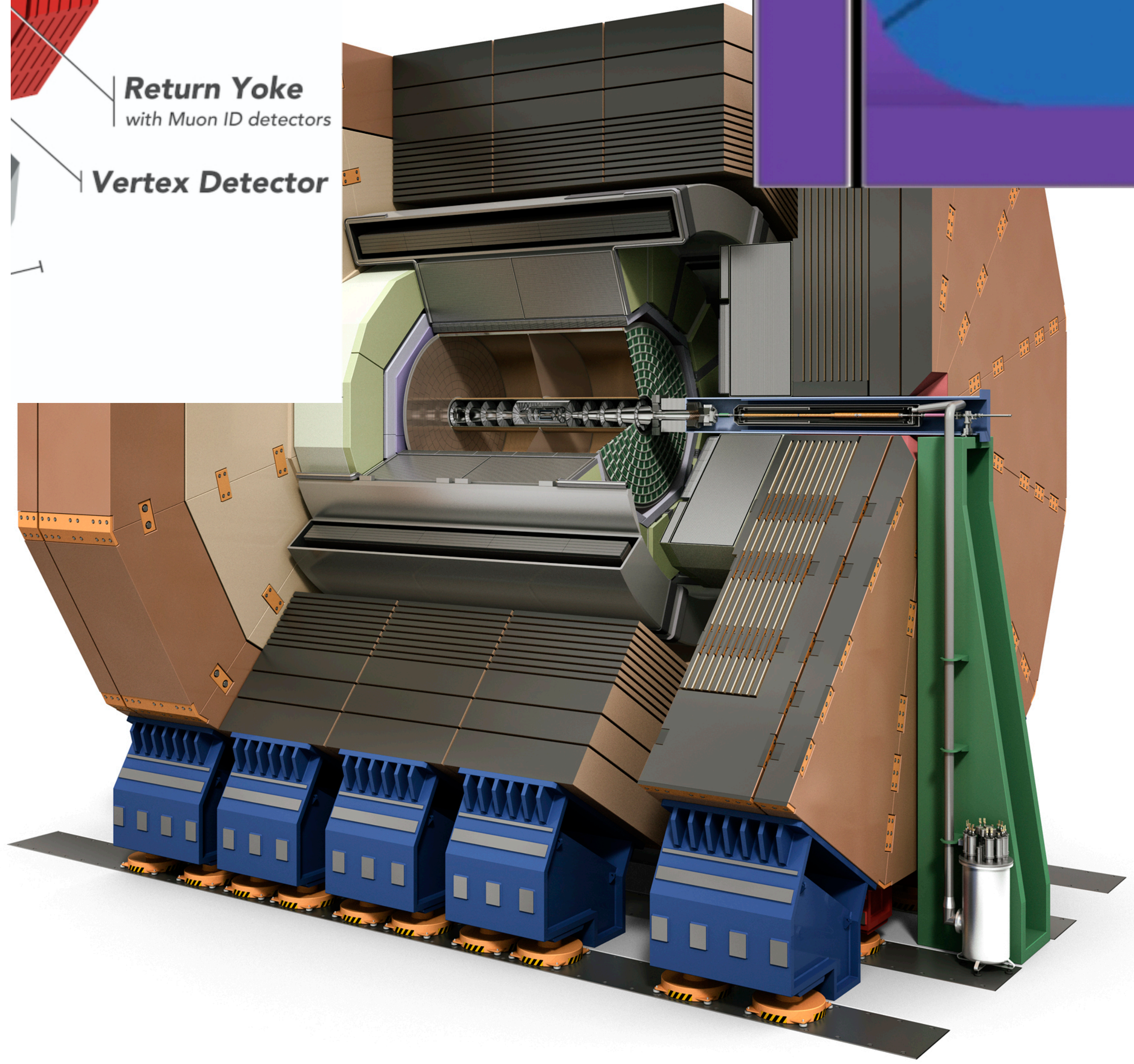

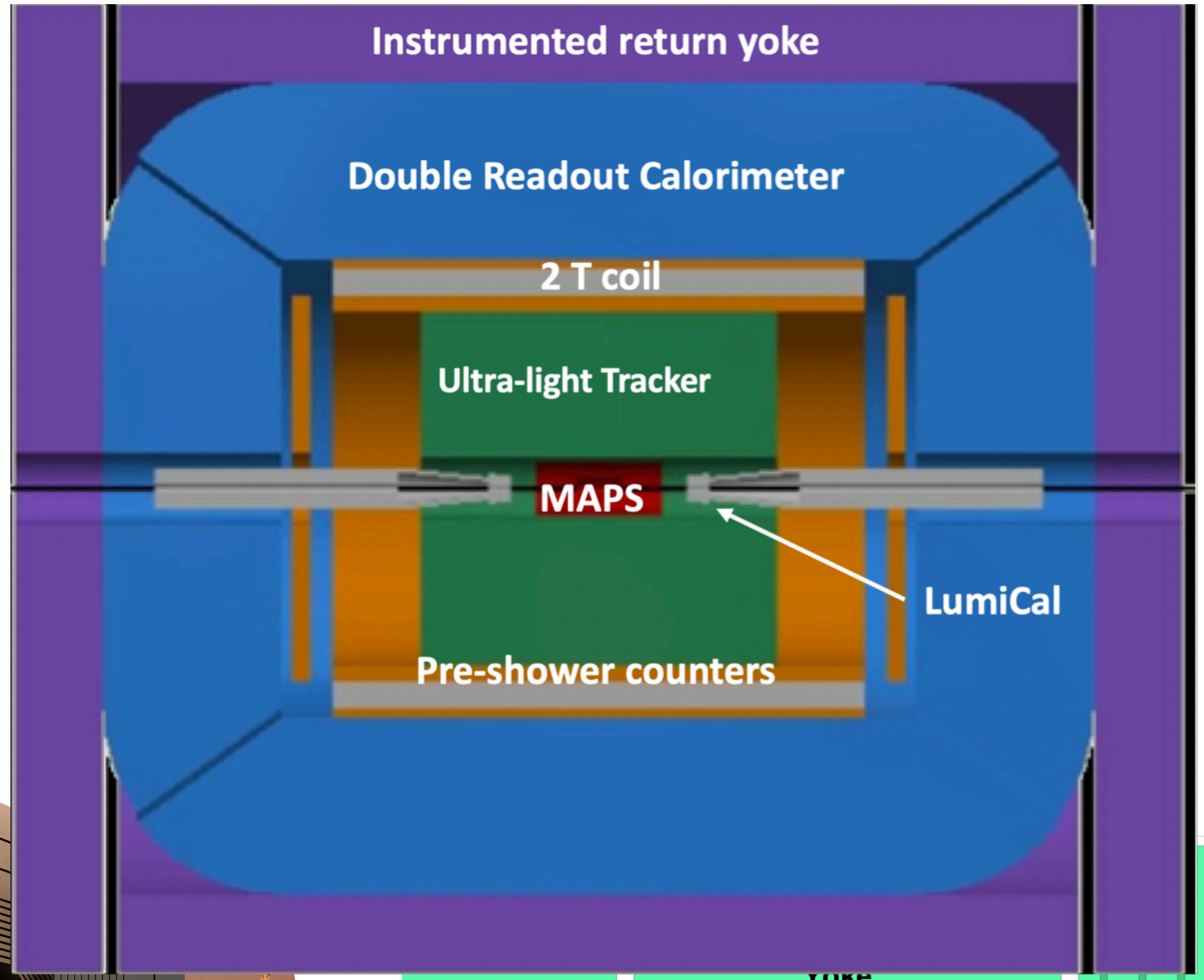

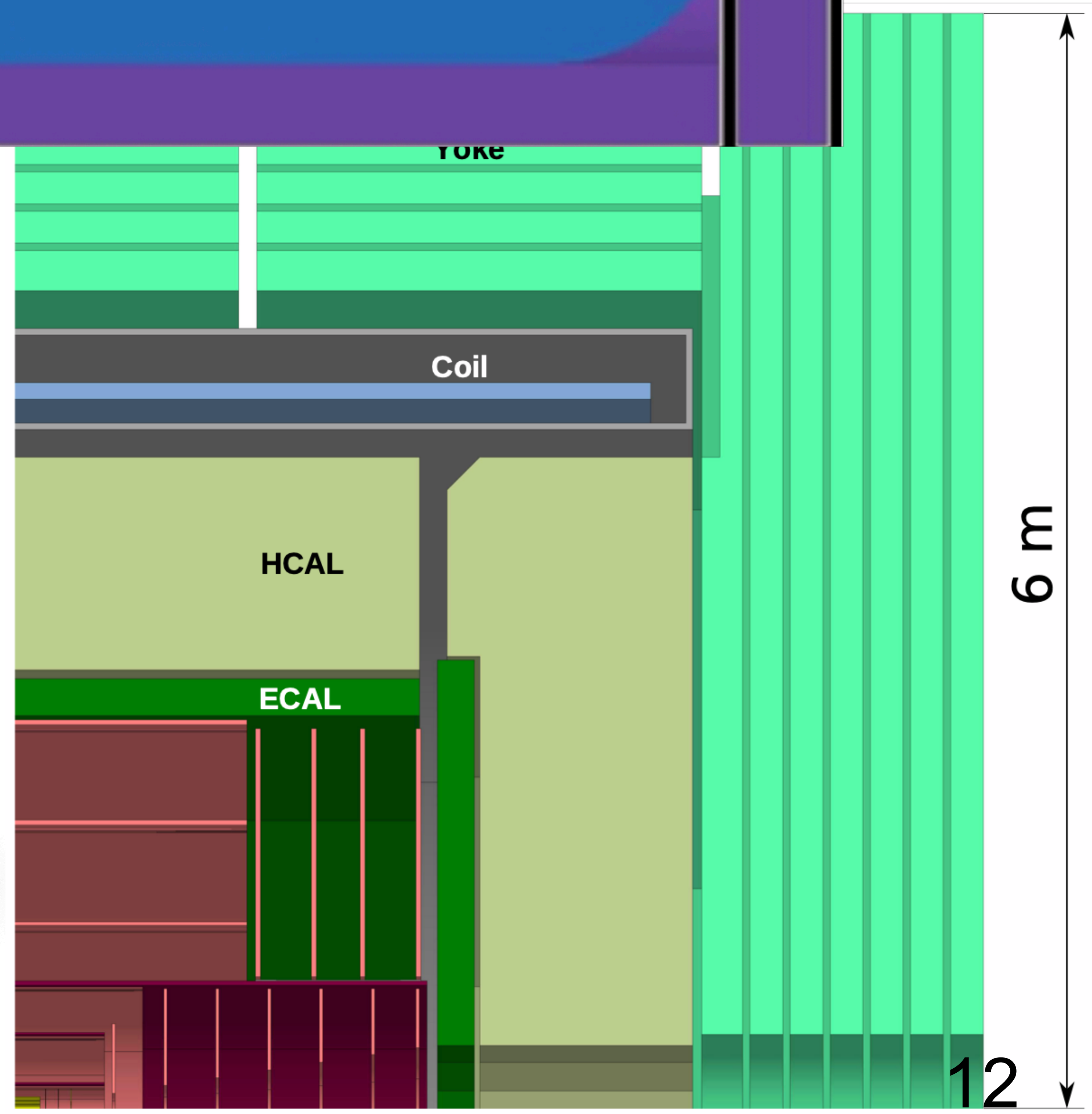

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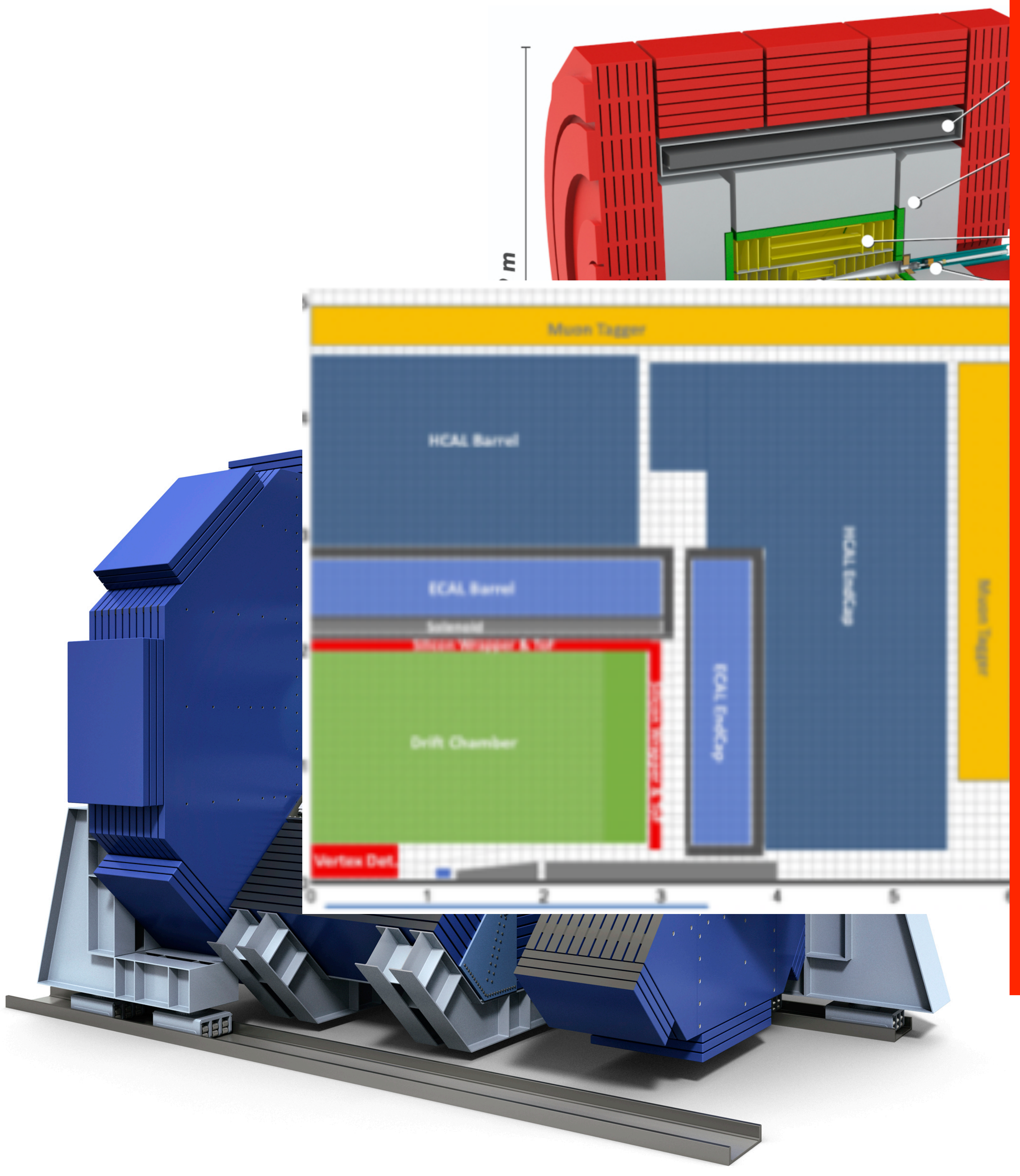

Key requirements from Higgs physics:

- **p_t resolution** (total ZH x-section)

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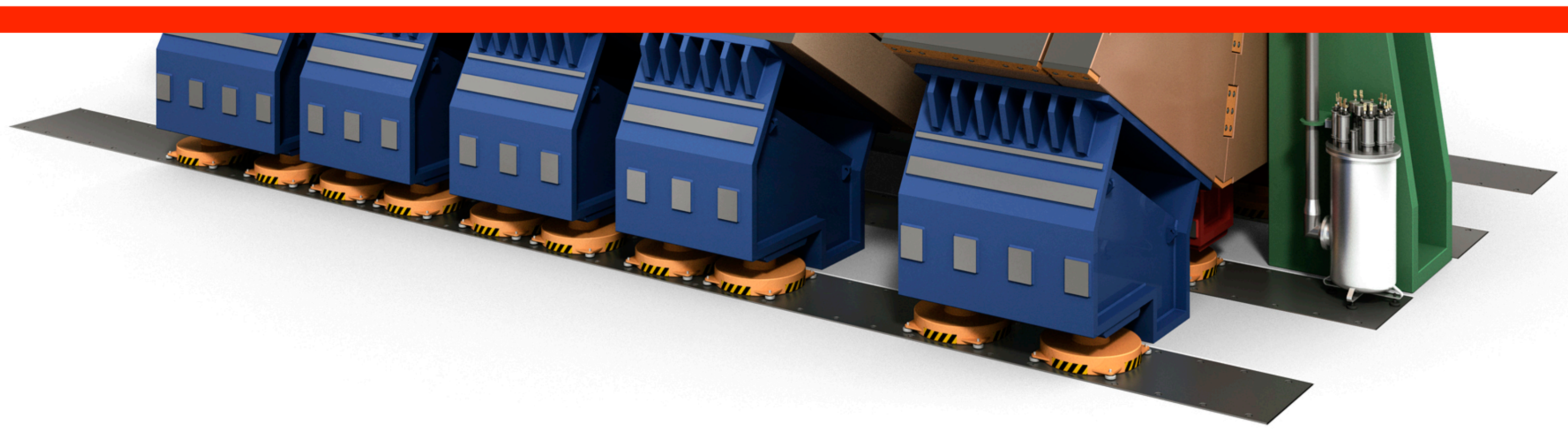
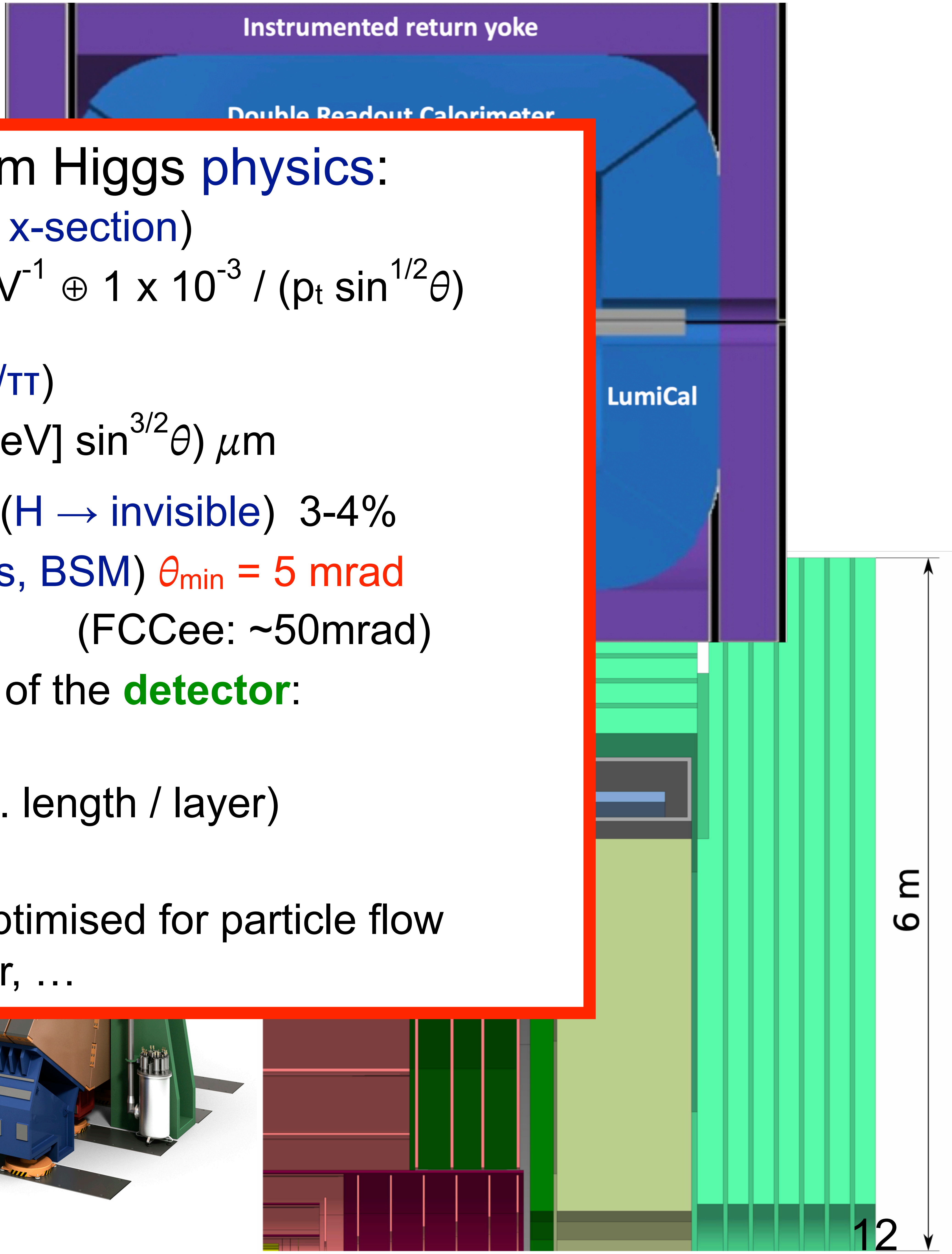
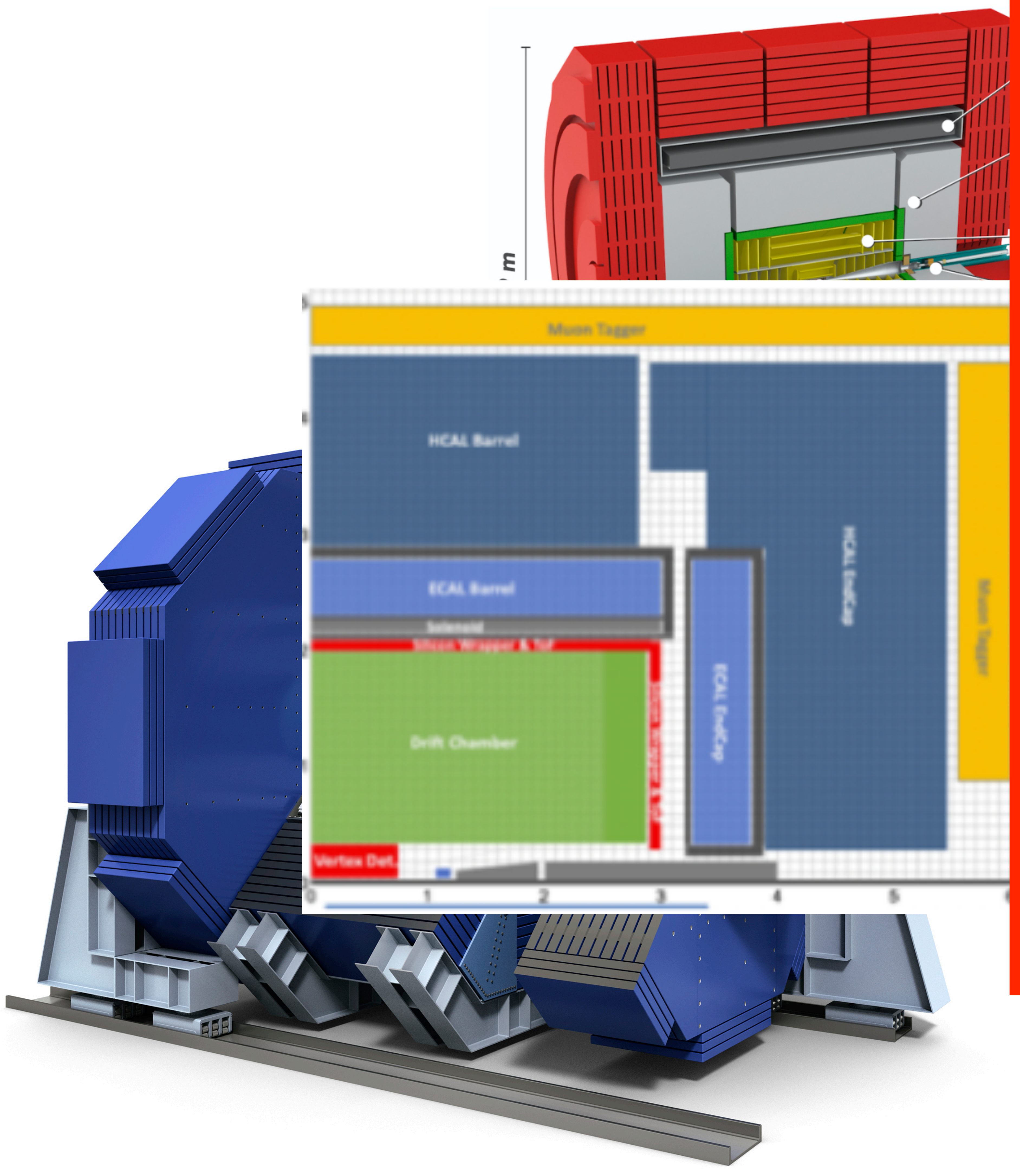
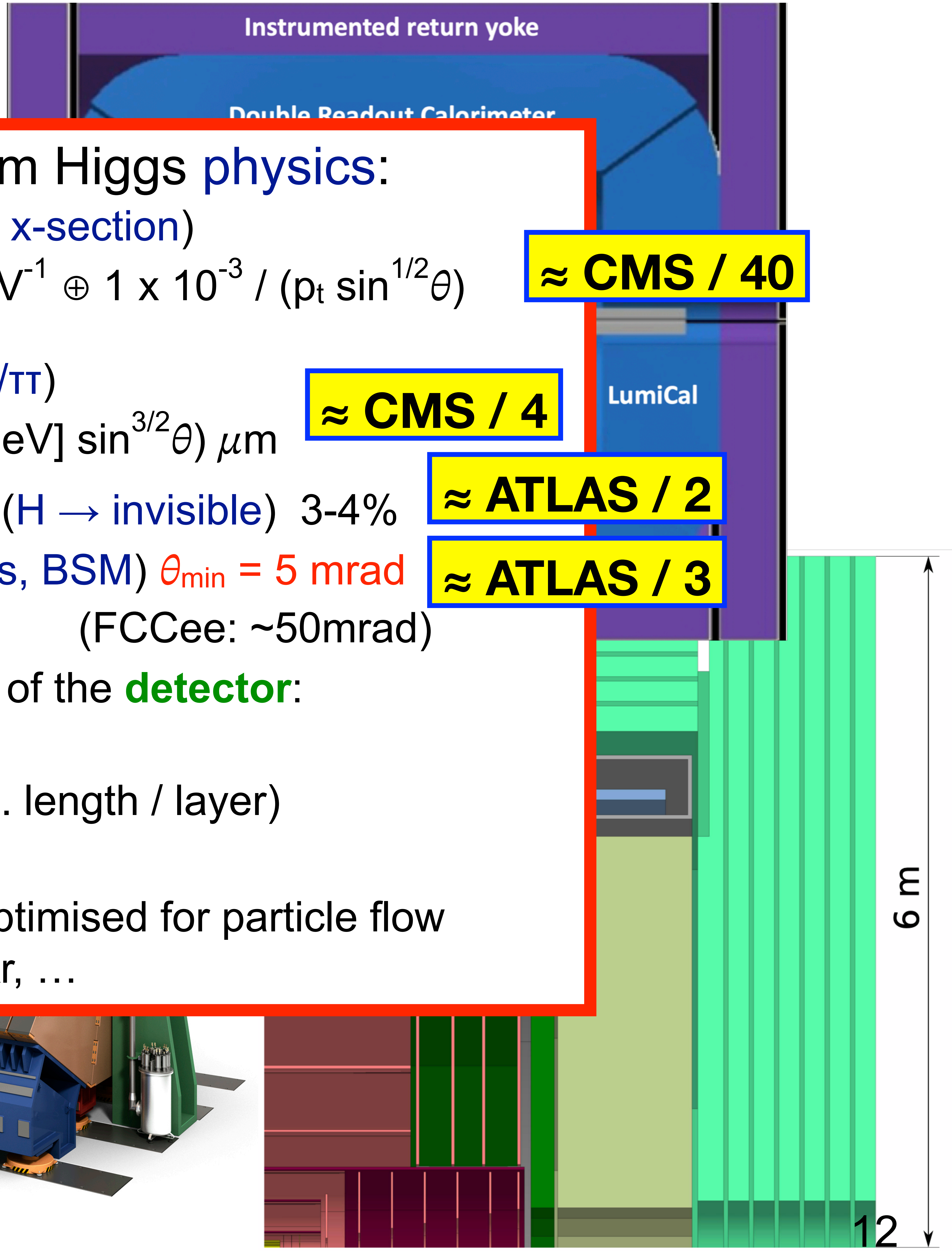




Higgs Factory Detector Concepts

for linear & circular





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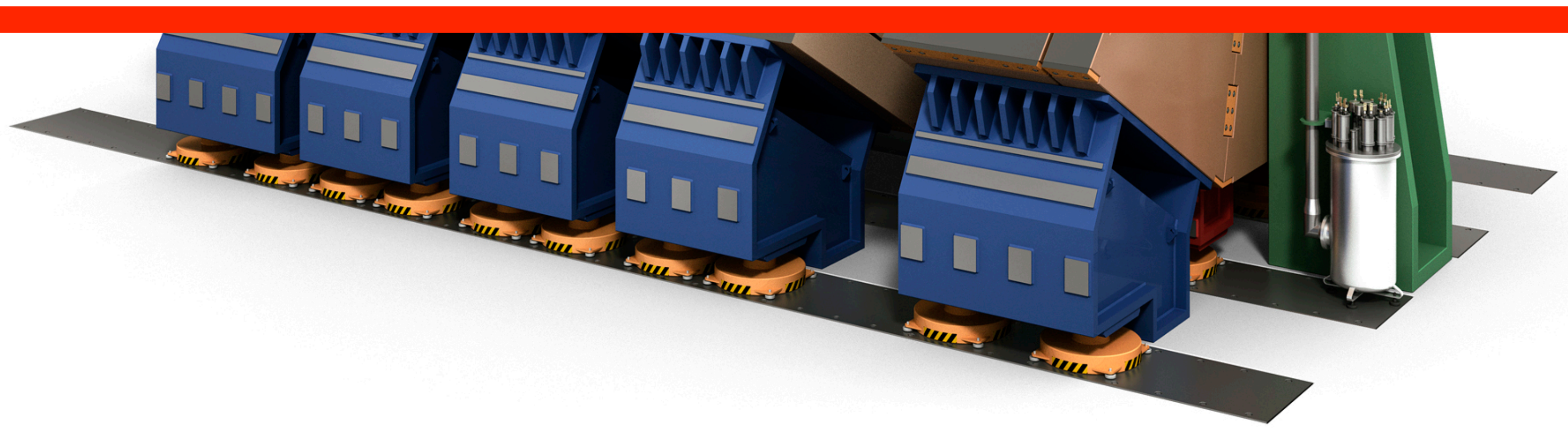

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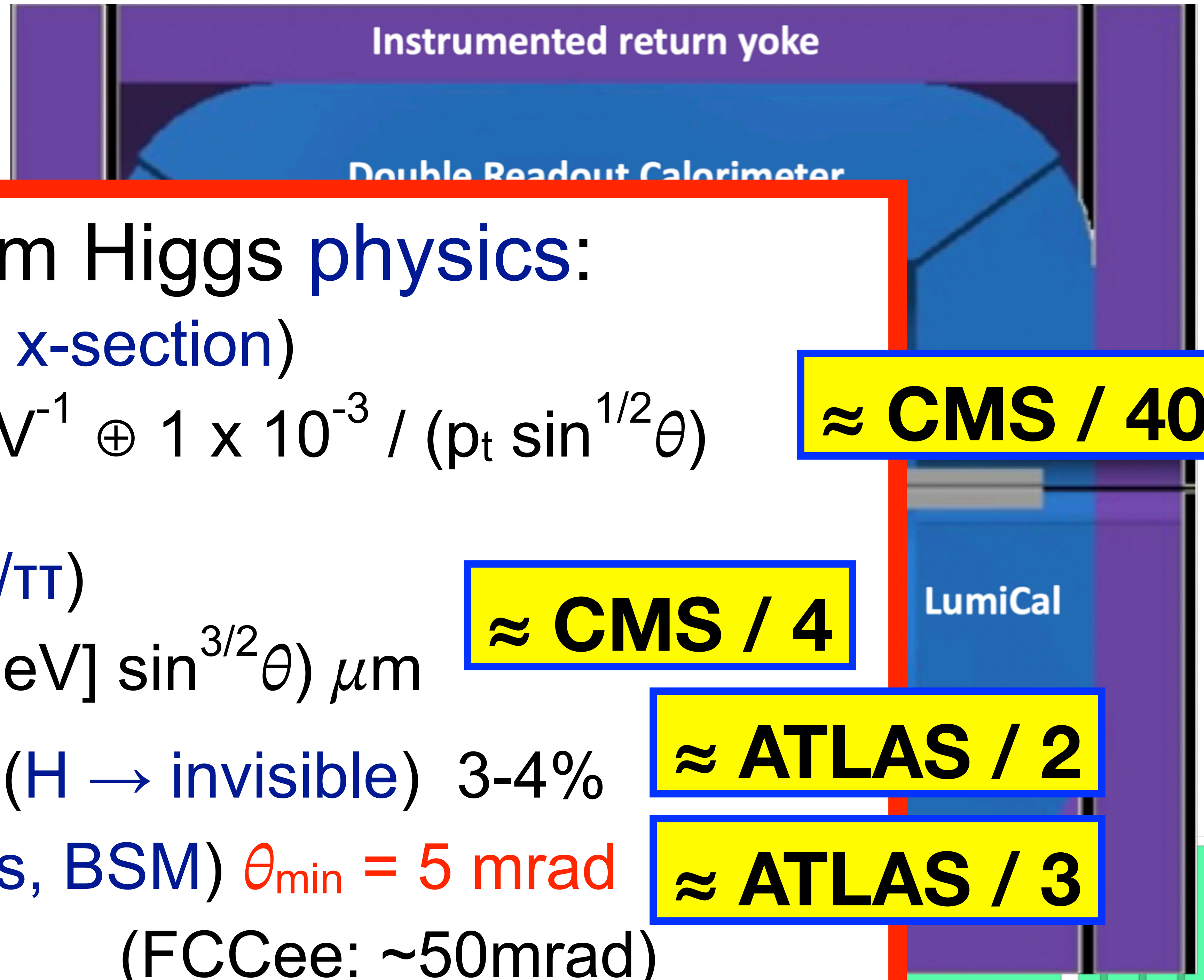

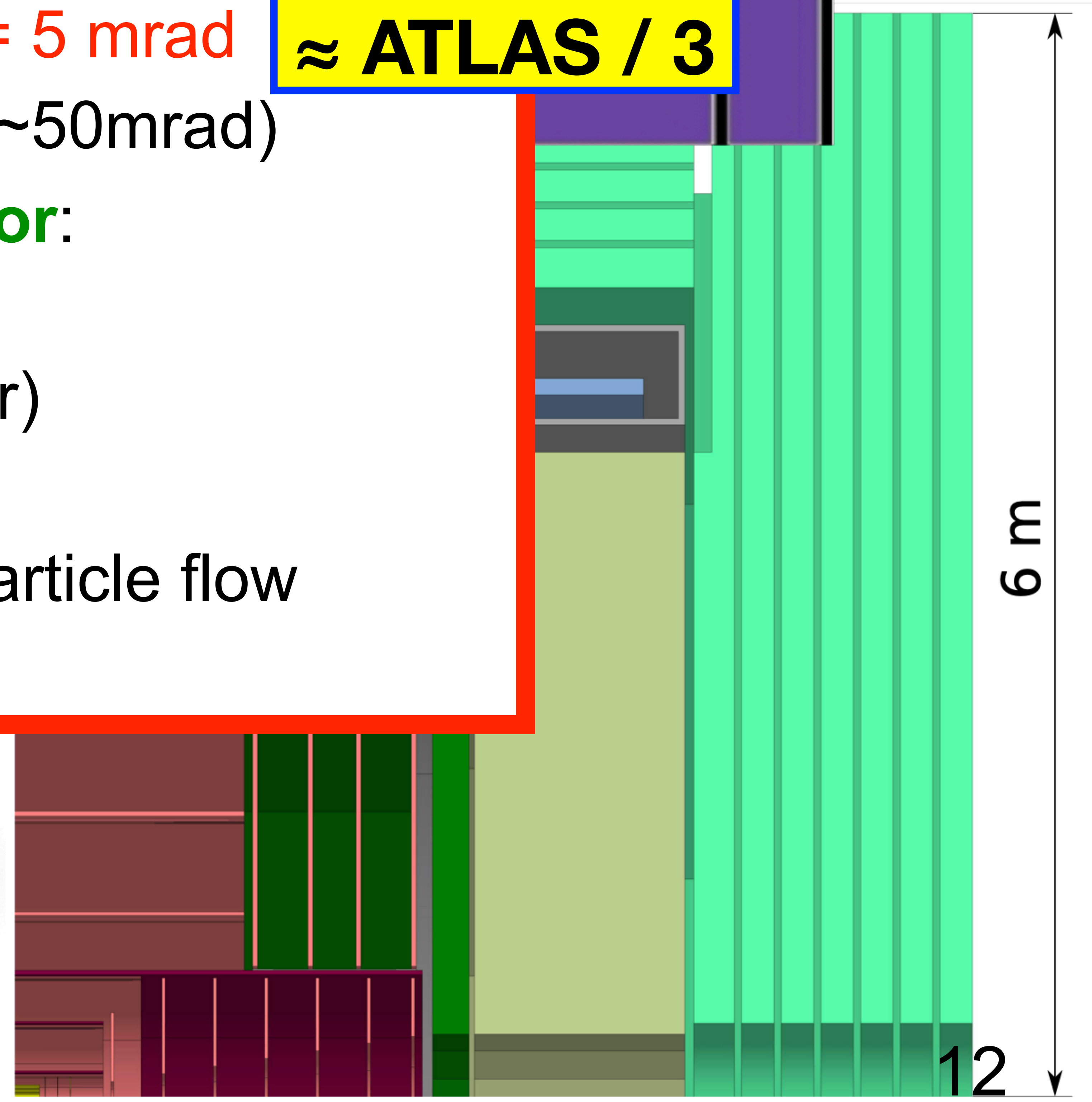

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Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

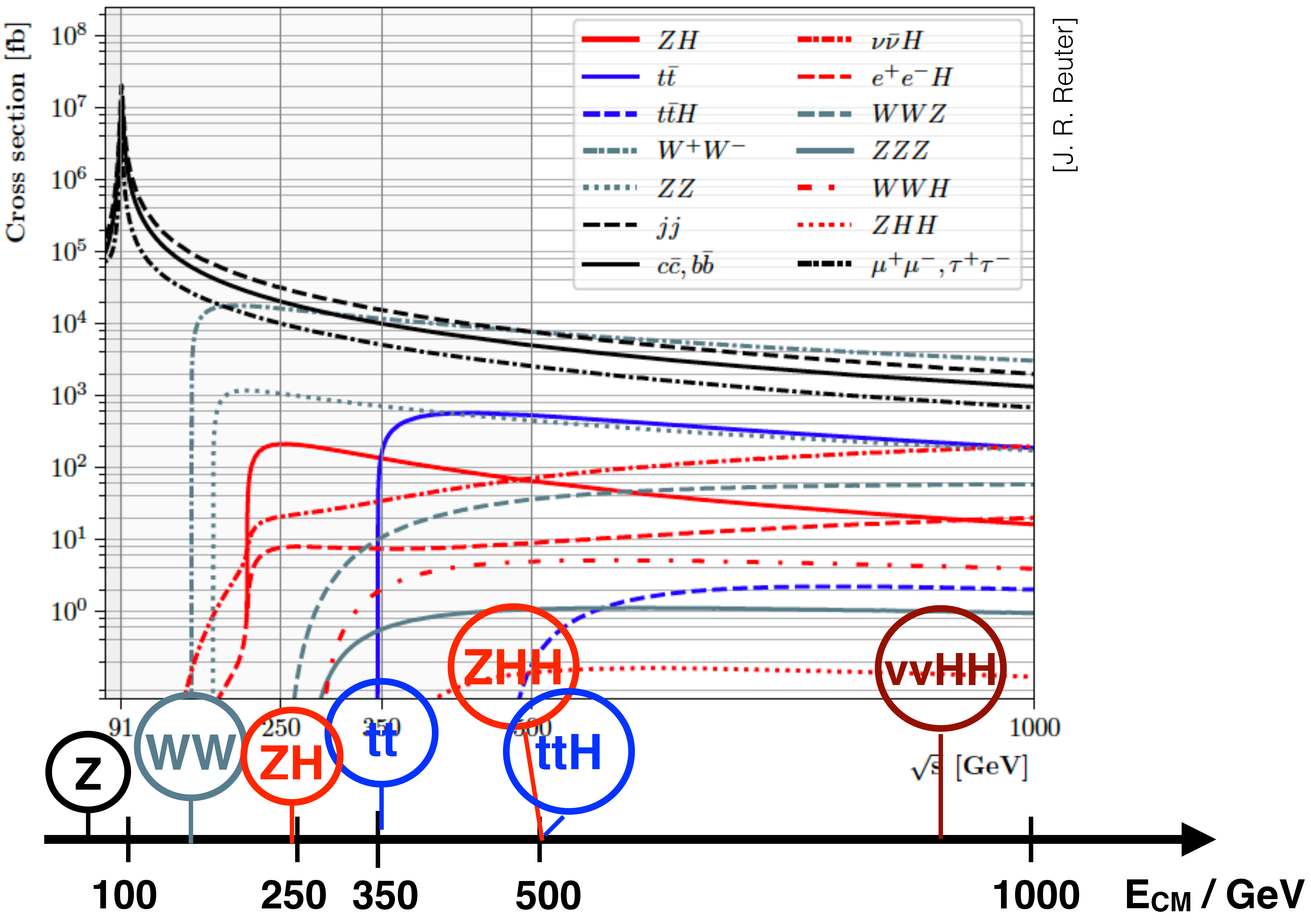
only Linear Colliders: lower collision rate enables

- **passive cooling only => low material budget**
- **triggerless operation**

The basic
Higgs Factory program

The key physics at a Higgs Factory

Production rates vs collision energy



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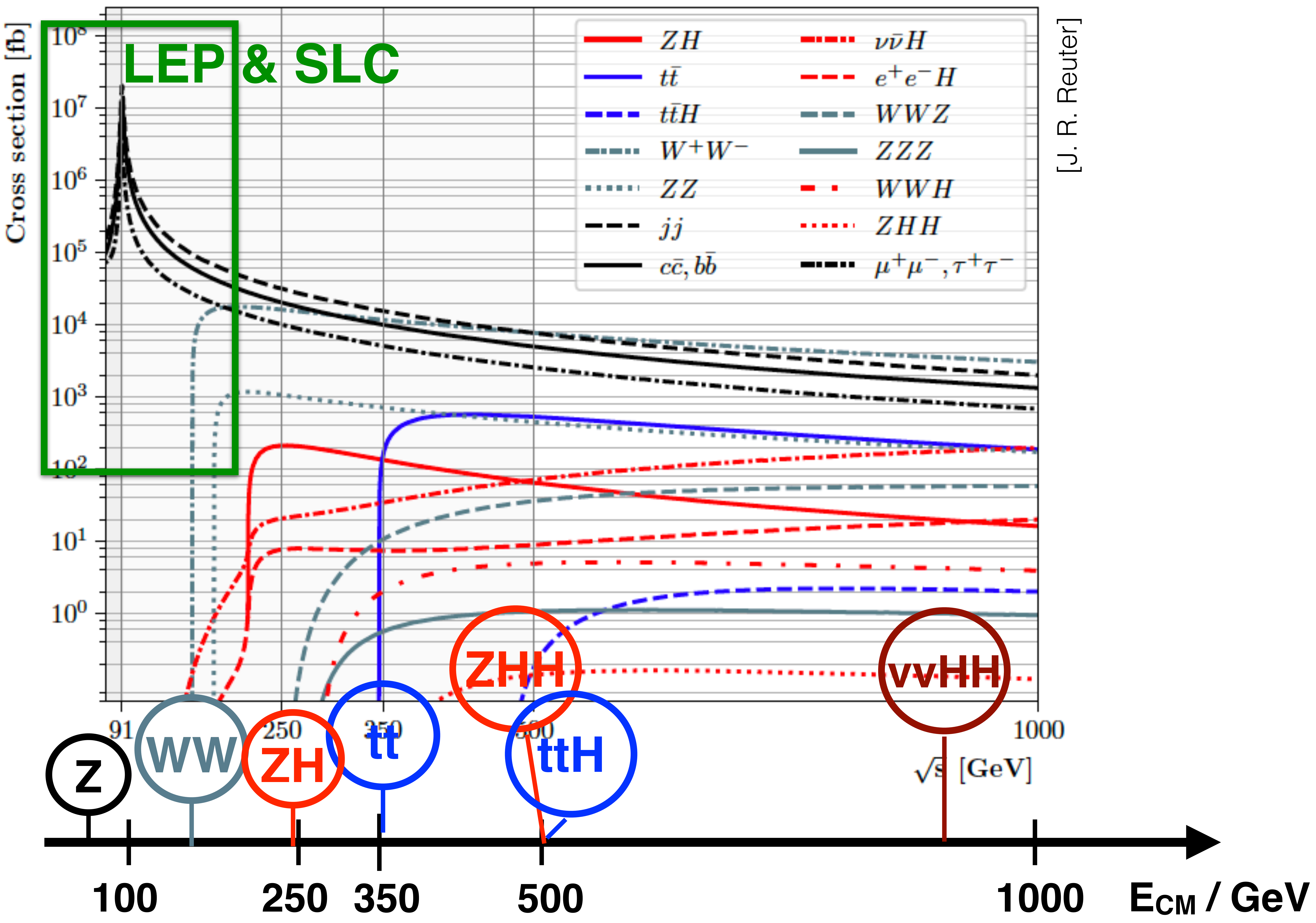

The key physics at a Higgs Factory

Production rates vs collision energy

considered
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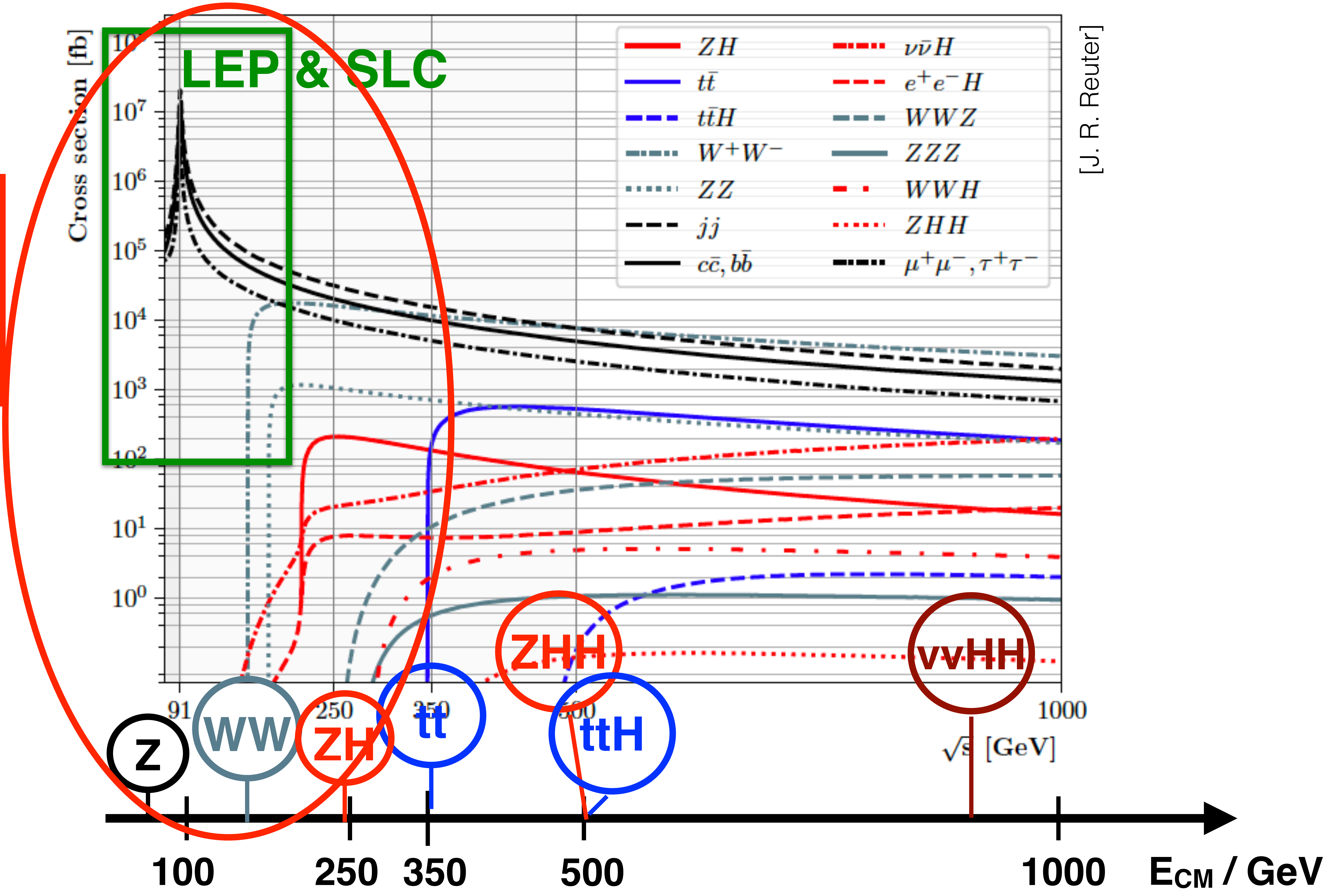

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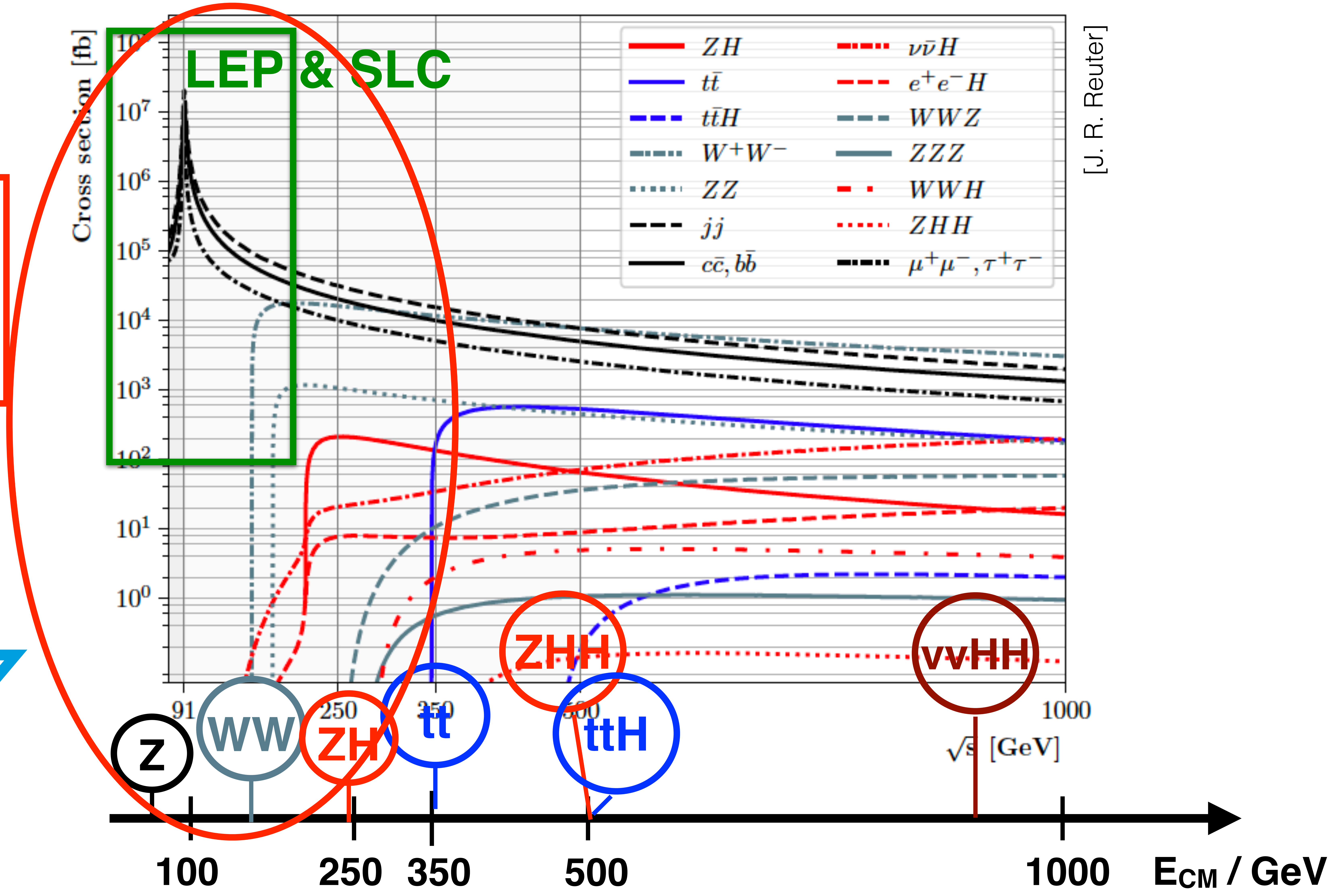
Circular Colliders



[J. R. Reuter]

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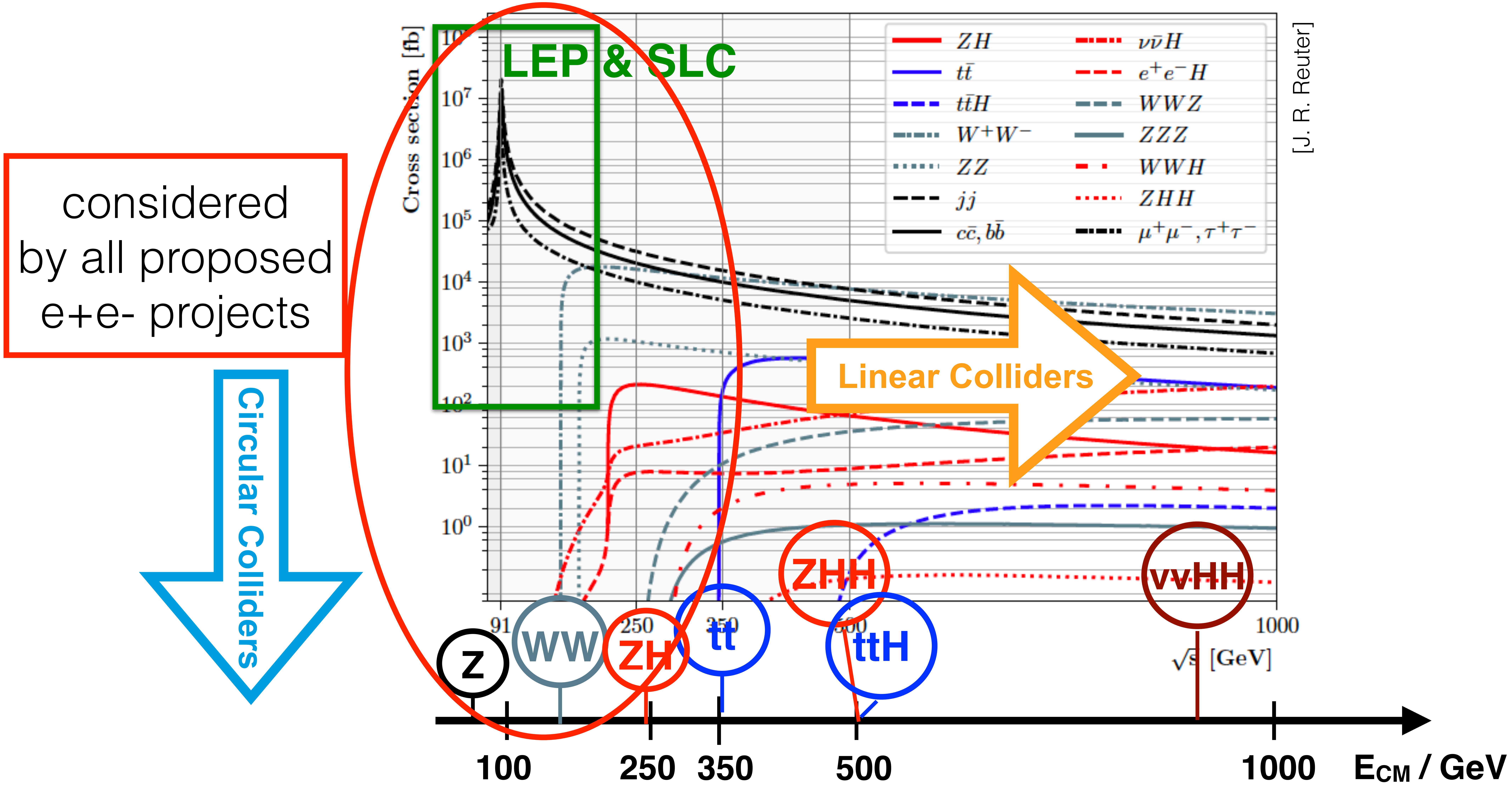

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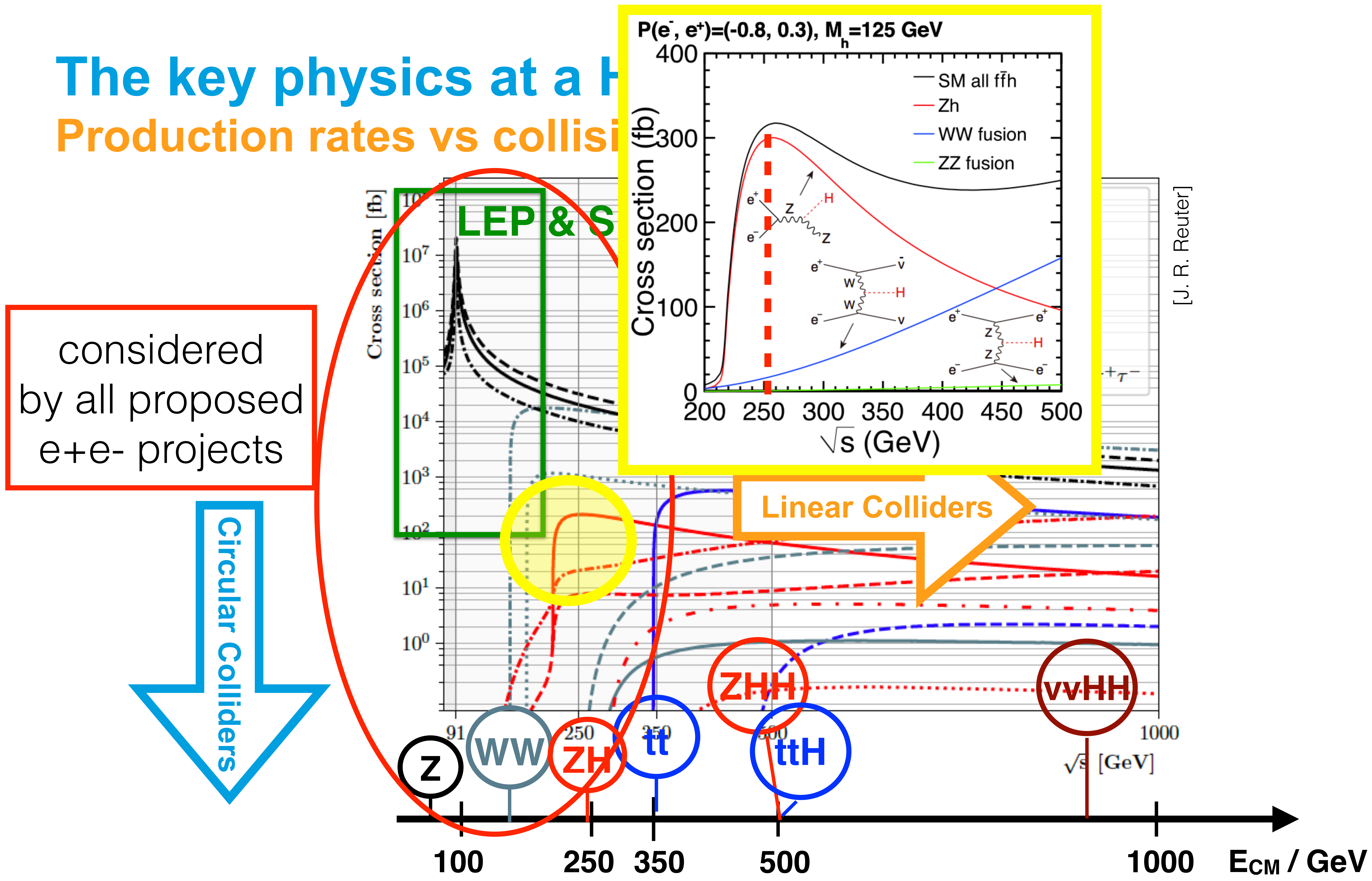

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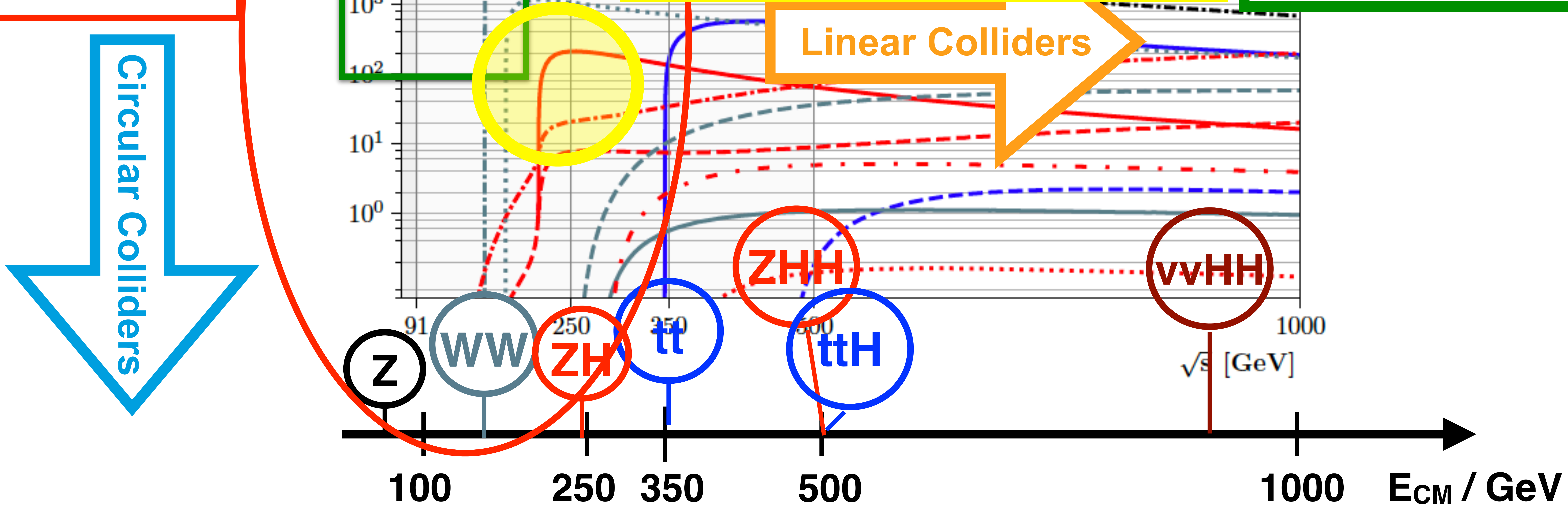

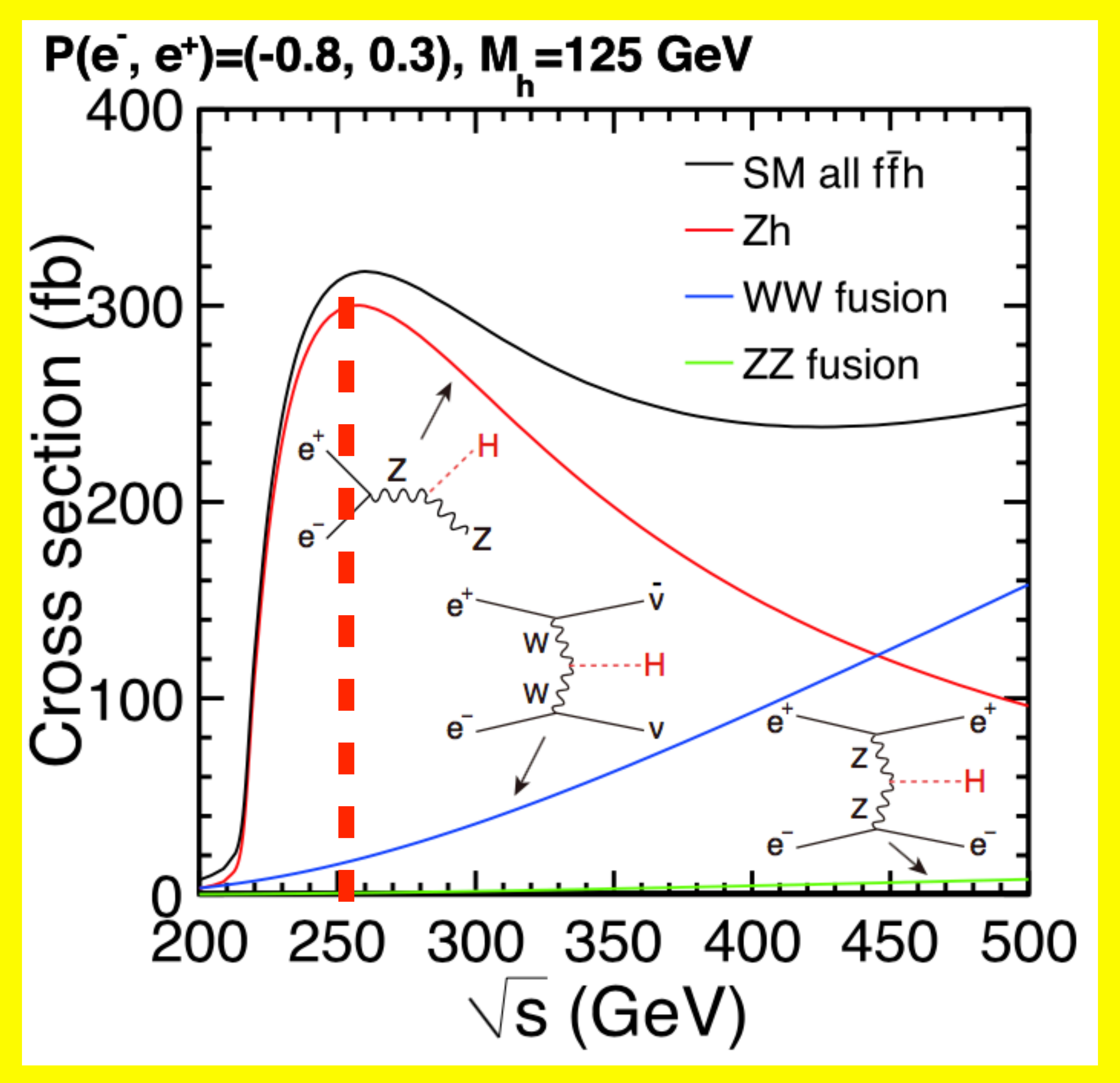

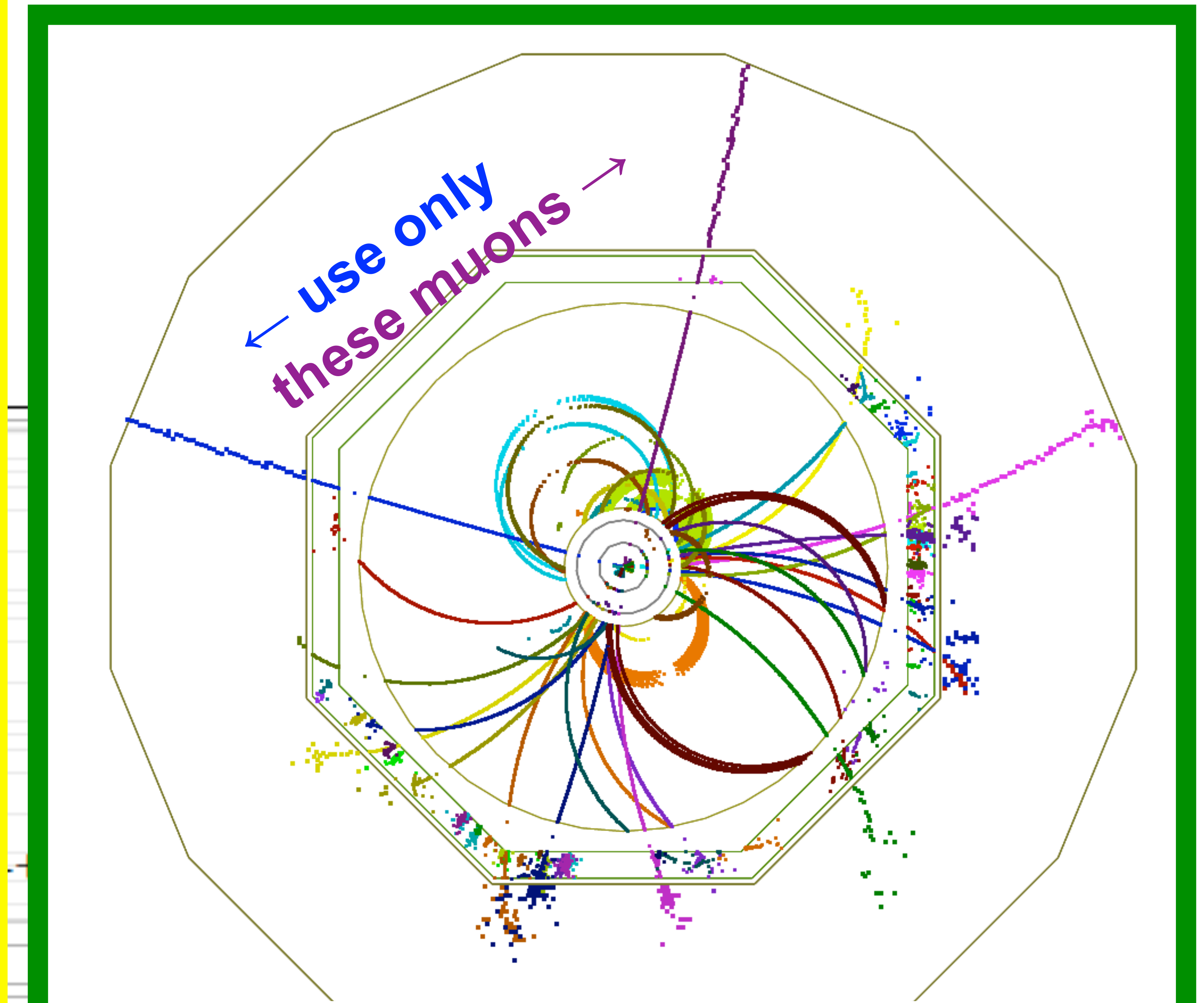

$e^+e^- \rightarrow \mu^+\mu^- H \rightarrow \mu^+\mu^-$ bb in ILD

The key physics at a H

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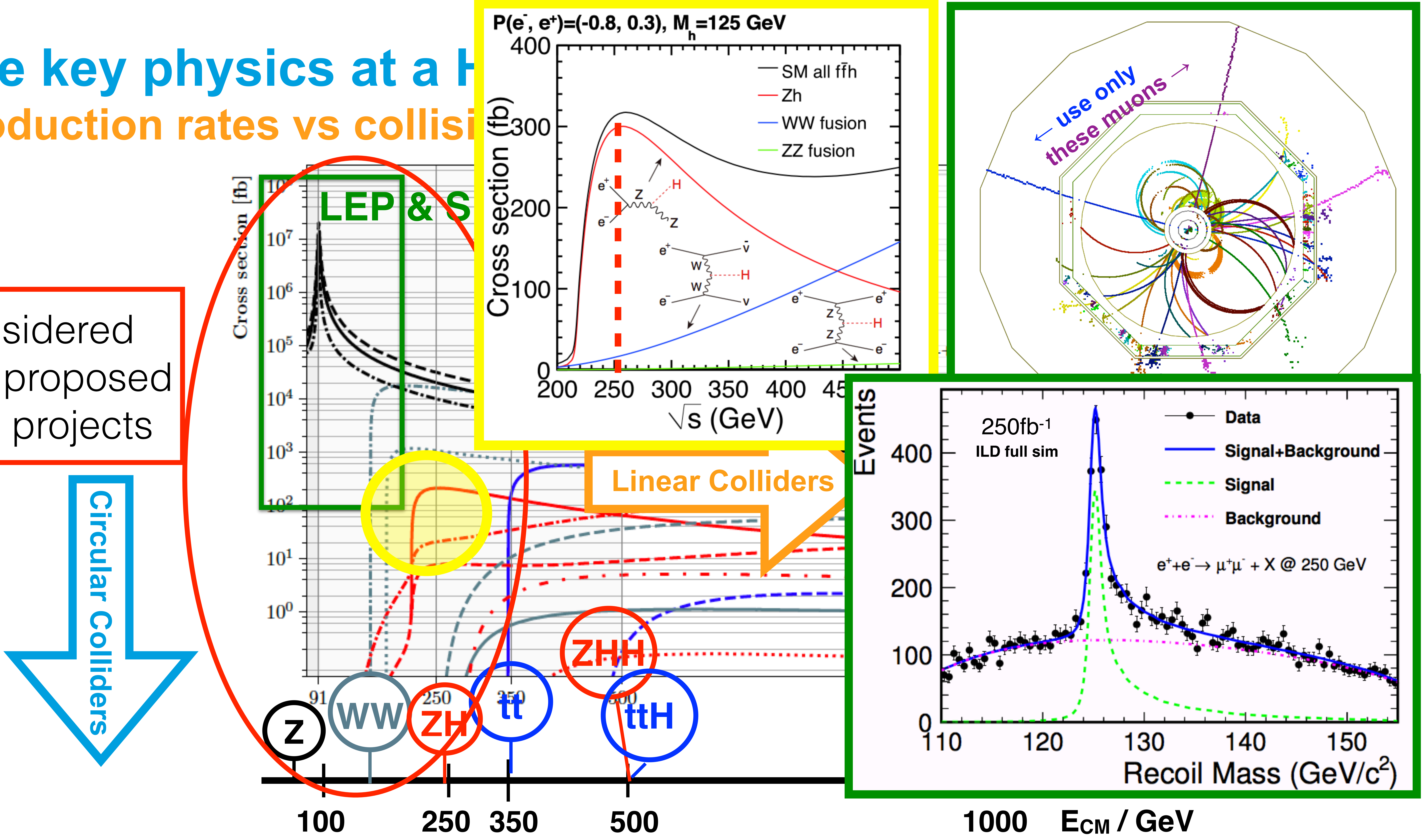

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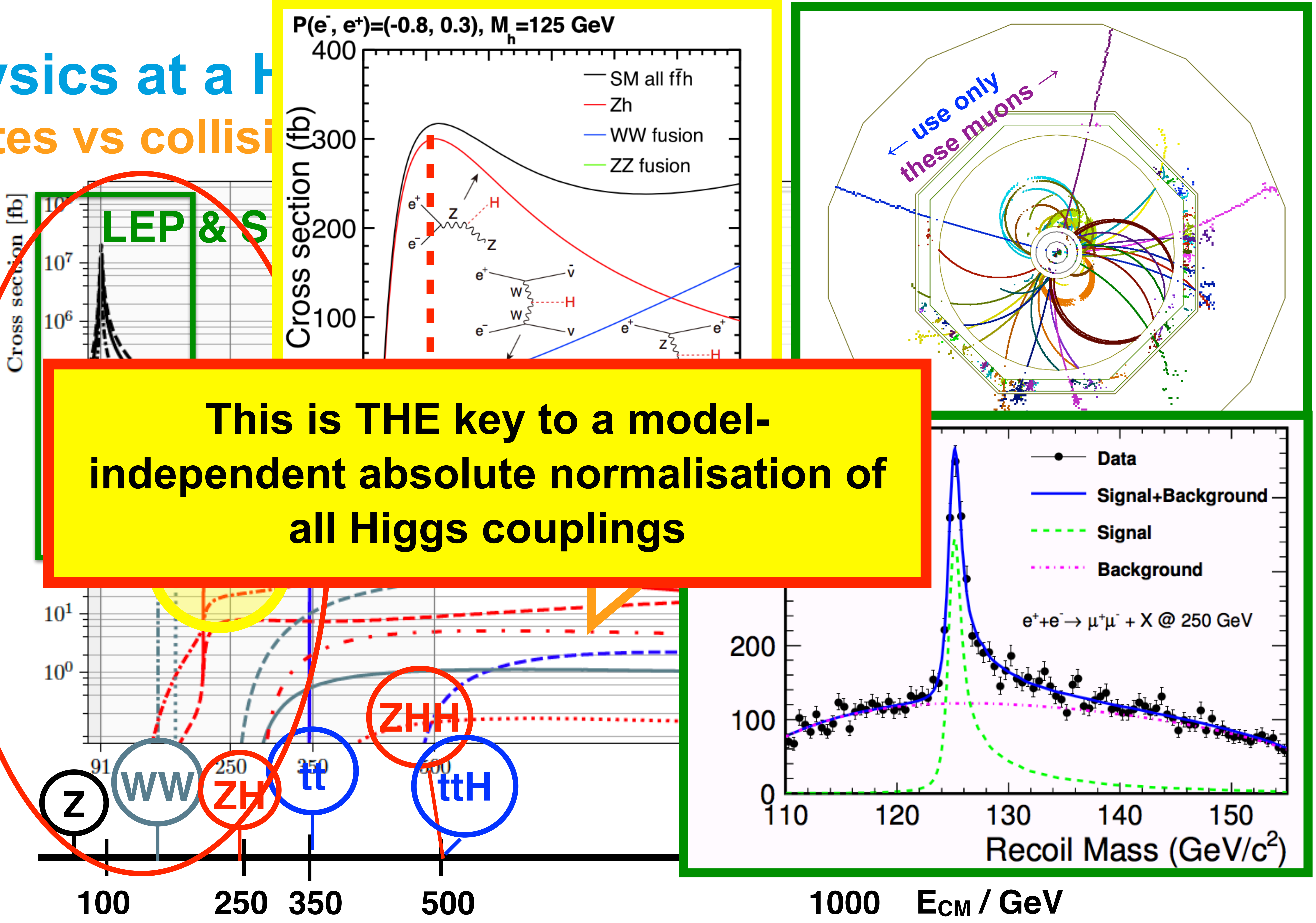
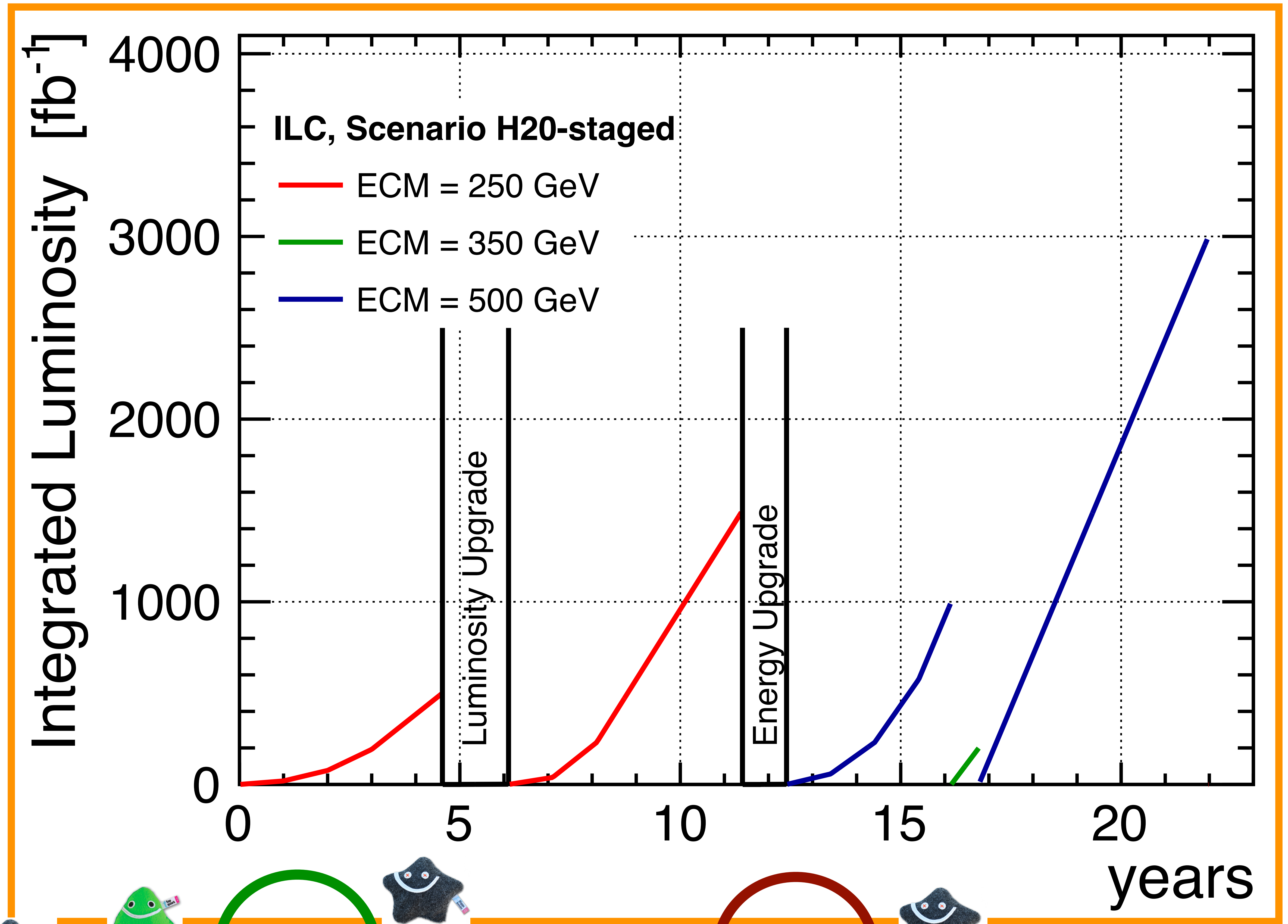


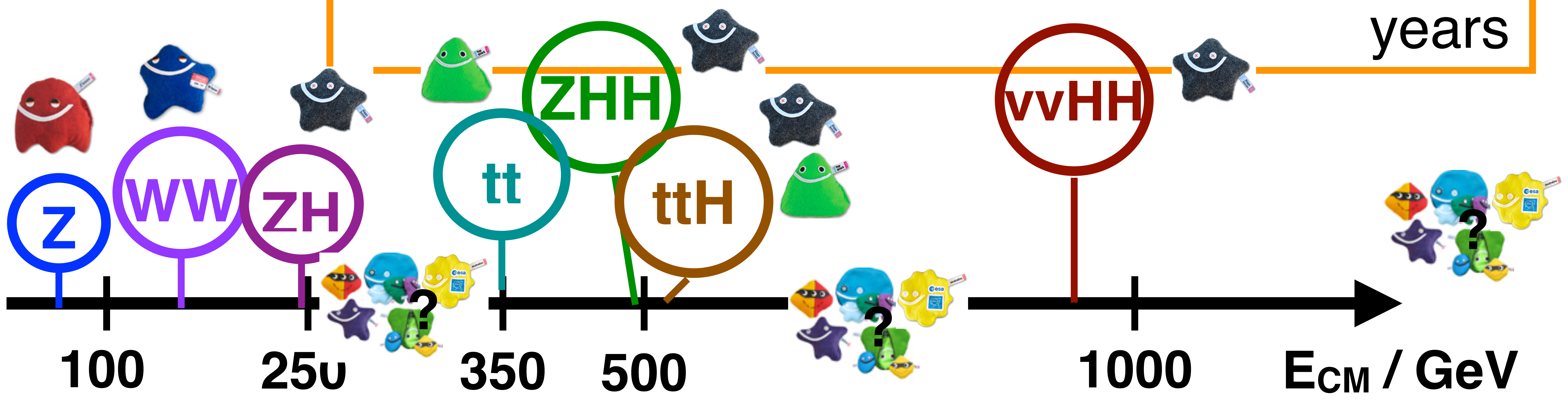
This is THE key to a model-independent absolute normalisation of all Higgs couplings

A physics-driven operating scenario for a Linear Collider

All with at least P(e-) > 80%

- **250 GeV, 2ab-1:**
  - precision Higgs mass and total ZH cross-section
  - basic ffbar and WW program
  - incl Z pole run with O(10^3)xLEP for EWPOs
  - optional: WW threshold scan
- **350 GeV, 200 fb-1:**
  - precision top mass from threshold scan
- **500…600 GeV, 4 ab-1:**
  - Higgs self-coupling in ZHH
  - top quark ew couplings
  - top Yukawa coupling incl CP structure
  - improved Higgs, WW and ffbar
- **1…1.5 TeV, 8ab-1:**
  - Higgs self-coupling in VBF
  - further improvements in tt, ff, WW, ….





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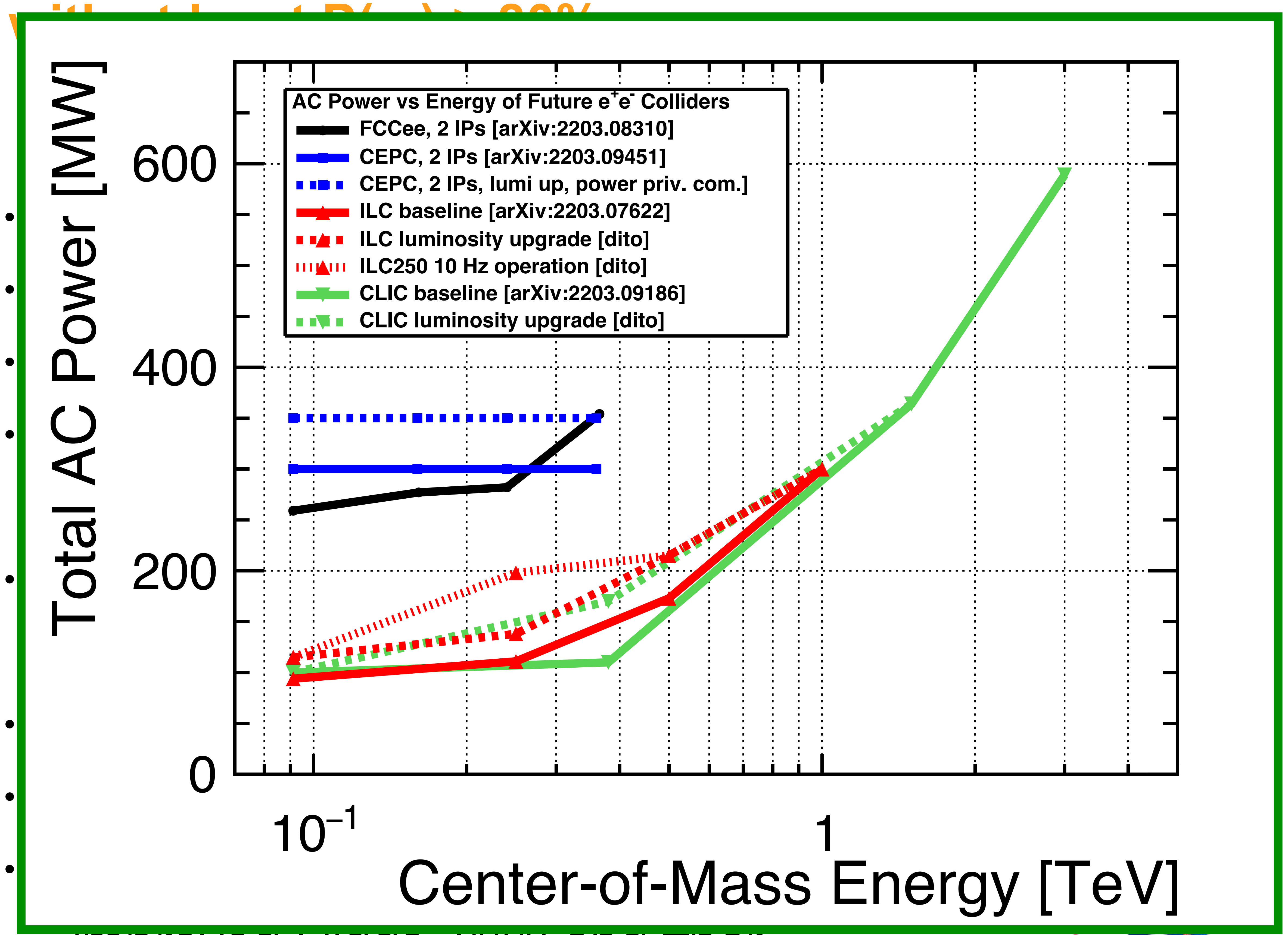

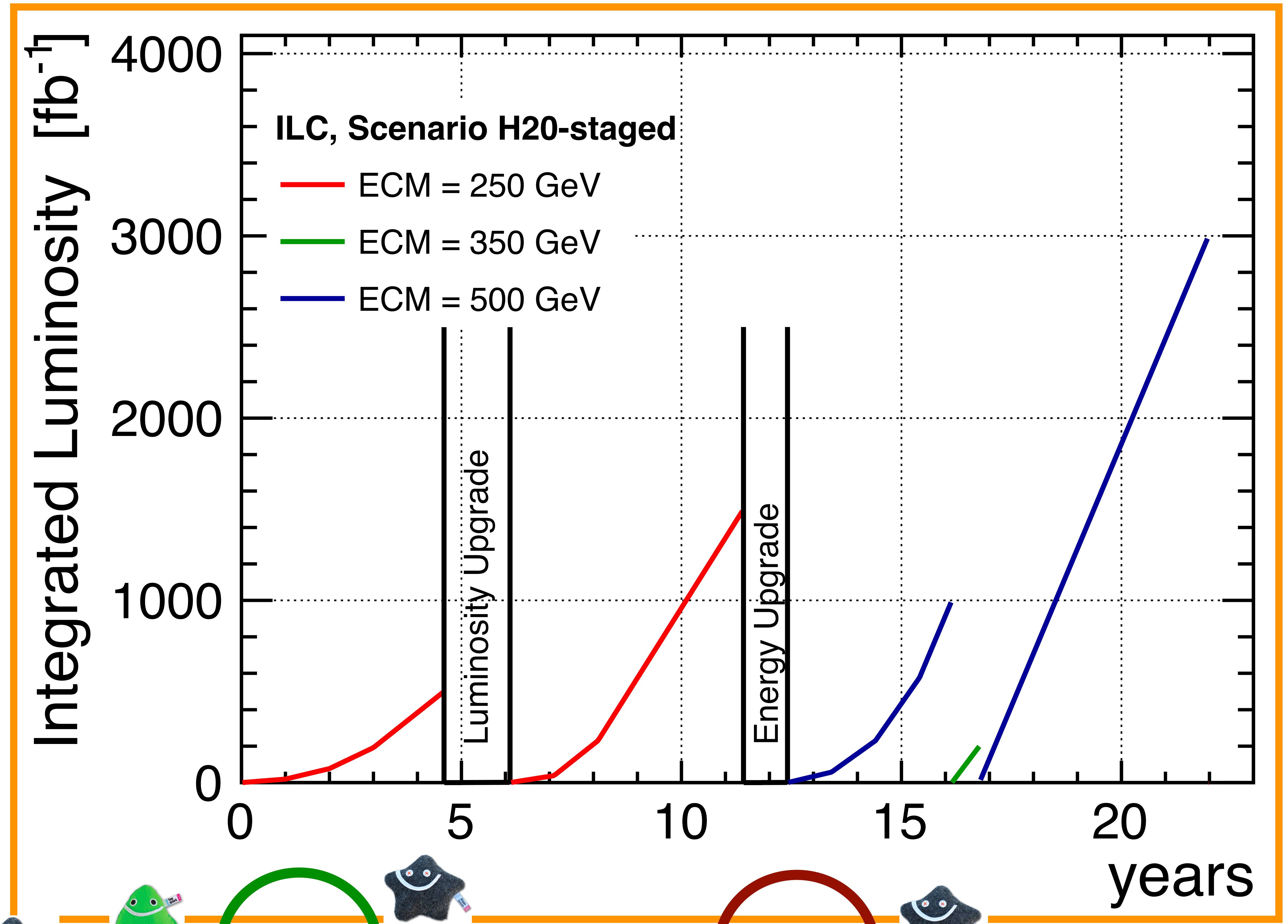

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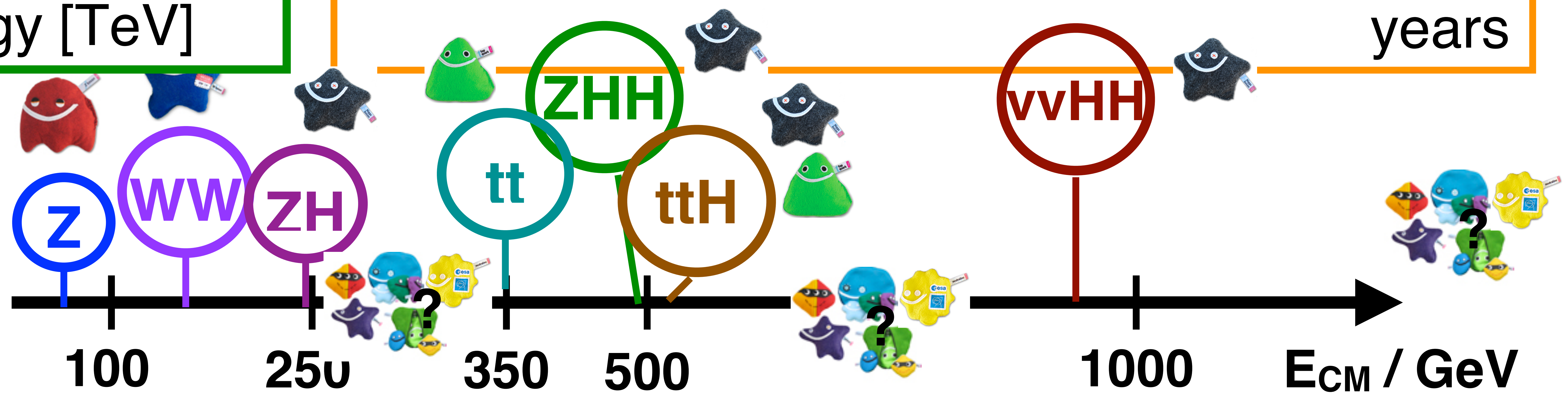

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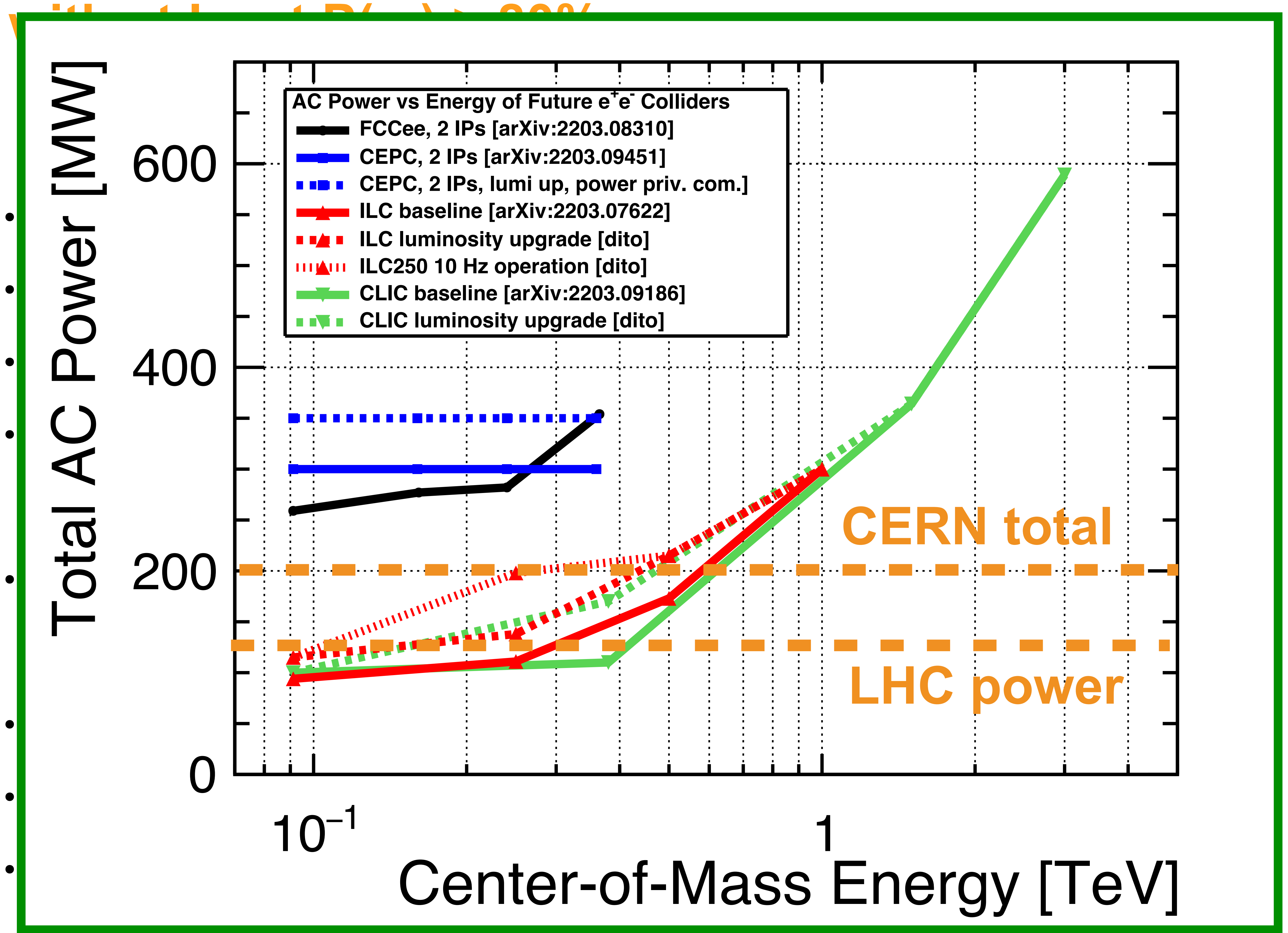

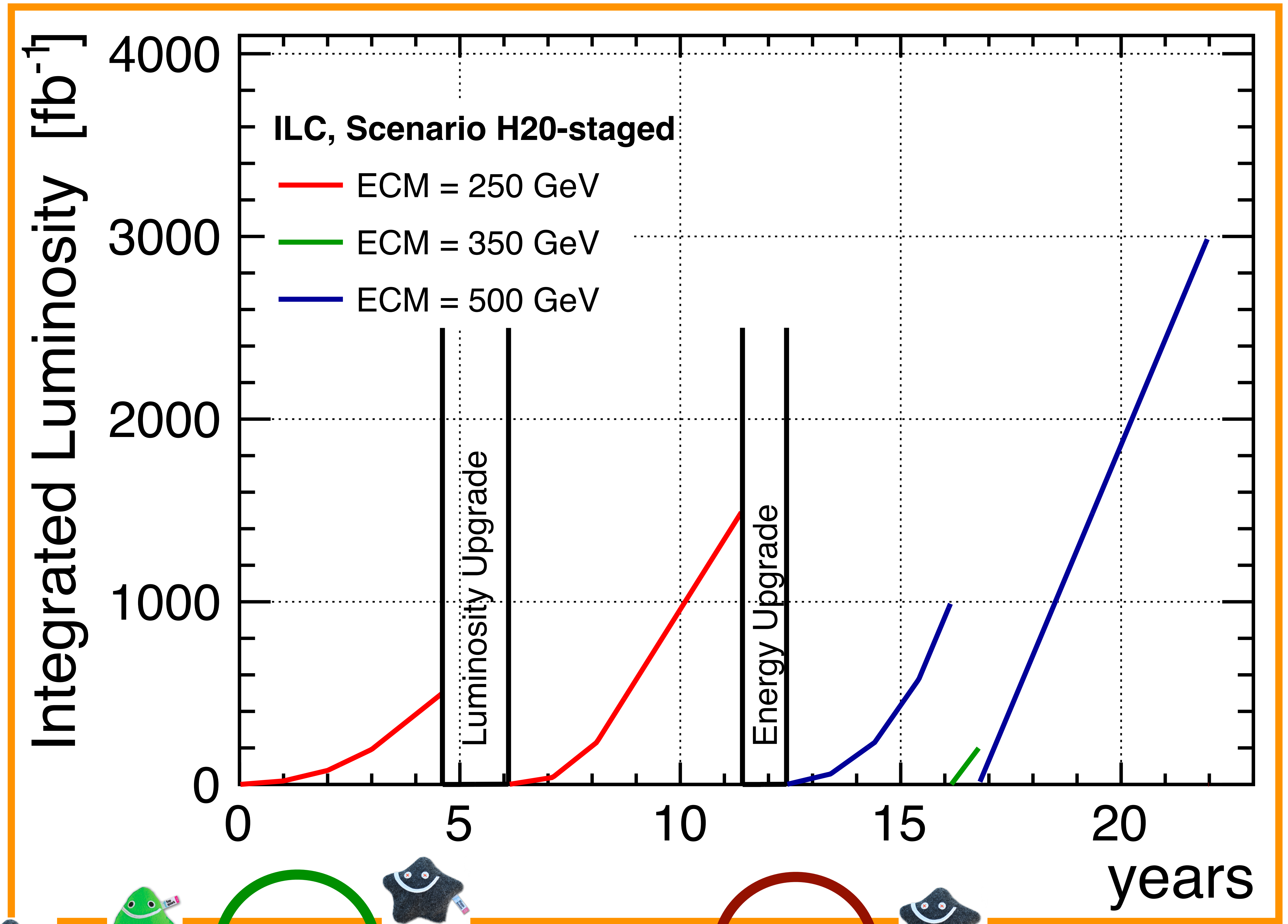

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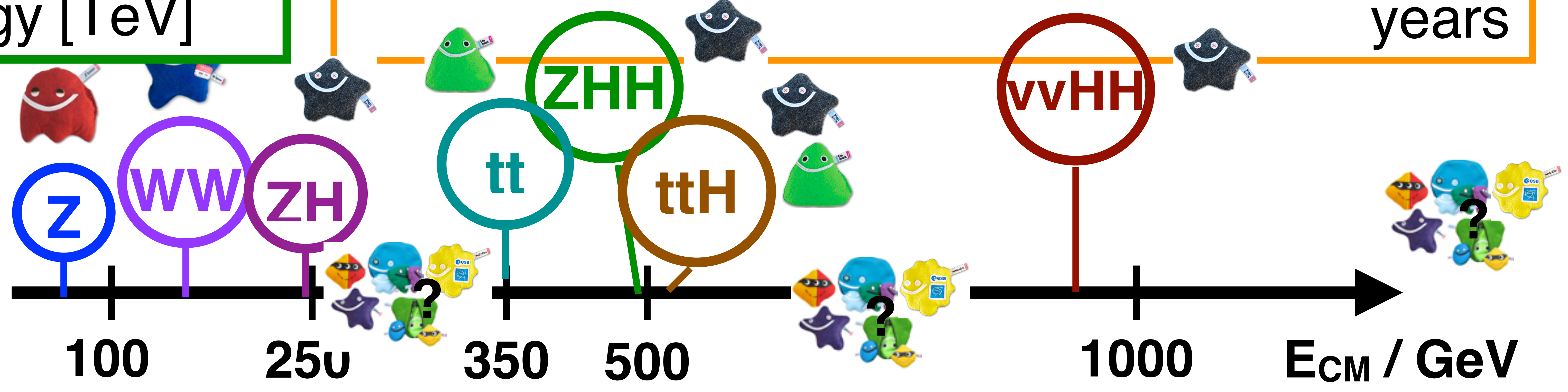
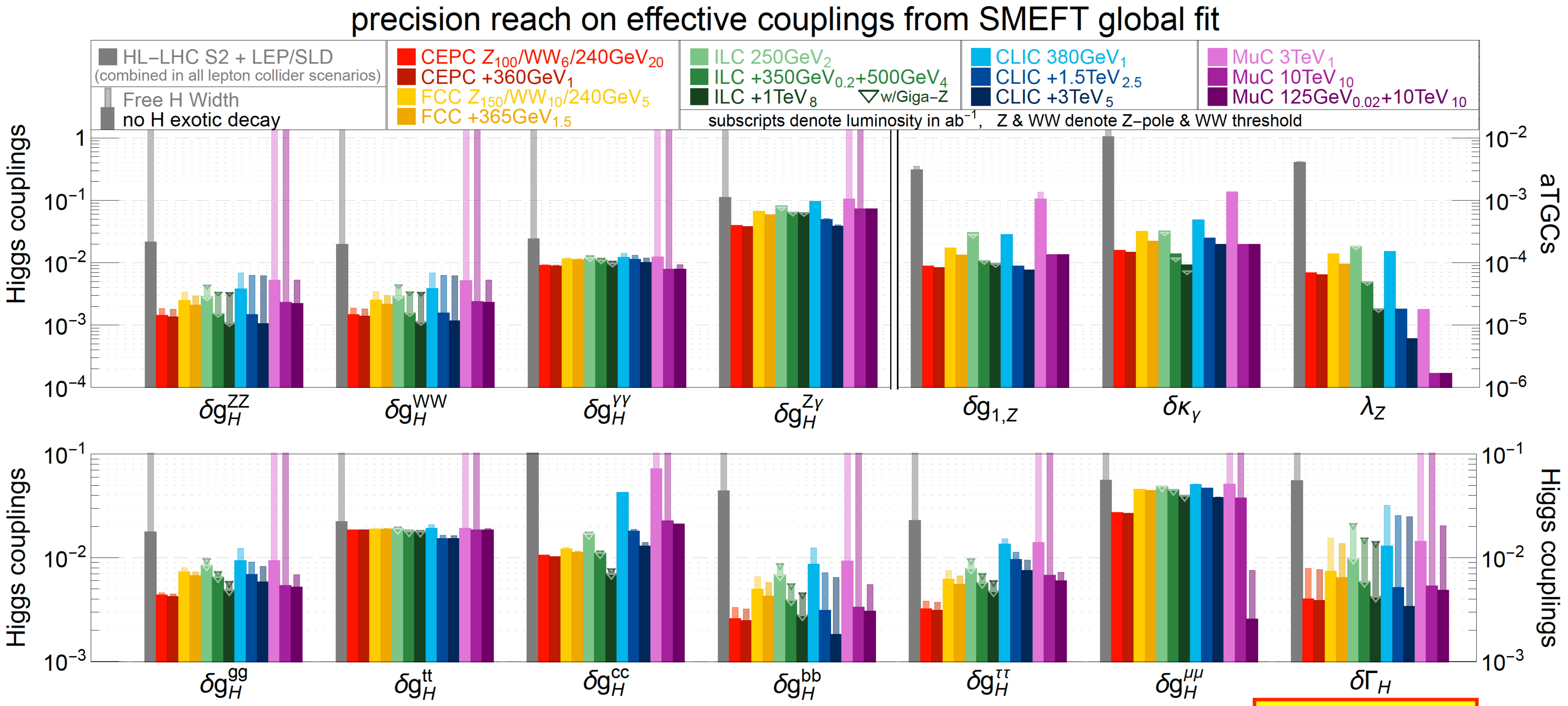


Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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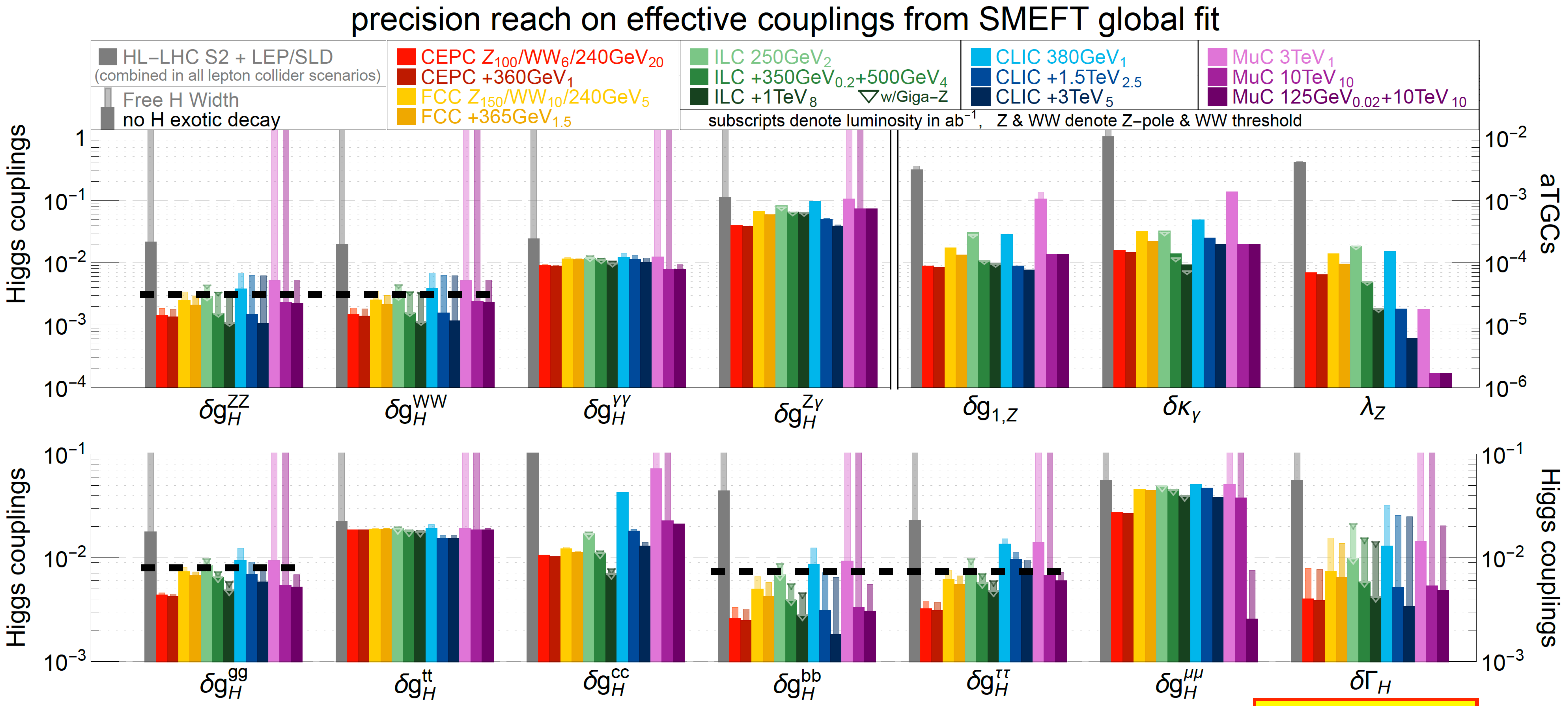

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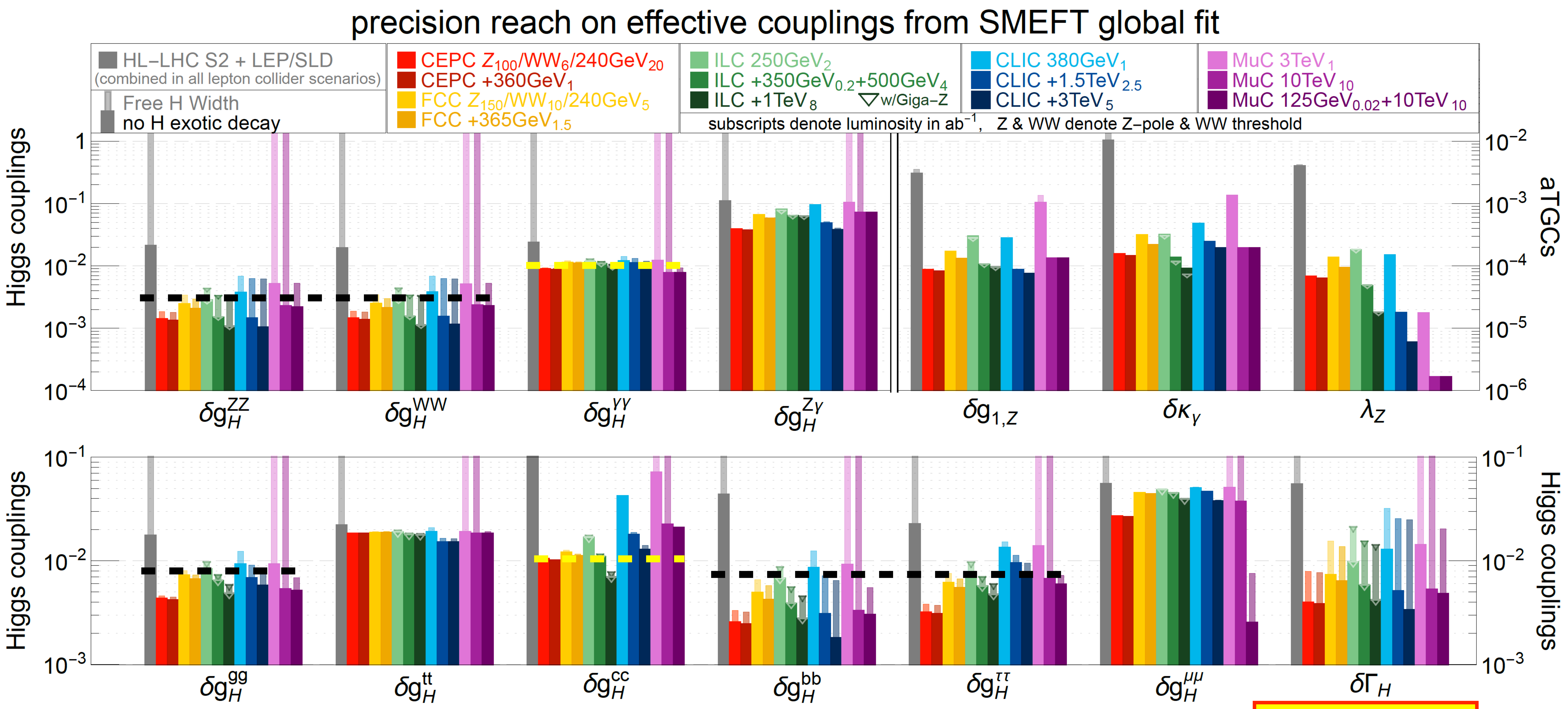

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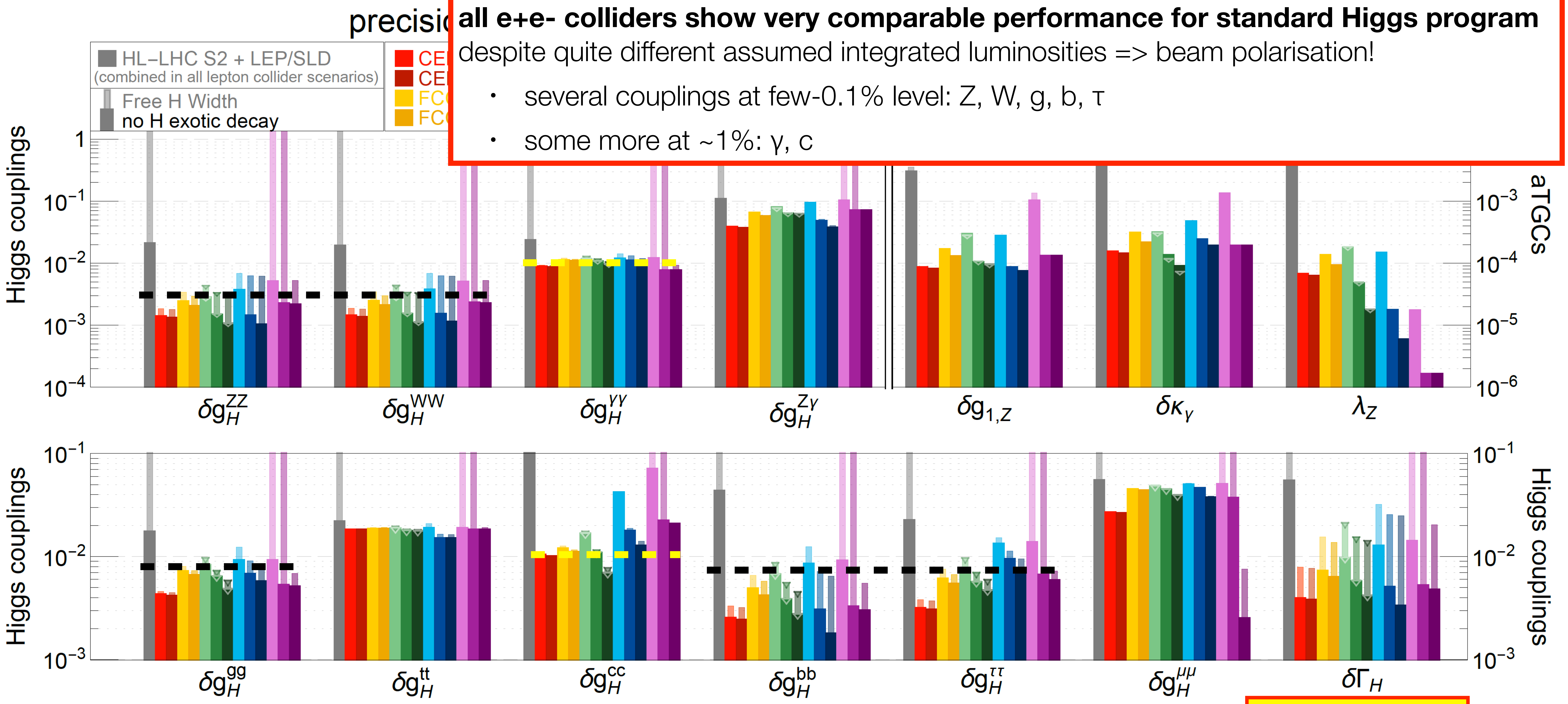

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despite quite different assumed integrated luminosities => beam polarisation!

- several couplings at few-0.1% level: Z, W, g, b, τ
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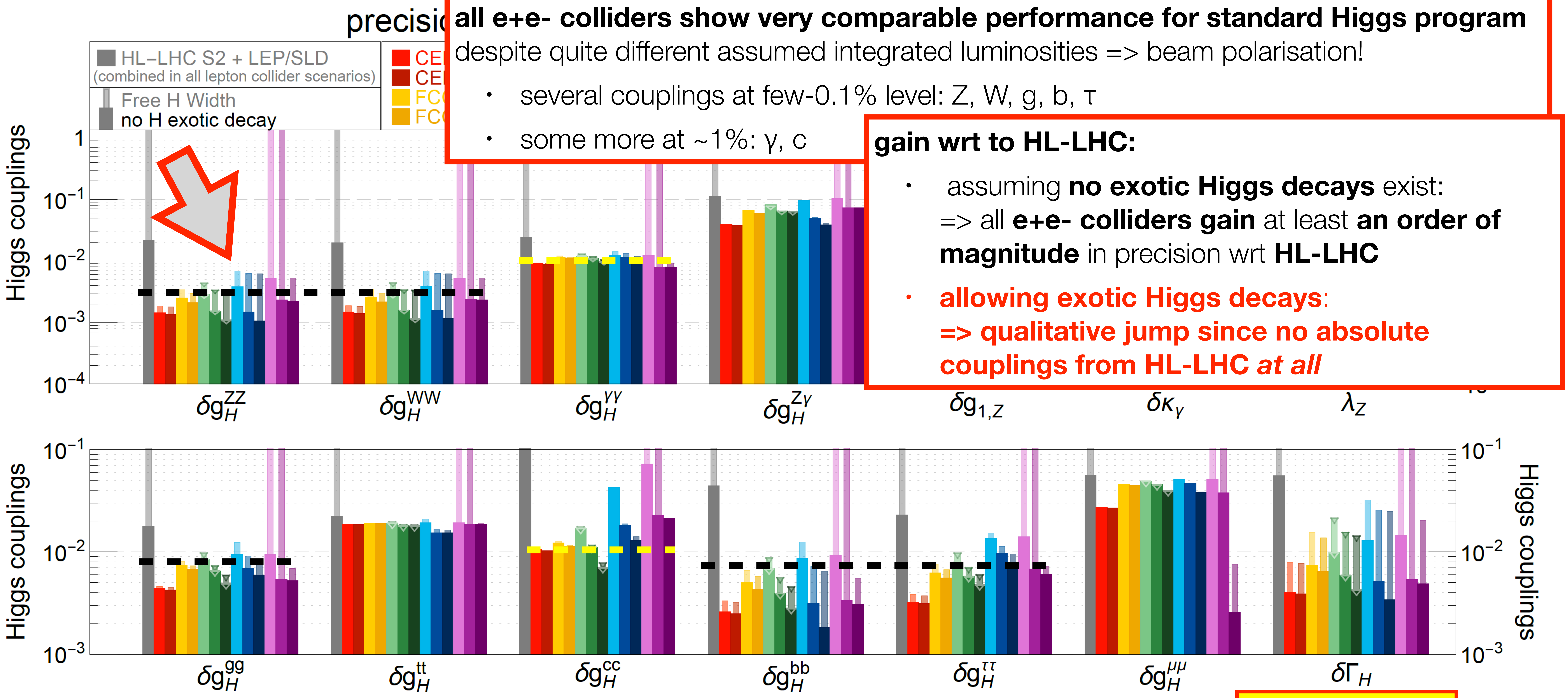

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gain wrt to HL-LHC:

- 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*

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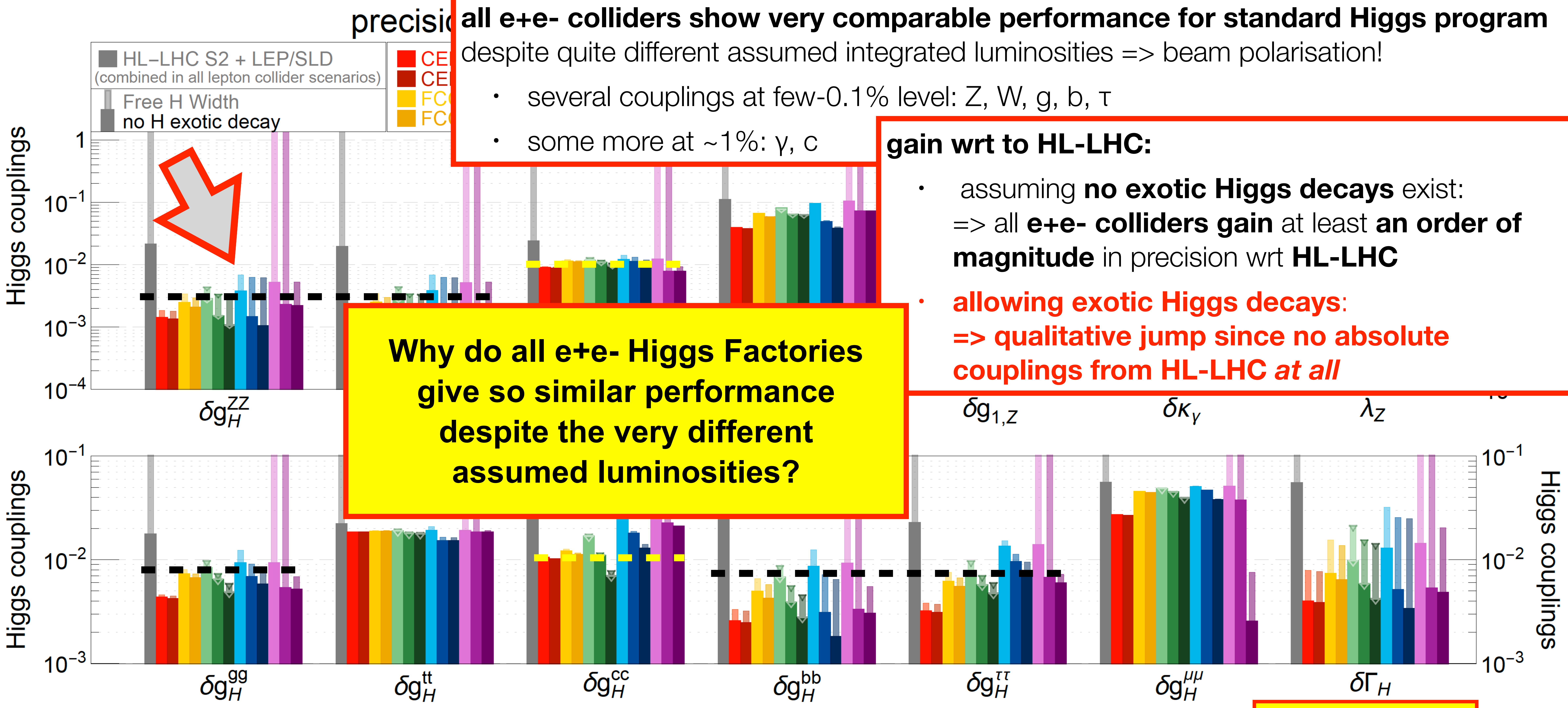

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Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

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

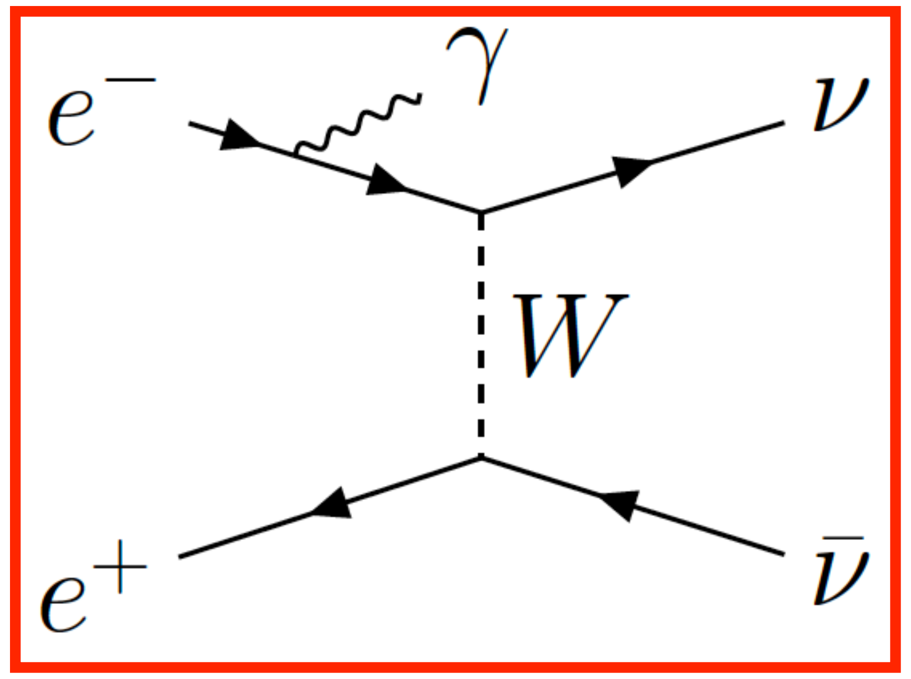
Much more than statistics!

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

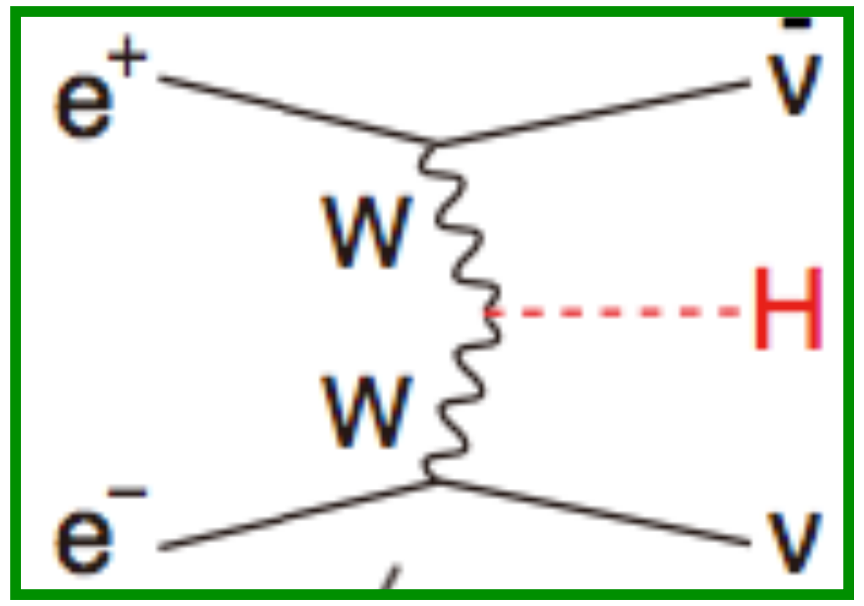
- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

background suppression:

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



signal enhancement:

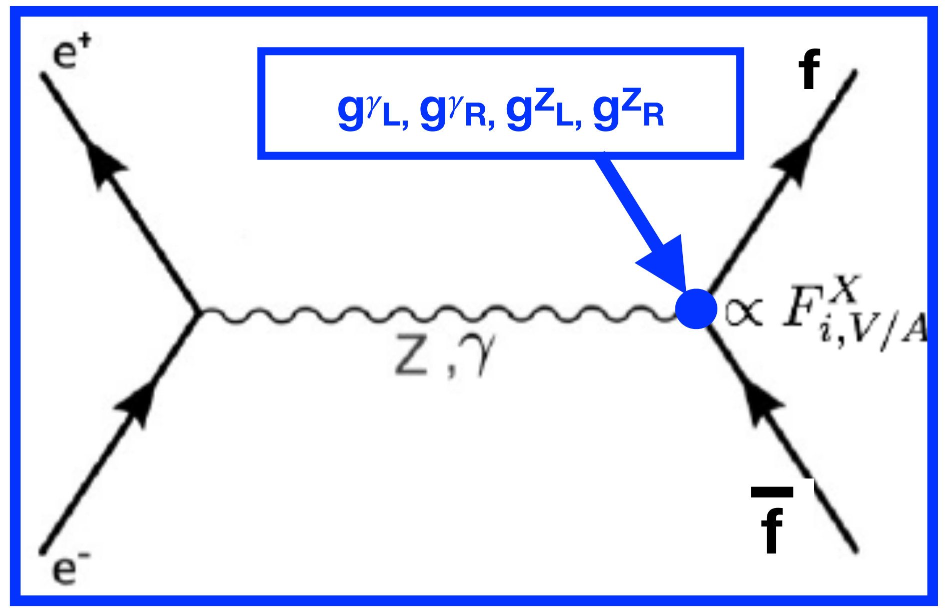


- Higgs production in WW fusion
- many BSM processes

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!

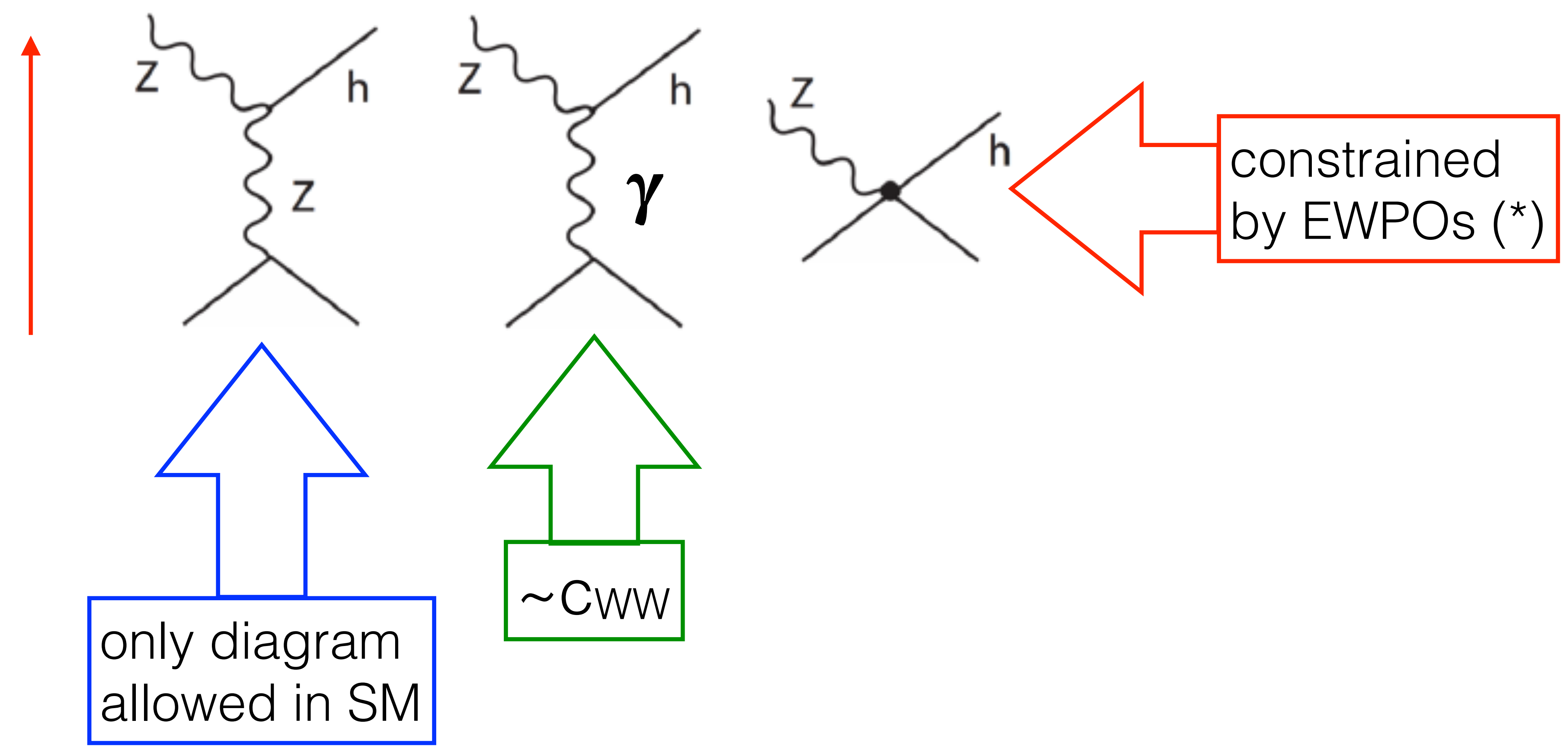
redundancy & control of systematics:

- “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 $e^+e^- \rightarrow Zh$
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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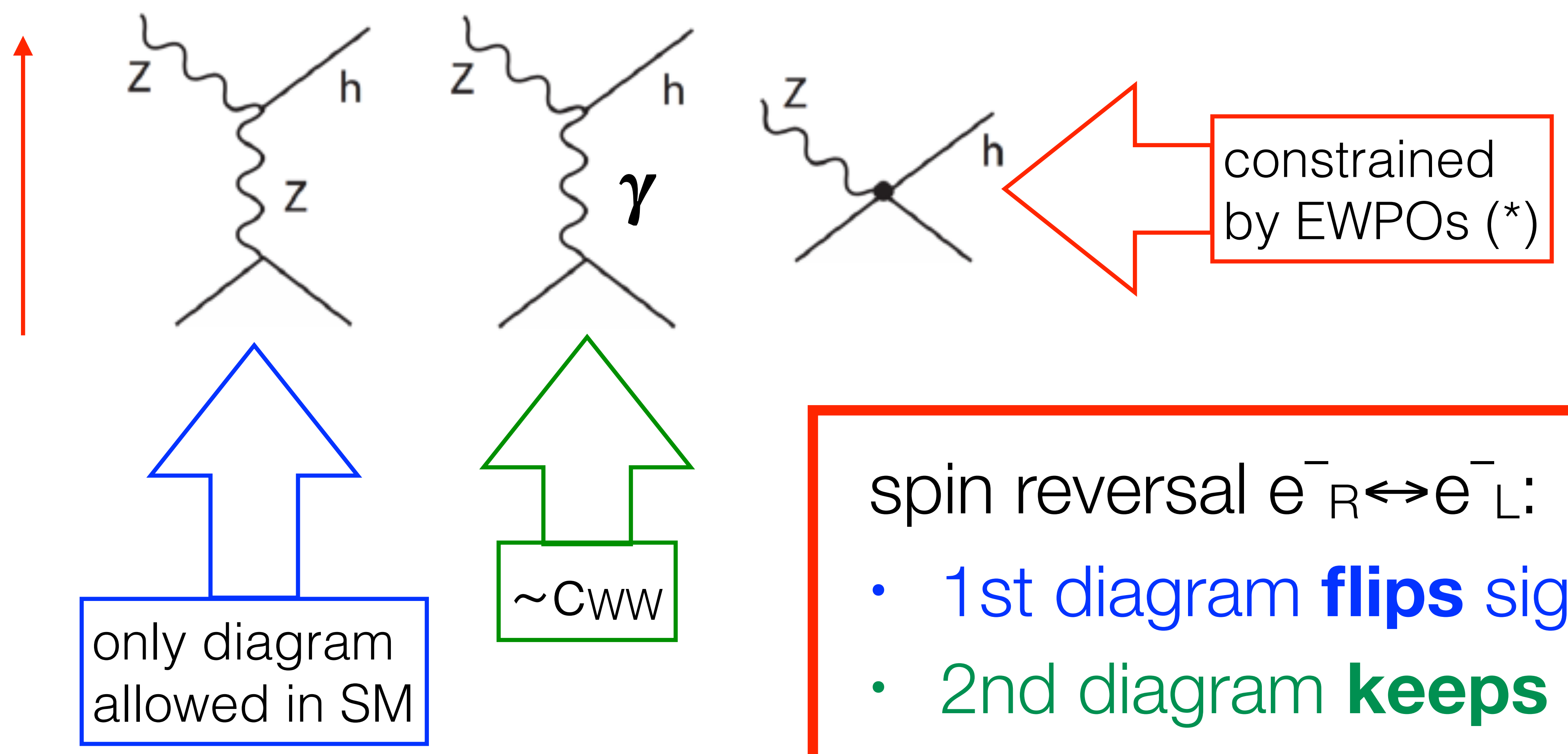

spin reversal $e^-_R \leftrightarrow e^-_L$:

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

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

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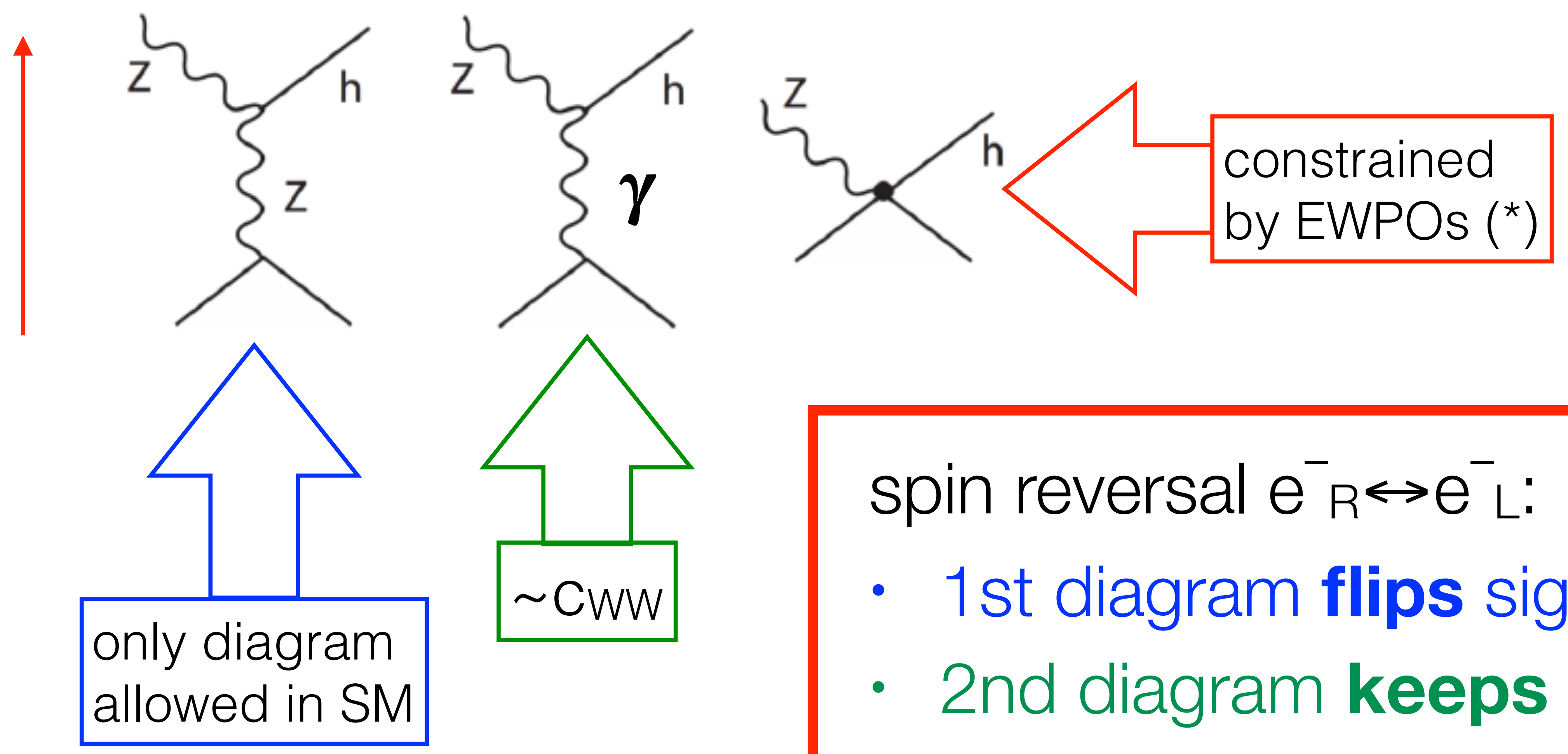

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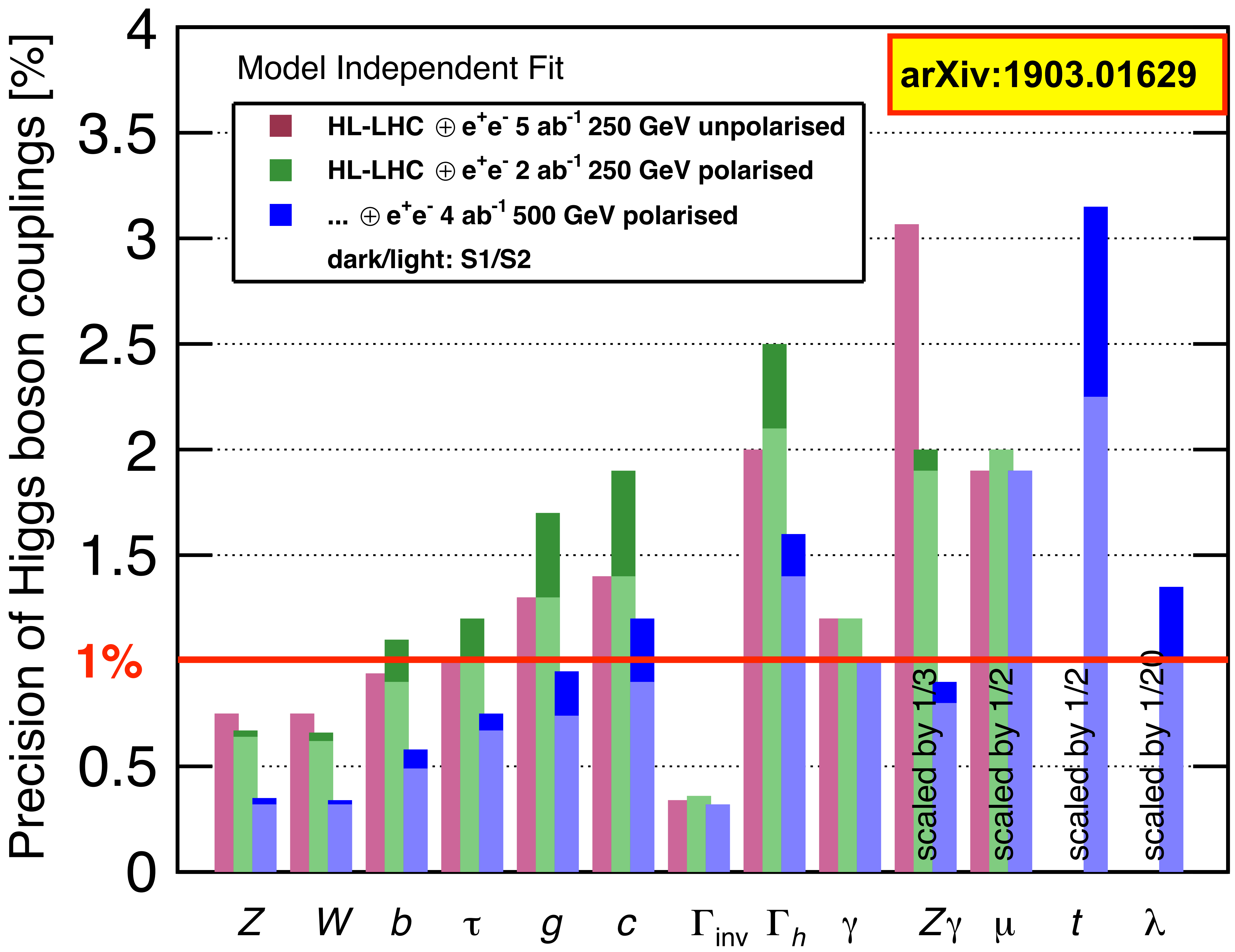

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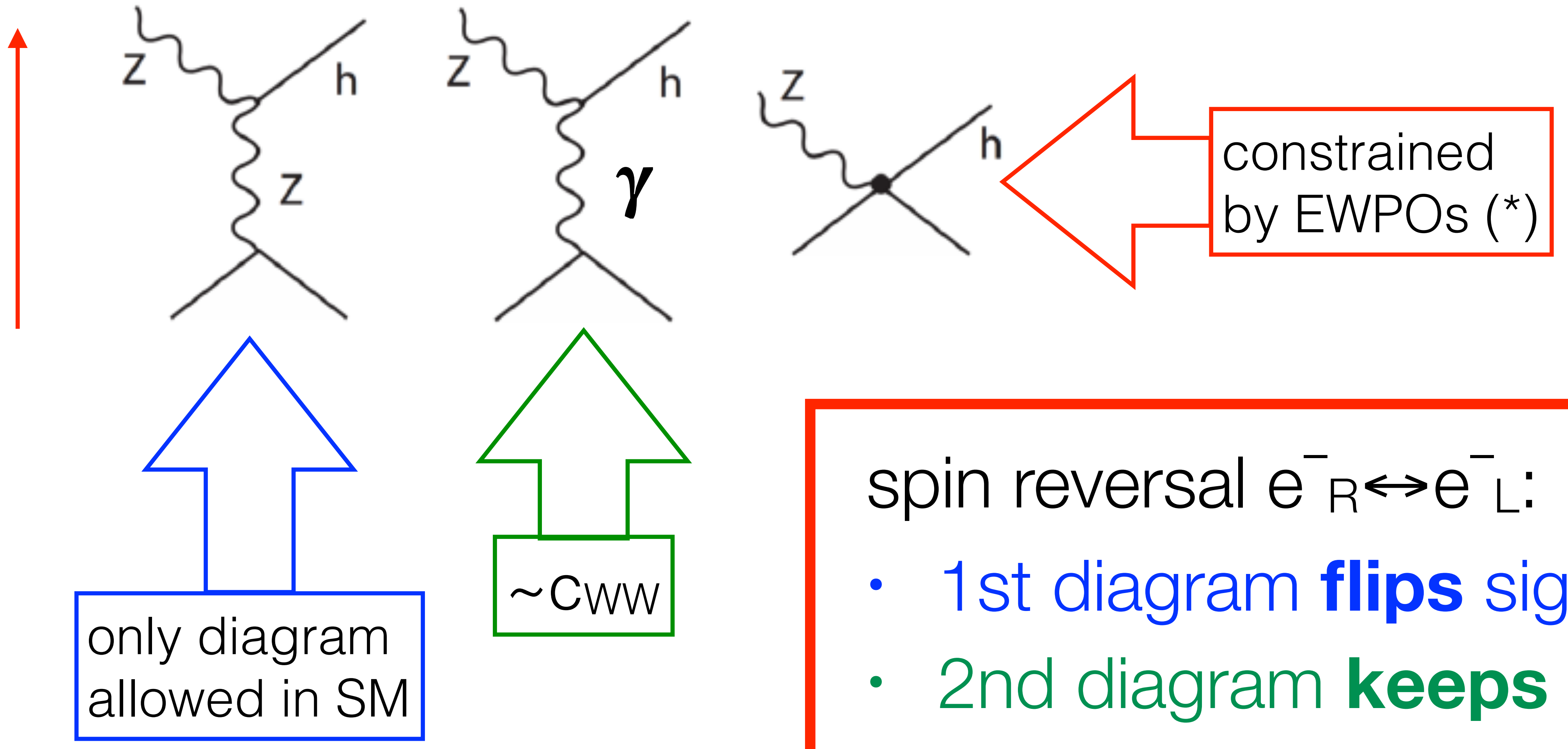

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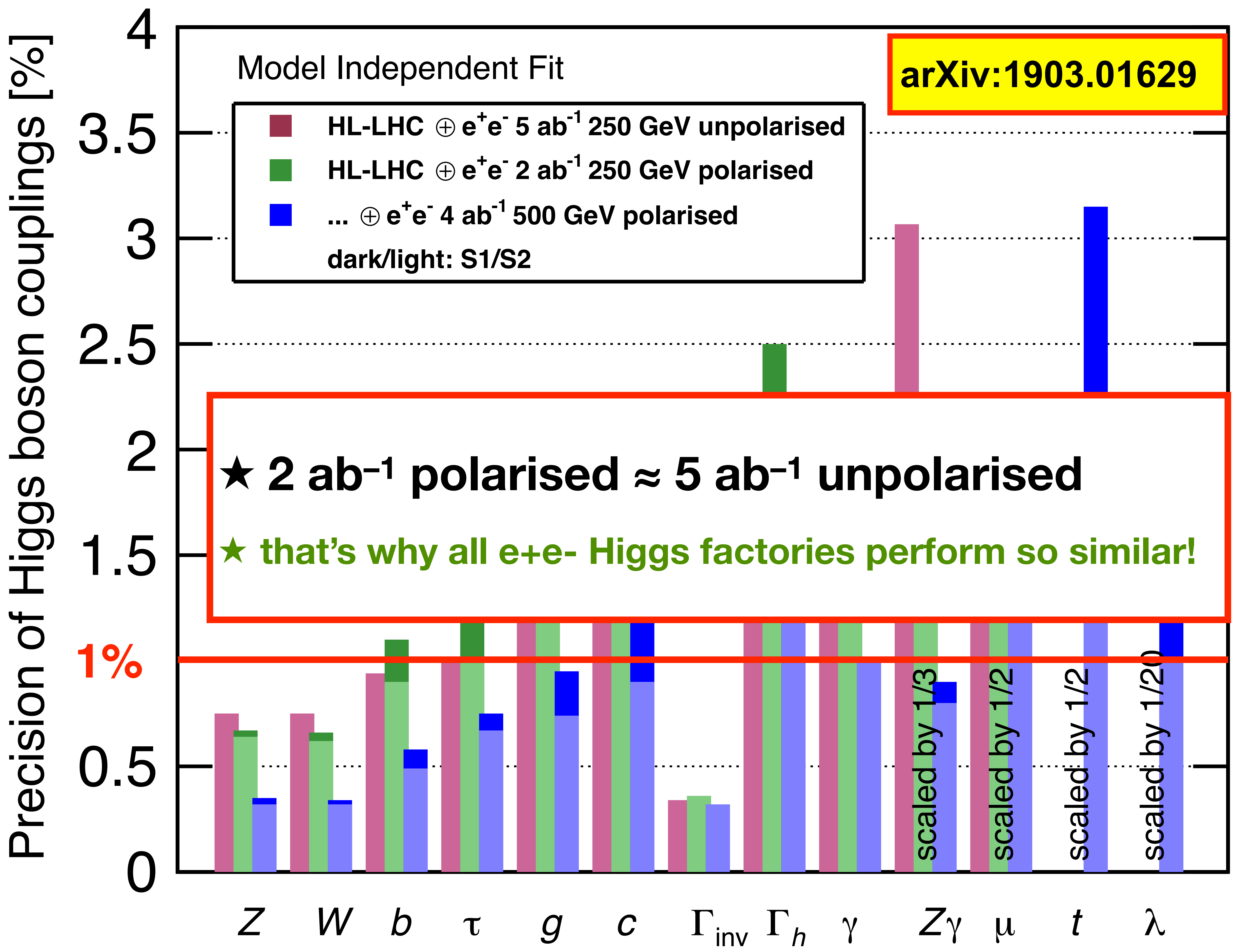

Why do we need to know the couplings of the Higgs boson?

Discovering new phenomena

- Any deviation from the SM prediction is a discovery of a new phenomenon
- Higgs couplings allow finger-printing new phenomena via their different *patterns* of deviations
- *size* of deviations depends on energy scale of new particles:
  the more precise the measurement, the larger the discovery potential
- need at least 1%-level of precision for Higgs couplings
- **all proposed Higgs factories can deliver this program - (HL-)LHC cannot do this**

arXiv:1708.08912

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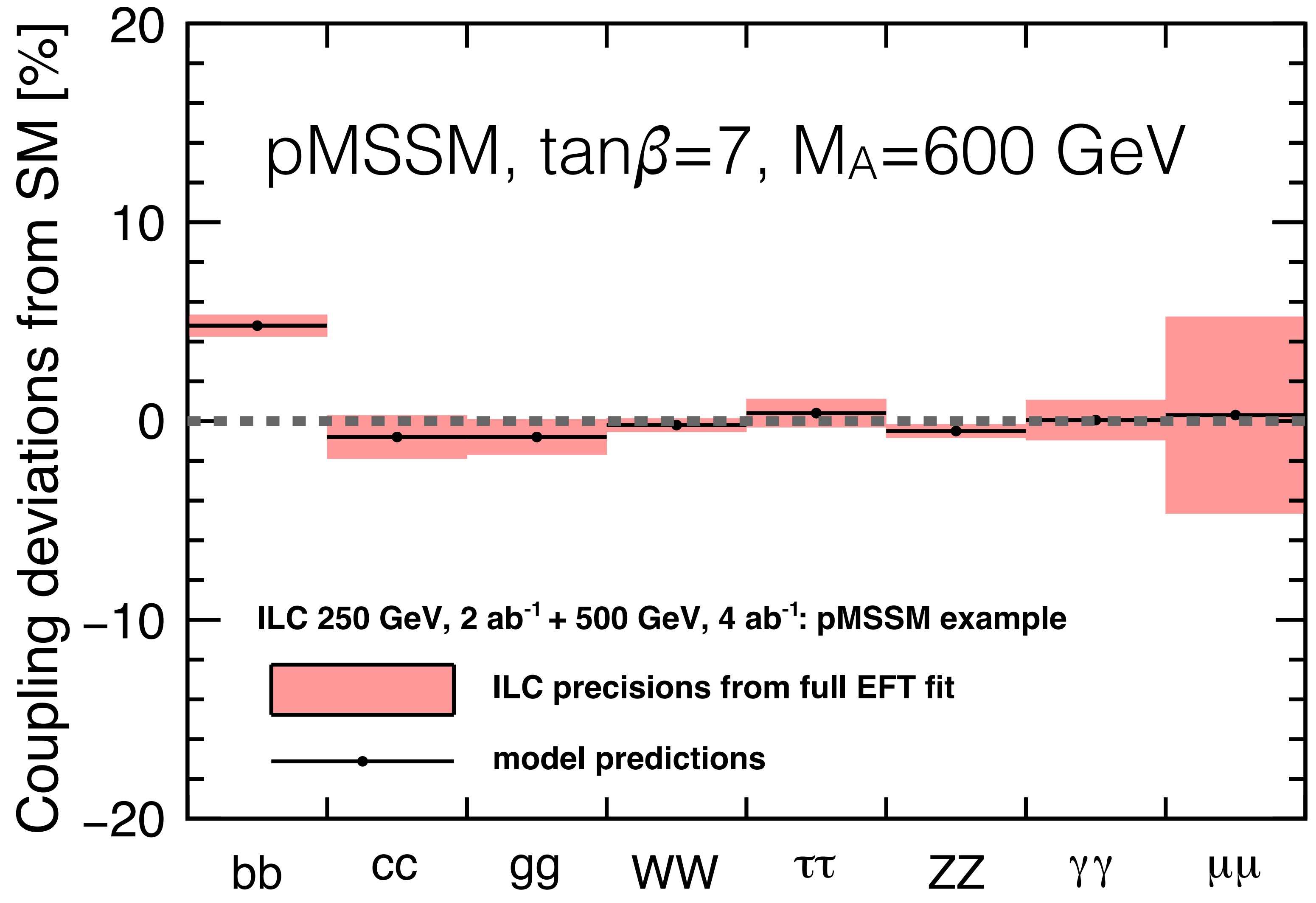

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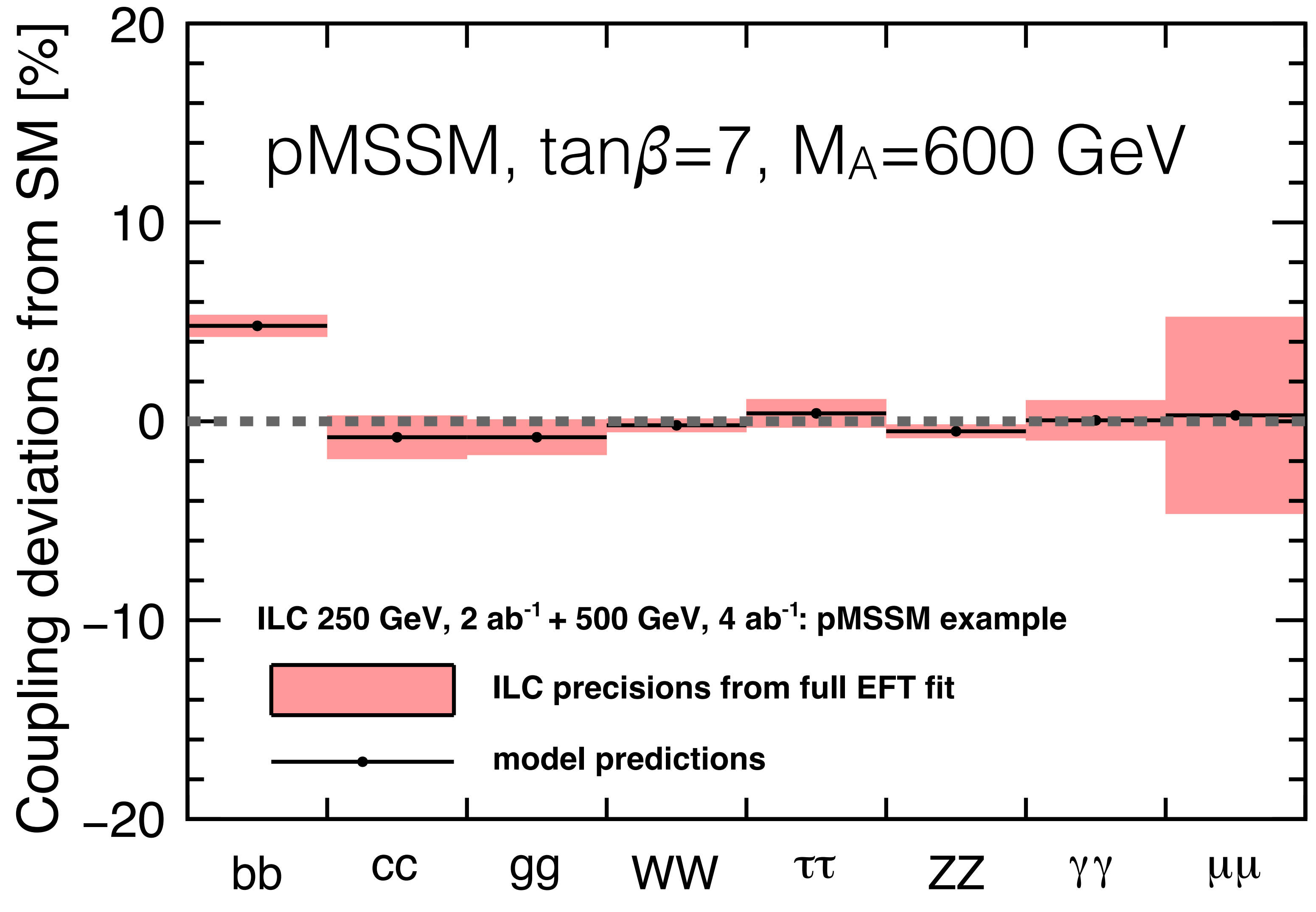

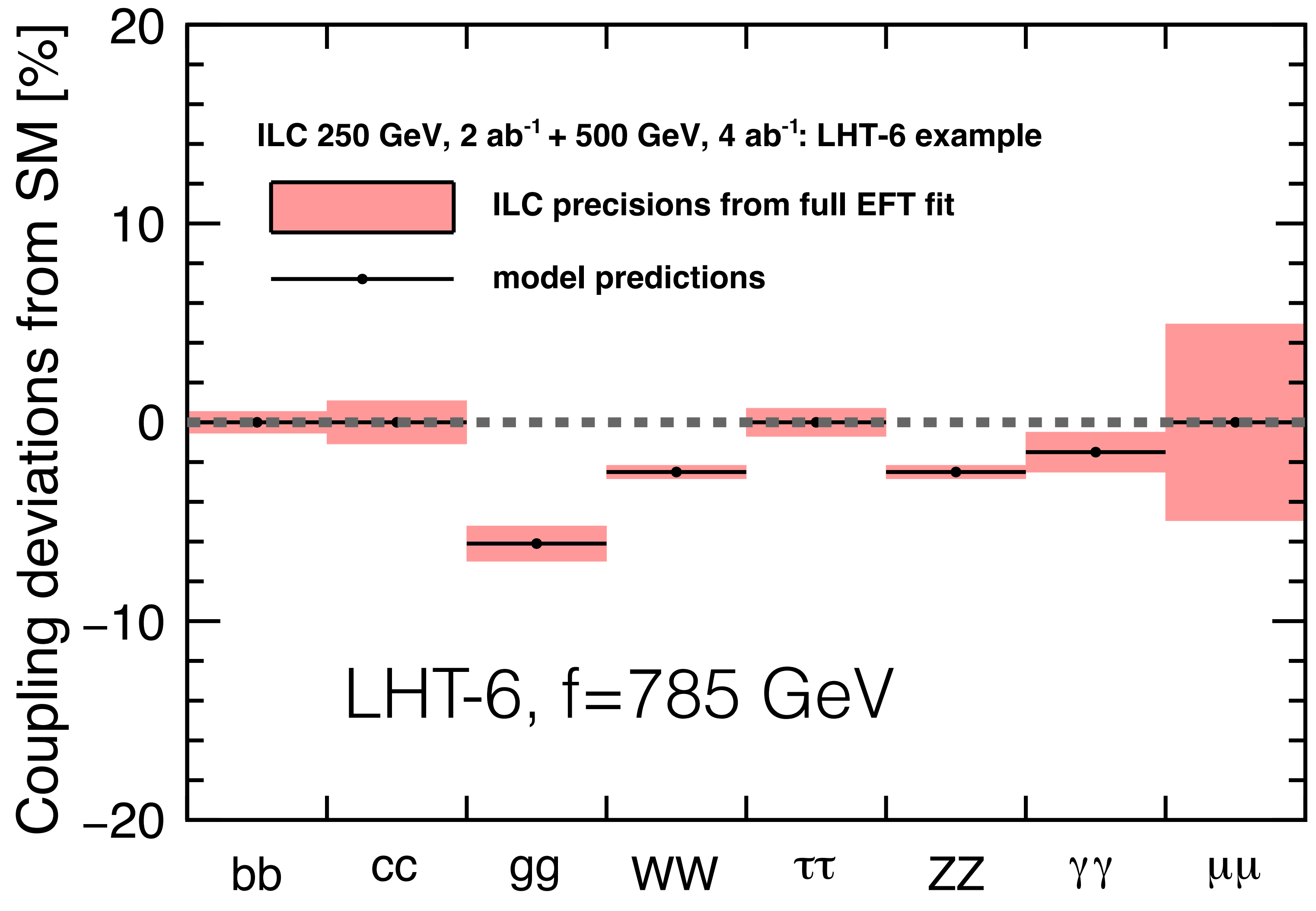

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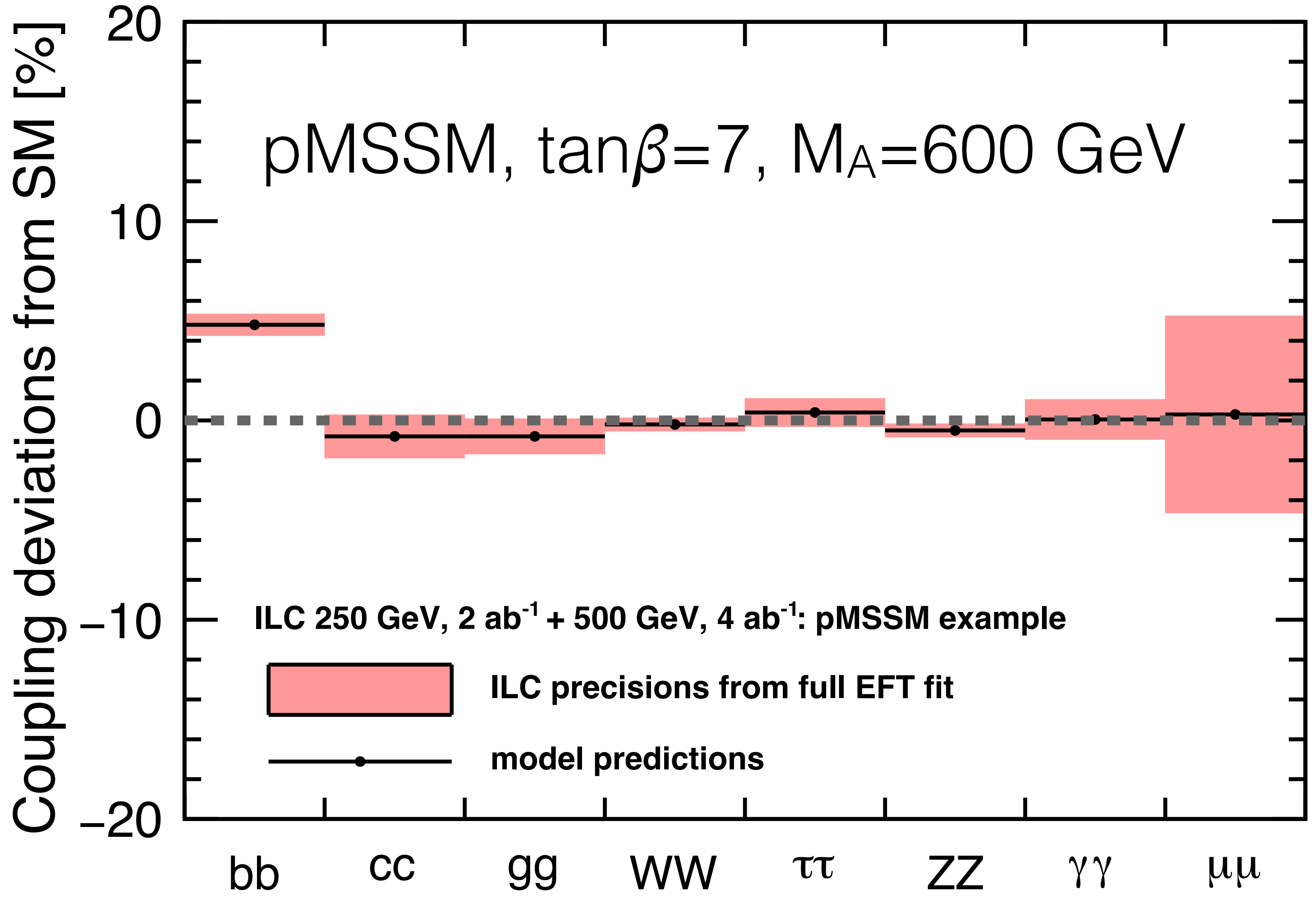
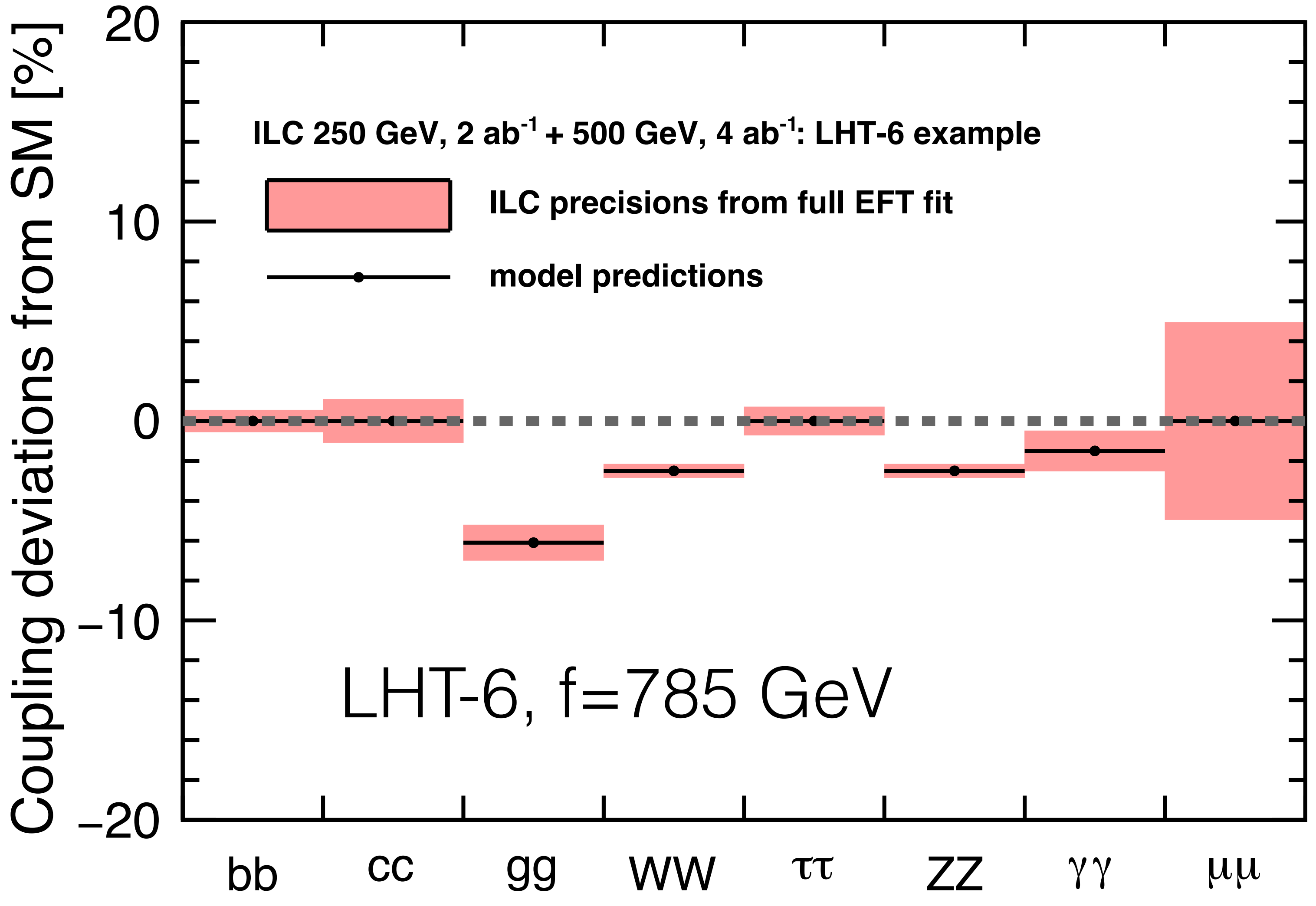
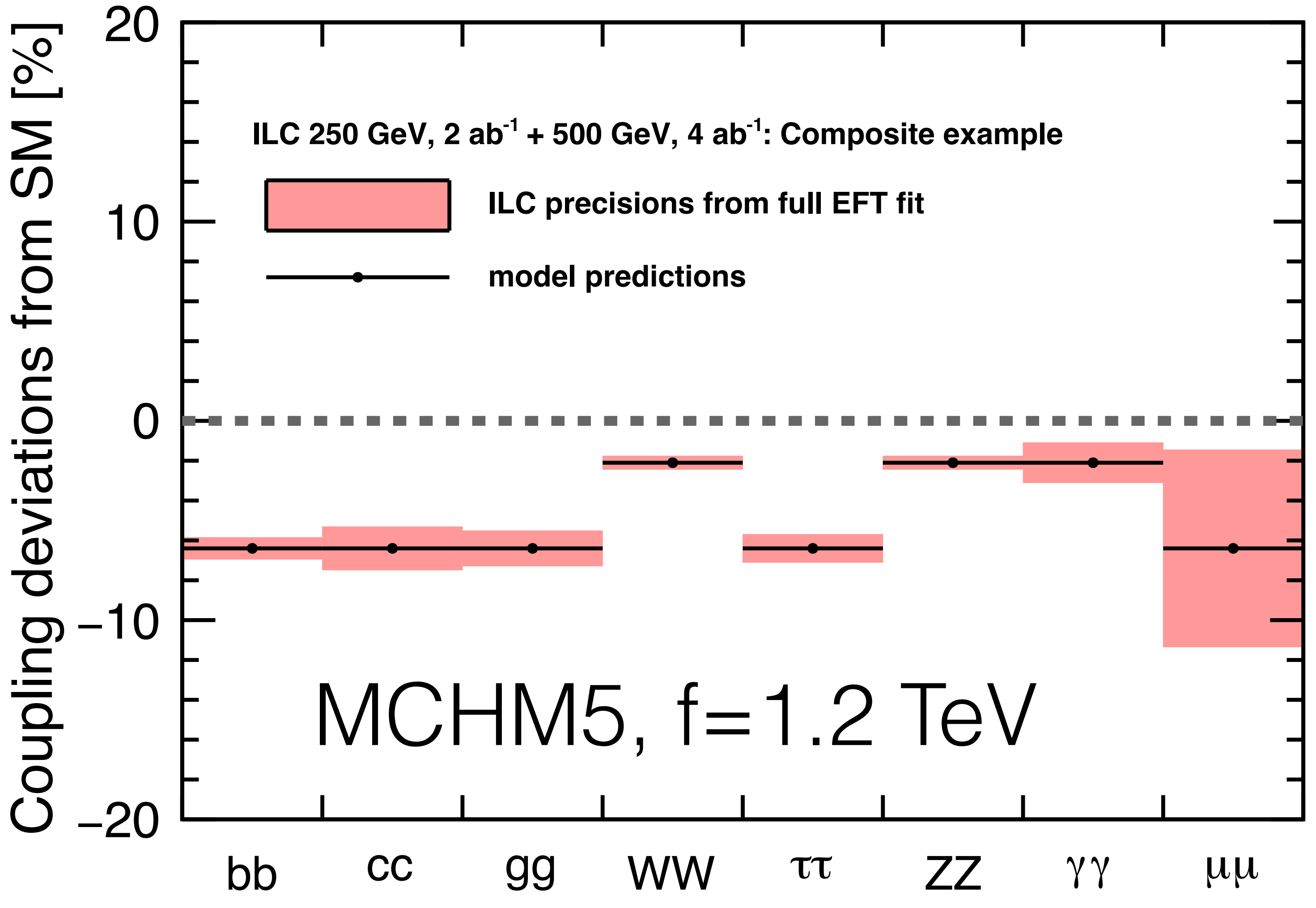
- **all proposed Higgs factories can deliver this program - (HL-)LHC cannot do this**







arXiv:1708.08912

Beyond the minimal Higgs program - Energy & Polarisation

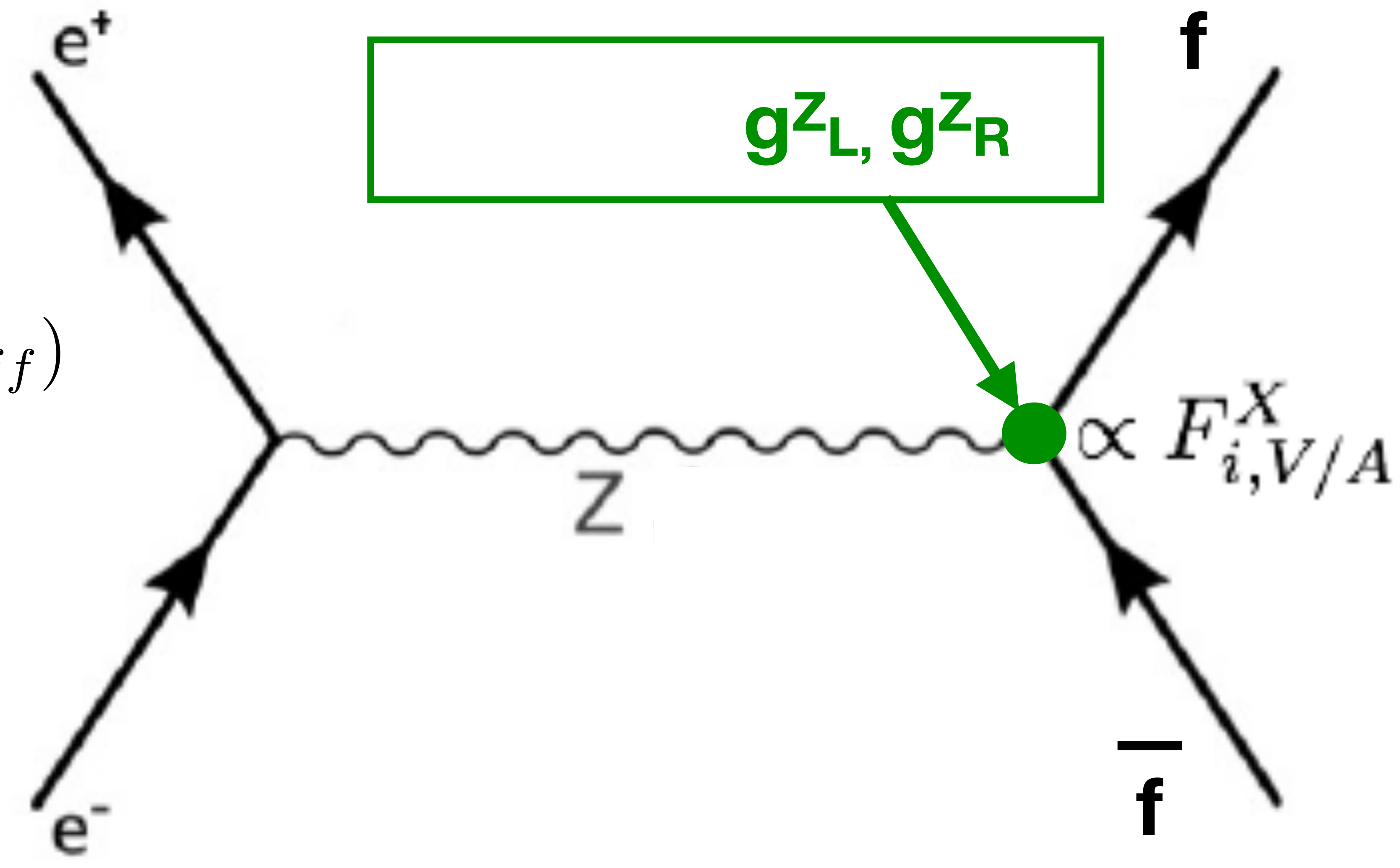
Polarisation & Electroweak Physics

let's first recall at the Z pole situation

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions - at the Z pole:

=> $$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

specifically for the electron: $$A_e = \frac{(\frac{1}{2} - \sin^2\theta_{eff})^2 - (\sin^2\theta_{eff})^2}{(\frac{1}{2} - \sin^2\theta_{eff})^2 + (\sin^2\theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2\theta_{eff})$$



at an ***un***polarised collider:

$$A^f_{FB} \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f$$

=> no direct access to A_e,
only via tau polarisation

While at a ***polarised*** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)}$$ and $$A^f_{FB,LR} \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$

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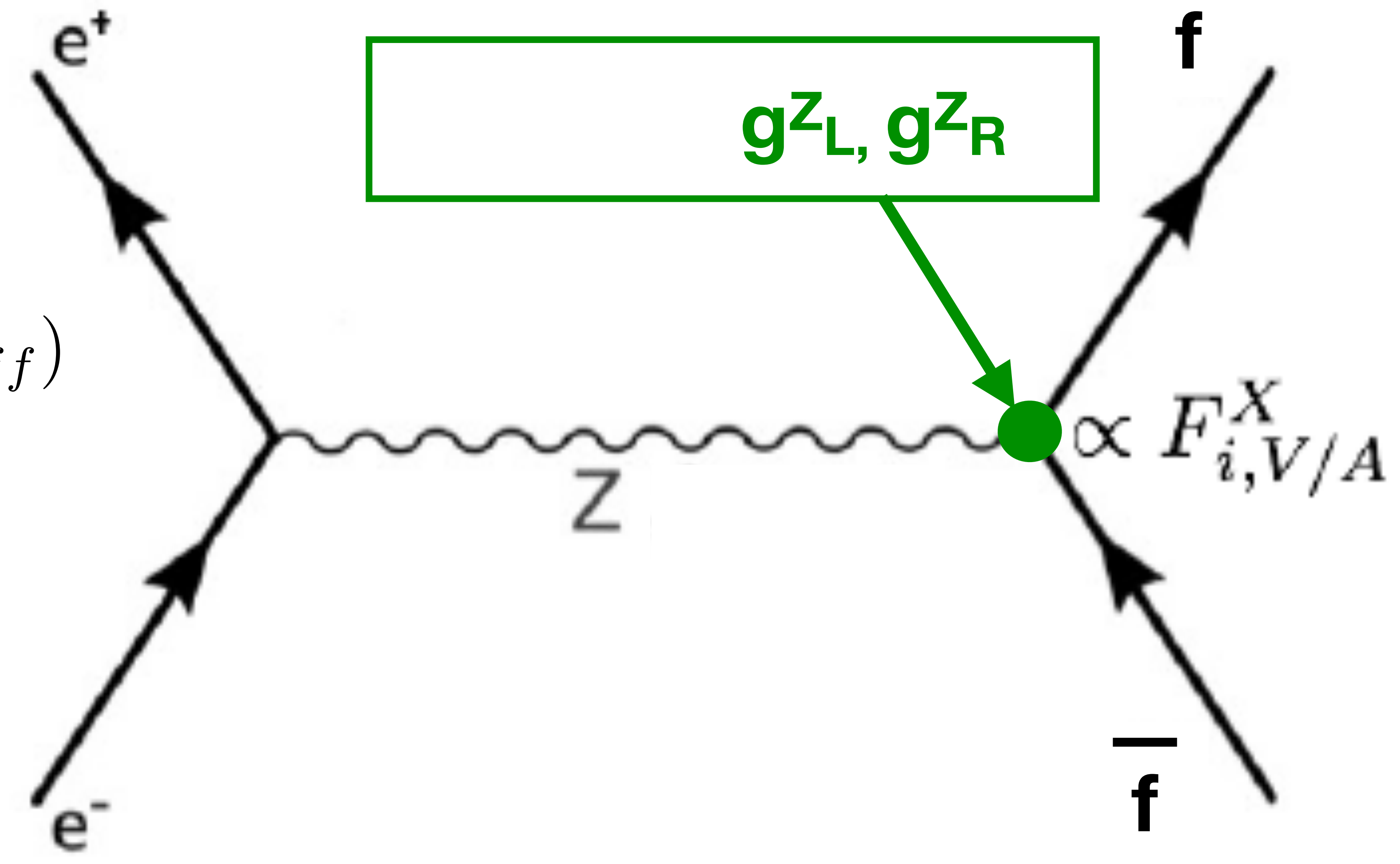

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trading theory uncertainy:

the **polarised** $A^f_{FB,LR}$ receives **7 x smaller radiative corrections** than the **unpolarised** A^f_{FB} !

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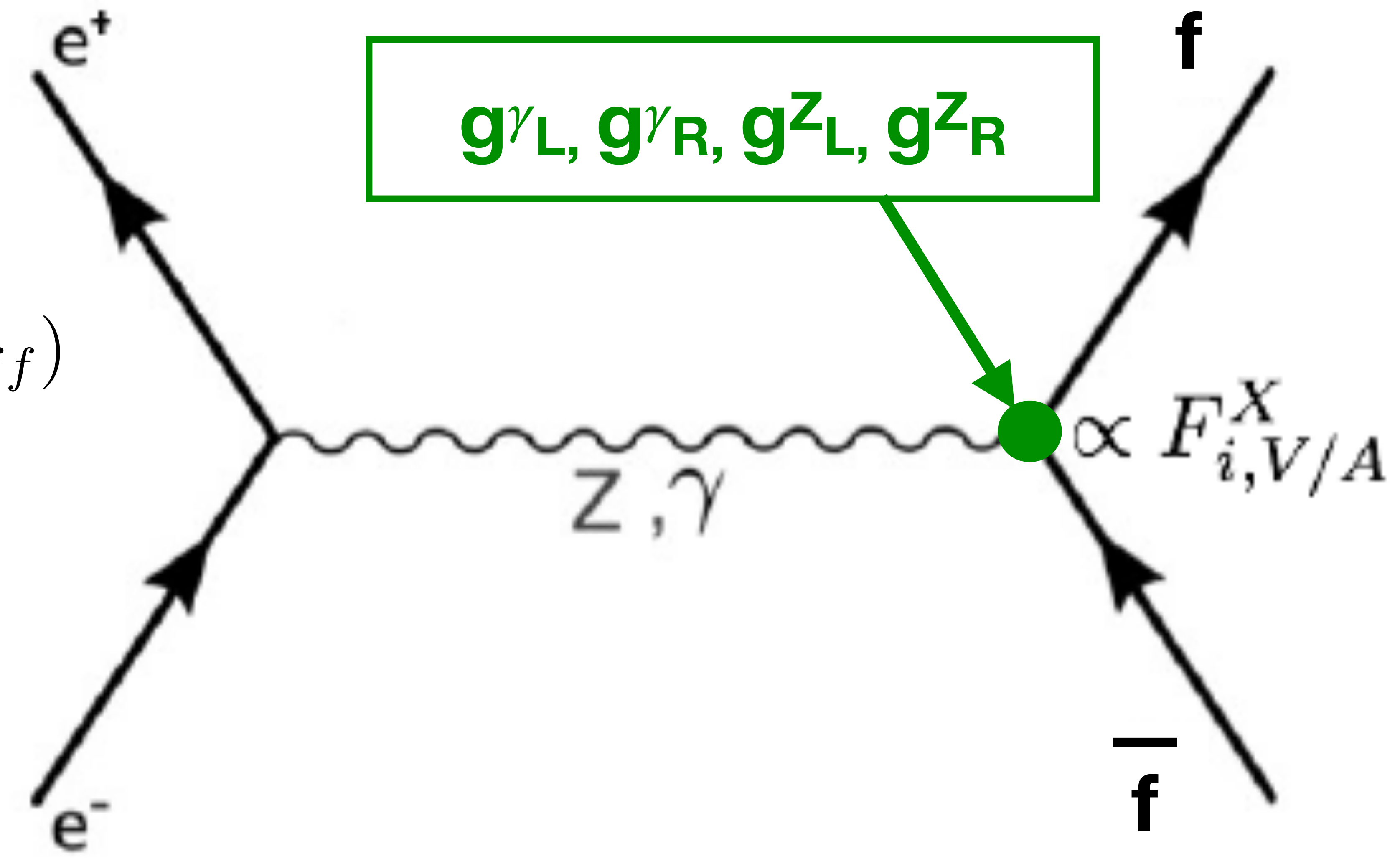

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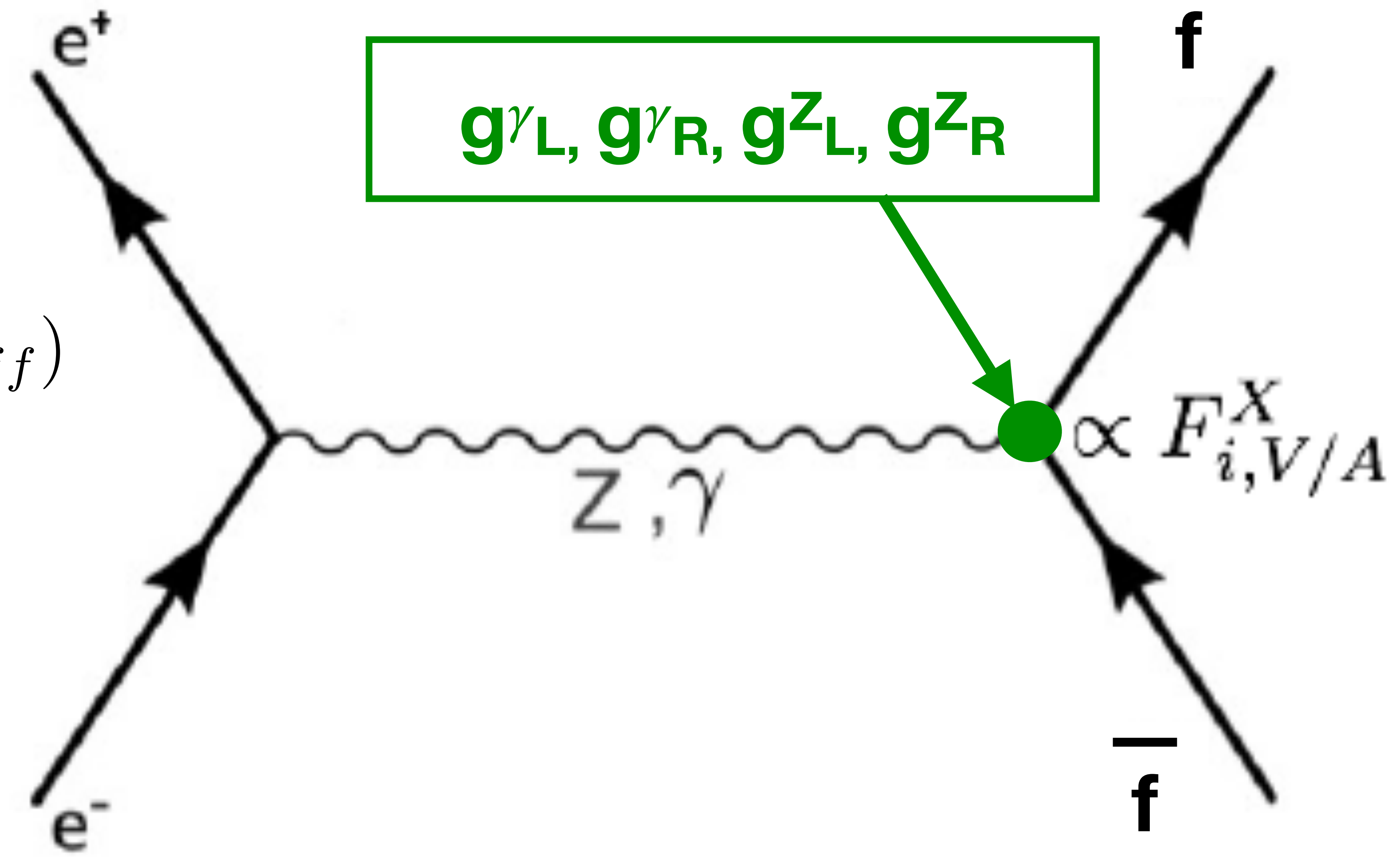

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above Z pole, polarisation essential to disentangle Z / γ exchange in $e^+e^- \to ff$

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
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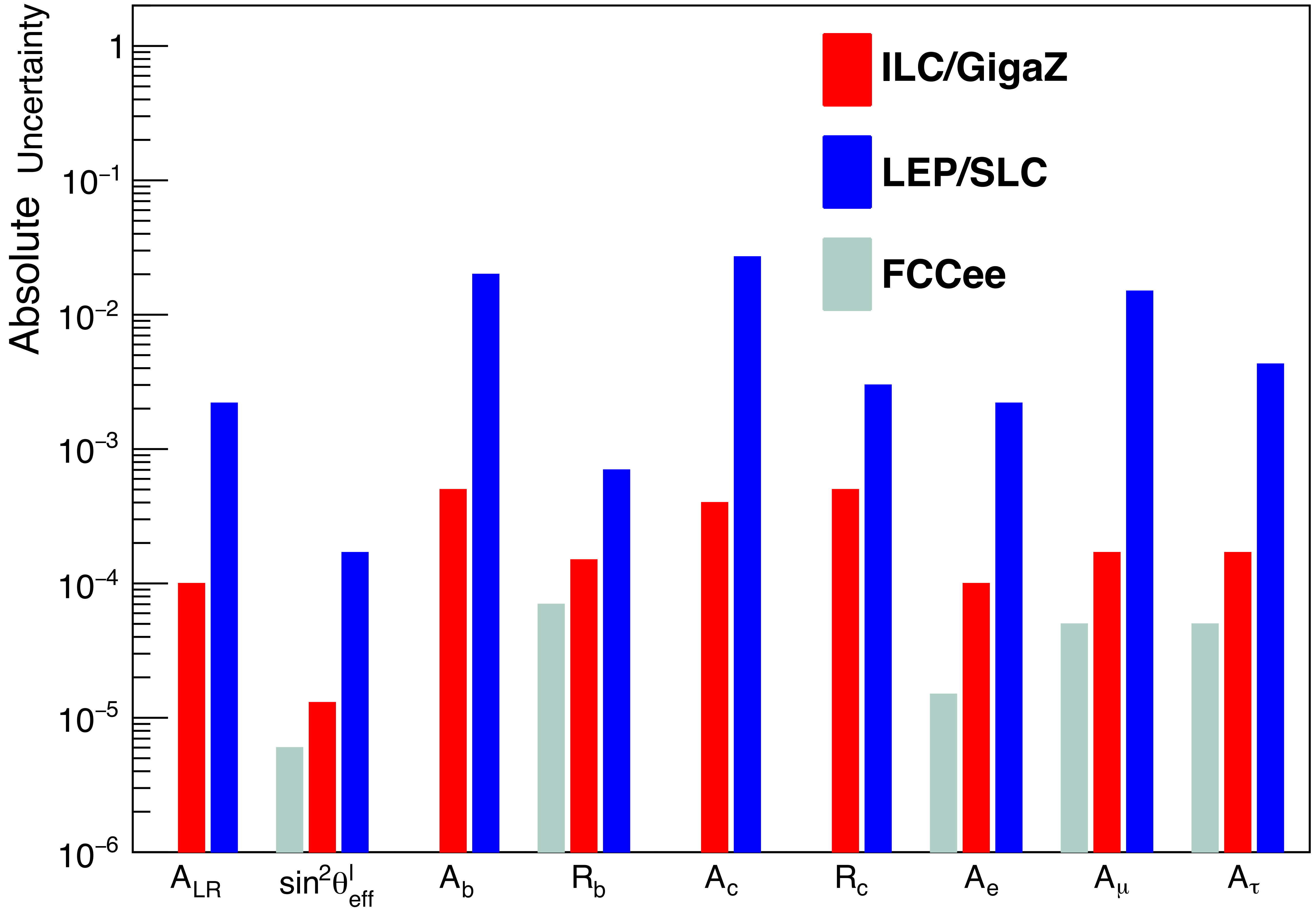

Note: not true for pure decay quantities!

arXiv:1908.11299

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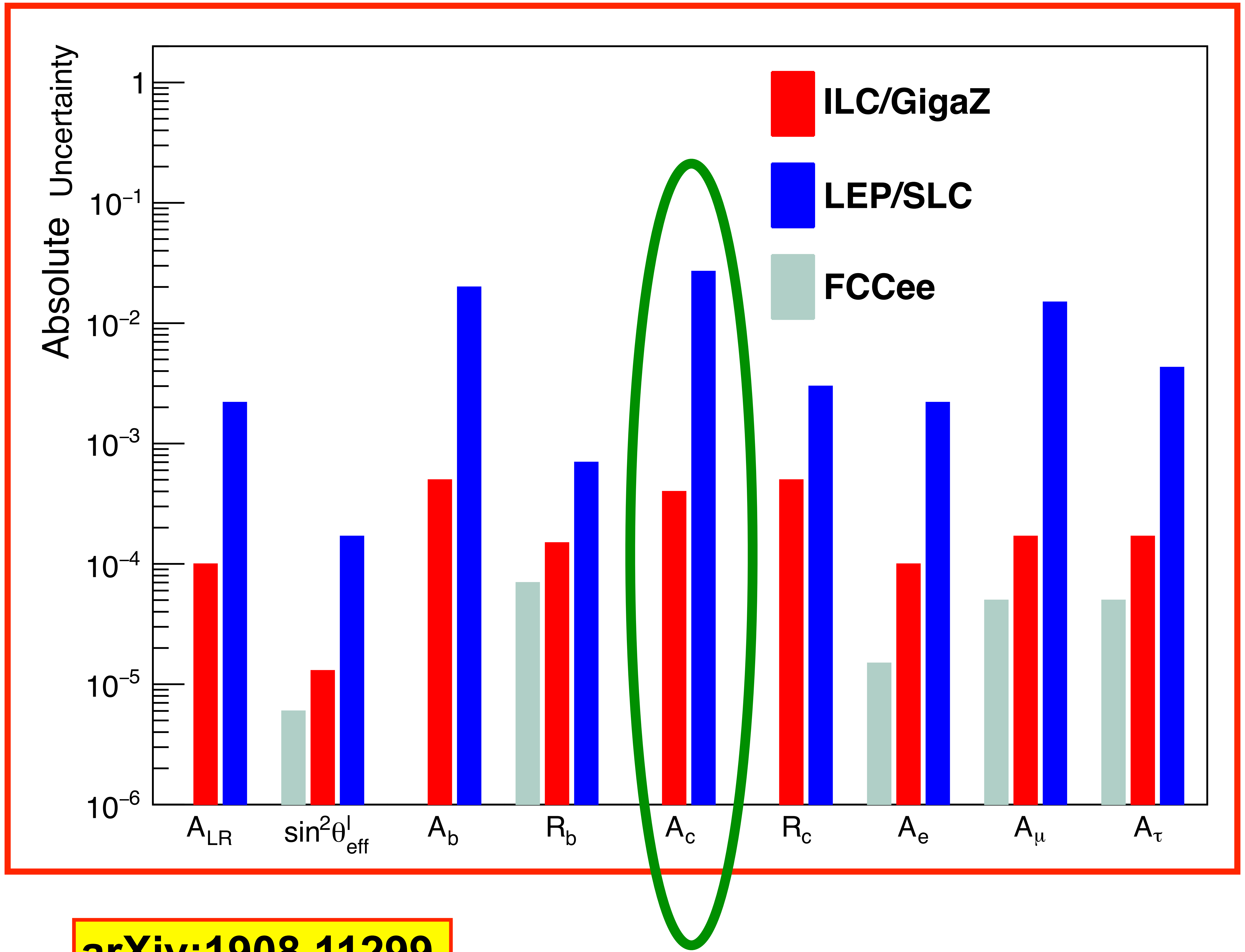

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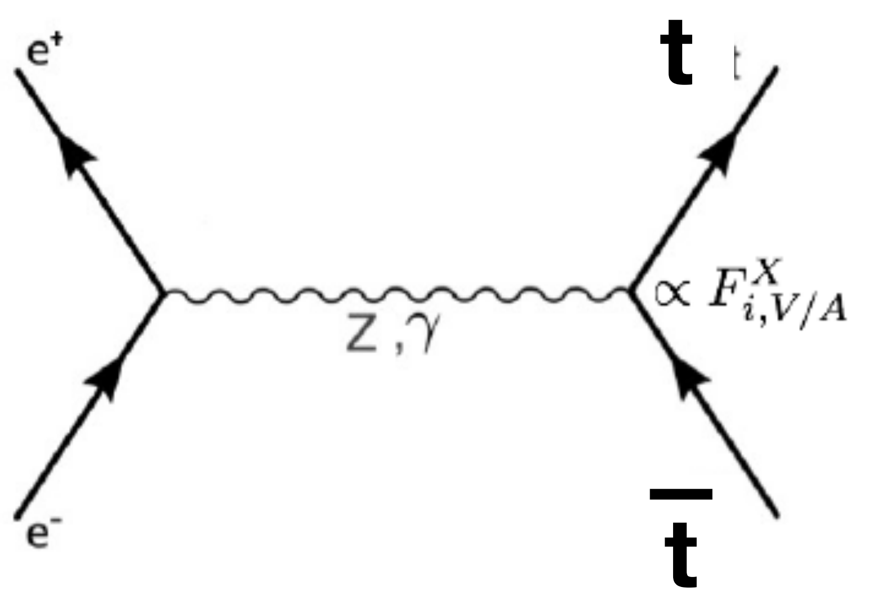
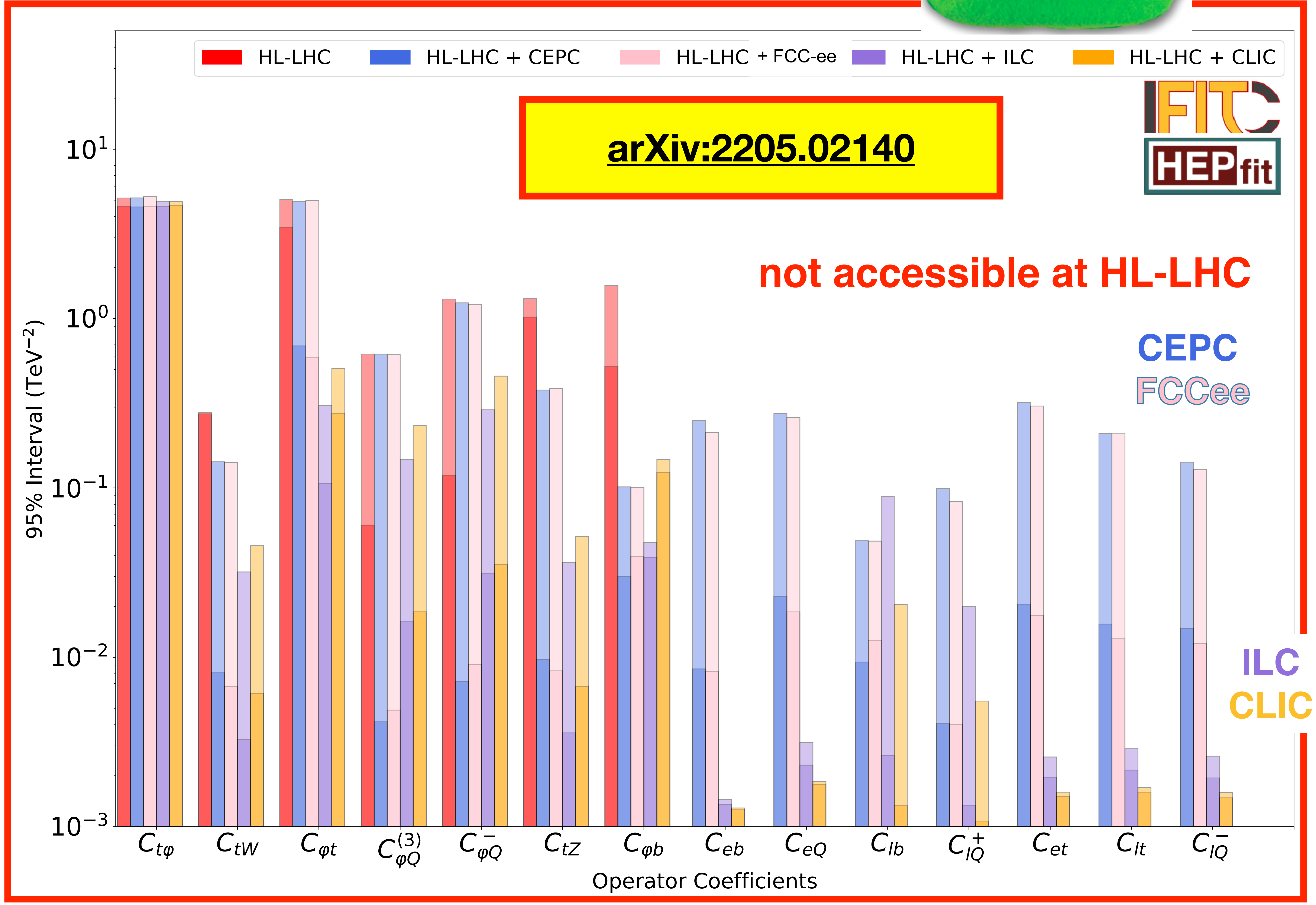
Full SMEFT analysis of Top Quark sector

Essential to understand special relation of top quark and Higgs boson



- 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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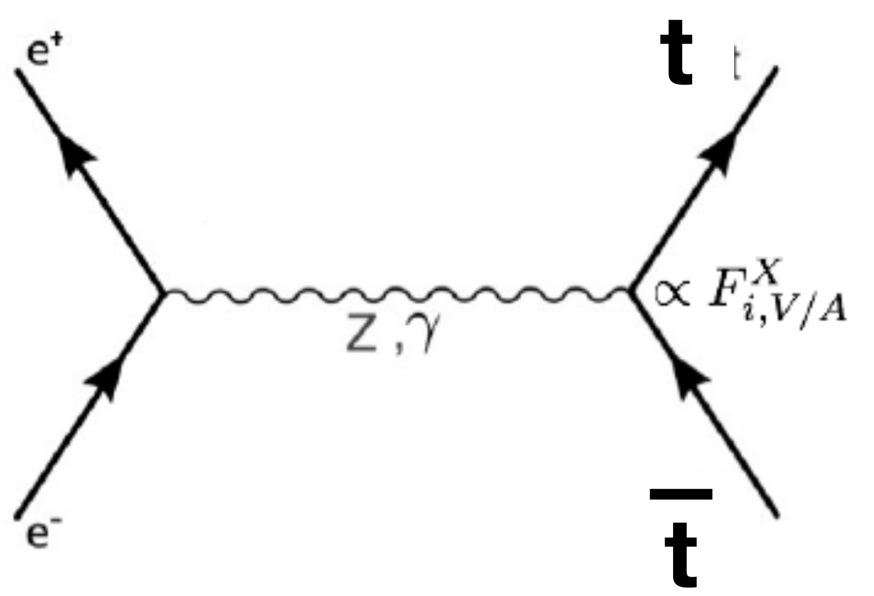

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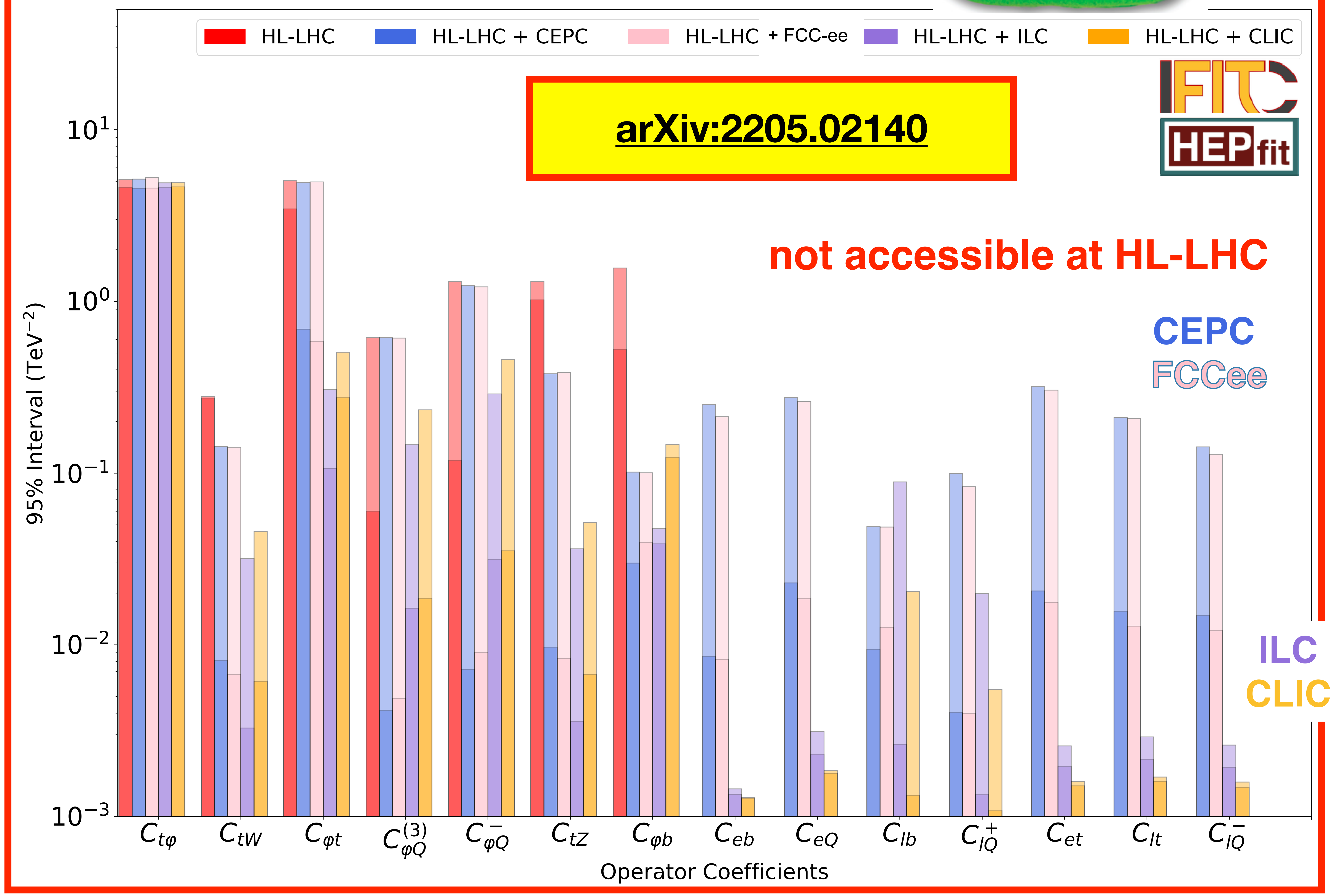
top-quark physics requires high center-of-mass energy AND polarised beams



BSM reach of ee → cc / bb

arXiv:2403.09144

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

Study of ee → cc / bb

- full Geant4-based simulation of **ILD**

BSM example: Gauge-Higgs Unification models

- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
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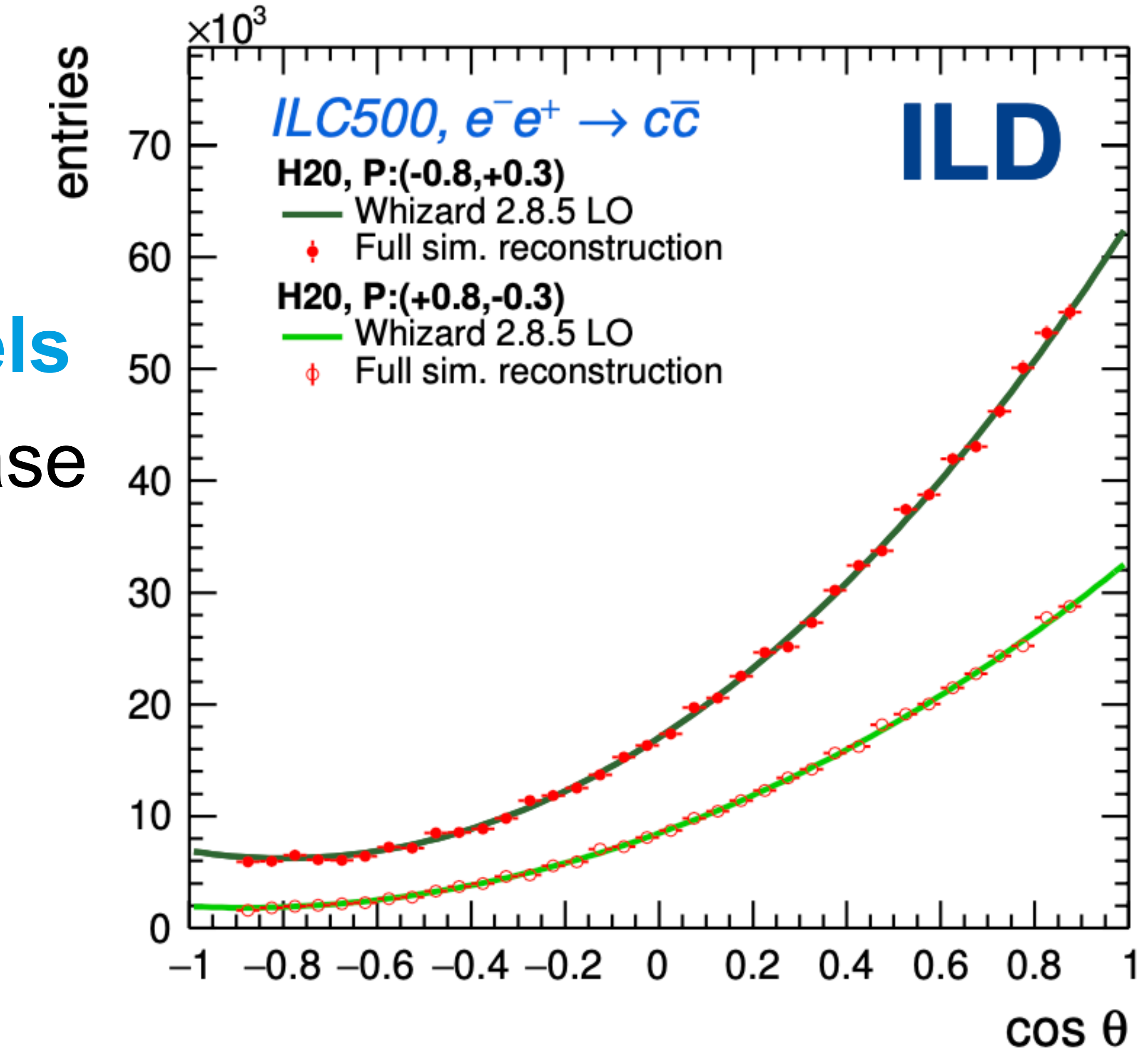

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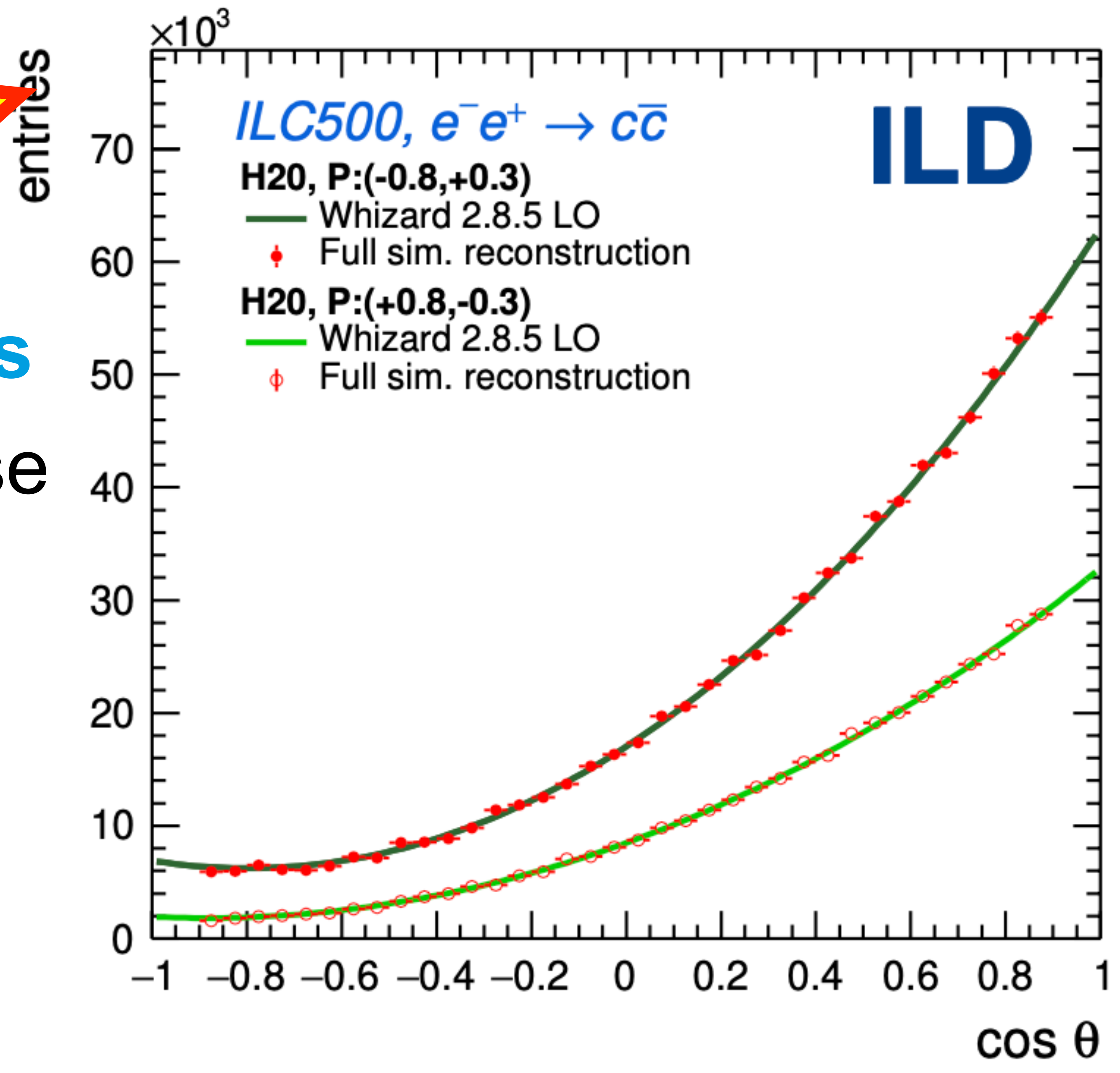

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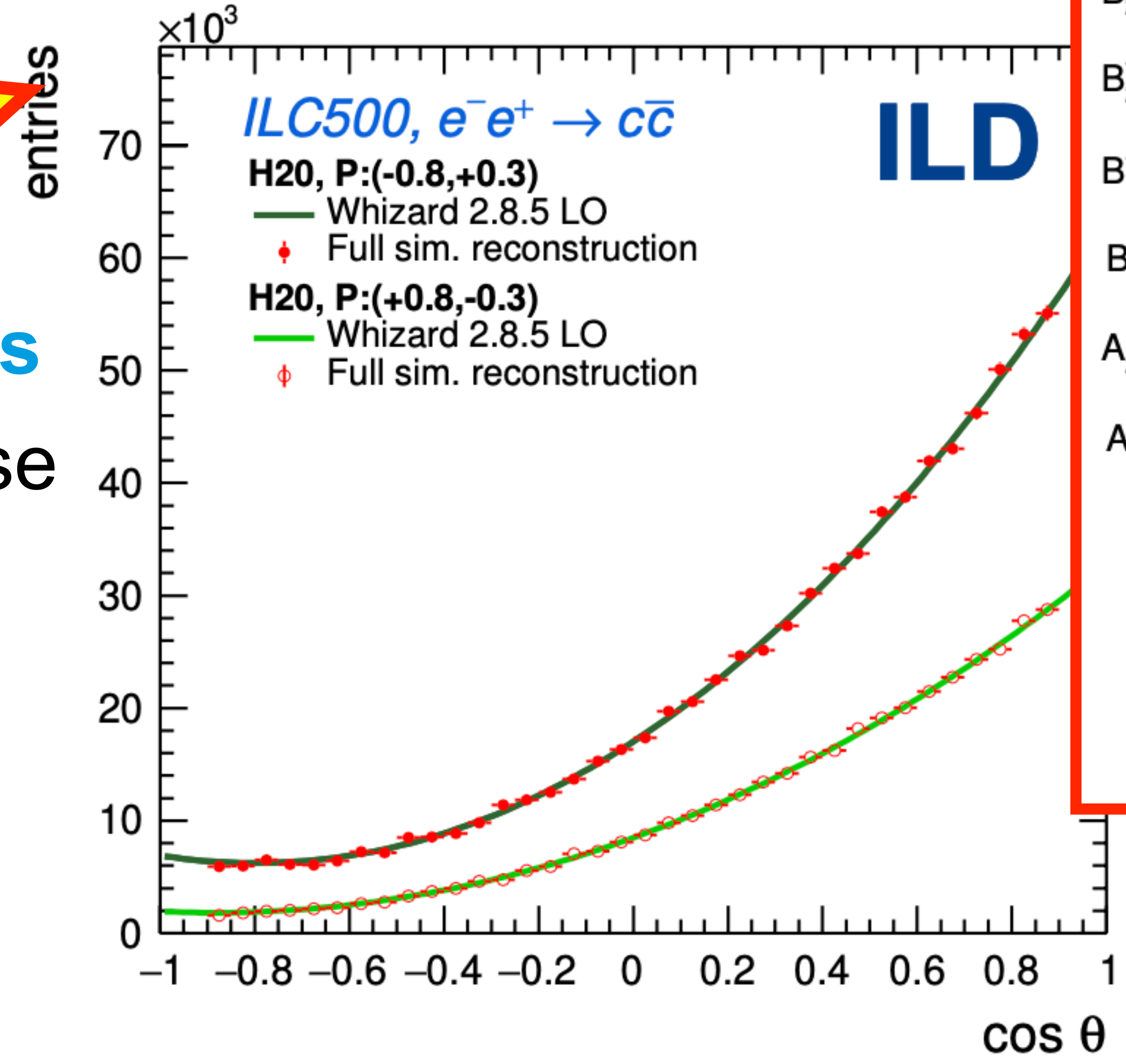

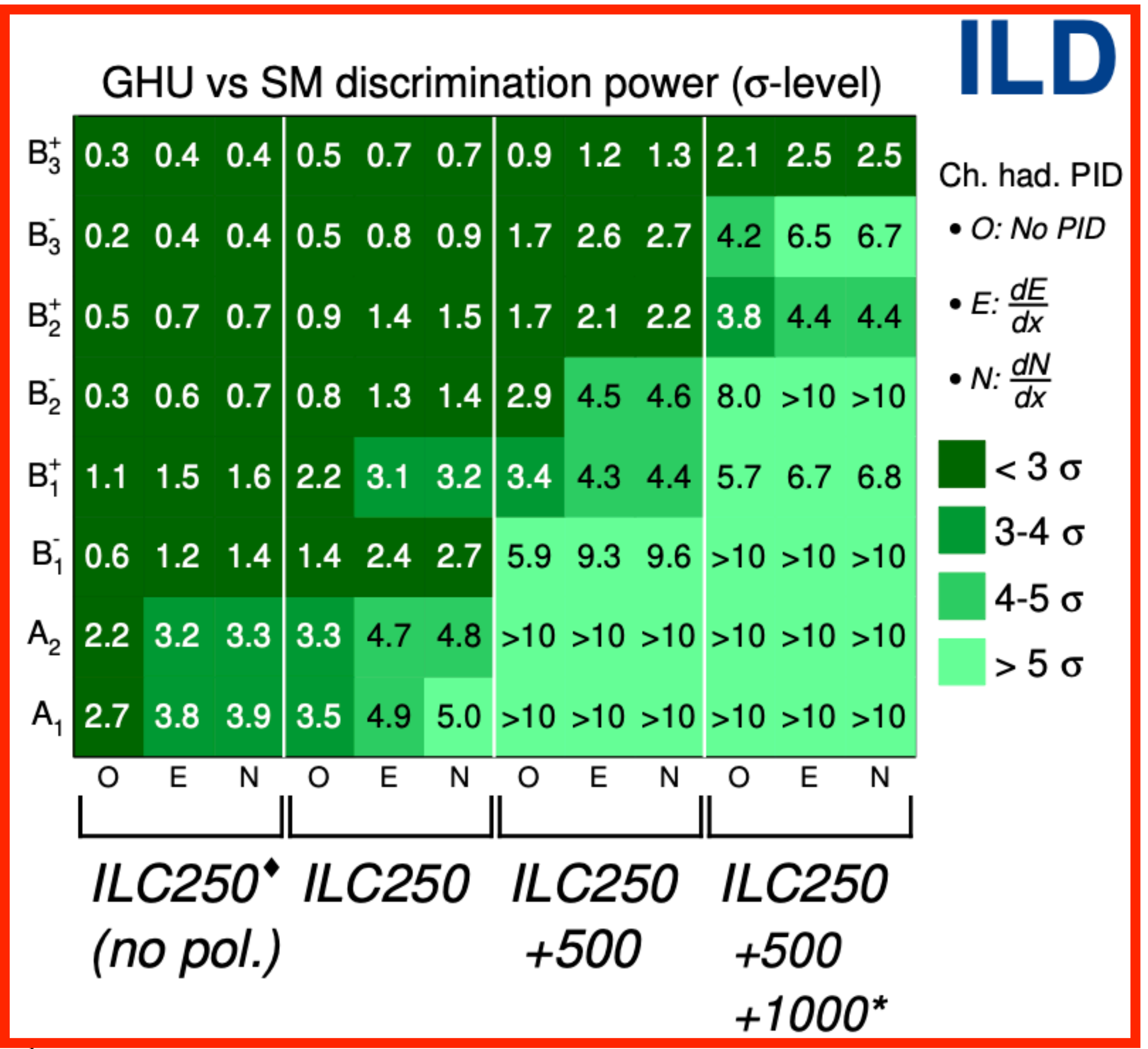

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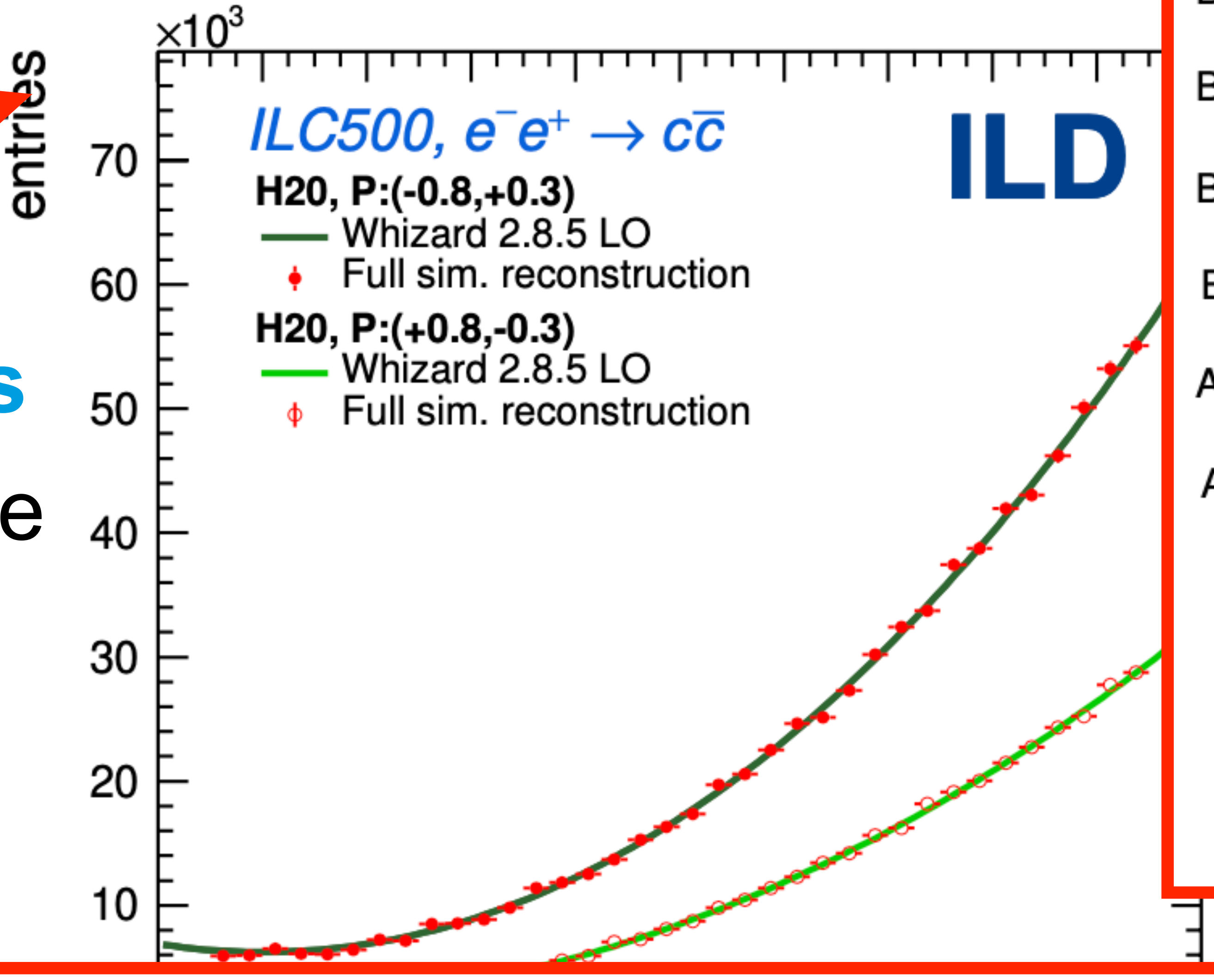

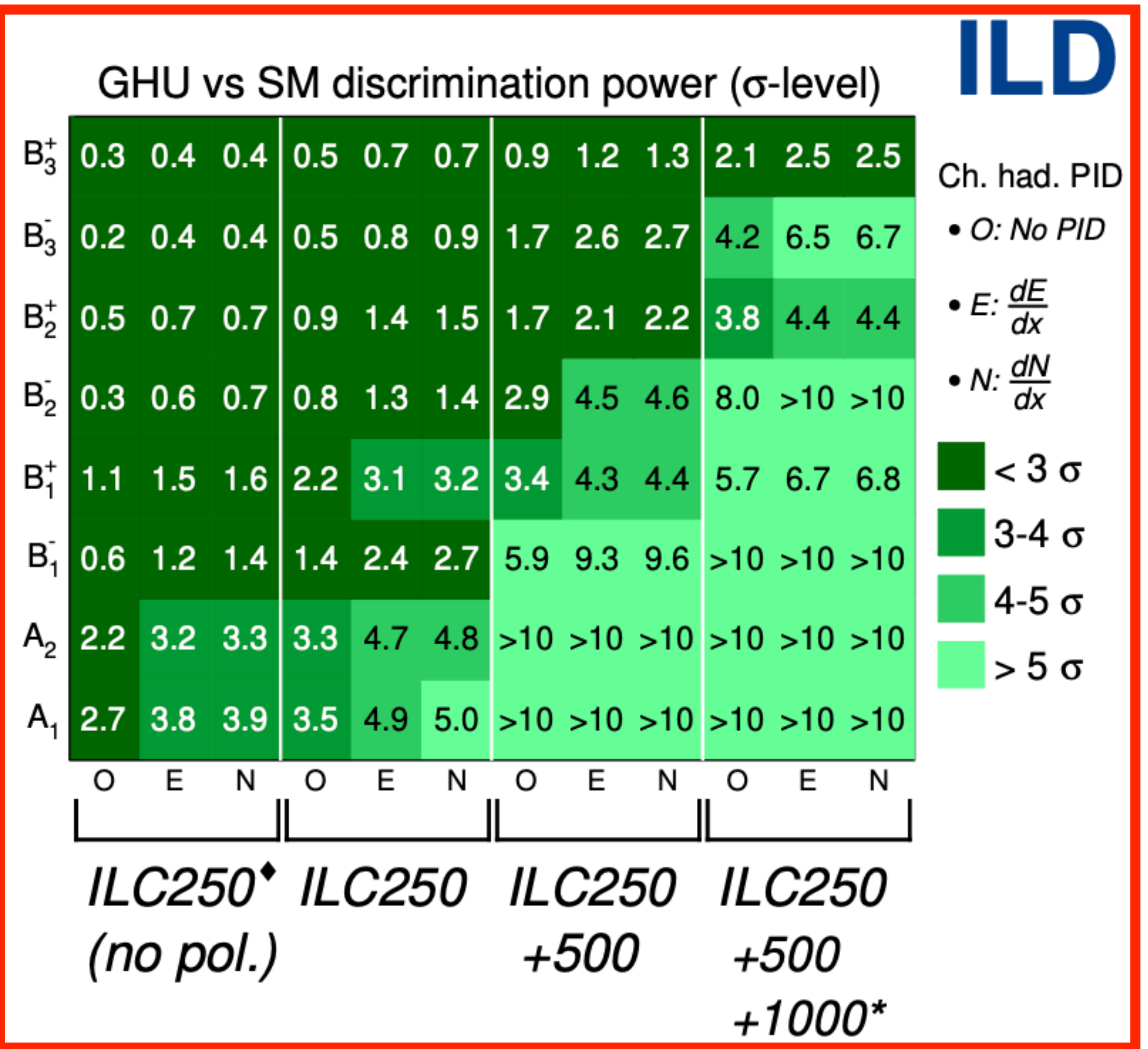

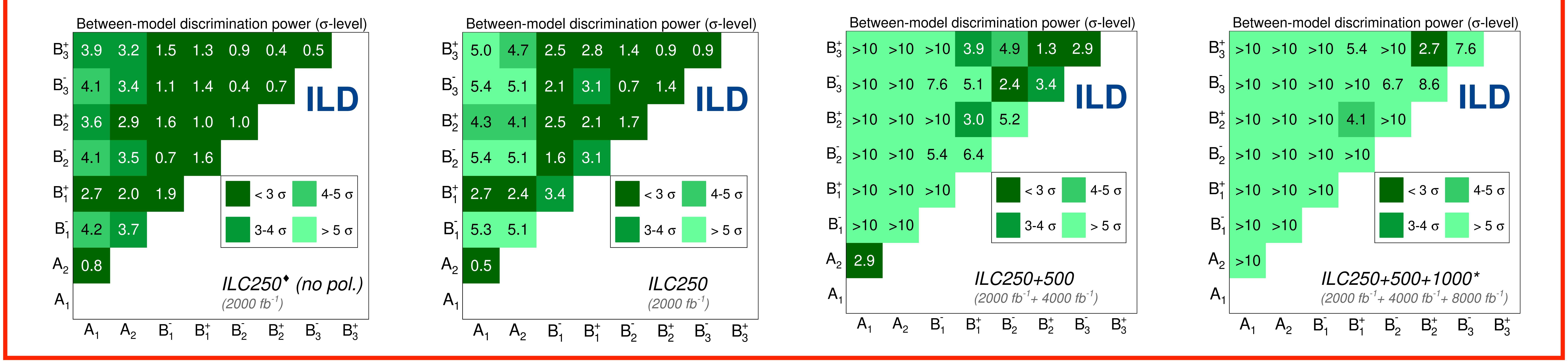

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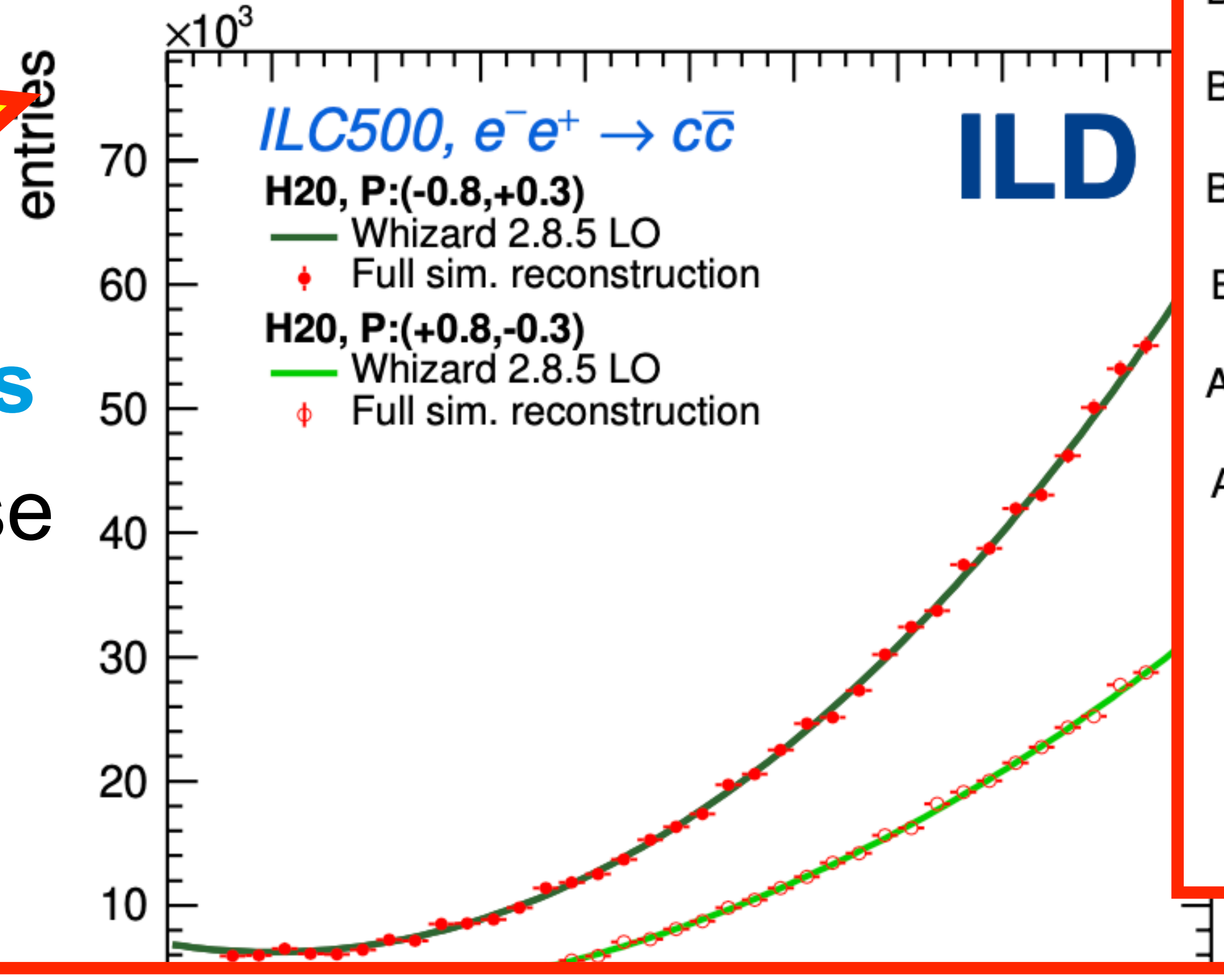

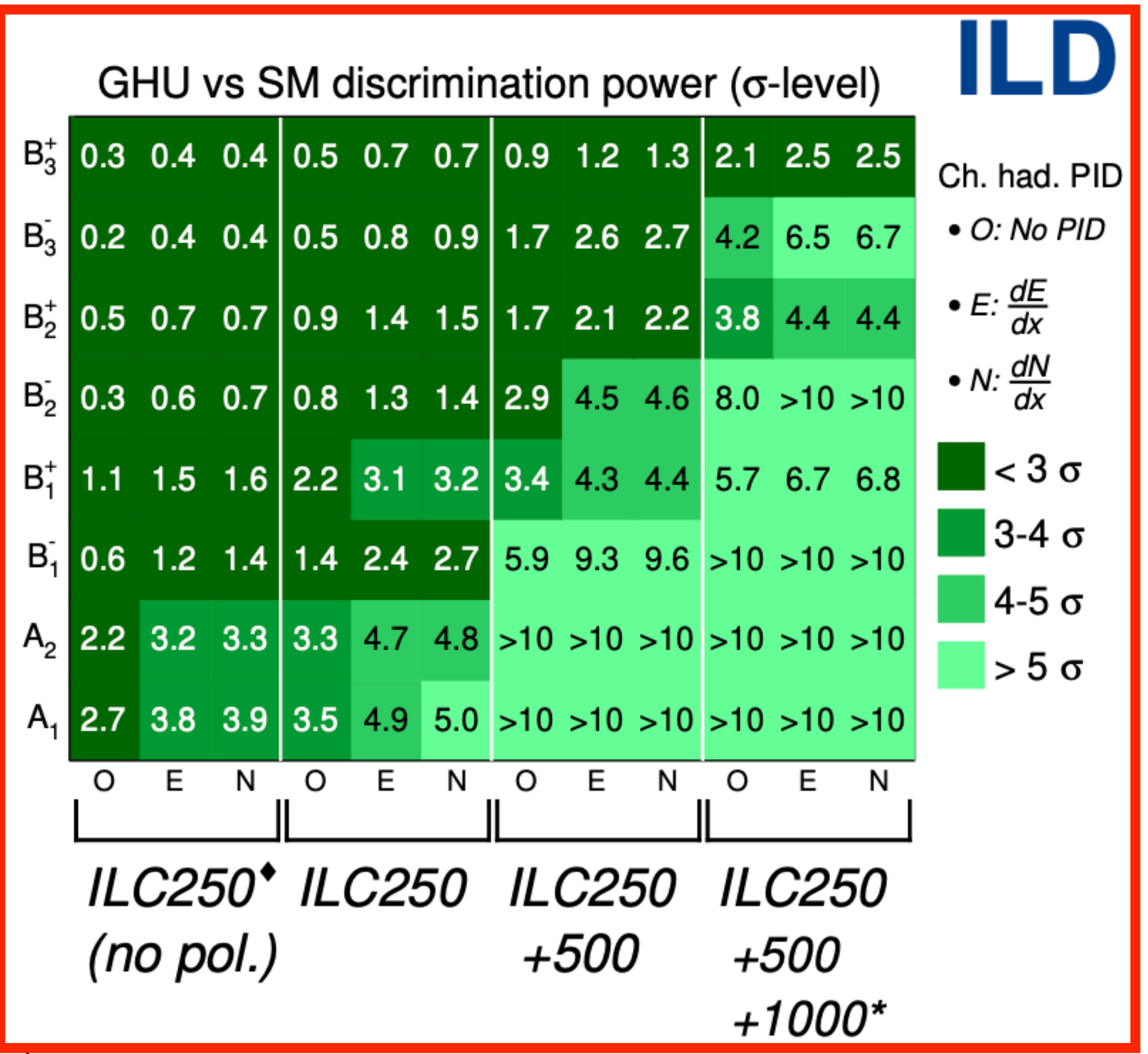

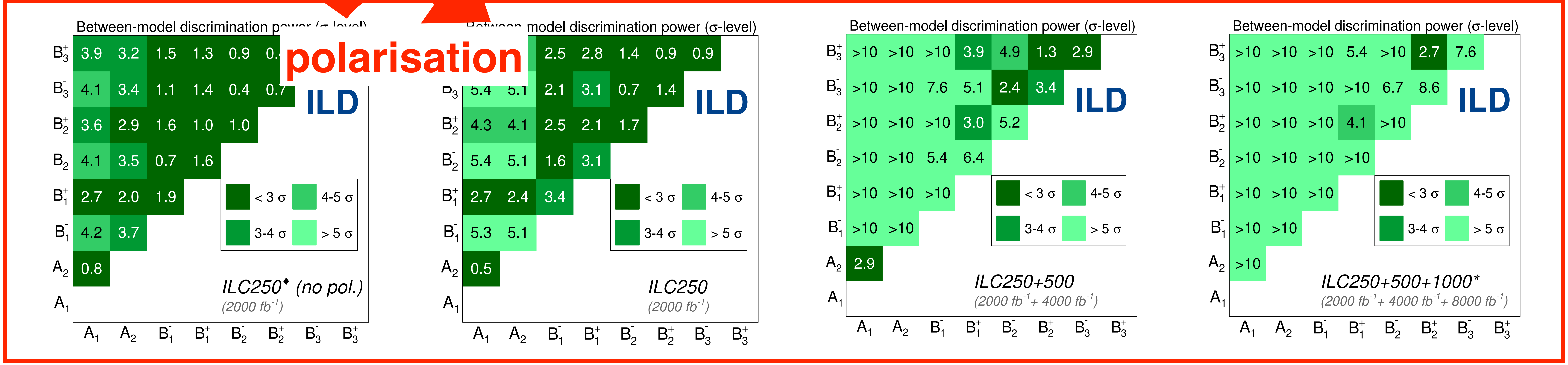

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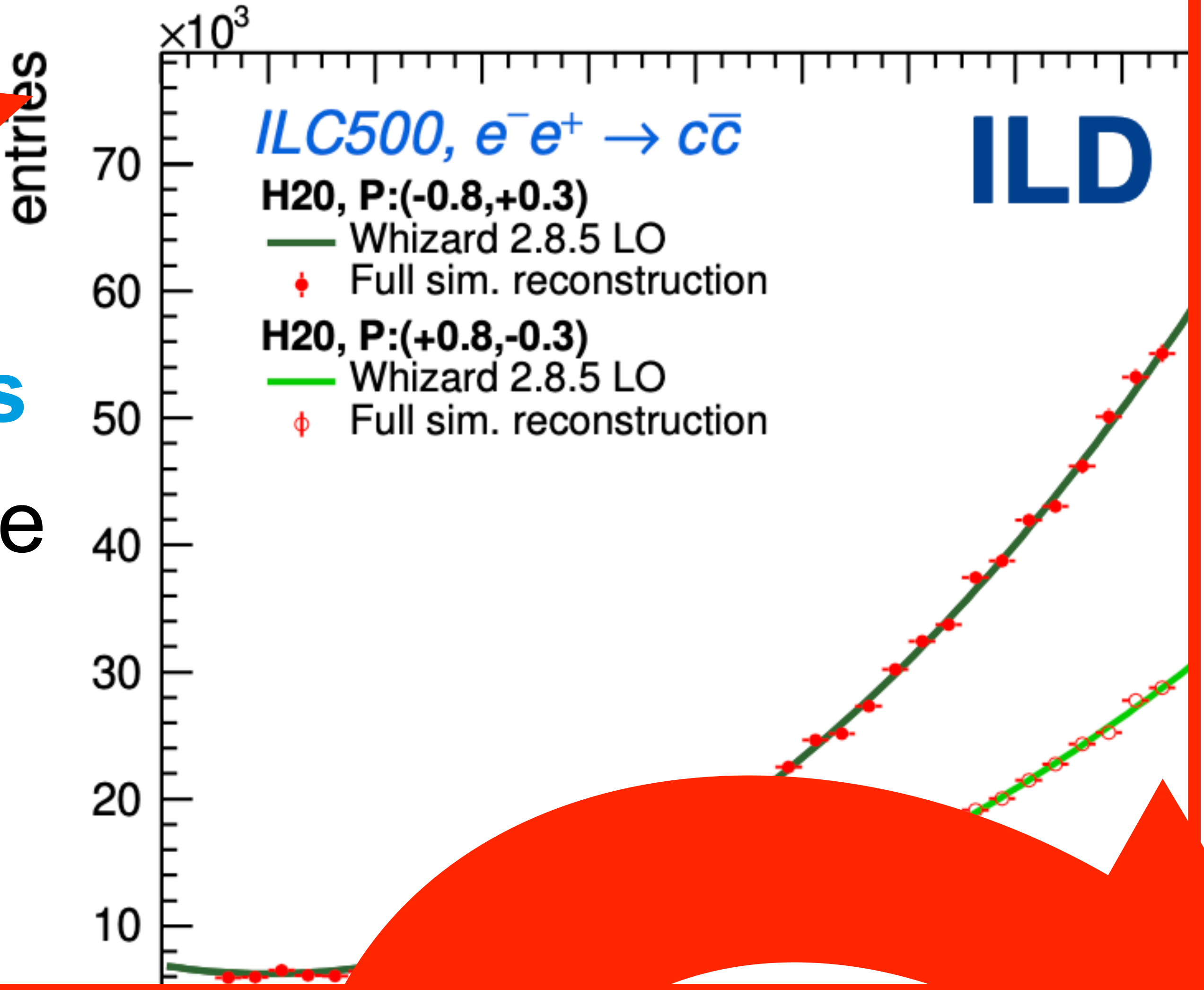
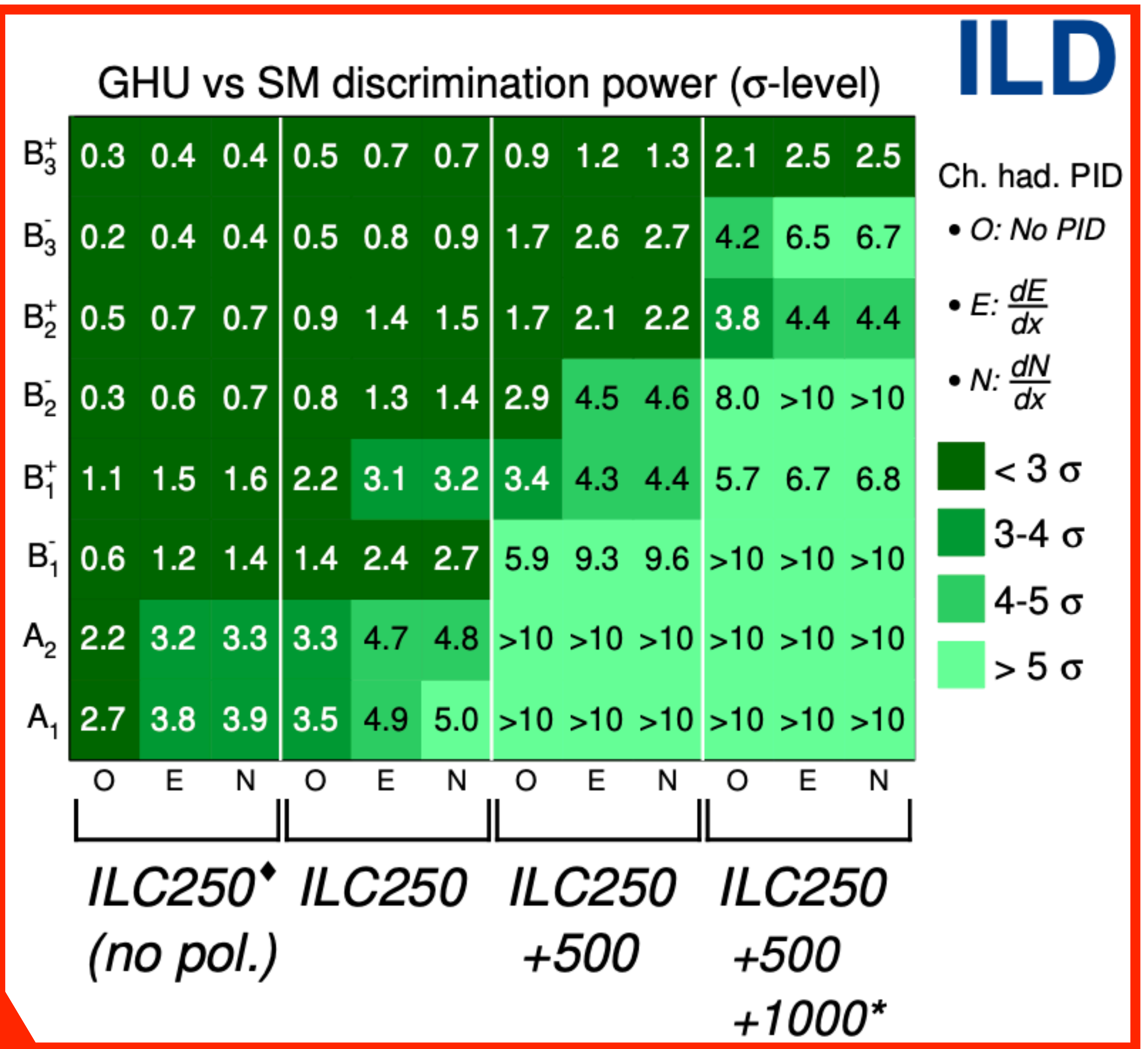
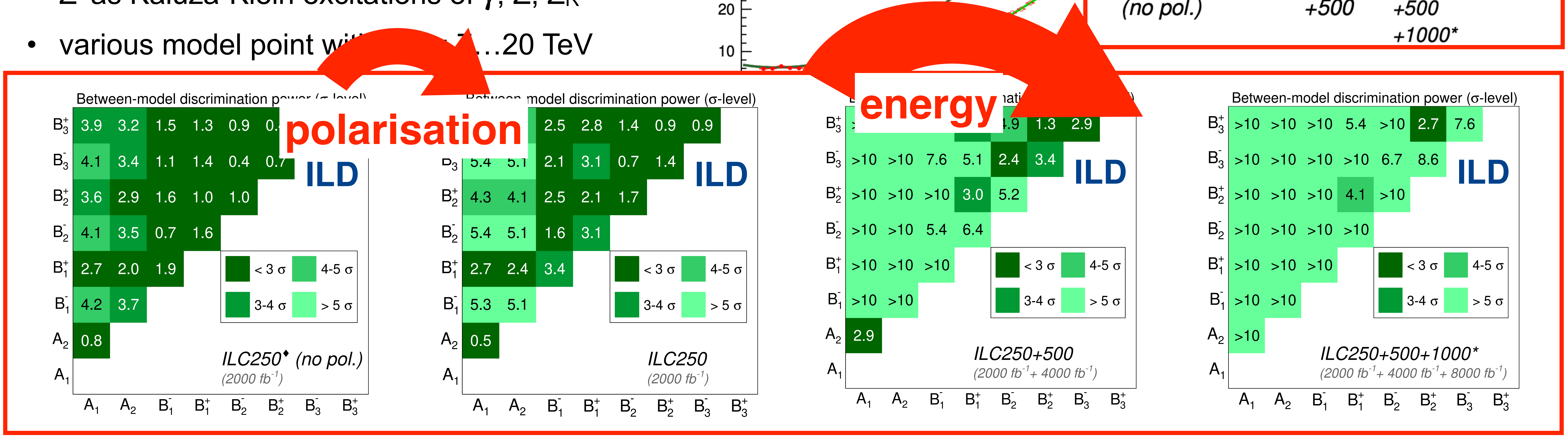






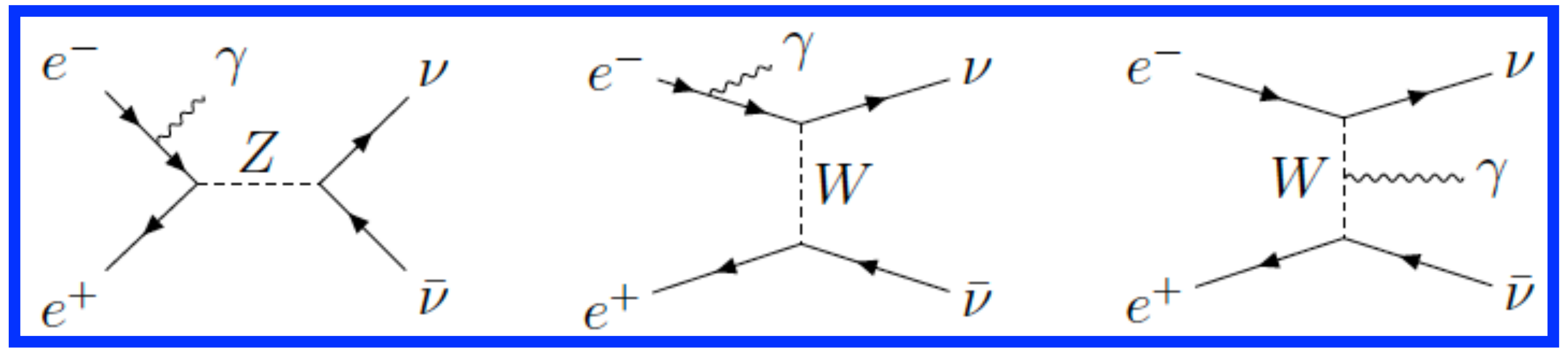
Phys. Rev. D 101 (2020) 7

Polarisation & Beyond the SM: Dark Matter

Background reduction & Systematics

- mono-photon search $e^+e^- \to \chi\chi\gamma$
- main SM background: $e^+e^- \to \nu\nu\gamma$

  reduced ~10x with polarisation



- shape of observable distributions changes with polarisation sign
  => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–)
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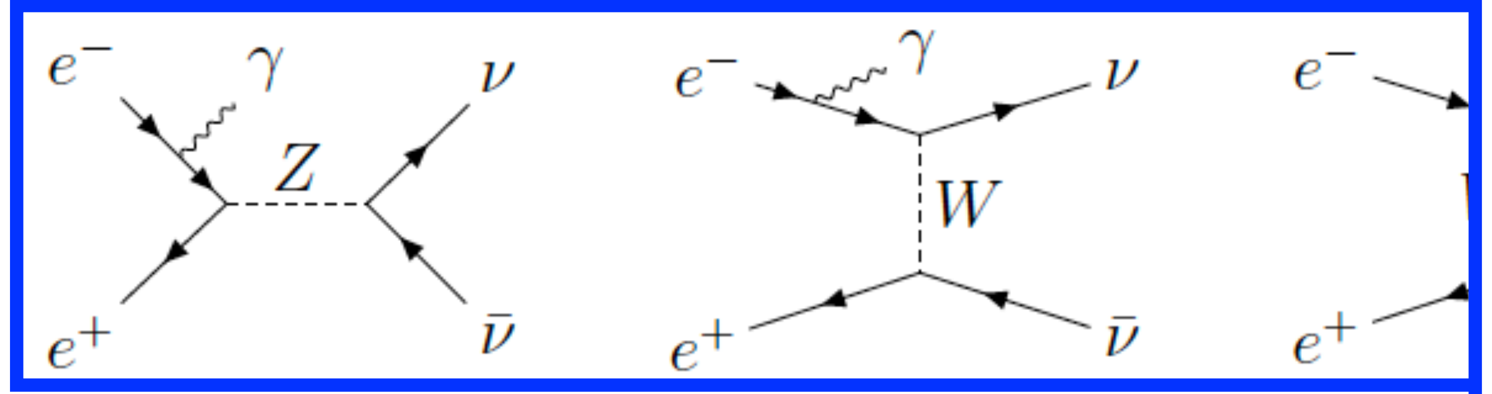

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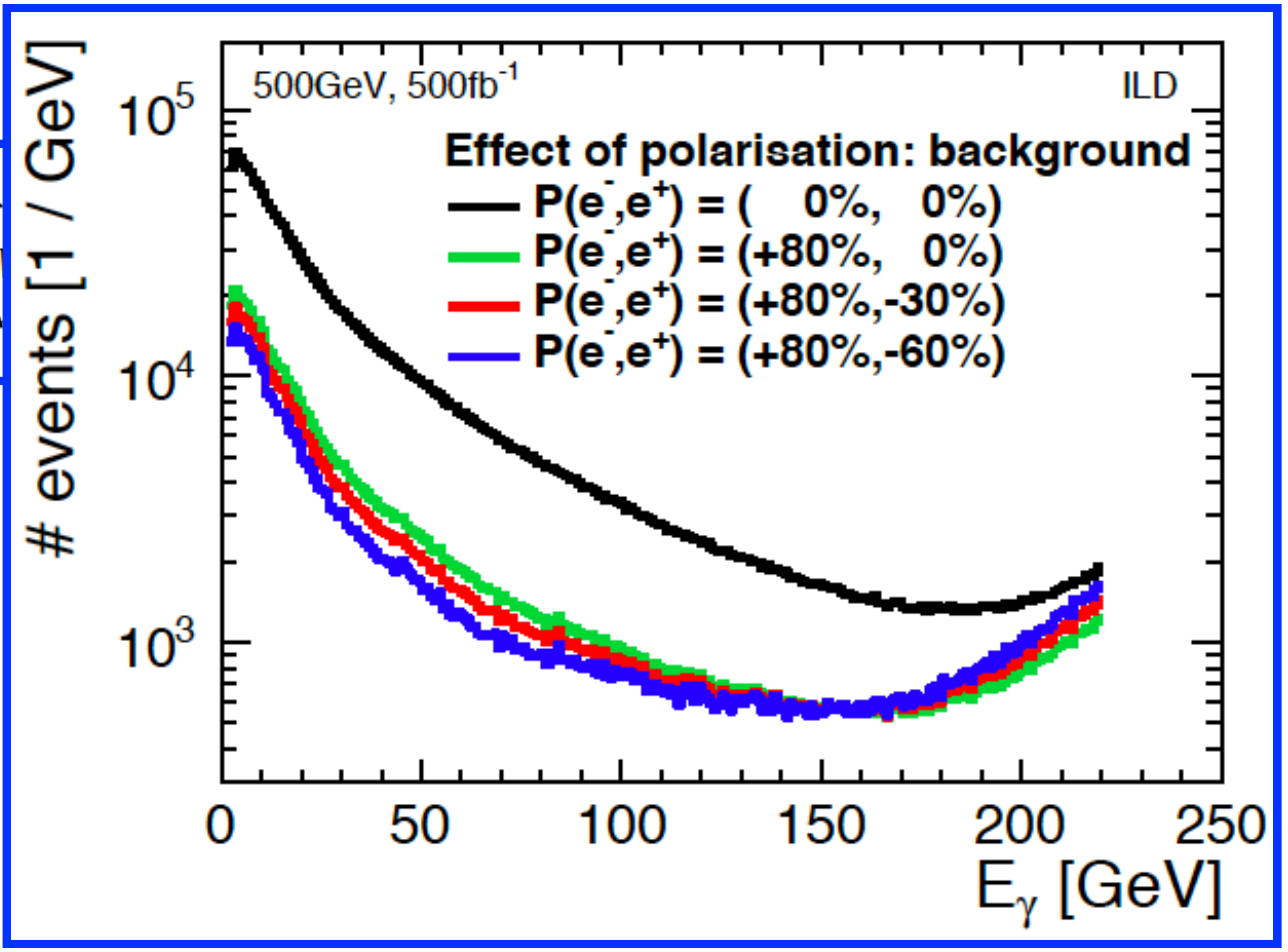

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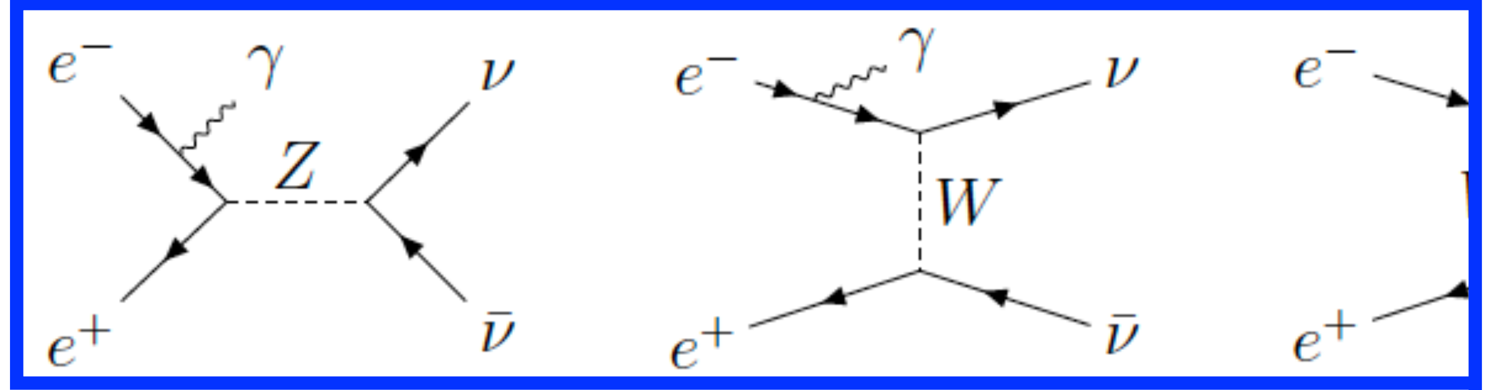

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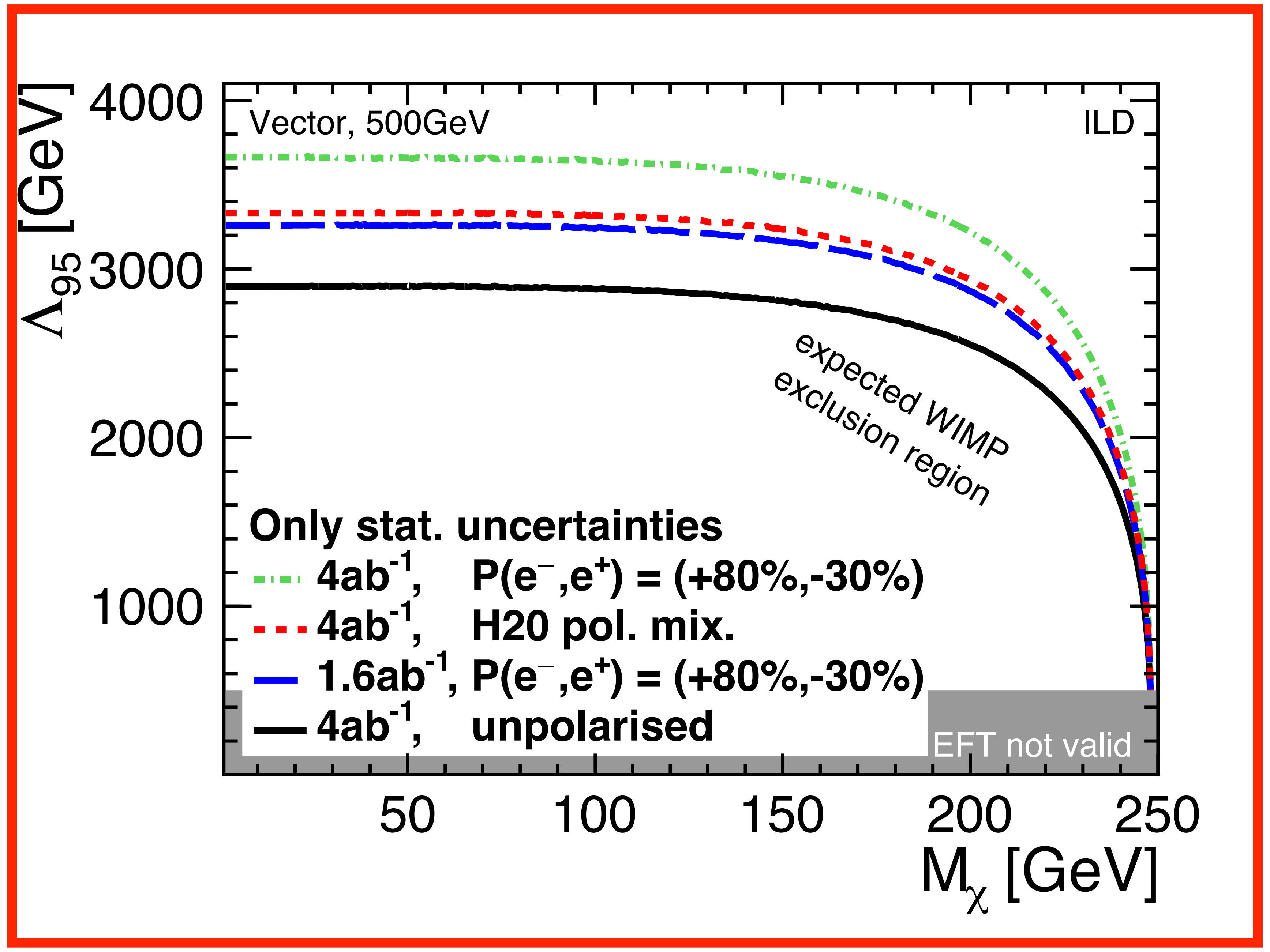

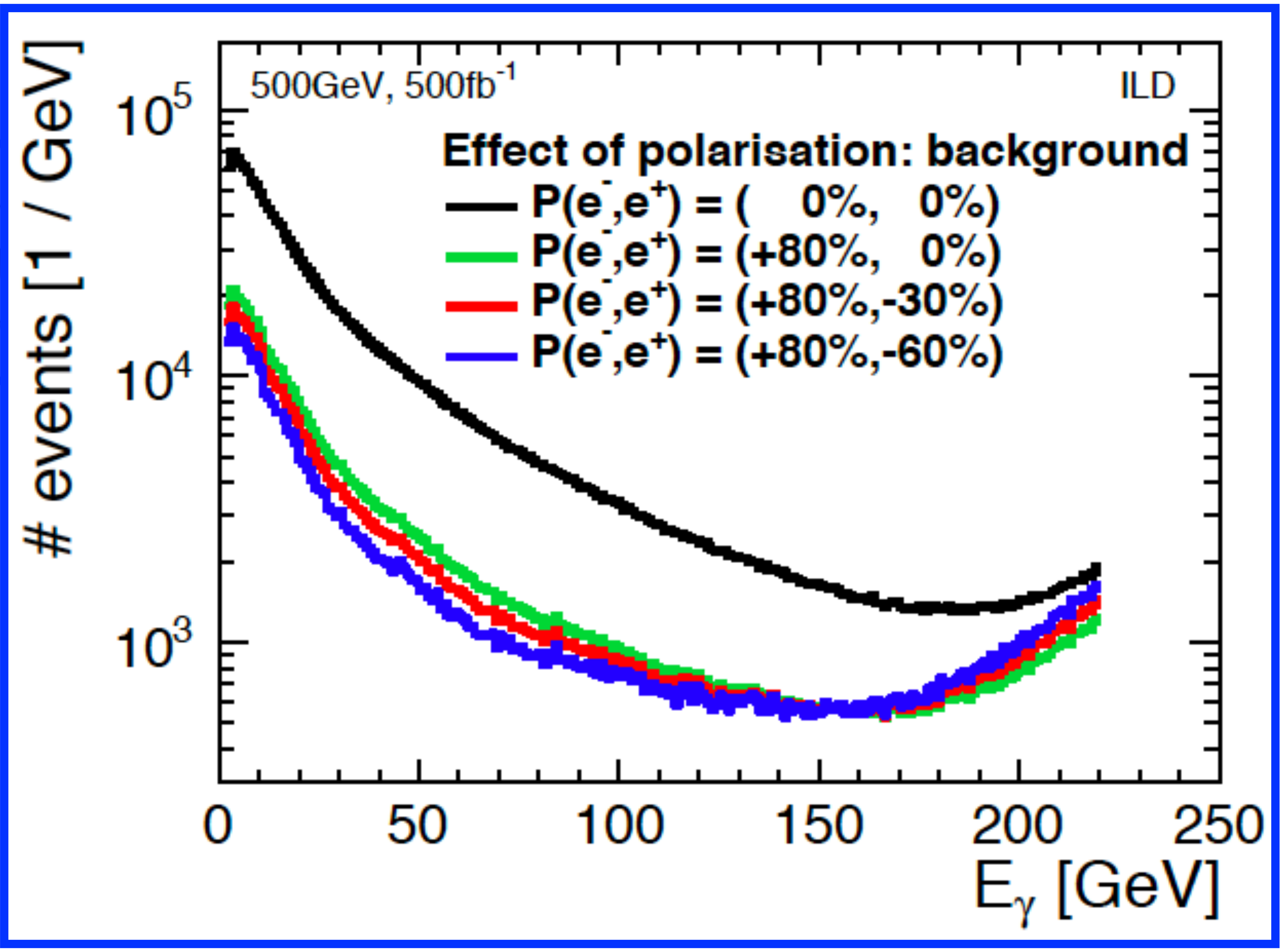

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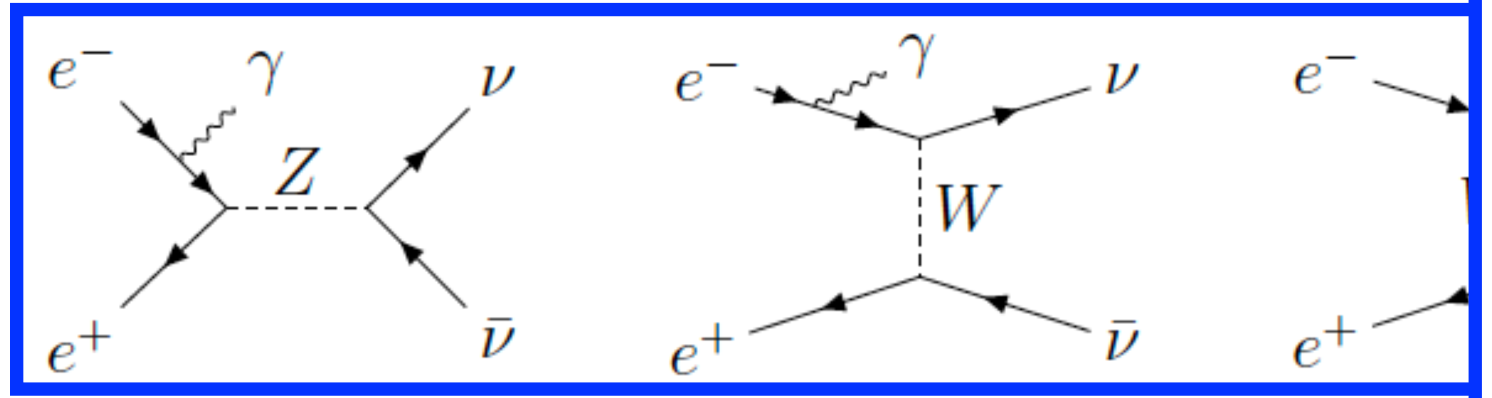

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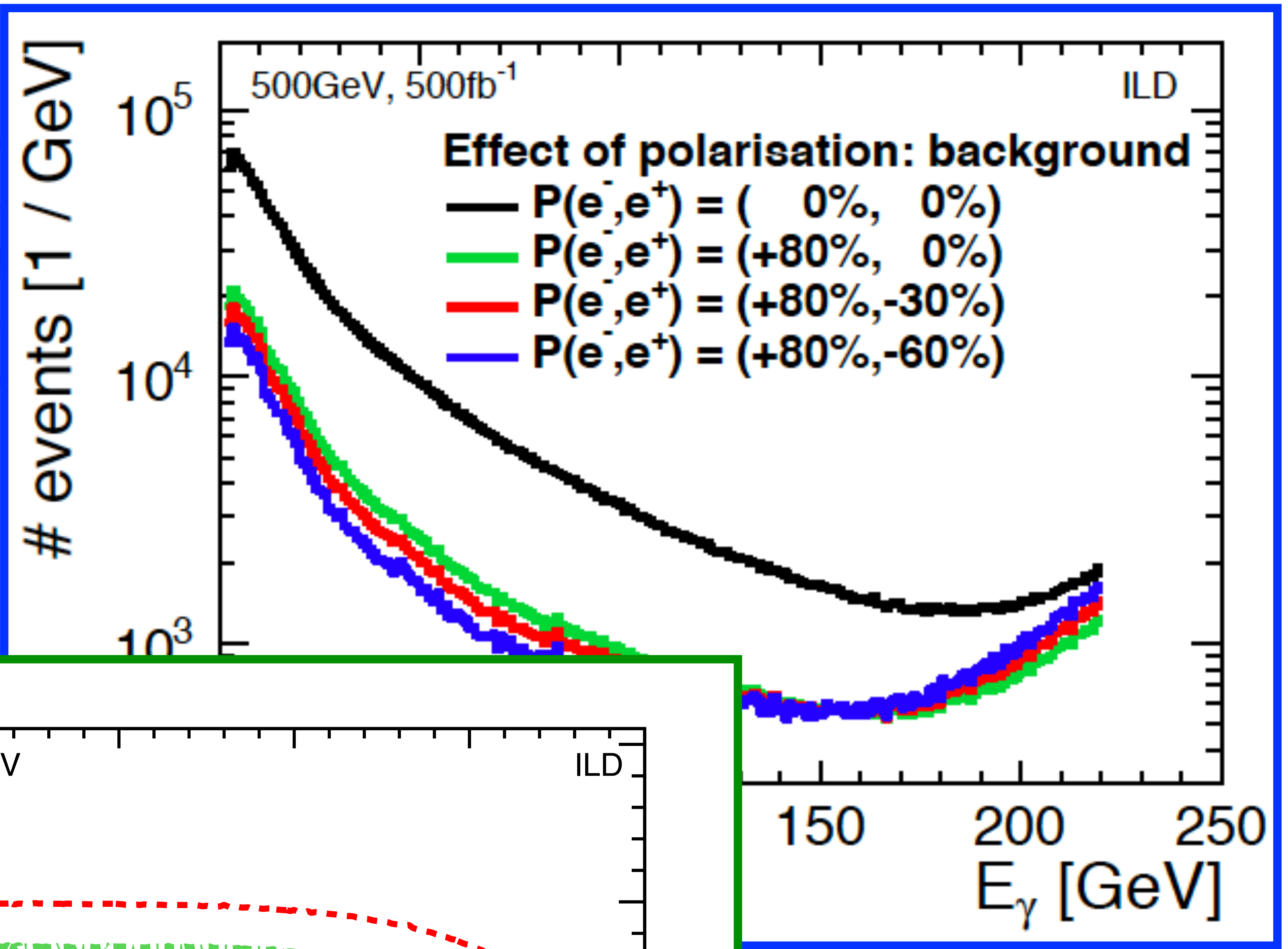

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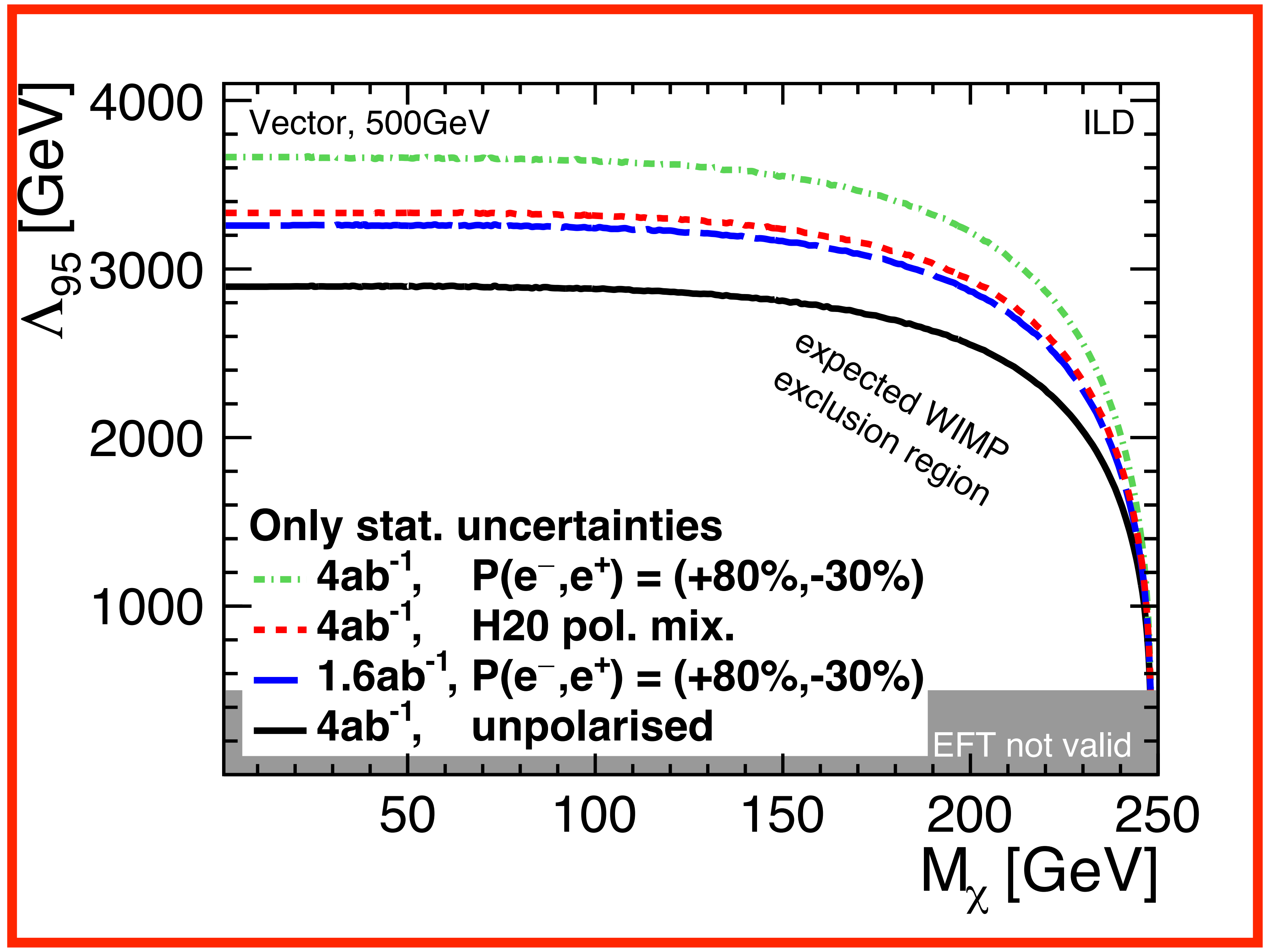

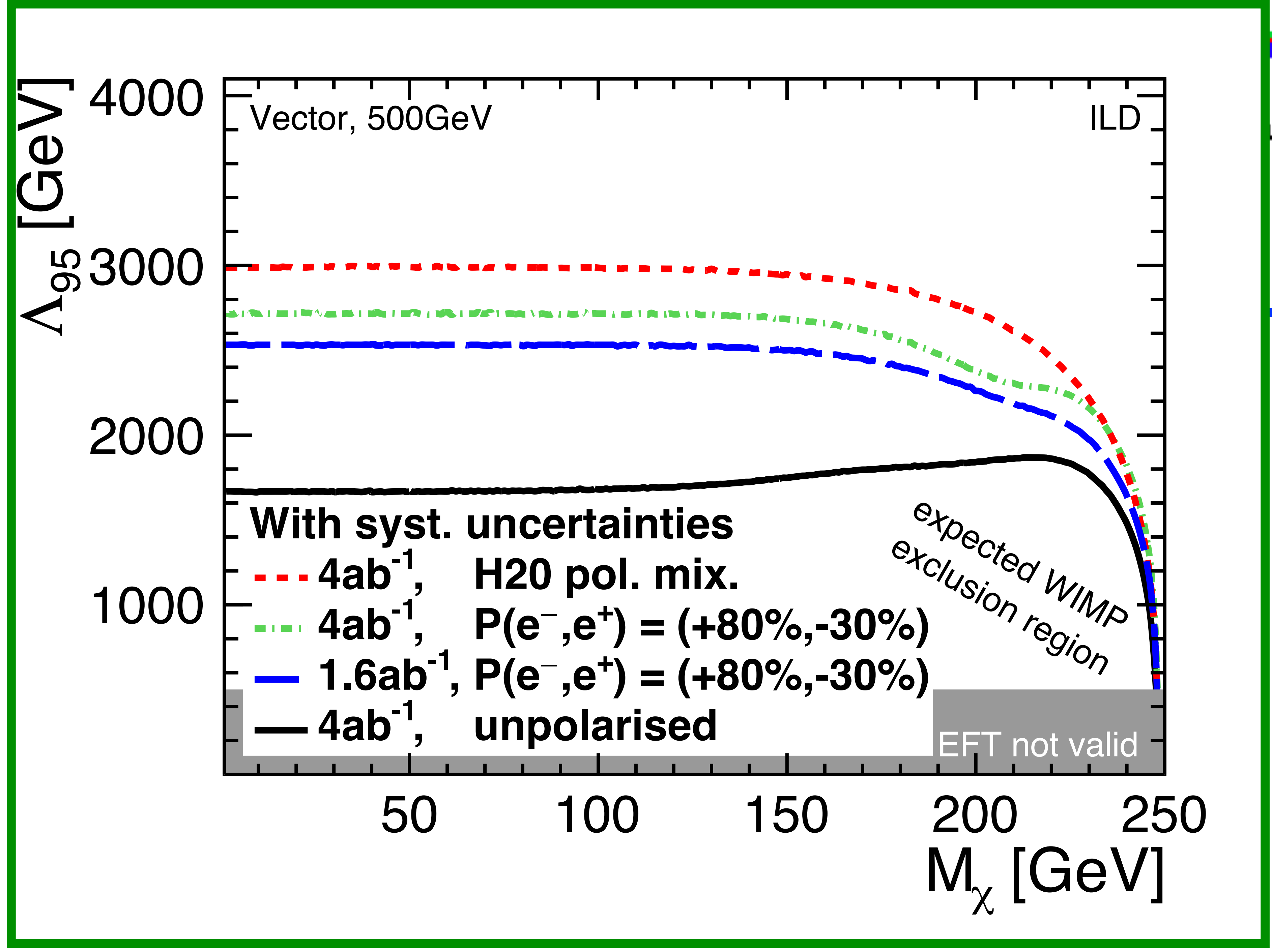

Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case

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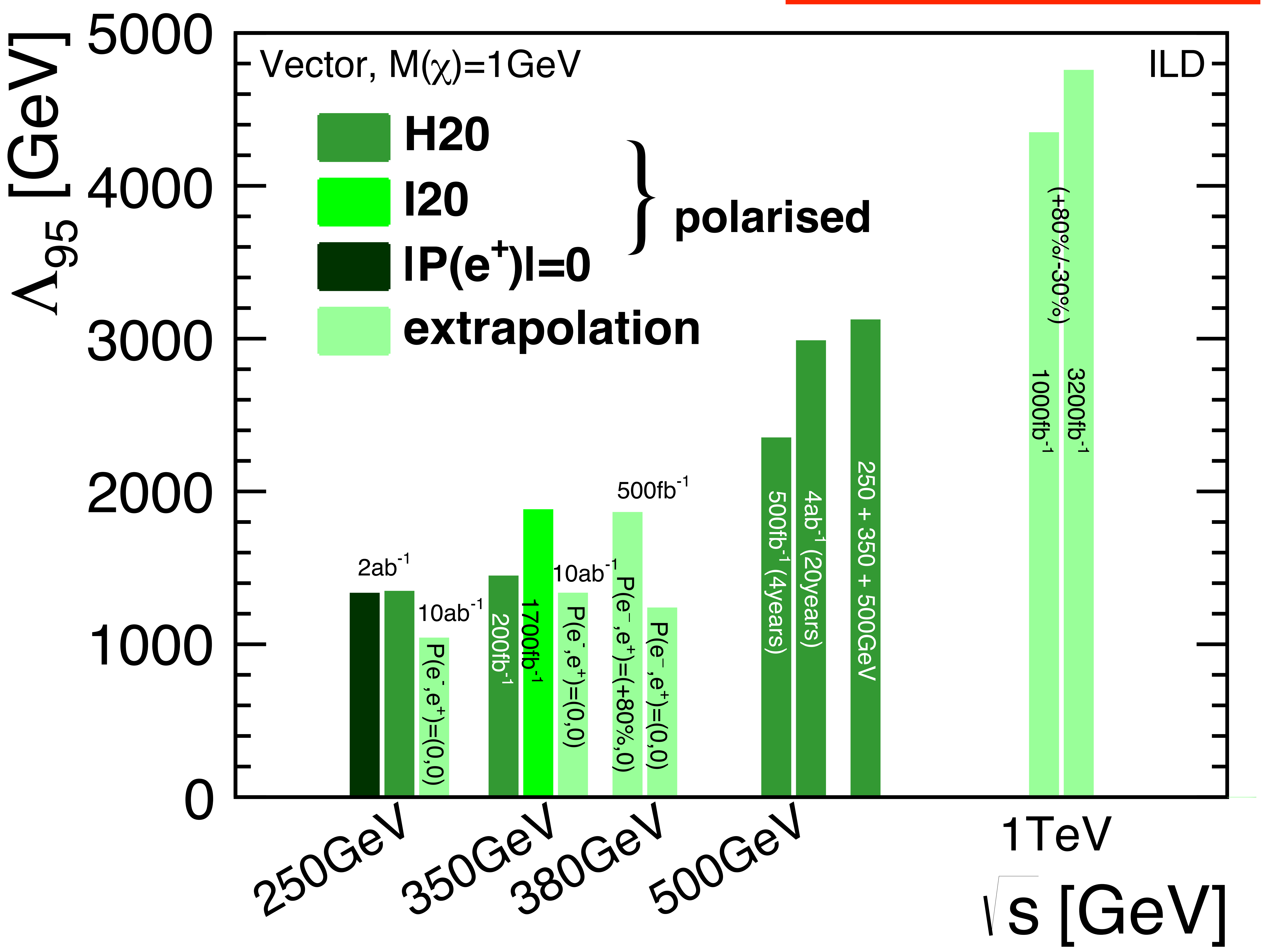

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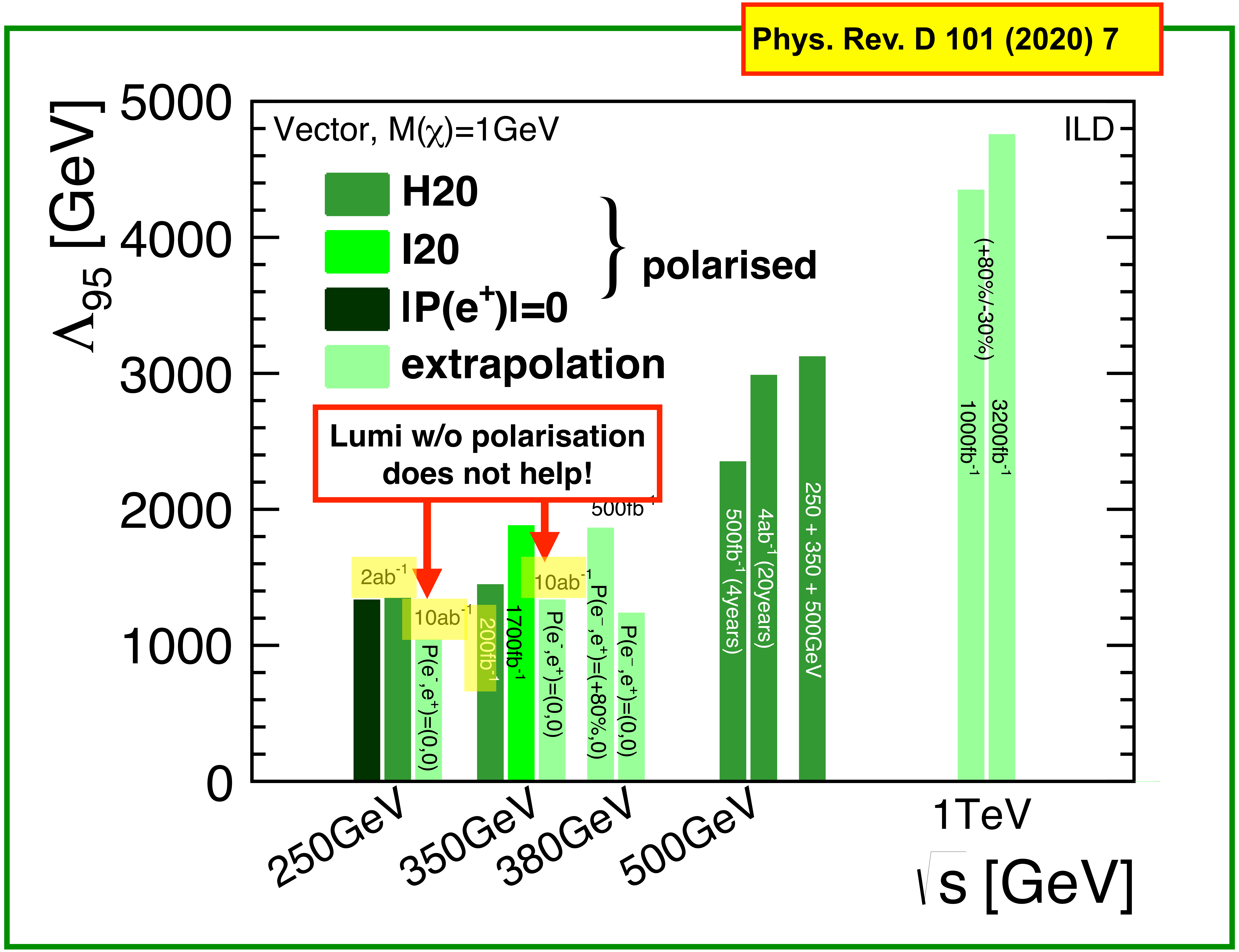

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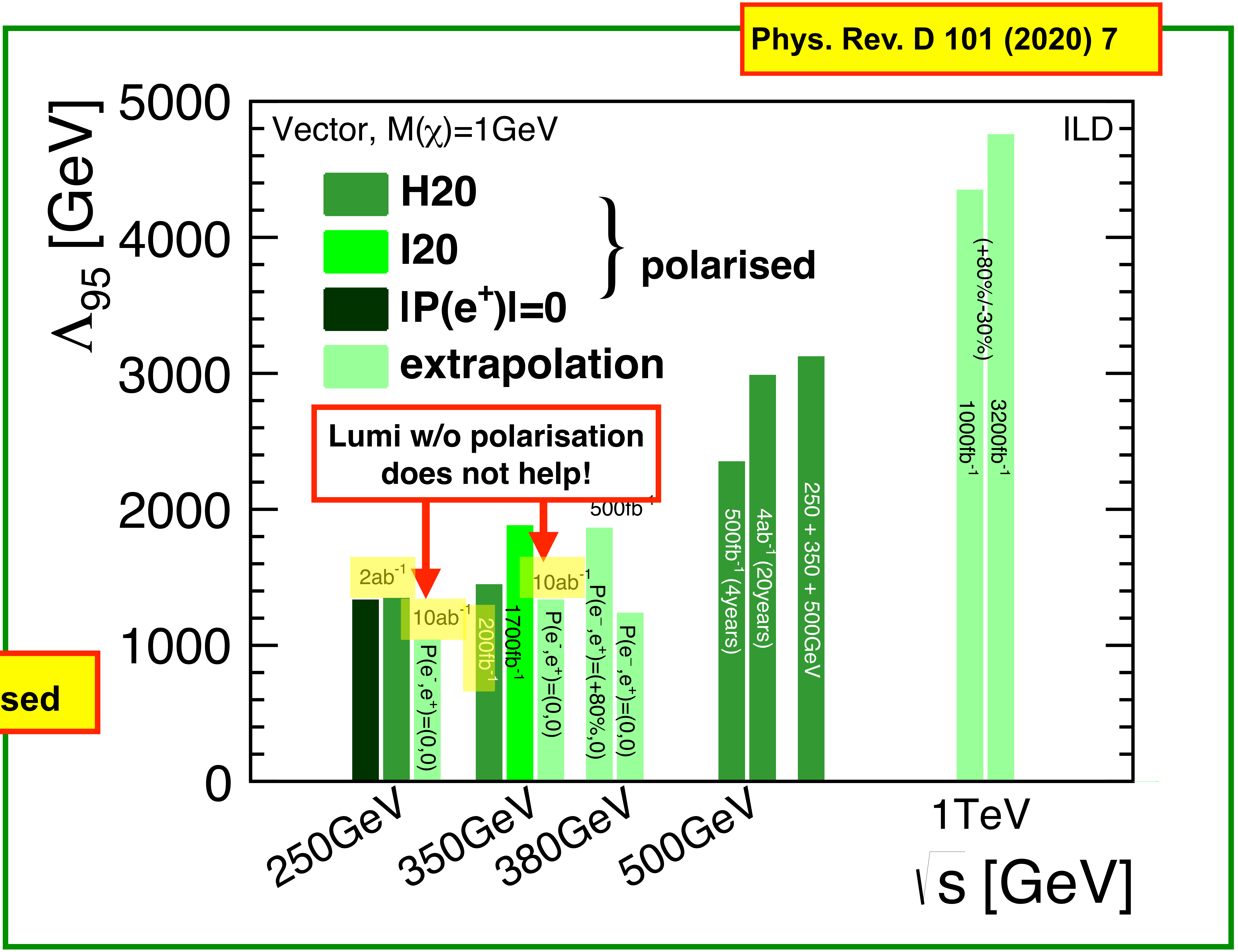

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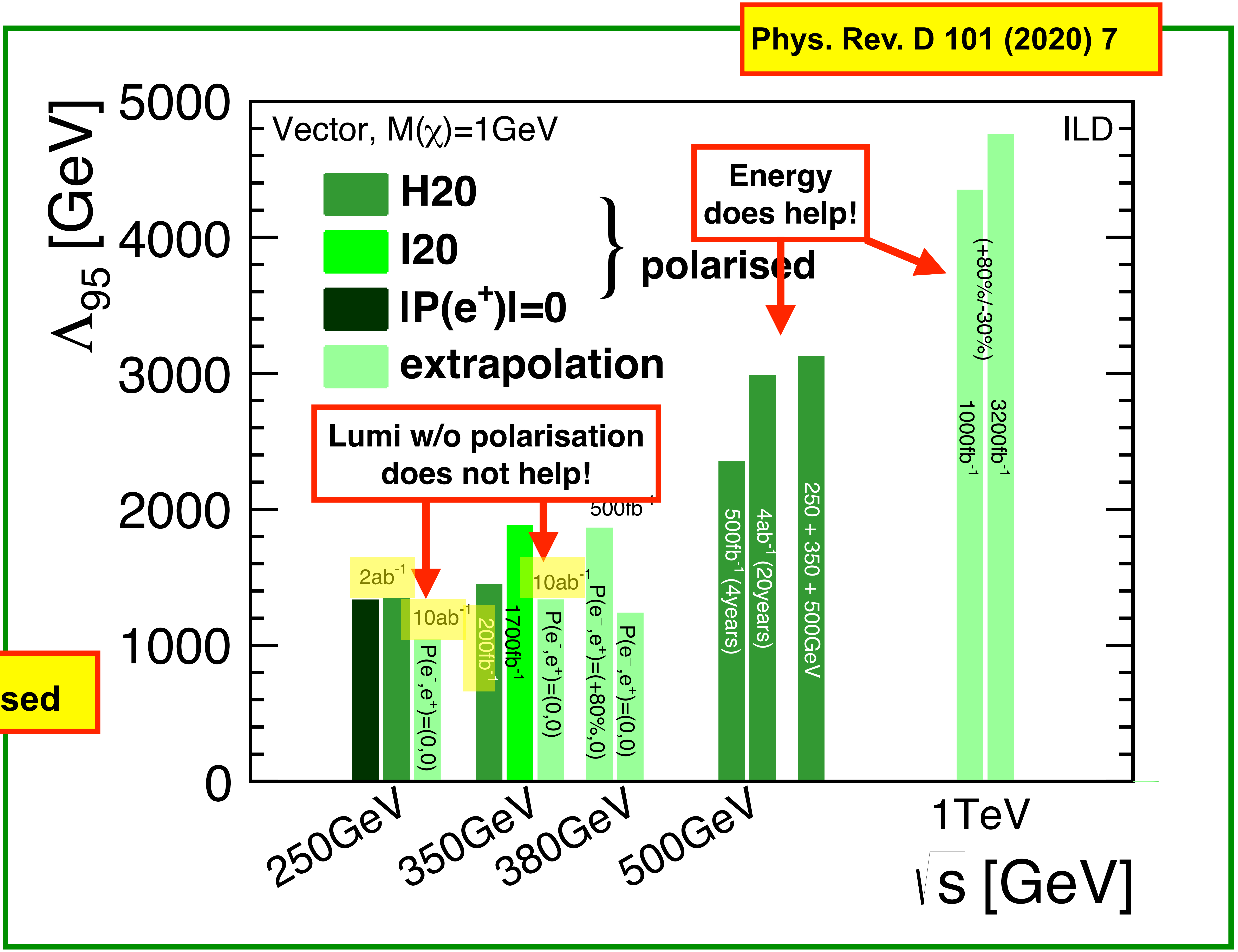
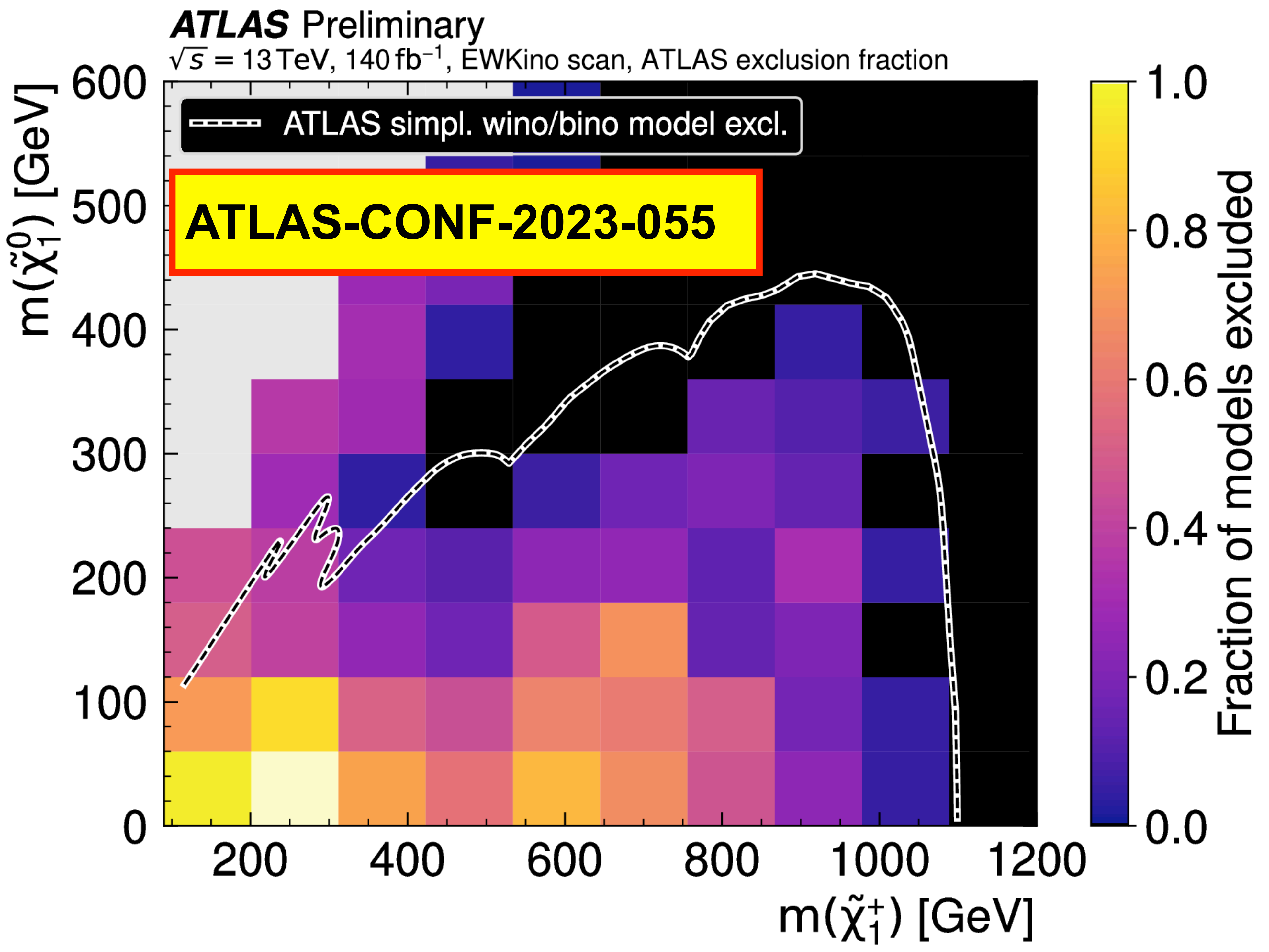


Light Higgsinos

Or: beware what LHC limits really mean!

- LHC does very well on exploring 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



Light Higgsinos

Or: beware what LHC limits really mean!

- LHC does very well on exploring 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
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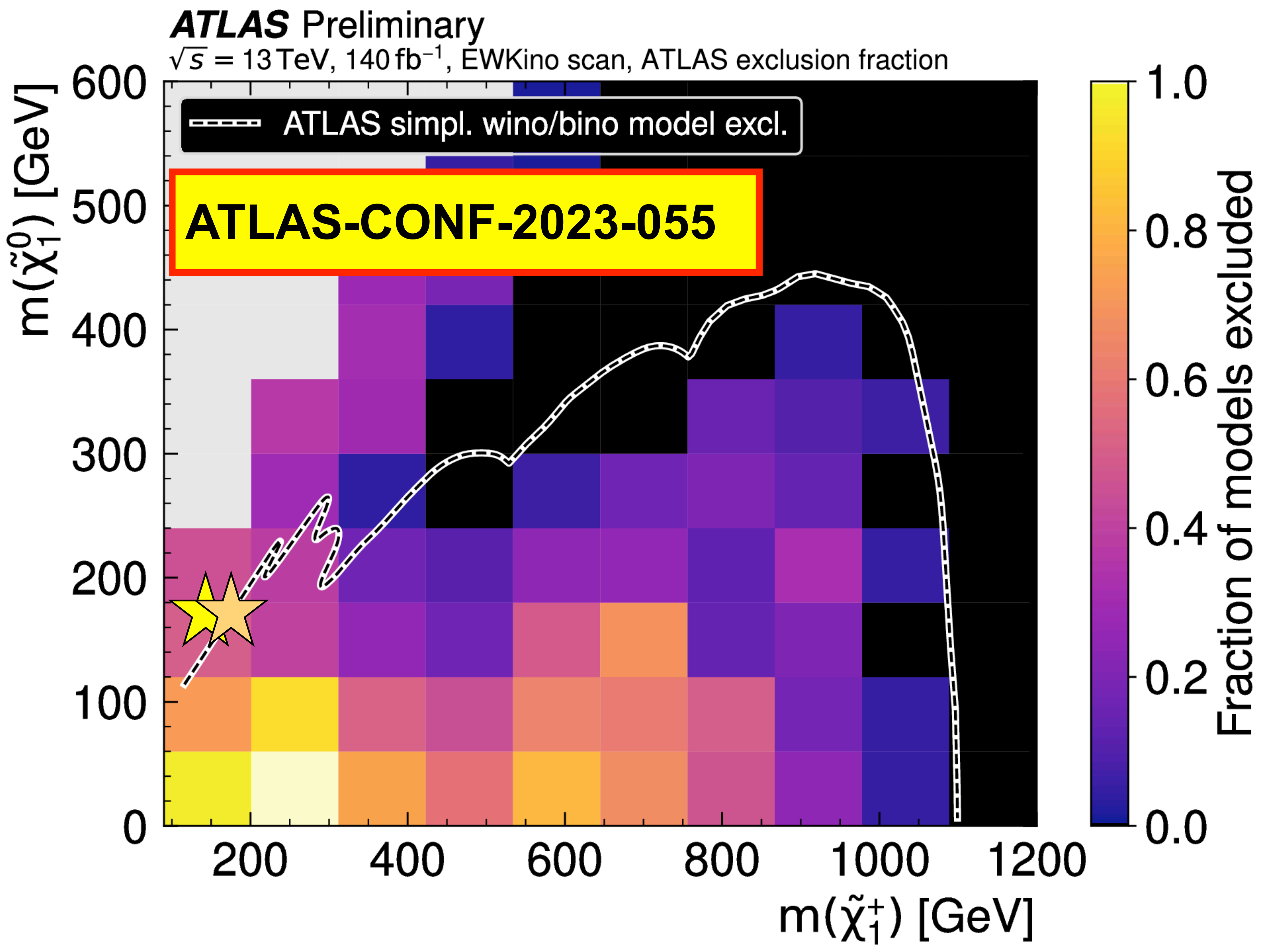

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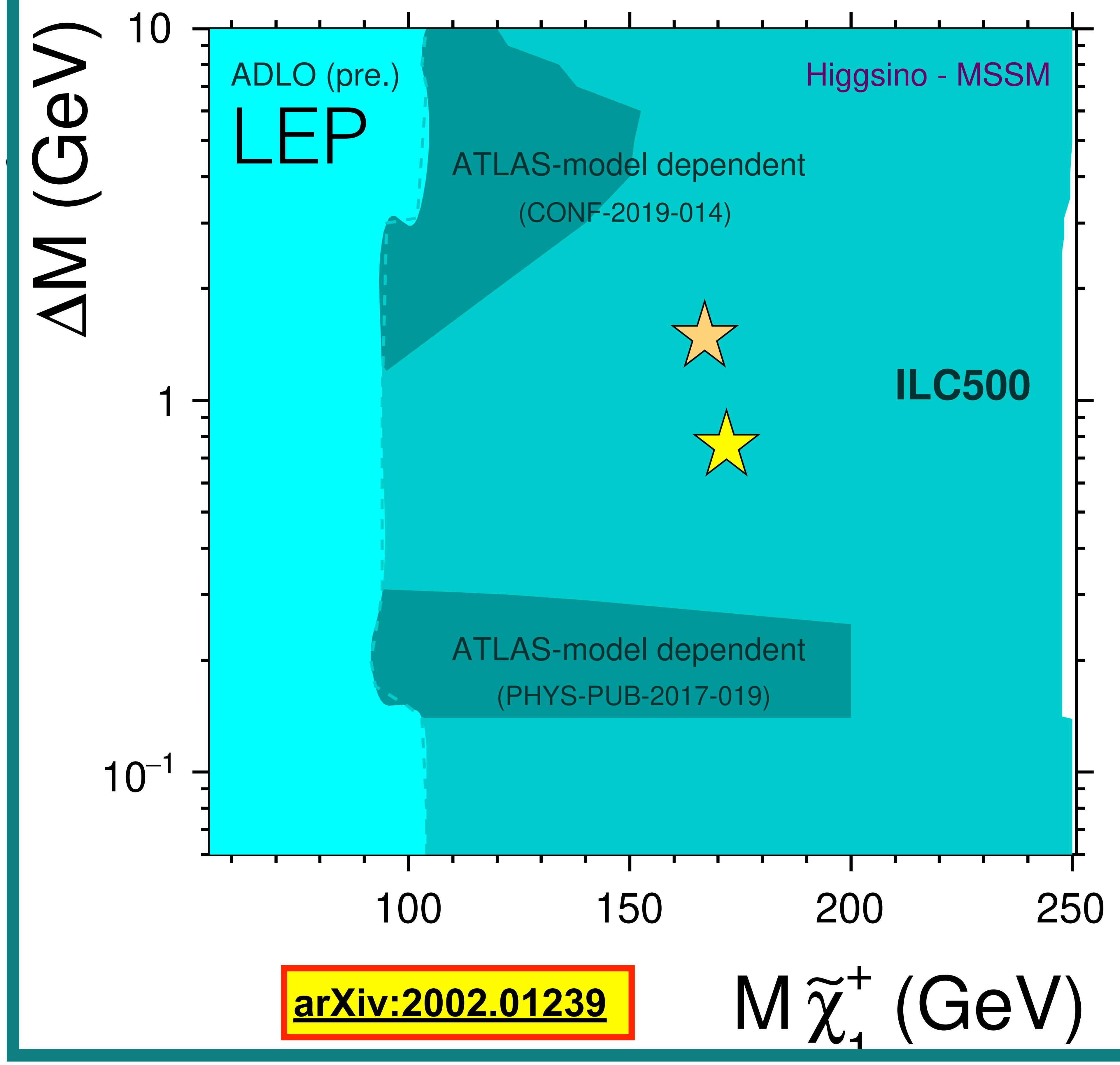

arXiv:2002.01239

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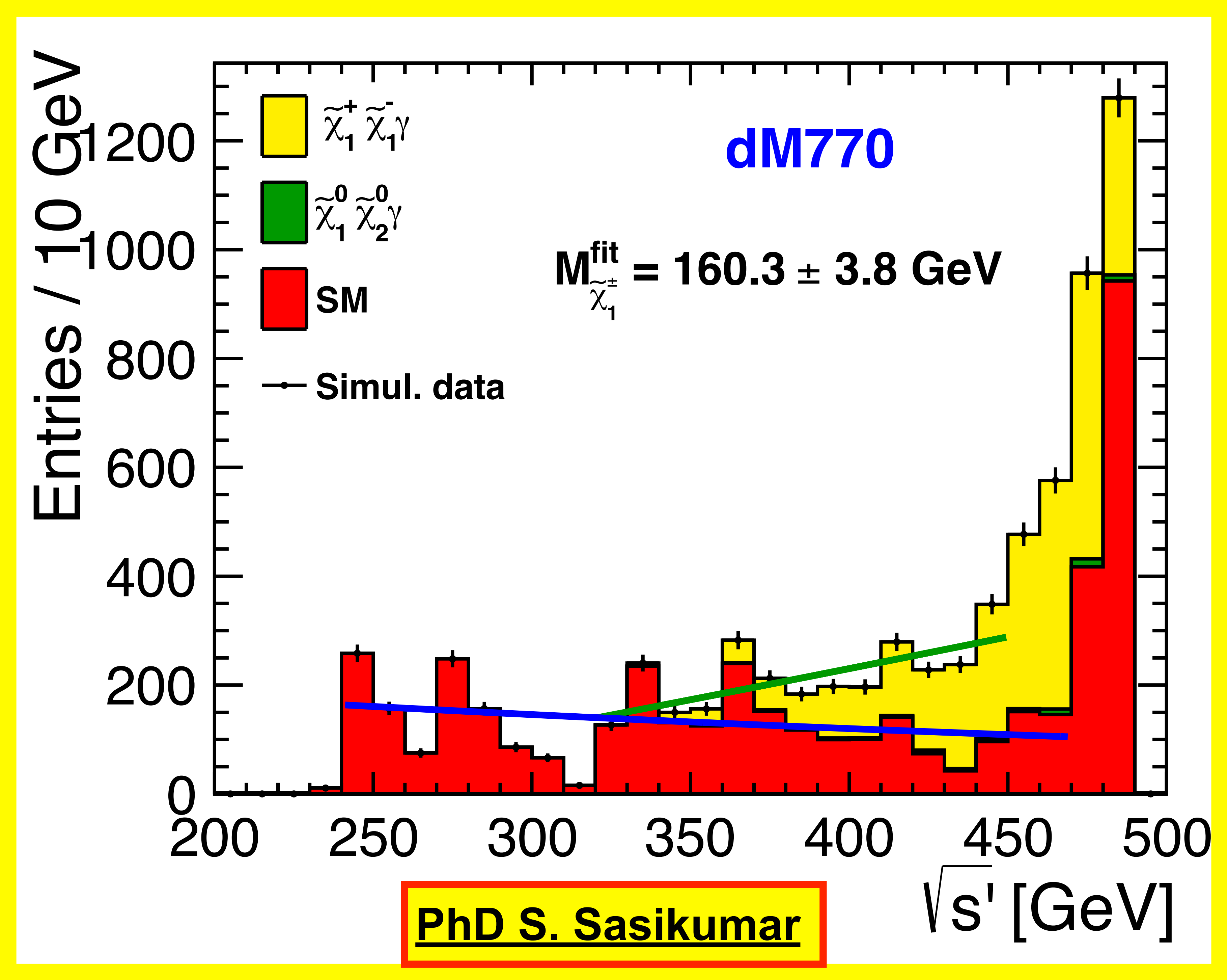

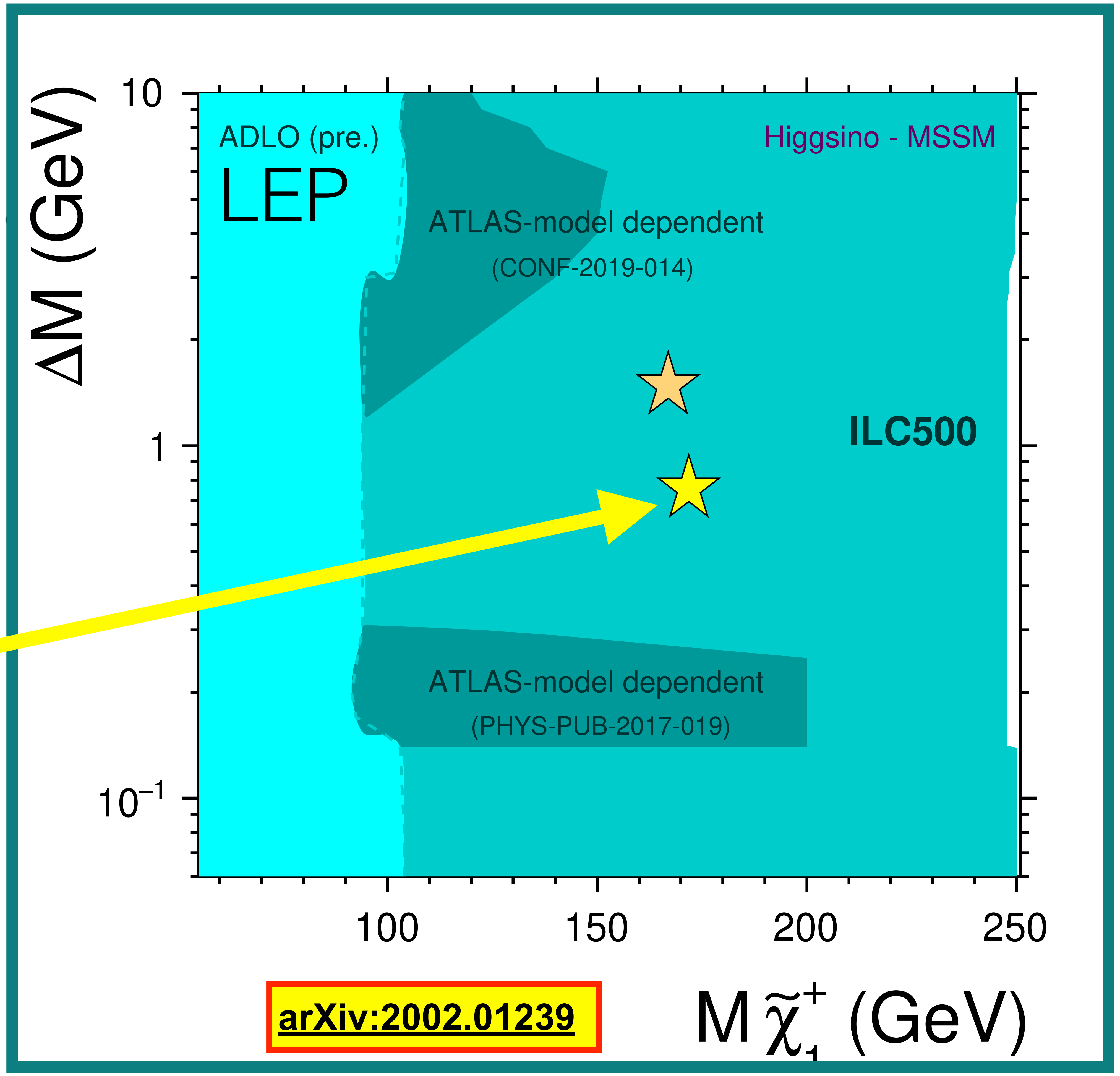

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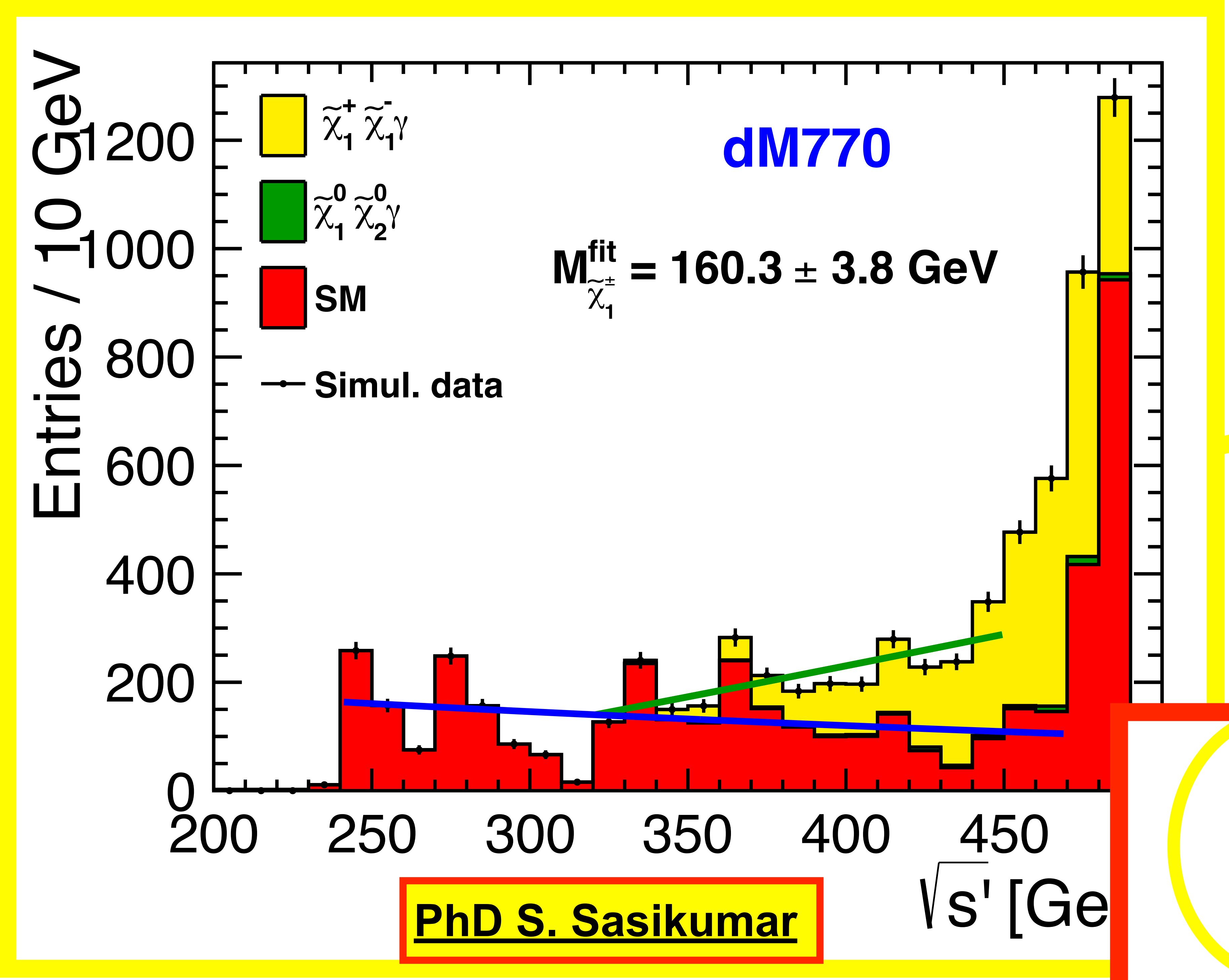

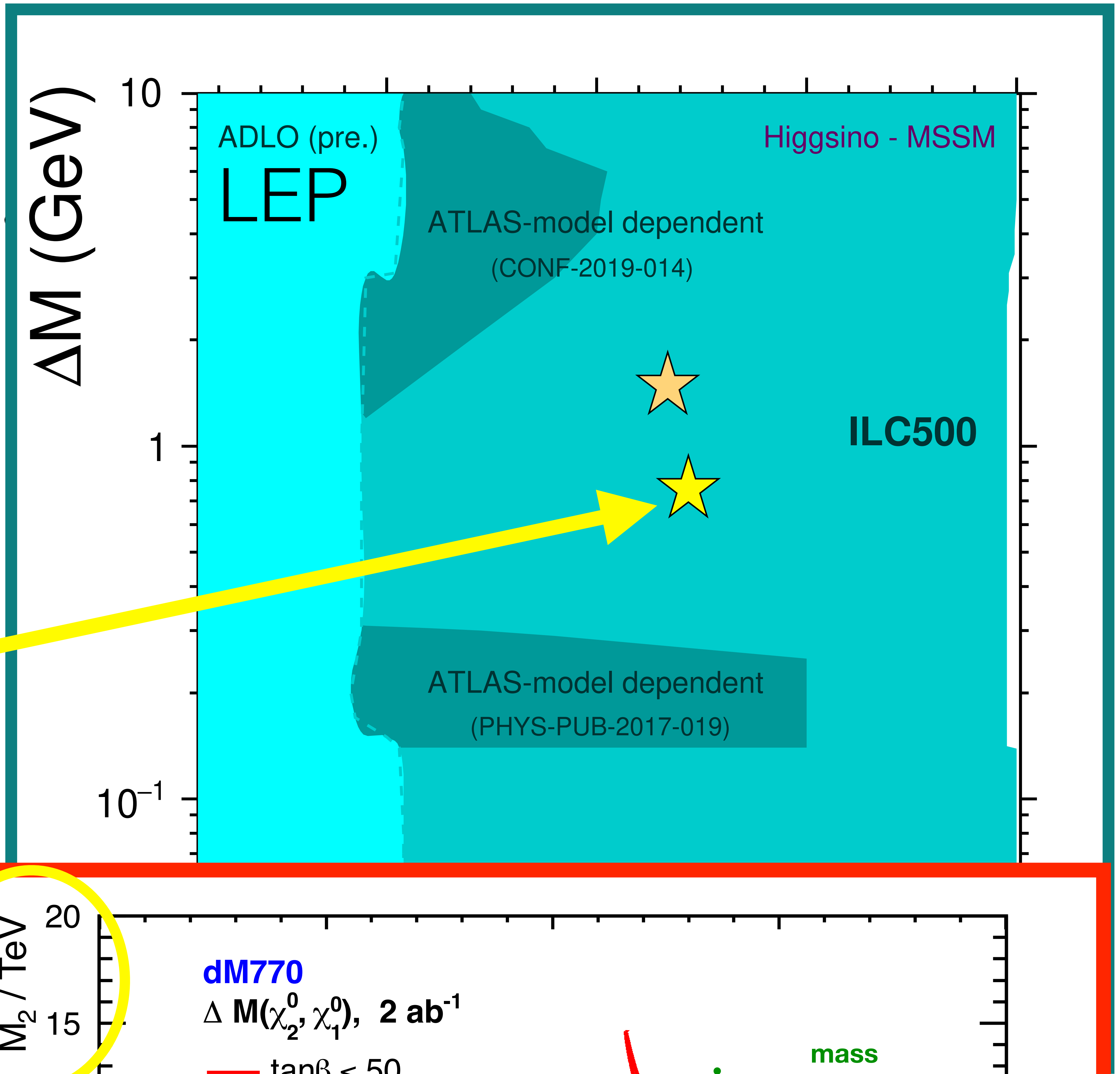

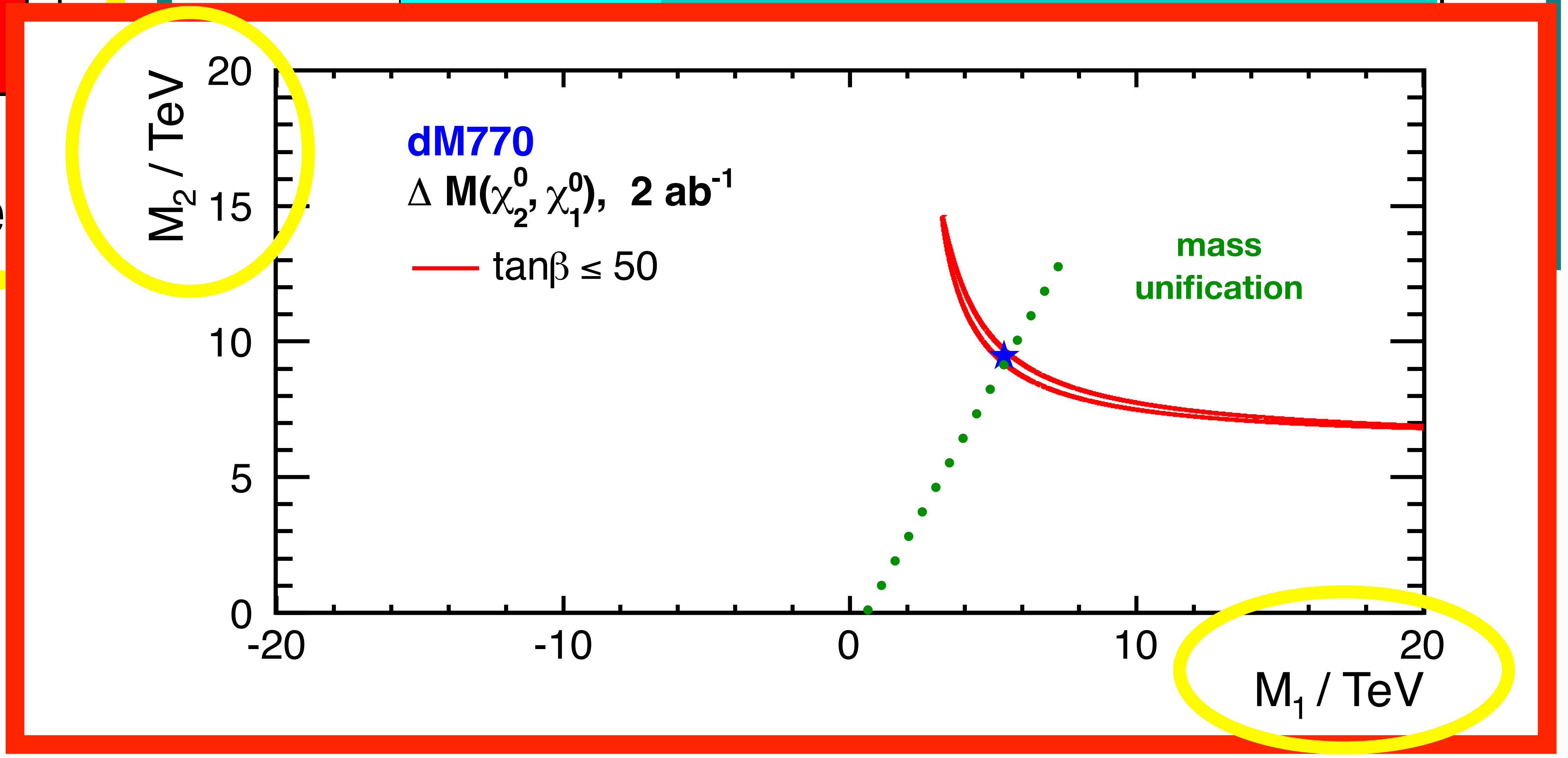

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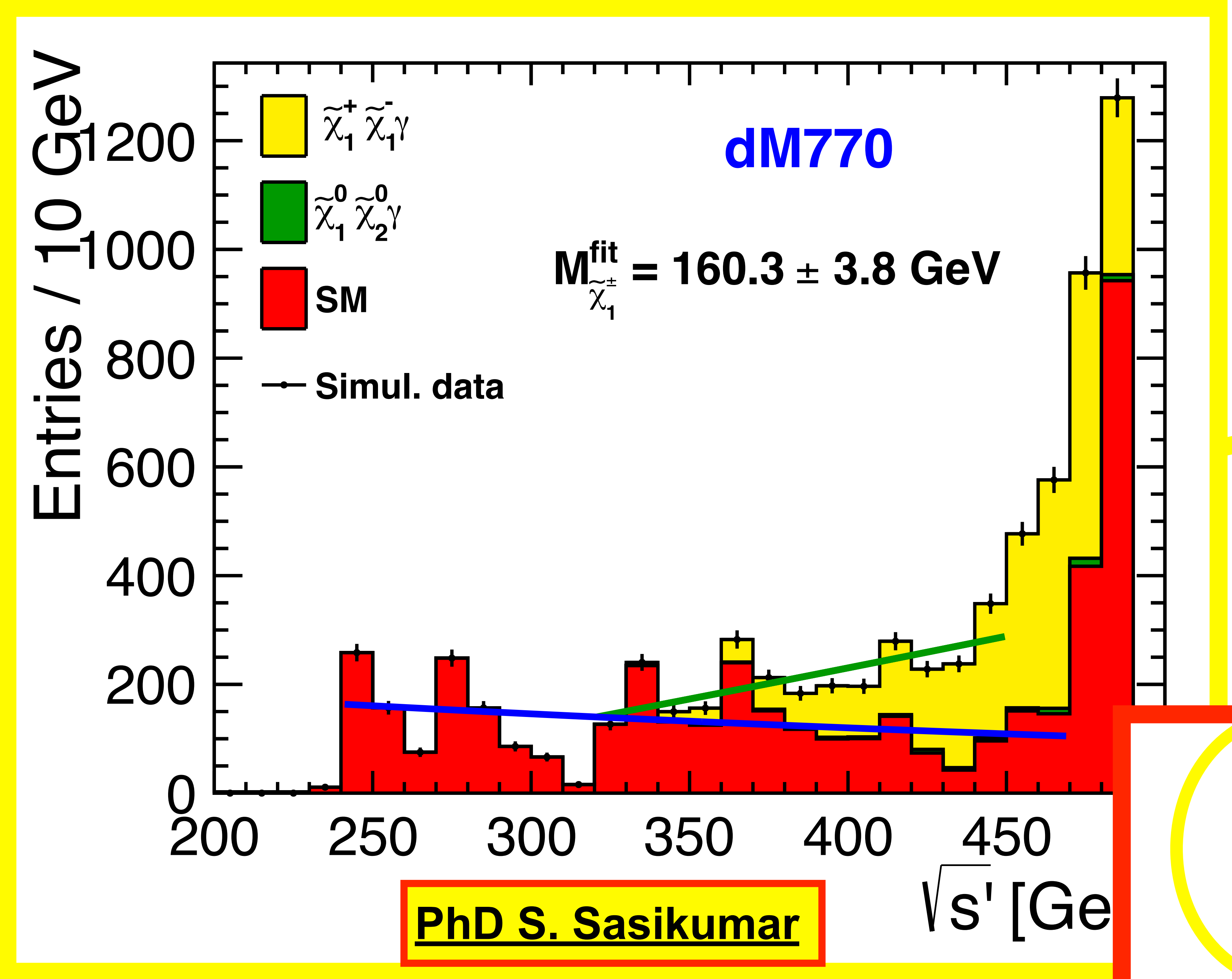
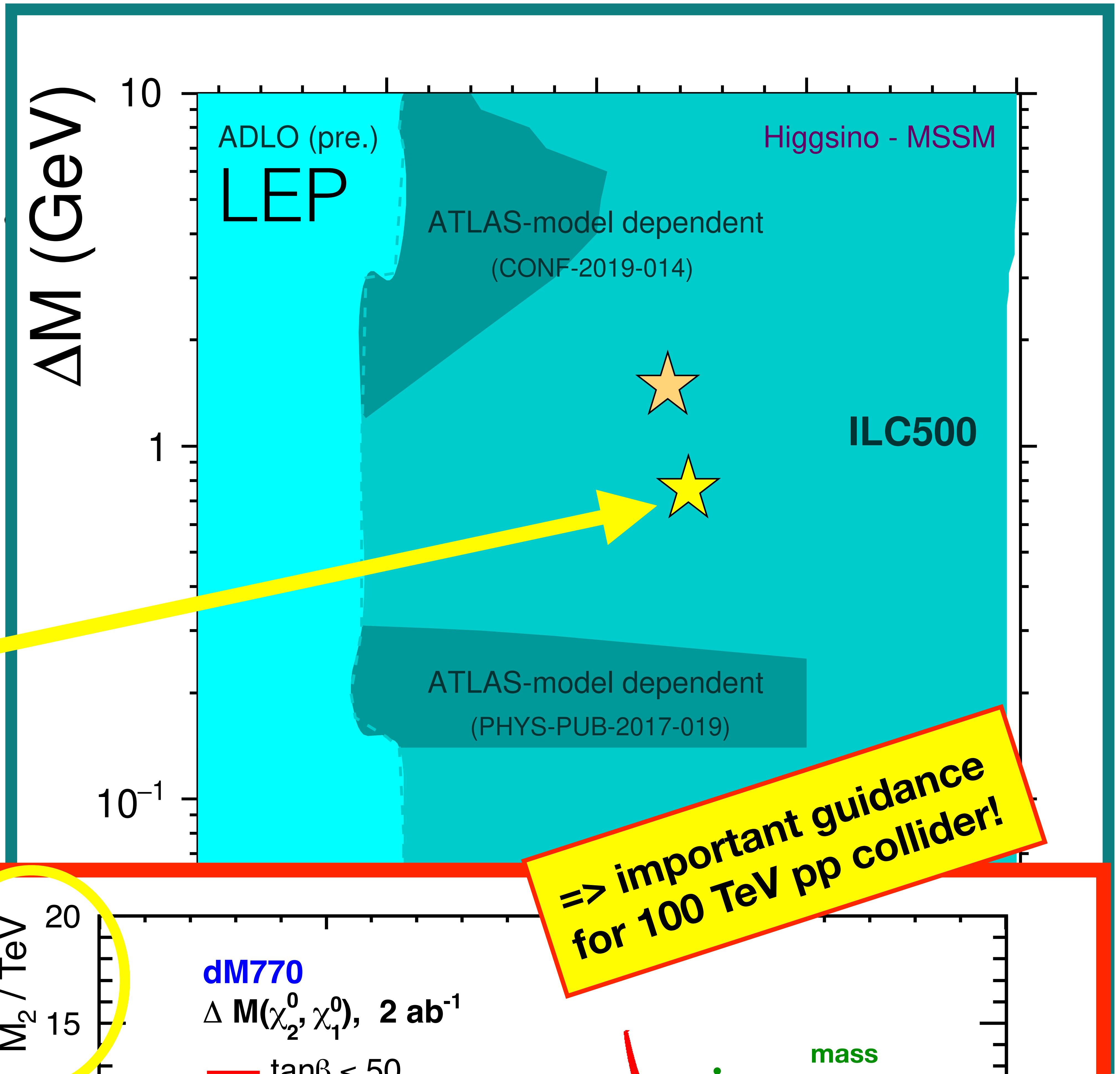
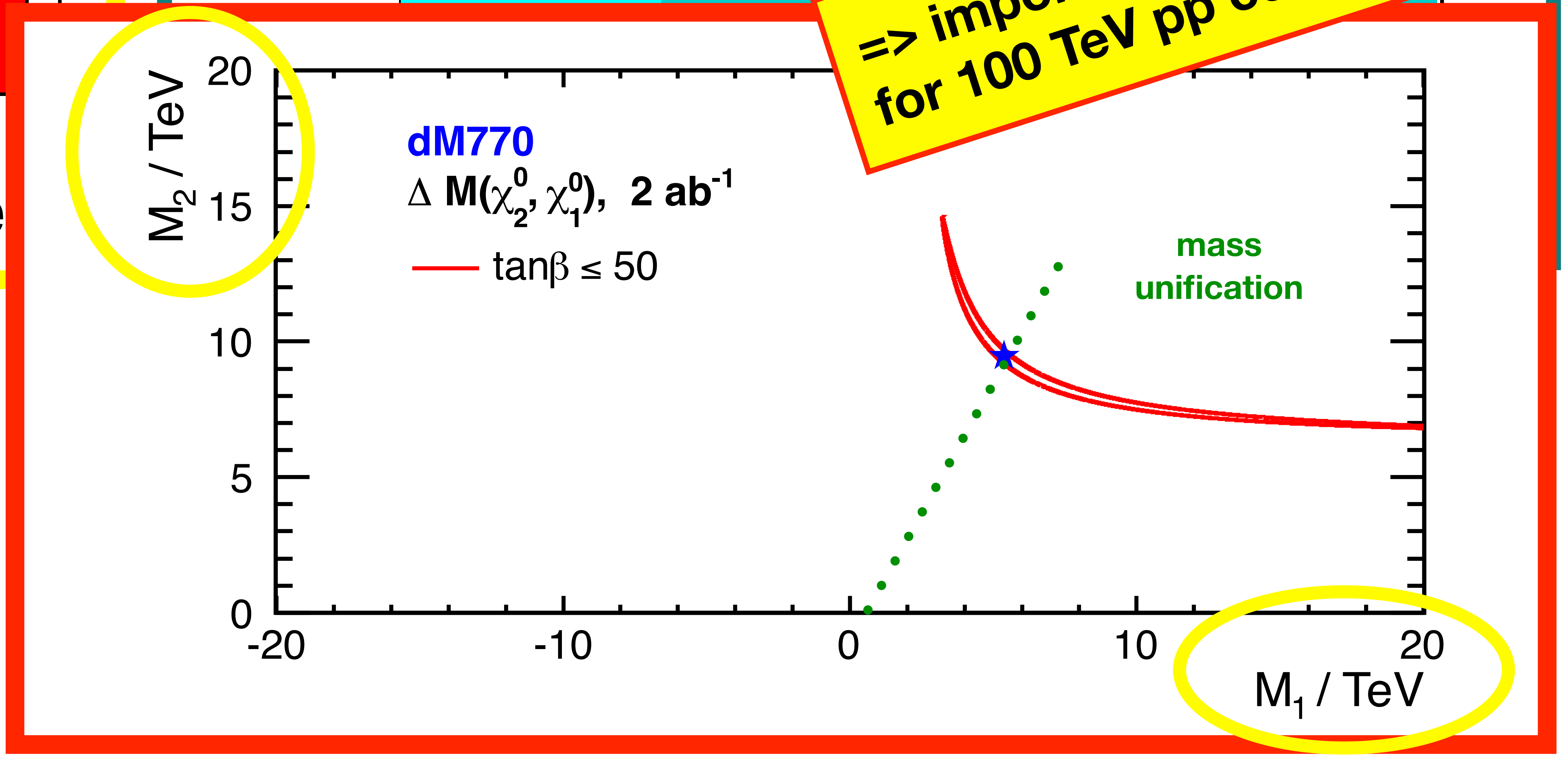




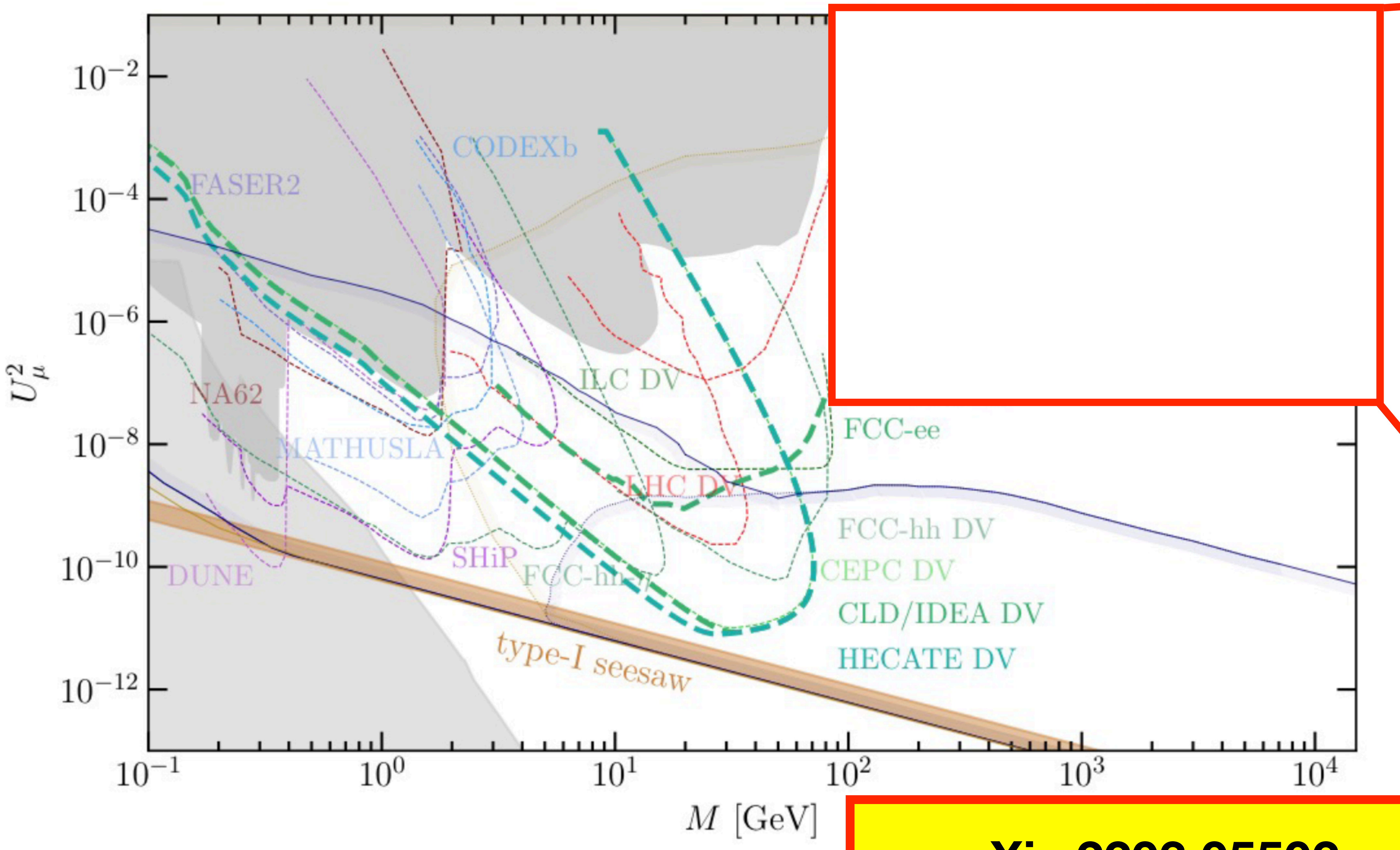


=> important guidance for 100 TeV pp collider!

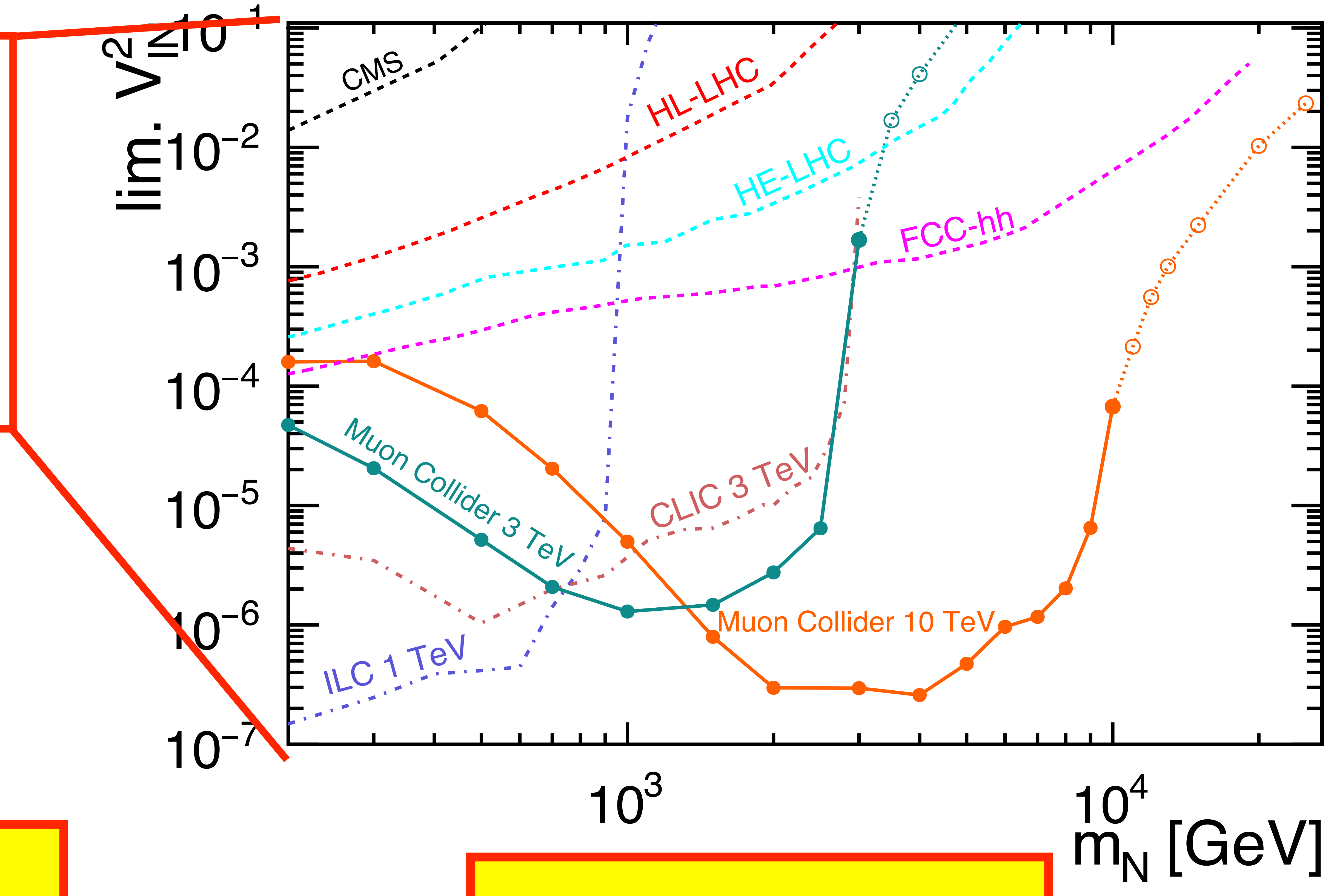
Heavy Neutral Leptons

Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices… …and at high masses in prompt decays



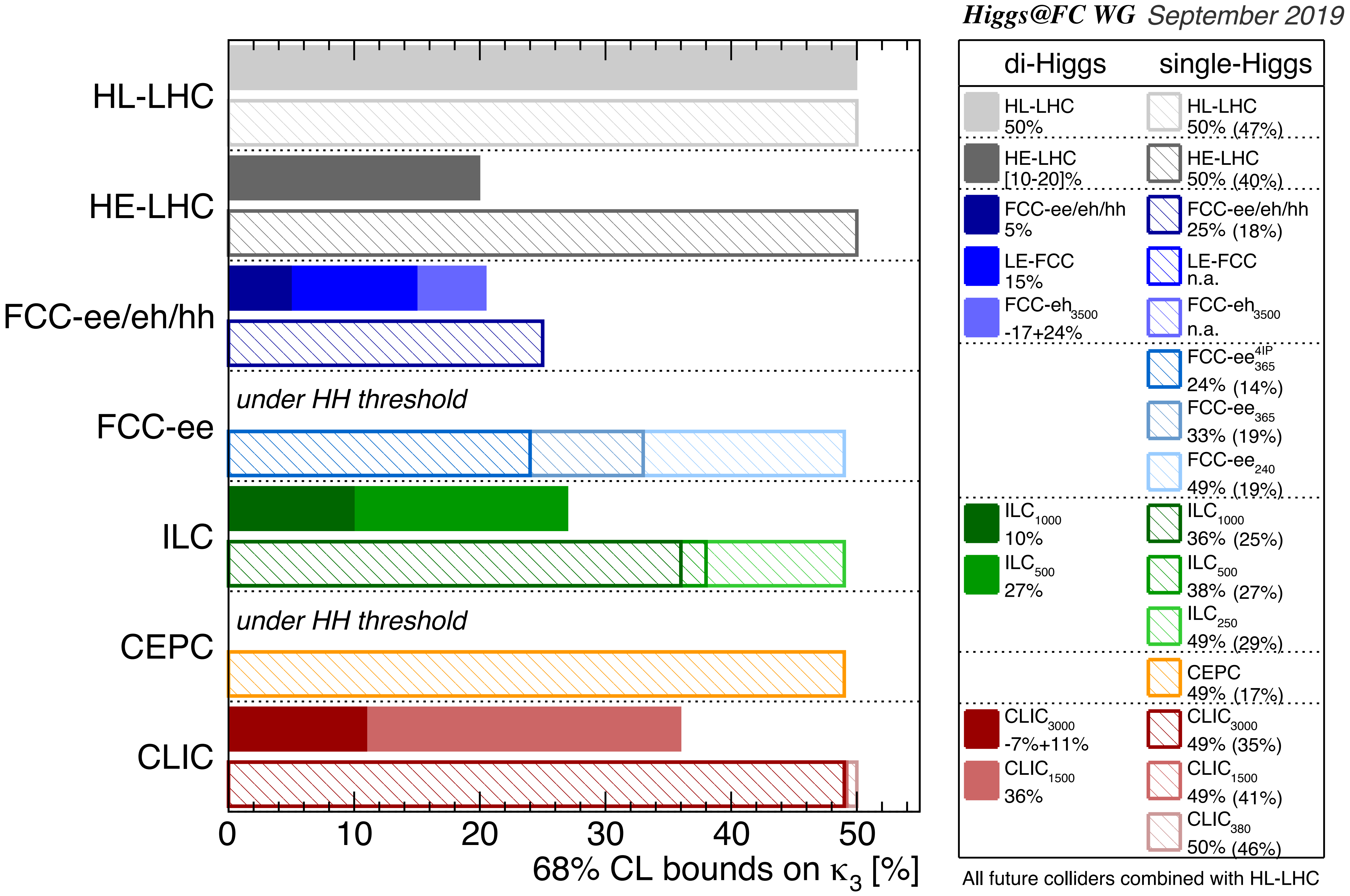
arXiv:2203.05502



arXiv:2301.02602

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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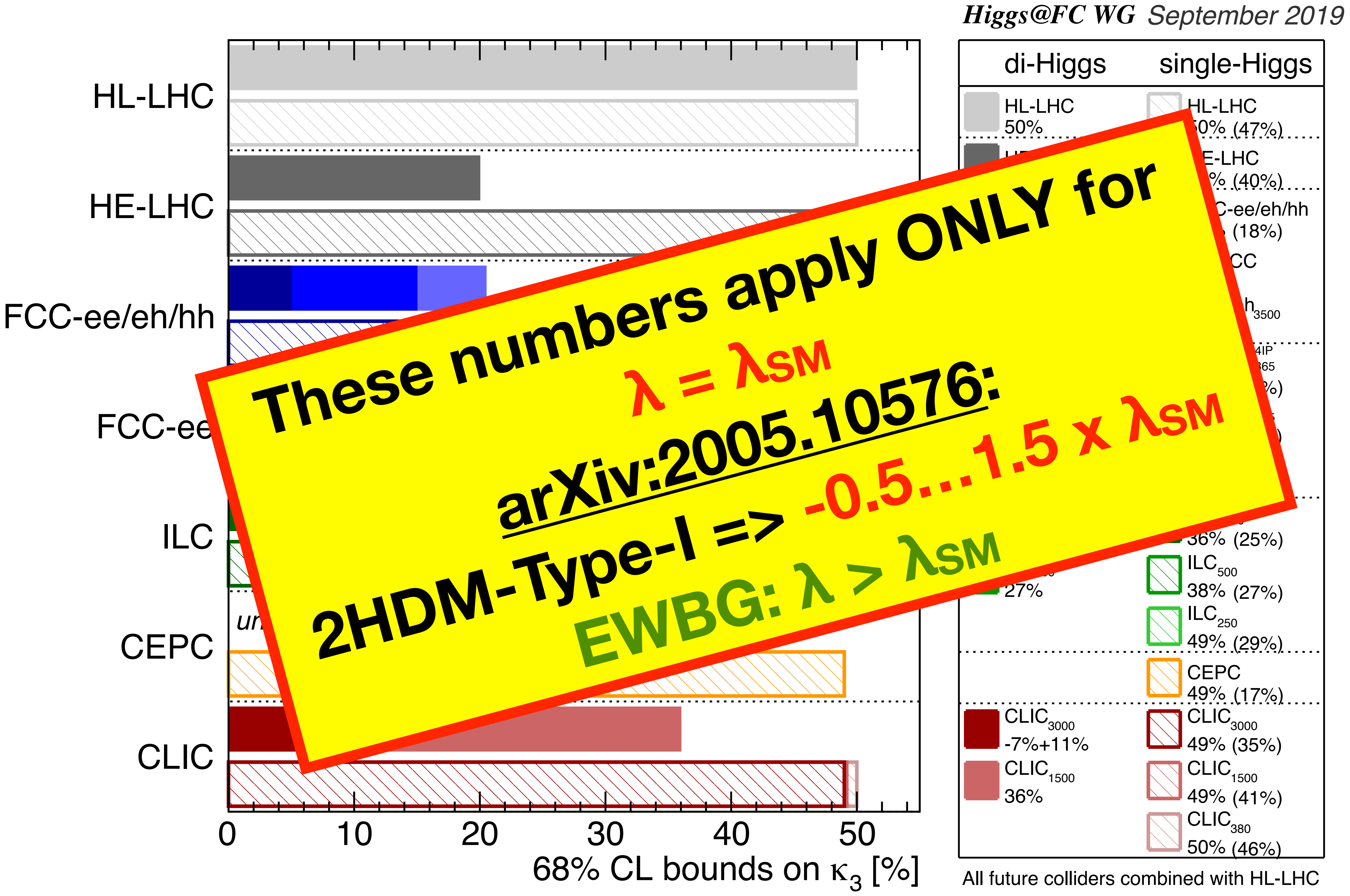

These numbers apply ONLY for $\lambda = \lambda_{SM}$

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2HDM-Type-I => -0.5...1.5 x λ_{SM}

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

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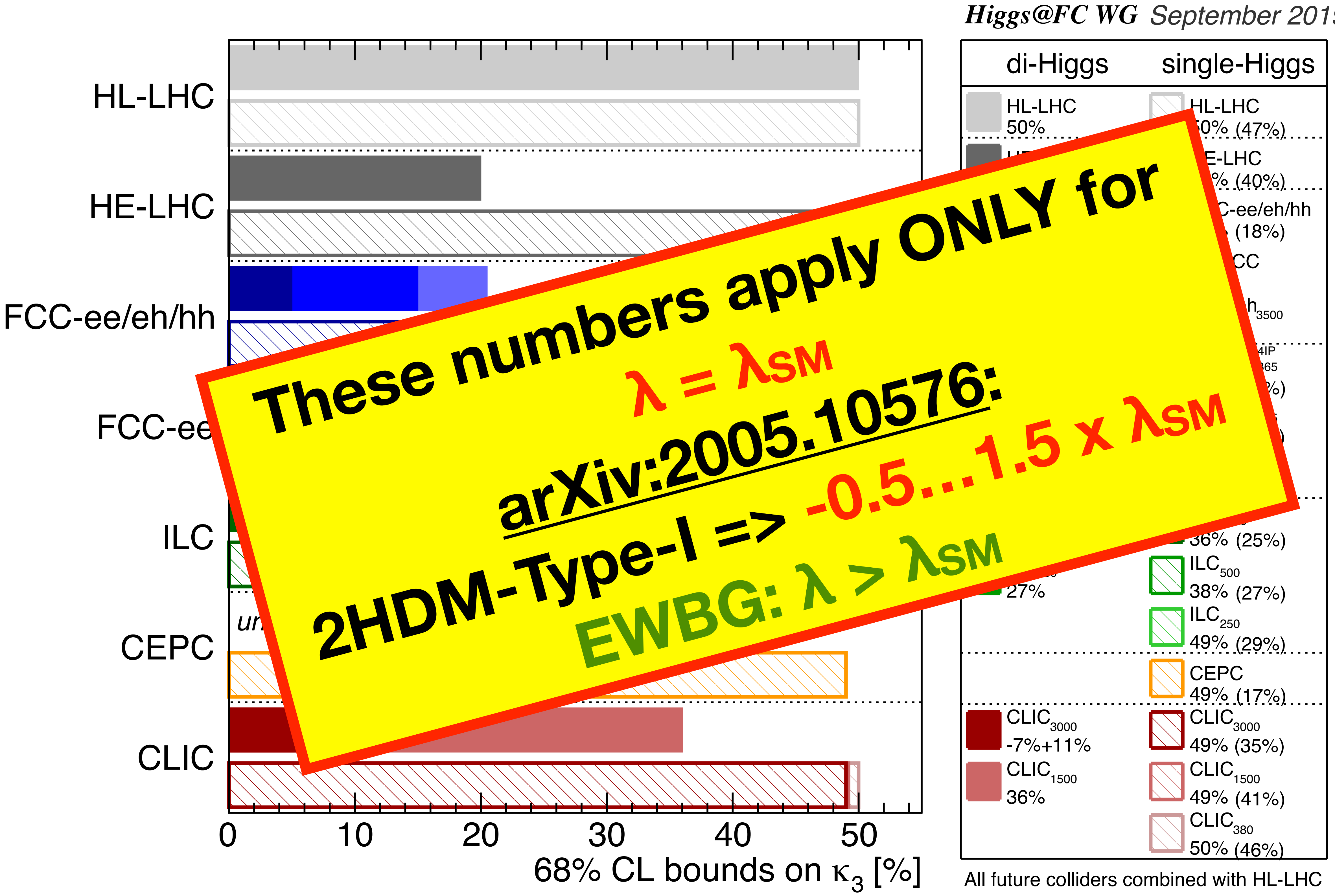

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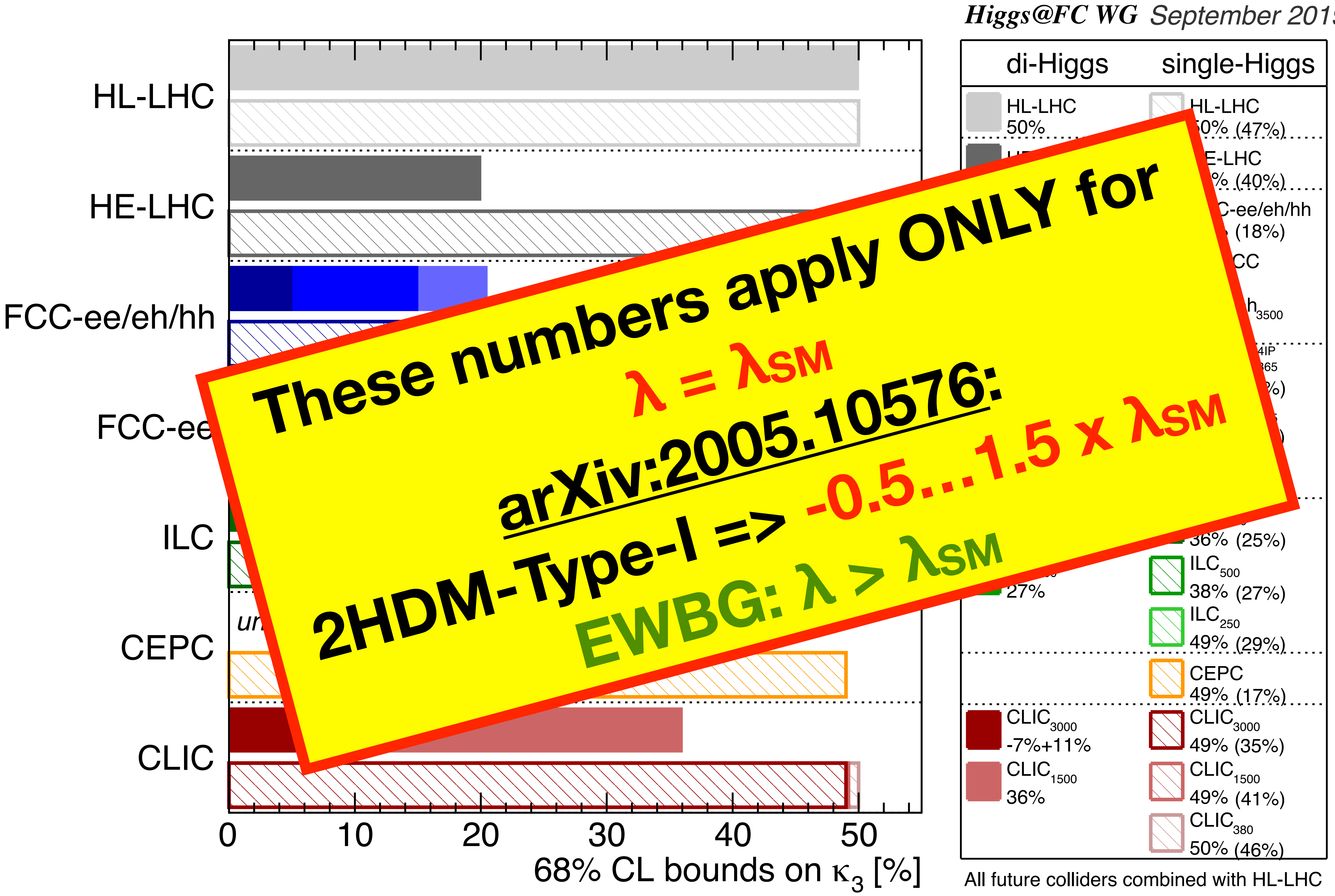

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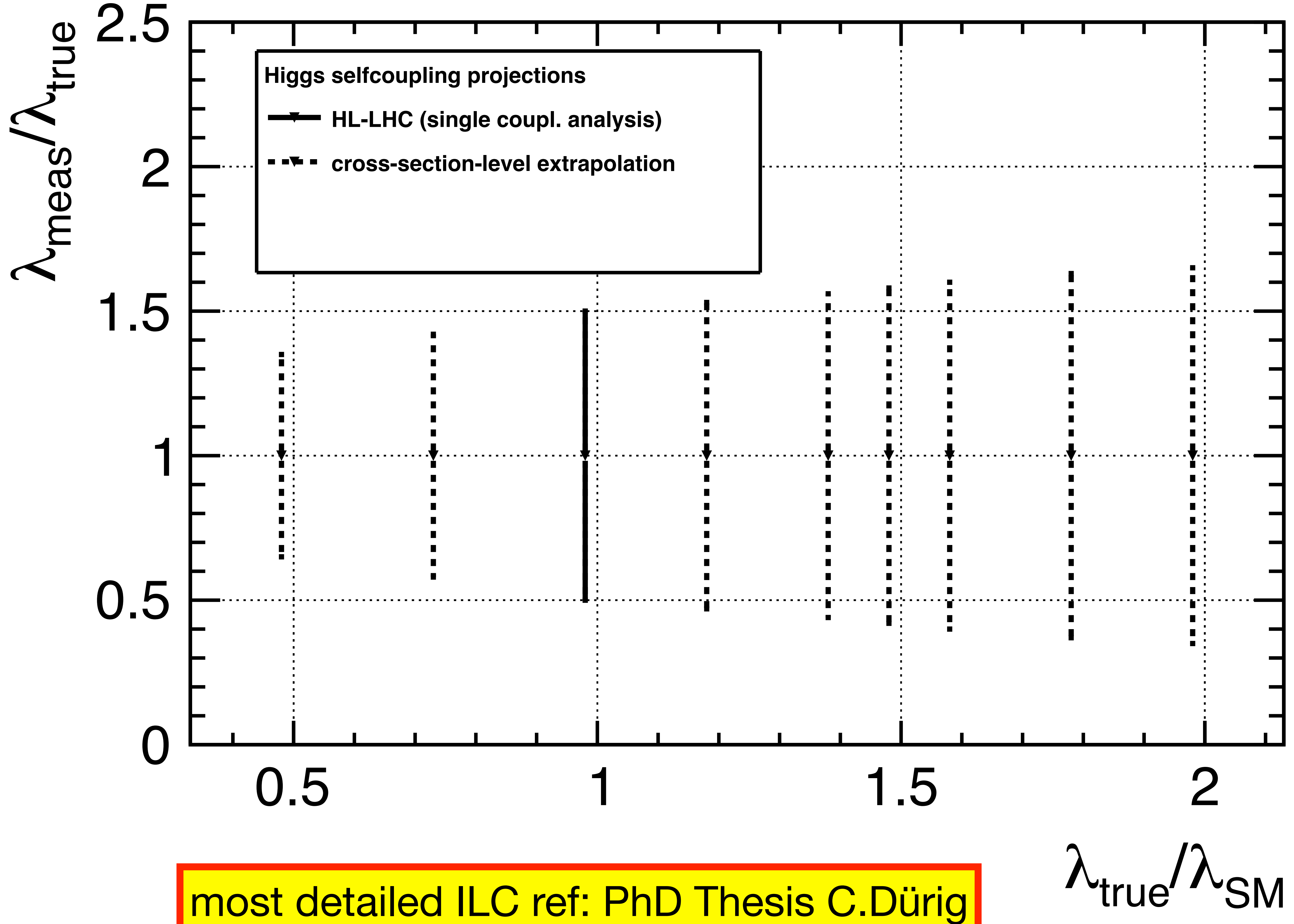

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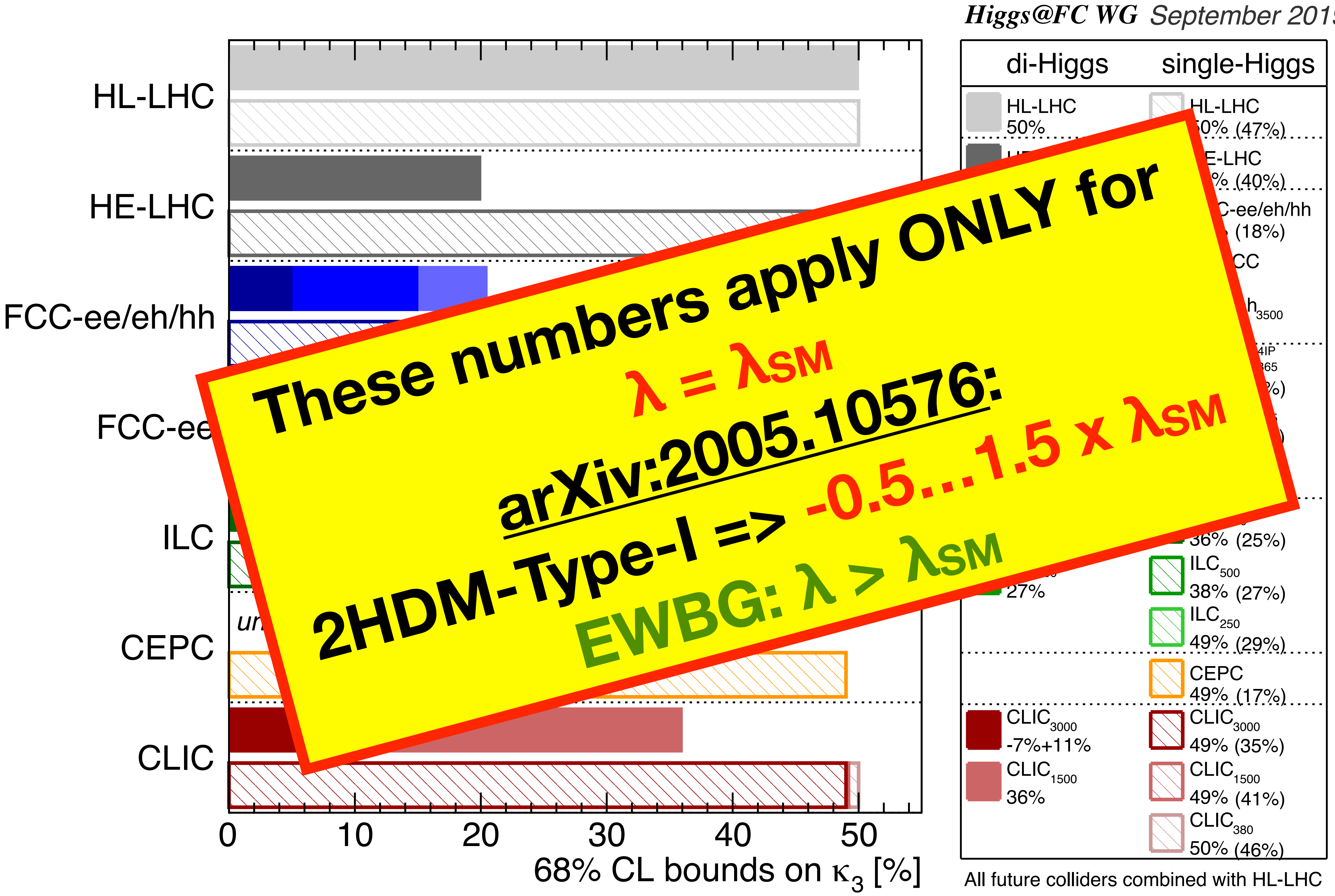
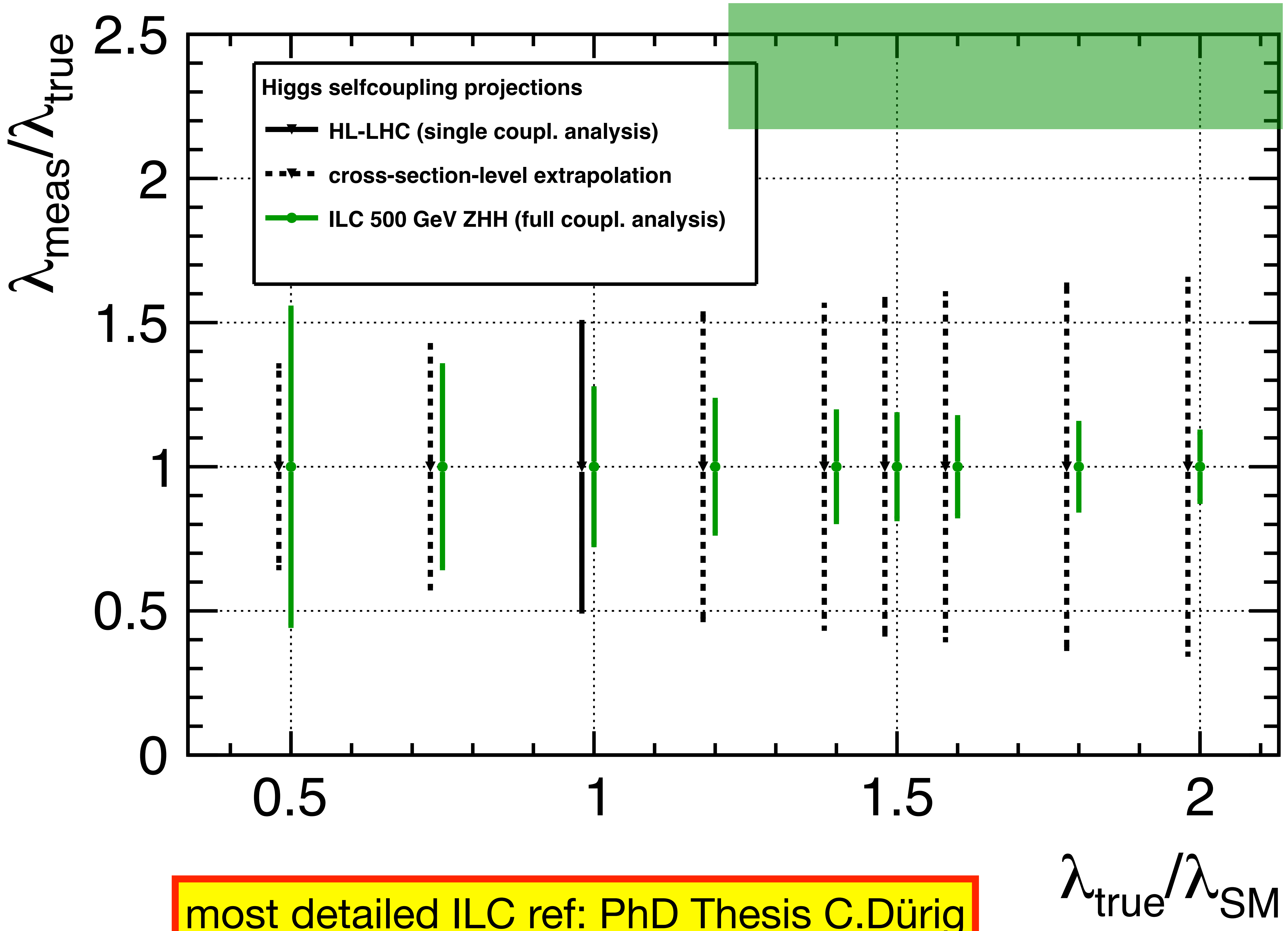


Region of interest for electroweak baryogenesis



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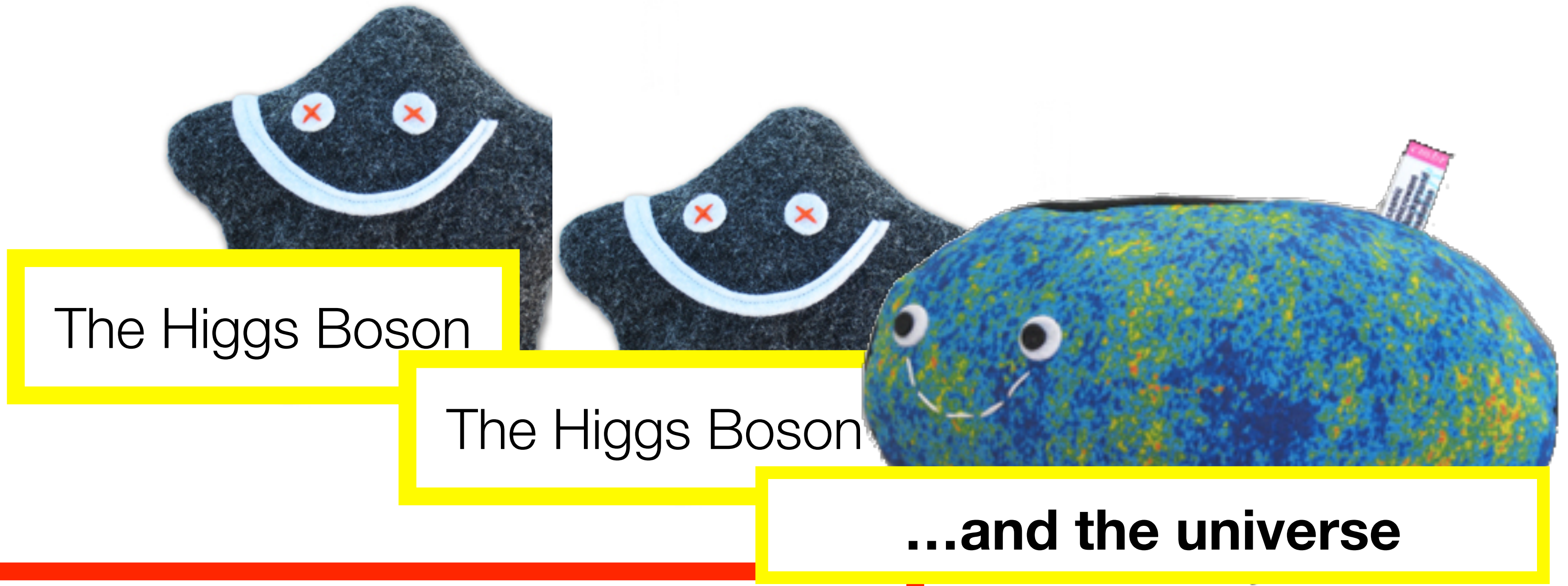

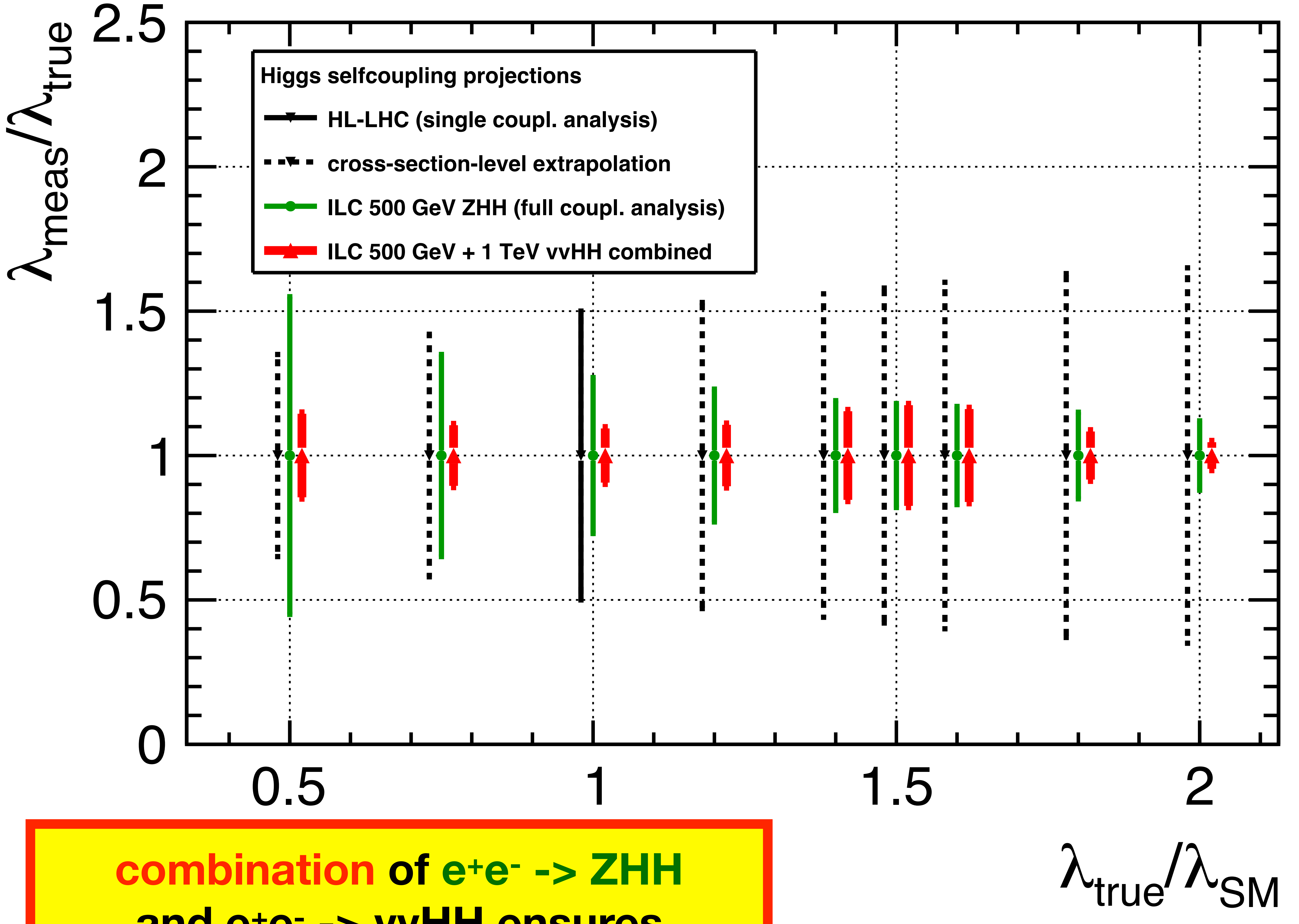

combination of e^+e^- -> ZHH and e^+e^- -> vvHH ensures at least 10-15% precision for all λ

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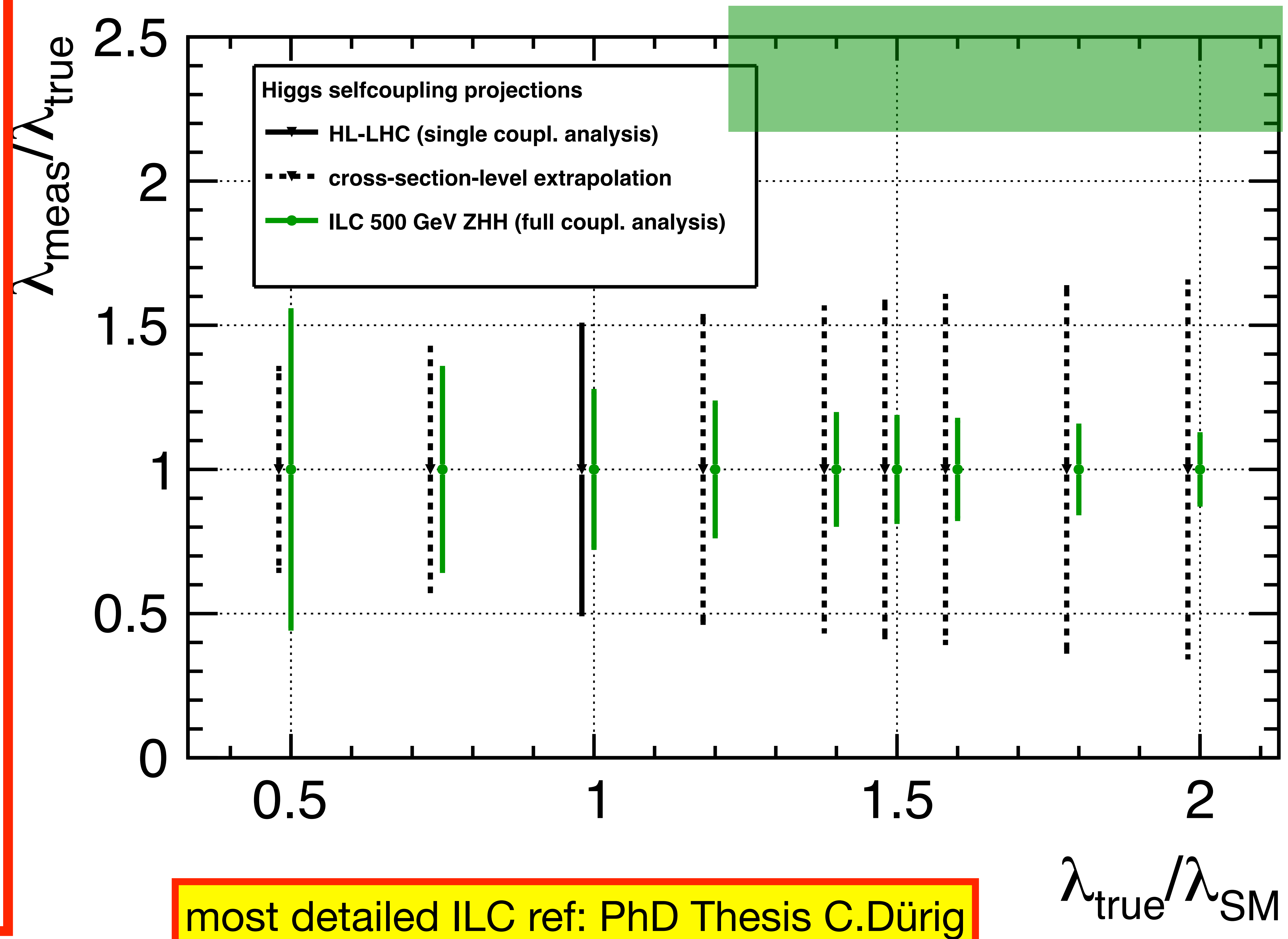

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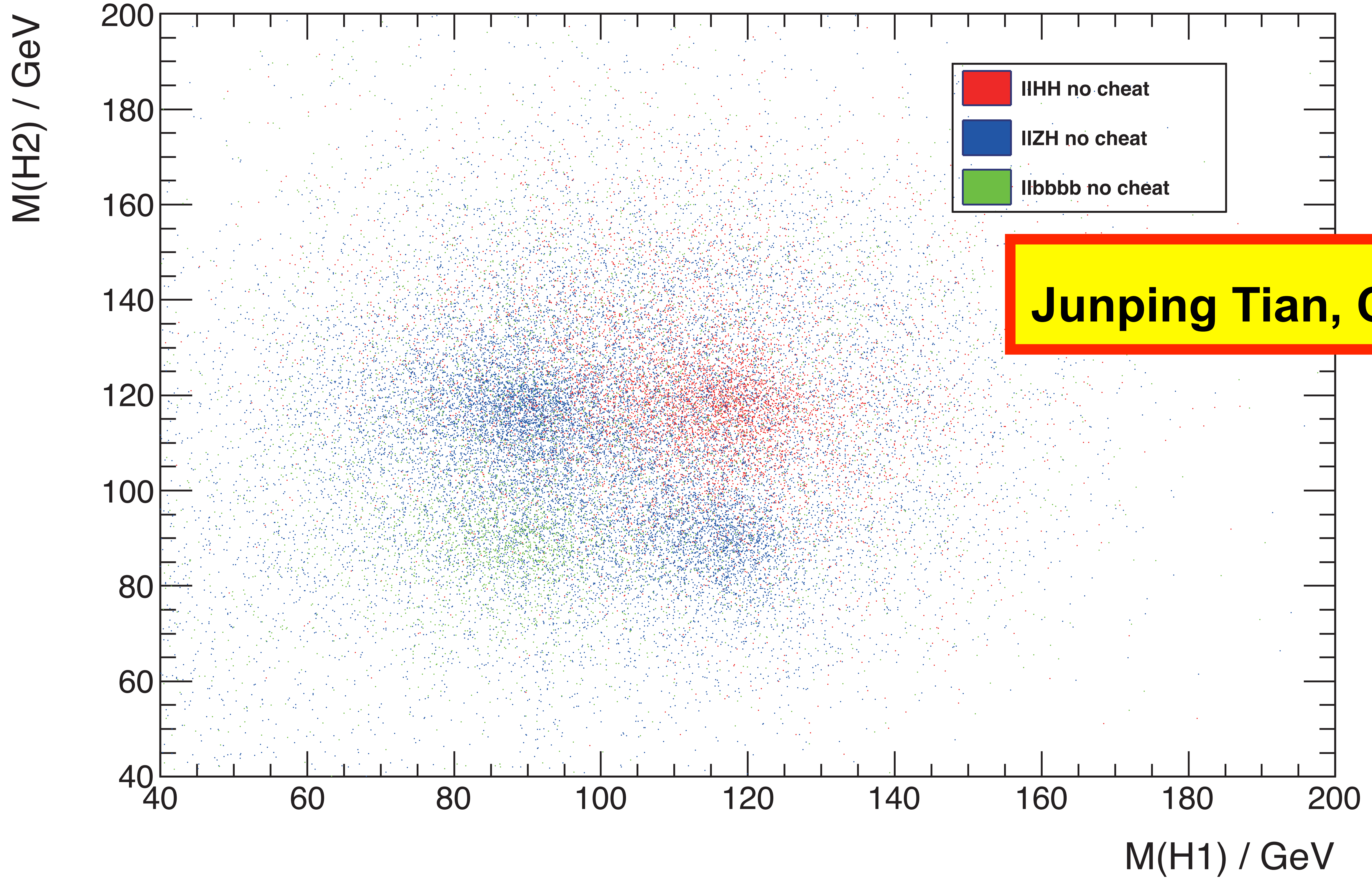
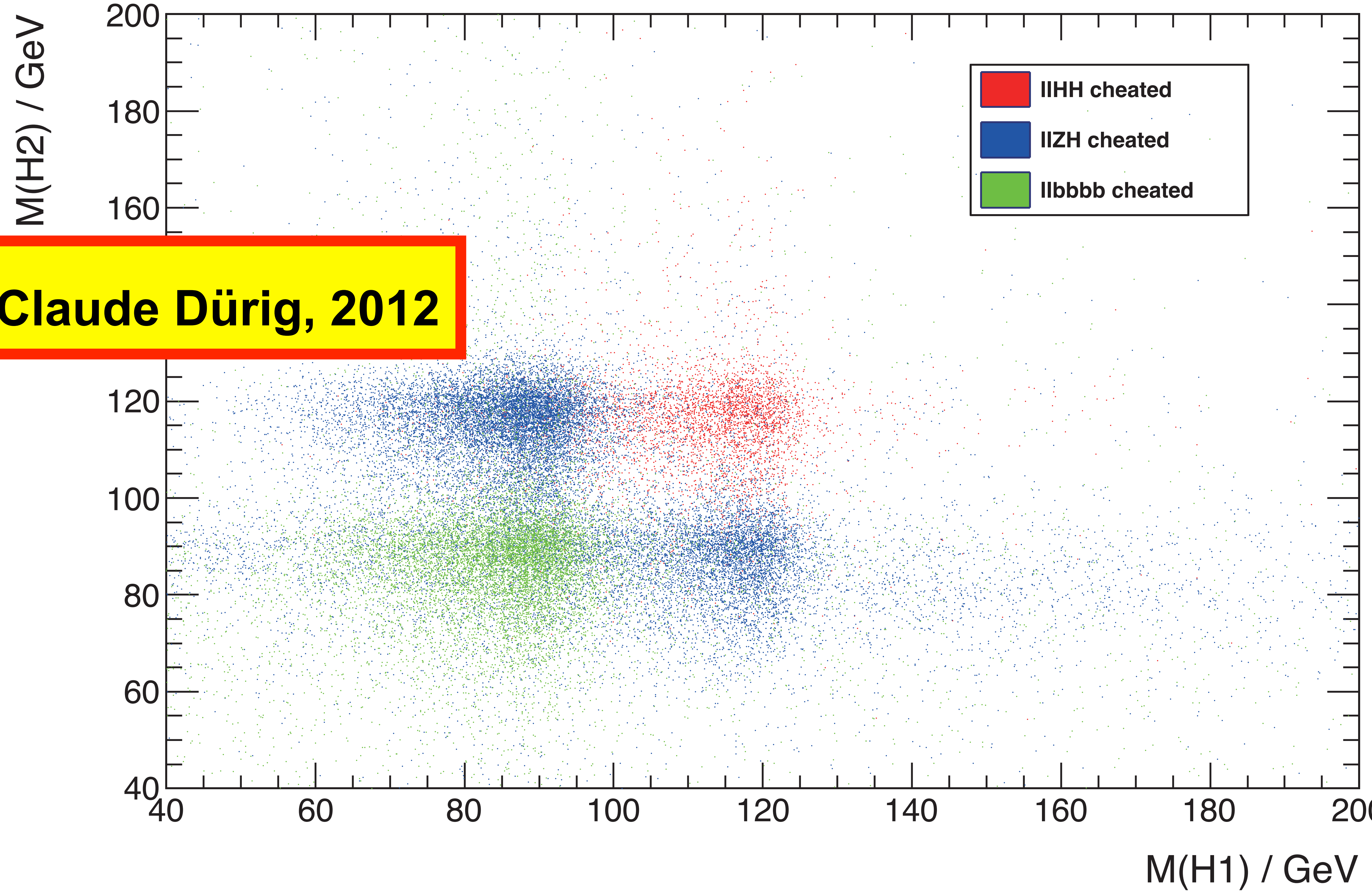
UPDATE ONGOING!

Urgently wanted: modern jet clustering

… bottle-neck for Higgs self-coupling precision





Junping Tian, Claude Dürig, 2012

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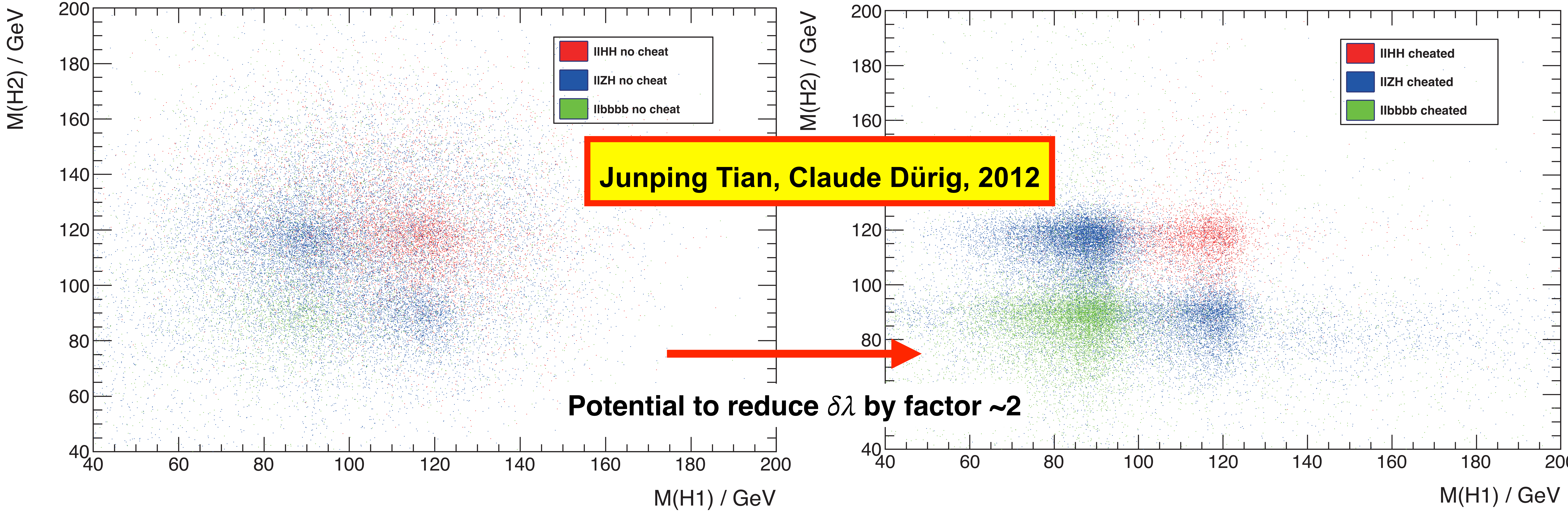

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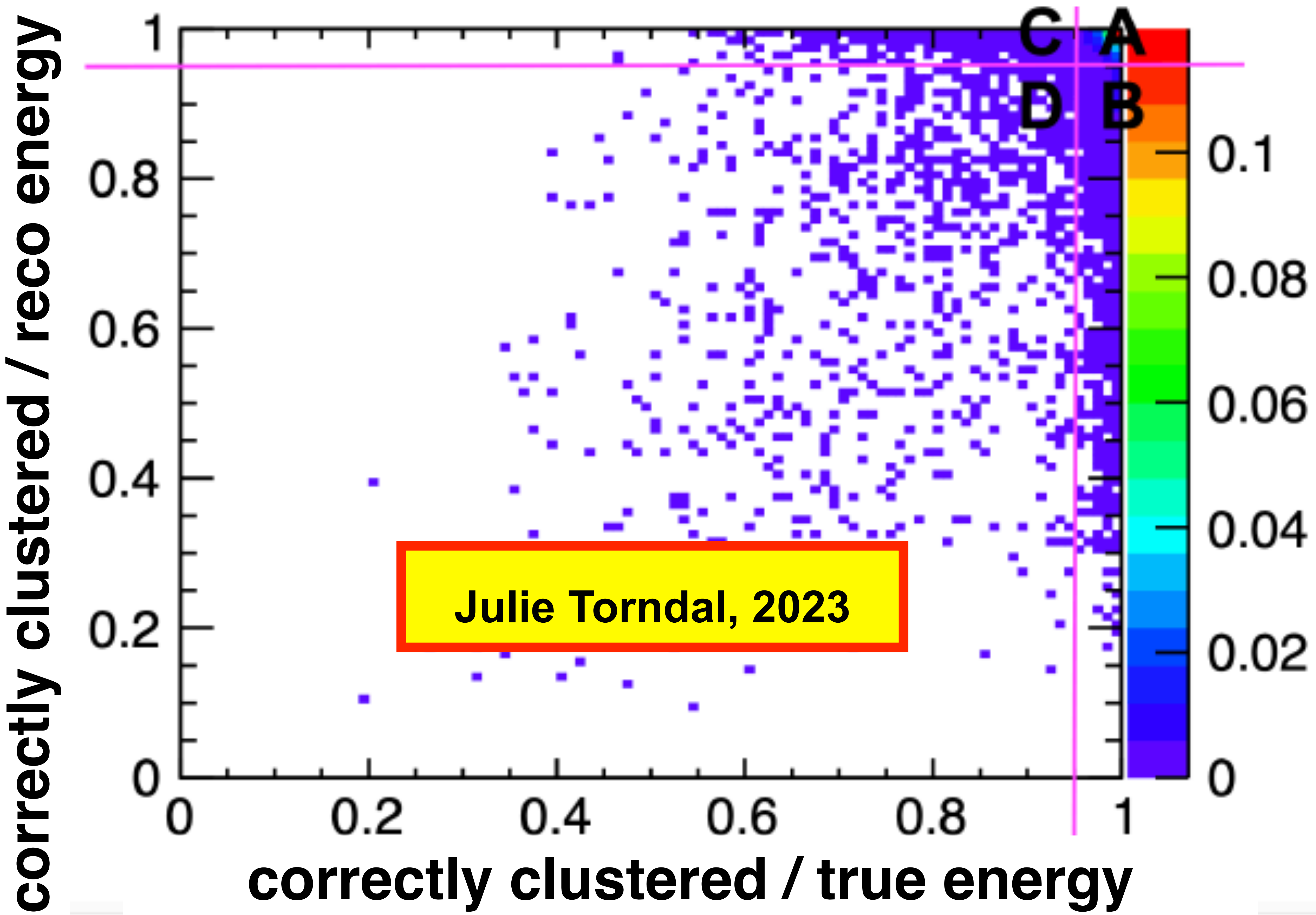

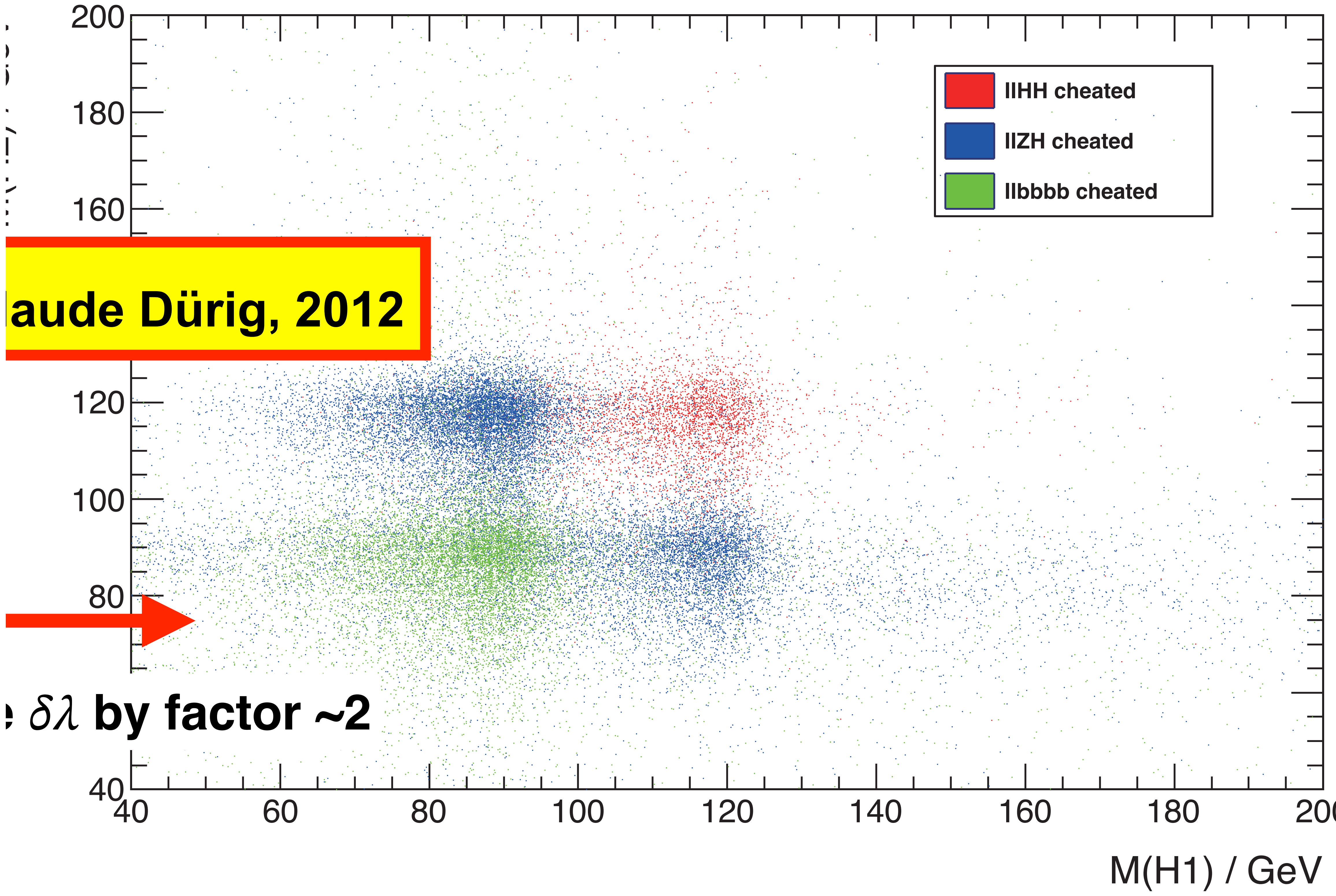

$\delta\lambda$ by factor ~2

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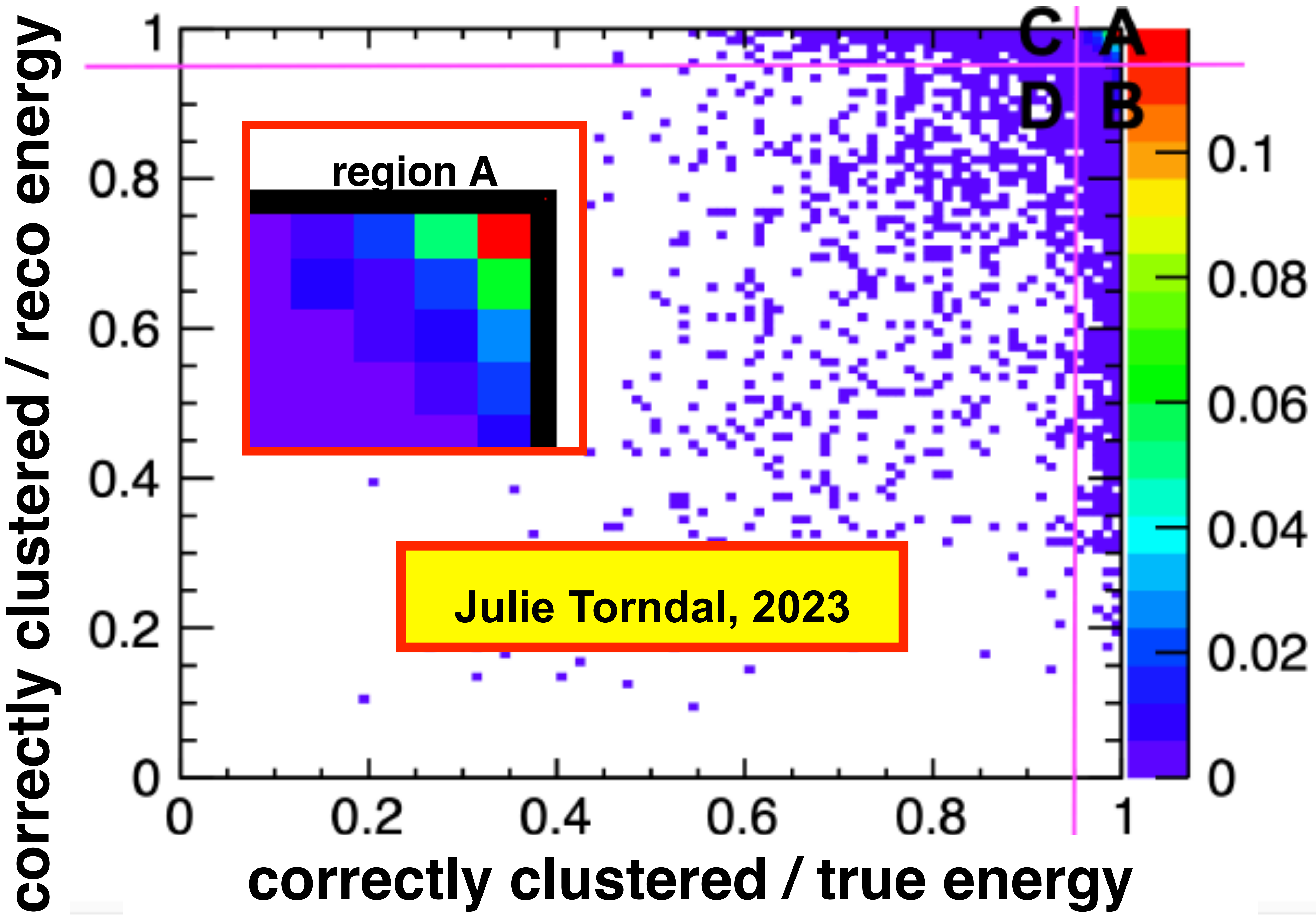

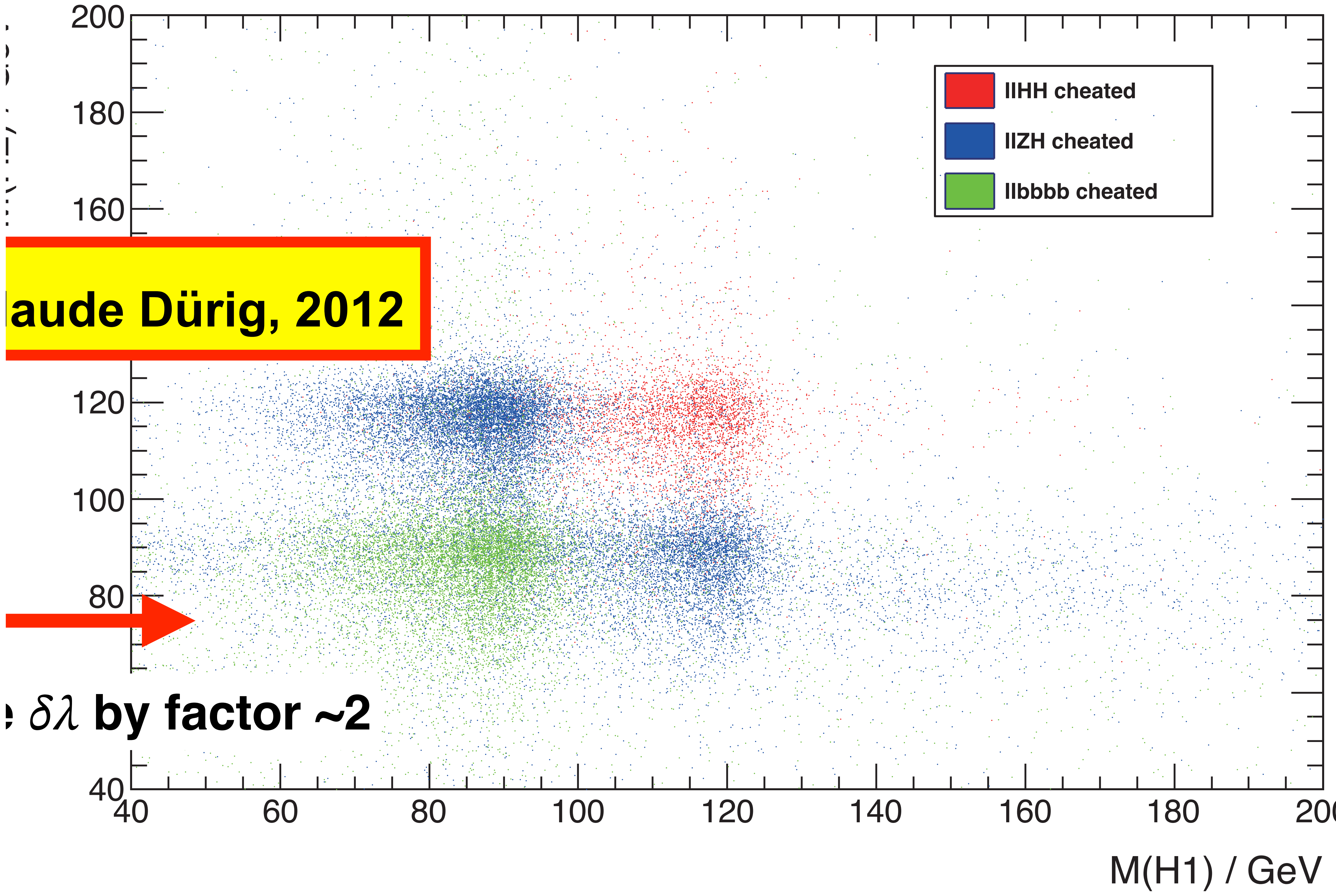

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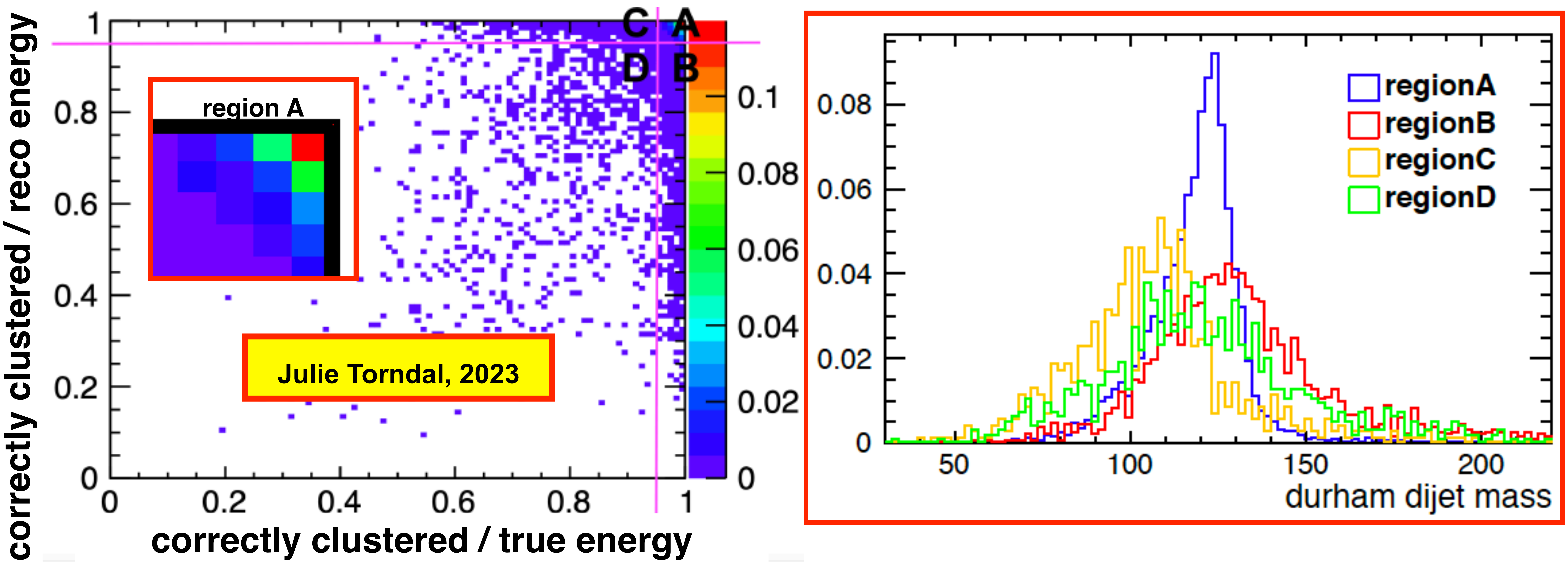

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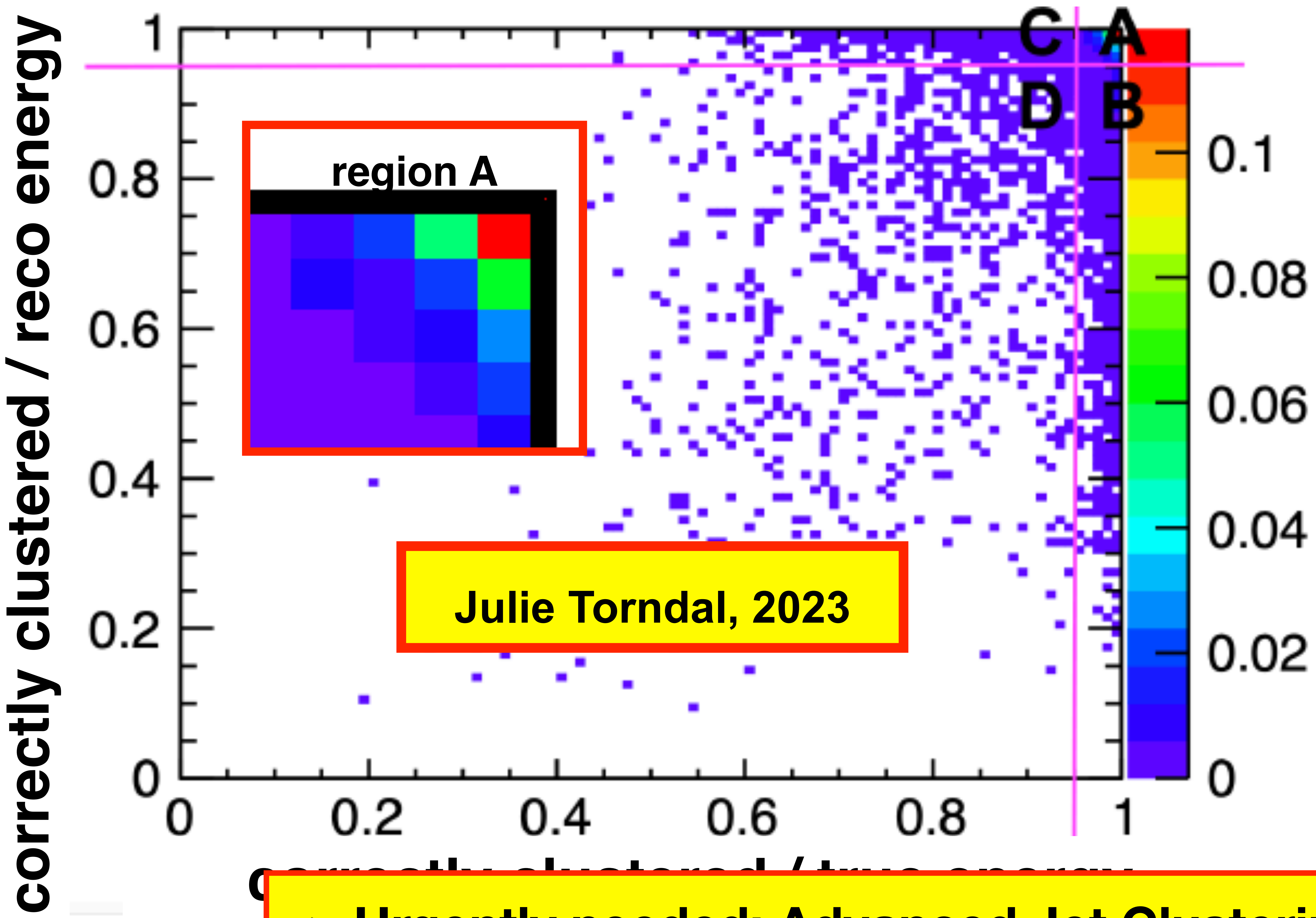
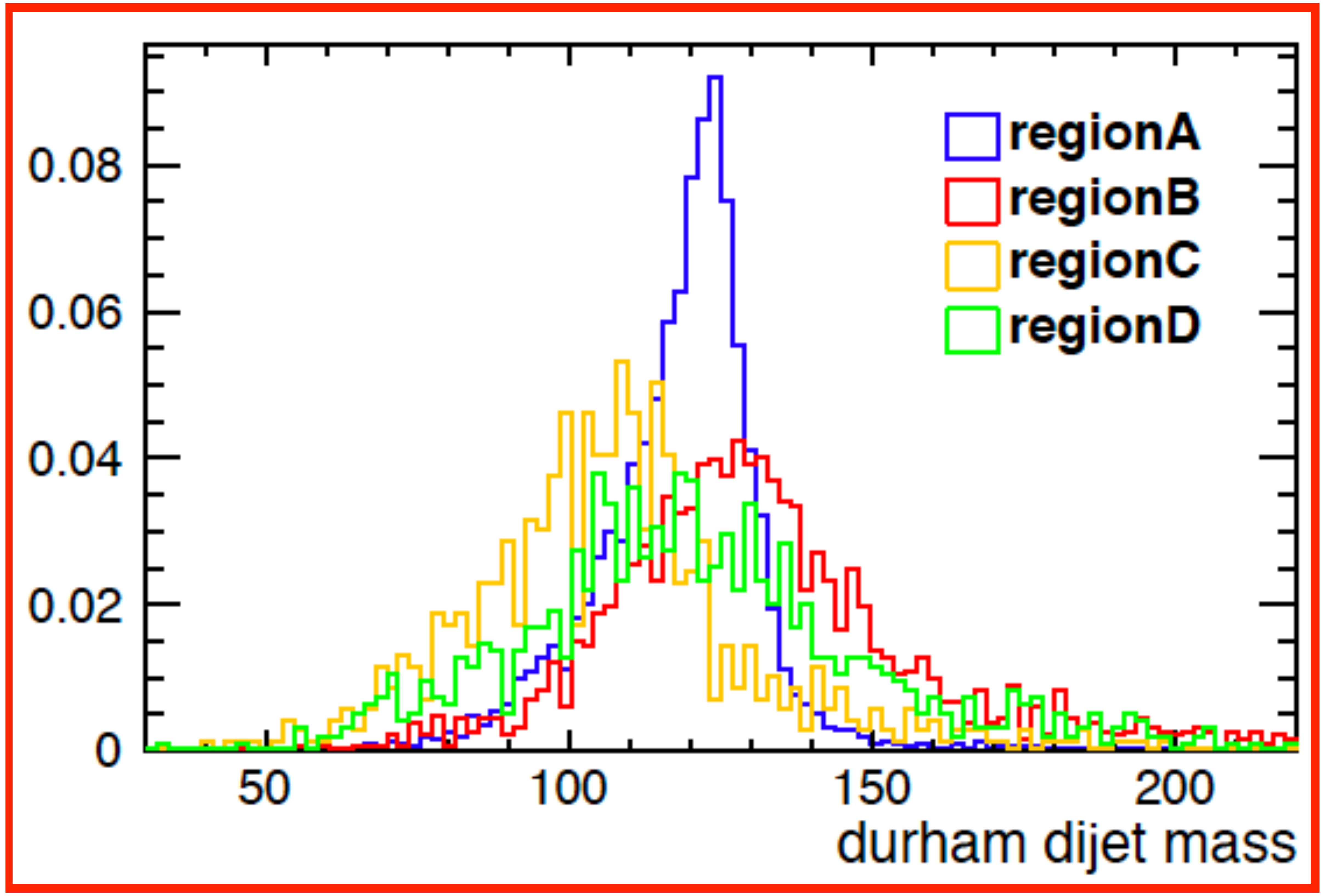




=> Urgently needed: Advanced Jet Clustering, ML, …can we get rid of B, C, D ???

which additional detector information would help?

This has the potential to reduce δλ/λ(SM) from 20% to 10% !

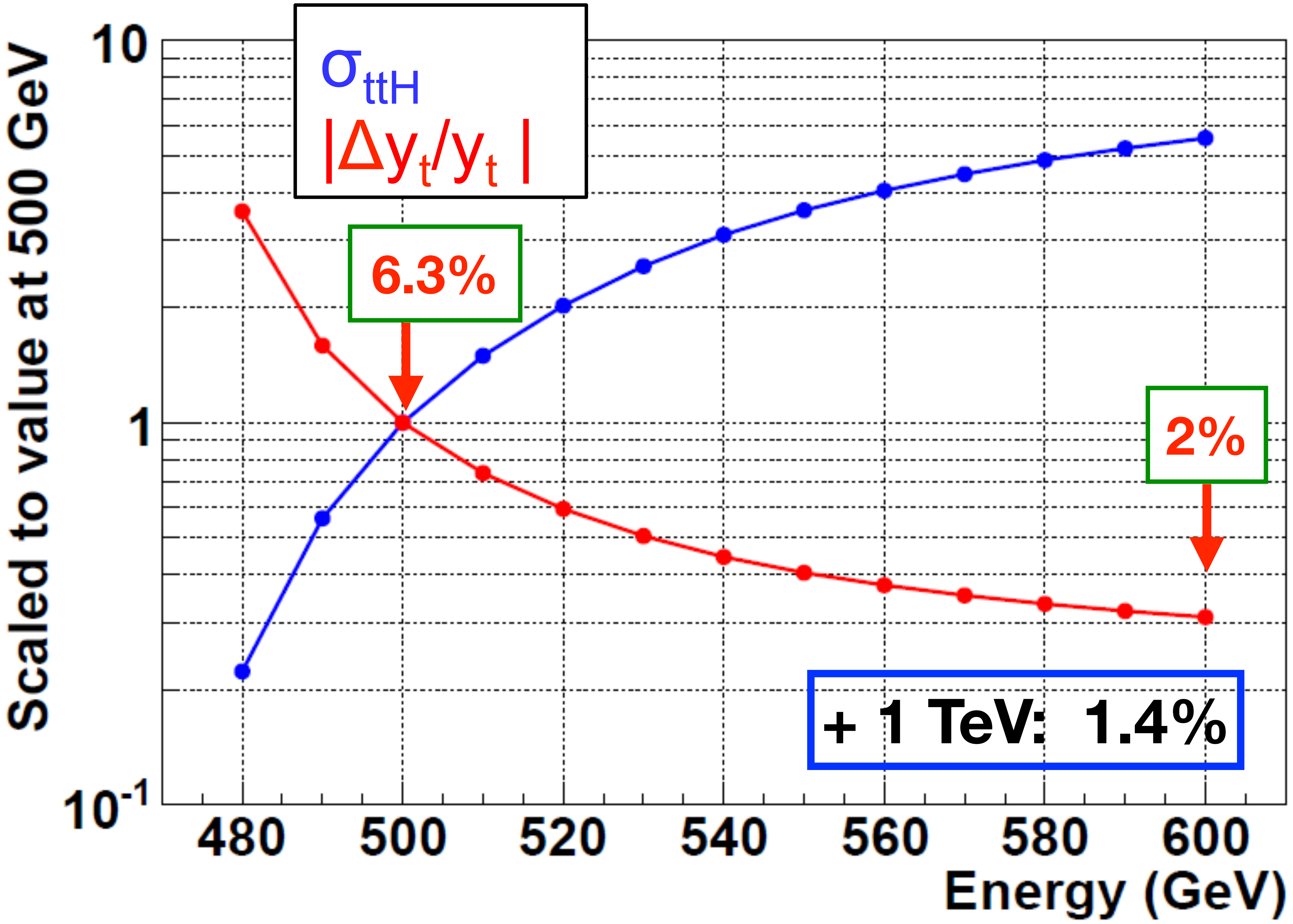
Top Yukawa coupling

Choosing the right energy

The Higgs and the Top

[Phys.Rev. D84 (2011) 014033 & arXiv:1506.07830]

- **absolute size of $|y_t|$:**
  - **HL-LHC:**
    - **$\delta\kappa_t$ = 3.2% with $|\kappa_V| \leq 1$ or 3.4% in $SMEFT_{ND}$**
  - **e+e- LC:**
    - current full simulation achieved **6.3% at 500 GeV**
    - ***strong dependence*** on exact choice of E_{CM}, e.g. **2% at 600 GeV**
    - *not* included:
      - experimental improvement with higher energy (boost!)
      - other channels than H->bb



to-do: real, full sim study @ 600 GeV!

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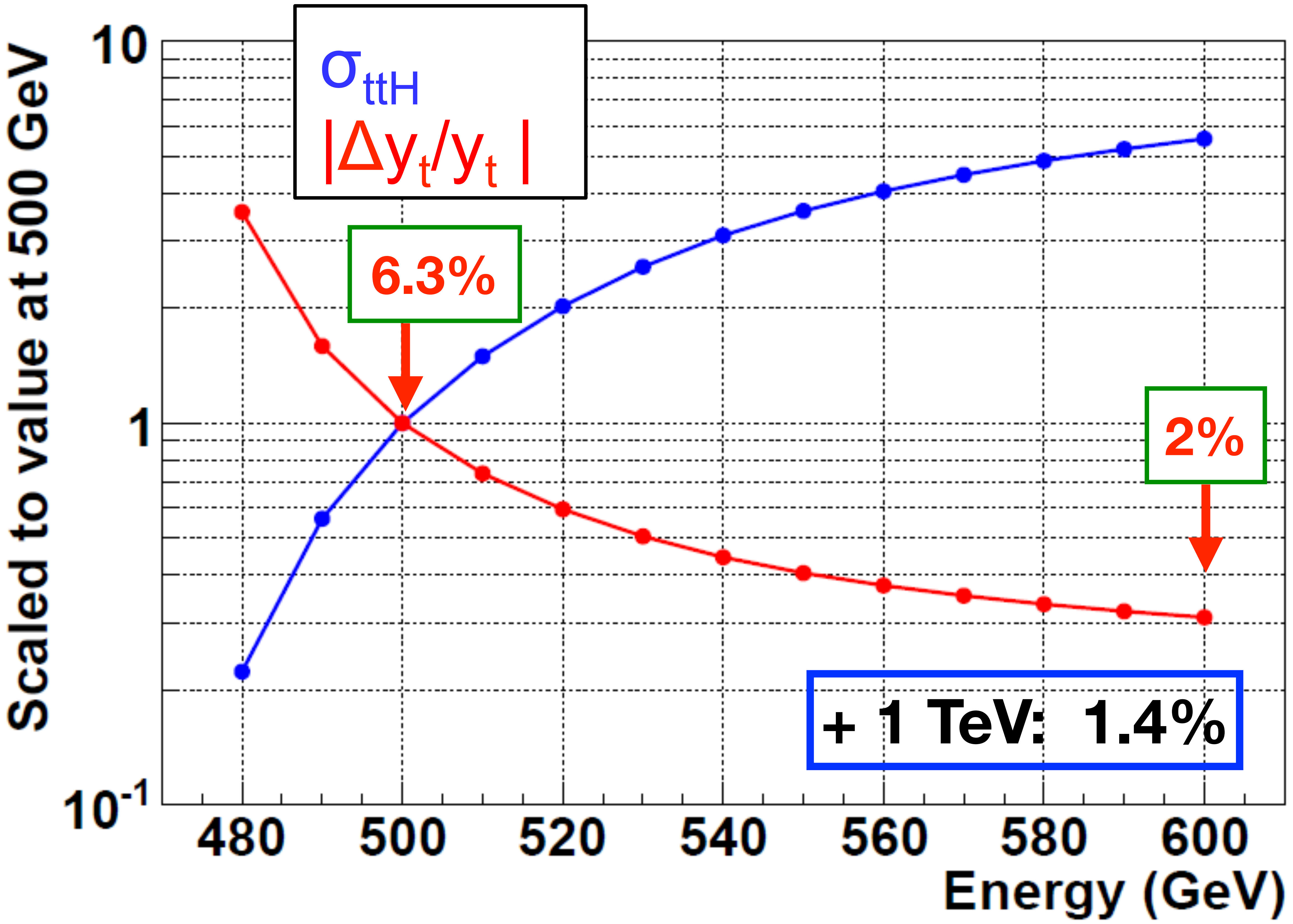
- **full coupling structure** of tth vertex, incl. CP:
  - **e^+e^- at E_{CM} ≥ ~600 GeV** => ***few percent sensitivity to CP-odd admixture***
  - **beam polarisation essential!**

[Eur.Phys.J. C71 (2011) 1681]



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Straight to the Future 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 km long 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

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Conclusions

And invitation

- **strong scientific consensus that an e+e- Higgs Factory is the highest-priority next collider**

- **open scientific 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?
- **next big project needs**
  - a compelling science case
  - readiness for fastest possible construction
  - technologically and scientifically exciting upgrade options
  - well justified usage of ressources - **money**; surface, electrical power, concrete, steel, rare earths, …

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

Bonus

Ready to take on one of these challenges?

How to contribute

- **Get involved**
  - **ECFA set up a workshop series on Physics, Experiments and Detectors at a Higgs, Top and Electroweak factory cf https://indico.cern.ch/event/1044297/**
    - address topics in common between all e^+e^- colliders, i.e. theory prediction, assessment of systematic uncertainties, software tools
    - will give important input to next update of European Strategy

  you don’t won’t to commit to a specific collider project ?
  => this is your way to contribute => get in touch!

- **All Higgs factories are using the same software framework (Key4HEP):**
  - share algorthmic developments
  - share / exchange data sets for comparable analyses etc

  => anybody who’d like to shape the experiments of the next collider would be wise to build up expertise on Key4HEP *now*

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.

Sustainability

2016 …..

Additional Design Considerations

- **power consumption:**
  - public acceptance for large scale projects significantly challenged if (substantial fractions of) extra power plant required!

✗

  - **ILC design driven by *self-imposed* limits on total site power:**
    - **200 MW for 500 GeV**
    - **300 MW for 1 TeV**

✔

- **cost awareness:**
  - from RDR to TDR critical review of design in order to reduce costs
  - value engineering
  - power reduction in favour of stronger focussing

- **at the end of the day: luminosity ~ power ~ money**

Sustainability

2016 …..

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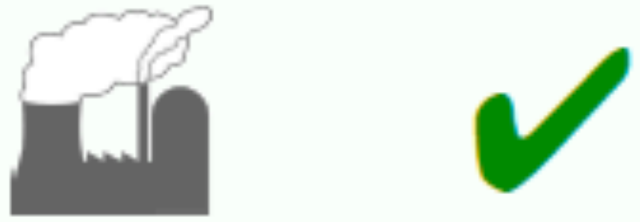

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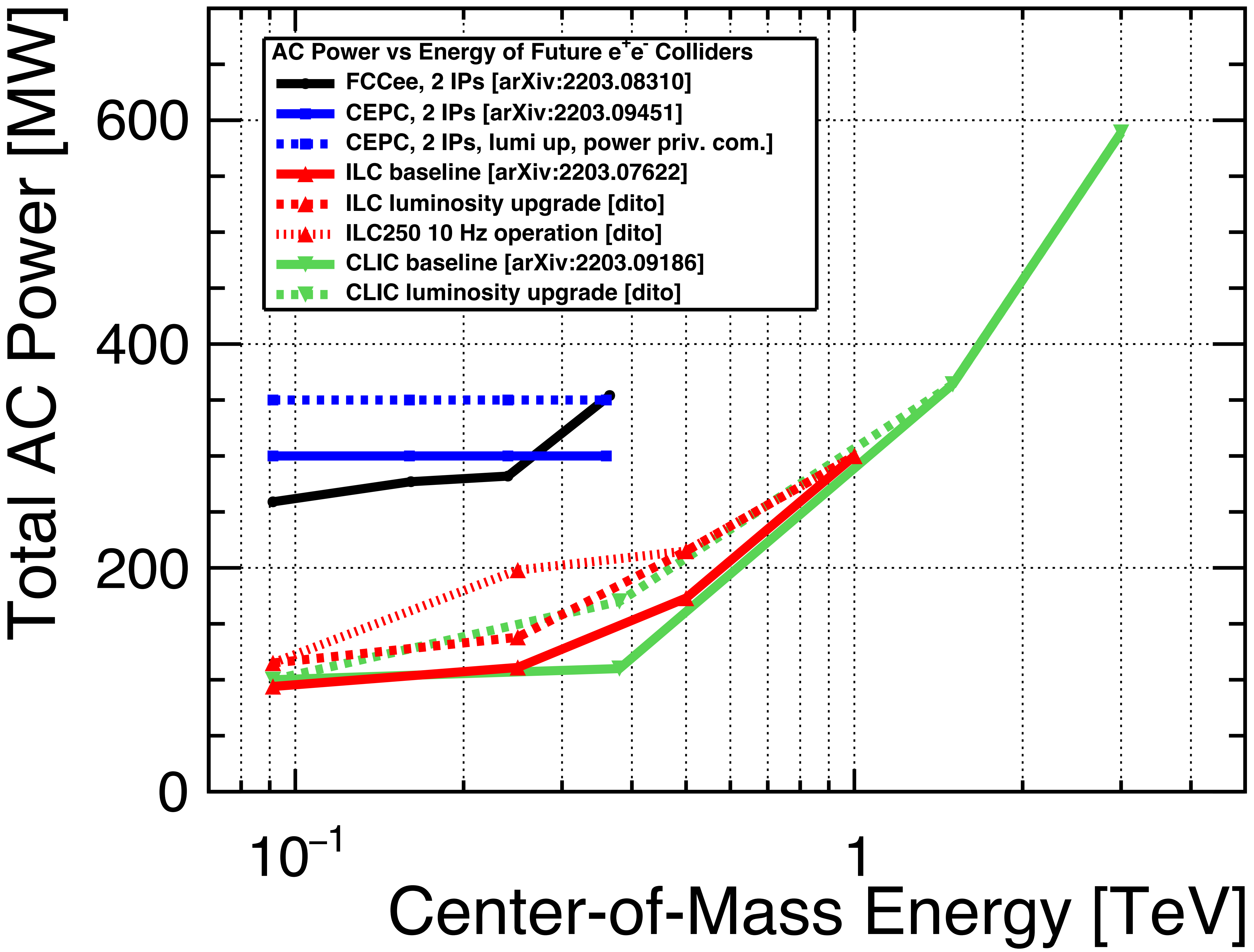
- **minimal usage of resources was always design criterion for serious projects**
- **but only a reduction of the energy consumption is not sufficient anymore**
- **change of paradigm:**
  => the next collider project must be sustainable in every aspect

… and tomorrow: Sustainability of new Accelerators

Much more than CO2 equivalents…

minimal use of resources to reach physics goals

- Operation -> **total electrical site power**:
  - **minimize**:
    - even if - or especially if - all power will come from regenerative sources, the competition with other human needs will be high
    - optimizing all components for minimal energy consumption
  - **be flexible**:
    - must be able to handle large variations in availability of regenerative power
    - could cooling capacities be used as buffer for energy, also for society in general?
- Construction, concrete etc
  - **tunnel as short as possible**
  - use concrete with low(er) CO2 emission => extra costs ?!
  - avoid usage of rare earths and other problematic substances



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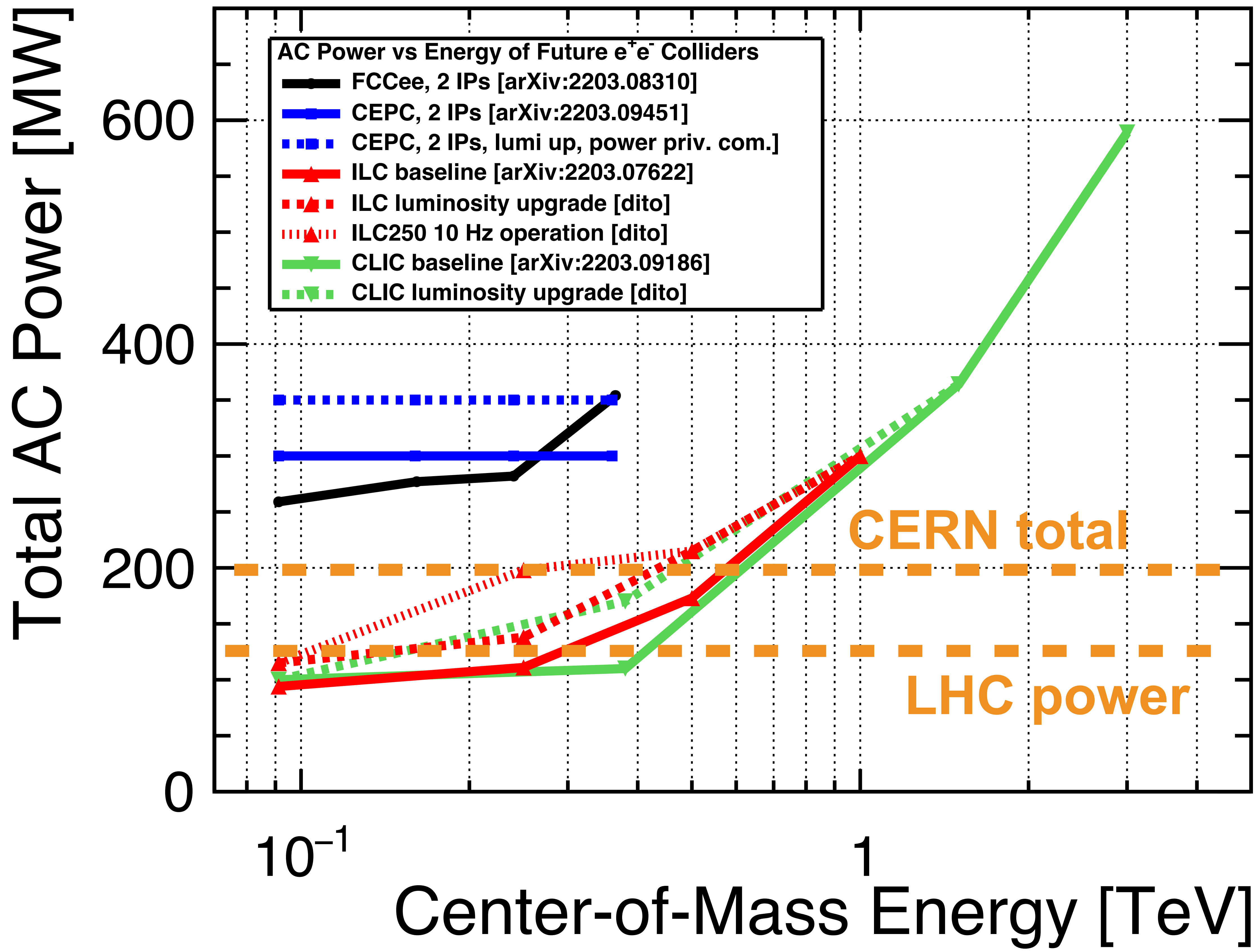
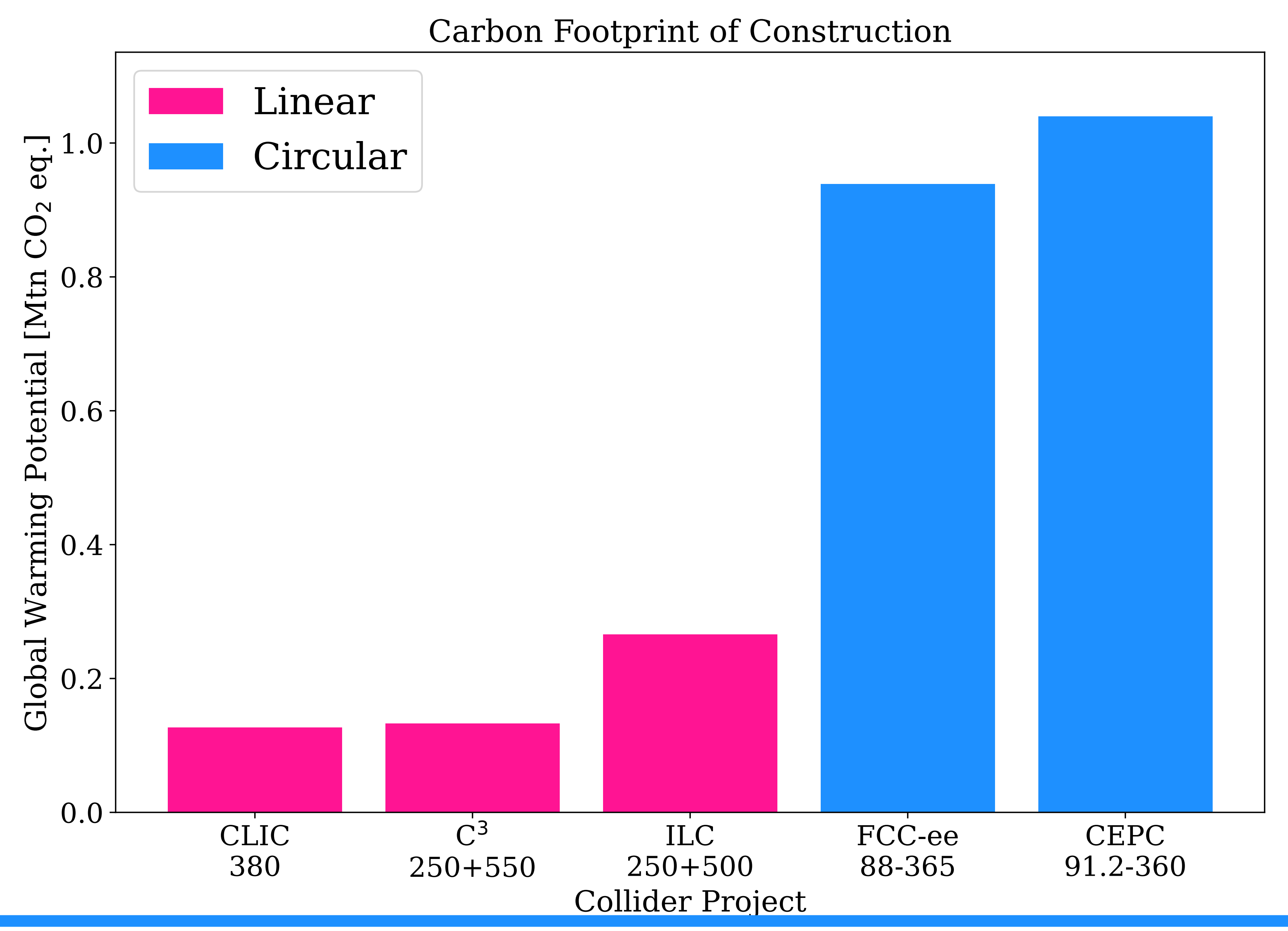


Global Warming Potential

Study by C3

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



arXiv:2307.04084

Global Warming Potential

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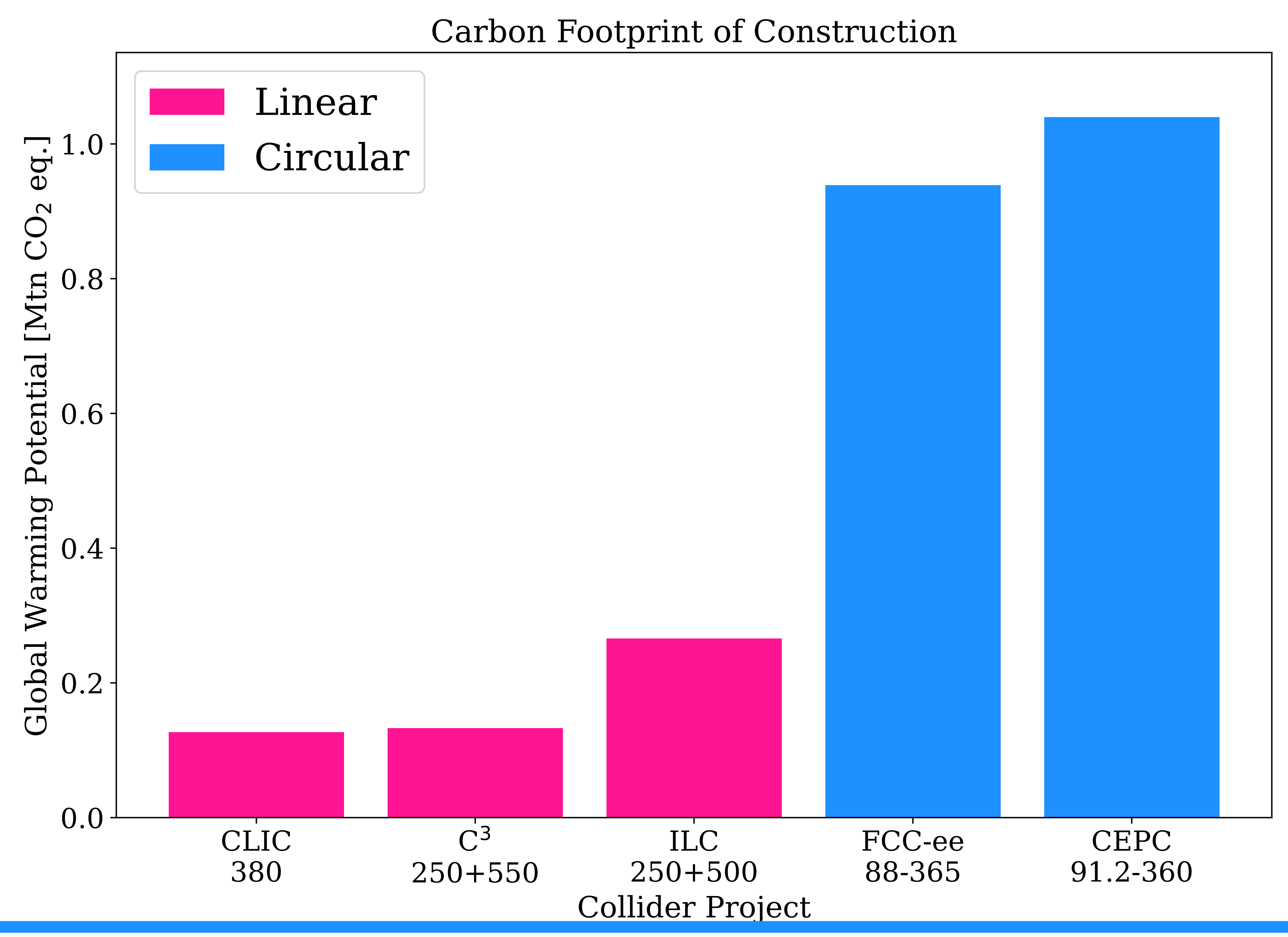
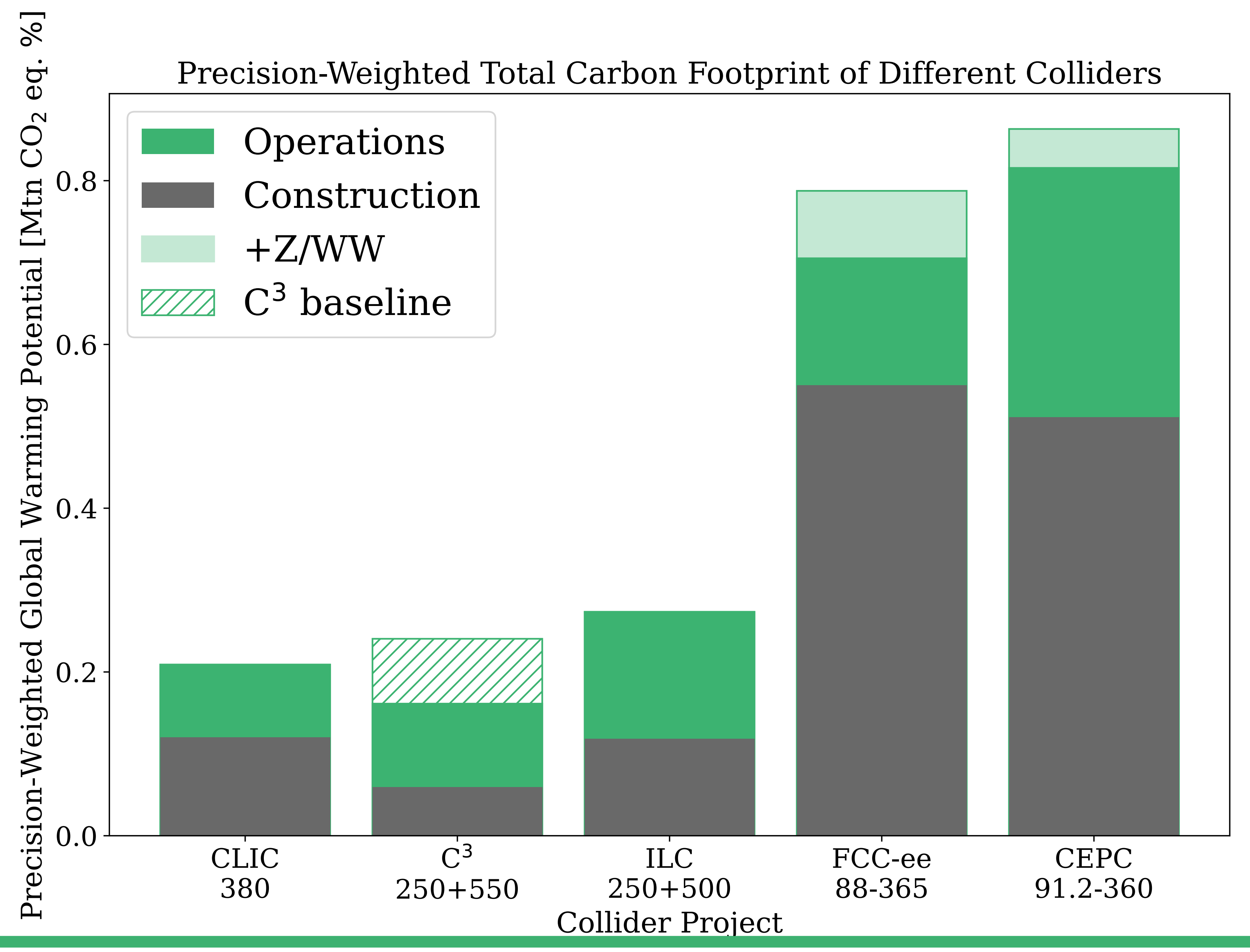




Adding operation GWP

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

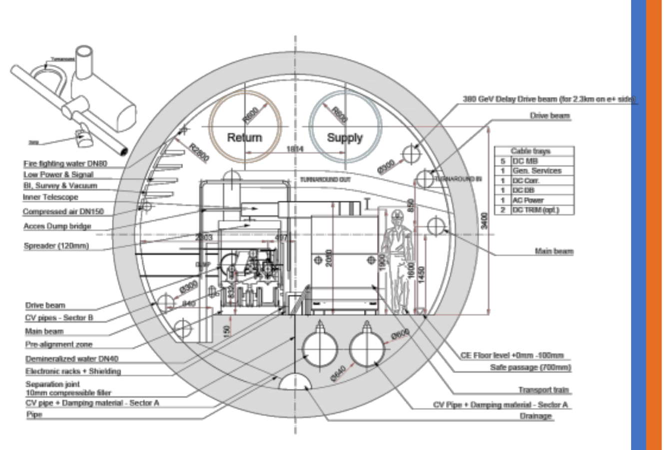
- **Operation dominates for LCs**
- **Construction dominates for CCs**

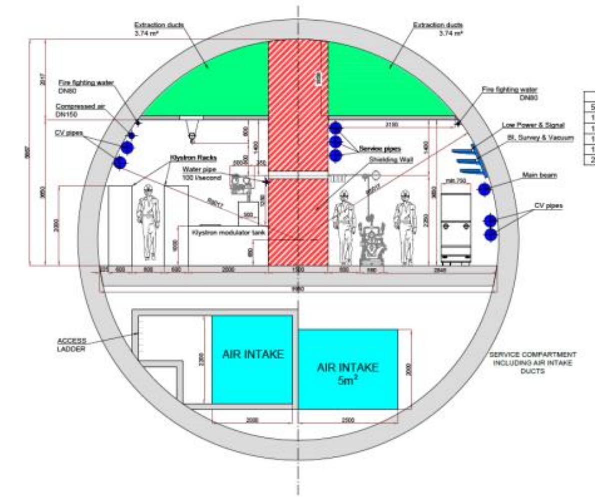
arXiv:2307.04084

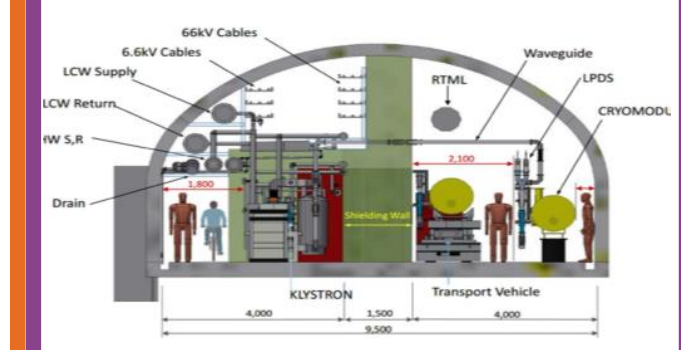
GWP of tunnel construction

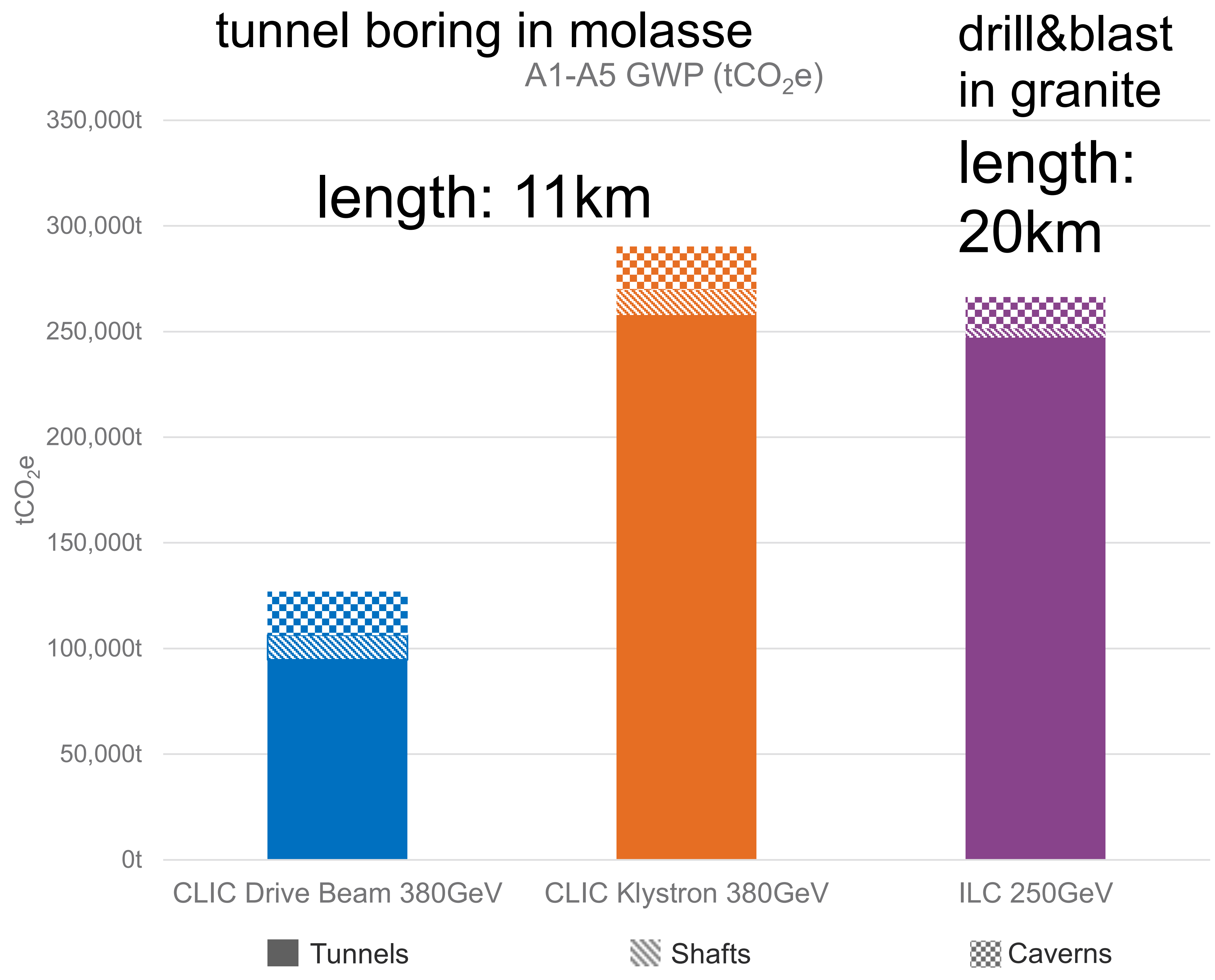
Study by CLIC and ILC

- **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



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

GWP of tunnel construction

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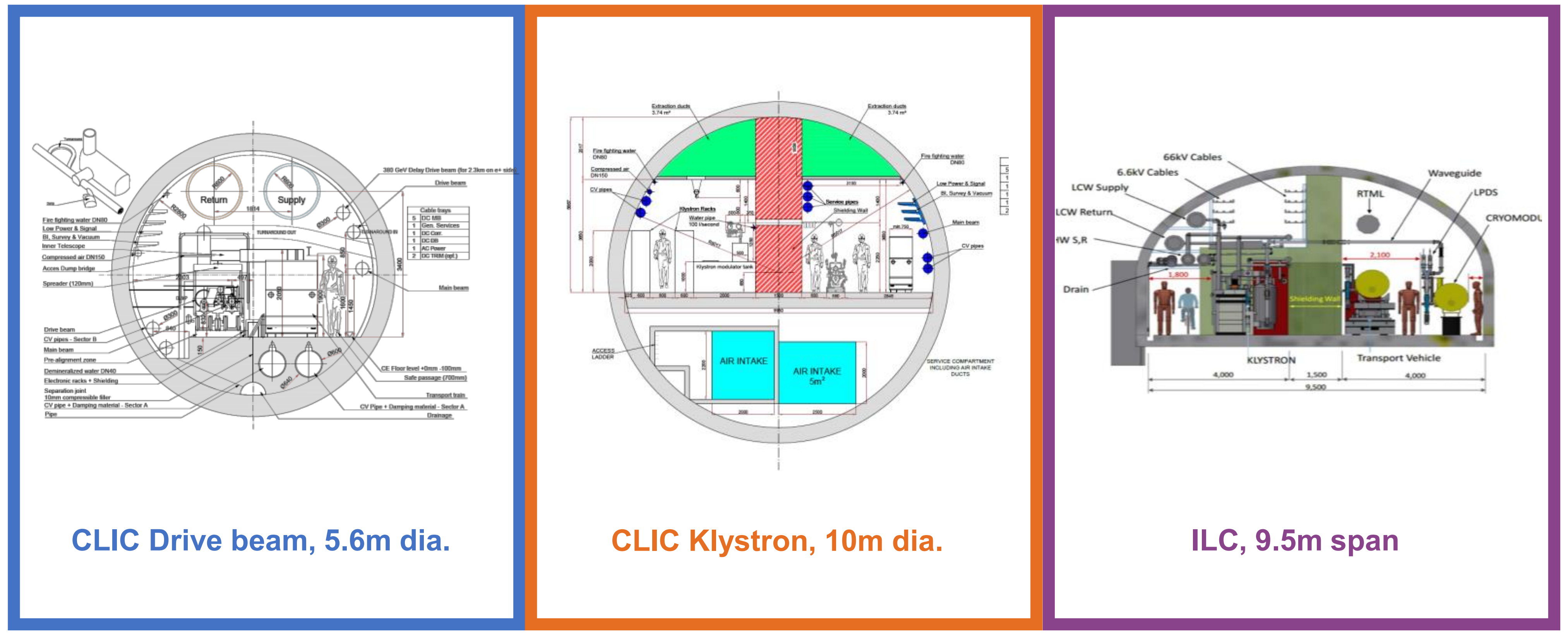
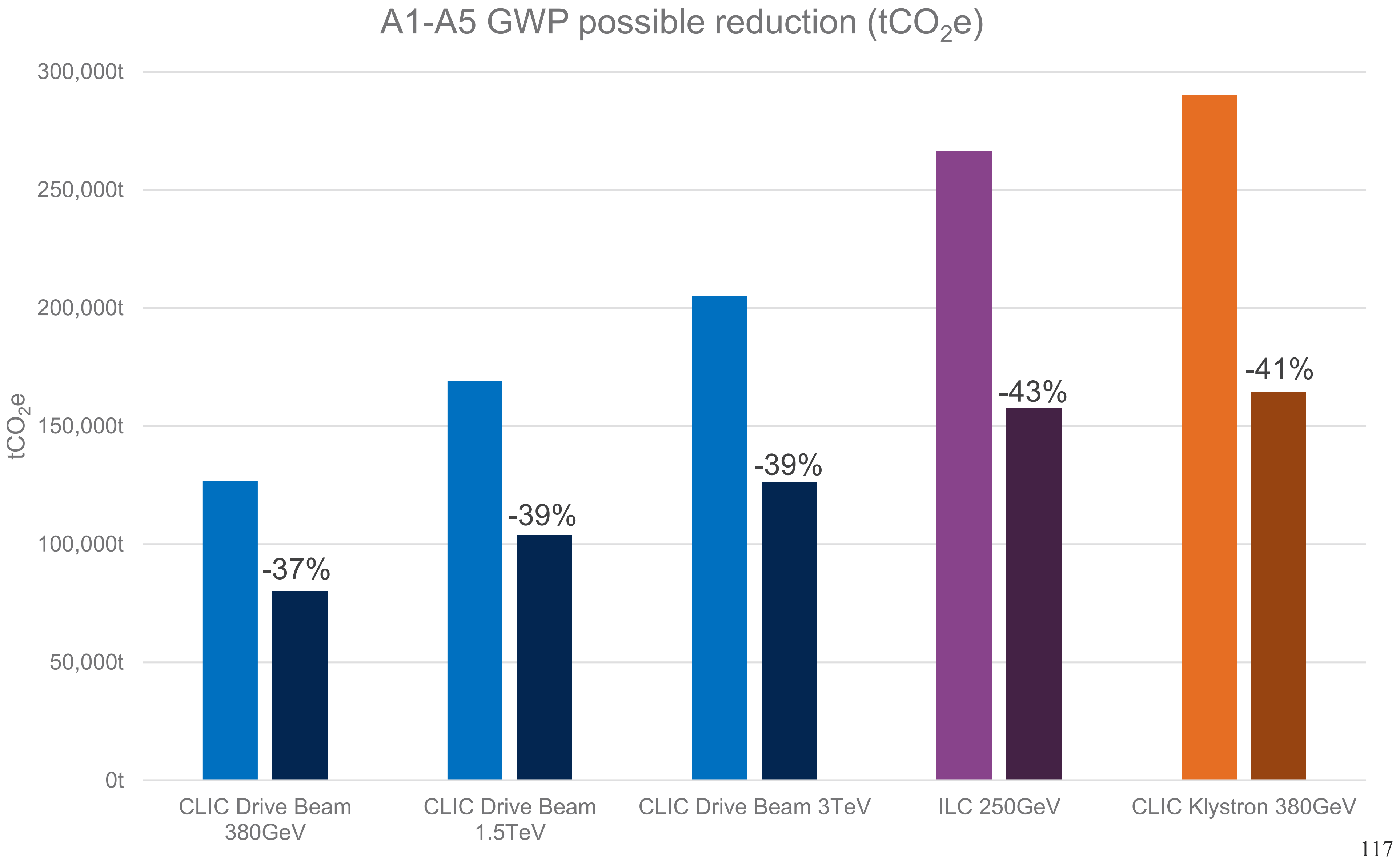
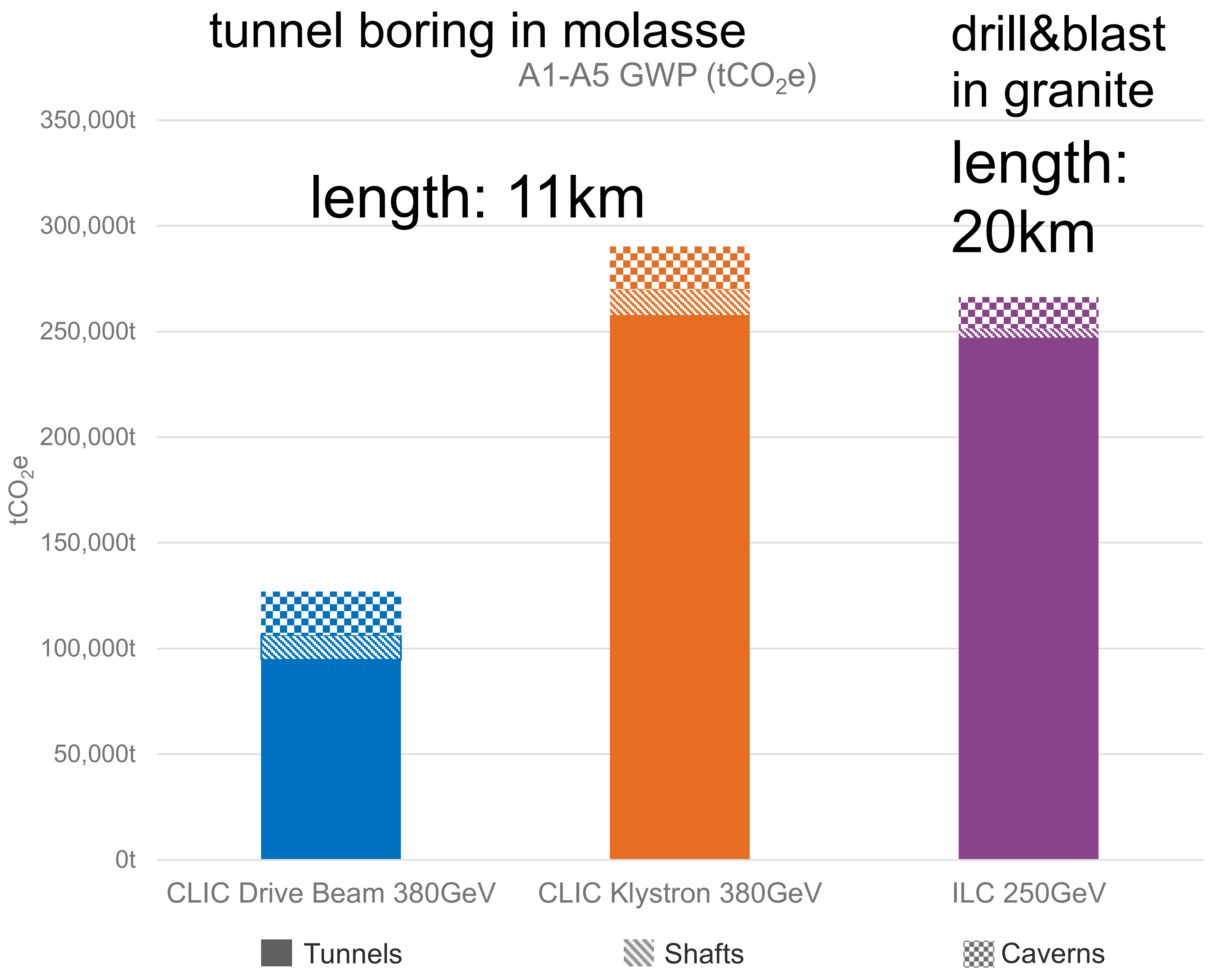
- **~40% of reduction potential by**
    - usage of low-CO2 materials (concrete, steel)
    - reduction of tunnel wall thickness







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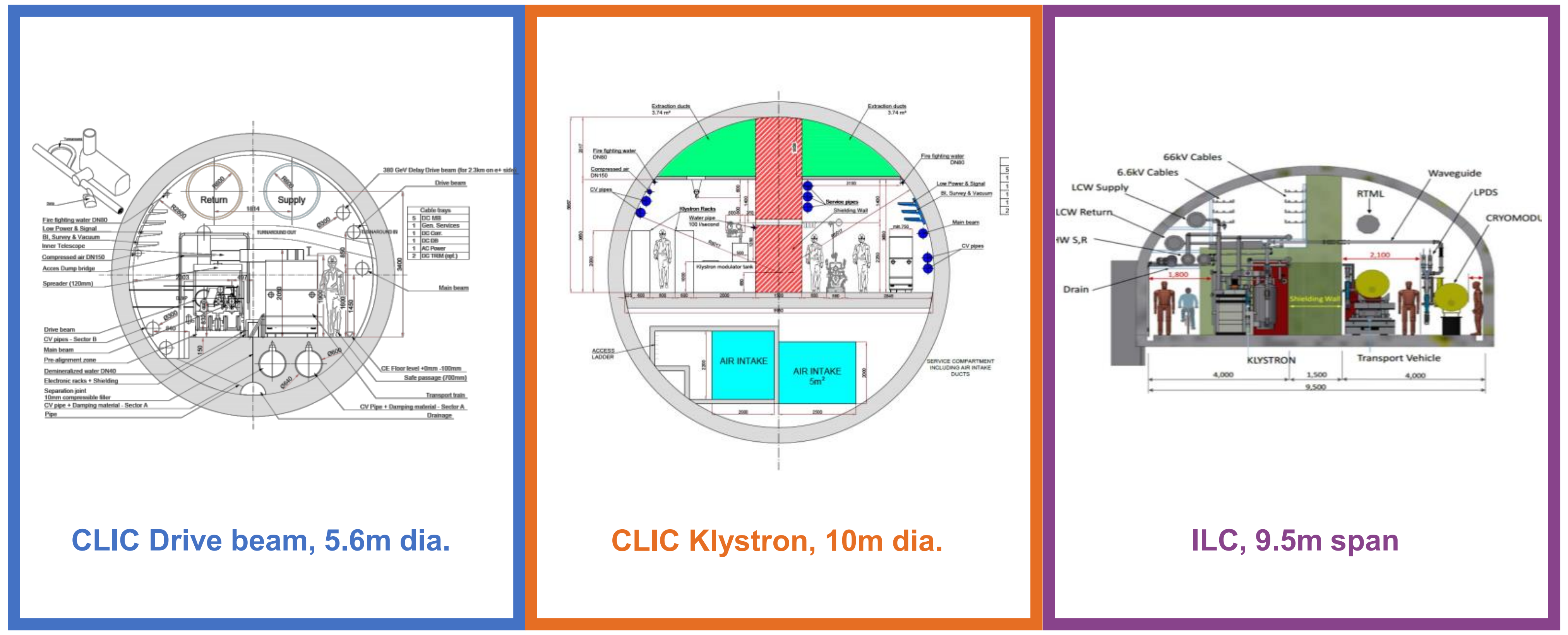

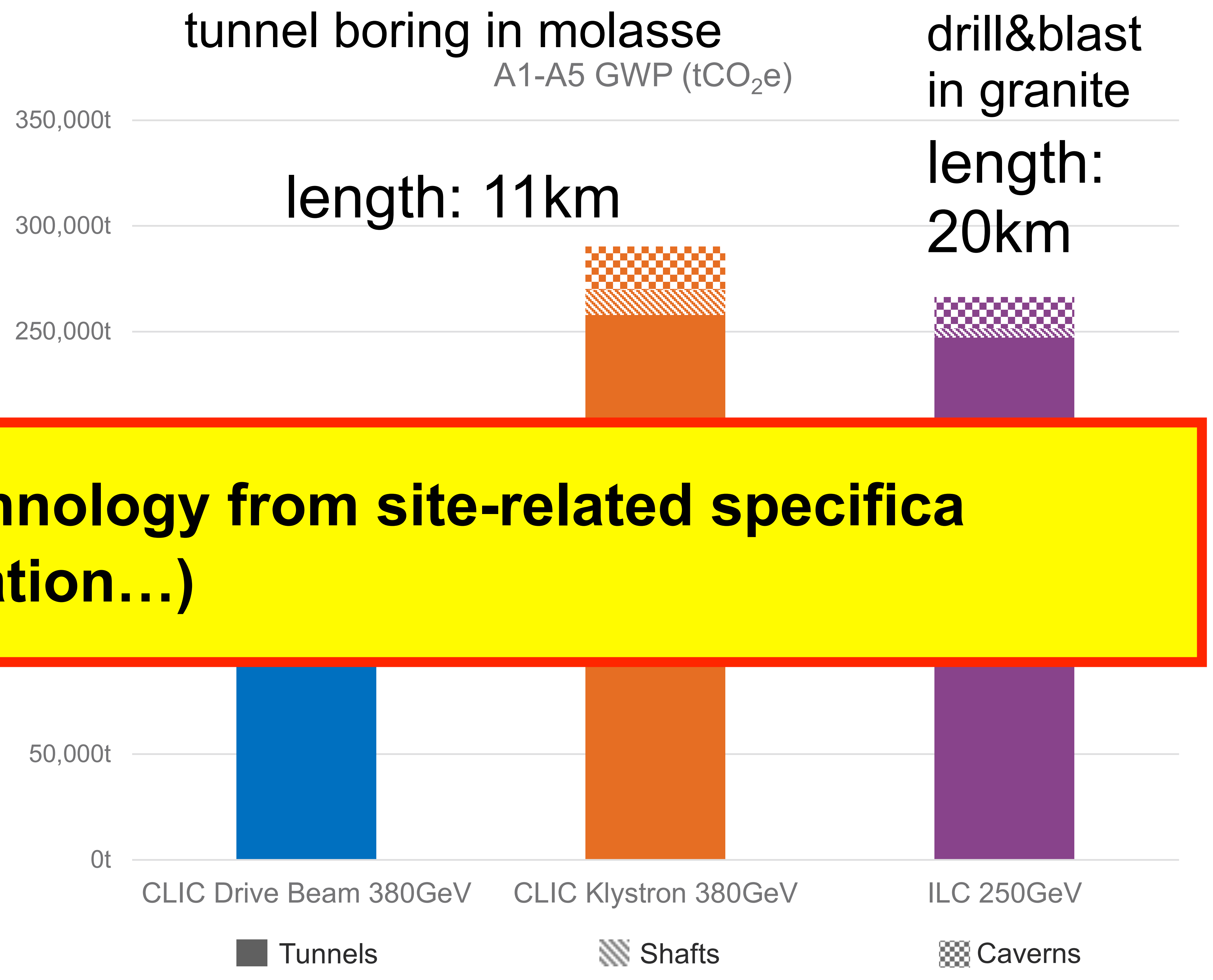

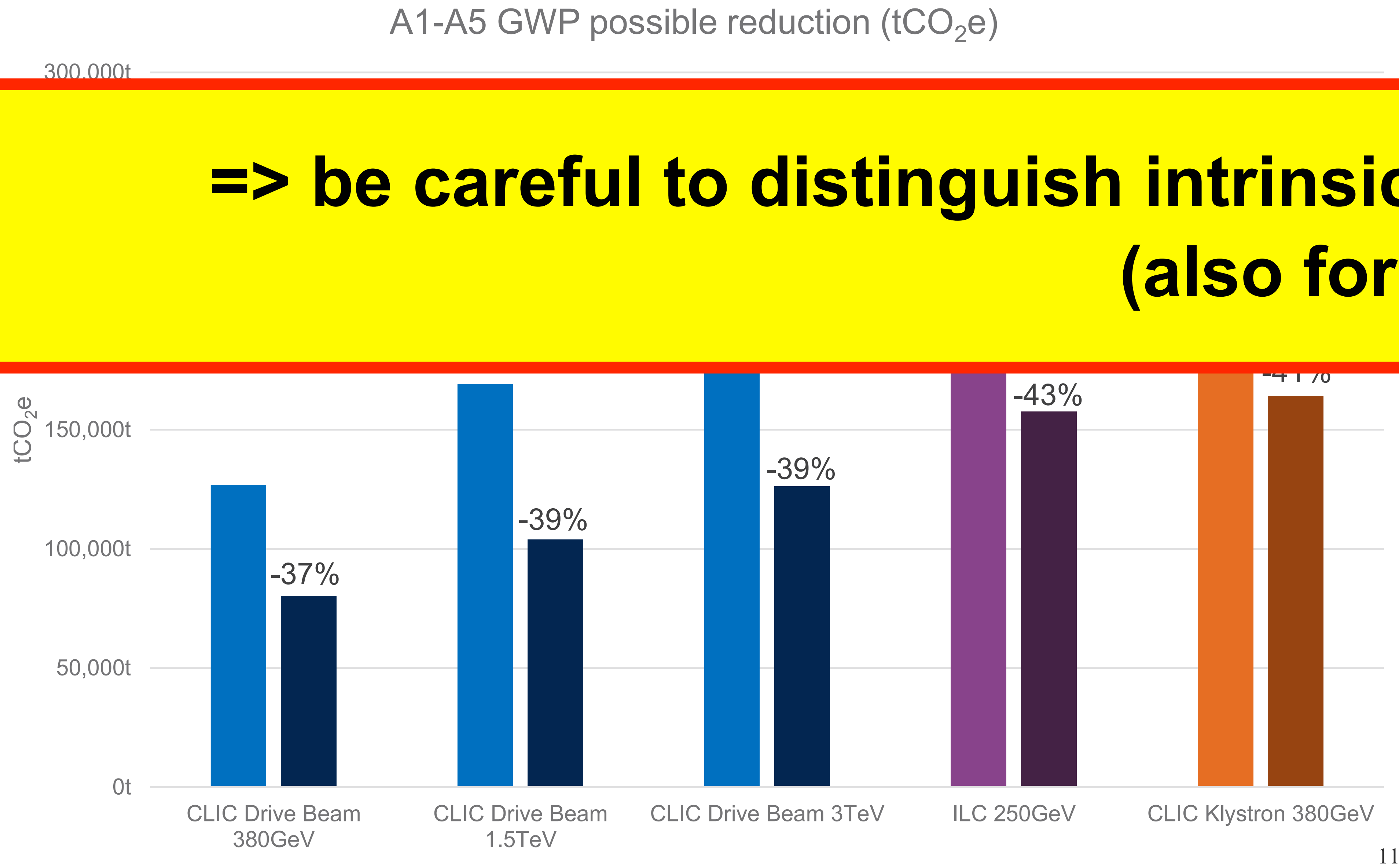

=> be careful to distinguish intrinsic needs of technology from site-related specifica (also for GWP of operation…)

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