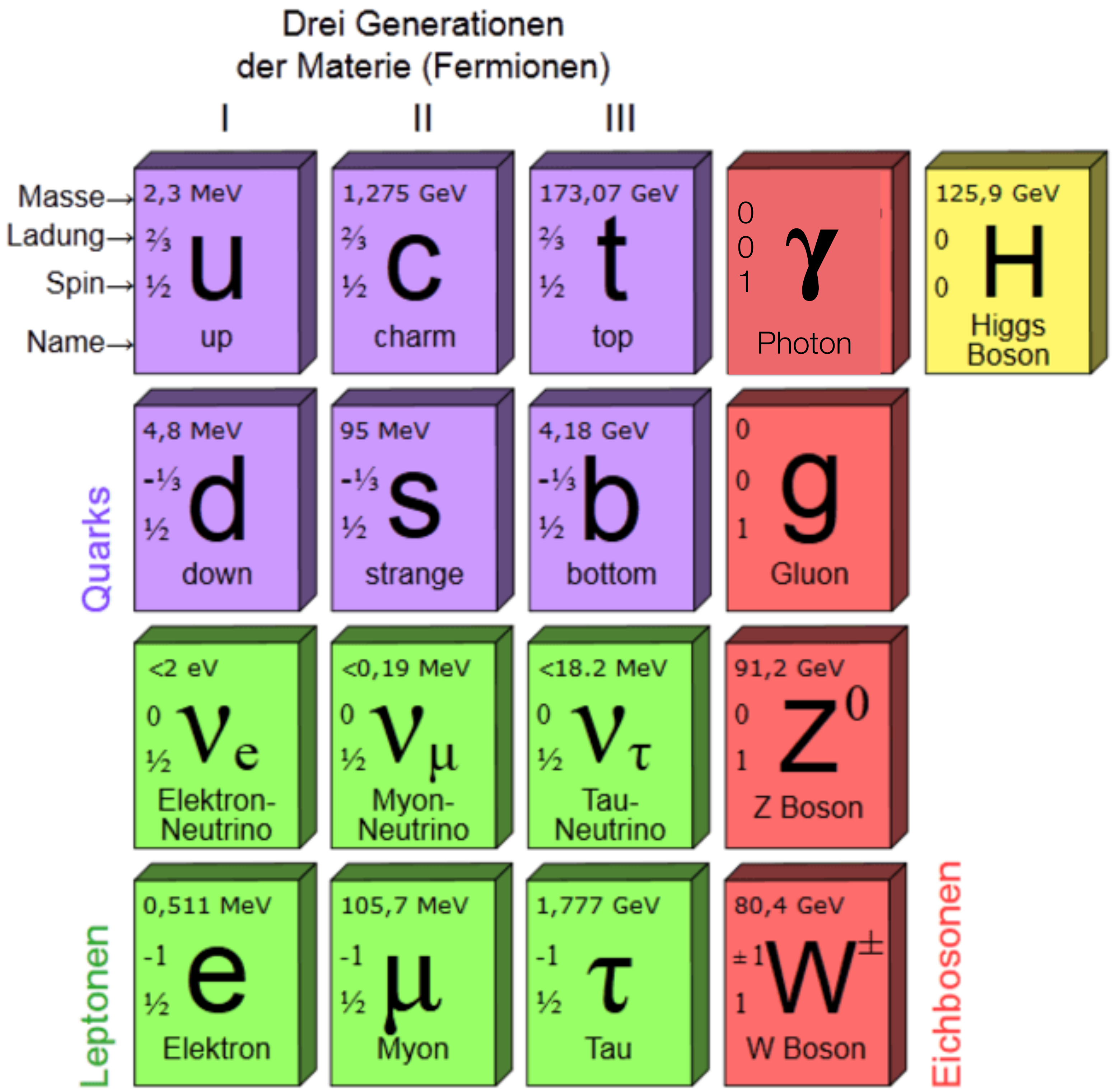
Straight to the Future: Physics Program and Status of the ILC

J. List (DESY/CERN)

International Conference on the Physics of Two Infinities, Kyoto, March 27-30, 2023

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: $SU(3)xSU(2)_LxU(1)_Y$

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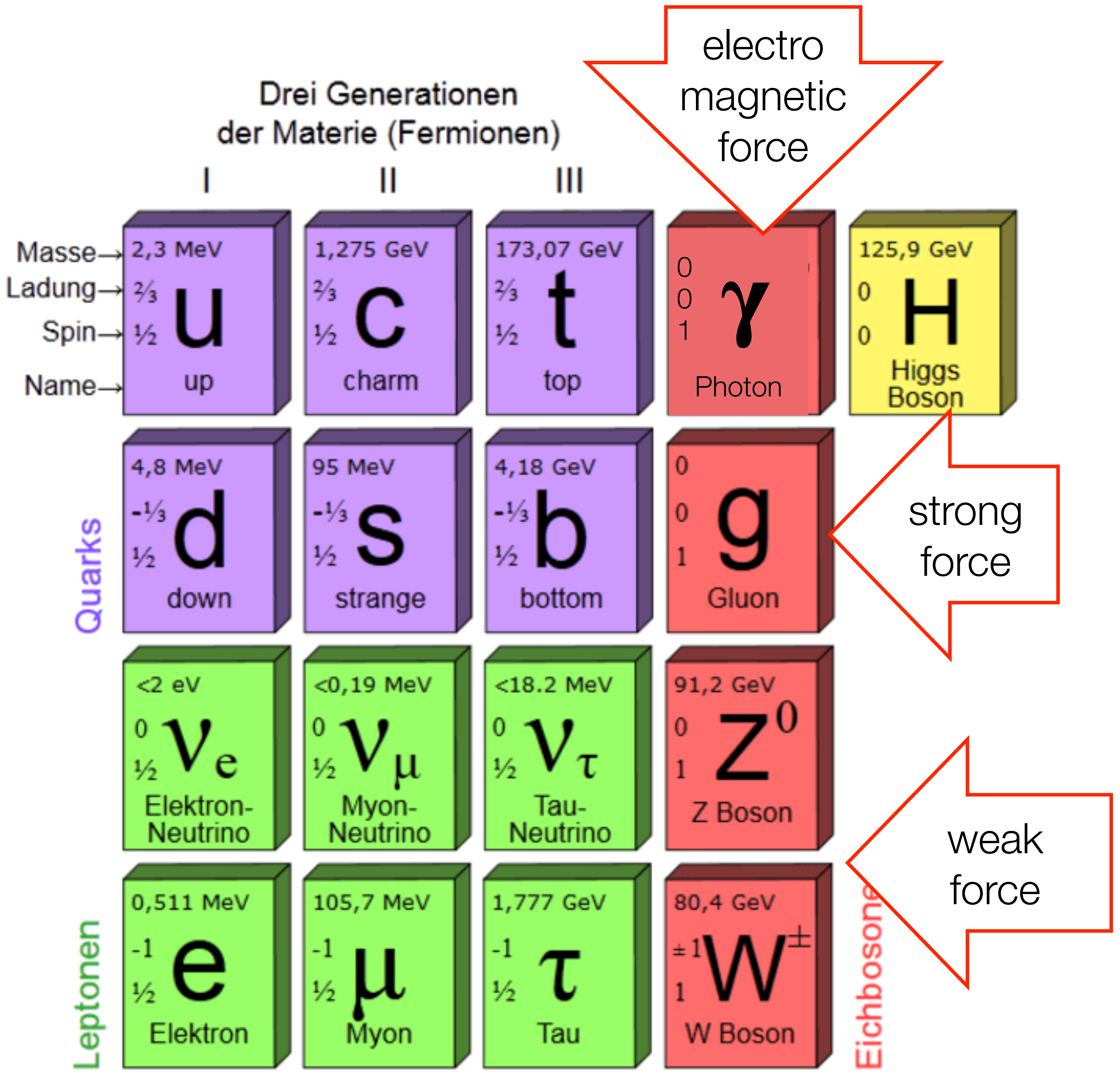

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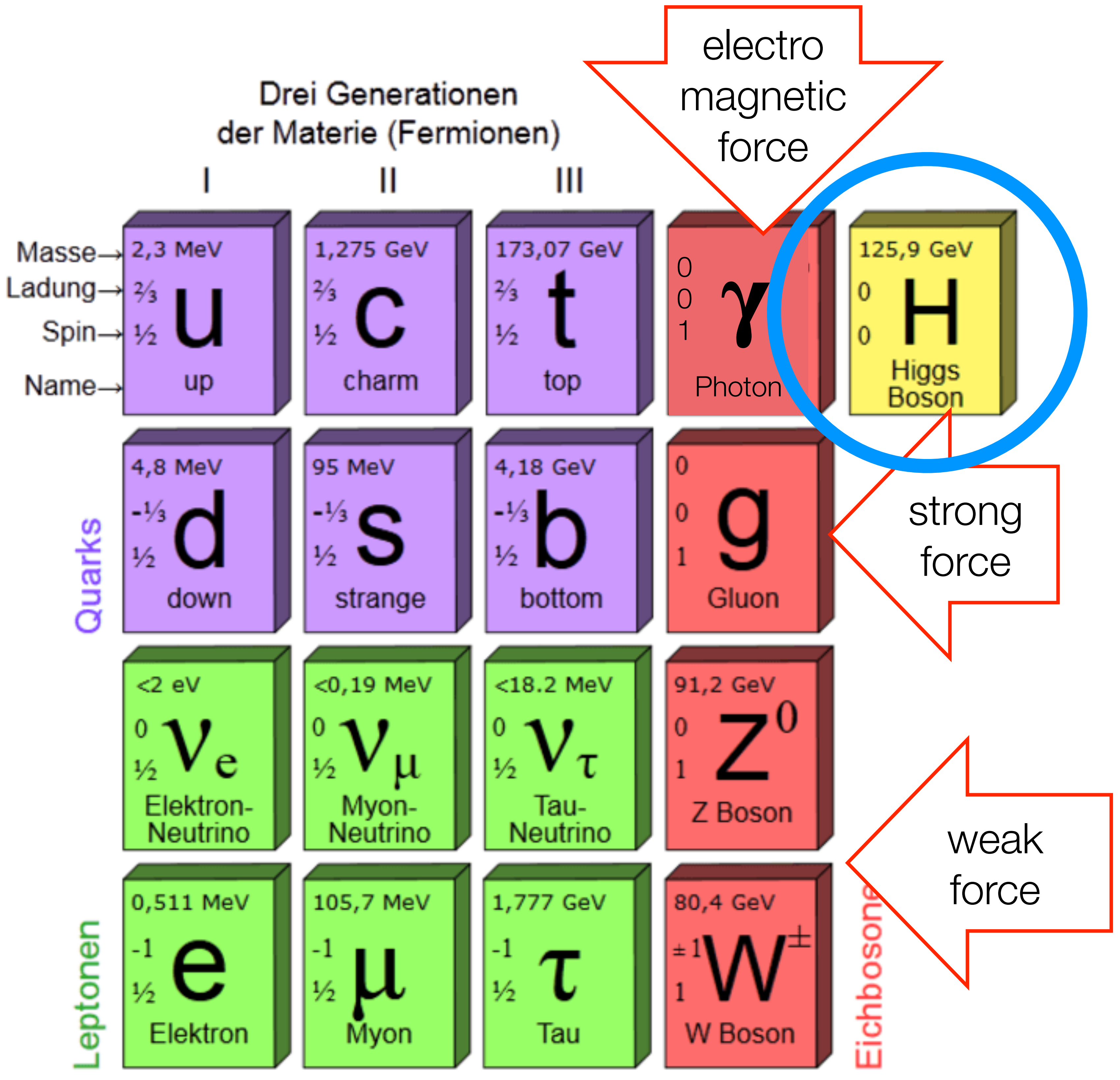

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2012: Discovery of a Higgs bosons at the LHC!

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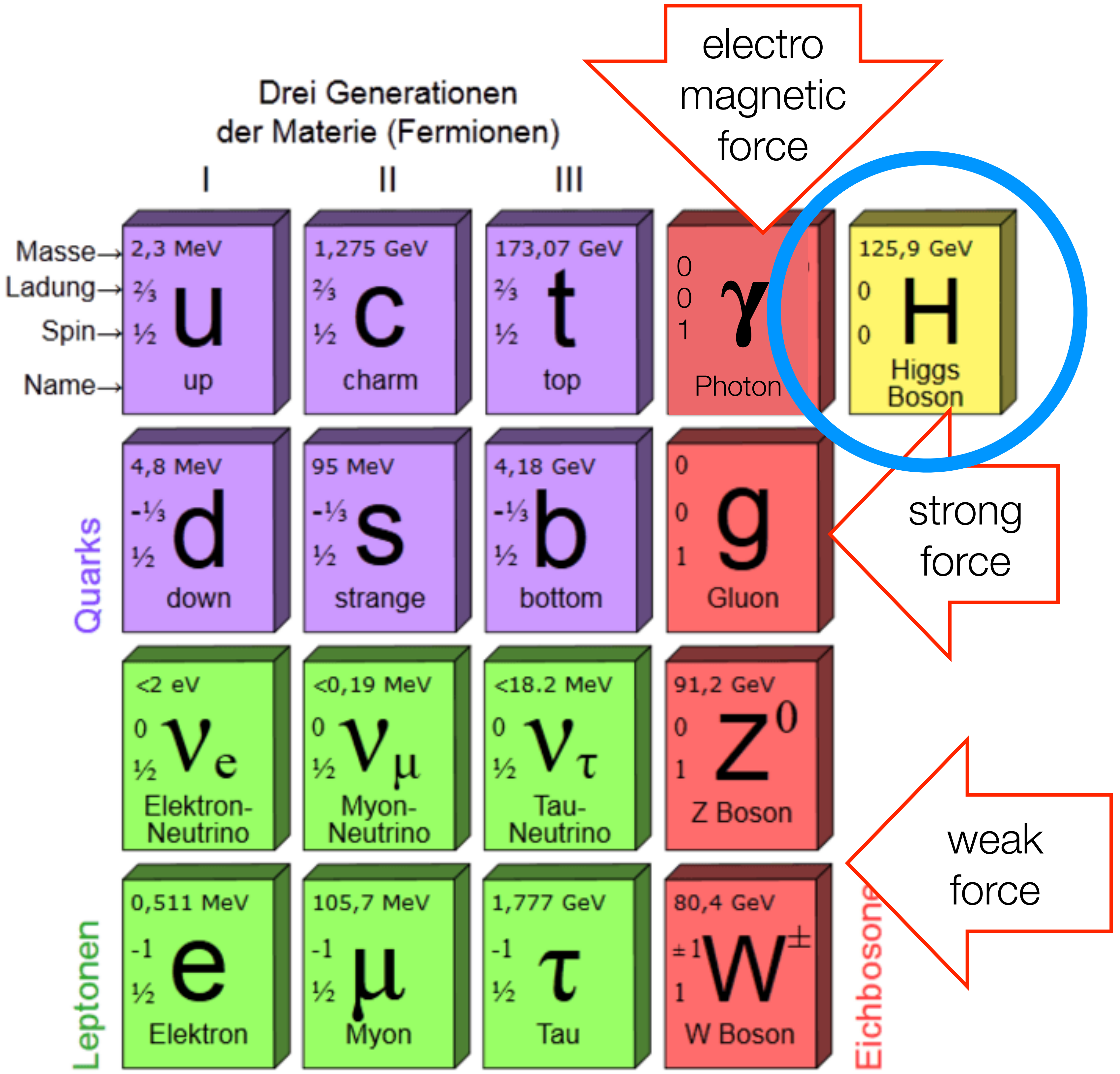

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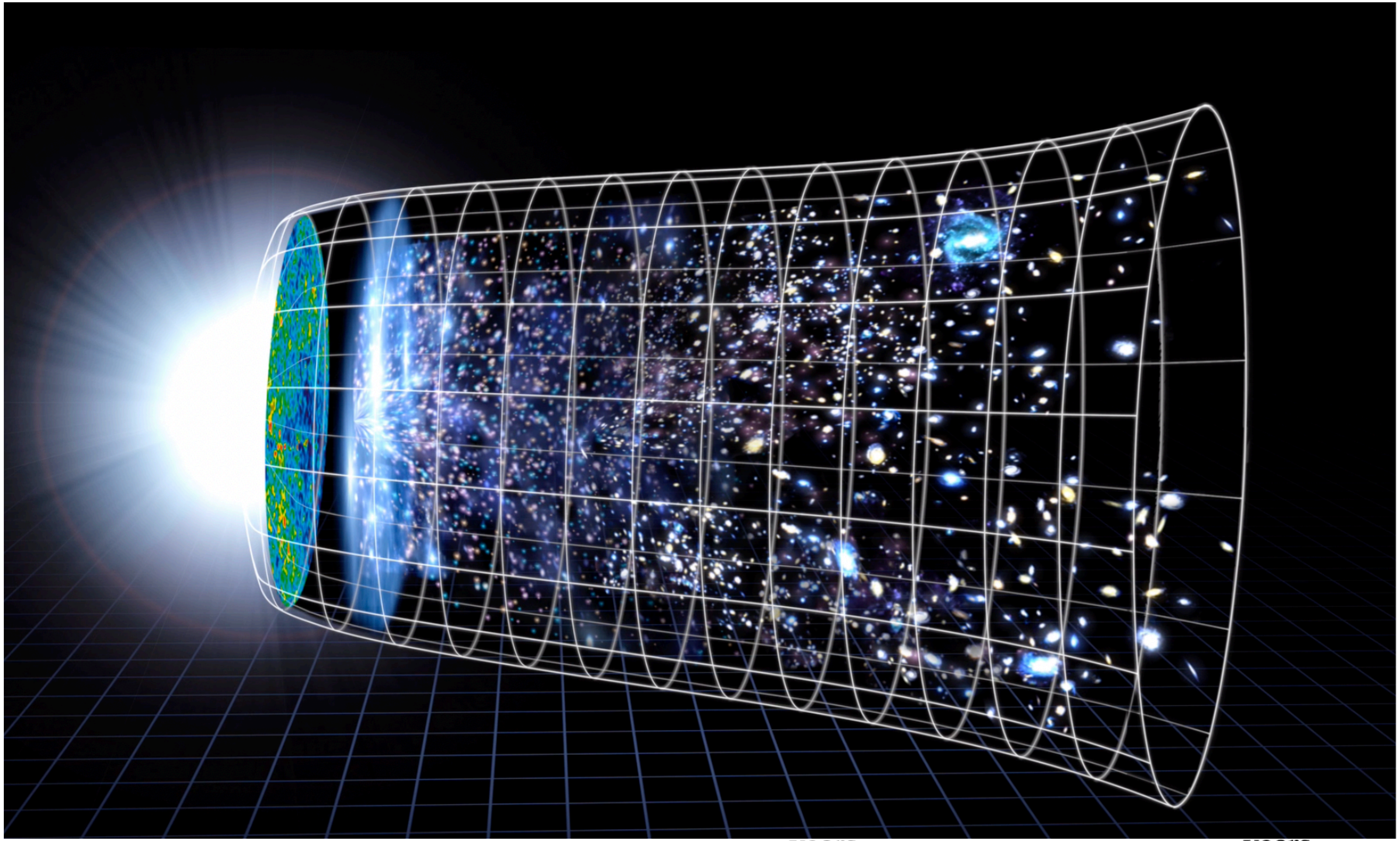
Are we done? — No! — The Higgs Boson is

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

see talk by Roberto Salerno for many more details!



years years

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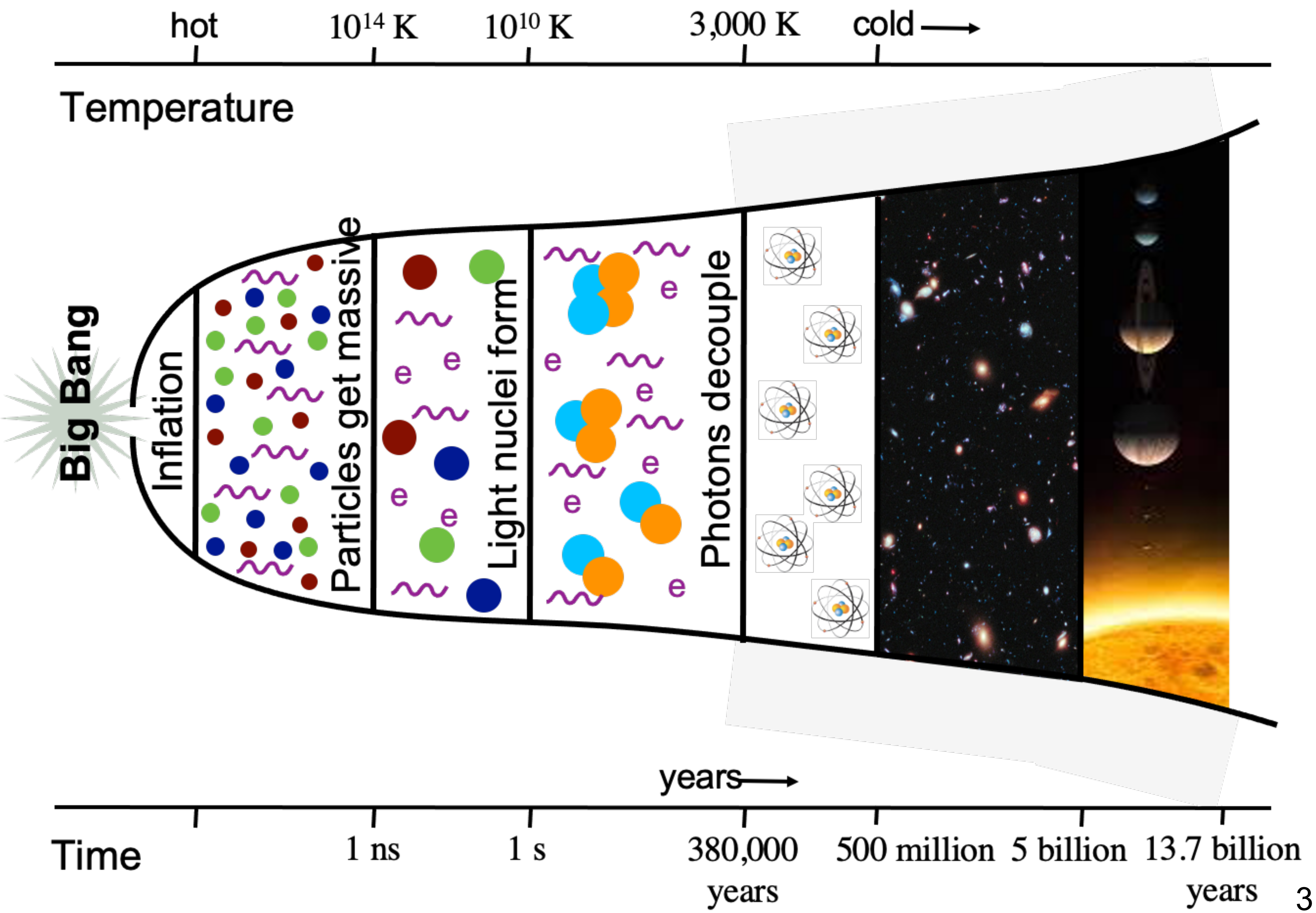

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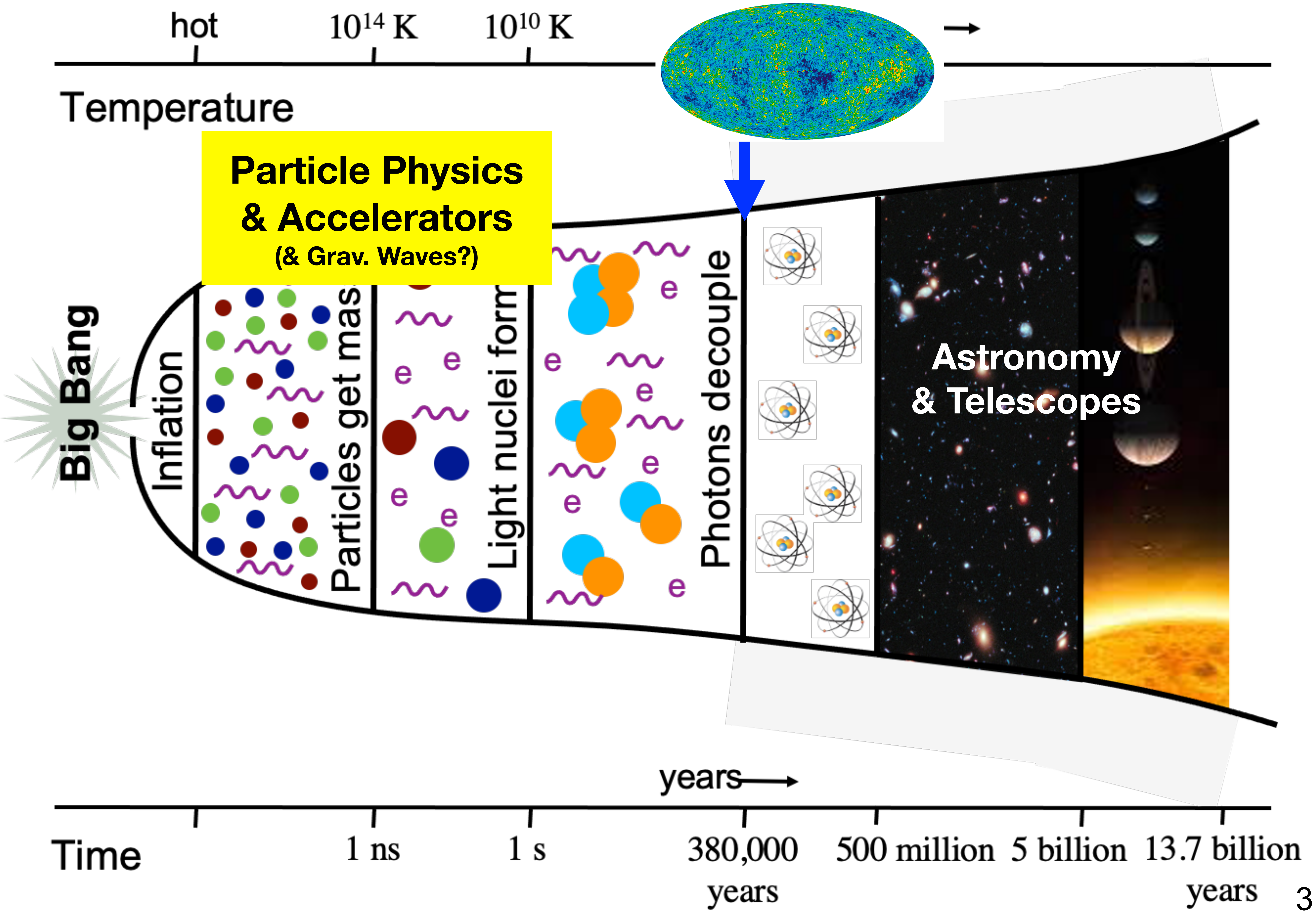

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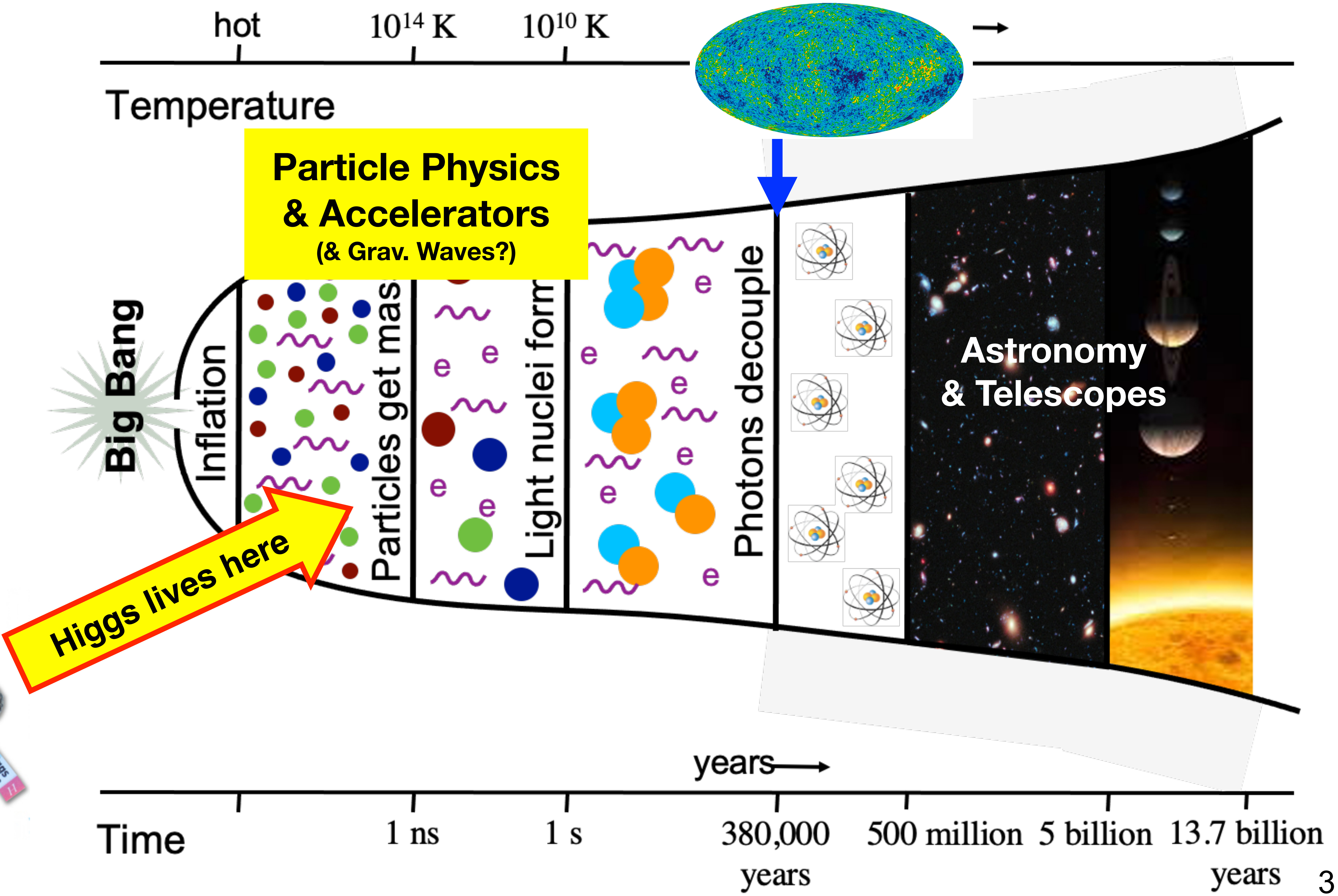

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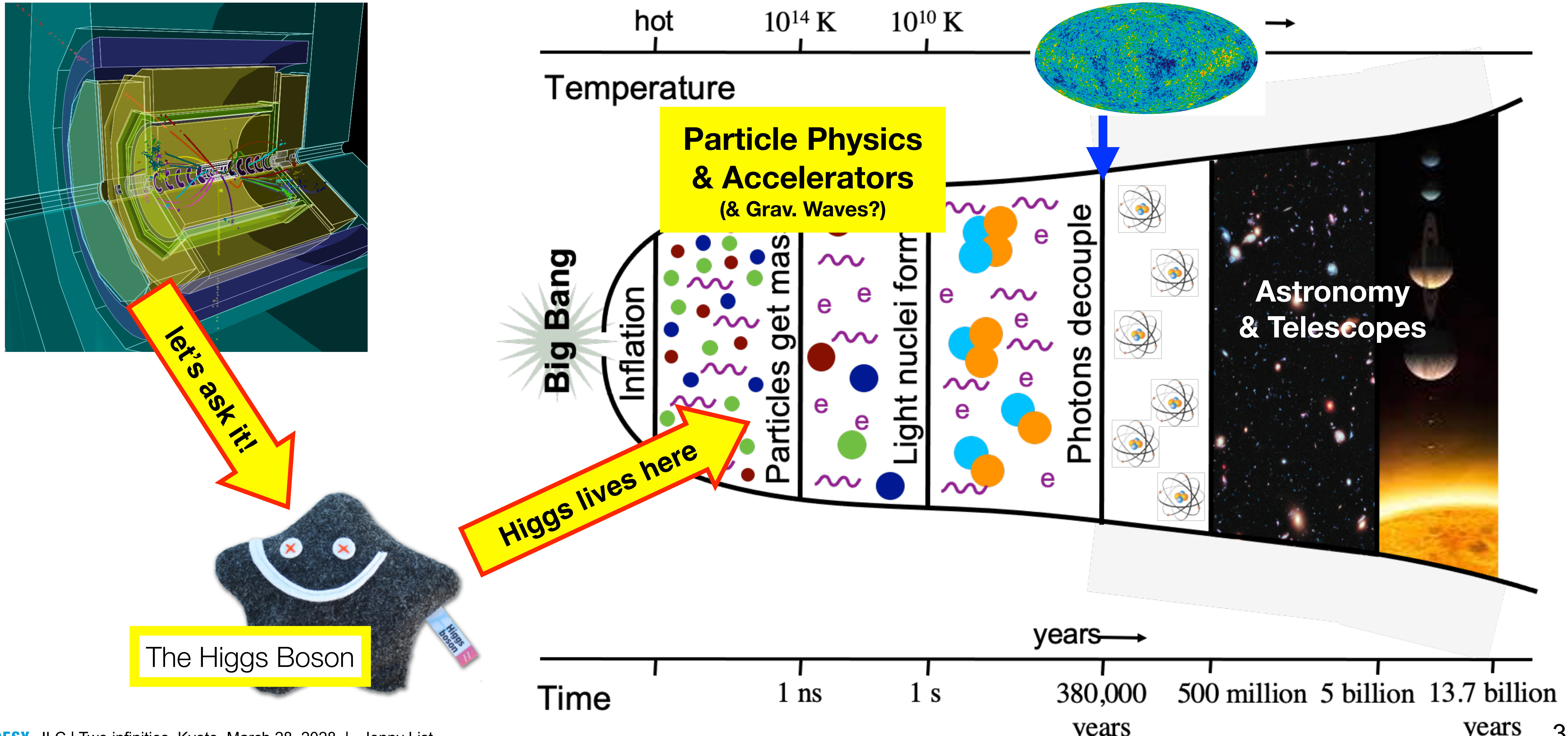
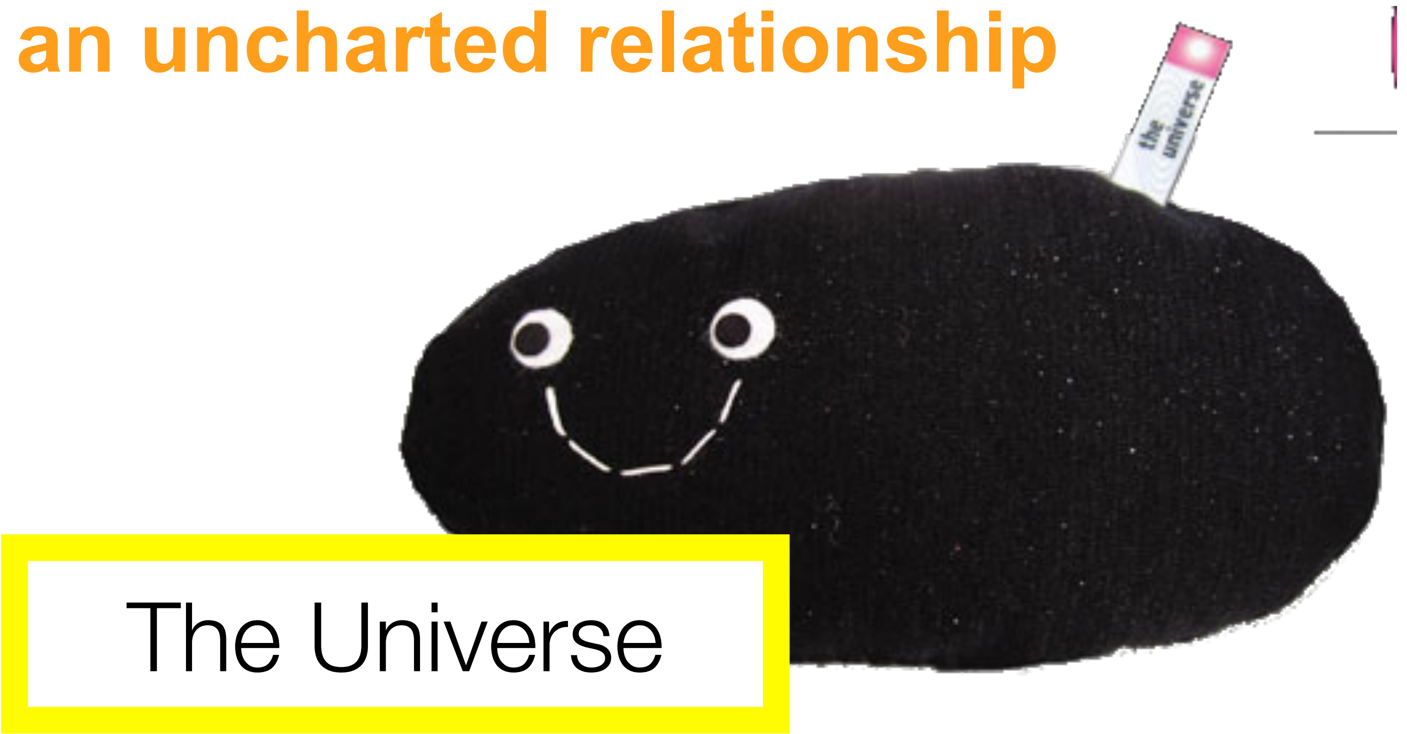


The Higgs Boson and the Universe

Exploration of an uncharted relationship



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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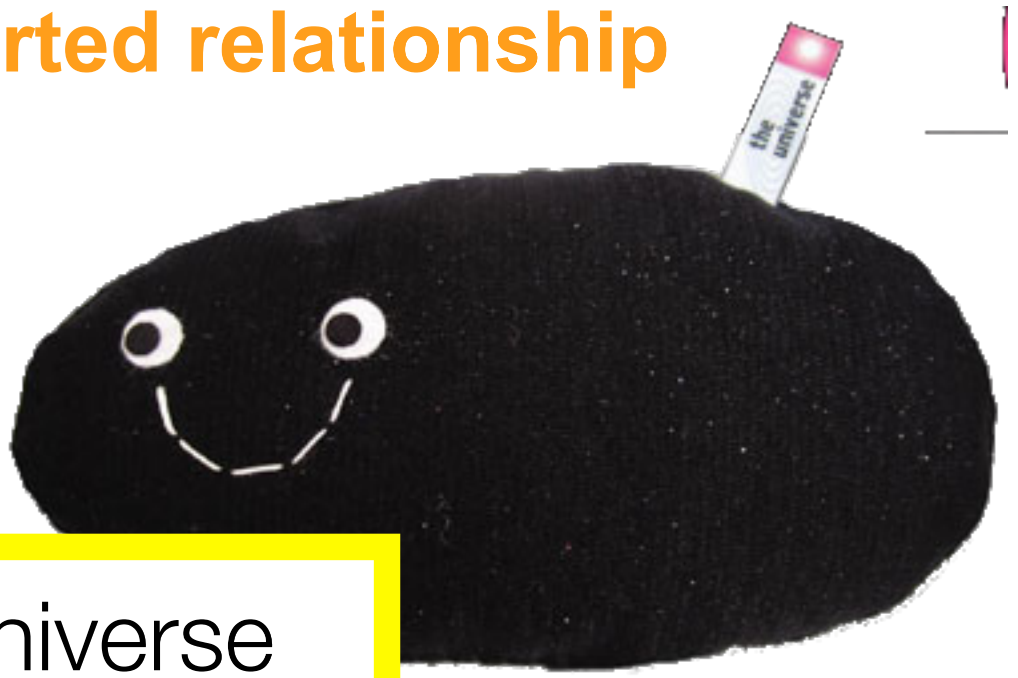

The Universe

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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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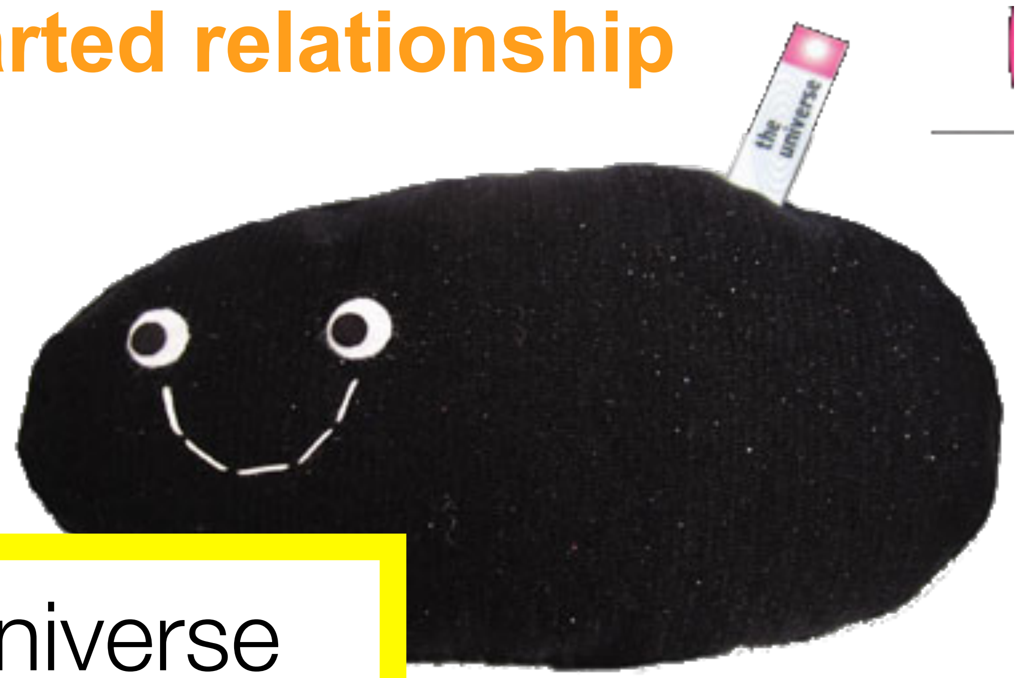

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Is the Higgs the portal to the Dark Sector?

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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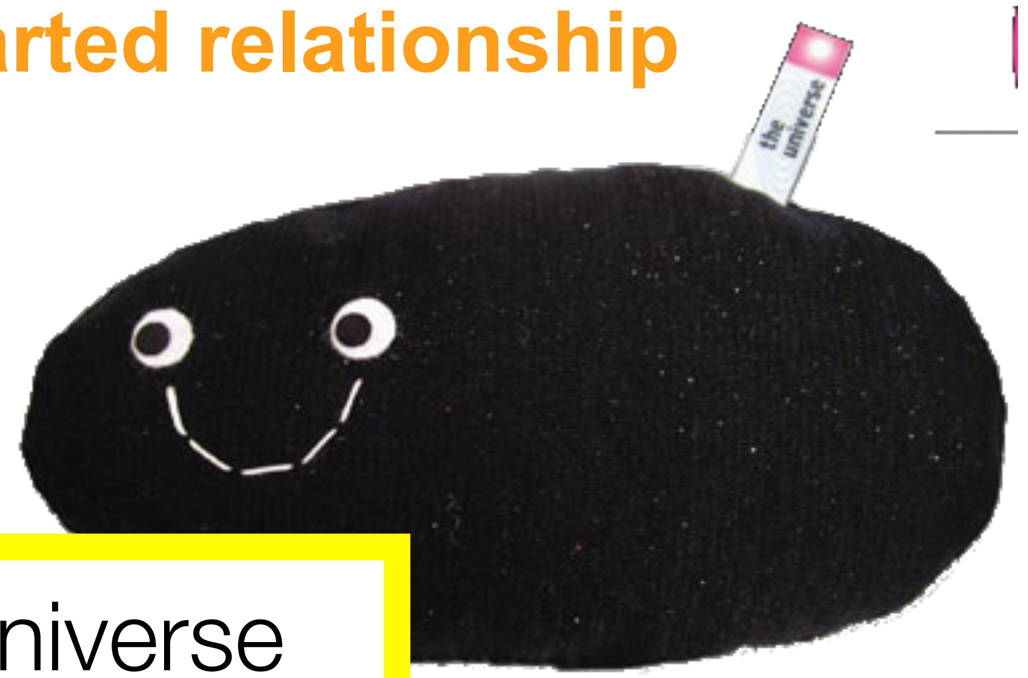

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Why is the Higgs-fermion interaction so different between the species?

- 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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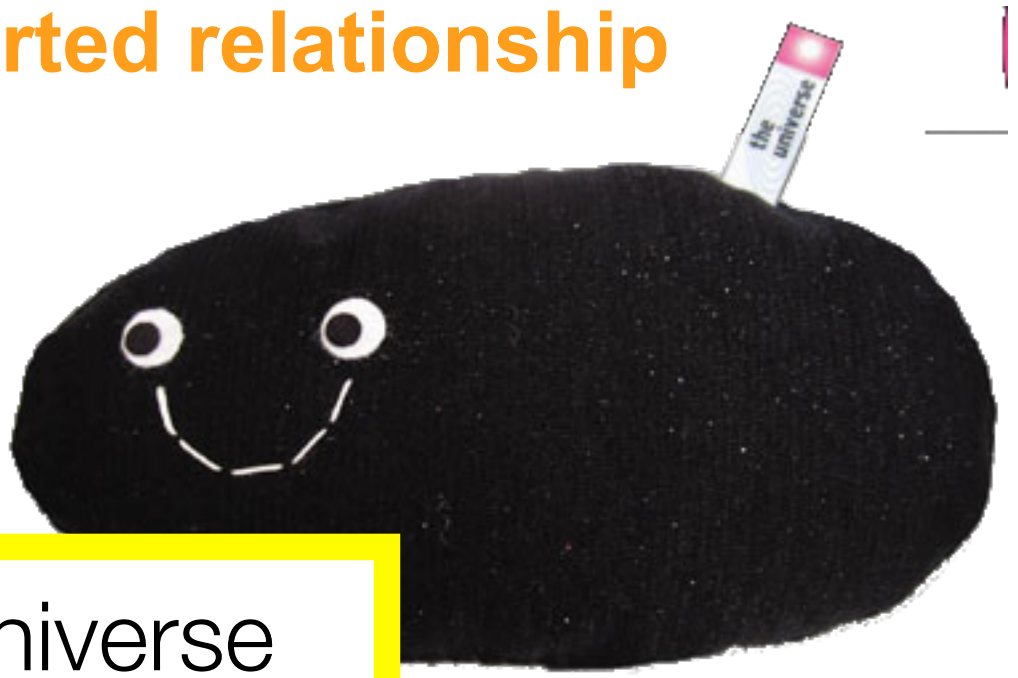

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Does the Higgs sector contain additional CP violation?

- 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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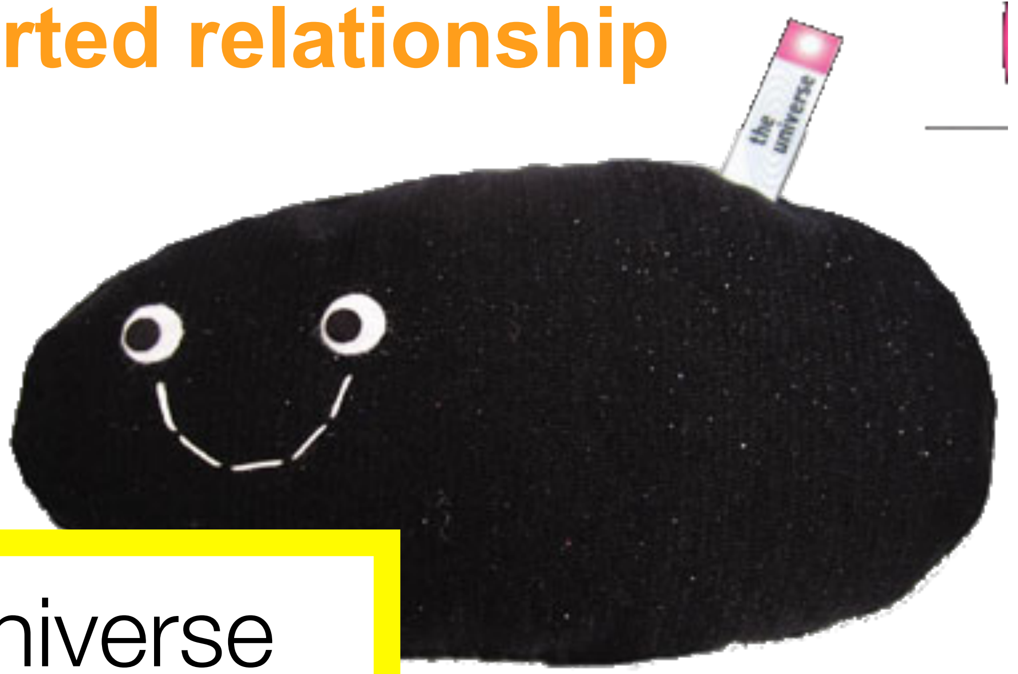

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What is the shape of the Higgs potential, and its evolution?

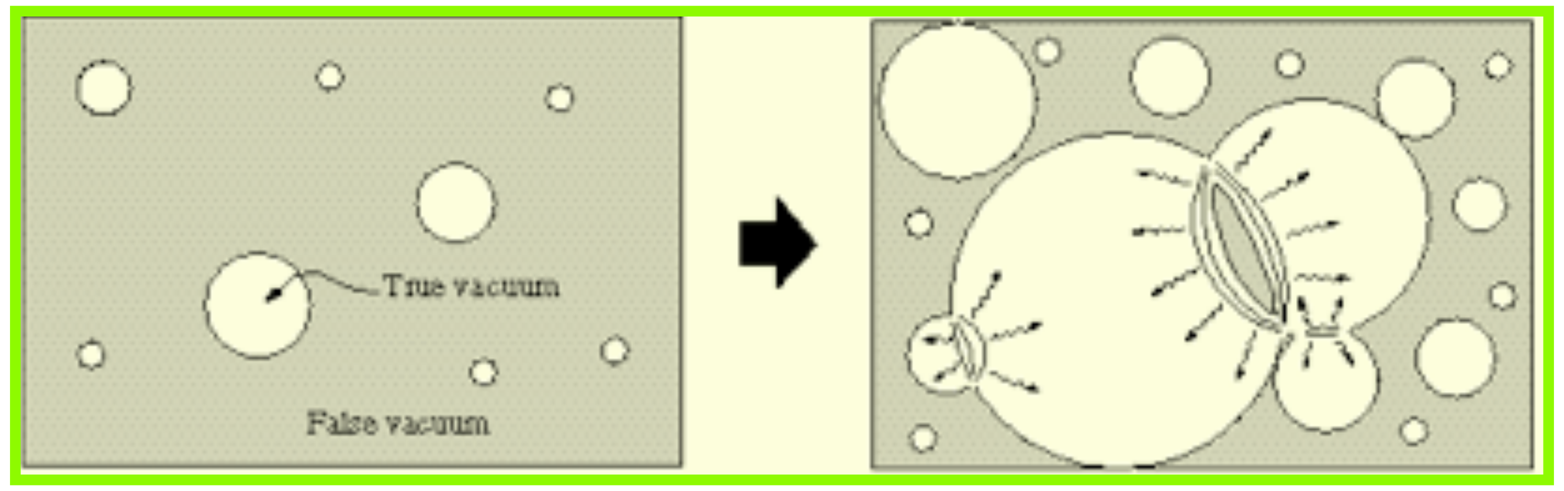
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

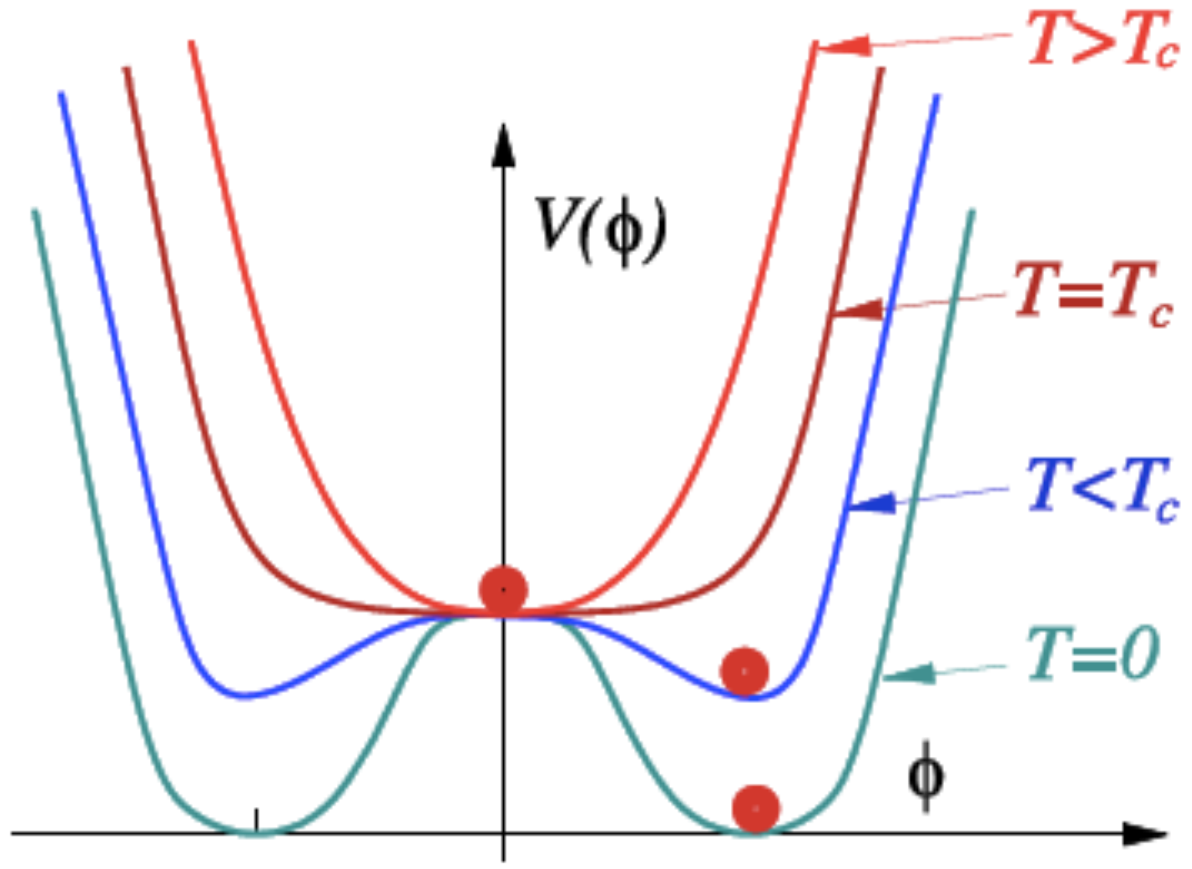
=> discover and study di-Higgs production

The Higgs potential, the Higgs self-coupling and Baryogenesis

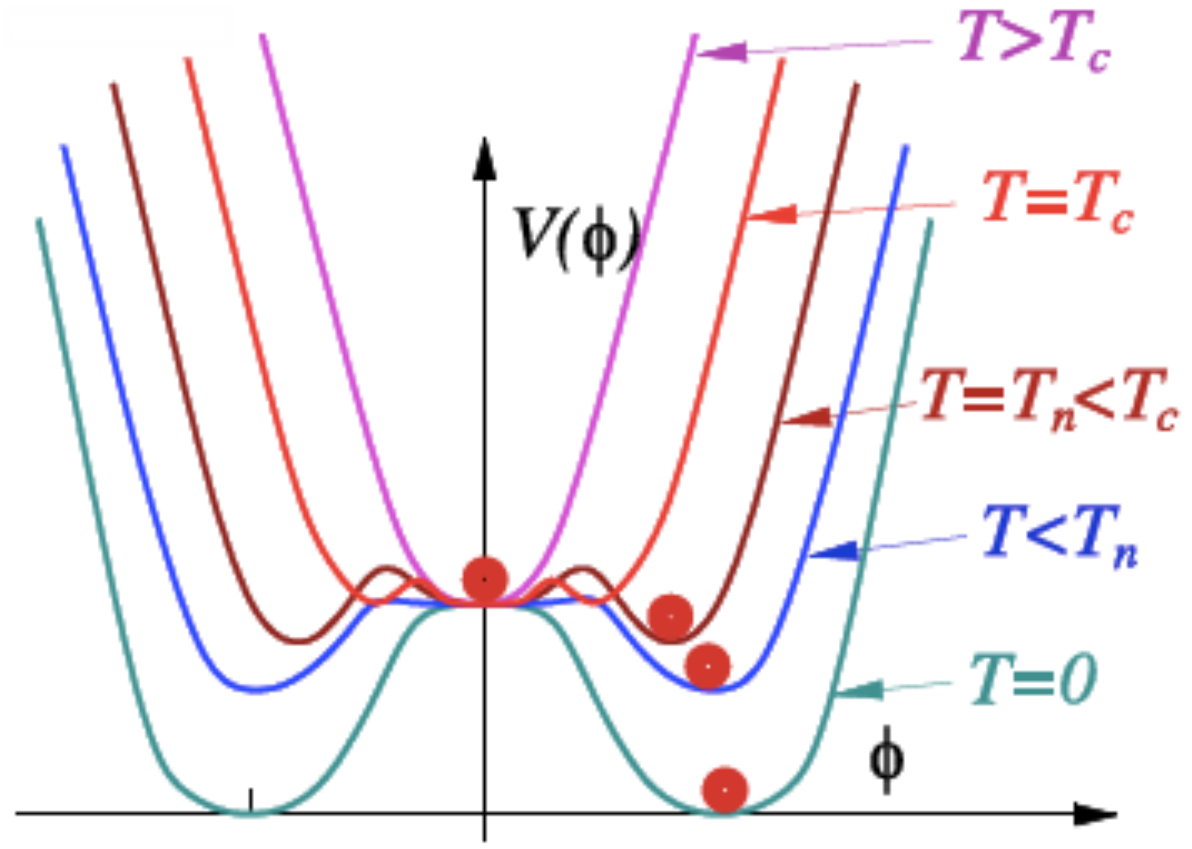
1st vs 2nd order phase transition

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





2nd order



1st order, requirement for EW baryogenesis

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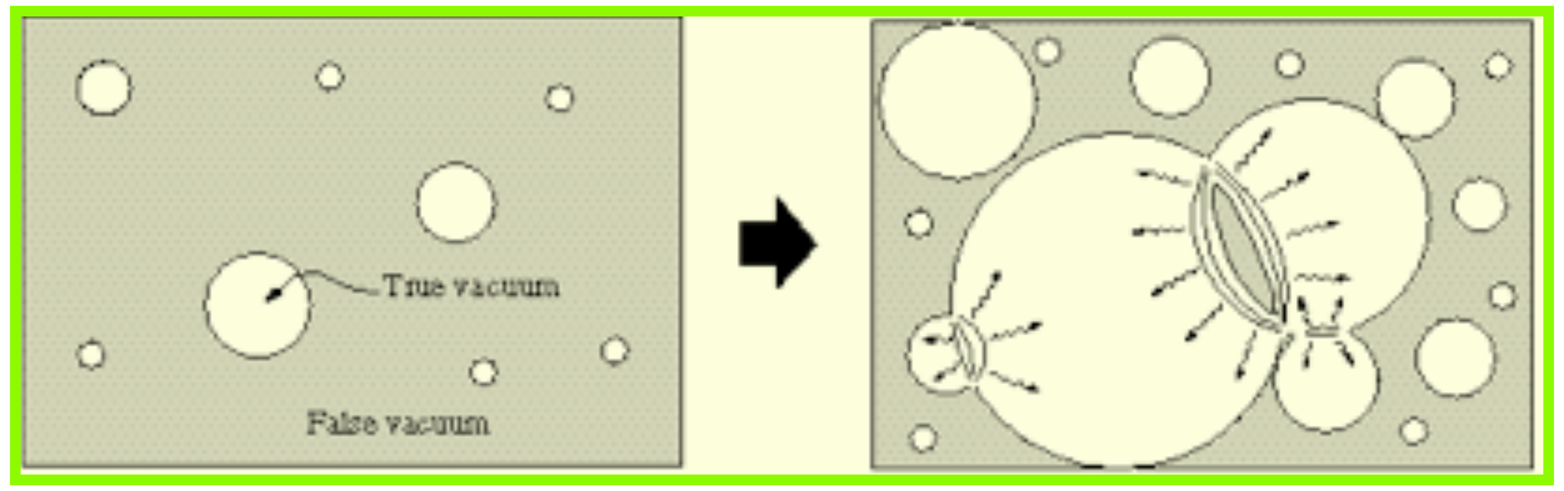

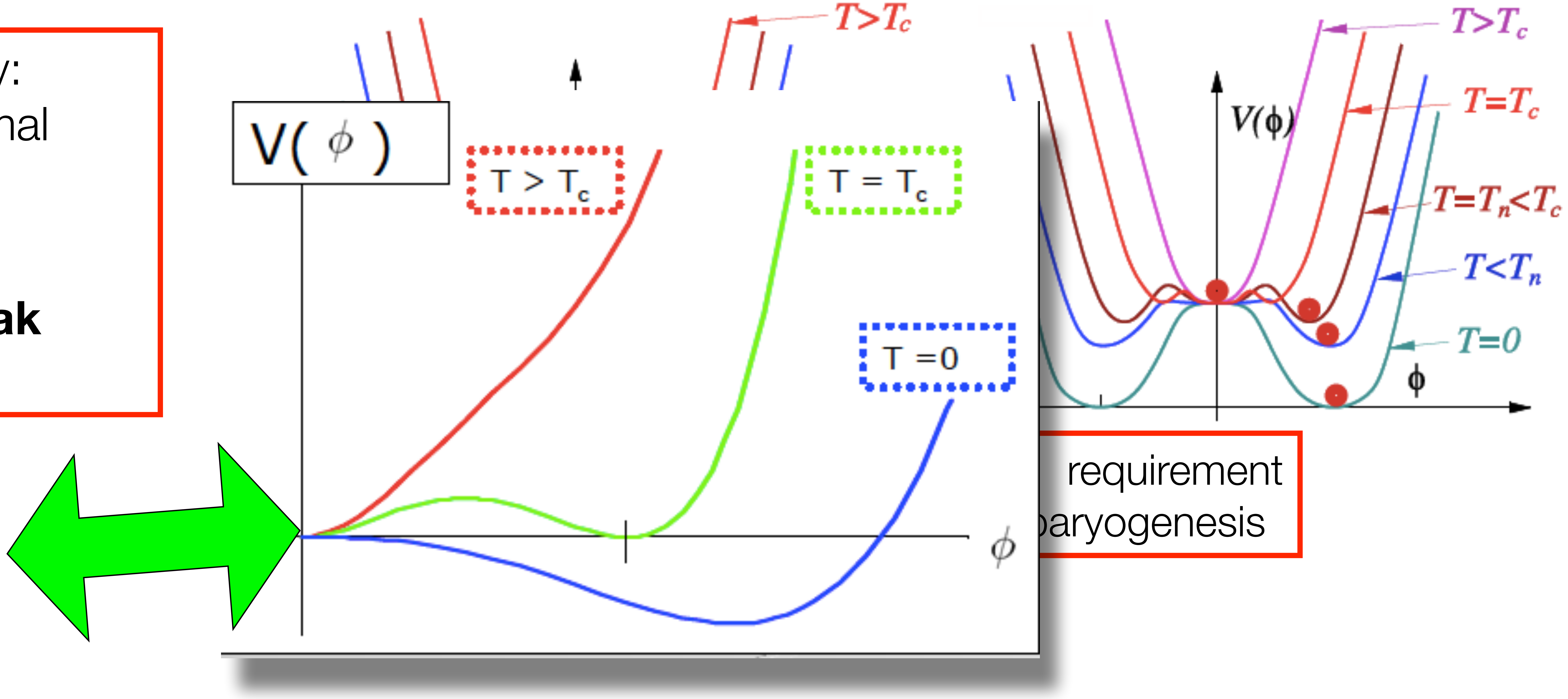

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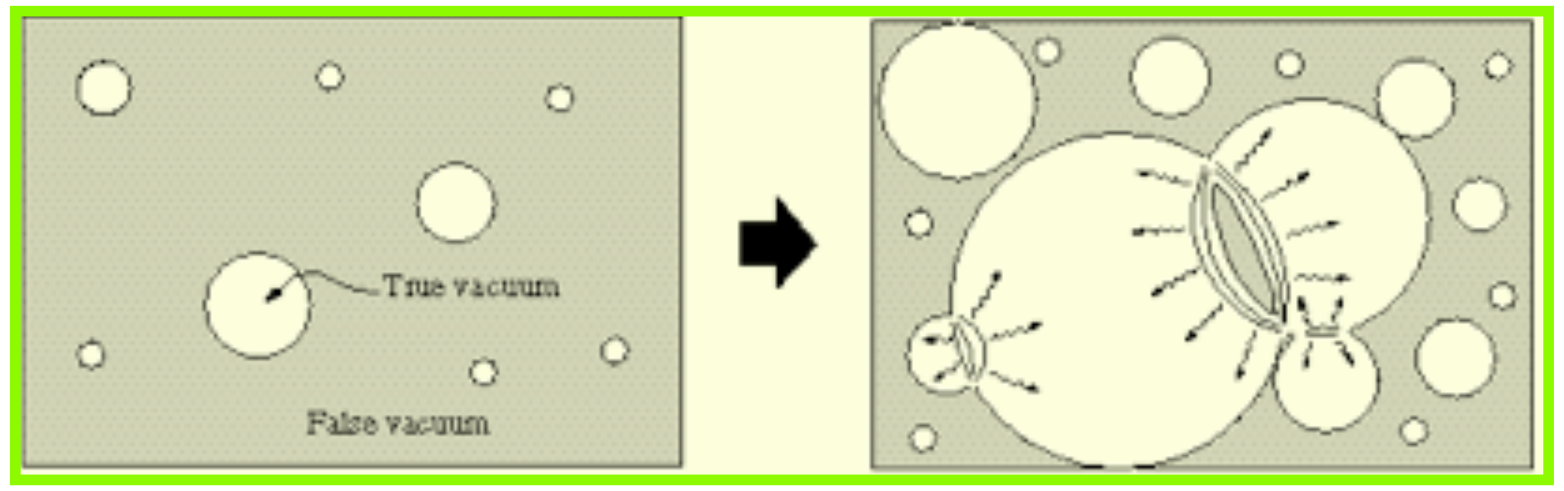

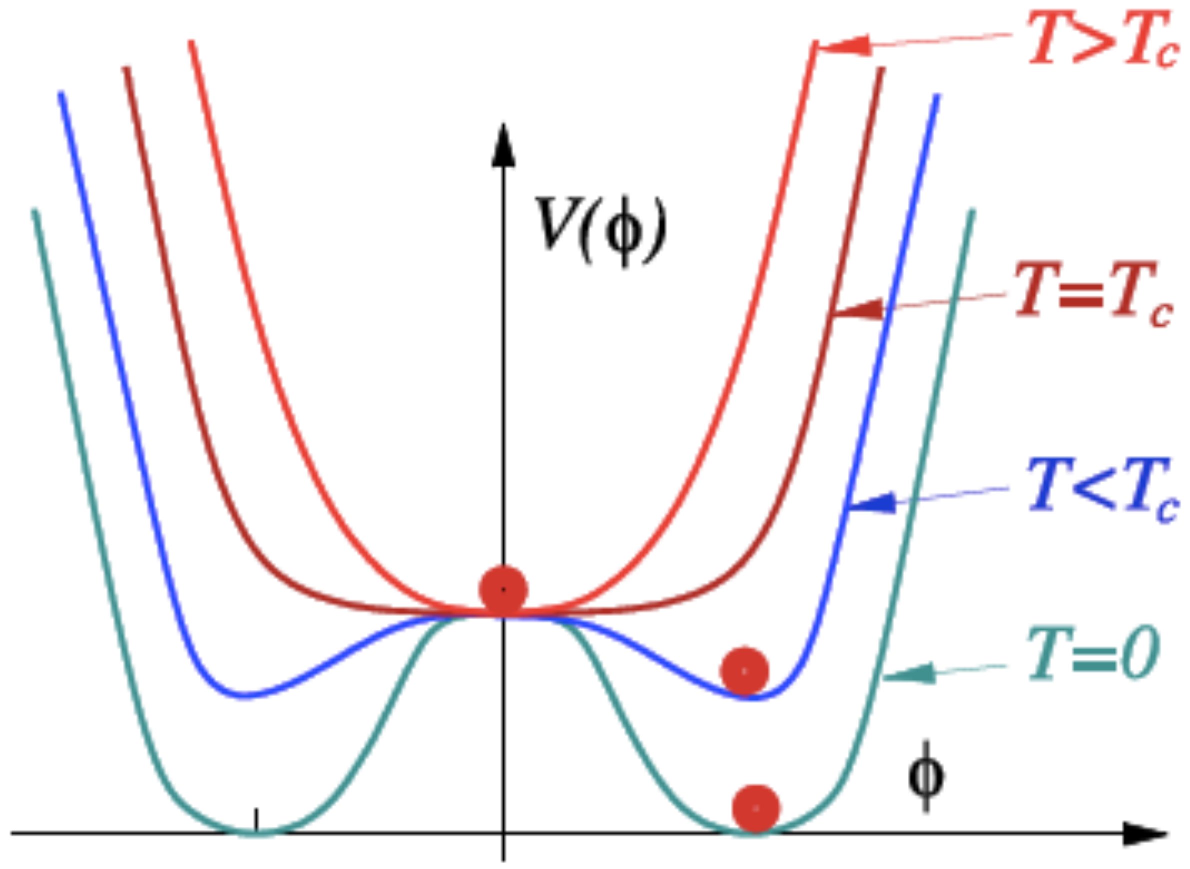

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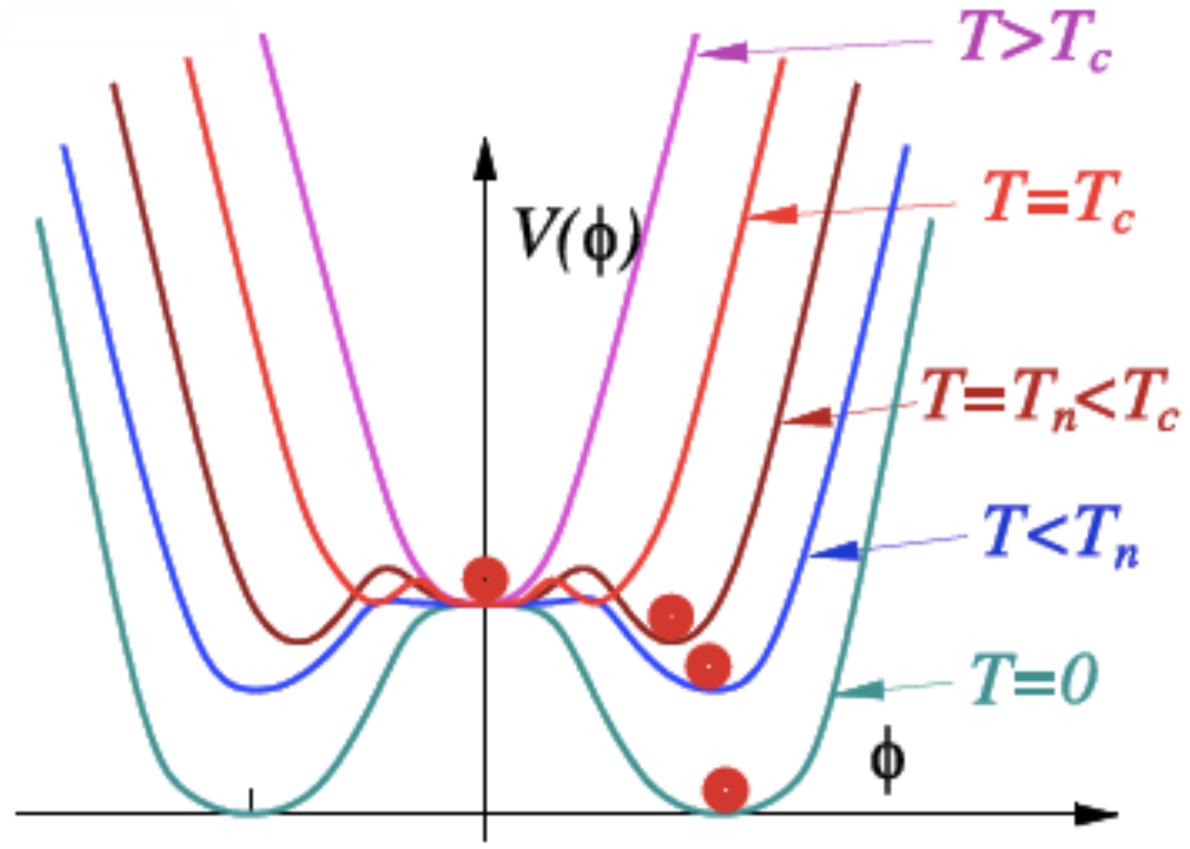

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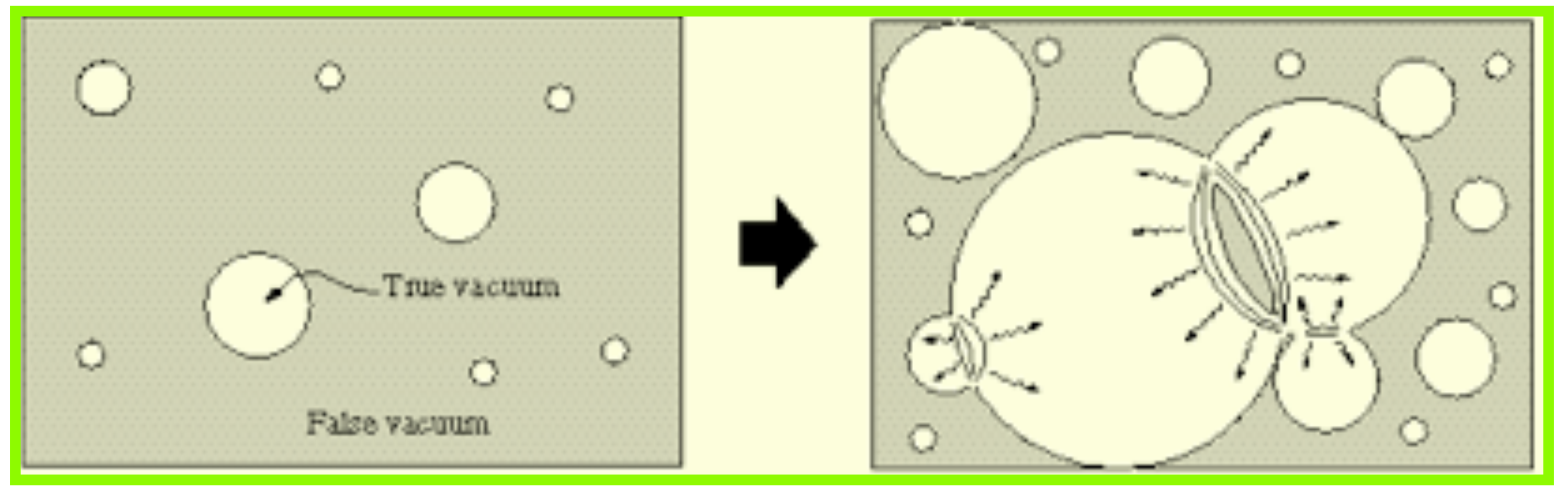

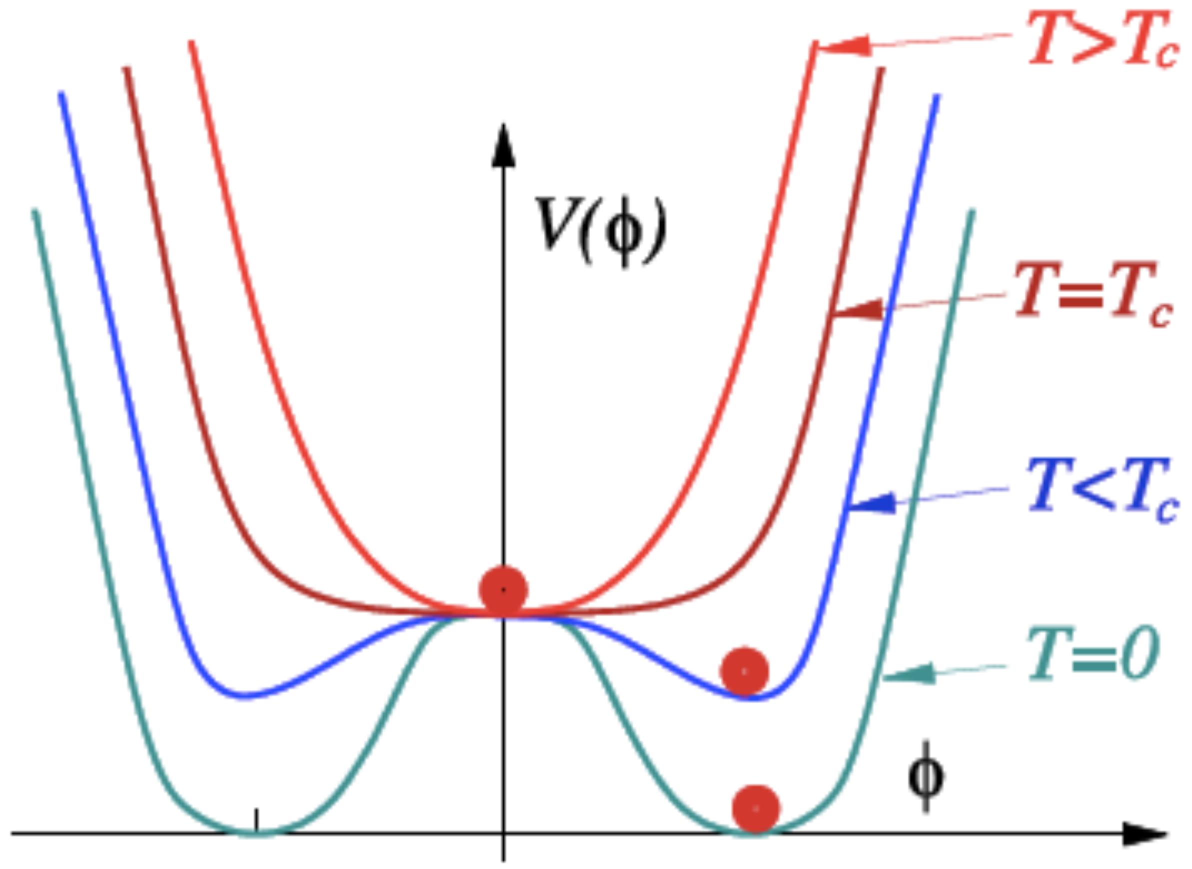

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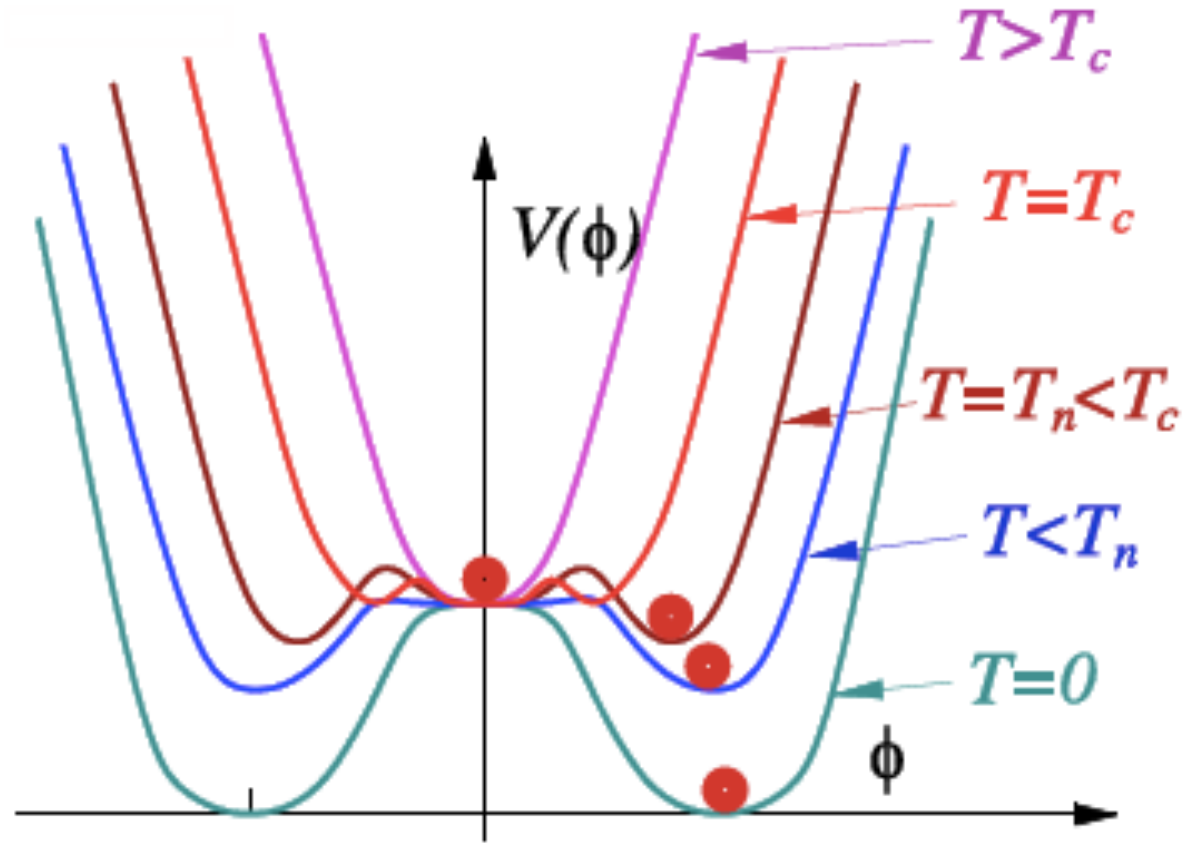

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- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
- electroweak baryogenesis possible in BSM scenarions with $\lambda > \lambda_{SM}$ (e.g. 2HDM, NMSSM, …)

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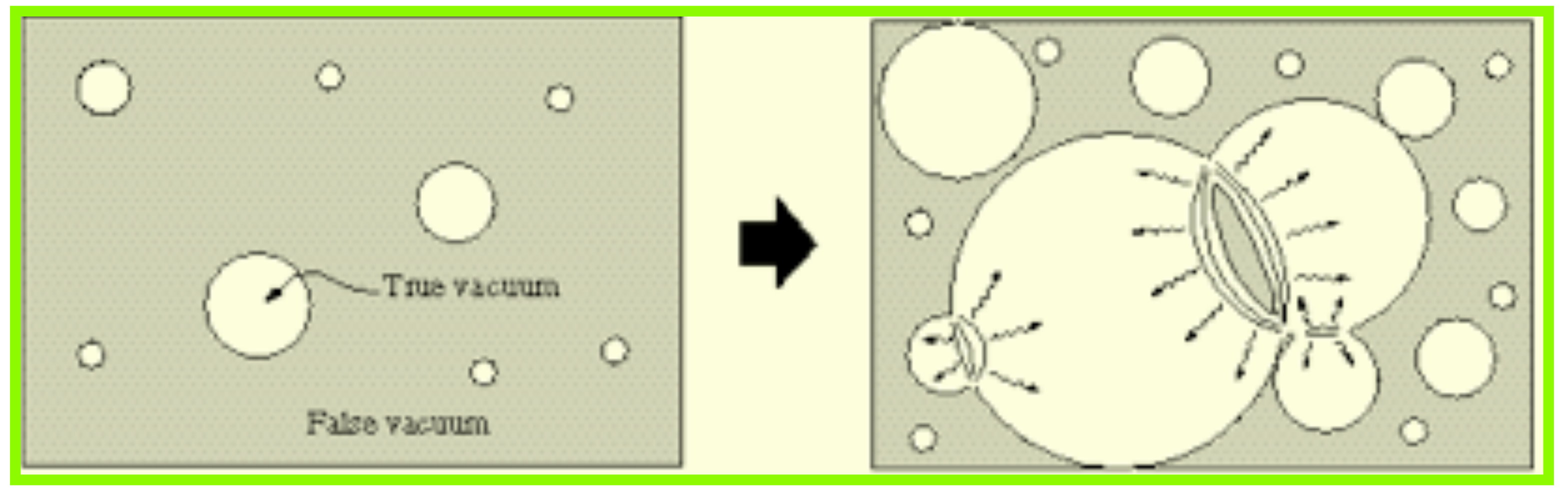

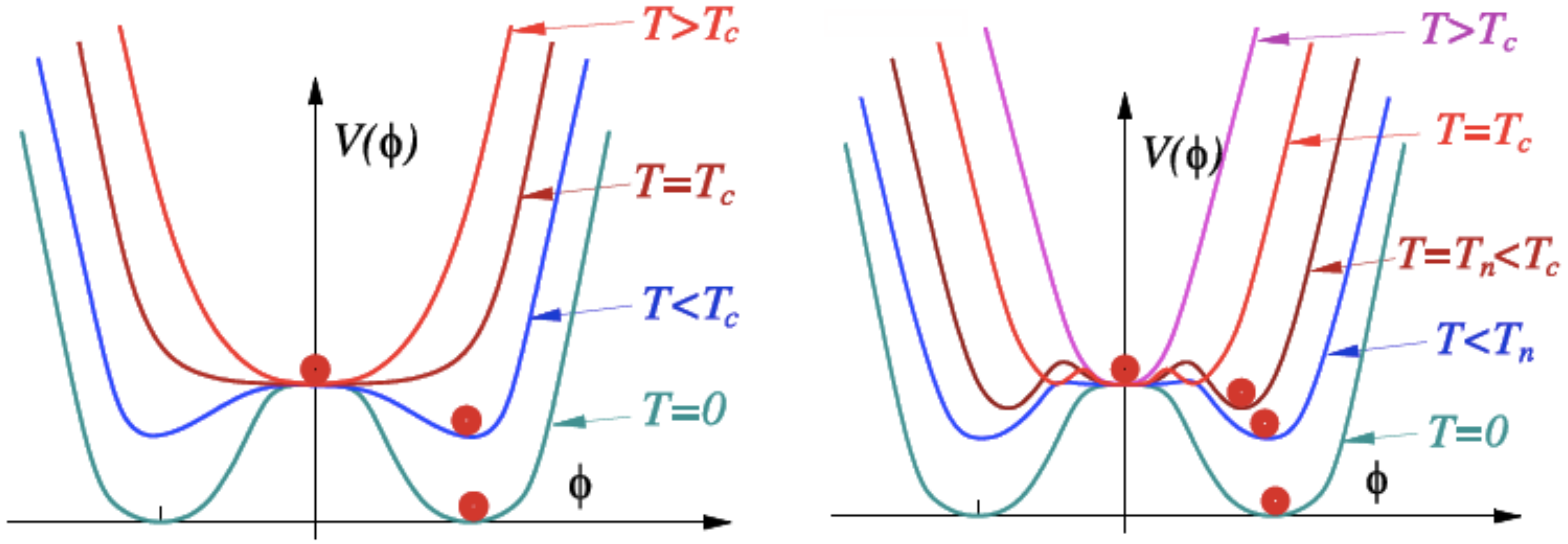

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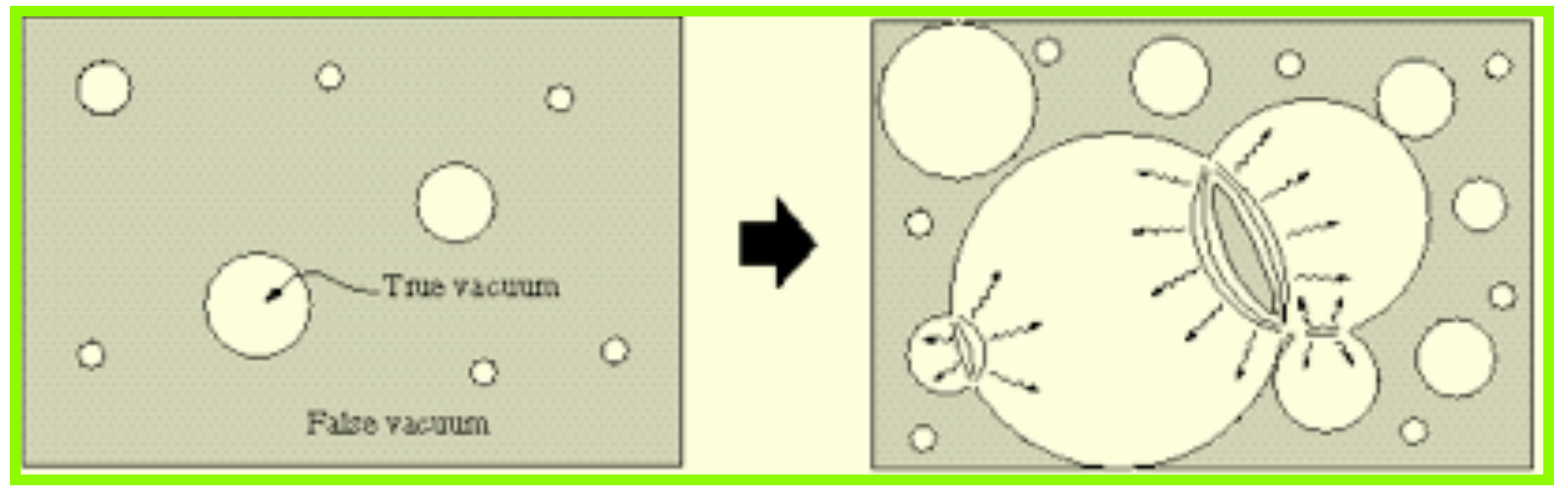

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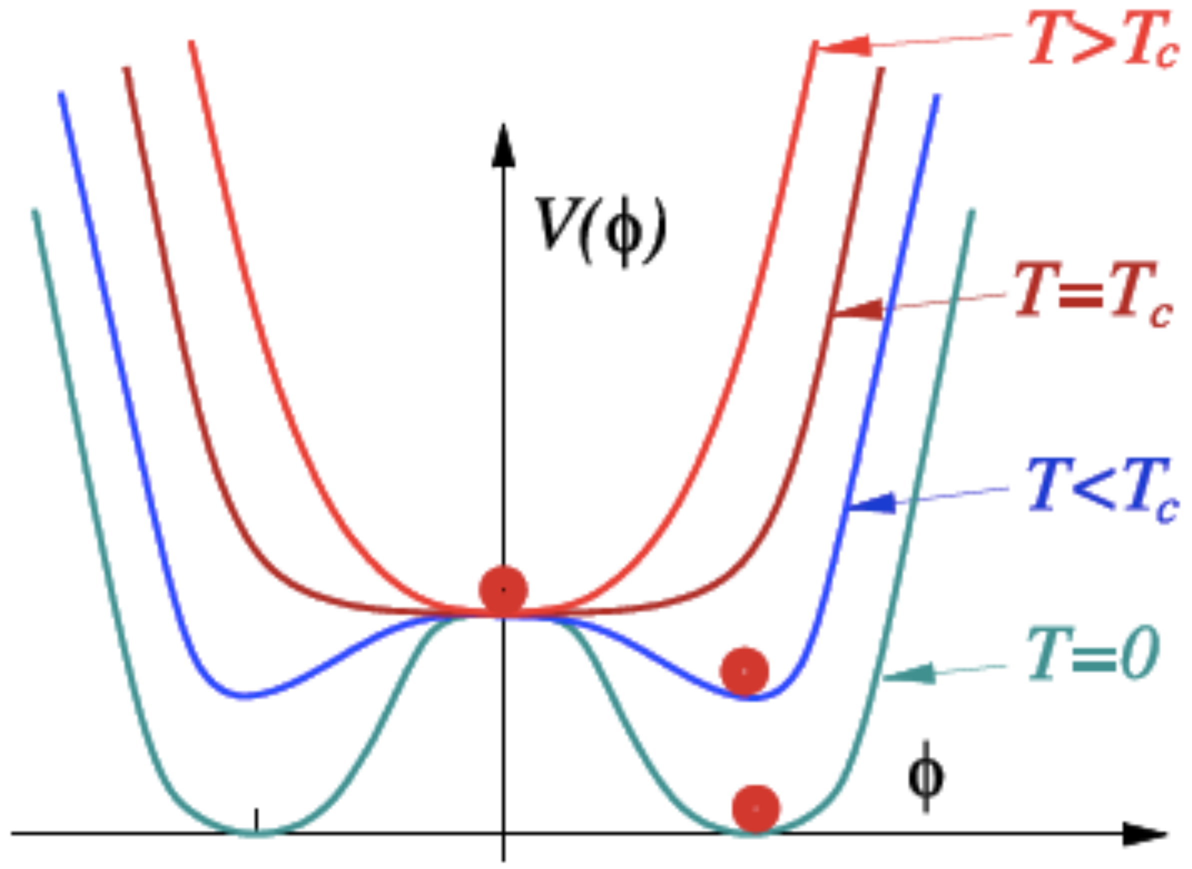

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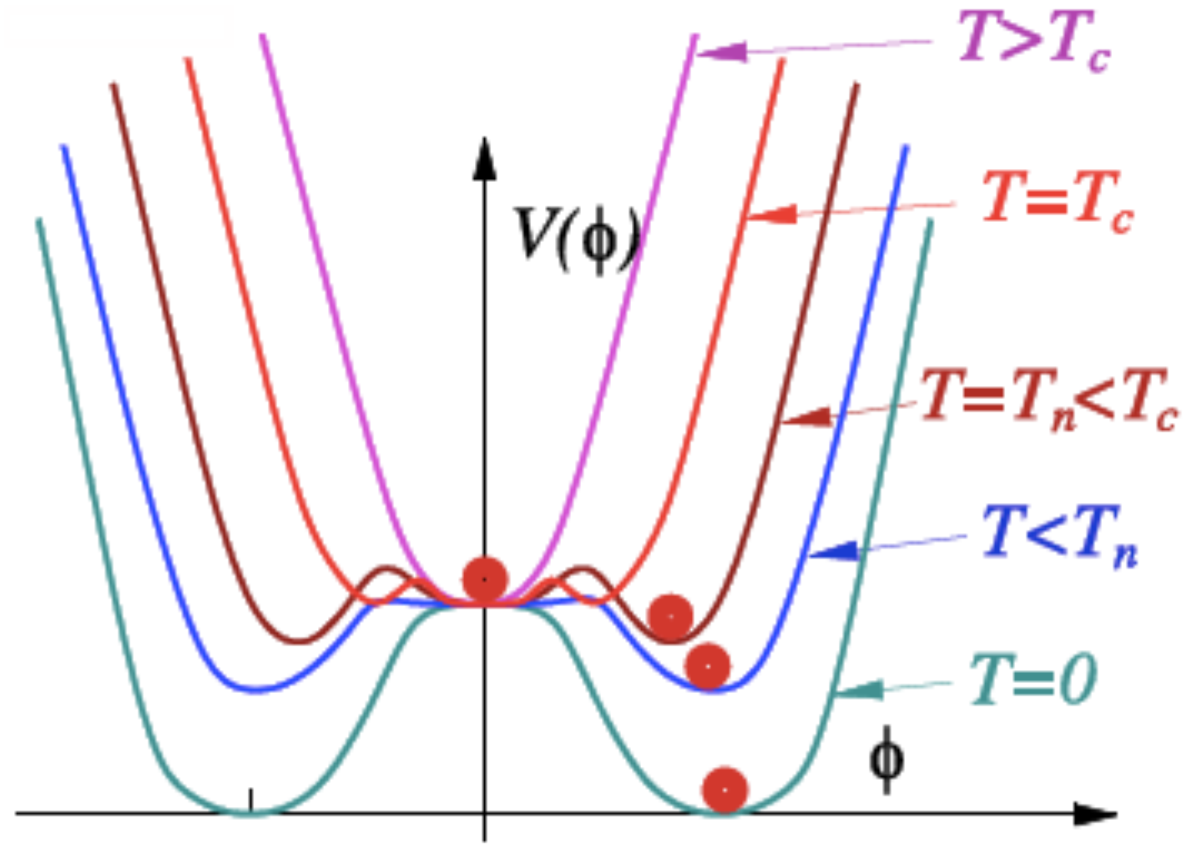

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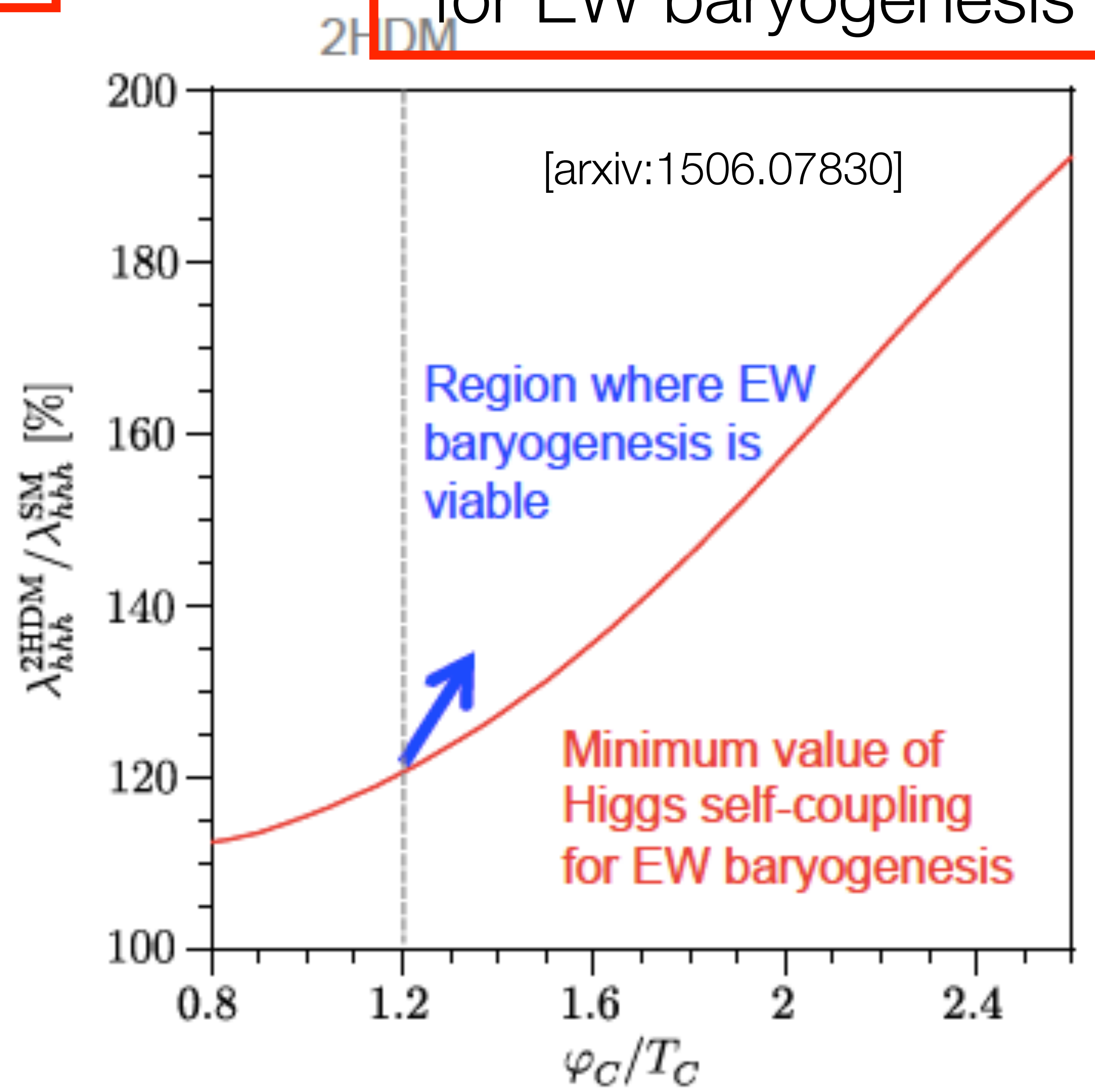

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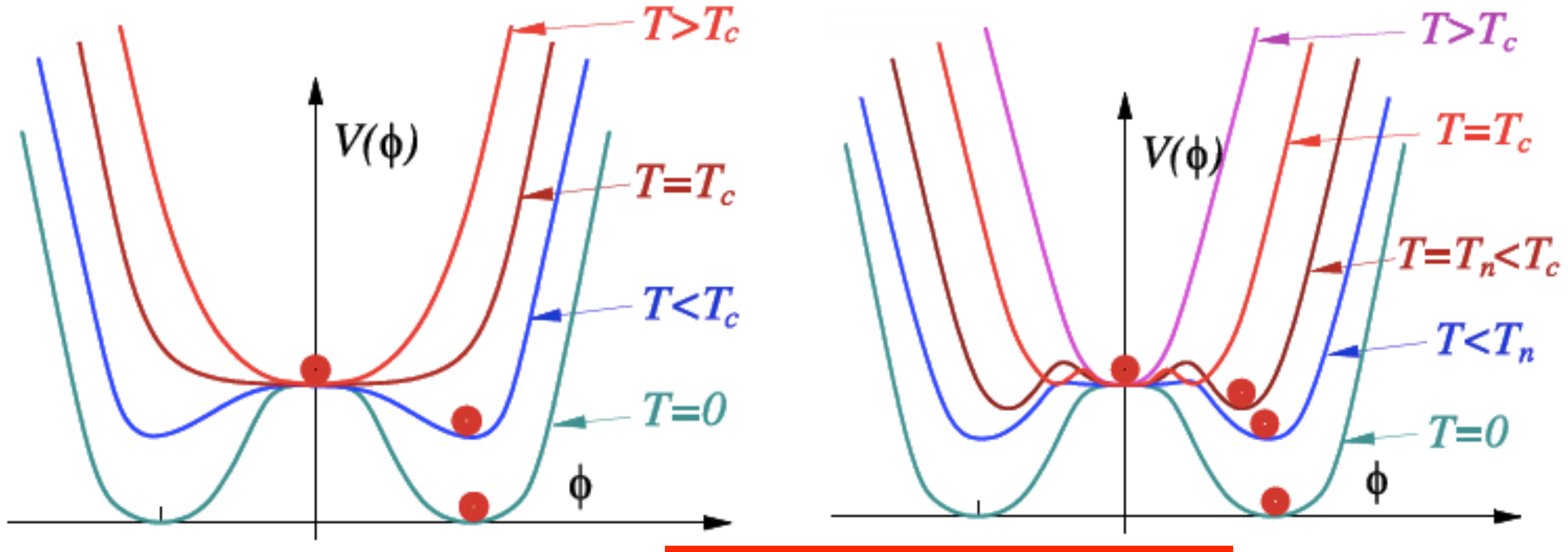

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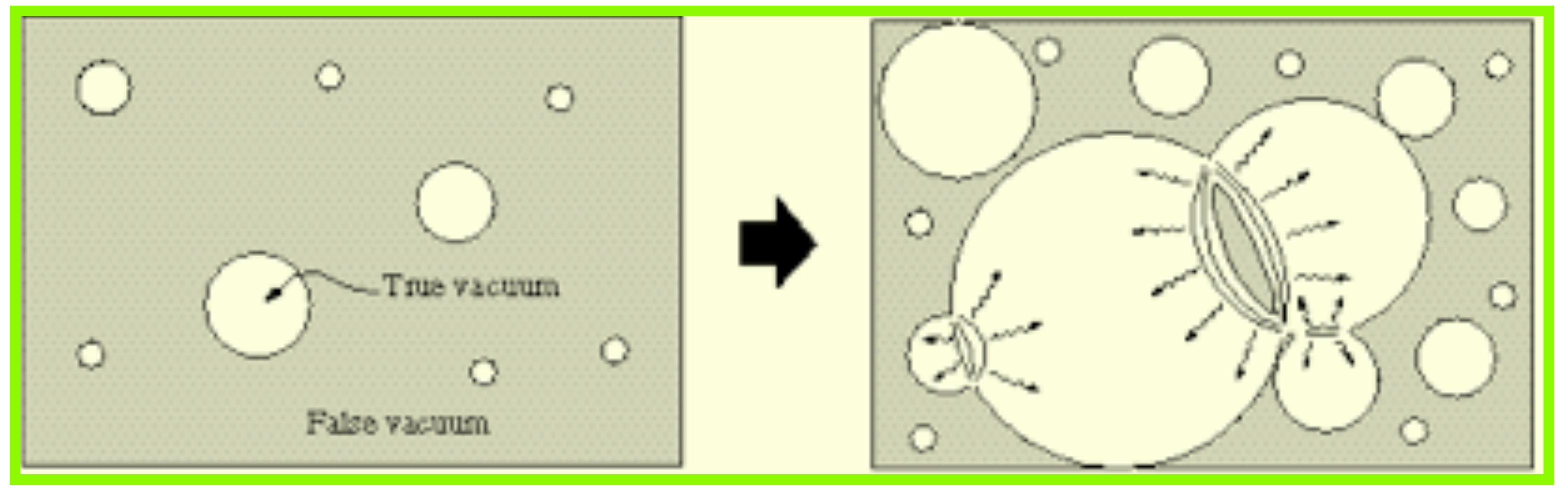

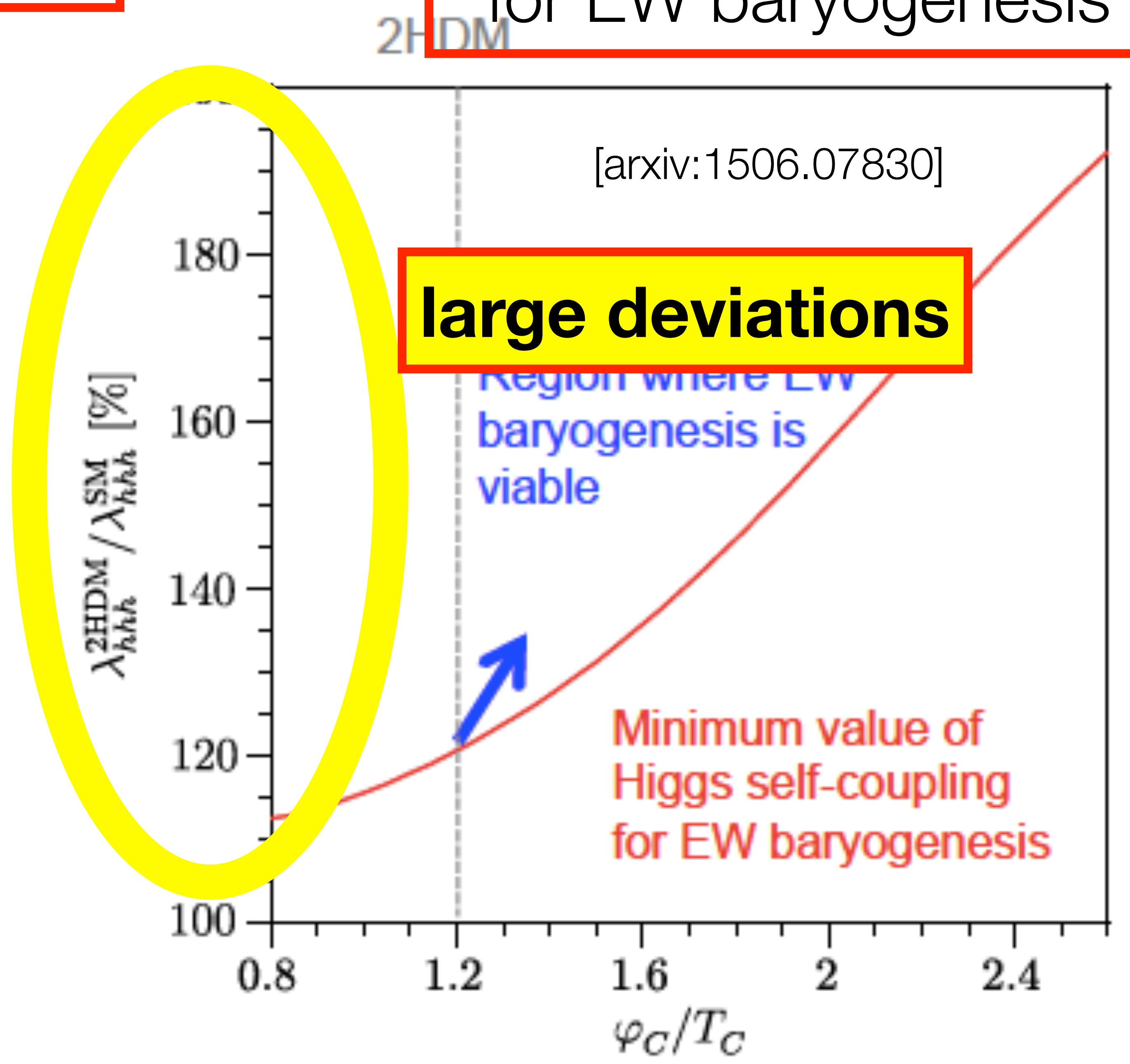

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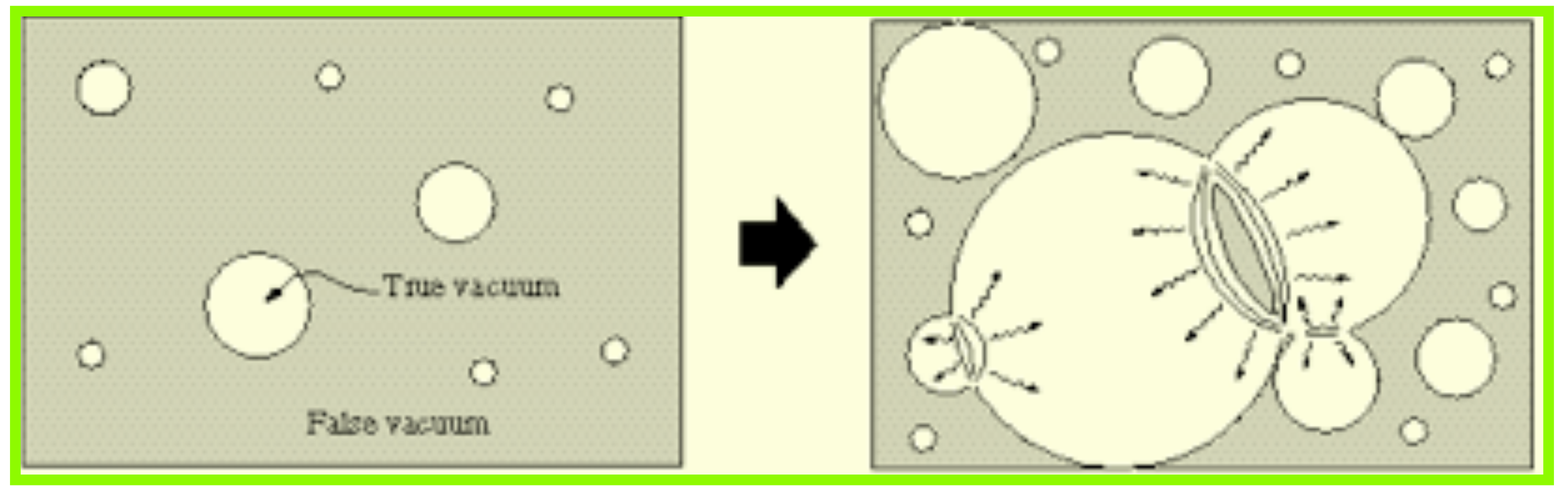

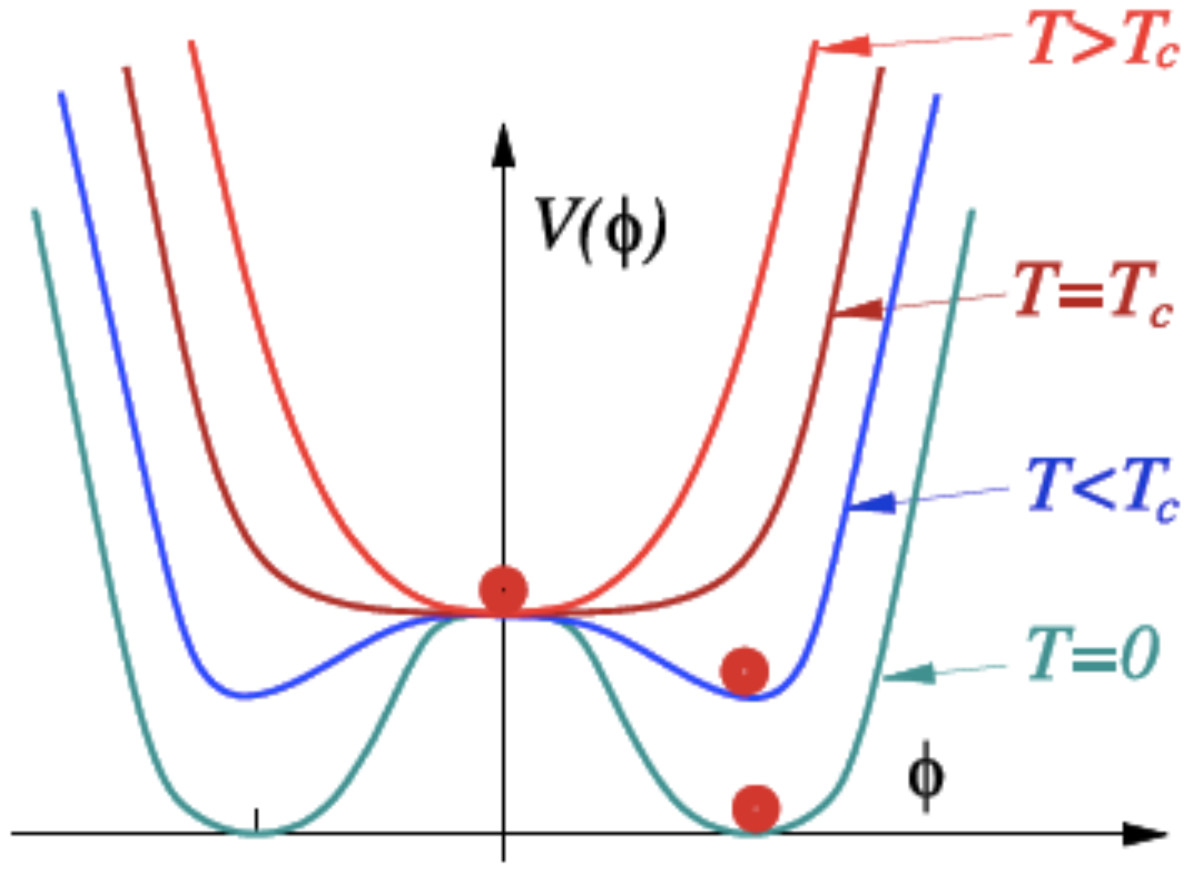

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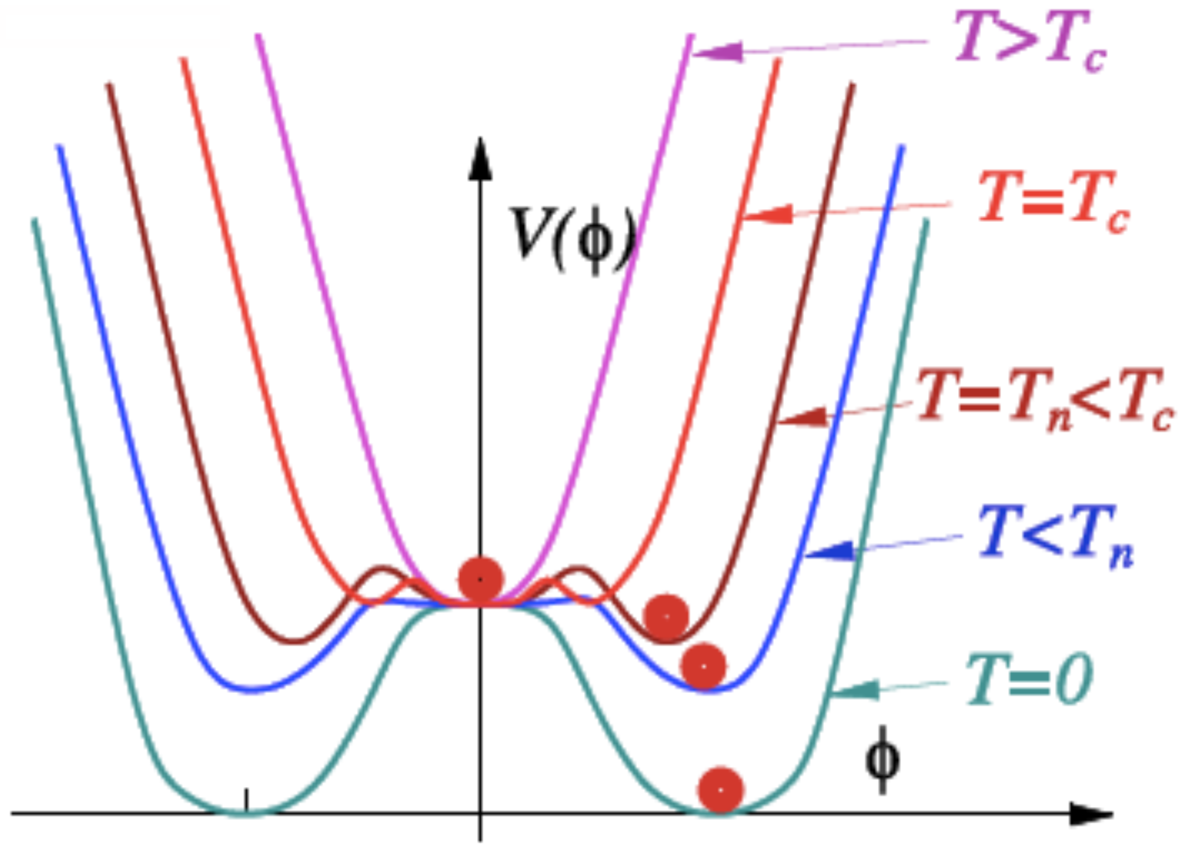

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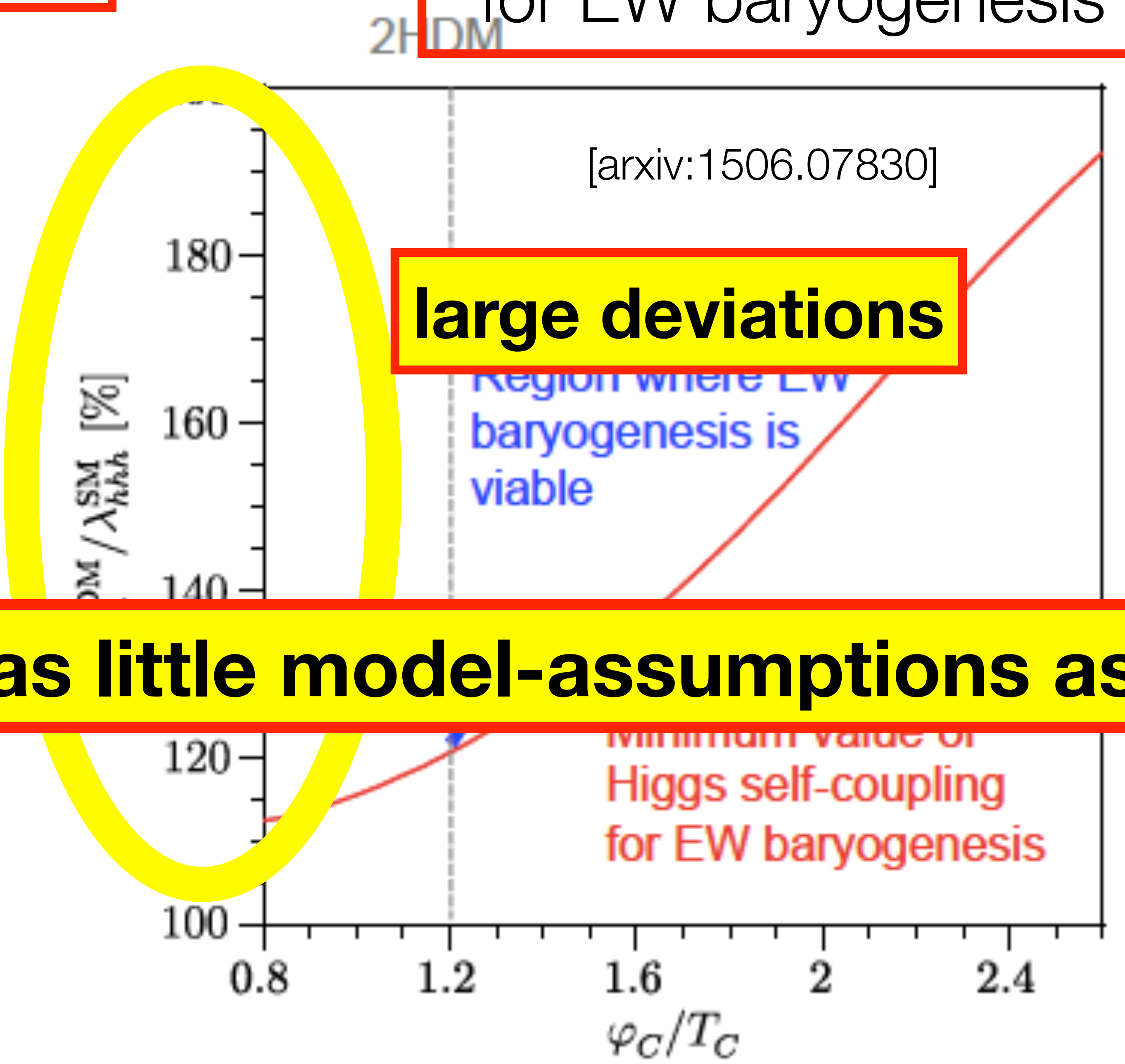

=> measure λ, with as little model-assumptions as possible!

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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- clean events
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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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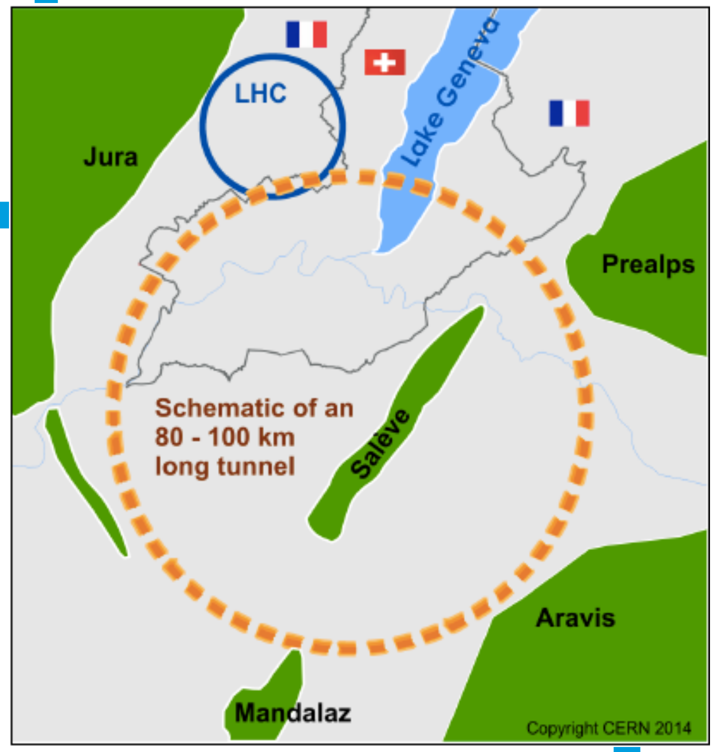
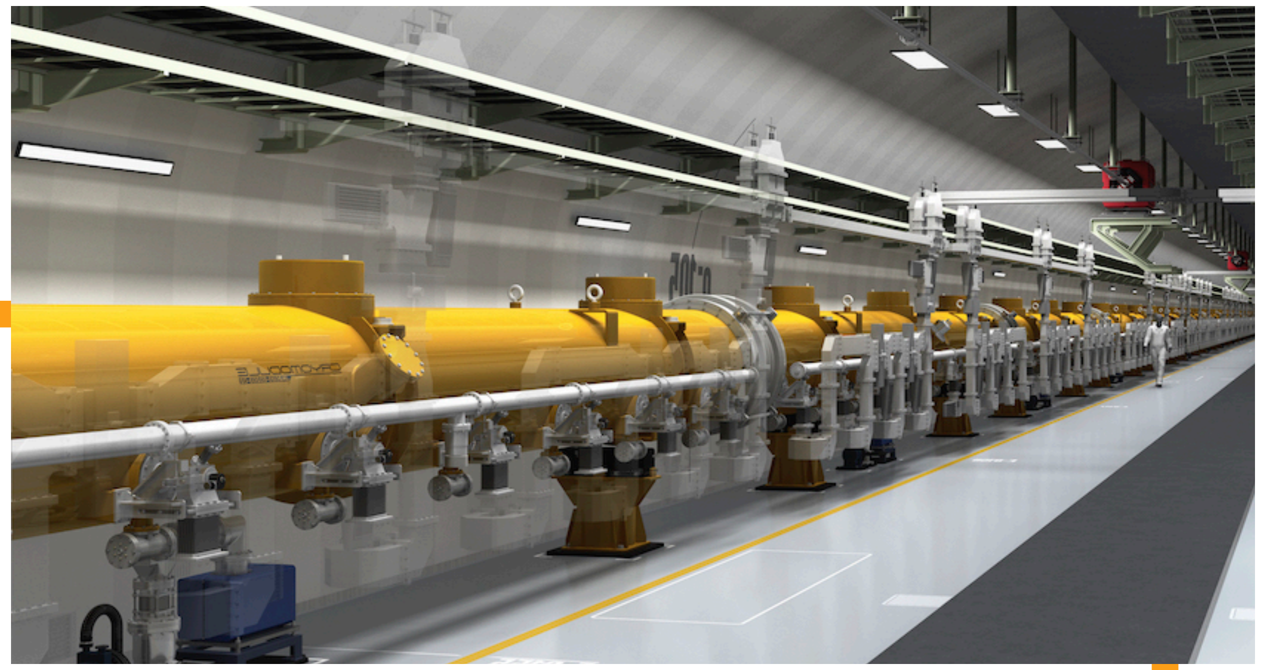
There are several proposed Higgs factories

Each have their advantages



Circular e+e- Colliders

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



Linear Colliders

- **ILC**, CLIC
- length 250 GeV: ~10…20 km
- high luminosity & power efficiency at **high energies**
- **spin-polarised beam(s)**

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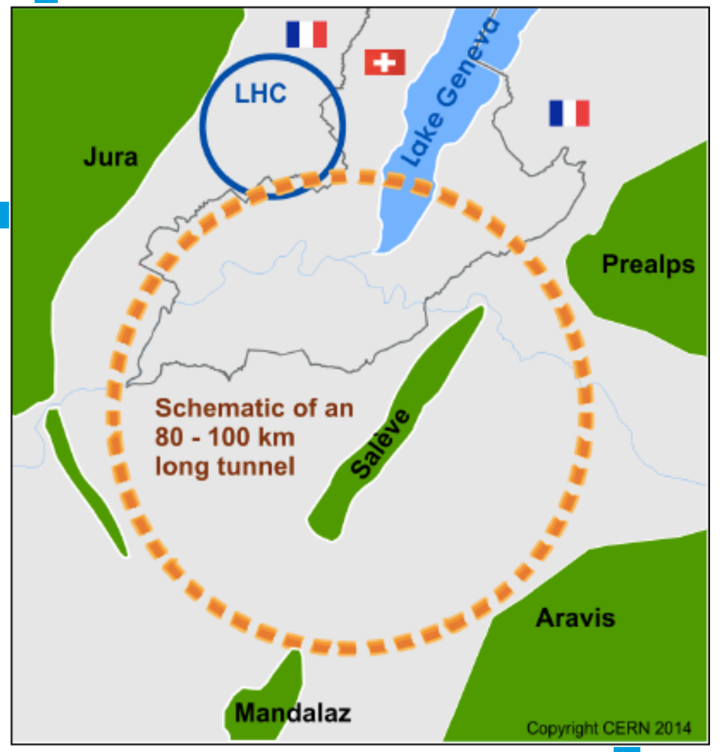

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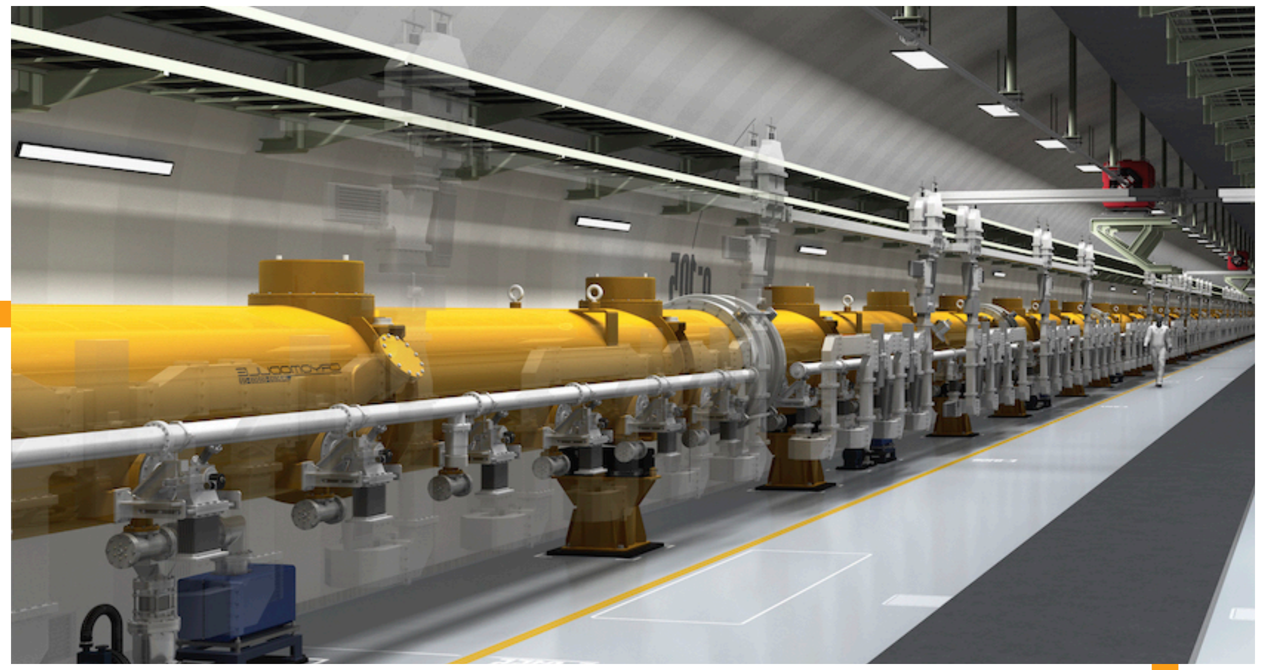


Linear Colliders

- **ILC**, CLIC
- length 250 GeV: ~10…20 km
- high luminosity & power efficiency at **high energies**
- **spin-polarised beam(s)**

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

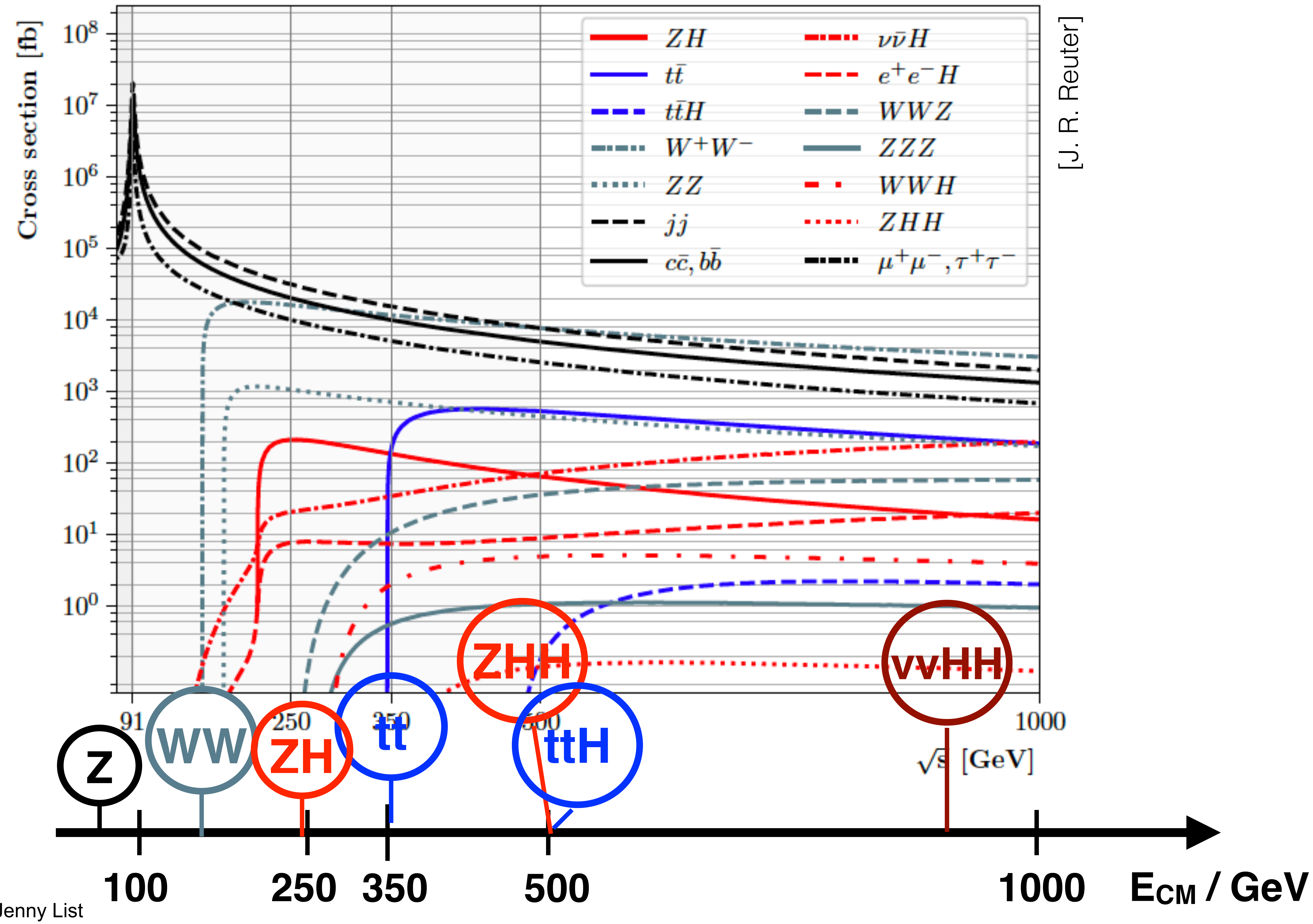
- technical and financial feasibility of required magnets still unclear

Long-term upgrades: energy extendability

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

Particle production thresholds in e+e- collisions

Production rates vs collision energy



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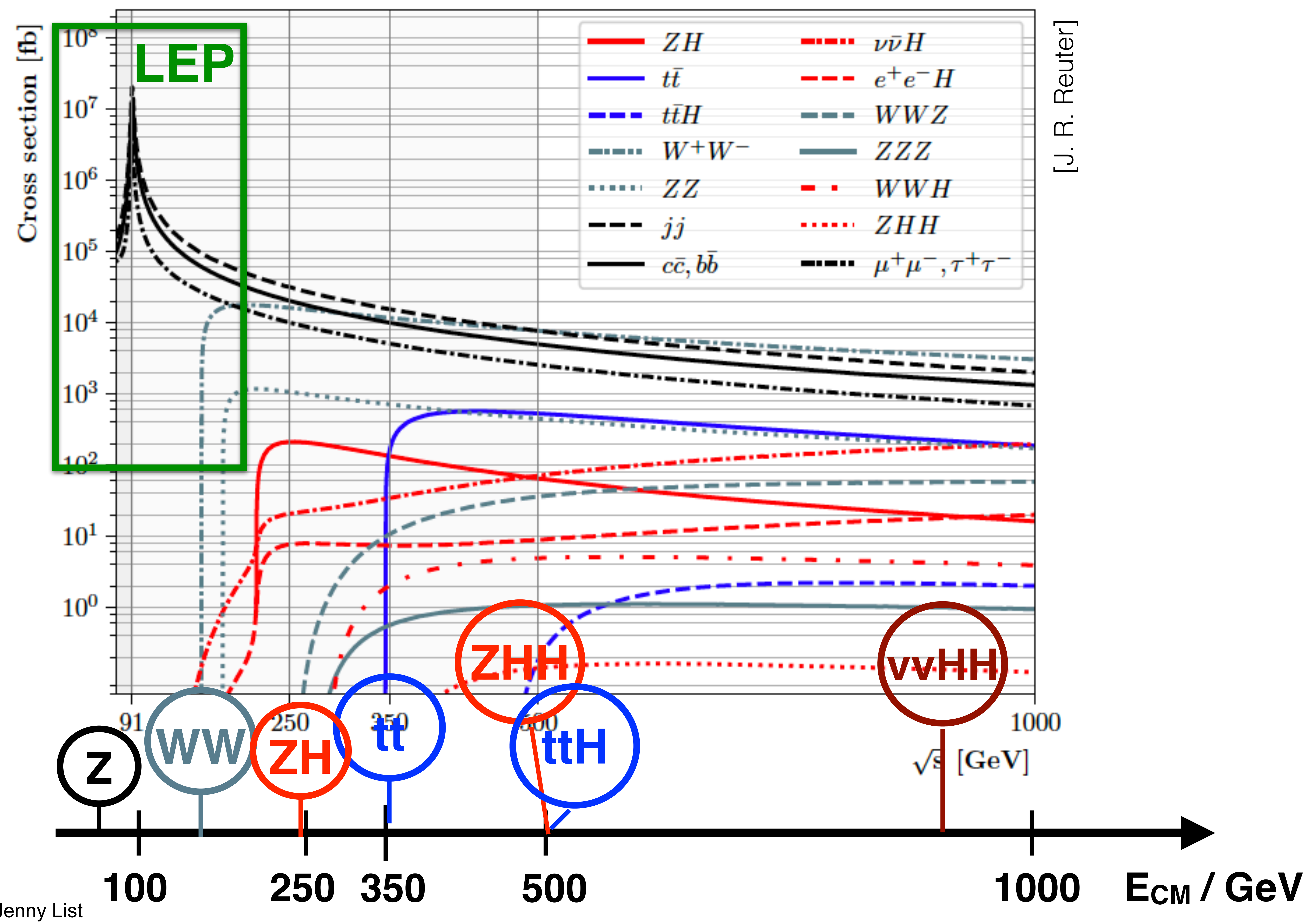

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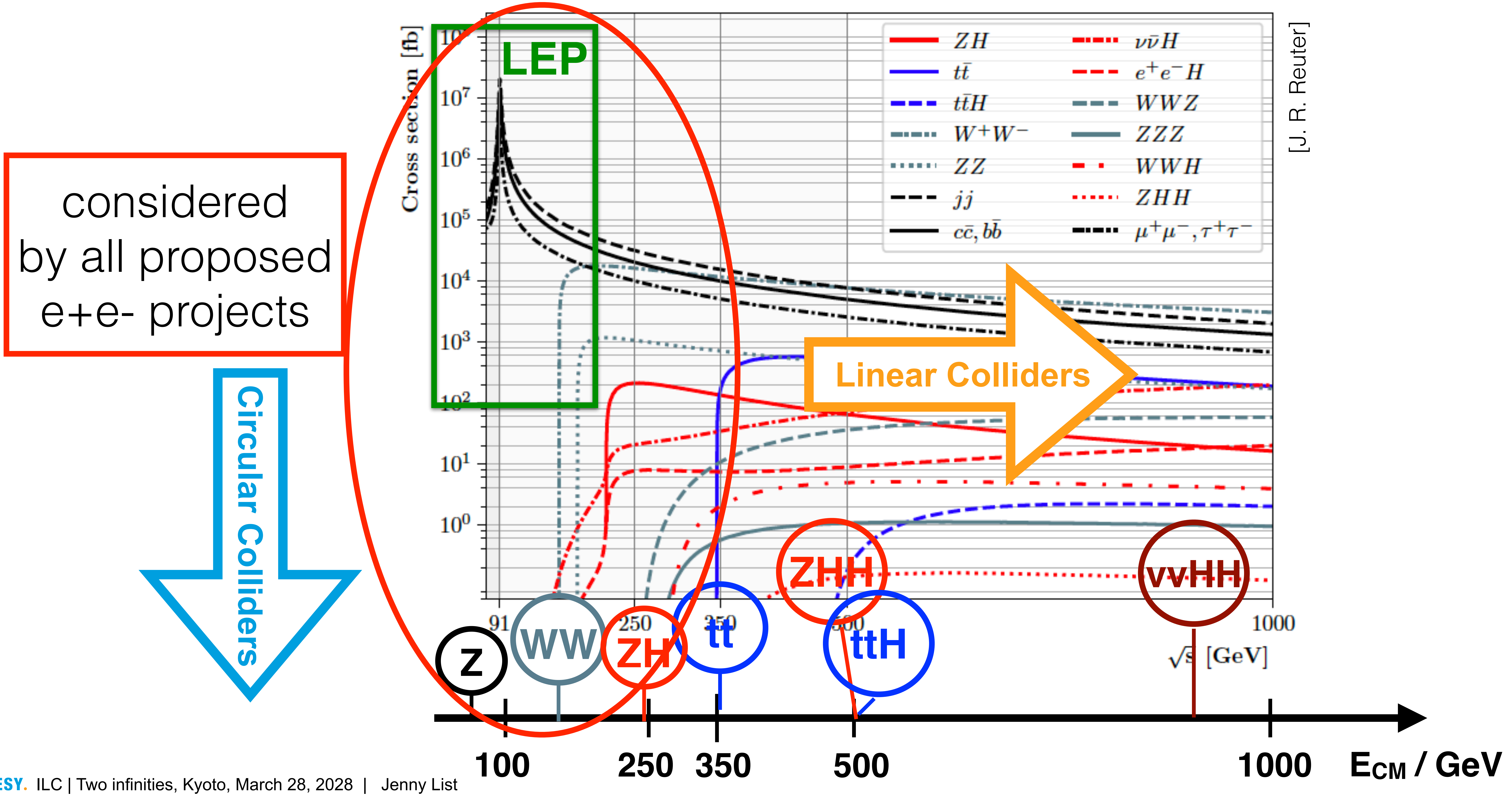

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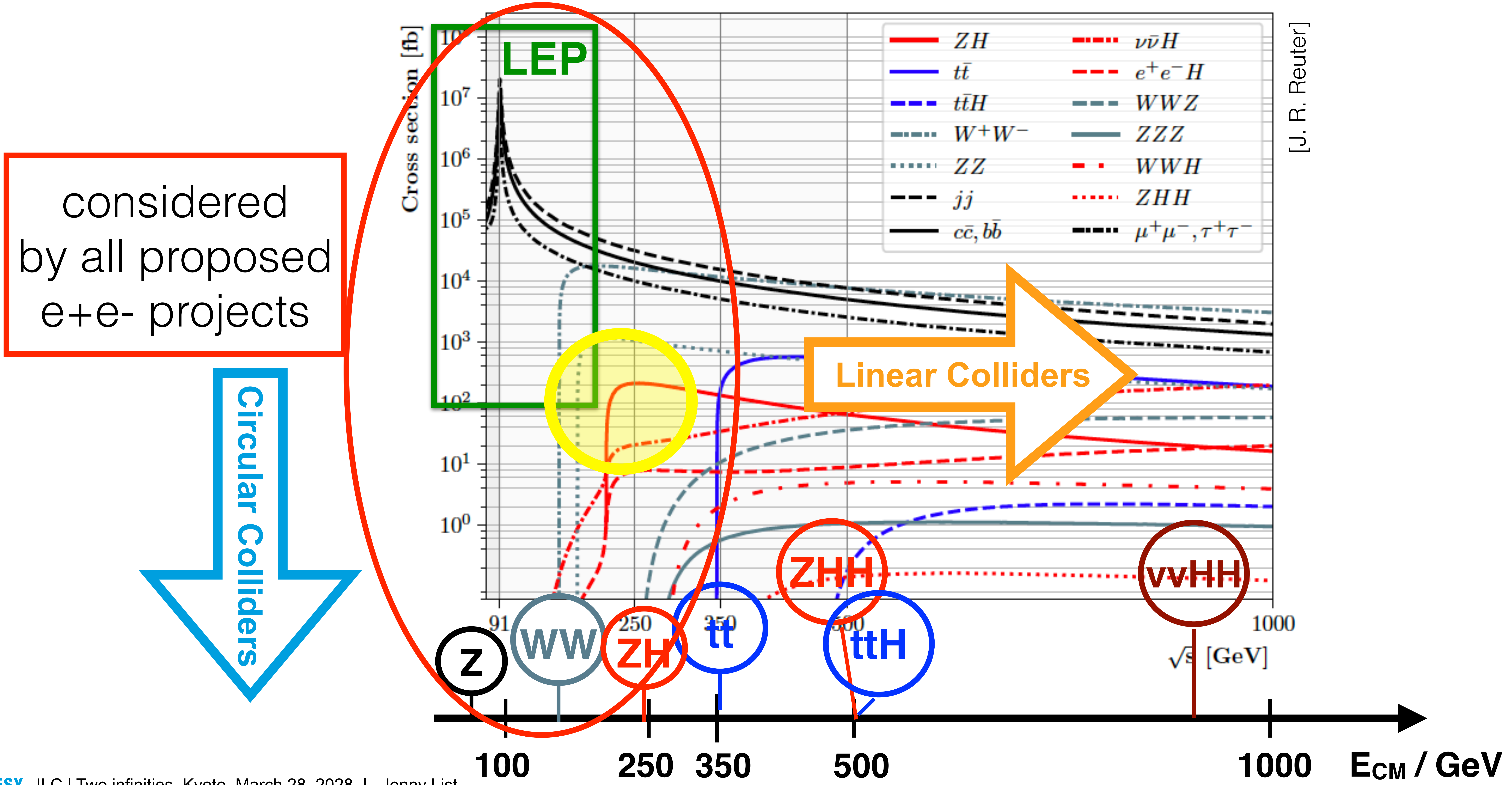


Absolute Higgs Production Rate

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 particles**
- **enables a plethora of further precision measurements**

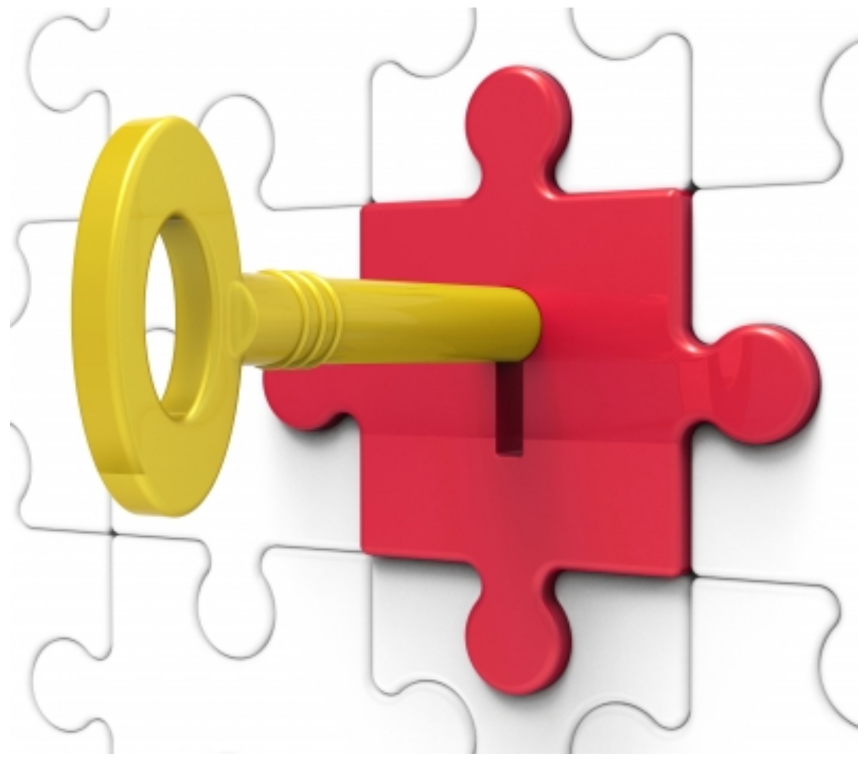
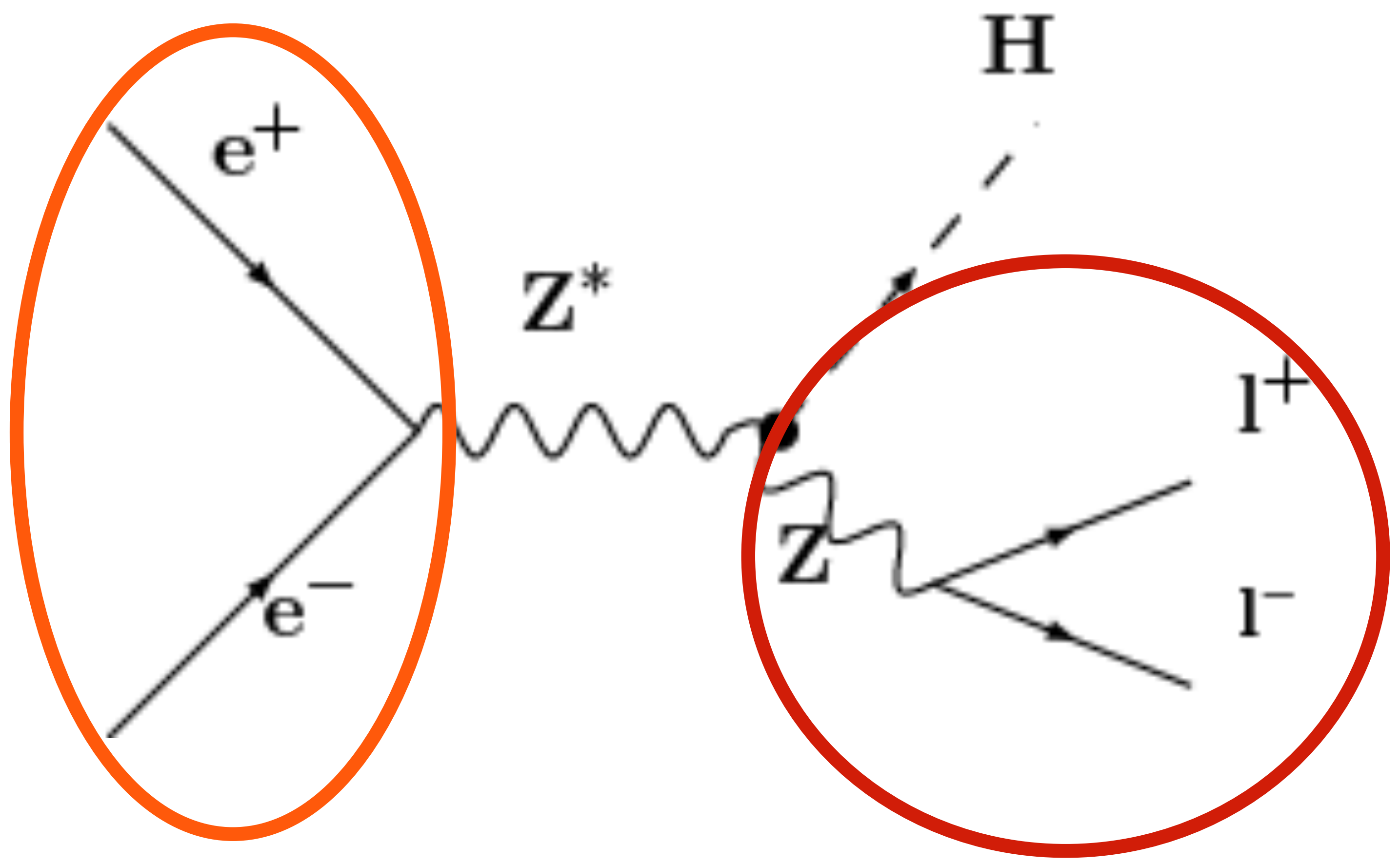
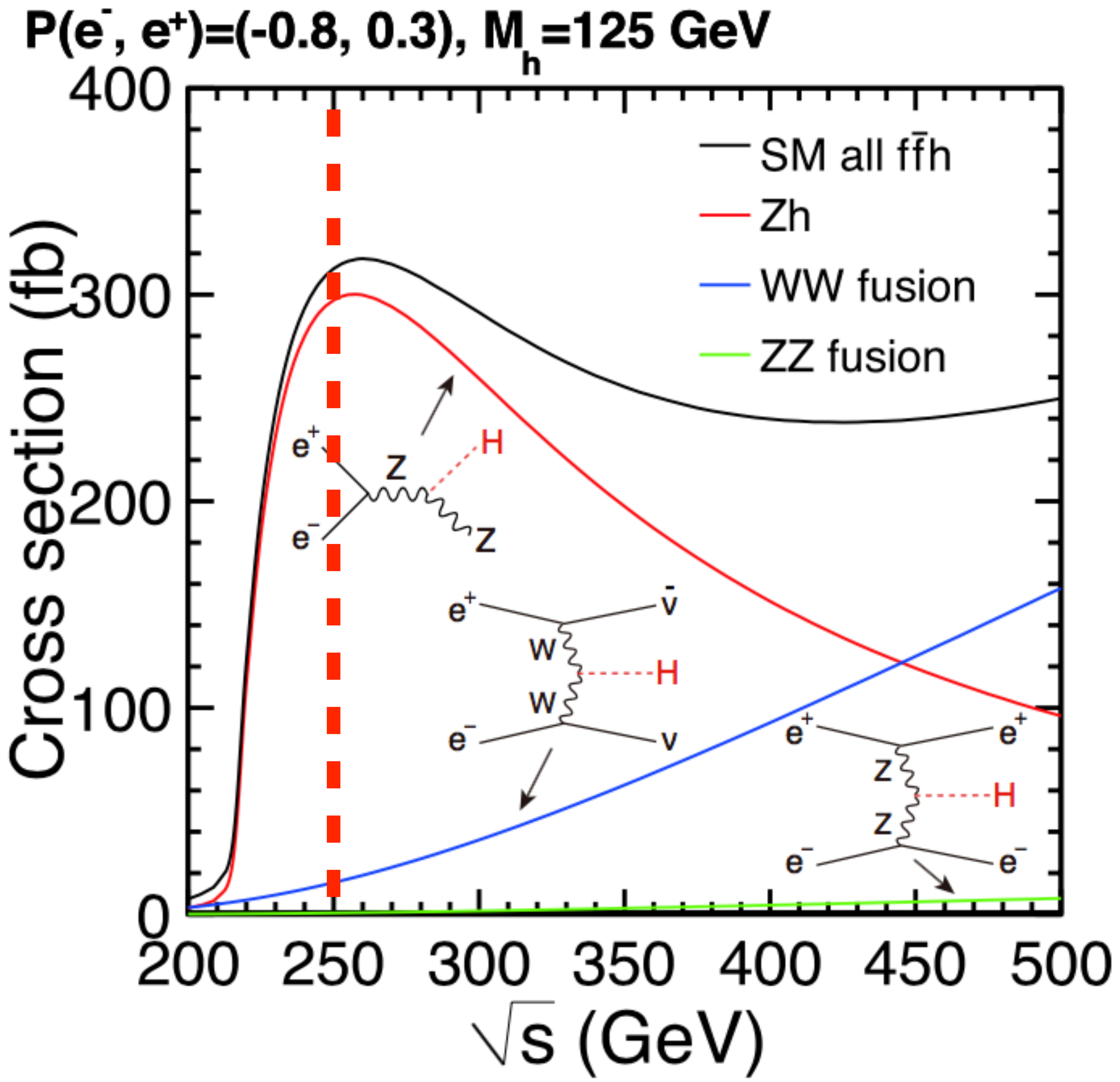


Image courtesy of Stuart Miles at FreeDigitalPhotos.net



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



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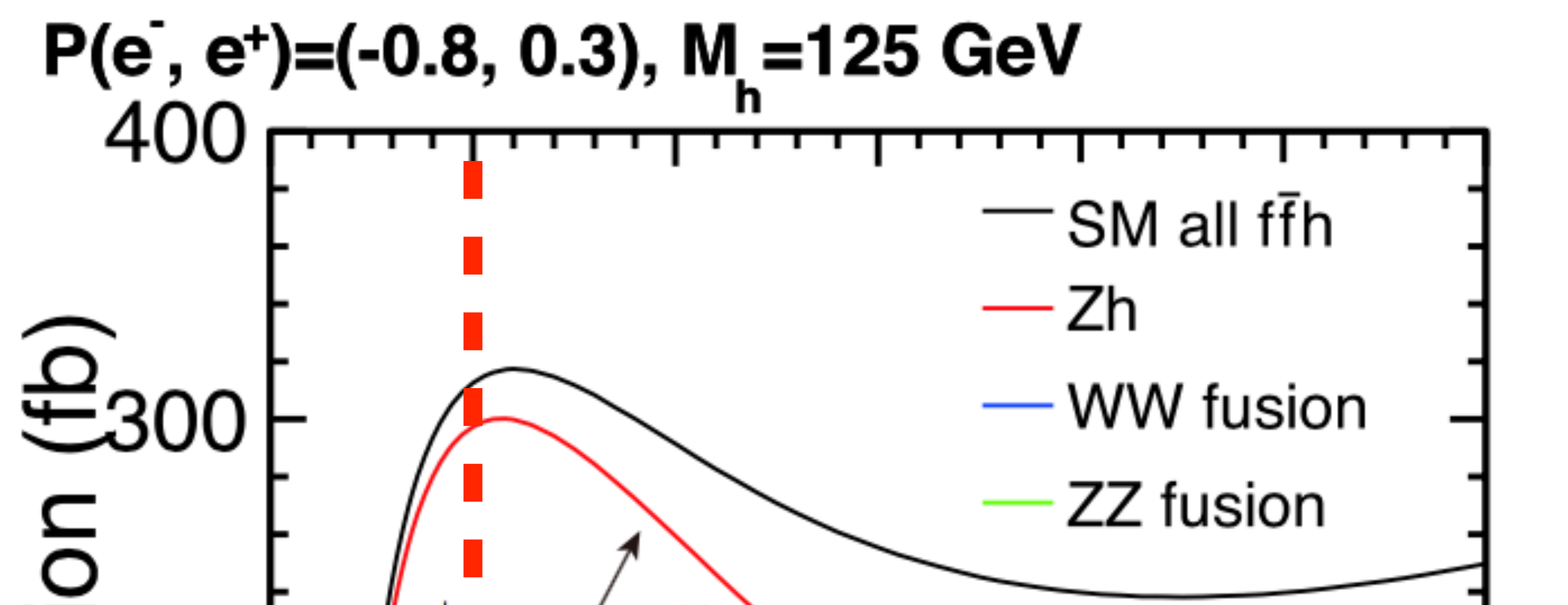

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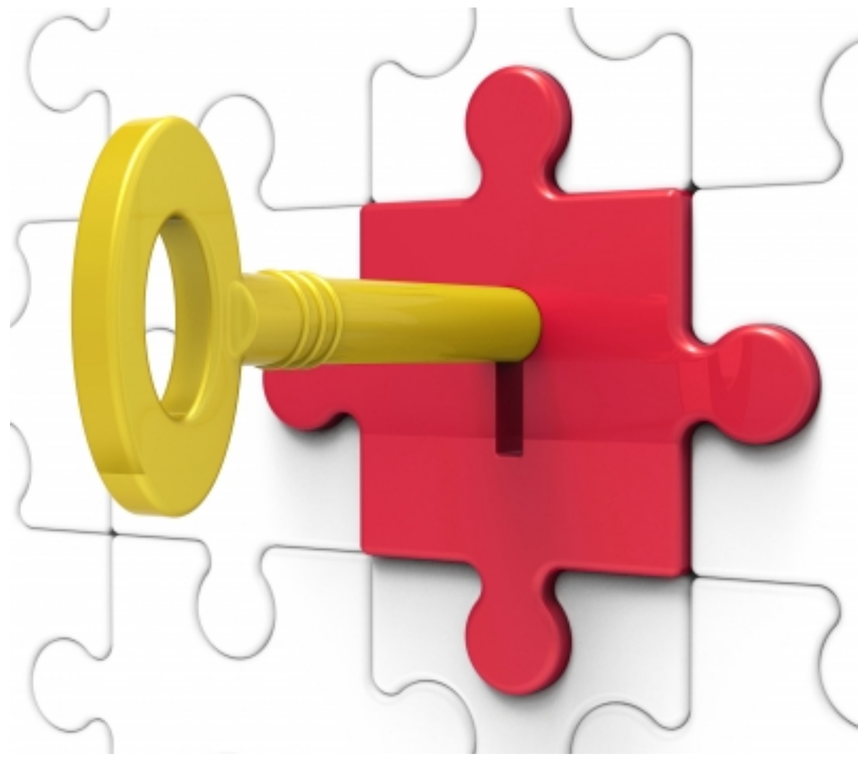

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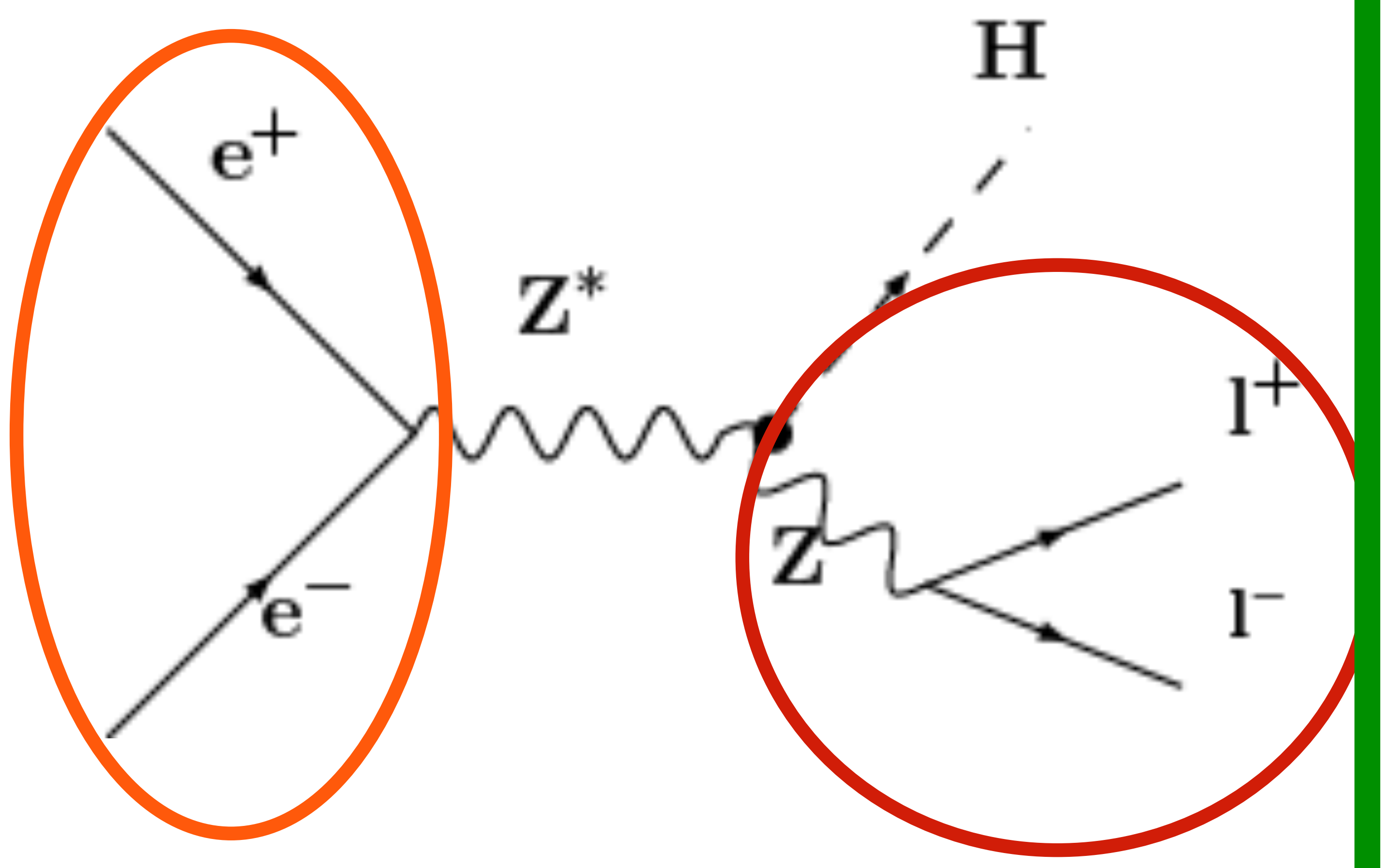
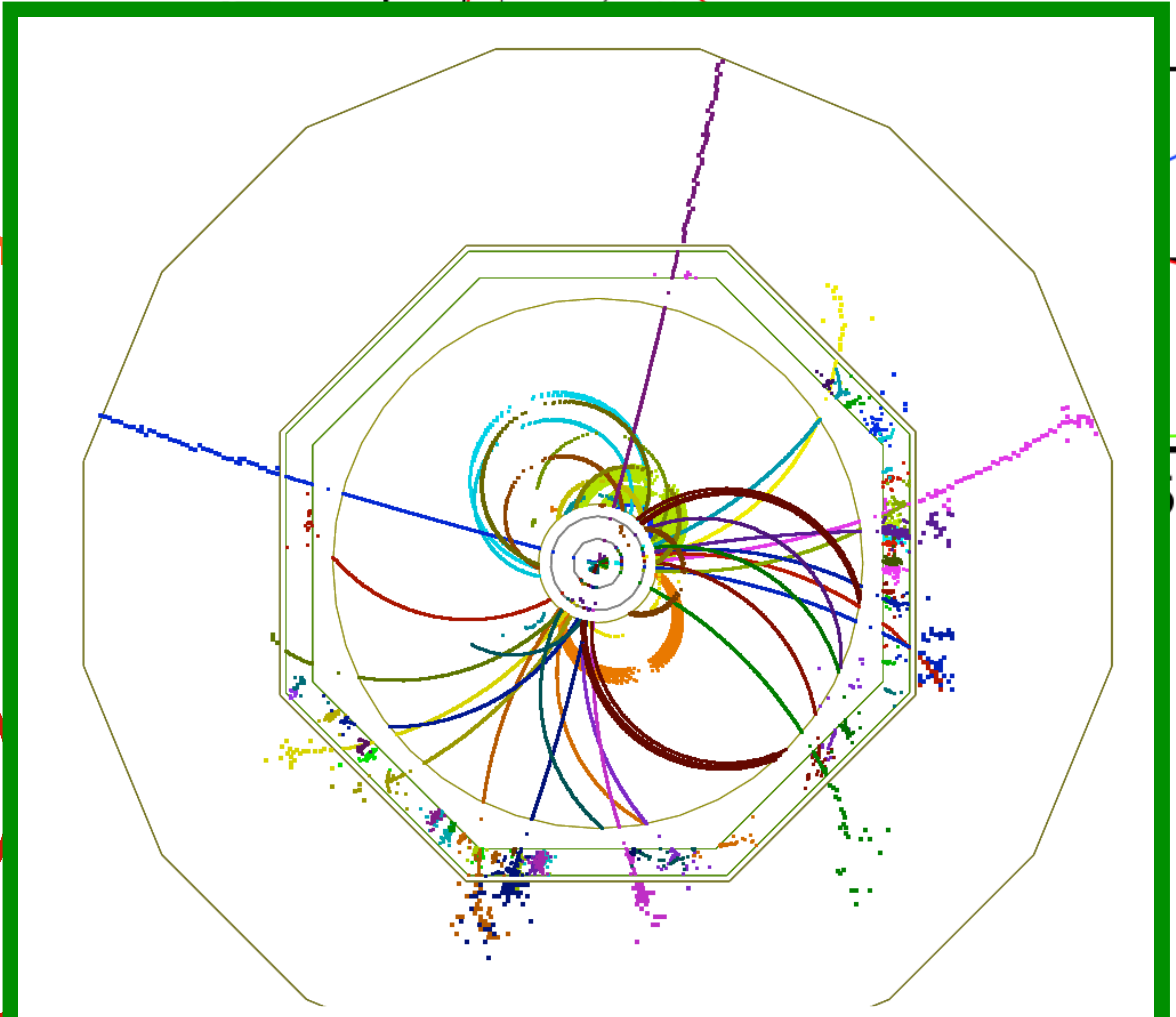


$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E$$



$e^+e^- \to \mu^+\mu^-H \to \mu^+\mu^-$ bb in ILD detector

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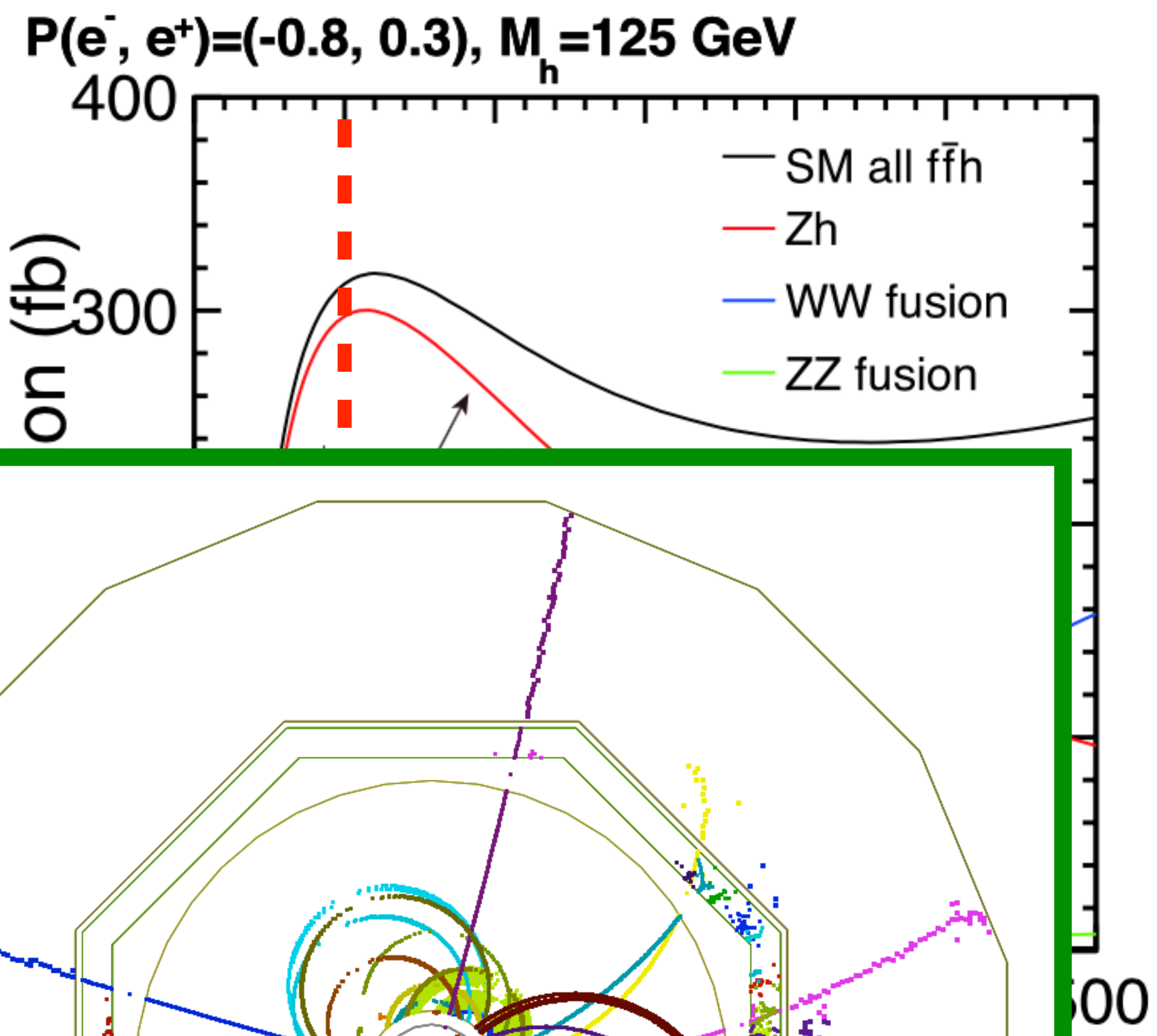

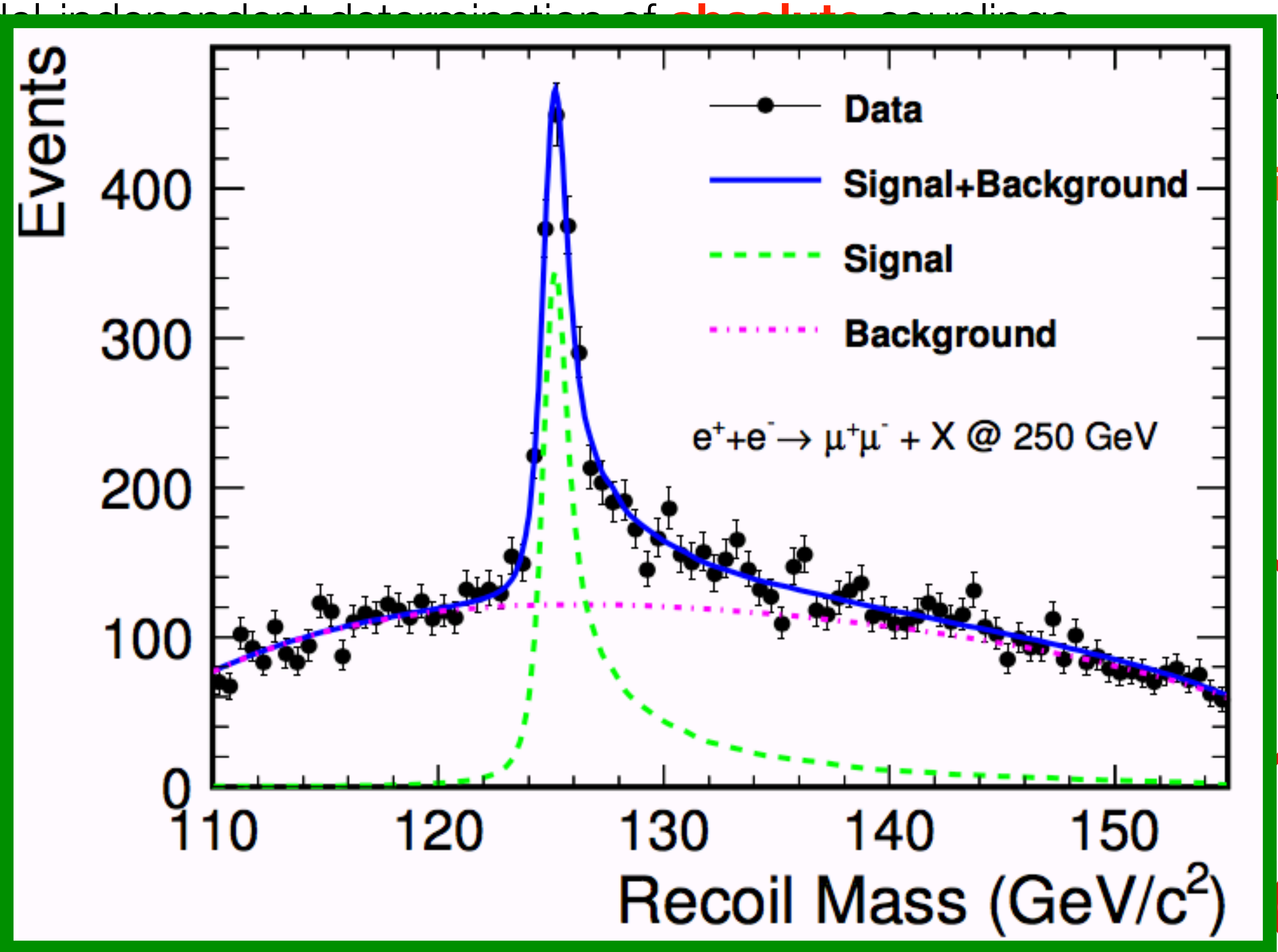

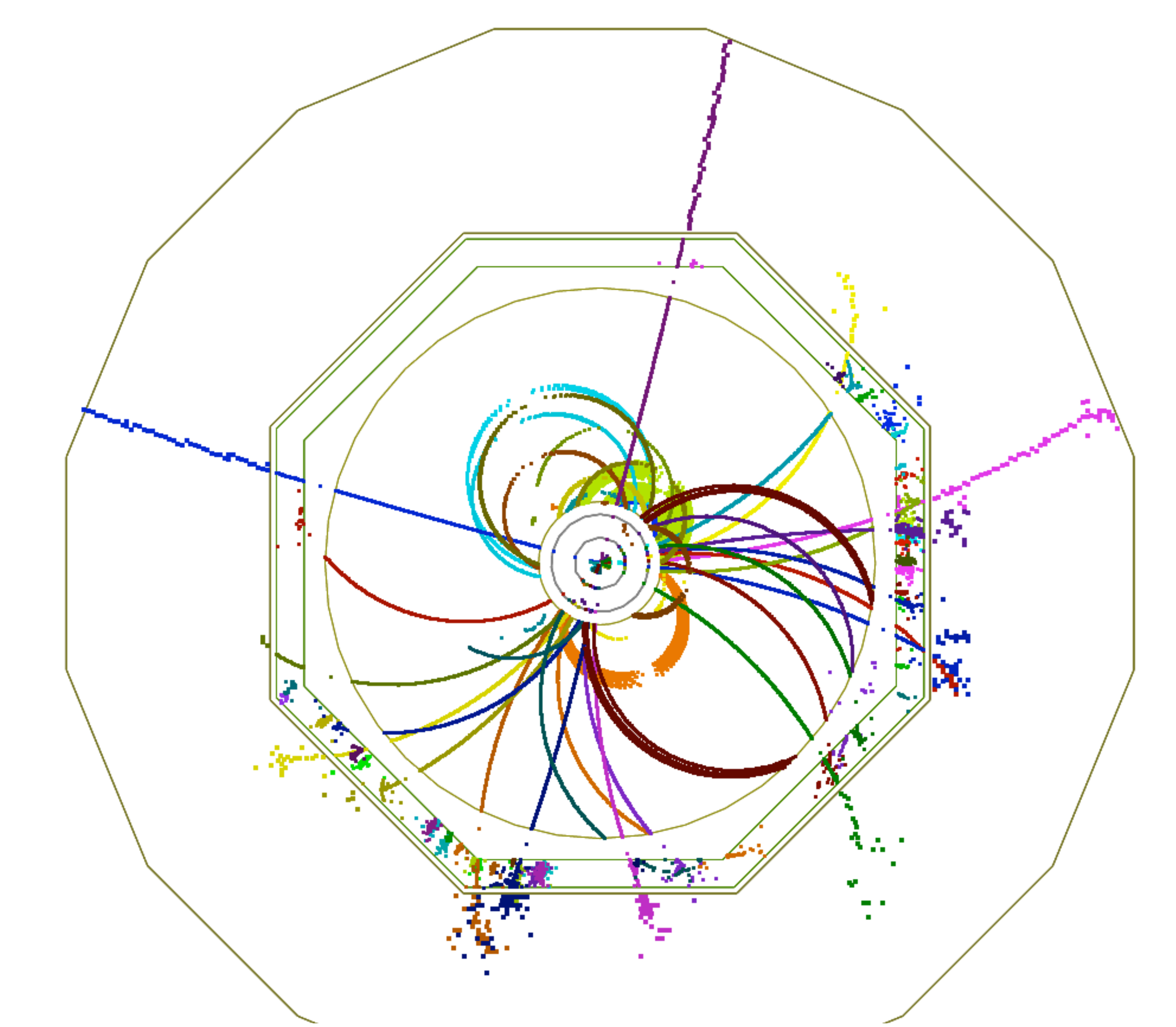

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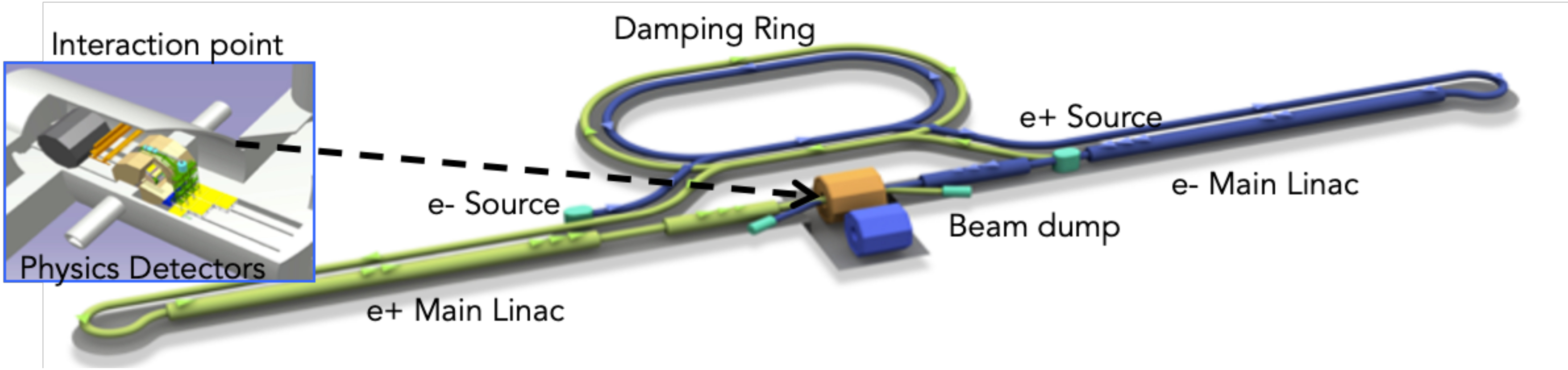
The International Linear Collider Facility

An overview - all up-to-date information in https://arxiv.org/abs/2203.07622

- **based on superconducting radio-frequency cavities => well established technology (EuXFEL, ESS, LCLS-II, …)**, with potential for continuous improvement by R&D
- **total length (250 GeV / ~500 GeV / ~1 TeV): 20.5 km / 30 km / 50 km** (with established technology)
- **construction in staged approach, starting from 250 GeV** (“Higgs factory”, incl. Z pole / WW threshold)
- **further stages can be chosen according to physics needs and technological developments**
- **2 detectors in push-pull mode => complementarity, cross-checks, competition!**



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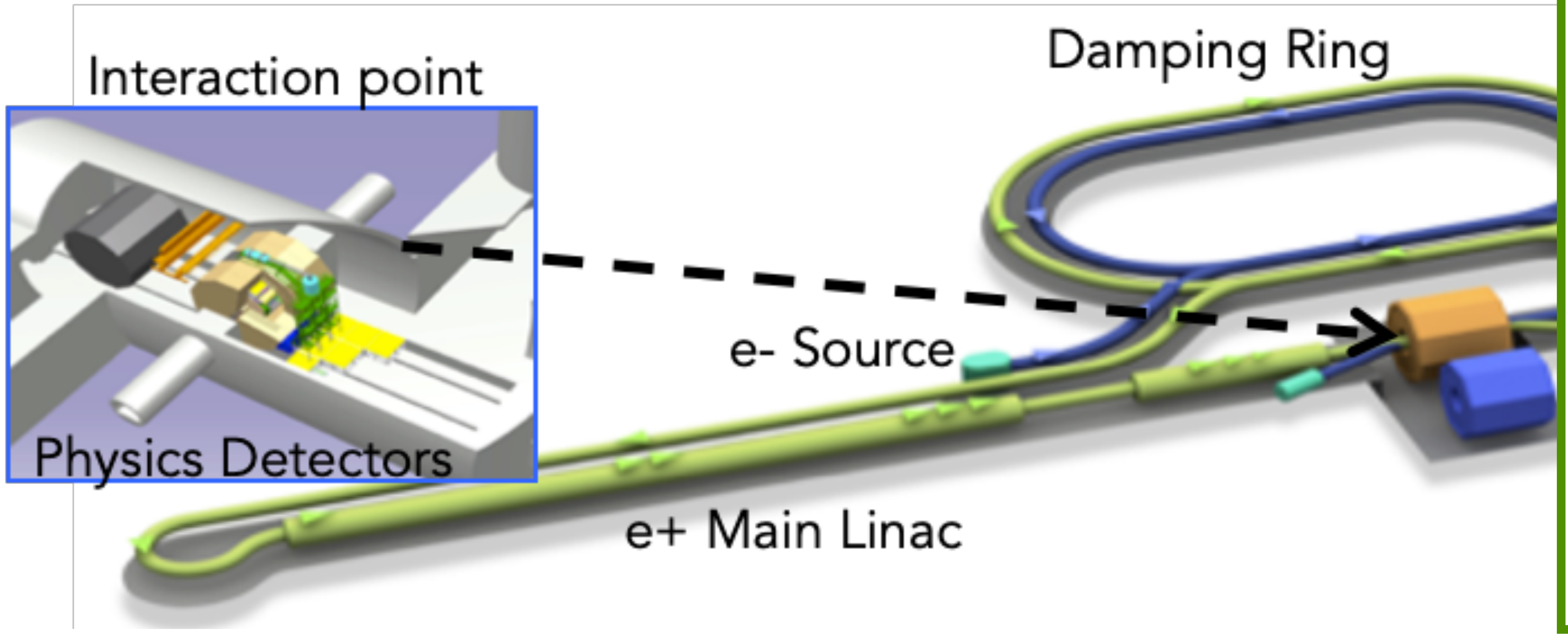

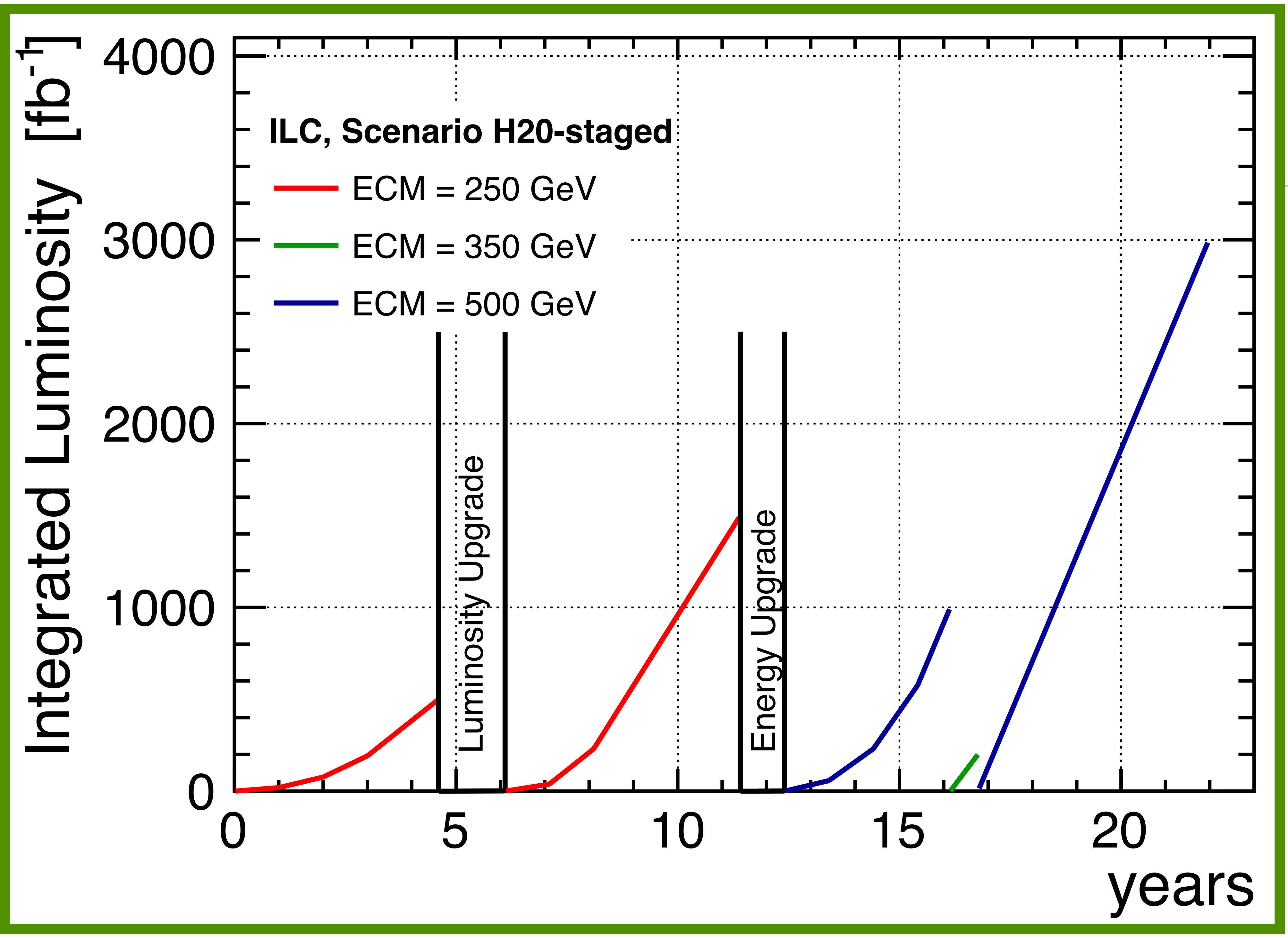

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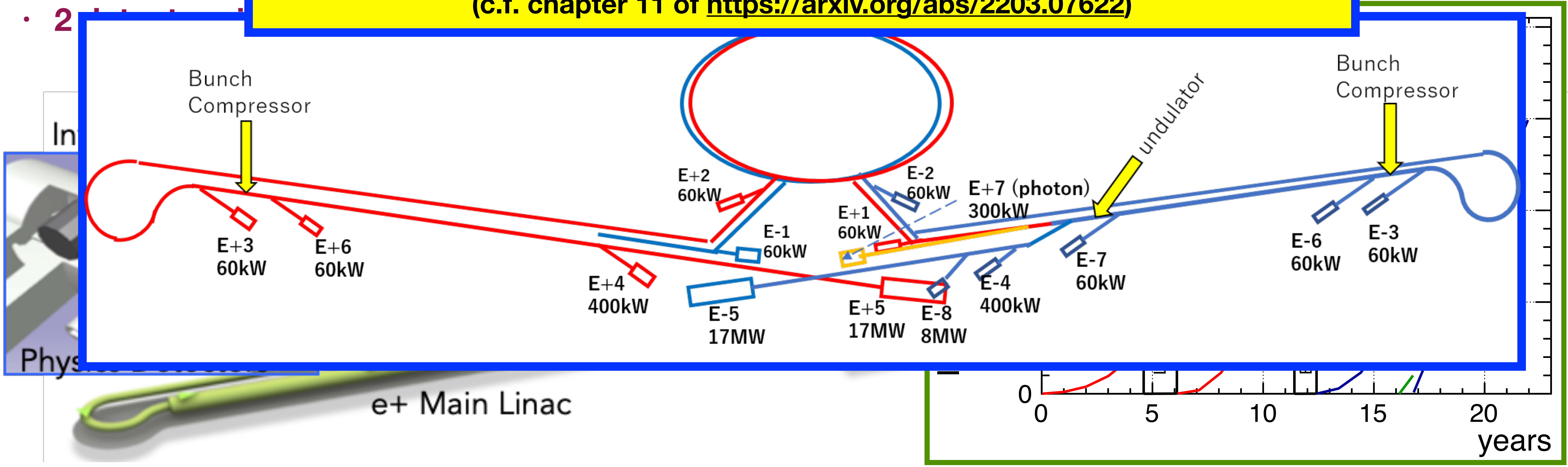
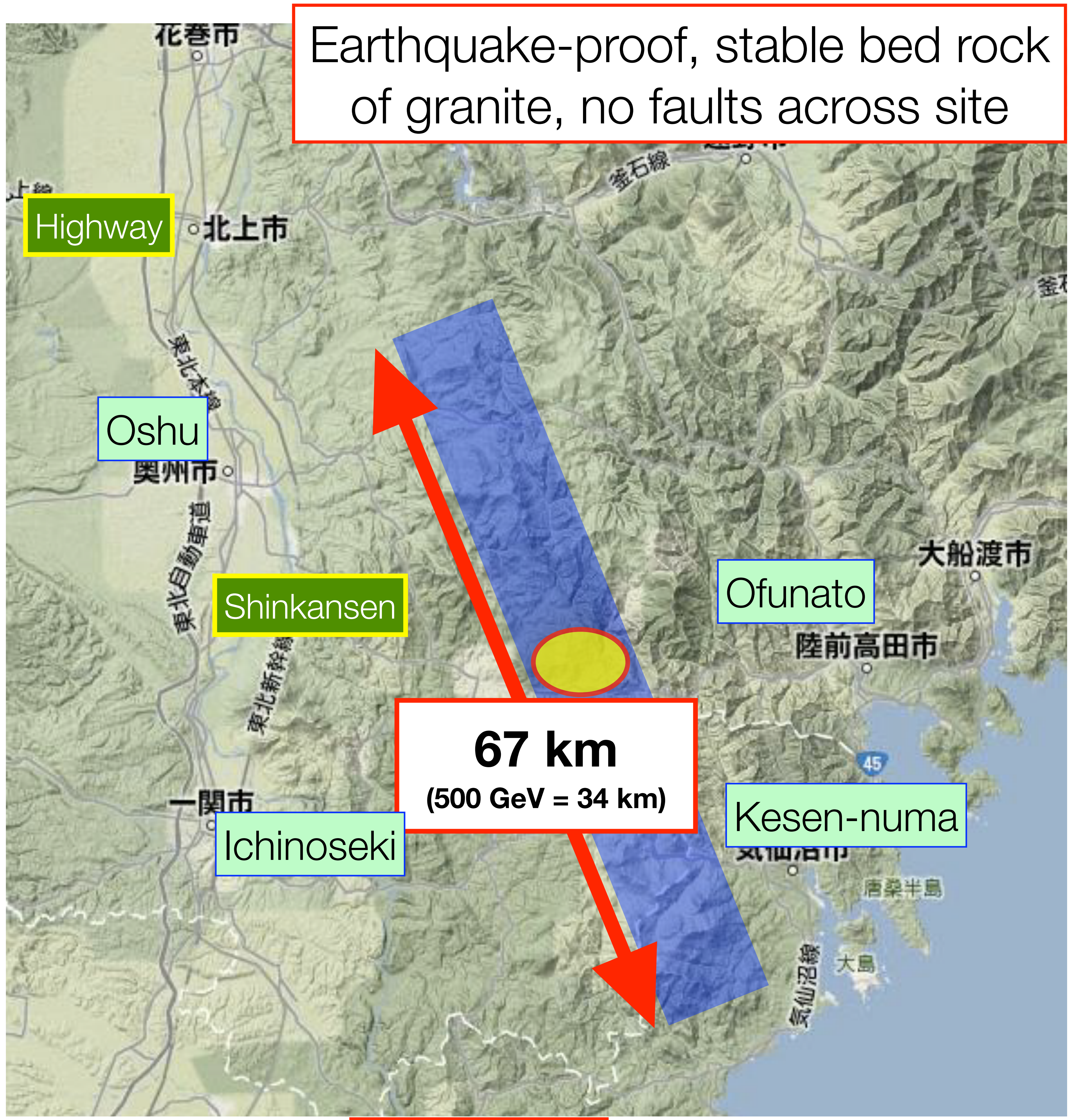
- **construction** … V threshold)
- **further stage** … **ents**
- **2** …

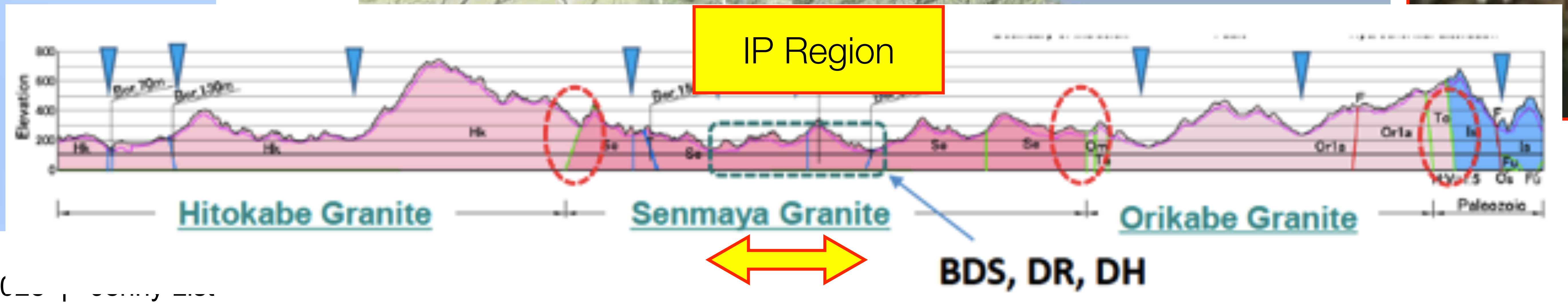
More than a collider:
ample opportunities for extra beamlines, fixed-target & beam-dump experiments!
(c.f. chapter 11 of https://arxiv.org/abs/2203.07622)



Candidate Site in Japan

Kitakami Mountains

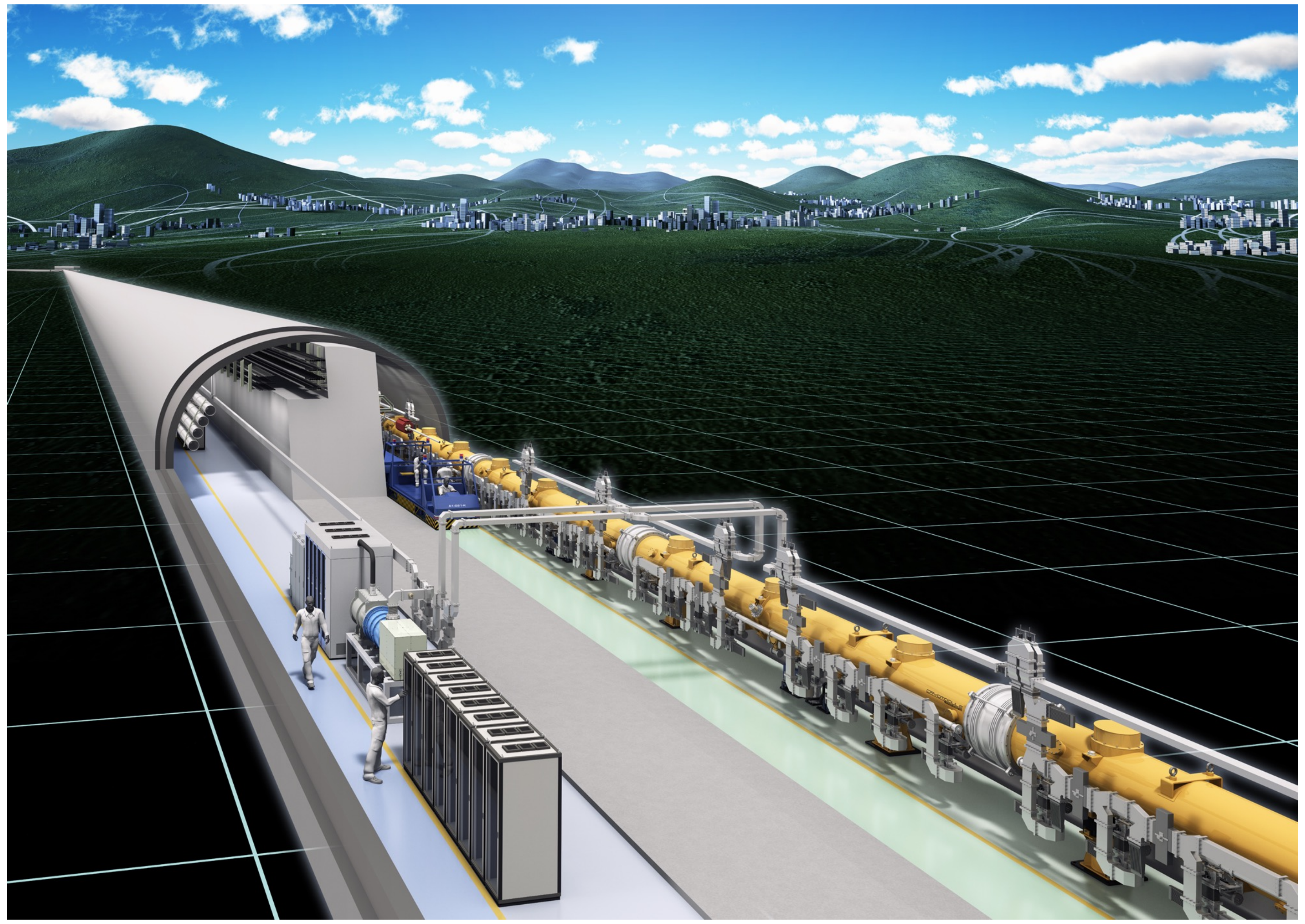




ILC Political Status

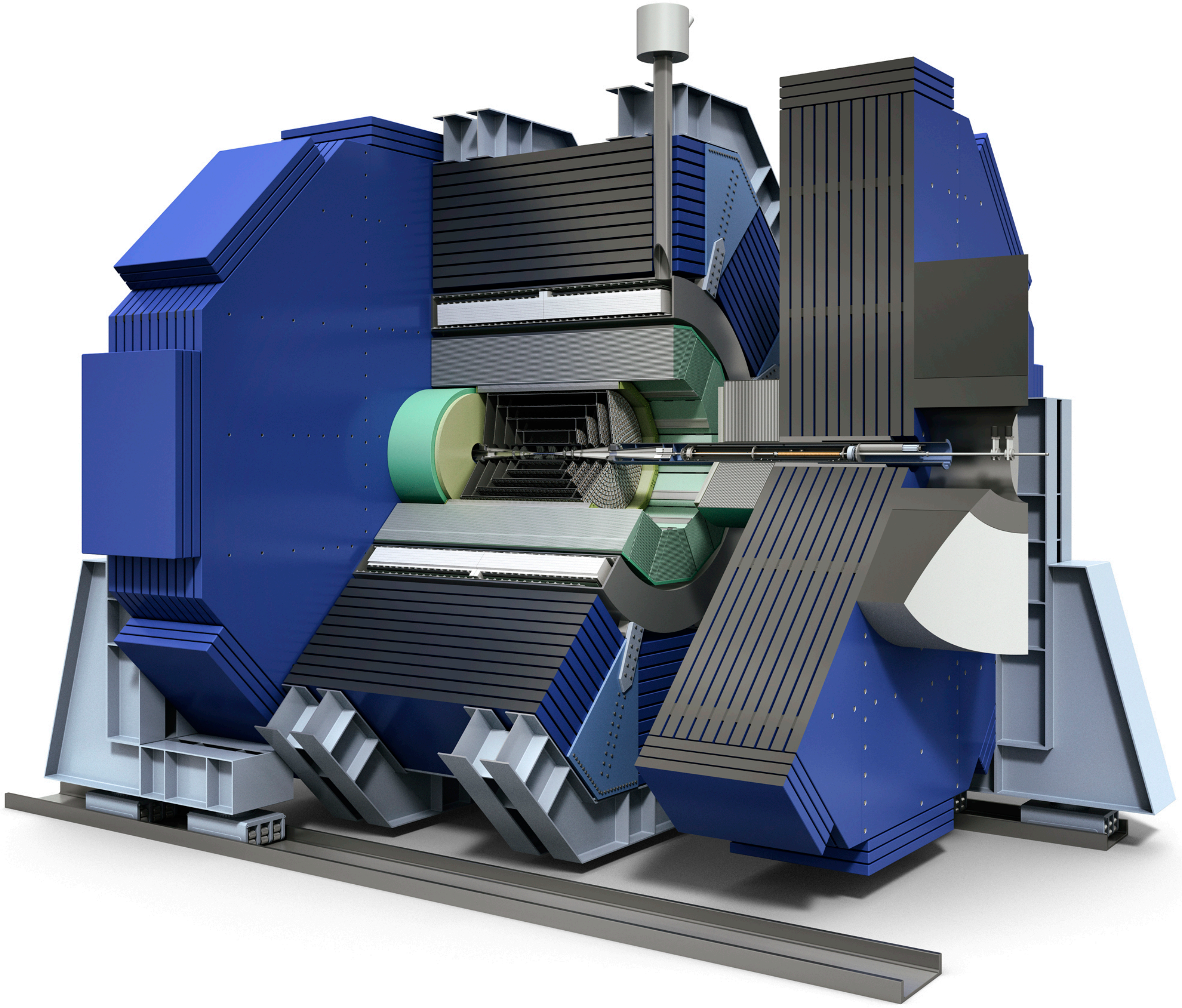
The International Development Team (IDT)

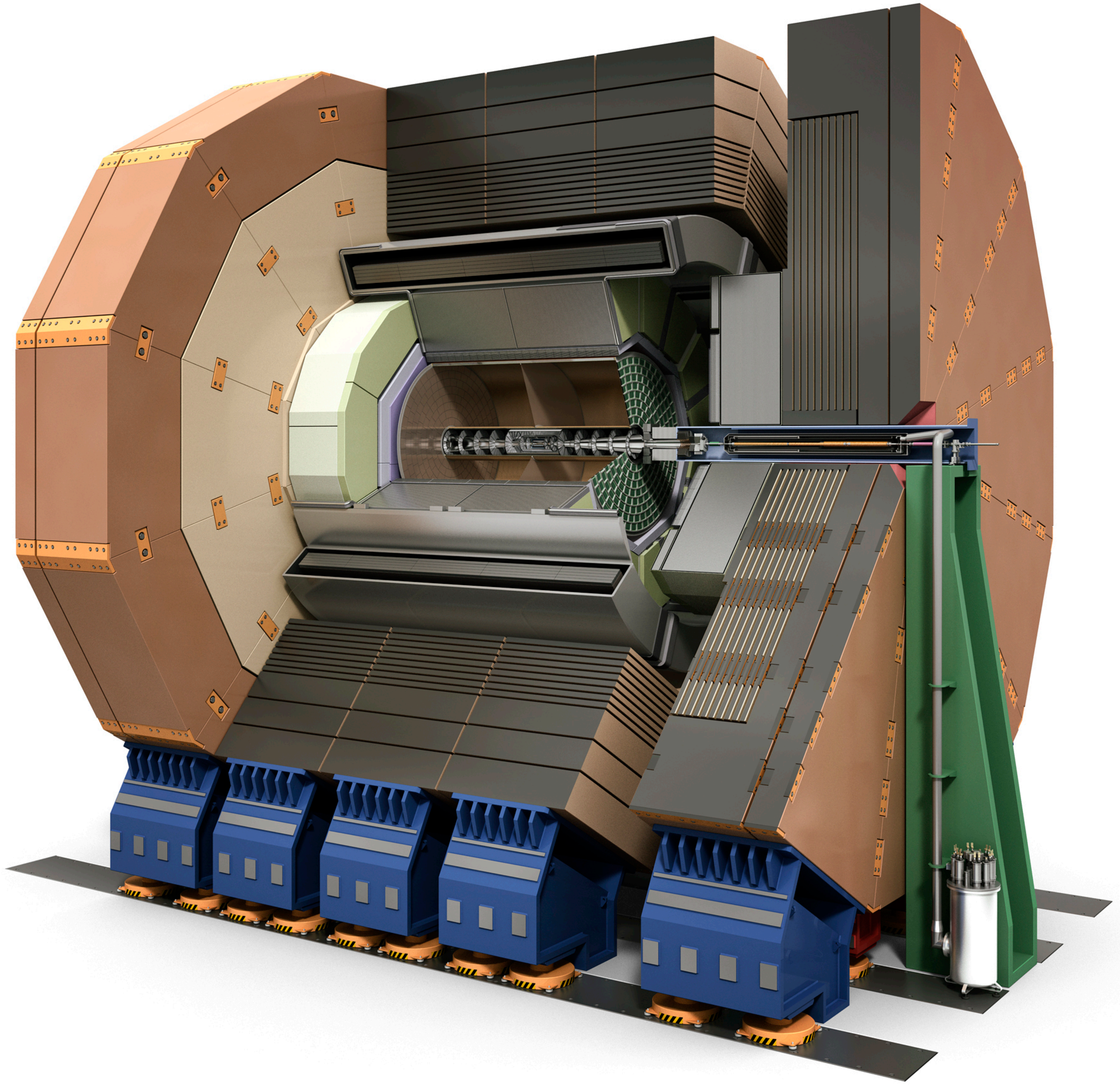
- **ILC project run by the International Development Team (IDT) mandated by ICFA**
- 2020: The IDT – created by ICFA and hosted by KEK – prepared the ILC Preparation Phase plan (“Pre-lab”), which would over a ~4 year period, lead to a complete Engineering Design as needed to start construction of the ILC.
- Late 2020 - early 2021: The plan was reviewed by a MEXT appointed panel and deemed premature, referring to that the prospects for an international cost sharing for ILC were not clear. However increased support for technical developments and accelerator R&D was recommended.
- During 2021- early 2022: Within the IDT a subset of the technical activities of the full preparation phase programme has been identified as priorities, to be addressed with an international effort. The required resources are at ~1/3 level of the original plans. The activities planned are foreseen to take 2-4 years.
- second half of 2022: These plans were included MEXT budget request and has been approved by the Finance Ministry. The funding can become available in May 2023 (DIET approval needed). It will double the KEK resourced available for ILC preparation, and in particular provides important new funding for ILC relevant hardware developments. Some parts of this funding can be used to foster international collaboration and efforts. The budget needs to be approved yearly, but the programme is set up for five years.
- We call this pre-preparation program the **ILC Technology Network (ITN)**
  Start: NOW



ILC Detectors

SiD & ILD





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SiD & ILD

Key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) $\theta_{min} = 5$ mrad

Determine to key features of the detector:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
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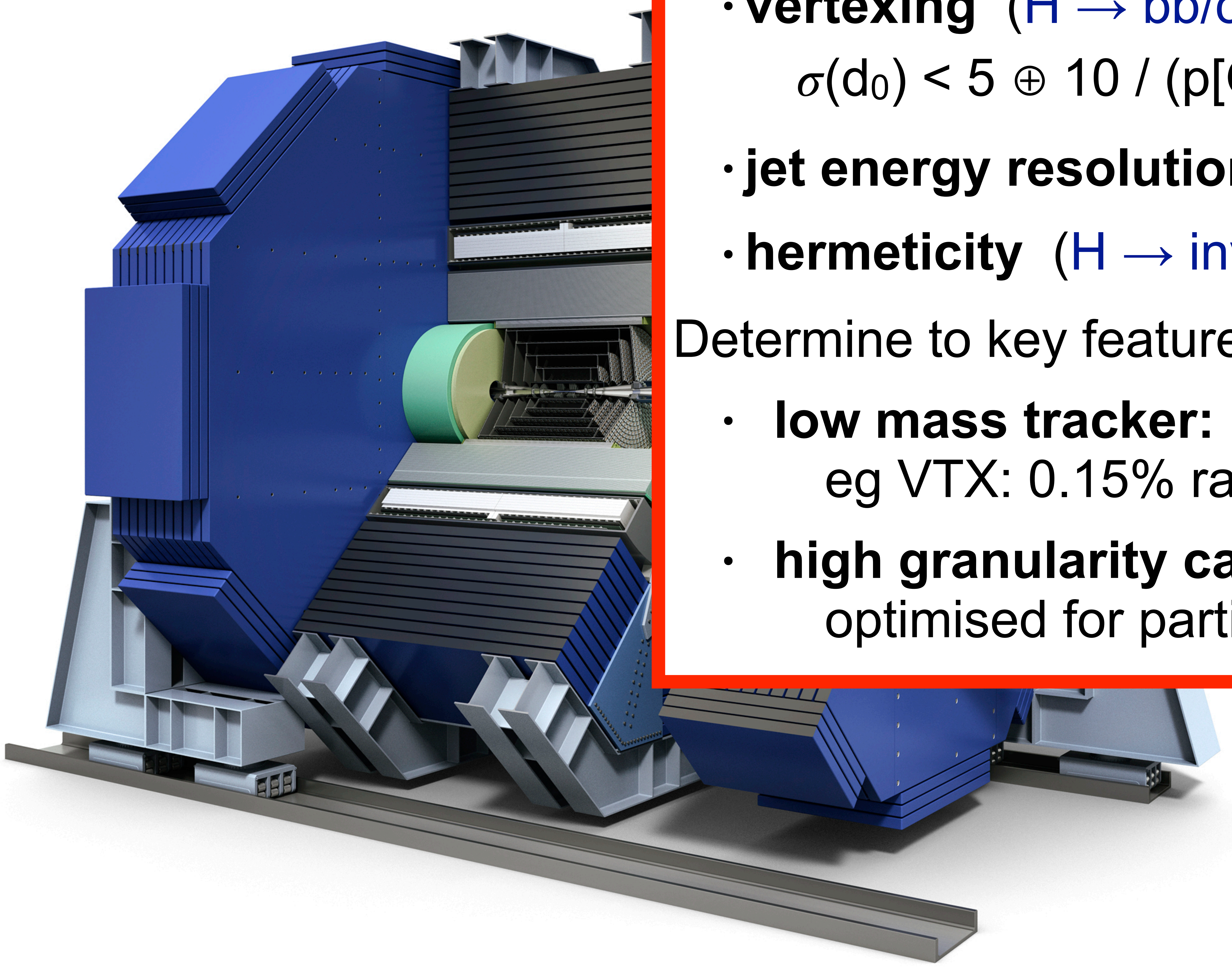

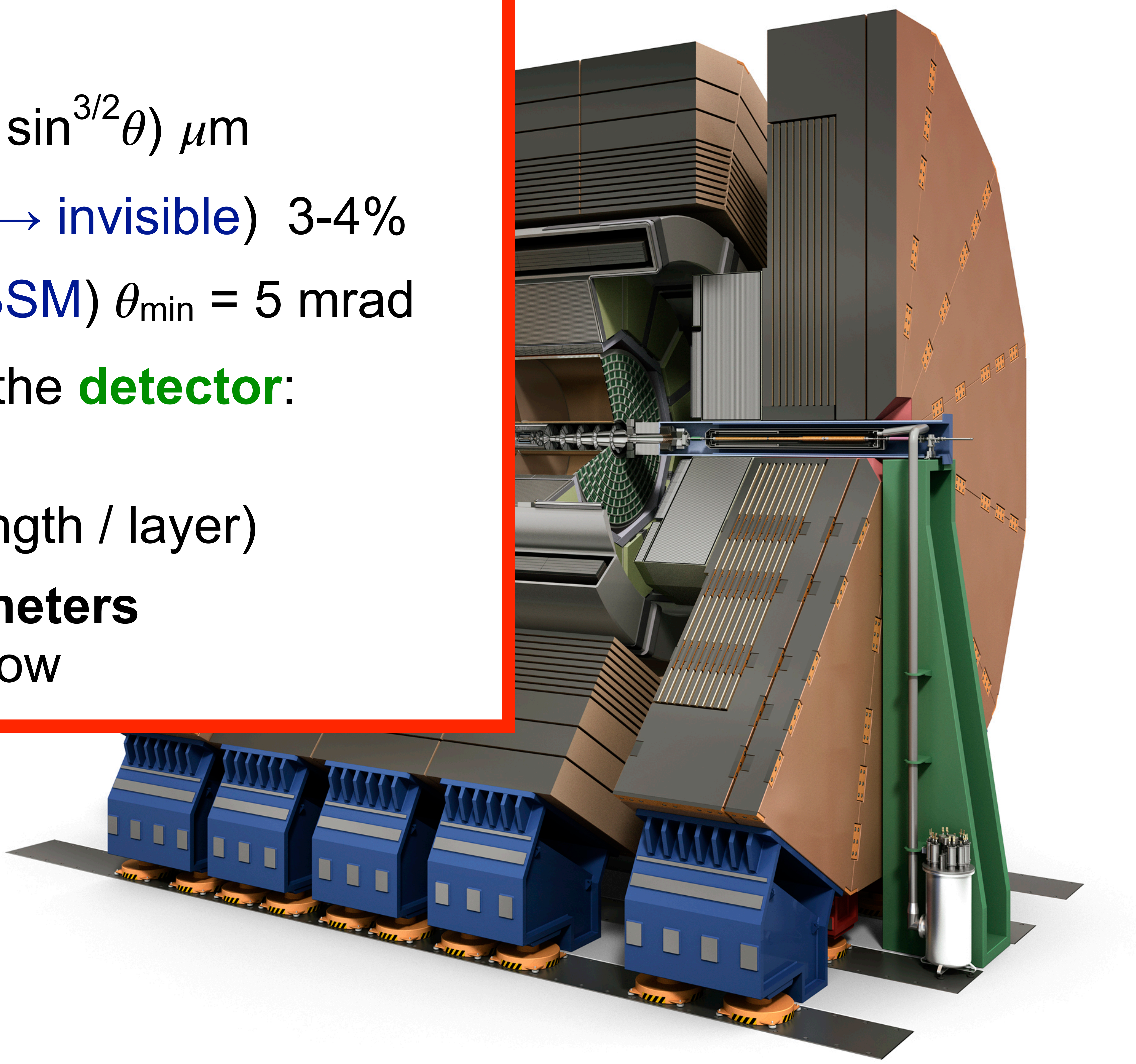

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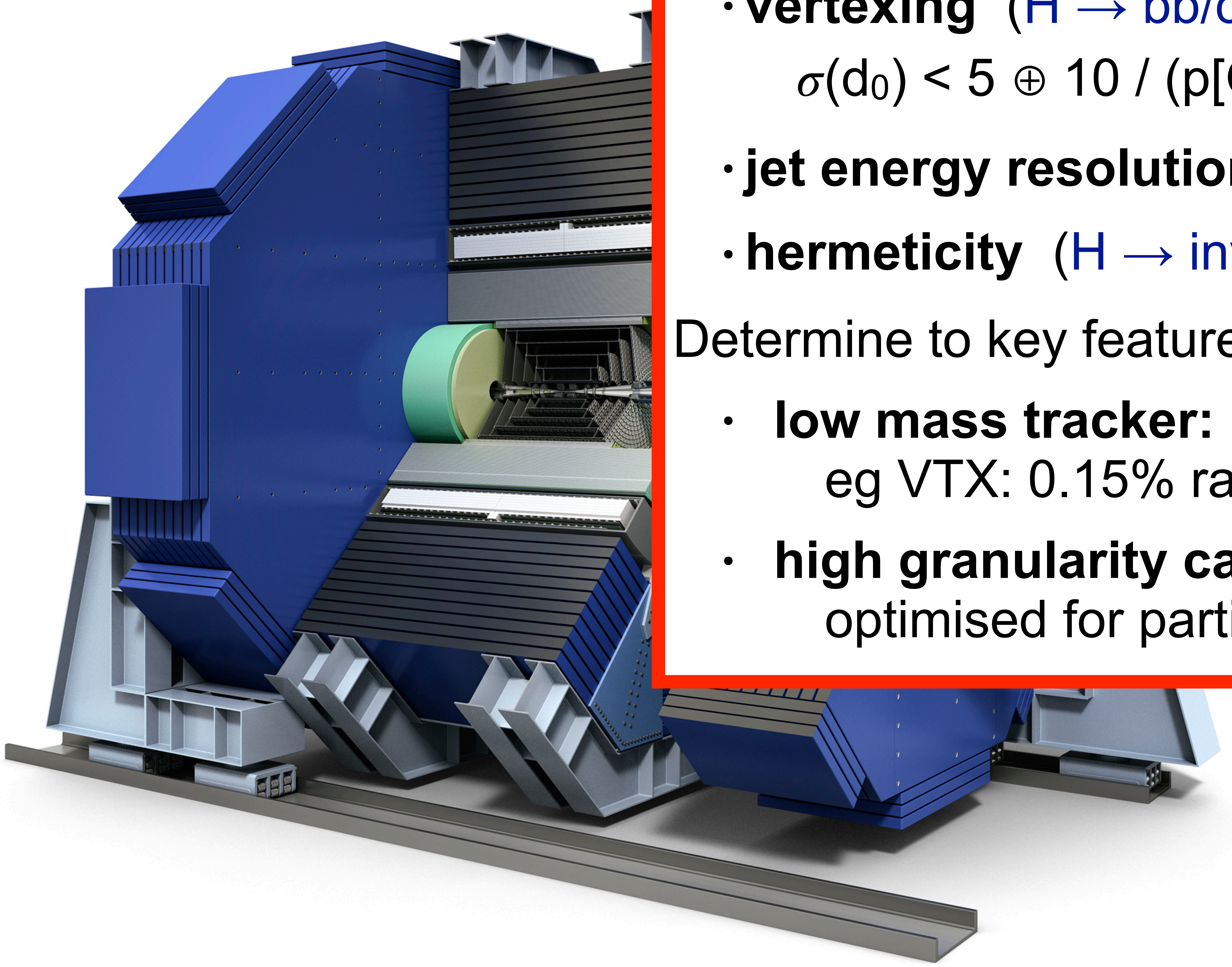

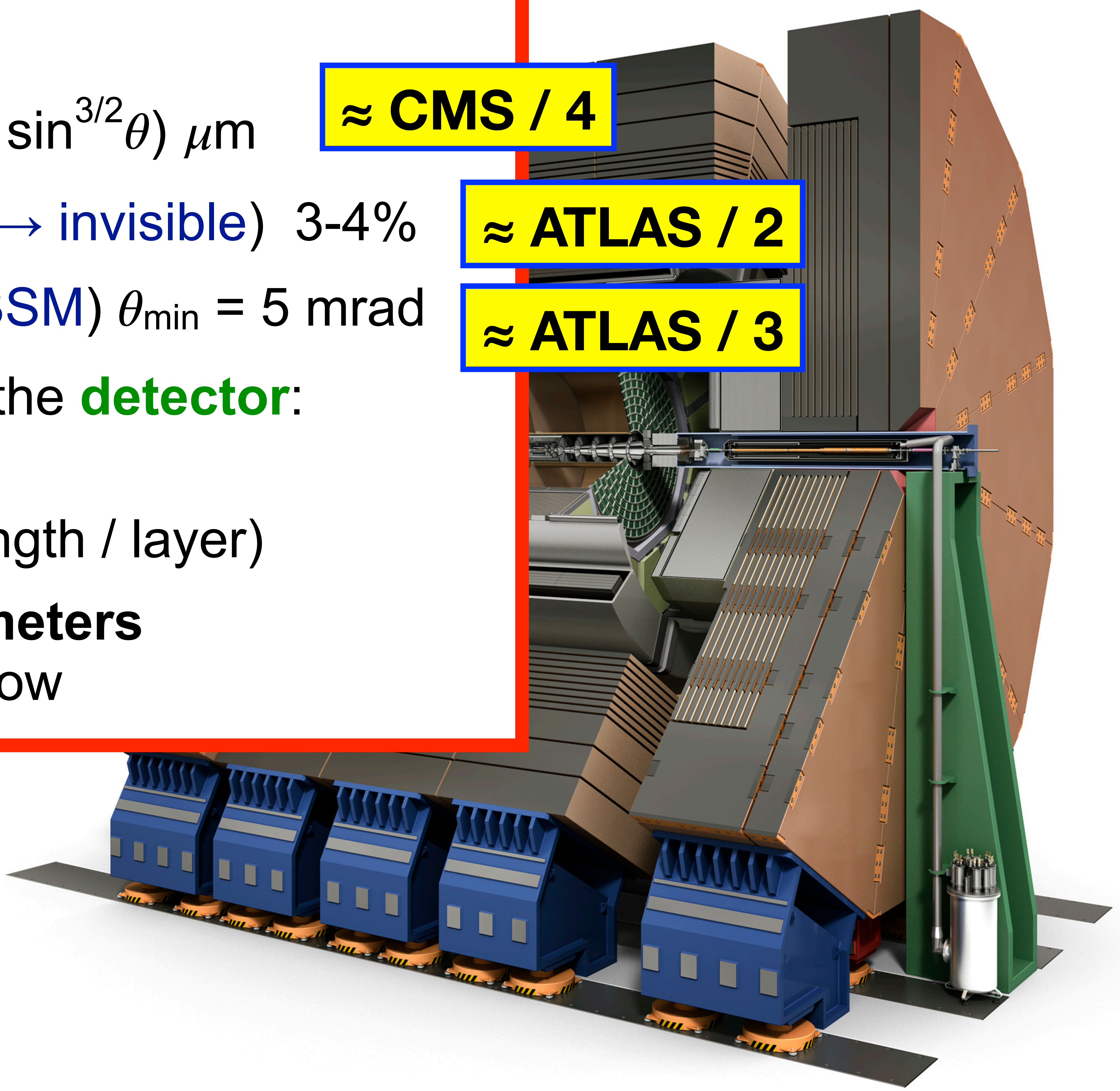

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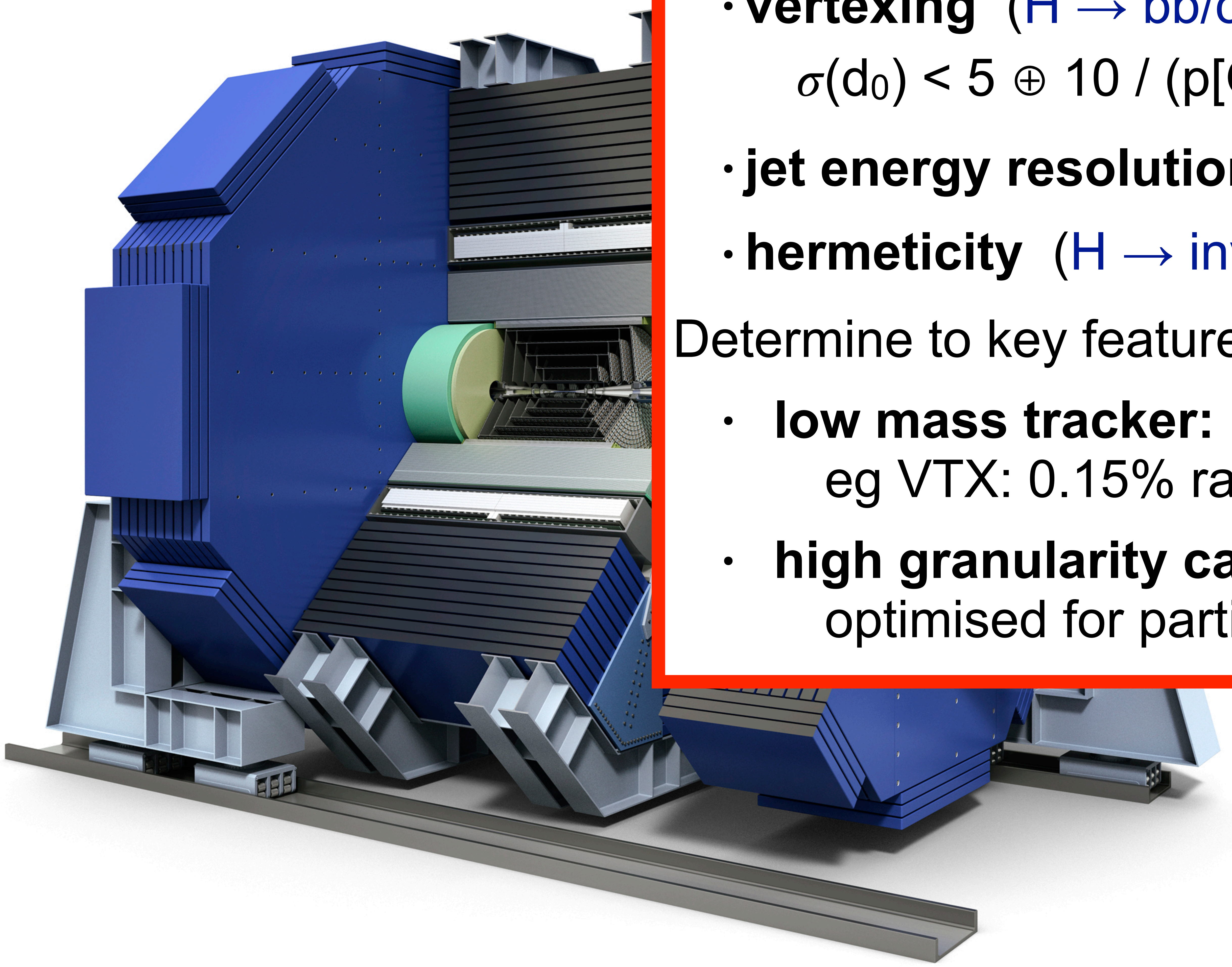
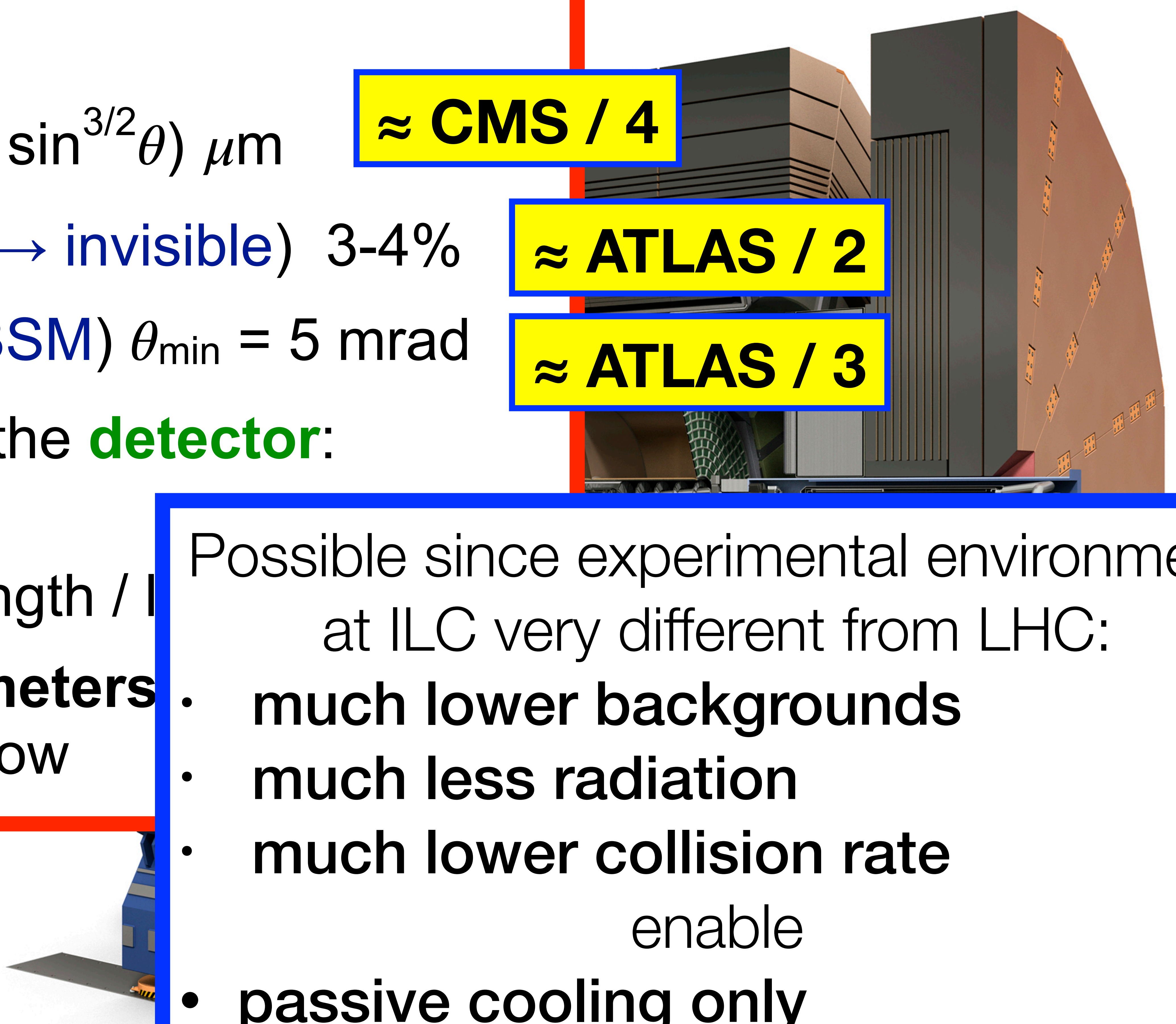




Possible since experimental environment at ILC very different from LHC:

- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**

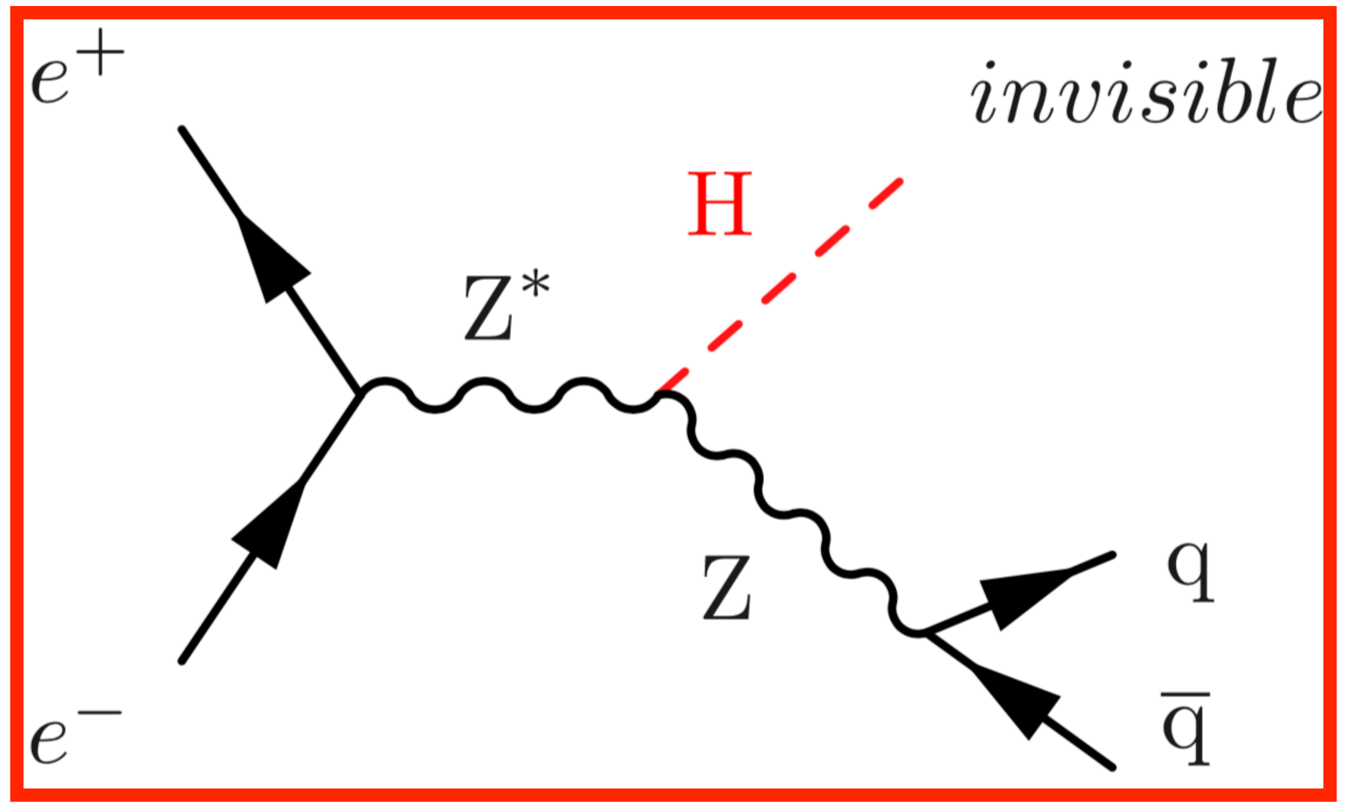
enable

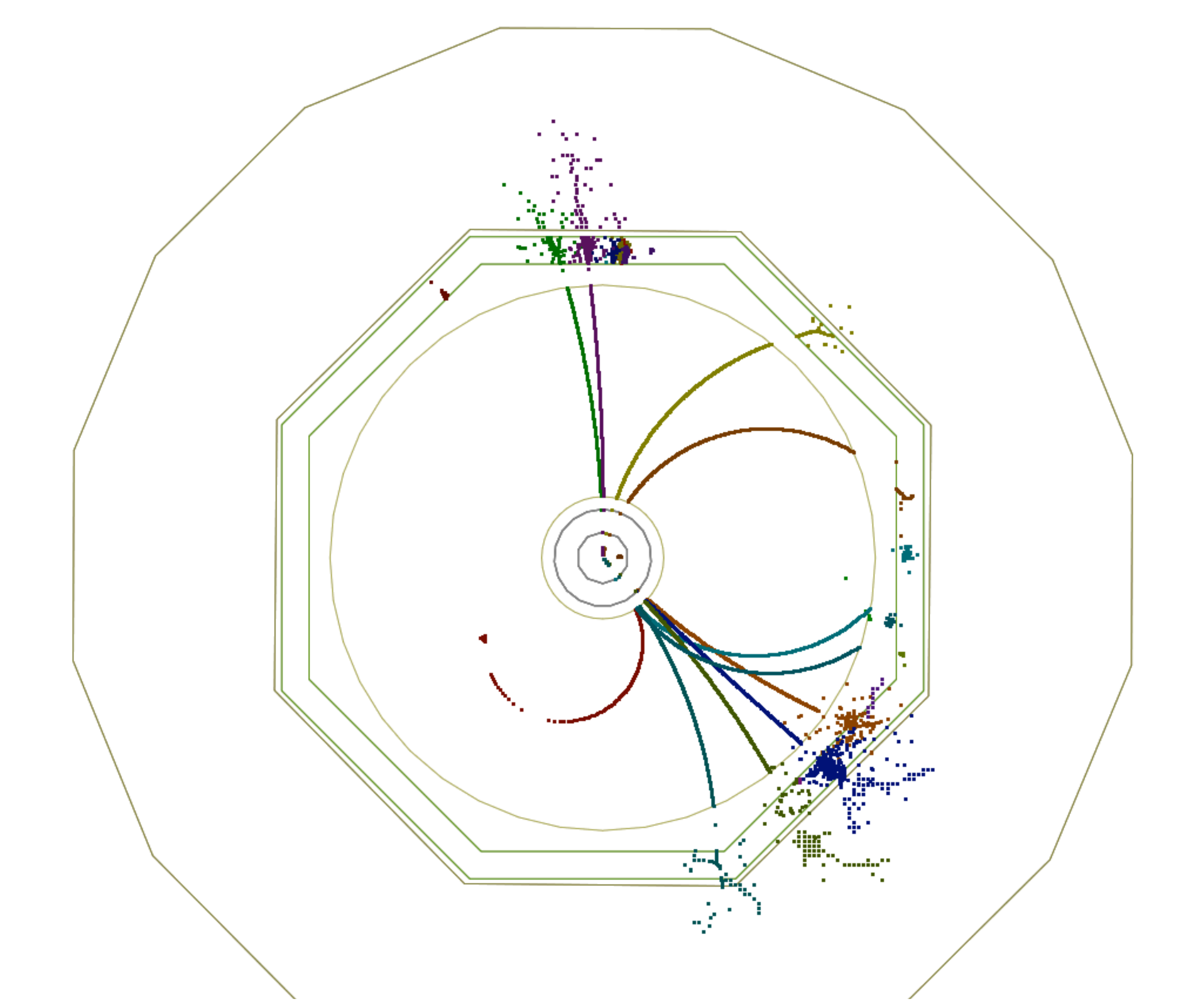
- **passive cooling only**
  => low material budget
- **triggerless operation**

Example: Higgs decay to "invisible"

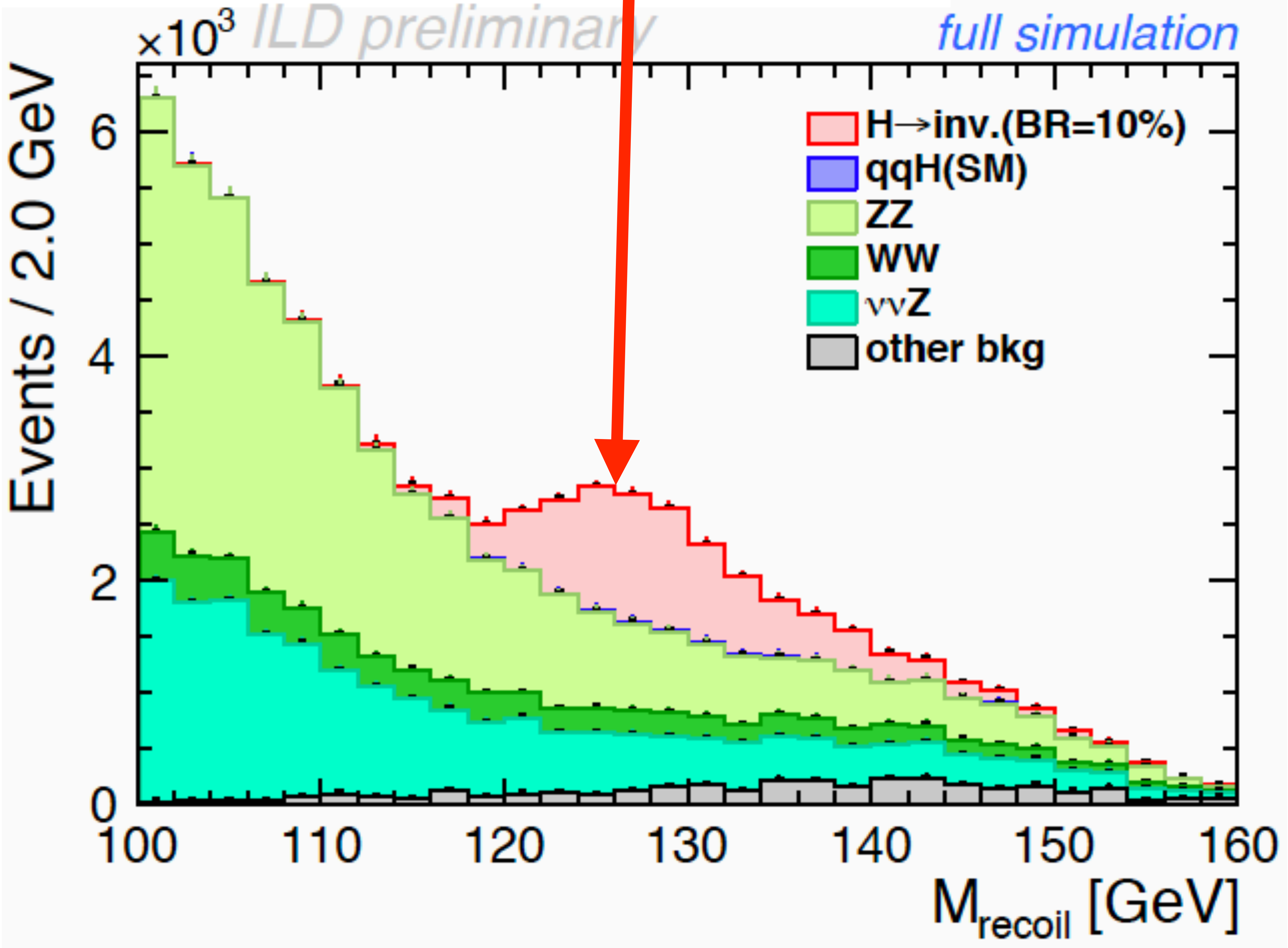
Dark Sector Portal?

- use $e^+e^- \rightarrow Z\,h$ process
- select a **visible final state (qq, ee, μμ) compatible with a Z decay**
- **recoiling against "nothing"**
- **if signal observed at ILC: discovery! Of Dark Matter?**
- **if no signal observed at ILC250: exclude BF > 0.16% at 95% CL (HL-LHC expectation: 2.5%, SM prediction: 0.12%)**





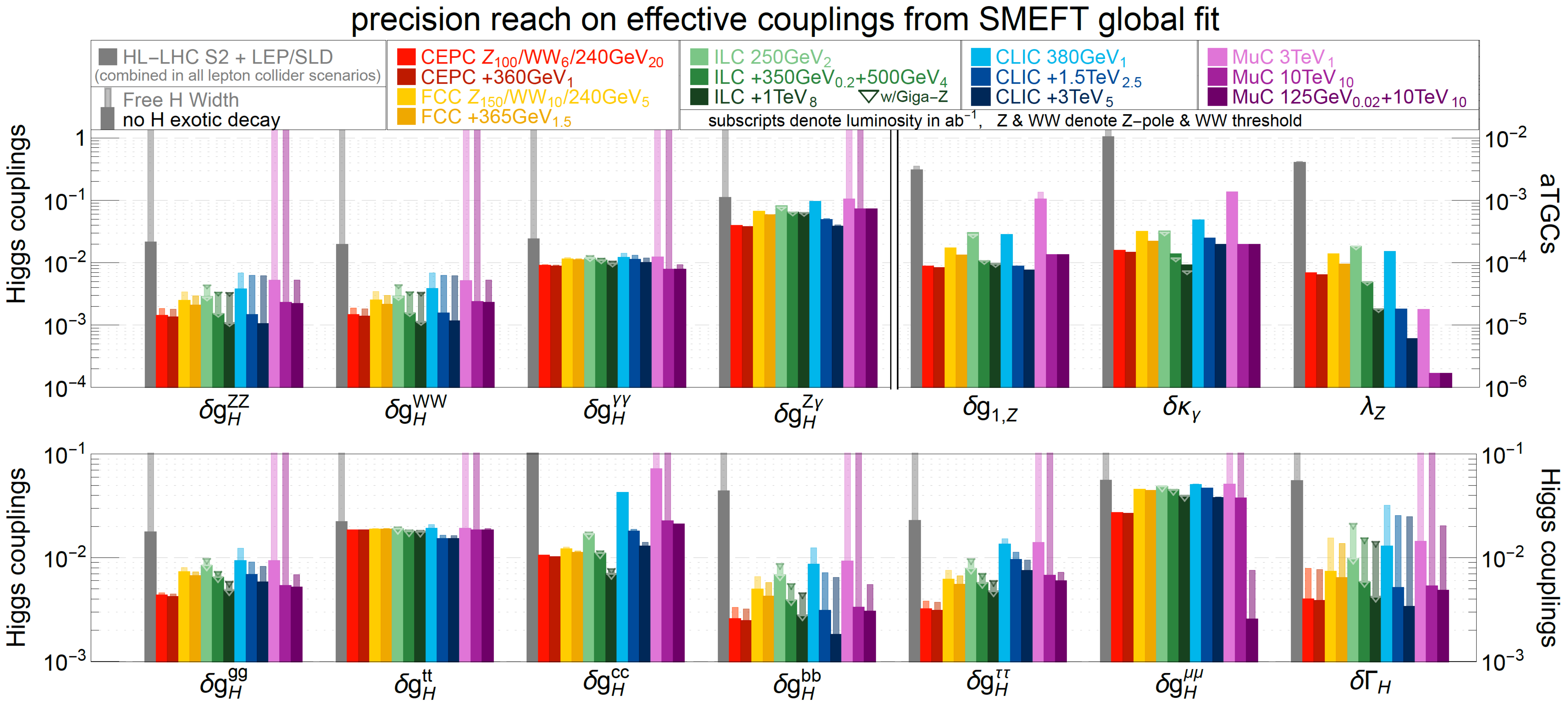
$e^+e^- \rightarrow q\bar{q}H \rightarrow qq$ inv in ILD detector



arXiv:2203.08330 (SiD) & *PoS* EPS-HEP2019 (2020) 358 (ILD)

The new Snowmass SMEFT fit

Rainbow-Manhattans



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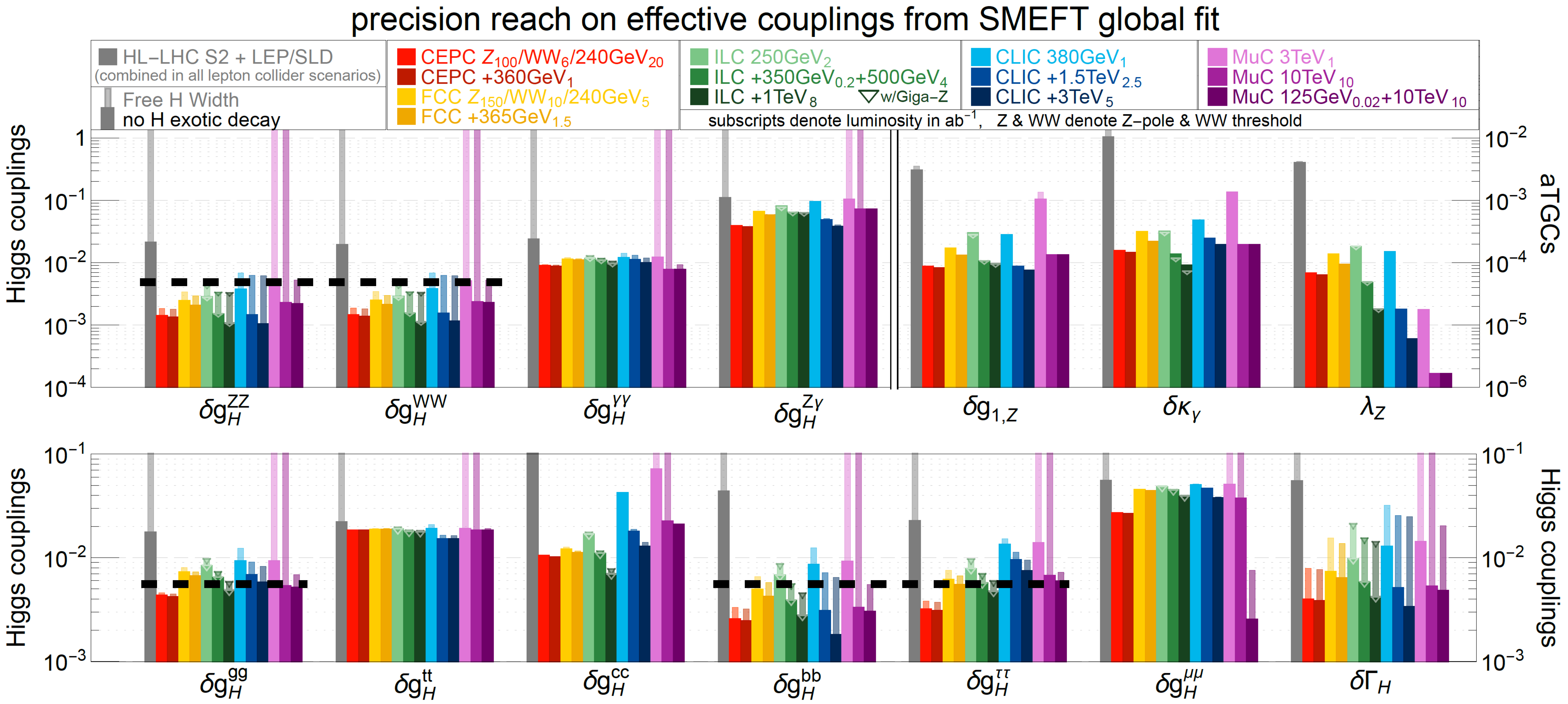

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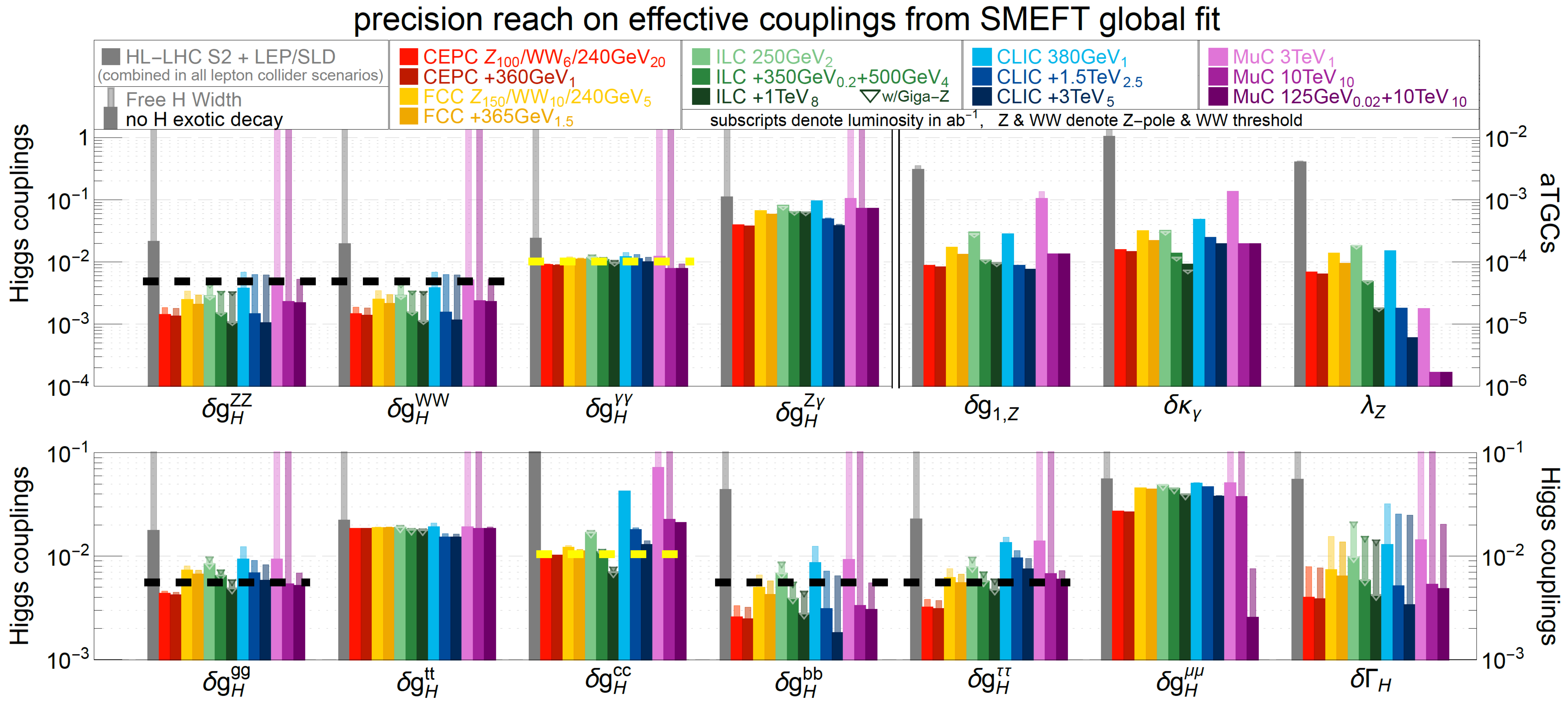

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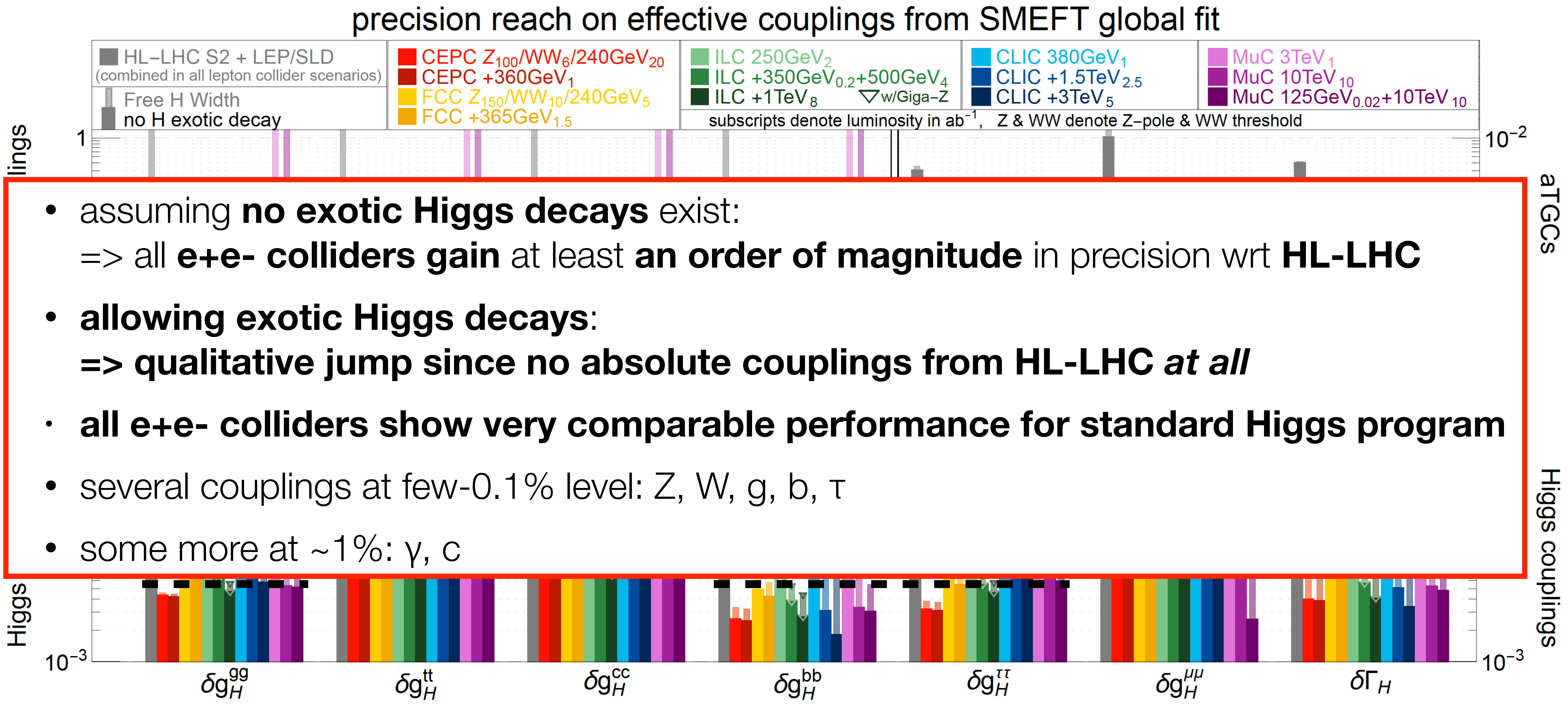


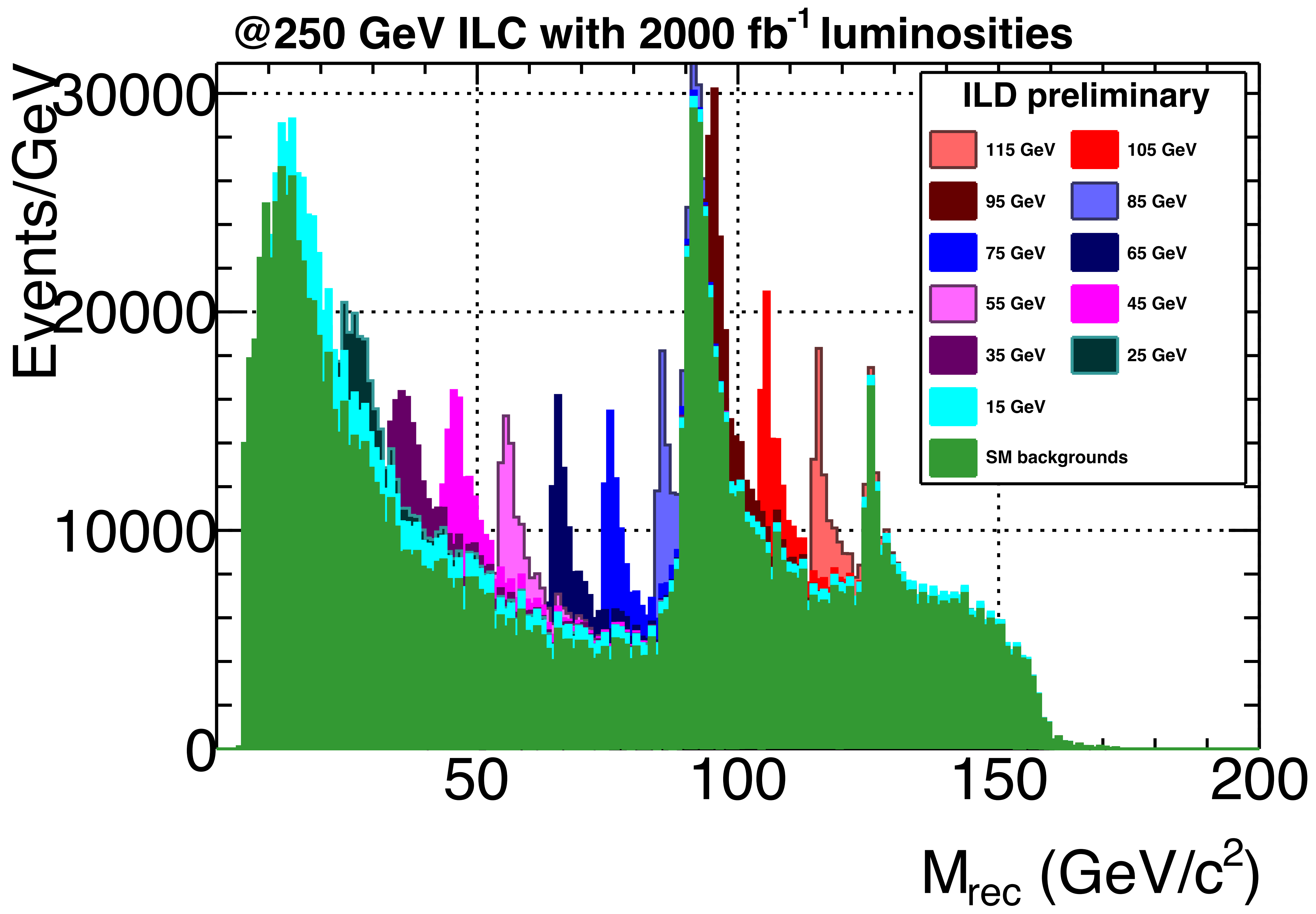
- assuming **no exotic Higgs decays** exist:
  => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays**:
  => qualitative jump since no absolute couplings from HL-LHC *at all*
- **all e+e- colliders show very comparable performance for standard Higgs program**
- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

Extra Higgs Bosons ?

Siblings of the Higgs

- must "share" coupling to the Z with the 125-GeV guy:
  - $g_{HZZ}^2 + g_{hZZ}^2 \leq 1$
  - 250 GeV Higgs measurements:
    $g_{hZZ}^2 < 2.5\%\ g_{SM}^2$ excluded at 95% CL
- probe smaller couplings by ***recoil* of h against Z**

=> decay mode independent!



ILD full detector simulation
@ ILC 250 GeV & 500 GeV,
arxiv:2005.06265

- **fully complementary to measurement of ZH cross section**
- **other possibility: ee -> bbh (via Yukawa coupling)**

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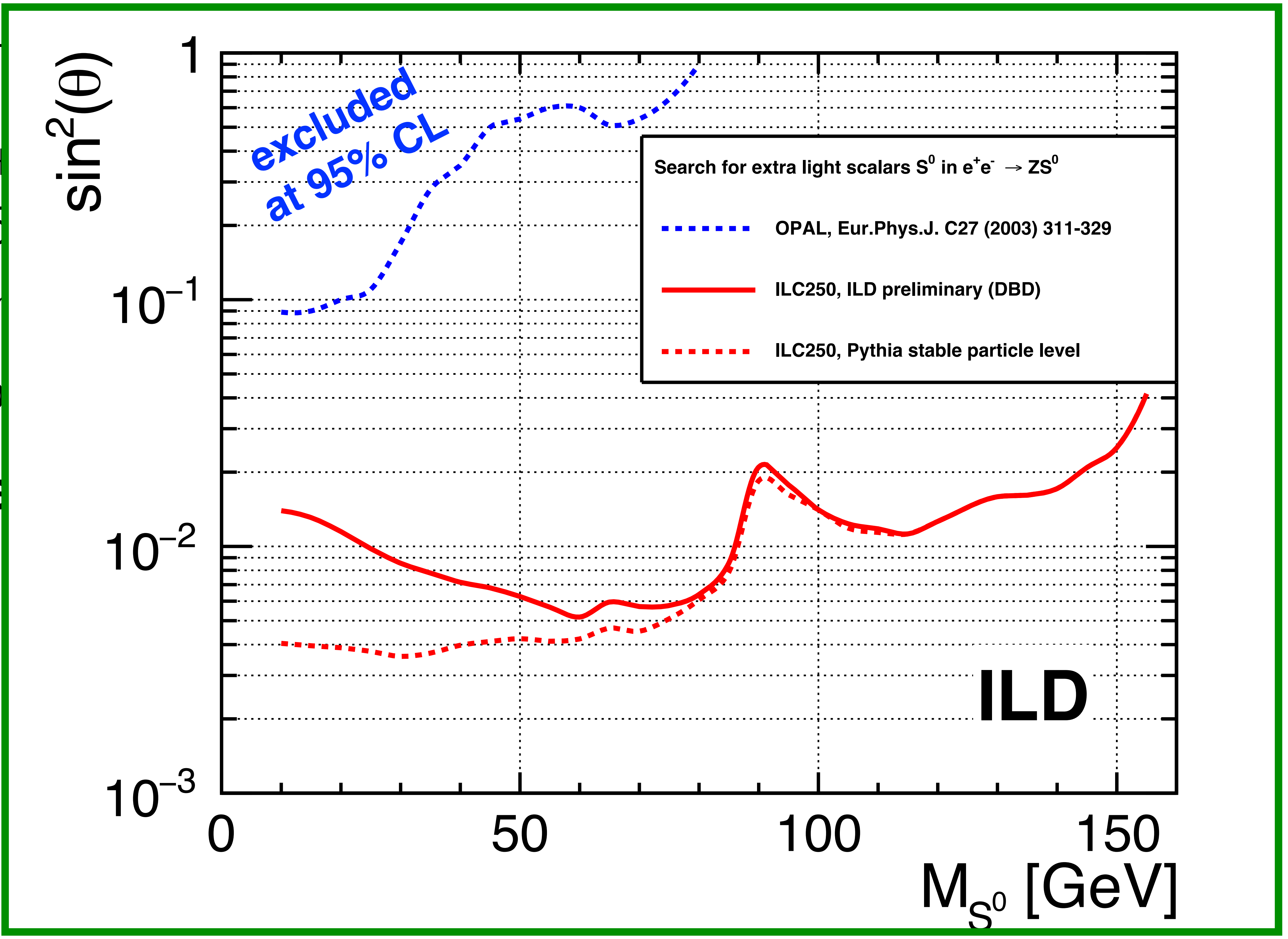
- mus
  - g
  - 25
    g
- prob

=> de



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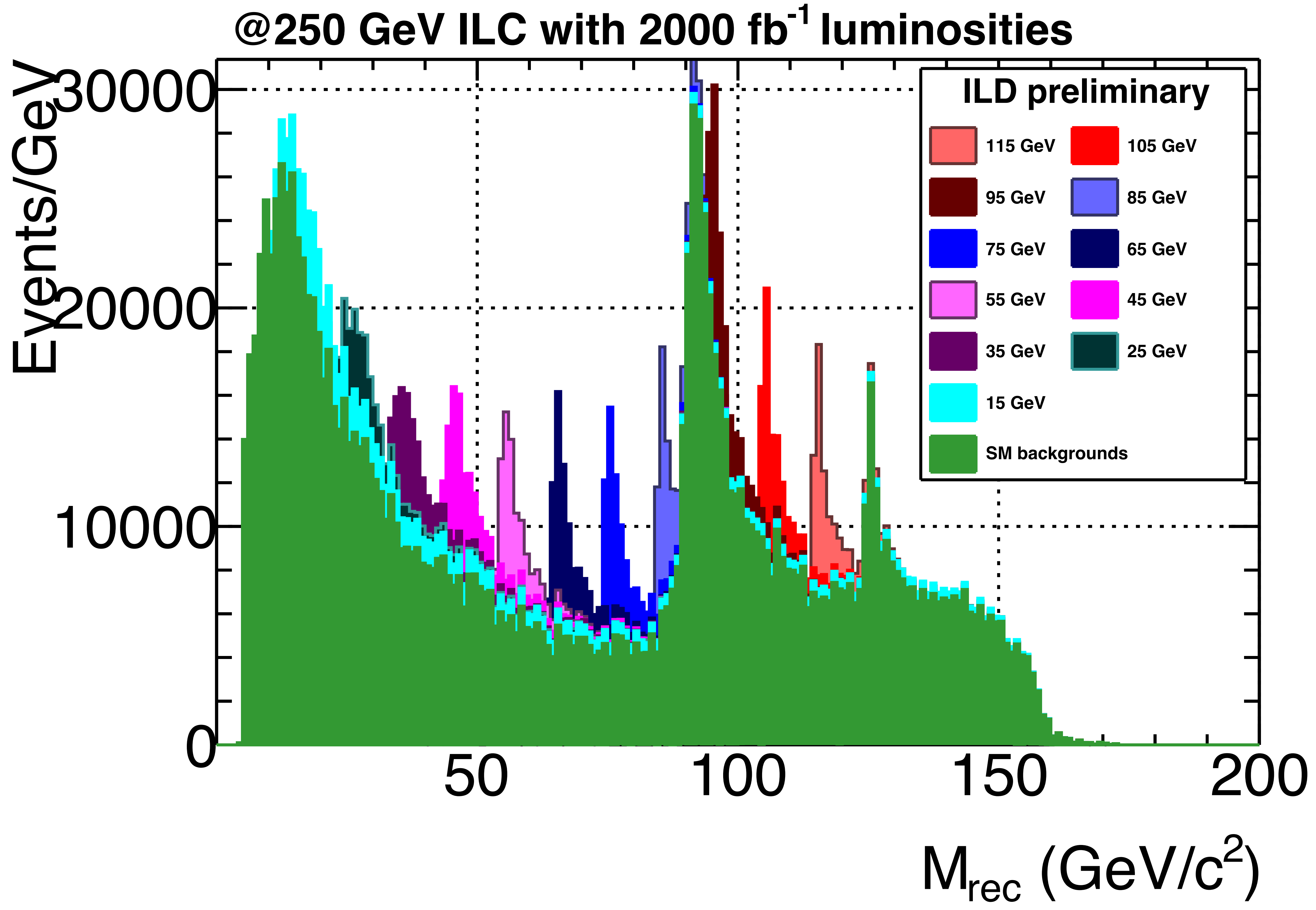

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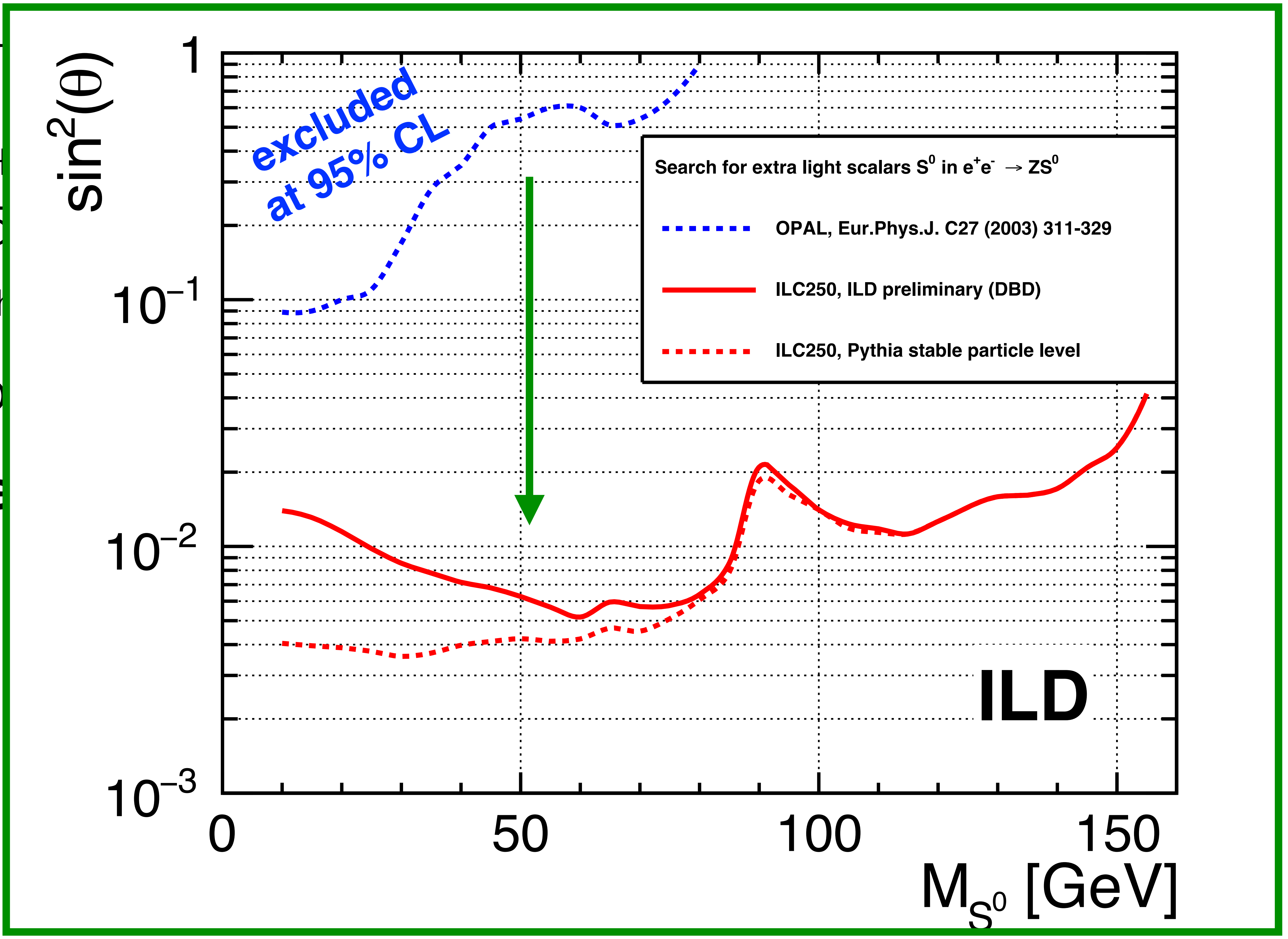

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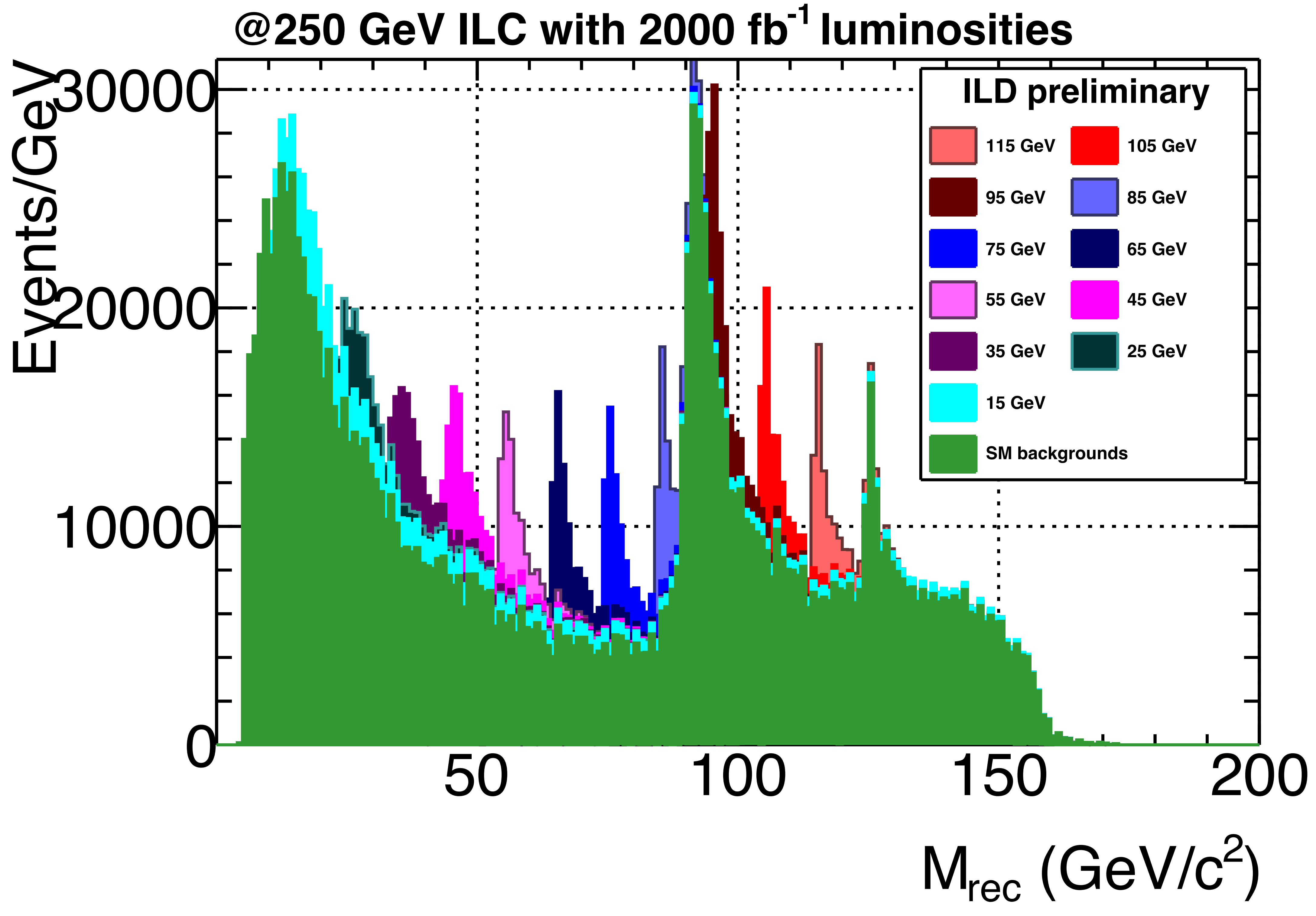

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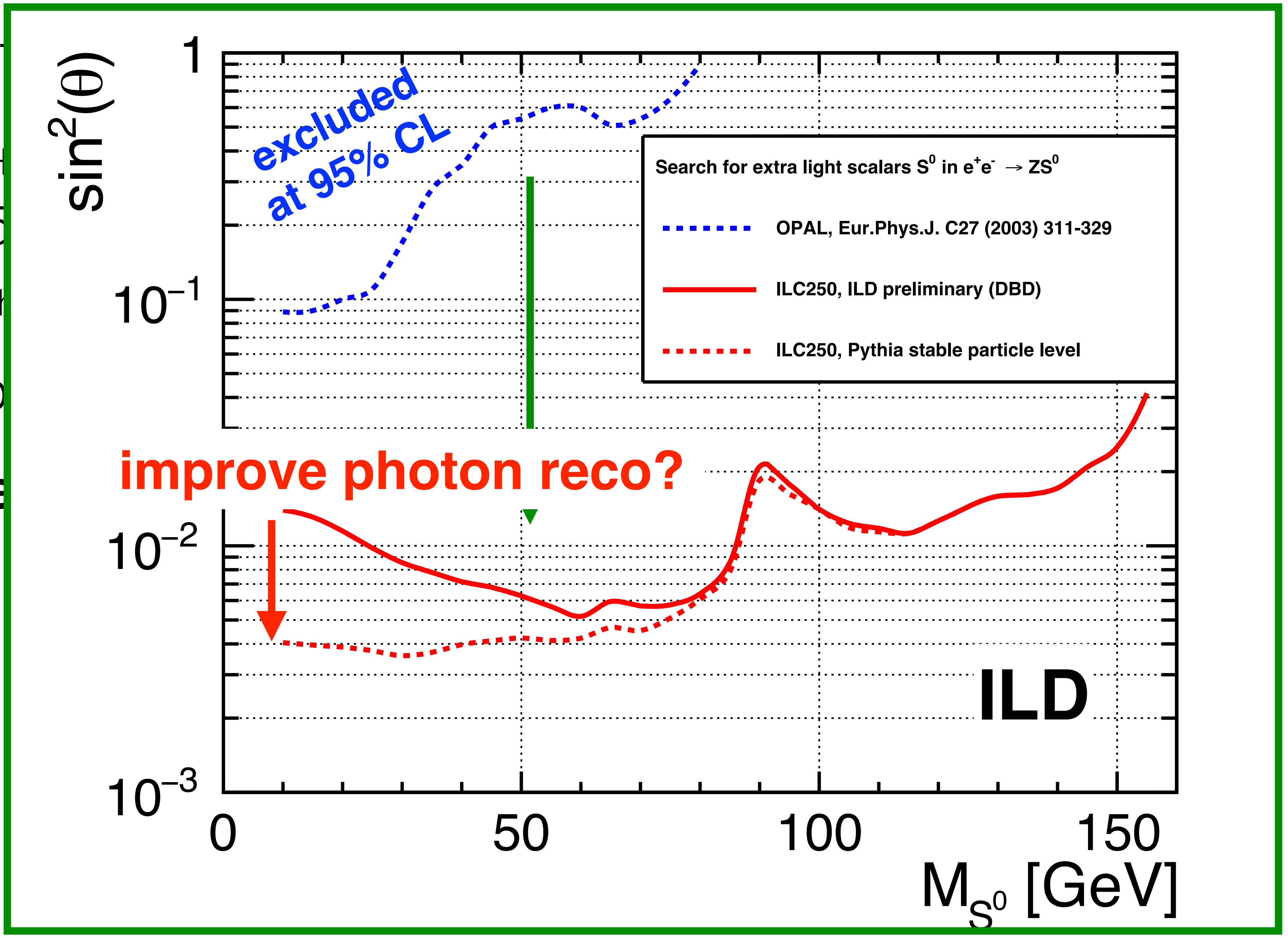

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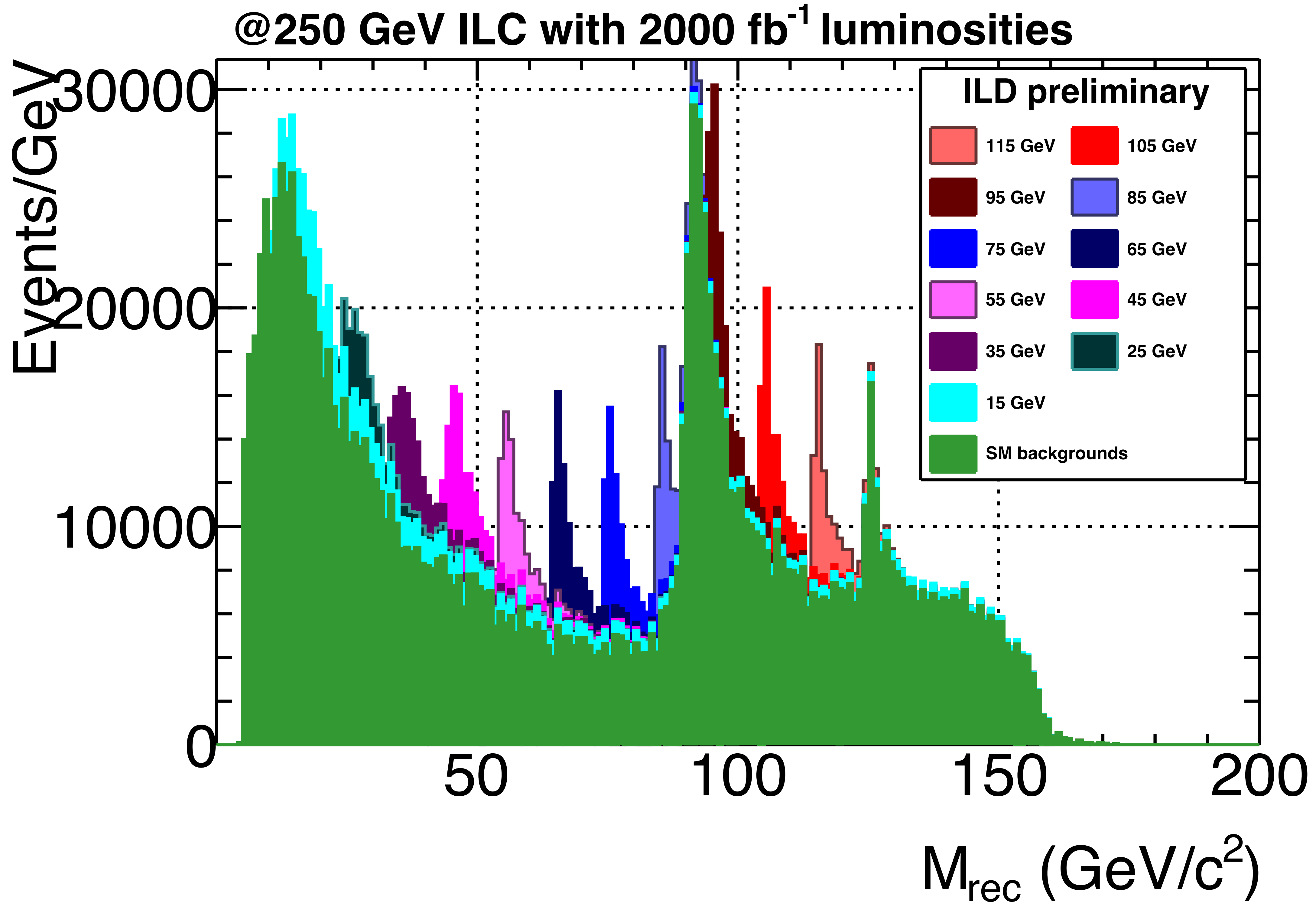

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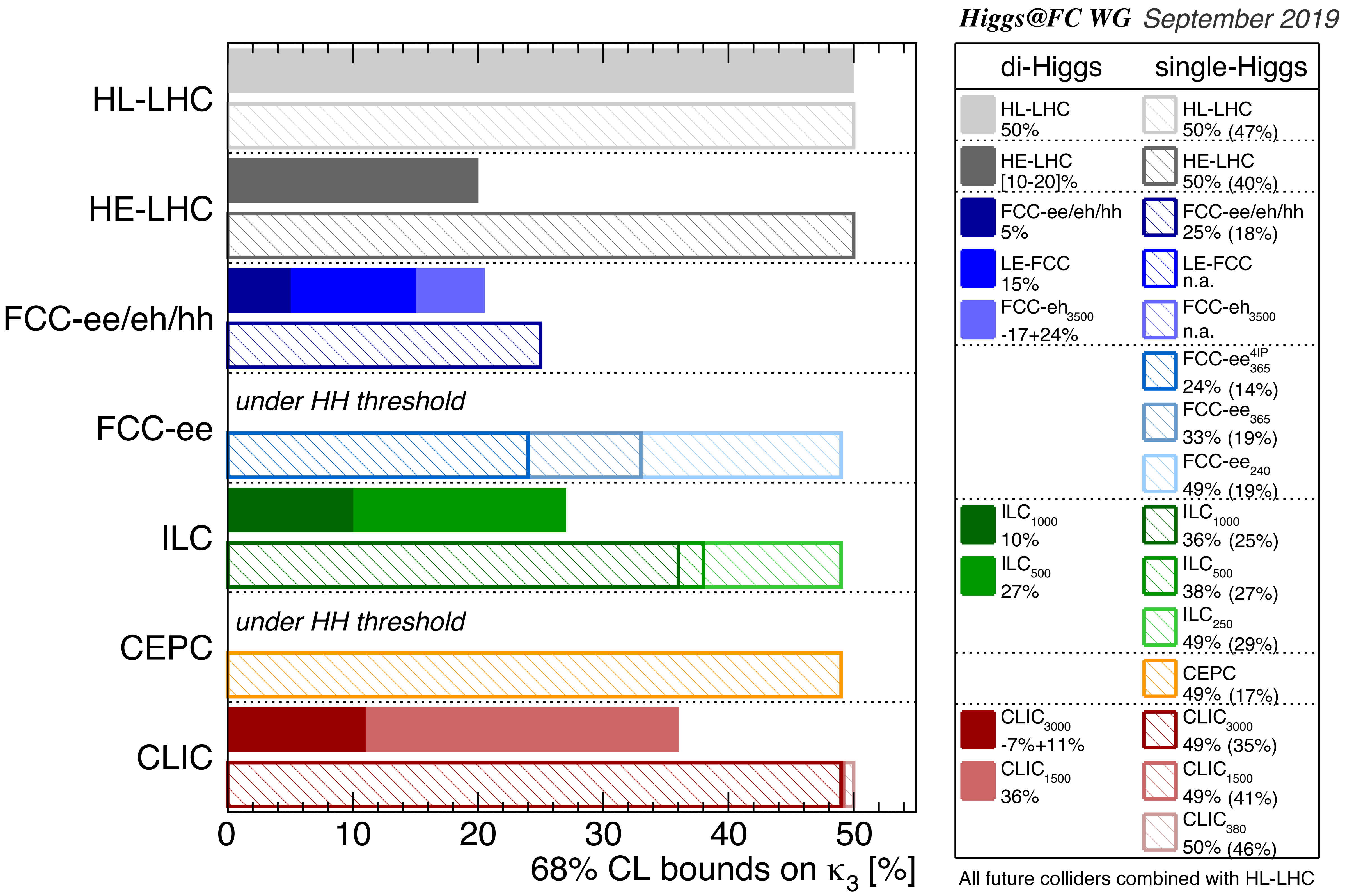
Higgs self-coupling

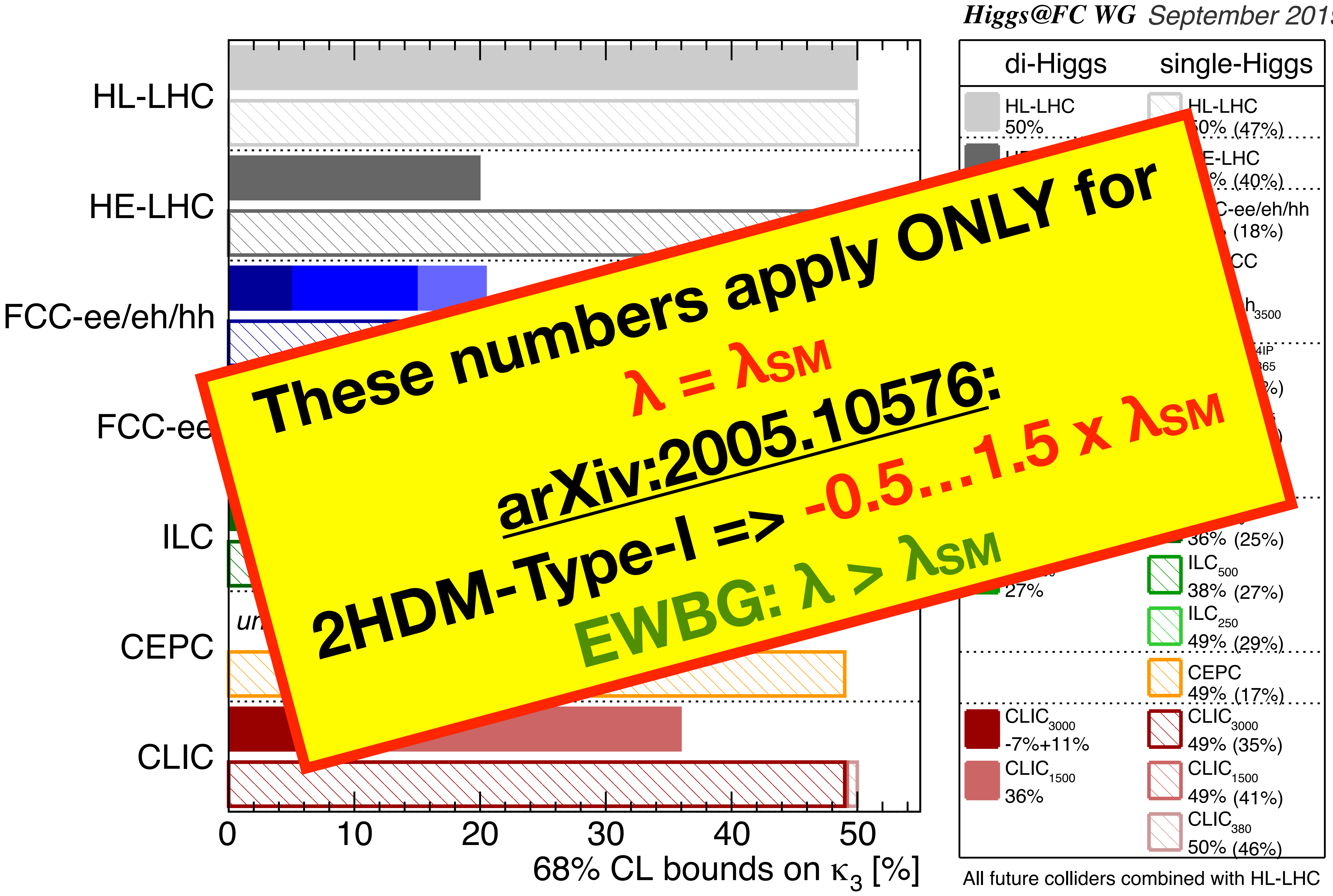
Electroweak Baryogenesis?



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

Higgs self-coupling

Electroweak Baryogenesis?



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

arXiv:2005.10576:

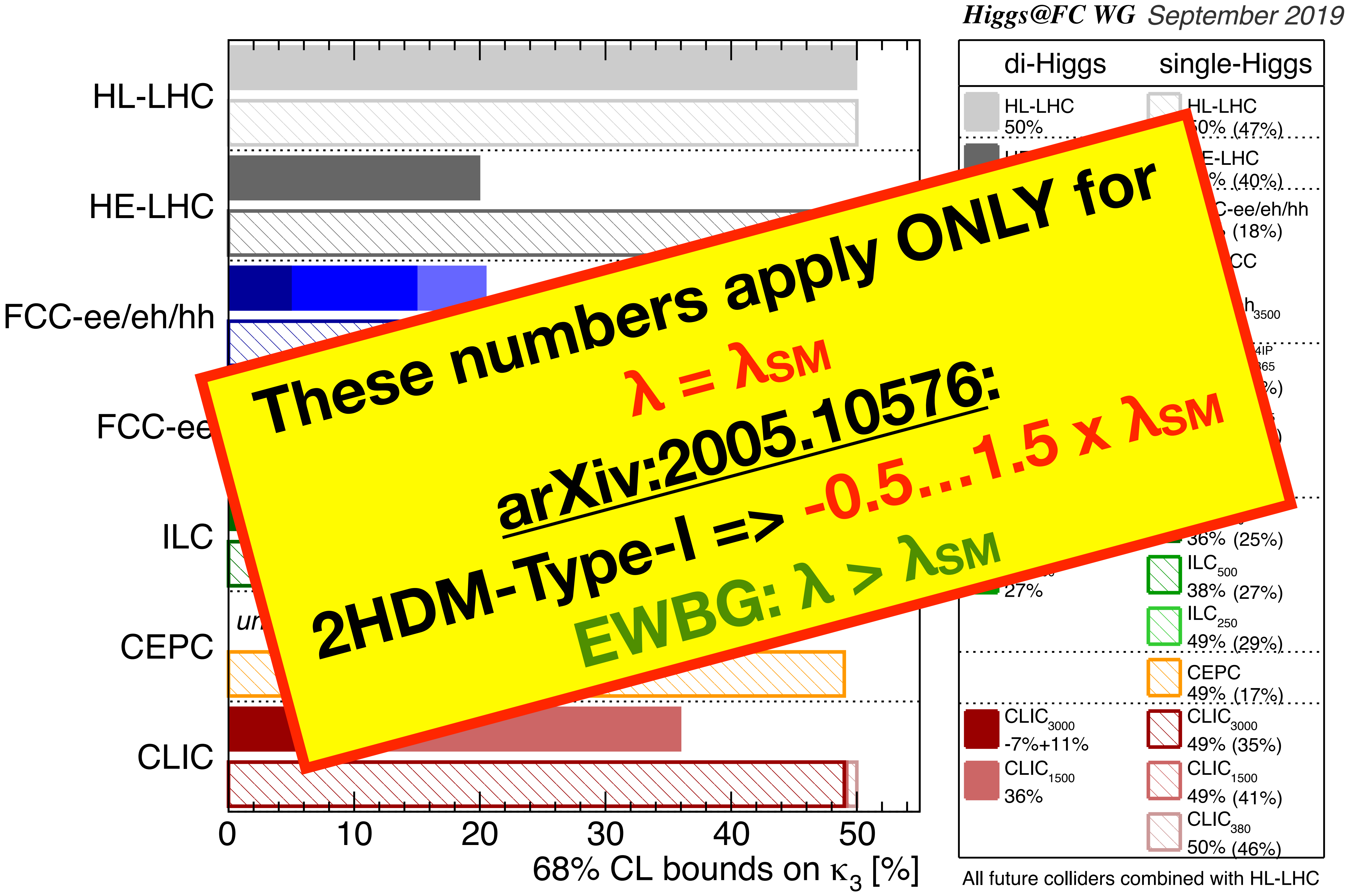
2HDM-Type-I => -0.5…1.5 x λ_{SM}

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

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

Higgs self-coupling

Electroweak Baryogenesis?



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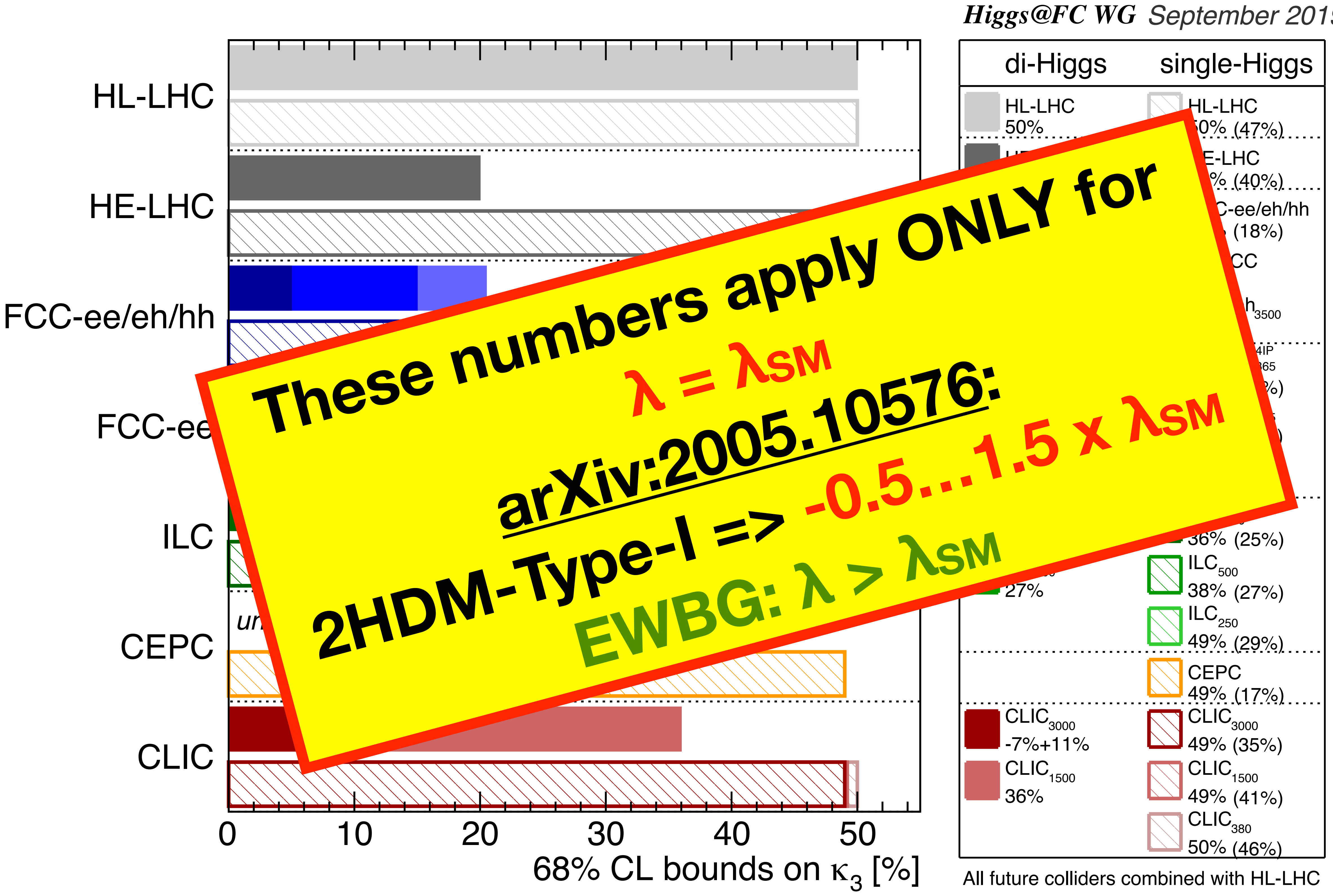

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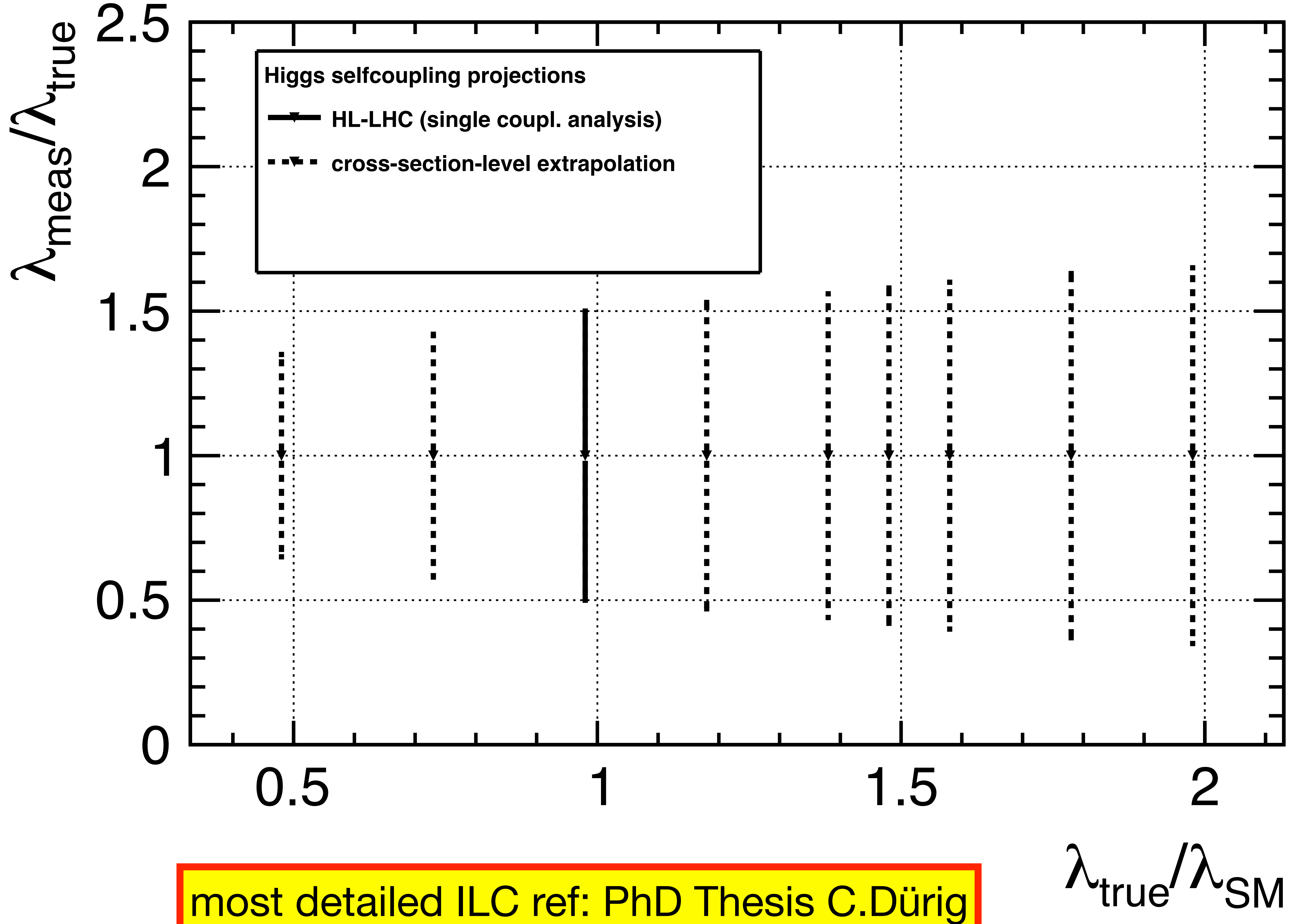

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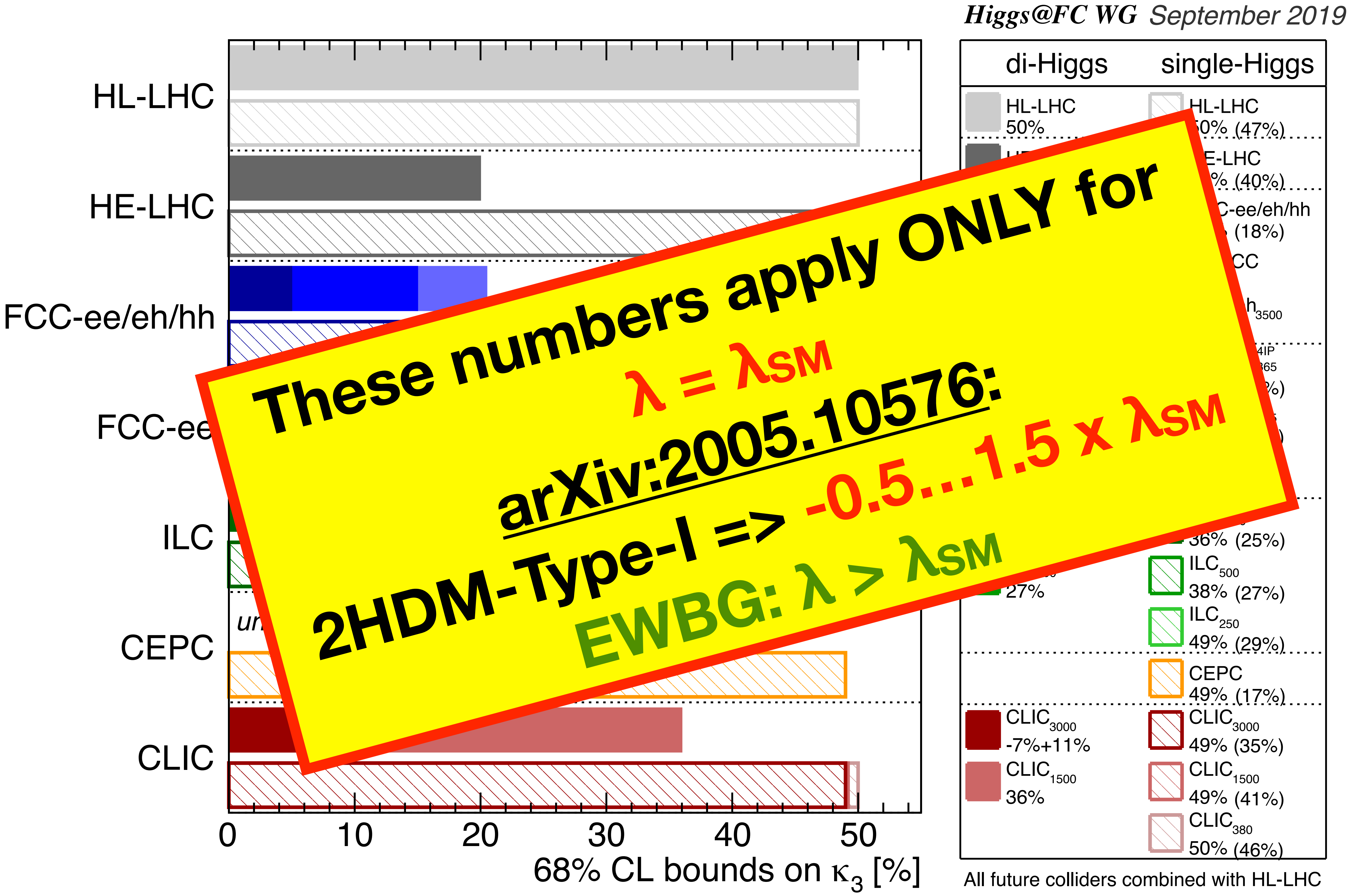
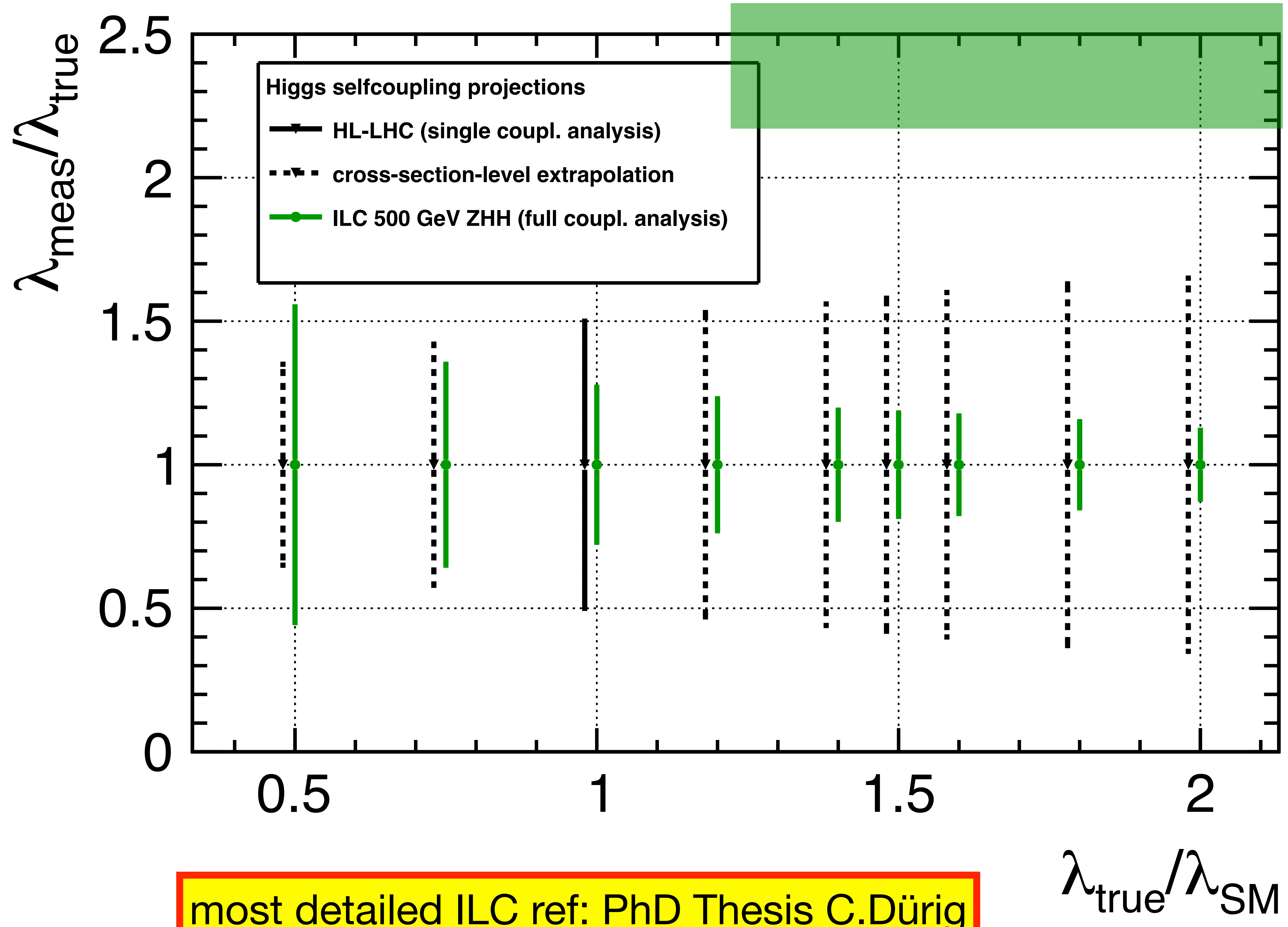


Region of interest for electroweak baryogenesis



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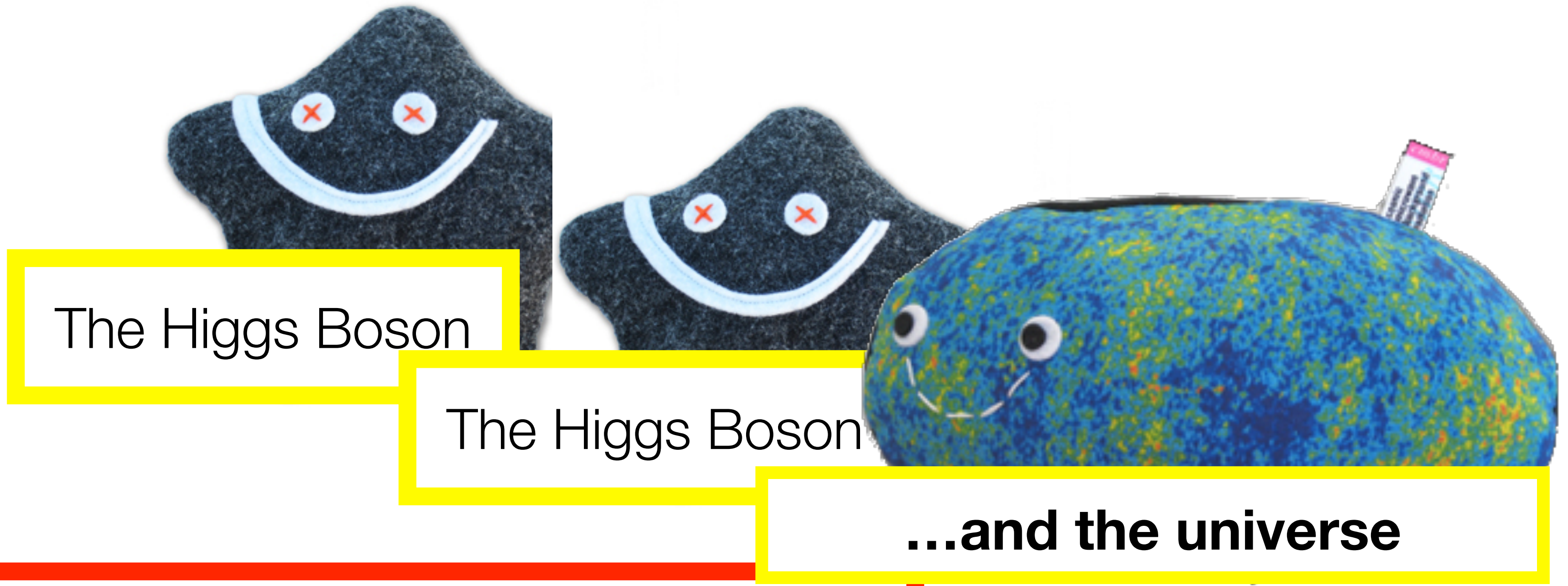

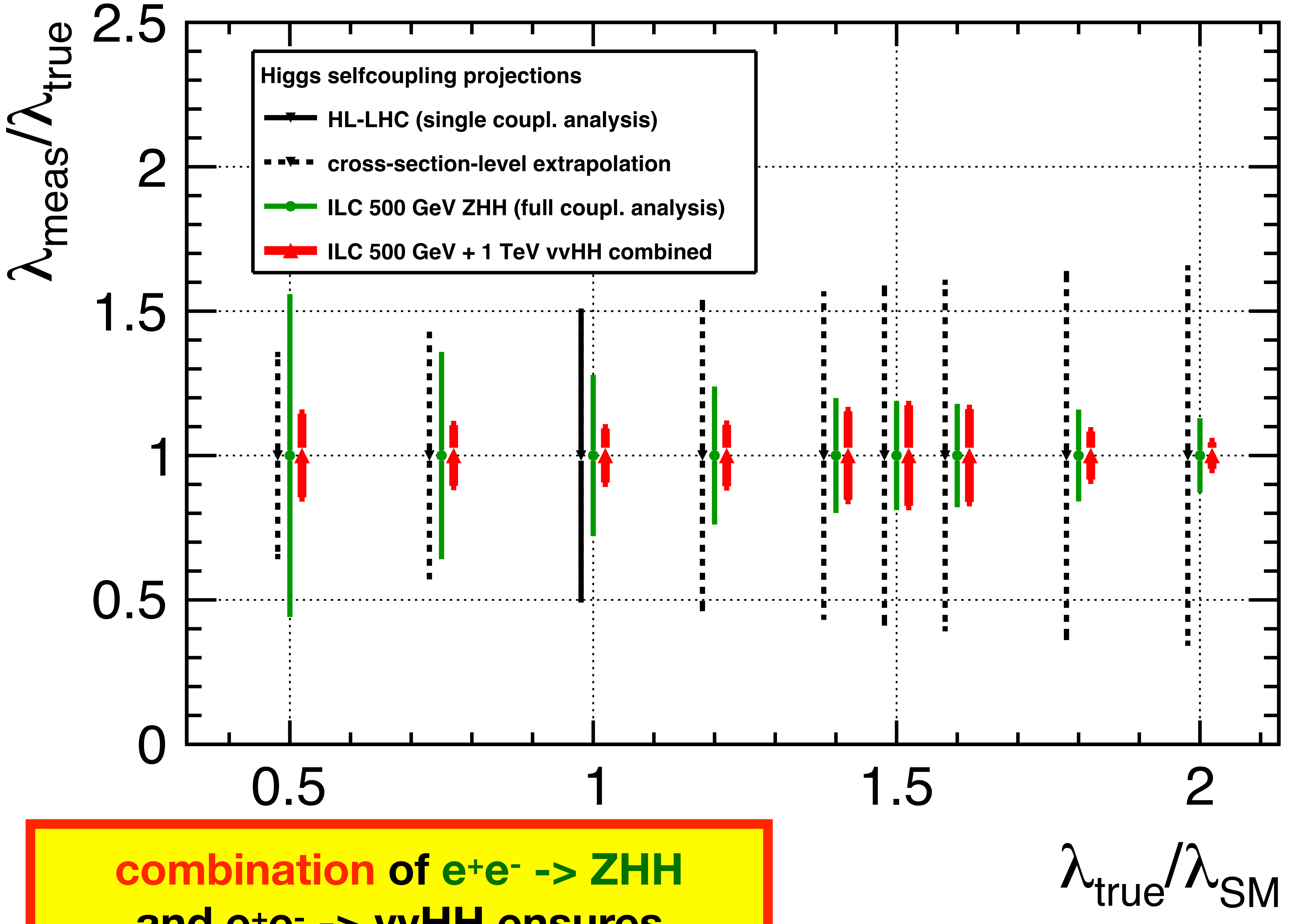

combination of e^+e^- -> ZHH and e^+e^- -> ννHH ensures at least 10-15% precision for all λ

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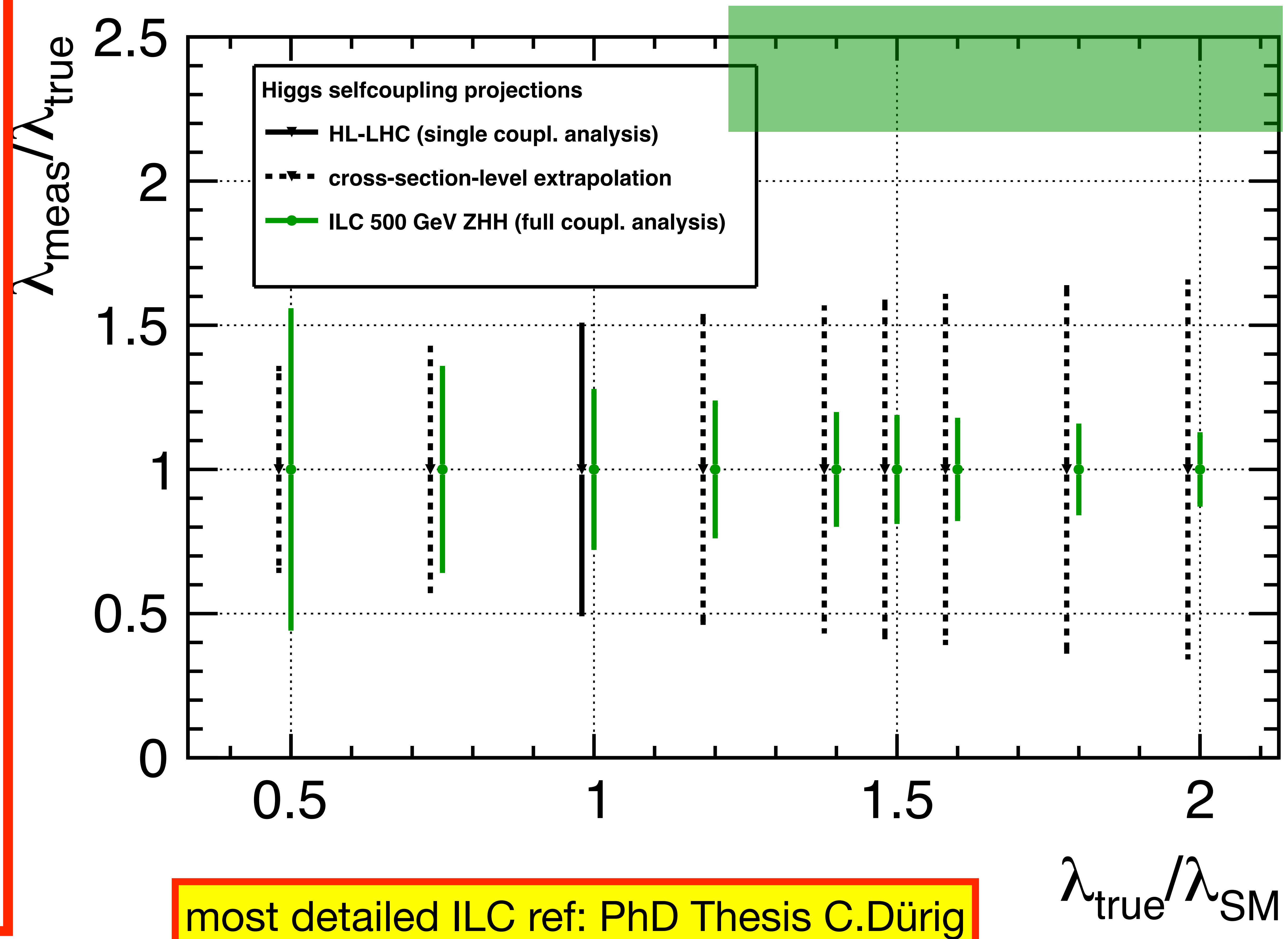

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And finally a word on Leptogenesis

Comprehensive exploration by neutrino physics…

- … but there are cases where colliders can make discoveries and give decisive input
- e.g. Leptogenesis and Gravitino Dark Matter [Buchmüller (2018)]:
    - gravitino is LSP, "NLSP" is a low-ΔM-triplet of Higgsinos
    - leptogenesis implies upper bound on SUSY masses since thermal production of light gravitinos ~ m^2
- full detector simulation for two leptogenesis-motivated benchmark points ☆★ 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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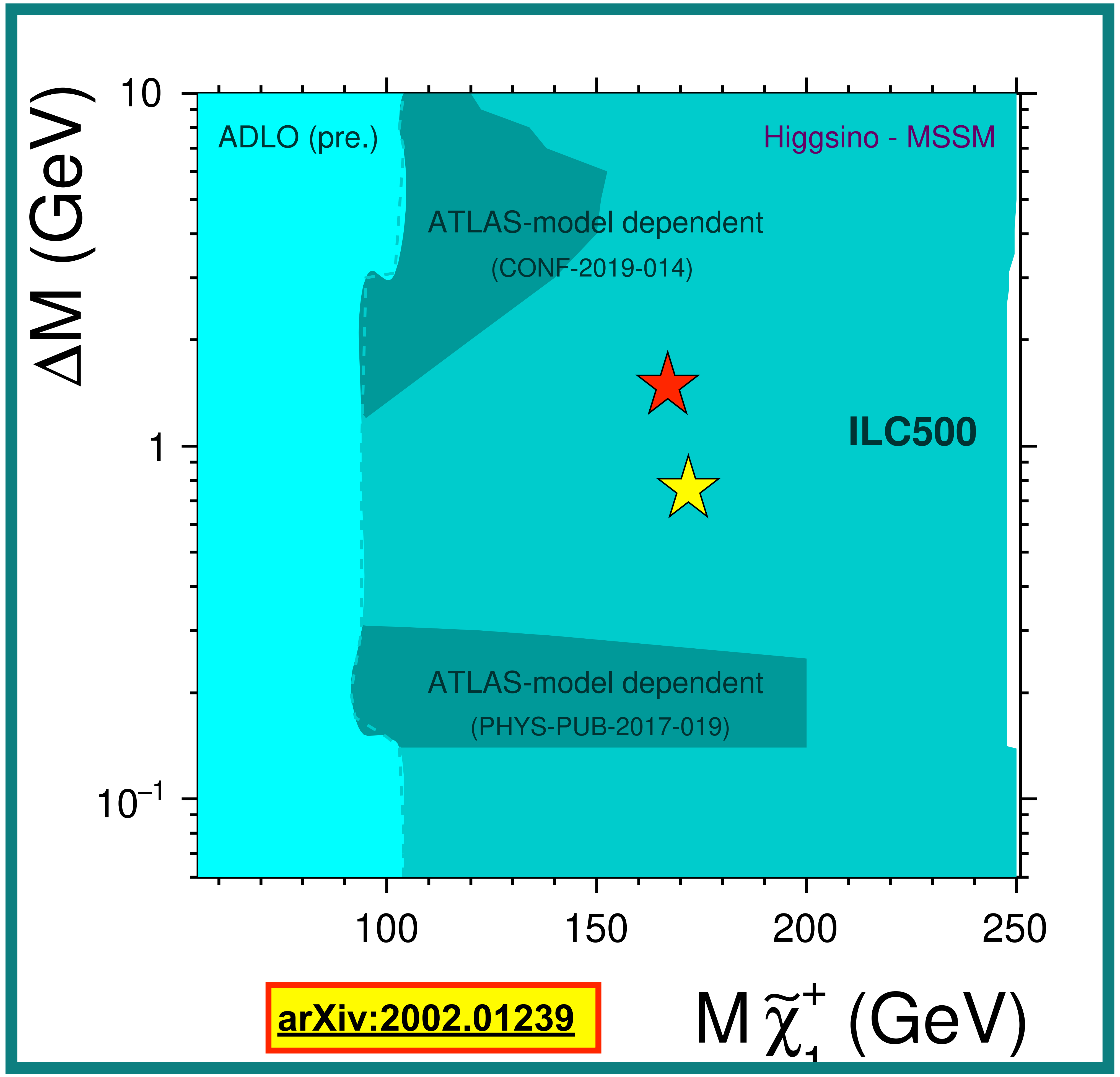

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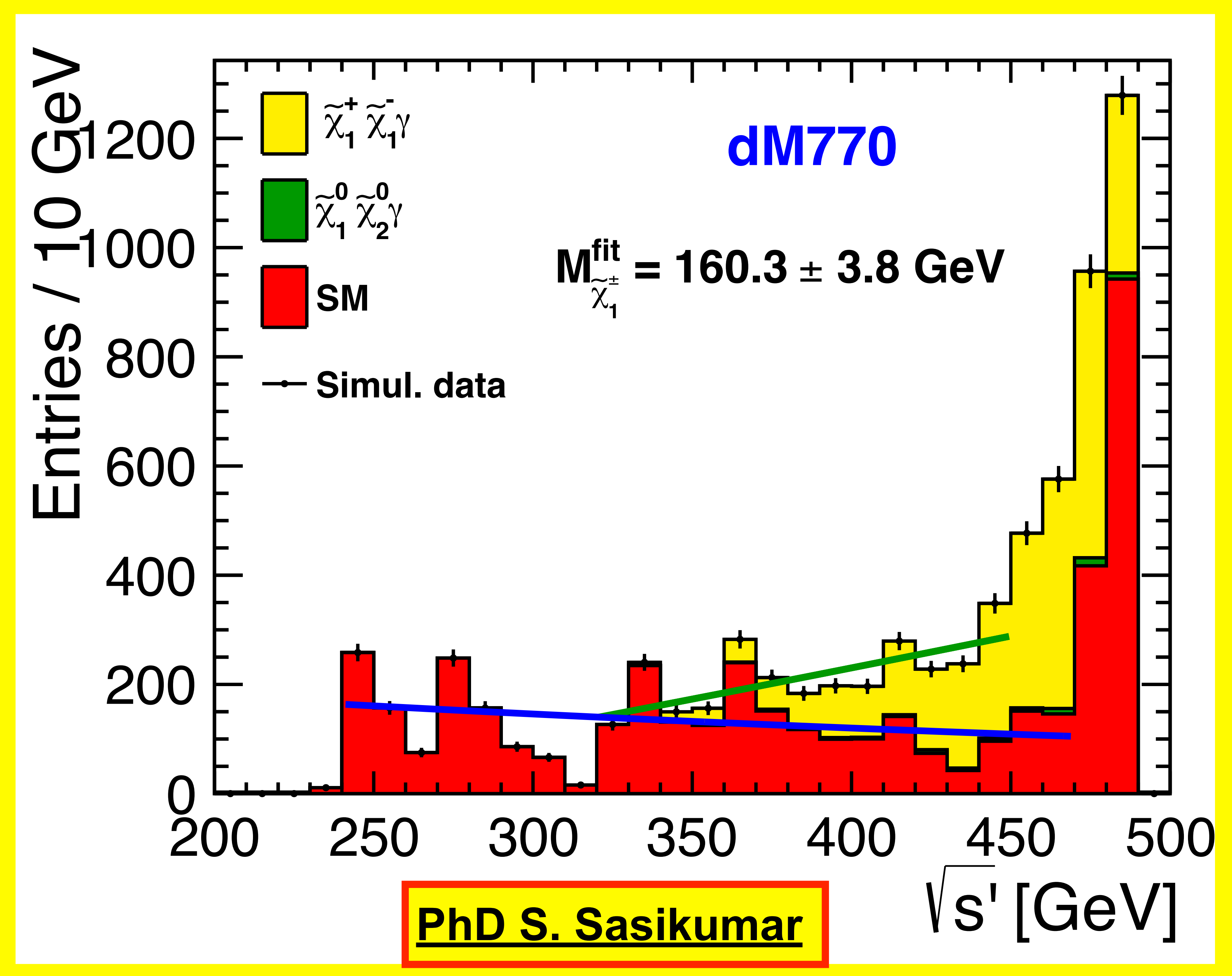

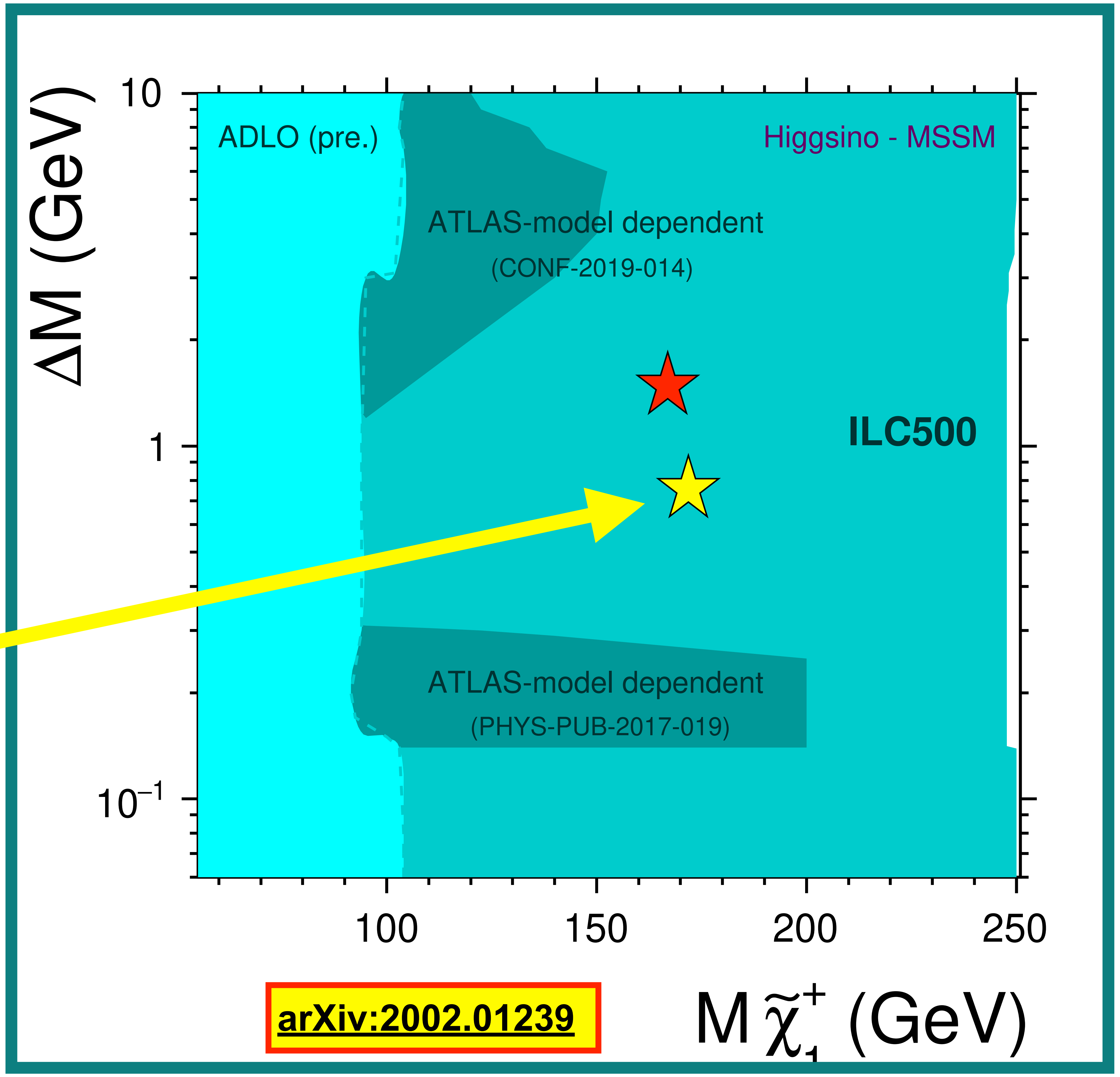

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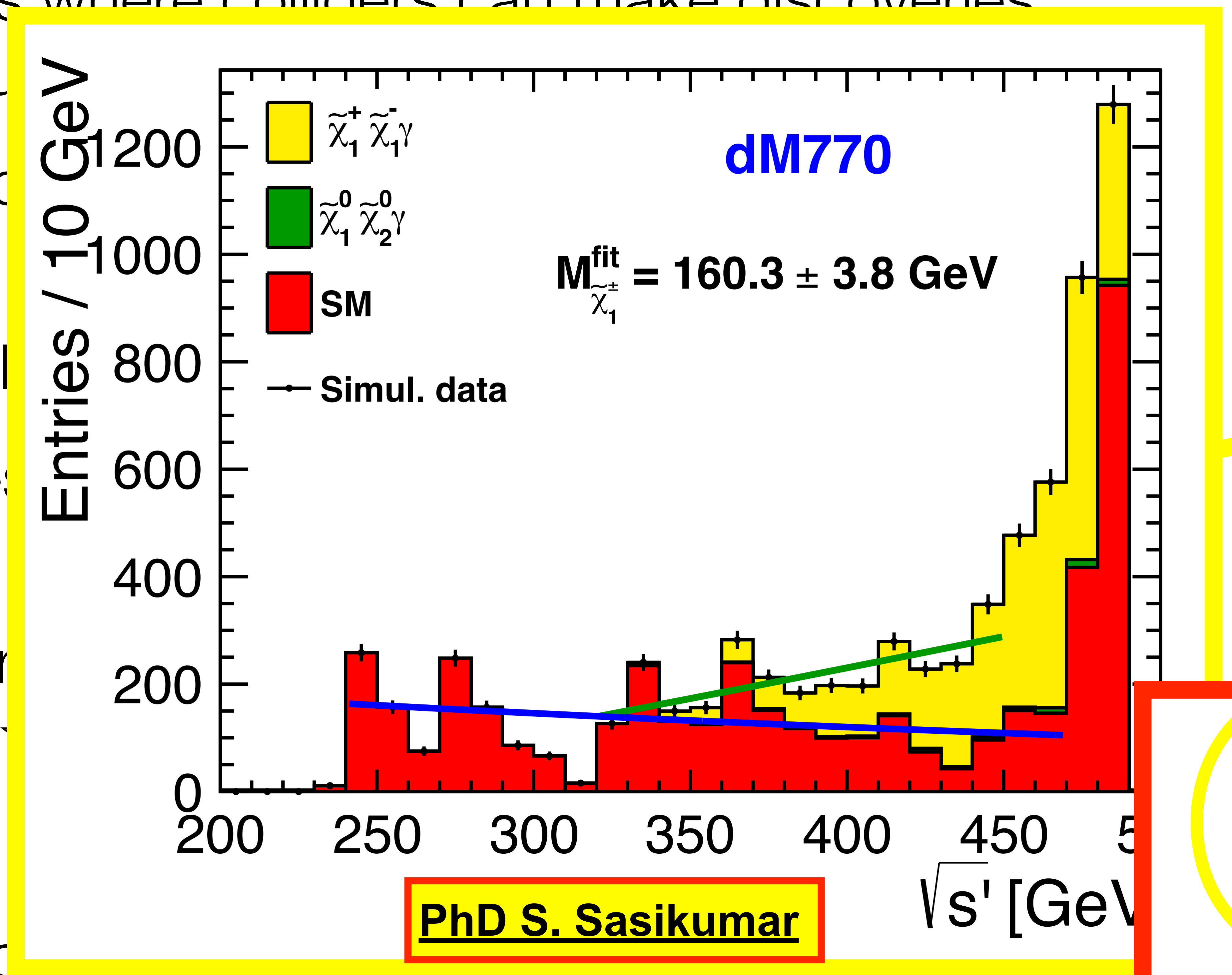

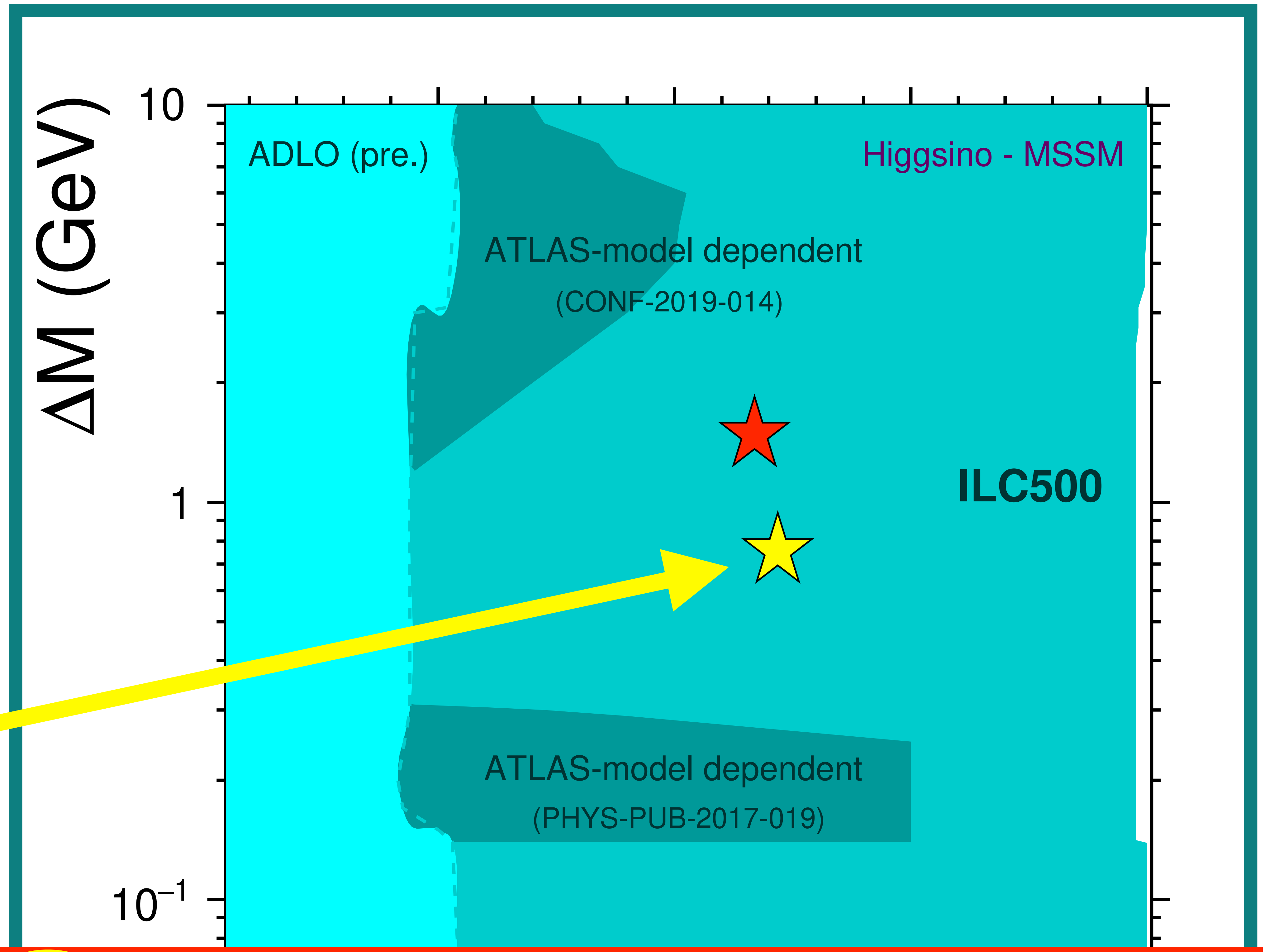

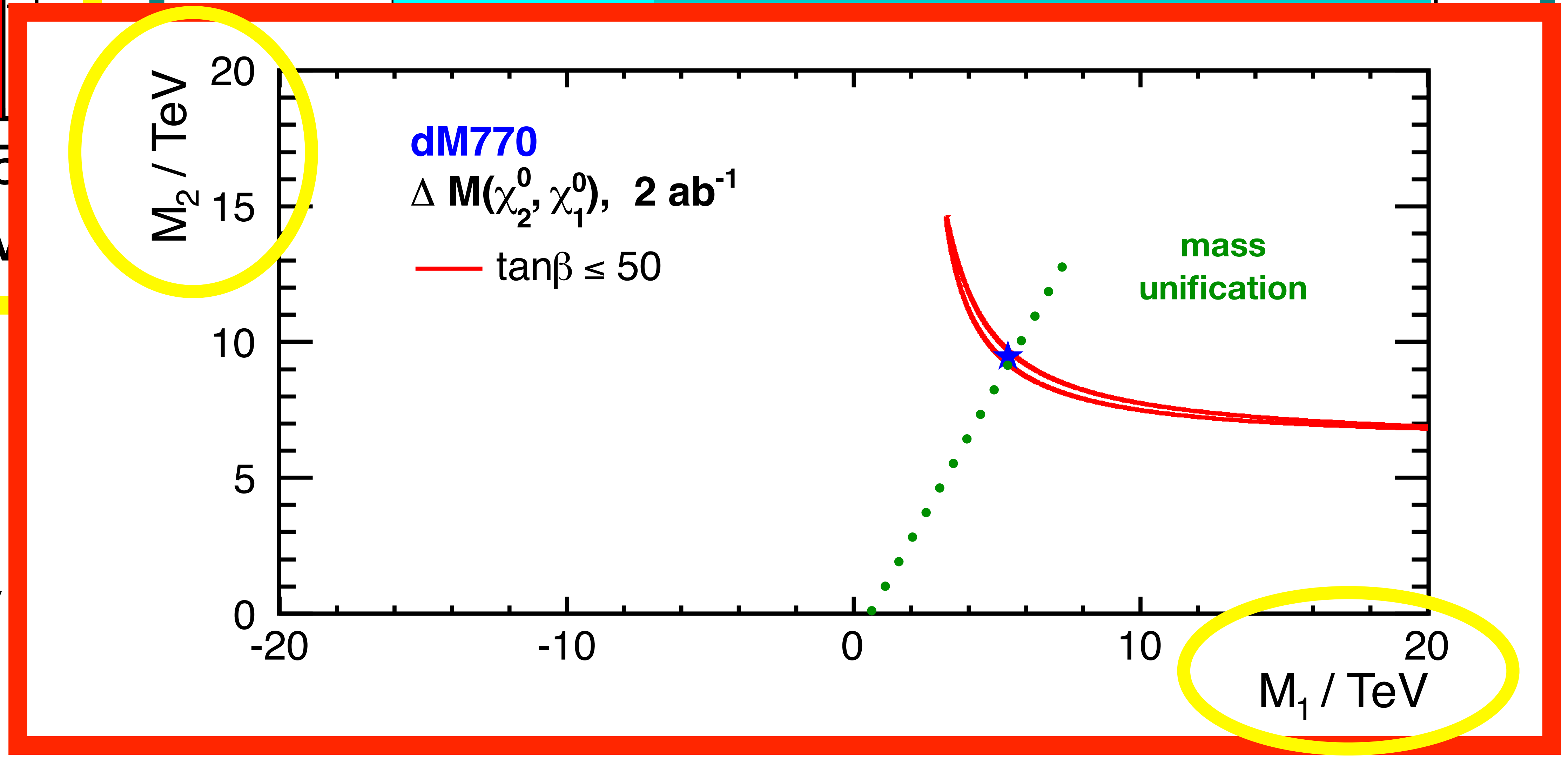

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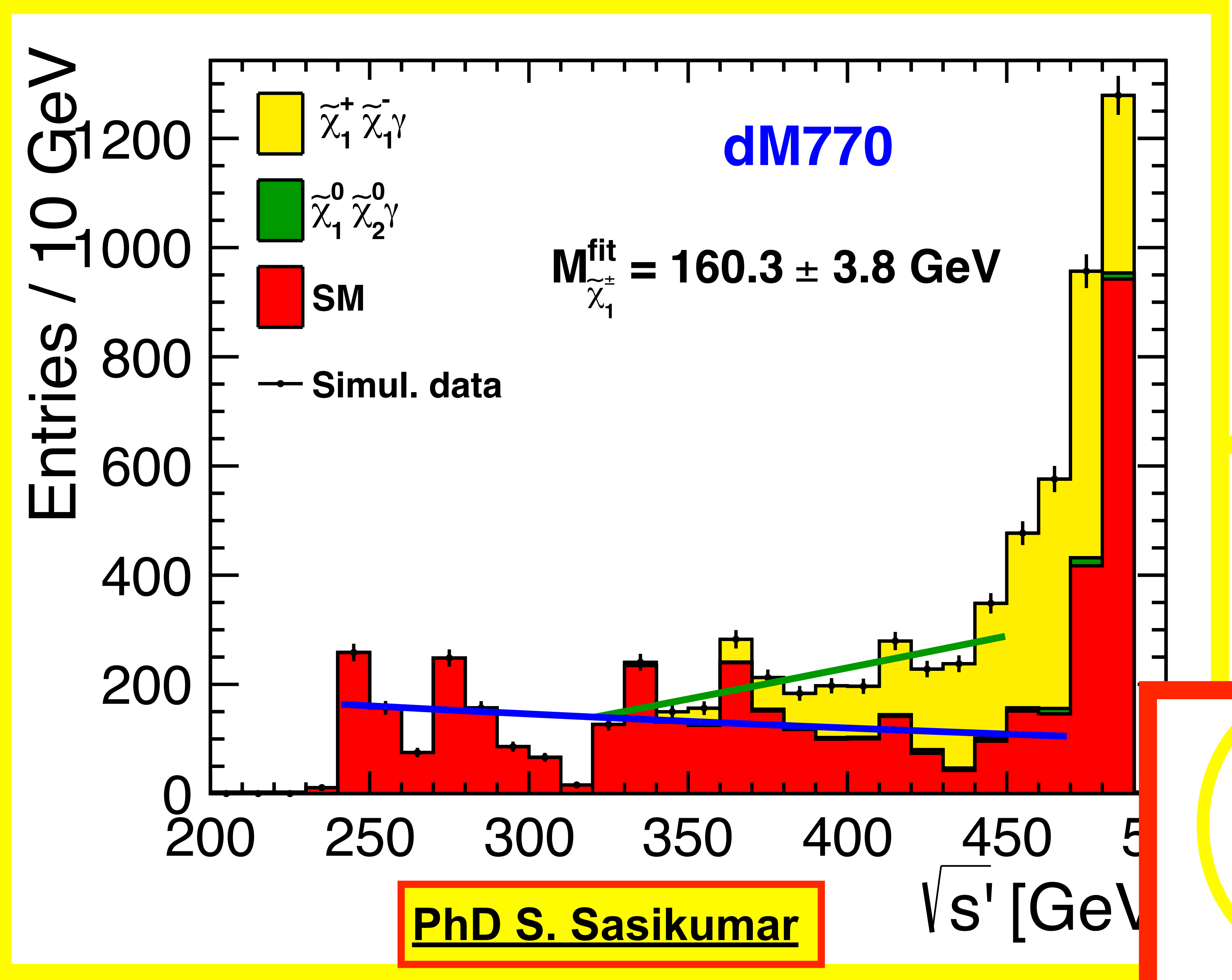

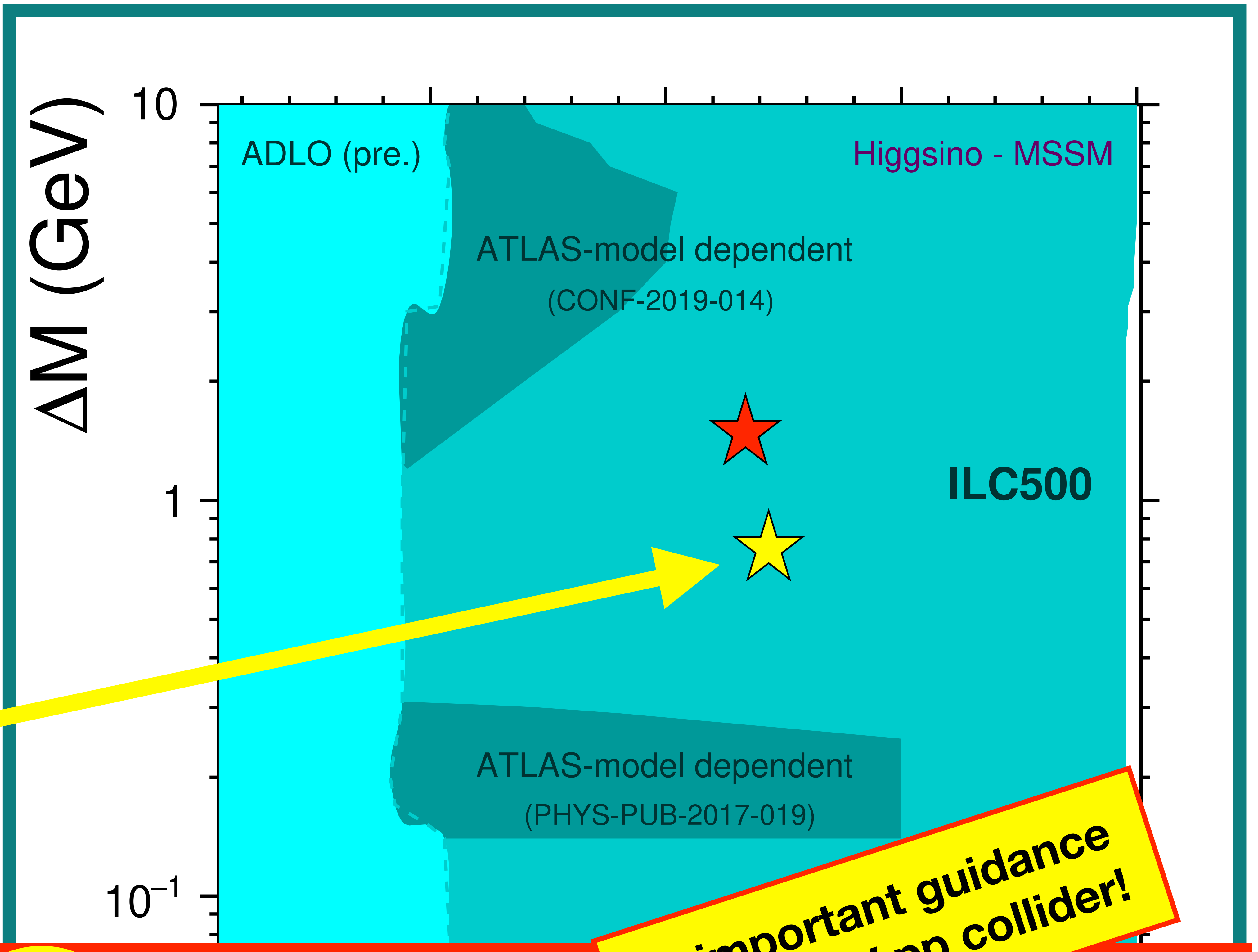

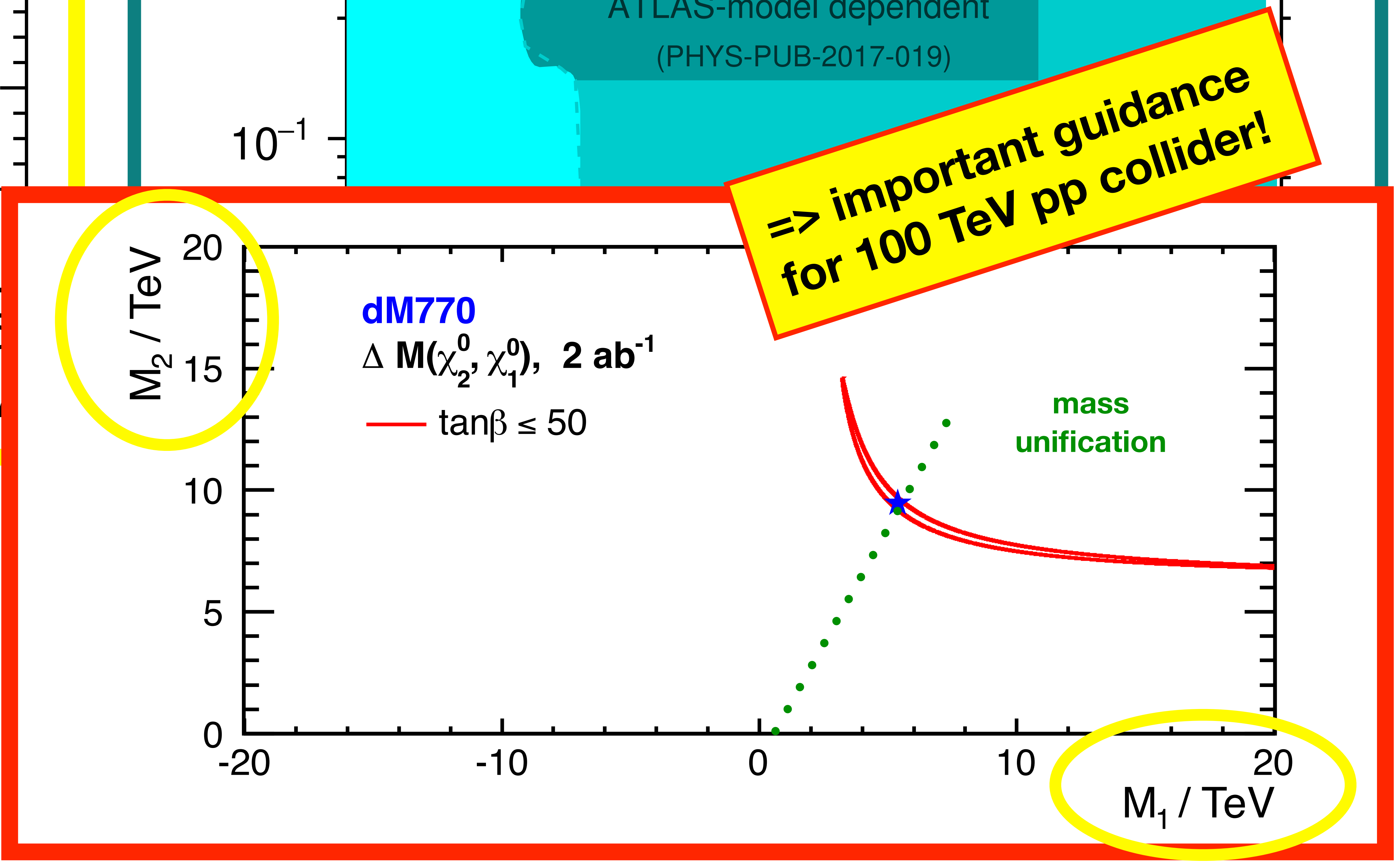

Conclusions

and outlook

- The discovery of the Higgs boson has provided us a new messenger from the early universe => an e+e- Higgs factory is needed in order to let this messenger speak to us!
- Several e+e- projects have been proposed
  - All provide similar performance for exploring single-Higgs production at E_{CM} = ~250 GeV and/or ~350 GeV
  - Only linear colliders like ILC are upgradable to higher energies ≥ 500 GeV for complete exploration of the Higgs (self-coupling!), the top quark and their possible - visible or “dark” - siblings
- The ILC is just NOW starting into a new phase, the ILC Technology Network, in which laboratories around the world will team up to advance the R&D, and work towards an engineering design - and a scientific and political consensus
- Interested to explore yourself what one can learn about the universe - at a future e+e- collider in general - or specifically at ILC ? => Get in touch jenny.list@desy.de