Physics at an e+e- Higgs Factory
- and its interplay with accelerator & detectors

J. List (DESY/CERN)

Workshop on Future Accelerators
Corfu, April 24, 2023

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

Focus on Higgs

- accelerator R&D, in particular high-field magnets
- investigate technical & financial feasibility of 100 TeV pp collider at CERN, with posssible e+e- first stage
- timely realisation of ILC in Japan would be compatible and European particle physics would wish to collaborate

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

3

High-priority future initiatives

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

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***
- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

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

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

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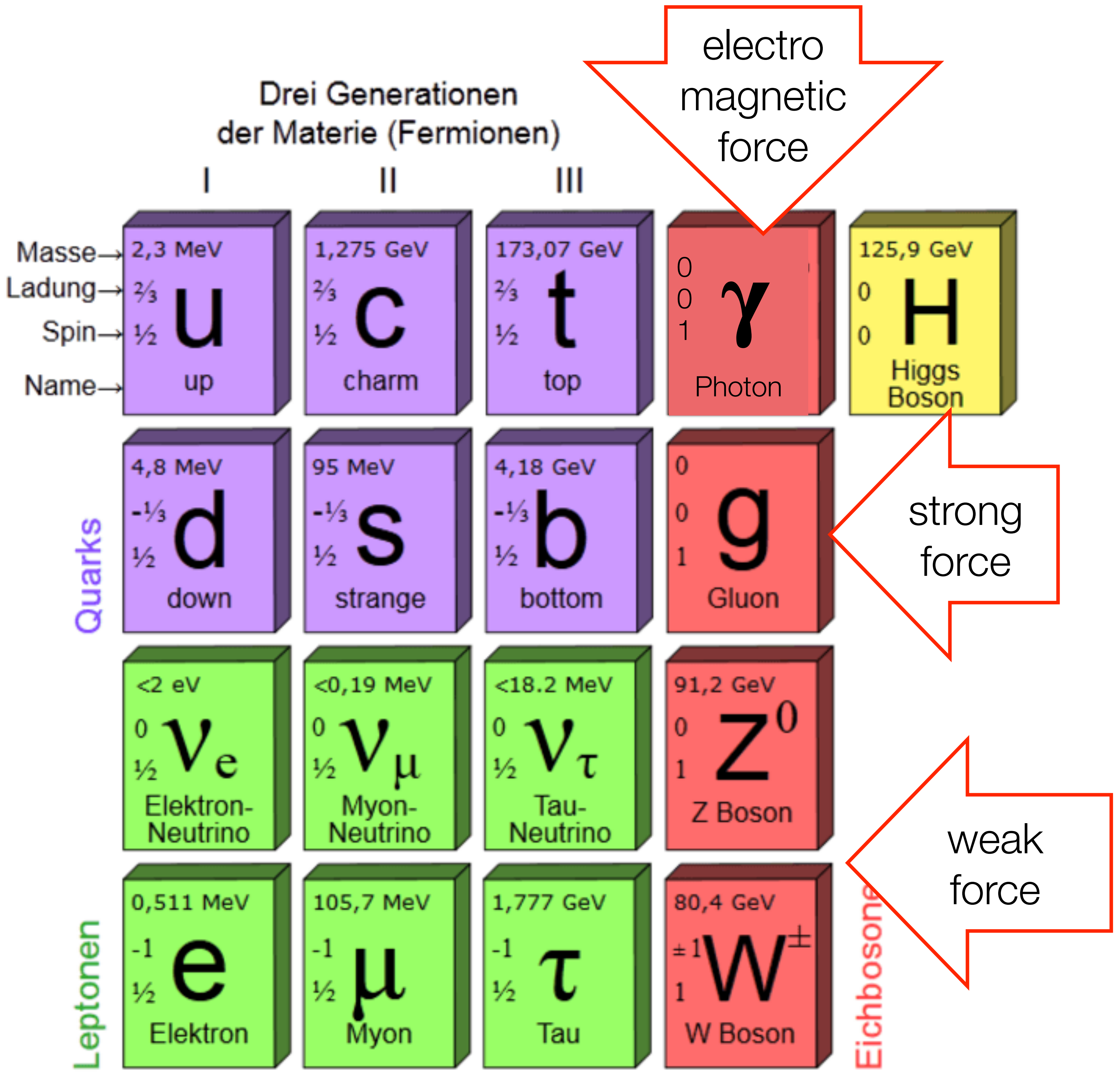
The Higgs Boson and the Standard Model of Particle Physics

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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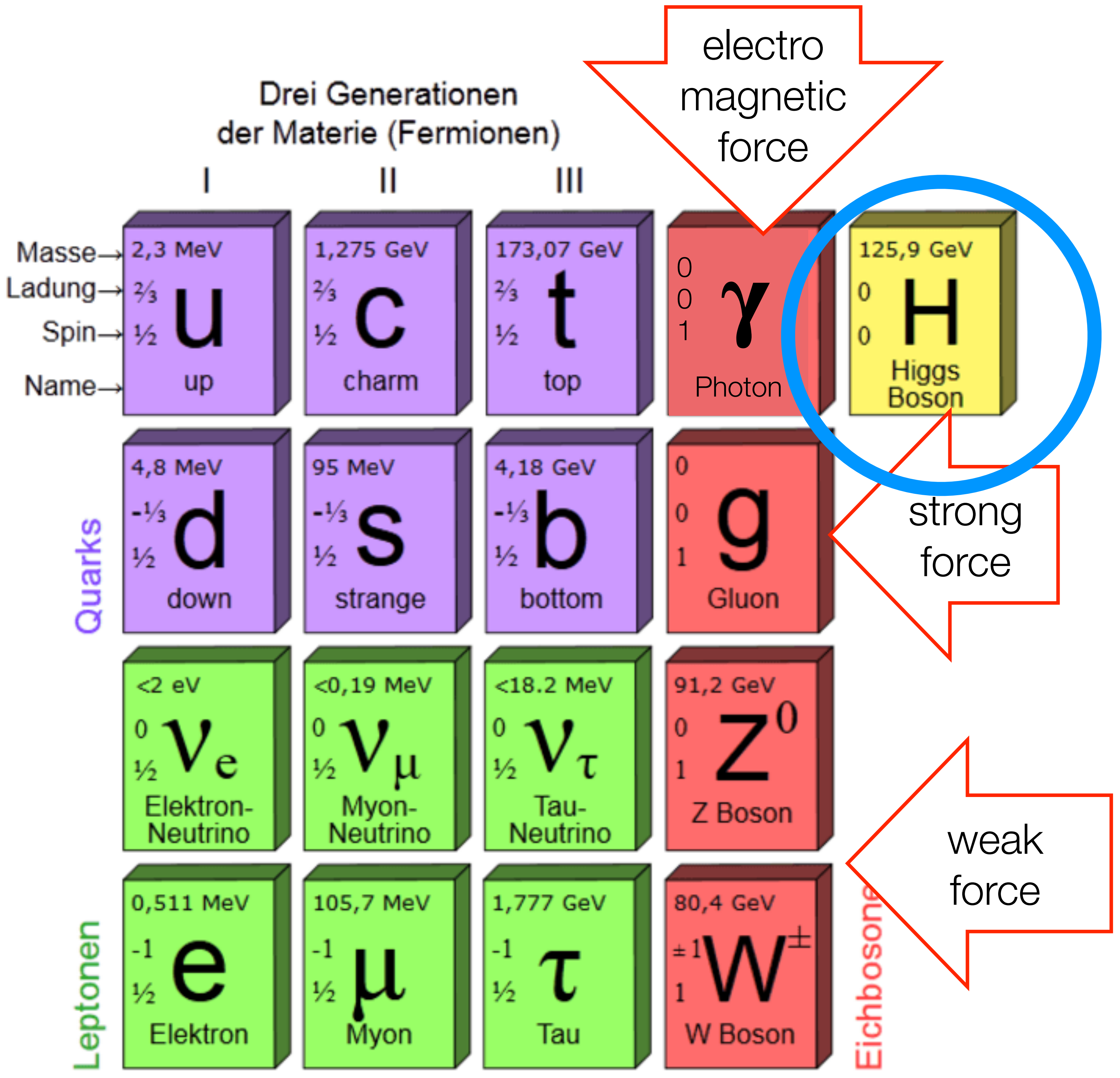

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2012: Discovery of a Higgs bosons at the LHC!

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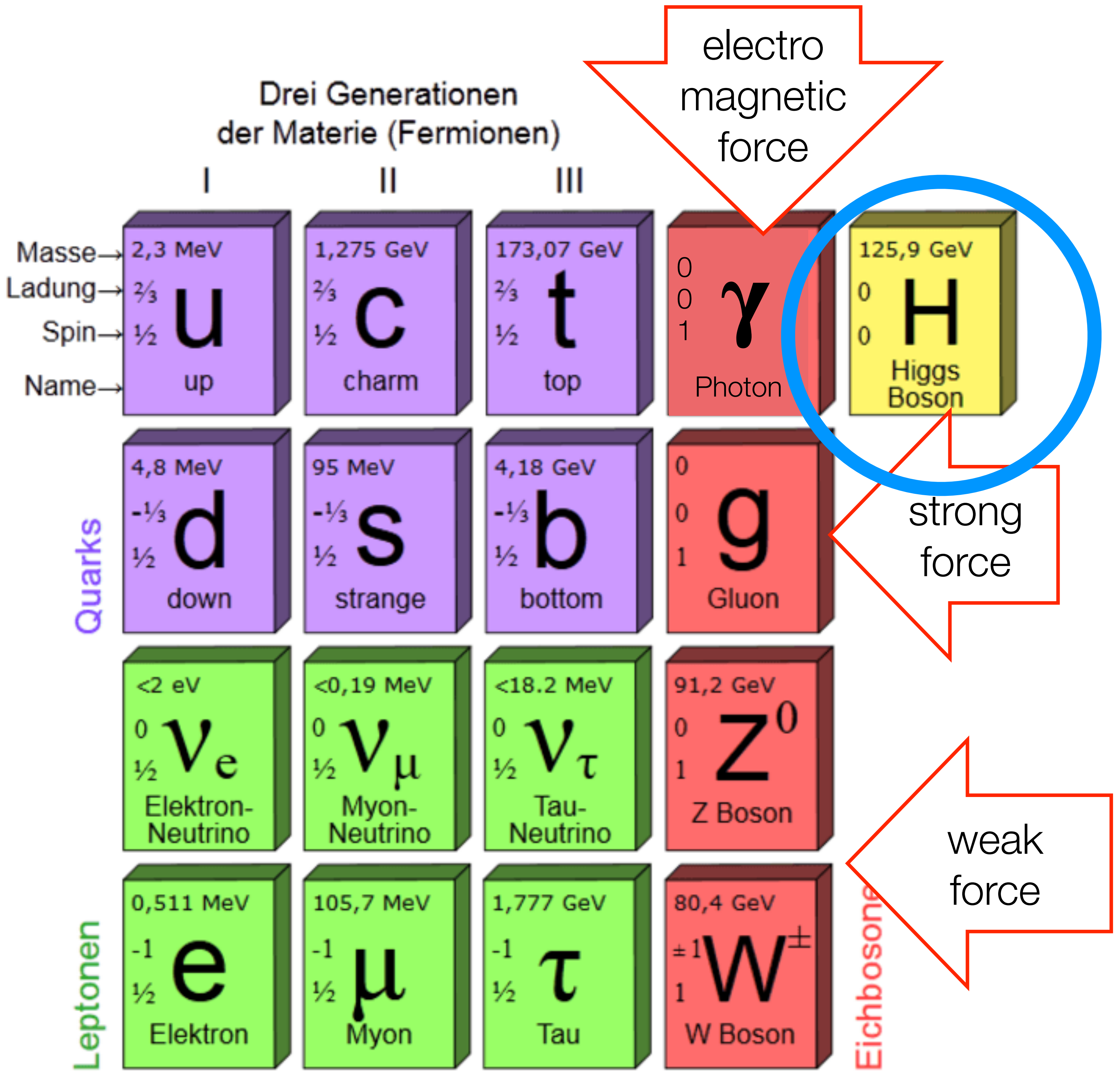

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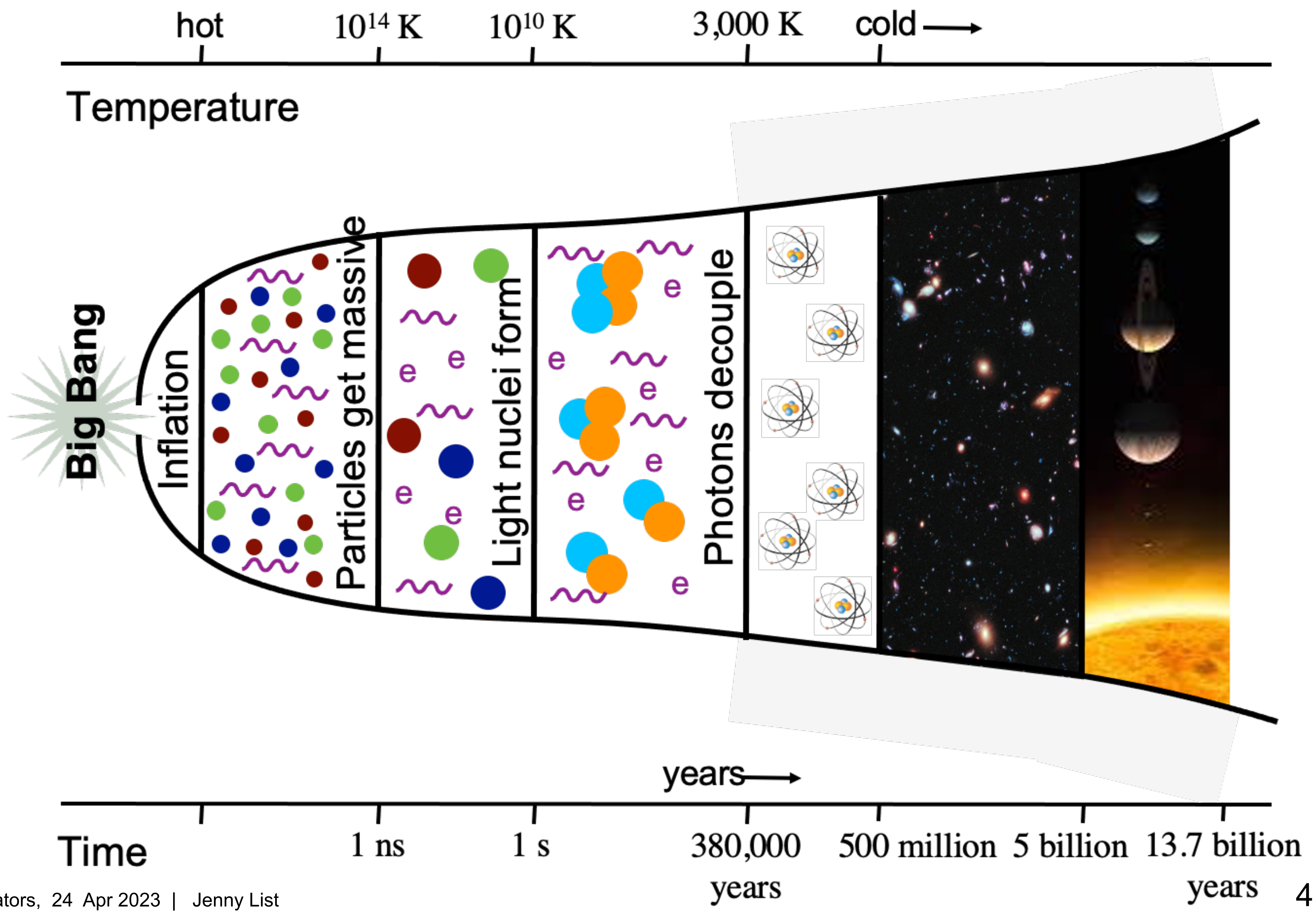
Are we done? — No! — The Higgs Boson is

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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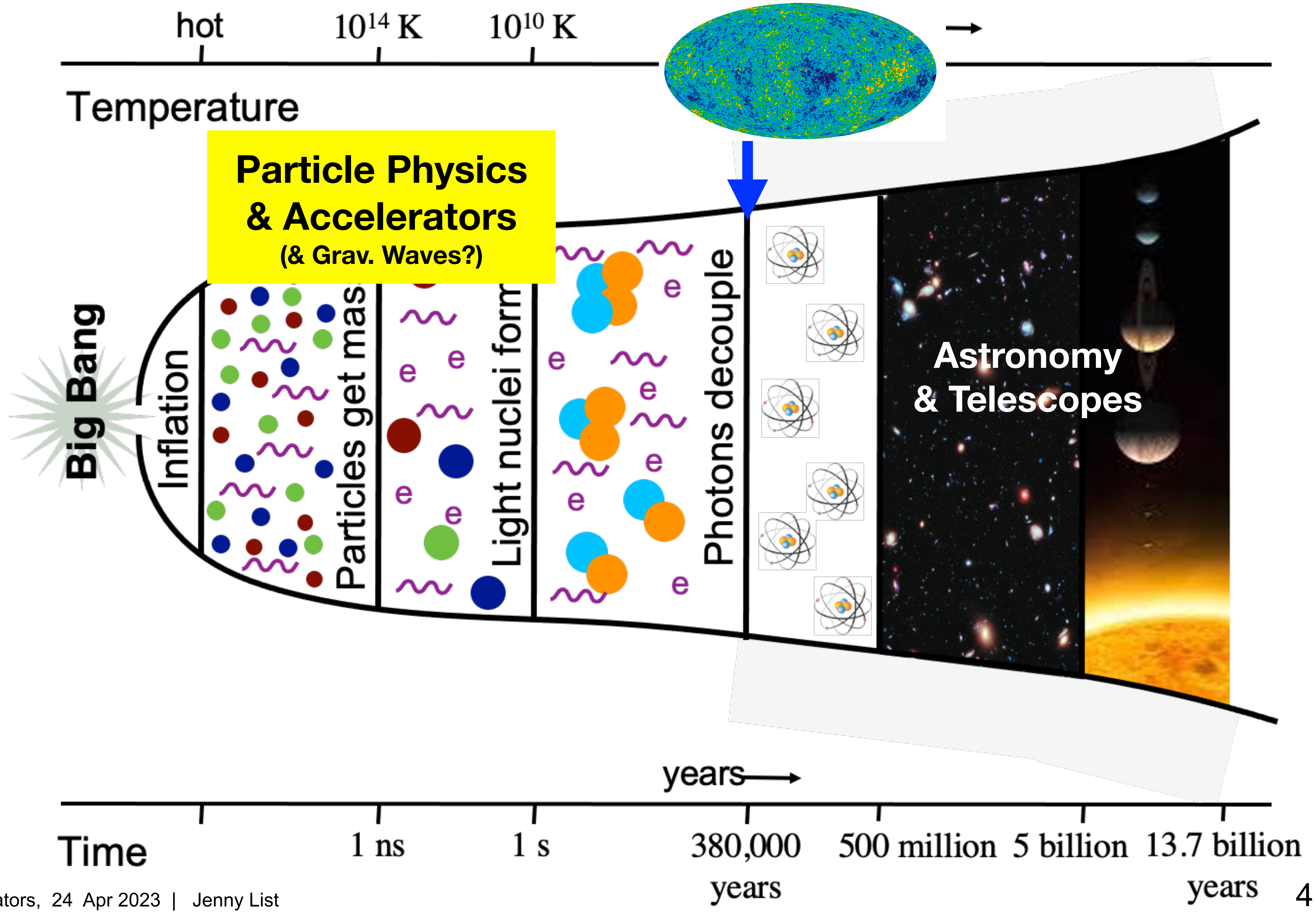

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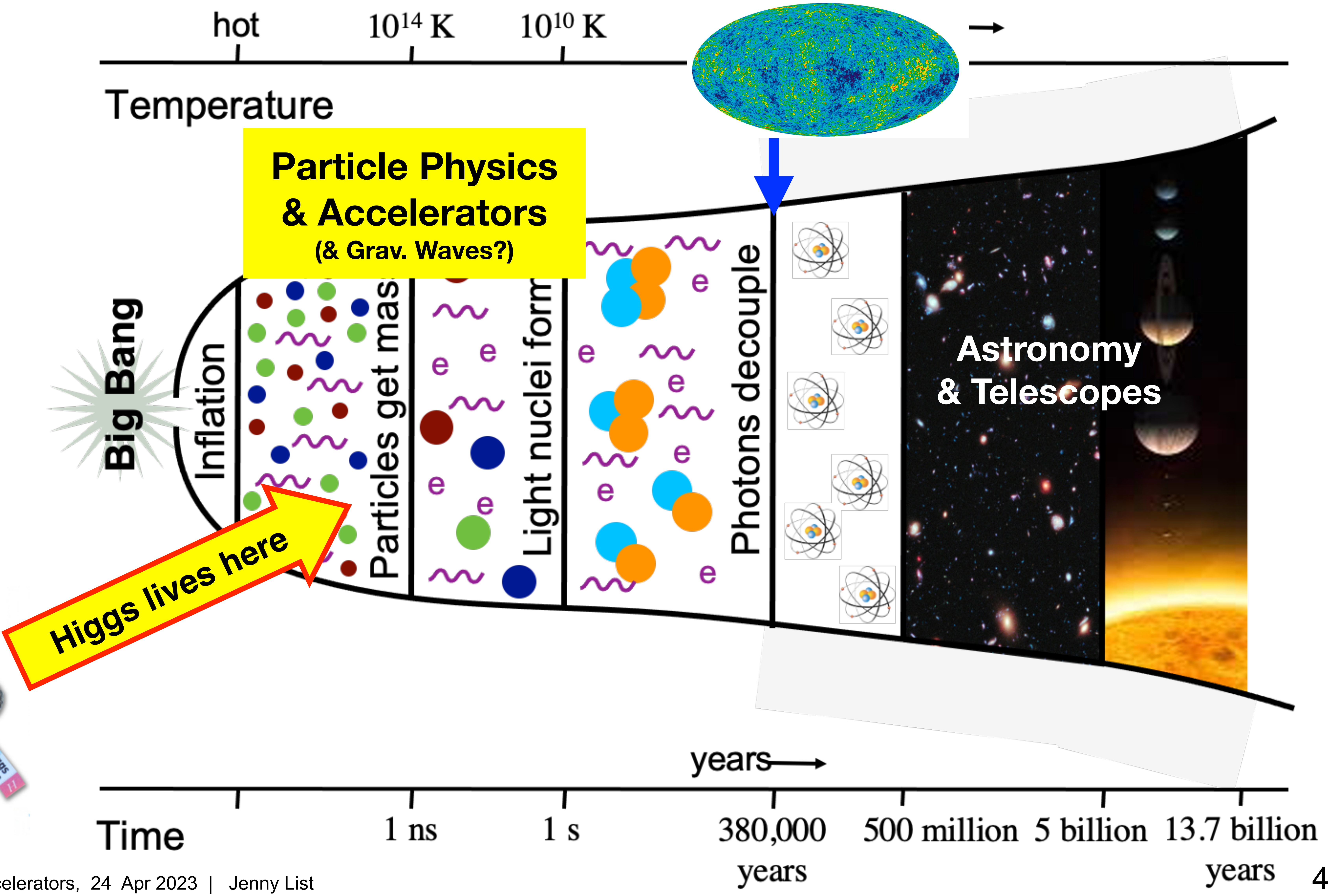

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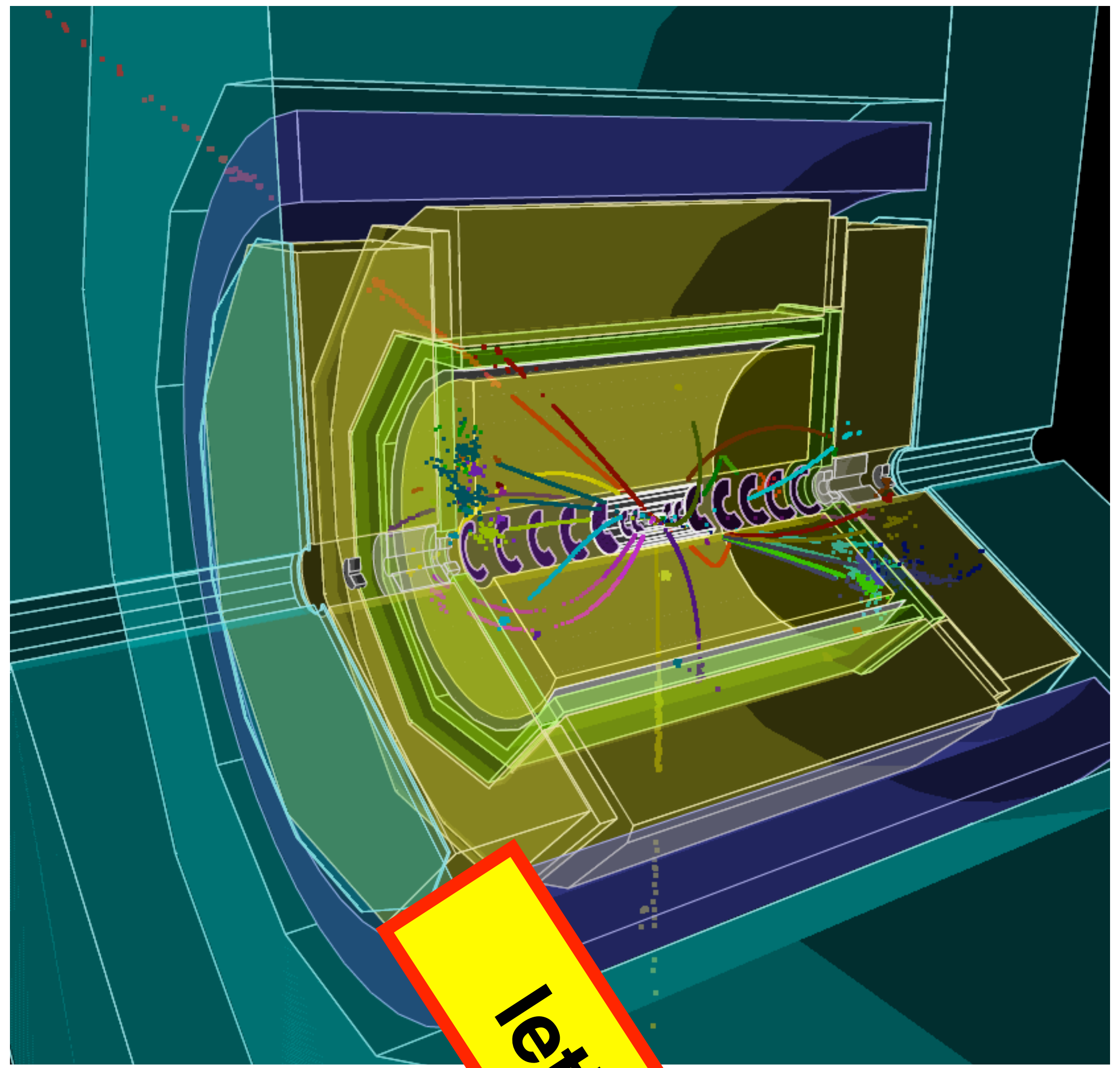
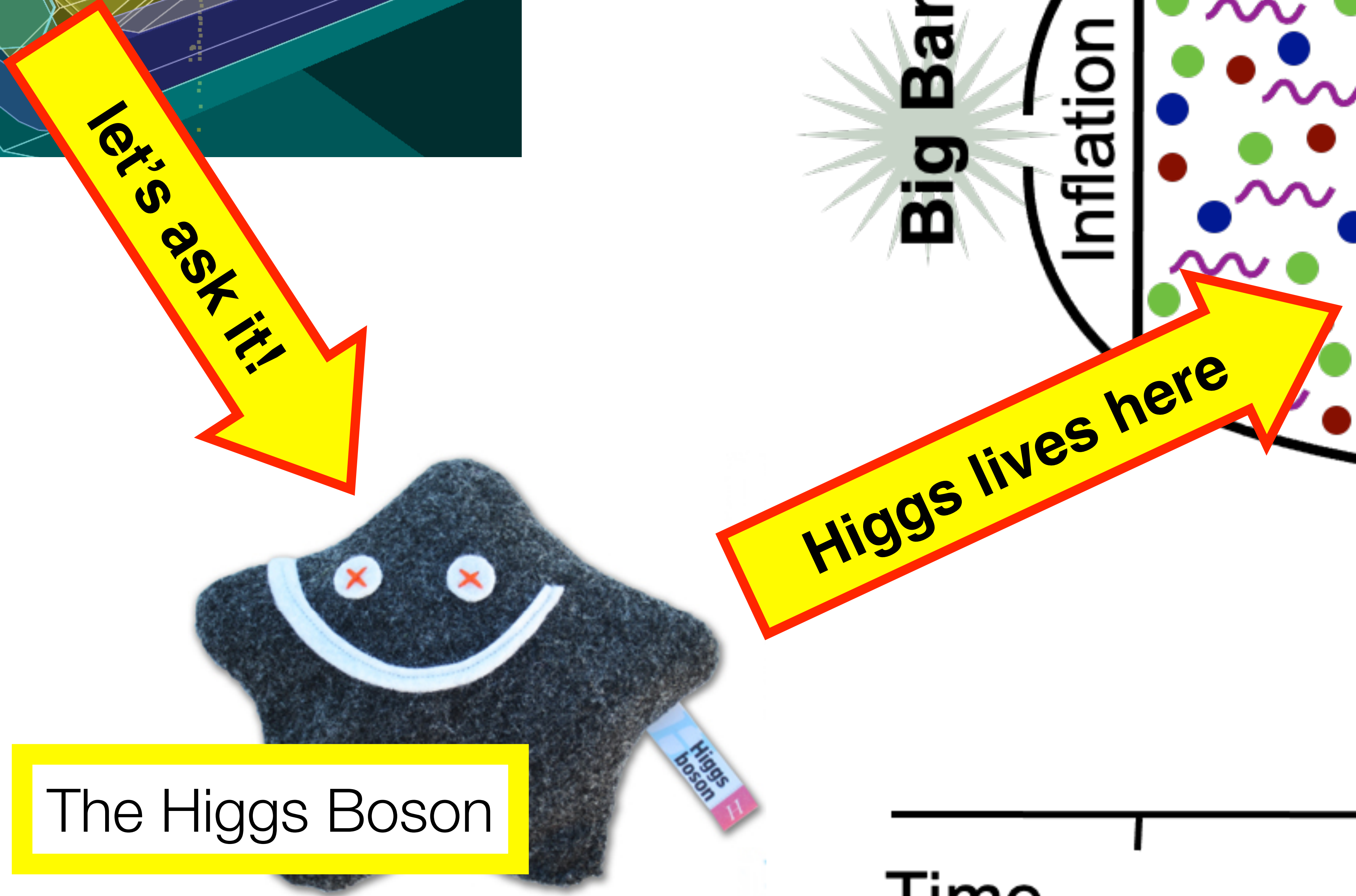
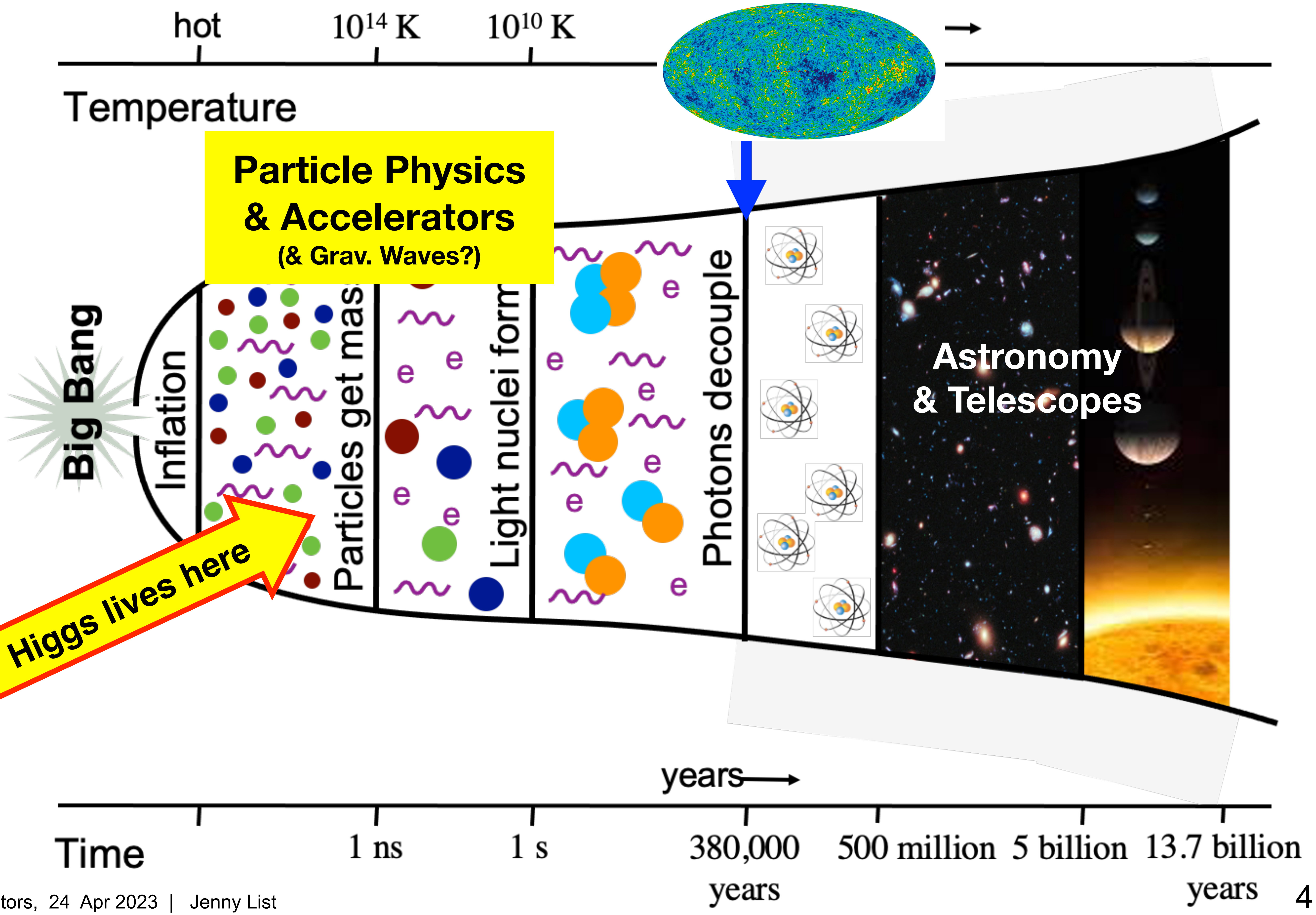
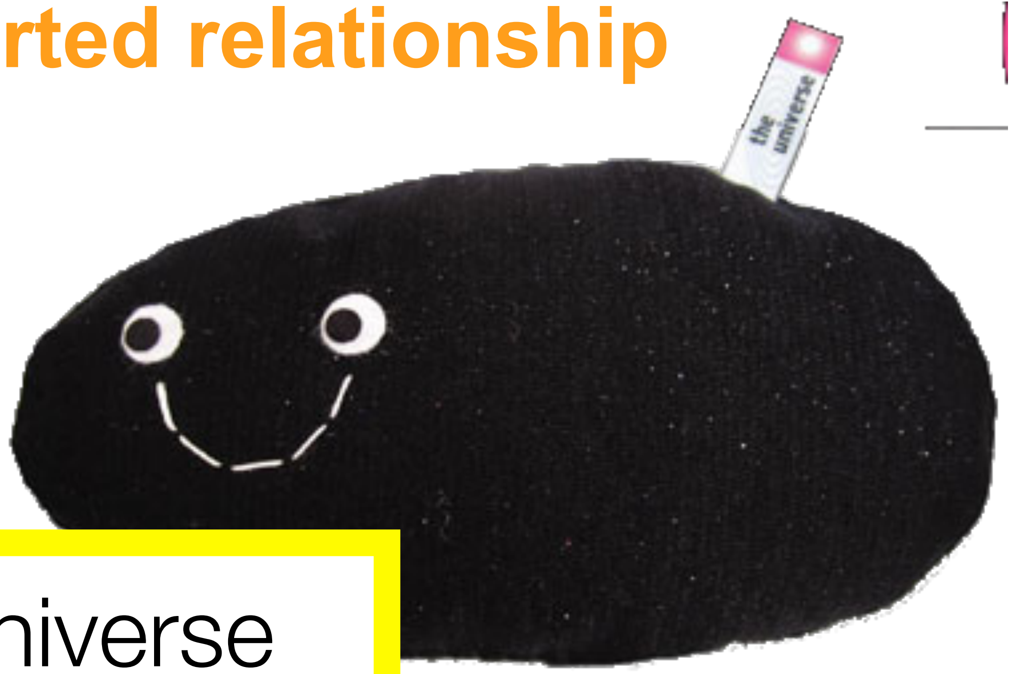






The Higgs Boson and the Universe

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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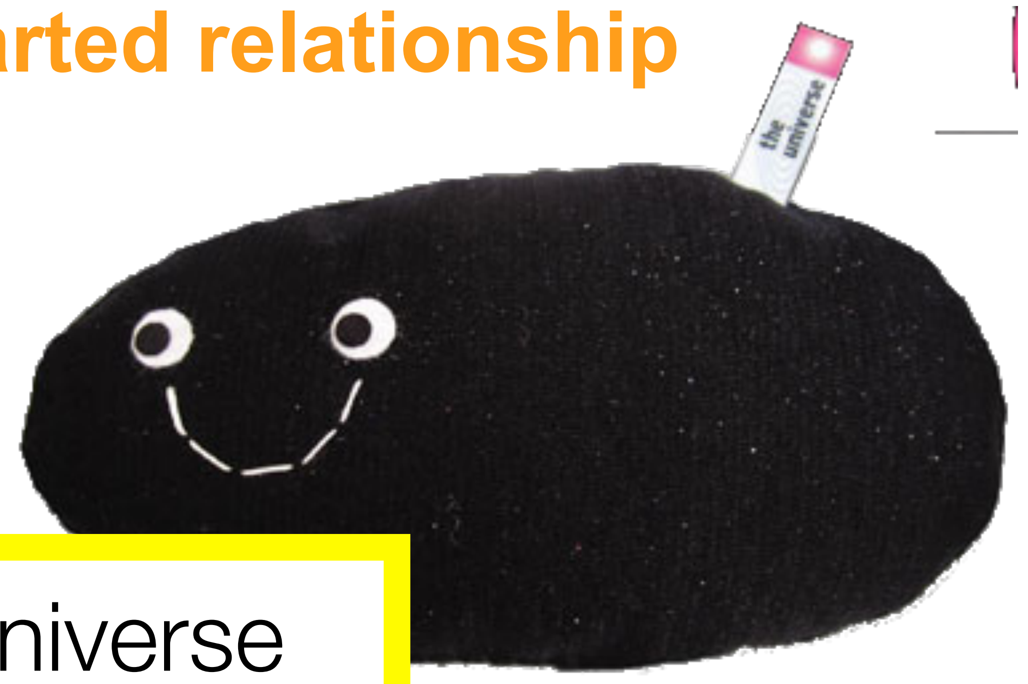

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Is the Higgs the portal to the Dark Sector?

- 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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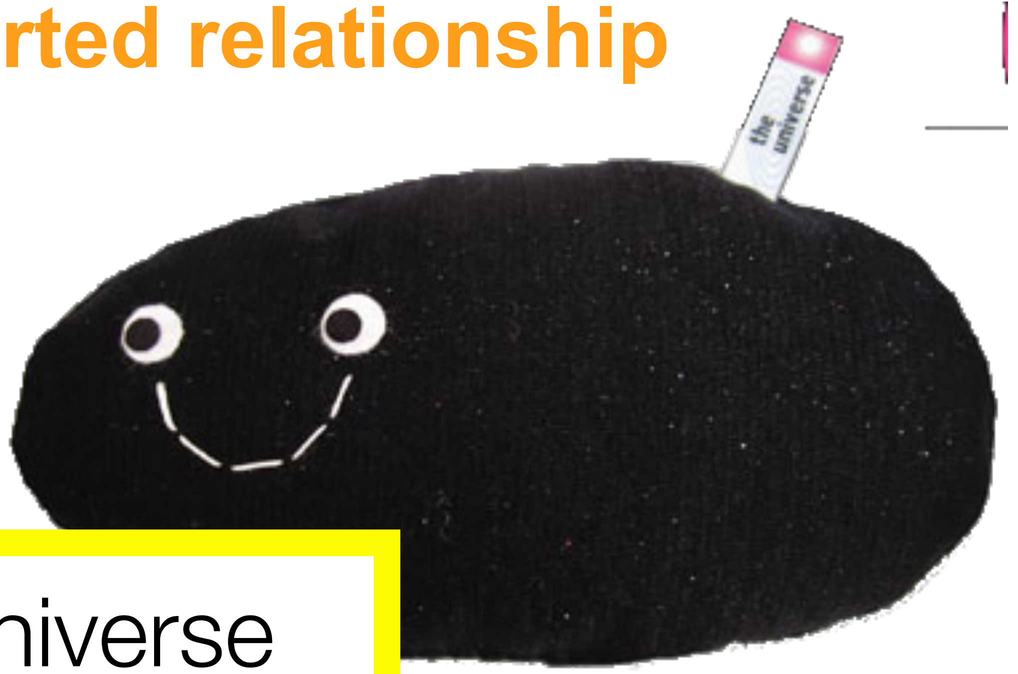

The Universe

The Higgs Boson

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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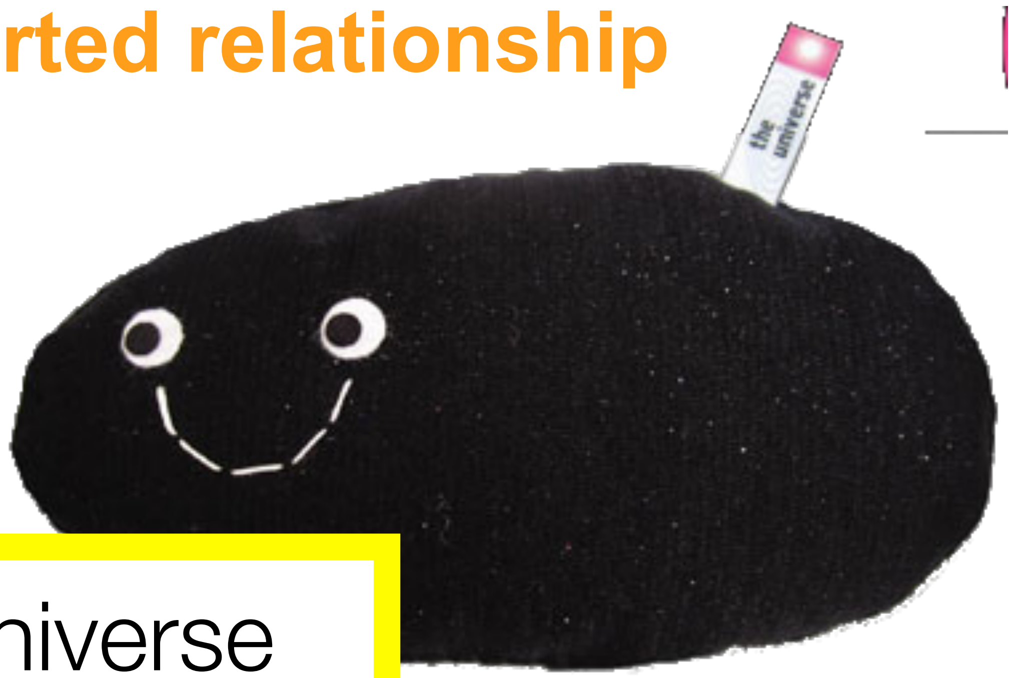

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Why is the Higgs-fermion interaction so different between the species?

- 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!

The Higgs Boson and the Universe

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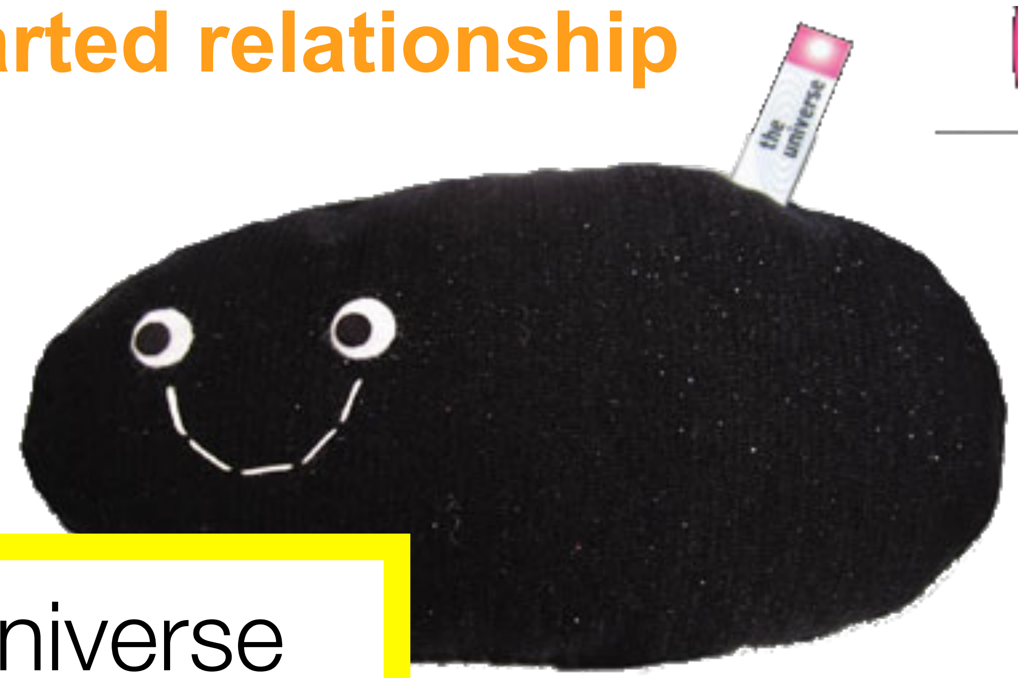

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Does the Higgs sector contain additional CP violation?

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

=> small contributions -> need precise measurements!

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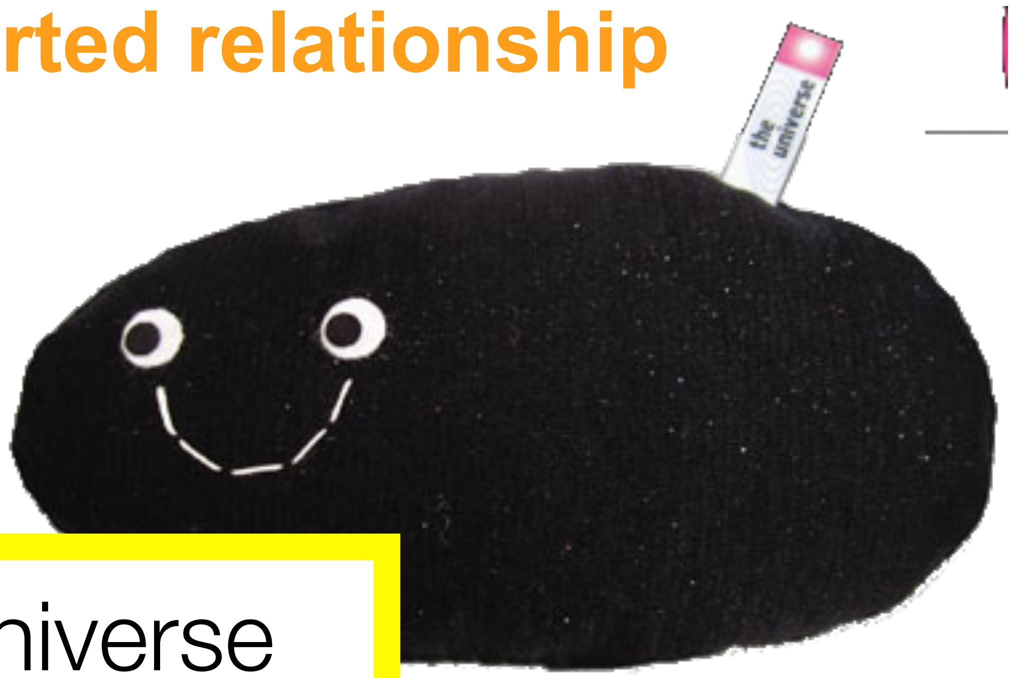

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What is the shape of the Higgs potential, and its evolution?

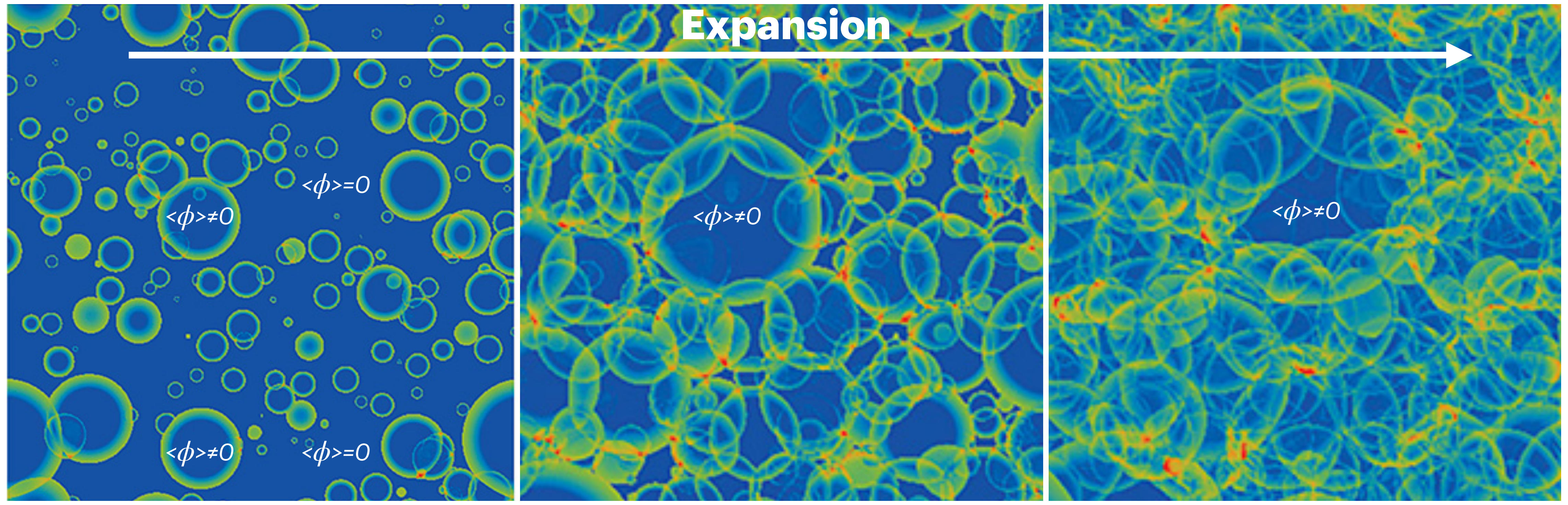
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

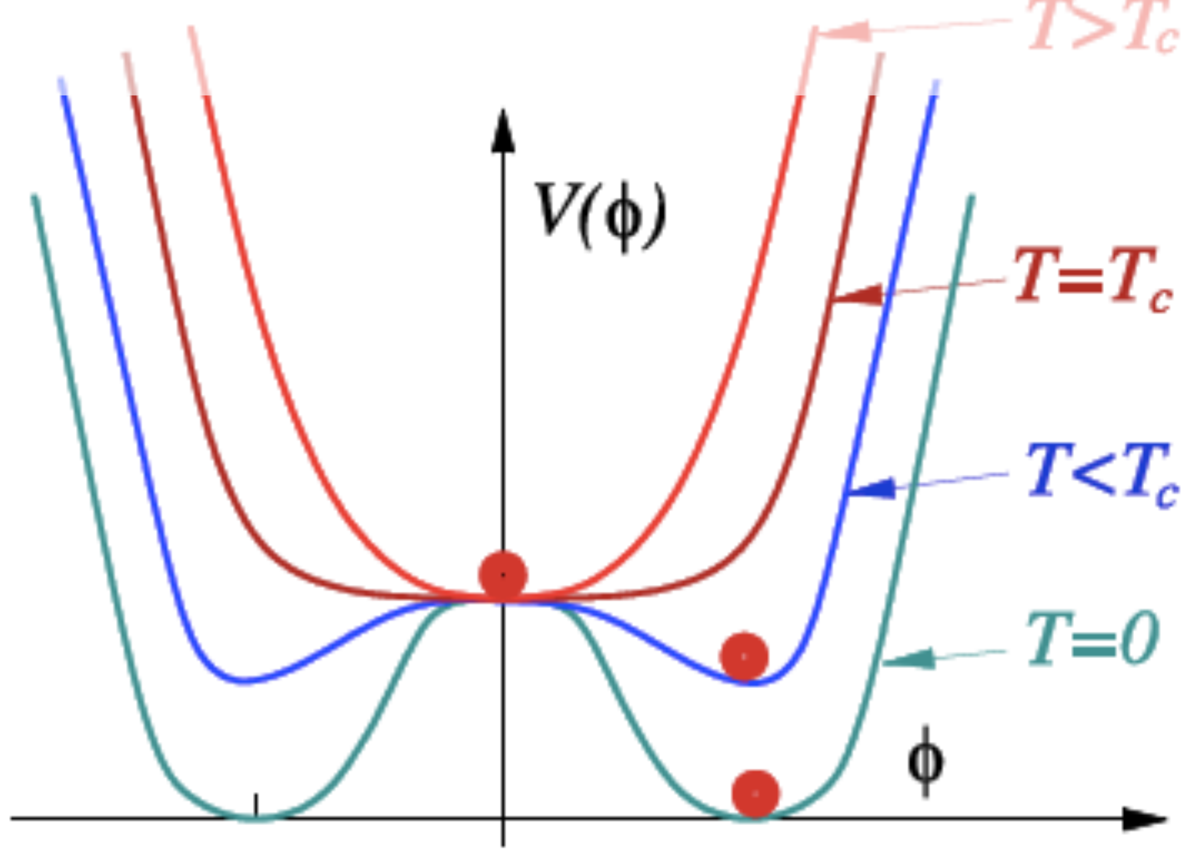
=> discover and study di-Higgs production

The Higgs potential, the Higgs self-coupling and Baryogenesis

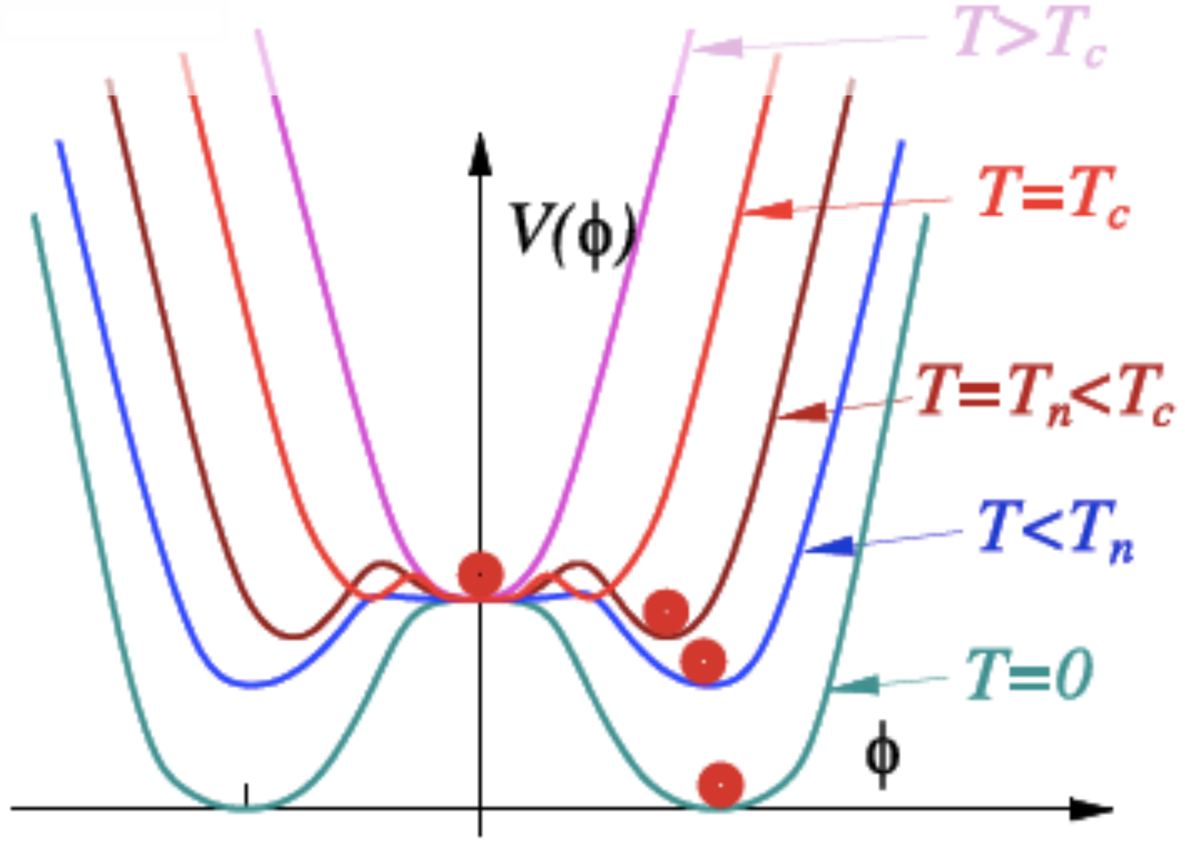
1st vs 2nd order phase transition

- 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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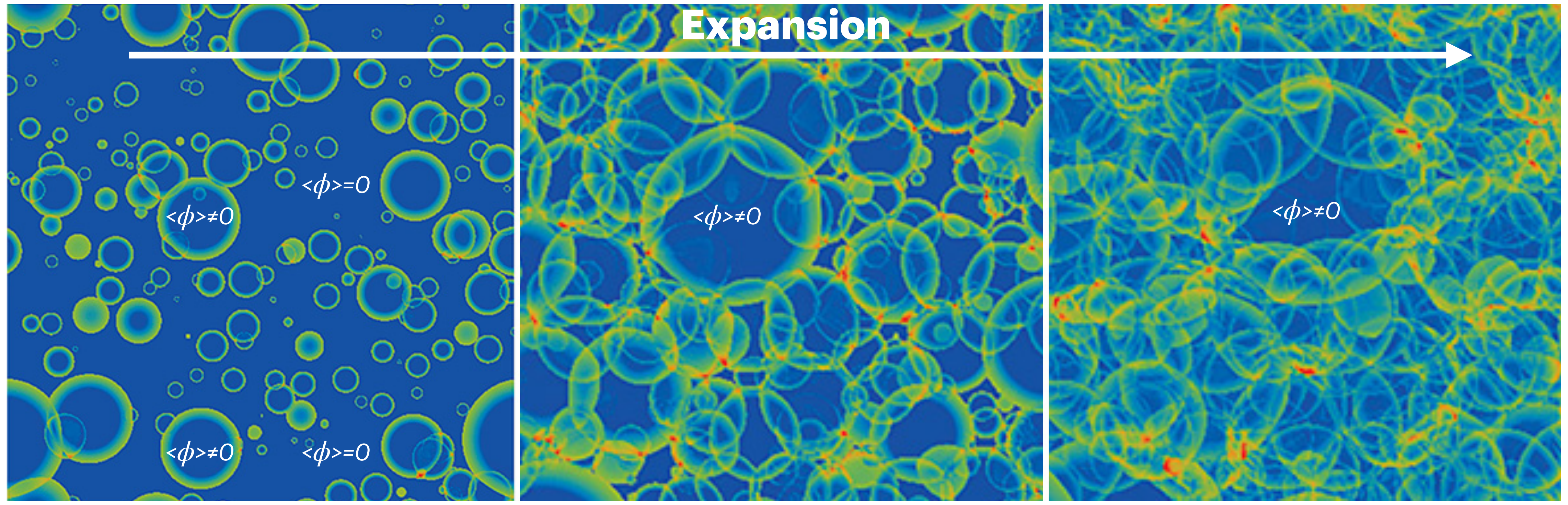

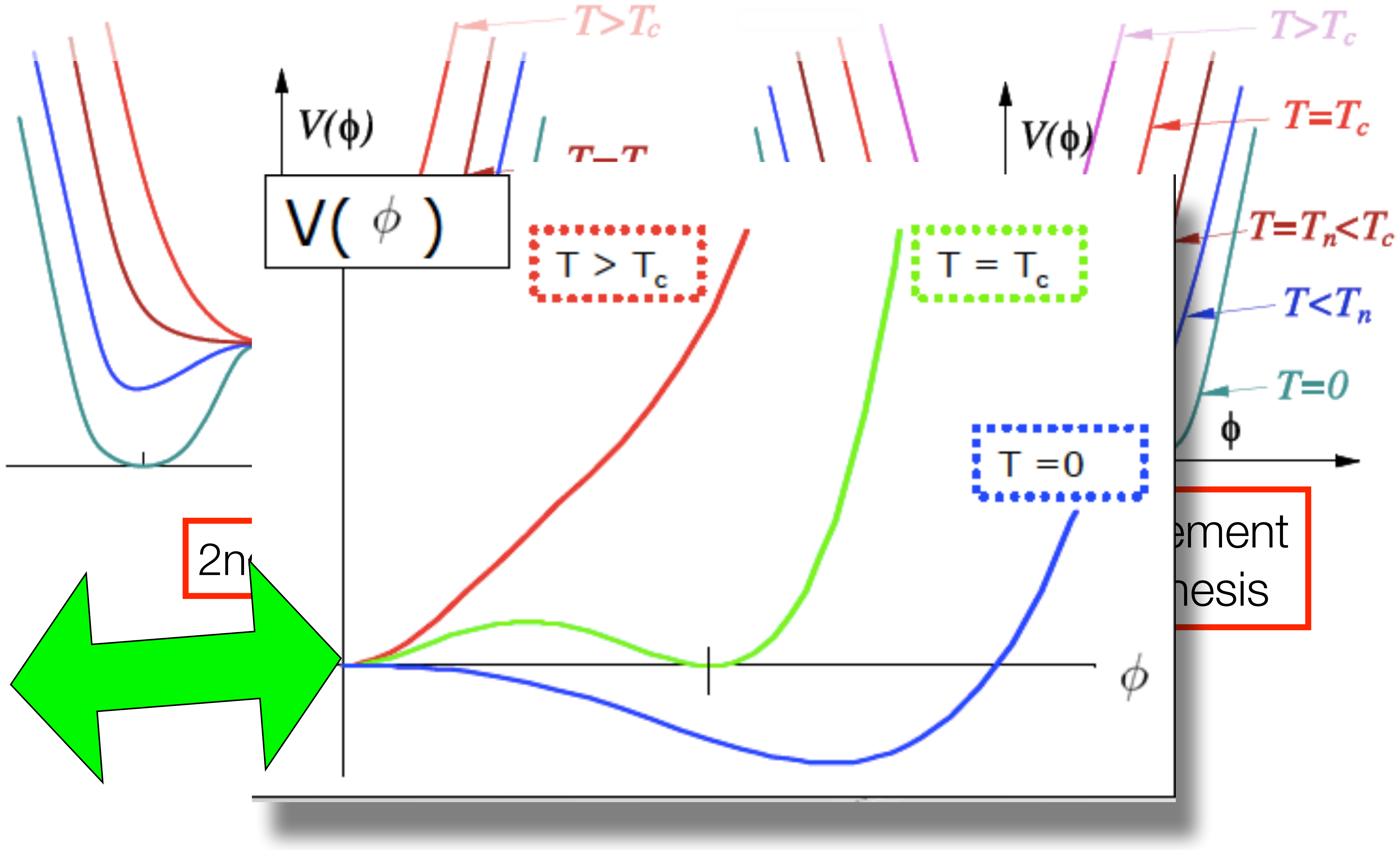

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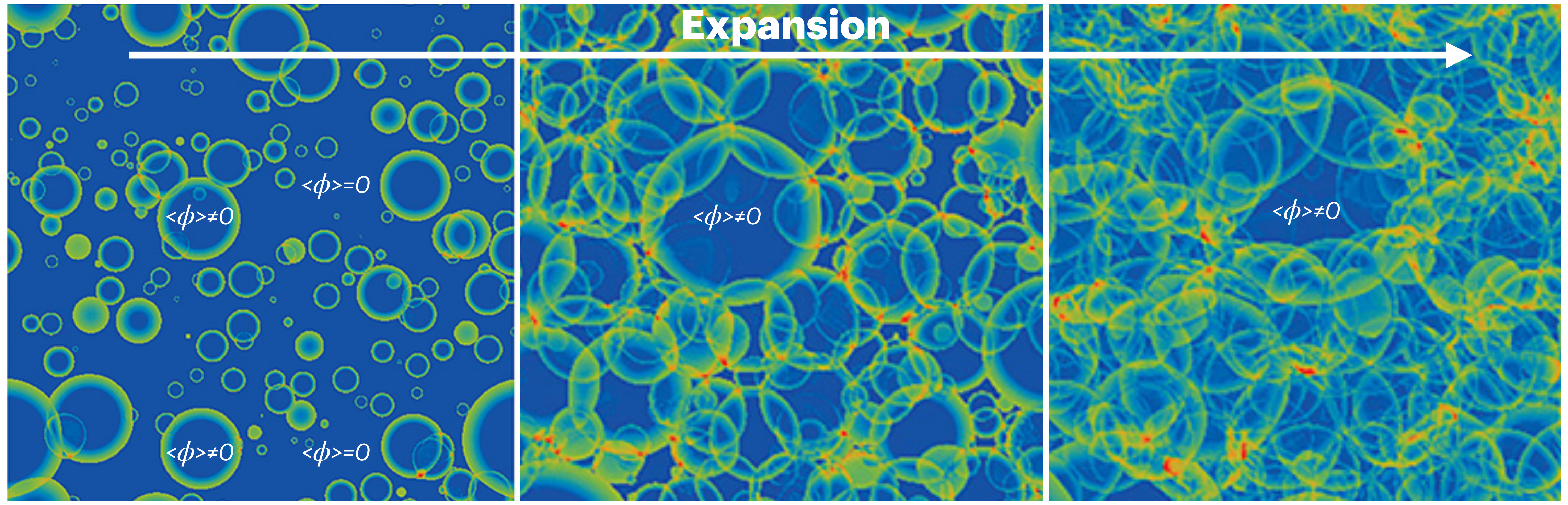

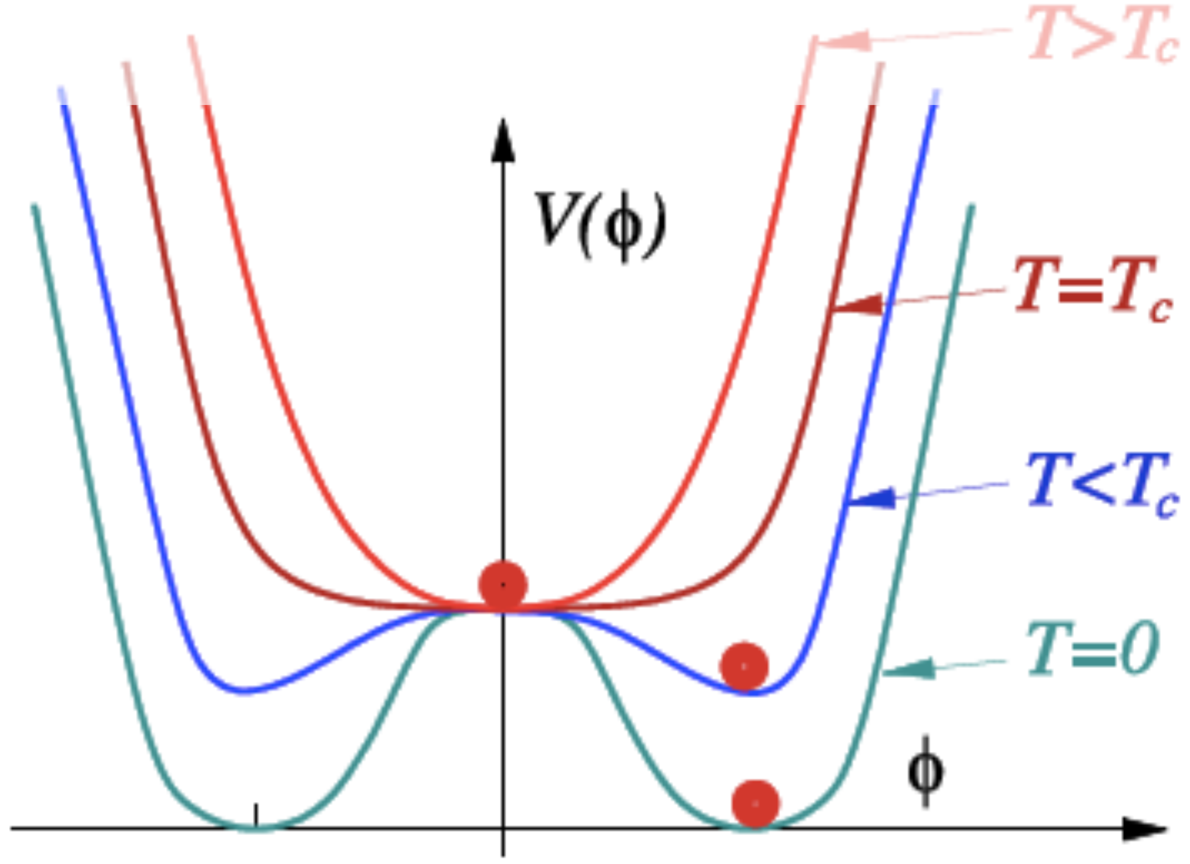

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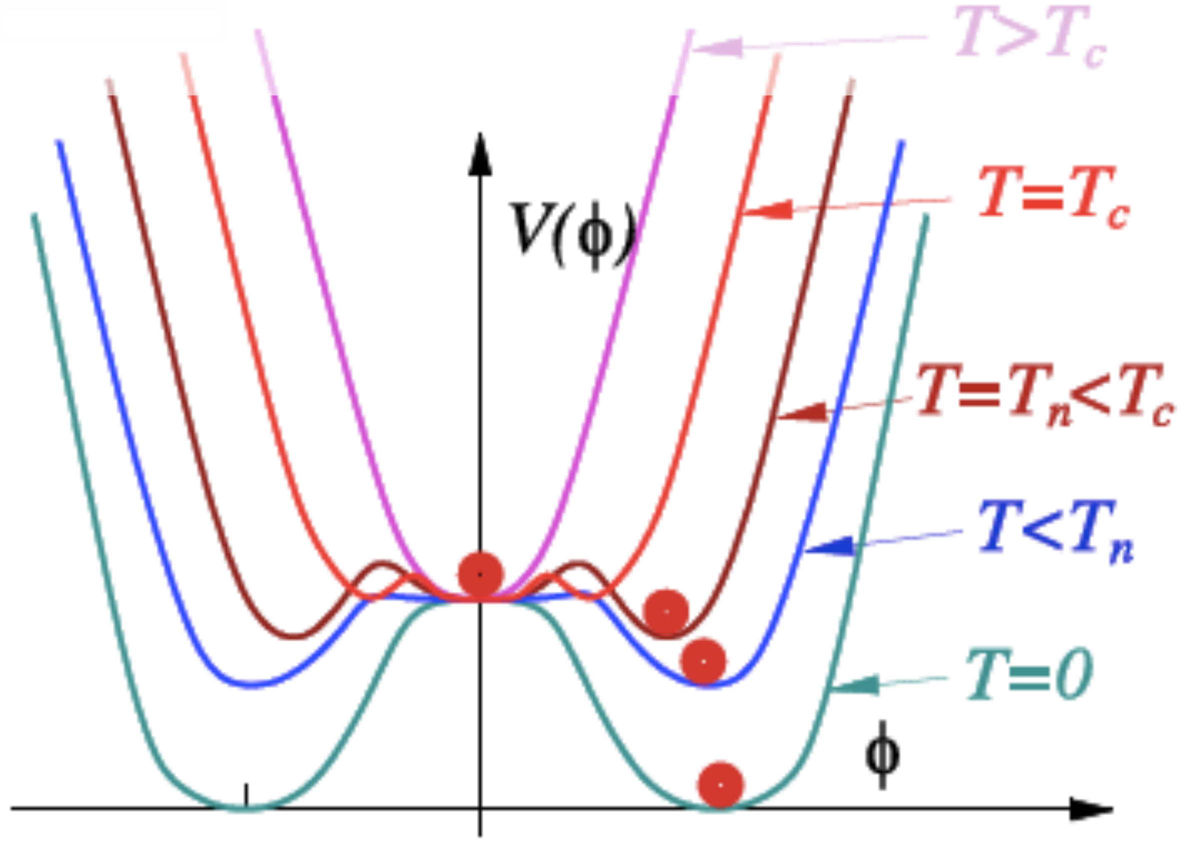

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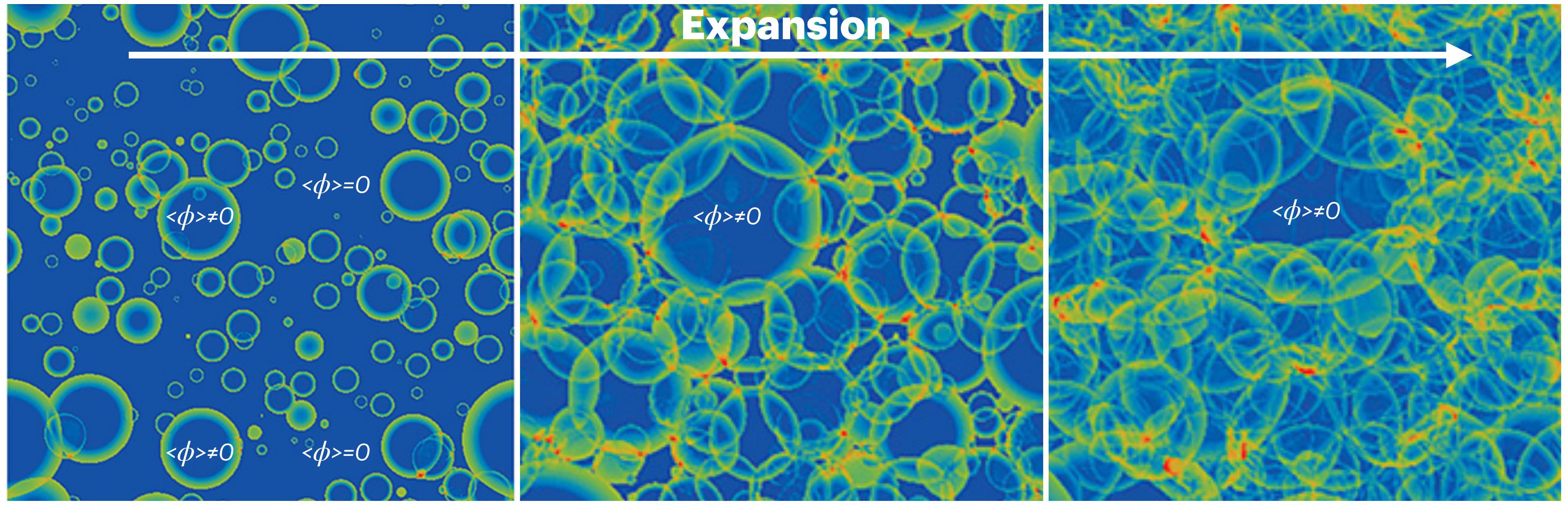

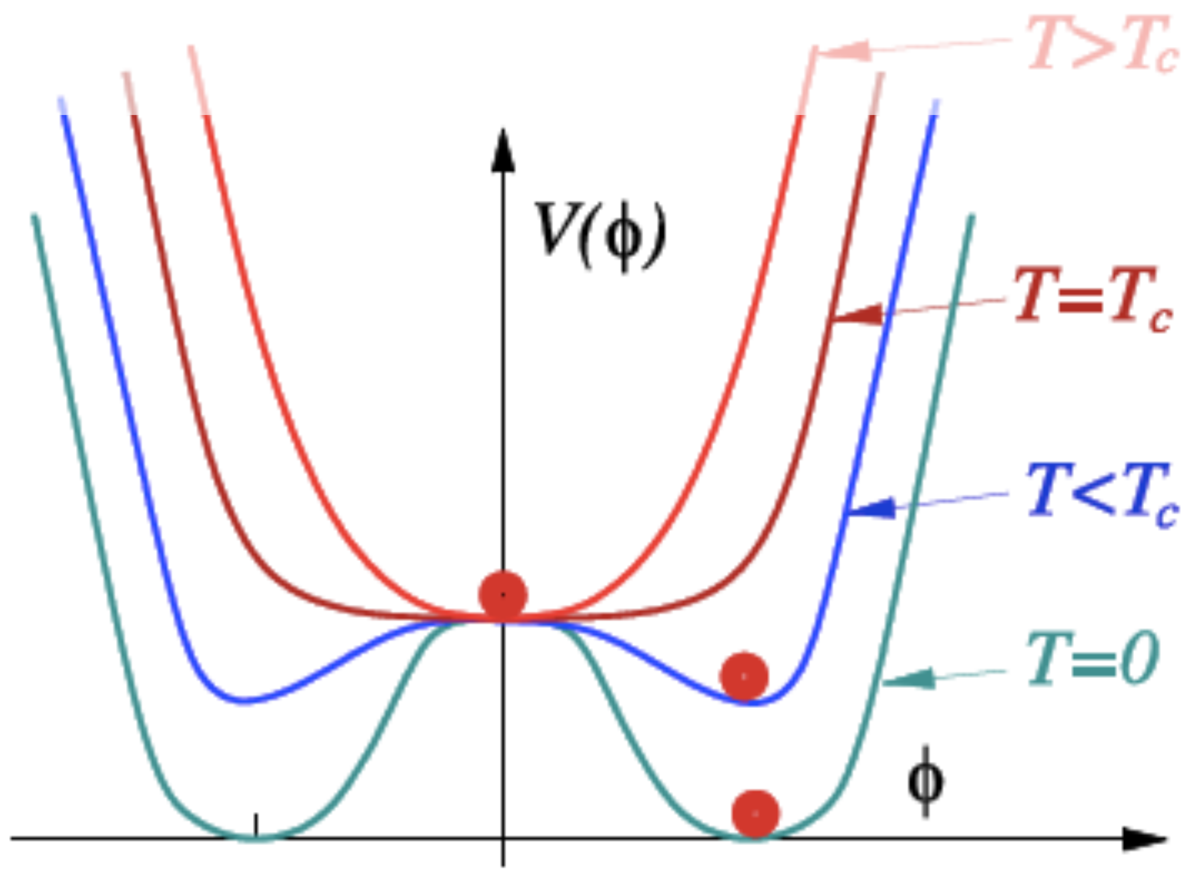

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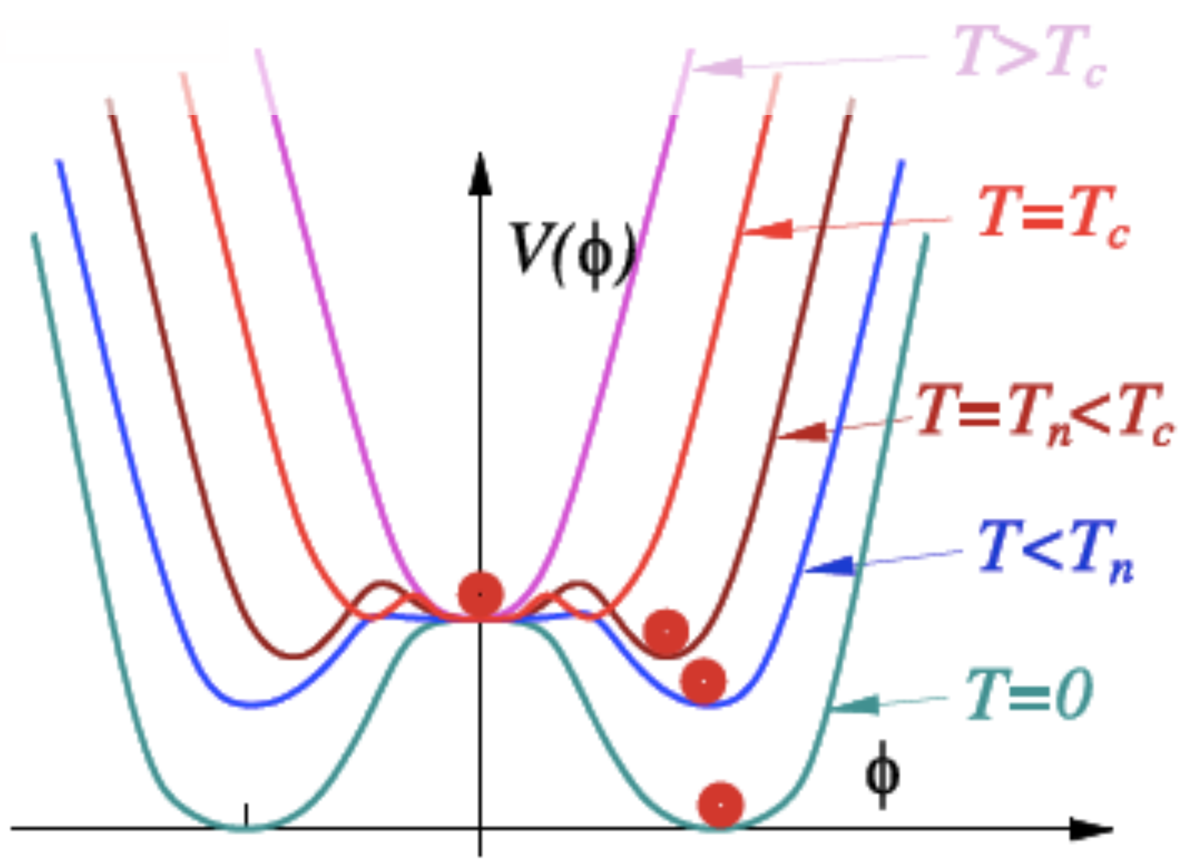

1st order, requirement for EW baryogenesis

- 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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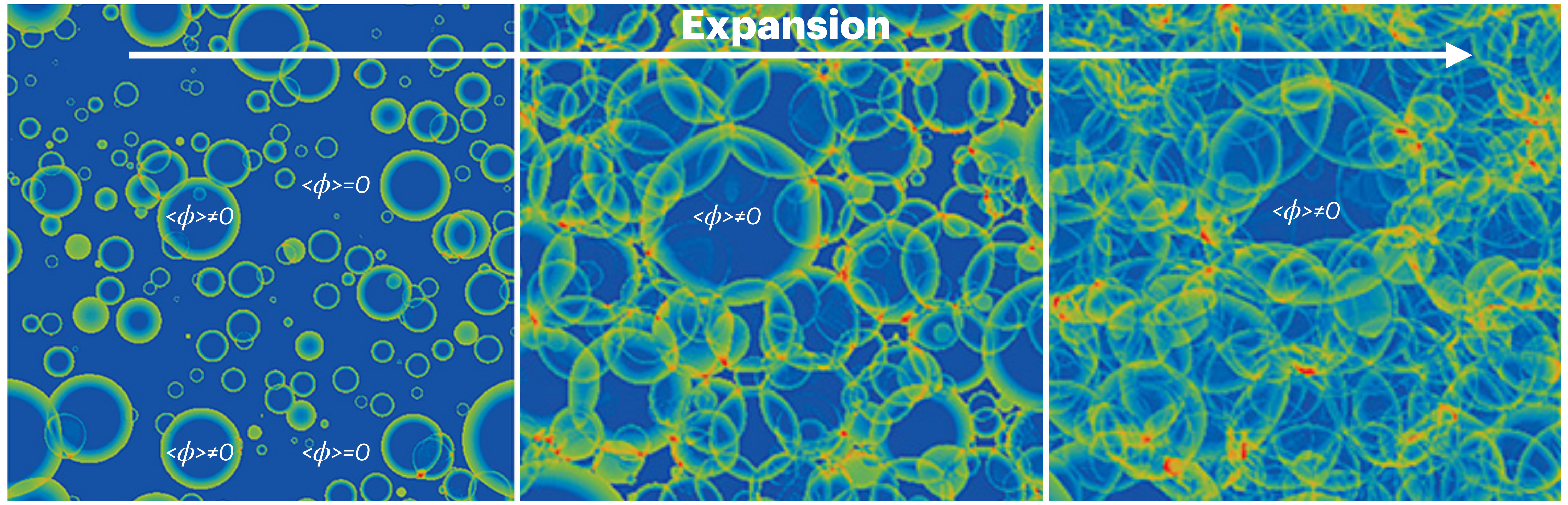

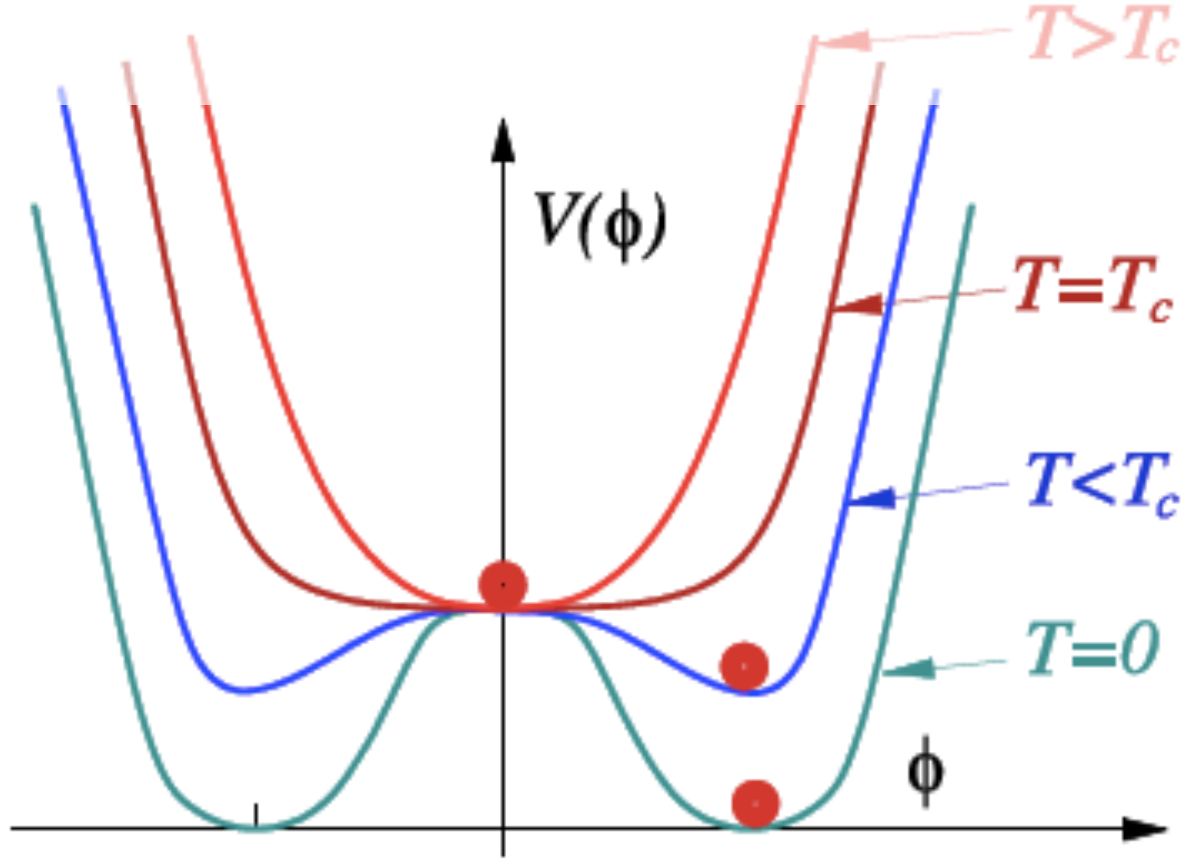

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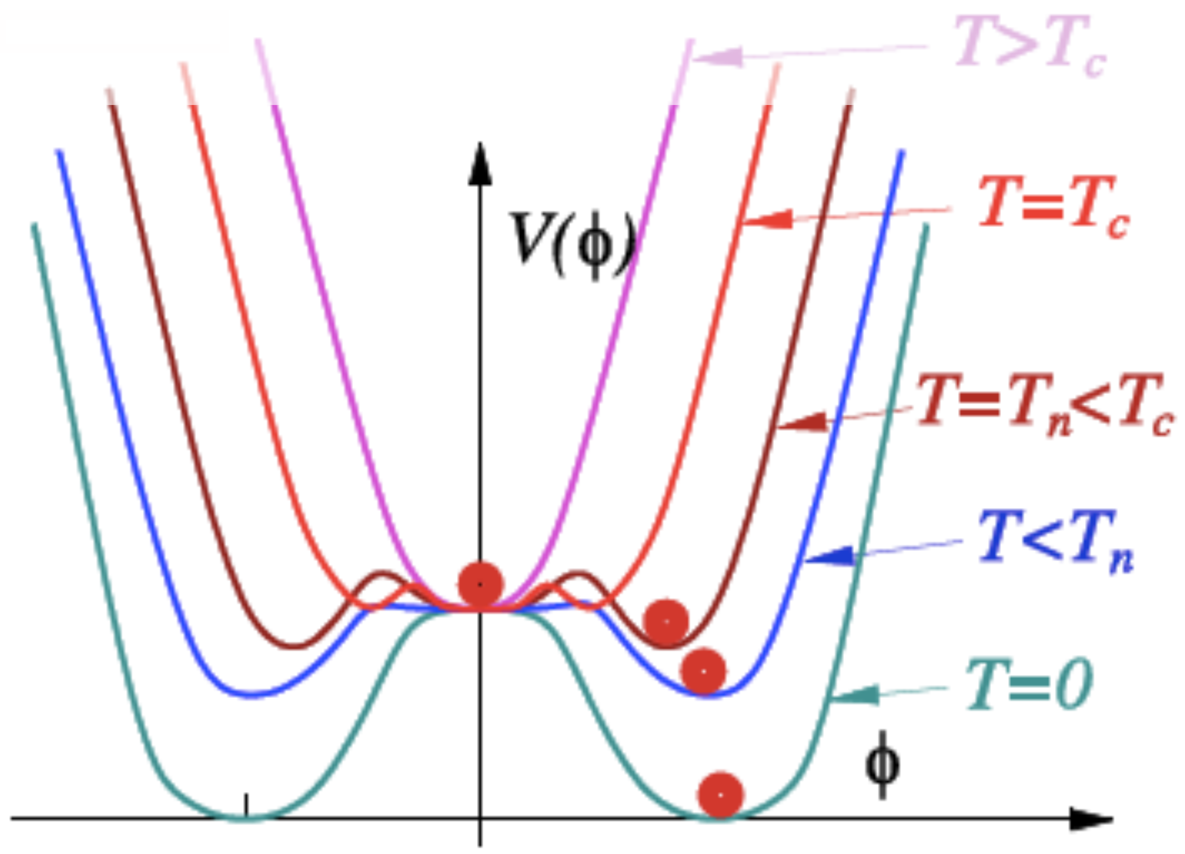

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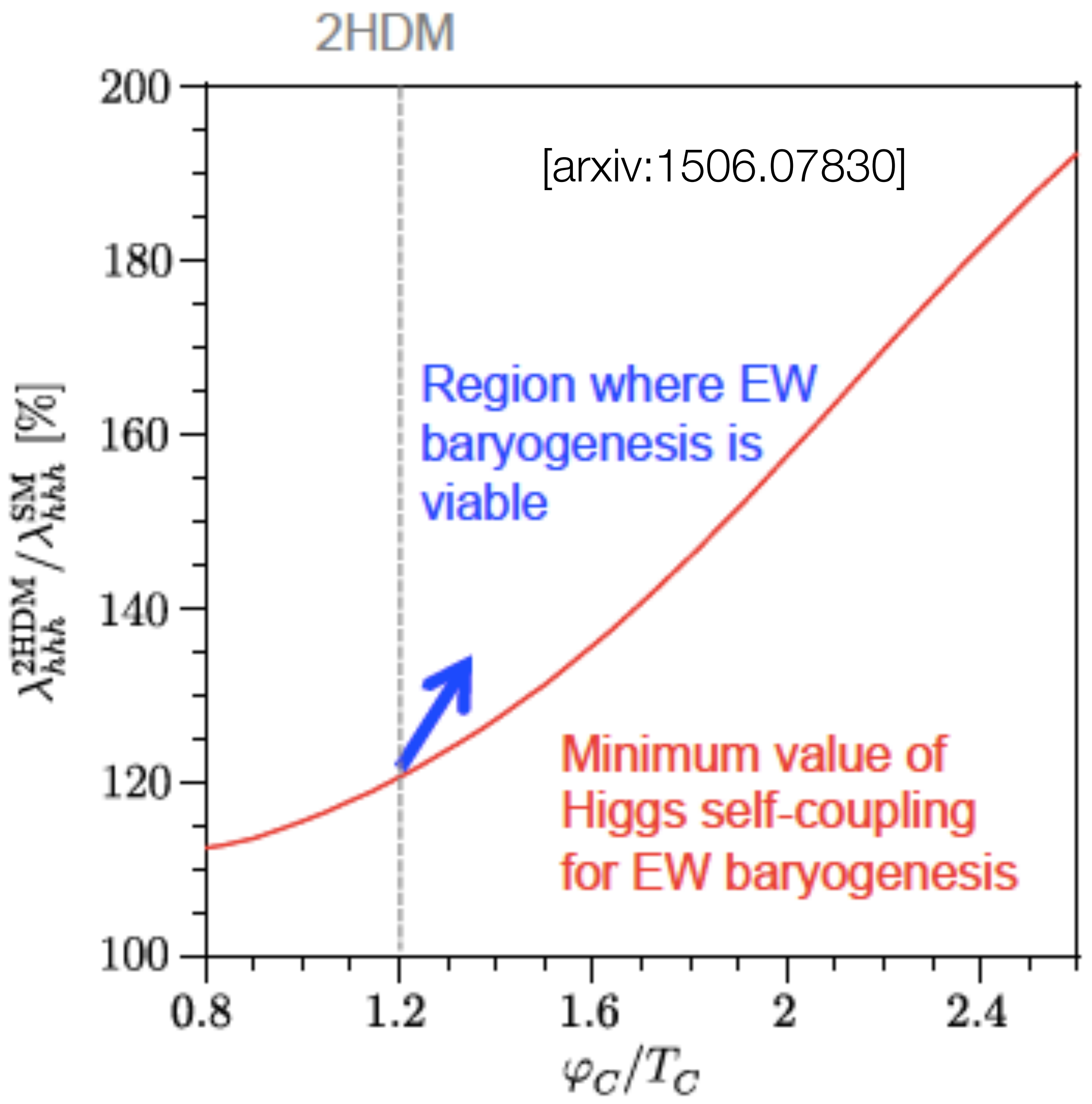

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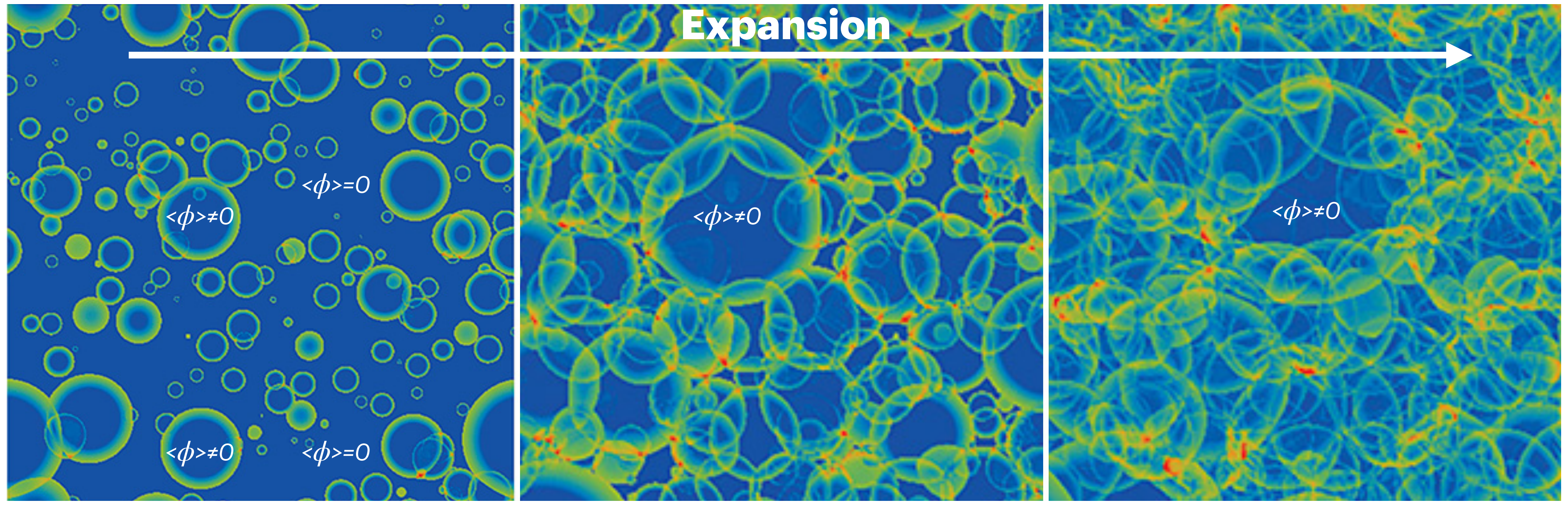

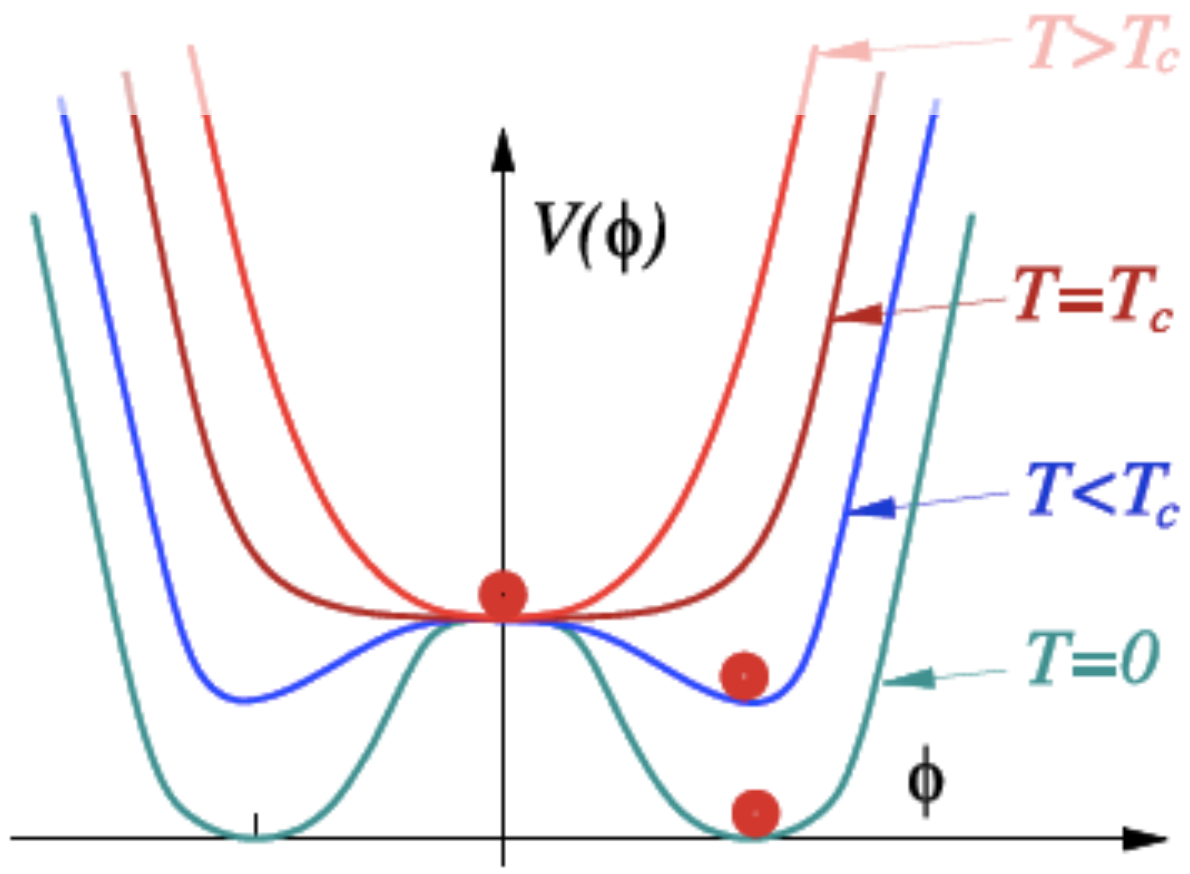

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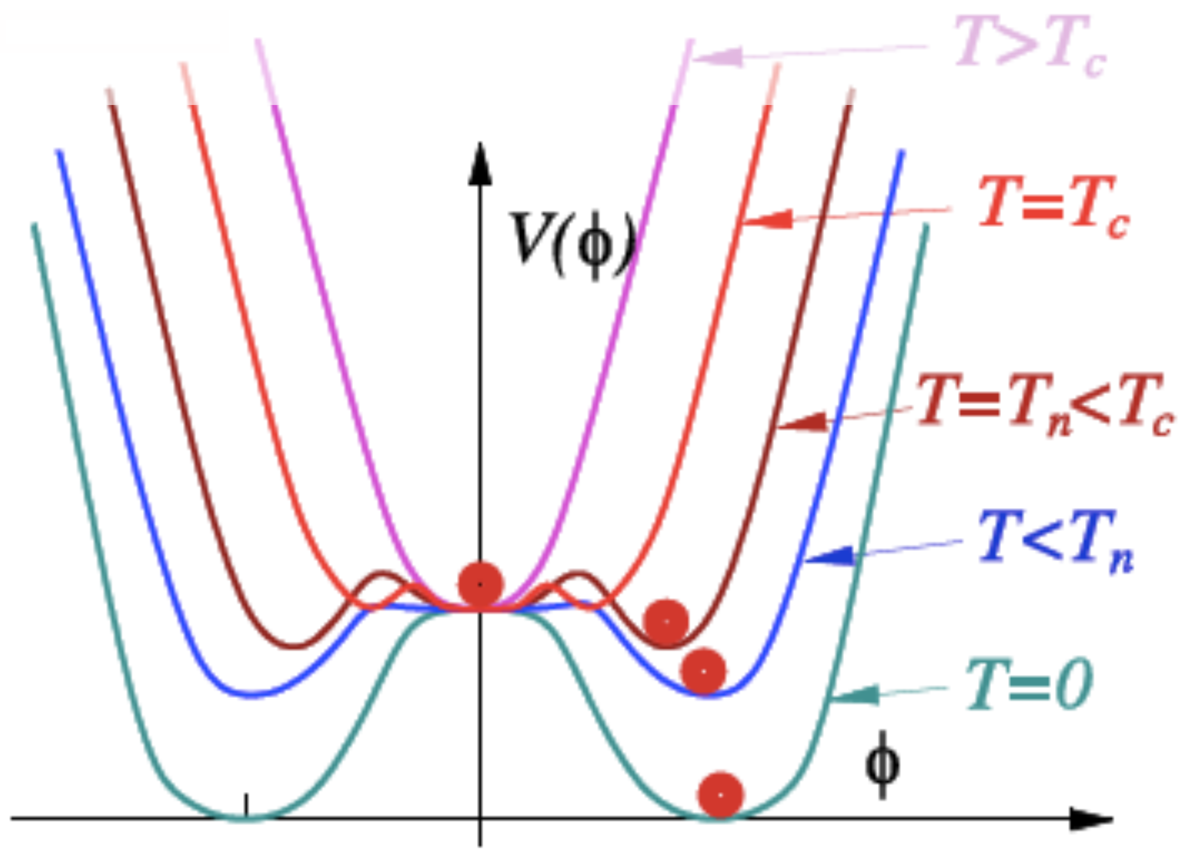

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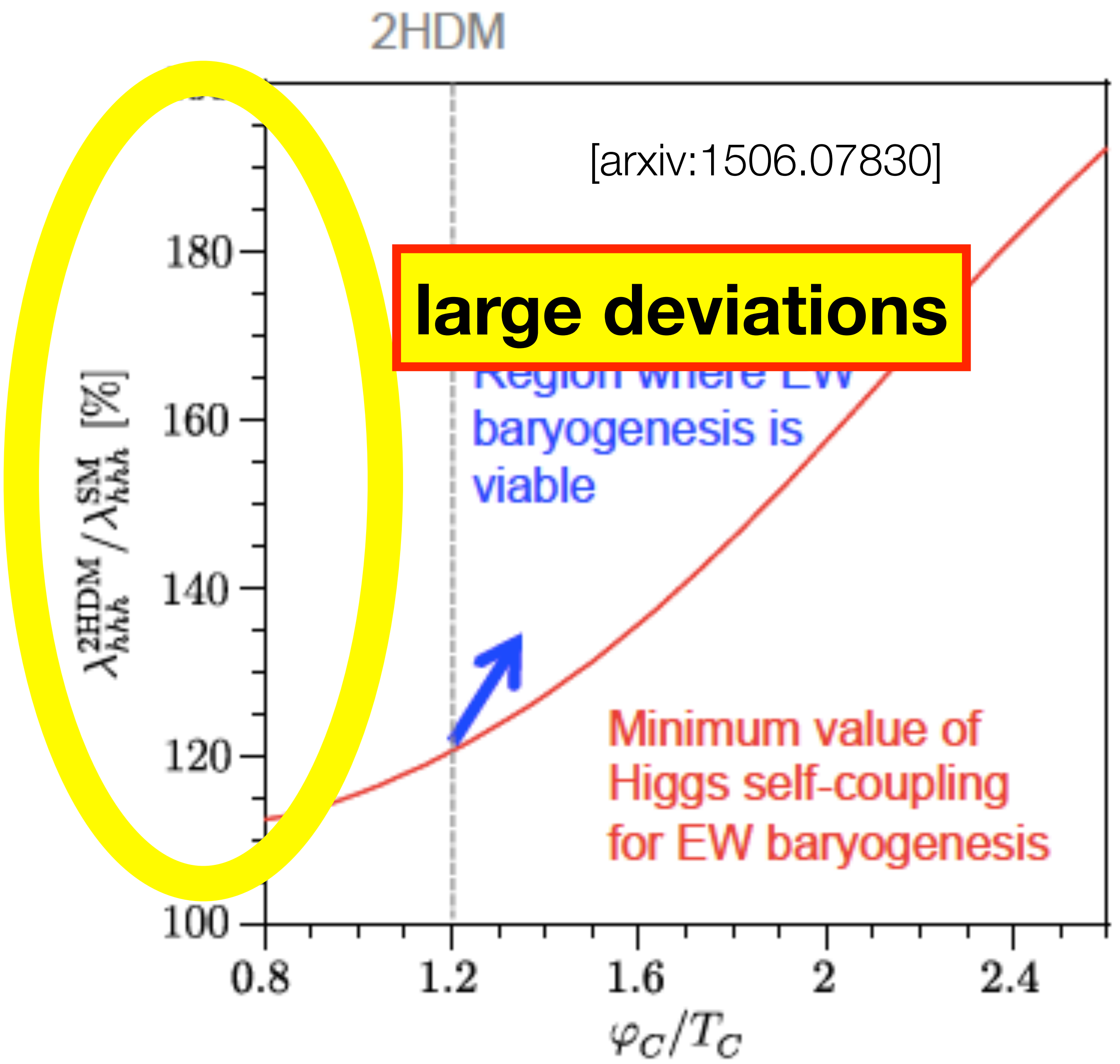

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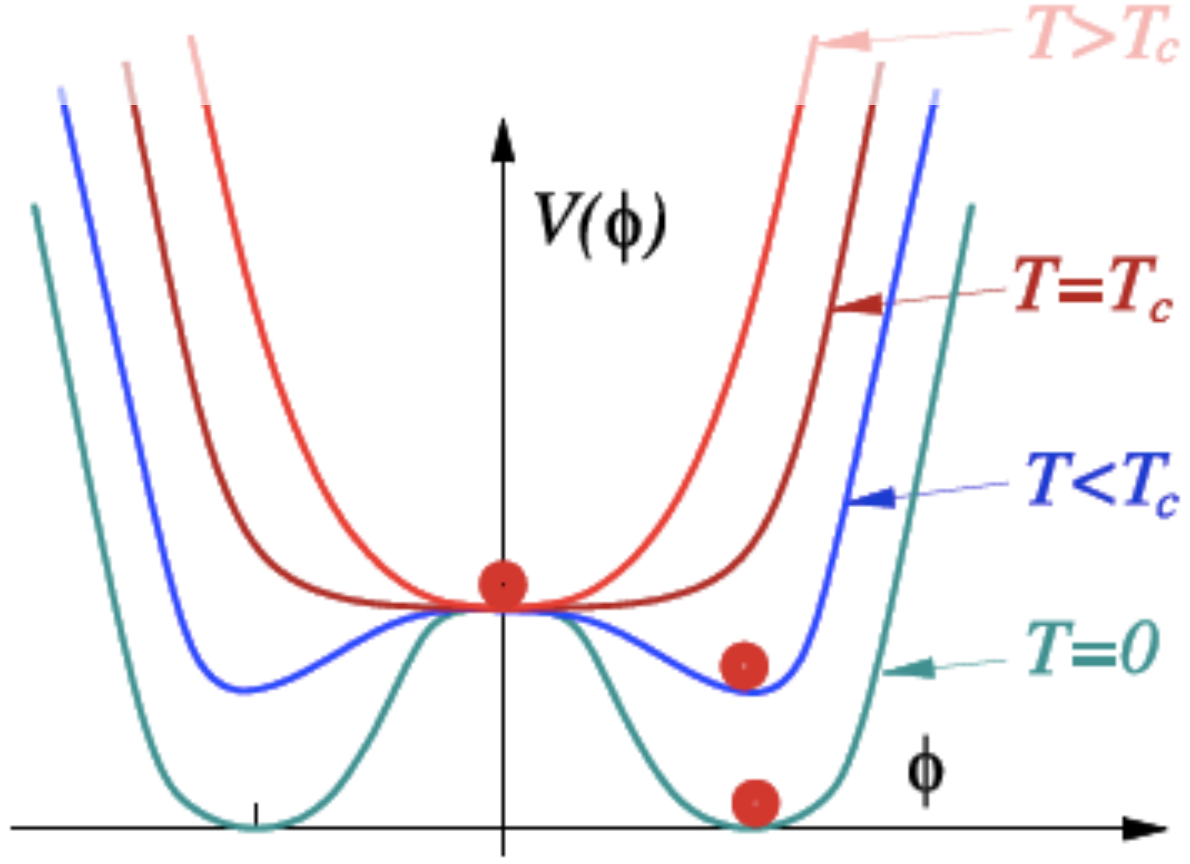

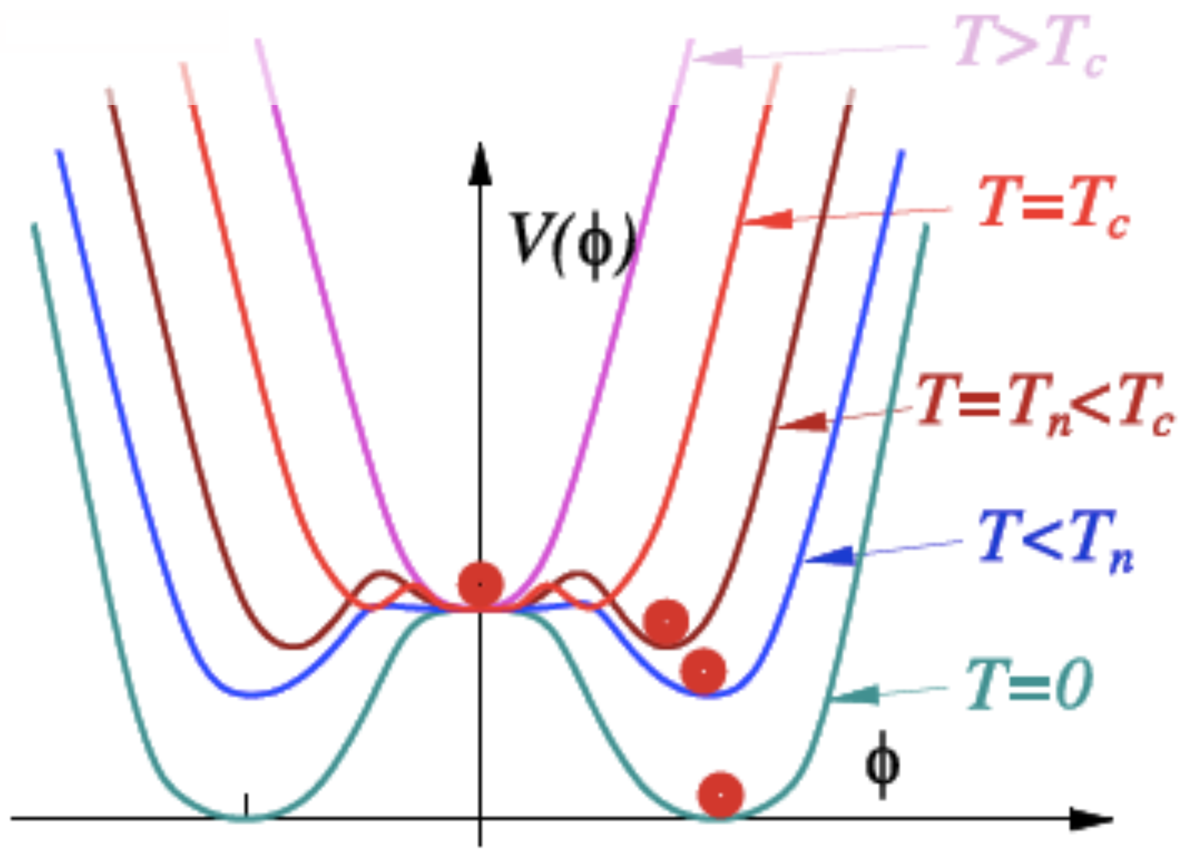

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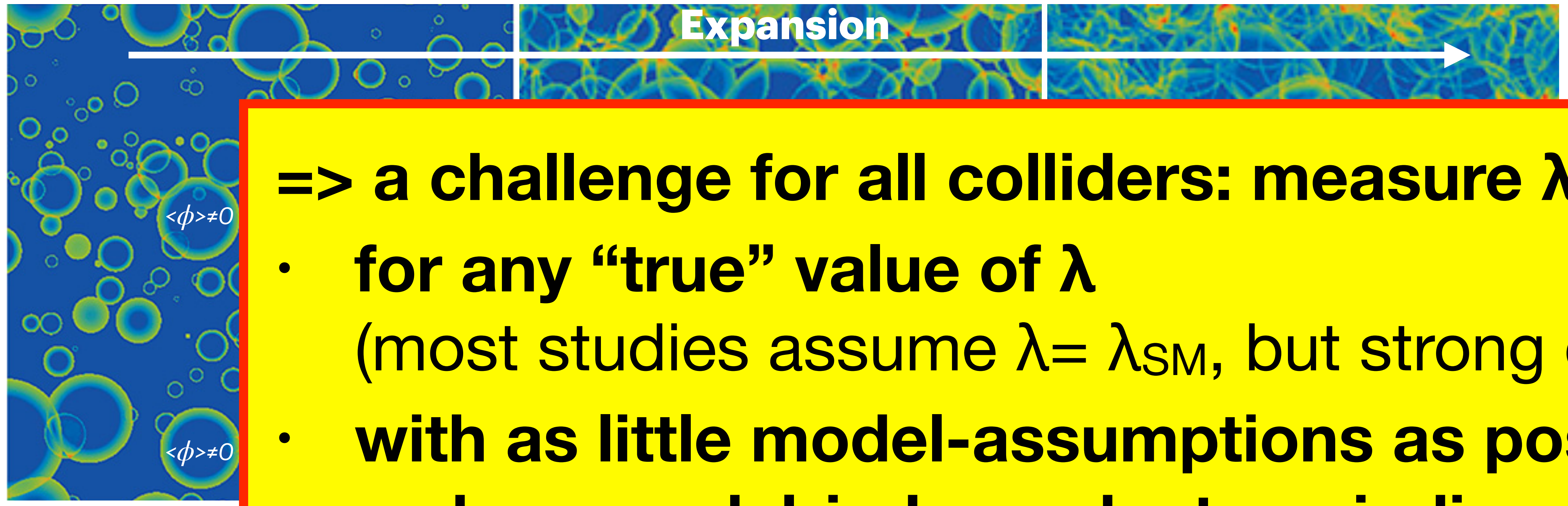

=> a challenge for all colliders: measure λ !

- **for any “true” value of λ**
  (most studies assume $\lambda = \lambda_{SM}$, but strong dependency of precision on actual value!)
- **with as little model-assumptions as possible**
  => how model-independent are indirect (eg SMEFT-based) determinations?
  => are they reliable enough if nature ≠ SM ?
- **indirect determination from singleH must include *all* operators entering at NLO**

- SM v
- value
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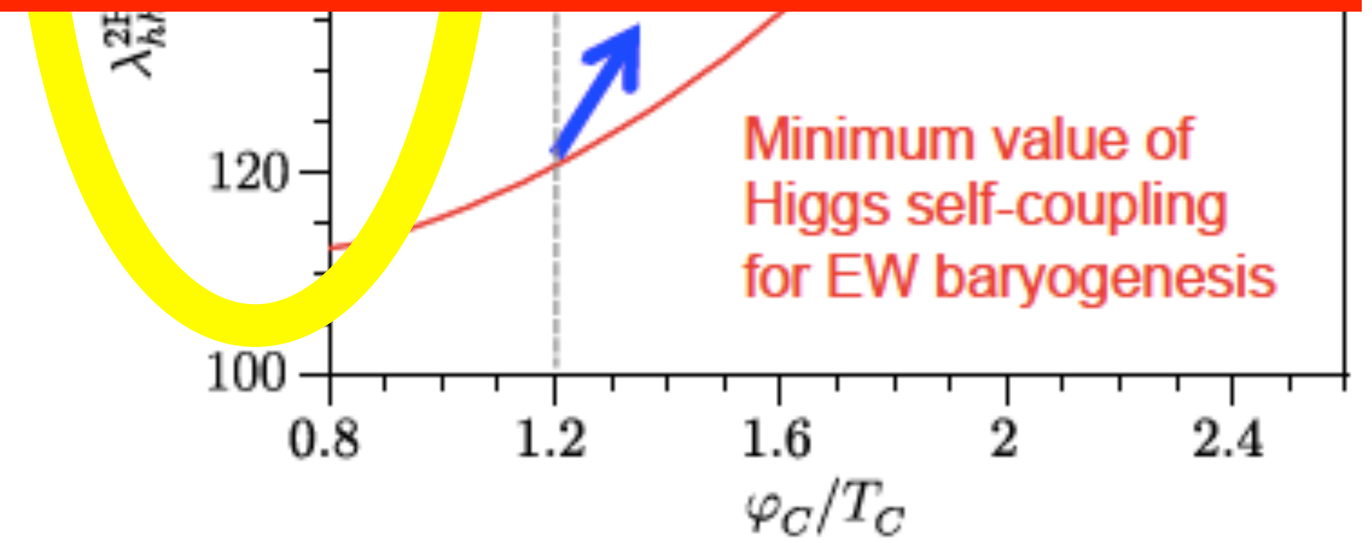
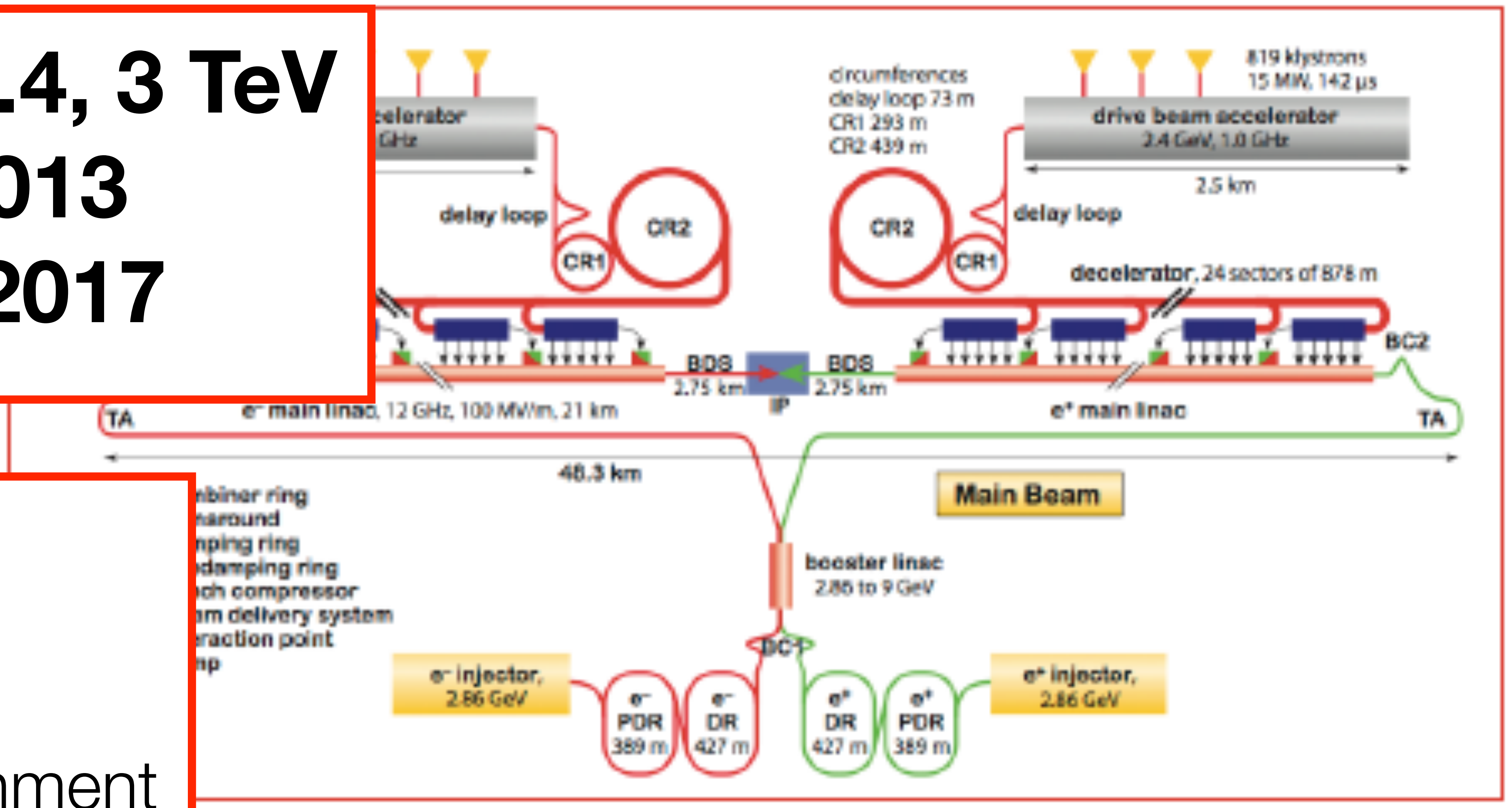


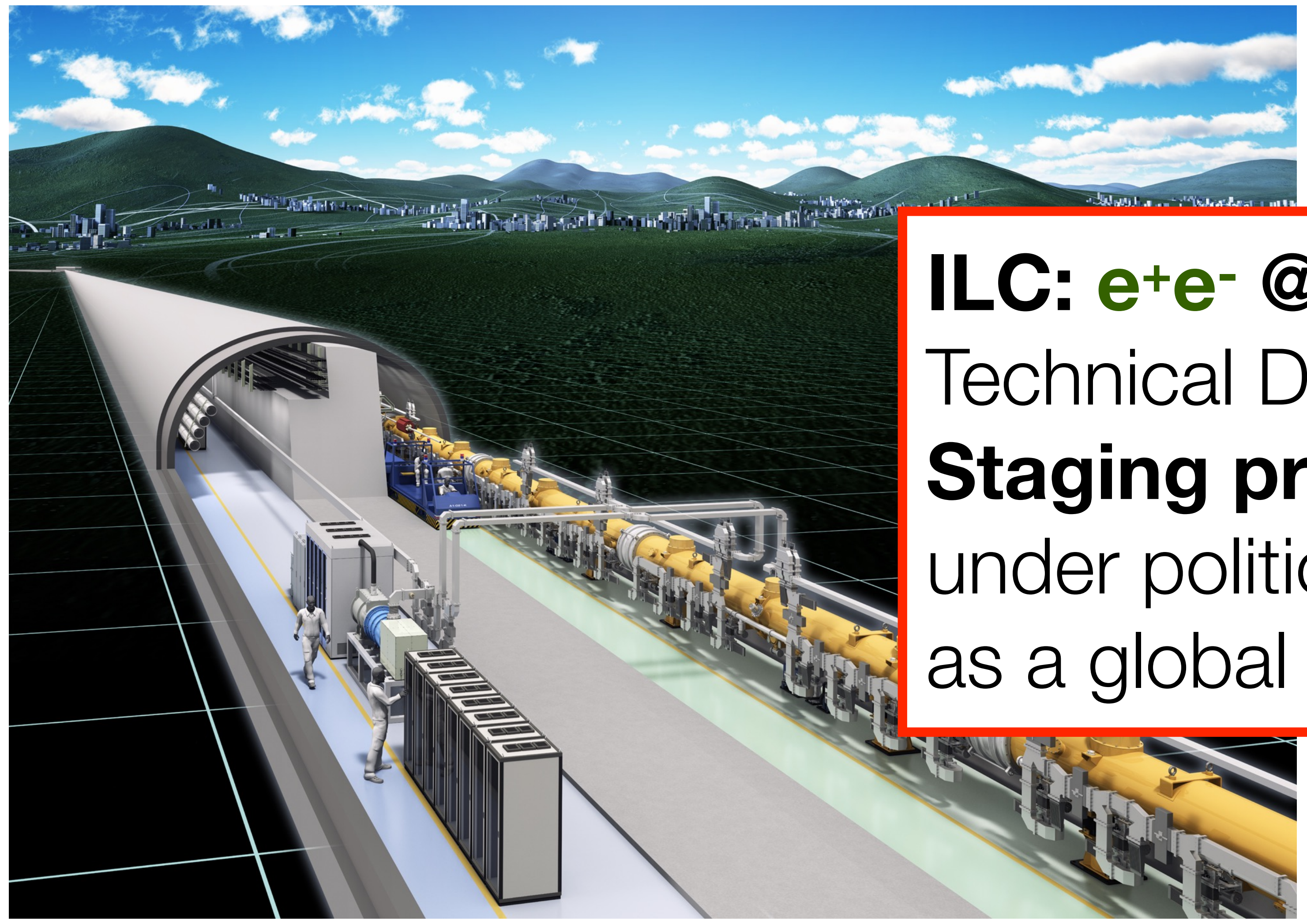
The key contenders

many ideas…

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

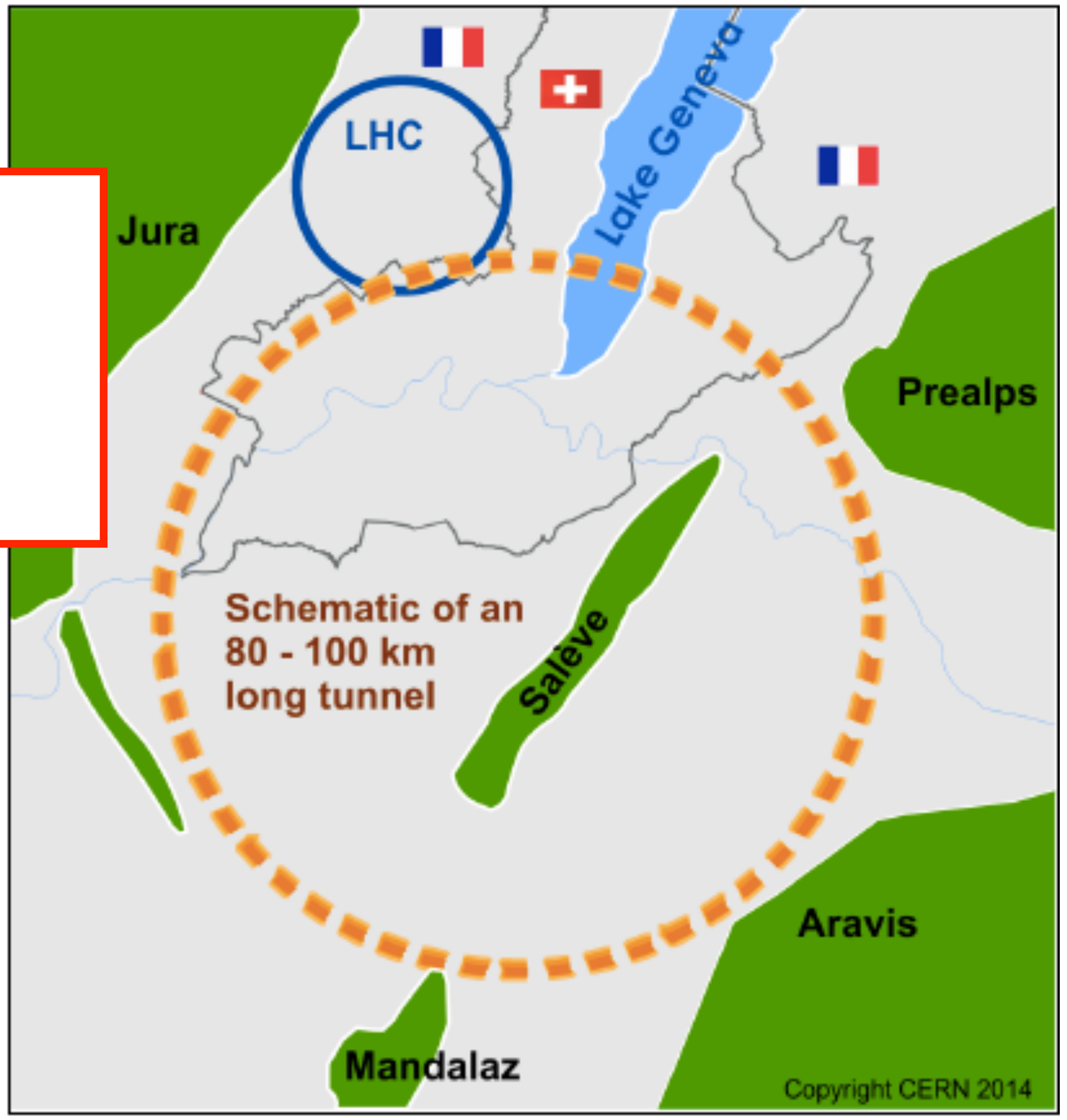


ILC: e^+e^- @ 200-500 GeV (-1TeV)
Technical Design Rep. in **2012**
Staging proposal 2017: start at 250 GeV
under political consideration by Japanese Government as a global project



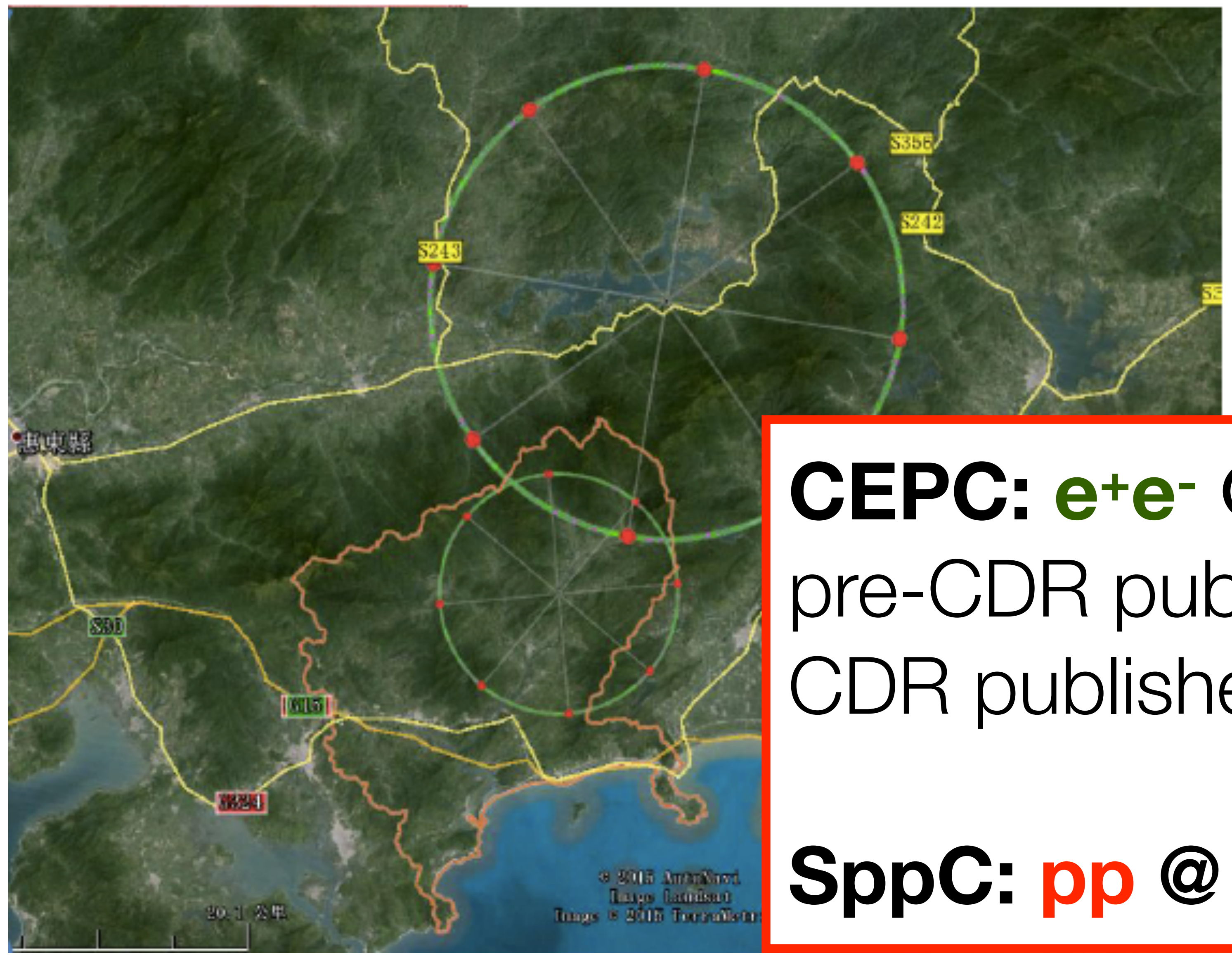
FCC: pp @ ~100 TeV
& precursor **FCCee e^+e^- @ 90-350 GeV**
Conceptual Design Rep. in **2018**

Currently: FCC Feasibility Study



CEPC: e^+e^- @ 240 GeV
pre-CDR published in **2014**
CDR published **2018**

SppC: pp @ 50-70 TeV



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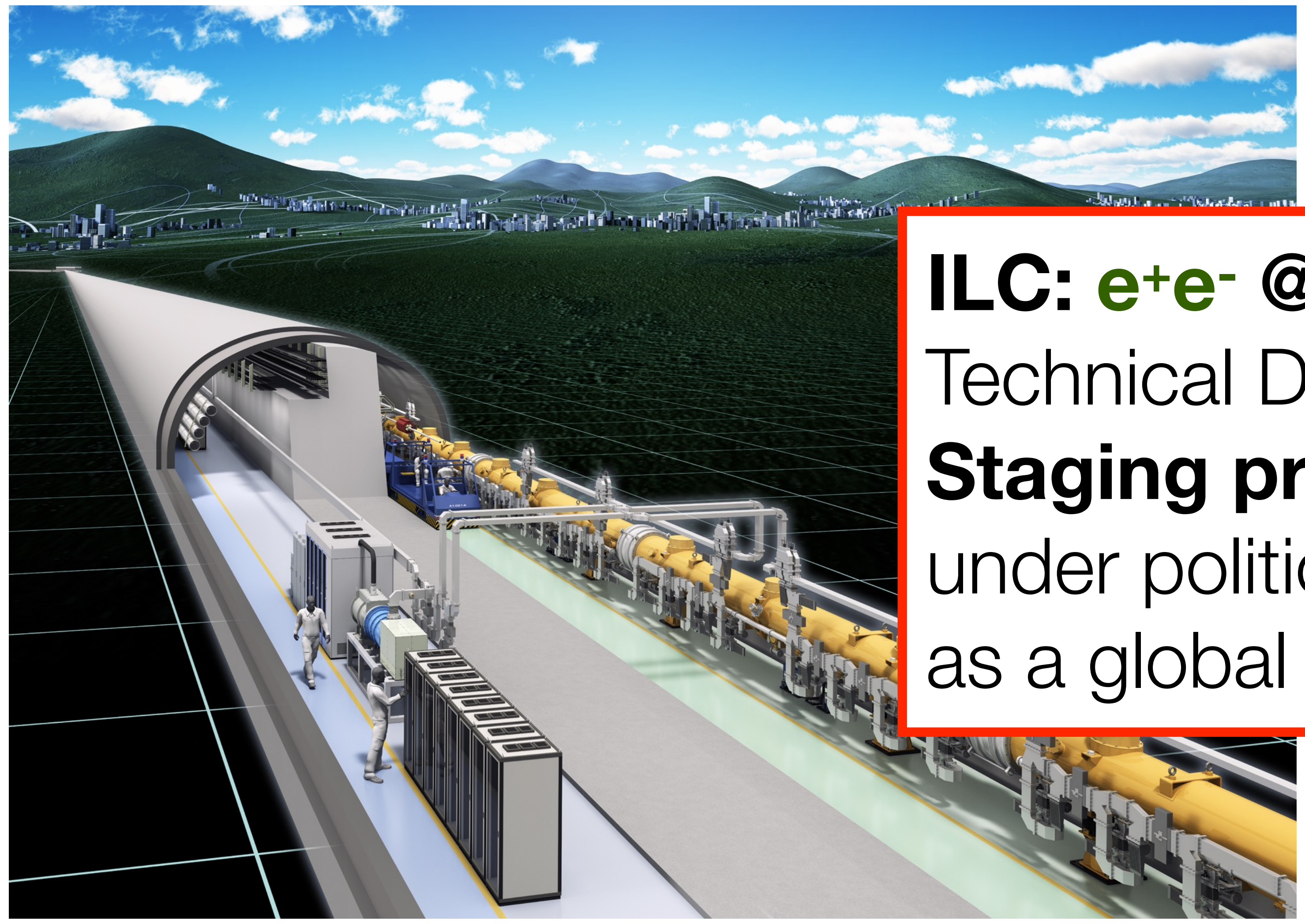

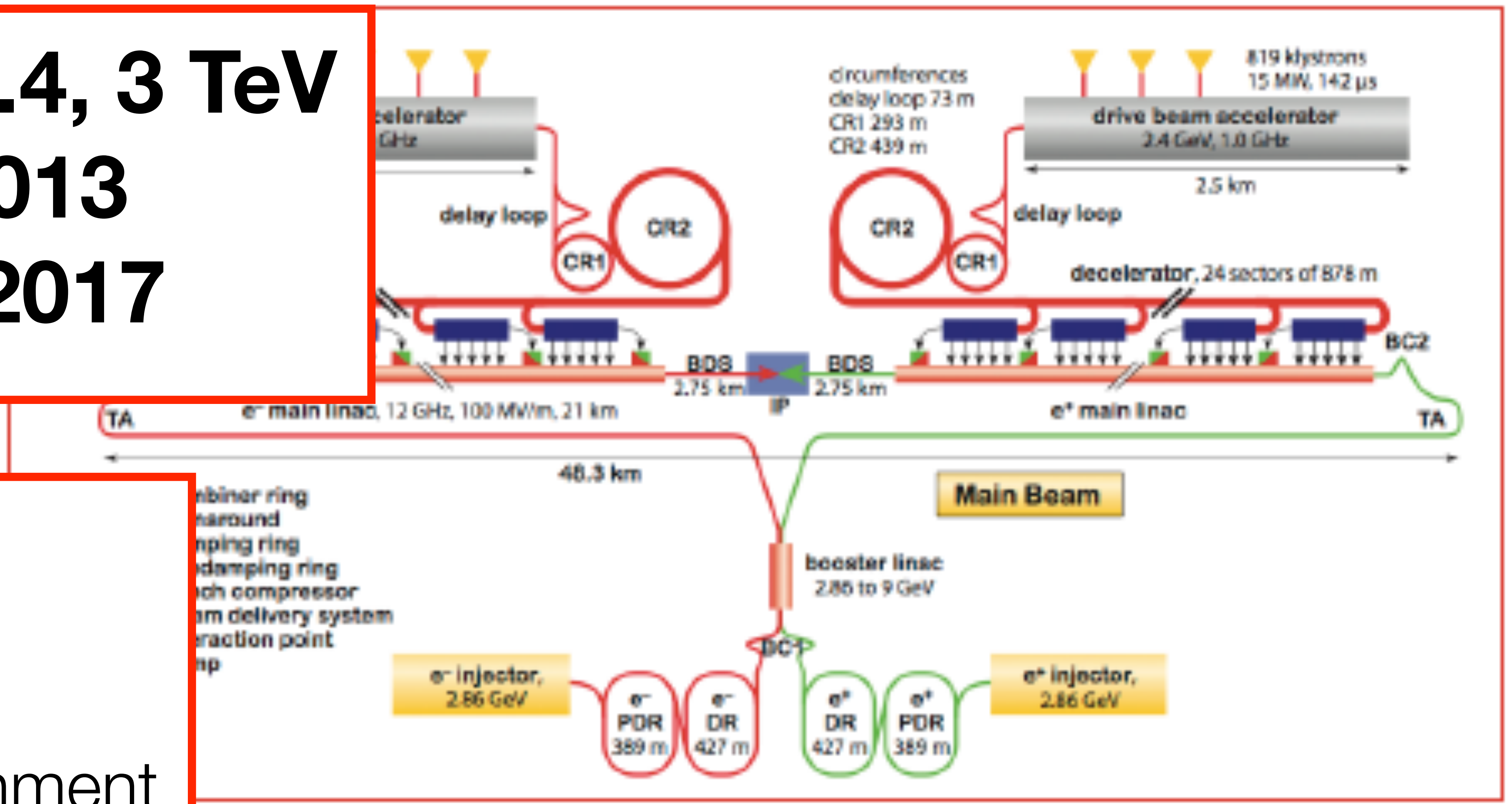

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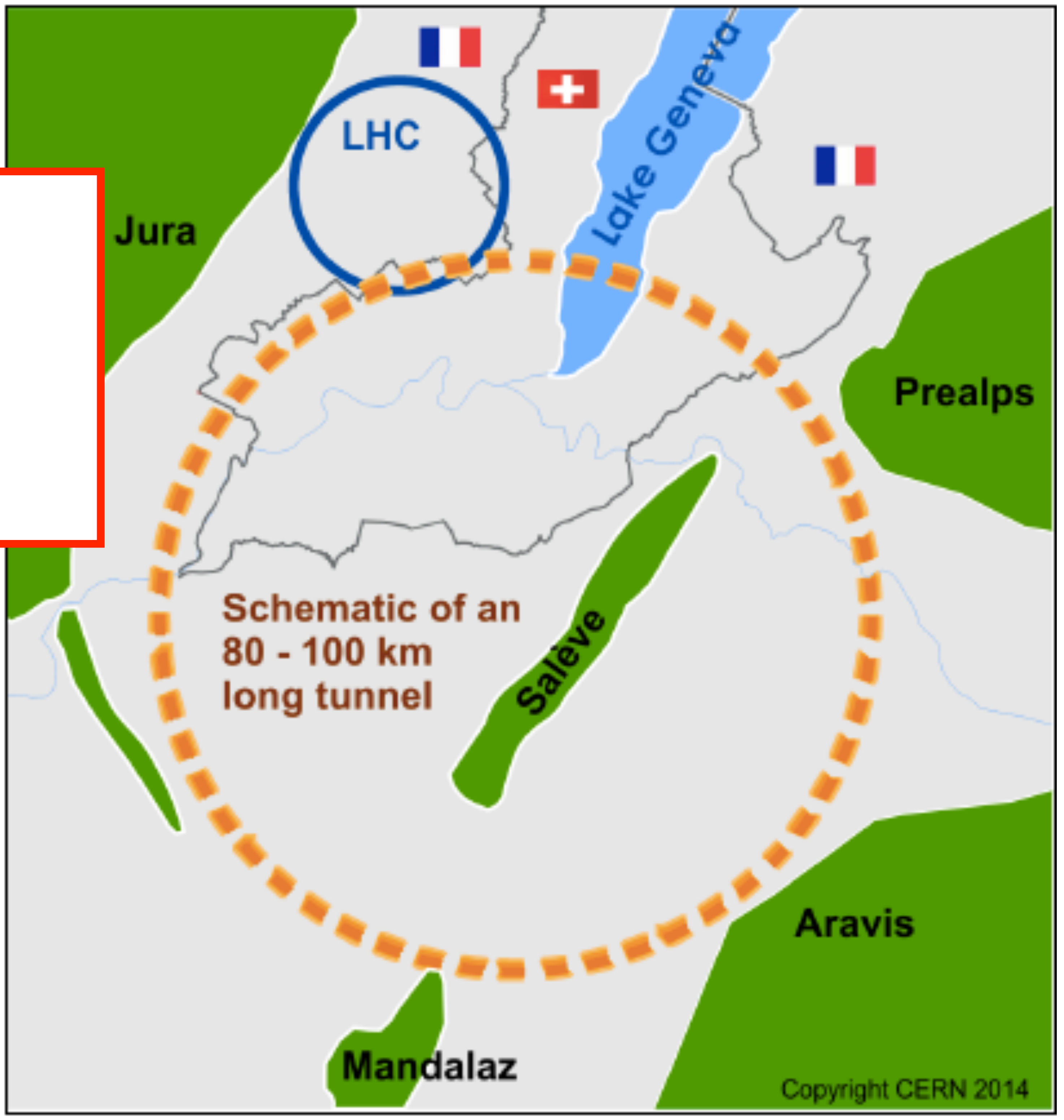
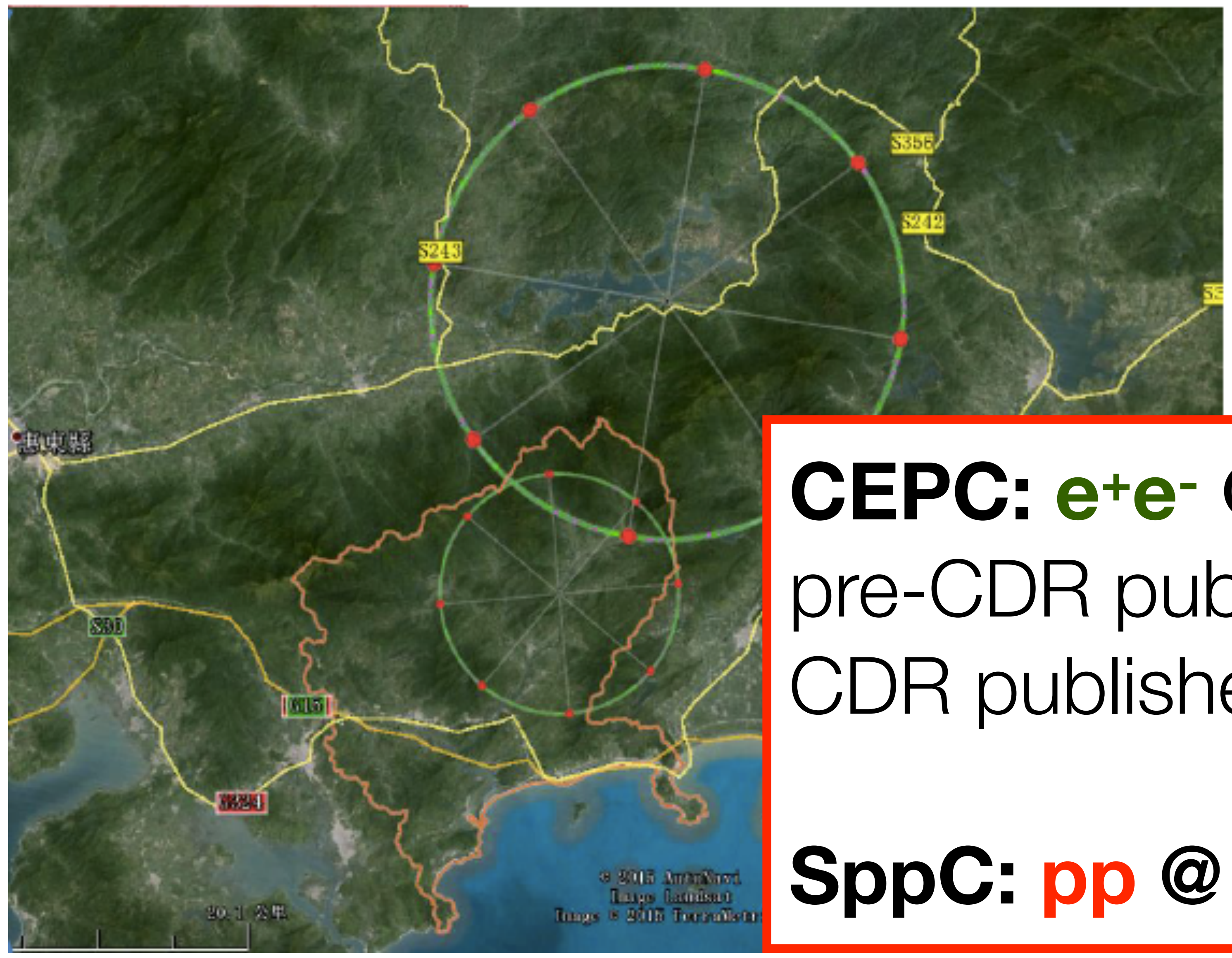


FCC: pp @ ~100 TeV
& precursor **FCCee e^+e^- @ 90-350 GeV**
Conceptual Design Rep. in **2018**

Currently: FCC Feasibility Study

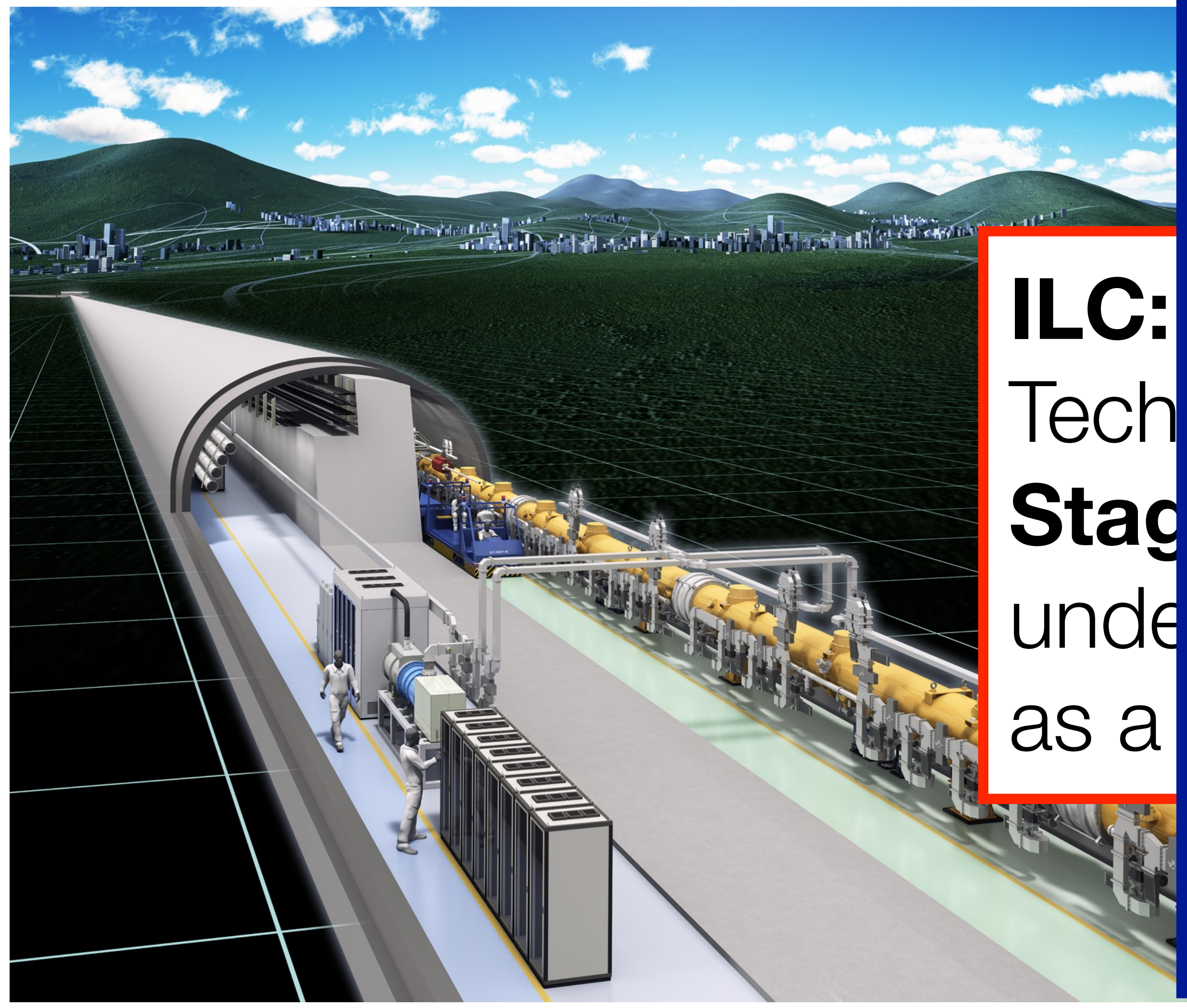


CEPC: e^+e^- @ 240 GeV
pre-CDR published in **2014**
CDR published **2018**

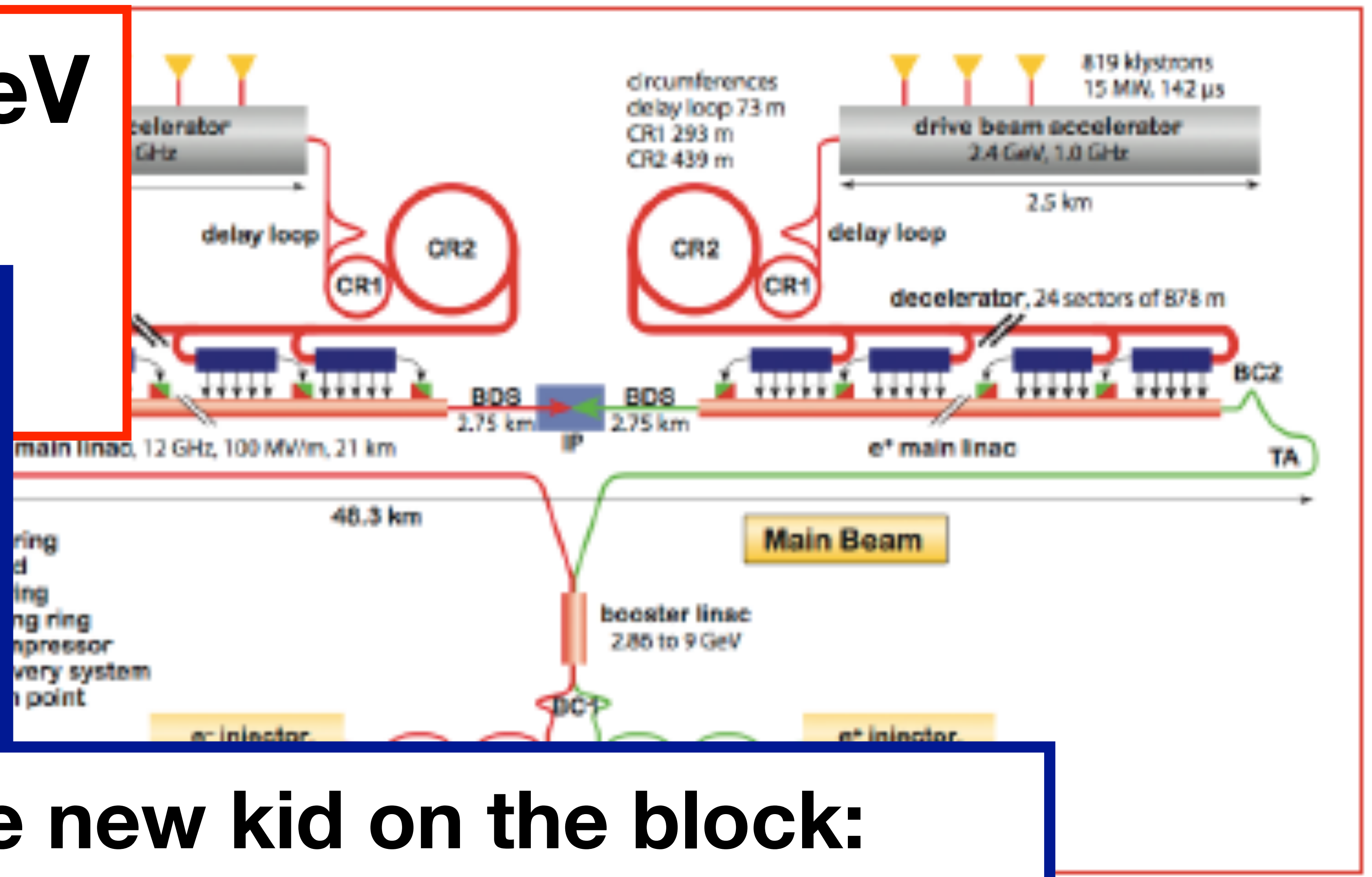
SppC: pp @ 50-70 TeV

The key contenders

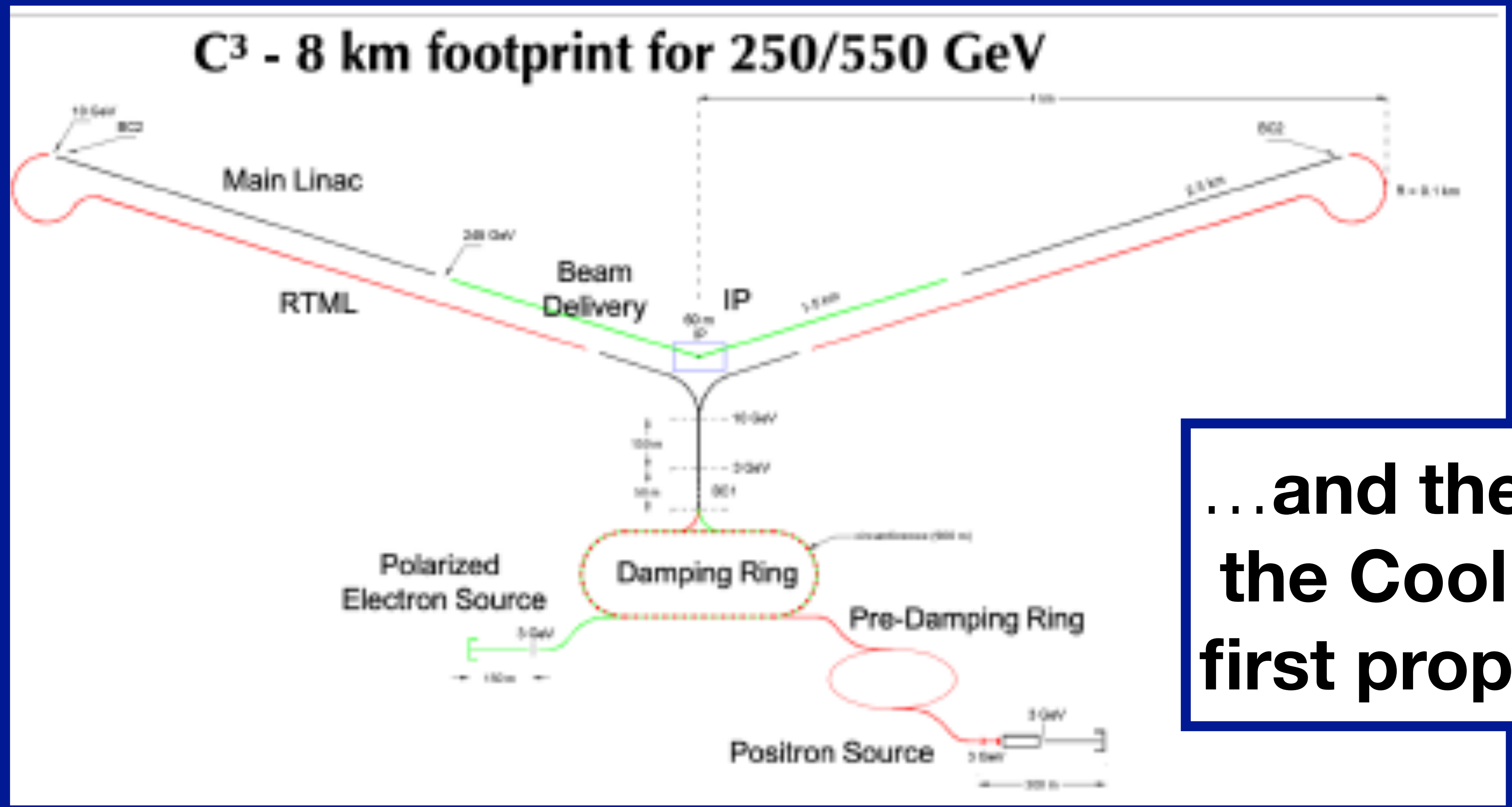
many ideas…



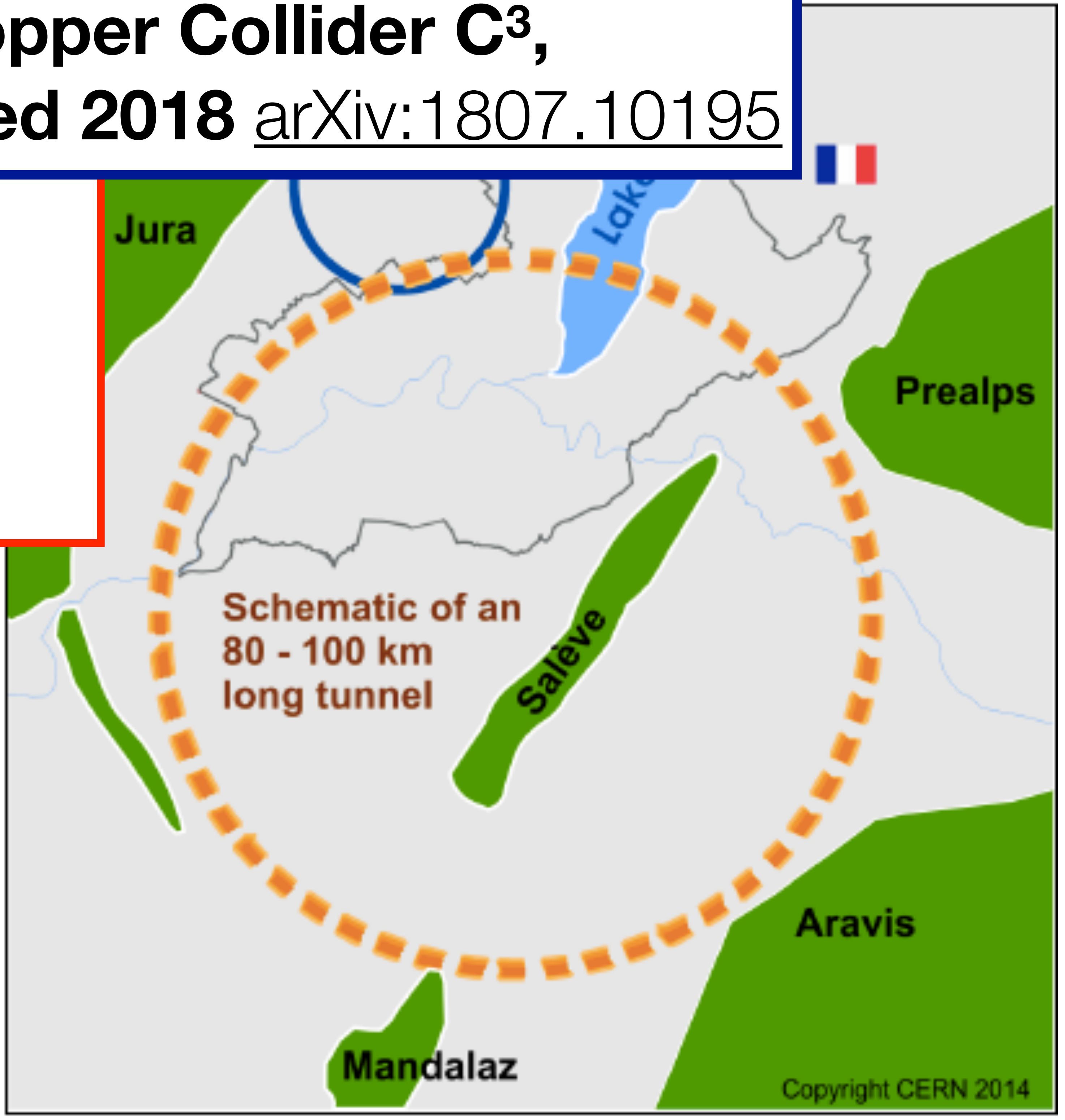
ILC:
Tech
Stag
unde
as a



CLIC: e^+e^- @ 0.38, 1.4, 3 TeV
Conceptual Design **2013**



…and the new kid on the block:
the Cool Copper Collider C^3,
first proposed 2018 arXiv:1807.10195



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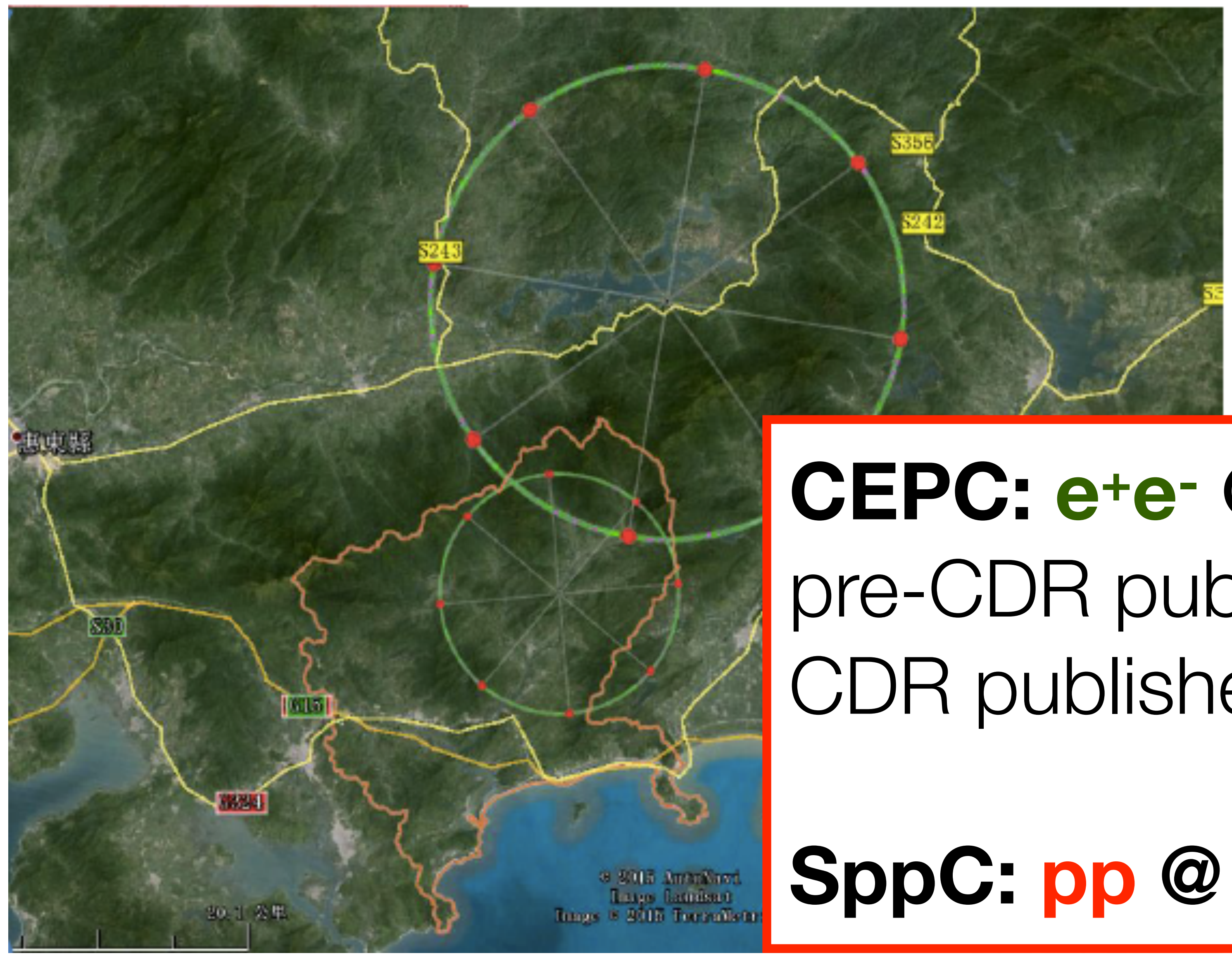

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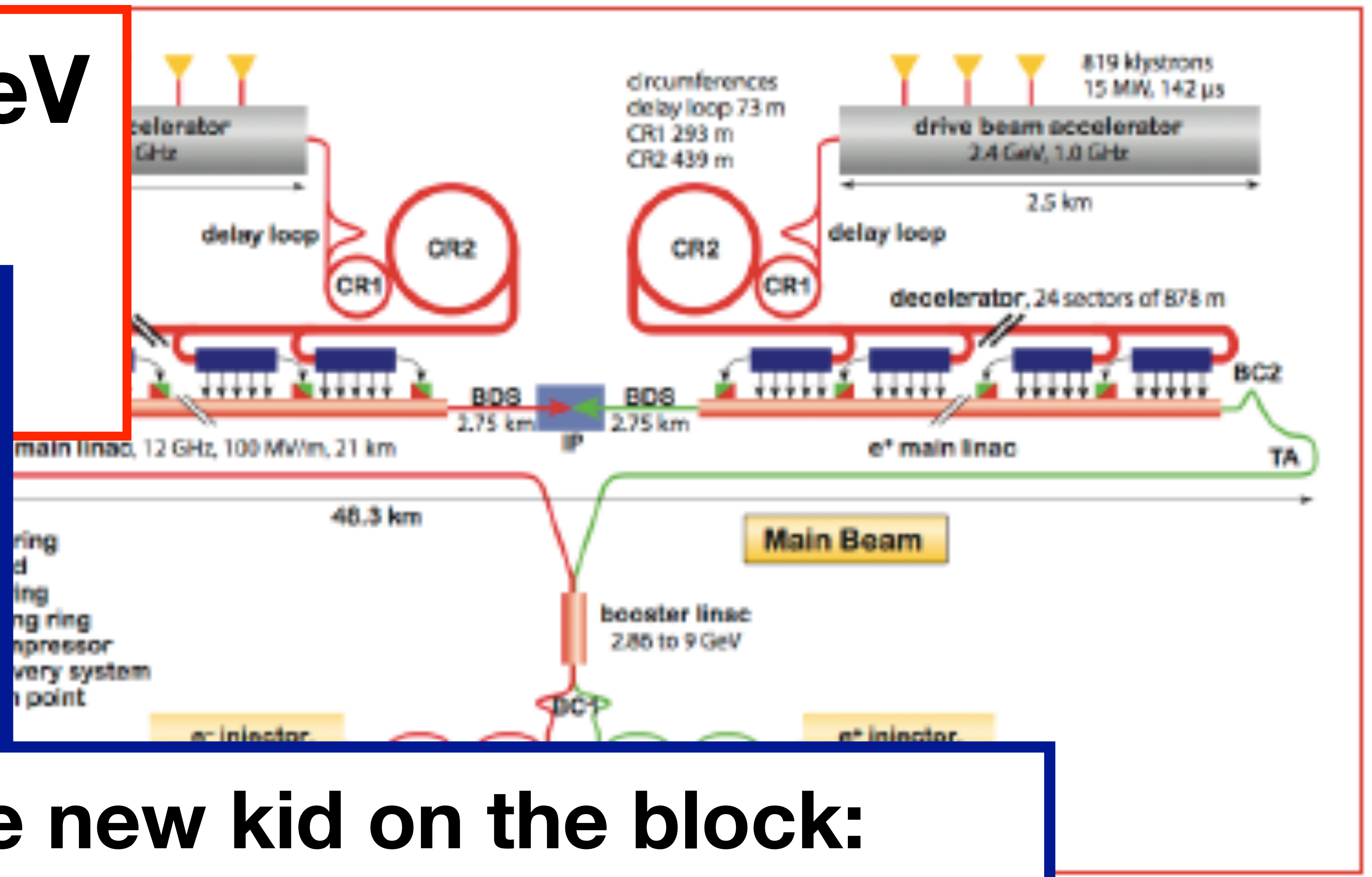

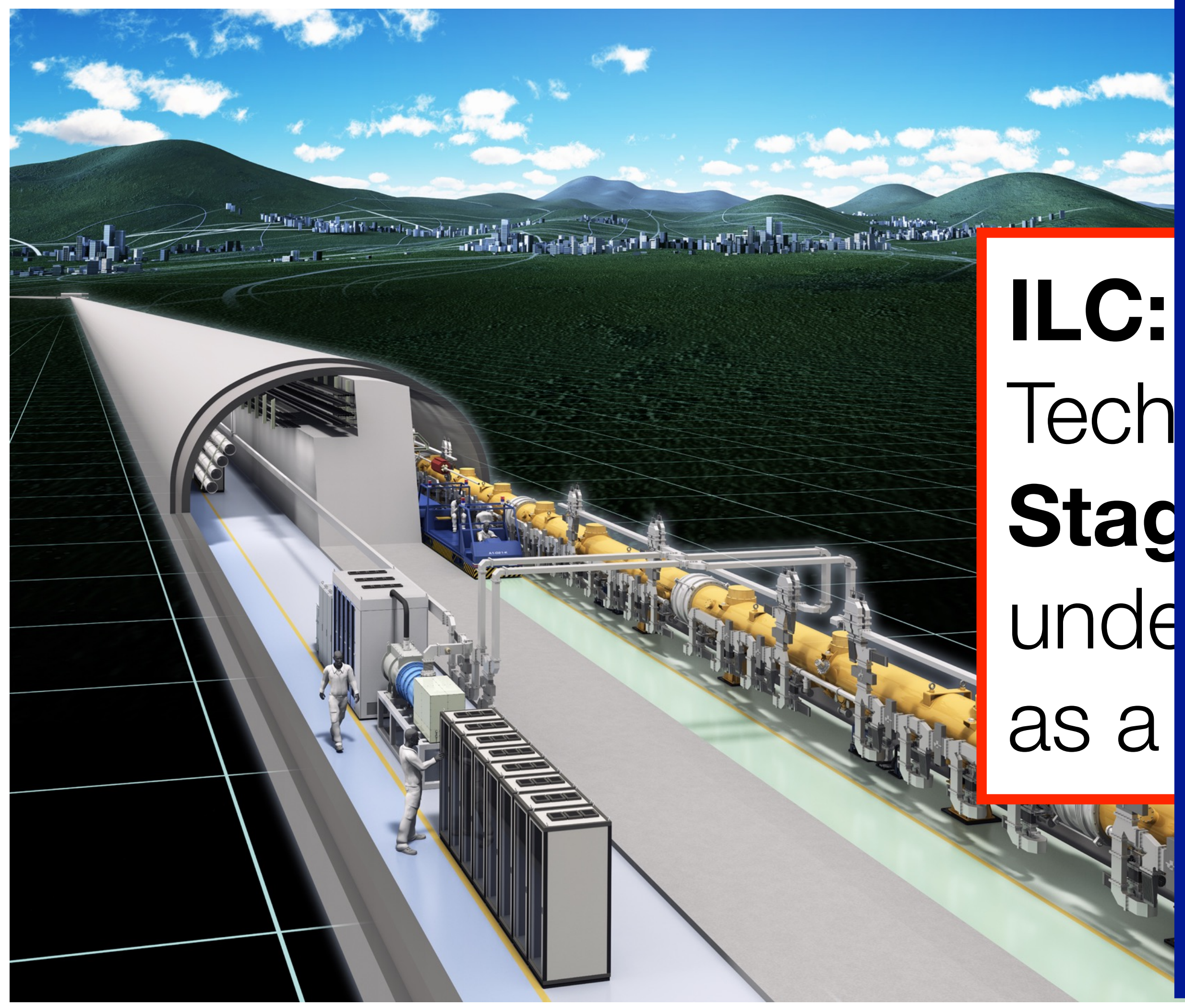

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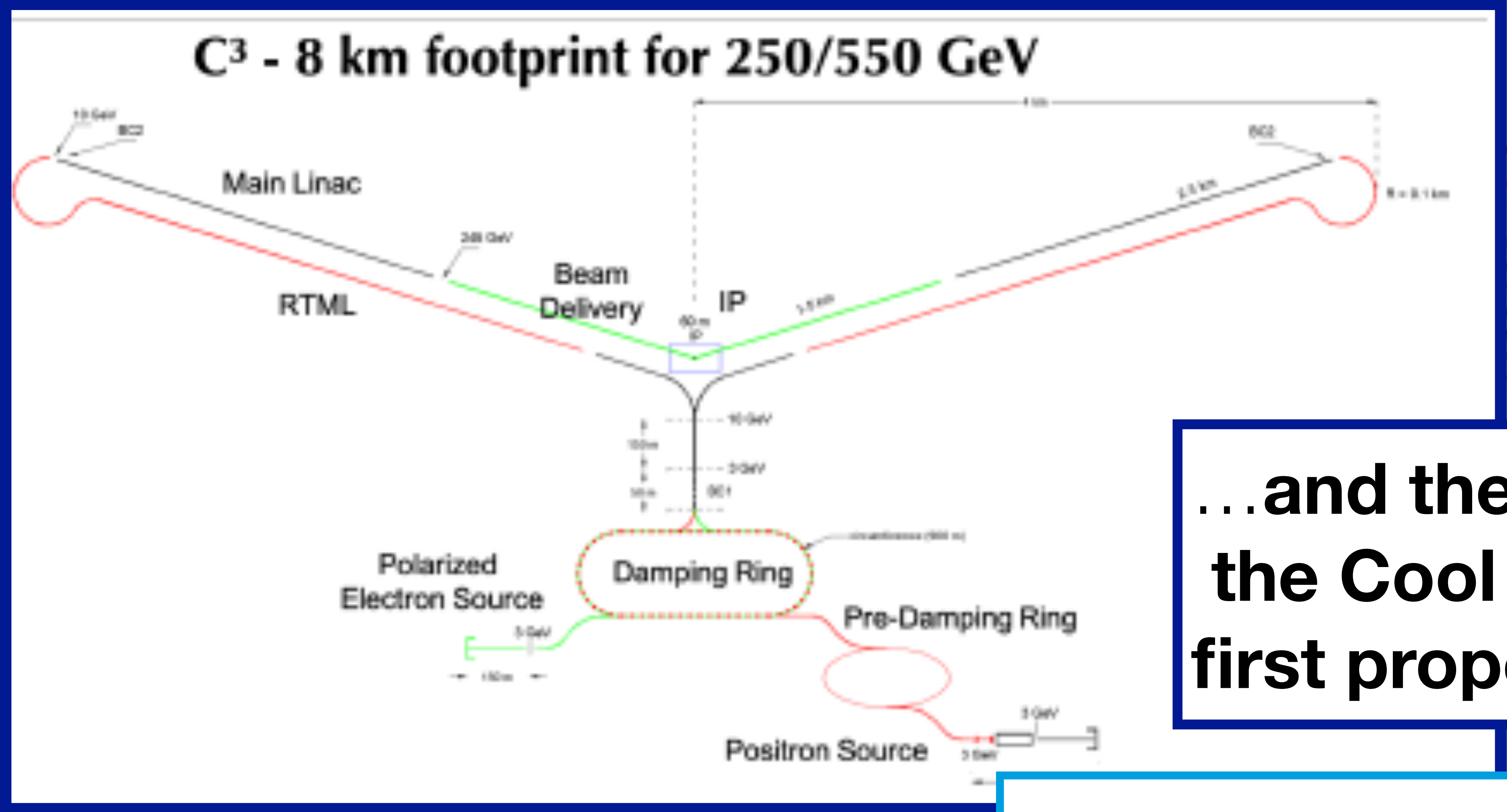

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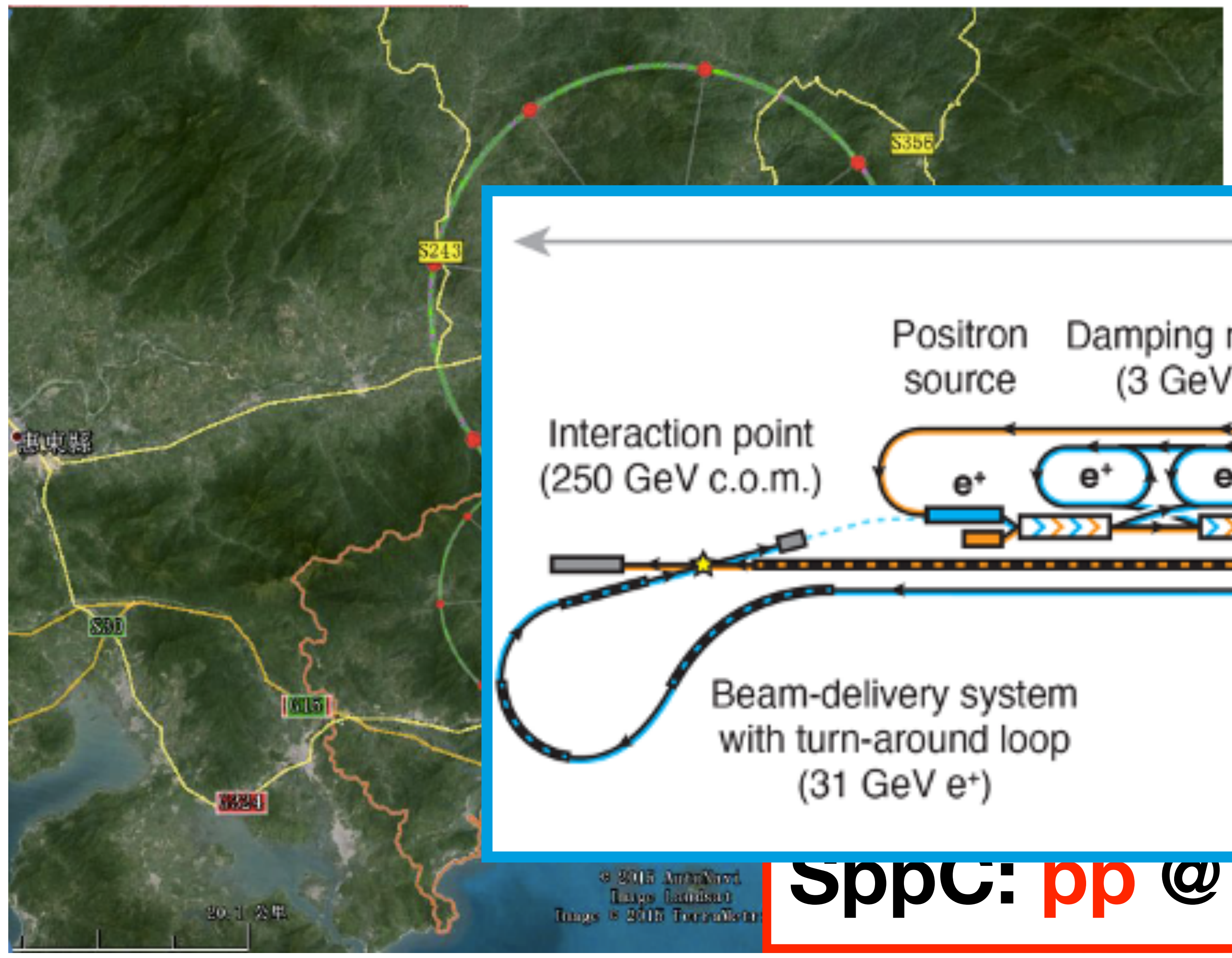

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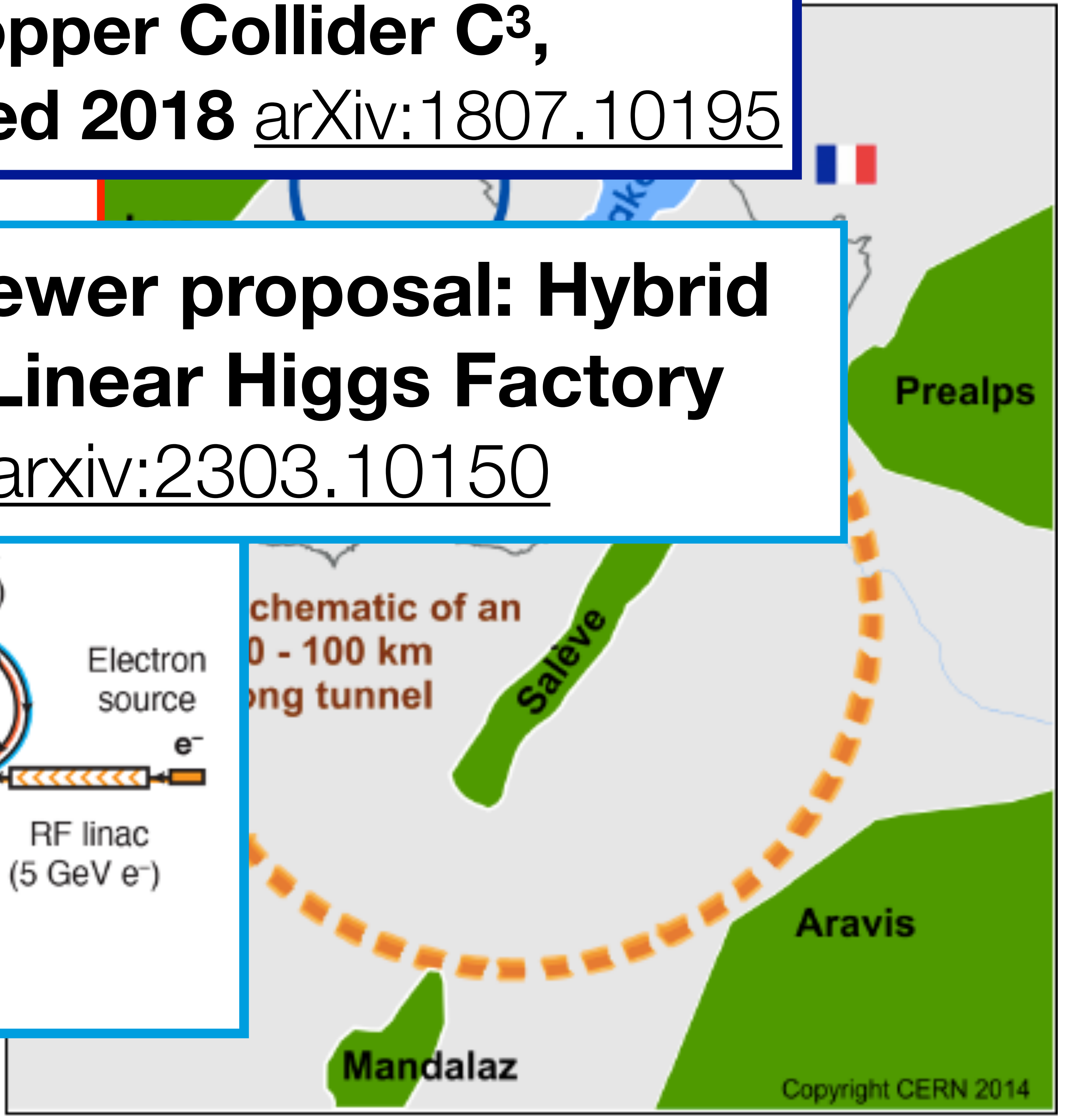
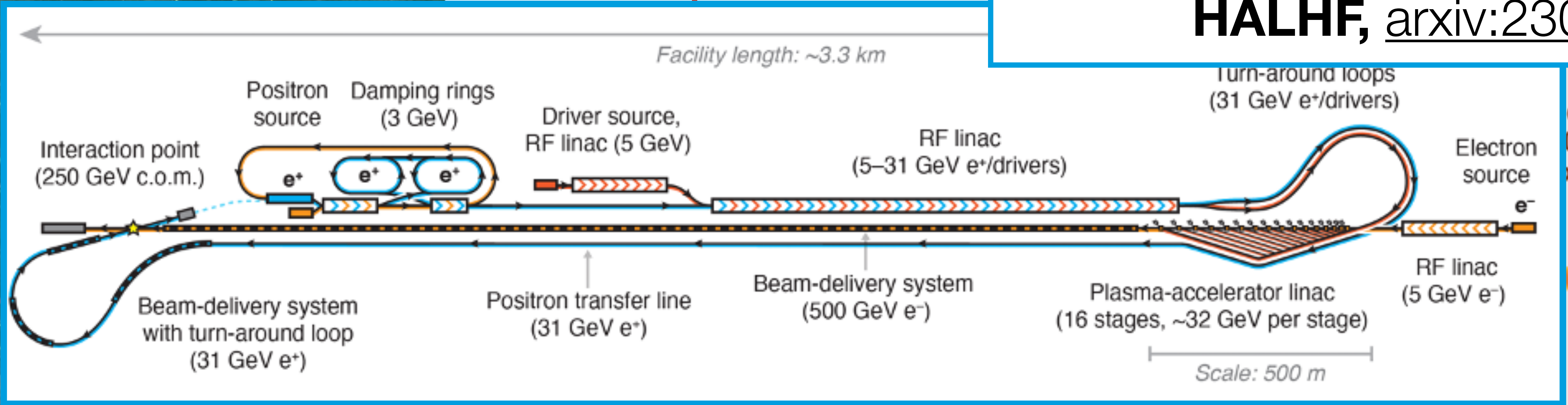


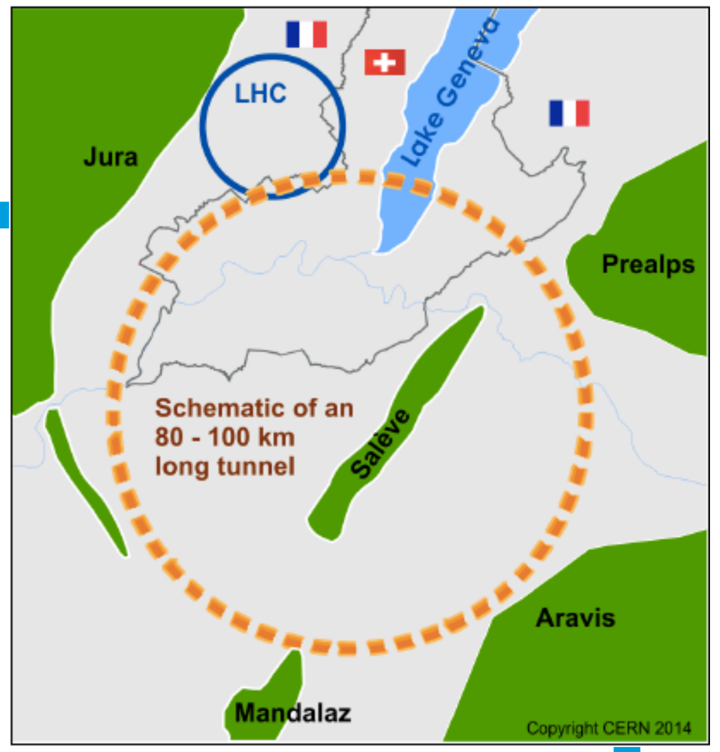
and an even newer proposal: Hybrid Asymmetric Linear Higgs Factory HALHF, arxiv:2303.10150



SppC: pp @ 50-70 TeV

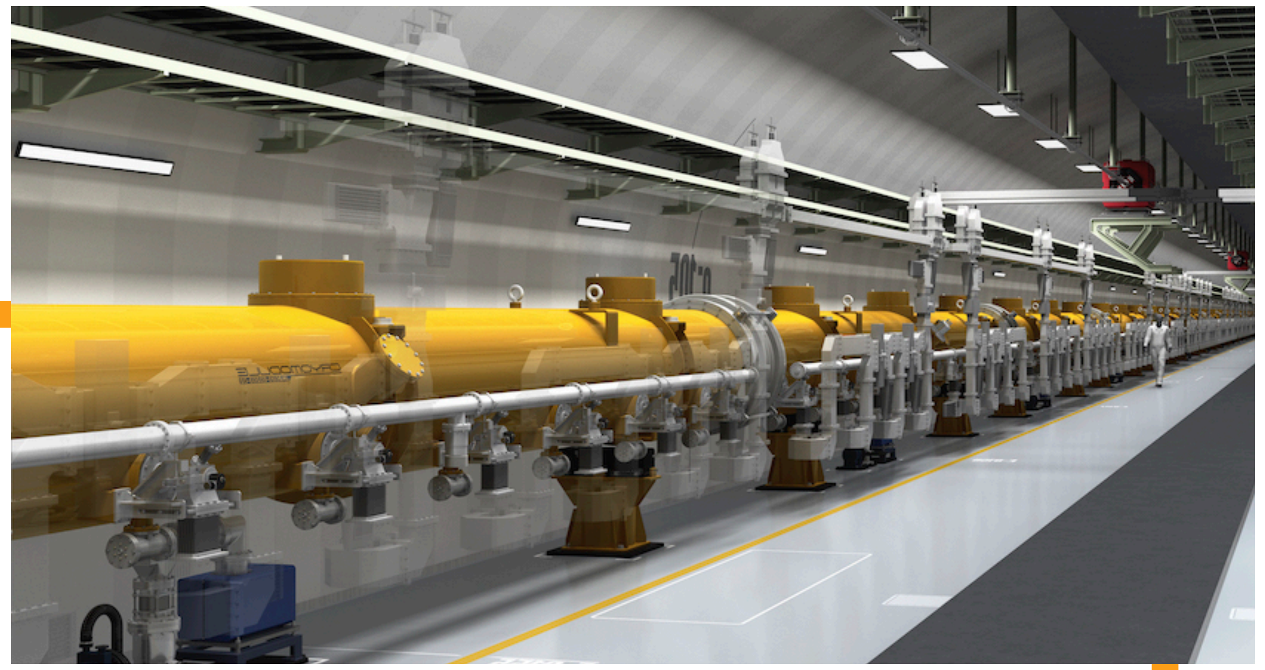
They fall into two classes

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, C^3, …
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- **spin-polarised beam(s)**

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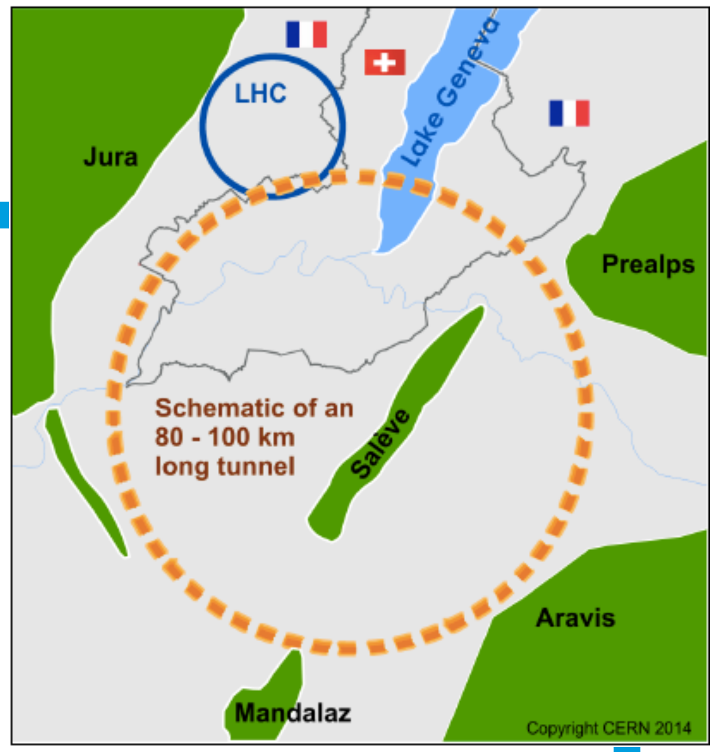

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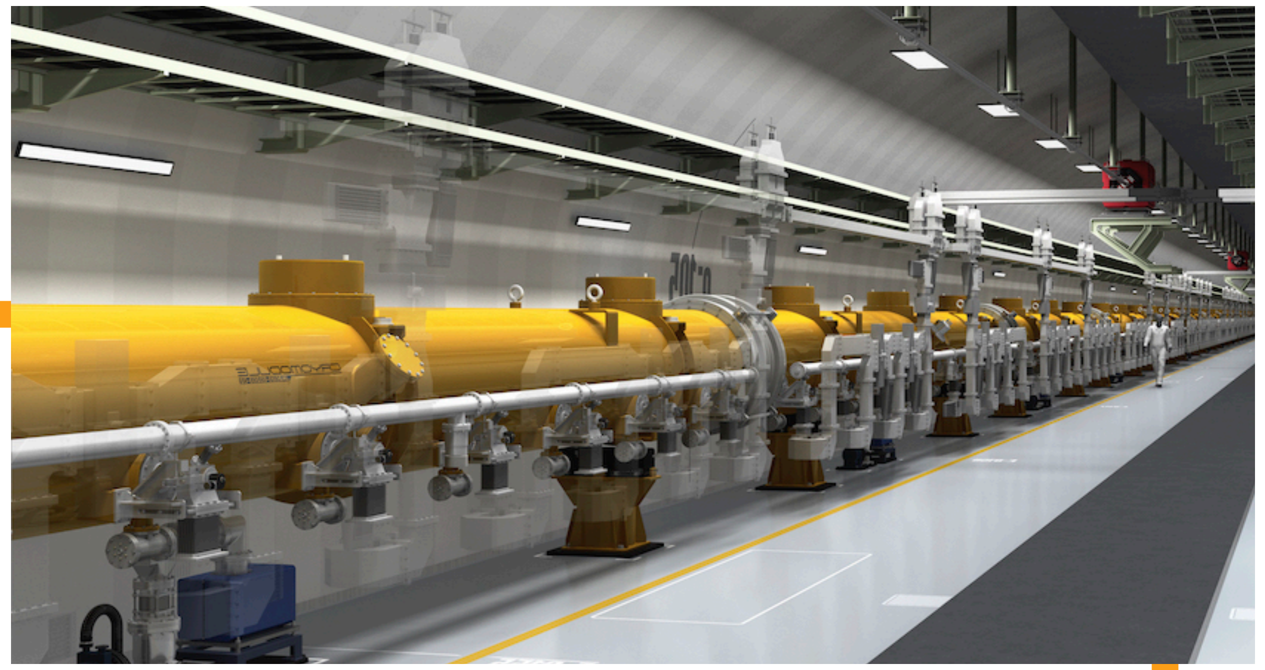

Linear Colliders

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- length 250 GeV: ~10…20 km
- high luminosity & power efficiency at **high energies**
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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 acceleration ?

Linear or circular - economically

accelerated charges radiate….

1978[1)]

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

    optimize => $R \sim E^2$ => $\$\$ \sim E^2$
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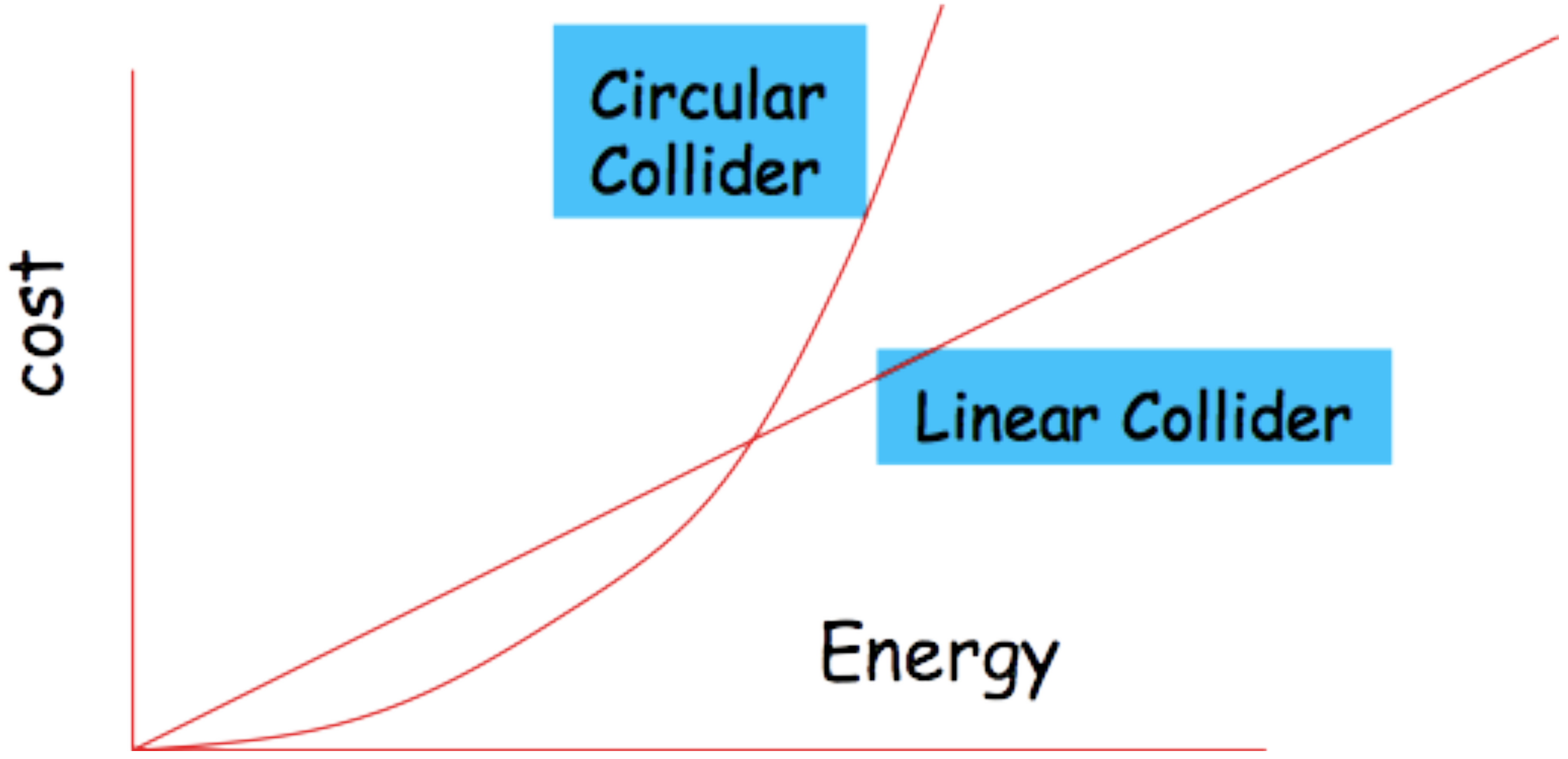

LIMITATIONS ON PERFORMANCE OF e^+e^- STORAGE RINGS AND LINEAR COLLIDING BEAM SYSTEMS AT HIGH ENERGY

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

Introduction

This note is the report of working Group I (J. Rees - Group Leader). We were assisted at times by U. Amaldi and E. Keil of CERN. We concerned ourselves primarily with the technical limitations which might present themselves to those planning a new and higher-energy electron-positron colliding-beam facility in a future era in which, it was presumed, a 70-GeV to 100-GeV LEP-like facility would already exist. In such an era, we reasoned, designers would be striving for center-of-mass energies of at least 700-GeV to 1-TeV. Two different approaches to this goal immediately came to the fore: one, a storage ring based on the principles of PEP, PETRA, and LEP and the other, a system in which a pair of linear accelerators are aimed at one another so that their beams will collide. We realized early in the study that a phenomenon which has been negligible in electron-positron systems designed to date would become important at these higher energies - synchrotron radiation from a particle being deflected by the collective electromagnetic field of the opposing bunch - and we dubbed this phenomenon "beam-strahlung." During the rest of the week we investigated the scaling laws for these two colliding-beam systems taking beam-strahlung into consideration.

1) allererstes Papier zum Thema: M.Tigner 1965

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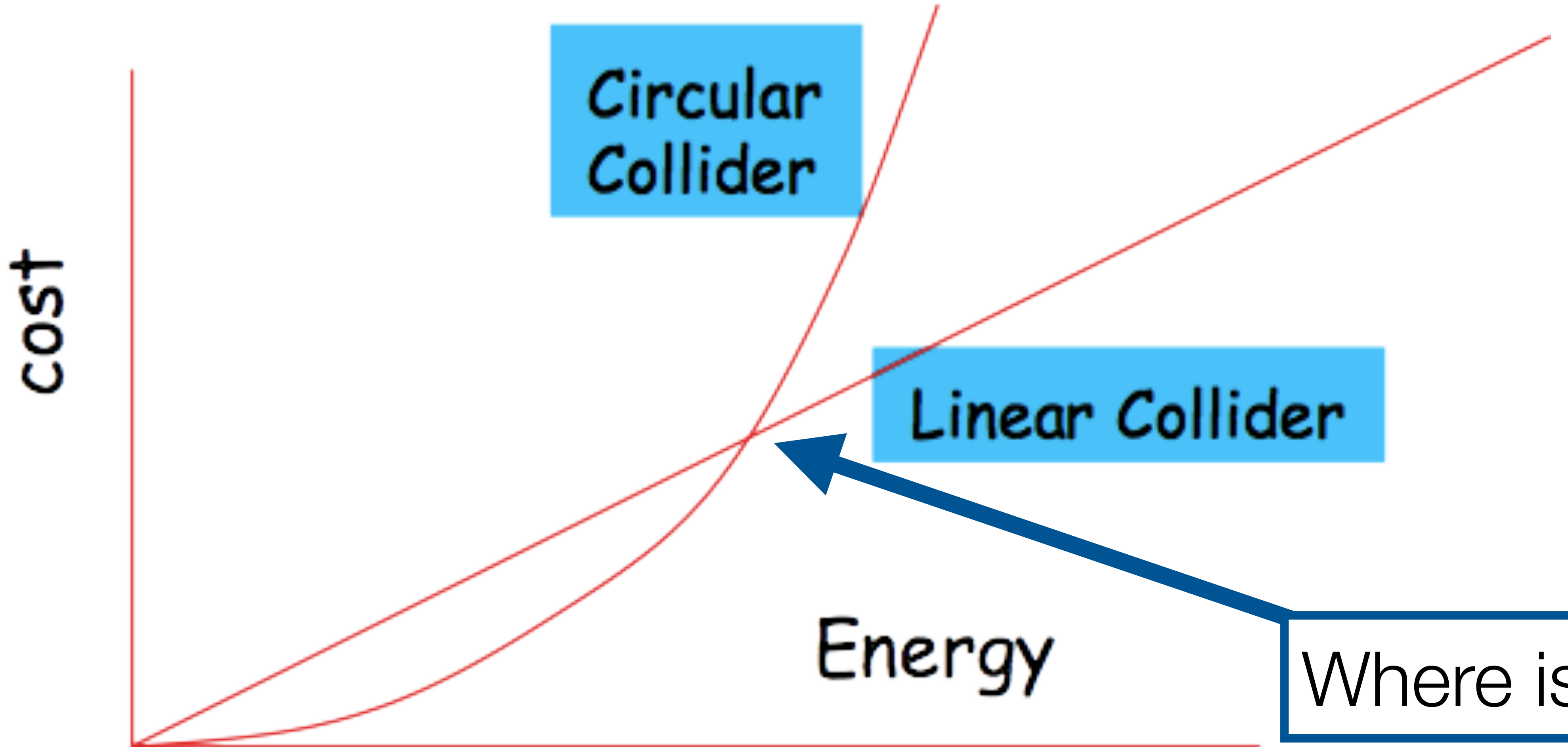
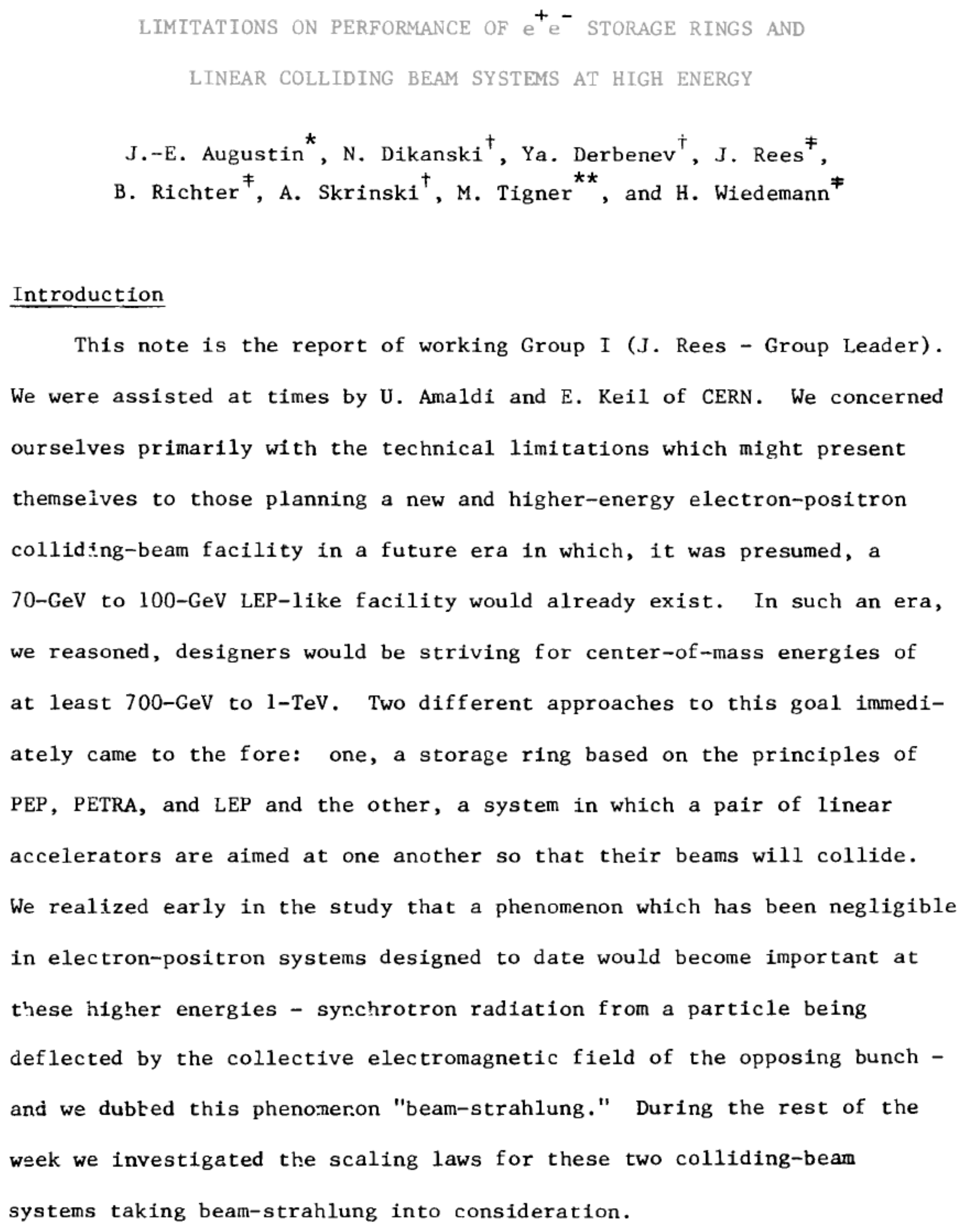


Where is the crossing point?

1978[1)]



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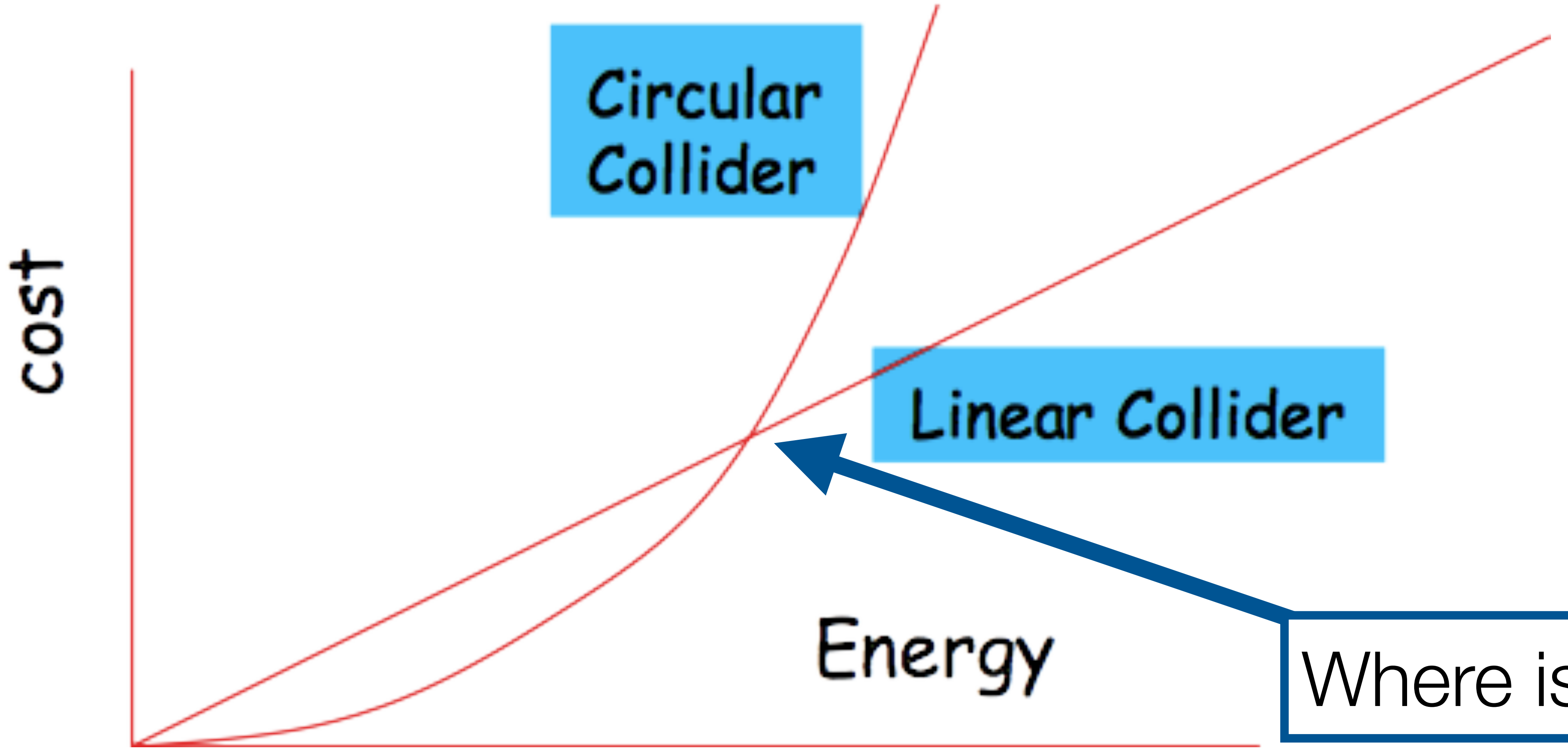

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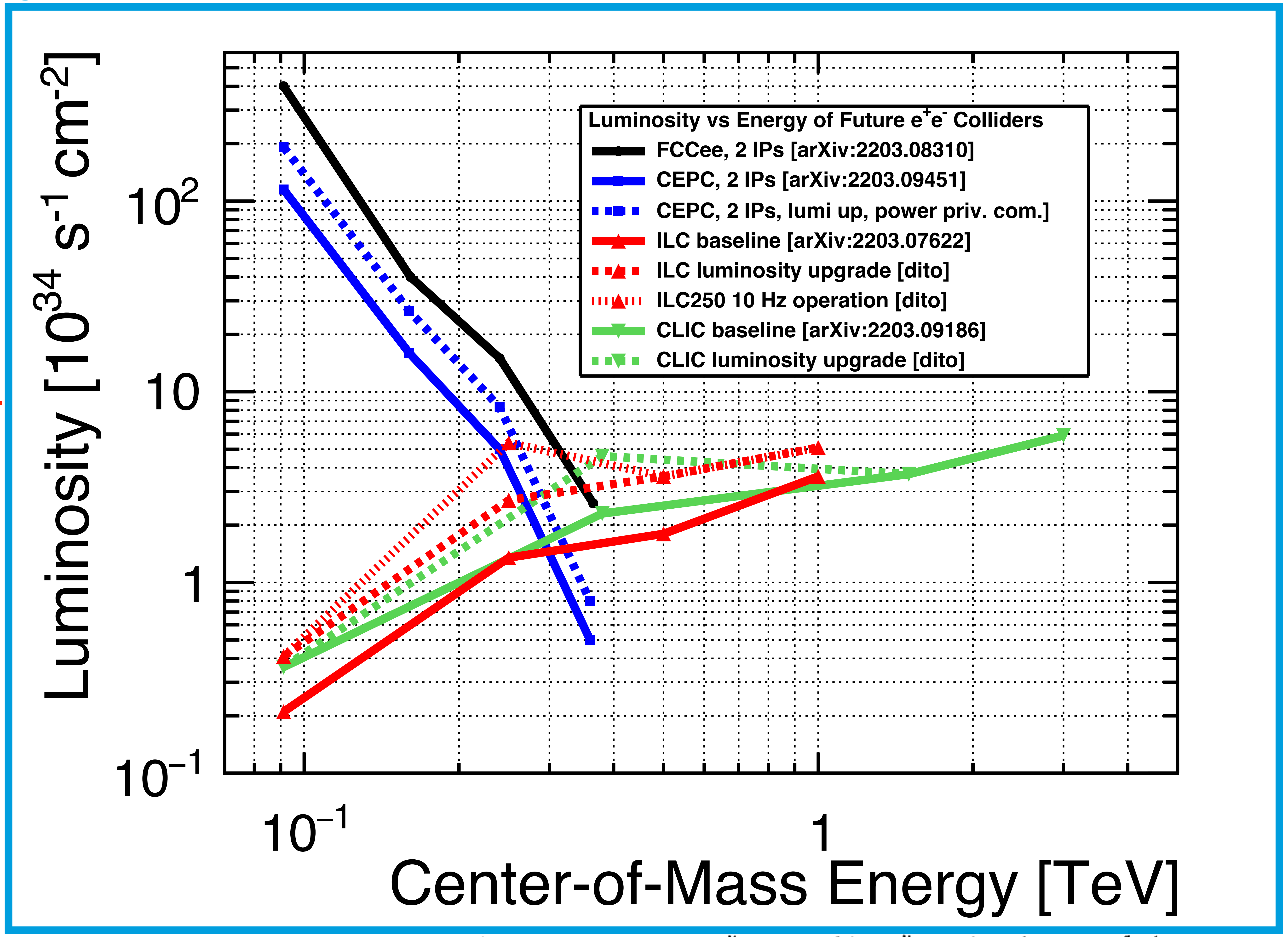

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Sustainability

In 2016 .....

Additional Design Considerations

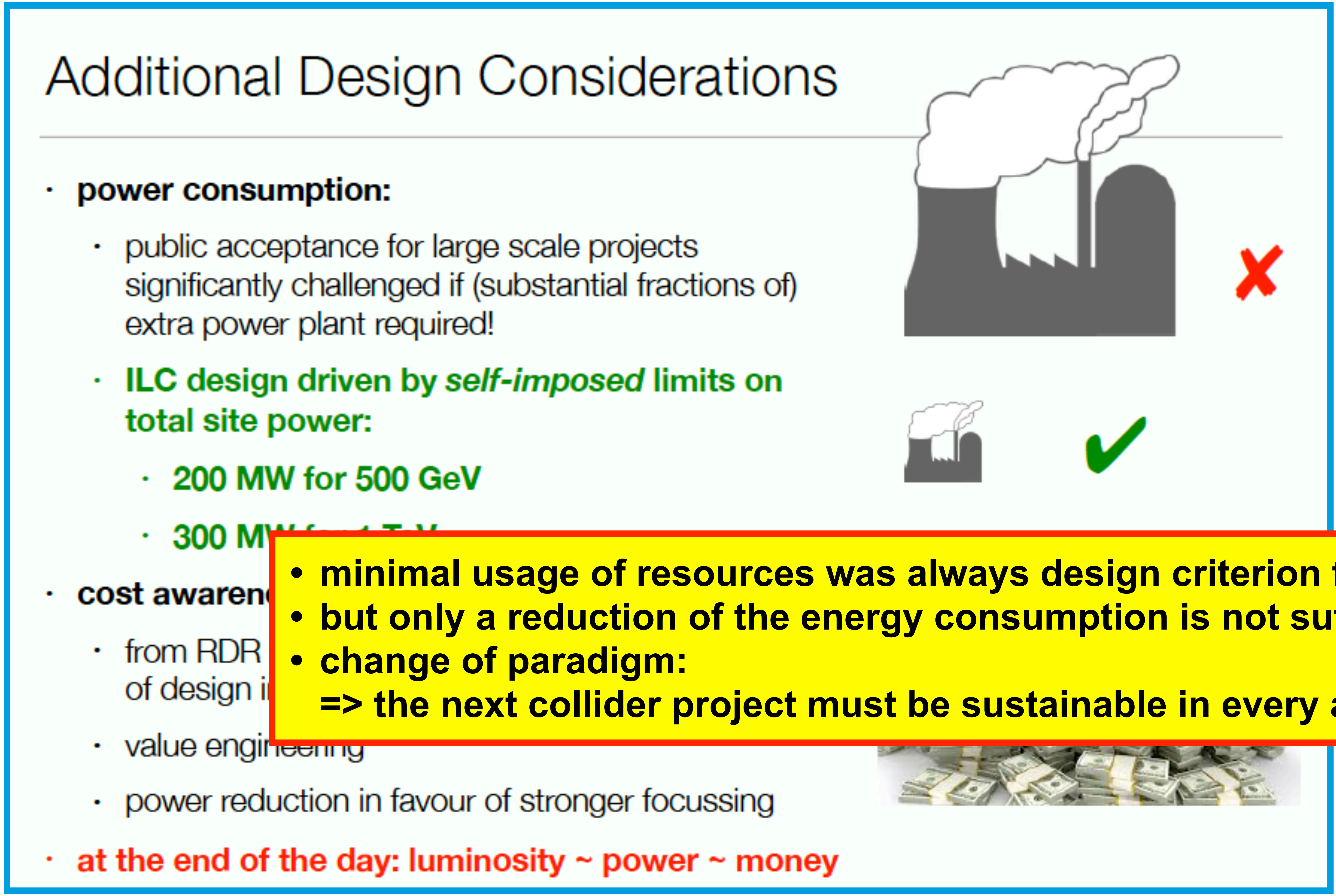
- **power consumption:**
  - public acceptance for large scale projects significantly challenged if (substantial fractions of) extra power plant required!
  - **ILC design driven by *self-imposed* limits on total site power:**
    - **200 MW for 500 GeV**
    - **300 MW for 1 TeV**

- **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

In 2016 …..



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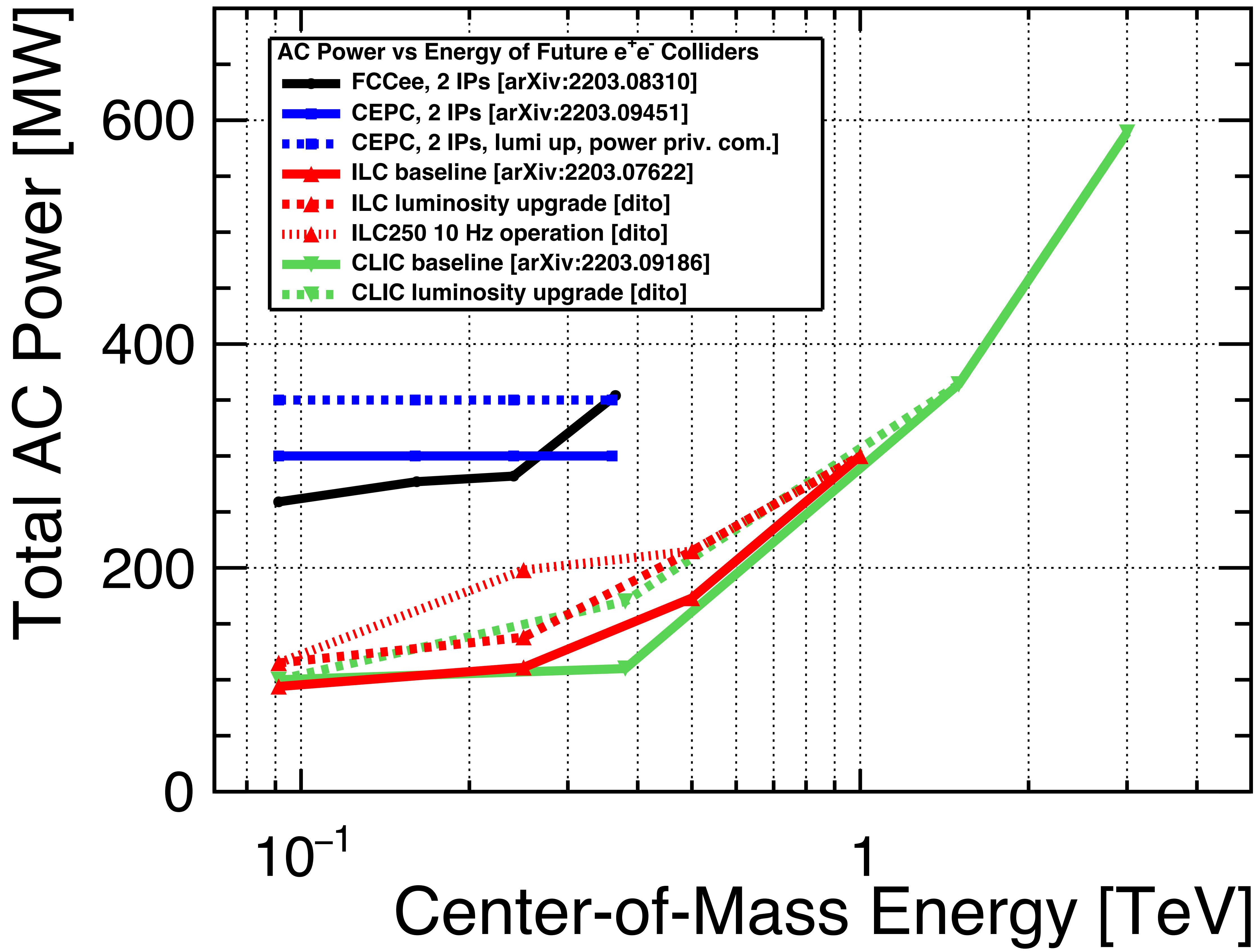
- **minimal usage of resources was always design criterion for serious projects**
- **but only a reduction of the energy consumption is not sufficient anymore**
- **change of paradigm:**
  => the next collider project must be sustainable in every aspect

… 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 consumtion
  - **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, components etc**
  - minimize civil construction
  - use concrete with low(er) CO2 emission
  - avoid usage of rare earths and other problematic substances



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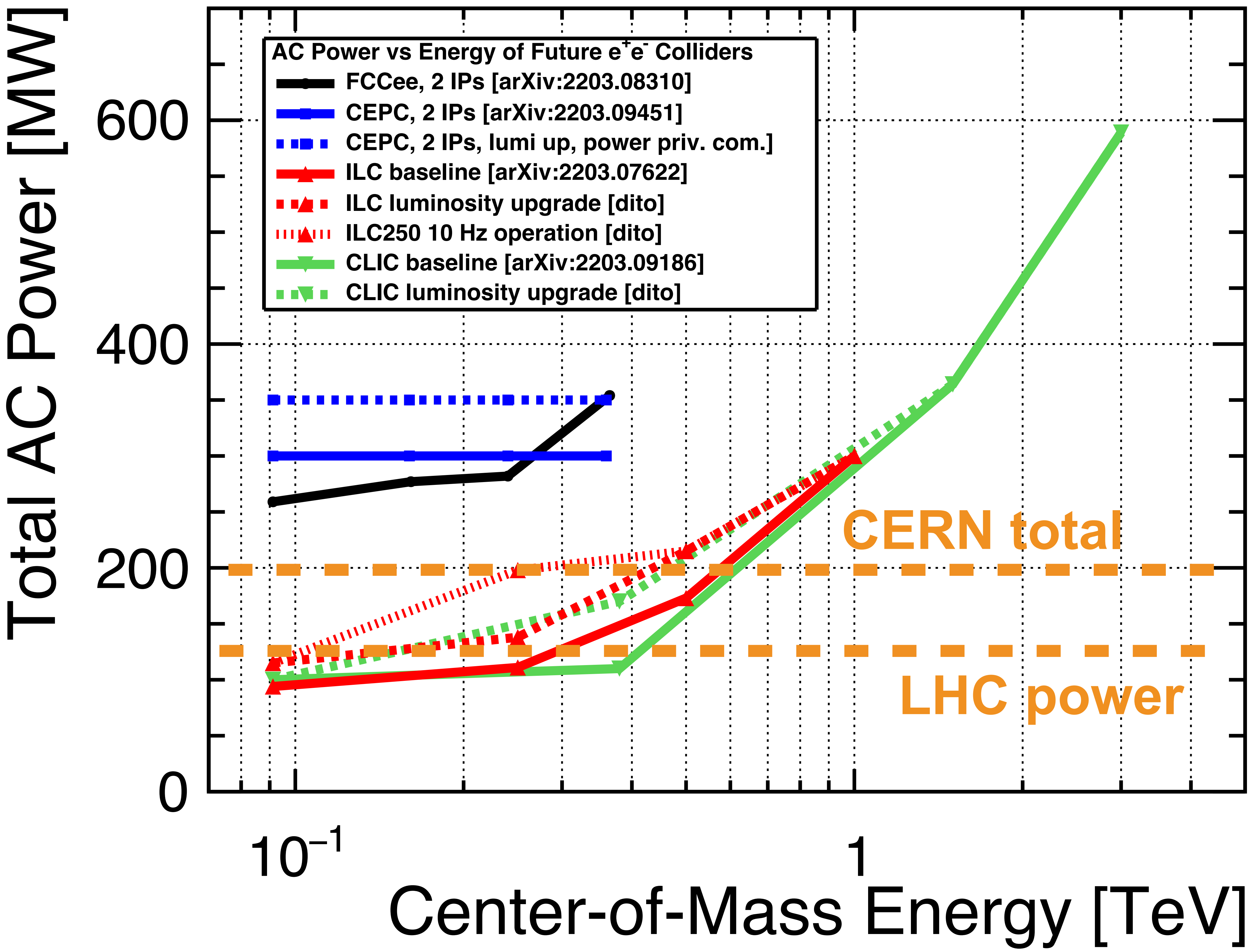

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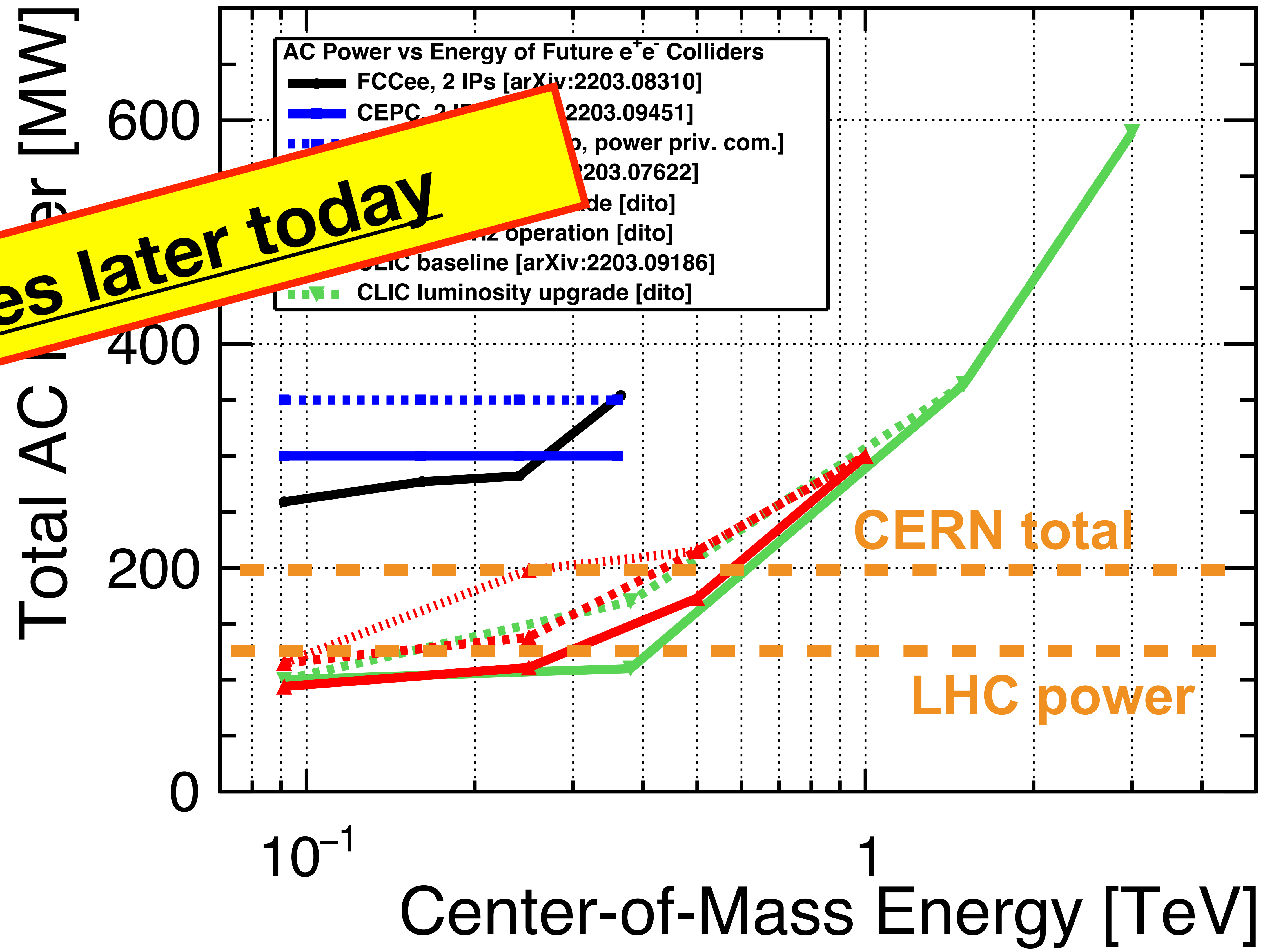
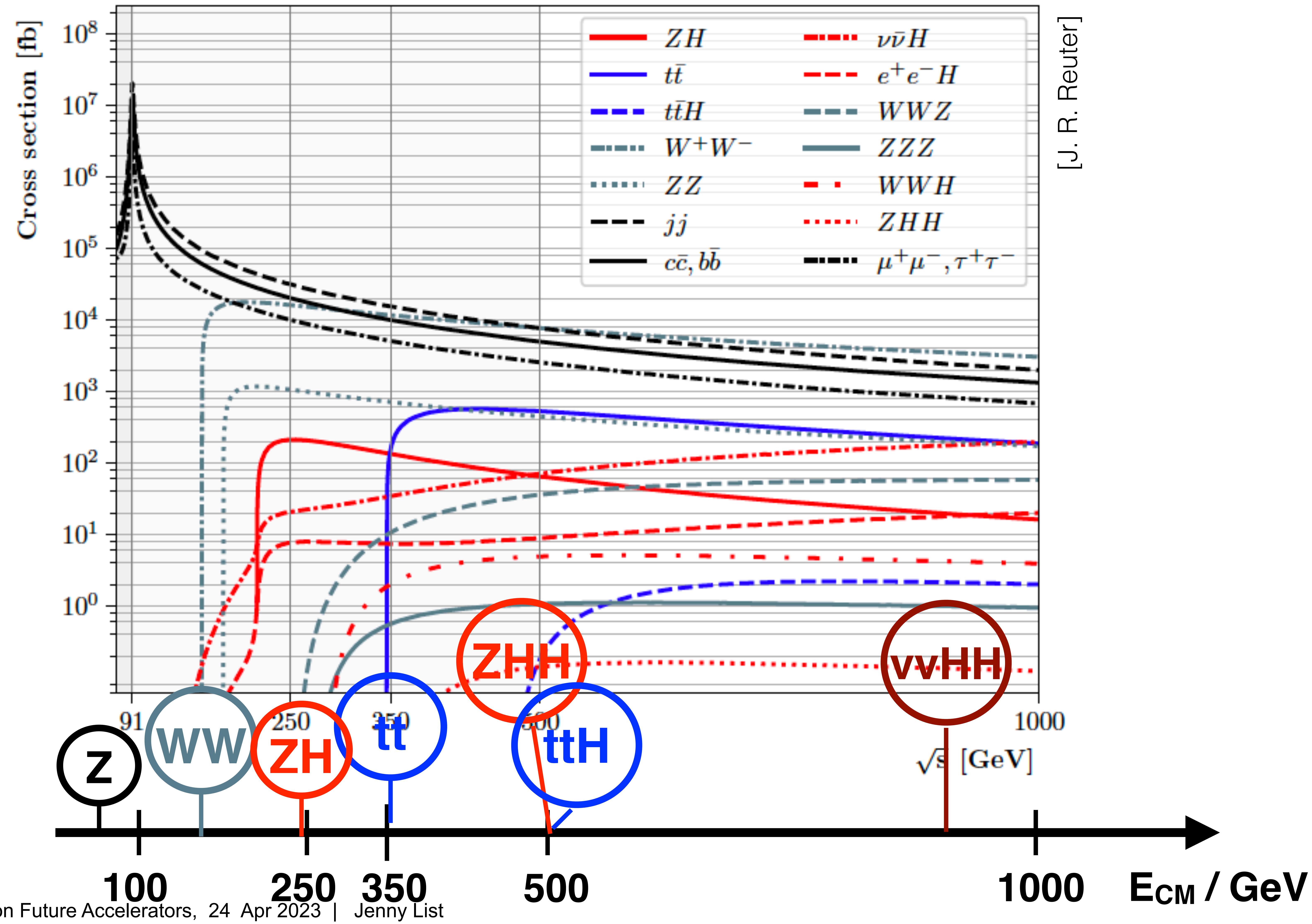
=> see talk by S.Stapnes later today



Linear or circular - physics

Production rates vs collision energy



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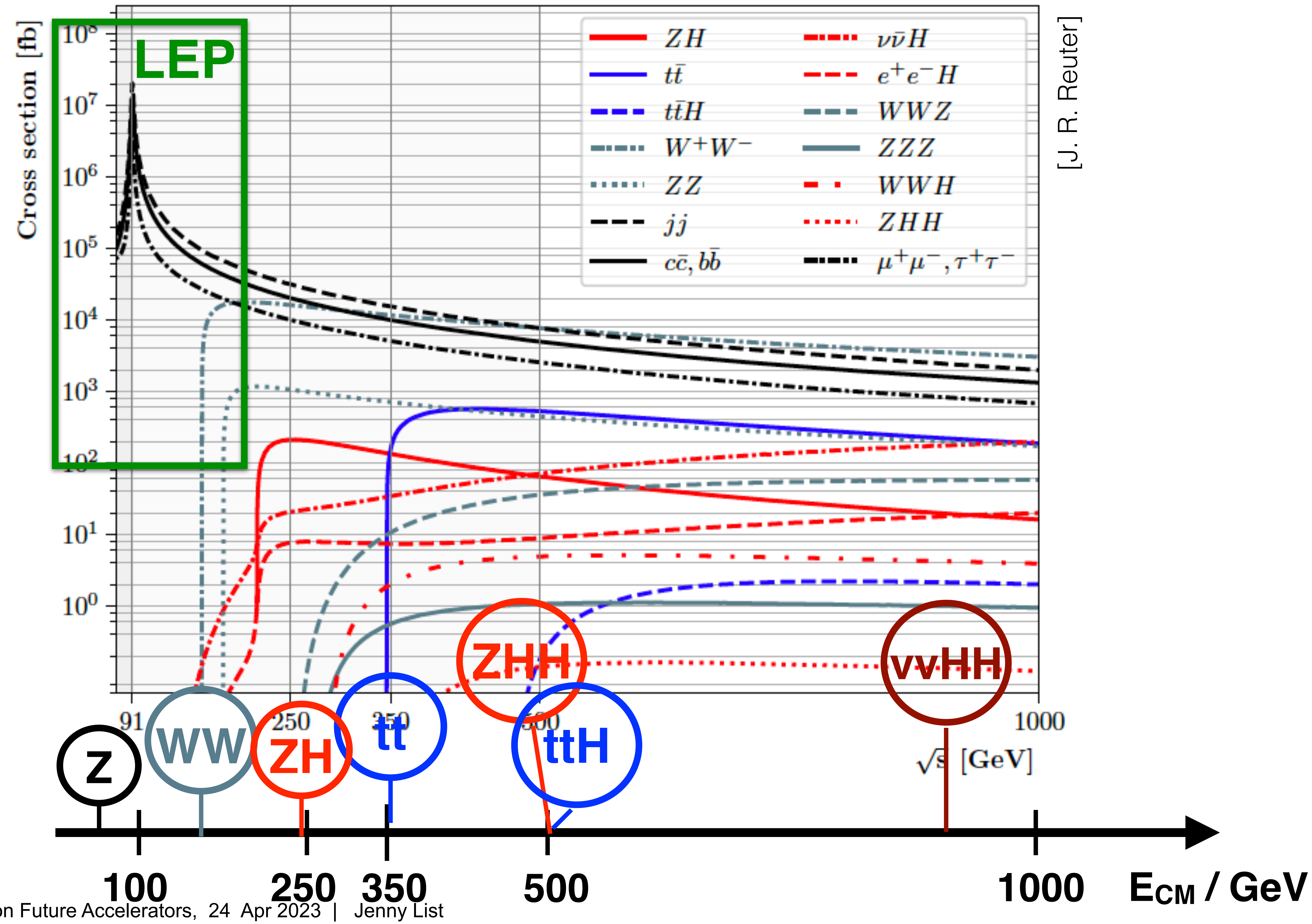

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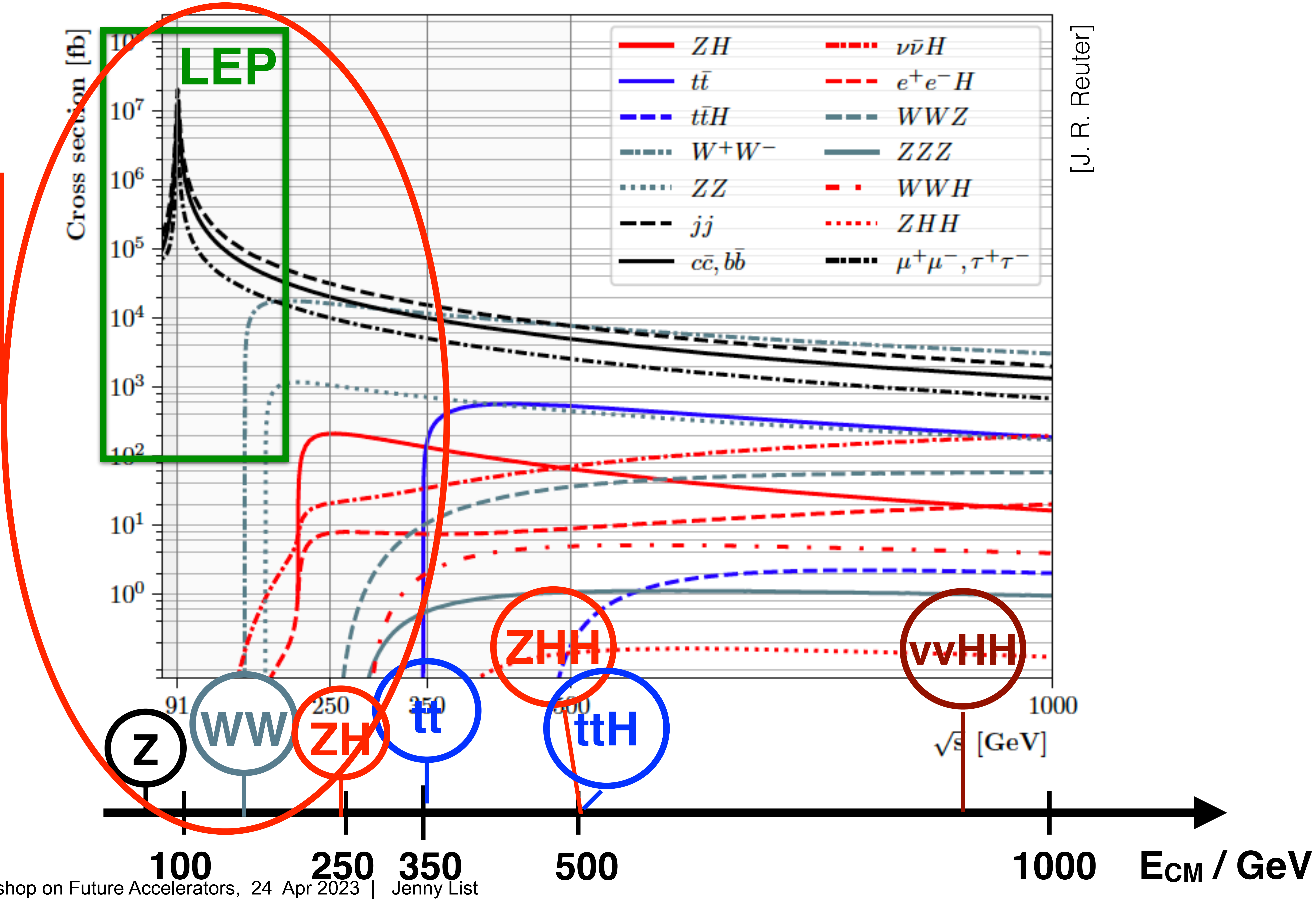

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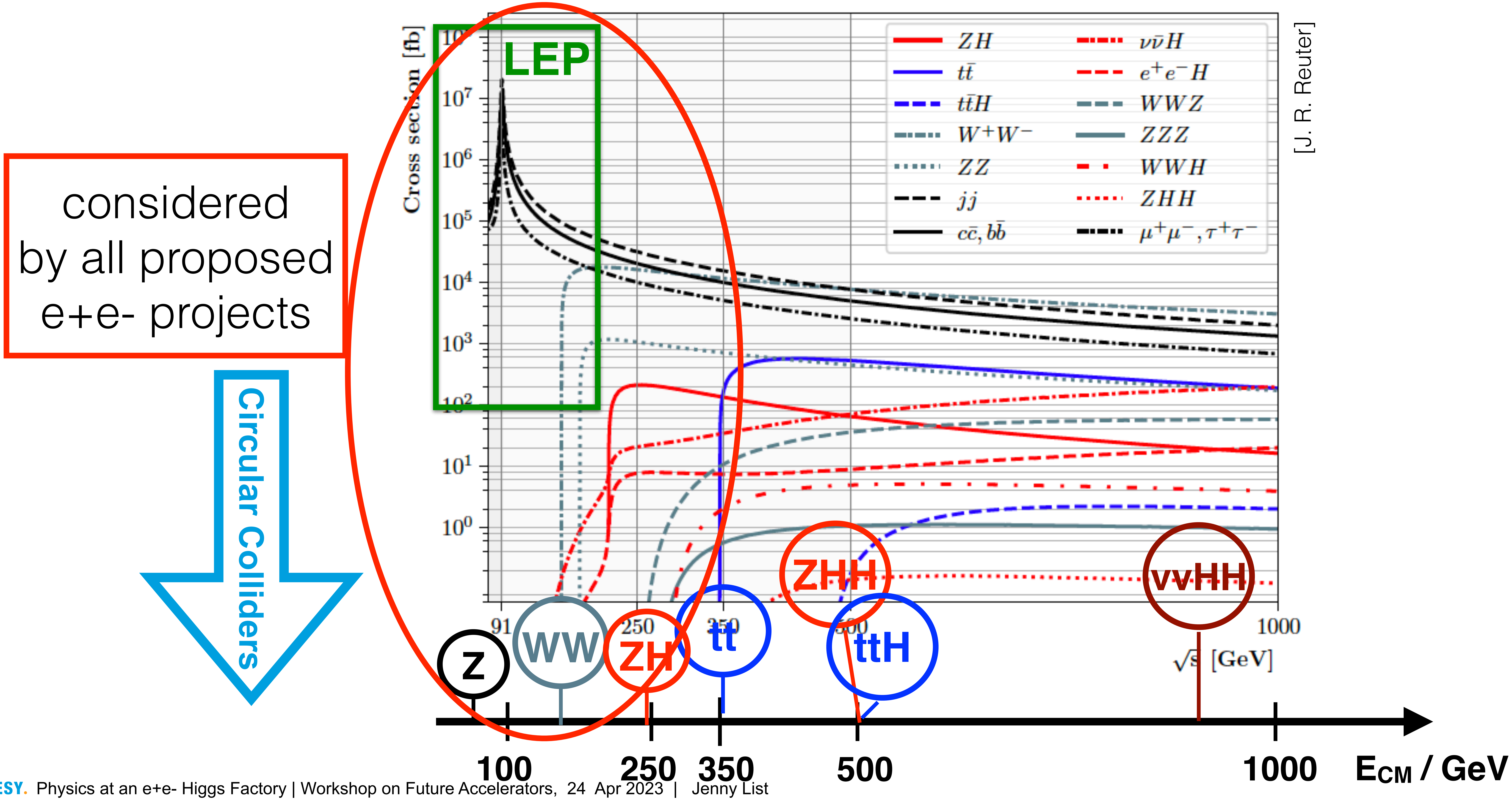

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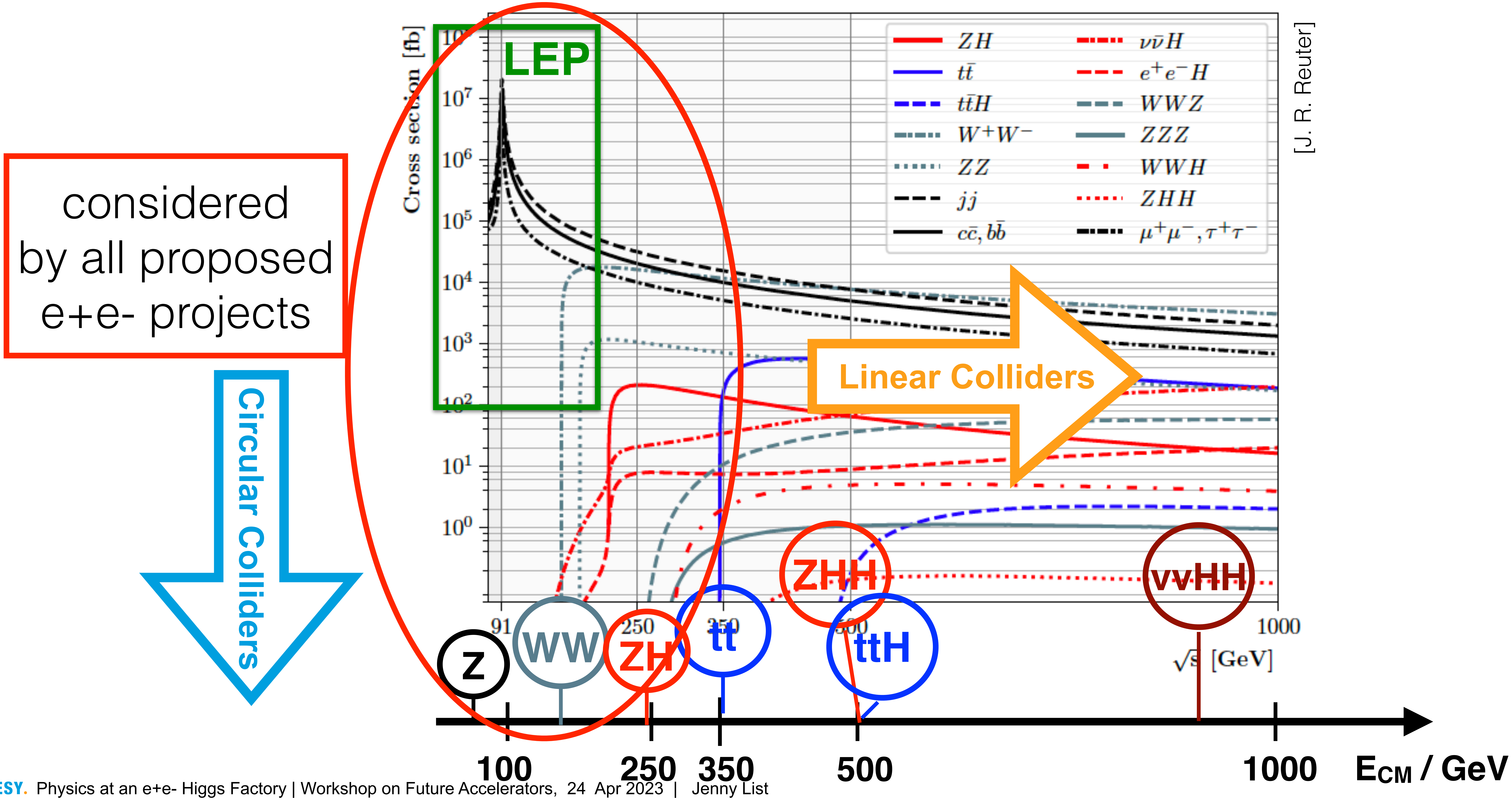

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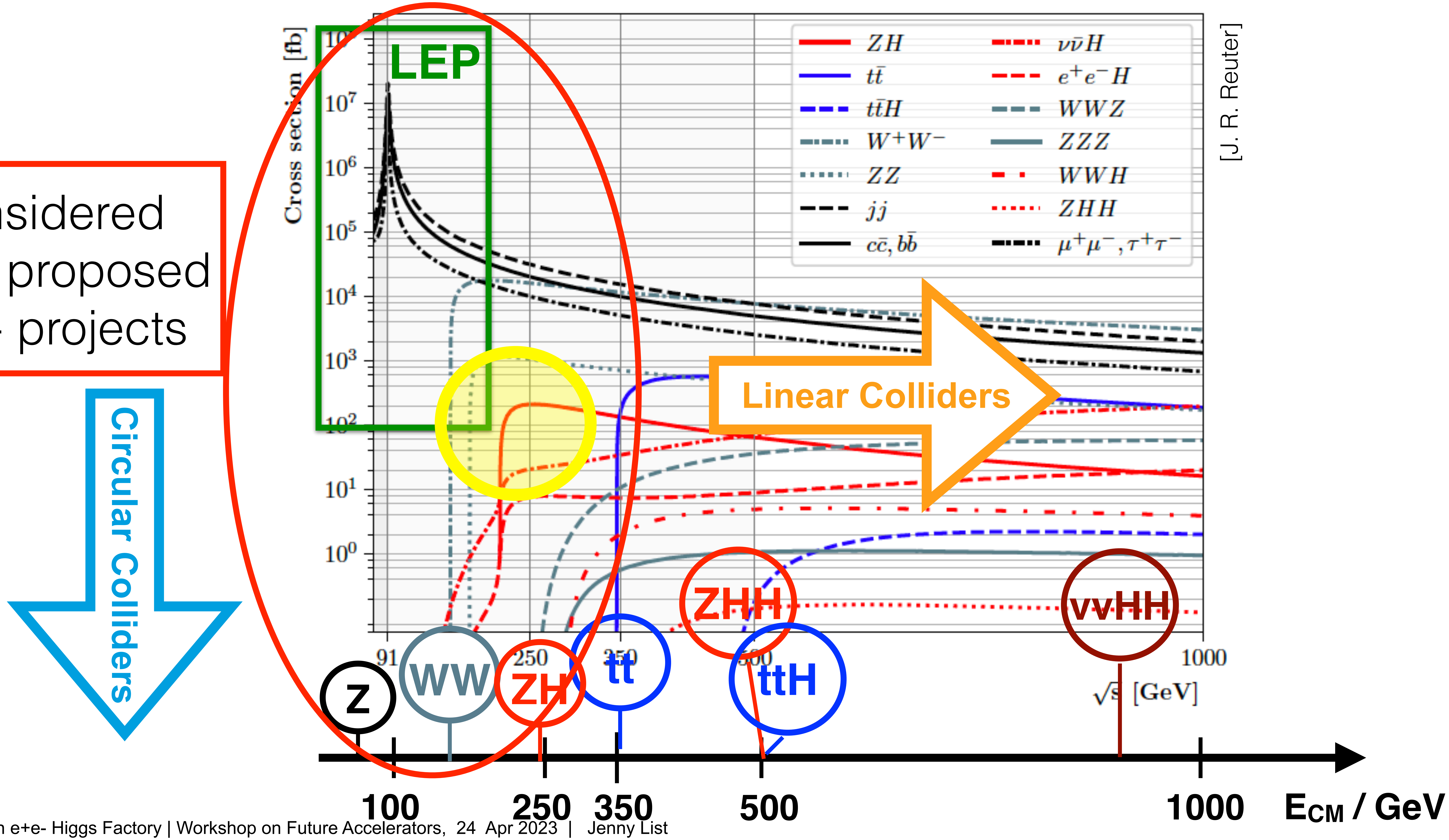


Absolute Higgs Production Rate

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**

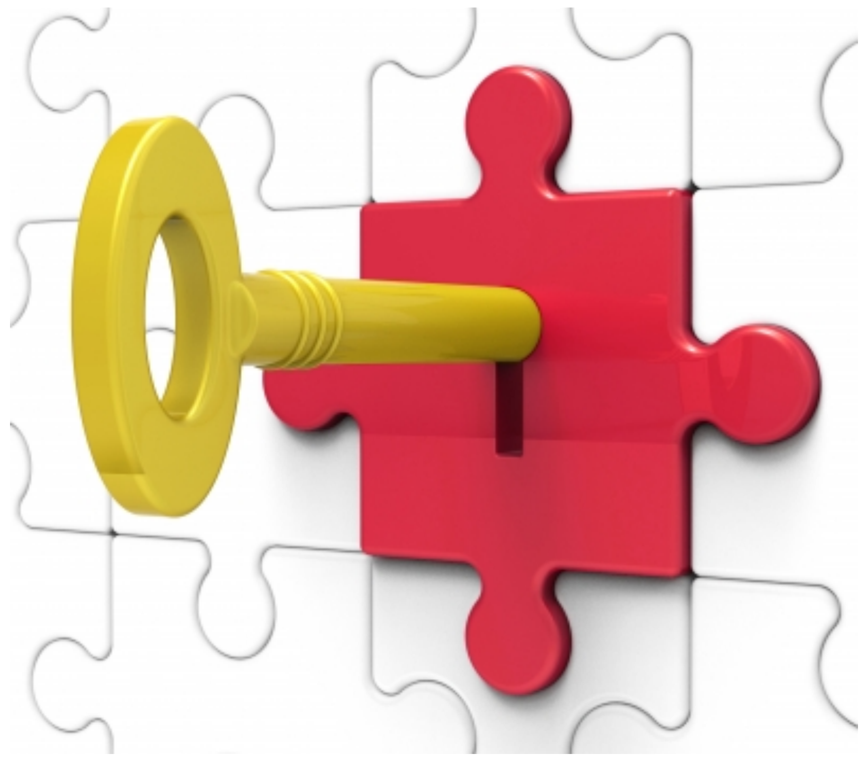
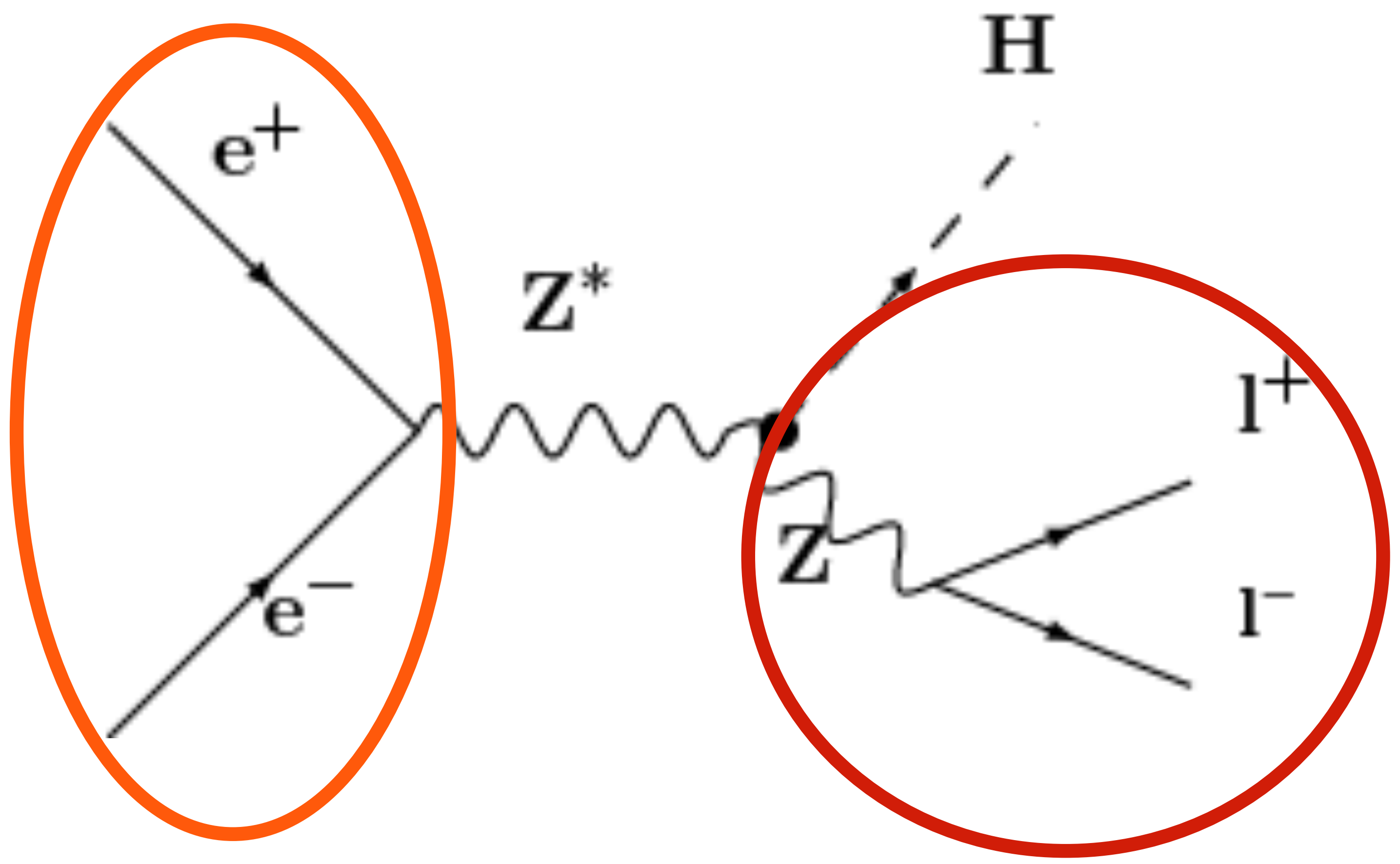
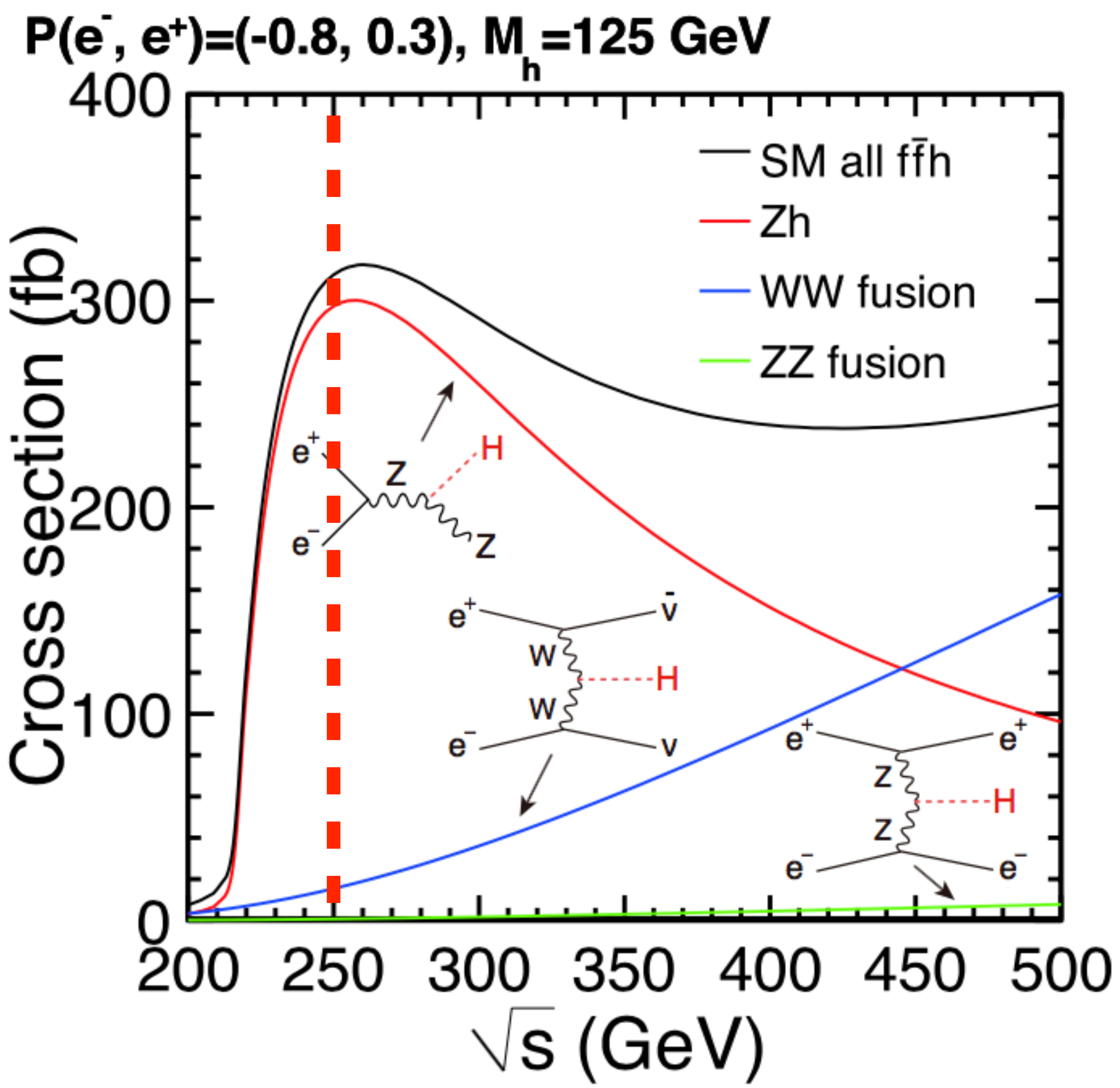


Image courtesy of Stuart Miles at FreeDigitalPhotos.net



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



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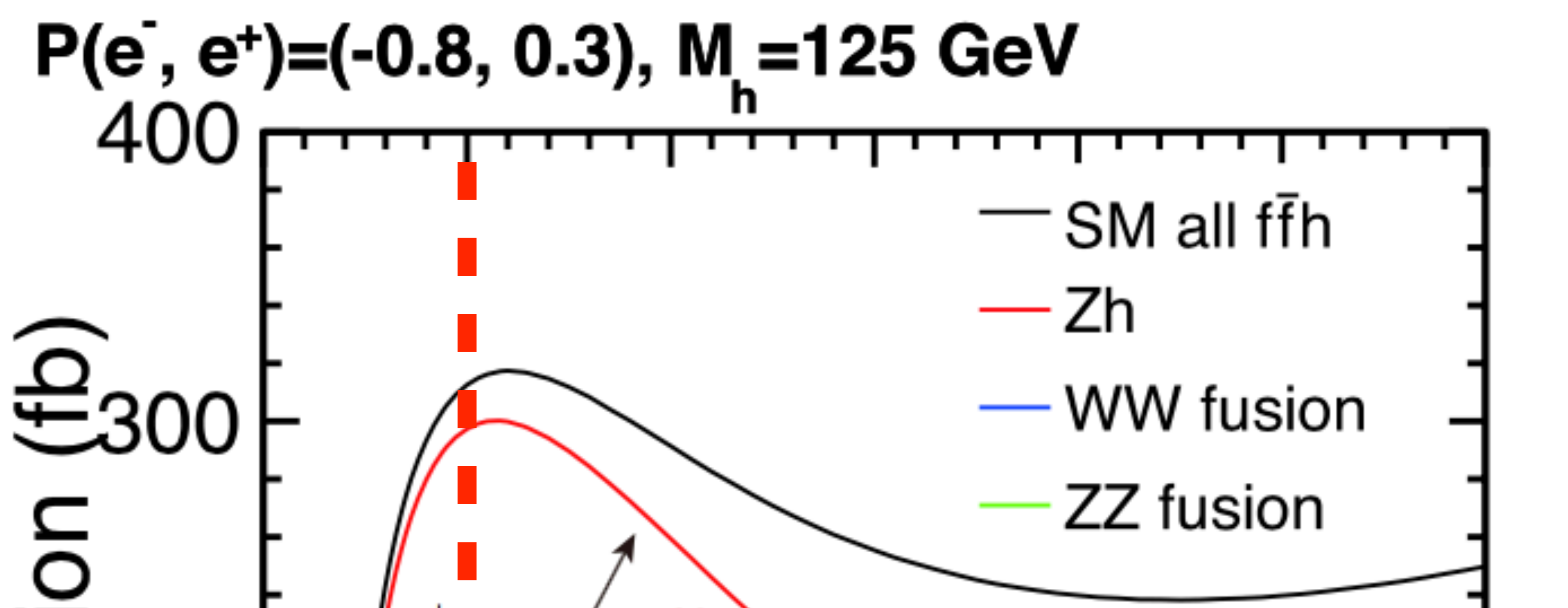

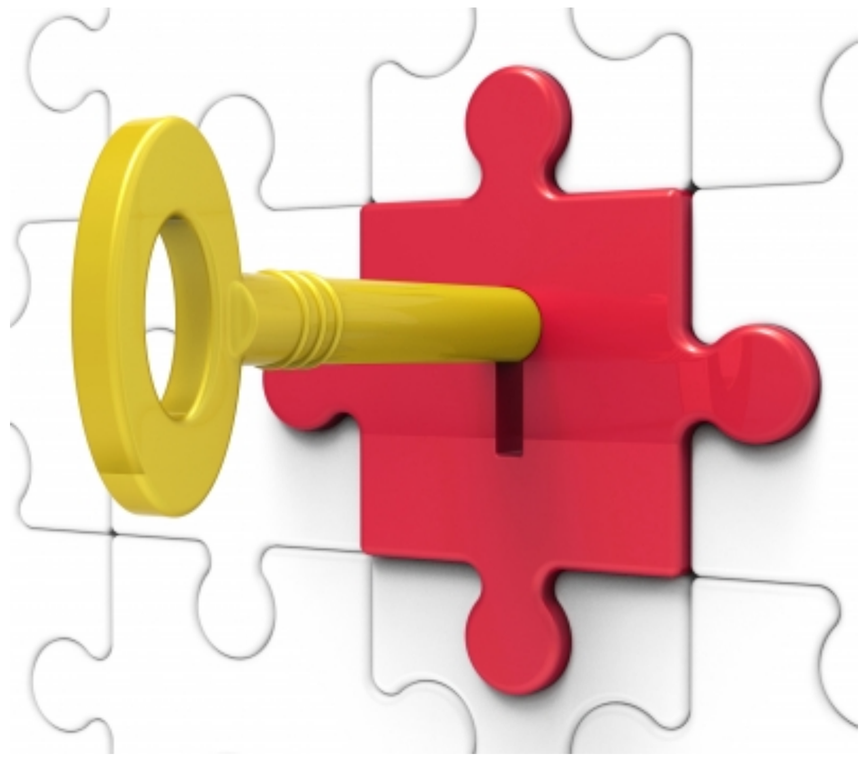

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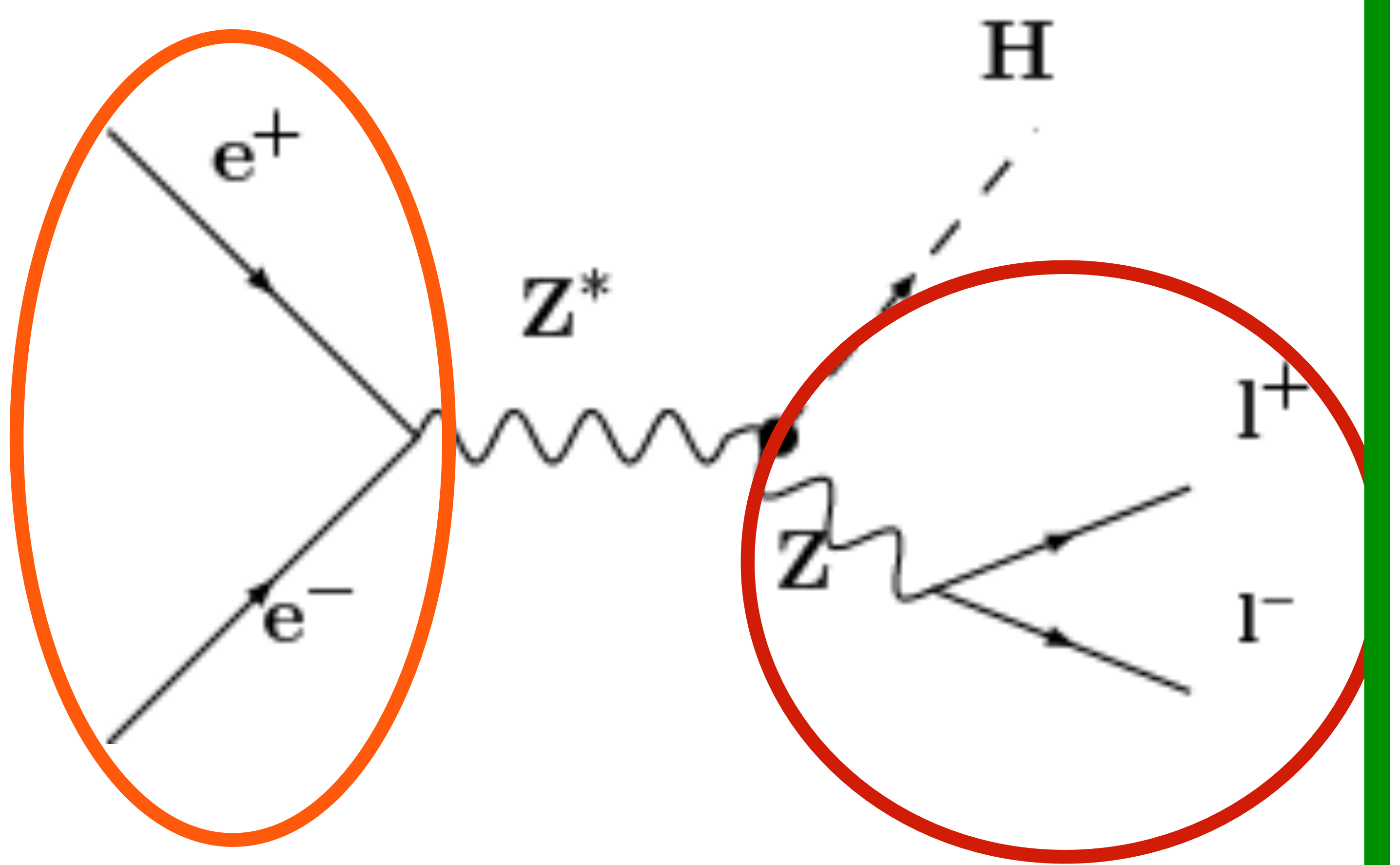

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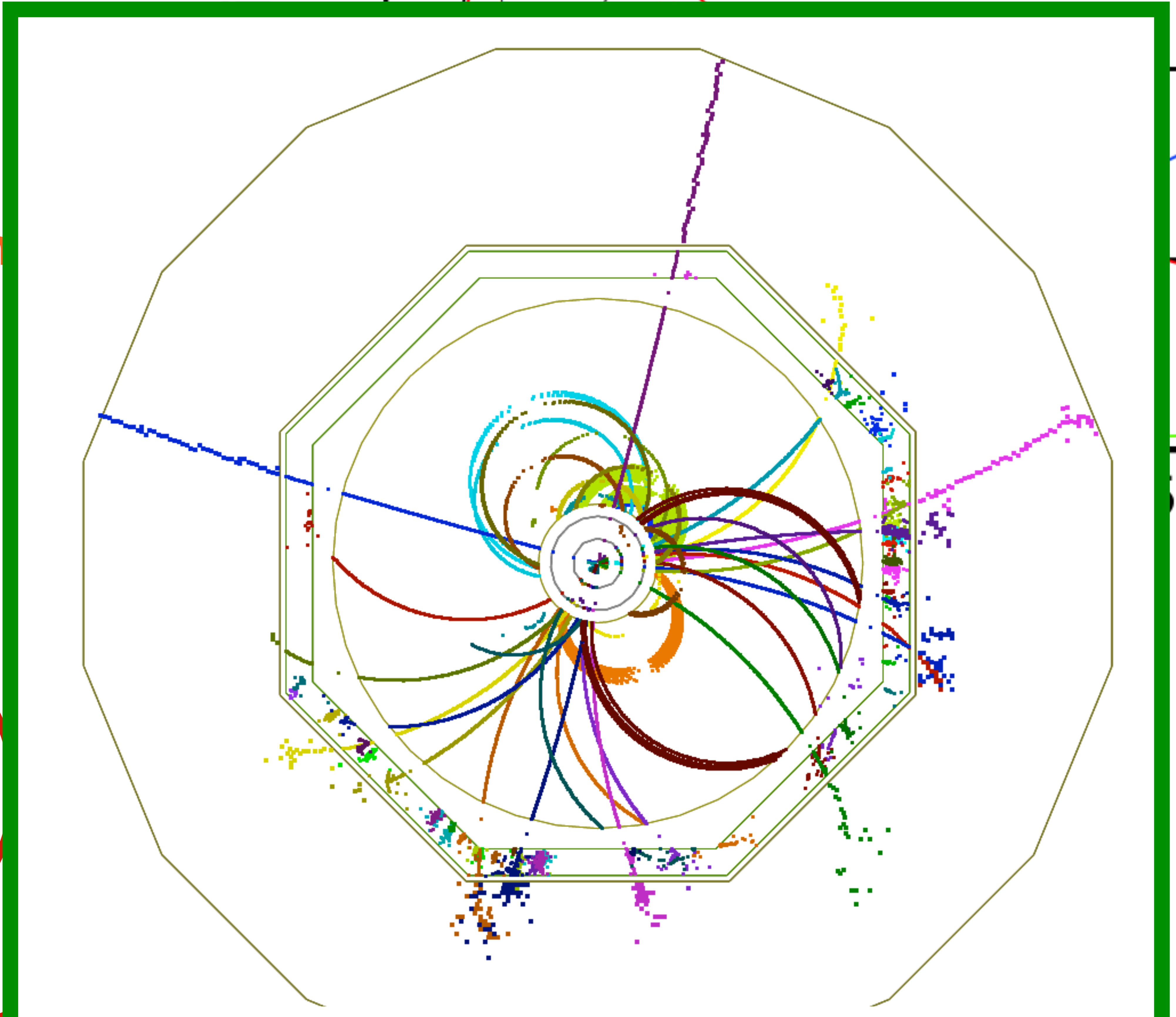

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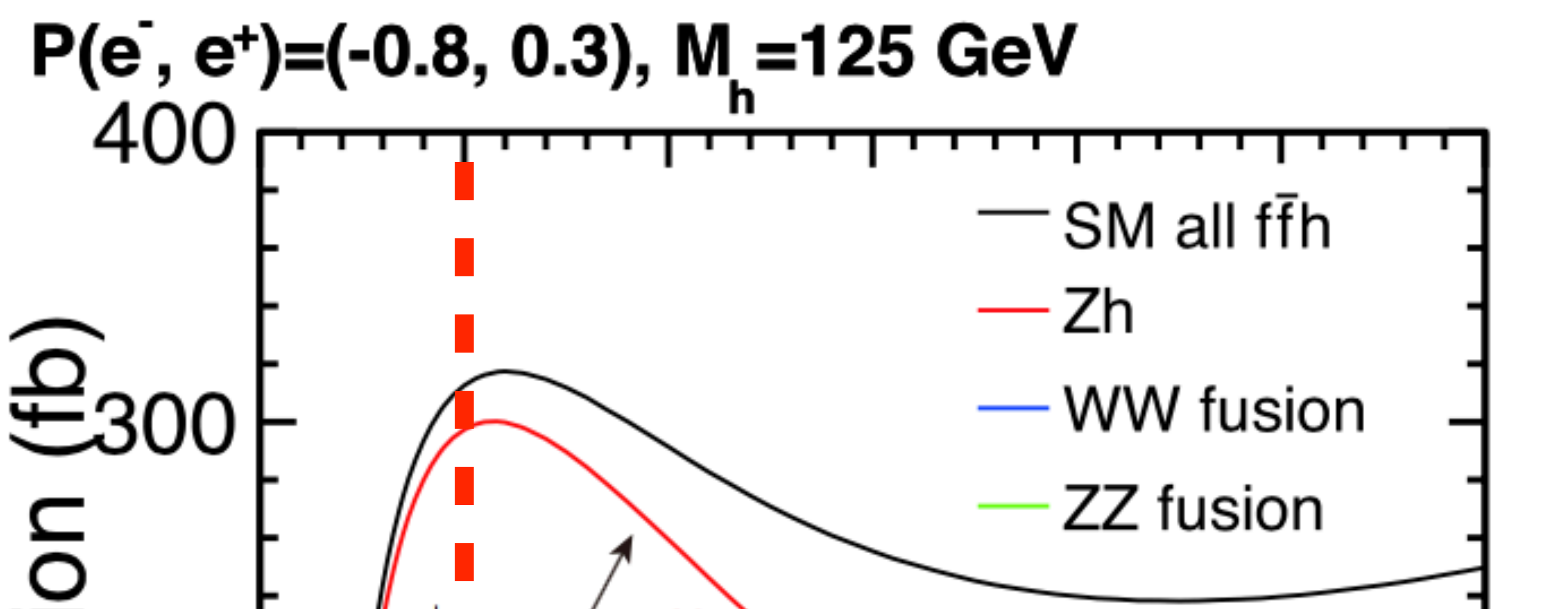

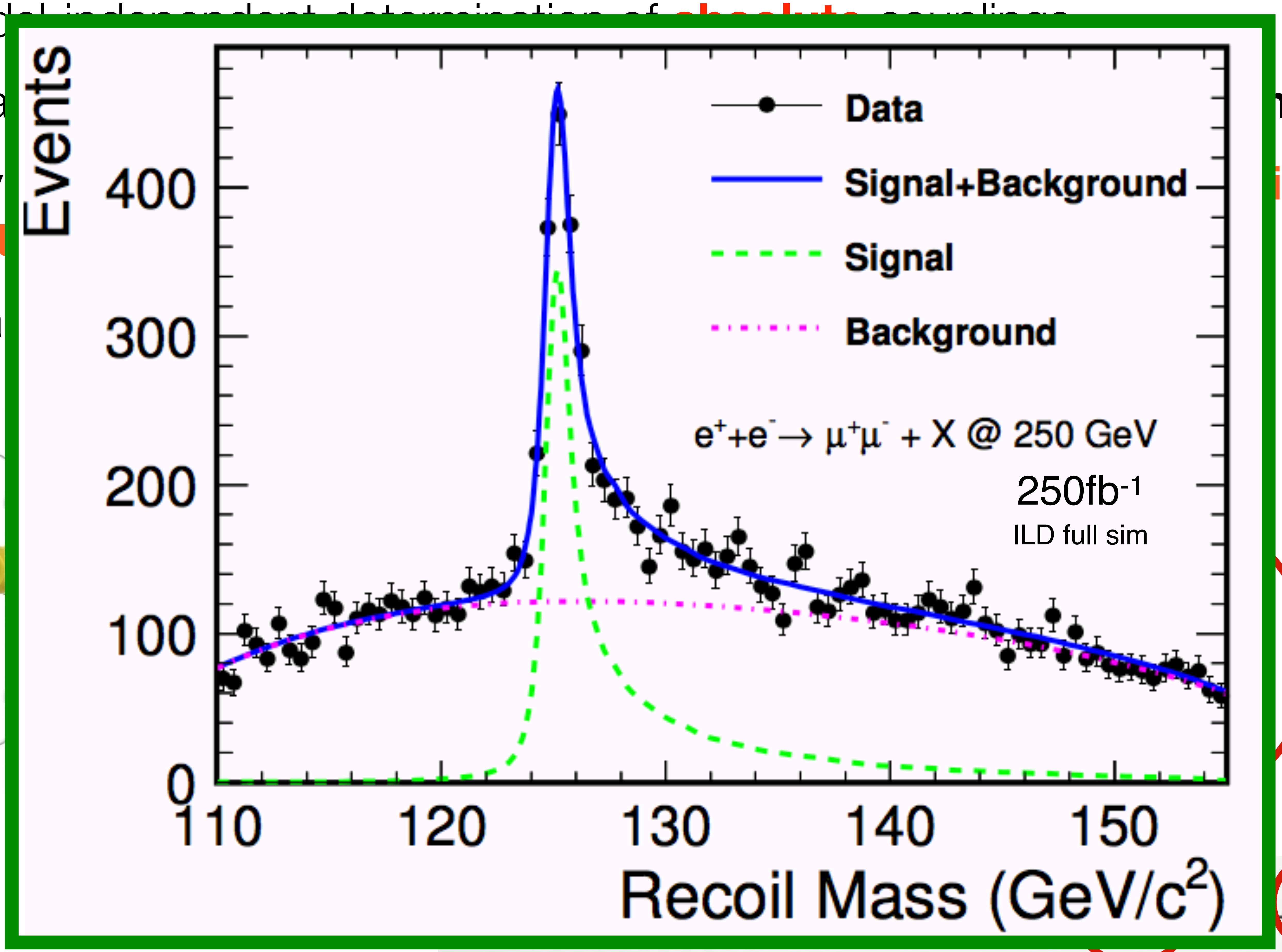

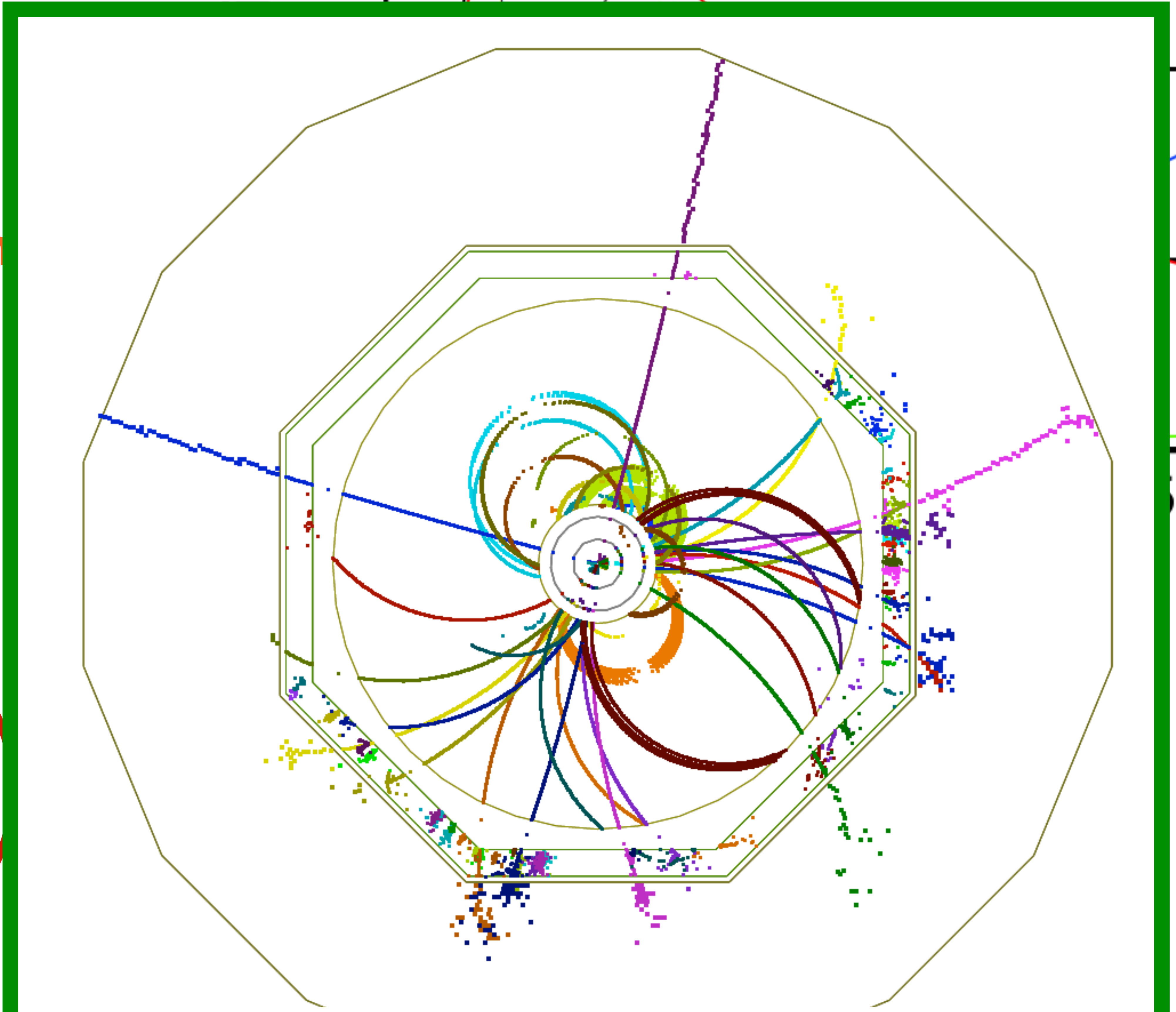

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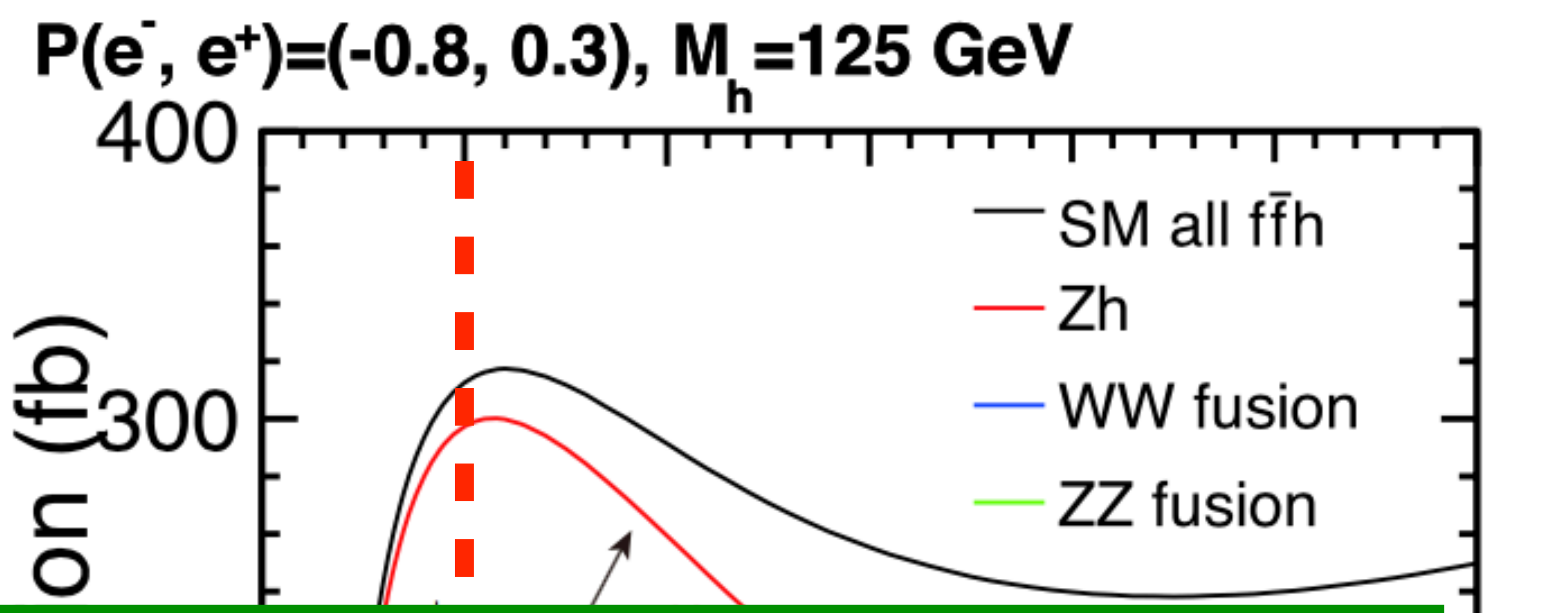
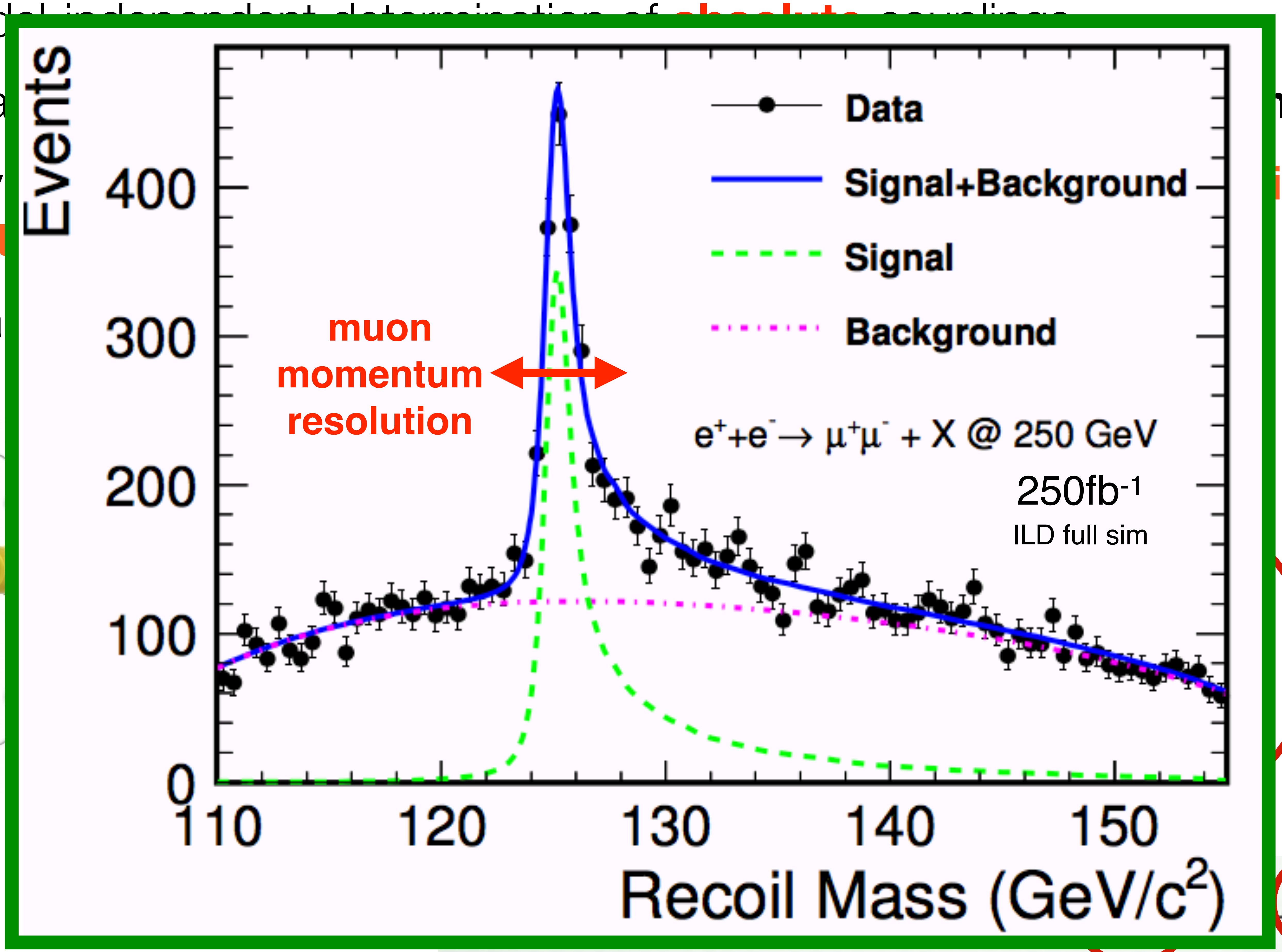
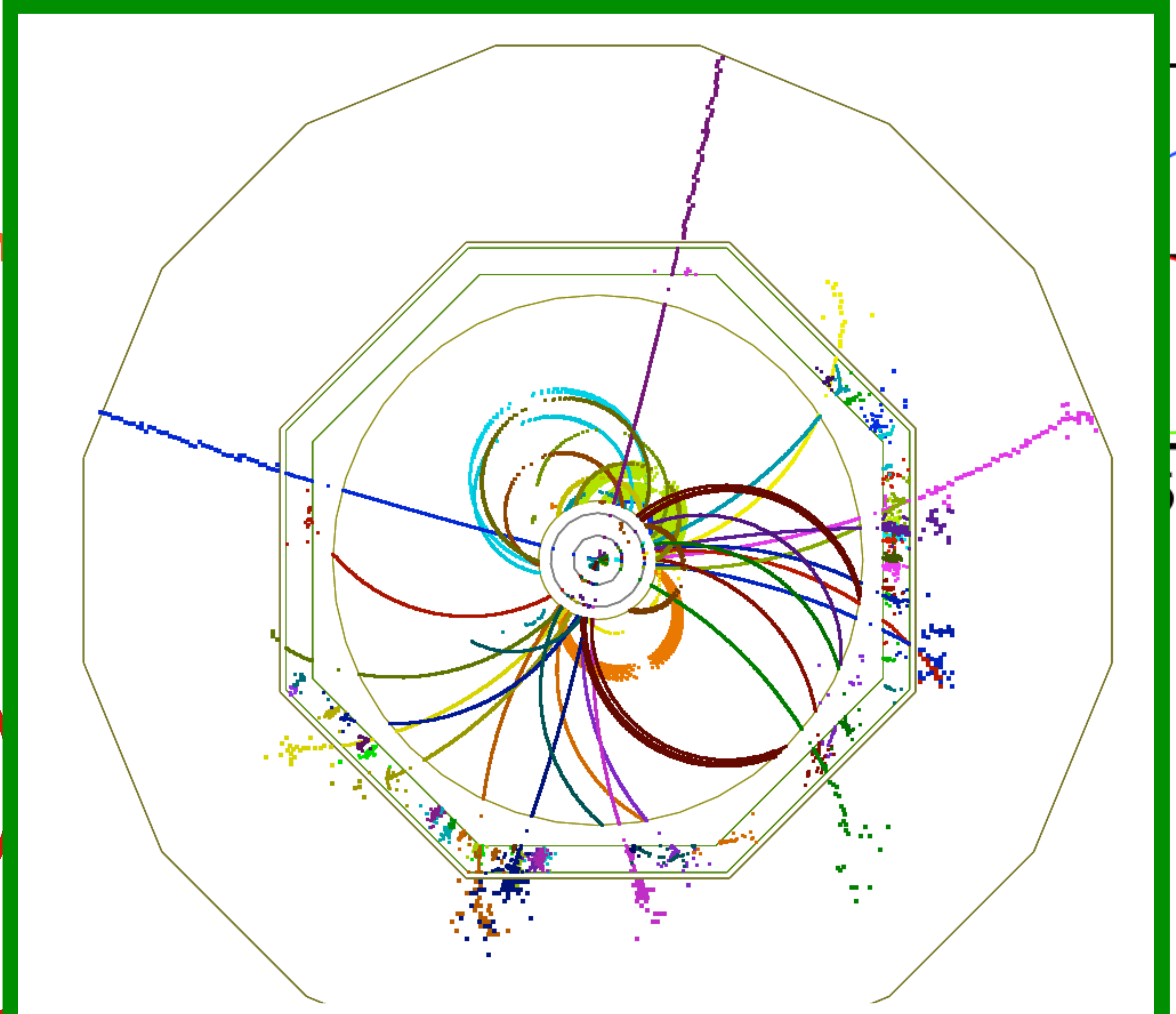


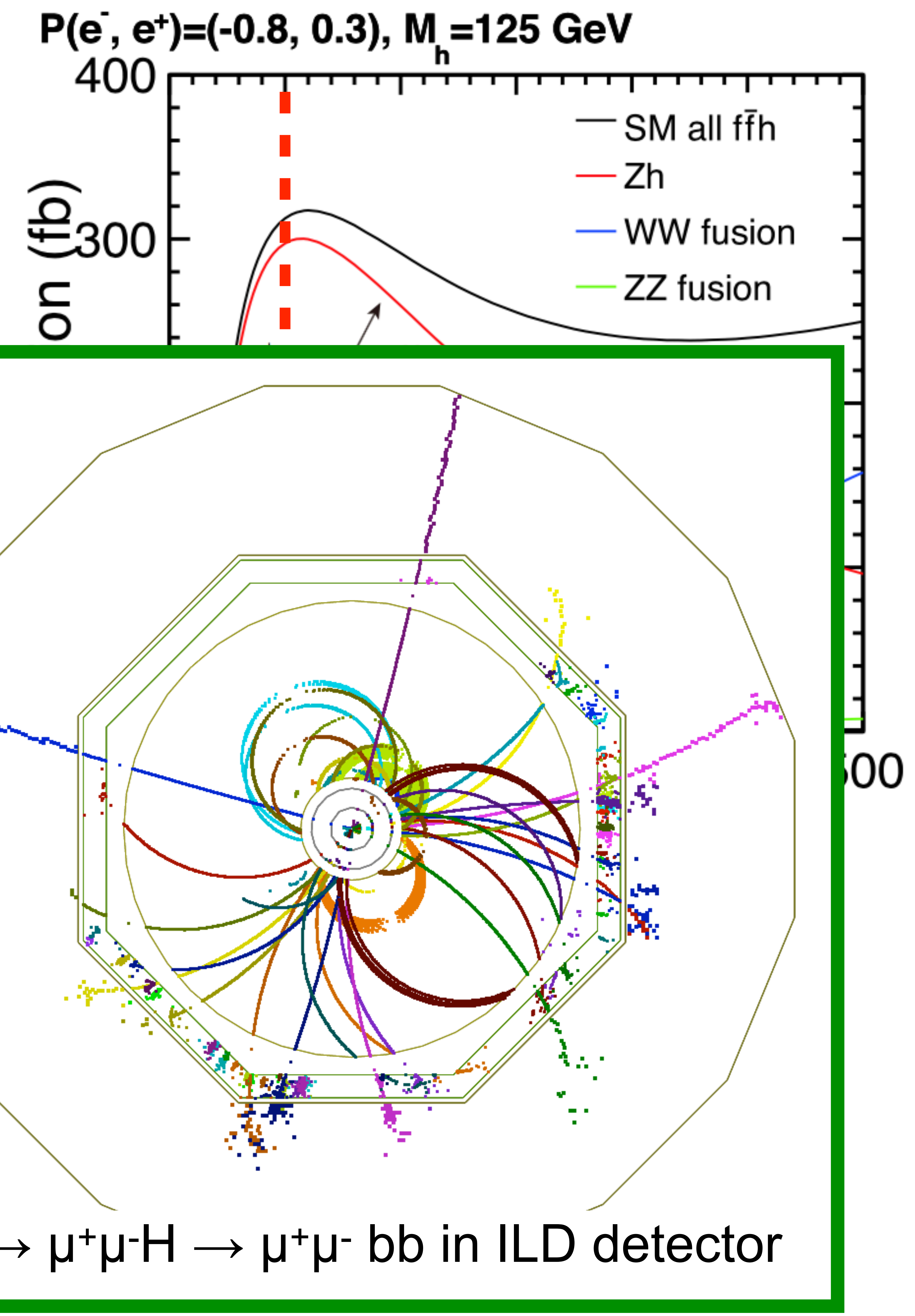


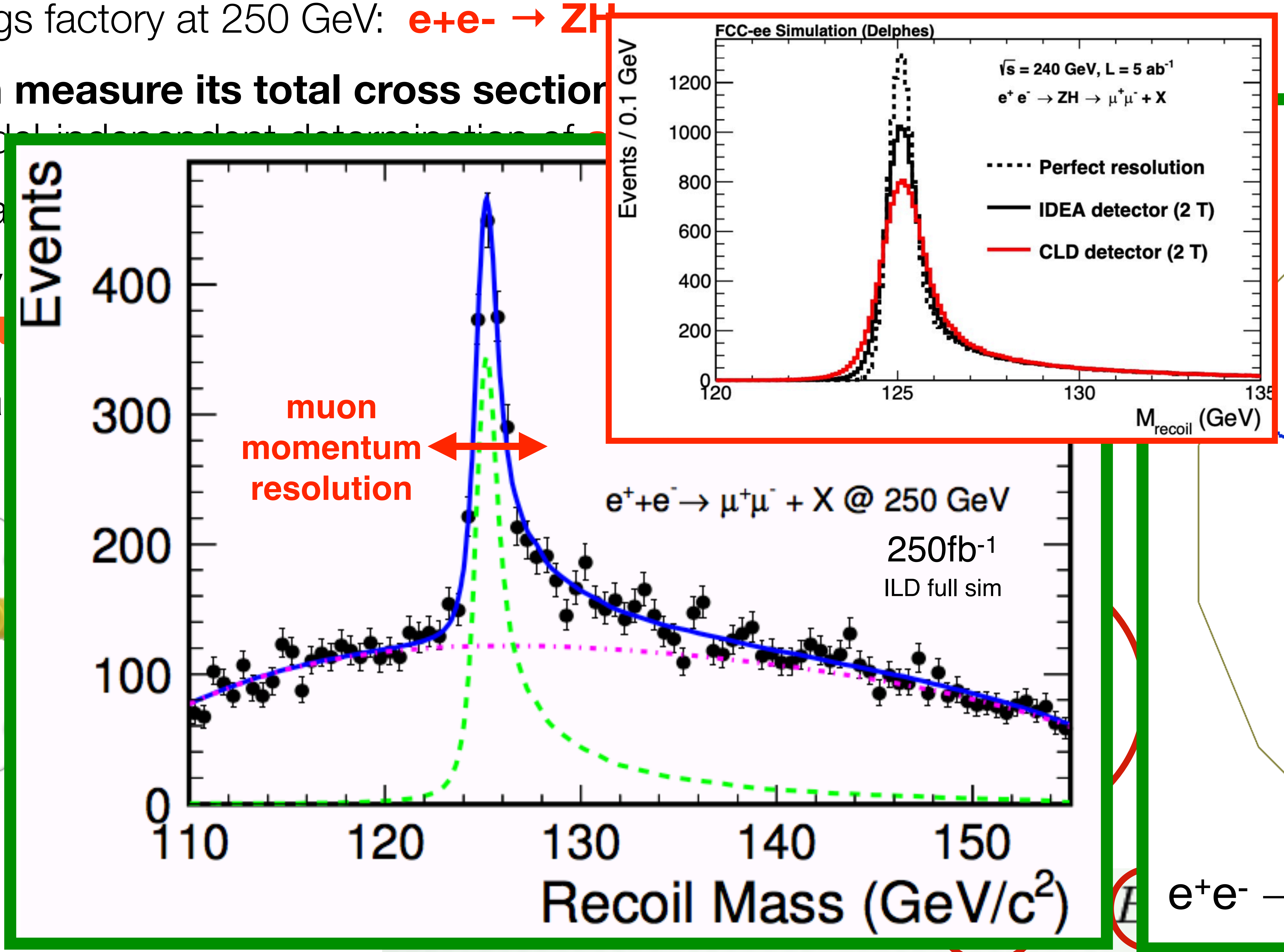

$e^+e^- \rightarrow \mu^+\mu^-H \rightarrow \mu^+\mu^-$ bb in ILD detector

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**
  model-independent determination of
- mea
- only
  part
- **ena**



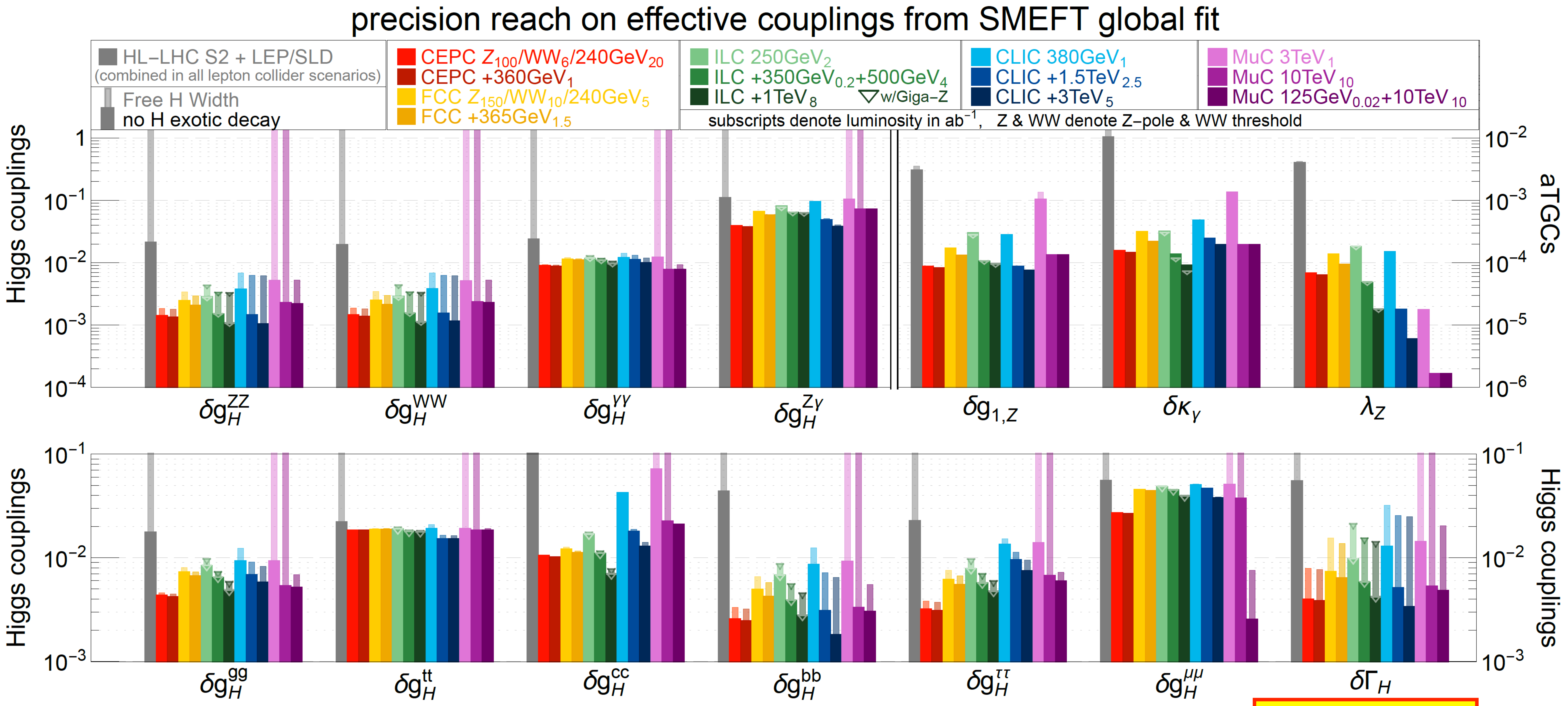


The new Snowmass SMEFT fit

Rainbow-Manhattans

Also essential:

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



arXiv:2206.08326

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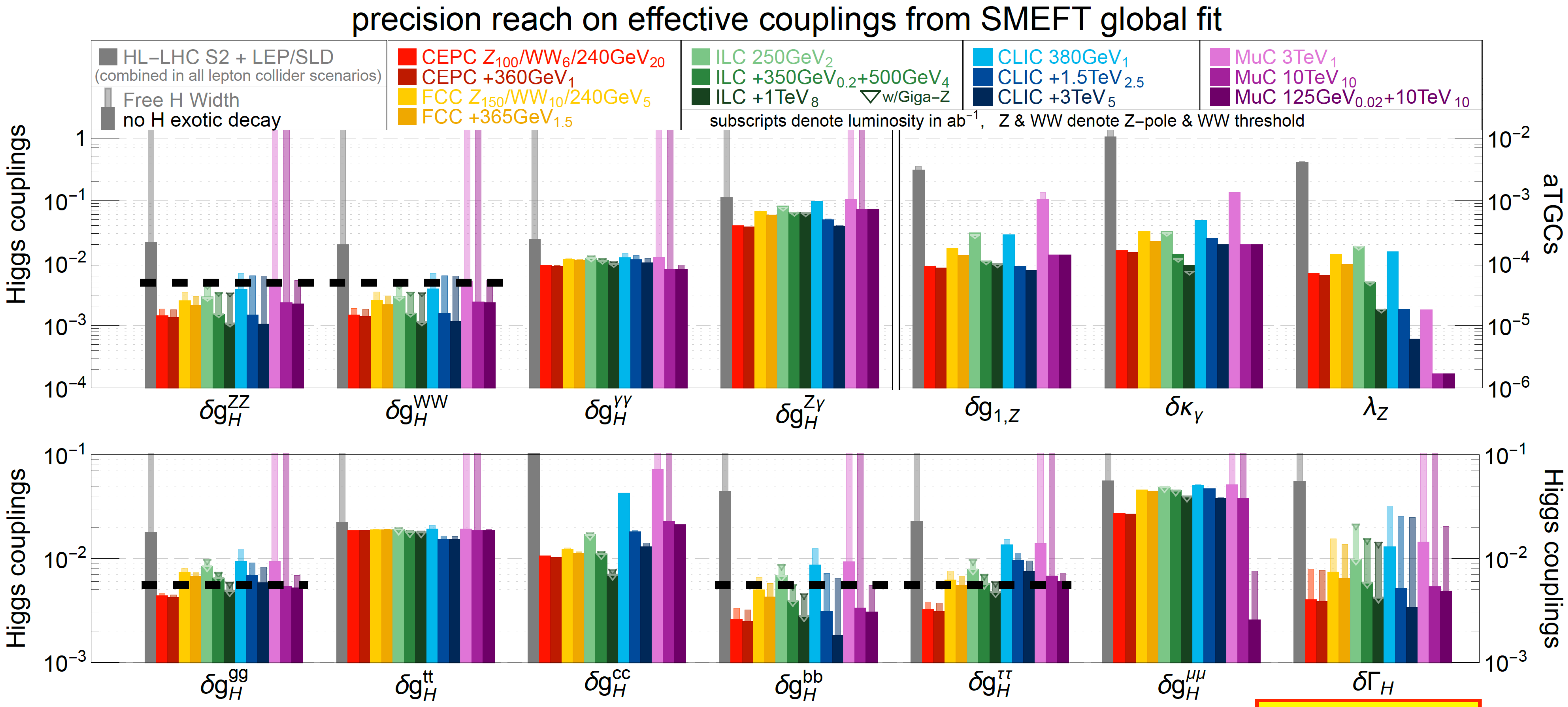

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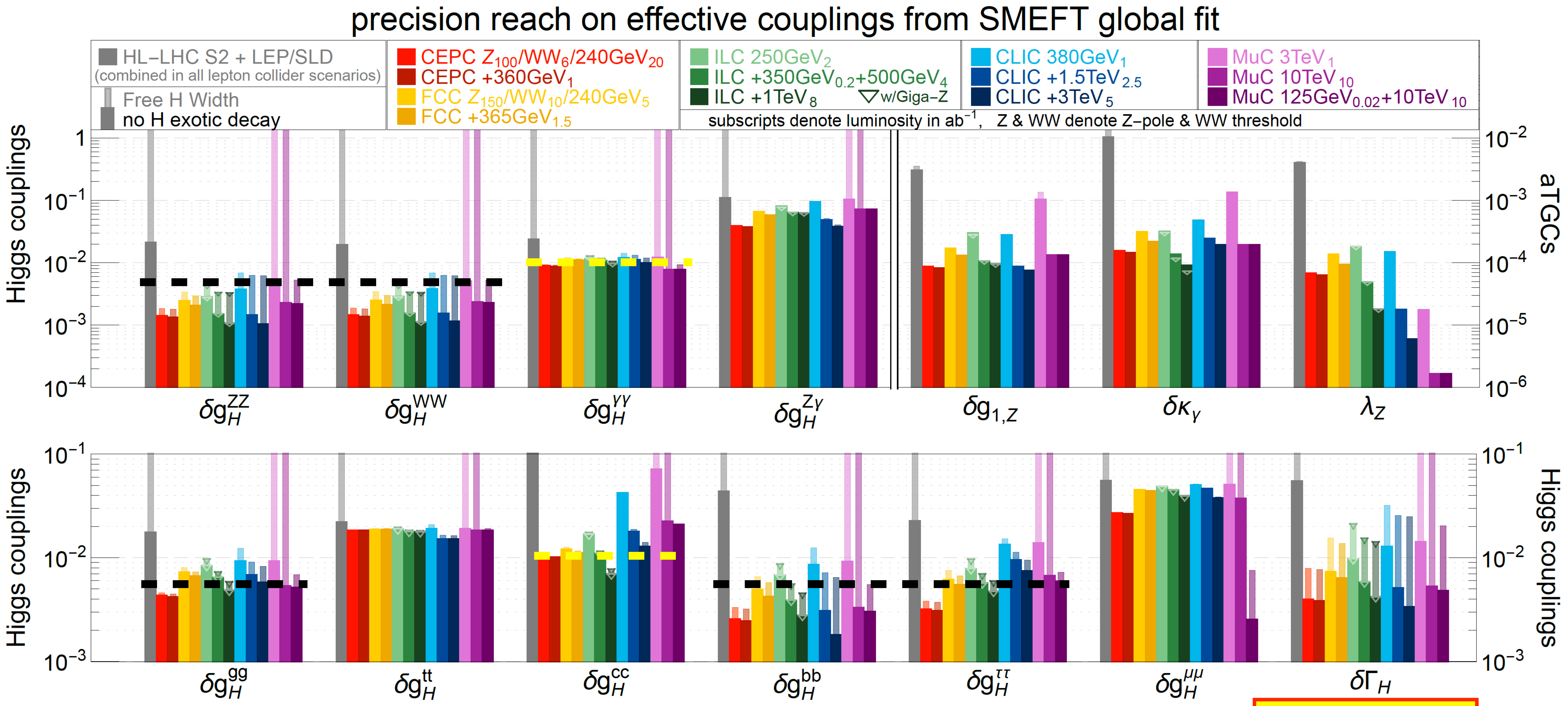

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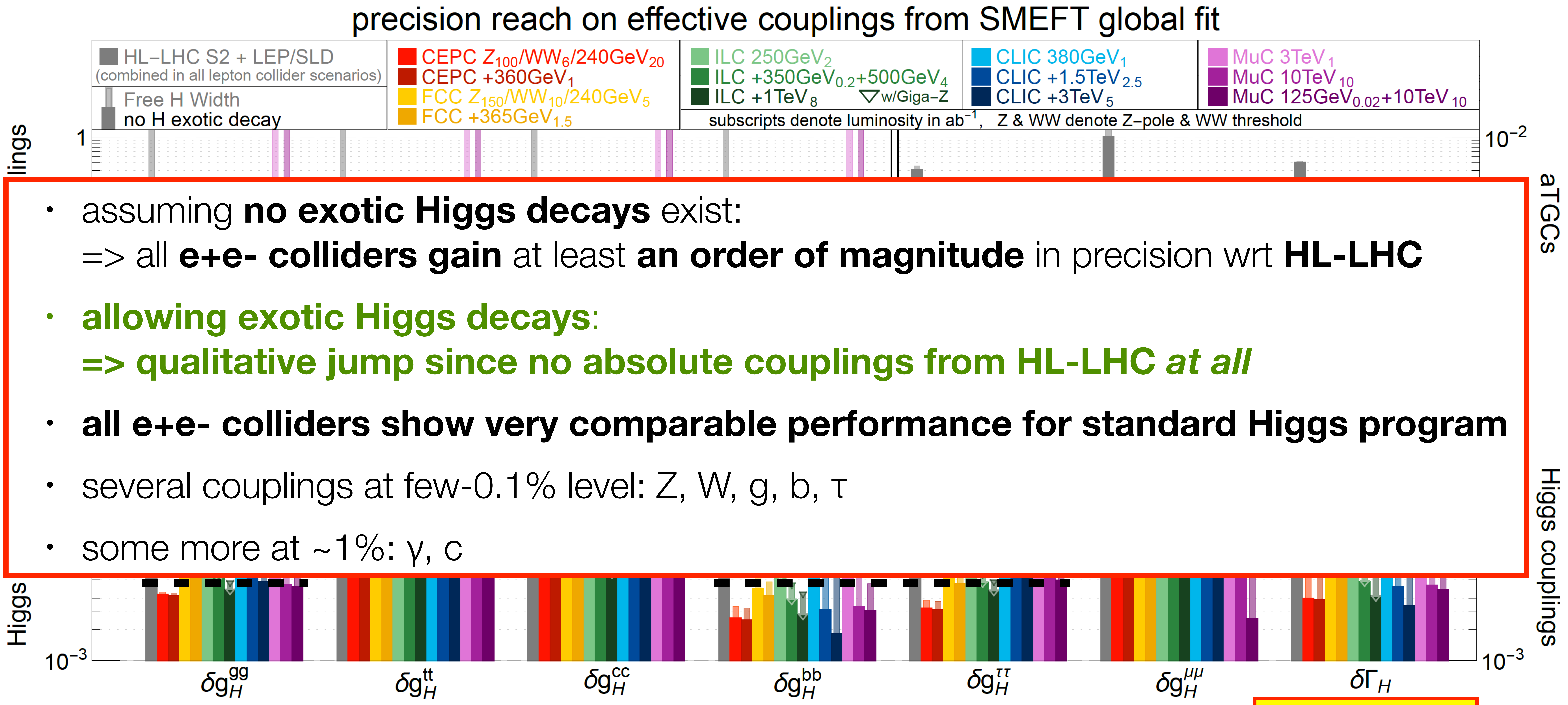

- assuming **no exotic Higgs decays** exist:
  => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays**:
  => qualitative jump since no absolute couplings from HL-LHC *at all*
- **all e+e- colliders show very comparable performance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

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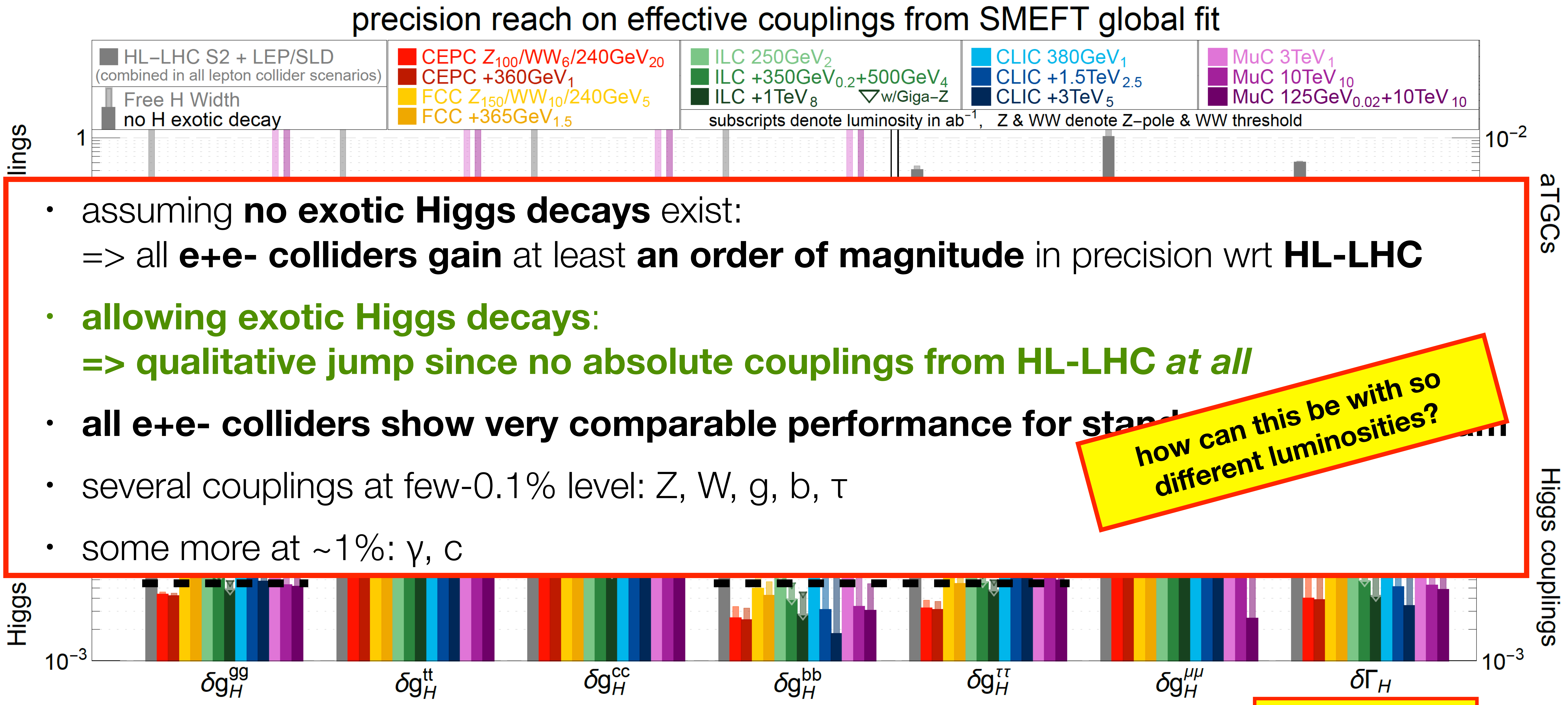

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how can this be with so different luminosities?

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

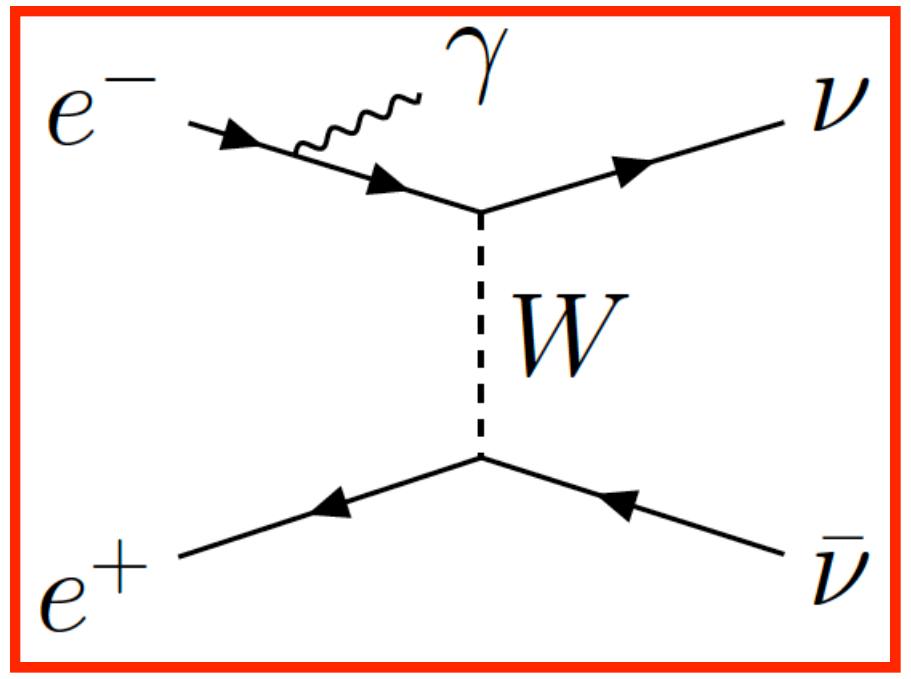
Much more than statistics!

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

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

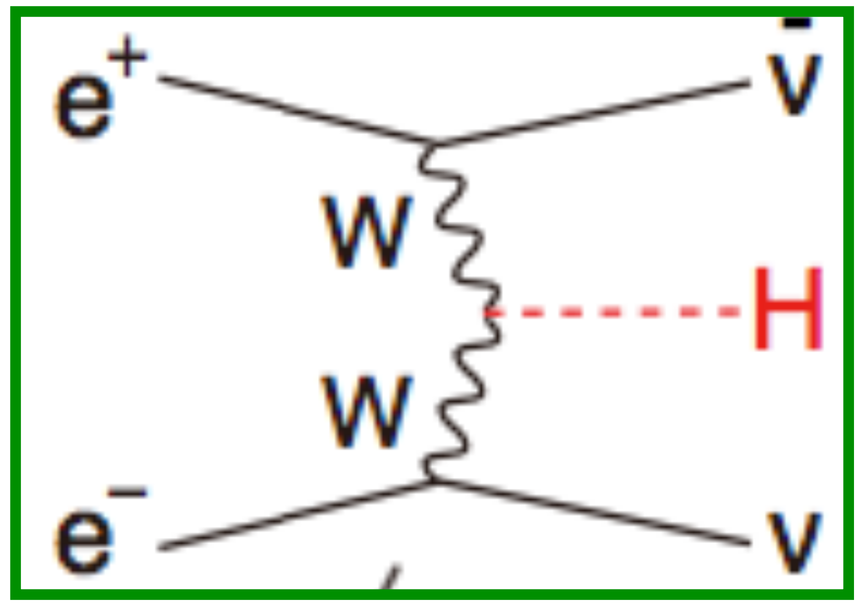
background suppression:

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



signal enhancement:

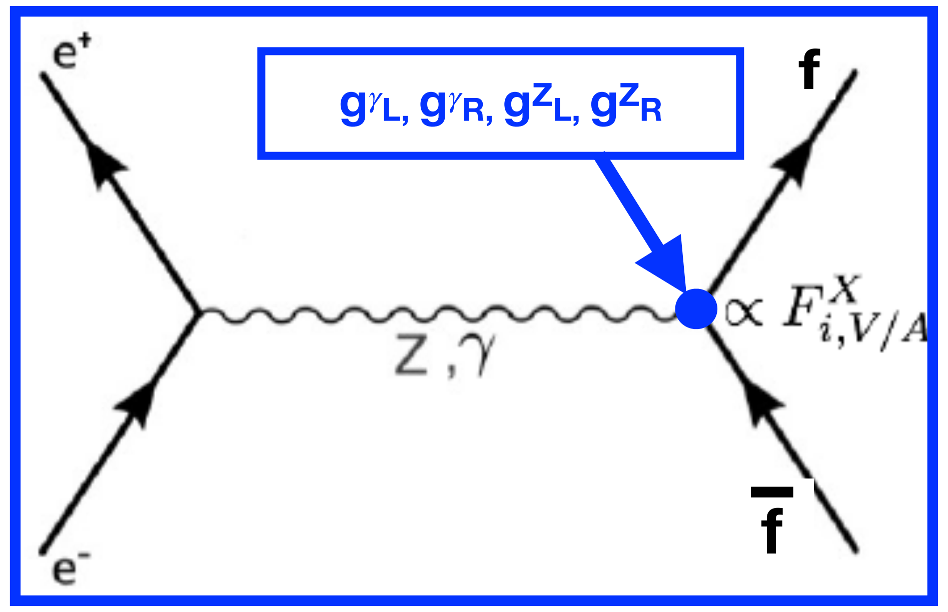
- Higgs production in WW fusion
- many BSM processes



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!

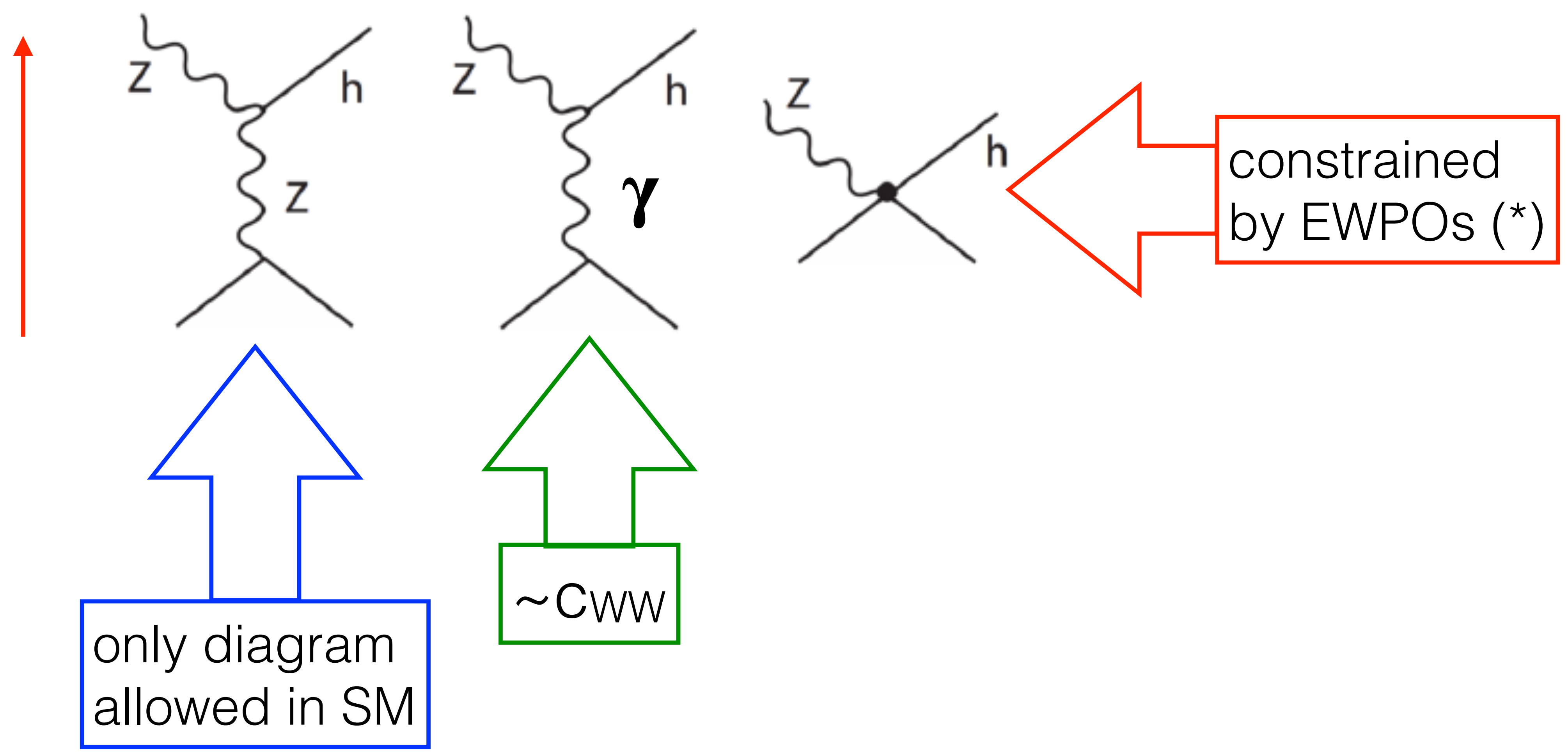
redundancy & control of systematics:

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



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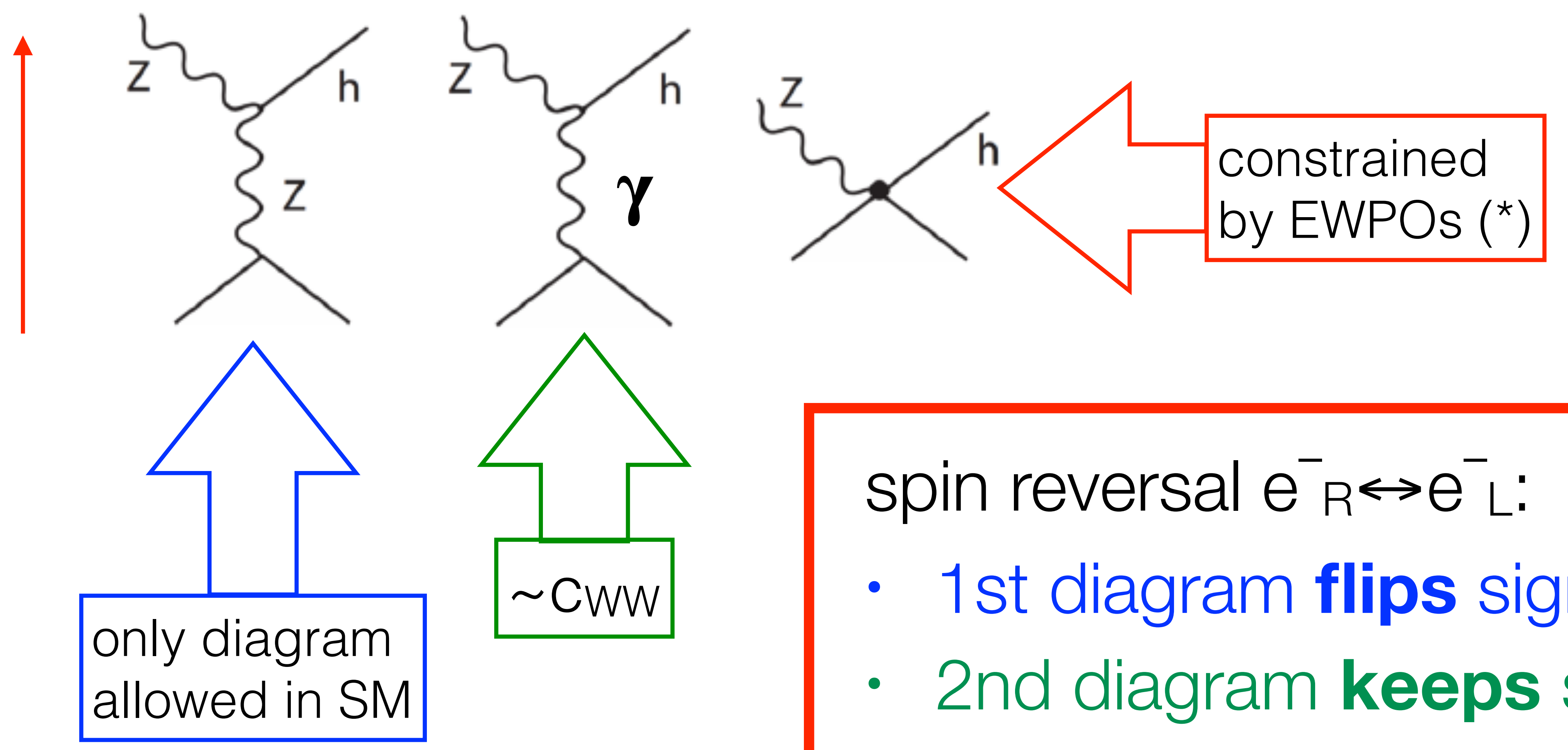

spin reversal $e^-_R \leftrightarrow e^-_L$:

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

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

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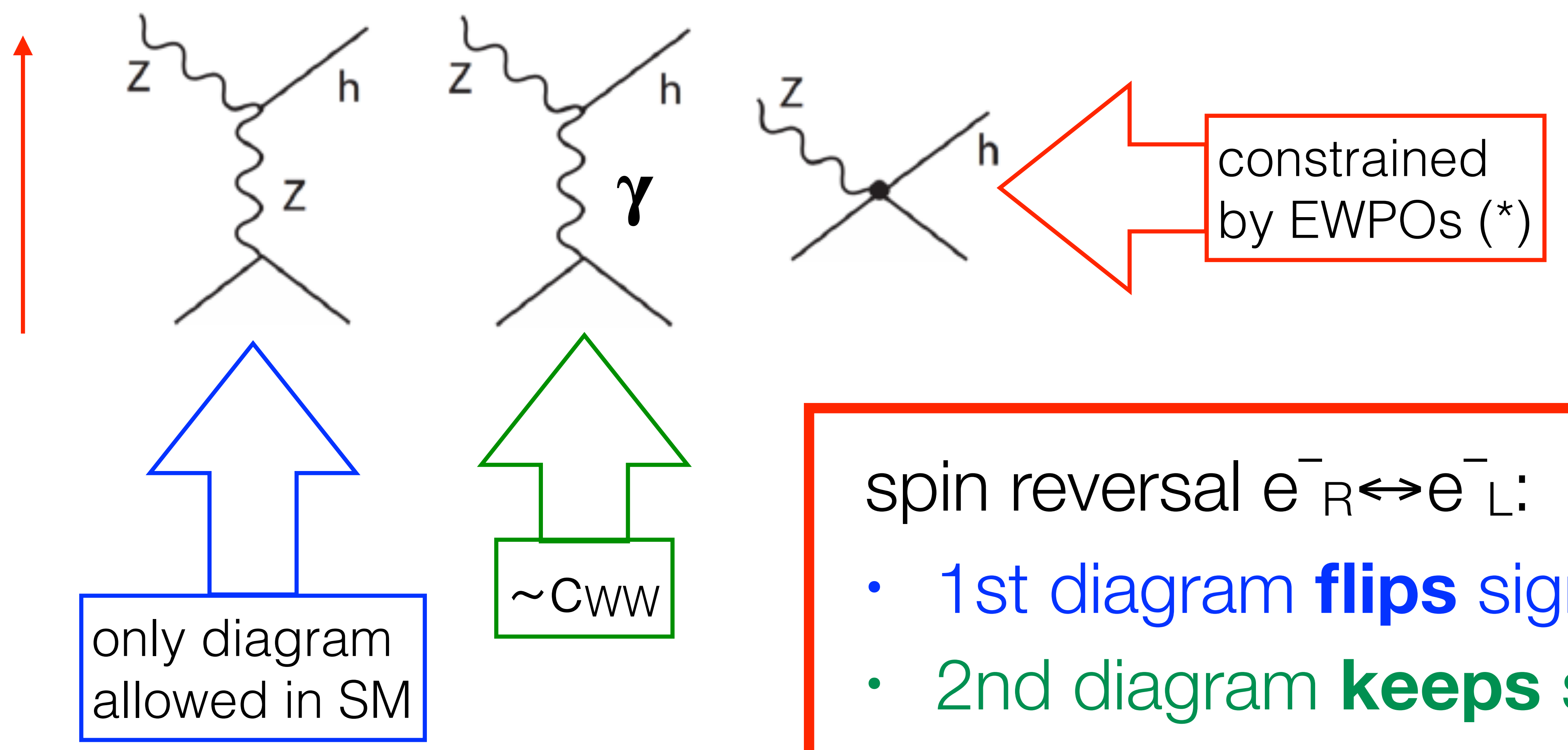

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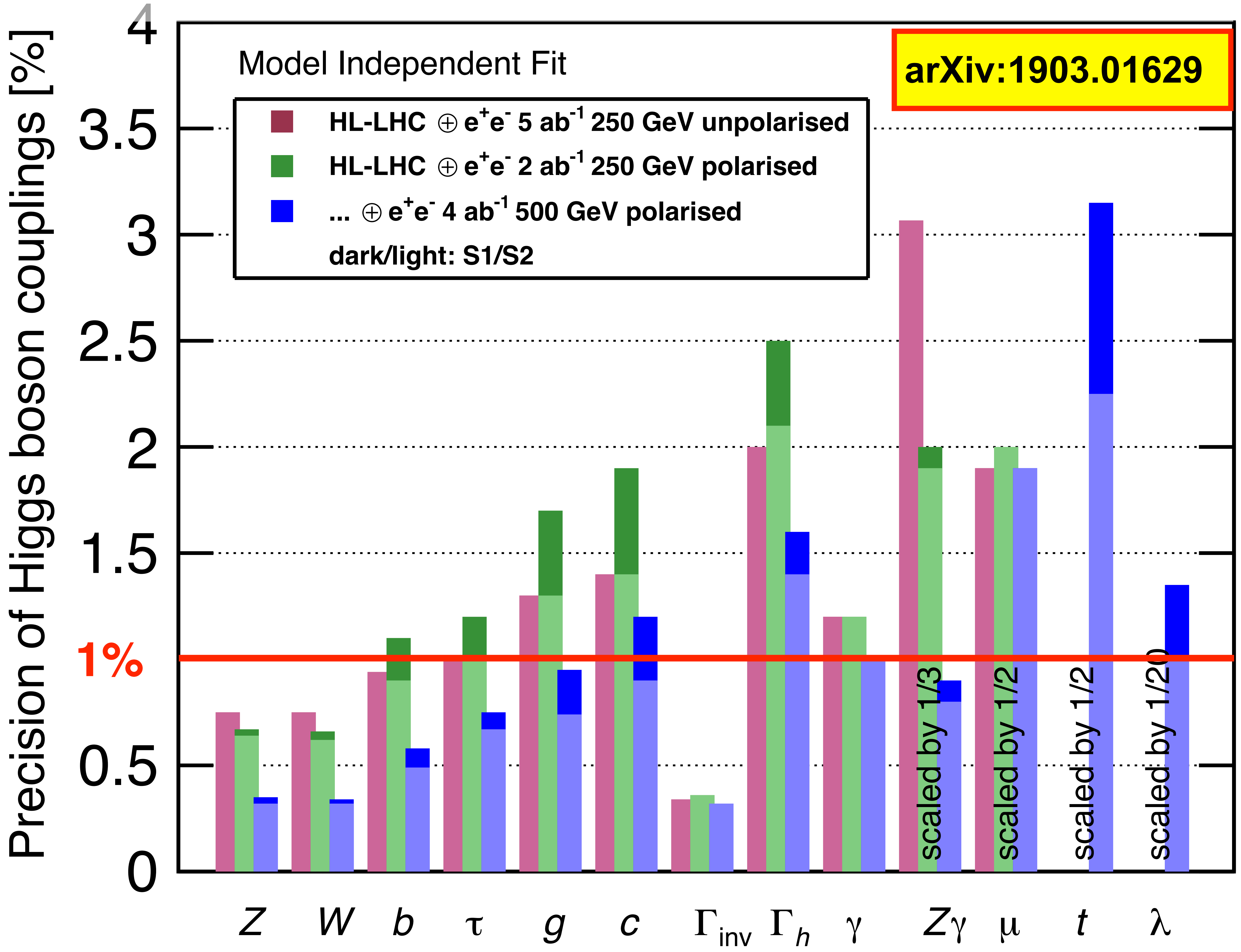

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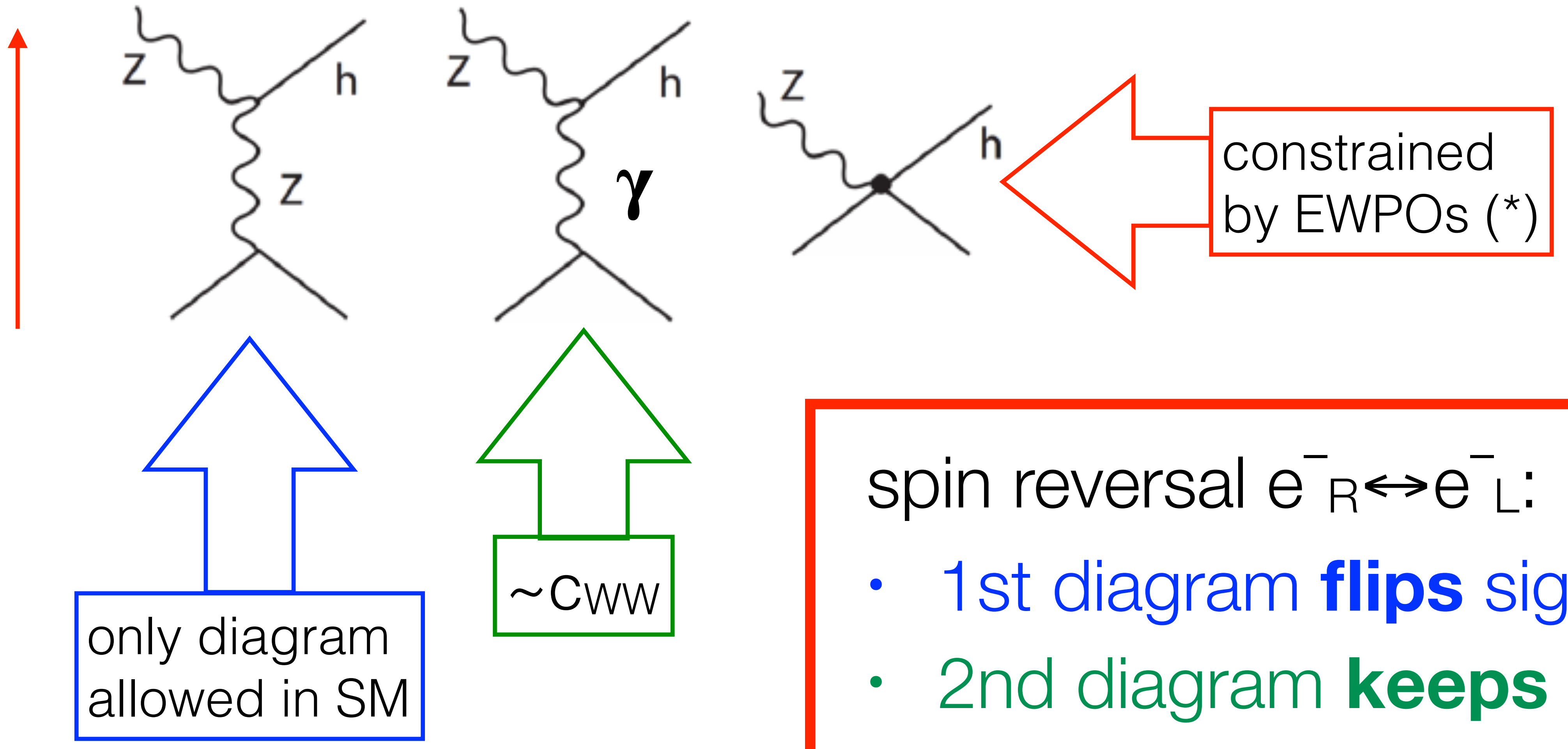

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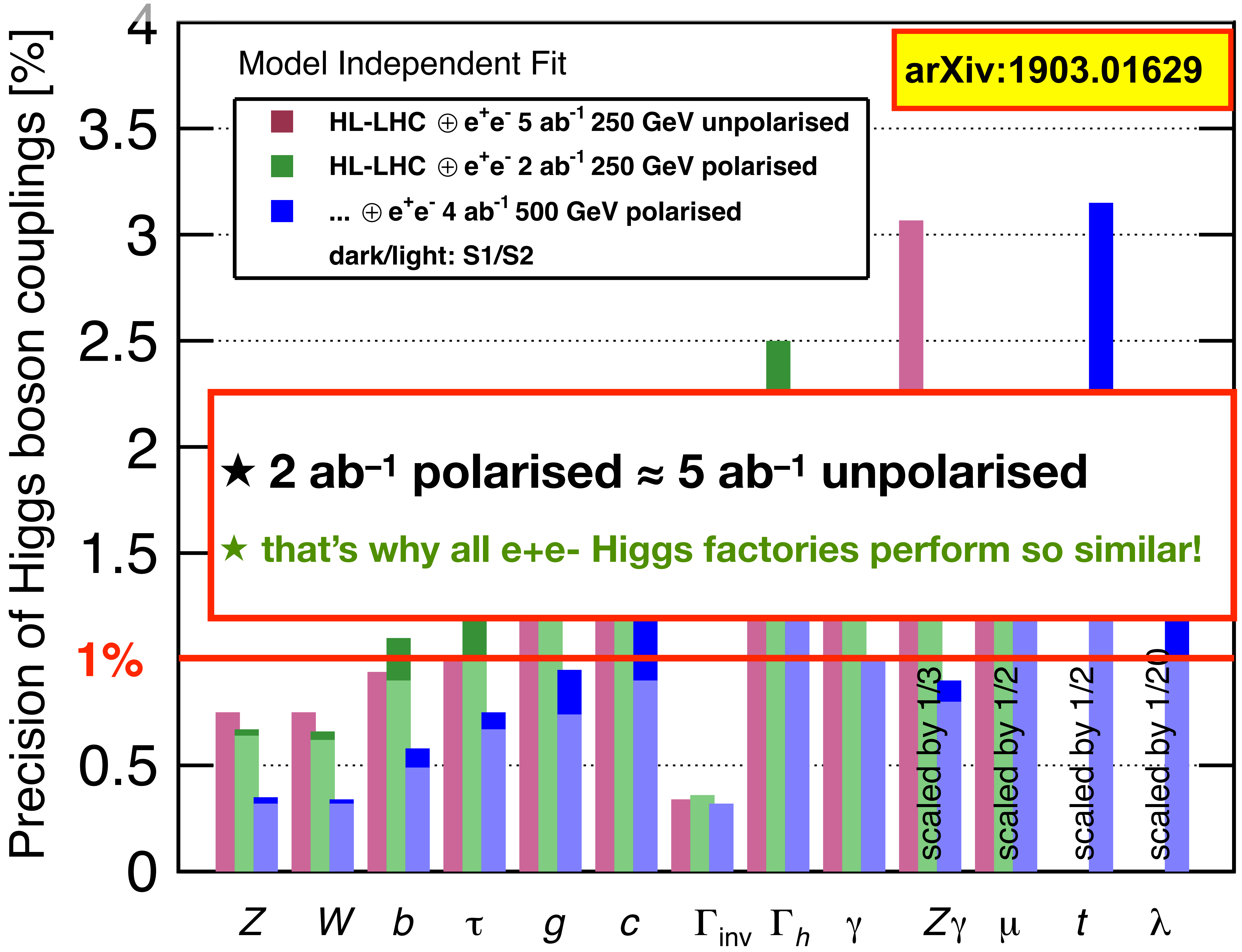
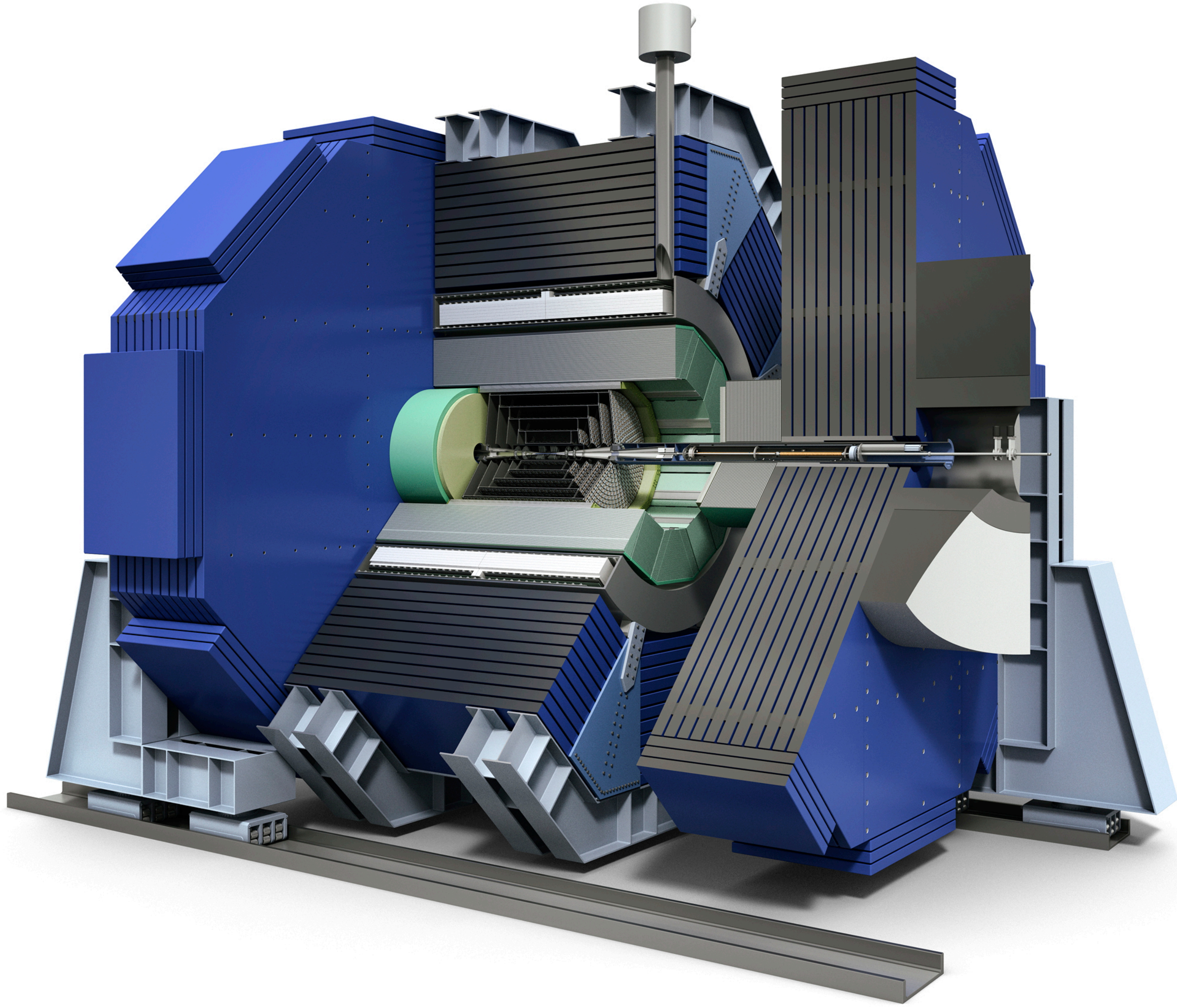
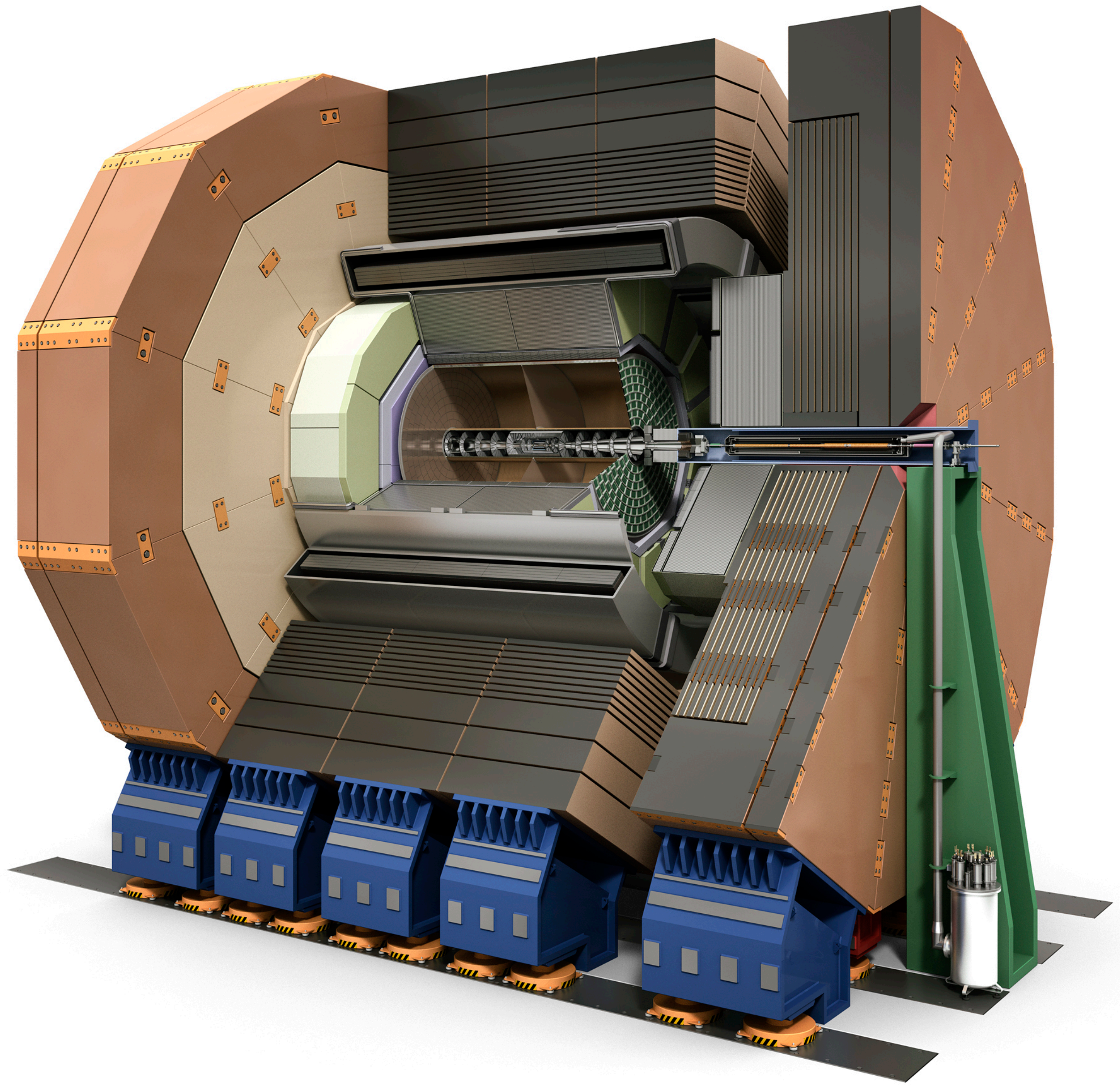


Higgs Factory Detector Concepts

for linear & circular





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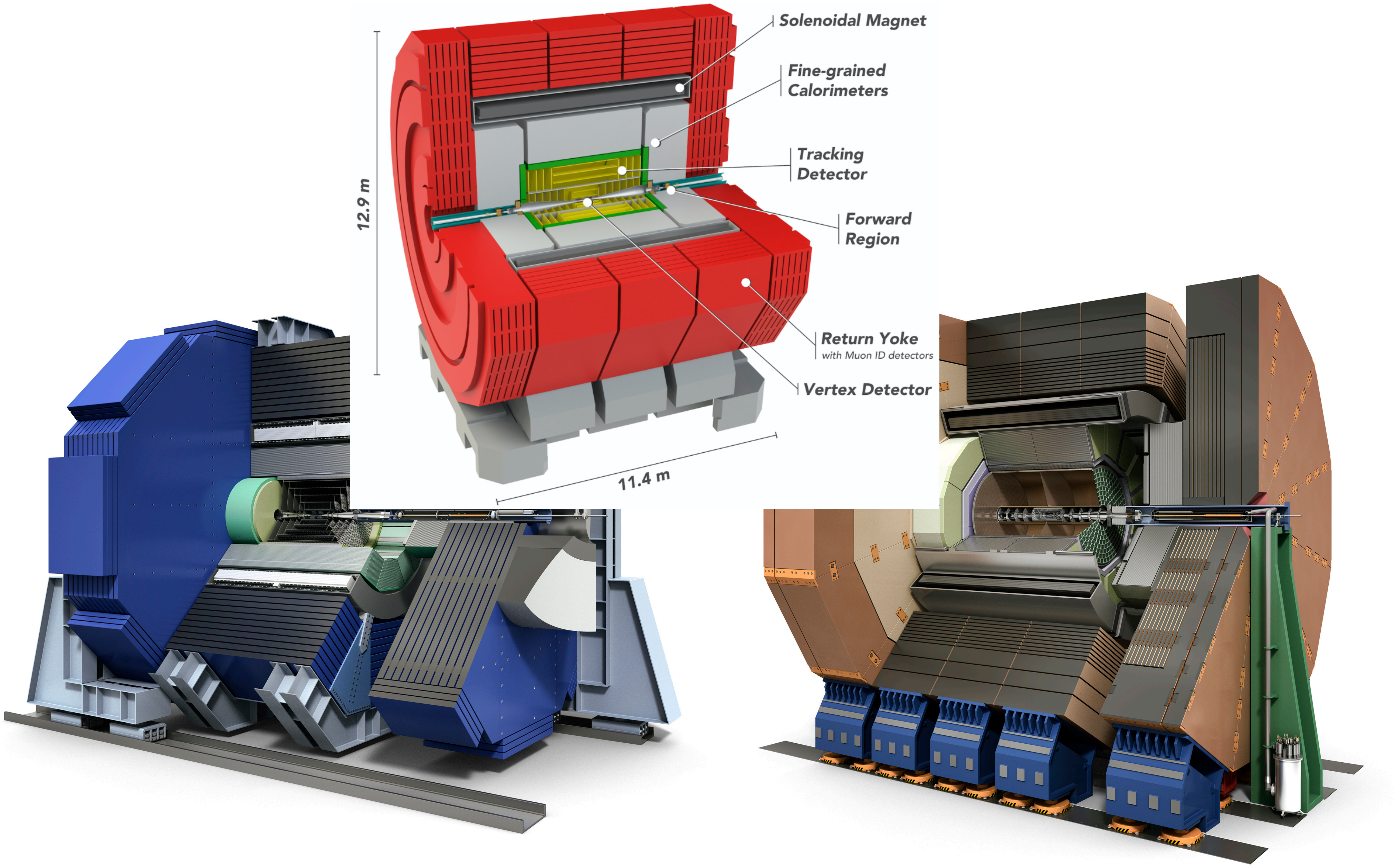

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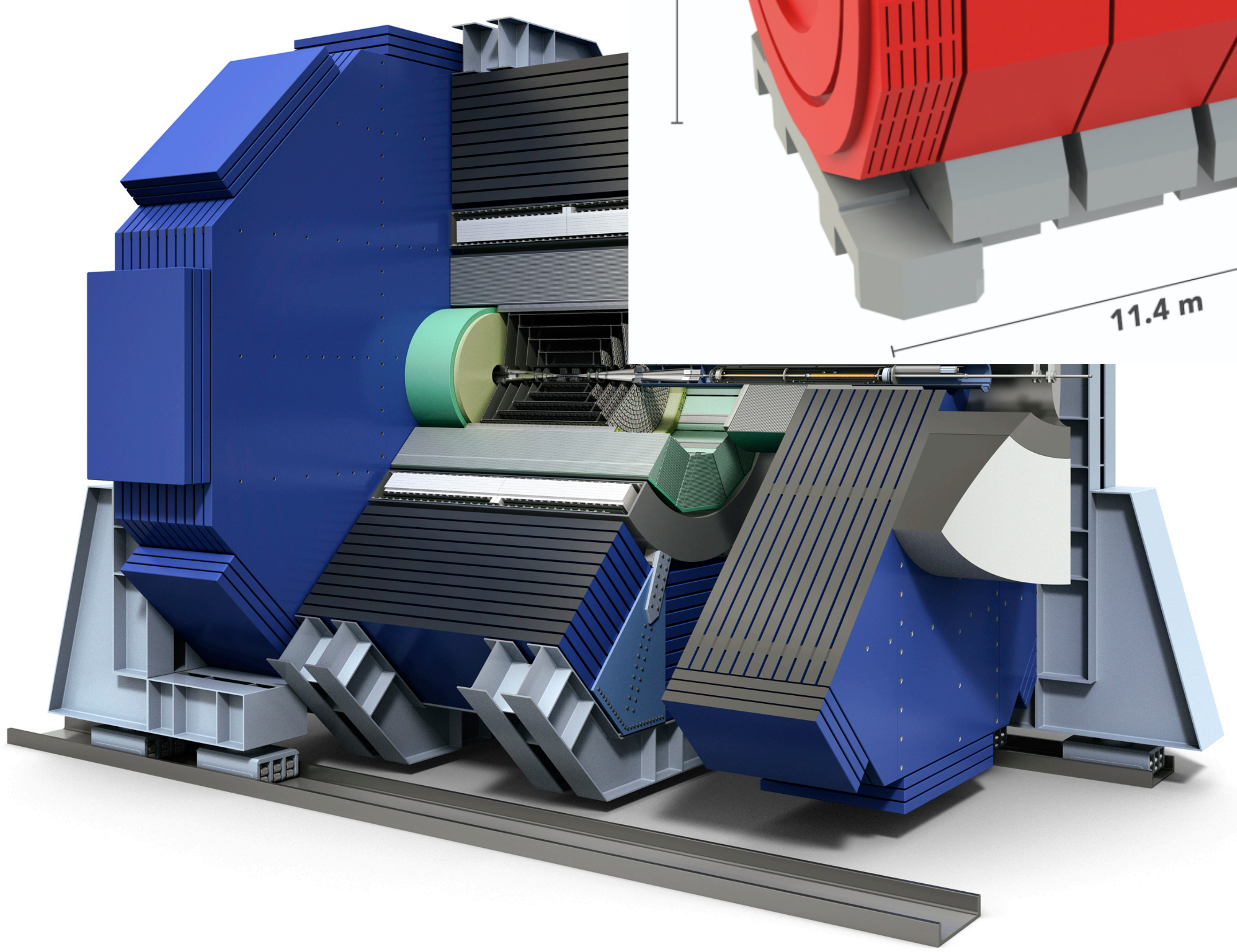

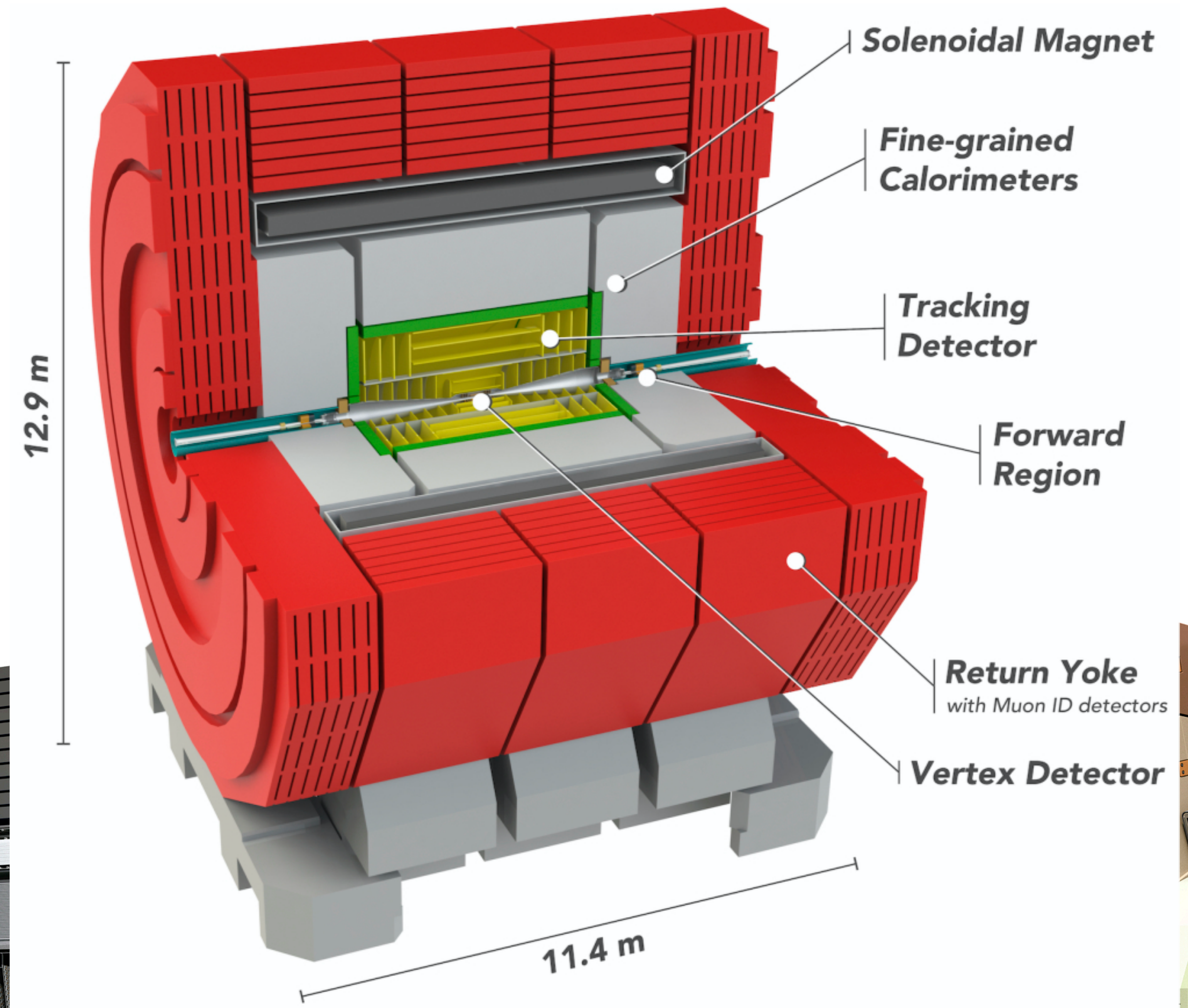

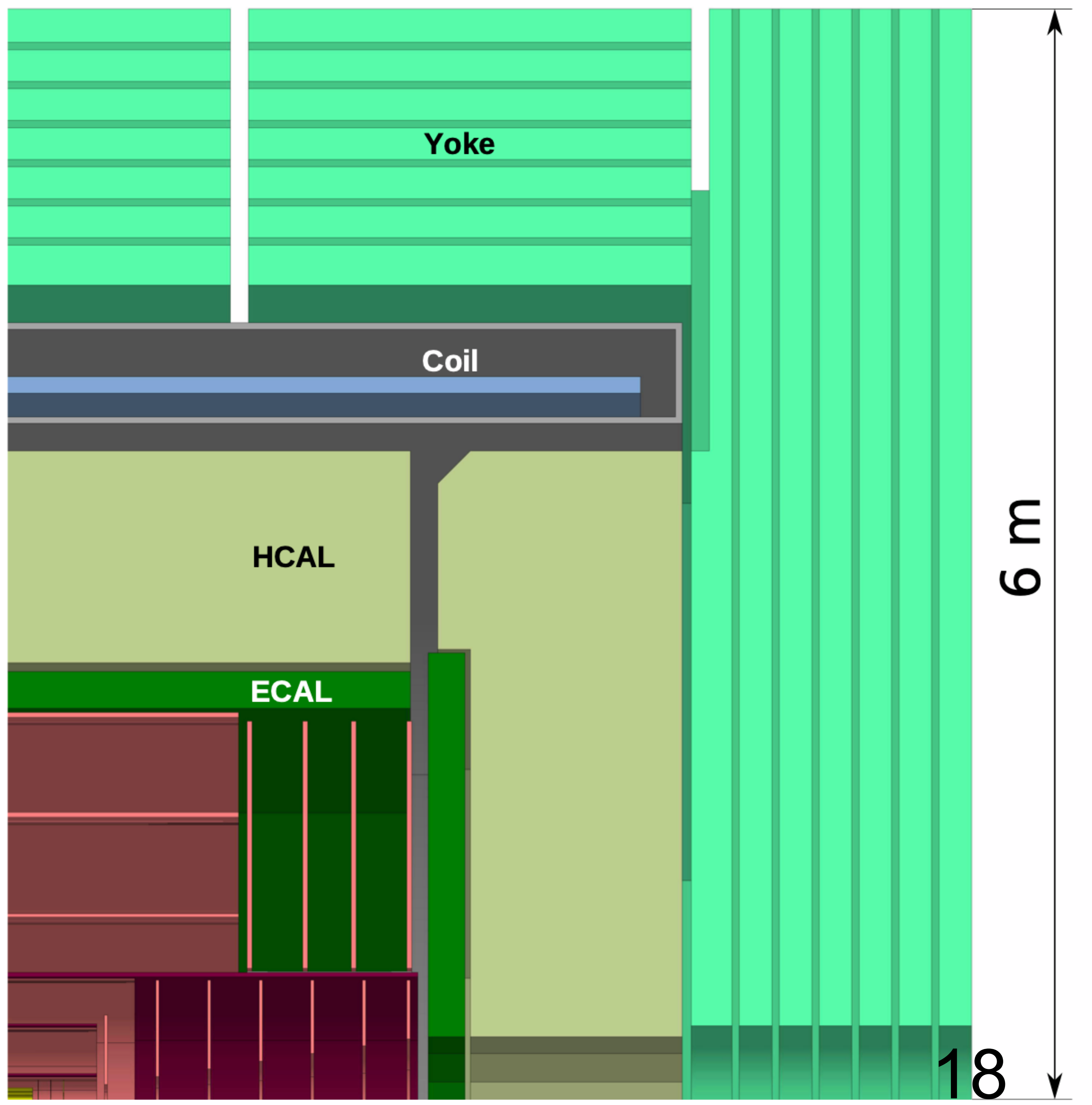

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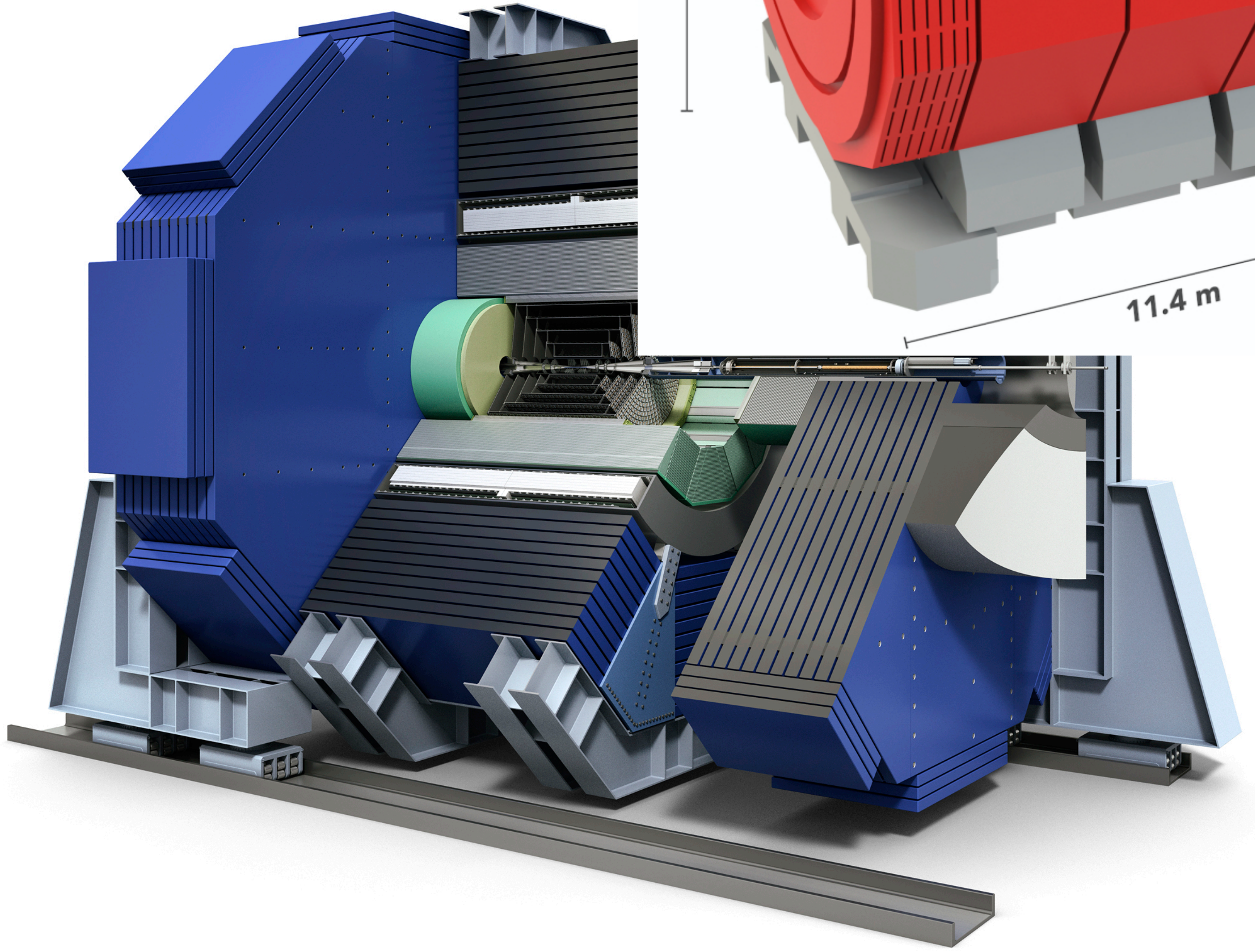

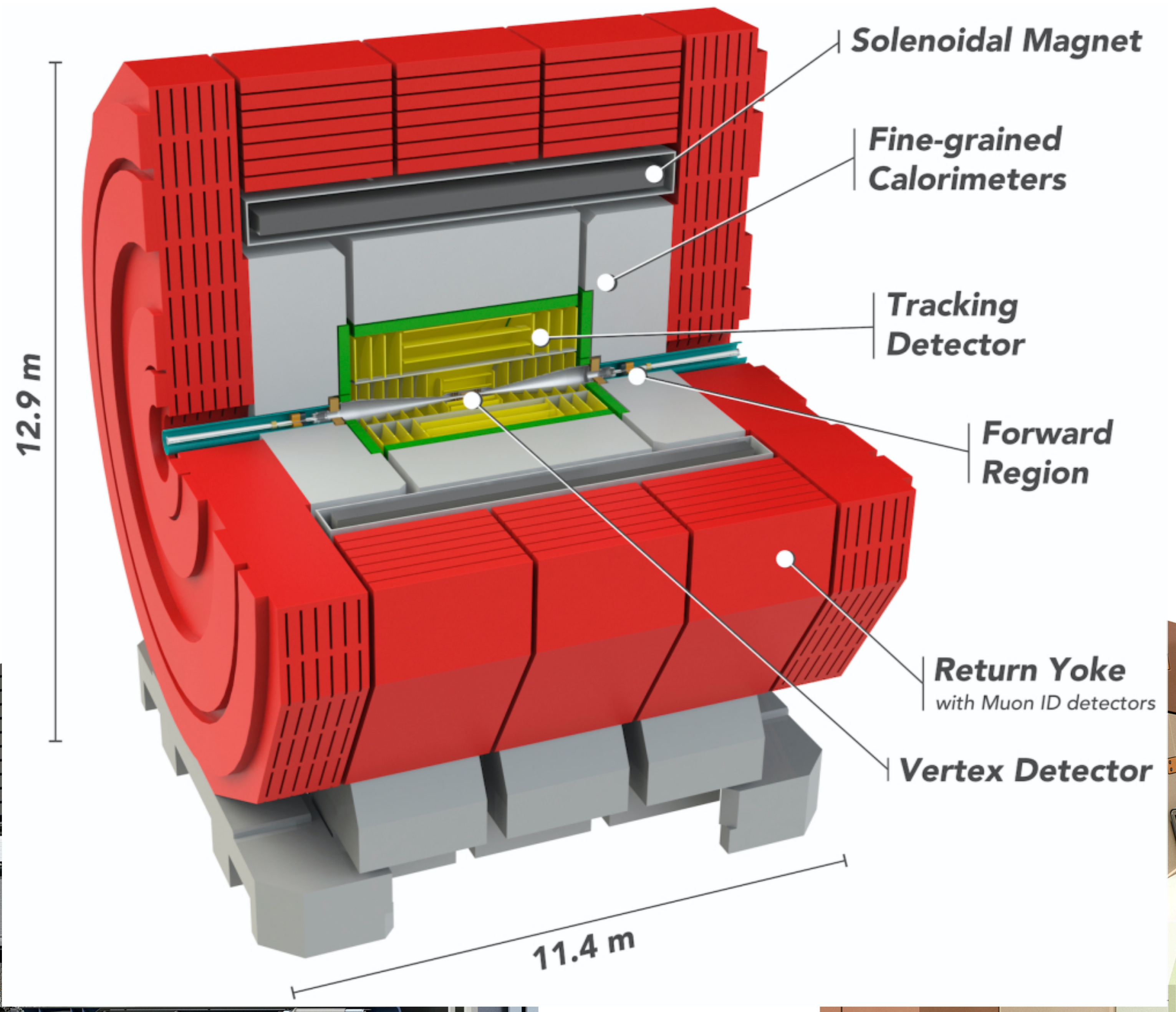

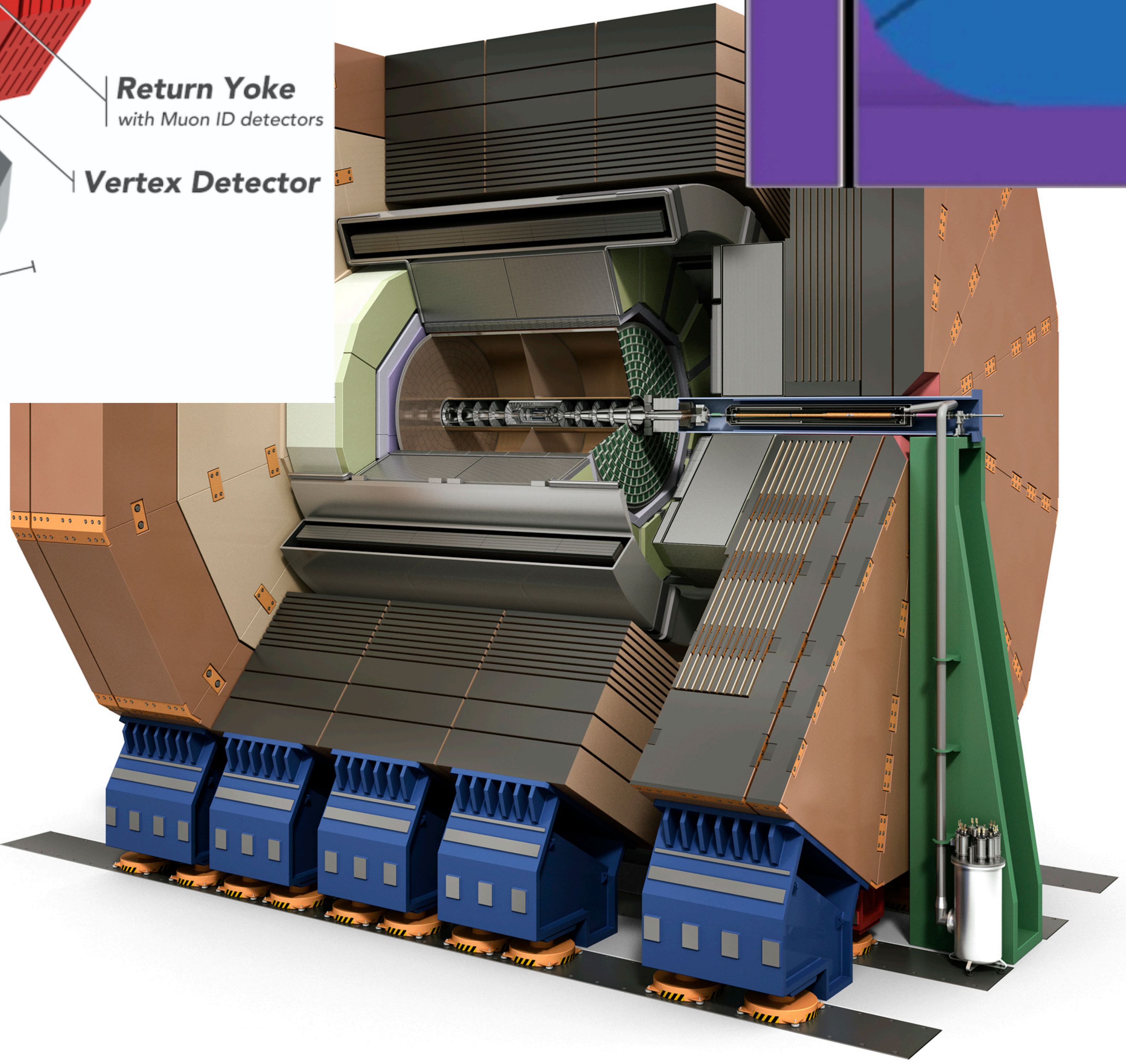

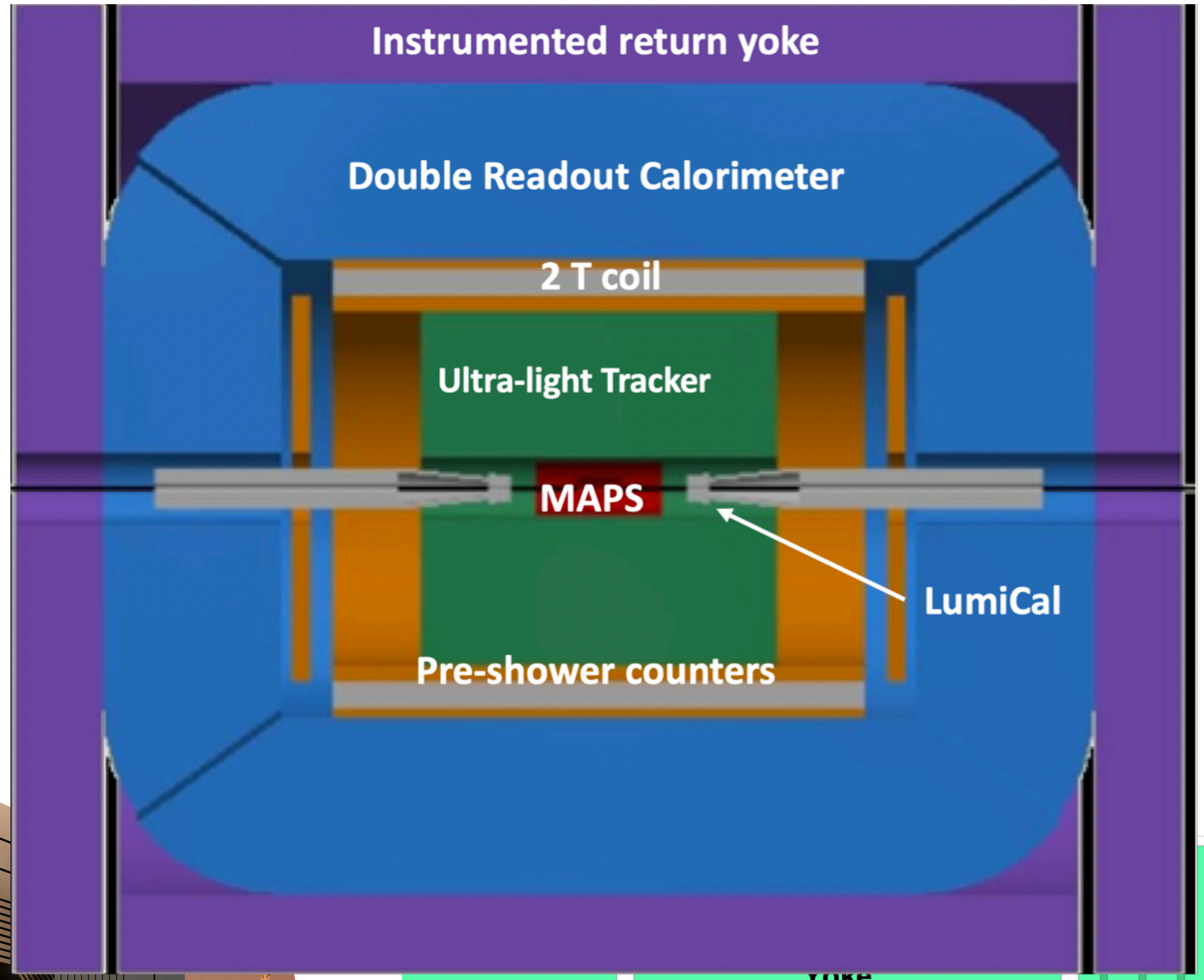

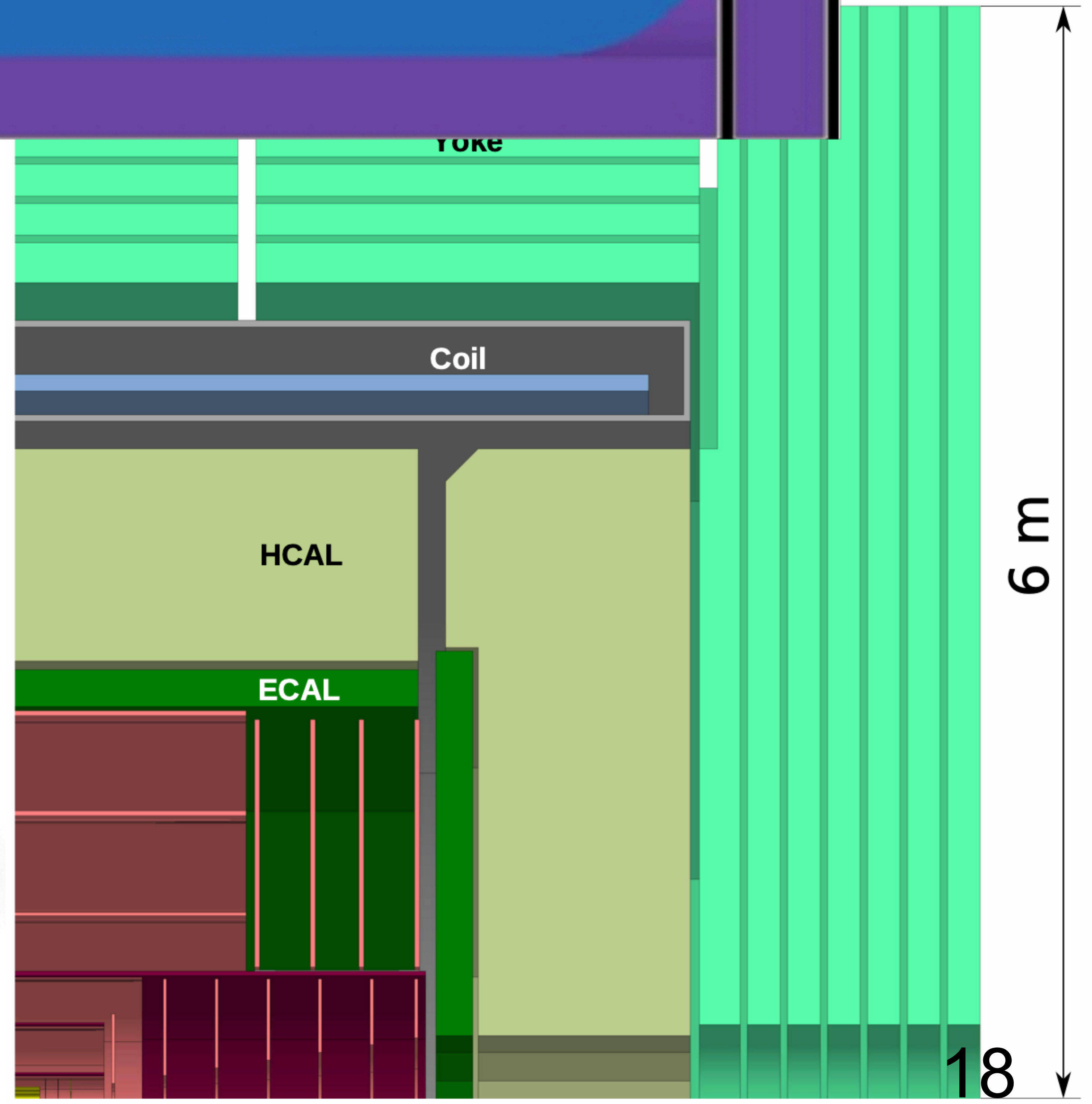

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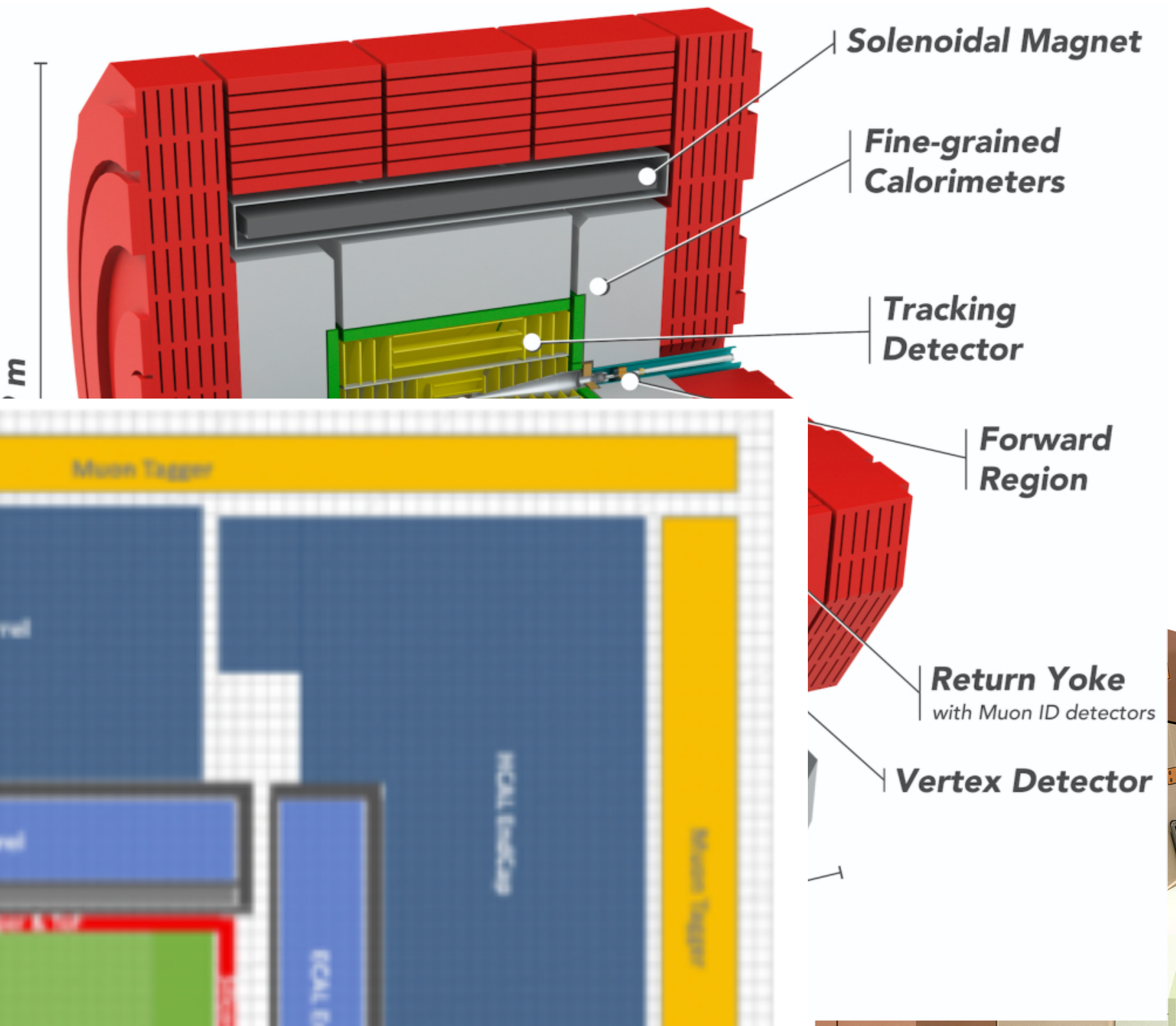

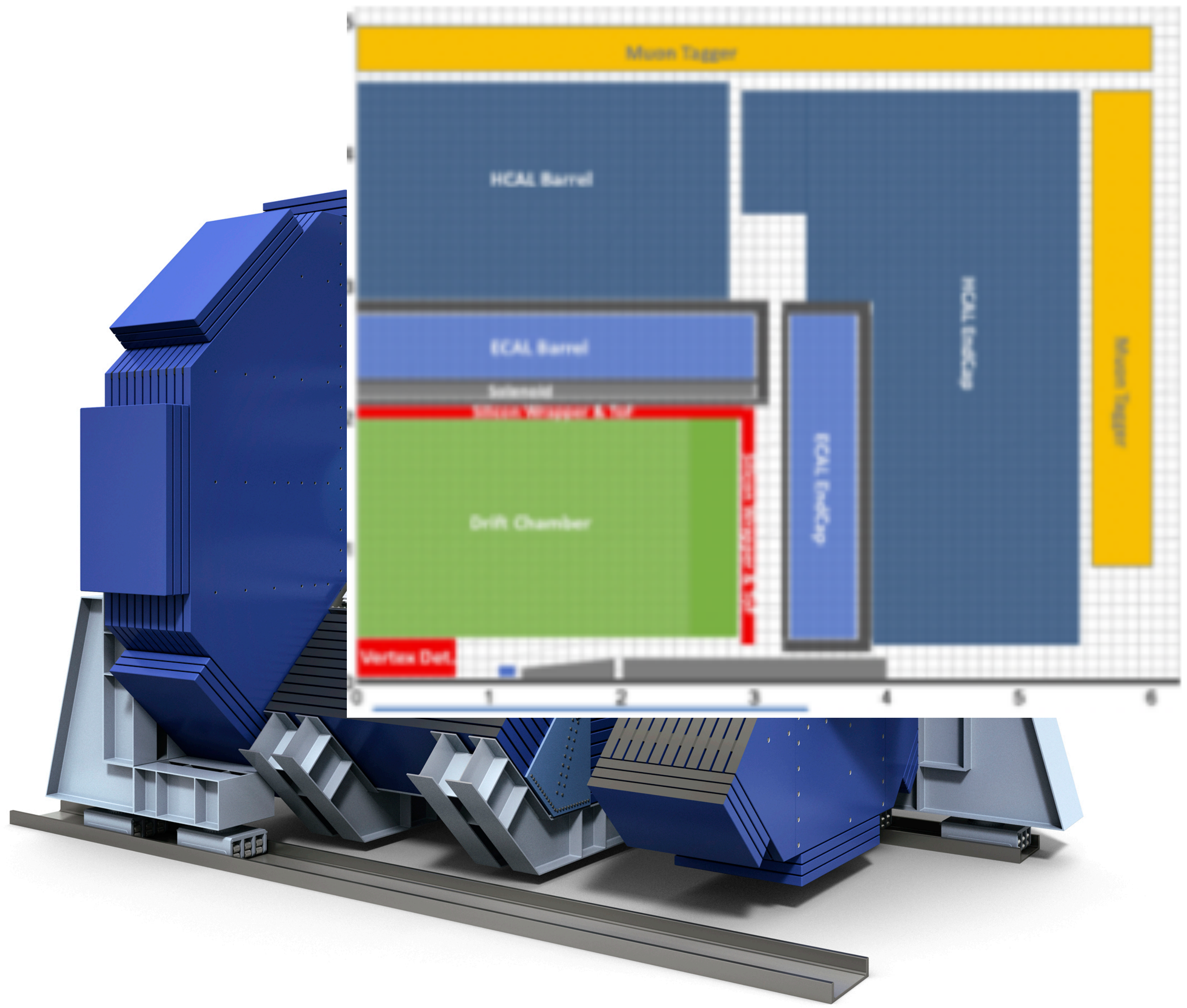

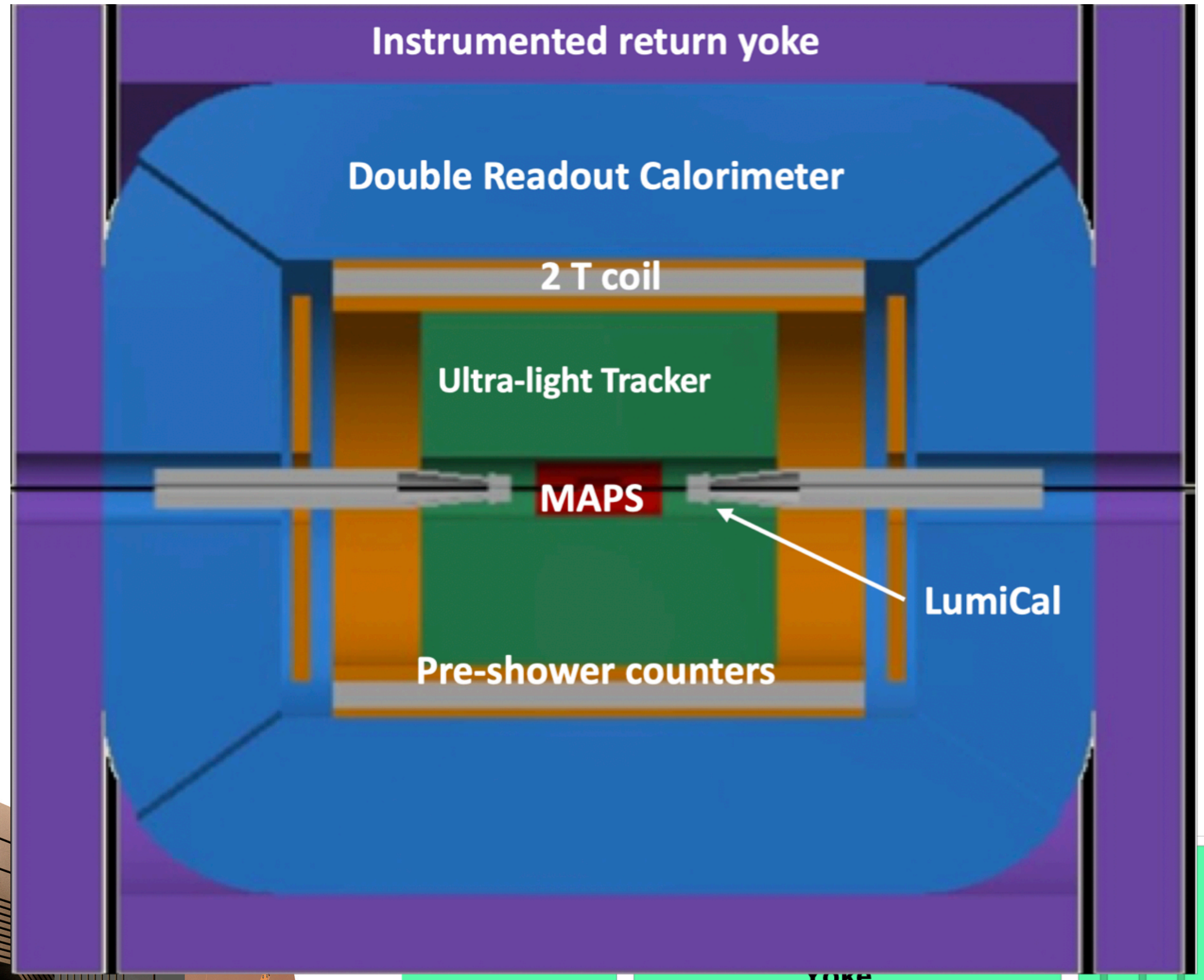

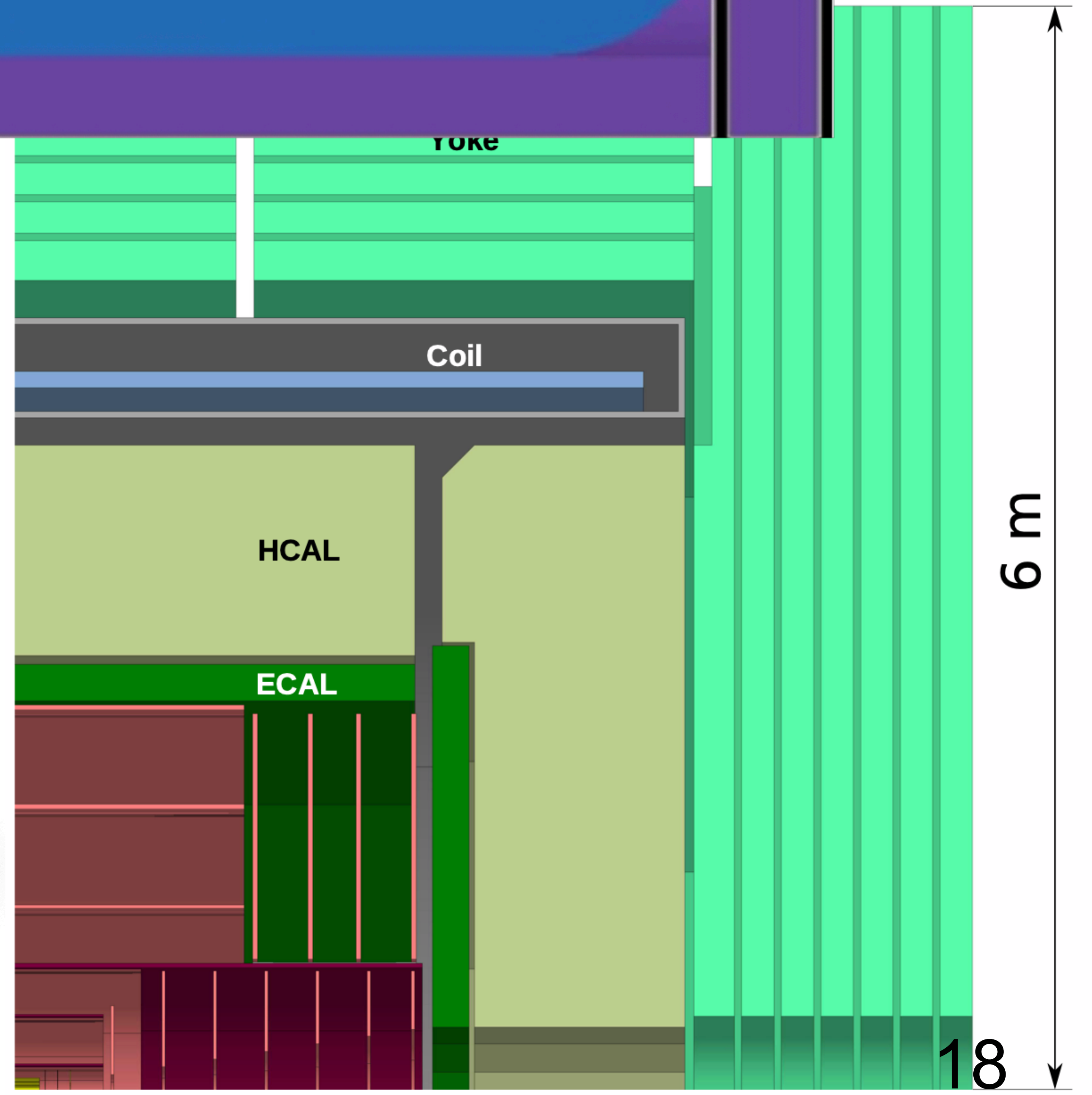

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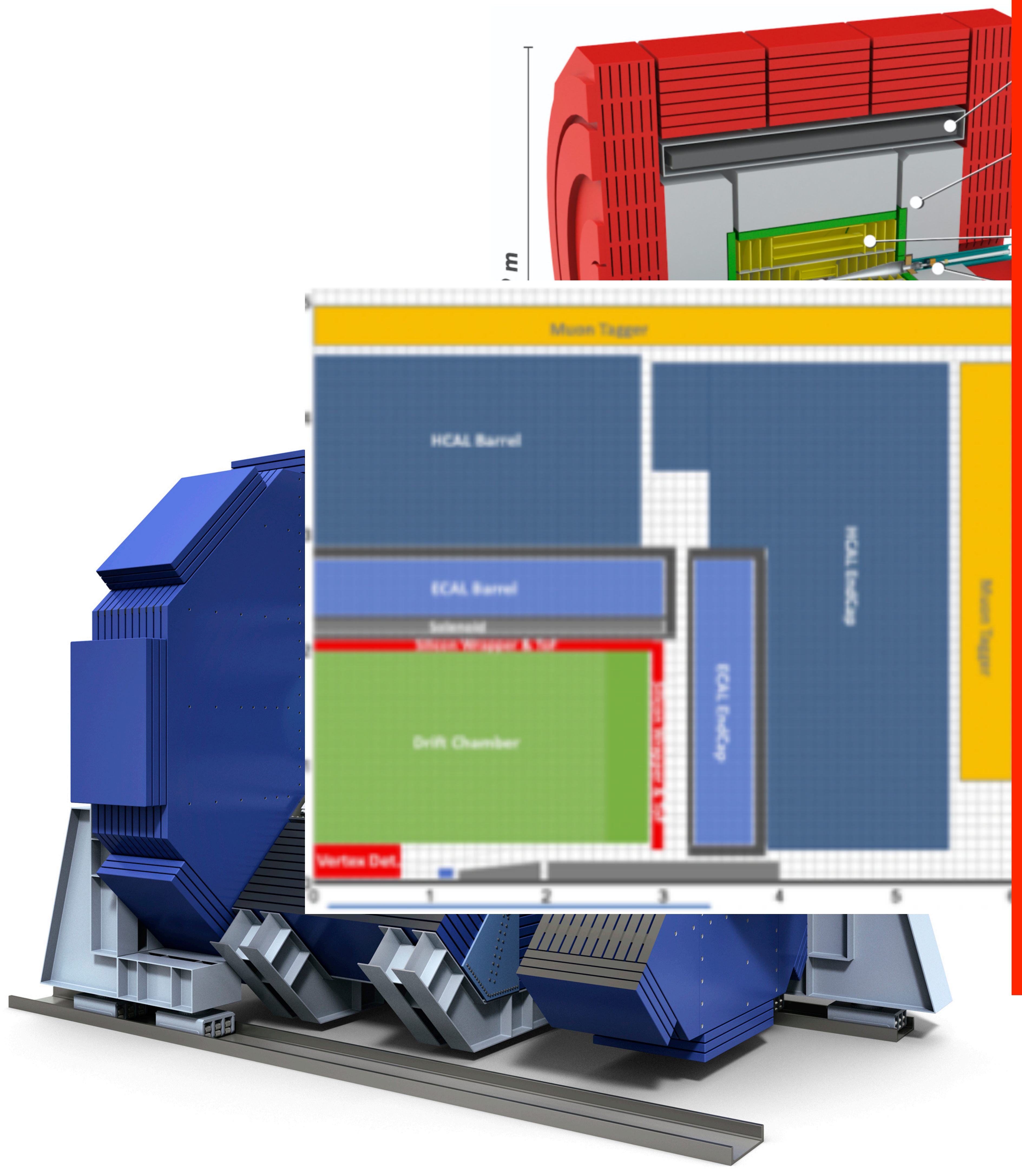

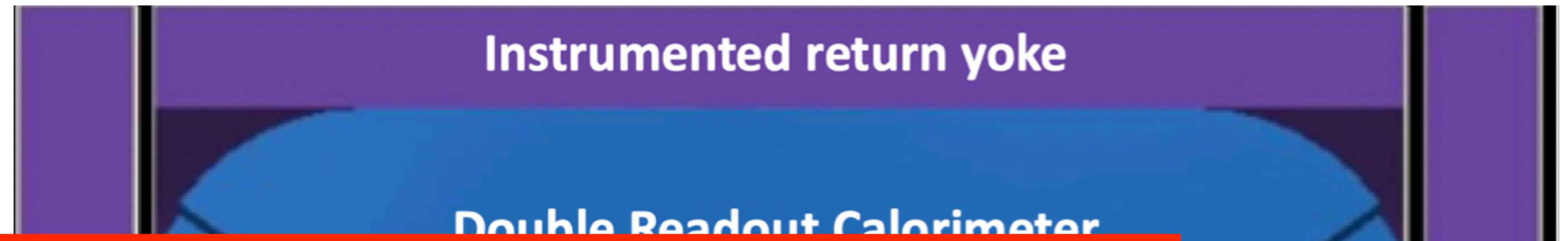

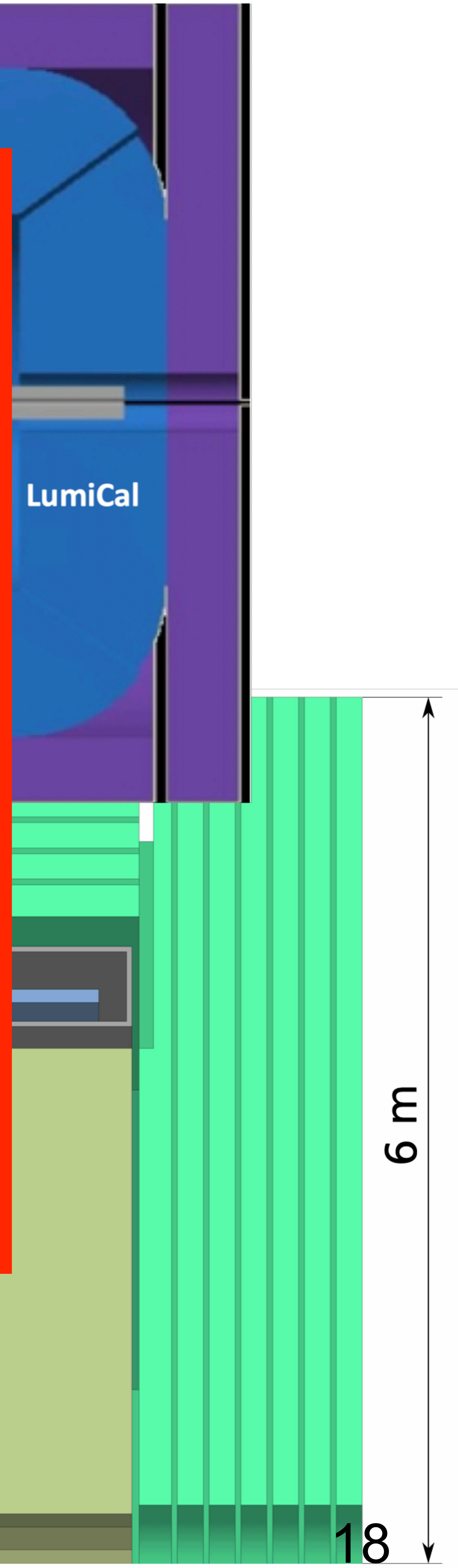

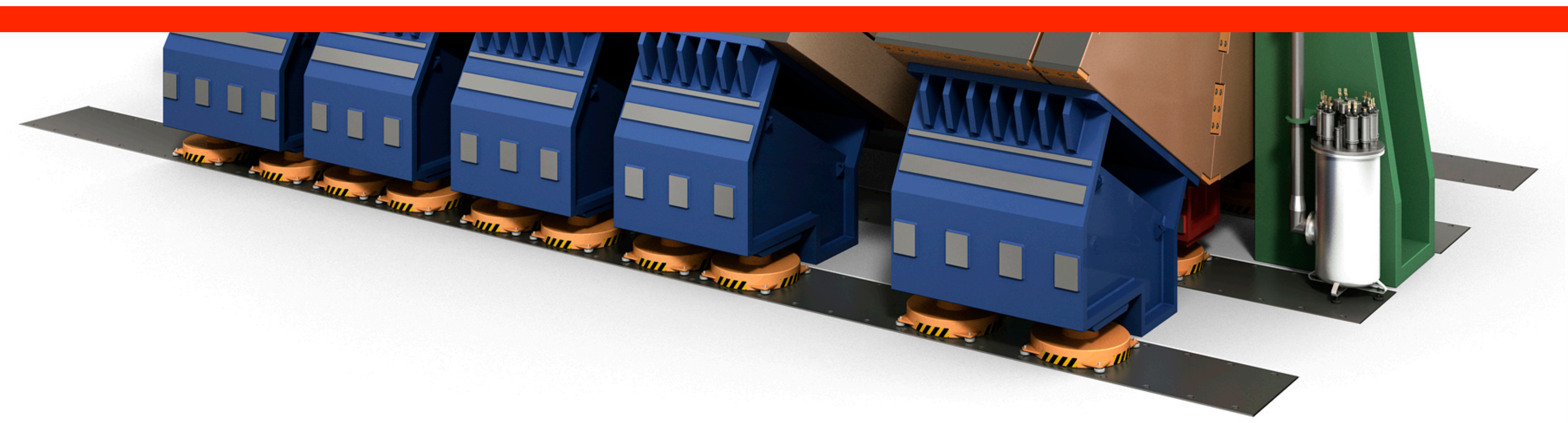

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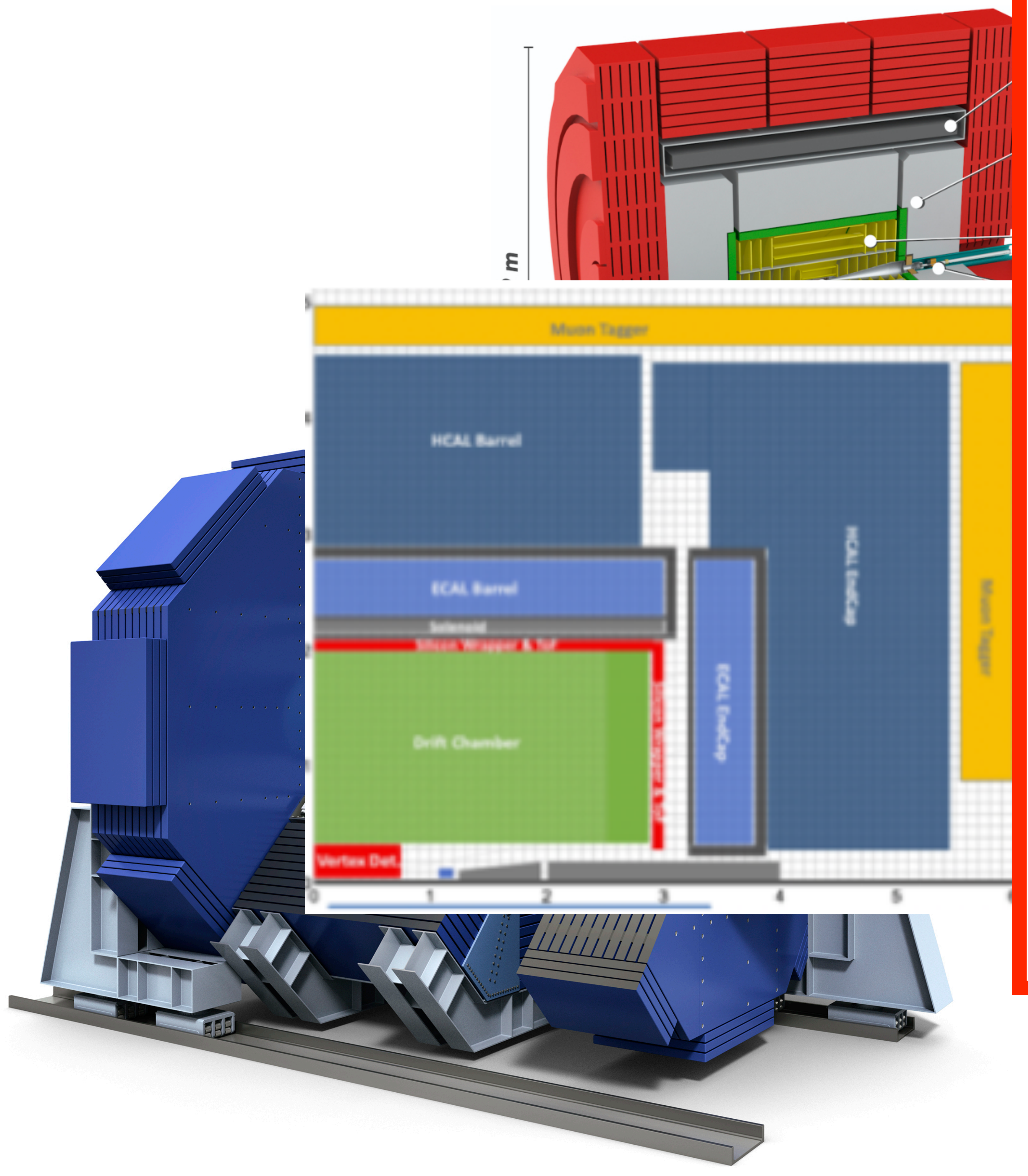

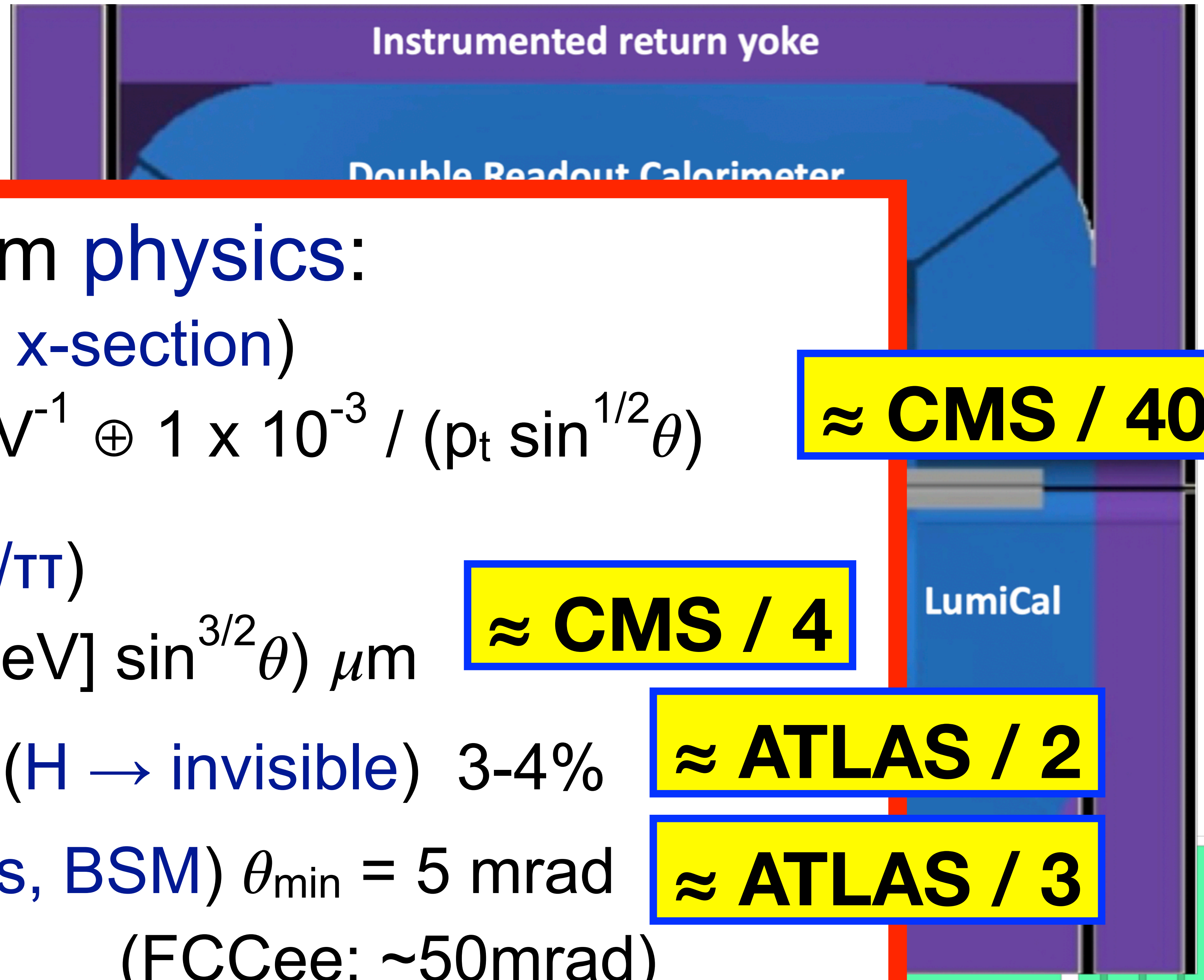

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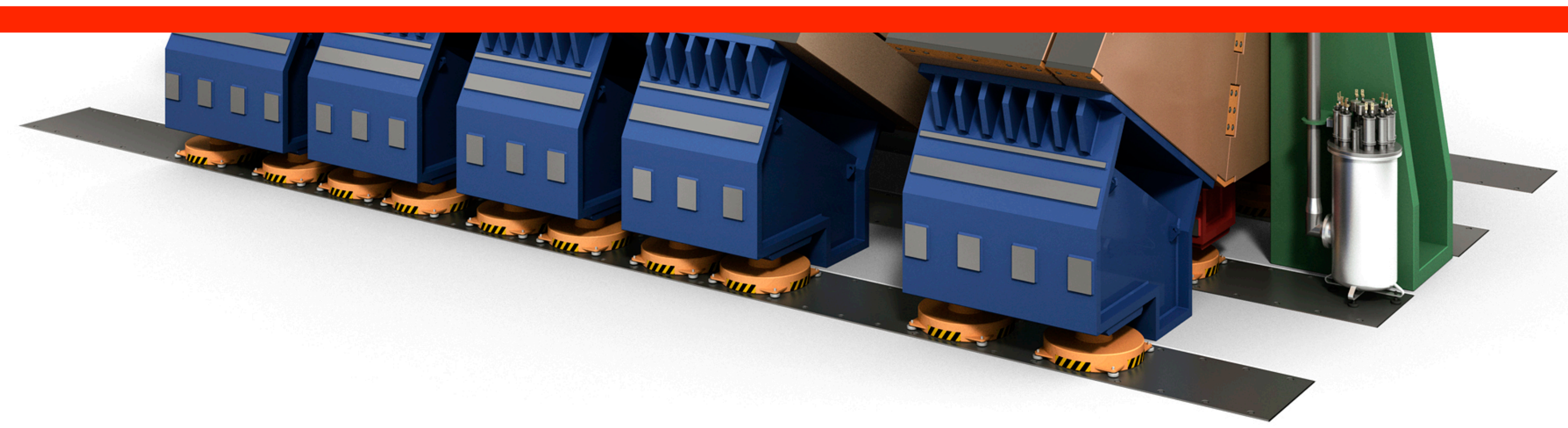

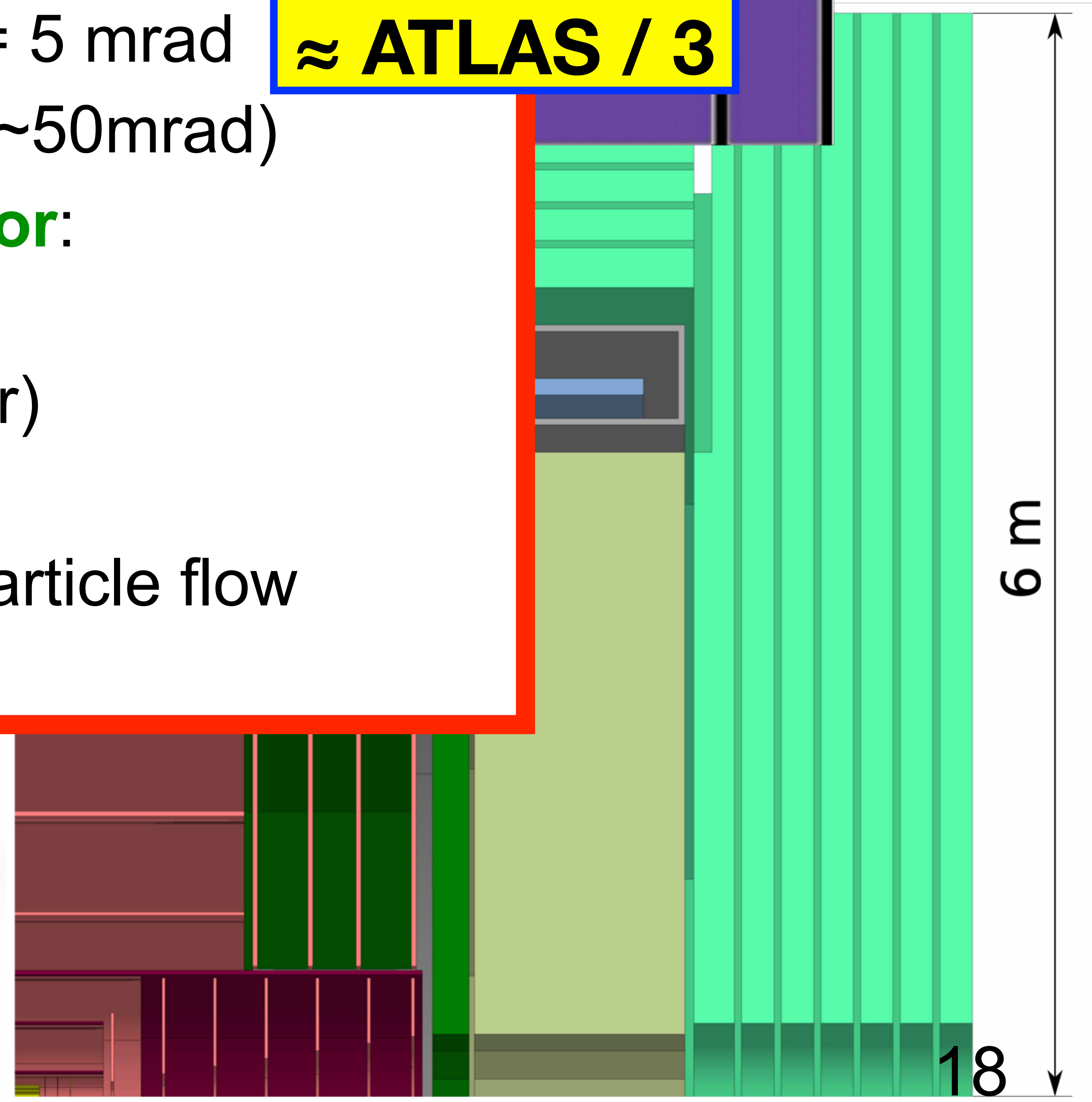

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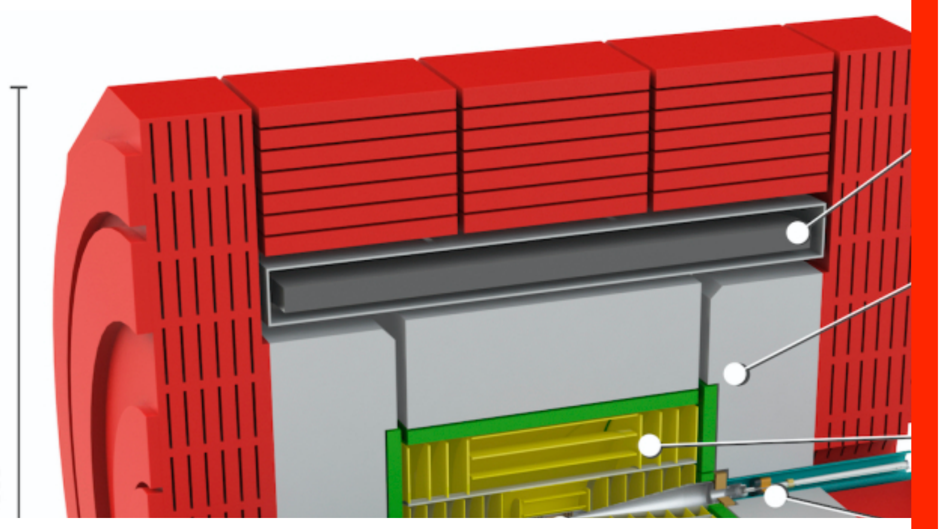

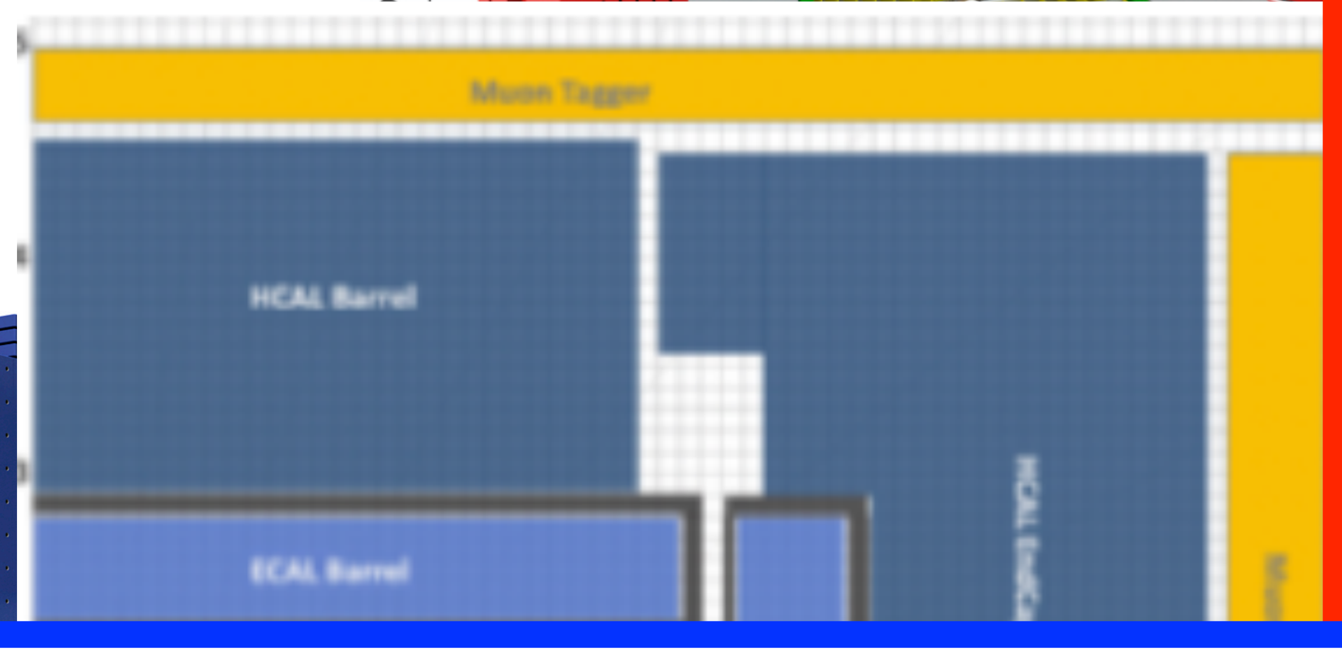

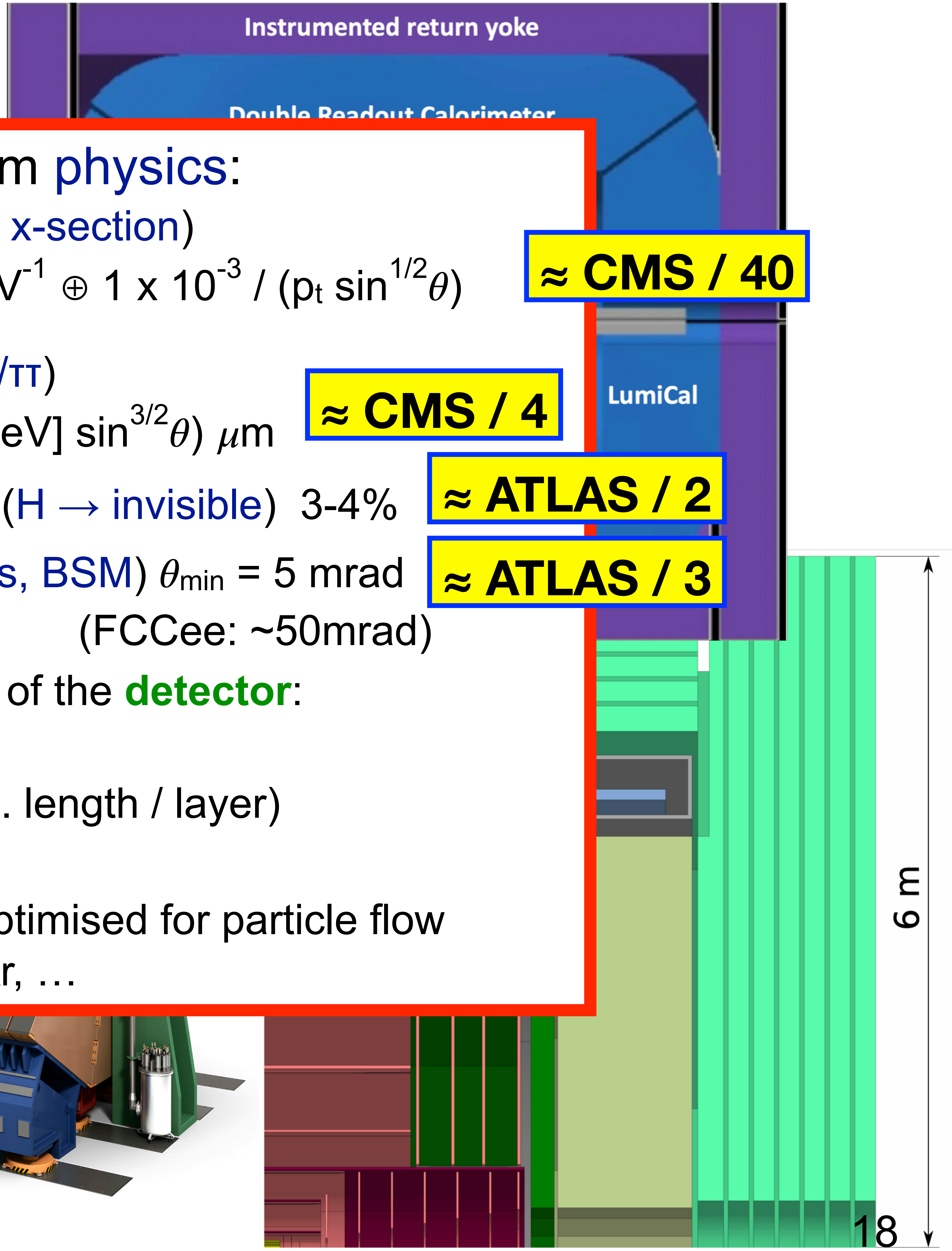

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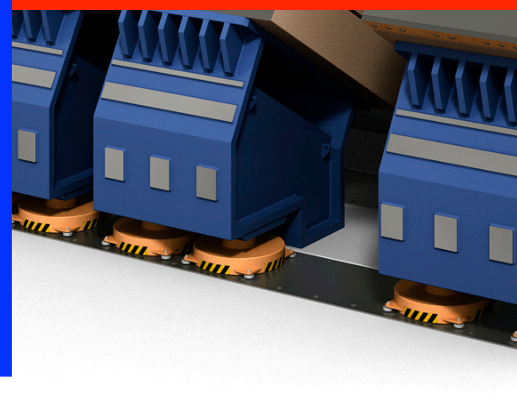

Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

only Linear Colliders: lower collision rate enables

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

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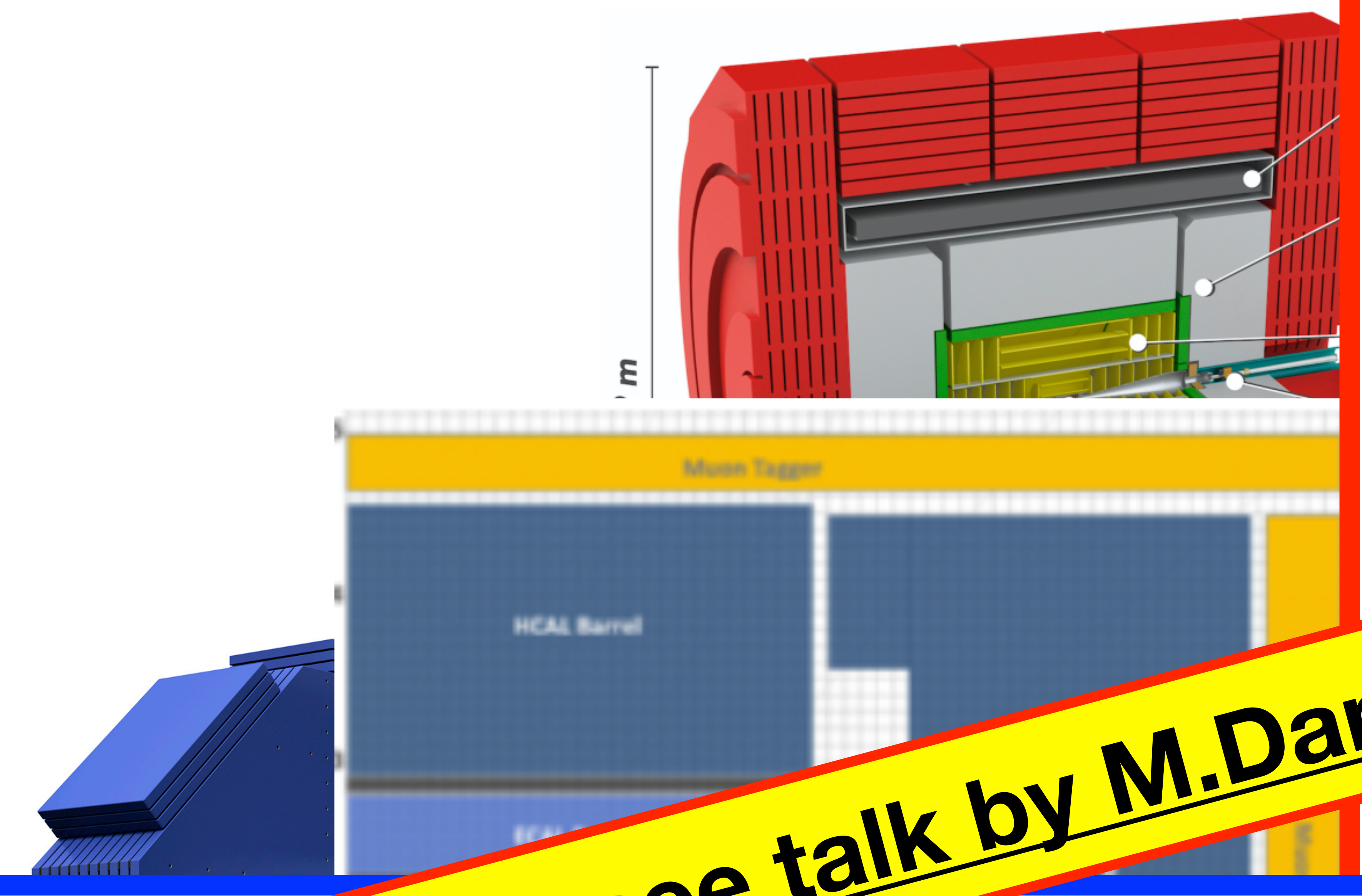

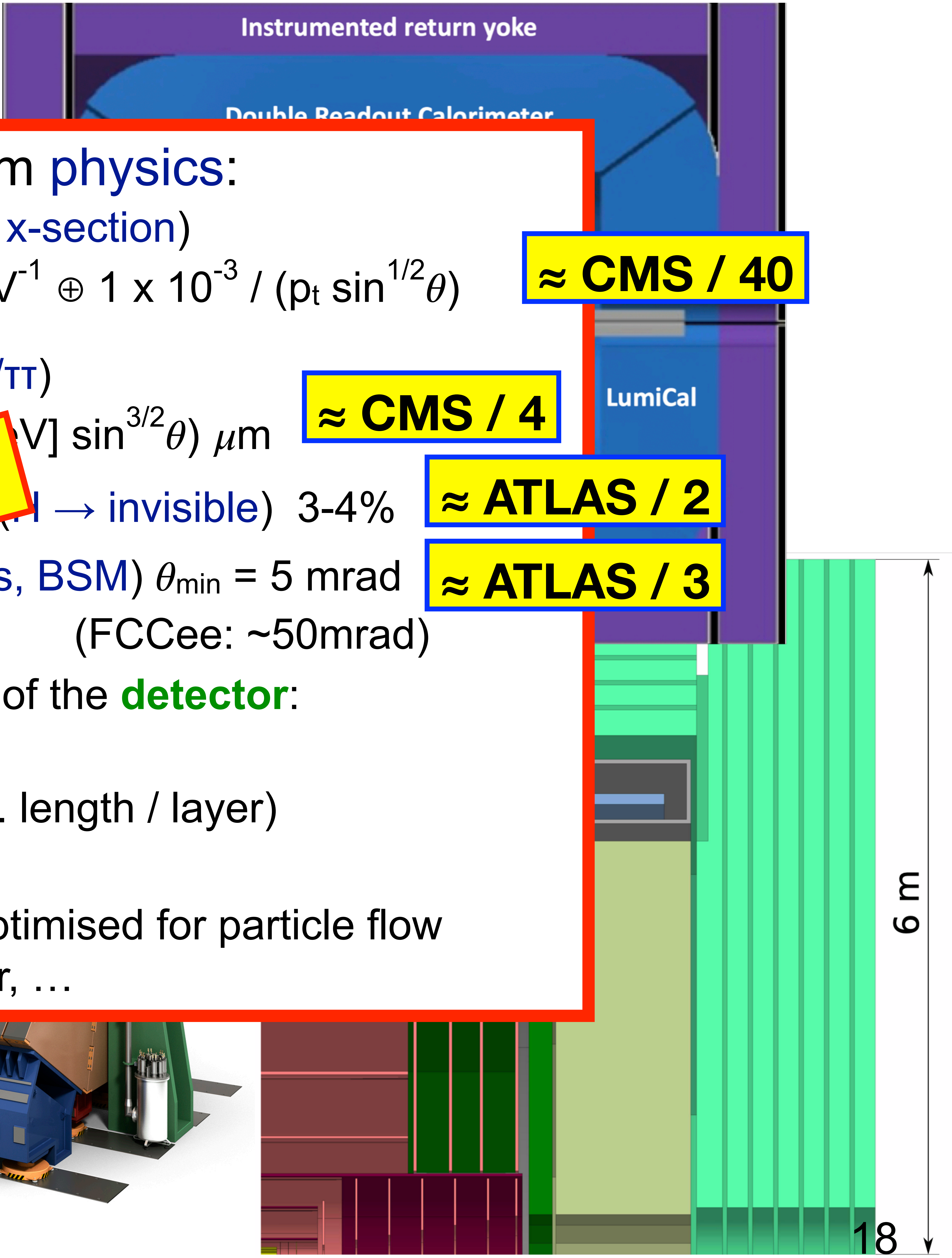

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=> see talk by M.Dams after coffee

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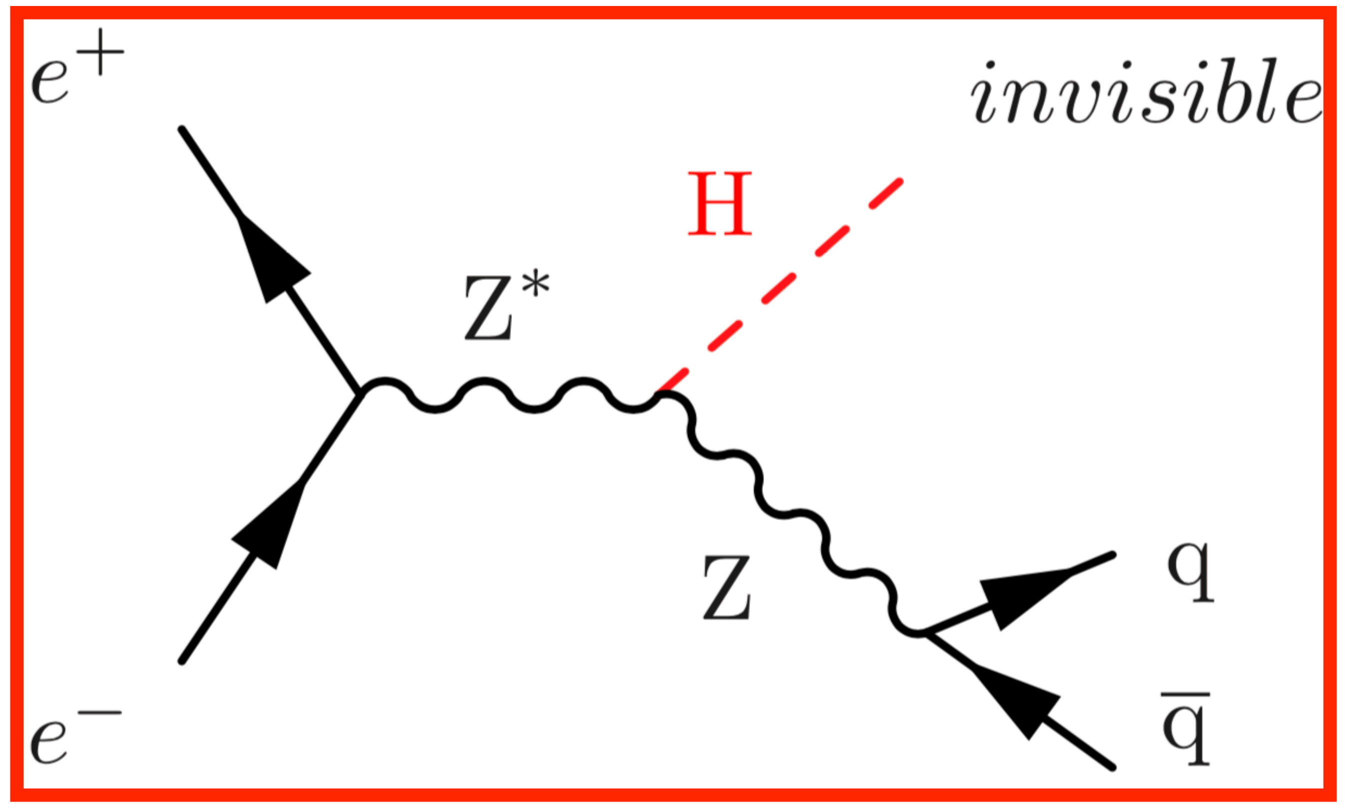
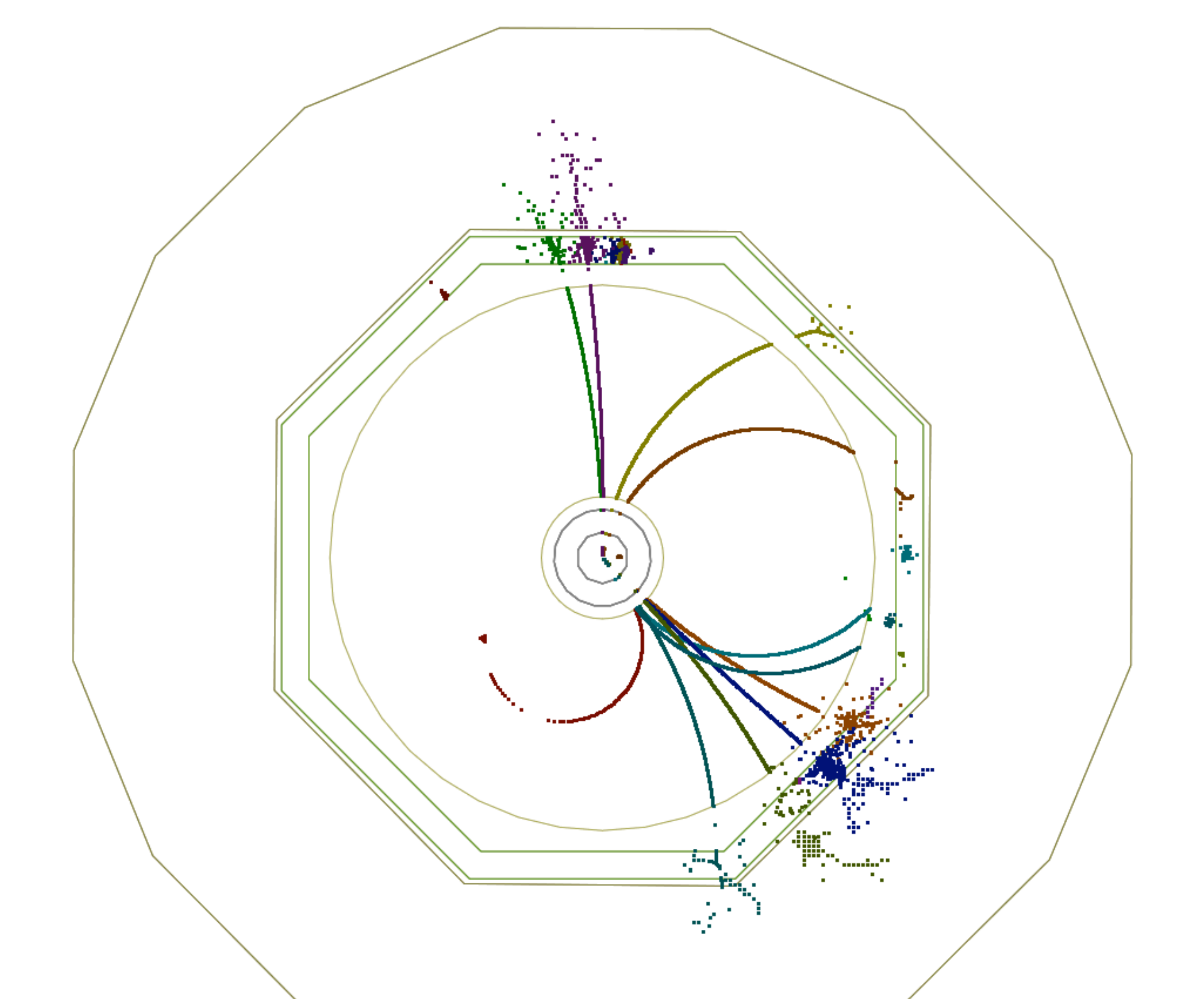
Example: Higgs decay to “invisible”

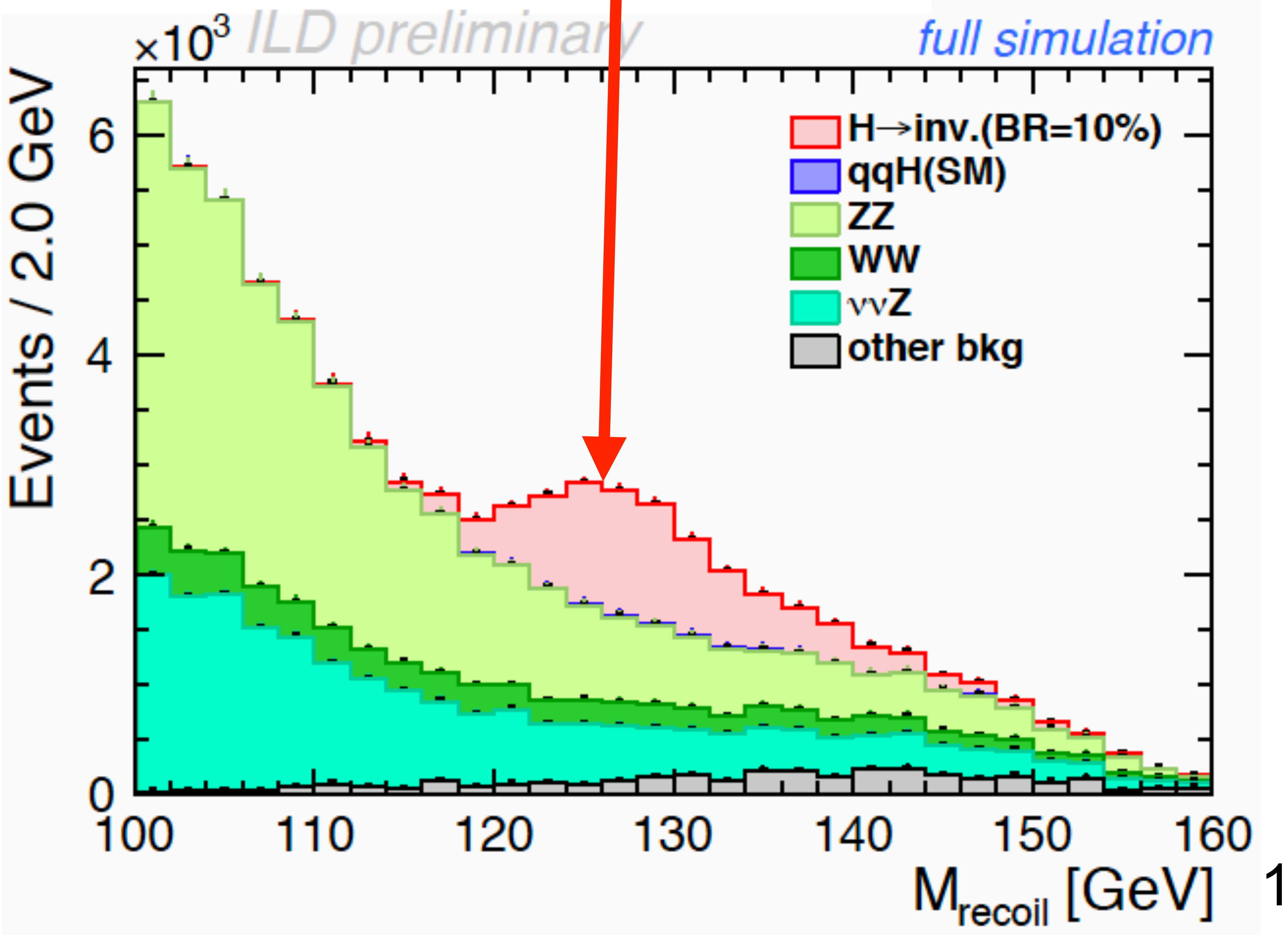
Dark Sector Portal?

- use **$e^+e^- \to Z\ h$** 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 250 GeV: exclude BF > 0.16% at 95% CL (HL-LHC expectation: 2.5%, SM prediction: 0.12%)**





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



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

Example: Higgs decay to "invisible"

Dark Sector Portal?

- use $e^+e^- \to Z\,h$ 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?**
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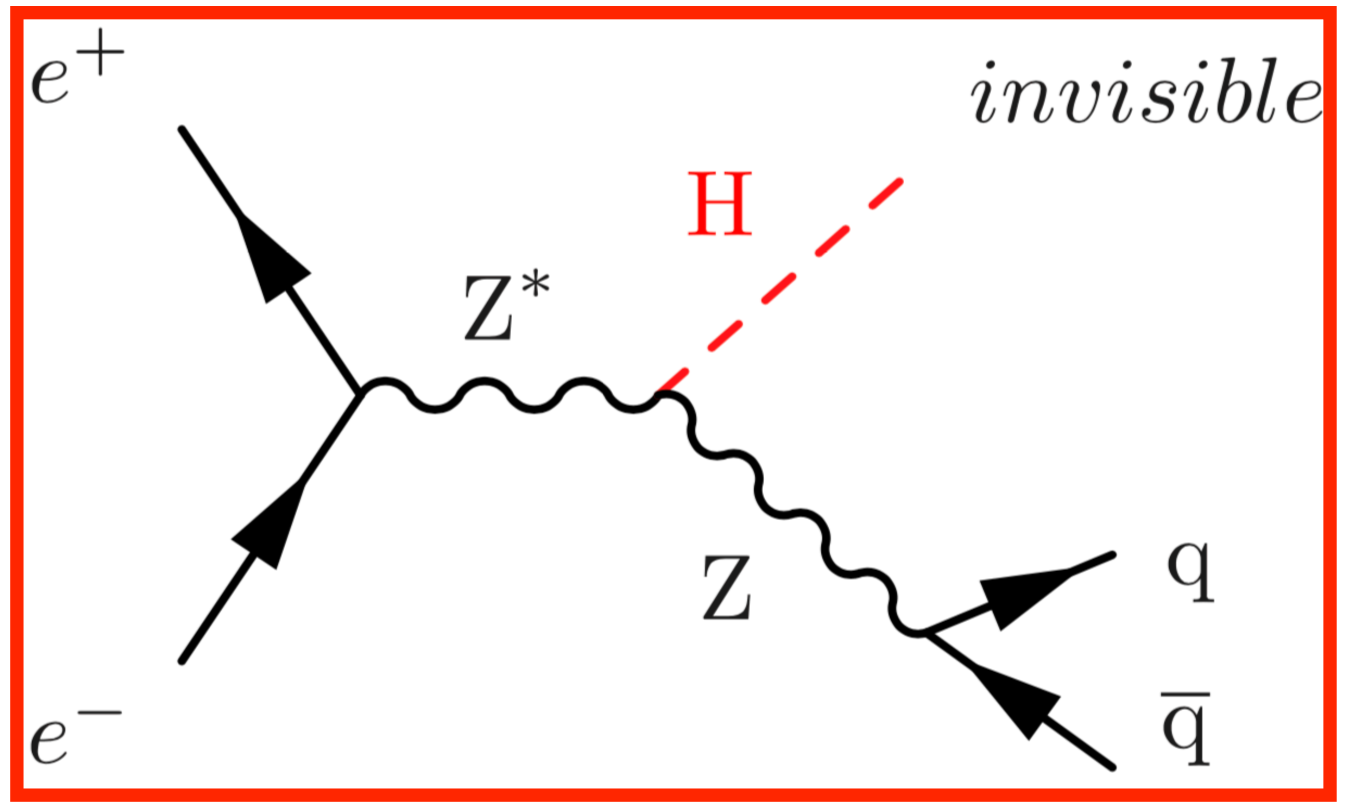

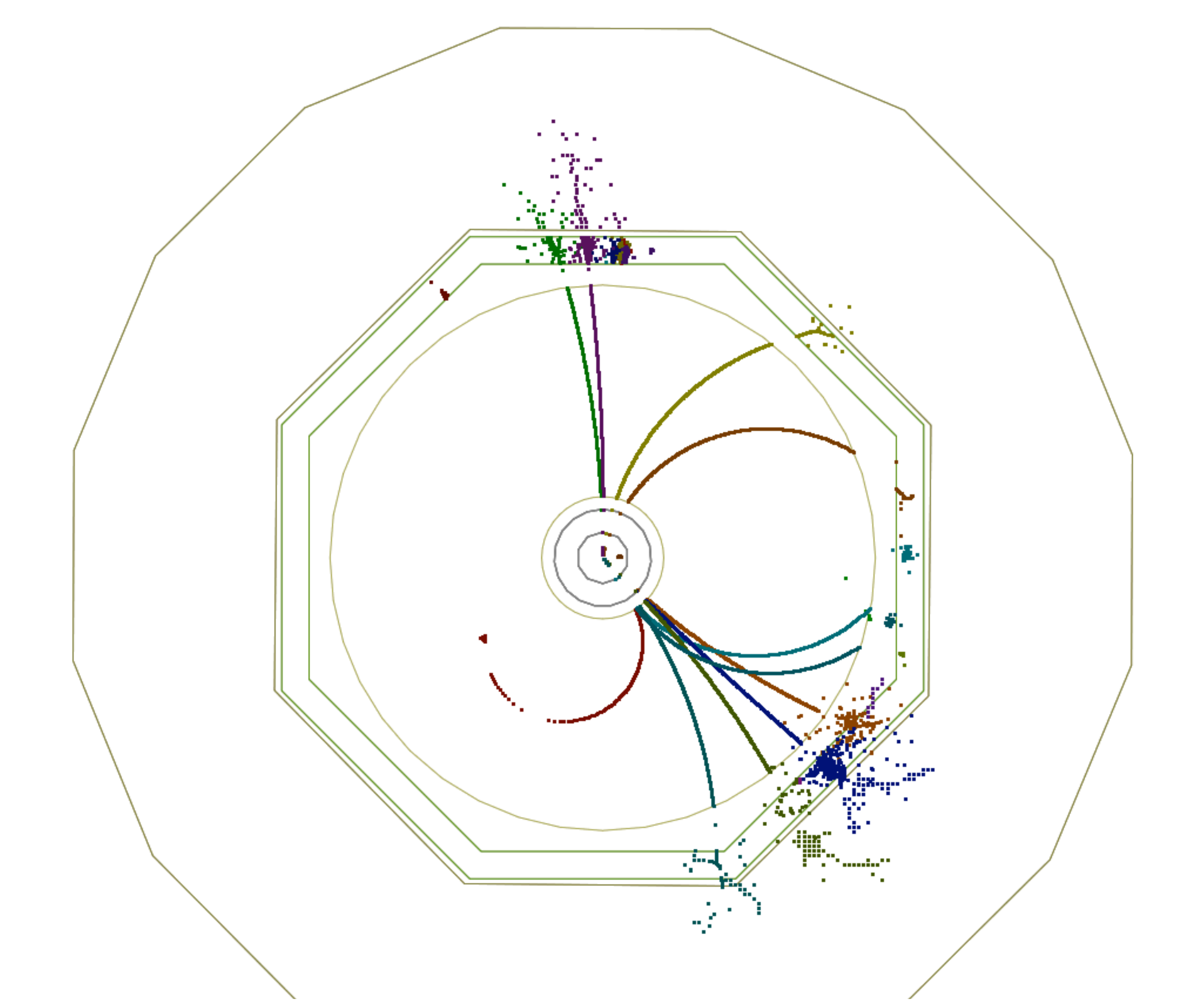

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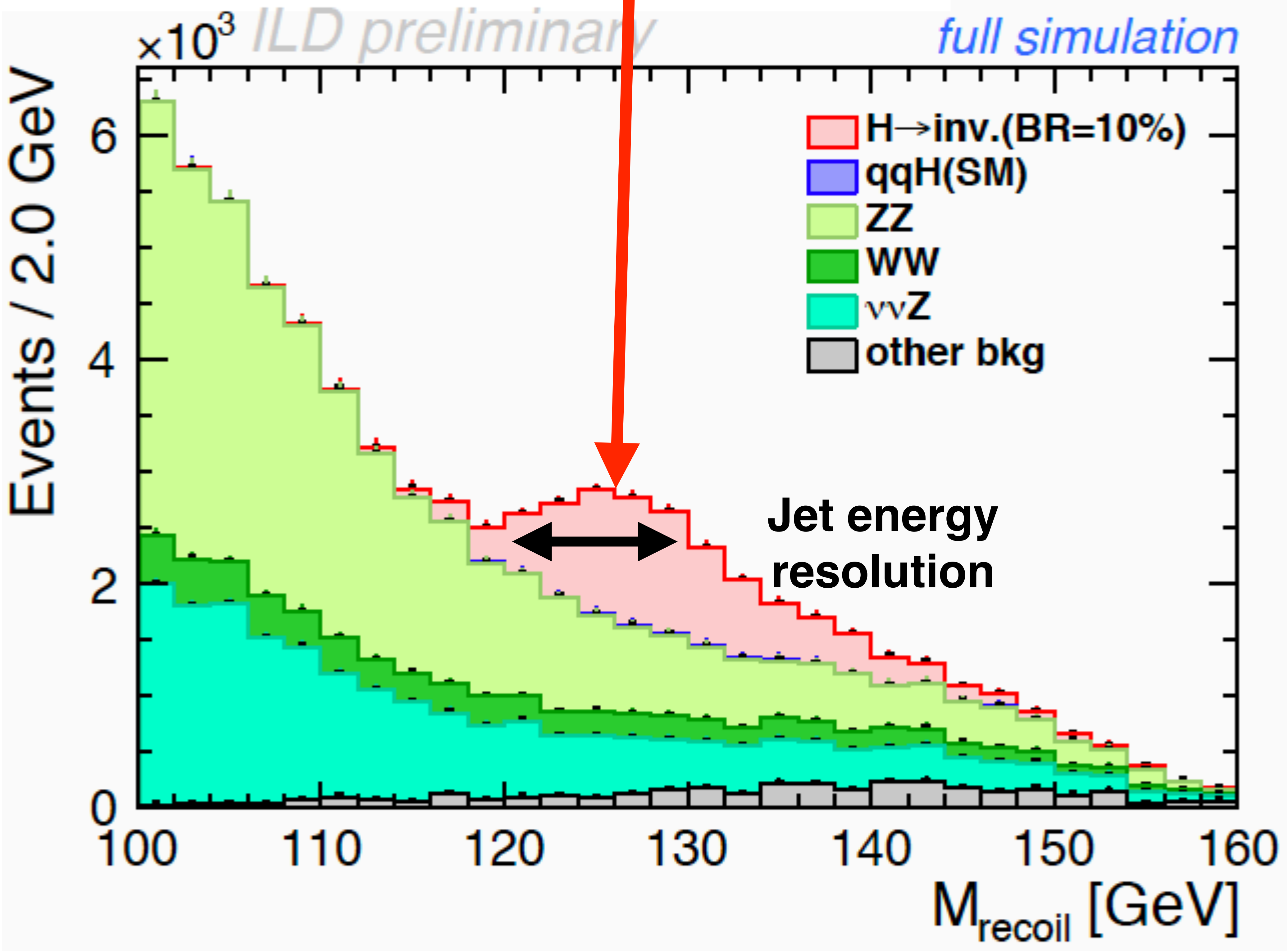

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Urgently wanted: modern jet clustering

… bottle-neck e.g. for many jet final-states, incl. Higgs self-coupling

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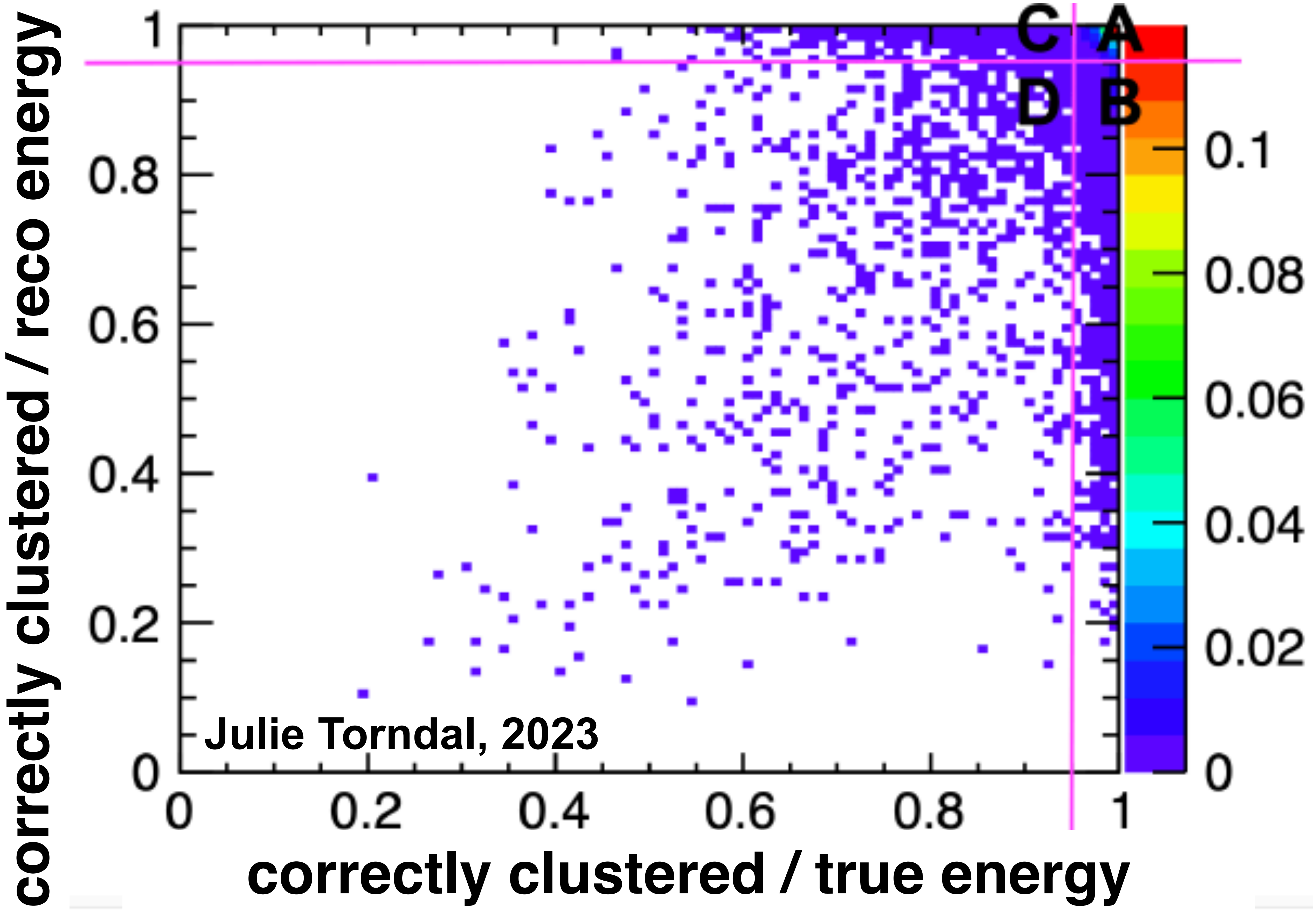

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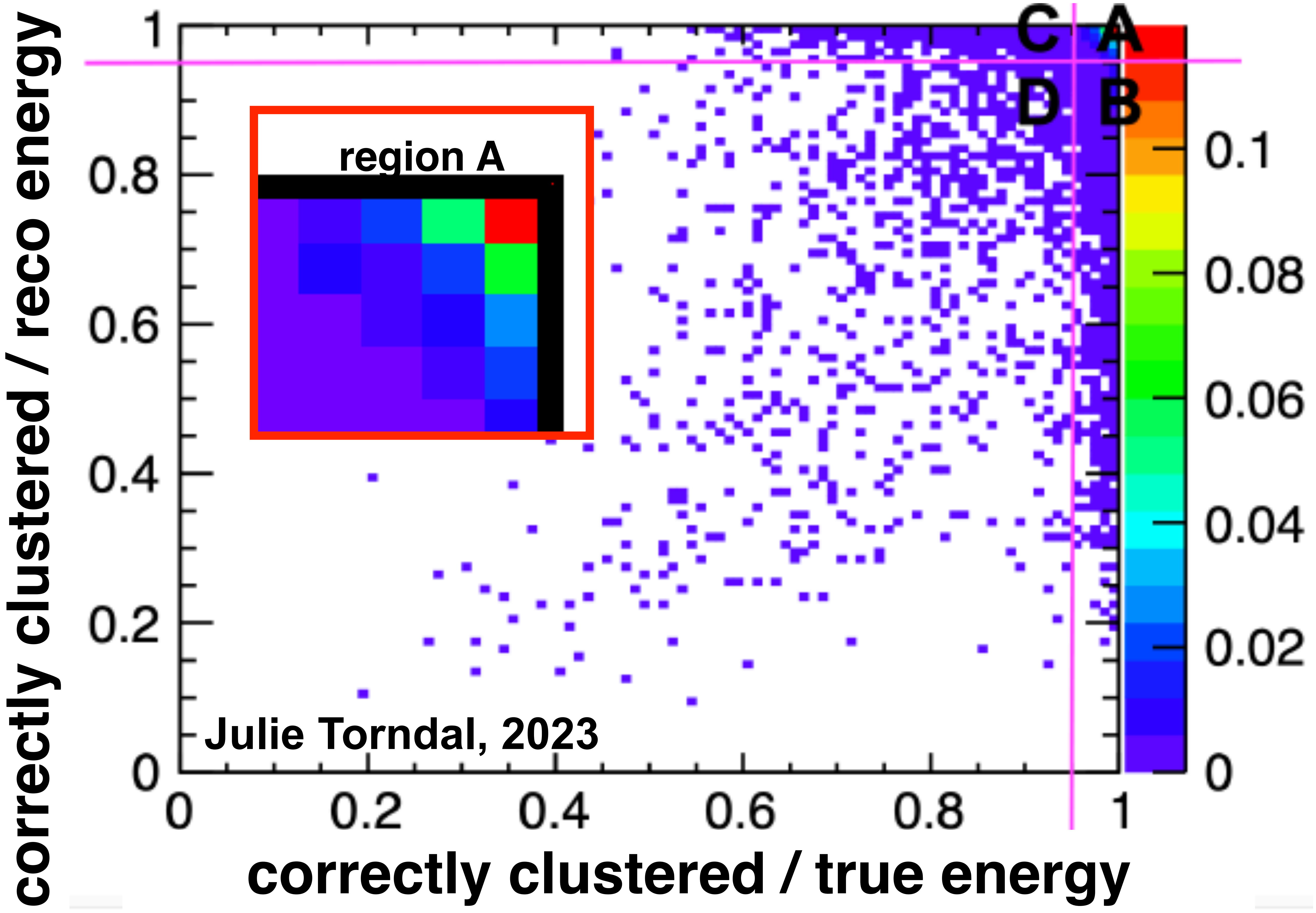

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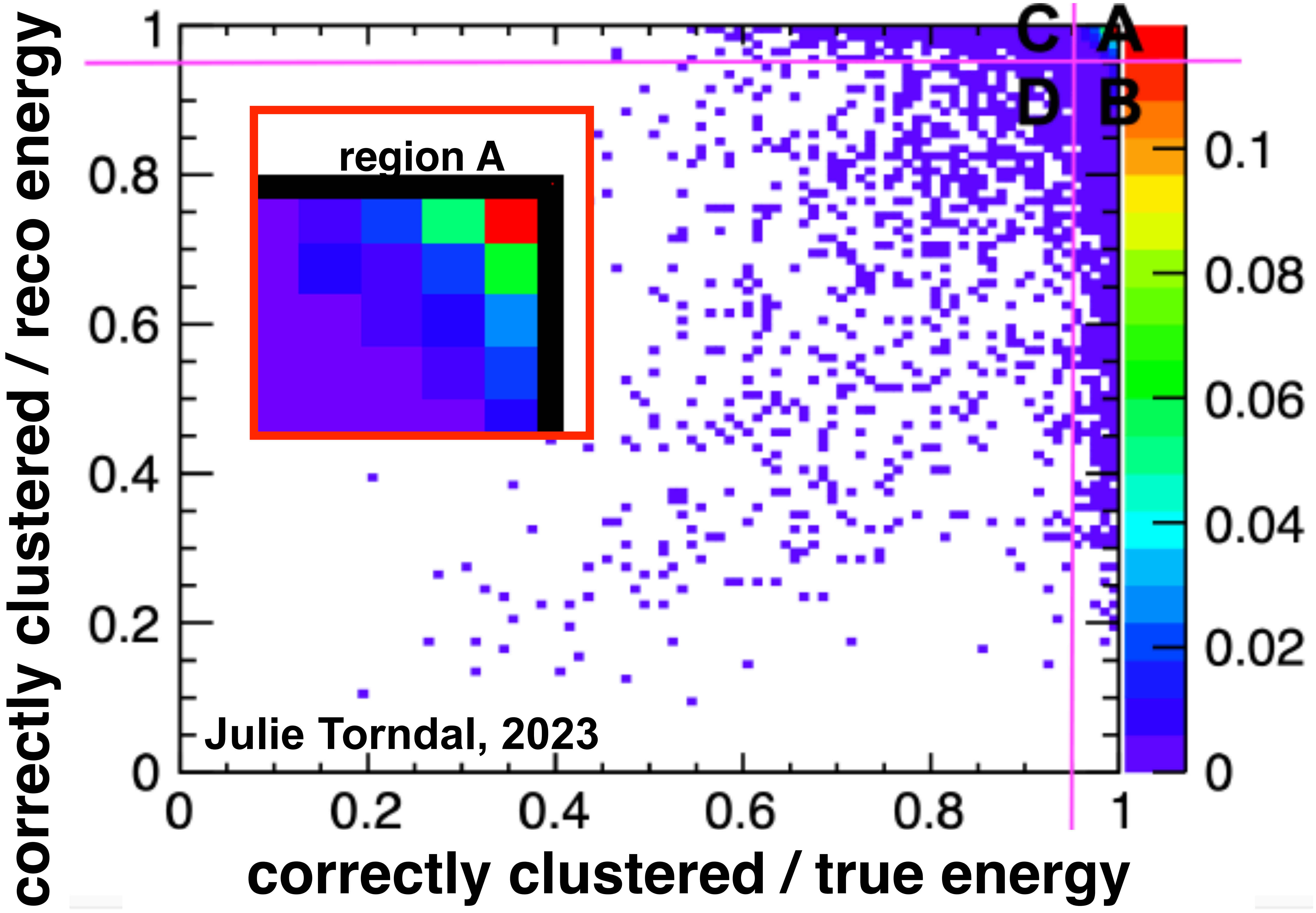

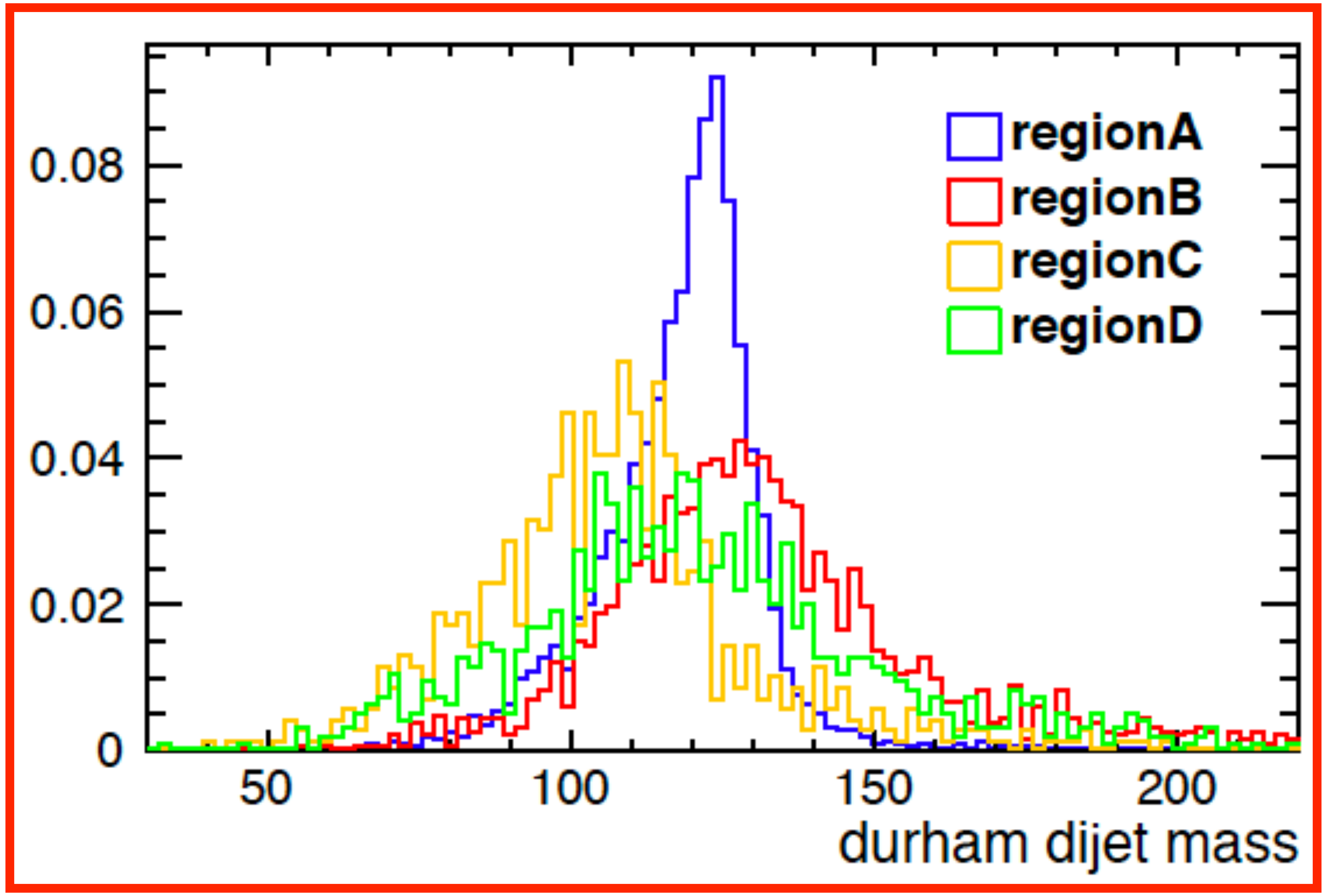

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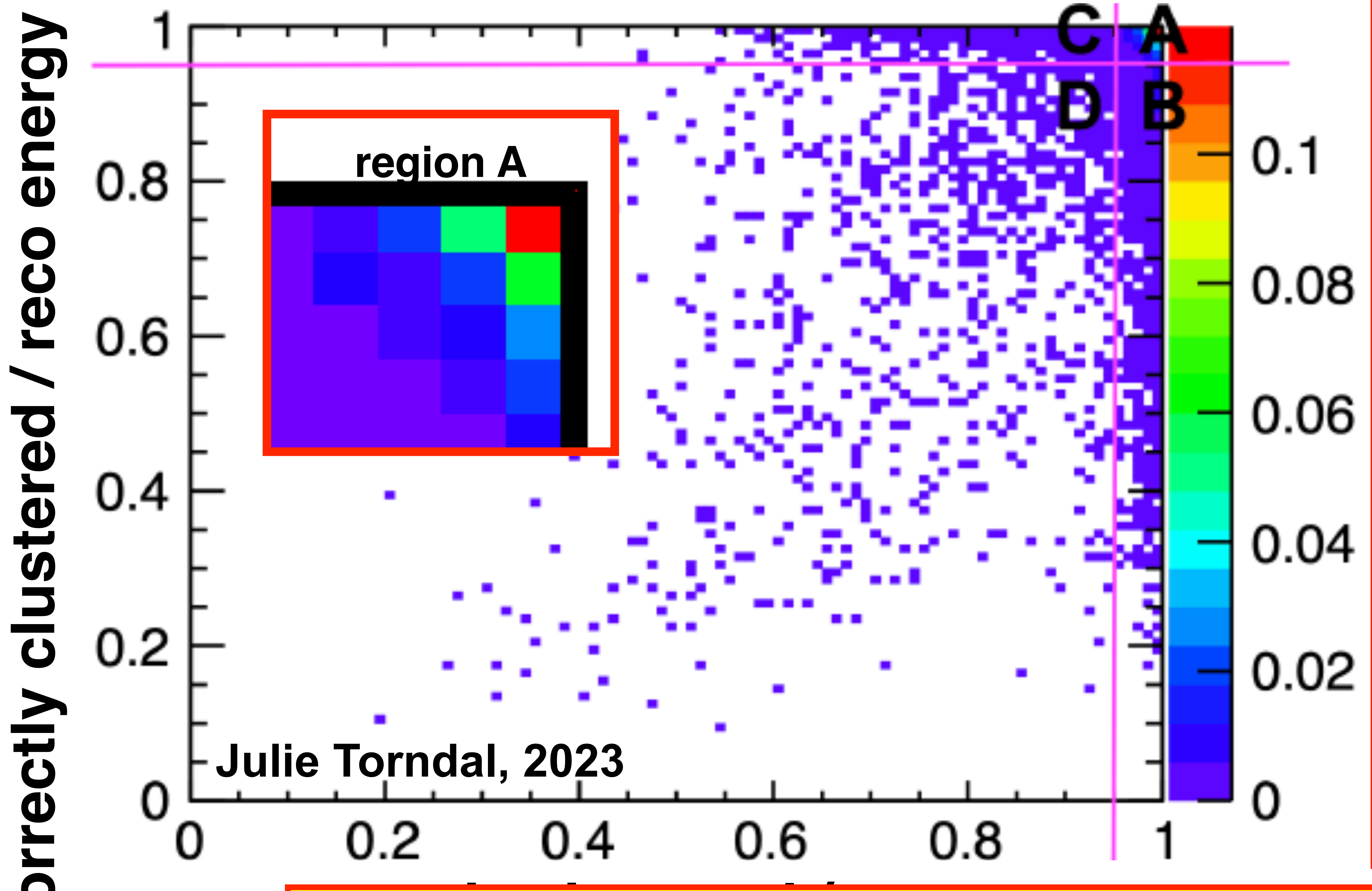
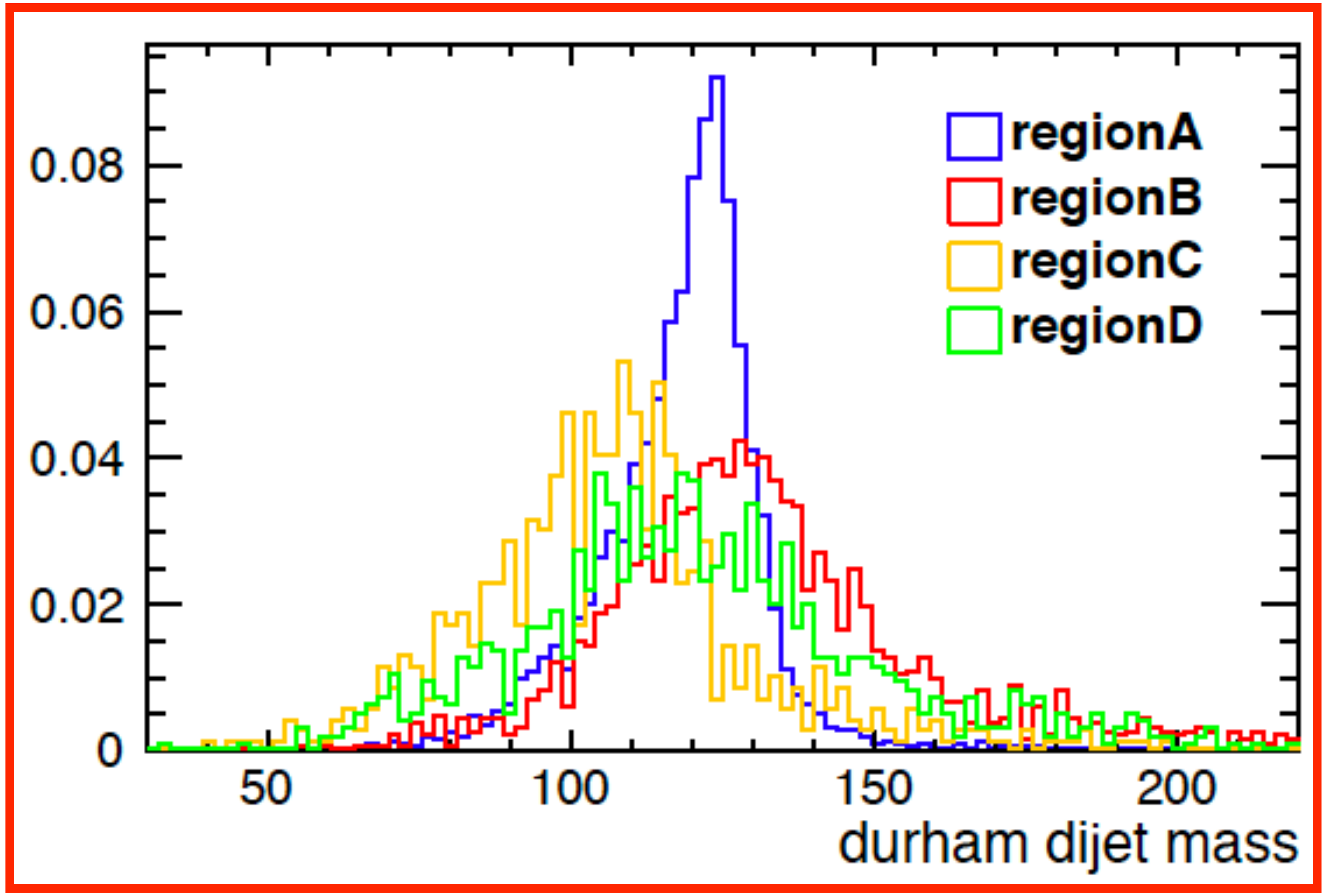




=> Urgently needed: better Jet Clustering!

can we get rid of B, C, D ???

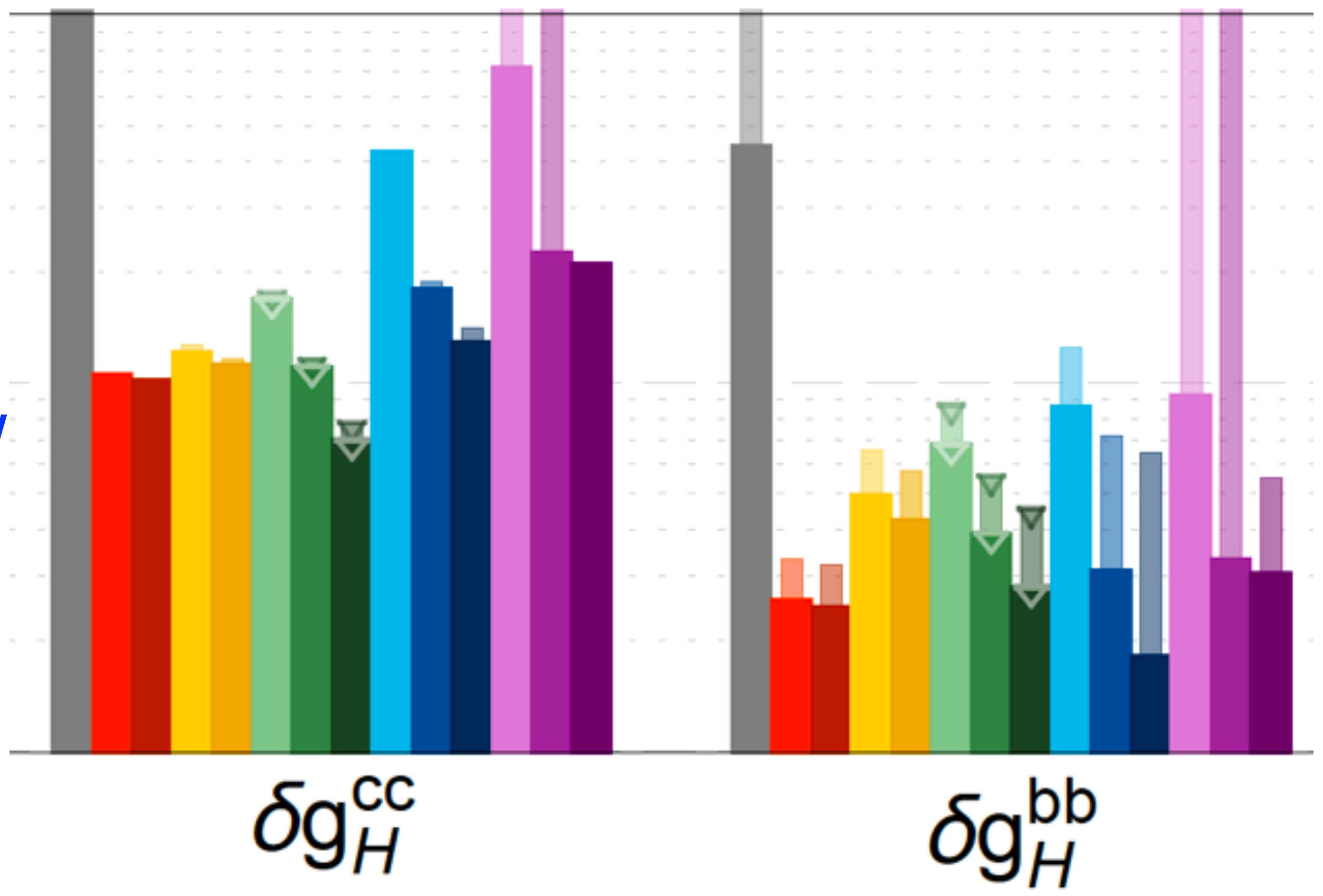
can machine-learning help? or additional detector information?

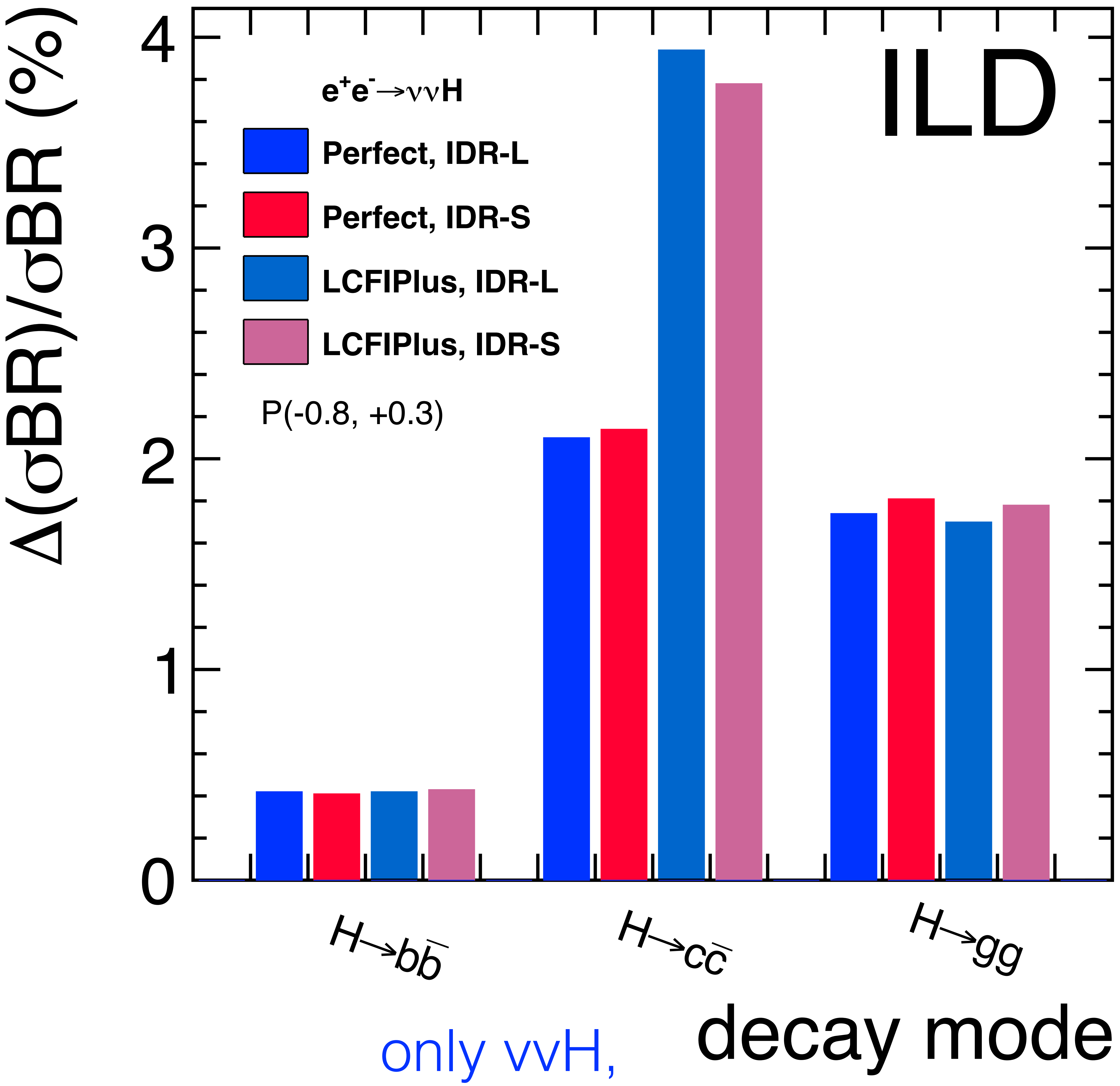
Higgs decay to bb/cc/gg

…the experimental situation

- use all visible decay modes of Z and ννH
- H->jets and Z->jets play important role!
- Example from ILD IDR:
  - **σxBR(bb) to ~0.4%** from one channel & data set alone
  - σxBR(cc) shows a lot (!) of room for improvement by smarter flavour tag algorithm

all channels / data sets





only ννH, 1.6ab-1 P(-0.8,+0.3) @ 500 GeV

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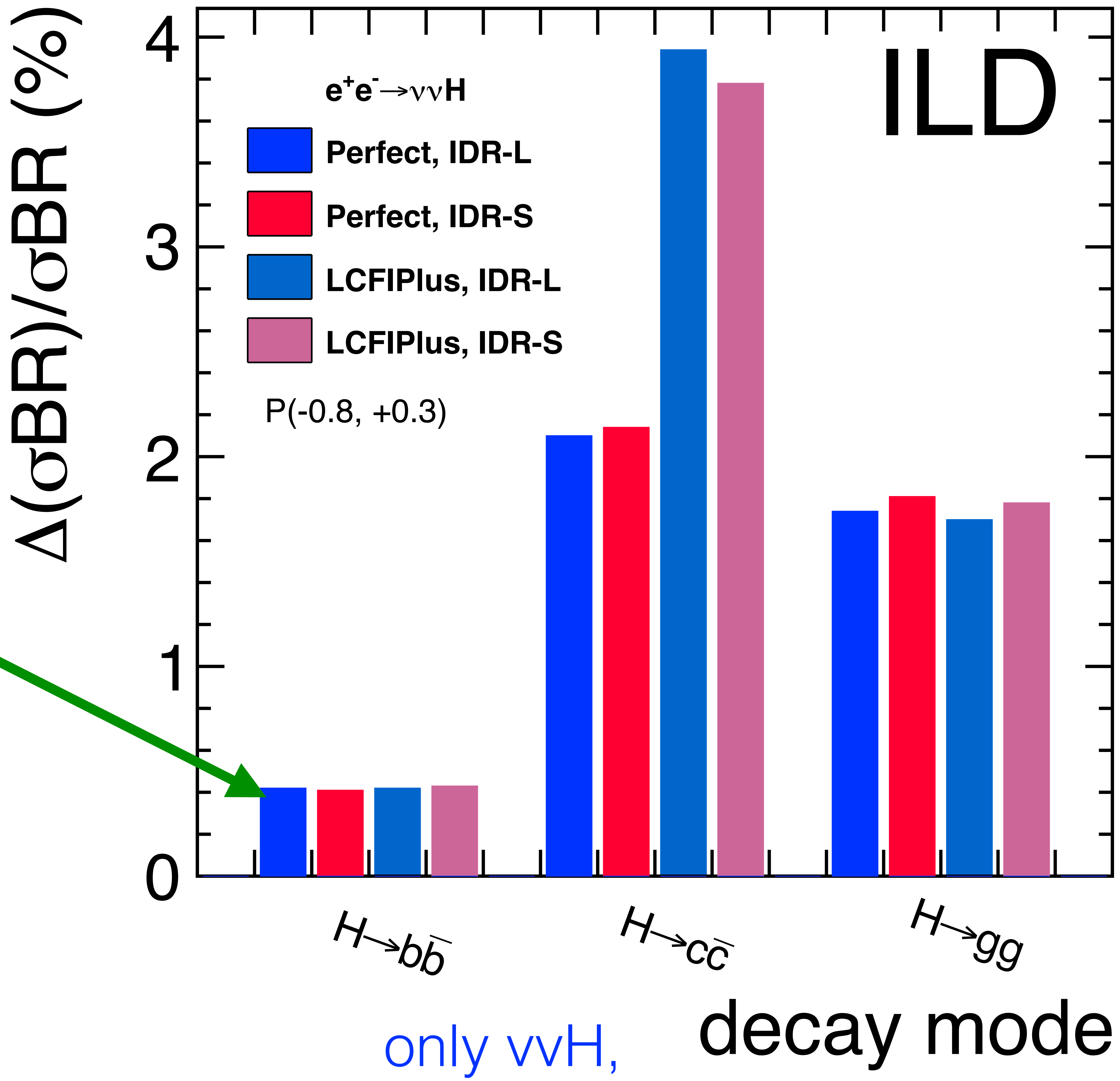

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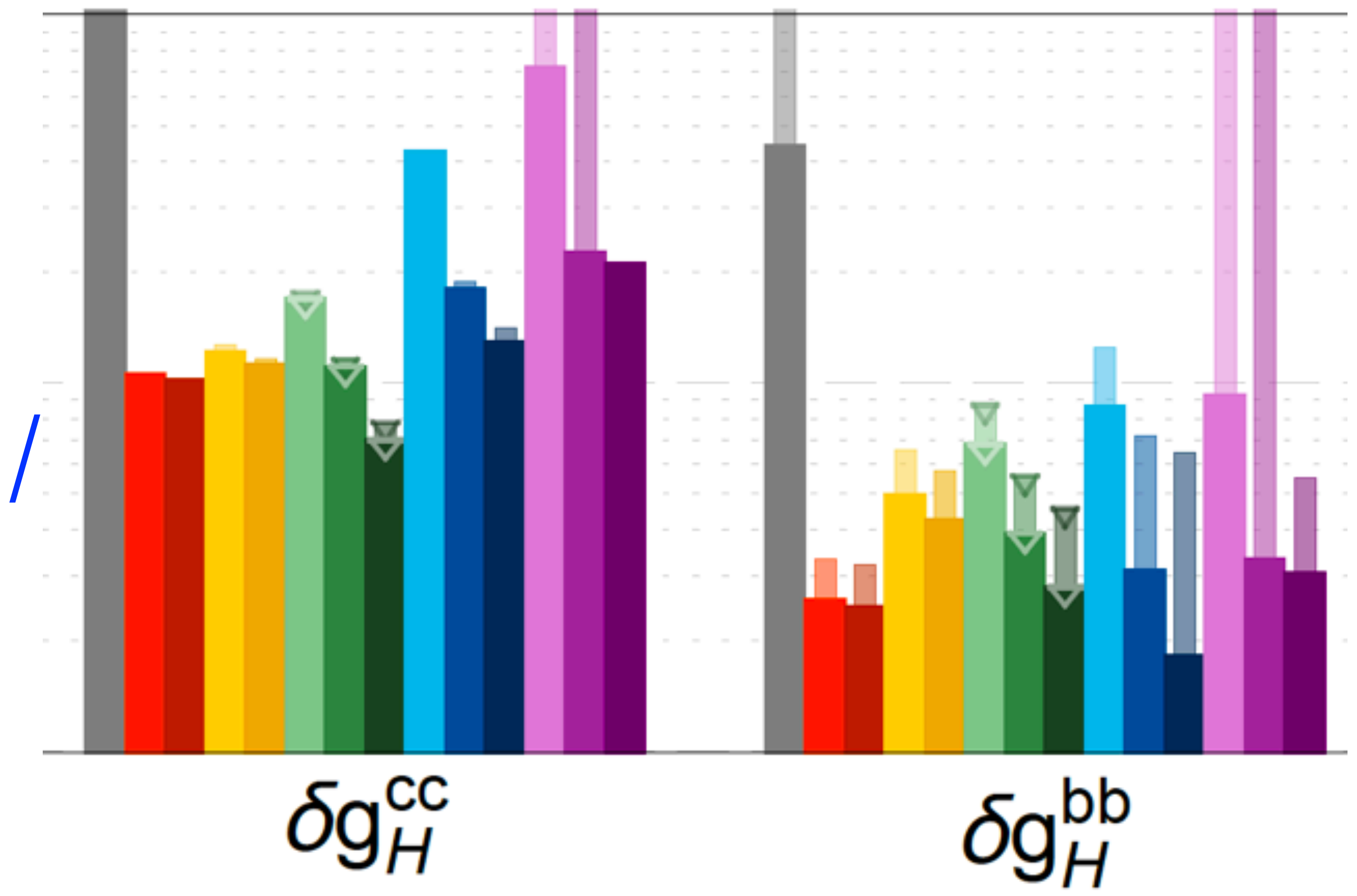

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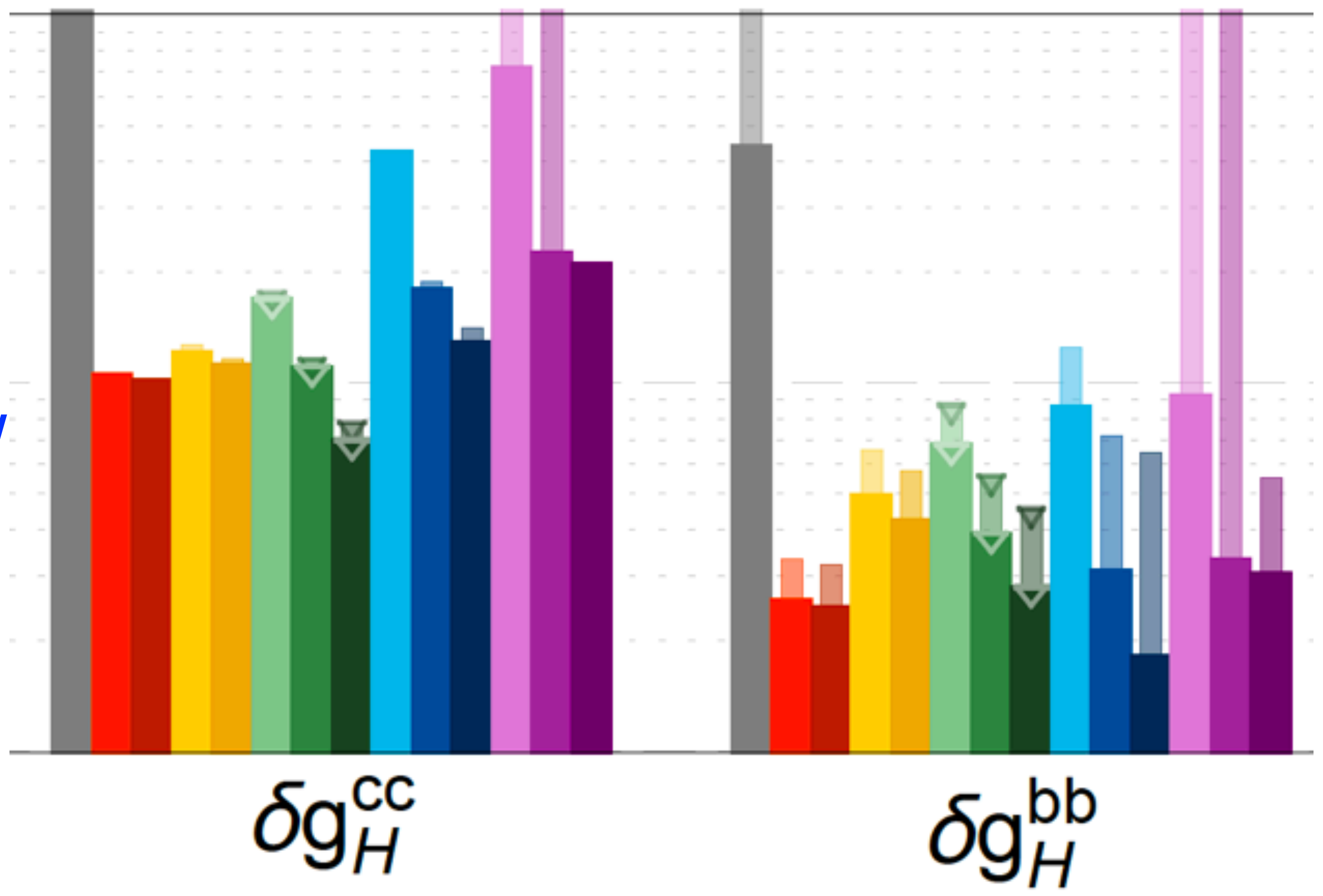

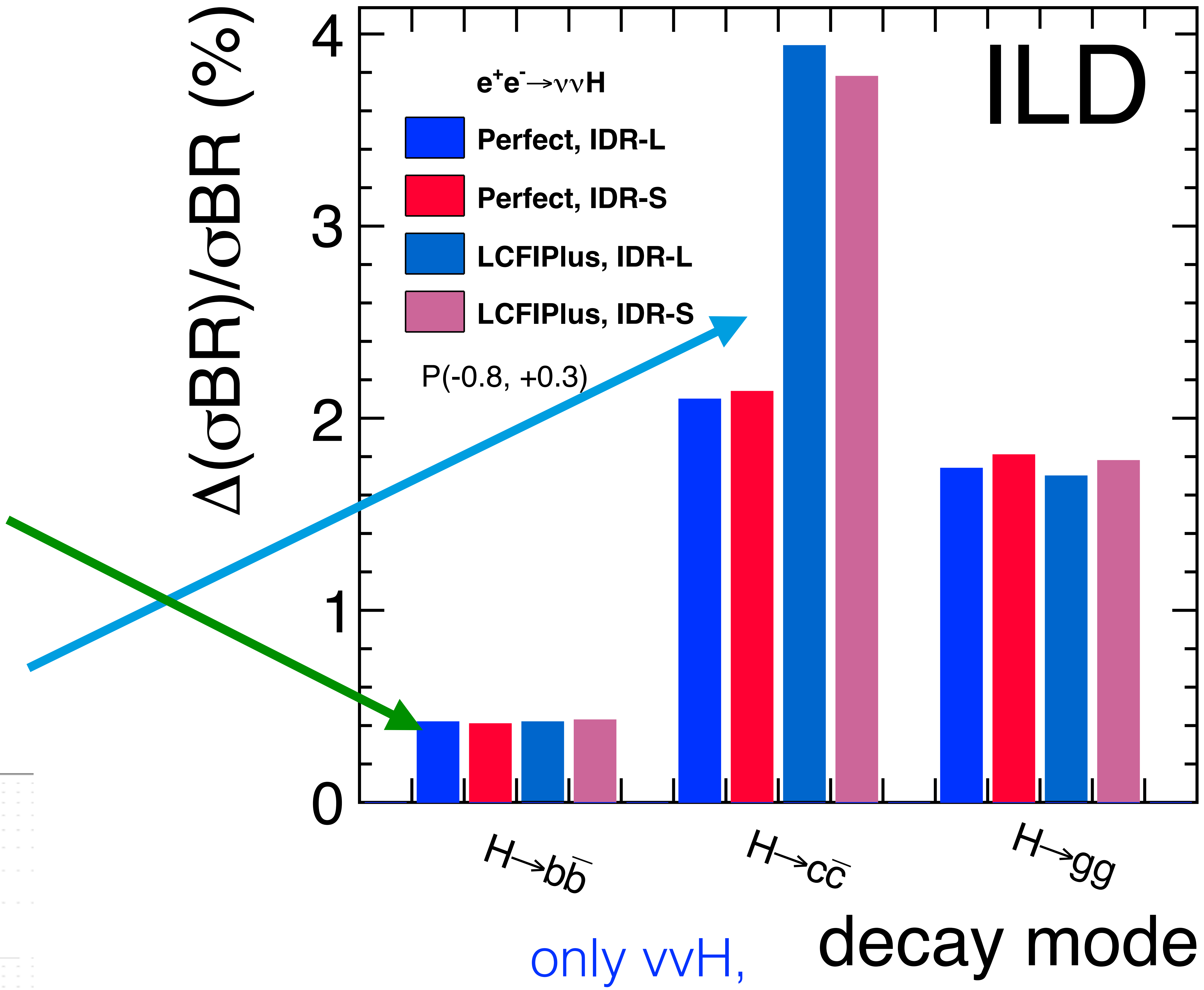

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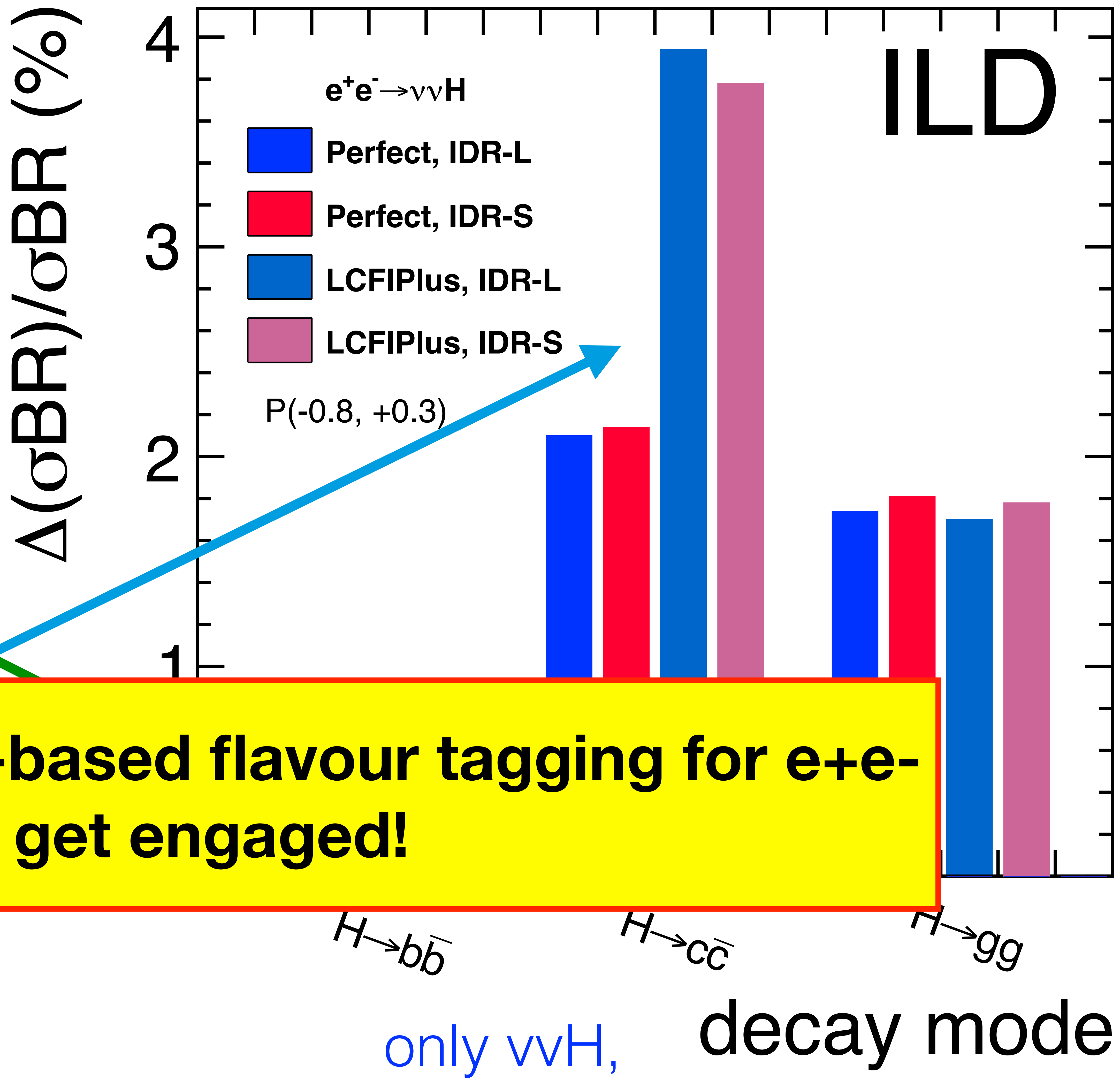
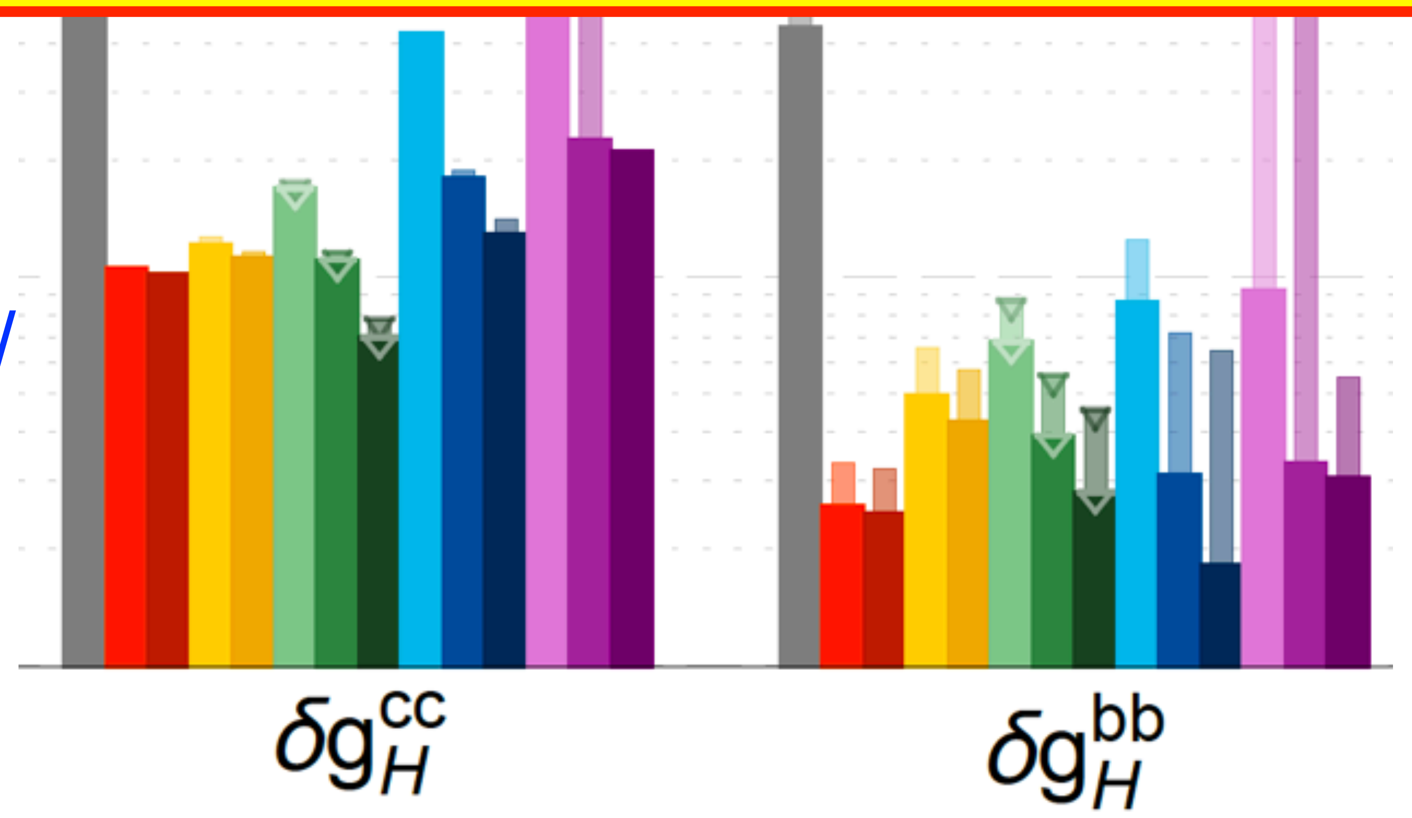


Just starting: development of ML-based flavour tagging for e+e- => ideal place to get engaged!

all channels / data sets



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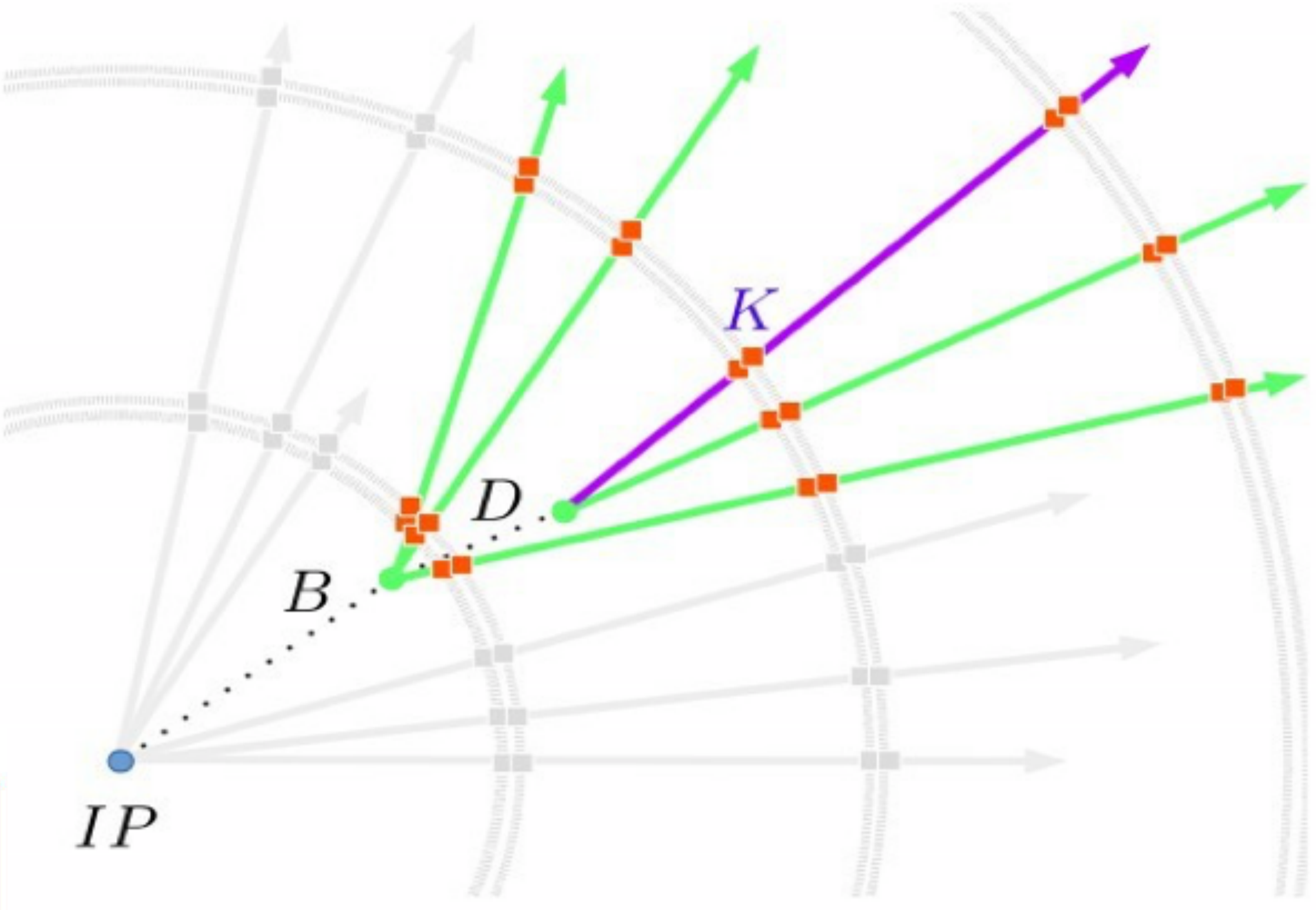
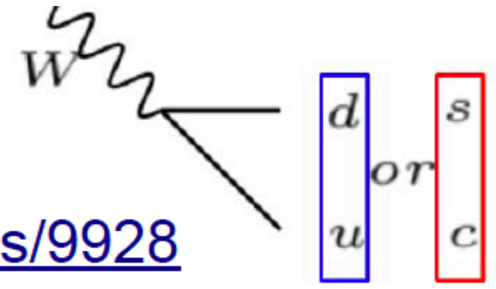
The new kid on the block: Particle ID

… only starting to be explored

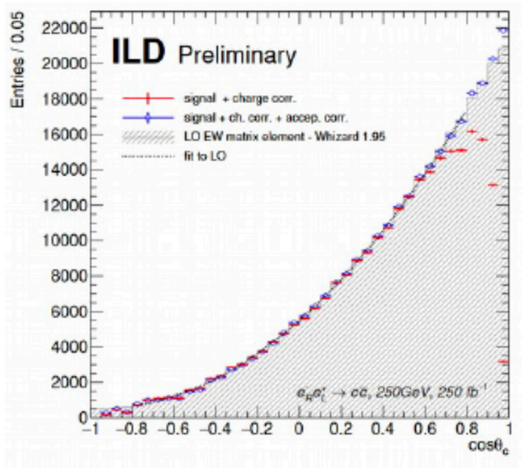


A boost of analyses using in particular Kaon ID - many of them intrisically not possible without!

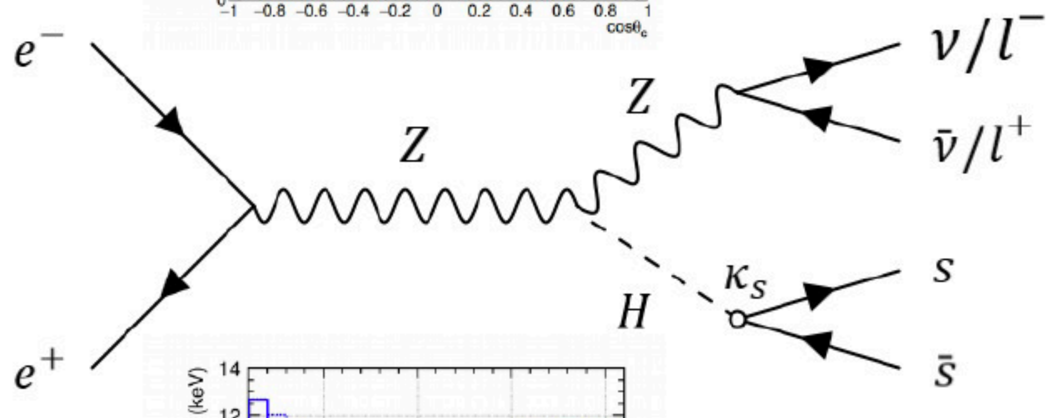
- Z and W hadronic decay branching fractions via flavour tagging
  → make connection between quark flavour and jet composition
  https://ediss.sub.uni-hamburg.de/handle/ediss/9634 , https://ediss.sub.uni-hamburg.de/handle/ediss/9928



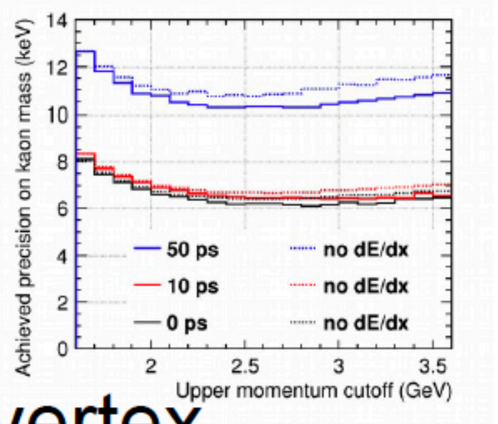
- Forward-backward asymmetry in e+e- → $q\bar{q}$
  → study asymmetry in each flavour channel exclusively
  overview: https://tel.archives-ouvertes.fr/tel-01826535
  e^+e^- → tt, bb: https://agenda.linearcollider.org/event/8147
  e^+e^- → bb/cc: https://arxiv.org/abs/2002.05805 ,
  https://agenda.linearcollider.org/event/9211/contributions/49358/
  e^+e^- → bb/cc, ss: https://agenda.linearcollider.org/event/9440 ,
  https://agenda.linearcollider.org/event/9285



- H → $s\bar{s}$ with s-tagging
  → identify high-momentum kaons to tag $s\bar{s}$ events
  https://arxiv.org/abs/2203.07535

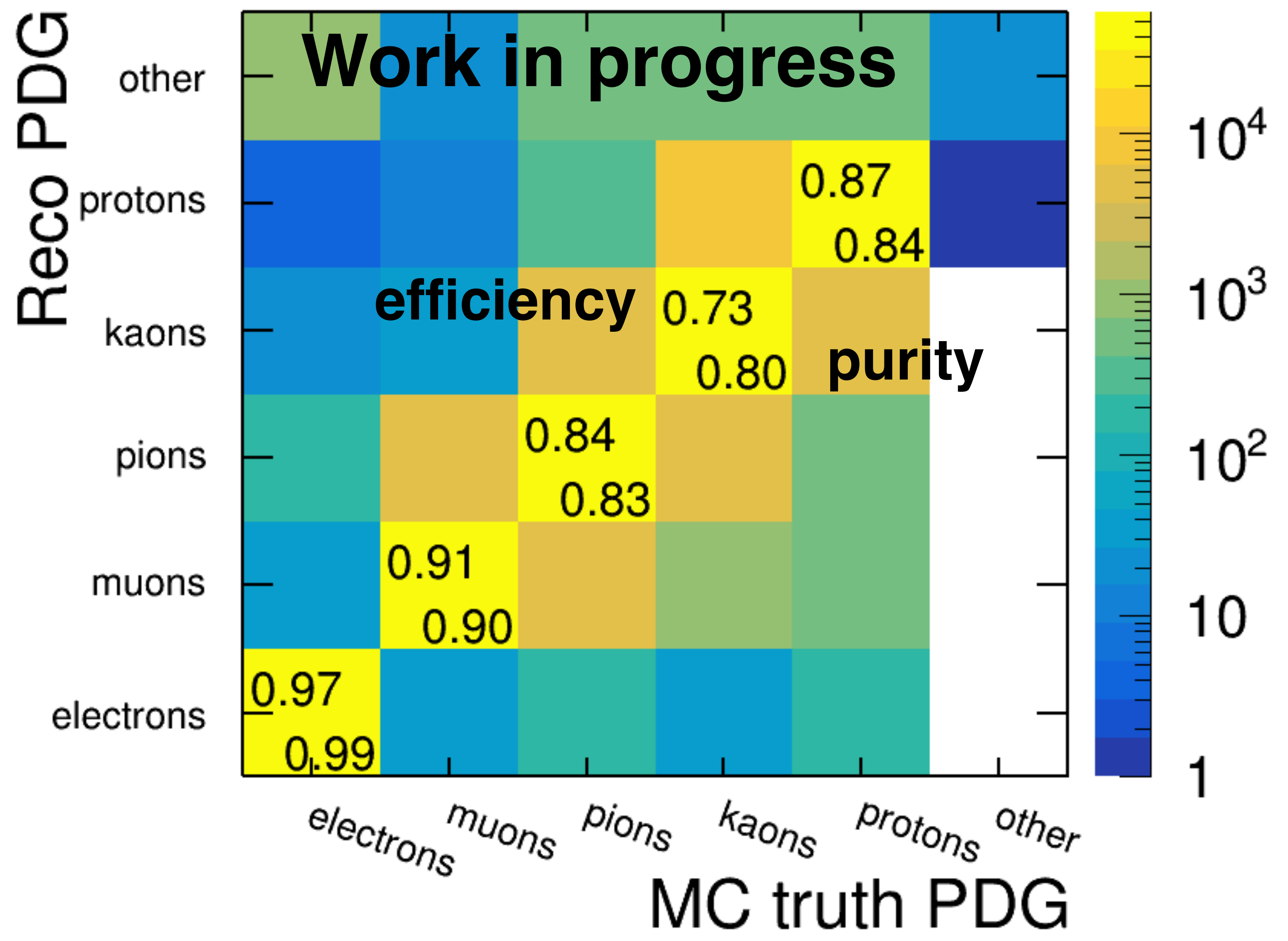


- Kaon mass with TOF
  https://pos.sissa.it/380/115/



- Track refit with correct particle mass for better momentum and vertex
  https://agenda.linearcollider.org/event/8498/

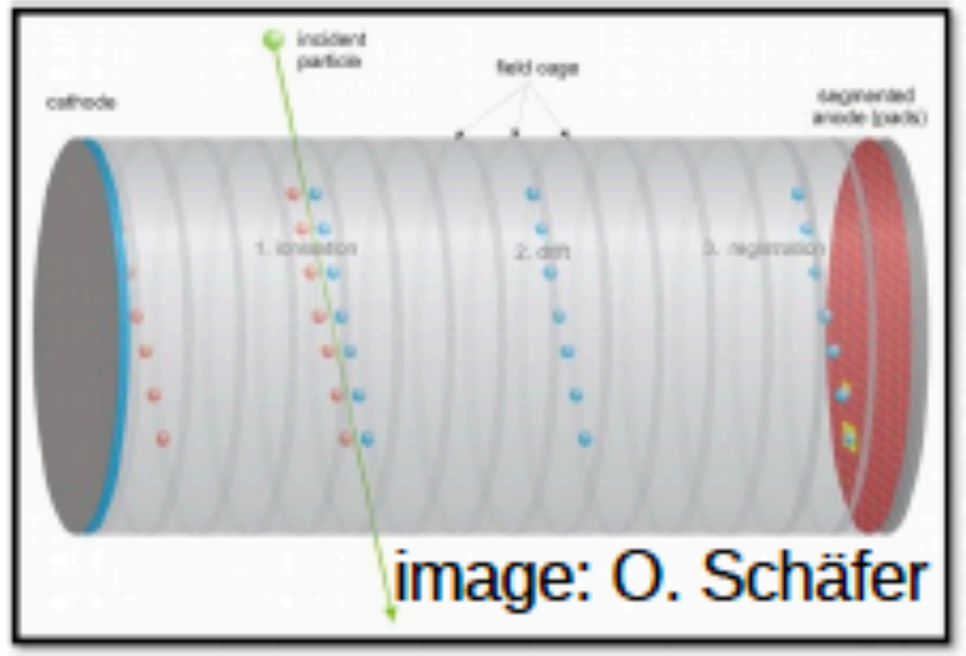
U.Einhaus



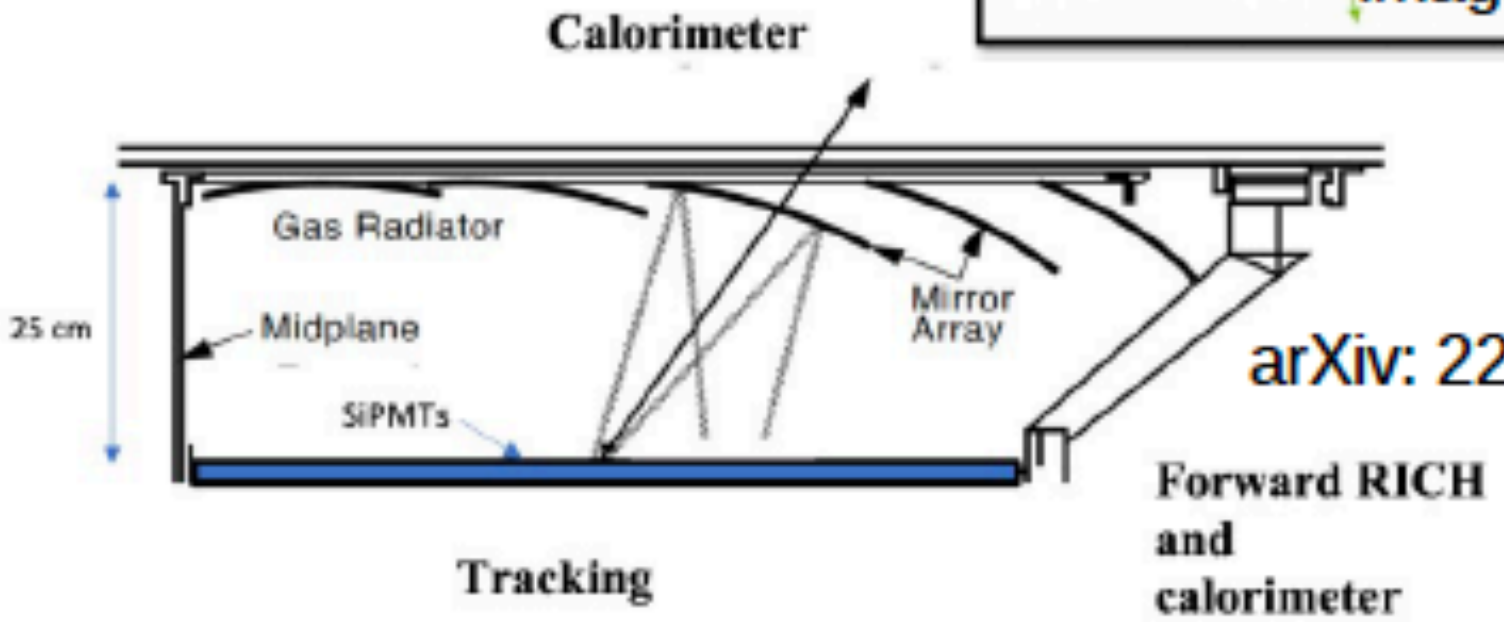
Particle ID - How to ?!

… many open questions

- Gaseous trackers (Time Projection Chamber, Drift Chamber): specific energy loss dE/dx, via gas ionisation, up to 20 GeV

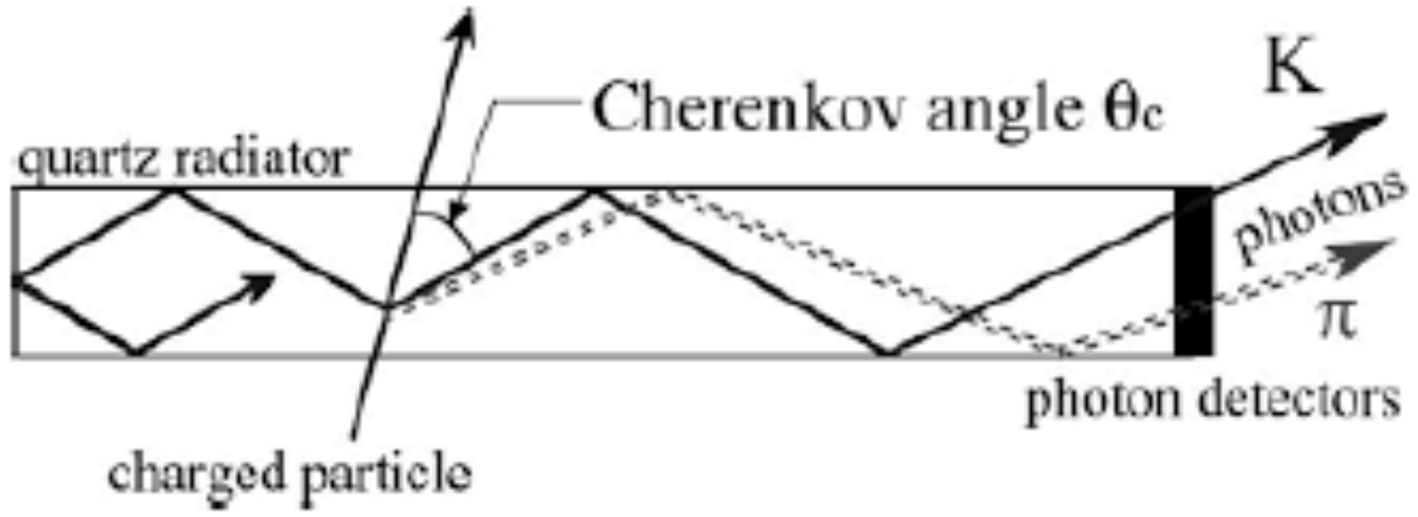


- Ring Imaging Cherenkov Detectors: Cherenkov angle, via imaging, 10 to 50 GeV



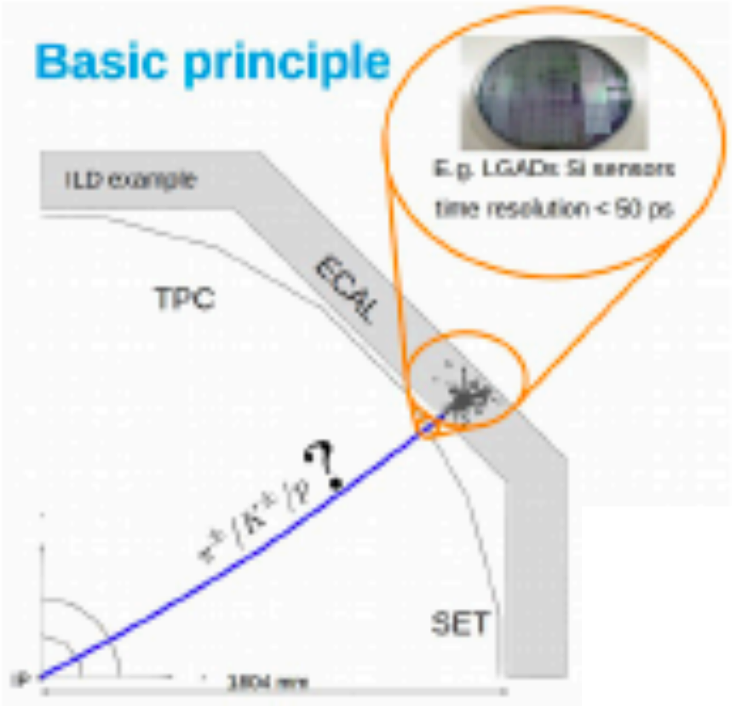
arXiv: 2203:07535

- Time of Propagation Counter: Cherenkov angle, via timing, up to 10 GeV



https://doi.org/10.1016/j.nima.2017.02.045

- Time of Flight: time, via Silicon timing, up to 5 GeV



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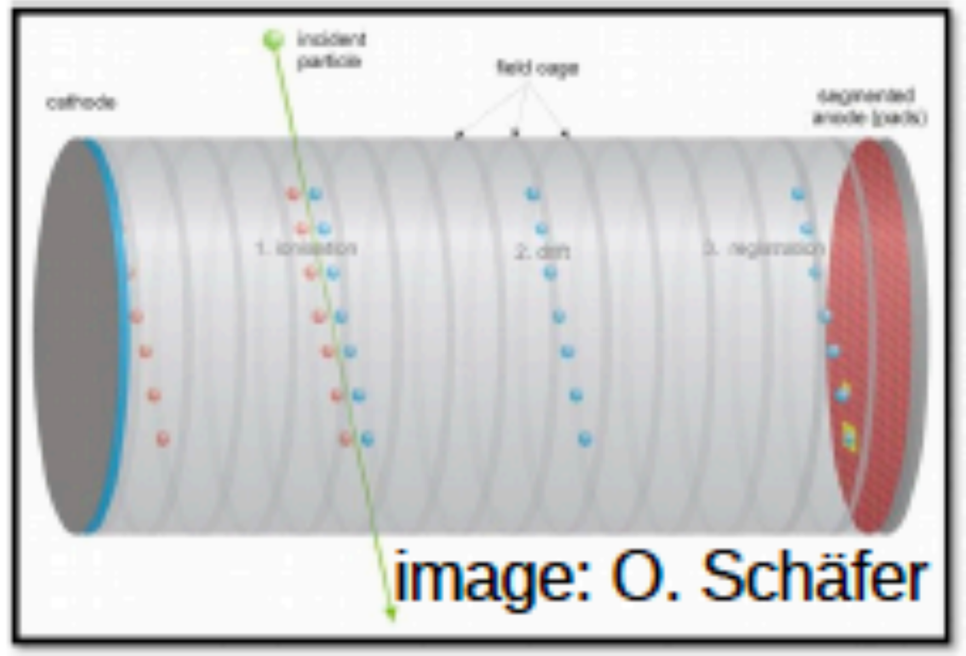

image: O. Schäfer

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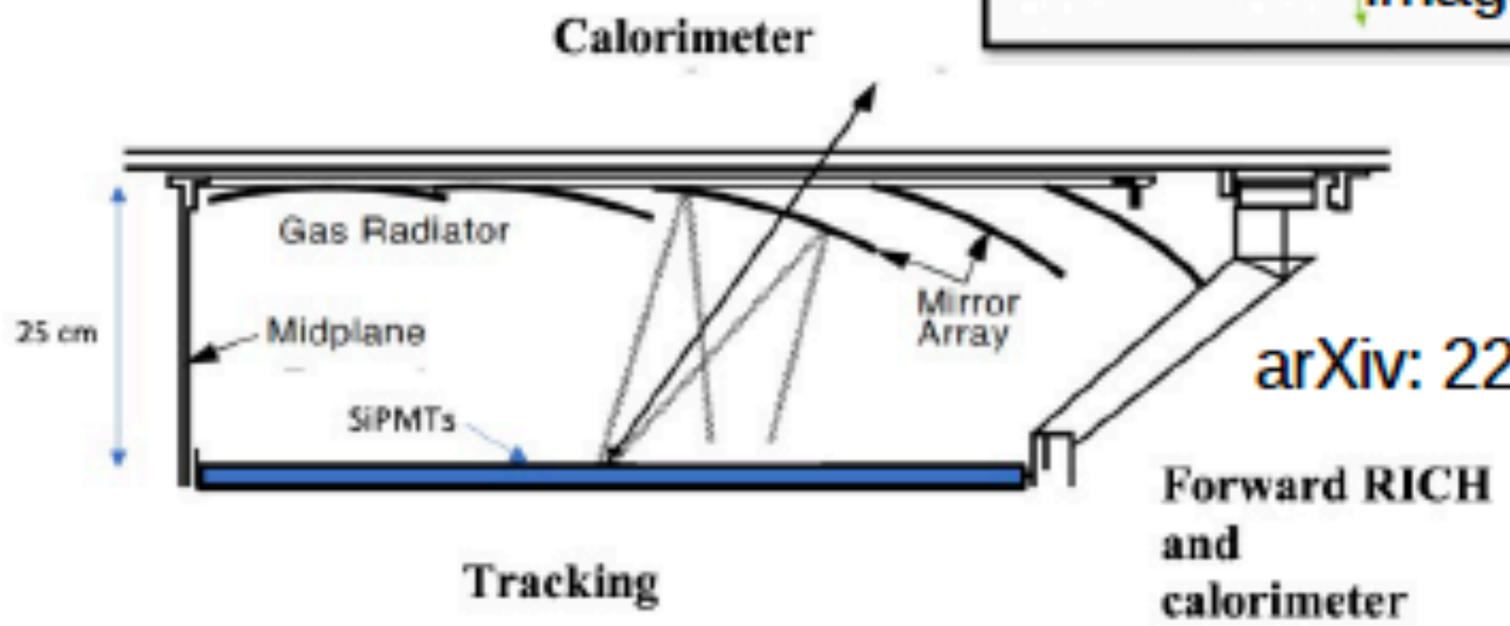

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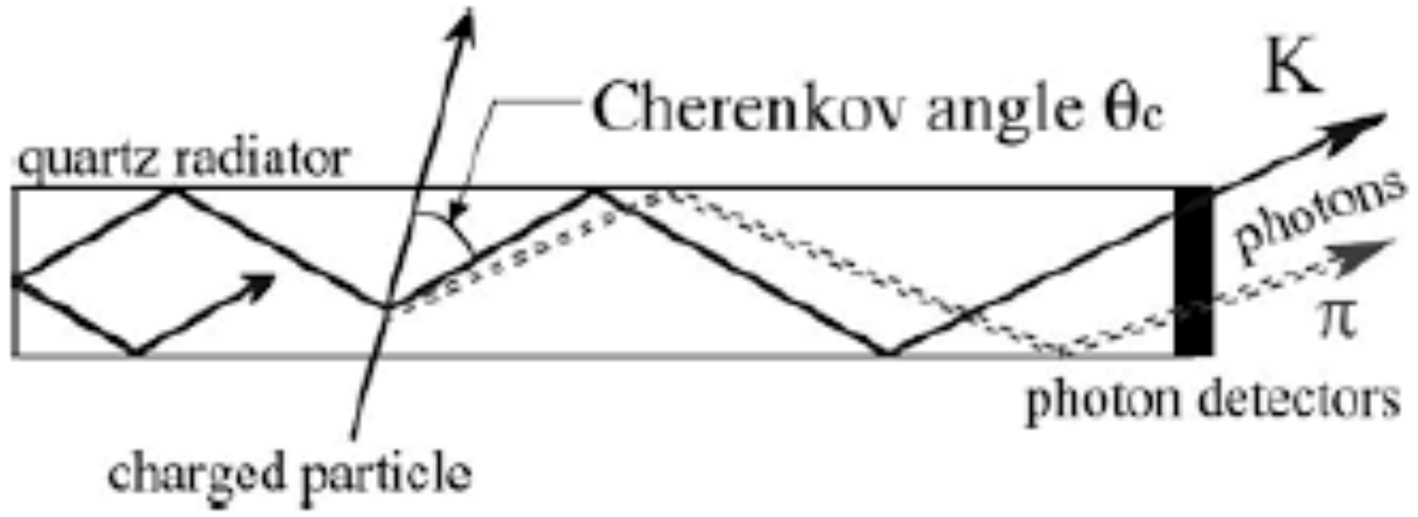

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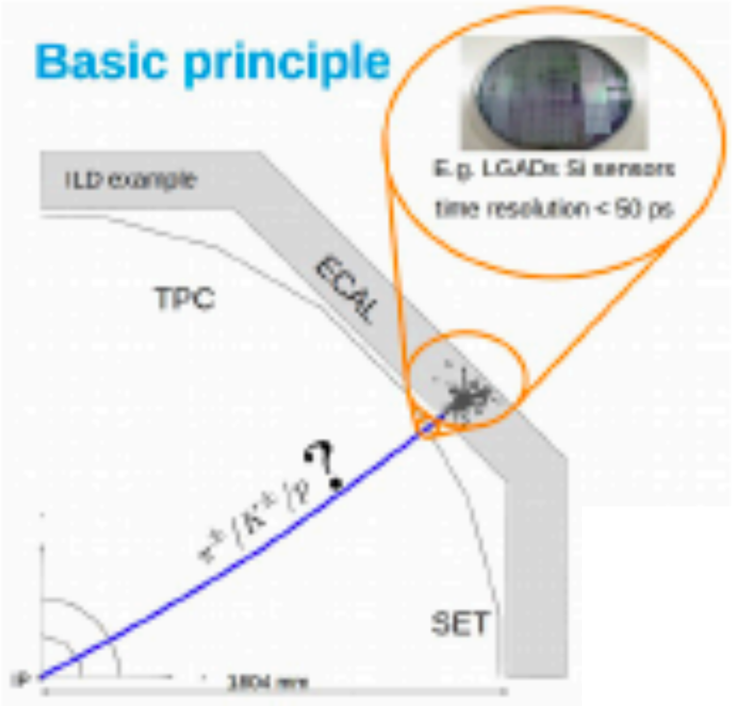

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Interesting momentum range
=> impact on ParticleFlow / Jet Energy Resolution?!

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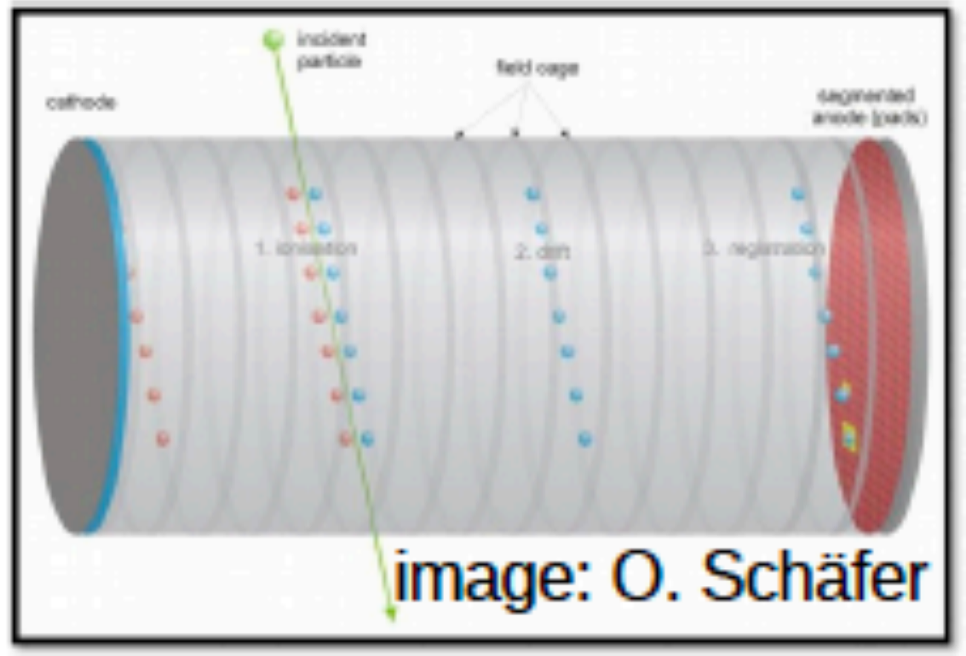

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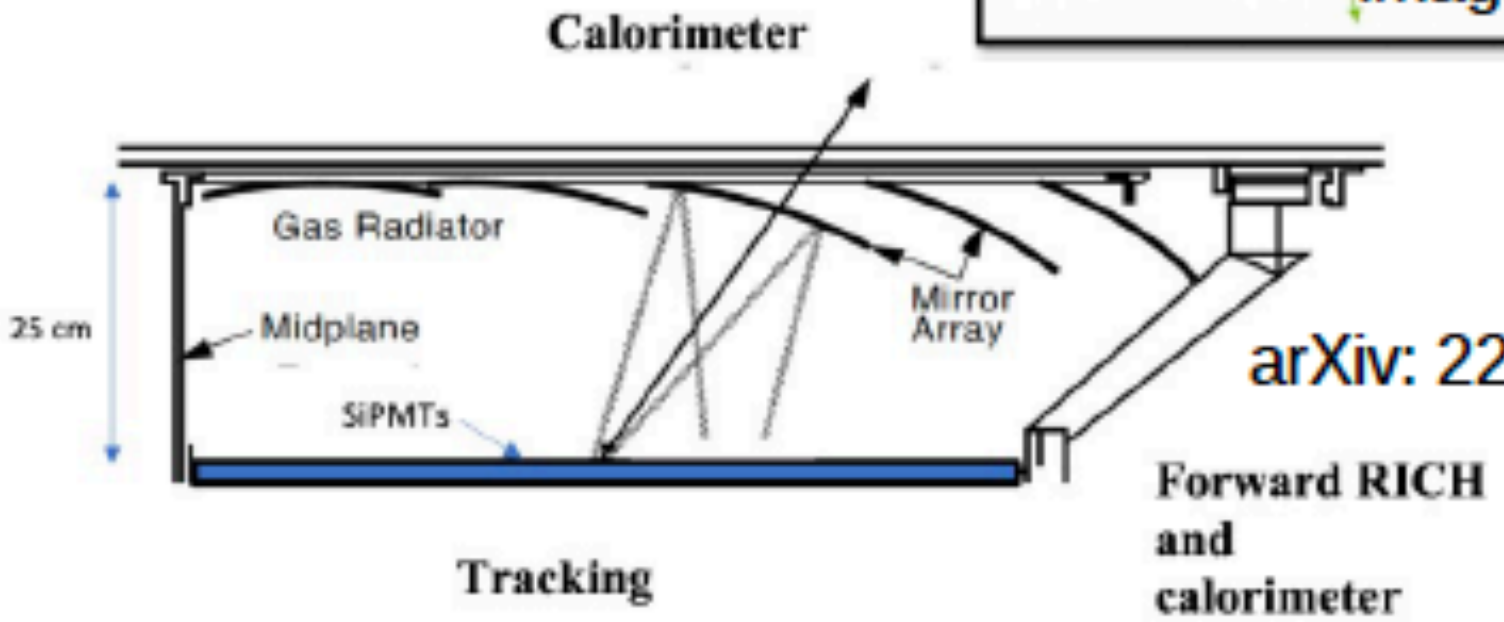

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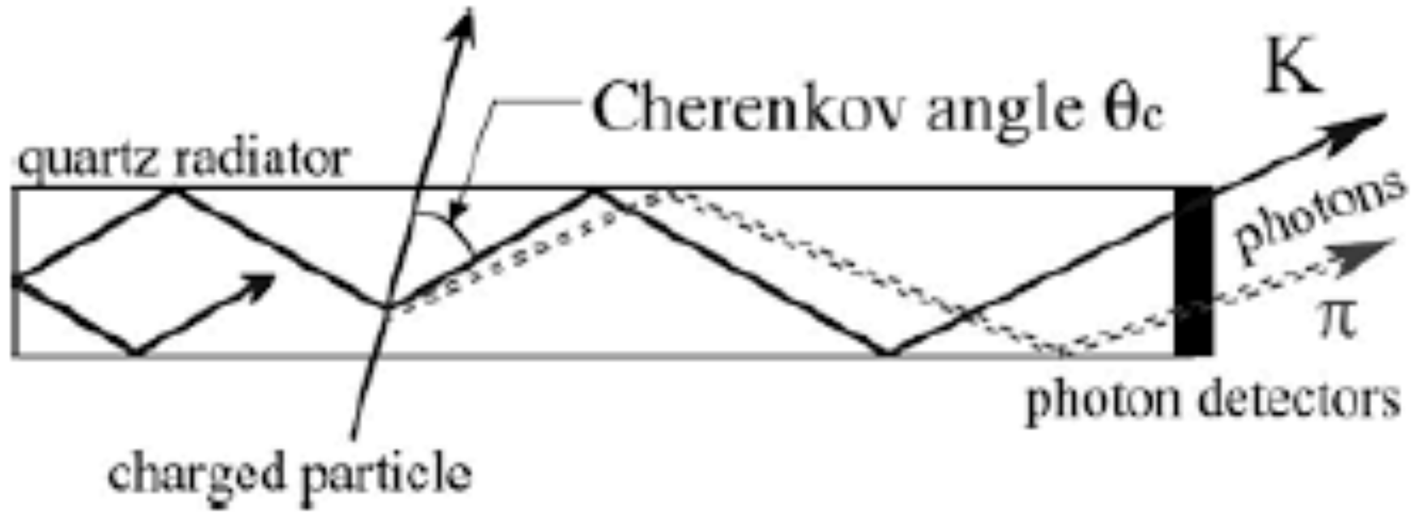

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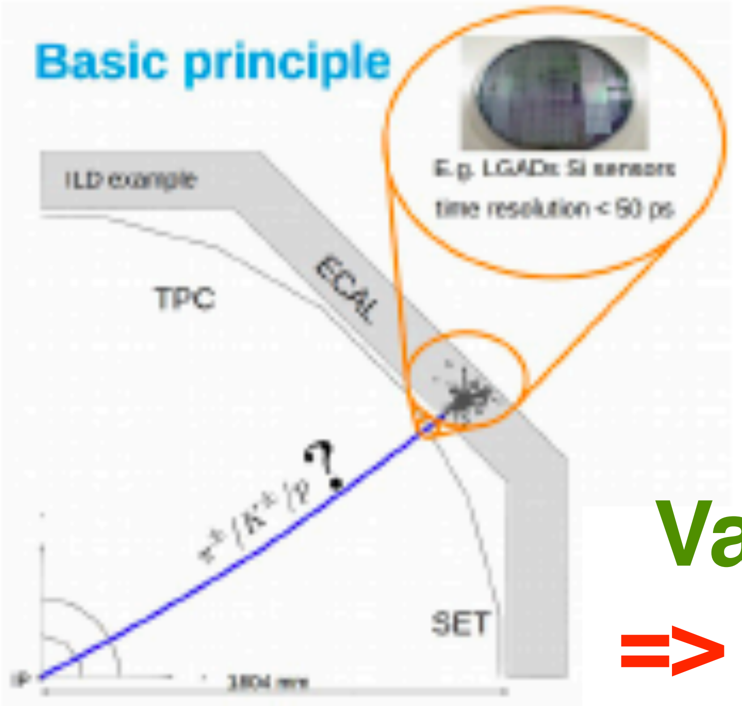

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Various implementation options in Si tracking or ECal
=> use-case for low-momentum PID not yet understood

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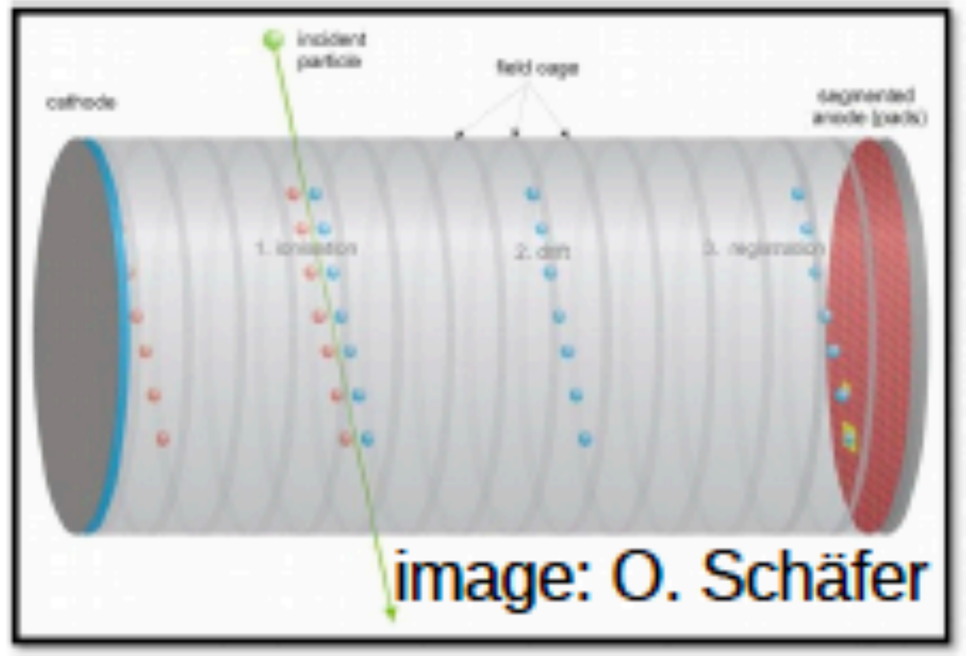

IDEA (DC) & ILD (TPC)

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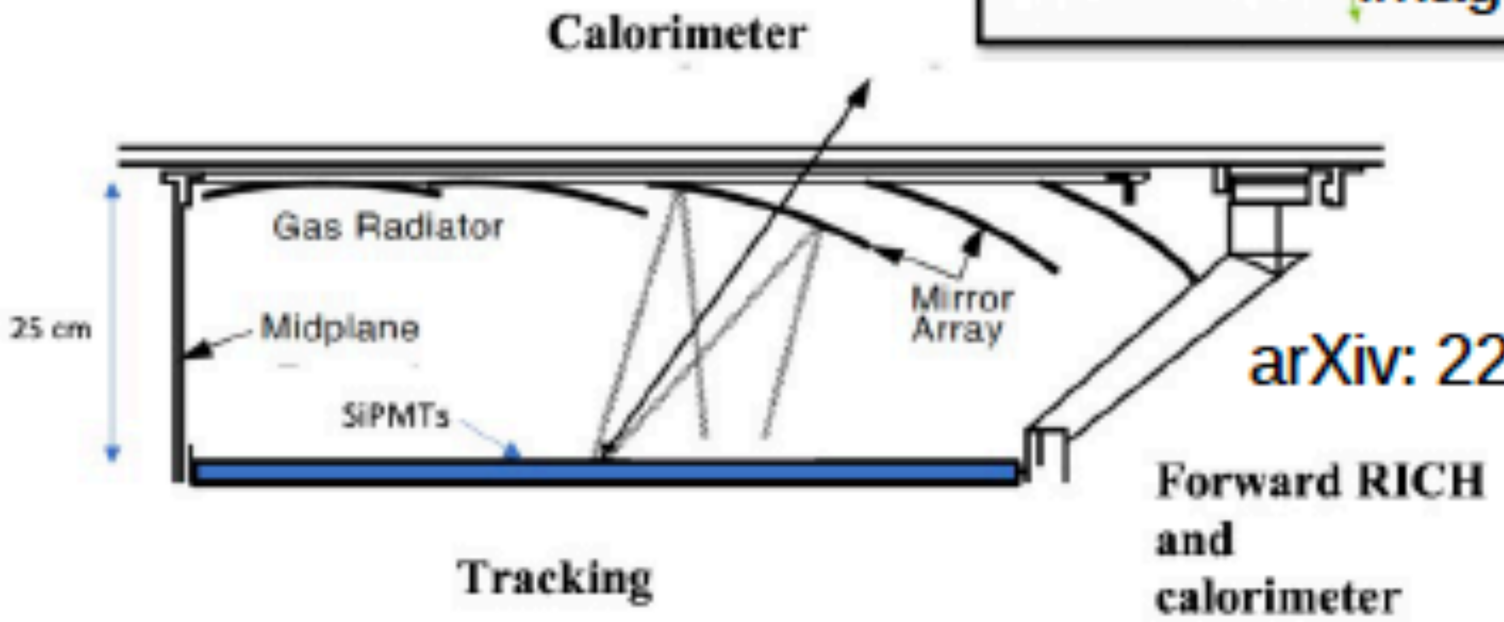

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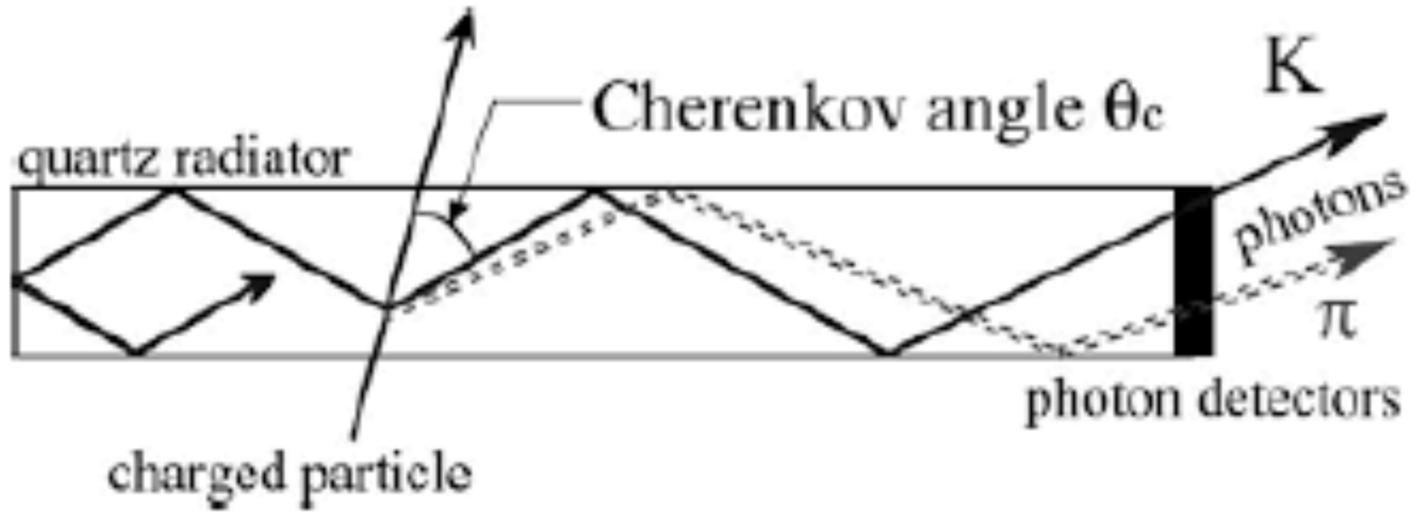

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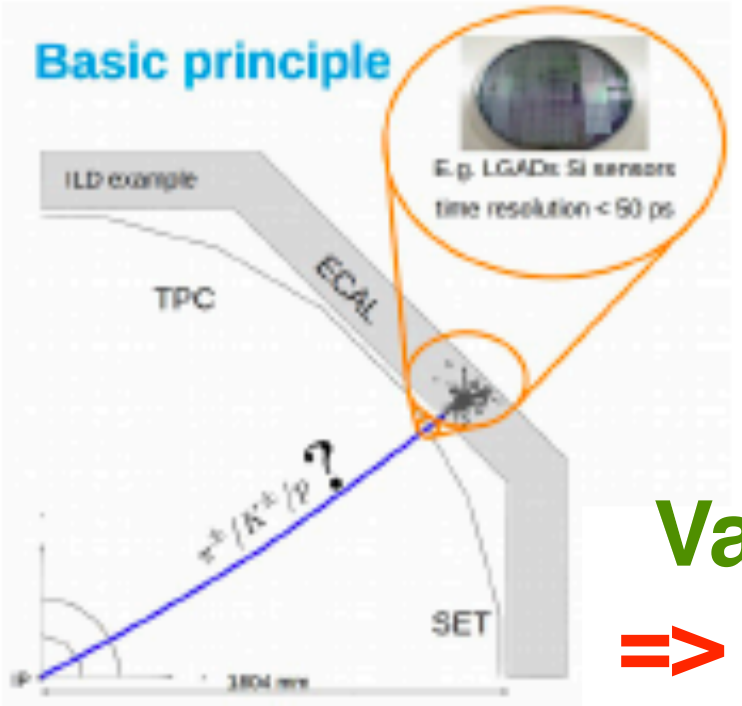

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These were just examples…

… there are many places to contribute

- **Detector concepts are actively evaluating new technologies & design ideas**
  - severely limited by person power.

- **ECFA launched a study on physics & detector at Higgs / Top / EW Factories**
  - many workshops, but also concrete studies starting up ~now
  - eg H->ss, H self-coupling, H CP, luminosity, top, WW, flavour, QCD, …
  - => all information, incl. egroups https://indico.cern.ch/event/1044297/
    - or simply drop me an email!

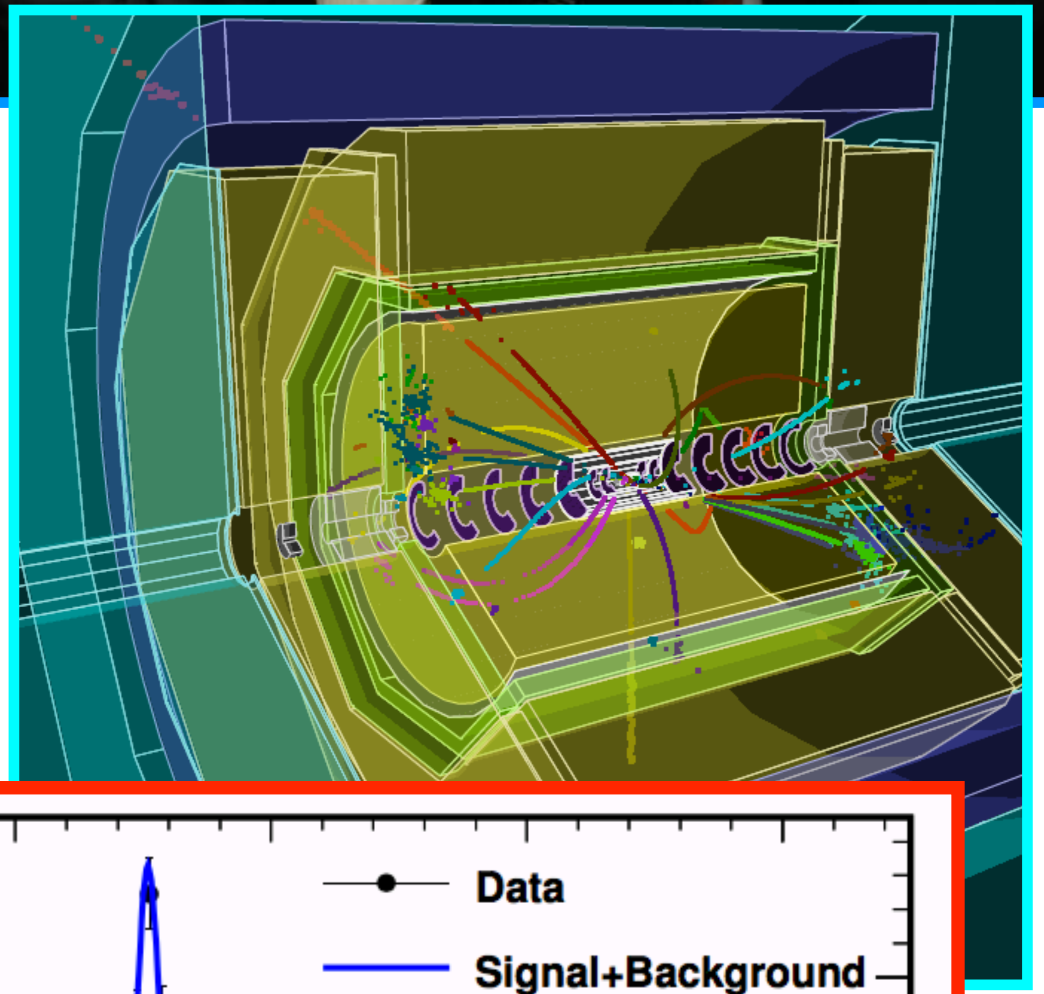
- **All Higgs factories are using the same software framework (Key4HEP):**
  - share algorthmic developments
  - share / exchange data sets for comparable analyses etc
  - recent tutorial at DESY covering all colliders https://indico.desy.de/event/36779/

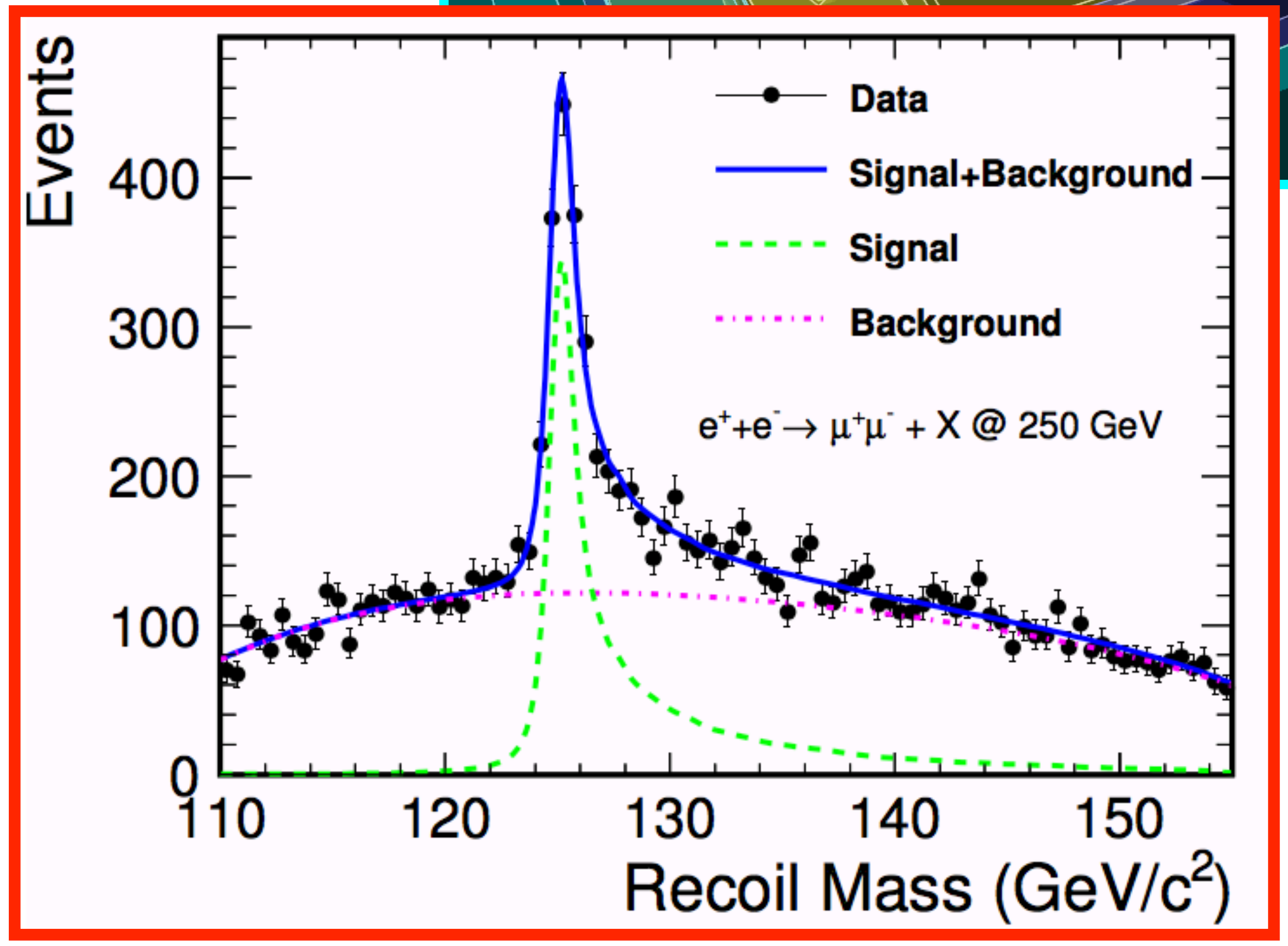
=> anybody who'd like to shape the experiments of the next collider would be wise to build up expertise on Key4HEP *now*

Conclusions

and invitation to get engaged!

- The discovery of the Higgs boson has provided a new messenger from the early universe => an e+e- Higgs factory will 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
  - Linear colliders are upgradable to higher energies / advanced technologies - Circular colliders could host a pp collider later
  - resources / sustainability will play a significant role
  - to realise a Higgs factory, much, much more engagement of the whole community is required, and especially the younger generations
- "Engagement" does not mean a lot of time:
  - Small contribution to one of the many open questions eg on the detector, modern reconstruction algorithms, …
    => a lot to learn from LHC, Belle-II etc & a lot room for new developments
  - Raise your voice in discussions (with your peers, at P5 Town Halls, conferences, European strategy, …)





Backup

Finger-printing the Higgs Boson

Is it really THE Higgs boson of the SM?

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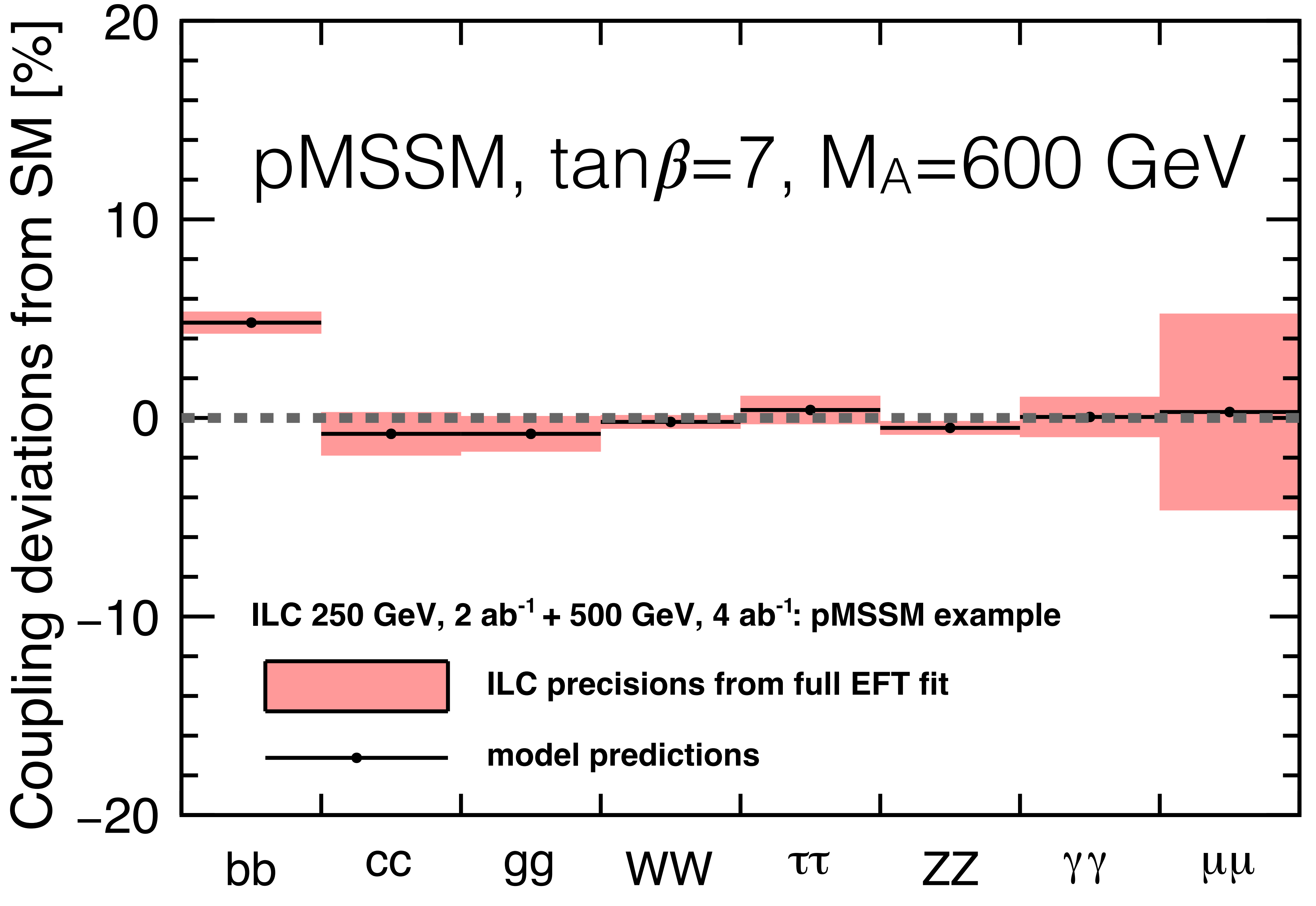

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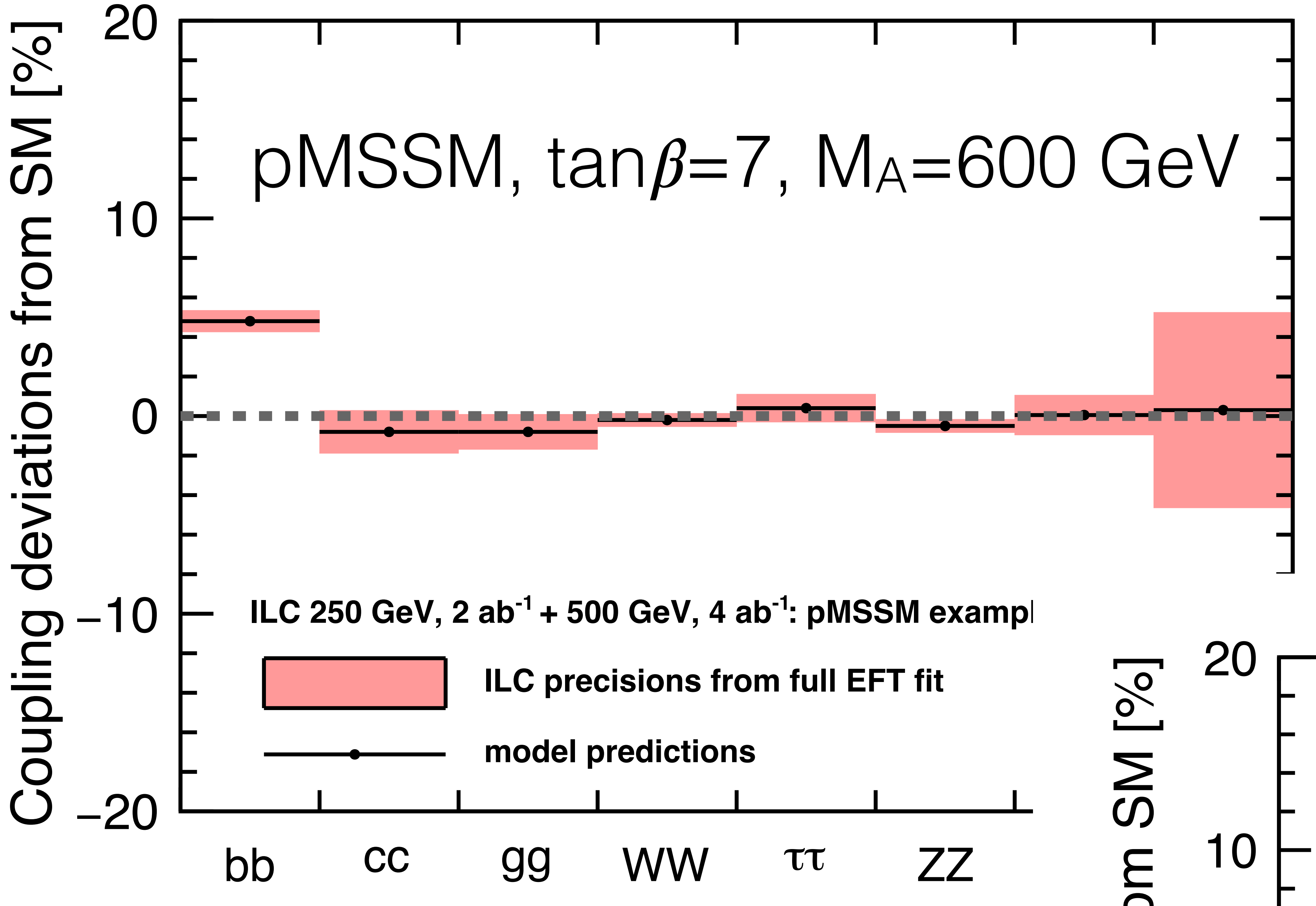

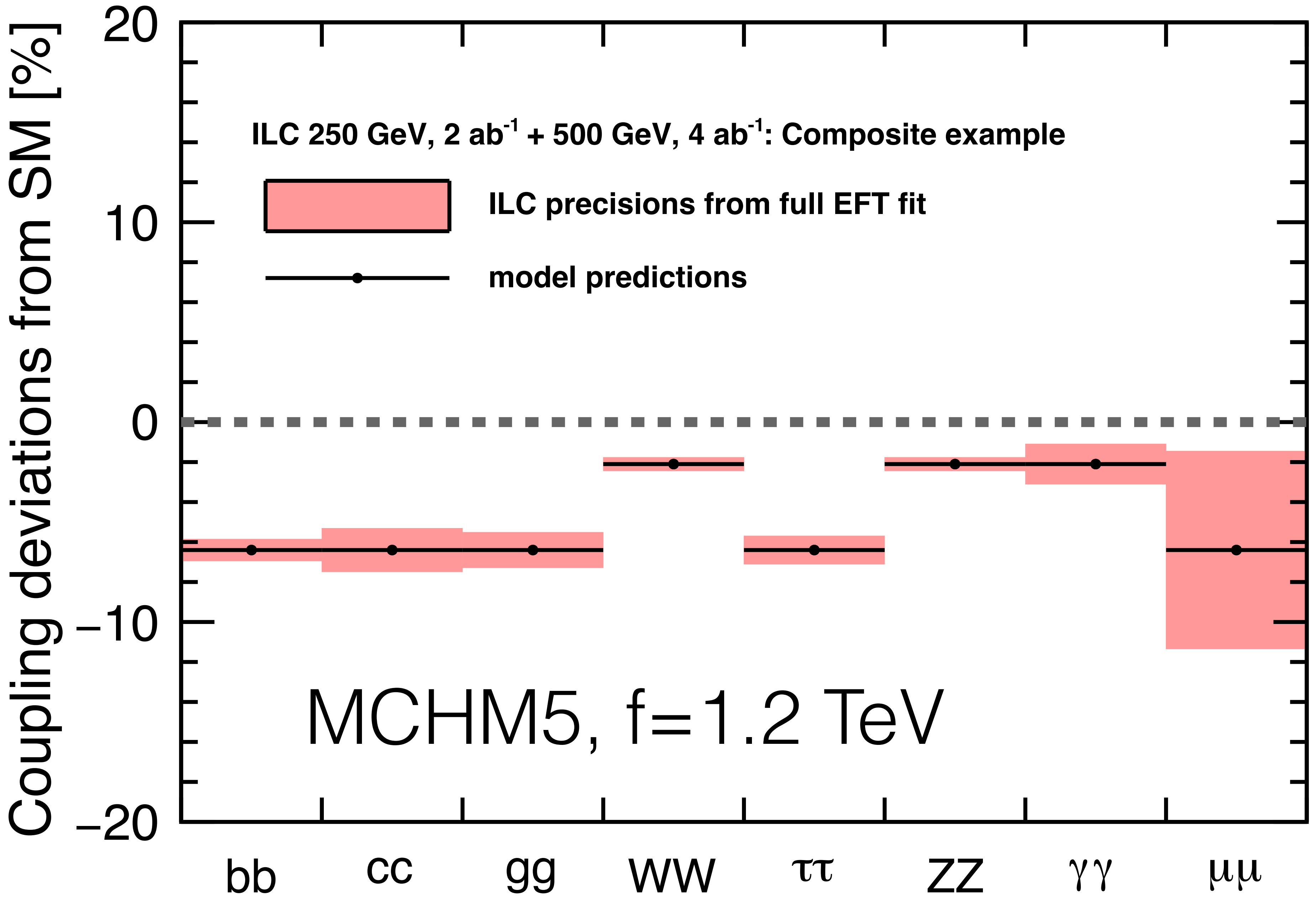

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And not to forget:

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

Discovery Potential

Or: beware what LHC limits really mean!

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

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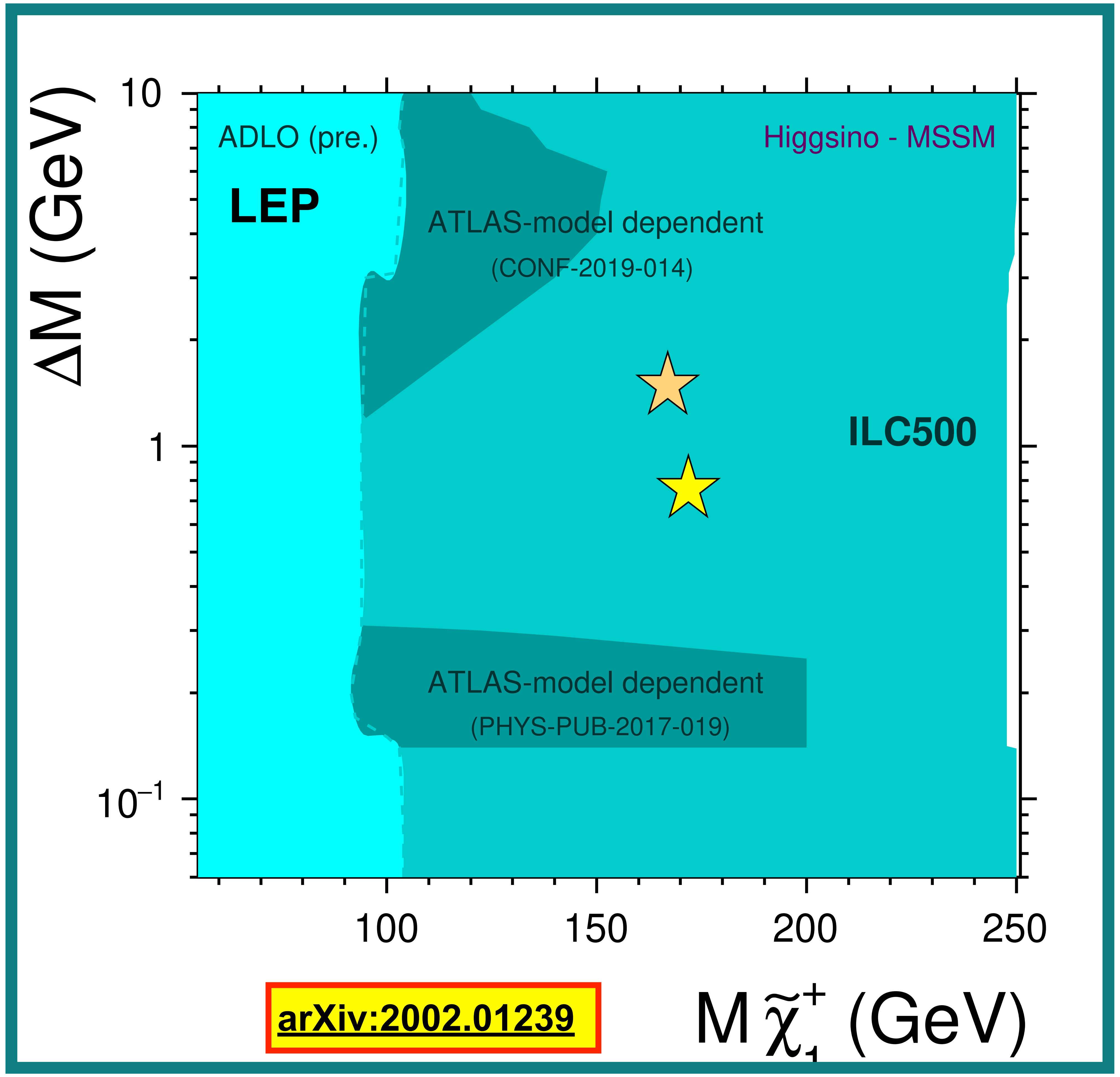

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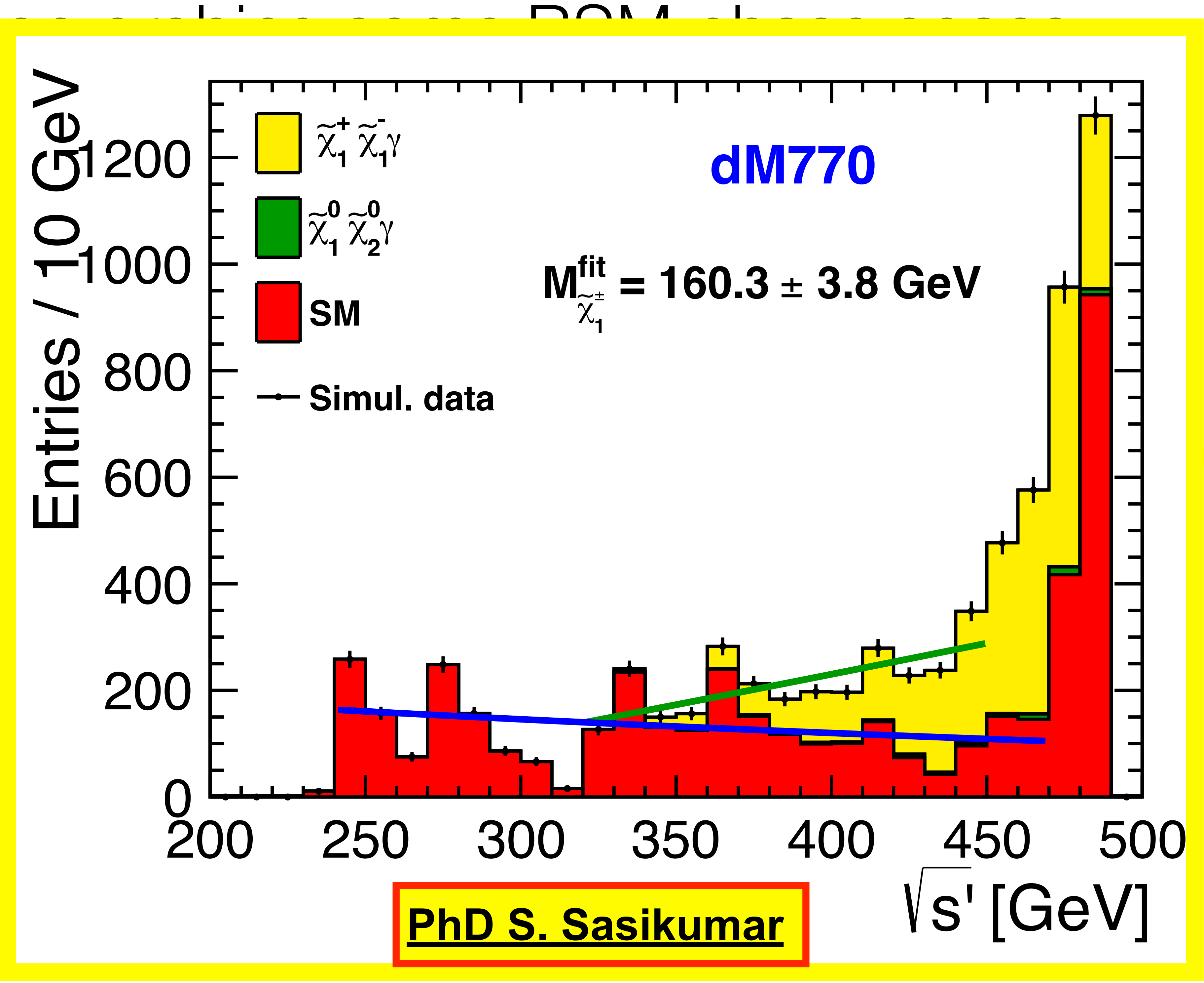

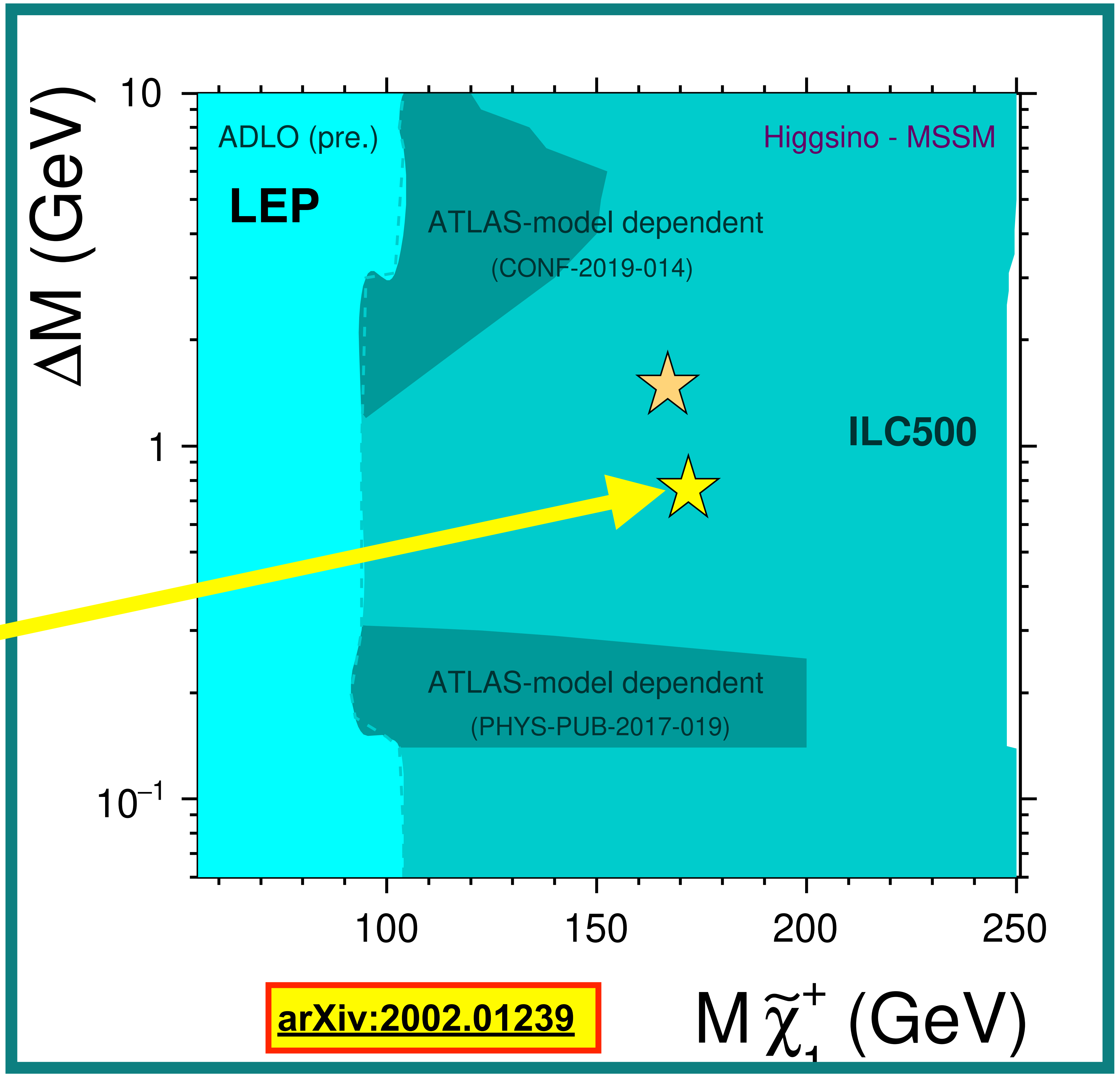

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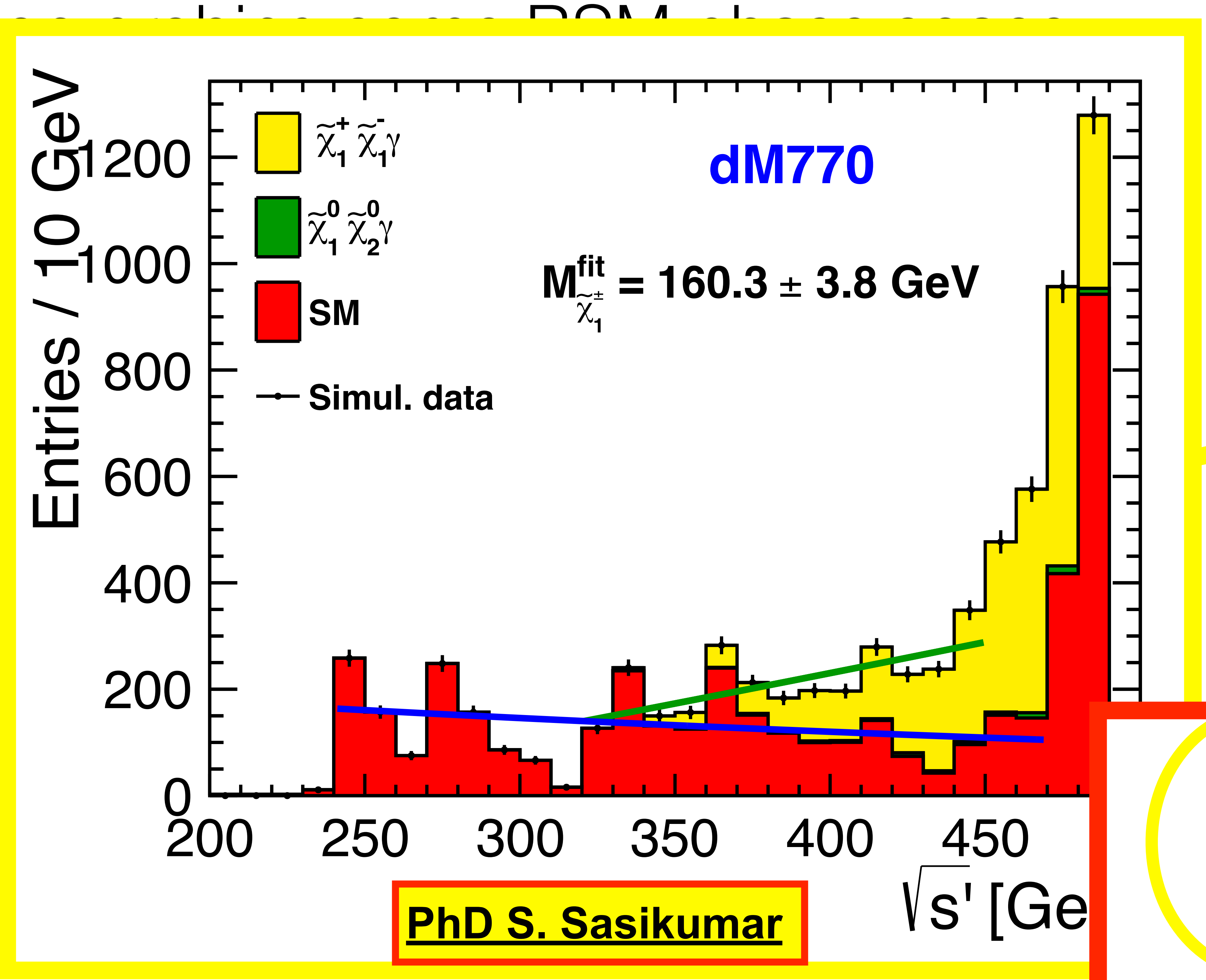

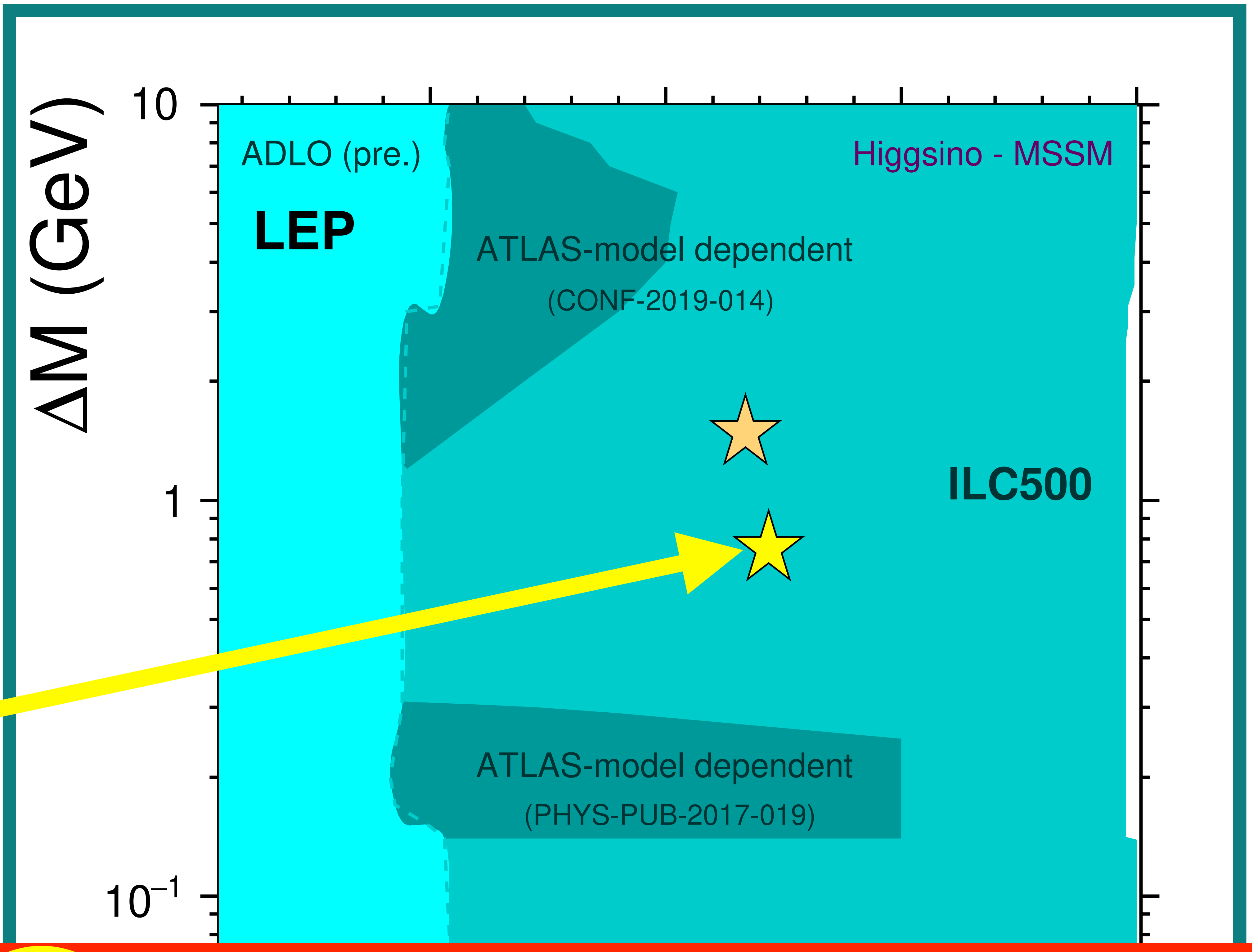

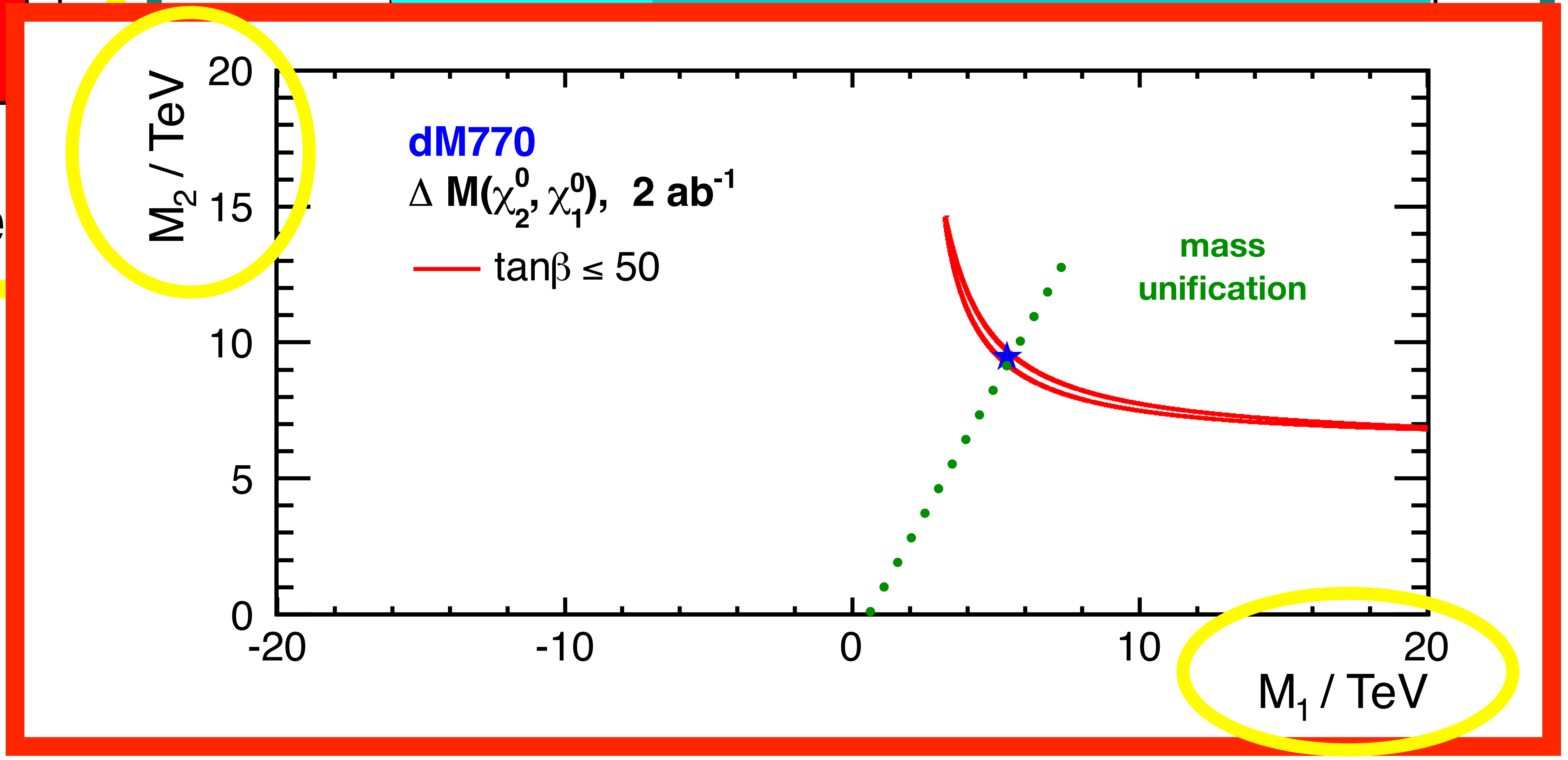

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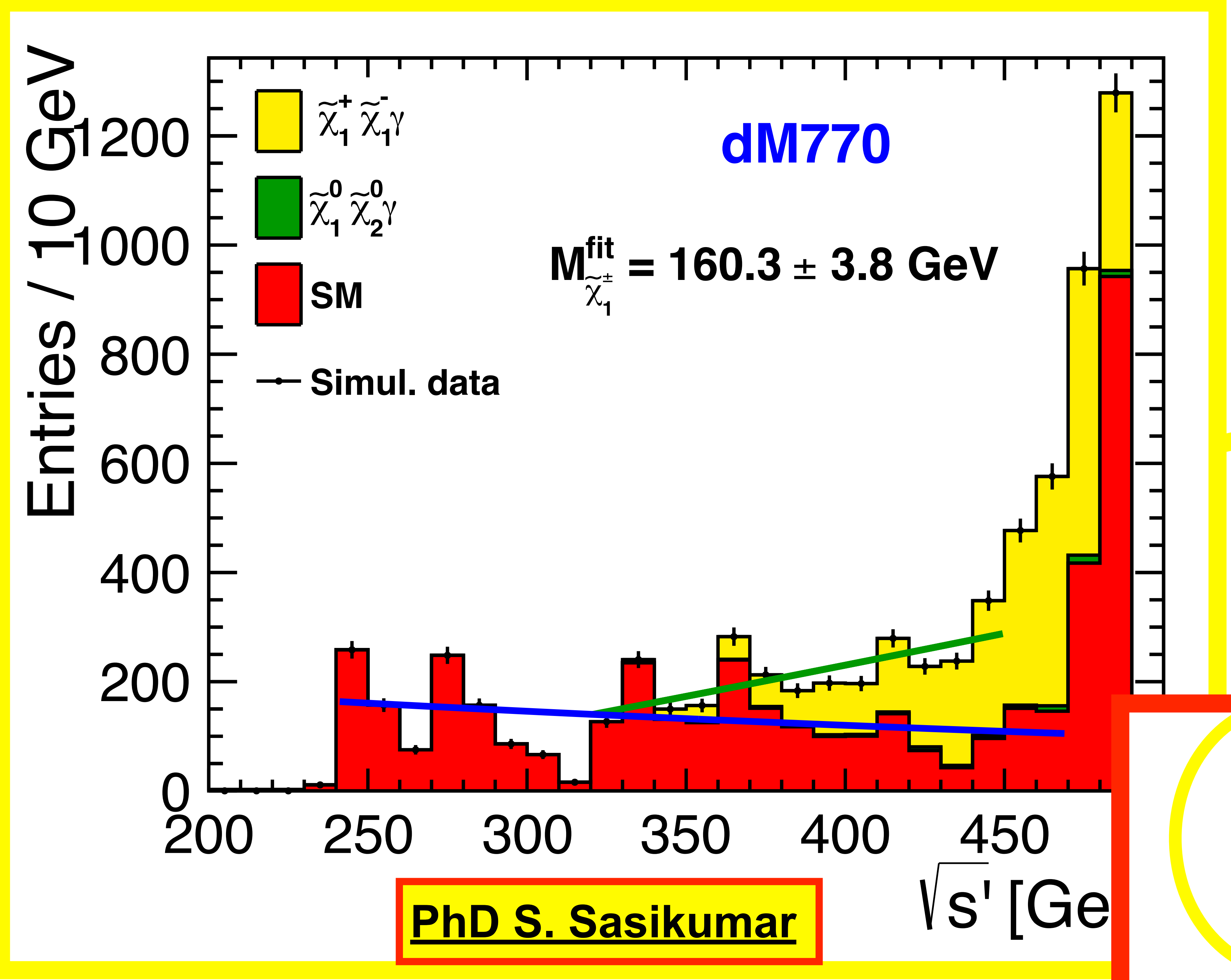
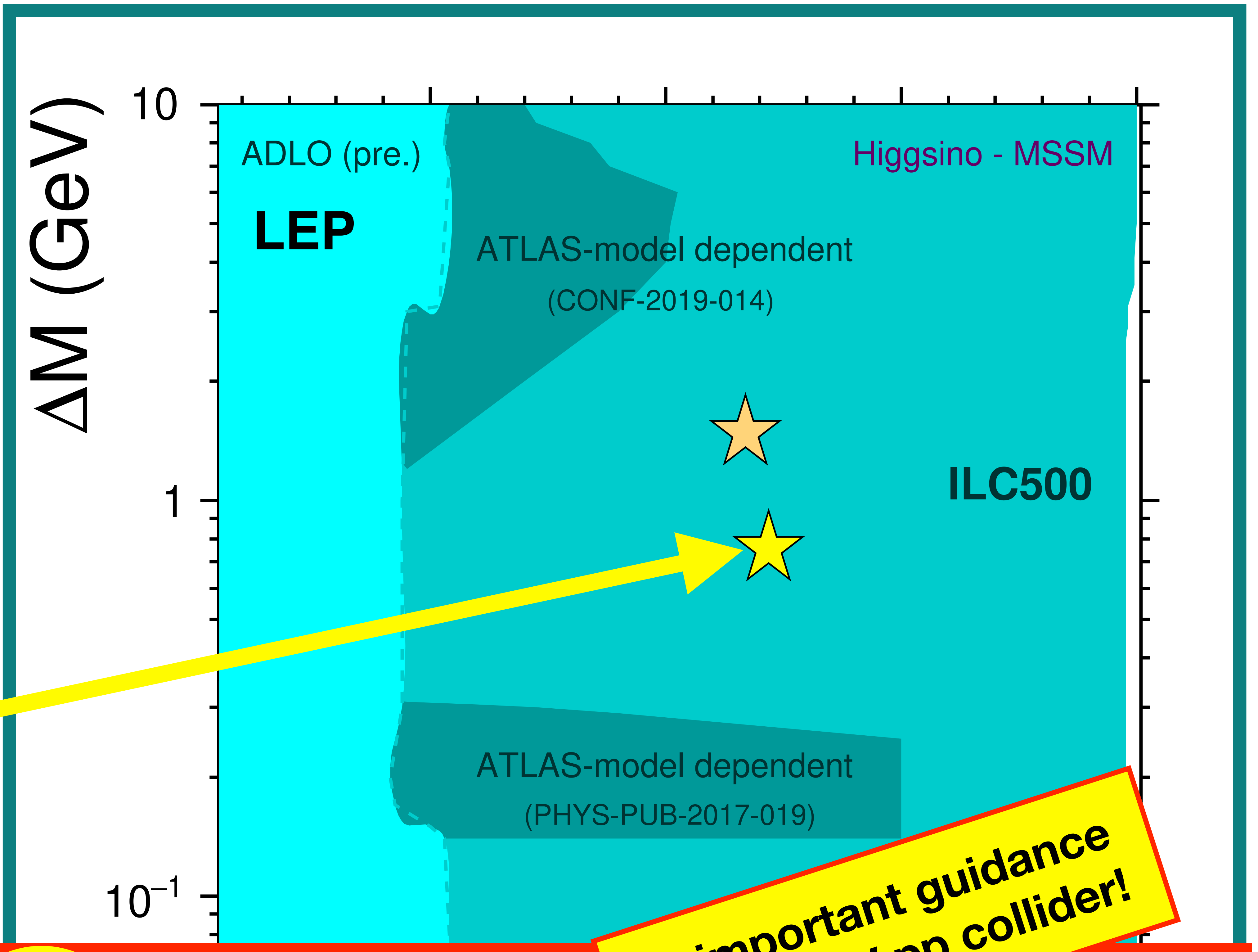
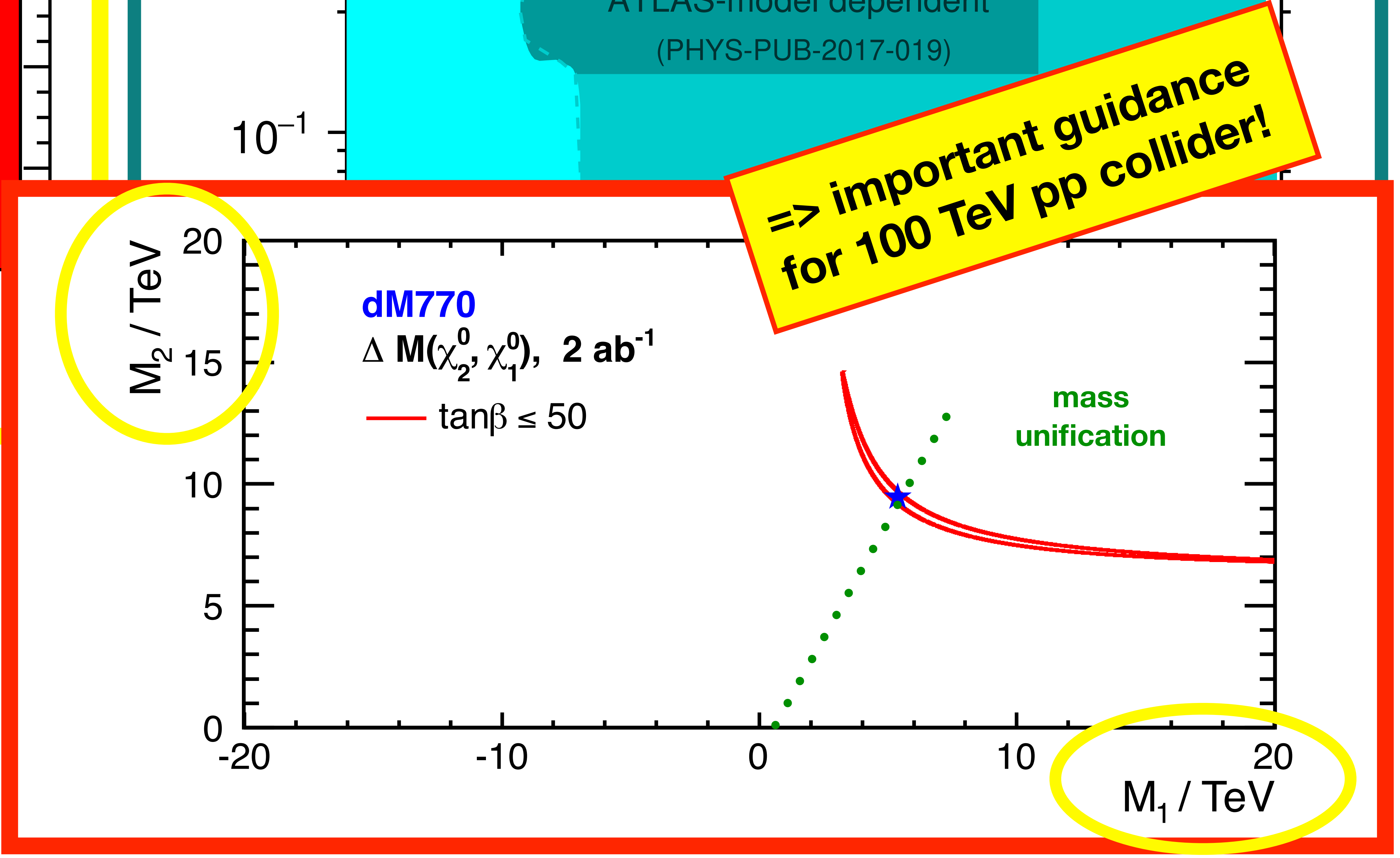
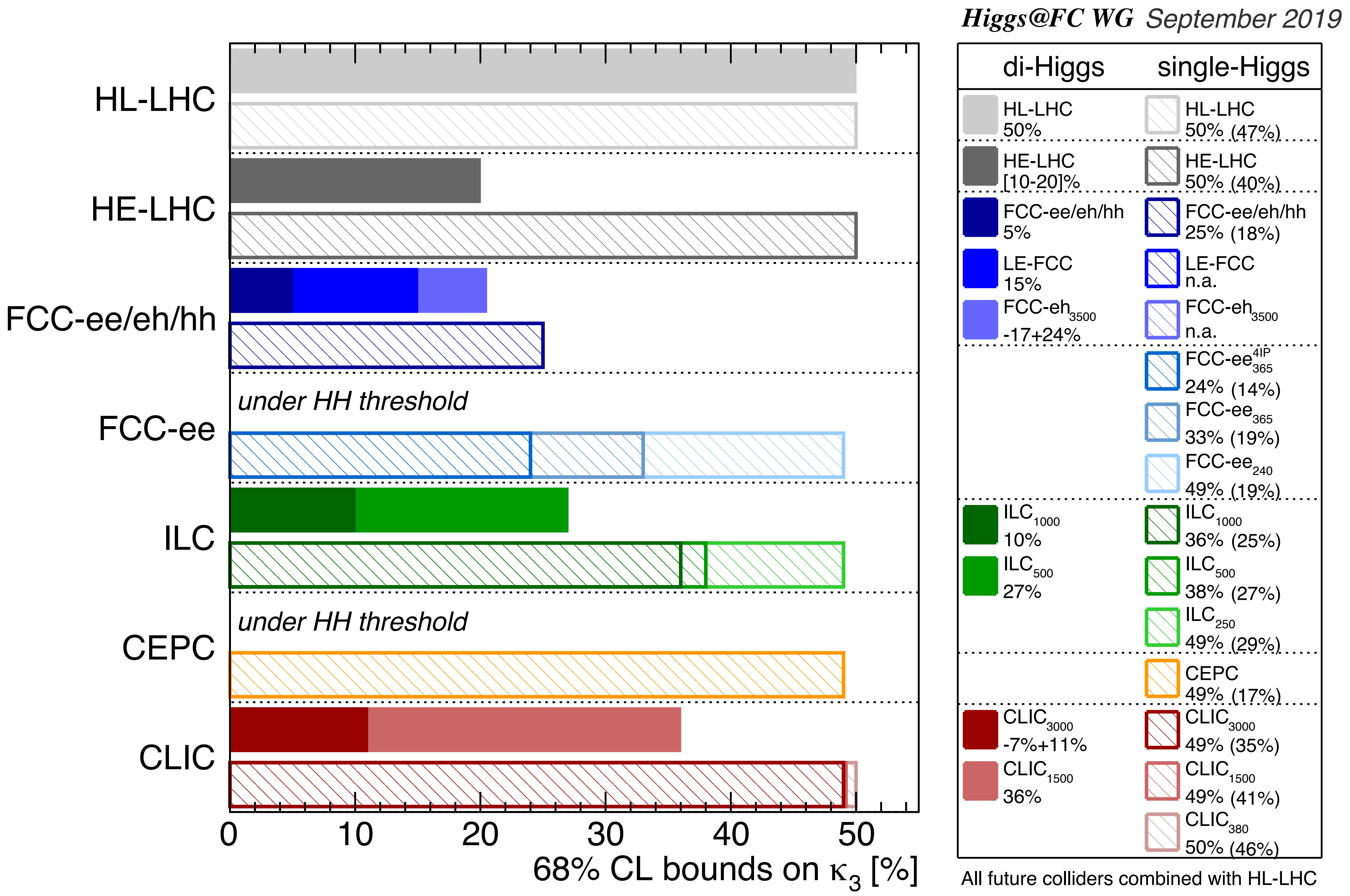






Higgs self-coupling

Electroweak Baryogenesis?



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Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING!

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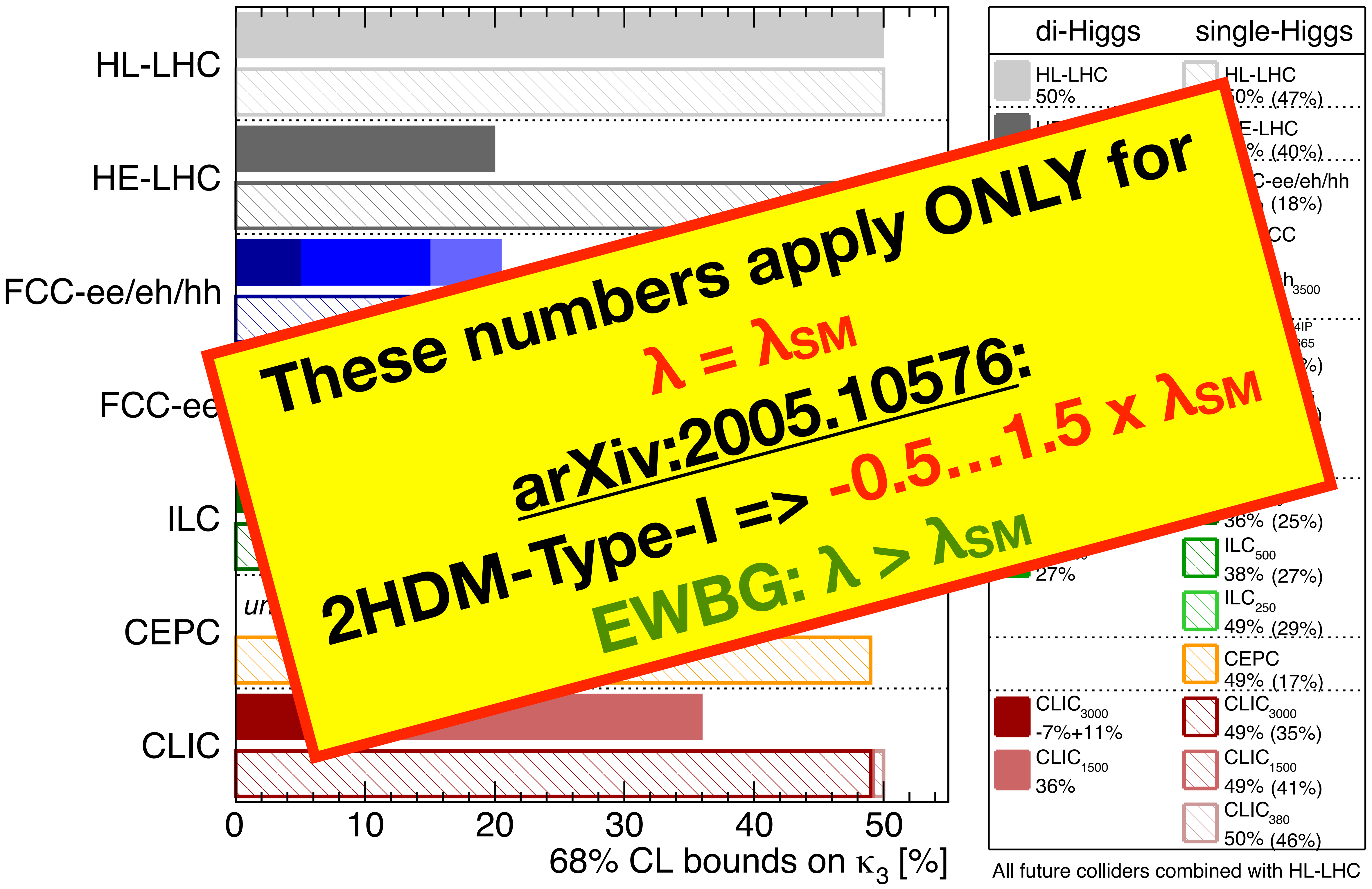

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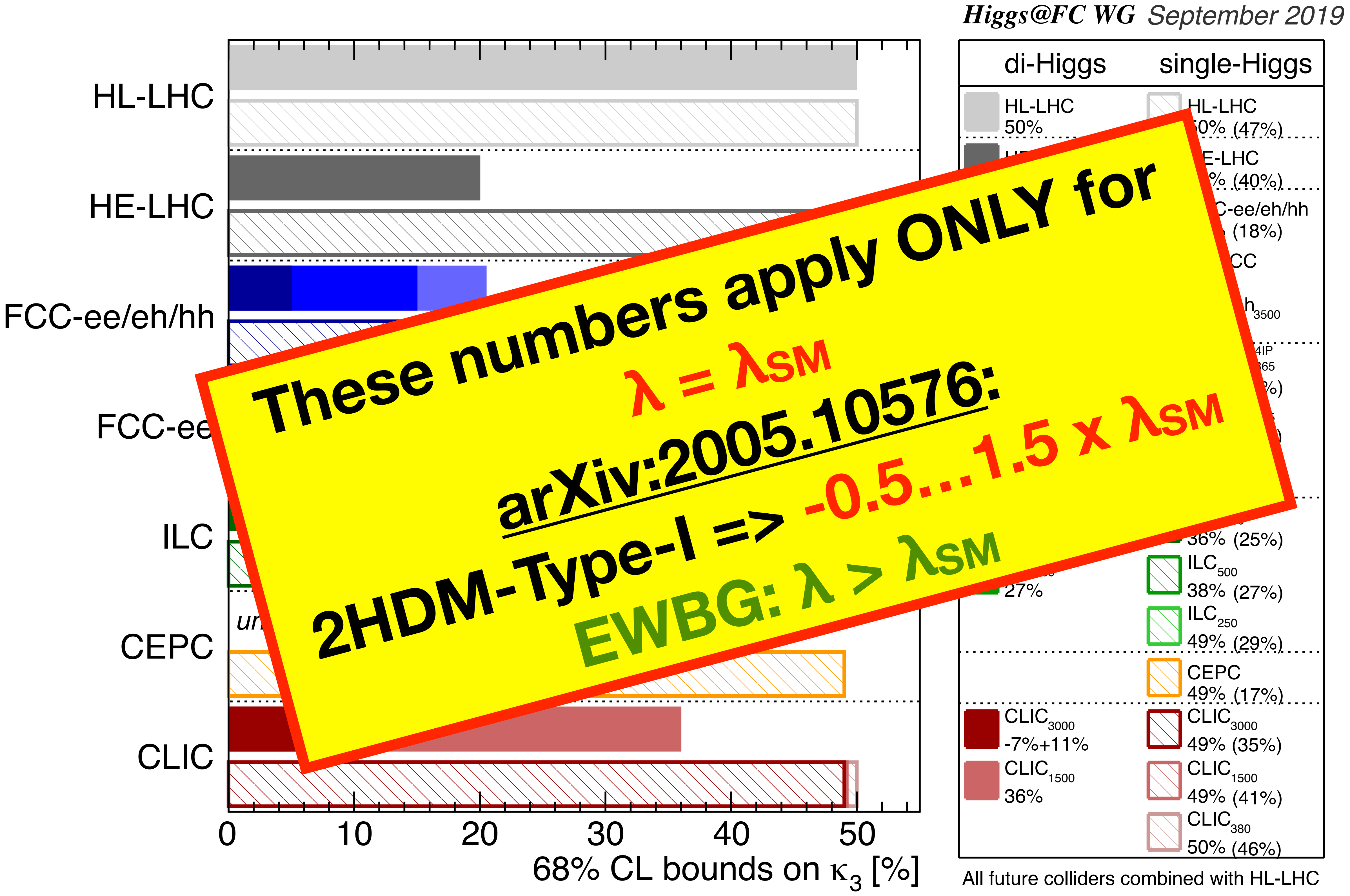

$\lambda > \lambda_{SM}$:

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

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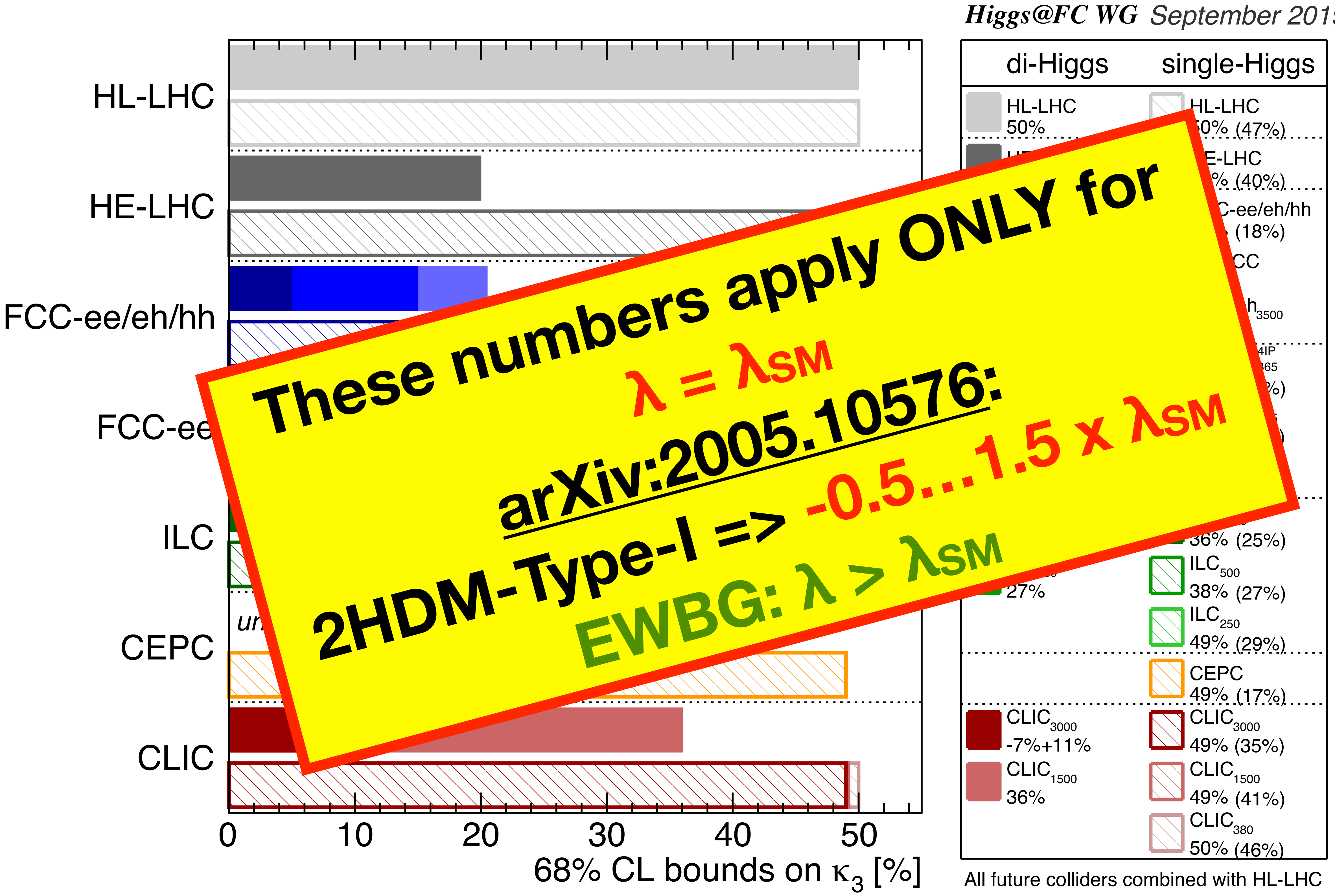

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arXiv:2005.10576:

2HDM-Type-I => $-0.5...1.5 \times \lambda_{SM}$

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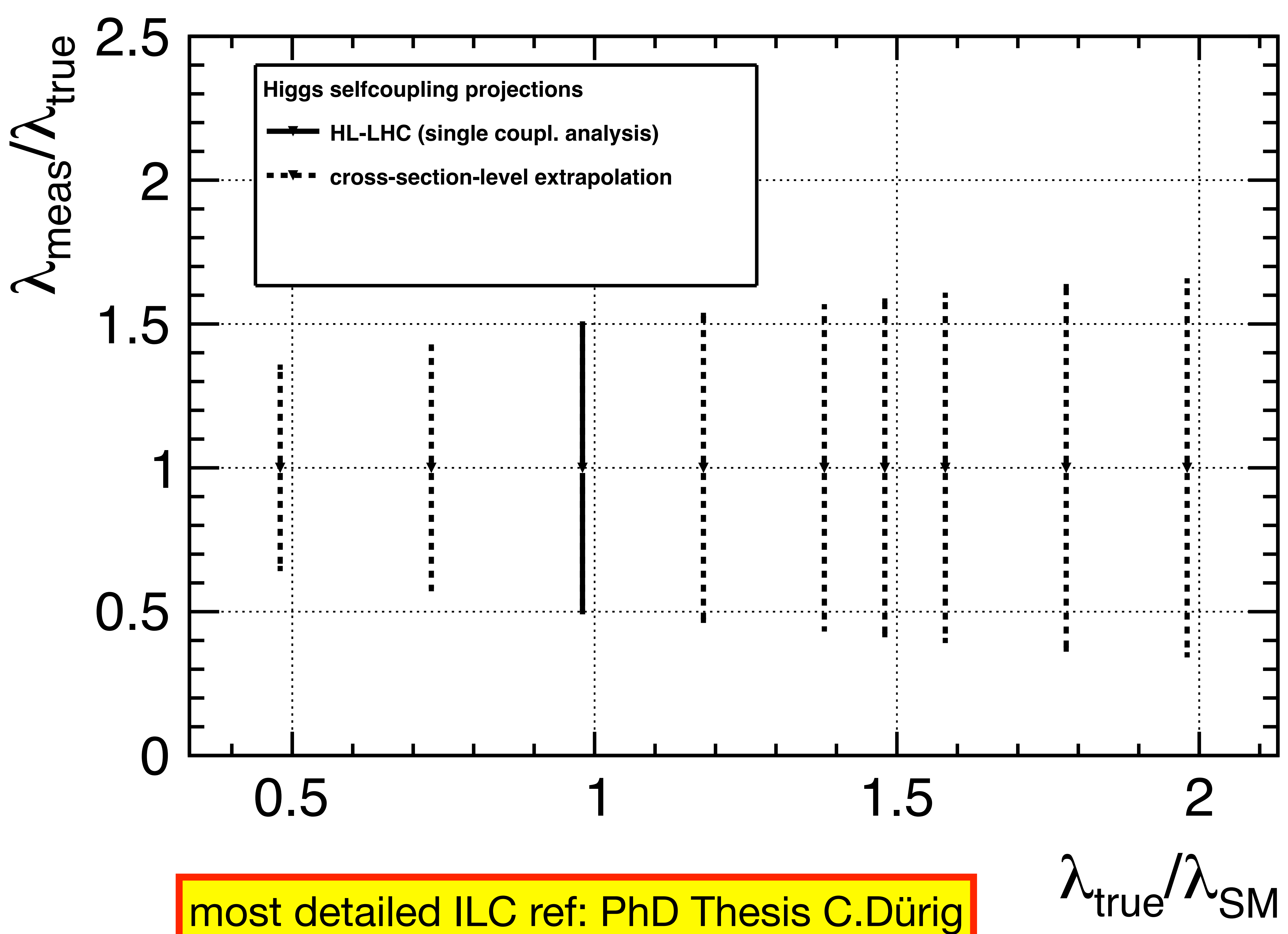

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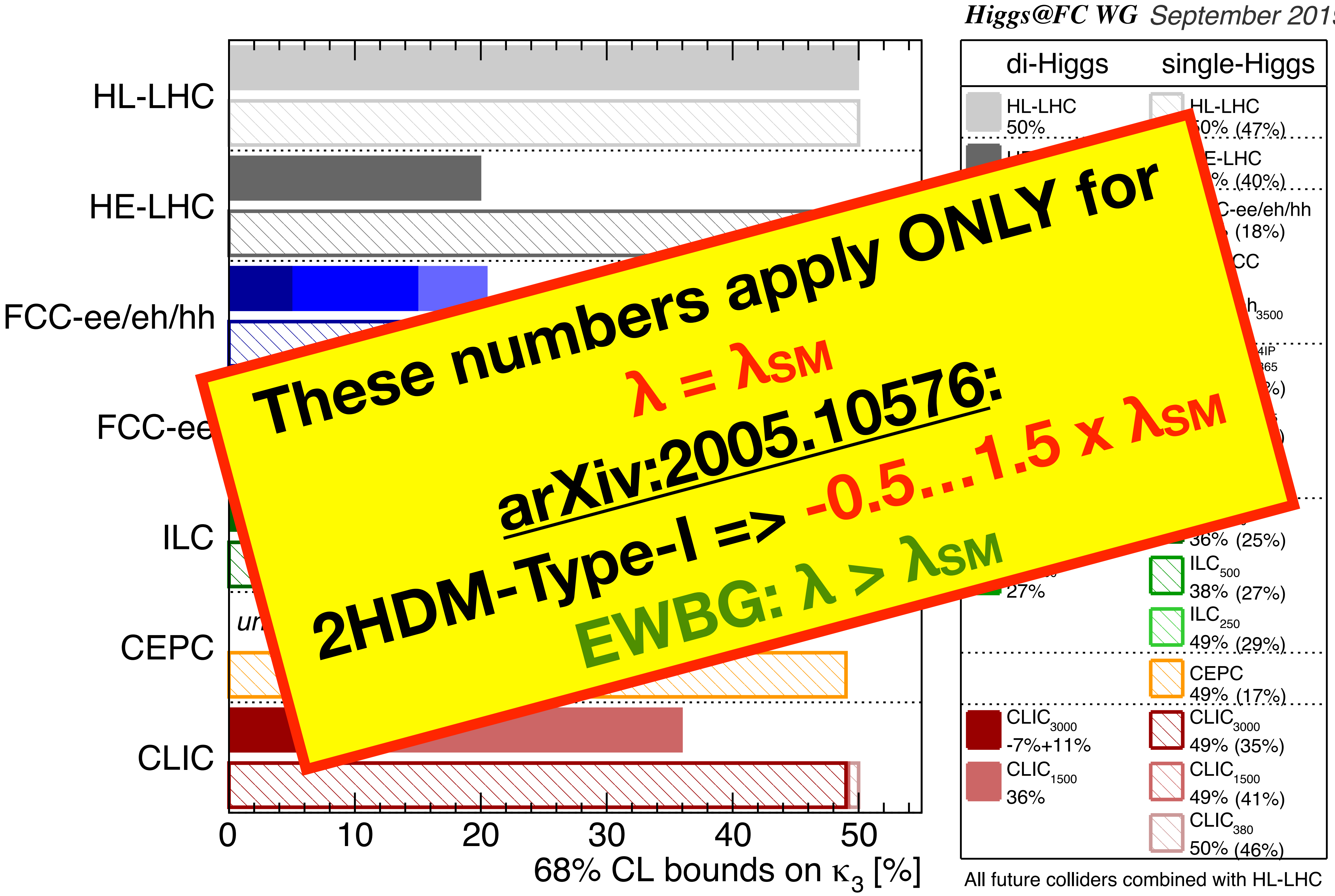

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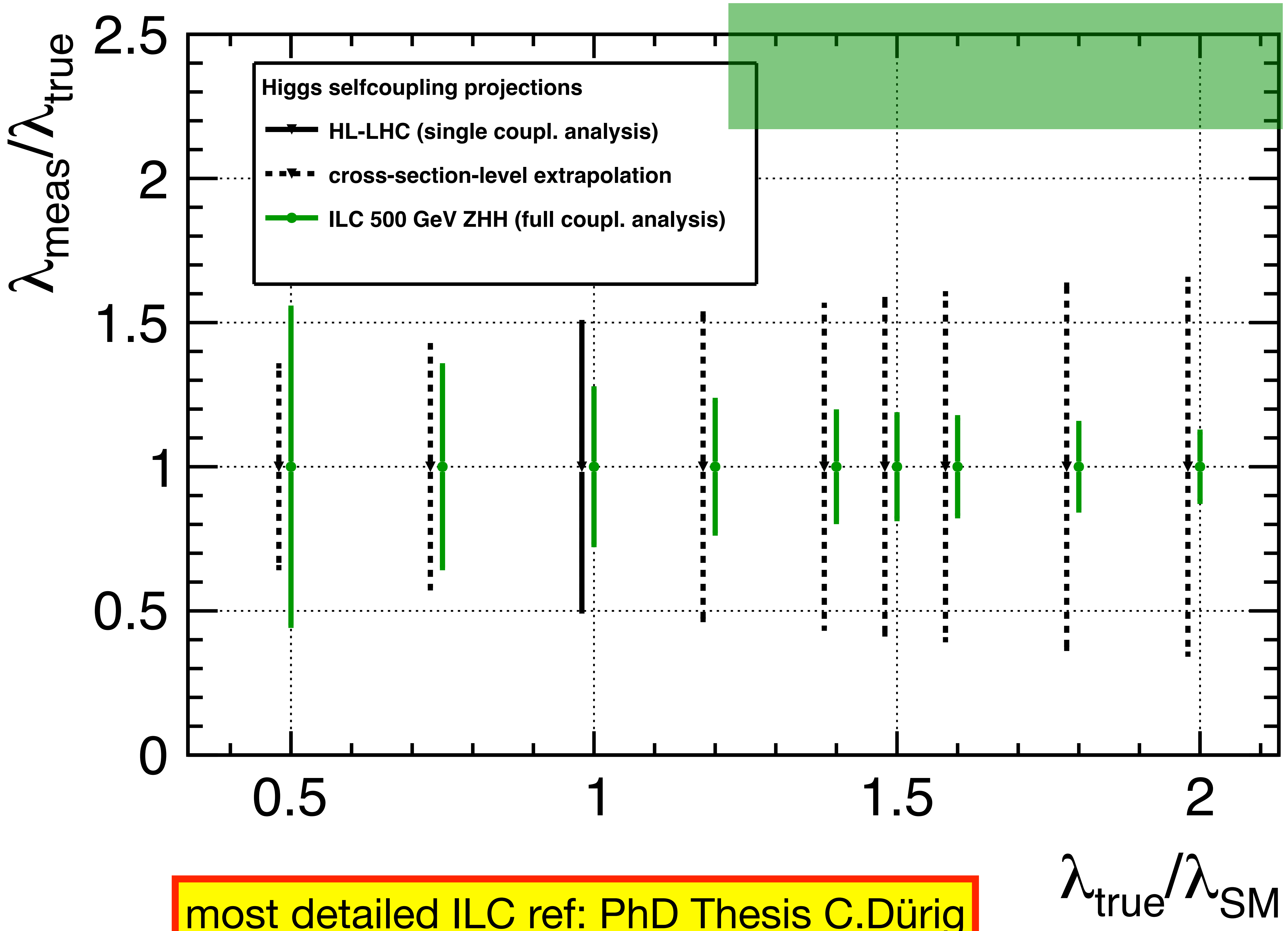

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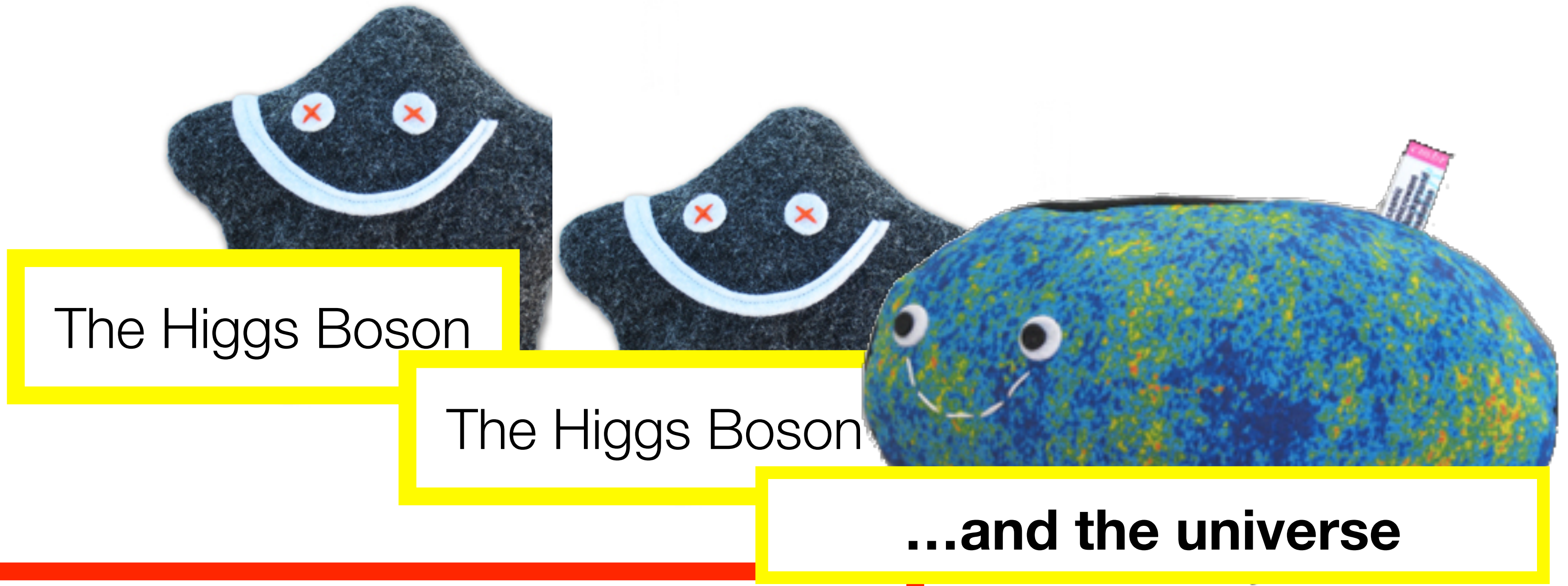

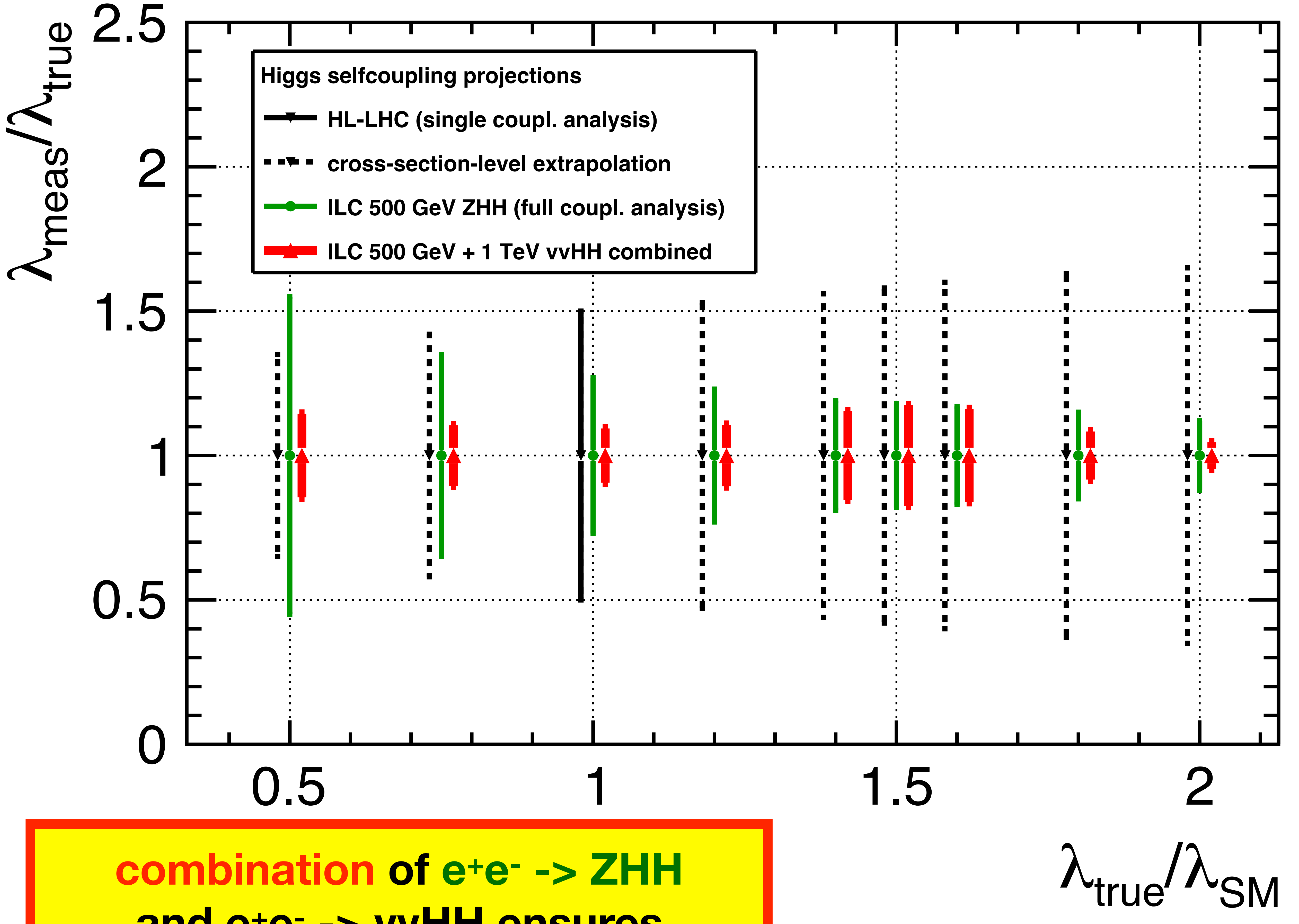

combination of e^+e^- -> ZHH
and e^+e^- -> vvHH ensures
at least 10-15% precision for all λ

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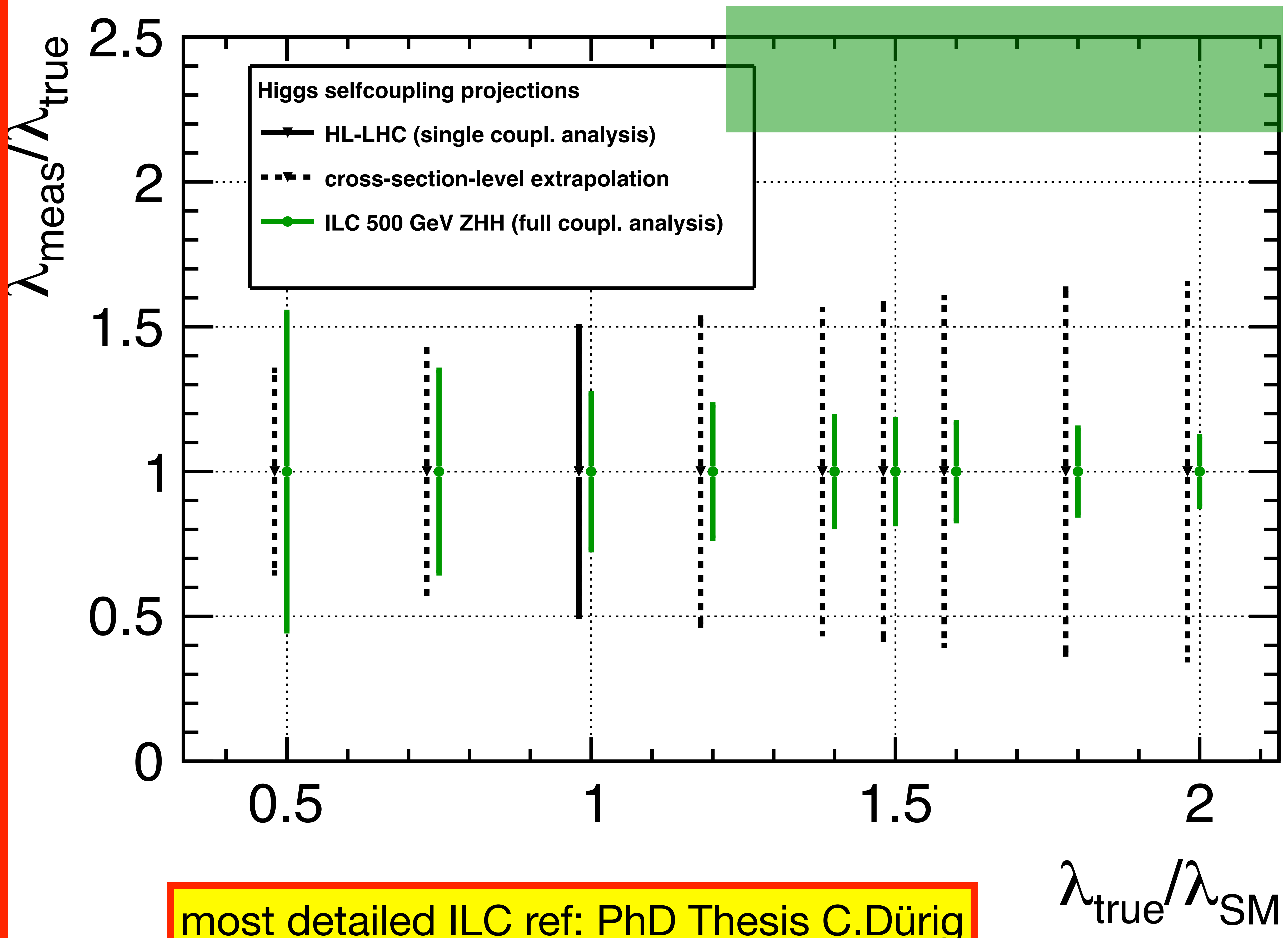

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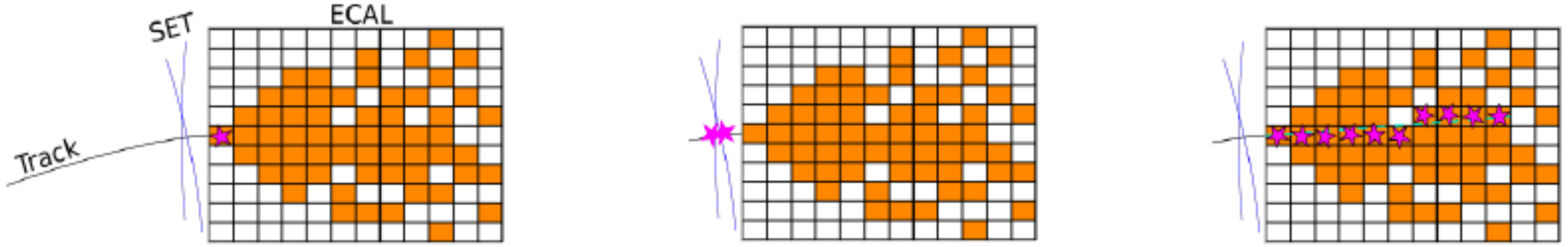
UPDATE ONGOING!

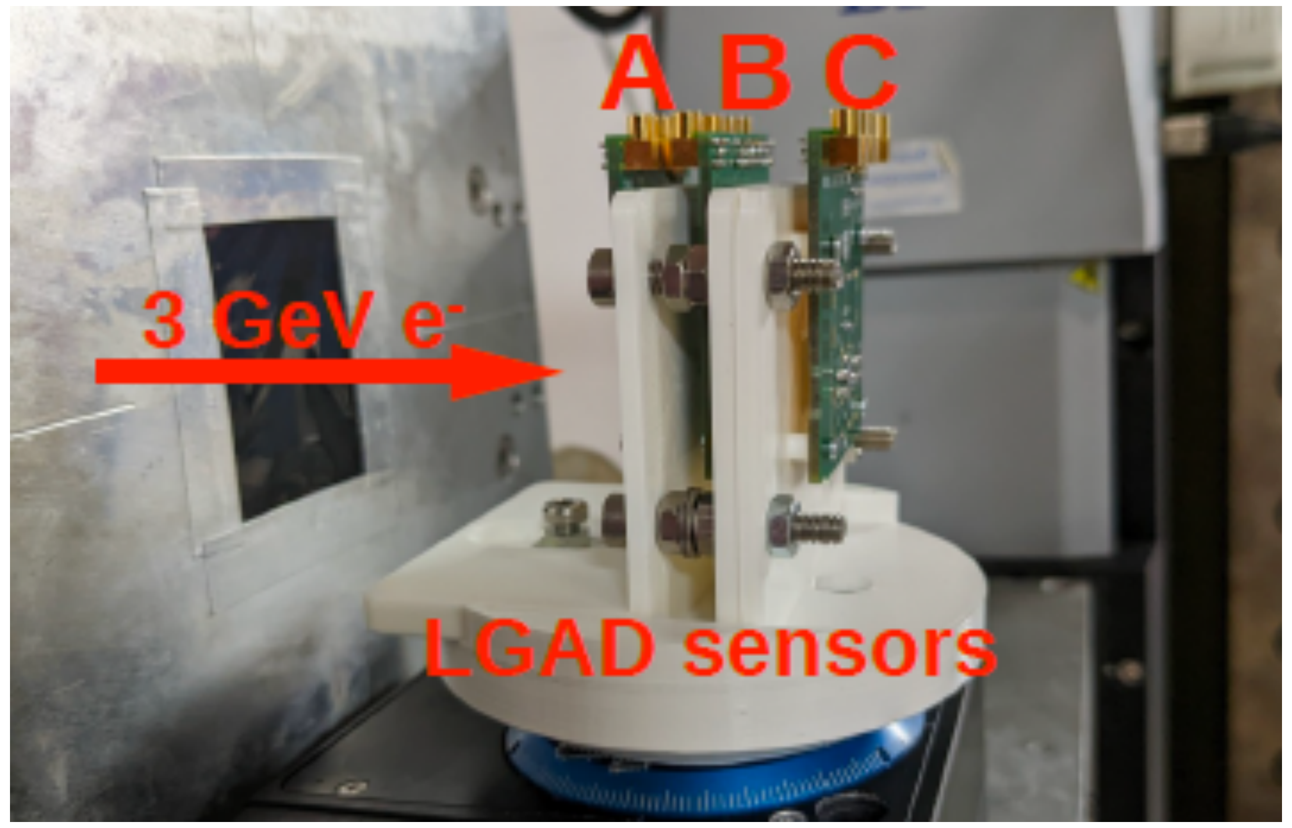
Fast Timing

not only PID!

Timing implementation in the ILD



Placement:	Dedicated ECAL timing layer (LGADs)	Two Si strips of external tracker (LGADs?)	10 ECAL layers (not LGADs)
Hit time resolution:	~ 30 ps	~ 50 ps	~ 100 ps
TOF resolution:	~ 30 ps	~ ? ps	~ ? ps

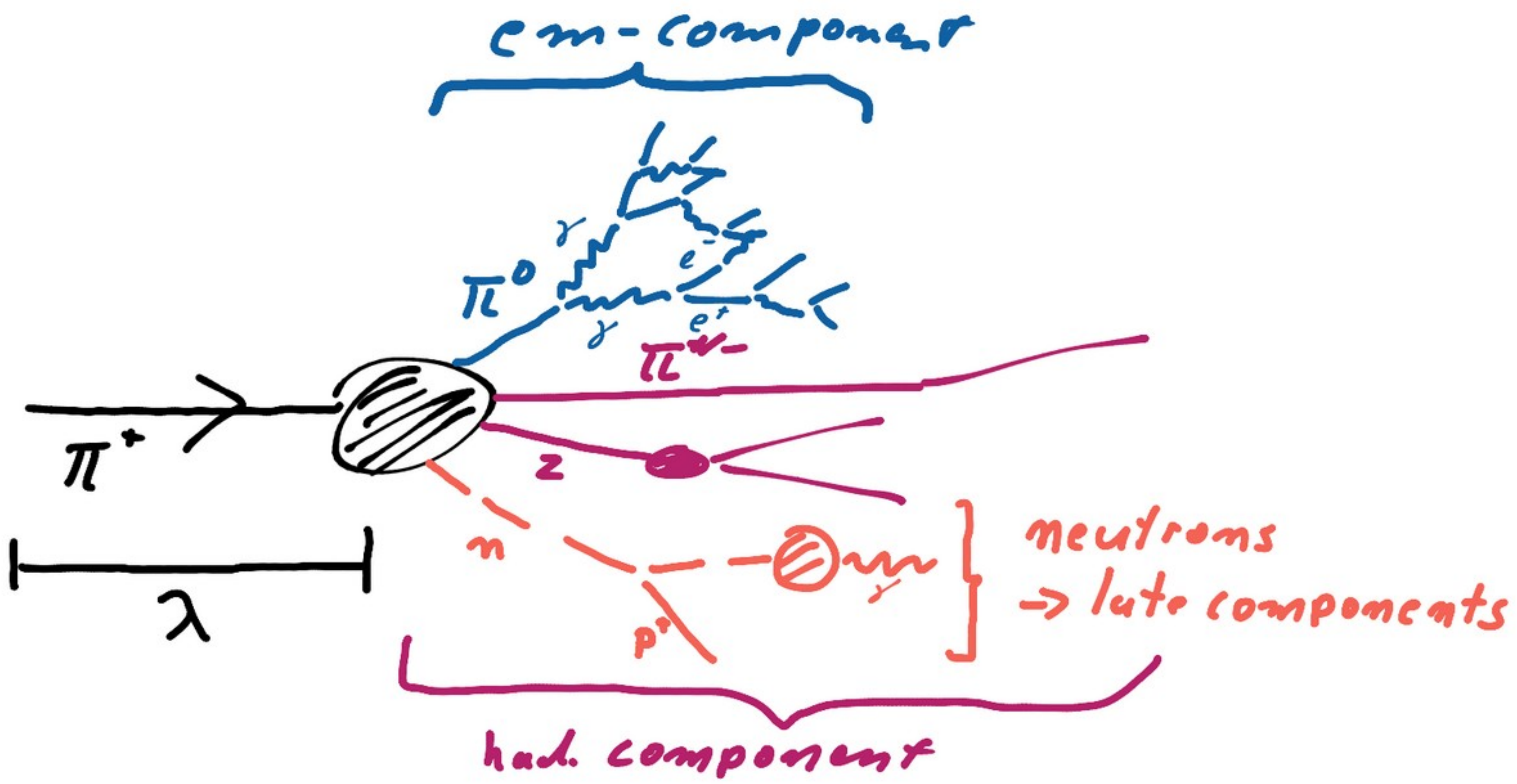


LGADs in the detector:
- → high power consumption
- → active cooling
- → space& material budget
- → not good

B.Dudar

Timing measurements for shower developments

- Neutral and slow components
  - Require ~ns precision
  - Reachable today with "standard" silicon, scintillators calorimeters
- ~0.1 ns scale: near the corner
- An even lower with GRPC (20ps)

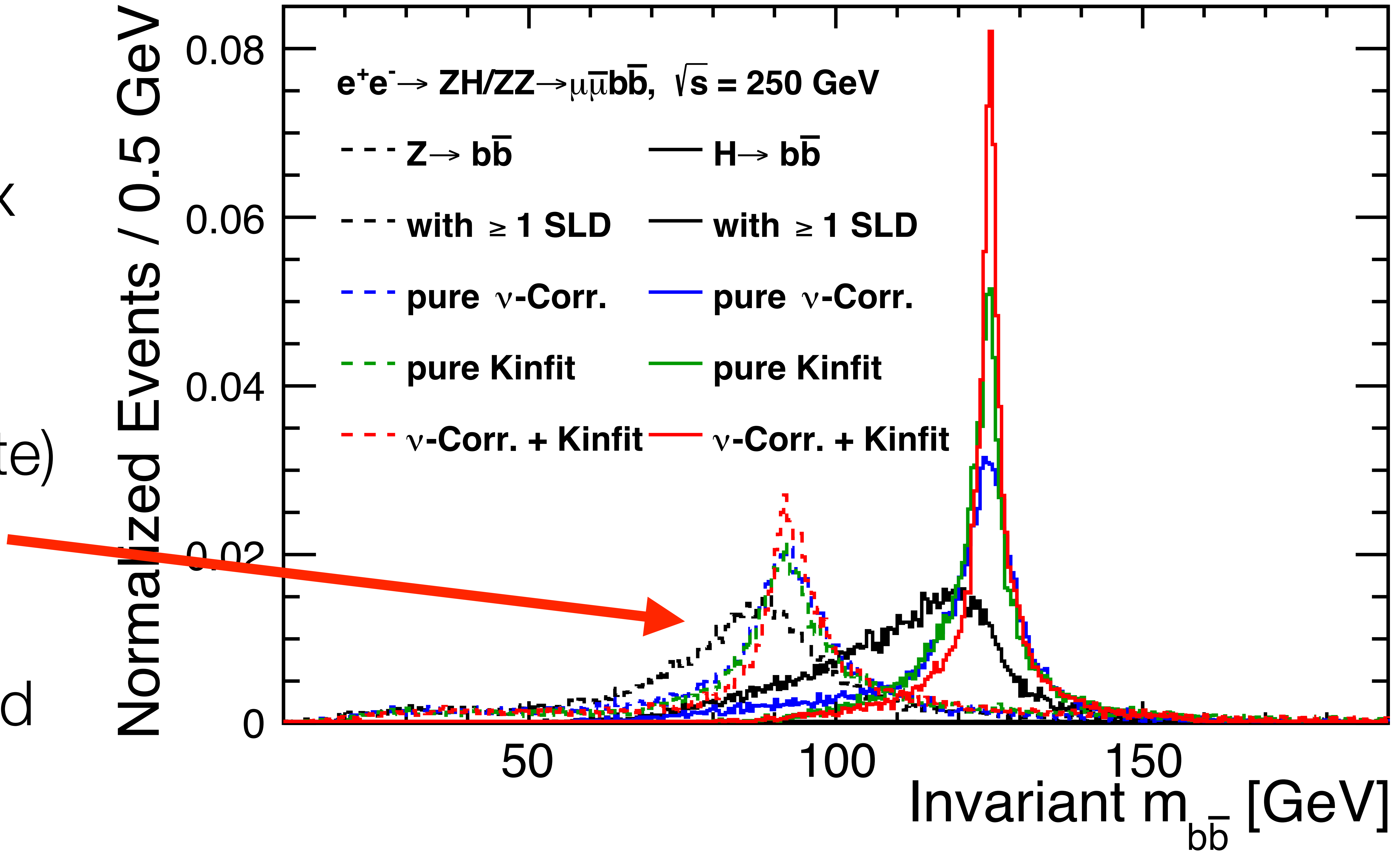


A. Irles

Recent developments

Improvements in reconstructing Z/H -> hadrons (Y. Radkhorrami, L. Reichenbach)

- correct semi-leptonic b/c decays
  - identify leptons in c- / b-jets
  - associate them to seondary / tertiary vertex
  - reconstruct neutrino kinematics (2-fold ambiguity)
- ErrorFlow (jet-by-jet covariance matrix estimate)
- feed both into kinematic fit
- (very) significant improvement in H->bb/cc and Z->bb/cc reconstruction
- ready to be applied to many analyses…



arXiv:2111.14775

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?
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  - The **UNEXPECTED** !

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Conditions at e+e- colliders very complementary to LHC:
- in particular low backgrounds
- clean events
- triggerless operation

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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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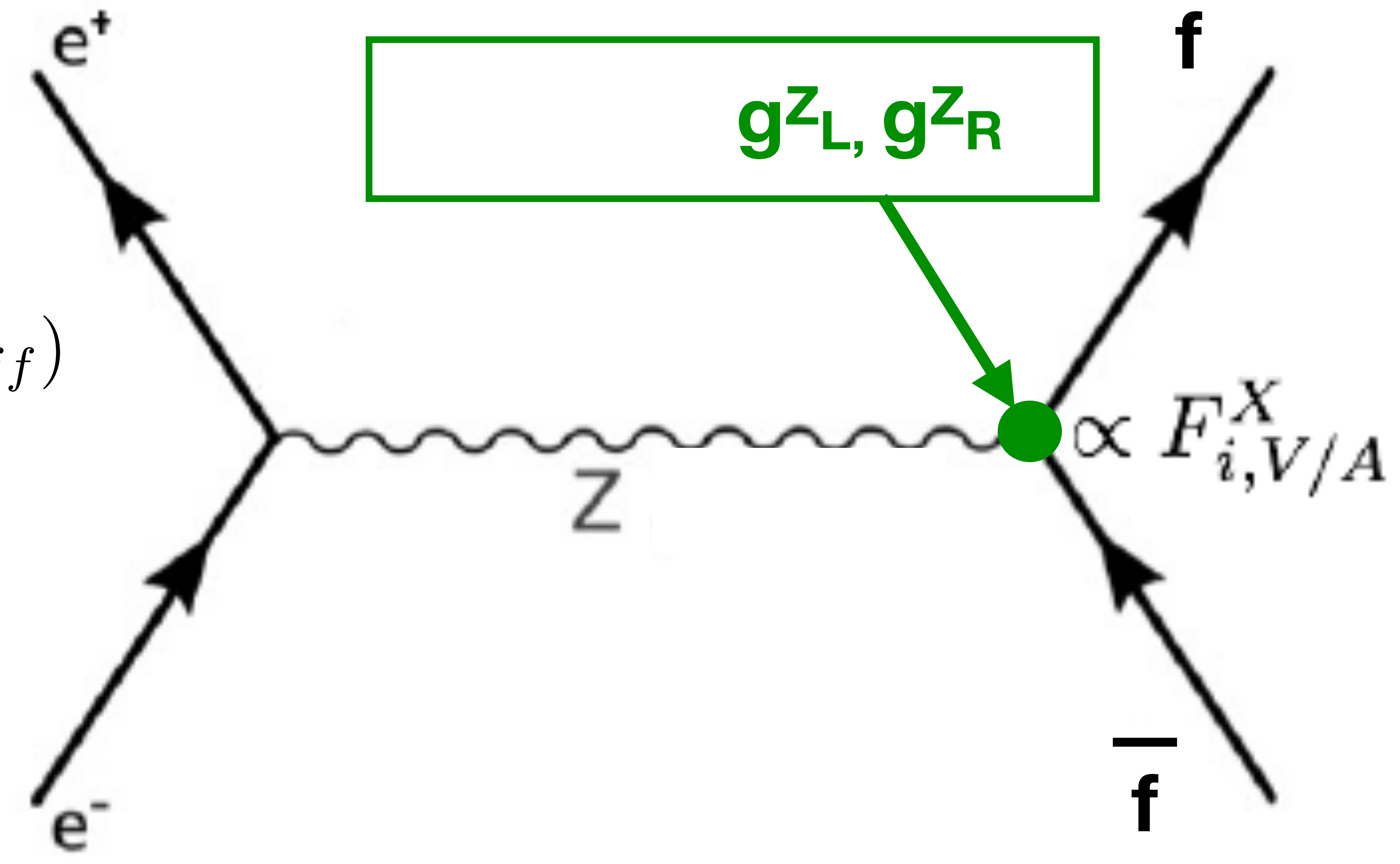
Polarisation & Electroweak Physics

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:

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

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

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

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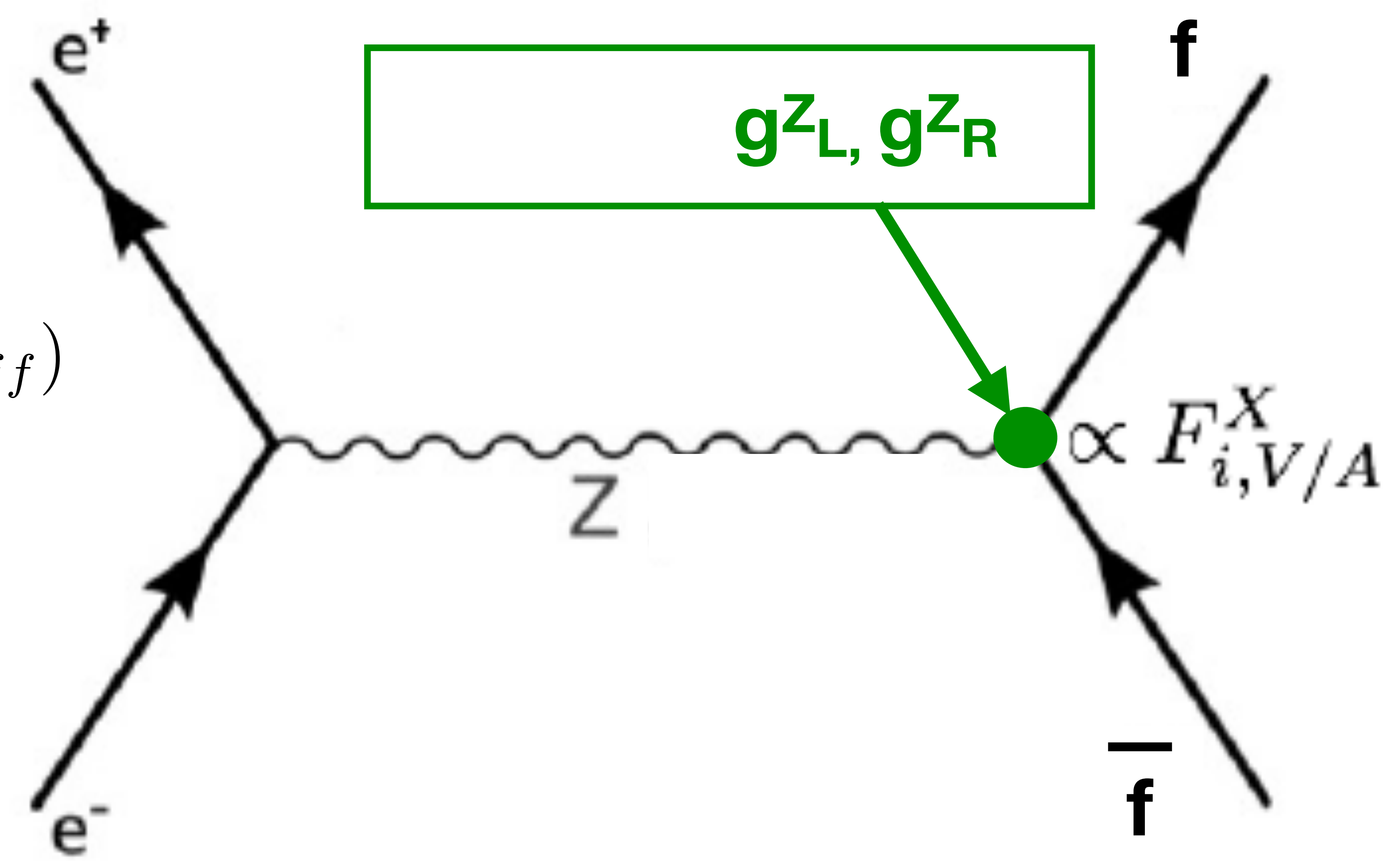

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trading theory uncertainy:

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

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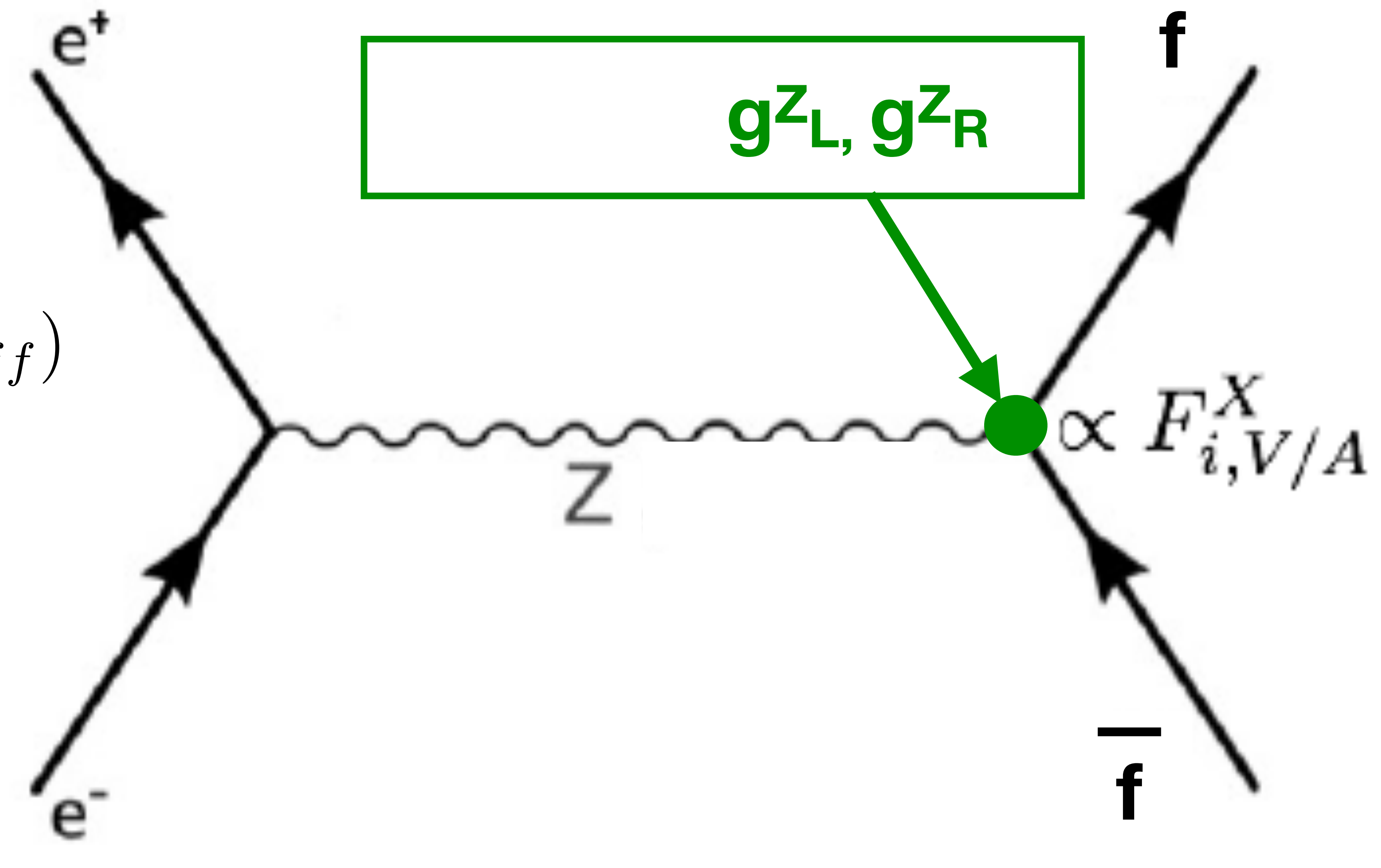

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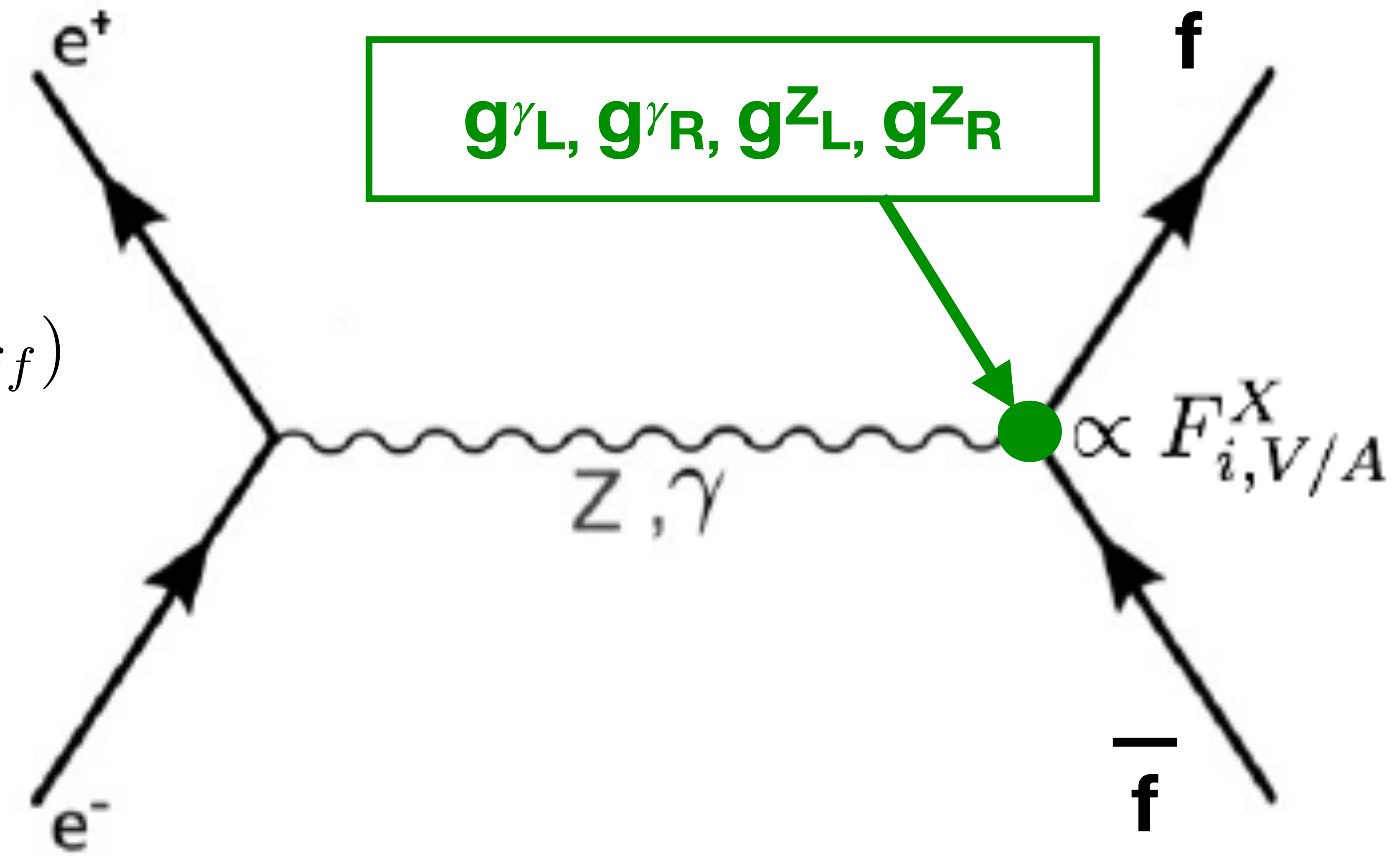

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Polarisation & Electroweak Physics at the Z pole

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

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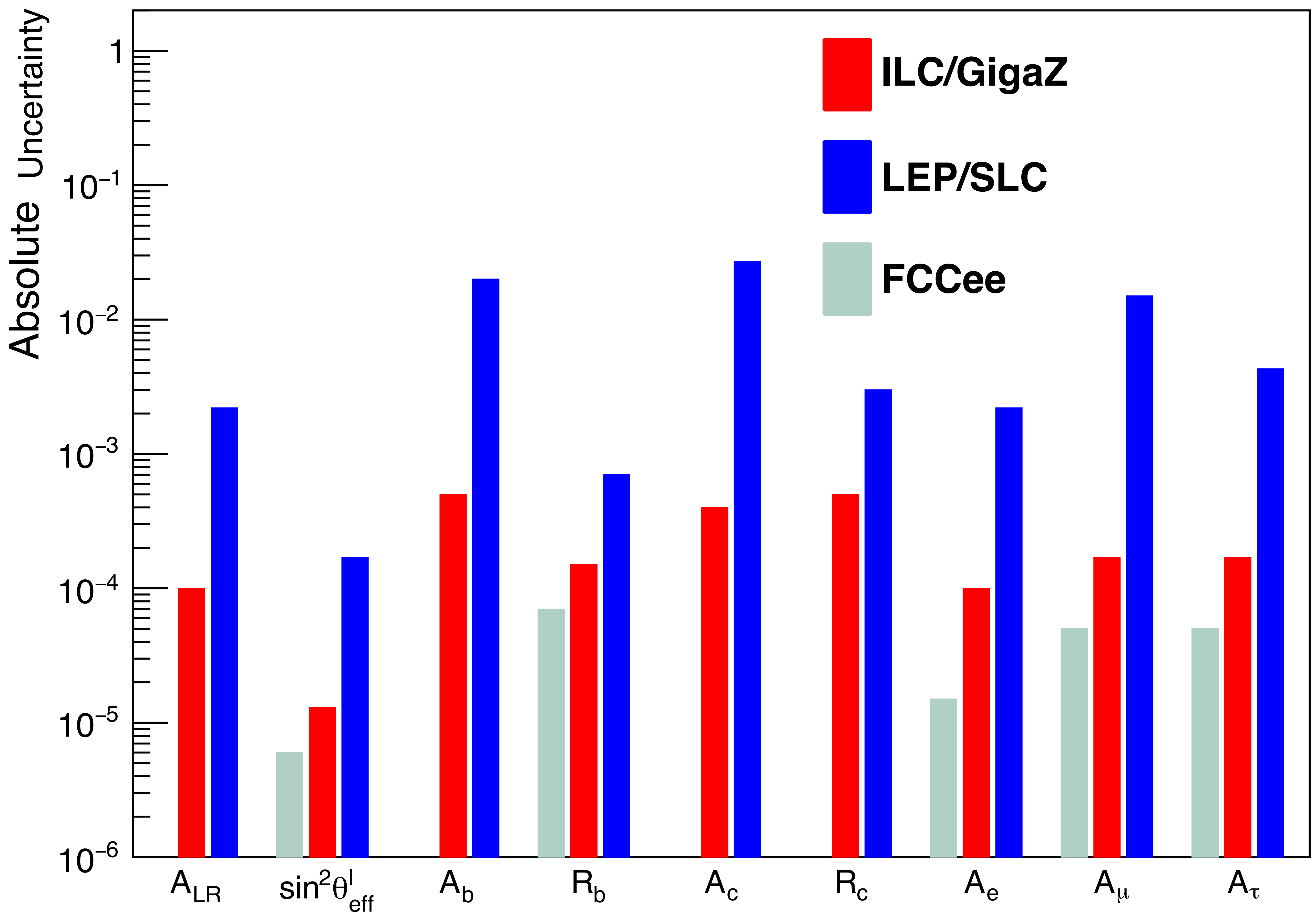

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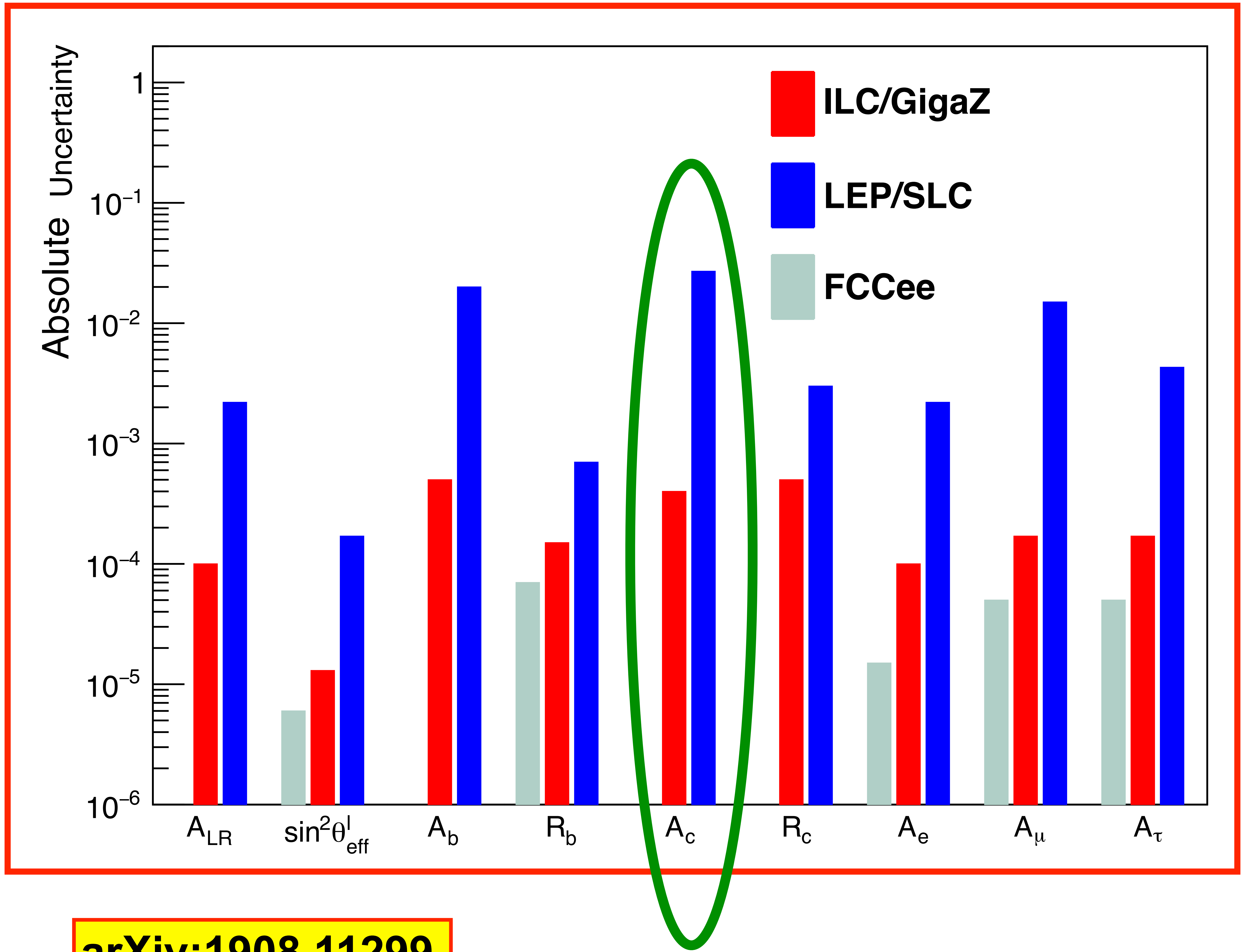

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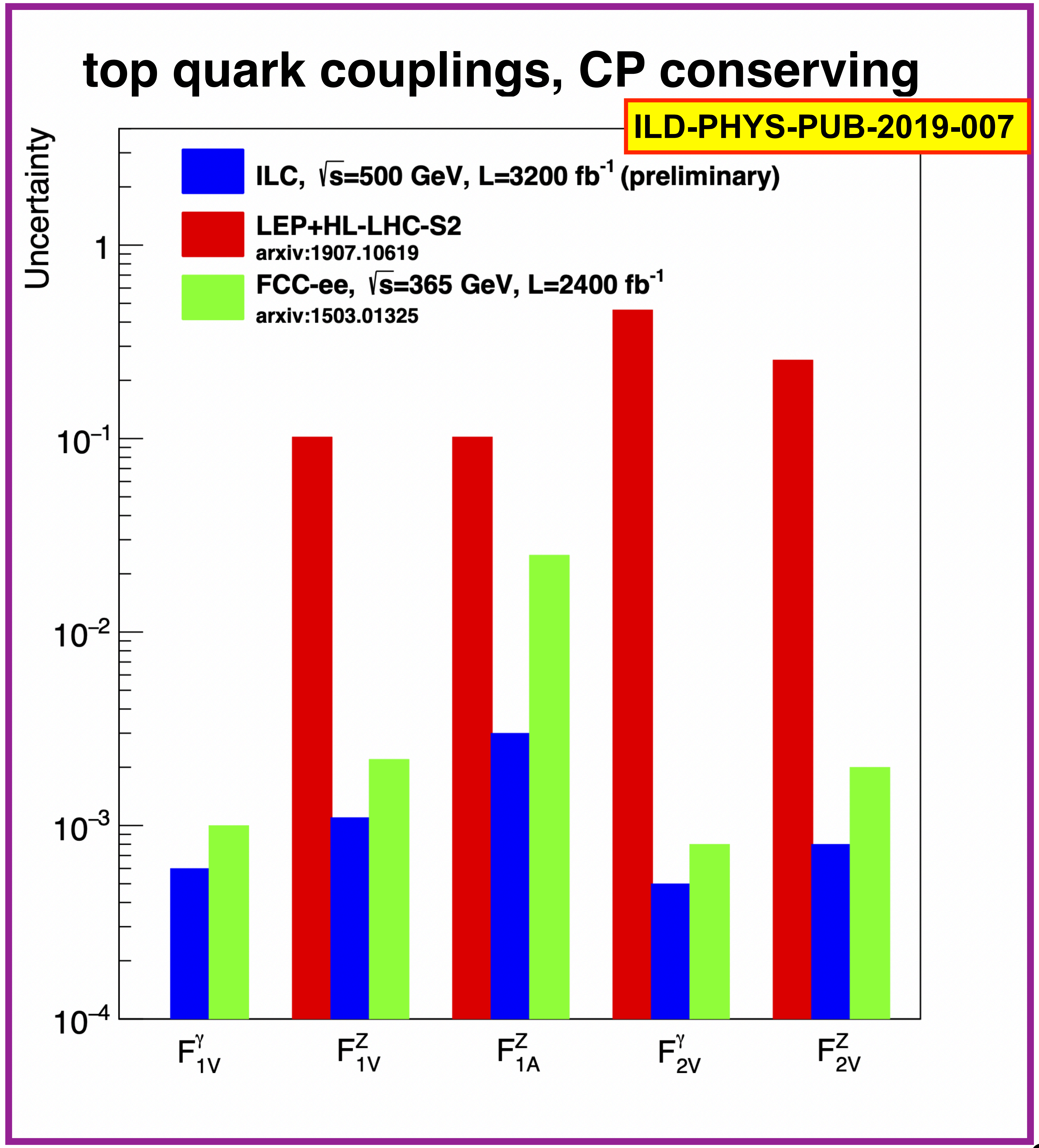
Polarisation & Electroweak Physics at high energies

e+e- at 500 GeV and 1 TeV

- ex1: top quark pair production - disentangle Z / γ:
  - unpolarised case: from final-state analysis only
  - polarised case: direct access
    - final state analysis can be done in addition
    => redundancy, control of systematics
- ex2: oblique parameters for 4-fermion operators
  - beam polarisation essential to disentangle Y vs W
  - ILC 250 outperforms HL-LHC
  - ILC 500 outperforms unpolarised e^+e^- machines



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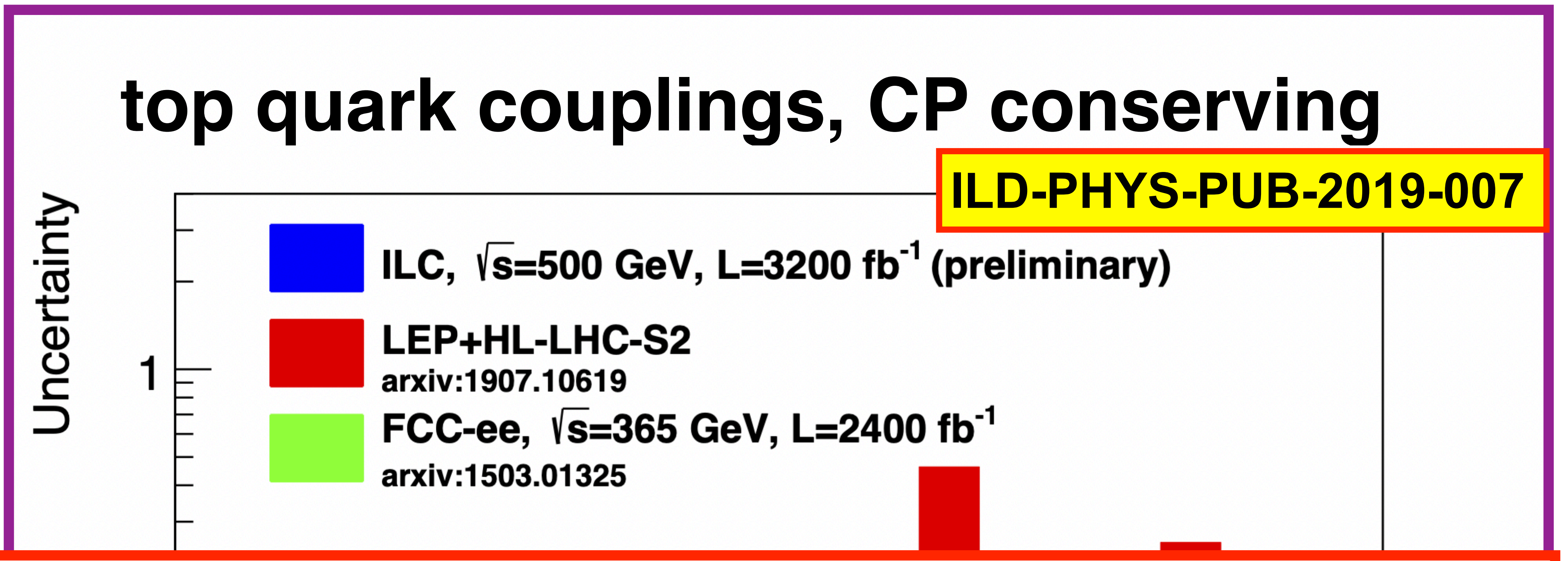
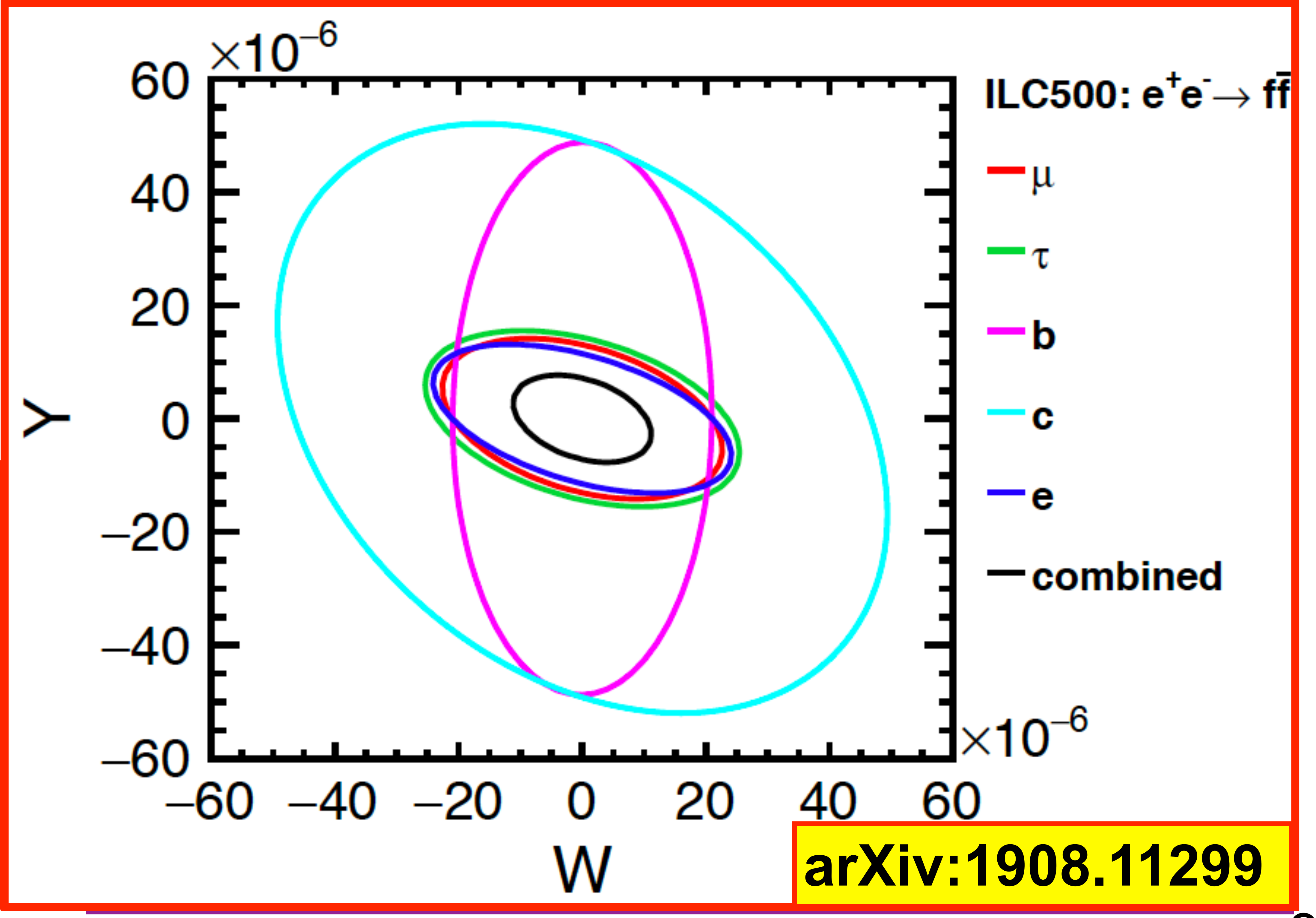


$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

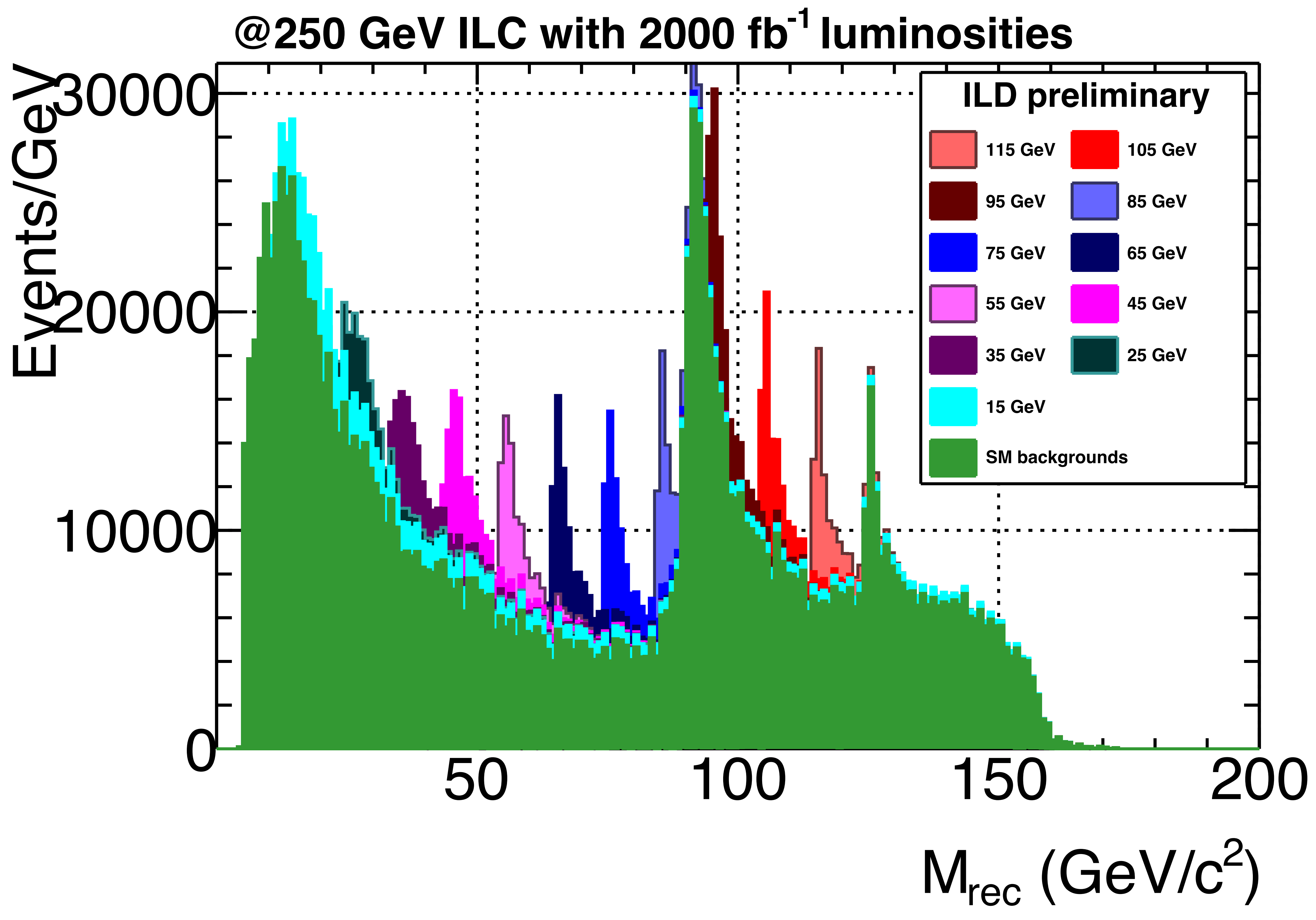


Extra Higgs Bosons ?

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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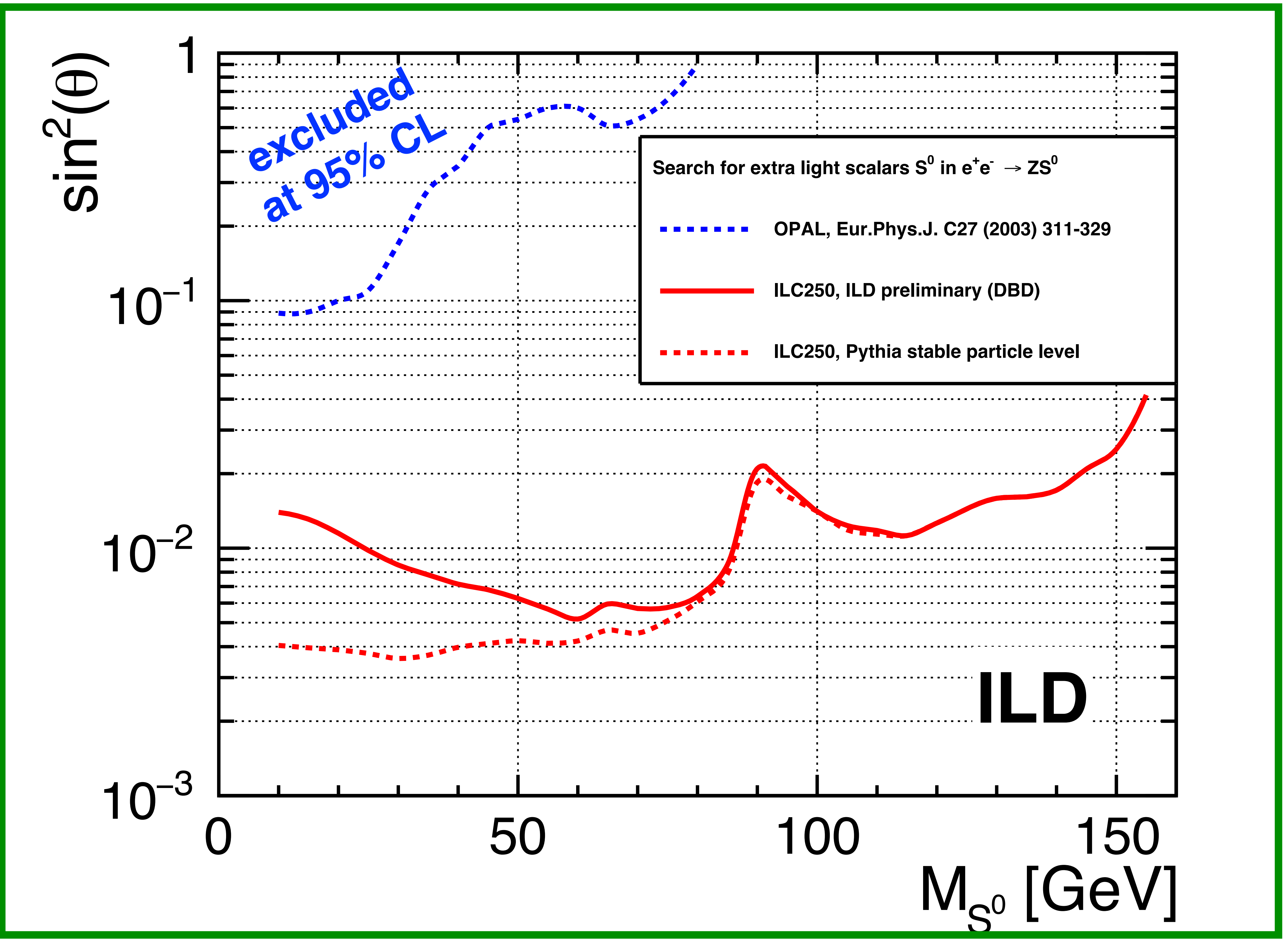
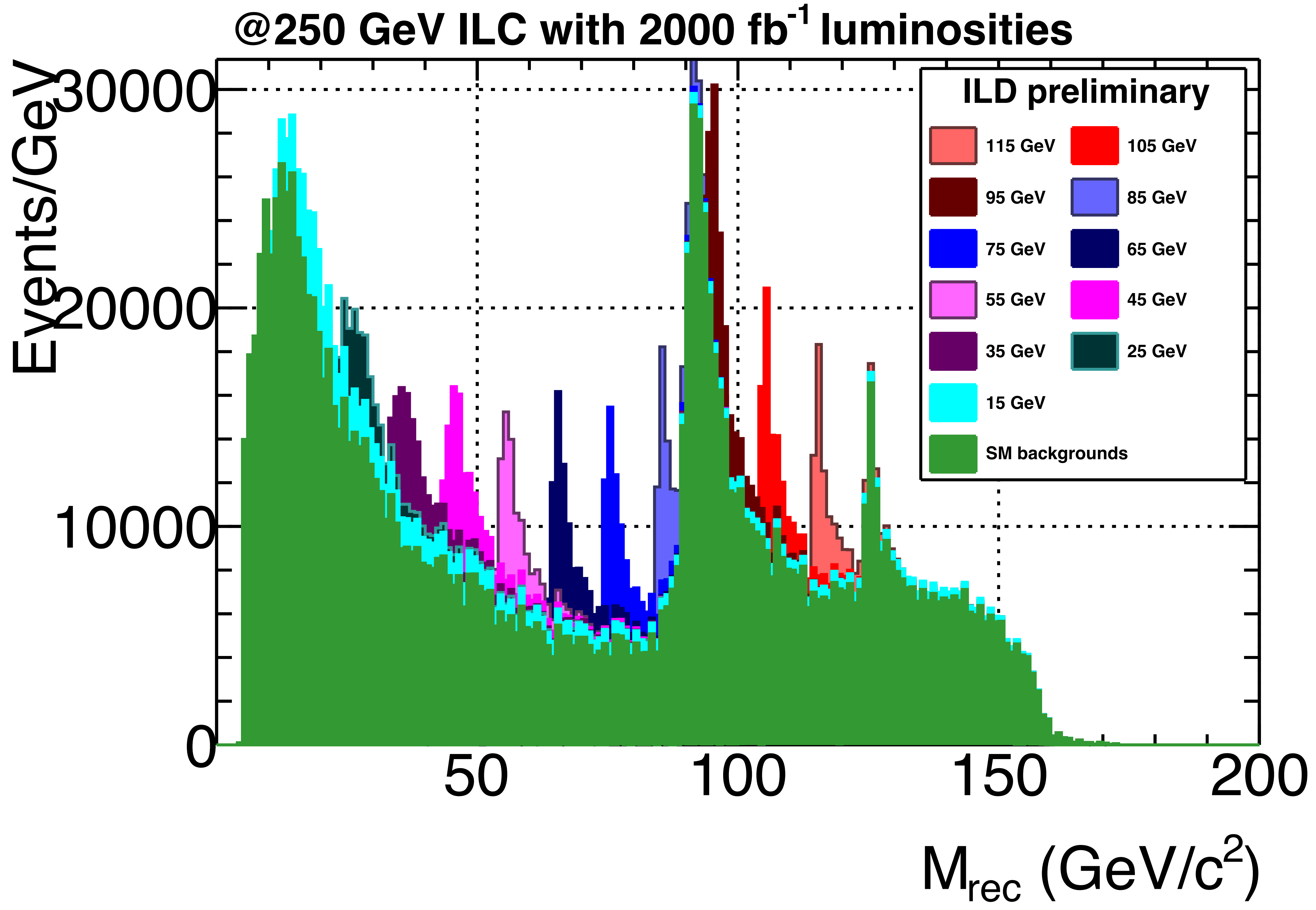
- mus
  - gH
  - 25
    gr
- prob

=> de



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



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

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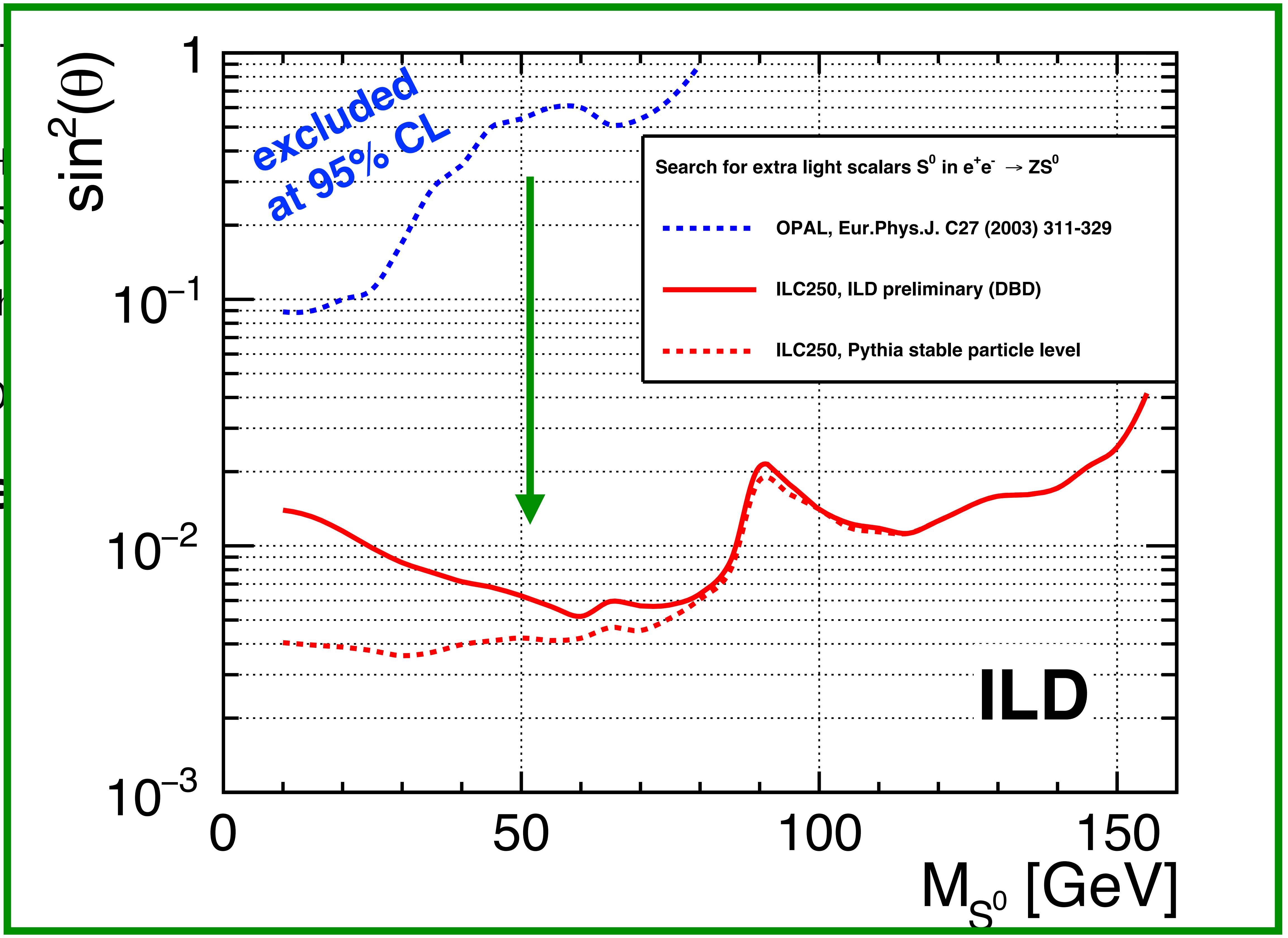

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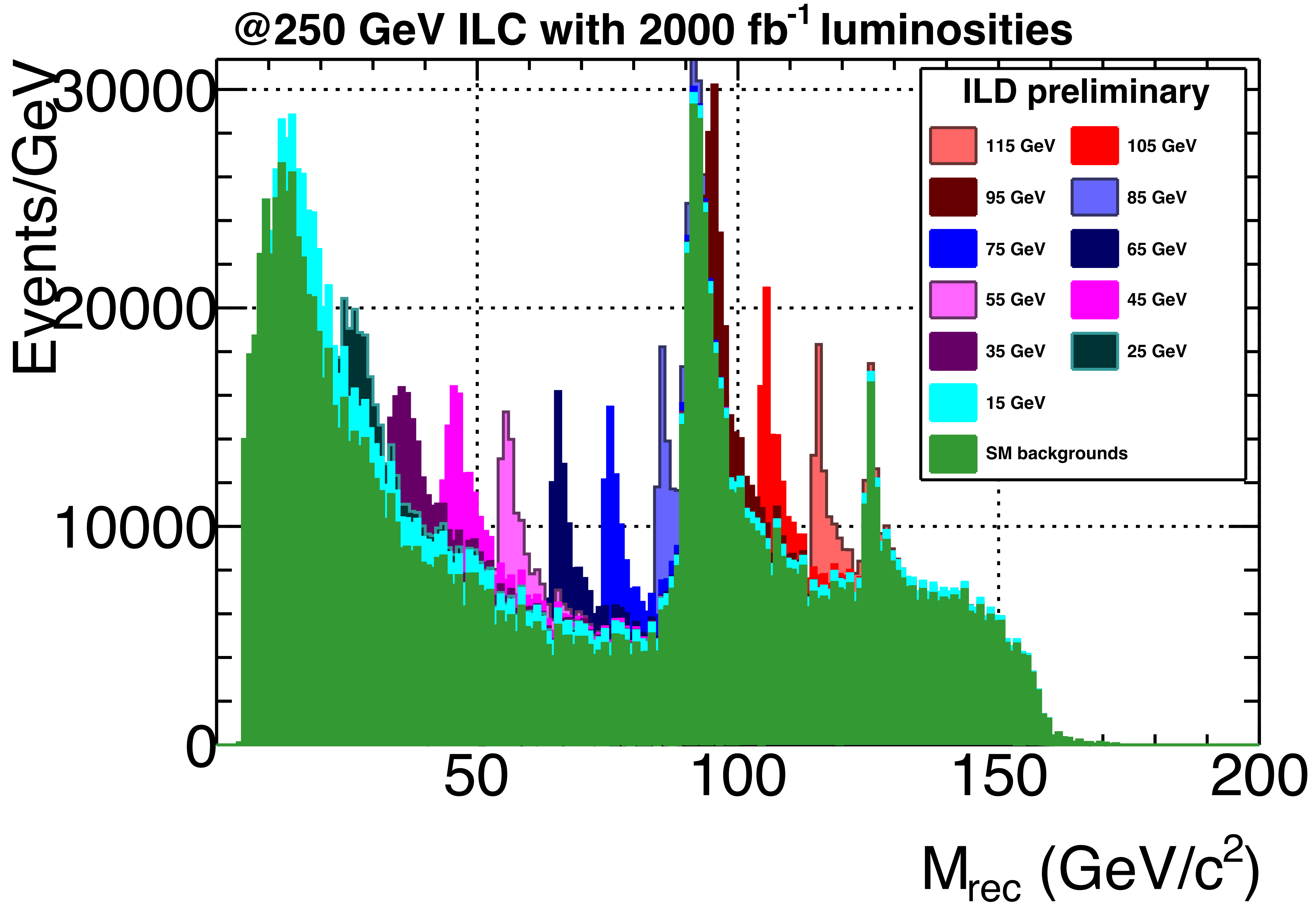

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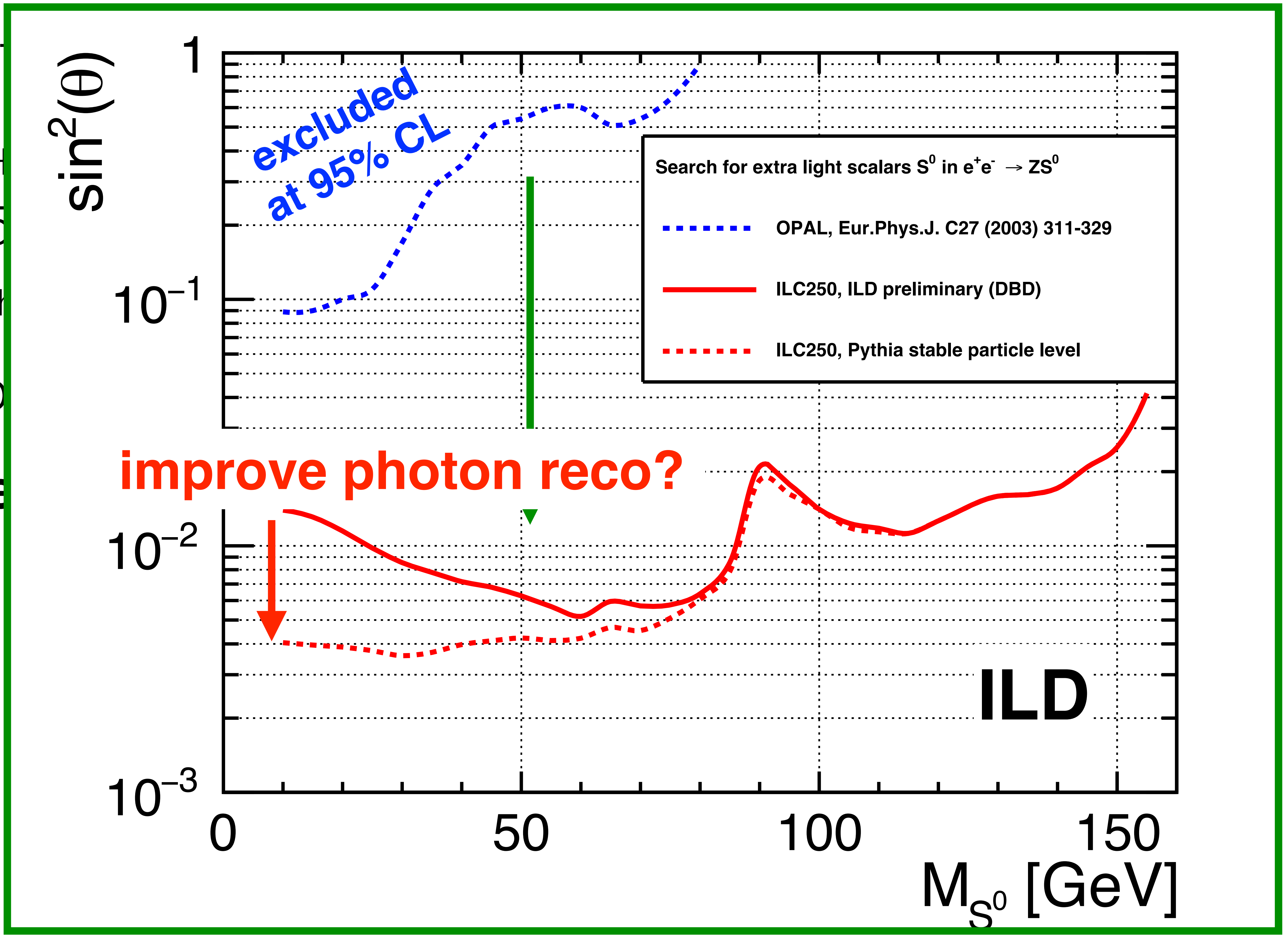

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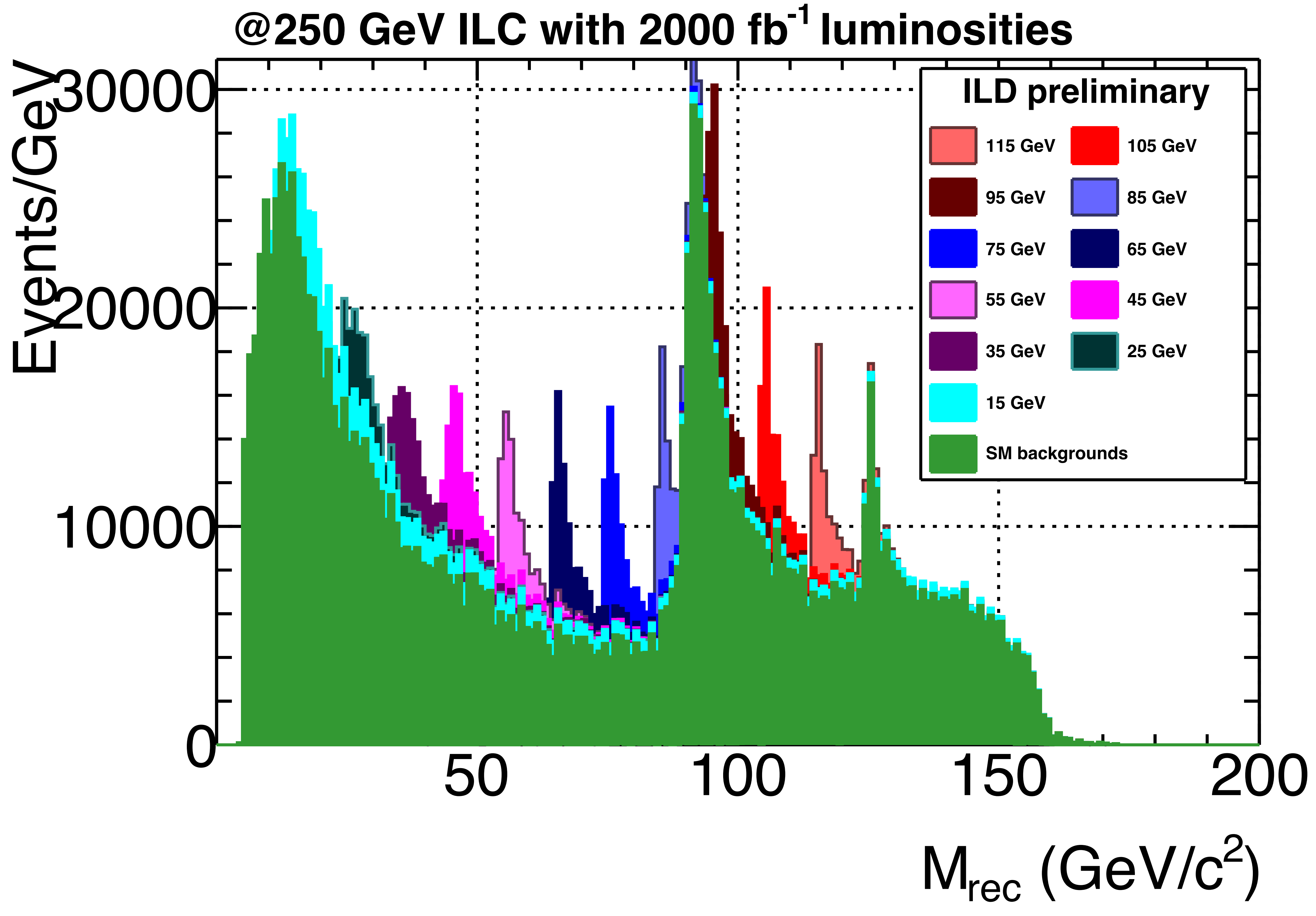

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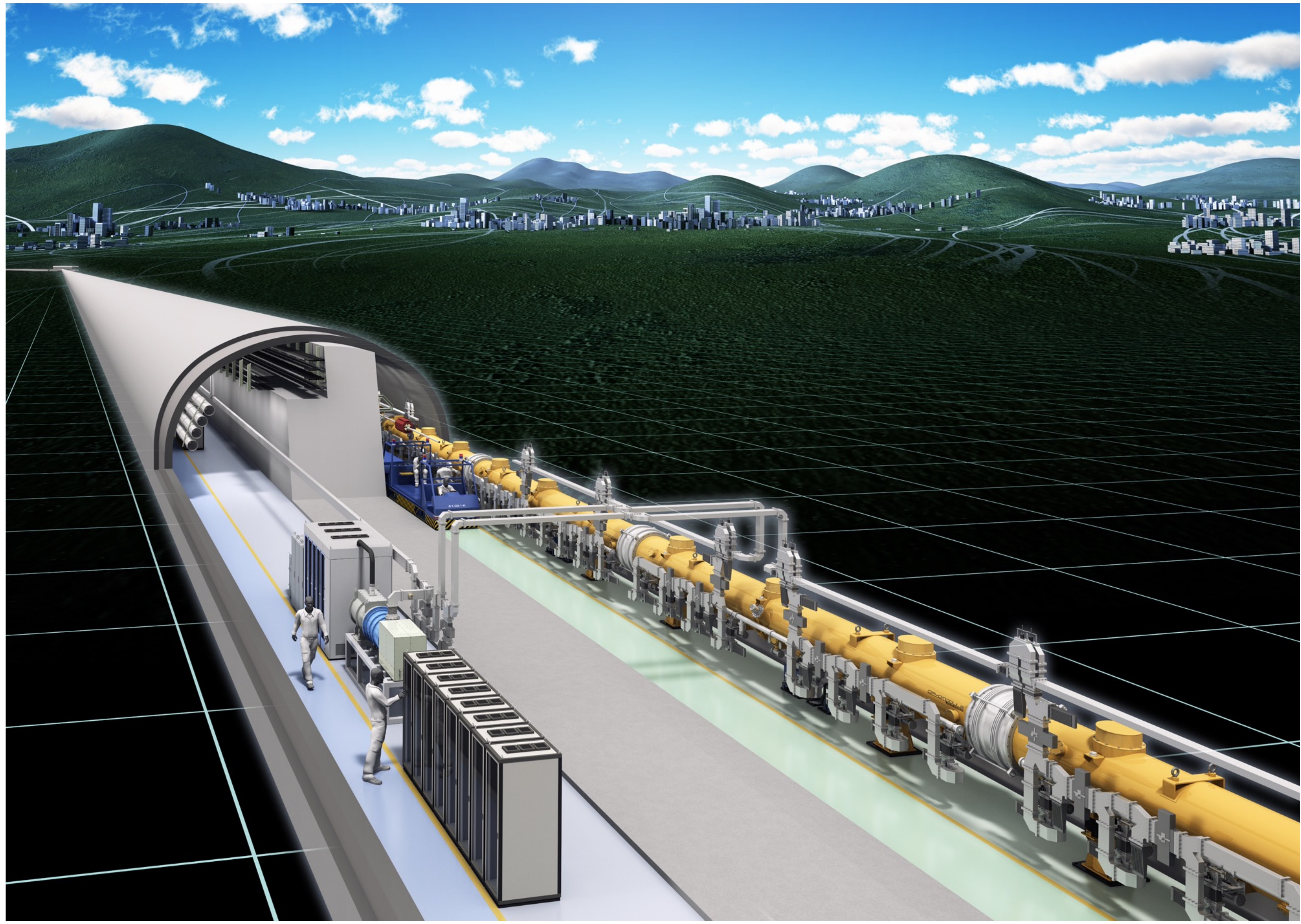
Currently Envisioned Location

Kitakami Mountains



- **e+e- centre-of-mass energy**
  - first stage: 250 GeV
  - tunable
  - upgrades: 500 GeV, 1 TeV
  - further options:
    running at Z pole & WW threshold
- **luminosity at 250 GeV**
  - 1.35 x 10^{34} /cm^2 /s
  - upgrade 2.7 x 10^{34} /cm^2 /s (cheap)
  - upgrade 5.4 x 10^{34} /cm^2 /s (expensive)
- **beam polarisation**
  - $P(e_-) \geq \pm 80\%$
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- **total length (250 GeV): 20.5 km**
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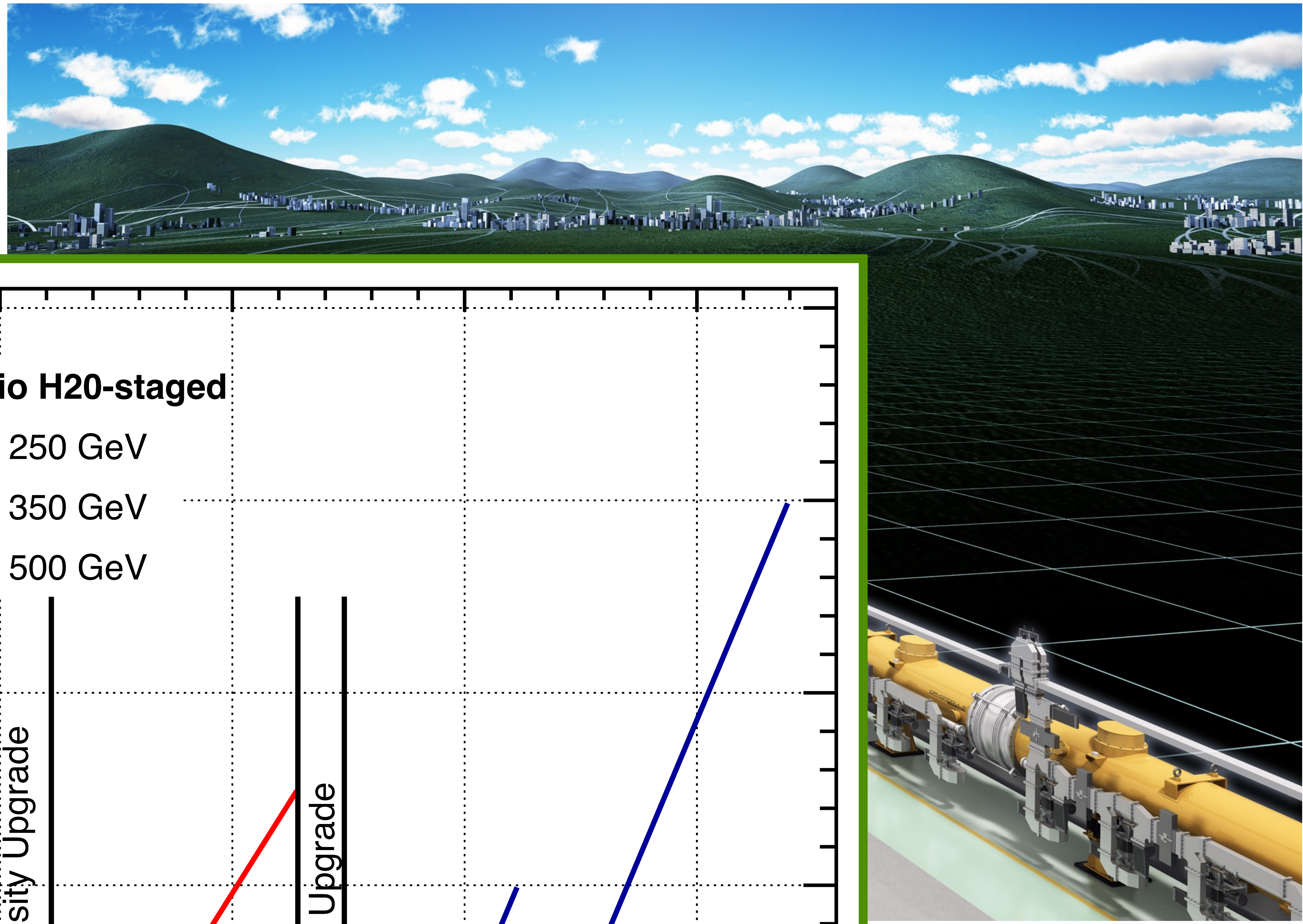

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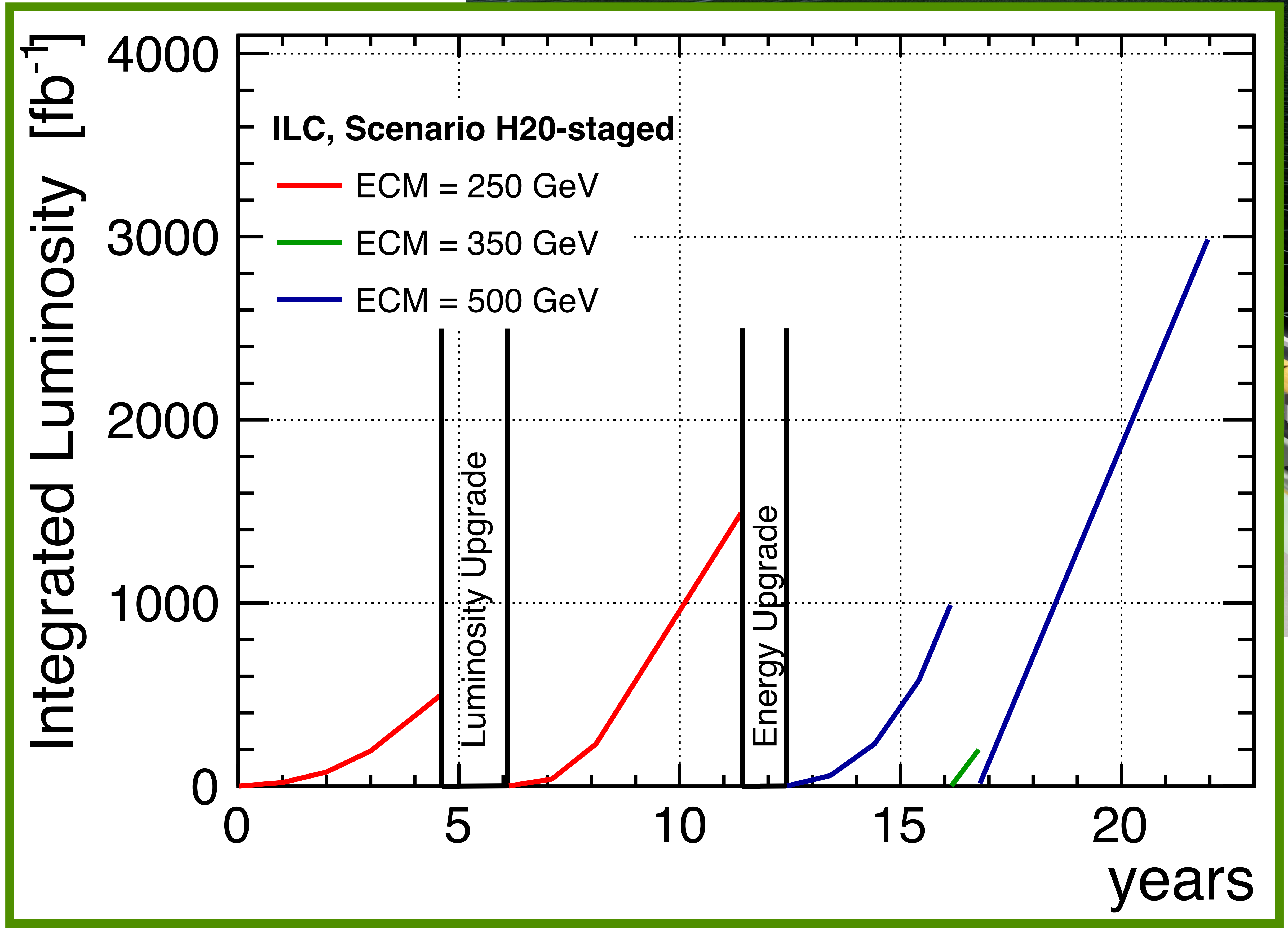

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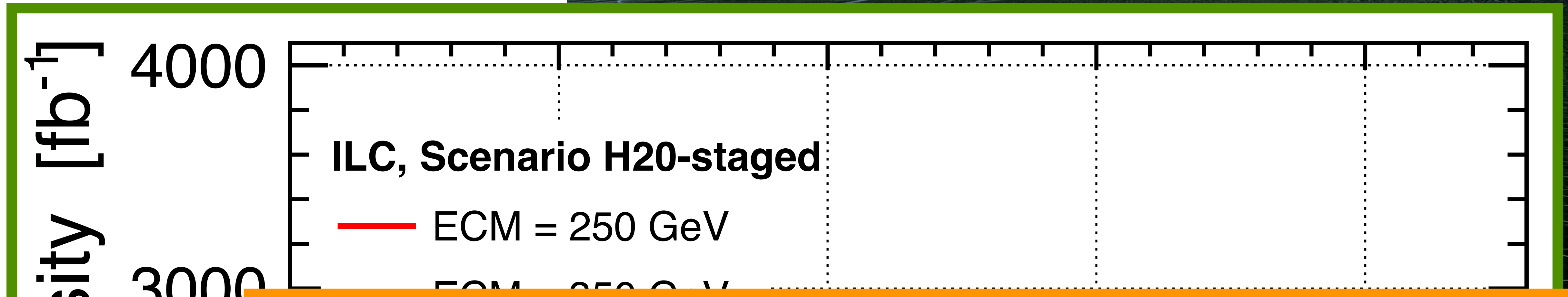
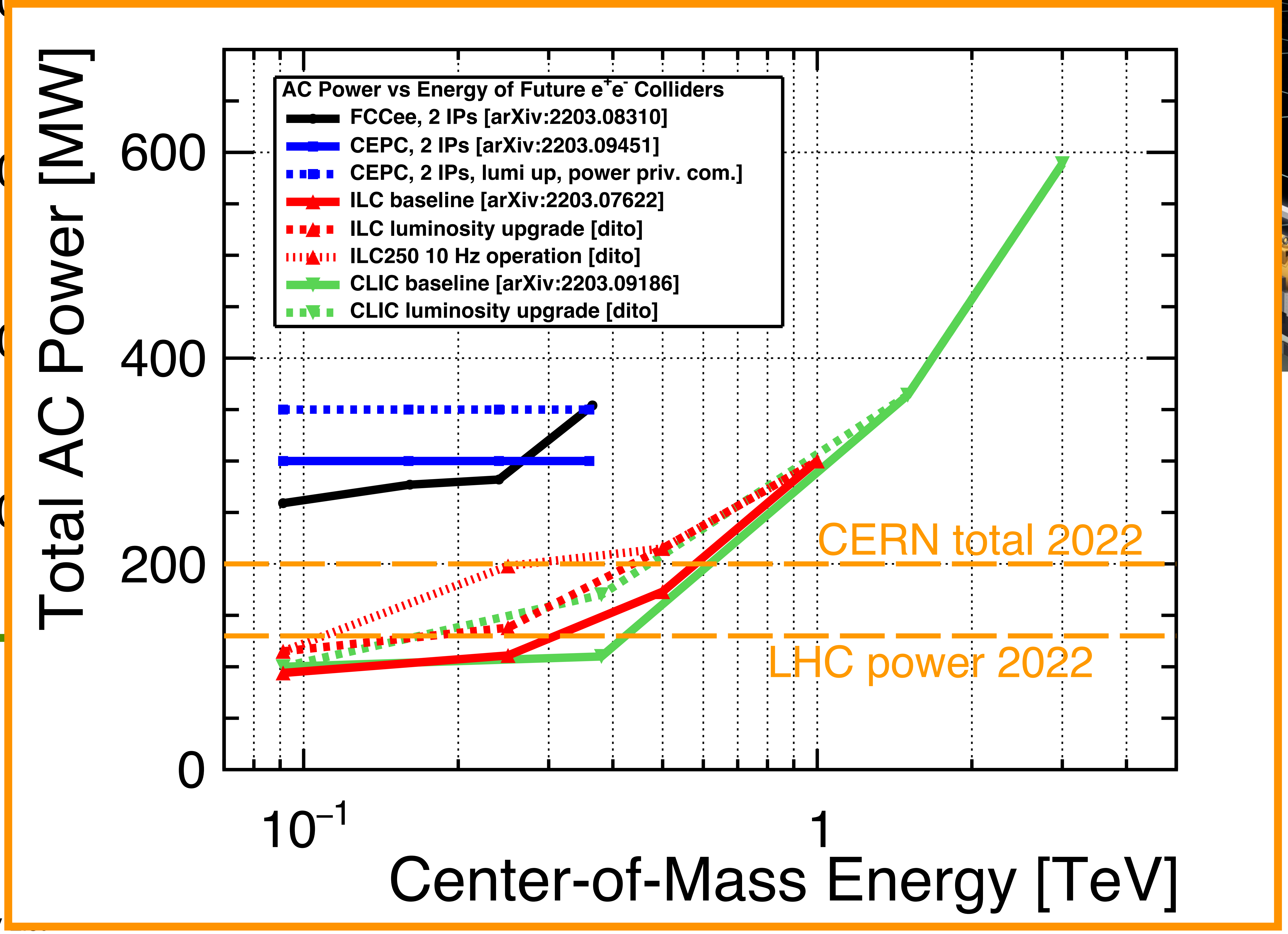
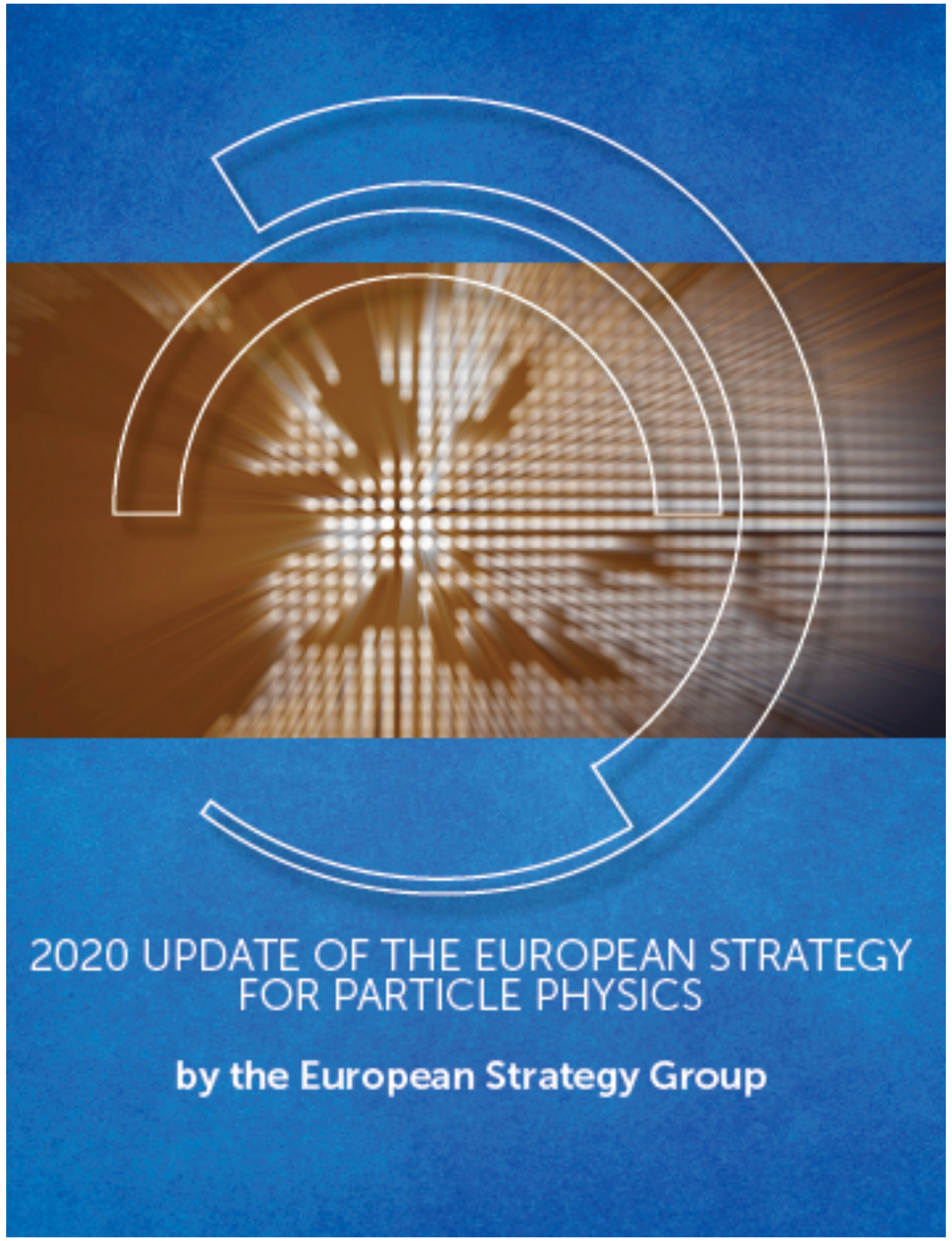




European Strategy for Particle Physics

2020 Update - Future Colliders

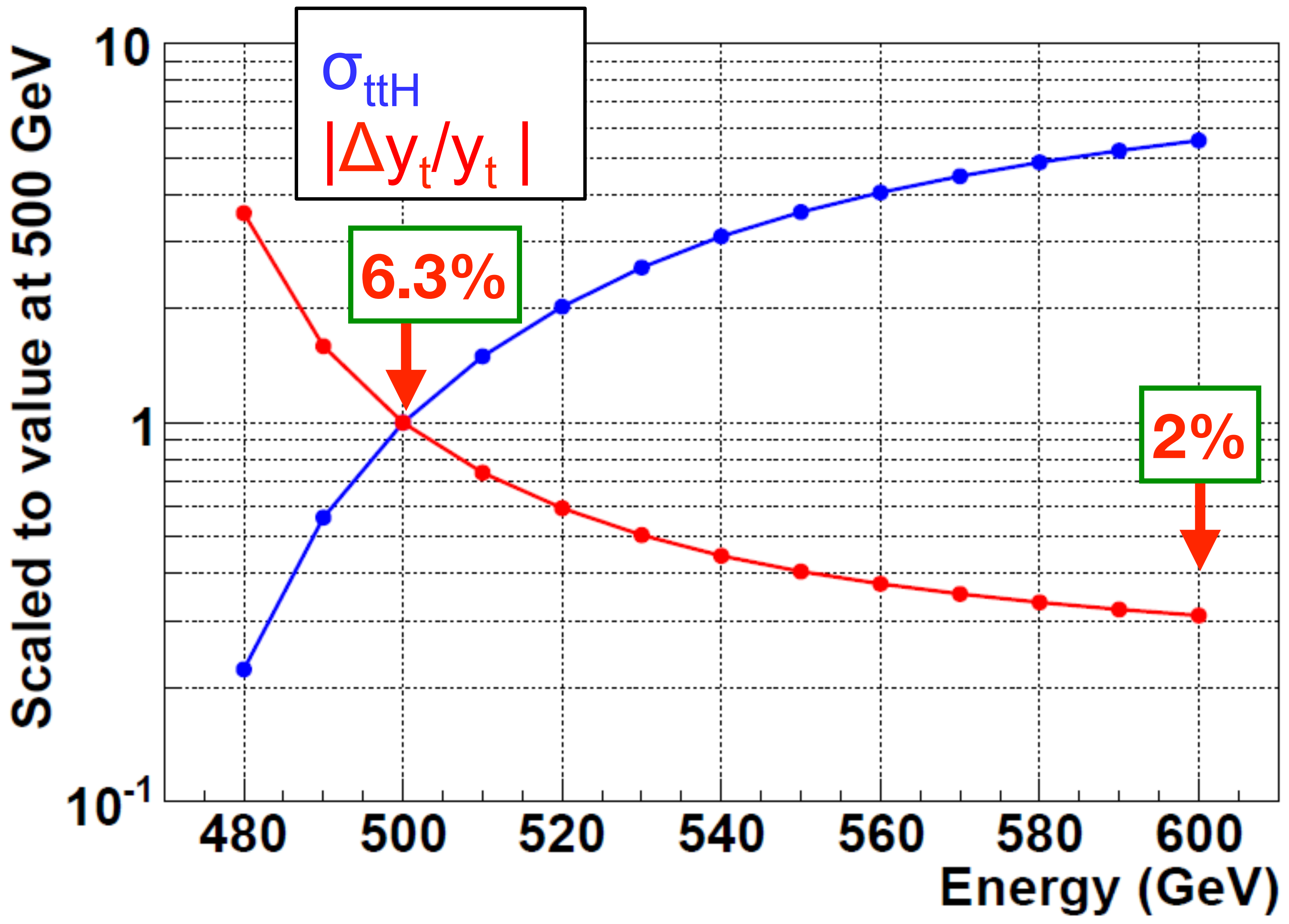
“An electron-positron Higgs factory is the highest-priority next collider.”



Top Yukawa coupling

- **absolute size of $|y_t|$:**
  - **HL-LHC:**
    - **$\delta\kappa_t$ = 3.2% with $|\kappa_V| \leq 1$ or 3.4% in $SMEFT_{ND}$**
  - **ILC:**
    - 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

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



+ 1 TeV: 1.4%

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The Higgs and the Top

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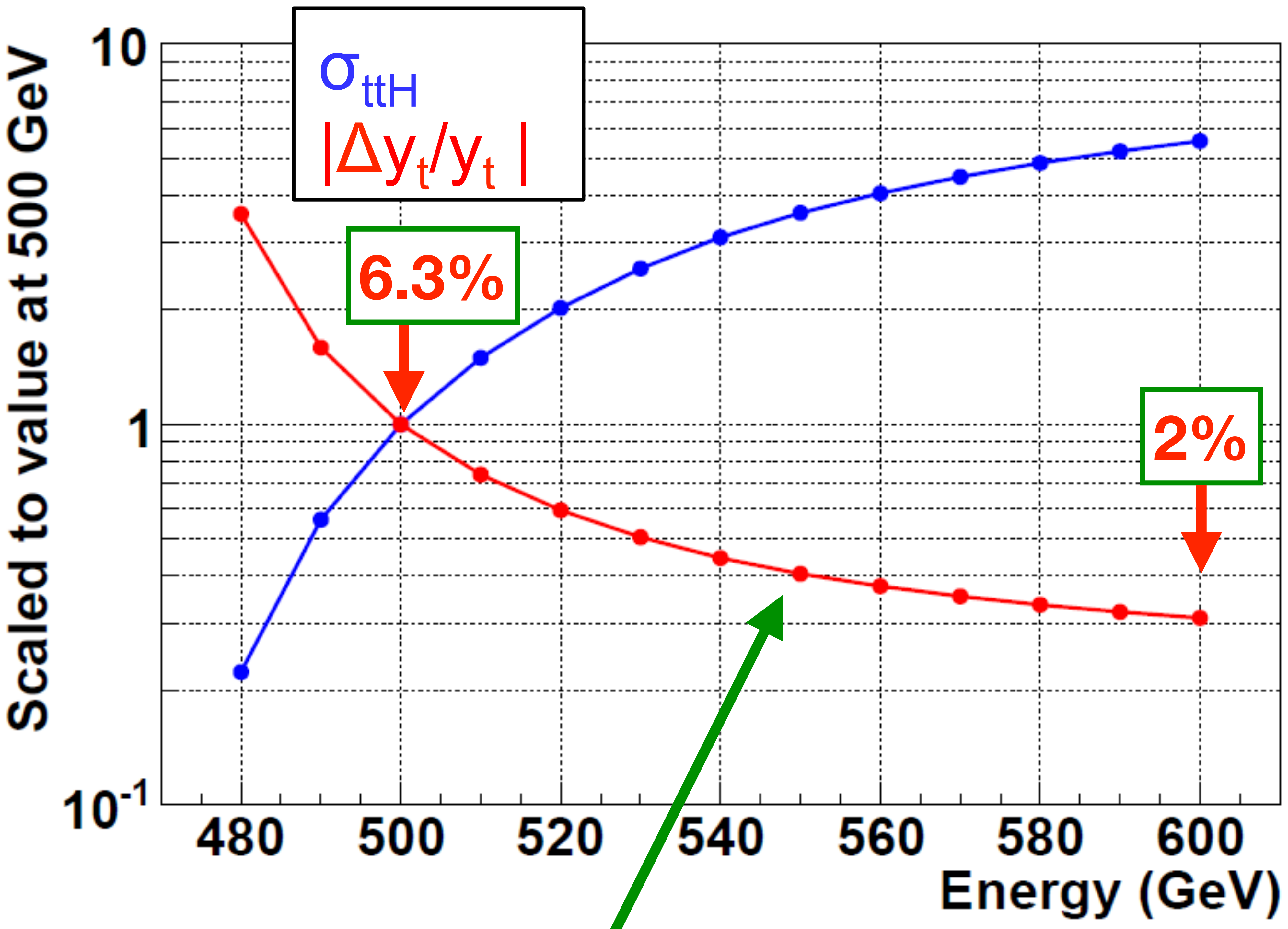

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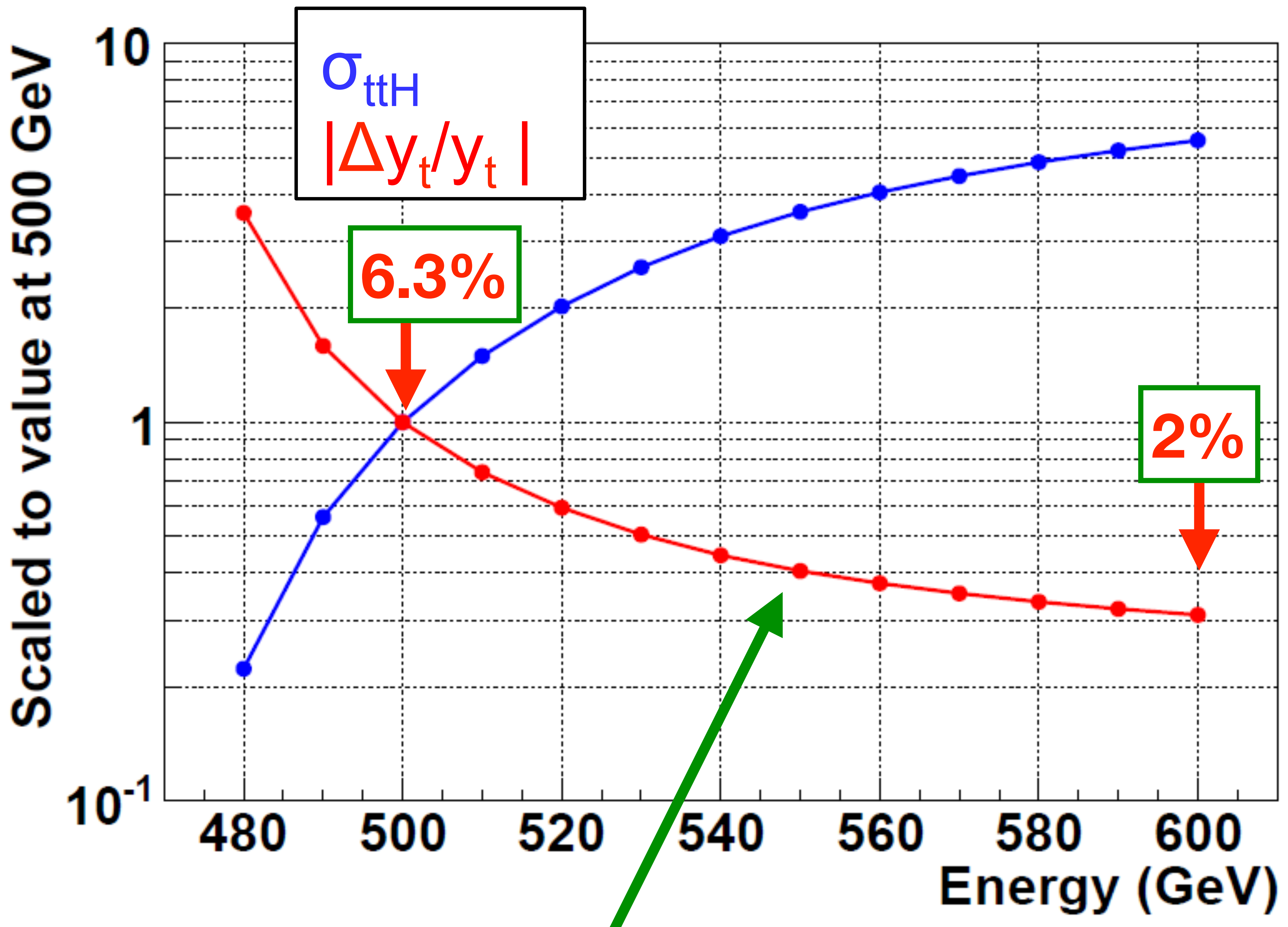
- **full coupling structure** of tth vertex, incl. CP:
  - **e^+e^- at E_{CM} ≥ ~600 GeV**
    => ***few percent sensitivity to CP-odd admixture***
  - **beam polarisation essential!**

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

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



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… and how to tackle them at colliders

electron-positron & proton-proton

Our tools:

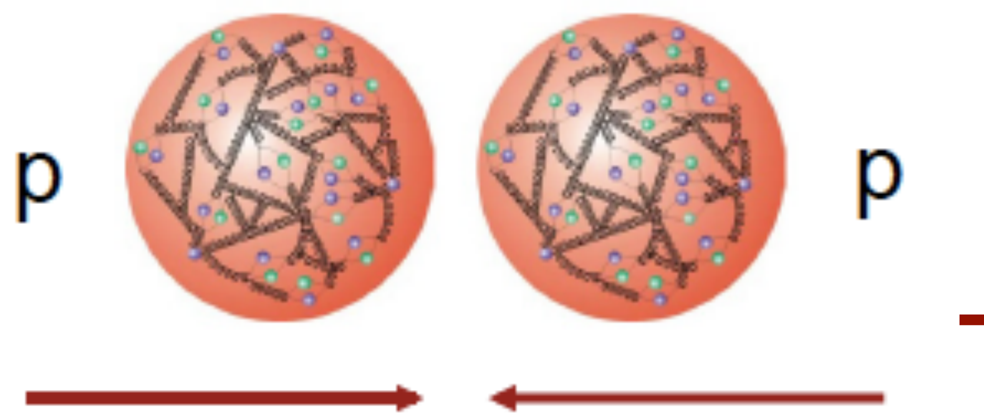
The Top and Bottom Quark

Z & W Bosons

The Higgs Boson

Discoveries of new particles ?

- elementary particles
- different E_{CM} via accelerator operation
- E_{CM} known on event-by-event level



- proton structure
- E_{CM} of “hard” interactions cover all energies < pp E_{CM}
- not known on event-by-event level

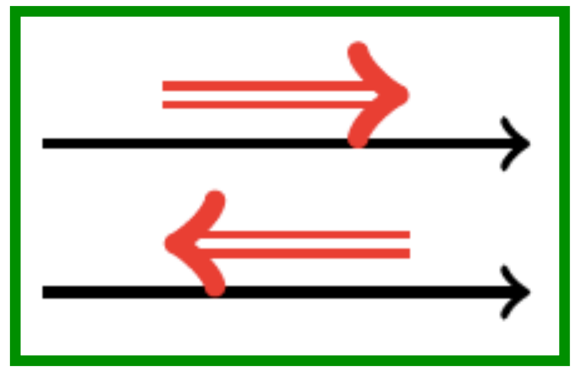
Other important parameters in e^+e^- collisions

Luminosity

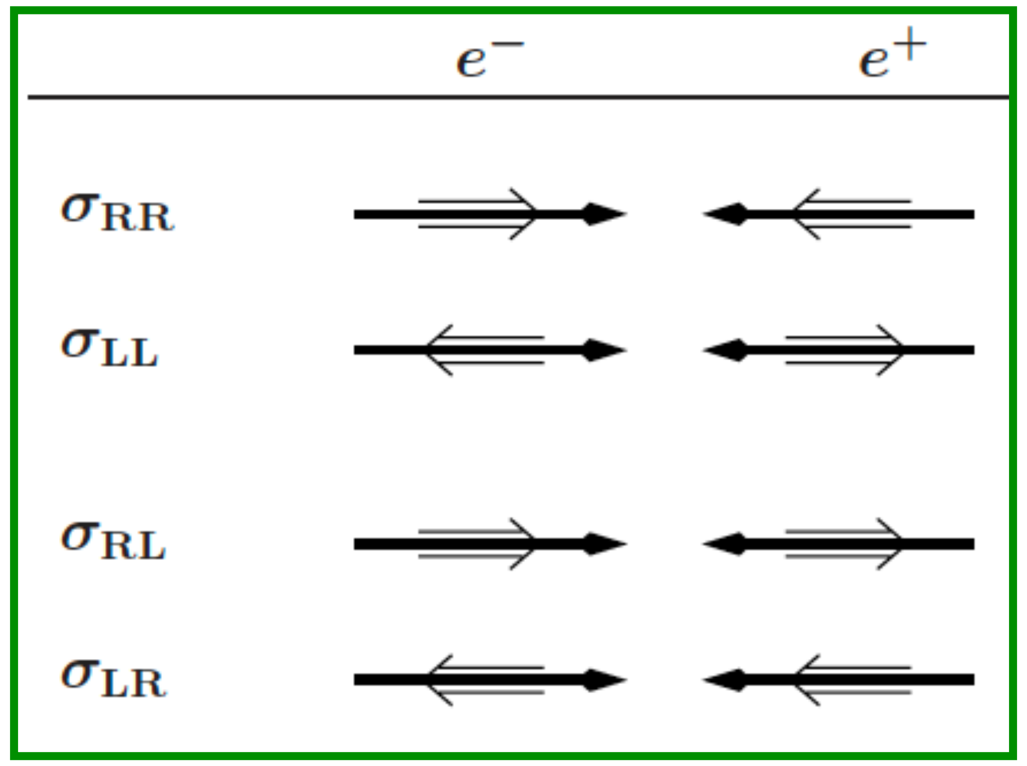
- Defines event rate => size of data set
- Future e^+e^- colliders aim for $10^3..10^6$ larger data sets than LEP
- Depends strongly on invest costs and power consumption => be careful to compare apples to apples!
- Are there fundamental boundaries *beyond* statistics? (e.g. theory & parametric uncertainties, detector resolution, …)

Beam polarisation:

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



- Electroweak interactions highly sensitive to chirality of fermions: $SU(2)_L \times U(1)$
- both beams polarised => "four colliders in one":



The minimal Higgs program

How big can BSM effects be?

- low scale new physics
  => modification of Higgs properties!
- different *patterns* of deviations from SM prediction for different NP models
- *size* of deviations depends on NP scale
  typically few percent on tree-level:
  - MSSM, eg:

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

  - Littlest Higgs, eg m_T=1TeV:

$$\frac{g_{hgg}}{g_{h_{SM}gg}} = 1 - (5\% \sim 9\%)$$
$$\frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} = 1 - (5\% \sim 6\%).$$

  - Composite Higgs, eg:

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & \mathrm{(MCHM4)} \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & \mathrm{(MCHM5)} \end{cases}$$

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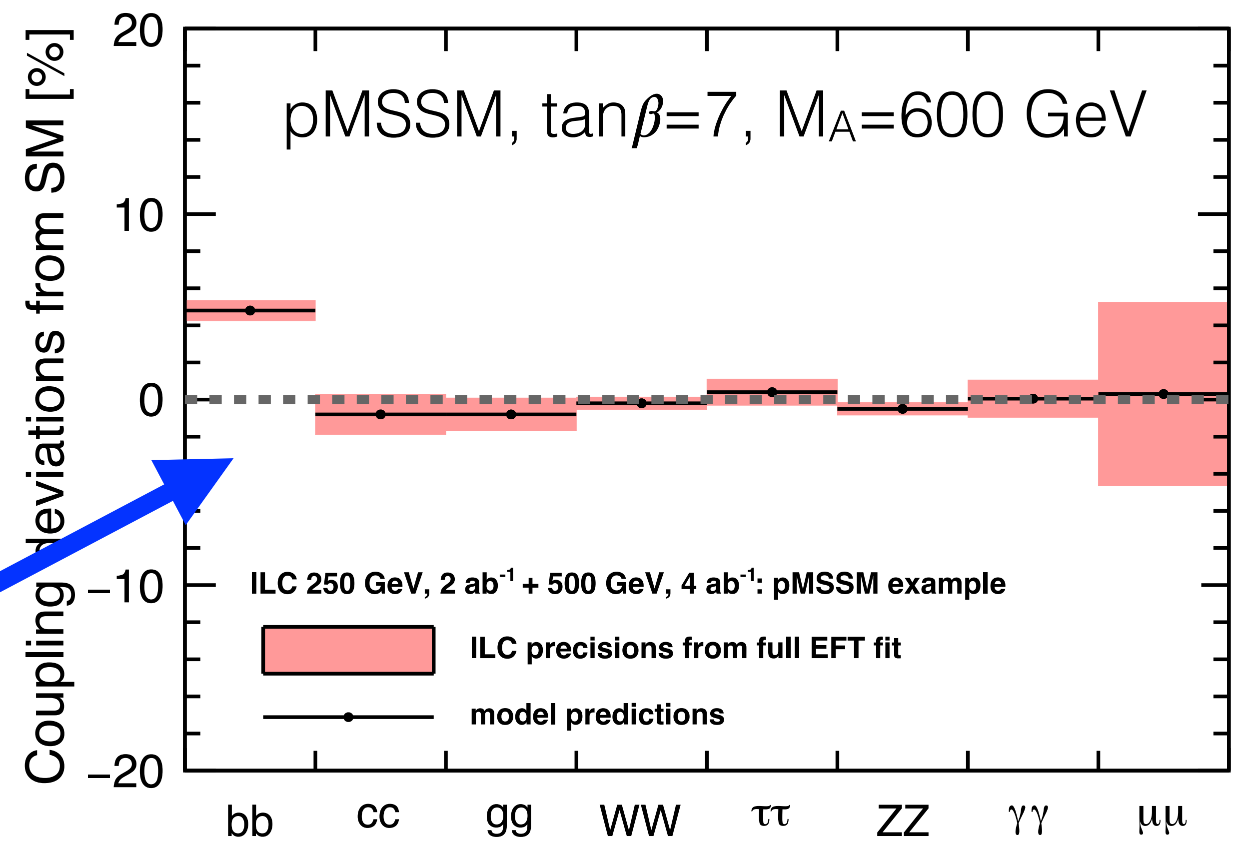

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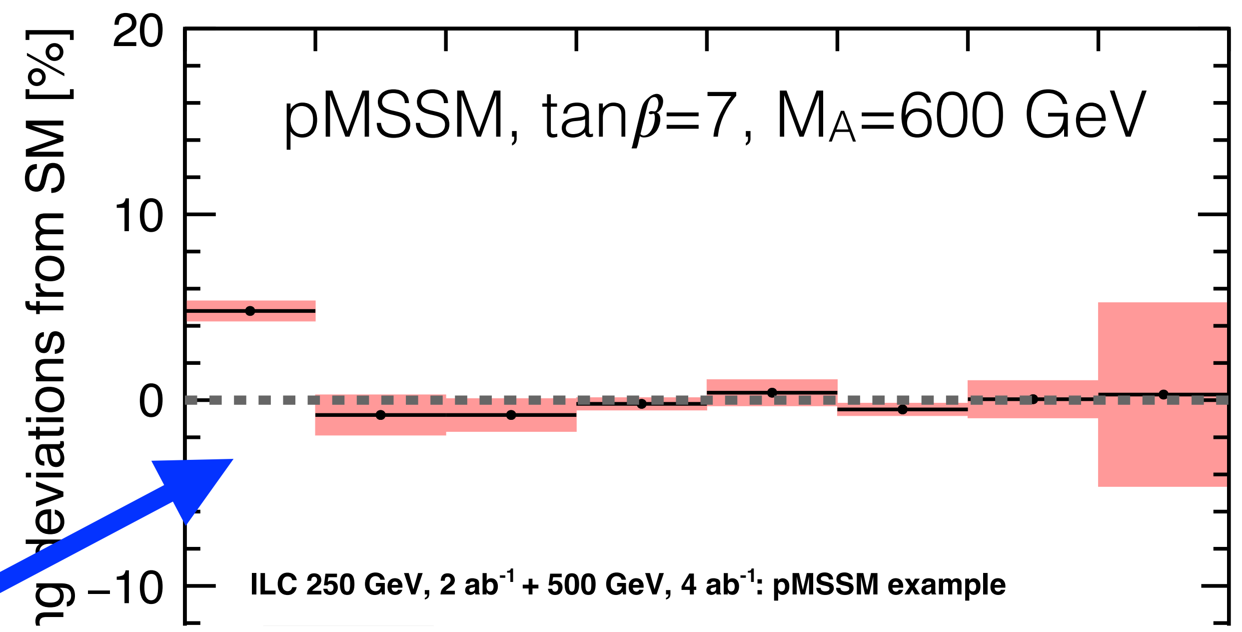

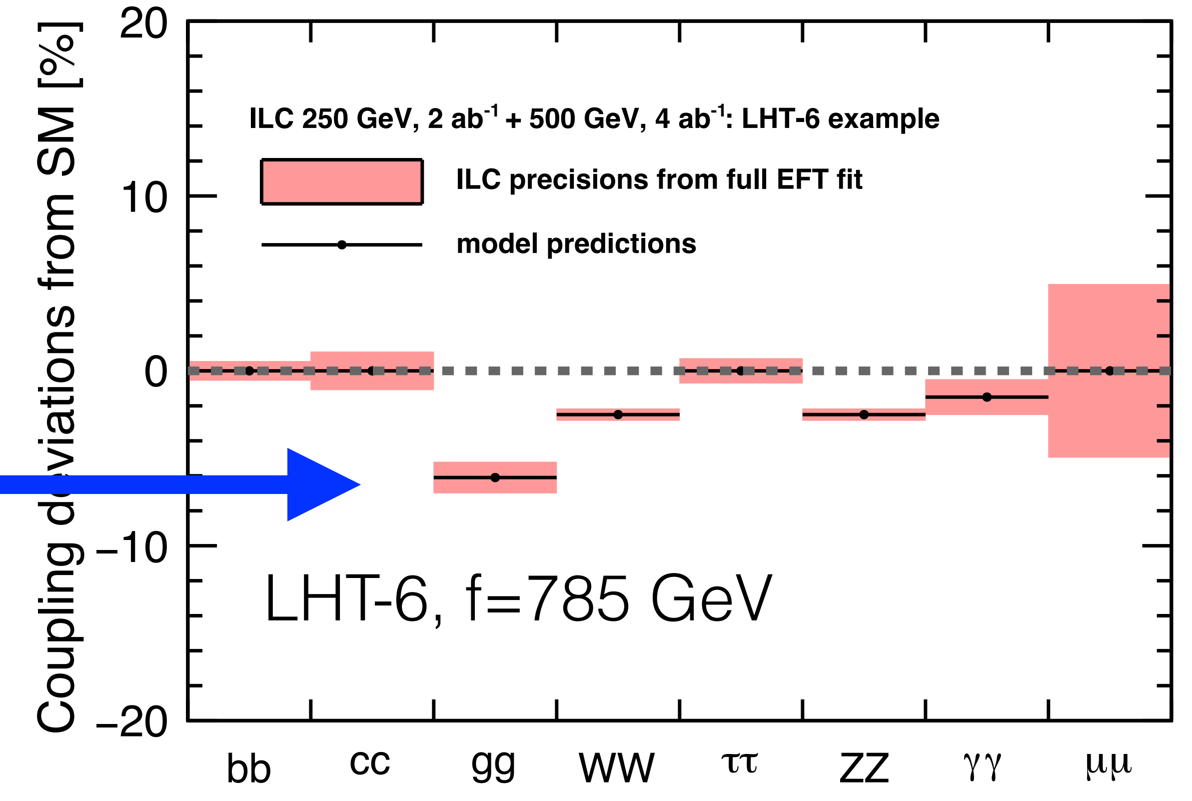

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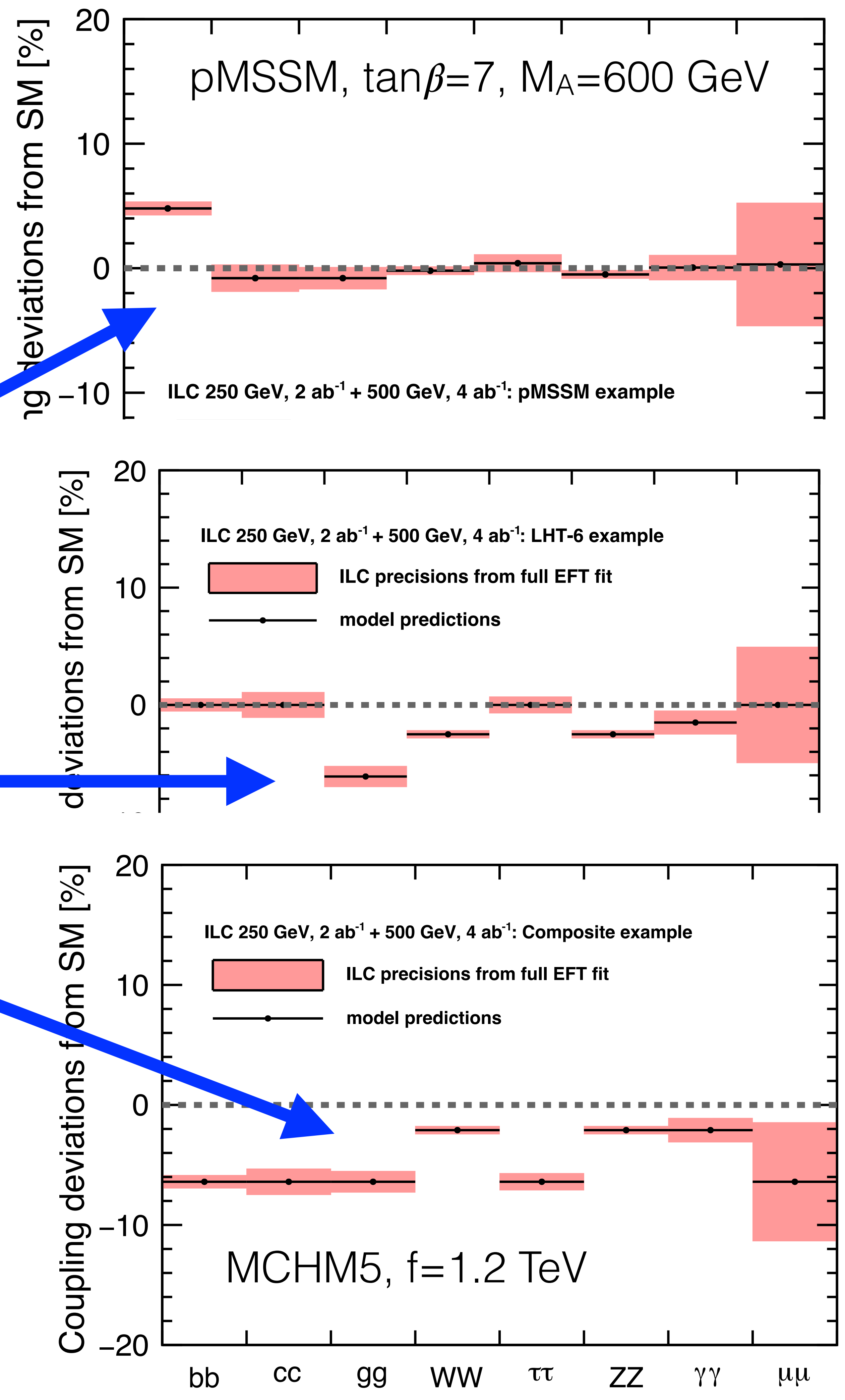

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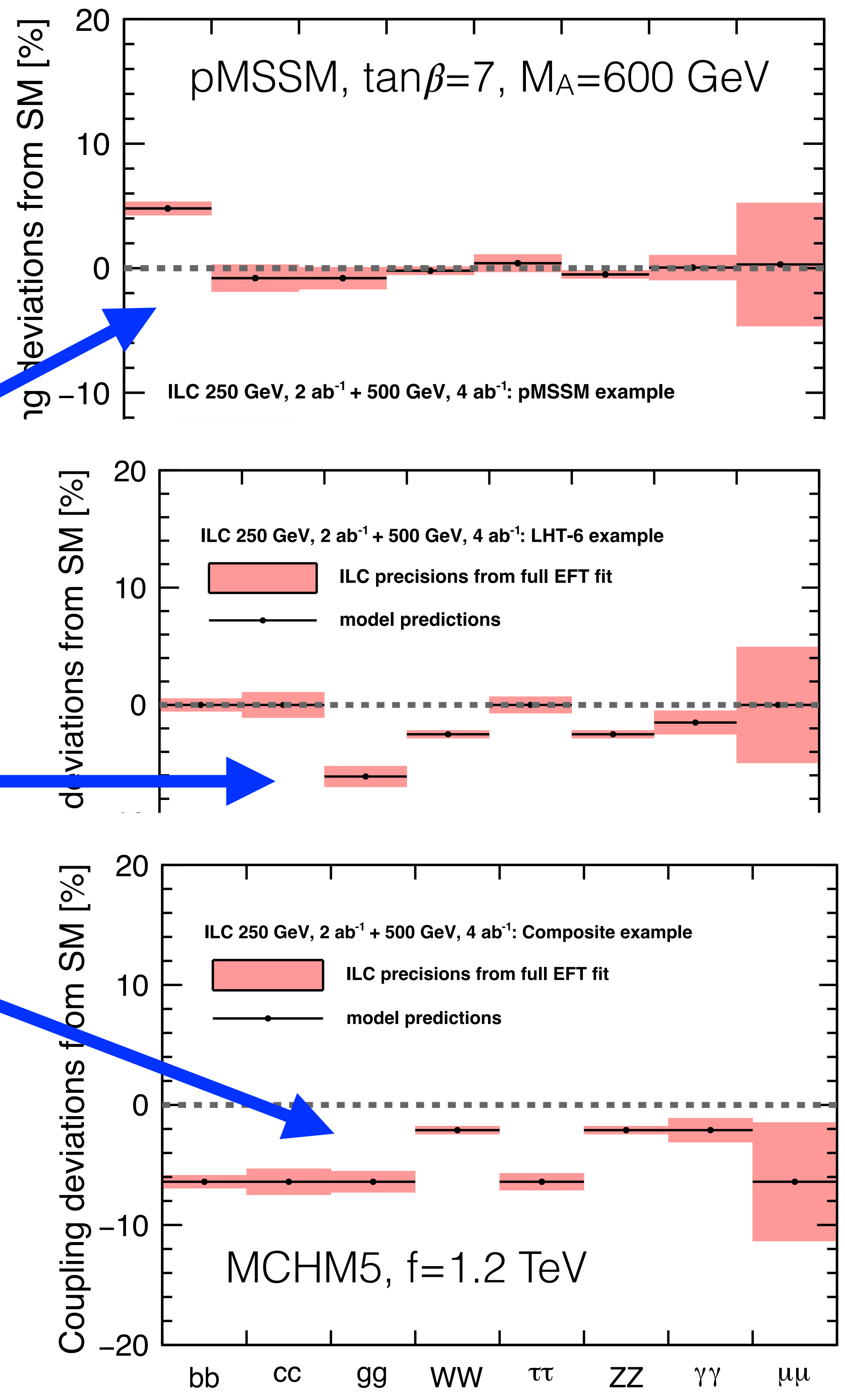
At least percent-level precision required!



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Test various example BSM points - all chosen such that no hint for new physics at HL-LHC

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
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2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
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6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
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9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era ($3\,\mathrm{ab}^{-1}$ of integrated luminosity). From [15].

arXiv:1708.08912

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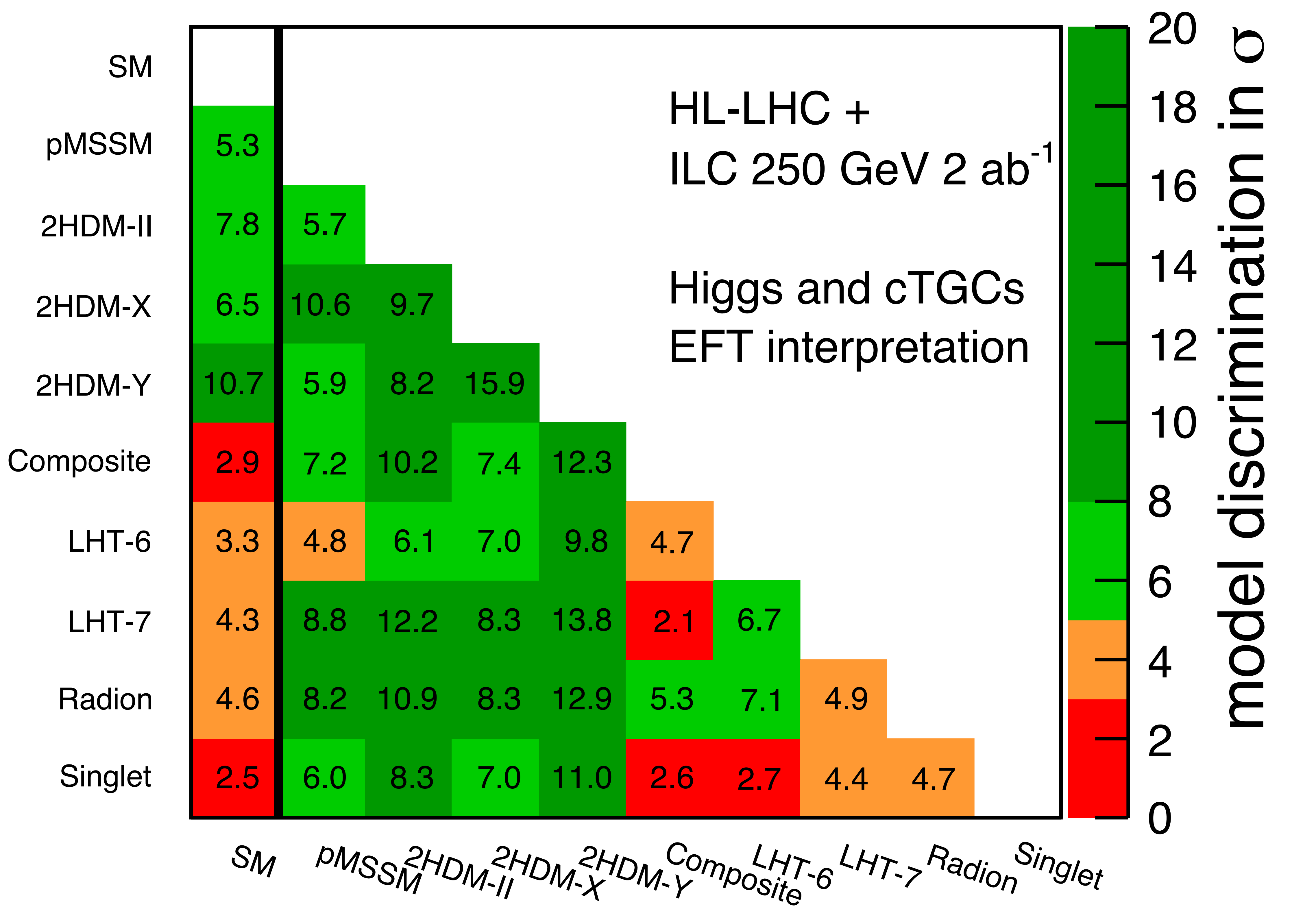

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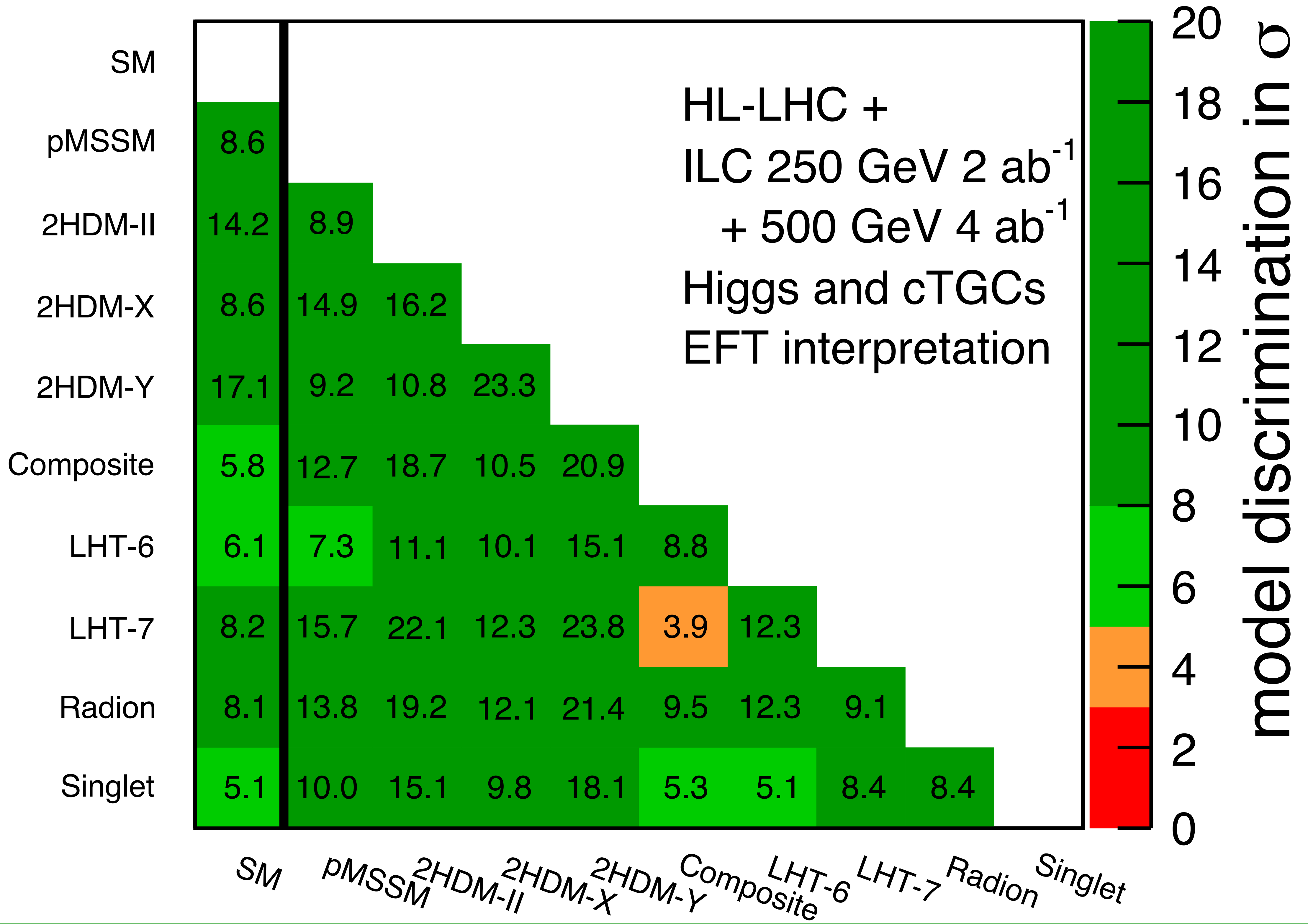

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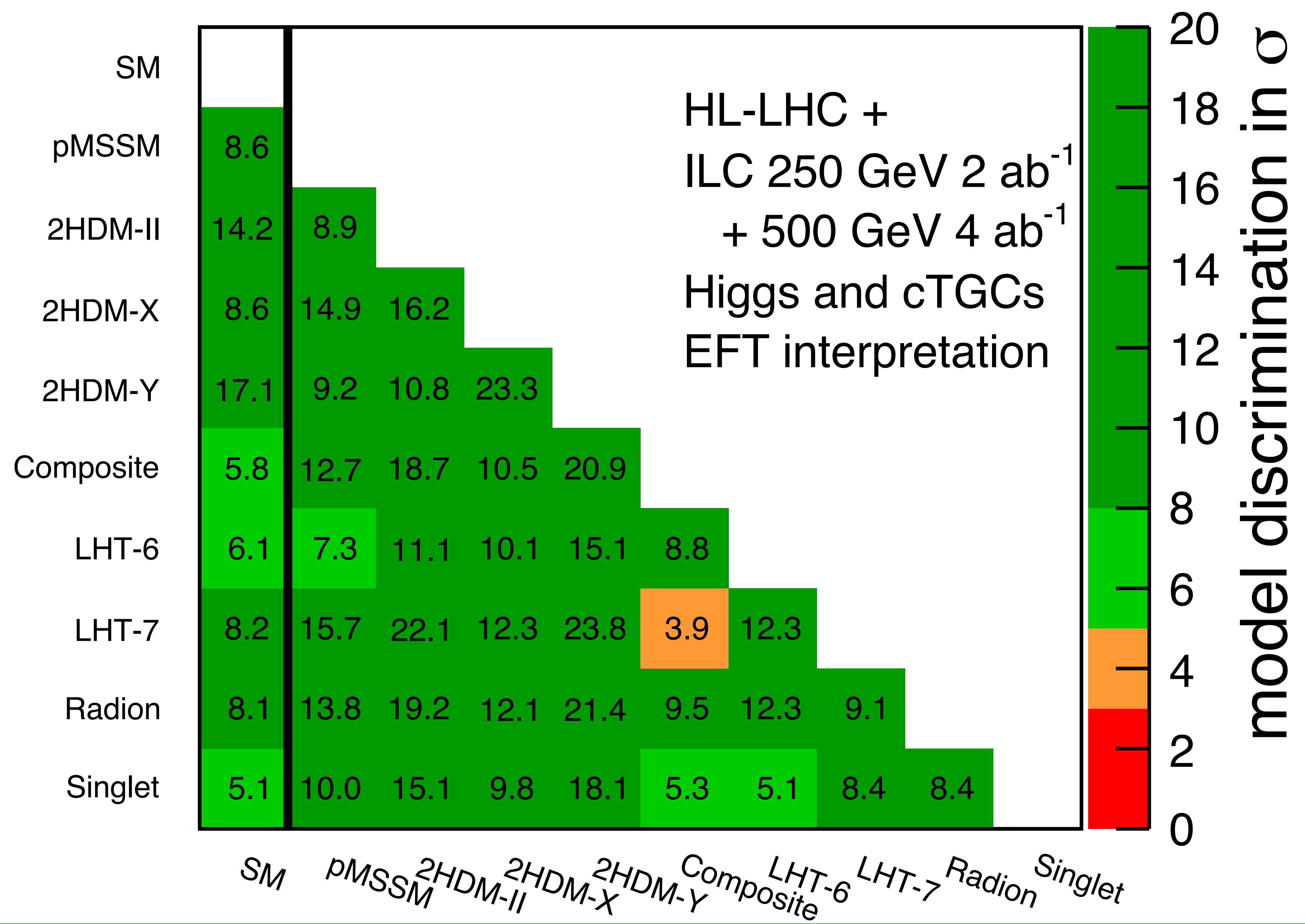
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [40]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era ($3\,\text{ab}^{-1}$ of integrated luminosity). From [15].

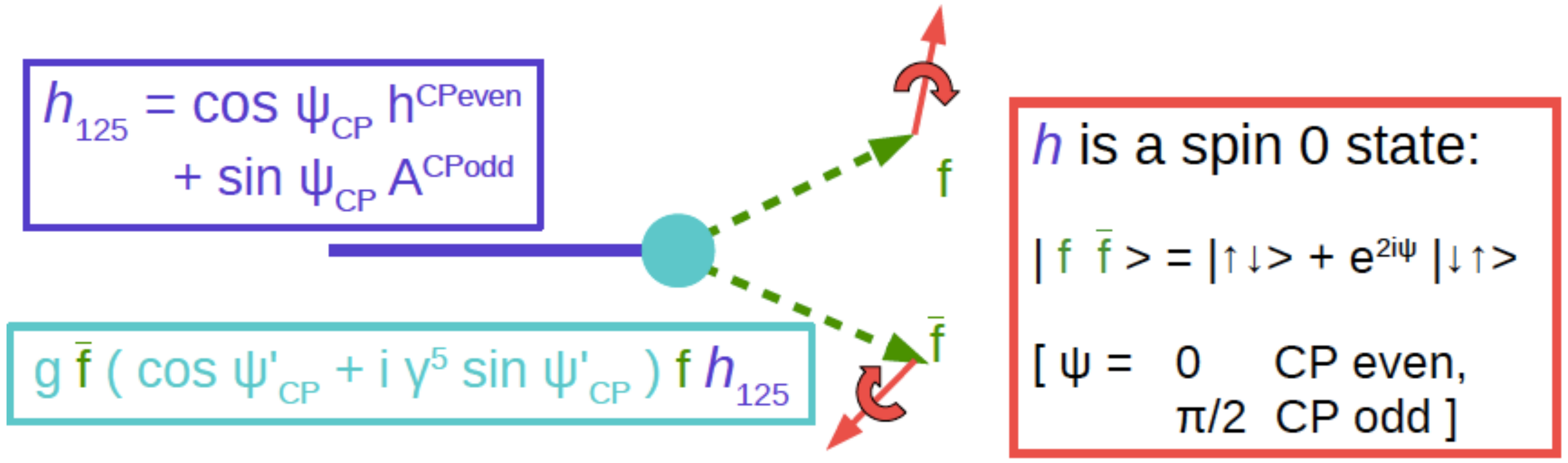
arXiv:1708.08912



illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

CP properties in h->$\tau\tau$

ZH production ideal



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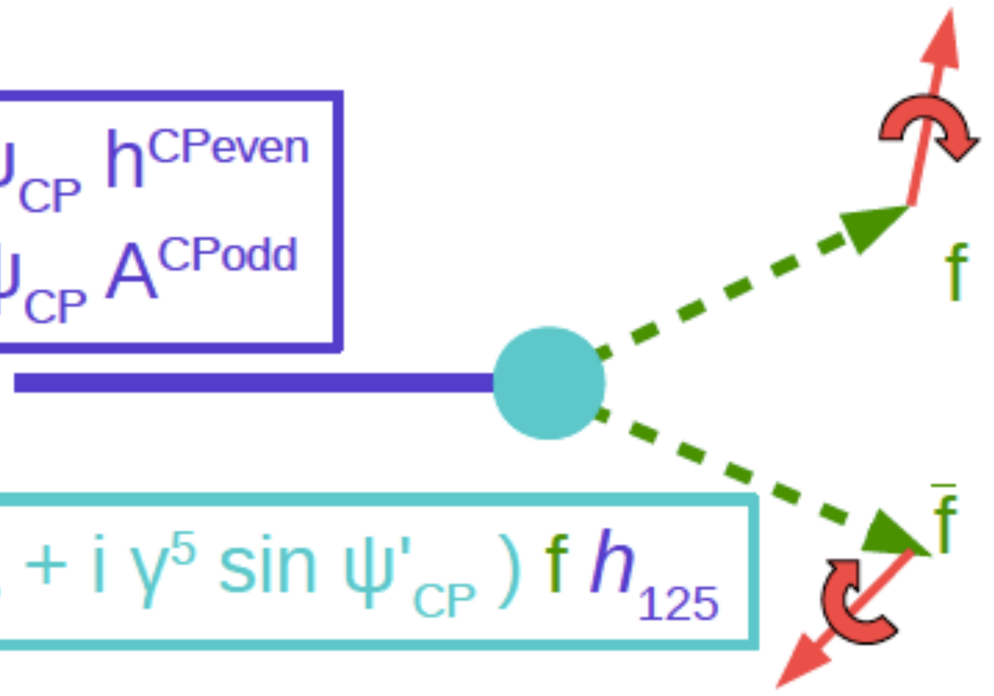
$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$



$g\,\bar{f}\,(\cos\psi'_{CP} + i\,\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$

h is a spin 0 state:

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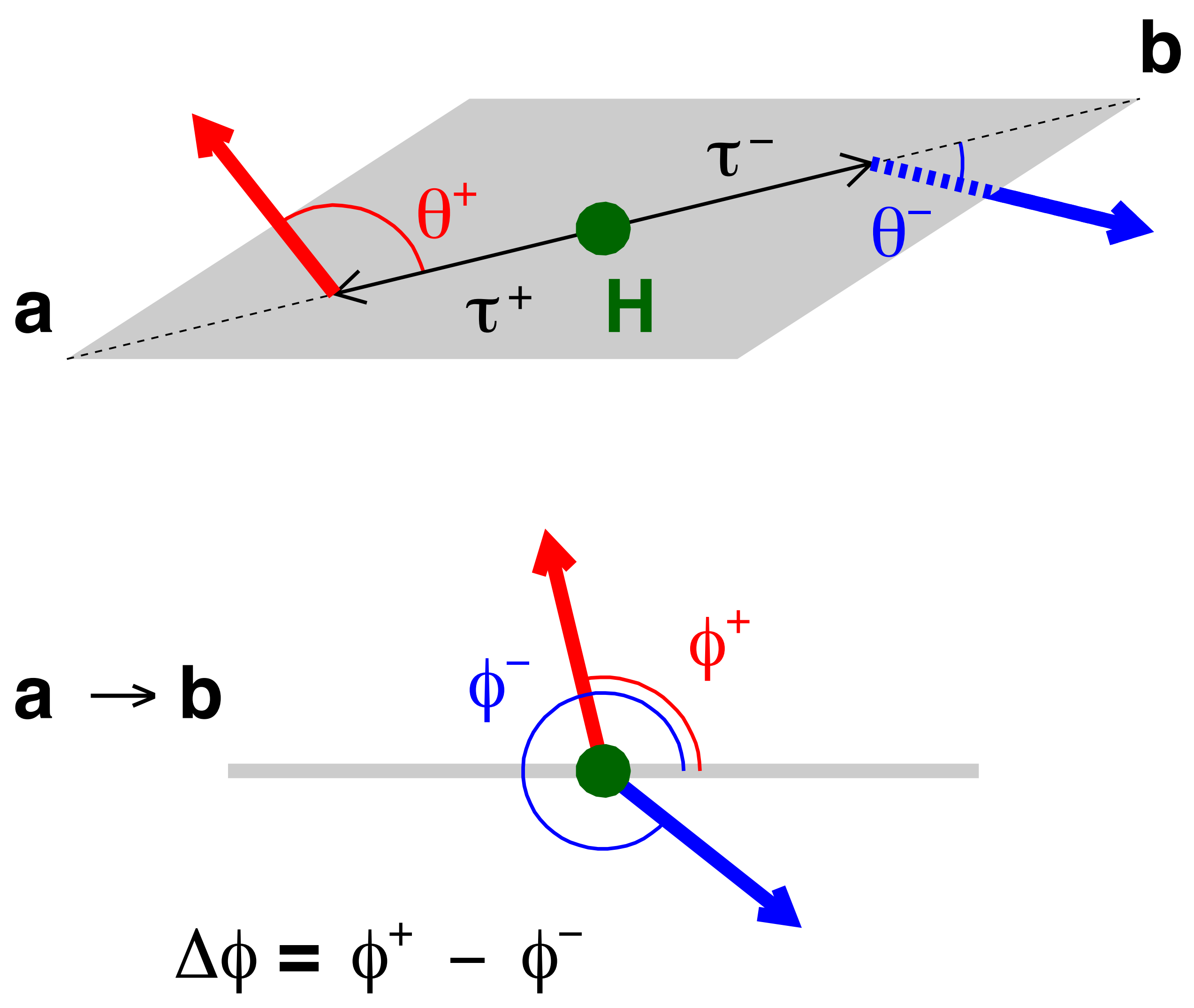

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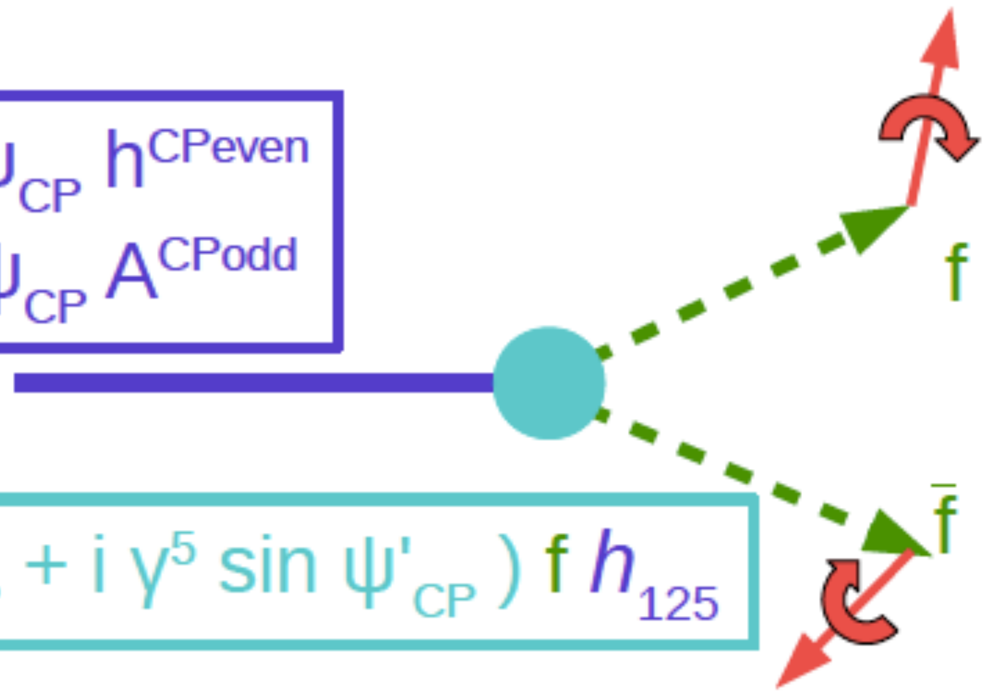

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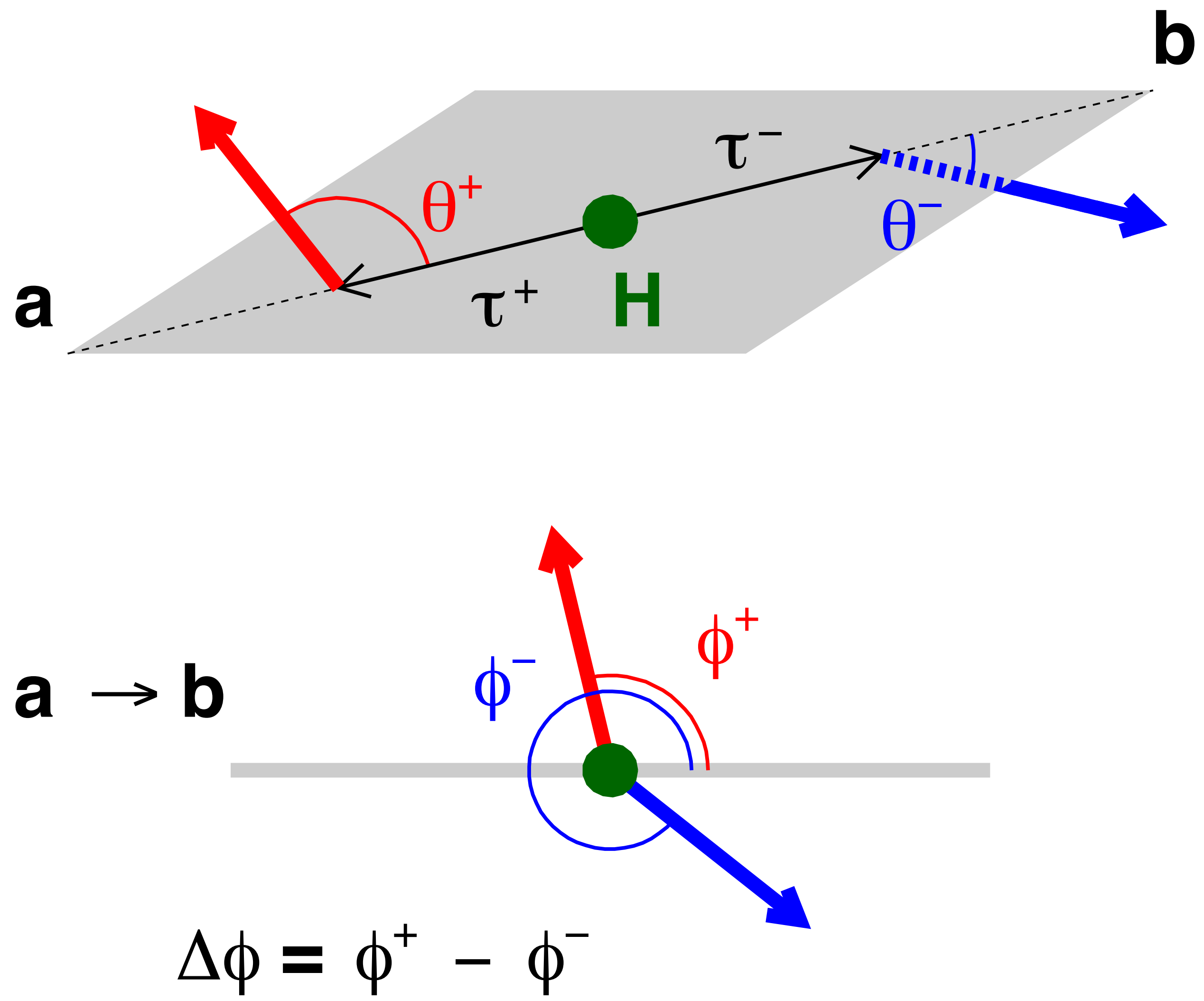

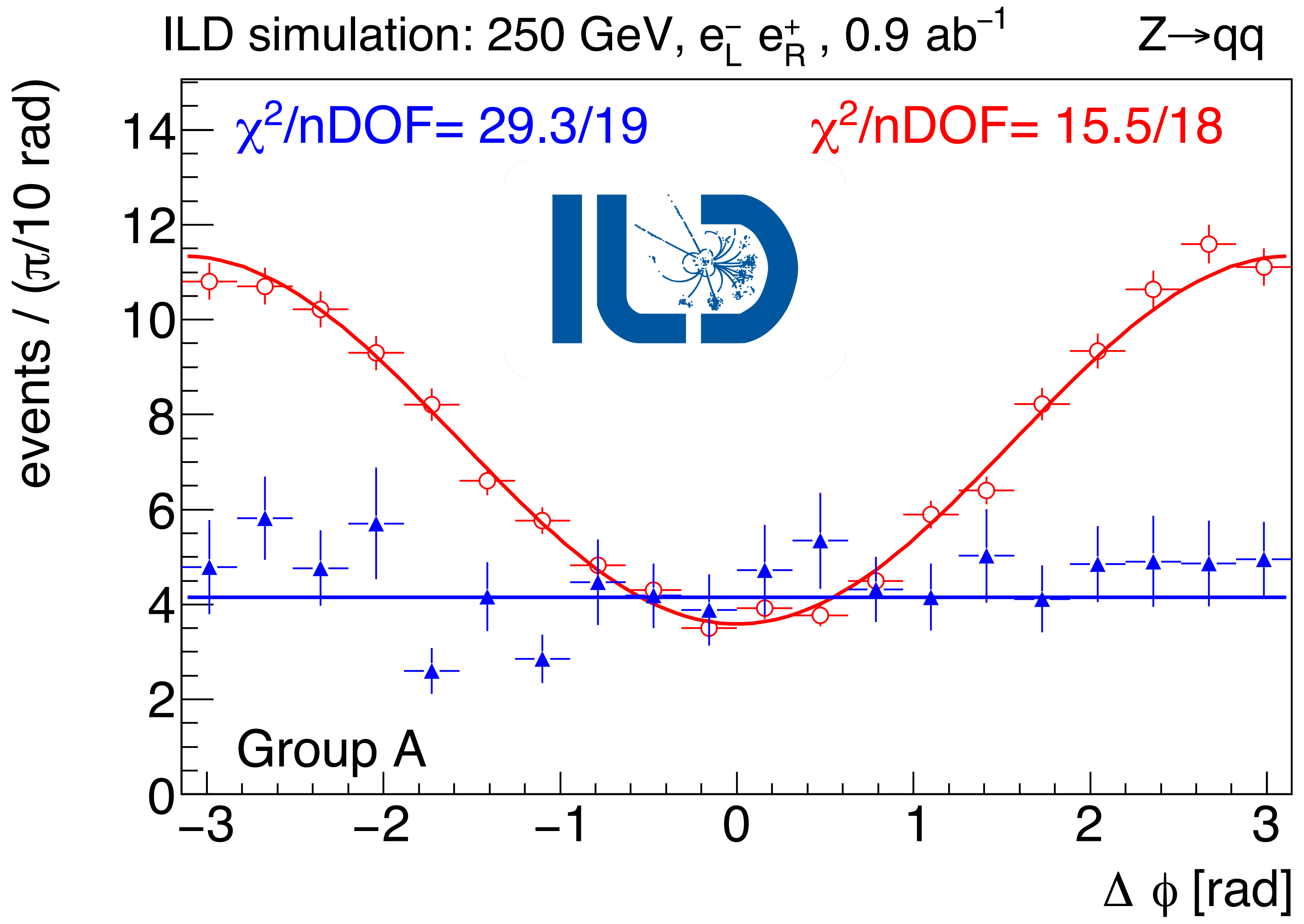

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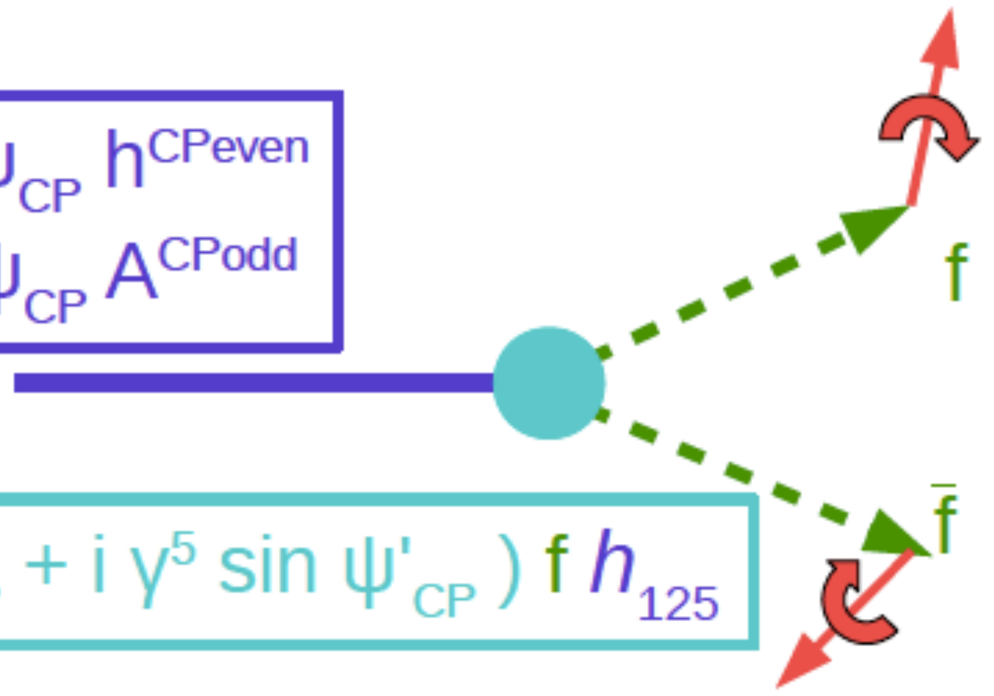

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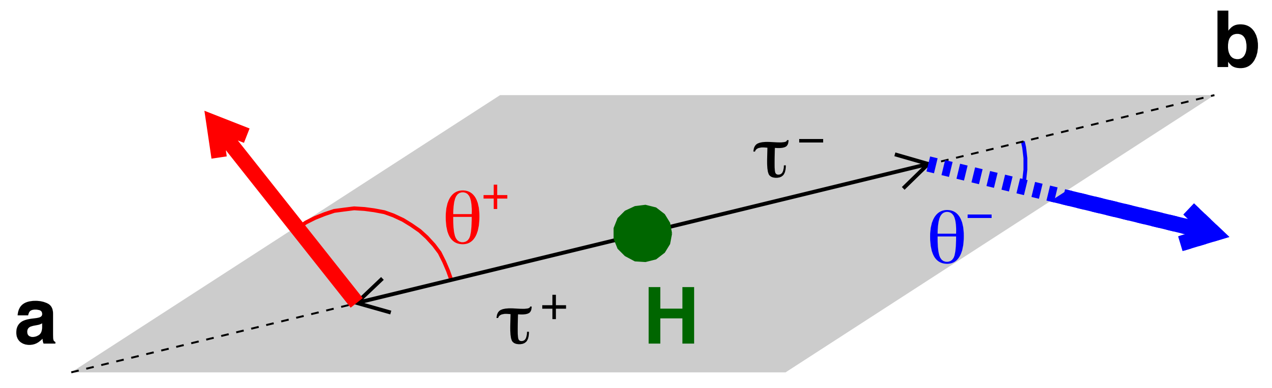
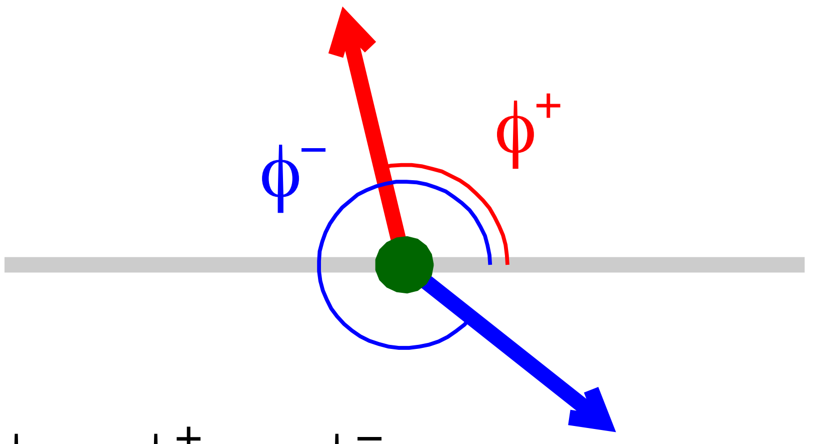
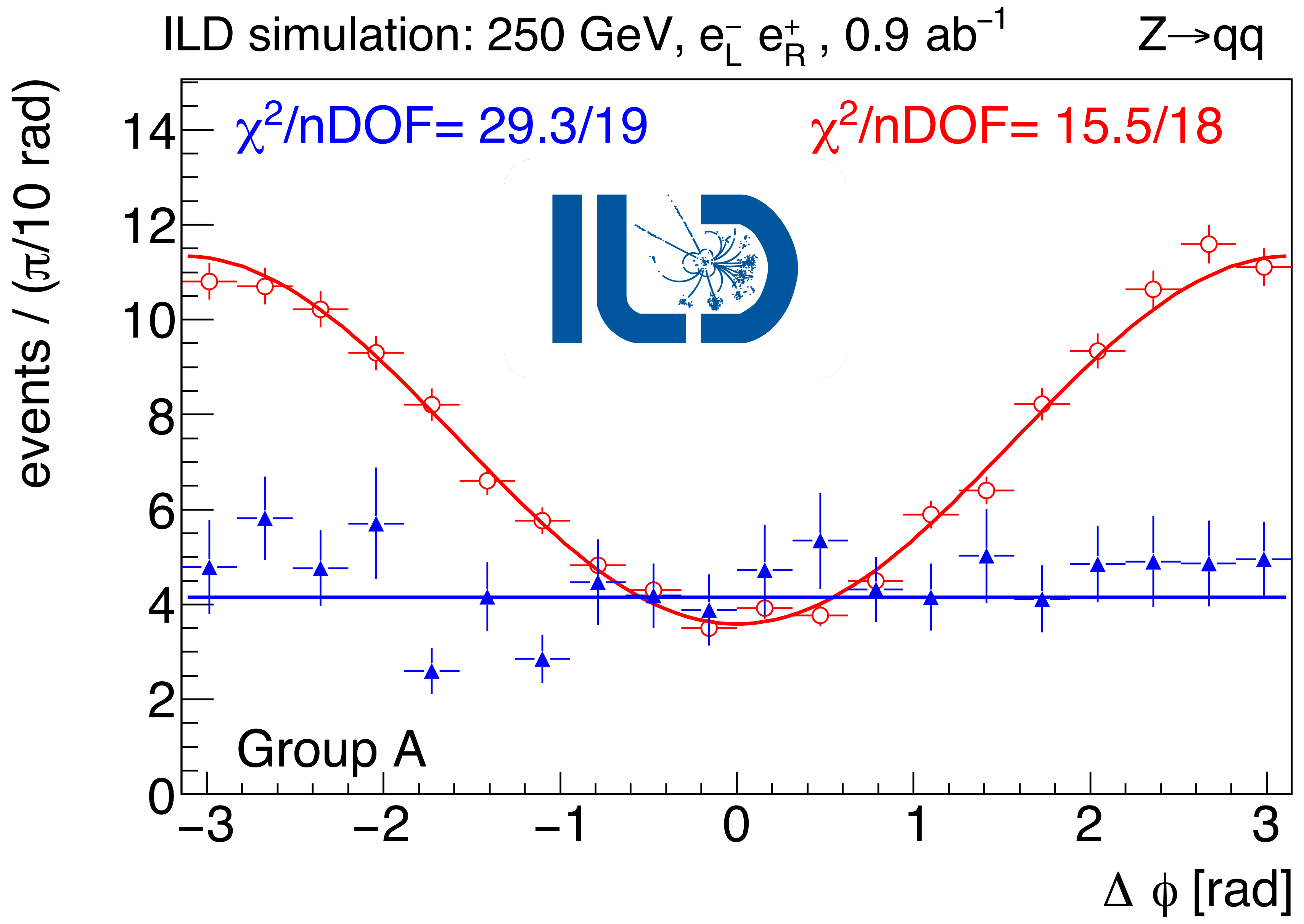
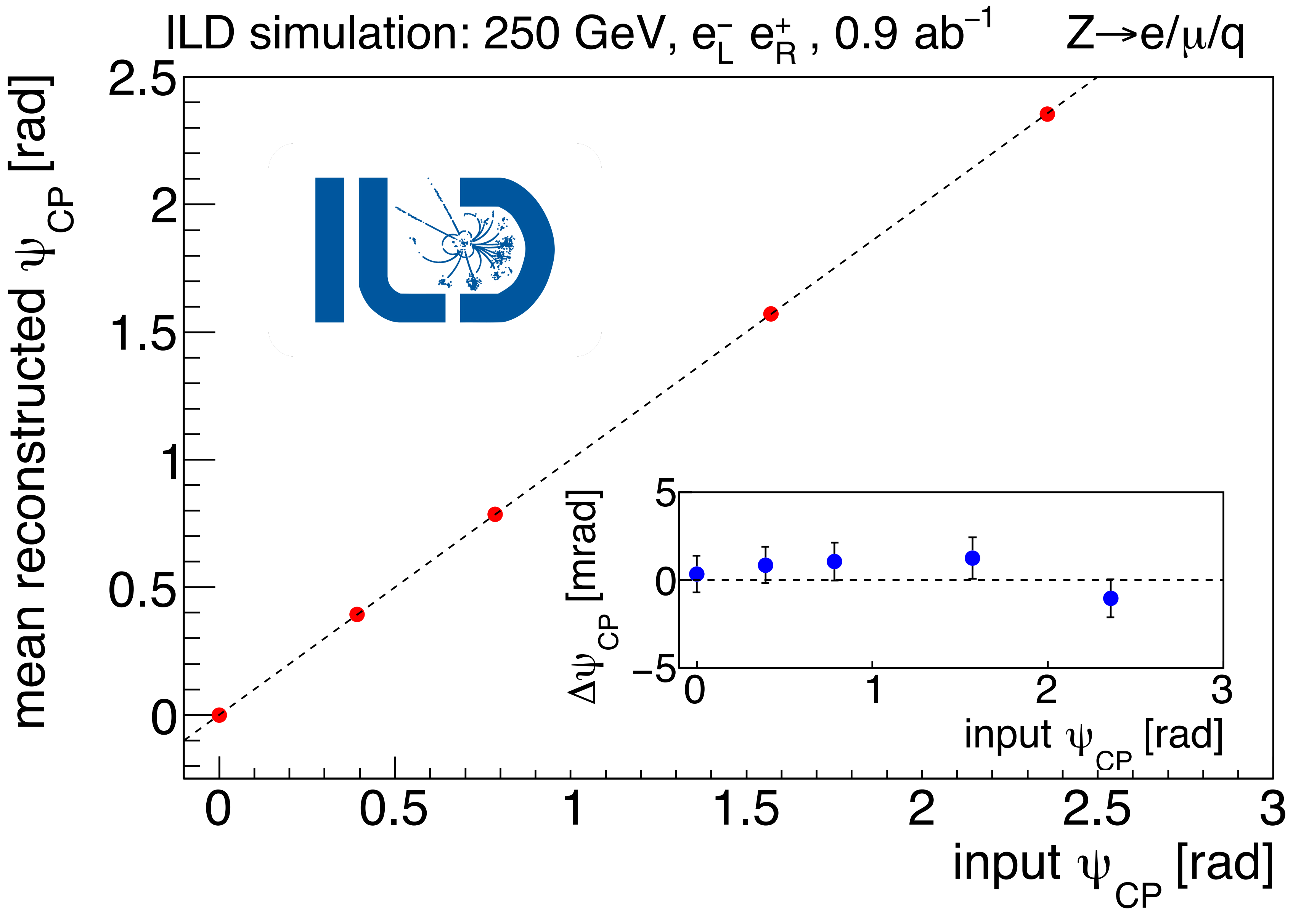




$\Delta\phi = \phi^+ - \phi^-$





arxiv:1804.01241

based on NIM A810 (2016) 51-58

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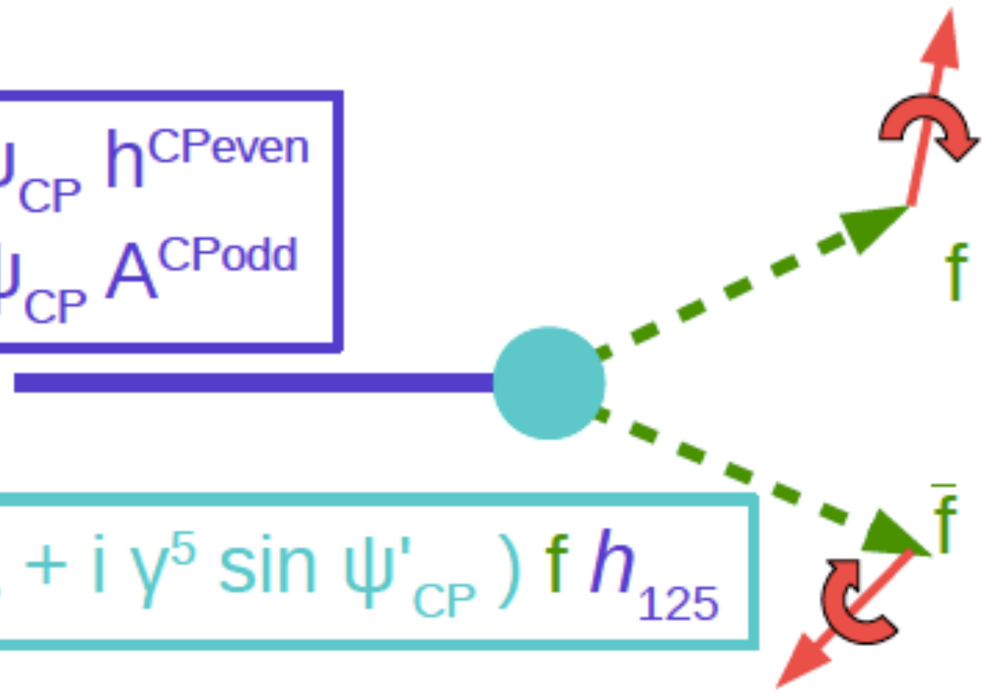

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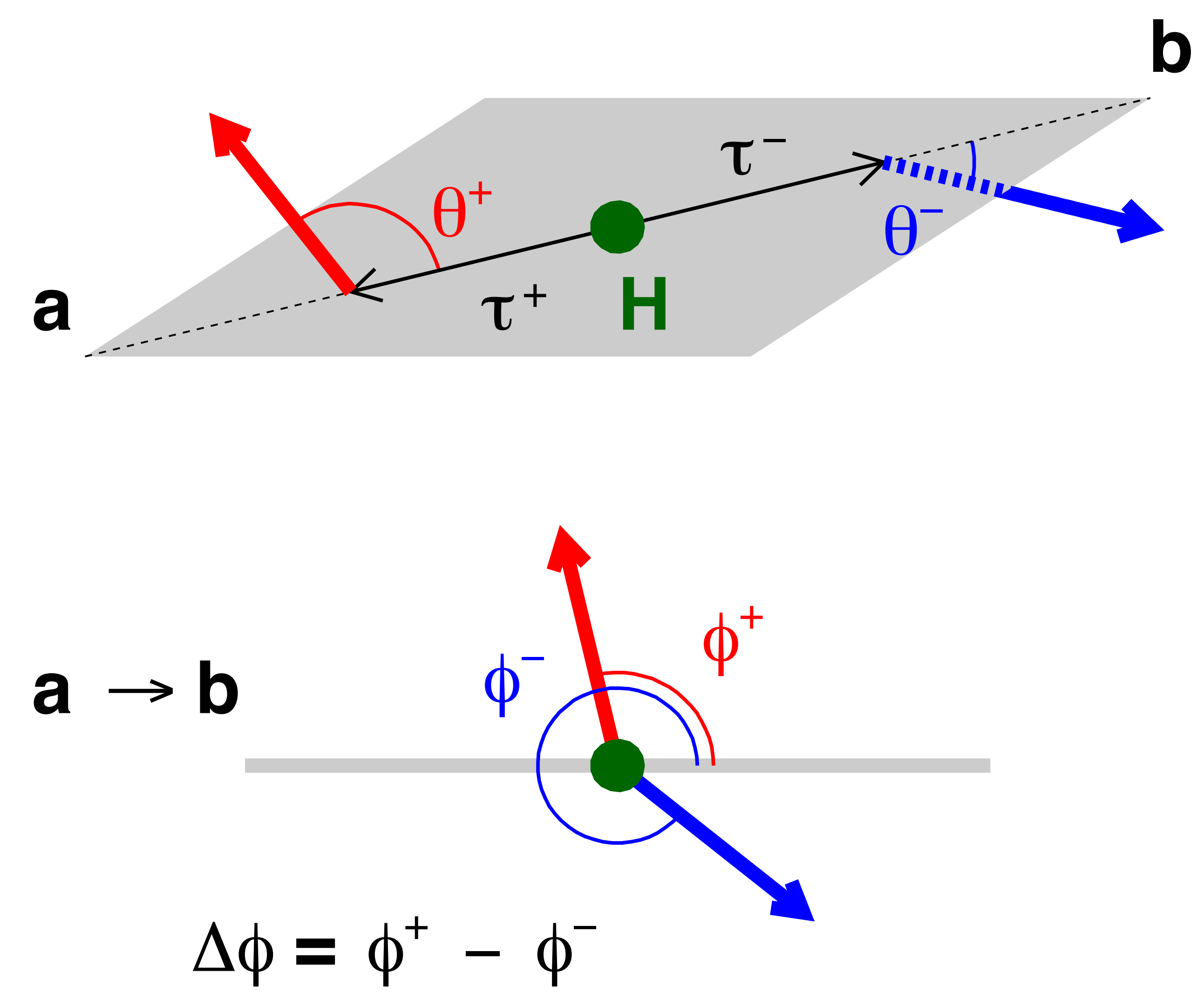

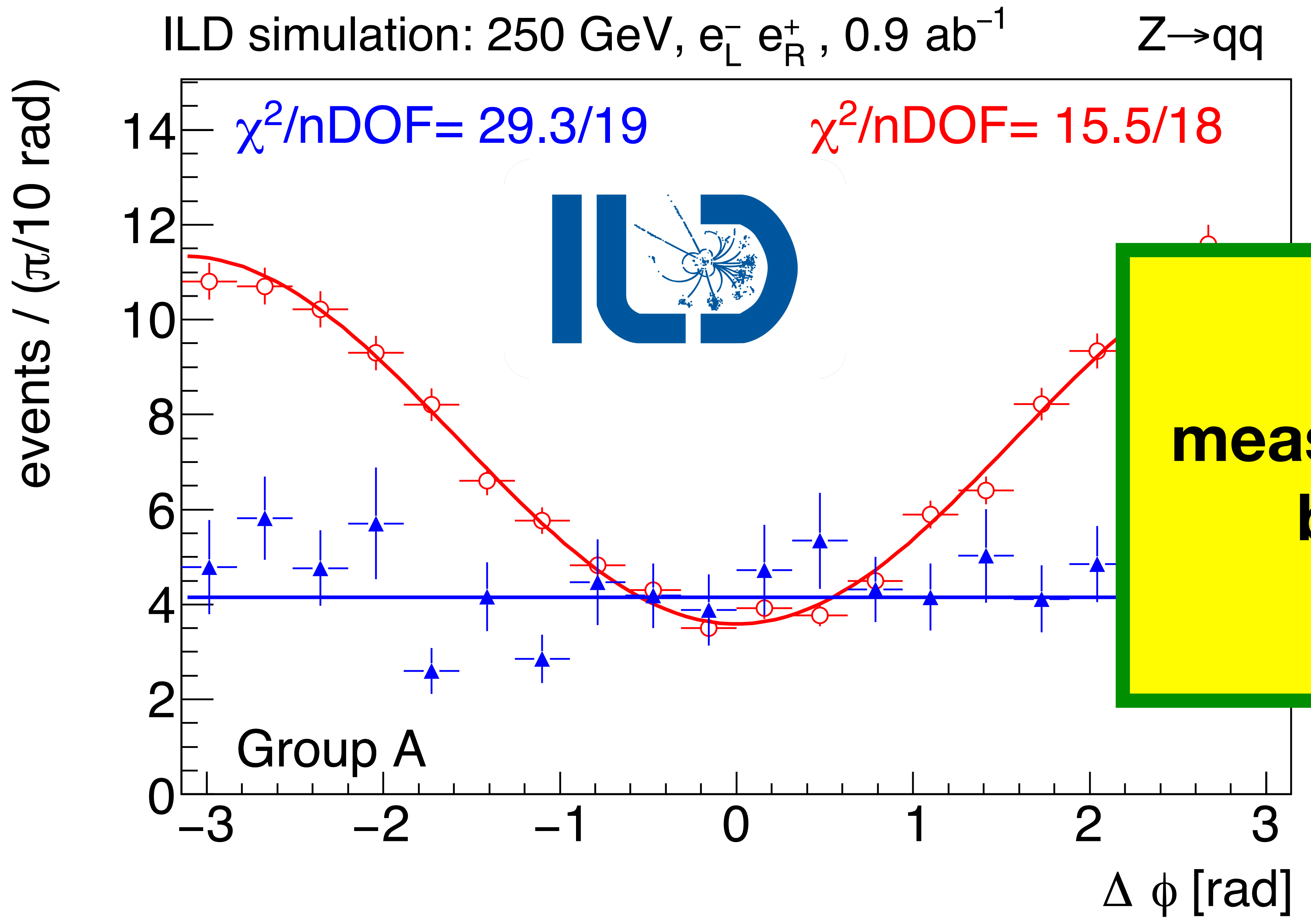

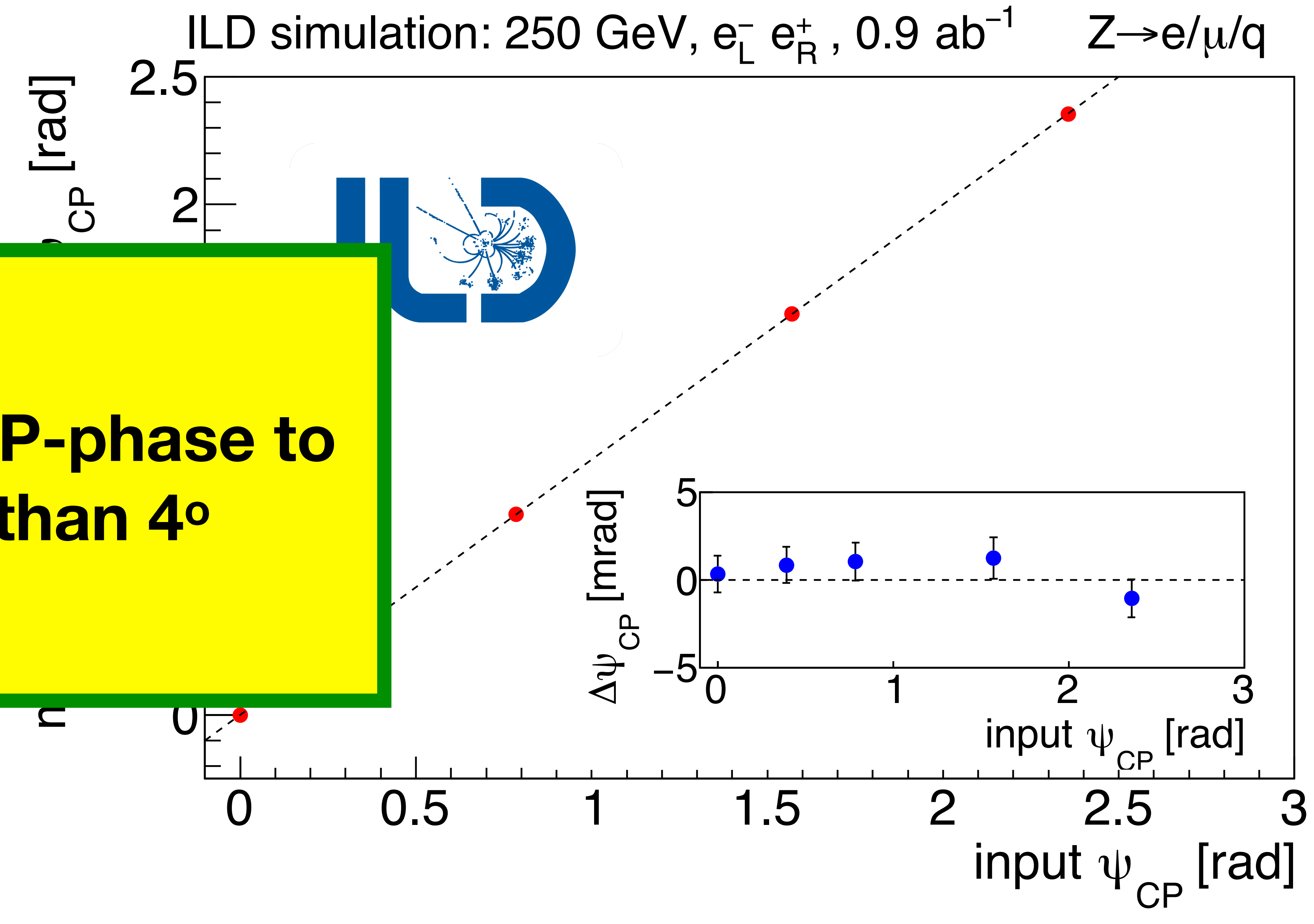

measure CP-phase to better than 4°

arxiv:1804.01241

based on NIM A810 (2016) 51-58

CP properties in h->$\tau\tau$

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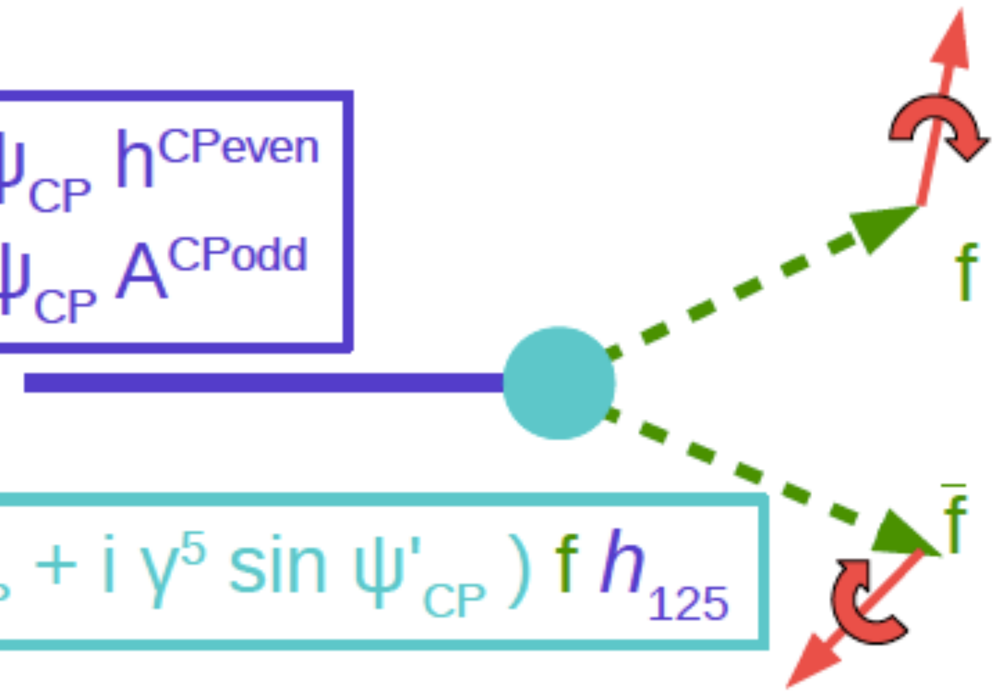

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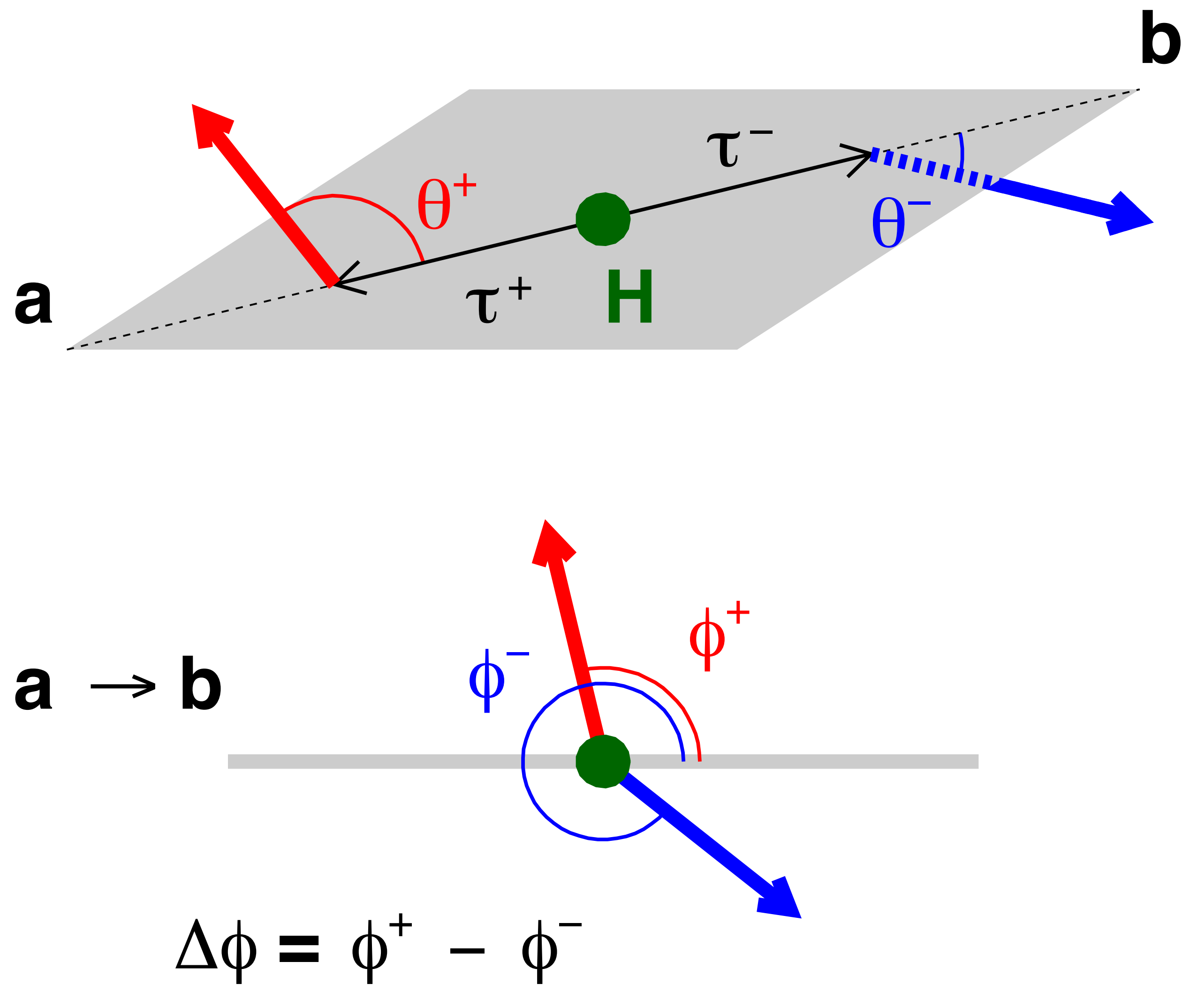

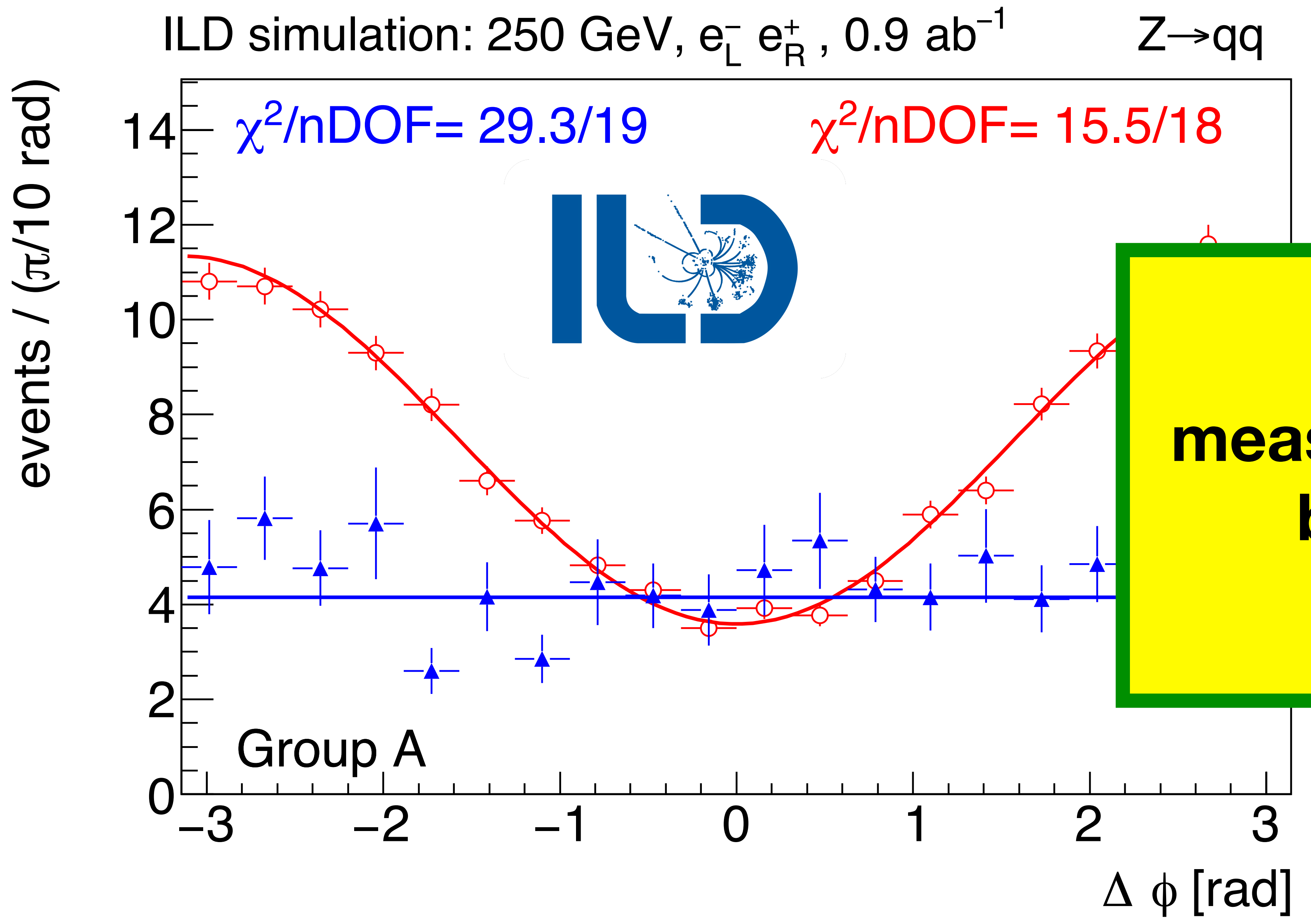

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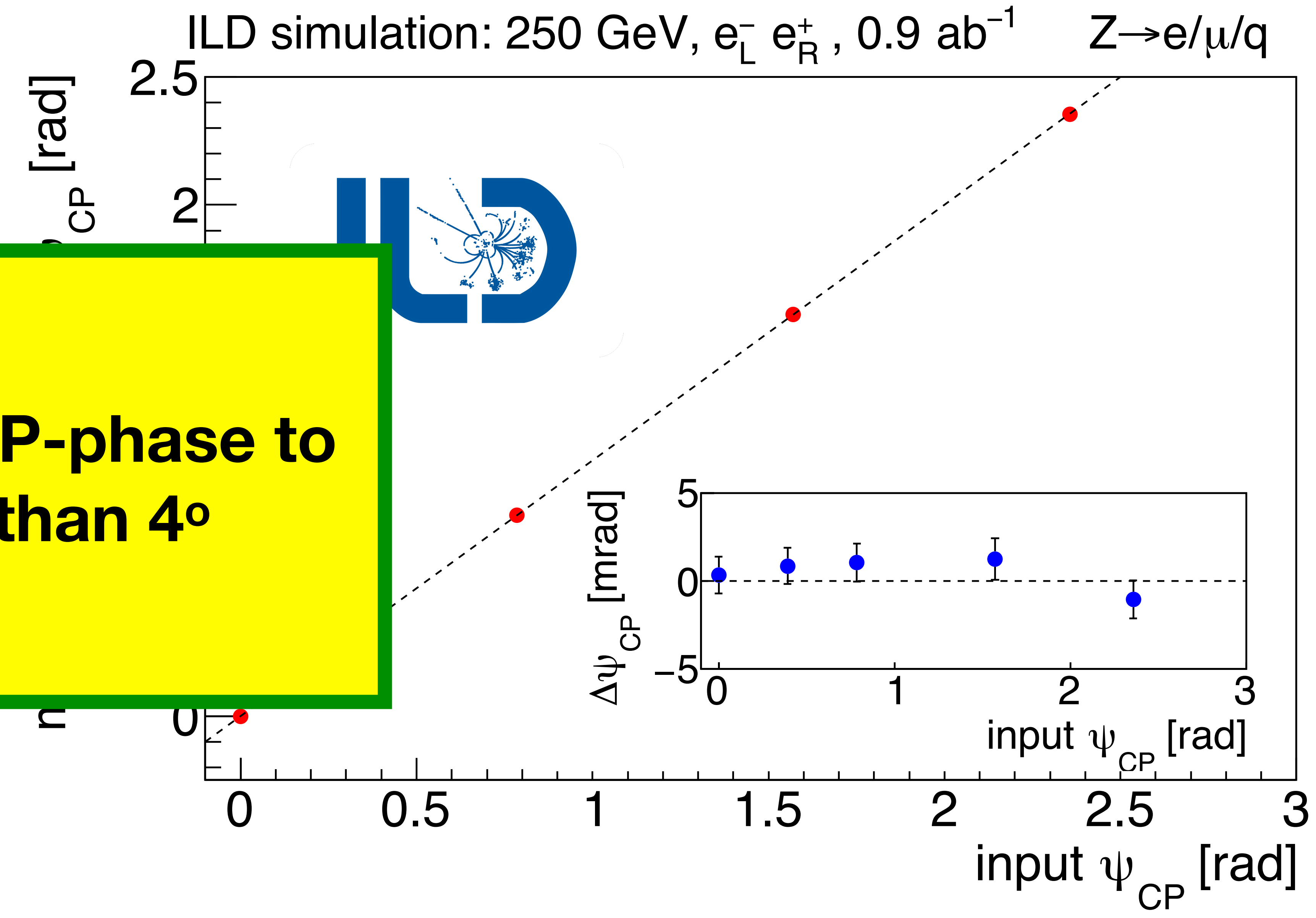


..and CPV in Zh coupling:

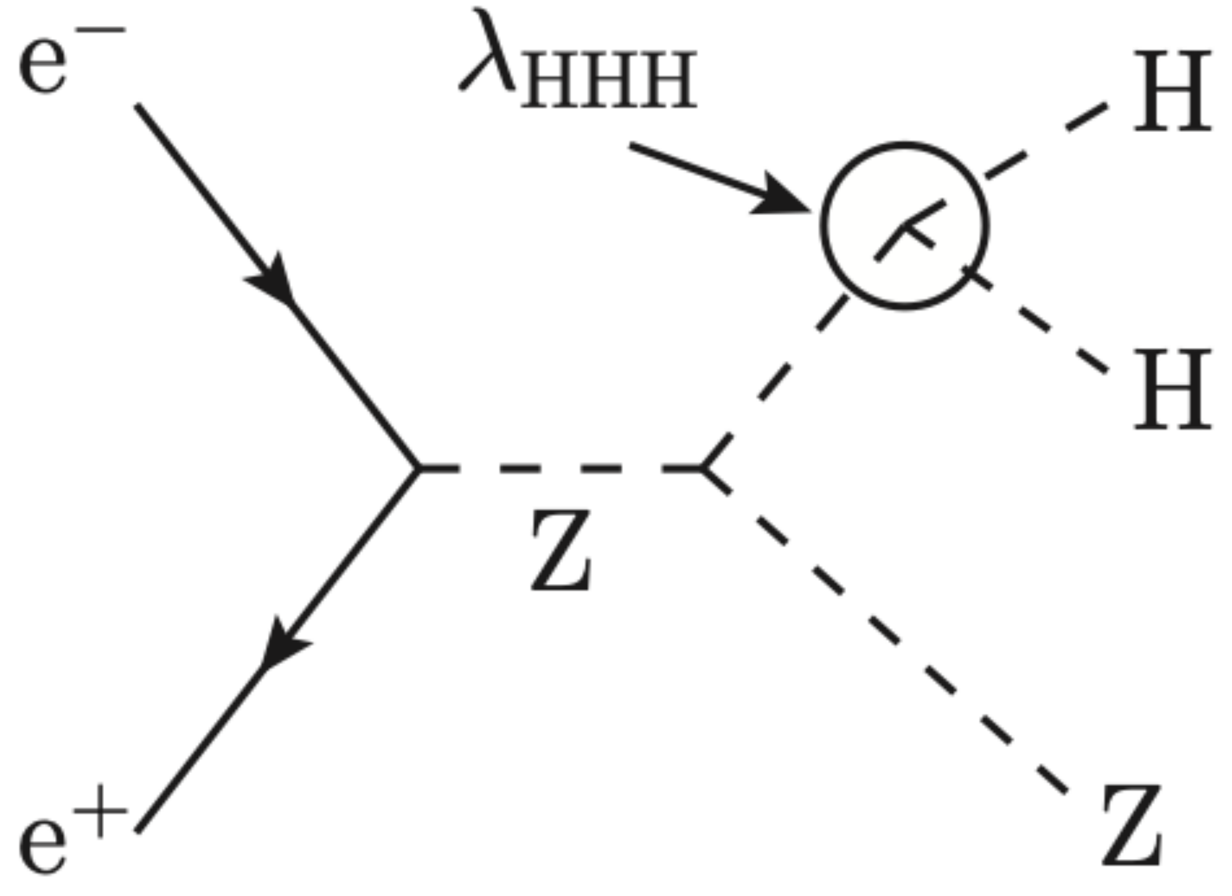
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

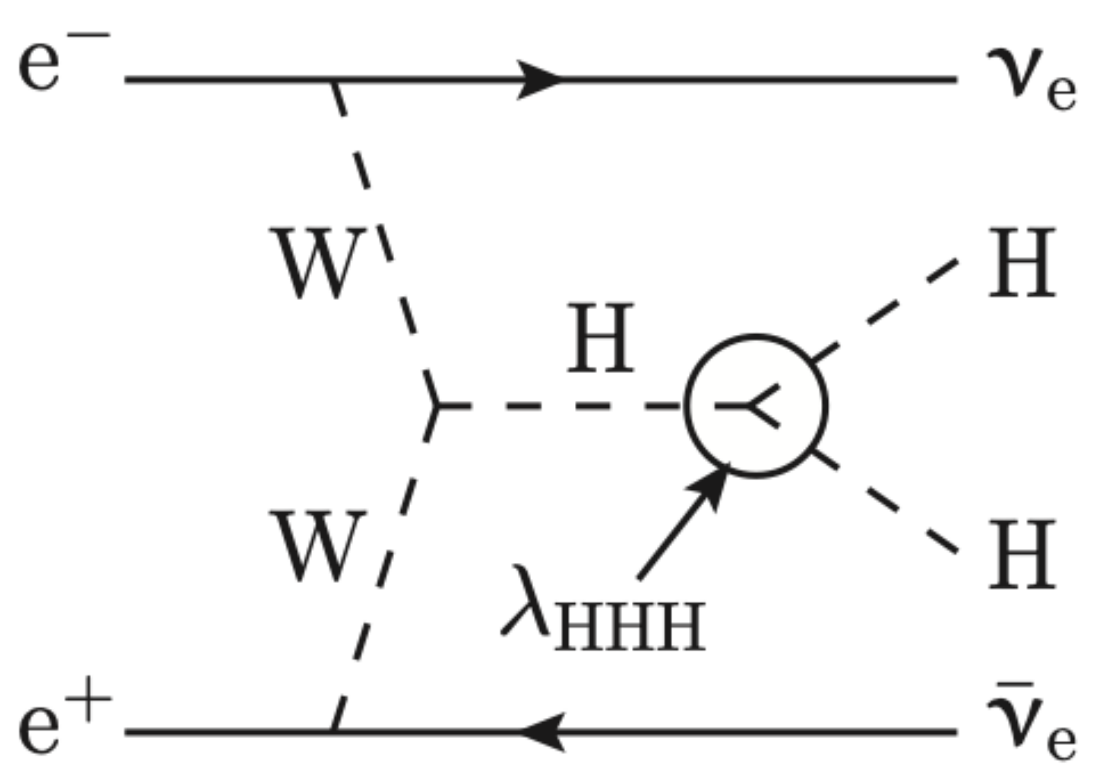
=> $\tilde{b}$ **to ±0.005**

arxiv:1804.01241

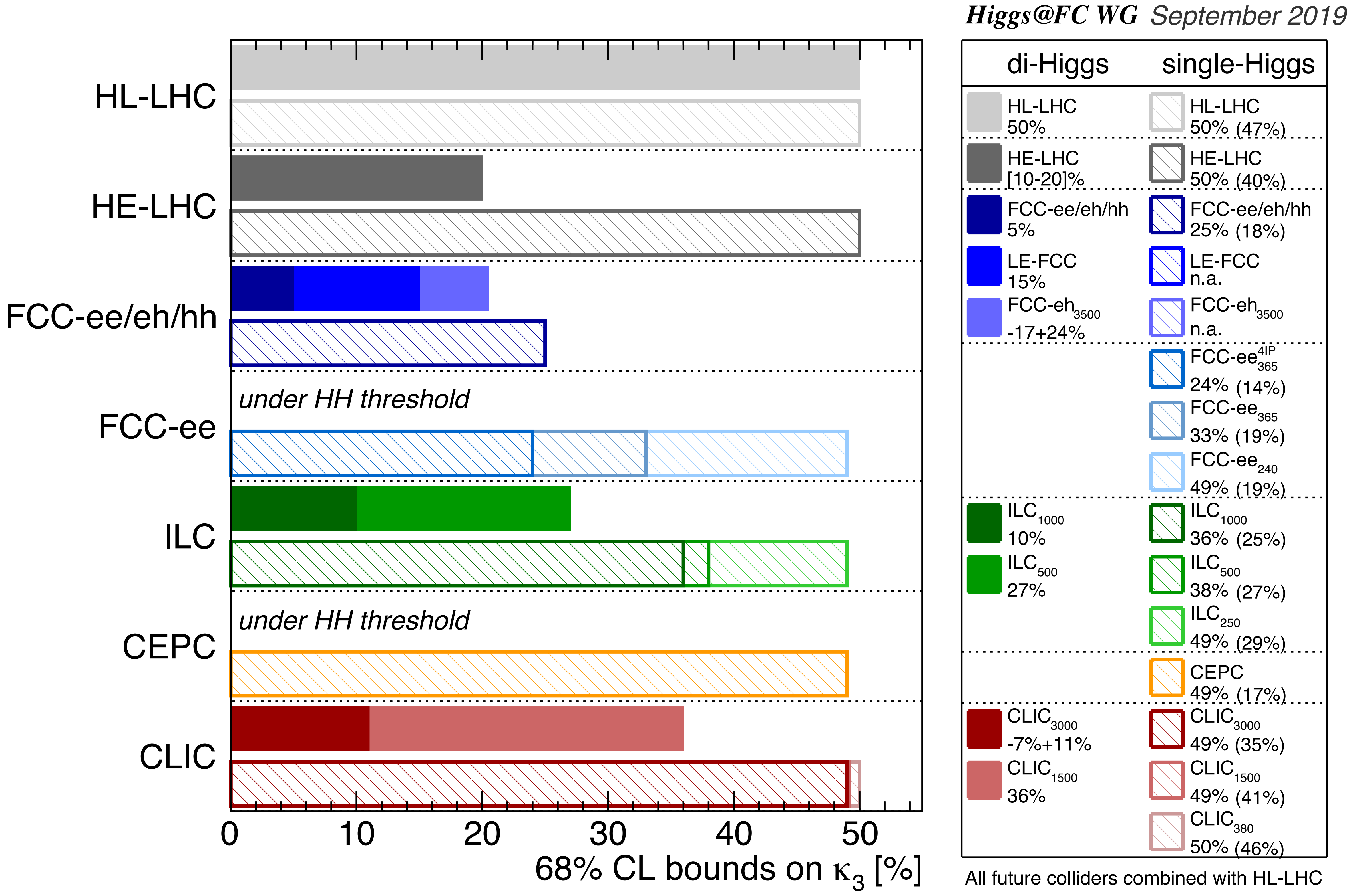
based on NIM A810 (2016) 51-58

Higgs measurements only possible at 500 GeV and above: di-Higgs and ttH production





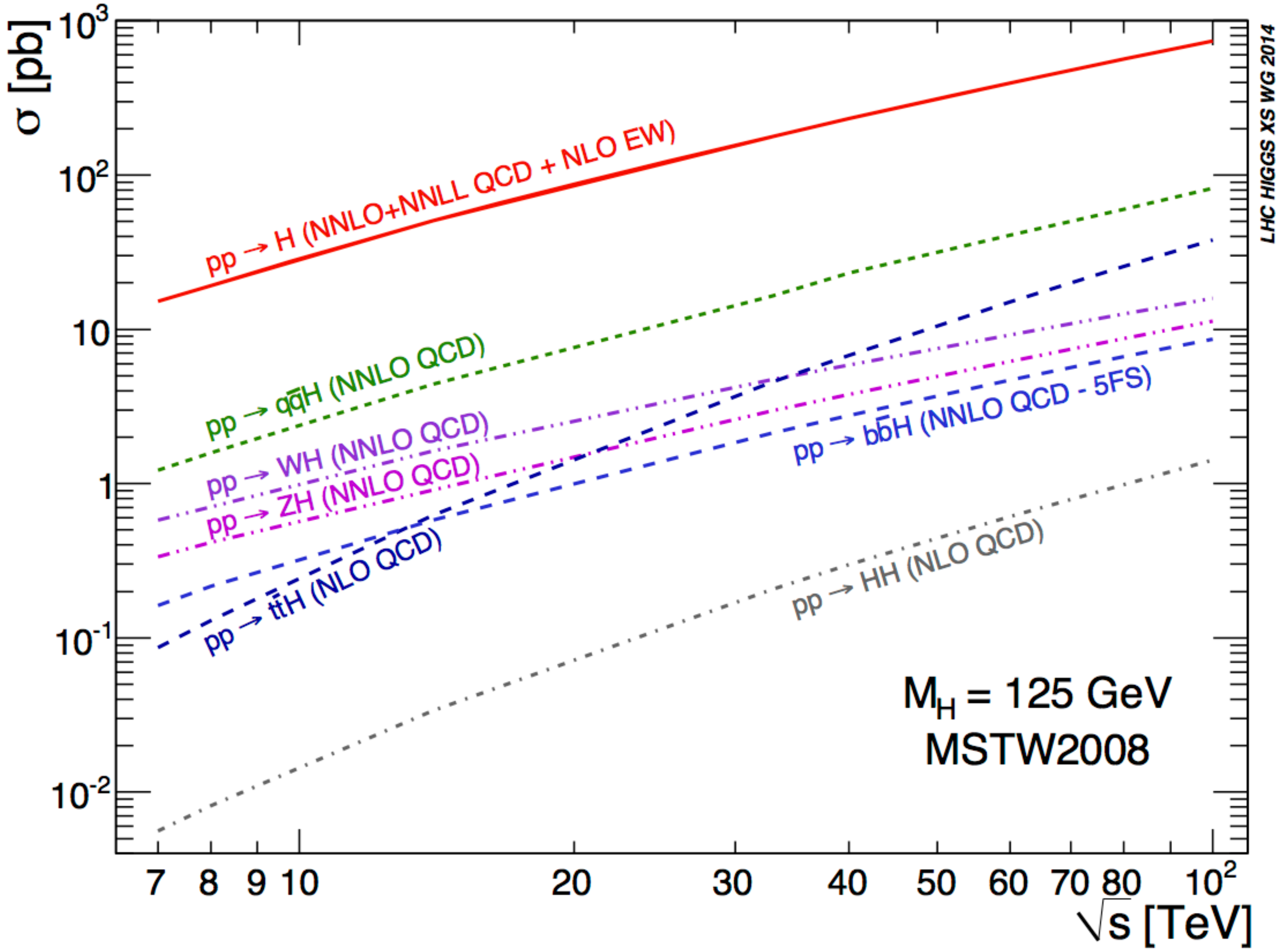
The ECFA Higgs@Future Report



At lepton colliders, double Higgs-strahlung, $e+e- \rightarrow$ *ZHH*, gives stronger constraints on positive deviations ($\varkappa 3 > 1$), while VBF is better in constraining negative deviations, ($\varkappa 3 < 1$). While at HL-LHC, values of $\varkappa 3 > 1$, as expected in models of strong first order phase transition, result in a smaller double-Higgs production cross section due to the destructive interference, at lepton colliders for the *ZHH* process they actually result in a larger cross section, and hence into an increased precision. For instance at ILC_{500}, the sensitivity around the SM value is 27% but it would reach 18% around $\varkappa_3 = 1.5$.

This figure applies ONLY for $\lambda = \lambda_{SM}$
no studies of BSM case apart from ILC

Di-Higgs Production Cross sections - pp



dependence on ECM:
14 TeV -> 100 TeV : ~40 x larger cross section
14 TeV -> 38 TeV: ~8 x larger cross section

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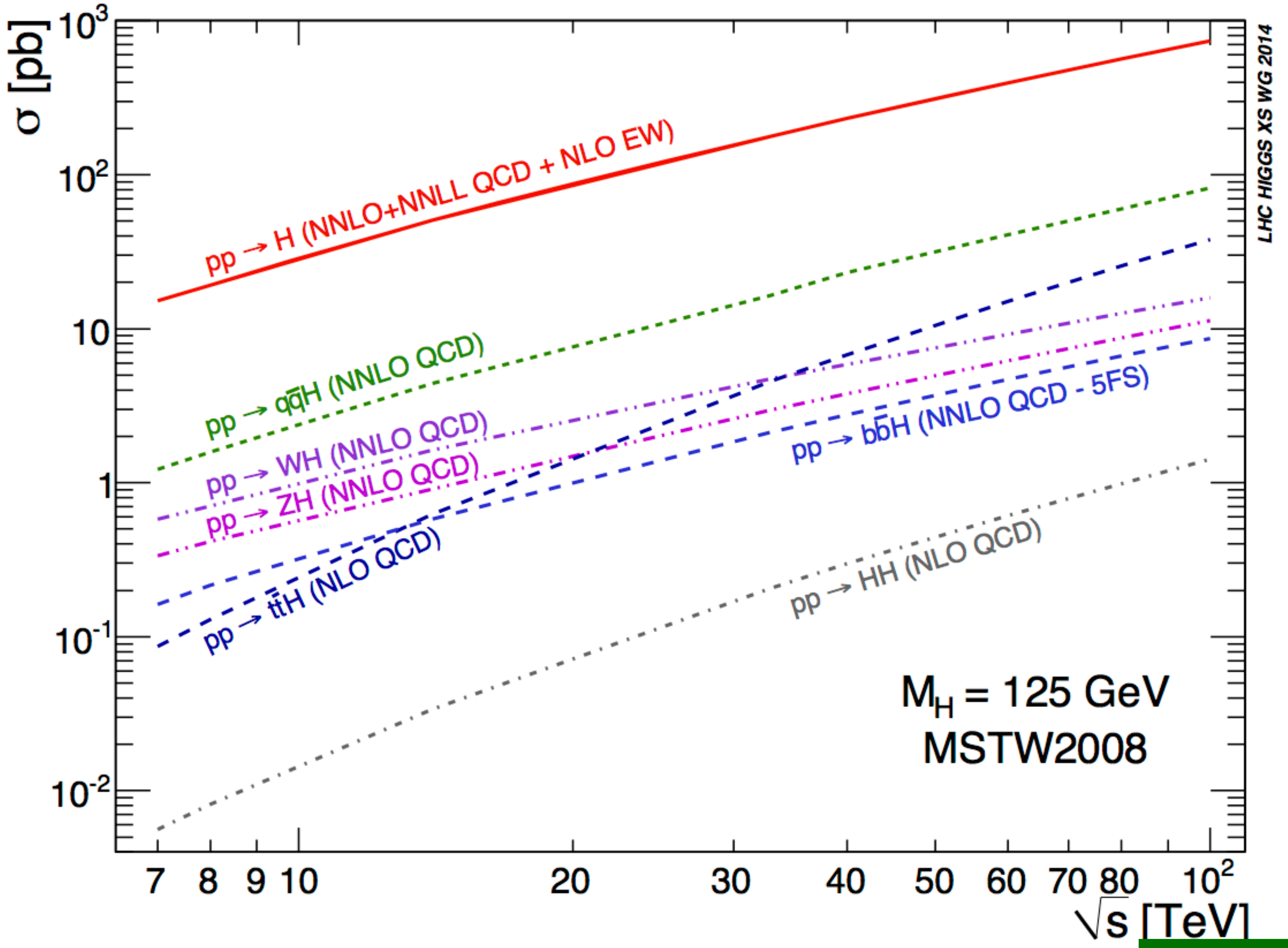

differential distributions!

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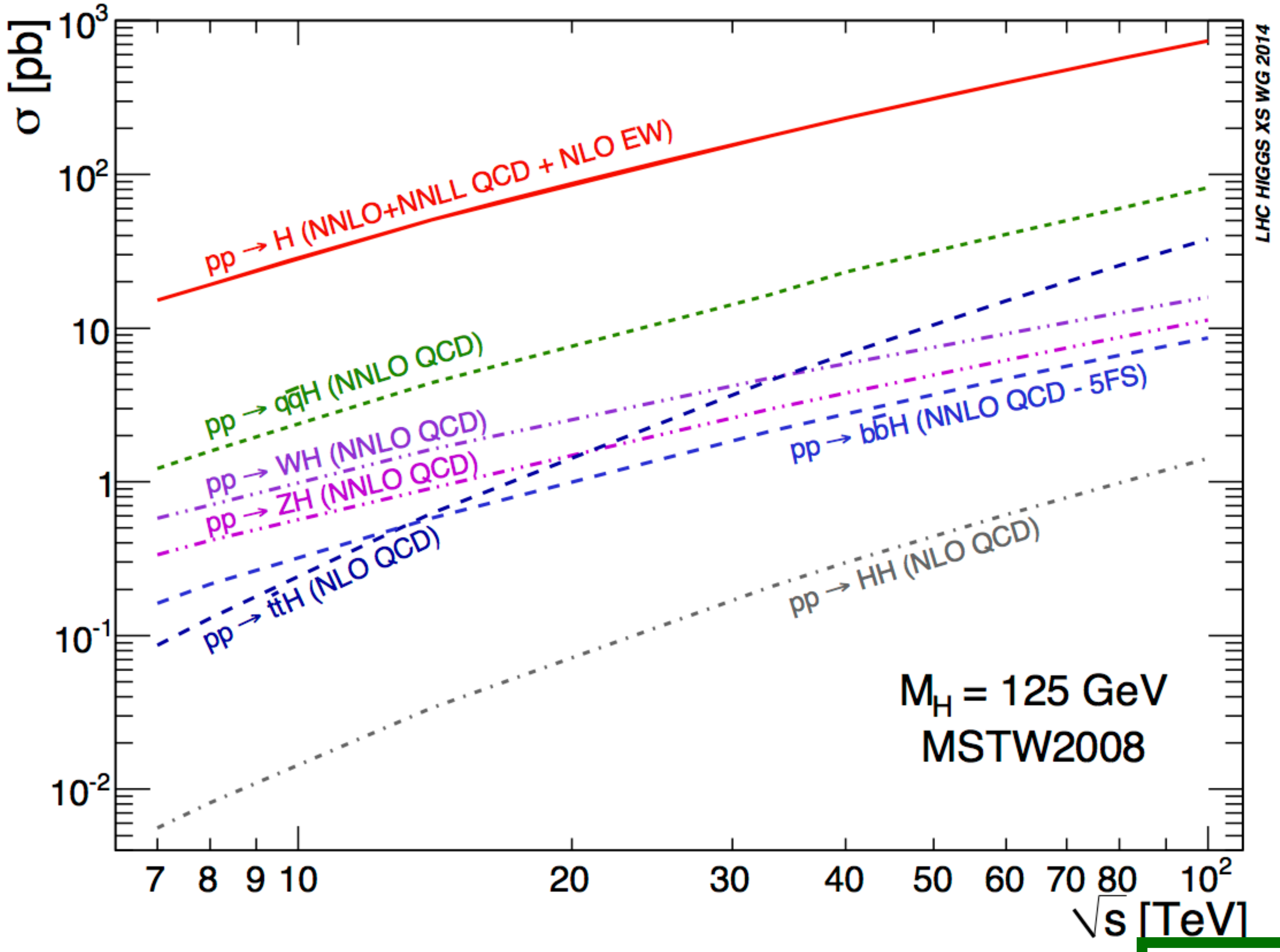

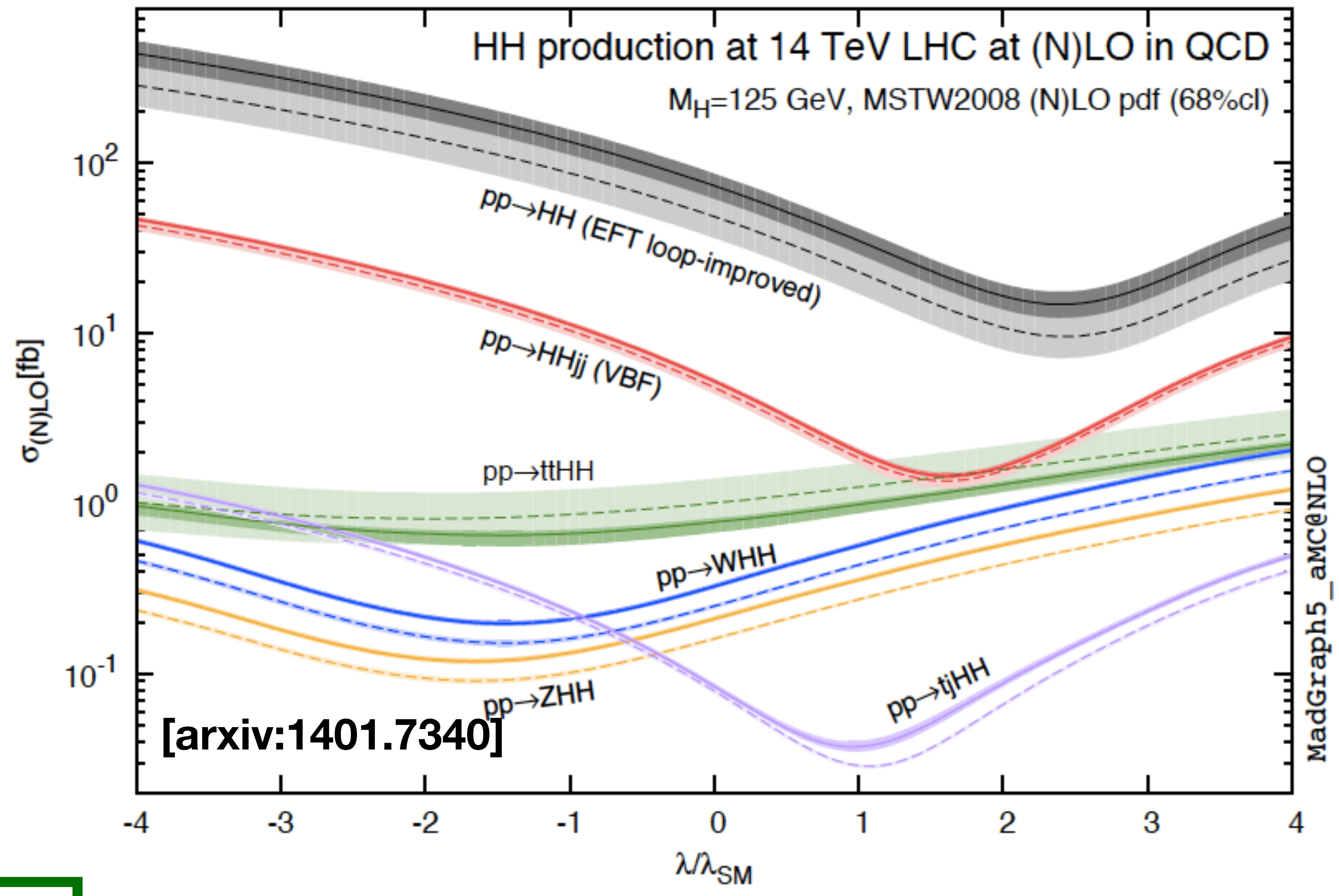

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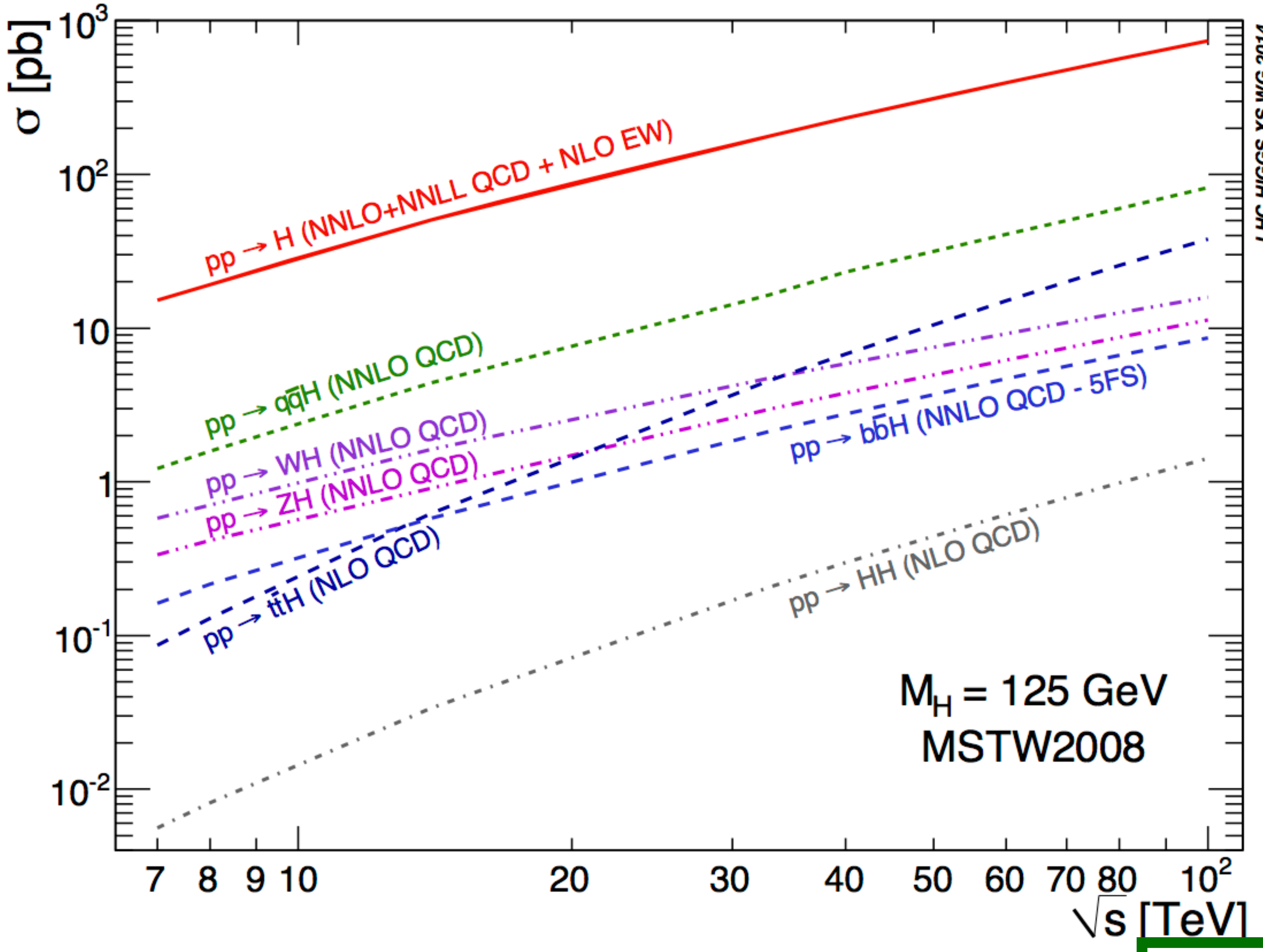

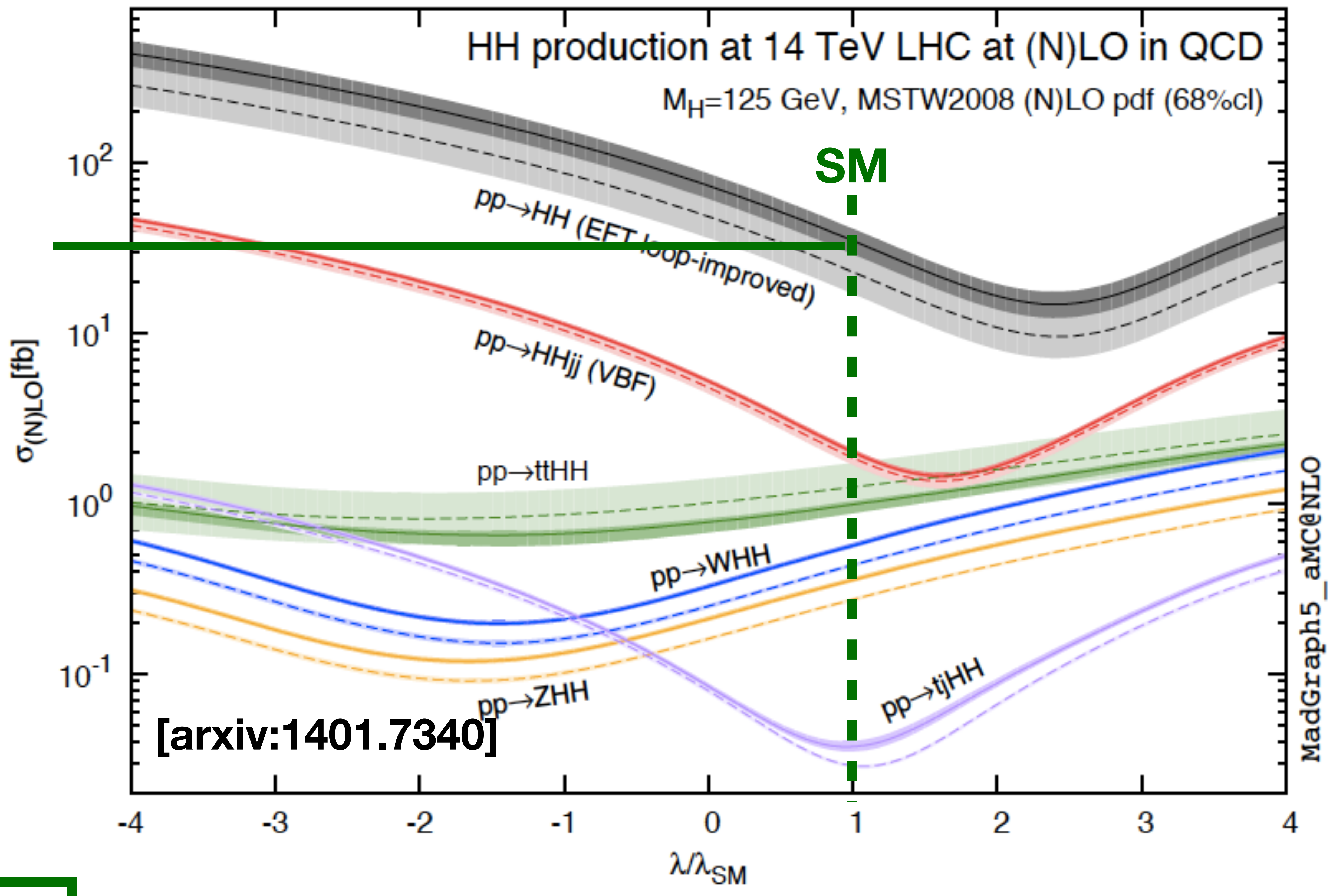

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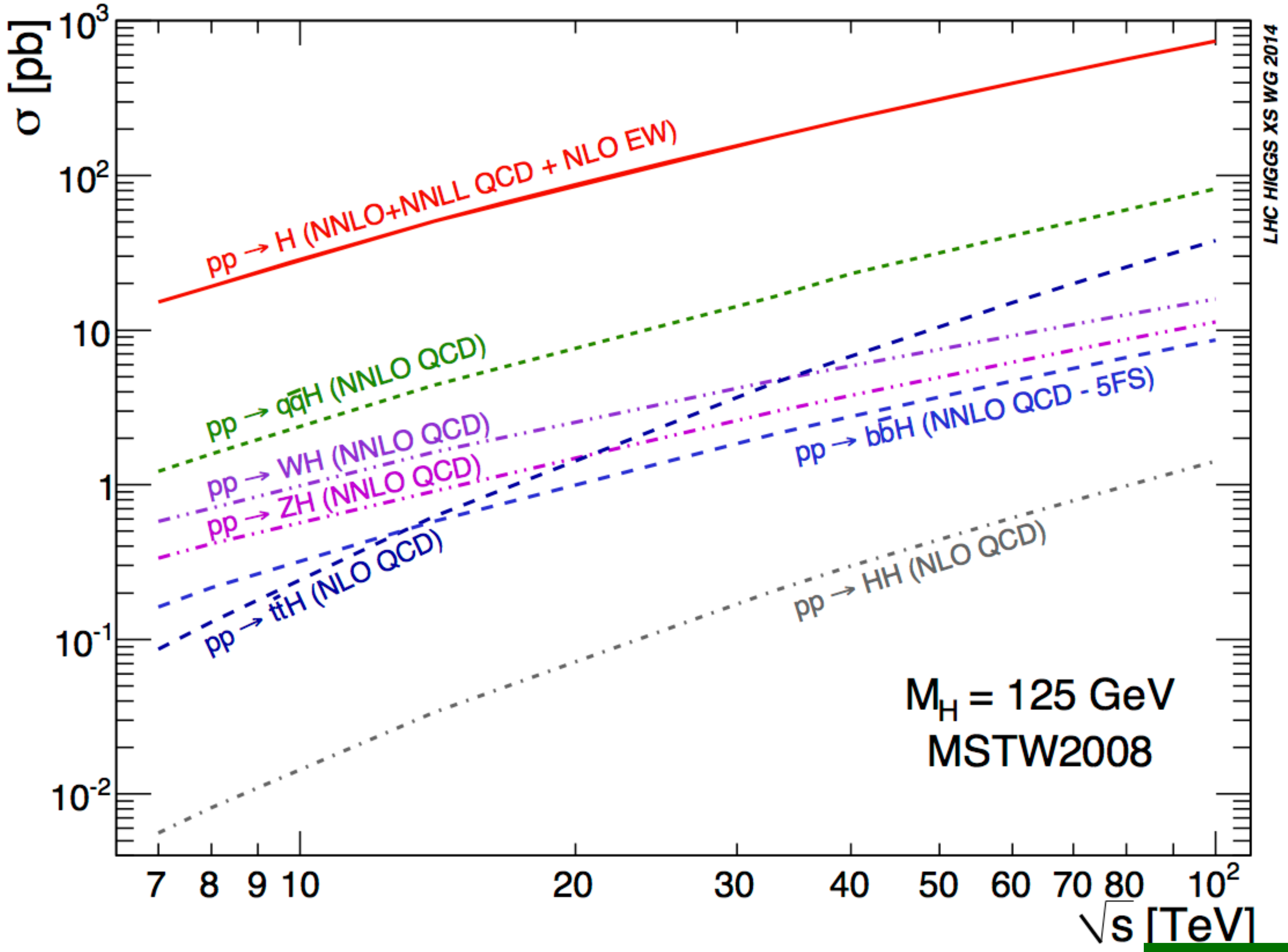

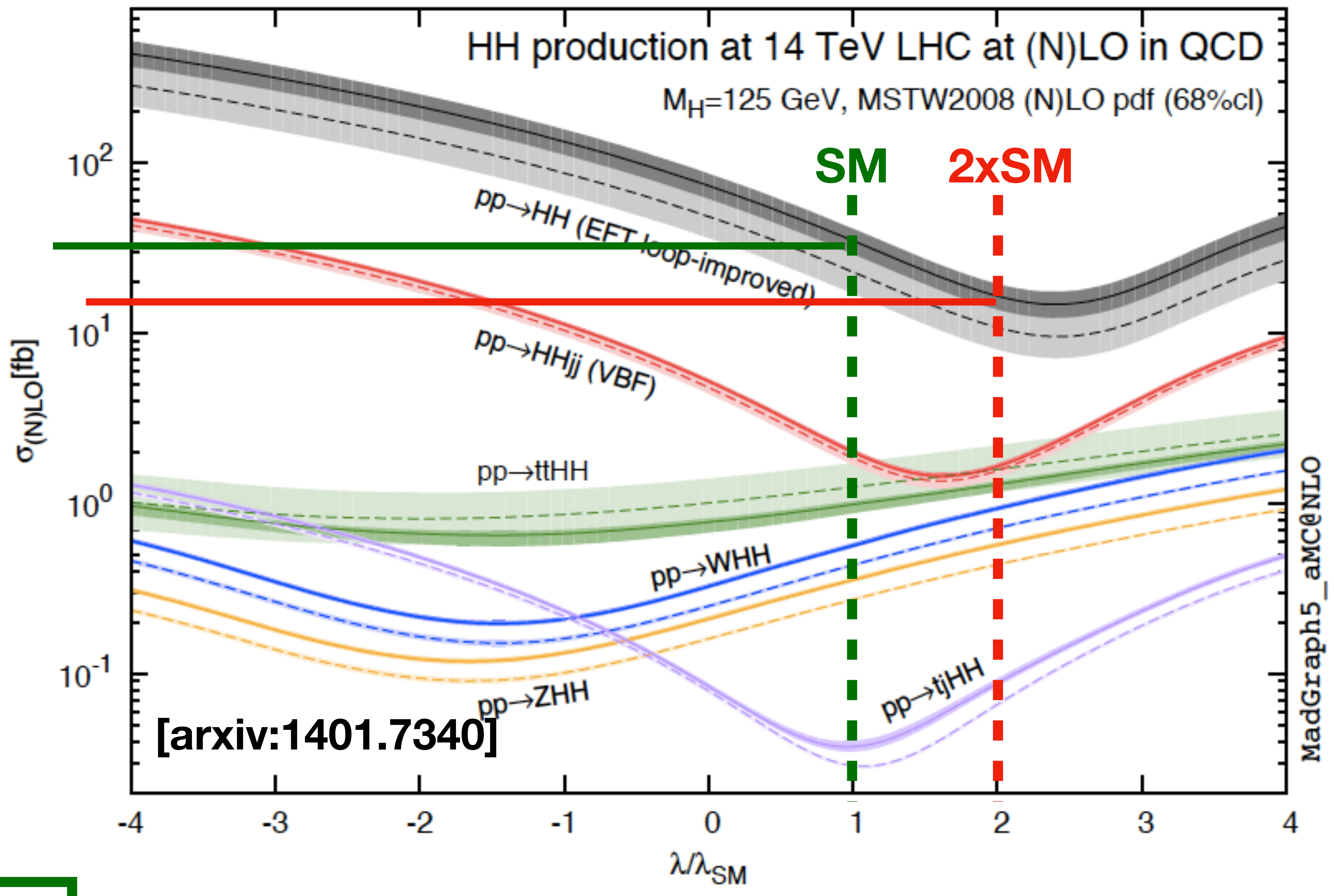

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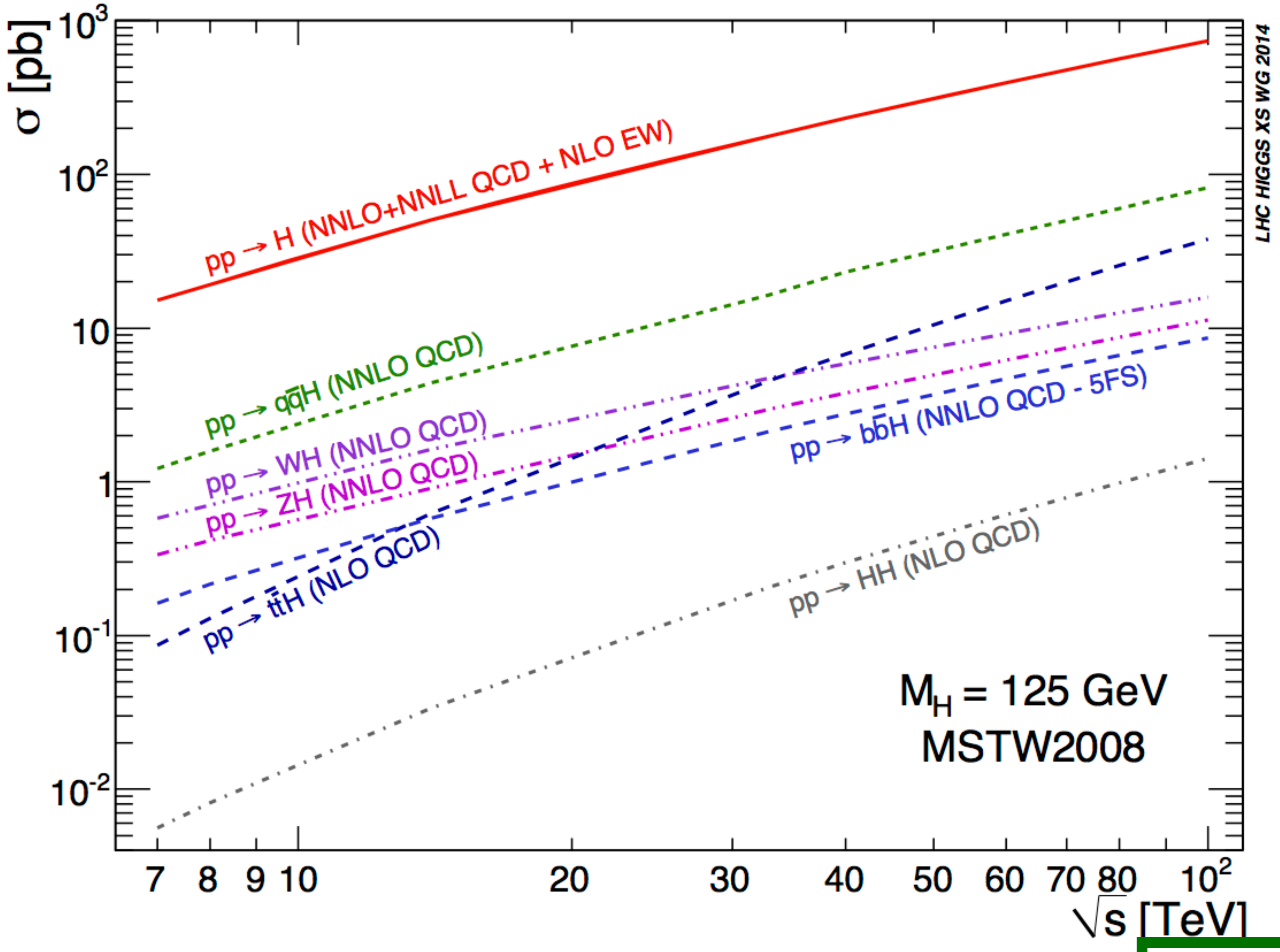

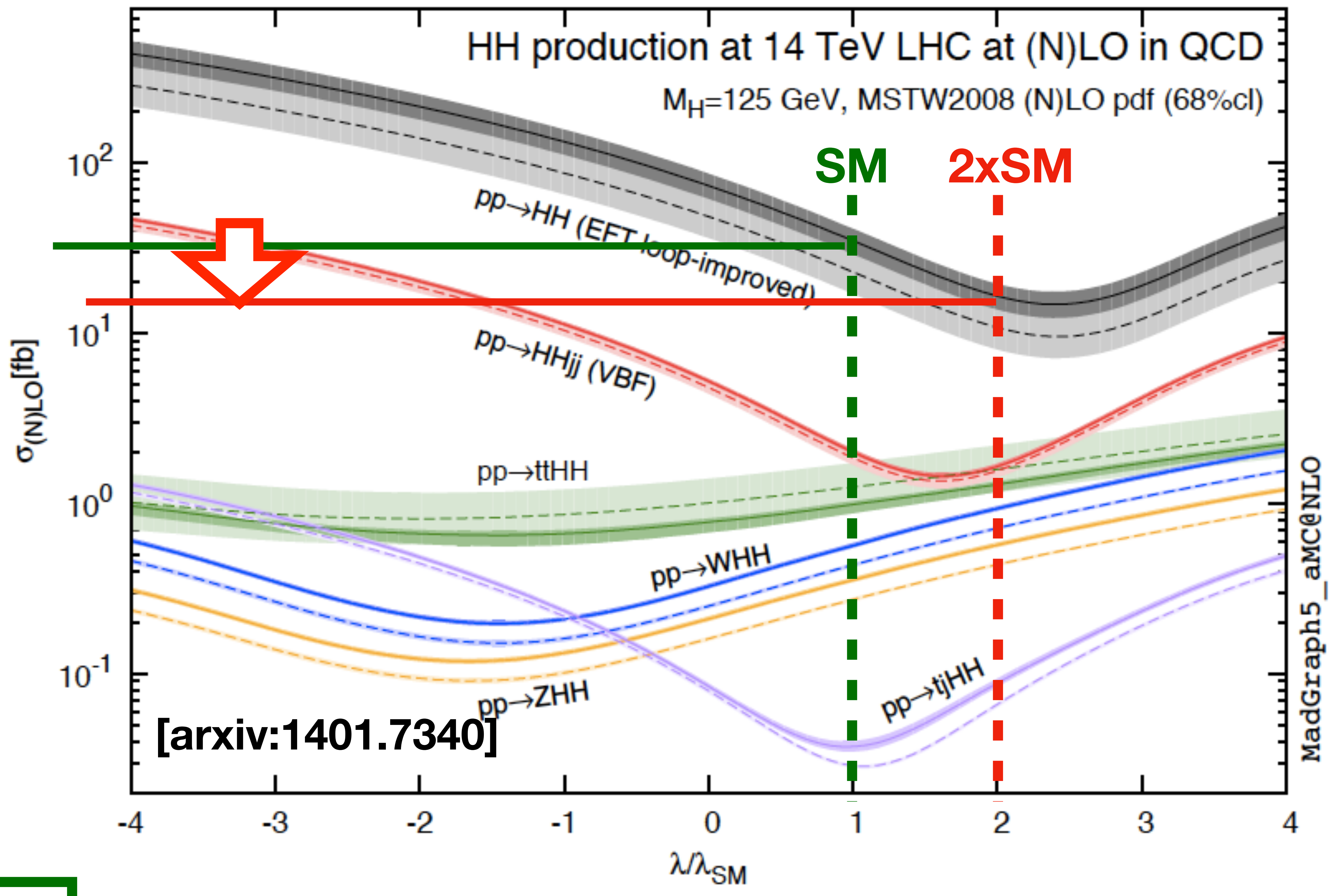

differential distributions!

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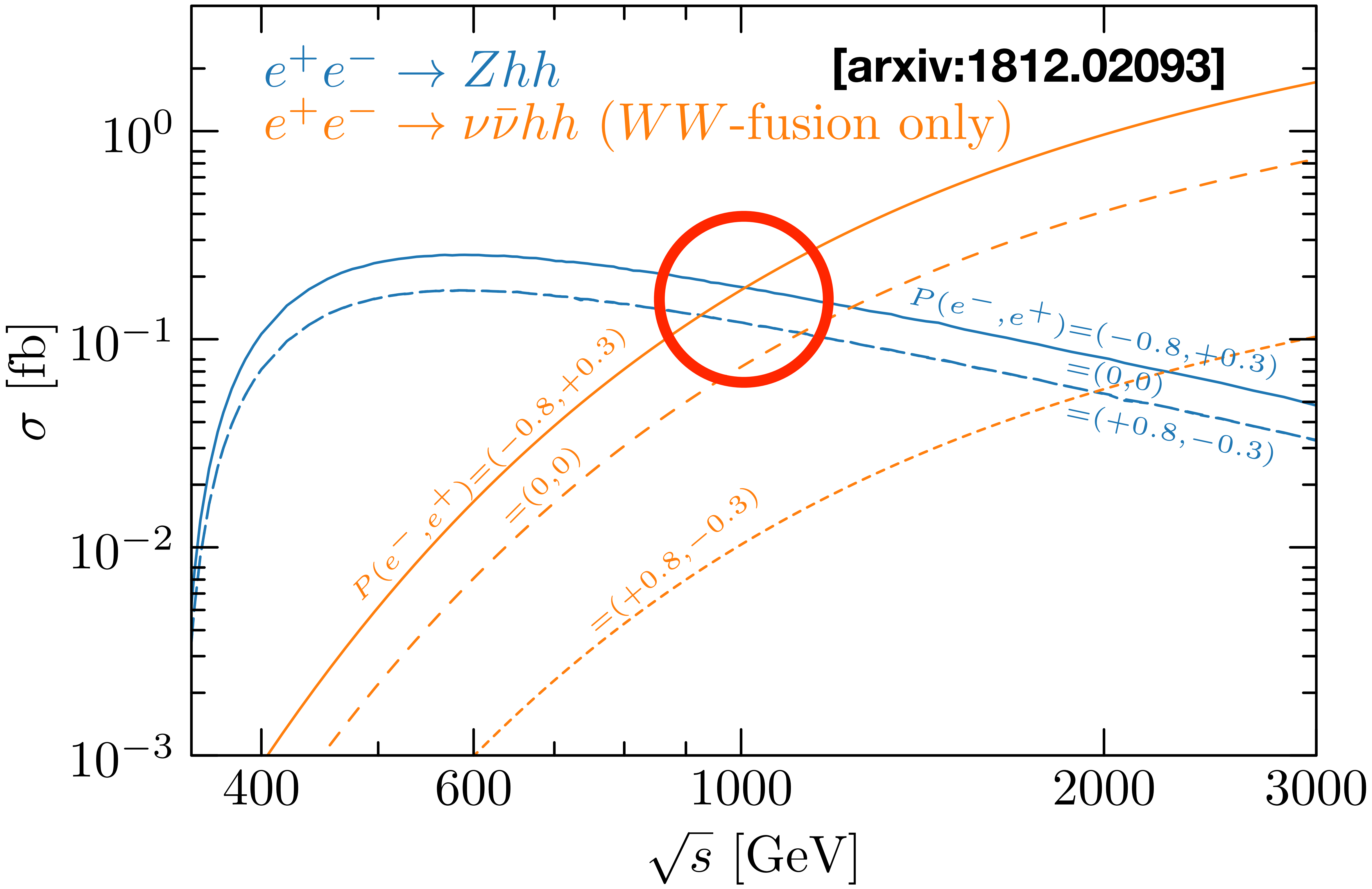
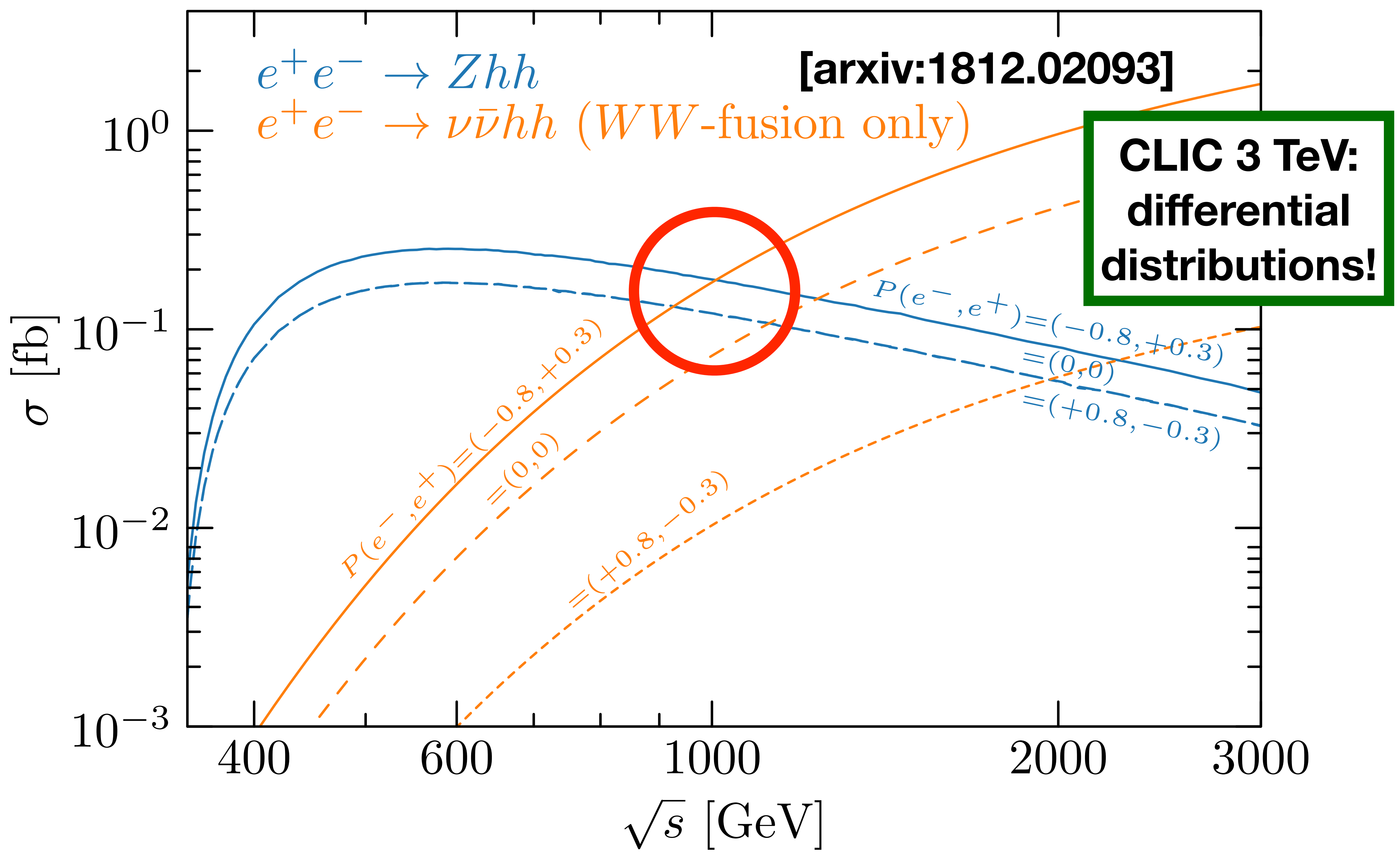
dependence on λ:
$\lambda > \lambda_{SM}$: cross section drops,
i.e. by factor ~2 for $\lambda = 2\,\lambda_{SM}$

Di-Higgs Production Cross sections - ee



ZHH: P(-80%,+30%) and P(+80%,-30%)
give about equal sensitivity
vvHH (fusion): effectively only P(-80%) counts

Di-Higgs Production Cross sections - ee



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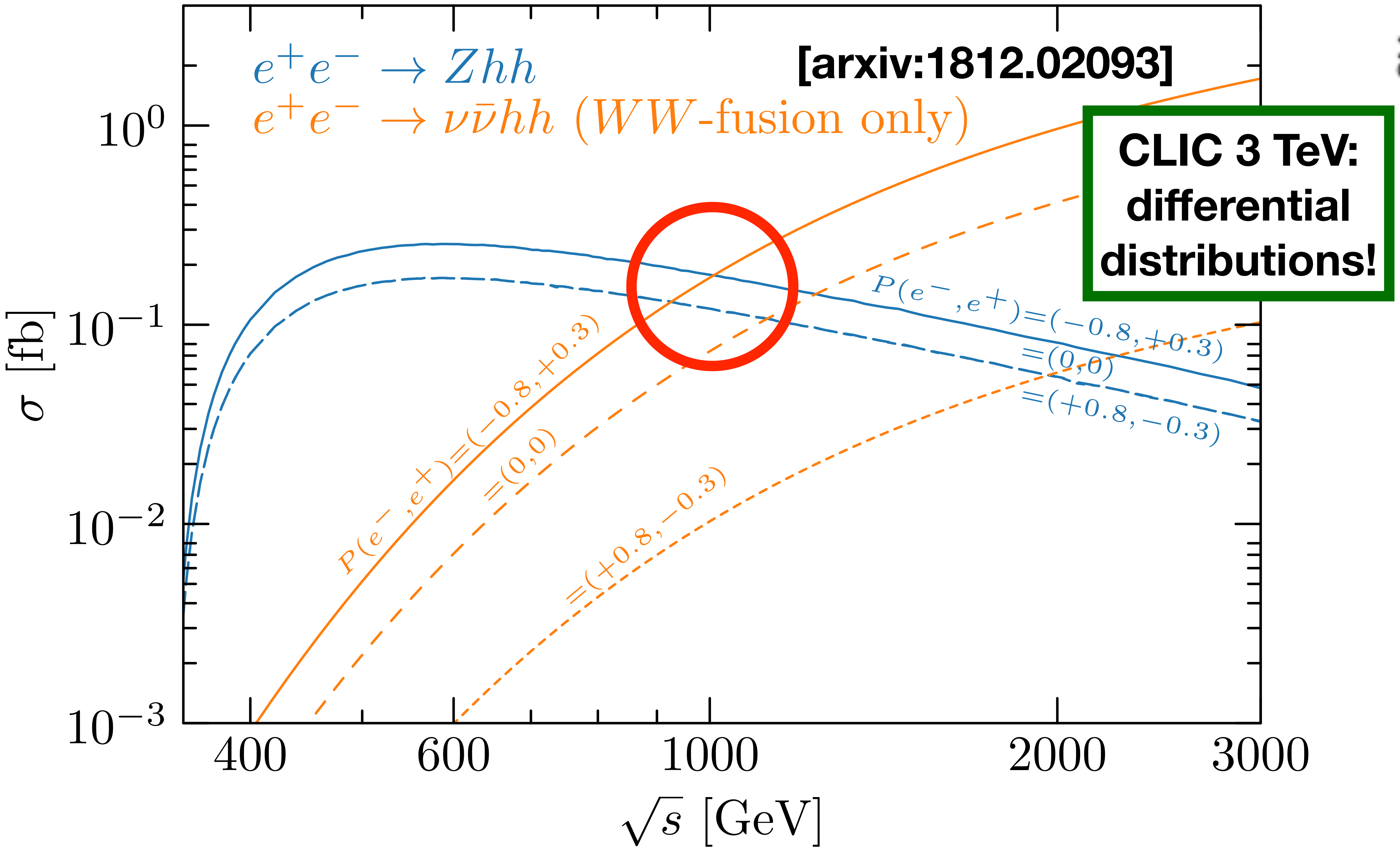

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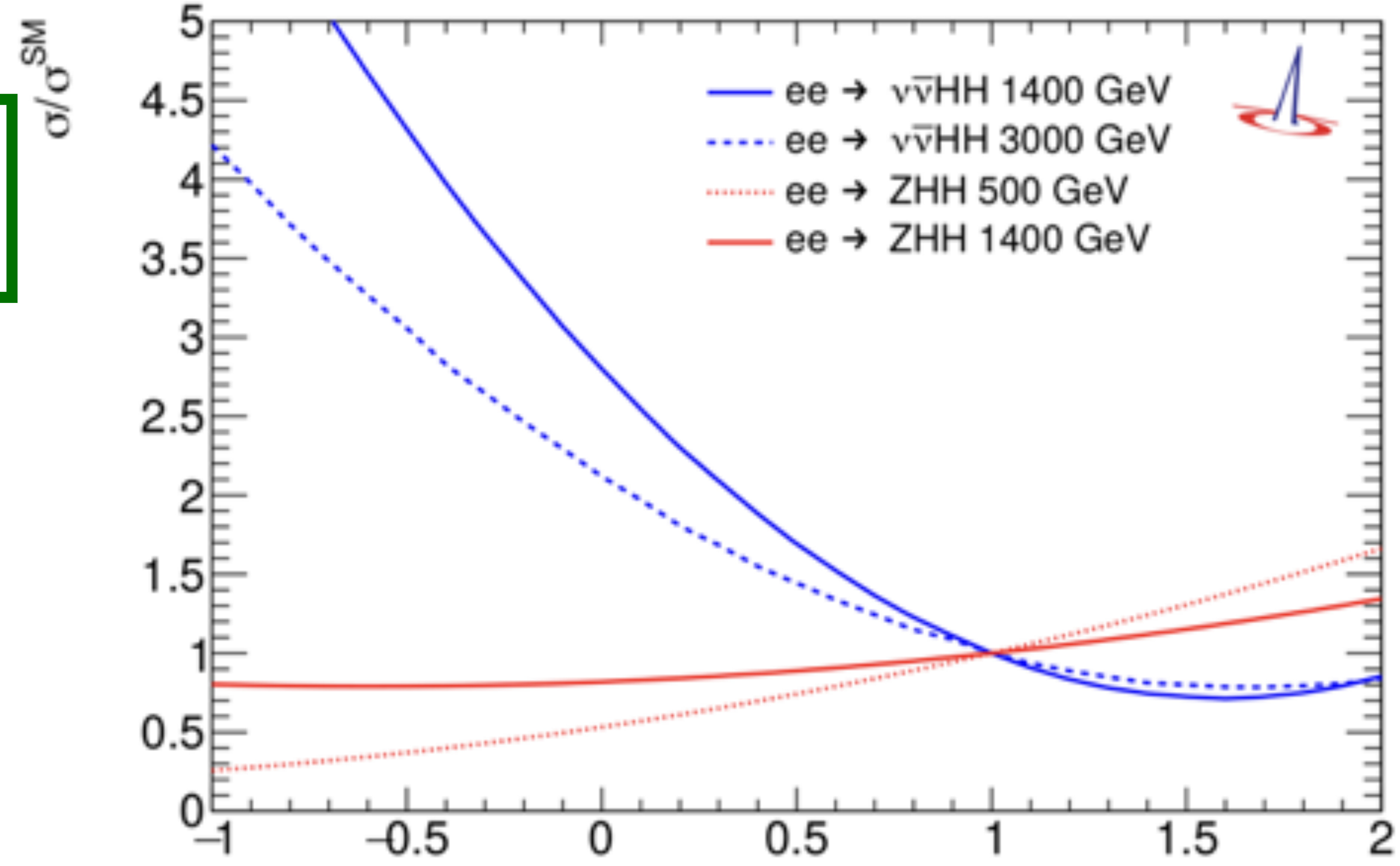

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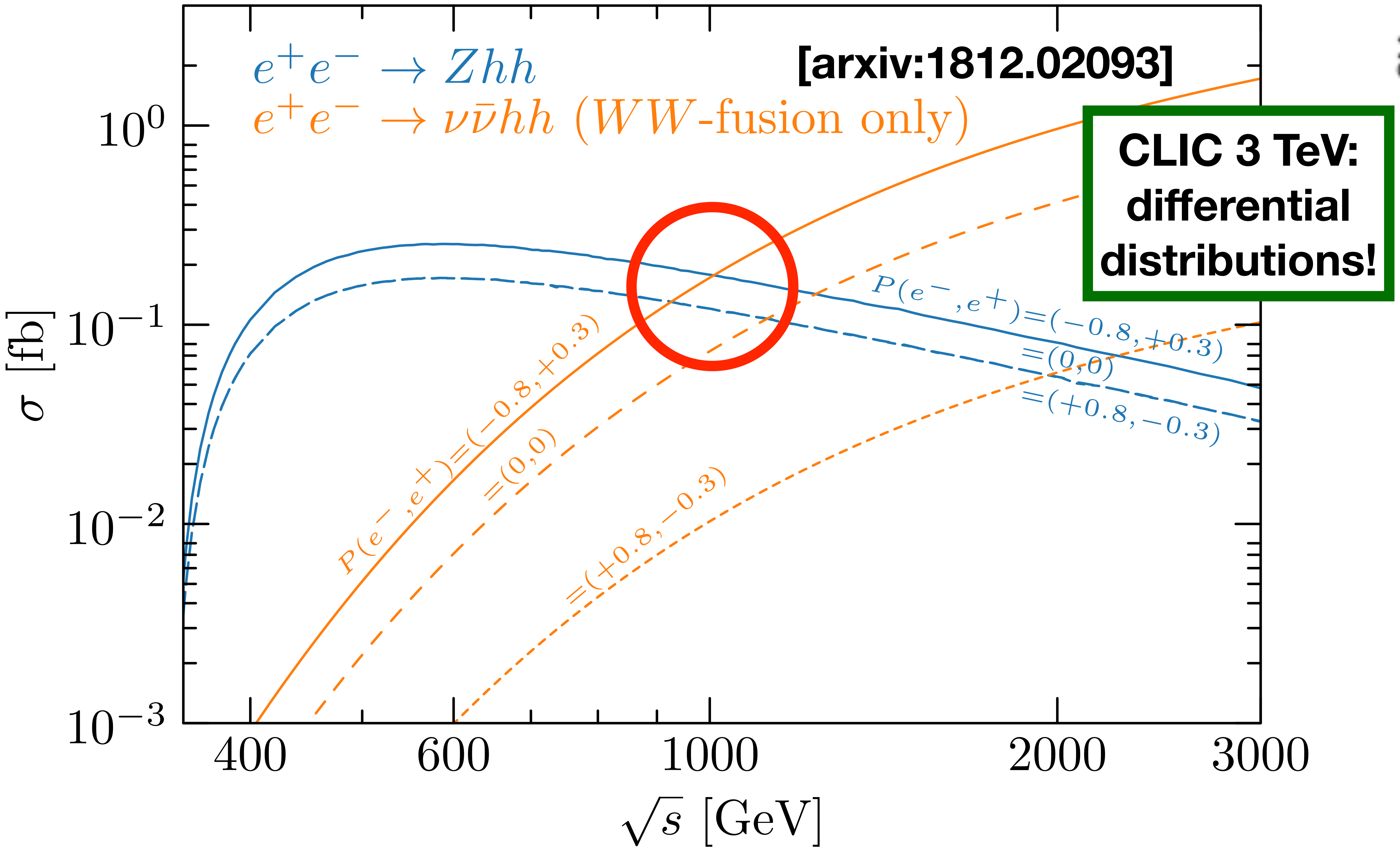

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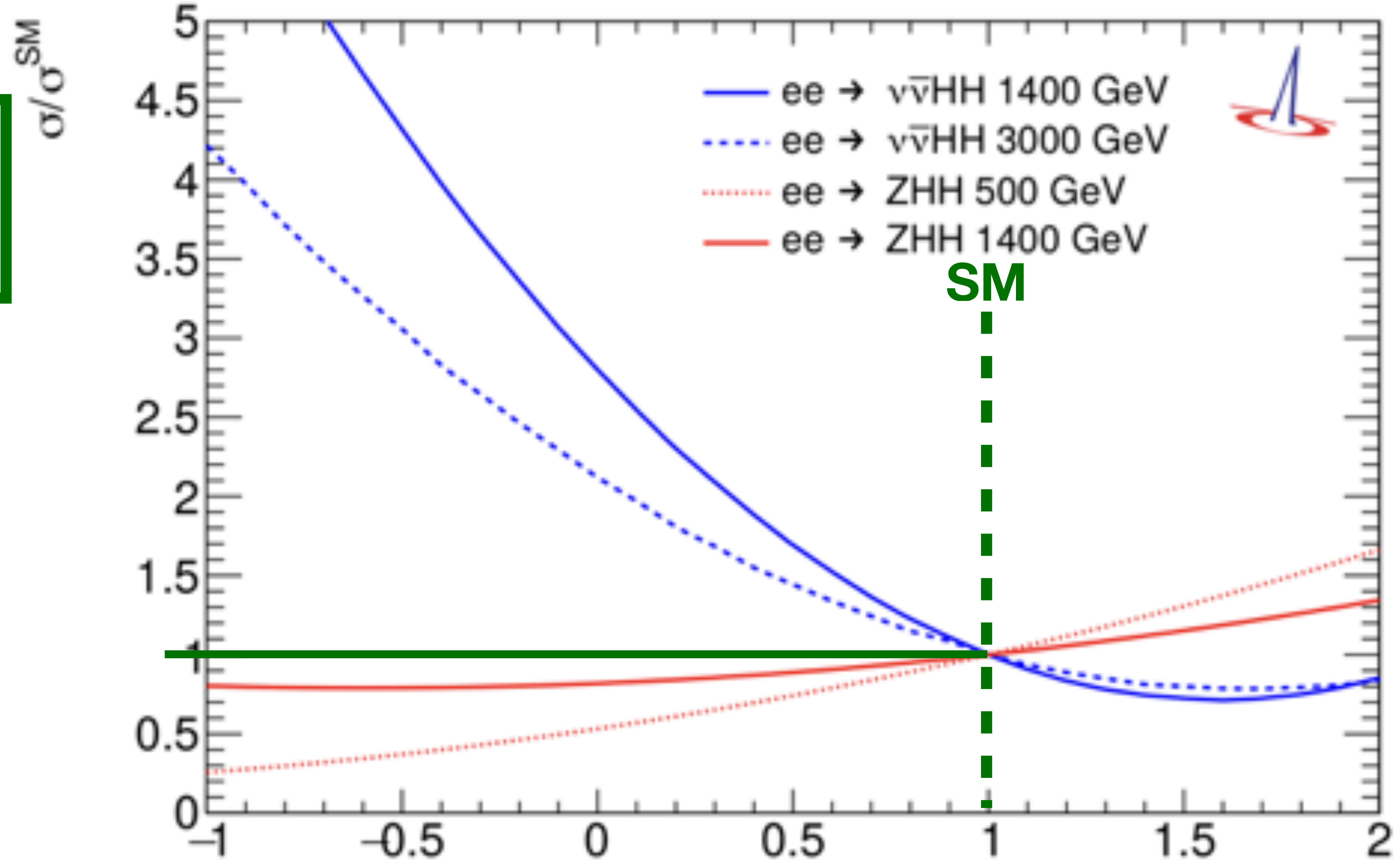

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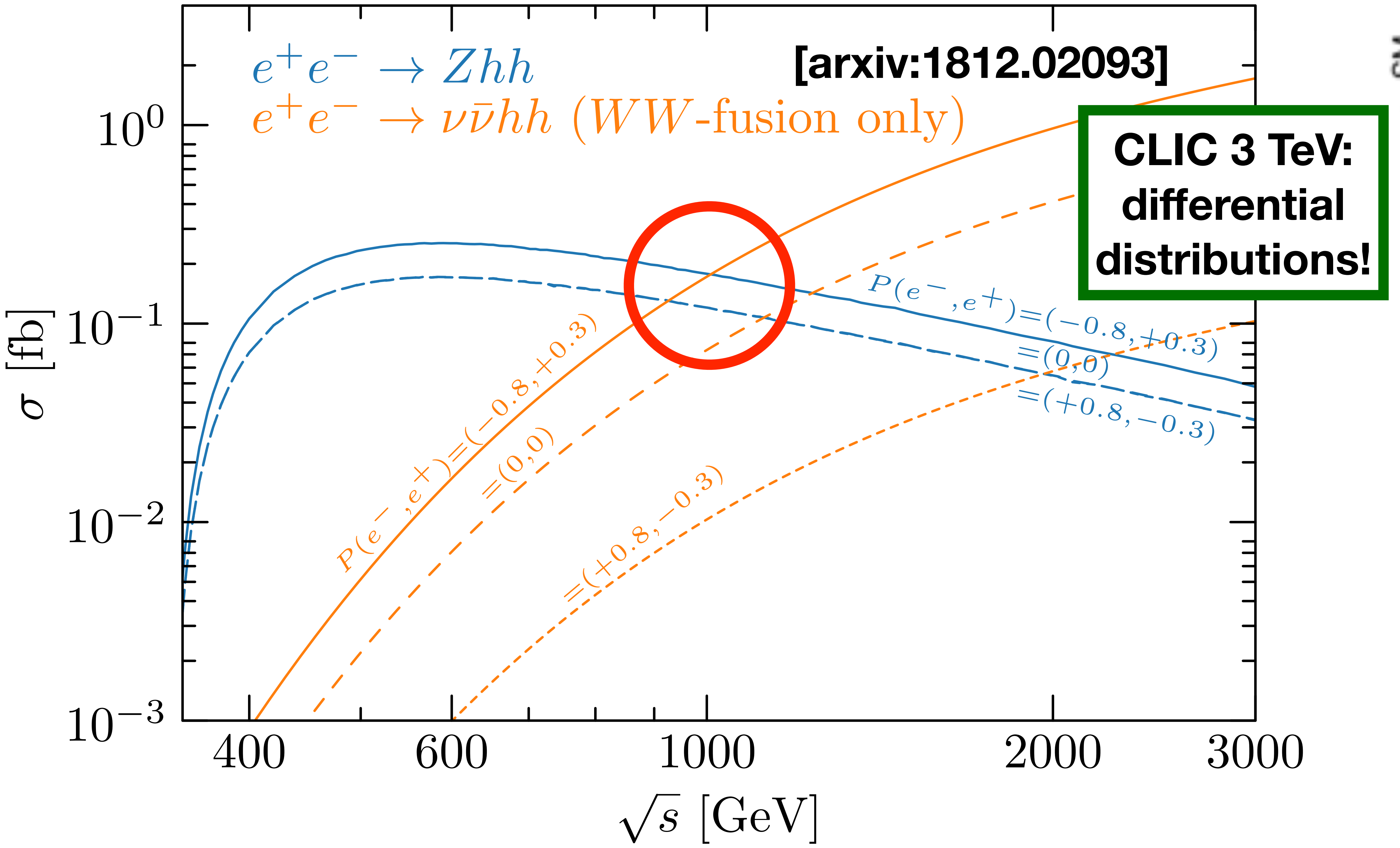

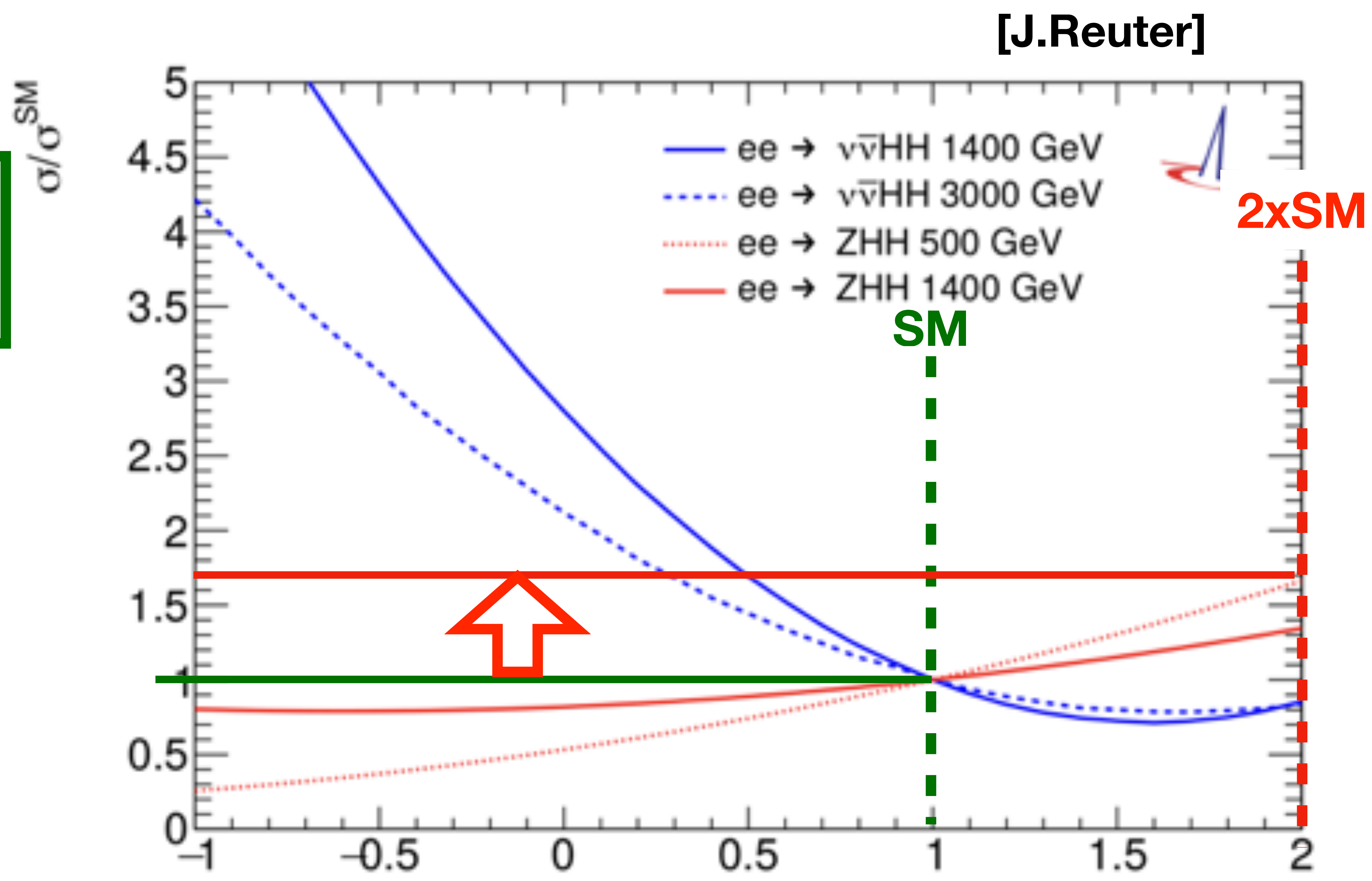

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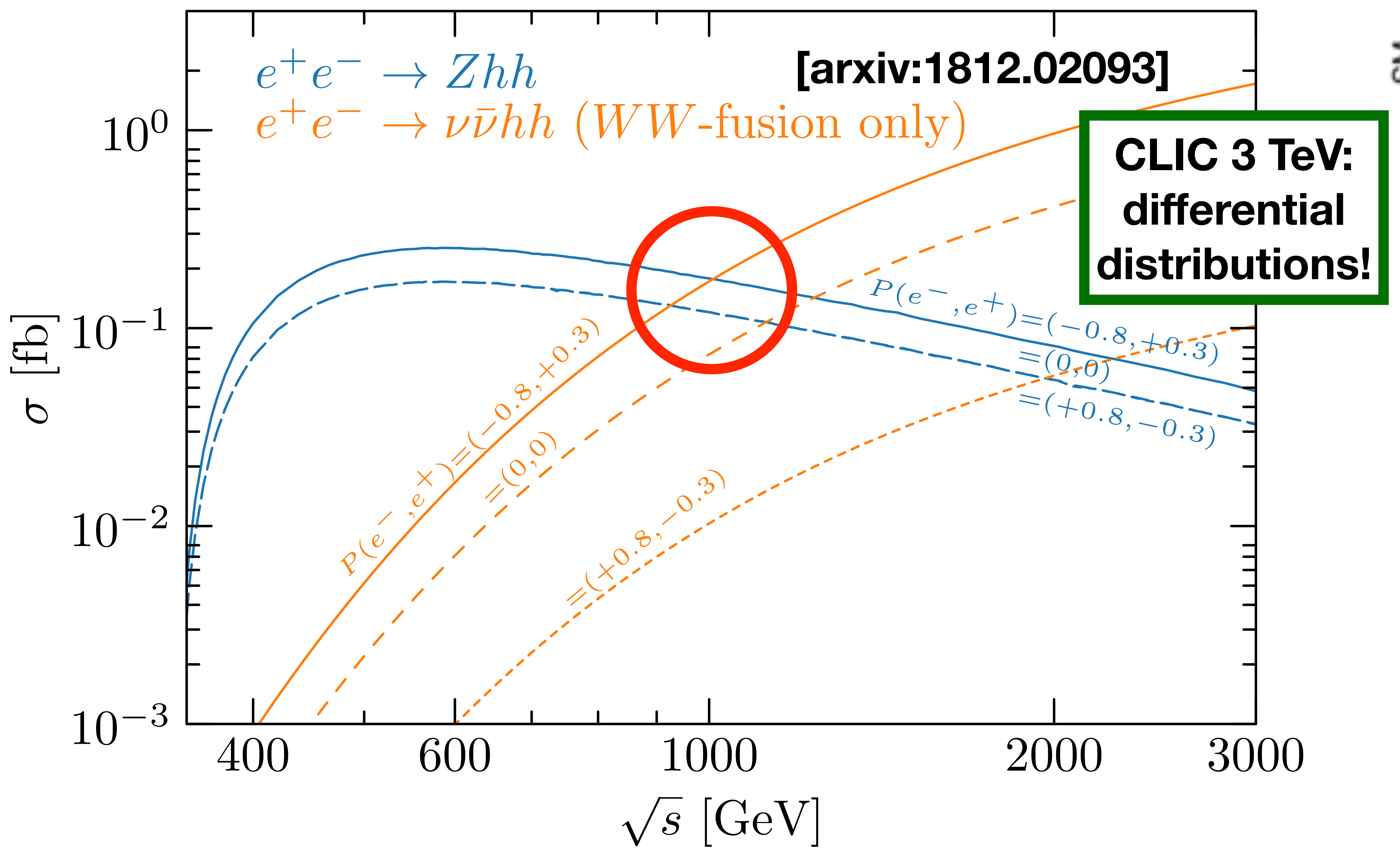

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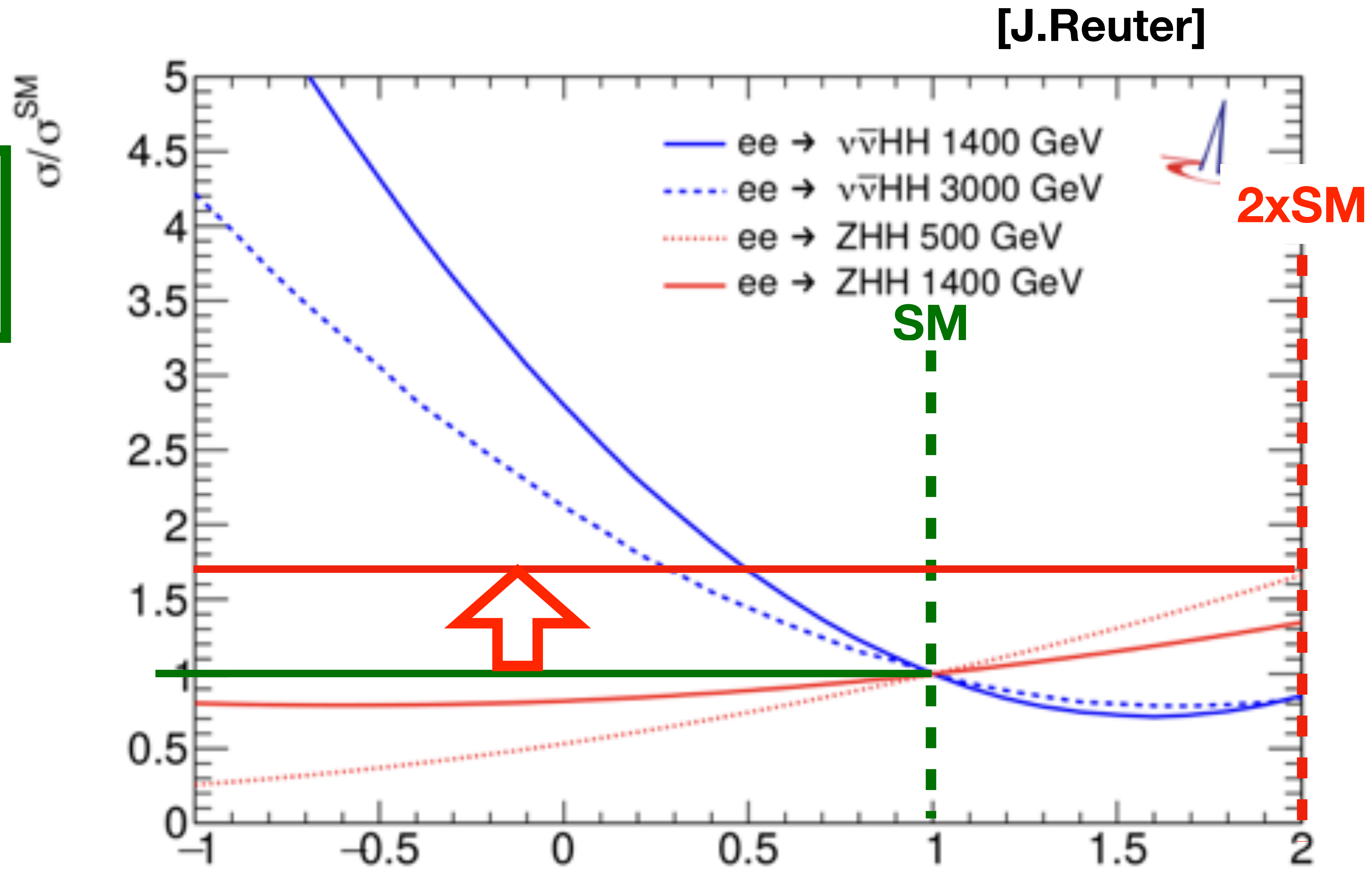


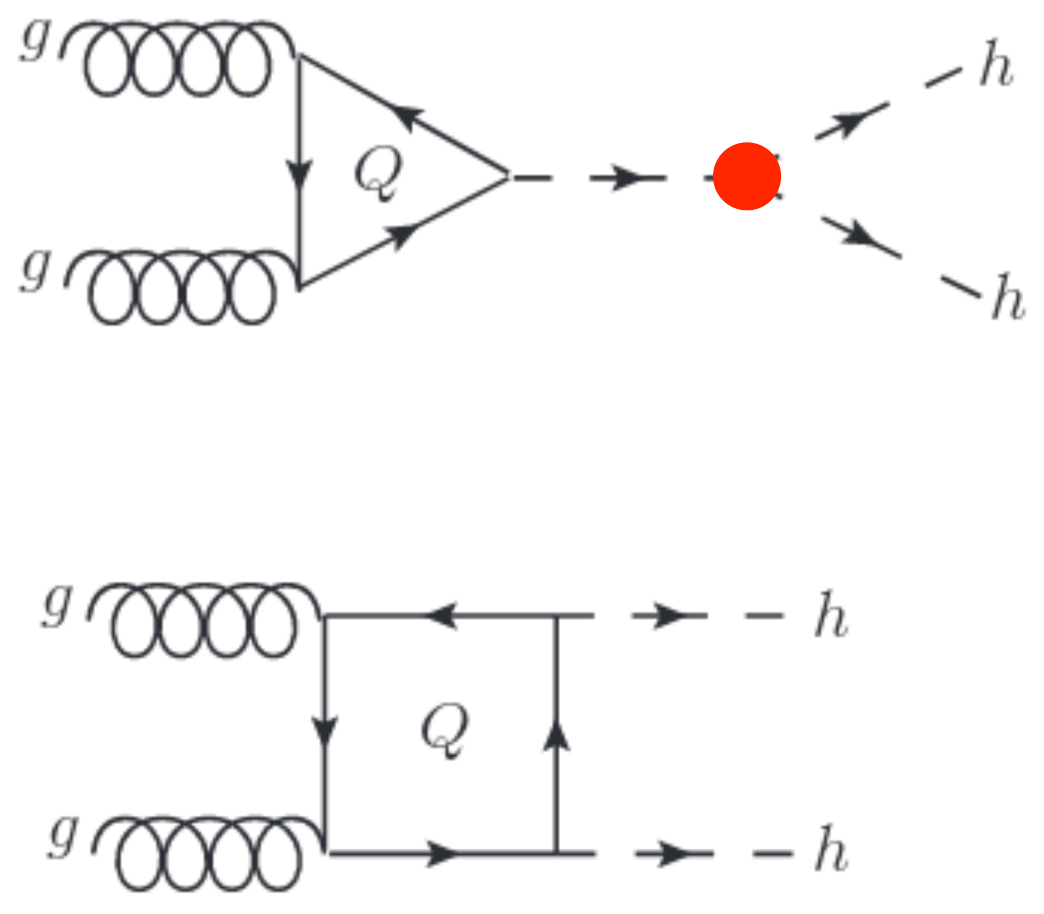
=> VBF(ee/pp)- and Higgsstrahlung (ee) di-Higgs production have orthogonal BSM behaviour

From di-Higgs production to λ

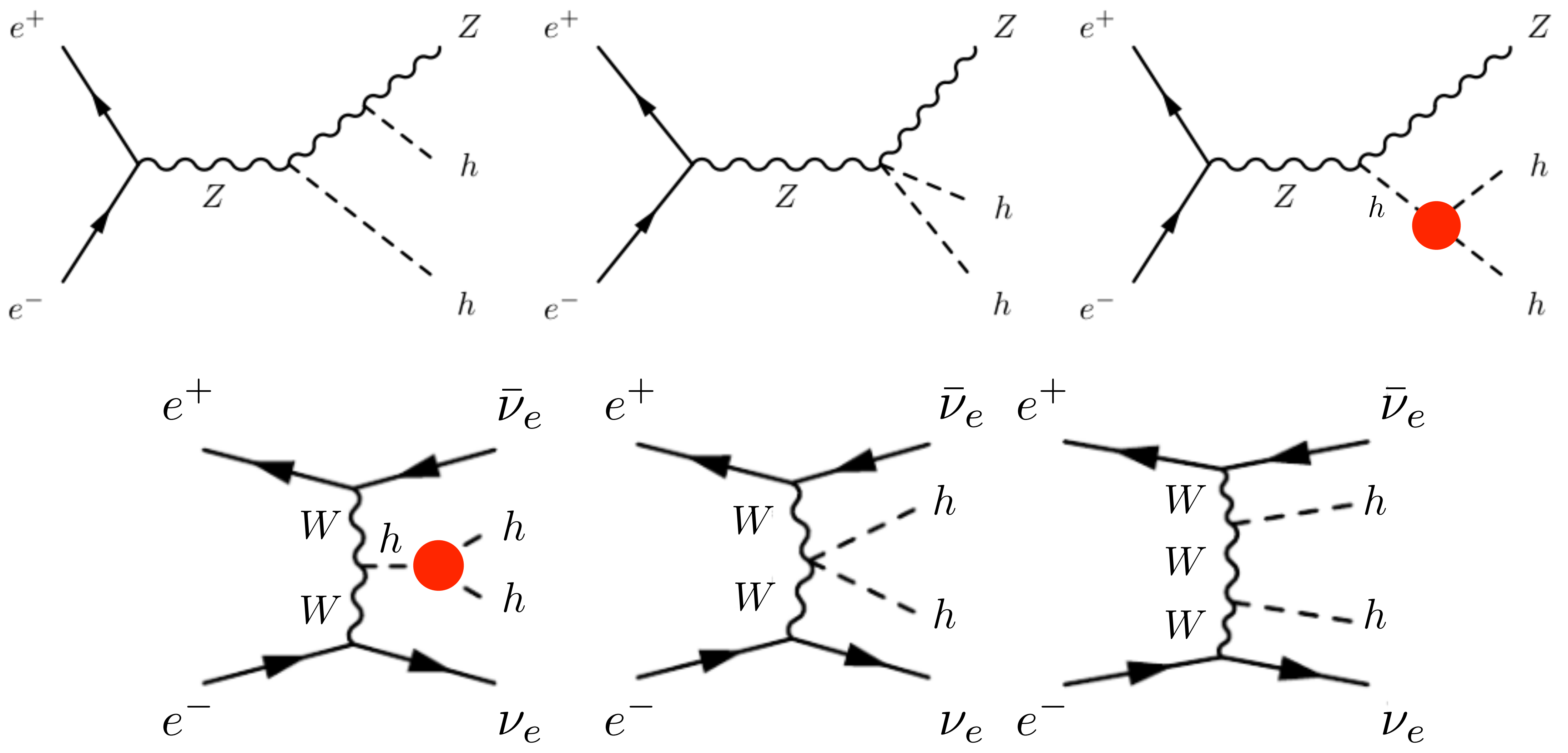
1. Discover di-Higgs production
2. Measure cross section (total and differential!)
3. Extract λ

- Interference of diagrams with / without triple Higgs vertex ●
  => **$k := (\delta\lambda/\lambda)/(\delta\sigma/\sigma) > 1/2$**
- k can be “improved” by using *differential* information
- **k depends on: process, *value of λ* and *E_{CM}***

Hadron collider



Lepton collider



ILC Sensitivity vs Lambda

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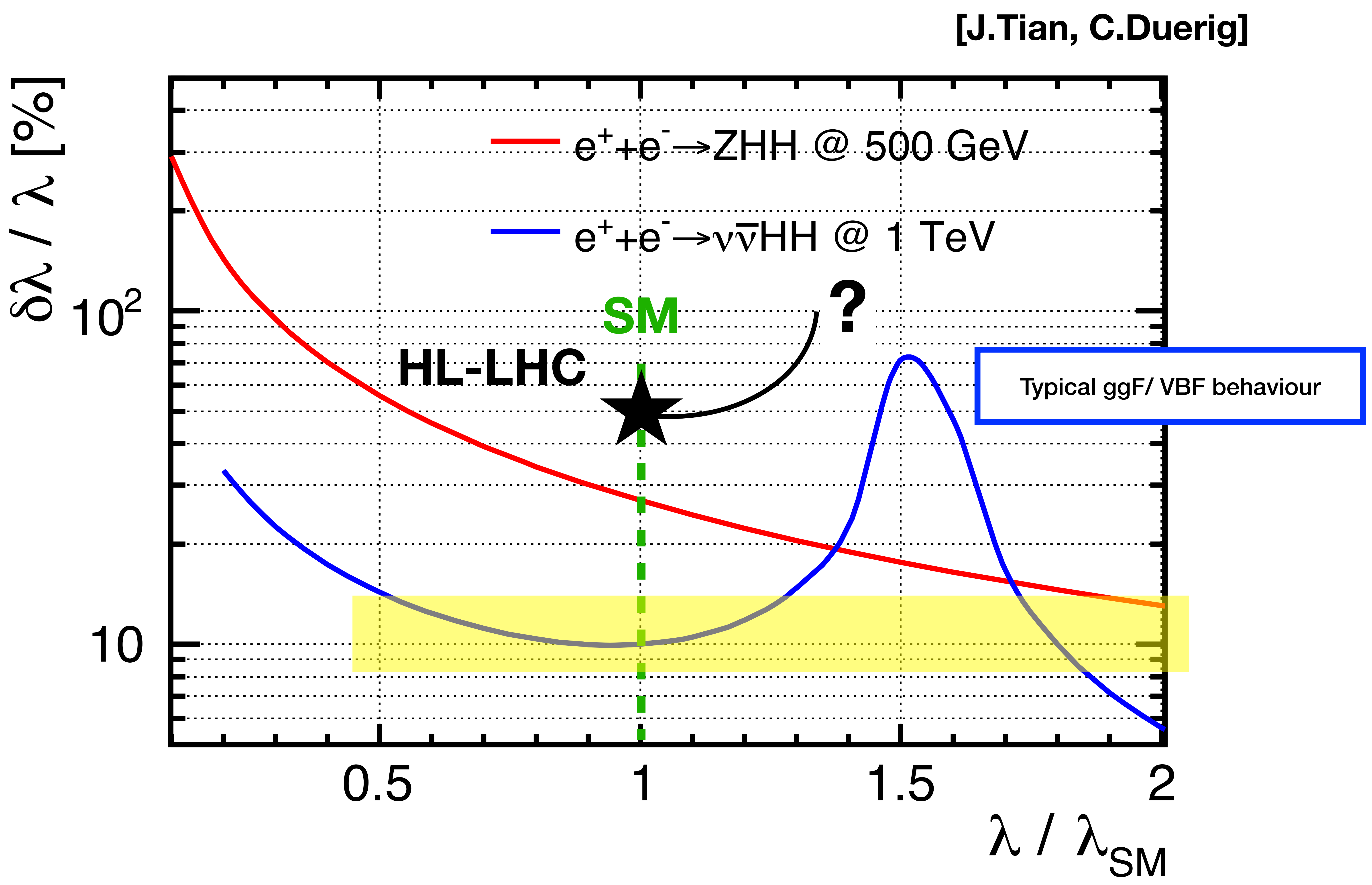

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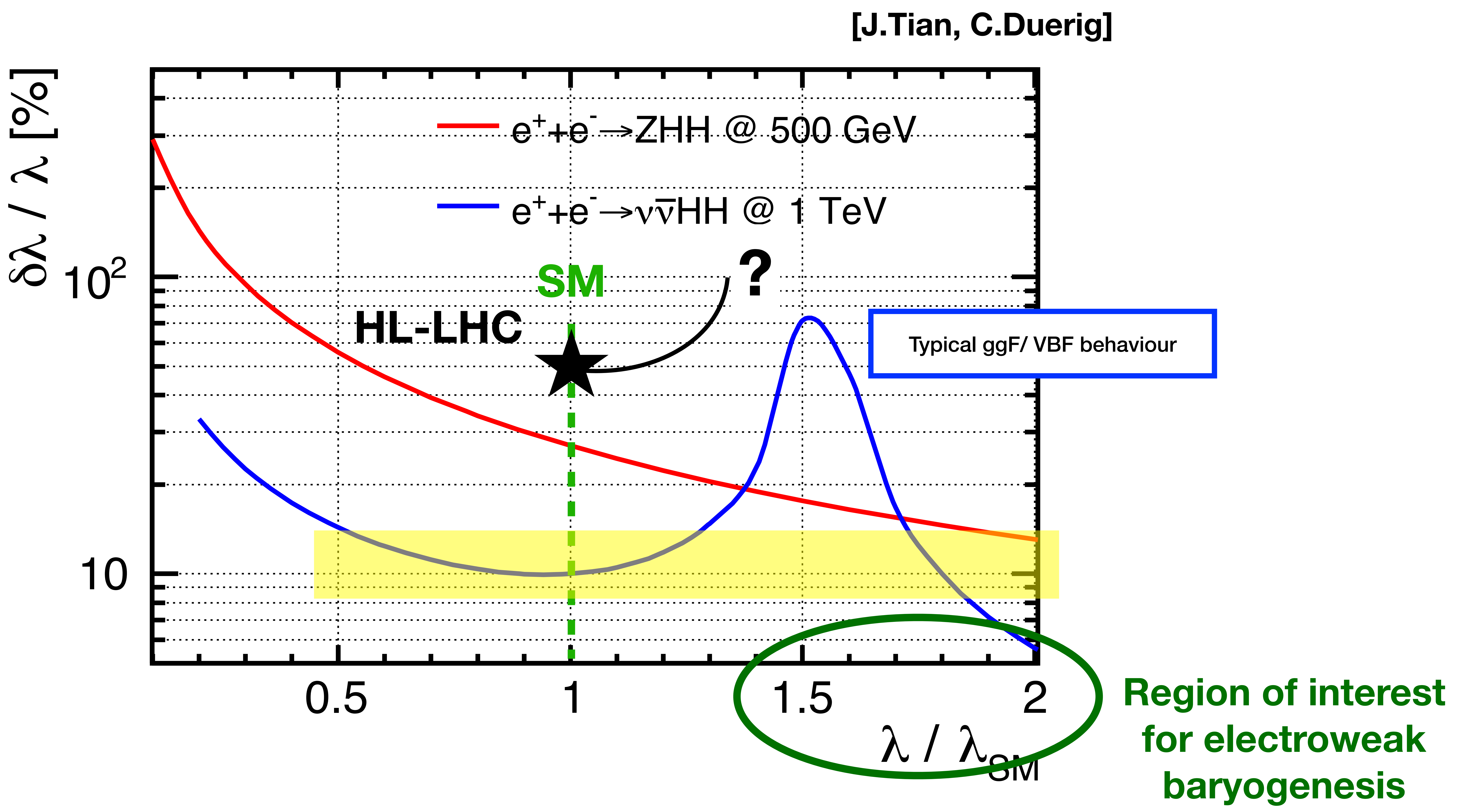
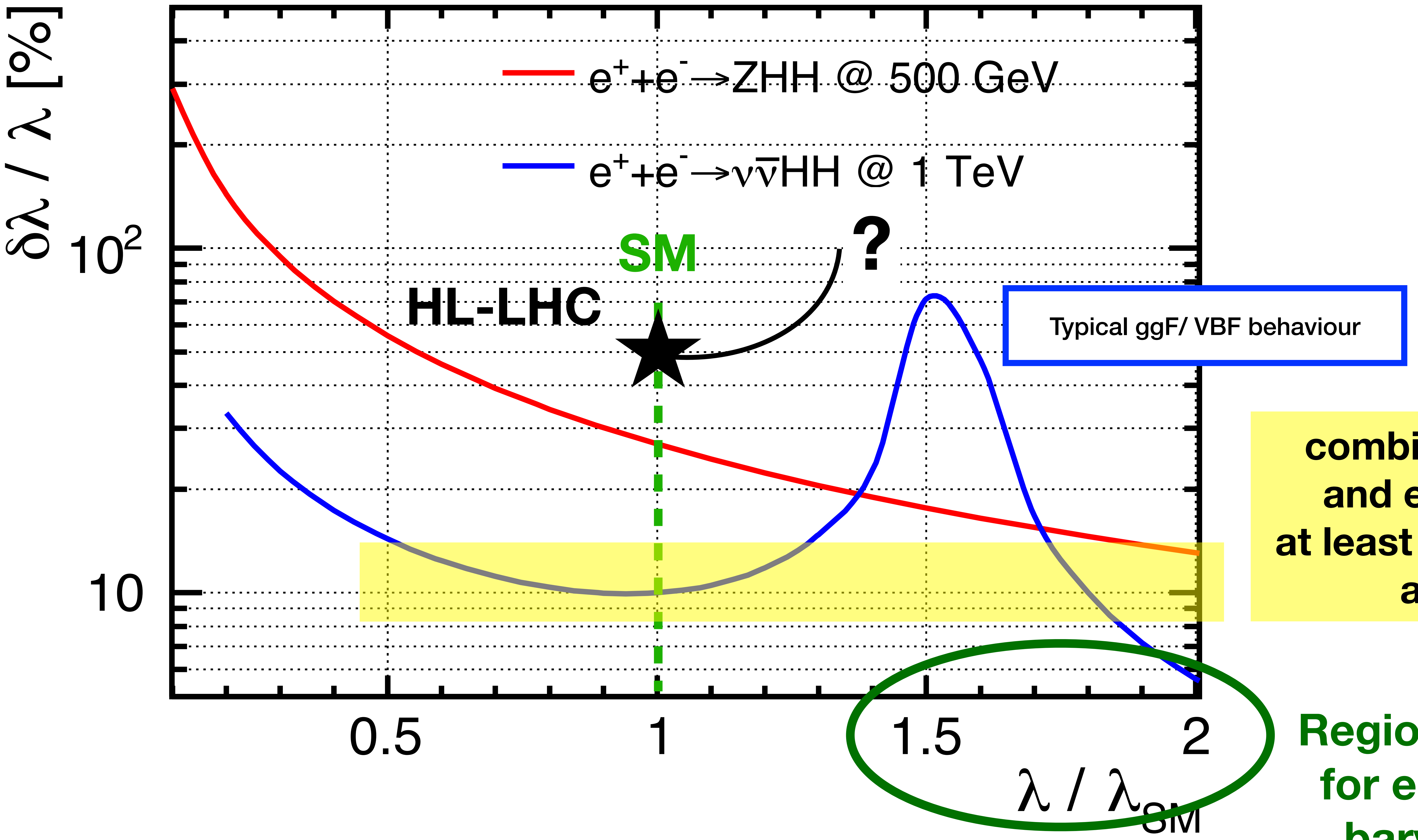


ILC Sensitivity vs Lambda

[J.Tian, C.Duerig]

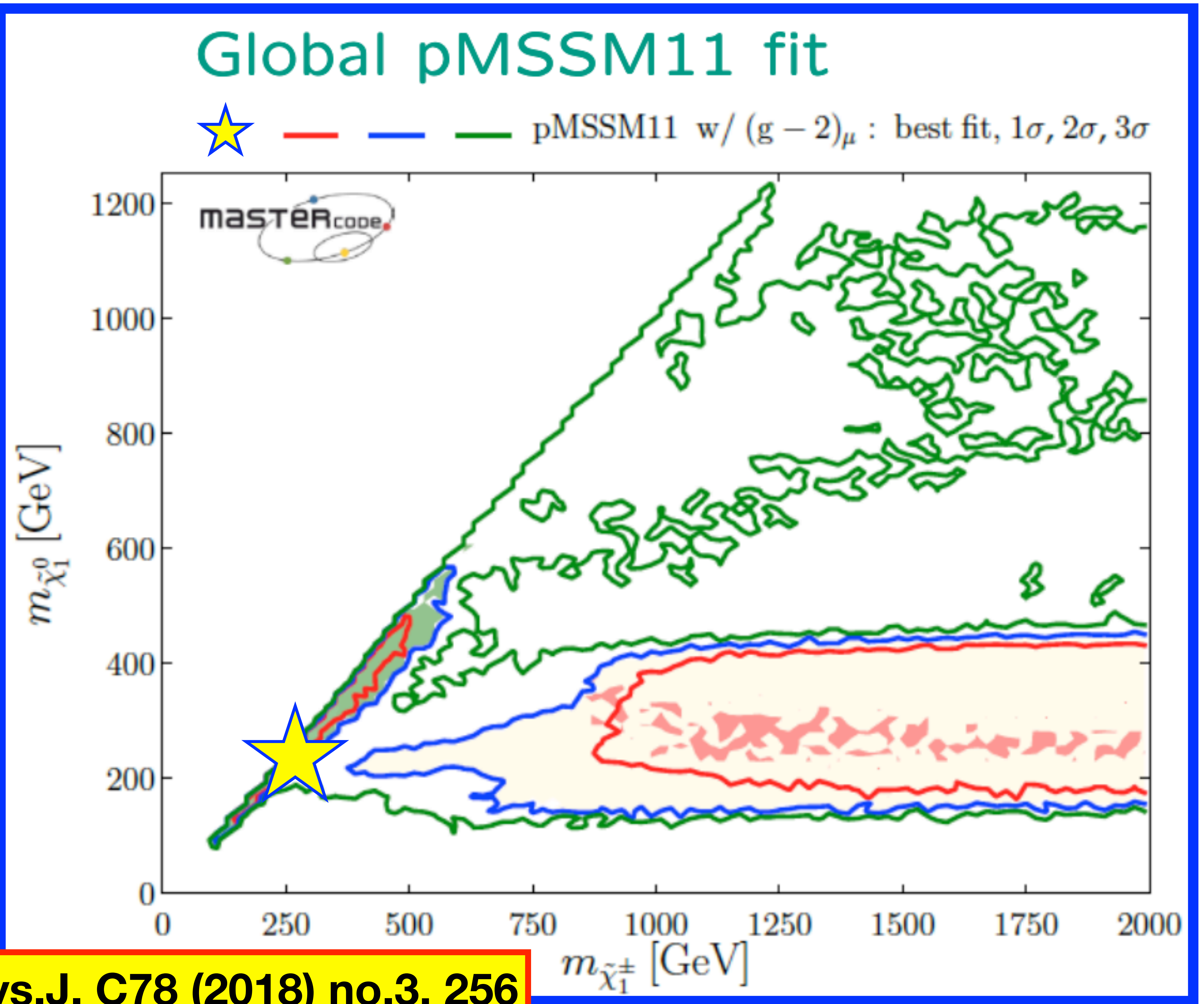


combination of e+e- -> ZHH and e+e- -> vvHH ensures at least 10-15% precision over a wide range in λ

Region of interest for electroweak baryogenesis

Higgsinos ?

- **lowish ΔM is THE region preferred by data, e.g. for charginos & neutralinos**
  => no *general* limit above LEP



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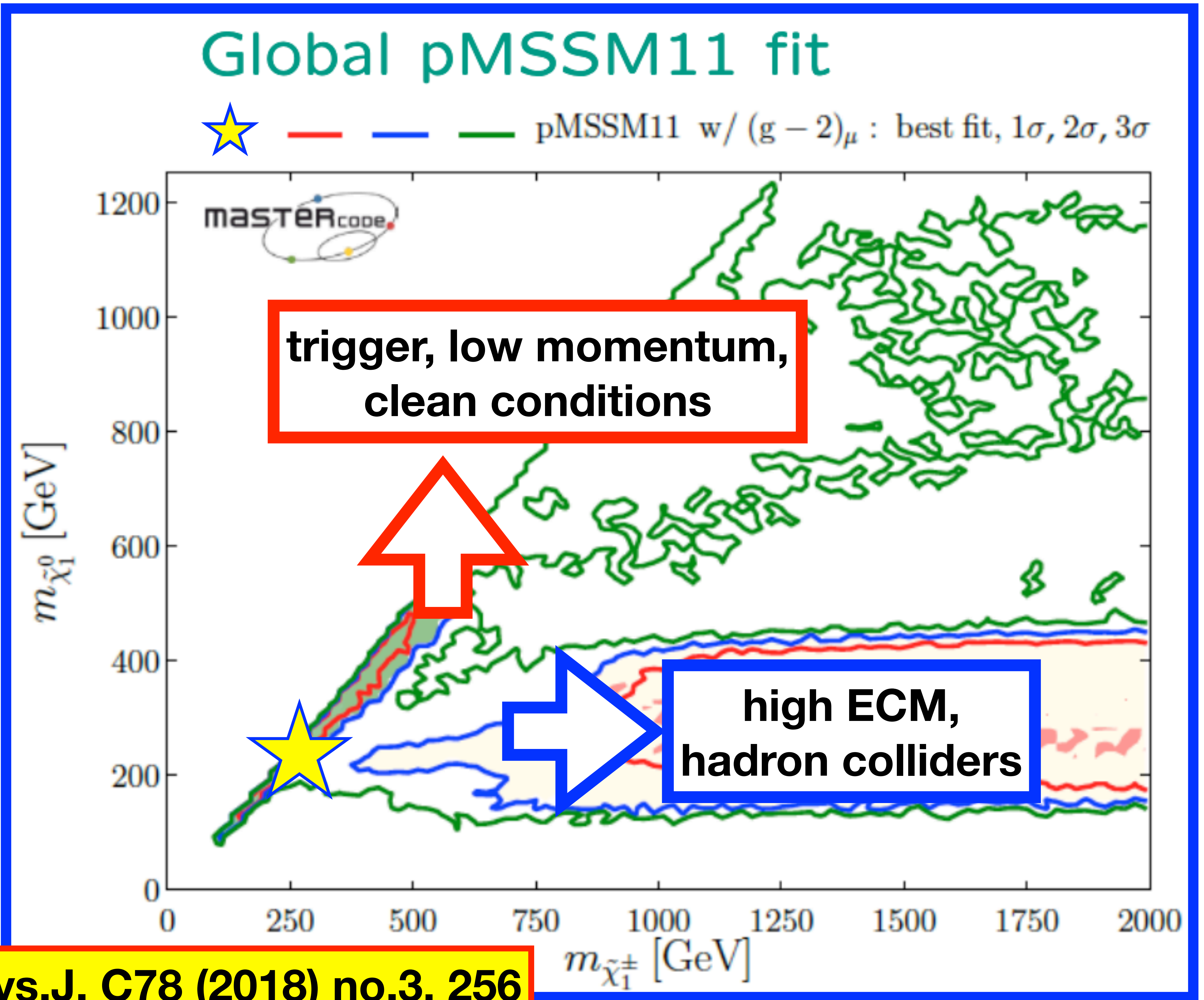

Eur.Phys.J. C78 (2018) no.3, 256

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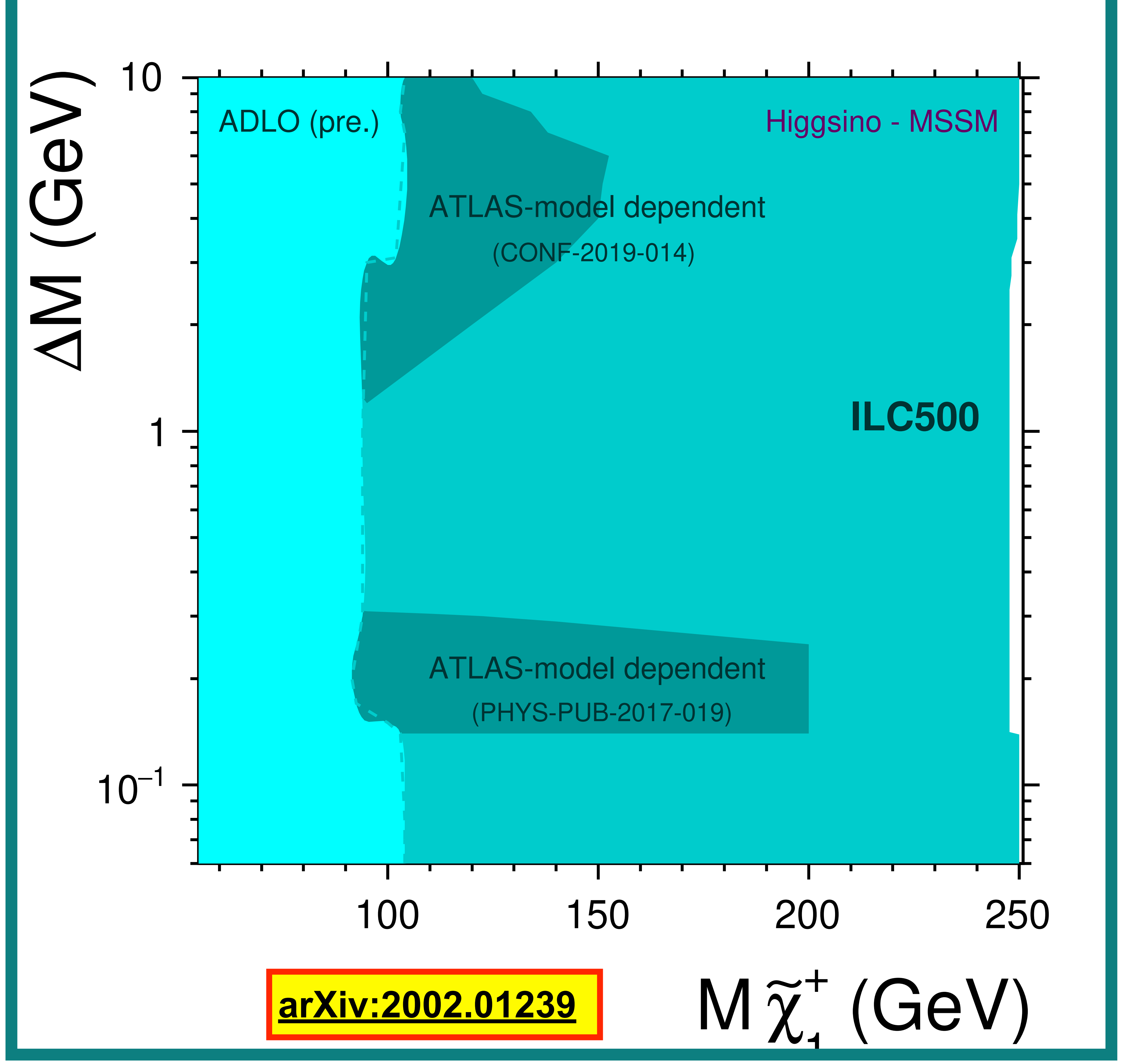
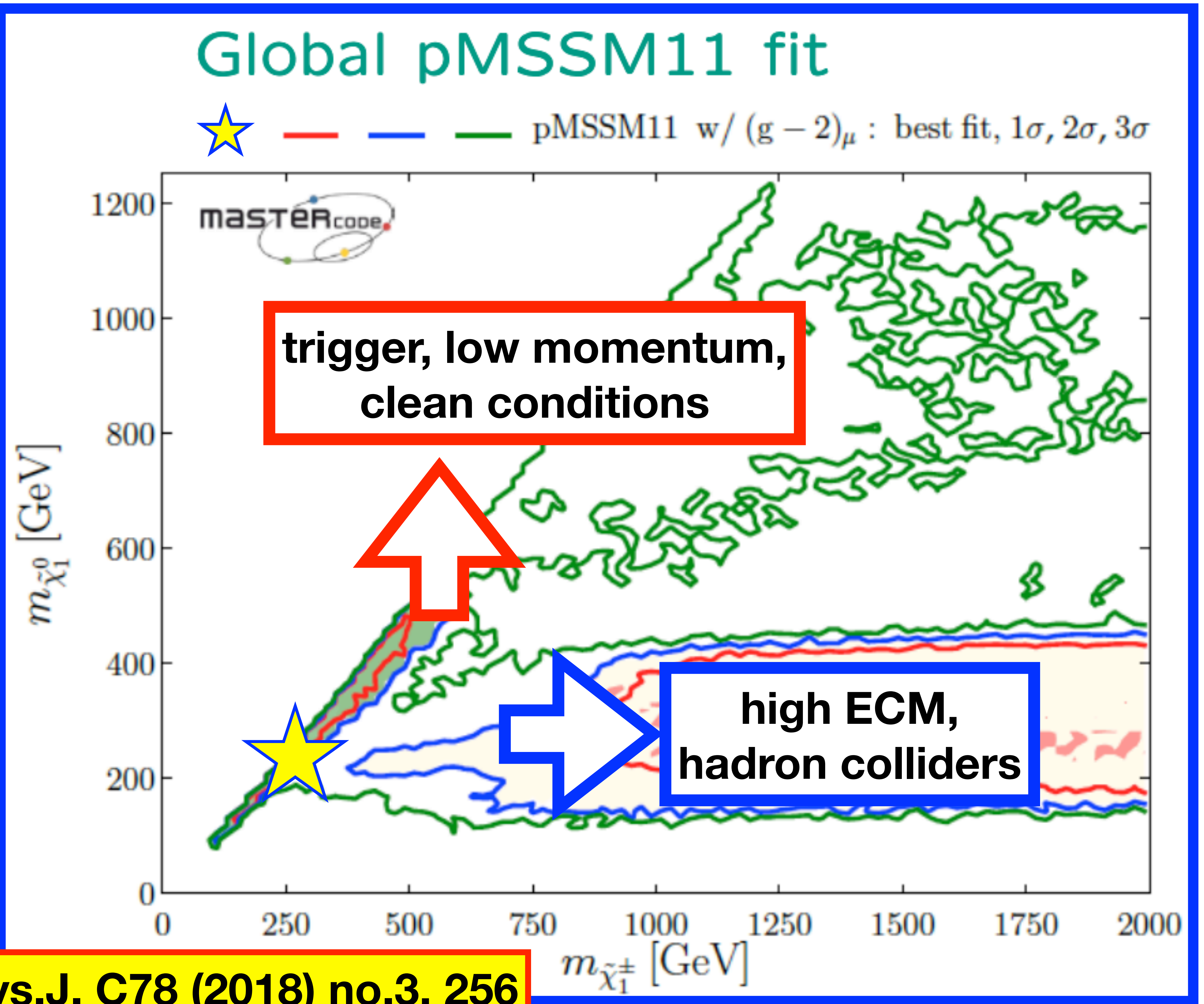


arXiv:2002.01239



Eur.Phys.J. C78 (2018) no.3, 256

ILC running modes - and Z production

ILC e^+e^- collider

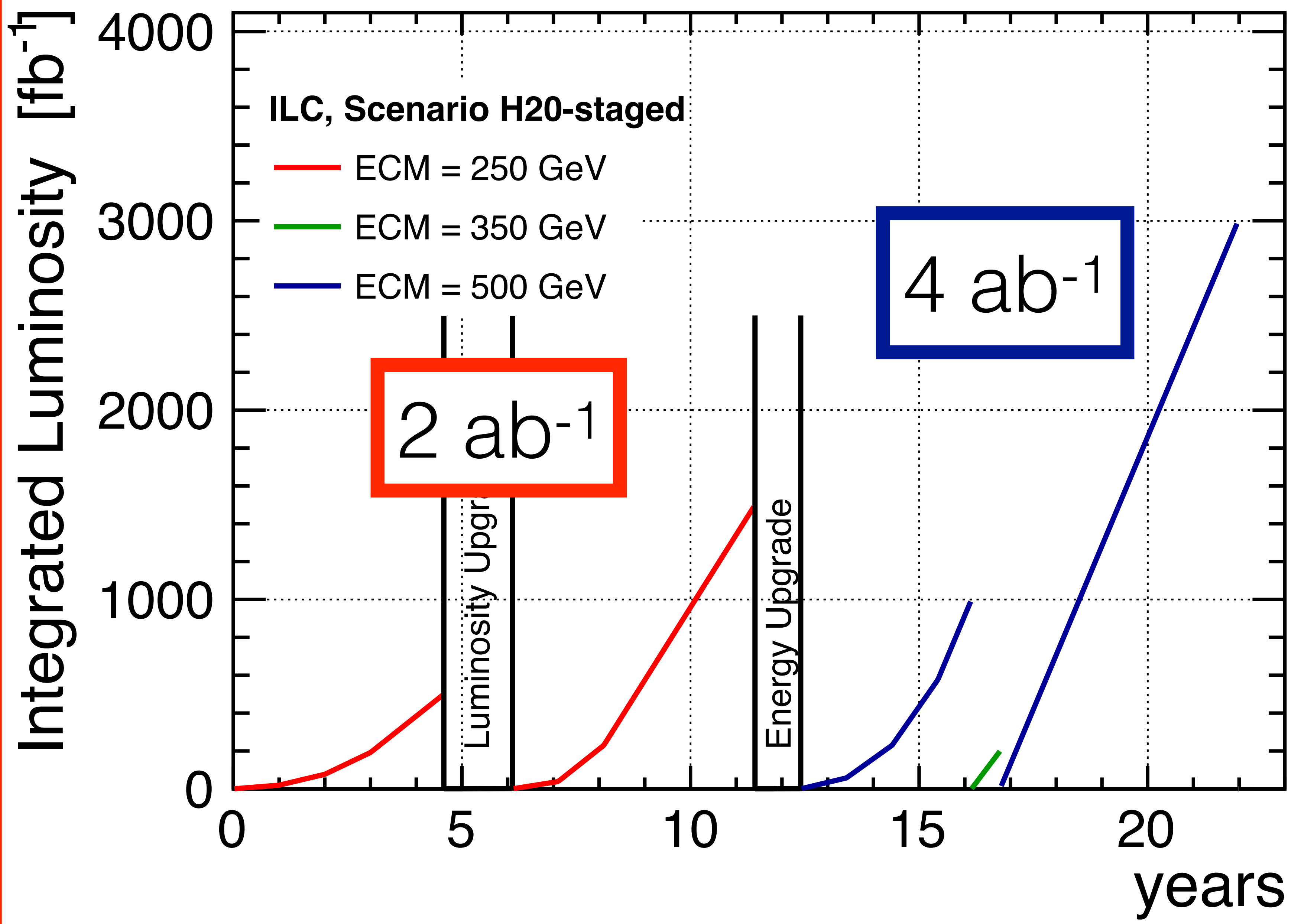
- first stage: 250 GeV
- GigaZ & WW threshold possible
- upgrades: 500 GeV, 1 TeV

polarised beams

- $P(e^-) \geq \pm 80\%$,
- $P(e^+) = \pm 30\%$,
  at 500 GeV upgradable to 60%

Since 2015
arXiv:1506.07830

$\sqrt{s}$	$\int \mathscr{L} dt$
250 GeV	2 ab^{-1}
350 GeV	0.2 ab^{-1}
500 GeV	4 ab^{-1}
1 TeV	8 ab^{-1}
91 GeV	0.1 ab^{-1}
161 GeV	0.5 ab^{-1}



(radiative) Z's in 2 ab^{-1} at **250 GeV**:

- ~77 10^6 Z->qq
- ~12 10^6 Z->ll

=> substantial increase over LEP,
….and polarised!

Z's in 0.1ab^{-1} at **91 GeV**:

- ~3.4 10^9 Z->qq
- ~0.5 10^9 Z->ll

~1-2 years of running (after lumi upgrade)

Accelerator implementation - arXiv:1908.08212

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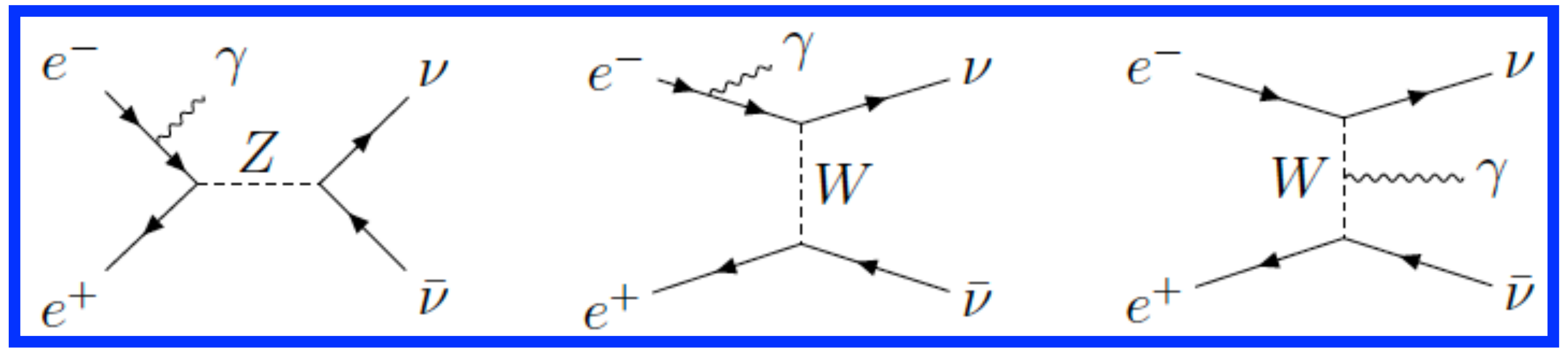
Polarisation & Beyond the SM: Dark Matter

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) = (–,+), (+,–), (+,+), (–,–)
  beats down the effect of systematic uncertainties

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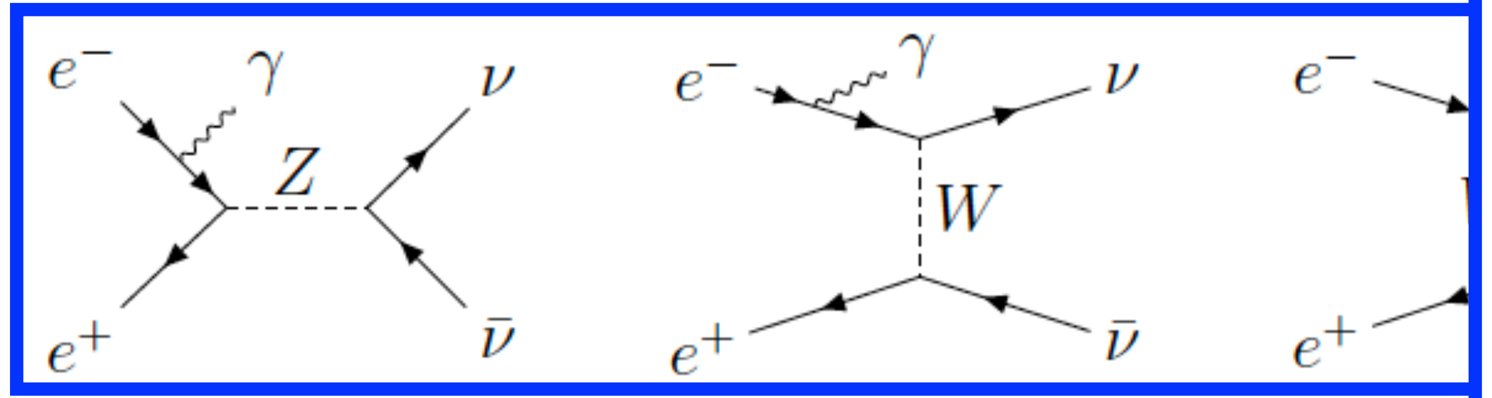

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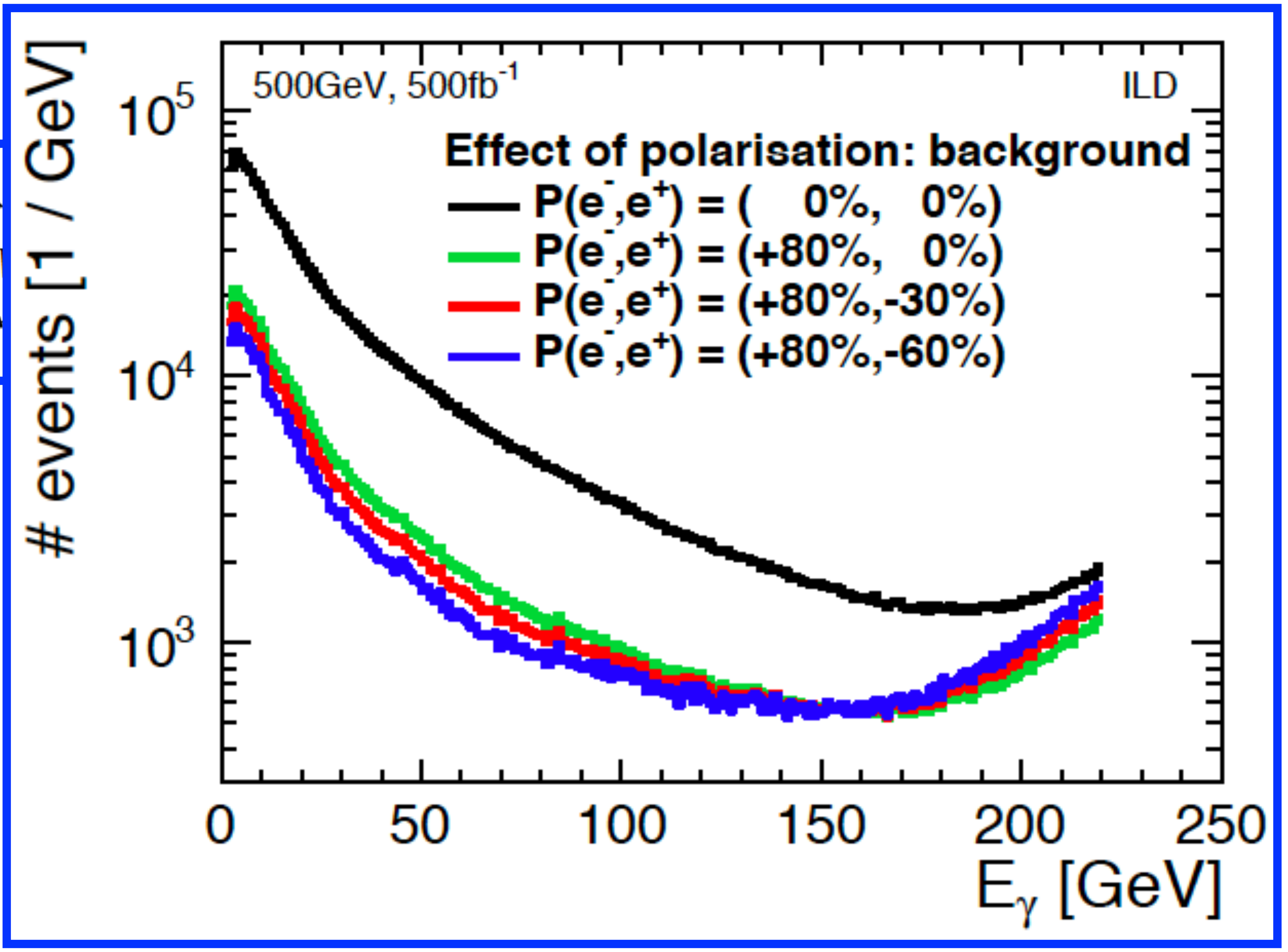

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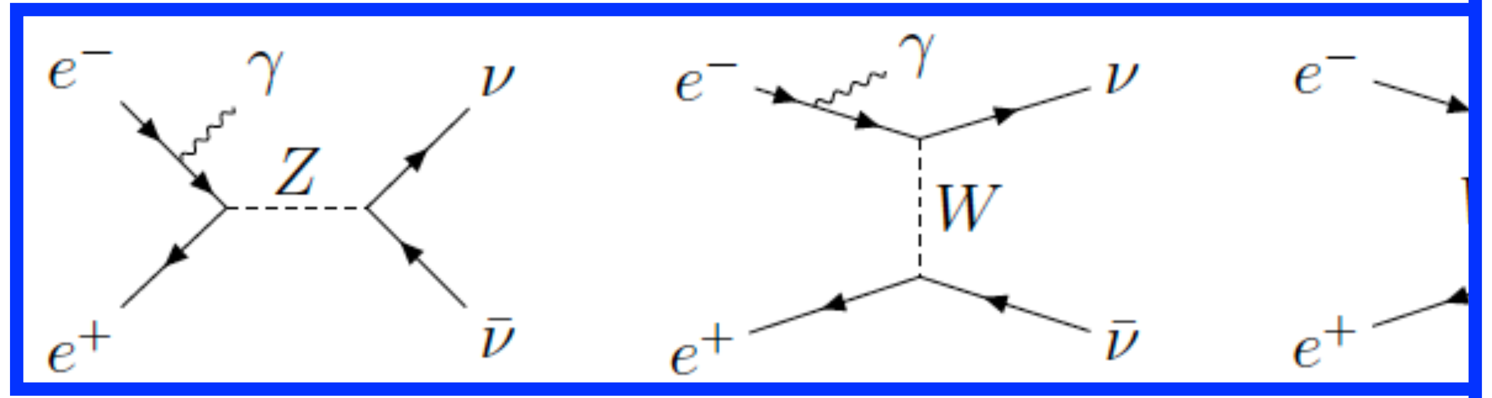

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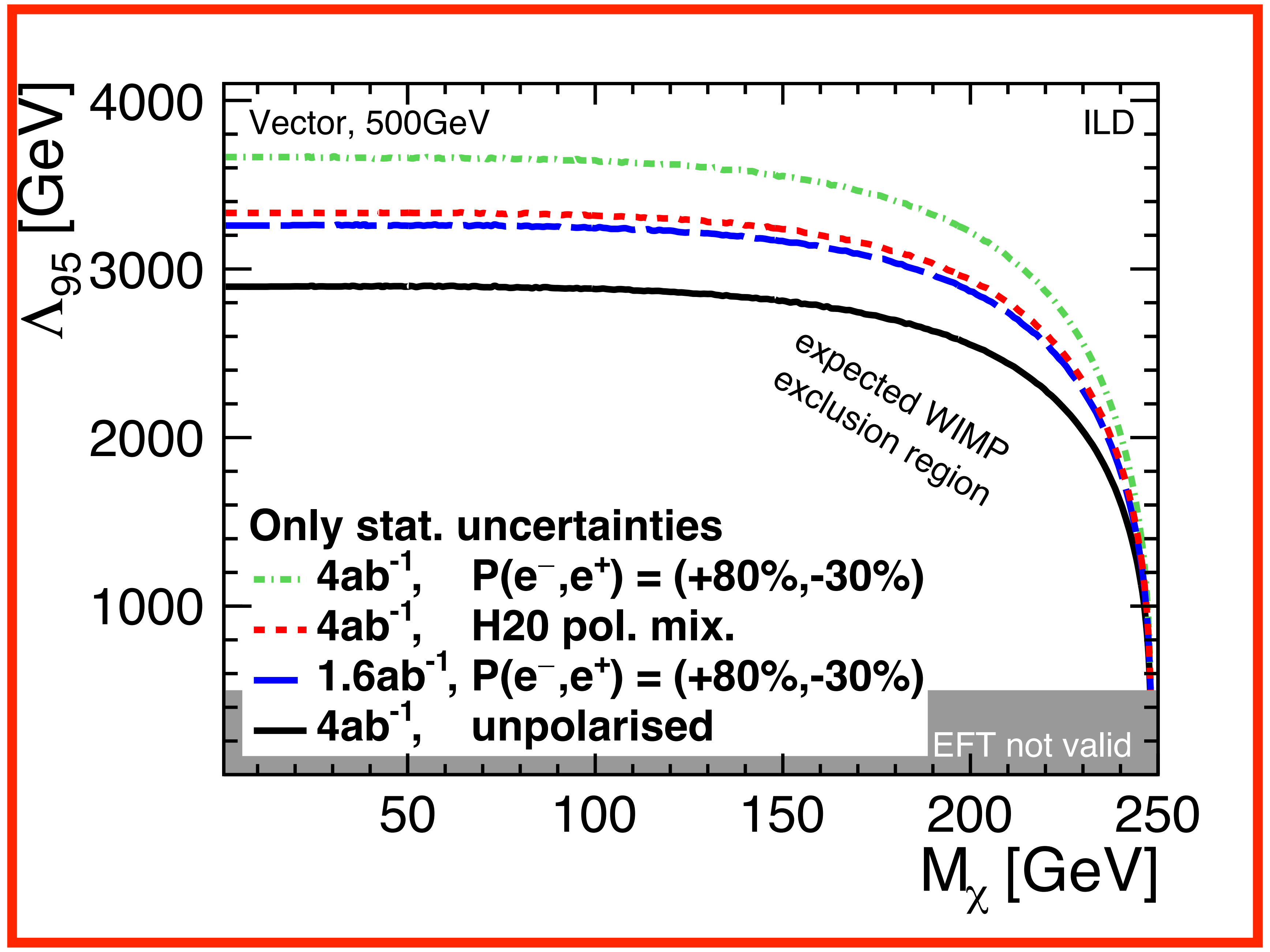

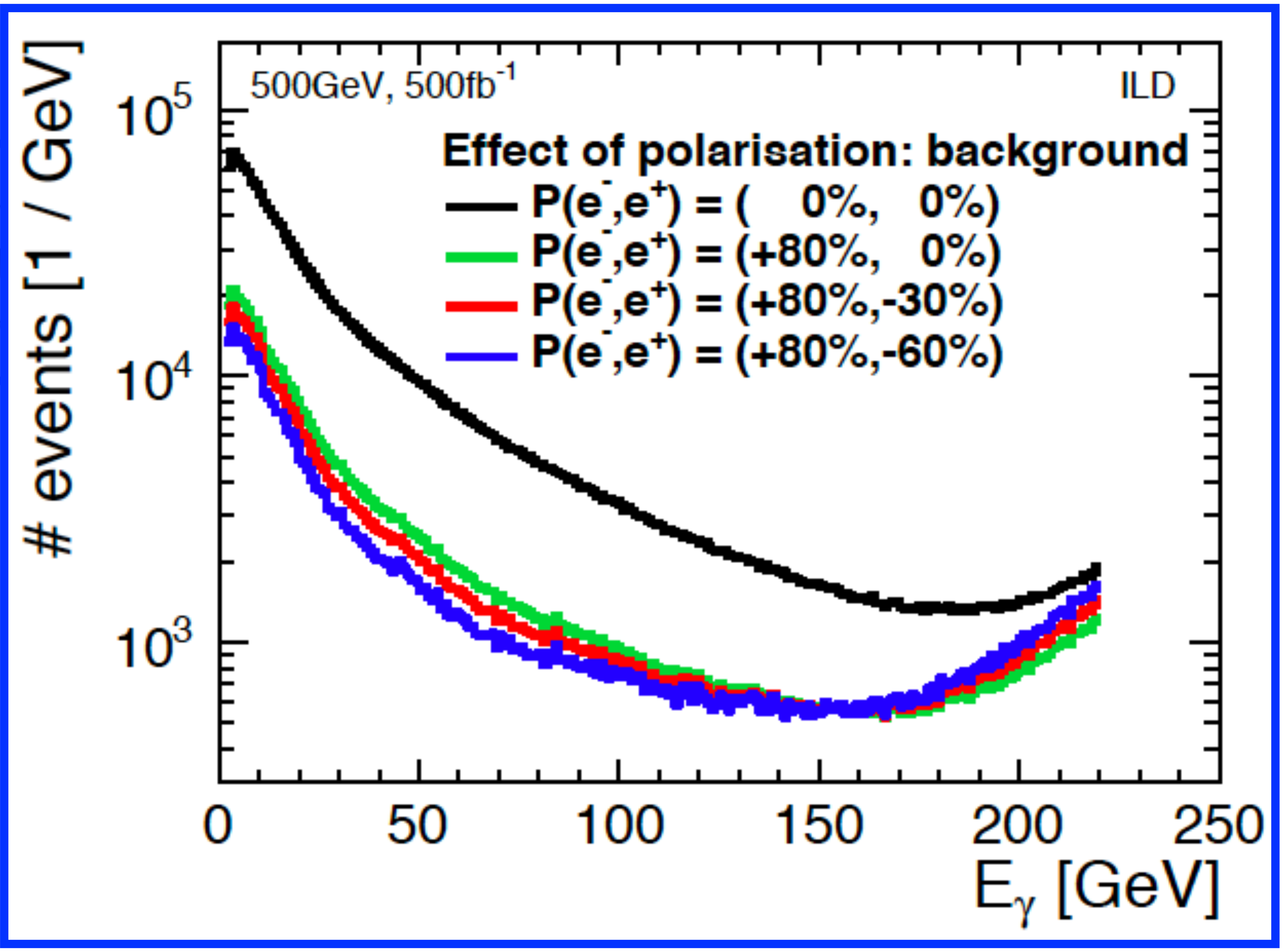

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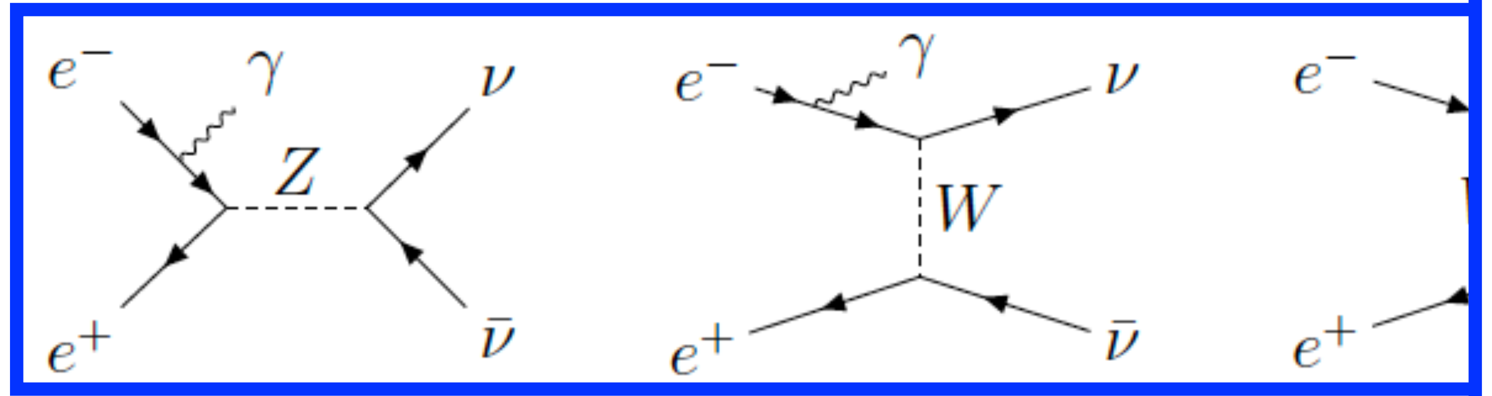
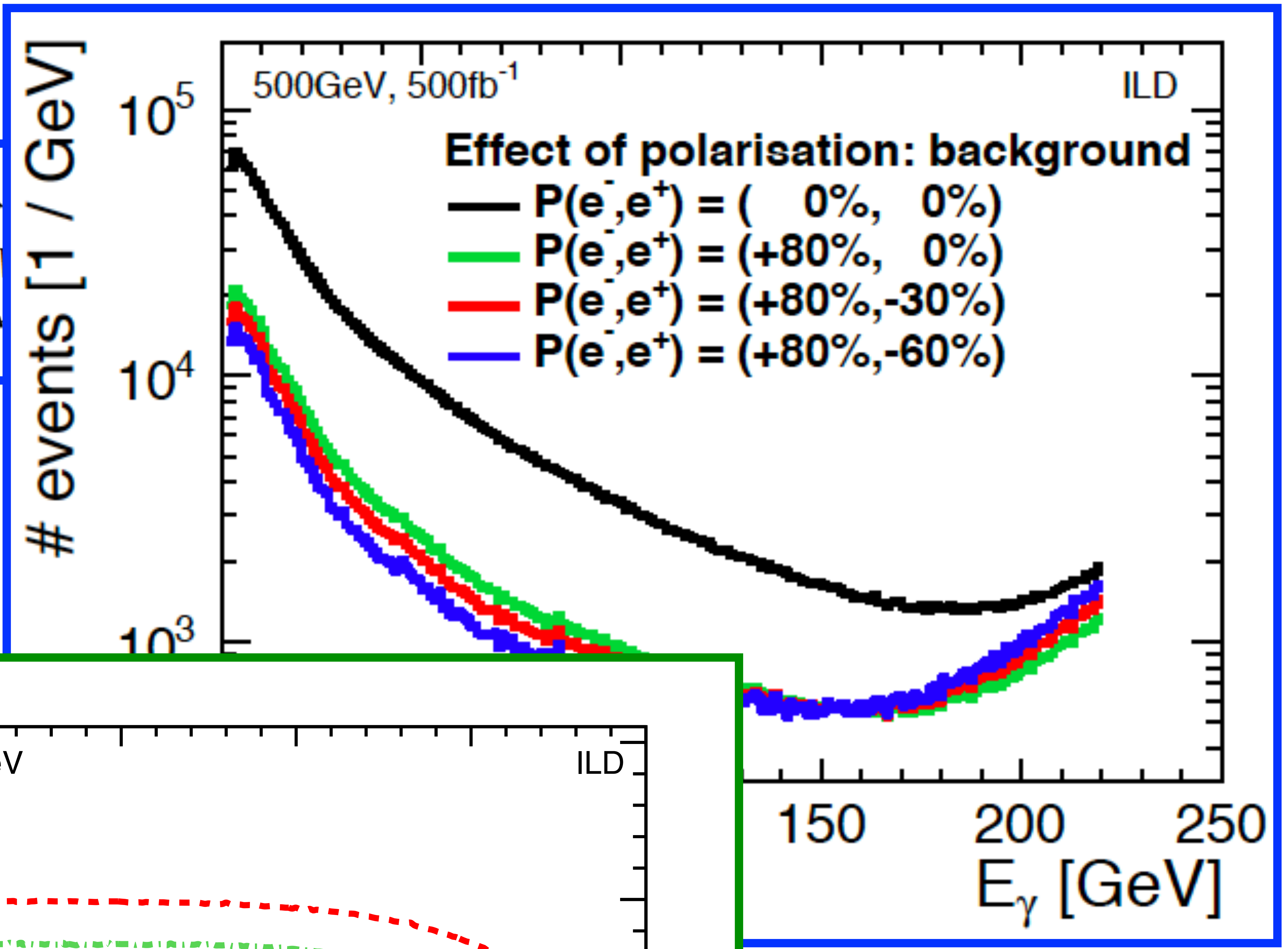


reduced ~10x with polarisation



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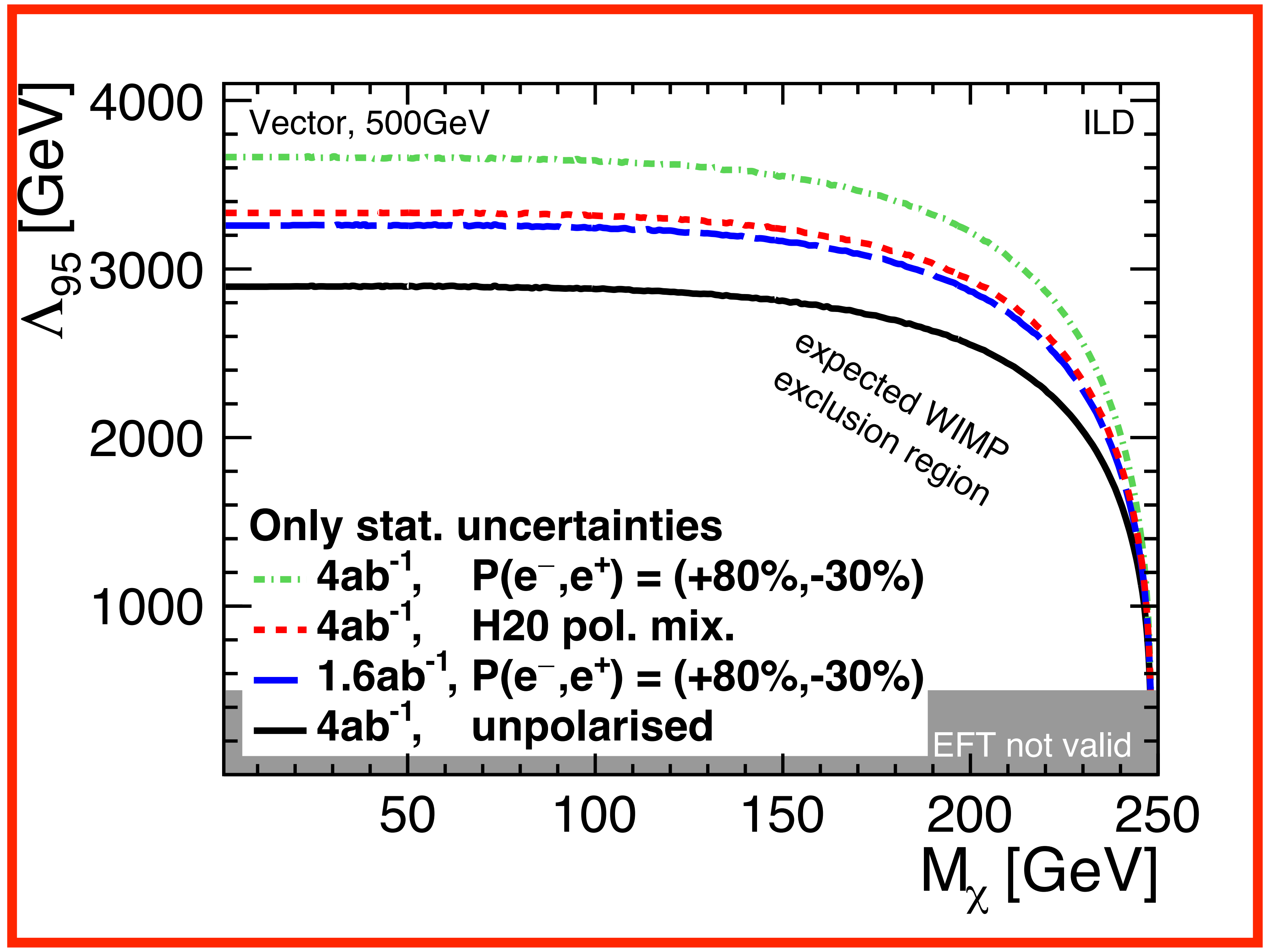
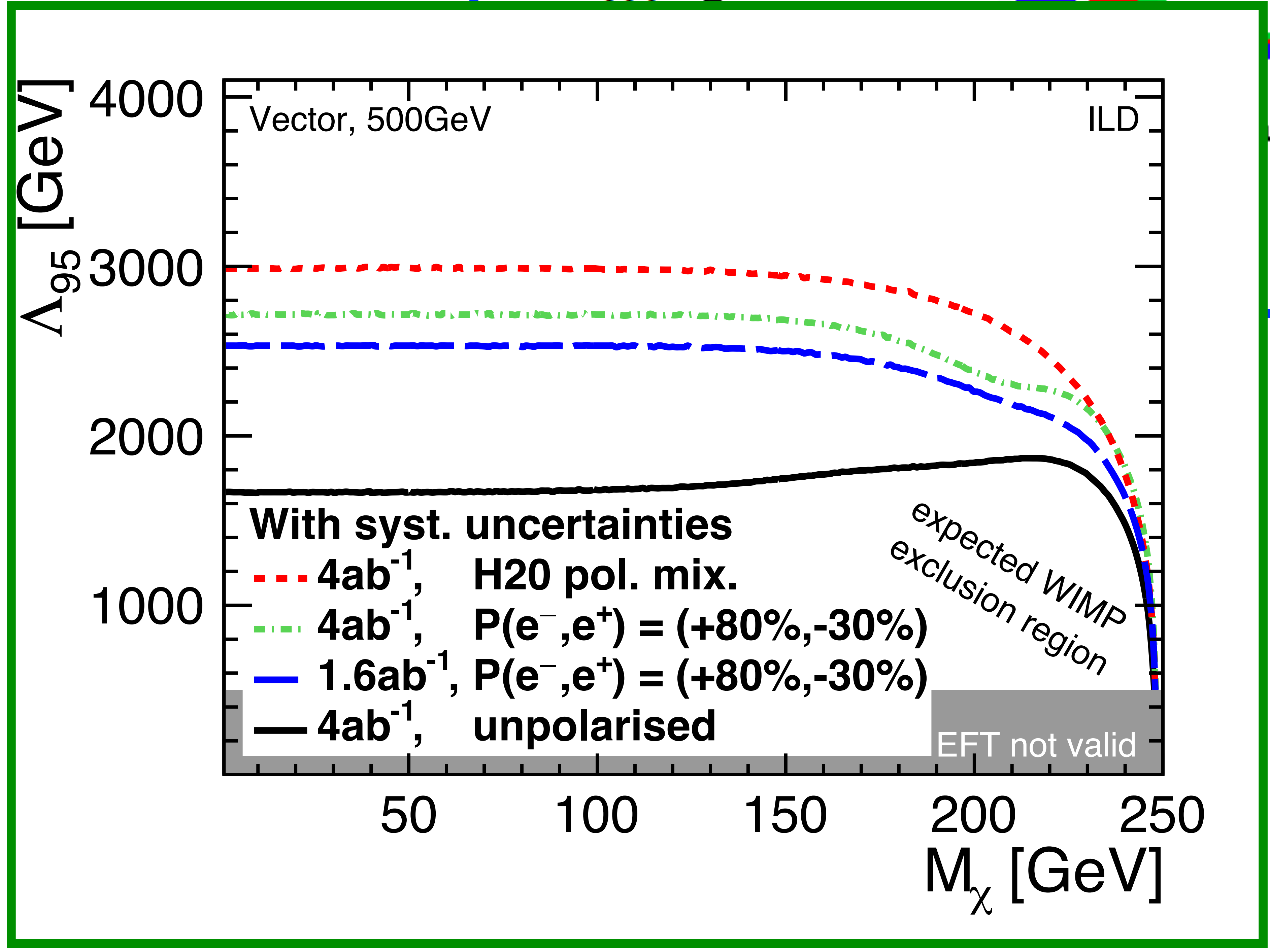




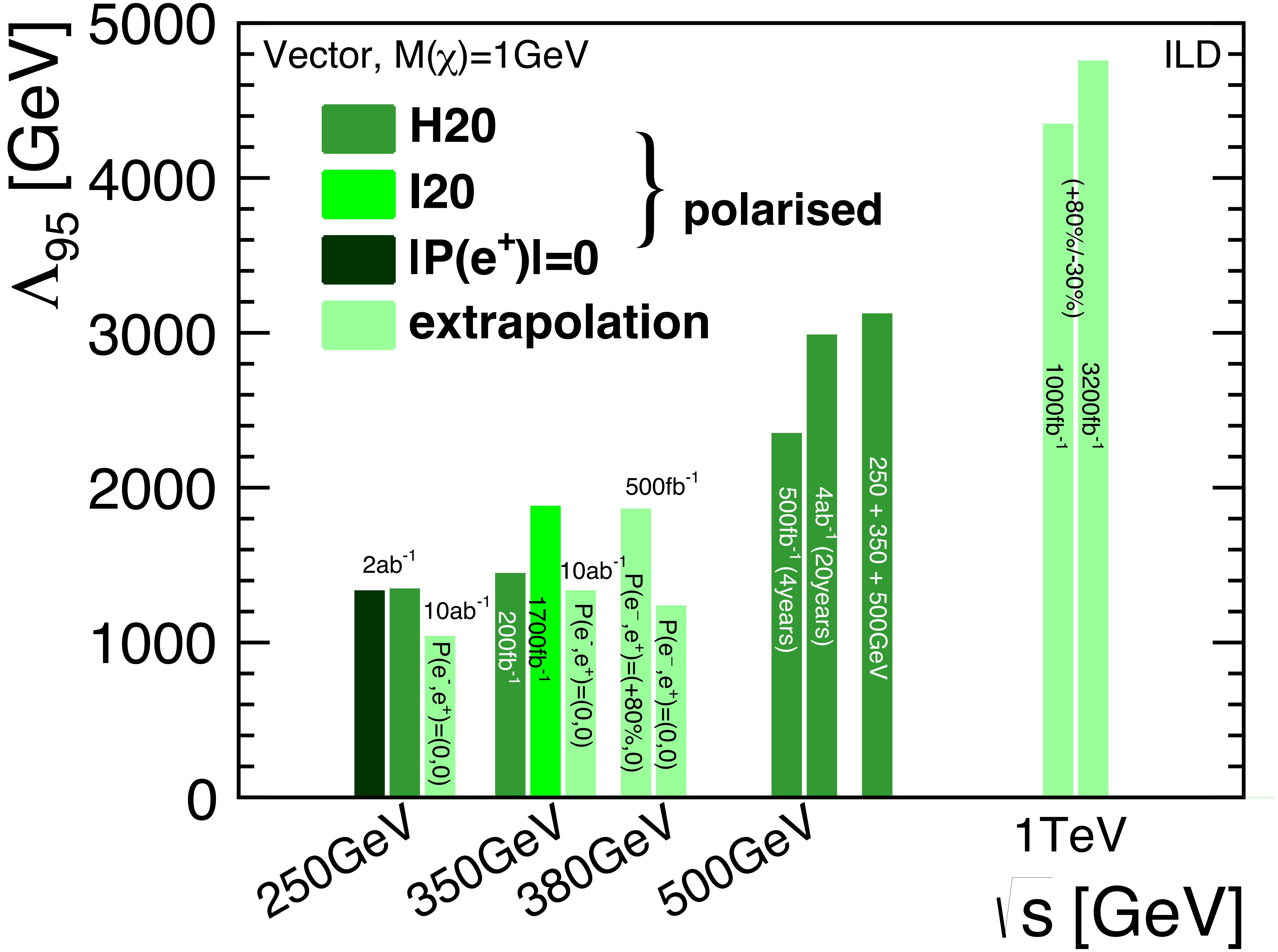
Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case

Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case

Phys. Rev. D 101 (2020) 7



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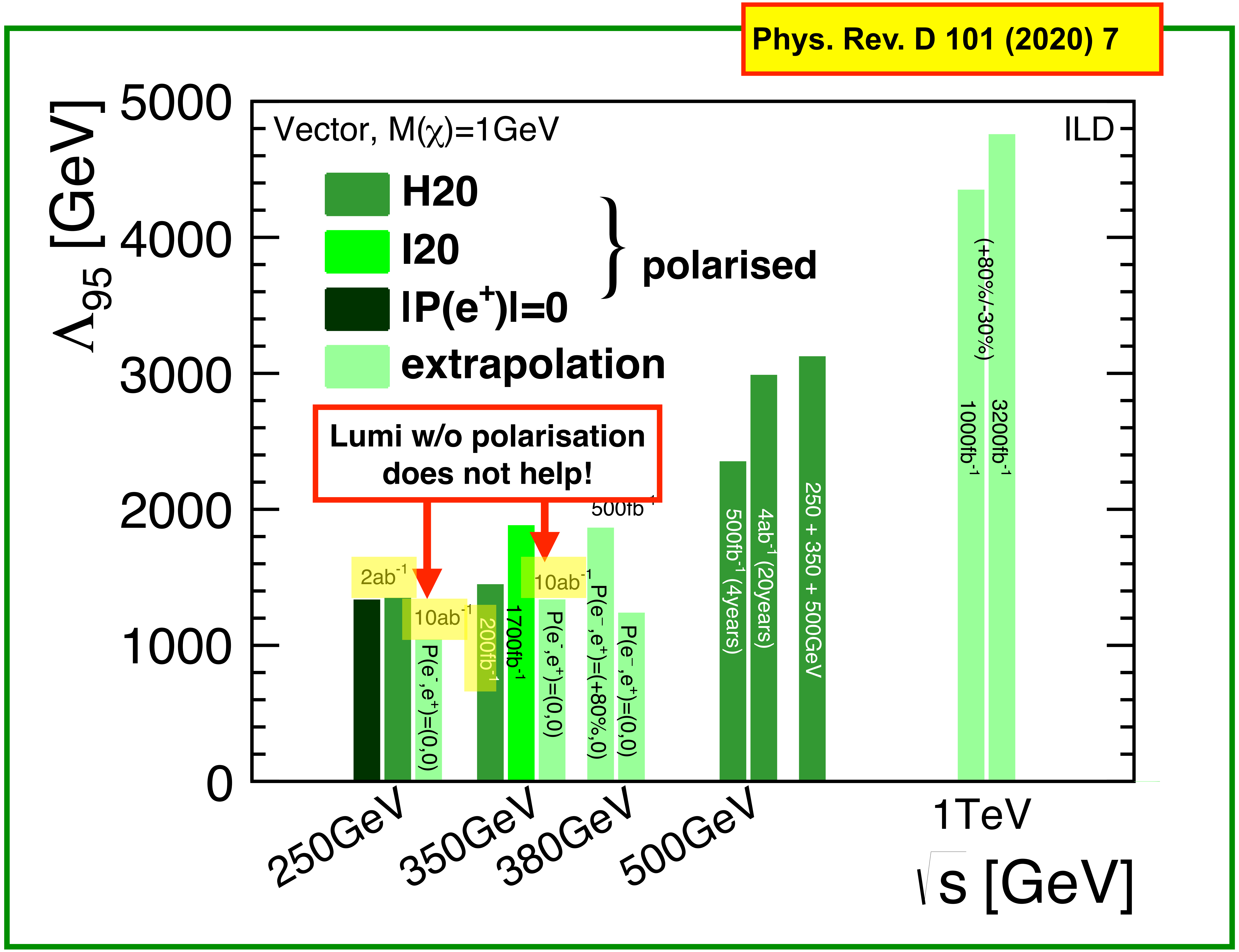
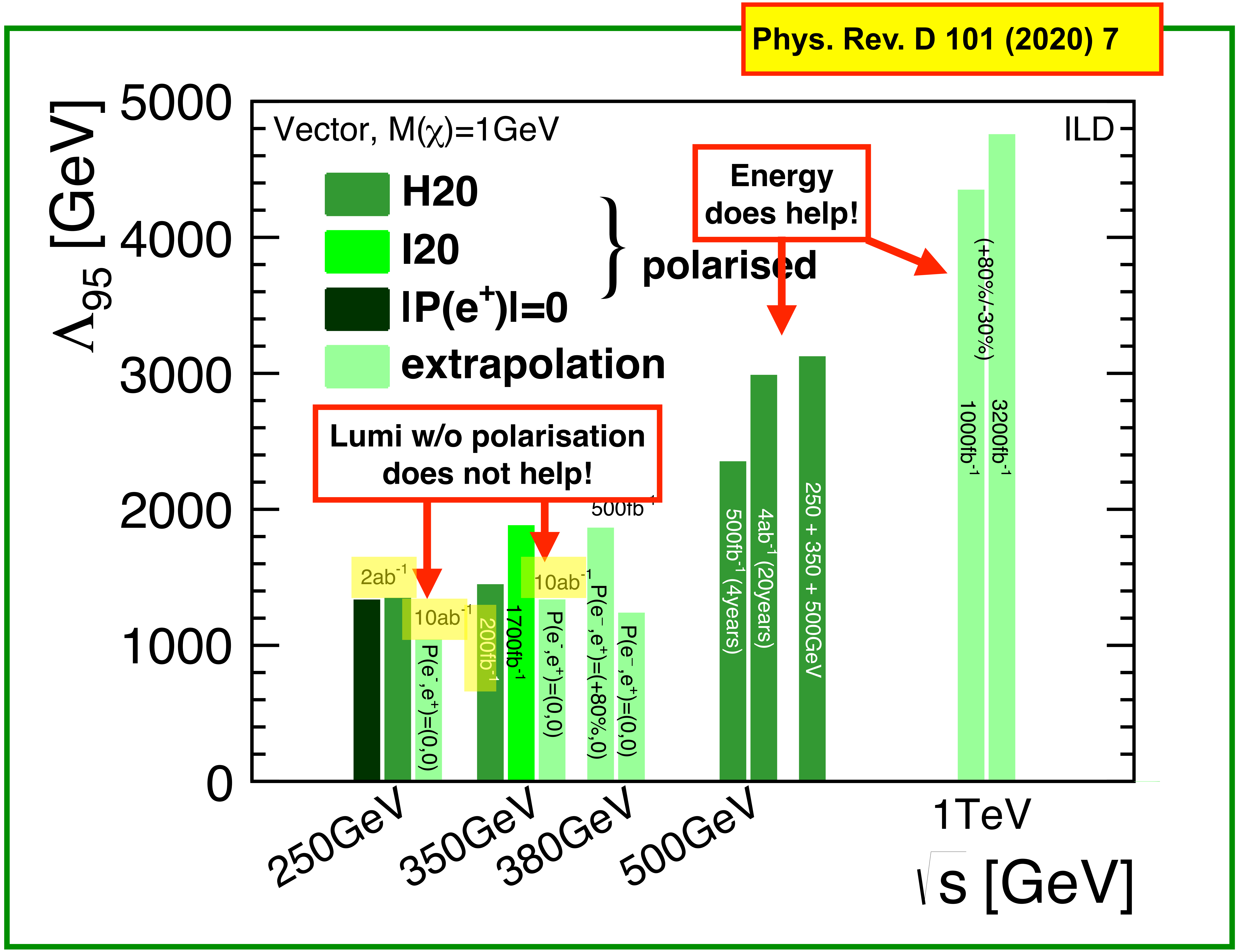


Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case



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Exmaple: Impact on reach in vector mediator case

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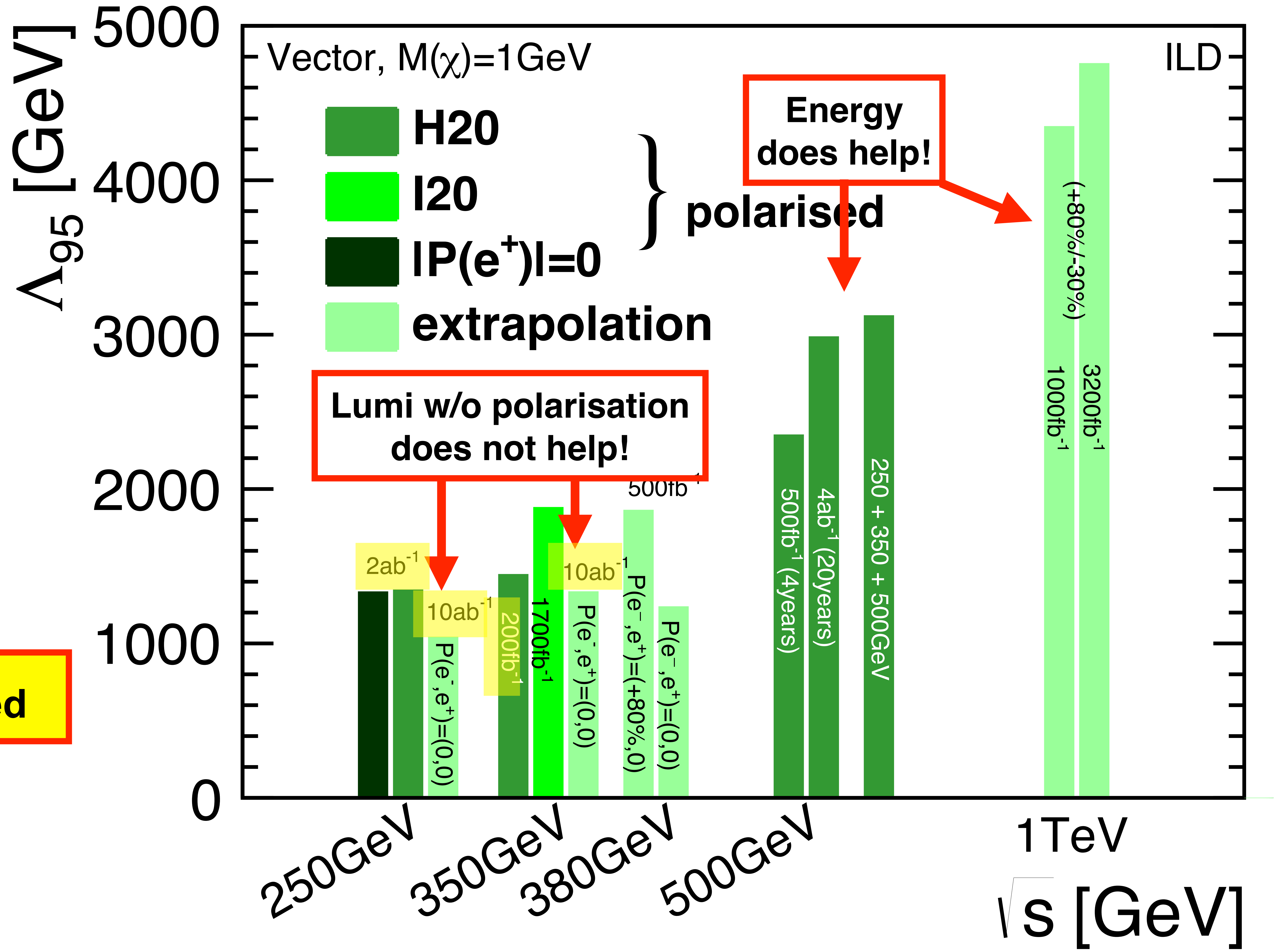


200 fb^{-1} polarised ≈ 10 ab^{-1} unpolarised

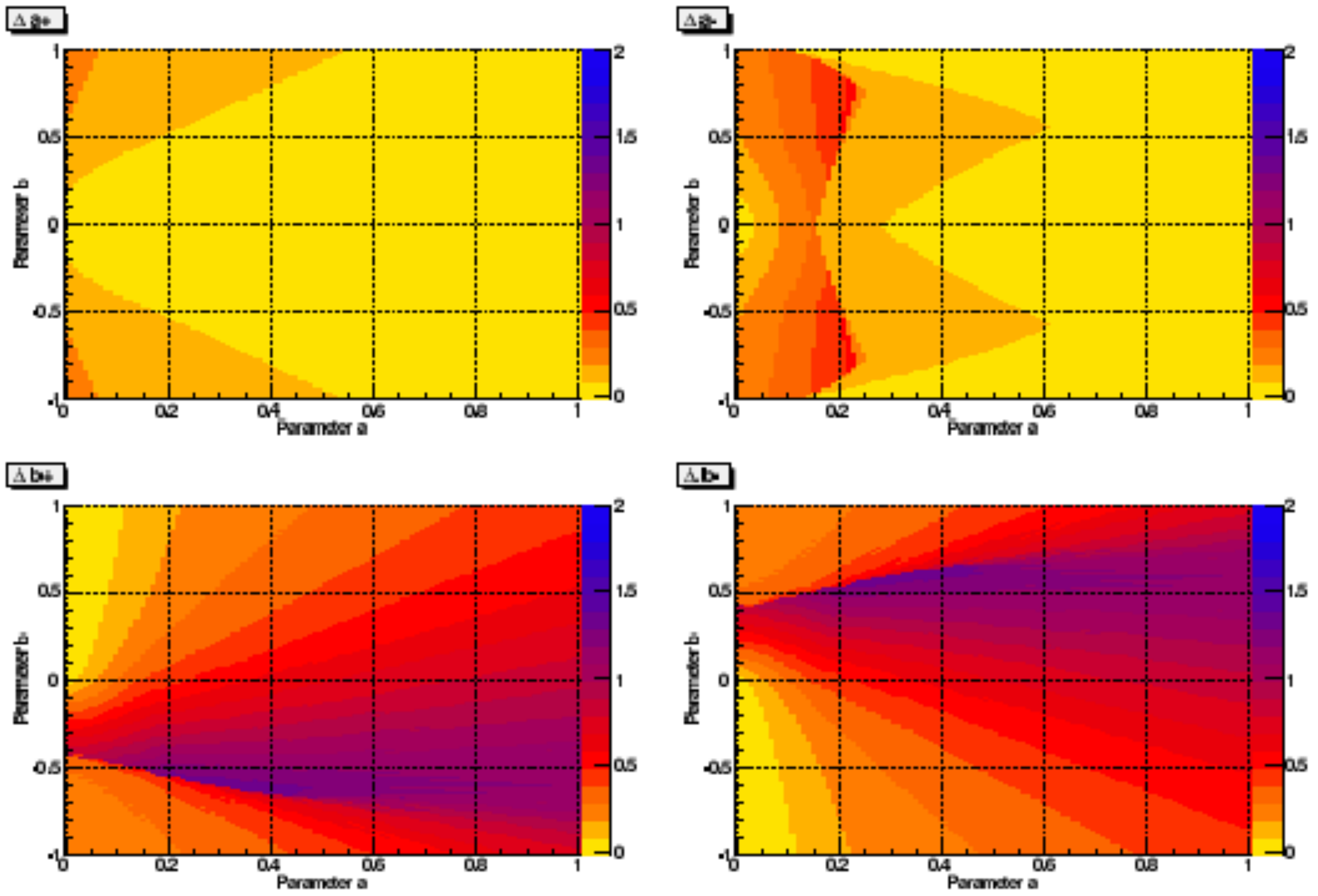
∗ coupling of a general CP-mixed state Φ to $t\bar{t}$: $a, b \in [-1, .., 1]$

CP odd admixture

$$C_{tt\Phi} = -i \frac{e}{\sin\theta_W} \frac{m_t}{2M_W} (a + ib\gamma_5) \equiv -i g_{ttH} (a + ib\gamma_5)$$

Accuracy on a, b from the Combined Observables σ, P_t, A_ϕ

Godbole,Hangst,MMM,Rindani,Sharma



$\sqrt{s} = 800$ GeV, $\int \mathcal{L} = 500$ fb^{-1}, polarised $e^{\pm}$ beams

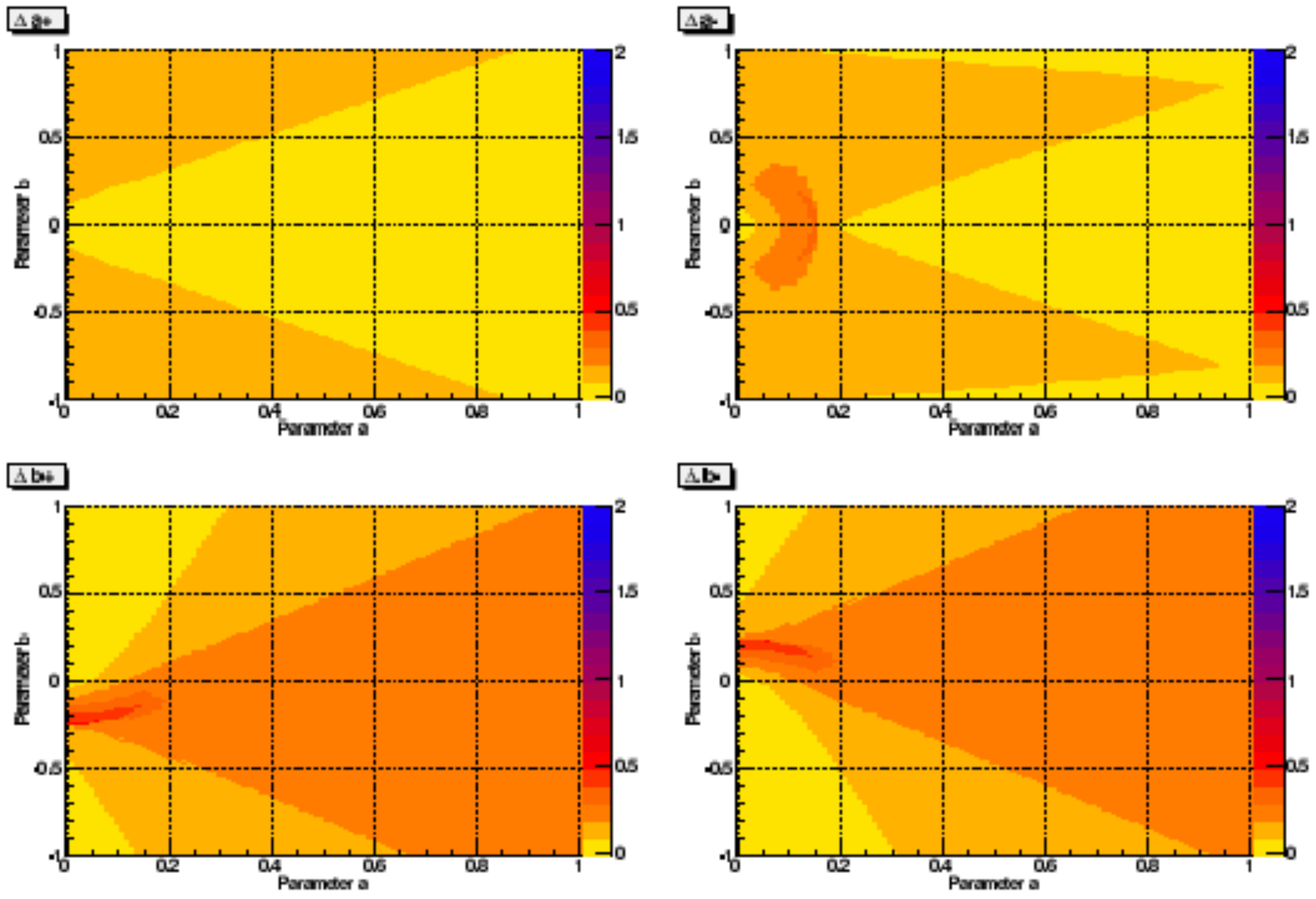
CP odd admixture

$*$ coupling of a general CP-mixed state Φ to $t\bar{t}$: $a, b \in [-1, .., 1]$

$$C_{tt\Phi} = -i \frac{e}{\sin\theta_W} \frac{m_t}{2M_W} (a + ib\gamma_5) \equiv -i g_{ttH} (a + ib\gamma_5)$$

Accuracy on a, b from Combined Observables σ, P_t, A_ϕ – $\sqrt{s} = 3$ TeV

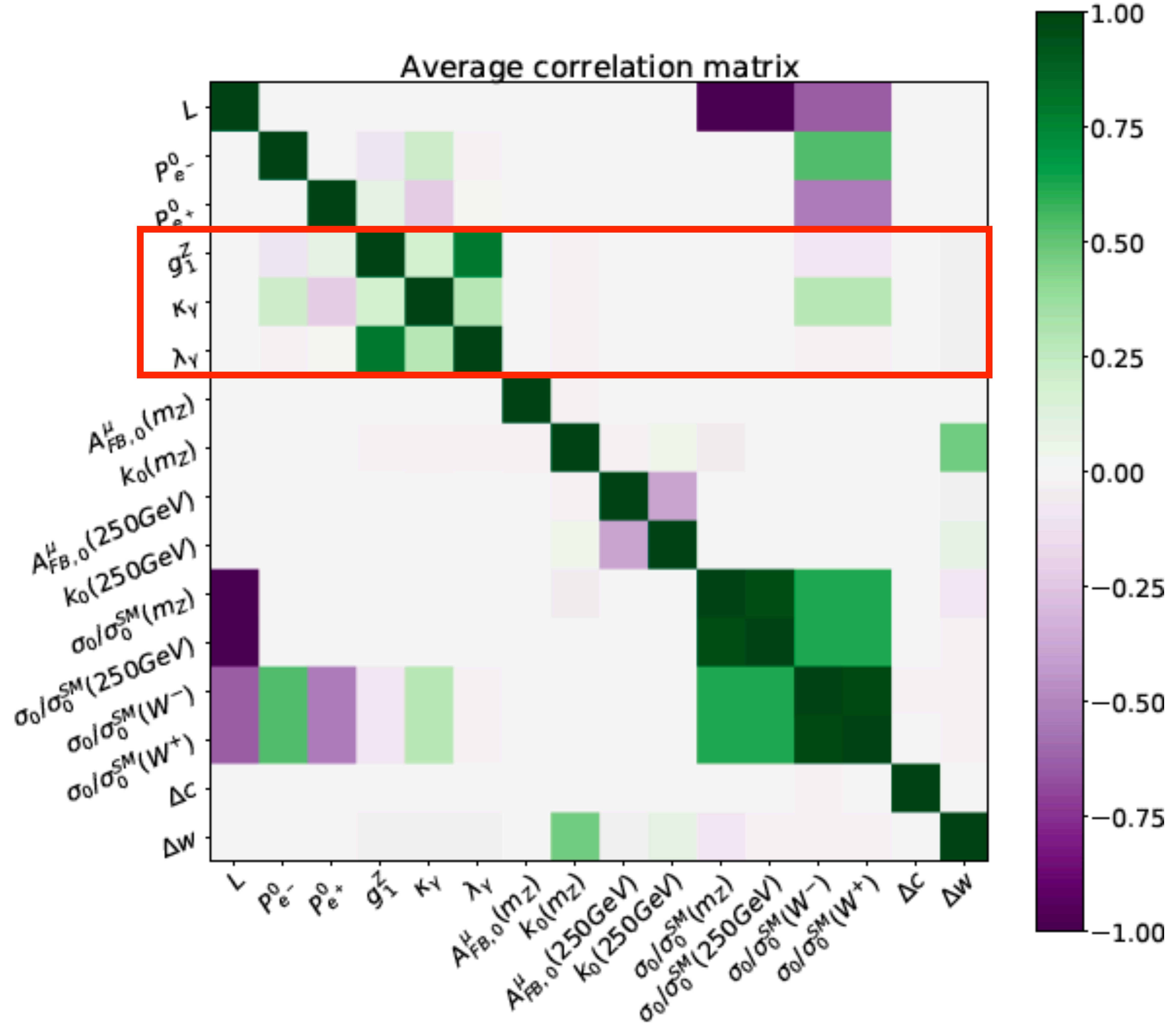
Godbole, Hangst, MMM, Rindani, Sharma

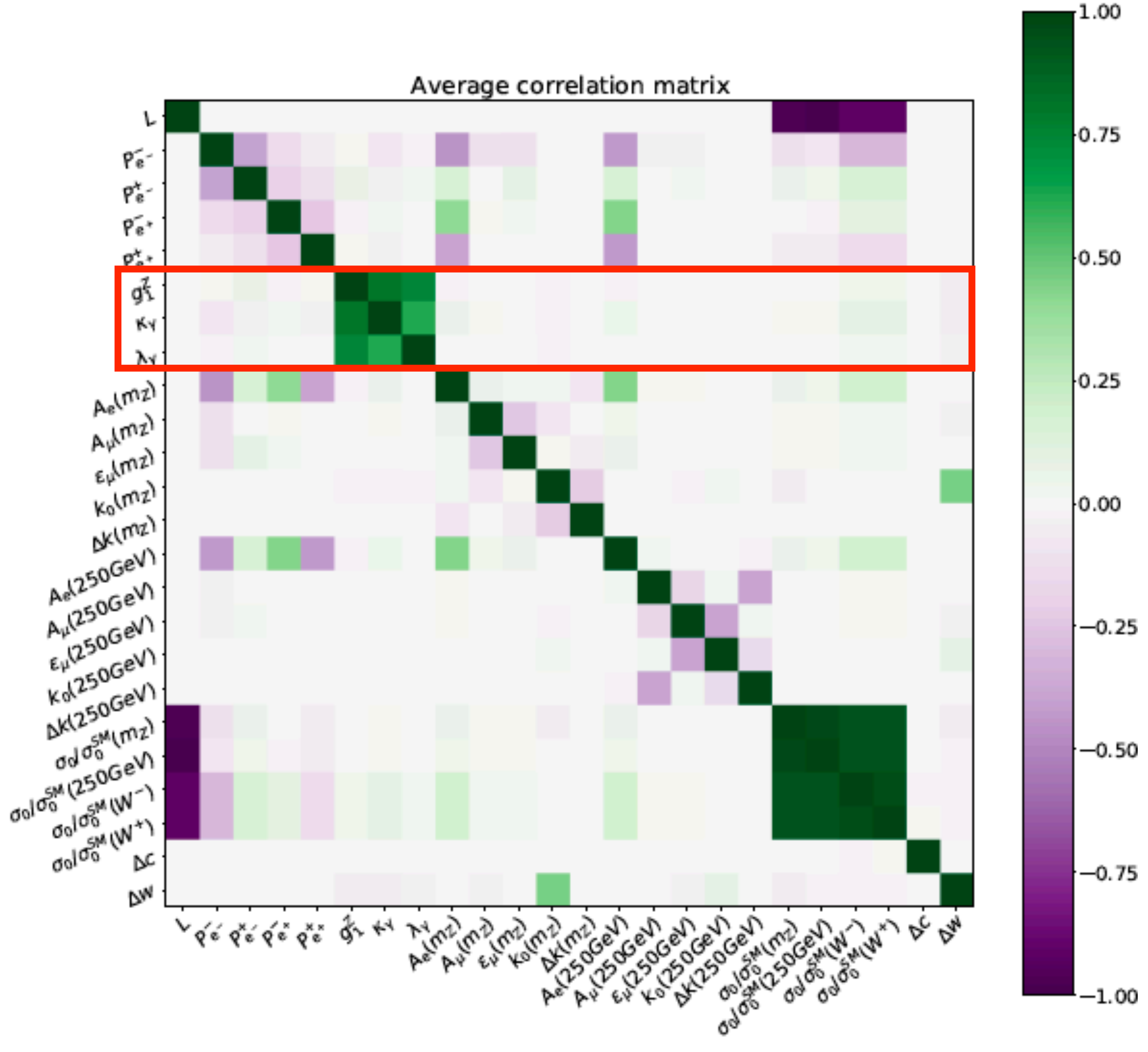


$\sqrt{s} = 3$ TeV, $\int \mathcal{L} = 3$ ab^{-1}, polarised $e^{\pm}$ beams

Can we determine polarisation AND devitions from SM?

P = (0%,0%) vs **P = (±80%, ∓30%)**





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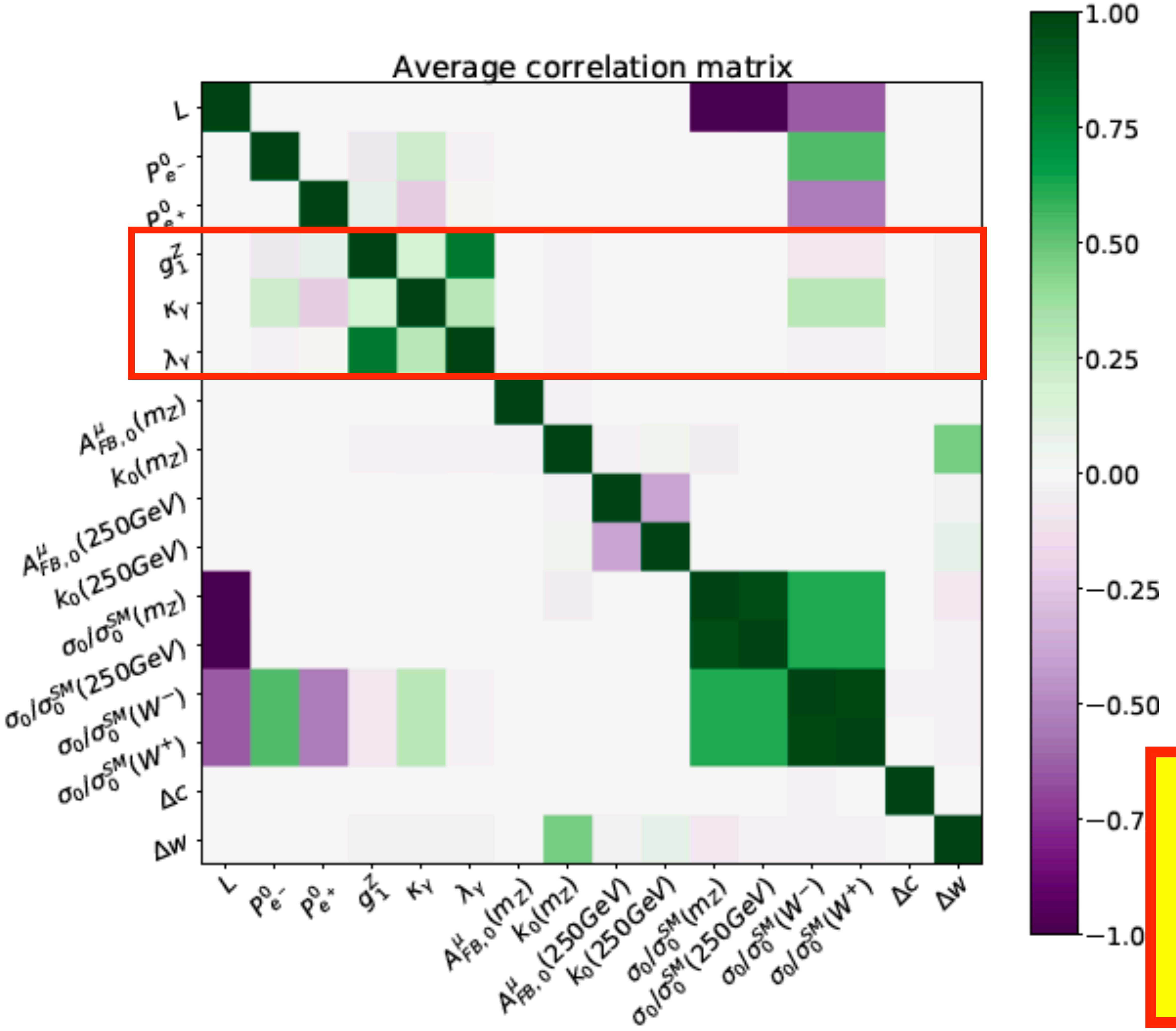
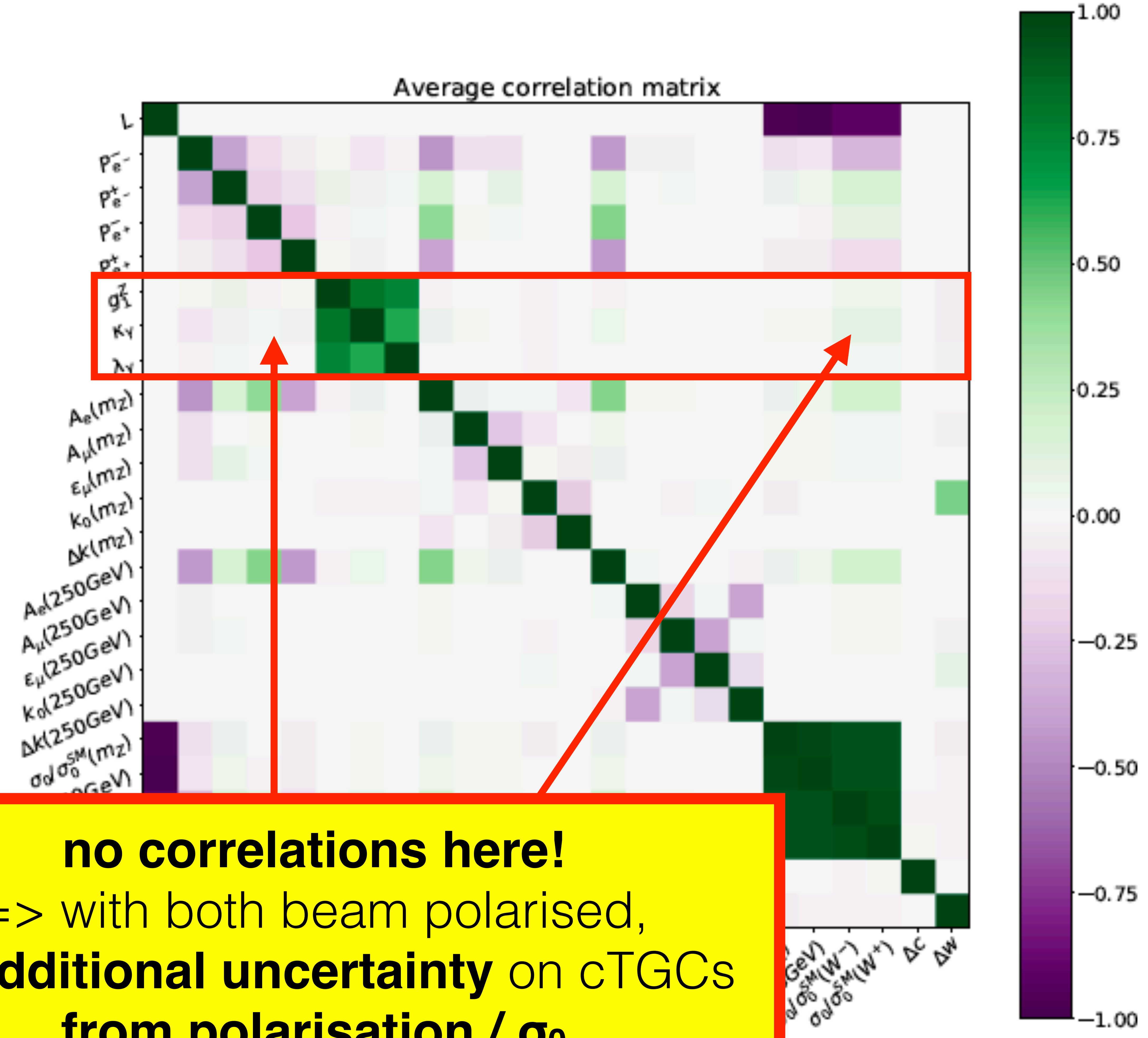
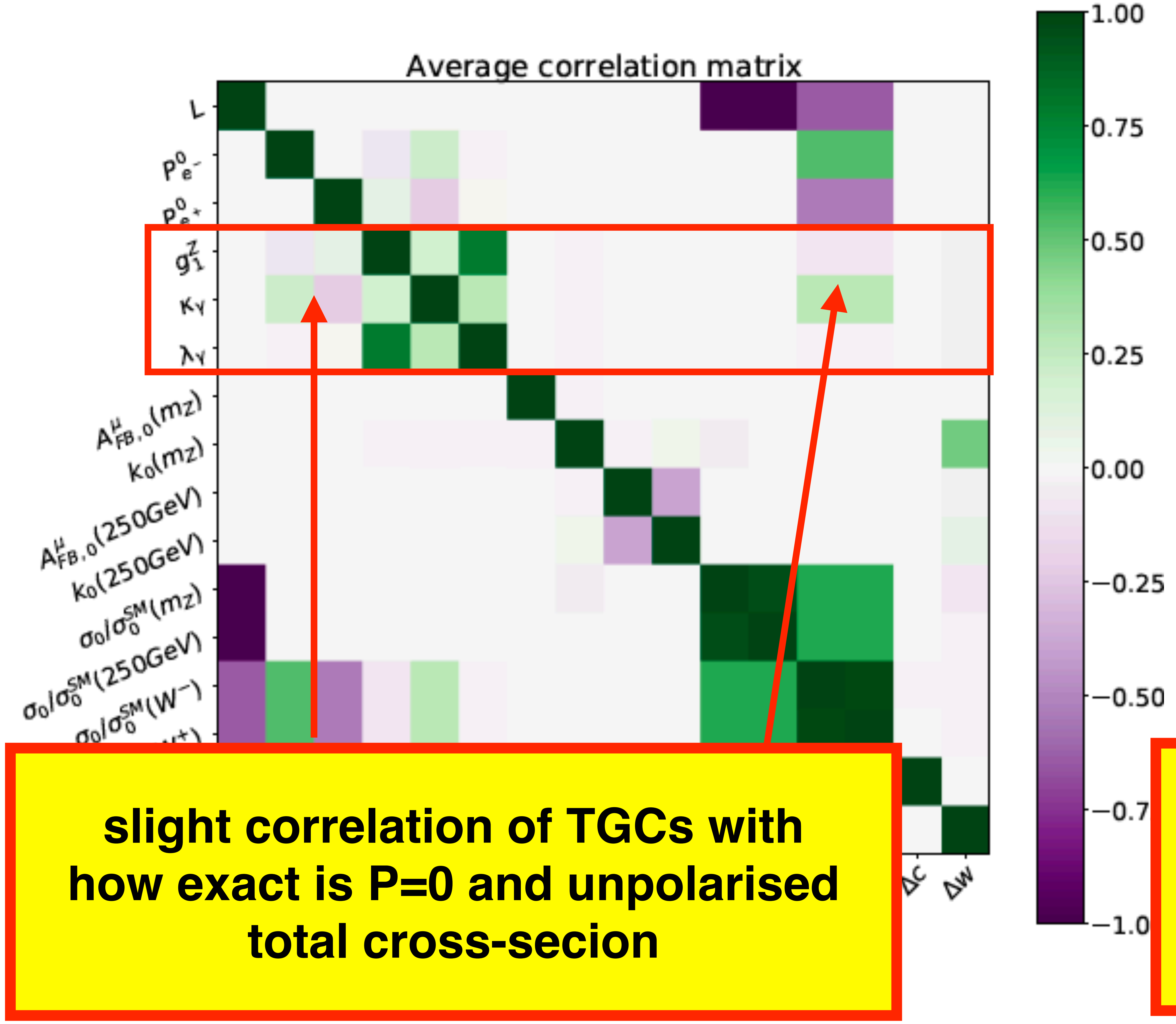


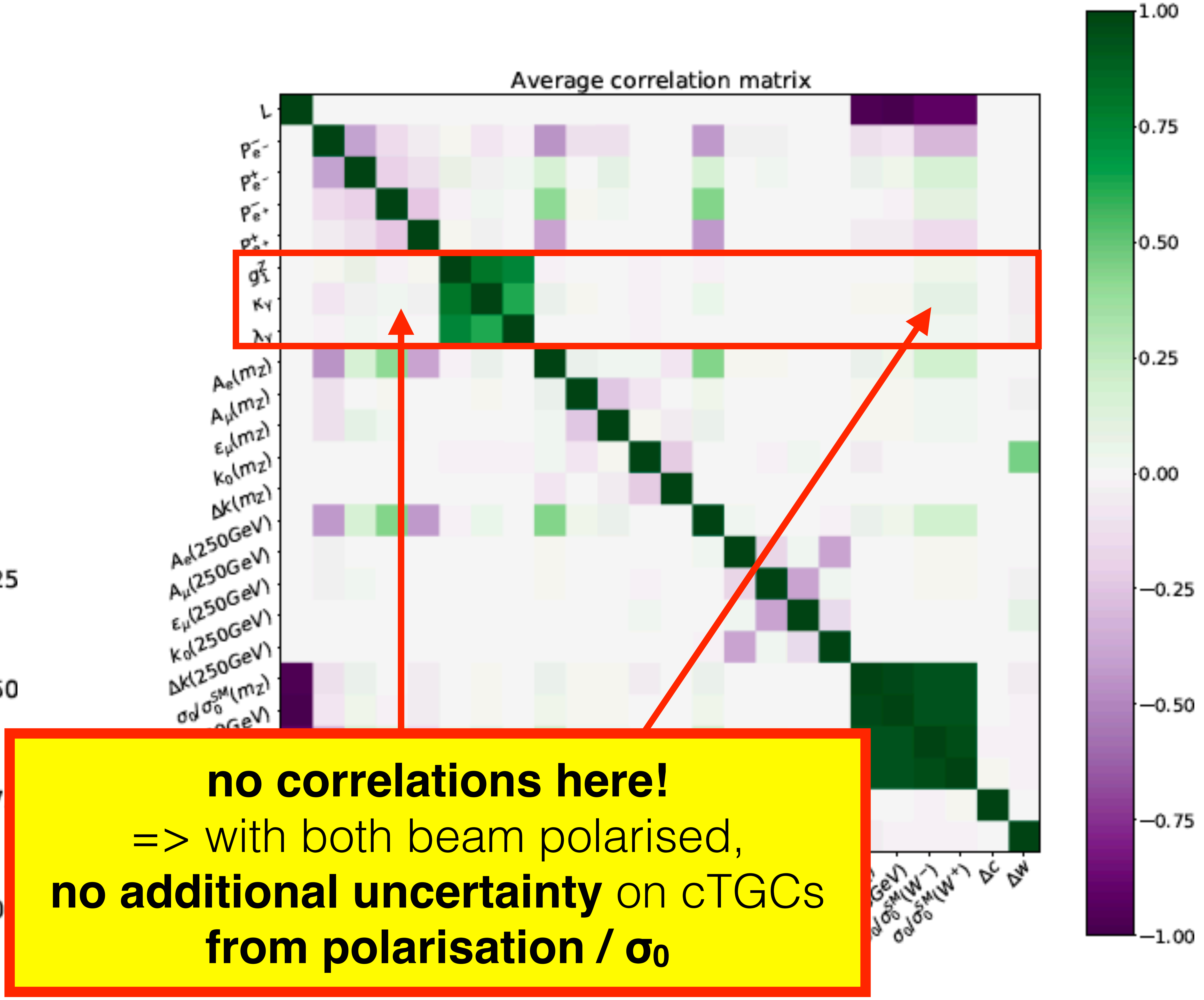


no correlations here!
=> with both beam polarised,
no additional uncertainty on cTGCs
from polarisation / σ_0

Can we determine polarisation AND devitions from SM?

P = (0%,0%) vs **P = (±80%, ∓30%)**





Impact of A_{LR}(WW)

- same effect seen in HL-LHC projections
- effect even stronger for HE-LHC

=> will require A_q's from lepton collider!

arXiv:1902.04070

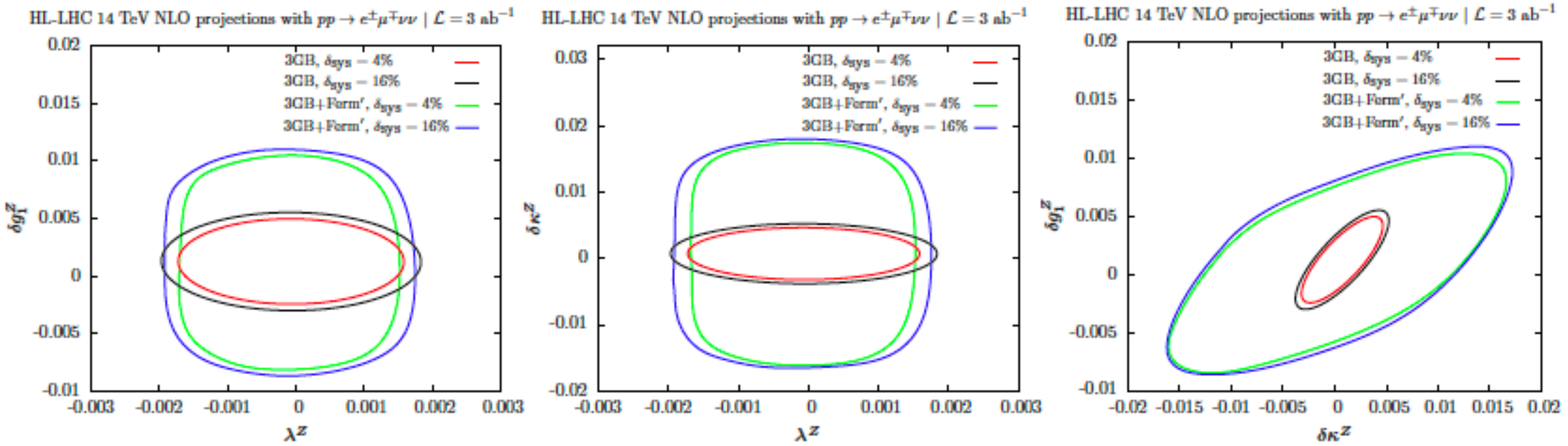


Fig. 40: Projections for 14 TeV with 3 ab^{-1}. $p_{T,cut} = 750$ GeV, corresponding to $\delta_{stat} = 16\%$ with $\delta_{sys} = 4\%$ and $\delta_{sys} = 16\%$. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.

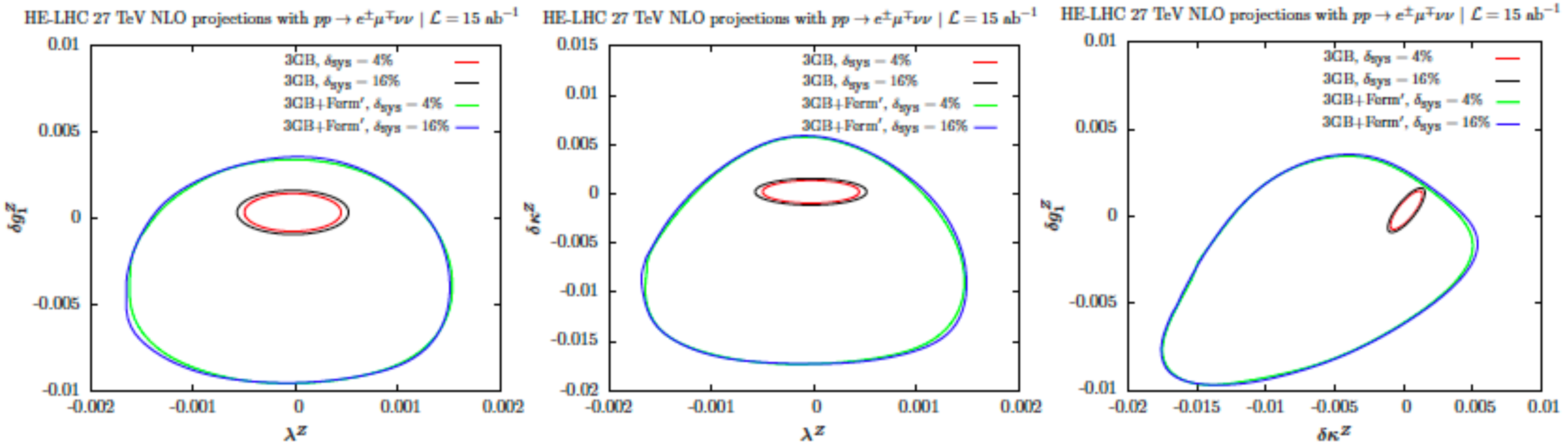


Fig. 41: Projections for 27 TeV with 15 ab^{-1}. $p_{T,cut} = 1350$ GeV, corresponding to $\delta_{stat} = 16\%$ with $\delta_{sys} = 4\%$ and $\delta_{sys} = 16\%$. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.