Why an e+e- Higgs /Top / EW factory

as next collider?

Jenny List (DESY)
NOCC
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HELMHOLTZ
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Outline

Today's menu

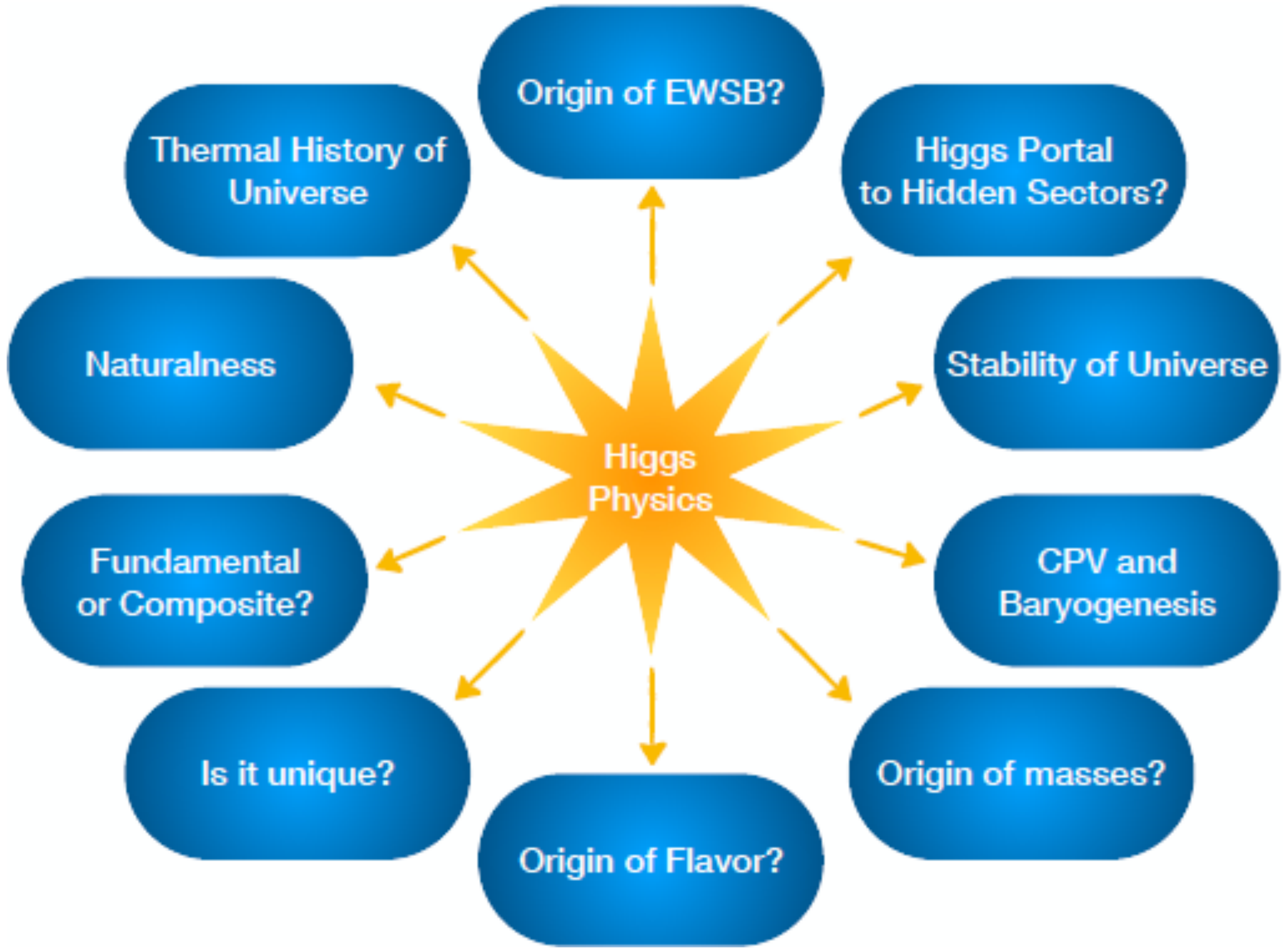
- **Why the Higgs is special**
- **Higgs factory basics for LHC experts**
- **Physics Highlights**
- **Conclusions**

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

Why the Higgs is special

The Higgs discovery poses more questions than it answers

The Higgs is connected to our fundamental questions about the universe



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

- **We don't know yet whether the particle we found is "the last piece of the SM"**
- or the first glimpse of BSM?!
- in either case it is very special:
  - the very first candidate for an elementary spin-0 particle
  - it mediates a completely new, non-gauge interaction!

=> THIS is why we need a much sharper view on the Higgs boson

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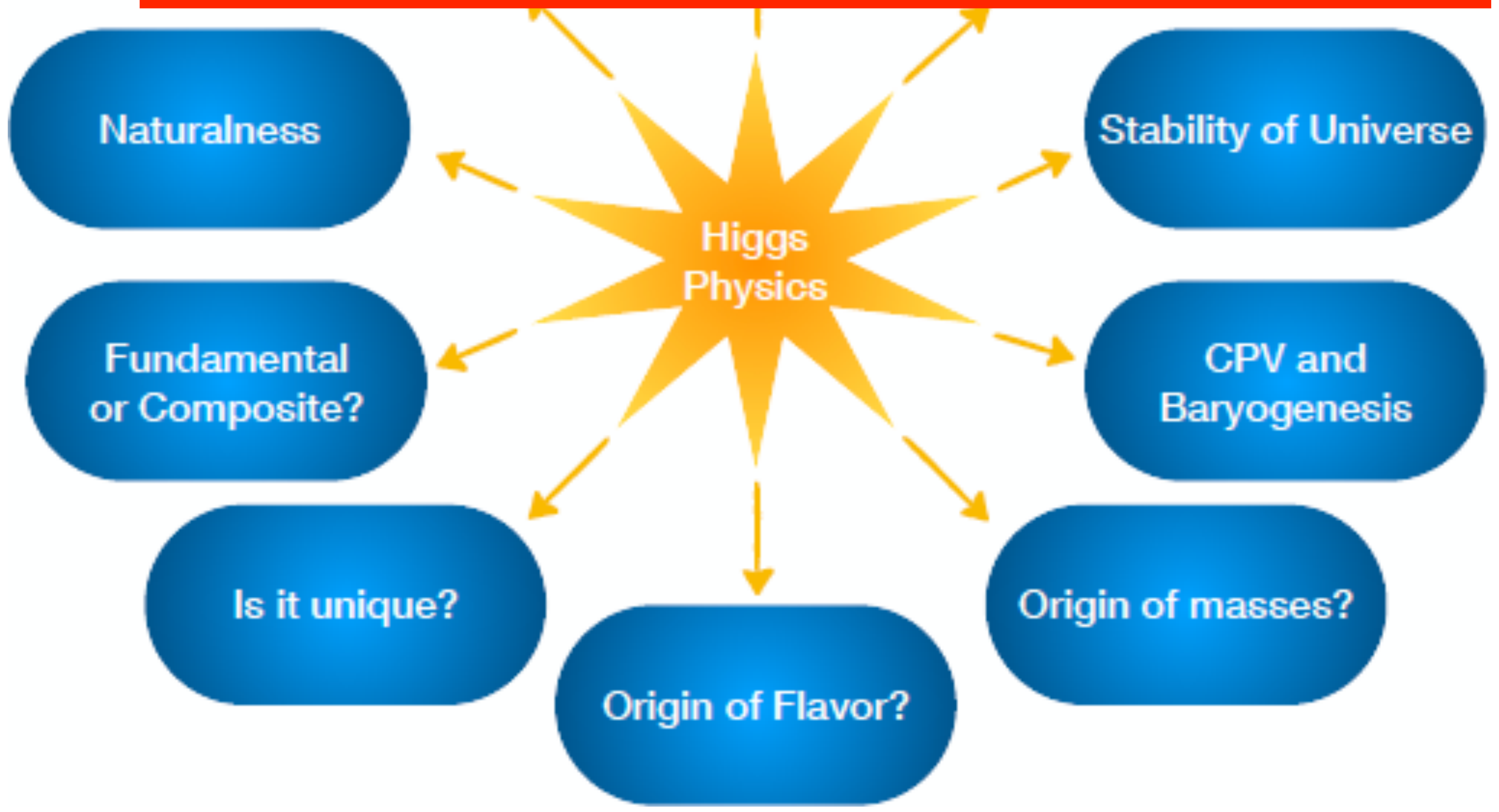
The Higgs is connected to our fundamental questions about the universe

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



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The Higgs Boson Mission

Why we need a Higgs Factory

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

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- in particular low backgrounds
- clean events
- triggerless operation (LCs)

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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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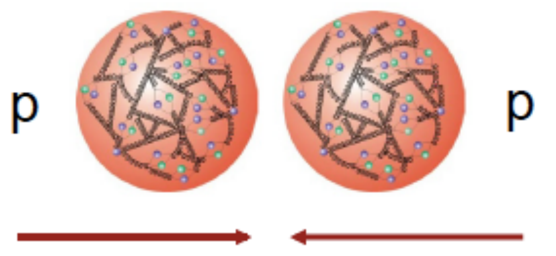
Higgs Factory basics for LHC experts

Energy and all that

Just a quick reminder…

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



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Luminosity

- “How much data can we claim we need?”
- Where are fundamental boundaries beyond statistics?
  (e.g. theory, parametric, detector resolution, …)

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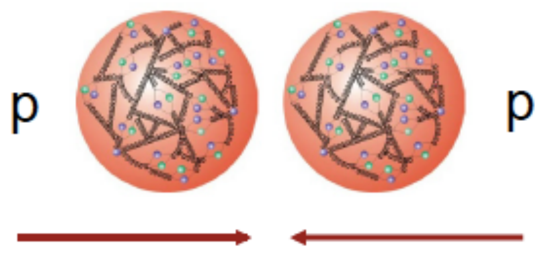

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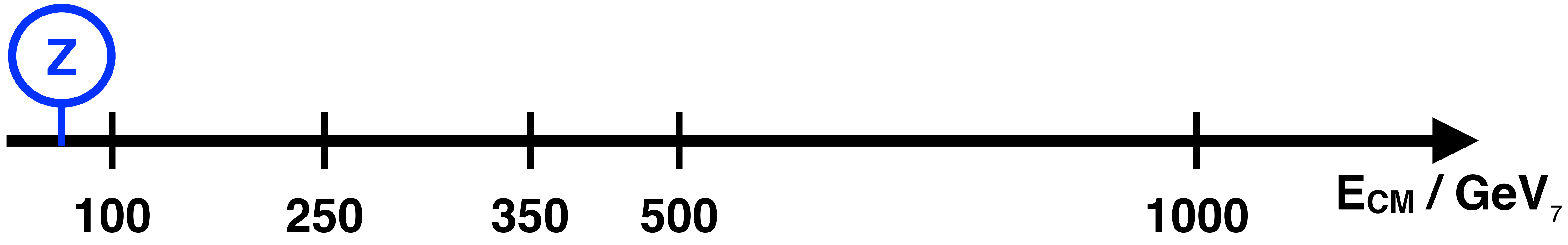

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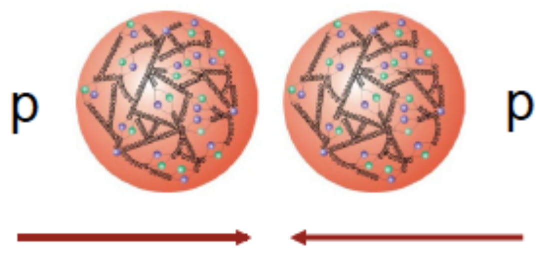

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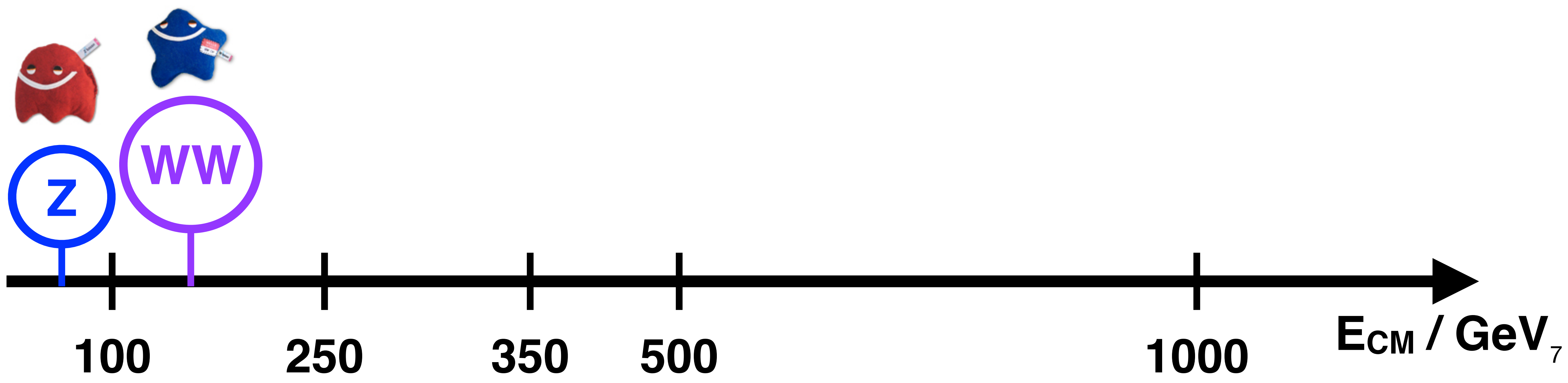

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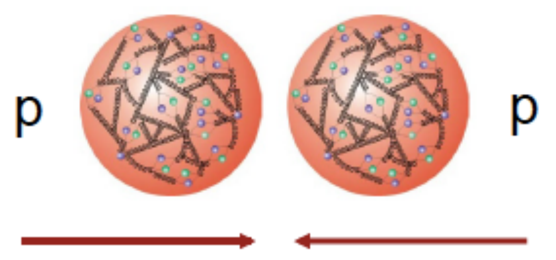

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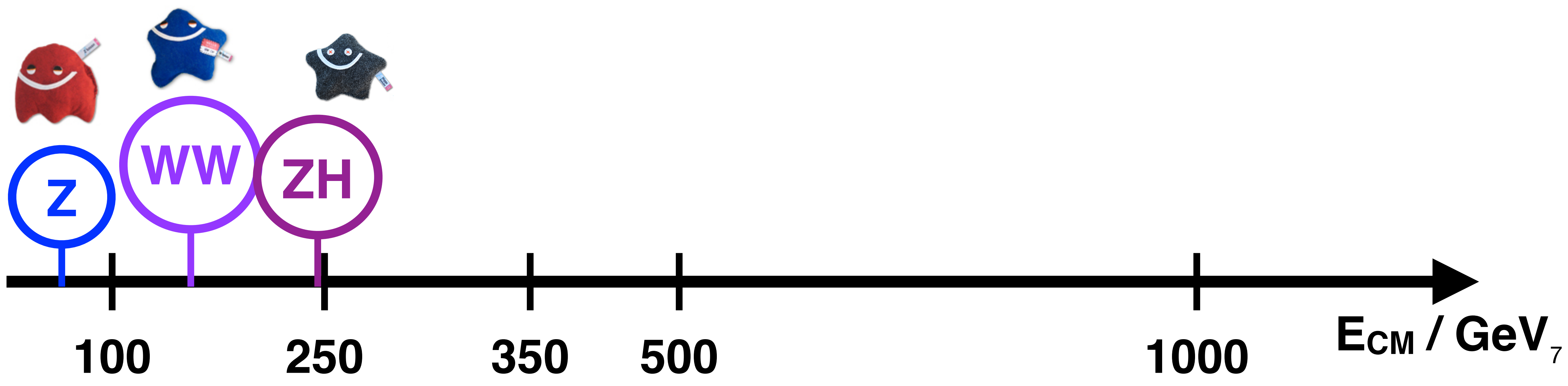

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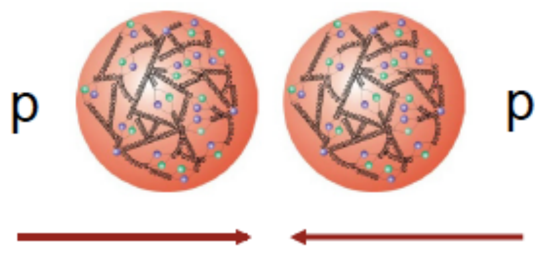

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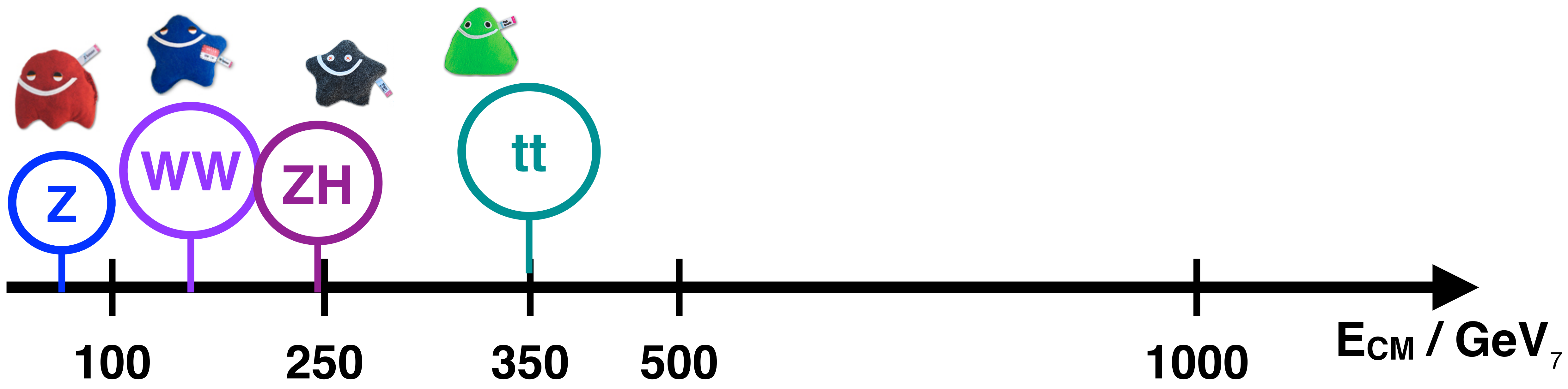

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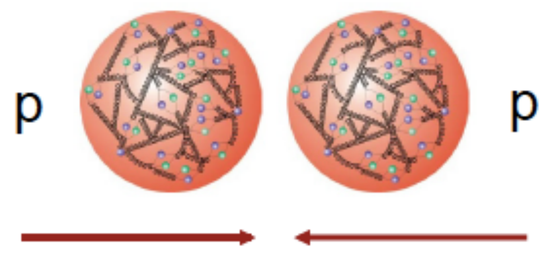

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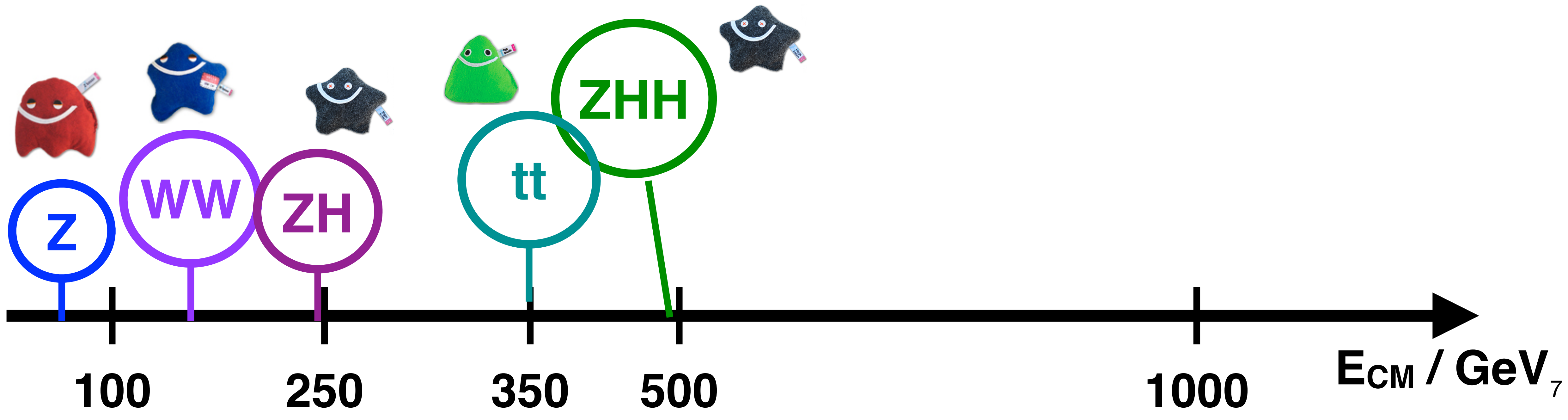

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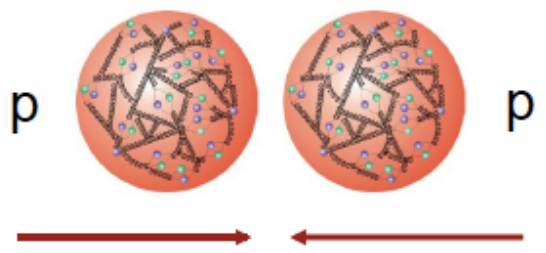

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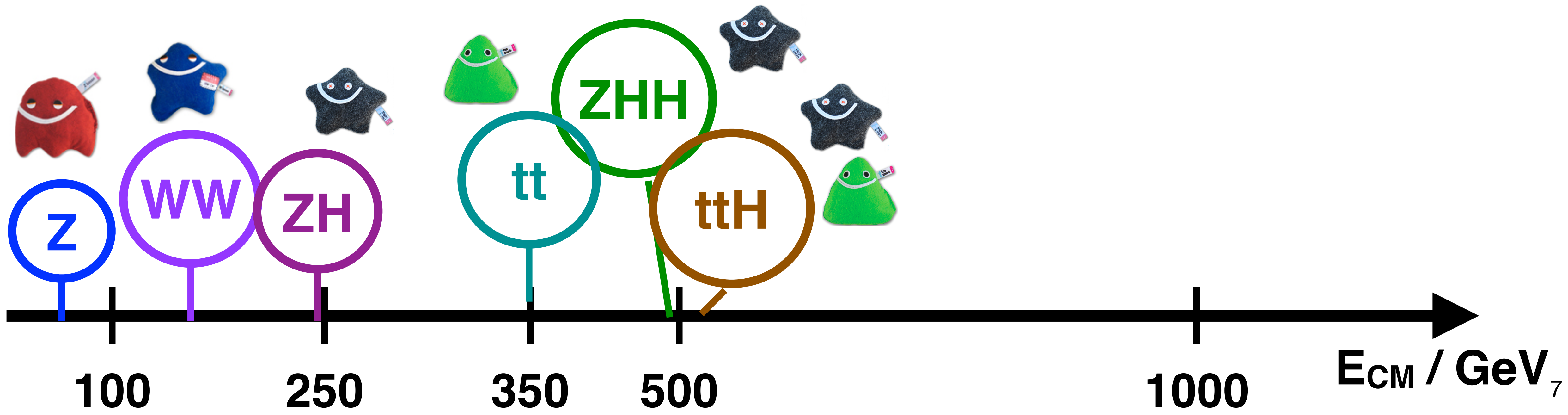

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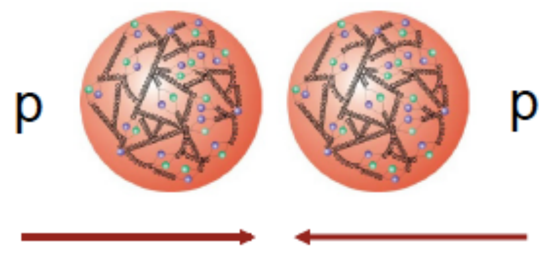

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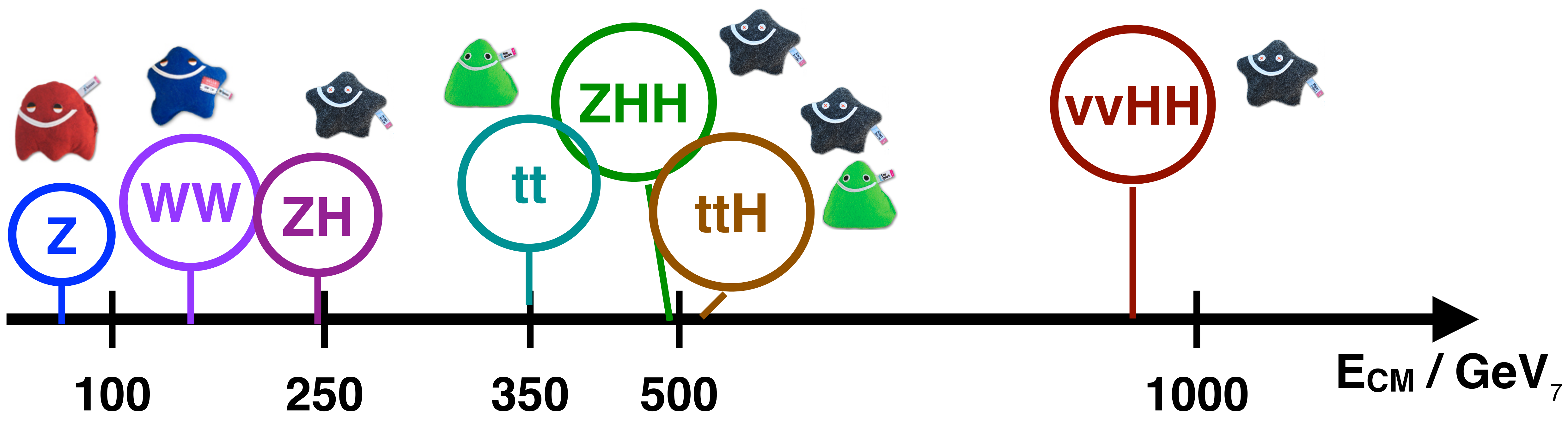

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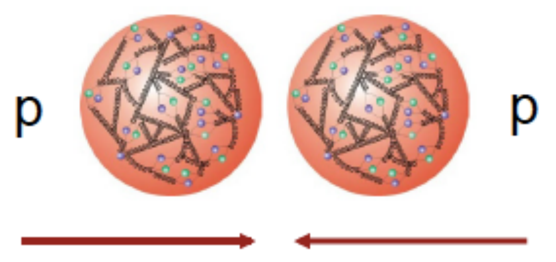

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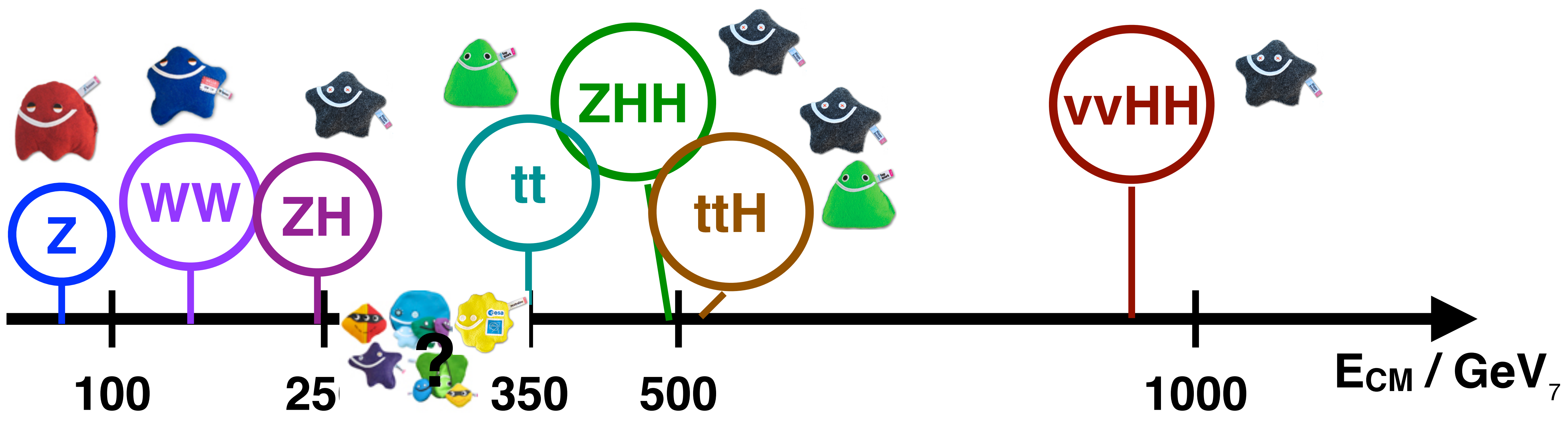

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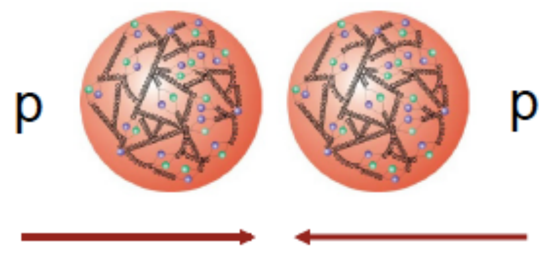

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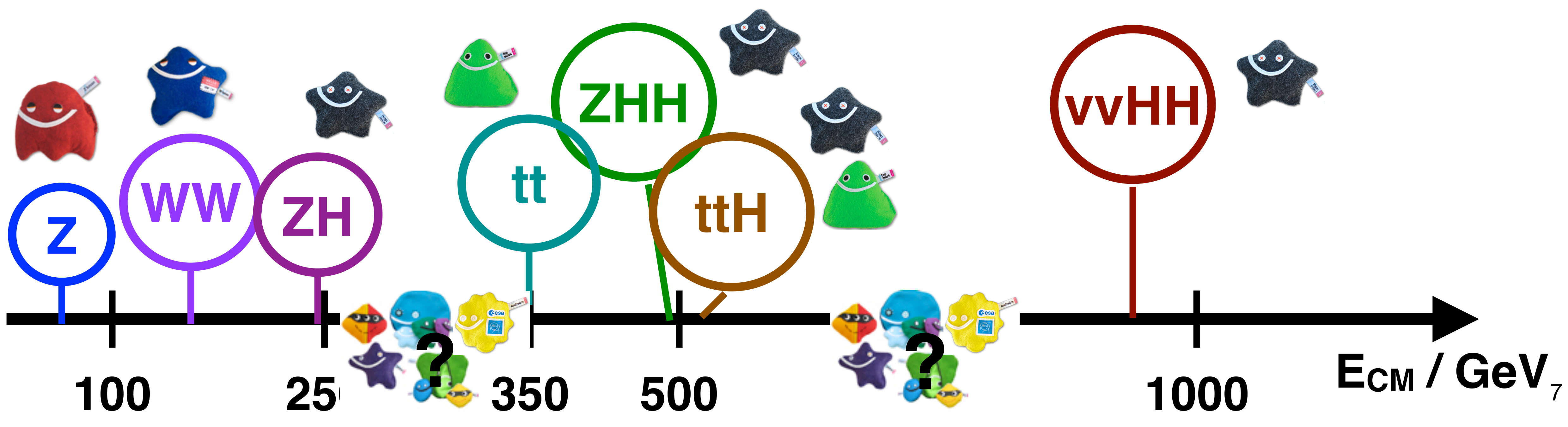

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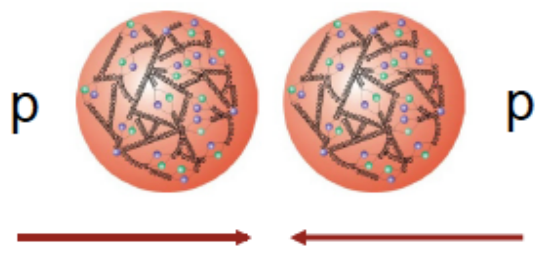

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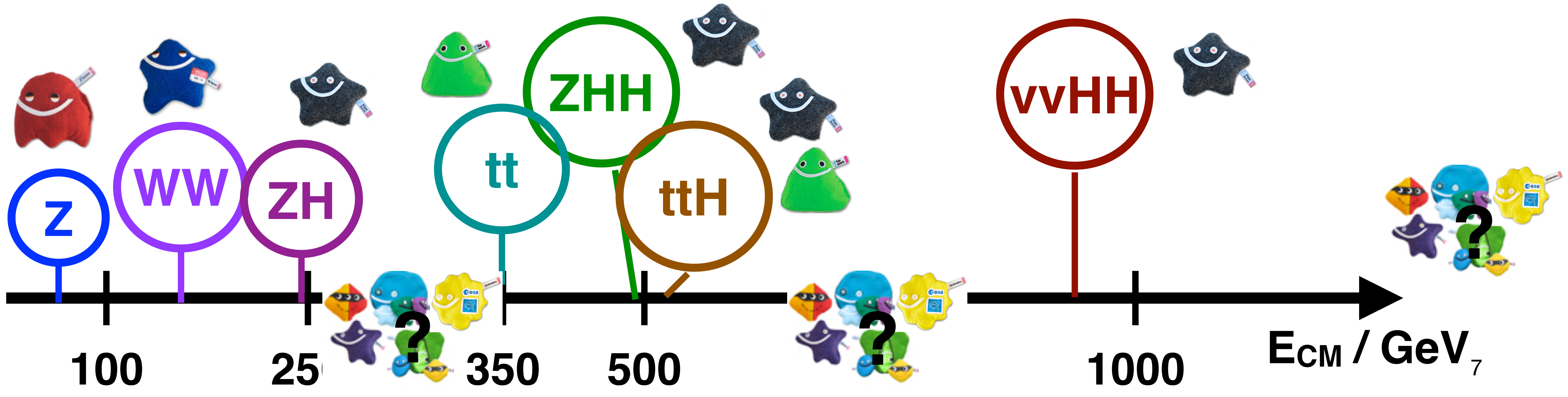

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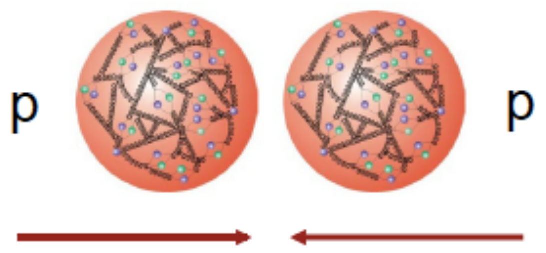

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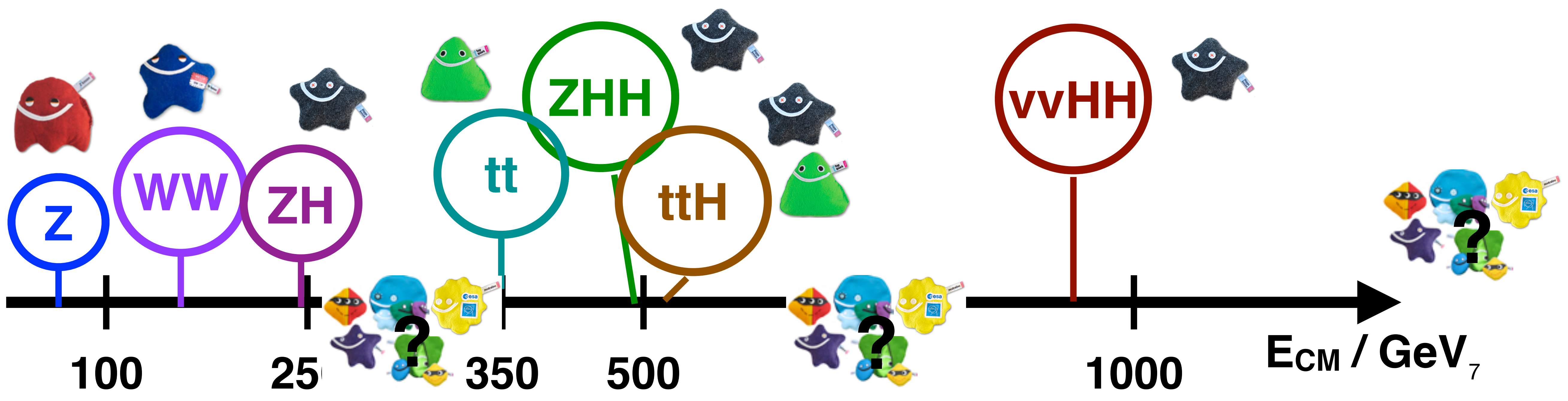
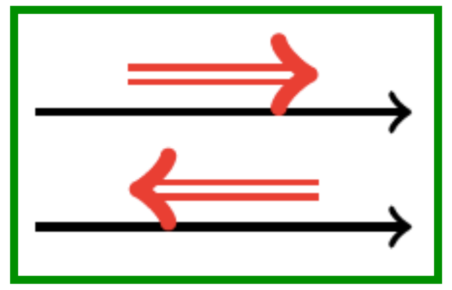


Beam polarisation

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



Interlude: Chirality in Particle Physics

Just a quick reminder…

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

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

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

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

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

Physics benefits of polarised beams

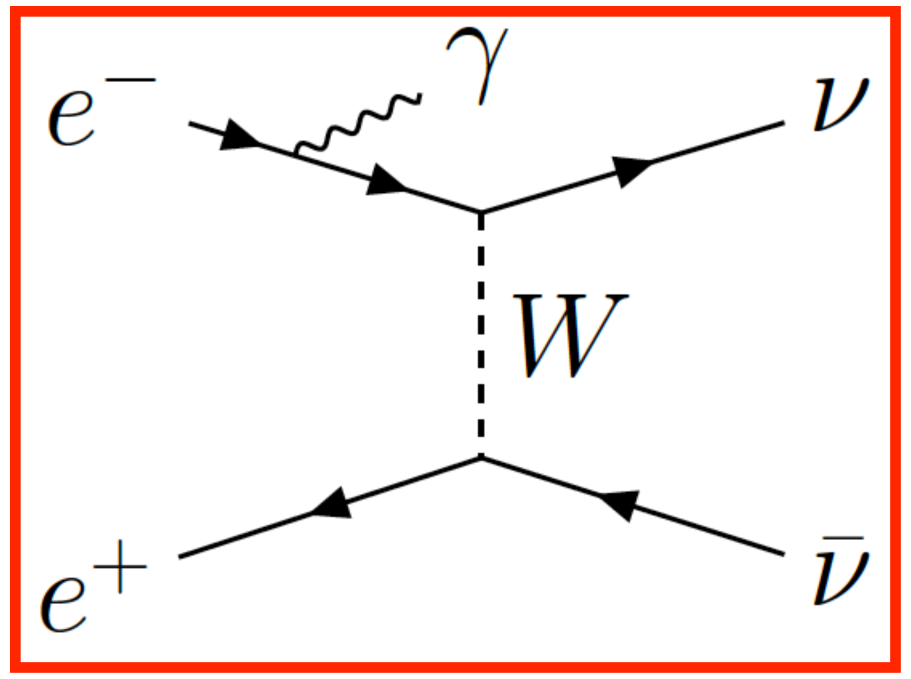
Much more than statistics!

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

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

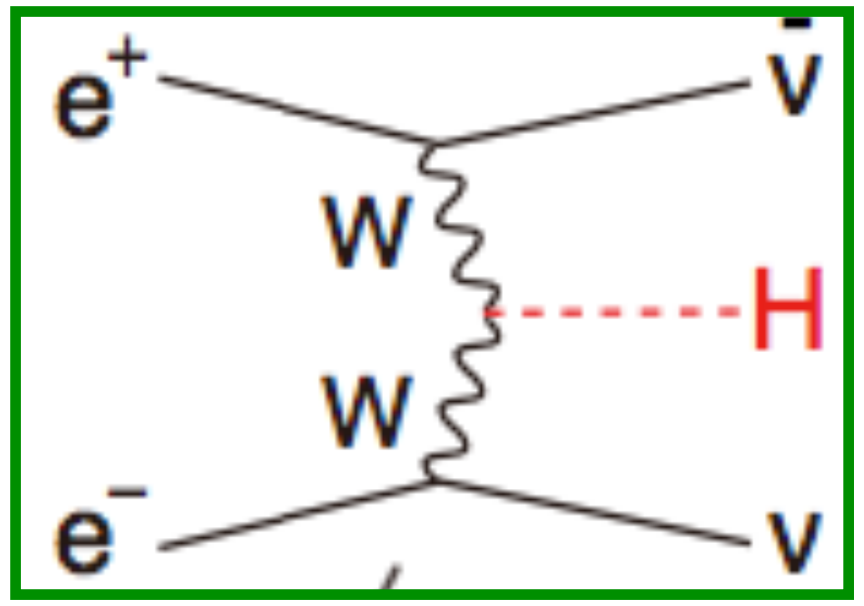
background suppression:

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



signal enhancement:

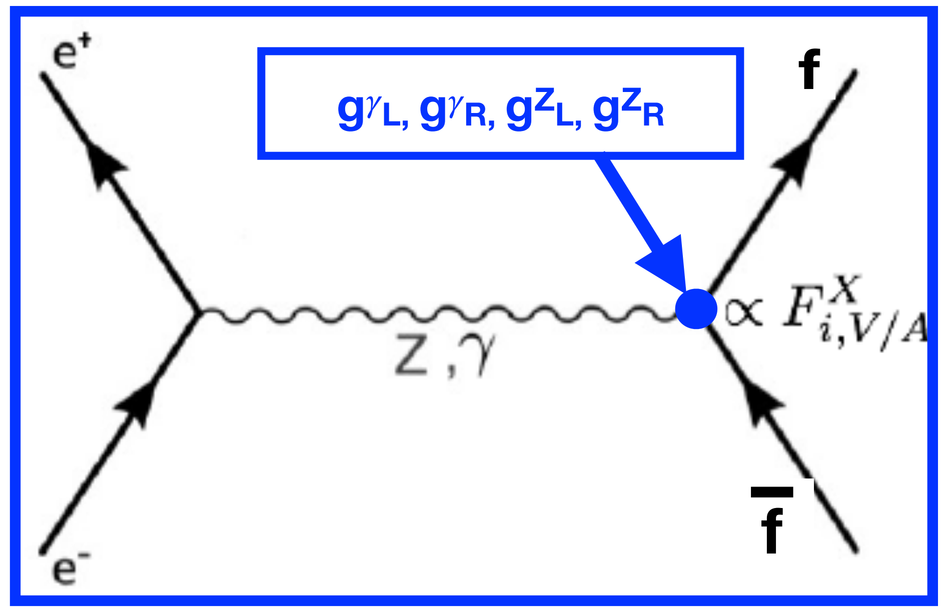
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

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



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

redundancy & control of systematics:

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

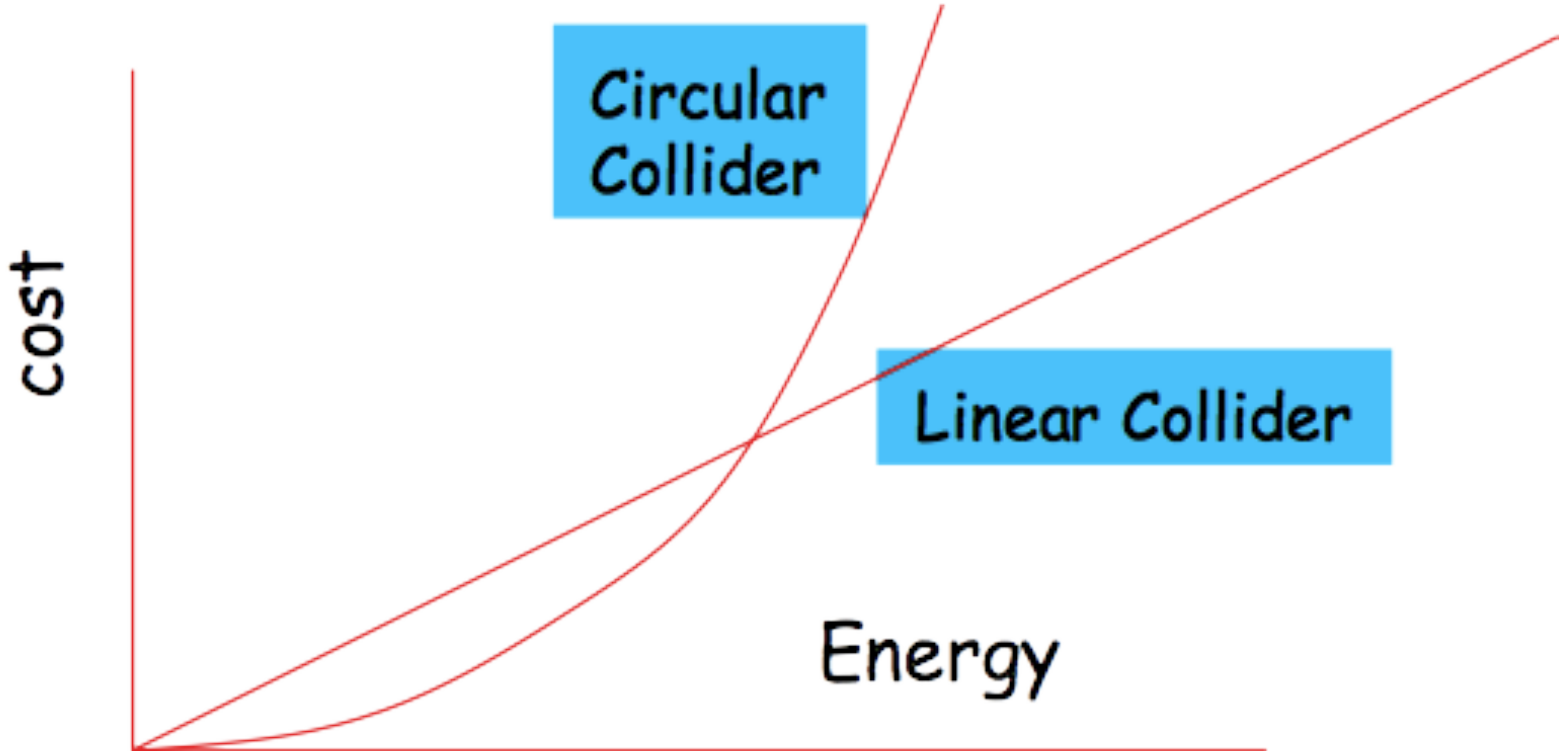
Luminosity vs Energy - a long debate…

1978[1)]

Reminder: accelerated charges radiate

- **Synchrotron radiation ~ operation cost:**
  - **$\Delta E \sim (E^4 / m^4 R)$** per turn => 2 GeV at LEP2 ~10 GeV at FCCee-365
- **Cost in high-energy limit:**
  - **circular :** $\$\$ \sim a R + b\, \Delta E \sim a R + b\, (E^4 / m^4 R)$

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



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

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

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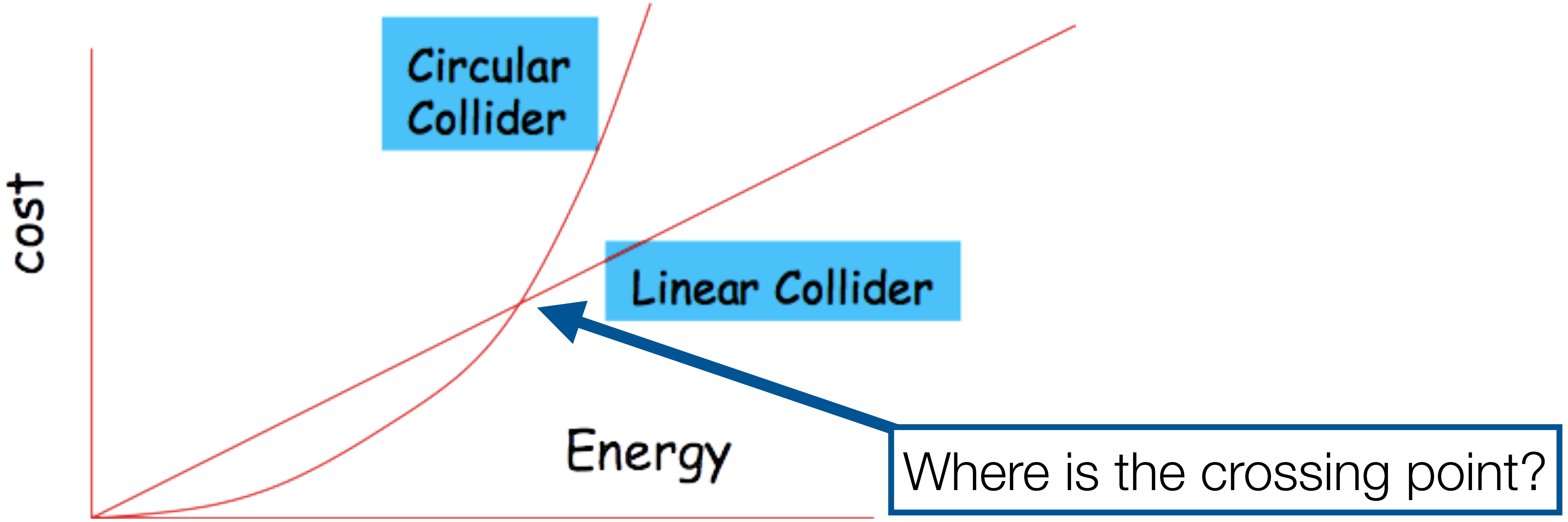

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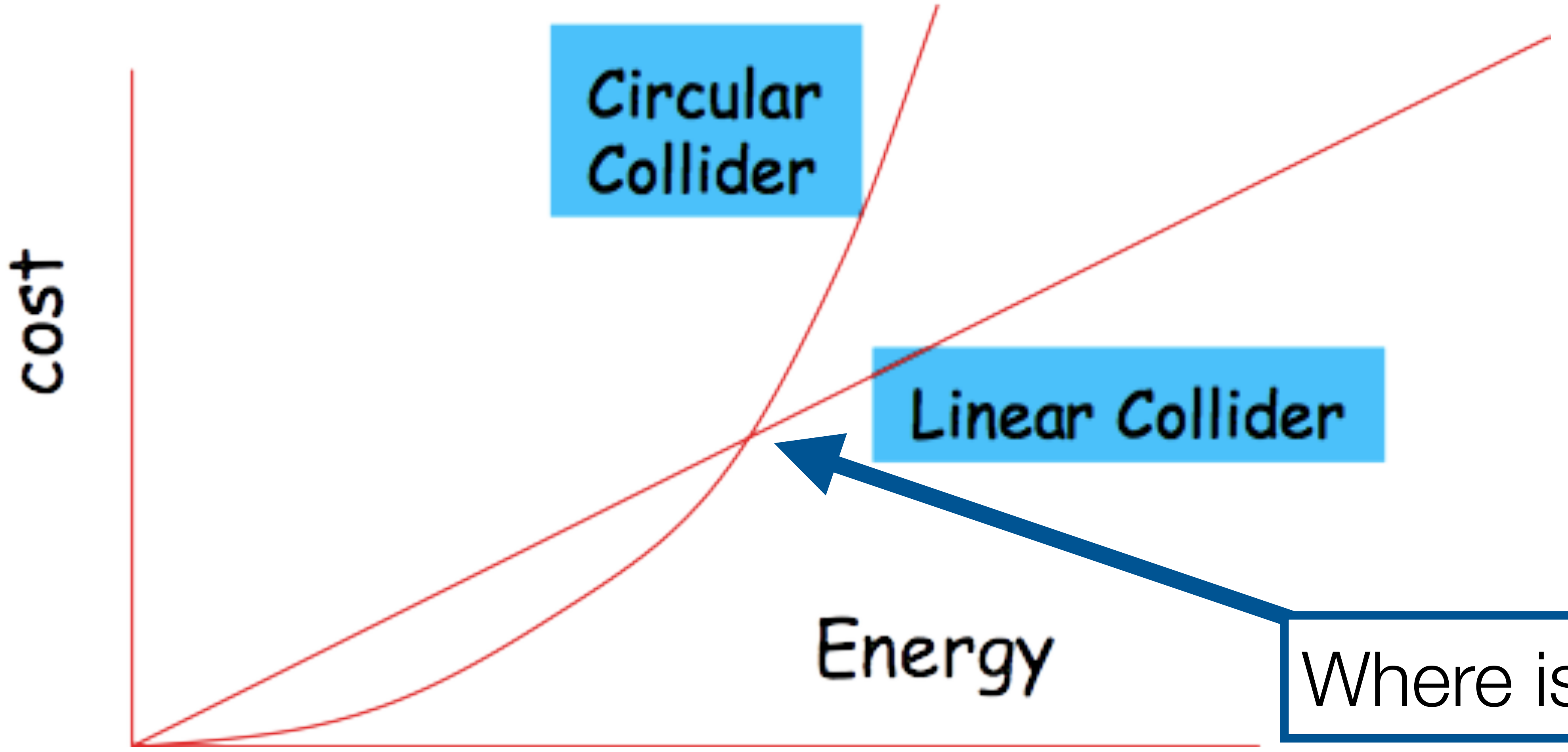

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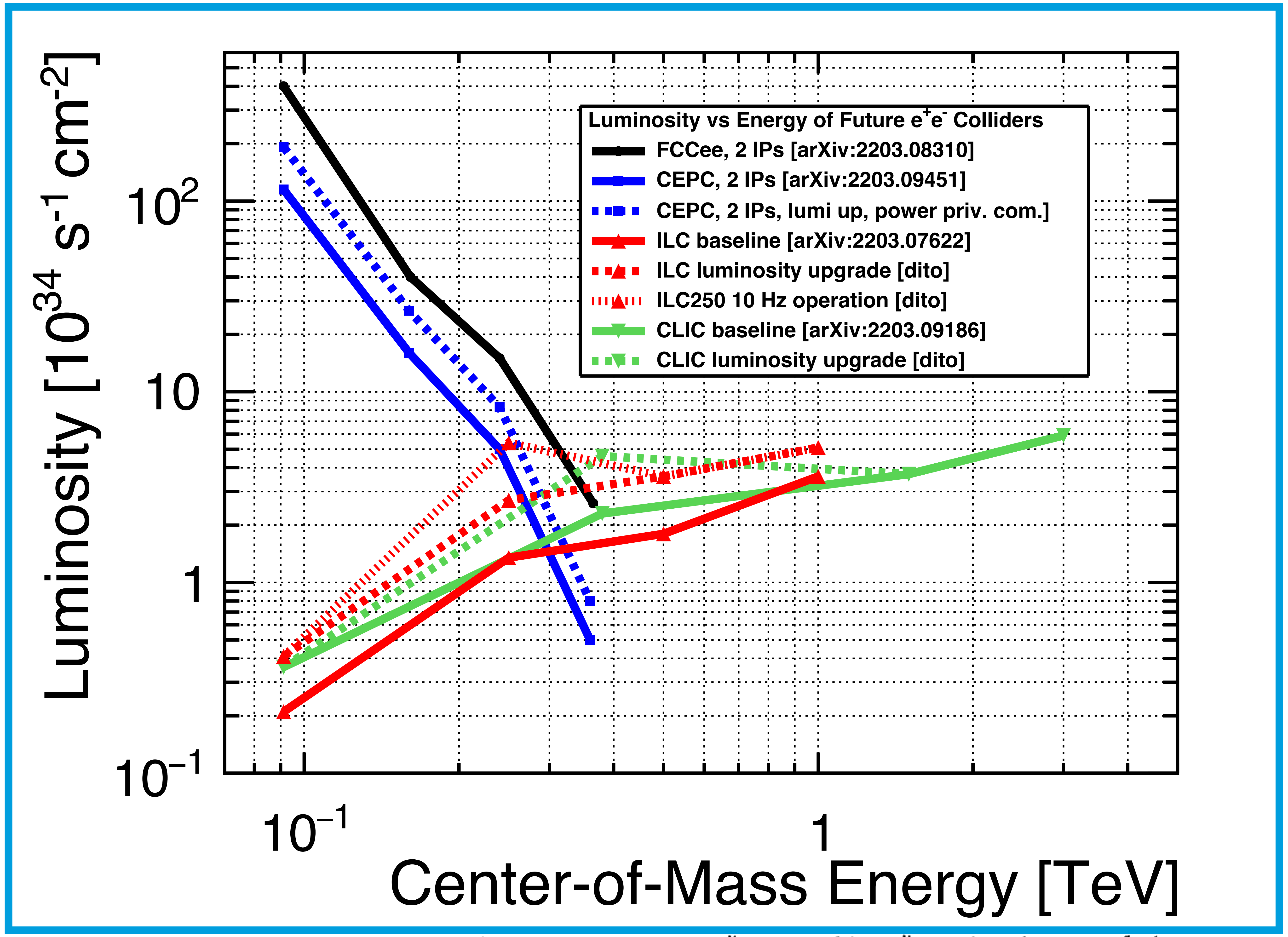

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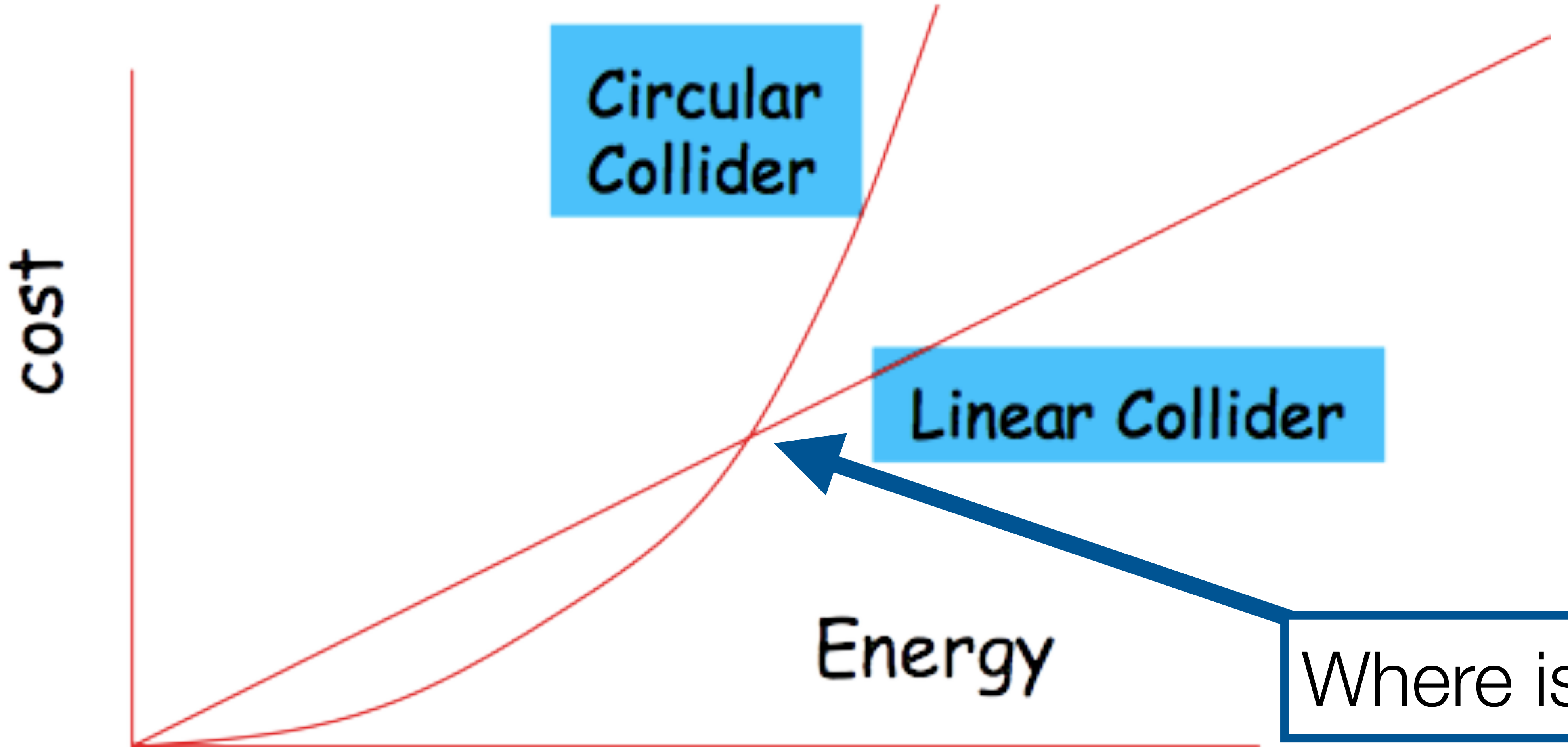
Luminosity vs Energy - a long debate…

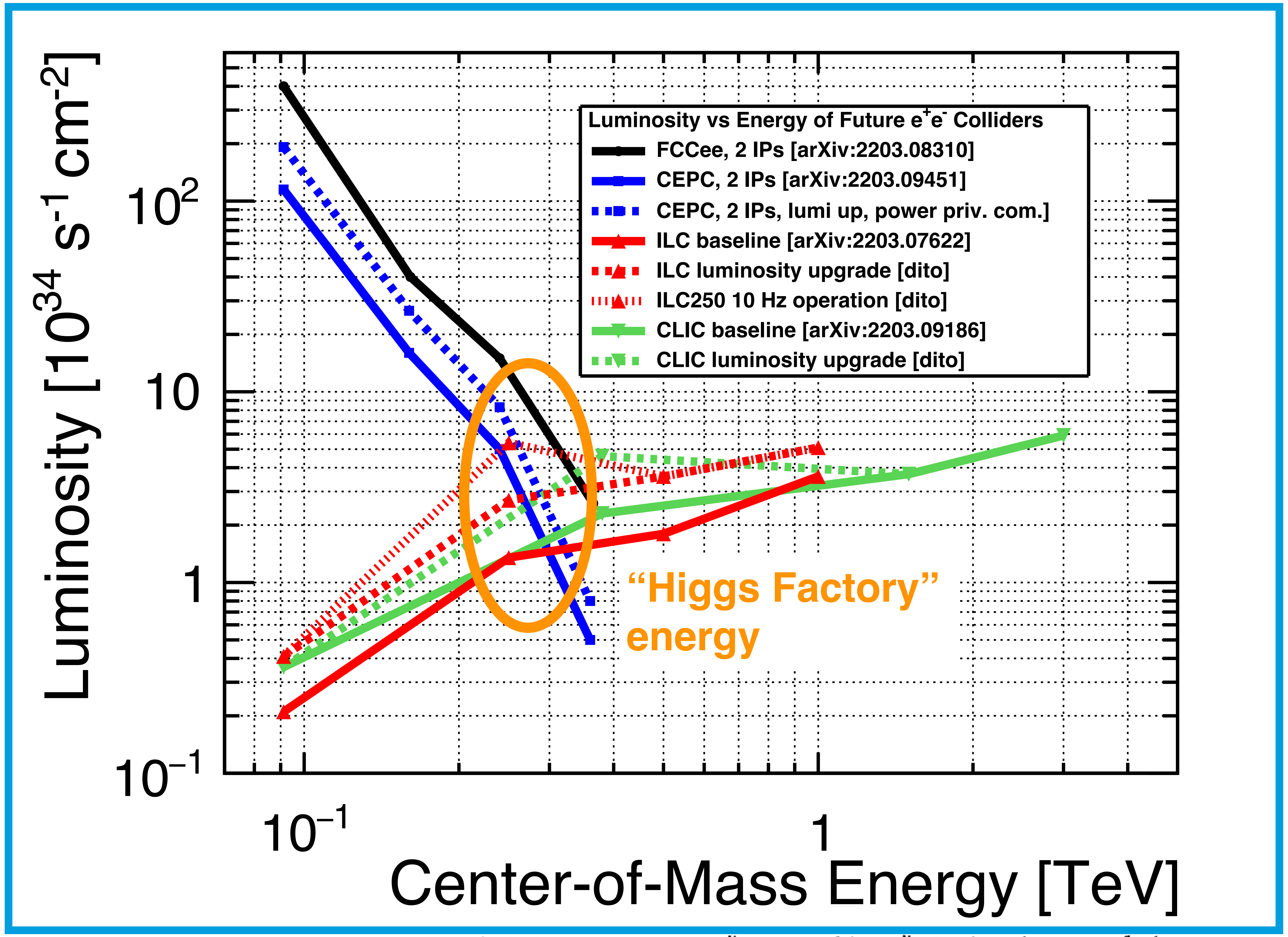
1978[1)]

Reminder: accelerated charges radiate

- **Synchrotron radiation ~ operation cost:**
  - **ΔE ~ (E^4 / m^4R)** per turn => 2 GeV at LEP2
    ~10 GeV at FCCee-365
- **Cost in high-energy limit:**
  - **circular :** $$ ~ a R + b **ΔE** ~ a R + b (**E^4 / m^4R**)
    optimize => R ~ E^2 => **$$ ~ E^2**
  - **linear :** $$ ~ **L**, with **L ~ E** => **$$ ~ E**



Where is the crossing point?

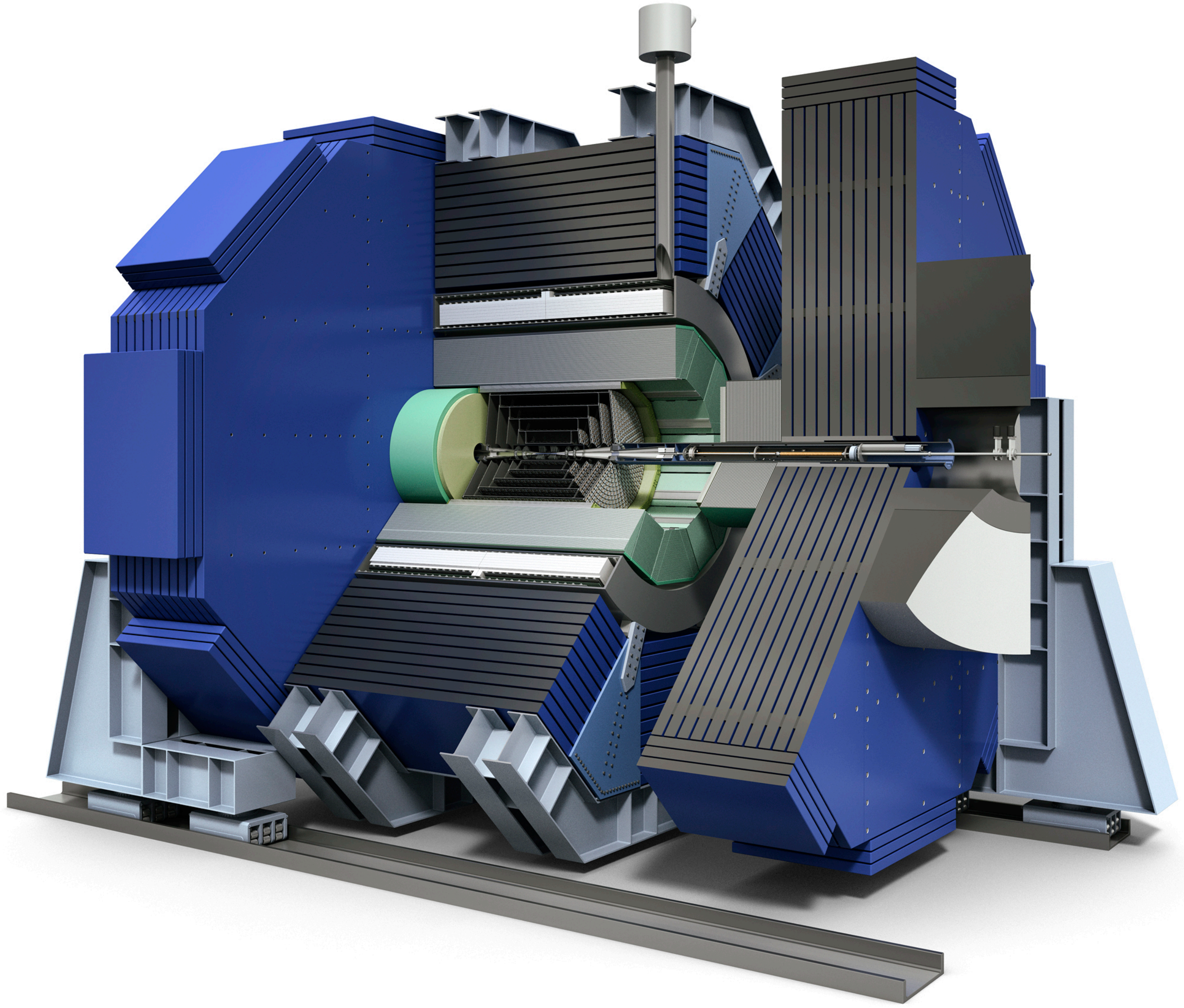


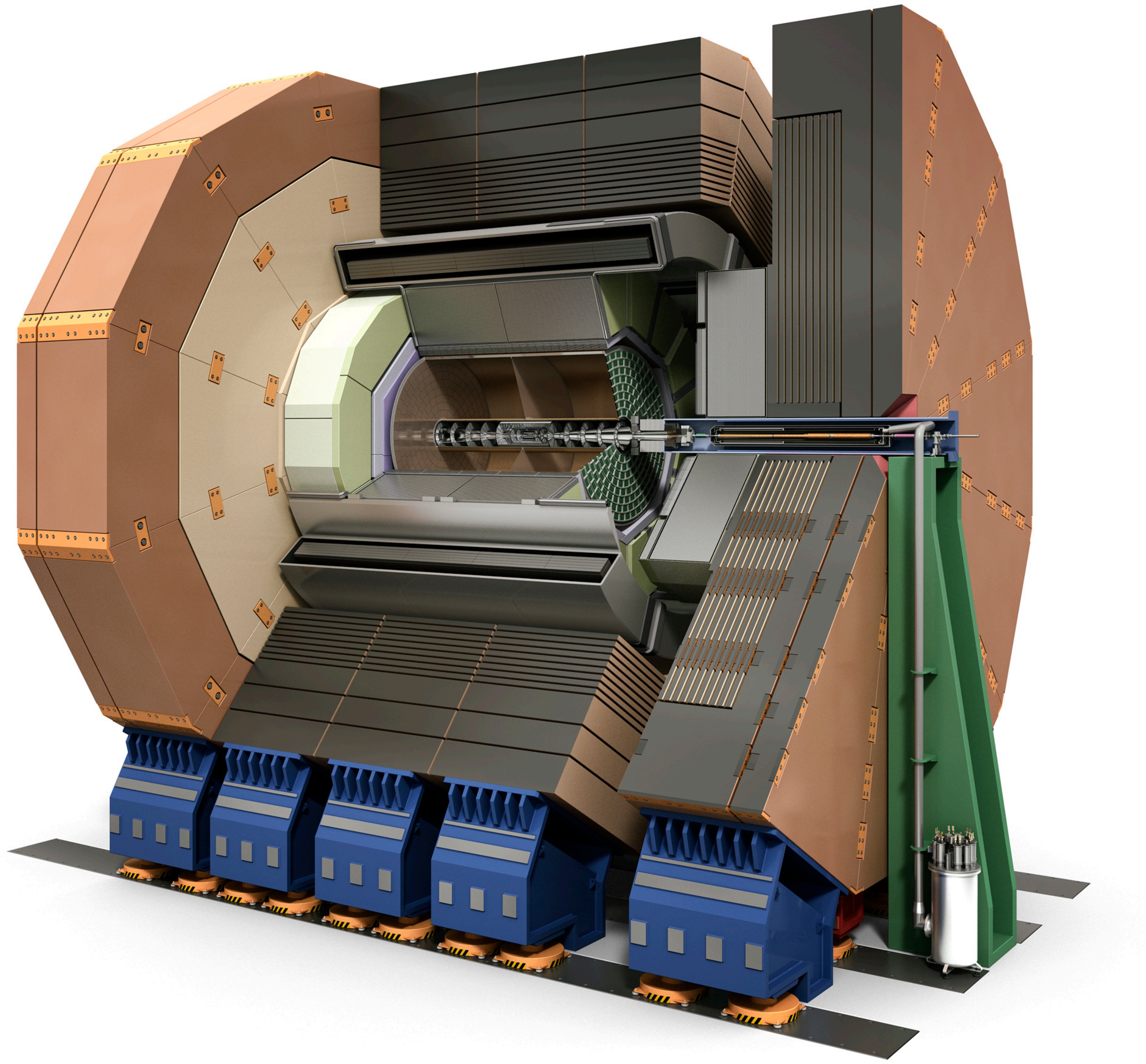
and we dubbed this phenomenon "beam-strahlung." During the rest of the week we investigated the scaling laws for these two colliding-beam systems taking beam-strahlung into consideration.

1) very first paper on this topic: M.Tigner 1965

Higgs Factory Detector Concepts

for linear & circular





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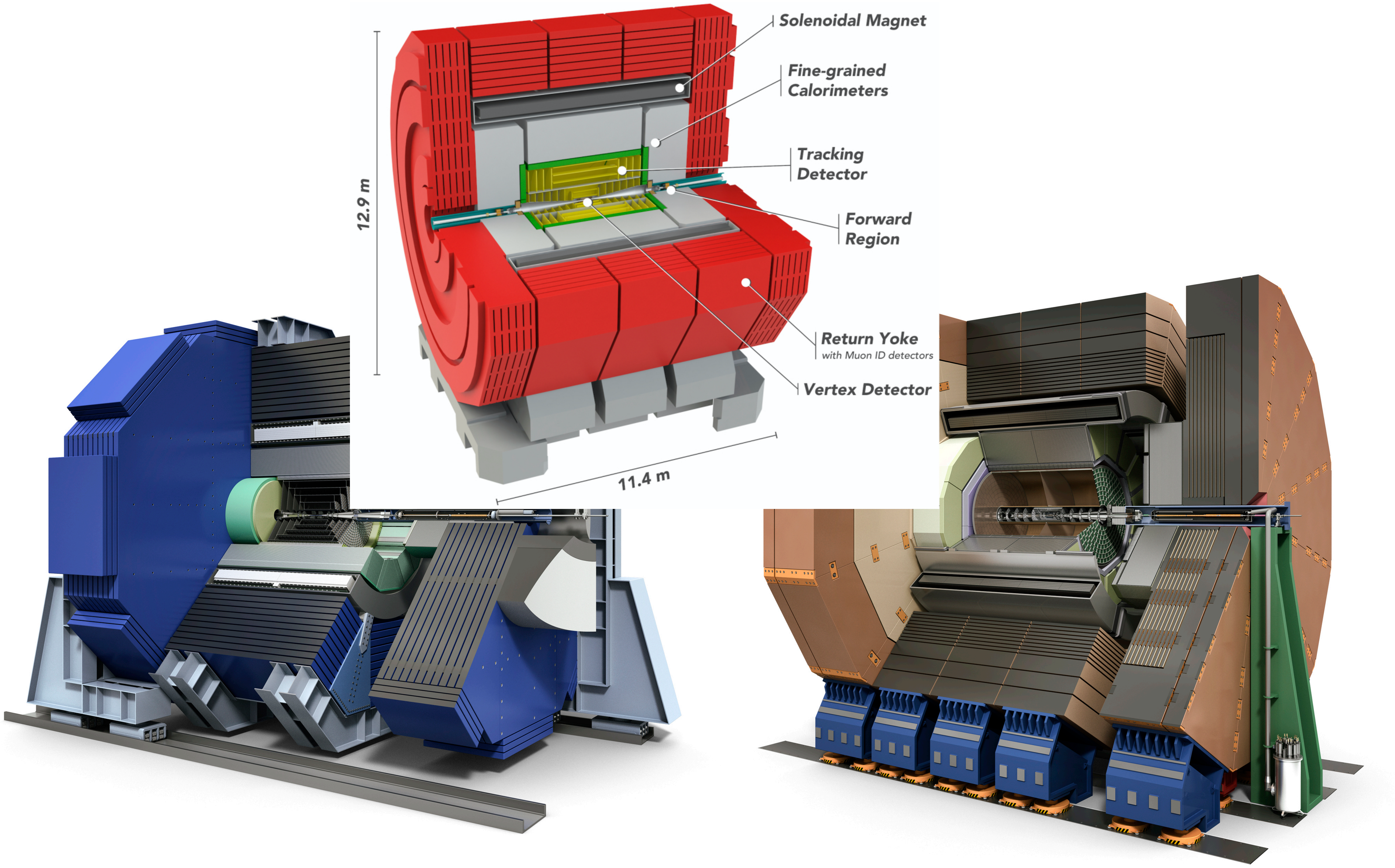

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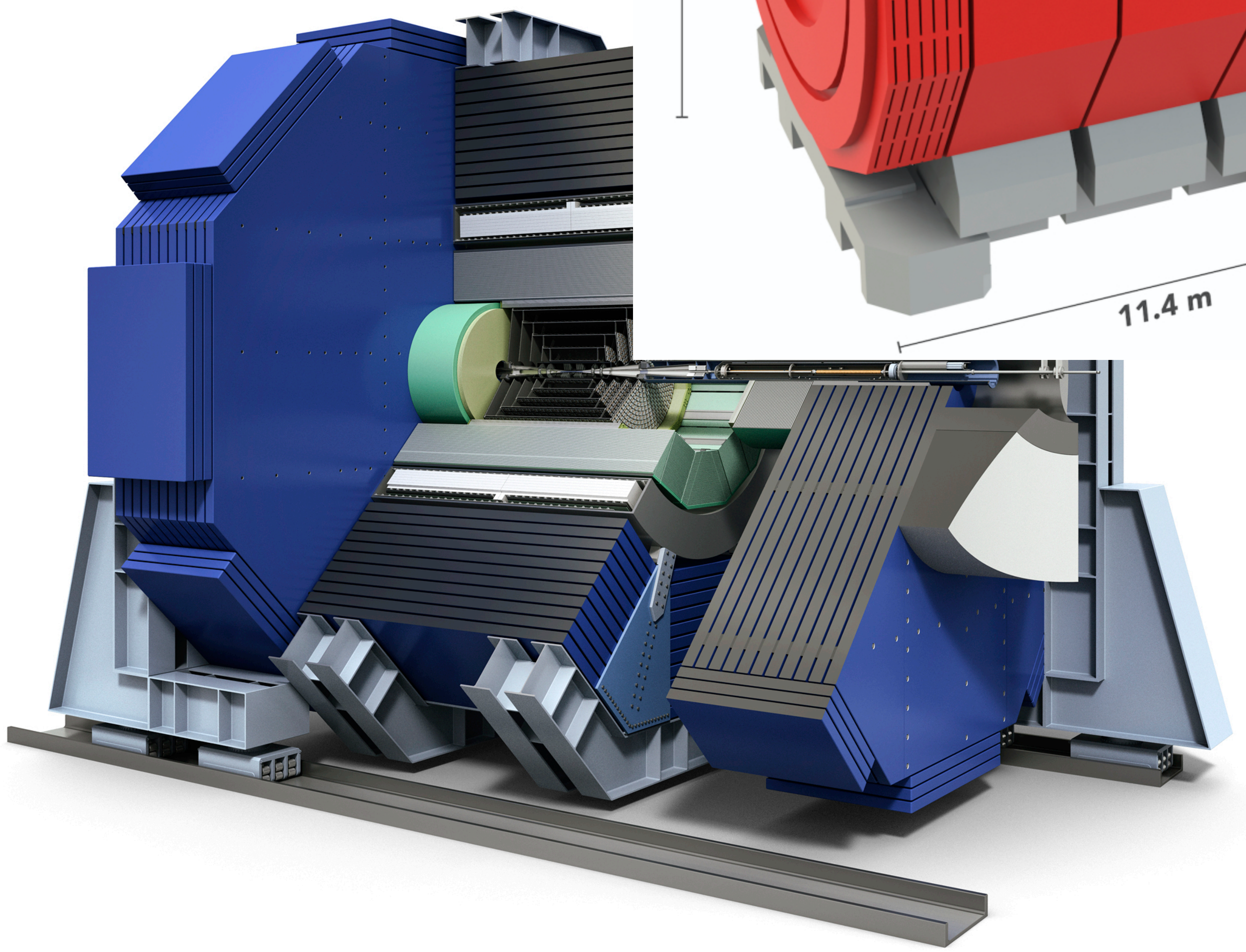

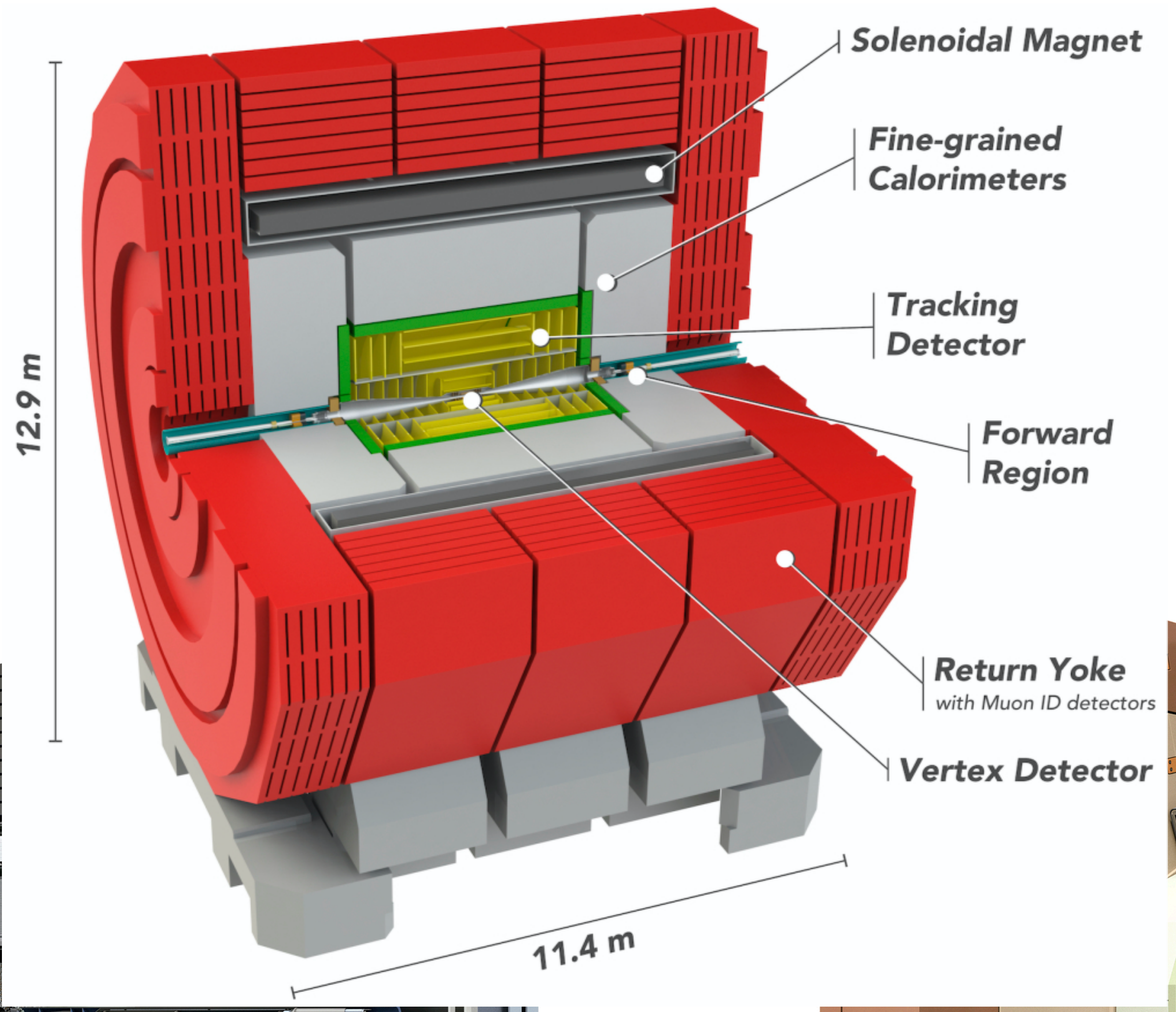

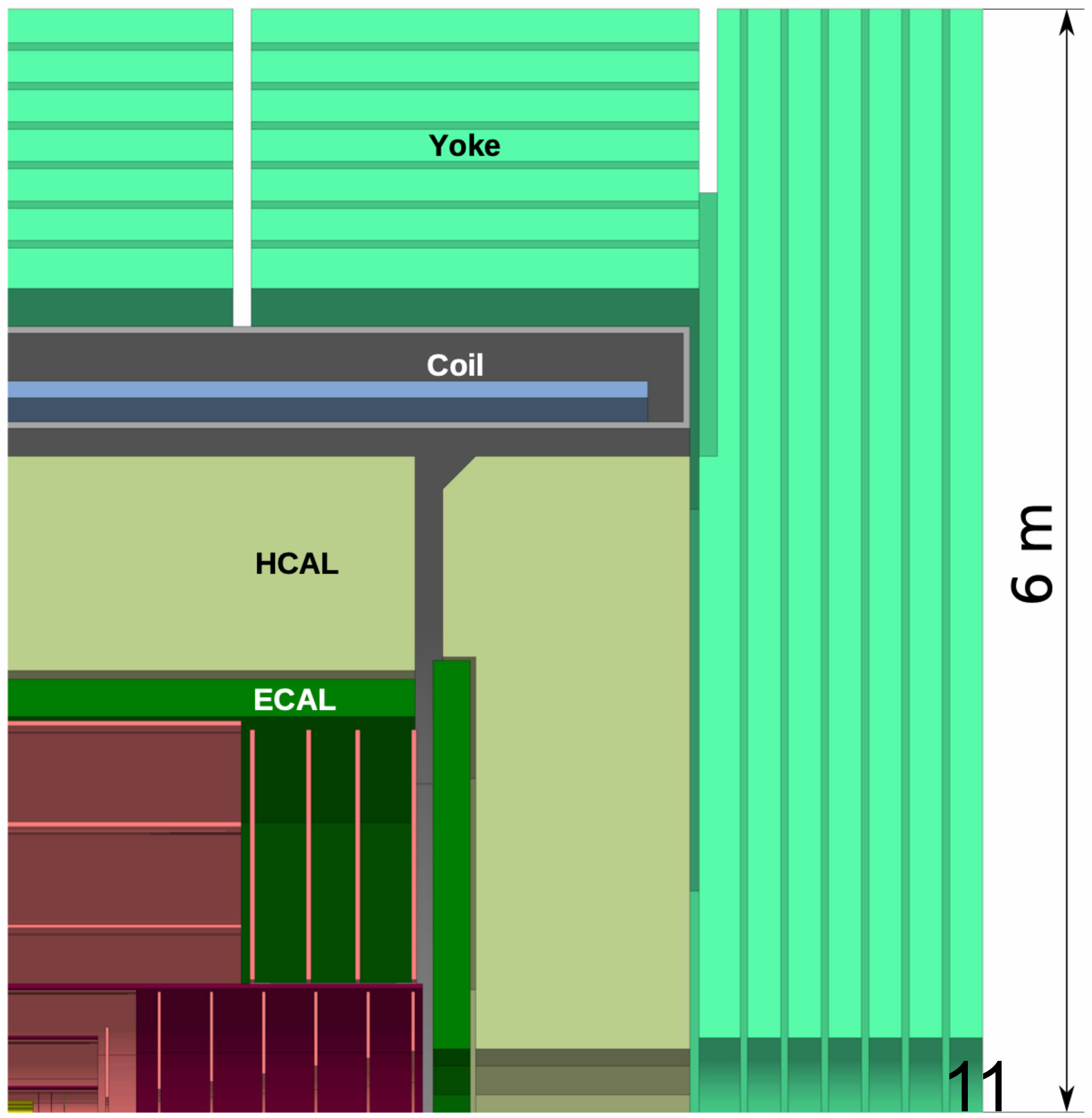

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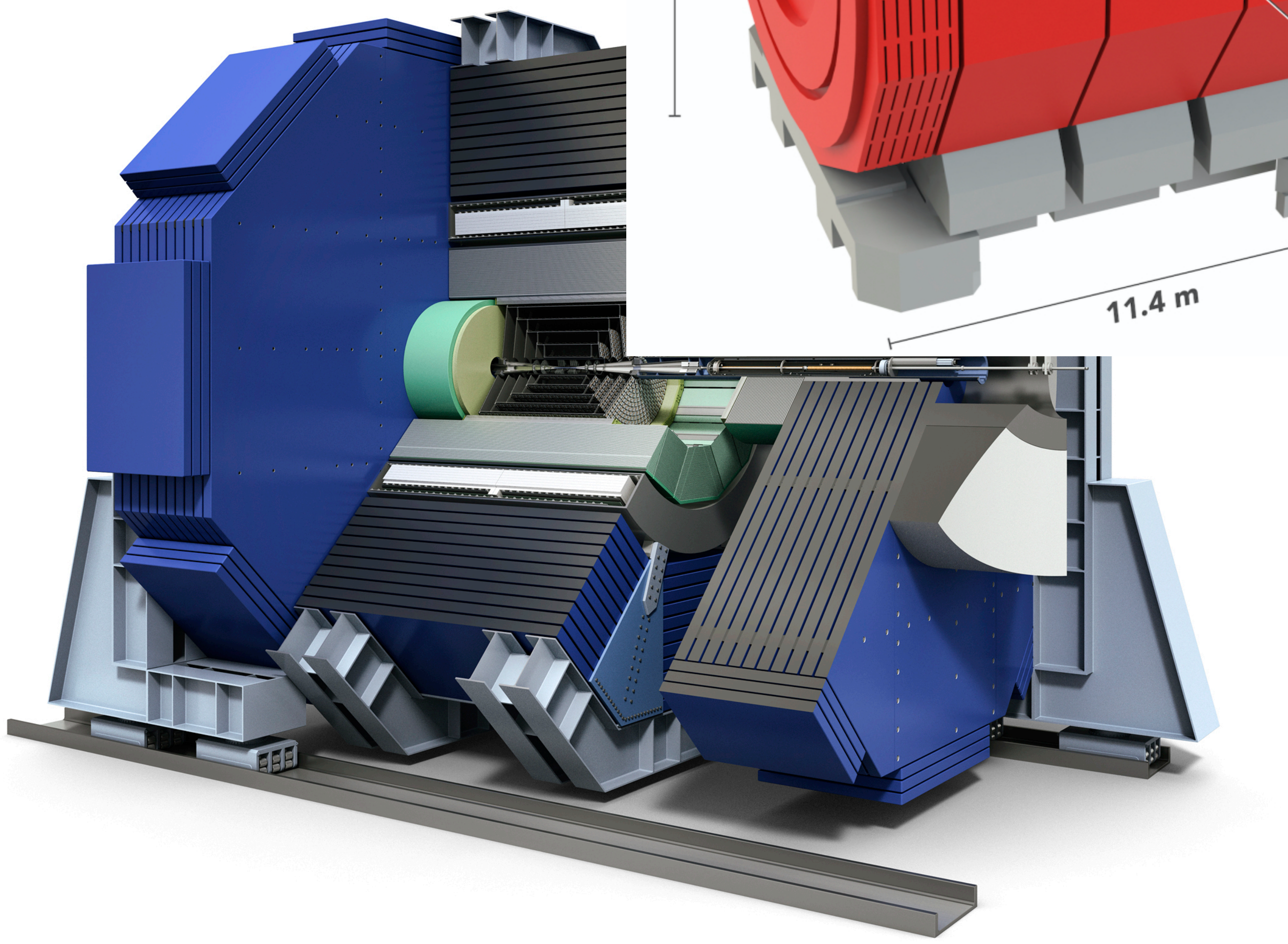

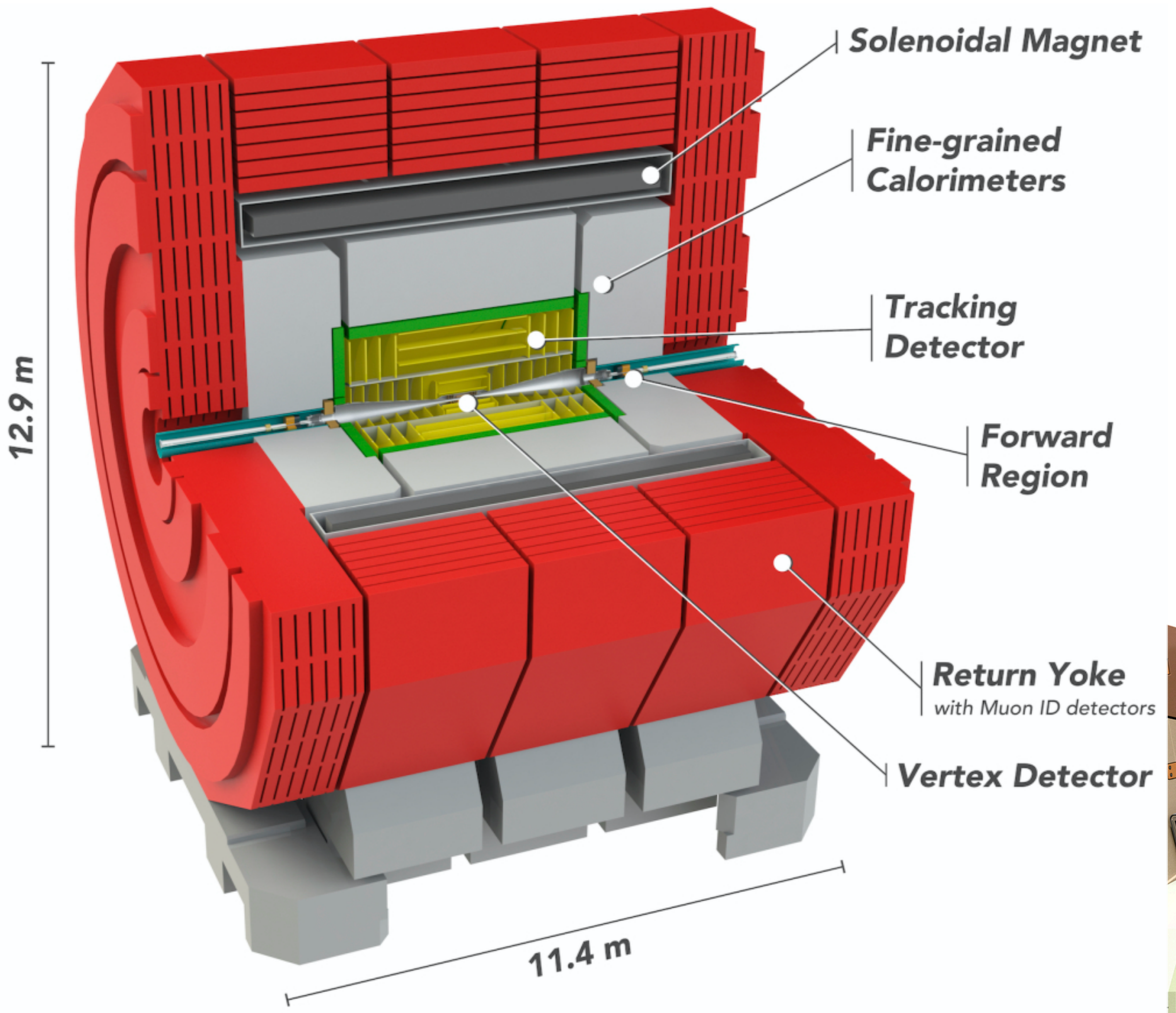

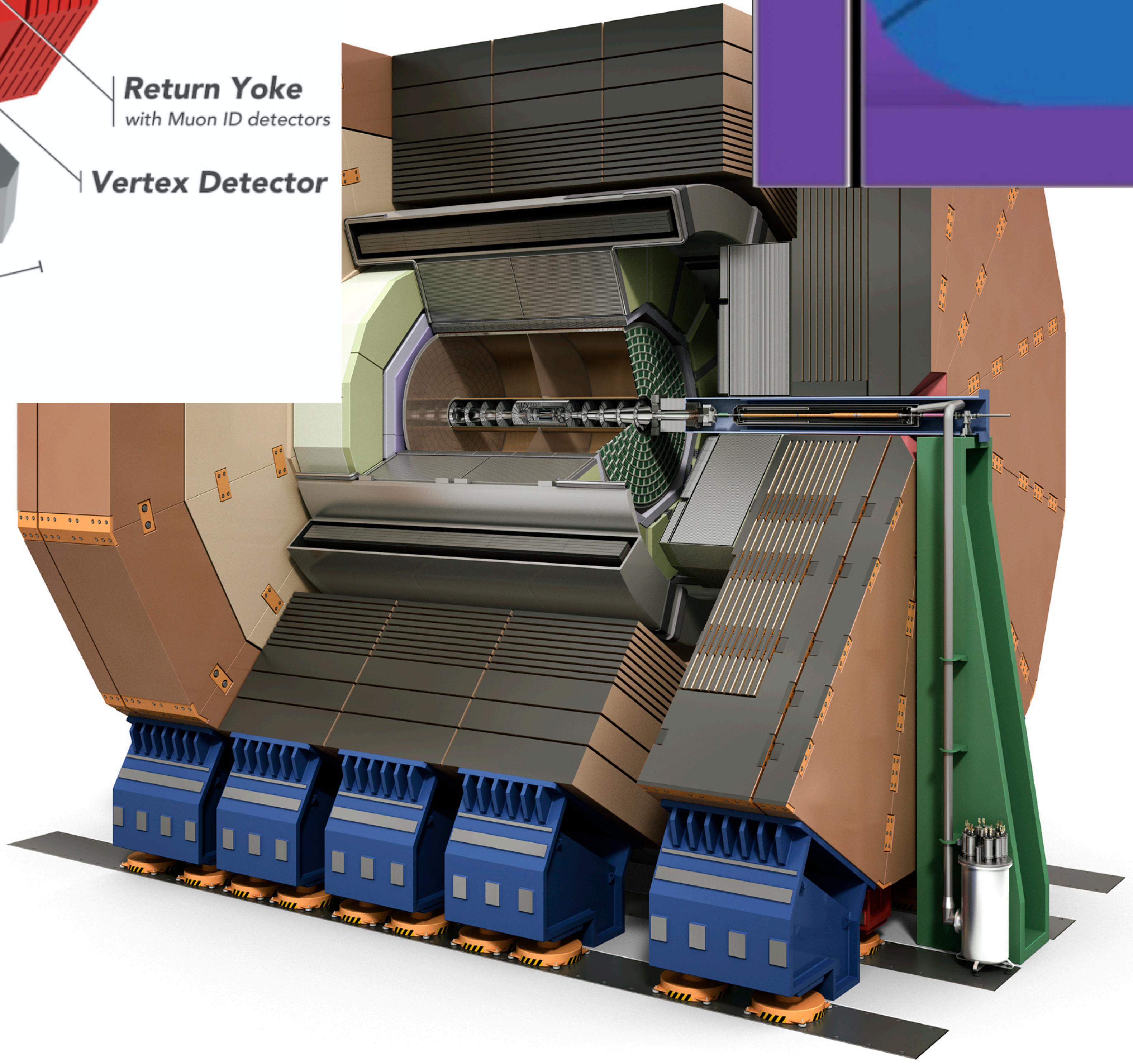

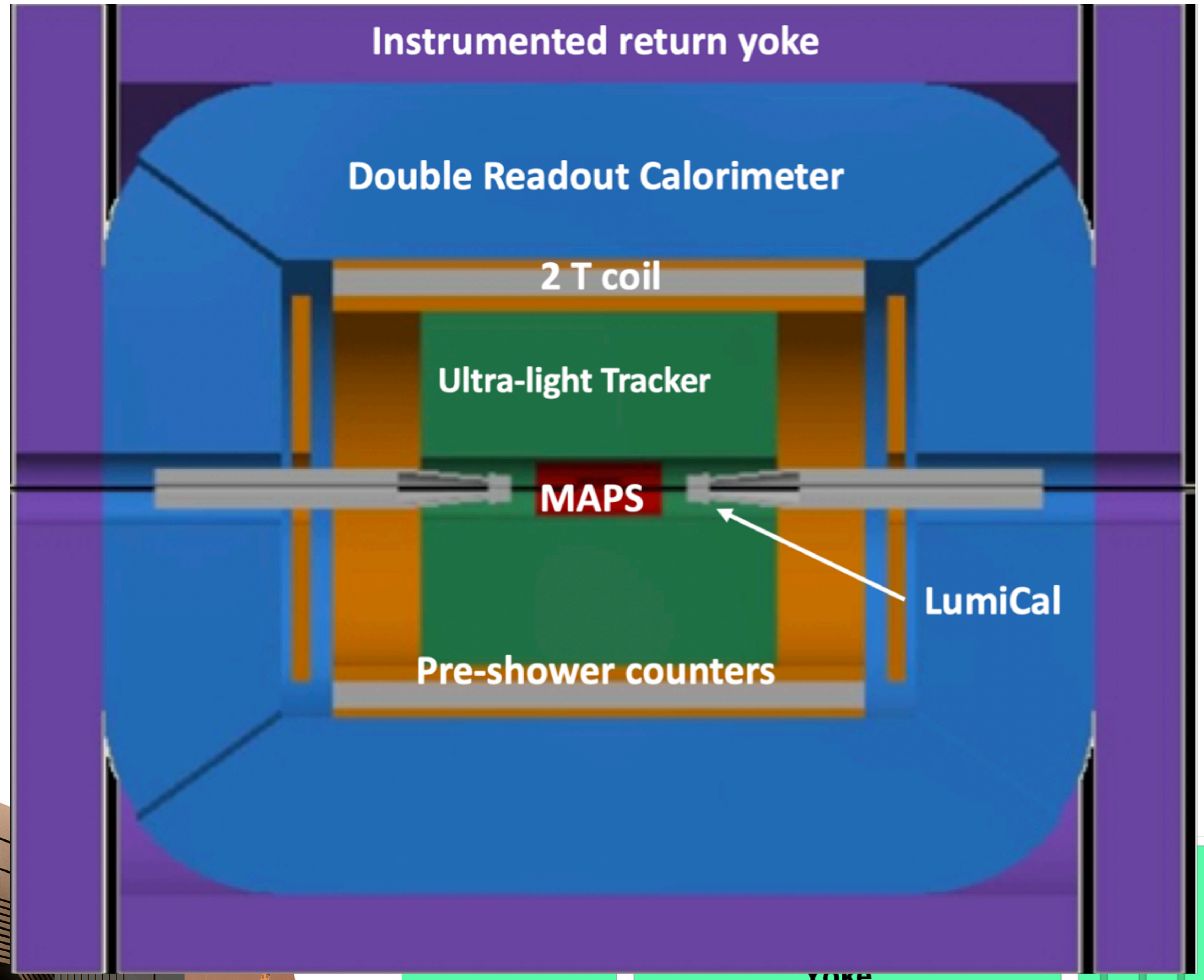

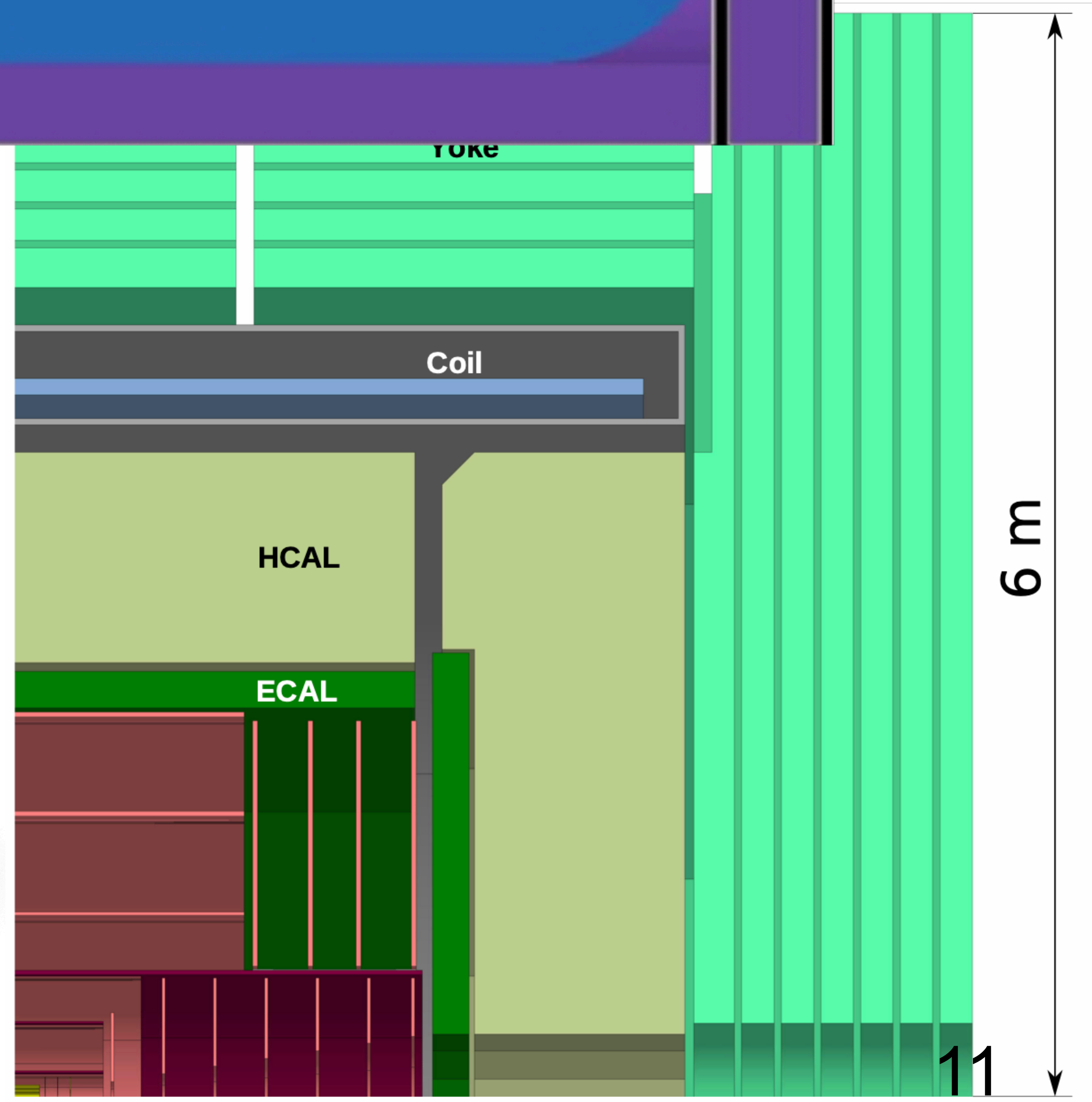

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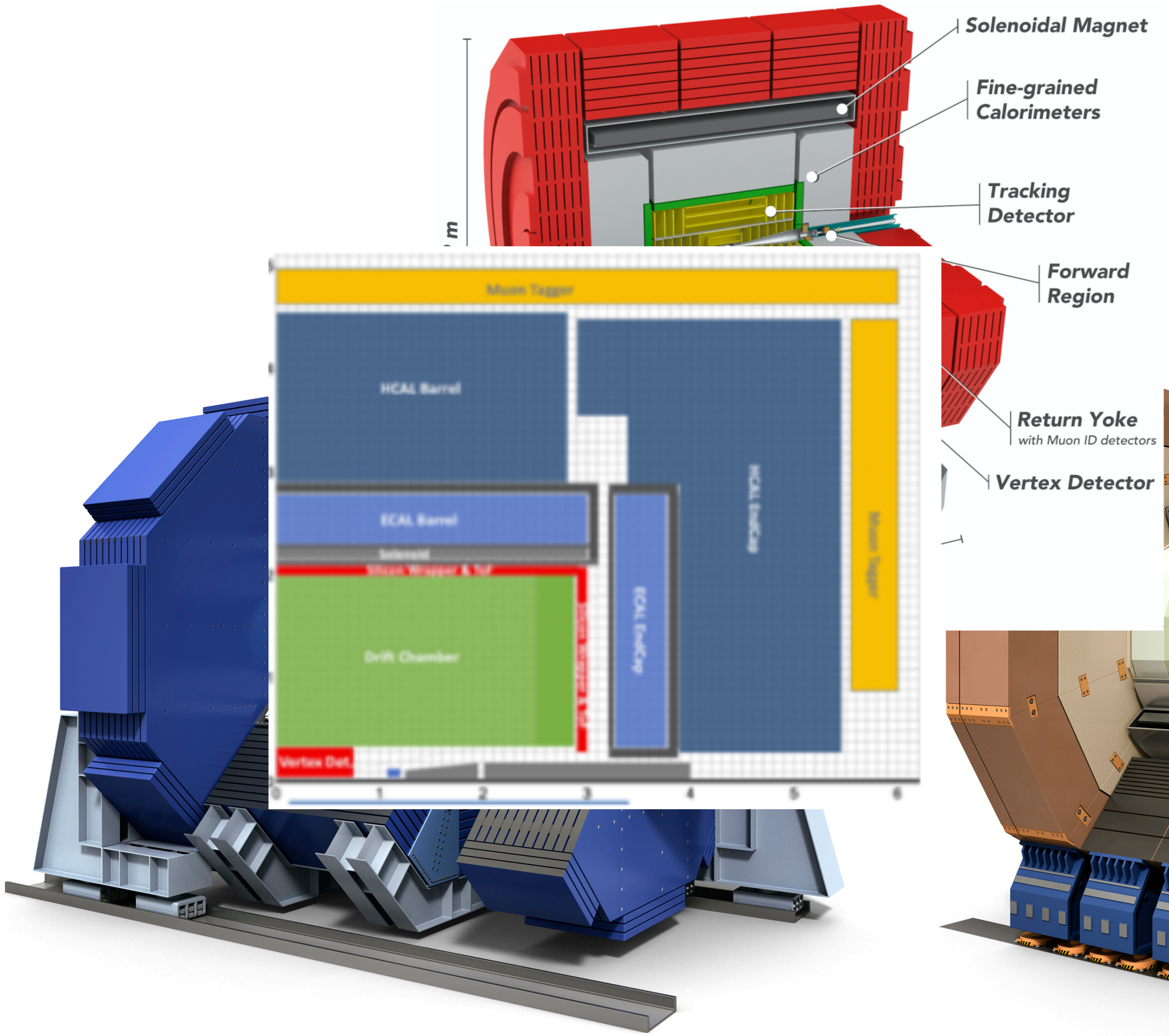

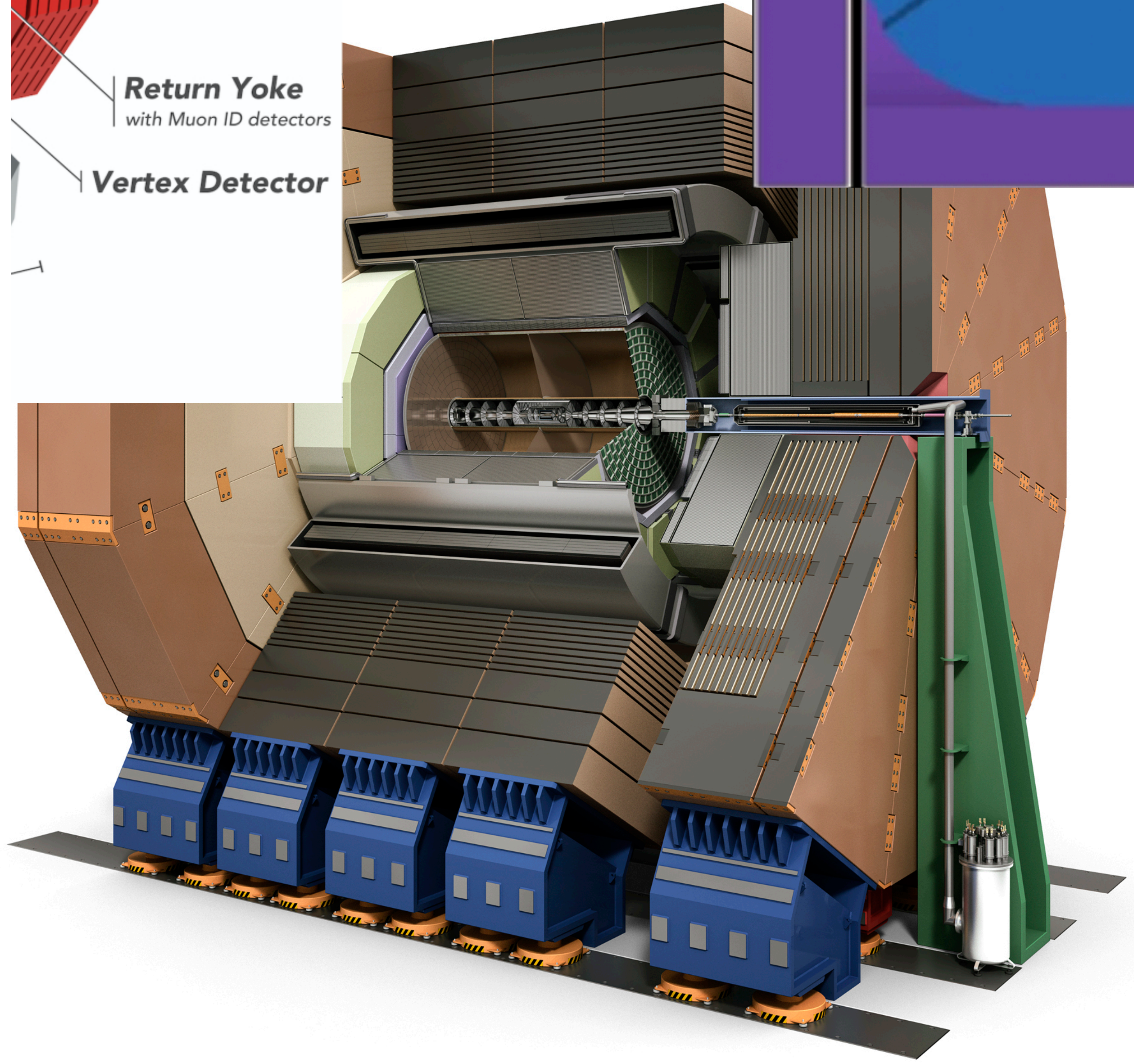

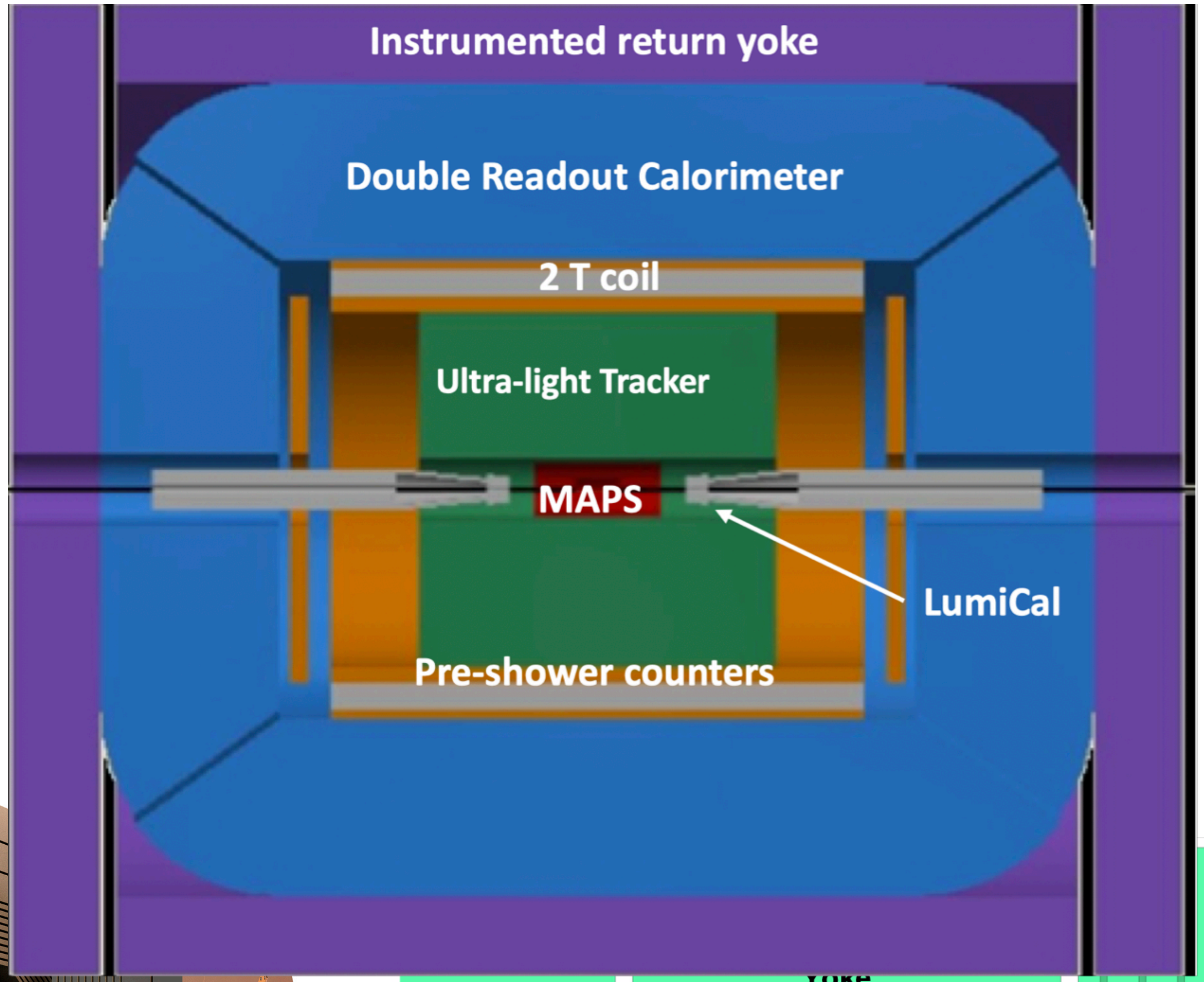

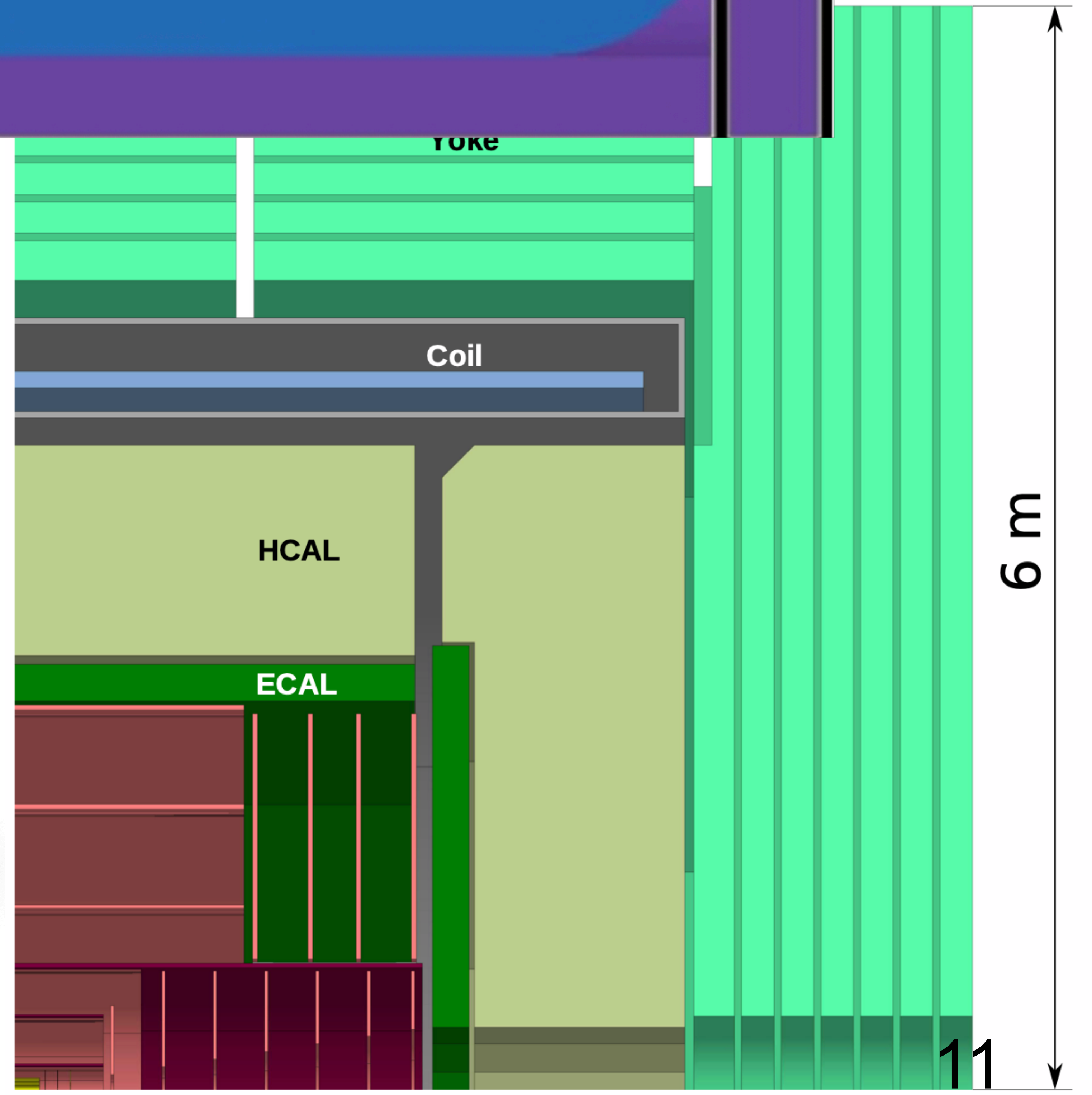

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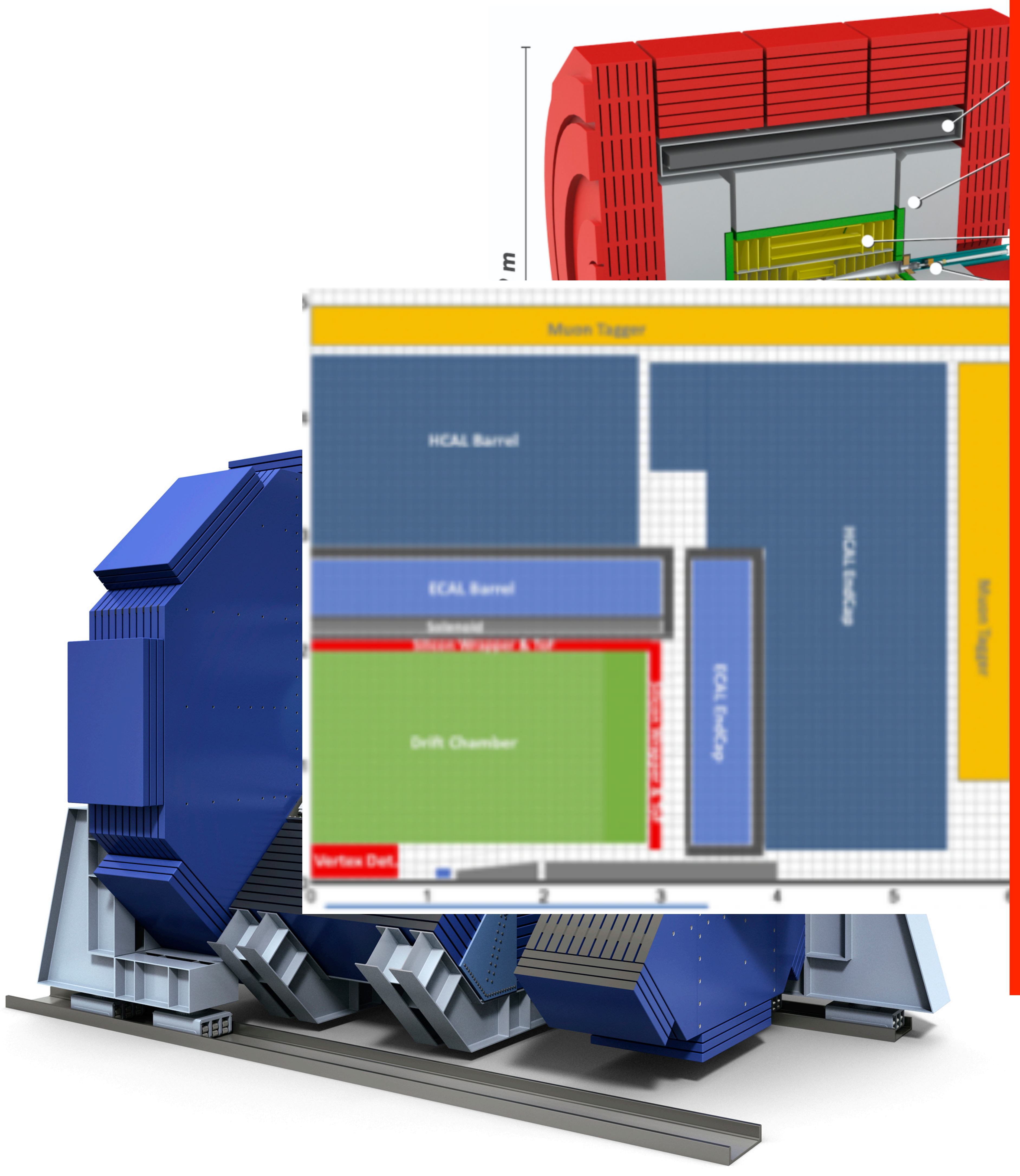

Key requirements from Higgs physics:

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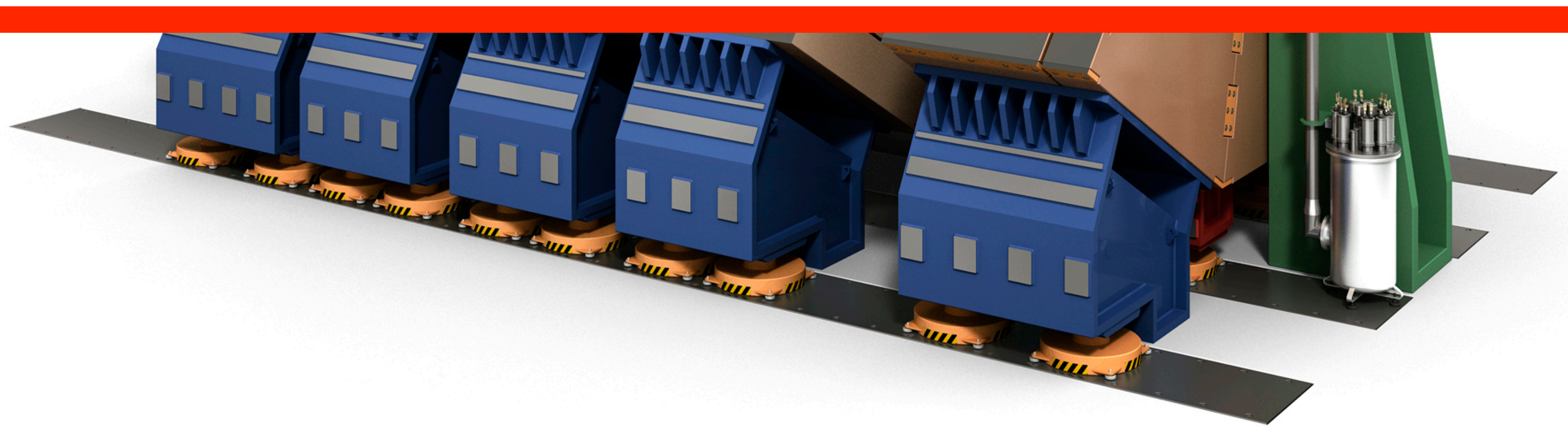

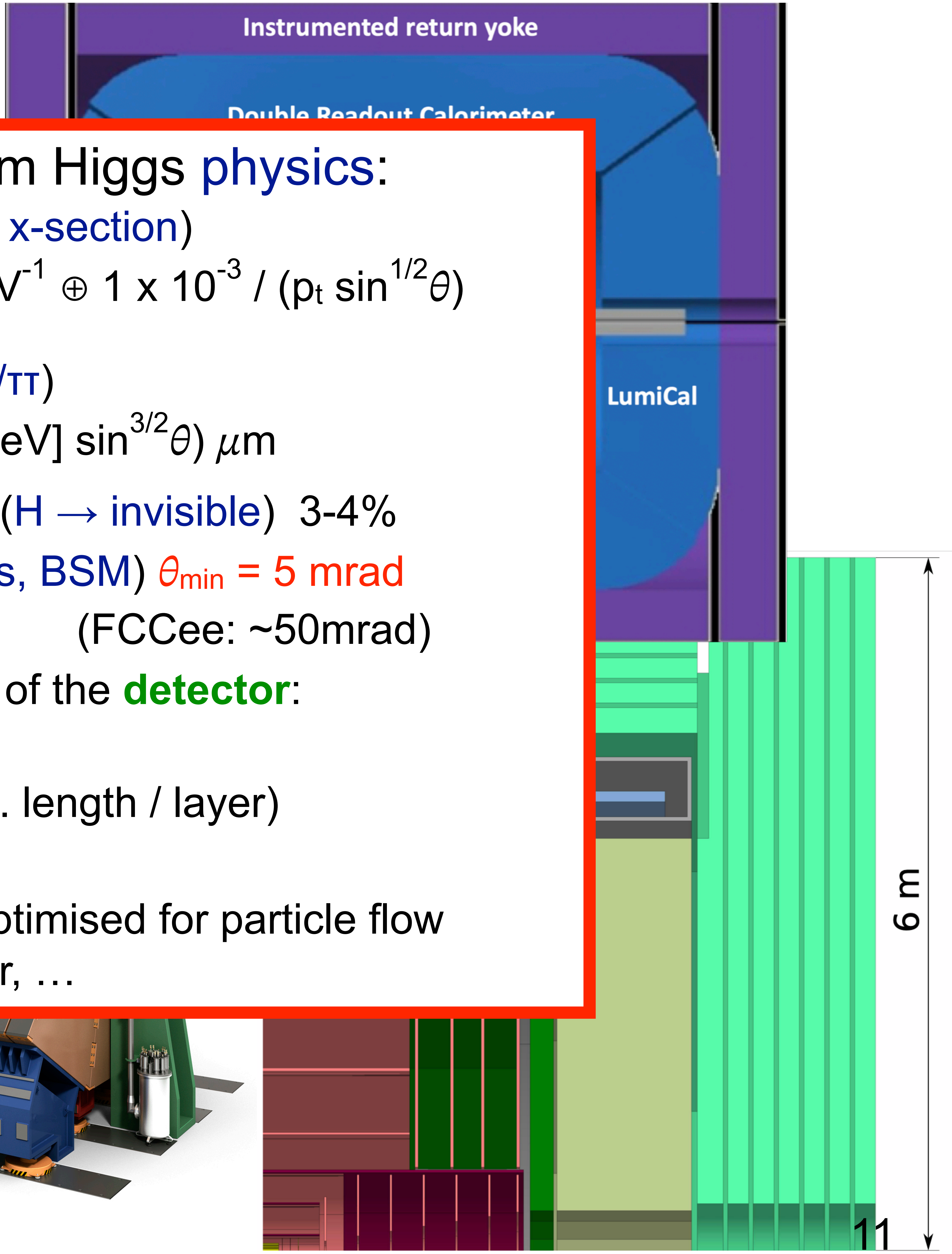

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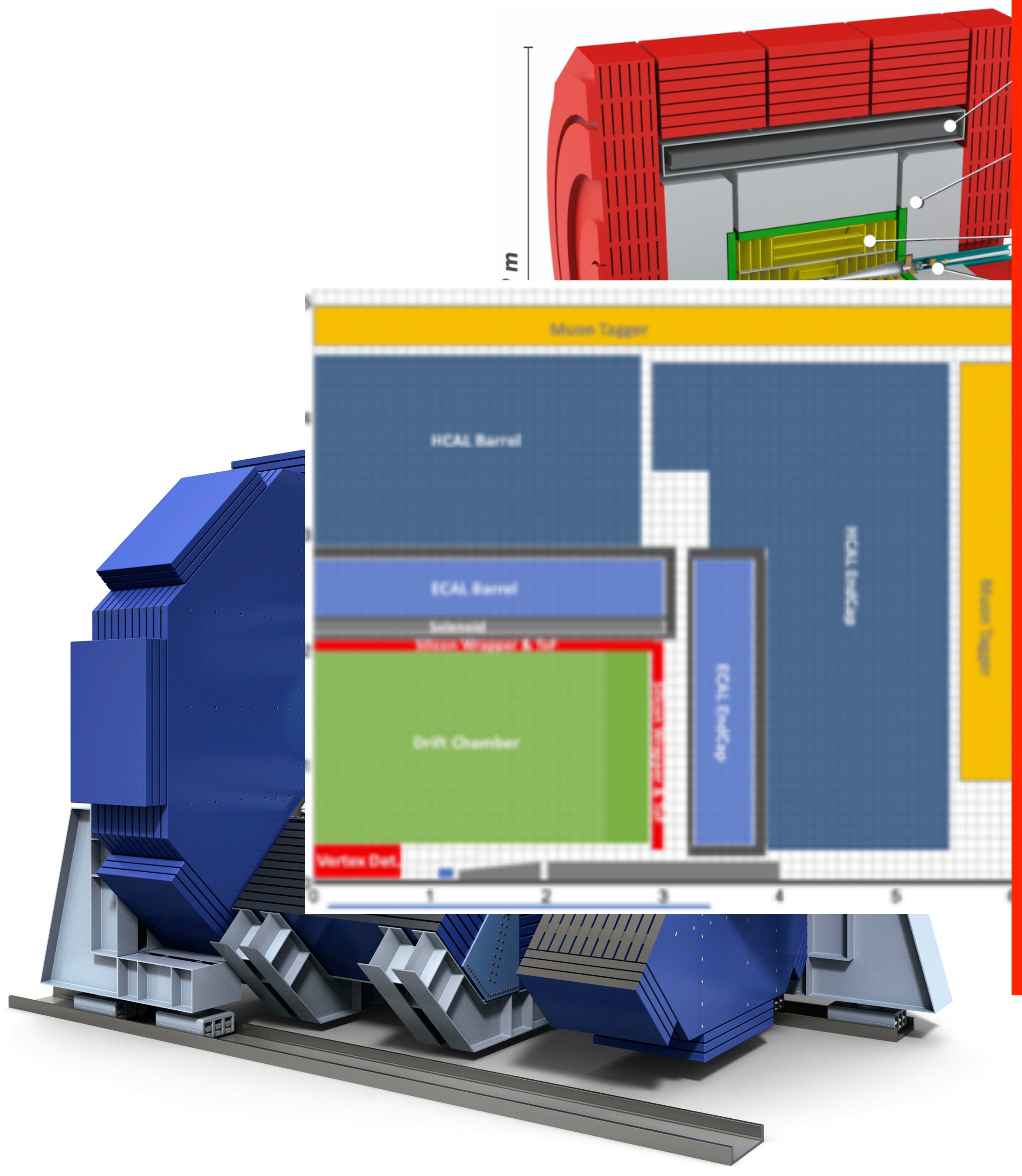

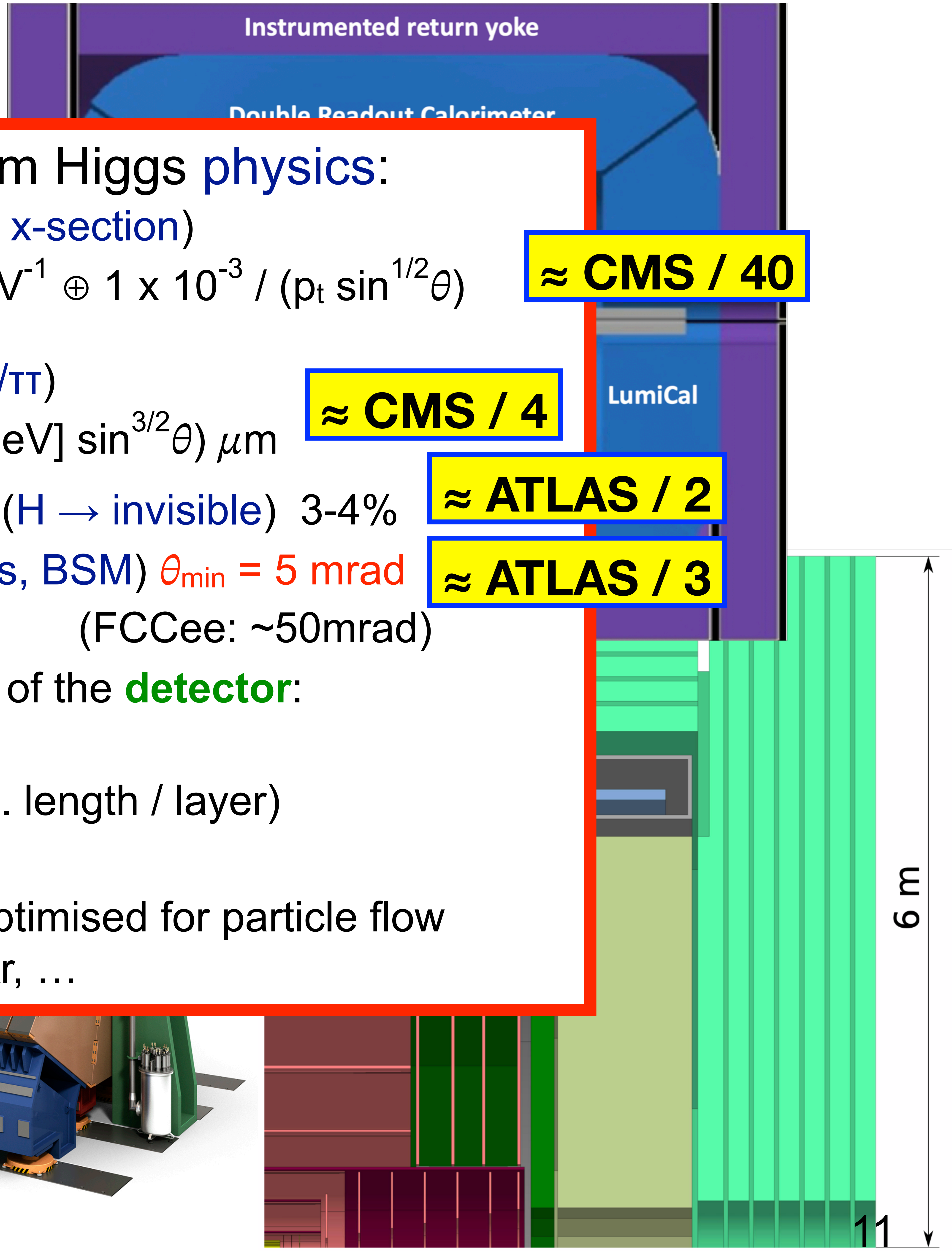

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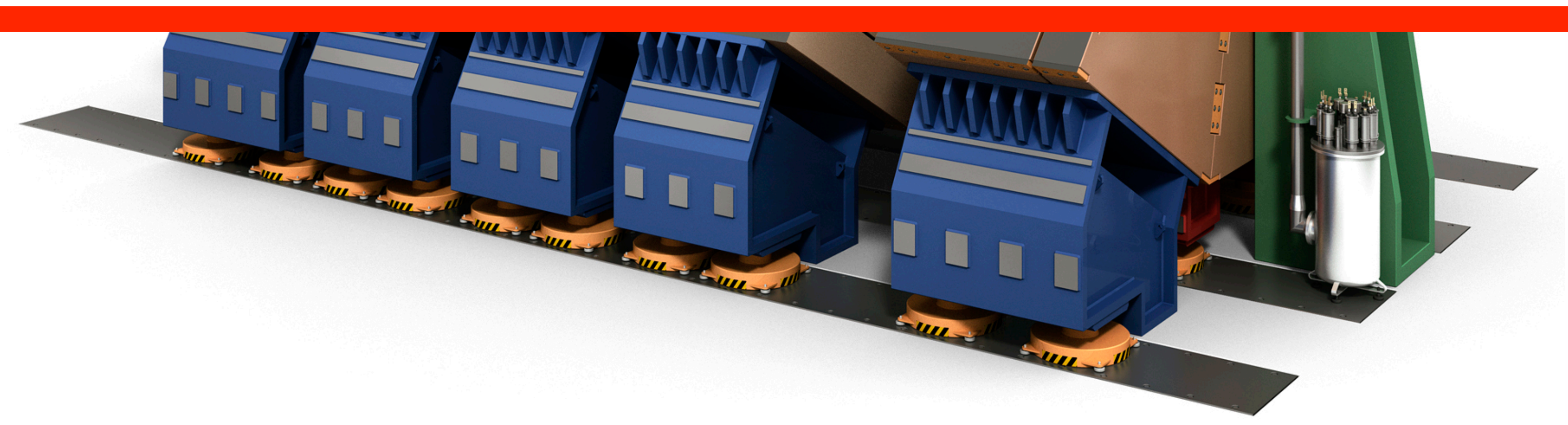

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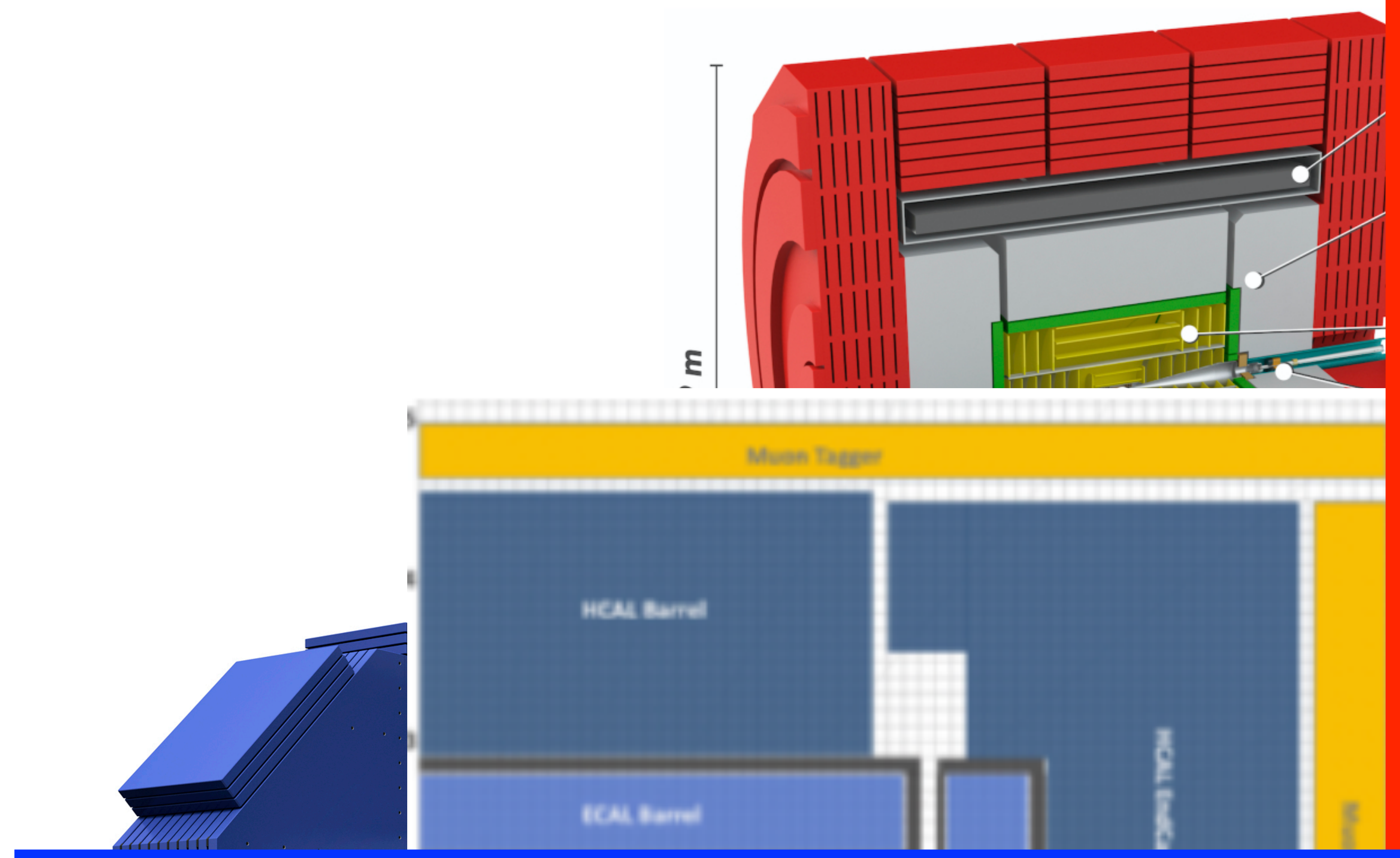

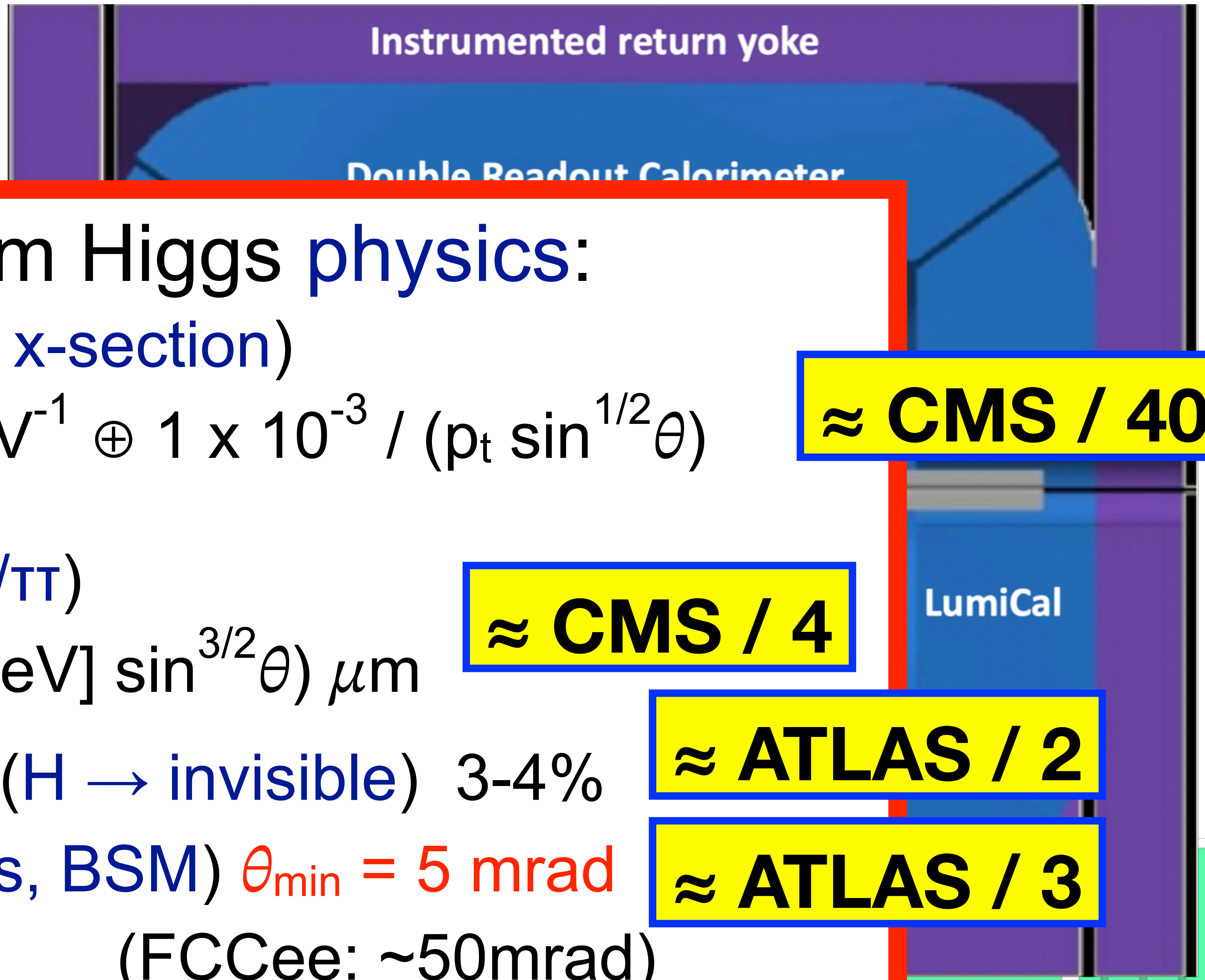

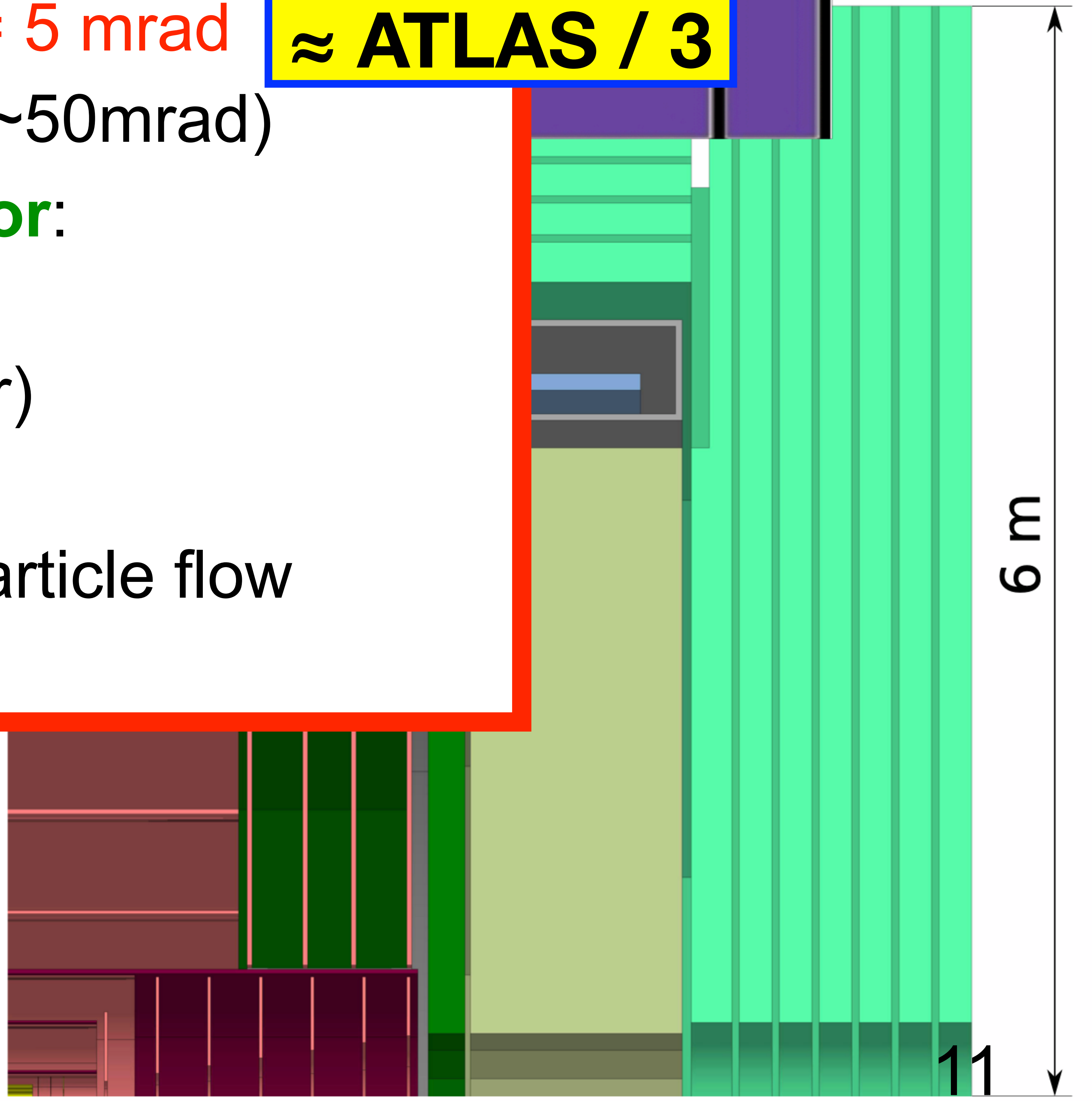

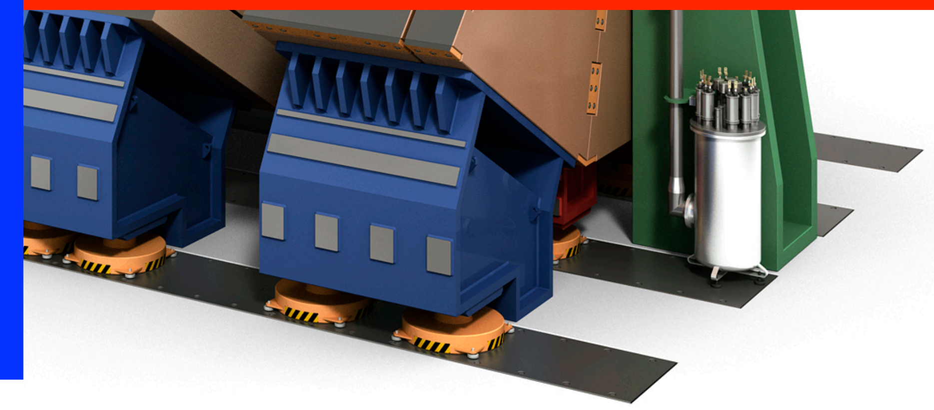

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Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

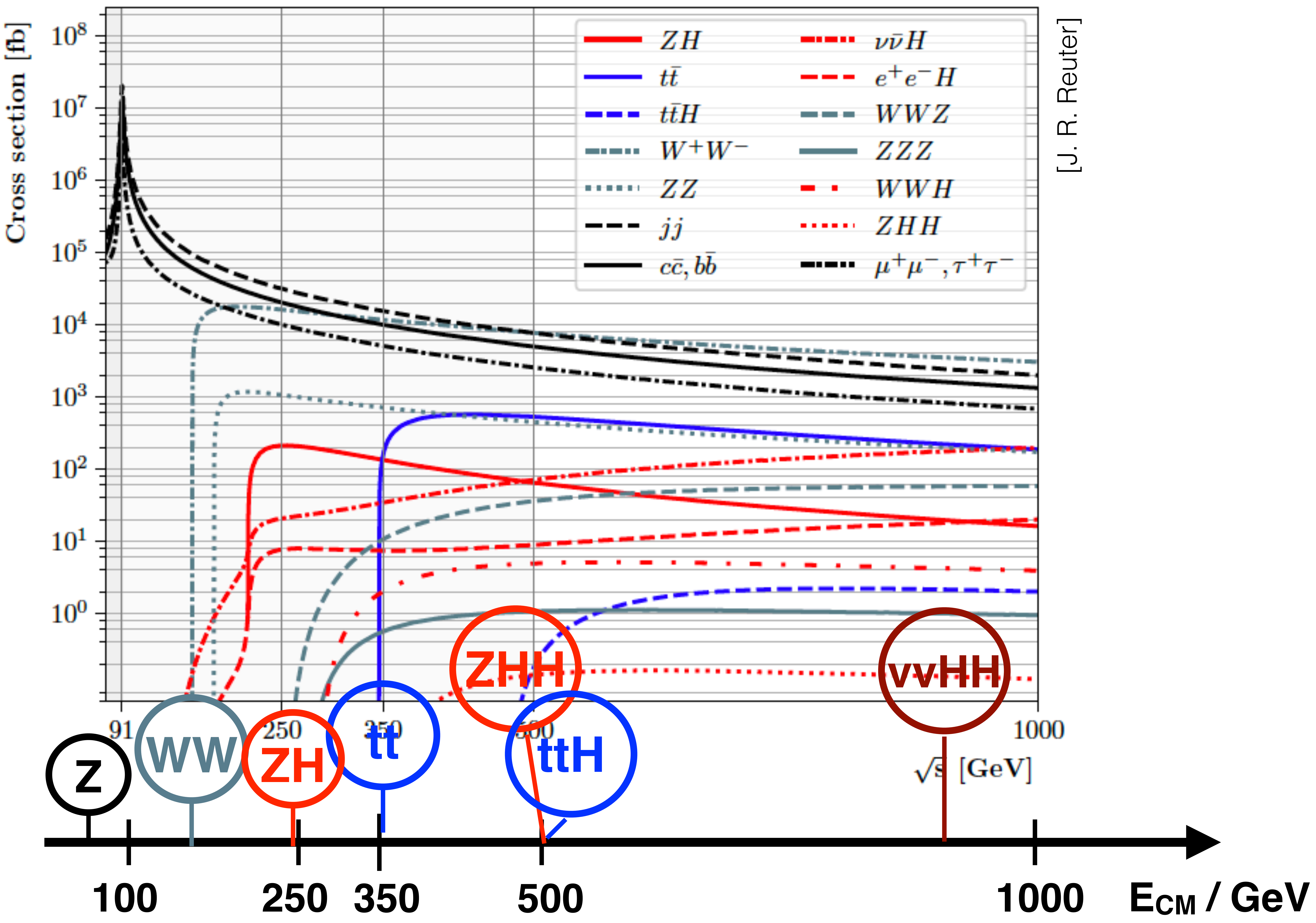
only Linear Colliders: lower collision rate enables

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

The basic
Higgs Factory program

The key physics at a Higgs Factory

Production rates vs collision energy



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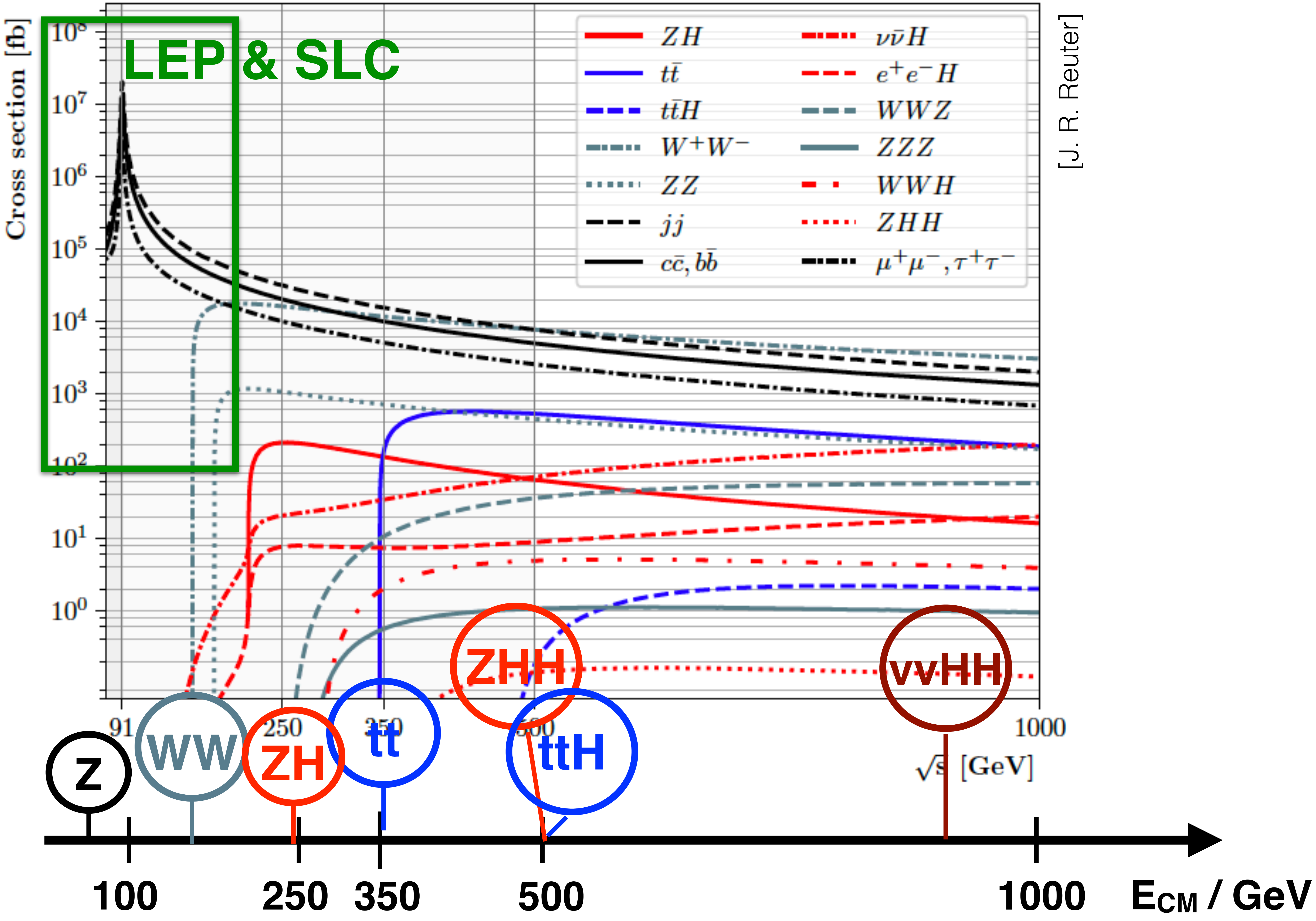
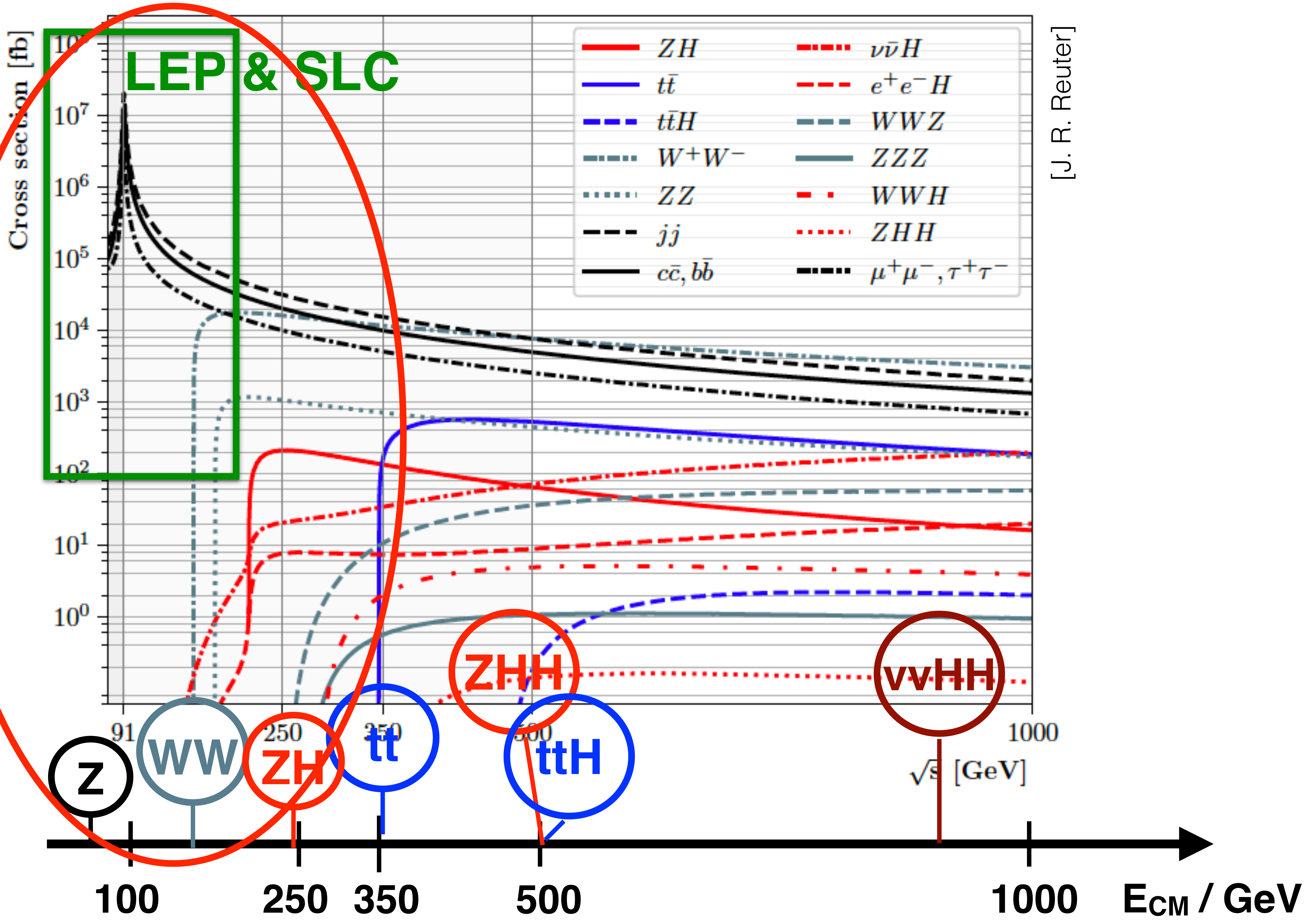


The key physics at a Higgs Factory

Production rates vs collision energy

considered by all proposed e+e- projects



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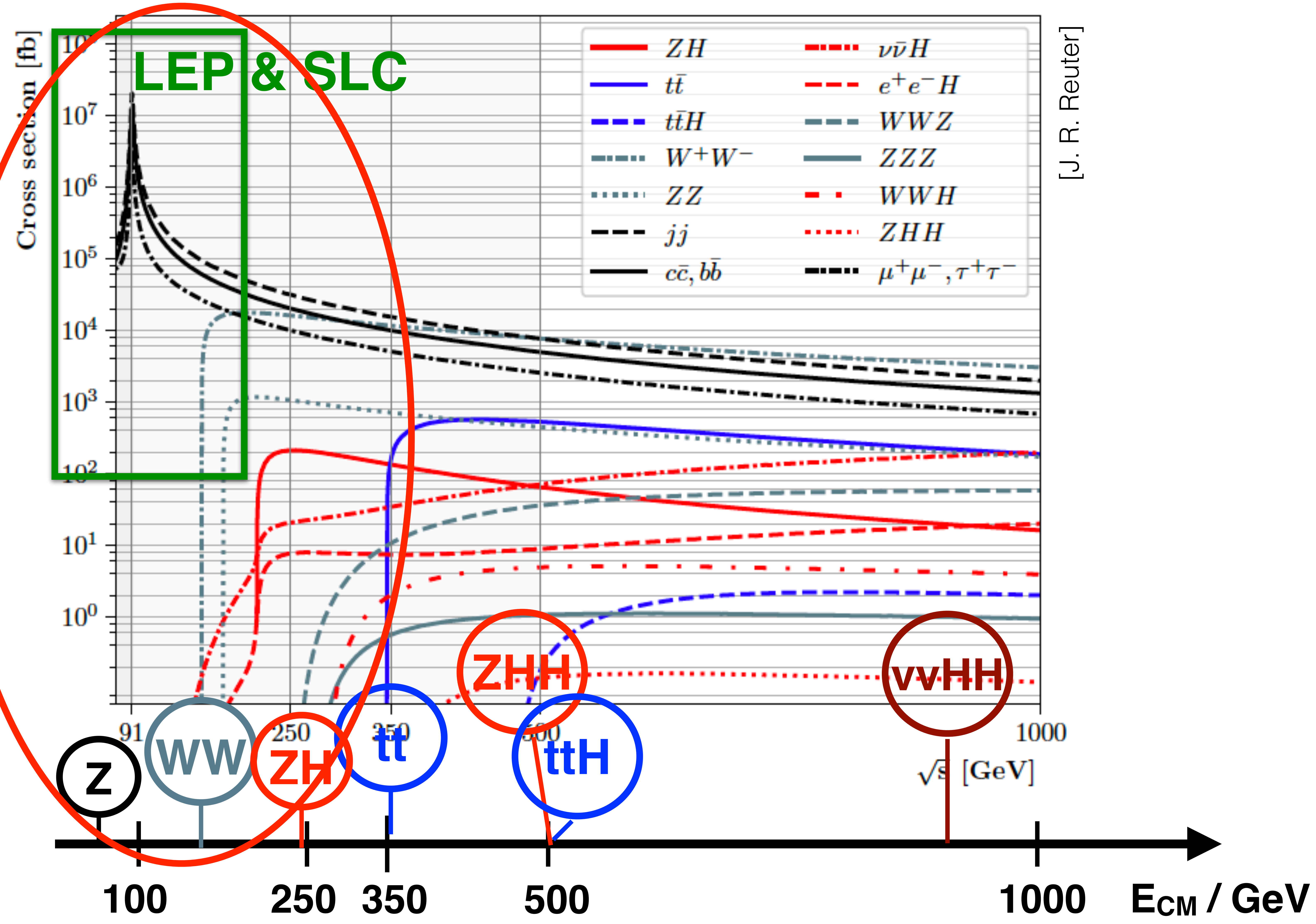
Circular Colliders



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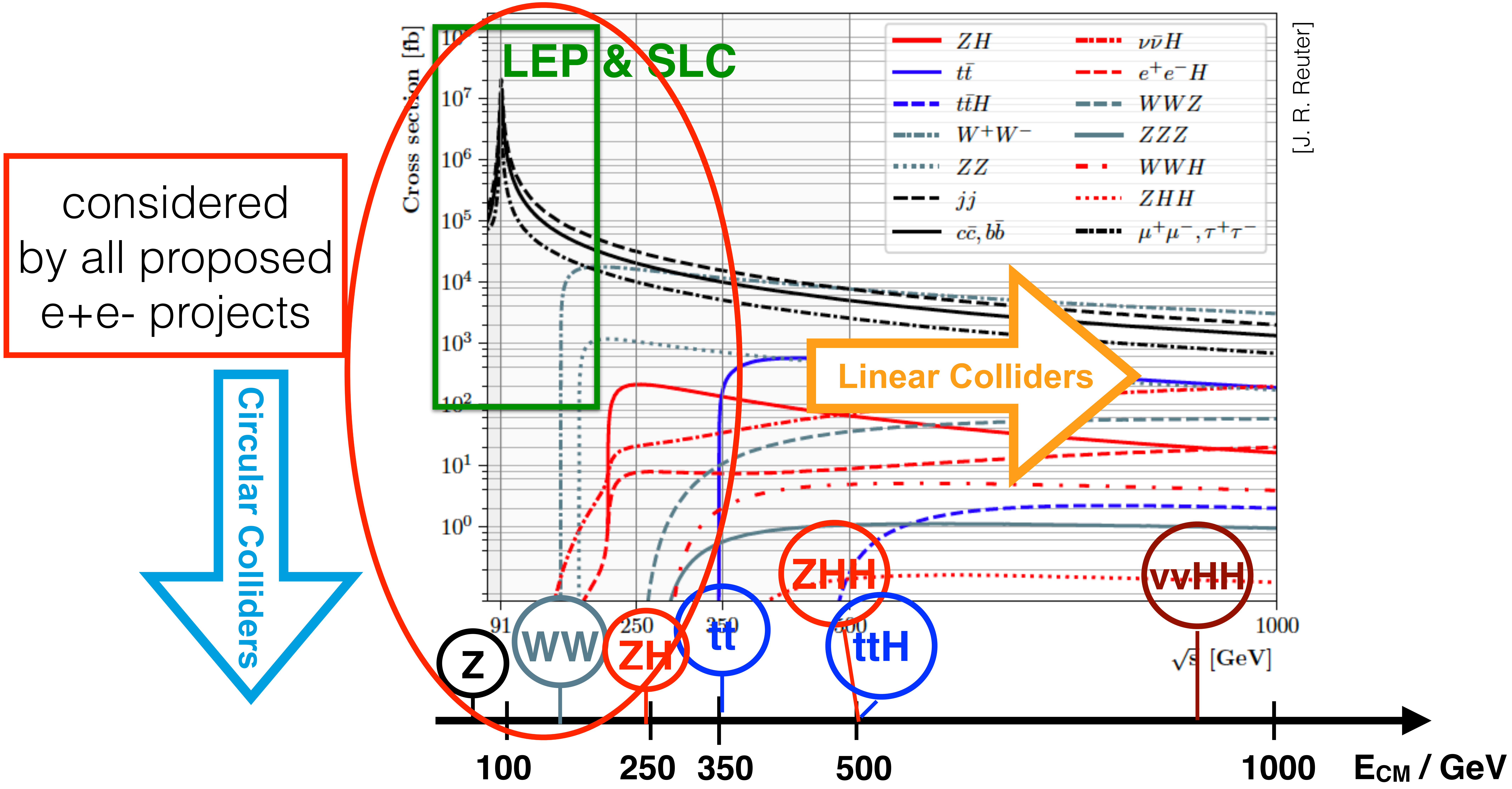

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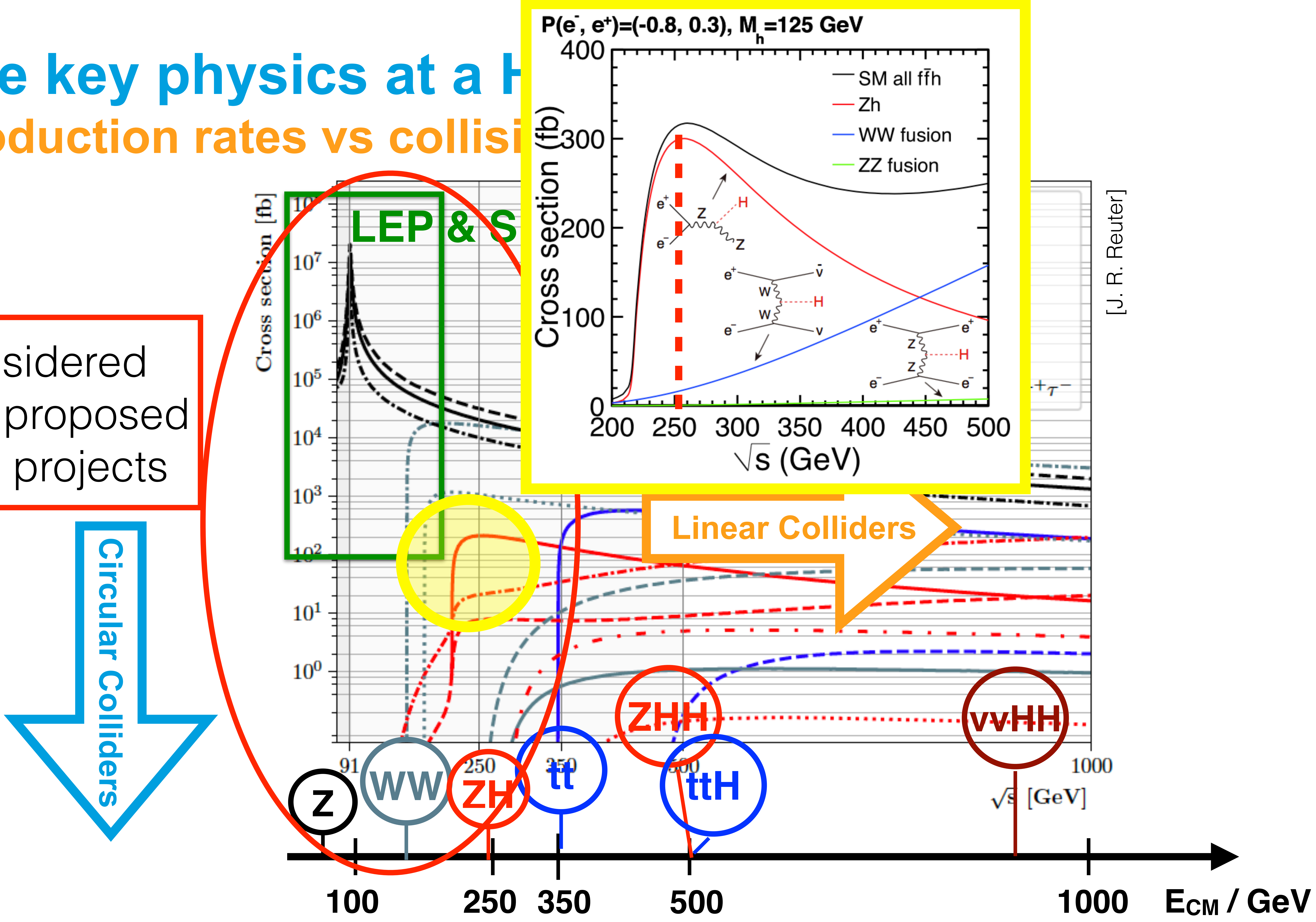

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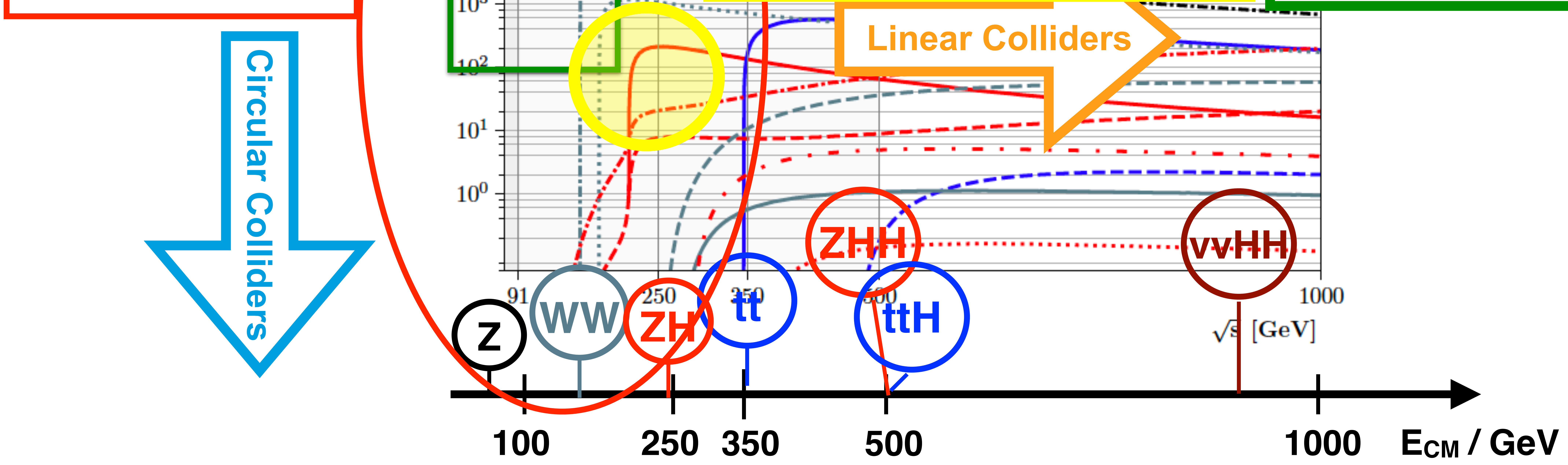

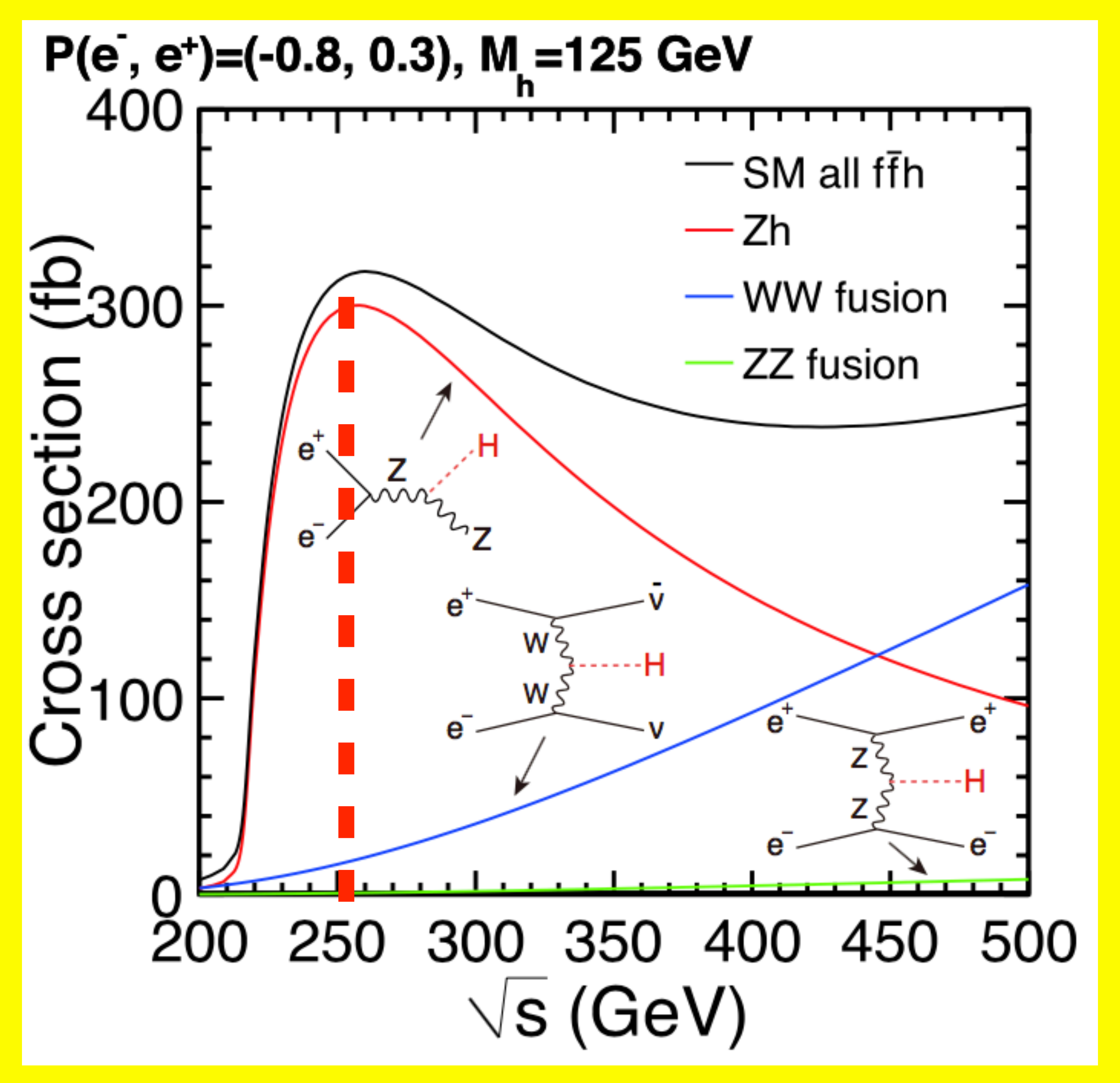

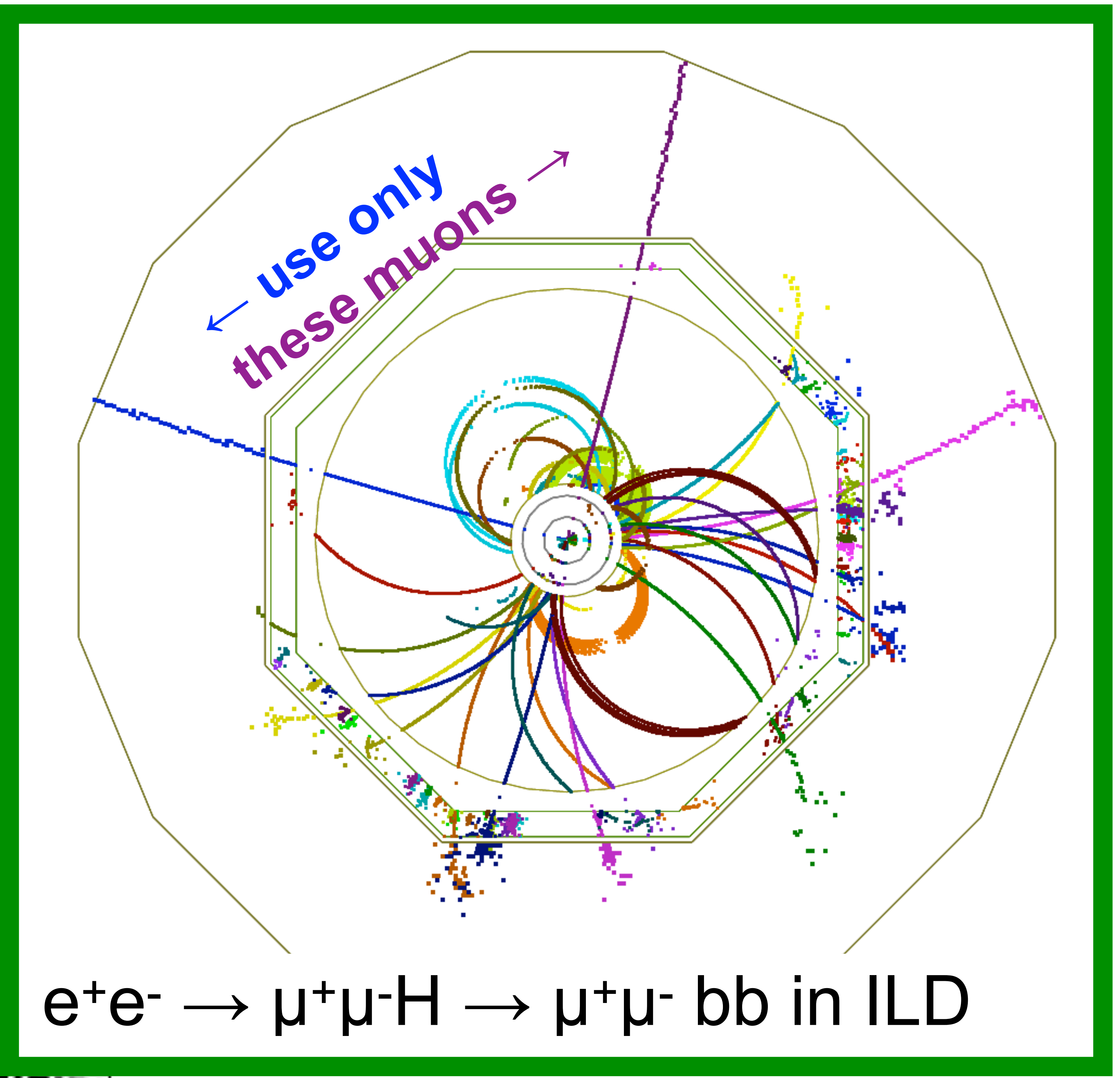

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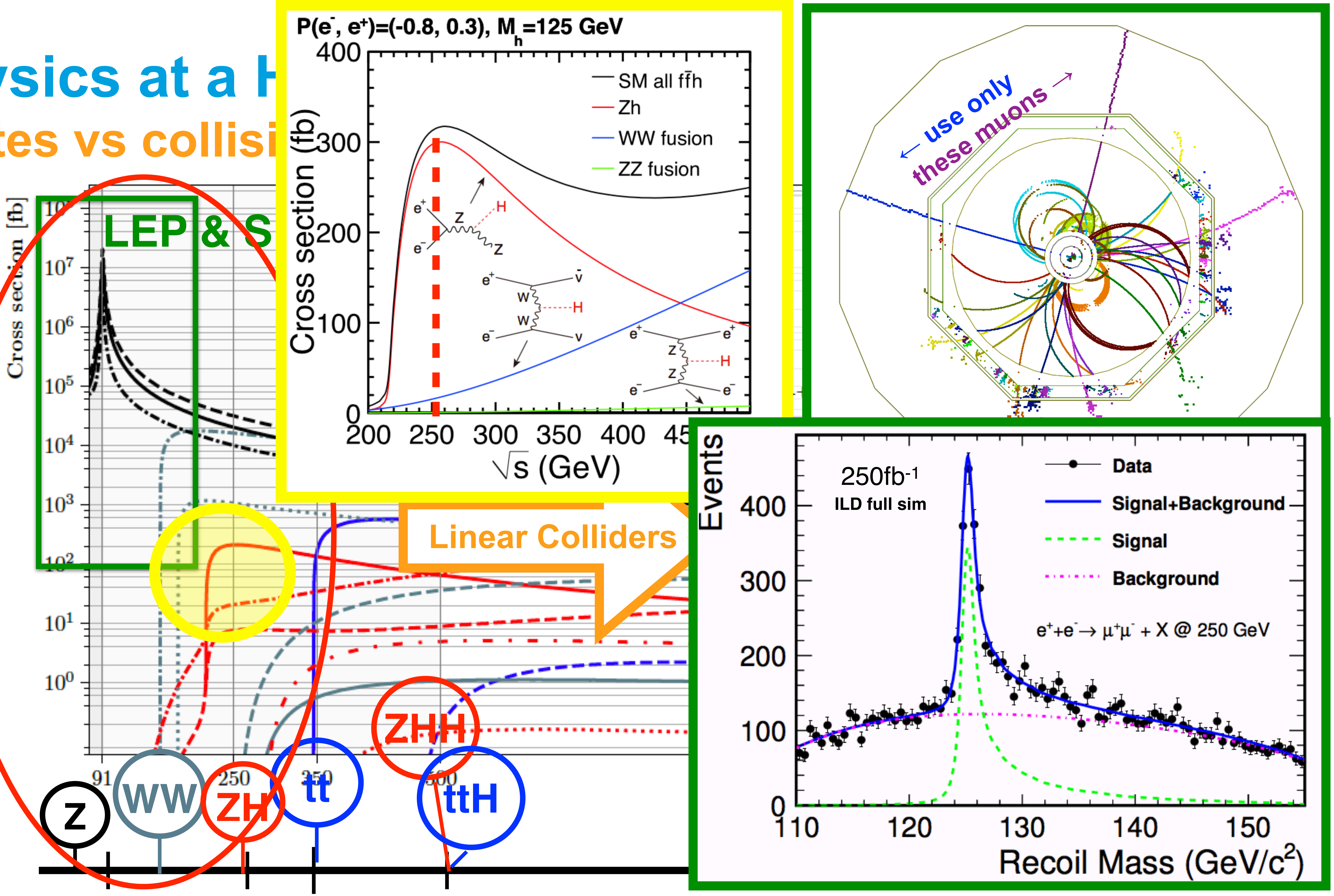

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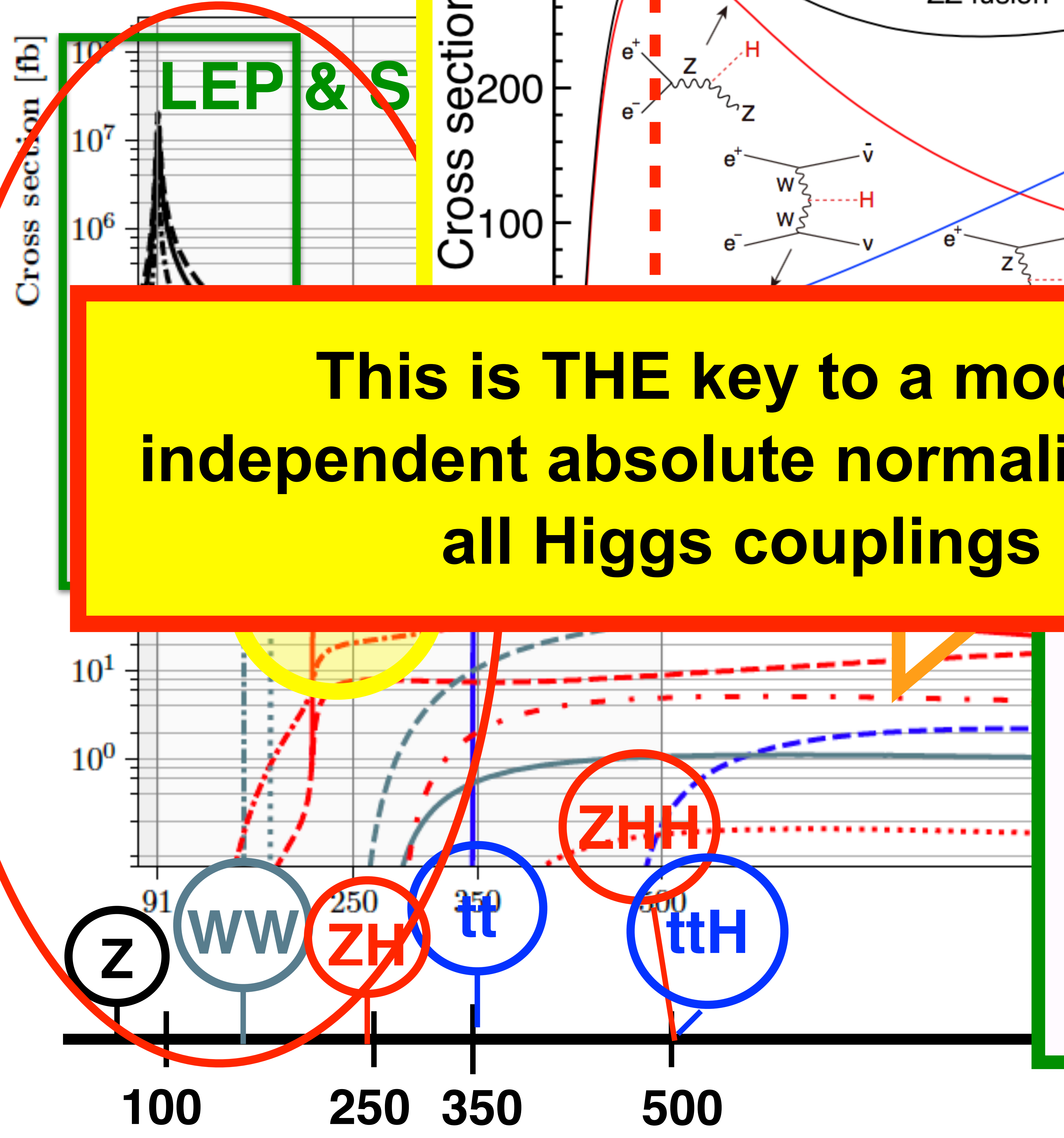
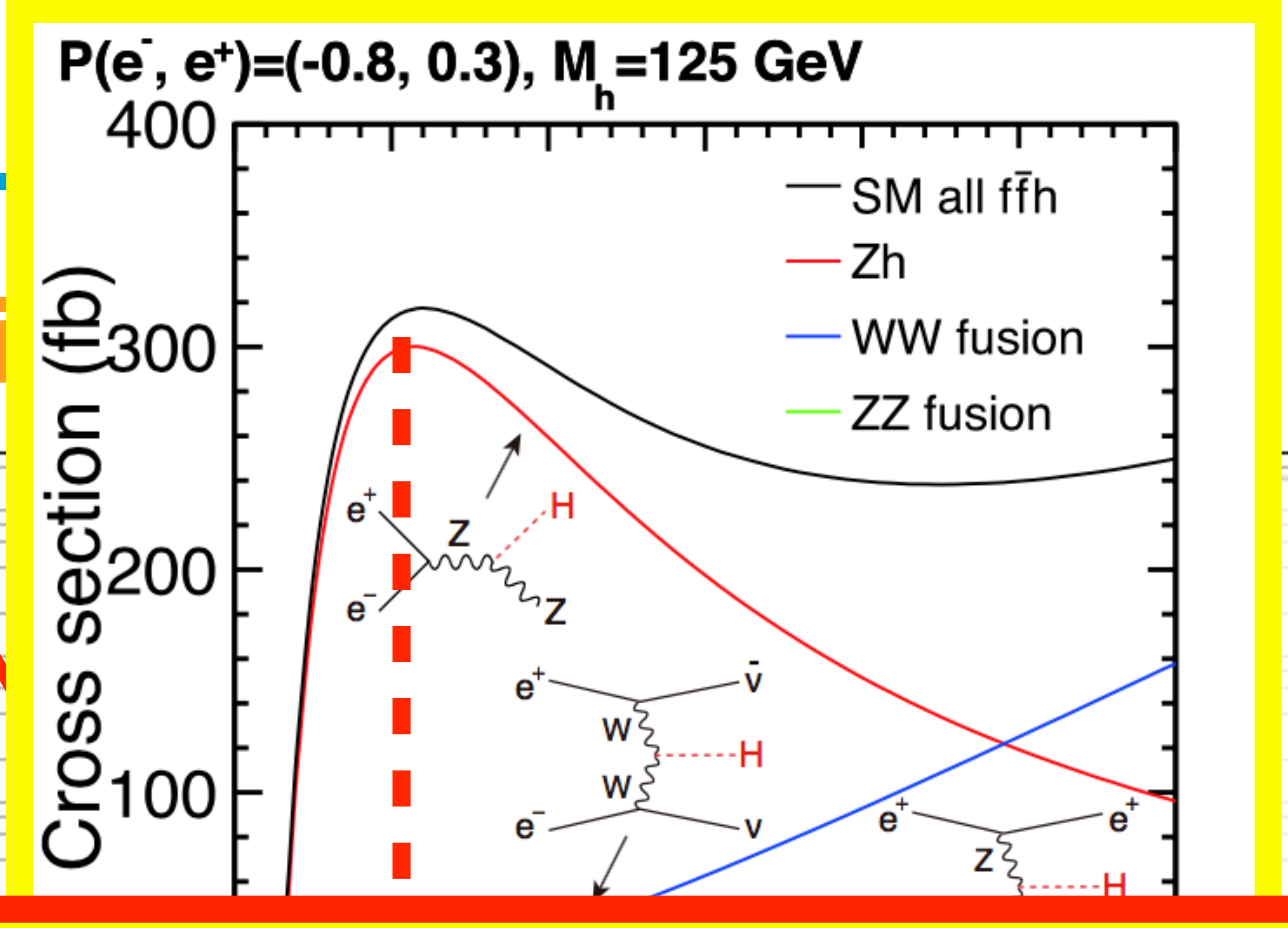
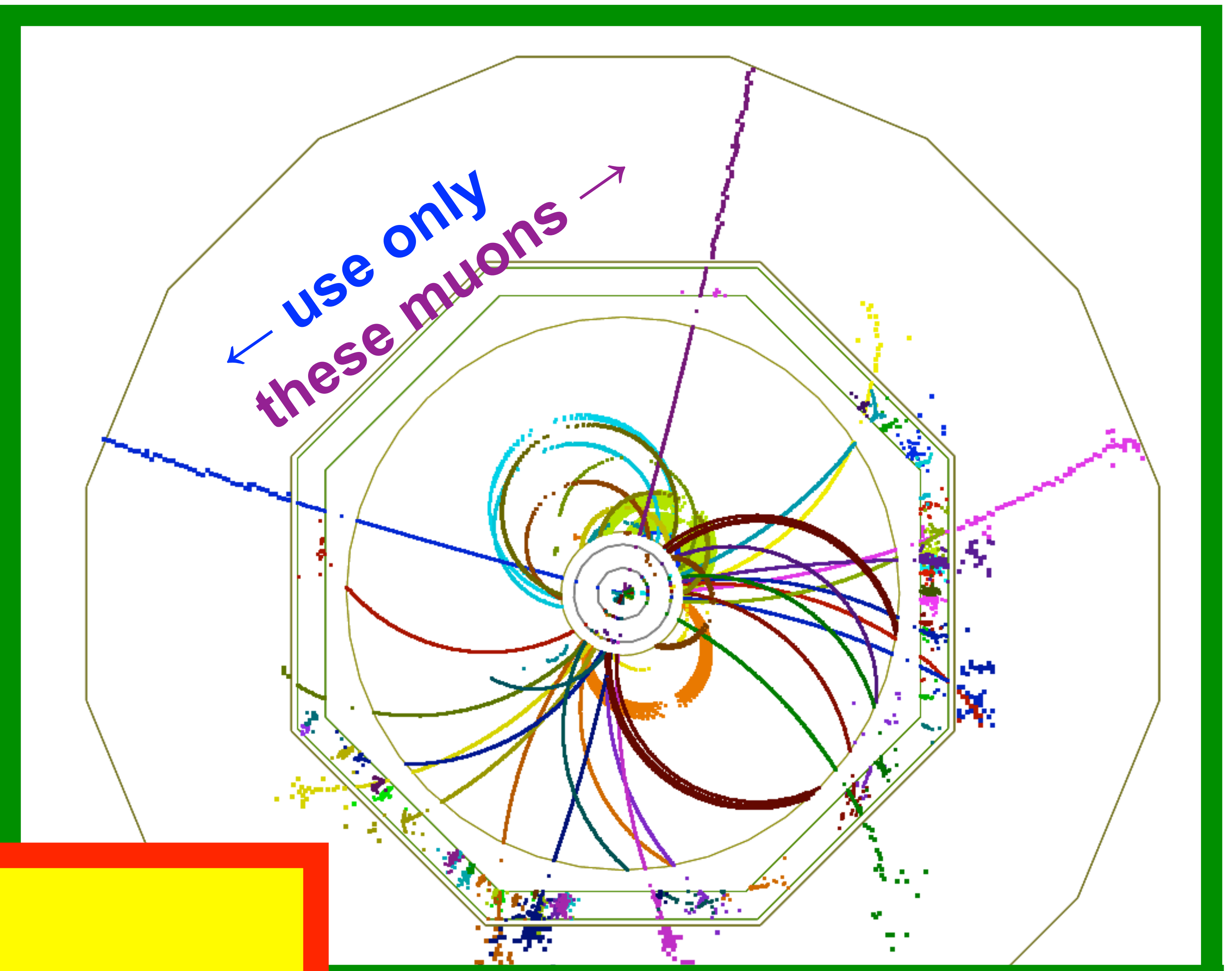
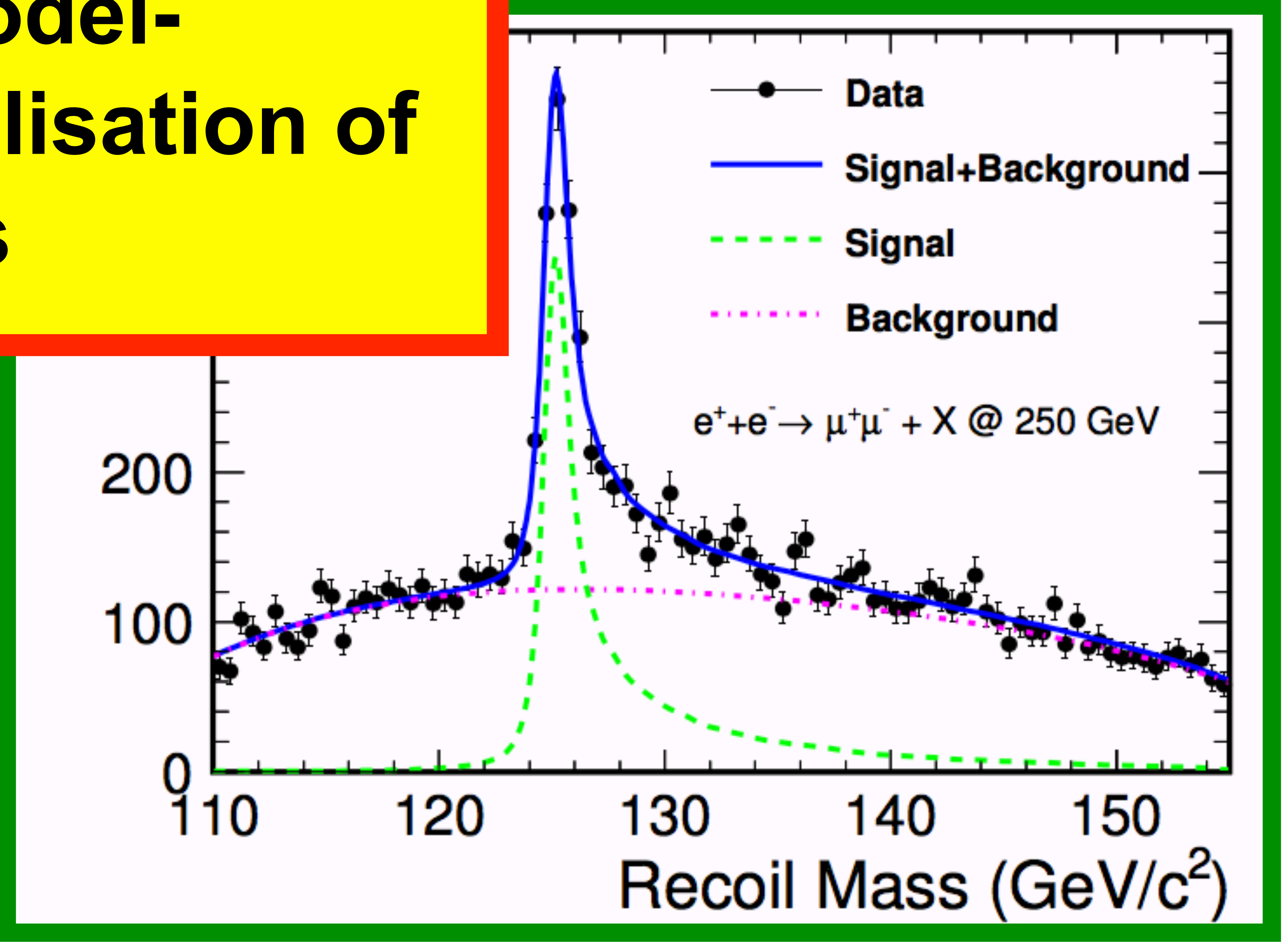






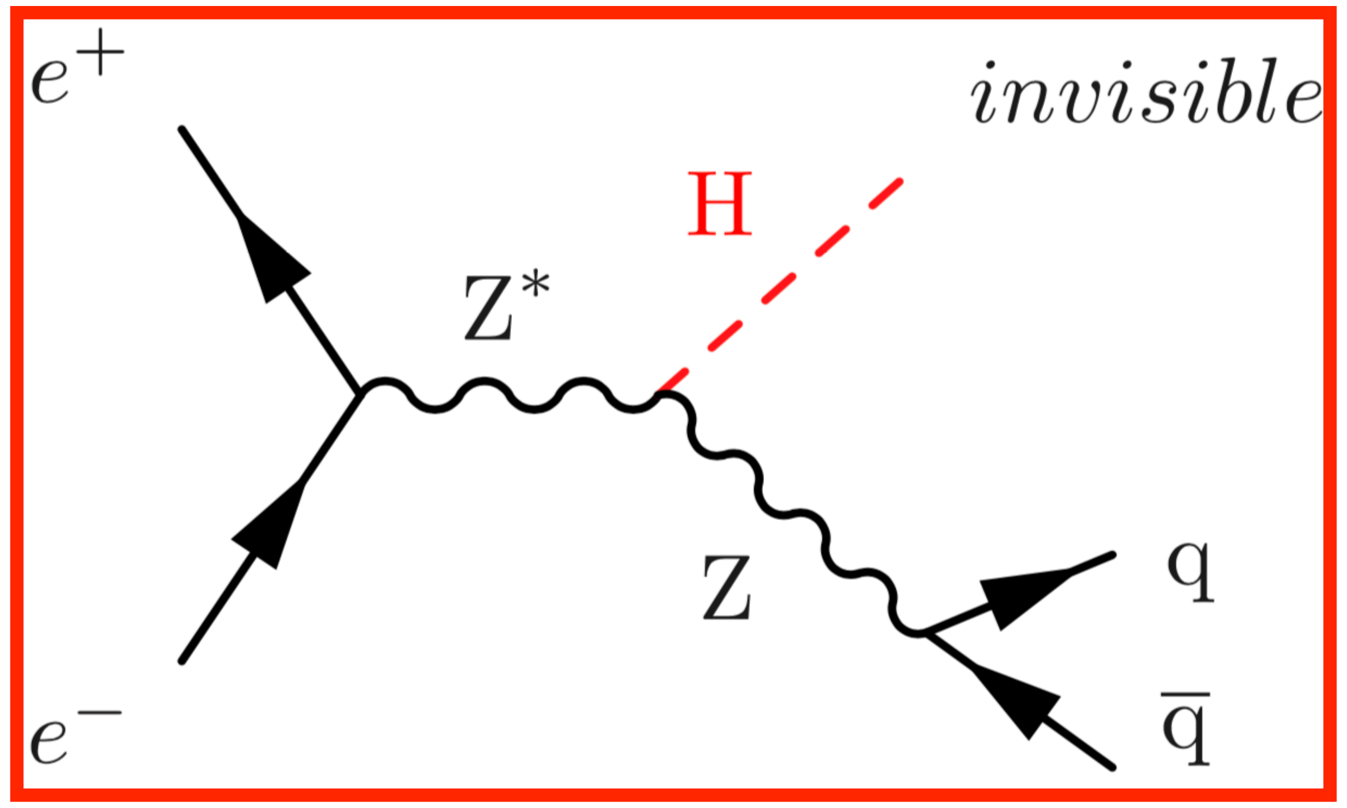


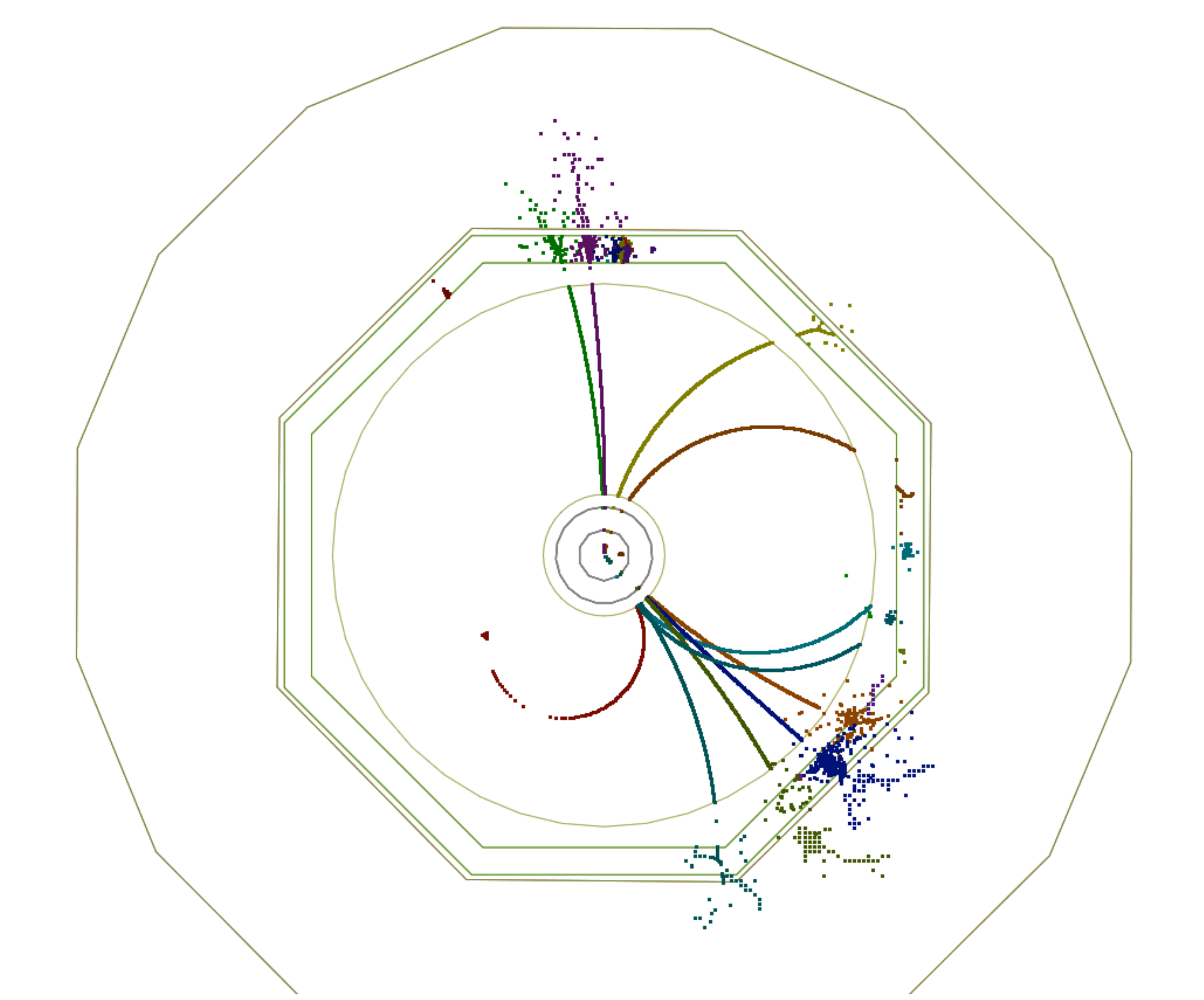
This is THE key to a model-independent absolute normalisation of all Higgs couplings

Example: Higgs decay to "invisible"

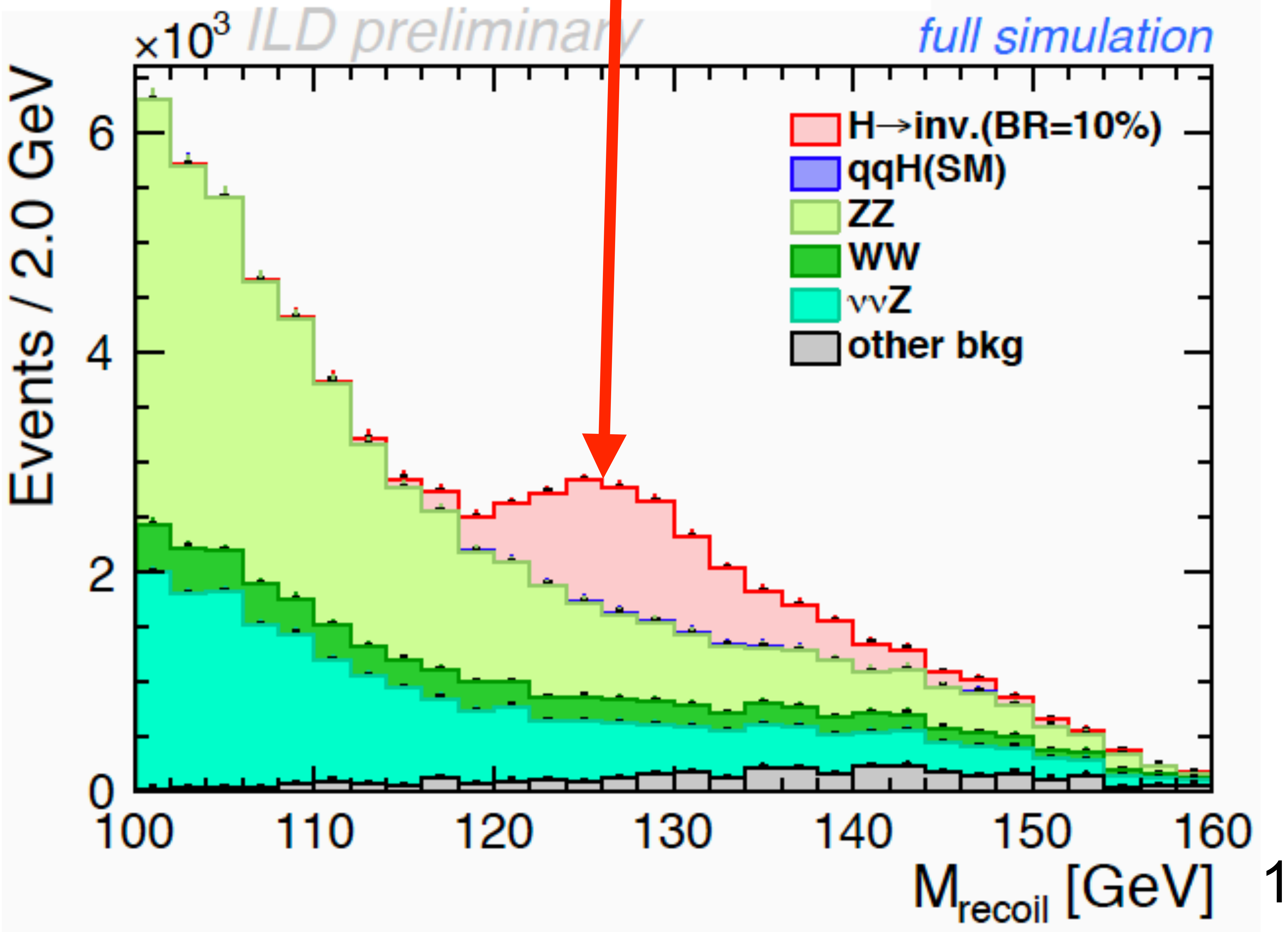
Dark Sector Portal?

- 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: discovery! Of Dark Matter?**
- **if no signal observed e.g. at ILC250: exclude BF > 0.16% at 95% CL (HL-LHC expectation: 2.5%, SM prediction: 0.12%)**





e⁺e⁻ → qq̄H → qq inv in ILD detector



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

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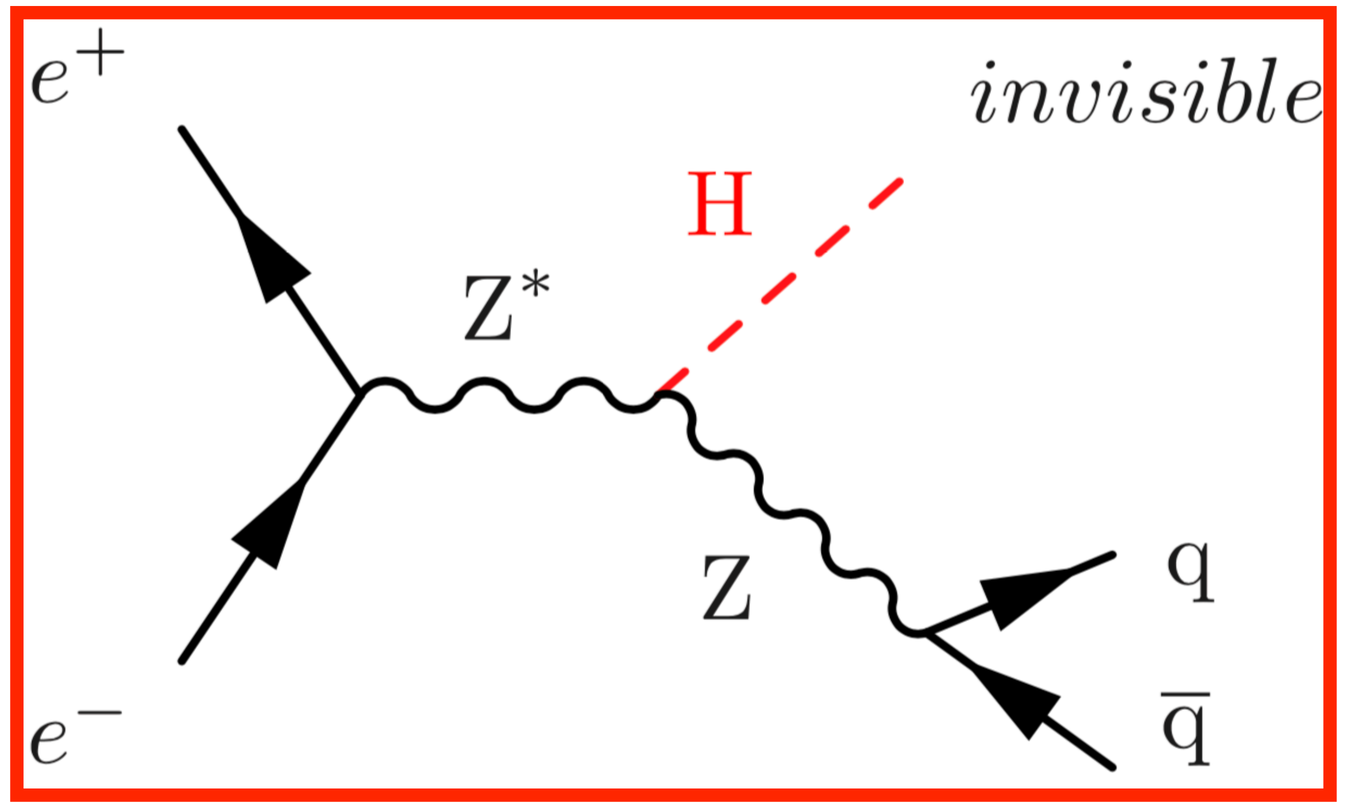

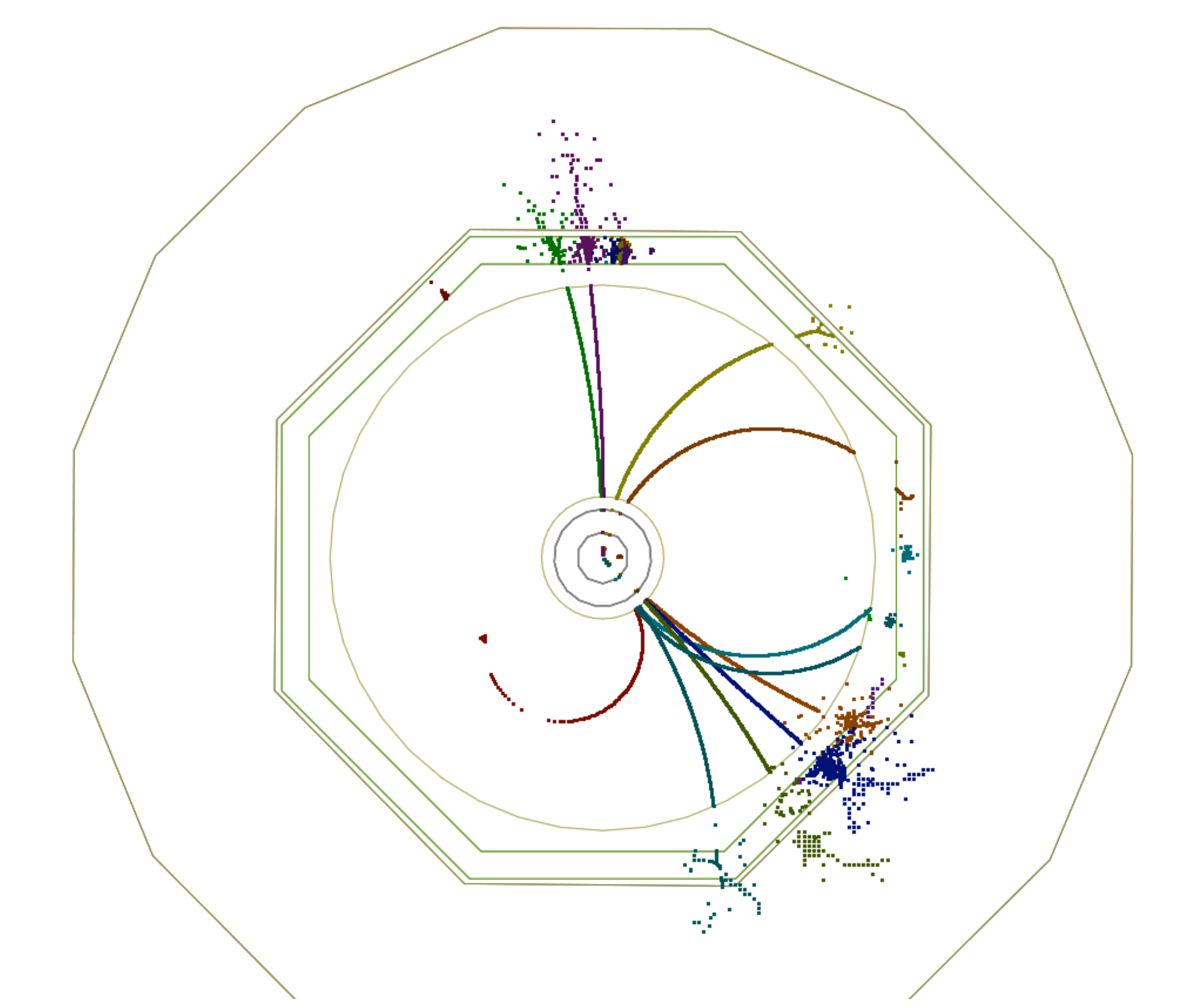

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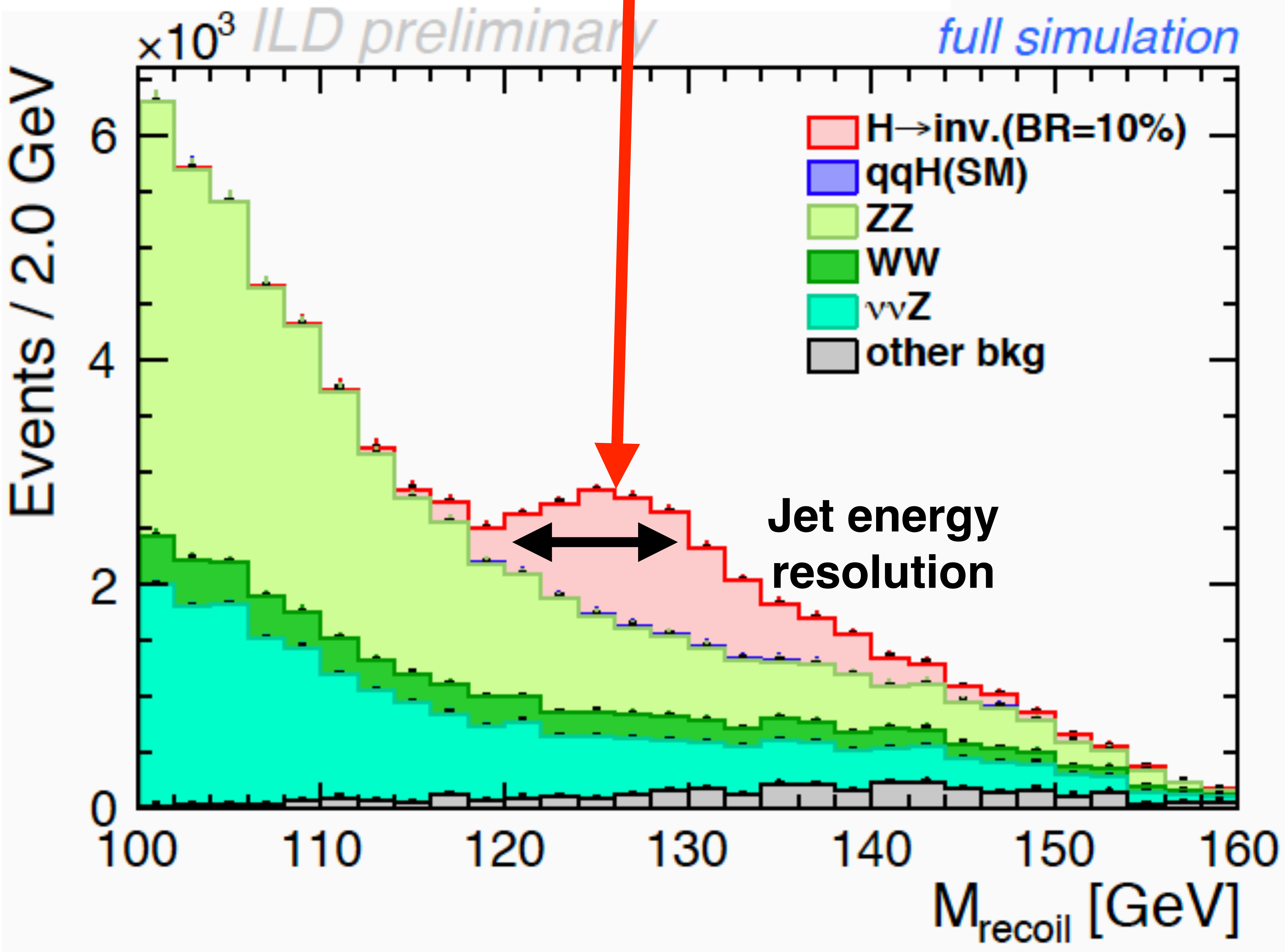

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How to map Higgs precision on BSM

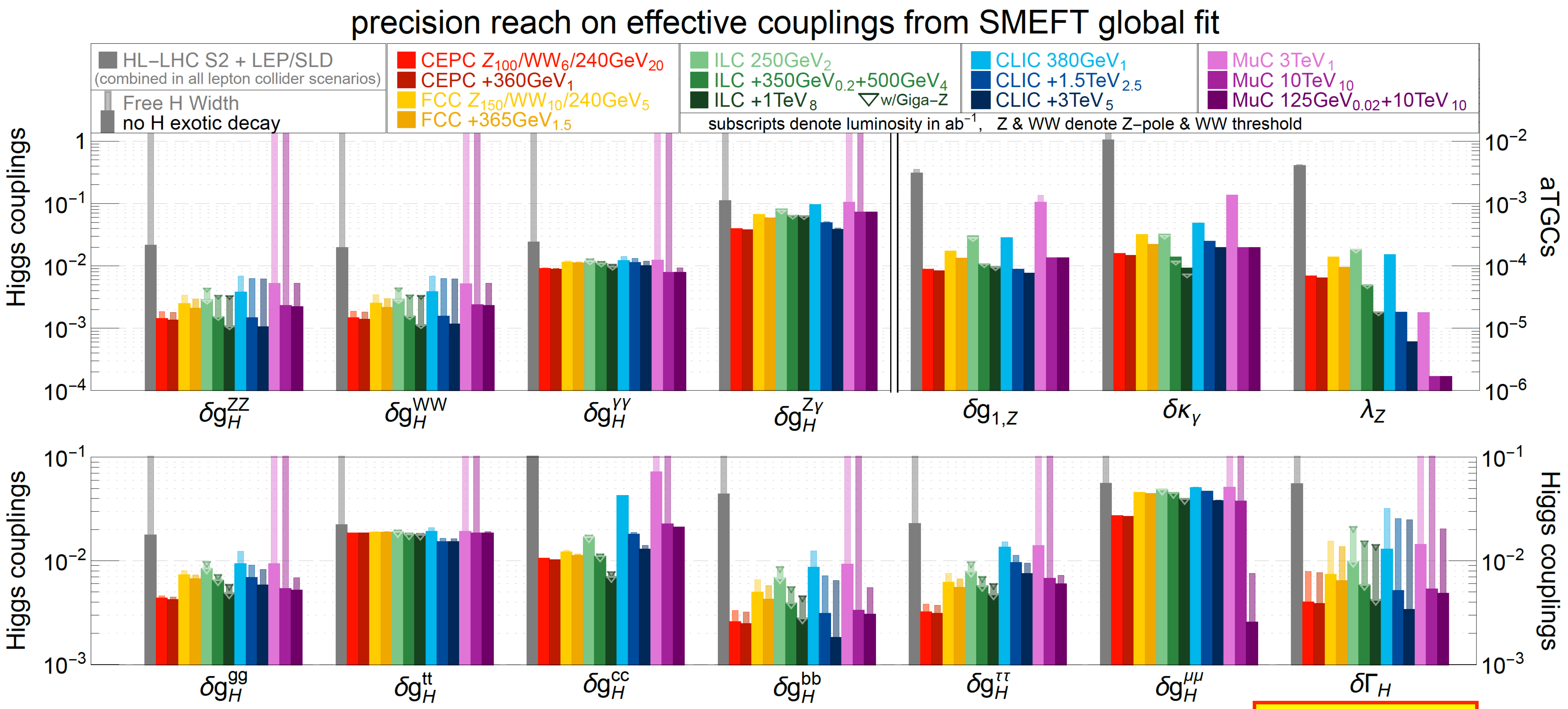
Two complementary approaches

- Ask your favorite theorist for his or her favorite model
- Fit to data
- most detailed
- correctly mapping interplay of “direct” and “indirect” information
- but there are so many models…
- **Mandatory as soon as any signal / deviation from SM is found!**

- generic approach: parametrize ignorance
- Effective field theory: turn every vertex into a “bubble”, just keep basic symmetry requirements
- like Fermi-Theory for weak interaction
- add next higher dimension(s) of operators to SM => “SMEFT”
- assumes all BSM is very heavy

Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



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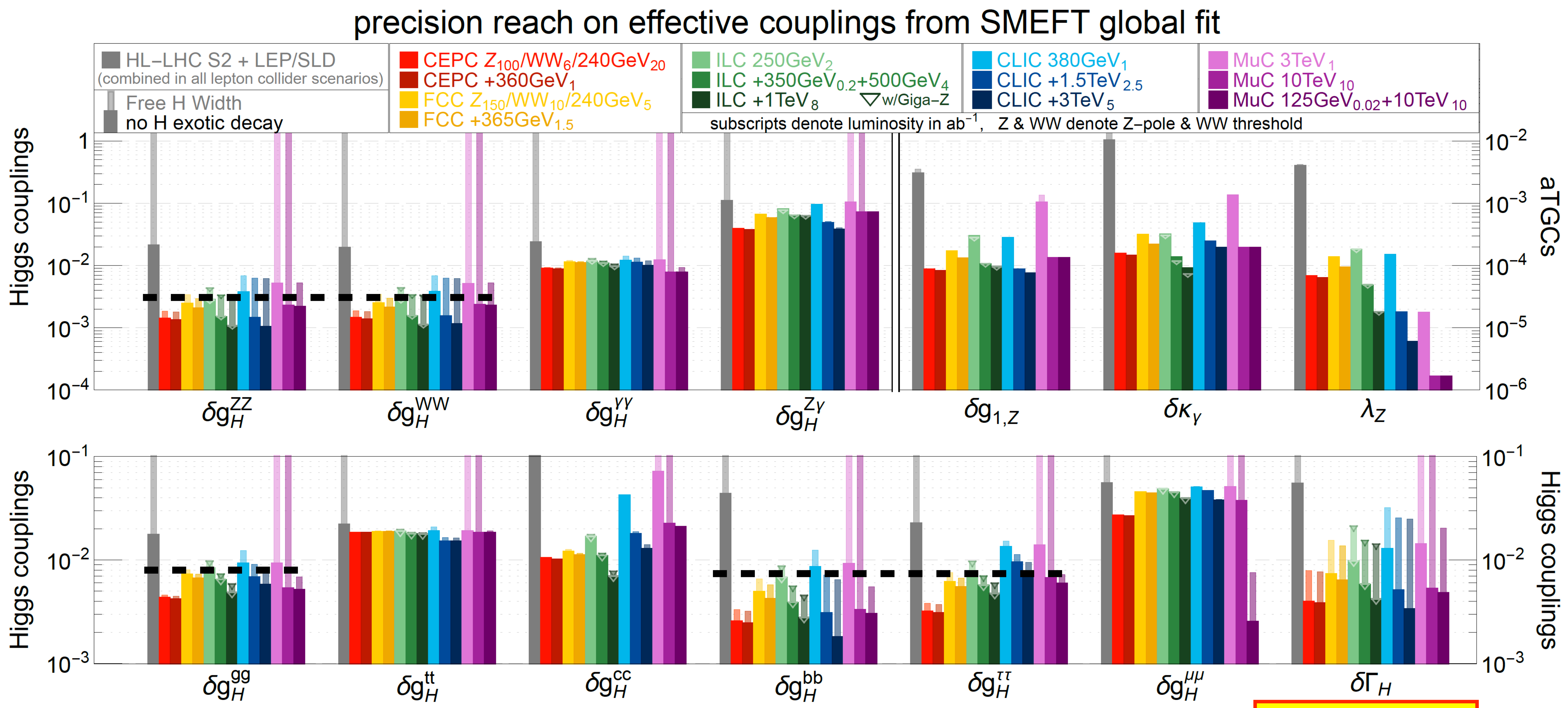

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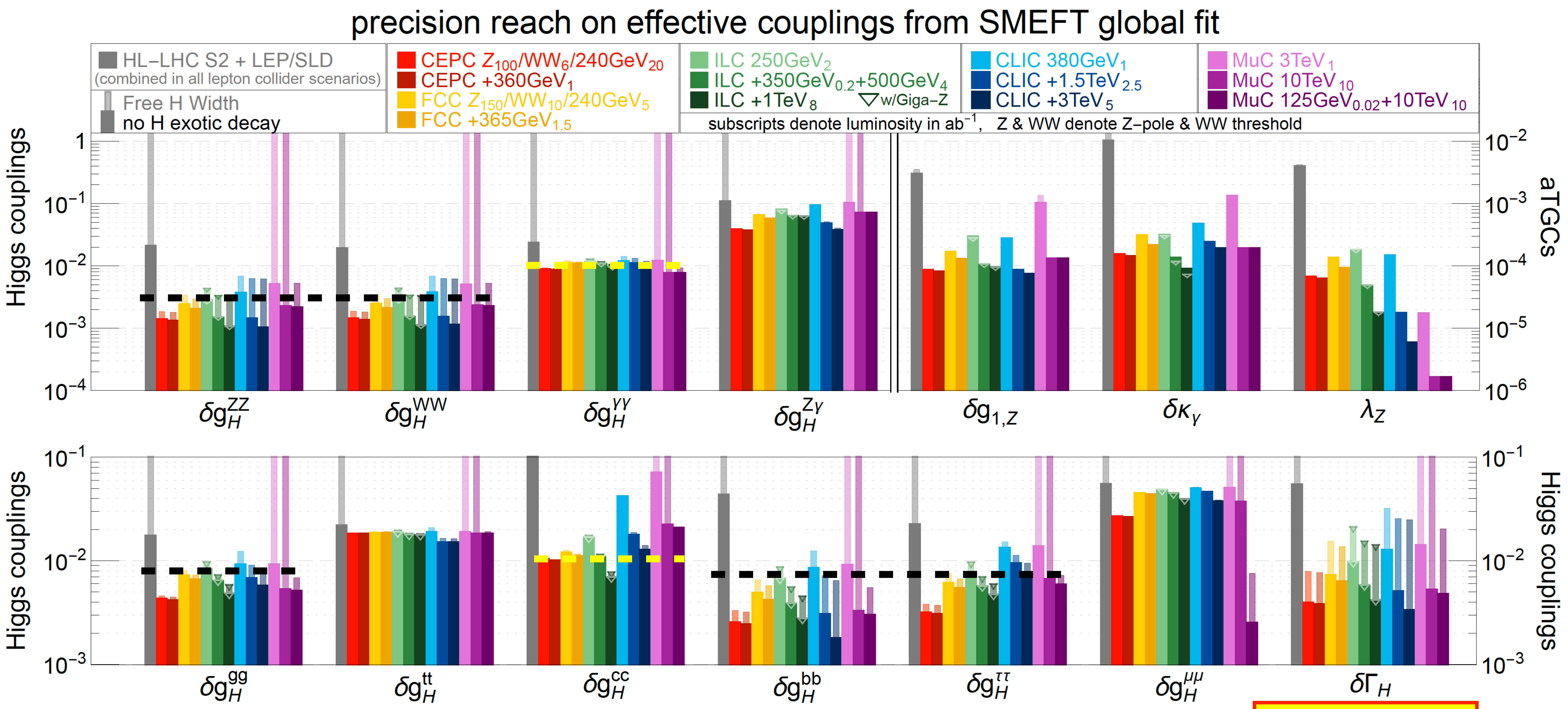

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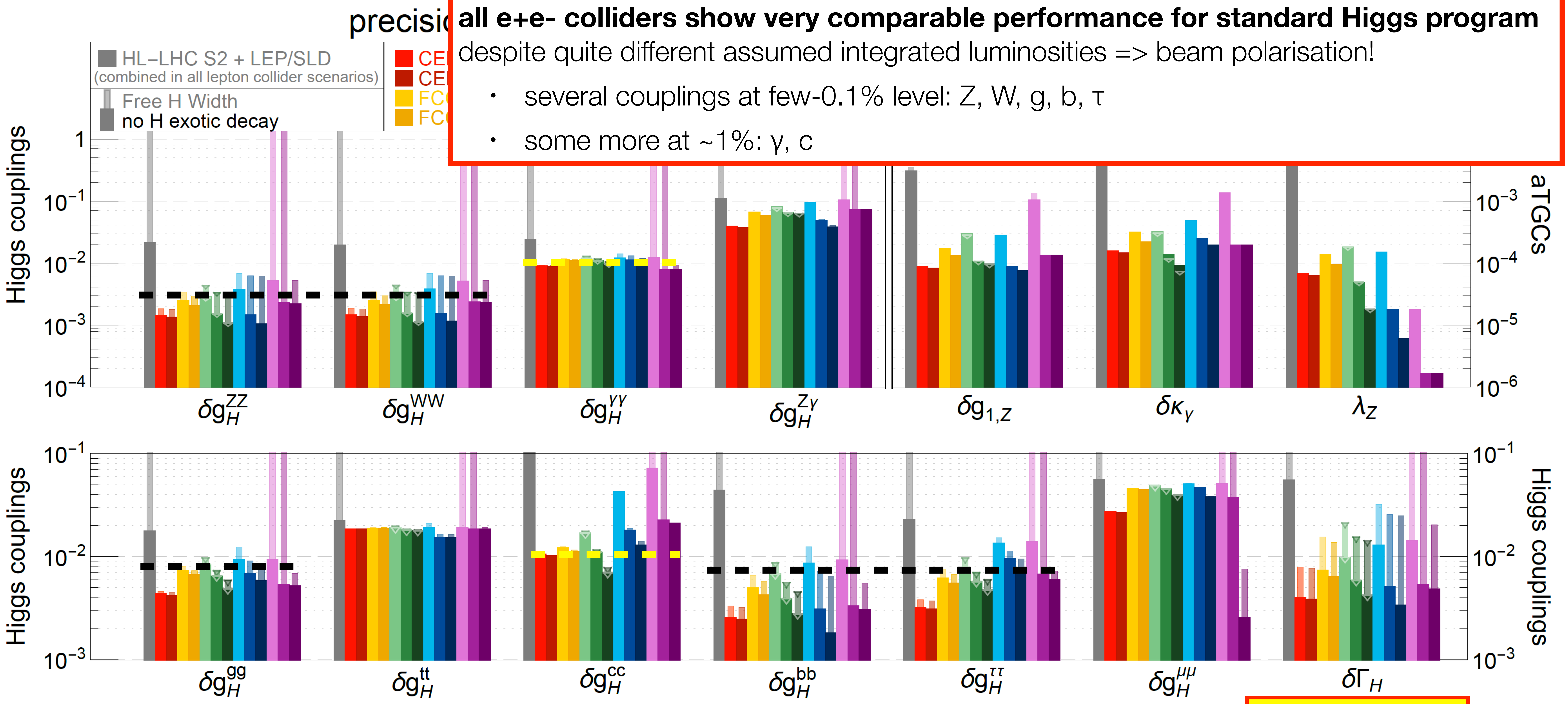

all e+e- colliders show very comparable performance for standard Higgs program

despite quite different assumed integrated luminosities => beam polarisation!

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

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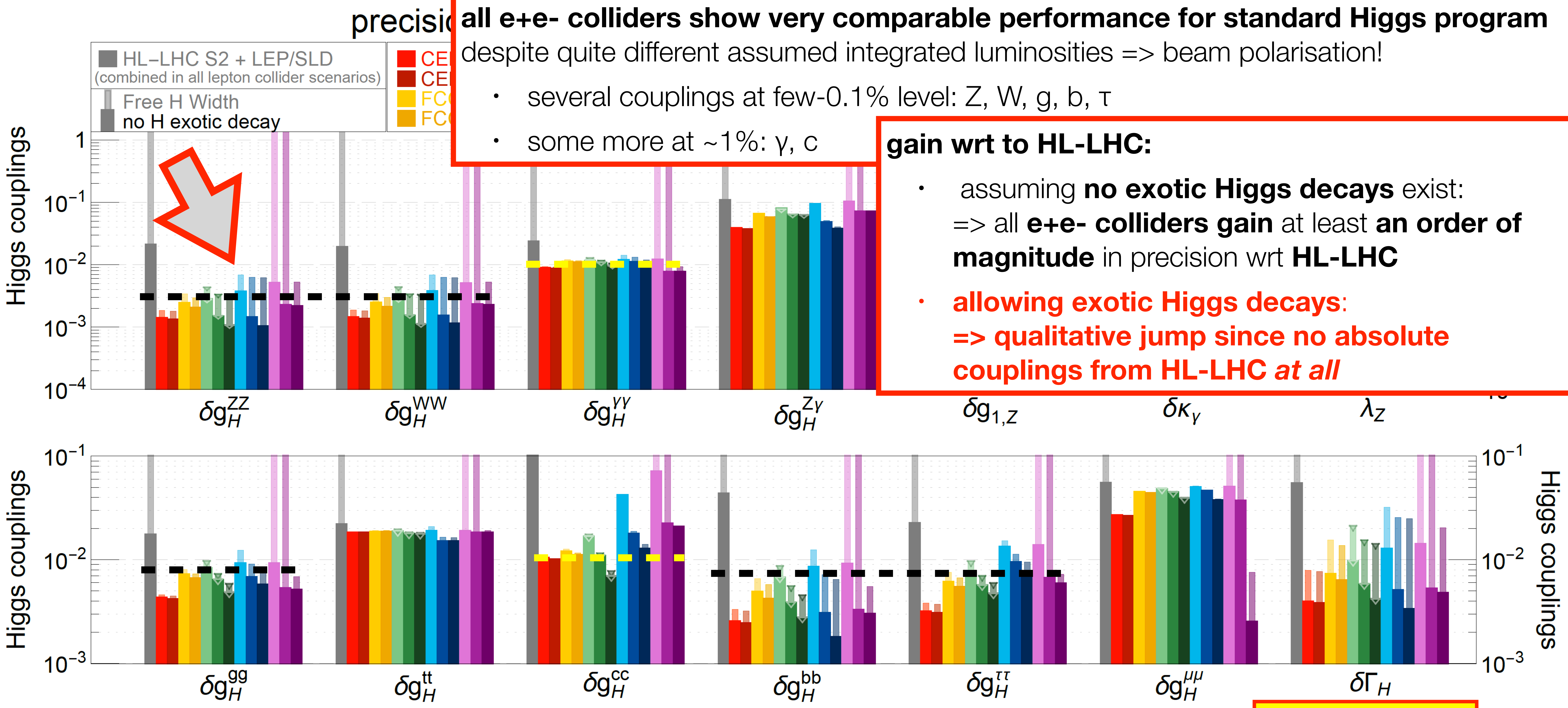

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gain wrt to HL-LHC:

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

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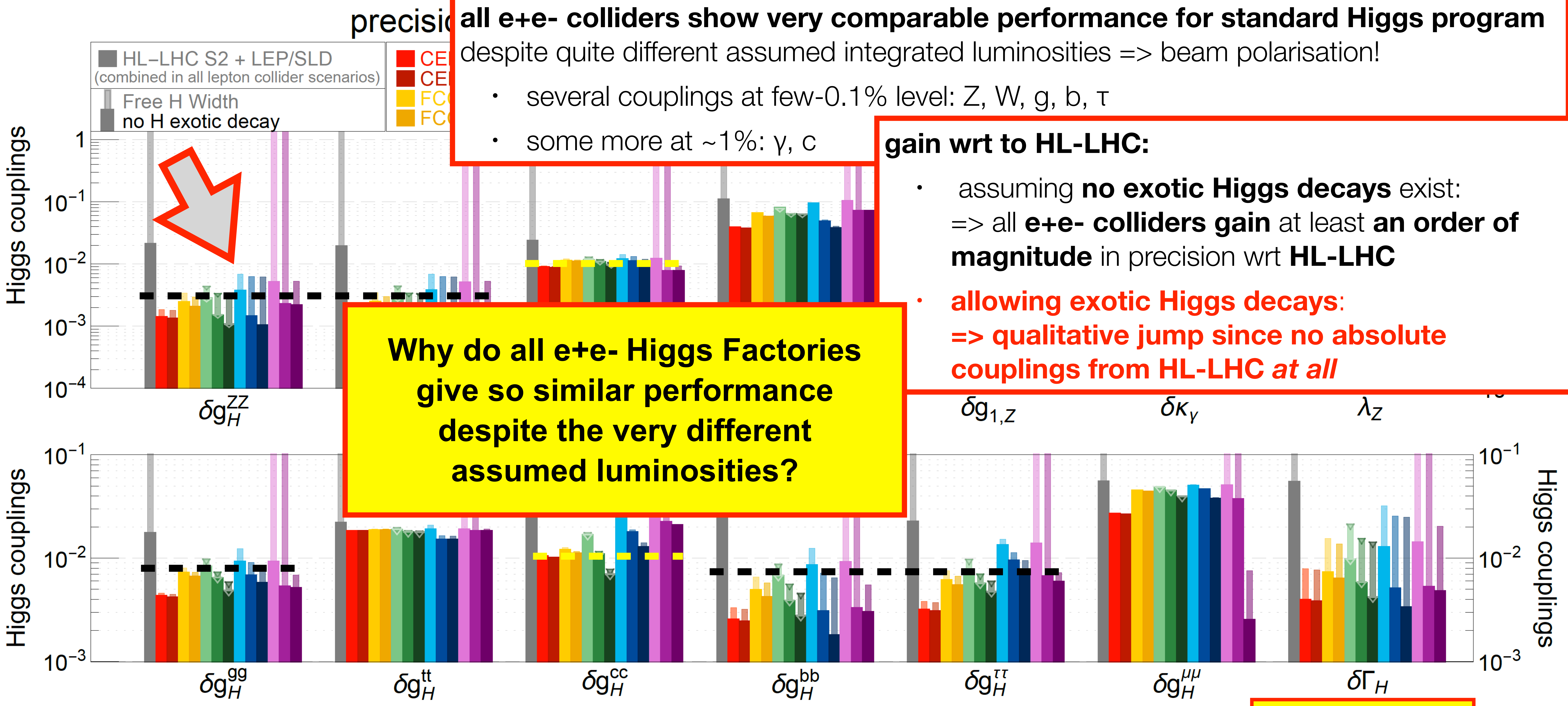

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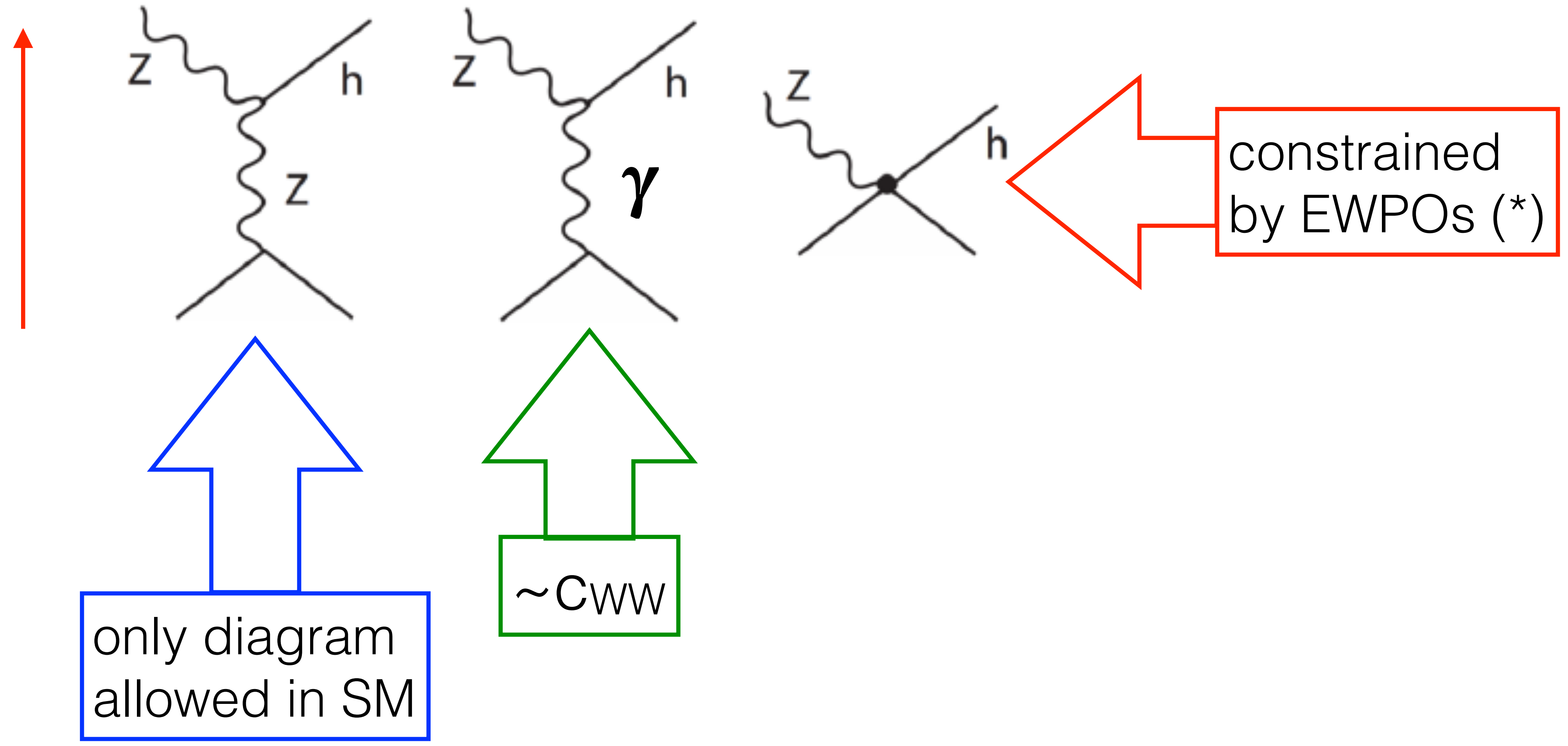
Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

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!**



Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

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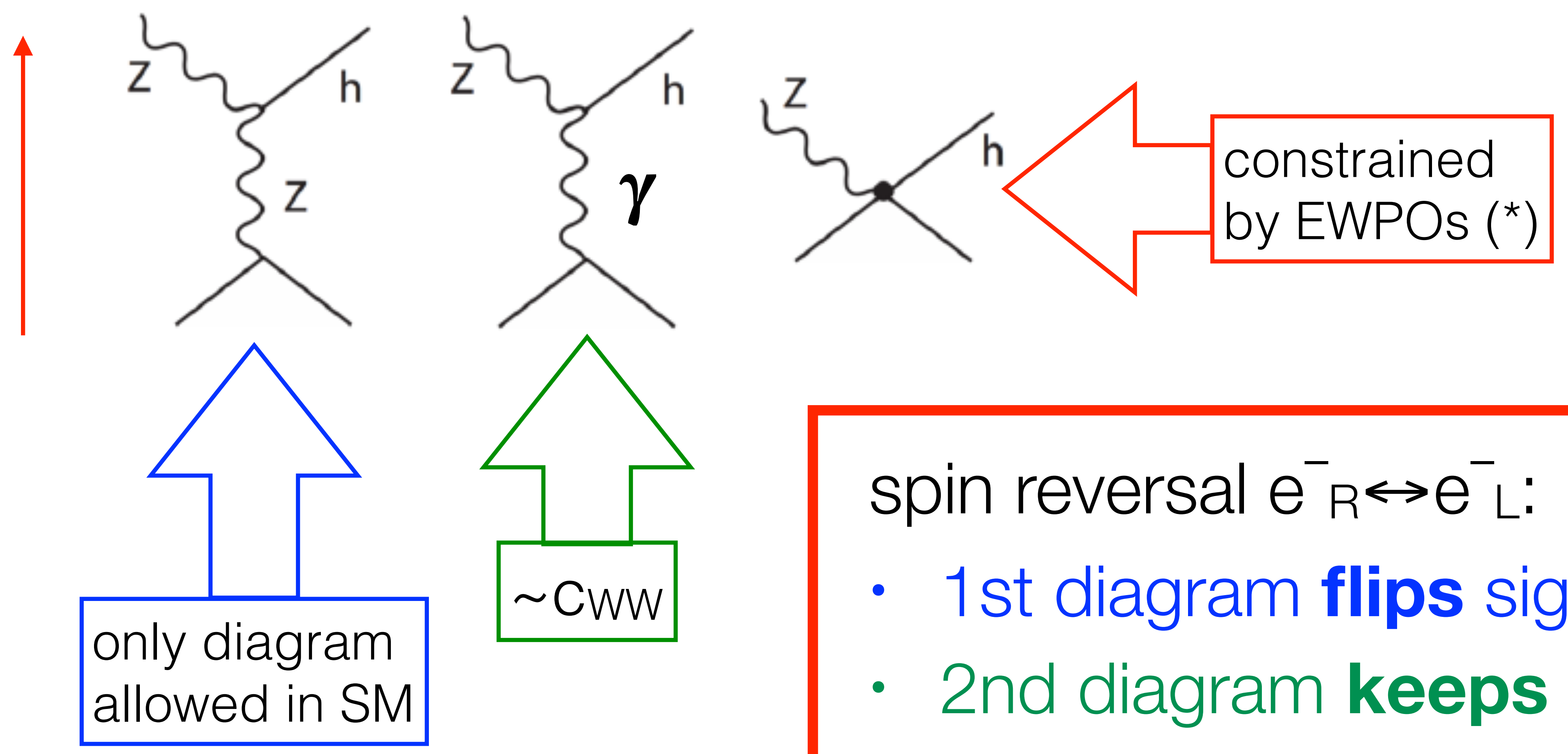

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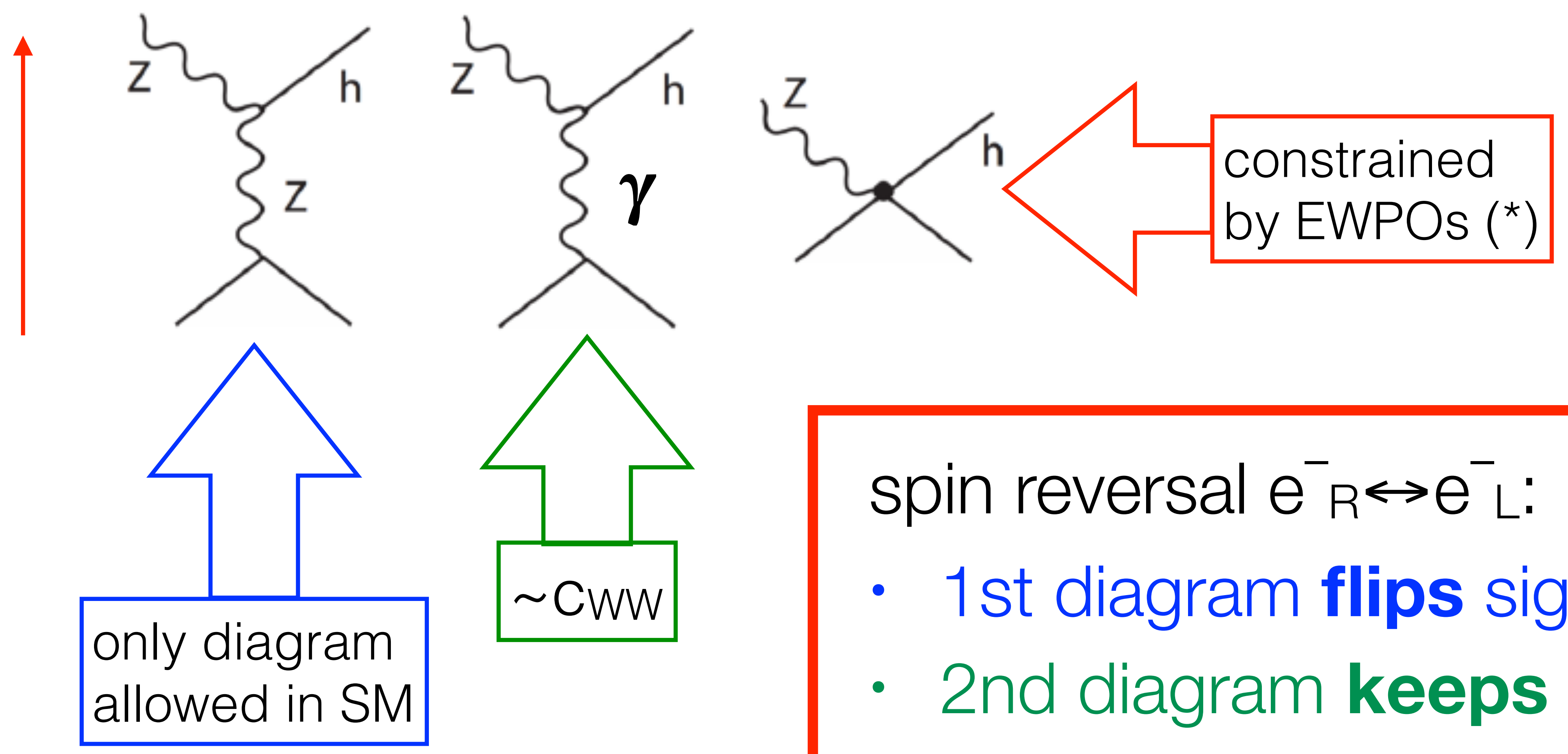

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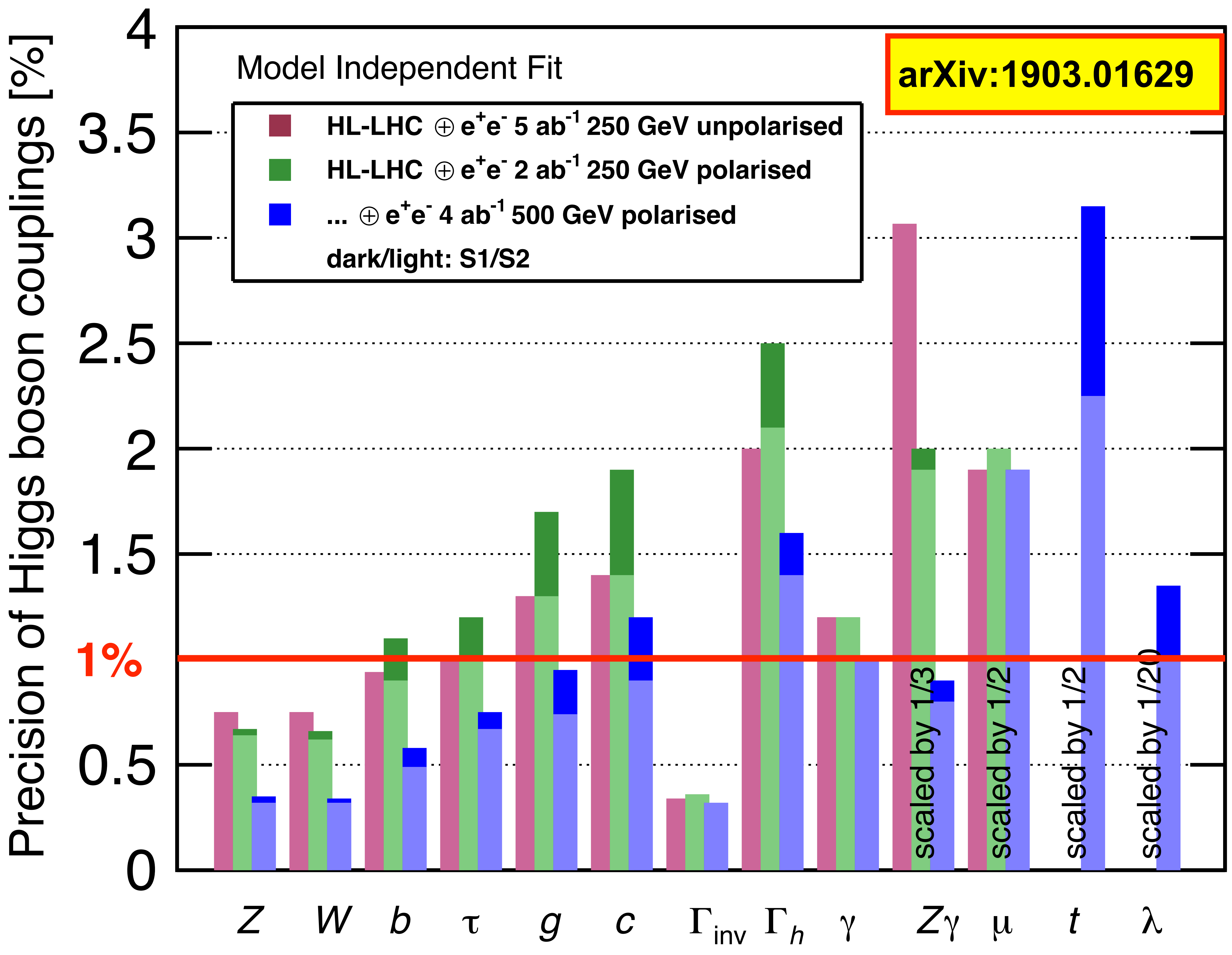

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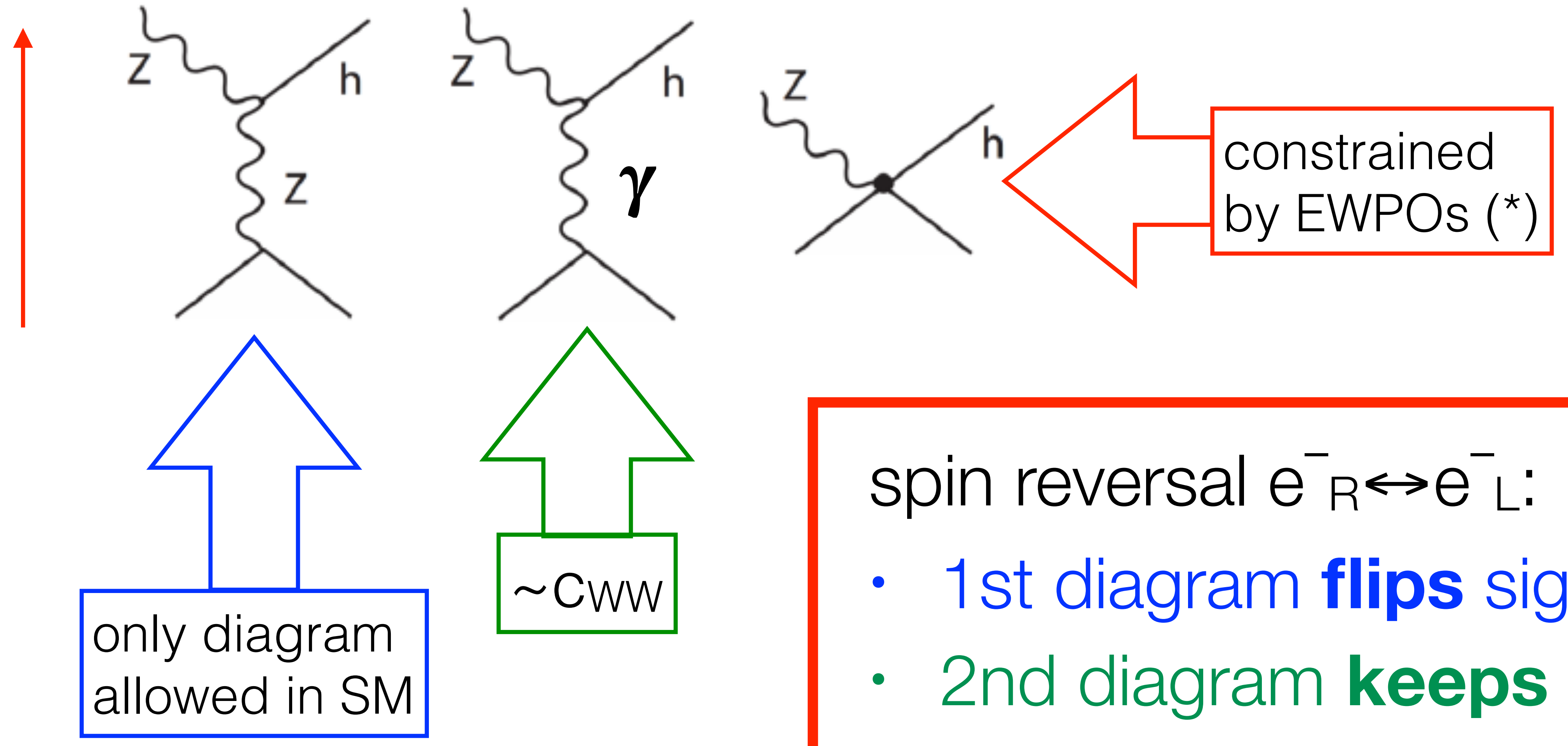

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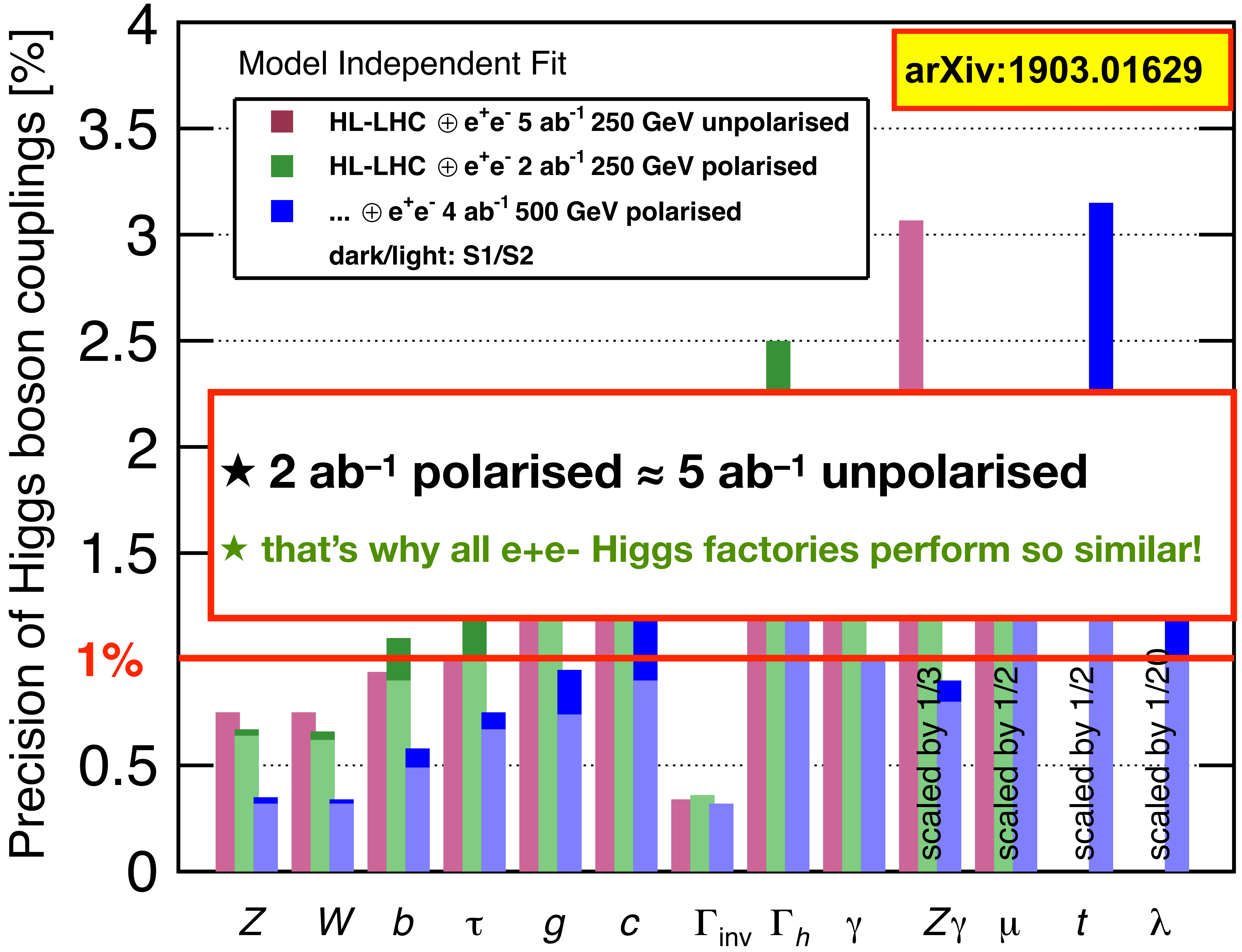

Why do we need to know the couplings of the Higgs boson?

Discovering new phenomena

- Any deviation from the SM prediction is a discovery of a new phenomenon
- Higgs couplings allow finger-printing new phenomena via their different *patterns* of deviations
- *size* of deviations depends on energy scale of new particles:
  the more precise the measurement, the larger the discovery potential
- need at least 1%-level of precision for Higgs couplings
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arXiv:1708.08912

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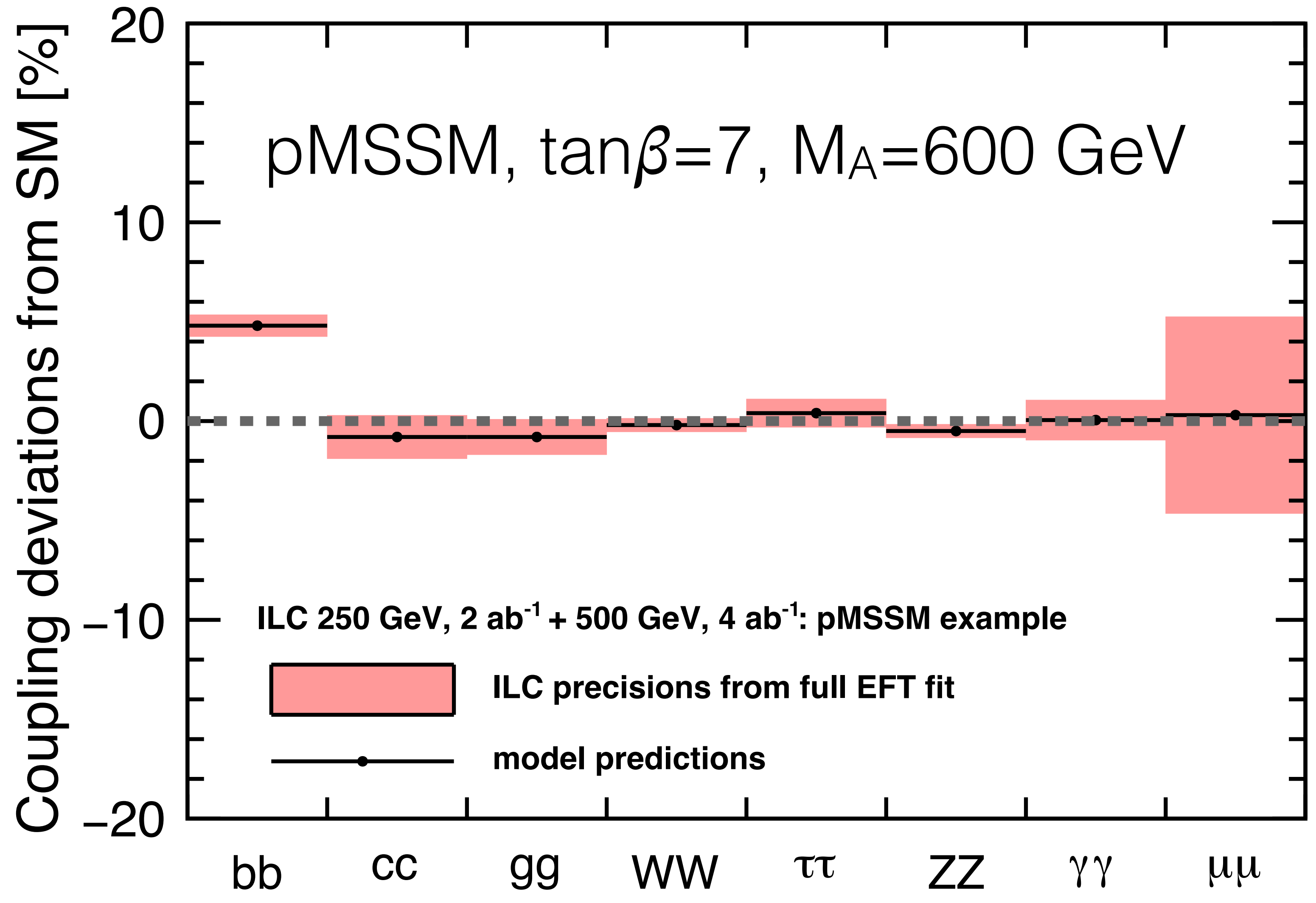

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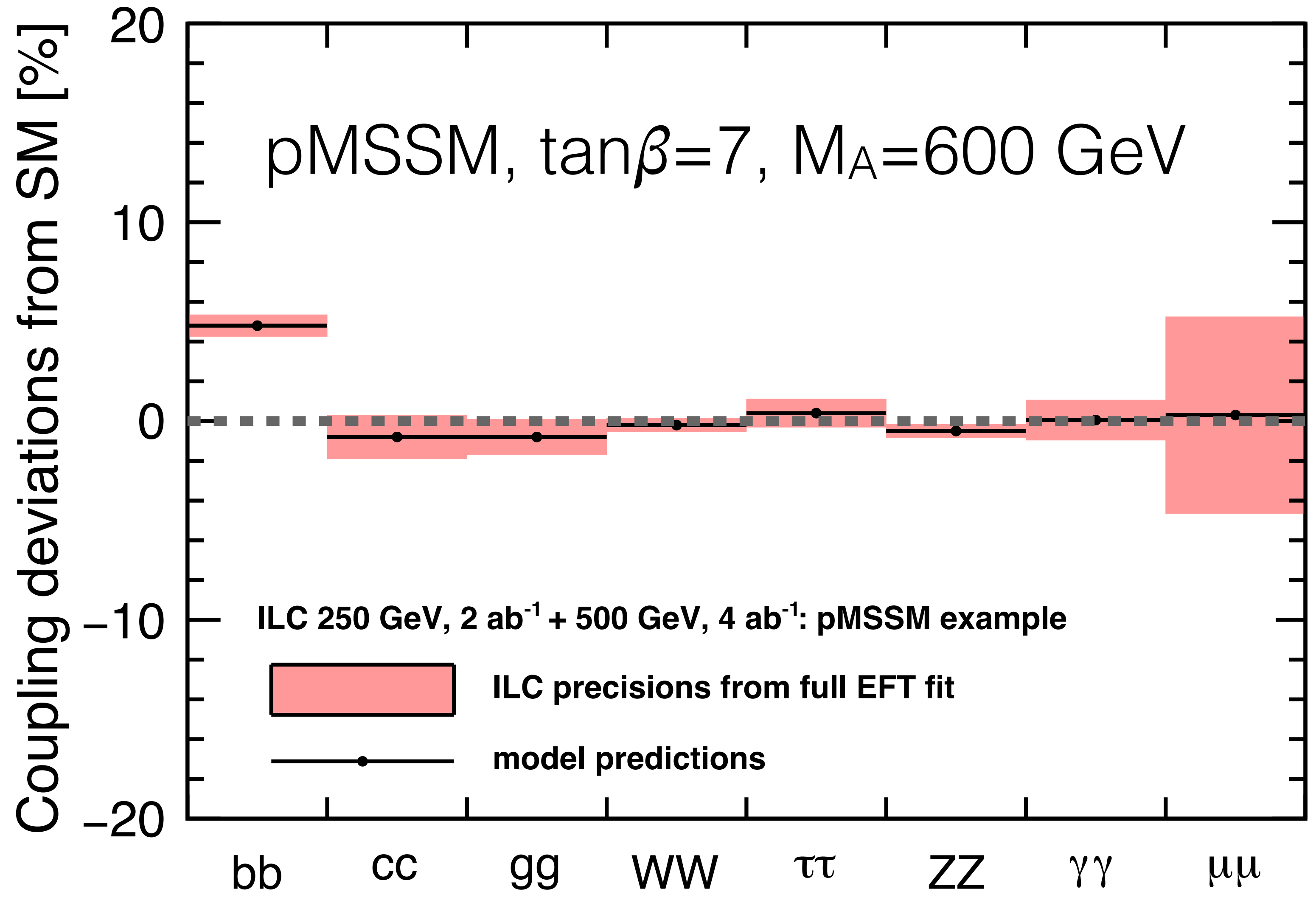

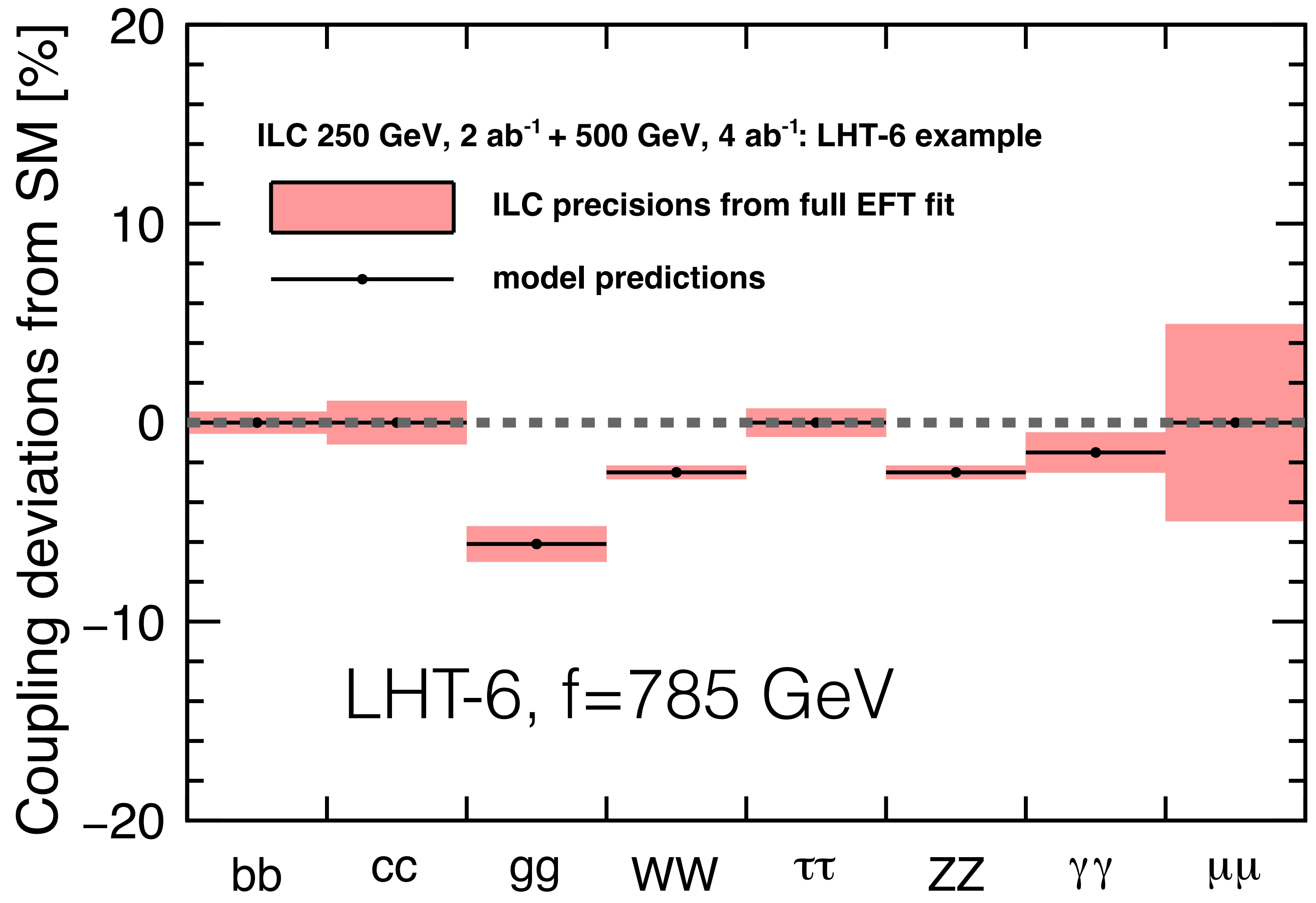

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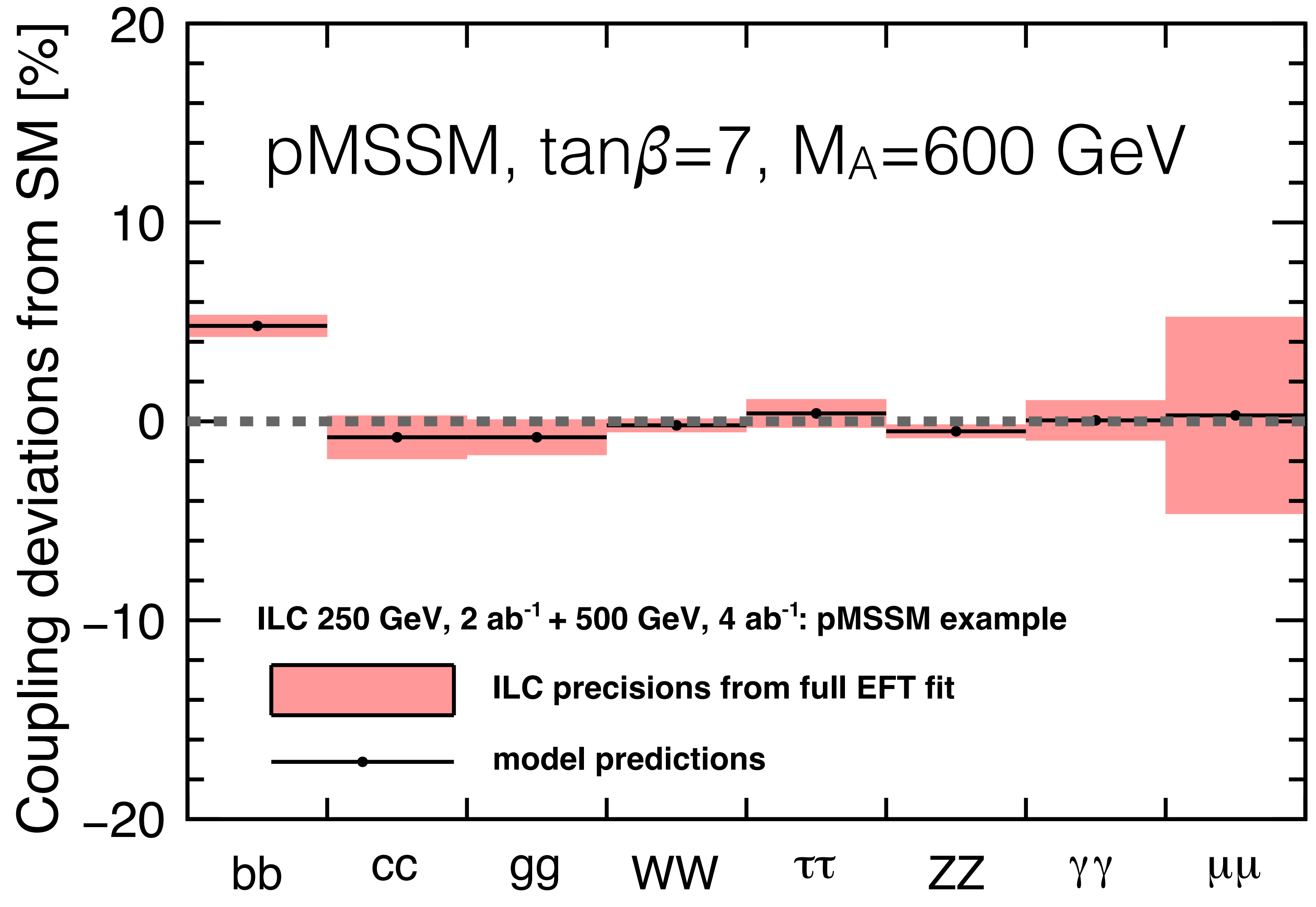

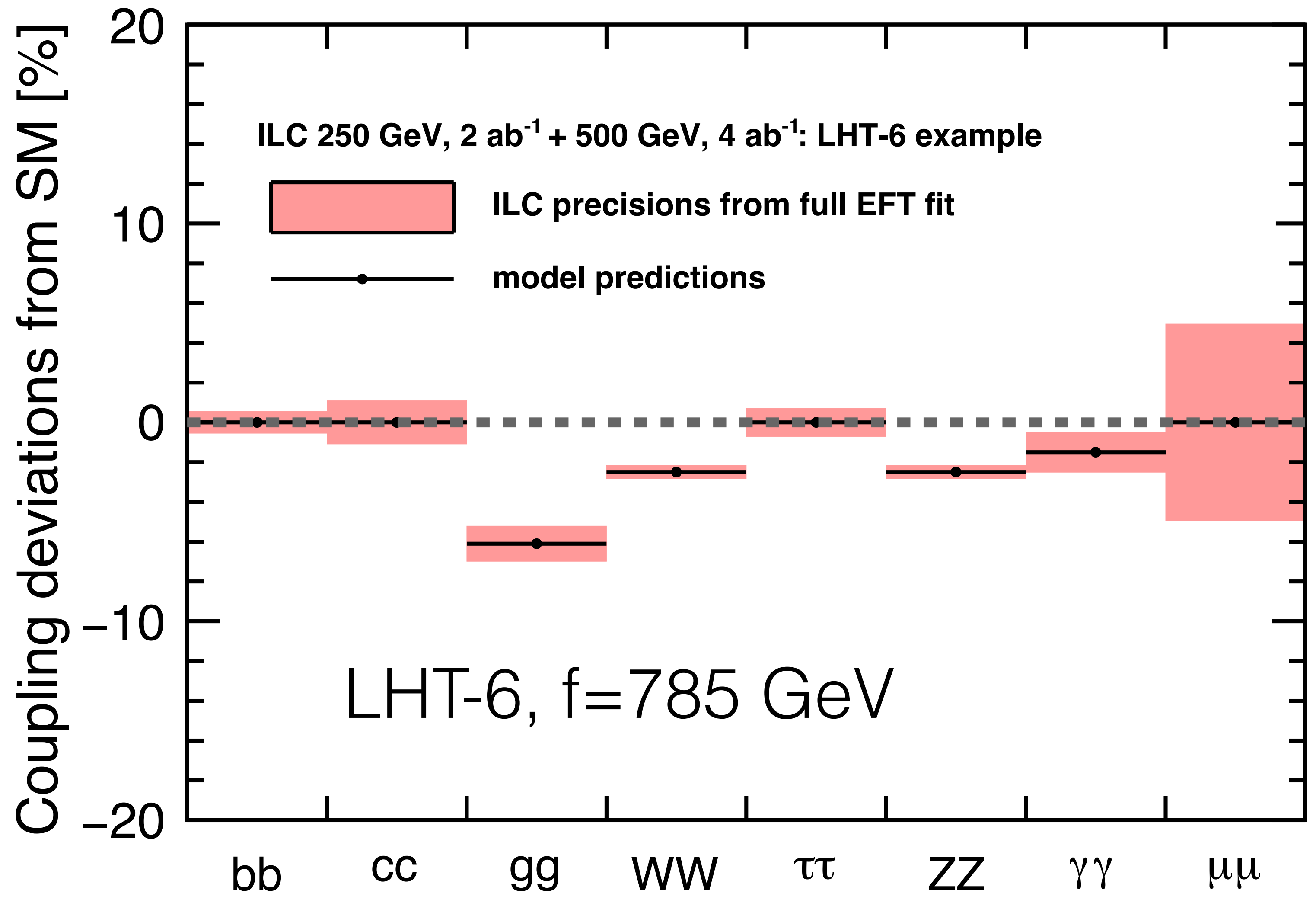

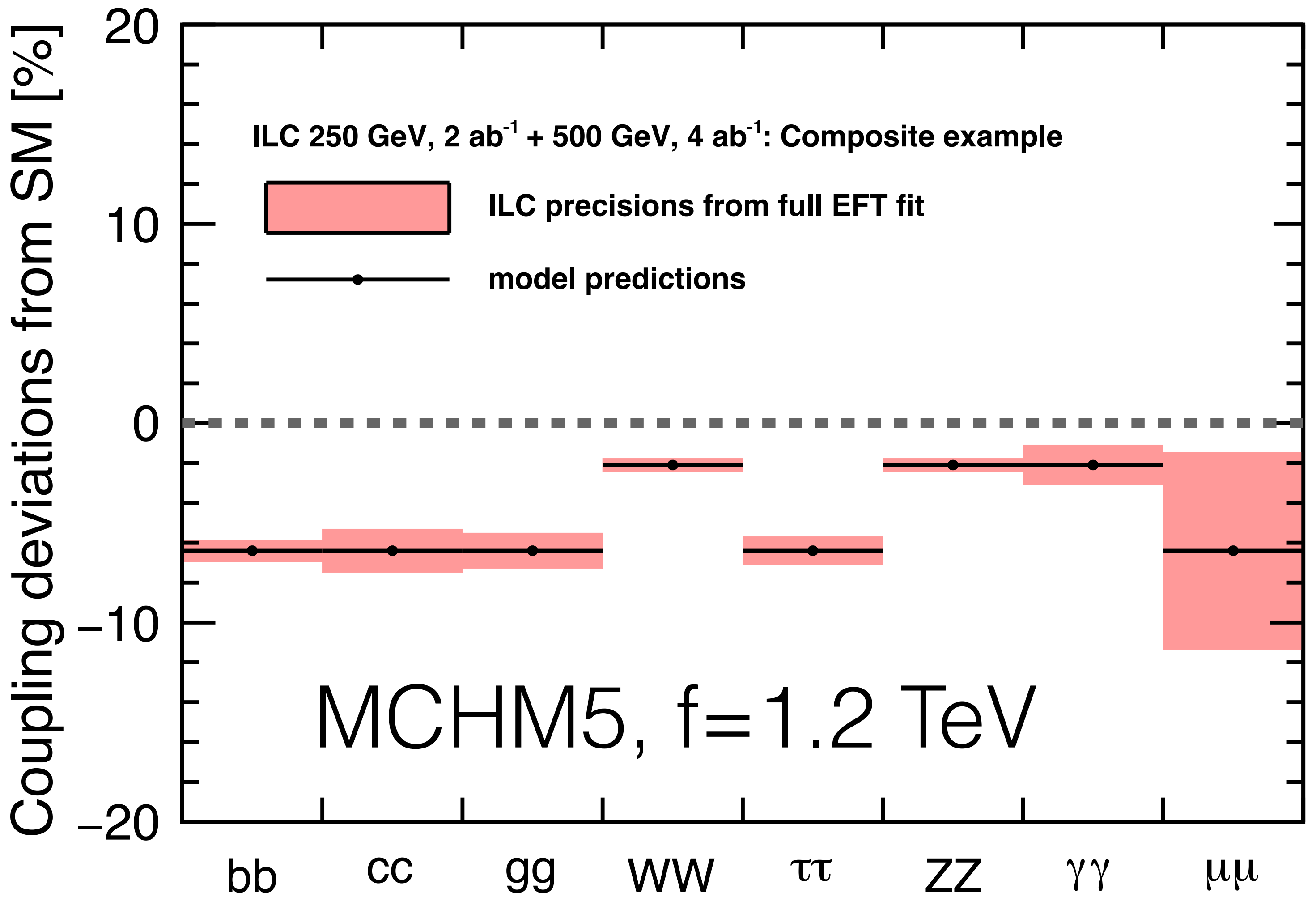

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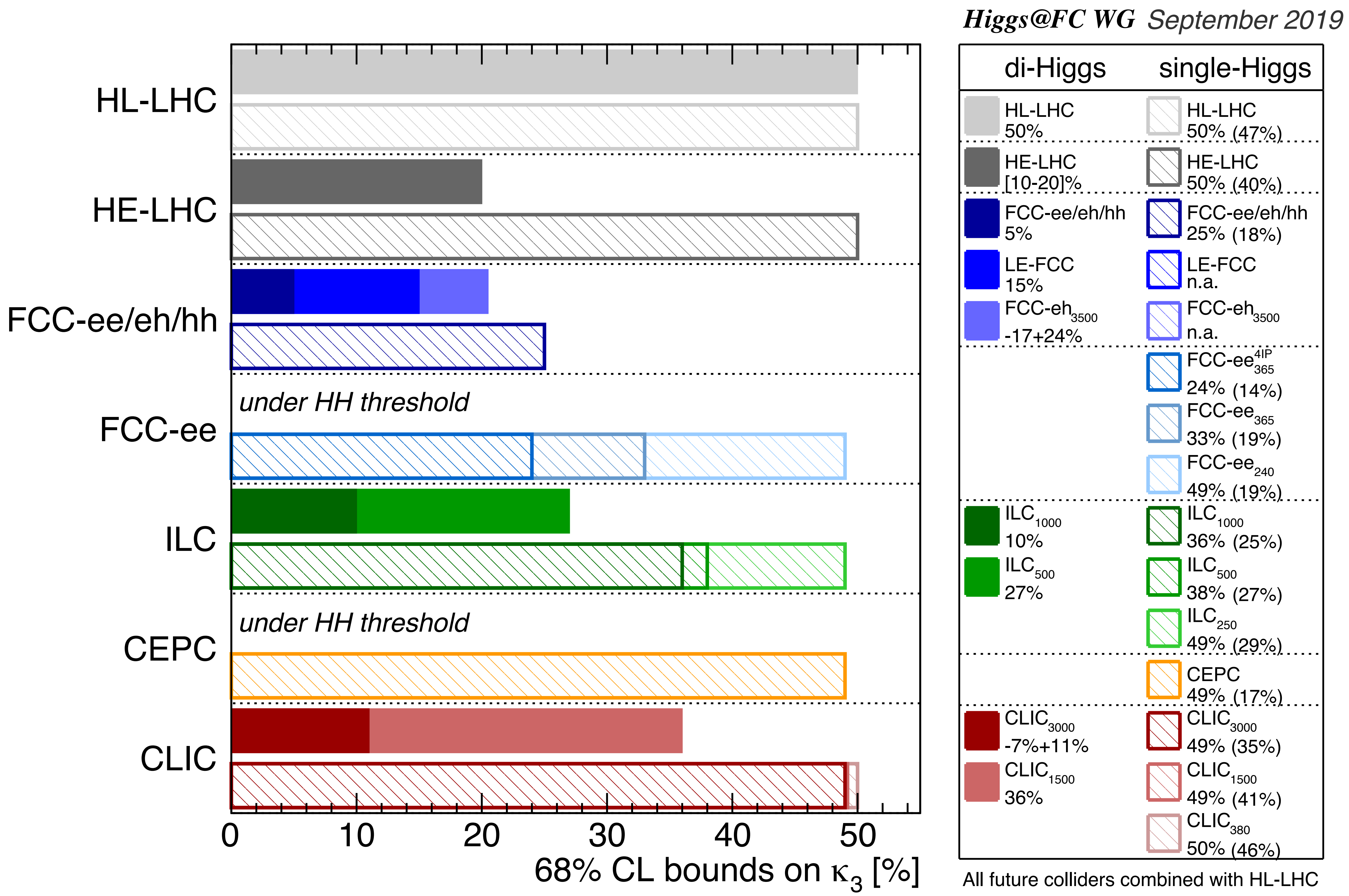
Beyond the minimal Higgs program - the self-coupling

The Higgs self-coupling: master plot of the last EPPSU



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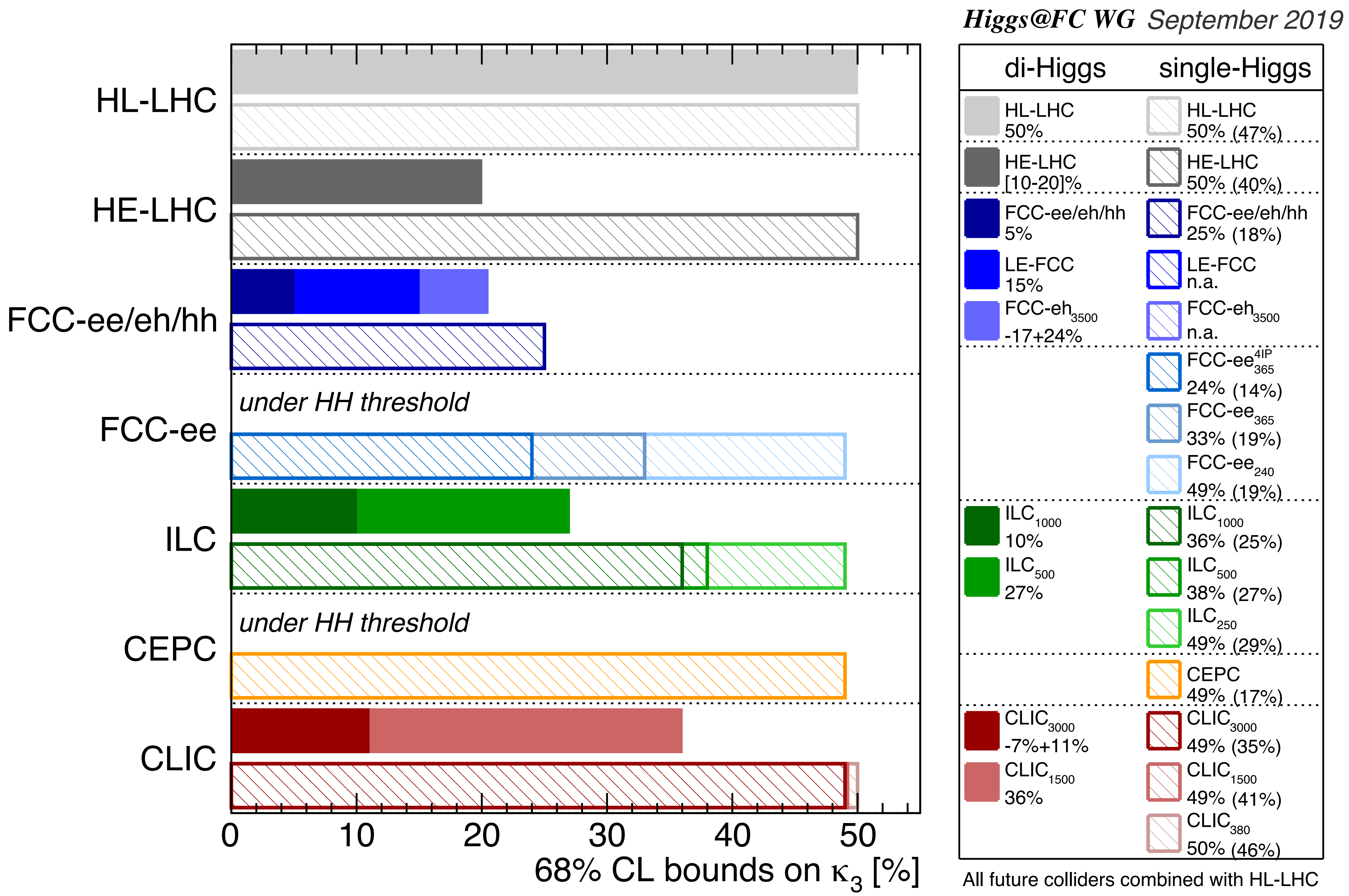

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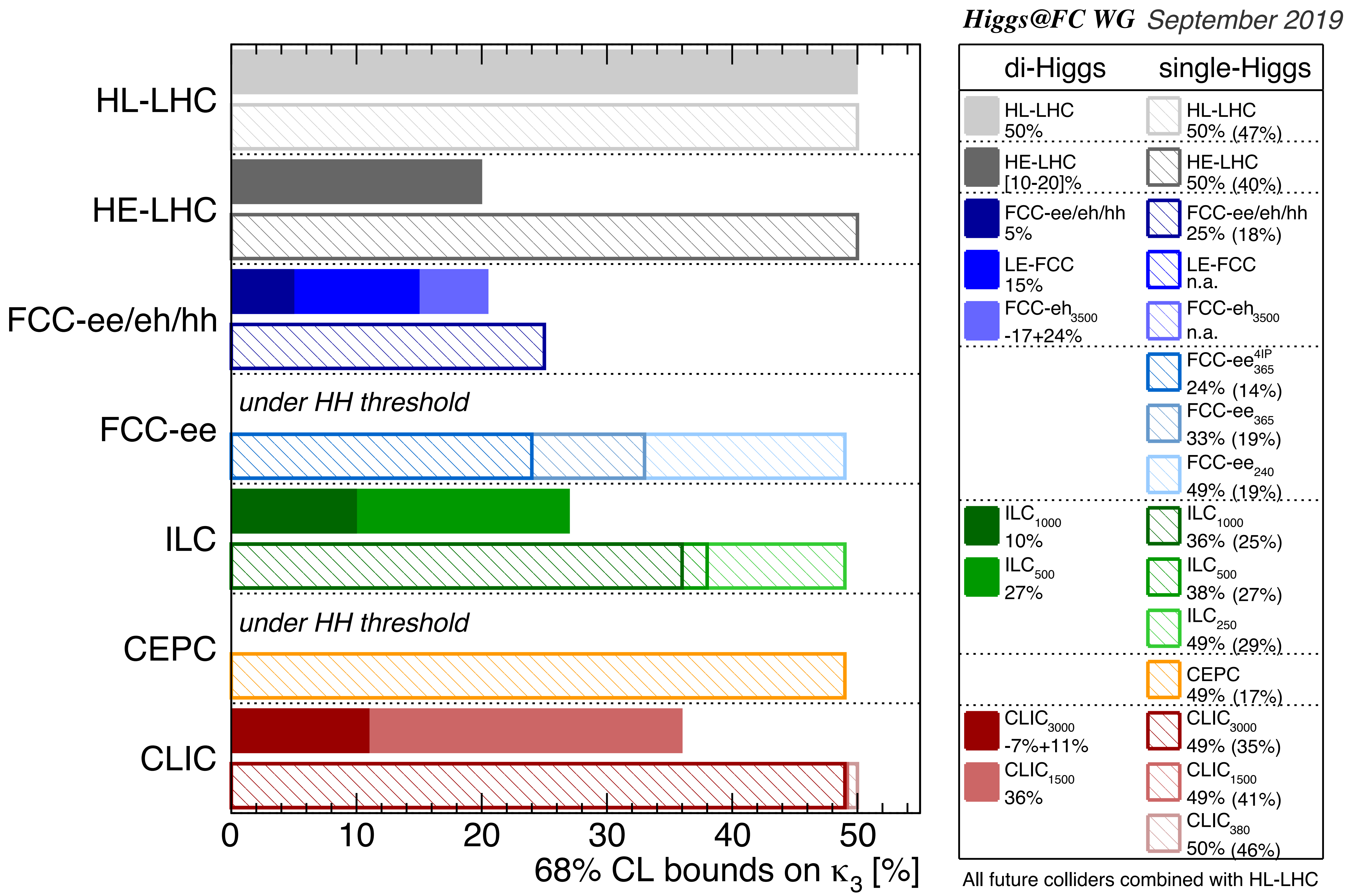

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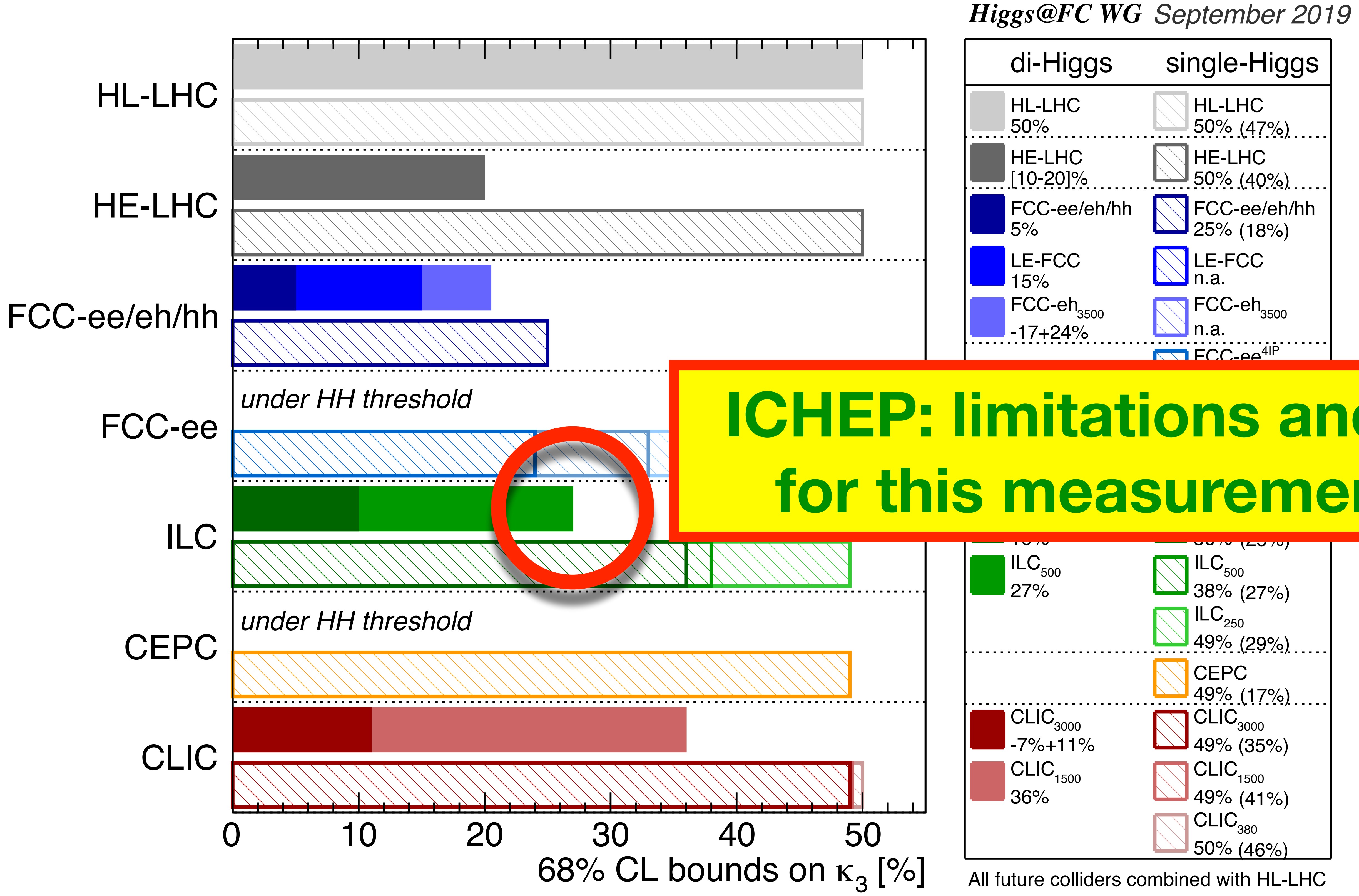

ICHEP: limitations and prospects for this measurement ("27%")

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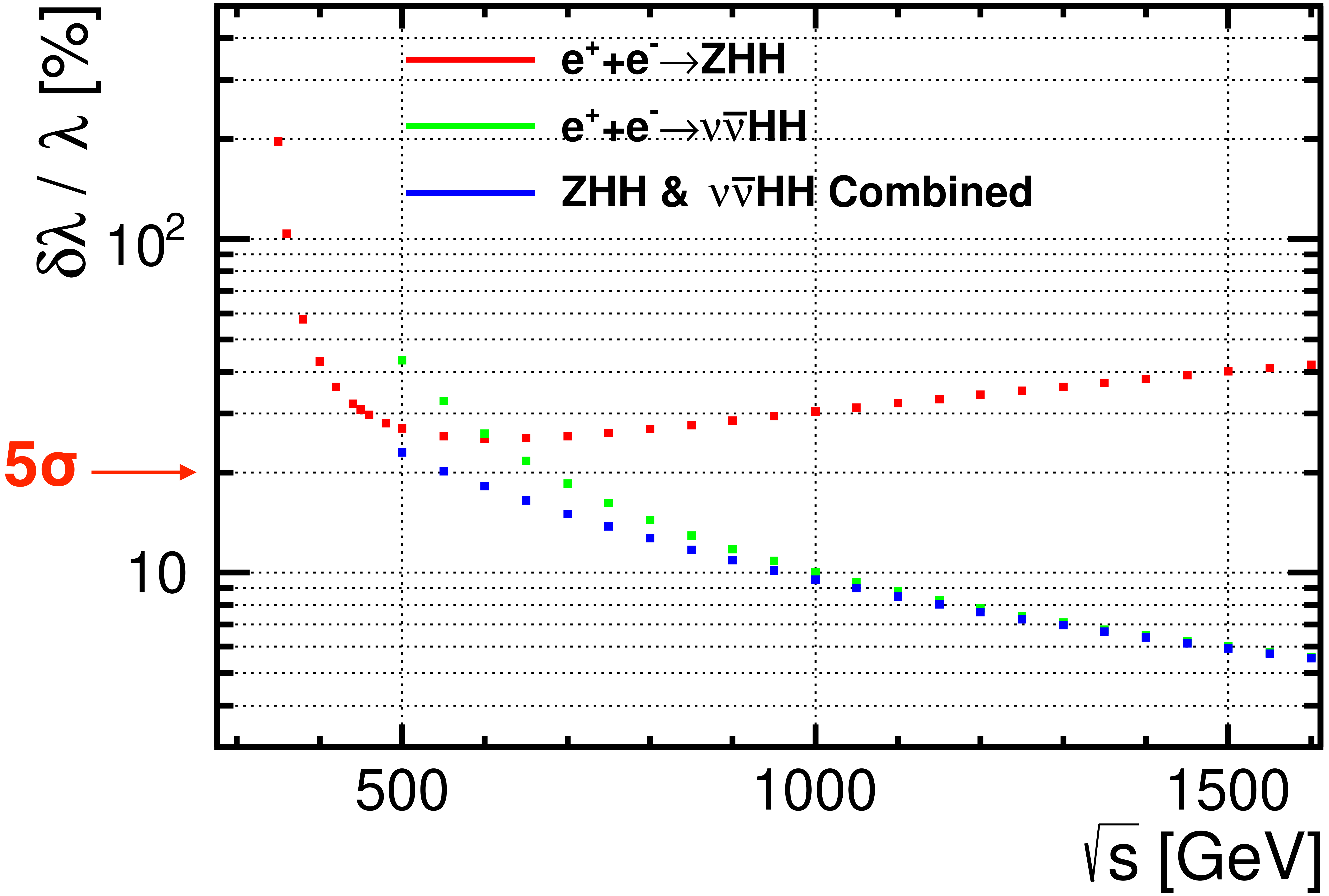
Combining ZHH & vvHH — as Function of ECM

J.Tian, LCWS2024



Discovery can be guaranteed

ILC500: 23%

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note: this is based on old DBD analysis; large room from new analysis

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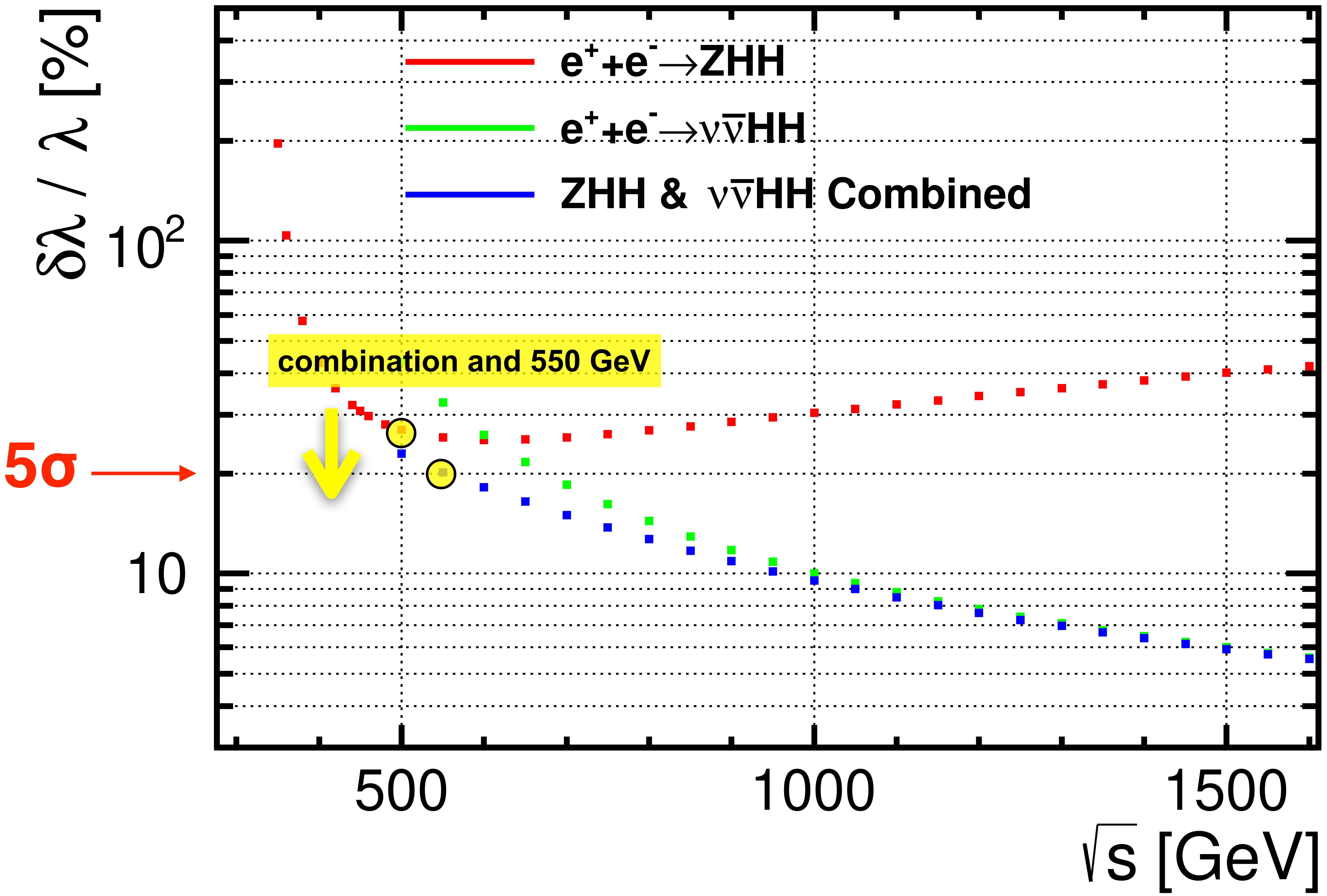

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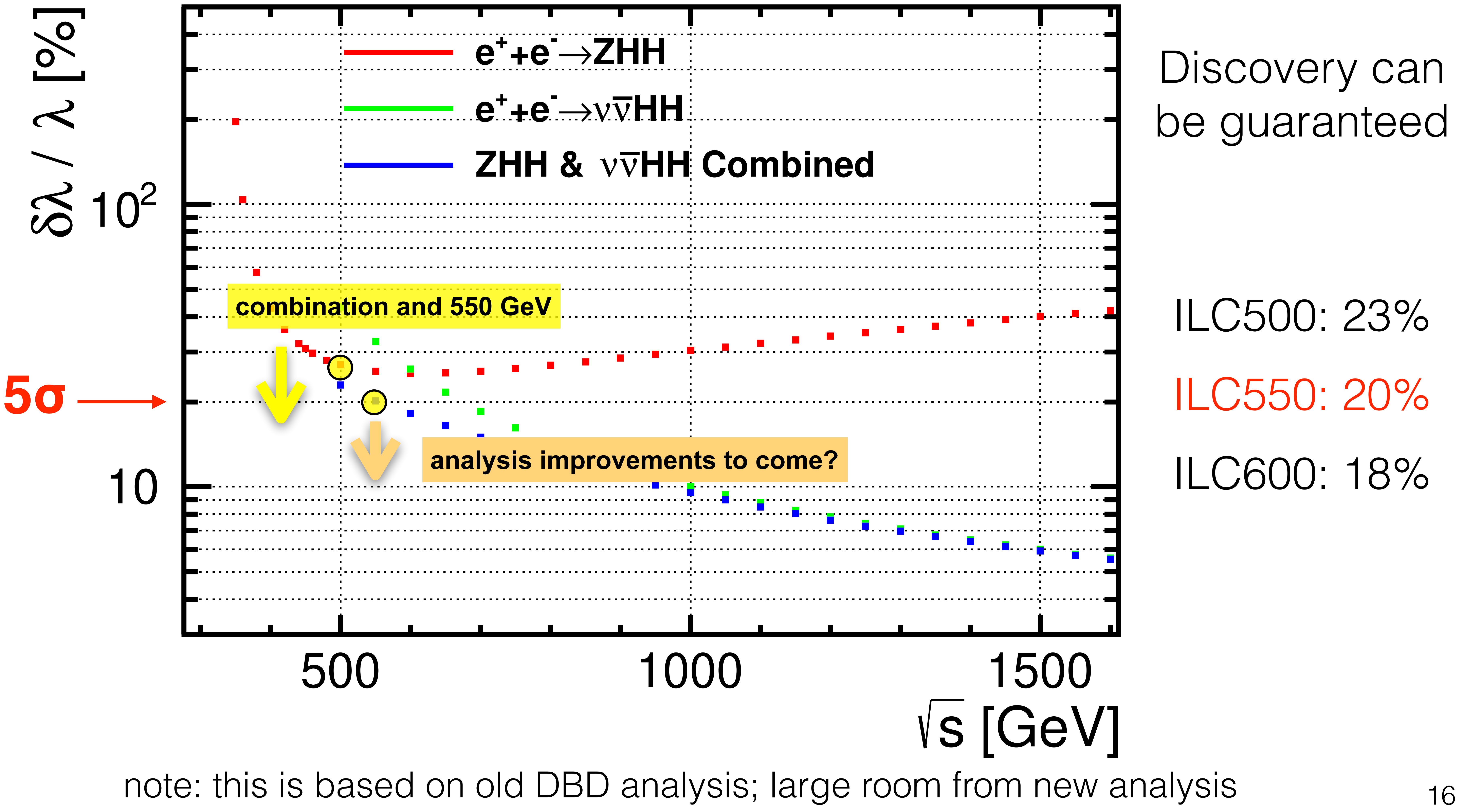

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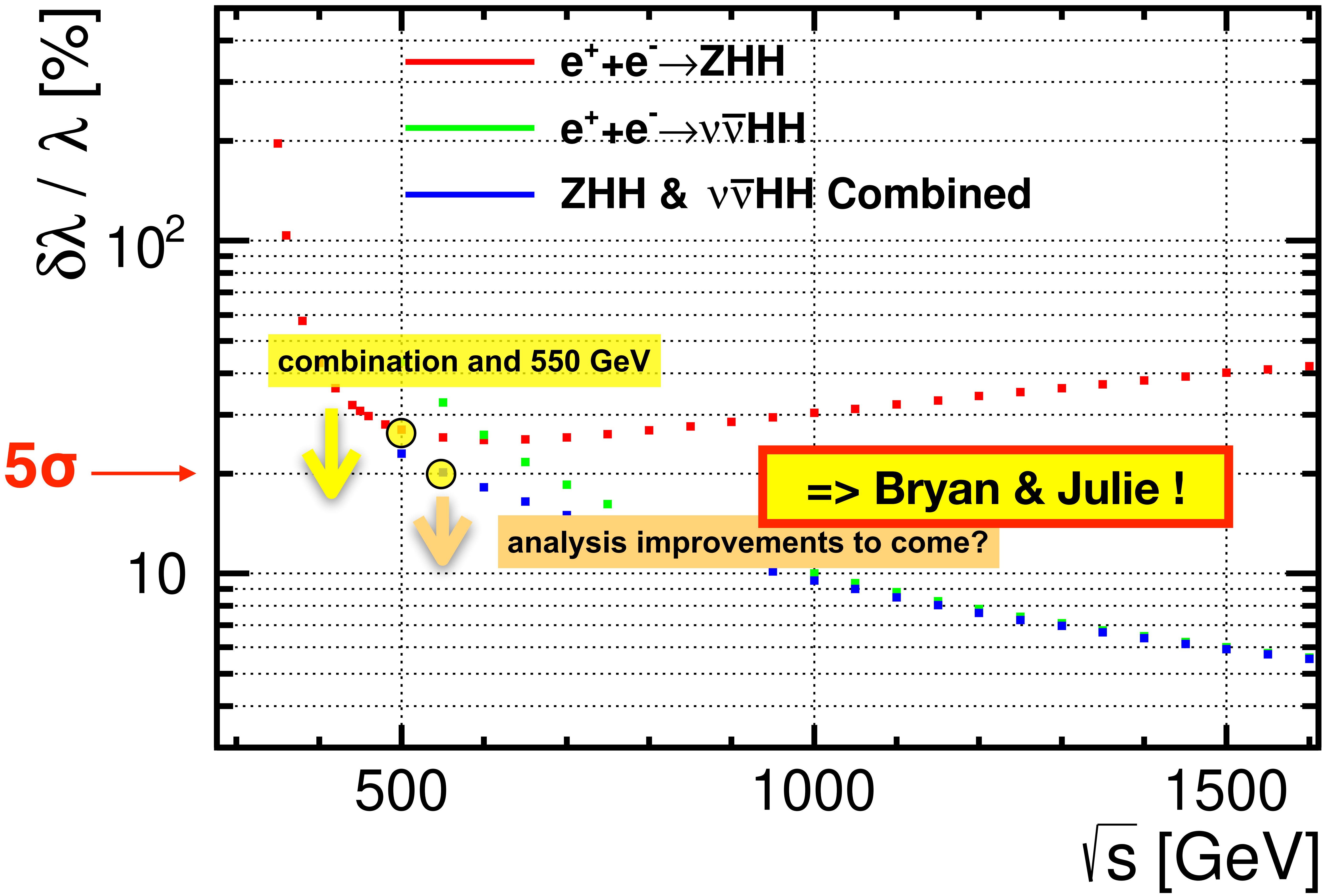

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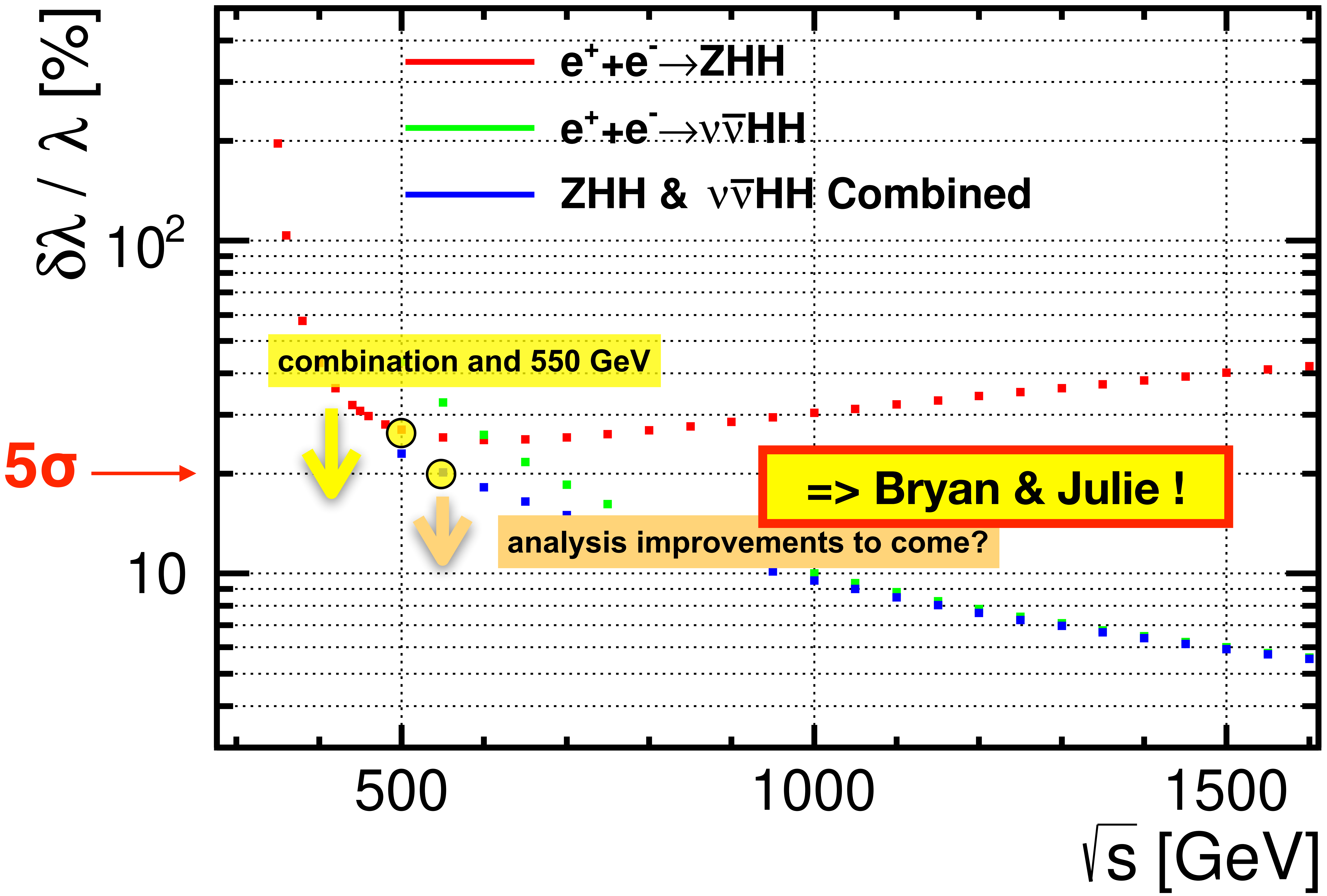

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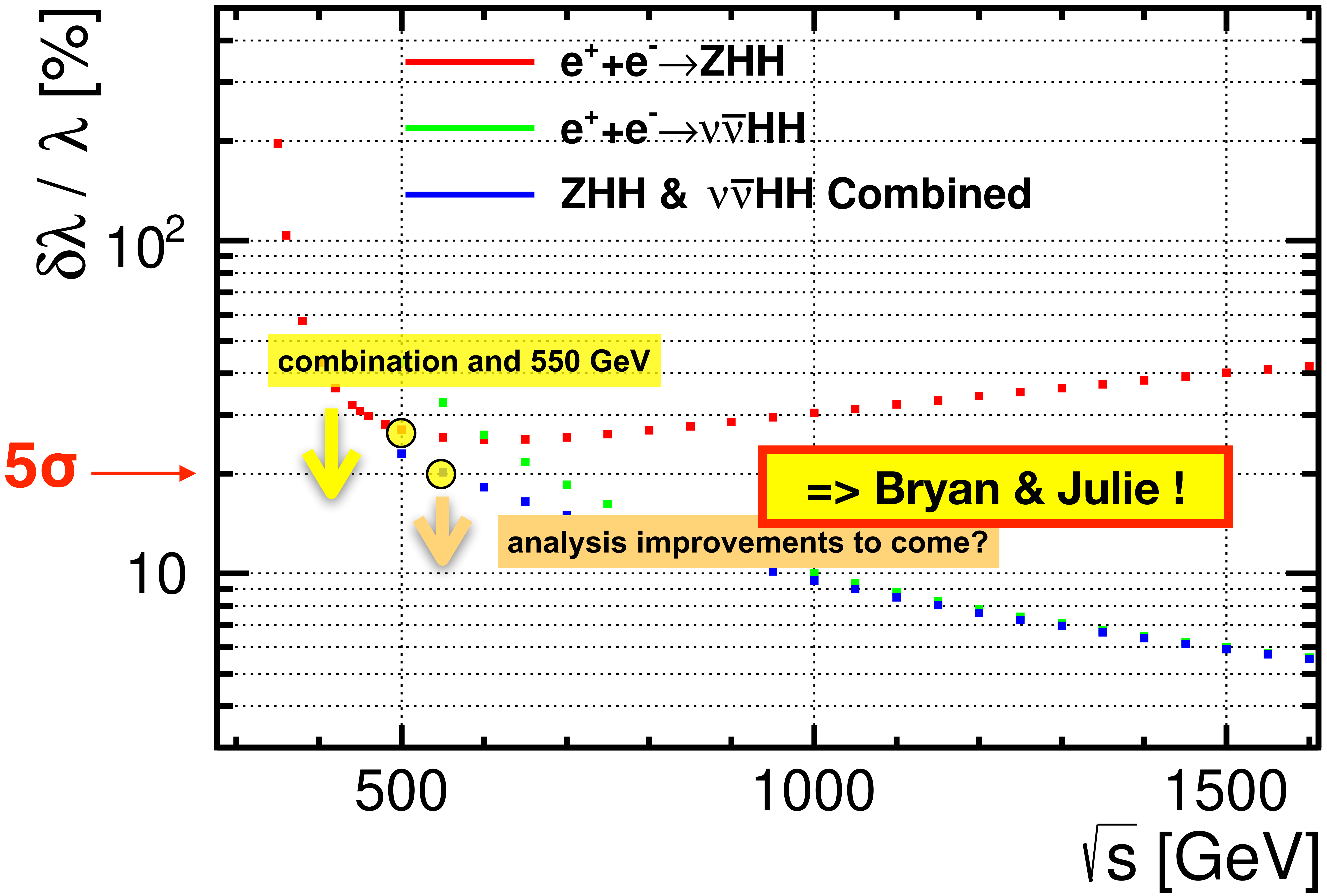

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Deviation of λ from SM prediction can be large

even if all other couplings are SM-like

from dimensional analysis

Self-Coupling Dominance

In other words, no obstruction to having Higgs self-coupling modifications a "loop factor" greater than **all** other couplings. Could have

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

without fine-tuning any parameters, as big as,

$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

Durieux, MM, Salvioni. 2022

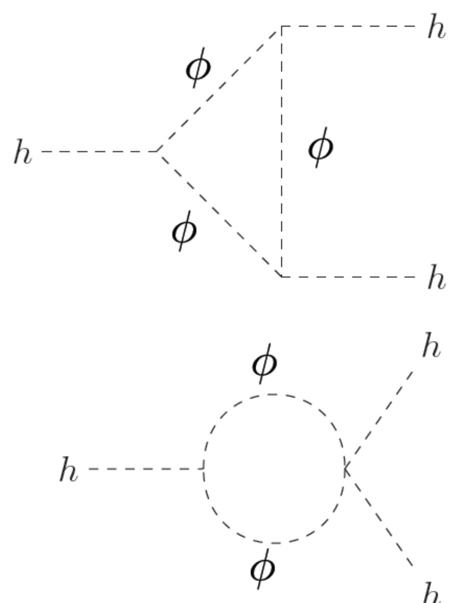
M. McCullough @ LCWS2024

or from UV complete BSM models

Concrete example: 2HDM: [taken from F. Arco '24]

Parameter scan in the 2HDM (all types):

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]



$\phi = H, A, H^\pm$

Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
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(results from the effective potential)

- Very large corrections are possible! $\lambda_{hhh}^{(1)} >> \lambda_{hhh}^{(0)}$
- h couplings to heavy Higgs bosons can be large ($\lambda_{h\phi\phi} \sim 15$)
  - Even at the *alignment limit* !!!

(In the SM, top-loops are ~ -8%)

⇒ effect of the extended BSM Higgs sector!

S.Heinemeyer @ LCWS2024

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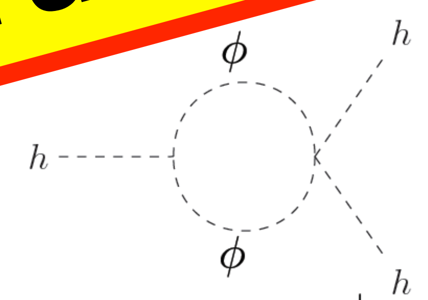

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Measurement with as little model-assumptions as possible is crucial!

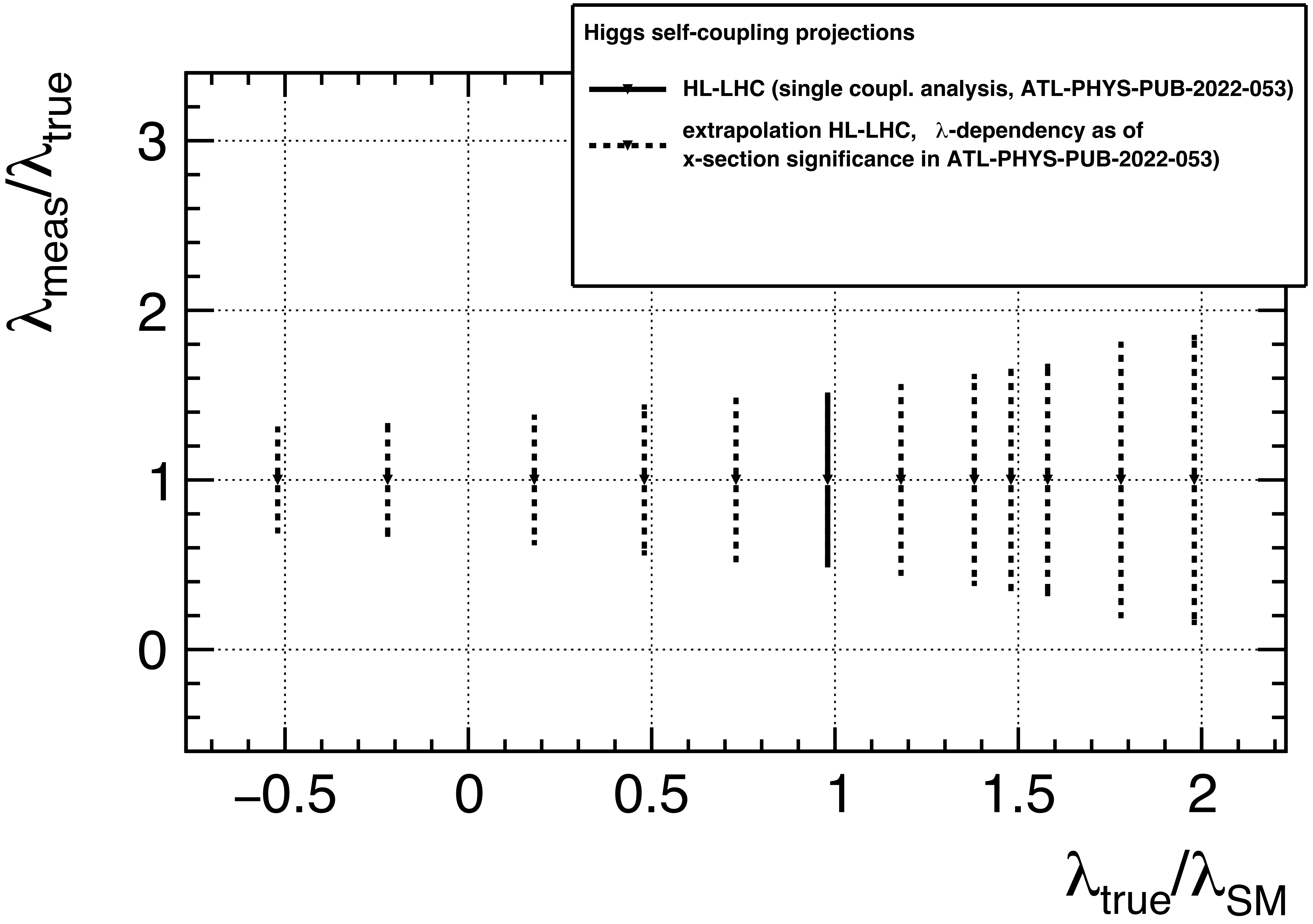
M. McCullough @ LCWS2024

S.Heinemeyer @ LCWS2024

Higgs self-coupling Beyond the SM

Electroweak Baryogenesis?

note: this is based on the old ZHH analysis, i.e. the "27%"



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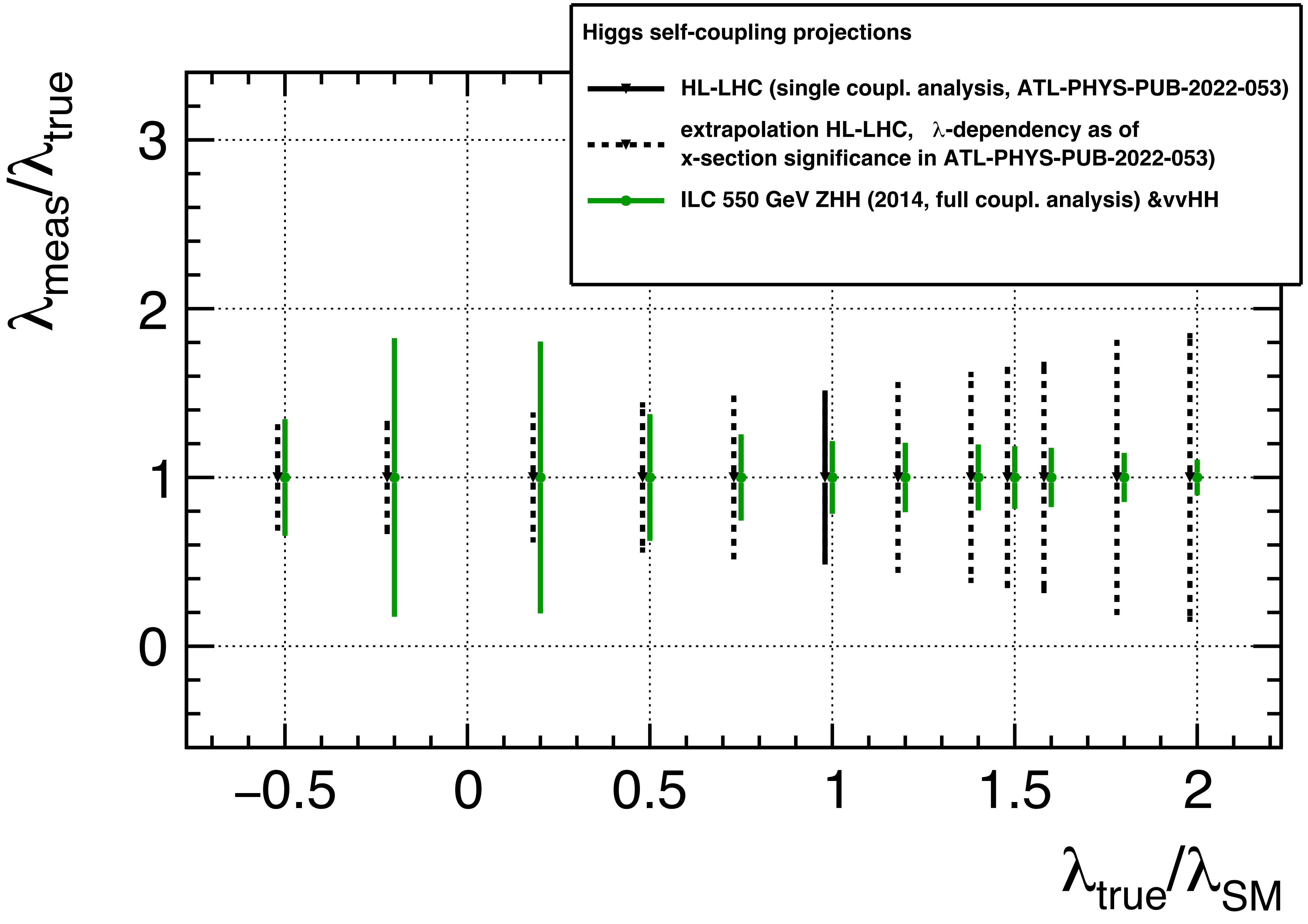

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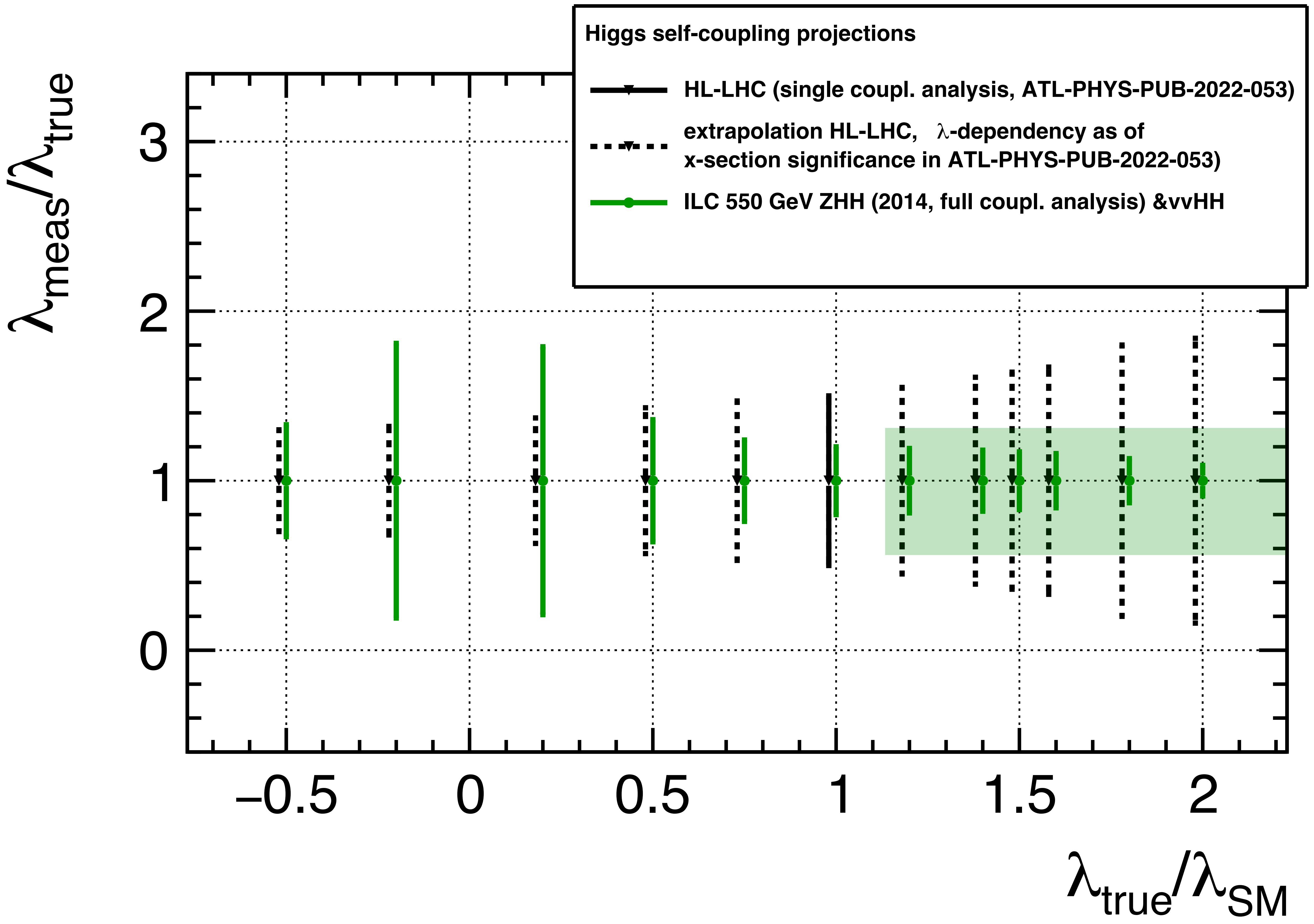

Region of interest for electroweak baryogenesis

Higgs self-coupling Beyond the SM

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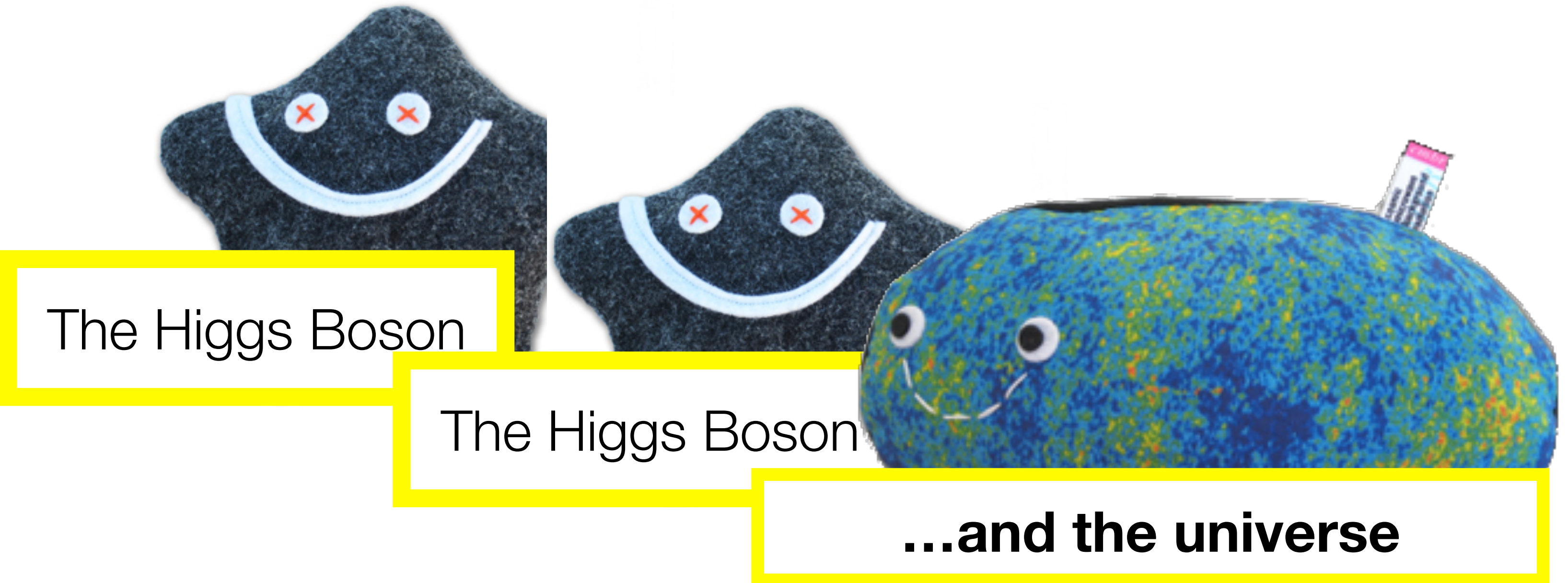
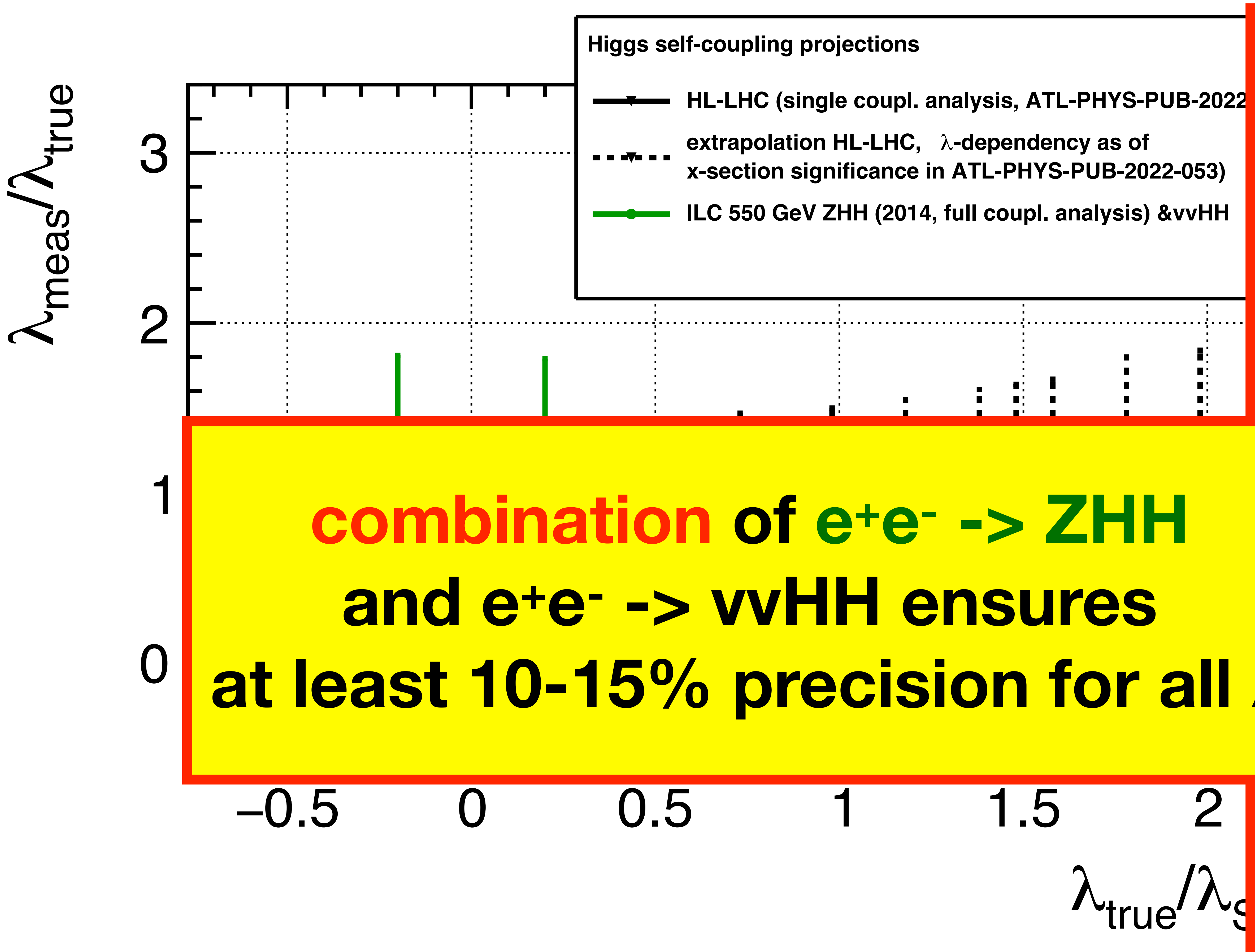
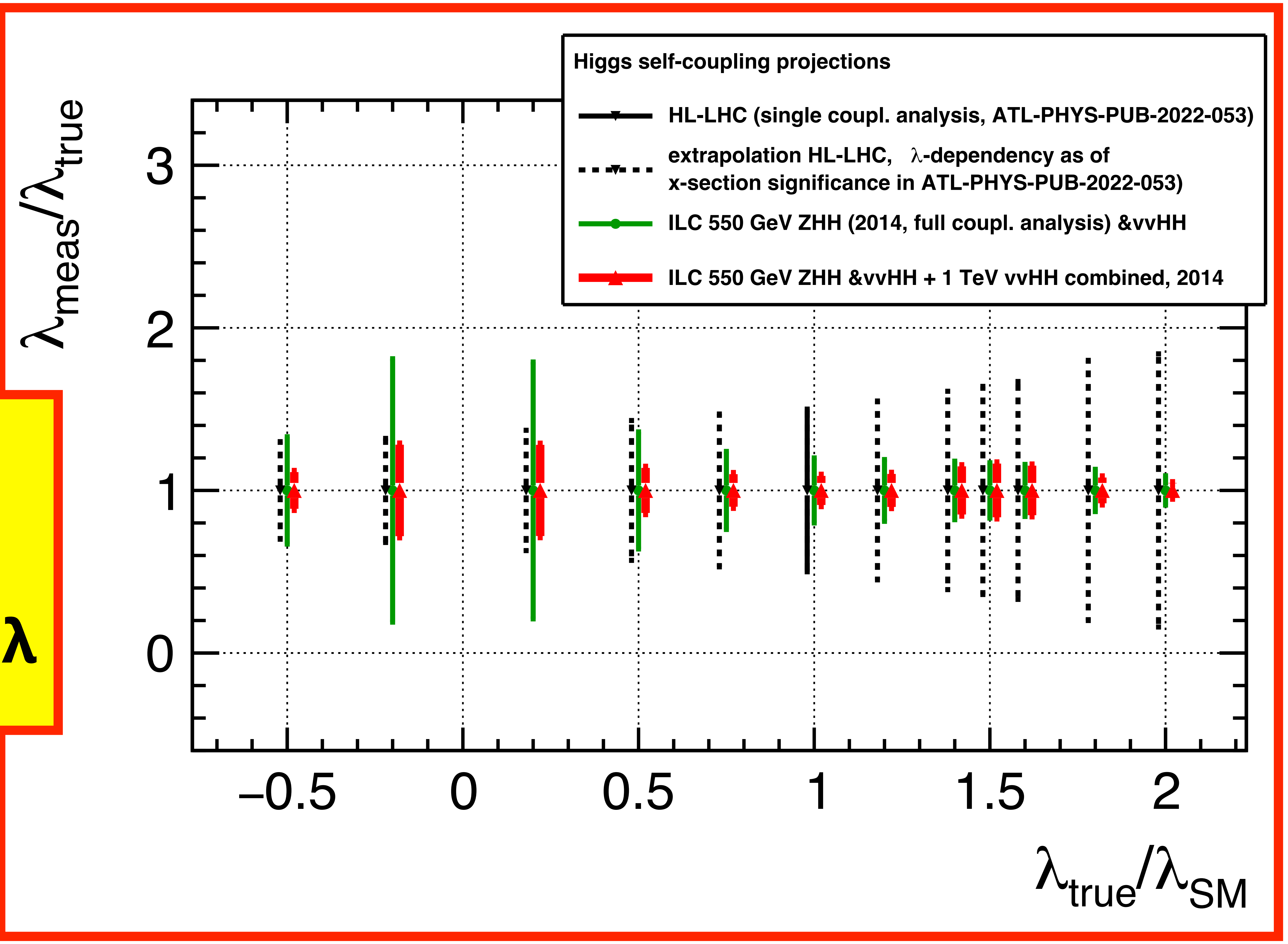




combination of e^+e^- -> ZHH and e^+e^- -> vvHH ensures at least 10-15% precision for all λ



There is so much more…

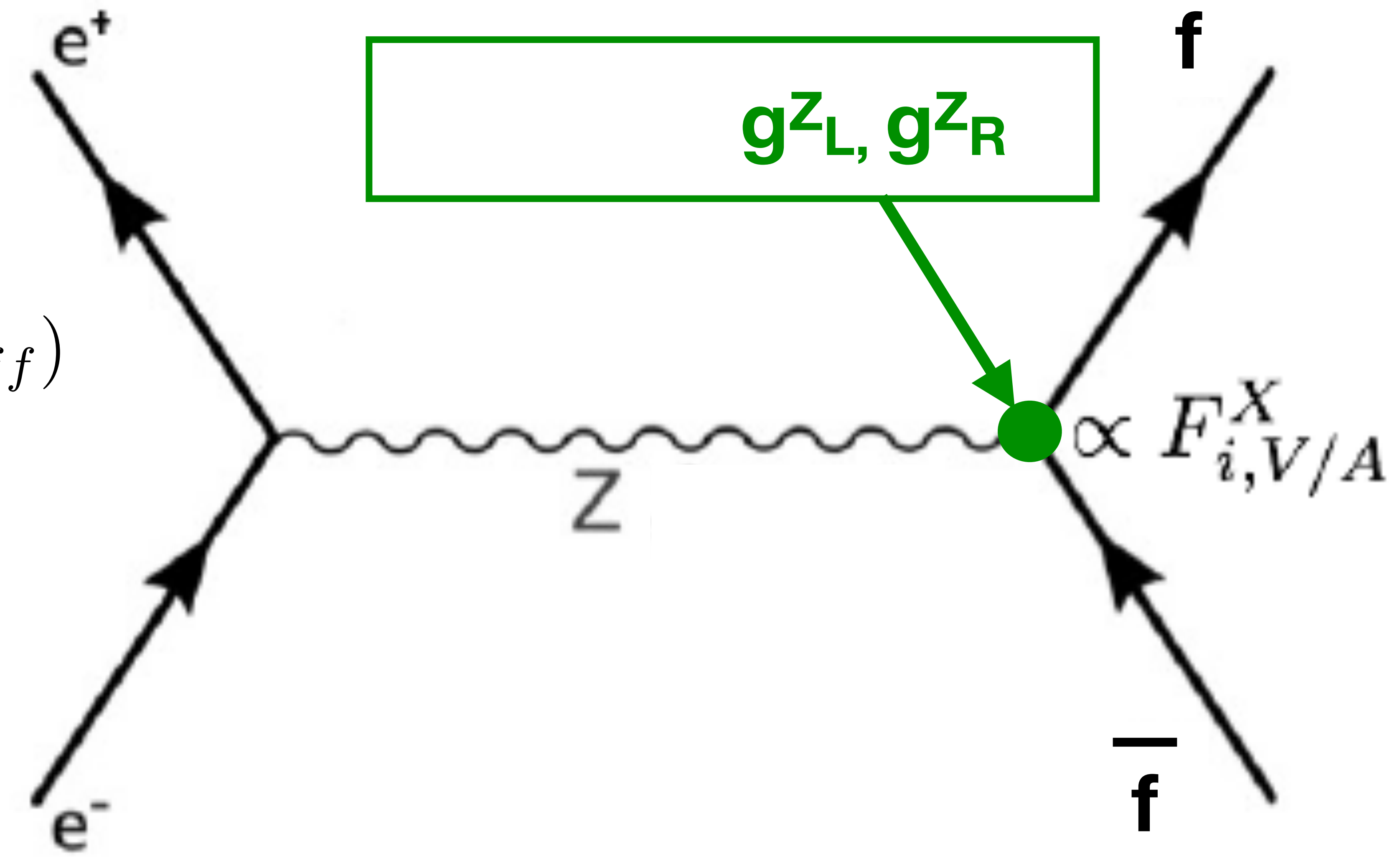
Polarisation & Electroweak Physics

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



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

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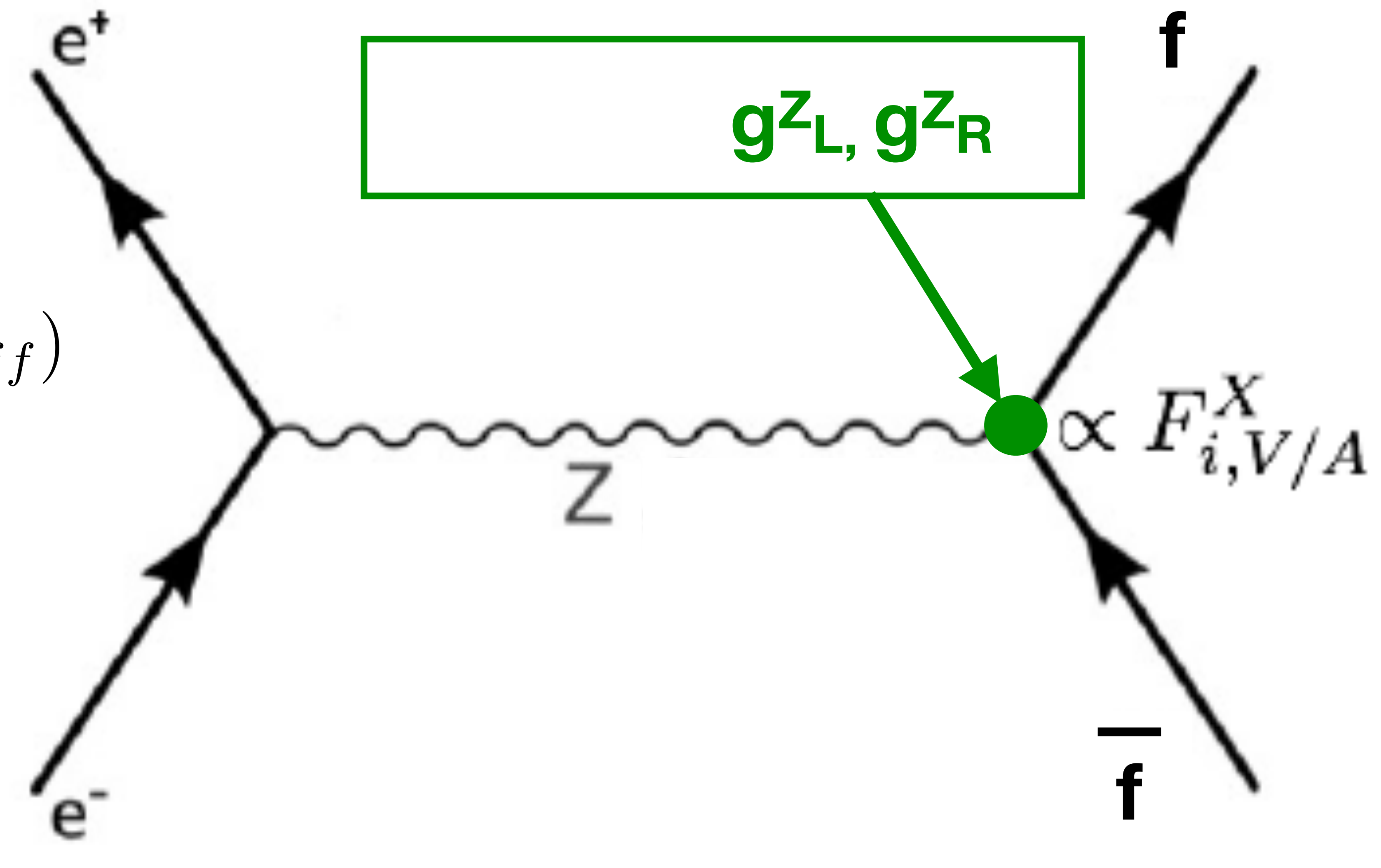

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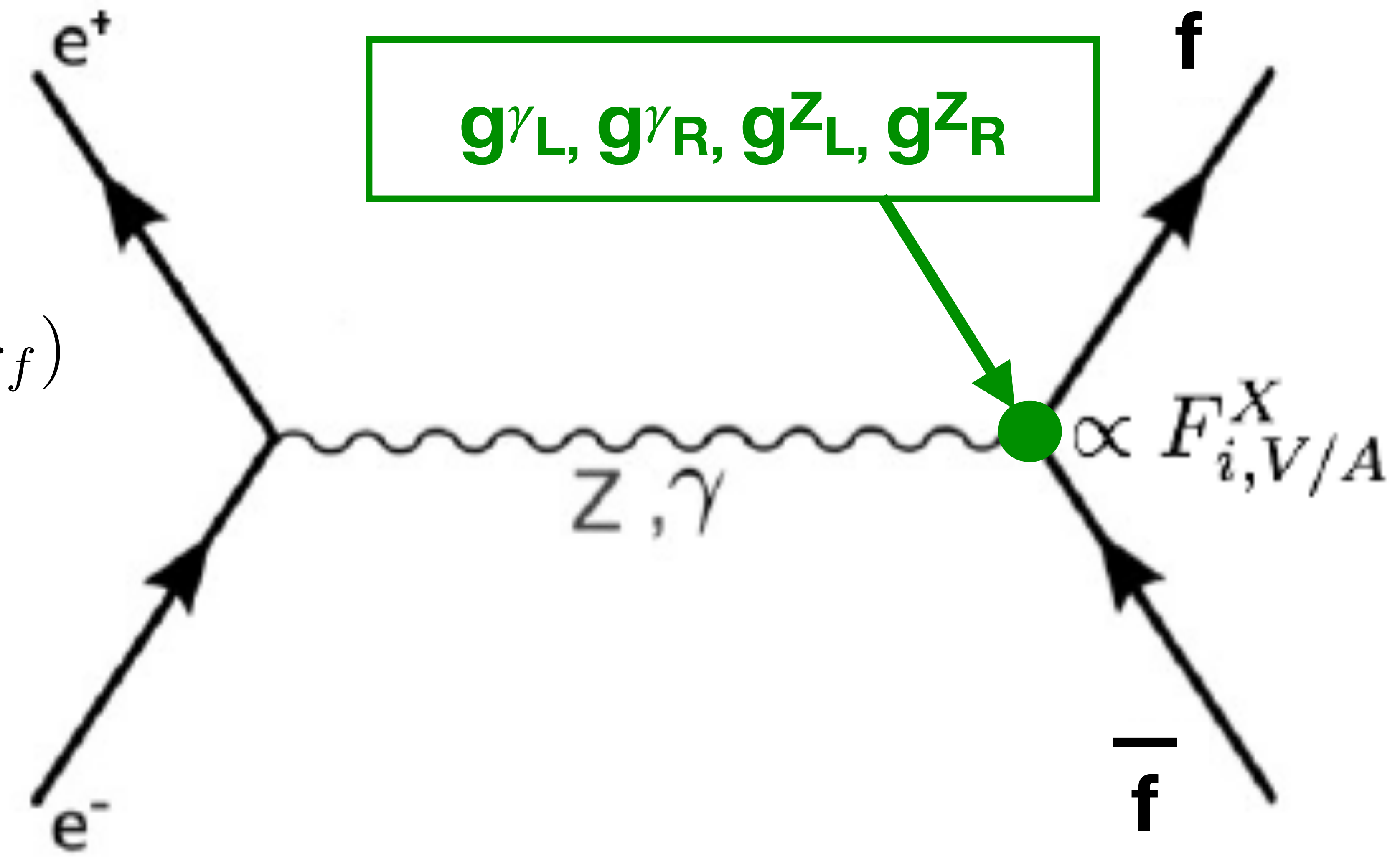

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g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions - at the Z pole:

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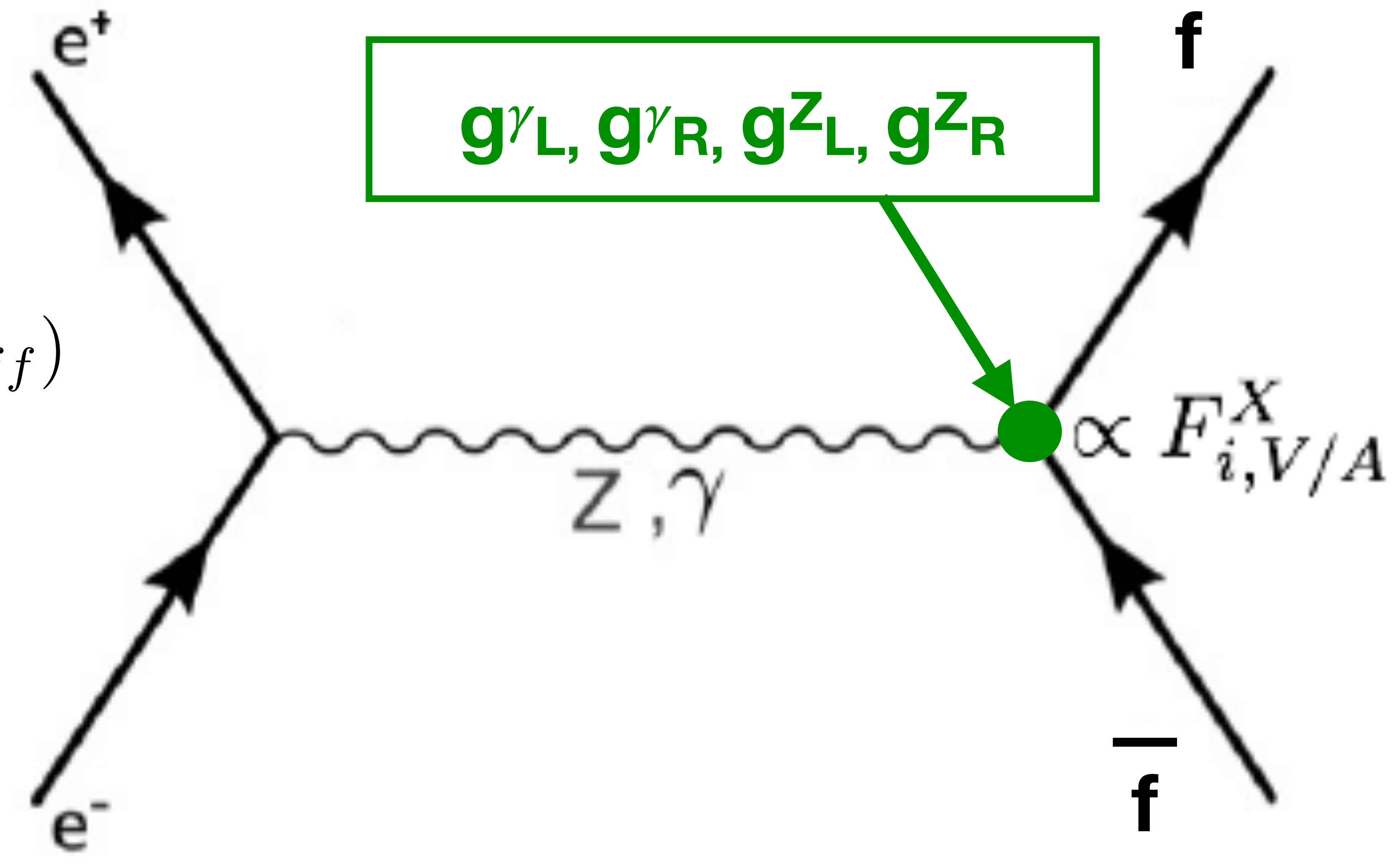
specifically for the electron: $$A_e = \frac{(\frac{1}{2} - \sin^2\theta_{eff})^2 - (\sin^2\theta_{eff})^2}{(\frac{1}{2} - \sin^2\theta_{eff})^2 + (\sin^2\theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2\theta_{eff})$$



at an *un*polarised collider:

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

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

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

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

trading theory uncertainy:

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

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

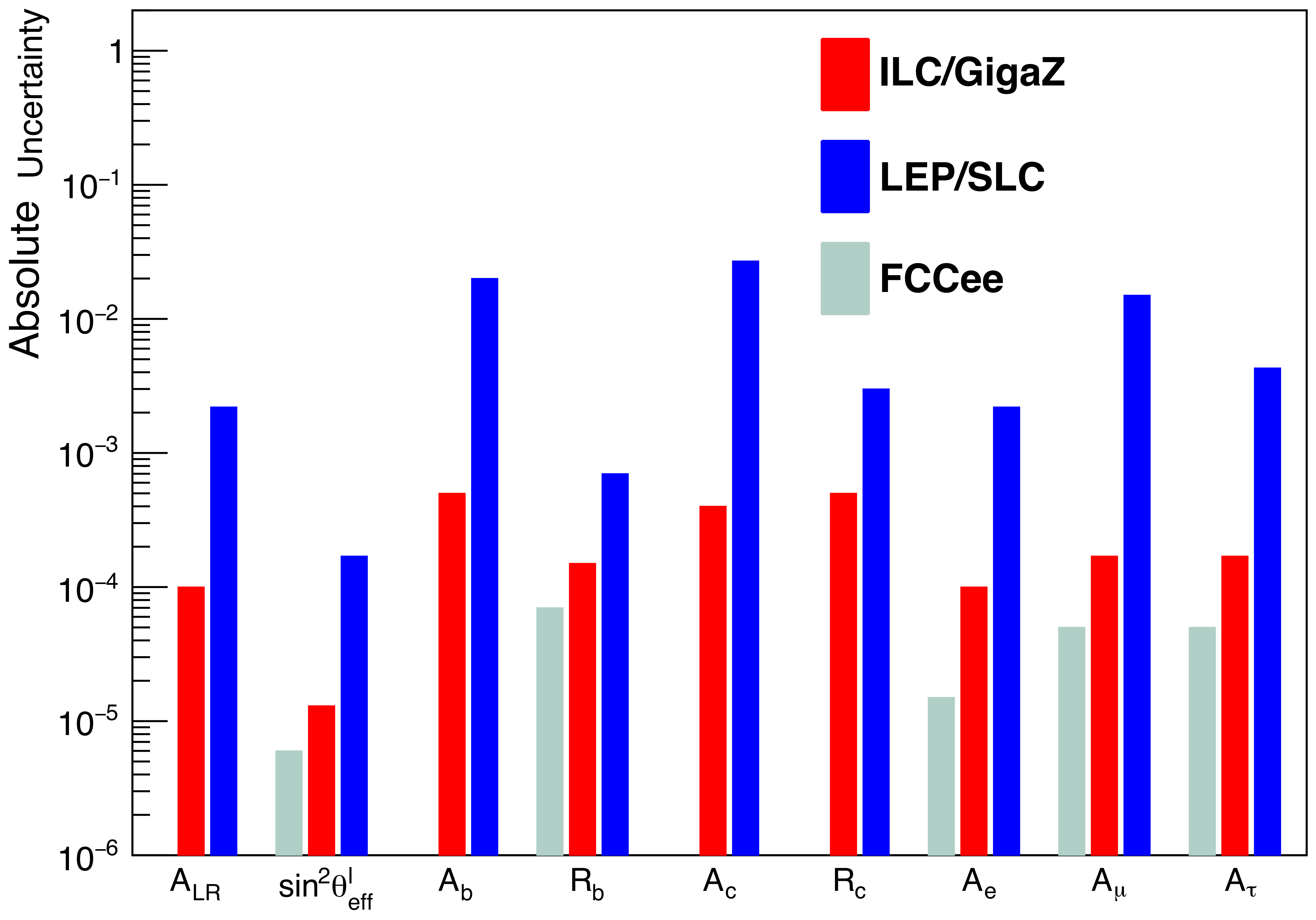
Polarisation & Electroweak Physics at the Z pole

LEP, ILC, FCCee

recent detailed studies by ILD@ILC:

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

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



Note: not true for pure decay quantities!

arXiv:1908.11299

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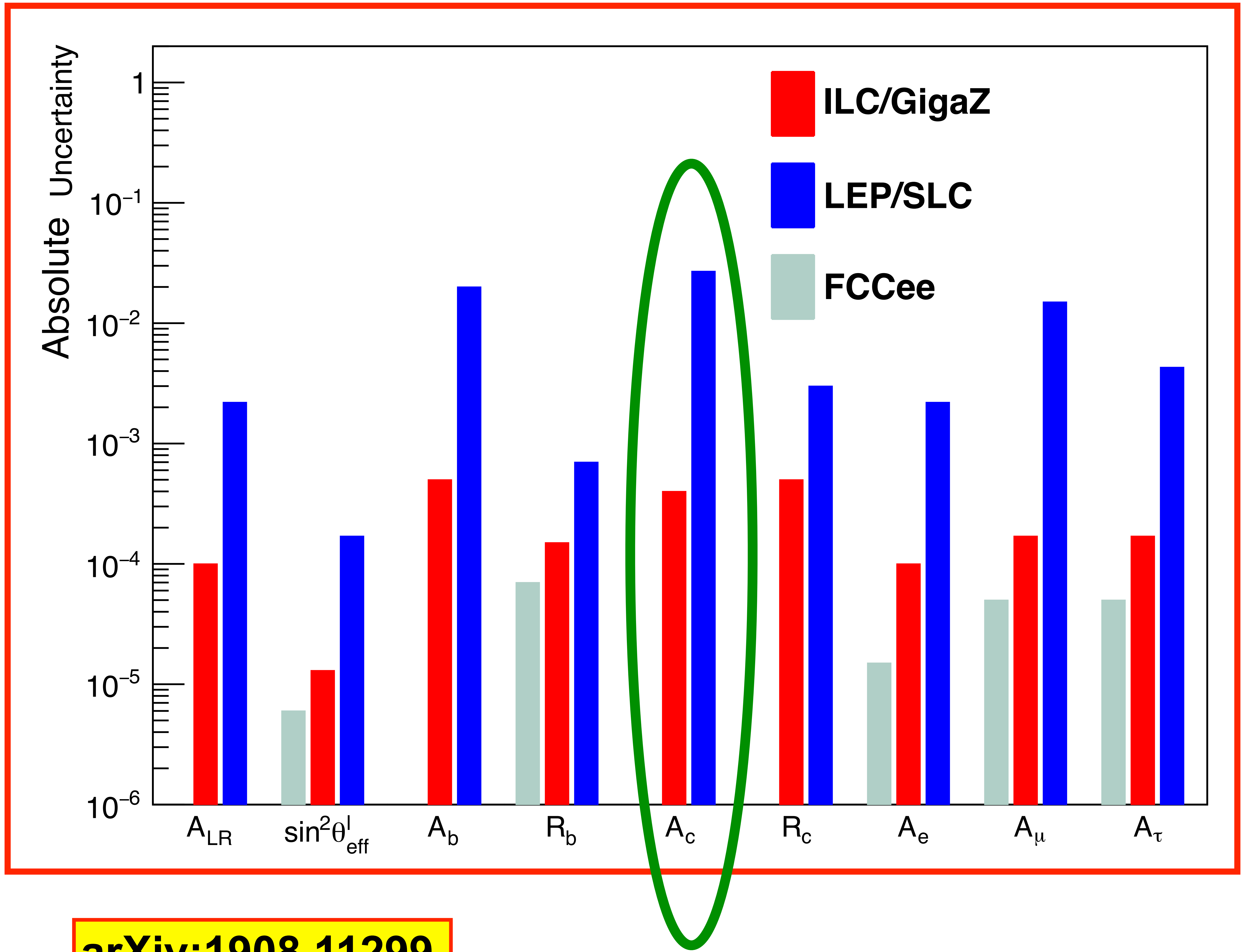

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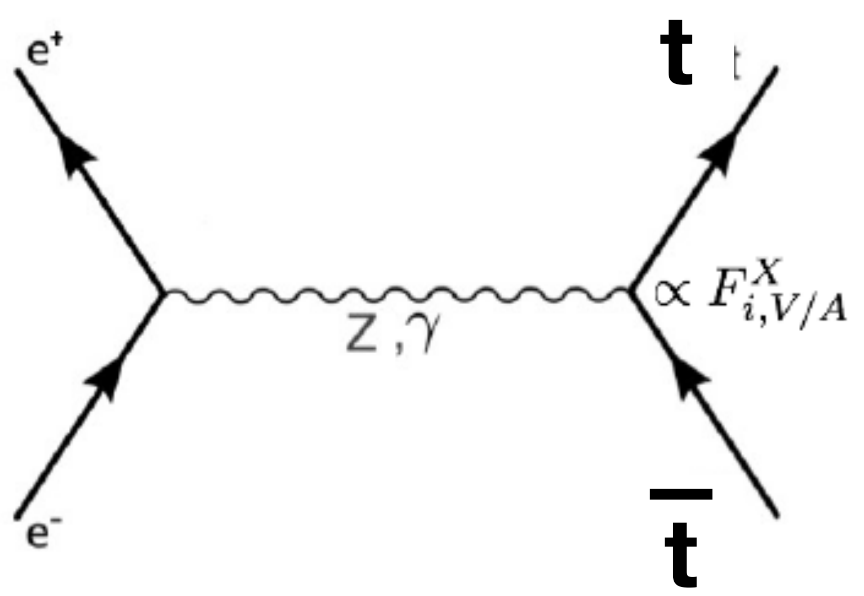
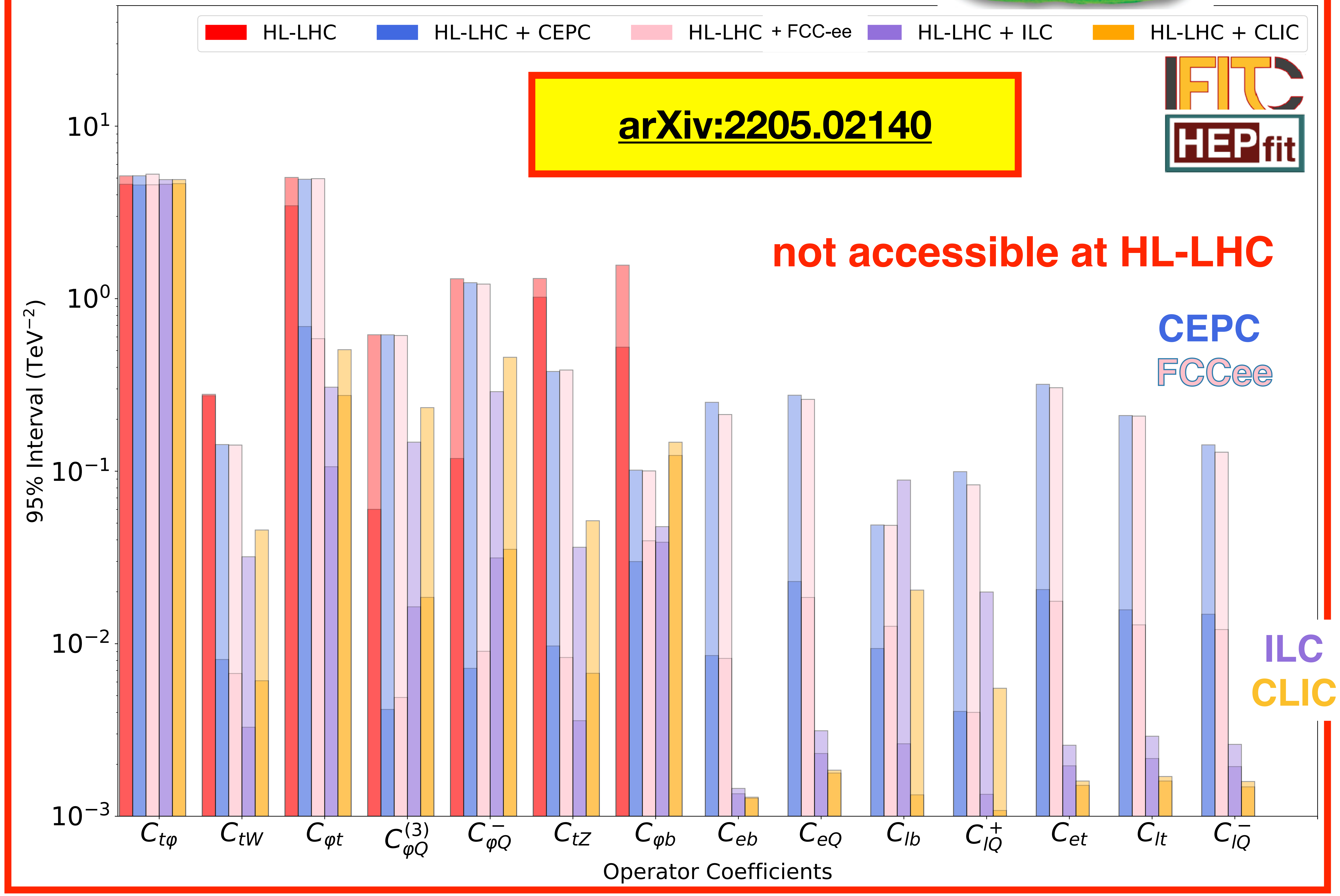
Full SMEFT analysis of Top Quark sector

Essential to understand special relation of top quark and Higgs boson



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



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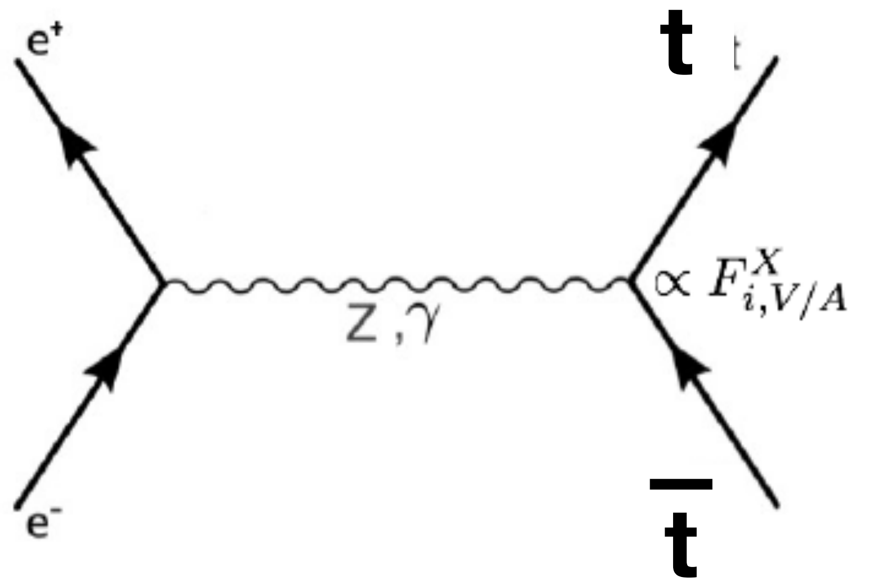

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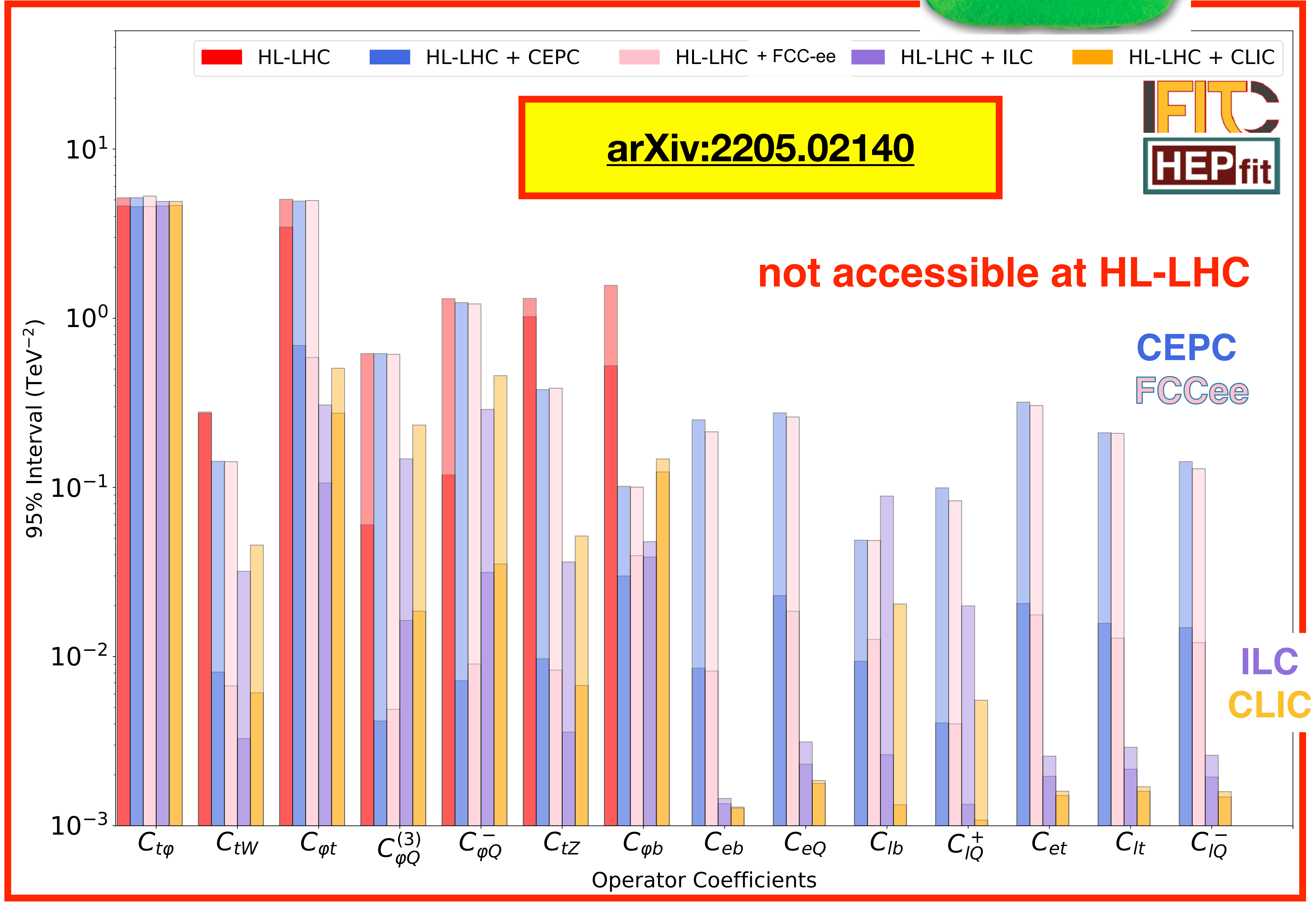
top-quark physics requires high center-of-mass energy AND polarised beams



BSM reach of ee → cc / bb

arXiv:2403.09144

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

Study of ee → cc / bb

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

BSM example: Gauge-Higgs Unification models

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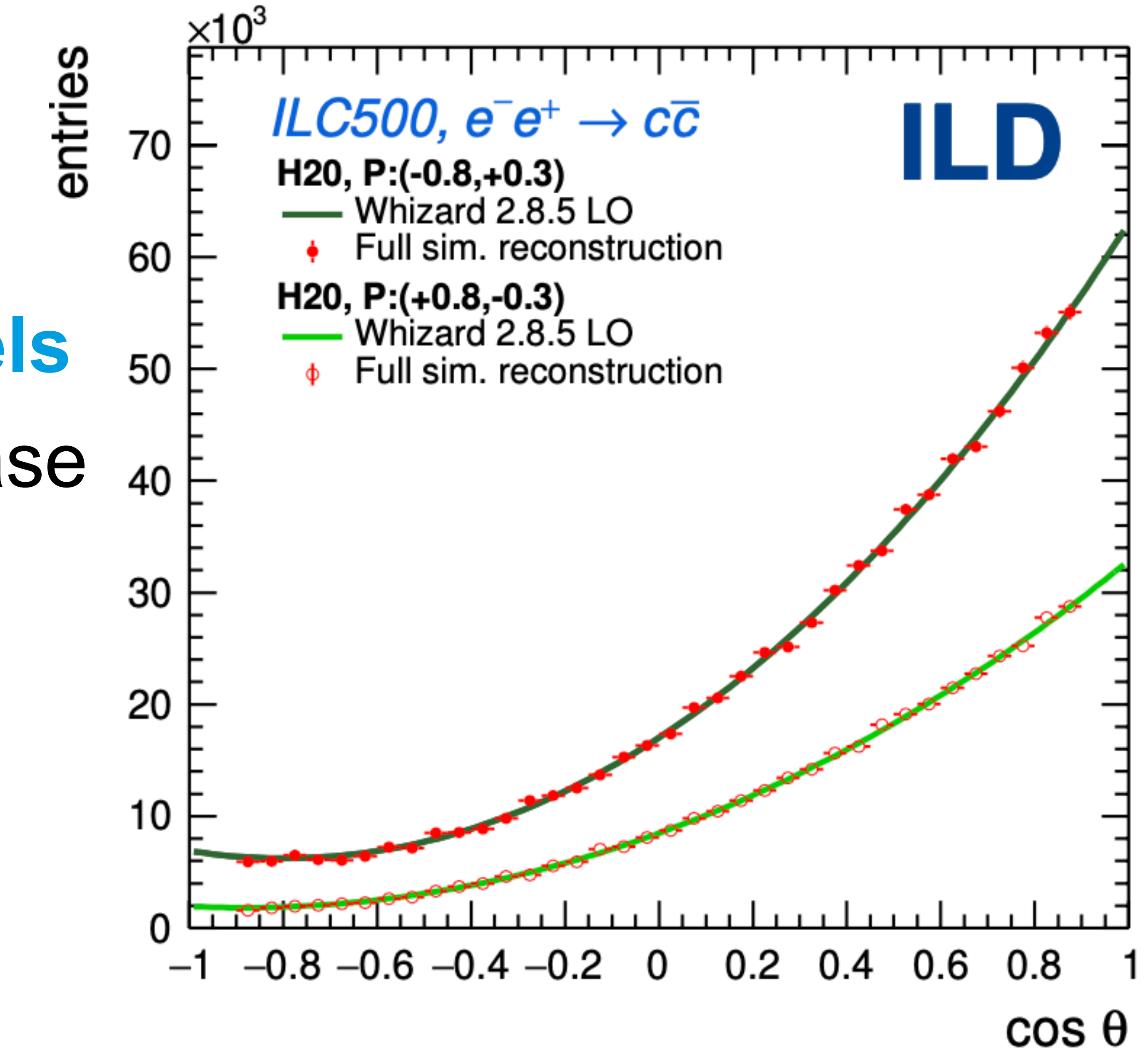

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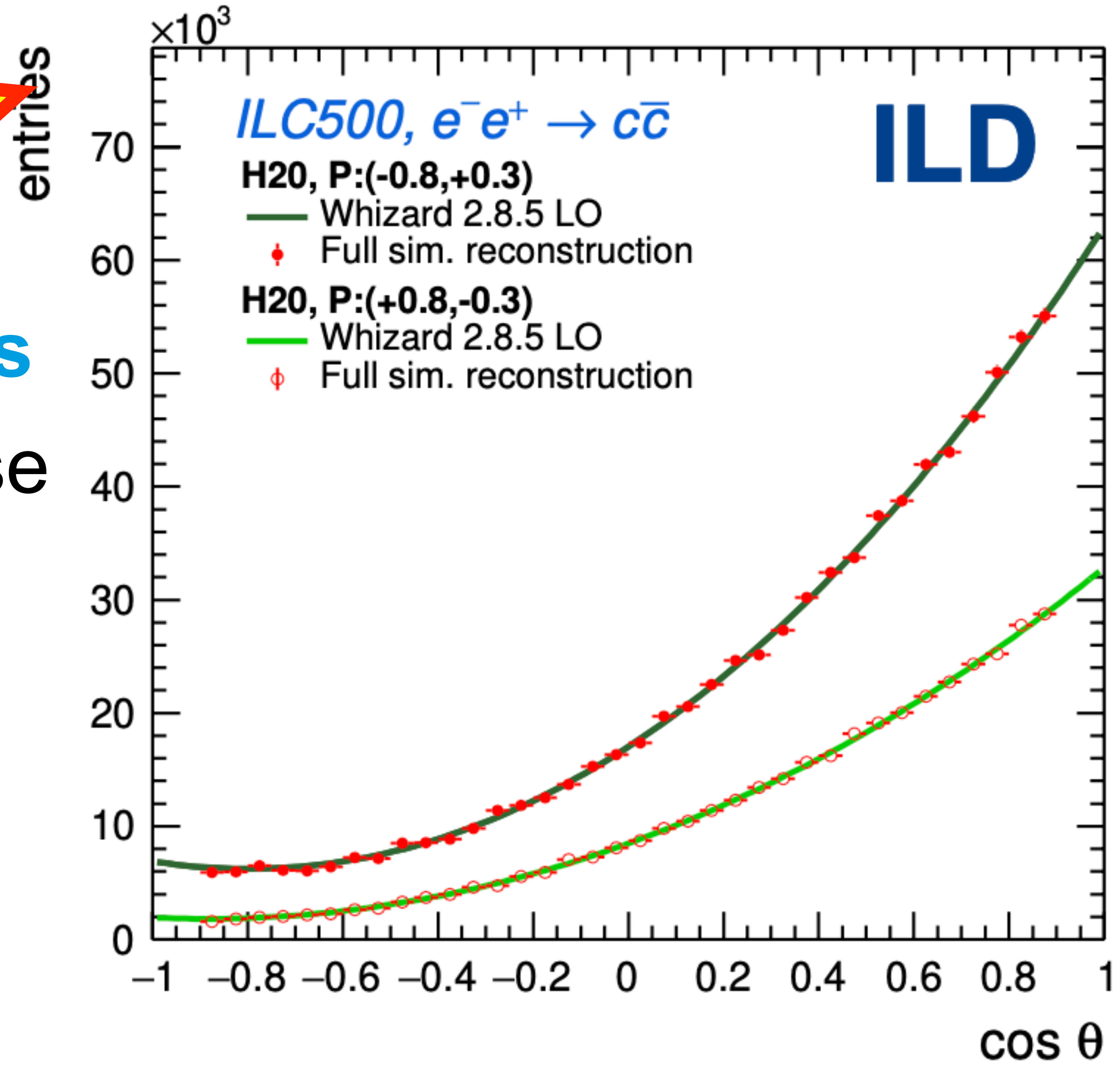

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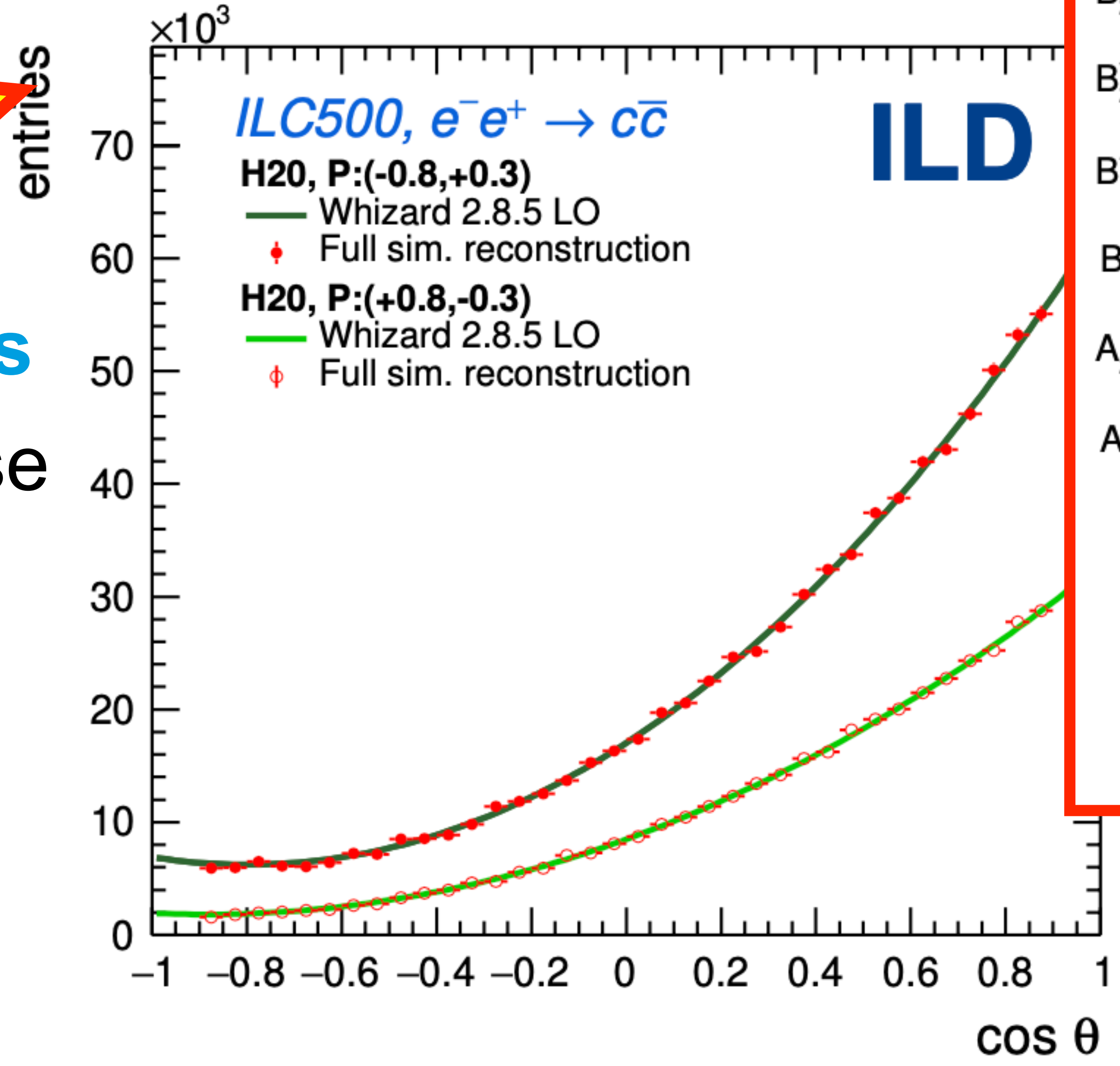

ILD — GHU vs SM discrimination power (σ-level)

	ILC250♦ (no pol.) O	E	N	ILC250 O	E	N	ILC250 +500 O	E	N	ILC250 +500 +1000* O	E	N
B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10

Ch. had. PID
- O: No PID
- E: $\frac{dE}{dx}$
- N: $\frac{dN}{dx}$

Legend: < 3 σ; 3-4 σ; 4-5 σ; > 5 σ

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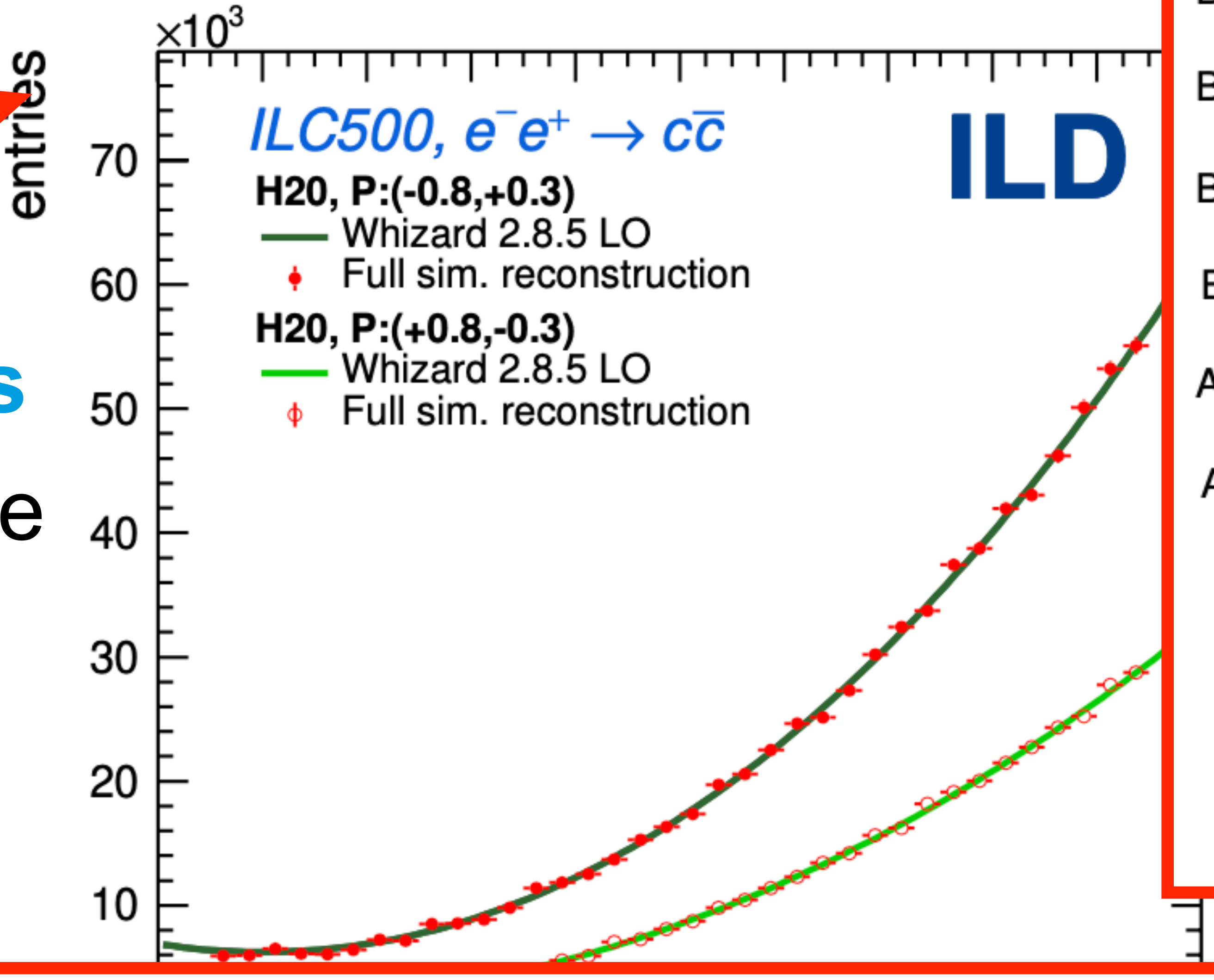

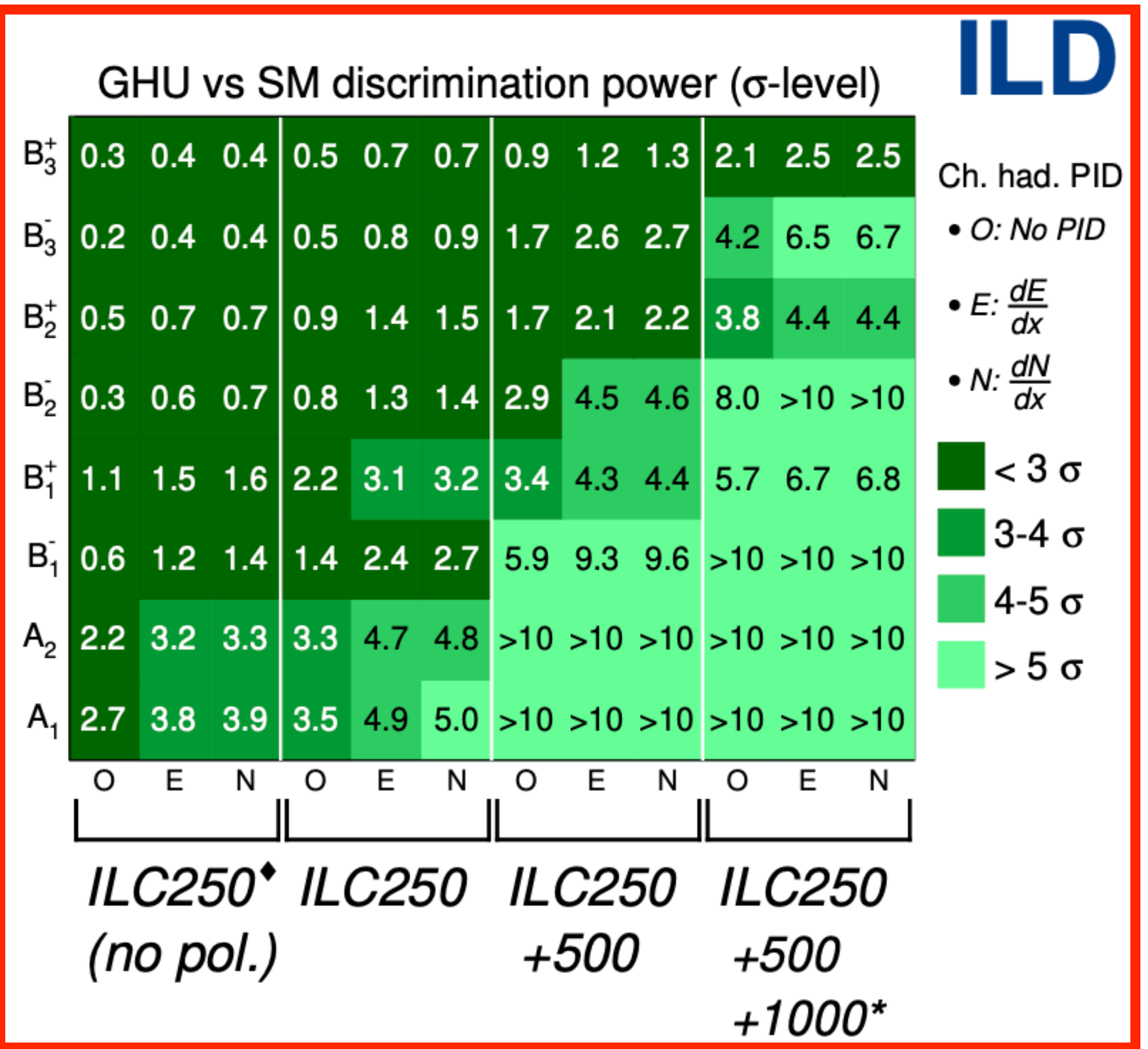

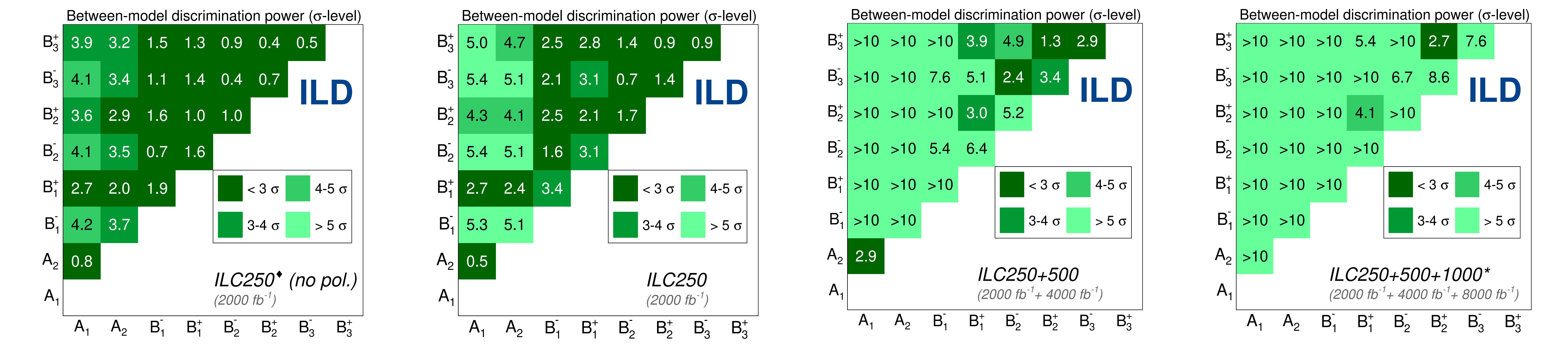

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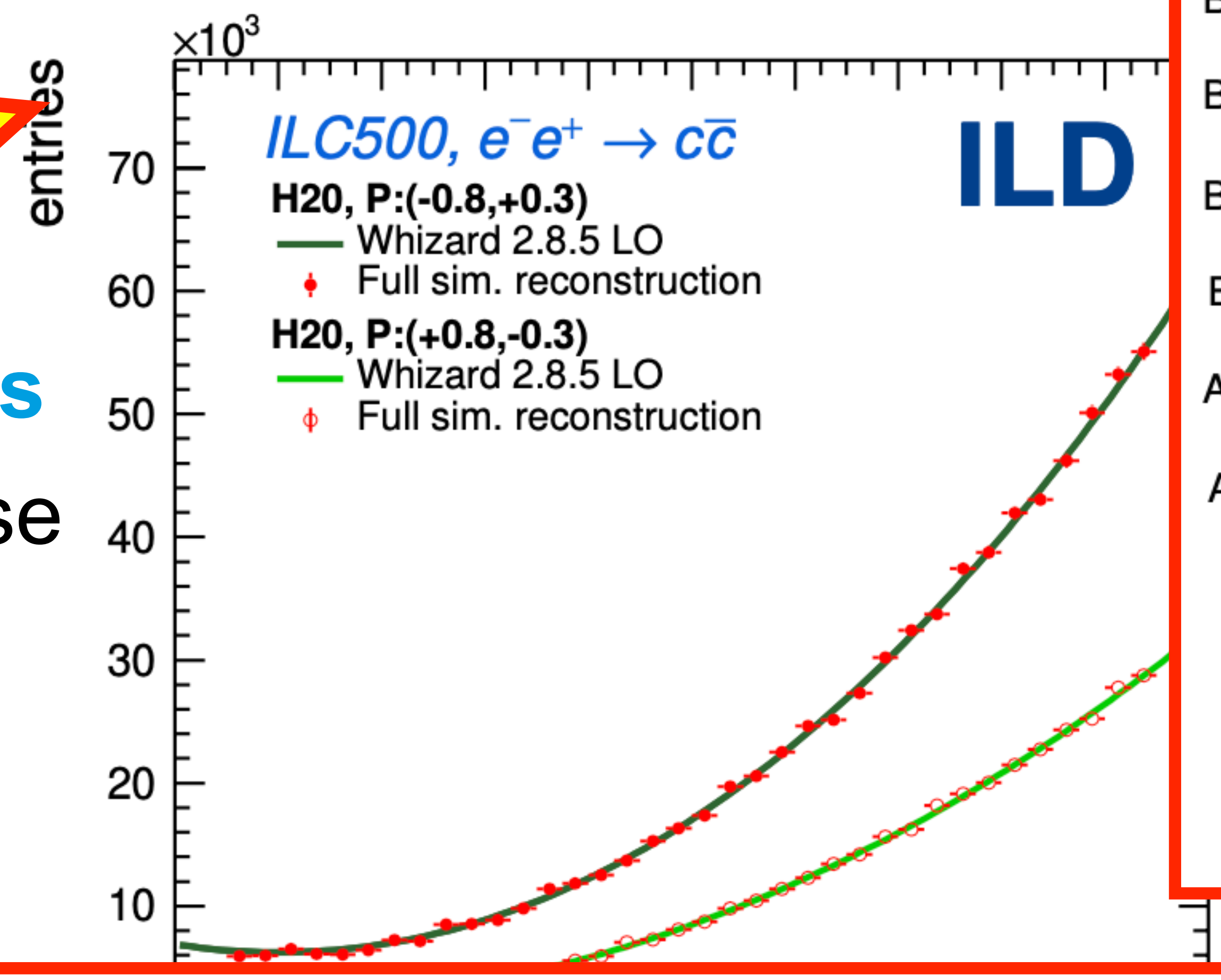

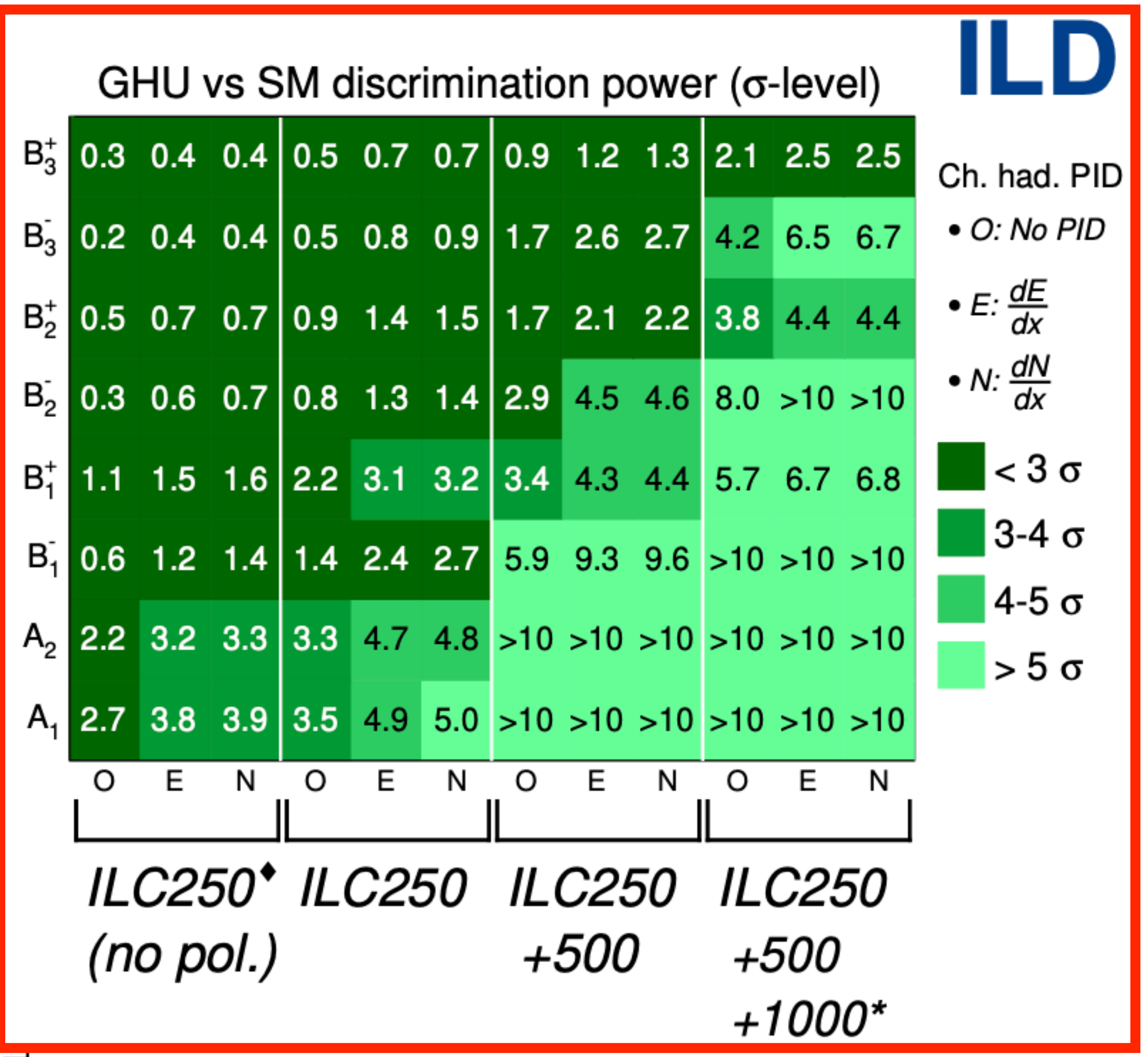

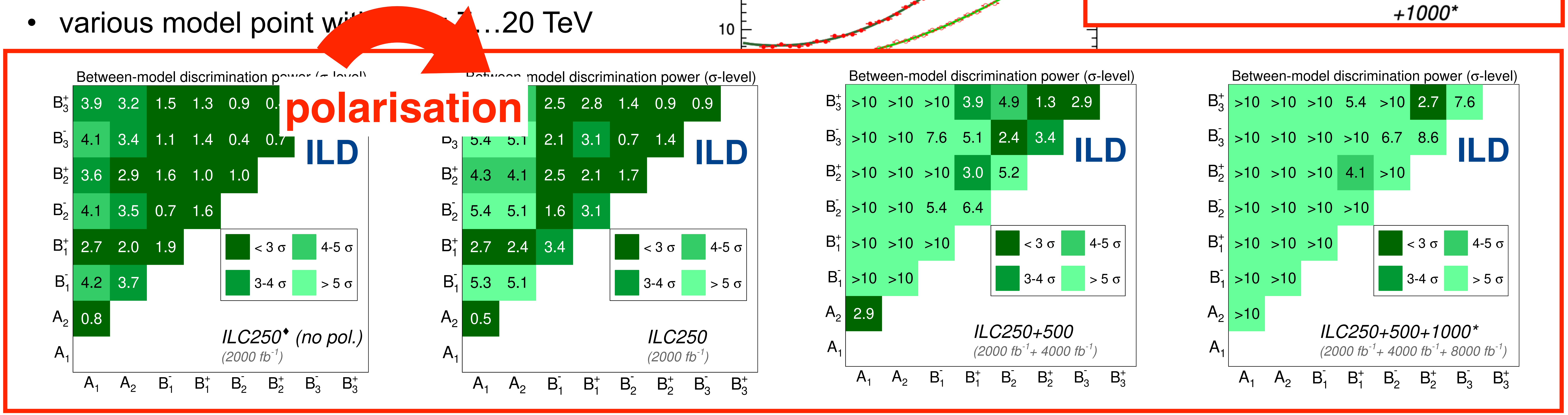

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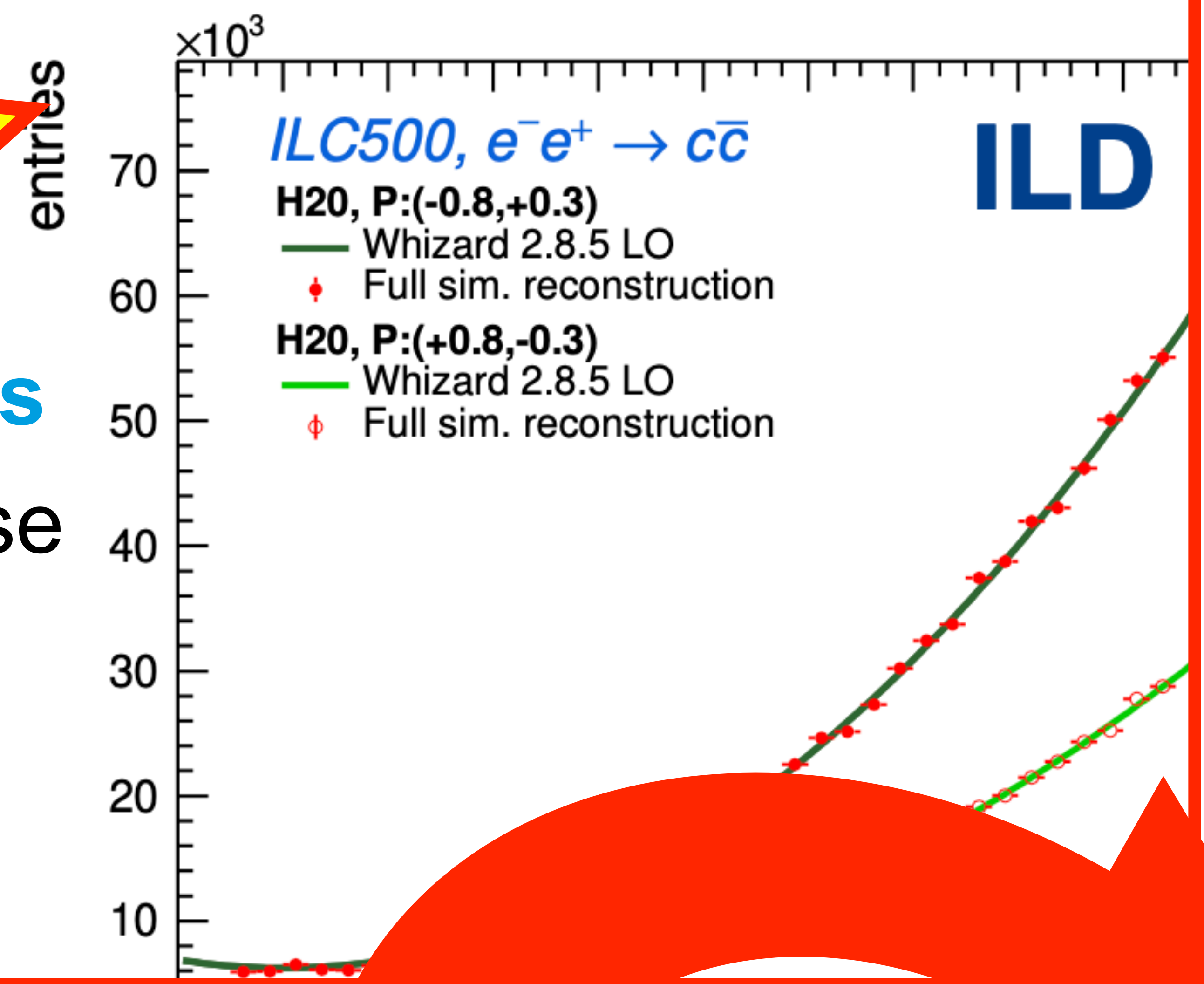
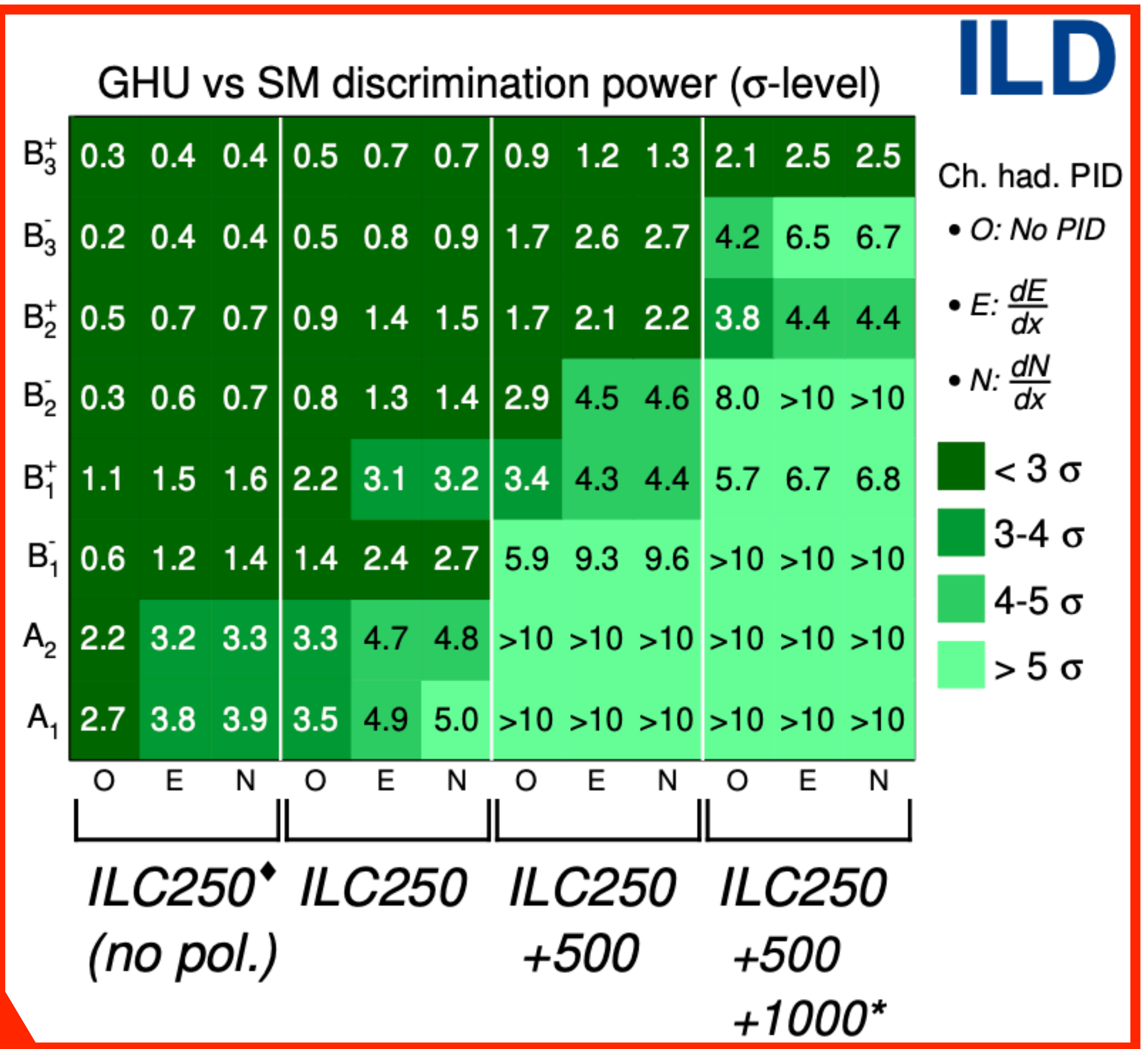
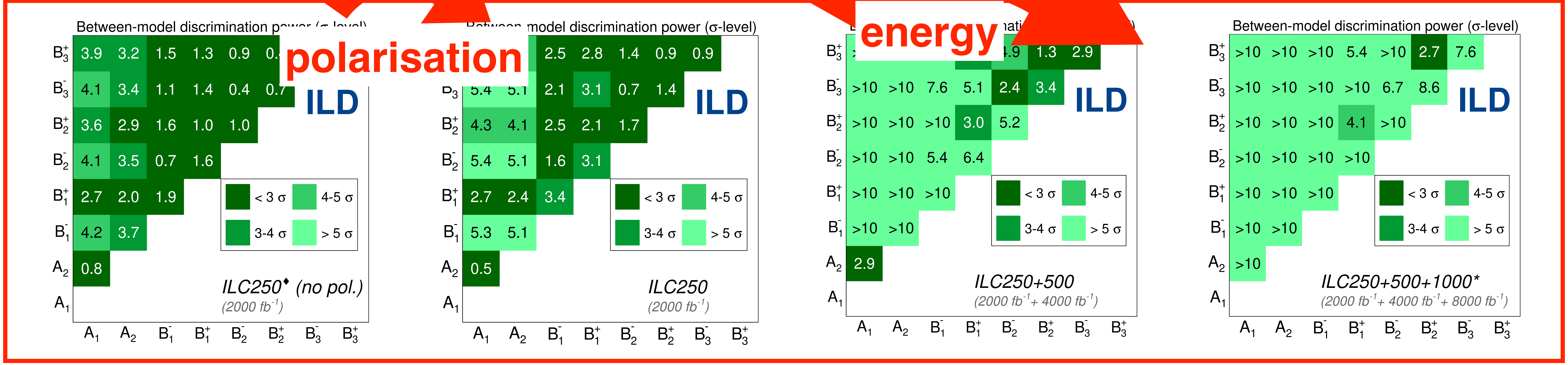




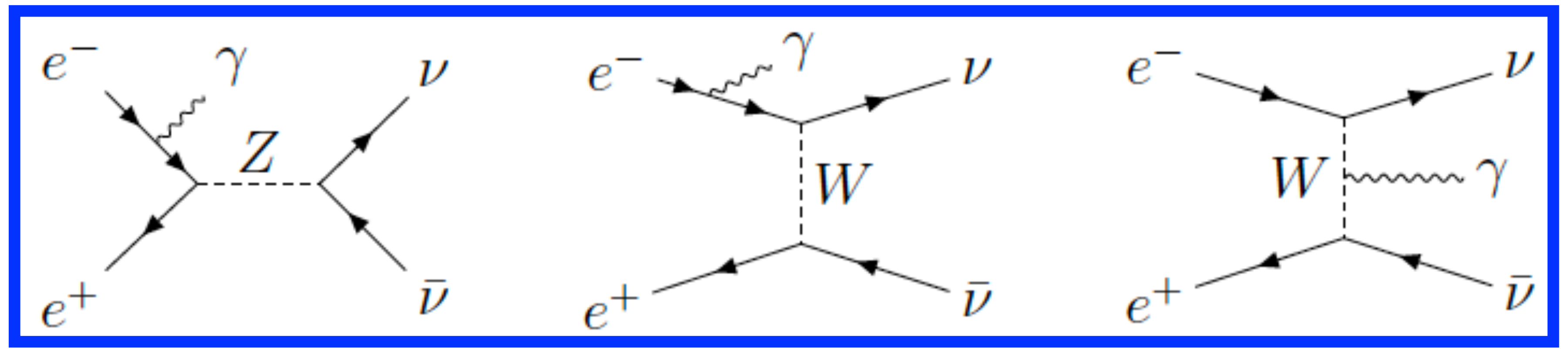


Phys. Rev. D 101 (2020) 7

Polarisation & Beyond the SM: Dark Matter

Background reduction & Systematics

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



reduced ~10x with polarisation

- shape of observable distributions changes with polarisation sign
  => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–)
  beats down the effect of systematic uncertainties

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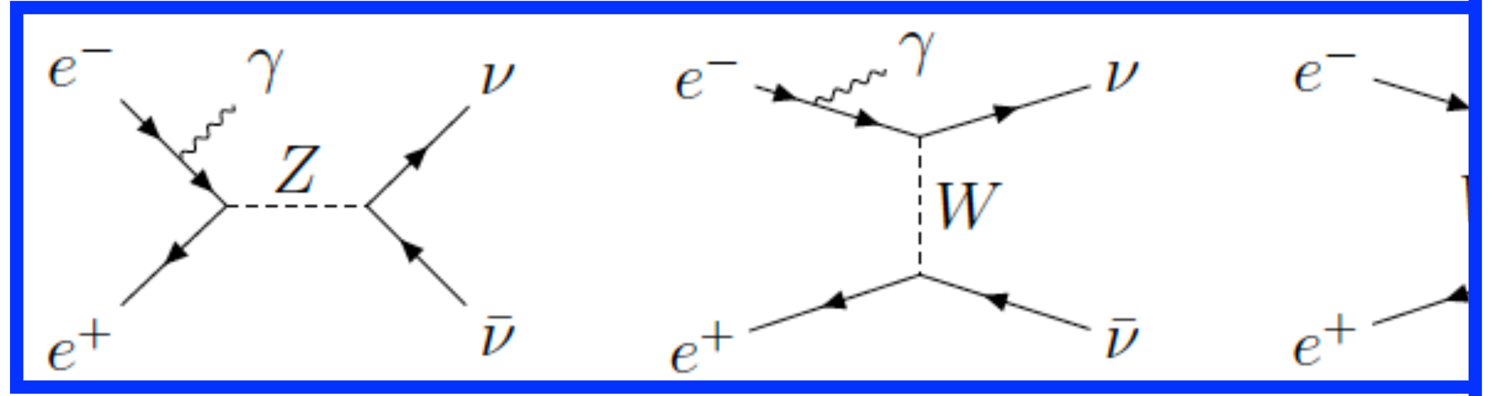

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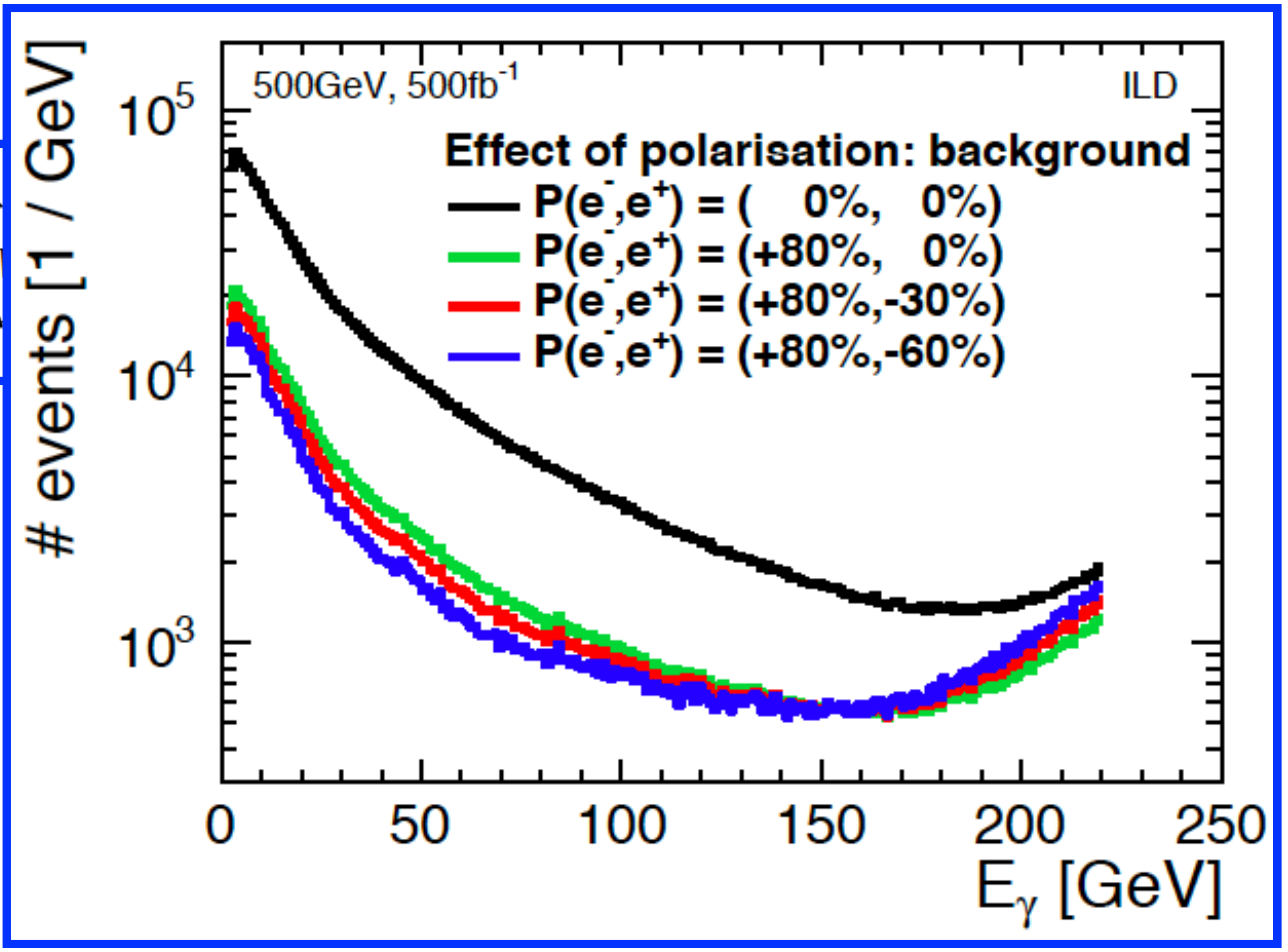

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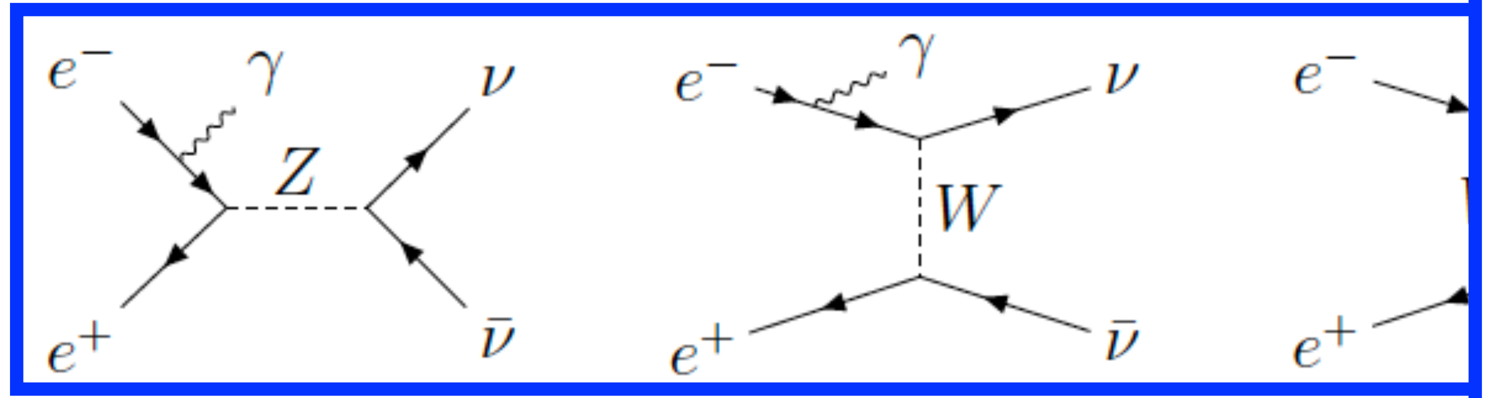

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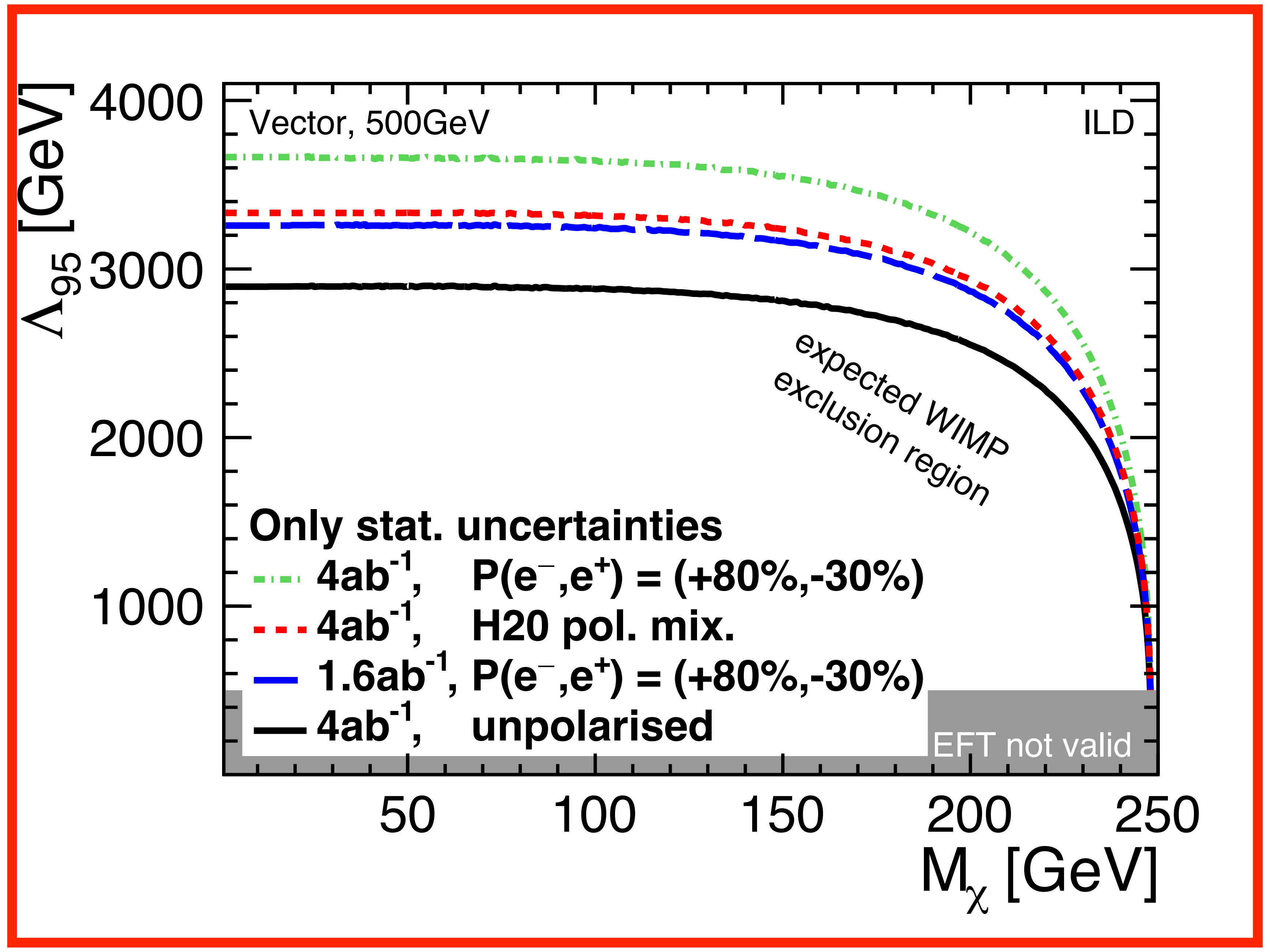

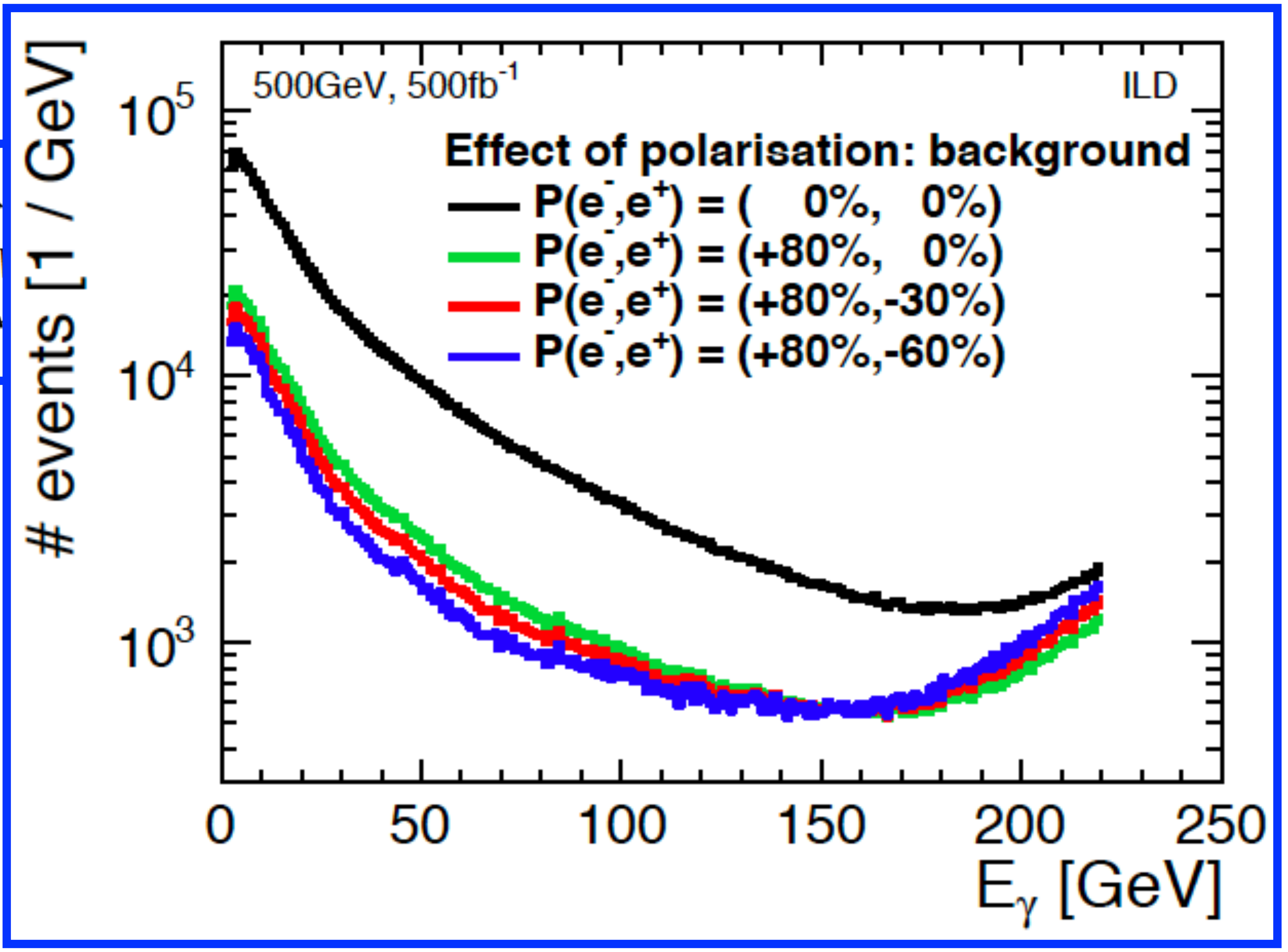

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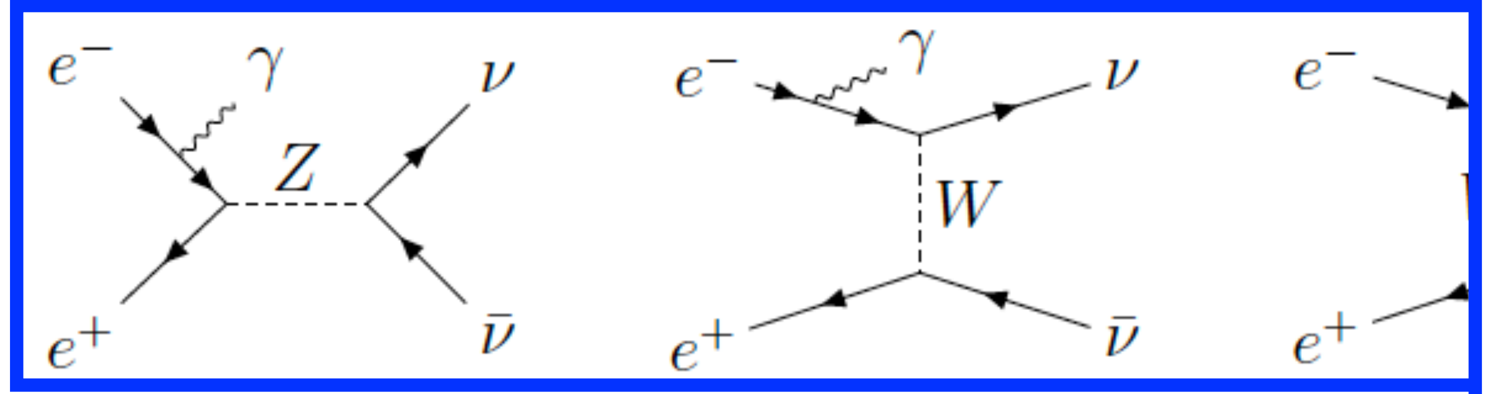

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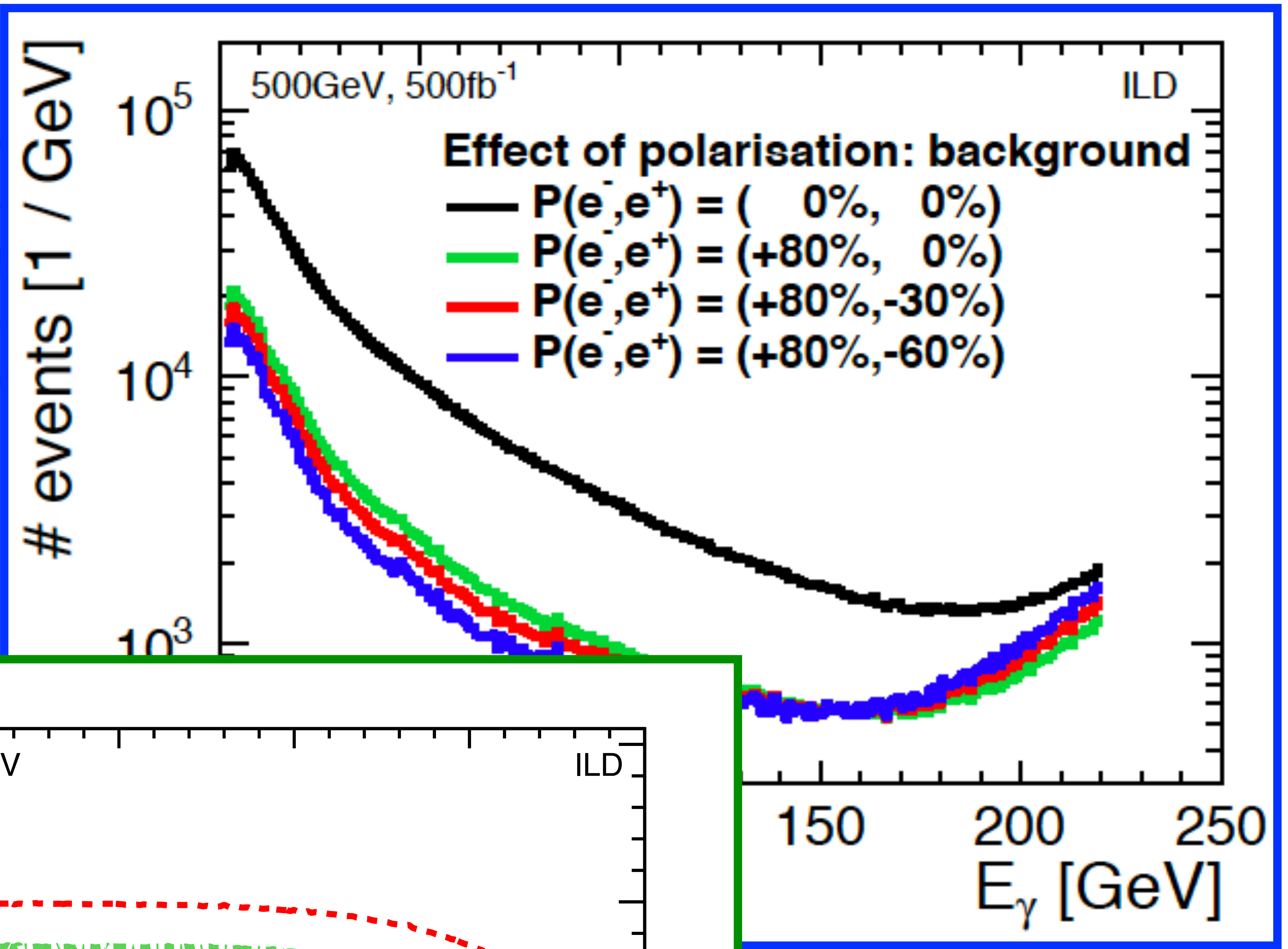

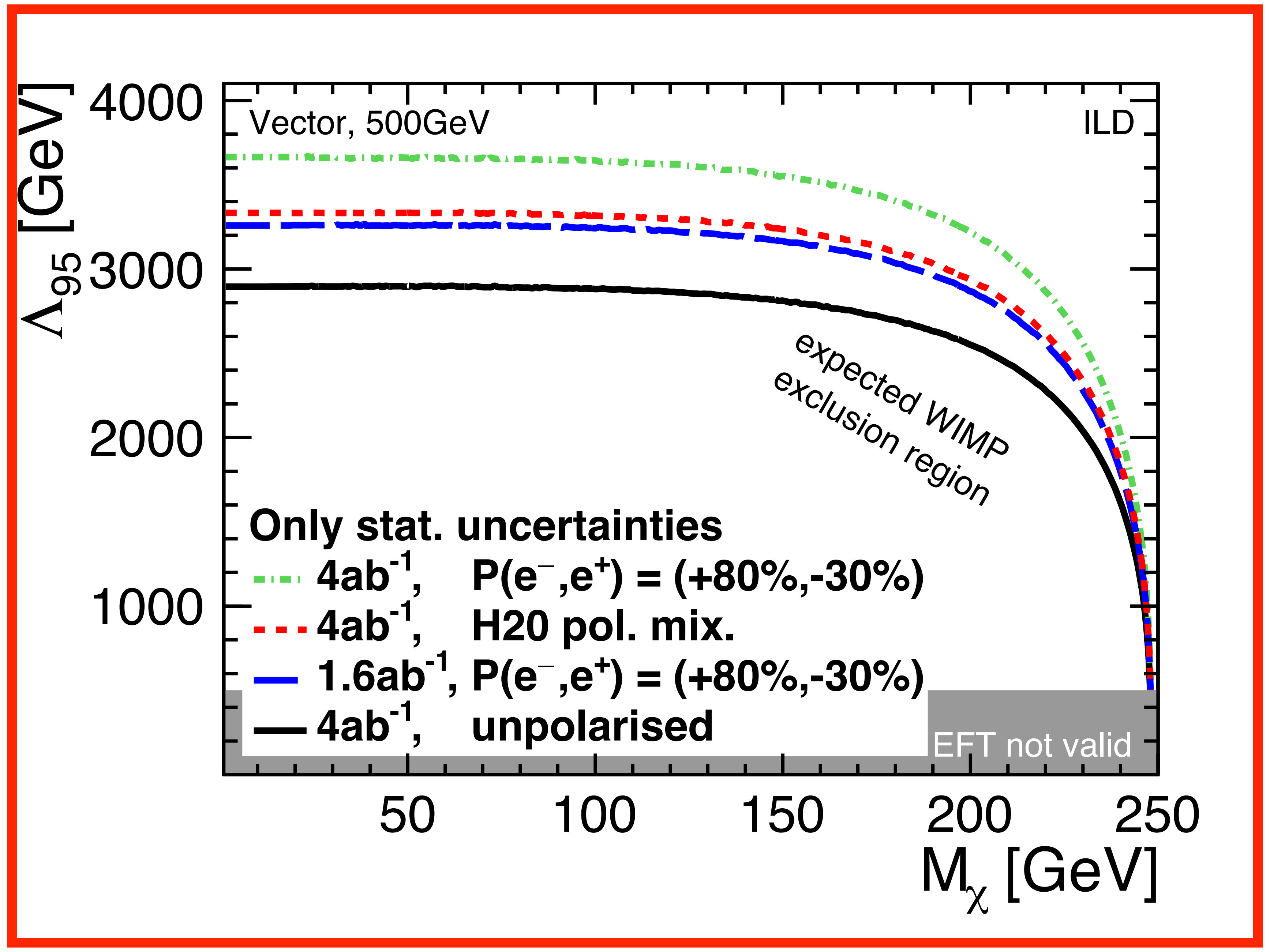

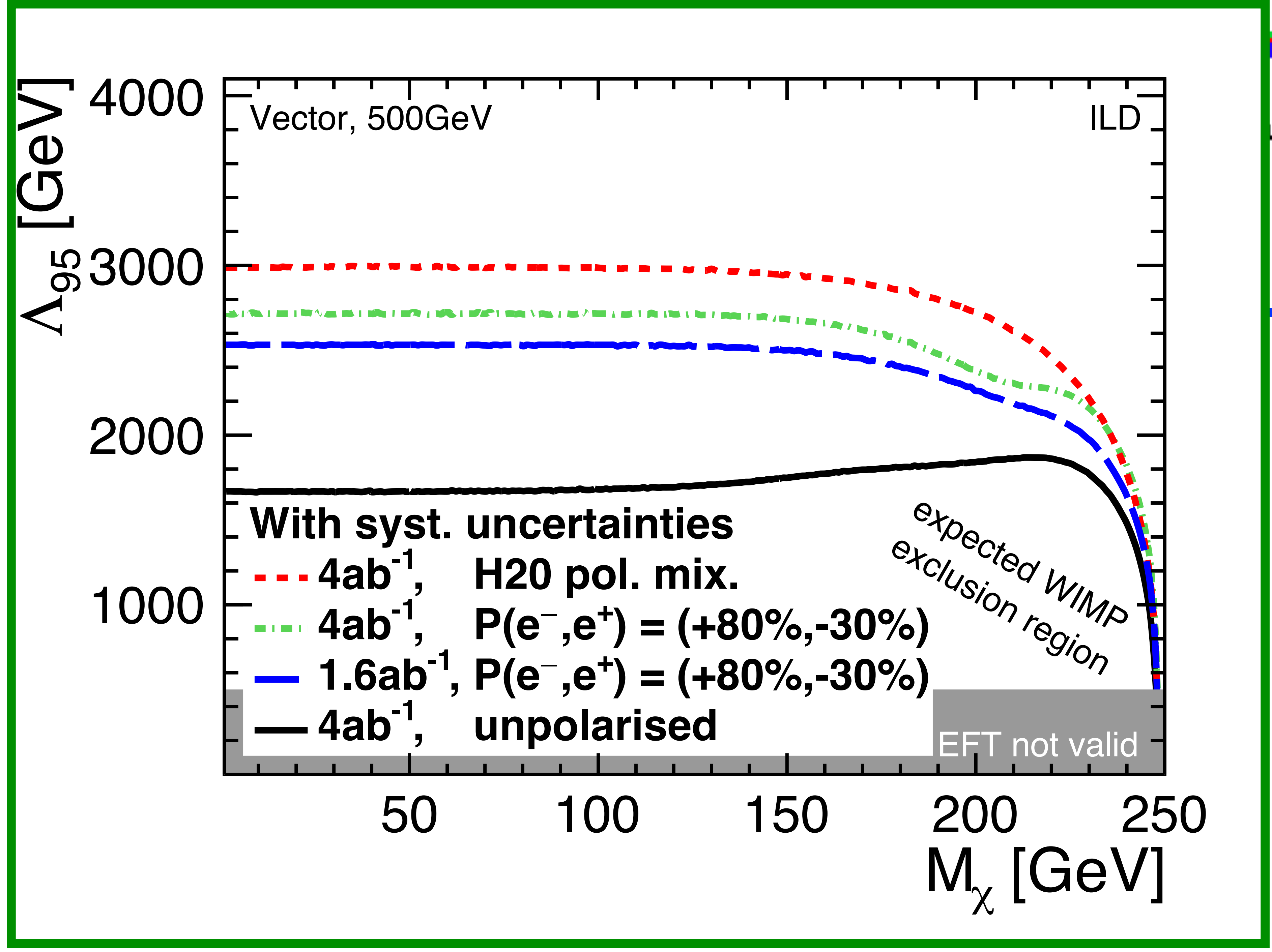

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Exmaple: Impact on reach in vector mediator case

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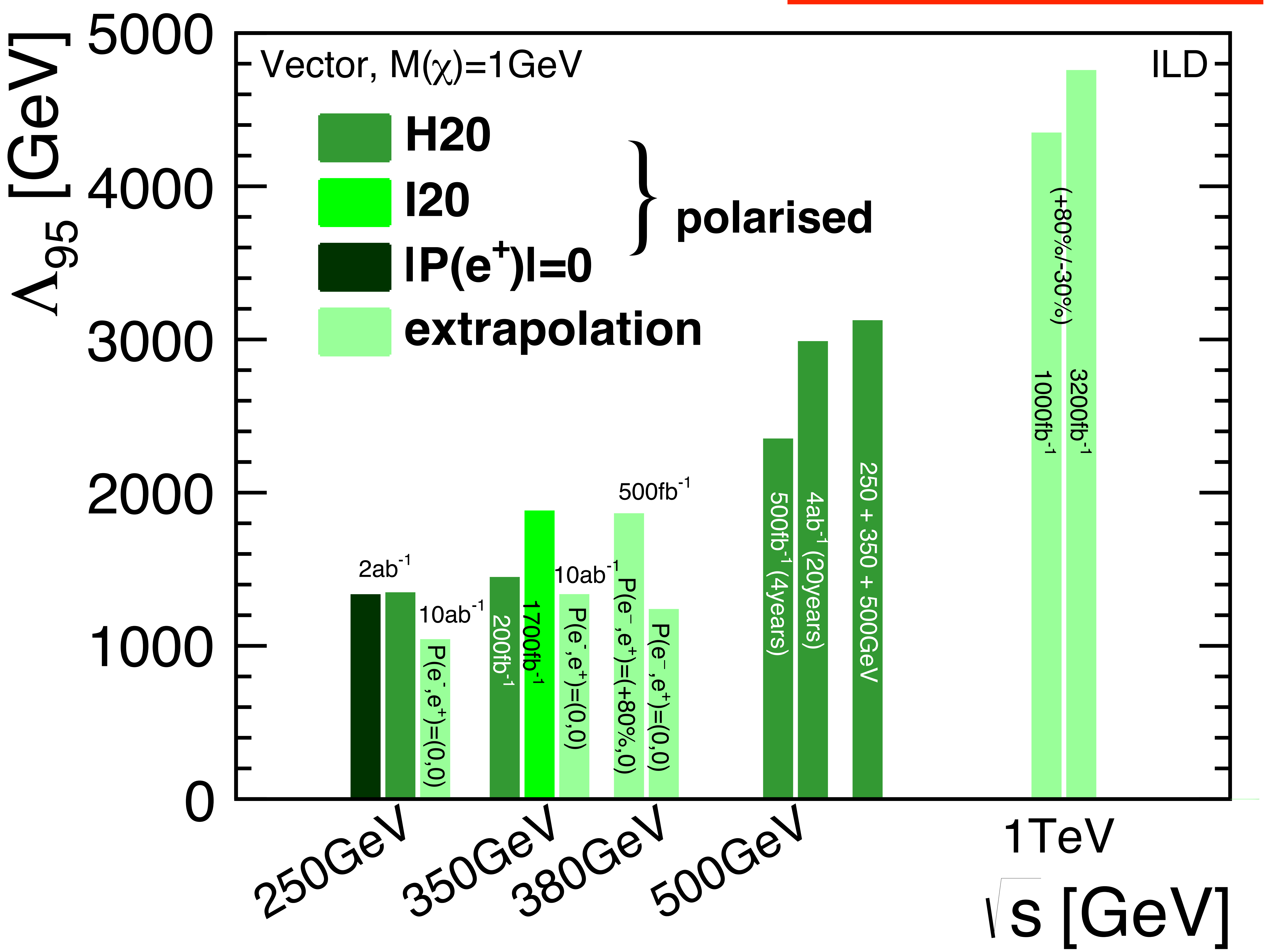

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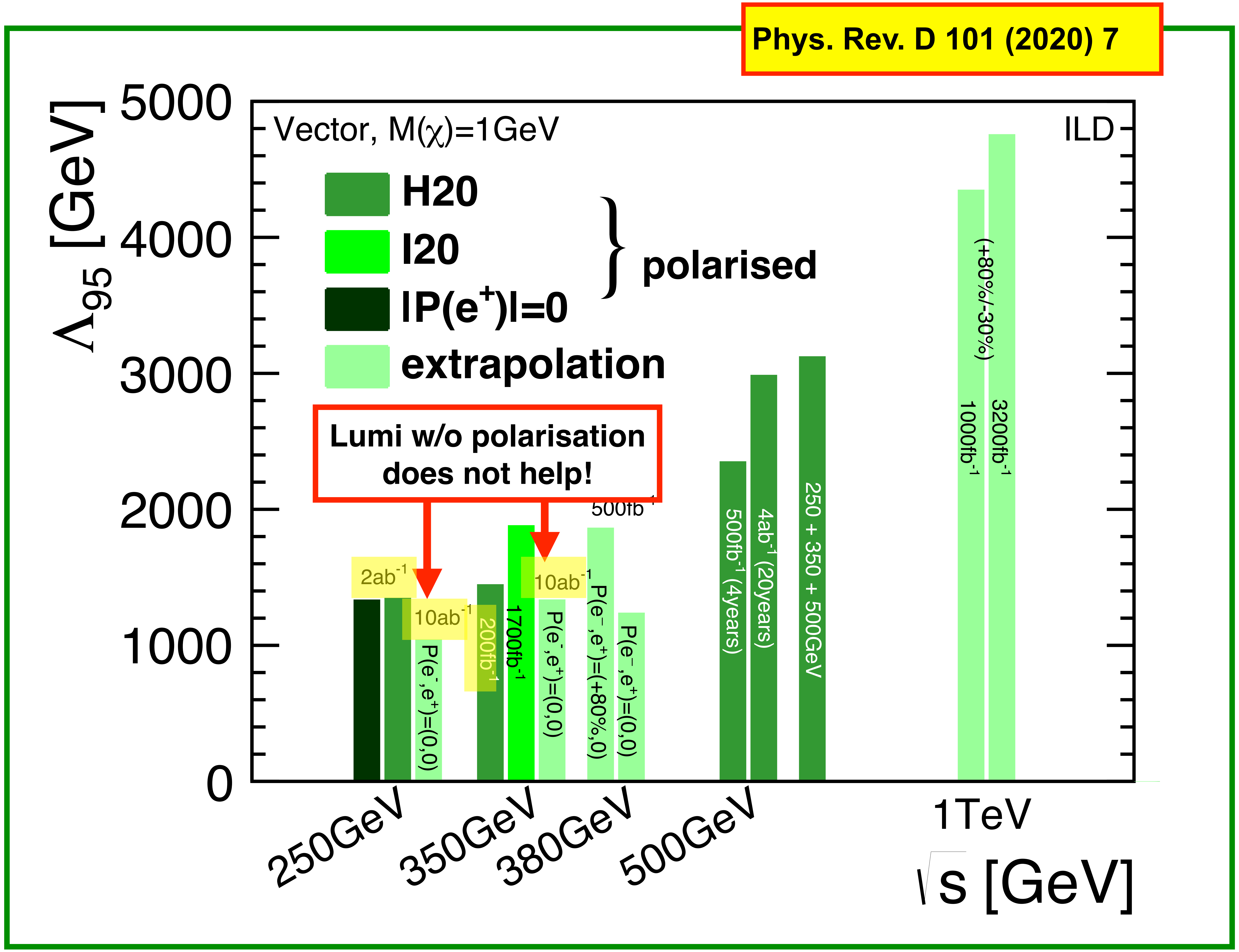

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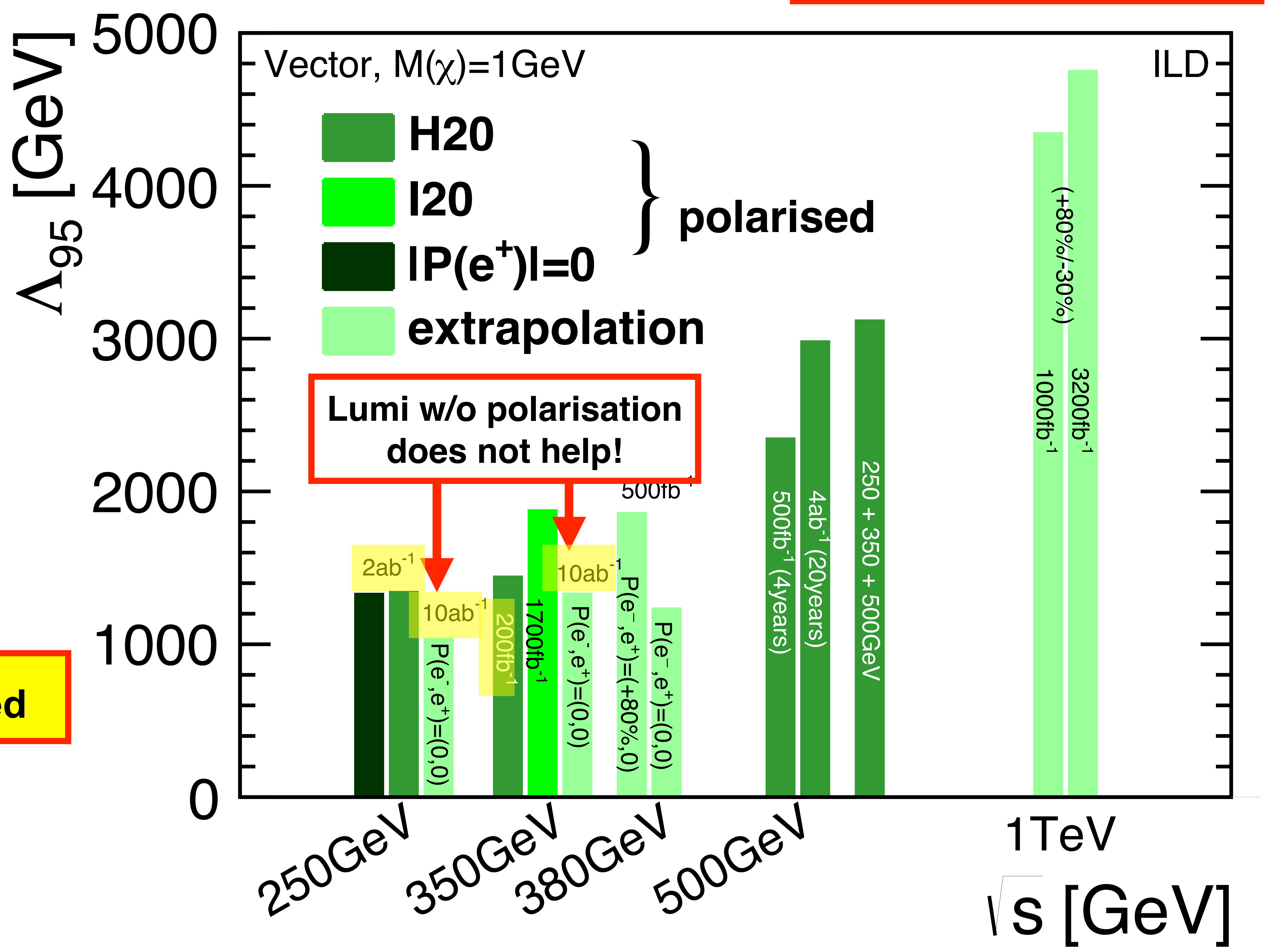

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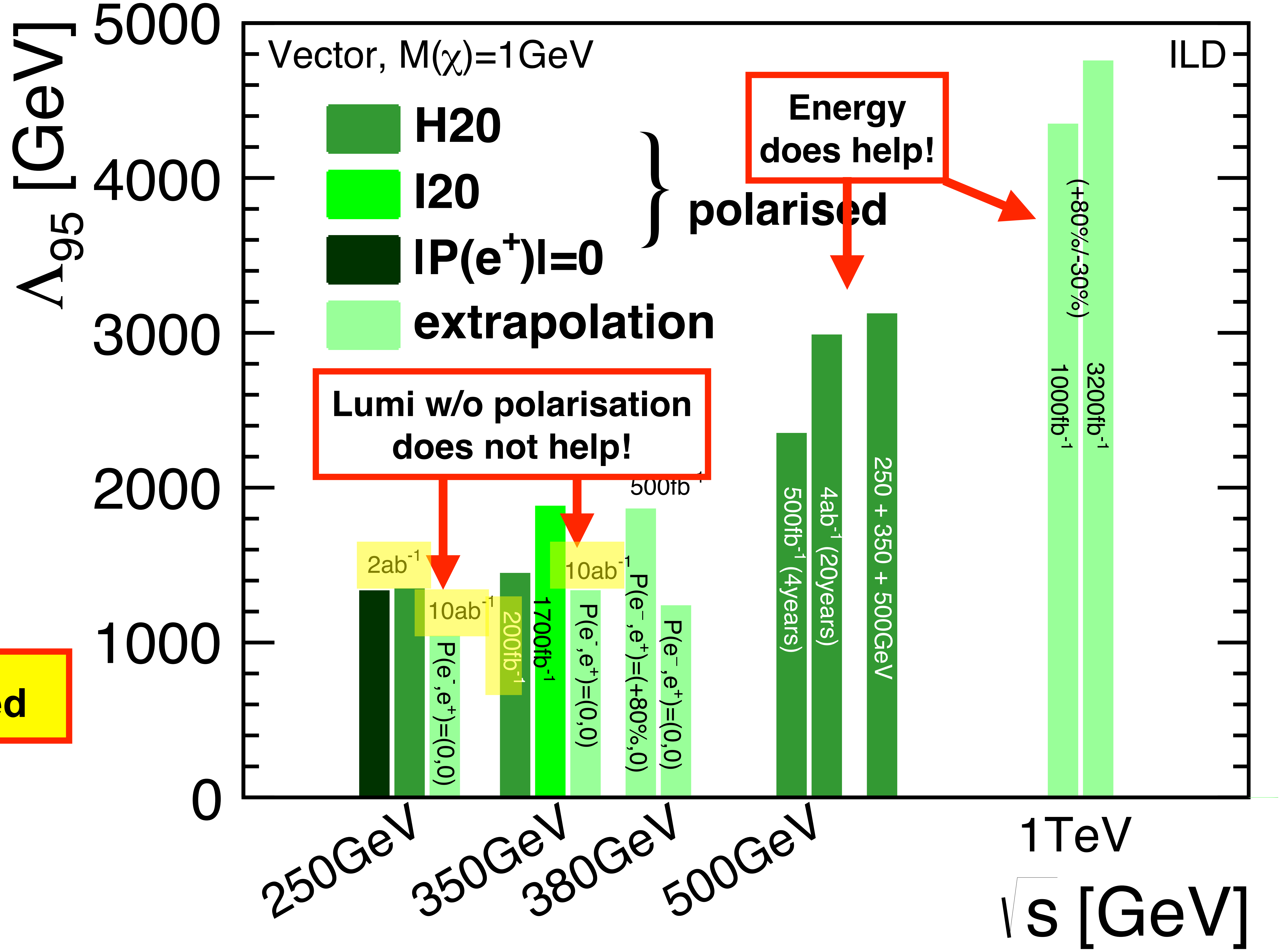

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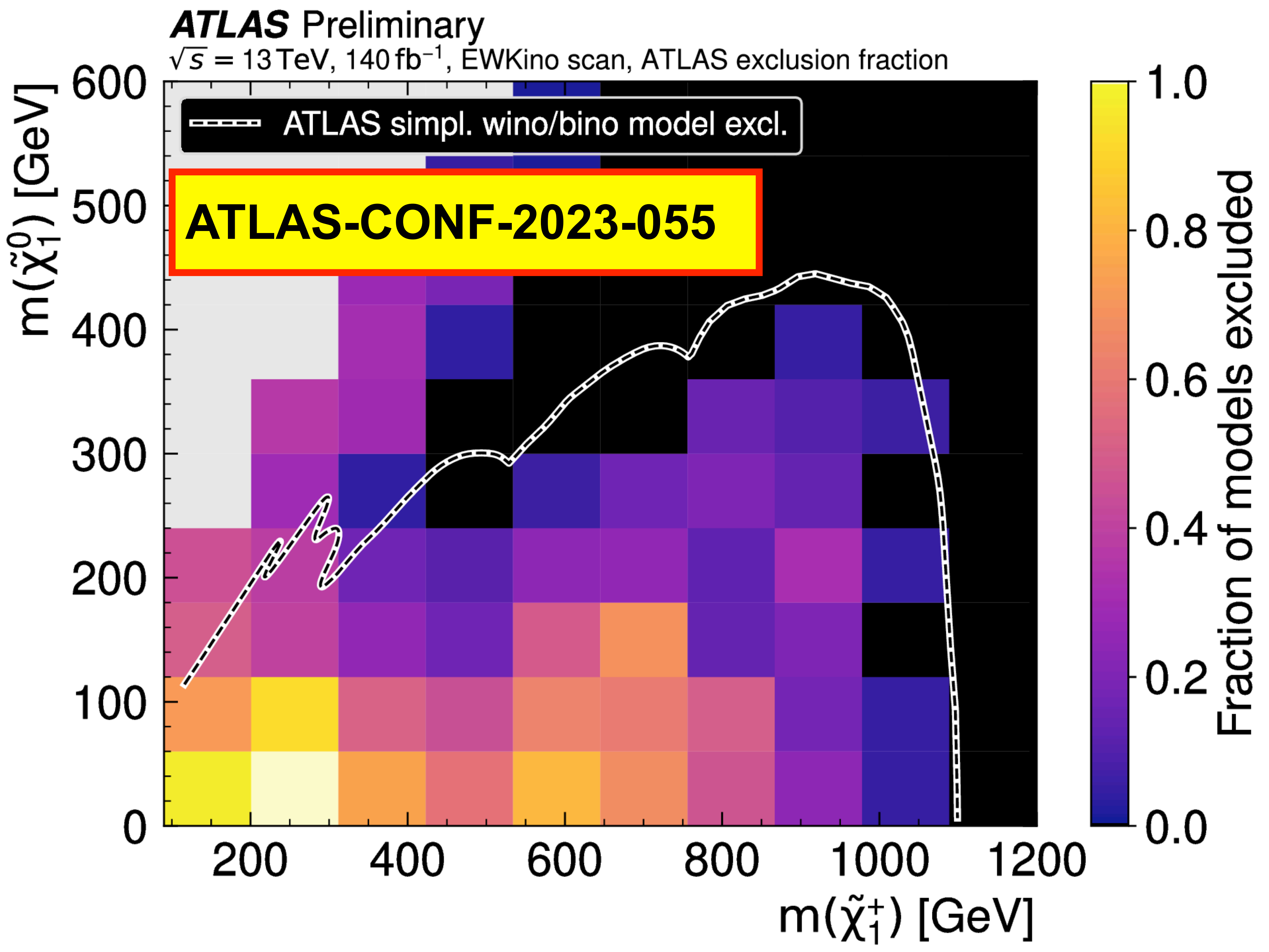
Light Higgsinos

Or: beware what LHC limits really mean!

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



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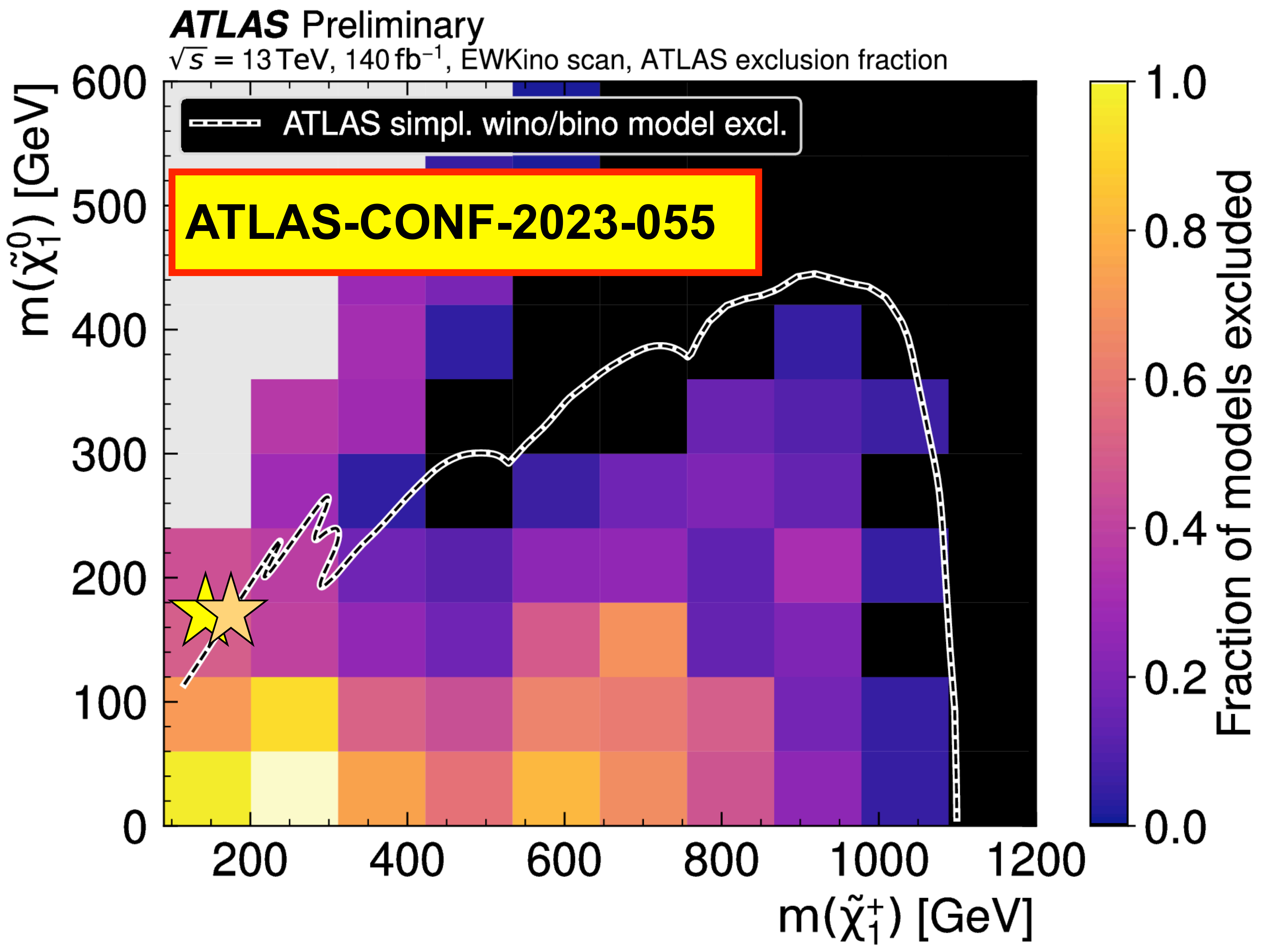

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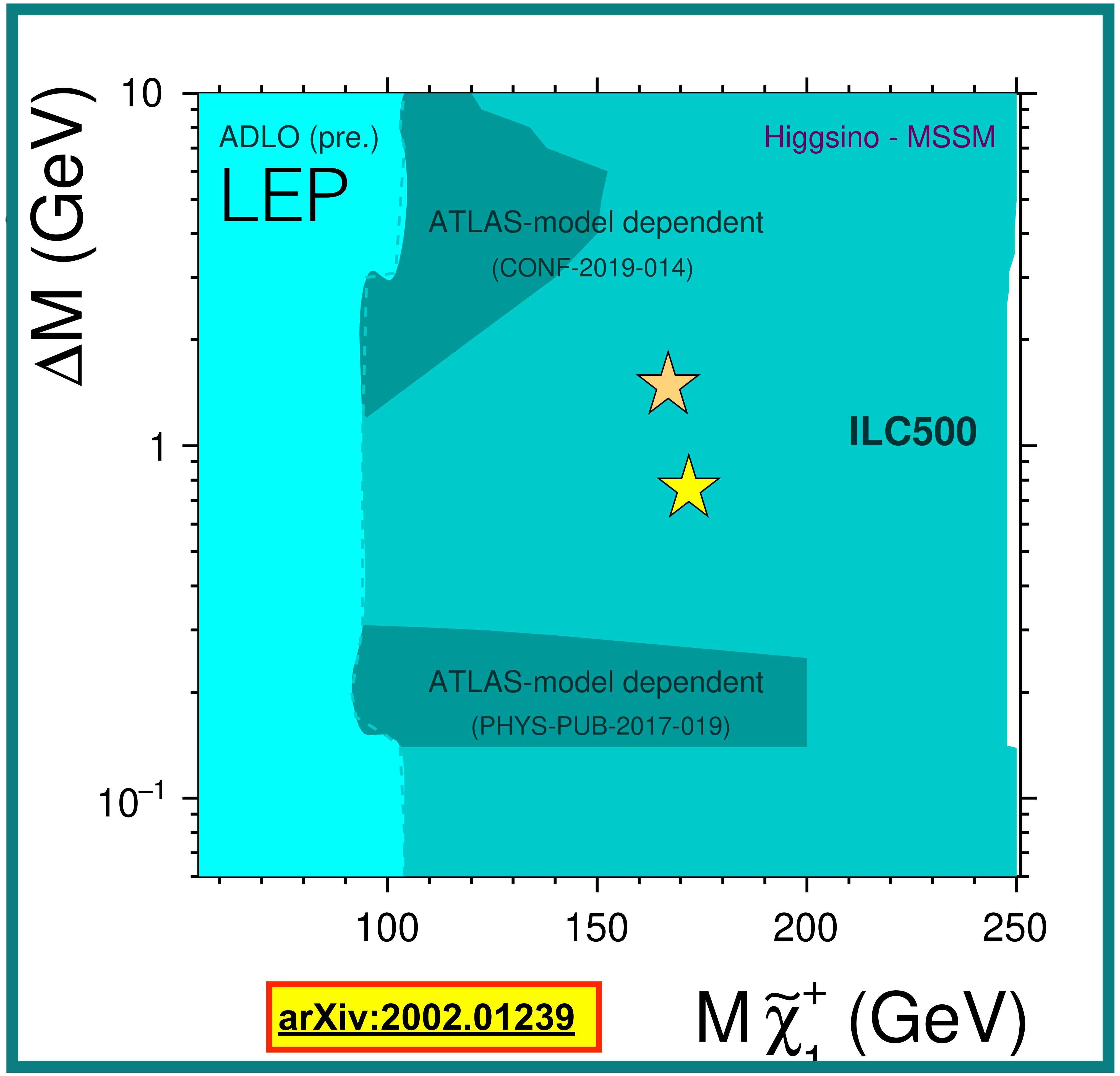

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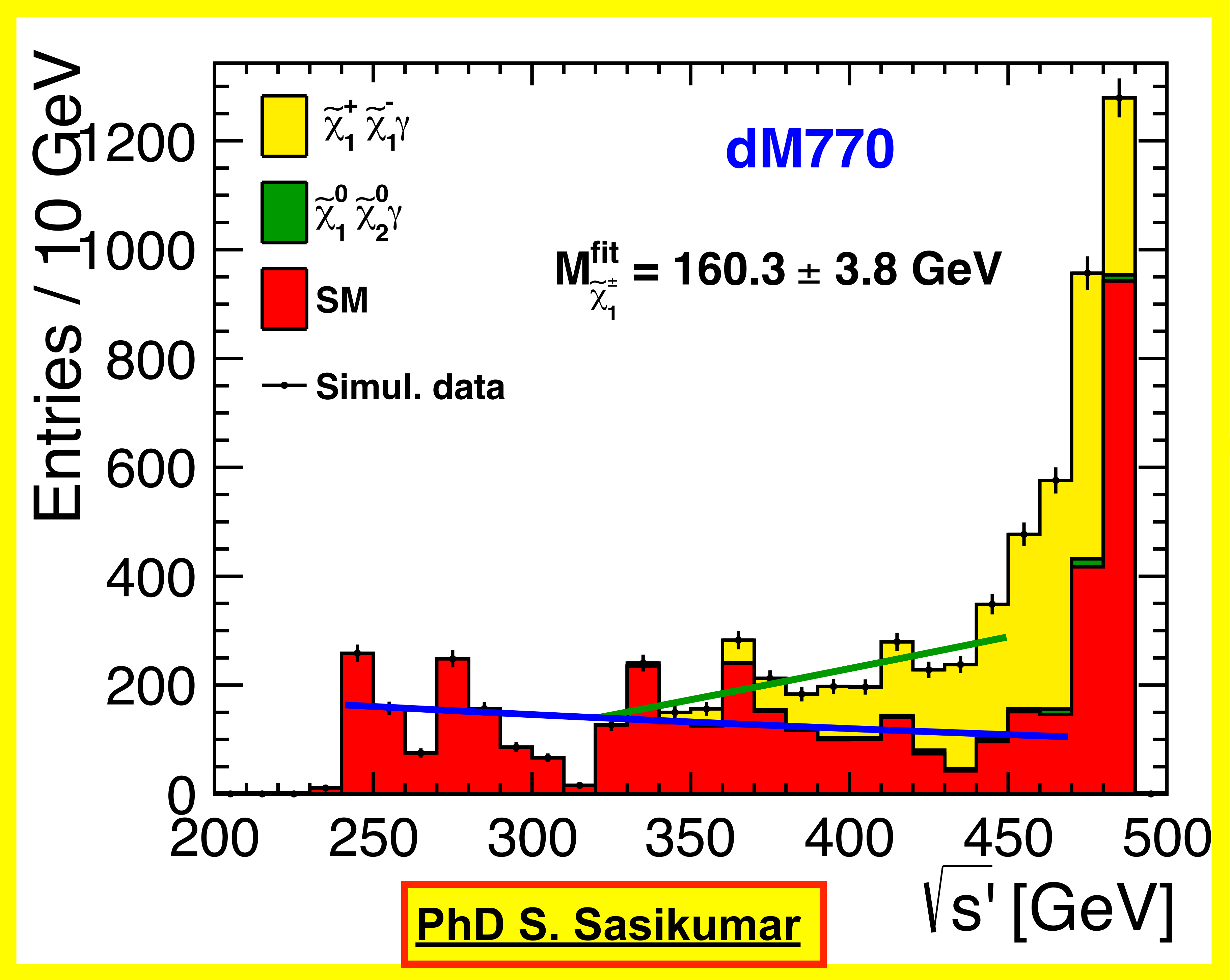

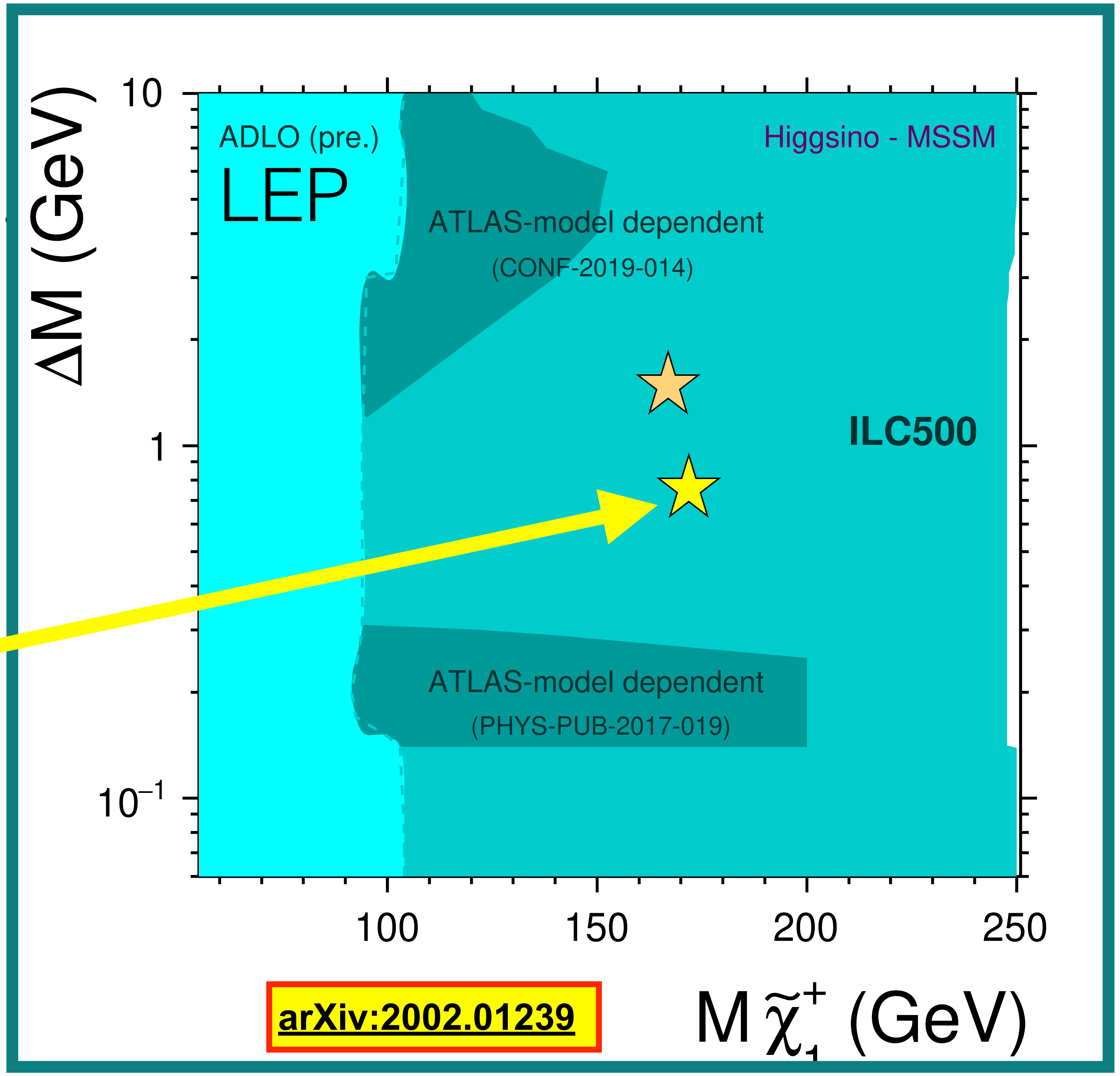

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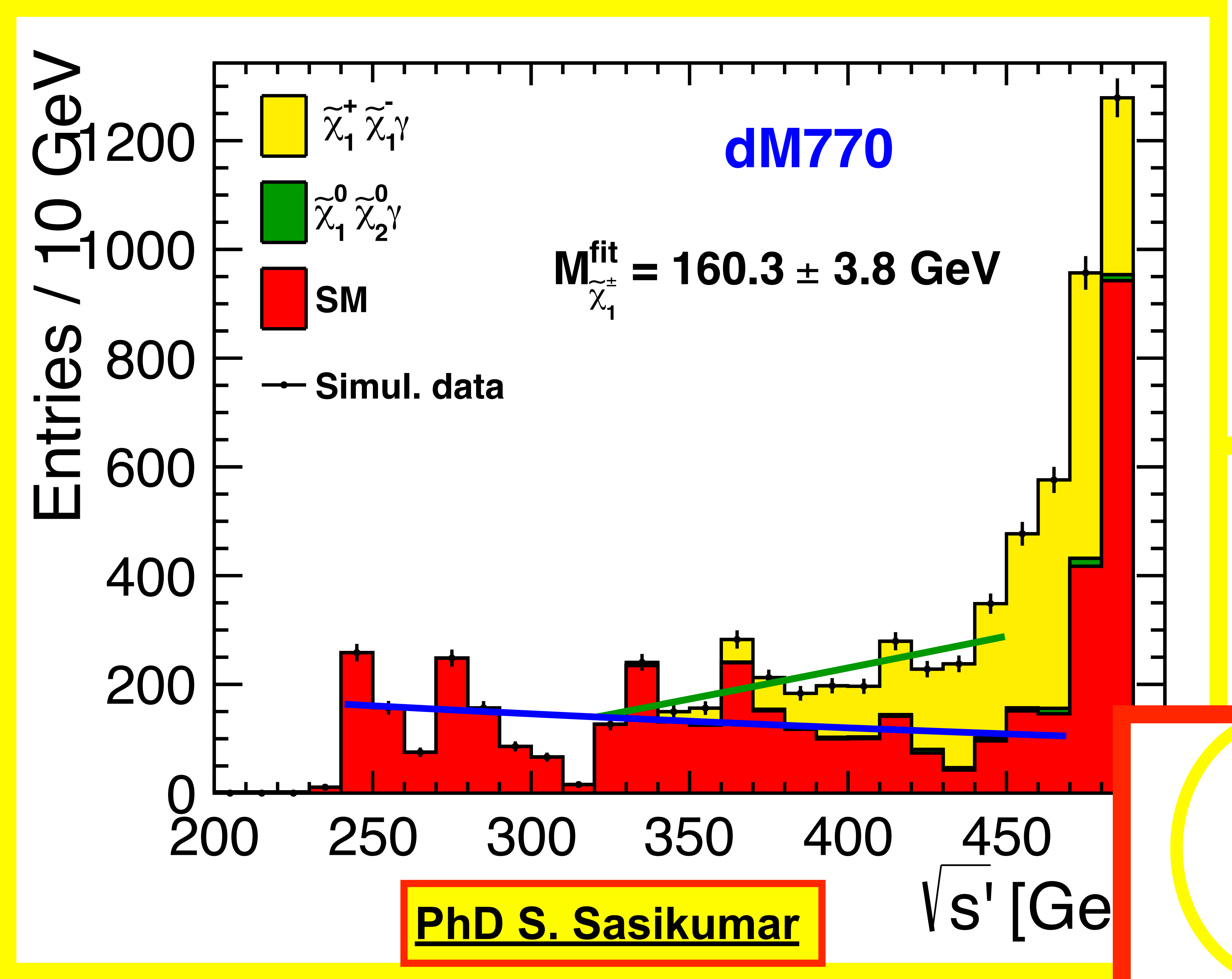

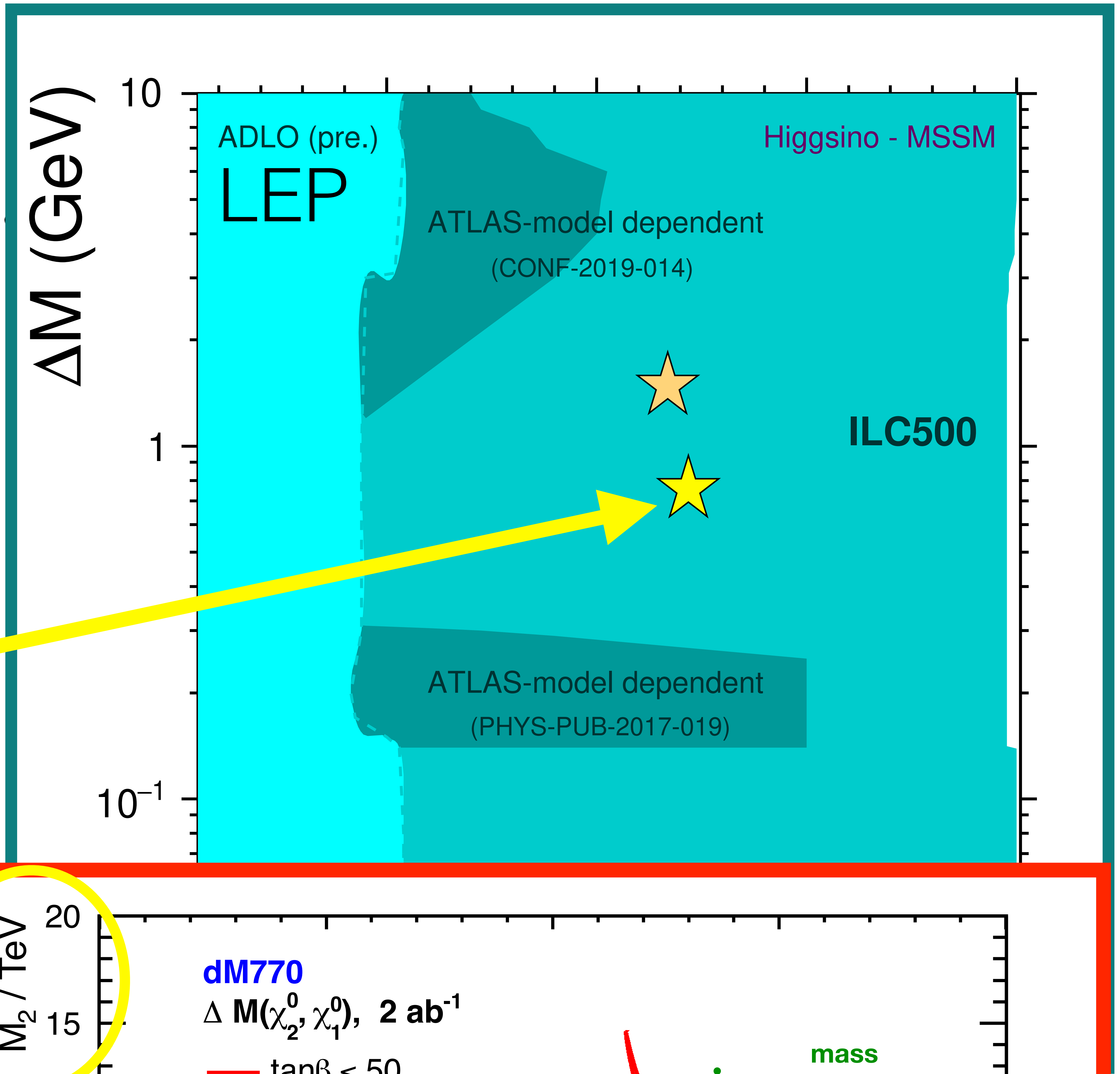

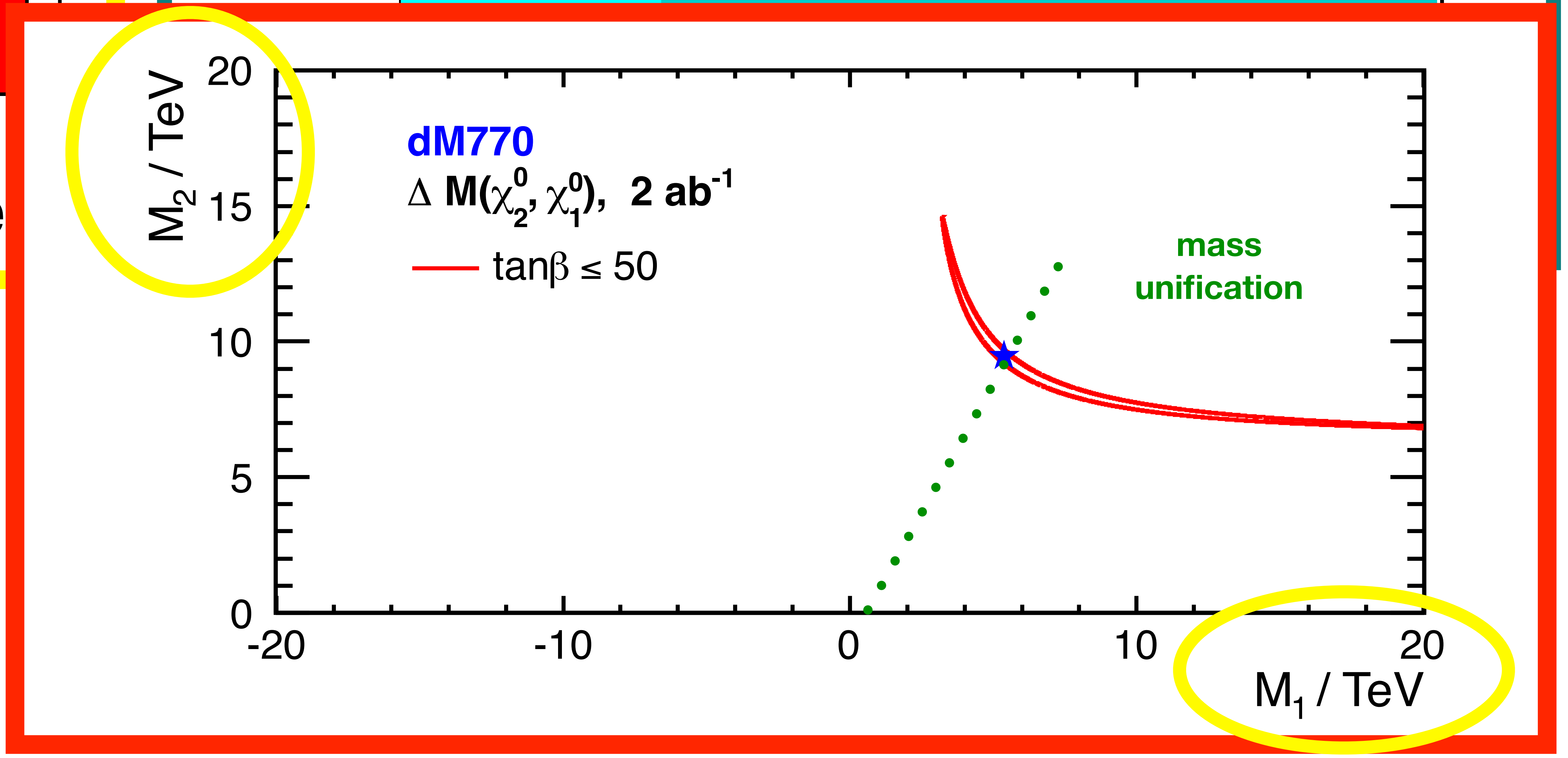

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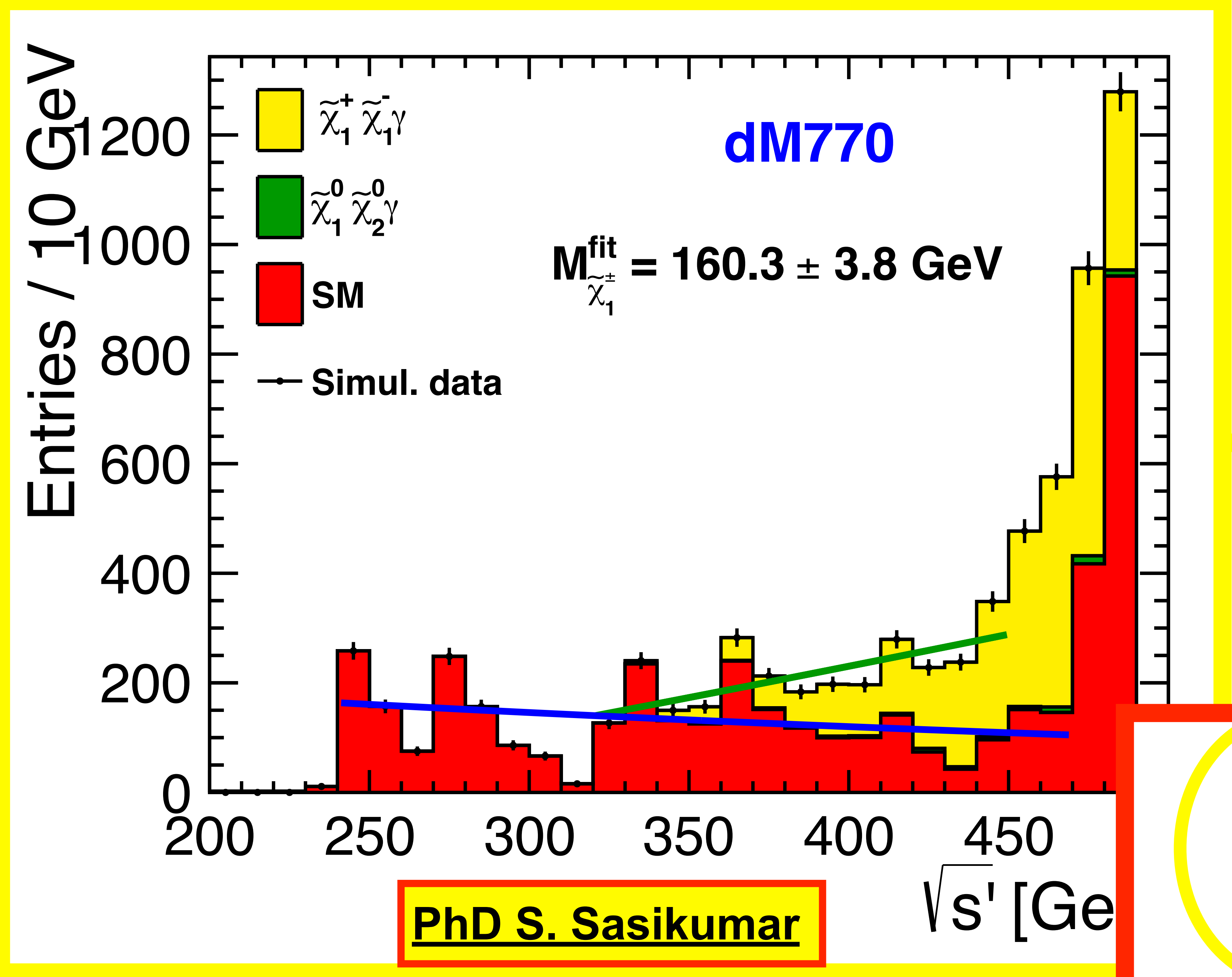
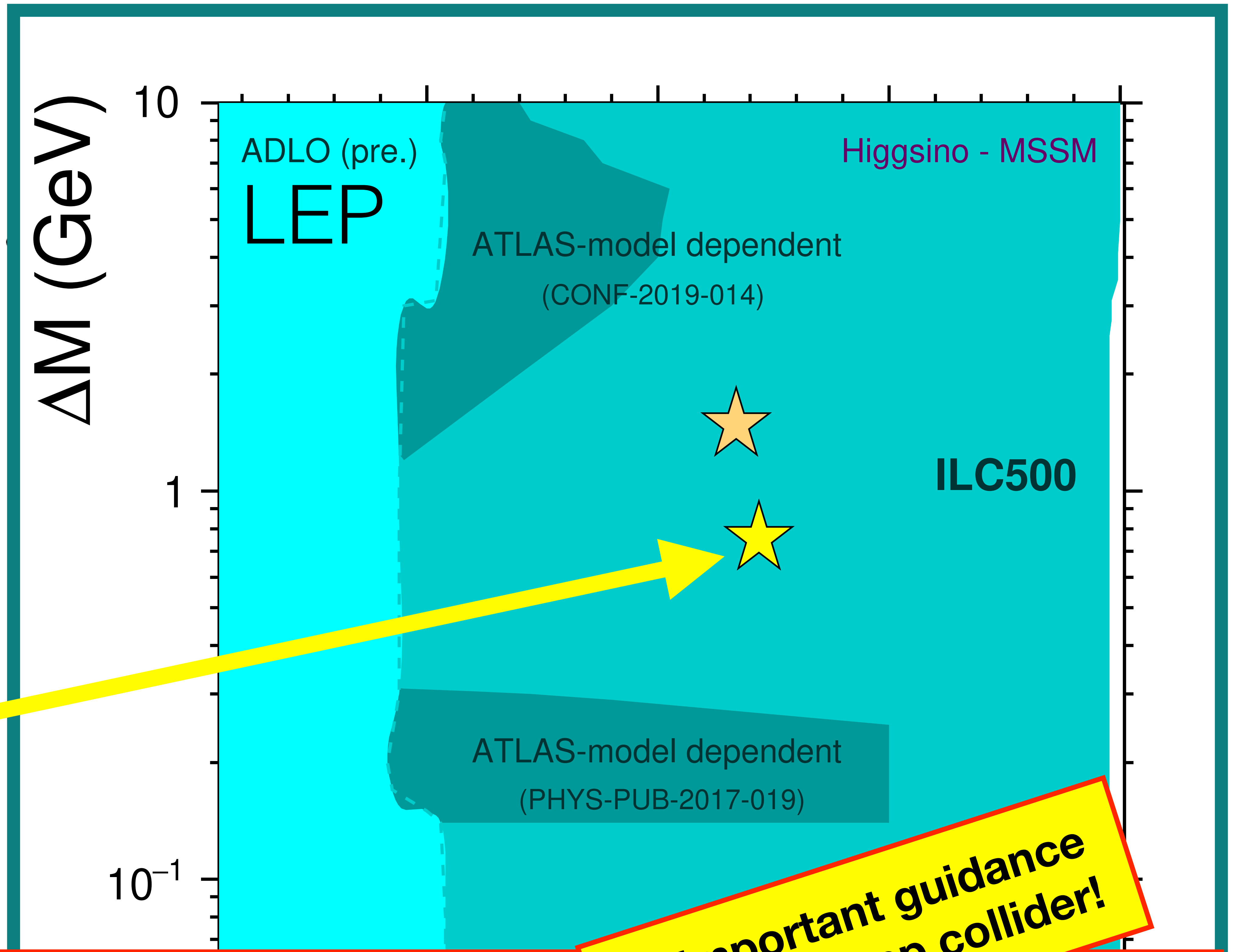
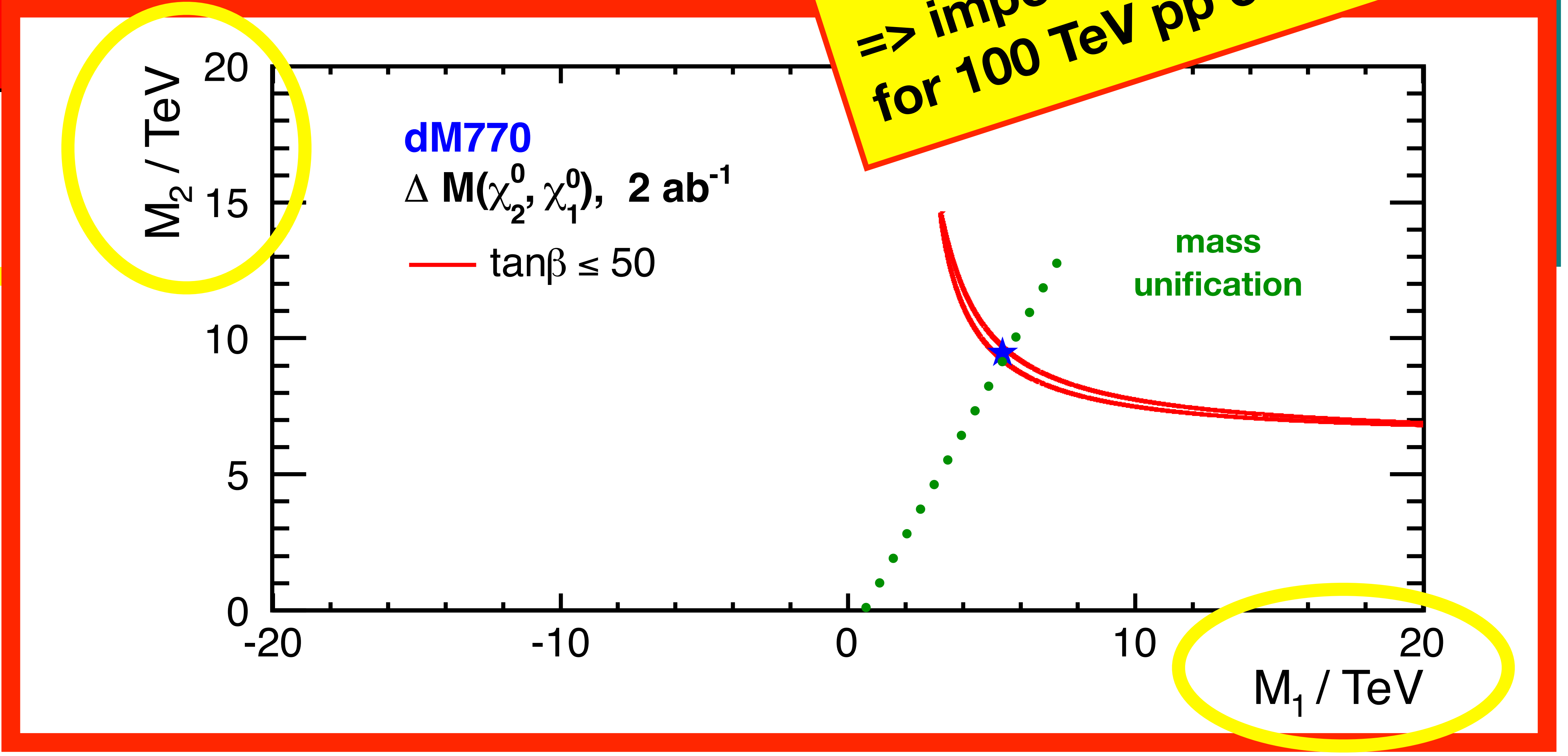




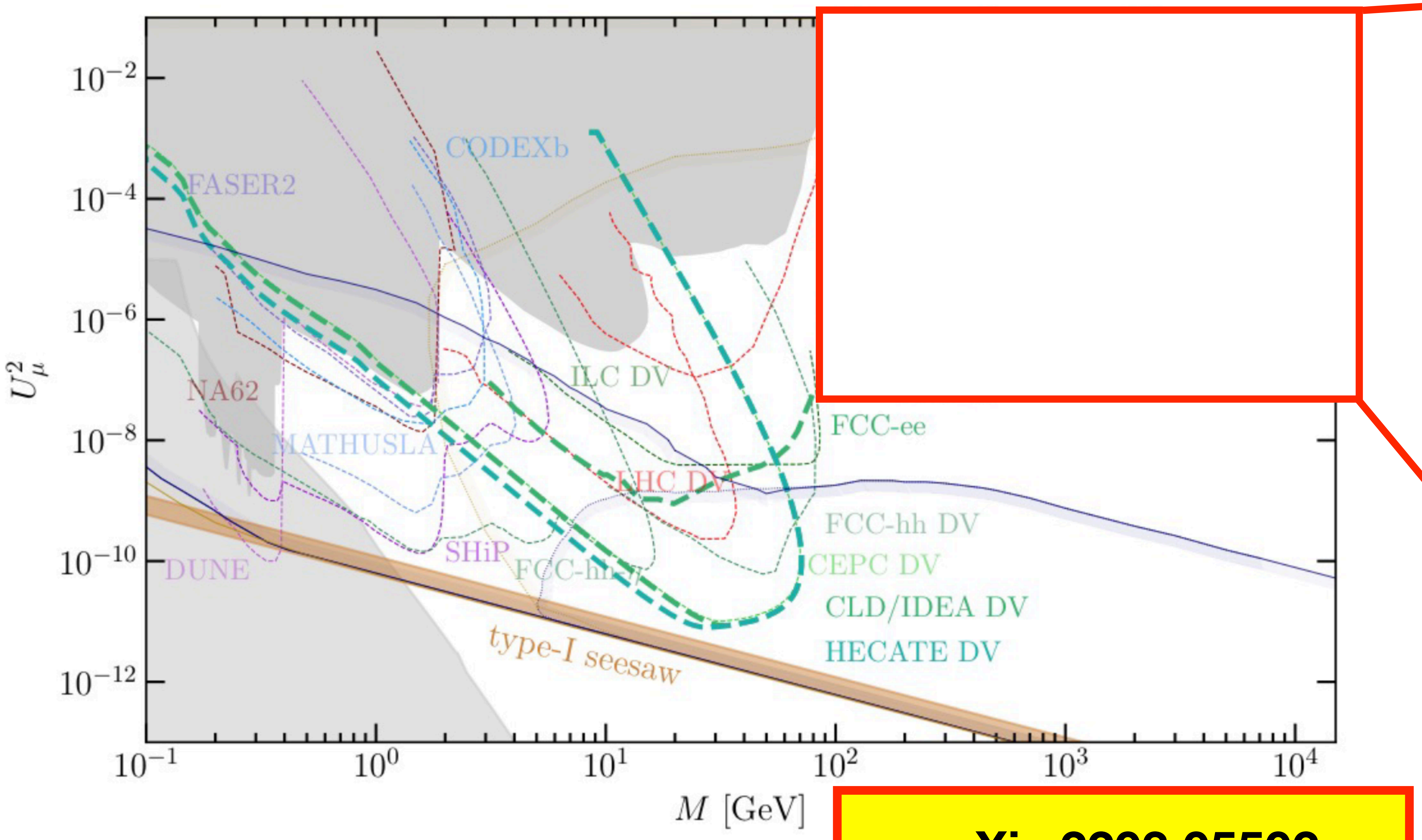


=> important guidance for 100 TeV pp collider!

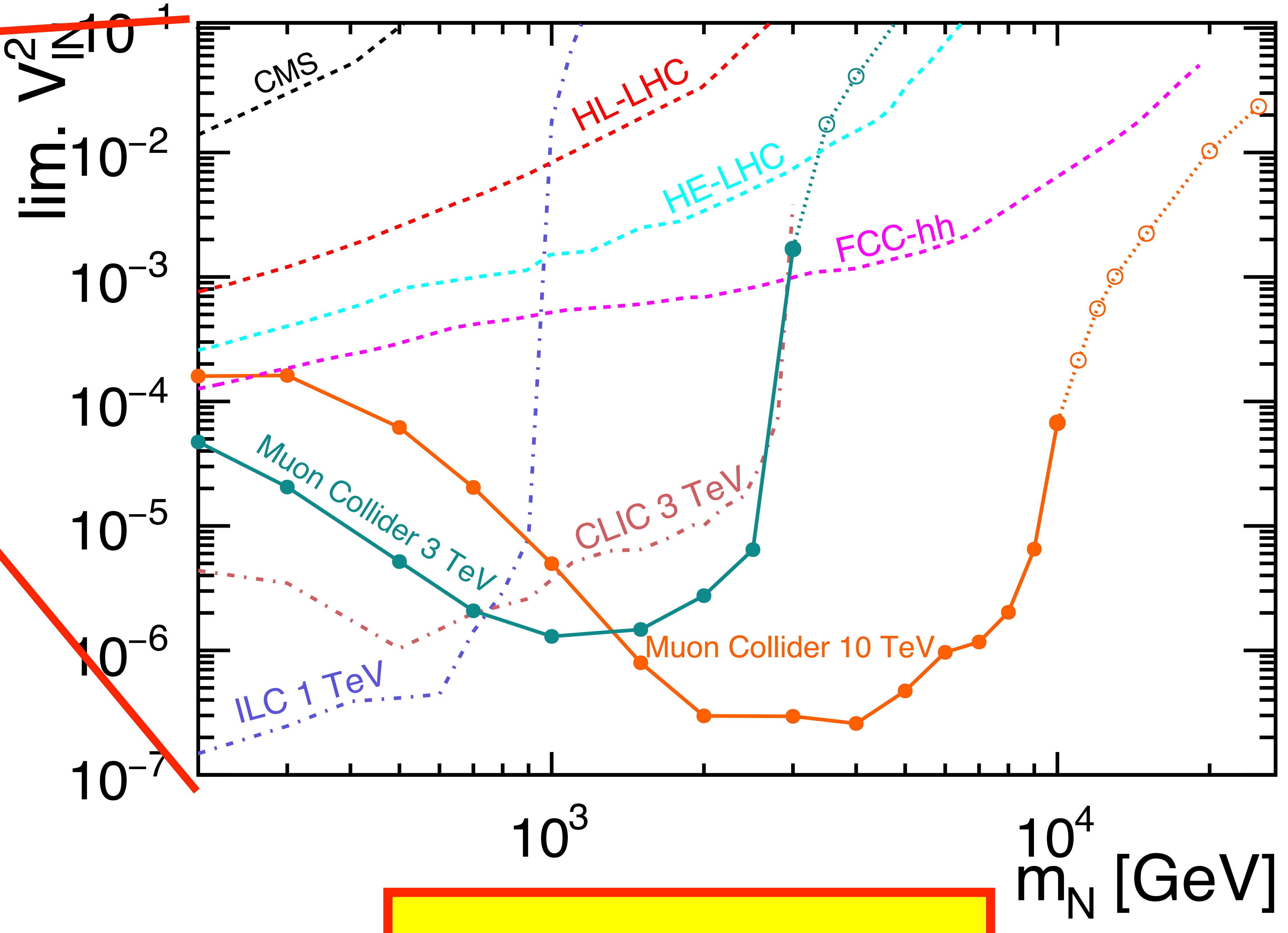
Heavy Neutral Leptons

Discovery reach for lepton colliders - complementary to FCC-hh

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



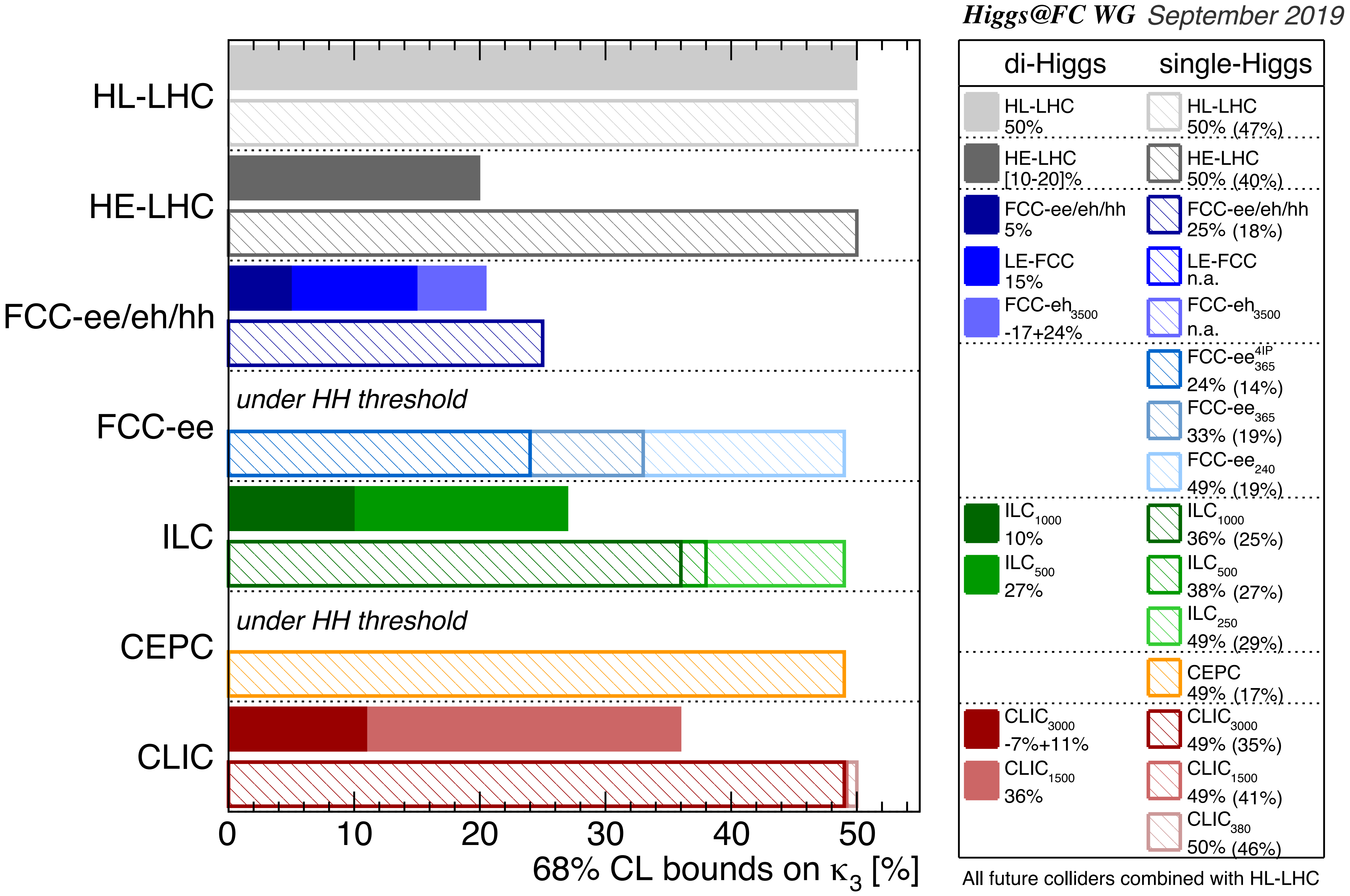
arXiv:2203.05502



arXiv:2301.02602

Higgs self-coupling

Electroweak Baryogenesis?



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

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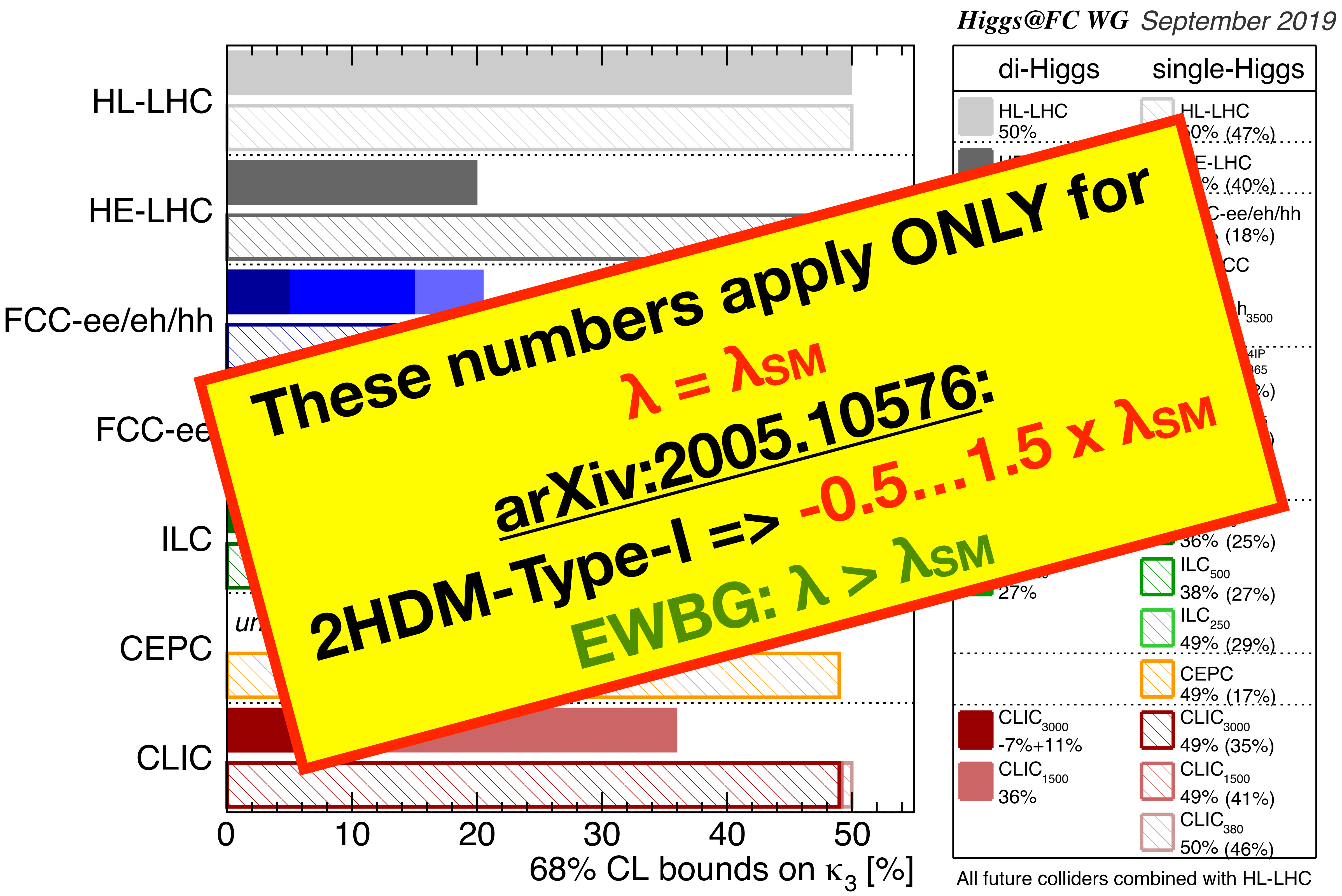

These numbers apply ONLY for $\lambda = \lambda_{SM}$

arXiv:2005.10576:

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

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

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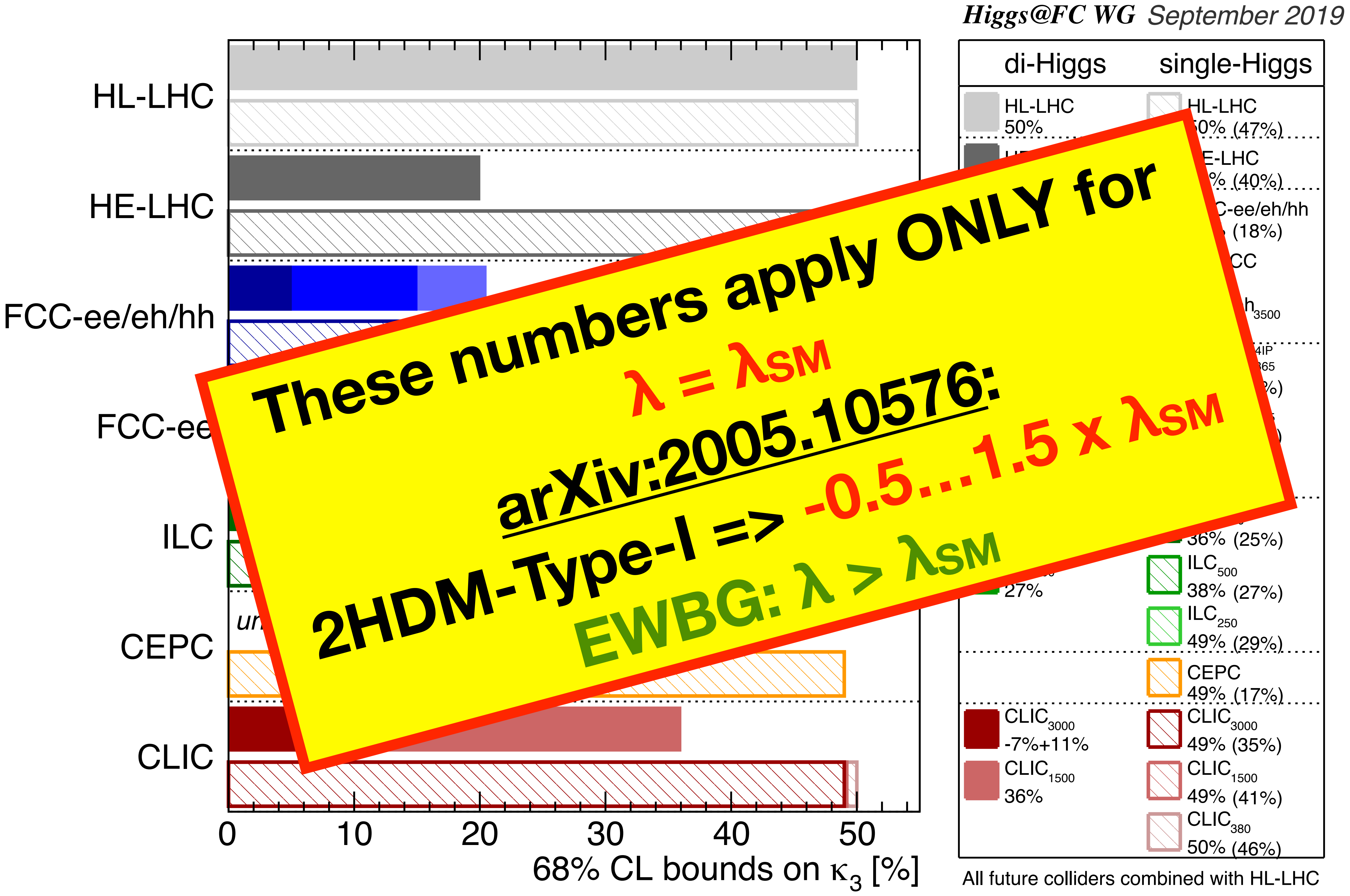

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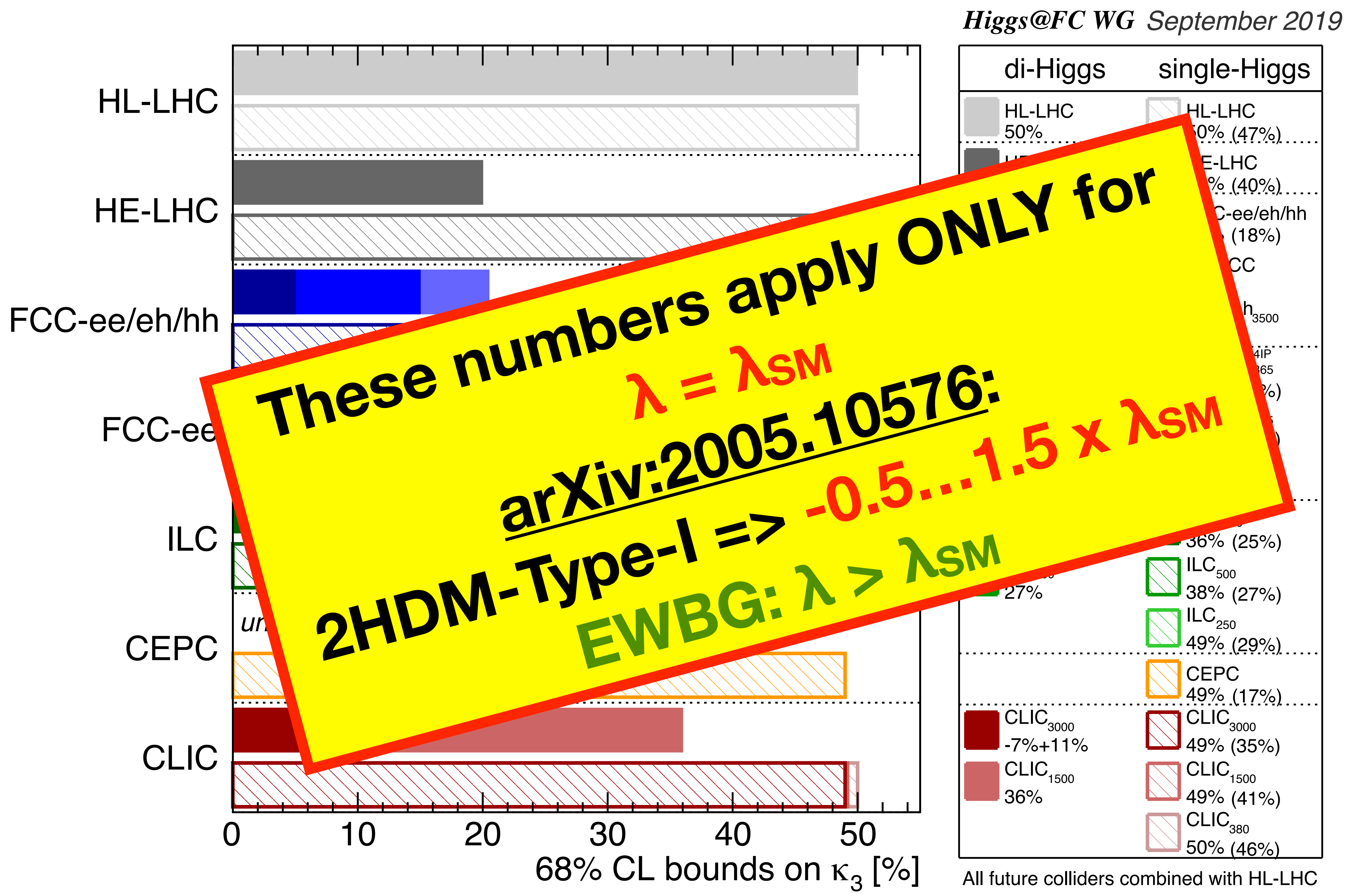

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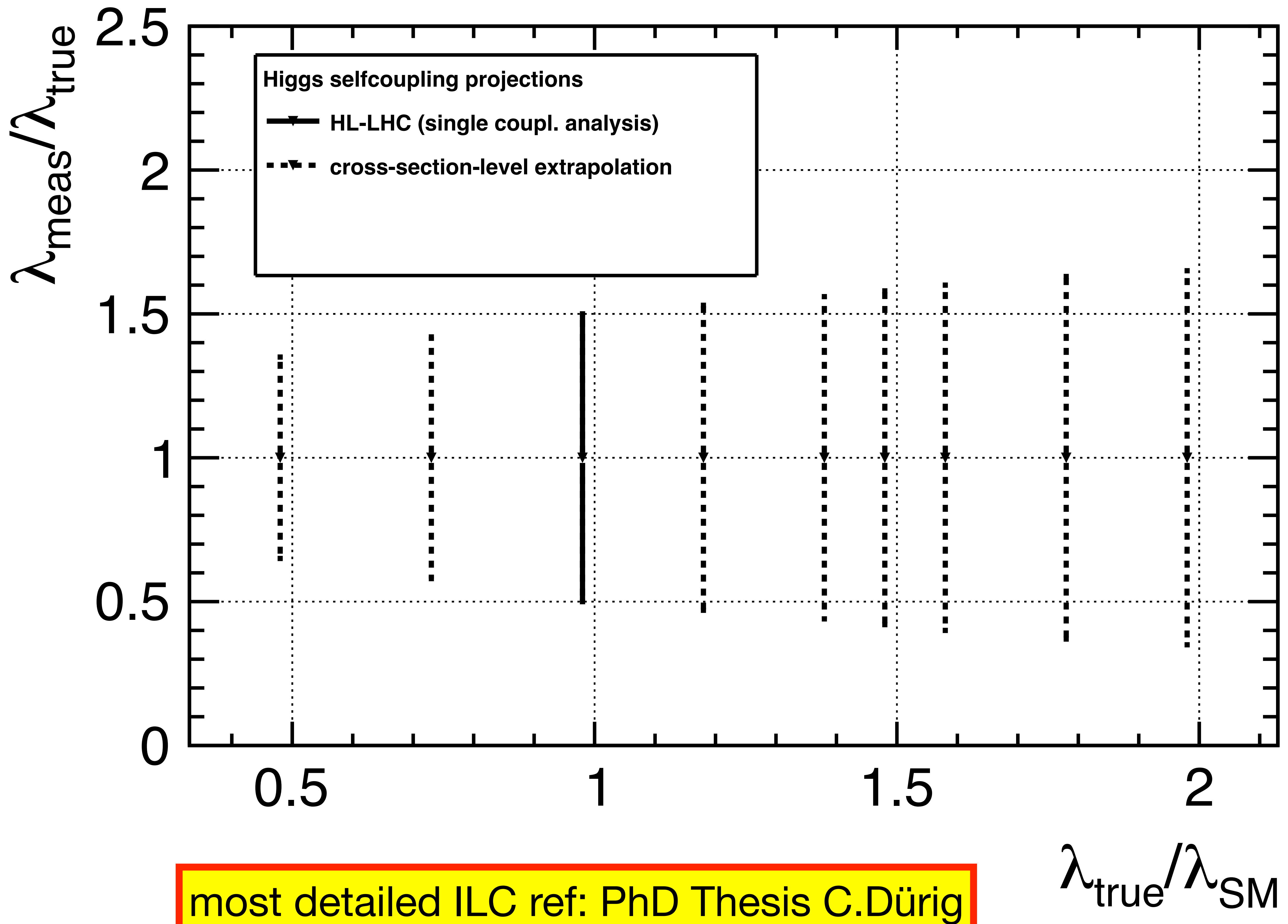

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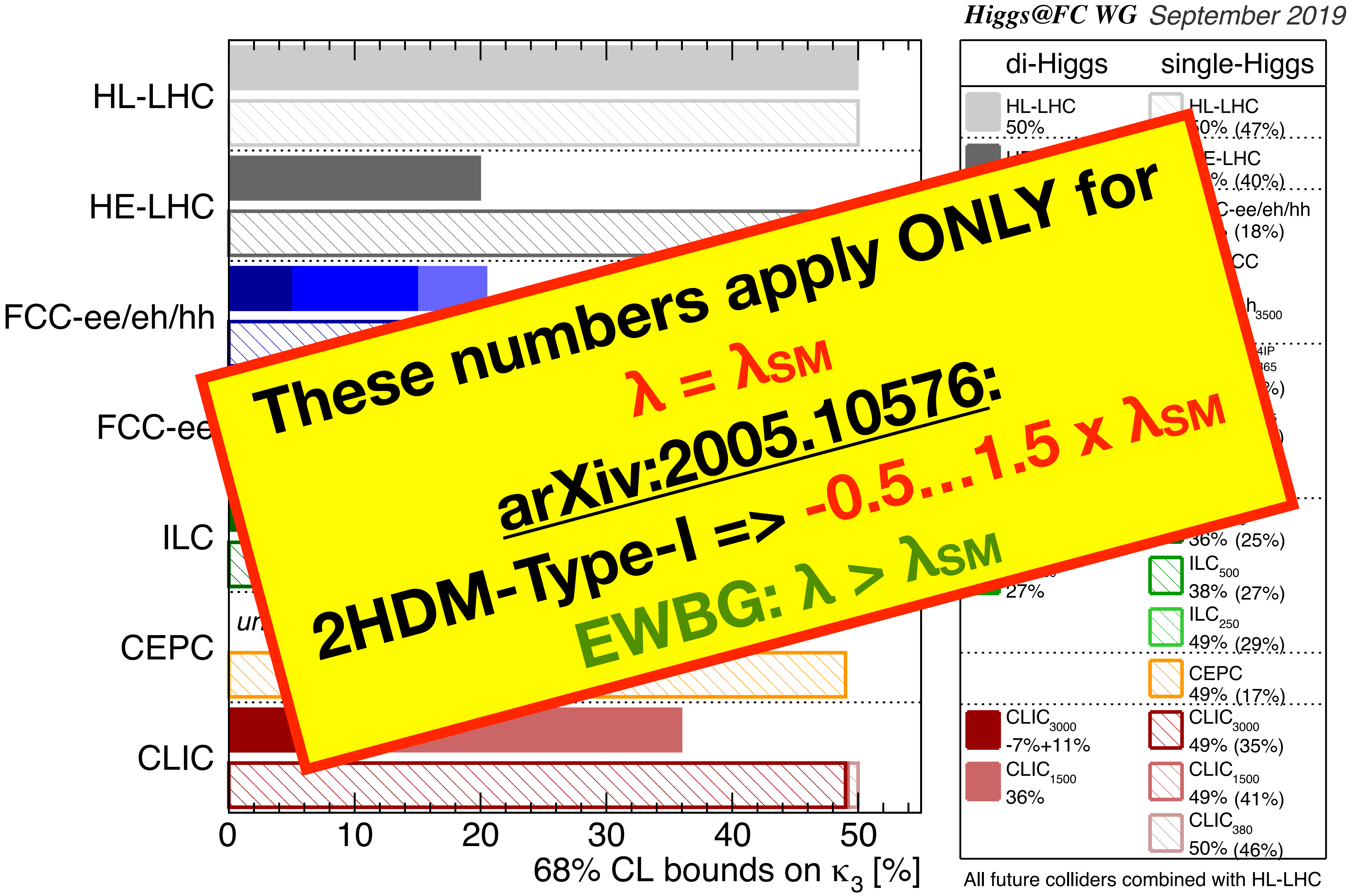

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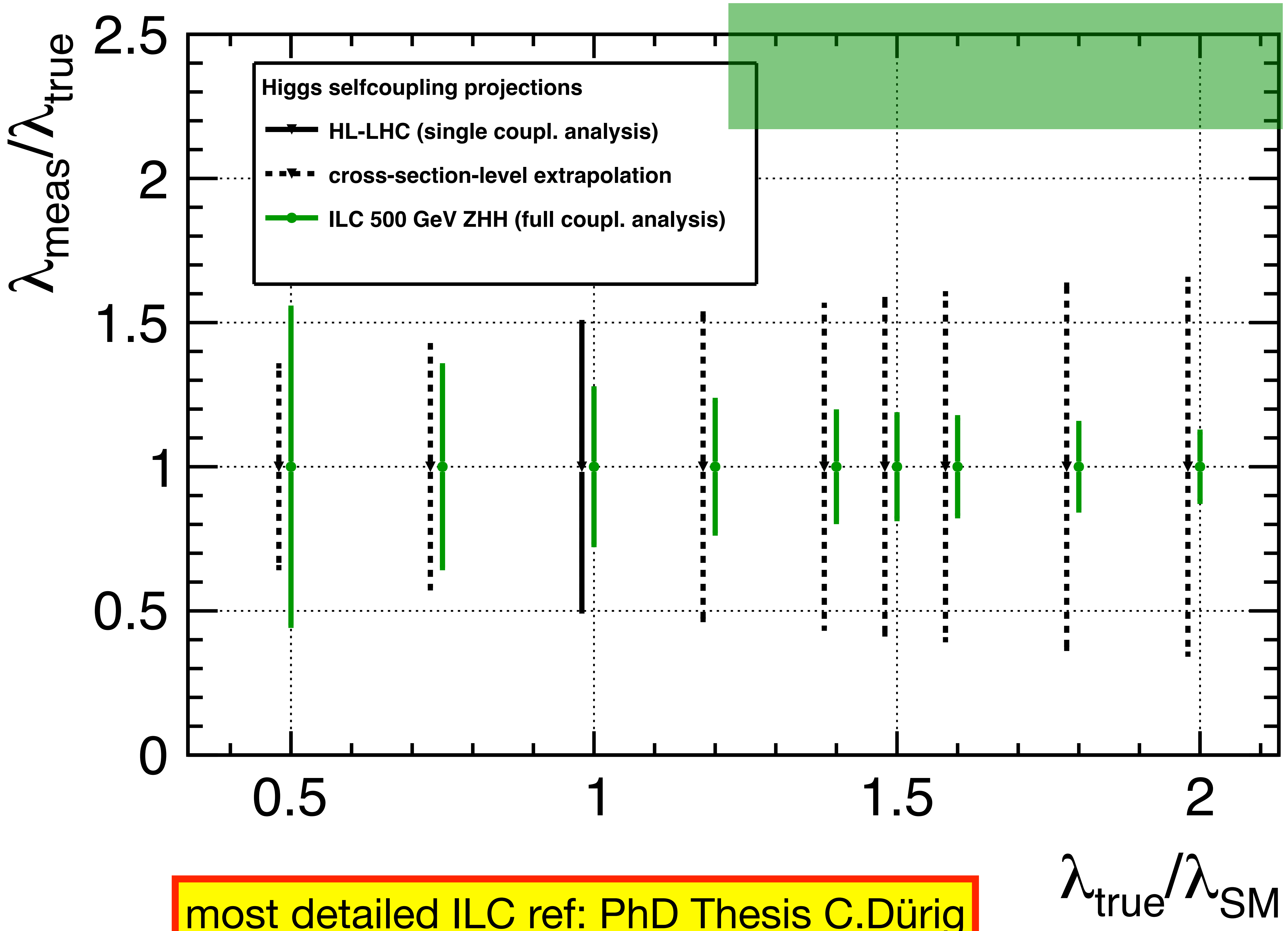

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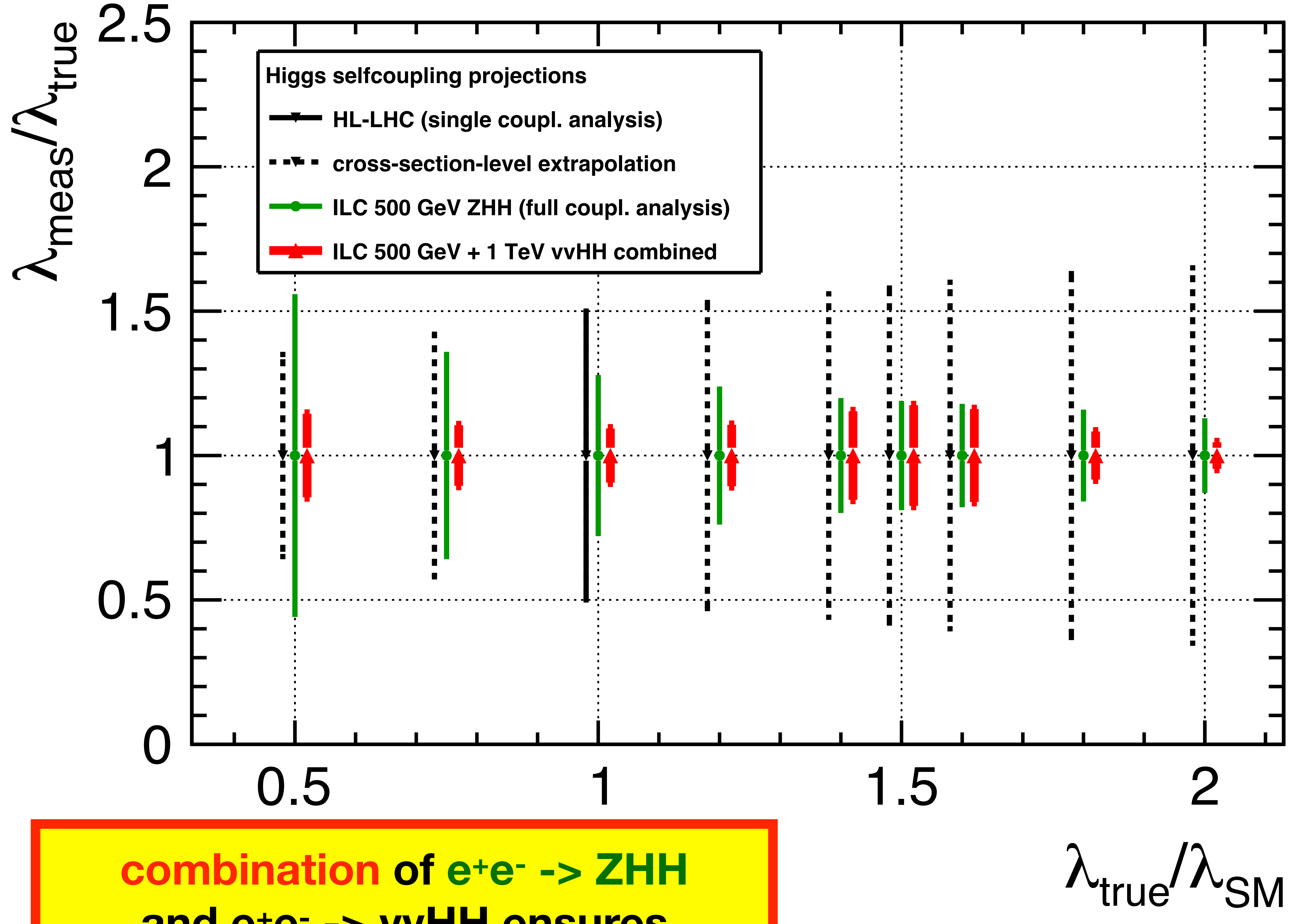

combination of e^+e^- -> ZHH and e^+e^- -> vvHH ensures at least 10-15% precision for all λ

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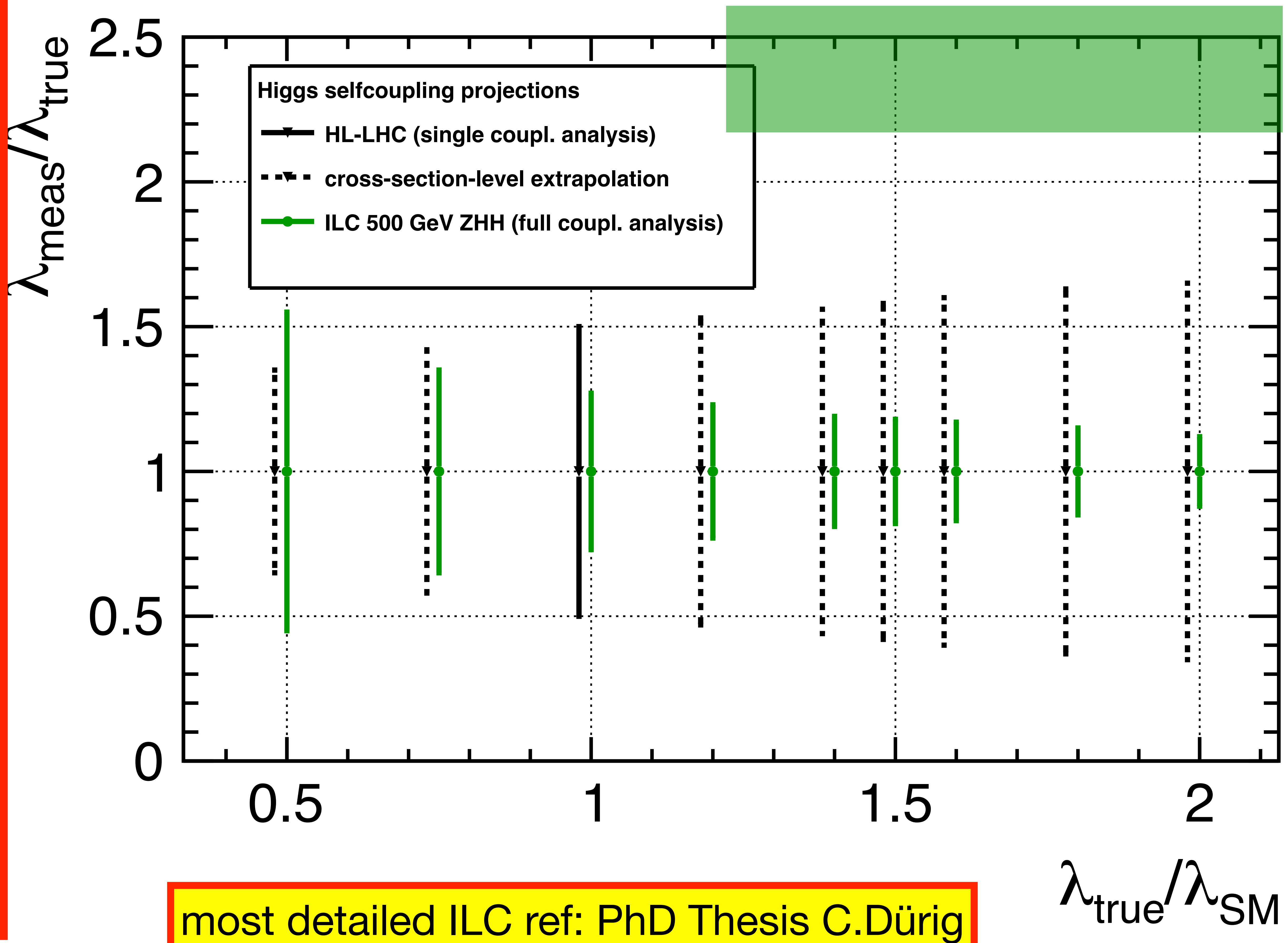

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UPDATE ONGOING!

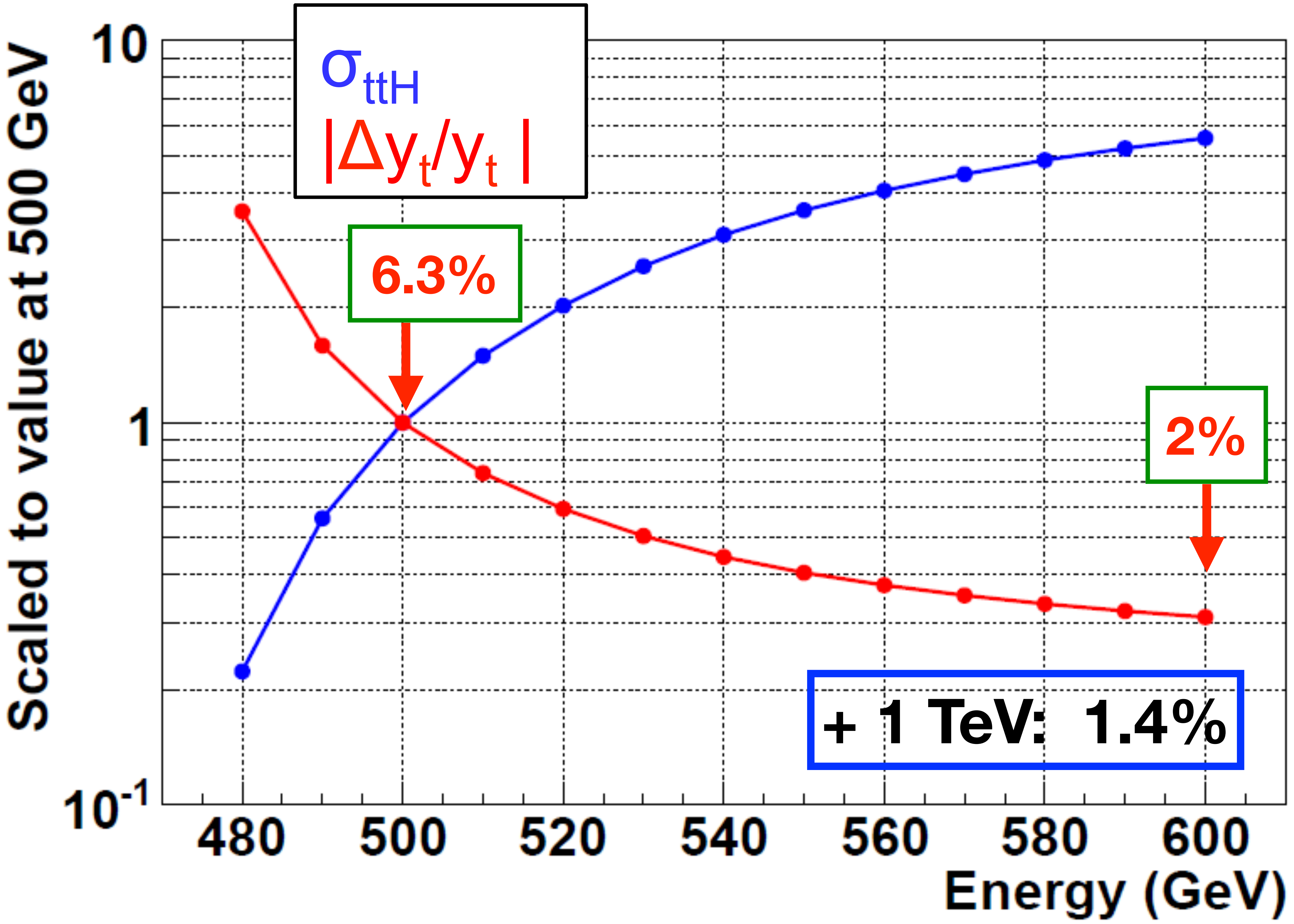
Top Yukawa coupling

Choosing the right energy

The Higgs and the Top

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

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



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

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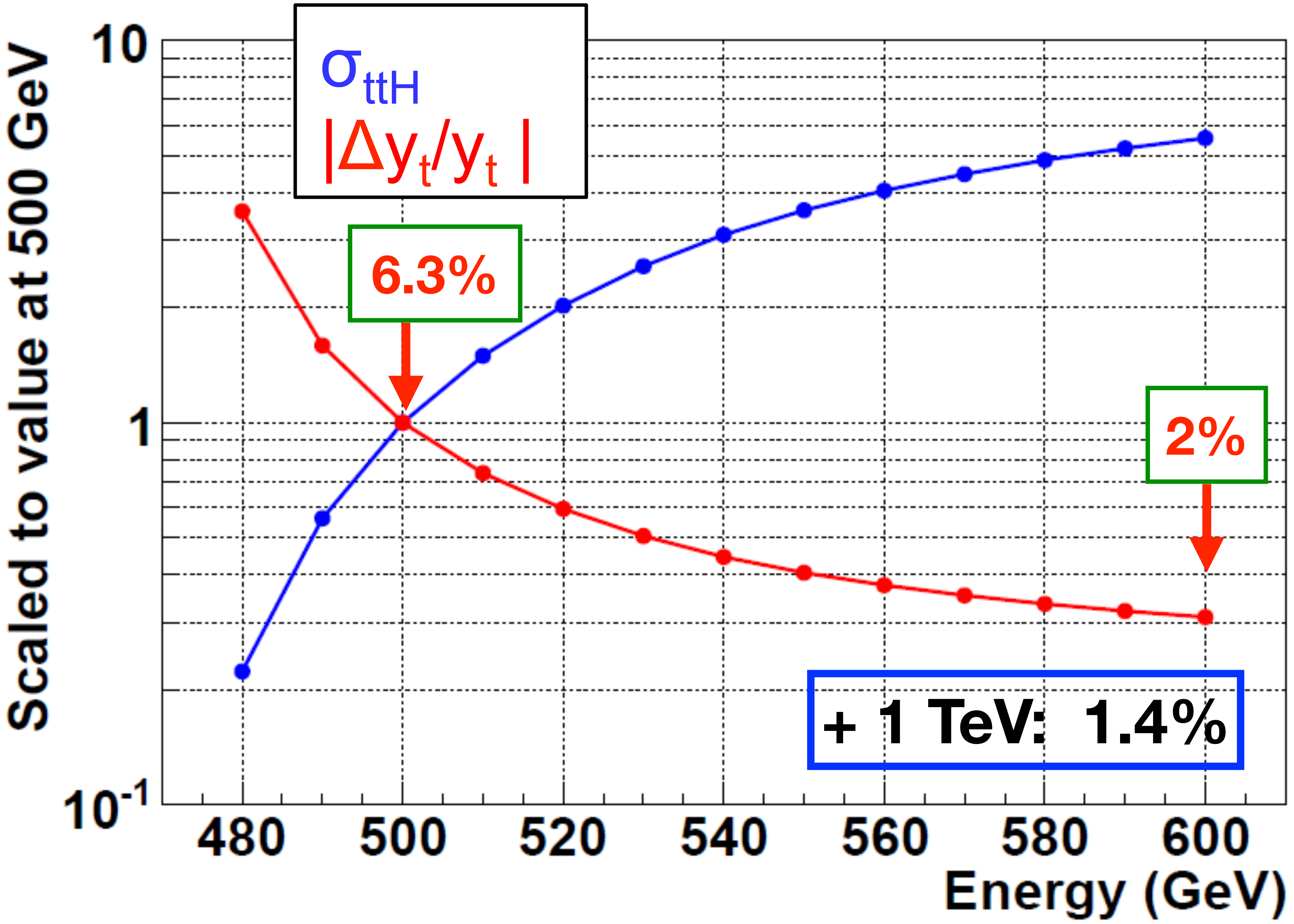

to-do: real, full sim study @ 600 GeV!

- **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]

Conclusions

And invitation

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

- **open scientific question: how to best complement the minimal Higgs Factory in e+e-?**
  - very strong Z pole program but limited in energy reach?
  - upgrades to higher energies but more modest Z program?
- **next big project needs**
  - a compelling science case
  - readiness for fastest possible construction
  - technologically and scientifically exciting upgrade options
  - well justified usage of ressources - **money**; surface, electrical power, concrete, steel, rare earths, …

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

Bonus

Ready to take on one of these challenges?

How to contribute

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

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

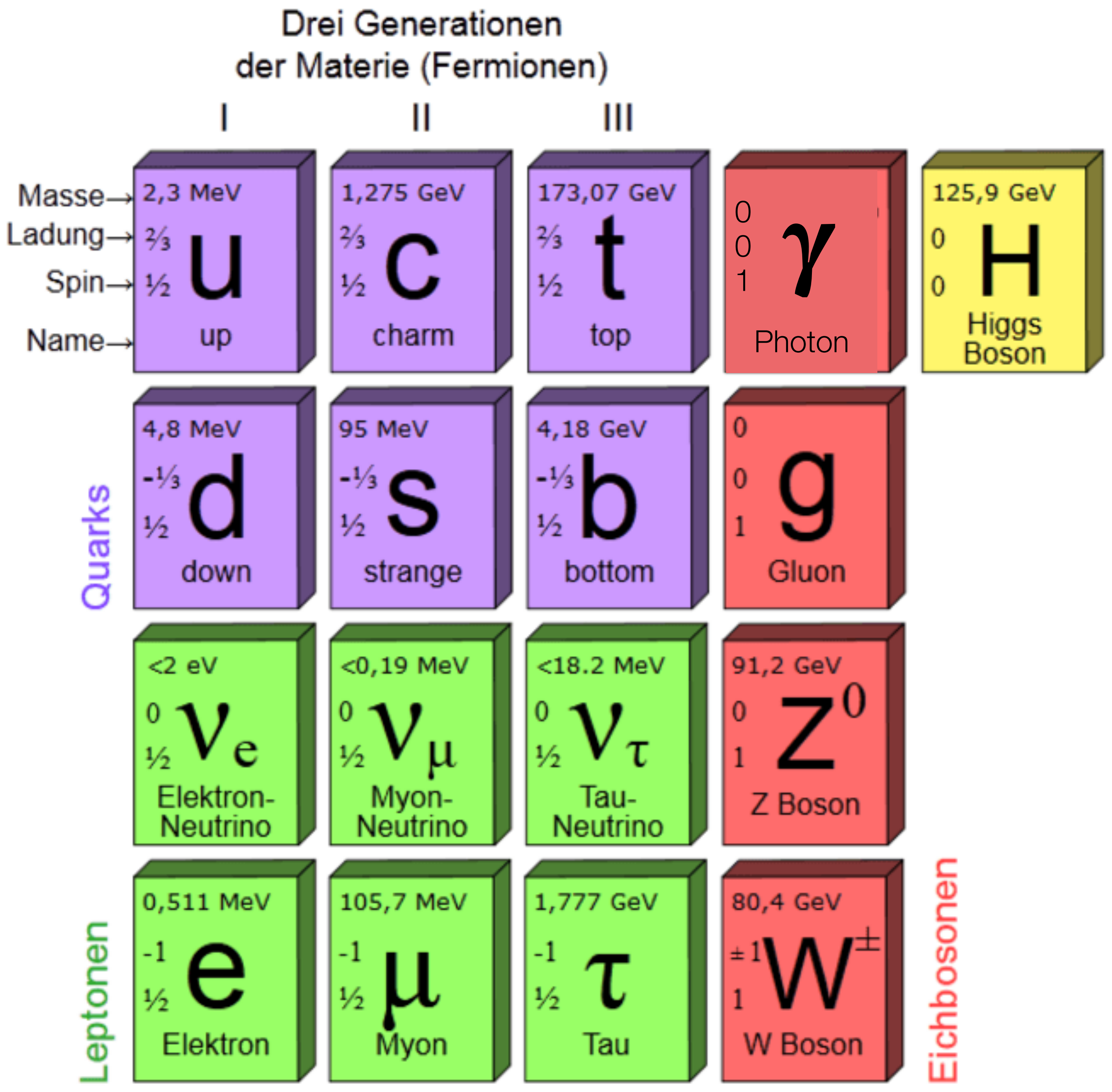
- **All Higgs factories are using the same software framework (Key4HEP):**
  - share algorthmic developments
  - share / exchange data sets for comparable analyses etc

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

Backup

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: $SU(3) x SU(2)_L x U(1)_Y$

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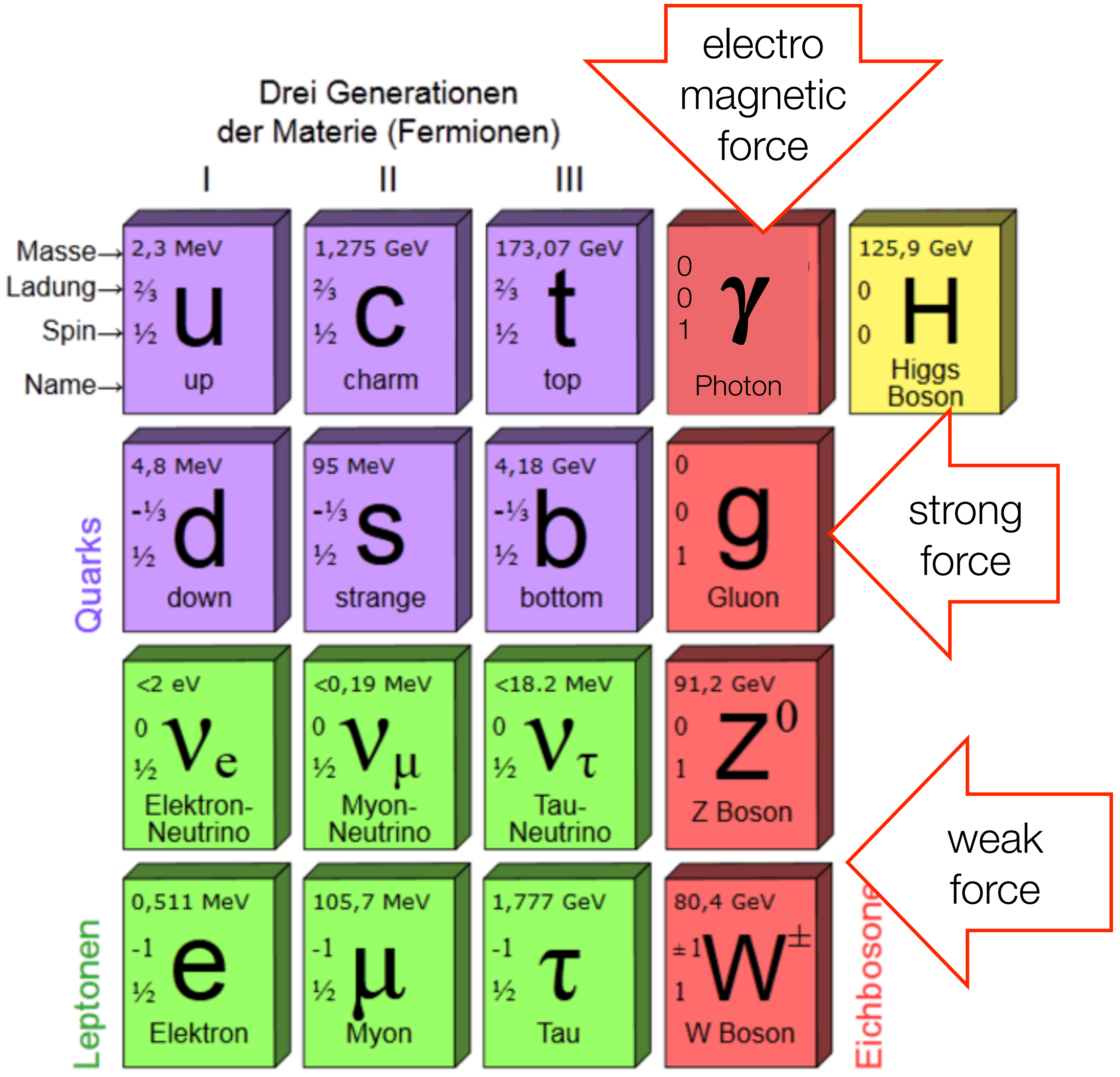

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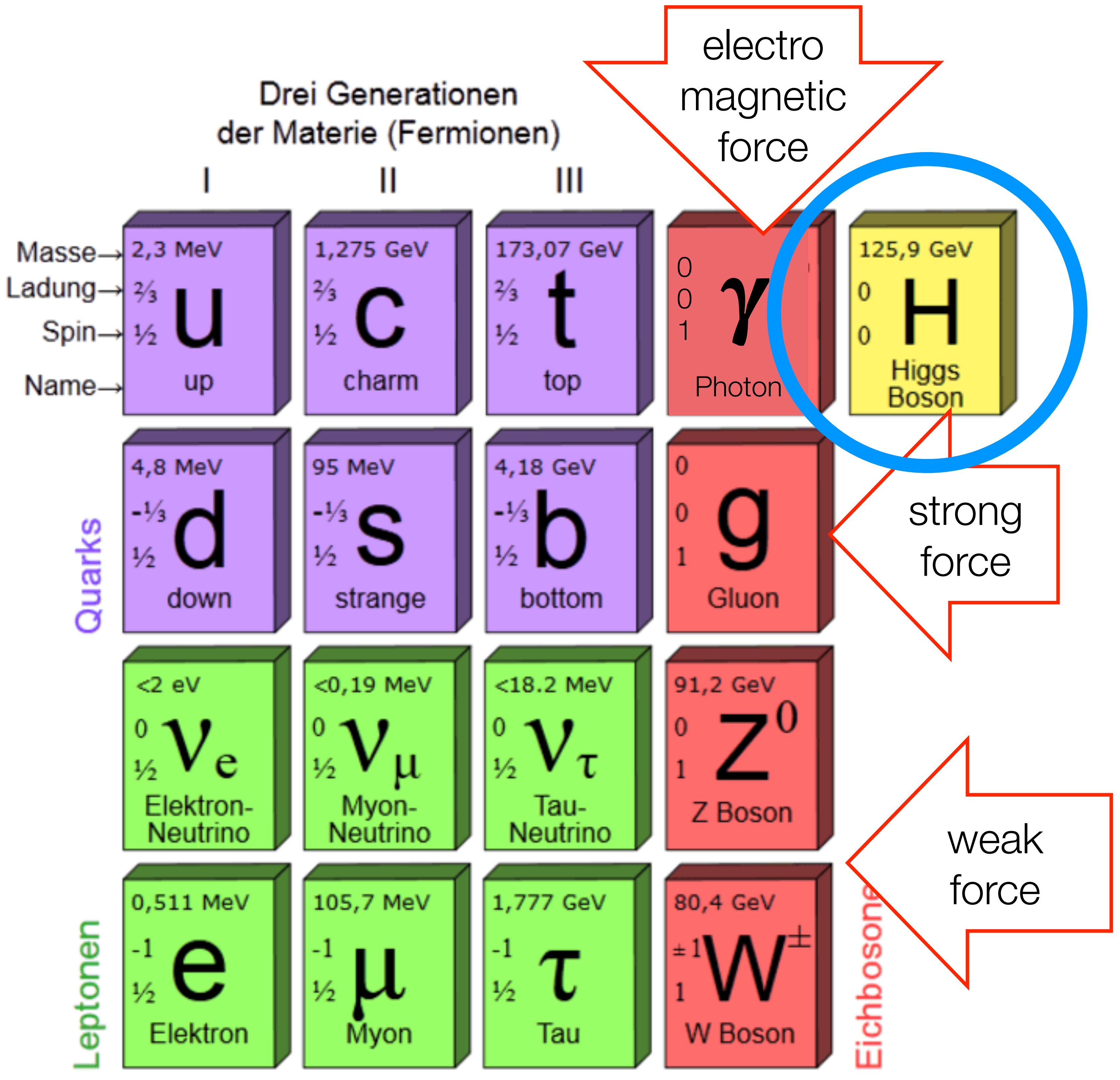

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2012: Discovery of a Higgs bosons at the LHC!

The Higgs Boson and the Standard Model of Particle Physics

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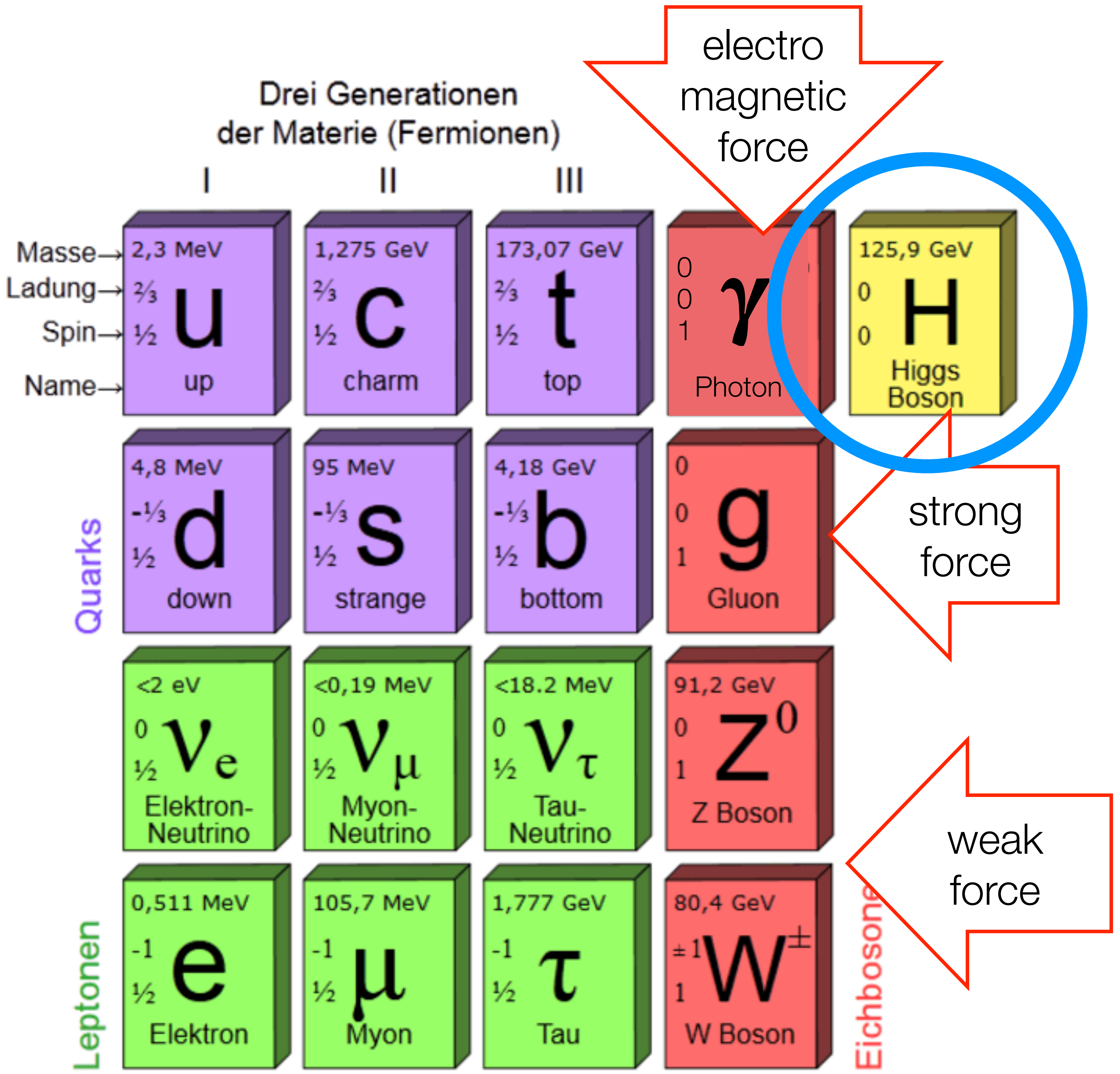

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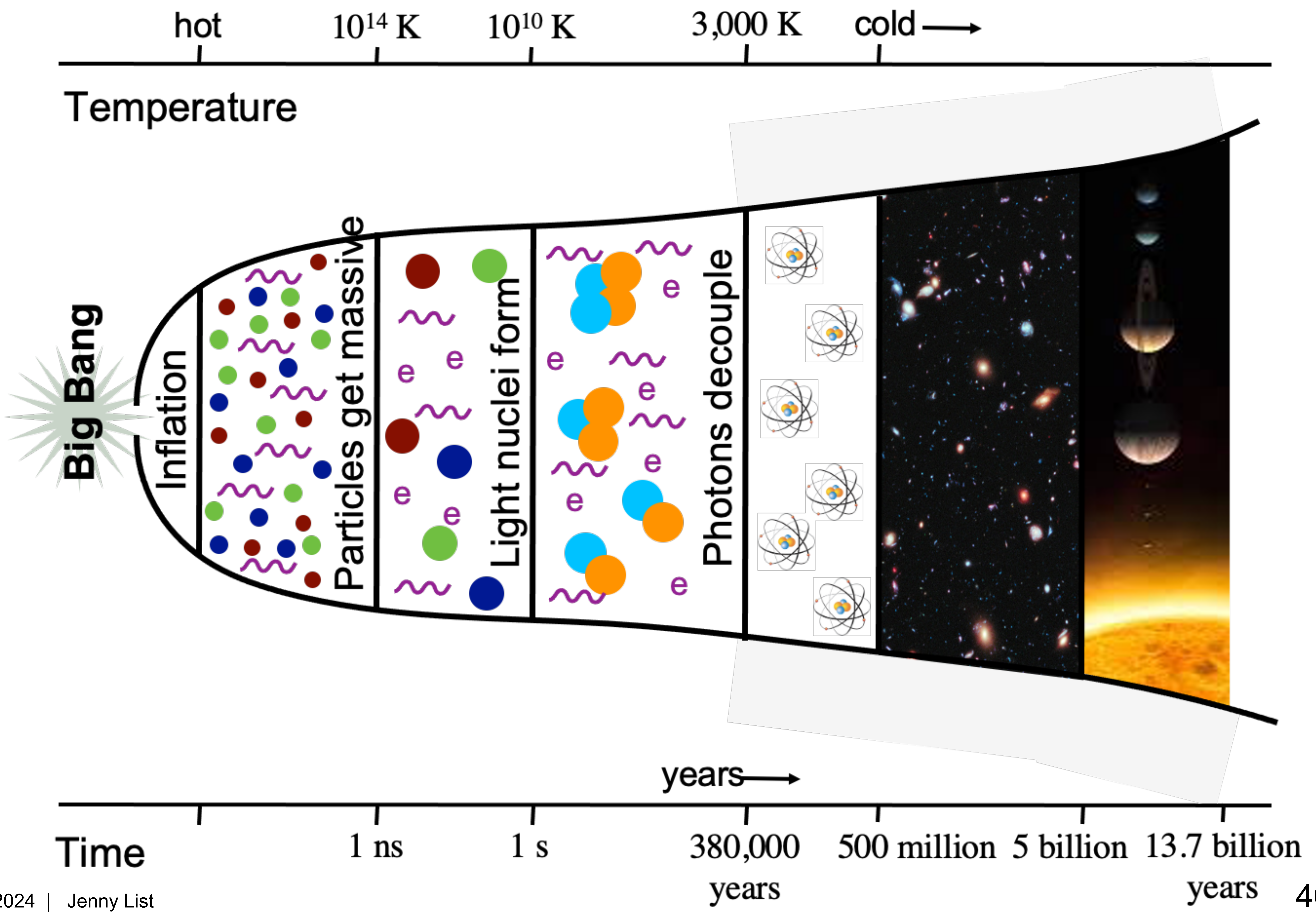
Are we done? — No! — The Higgs Boson is

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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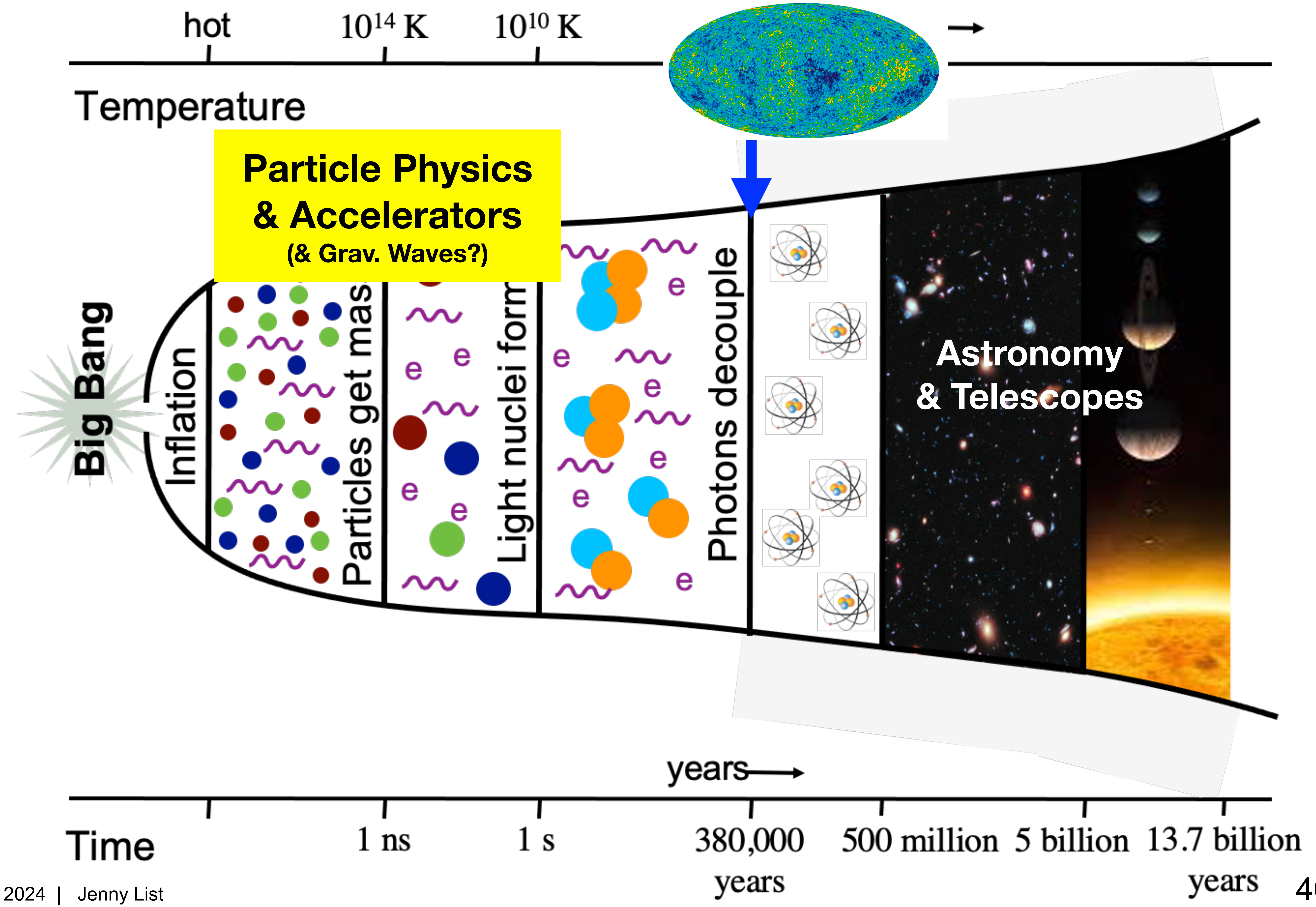

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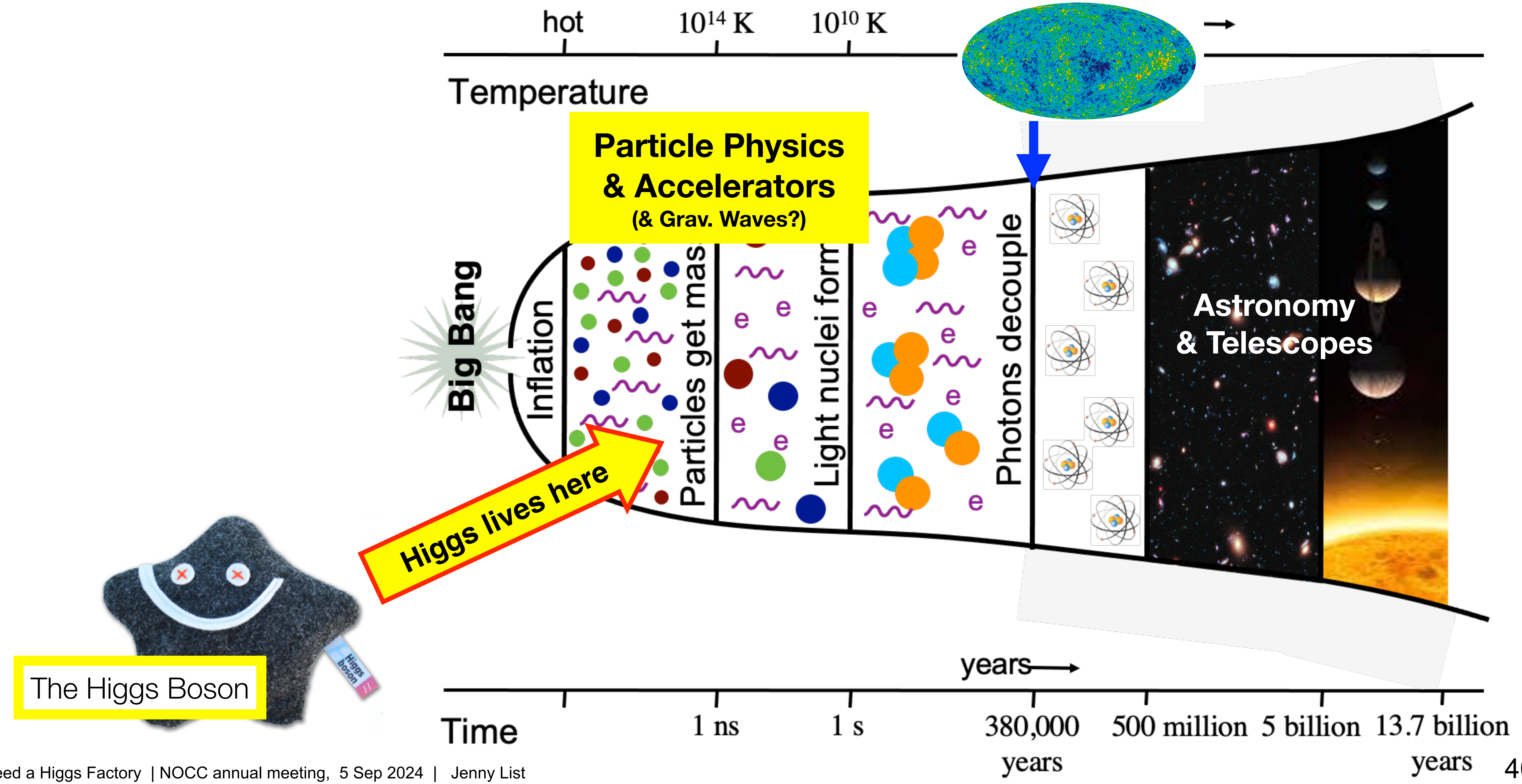

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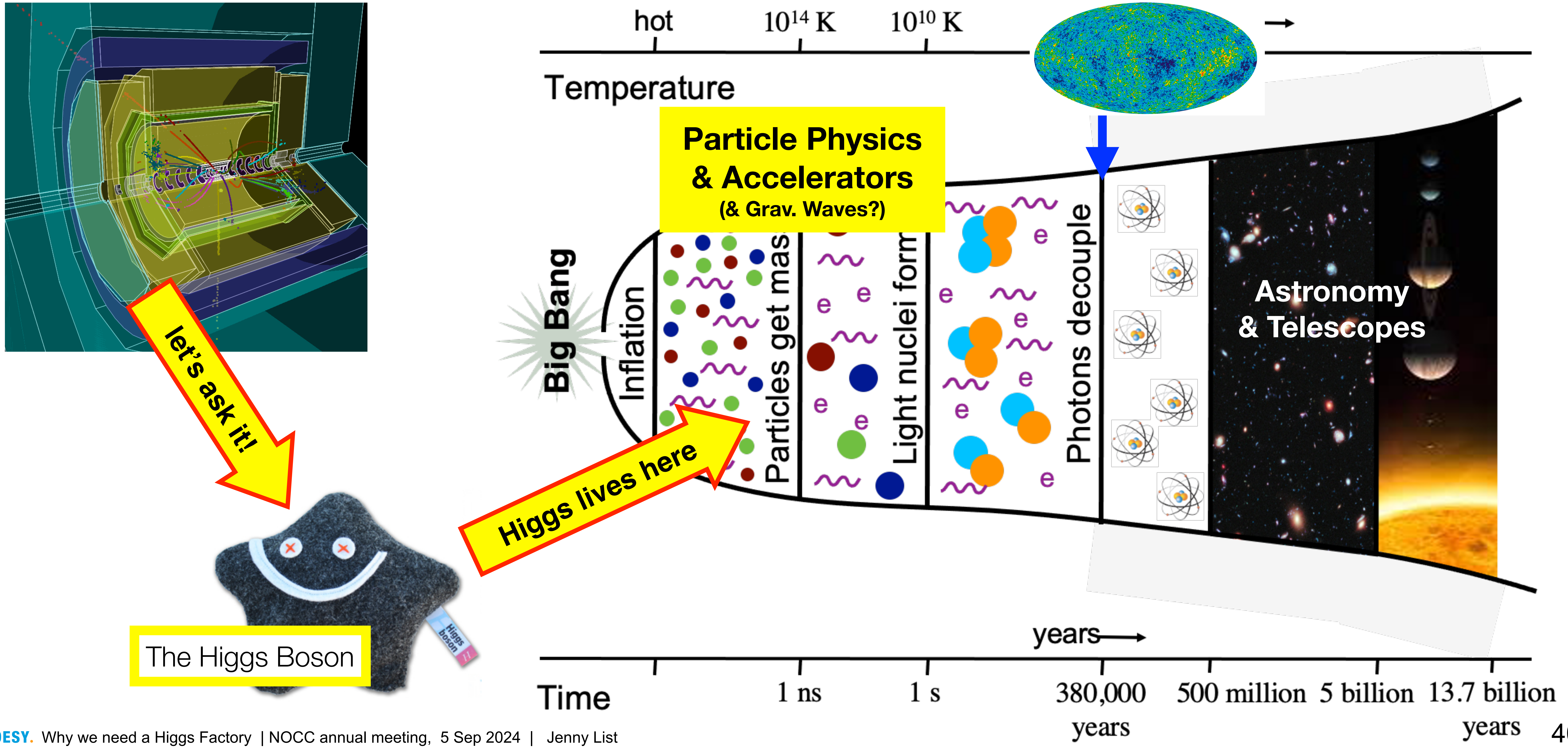
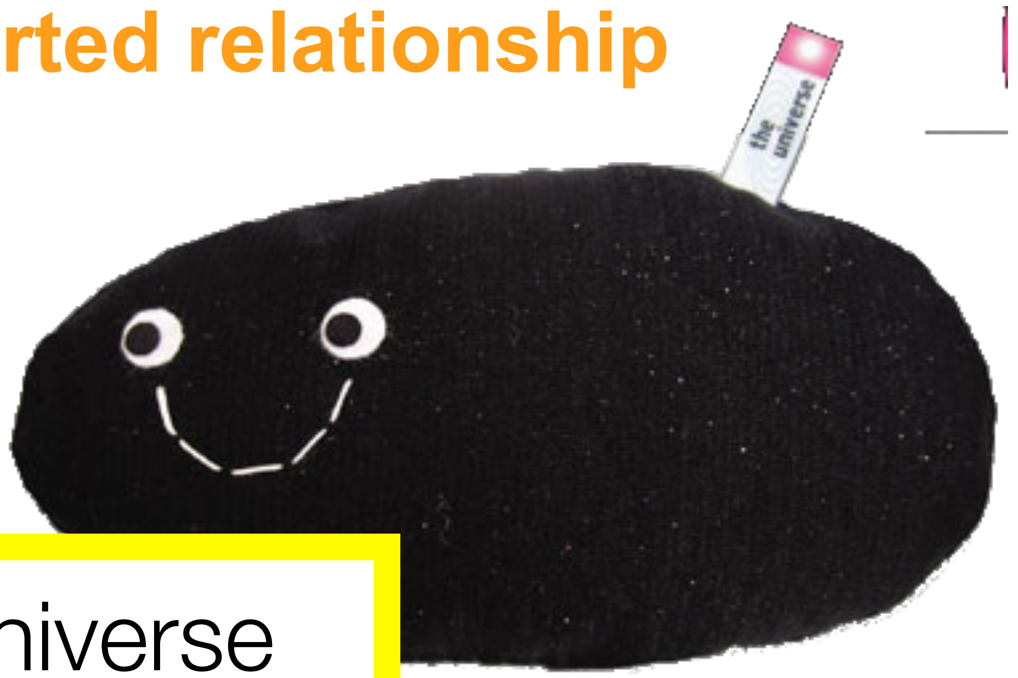


The Higgs Boson and the Universe

Exploration of an uncharted relationship



What we'd really like to know

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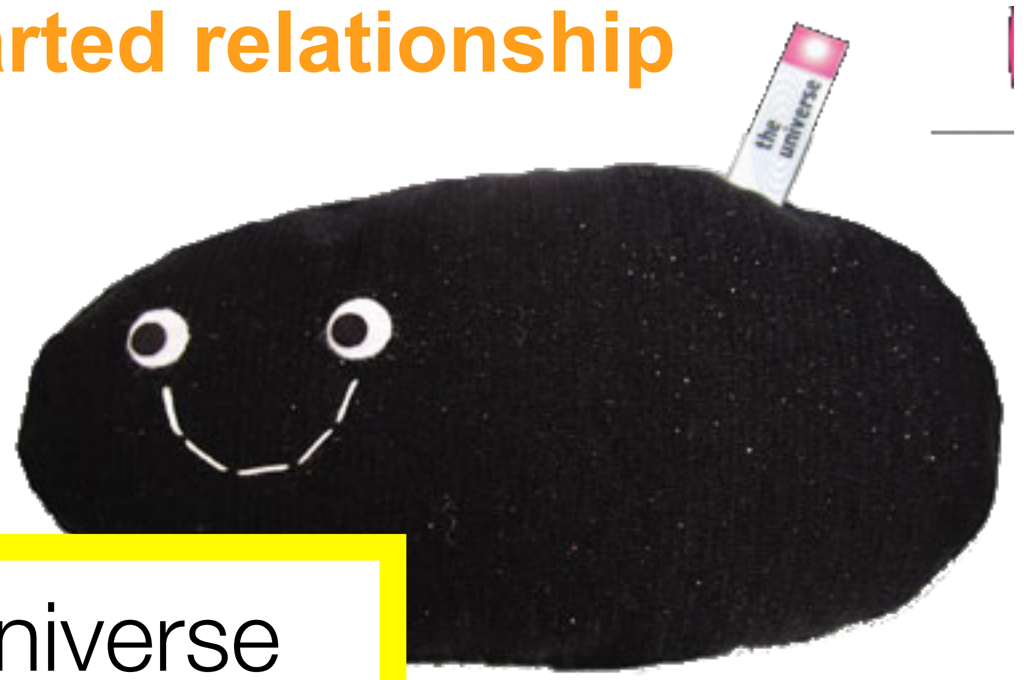

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Is the Higgs the portal to the Dark Sector?

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

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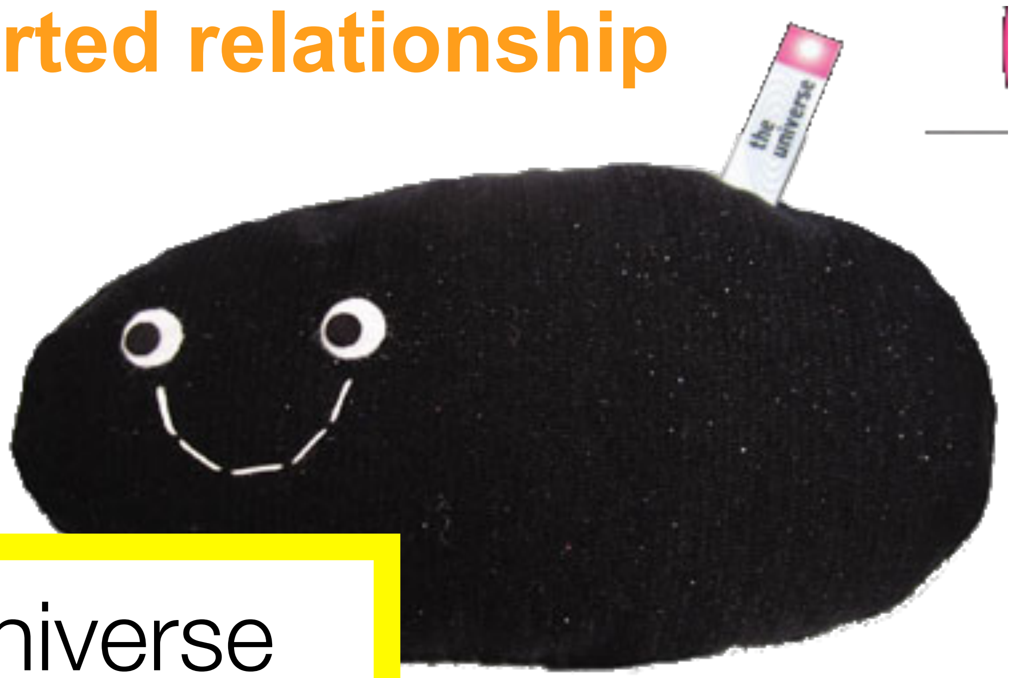

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The Higgs could be first "elementary" scalar we know -

- 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

The Higgs Boson and the Universe

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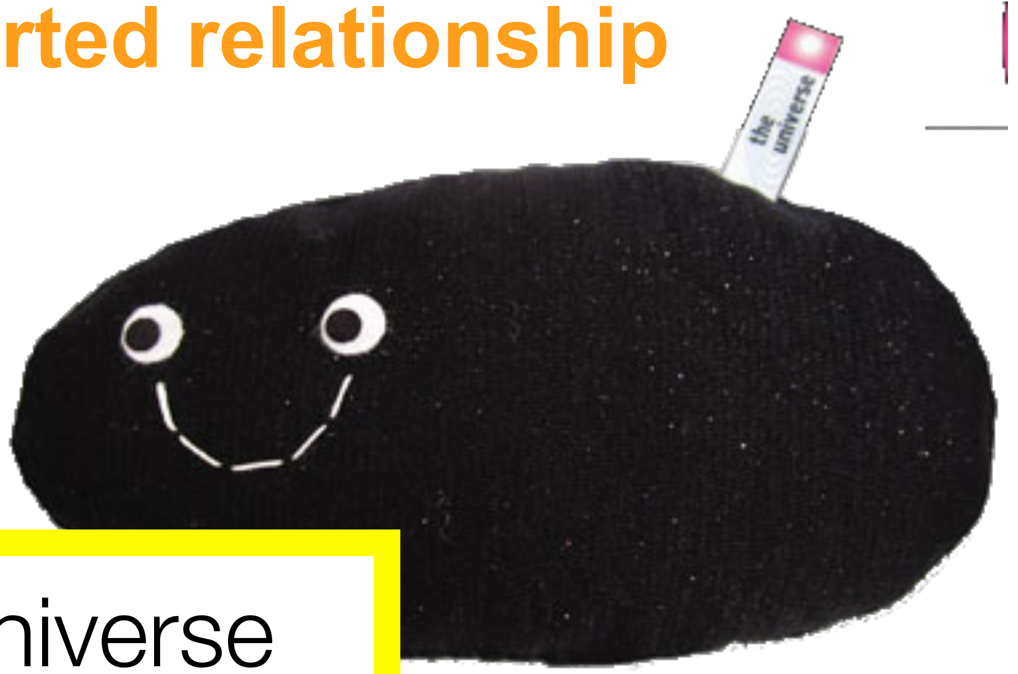

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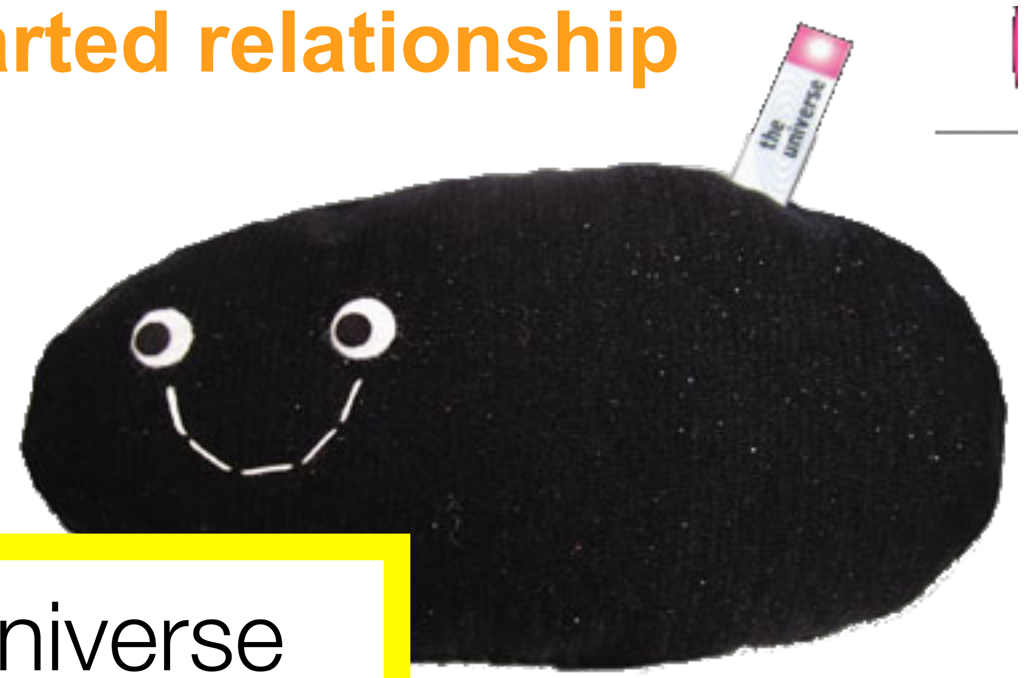
Why is the Higgs-fermion interaction so different between the species?

- 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

Exploration of an uncharted relationship



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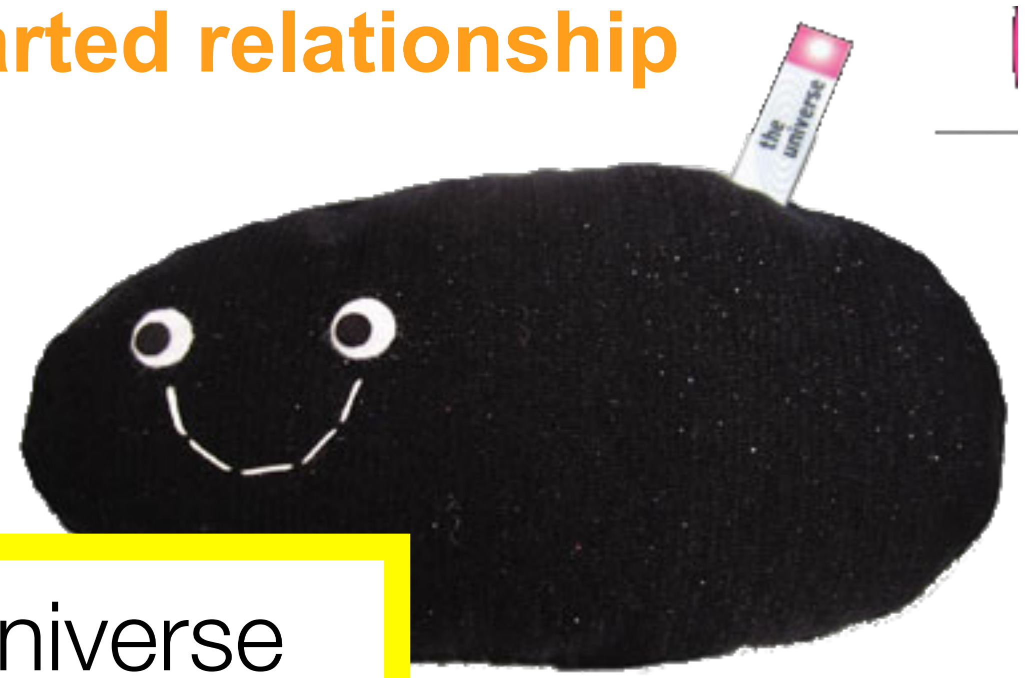
- in particular in couplings to fermions?
- or do its siblings have non-trivial CP properties?

=> small contributions -> need precise measurements!

The Higgs Boson and the Universe

Exploration of an uncharted relationship



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

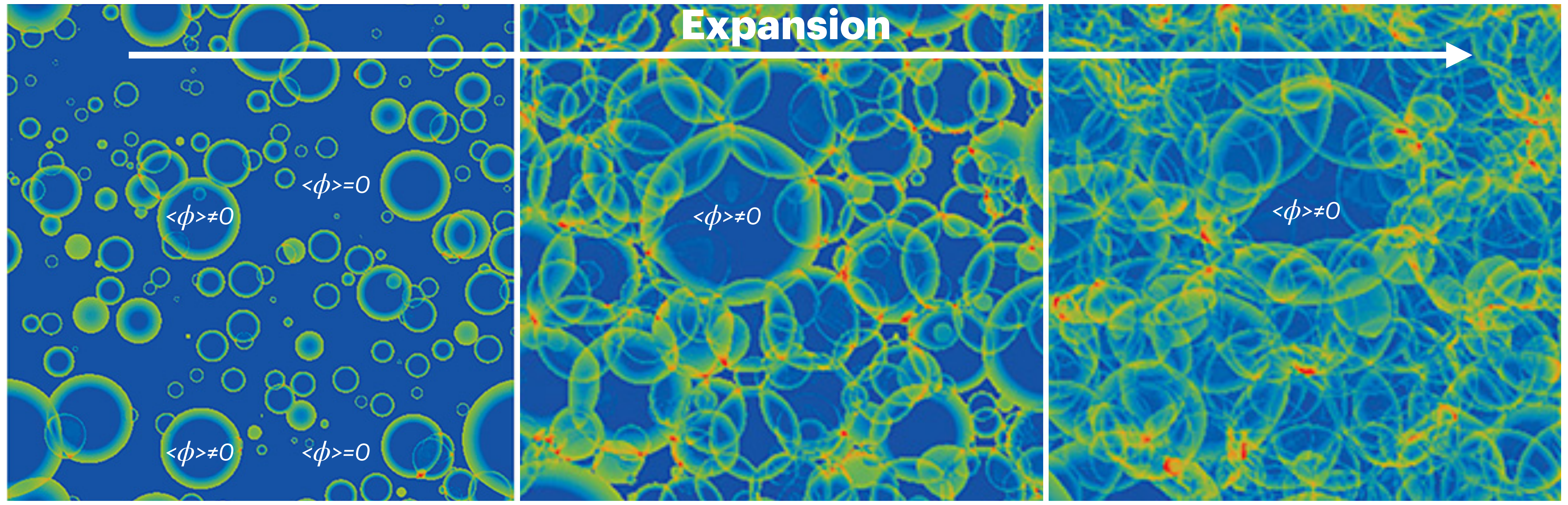
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

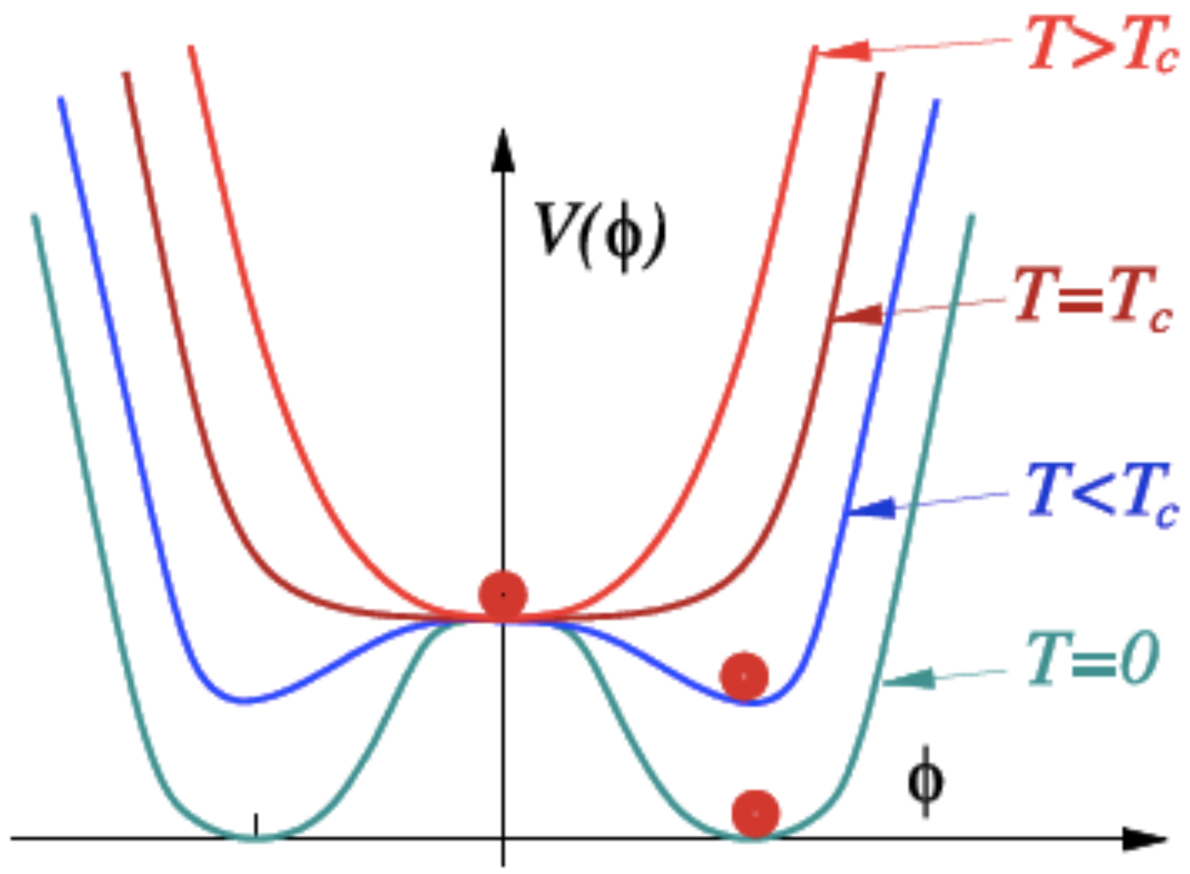
=> discover and study di-Higgs production

The Higgs potential, the Higgs self-coupling and Baryogenesis

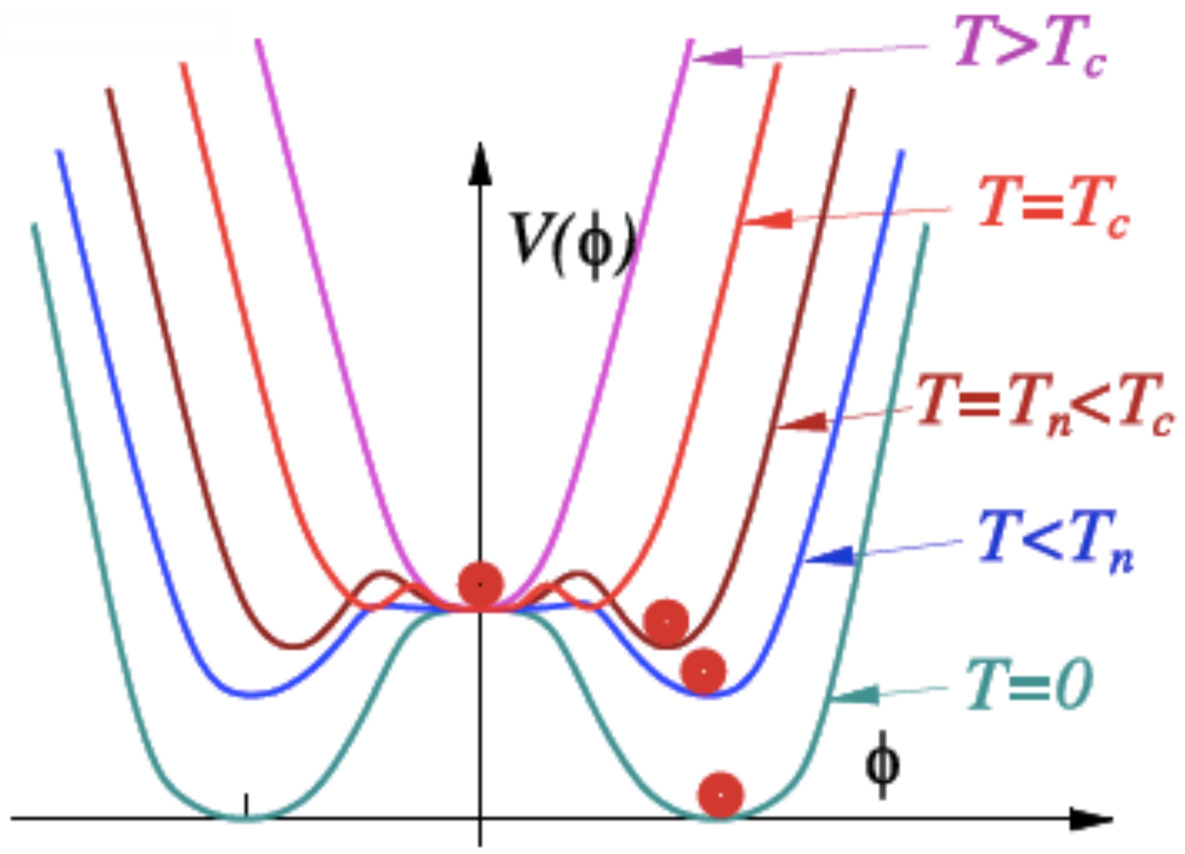
1st vs 2nd order phase transition

- 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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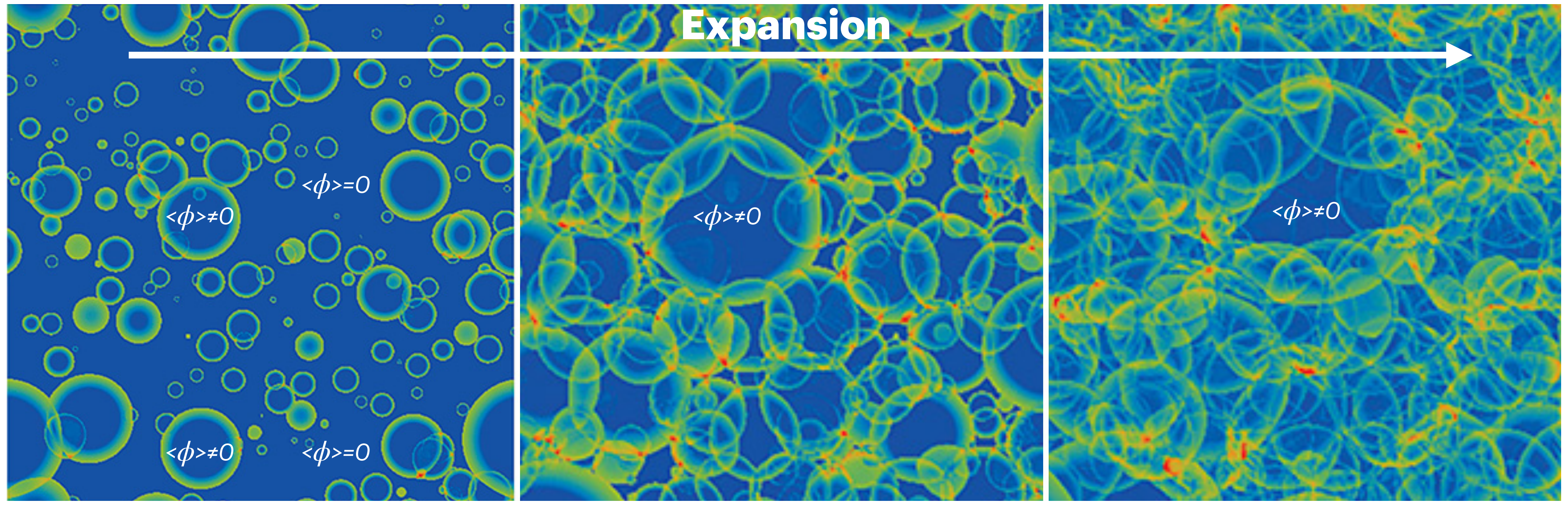

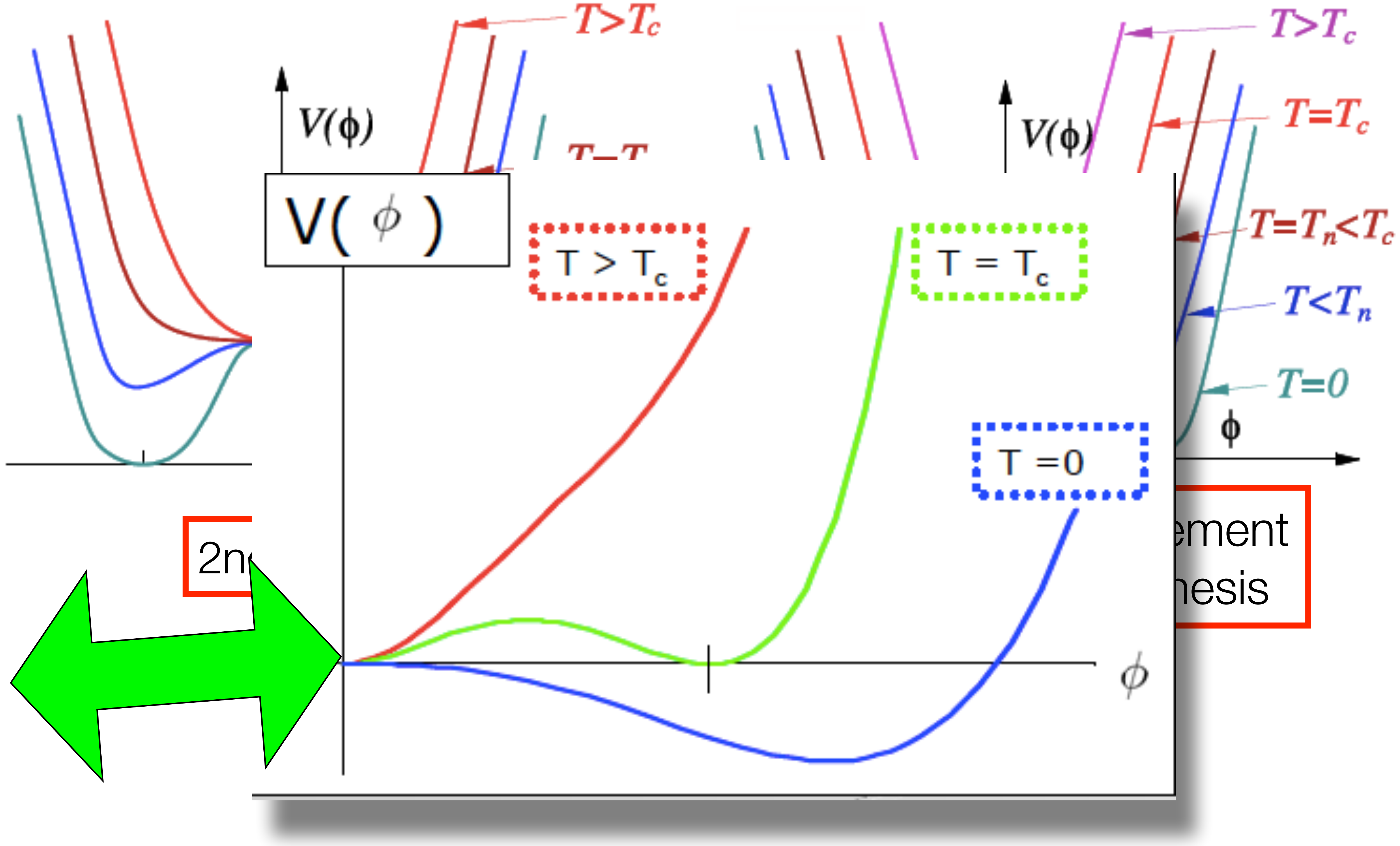

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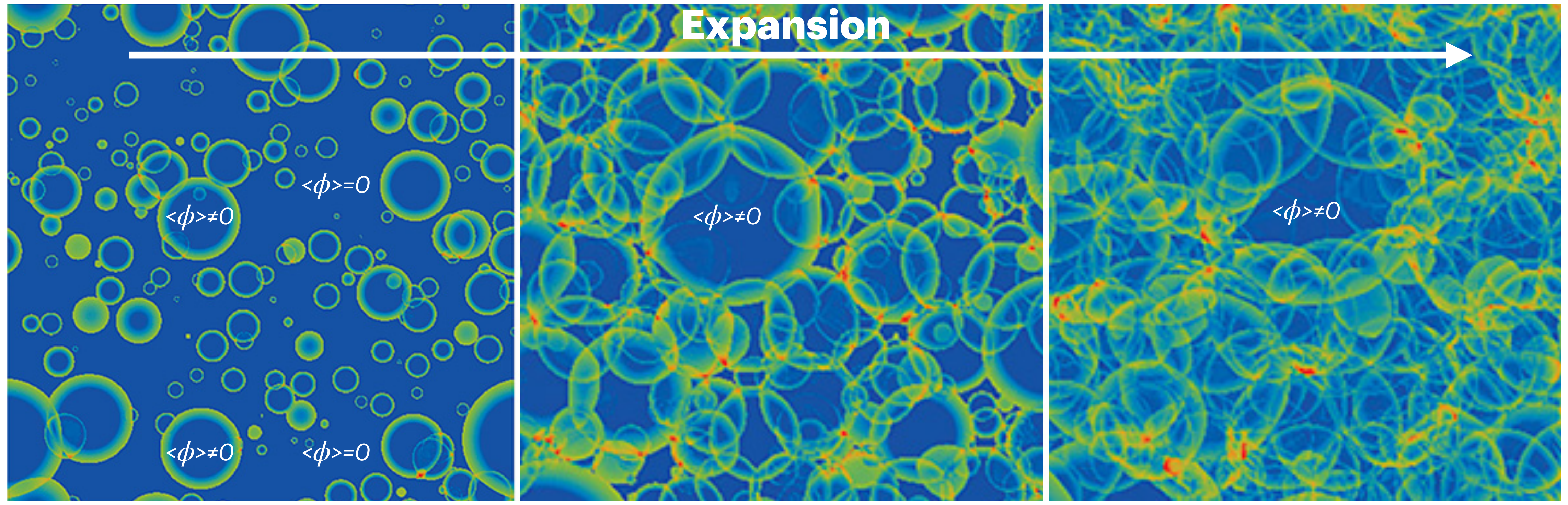

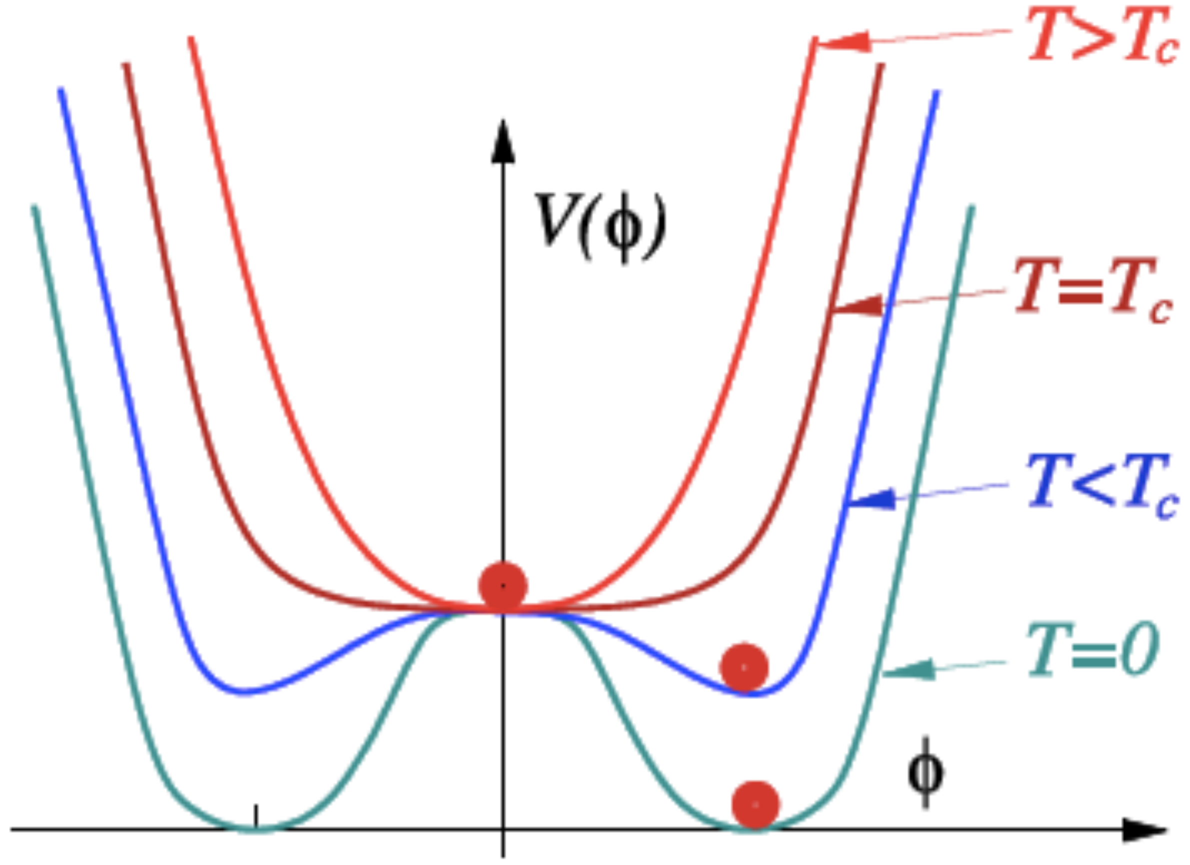

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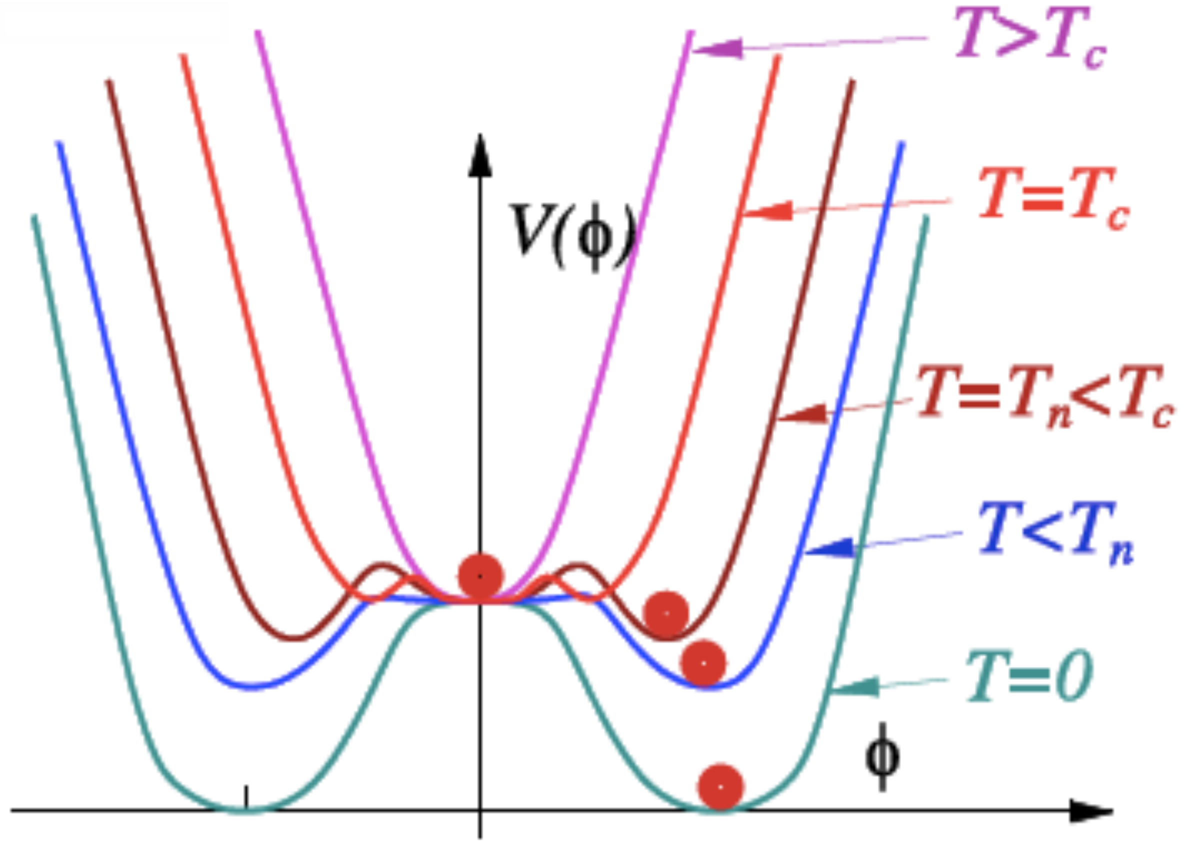

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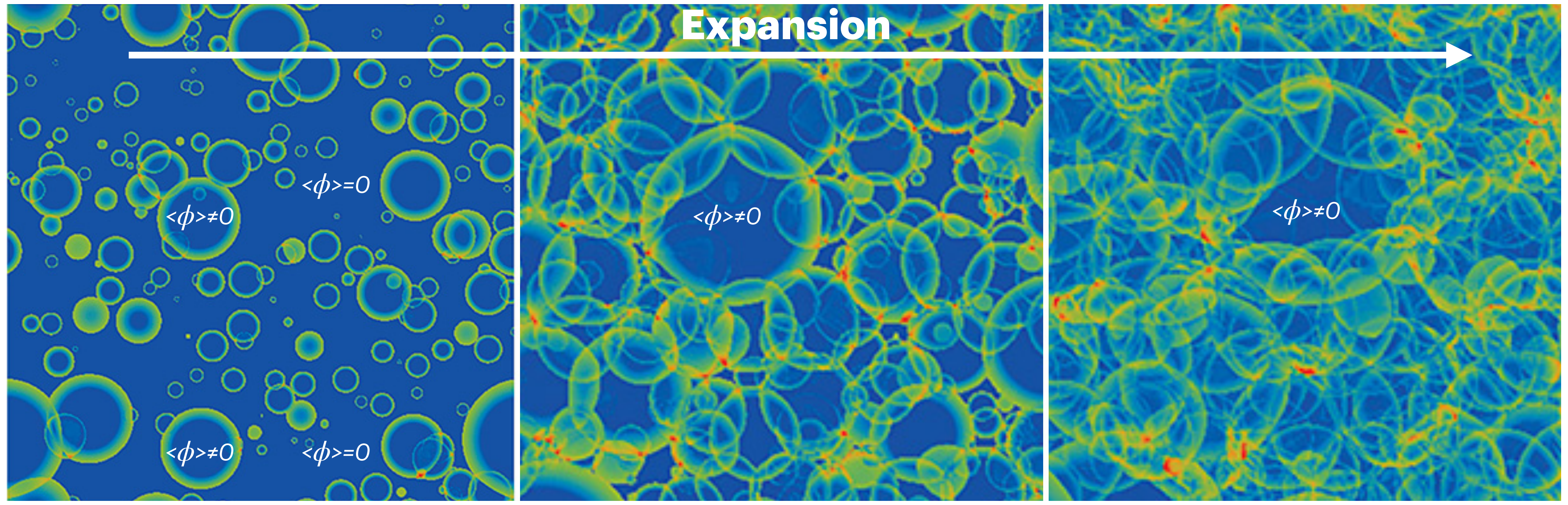

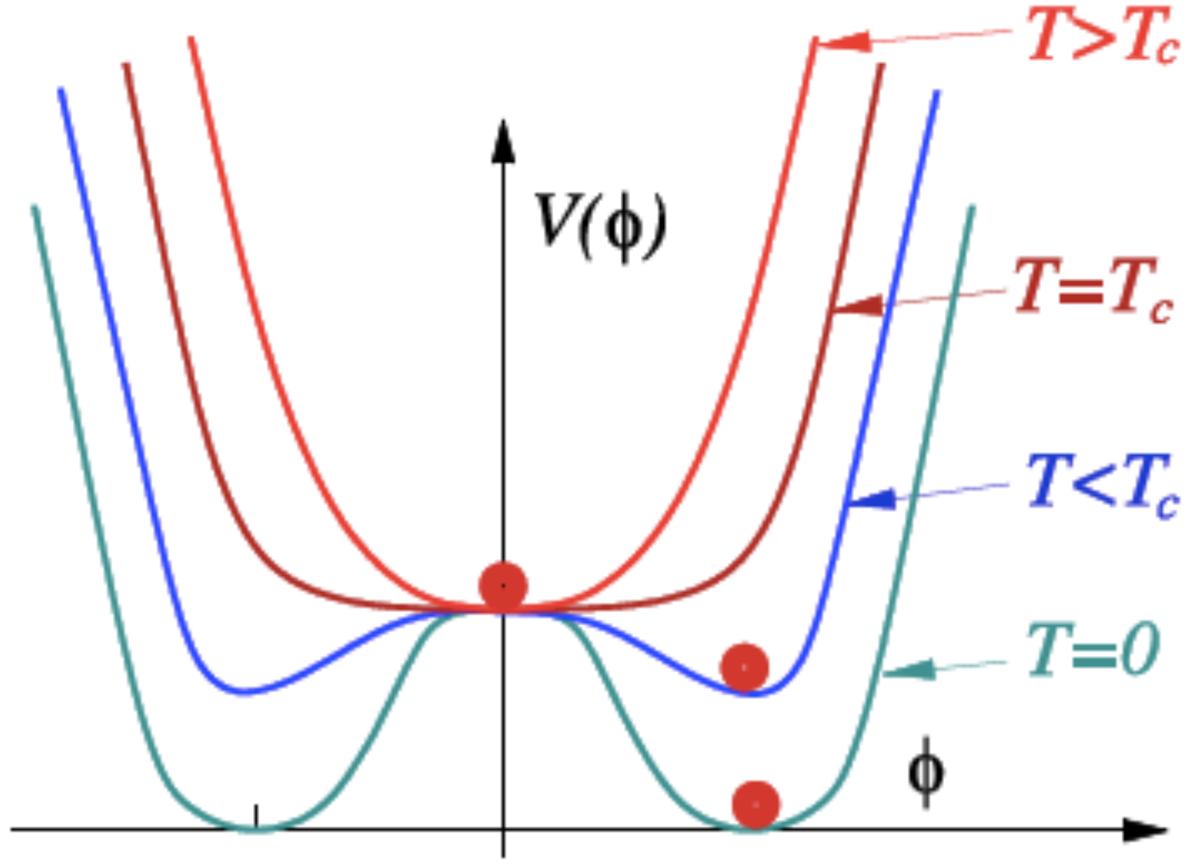

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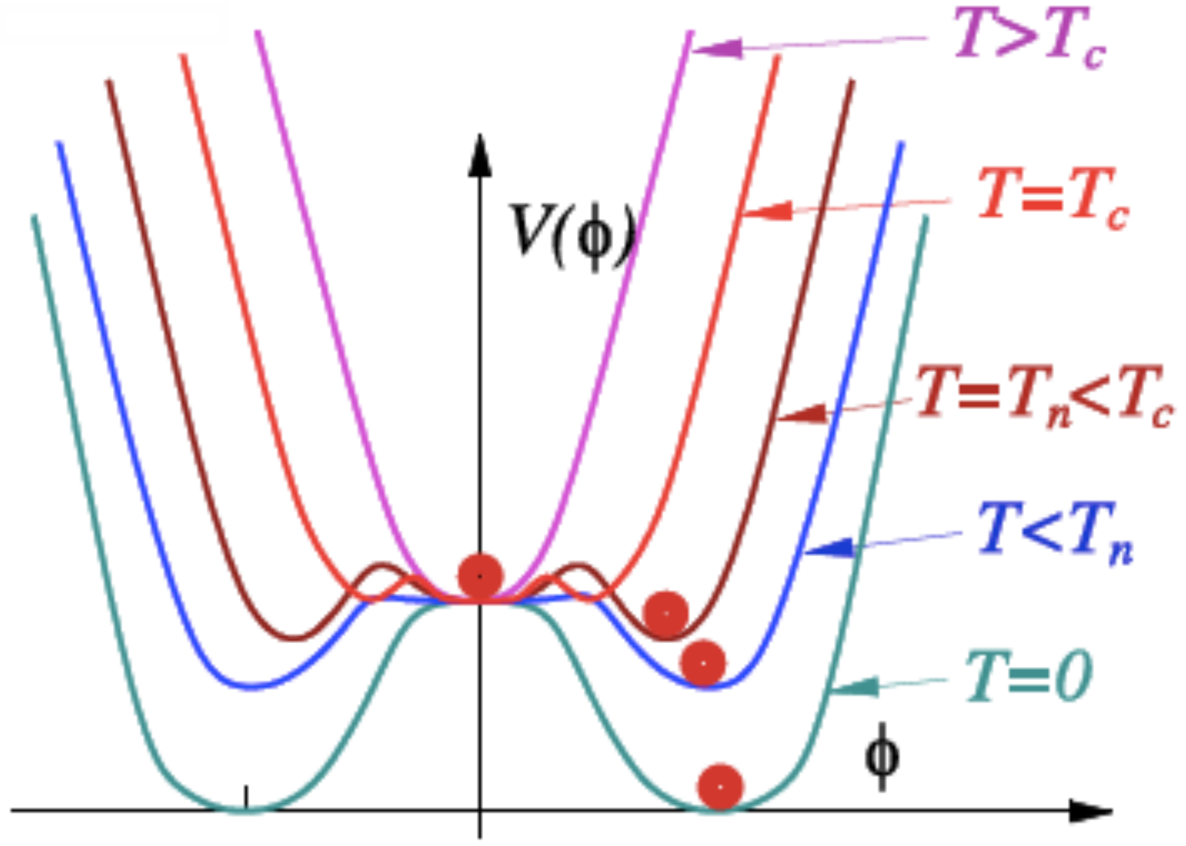


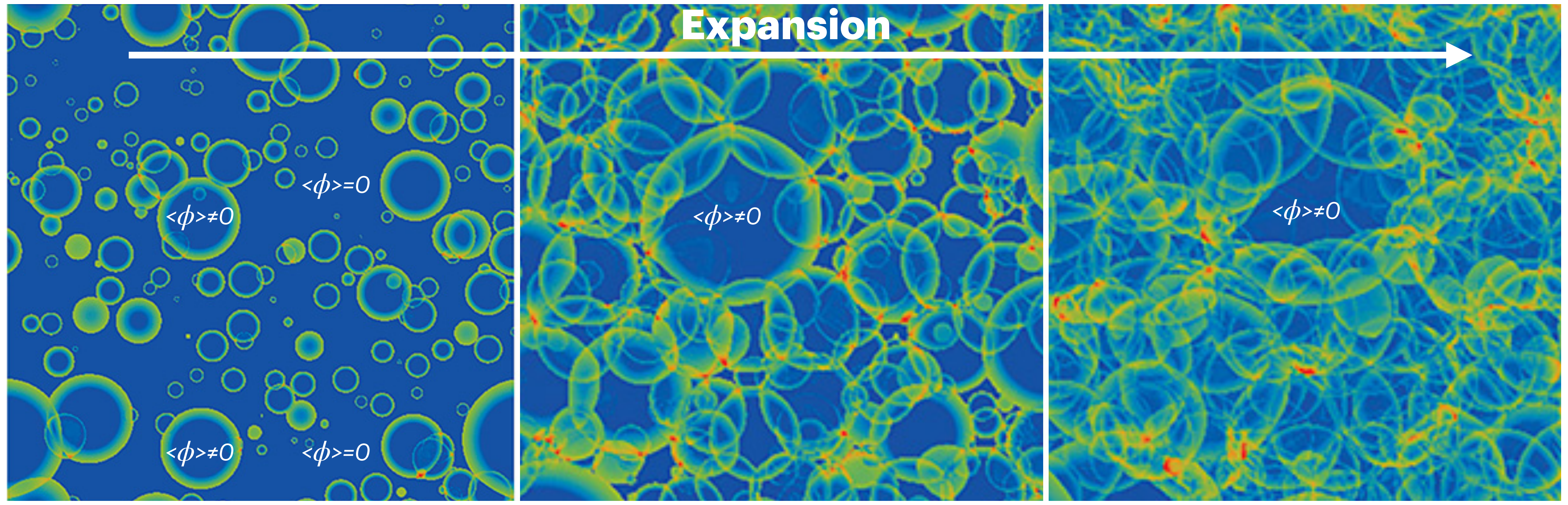
1st order, requirement for EW baryogenesis

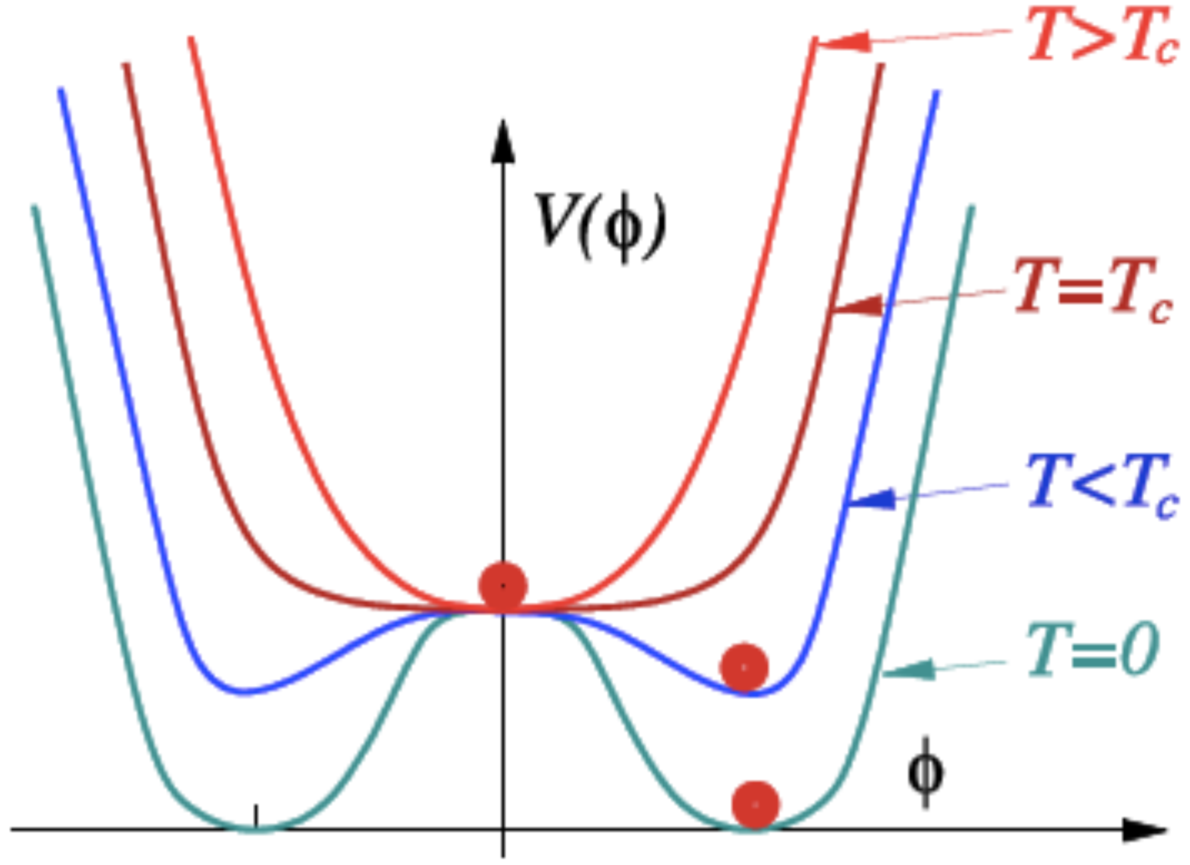
- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
- electroweak baryogenesis possible in BSM scenarions with $\lambda > \lambda_{SM}$ (e.g. 2HDM, NMSSM, …)

The Higgs potential, the Higgs self-coupling and Baryogenesis

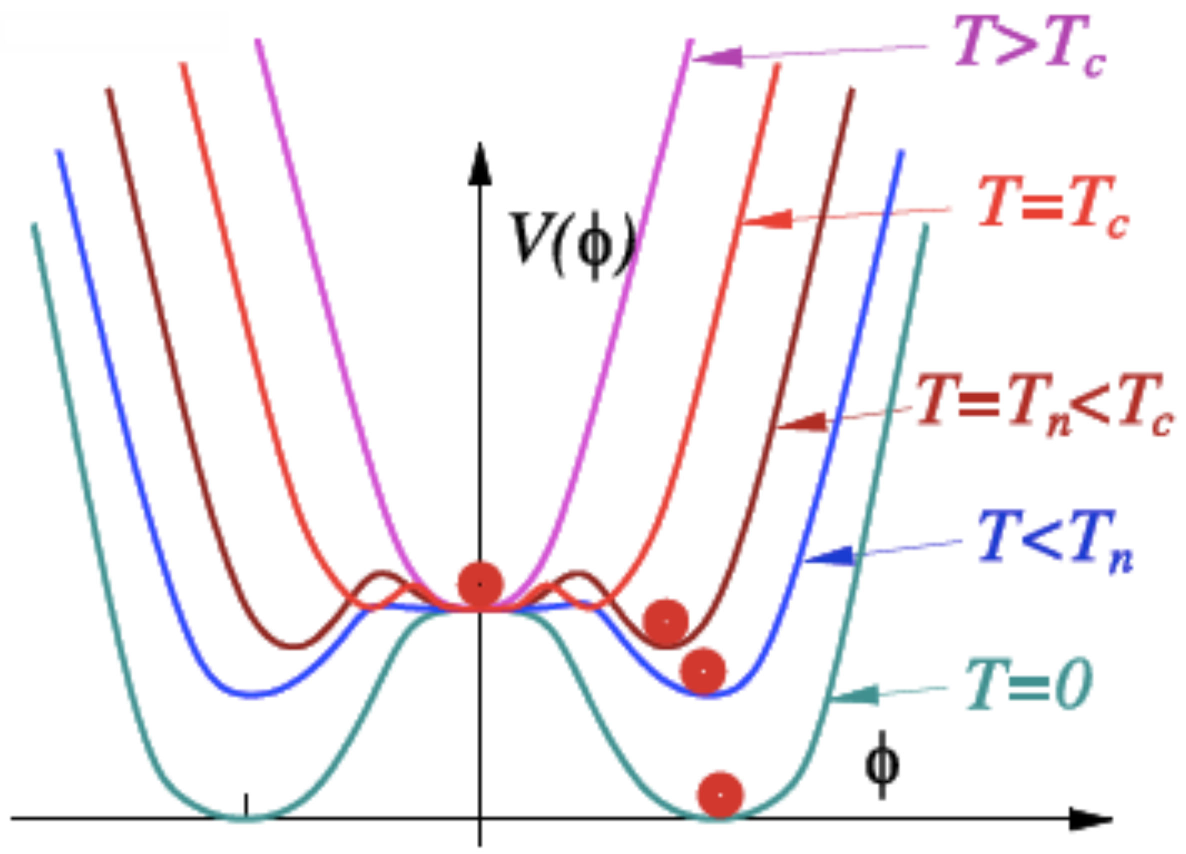
1st vs 2nd order phase transition

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



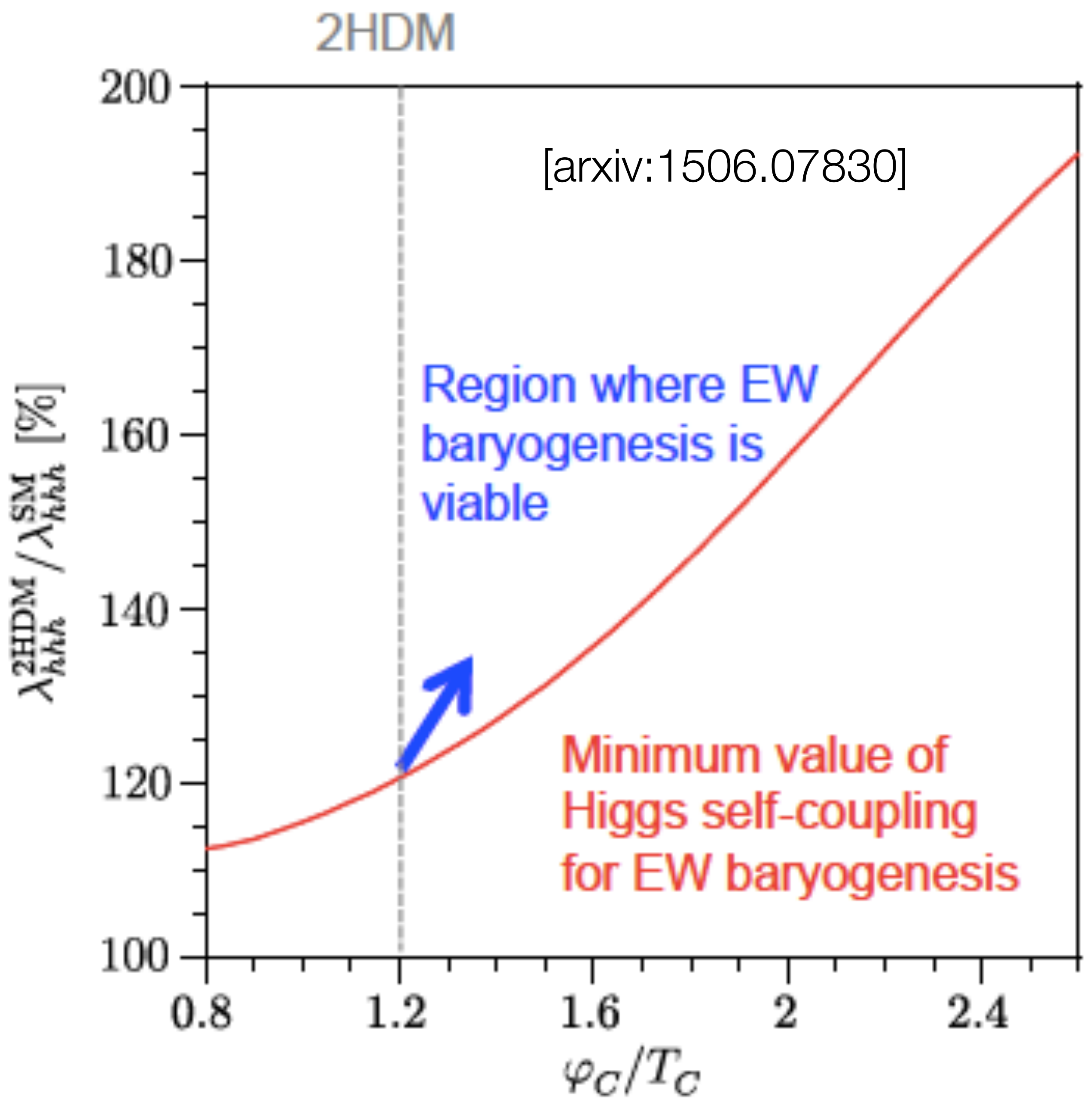


2nd order



1st order, requirement for EW baryogenesis

- 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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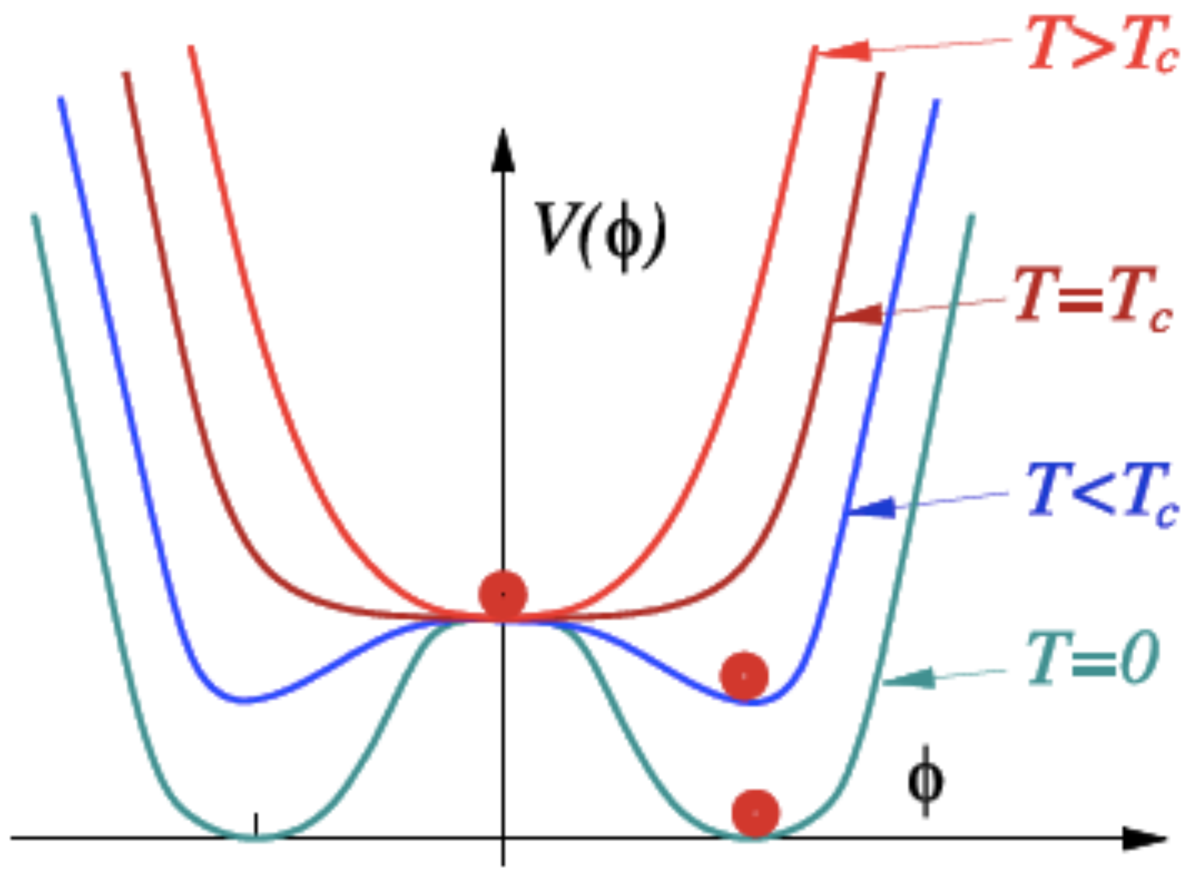

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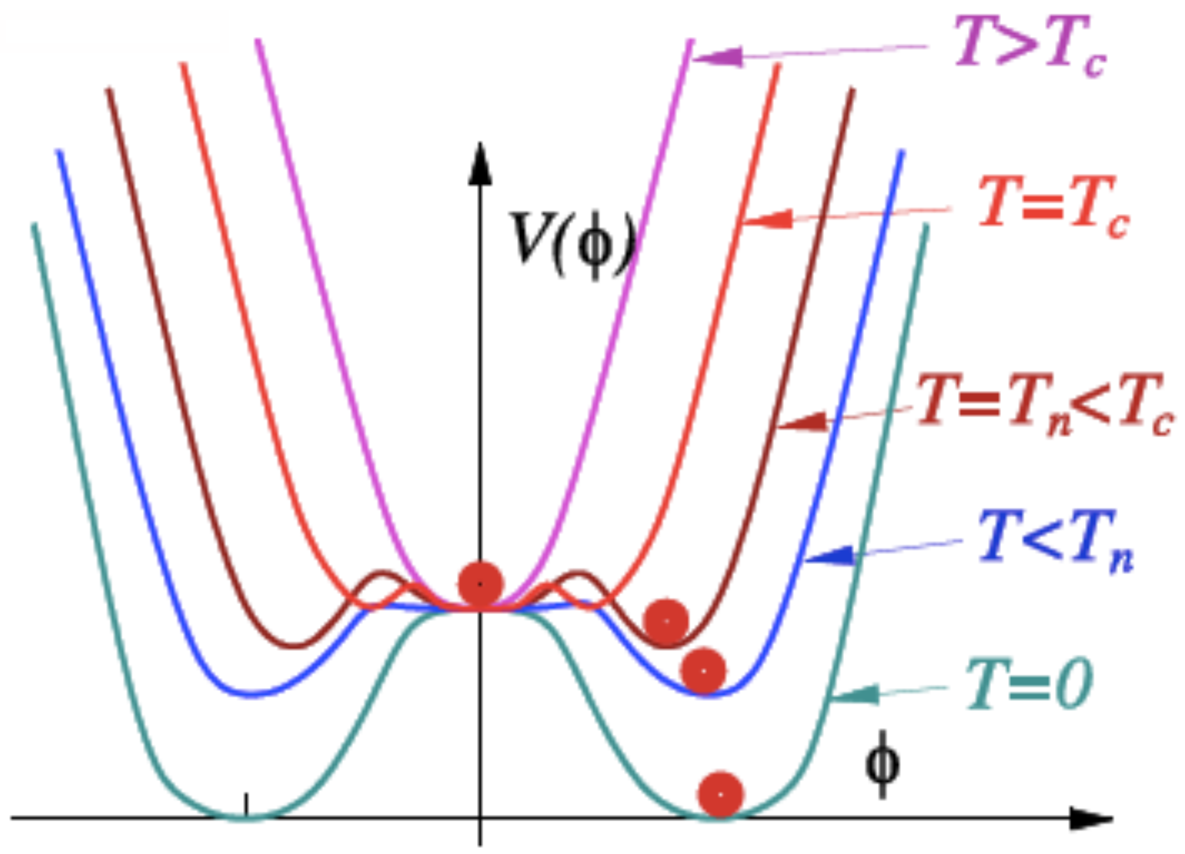

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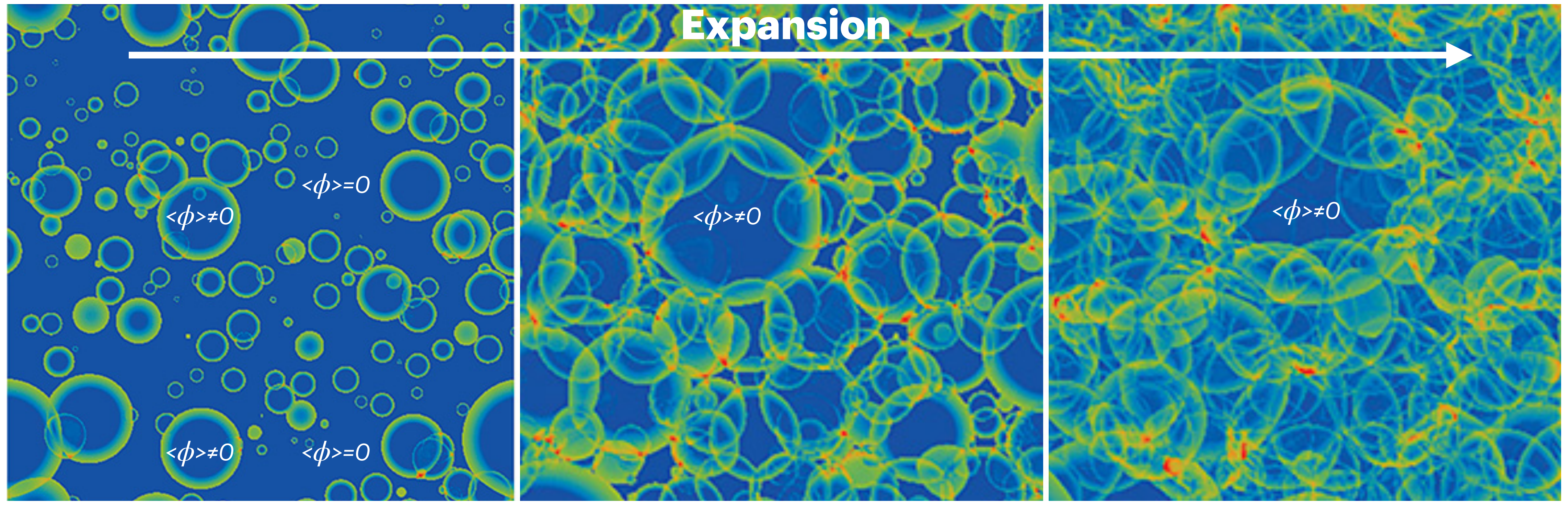

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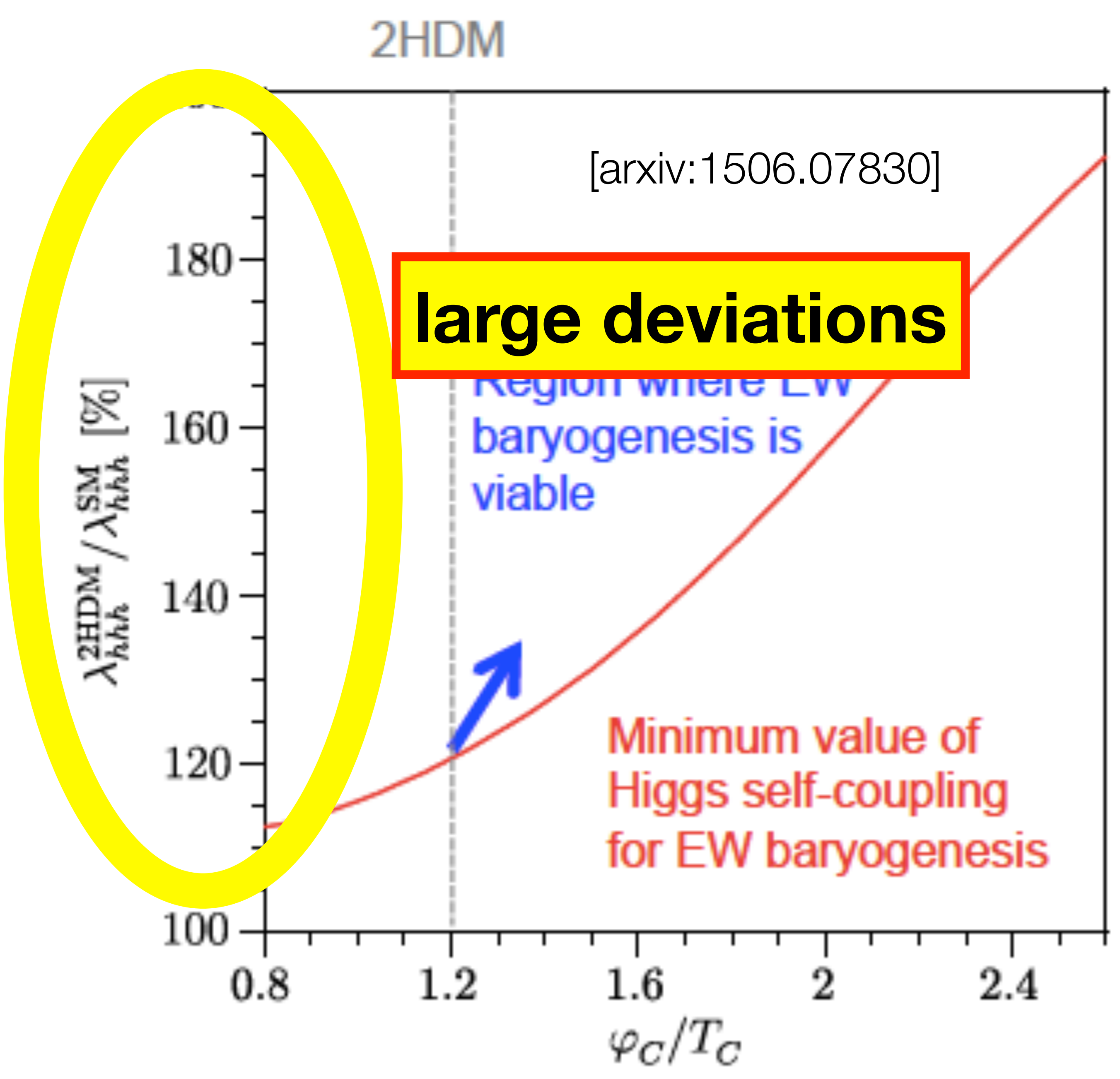

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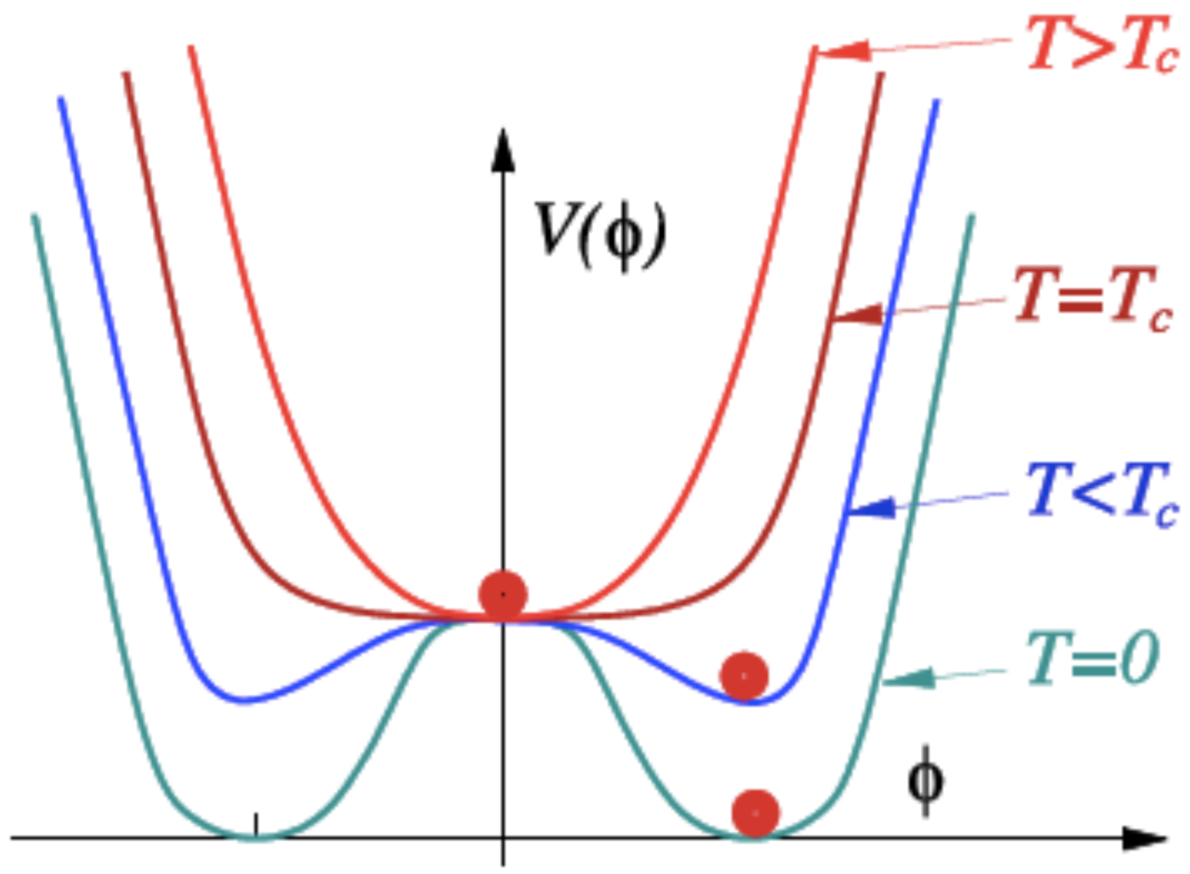

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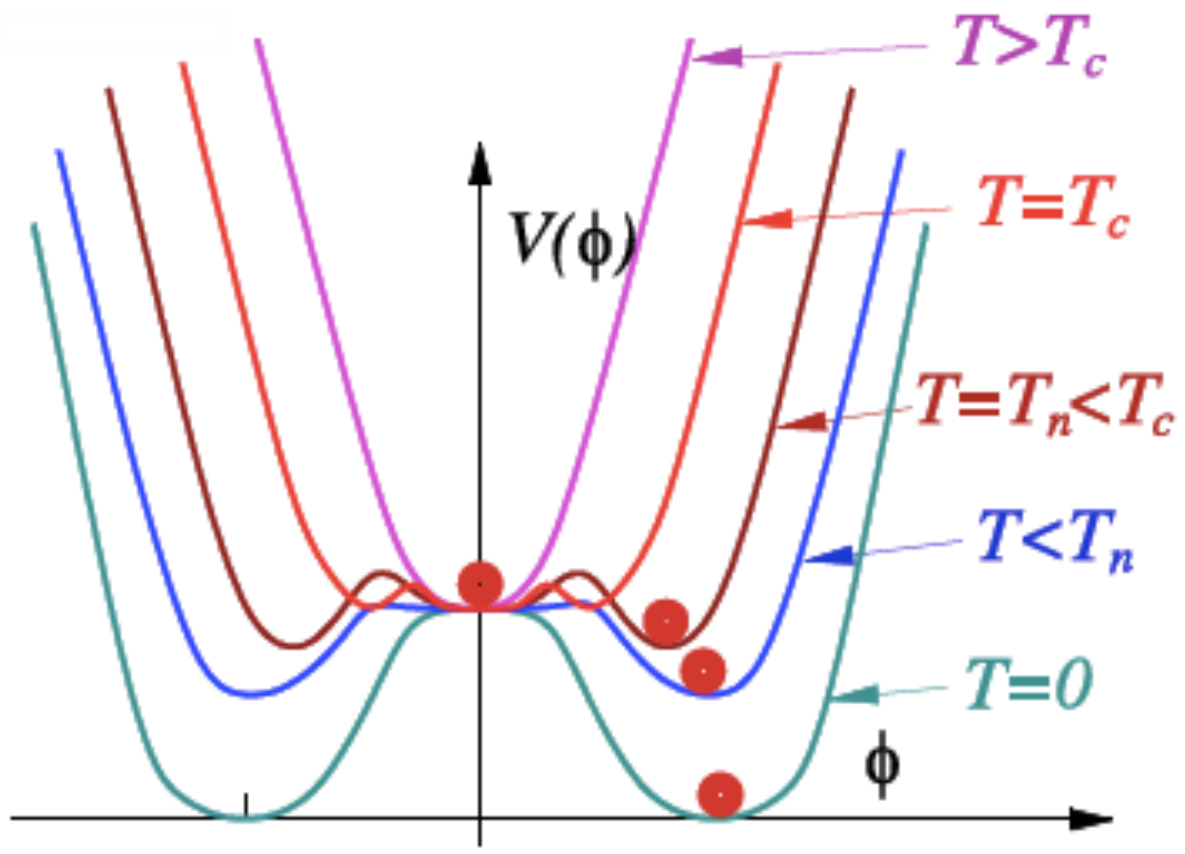

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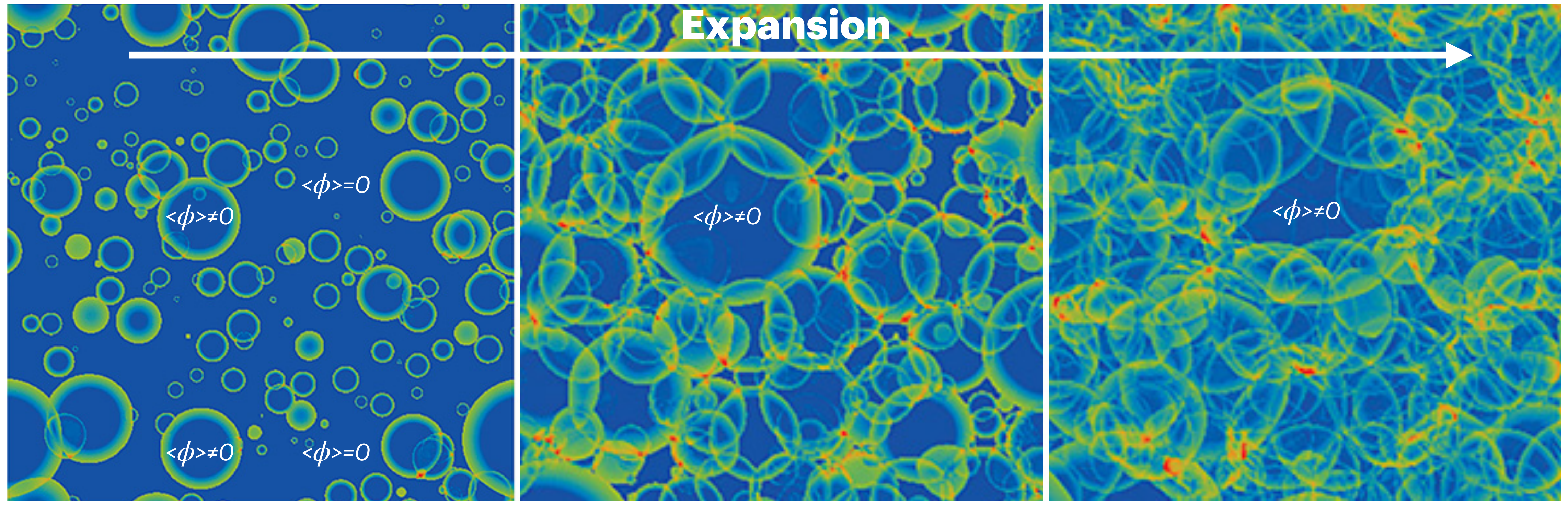
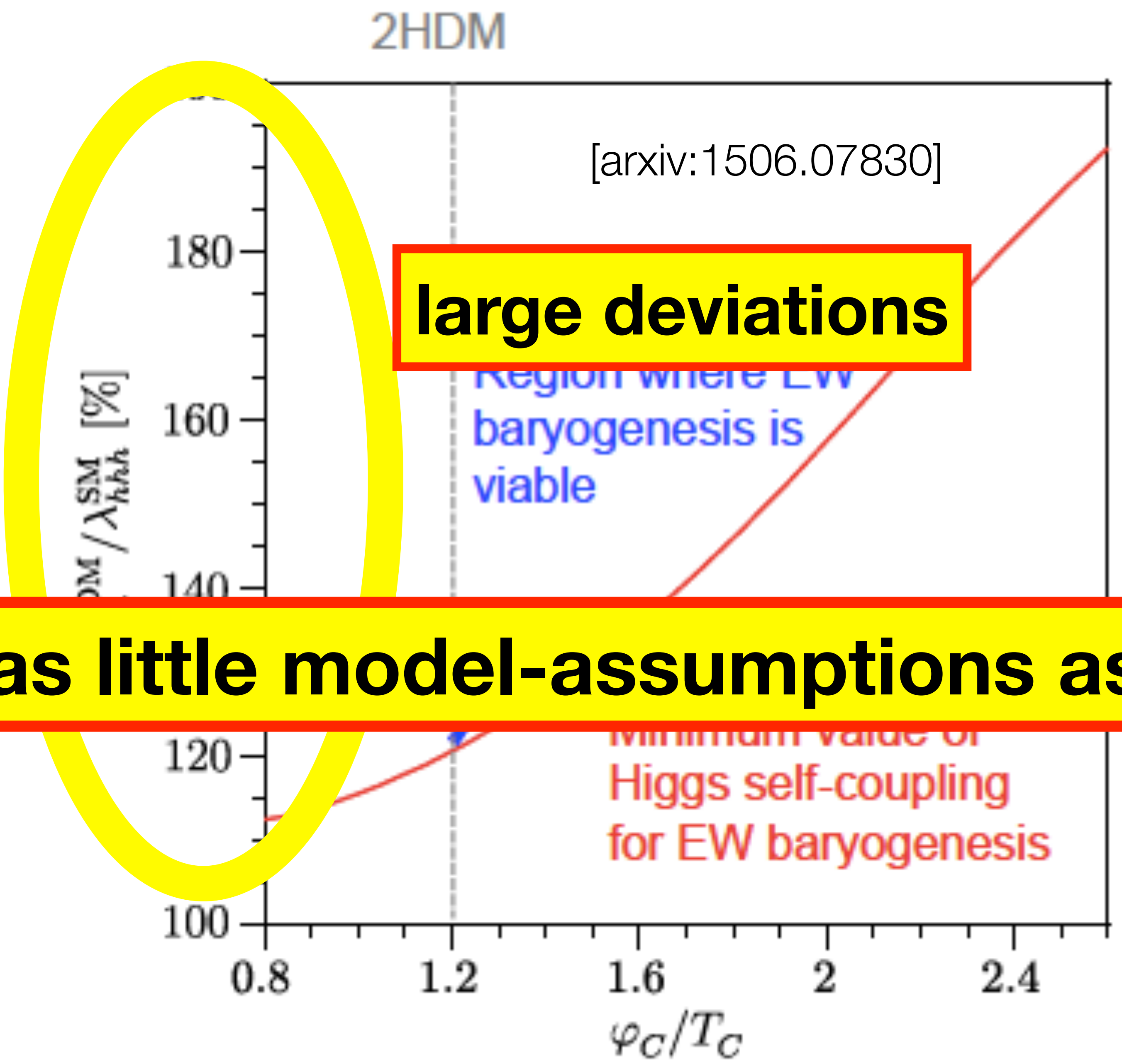




large deviations

- 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, …)

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

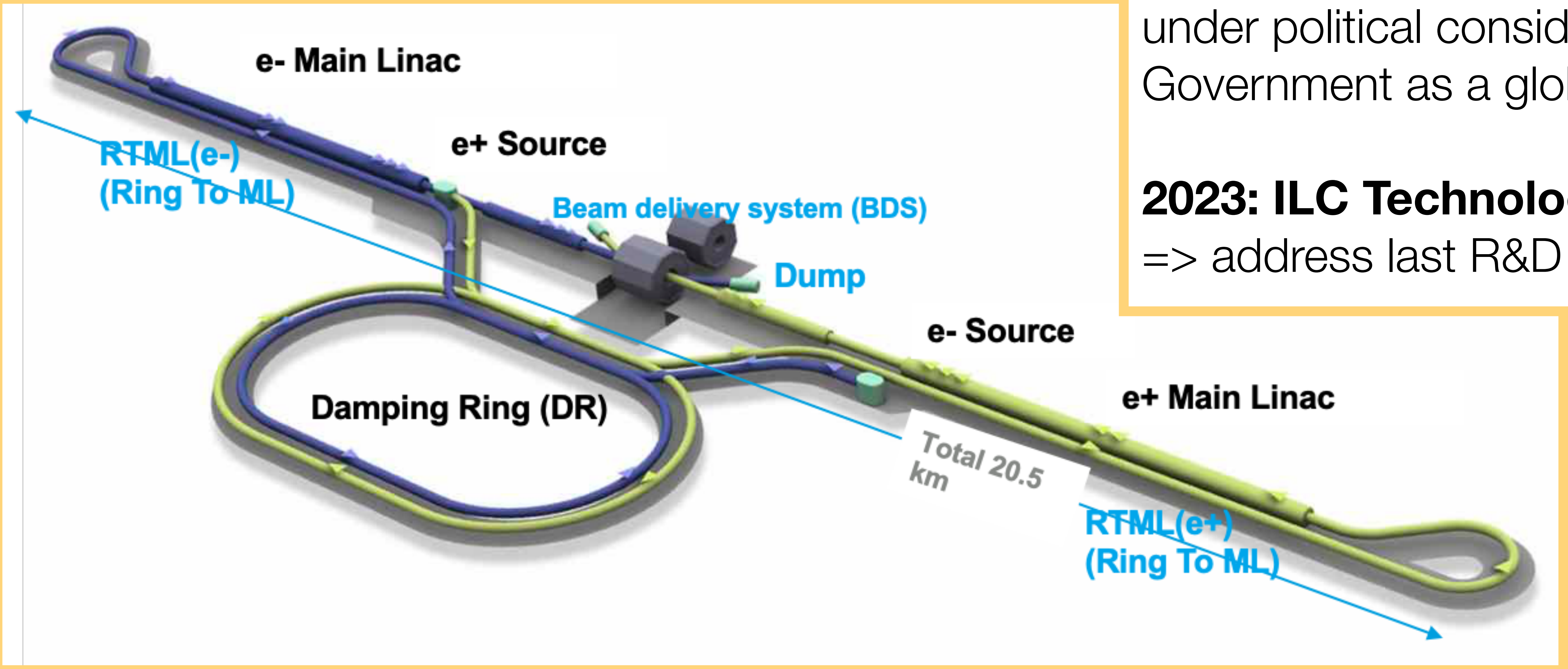
The key contenders

Status overview

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

under political consideration by Japanese Government as a global project

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



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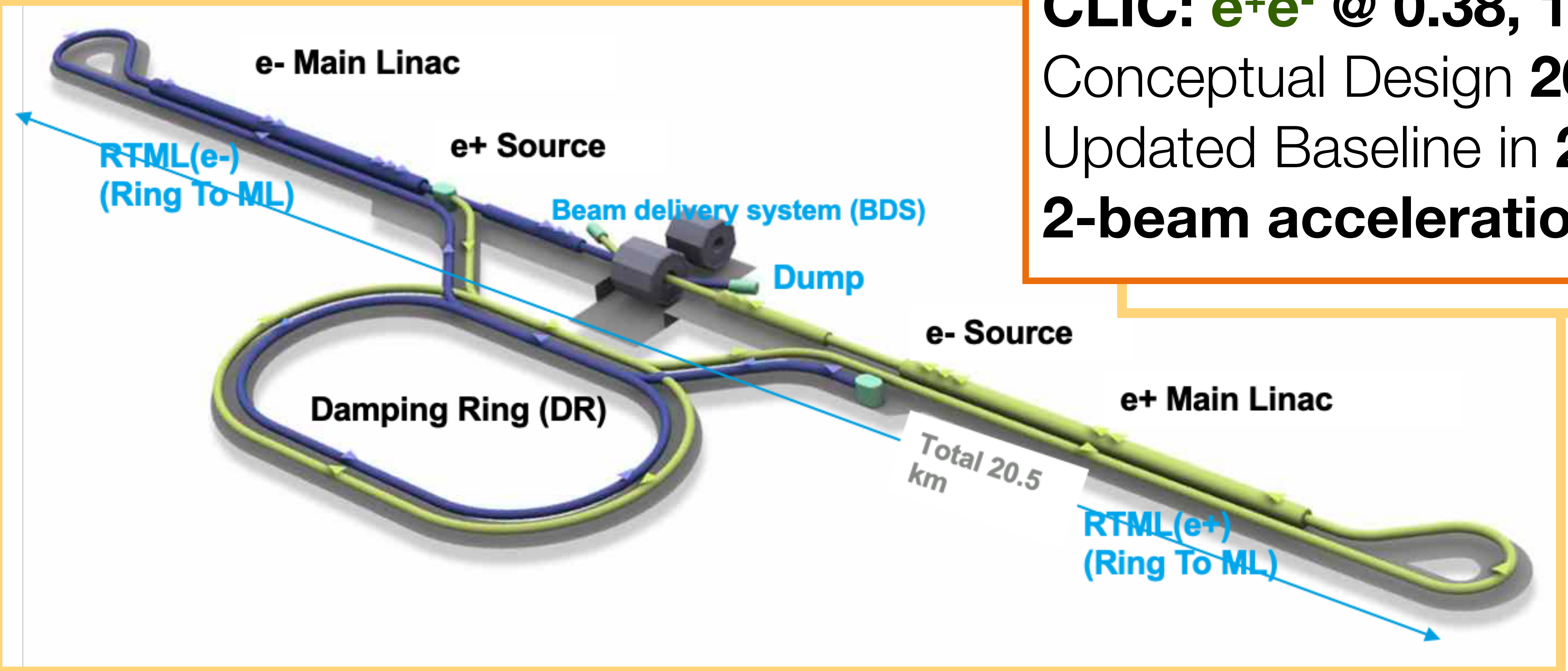

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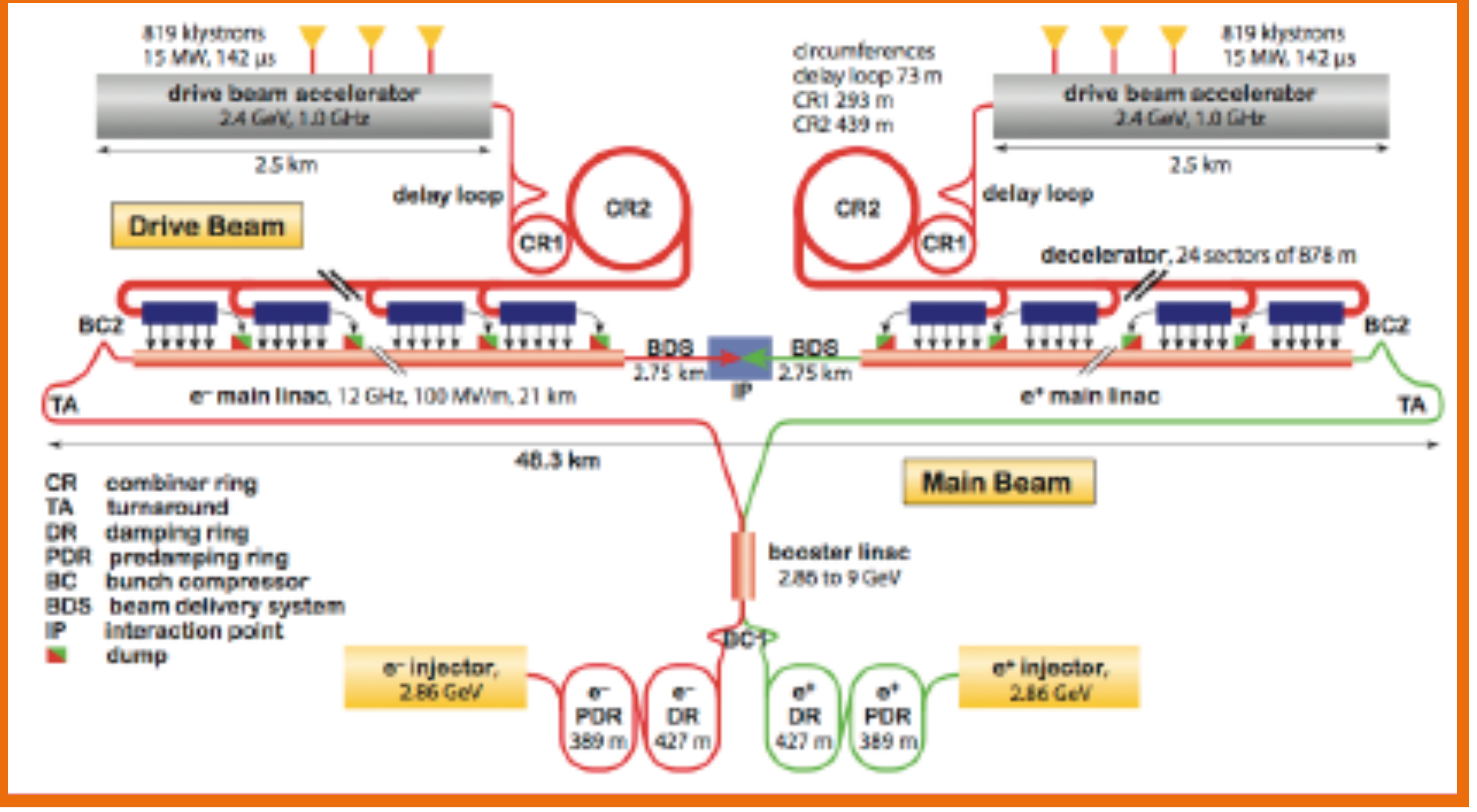

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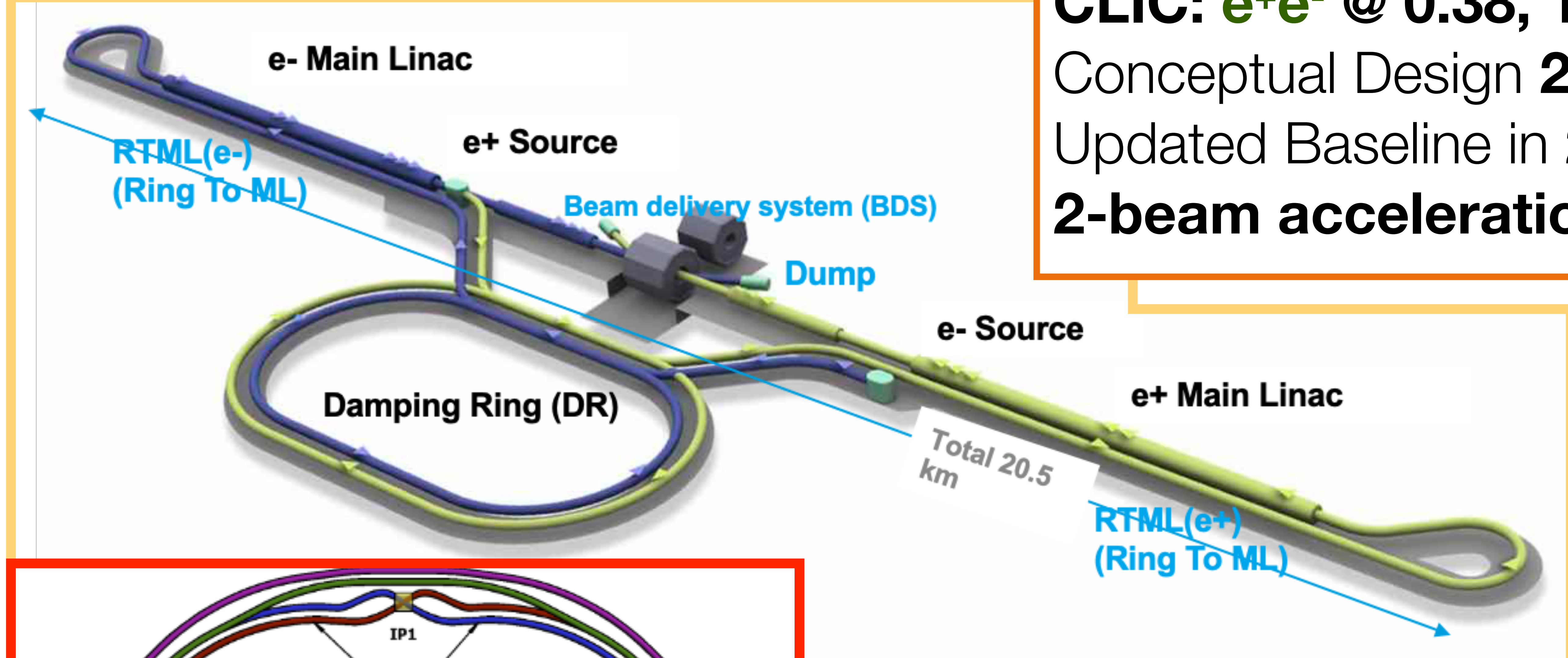

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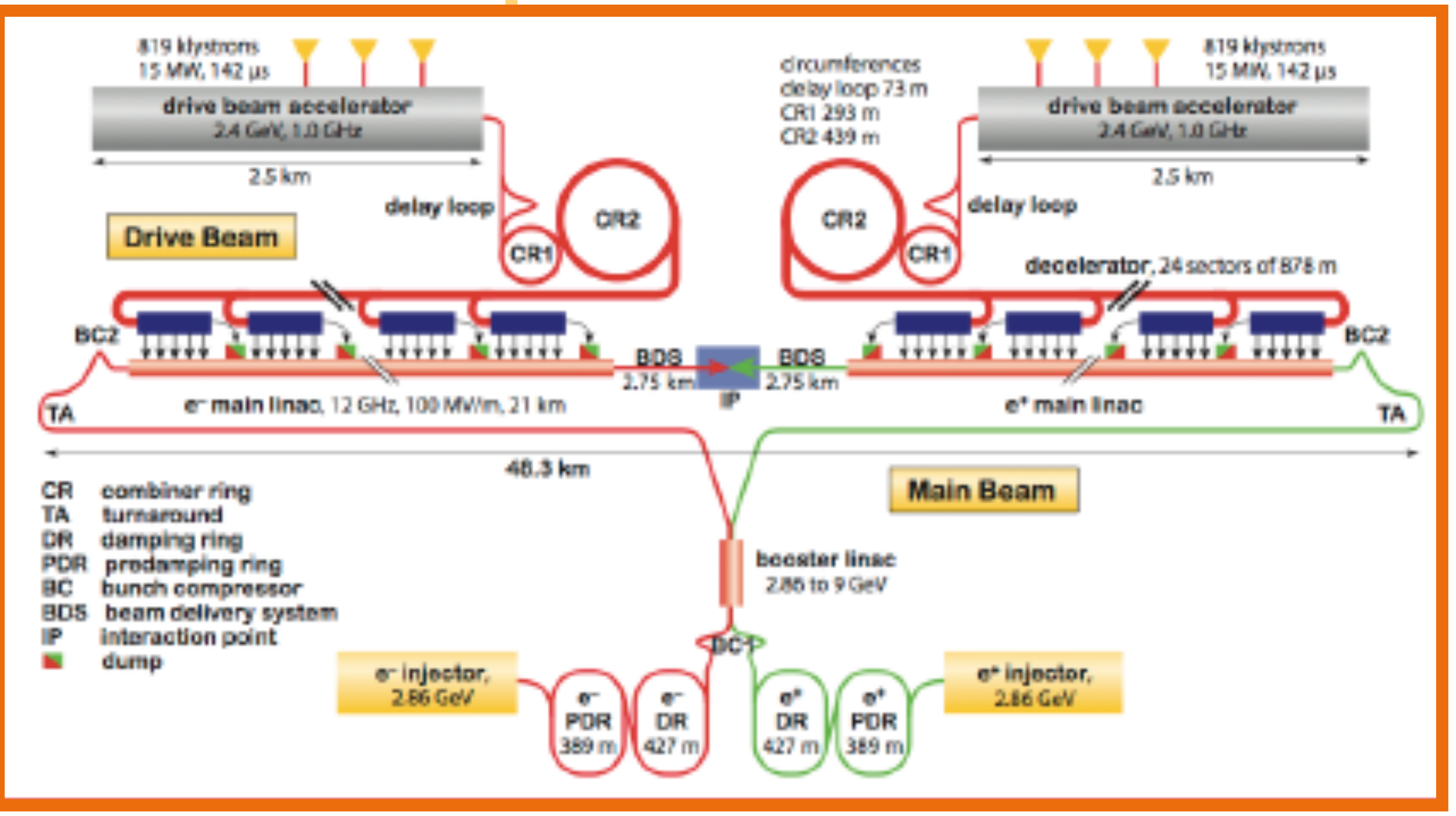

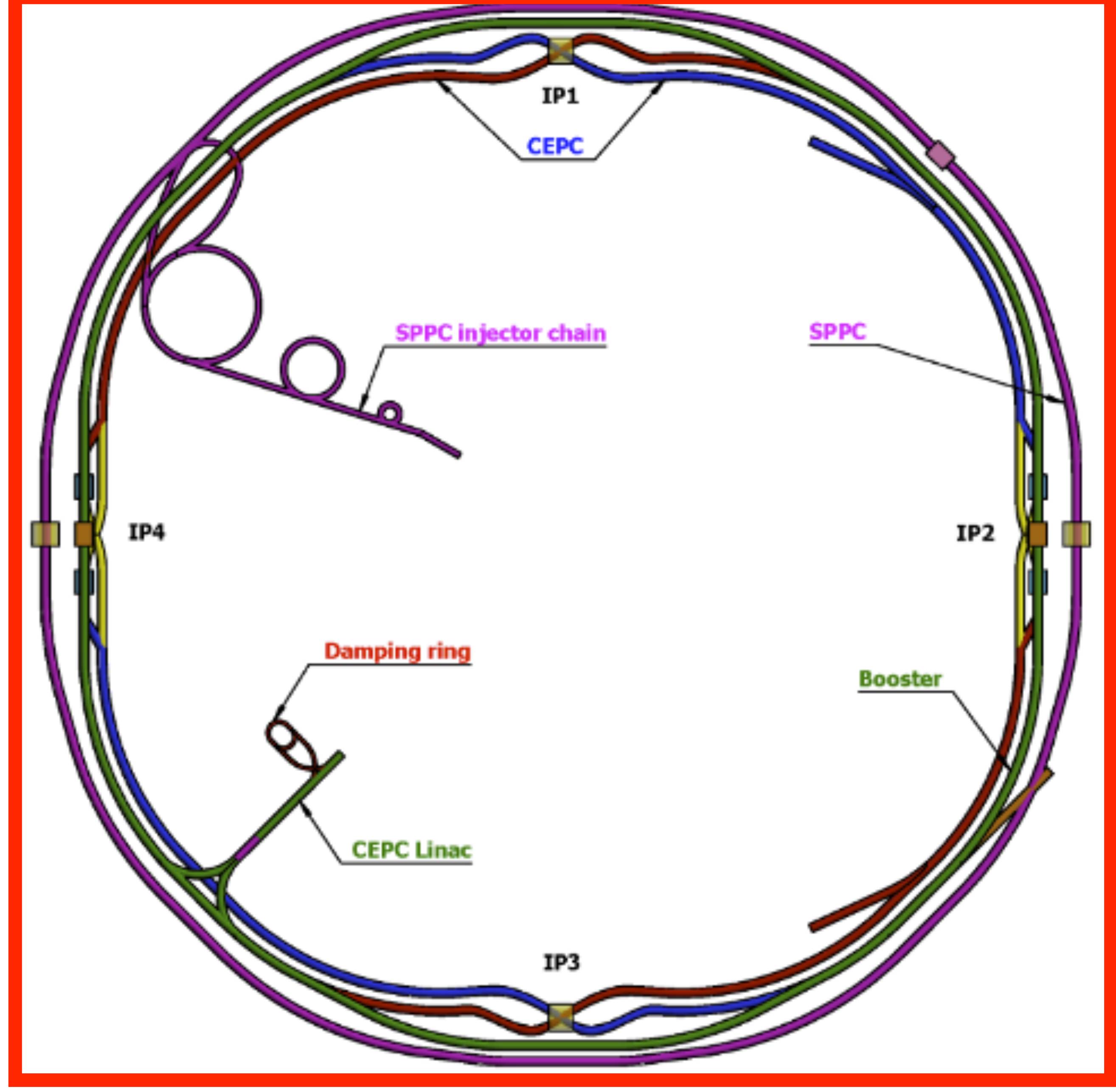

CEPC: e+e- @ 90-365 GeV

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

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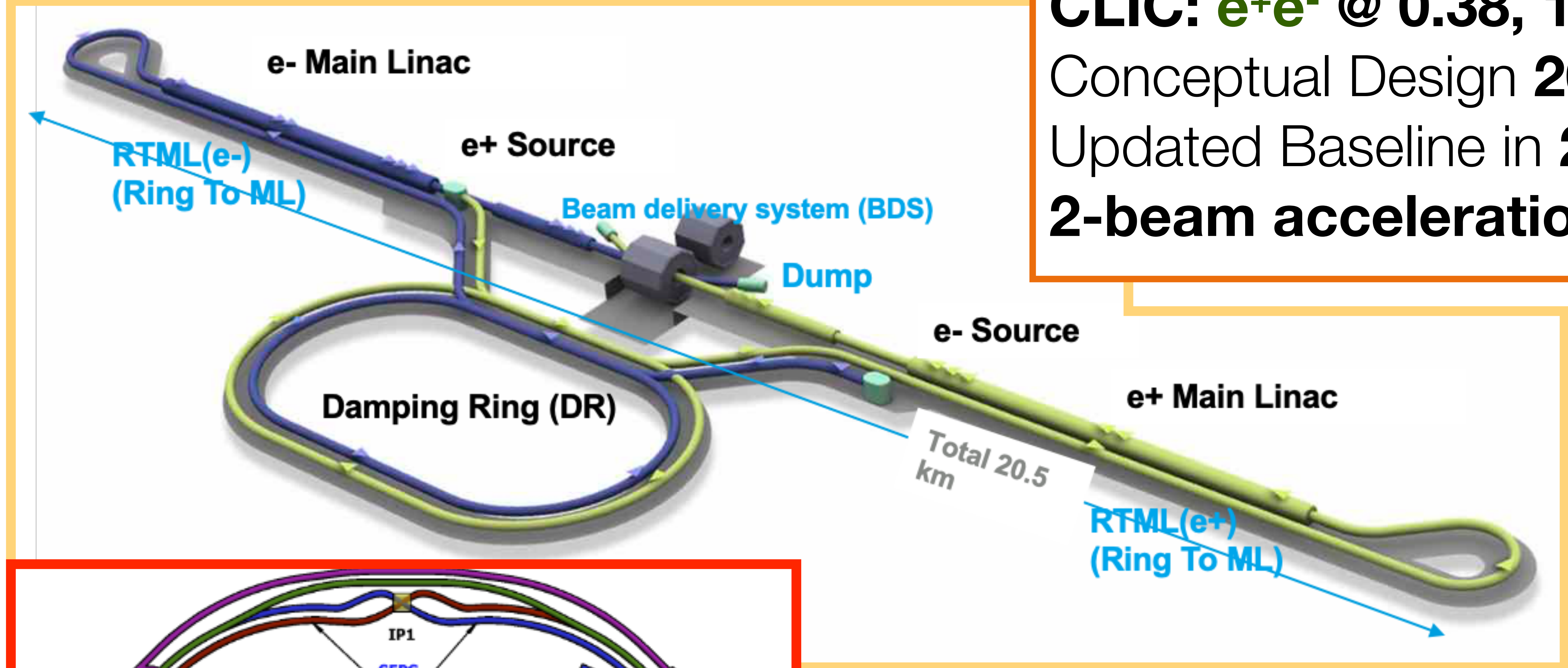

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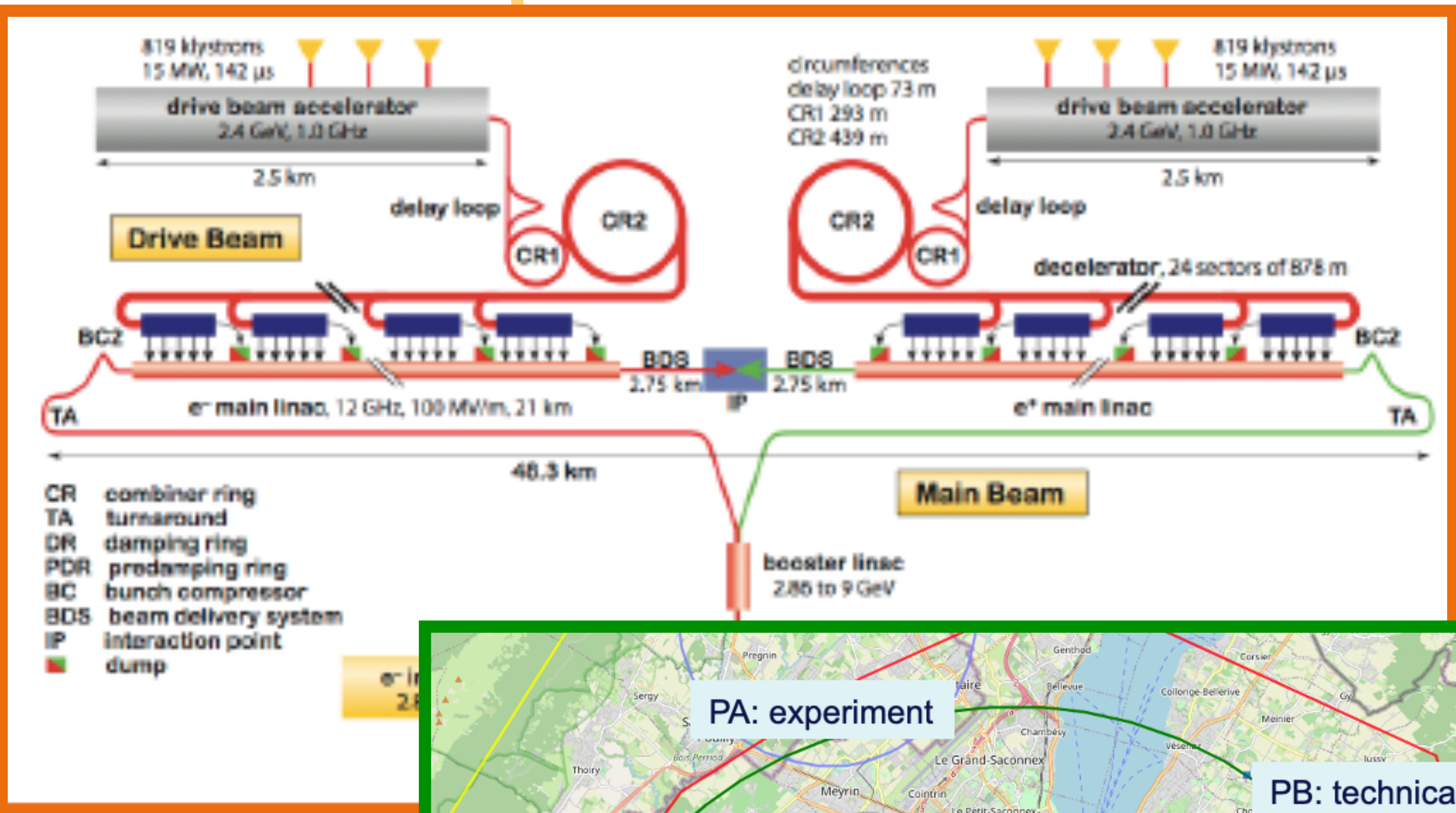

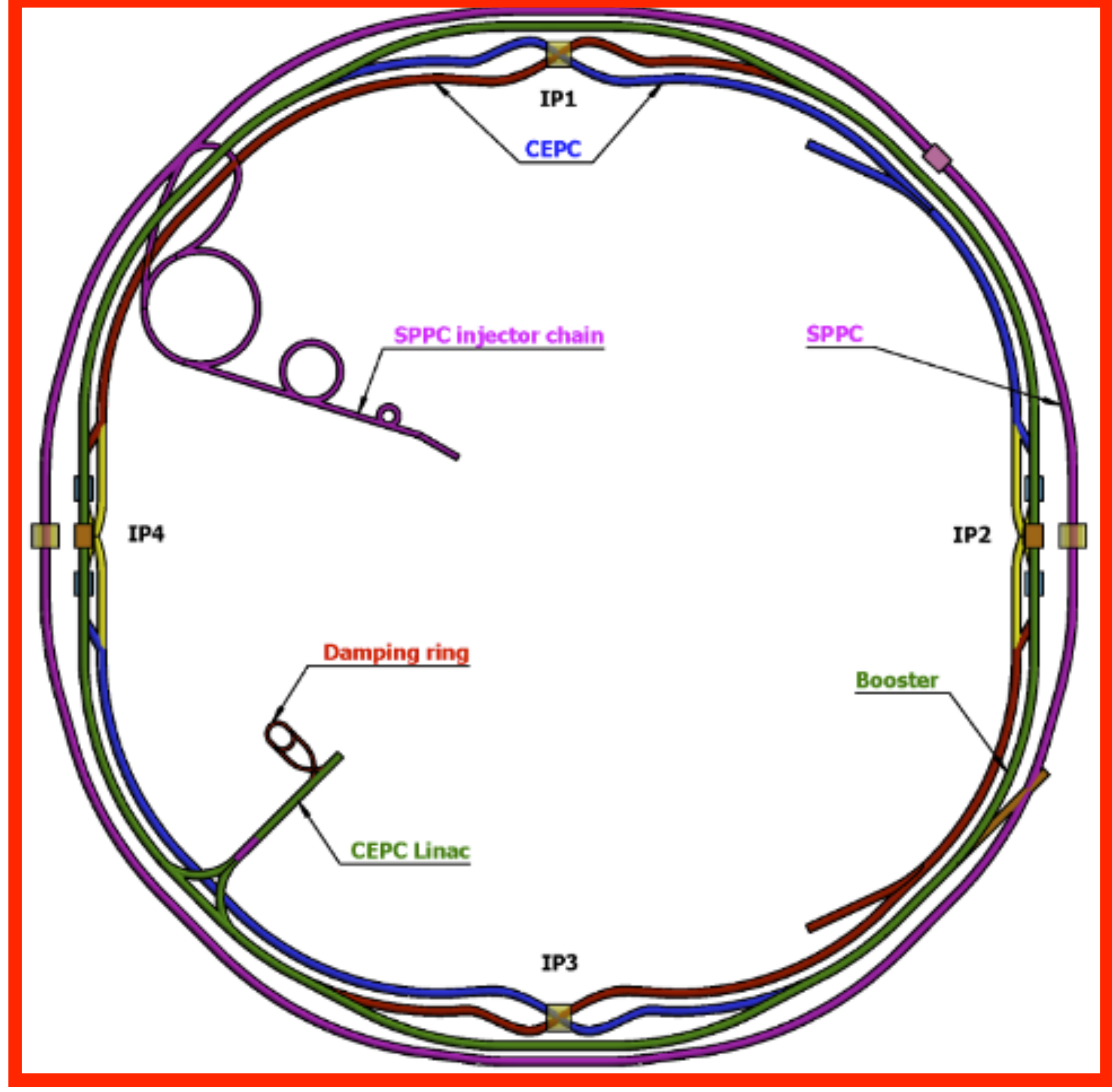

CEPC

CDR p
TDR i
aimin
ranke

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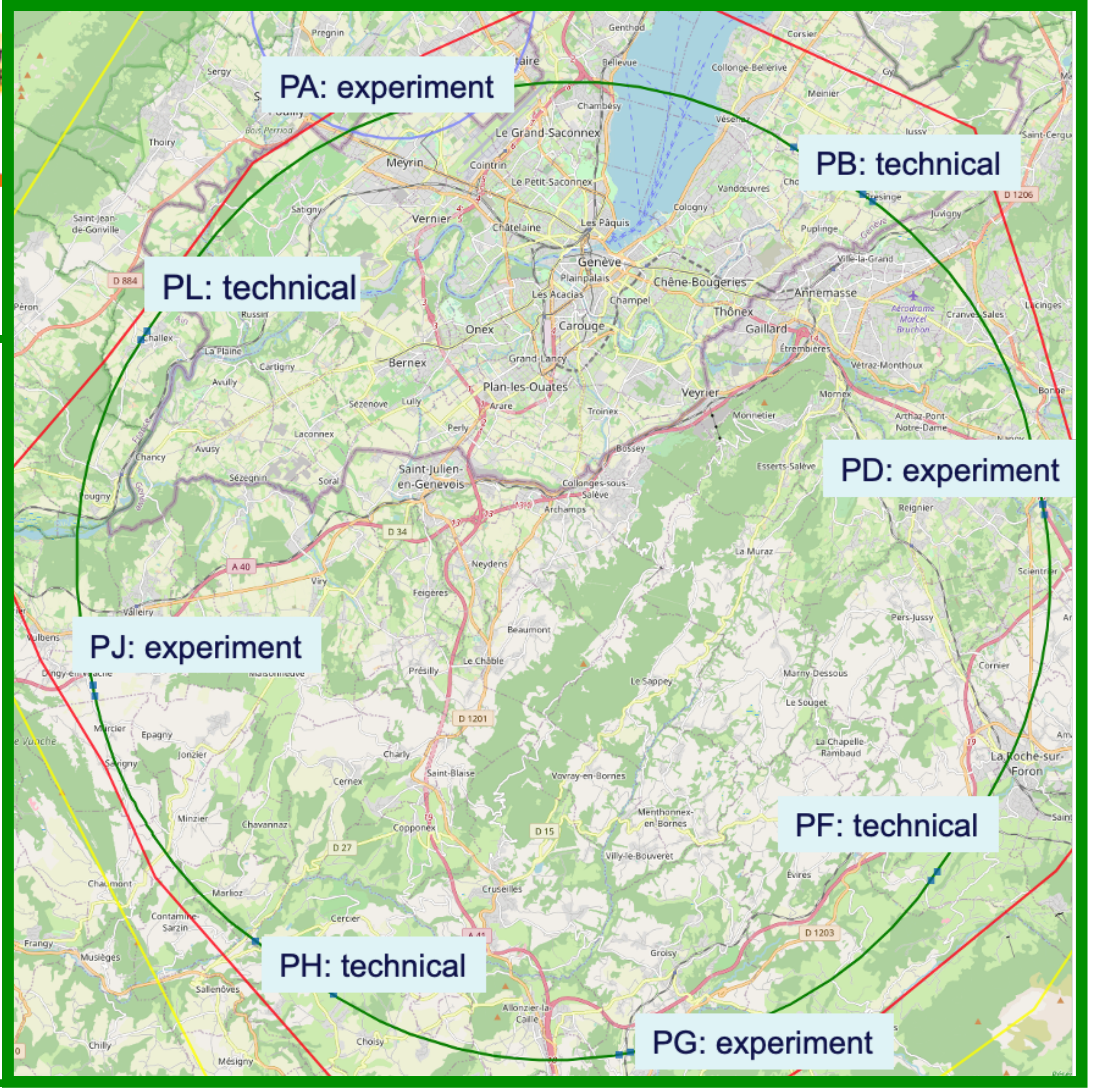
Since 2021: FCC Feasibility Study
(implementation scenario, environmental analysis, high-field magnets, ..)
=> demonstrate feasibility of FCC-ee by 2025

Special Council Session in Feb 2024



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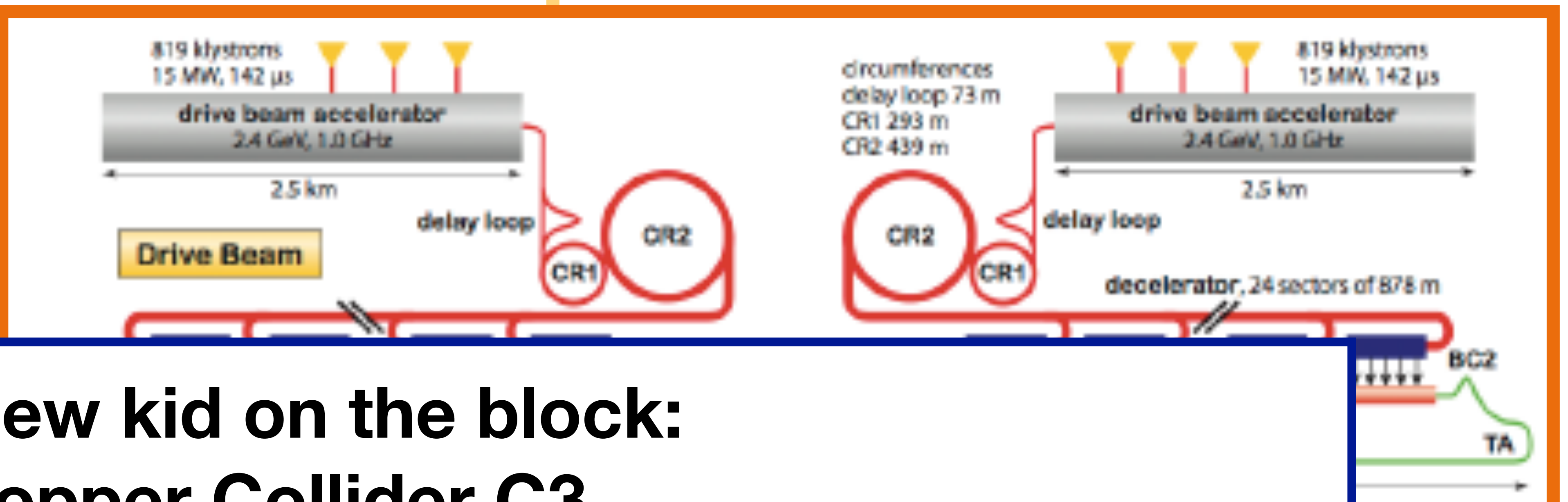
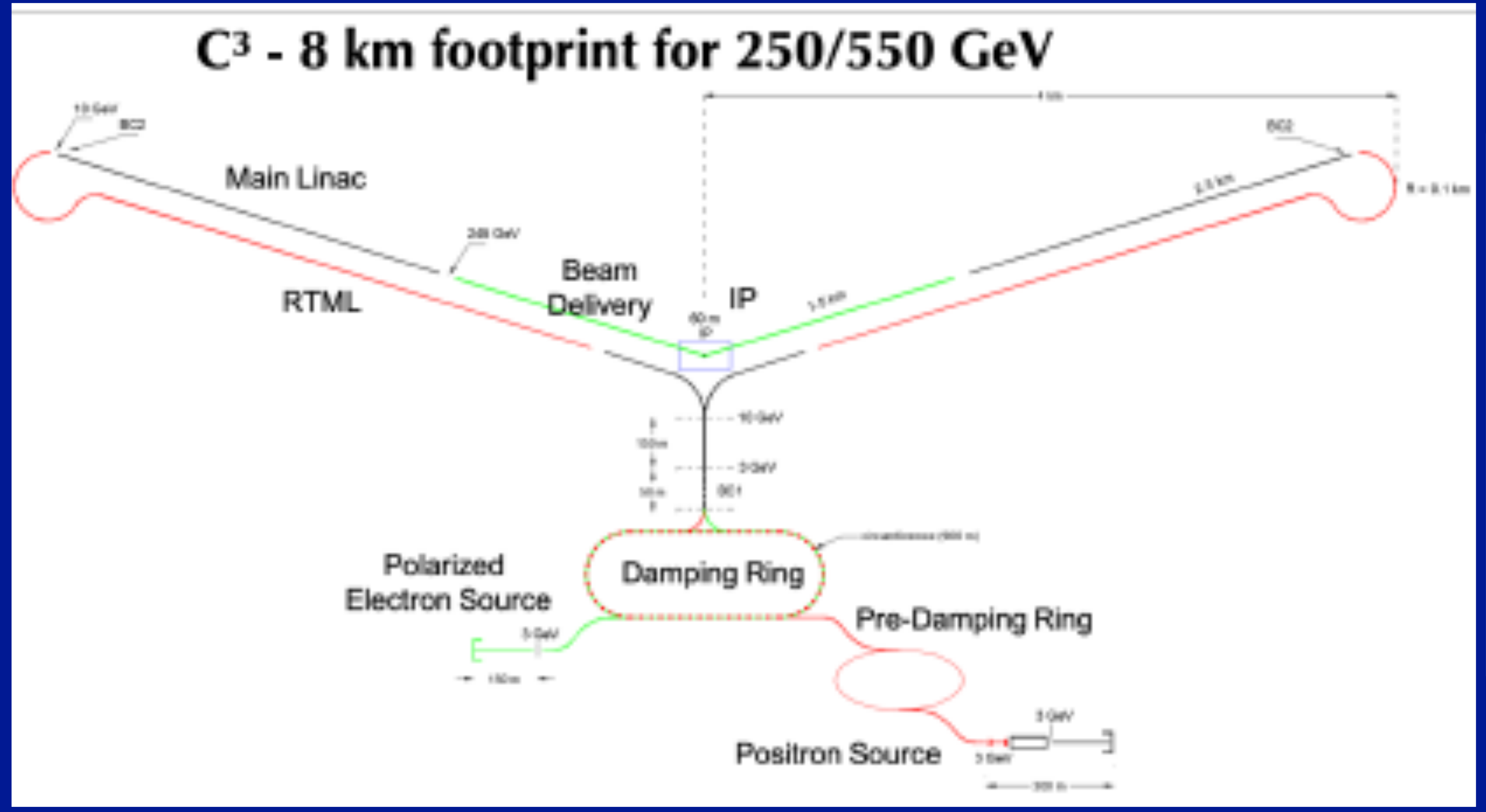
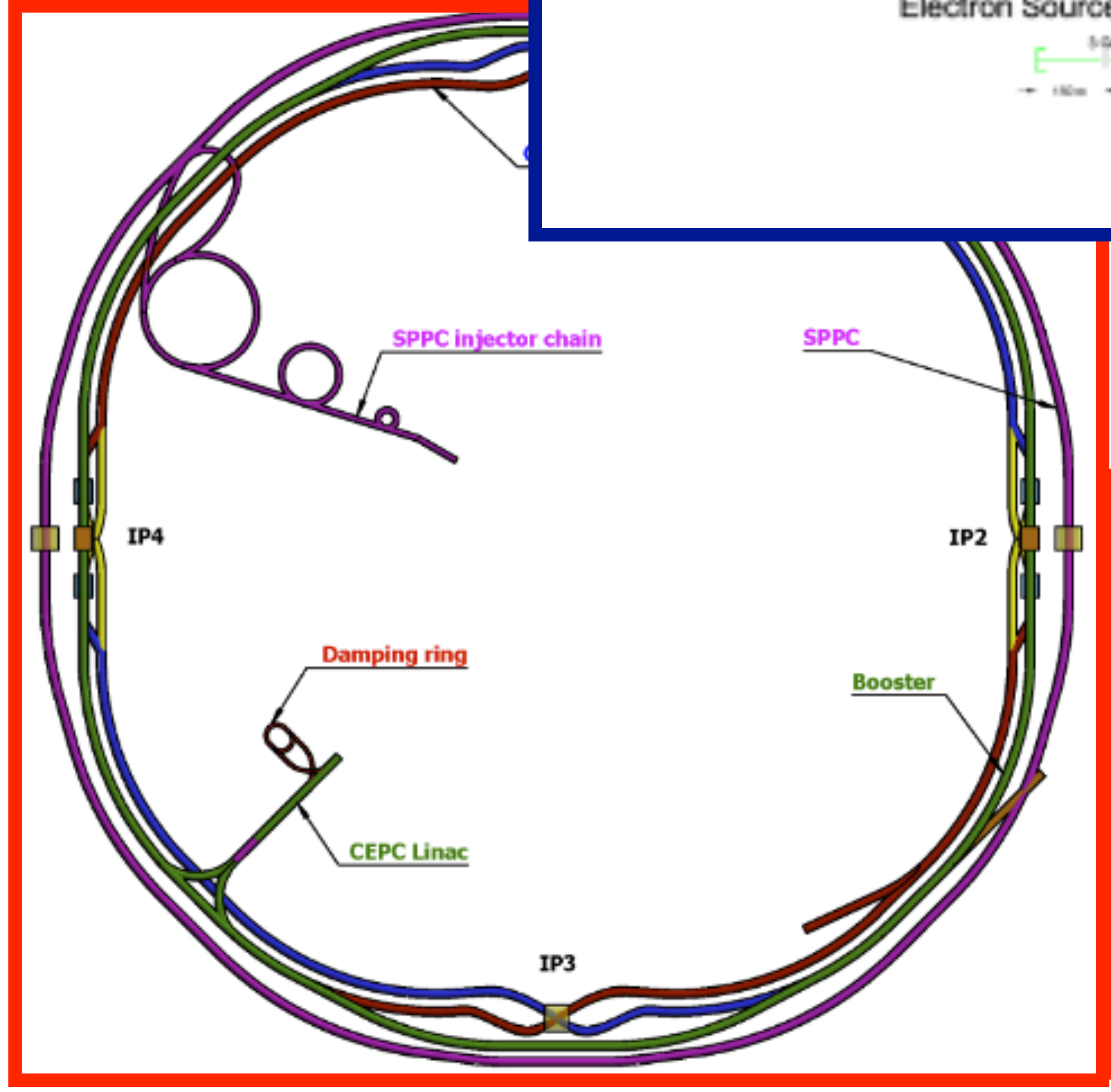




...and the new kid on the block:
the Cool Copper Collider C3,
first proposed 2018, arXiv:1807.10195

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



CEPC
CDR ...
TDR i...
aimin...
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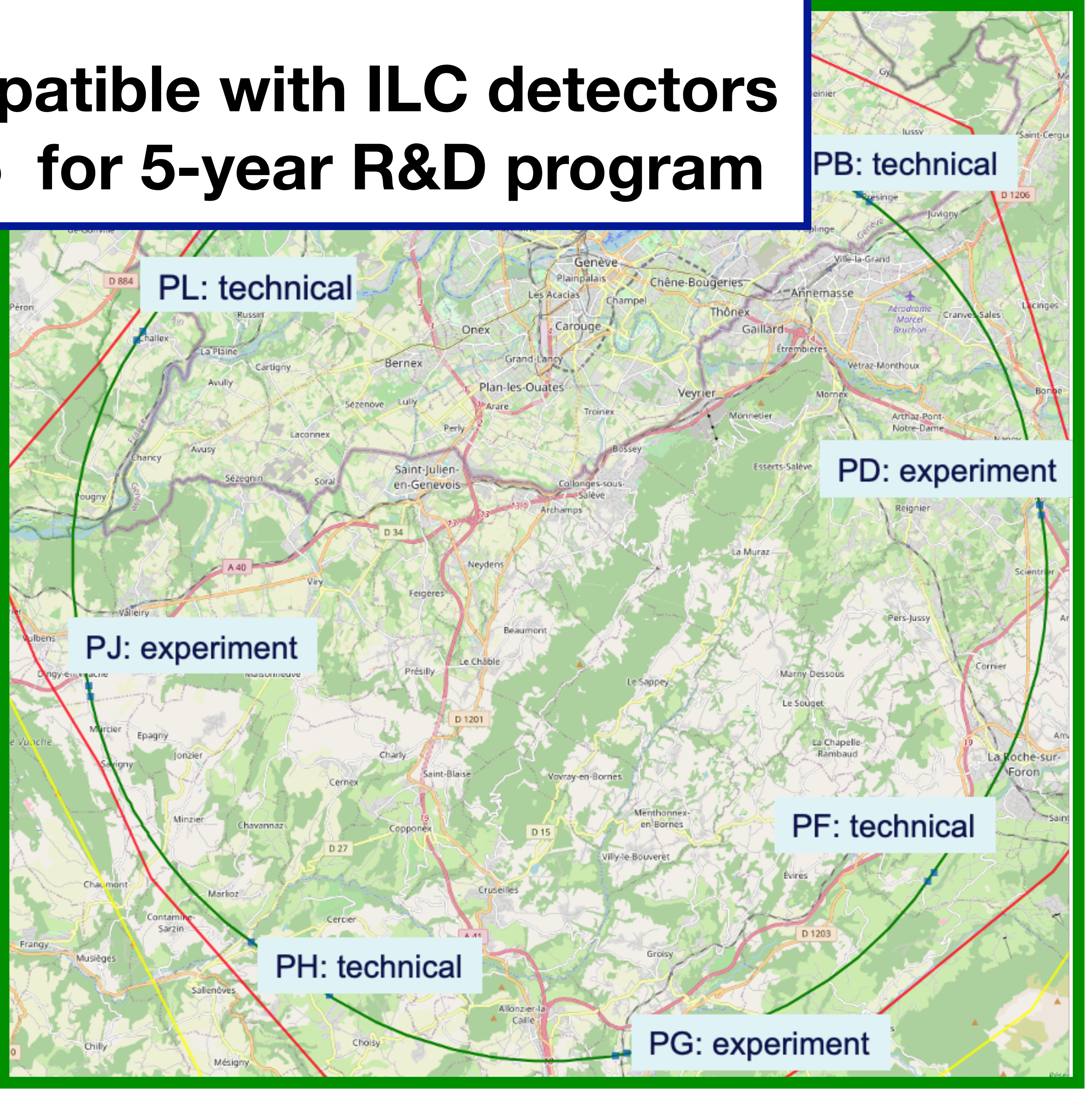

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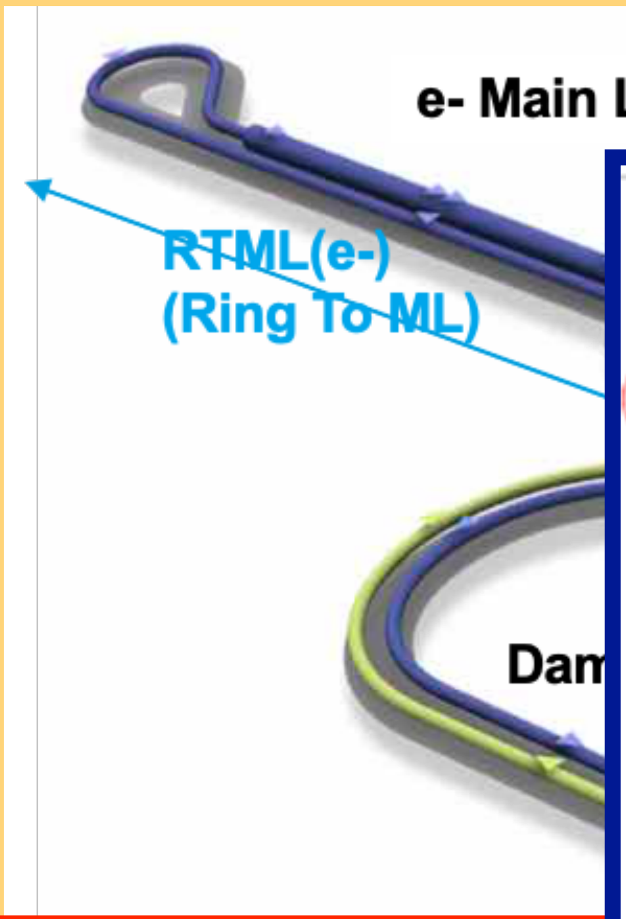

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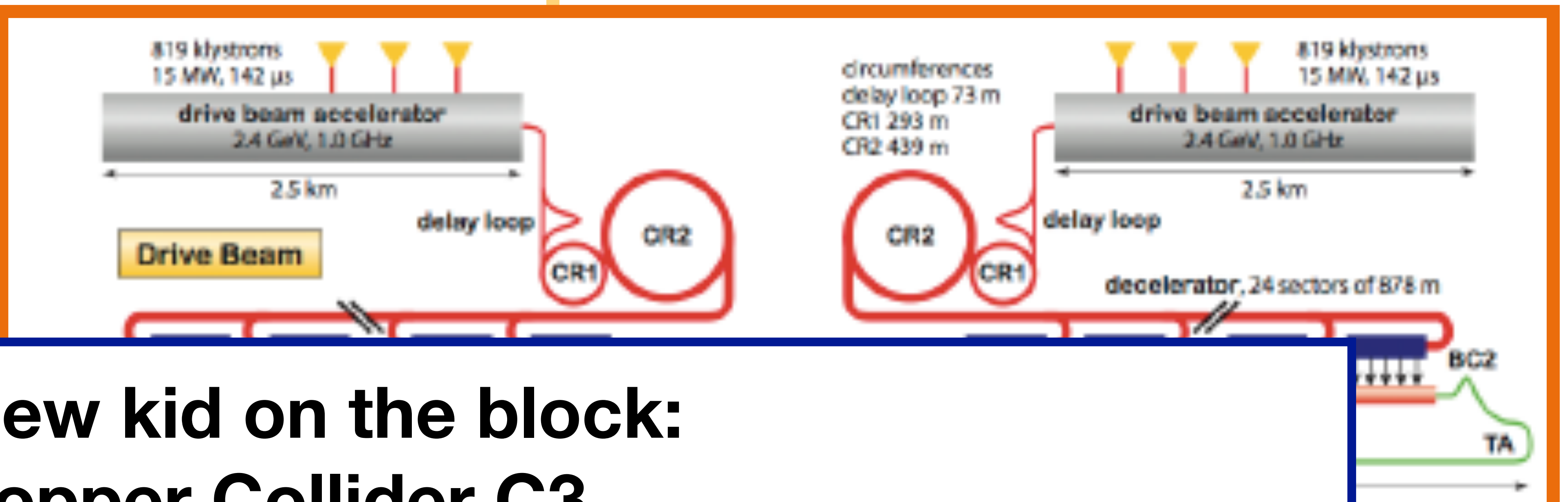

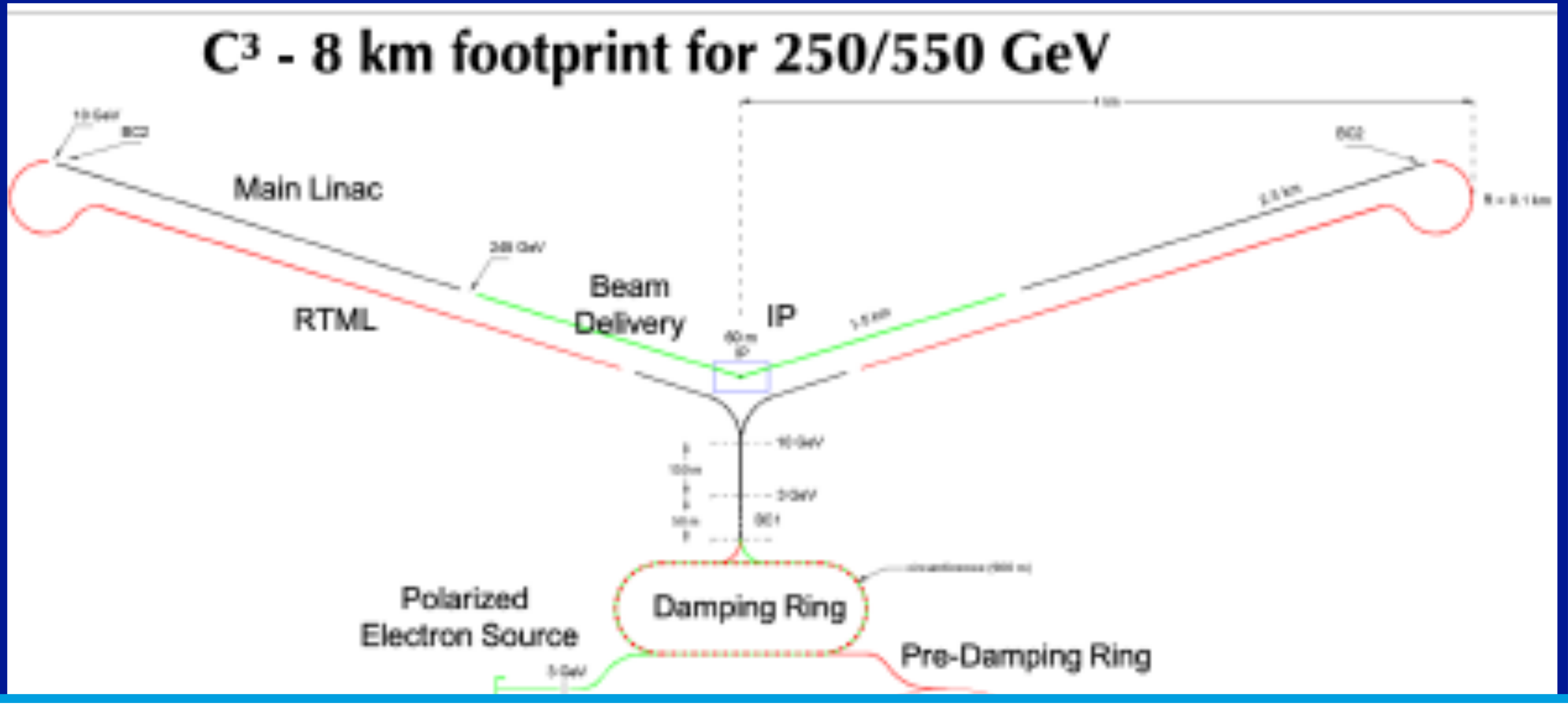

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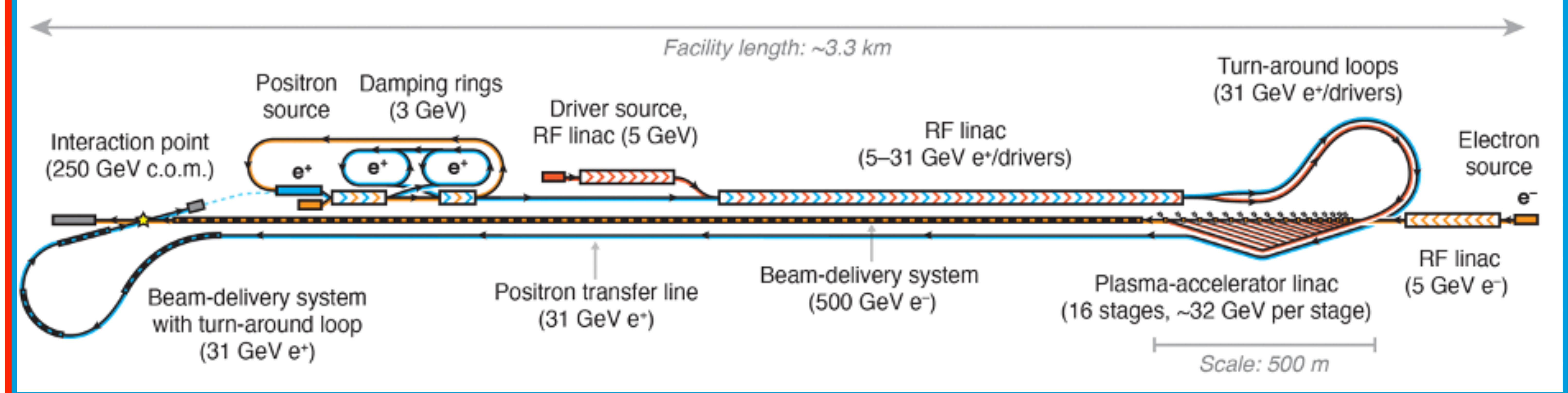
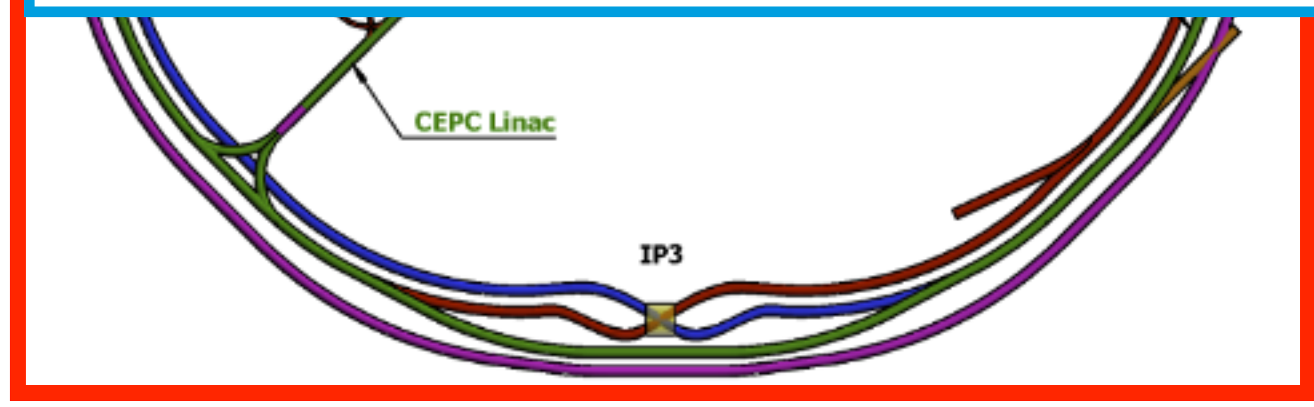


and an even newer proposal: Hybrid Asymmetric Linear Higgs Factory HALHF,
arxiv:2303.10150

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



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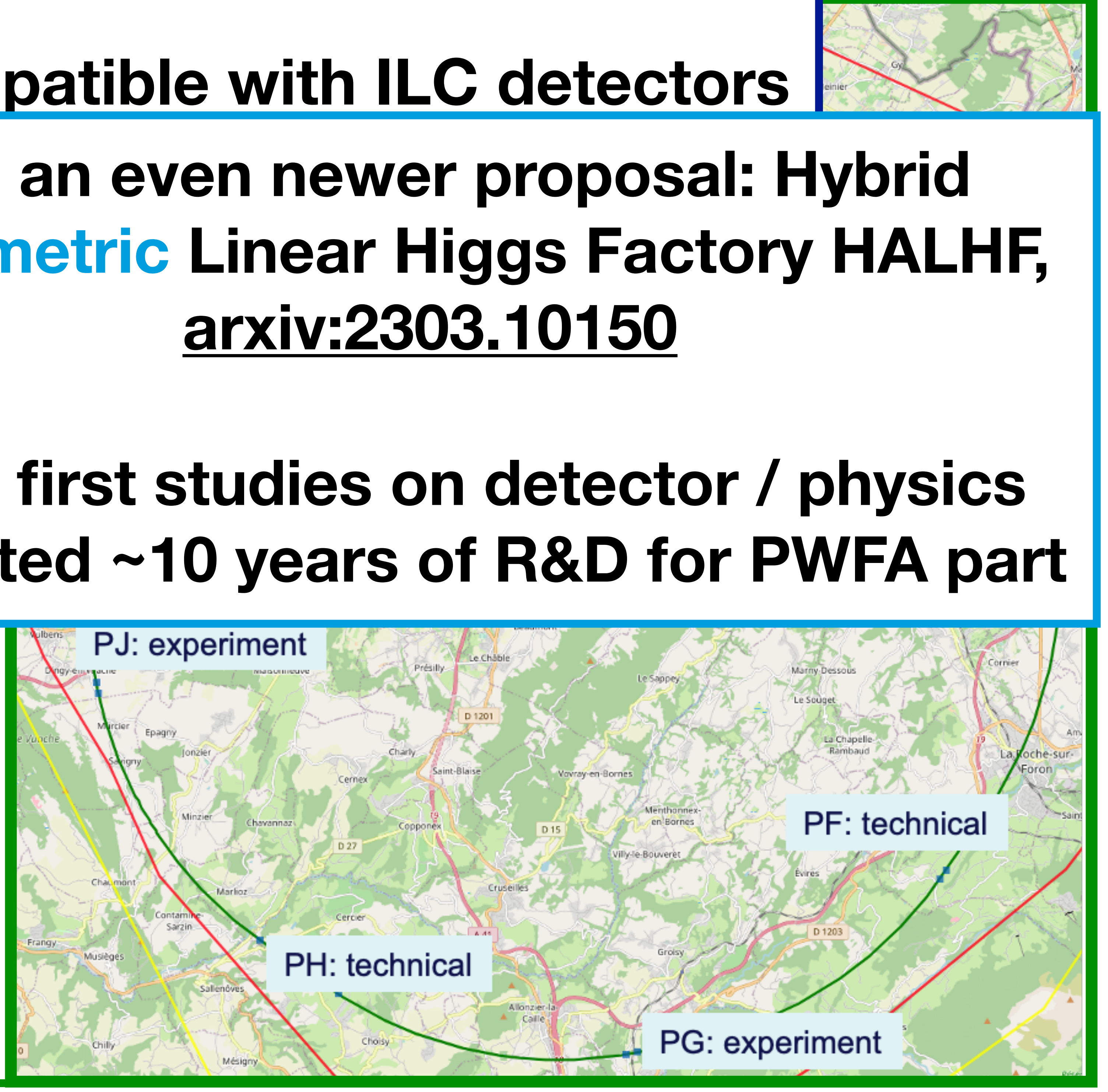

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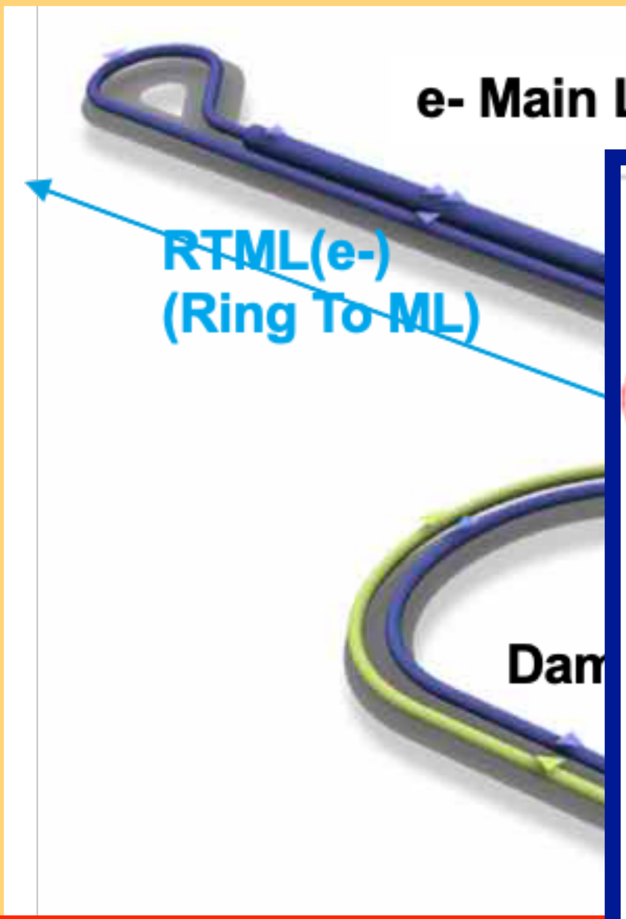

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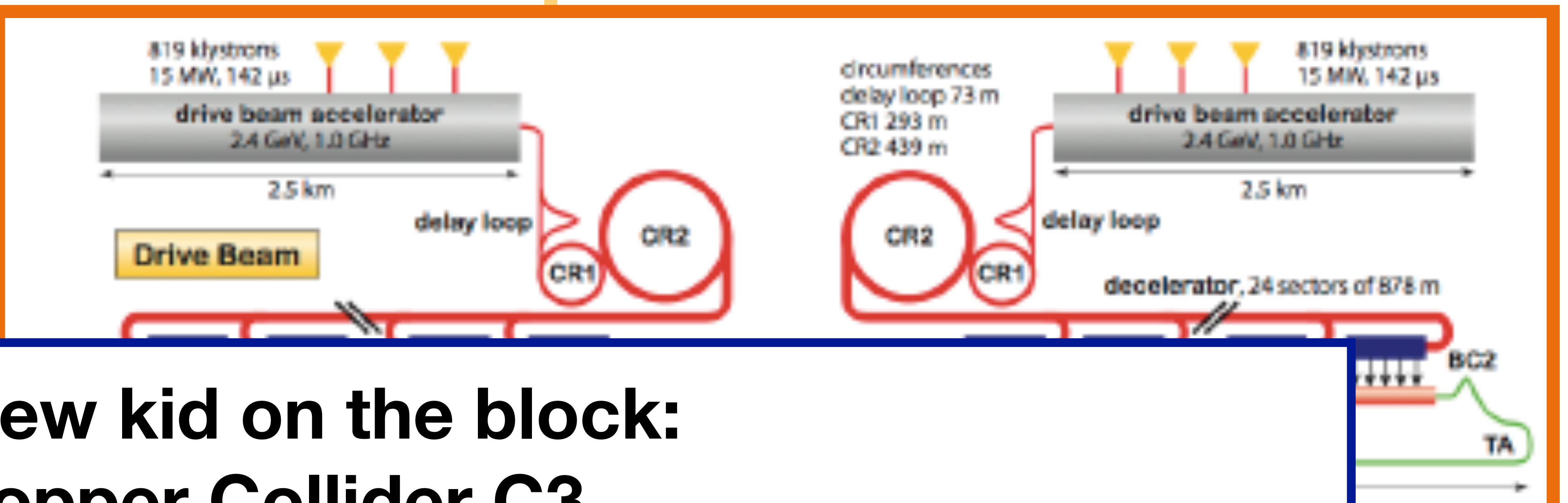

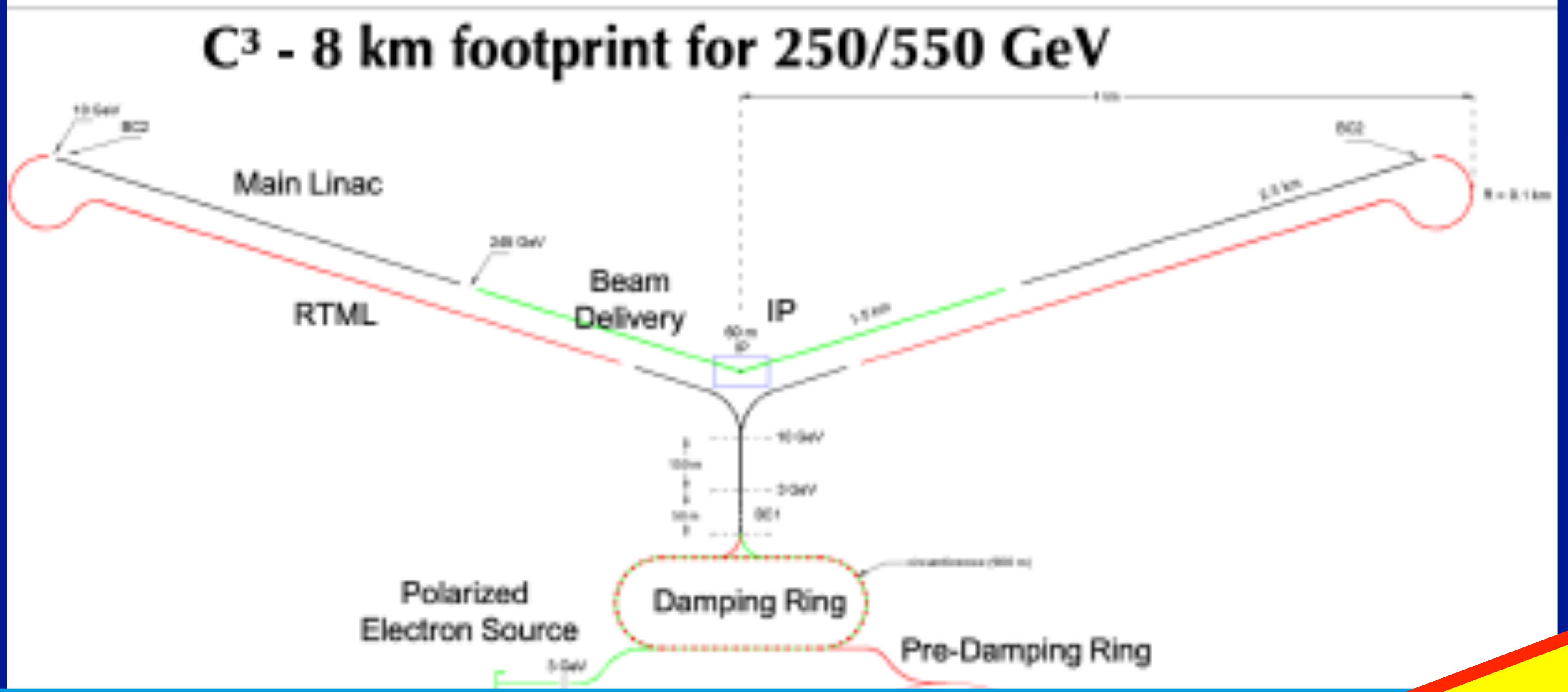

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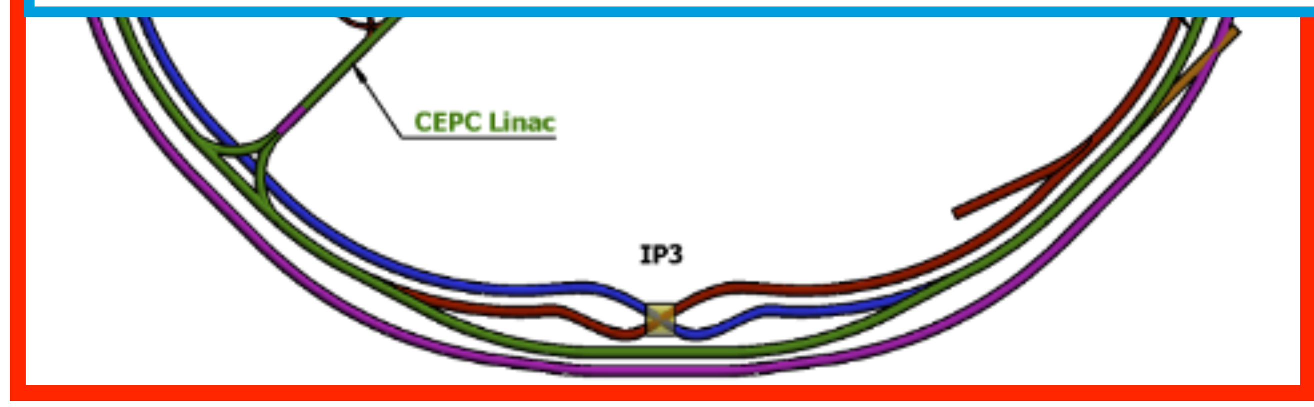

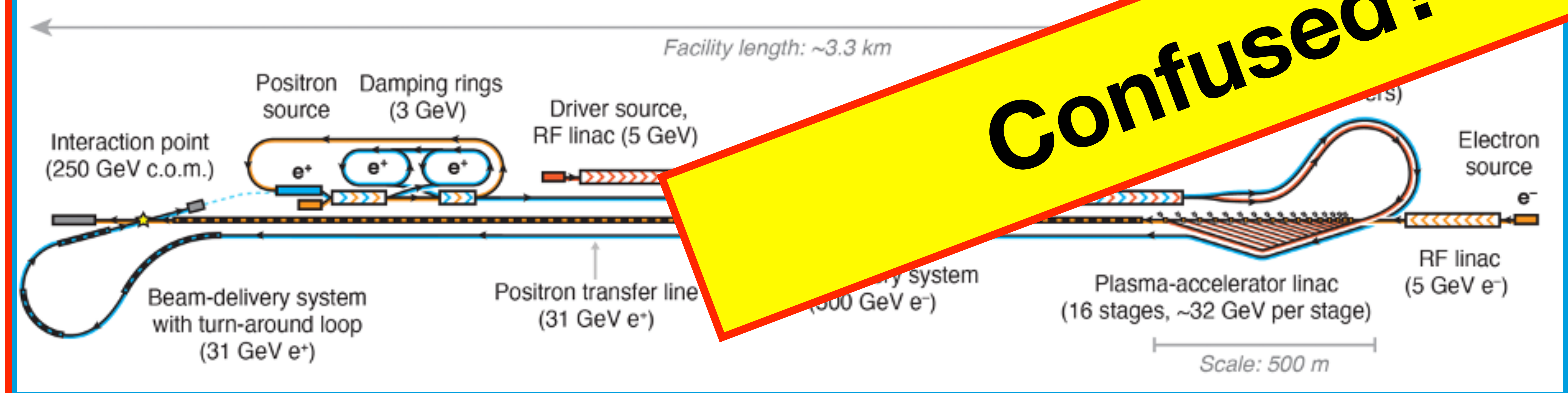

Confused?

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some first studies on detector / physics
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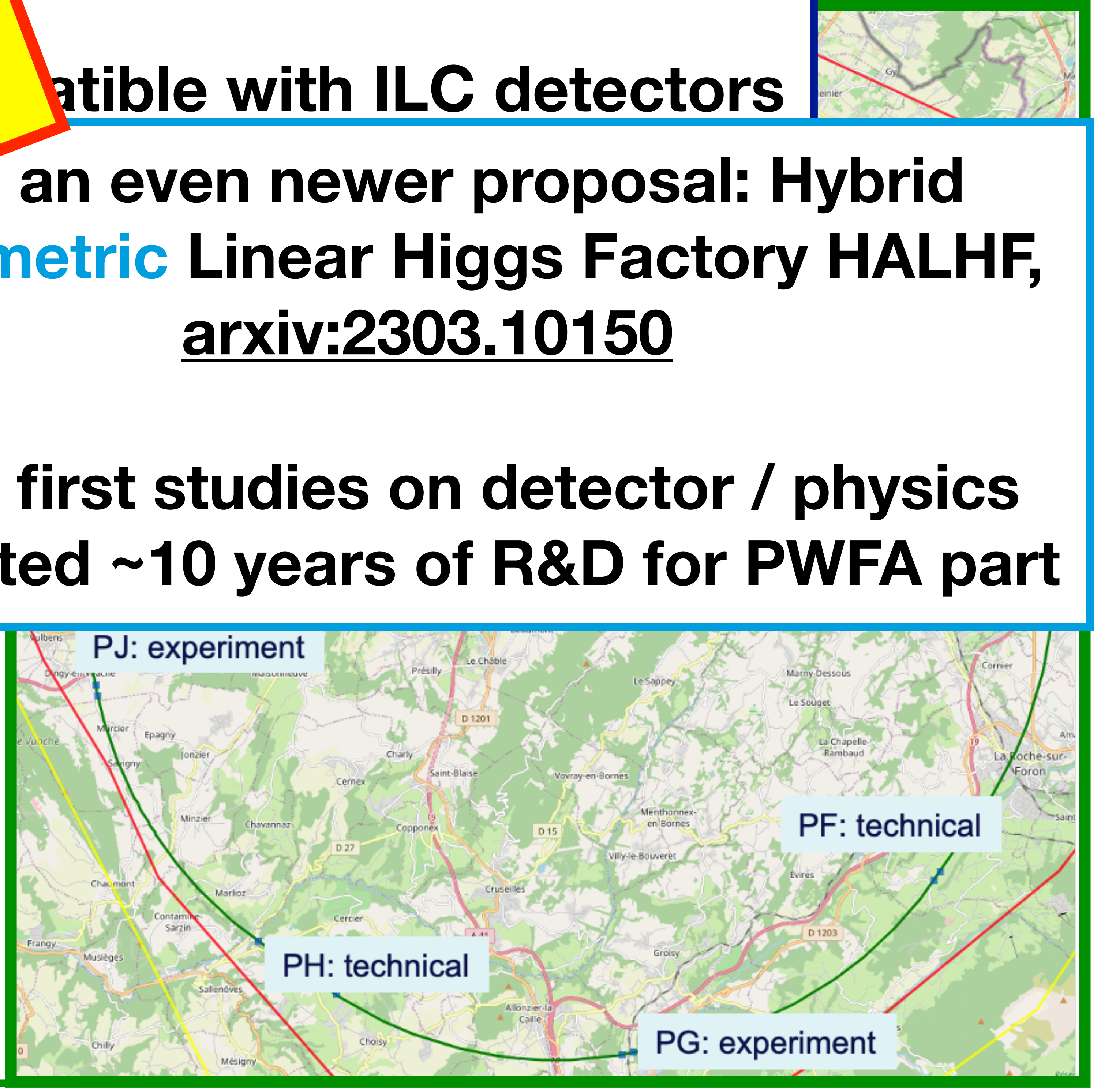

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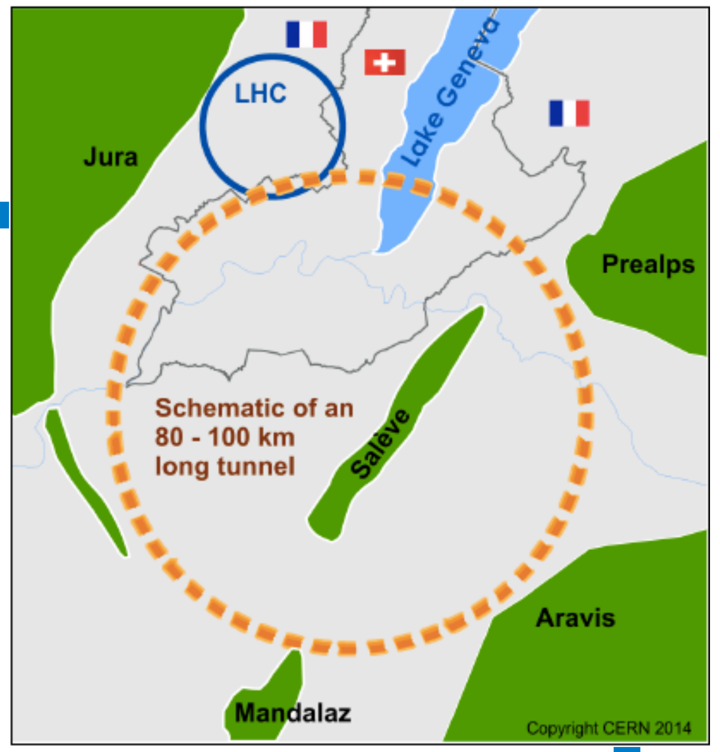
Special Council Session in Feb 2024

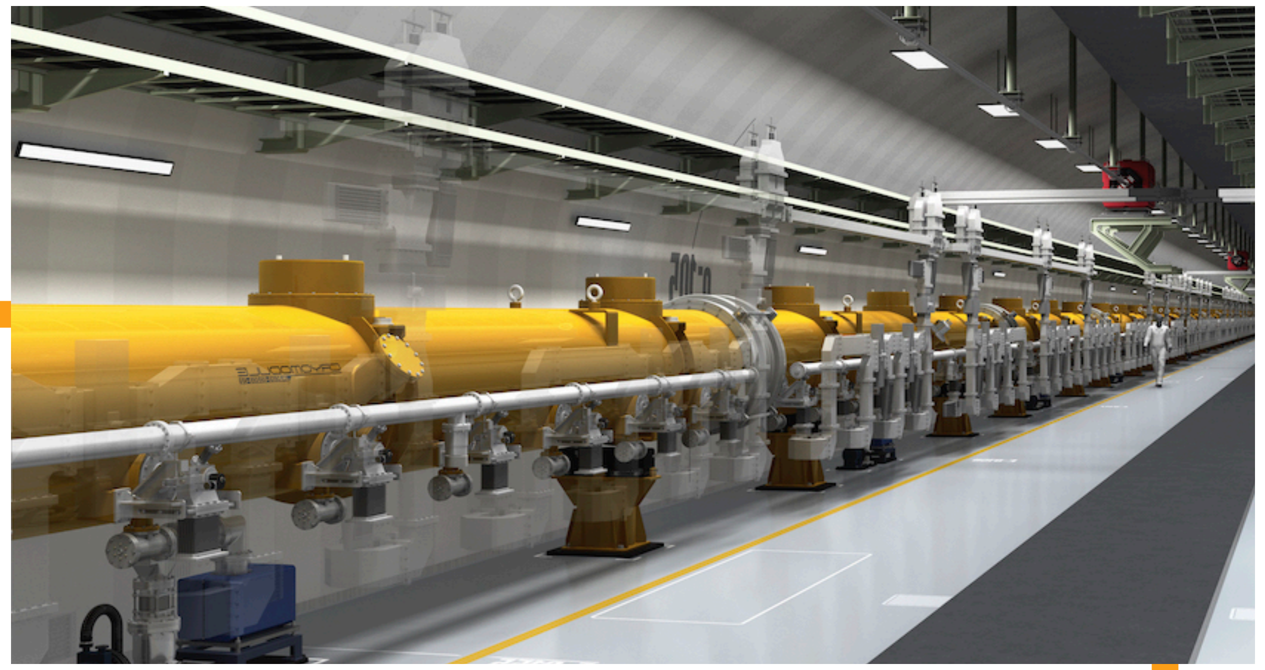
They fall into two classes

Each have their advantages



Circular e+e- Colliders

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



Linear Colliders

- ILC, CLIC, C^3, …
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- **longitudinally spin-polarised beam(s)**

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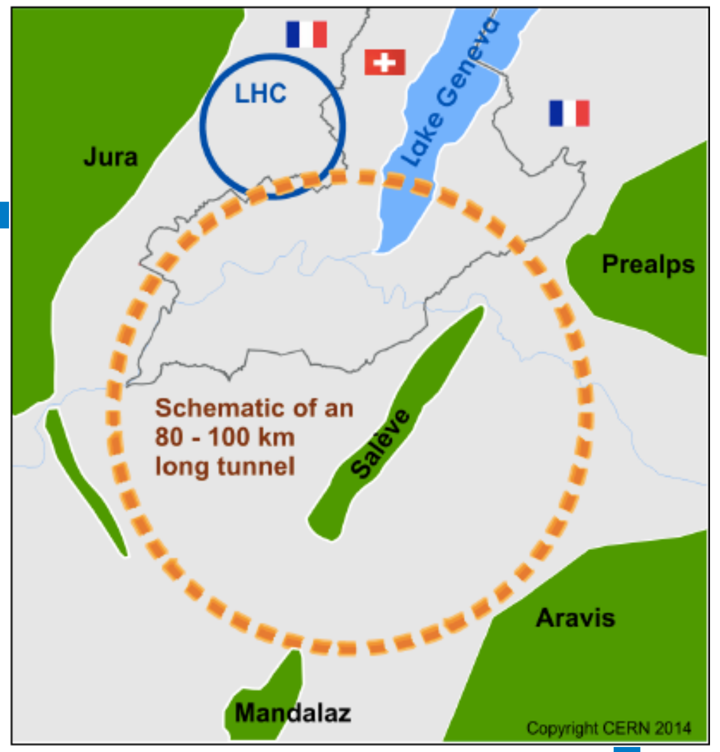

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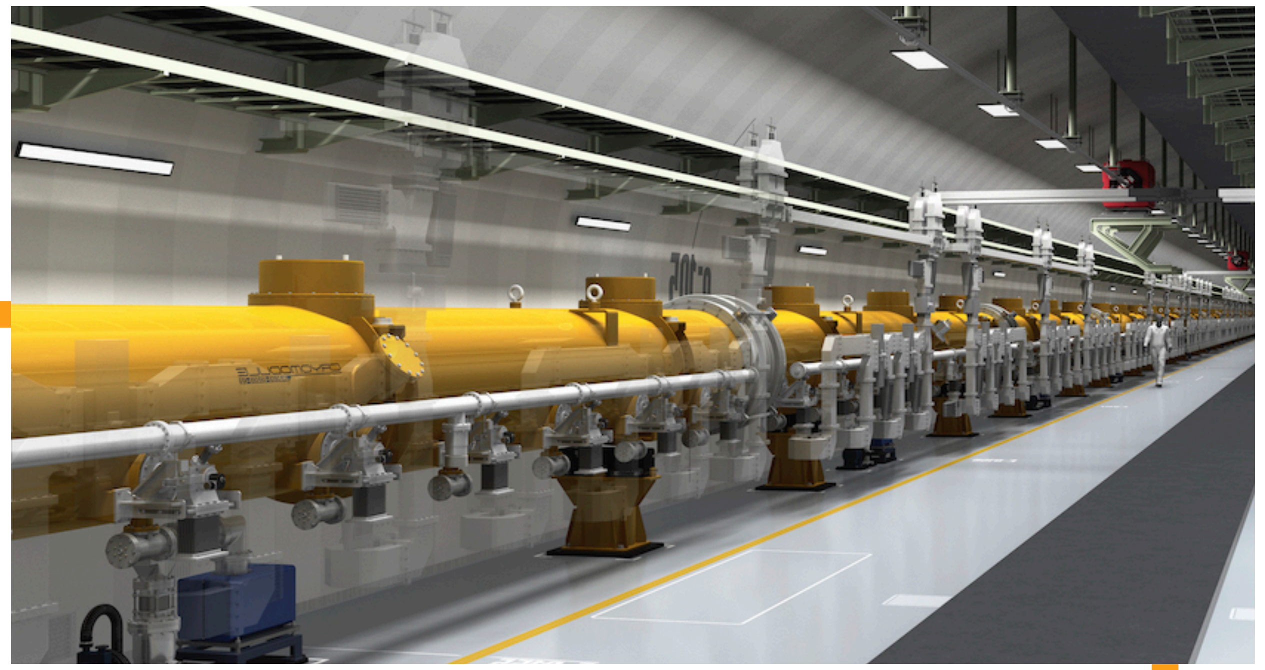
Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge



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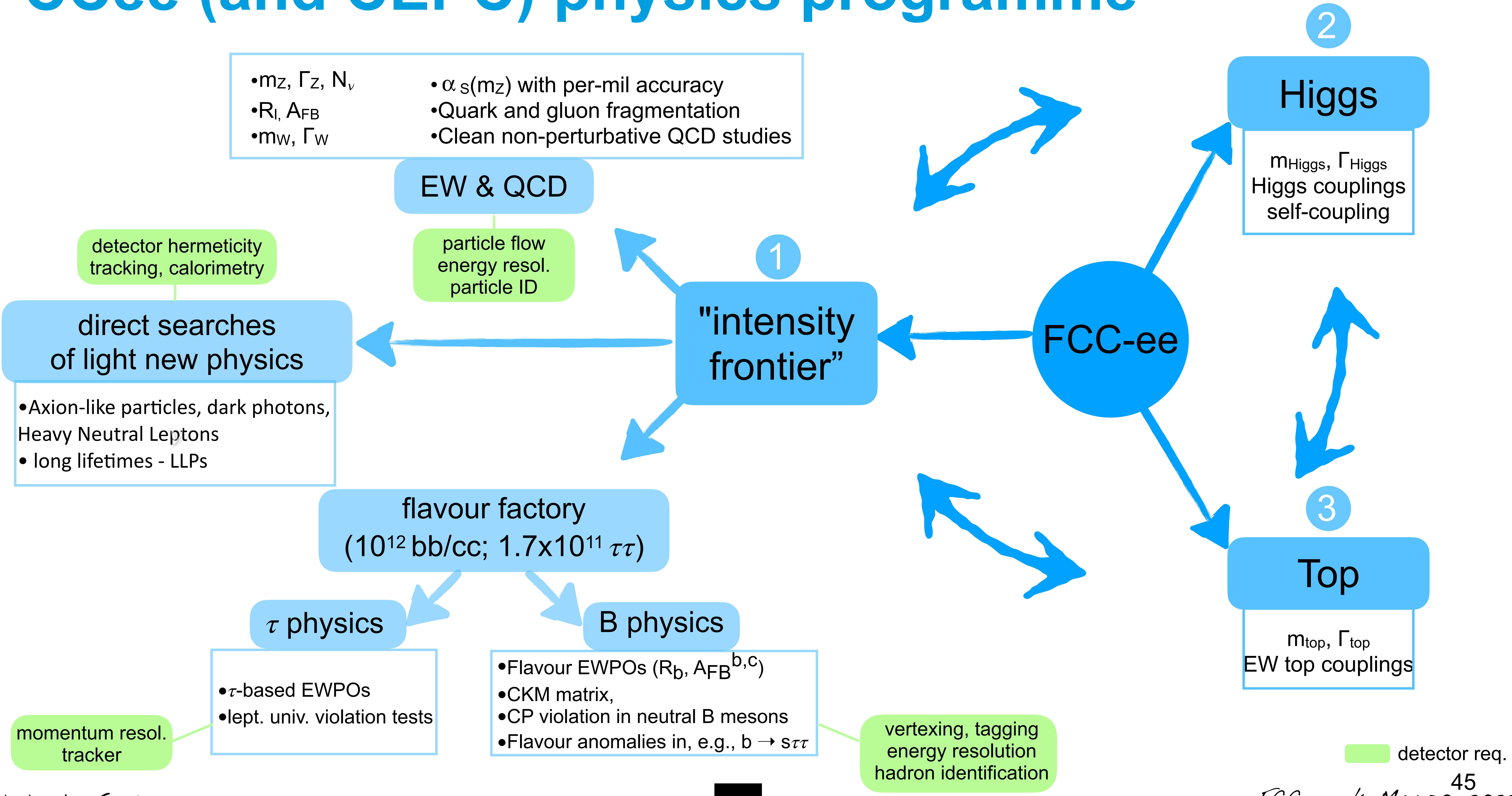
Long-term upgrades: energy extendability

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

FCCee (and CEPC) physics programme



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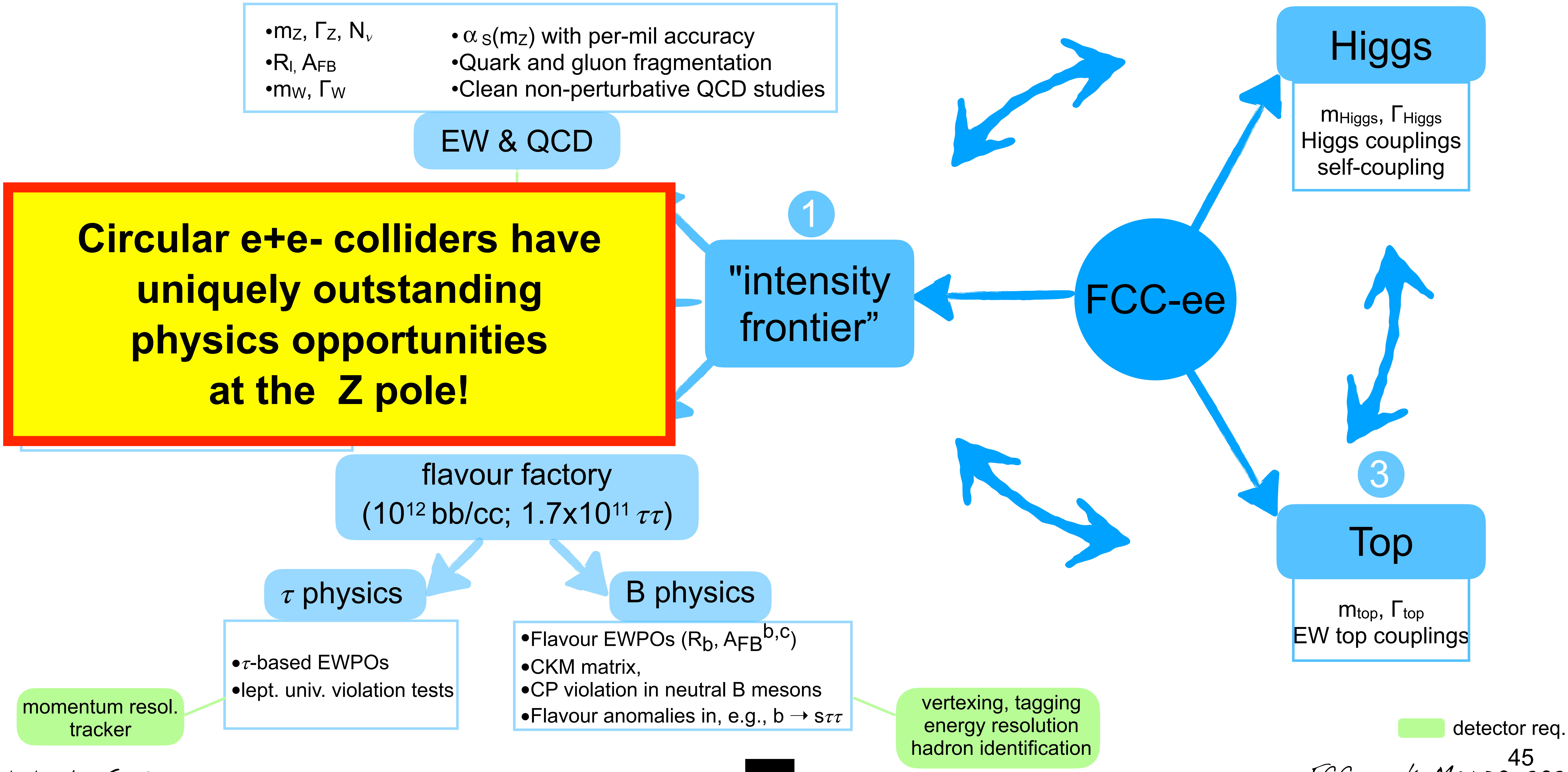


And also outstanding challenges

Overview on Z lineshape parameter precisions….

Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, …)

From: P.Janot talk at FCC theory workshop in June 2022

… similar for asymmetries

but note again effect of polarised beams

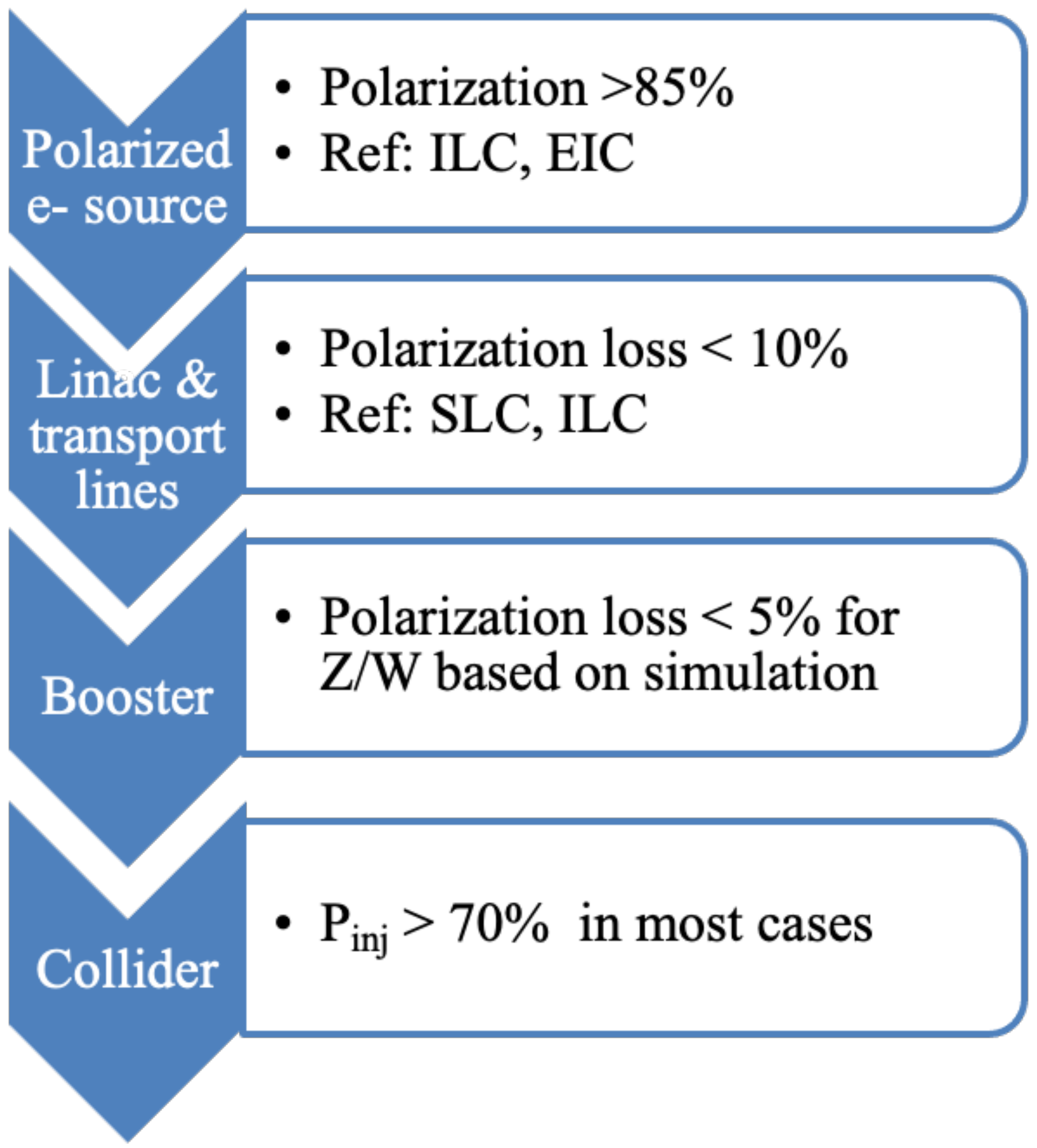
Observables	Present value ($\times 10^4$)	TeraZ / GigaZ stat.	TeraZ / GigaZ current syst.	Theory input (not exhaustive)
A_e from P_τ (FCC-ee)	1514 ± 19	0.07	0.20	SM relation to measured quantities
A_e from A_{LR} (ILC)		0.15	0.80	
A_μ from A_{FB} (FCC-ee)	1456 ± 91	0.23	0.22	Accurate QED (ISR, IFI, FSR)
A_μ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_τ from P_τ (FCC-ee)	1449 ± 40	0.05	2.00	Prediction for non-τ backgrounds
A_τ from A_{FB} (FCC-ee)		0.23	1.30	
A_τ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_b from A_{FB} (FCC-ee)	8990 ± 130	0.24	2.10	QCD calculations
A_b from A_{FB}^{pol} (ILC)		0.90	5.00	
A_c from A_{FB} (FCC-ee)	65400 ± 210	2.00	1.50	
A_c from A_{FB}^{pol} (ILC)		2.00	3.70	

From: P.Janot talk at FCC theory workshop in June 2022

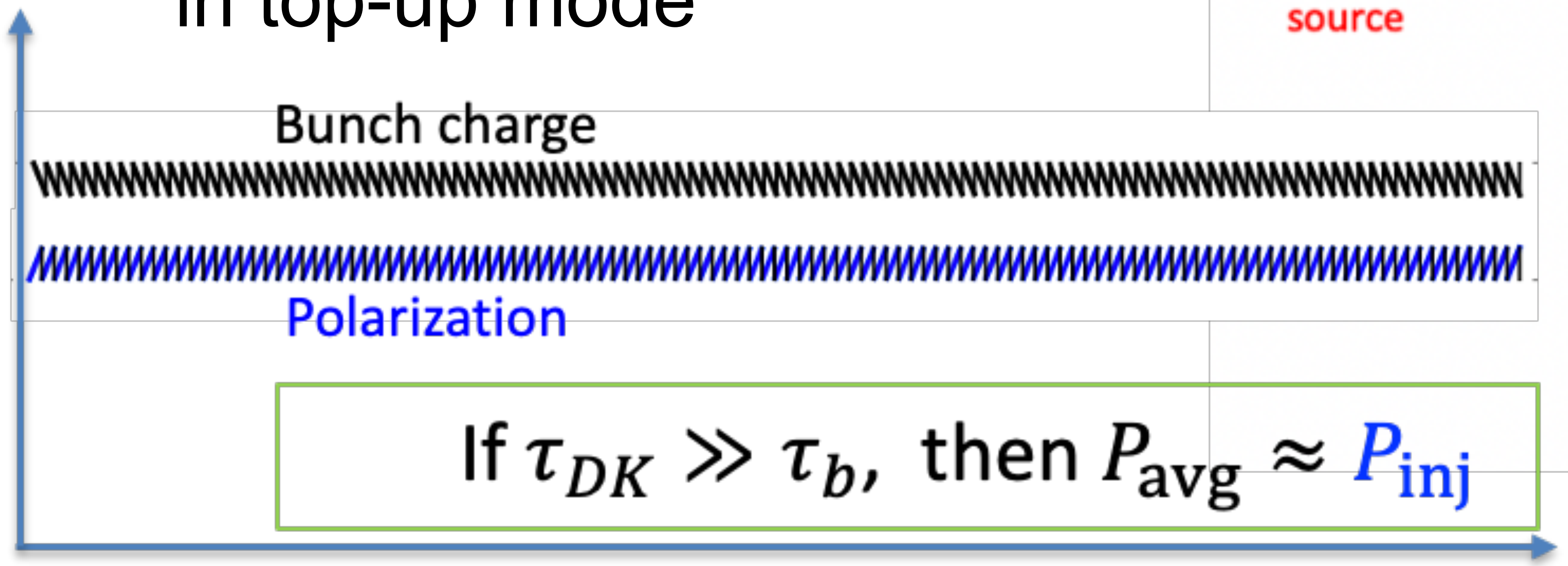
Polarisation for CEPC

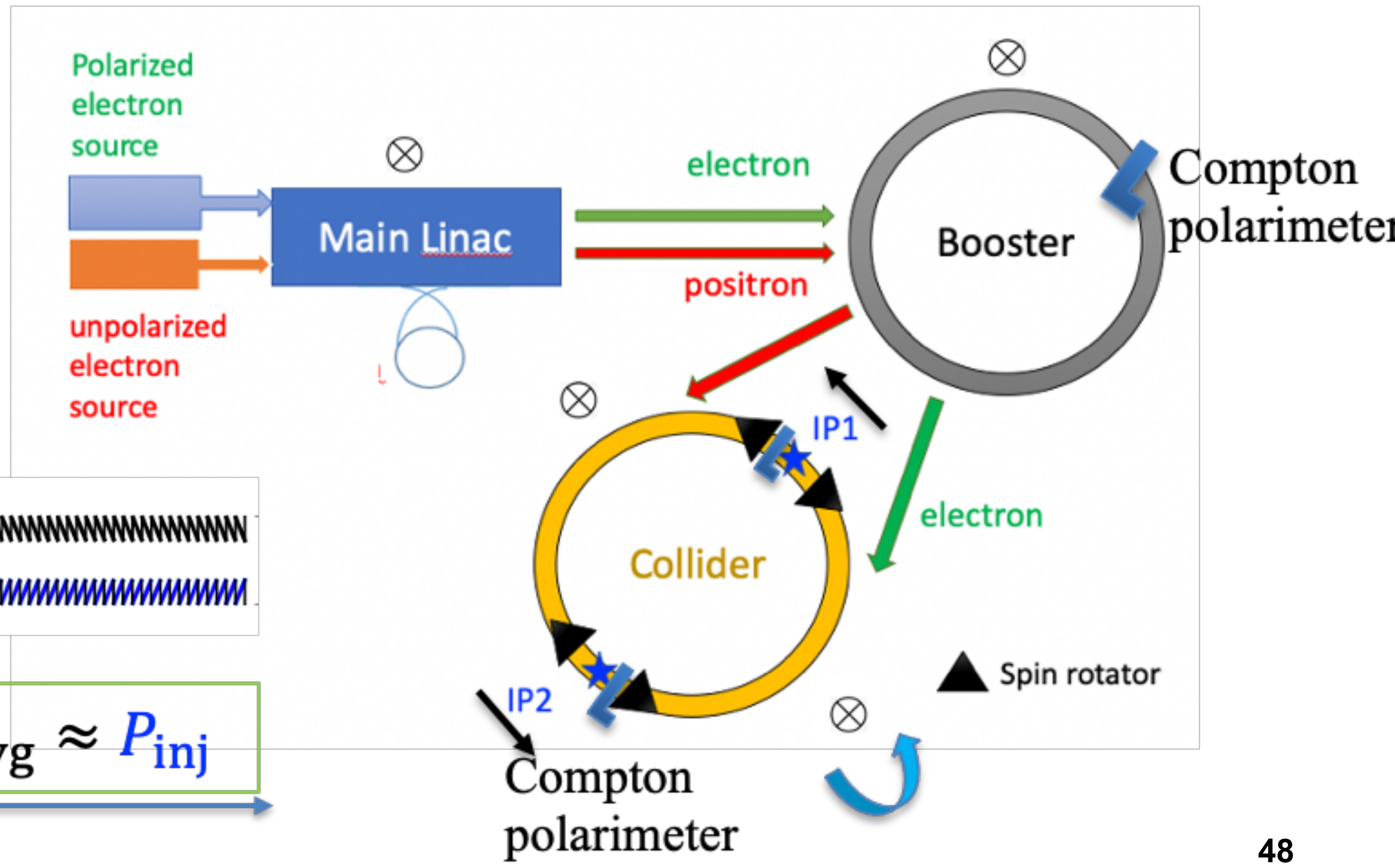
Longitudinal polarization for physics?

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



Colliding bunches in top-up mode





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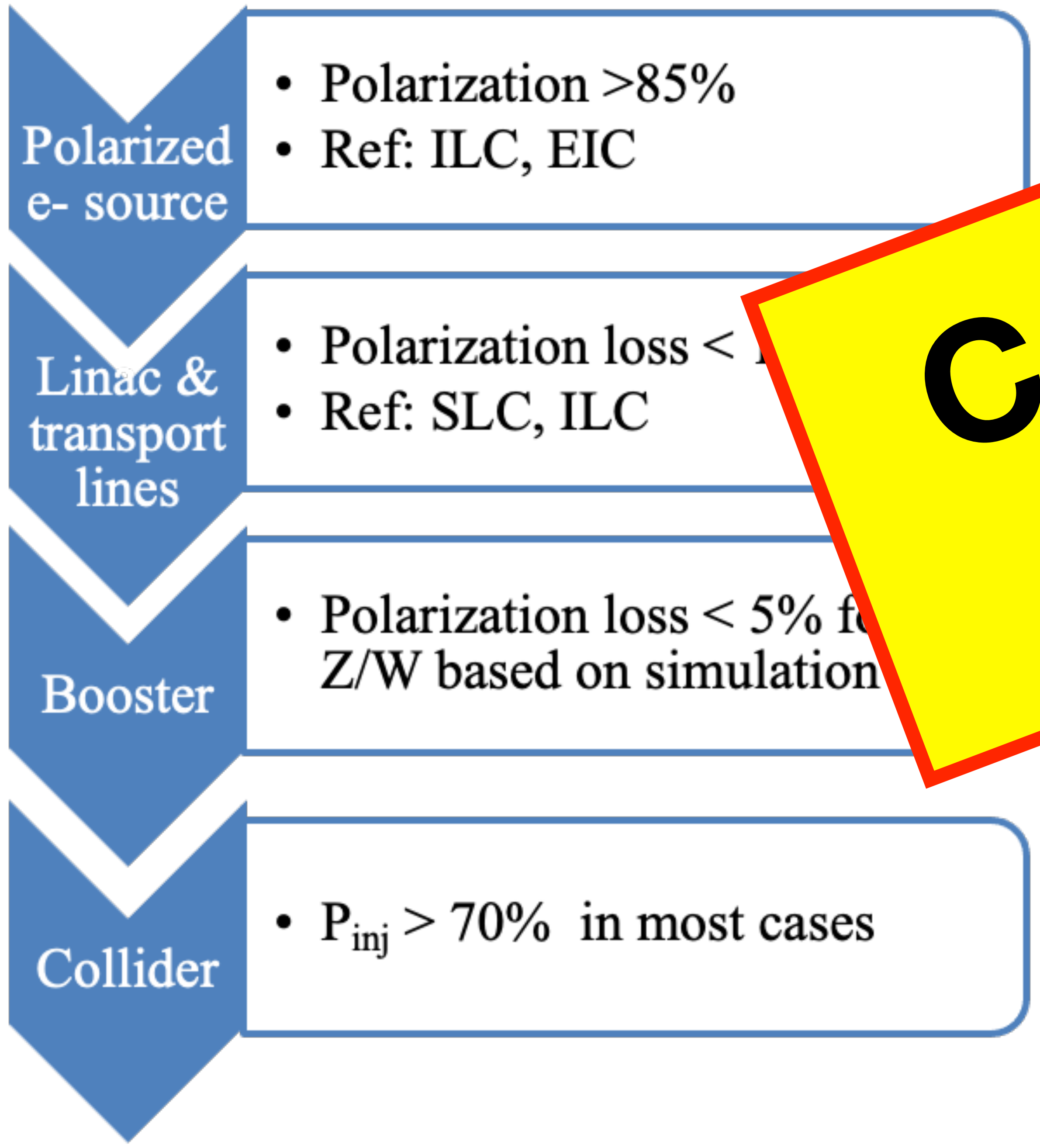
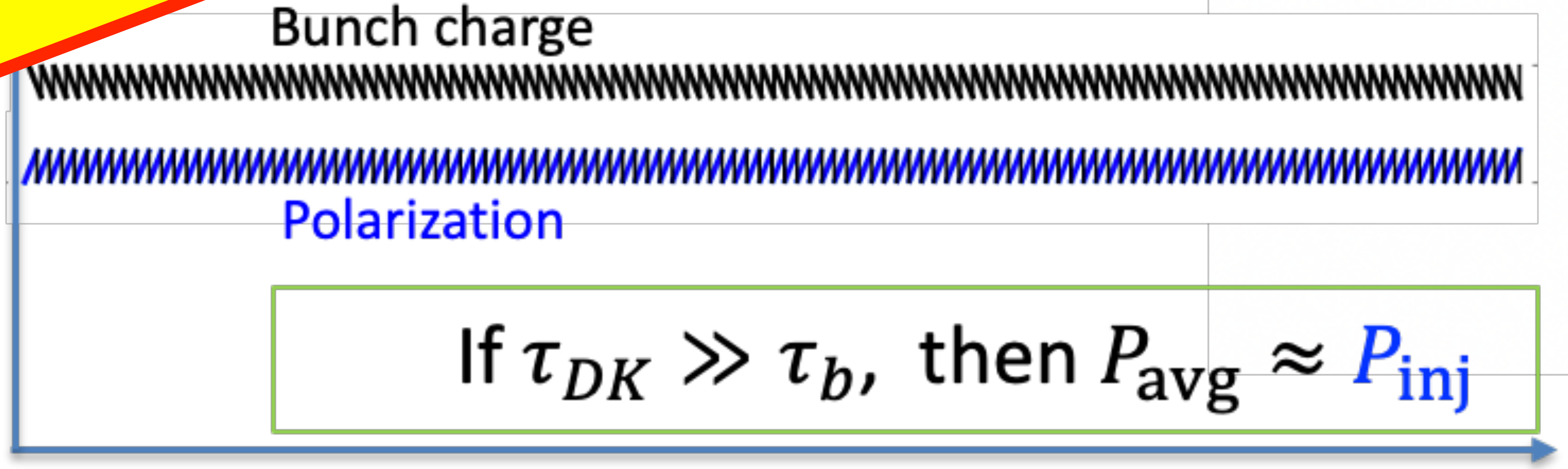
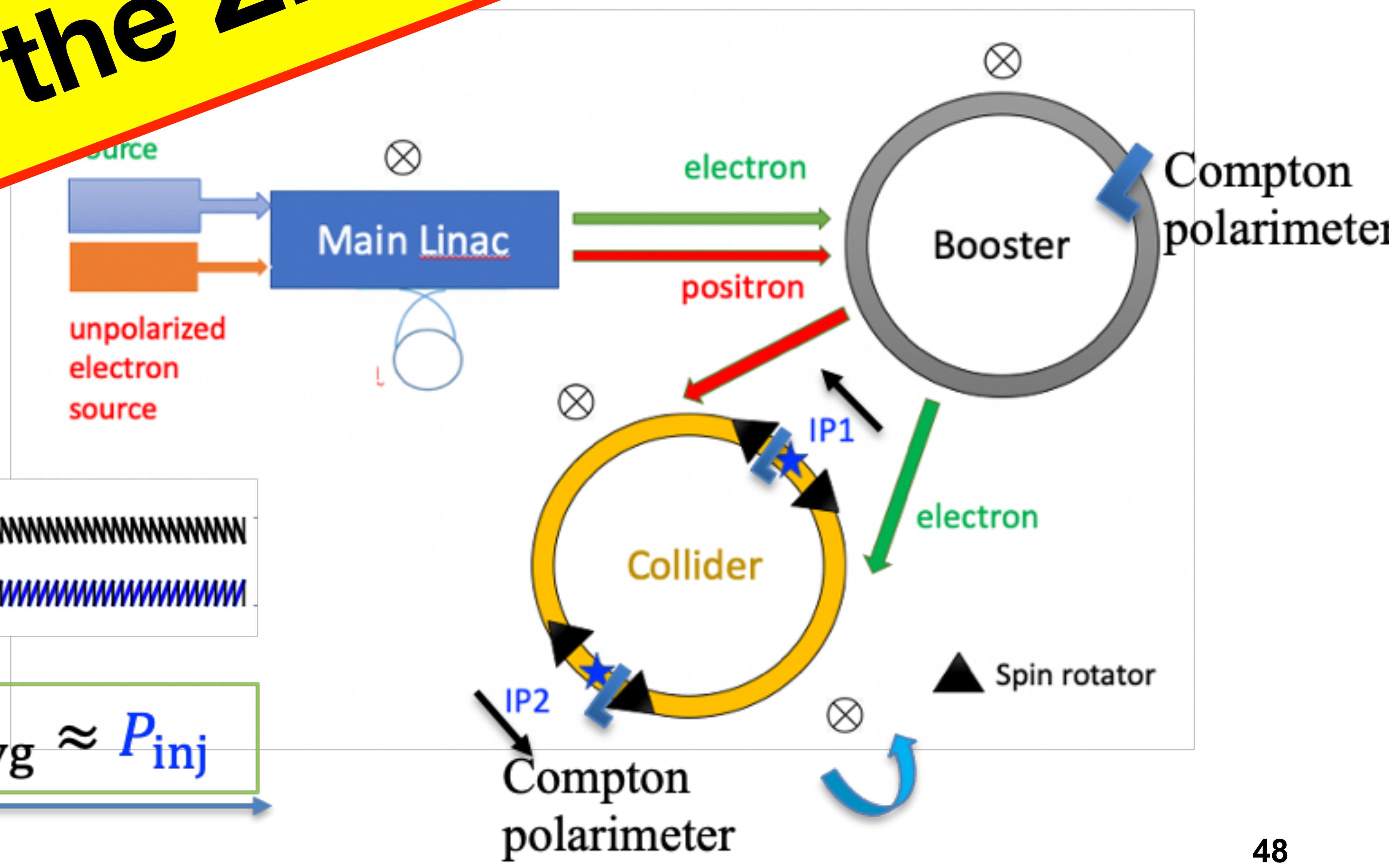
Could this work also at FCC-ee ?
And what about the ZH run?



…ches
…p mode

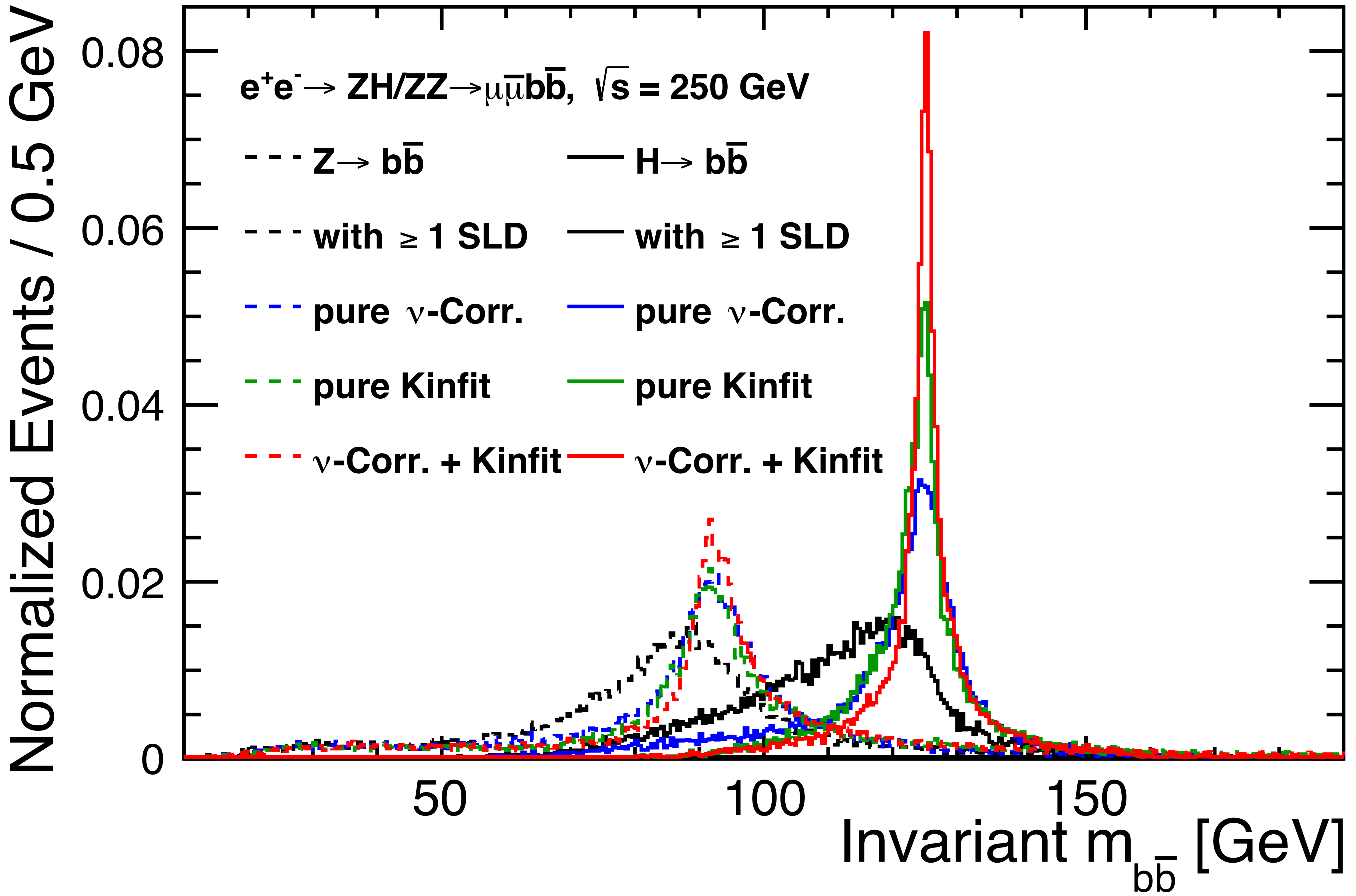




Recent developments

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 secondary / 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…



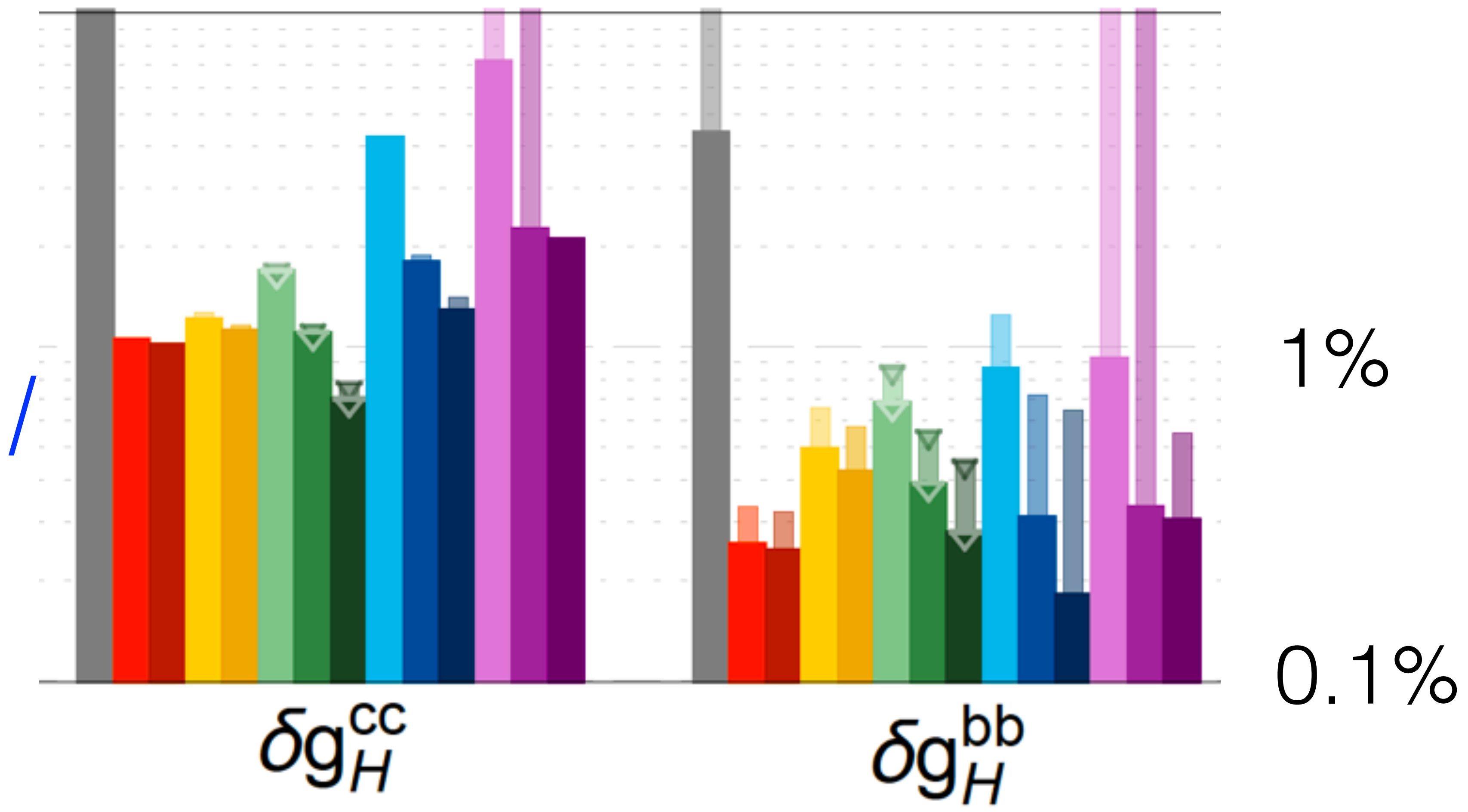
arXiv:2111.14775

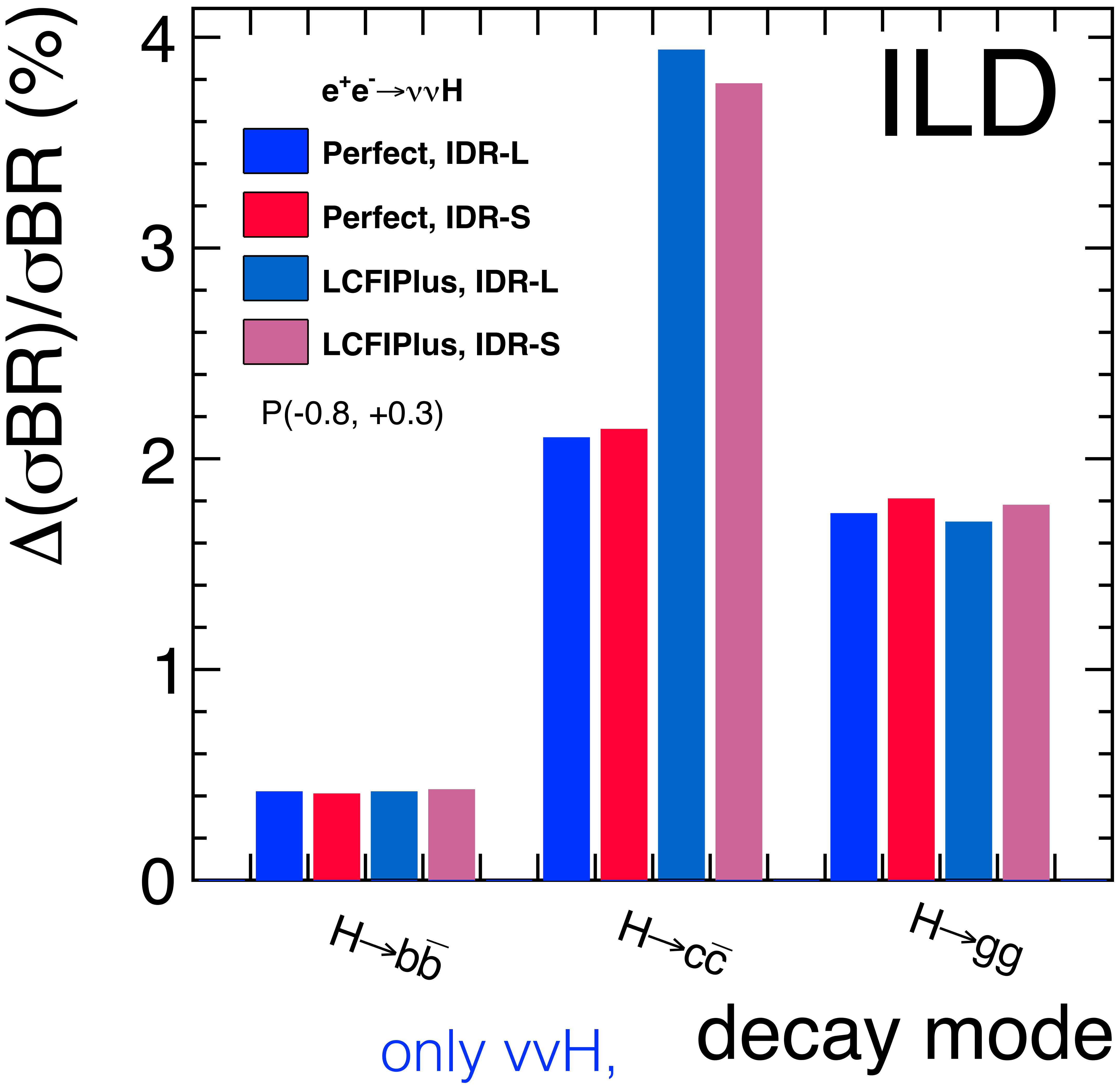
Higgs decay to bb/cc/gg

…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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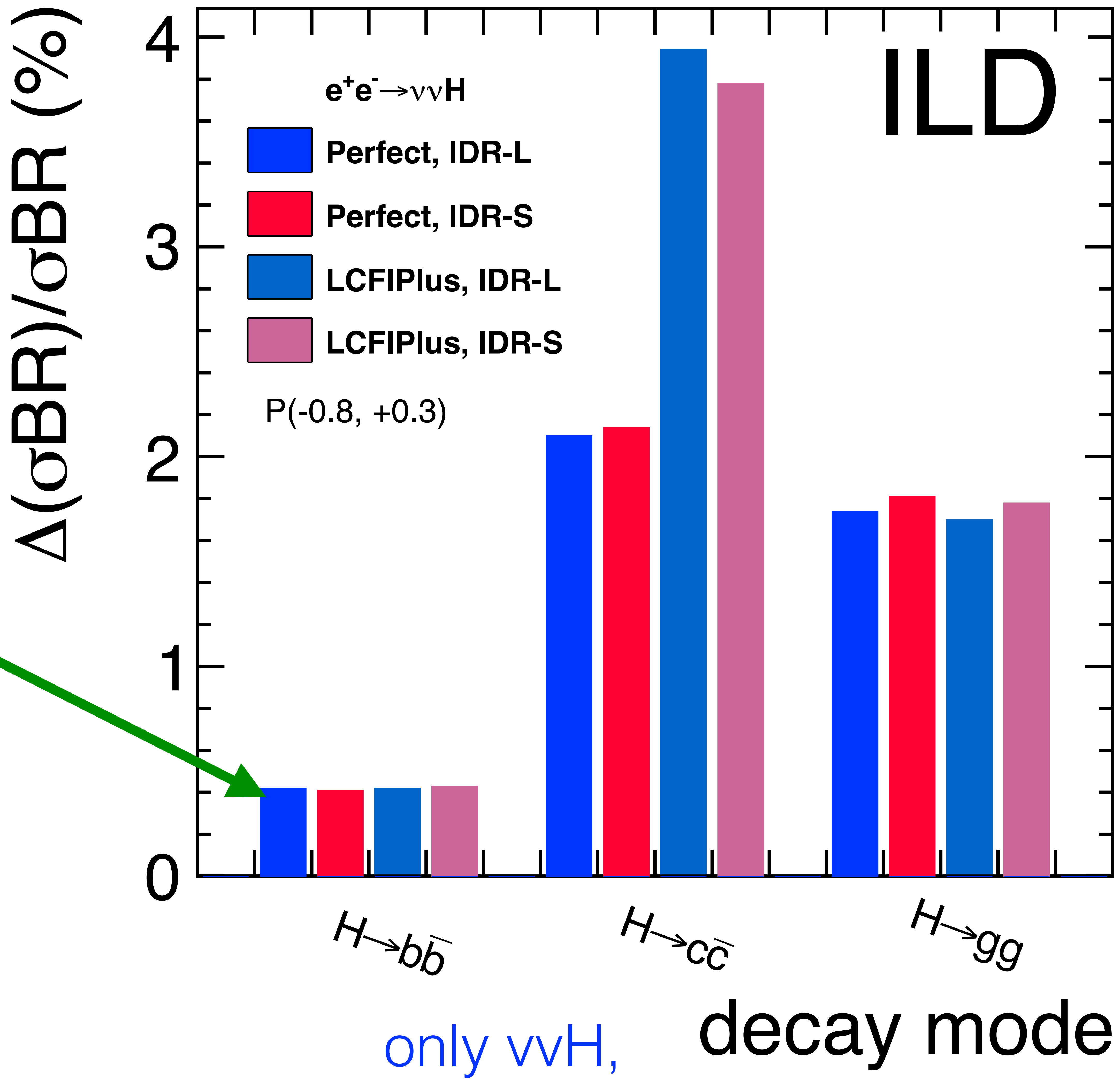

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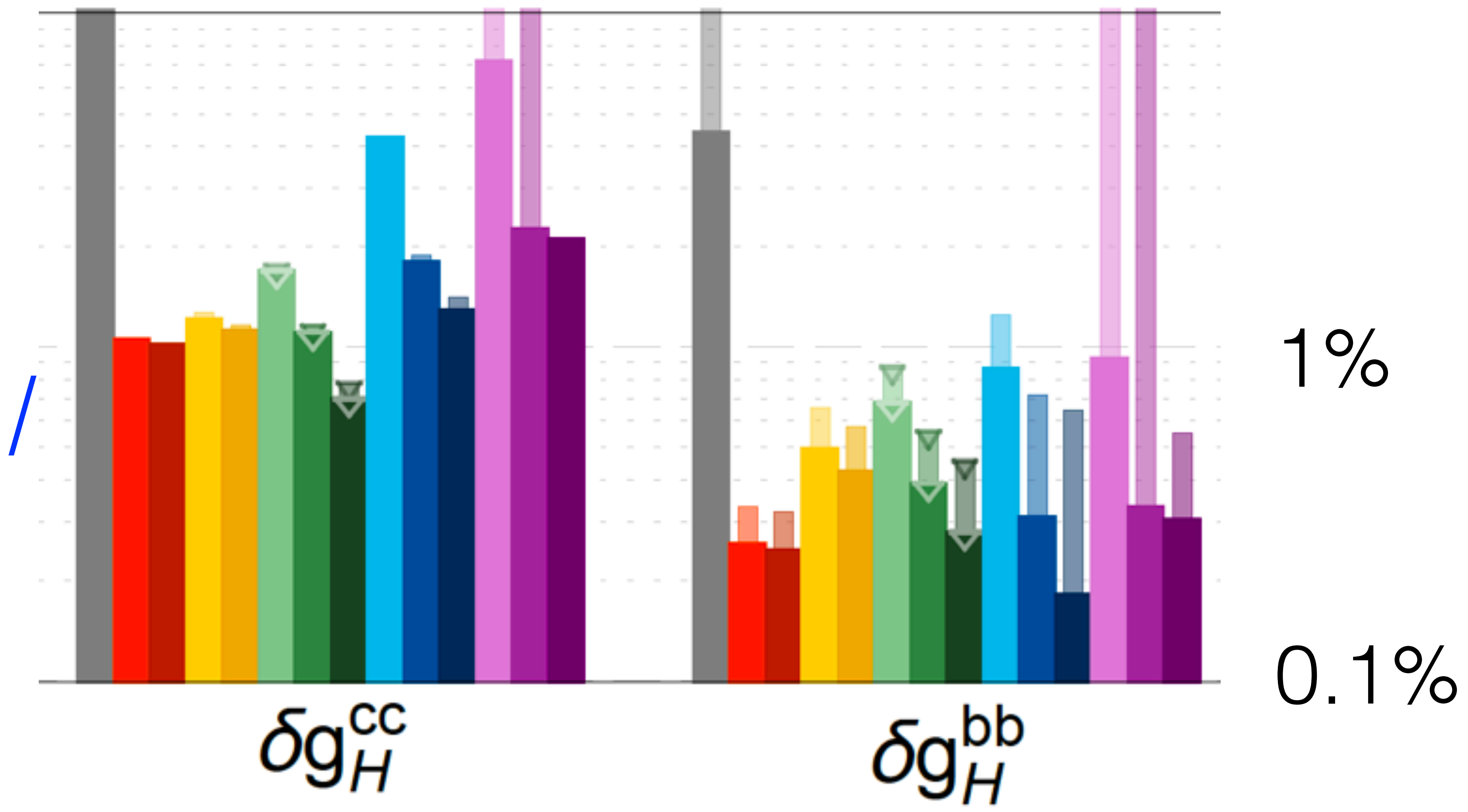

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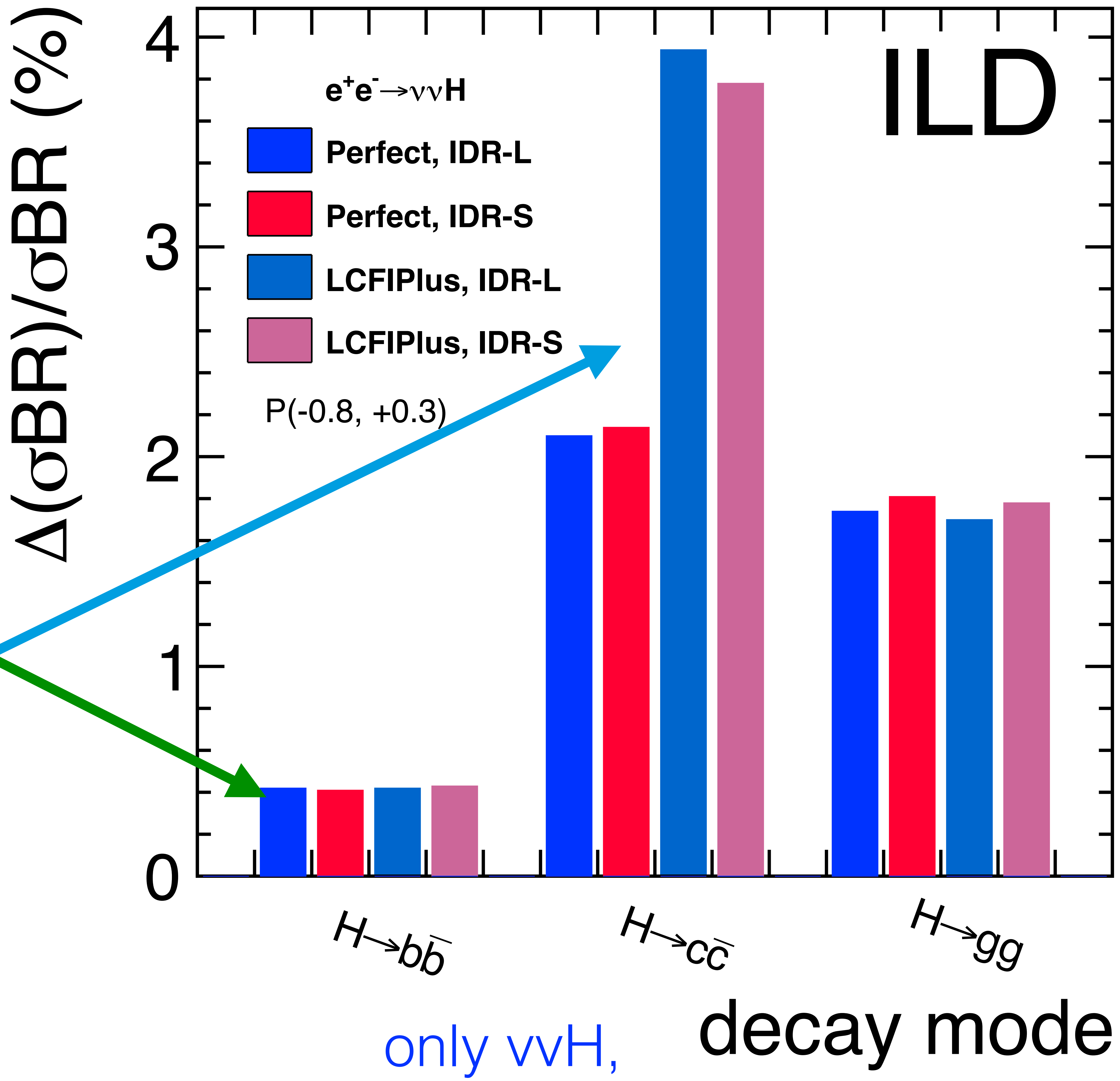

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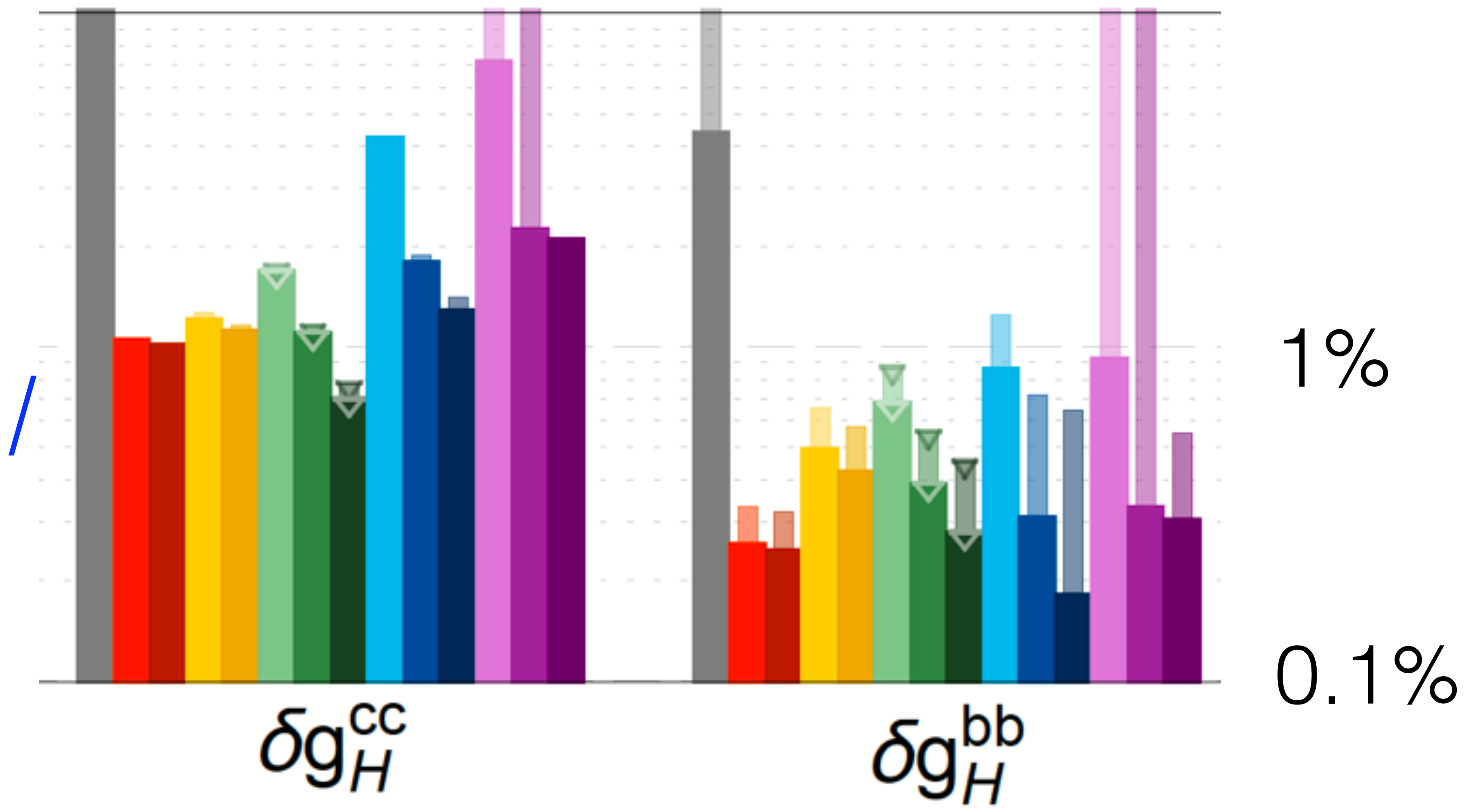

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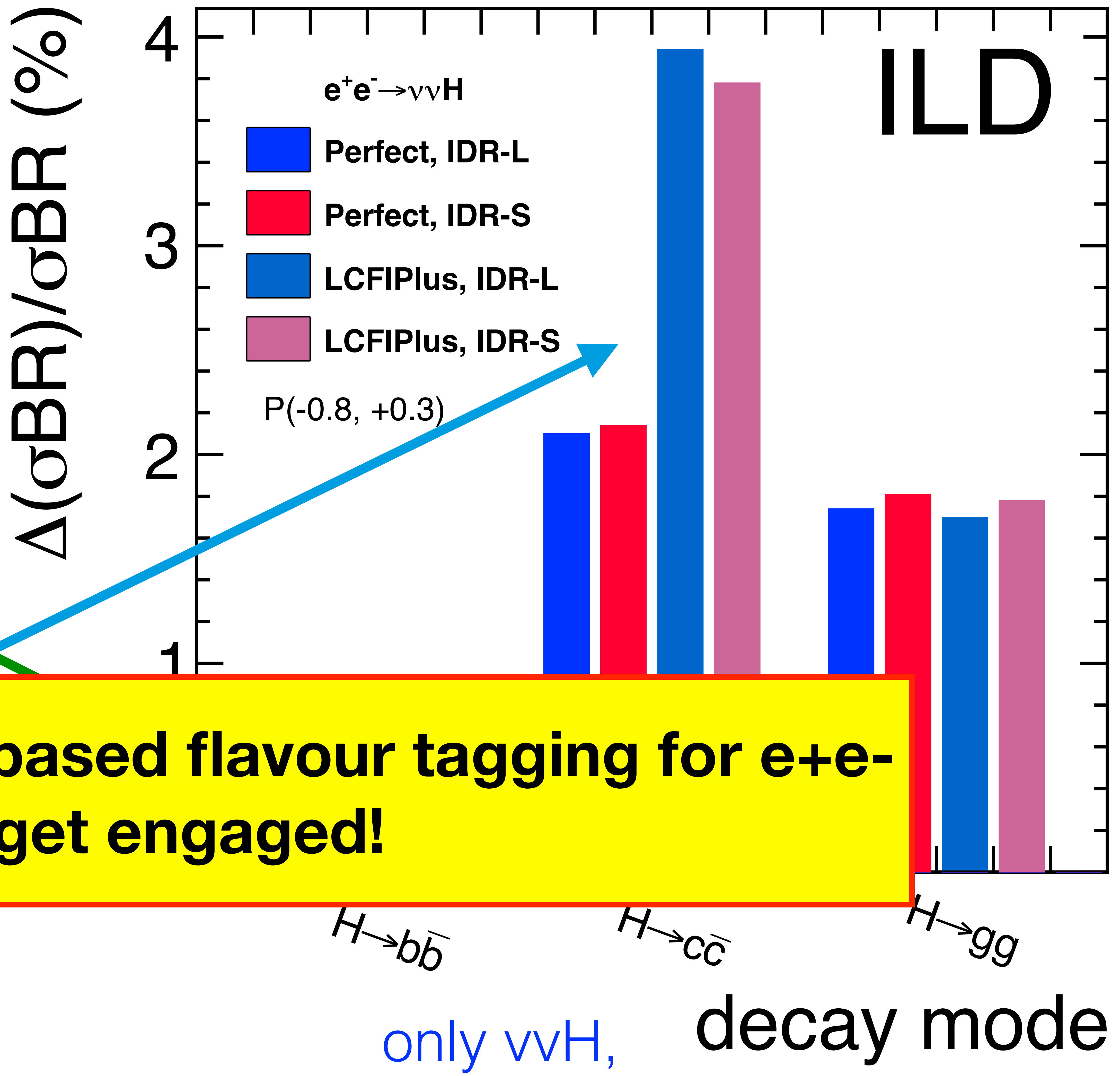
Just starting: development of ML-based flavour tagging for e+e-
=> ideal place to get engaged!



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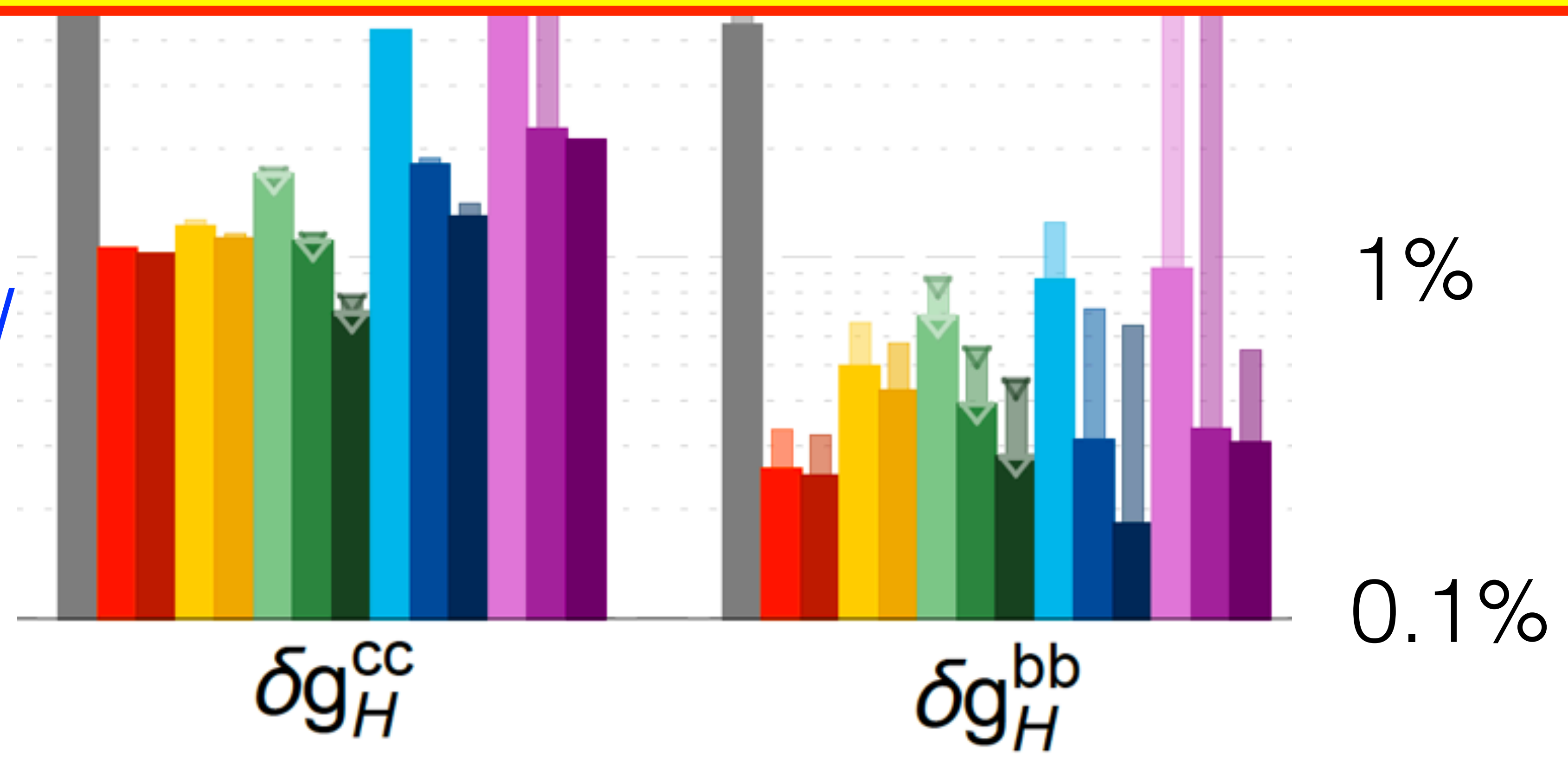
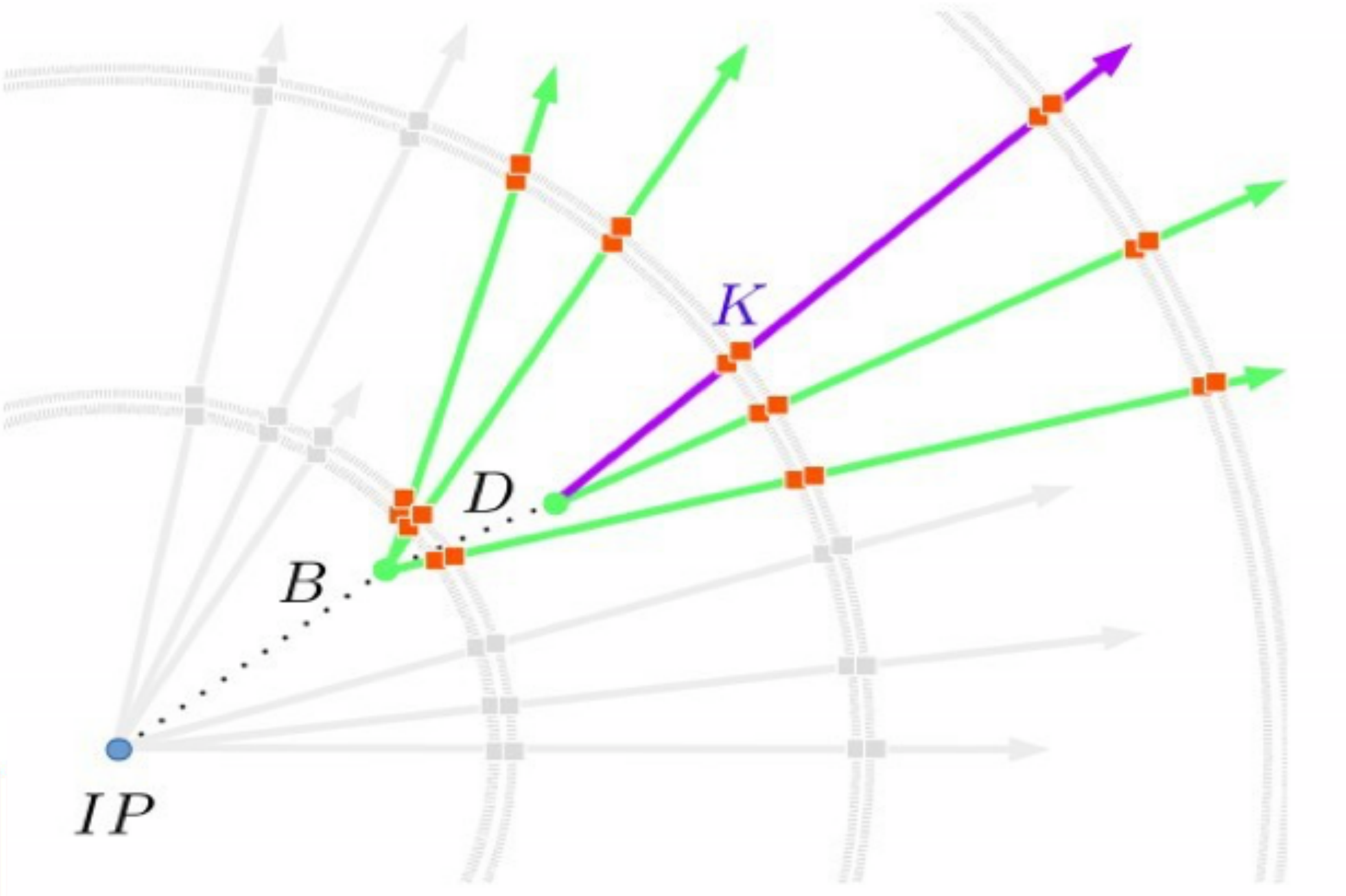


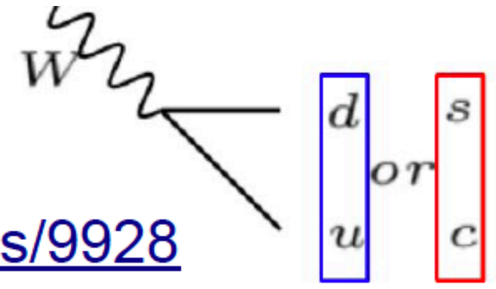
The new kid on the block: Particle ID

… only starting to be explored

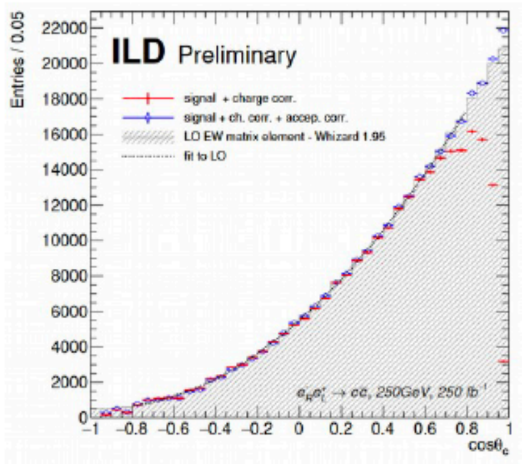
A boost of analyses using in particular Kaon ID - many of them intrisically not possible without!



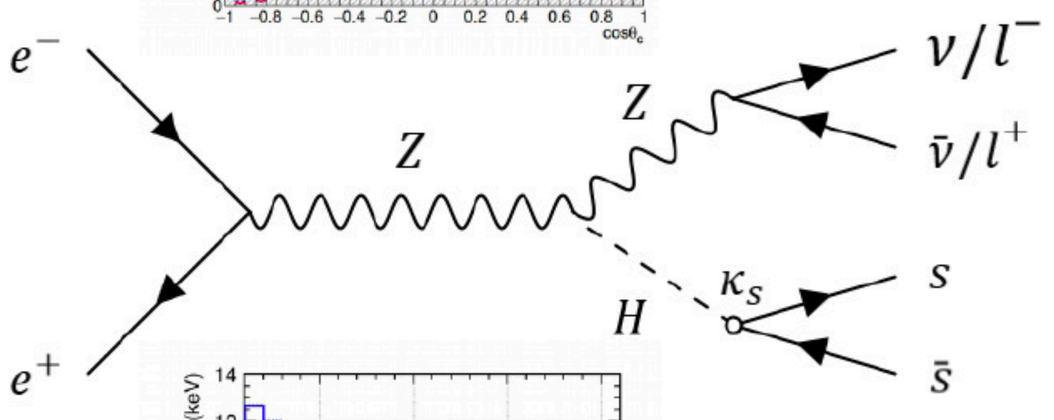
- Z and W hadronic decay branching fractions via flavour tagging
  → make connection between quark flavour and jet composition
  https://ediss.sub.uni-hamburg.de/handle/ediss/9634 , https://ediss.sub.uni-hamburg.de/handle/ediss/9928



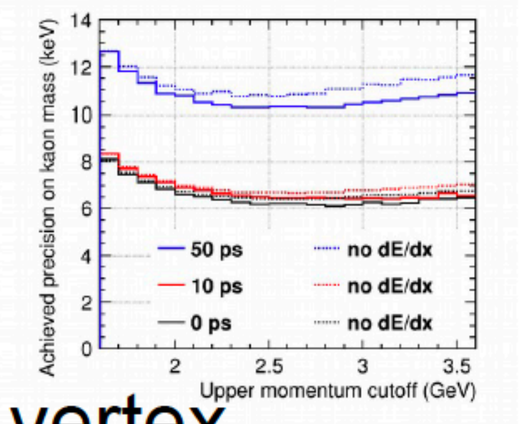
- Forward-backward asymmetry in $e^+e^- \to q\bar{q}$
  → study asymmetry in each flavour channel exclusively
  overview: https://tel.archives-ouvertes.fr/tel-01826535
  $e^+e^- \to$ tt, bb: https://agenda.linearcollider.org/event/8147
  $e^+e^- \to$ bb/cc: https://arxiv.org/abs/2002.05805 ,
  https://agenda.linearcollider.org/event/9211/contributions/49358/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



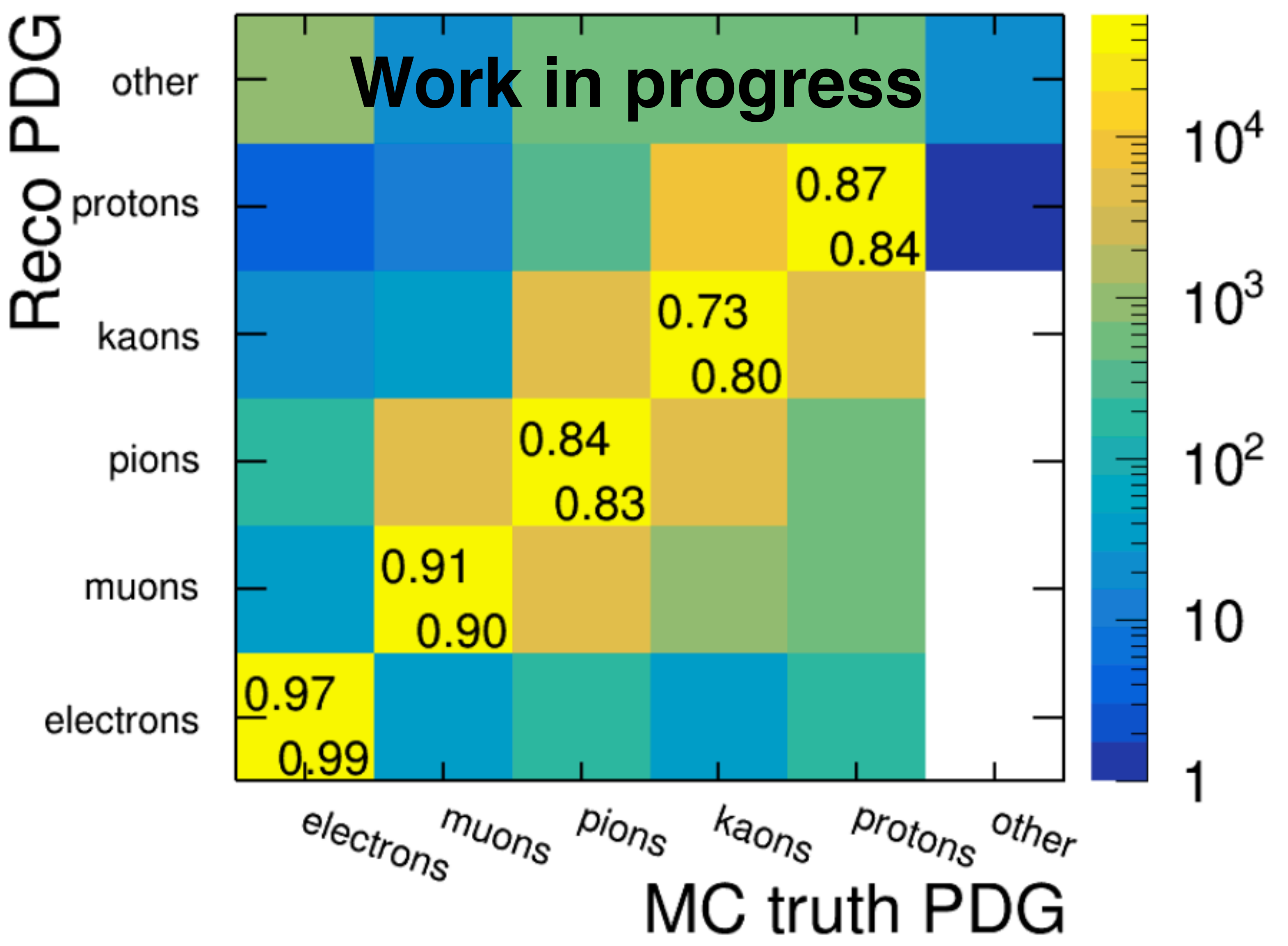
- $H \to s\bar{s}$ with s-tagging
  → identify high-momentum kaons to tag $s\bar{s}$ events
  https://arxiv.org/abs/2203.07535



- 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

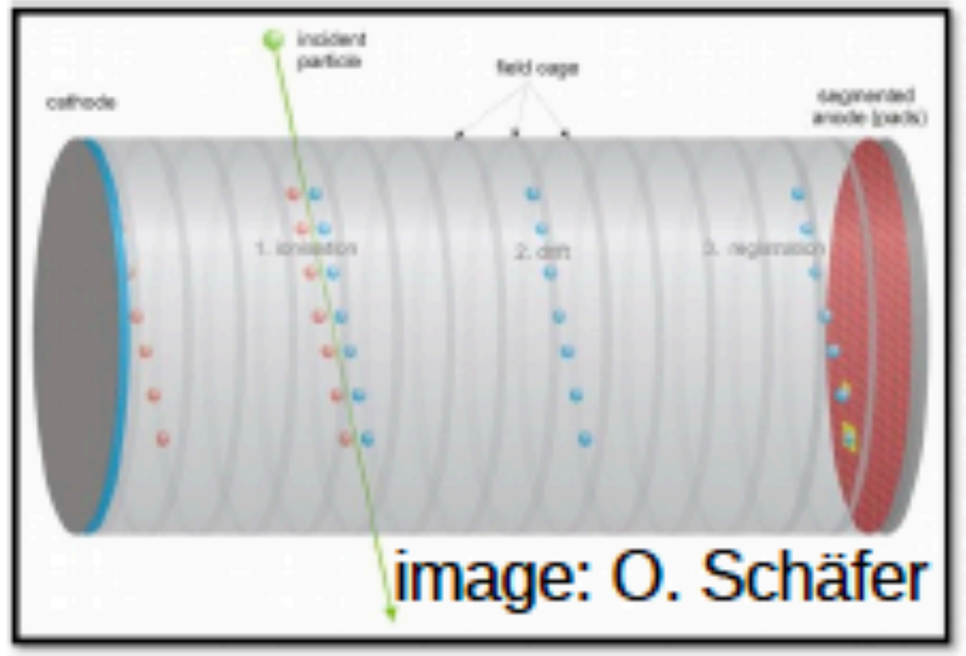
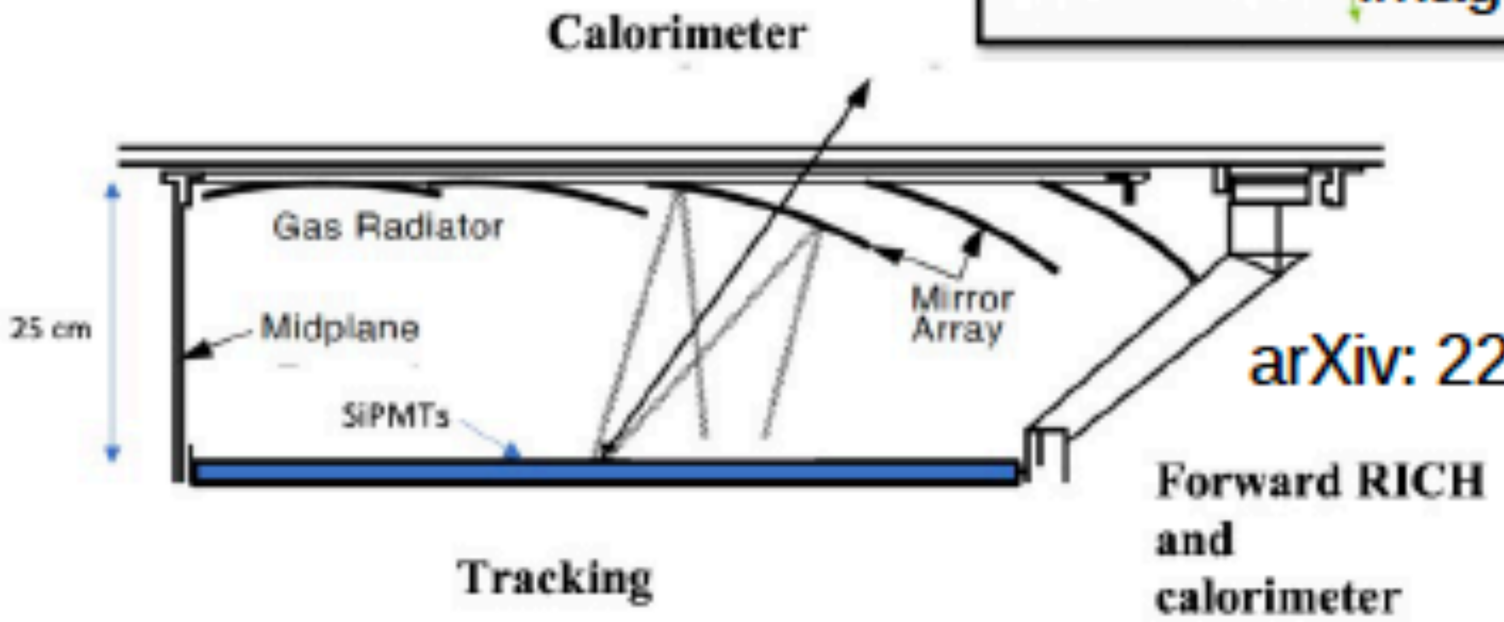


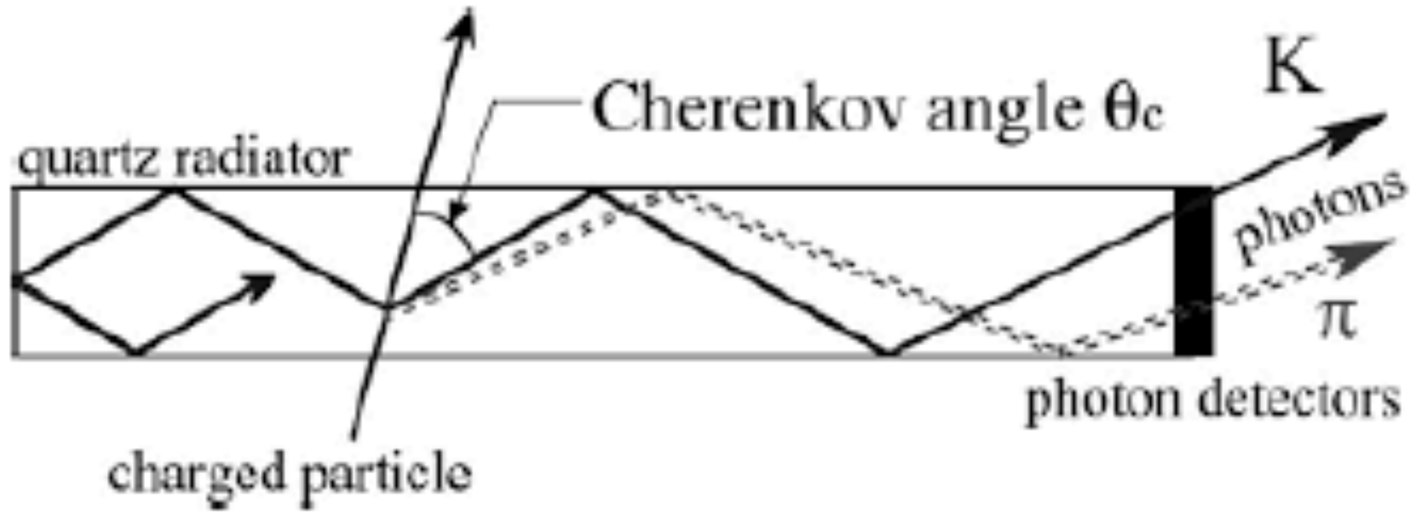
image: O. Schäfer

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



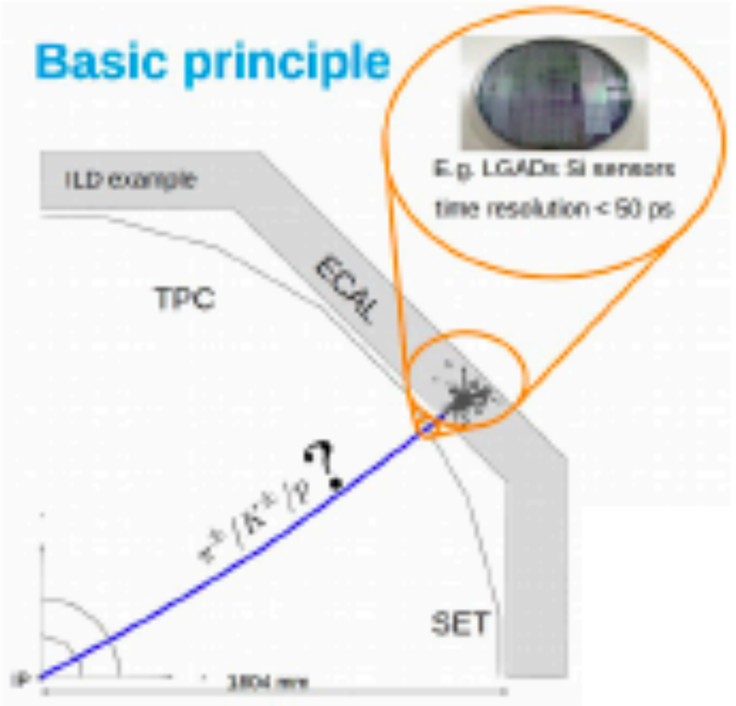
arXiv: 2203:07535

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



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

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



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

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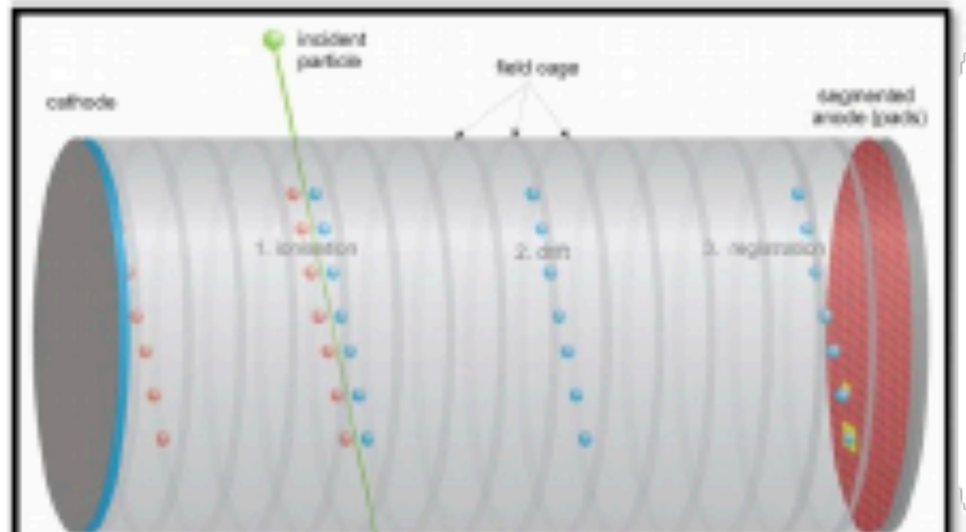

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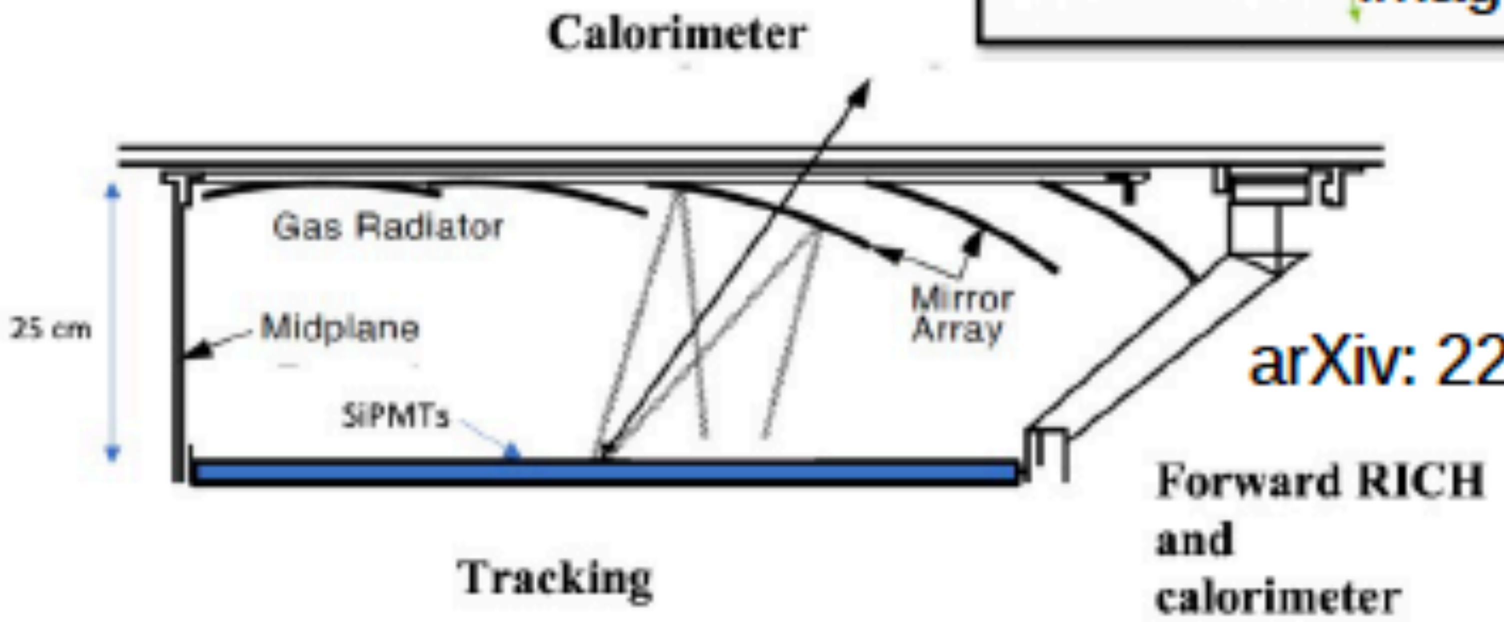

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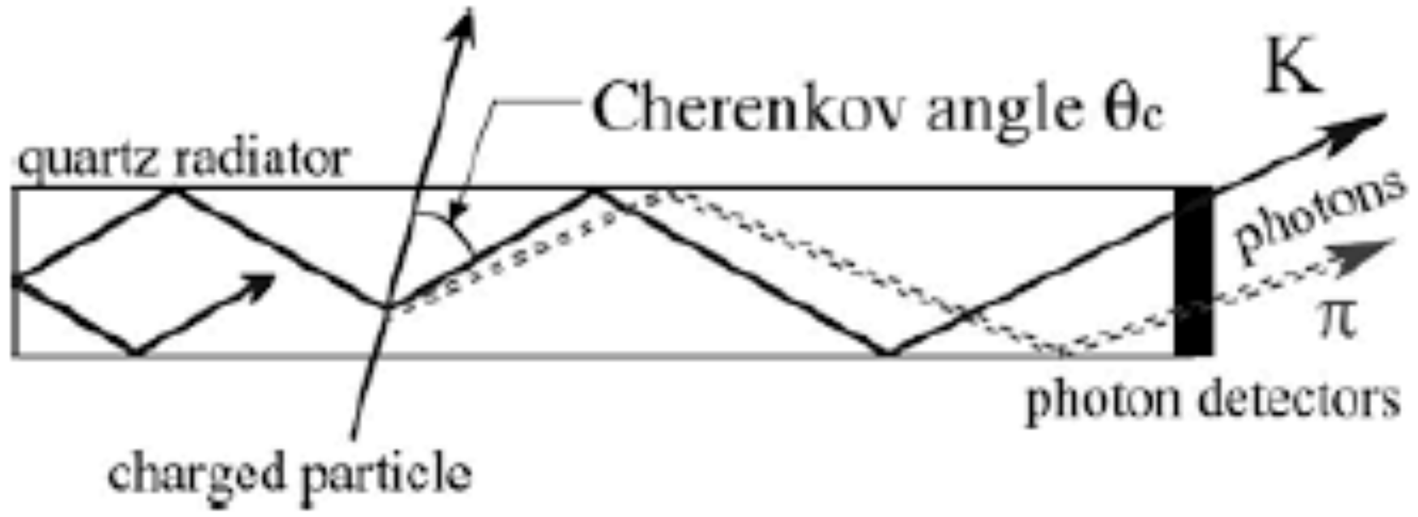

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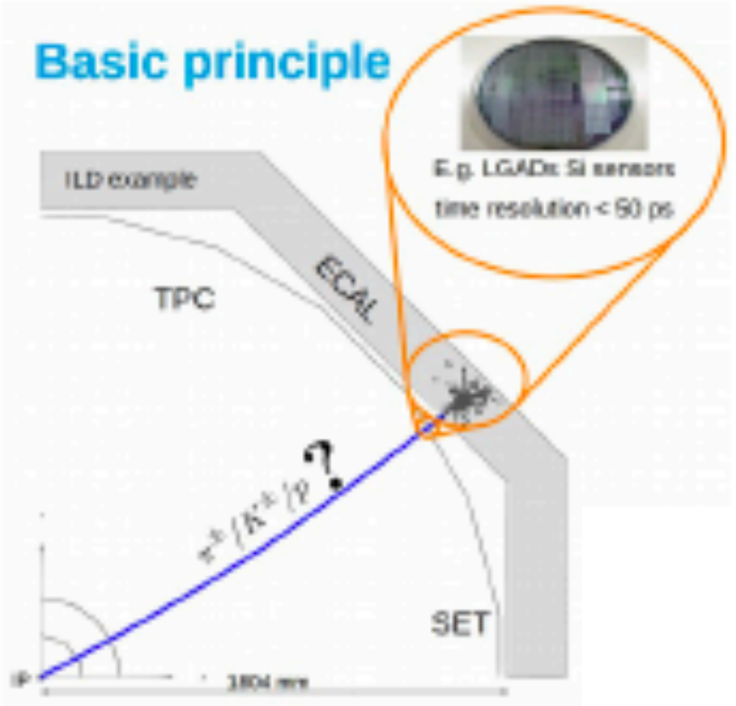

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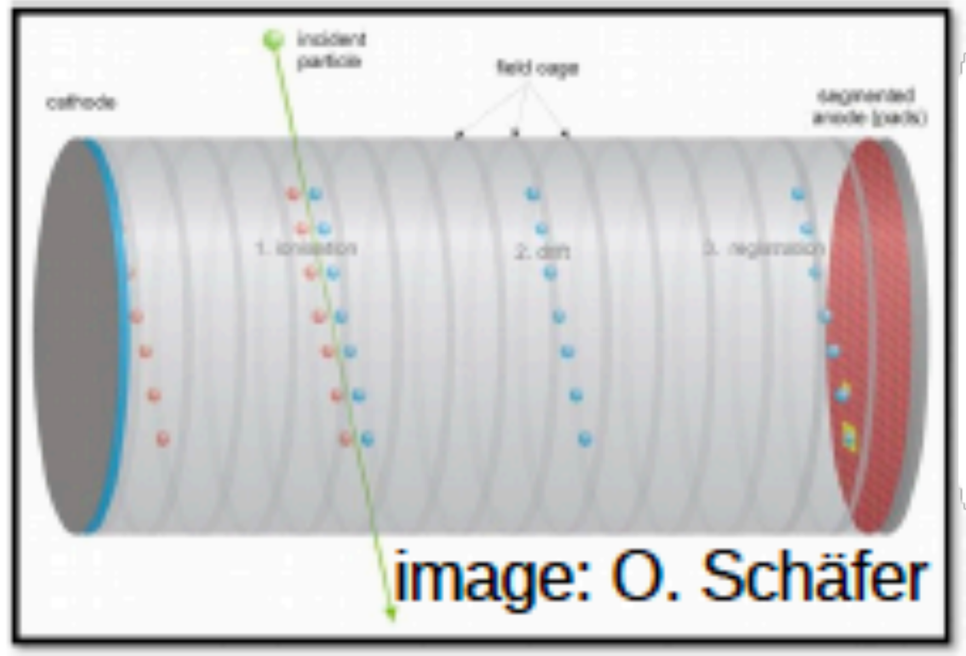

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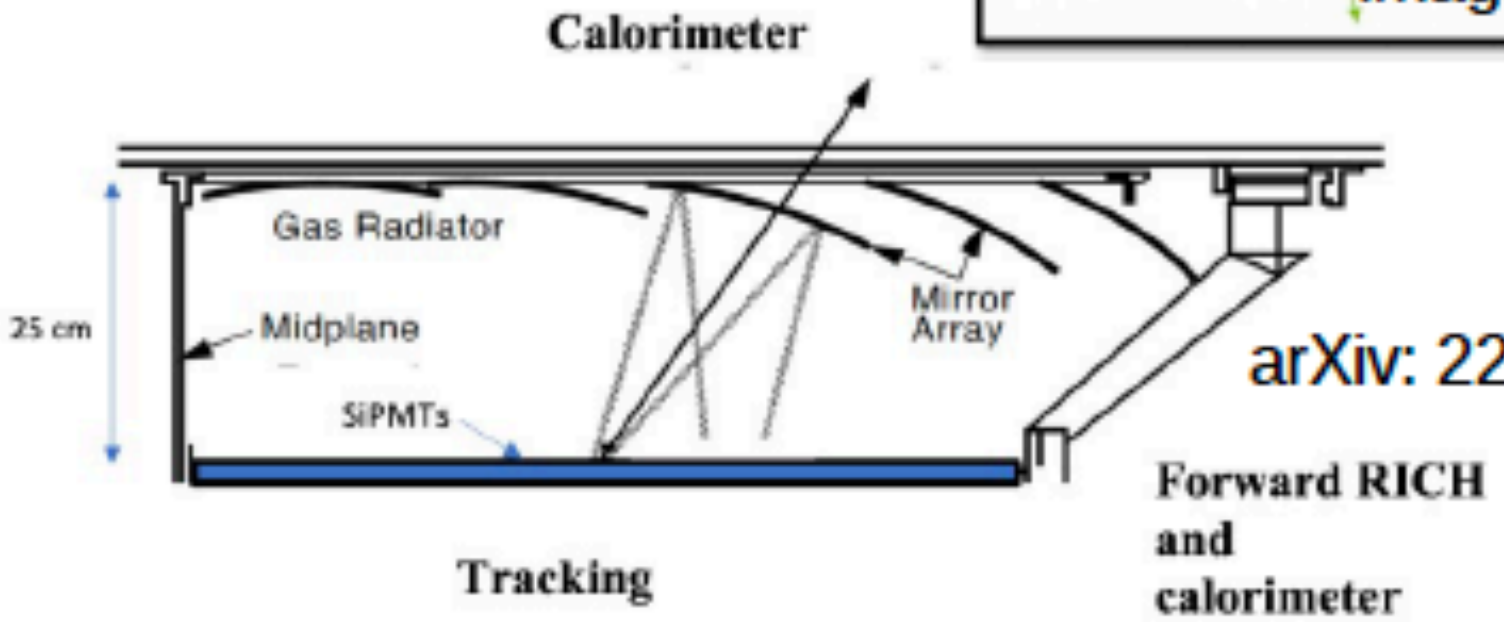

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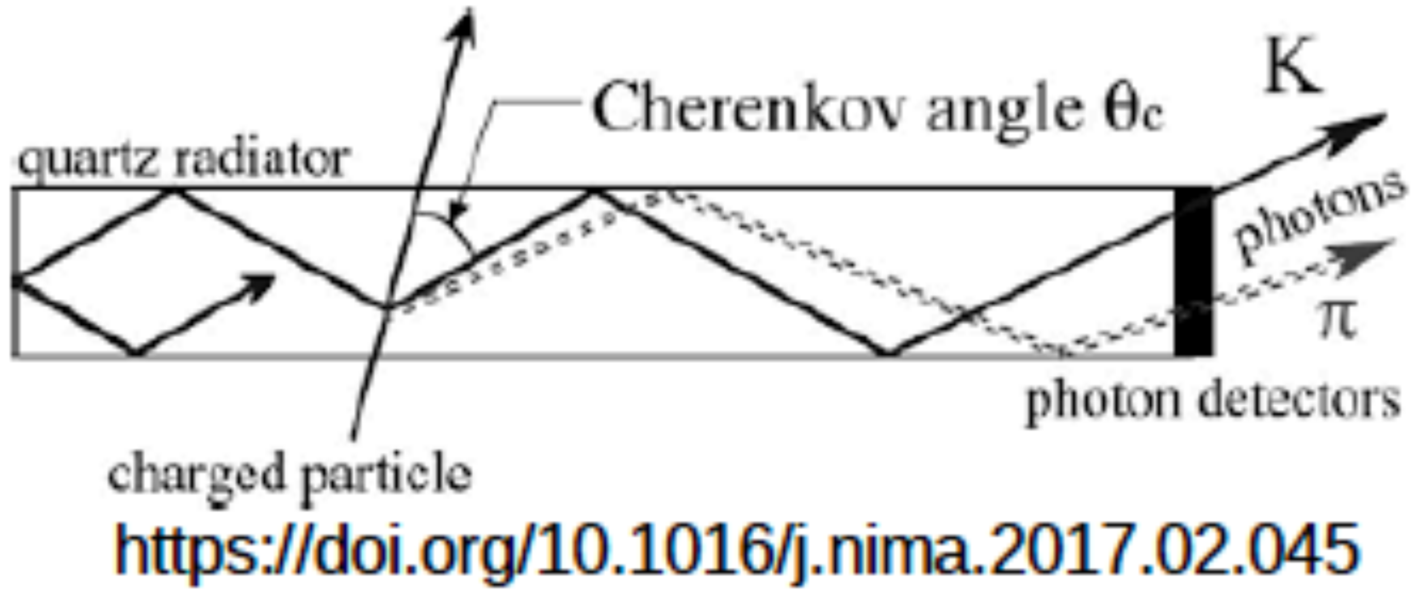

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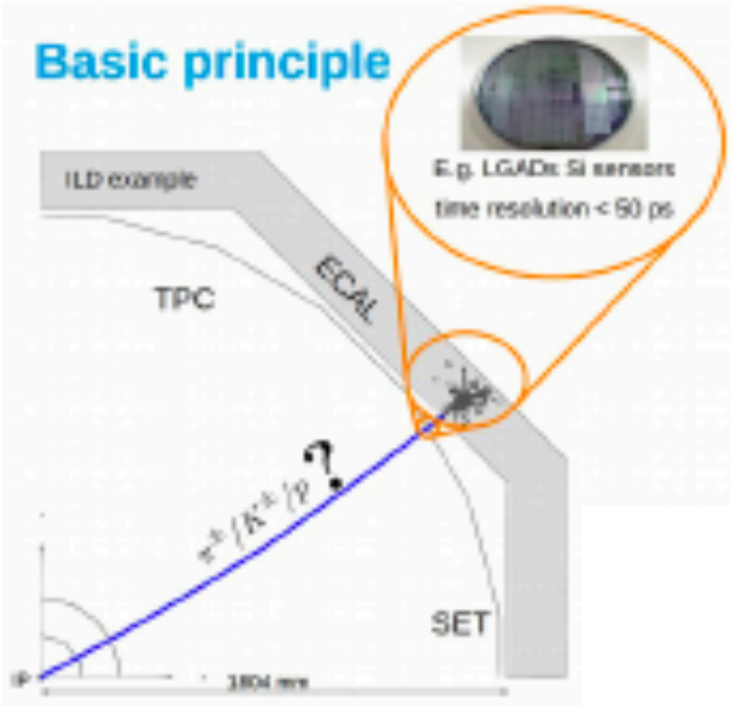

Interesting momentum range
=> impact on ParticleFlow /
Jet Energy Resolution?!

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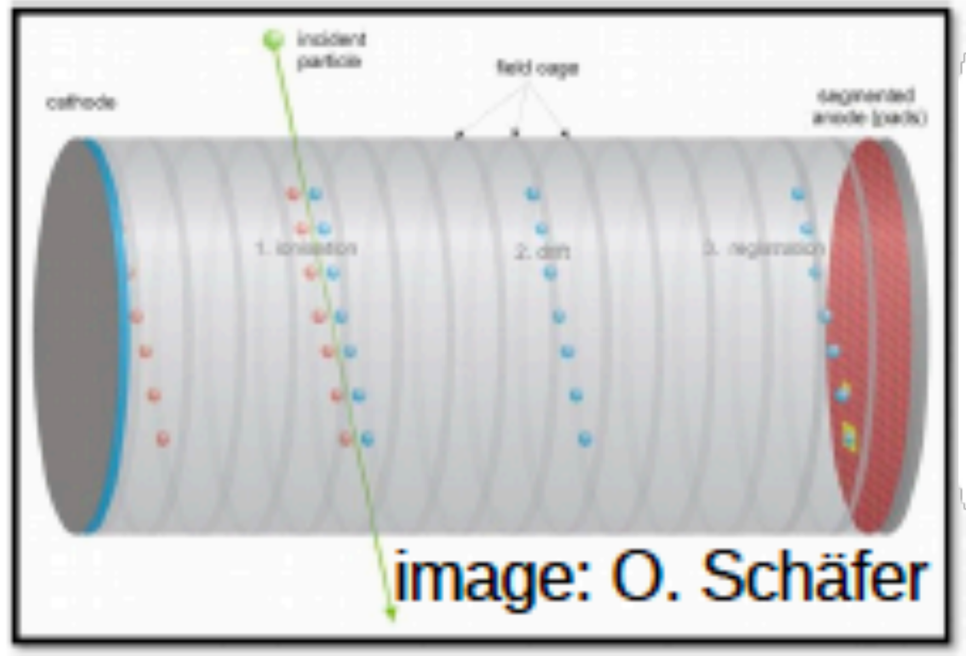

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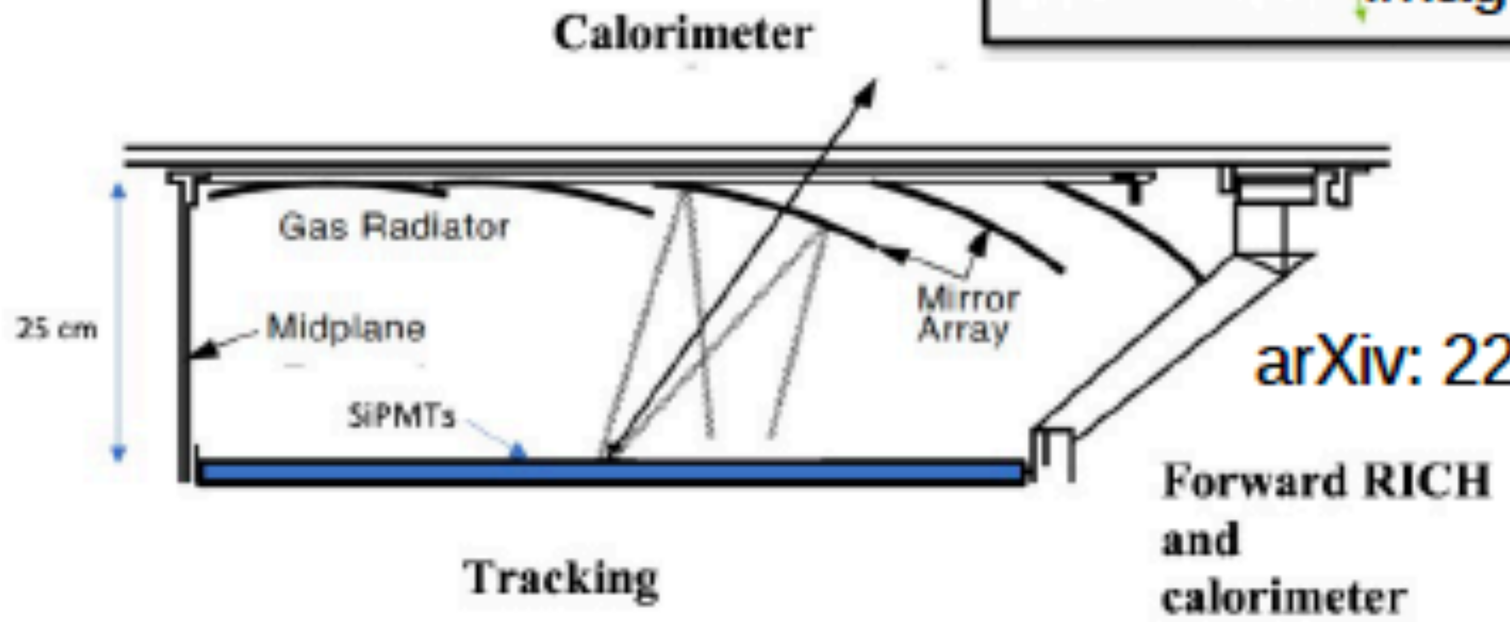

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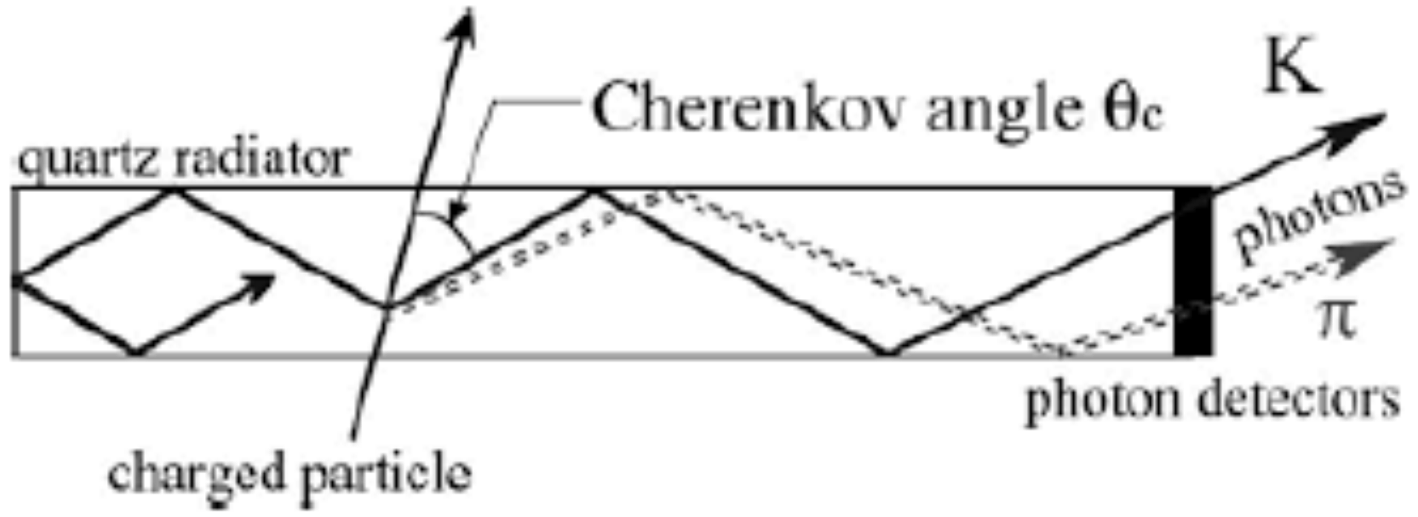

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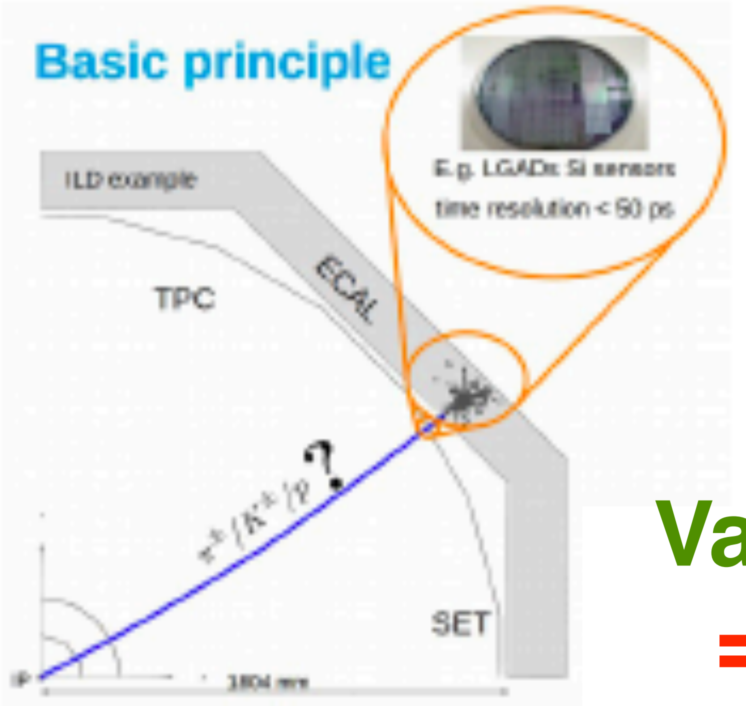


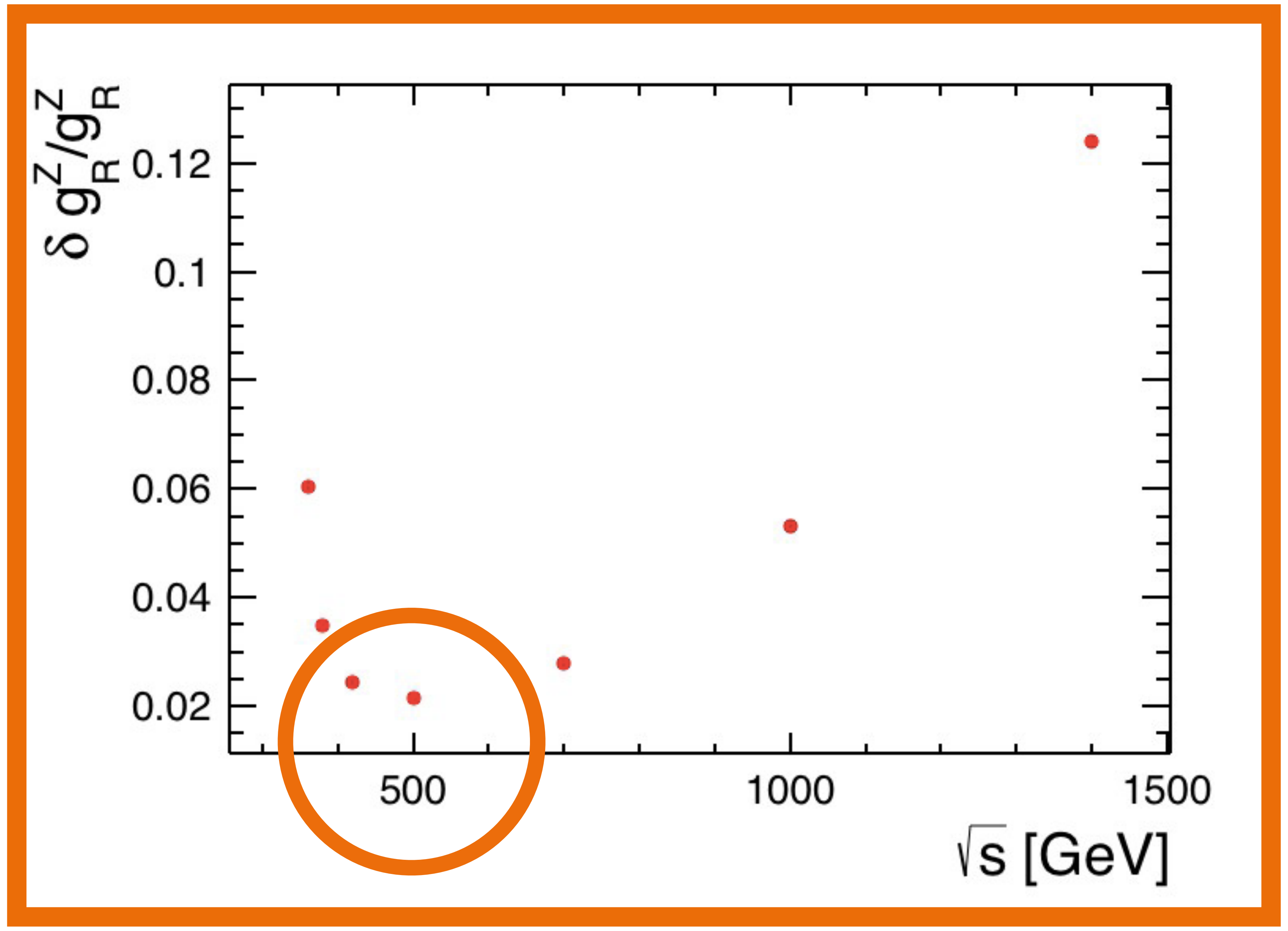
Interesting momentum range
=> impact on ParticleFlow / Jet Energy Resolution?!

Various implementation options in Si tracking or ECal
=> smoking-gun use-case for low-momentum PID?

“2nd stage” energy for LCs

500…550…600 GeV?

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



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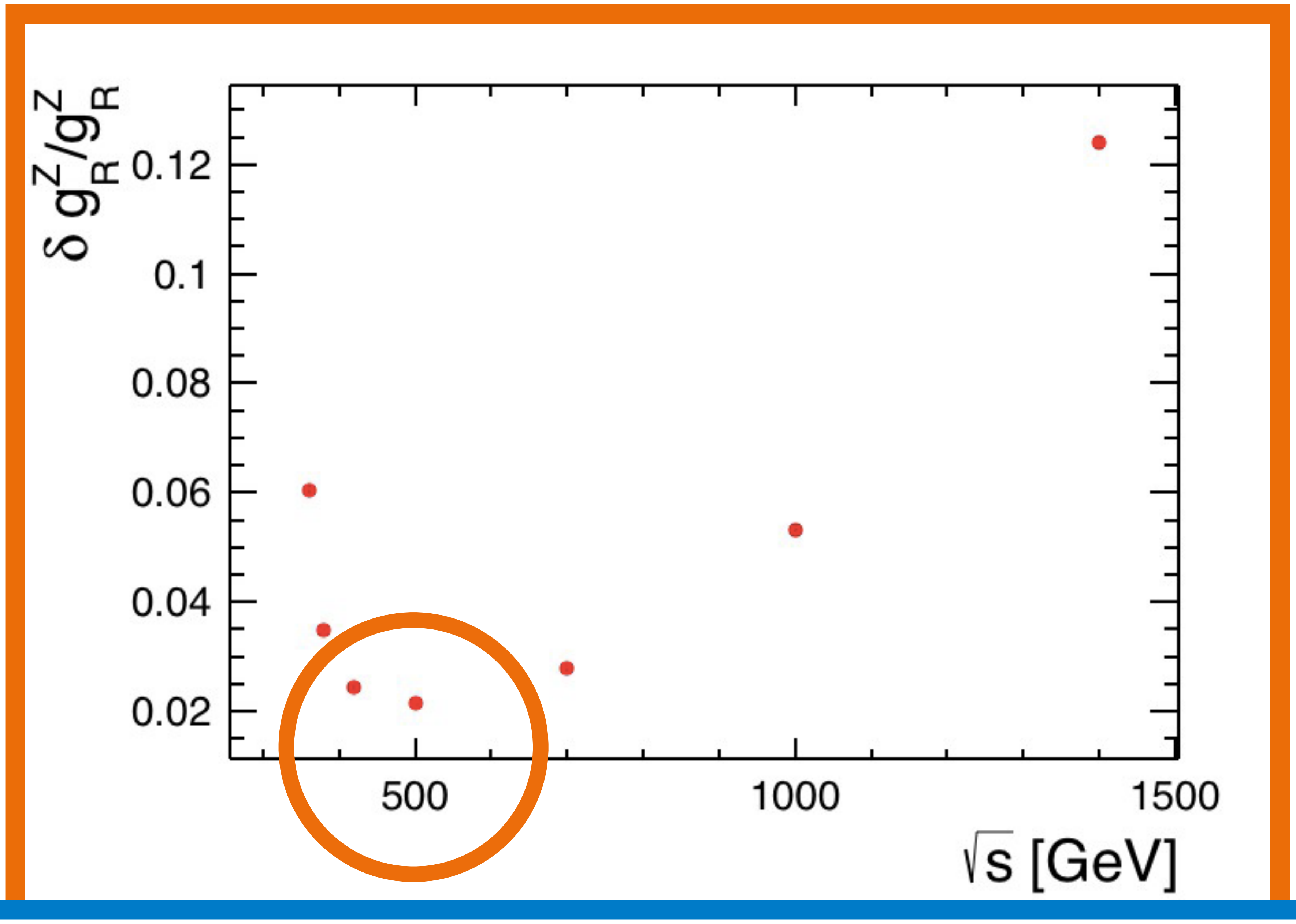

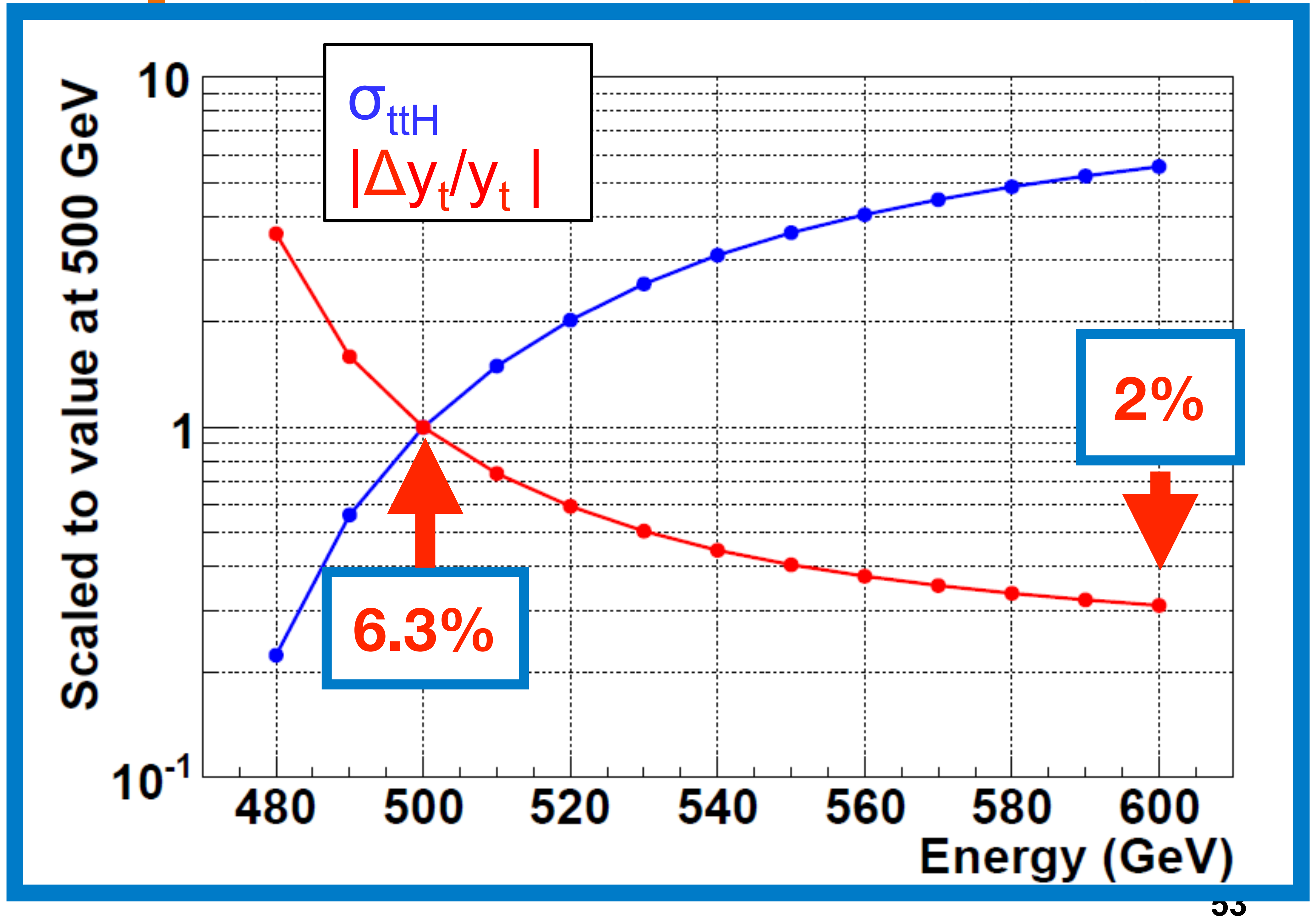

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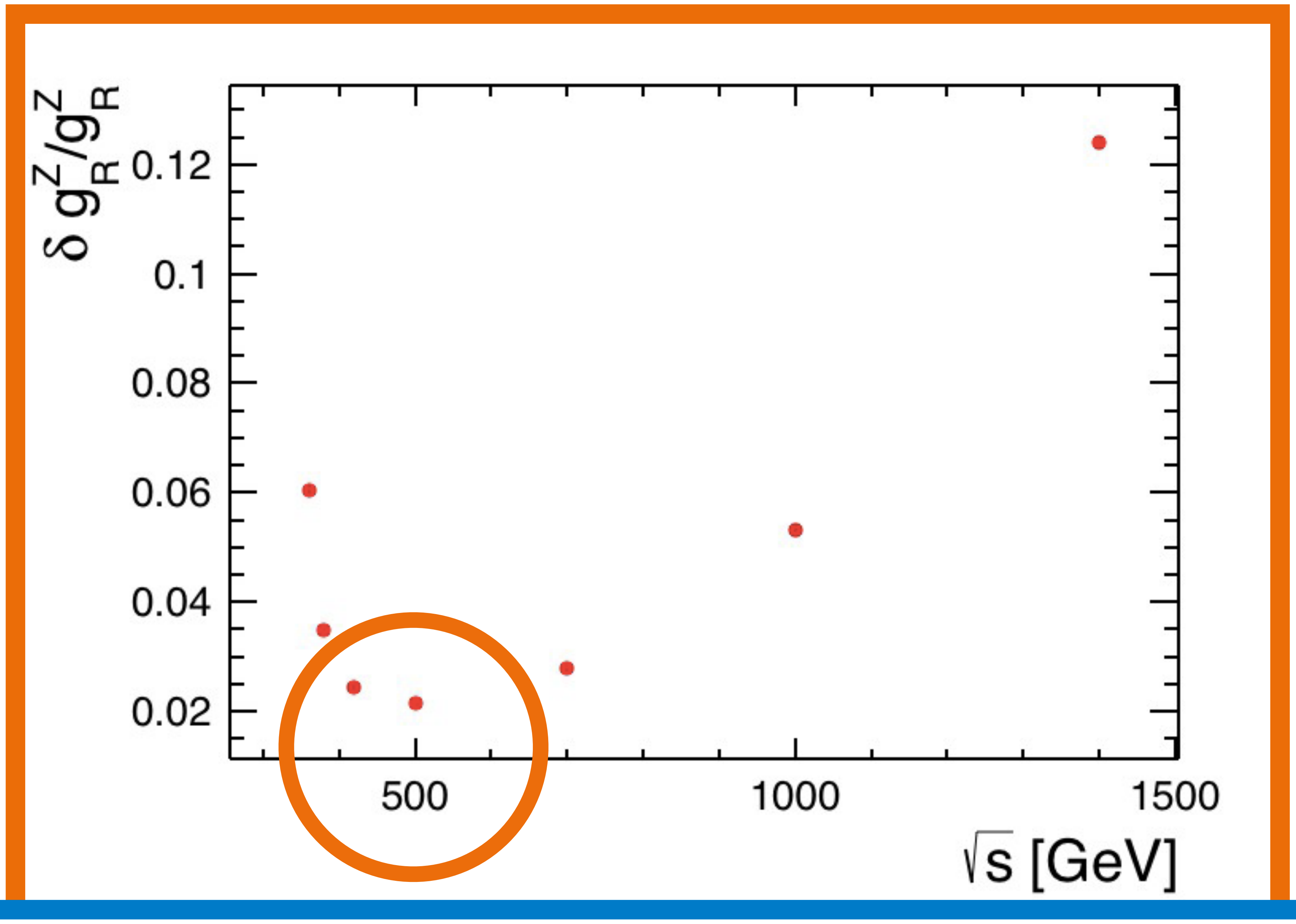
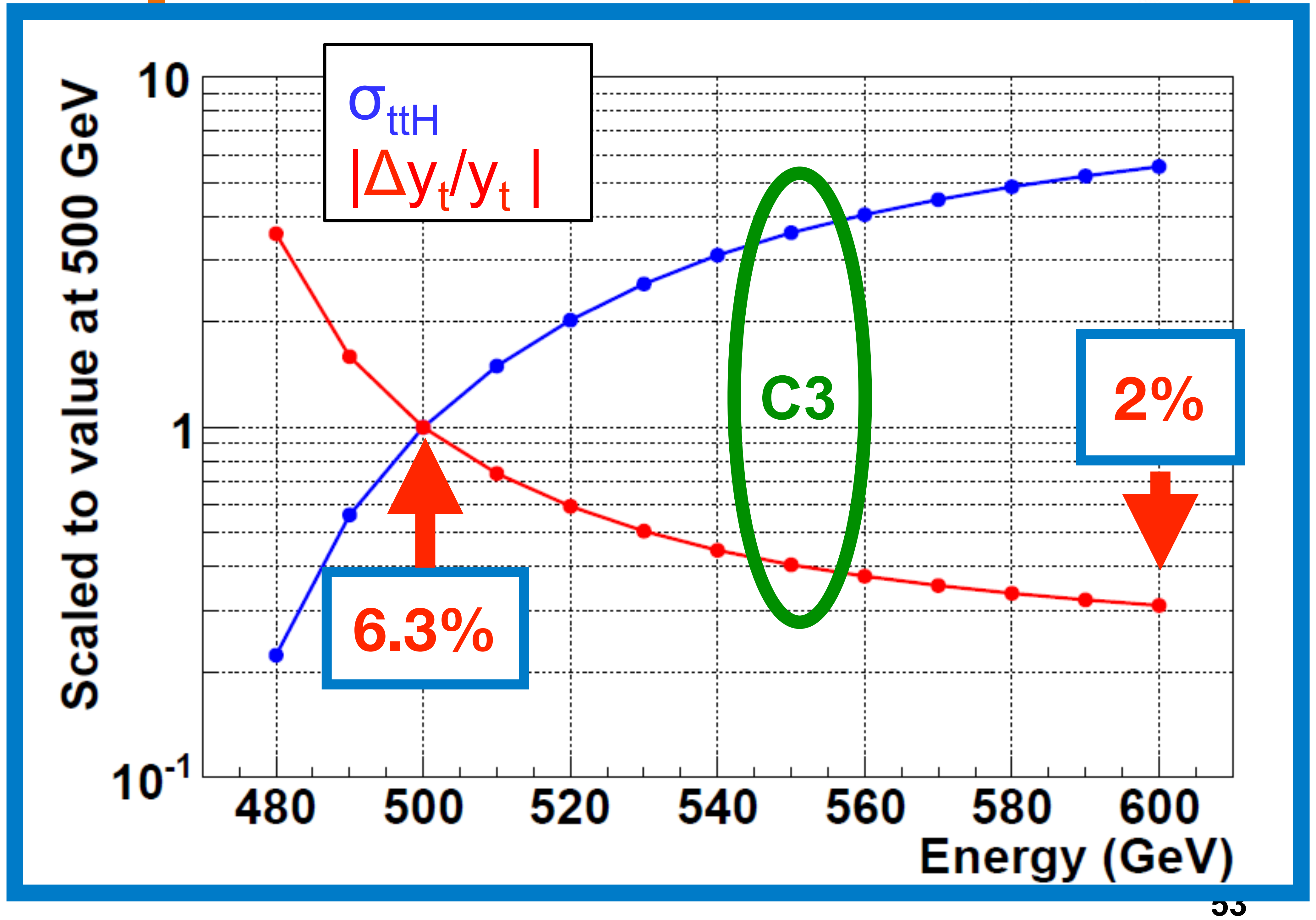
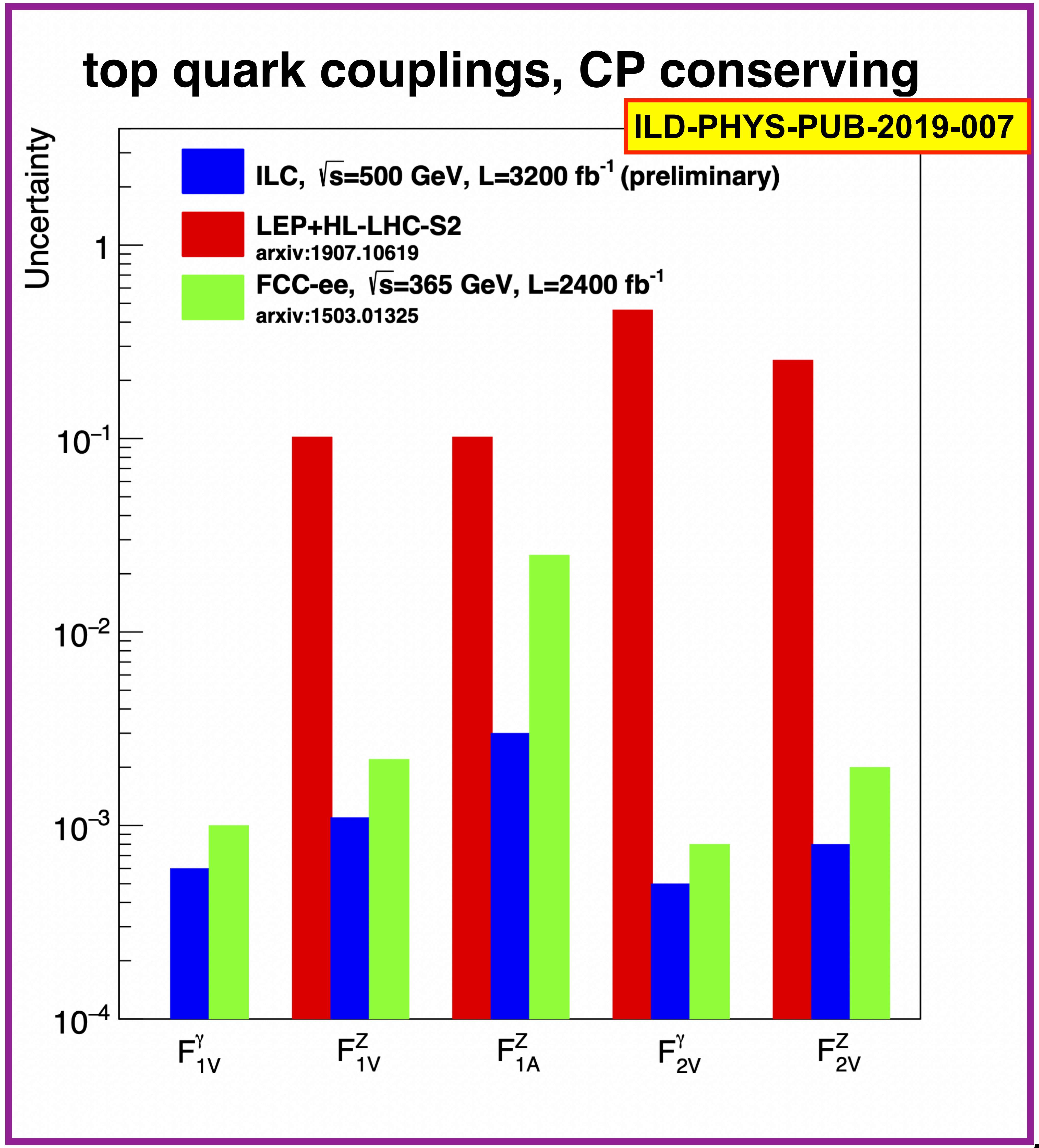




Polarisation & Electroweak Physics at high energies

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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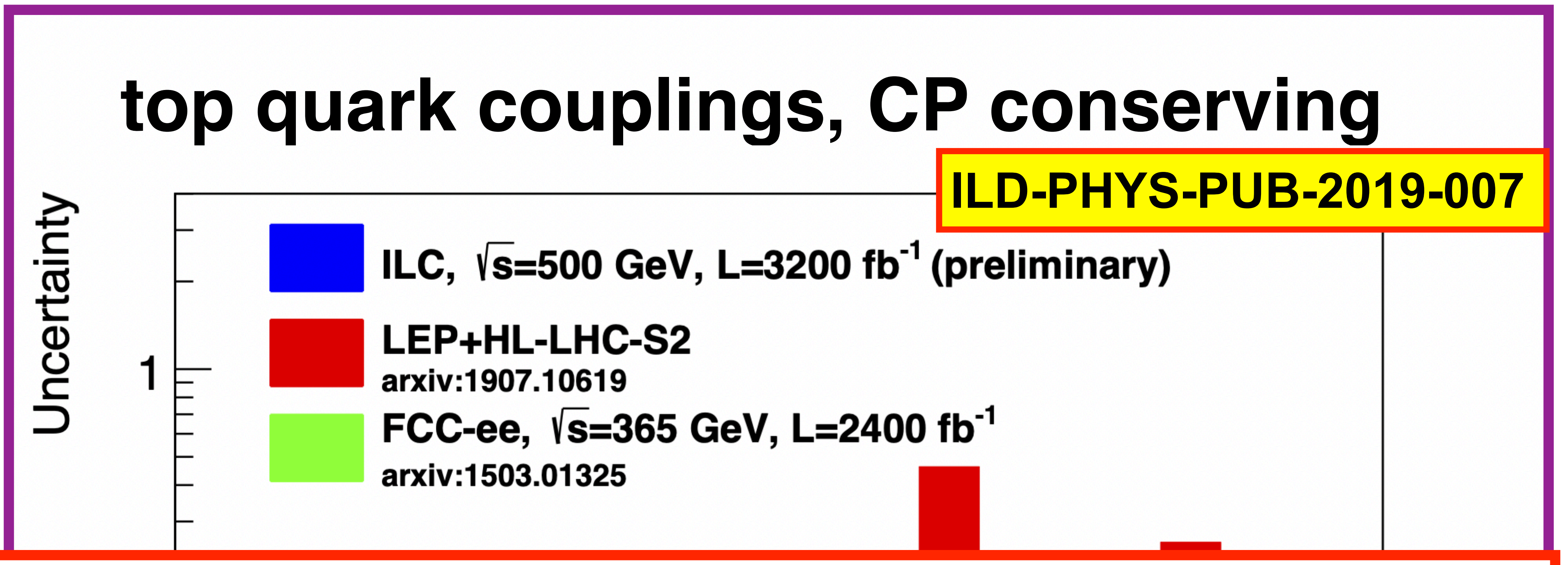
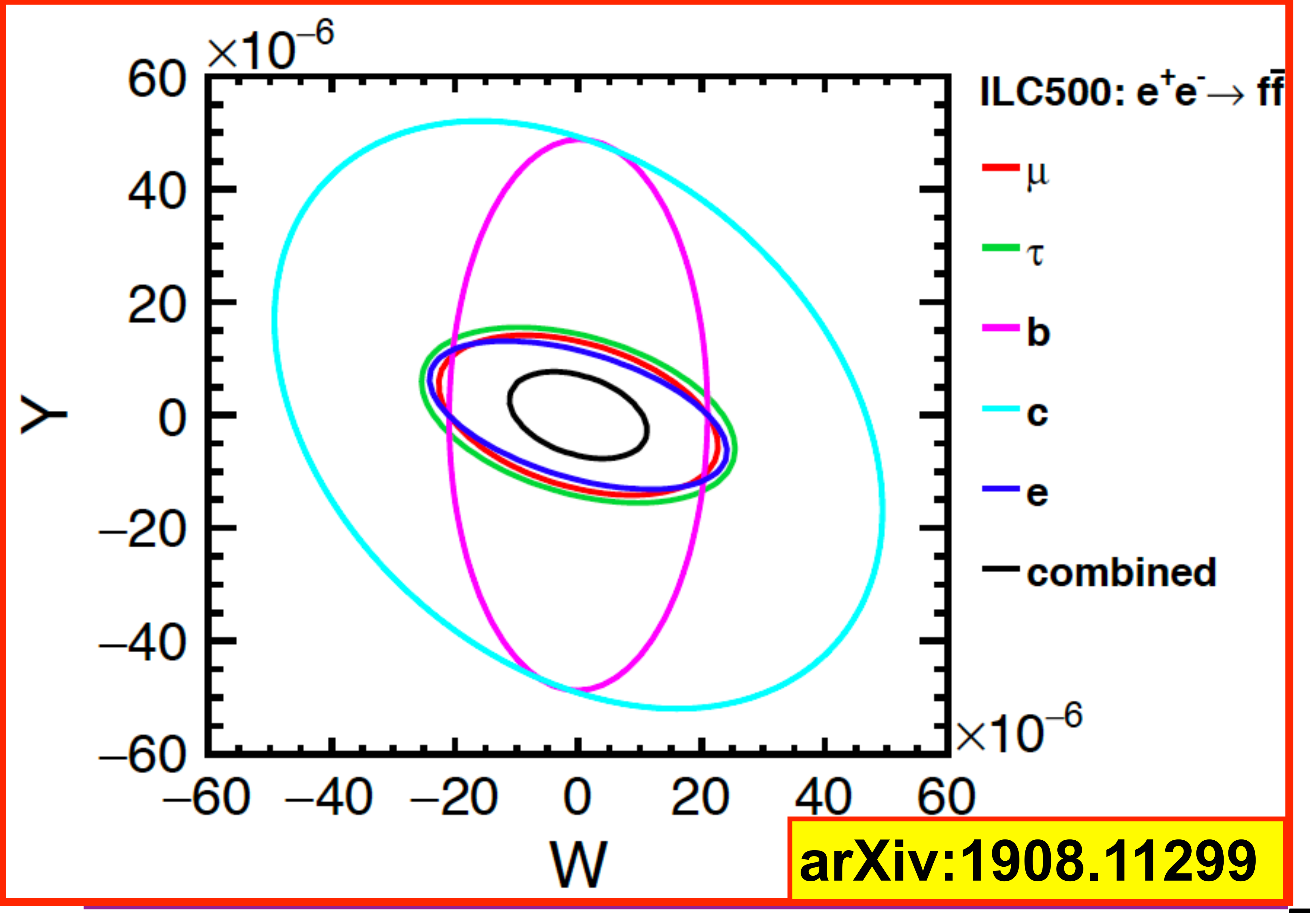


$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78



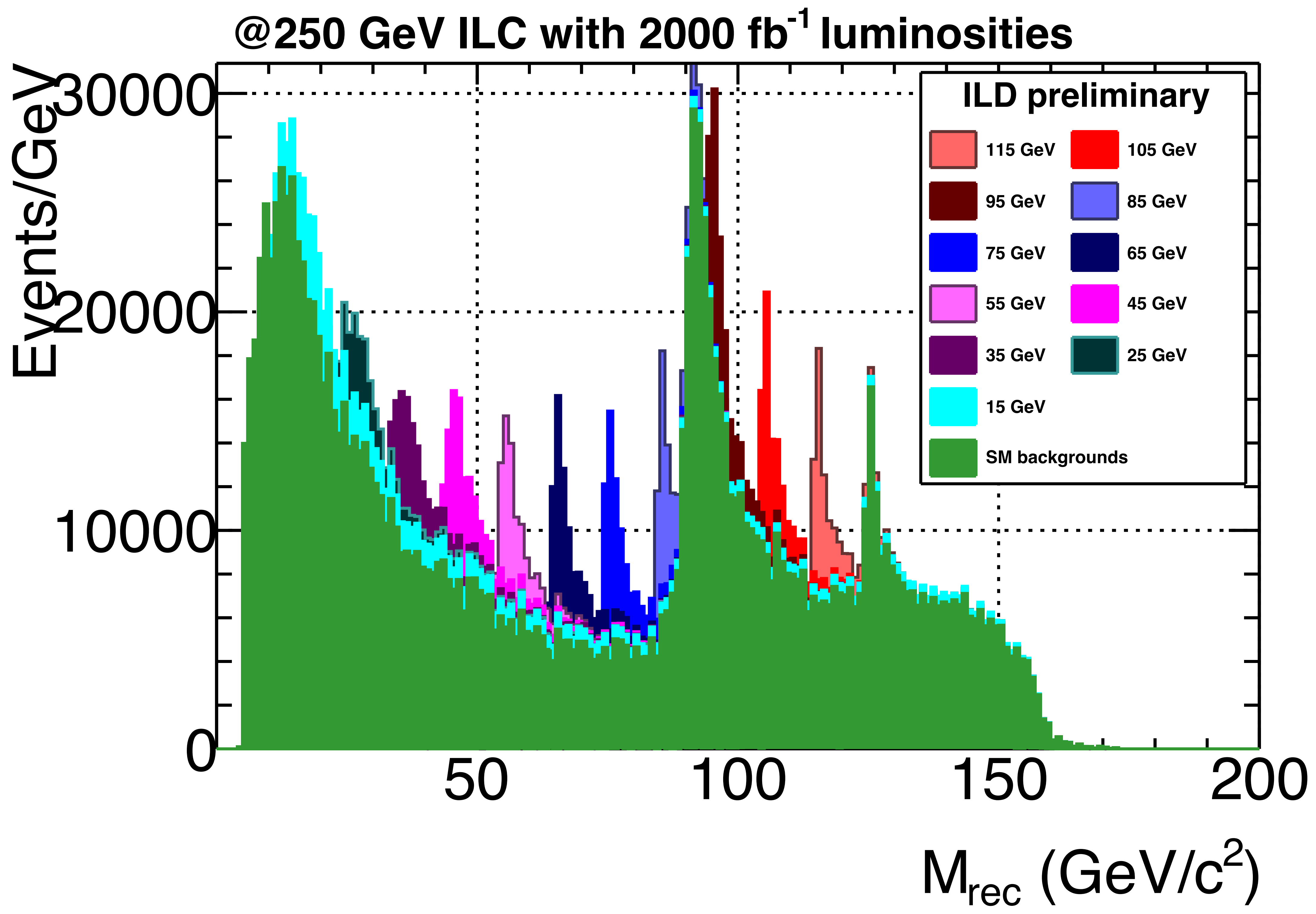
arXiv:1908.11299

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

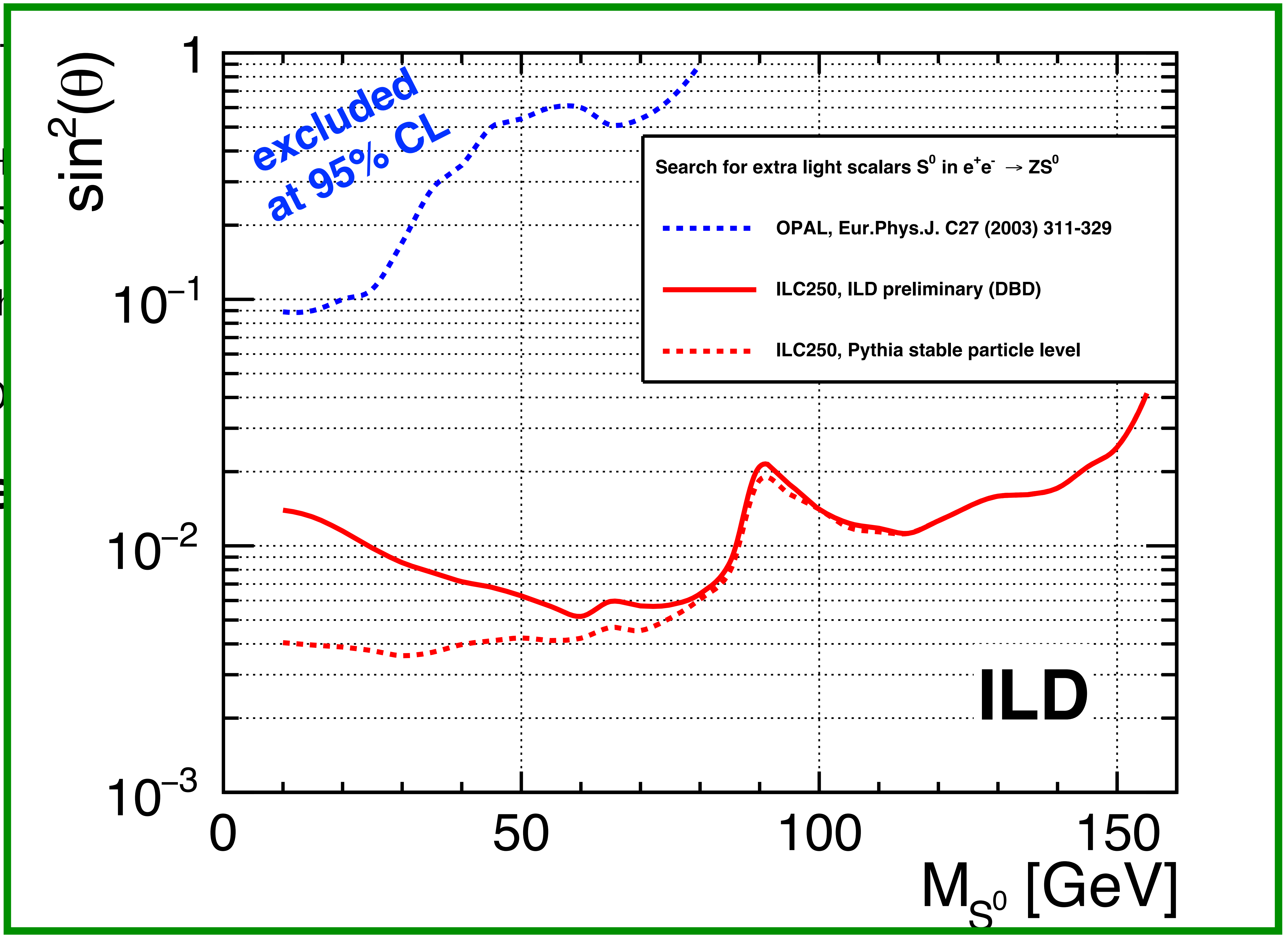
- **fully complementary to measurement of ZH cross section**
- **other possibility: ee -> bbh (via Yukawa coupling)**

Extra Higgs Bosons ?

Siblings of the Higgs

- mus
  - g_H
  - 25
    g
- prob

=> de



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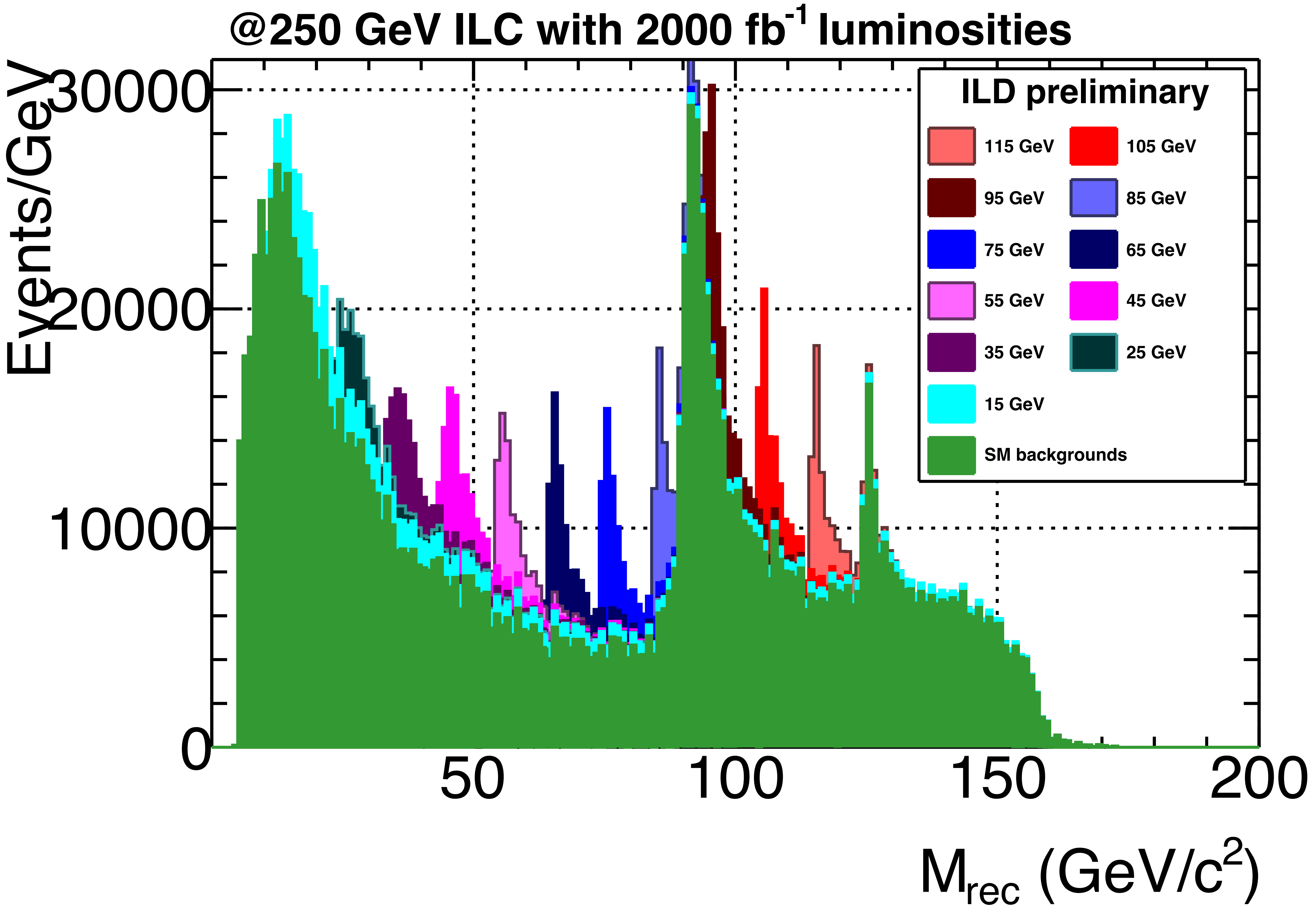

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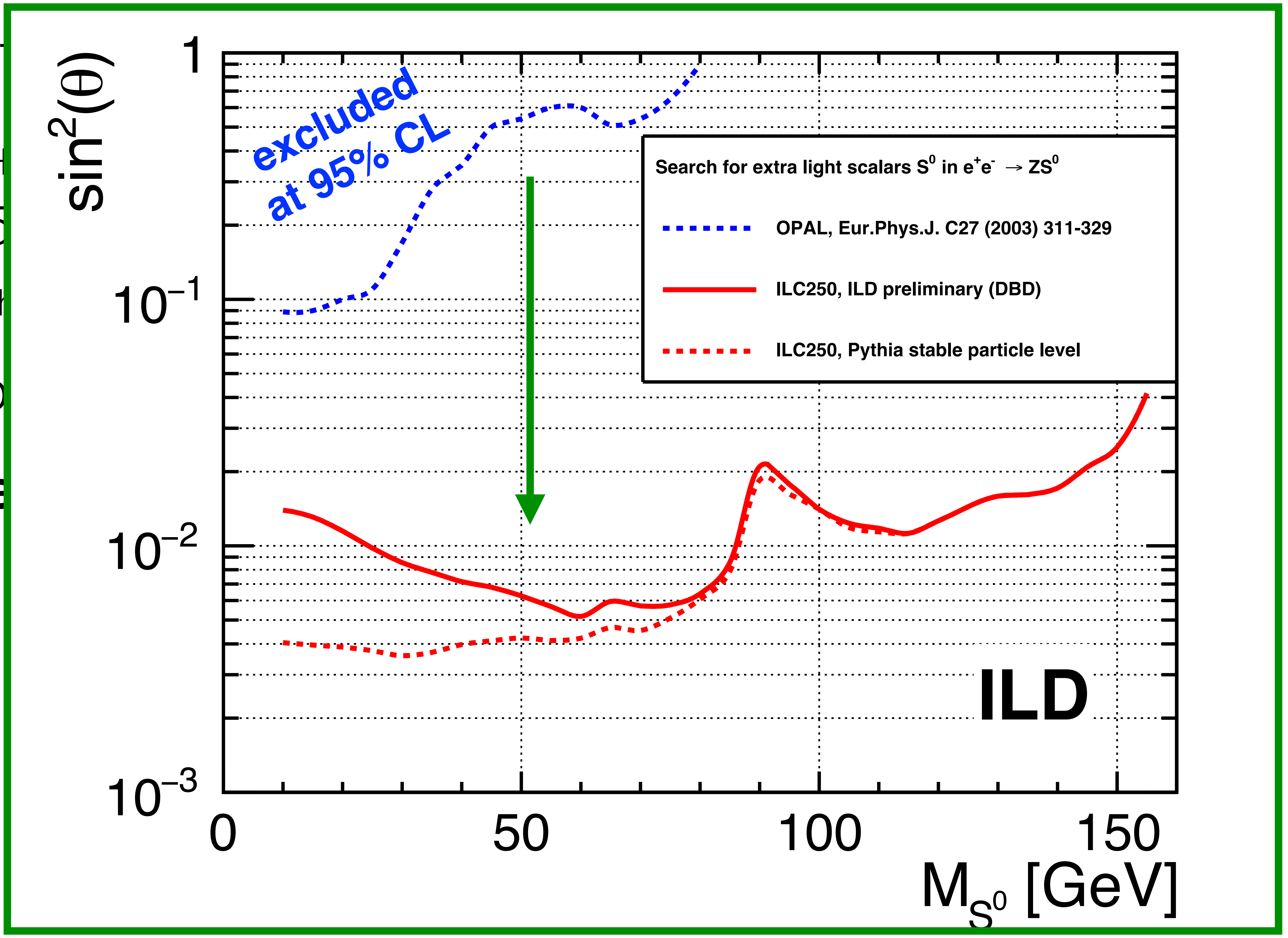

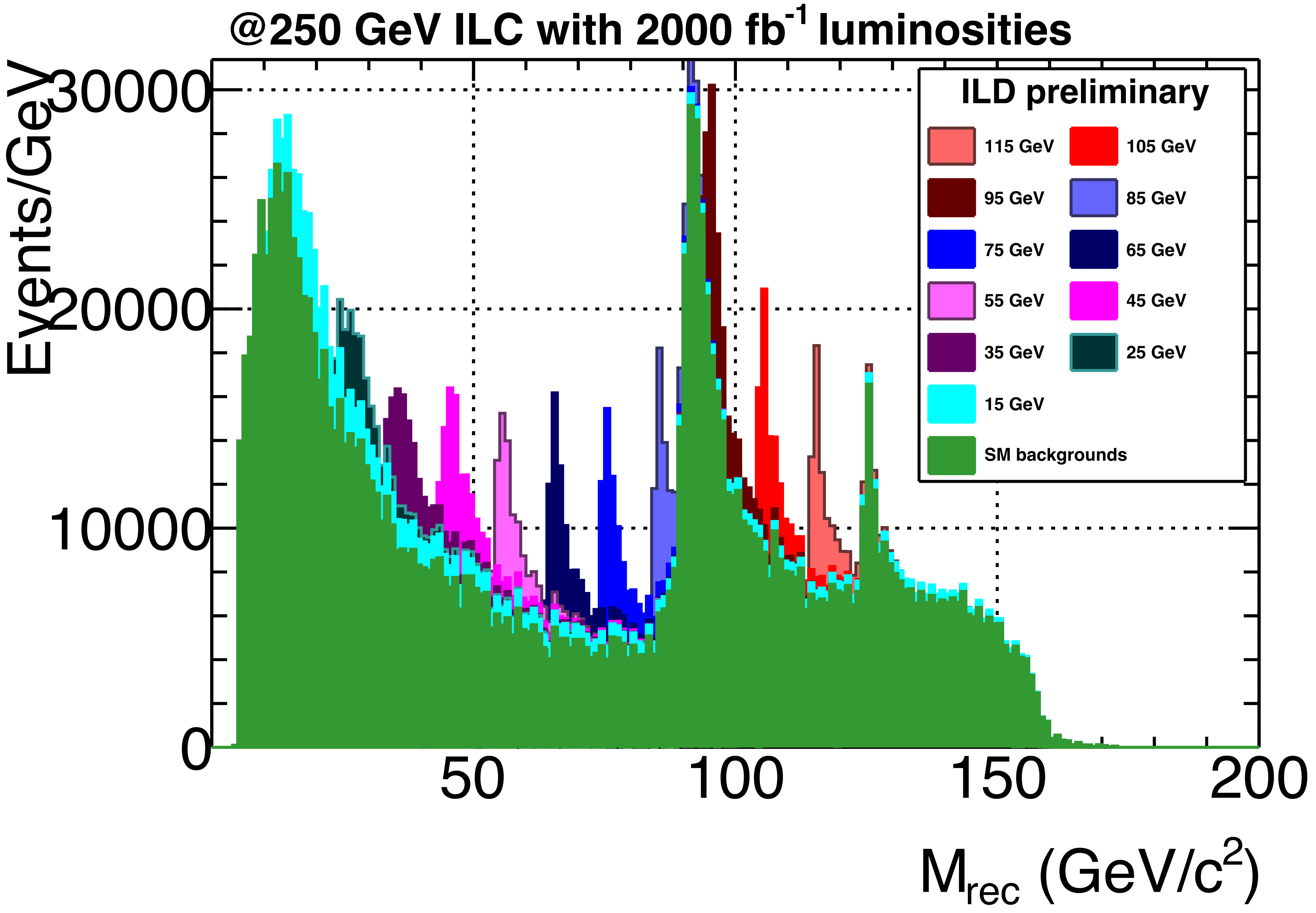

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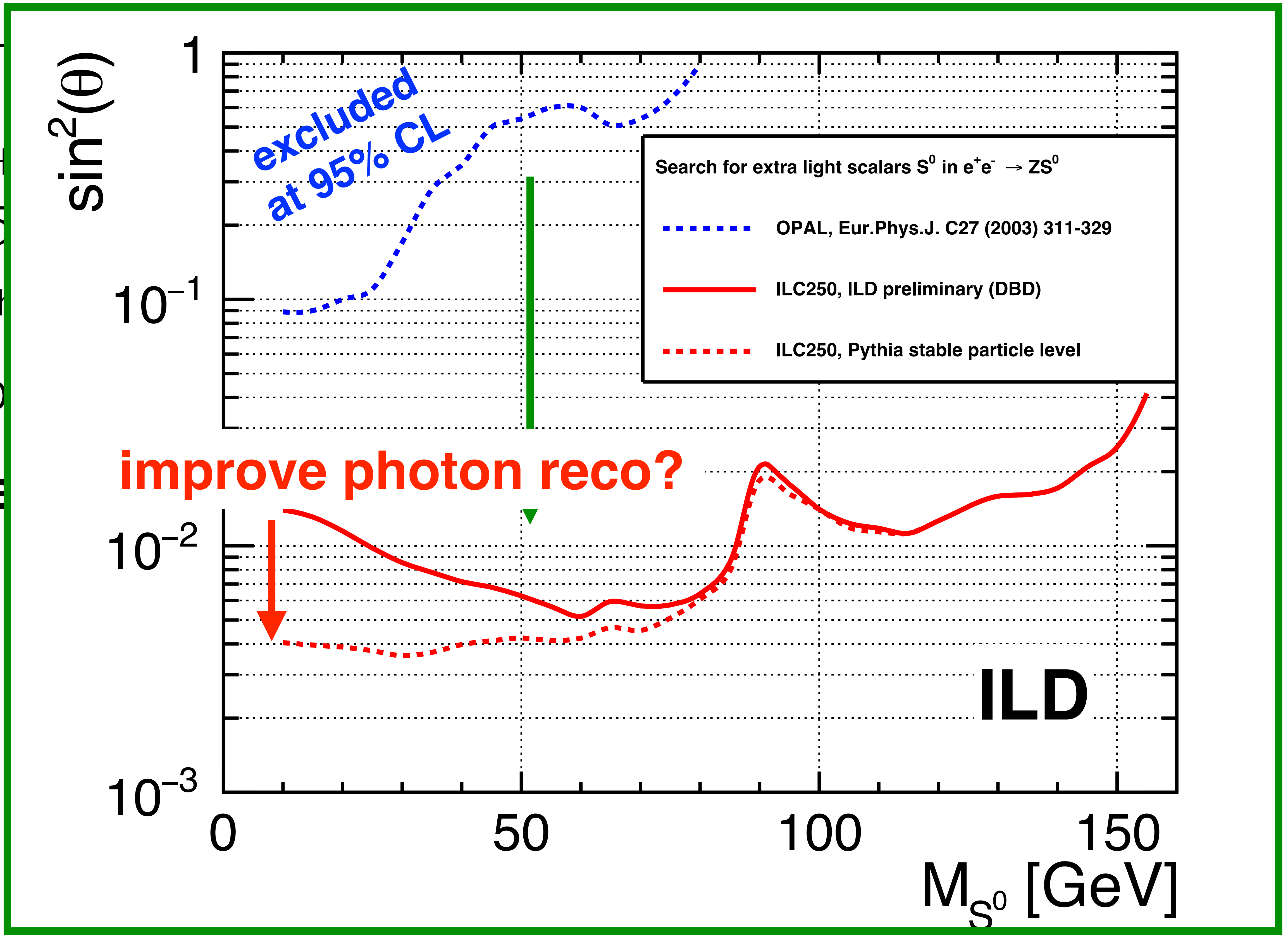

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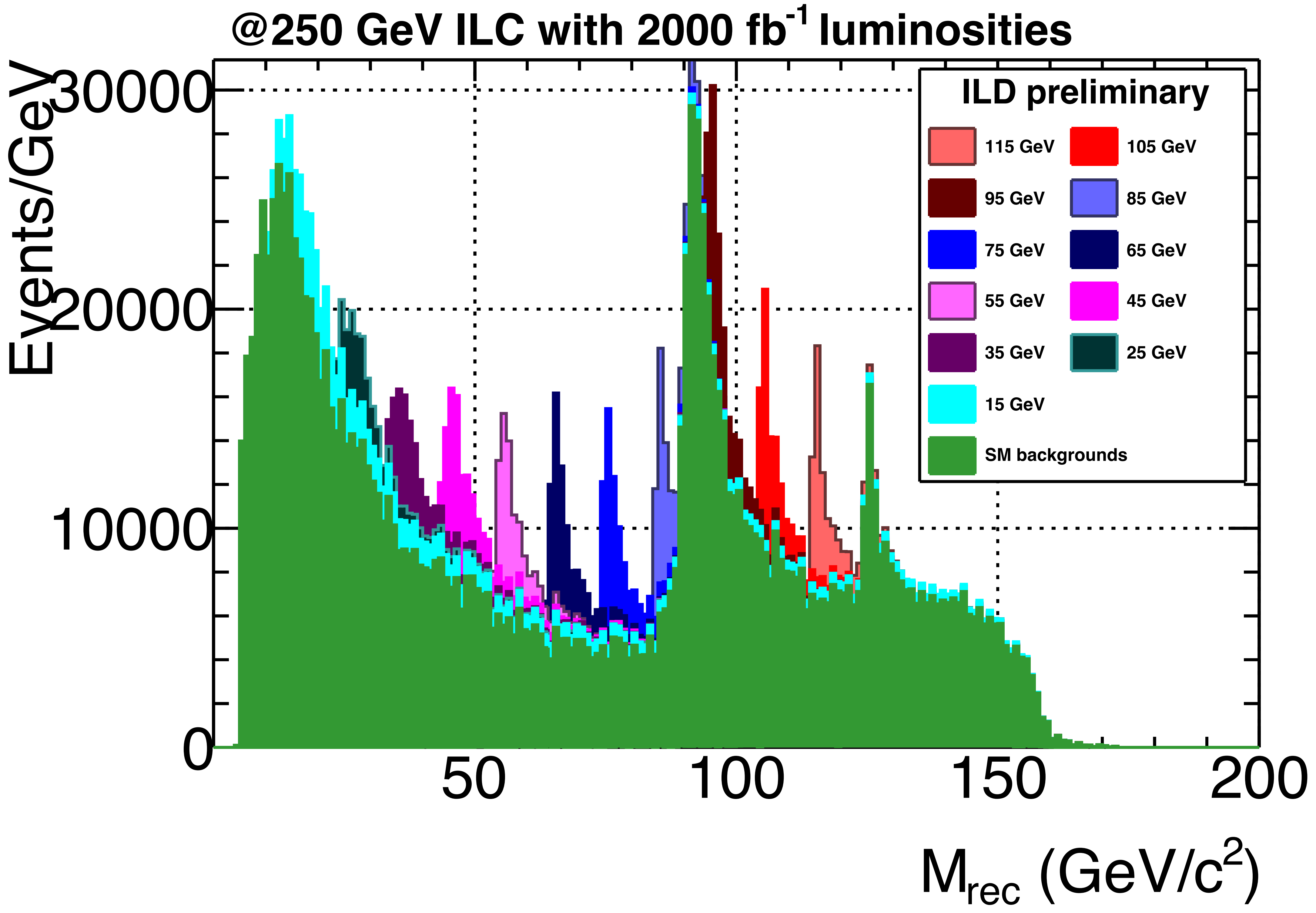

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… and how to tackle them at colliders

electron-positron & proton-proton

Our tools:

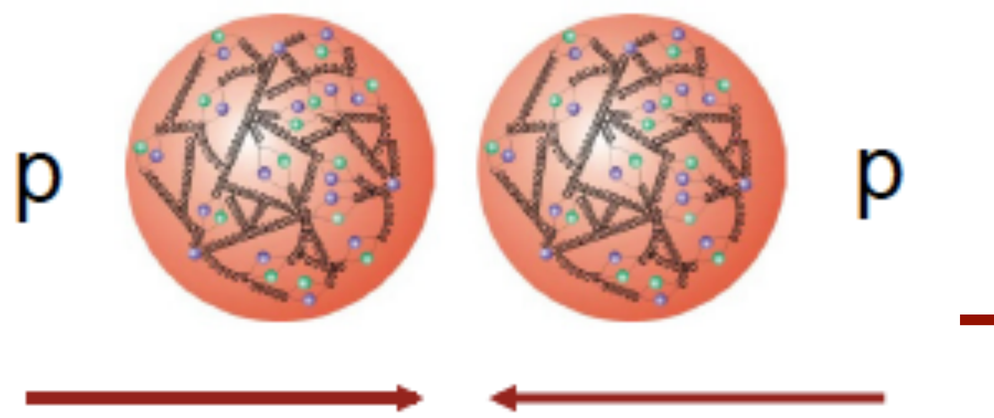
The Top and Bottom Quark

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

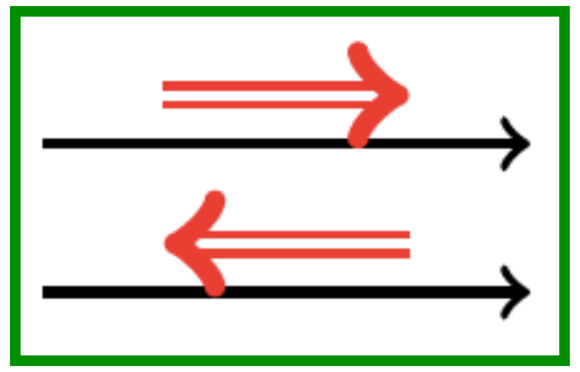
Other important parameters in e^+e^- collisions

Luminosity

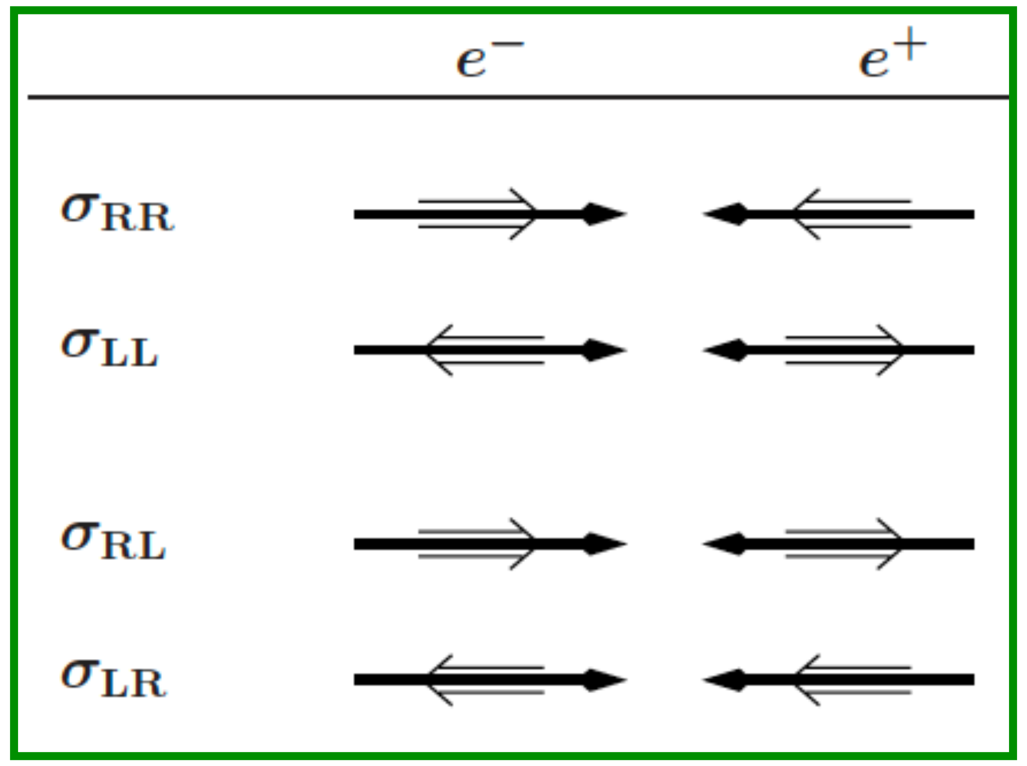
- Defines event rate => size of data set
- Future e^+e^- colliders aim for $10^3..10^6$ larger data sets than LEP
- Depends strongly on invest costs and power consumption => be careful to compare apples to apples!
- Are there fundamental boundaries *beyond* statistics?
(e.g. theory & parametric uncertainties,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



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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	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
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 ($3\,\mathrm{ab}^{-1}$ of integrated luminosity). From [15].

arXiv:1708.08912

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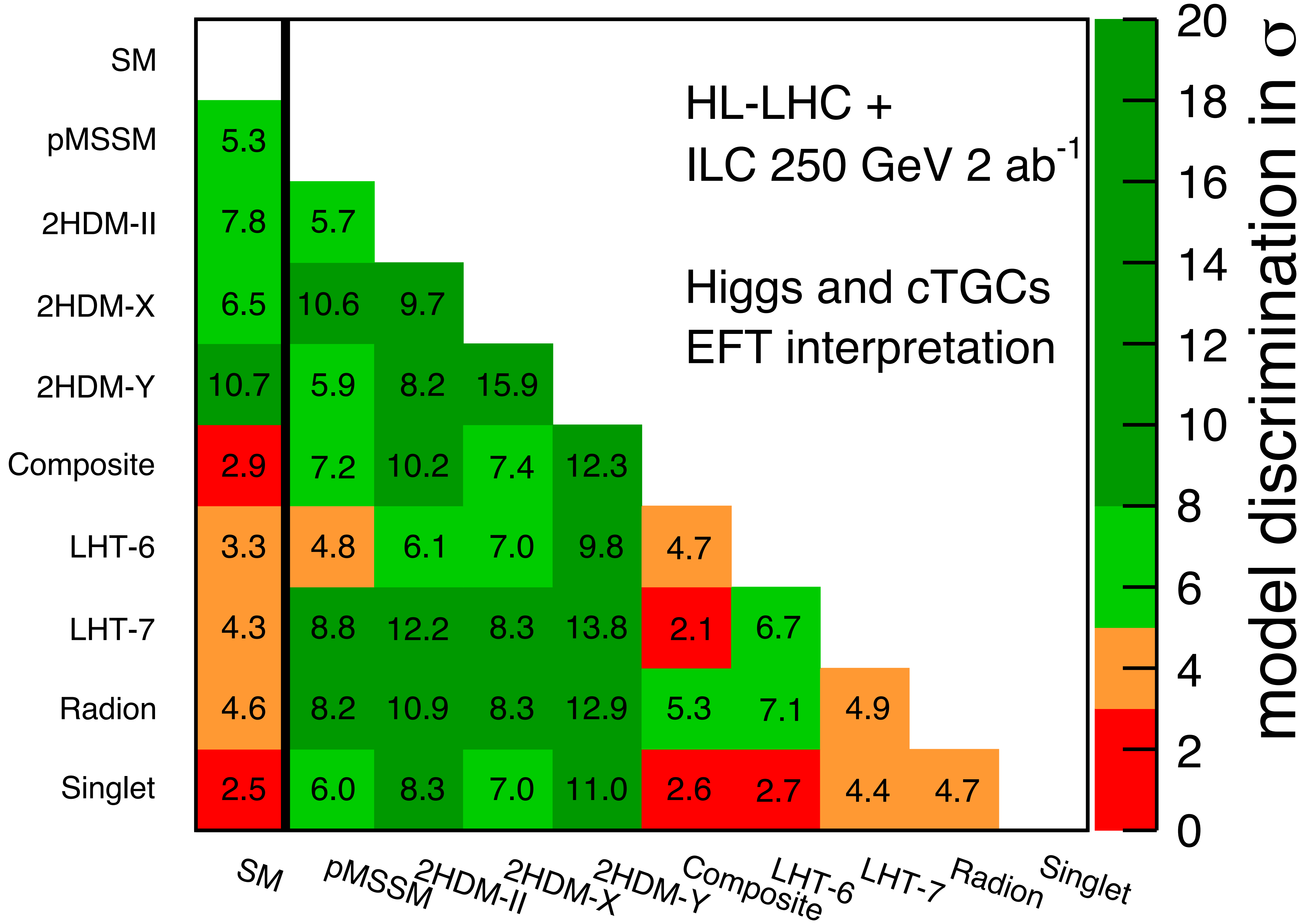

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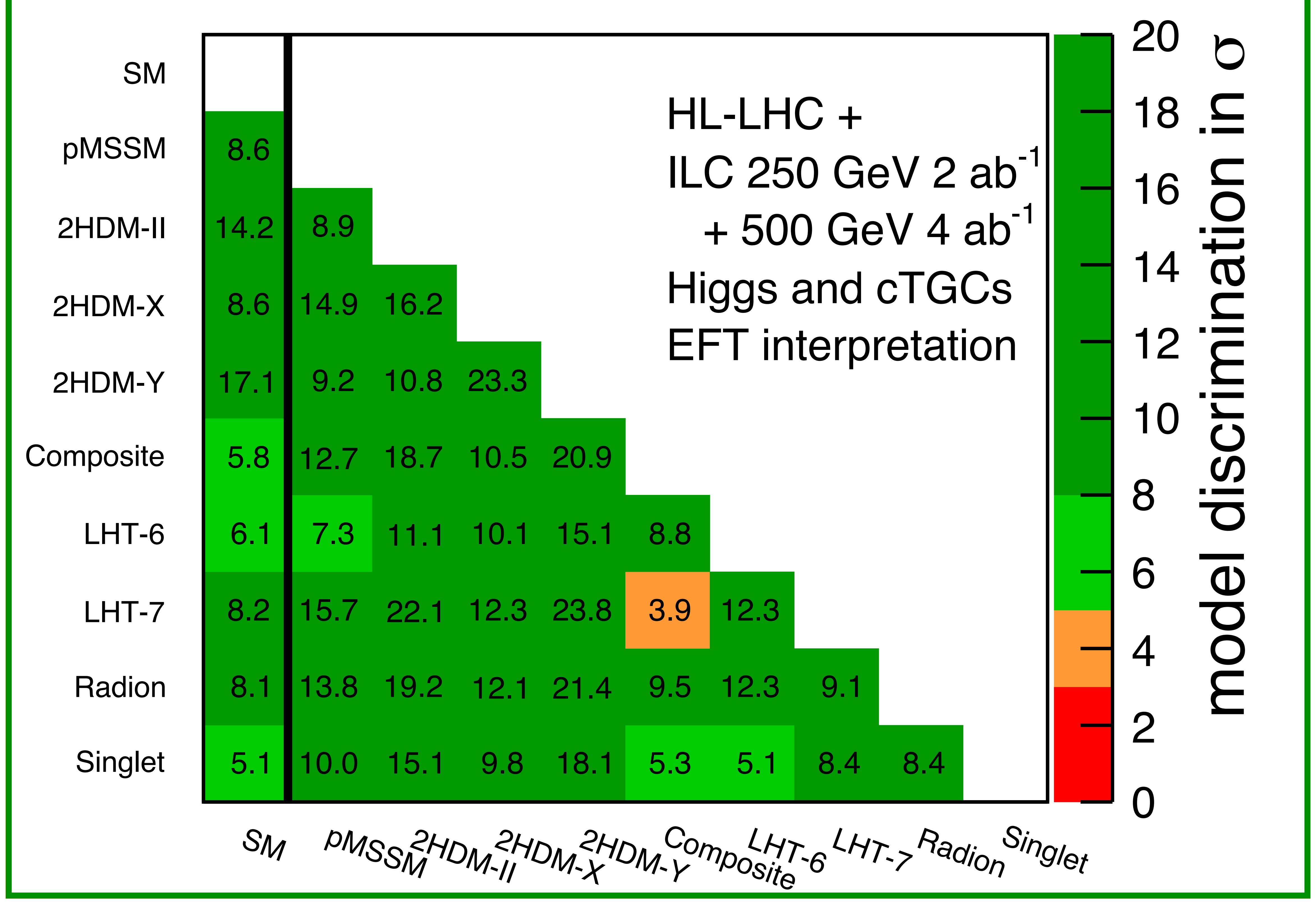

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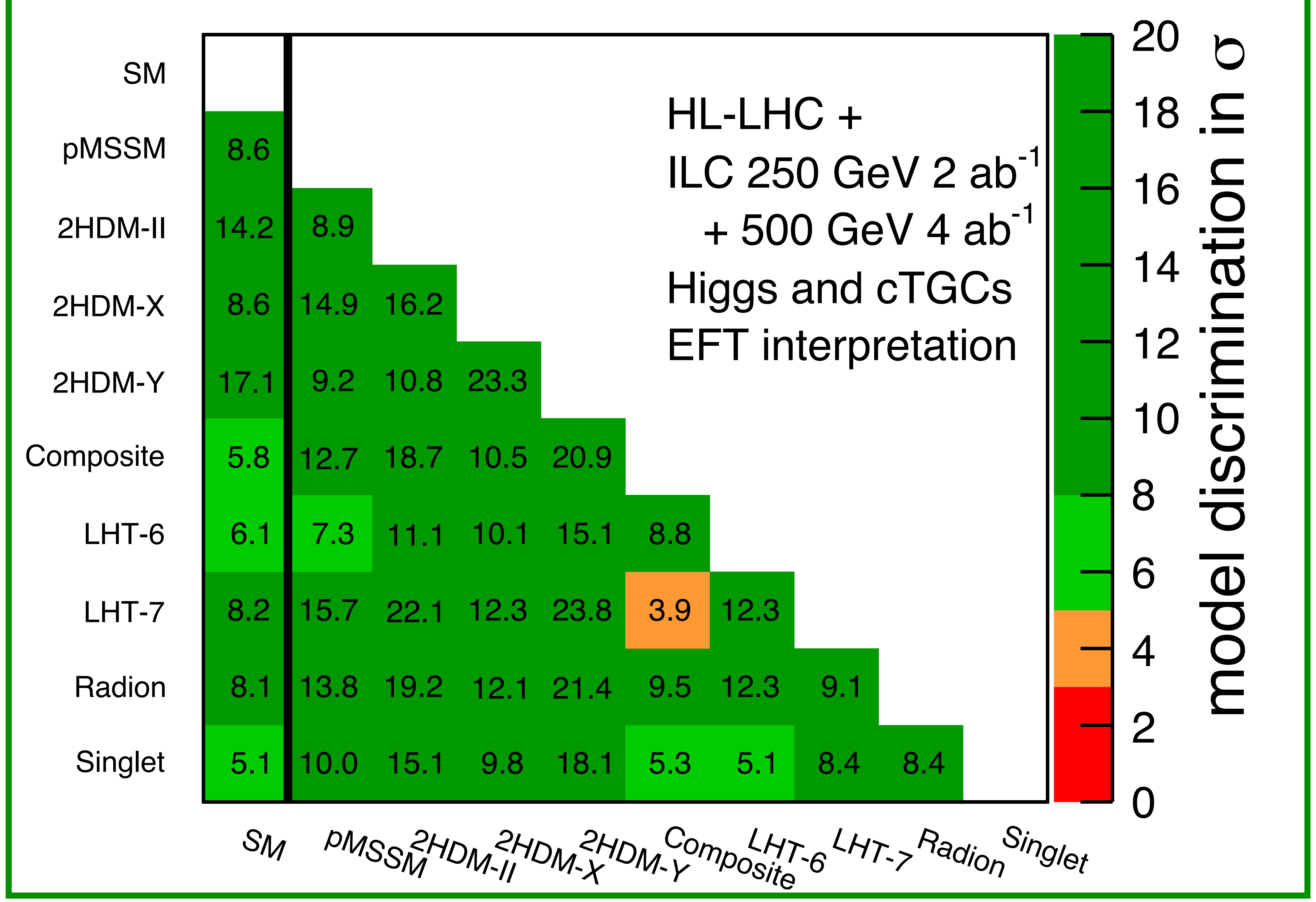
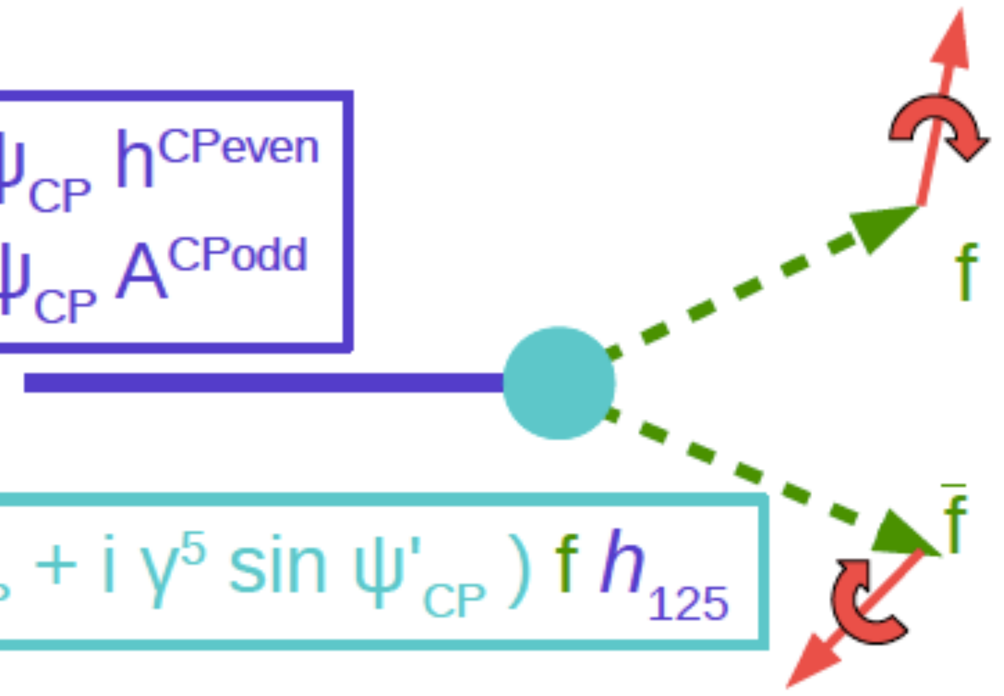


illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

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

ZH production ideal

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



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

h is a spin 0 state:

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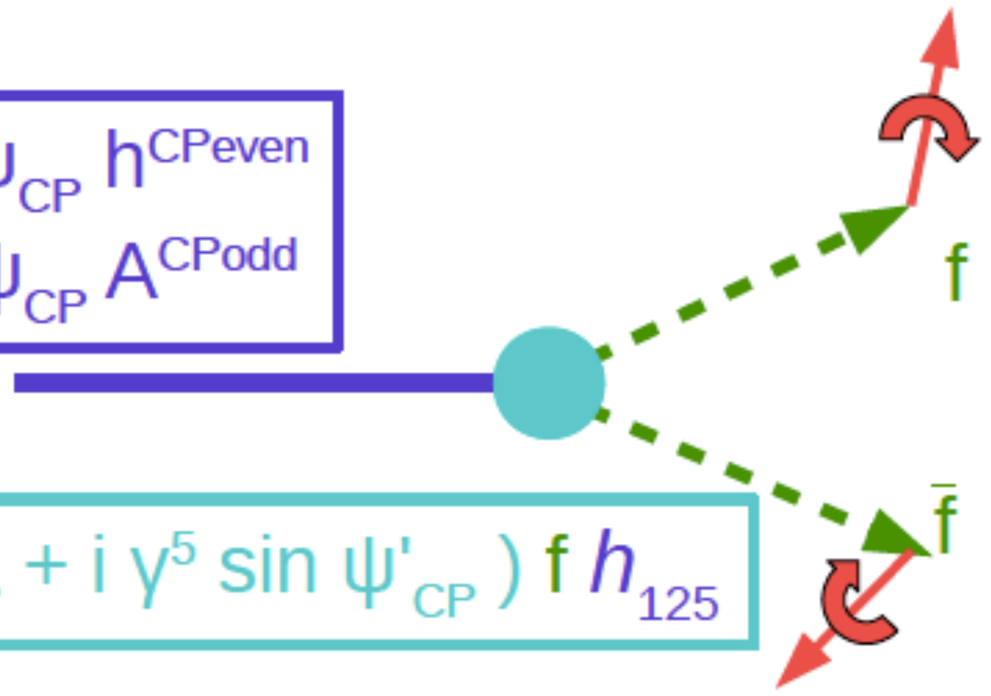

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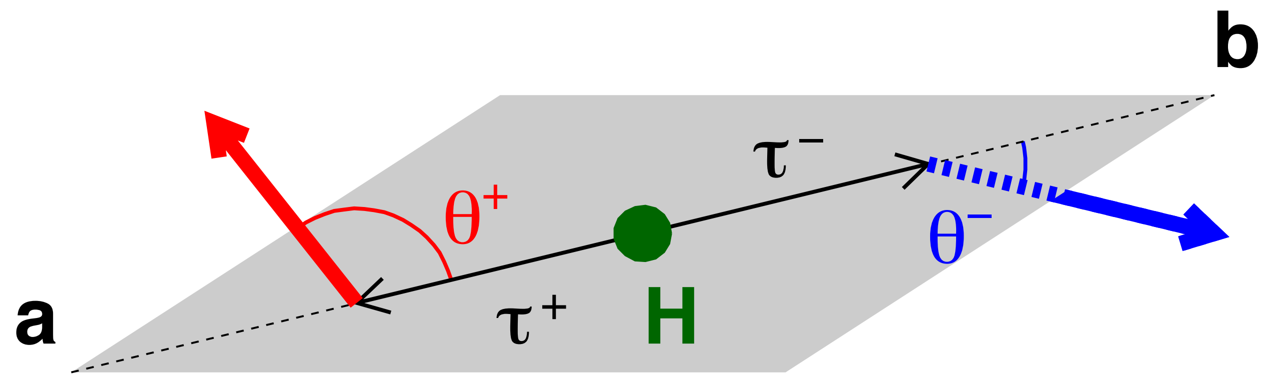

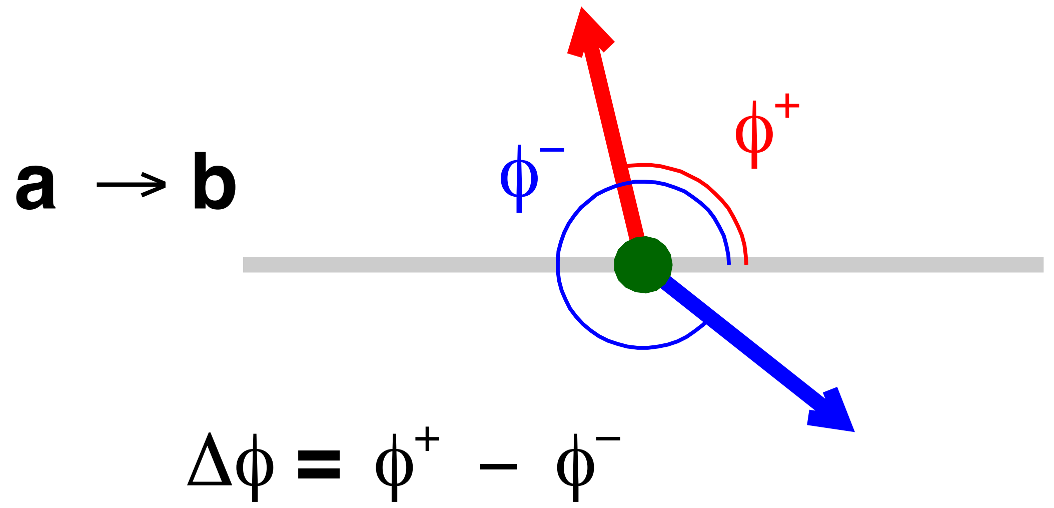

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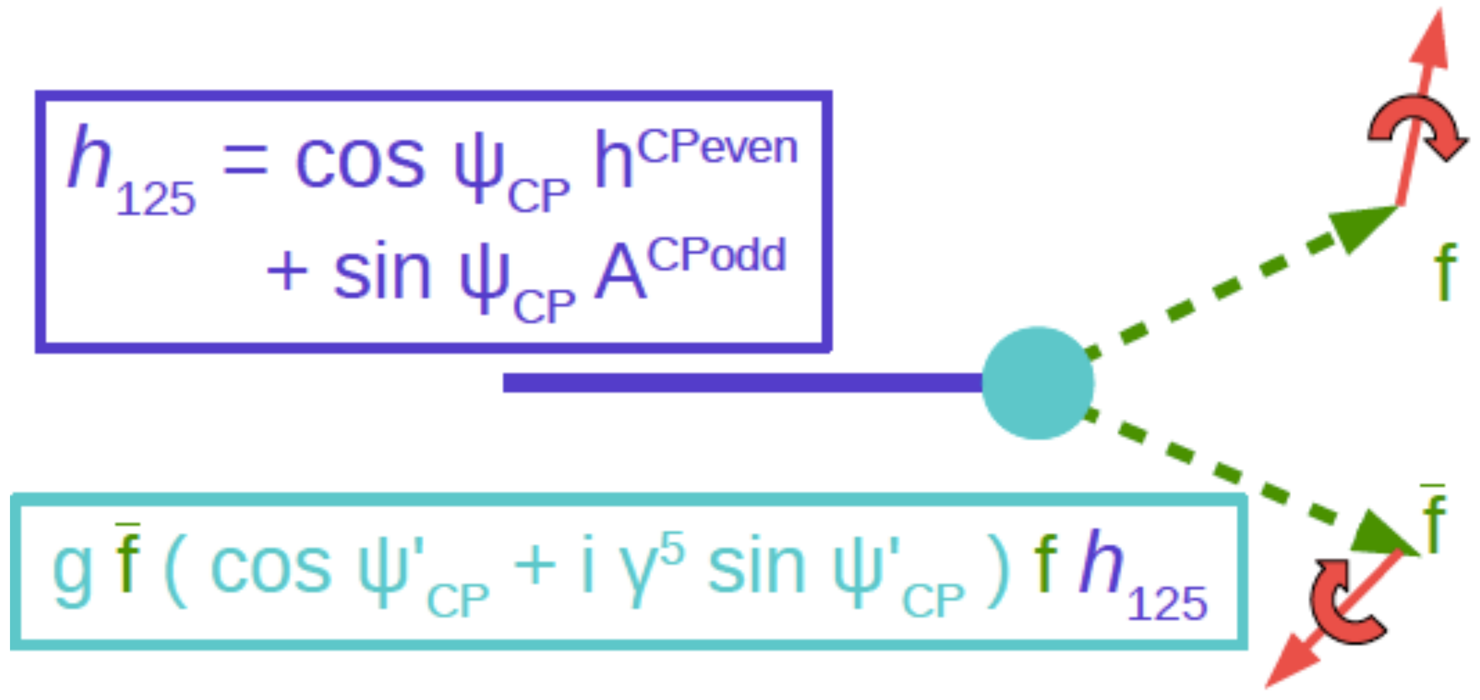

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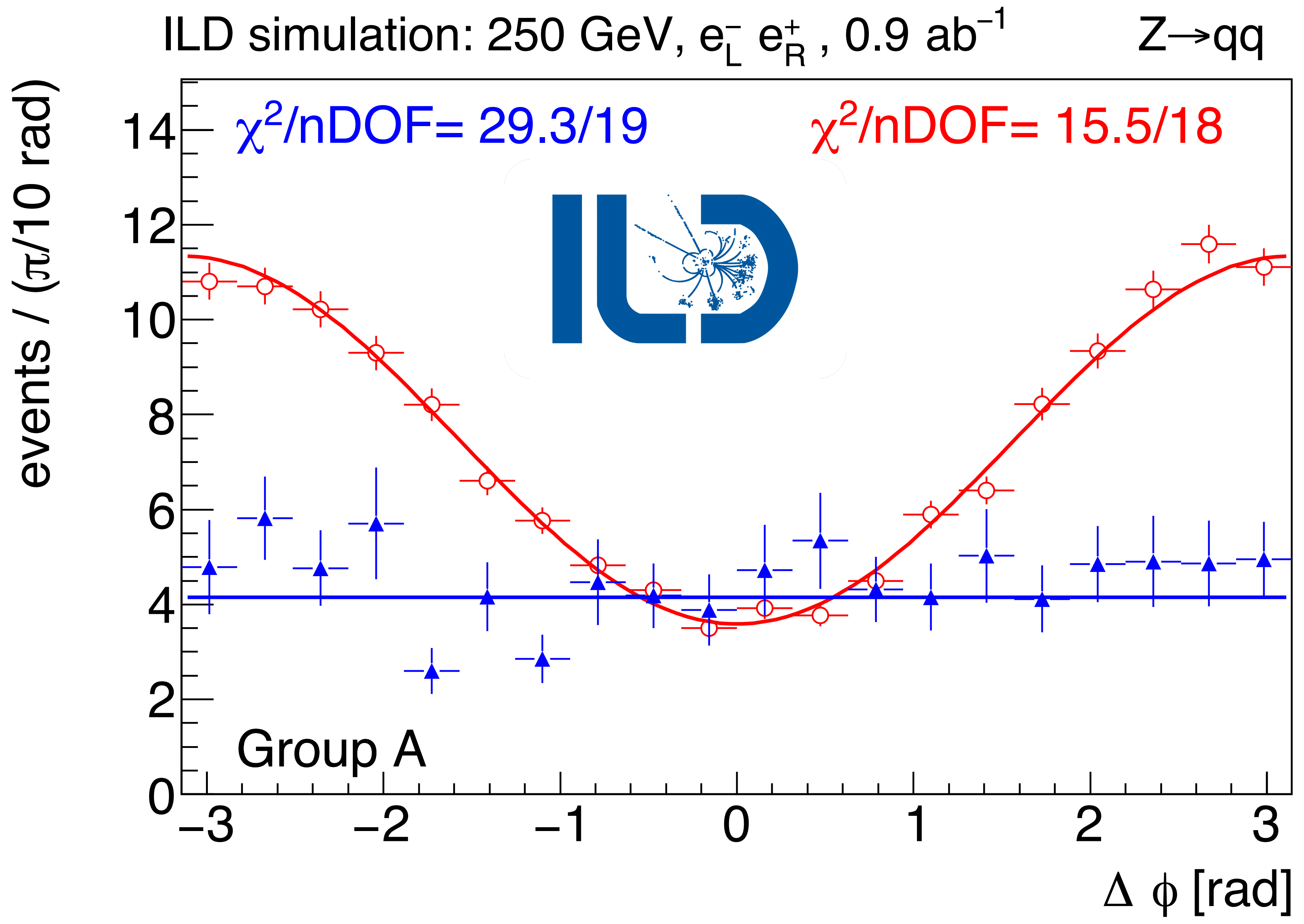

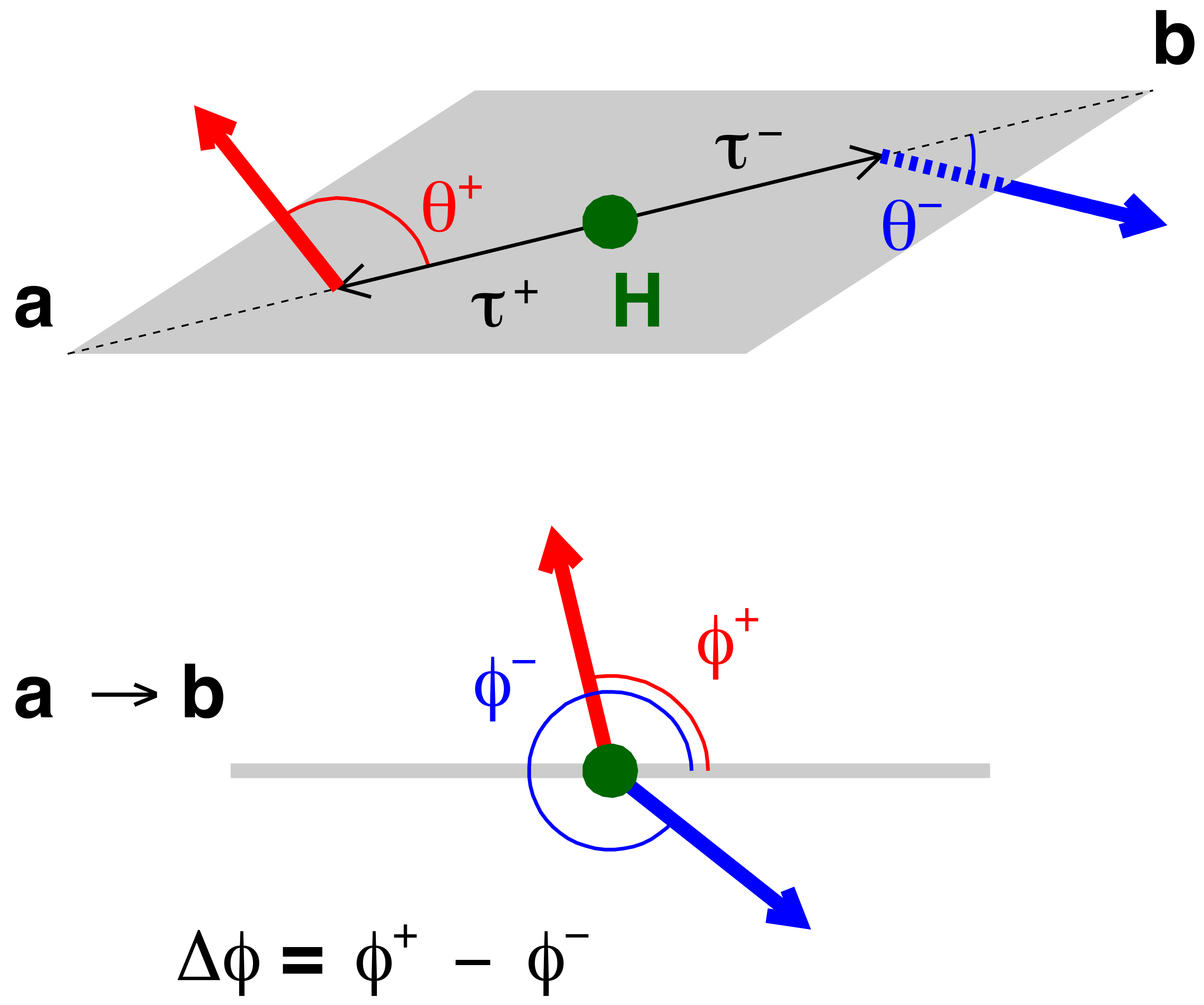

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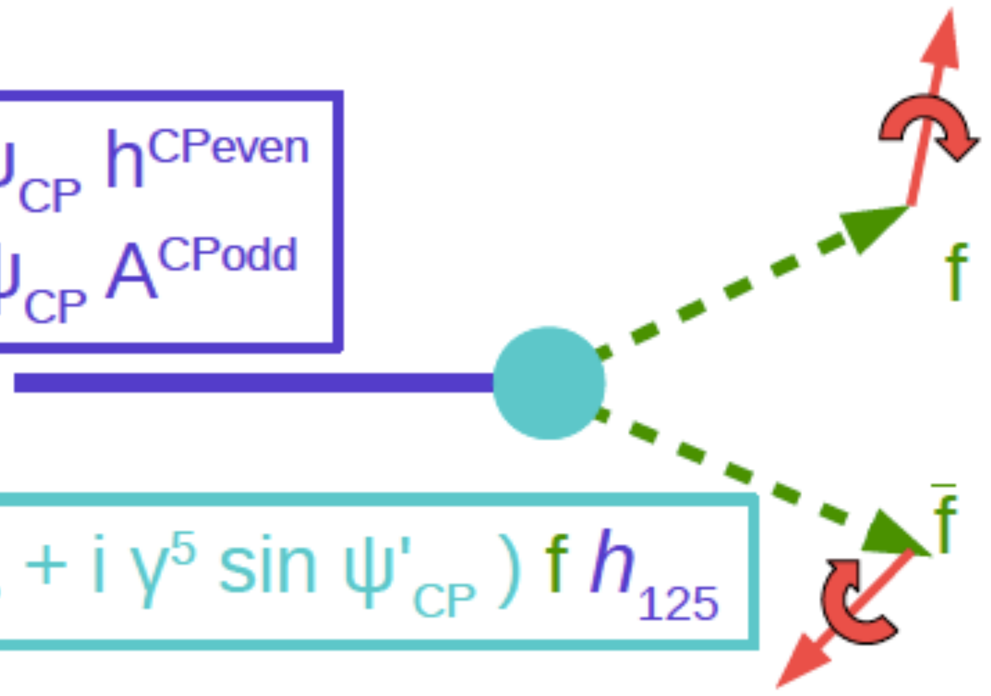

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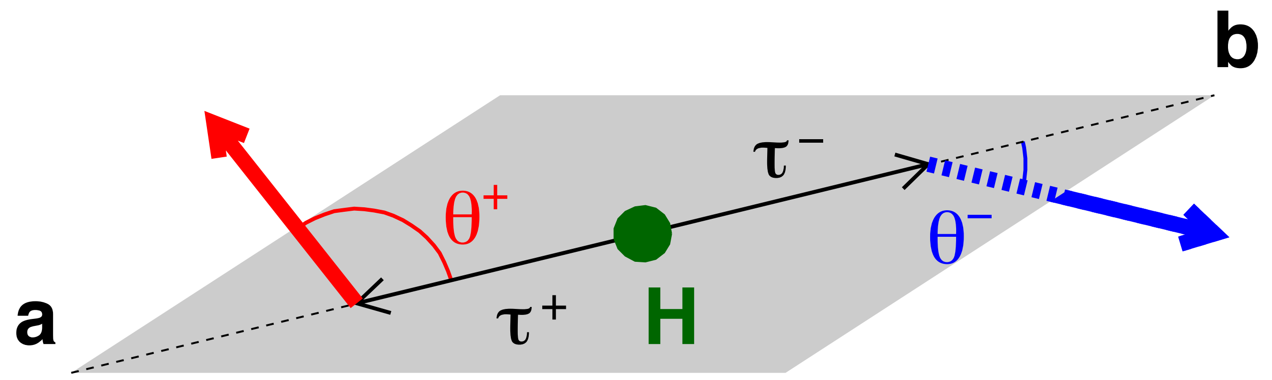

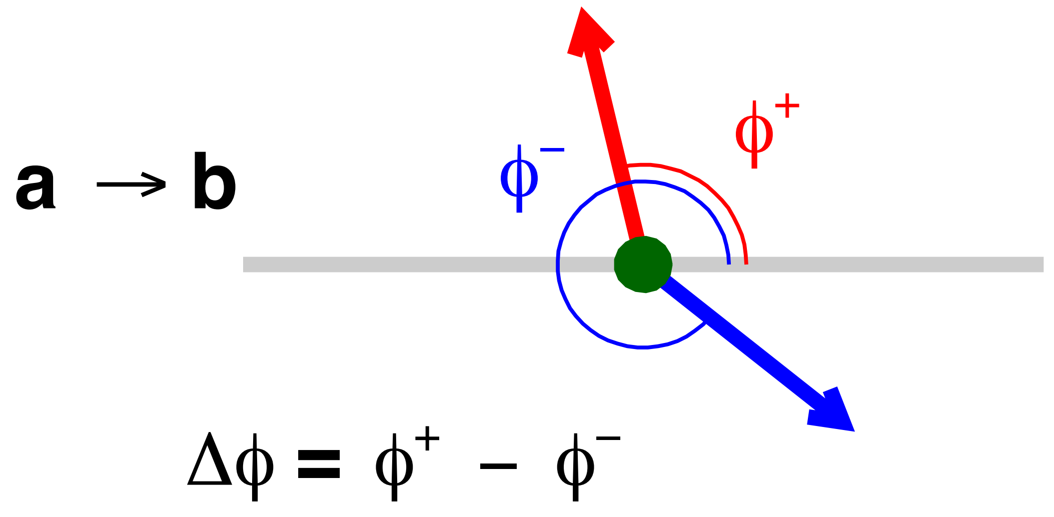

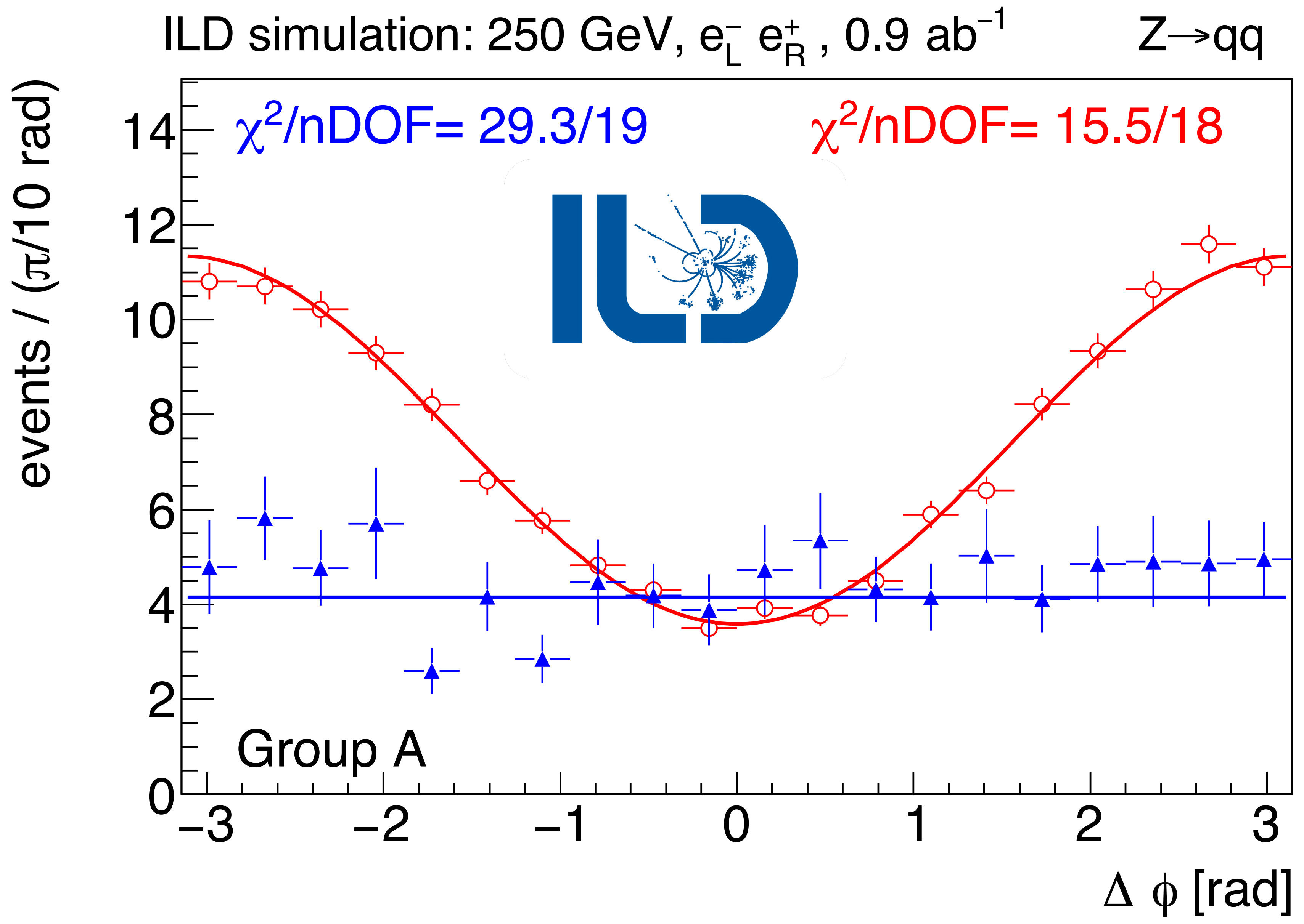

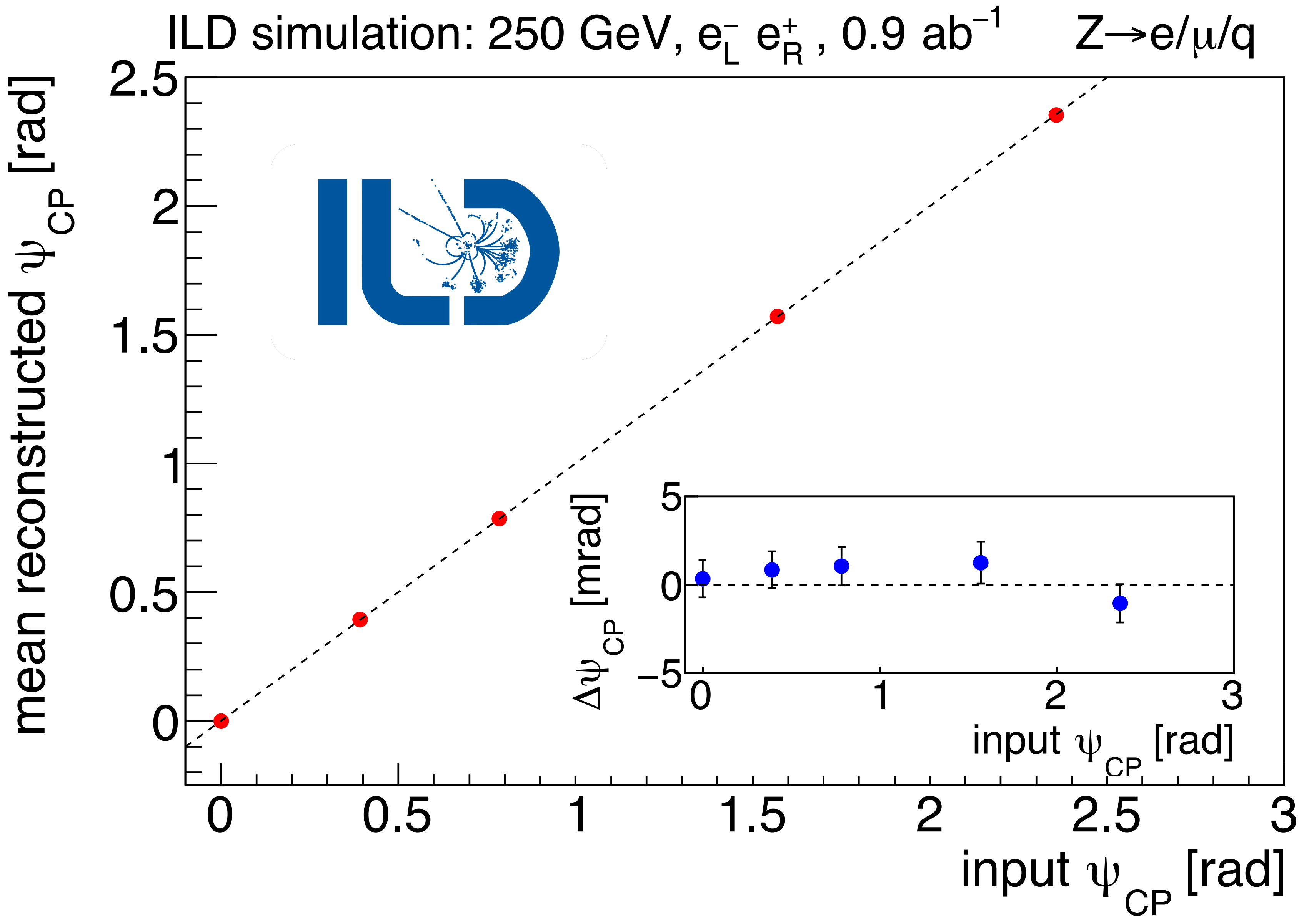

arxiv:1804.01241

based on NIM A810 (2016) 51-58

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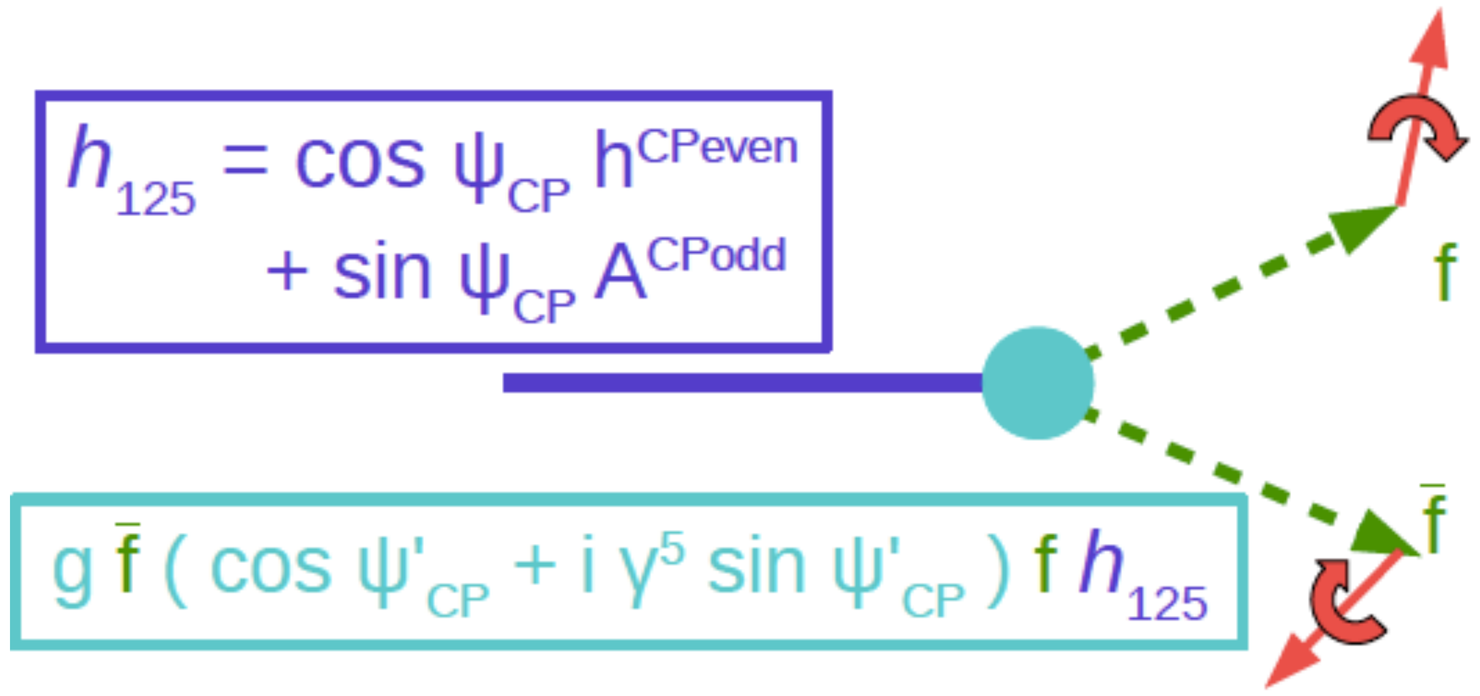

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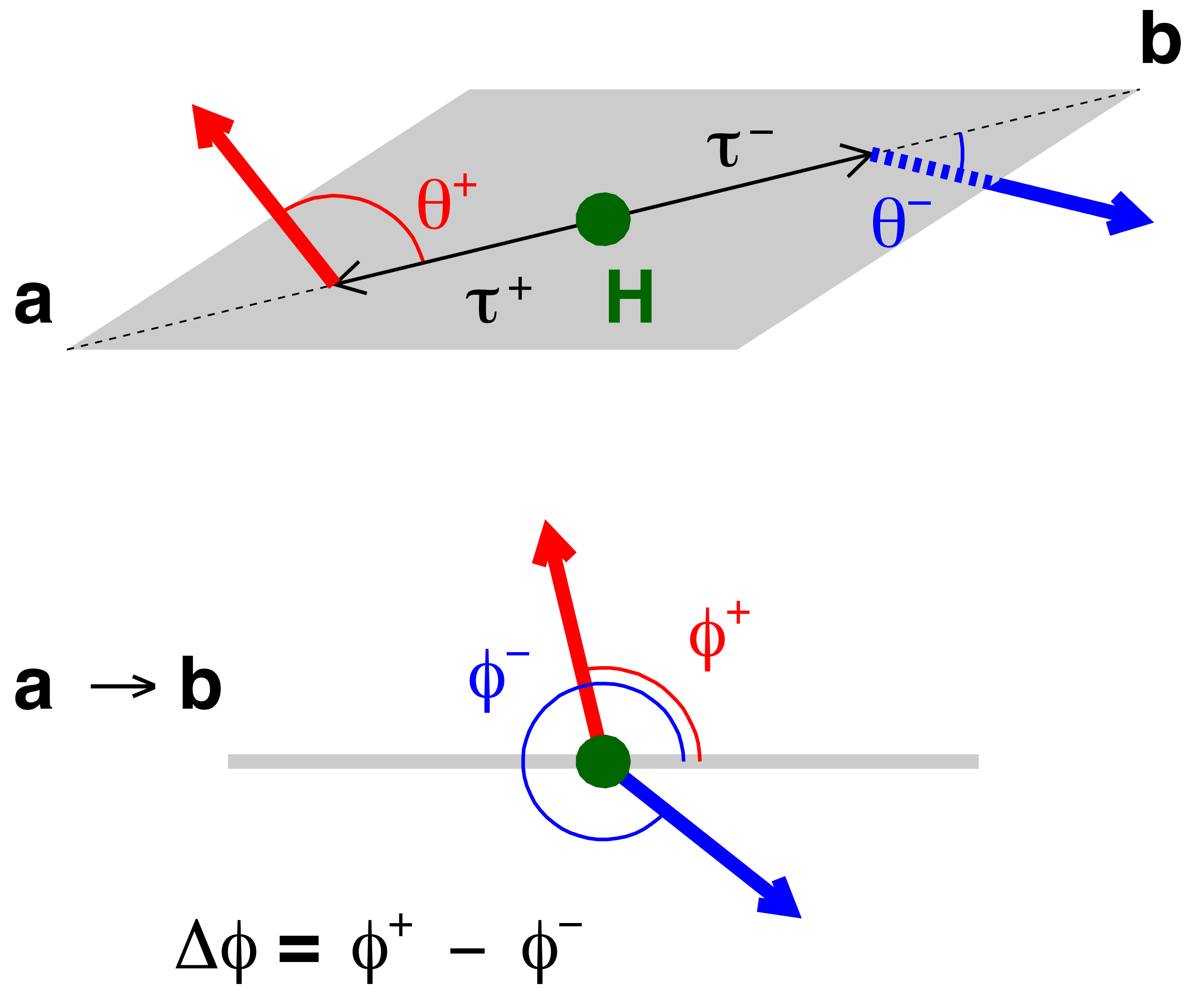
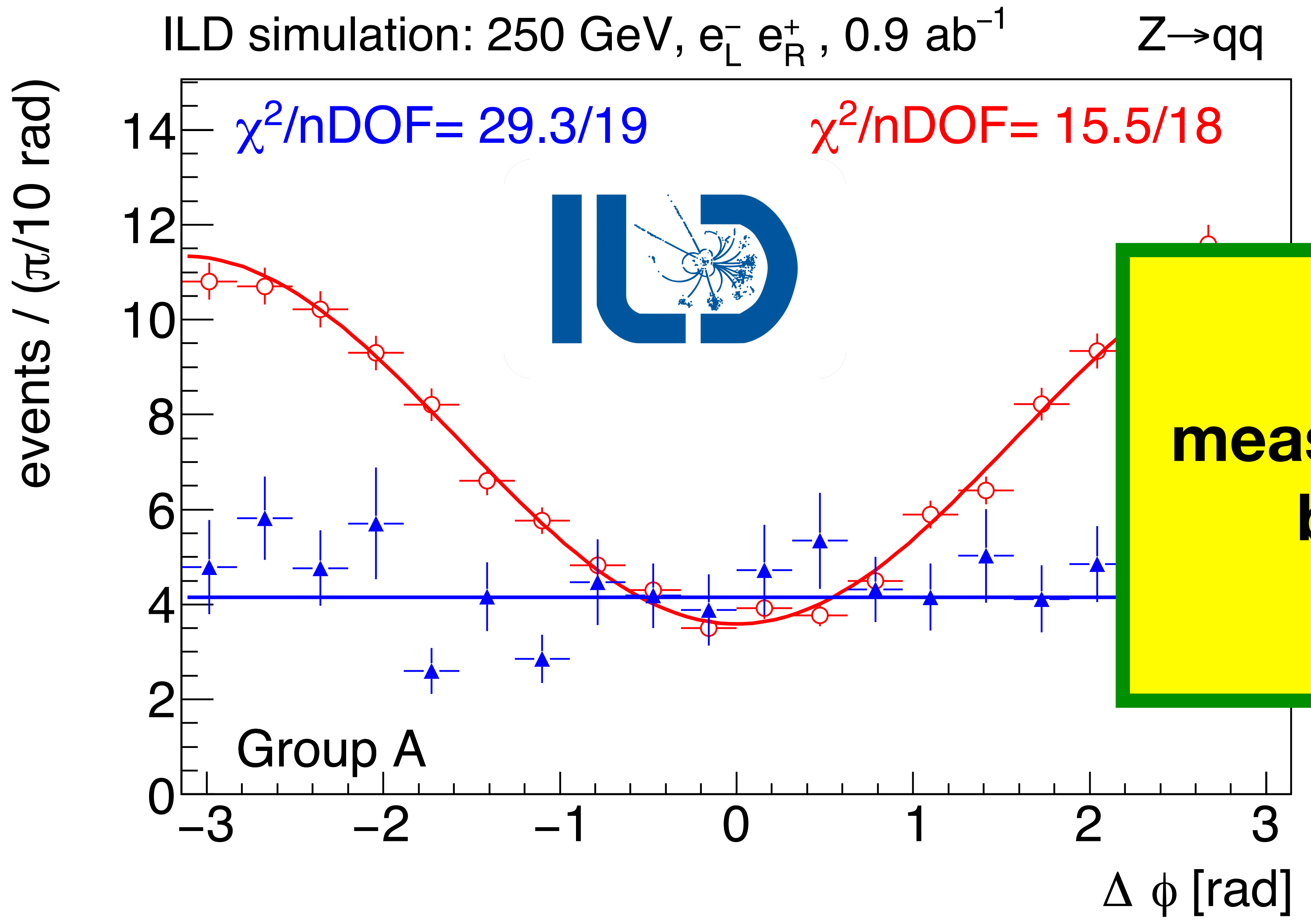
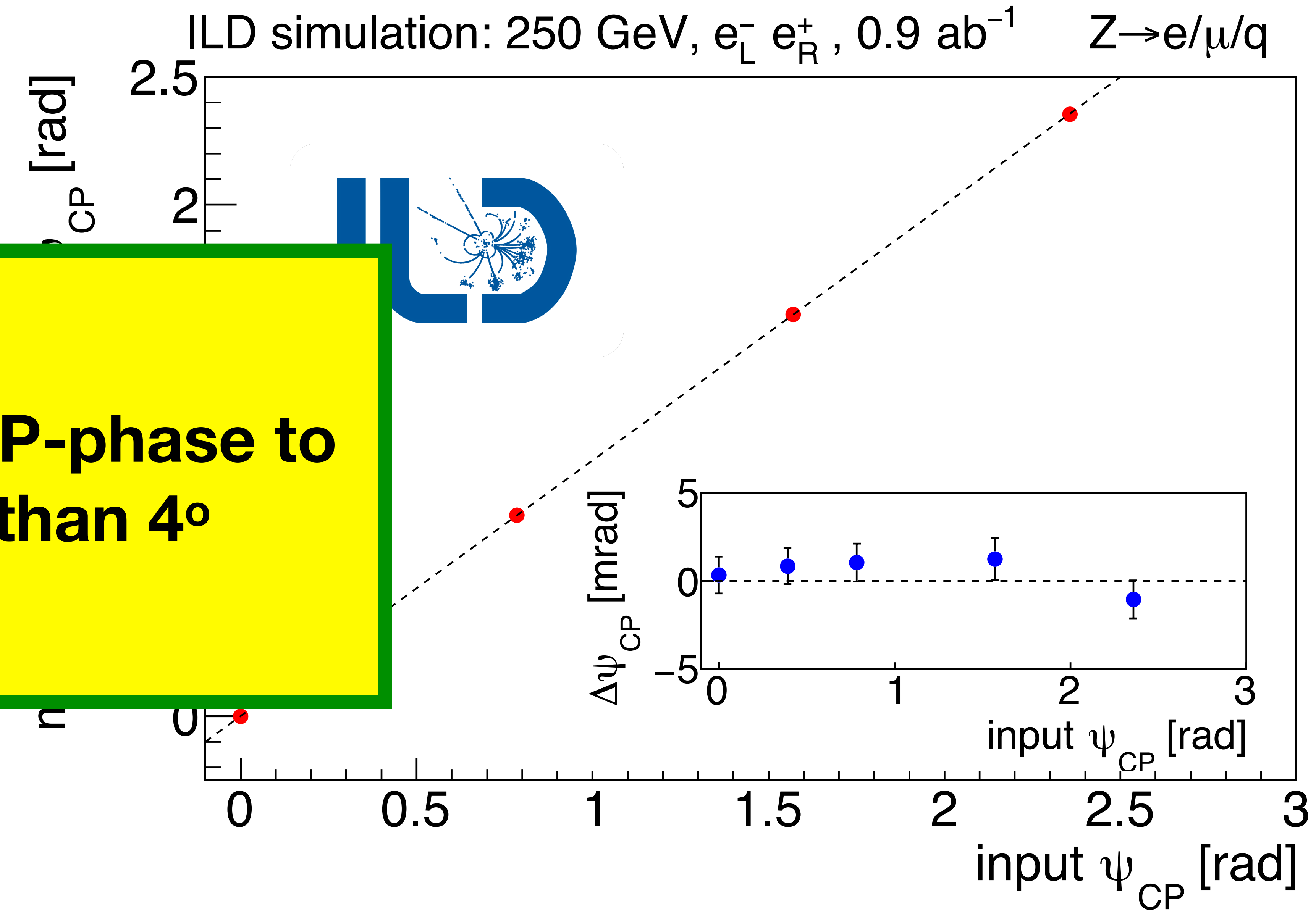




measure CP-phase to better than 4°



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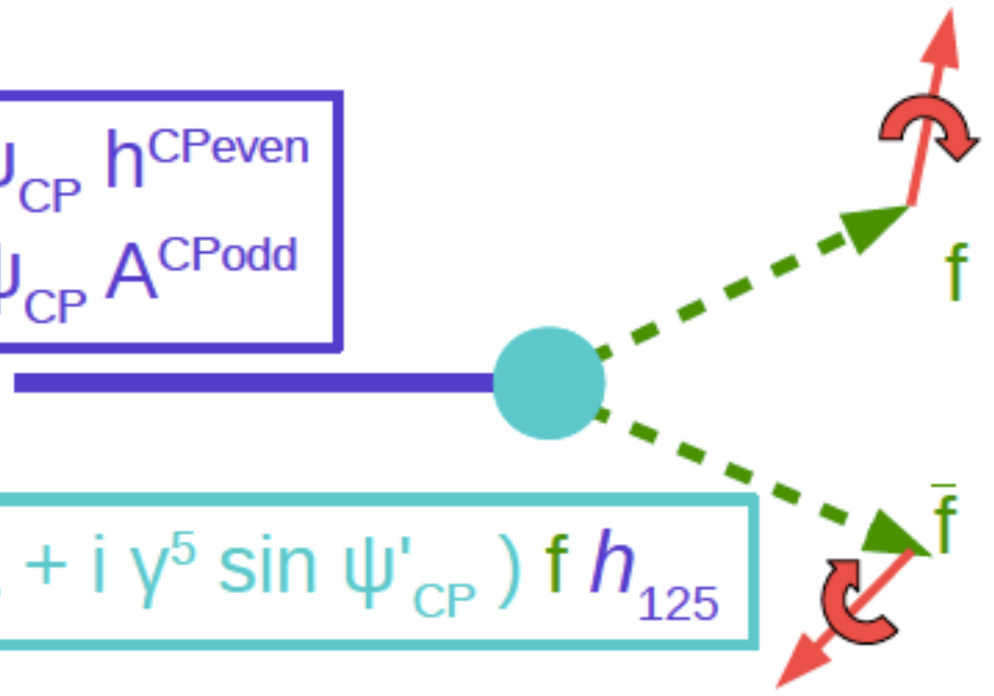

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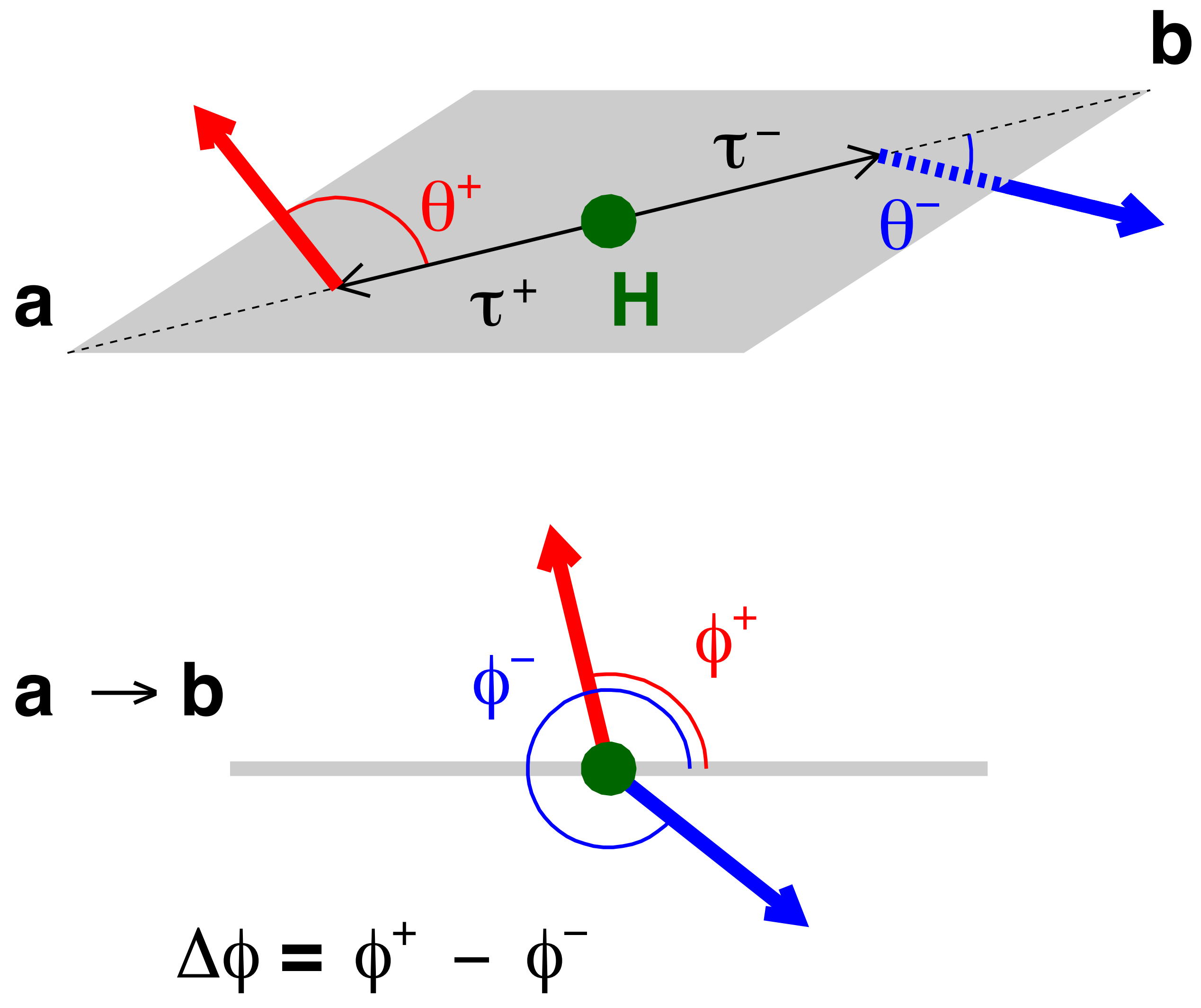
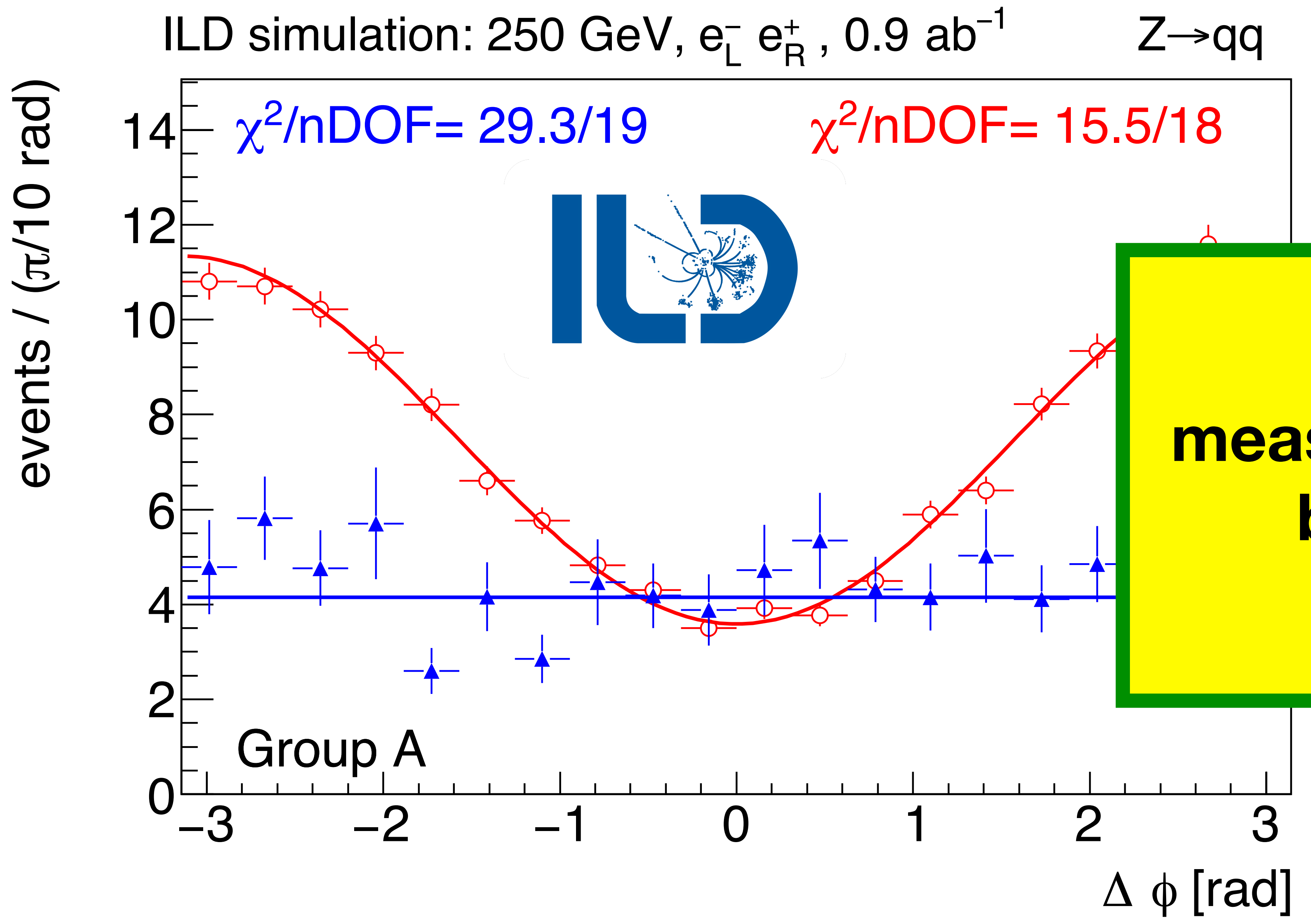
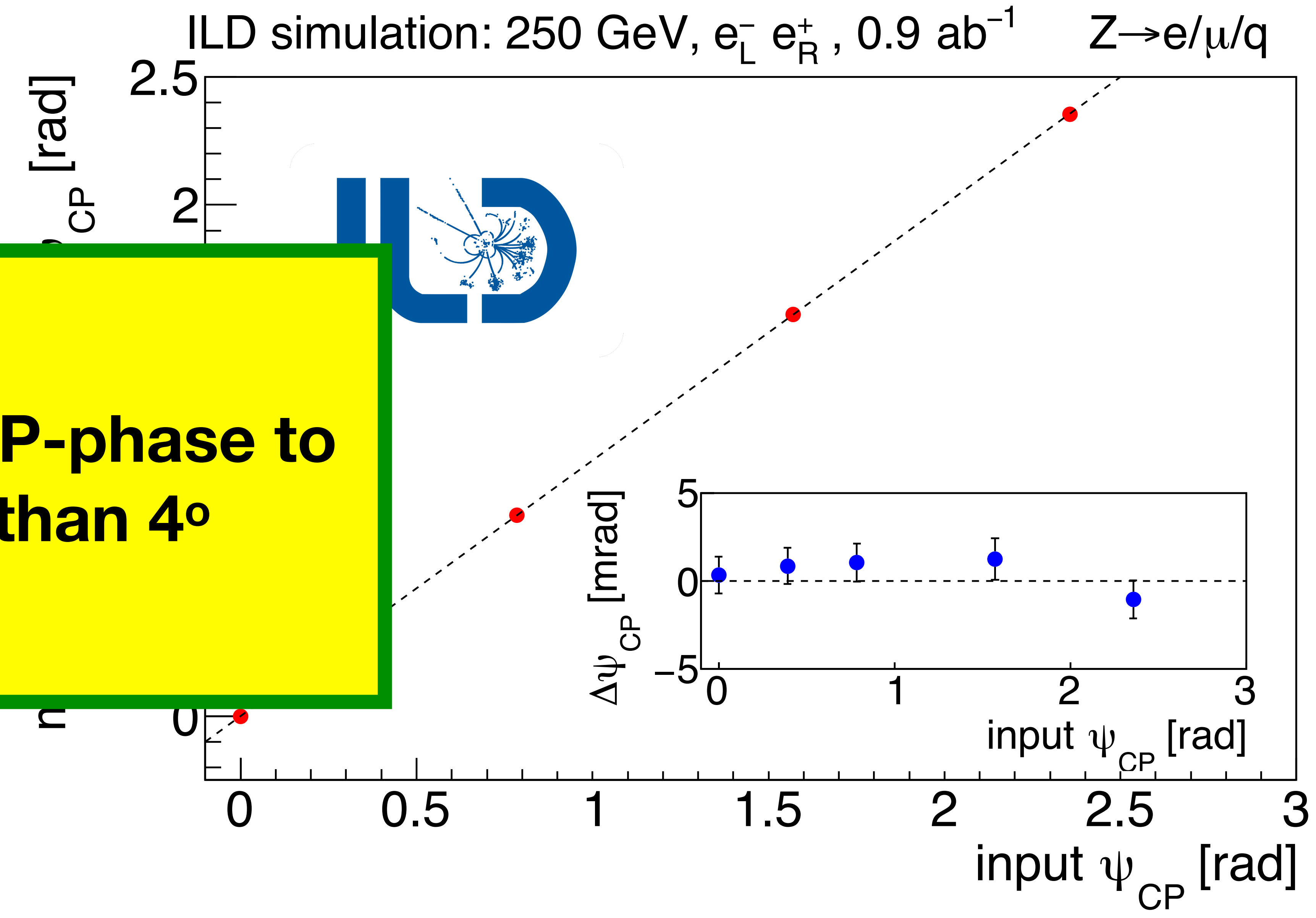






measure CP-phase to better than 4°

..and CPV in Zh coupling:

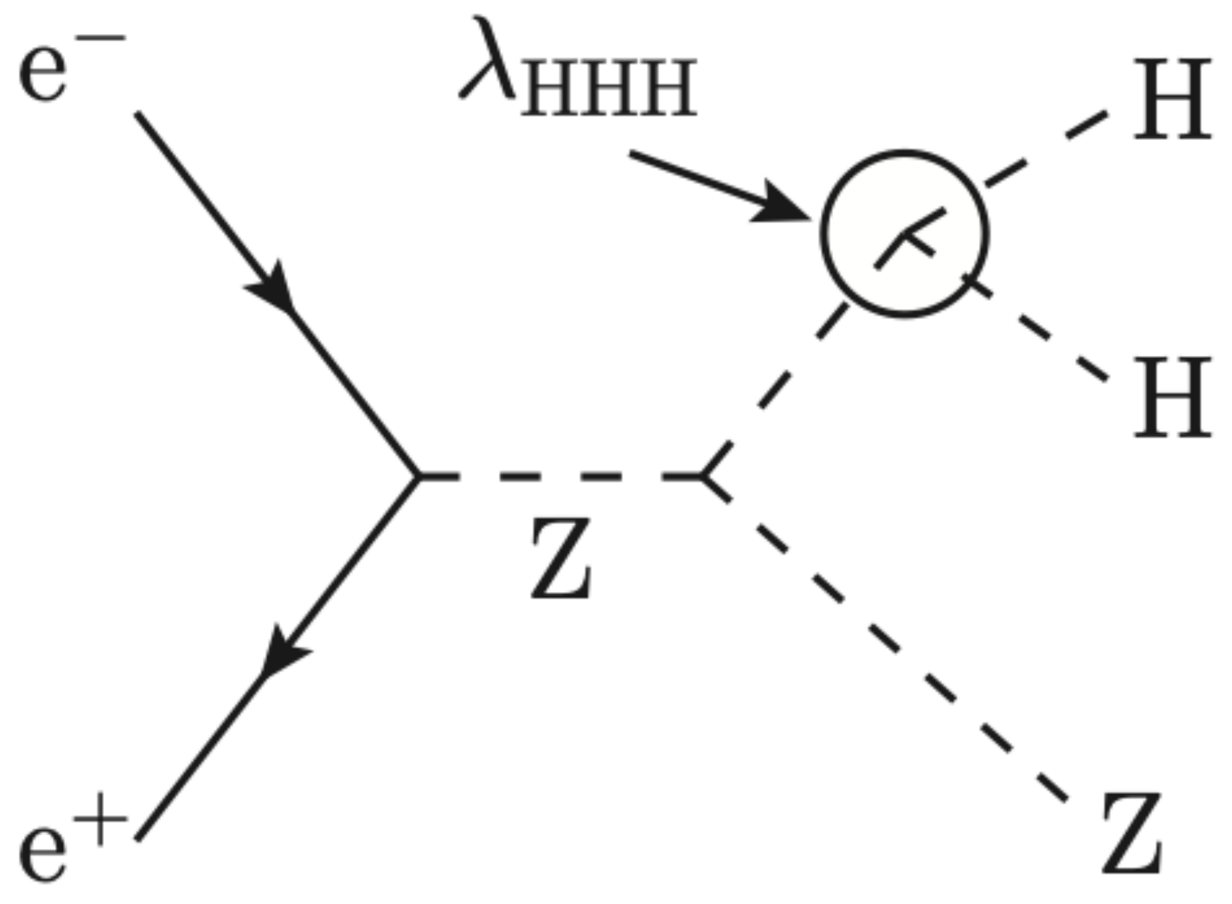
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

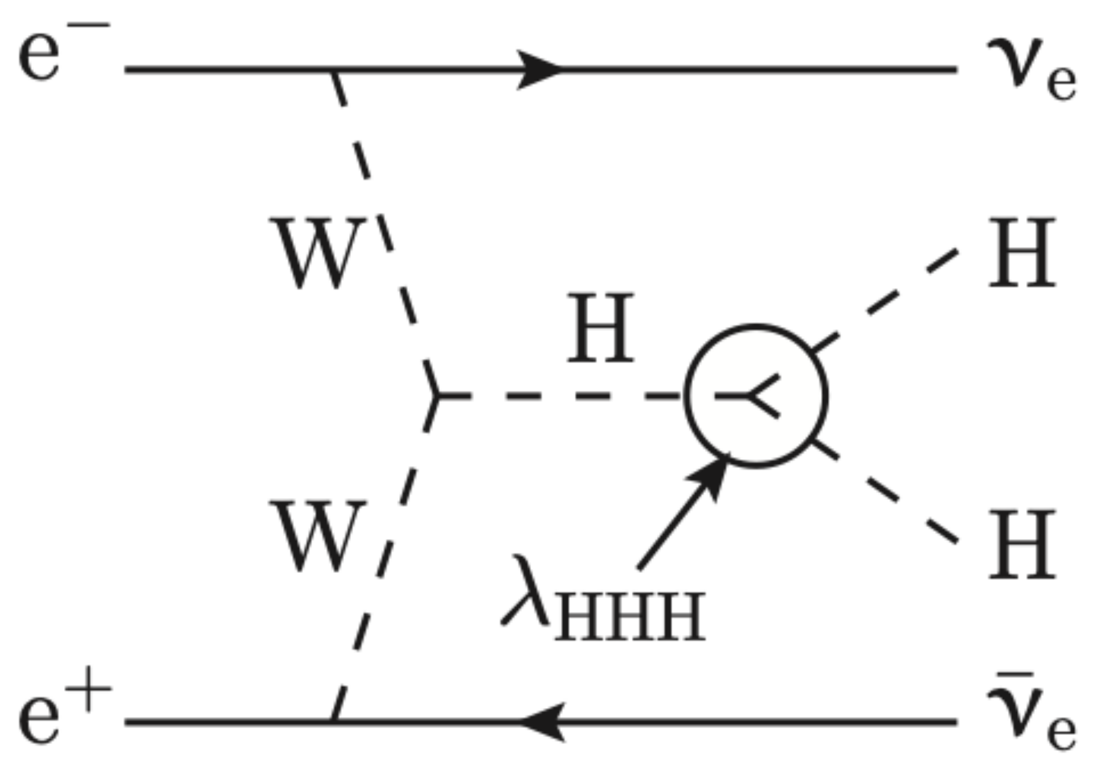
=> $\tilde{b}$ **to ±0.005**

arxiv:1804.01241

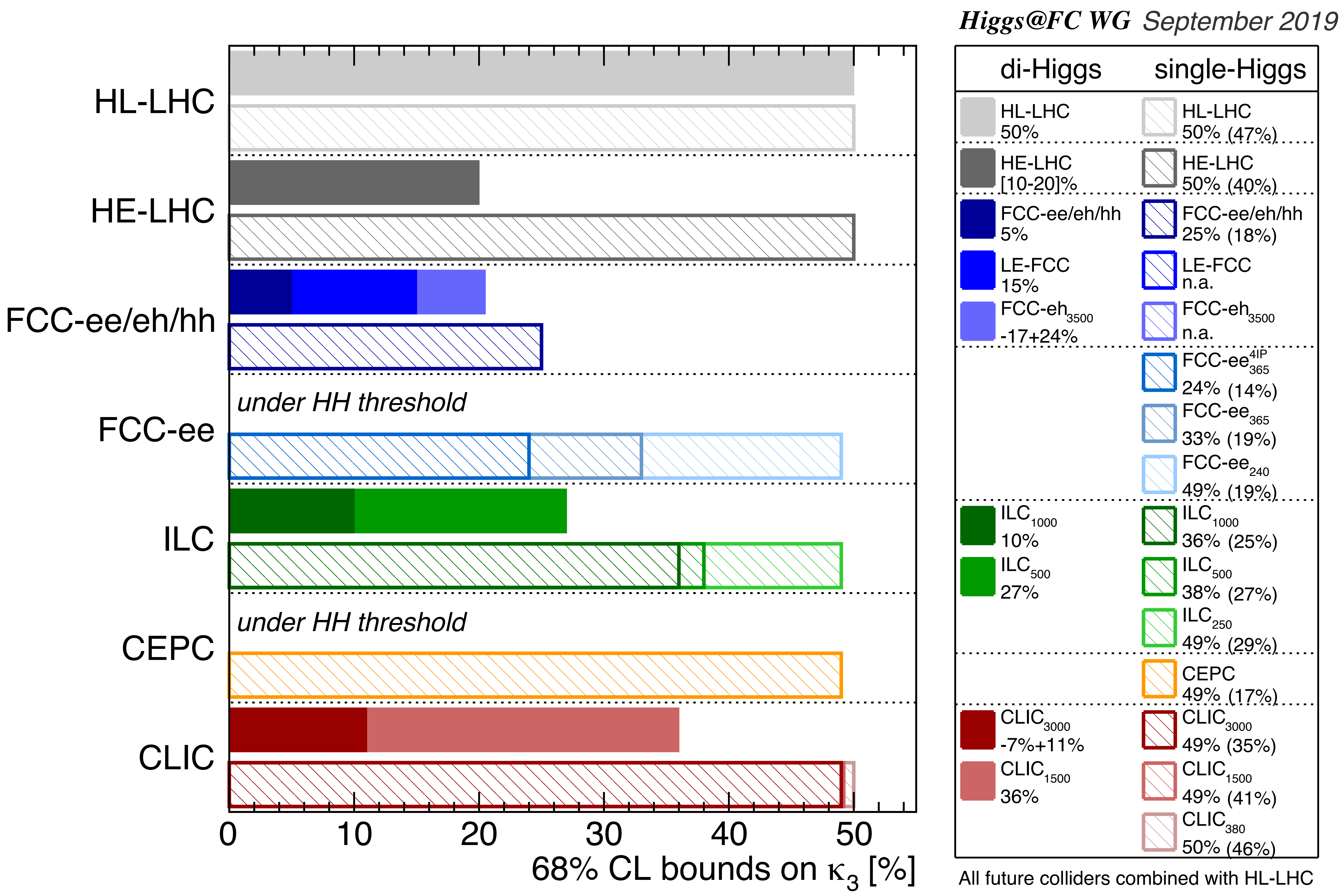
based on NIM A810 (2016) 51-58

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





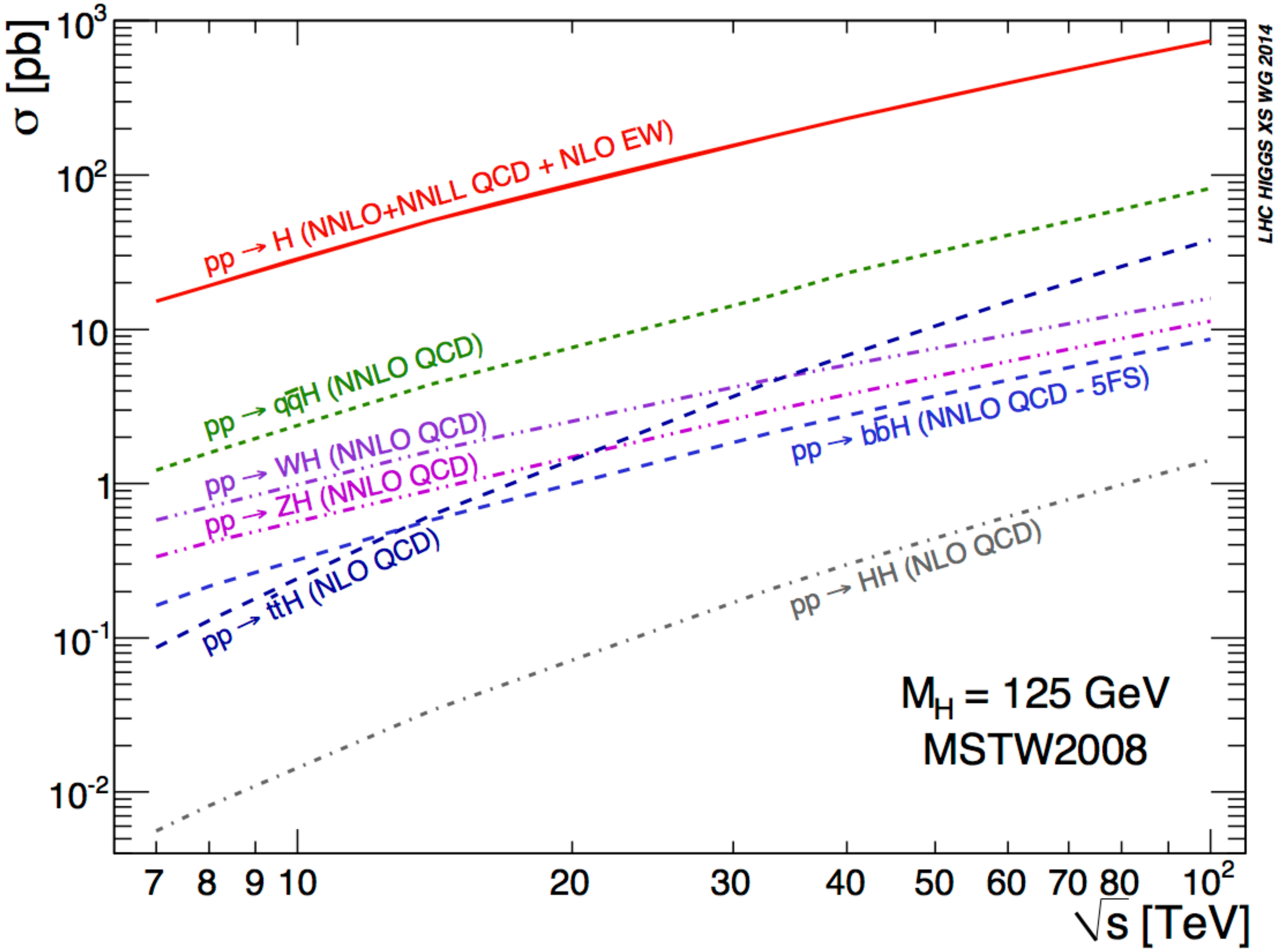
The ECFA Higgs@Future Report



At lepton colliders, double Higgs-strahlung, $e^+e^- \to ZHH$, 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
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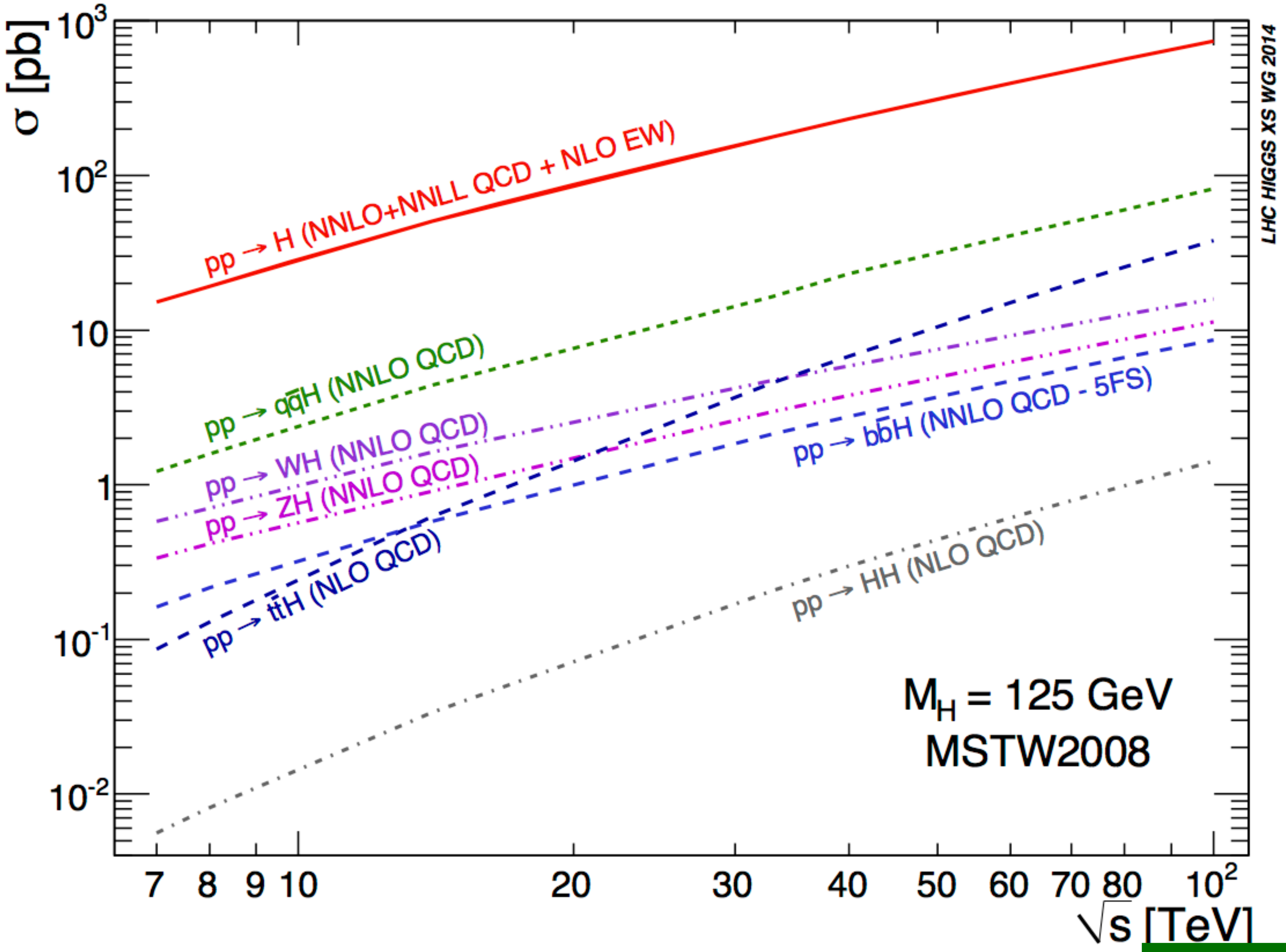

differential distributions!

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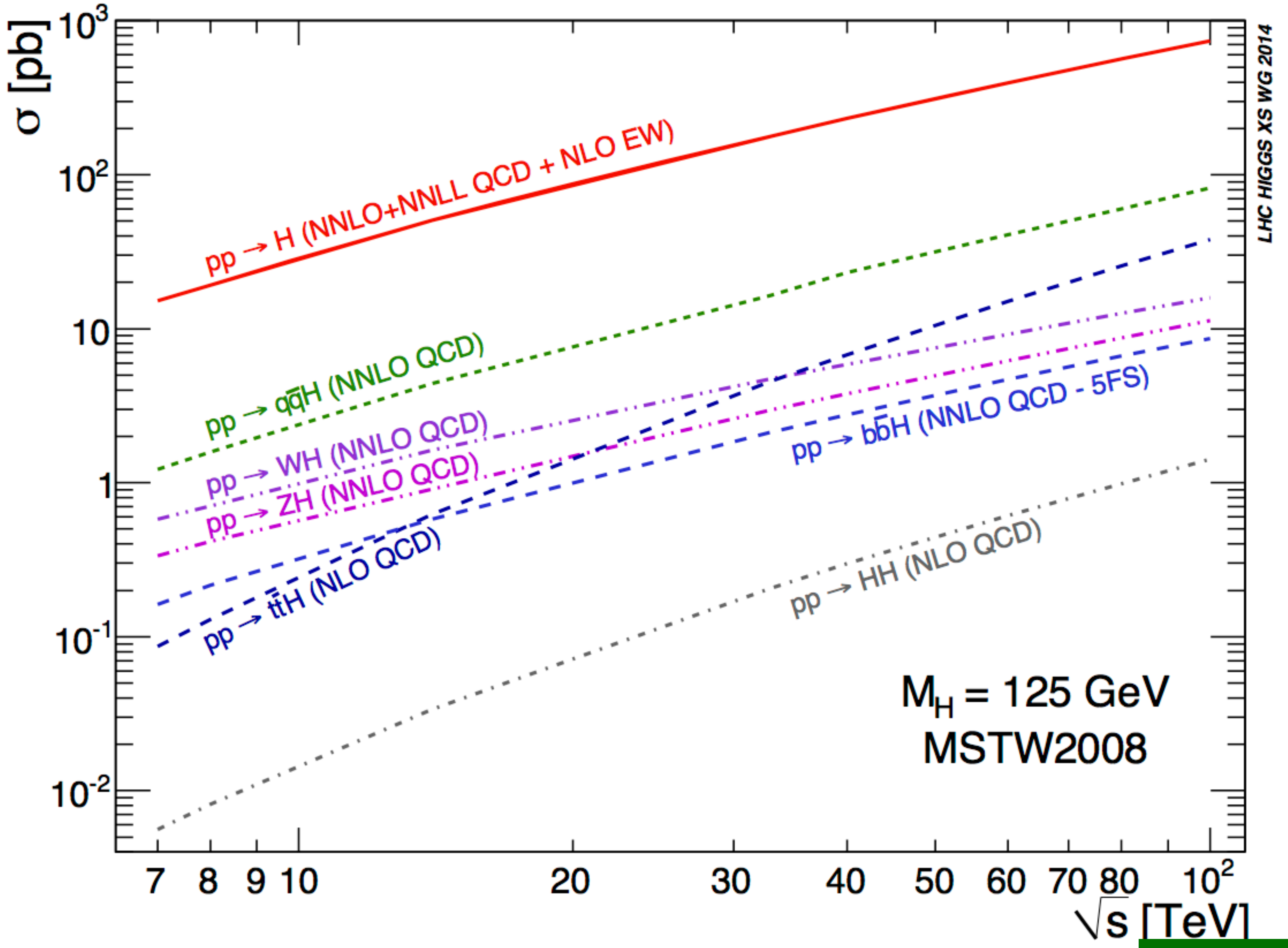

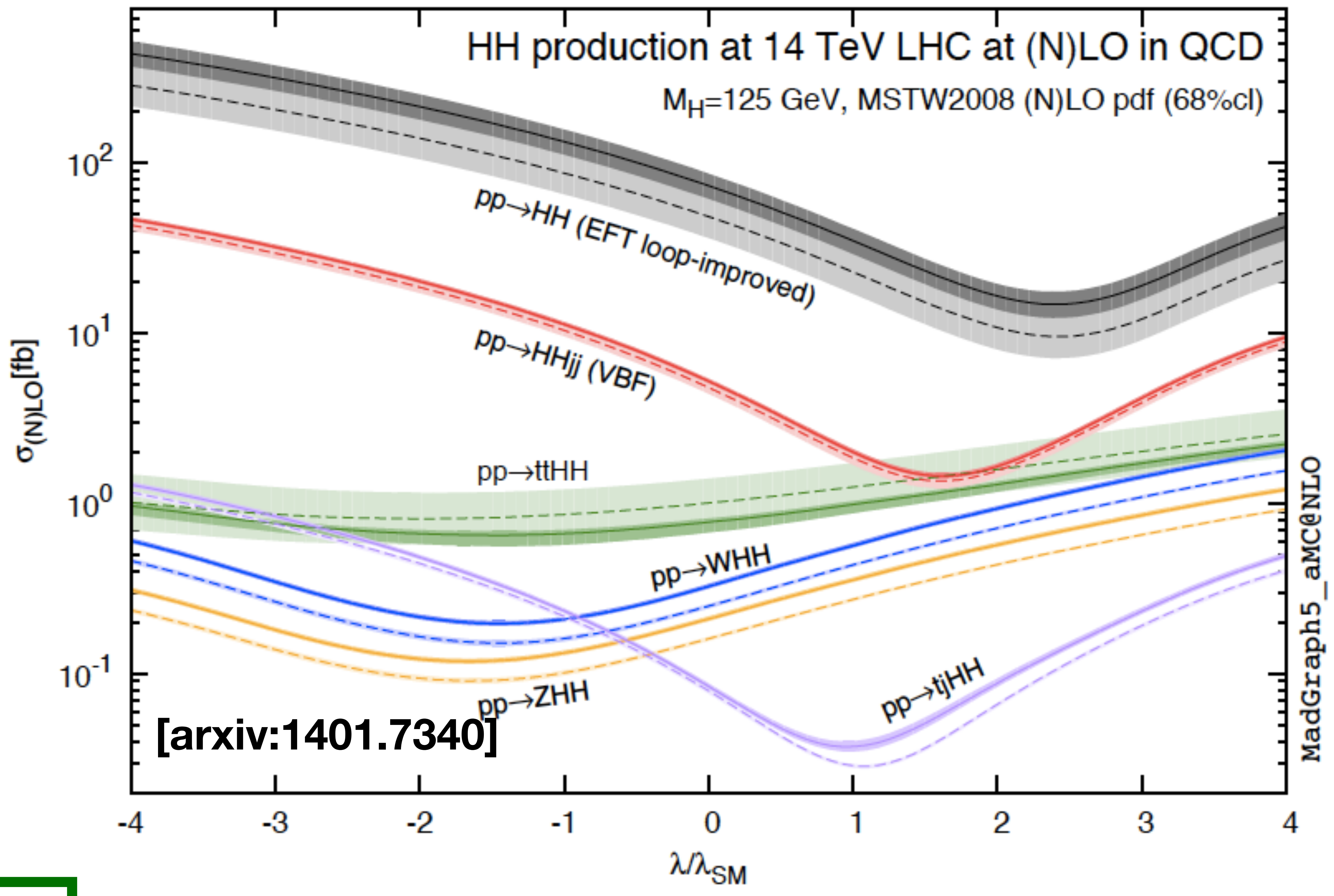

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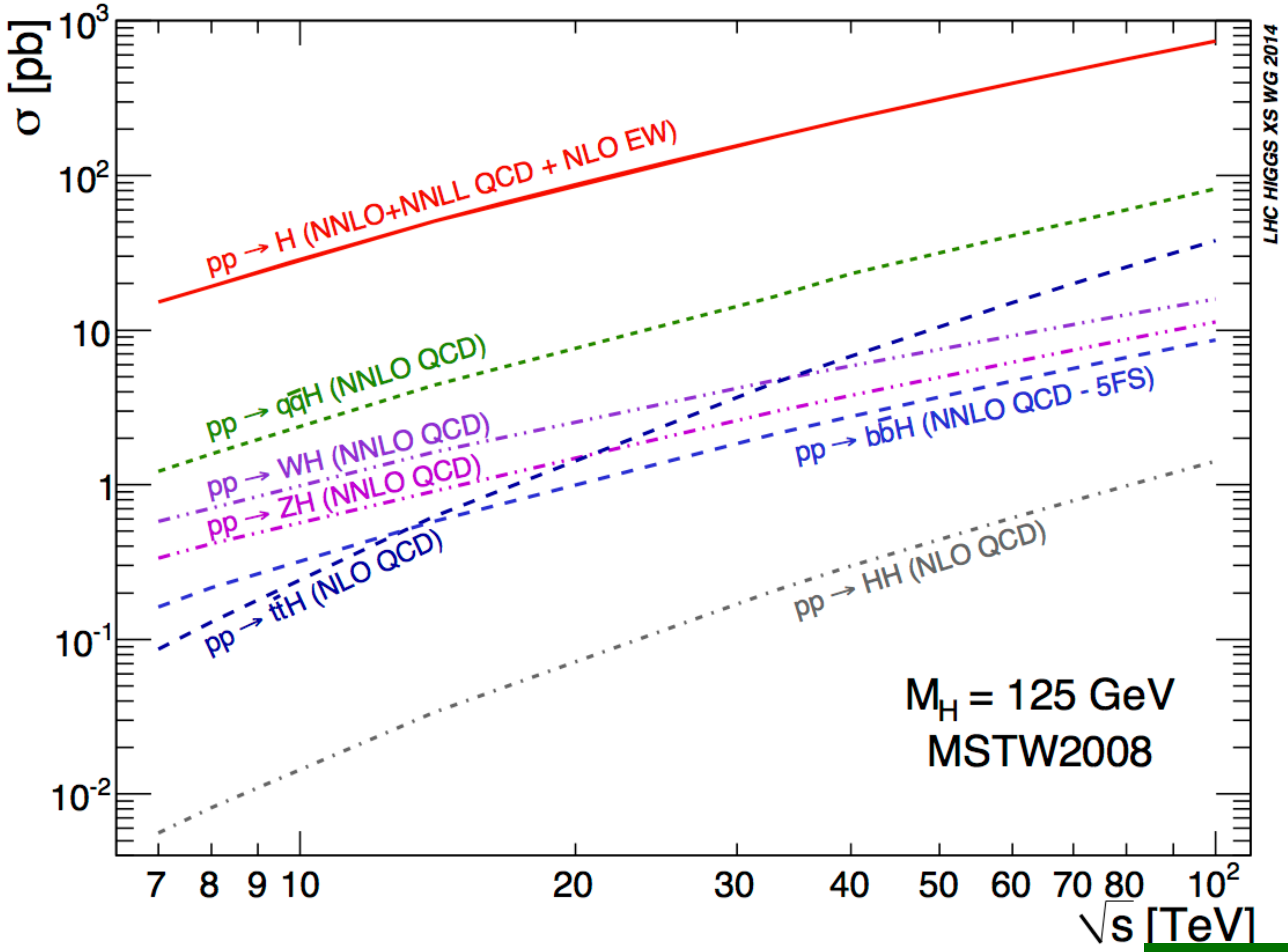

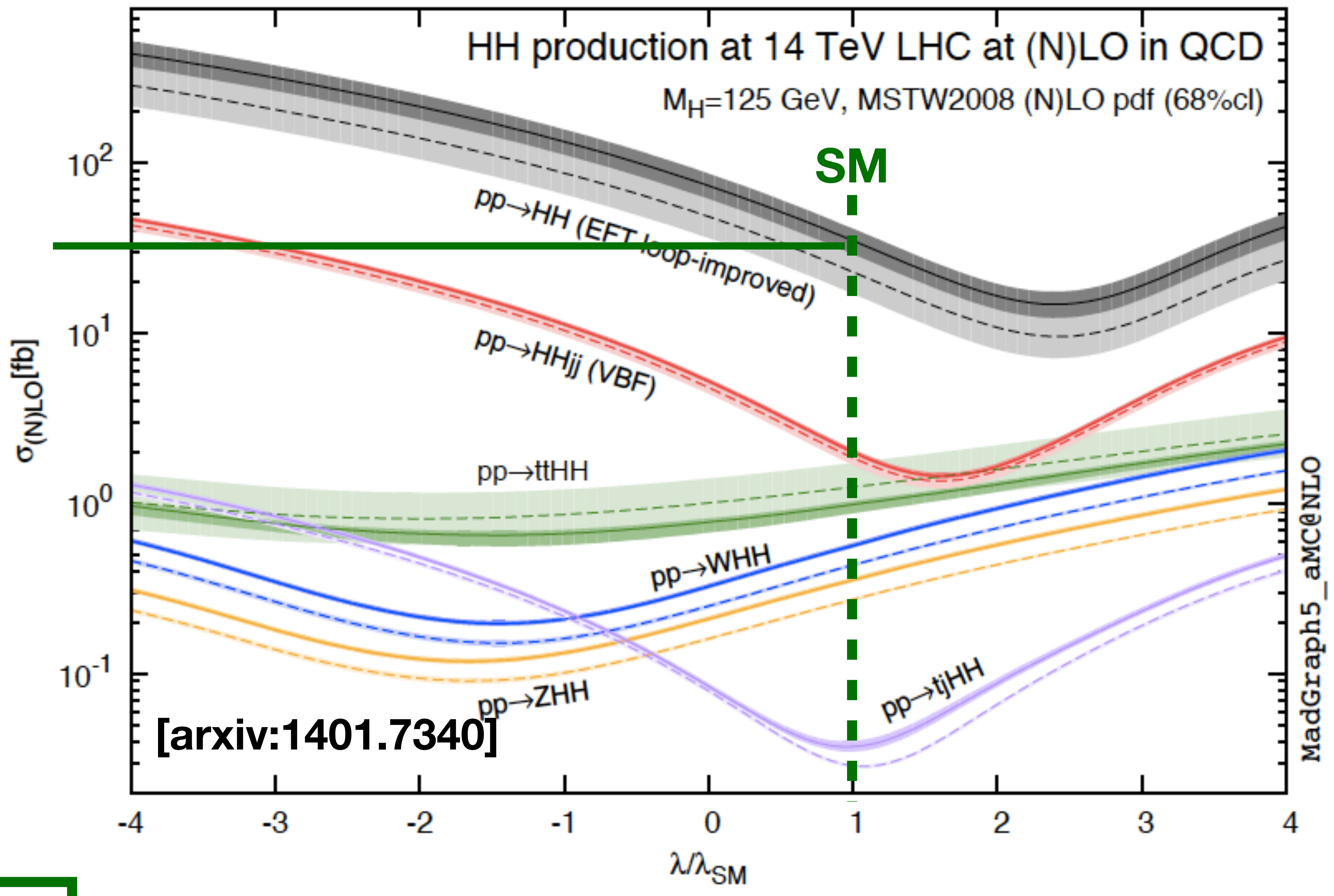

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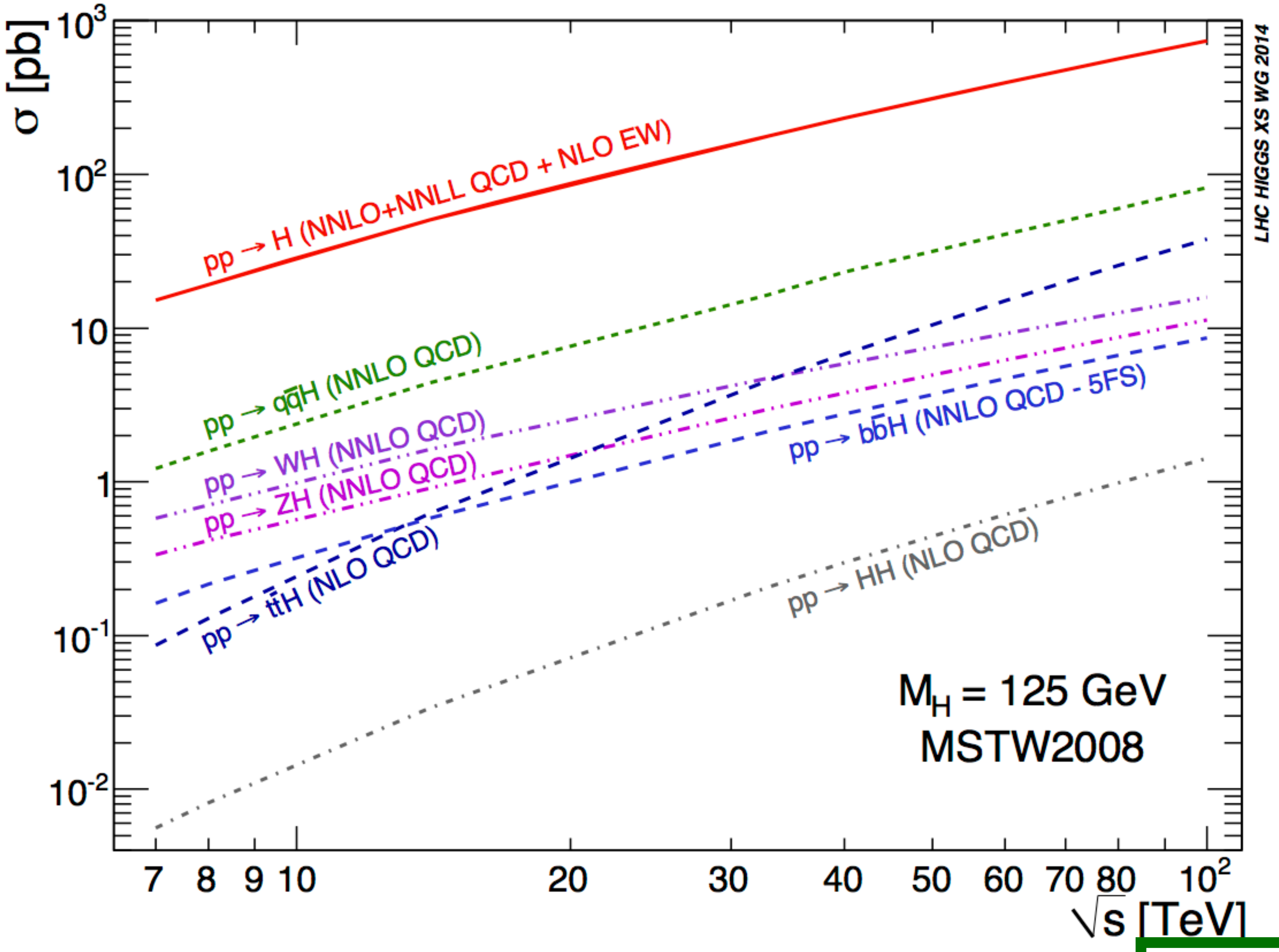

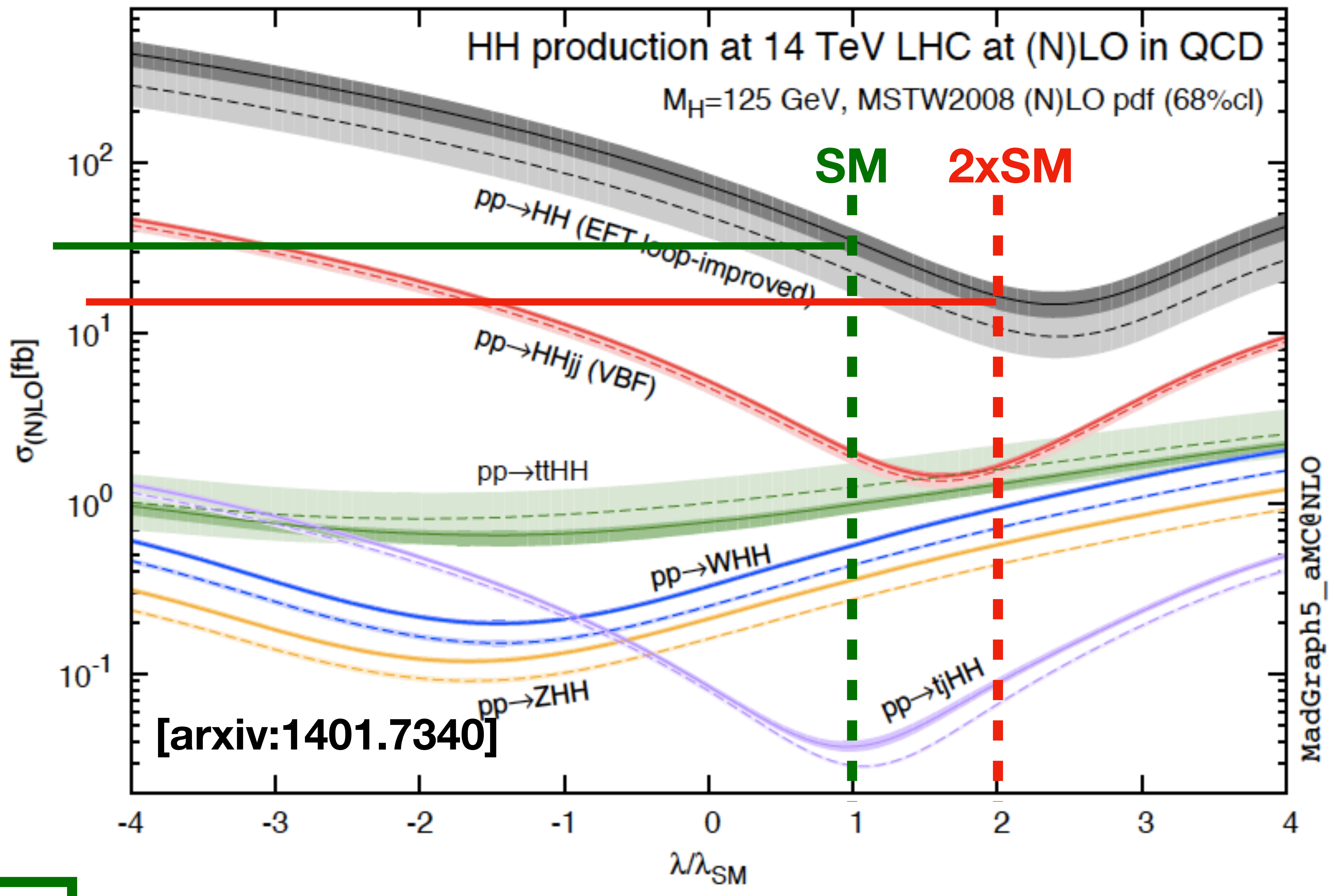

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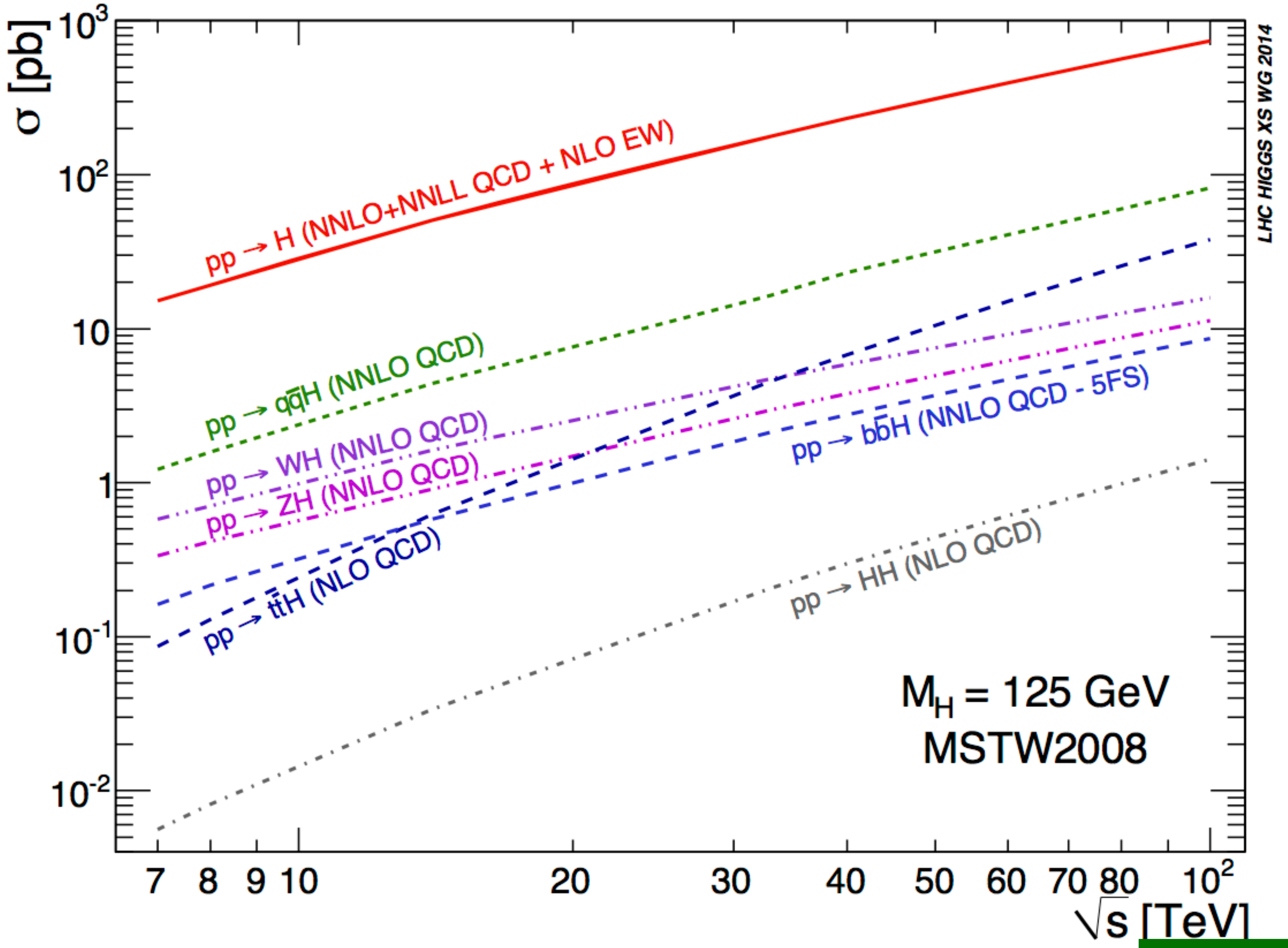

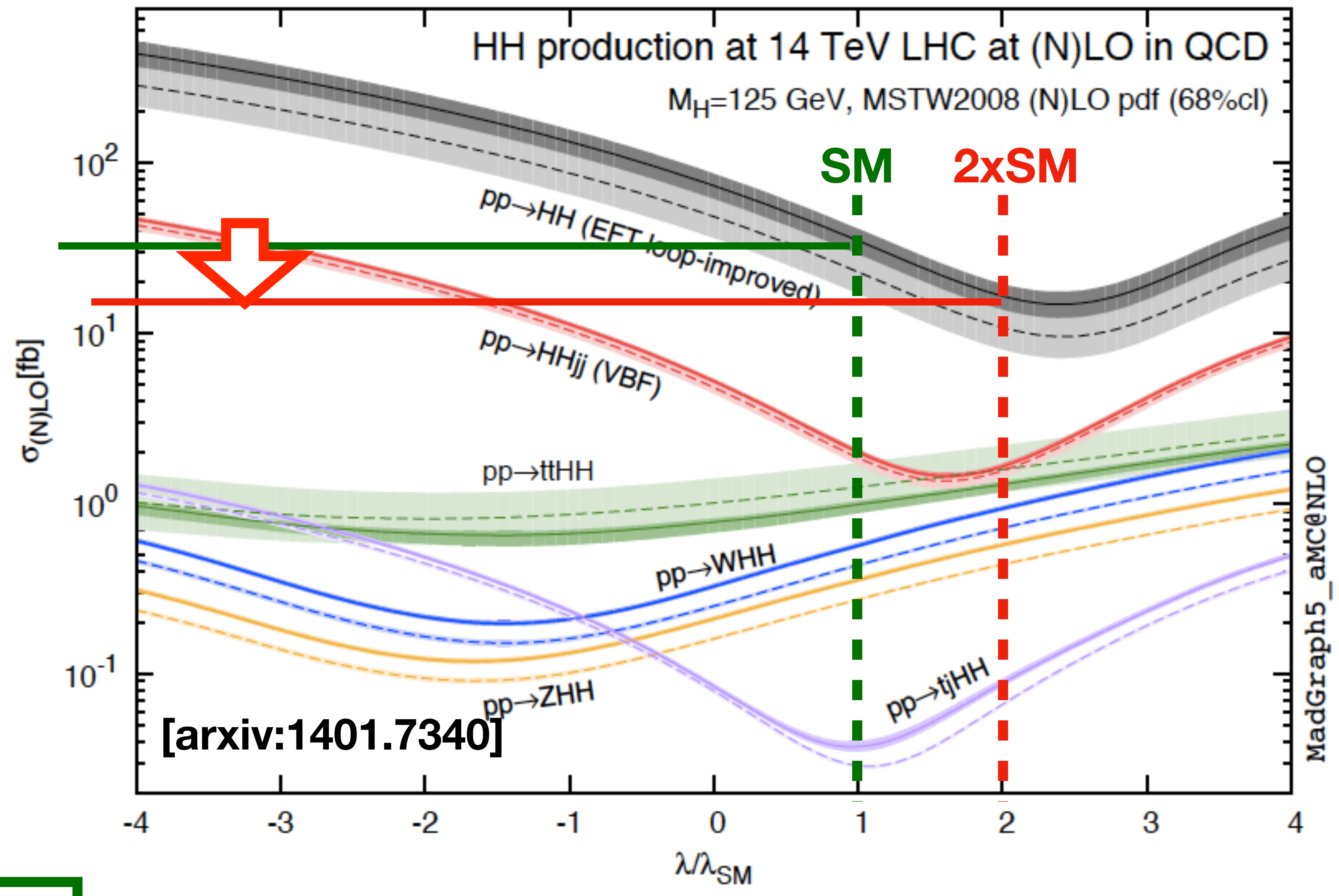

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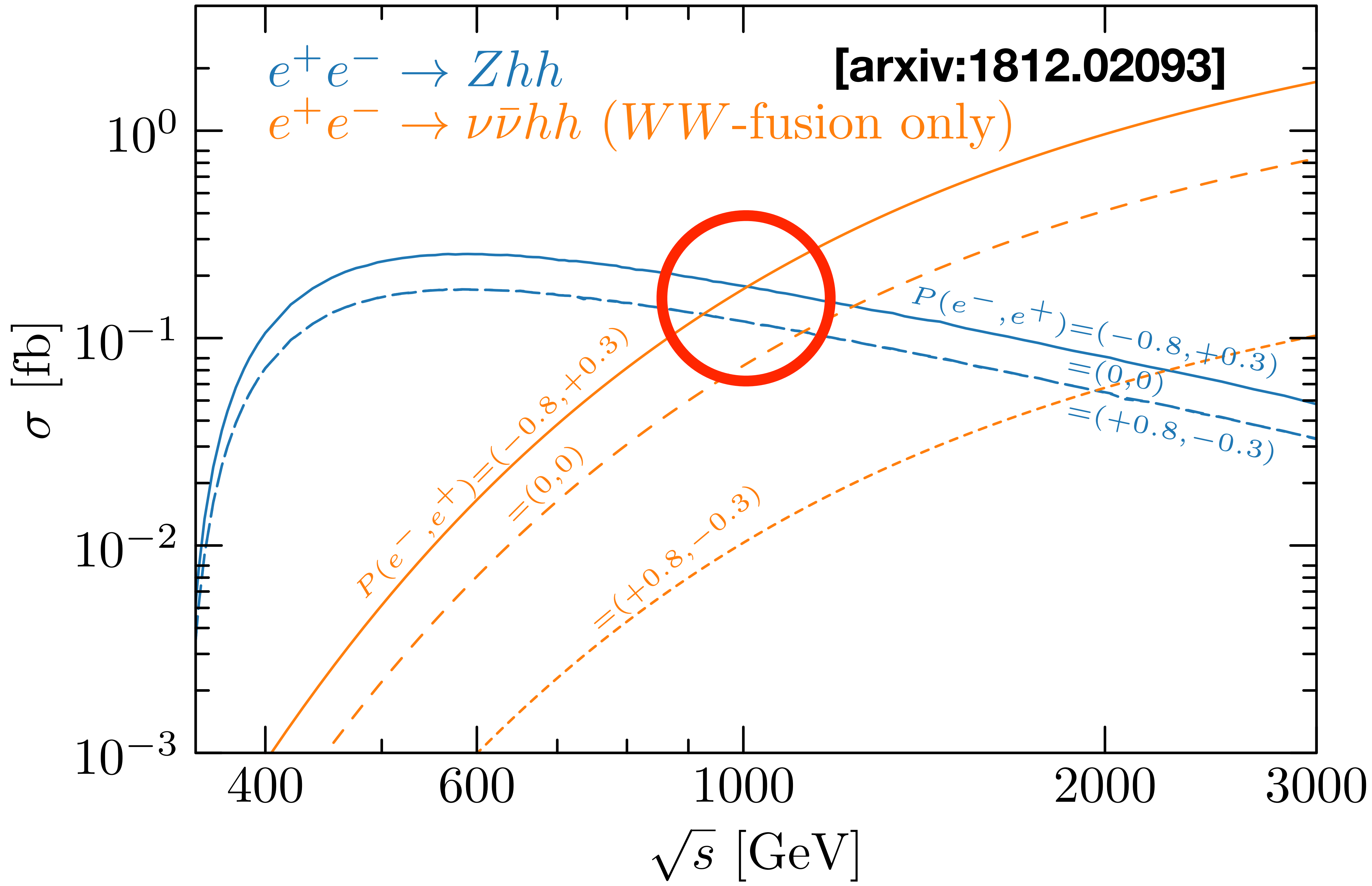
dependence on λ:
$\lambda > \lambda_{SM}$: cross section drops,
i.e. by factor ~2 for $\lambda = 2\,\lambda_{SM}$

Di-Higgs Production Cross sections - ee



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vvHH (fusion): effectively only P(-80%) counts

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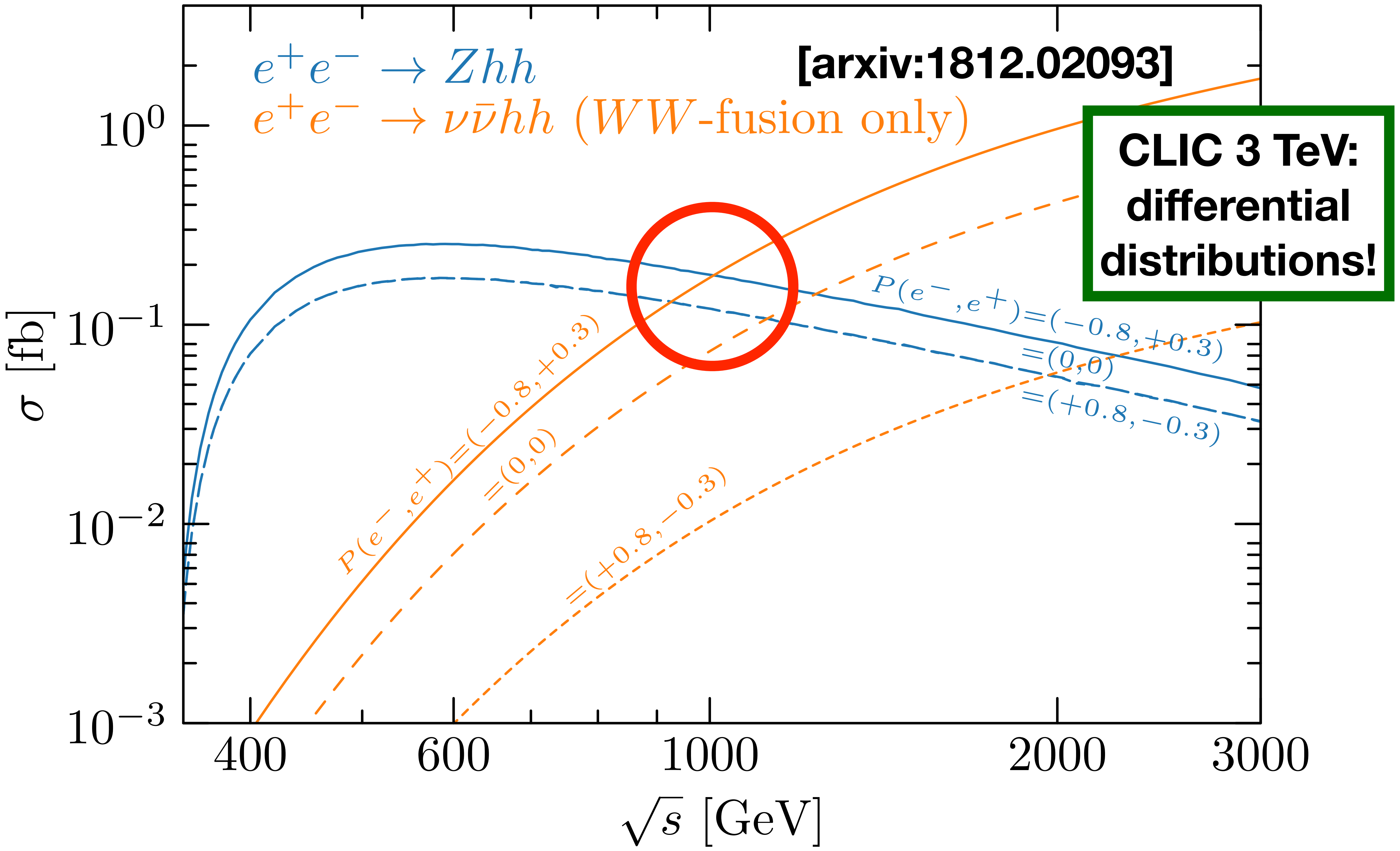

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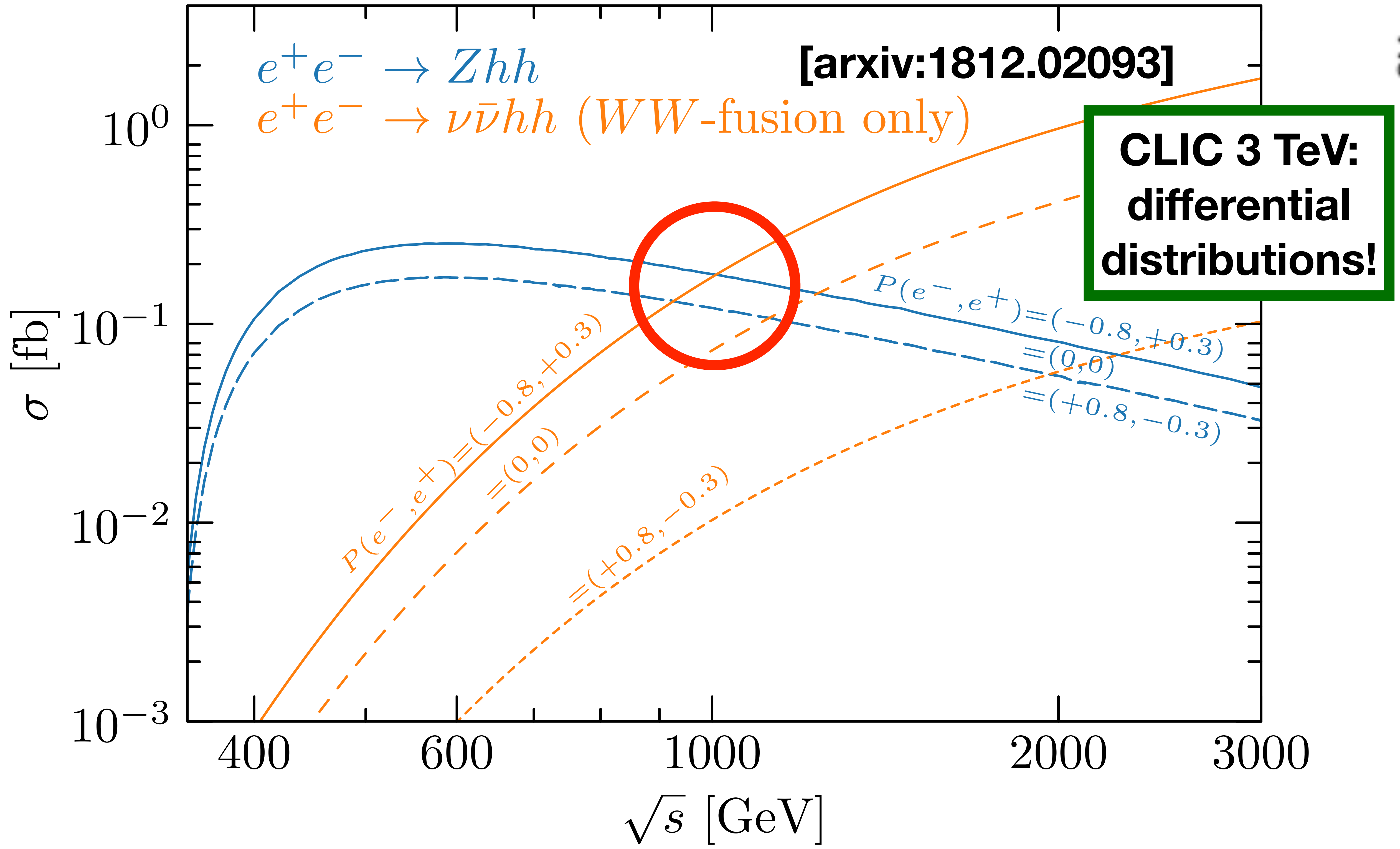

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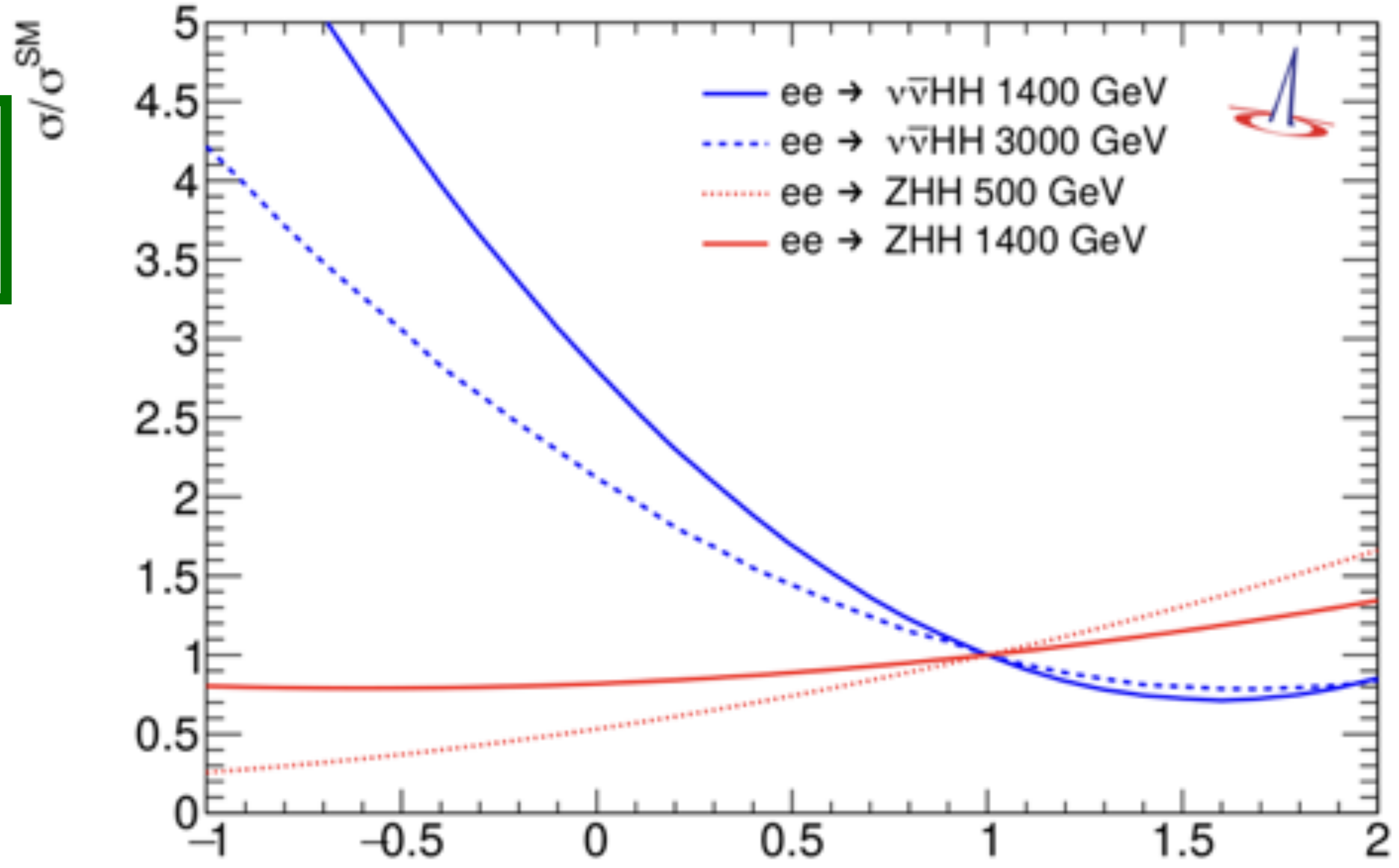

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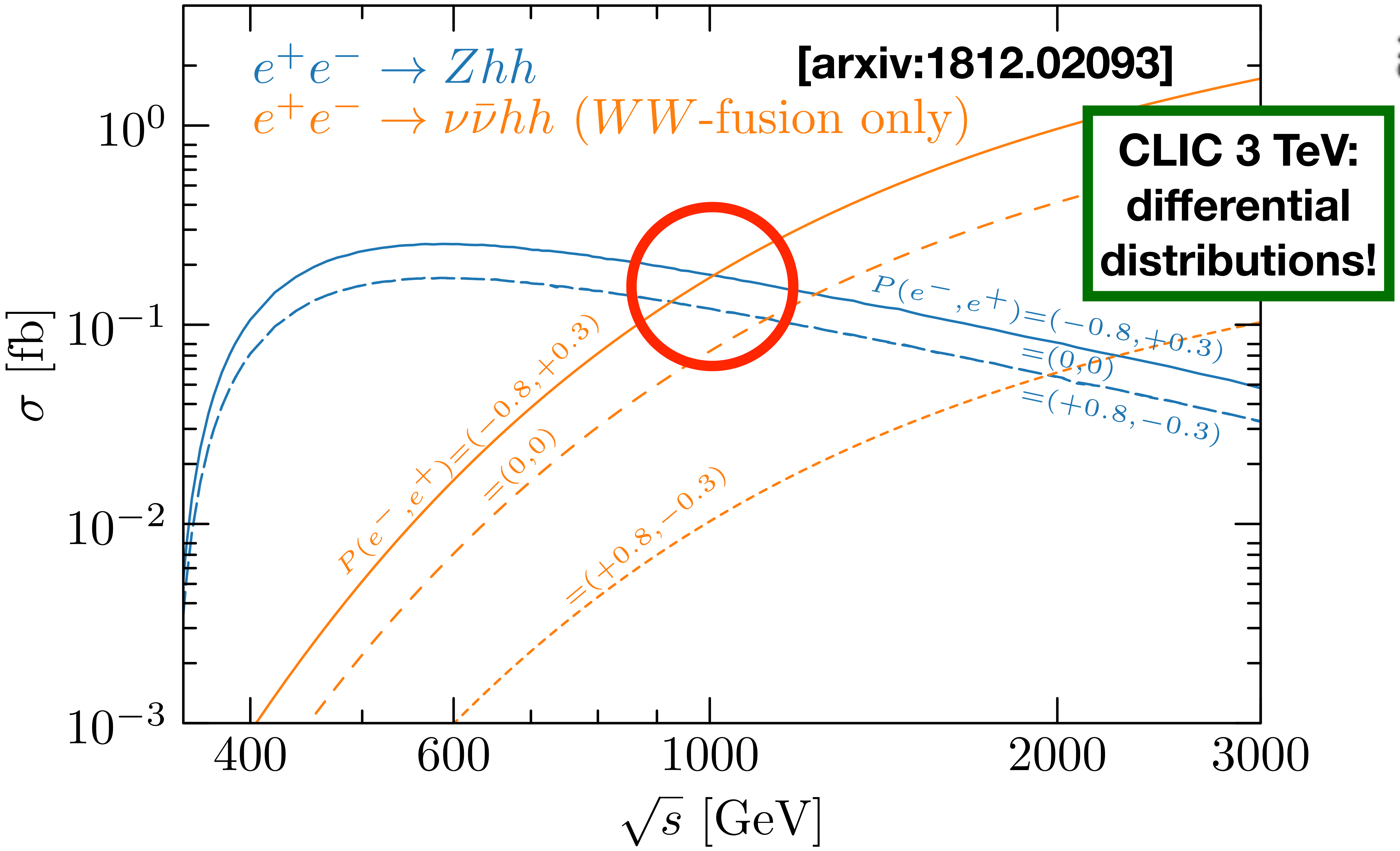

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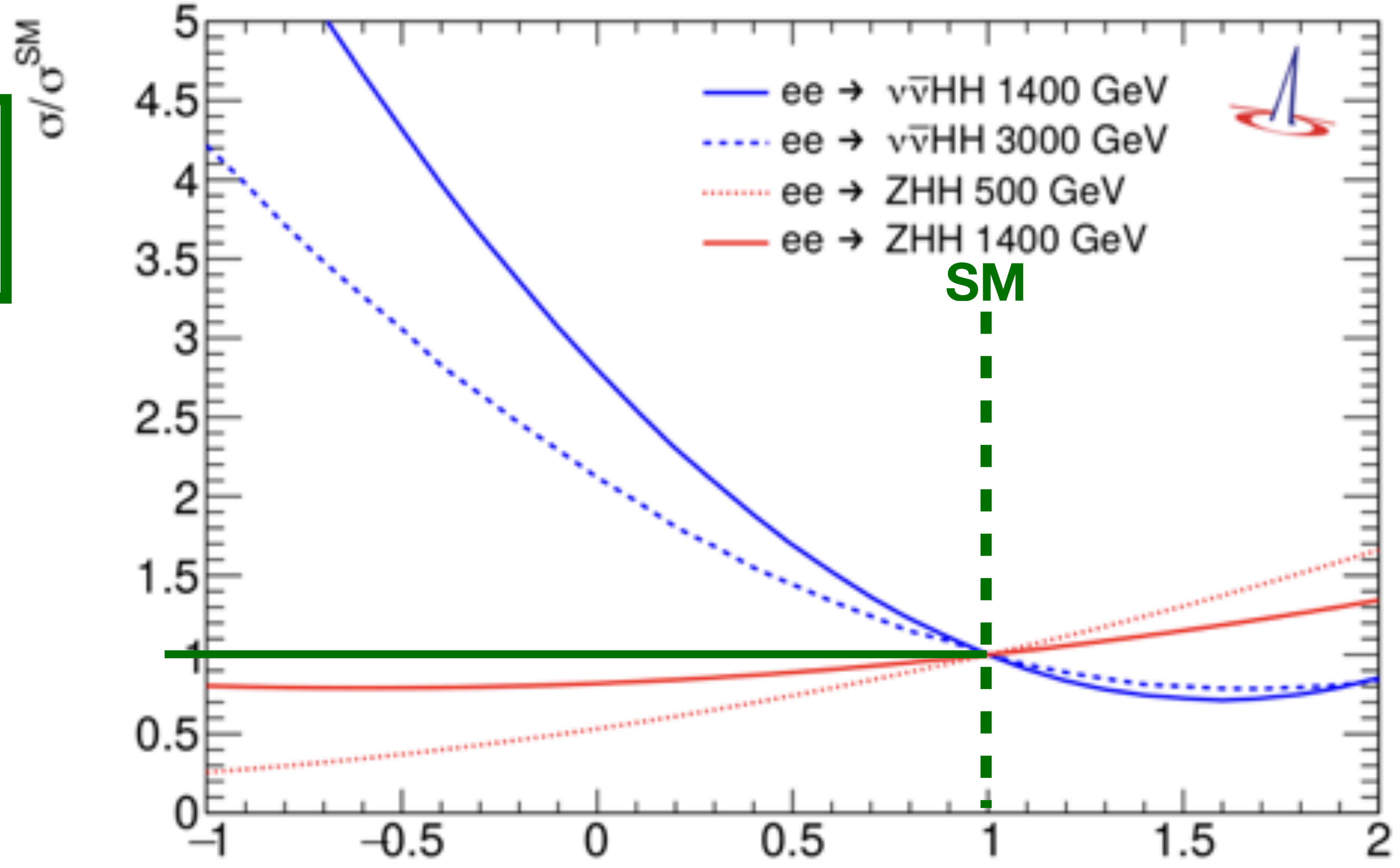

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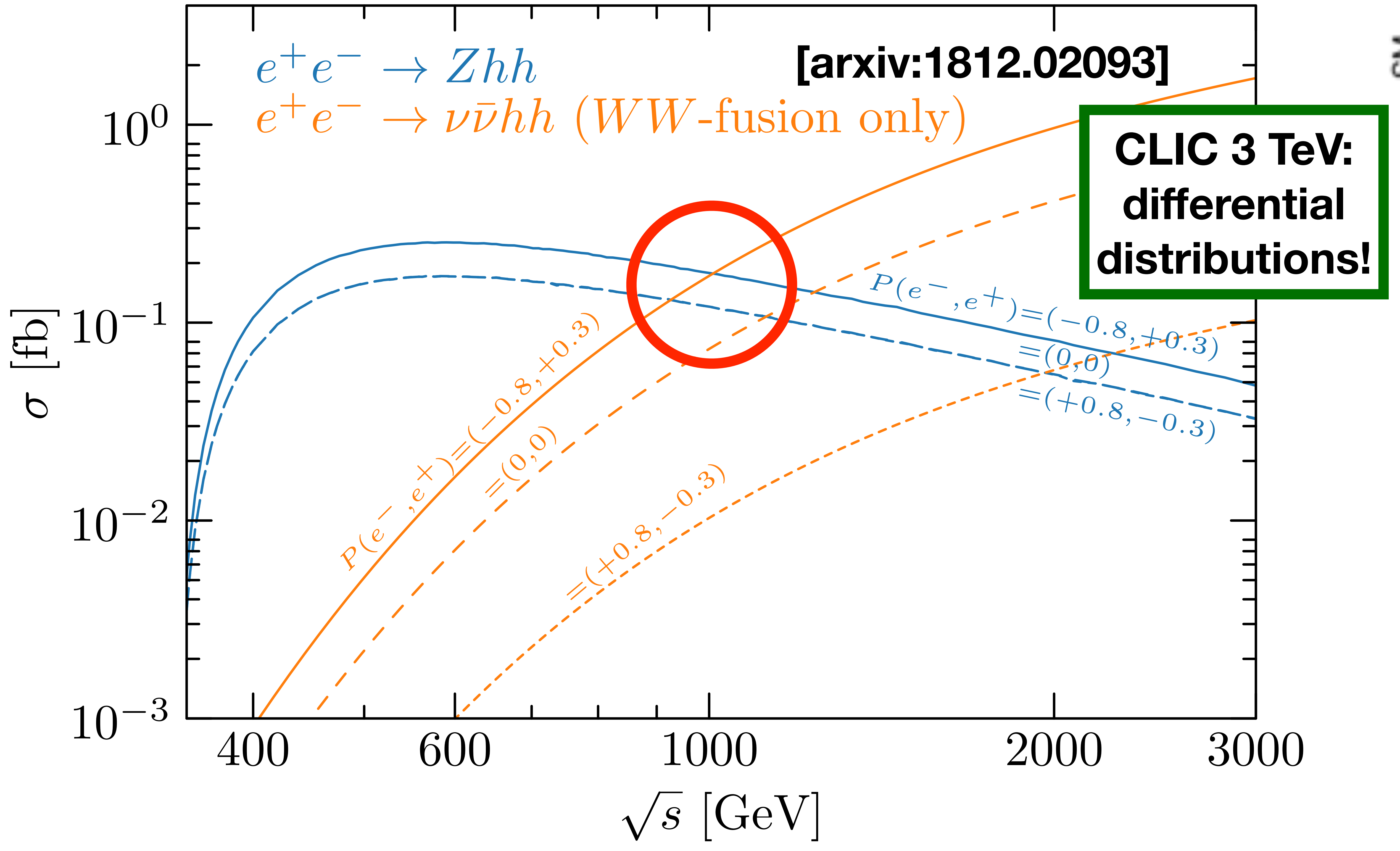

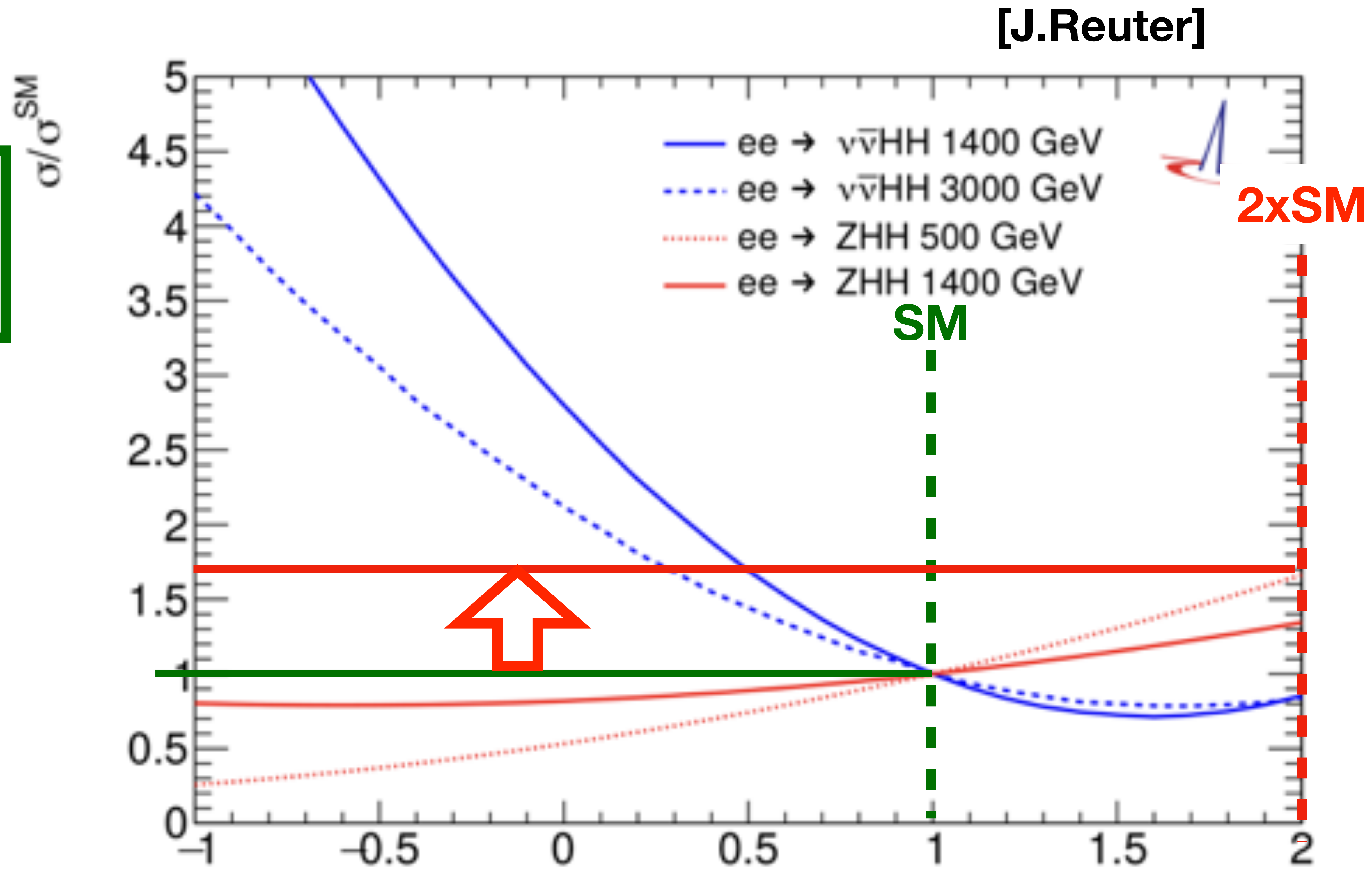

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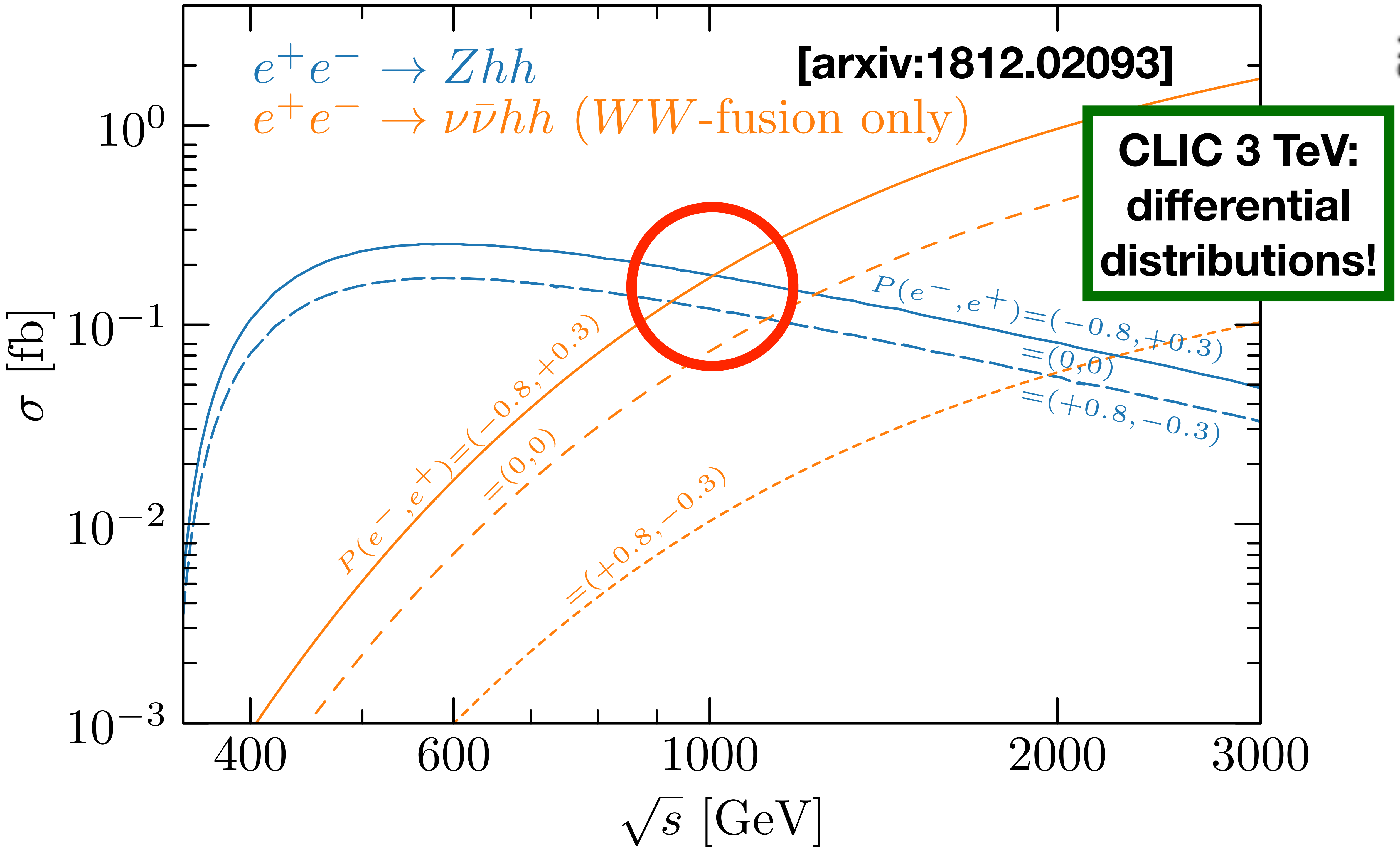

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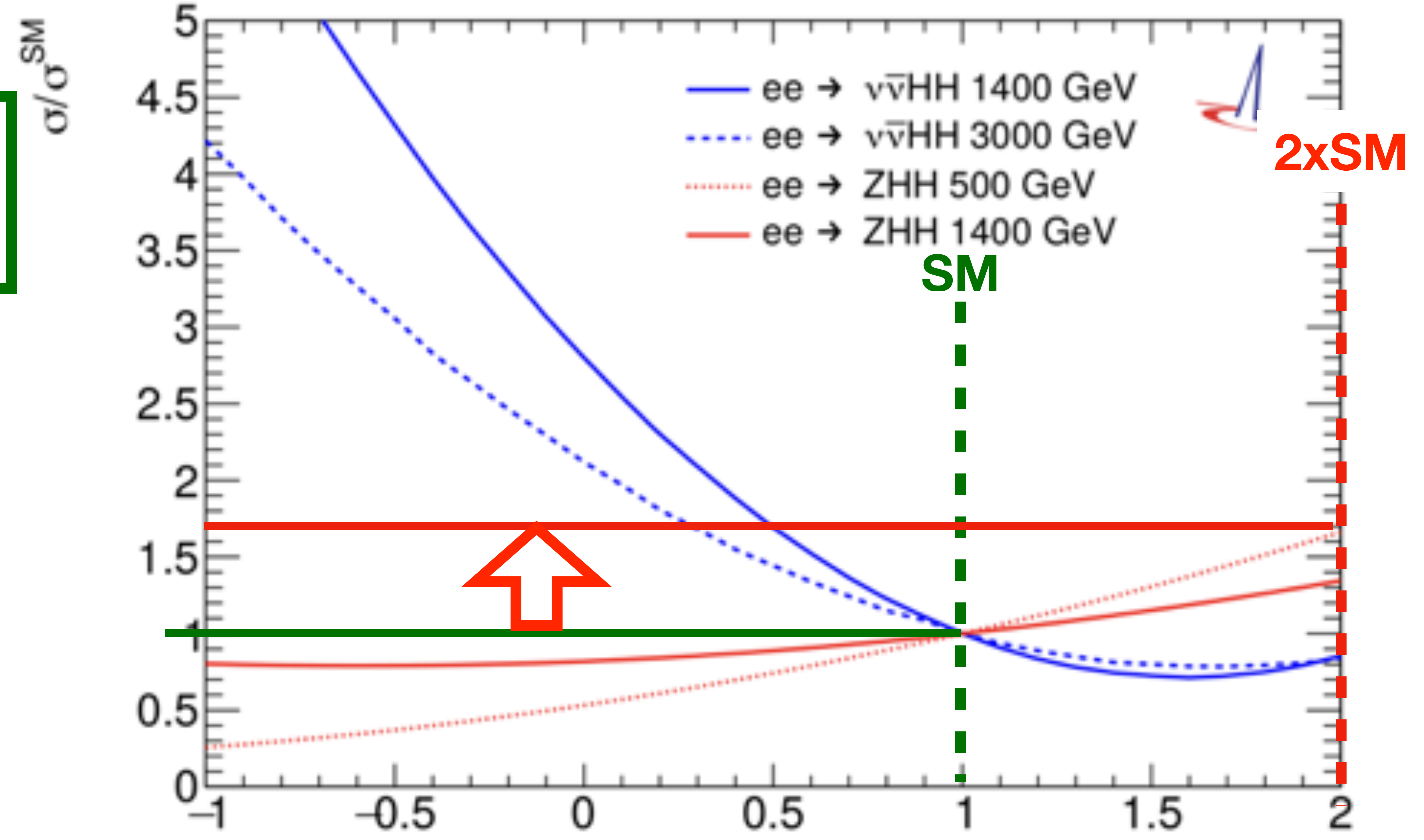


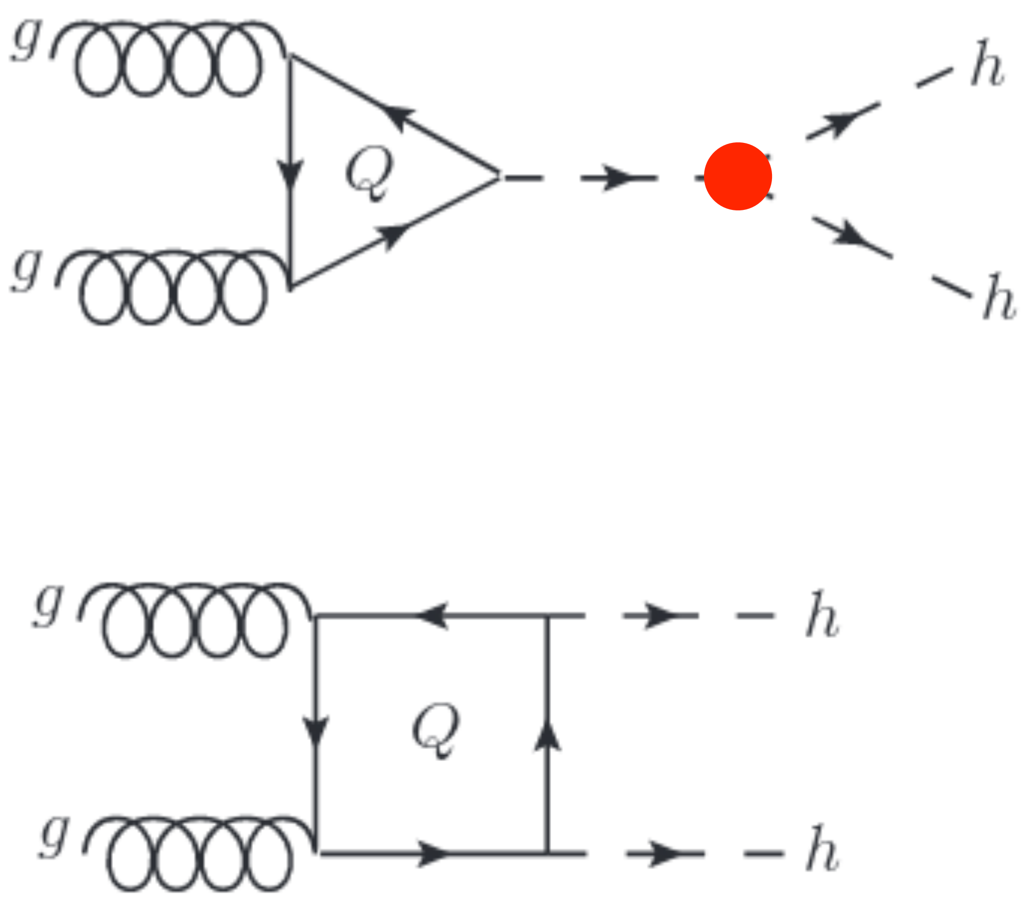
=> VBF(ee/pp)- and Higgsstrahlung (ee) di-Higgs production have orthogonal BSM behaviour

From di-Higgs production to λ

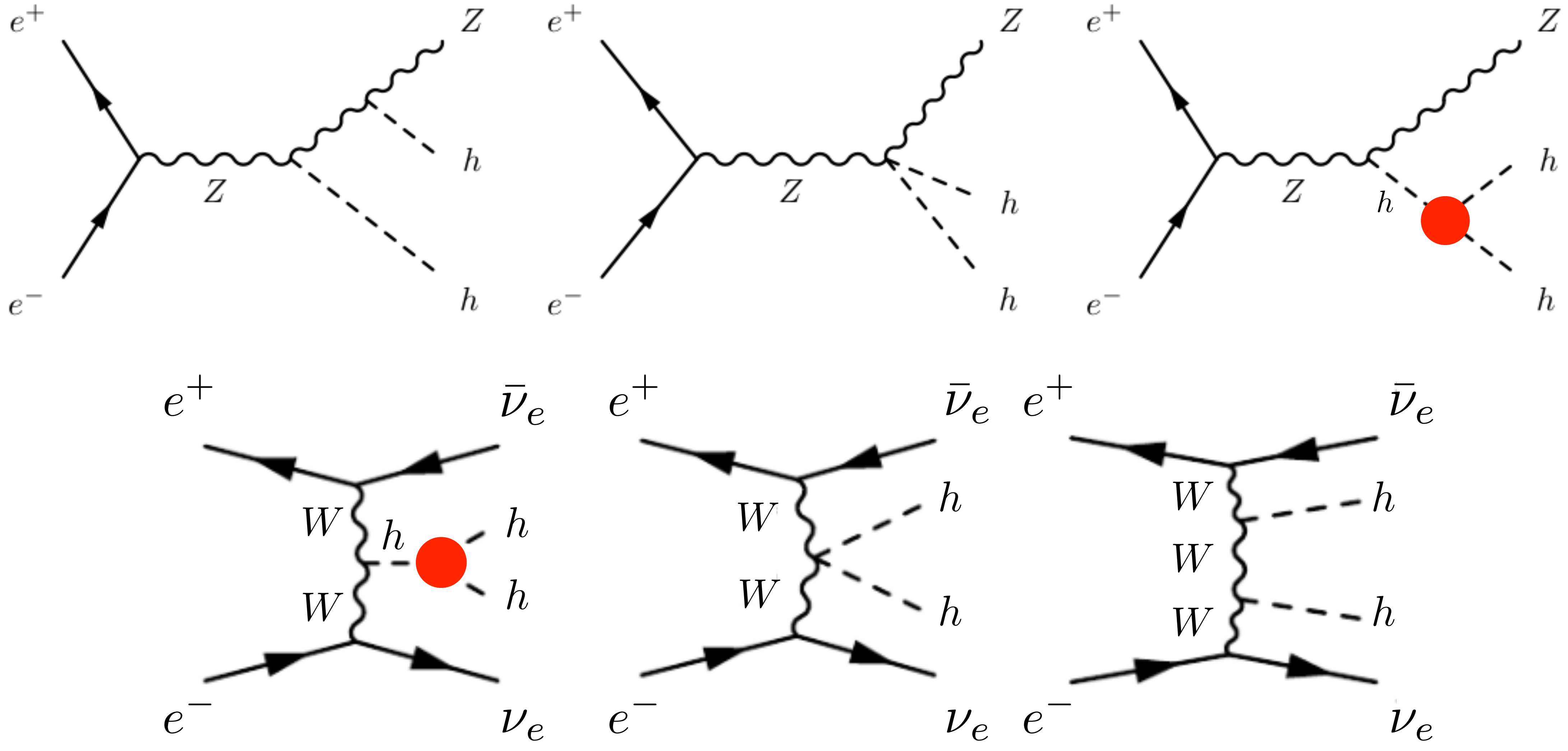
1. Discover di-Higgs production
2. Measure cross section (total and differential!)
3. Extract λ

- 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



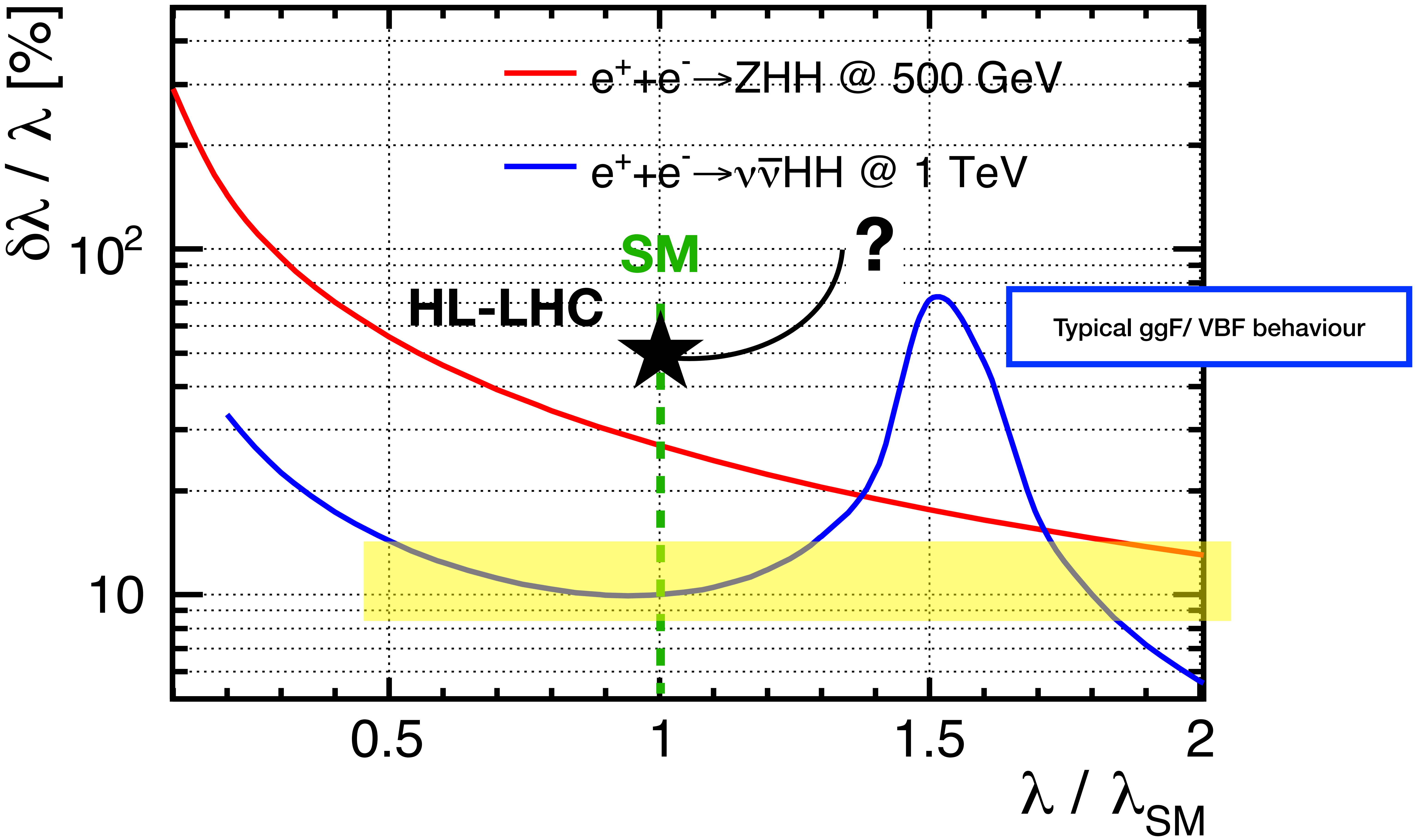
Lepton collider



ILC Sensitivity vs Lambda

ILC Sensitivity vs Lambda

[J.Tian, C.Duerig]



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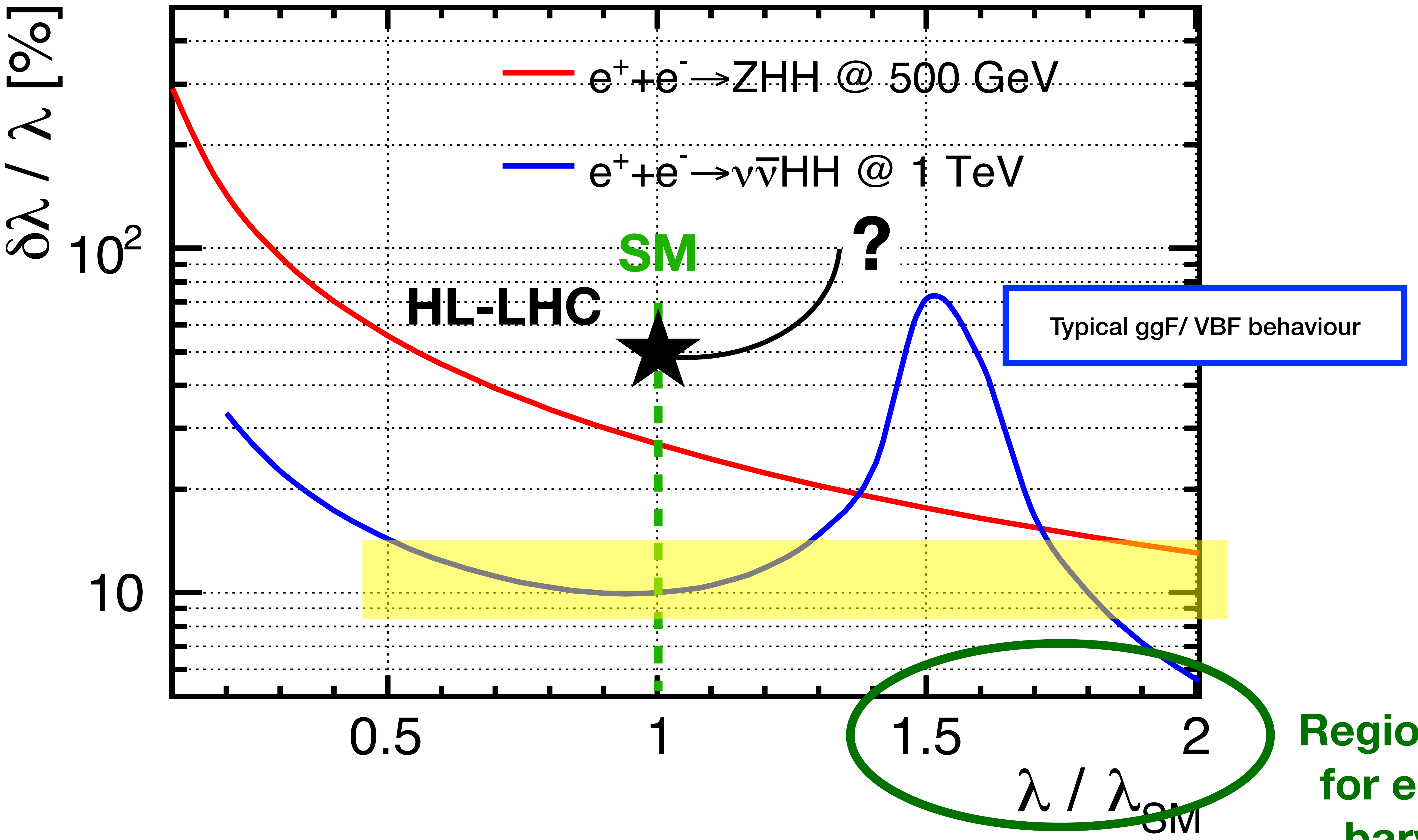
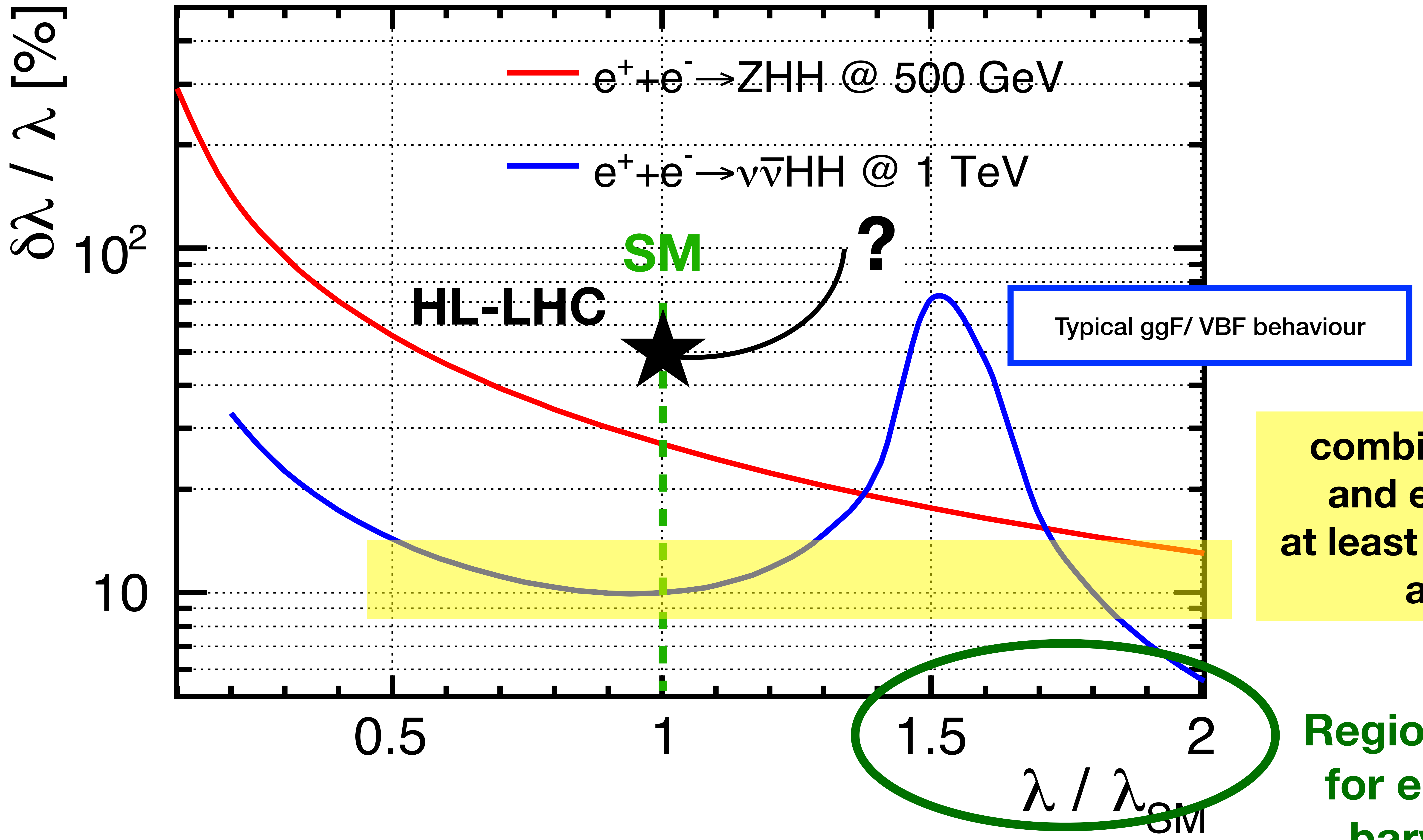


Region of interest for electroweak baryogenesis

ILC Sensitivity vs Lambda

[J.Tian, C.Duerig]

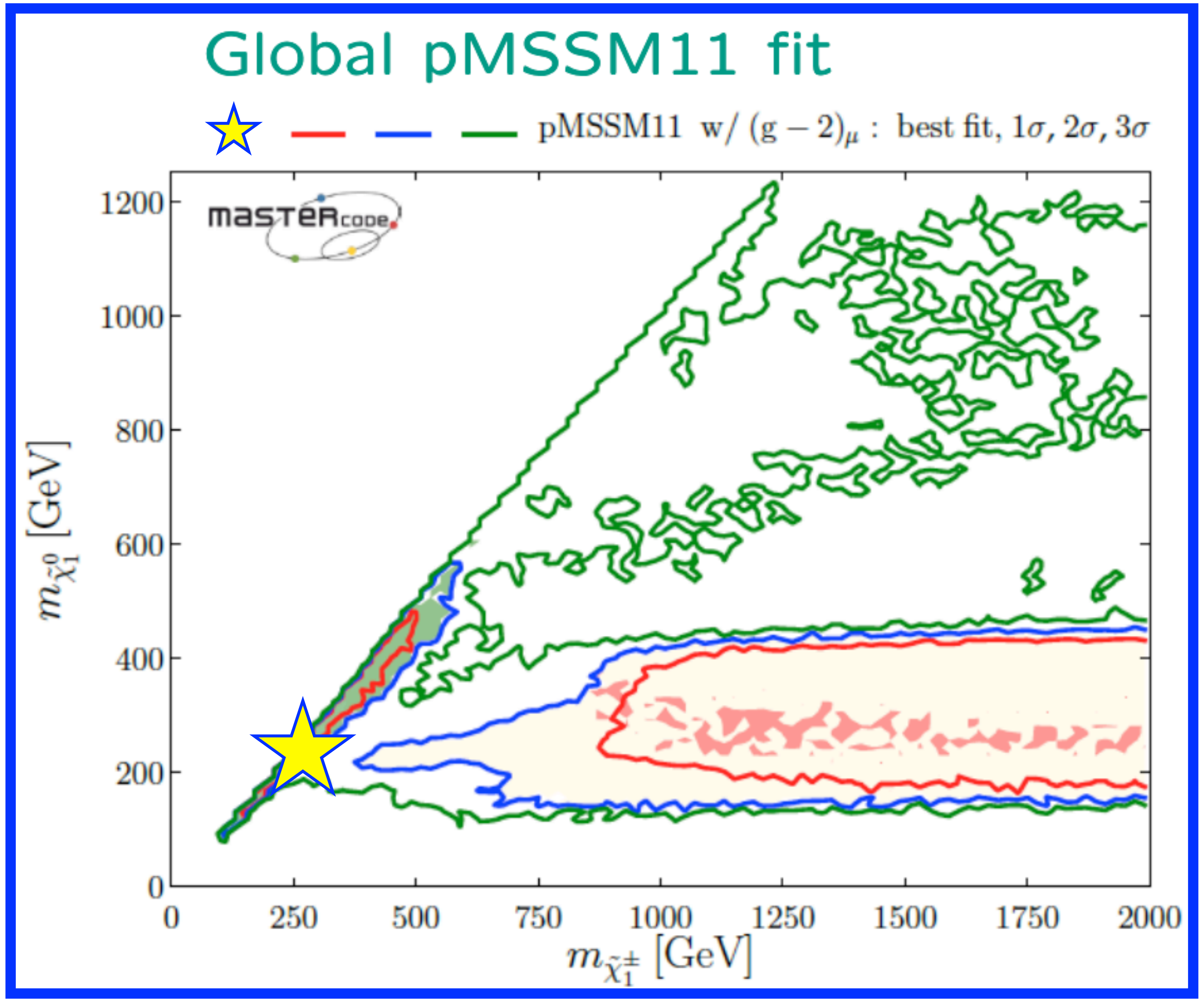


combination of e^+e^- -> ZHH and e^+e^- -> νvHH ensures at least 10-15% precision over a wide range in λ

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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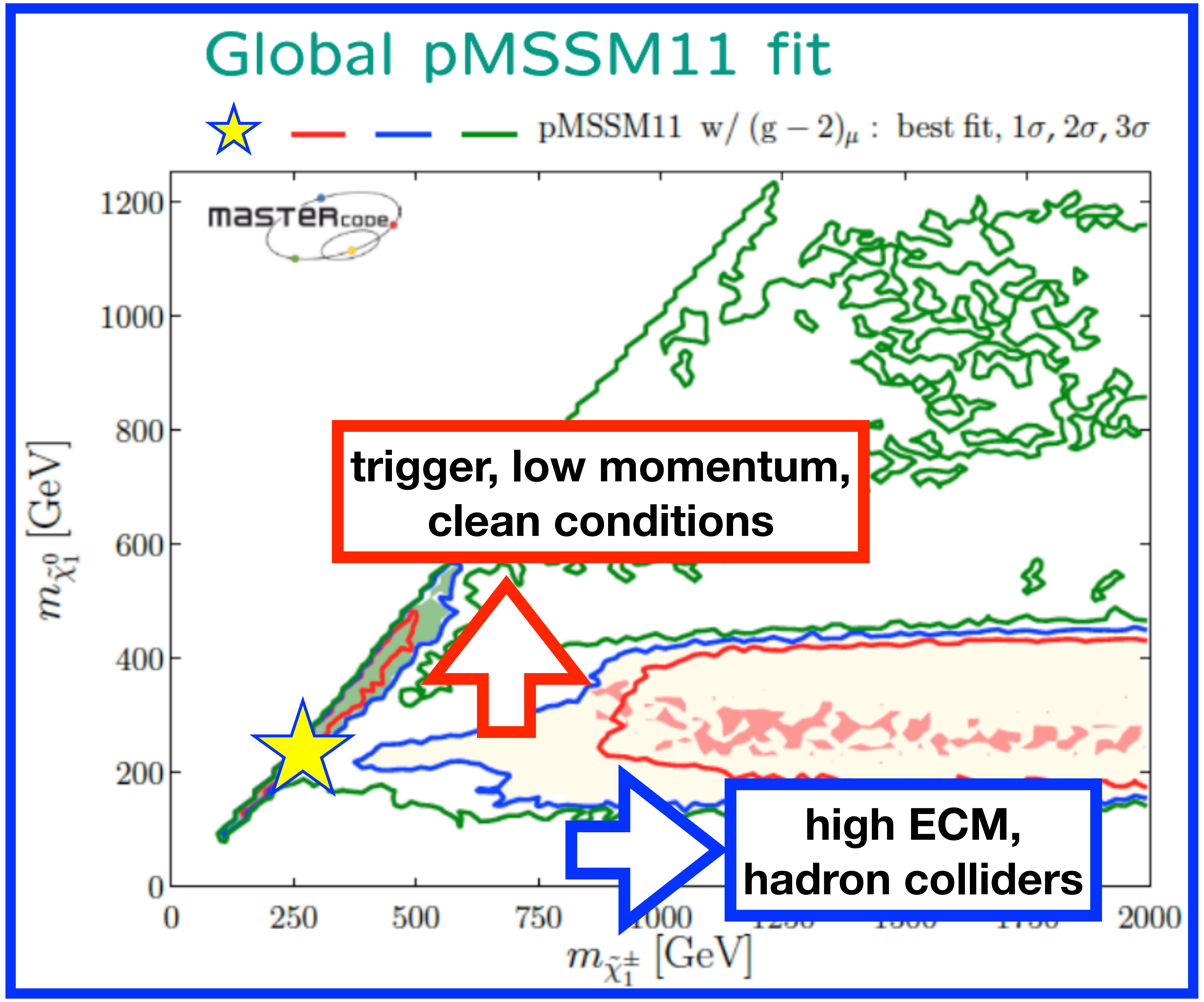

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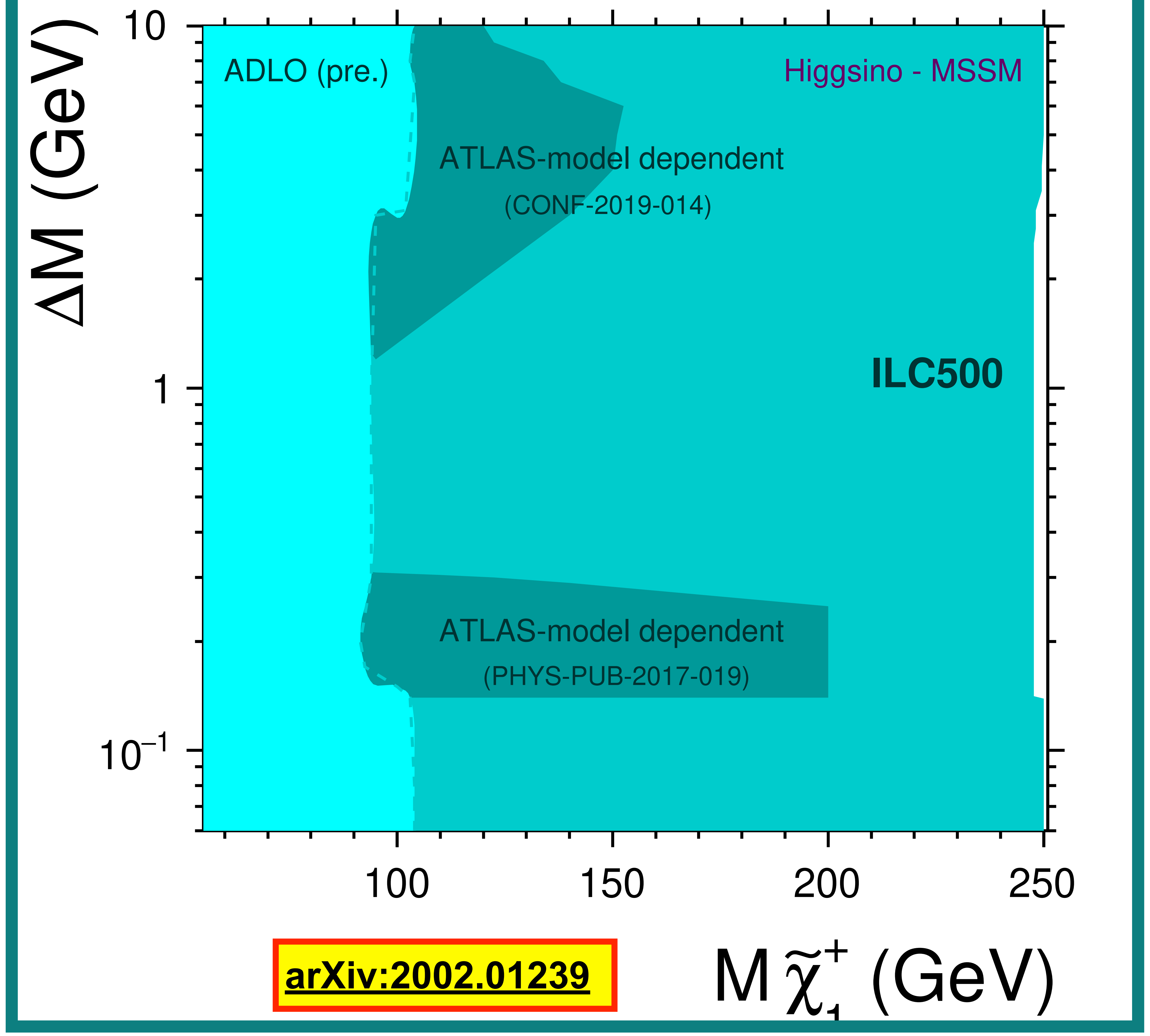
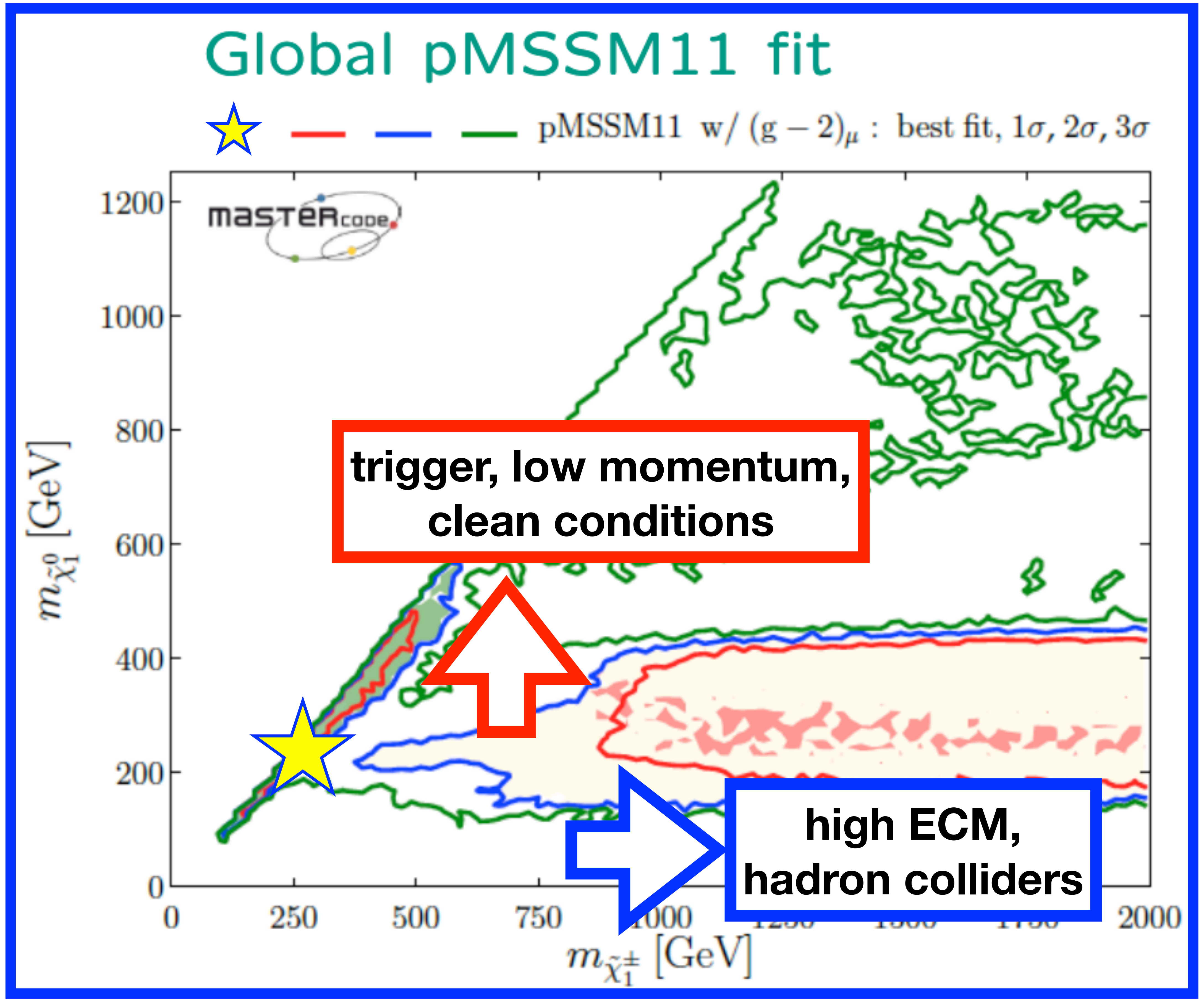


arXiv:2002.01239



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