Roberto Salerno
Yves Sirois

Interplay between Particle Physics Results and Cosmology

Today our Universe is almost flat, homogeneous and isotropic

IMAGE PROCESSING: NASA, ESA, CSA

Today our Universe is almost flat, homogeneous and isotropic

This can be explained simultaneously by the accelerated expansion of the Universe in the very first moments after the Big Bang. At some early time the **fundamental interactions** and the **particle content** were established !

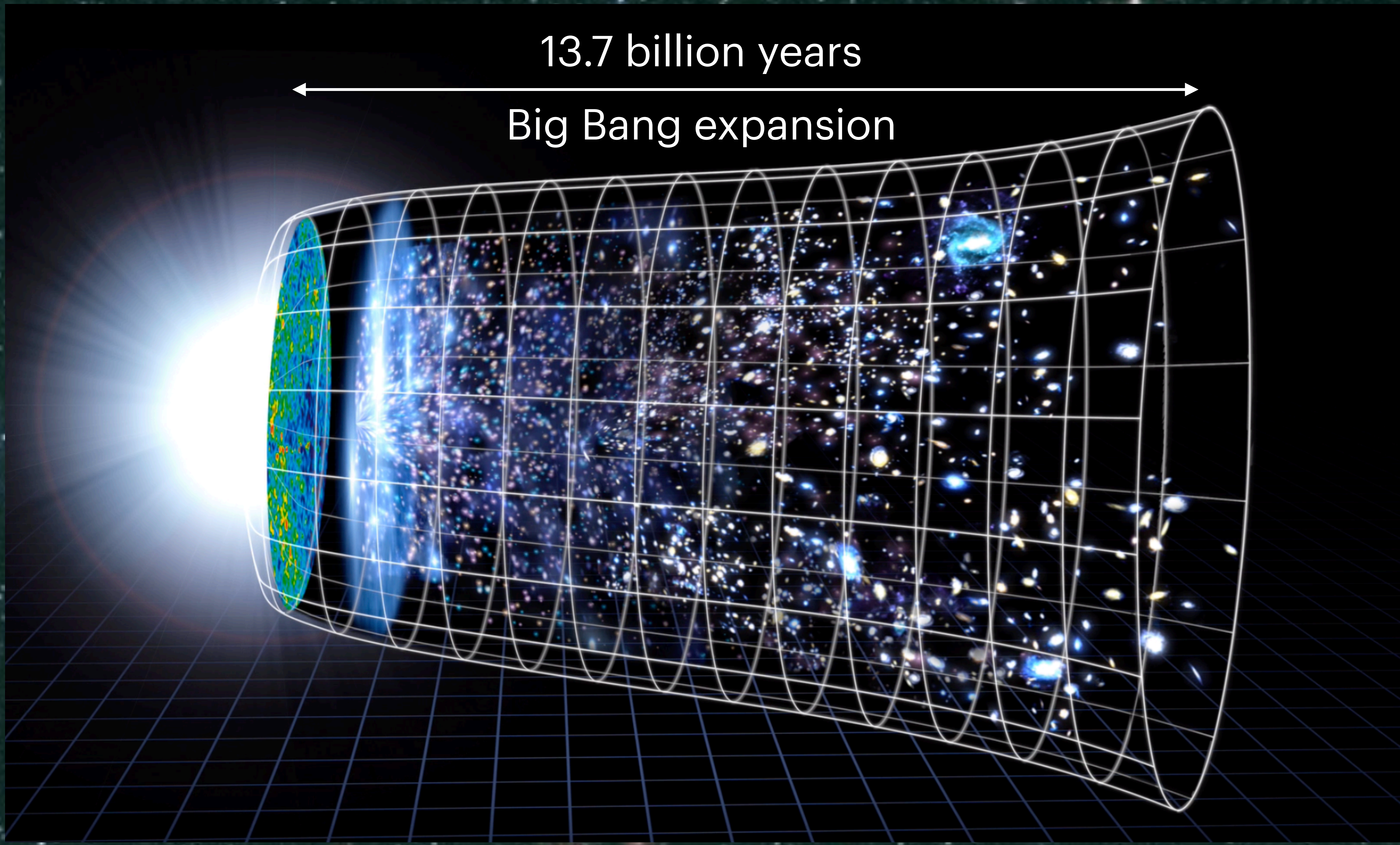


IMAGE PROCESSING: NASA, ESA, CSA

Today our Universe is almost flat, homogeneous and isotropic

Inflation epoch

This can be explained simultaneously by the accelerated expansion of the Universe in the very first moments after the Big Bang. At some early time the **fundamental interactions** and the **particle content** were established !

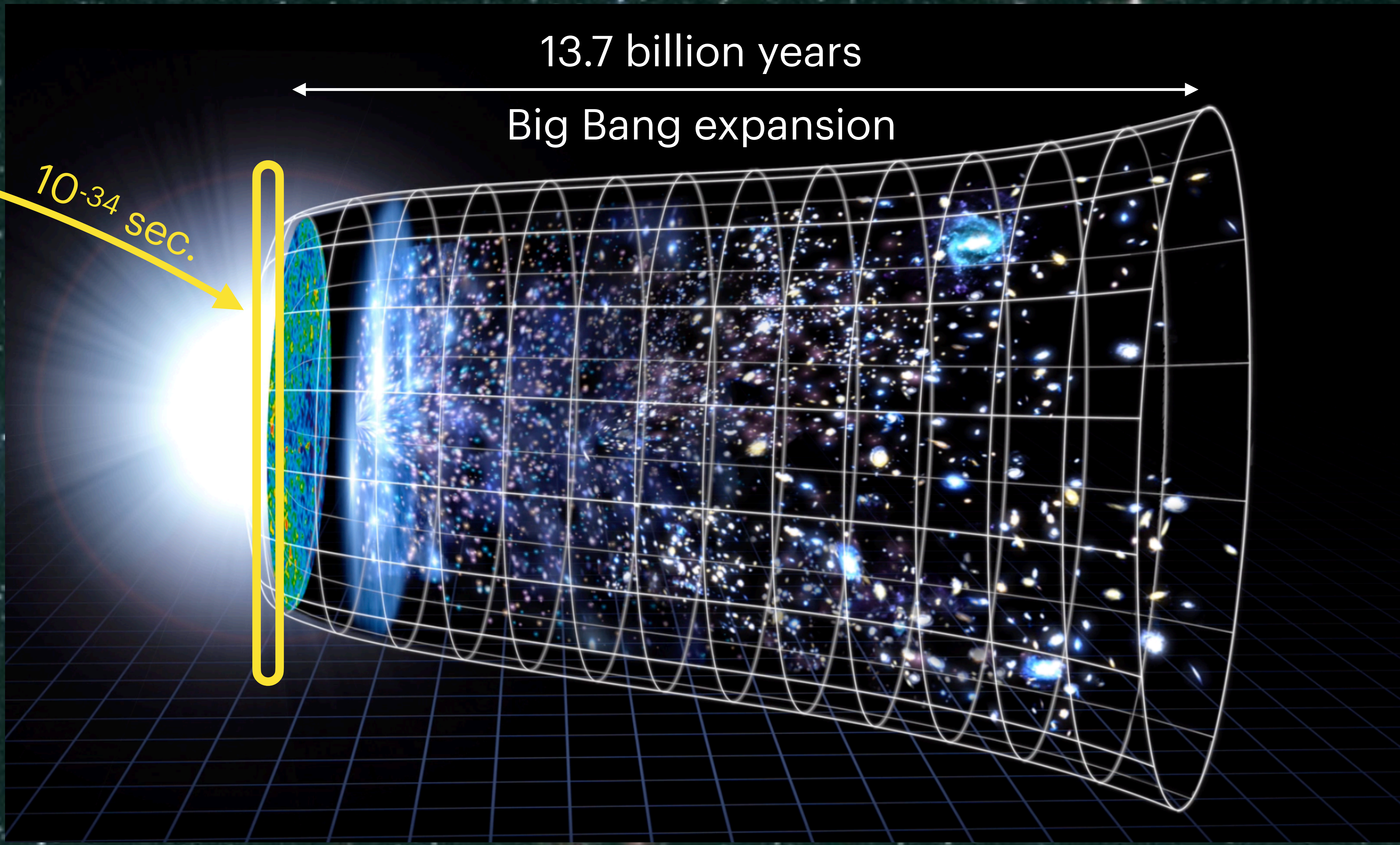


IMAGE PROCESSING: NASA, ESA, CSA

Inflation

This epoch is presumed to be driven by some scalar field called the **“inflaton”**.

Towards the end of inflation, all particle states remain massless and travel at the speed of light. Then, EW symmetry is broken, the particle states interact with a scalar field and massive matter particles are created.

Inflation

This epoch is presumed to be driven by some scalar field called the **"inflaton"**.

Towards the end of inflation, all particle states remain massless and travel at the speed of light. Then, EW symmetry is broken, the particle states interact with a scalar field and massive matter particles are created.

Most economic inflationary scenario : **"inflaton" is the SM Higgs field**

The theory is nothing but the SM with the non-minimal coupling of the Higgs field to gravity, as required for consistency of the SM in curved space–time background.

Bezrukov, F. L. & Shaposhnikov, M. The Standard Model Higgs boson as the inflaton. *Phys. Lett. B* 659, 703–706 (2008)

Inflation

This epoch is presumed to be driven by some scalar field called the **"inflaton"**.

Towards the end of inflation, all particle states remain massless and travel at the speed of light. Then, EW symmetry is broken, the particle states interact with a scalar field and massive matter particles are created.

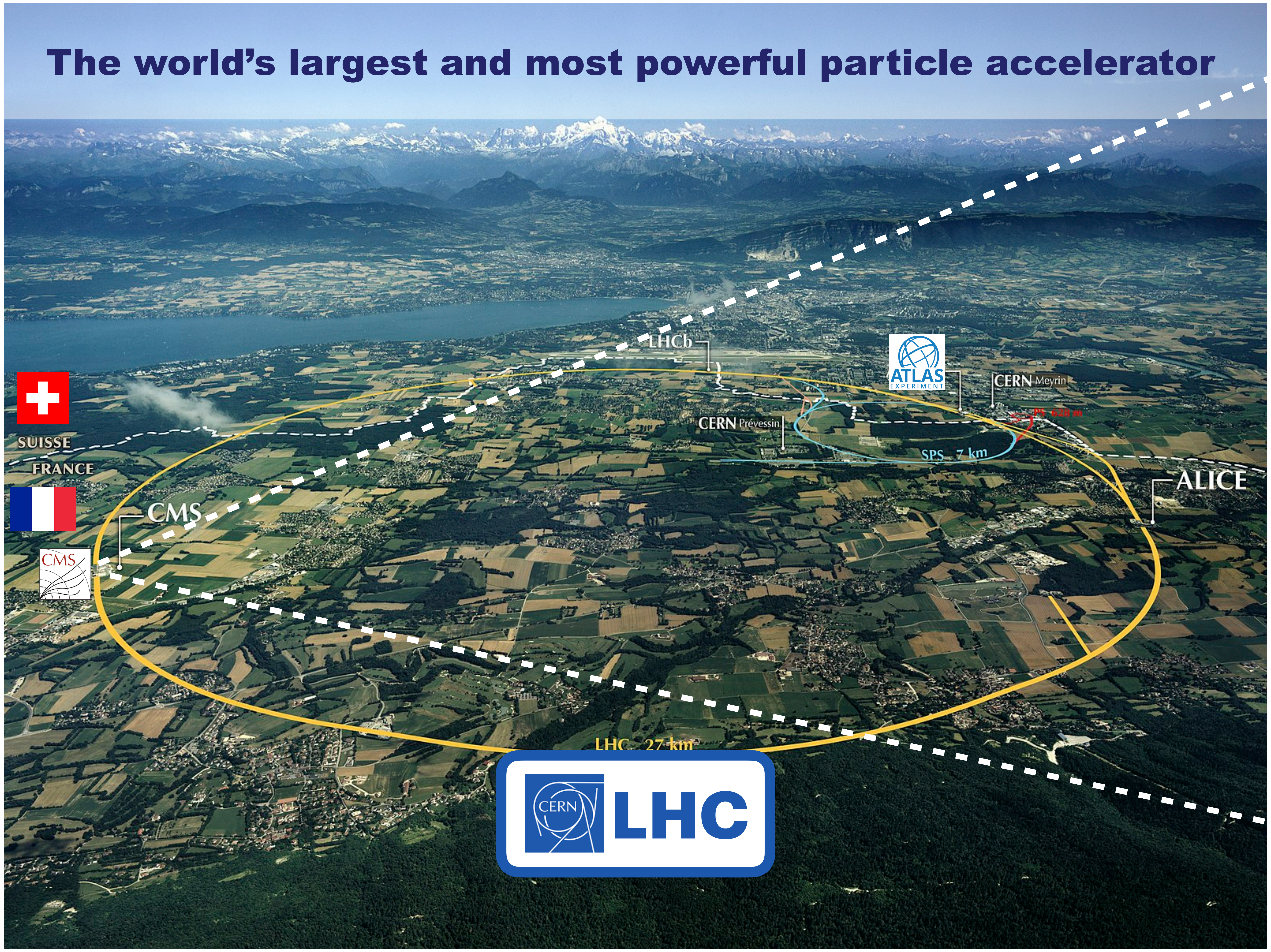
Most economic inflationary scenario : **"inflaton" is the SM Higgs field**

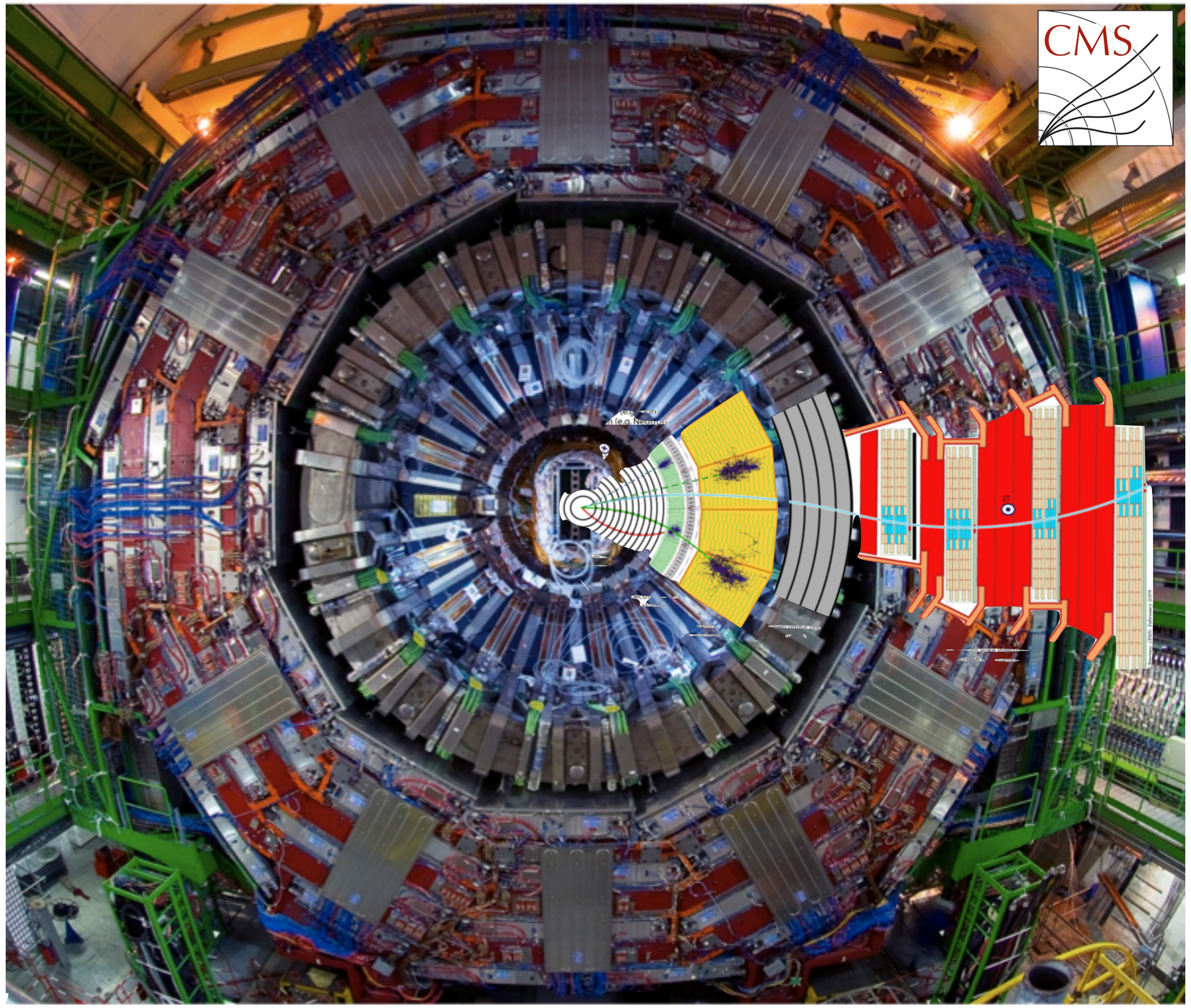
The theory is nothing but the SM with the non-minimal coupling of the Higgs field to gravity, as required for consistency of the SM in curved space–time background.

Bezrukov, F. L. & Shaposhnikov, M. The Standard Model Higgs boson as the inflaton. *Phys. Lett. B* 659, 703–706 (2008)

How can we explore **the first instants of our Universe**?

LHC : a new dimension in particle physics





14000-tonne weight
21 metres long, 15 metres wide and 15 metres high
4 Tesla field (~10^6 times the magnetic field of the Earth)

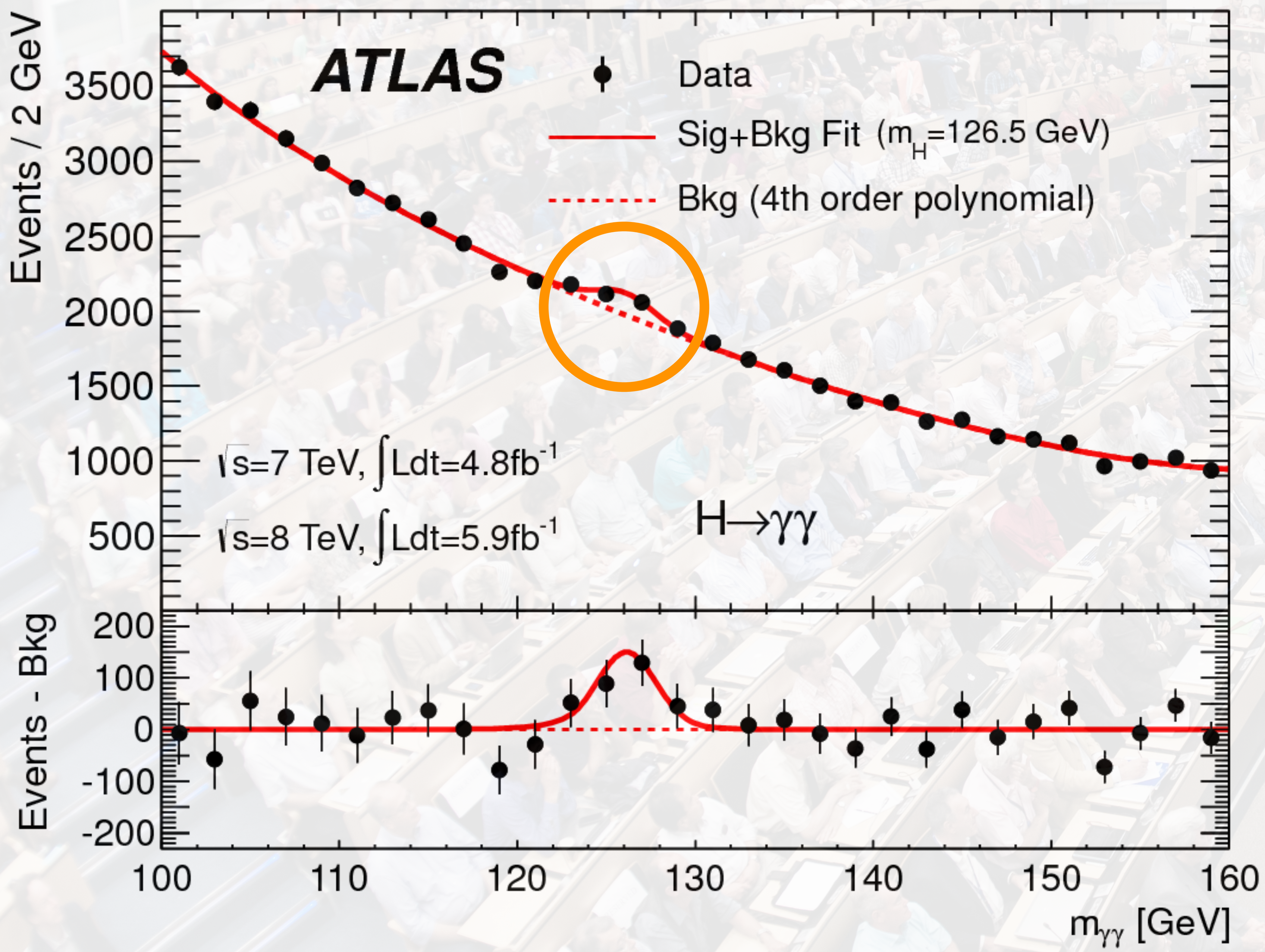
The first instants of our Universe

The first instants of our Universe

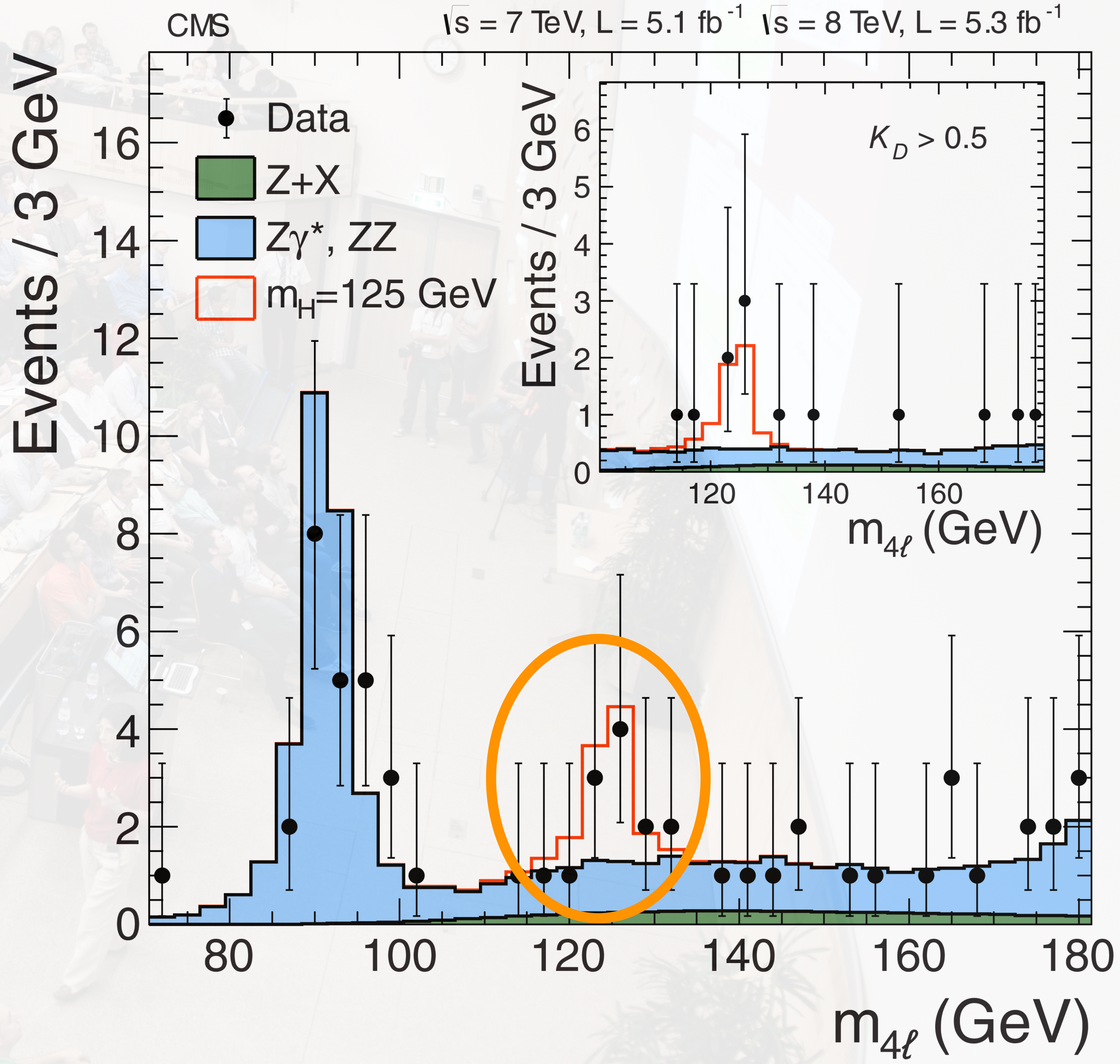
CERN announcement seminar on 4 July 2012

Discovery of a fundamental scalar particle

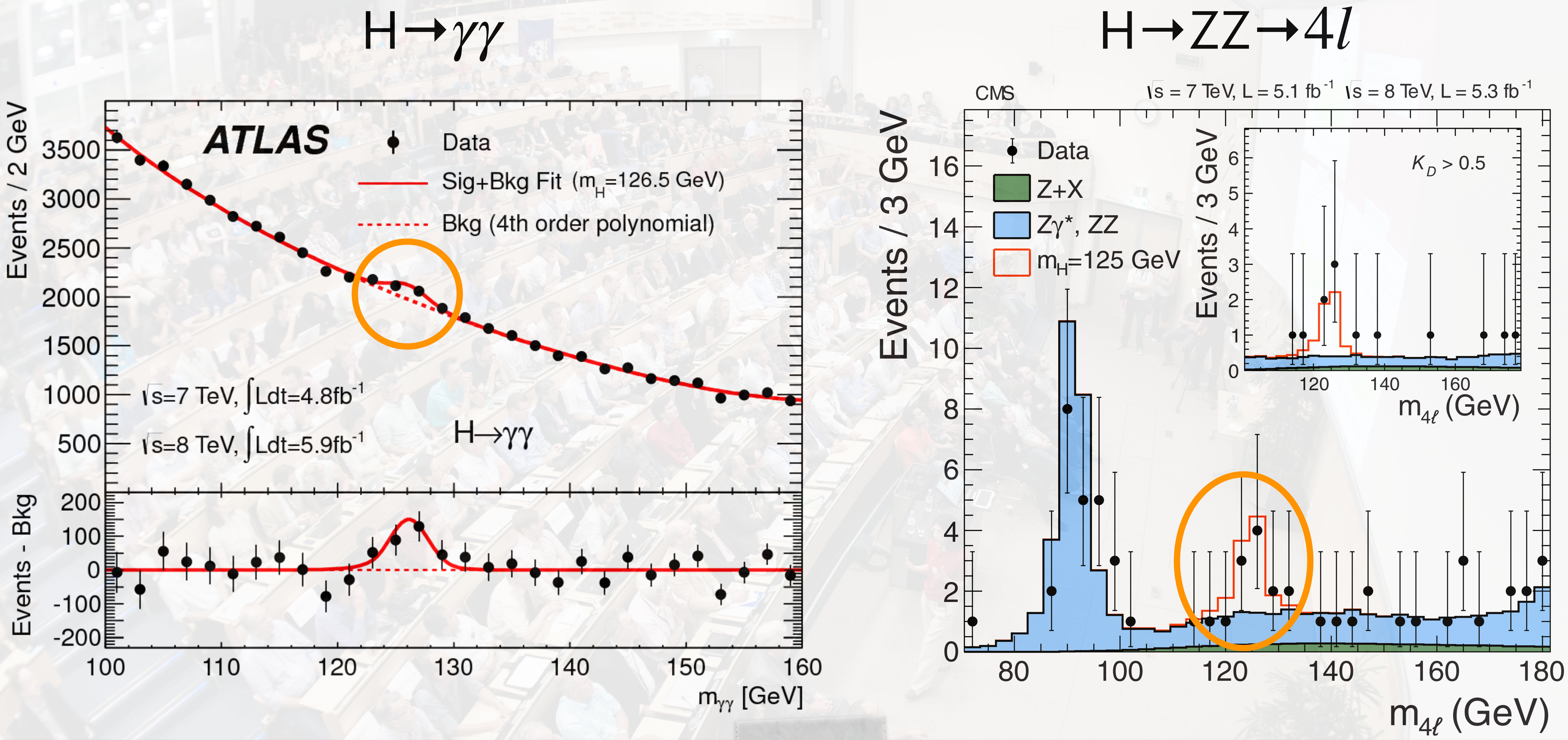
$H \to \gamma\gamma$



$H \to ZZ \to 4l$



Discovery of a fundamental scalar particle

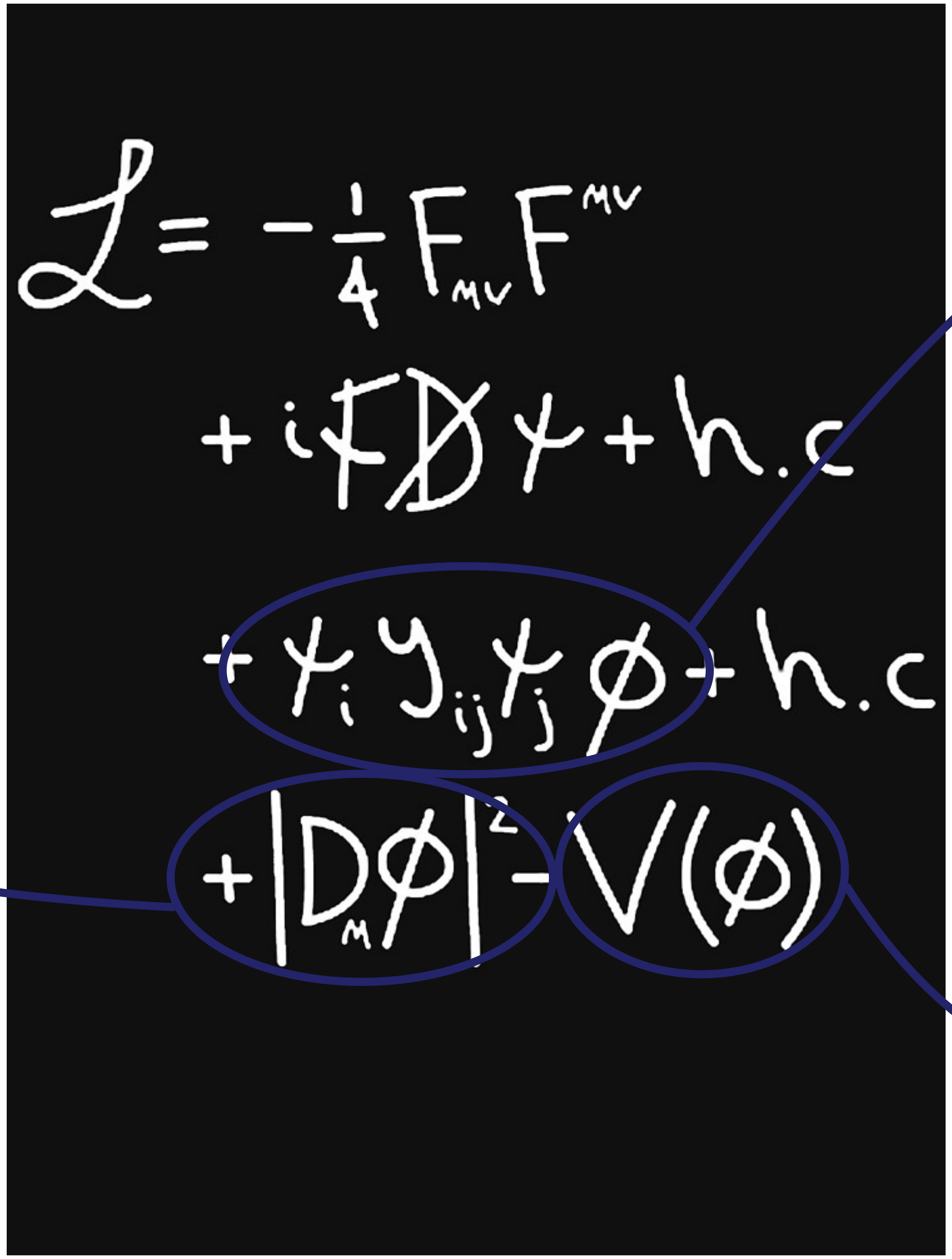


Discovery of the **Higgs boson**, a fundamental scalar particle.
Proof that elementary scalar fields exist !

The Higgs boson is special

It is a **fundamental scalar particle** (spin 0) and
its theory is unlike anything else has been seen in Nature!

A gauge interaction
with vector bosons



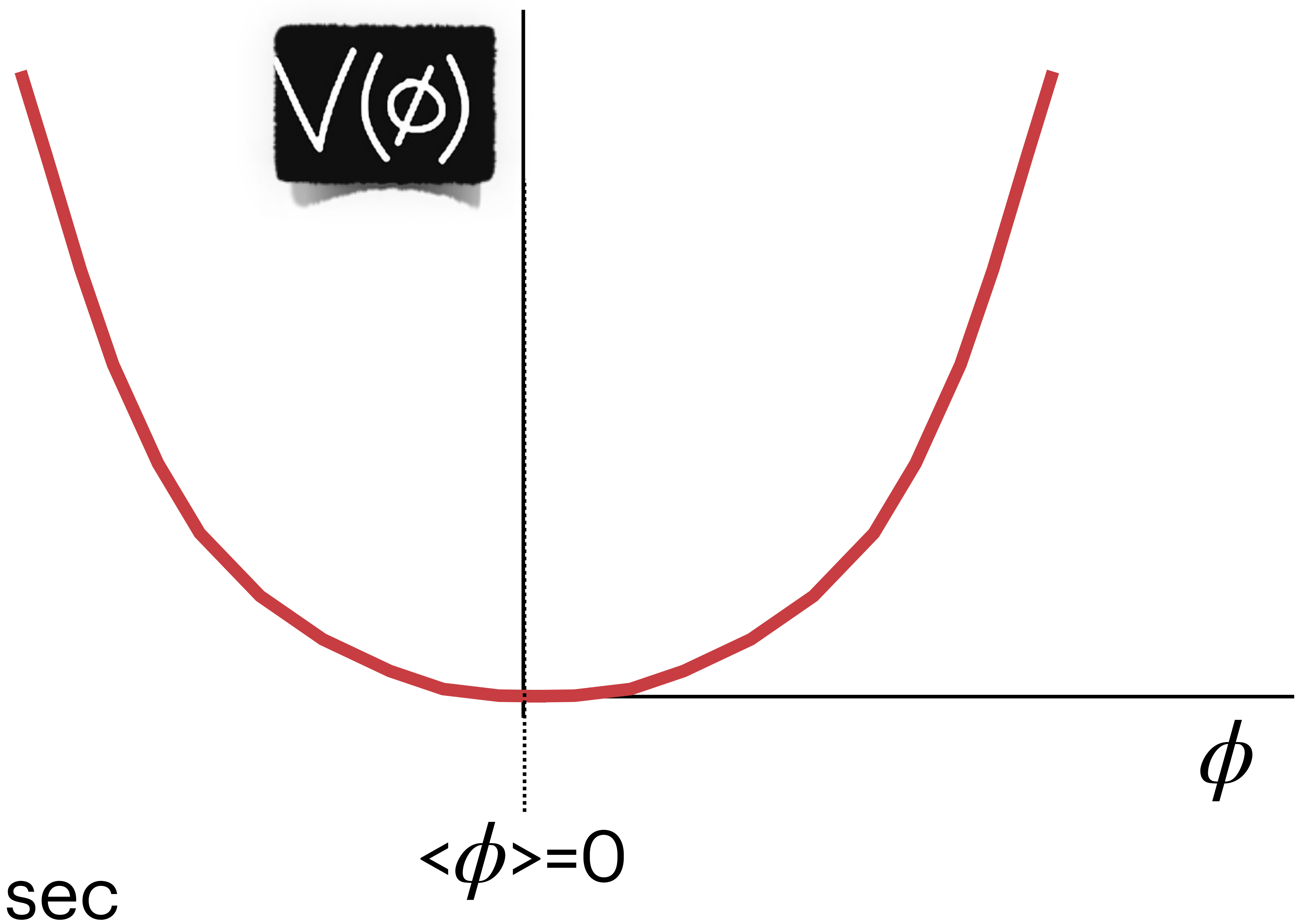
A Yukawa interaction
with the fermions

A potential $V(\phi) \sim -\mu^2(\phi\phi^\dagger) + \lambda(\phi\phi^\dagger)^2$
the keystone of the Higgs[1)]
mechanism and SM

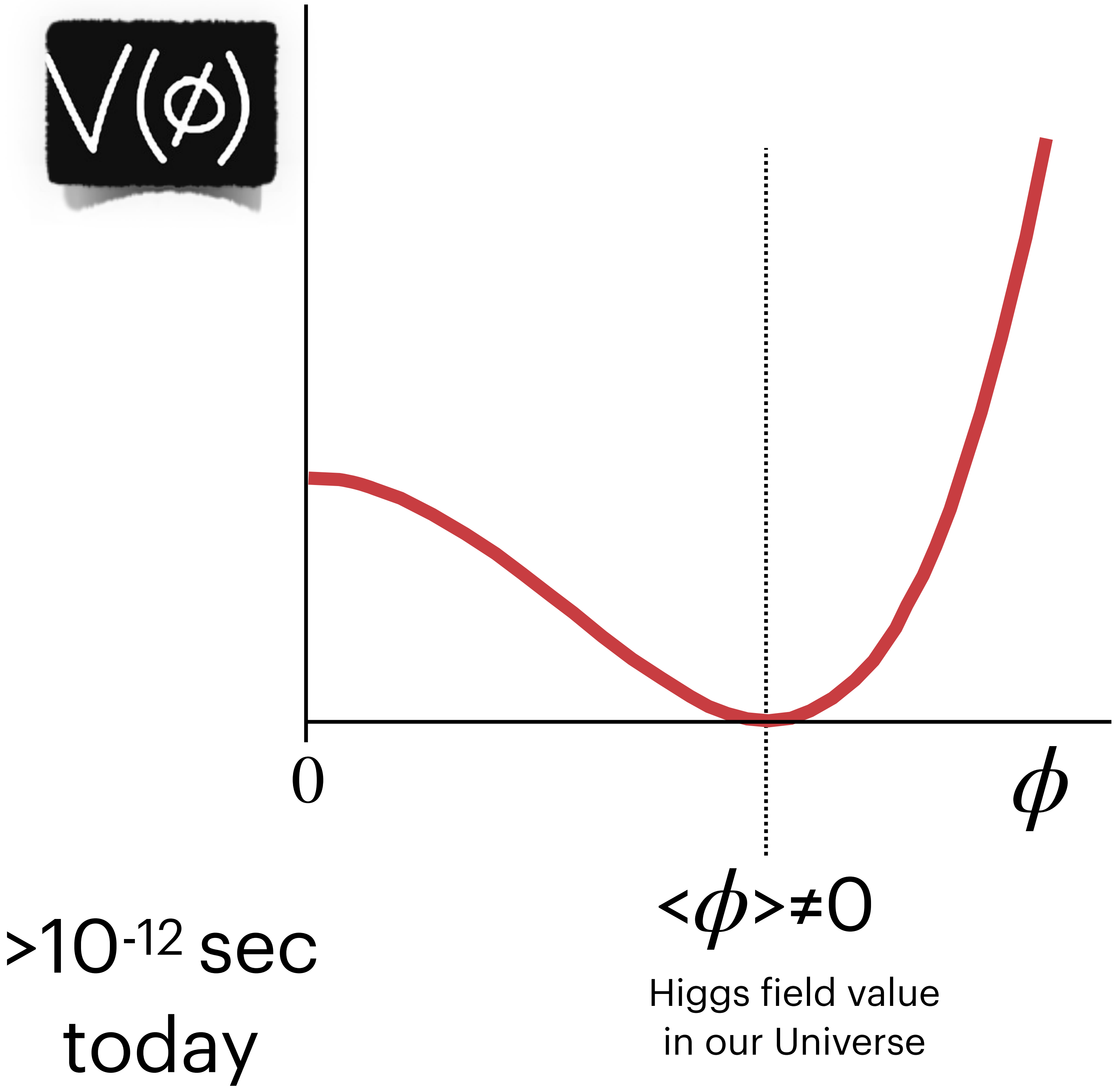
1) Seminal papers PRL 13, 321-323 (1964) Englert and Brout , PRL 13, 508-509 (1964) Higgs

The Higgs potential

Higgs field is **non-zero everywhere** ($<\phi>\neq 0$) **in the vacuum** of our Universe, and thus can produce non-zero masses for fermions and electroweak bosons.



10^{-35} sec

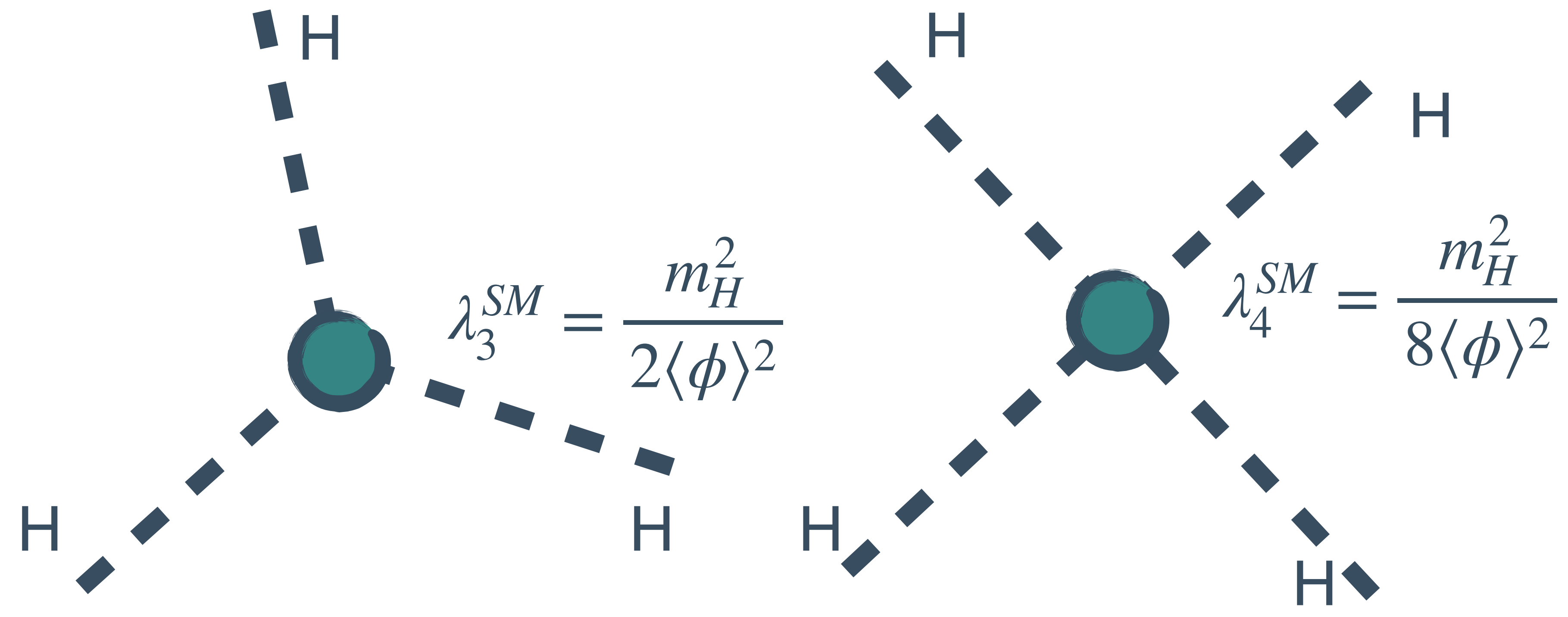


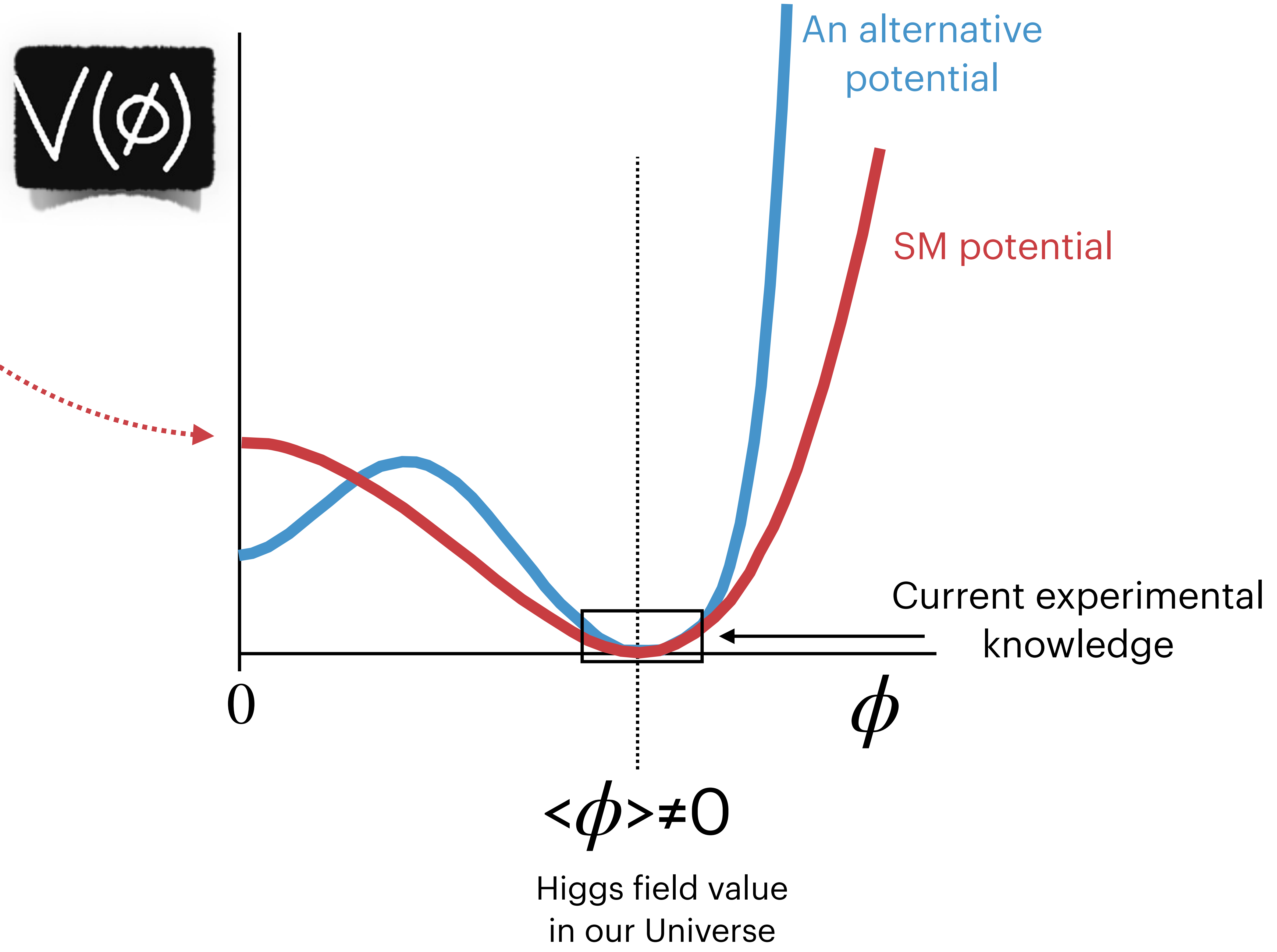
$>10^{-12}$ sec
today

The Higgs potential

Higgs field is **non-zero everywhere** (<ϕ>≠0) **in the vacuum** of our Universe, and thus can produce non-zero masses for fermions and electroweak bosons.

The the structure of the **vacuum of our Universe** is intimately related to how the Higgs boson interacts with itself!

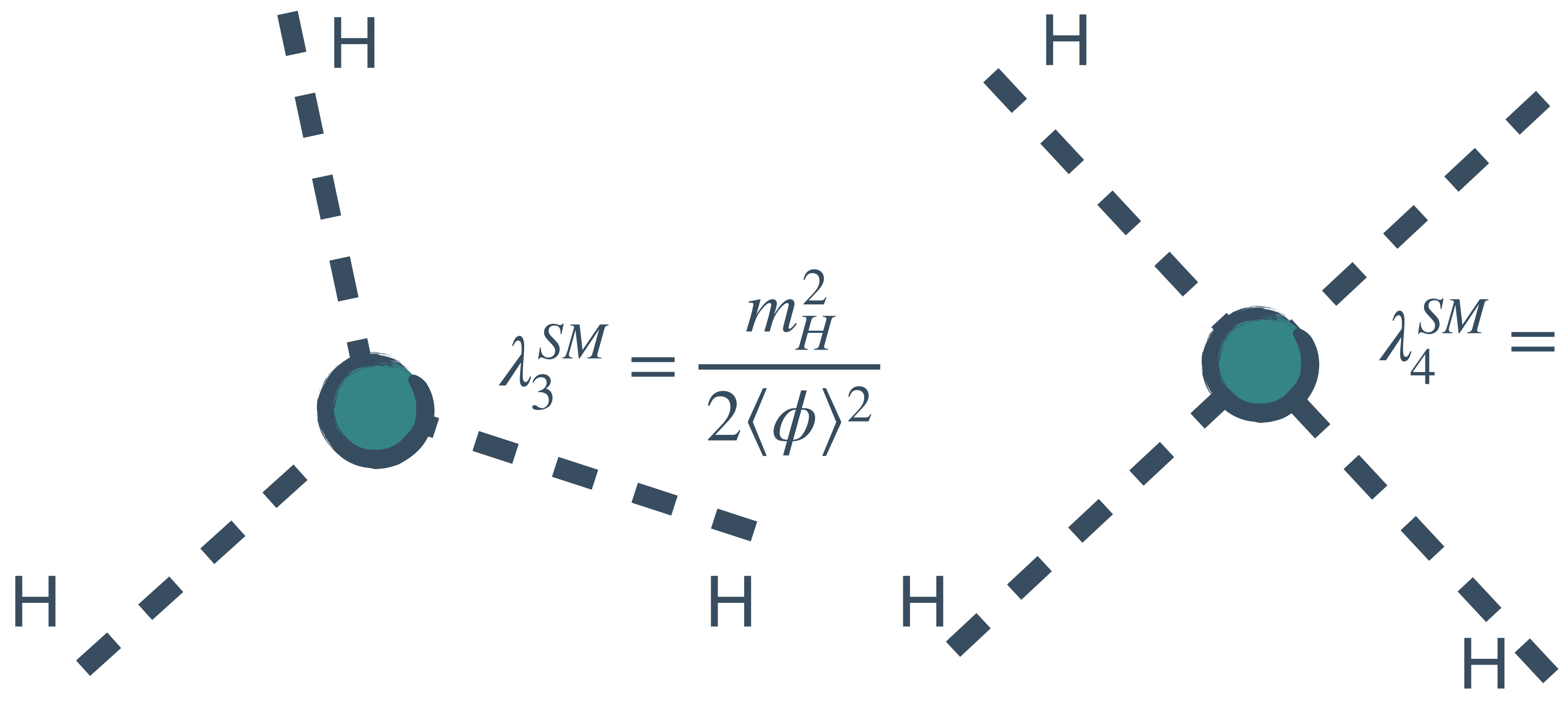




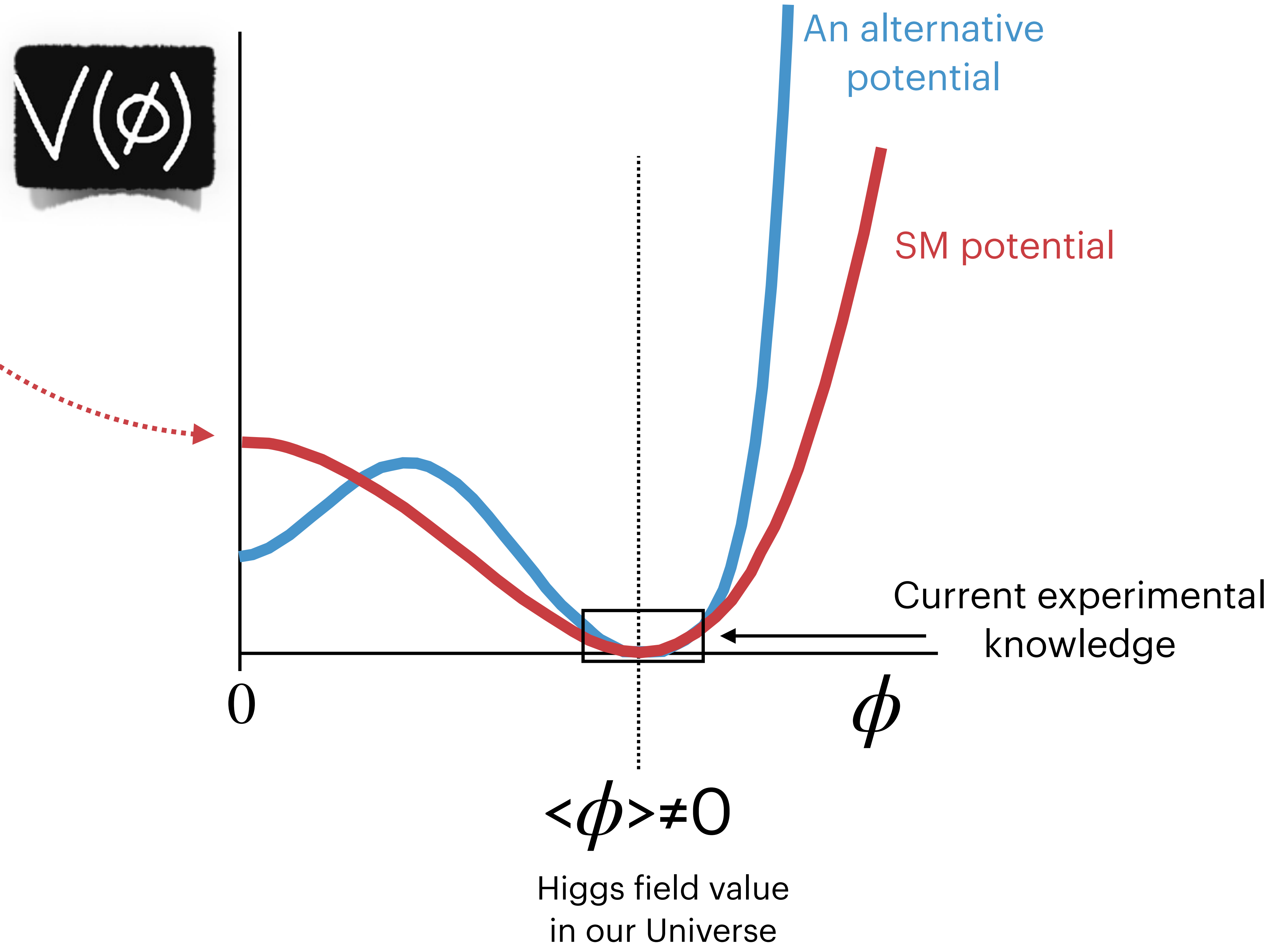
The Higgs potential

Higgs field is **non-zero everywhere** (<ϕ>≠0) **in the vacuum** of our Universe, and thus can produce non-zero masses for fermions and electroweak bosons.

The the structure of the **vacuum of our Universe** is intimately related to how the Higgs boson interacts with itself!



$$\lambda_3^{SM} = \frac{m_H^2}{2\langle\phi\rangle^2} \qquad \lambda_4^{SM} = \frac{m_H^2}{8\langle\phi\rangle^2}$$



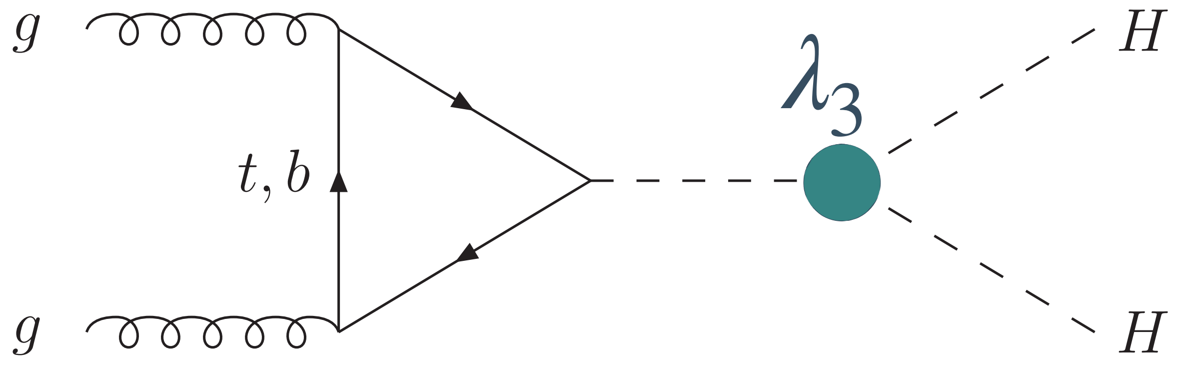
Fundamental question : does the Higgs boson interact with itself?

To probe this phenomenon we can study the production of Higgs boson pairs.

Higgs boson pair (HH) production

HH production channels similar to H production

$\Longrightarrow$ **but** there is a very important difference



gluon fusion production

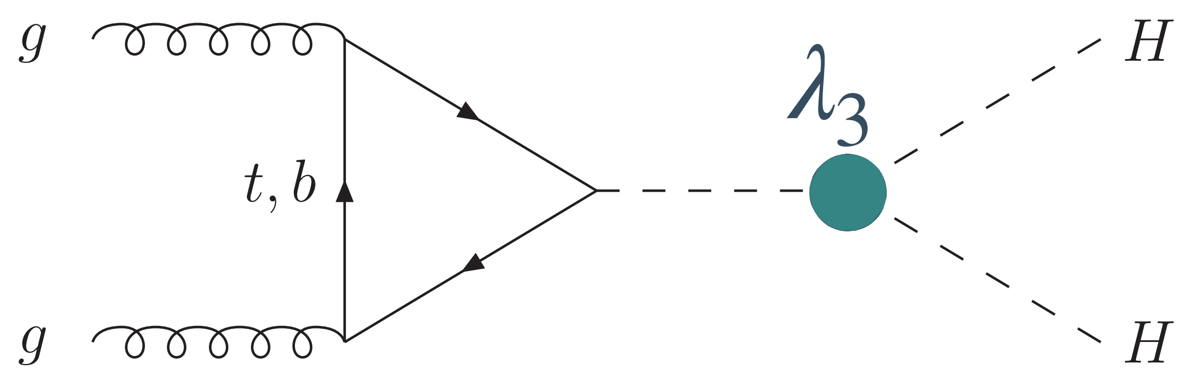
$$\sigma(\mathrm{pp} \to \mathrm{HH}) \sim \frac{\sigma(\mathrm{pp} \to \mathrm{H})}{1000}$$

Higgs boson pairs are predicted to be 1000× rarer than single Higgs

Higgs boson pair (HH) production

HH production channels similar to H production

$\Longrightarrow$ **but** there is a very important difference



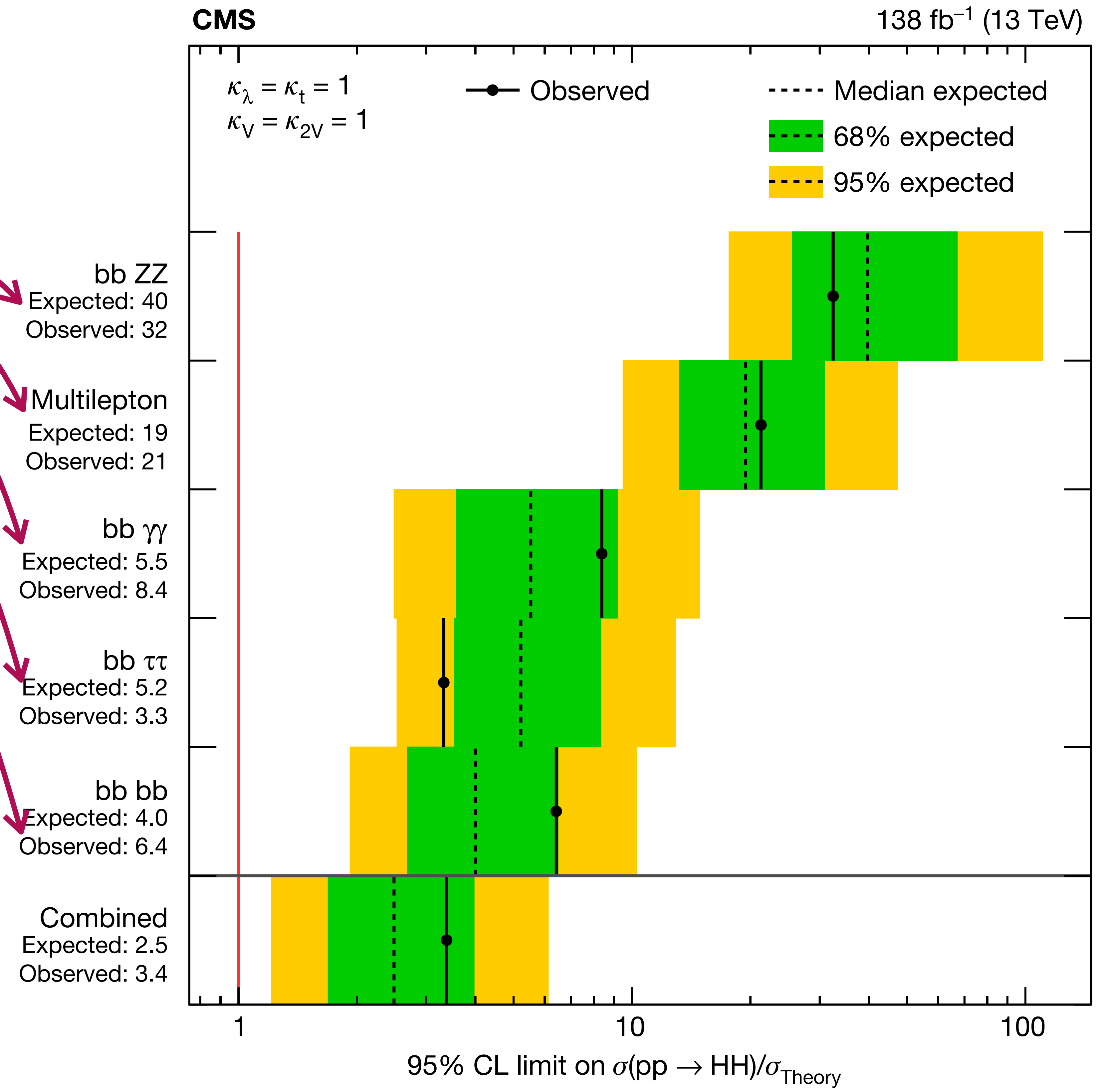
gluon fusion production

$$\sigma(\mathrm{pp} \to \mathrm{HH}) \sim \frac{\sigma(\mathrm{pp} \to \mathrm{H})}{1000}$$

Higgs boson pairs are predicted to be 1000× rarer than single Higgs

Must bring together **many channels** to achieve the best sensitivity.

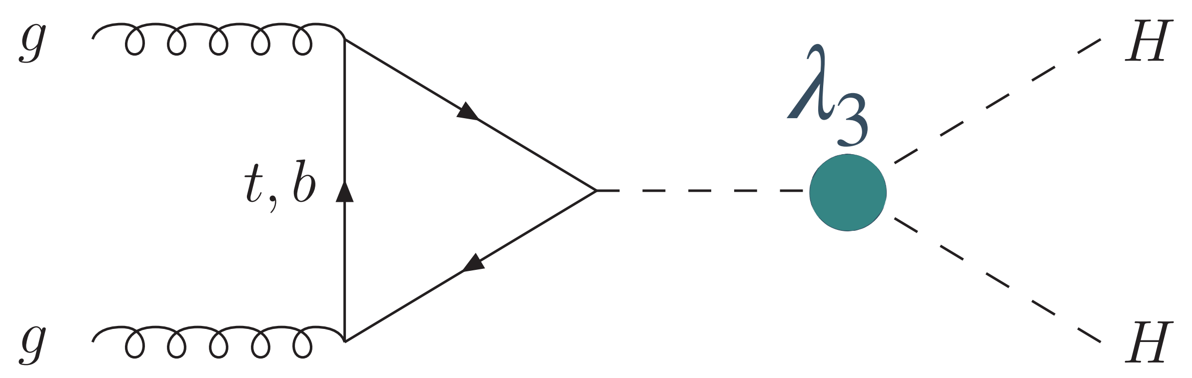
HH $\rightarrow$ bbZZ, Multilepton, bb$\gamma\gamma$, bb$\tau\tau$, bbbb



CMS Collaboration : Nature 607, 60-68 (2022)

Higgs boson pair (HH) production

HH production channels similar to H production
$\Longrightarrow$ **but** there is a very important difference



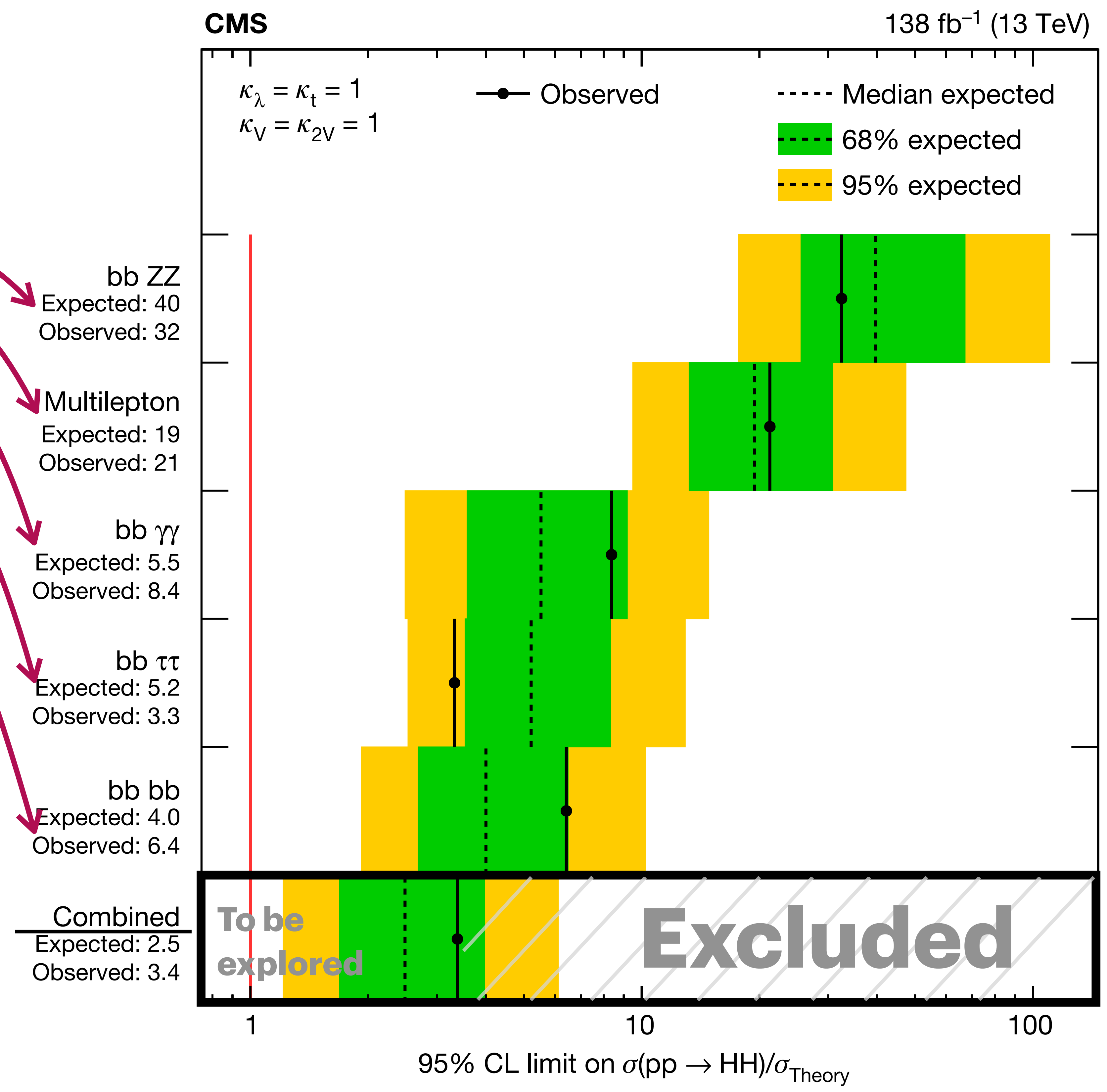
gluon fusion production

$$\sigma(pp \to HH) \sim \frac{\sigma(pp \to H)}{1000}$$

Higgs boson pairs are predicted to be 1000× rarer than single Higgs

Must bring together **many channels** to achieve the best sensitivity.

$HH \to bbZZ$, Multilepton, $bb\gamma\gamma$, $bb\tau\tau$, bbbb

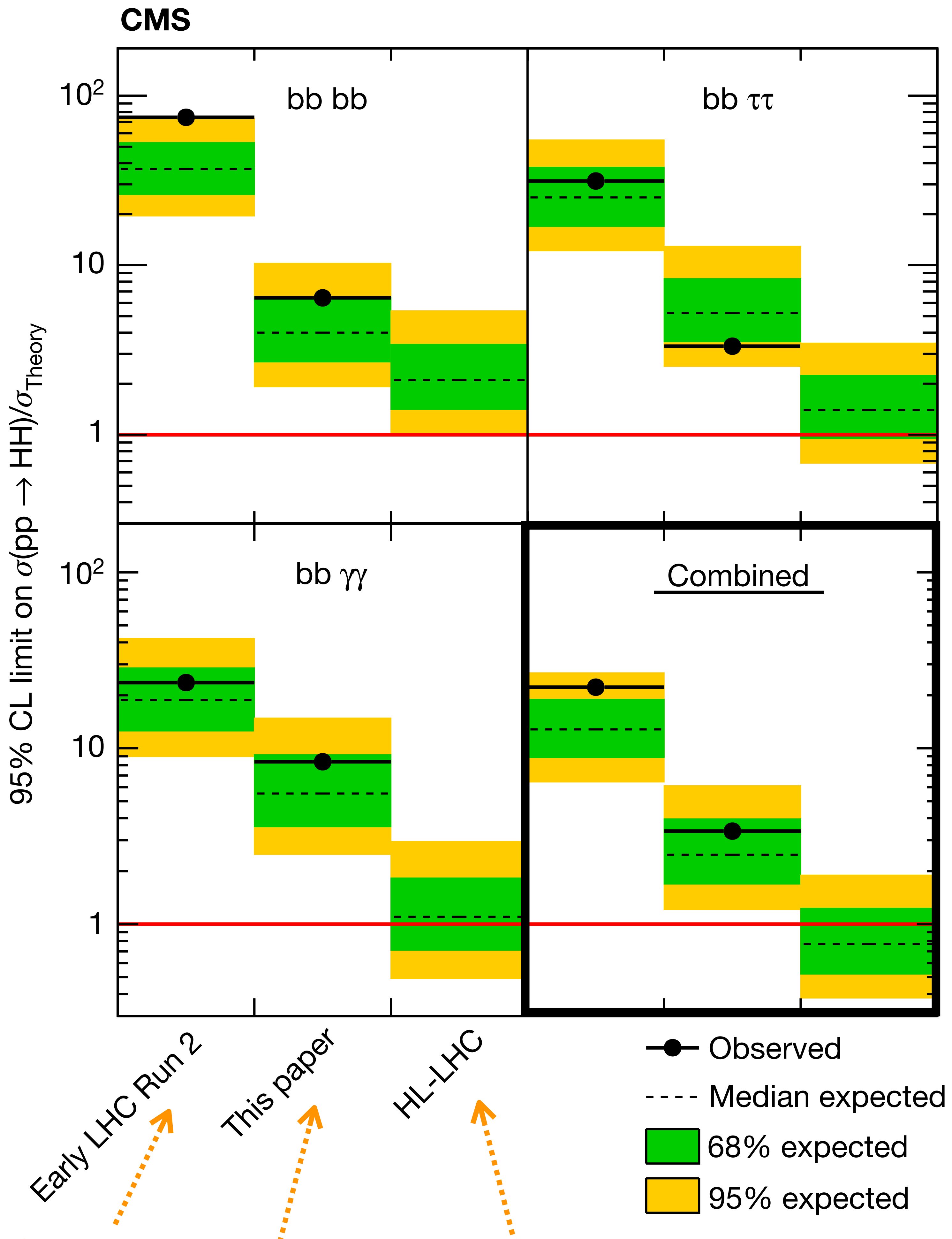


CMS Collaboration : Nature 607, 60-68 (2022)

Sensitivity better than **3×SM**.
On the way to challenge SM prediction.

HH : the future at HL-LHC

Exp. and Obs. limits on HH production in different datasets (36 fb^{-1}, 140 fb^{-1}, 3000 fb^{-1})



CMS Collaboration : Nature 607, 60-68 (2022)

36 fb^{-1}

140 fb^{-1} (Run2)

x20 more data

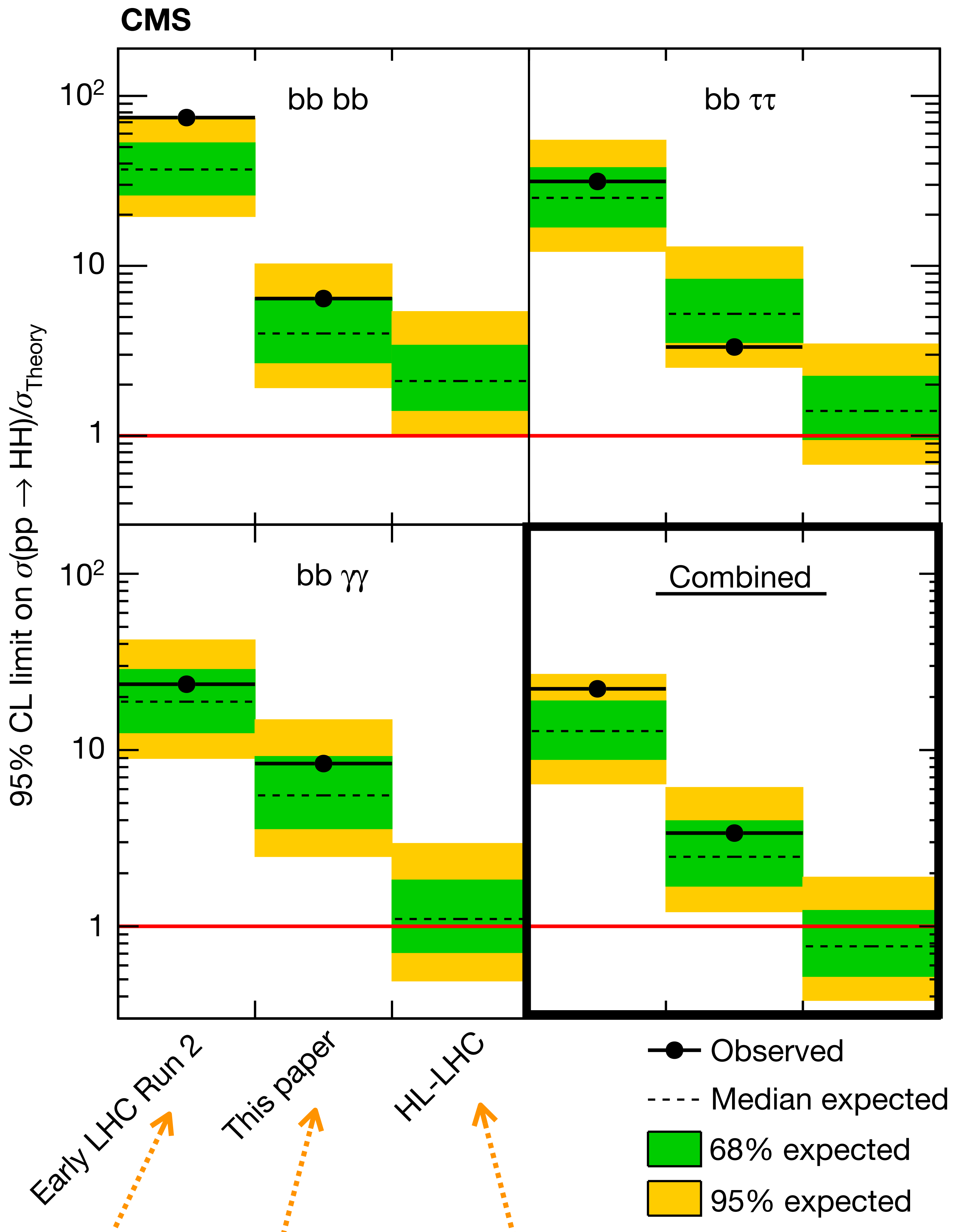
3000 fb^{-1} (HL-LHC)

In LHC lifetime we expect to collect **x20 more data** than actual

HH : the future at HL-LHC and beyond

Exp. and Obs. limits on HH production in different datasets (36 fb^{-1}, 140 fb^{-1}, 3000 fb^{-1})

CMS Collaboration : Nature 607, 60-68 (2022)

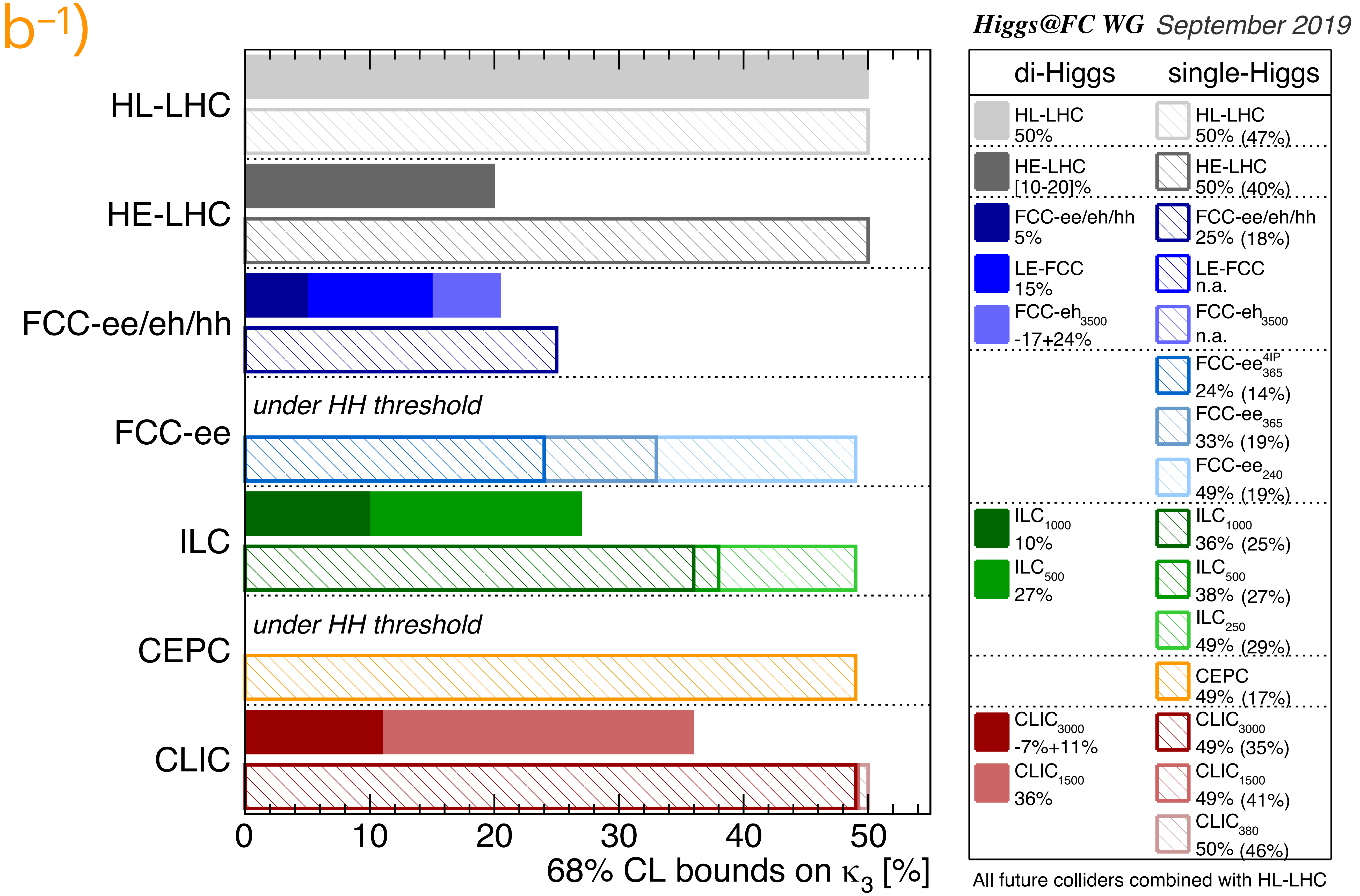


36 fb^{-1}

140 fb^{-1} (Run2)

x20 more data

3000 fb^{-1} (HL-LHC)

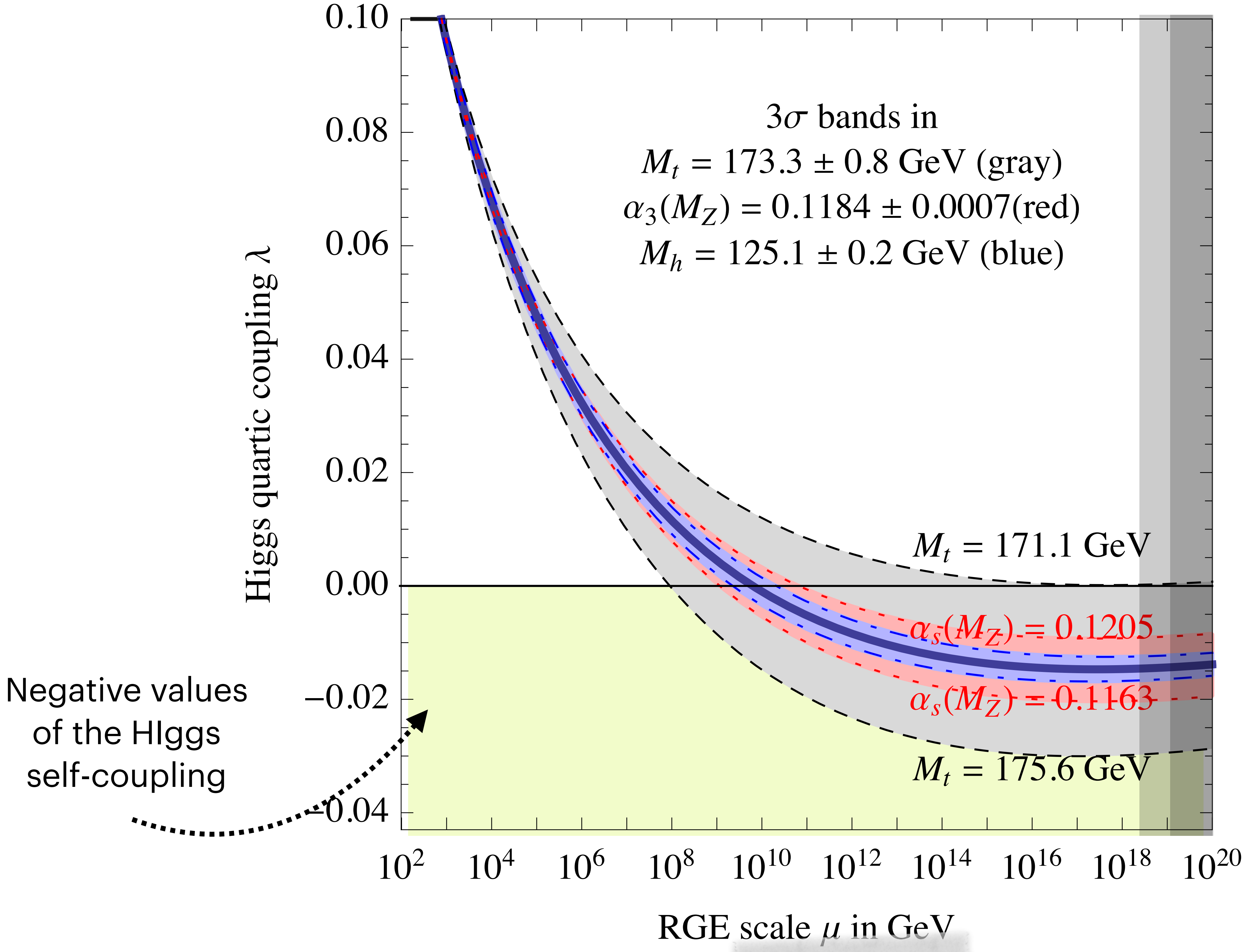


Higgs self-coupling is a science driver at future colliders

HL-LHC will lead the scene the next ≥20 years

The fate of our vacuum?

The combination of top-quark and Higgs boson masses is very close to the stability bound of the SM



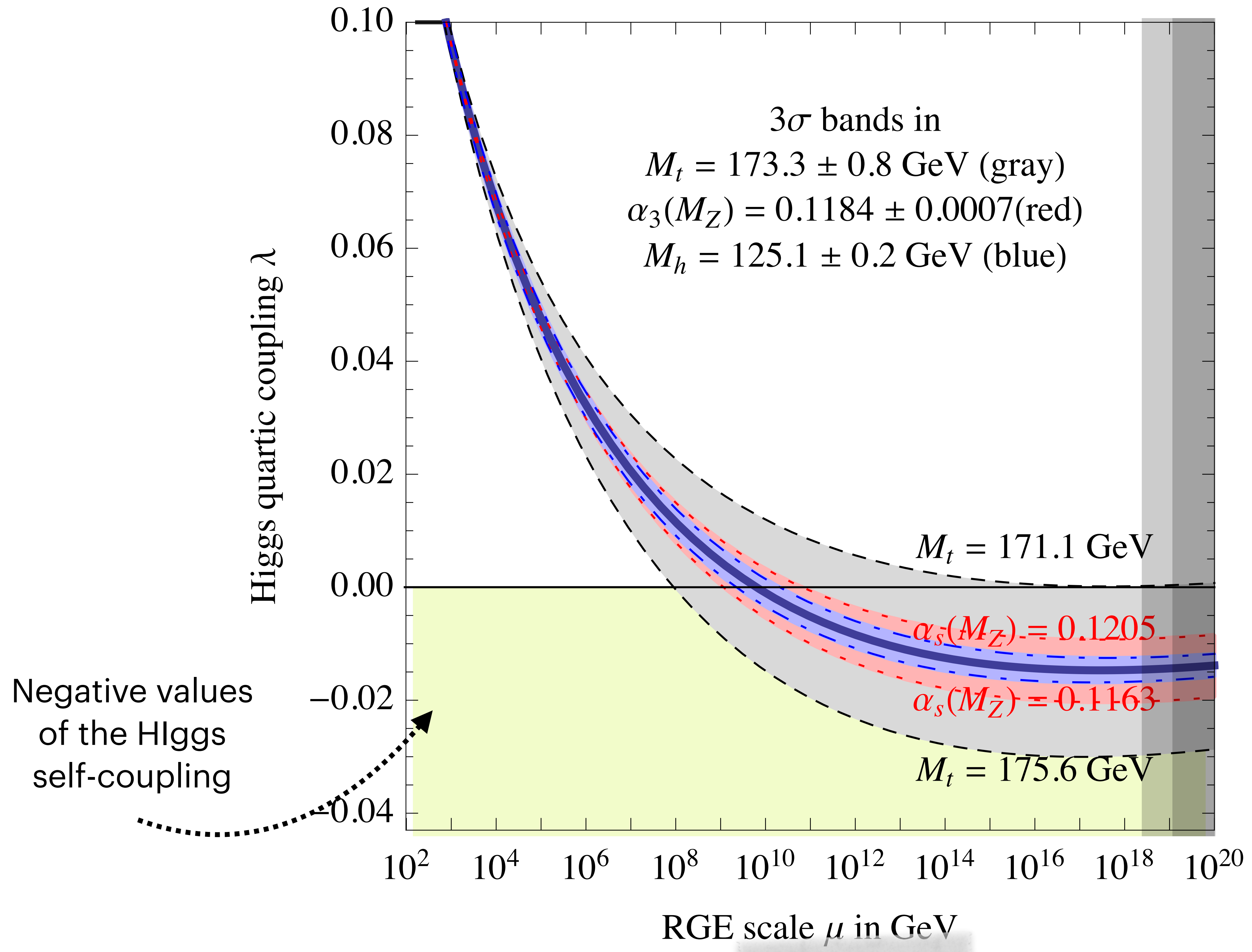
JHEP 12 (2013) 089

SM does not work up to the Plank scale.

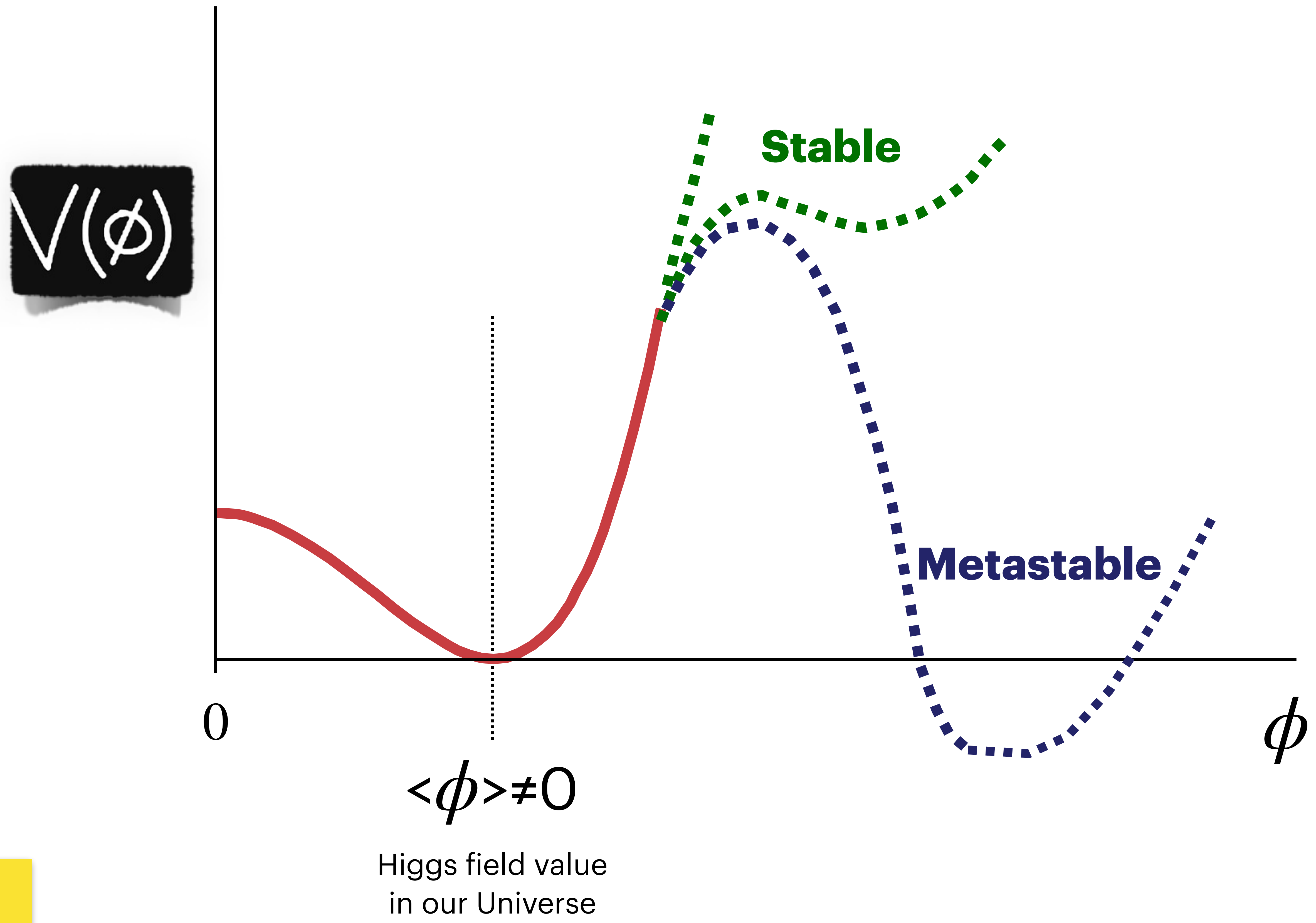
Vacuum that we know could disappear.

The fate of our vacuum?

The combination of top-quark and Higgs boson masses is very close to the stability bound of the SM



JHEP 12 (2013) 089



SM does not work up to the Plank scale.

Vacuum that we know could disappear.

… but more could be asked

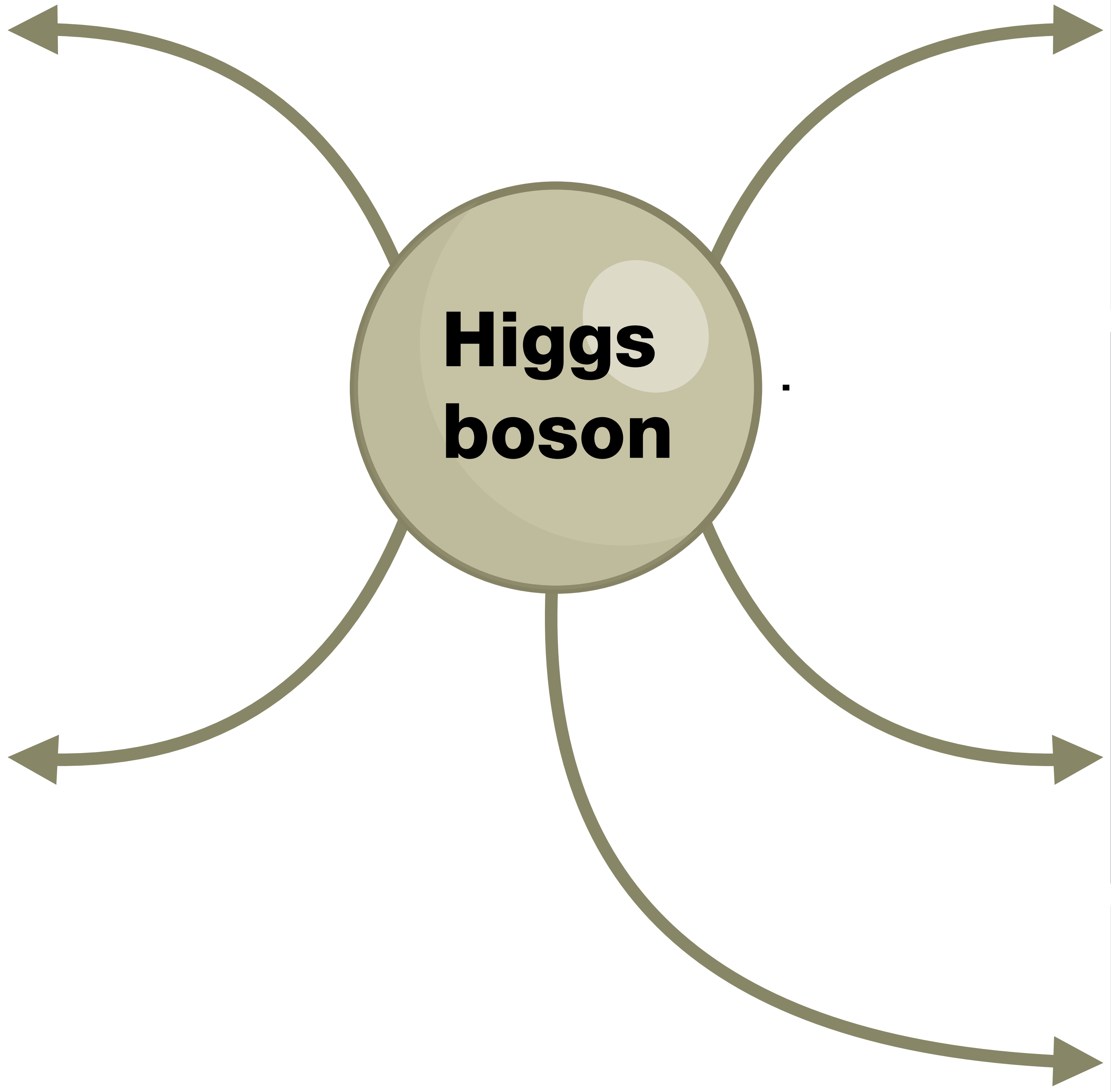
Higgs and **major open questions** of particle physics and cosmology

Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the *W* and *Z* bosons?

Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?



What is dark matter?

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \rightarrow \mu^+ \tau^-$)?

What is the origin of the early Universe inflation?

- Any imprint in cosmological observations?

G. P. Salam, L. Wang, G. Zanderighi : Nature 607, 41-47 (2022)

Hierarchy problem

One major puzzle is that the weak and Higgs interactions are much stronger, by a factor of about 10^{32}, than the gravitational interaction

Hierarchy problem

One major puzzle is that the weak and Higgs interactions are much stronger, by a factor of about 10^{32}, than the gravitational interaction

One possibility is for the Higgs boson not to be an elementary particle, but rather a **composite object** made of other, as yet undiscovered particles.

Kaplan, D. B. & Georgi, H. SU(2) x U(1) breaking by vacuum misalignment. Phys. Lett. B 136, 183–186 (1984).

Is the Higgs boson elementary or composite?

Measure the size of the Higgs boson

of the operator extending the SM that is linked to the interaction indicative of composite origin

The SM Lagrangian is extended by $\frac{c_H}{\Lambda^2}\mathcal{O}_H = \frac{c_H}{\Lambda^2}\frac{1}{2}(\partial_\mu(H)^2)^2$

Giudice,Grojean,Pomarol,Rattazzi
hep-ph/0703164

The operator shifts all couplings by the same amount.
It can only be measured directly in the total Higgs boson width.

Is the Higgs boson elementary or composite?

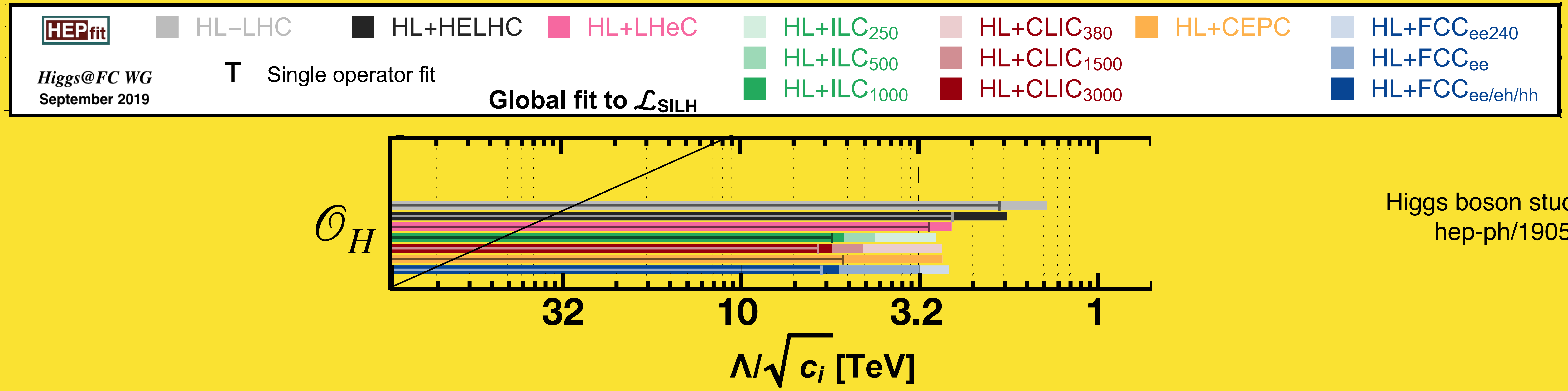
Measure the size of the Higgs boson

of the operator extending the SM that is linked to the interaction indicative of composite origin

The SM Lagrangian is extended by $\frac{c_H}{\Lambda^2}\mathcal{O}_H = \frac{c_H}{\Lambda^2}\frac{1}{2}(\partial_\mu (H)^2)^2$

Giudice,Grojean,Pomarol,Rattazzi
hep-ph/0703164

The operator shifts all couplings by the same amount.
It can only be measured directly in the total Higgs boson width.



Higgs boson study for ESPP
hep-ph/1905.03764

Bounds on Higgs boson "radius"

Figure of merit: Higgs boson "size" vs. (reduce) Compton wavelength.

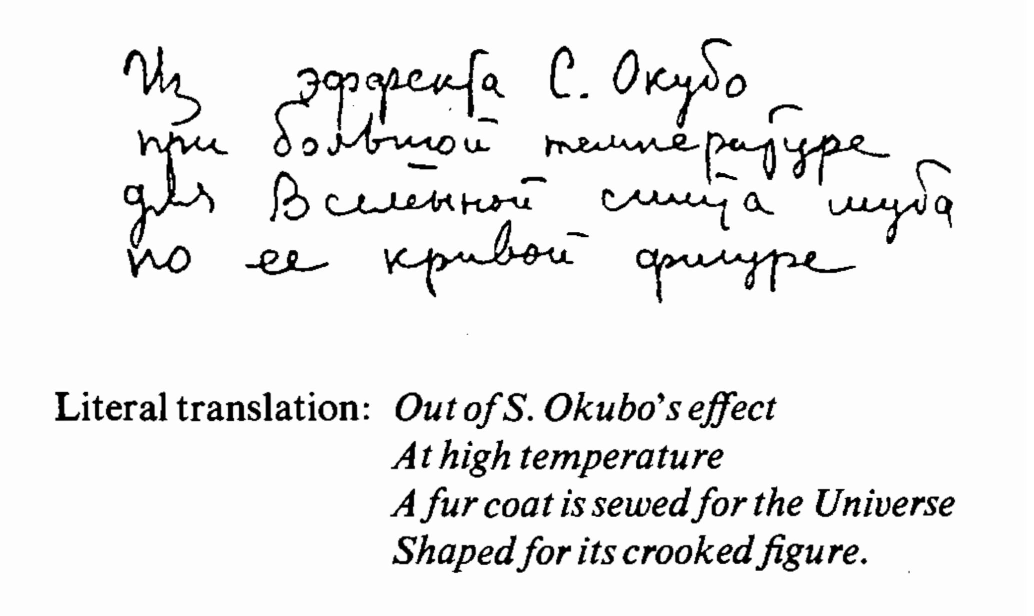
Baryon Asymmetry in the Universe (BAU)

The origin of the matter–antimatter asymmetry[1)] of the Universe remains unexplained in the SM of particle physics.

Baryogenesis is the hypothesized physical process taken place in the early Universe that has produce the observed imbalance of matter.

It should verify the **Sakharov's conditions**

I. Baryon number violation
II. C (Charge conjugation) and CP (Charge conjugation × Parity) violation
III. Departure from the thermal equilibrium



1) measured in terms of the baryon-to-photon number density ratio : $\eta \approx 6\times10^{-10}$

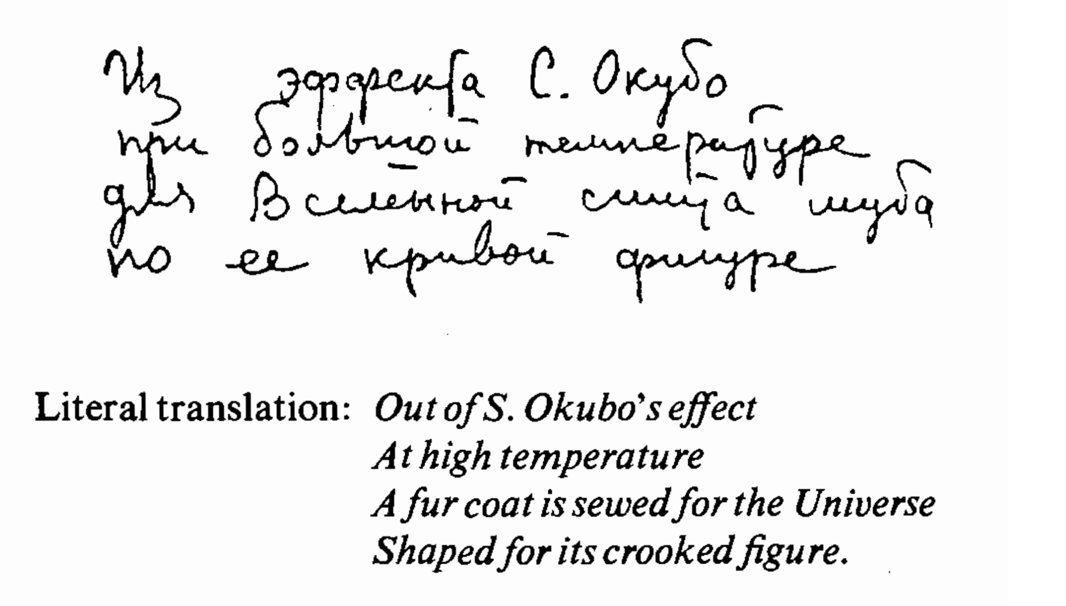
Baryon Asymmetry in the Universe (BAU)

The origin of the matter–antimatter asymmetry[1)] of the Universe remains unexplained in the SM of particle physics.

Baryogenesis is the hypothesized physical process taken place in the early Universe that has produce the observed imbalance of matter.

It should verify the **Sakharov's conditions**

I. Baryon number violation
II. C (Charge conjugation) and CP (Charge conjugation × Parity) violation
III. Departure from the thermal equilibrium



Two possibilities to achieve baryogenesis

EW baryogenesis

Can be tested at LHC and beyond

Leptogenesis

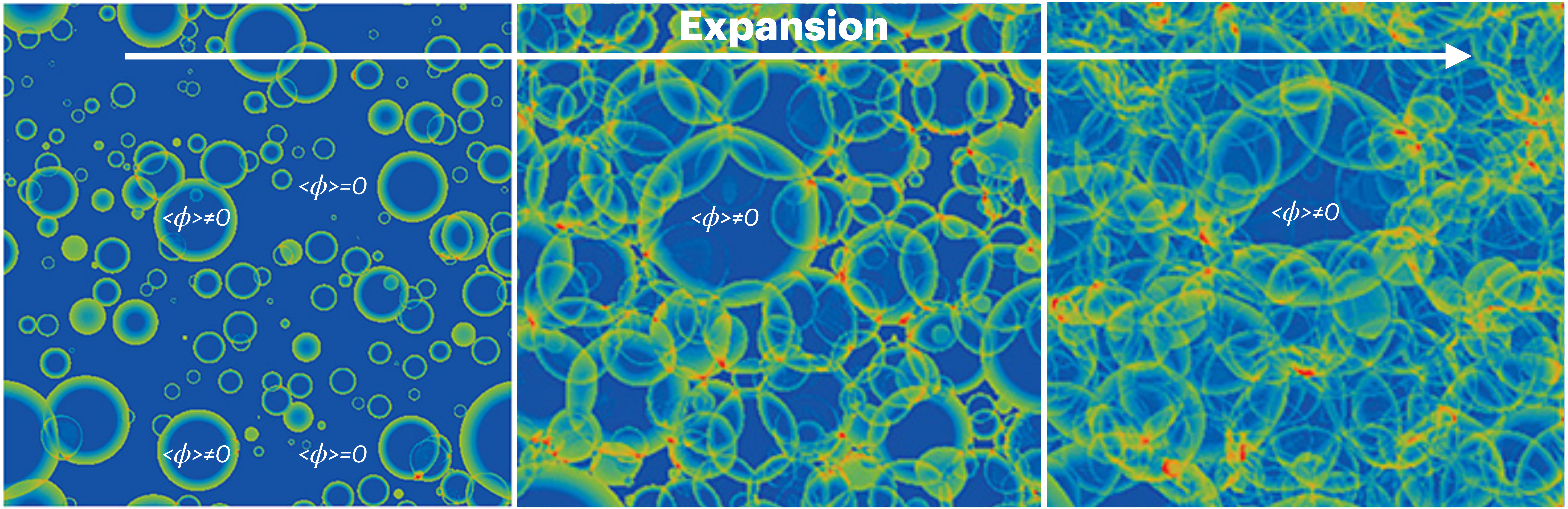
Harder to test

1) measured in terms of the baryon-to-photon number density ratio : $\eta \approx 6\times10^{-10}$

EW baryogenesis

"In one slide"

During a first-order EW phase transition our Universe tunnels from $<\phi>=0$ (false vacuum) to $<\phi>\neq 0$ (true vacuum) via Higgs-bubble nucleation. The bubbles expand at near speed of light.



Particle flow into the expanding bubble wall and CP violation implies that the wall exerts different forces on particles and antiparticles $\Longrightarrow$ create a chiral asymmetry $\Longrightarrow$ generate a net baryon asymmetry

To preserve the baryon asymmetry demands a strong first-order EW phase transition, namely $<\phi>_c/T_C \gtrsim 1.3$

Probing EW baryogenesis at colliders

✔ **Complex function** of the Higgs potential[1)]

$\Longrightarrow$ O(1) modification

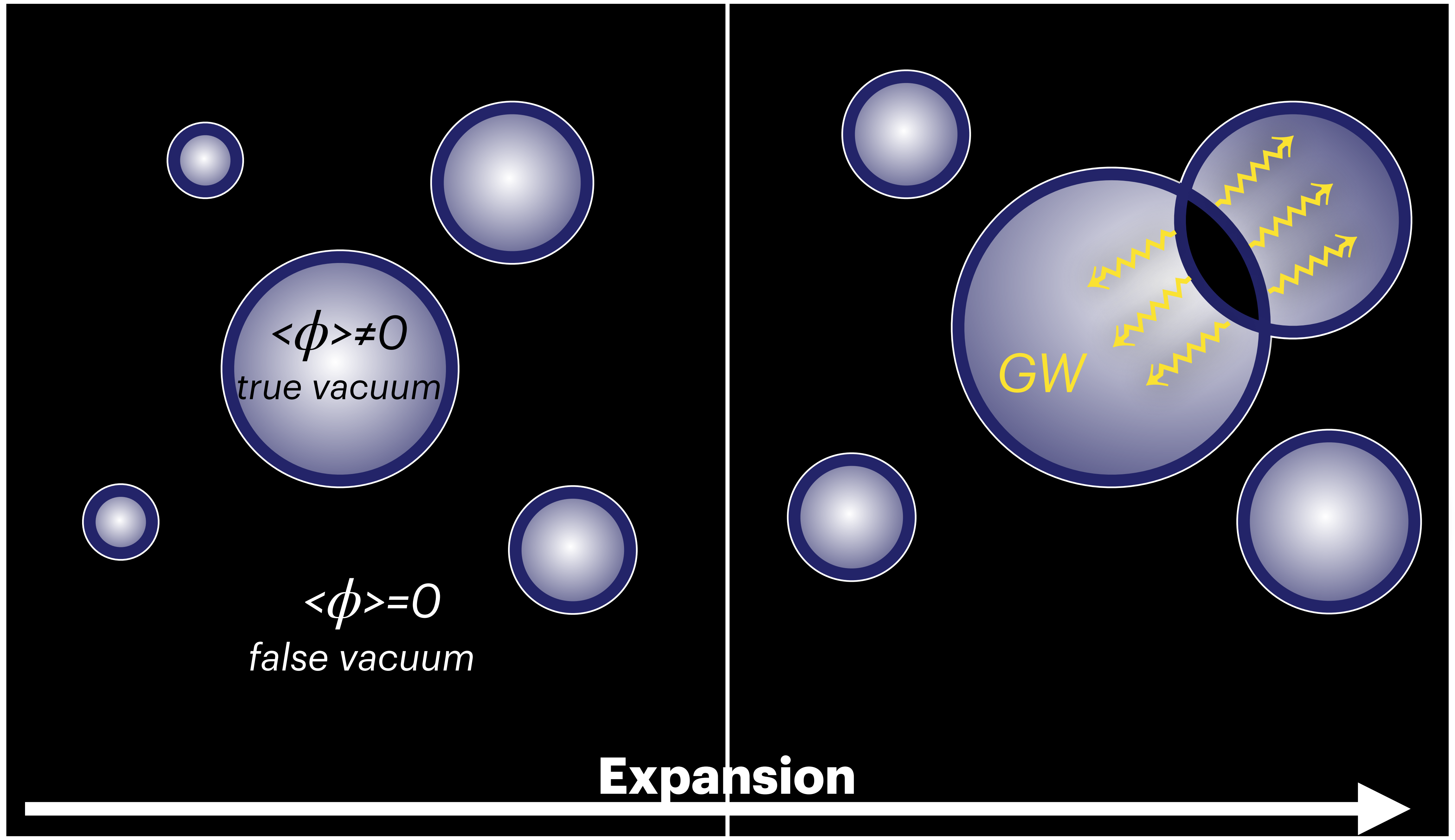
✔ **Extra EW-scale scalar(s)** coupled to the Higgs boson

$\Longrightarrow$ it can be searched through its <u>direct</u> production if kinematically allowed

$\Longrightarrow$ it can be searched through its <u>indirect</u> impact on the Higgs boson couplings

1) It is needed because the CP violation in CKM is not sufficient, other mechanisms are possible as modified Yukawa couplings

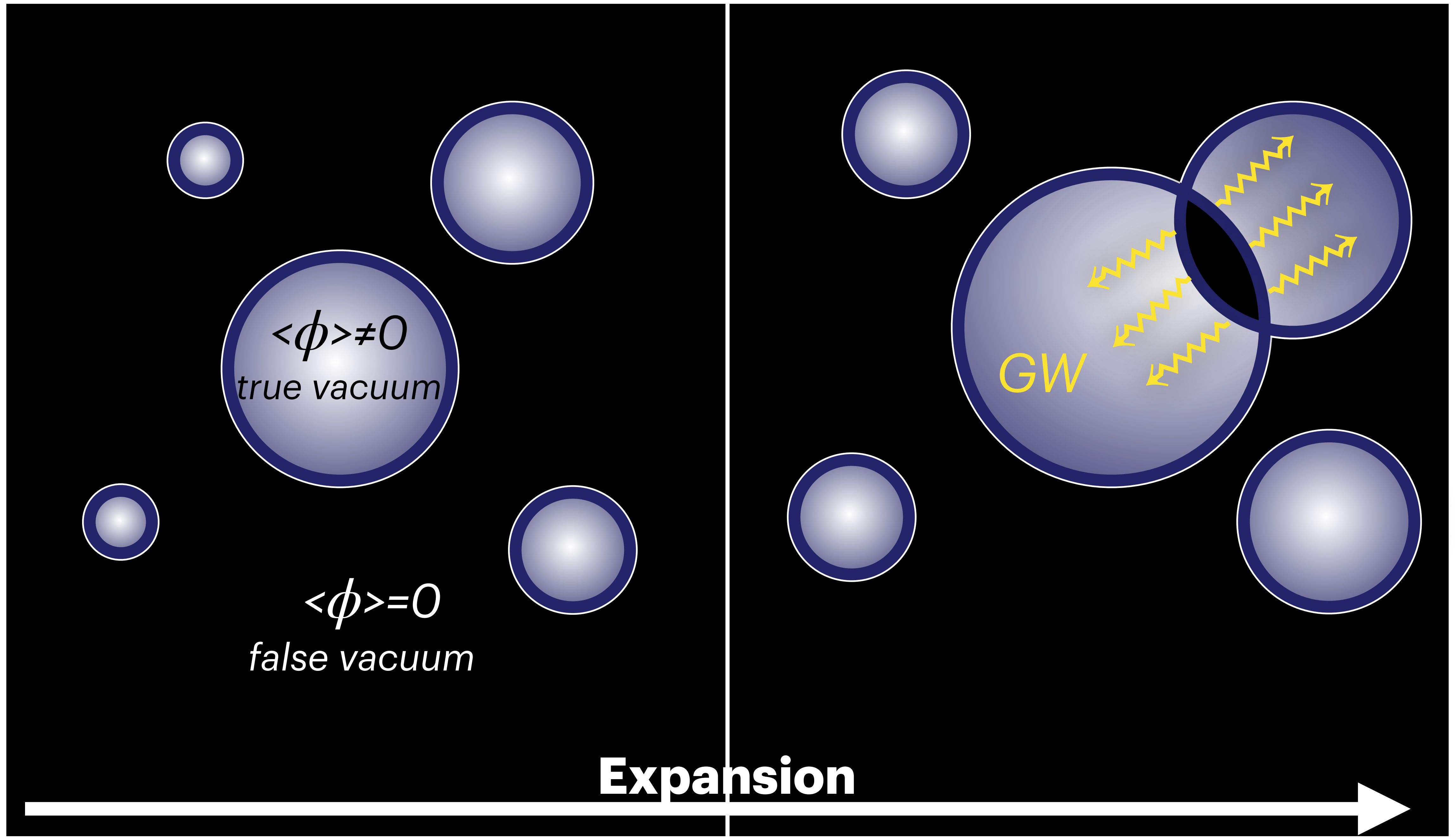
Probing EW baryogenesis with GW



Bubbles nucleation *Bubbles percolation*

Violent process forming milli-HZ GW
stochastic background of gravitational radiation

Probing EW baryogenesis with GW

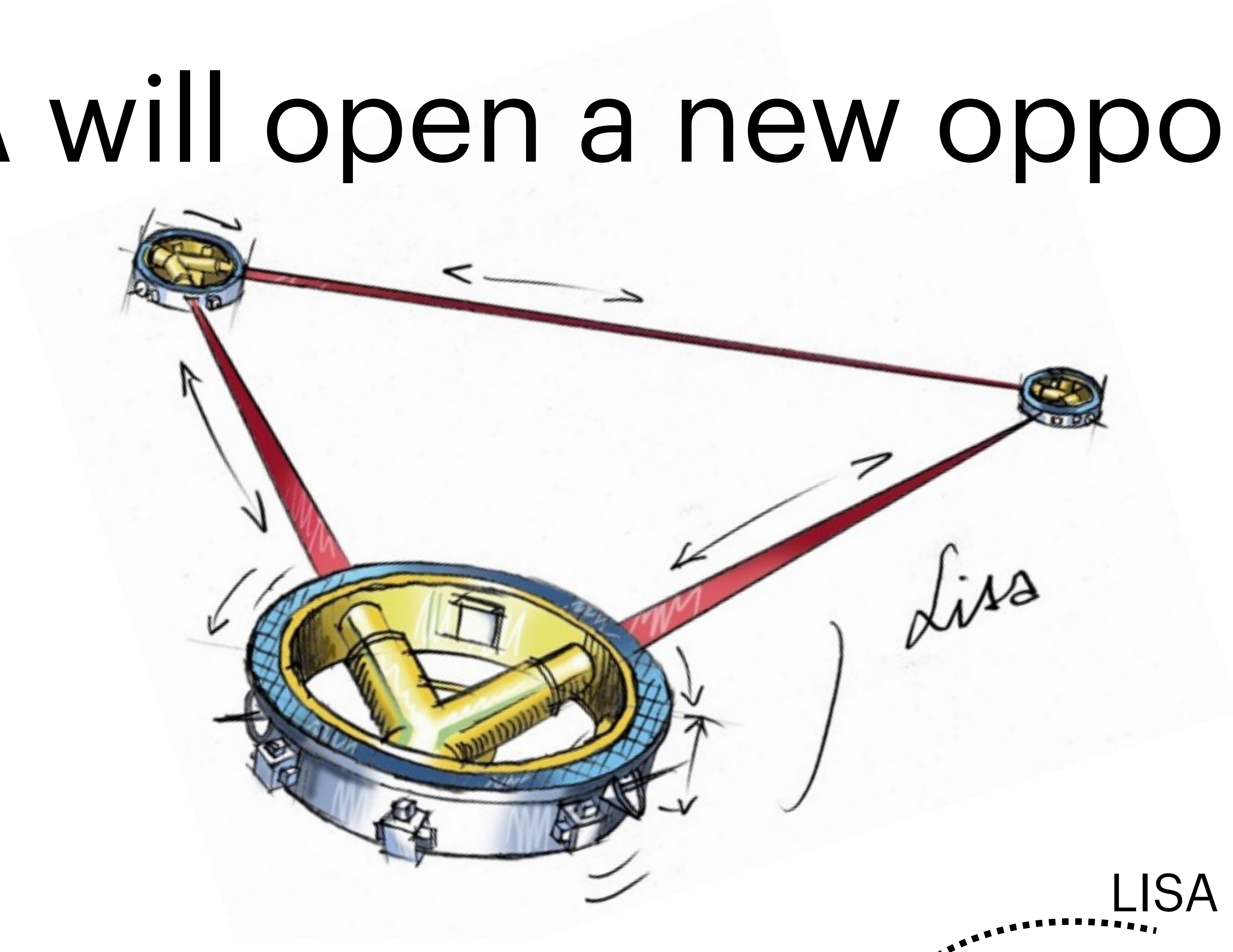


Bubbles nucleation *Bubbles percolation*

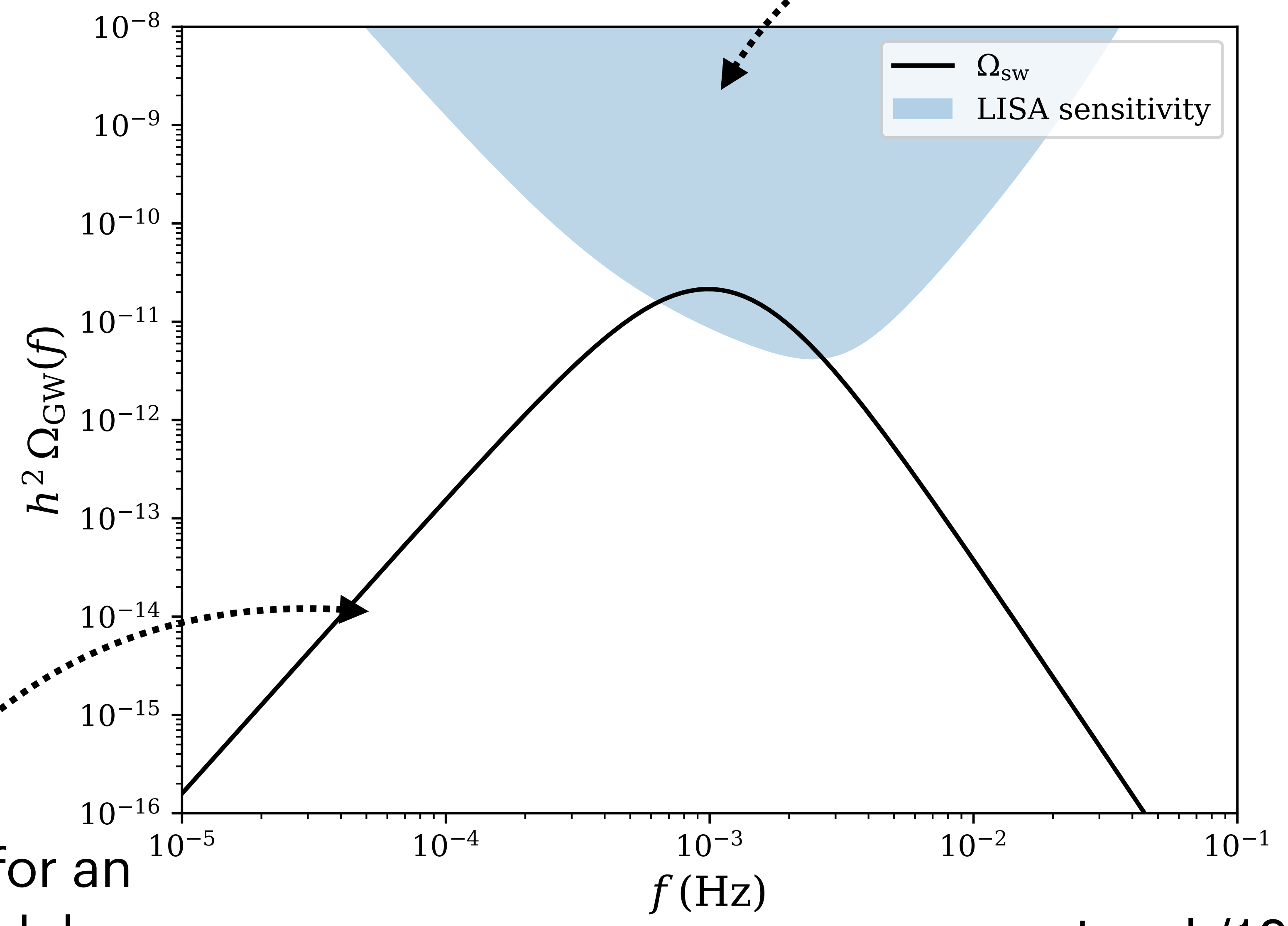
Violent process forming milli-HZ GW

stochastic background of gravitational radiation

LISA will open a new opportunity



LISA sensitivity

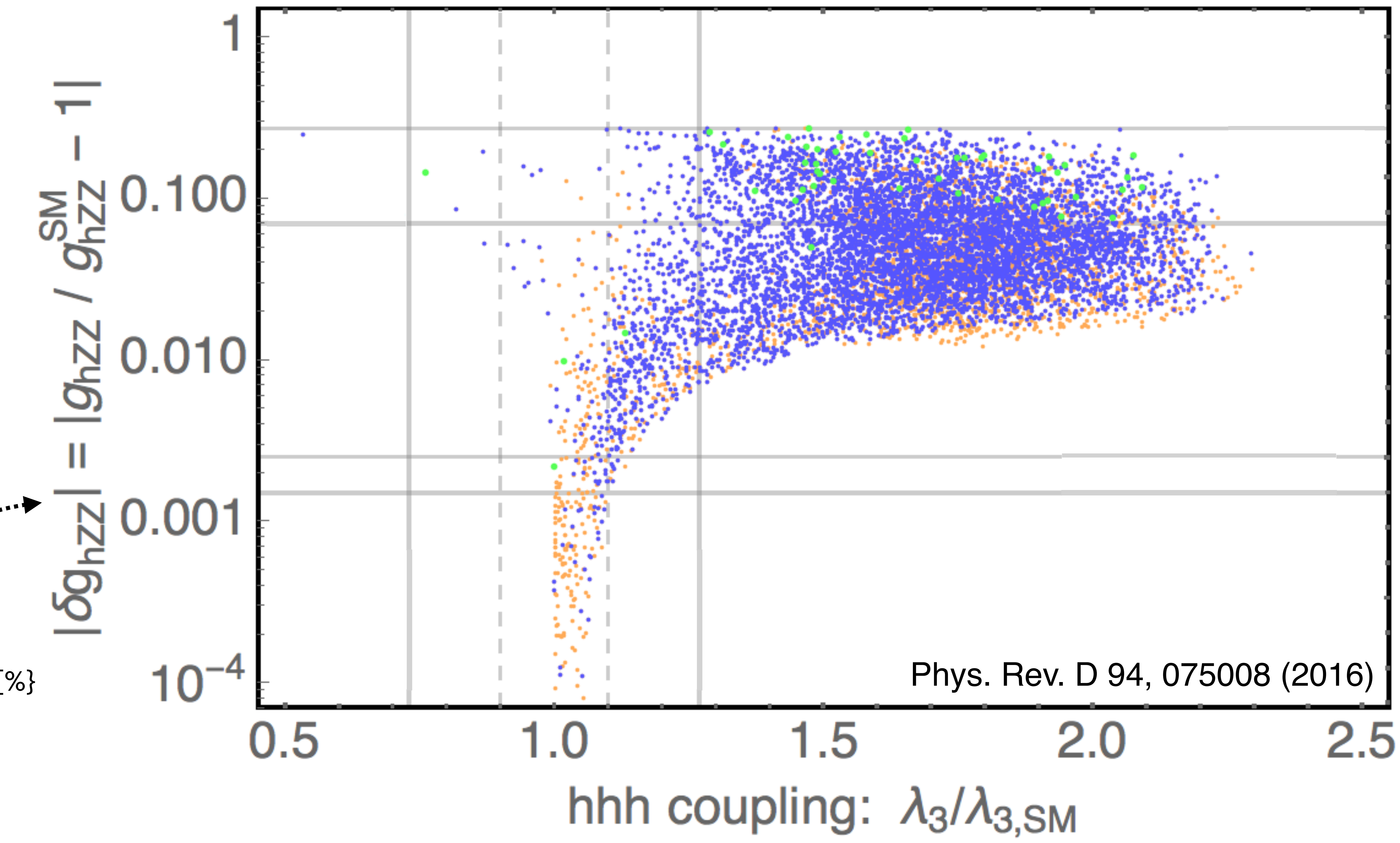


GW spectrum for an example model

astro-ph/1910.13125

EW baryogenesis: colliders and GW interplay

The SM is extended by a real scalar singlet which is able to mix with the SM Higgs boson. The mixing leads to a modification of the HZZ and HHH couplings.



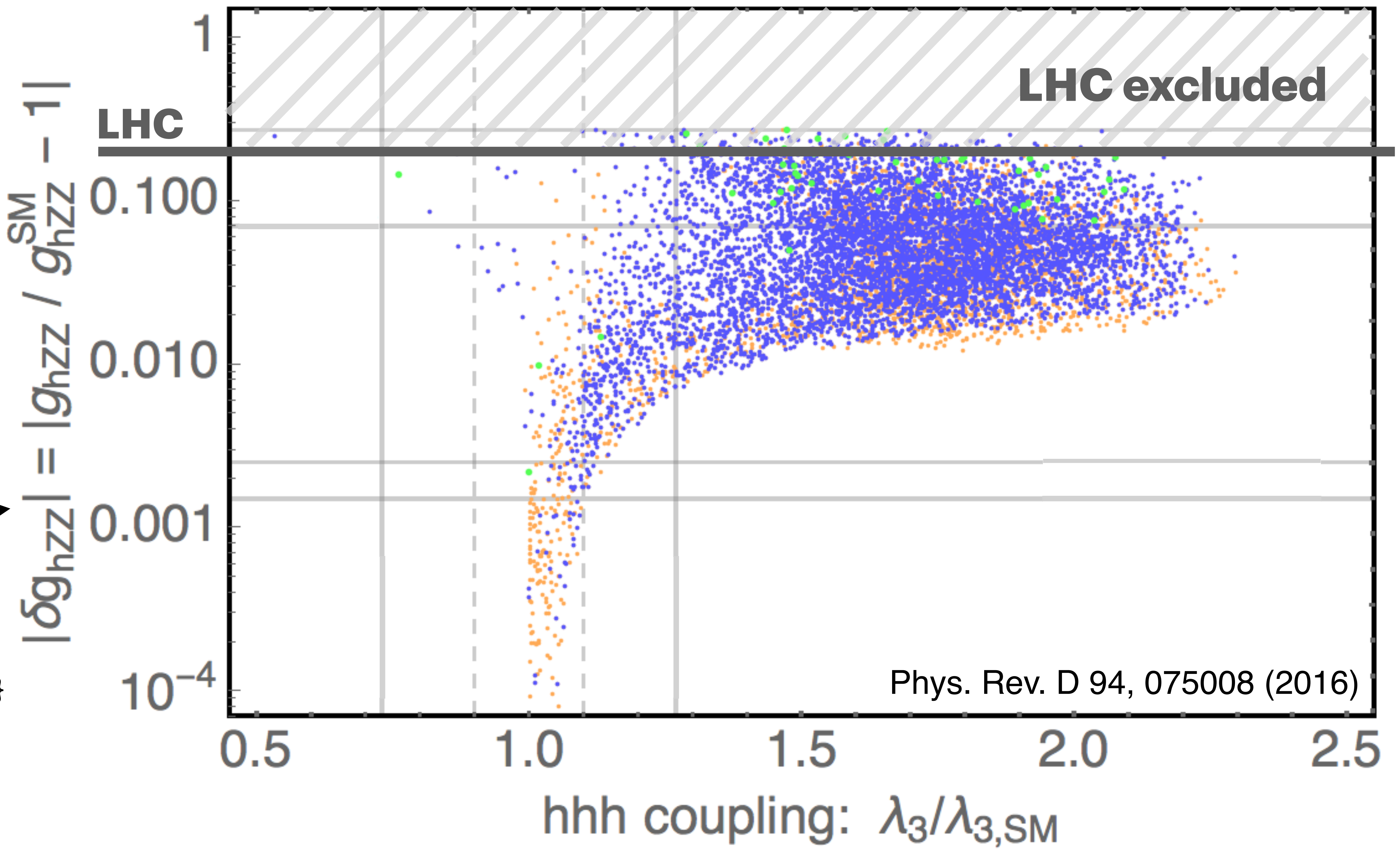
Absolute modification [%} of HZZ coupling

Modification of HHH coupling

- first order phase transition
- strong first order phase transition
- very-strong first order phase transition (potentially detectable GW signal)

EW baryogenesis: colliders and GW interplay

The SM is extended by a real scalar singlet which is able to mix with the SM Higgs boson. The mixing leads to a modification of the HZZ and HHH couplings.



Absolute modification [%} of HZZ coupling

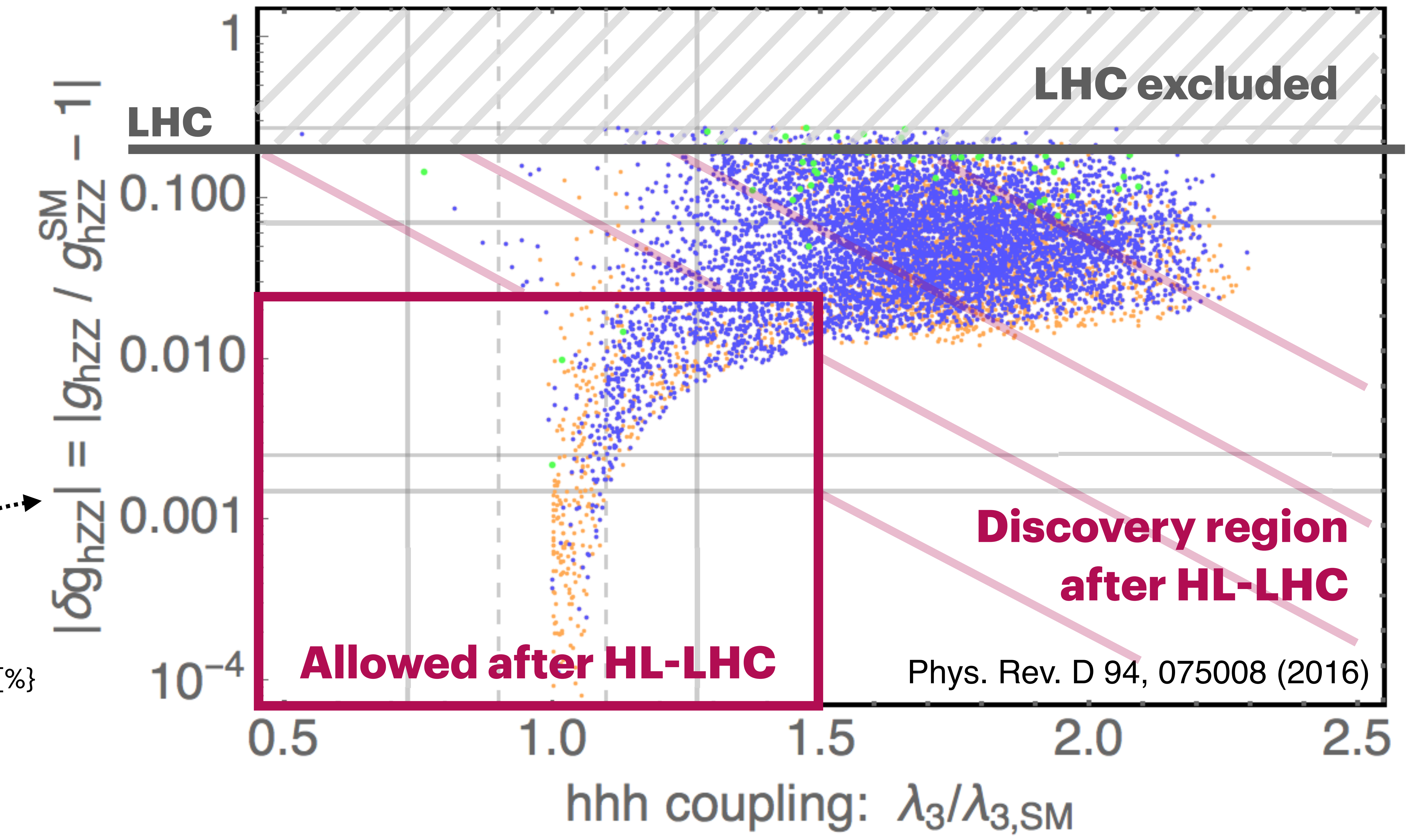
Modification of HHH coupling

- first order phase transition
- strong first order phase transition
- very-strong first order phase transition (potentially detectable GW signal)

LHC start to exclude a part of the phase space

EW baryogenesis: colliders and GW interplay

The SM is extended by a real scalar singlet which is able to mix with the SM Higgs boson. The mixing leads to a modification of the HZZ and HHH couplings.



Absolute modification [%} of HZZ coupling

Modification of HHH coupling

- first order phase transition
- strong first order phase transition
- very-strong first order phase transition (potentially detectable GW signal)

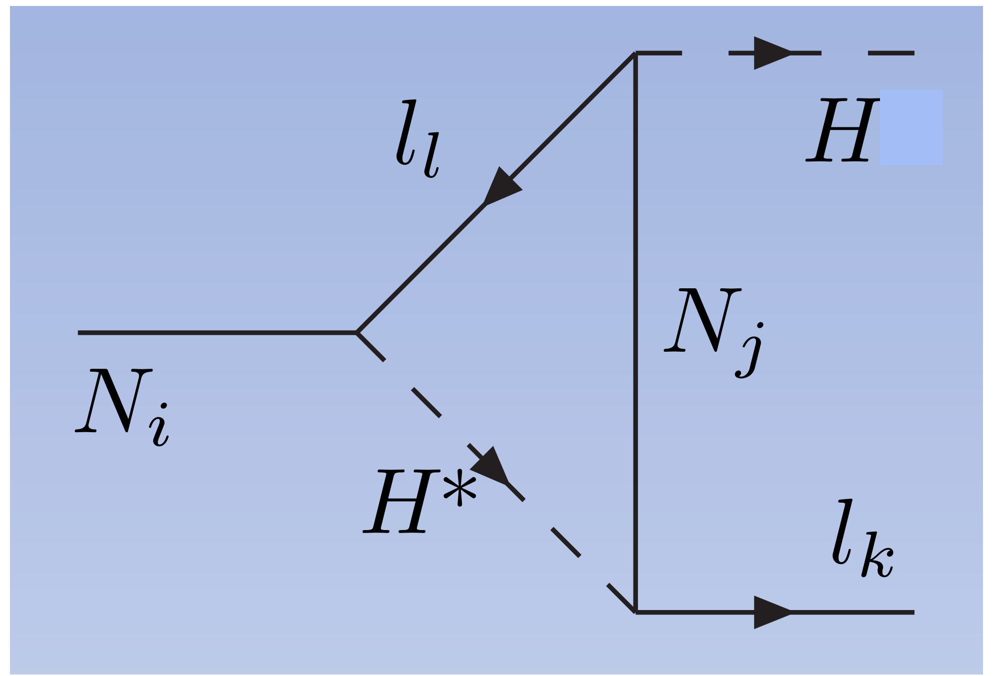
LHC start to exclude a part of the phase space

After **HL-LHC** a large discovery region will be probed and still an allow region will remain

$\Longrightarrow$ synergy colliders and GW experiment

Leptogenis

Heavy right-handed neutrinos with Majorana mass terms decay out of equilibrium and produce a lepton asymmetry that is converted into the observed BAU by (B+L)-violating sphaleron interactions.

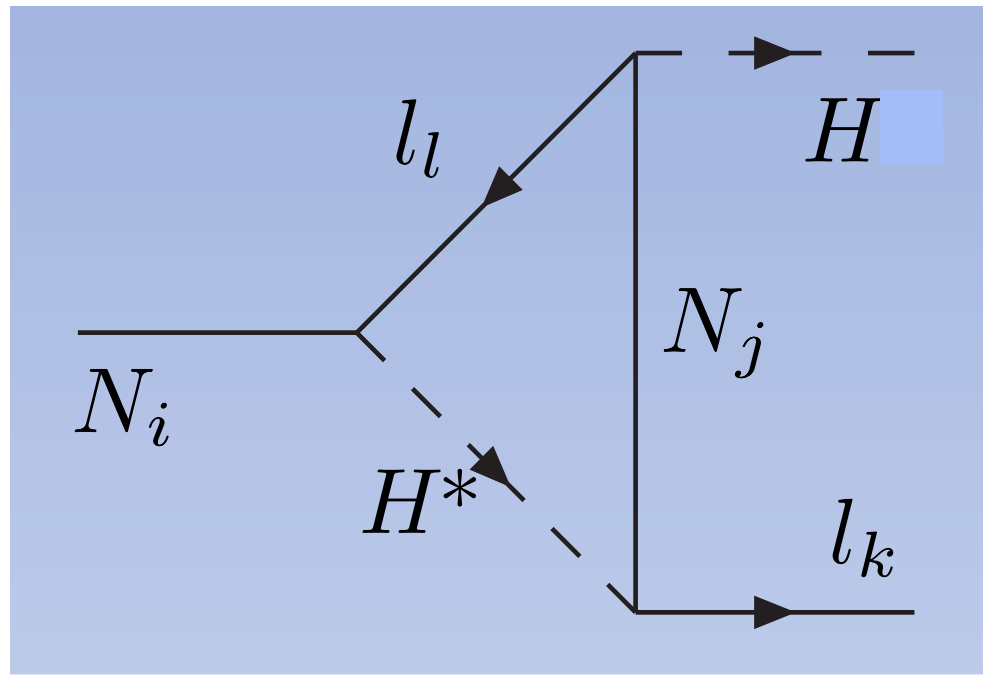


M. Fukugita, T. Yanagida Phys. Lett. B 174 45 (1986)

Crucial ingredient is CPV in the lepton sector.

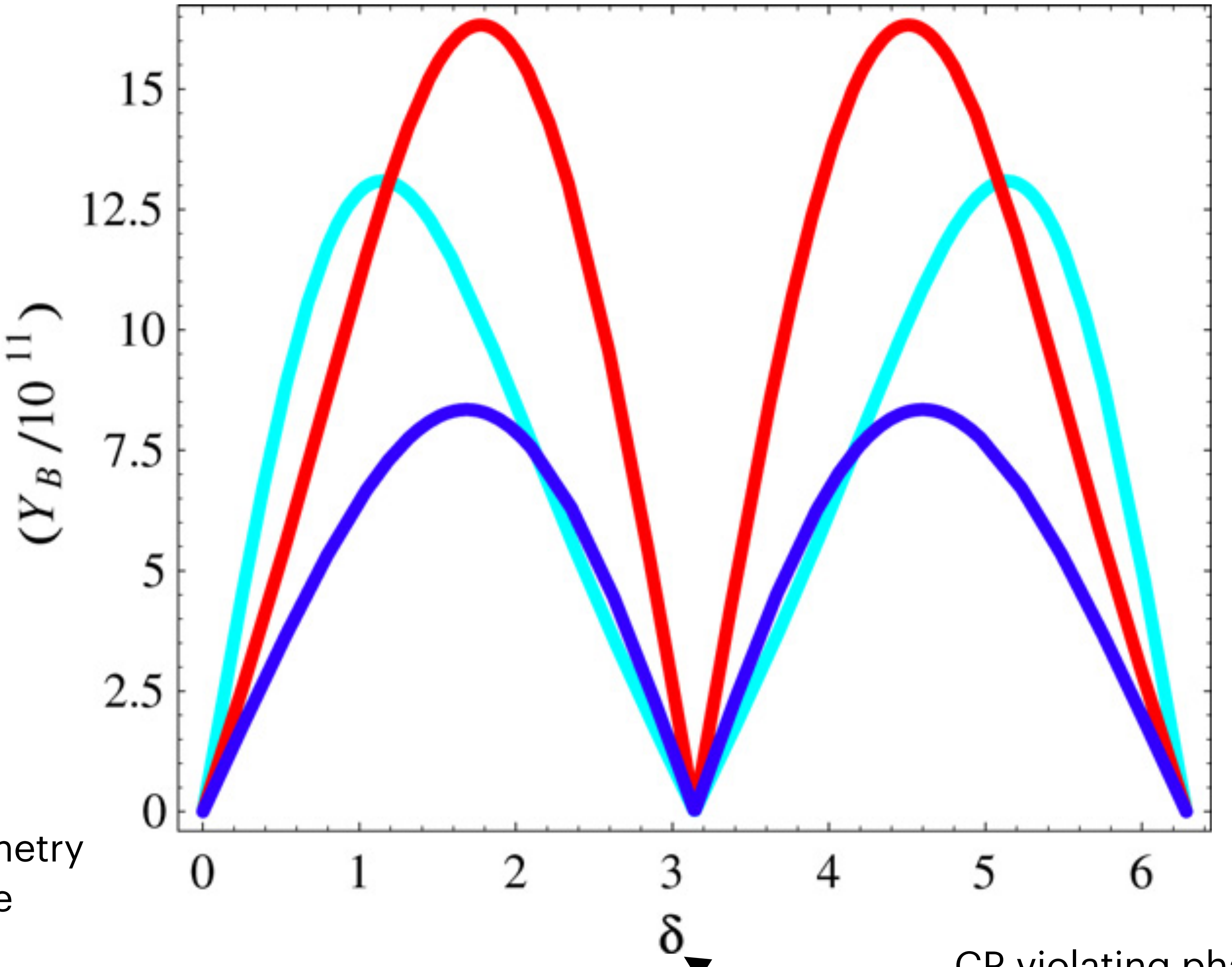
Leptogenis

Heavy right-handed neutrinos with Majorana mass terms decay out of equilibrium and produce a lepton asymmetry that is converted into the observed BAU by (B+L)-violating sphaleron interactions.



Crucial ingredient is CPV in the lepton sector.

M. Fukugita, T. Yanagida Phys. Lett. B 174 45 (1986)



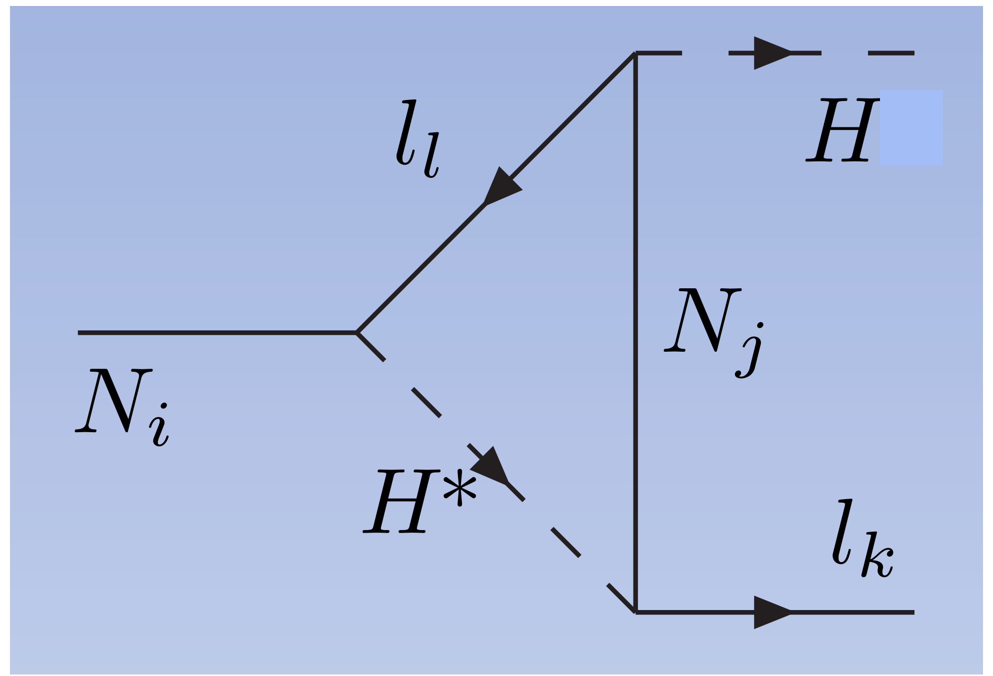
Nuclear Physics B 774 (2007) 1–52

The baryon asymmetry in our Universe

CP-violating phases in the PMNS neutrino mixing matrix

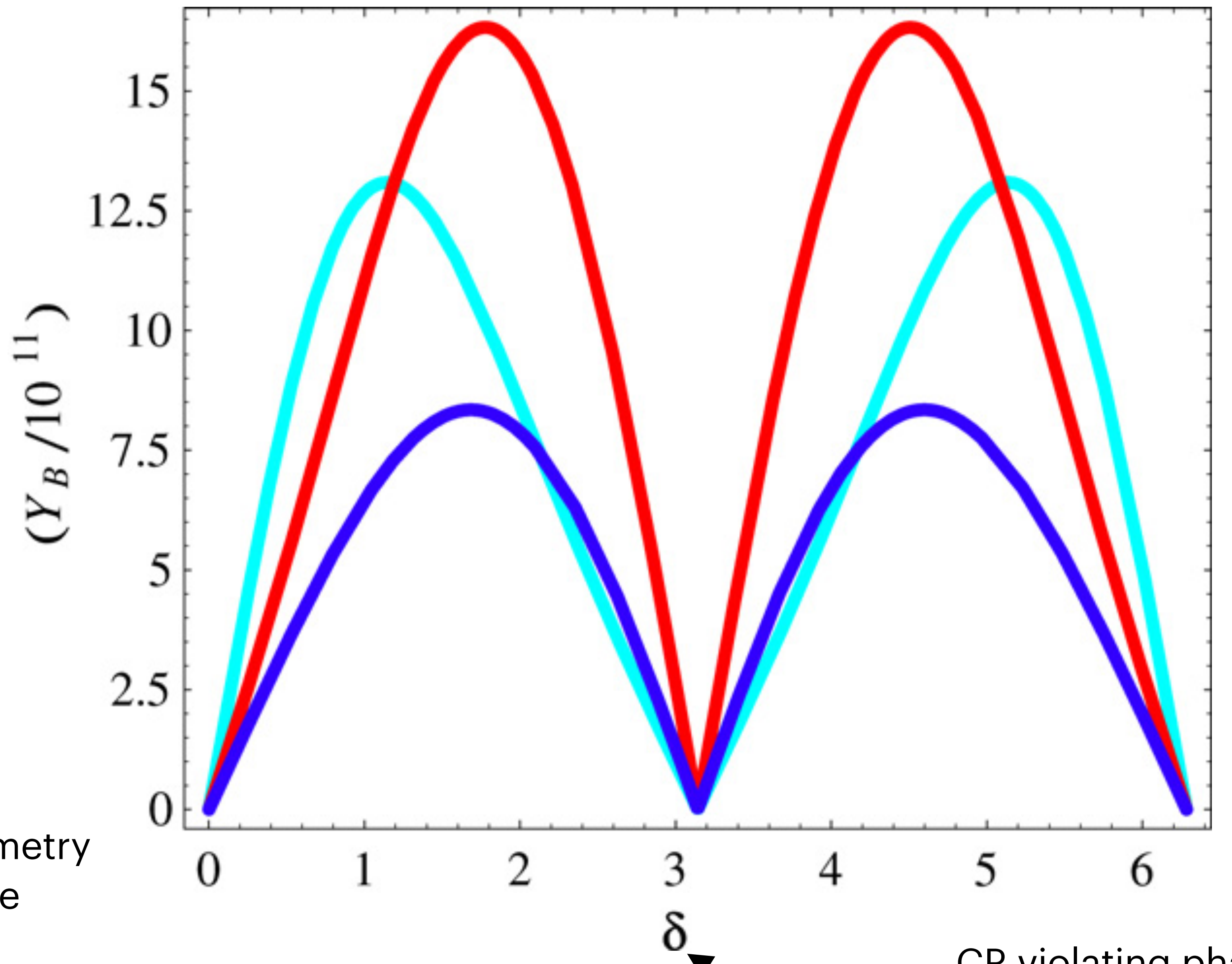
Leptogenis

Heavy right-handed neutrinos with Majorana mass terms decay out of equilibrium and produce a lepton asymmetry that is converted into the observed BAU by (B+L)-violating sphaleron interactions.



Crucial ingredient is CPV in the lepton sector.

M. Fukugita, T. Yanagida Phys. Lett. B 174 45 (1986)



The baryon asymmetry in our Universe

CP-violating phases in the PMNS neutrino mixing matrix

Nuclear Physics B 774 (2007) 1–52

Observations of (low energy) CP violation in neutrino physics and/or Majorana neutrino are fundamental tests to establish that (some of) the Sakharov conditions for leptogenesis are realized in Nature.

Hyper-Kamiokande experiment will be the key player

Conclusions

Fundamental physics, as we know, was frozen in the very early Universe.

Particle colliders currently **probe the EW symmetry breaking phase transition** (reheating) which happened after the end of inflation about 10^{-12}s after the Big Bang.

The **discovery of the Higgs boson** at the LHC has changed our understanding of the role of the vacuum in the history of the Universe.

The **nature of the vacuum** crucially depends on the existence of the self-coupling of the Higgs boson which can be measured at LHC / HL-LHC.

A fundamental scalar field has been discovered. This connects particle physics to the history of matter and interactions in our Universe and invites to revisit BSM physics (structure of matter the SM, dark matter, extended neutrino sector, ...).

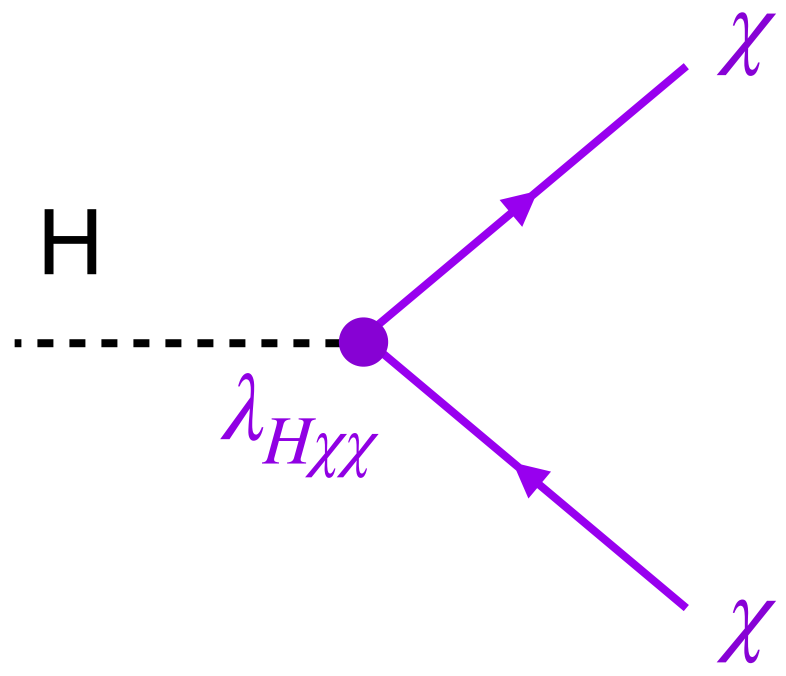

B A C K U P

Higgs boson to invisible decay

The expected SM H branching fraction to invisible decay ($\mathscr{B}_{\text{inv}}$) is 0.12% due to $H \to ZZ^* \to \nu\bar{\nu}\nu\bar{\nu}$

Several BSM scenario ⇒ anomalous and sizeable values, $\mathscr{B}_{\text{inv}}$ is significantly enhanced.

In one class of models H decay in a pair of stable WIMPs.
They represent a simple extension of the SM to provide a Dark Matter (DM) candidate and are able to predict the observed relic DM density via s-channel $\chi\chi \to f\bar{f}$ annihilation.



The solution of the DM problem could be found within the Higgs sector.

Common signature : significant missing transverse momentum from the Higgs boson decay.
Identify the event : profit of visible particles recoiling against the Higgs boson.

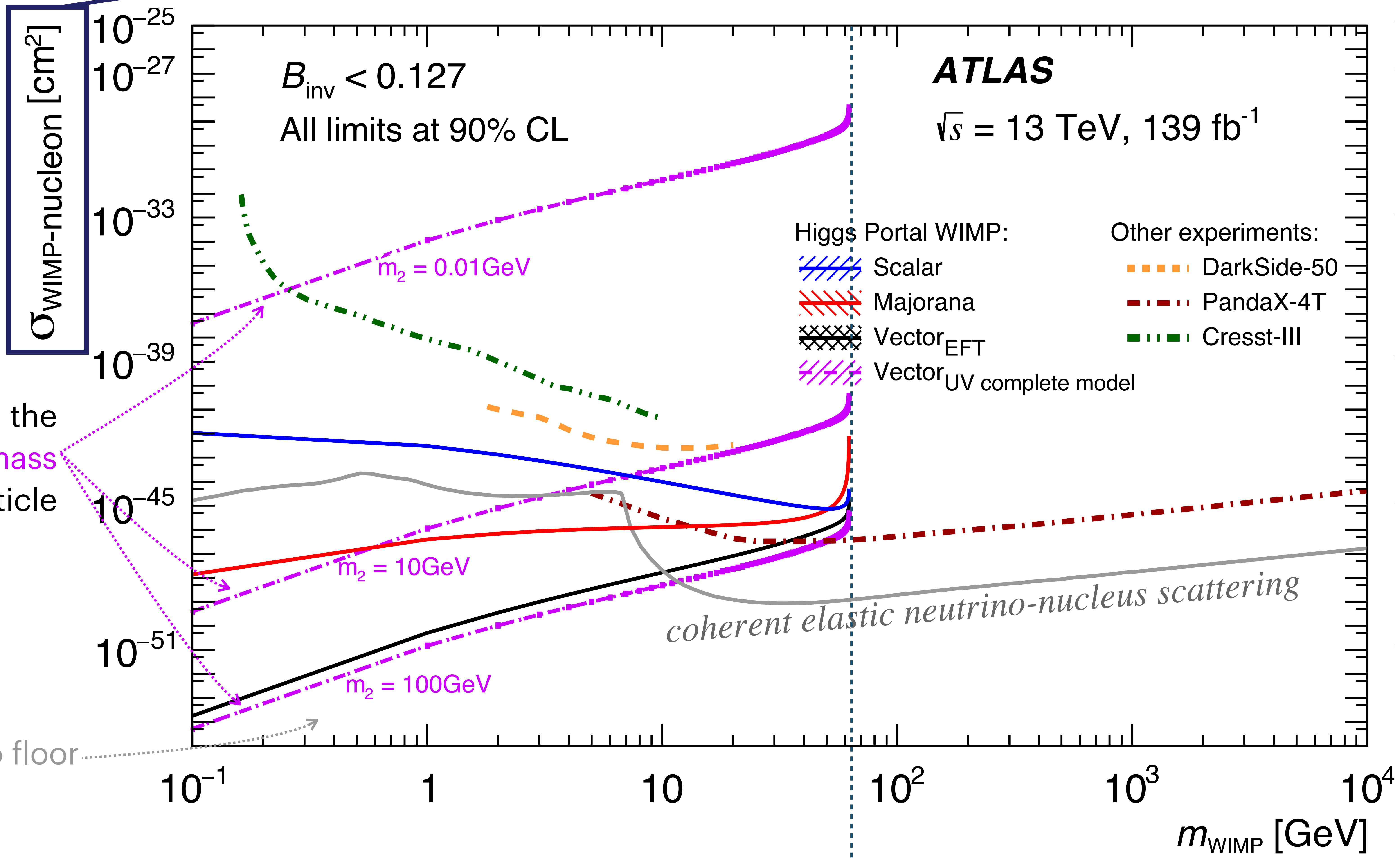
Interpretations

arXiv:2202.07953

Phys.Rev.D 105 (2022) 092007

Upper limits on the spin-independent **WIMP–nucleon cross section**

For the vector$_{UV}$ models, the dependence on the mass m_2, new scalar particle



Down in the neutrino floor

Kinematical threshold

$m_{WIMP} = m_{DM} = m_{H/2}$ = 62.5 GeV

Outperforms direct searches experiments for low m_{DM}

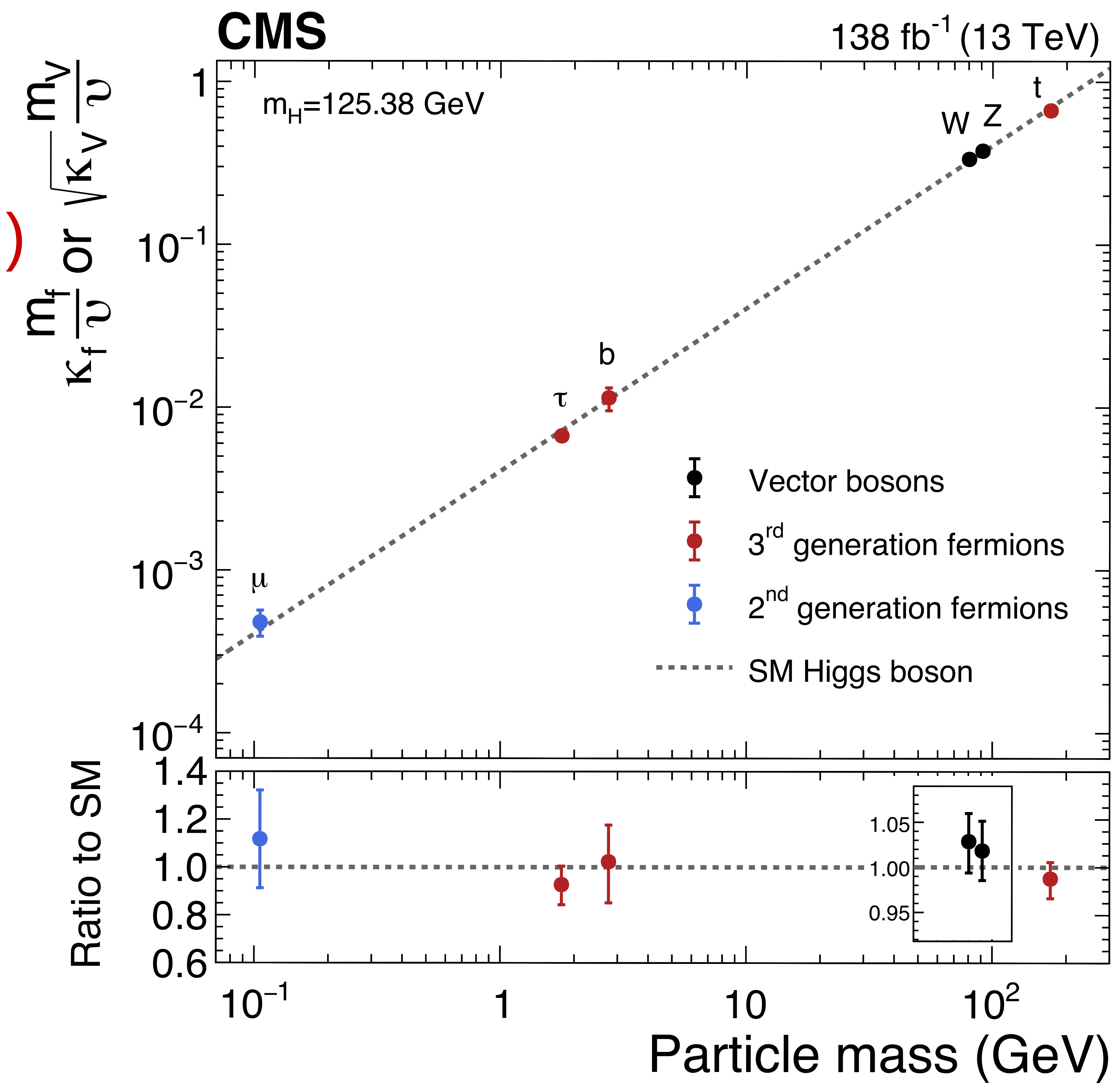
Does the Higgs boson mediate the Yukawa force?

The Yukawa force is a fundamental interaction
as important as fundamental particles

It was never seen until LHC Run2 !

>5σ observation of ttH, H→bb, and H→ττ (3rd generation)

>3σ evidence of H→μμ (2nd generation)



Does the Higgs boson mediate the Yukawa force?

The Yukawa force is a fundamental interaction
as important as fundamental particles

It was never seen until LHC Run2 !

>5σ observation of ttH, H→bb, and H→ττ (3rd generation)

>3σ evidence of H→μμ (2nd generation)

Relative lightness makes flavour puzzle compelling, measurements could hold key to flavour puzzle.

Can we prove Yukawa force for stable (u,d,e,ν) matter in our Universe?