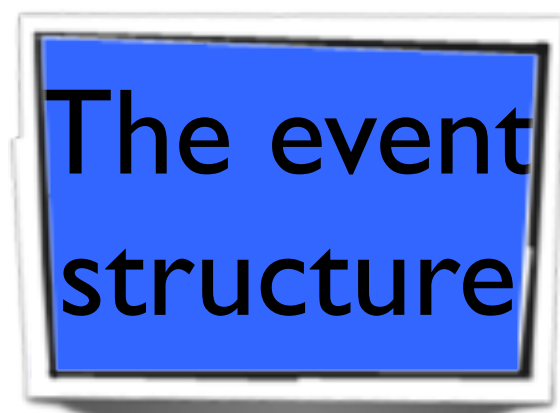


1, 2 or 3 Higgses at the LHC and in the future

Pamela Ferrari
(Nikhef and Radboud University)

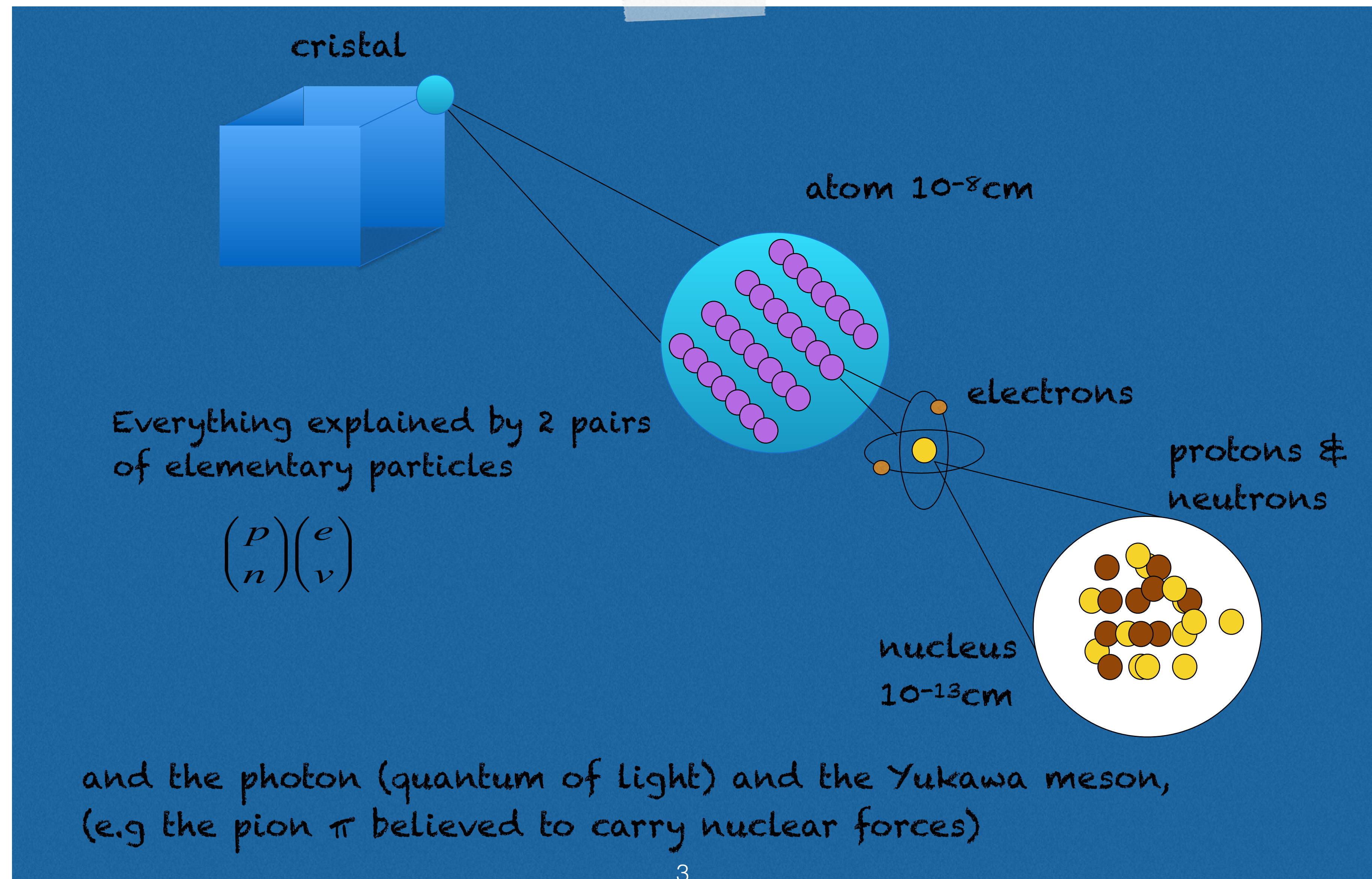




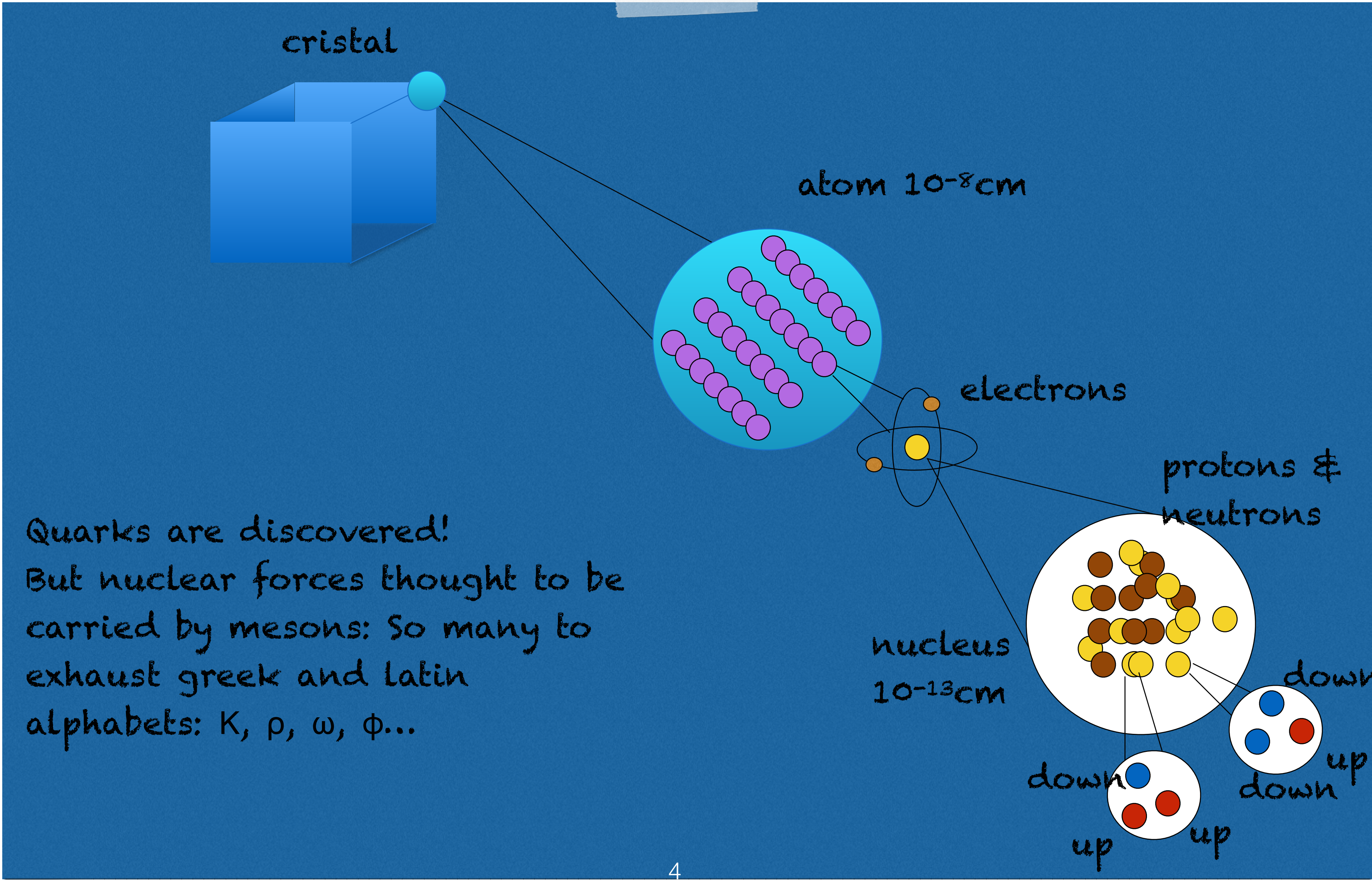
Historical background

Shortly introducing the Standard Model and its shortcomings to motivate our studies at the LHC

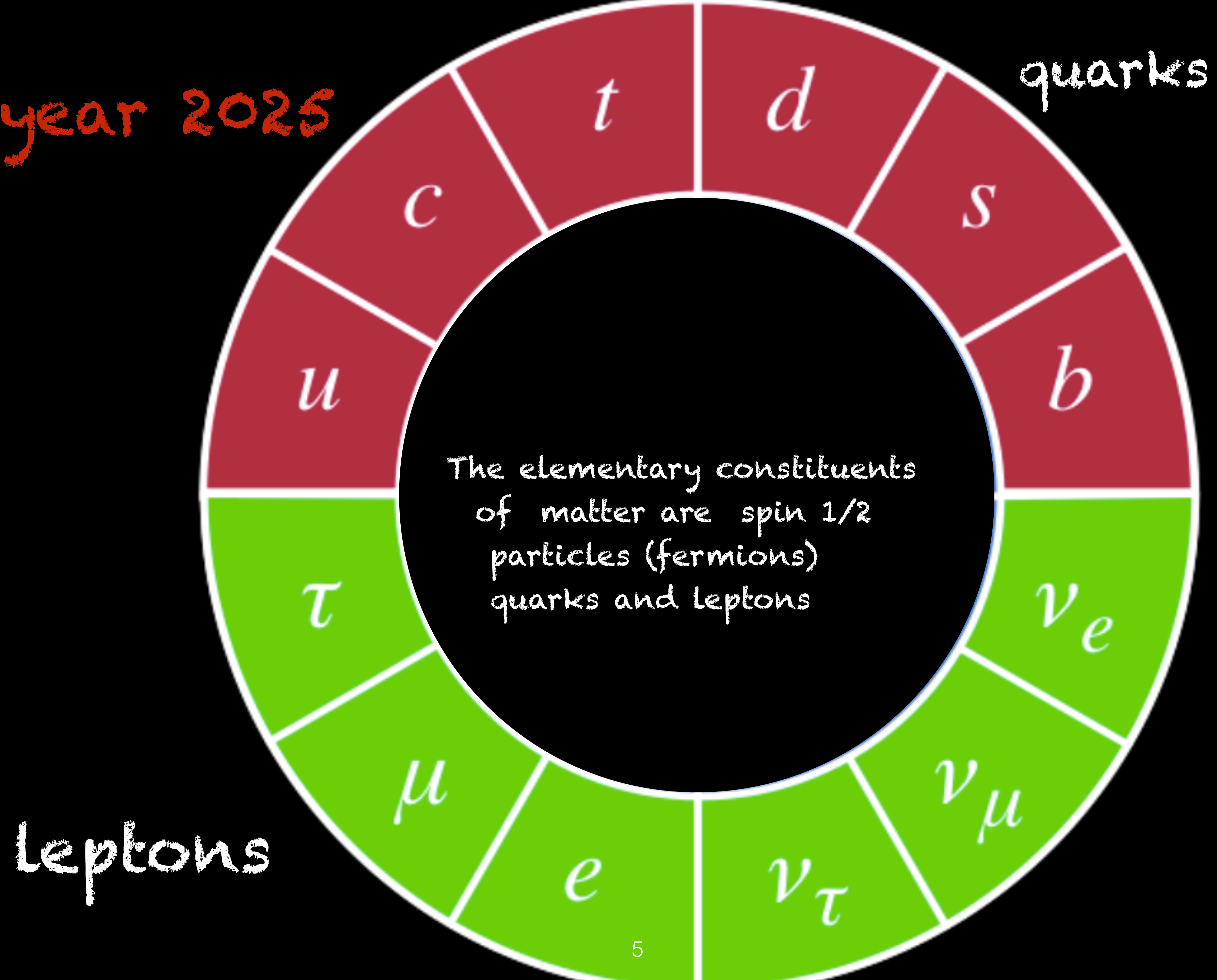
1930: The knowledge of matter



1960-70 new level: QUARKS



year 2025

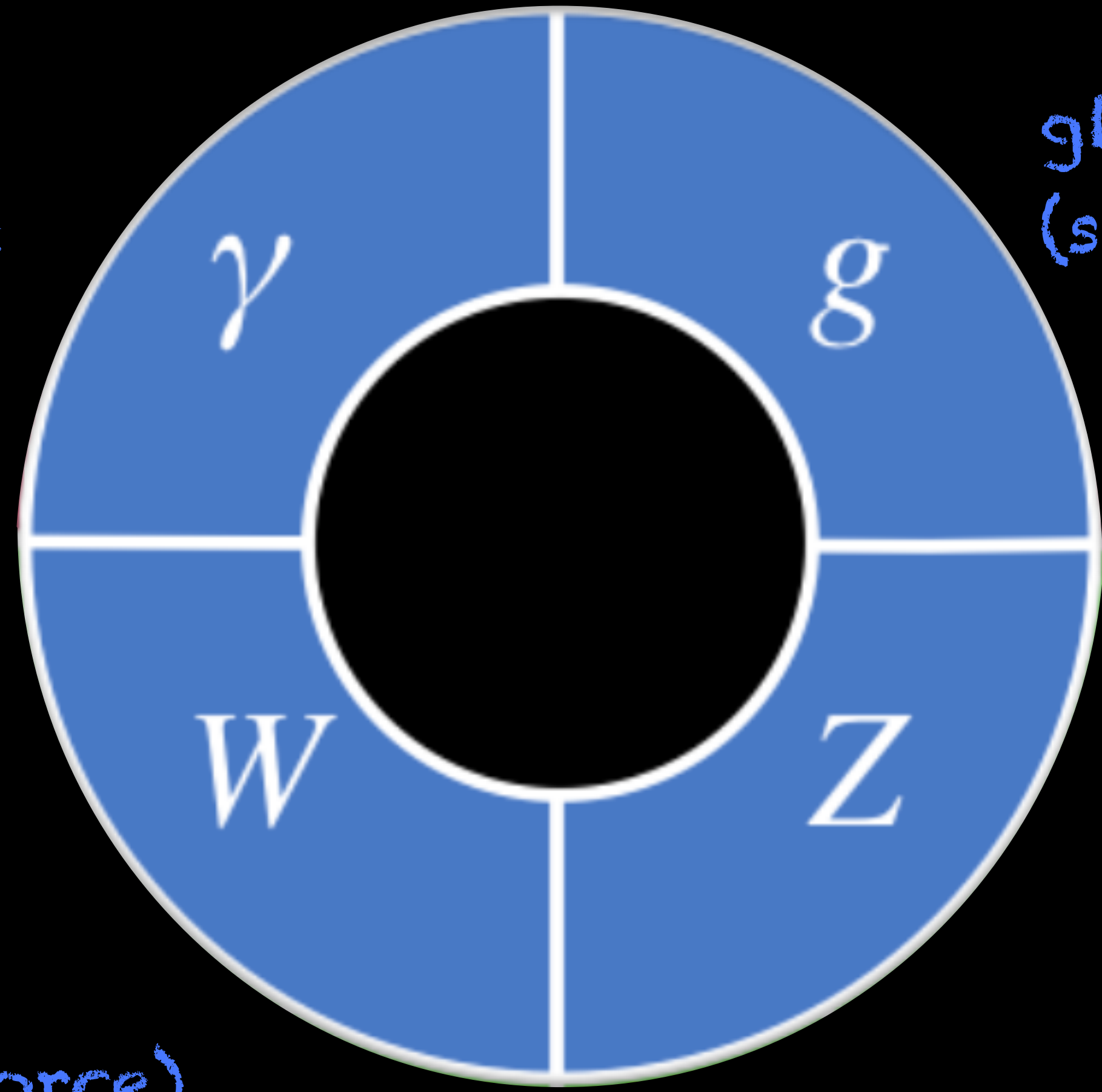


What about forces?

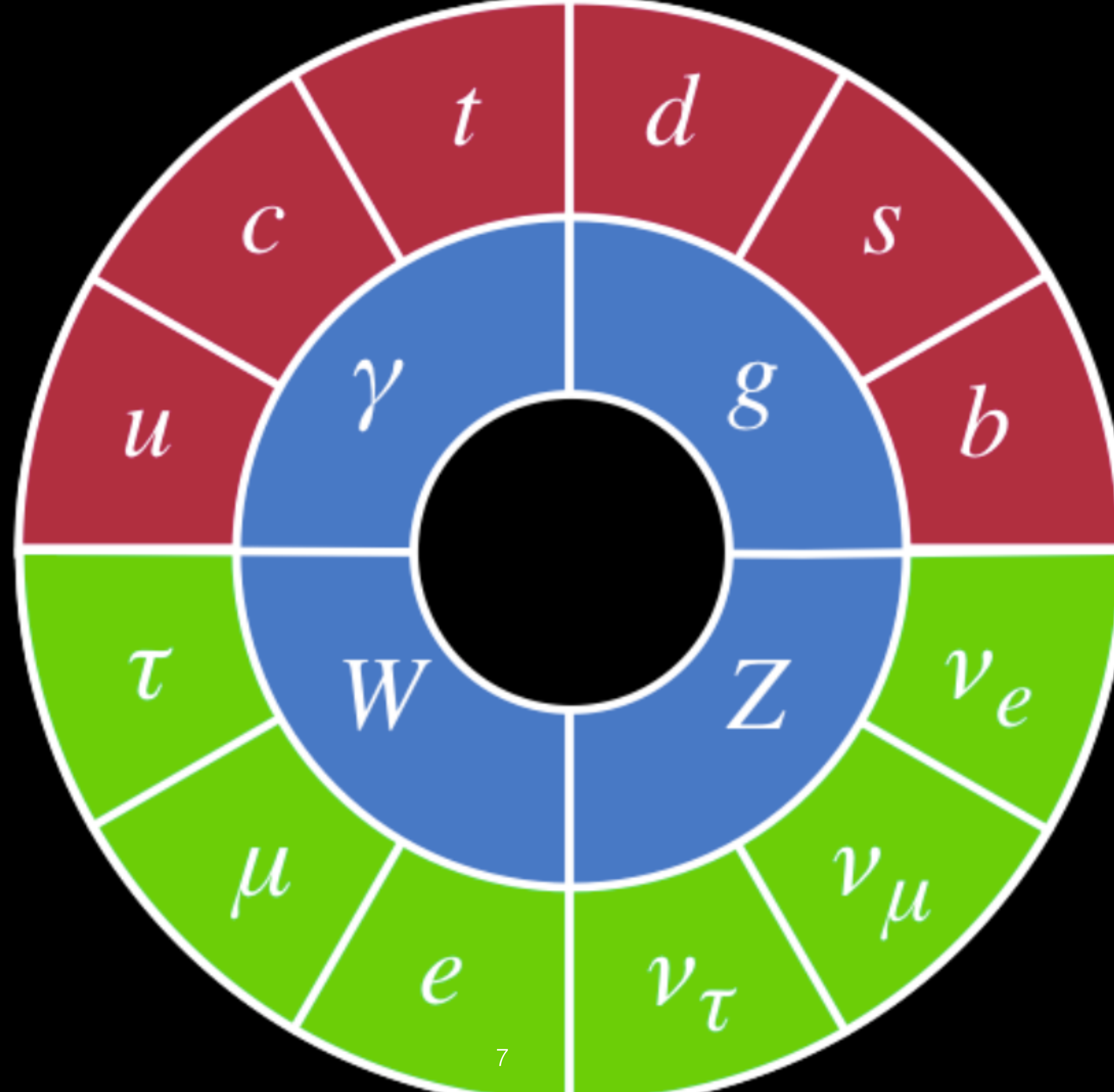
The force carriers are integer spin particles (bosons)

photon γ
(electromagnetic
force)

gluon g
(strong force)

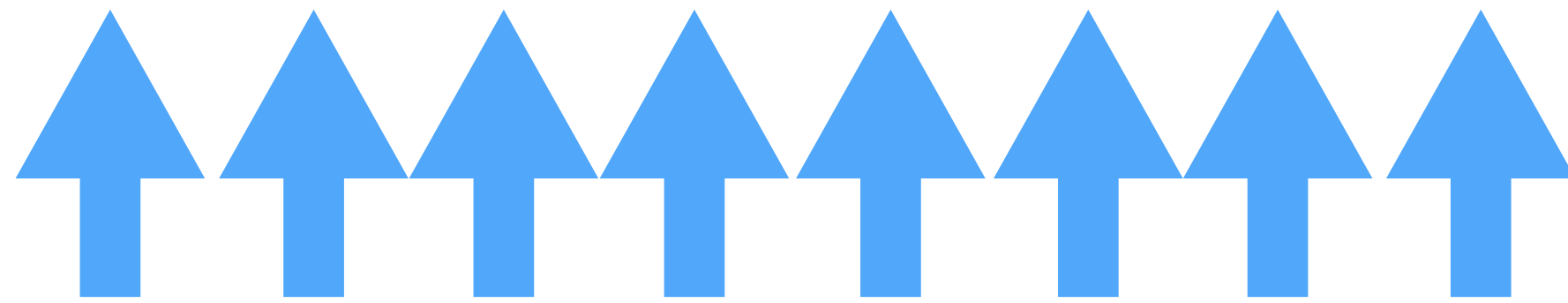


W/Z
(weak force)

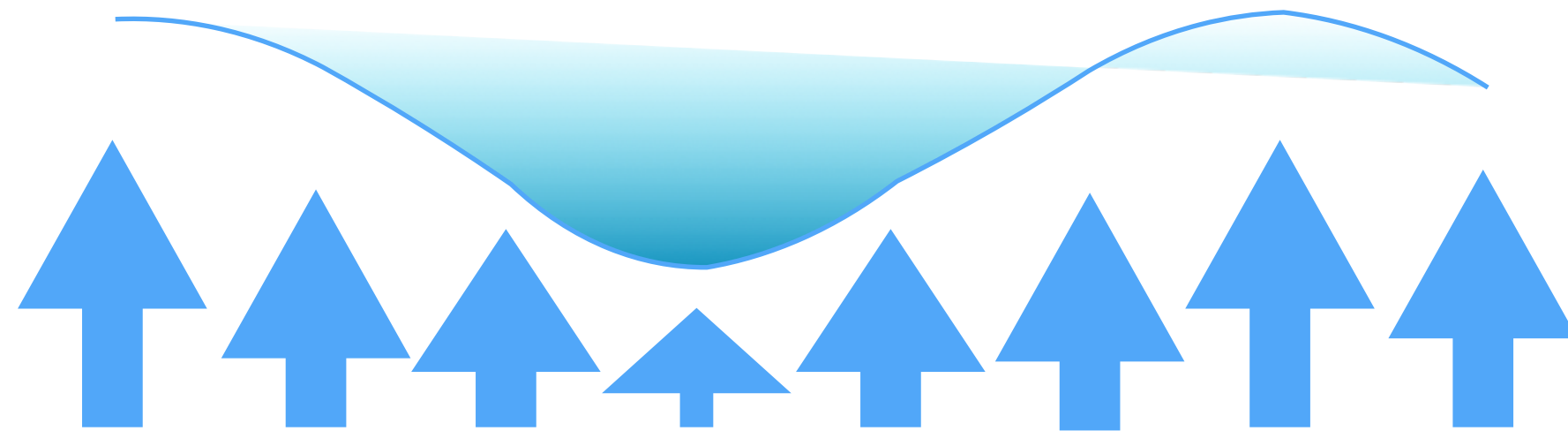


What is responsible of particles masses?

The Higgs field that fills the space. Particles get mass by interacting with it. ¹



The vacuum is like the surface of still lake



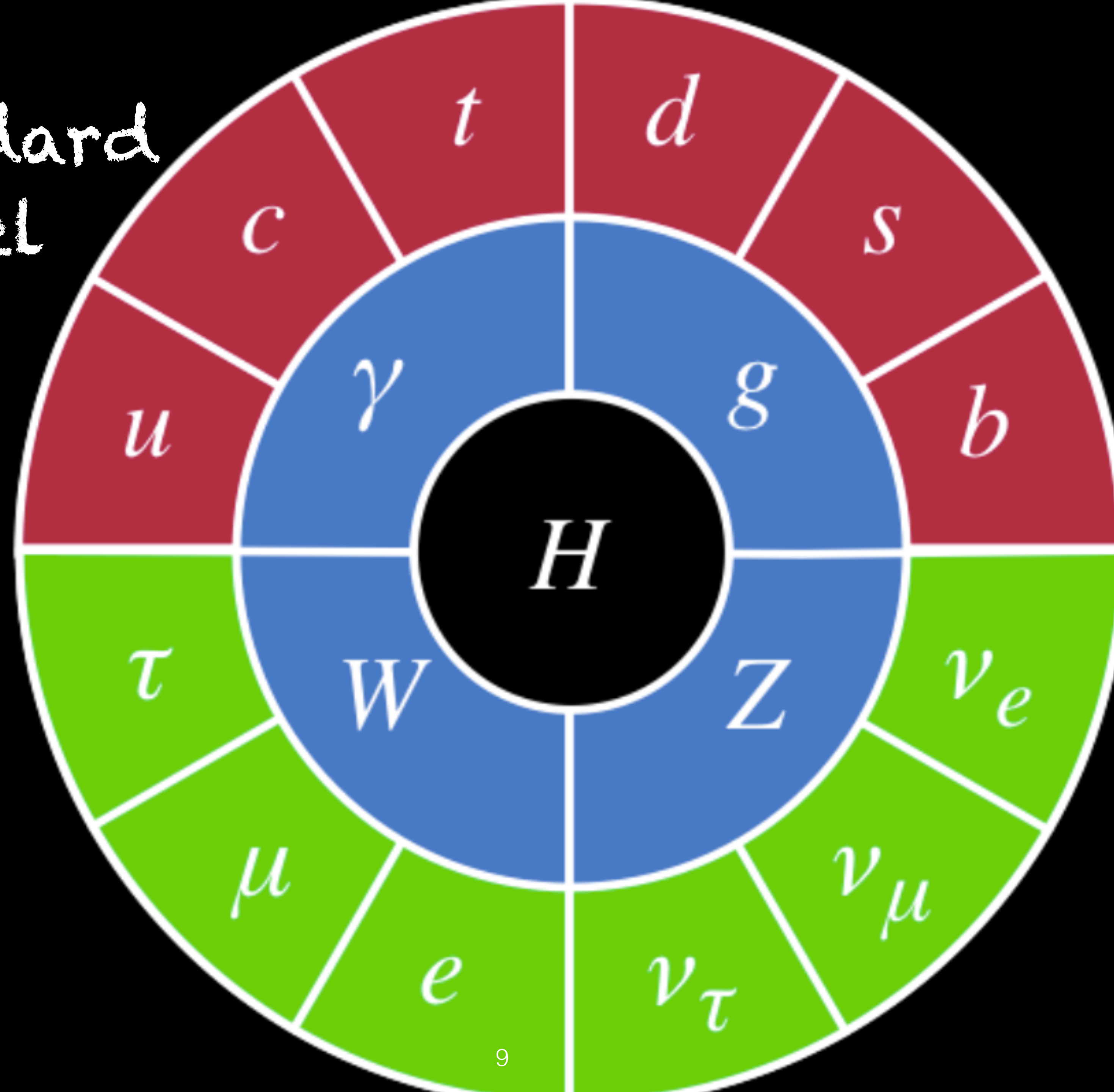
collisions produce waves
(oscillation of field = particle)



Higgs boson
spin zero particle, $m \sim 125 \text{ GeV}$

Vacuum is filled!

The Standard Model (SM)



- The Standard Model predicts that the Higgs boson and field acts as a sole player in the game of Electroweak symmetry breaking.
- This is a strong prediction that has yet to be verified experimentally.
- Answering this question is one of the pressing goals for the future

What is the mass/energy scale we are talking about?

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
	≈4.8 MeV/c ²	≈95 MeV/c ²	≈4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	91.2 GeV/c ²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	80.4 GeV/c ²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	



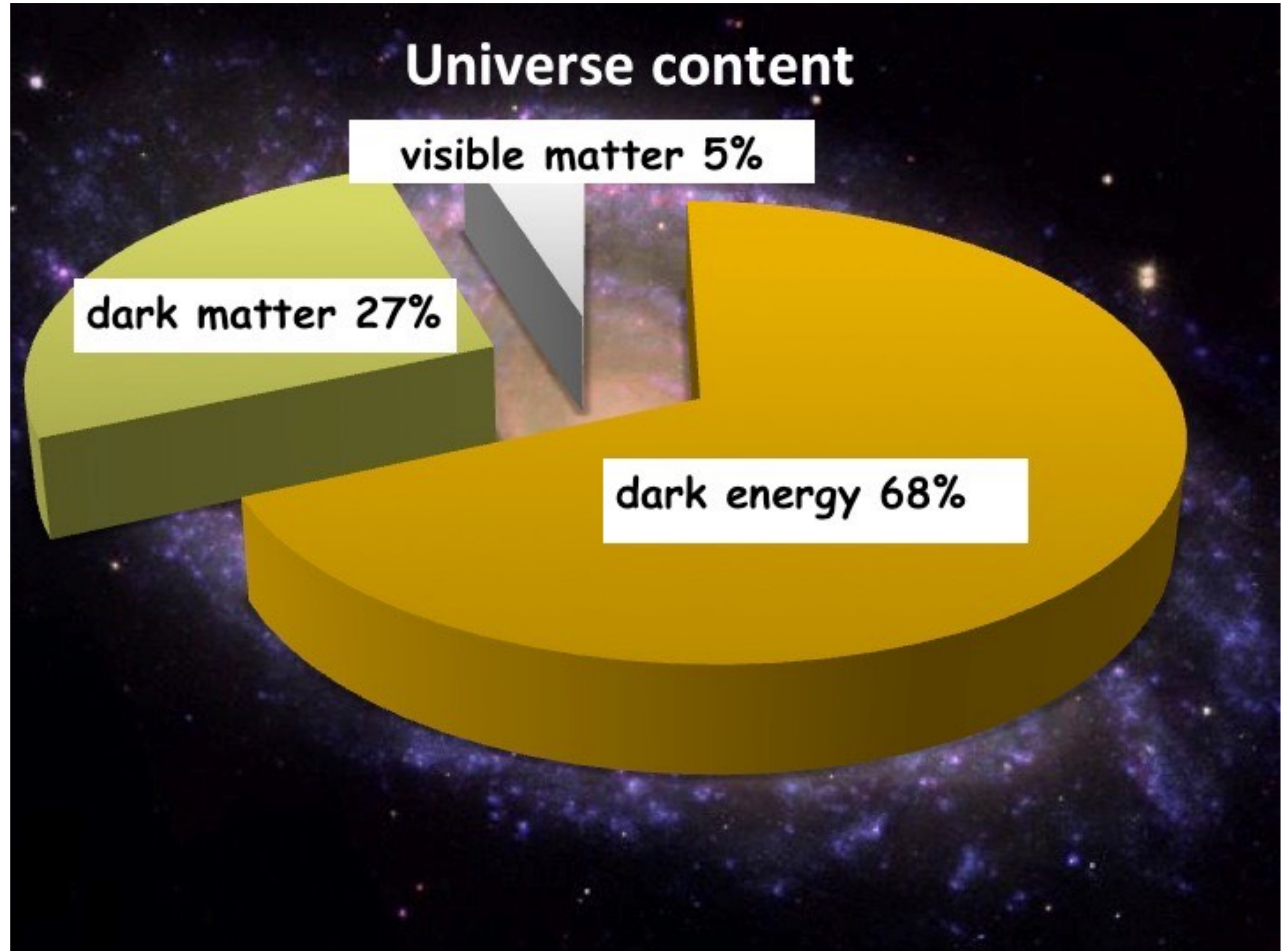
New physics may appear at higher scales

below 200 Giga-electronVolt = GeV

Dark Matter: the first puzzle

Stable Ordinary particles
Can they explain everything?

No!

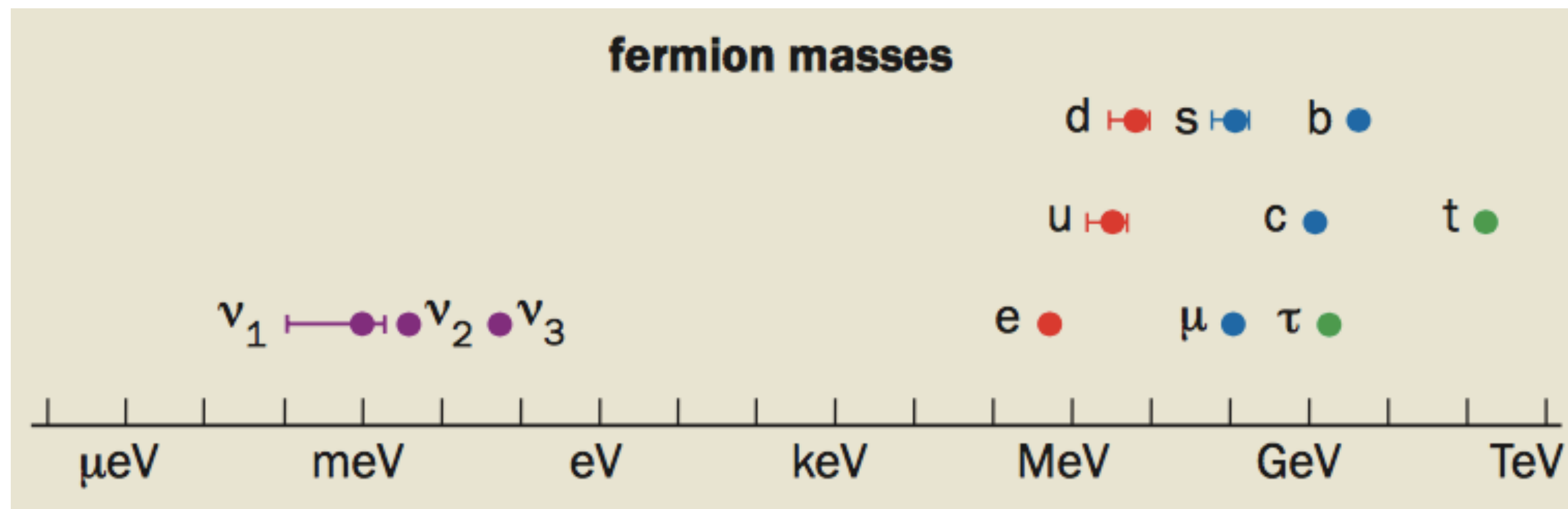


Why is our universe made of matter and not anti-matter?

2. One of the major shortcomings of our understanding of particle physics is the matter over anti-matter asymmetry in the universe.
3. While the Standard Model does predict a matter vs. anti-matter asymmetry, it is much too small compared to what we observe.
4. Moreover, the thermal history of electroweak symmetry breaking is important for particle physics and cosmology. If in the early universe, there was a first order electroweak phase transition (think boiling water), this could explain the matter vs. anti-matter asymmetry as well as sources for potentially observable gravitational radiation.
5. The Standard Model's prediction is again clear – no first- order transition. Therefore if such a transition took place, the Higgs doesn't act alone and some new physics is present.

The neutrino masses....

2. How to incorporate in SM neutrino masses?
Why are they so small?



New physics should appear in the worst case at Planck scale where quantum gravity effects become important and quantum field theory breaking down. Very large scale $1.22 \times 10^{19} \text{ GeV}$!

Hierarchy Problem

If SM is a complete description of Nature



no hierarchy problem.

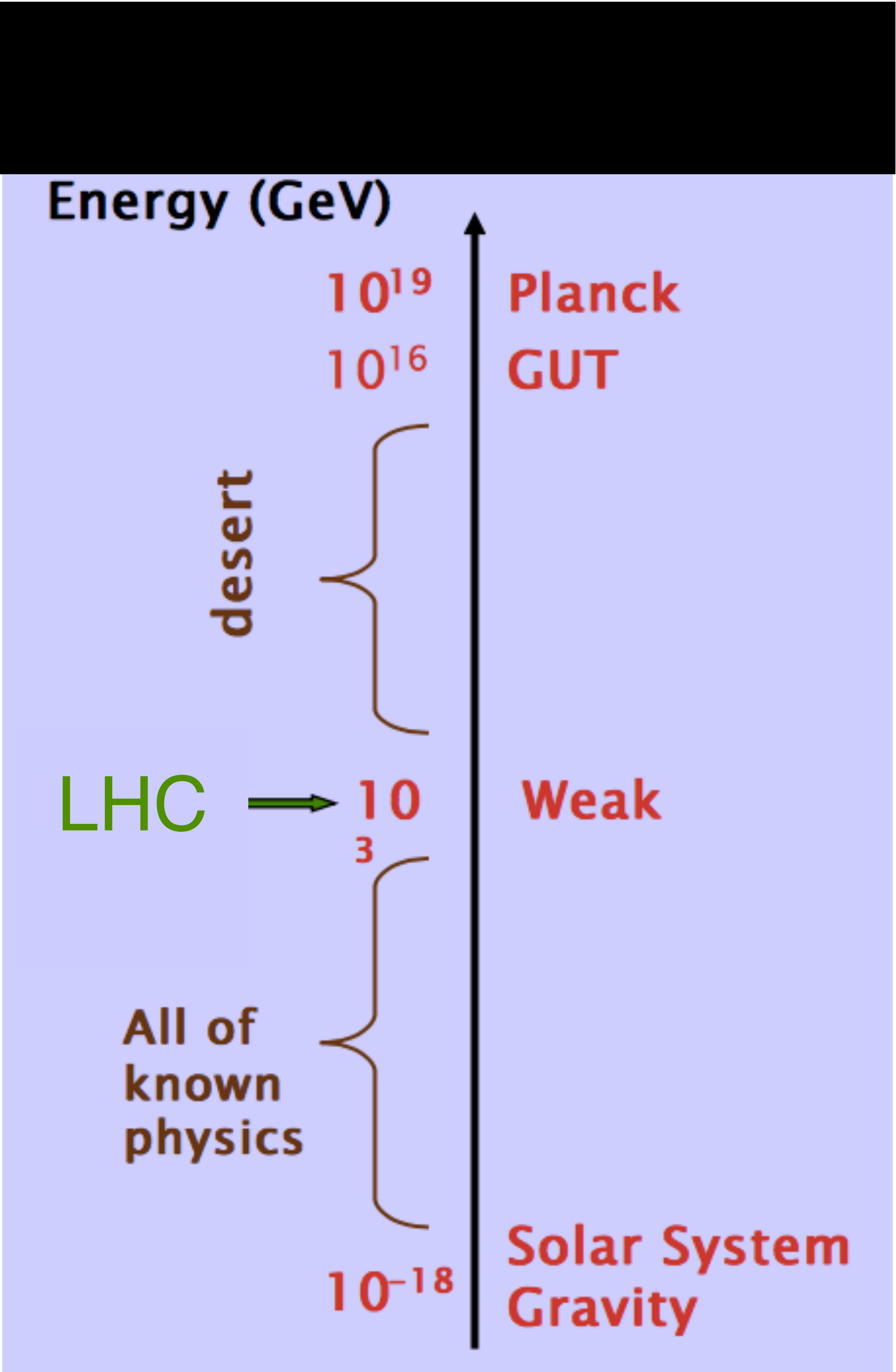
But the SM has unresolved issues which point to New Physics (NP)

If NP appears at Planck scale unnatural large difference wrt EW Scale

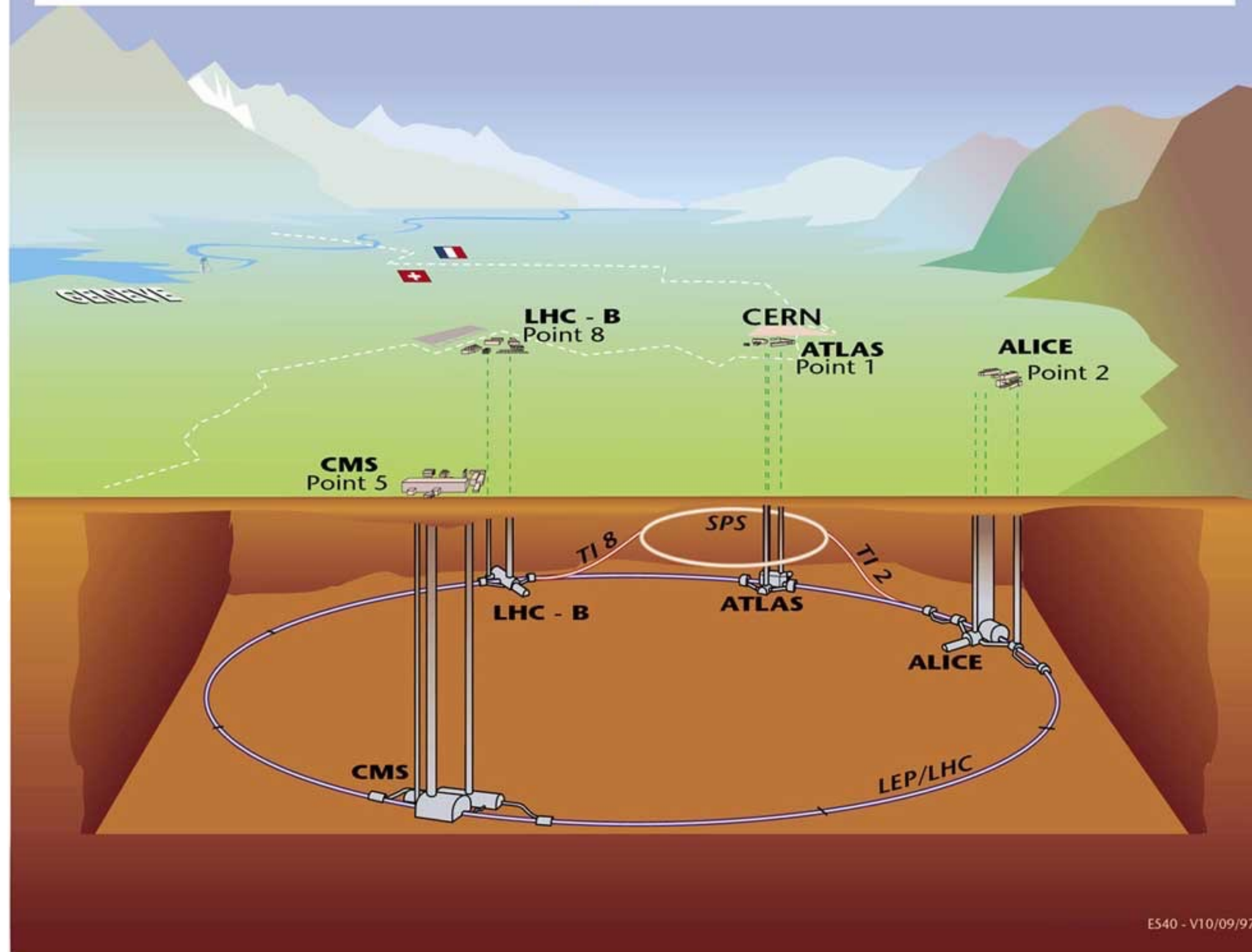
Most accredited models
predict NP @TeV scale.
1TeV=1000GeV



LHC range



Overall view of the LHC experiments.

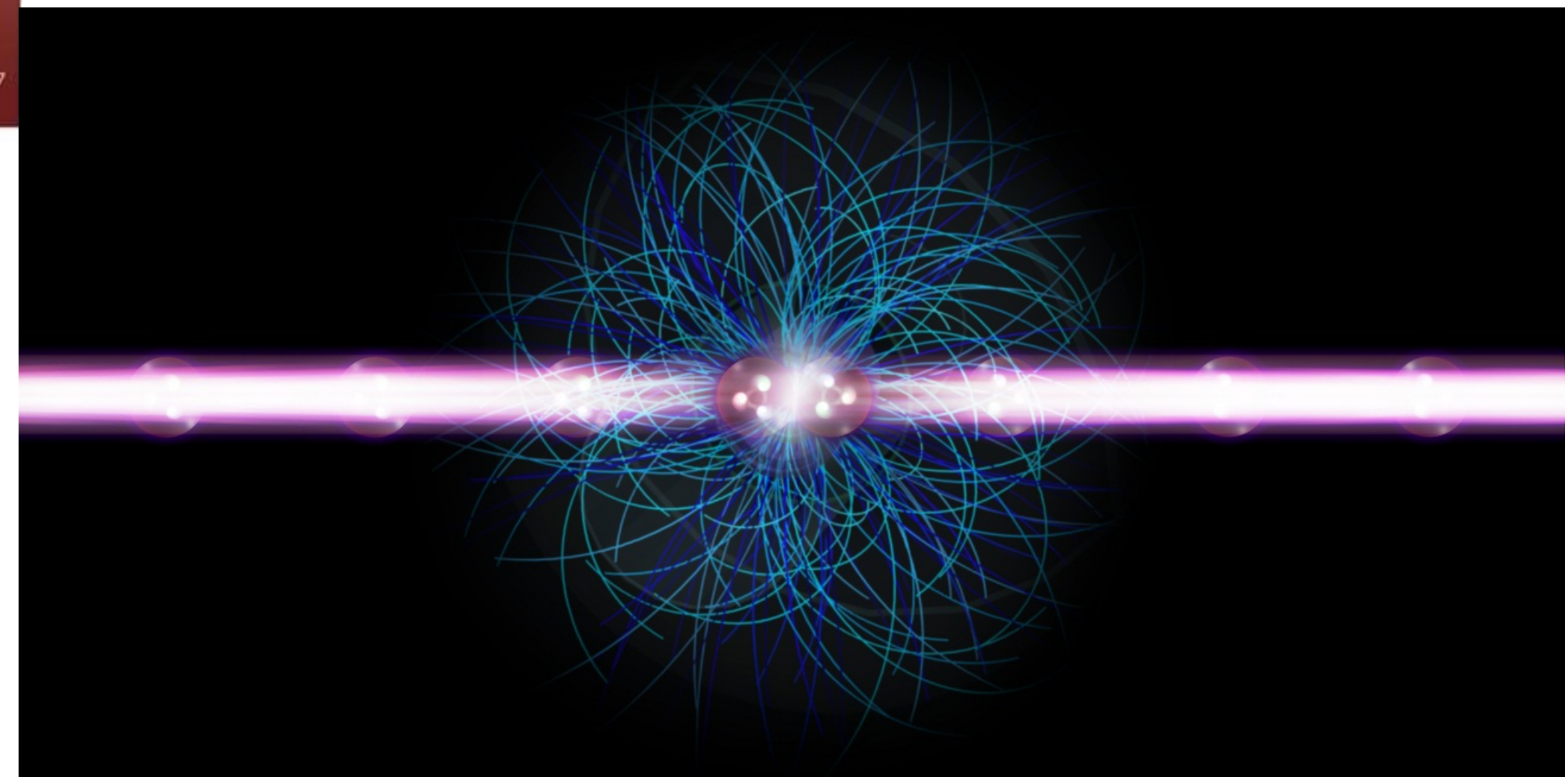


LHC

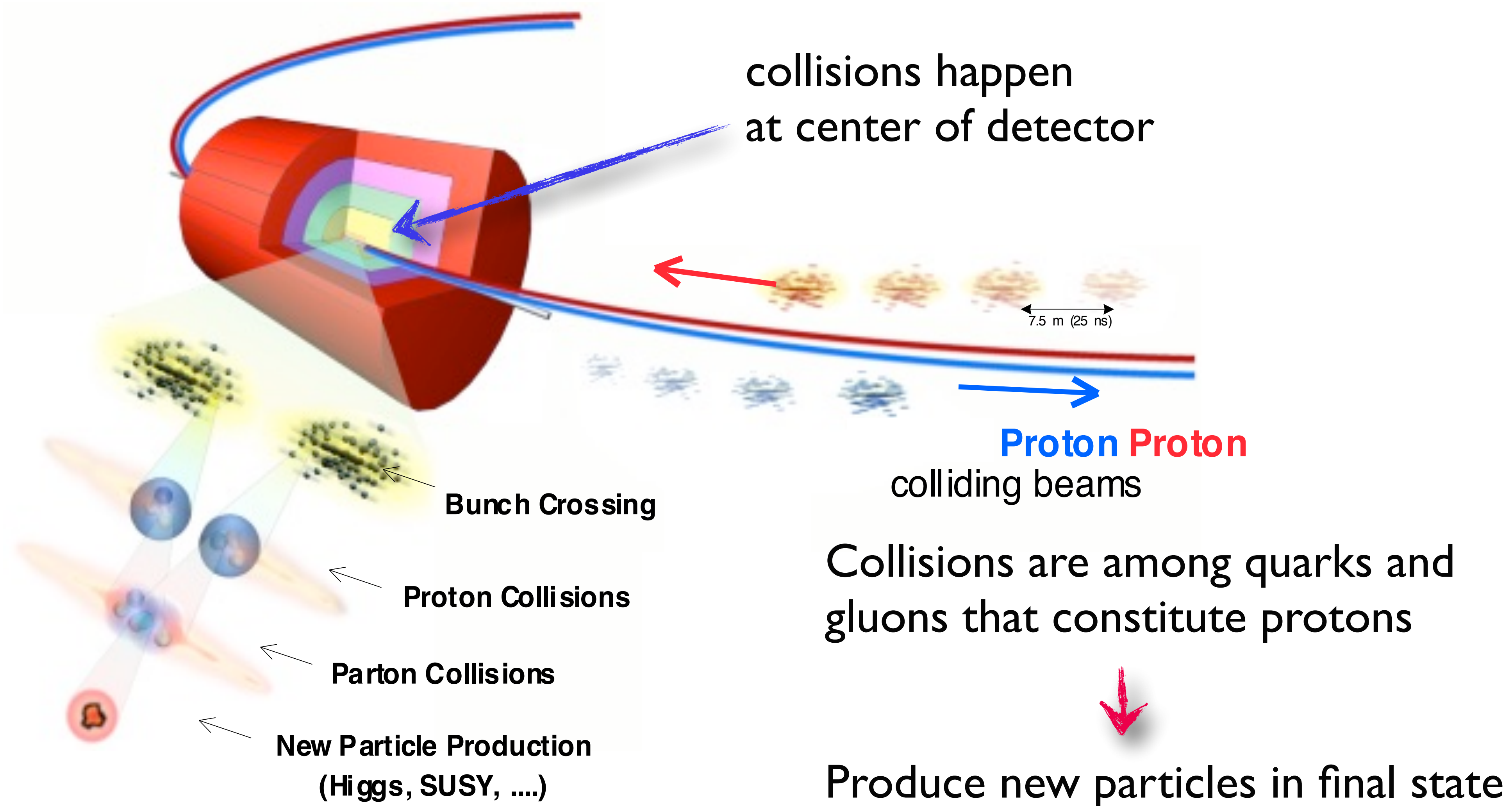
LHC accelerates protons in opposite directions along a 28 km ring.

Protons collide at experiments @13.6 TeV

**Collisions bring us back to Big Bang
producing particles abundant at that time**

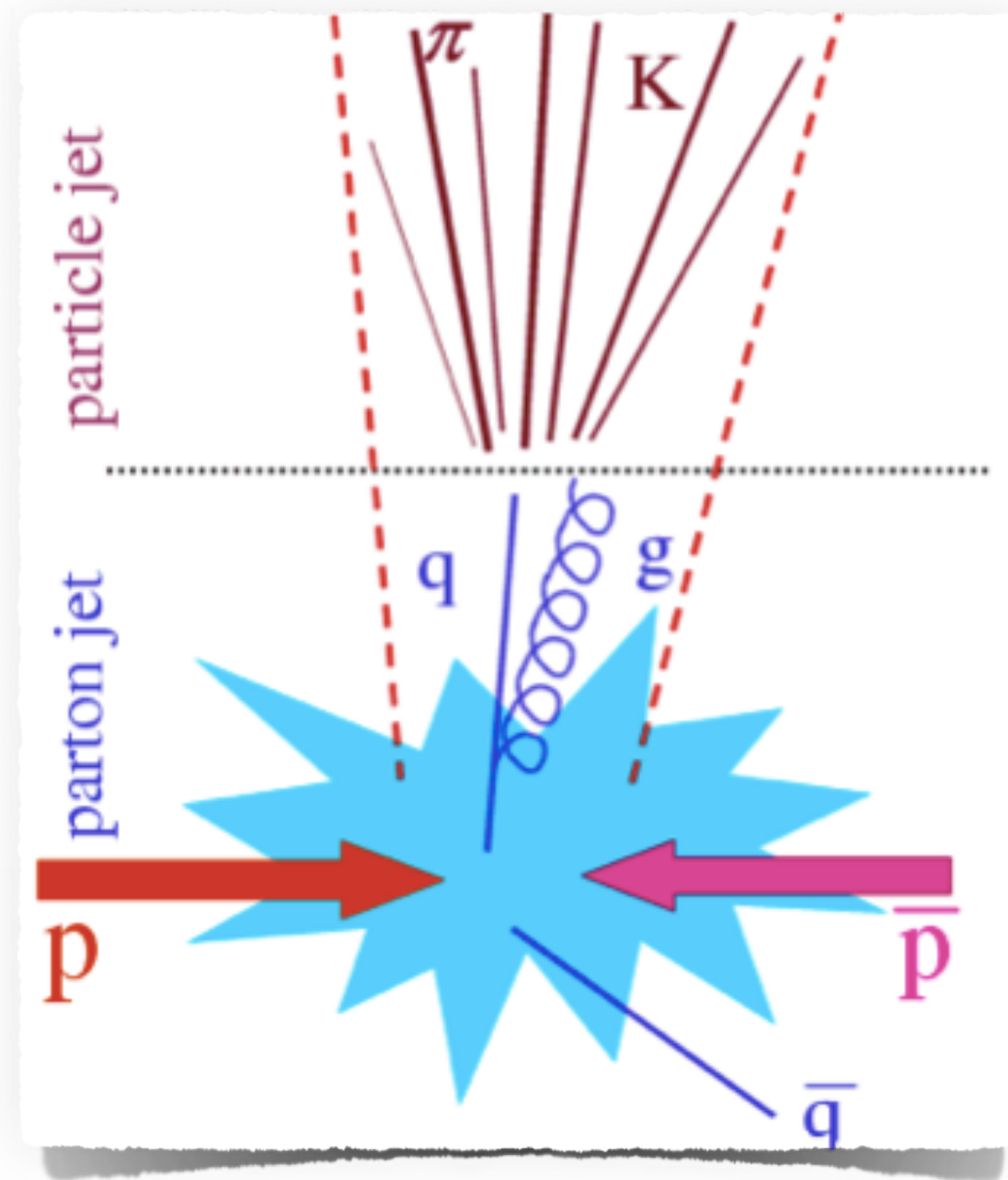


TeV collisions



Typical detector

Detectors built to observe particles produced in collisions

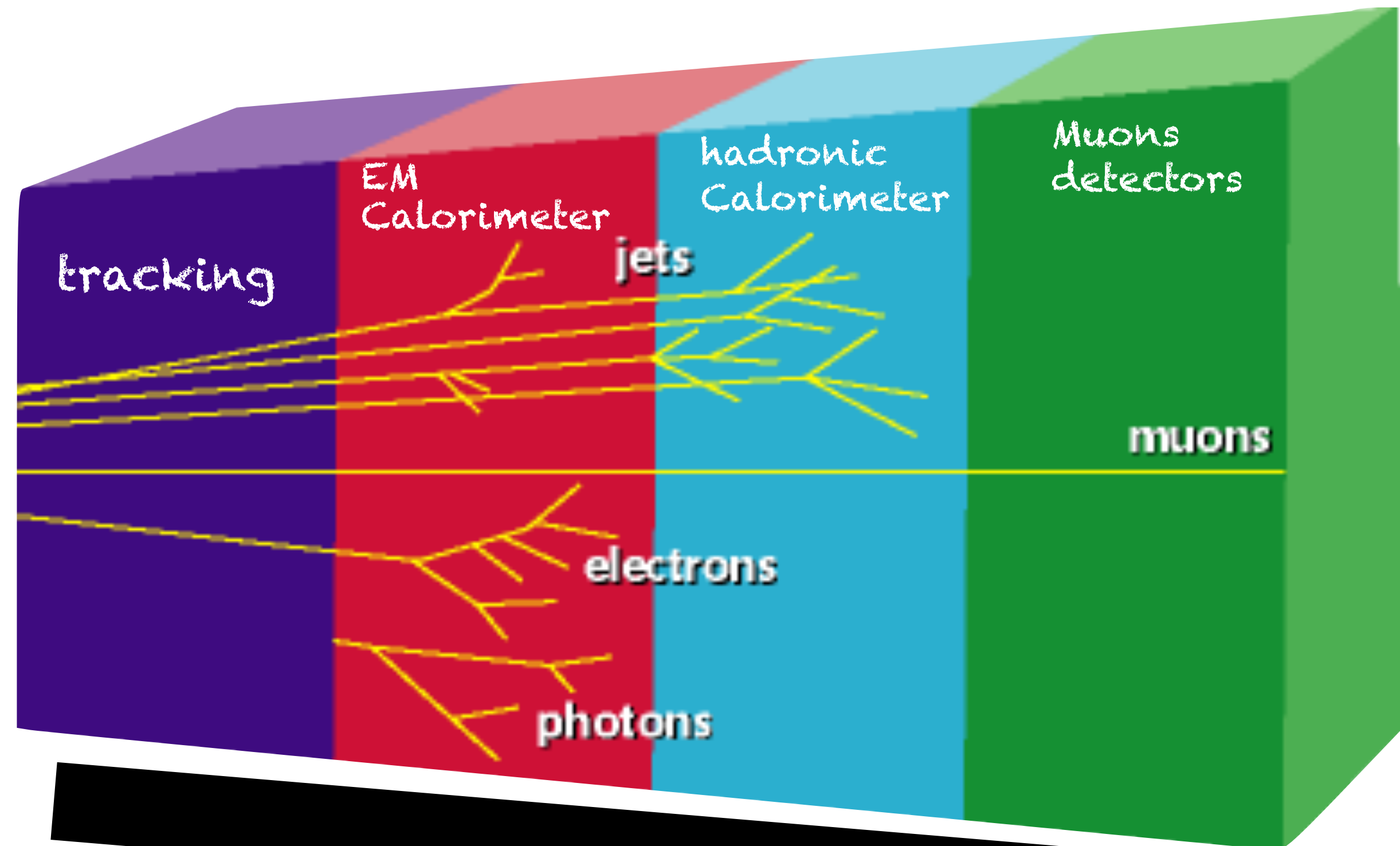


quark/gluons seen as jets of particles in a narrow cone

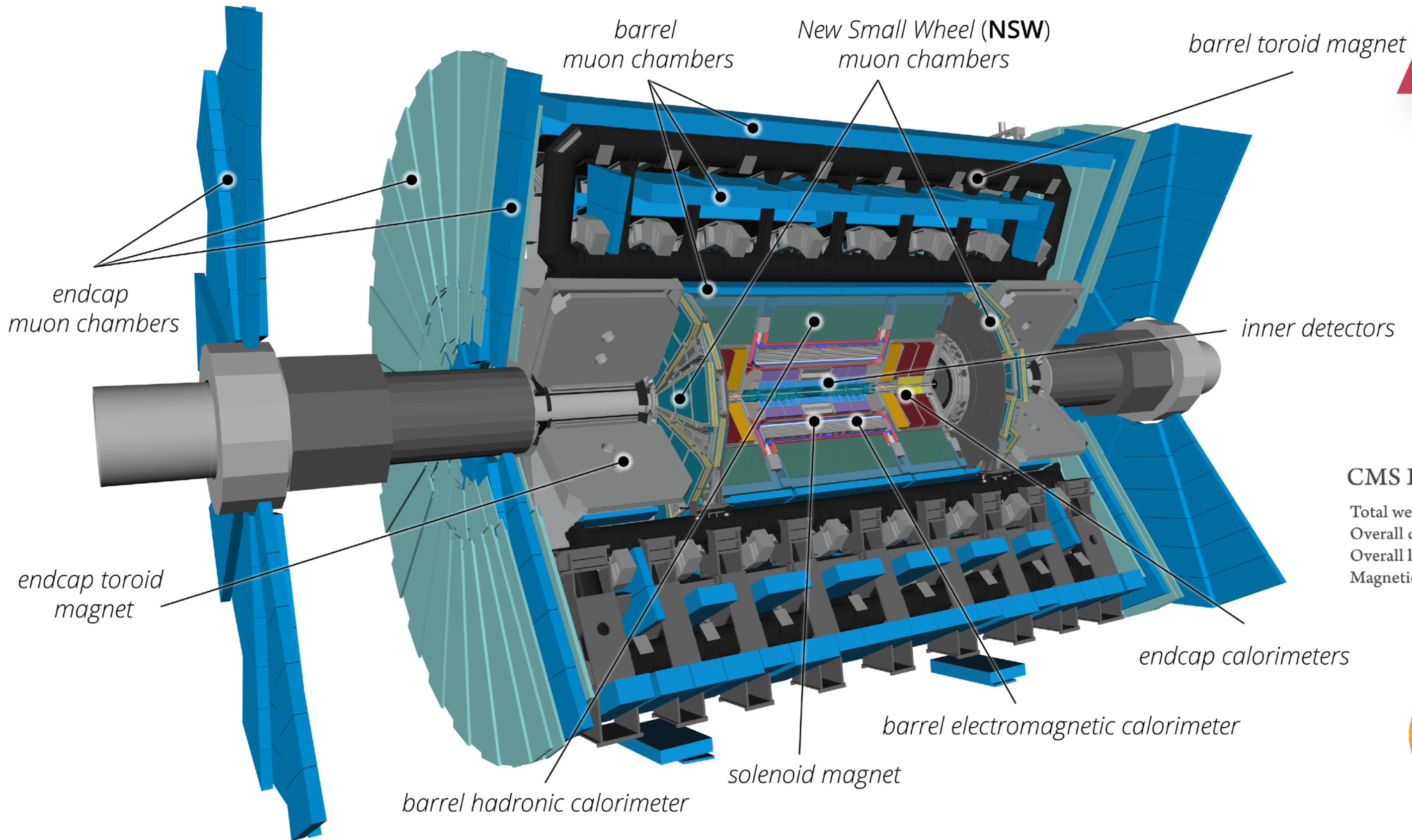
particles interact differently with detector



used to disentangle them

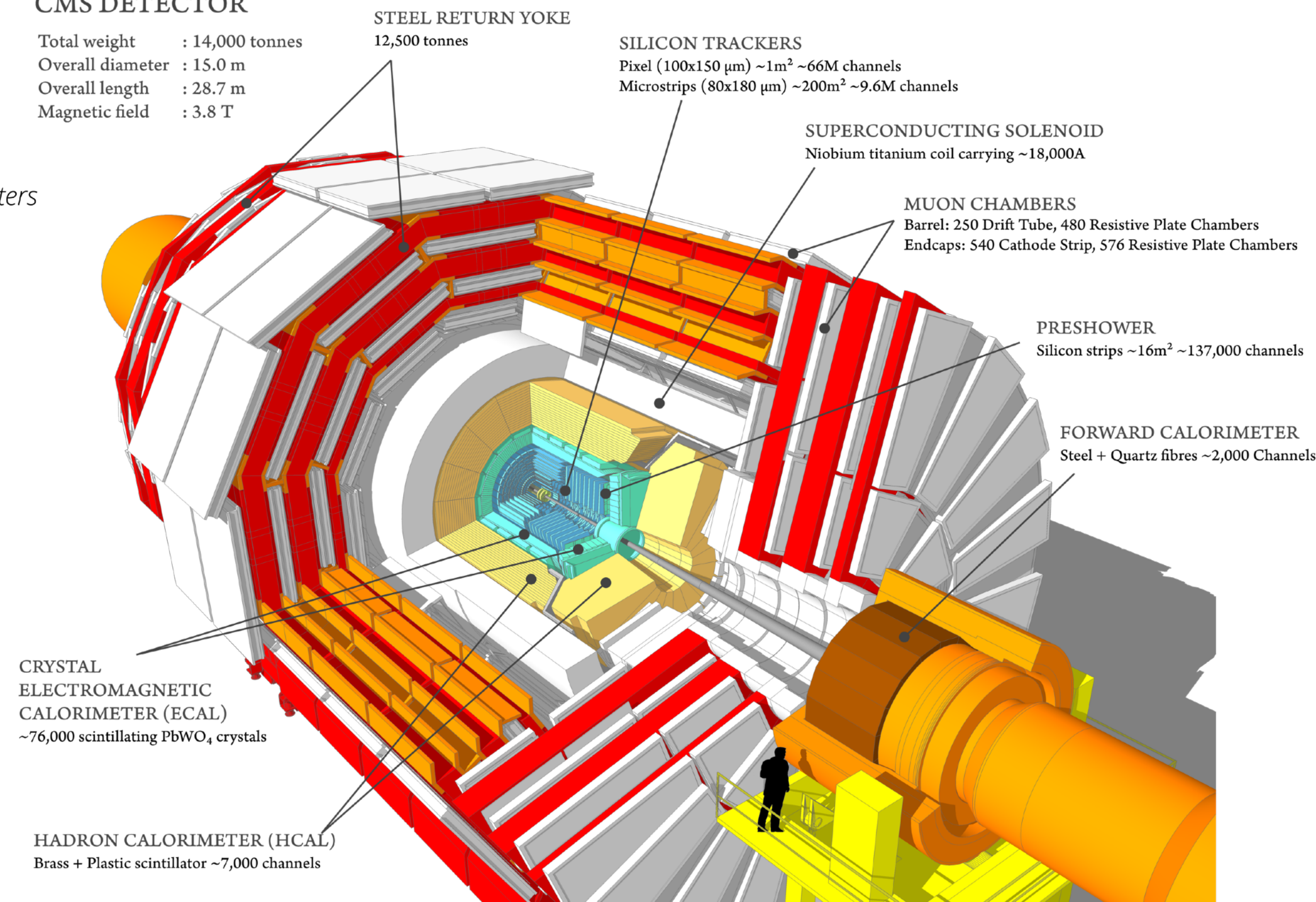


ATLAS and CMS



CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T



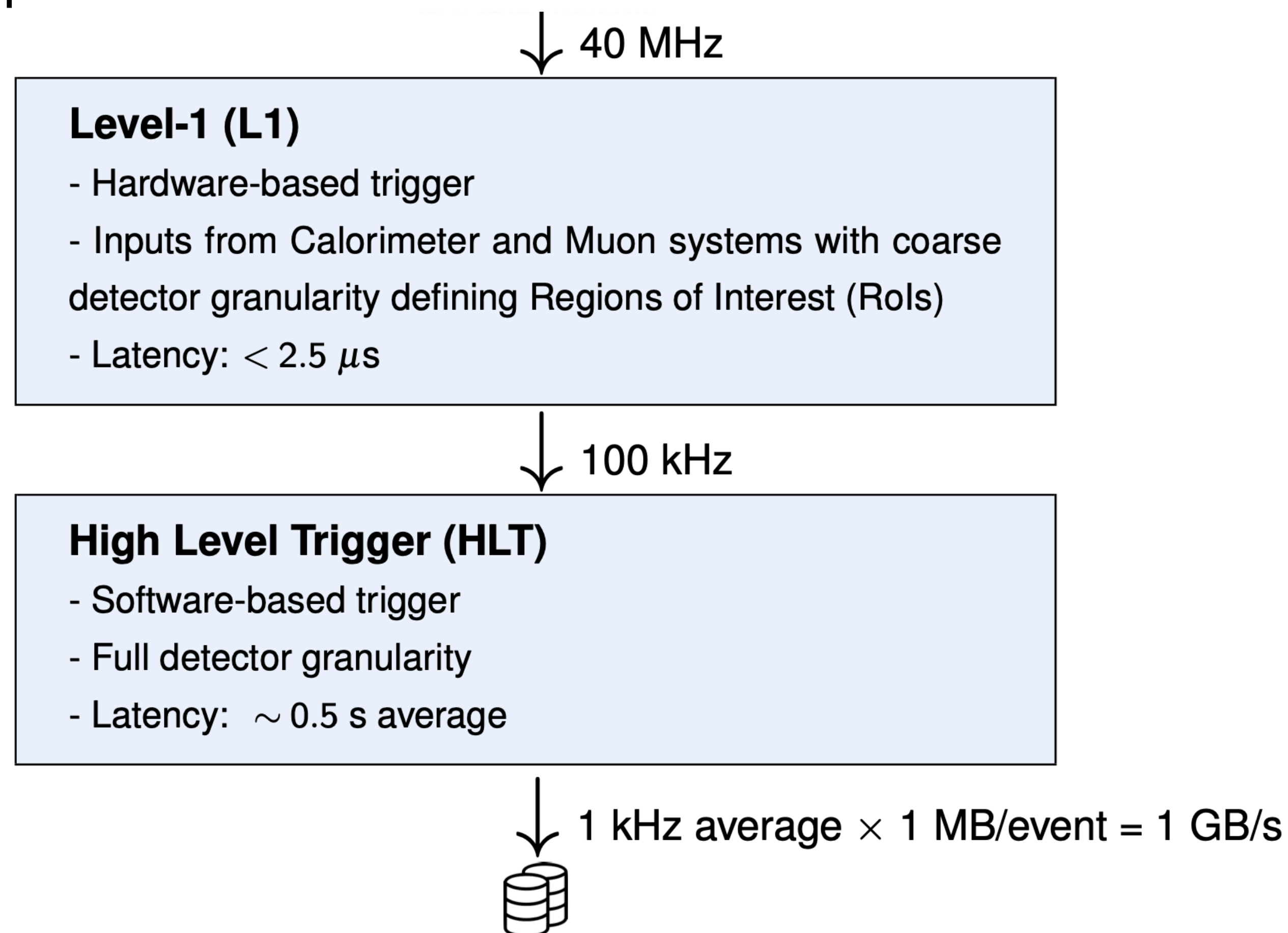
ATLAS and CMS in Berlin





ATLAS Detector Trigger

- Trigger (online event selection for permanent storage) is of paramount importance since is the first cut applied any physics analysis
- Two level trigger system



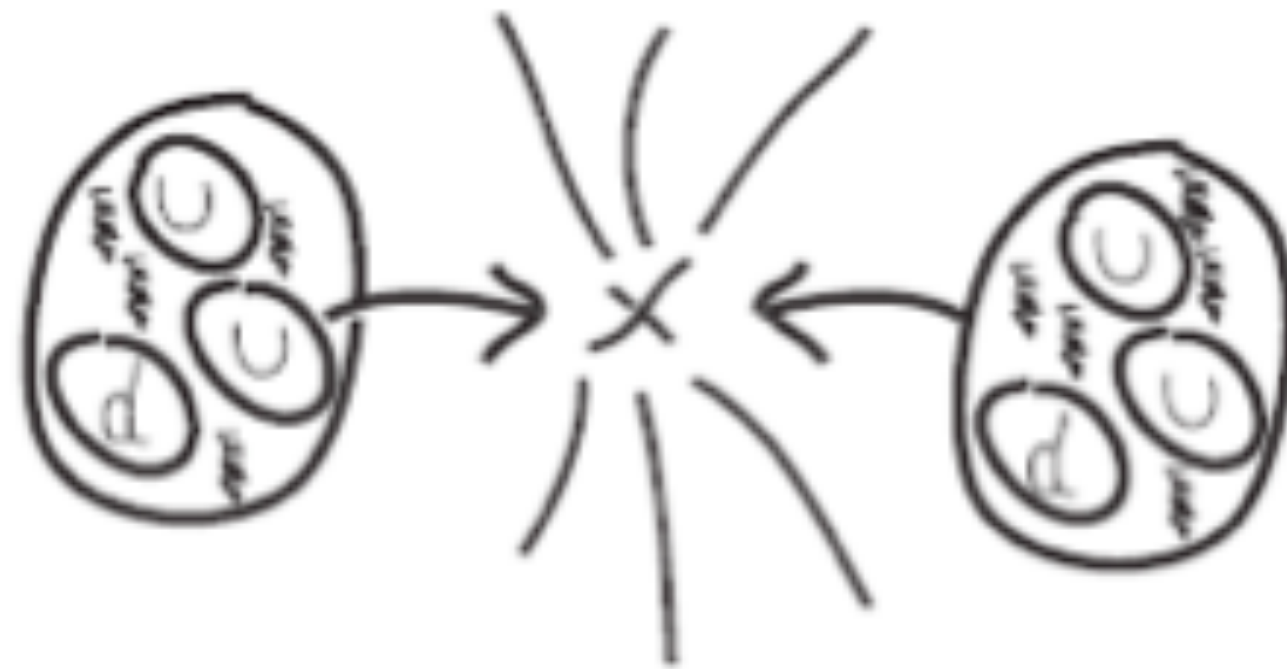
The Structure of an event

I will here introduce few concepts by showing what happens when two protons interact, i.e:

- hard scatters
- Radiation: ISR/FSR
- Pile-up
- Parton Density Functions (PDF's)

Few useful reminders on hadron collider kinematics

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



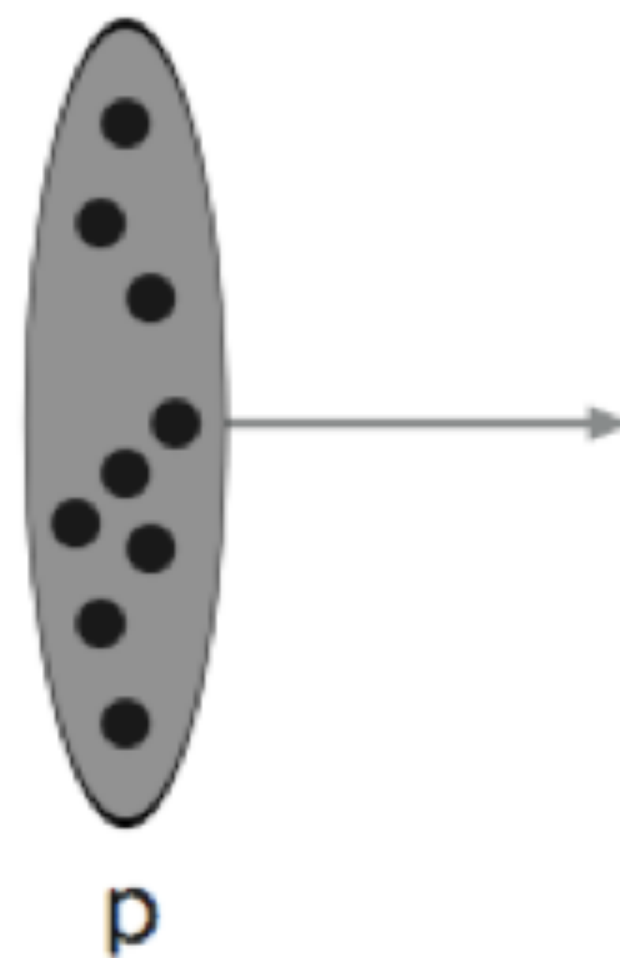
The energy of each beam is carried not by the entire proton, but by one of its constituents

$$E_{\text{collision}} < 2E_b$$

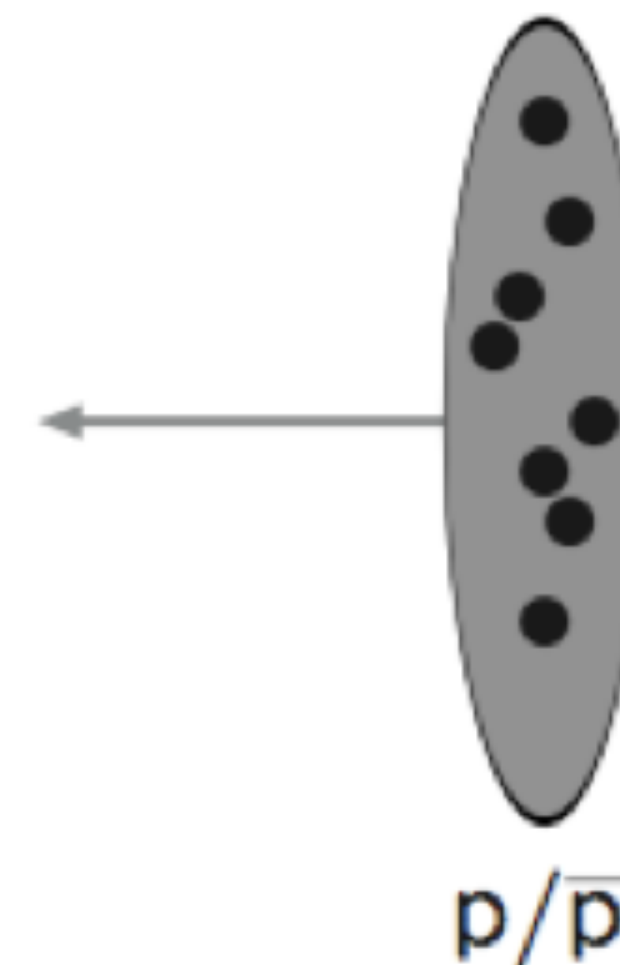
Pros: with a single energy possible to scan different processes at different energies

Cons: the energy available for the collision is lower than the accelerator energy

The Structure of an event: PDFs



Initially two beam particles are coming in towards each other. Normally each particle is characterized by a set of parton distributions, which defines the partonic substructure in terms of flavour composition and energy sharing. This determines the energy of the interacting partons (x_1, x_2)

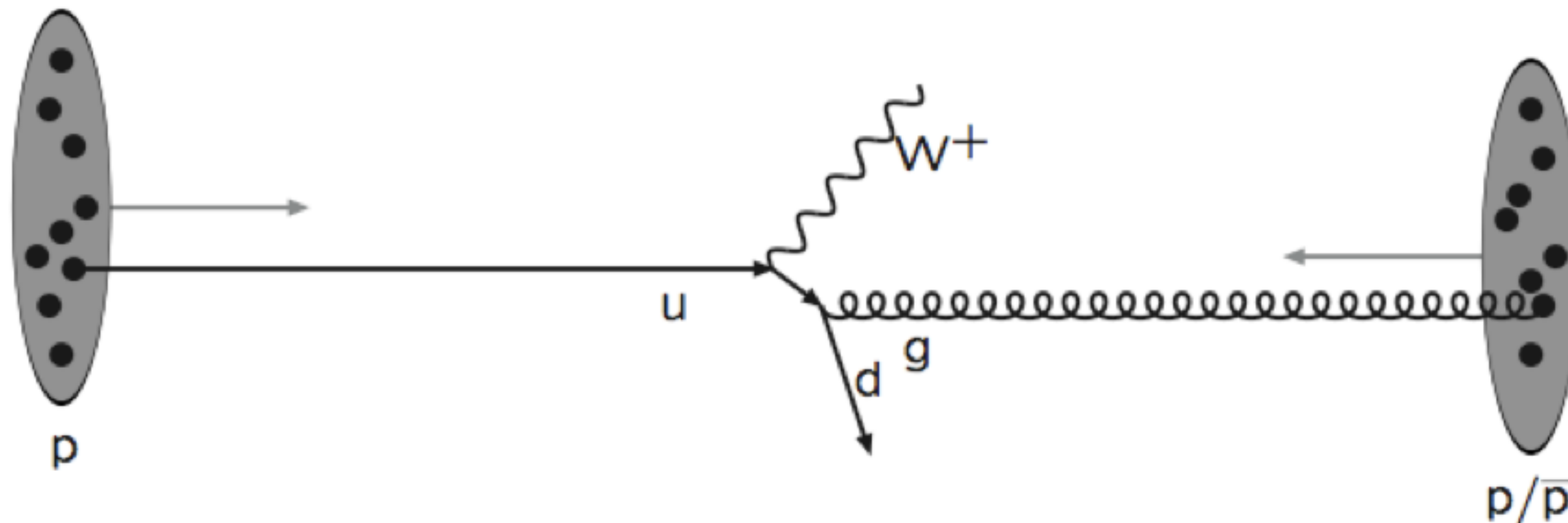


$$|\sigma(p(P_1) + p(P_2) \rightarrow Y)| = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \rightarrow Y)$$

Incoming beams: parton densities

partonic x-section:
phase space* matrix element

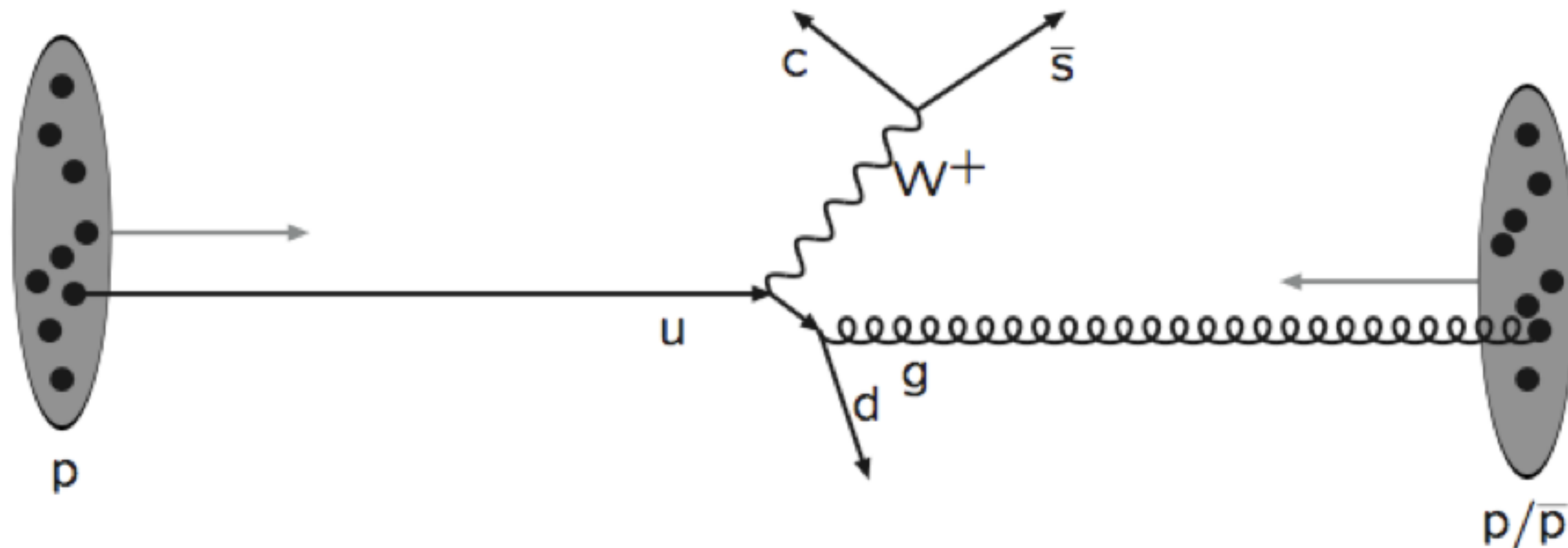
The Structure of an event



→ One incoming parton from each of the protons enters the hard process, where then a number of outgoing particles are produced. It is the nature of this process that determines the main characteristics of the event.

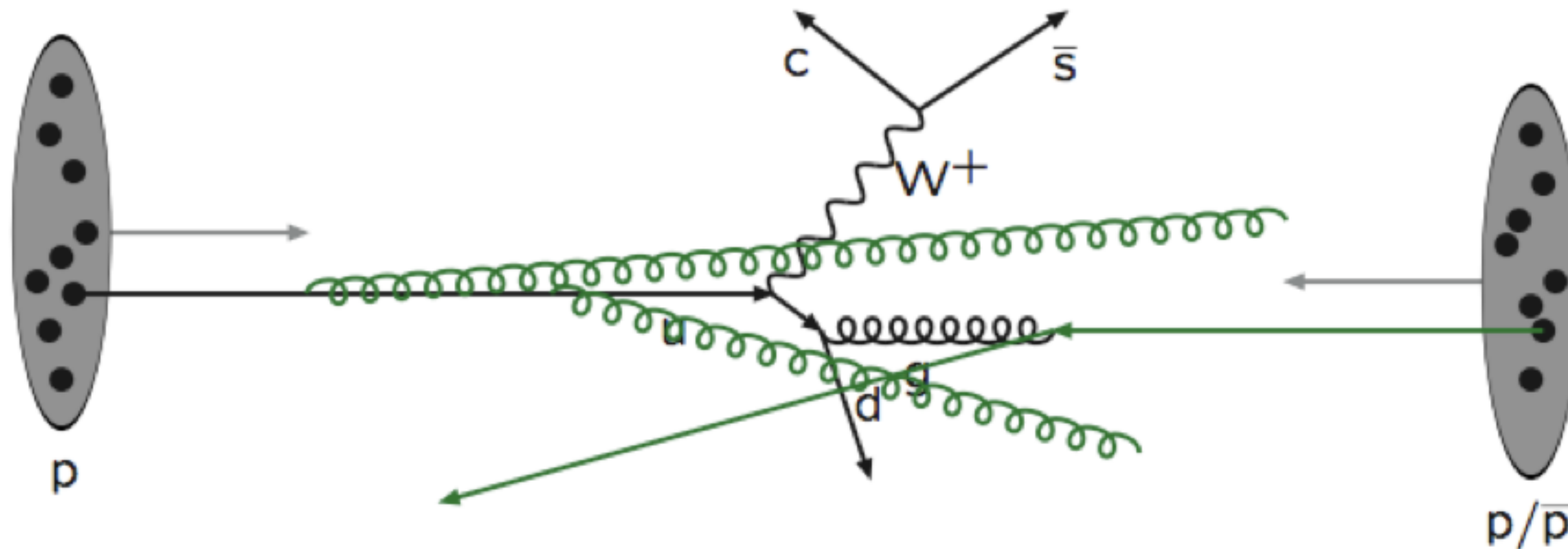
Hard subprocess: described by matrix elements

The Structure of an event: resonances



The hard process may produce a set of short-lived resonances,
like the $Z^0/W^\pm$ gauge bosons.

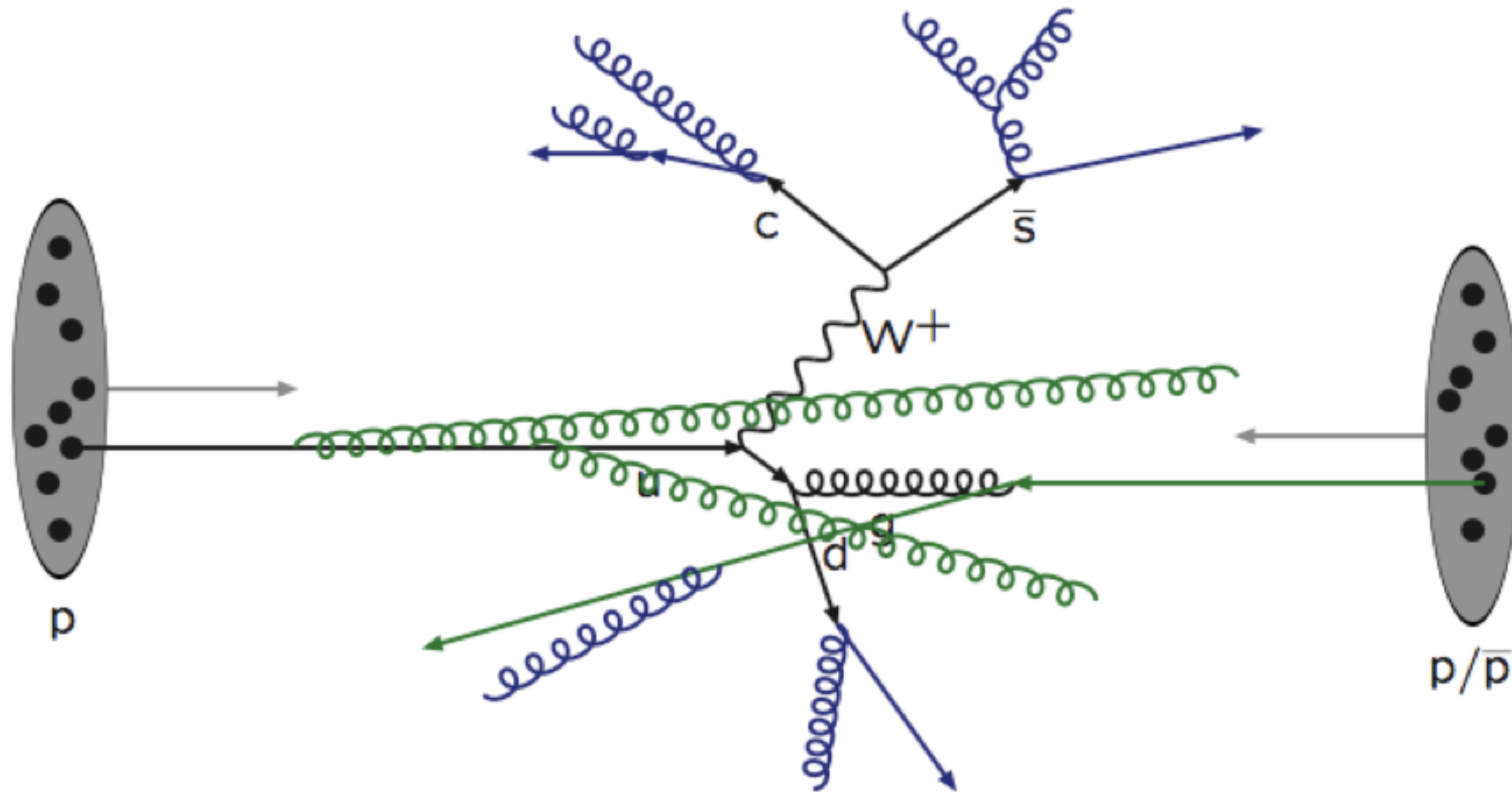
The Structure of an event: ISR



One shower initiator parton from each beam may start off a sequence of branchings, such as $q \rightarrow qg$, which build up an initial-state shower.

Initial-state radiation: spacelike parton showers

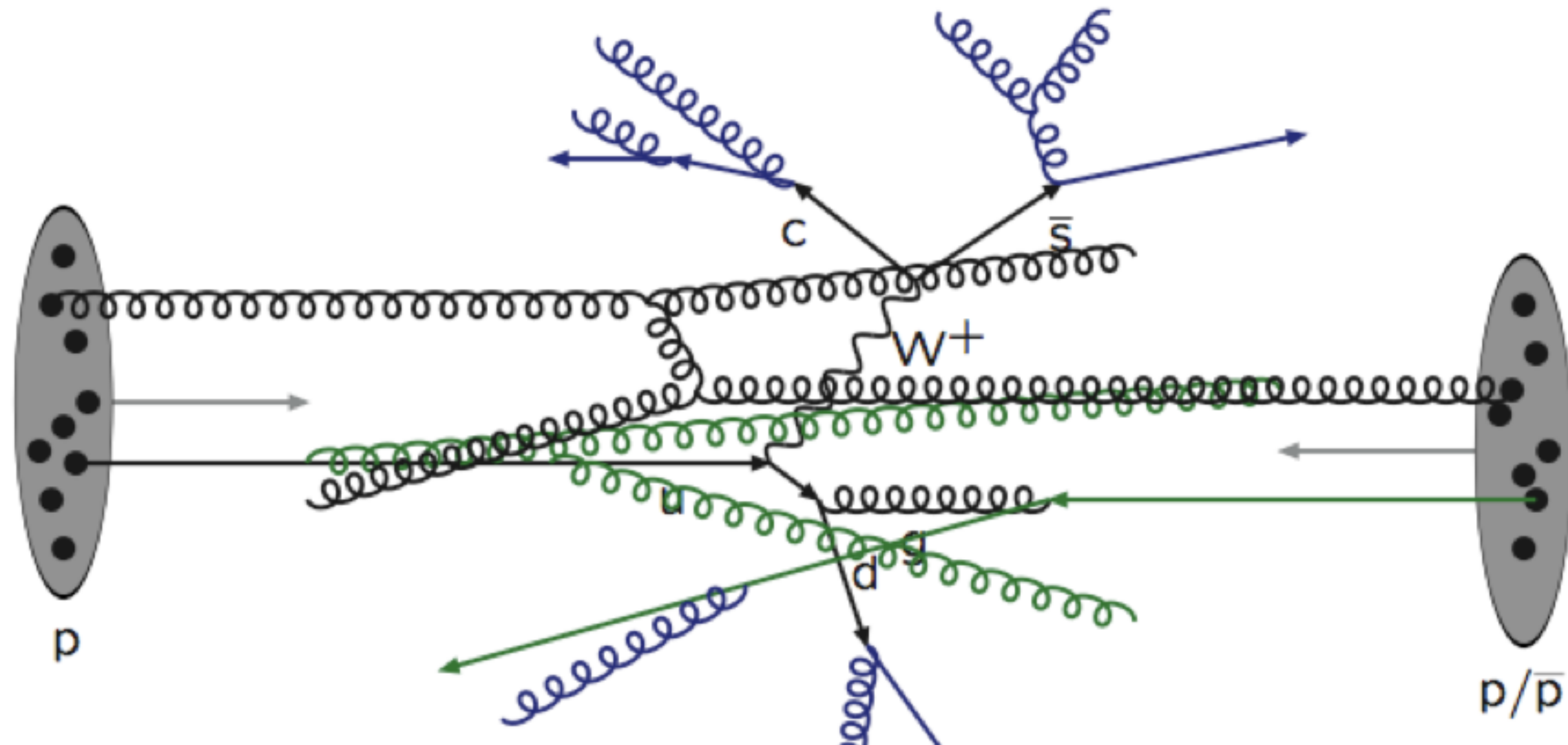
The Structure of an event: FSR



The outgoing partons may branch, just like the incoming did, to build up final-state showers.

Final-state radiation: timelike parton showers

The Structure of an event: pile-up



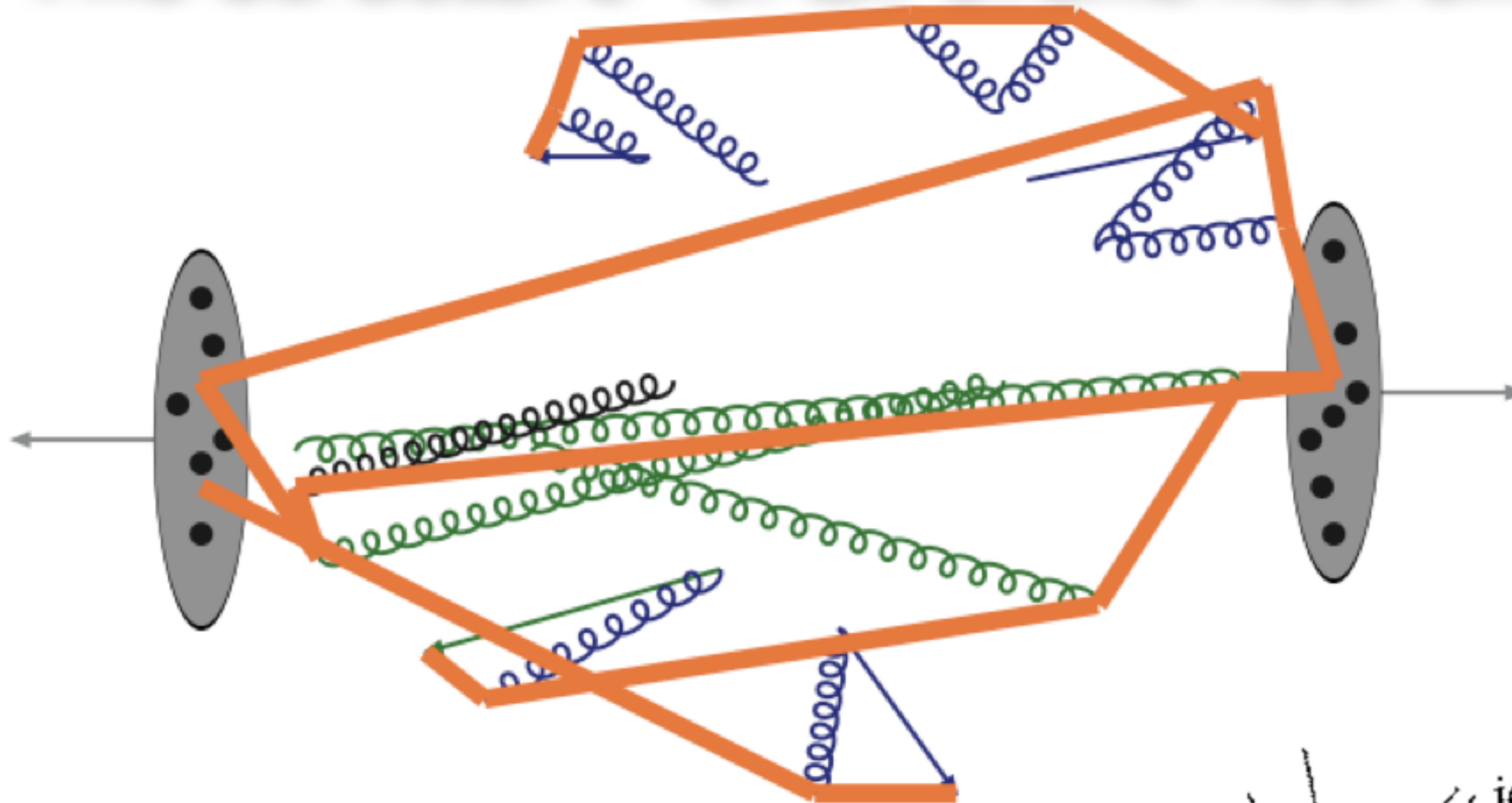
In addition to the hard process, further semihard interactions may occur between the other partons of two incoming hadrons.

There is in time pile-up which comes from the same bunch of protons from the interaction of interest, and can be resolved by setting the interaction points location by identifying vertices.

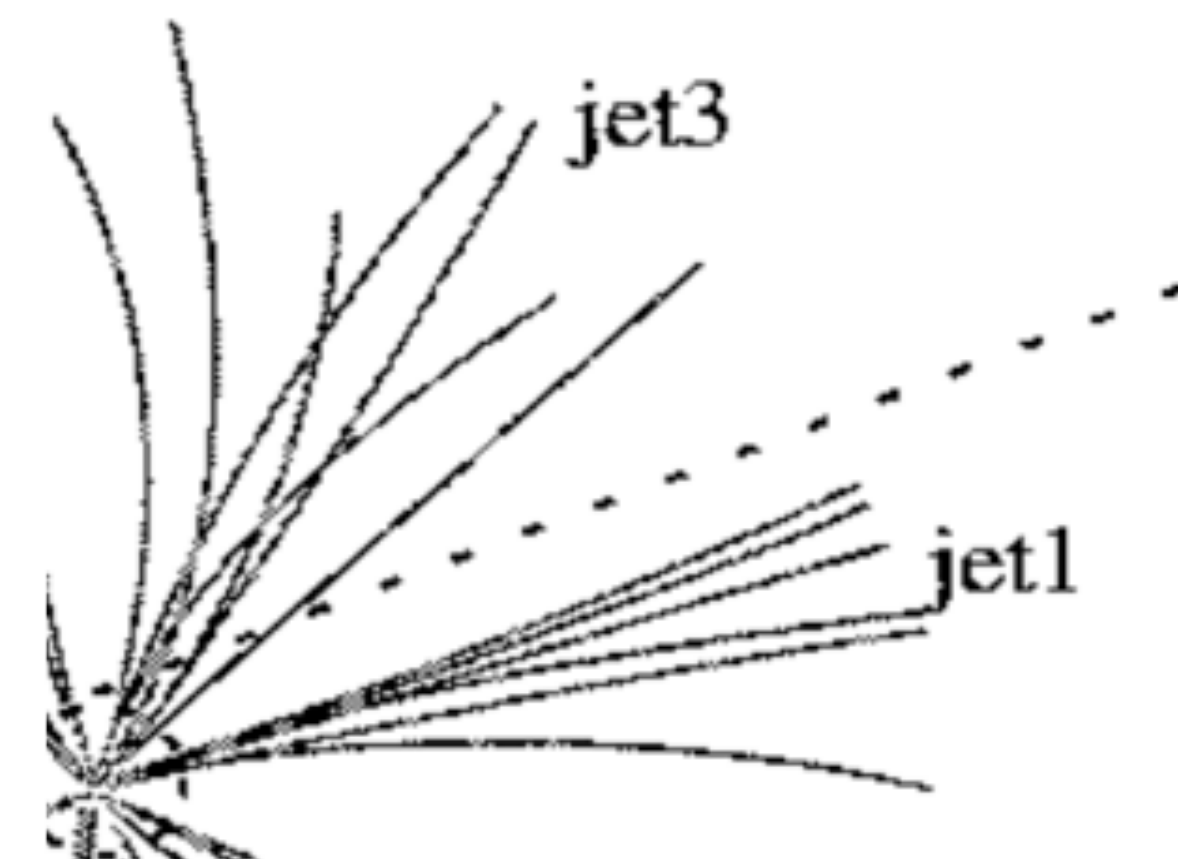
The second type is out-time pile-up, which comes from other proton bunches when the detector has not yet recorded the signal completely due to dead time, the time needed for a certain detector to be able to record an event after a previous one

The event
structure

The Structure of an event: hadronisation



The result of the hadronization is that quark and gluons are not observed as free particles but as Hadrons, and actually in the detector as jets of particles in a narrow cone



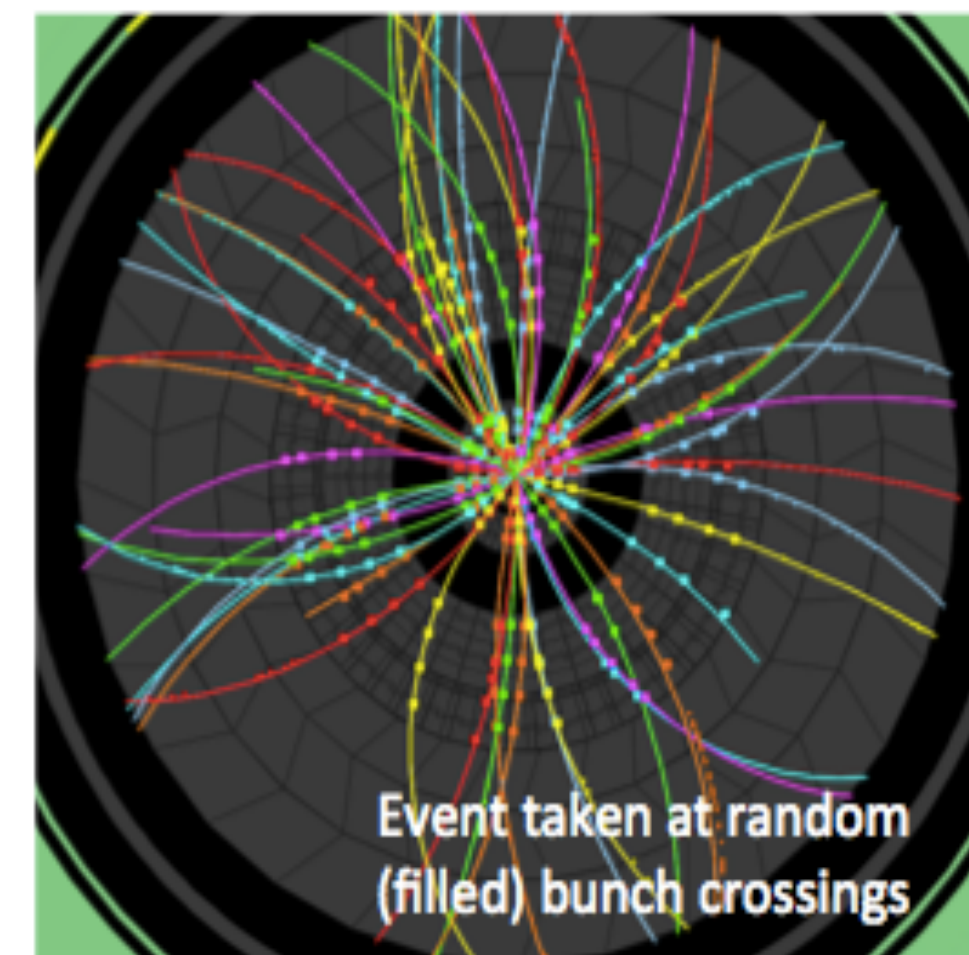
The event
structure

Pile-up

2010

O(2) Pile-up events

150 ns inter-bunch spacing



2011

O(10) Pile-up events

50 ns inter-bunch spacing



- Design value
(expected to be
reached at $L=10^{34}$!)

2012

O(20) Pile-up events

50 ns inter-bunch spacing



The event structure

the cross-section

number of observed events

background contamination in the sample

cross section: $\sigma = \frac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt}$

analysis efficiency
 $\varepsilon = \varepsilon_{tr} \cdot \varepsilon_{reco} \cdot \varepsilon_{ID} \cdot \varepsilon_{sel}$

luminosity delivered by LHC

1 barn = $10^{-28} \text{ m}^2 = 10^{-24} \text{ cm}^2$

The luminosity is a parameter of the LHC and can be increased

The Cross-section

Number of observed events is proportional to

- 1) Luminosity
- 2) analysis efficiency
- 3) cross section of the process

$$N_{obs} = \int \mathcal{L} dt \cdot \varepsilon \cdot \sigma$$

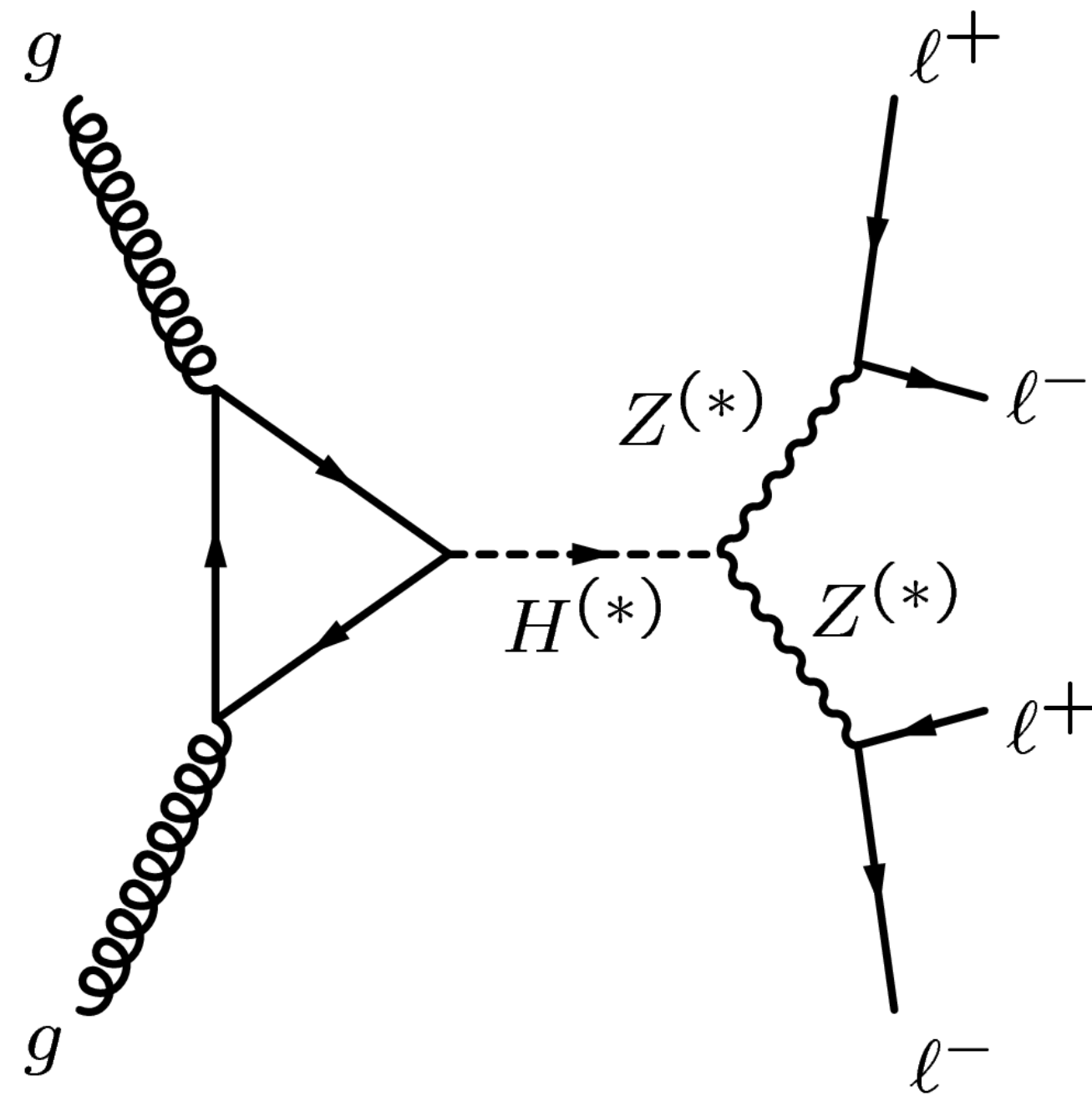
$$L = \frac{f_{rev} n_{bunch} N_p^2}{4 \pi \sigma_x \sigma_y}$$

revolving frequency: $f_{rev} = 11245.5/s$
 #bunches: $n_{bunch} = 2808$
 #protons / bunch: $N_p = 1.15 \times 10^{11}$
 Area of beams: $4\pi\sigma_x\sigma_y \sim 40 \mu\text{m}$

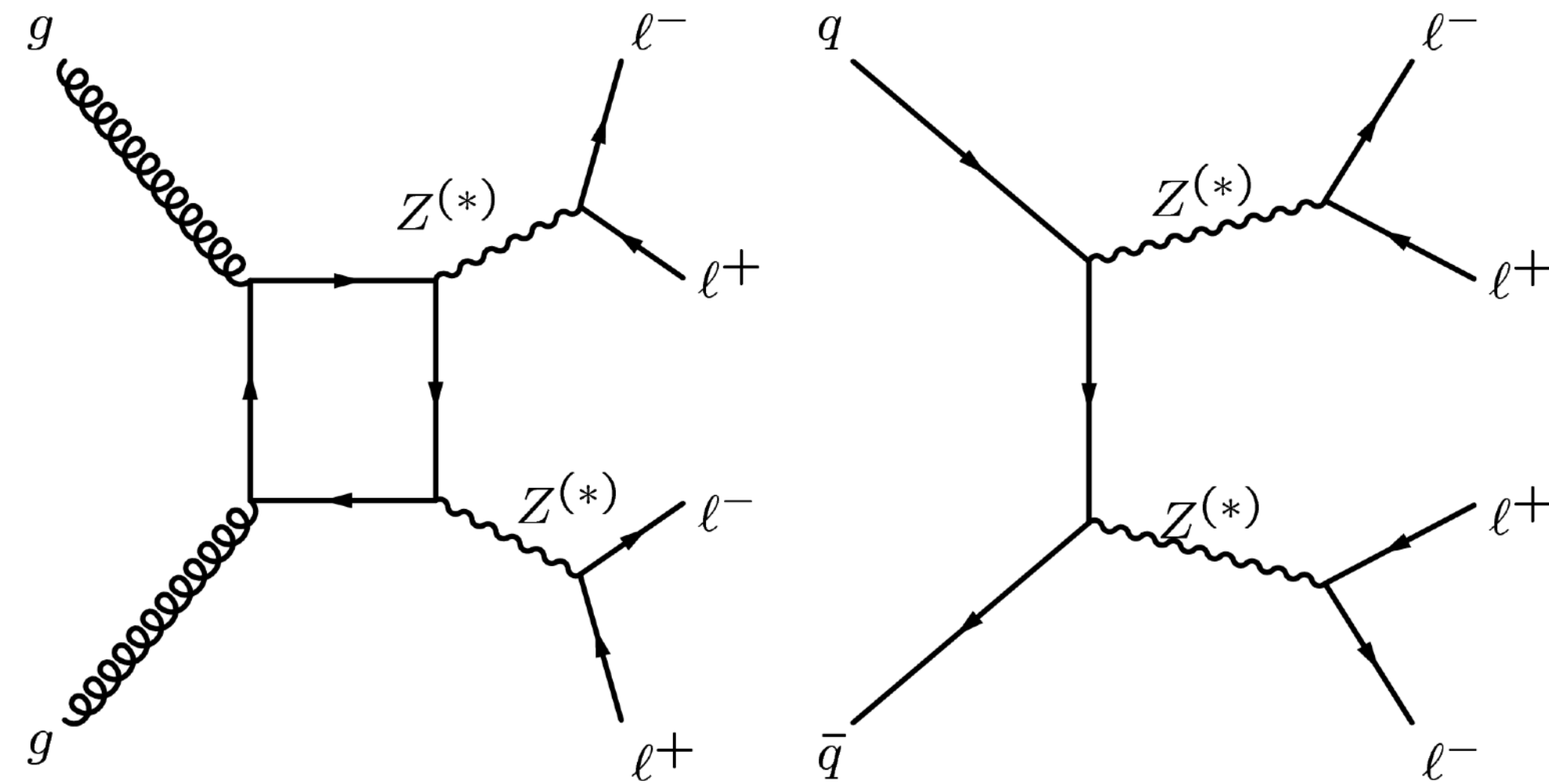
Signal and backgrounds

Other processes (background) can mimic signal final state.
Same particles in the final state!

HIGGS Signal

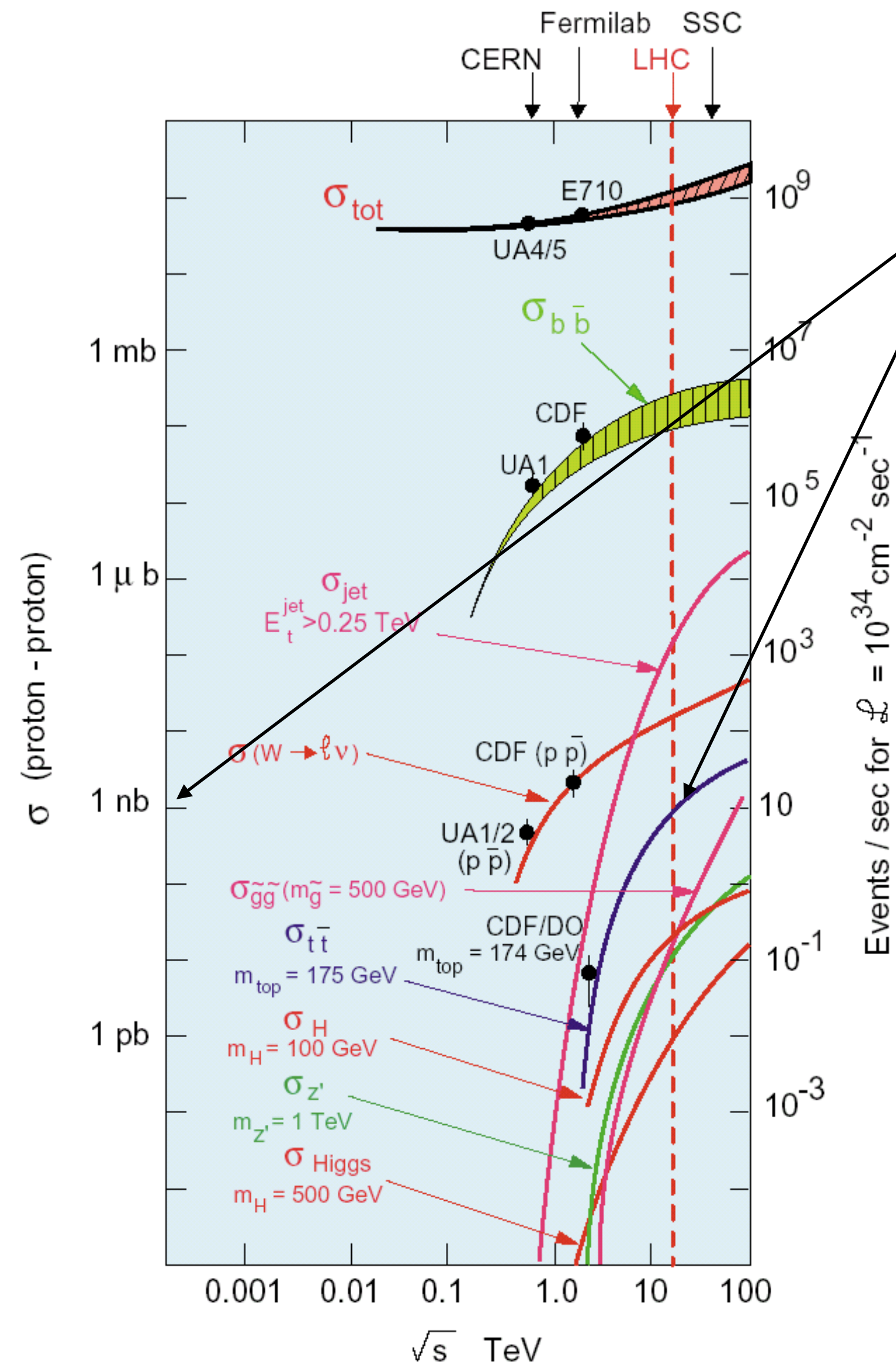


SM backgrounds



The event structure

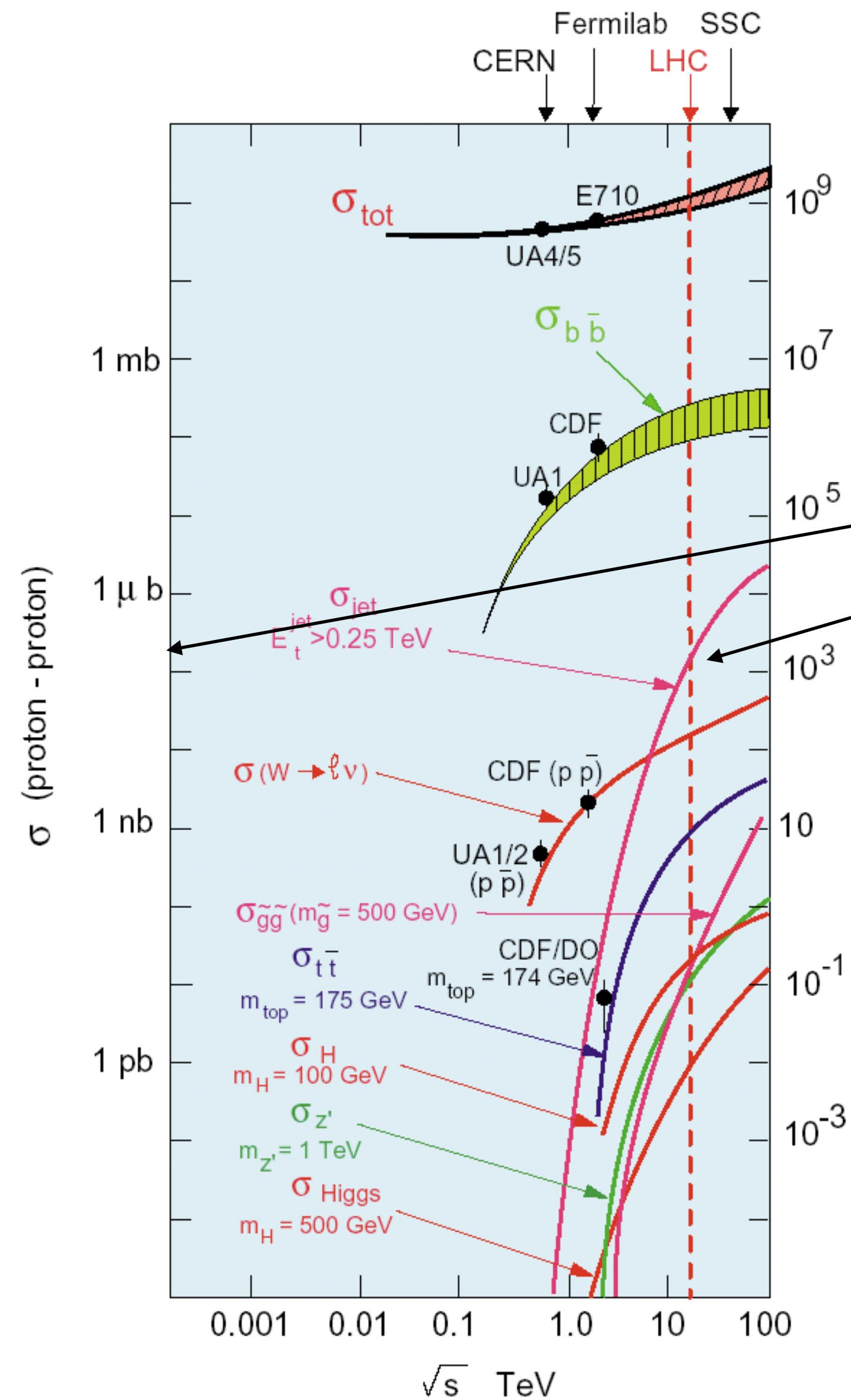
Cross-sections/ number of Events



Large cross-sections and what is interesting is rare:
 - x-section $t\bar{t}$ $\sim 1 \text{ nb}$ (800pb)

The event structure

Cross-sections/ number of Events



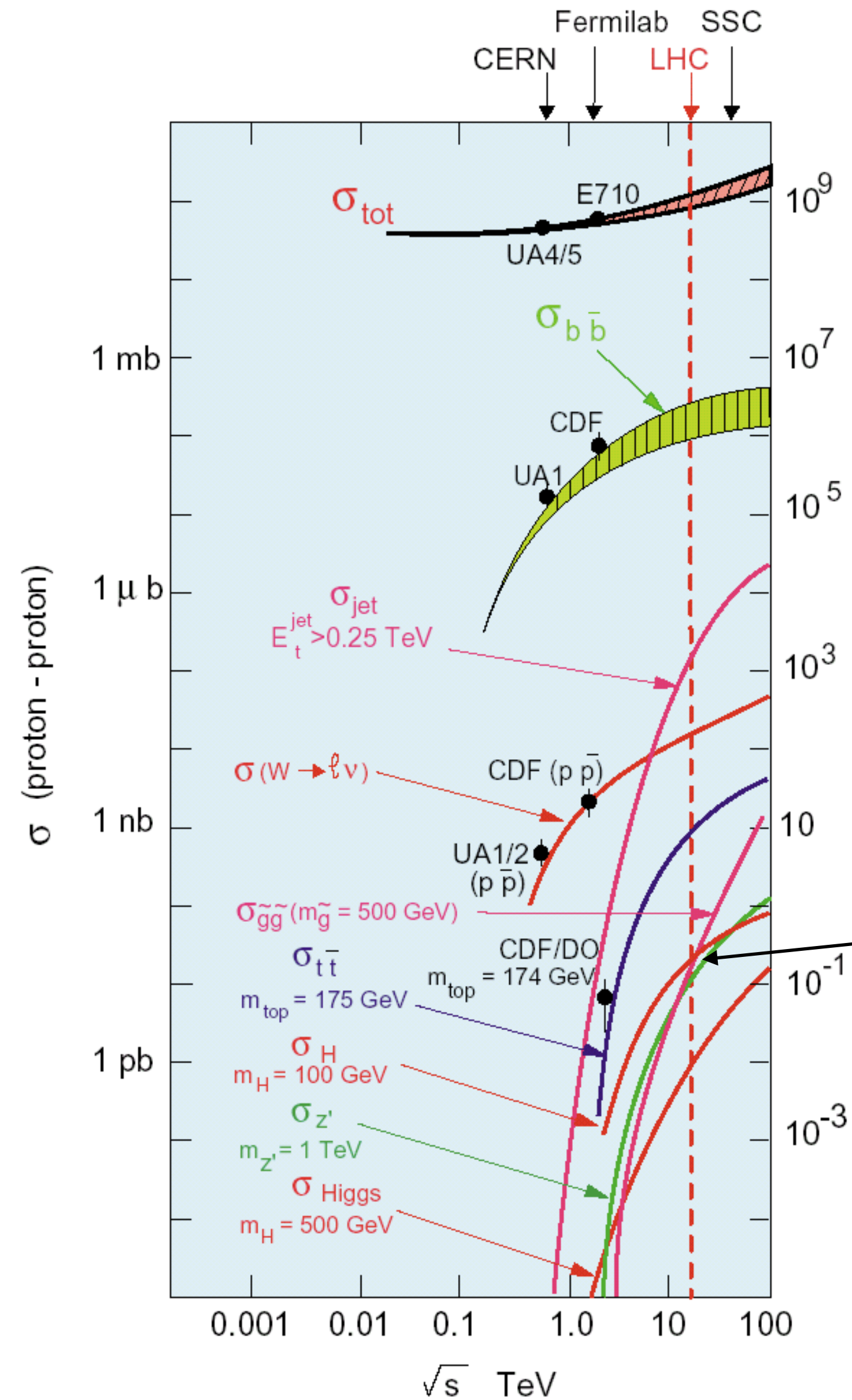
Large cross-sections and what is interesting is rare:

- x-section $t\bar{t}$ $\sim 1 \text{ nb}$ (800pb)

- x-section jet production $\sim 100 \text{ nb}$ (100000pb)

The event structure

Cross-sections/ number of Events



Large cross-sections and what is interesting is rare:

- x-section jet production $\sim 100\text{nb}$ (1000000pb)

- x-section Higgs production $\sim 10\text{pb}$

The event
structure

Looking for diamonds!



Run 1

Run 2

LHC Schedule

We are here

Run 3



The luminosity (L) is a parameter of the accelerator, related to how many collisions one gets and is measured in fb⁻¹

Single Higgs



Single Higgs

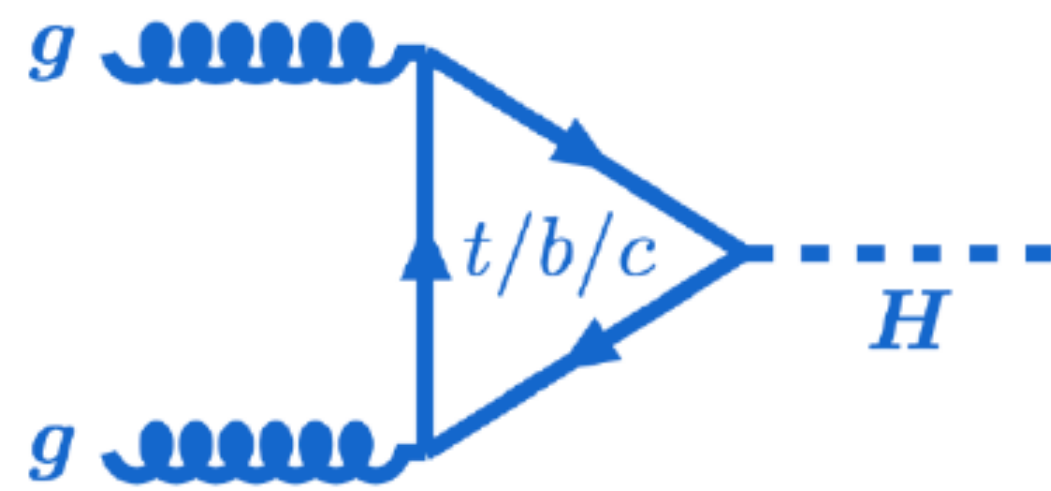


and François Englert & Robert Brout



Single Higgs Production

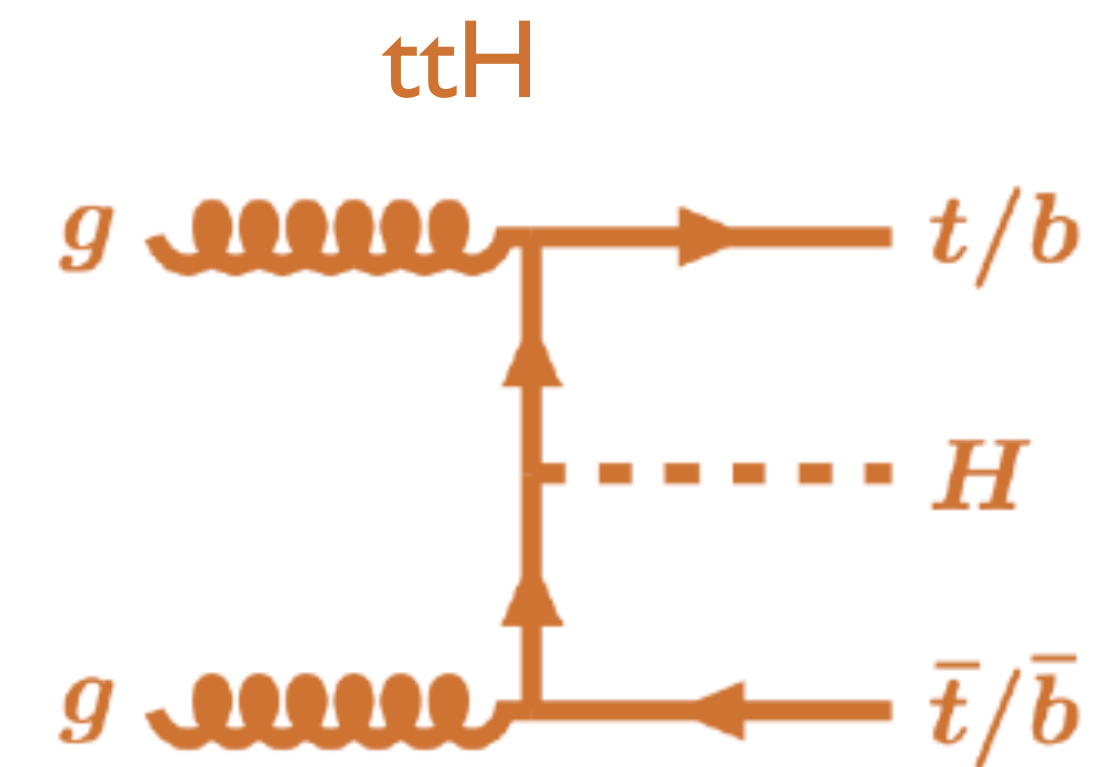
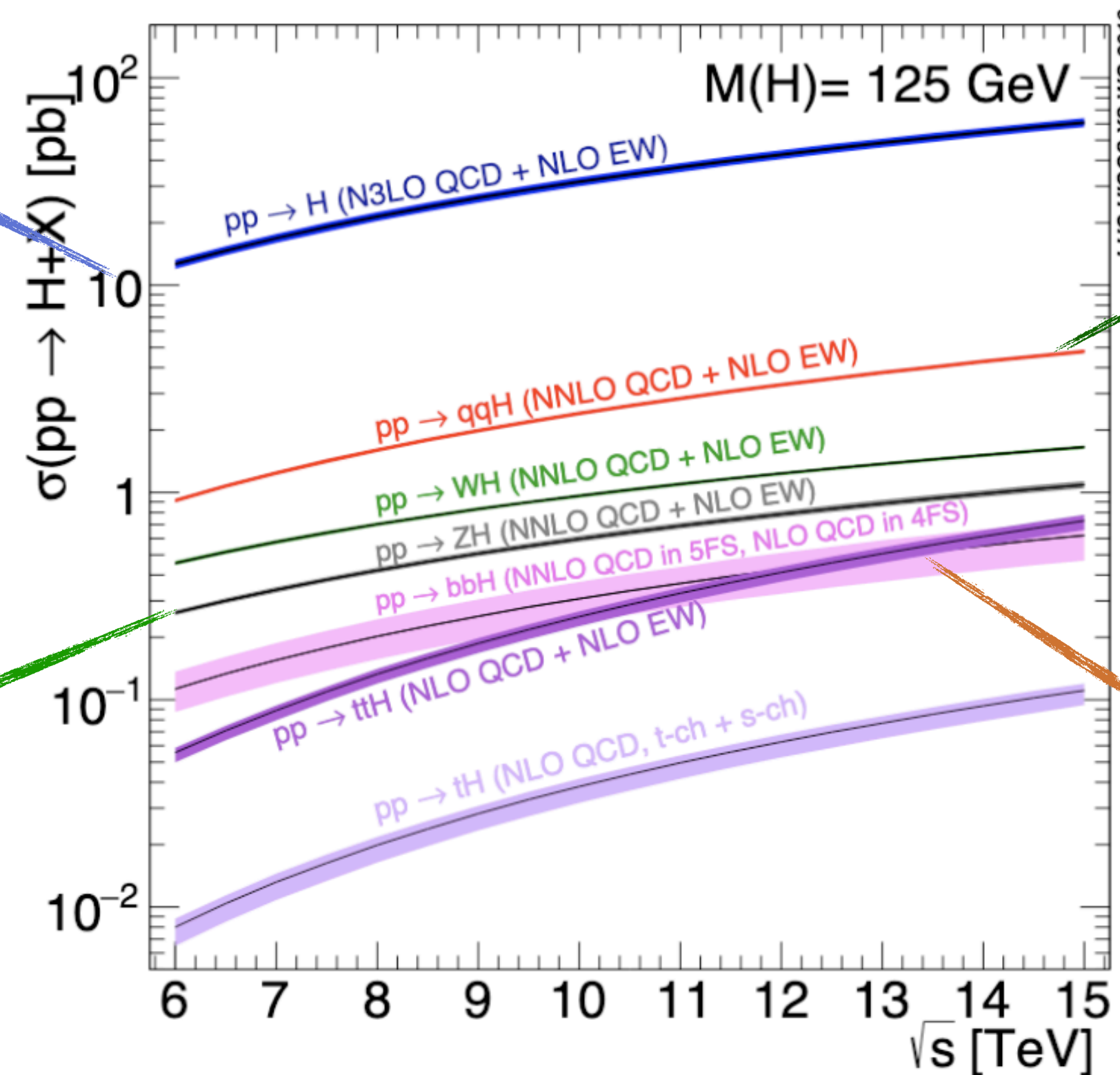
ggH Gluon fusion



VH: associated production

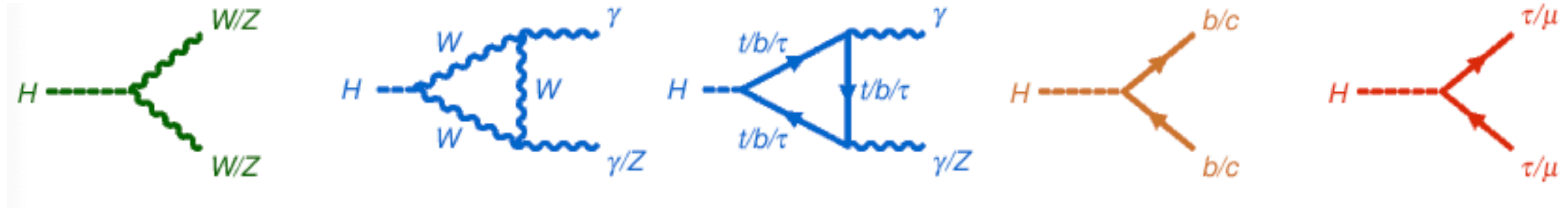


Vector Boson Fusion VBF



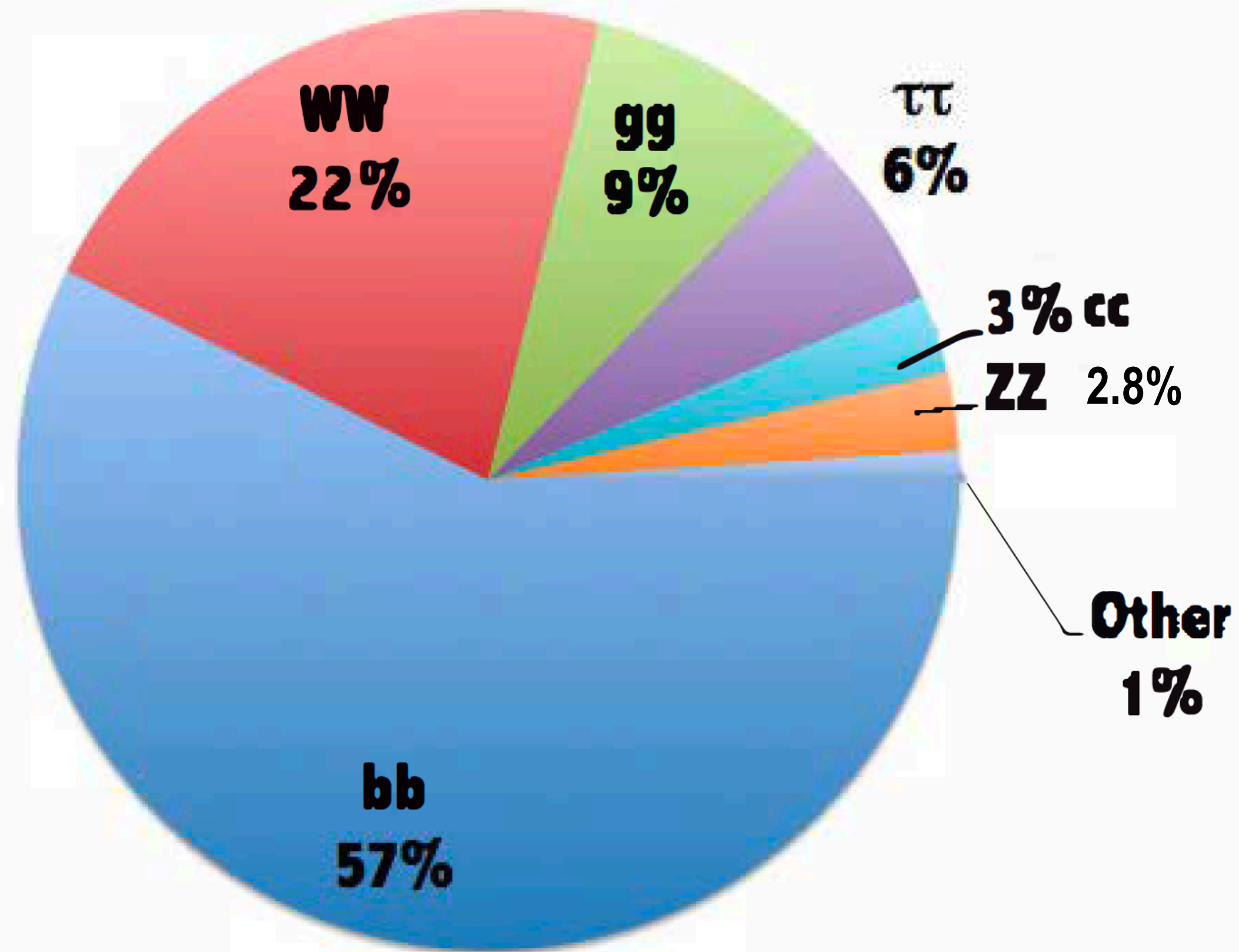
Higgs bosons are produced by a variety of mechanisms, the most important of which is gluon-gluon fusion (ggF).

Higgs decays



- Once produced, the Higgs boson can decay into a variety of final states.
- By analyzing rates in each production&decay channel, we can determine Higgs couplings.

Higgs decays



	BR(%)
bb	57
WW	22
ττ	6.2
ZZ	2.8
γγ	0.23
Zγ	0.15
μμ	0.02

- Once produced, the Higgs boson can decay into a variety of final states.
- By analyzing rates in each production&decay channel, we can determine Higgs couplings.

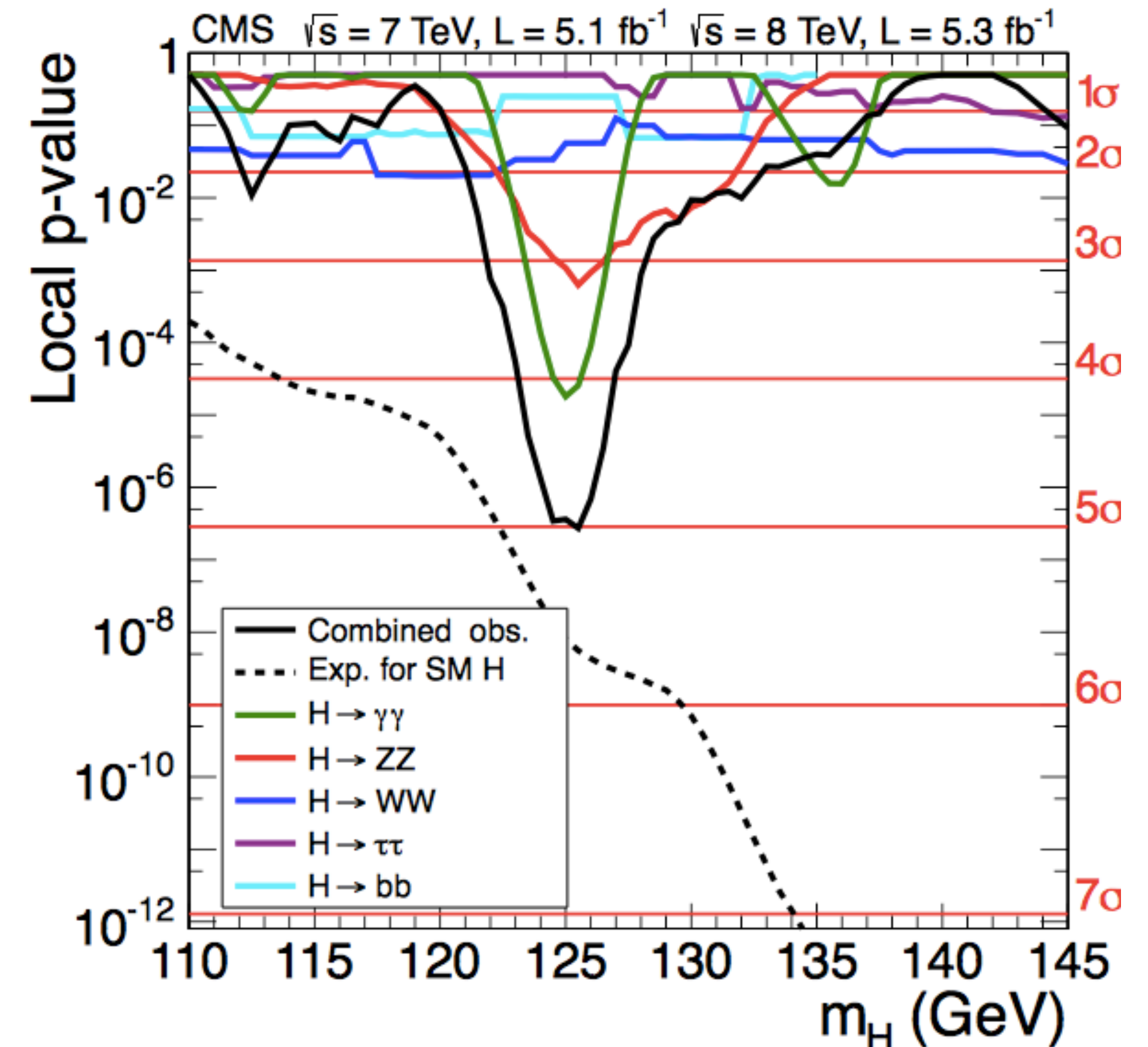
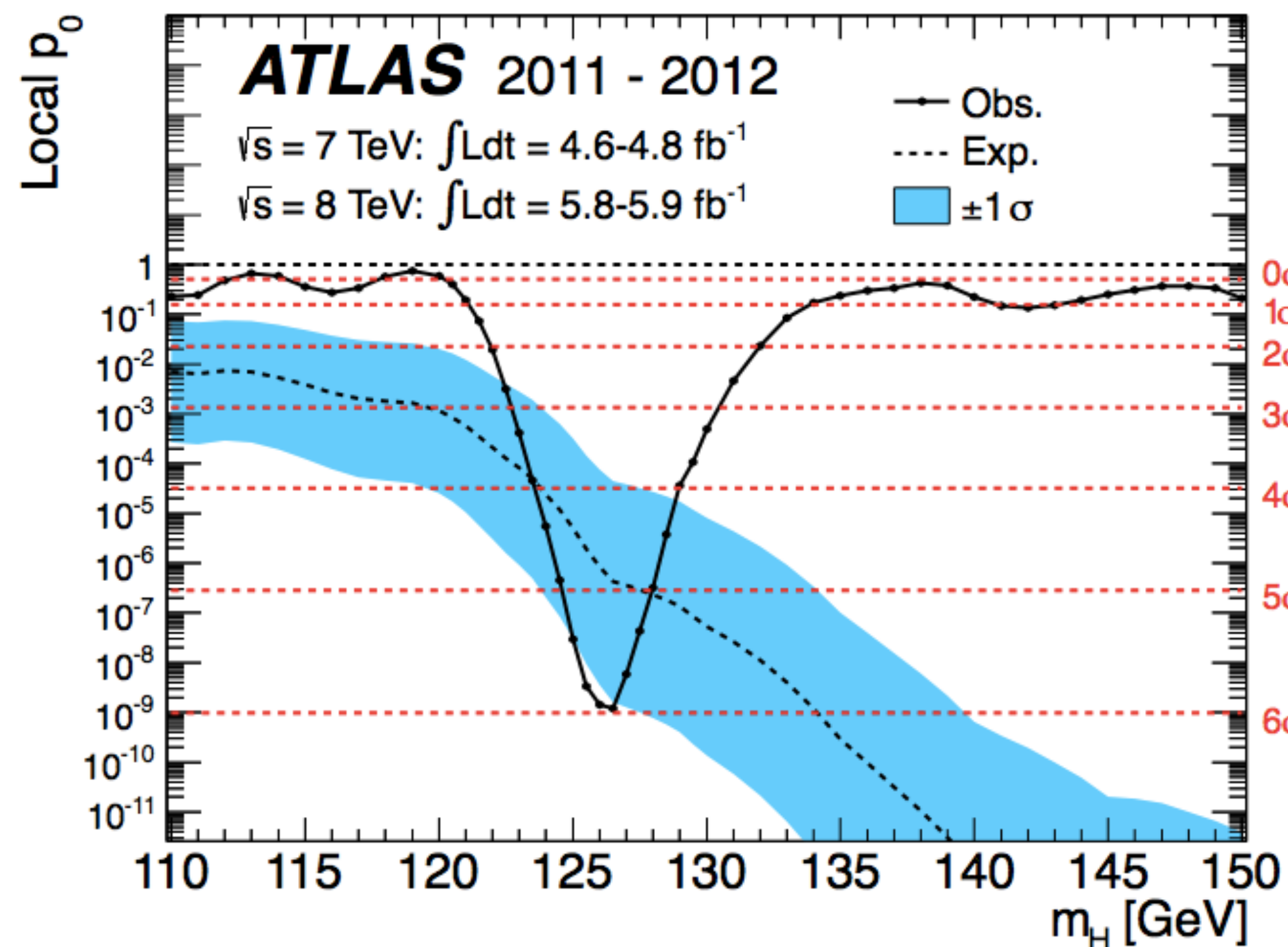
Higgs discovery in run I

A scalar boson compatible with the SM Higgs has been discovered in run I as shown by the combination of ATLAS and CMS run I results

Greatest achievement of run I

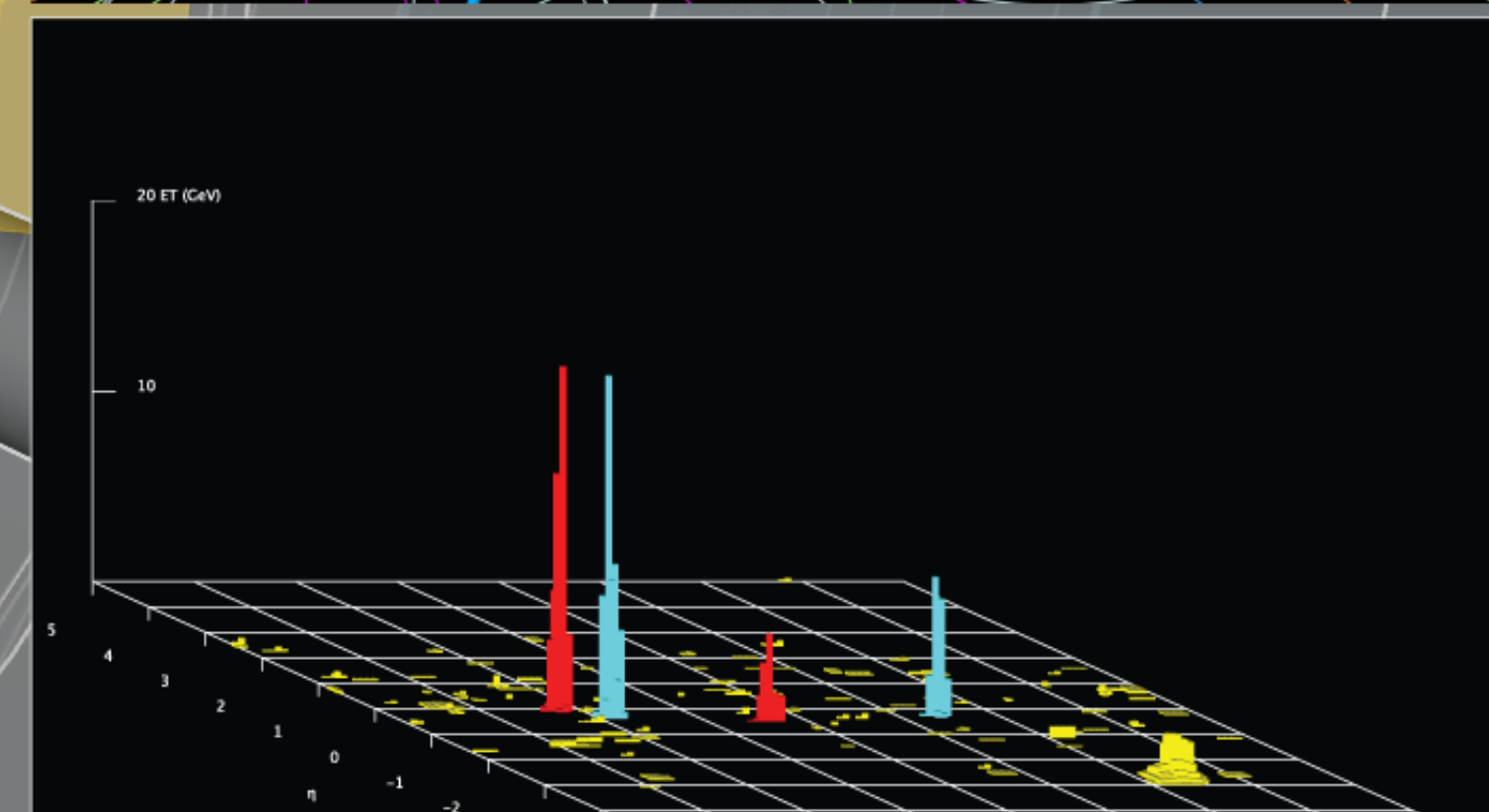
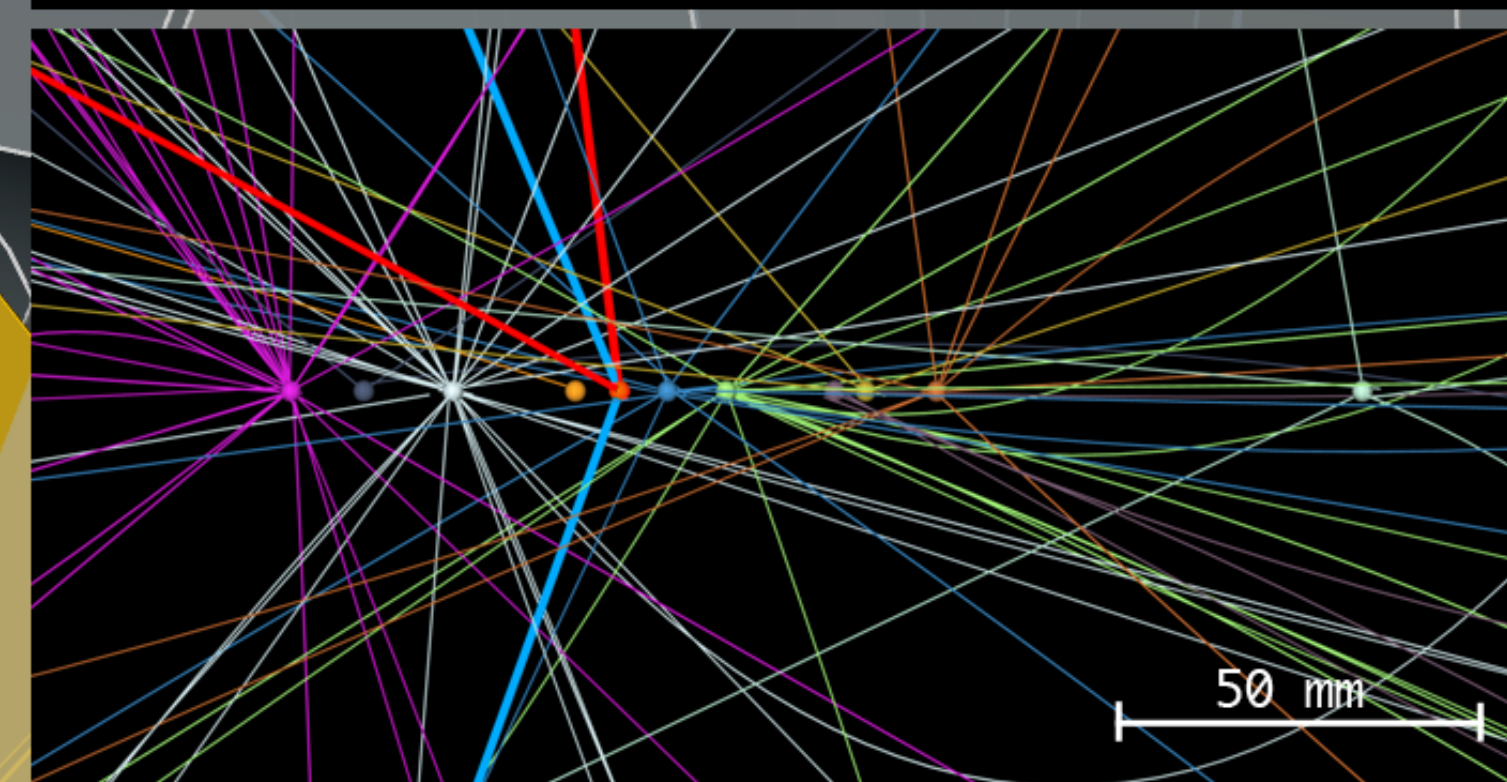
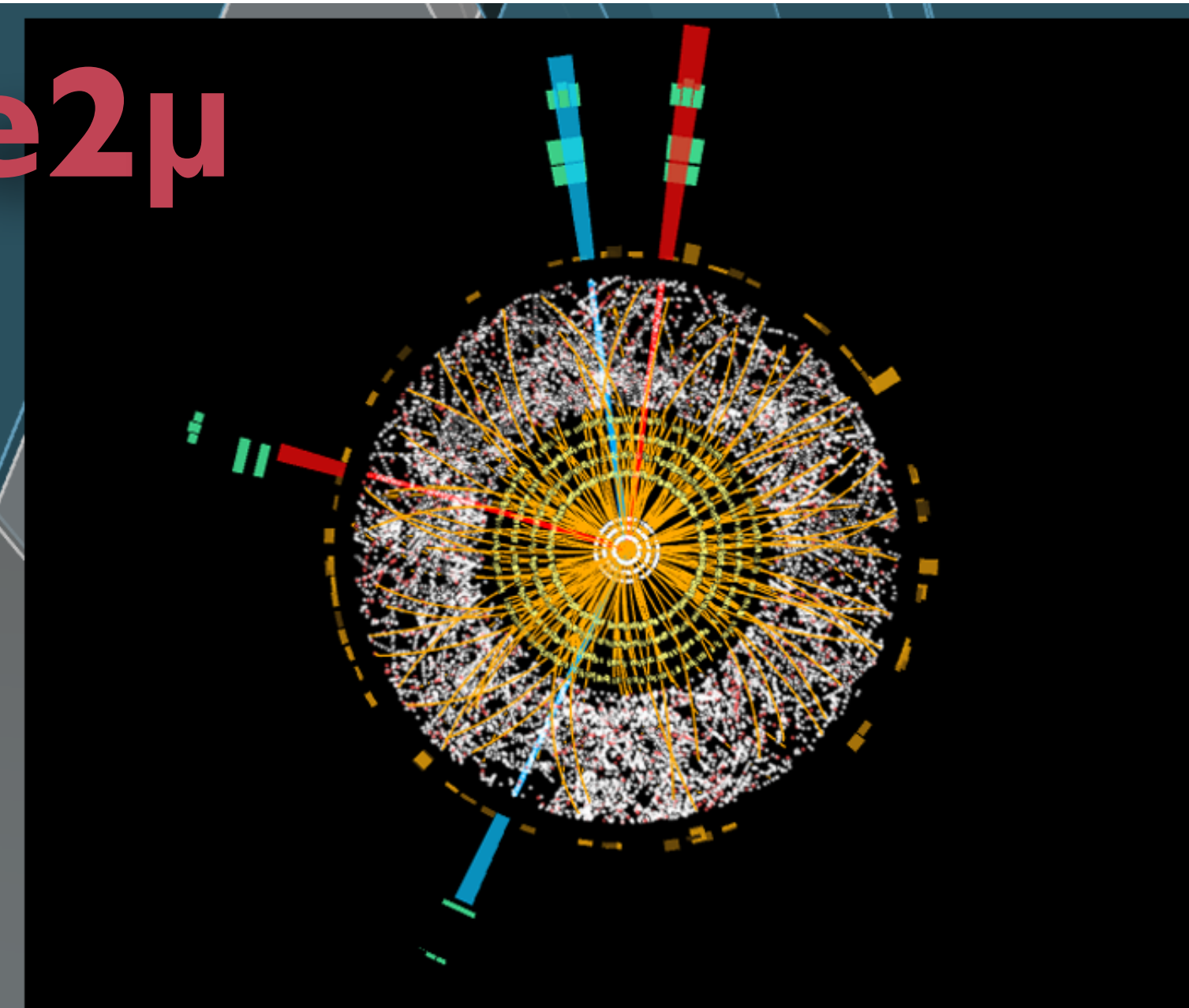
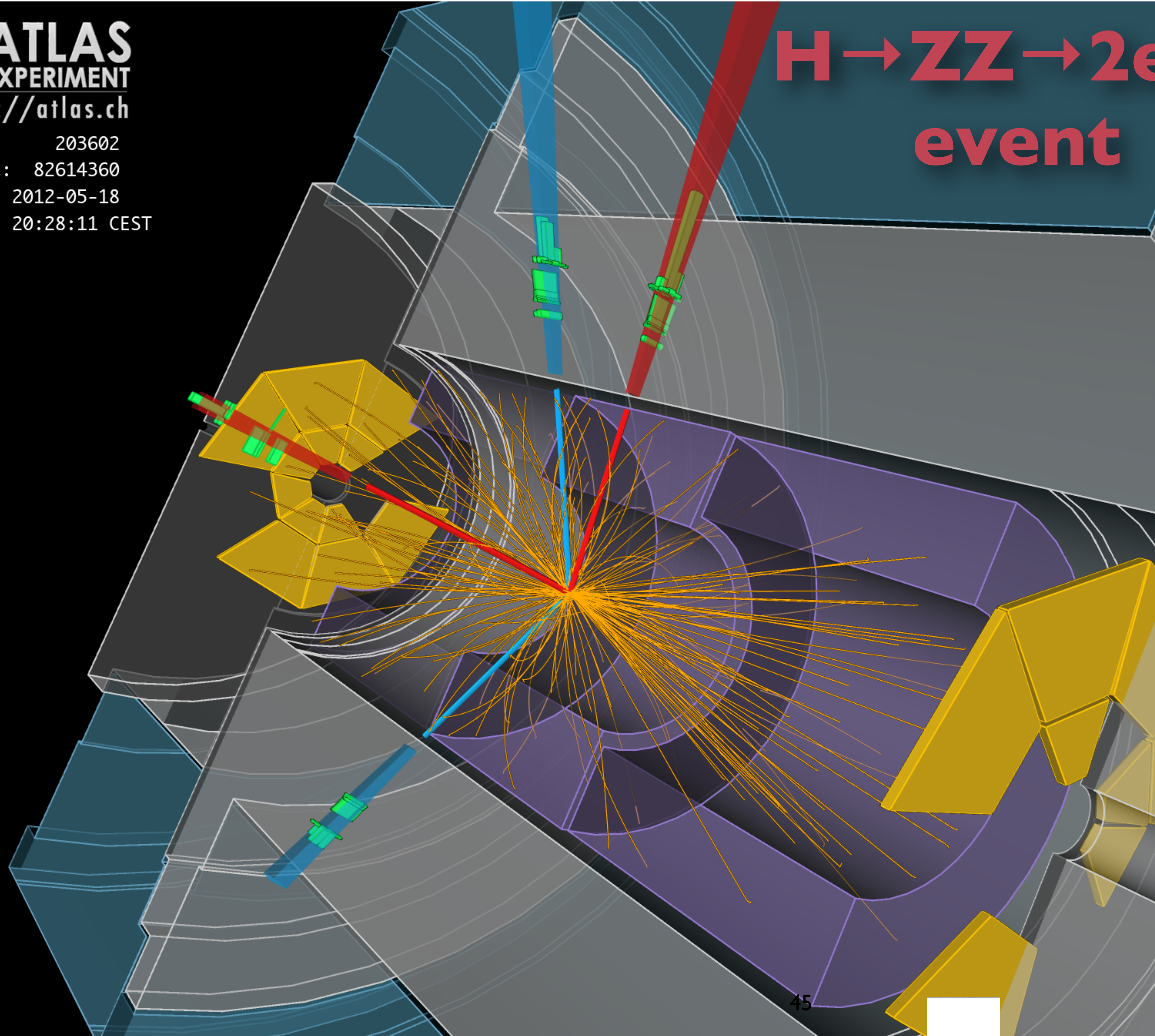
concentrated effort on its properties:

- magnitude of couplings
- mass measurements
- spin/CP

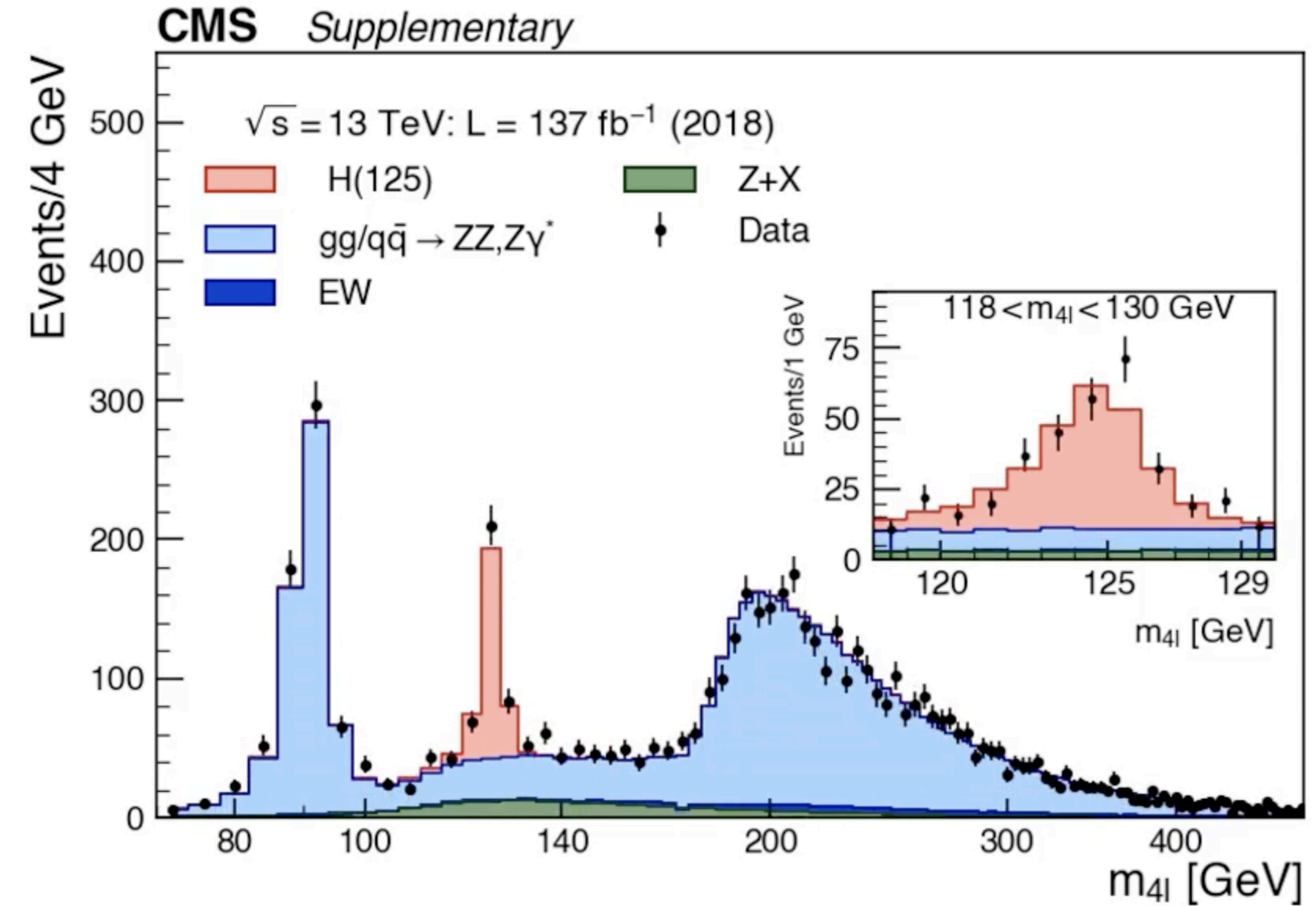
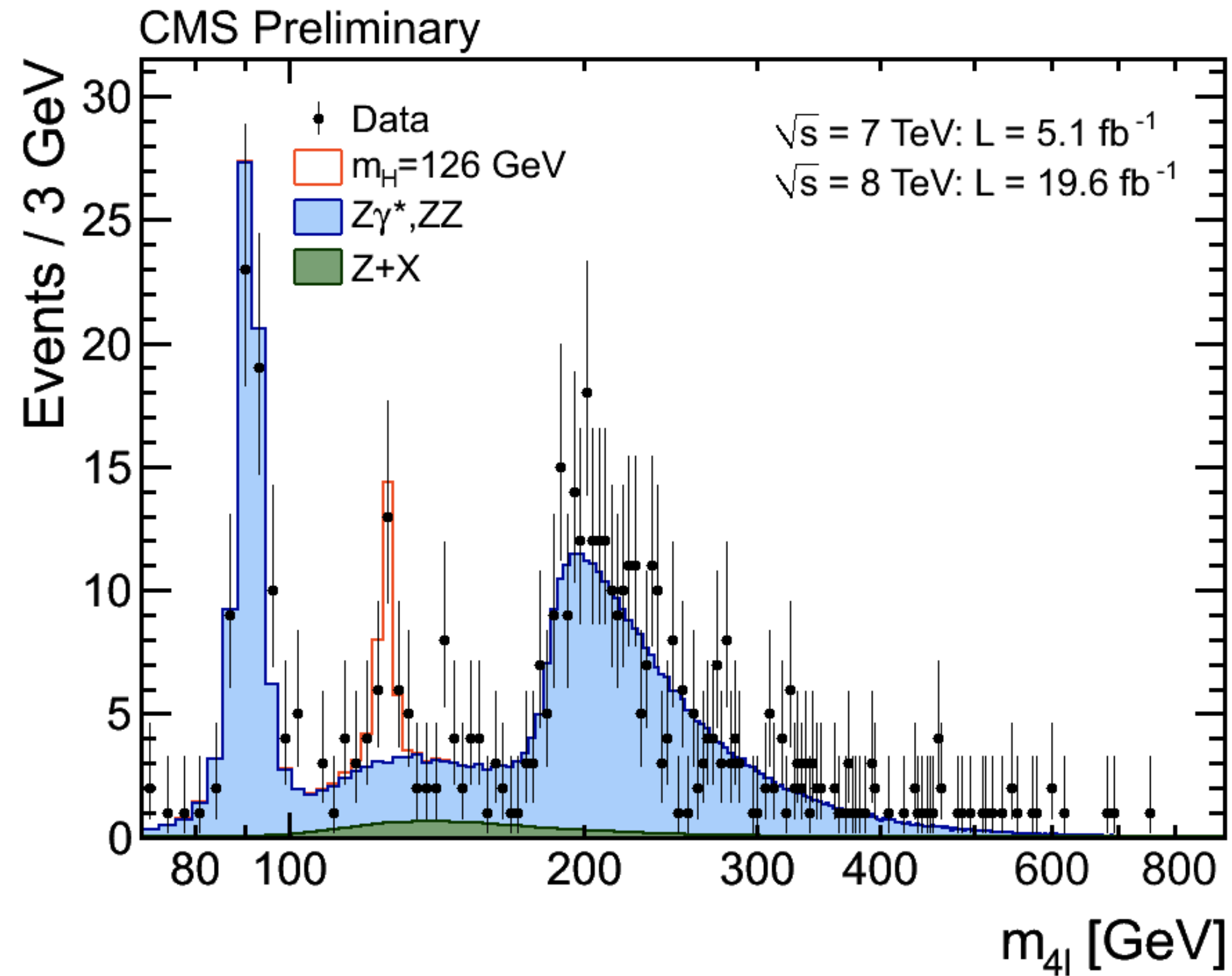


Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST

$H \rightarrow ZZ \rightarrow 2e2\mu$
event



Run I discovery $\Rightarrow$ Run2 precision



Run 3 trigger detector and analysis improvements!

Object reconstruction is fundamental

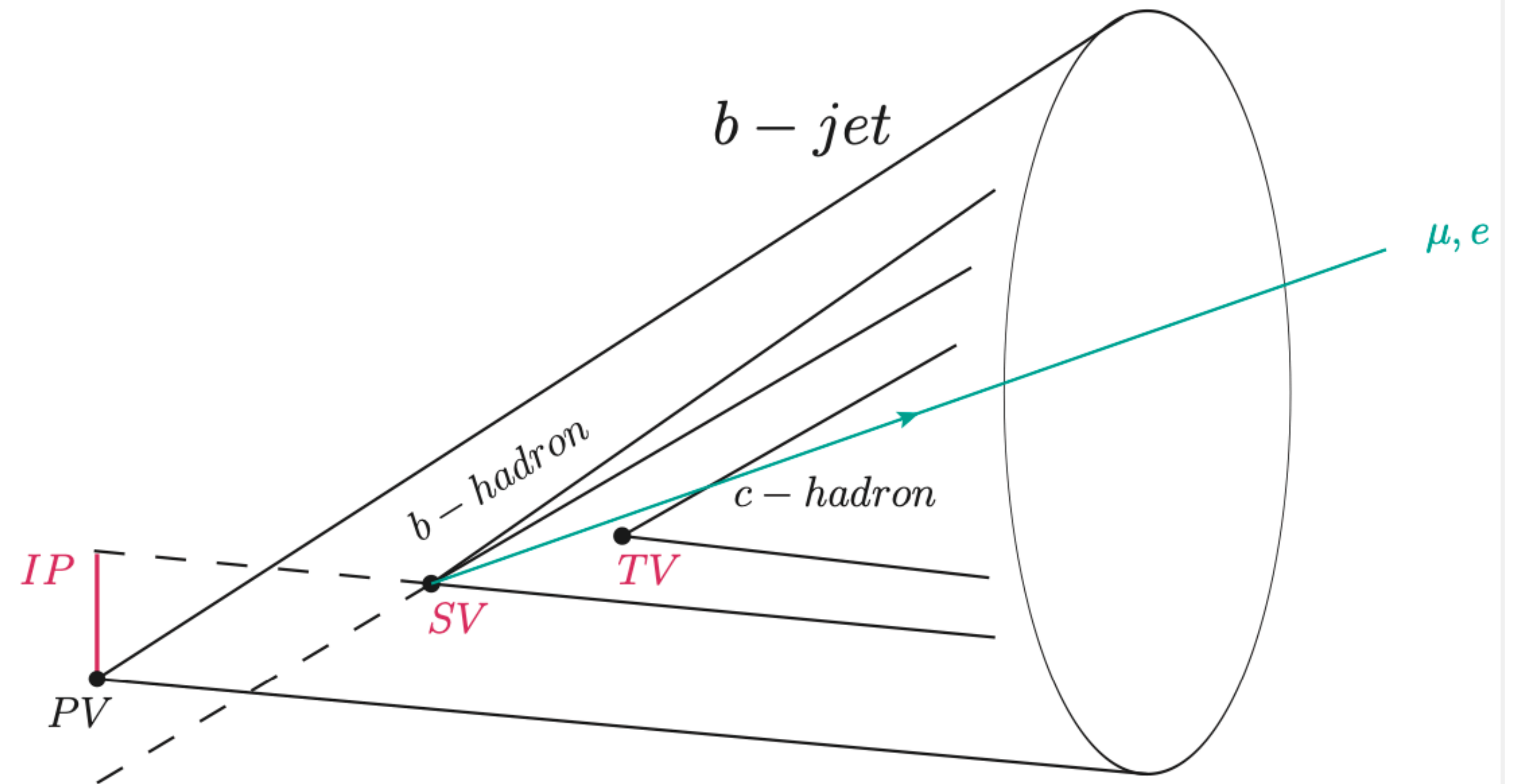
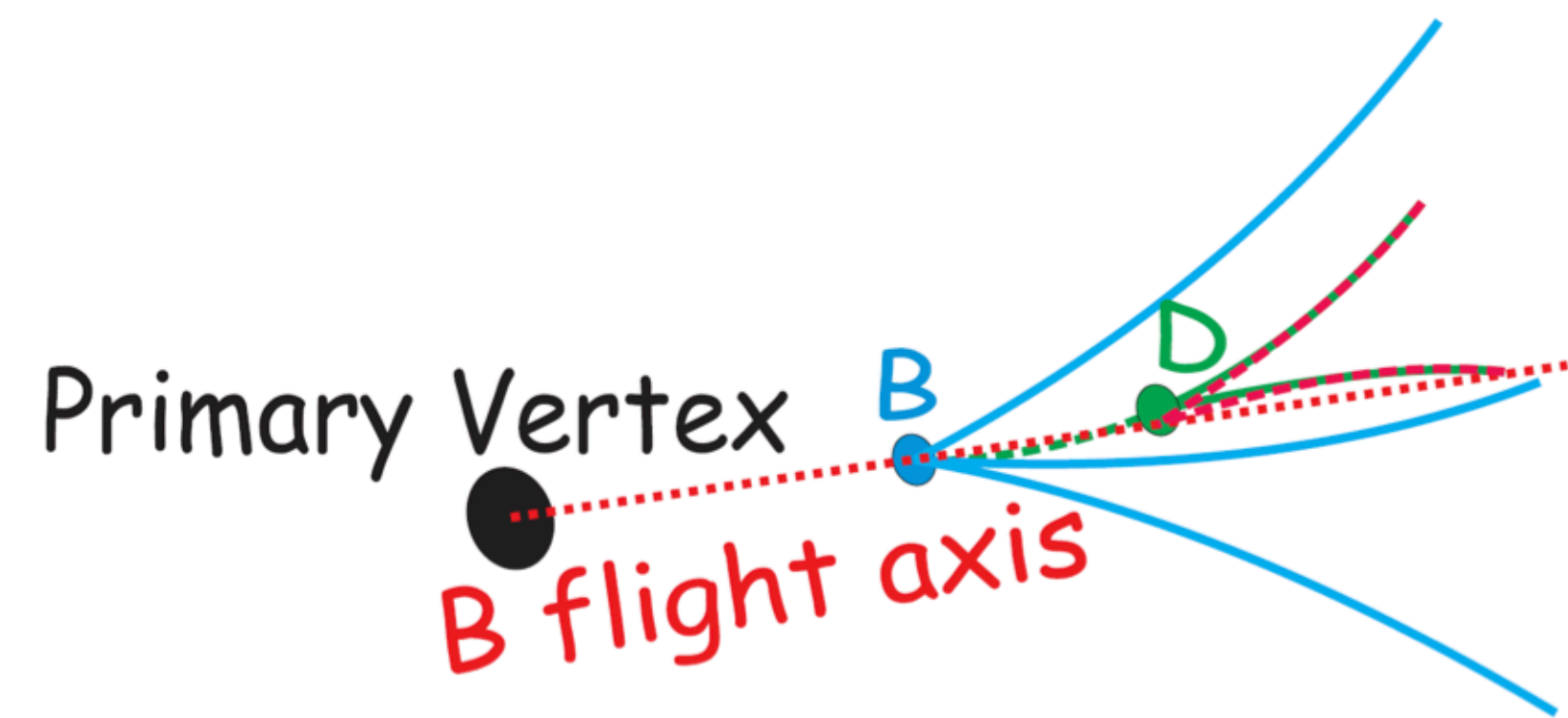
We have to reconstruct the particles in which the Higgs decays in the best possible way.
This really pays off, as you will see in these lectures.

Fundamental are the reconstructions of

- leptons (muons, taus, electrons)
- photons
- b-quarks and c-quarks (flavor tagging)
- Boosted objects

Flavor tagging

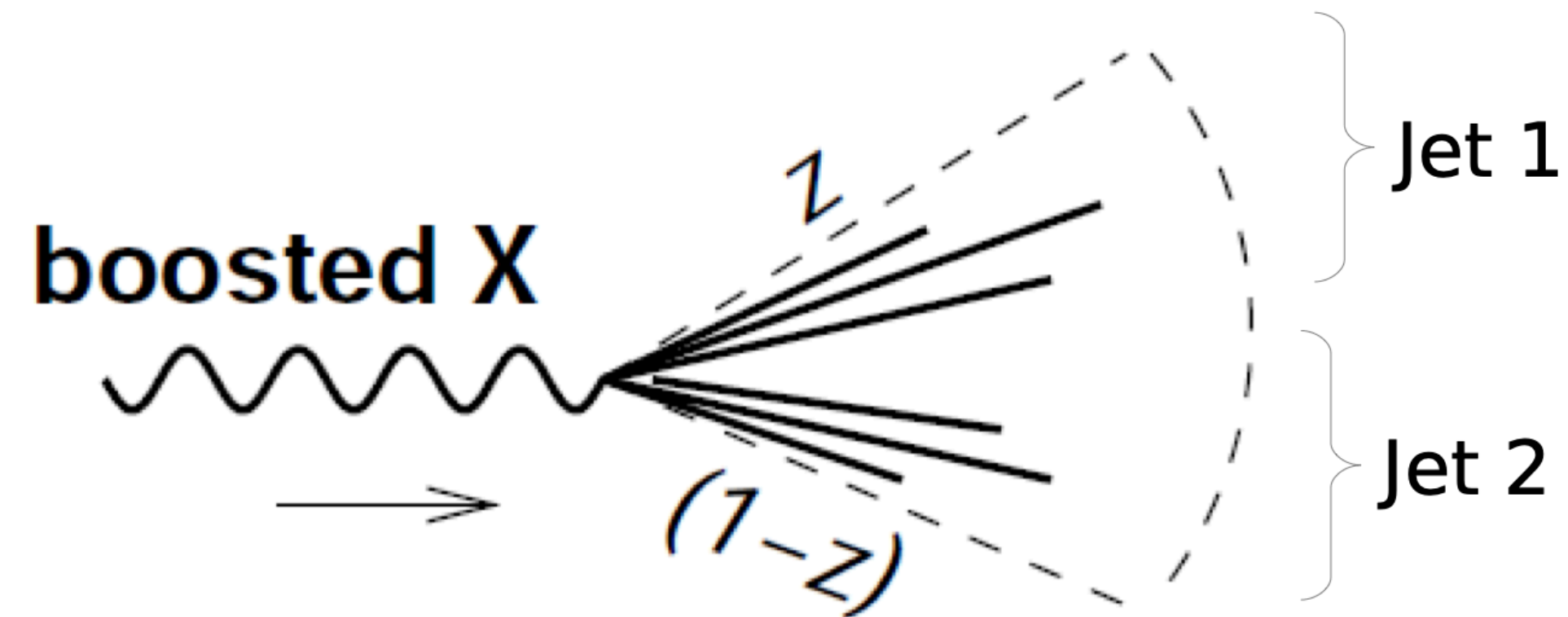
We tag b-hadrons and c-hadrons thanks to the fact that there is a secondary vertex



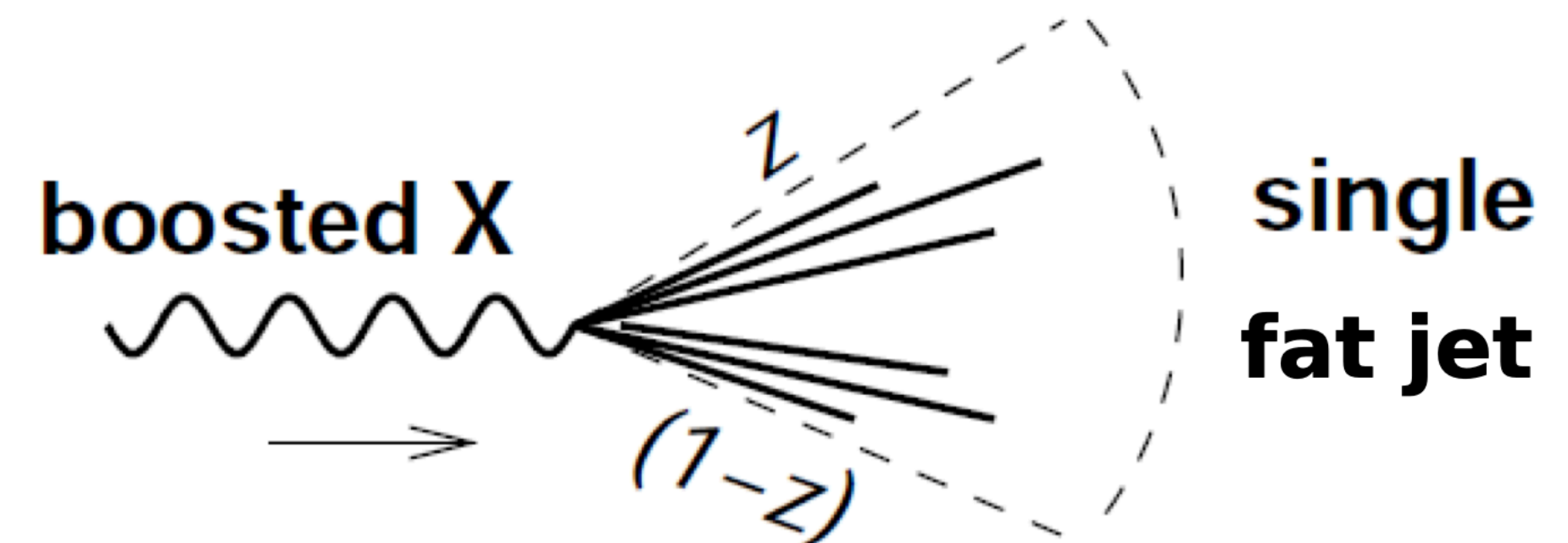
Boosted objects

At the LHC given the large center of mass energy and given that the SM particles have masses below 200 GeV, also the heaviest SM particles often acquire large momentum $\gg m \rightarrow$ production of “boosted objects”

Normally we reconstruct jets with $R=0.4$, if the object is boosted the jets in which it decays cannot be resolved in small r -jets



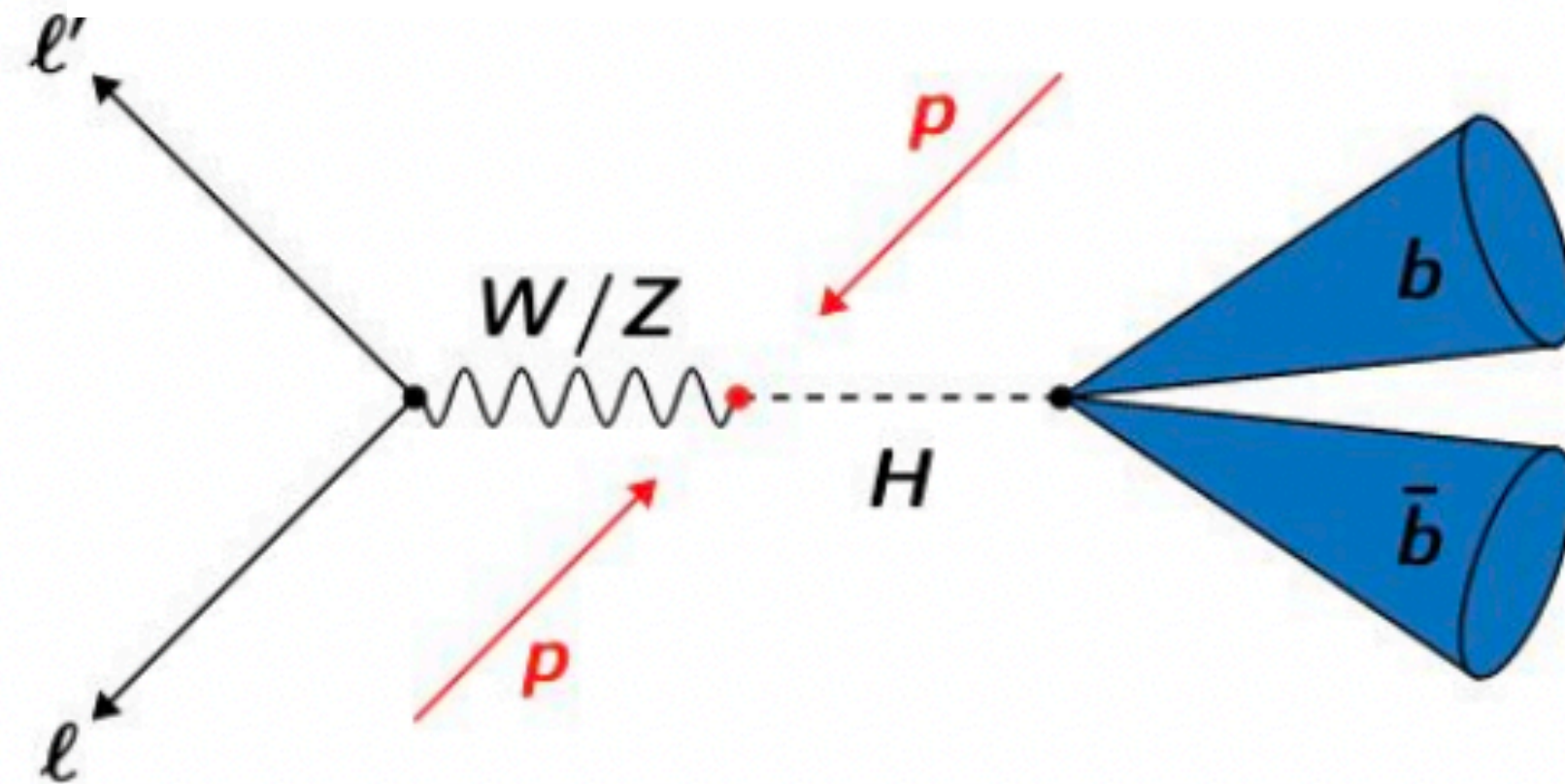
Recover sensitivity to boosted objects by developing boosted taggers, using larger R



Boosted objects

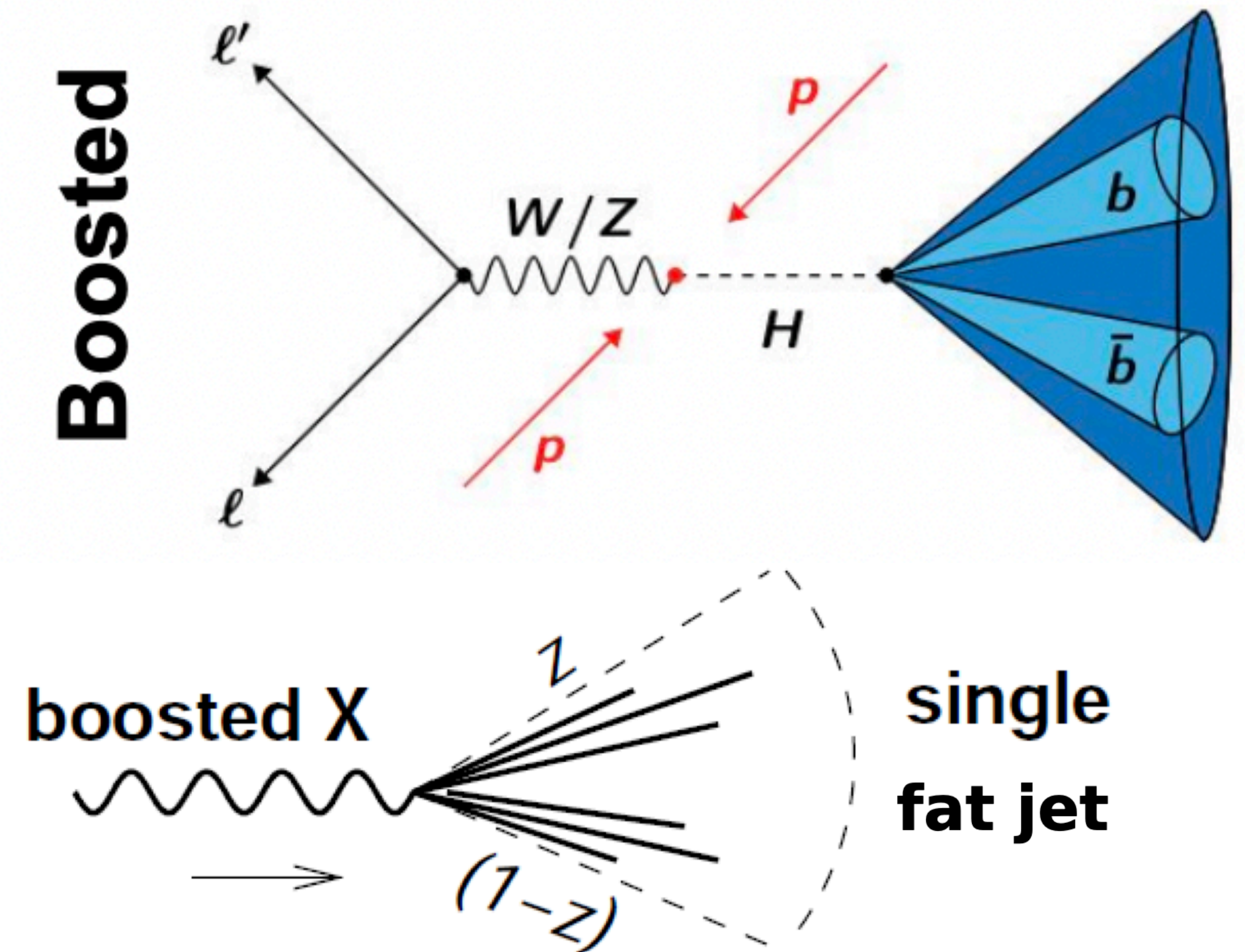
At the LHC given the large center of mass energy and given that the SM particles have masses below 200 GeV, also the heaviest heaviest SM particles often acquire $p_T \gg m \rightarrow$ production of “boosted objects”

Resolved



Recover sensitivity to boosted objects by developing boosted taggers, using larger R

Boosted



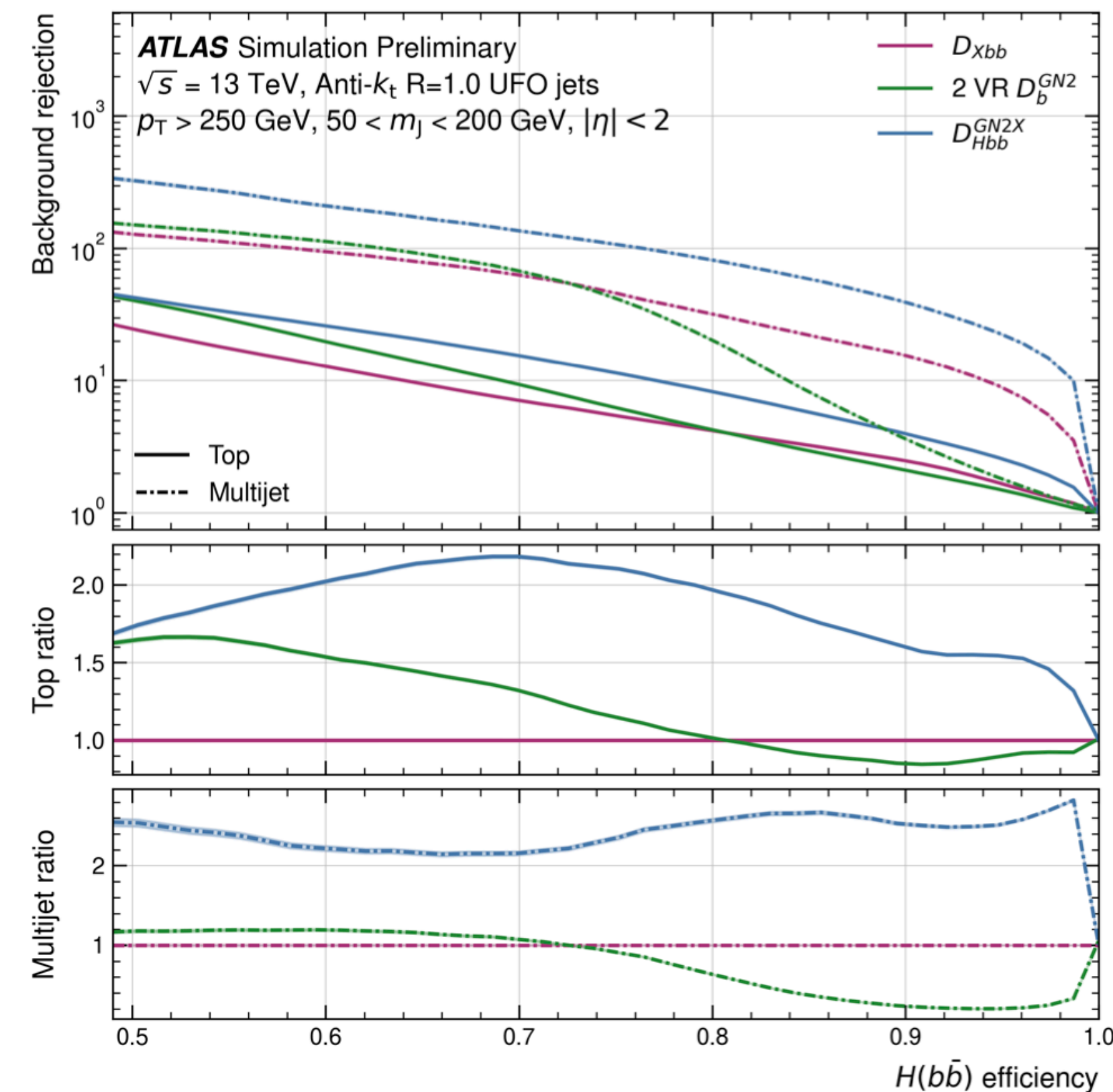
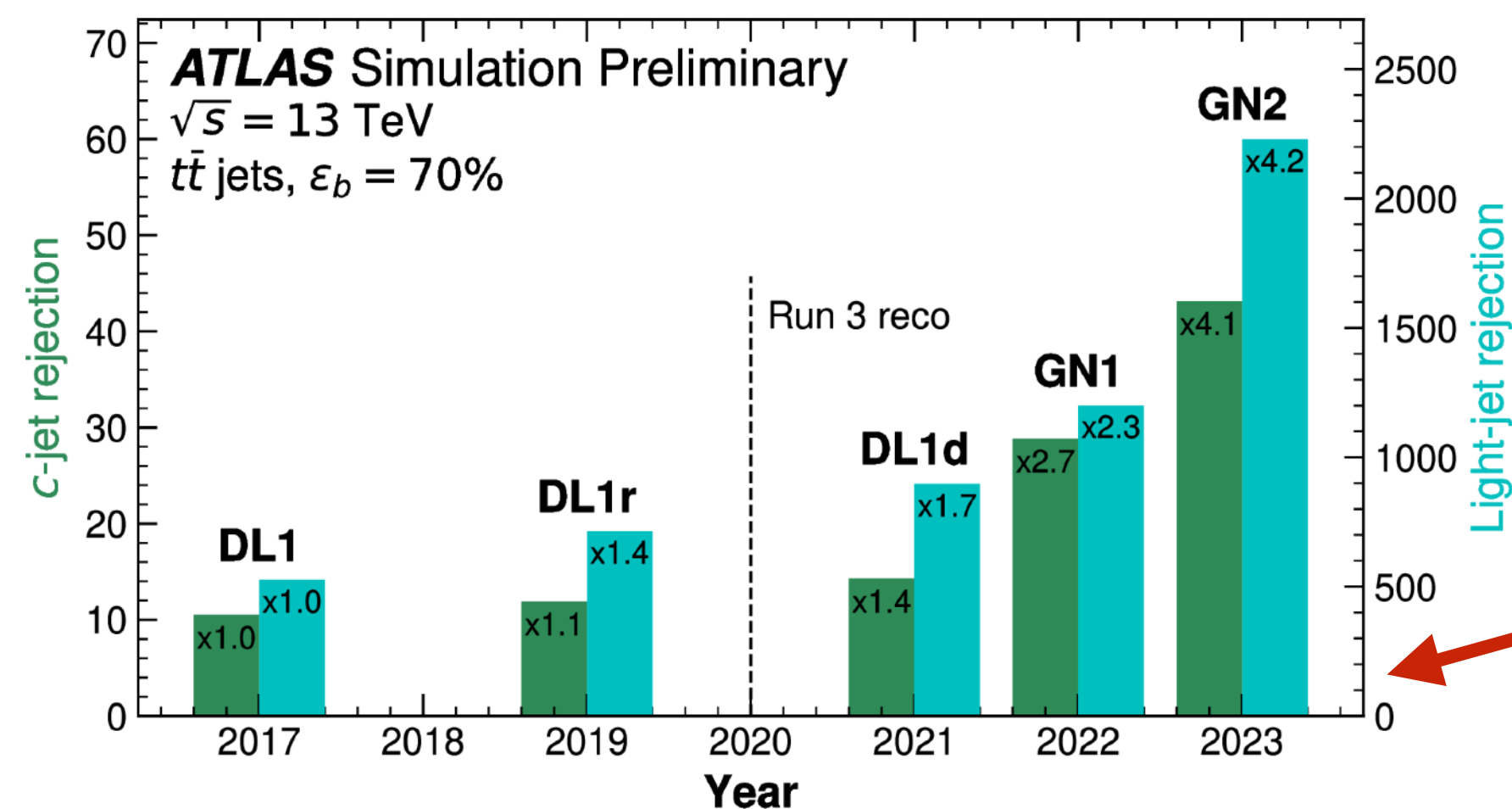
Flavor tagging in continuous evolution

Boosted H→bb/cc tagging ATL-PHYS-PUB-2023-021

- Boosted b-tagging: new algorithm, GN2X for large-radius jets: tagging boosted H(bb) jets and H(cc) jets.



small R-jet tagging Jet Flavour Tagging With GN1 and DL1d



- GN2X benefits from advances in flavour tagging of small-radius jets with Graph Neural Networks (GNNs)

Higgs terminology

We talk of signal strength, defined as the μ parameter:

- μ is the ratio of the measured cross-section with respect to the SM expectation.
- $\mu=1$ means that we measure back the SM

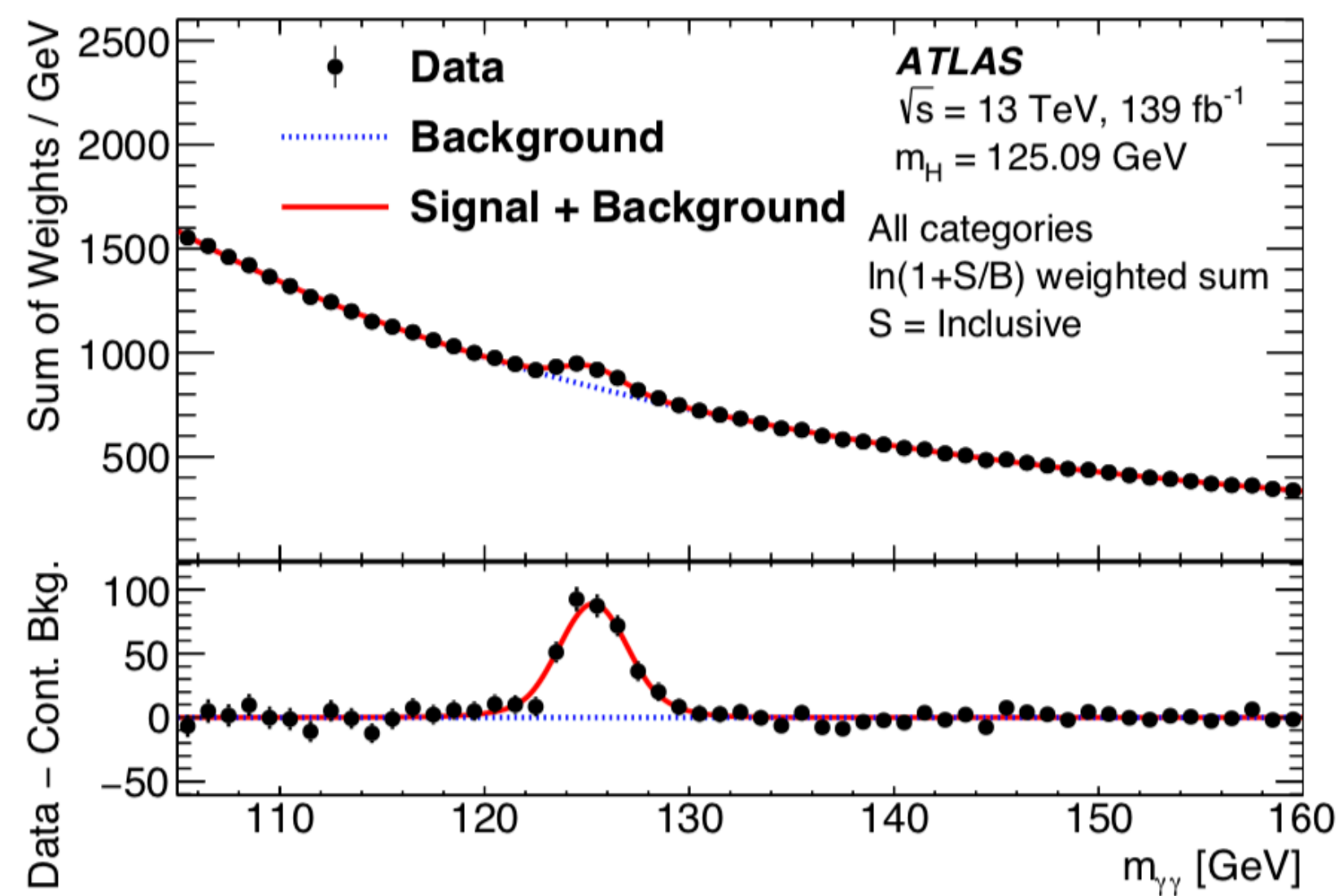
We also have introduced kappa's k-framework:

- k is the ratio of the a Higgs coupling with respect to the coupling from SM expectation.
- $k=1$ means that we measure back the SM

10 % precision

$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06 \text{ (stat.)}^{+0.06}_{-0.05} \text{ (theory syst.)}^{+0.05}_{-0.04} \text{ (exp. syst.)}.$$

Please note that theoretical error is at level of other errors!

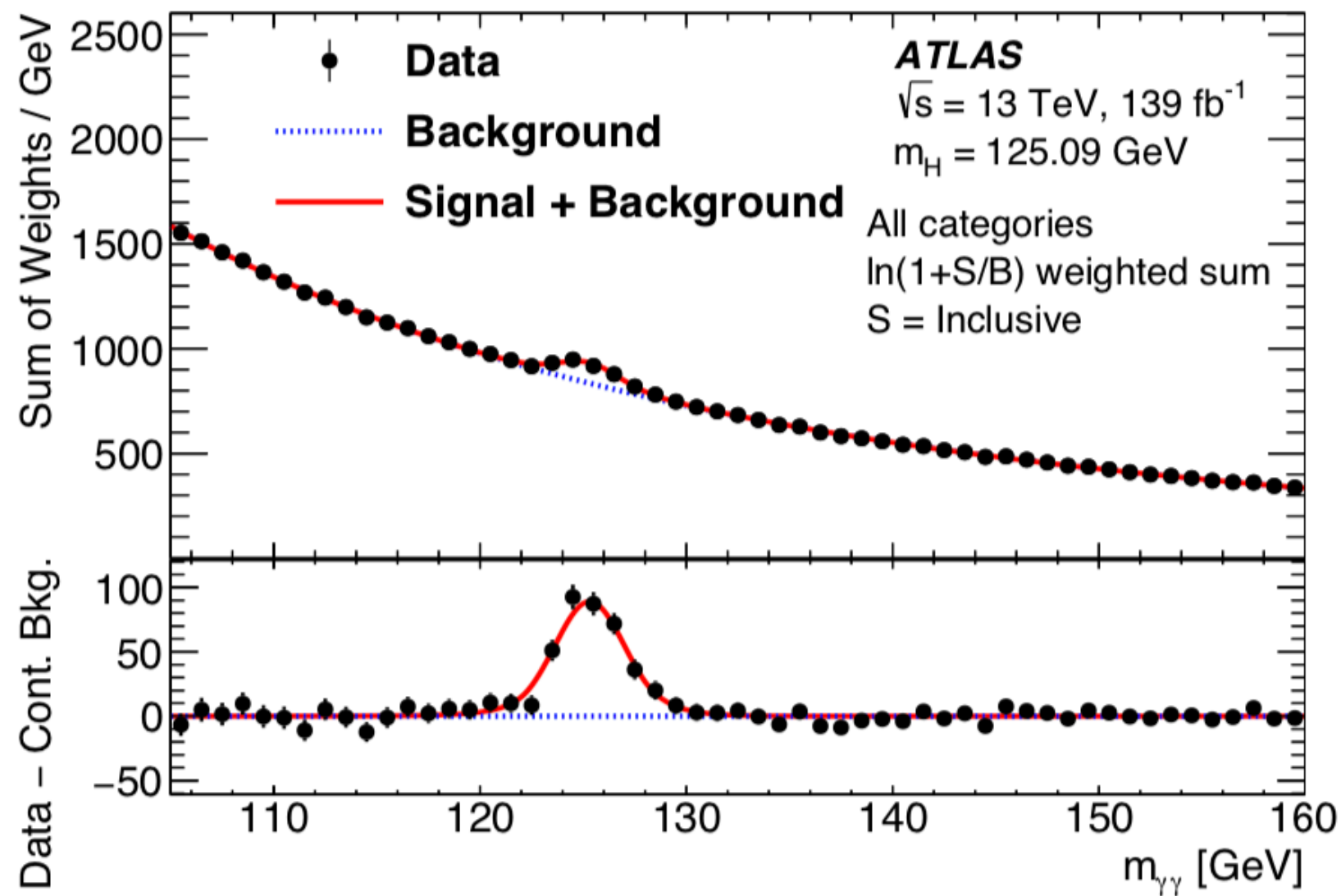


H → γγ

10 % precision

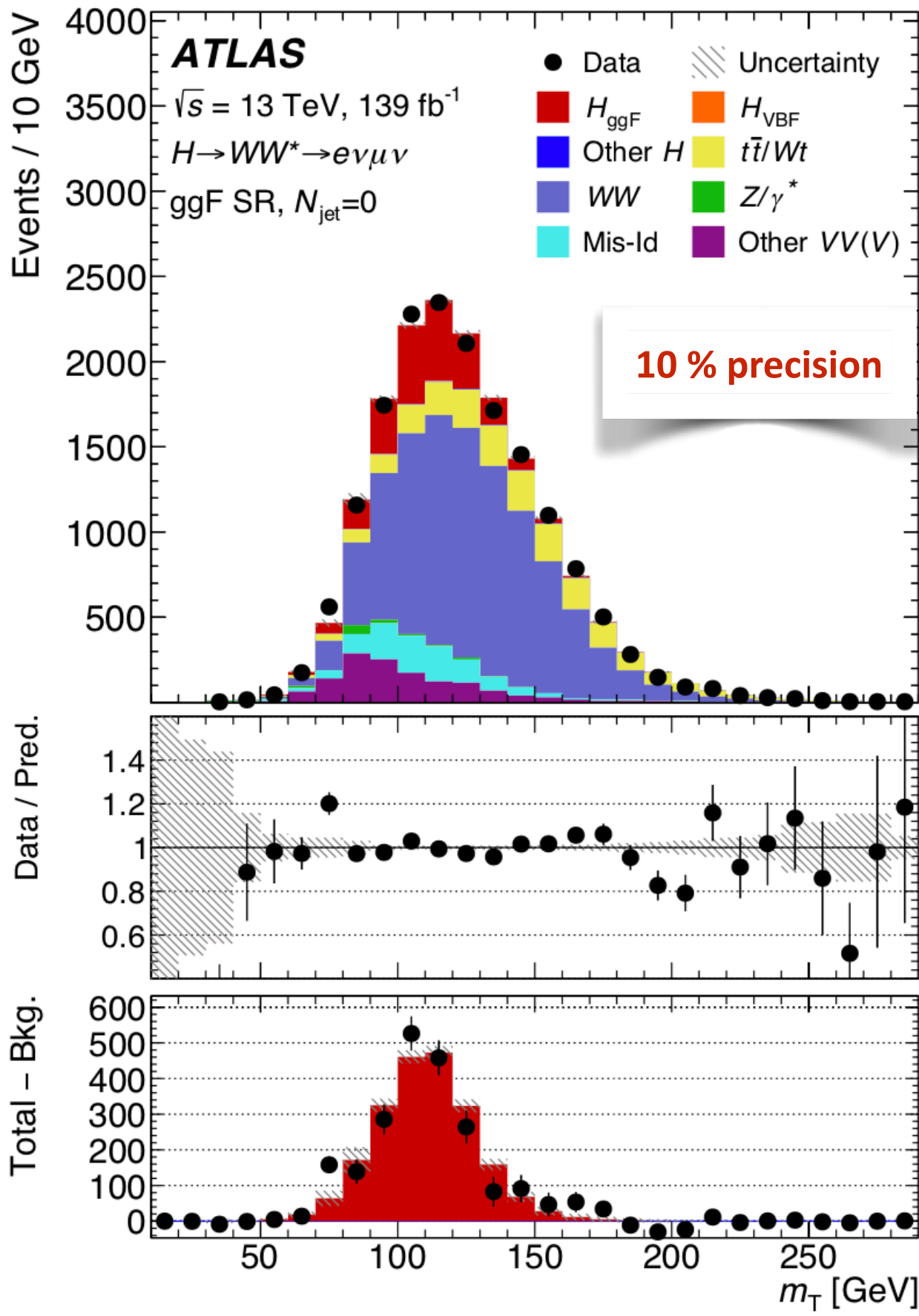
$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06 \text{ (stat.)}^{+0.06}_{-0.05} \text{ (theory syst.)}^{+0.05}_{-0.04} \text{ (exp. syst.)}$$

Please note that theoretical error is at level of other errors!



Total	(Stat., Syst.)	SM Unc.
1.09	$\begin{pmatrix} +0.11 \\ -0.11 \end{pmatrix} \left(\begin{pmatrix} +0.06 & +0.10 \\ -0.06 & -0.09 \end{pmatrix} \right)$	± 0.07

H → WW*

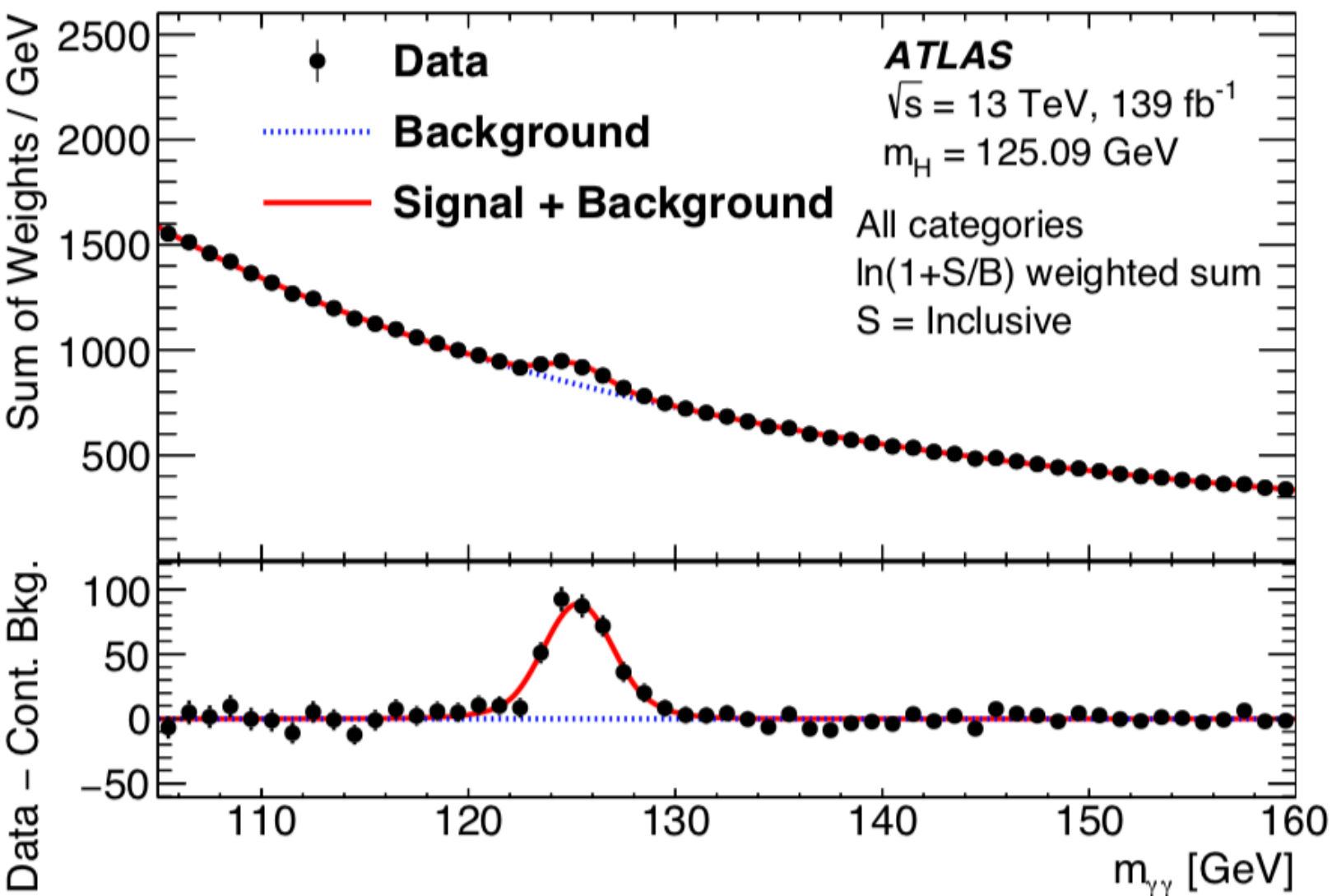


$H \rightarrow \gamma\gamma$

10 % precision

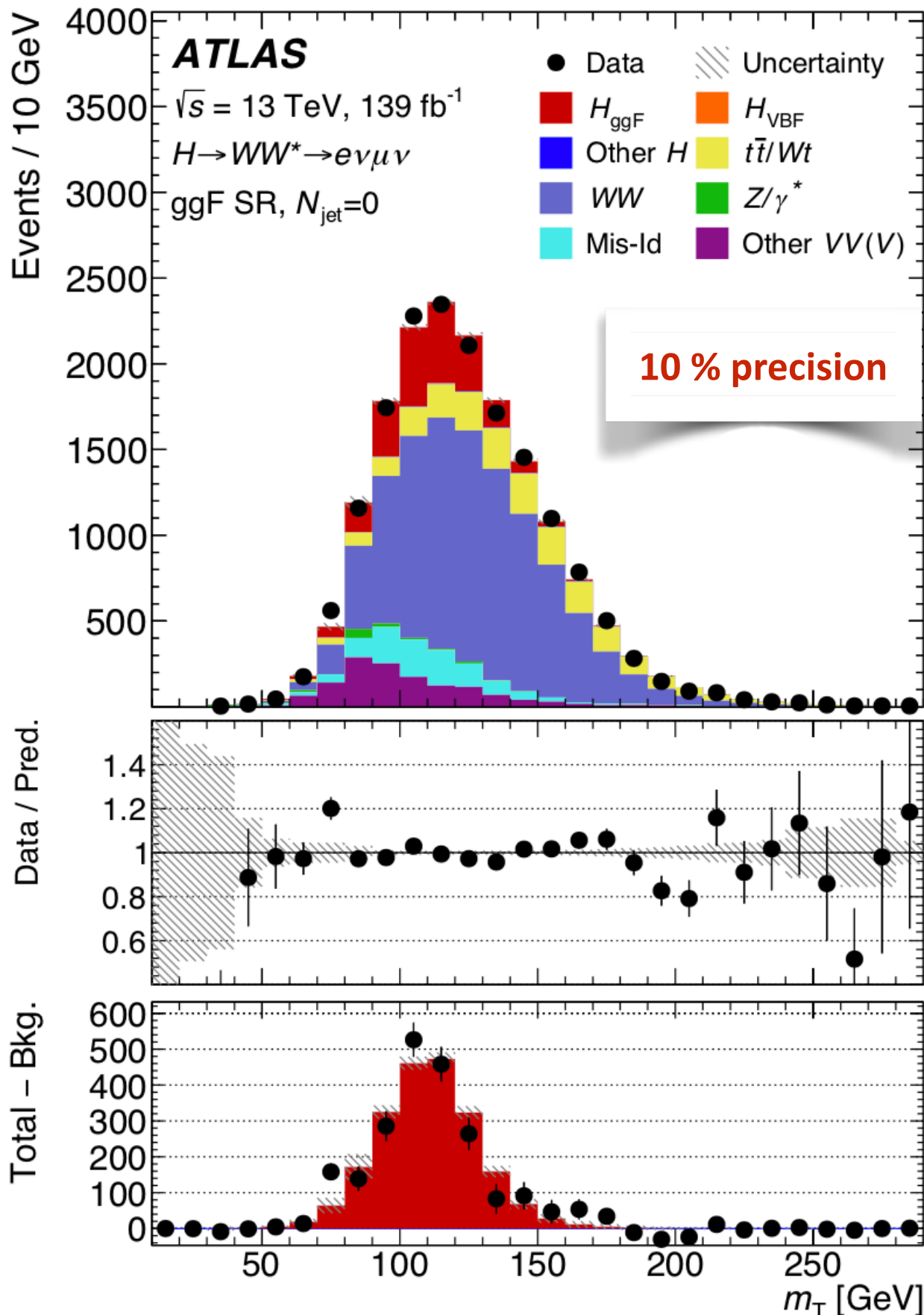
$$\mu = 1.04^{+0.10}_{-0.09} = 1.04 \pm 0.06 \text{ (stat.)}^{+0.06}_{-0.05} \text{ (theory syst.)}^{+0.05}_{-0.04} \text{ (exp. syst.)}.$$

Please note that theoretical error is at level of other errors!



Total	(Stat., Syst.)	SM Unc.
1.09	$\begin{pmatrix} +0.11 \\ -0.11 \end{pmatrix}$	$\begin{pmatrix} +0.06 & +0.10 \\ -0.06 & -0.09 \end{pmatrix} \pm 0.07$

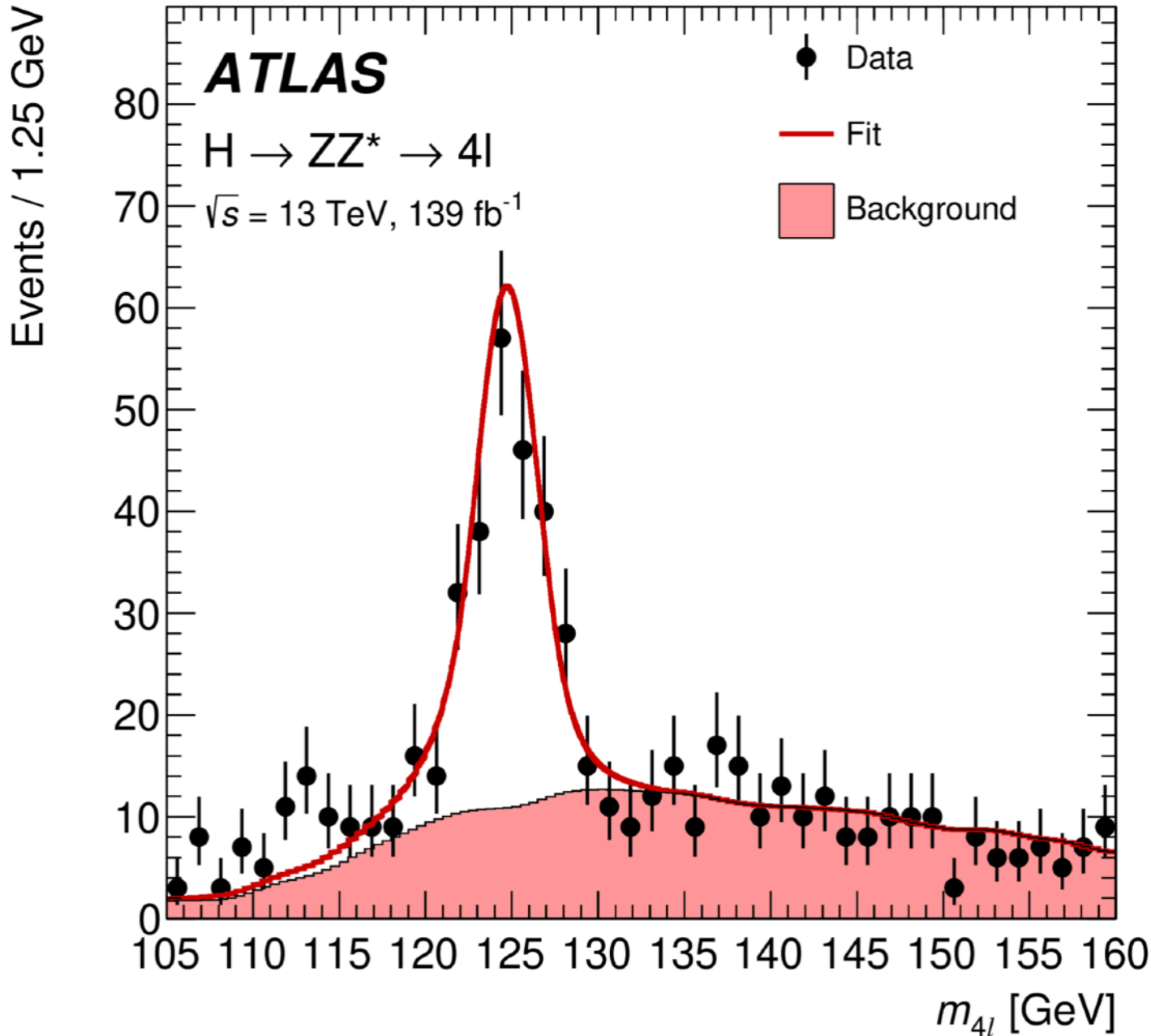
$H \rightarrow WW^*$



$H \rightarrow ZZ \rightarrow 4l$

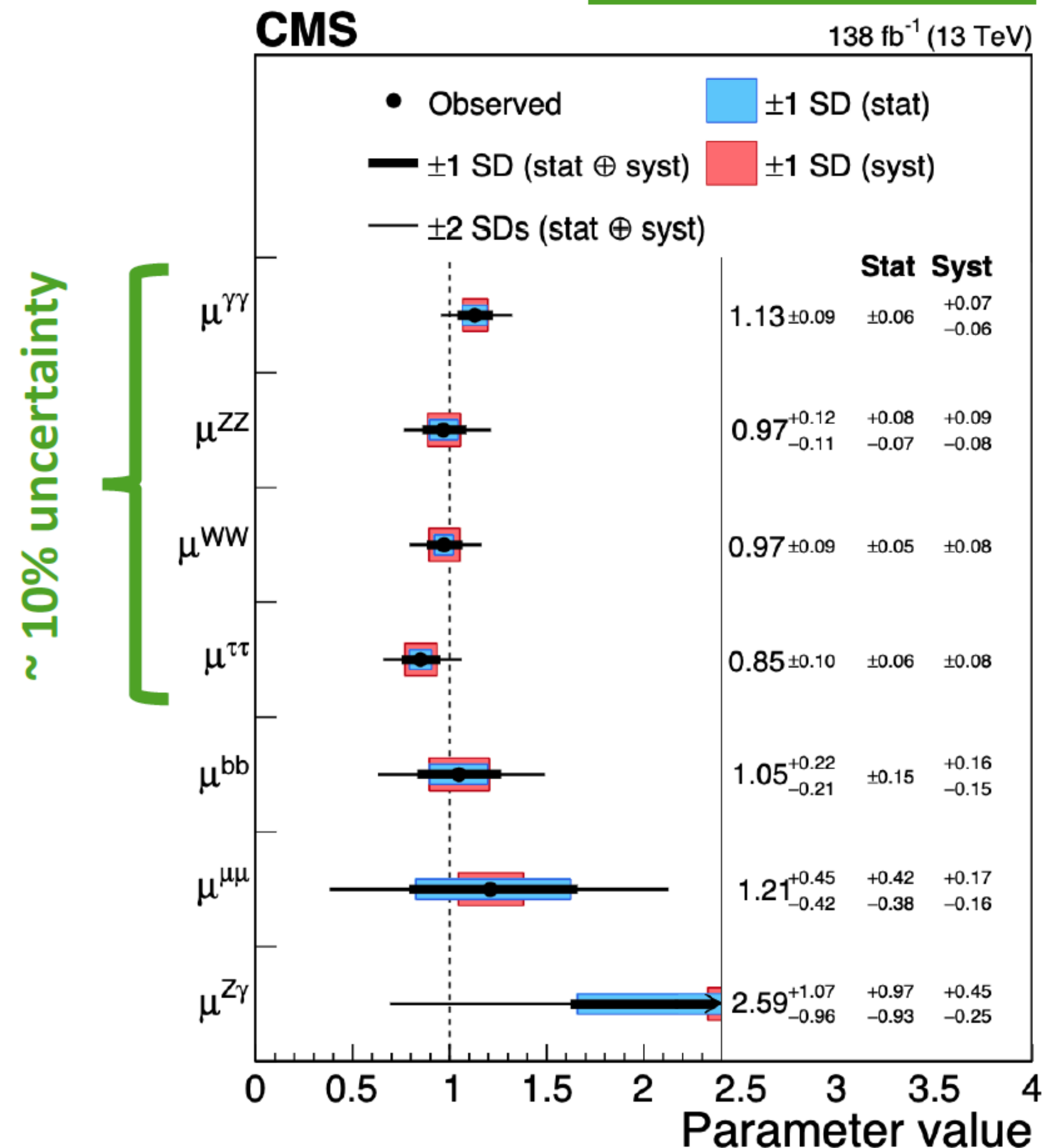
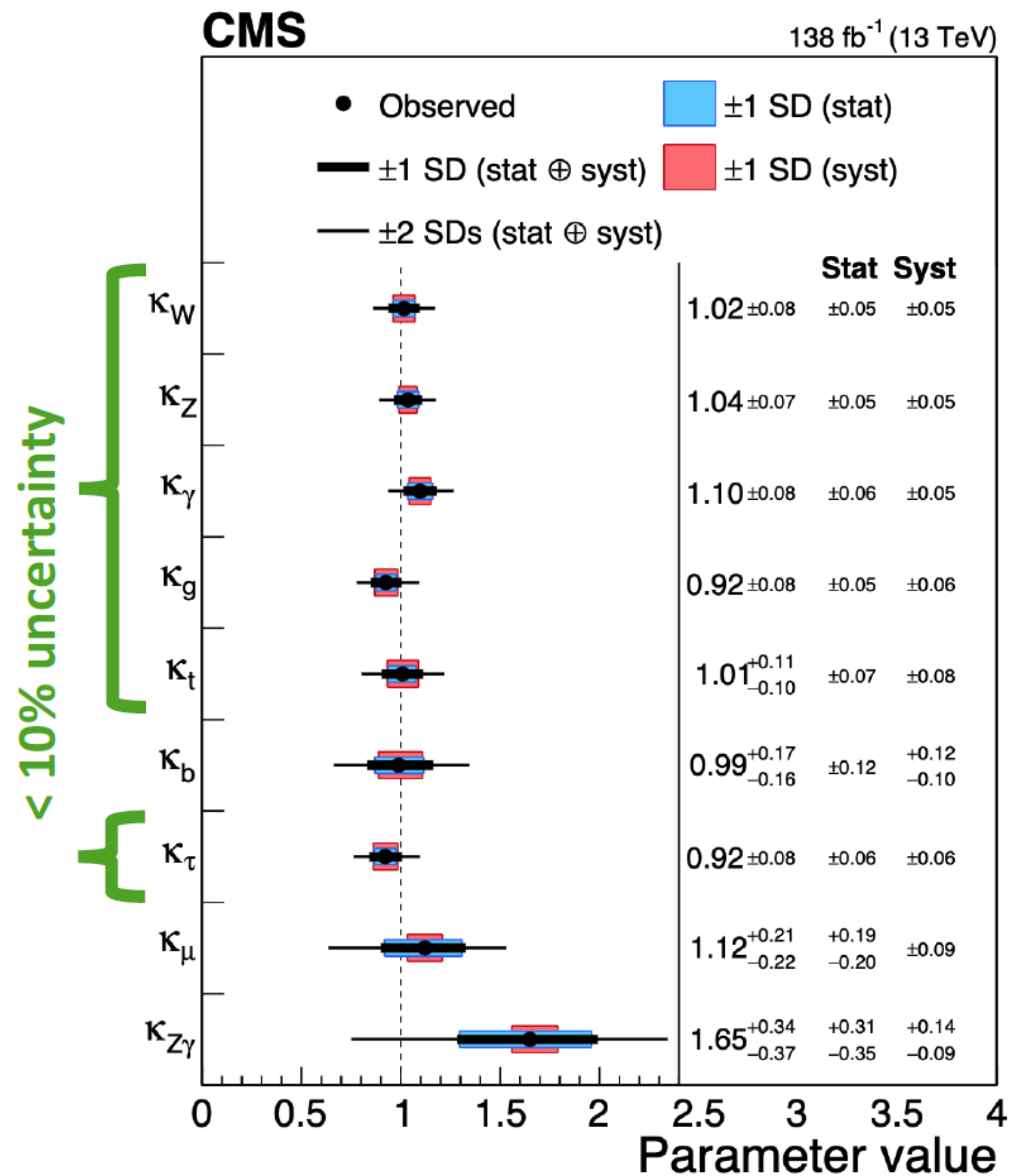
precision on $\mu \sim 10\%$

$$\mu = 1.01 \pm 0.08 \text{ (stat.)} \pm 0.04 \text{ (exp.)} \pm 0.05 \text{ (th.)}$$



Higgs Couplings

Nature 607 (2022) 60

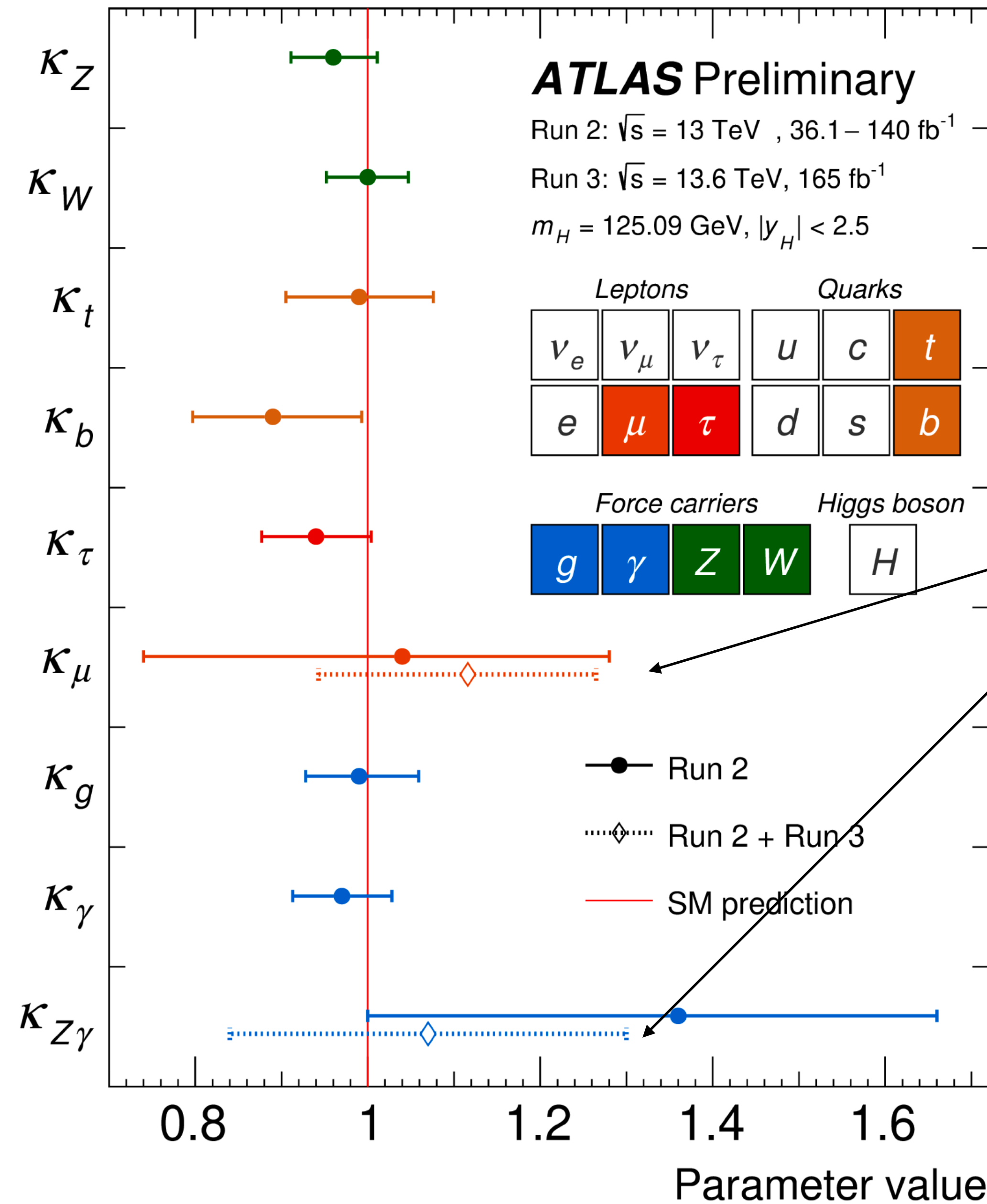


Run 2 Great precision on Higgs Couplings 30 times discovery statistics

Couplings to gauge bosons $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$ < 10%

and 3rd generation fermions $H \rightarrow \tau\tau$, tt precision 10-12%; $H \rightarrow bb$ observed (7 sigma)

Higgs Couplings

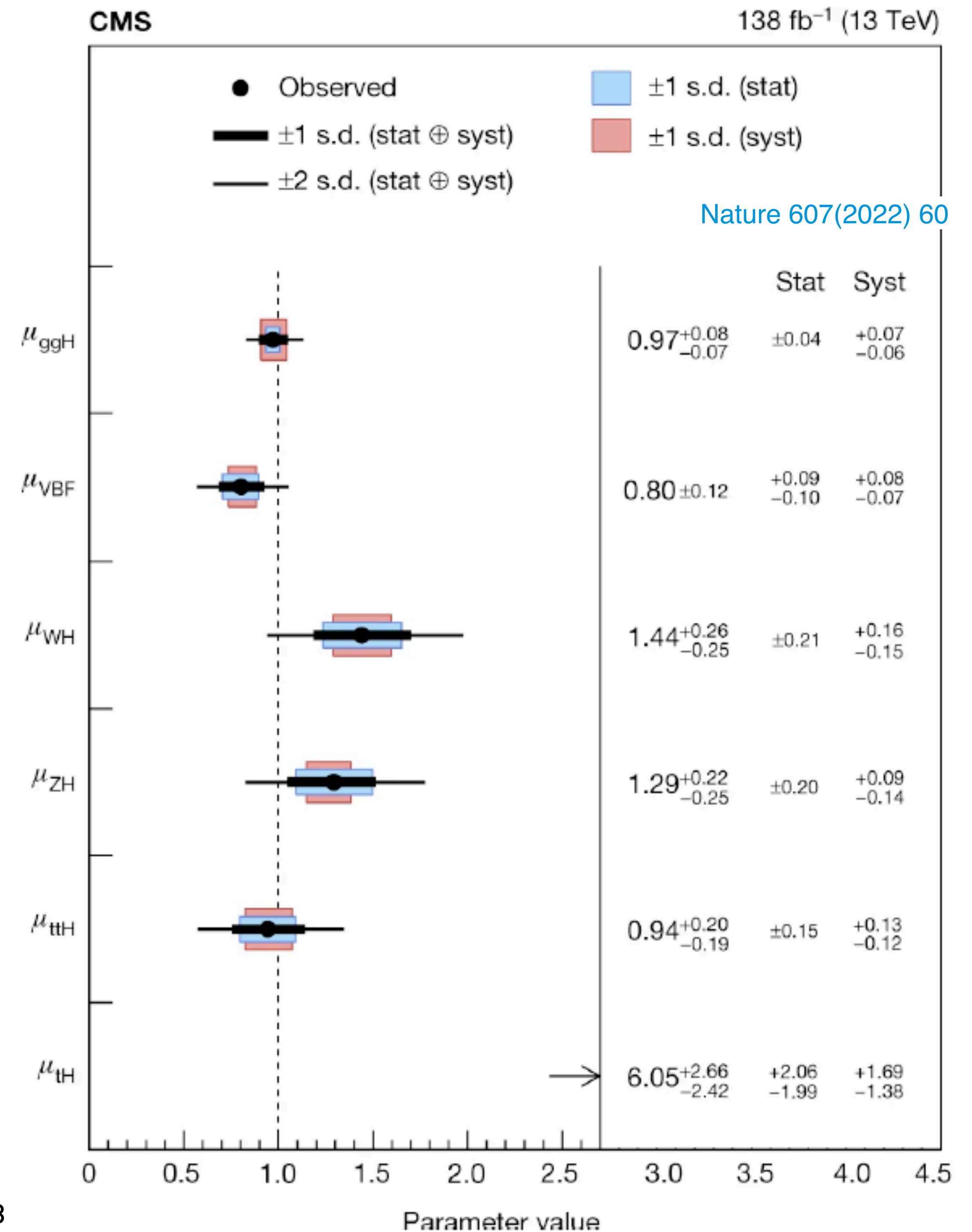


**First run 3 measurements
 entering the coupling plots!
 30% / 38% improvement in κ_μ / $\kappa_{Z\gamma}$**

Higgs Production

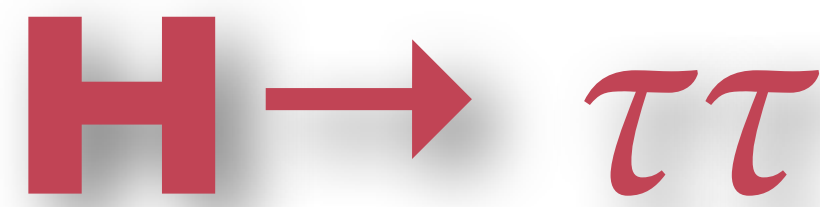
All the main production modes have been observed with a 5σ significance

- Main production modes (ggH, VBF) probed at $\sim 10\%$ level
- ttH $\sim 21\%$ level , VH $\sim 18\%$



**We are continuously significantly
improving wrt to projections.
Few very recent examples!**

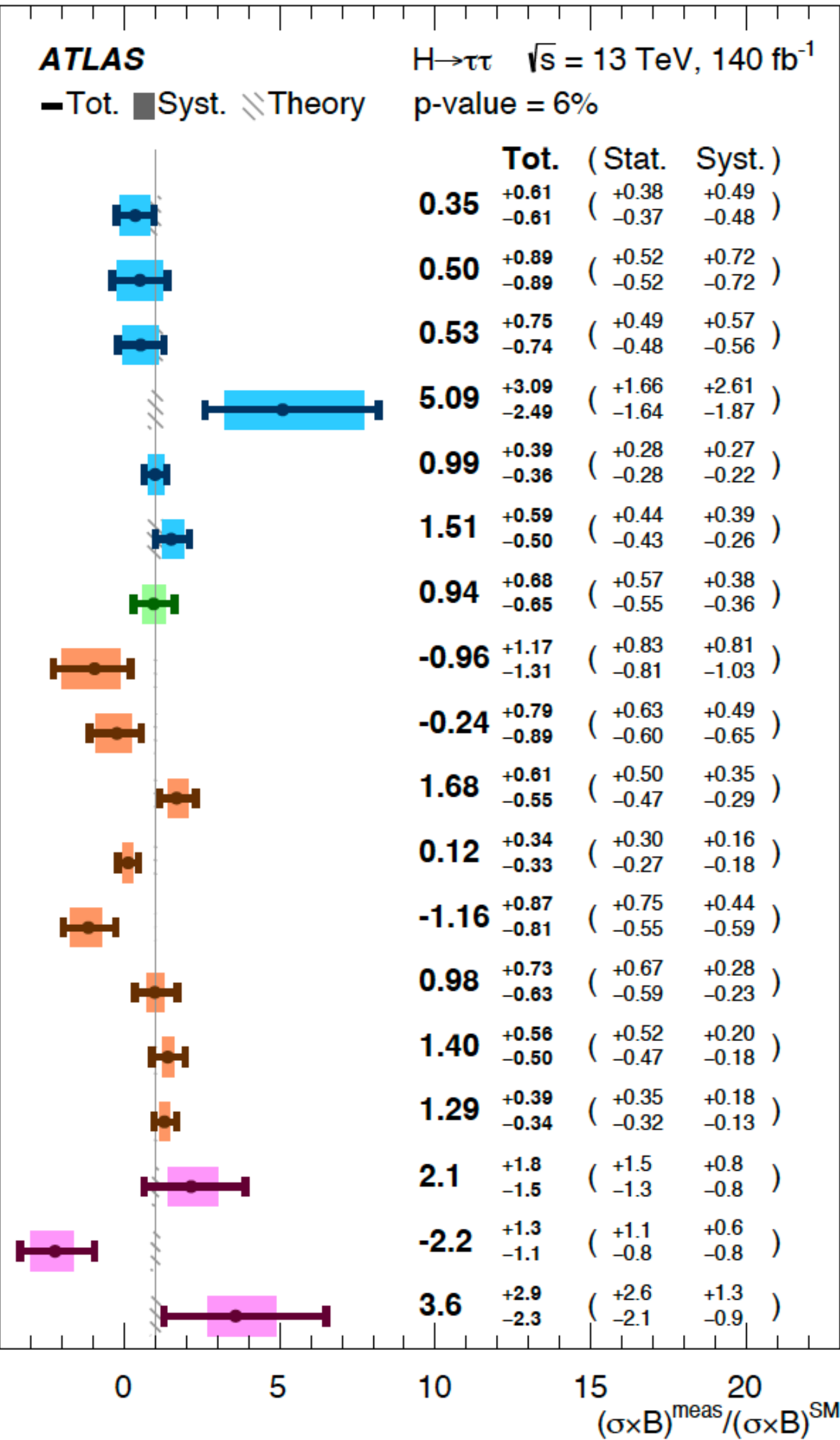
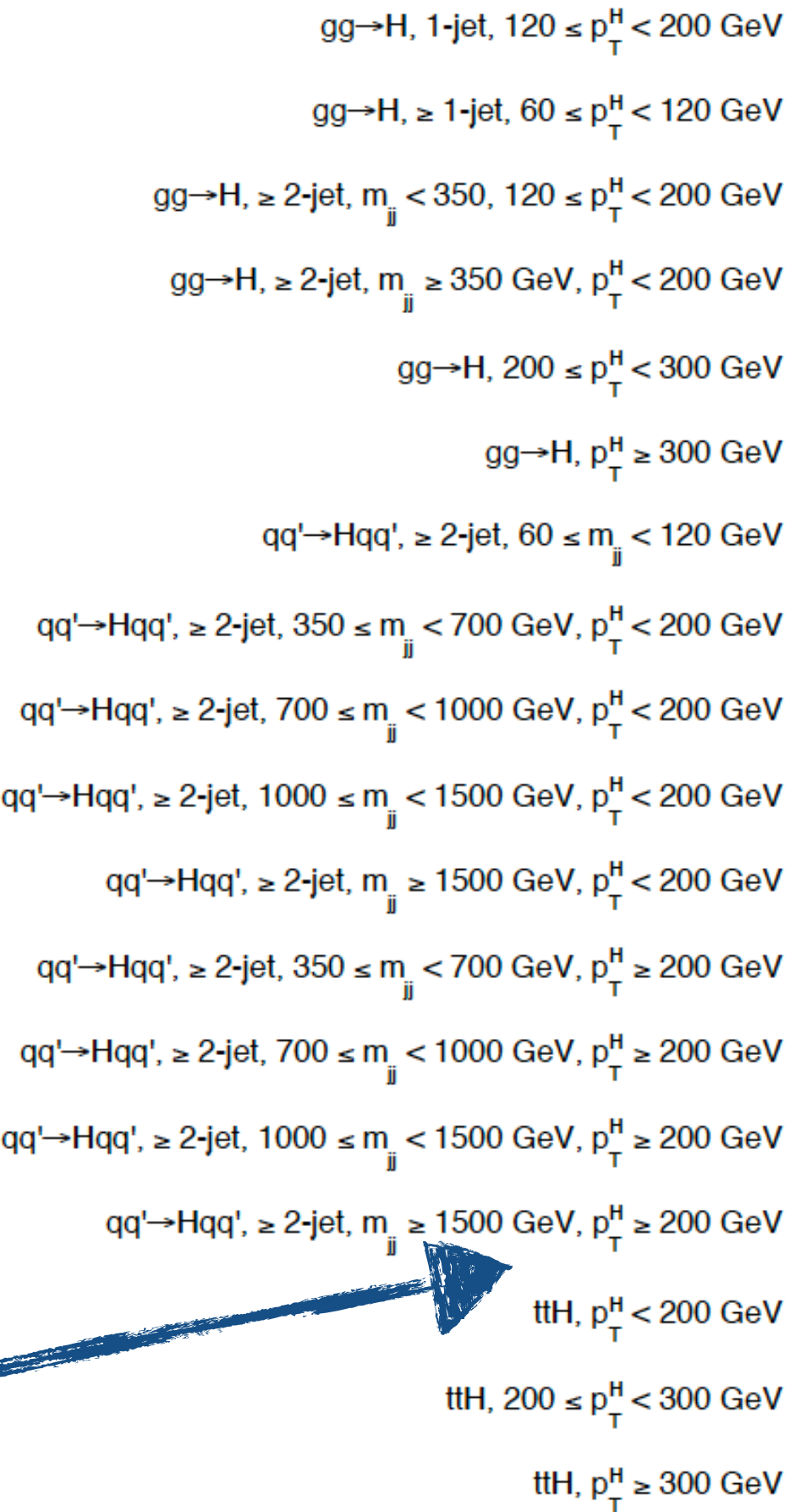
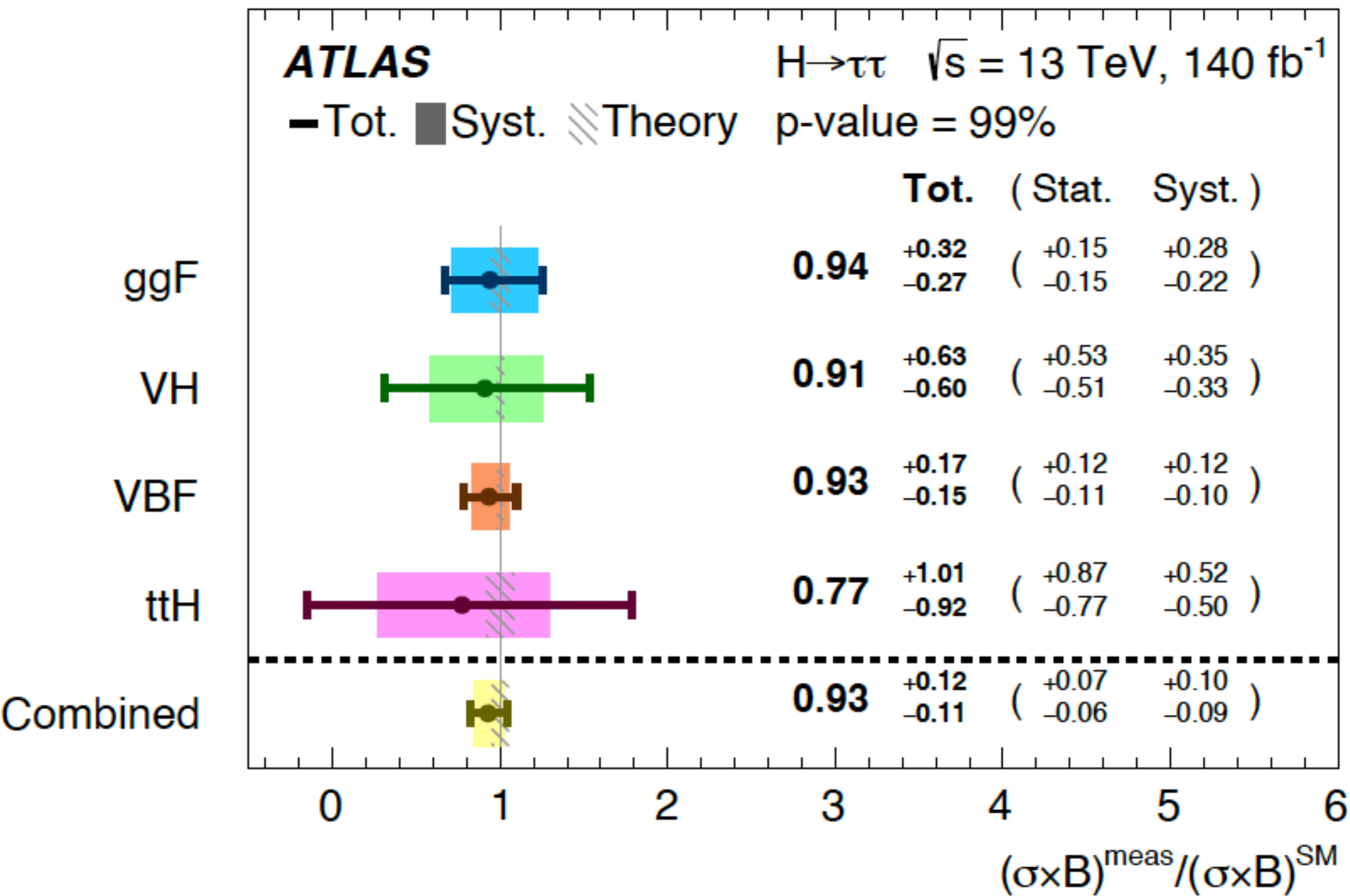
- **$H \rightarrow \tau\tau$**
- **VH, $H \rightarrow cc$ and $H \rightarrow bb$ combination**
- **Couplings to 2nd generation**
- **rare processes**
- **Run 3 measurements**



Re-analysis of run 2 data H → ττ has the strongest BR to leptons: Neural Network improves pTH resolution by 50%

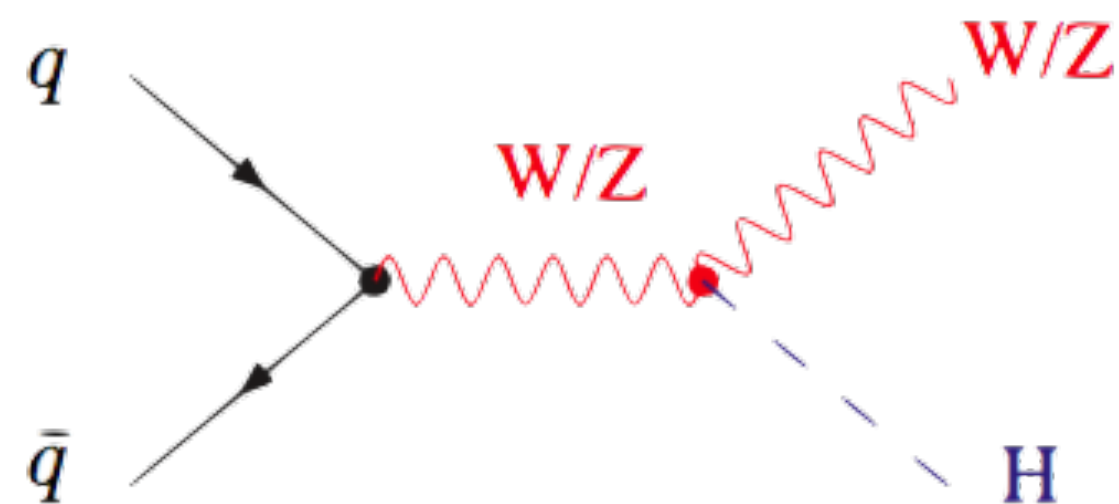
arXiv 2407.16320

all production modes

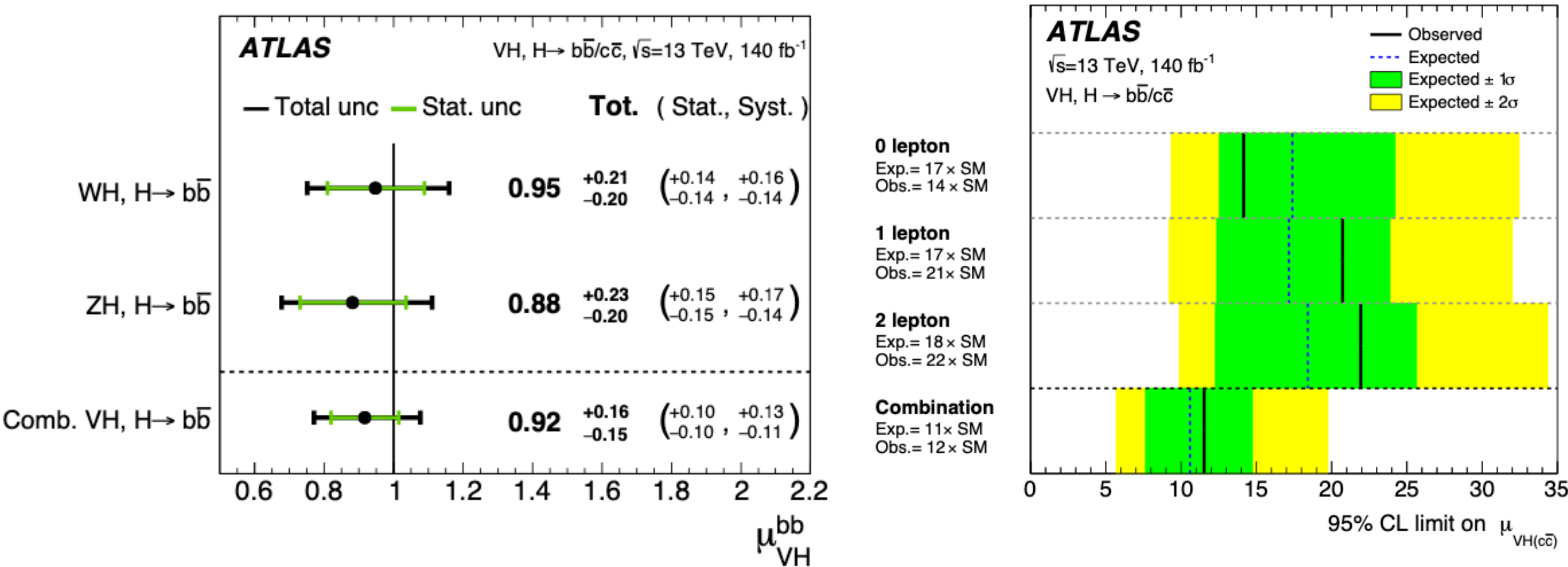


Most precise VBF measurement VBF at lowest pT
First VBF measurements for pTH>200 GeV (30-50% accuracy)

VH, H→cc and H→bb combination



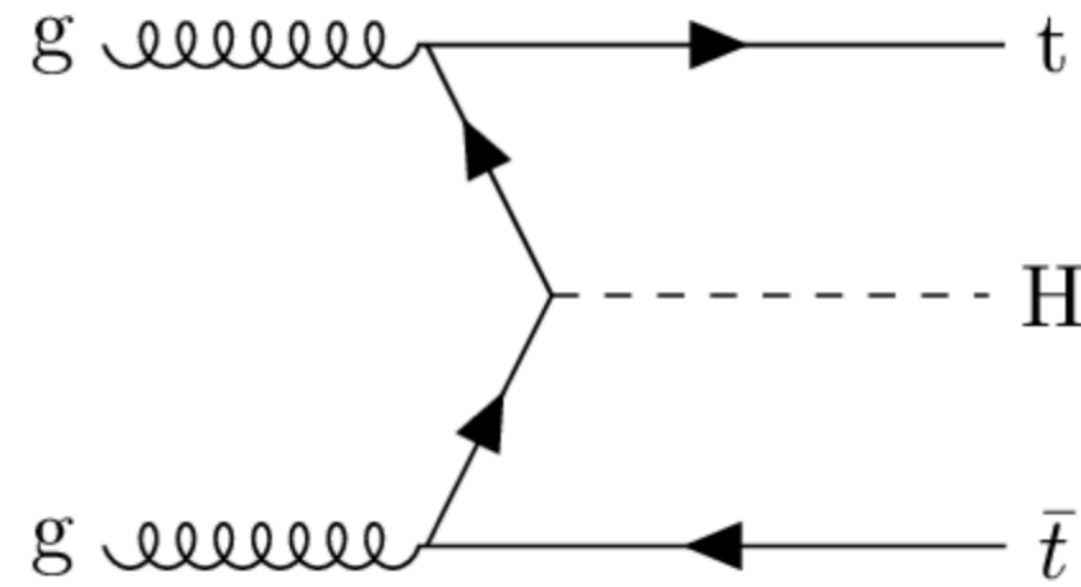
Run2 re-analysis: better reconstruction, better flavor tagging with b and c identification, better calibration, machine learning



H->cc limit on signal strength improved by a factor of 3 wrt first full Run 2 result !!

ttH(bb)

arXiv:2407.10904



4.6 sigma observation in this channel alone.

**expected sensitivity improved
from 2,7 to 5.4 sigma with same data**

**Various improvements NN-based classifier using
transformers with attention mechanism,
improvements in MC modeling**

$p_T^H \in [0, 60)$ GeV

$p_T^H \in [60, 120)$ GeV

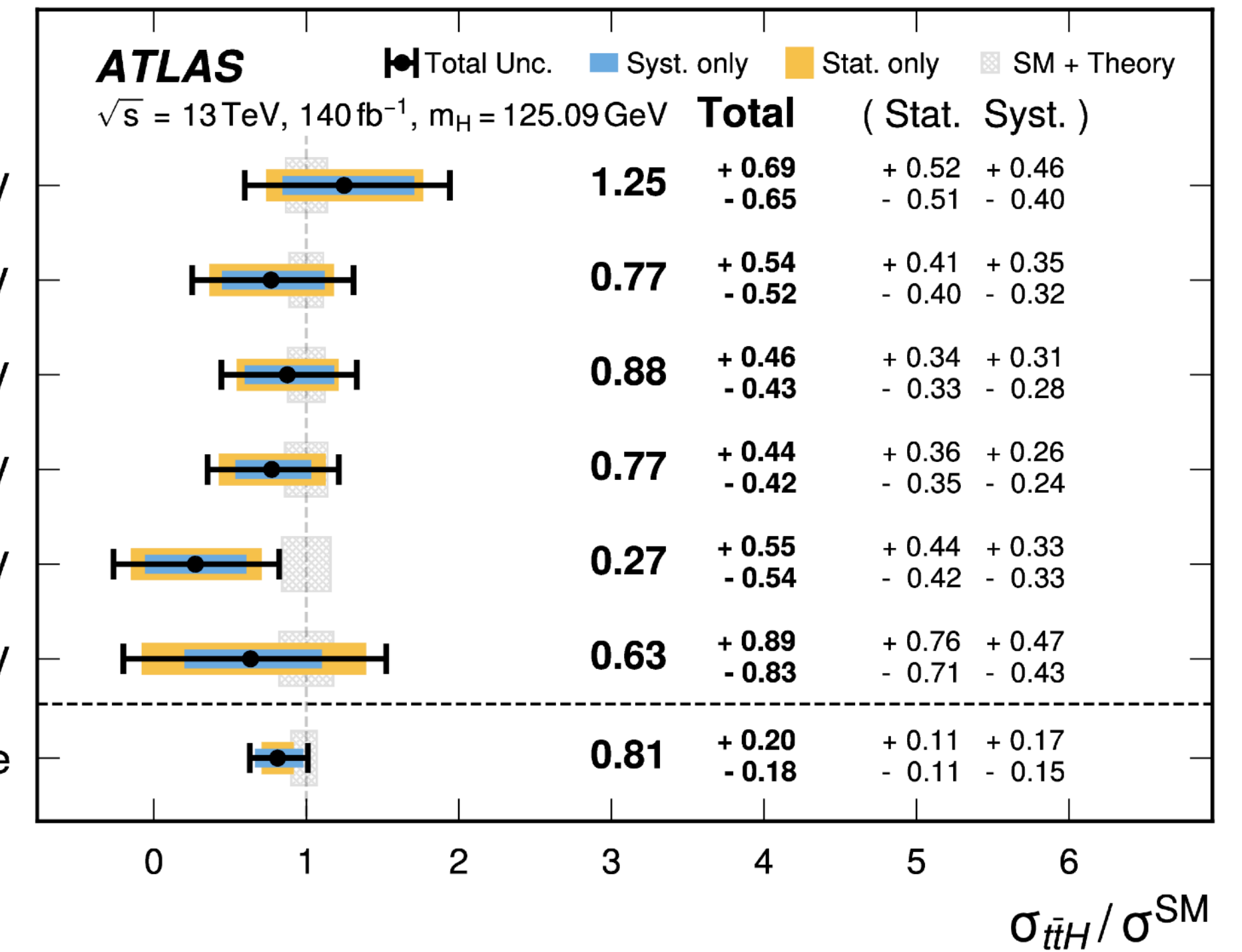
$p_T^H \in [120, 200)$ GeV

$p_T^H \in [200, 300)$ GeV

$p_T^H \in [300, 450)$ GeV

$p_T^H \in [450, \infty)$ GeV

Inclusive



Higgs couples to mass, 2nd generation?

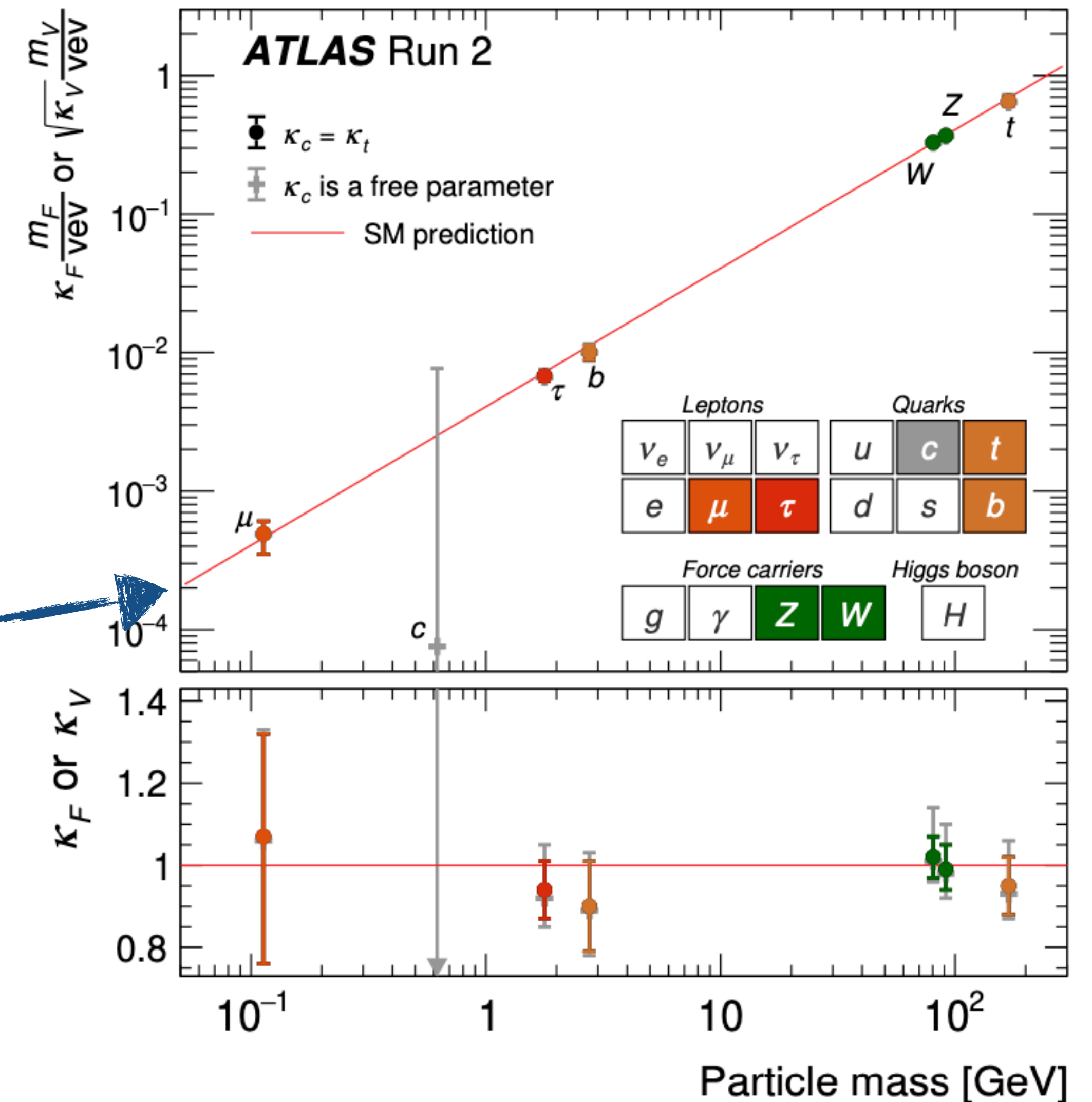
Evidence that the Higgs couples to mass

Third generation and gauge boson couplings follow the SM predictions

Next goal is to observe couplings to second generation (muons, c-quarks)

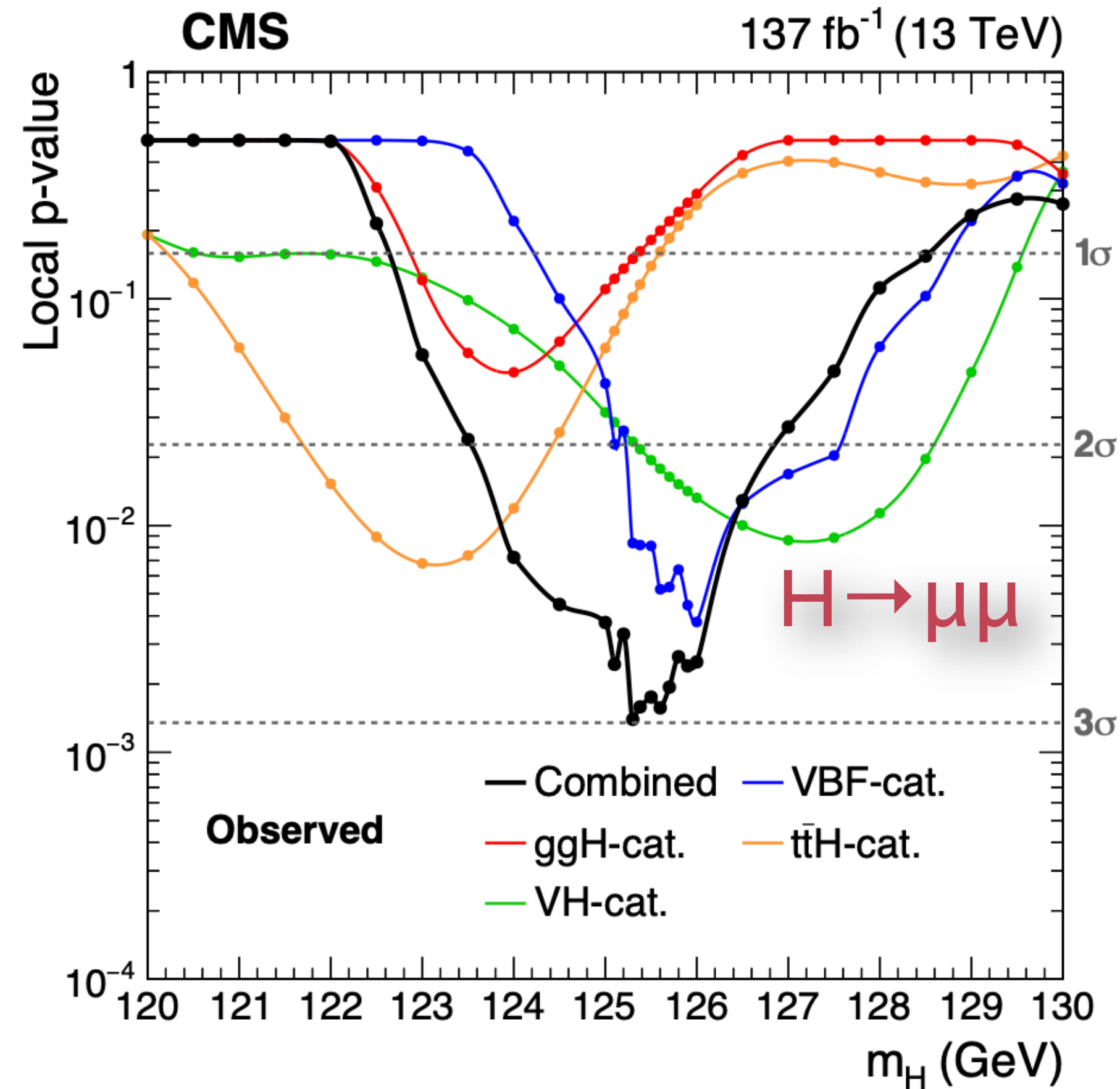
muons in reach soon (both experiments have already 3 sigma evidence)

arXiv:2404.05498



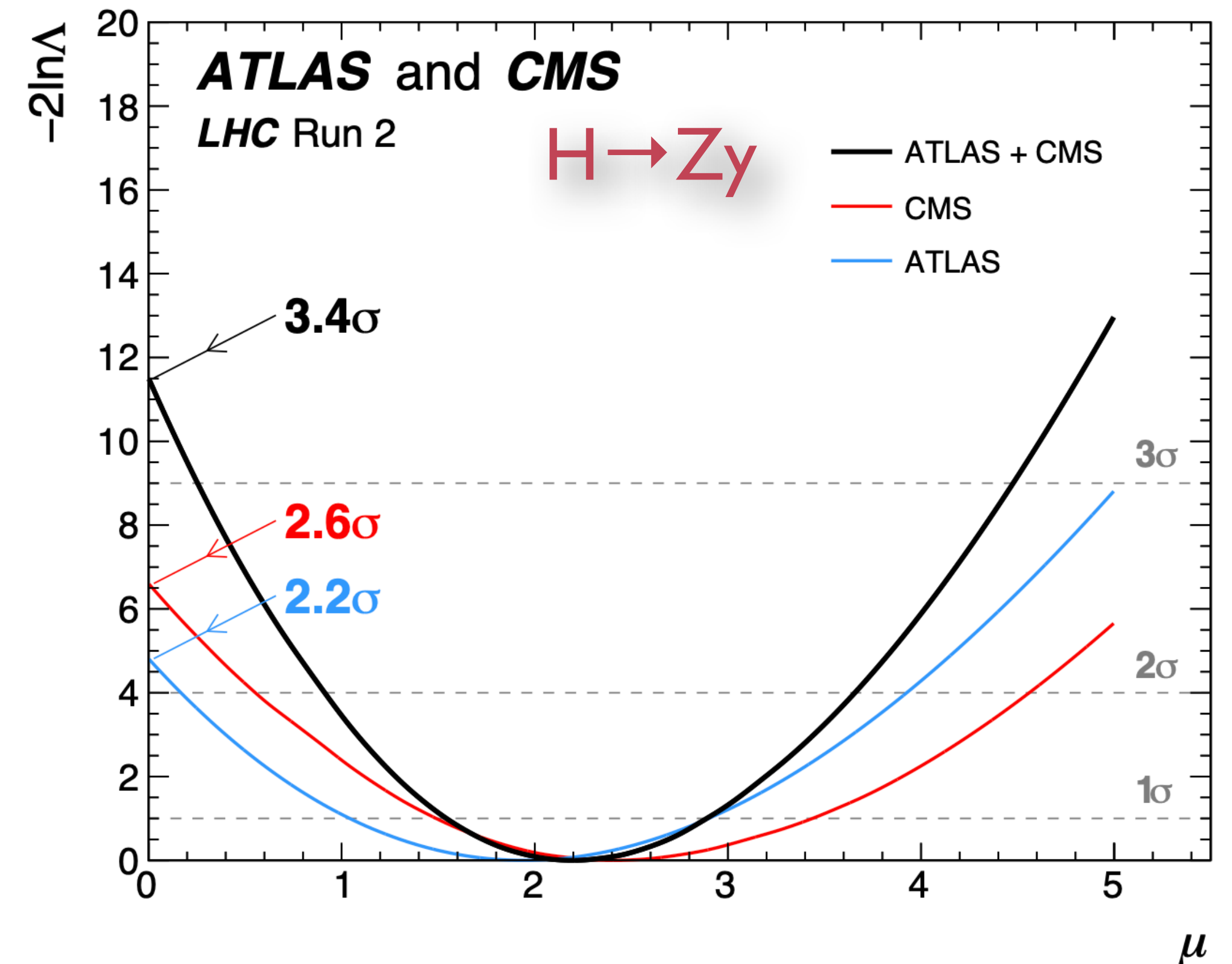
Rare decays

JHEP 01 (2021) 148



First evidence for the SM Higgs decay to fermions of the 2nd generation ggH, VBF, VH and TT

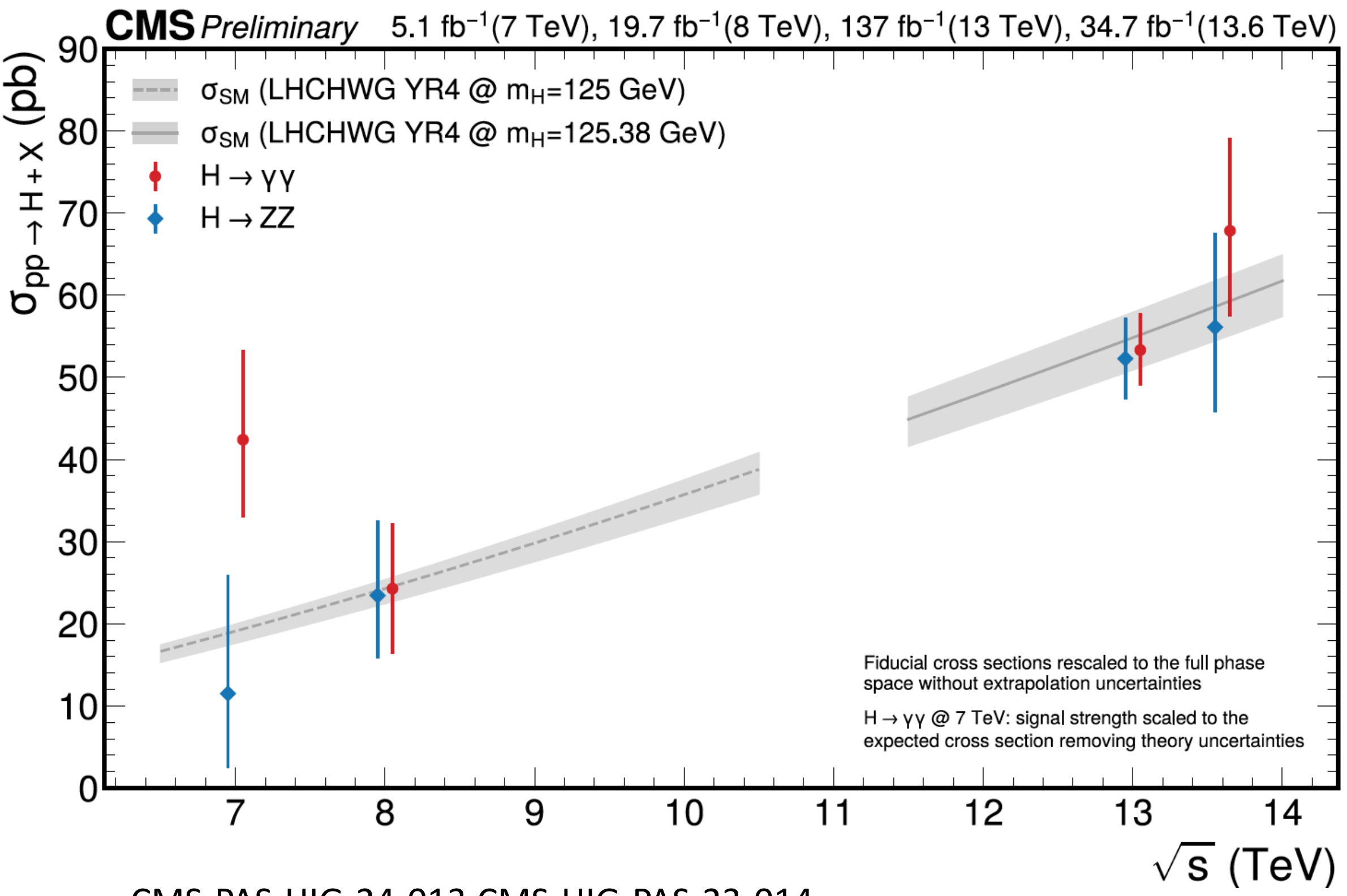
Phys. Rev. Lett. 132 (2024) 021803



**combination ATLAS+CMS
evidence at 3.4 σ**

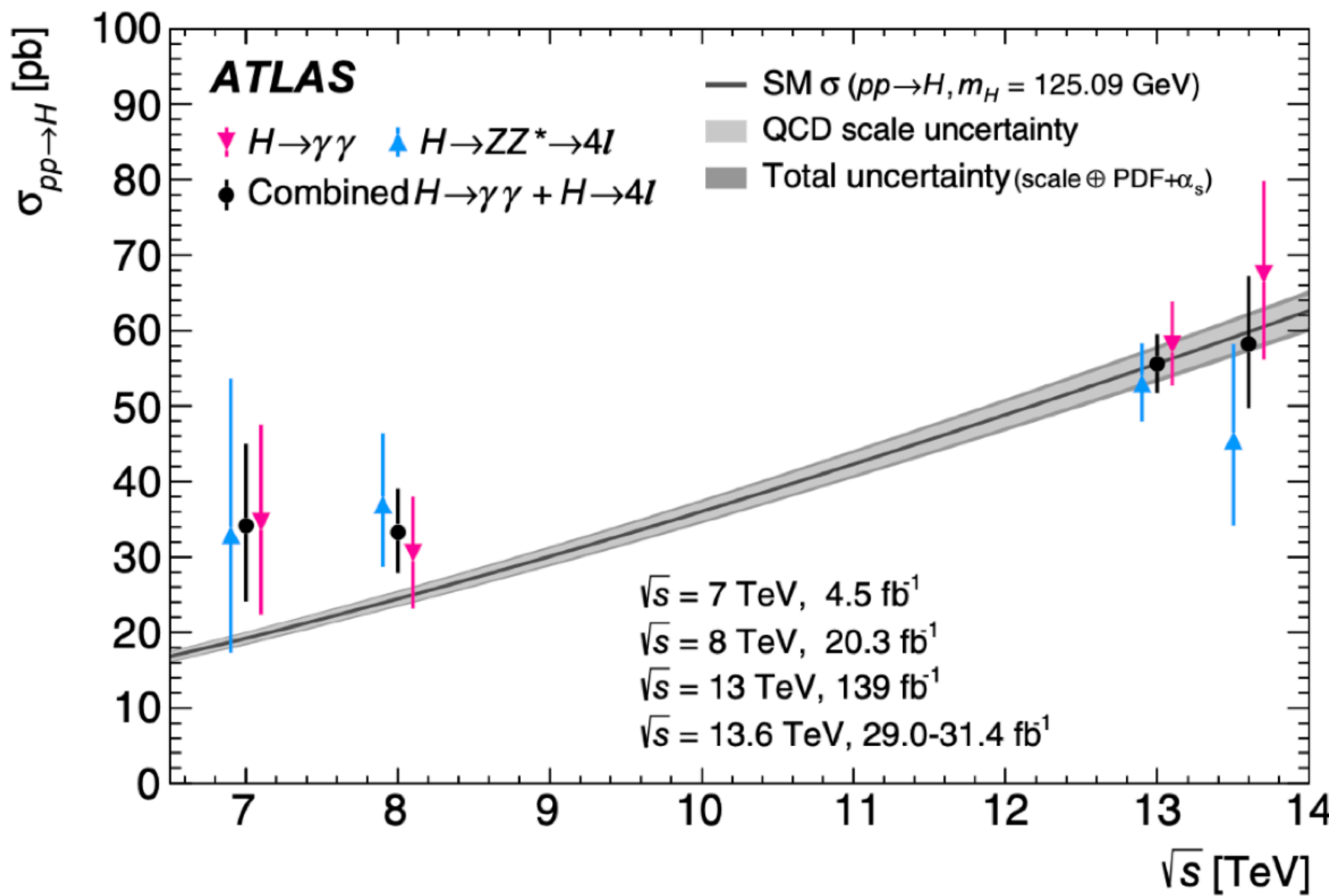
Run 3 measurements!

Fiducial cross-sections (rescaled to inclusive)



CMS-PAS-HIG-24-013, CMS-HIG-PAS-23-014

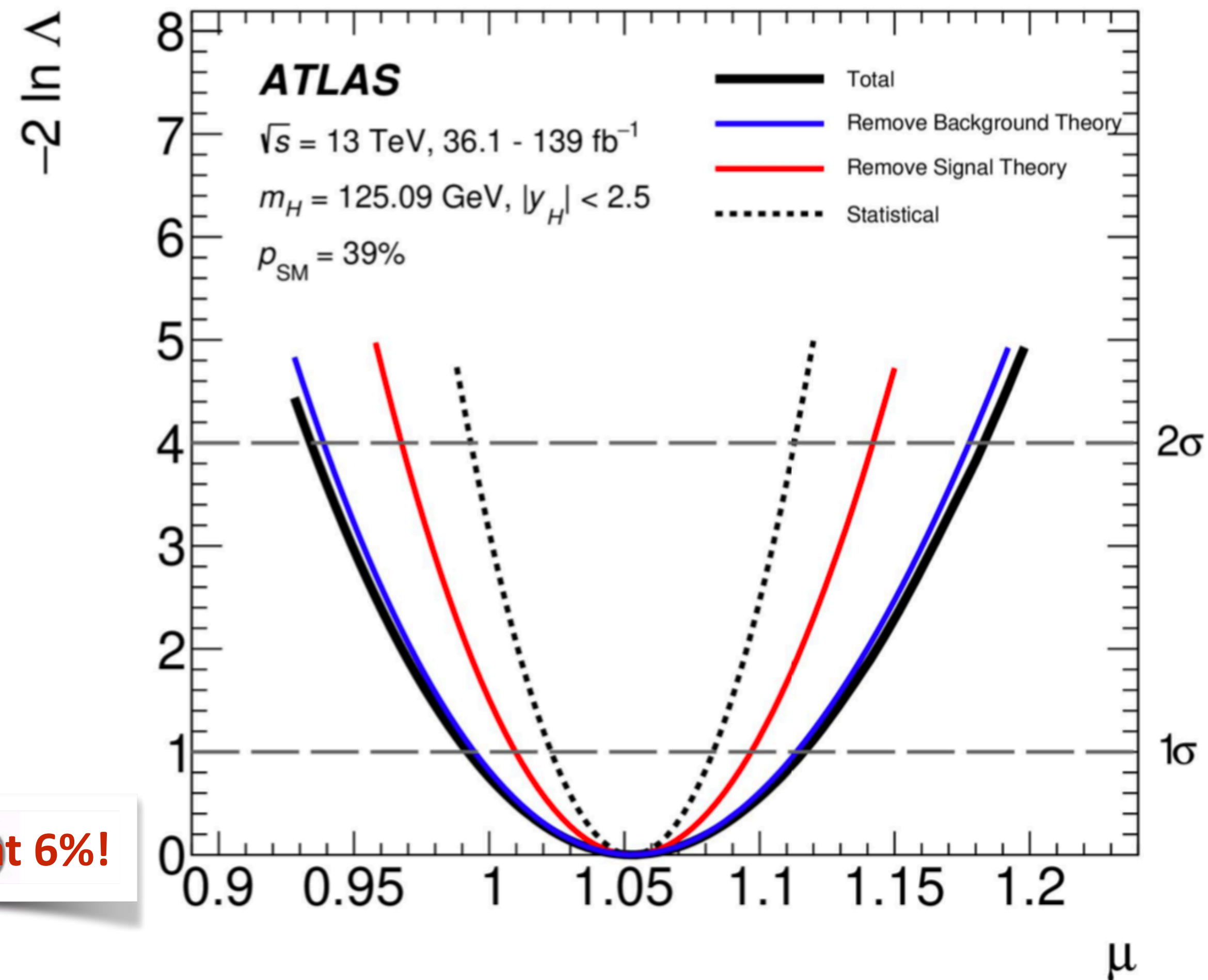
Eur. Phys. J. C 84, 78 (2024)



Putting it all together

Higgs Combination

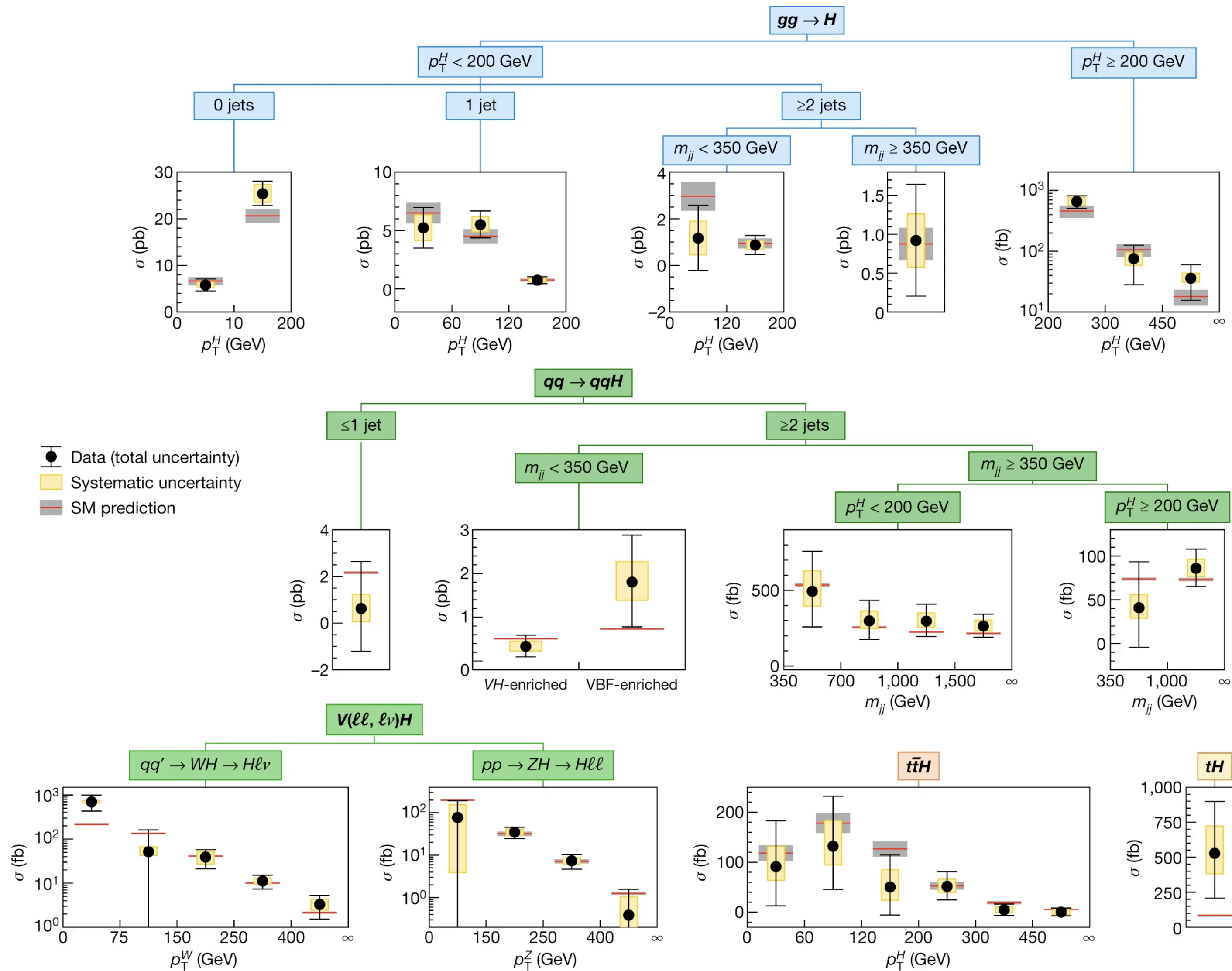
Nature 607, 52–59 (2022)



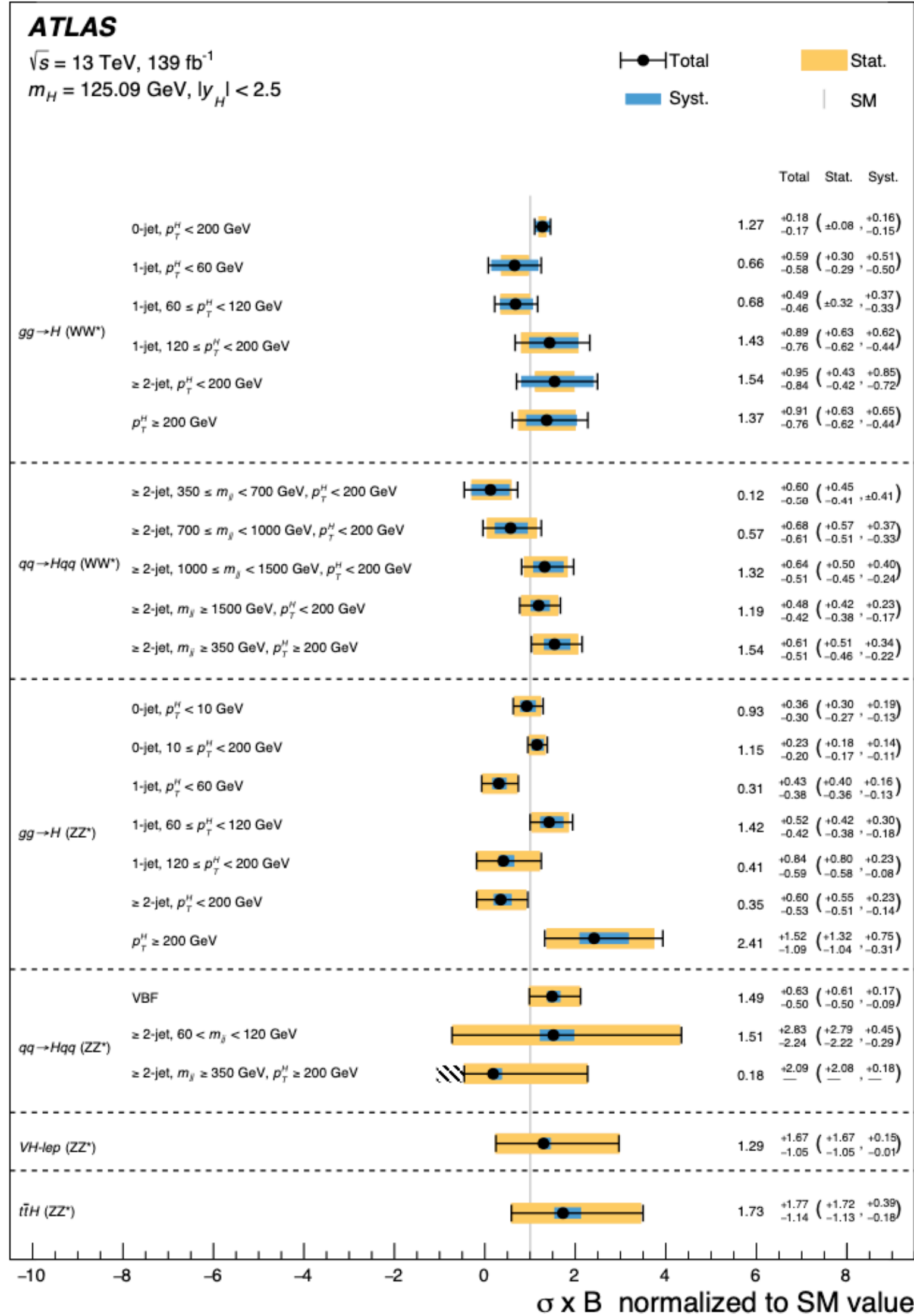
Measurement at 6%!

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03 \text{ (stat.)} \pm 0.03 \text{ (exp.)} \pm 0.04 \text{ (sig. th.)} \pm 0.02 \text{ (bkg. th.)}.$$

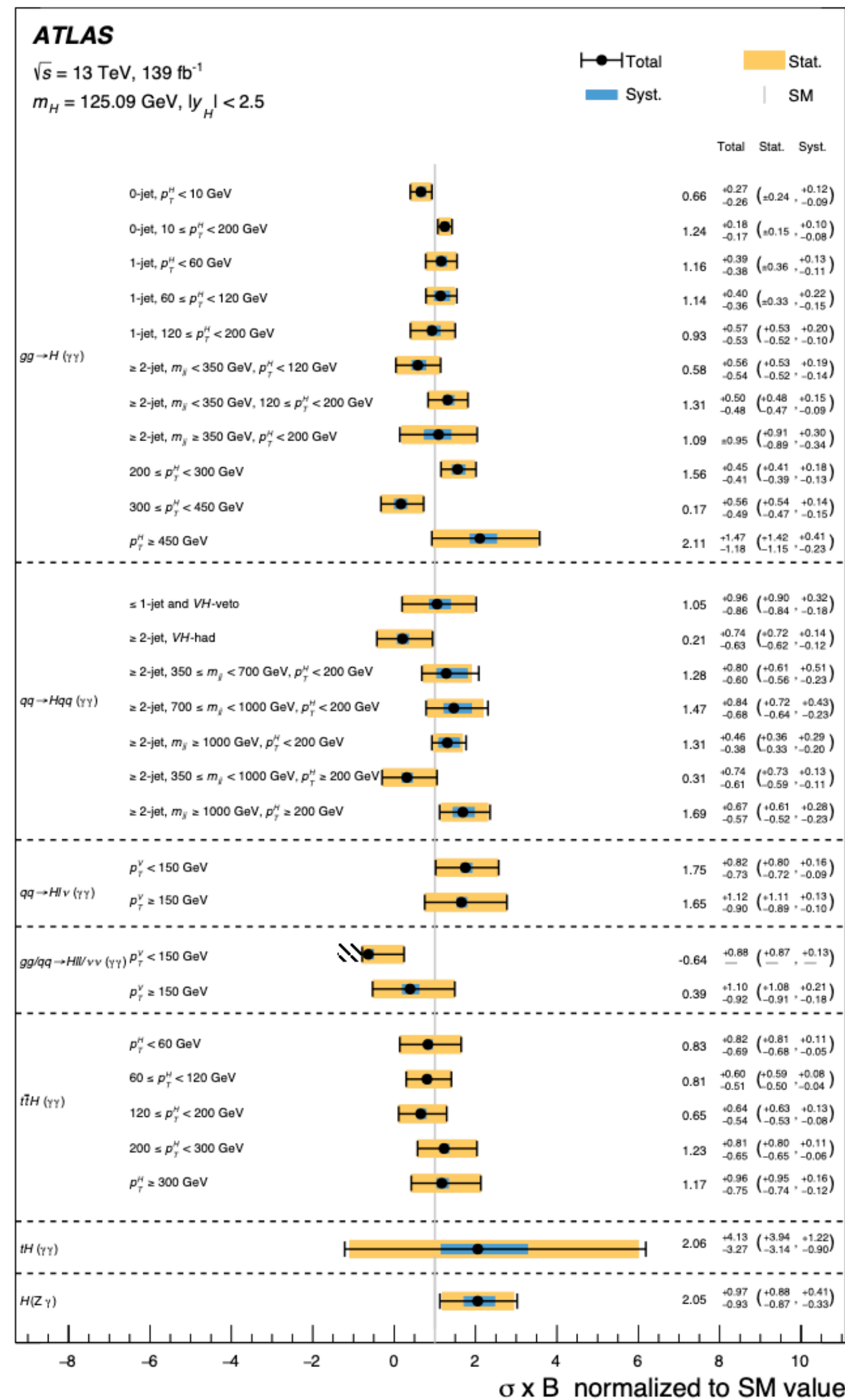
Simplified Template X-Sections full Run 2



- Measurements of cross sections σ in mutually exclusive regions split based on Higgs kinematics (+ W or Z bosons and associated jets)
- Reduce large theory uncertainties and minimize model-dependence when extrapolating to signal regions
- Maximize sensitivity to possible BSM

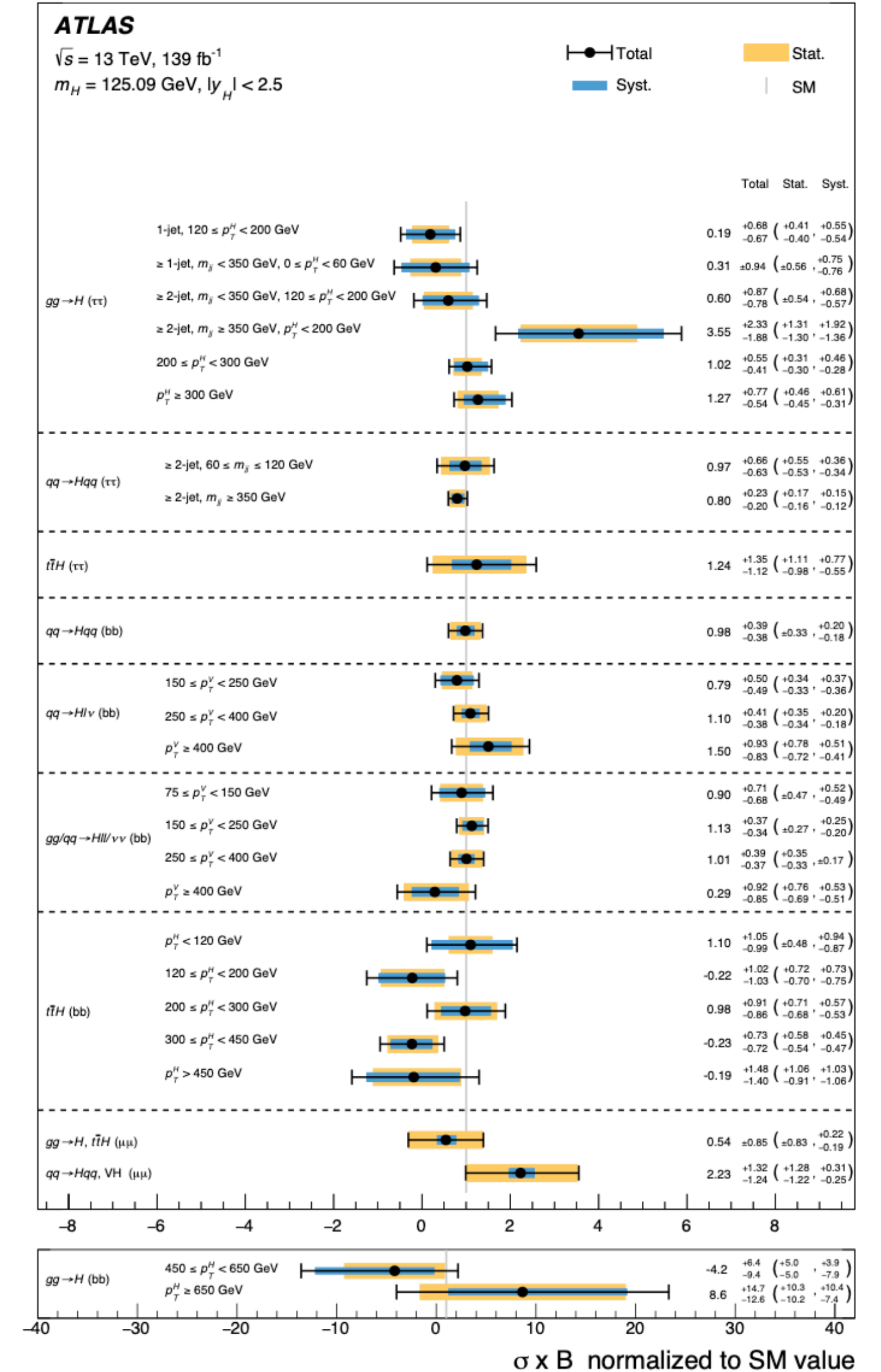


H→WW and ZZ



H→γγ,Zγ

69



H→ττ, bb, μμ

Effective Field Theories

How to be sensitive to New Physics beyond the Standard Model in a Model Independent way?

Effective Field Theory parametrizes Beyond Standard Model (BSM) effects at high energies ($\Lambda \gg v$, above electroweak scale) at low energies, $E \ll \Lambda$, in terms of higher-dimensional operators in an effective Lagrangian:

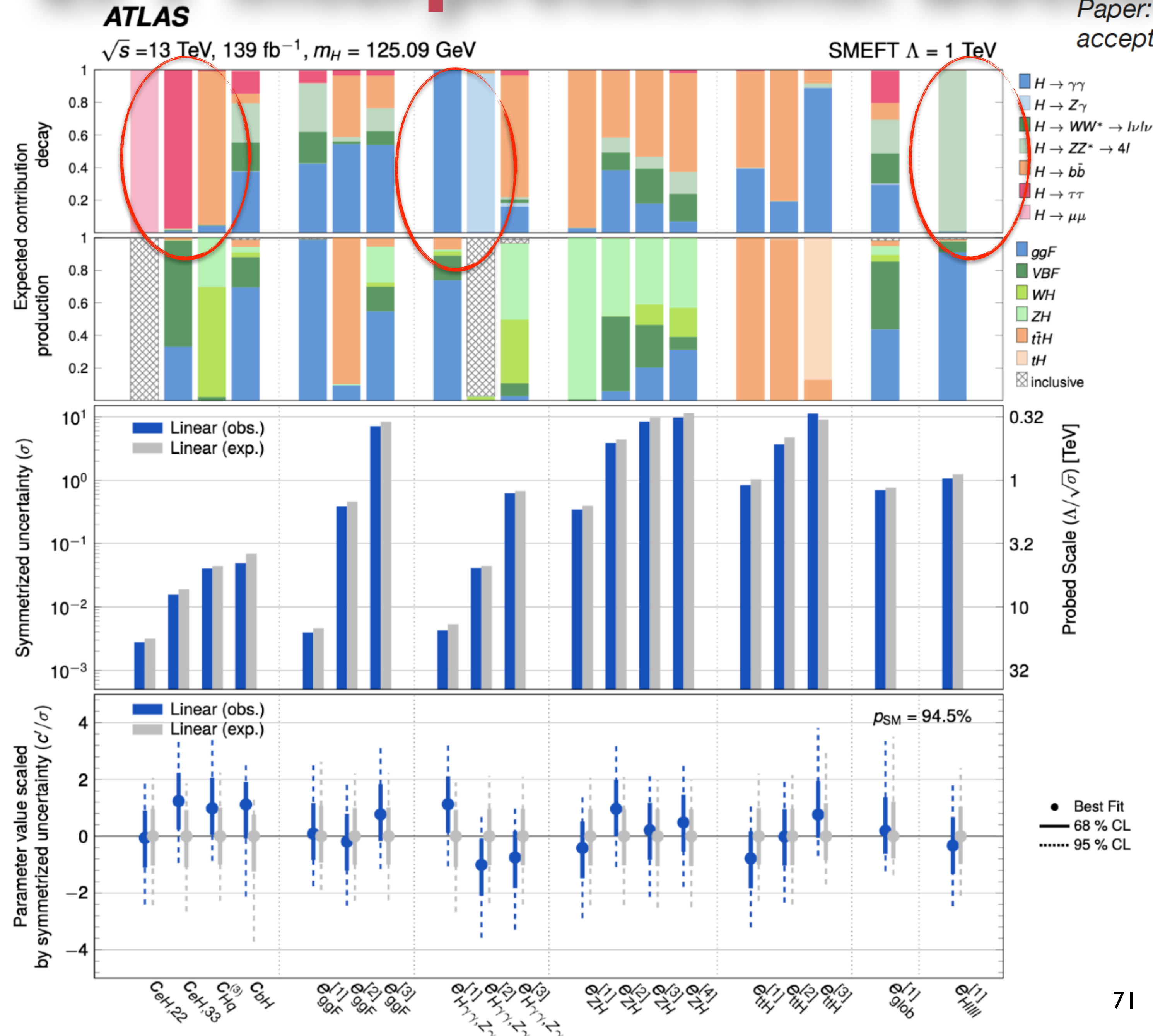
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d=8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots,$$



dimensionless Wilson coefficients of higher dimension operators

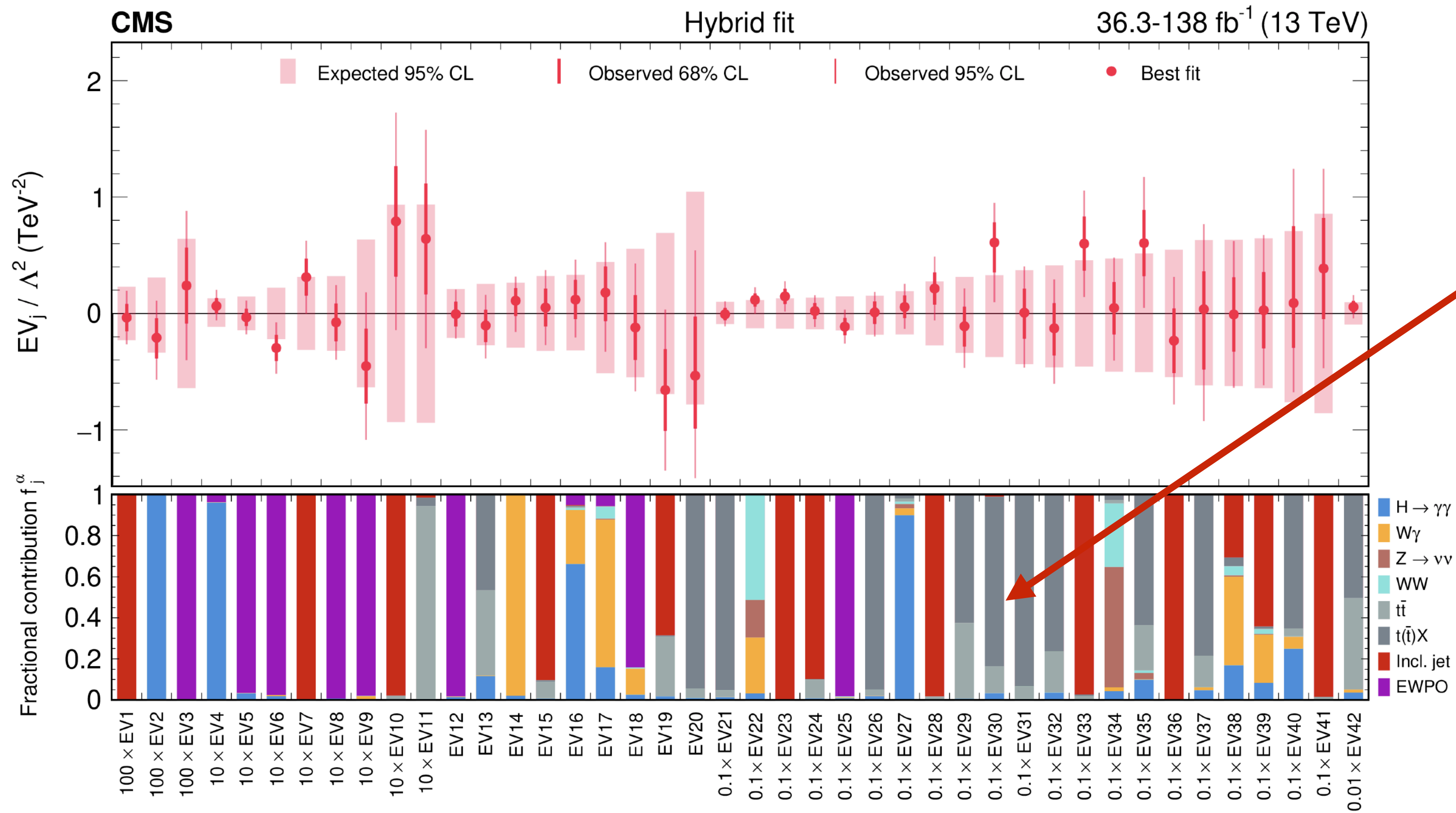
EFT interpretations: Bottom up approach

Paper: [arXiv:2402.05142v1](https://arxiv.org/abs/2402.05142)
accepted by JHEP



Bottom up approach means that we are on new physics model.
6 parameters nearly exclusively measured in 1 decay mode

Higgs+EW+top+EWPO EFTs



This is just NOT just Higgs!
We use EW+top+Higgs +EW Precision
Observables from LEP

We also adding in the game the Charge and
Parity of the Higgs.

The Higgs sector could contain a partial
violation of the Charge and Parity that could
explain the matter antimatter asymmetry.

EFT: Top down approach

What about guiding the measurements such that they can be more sensitive to Wilson Coefficients that would present larger variations within specific models?

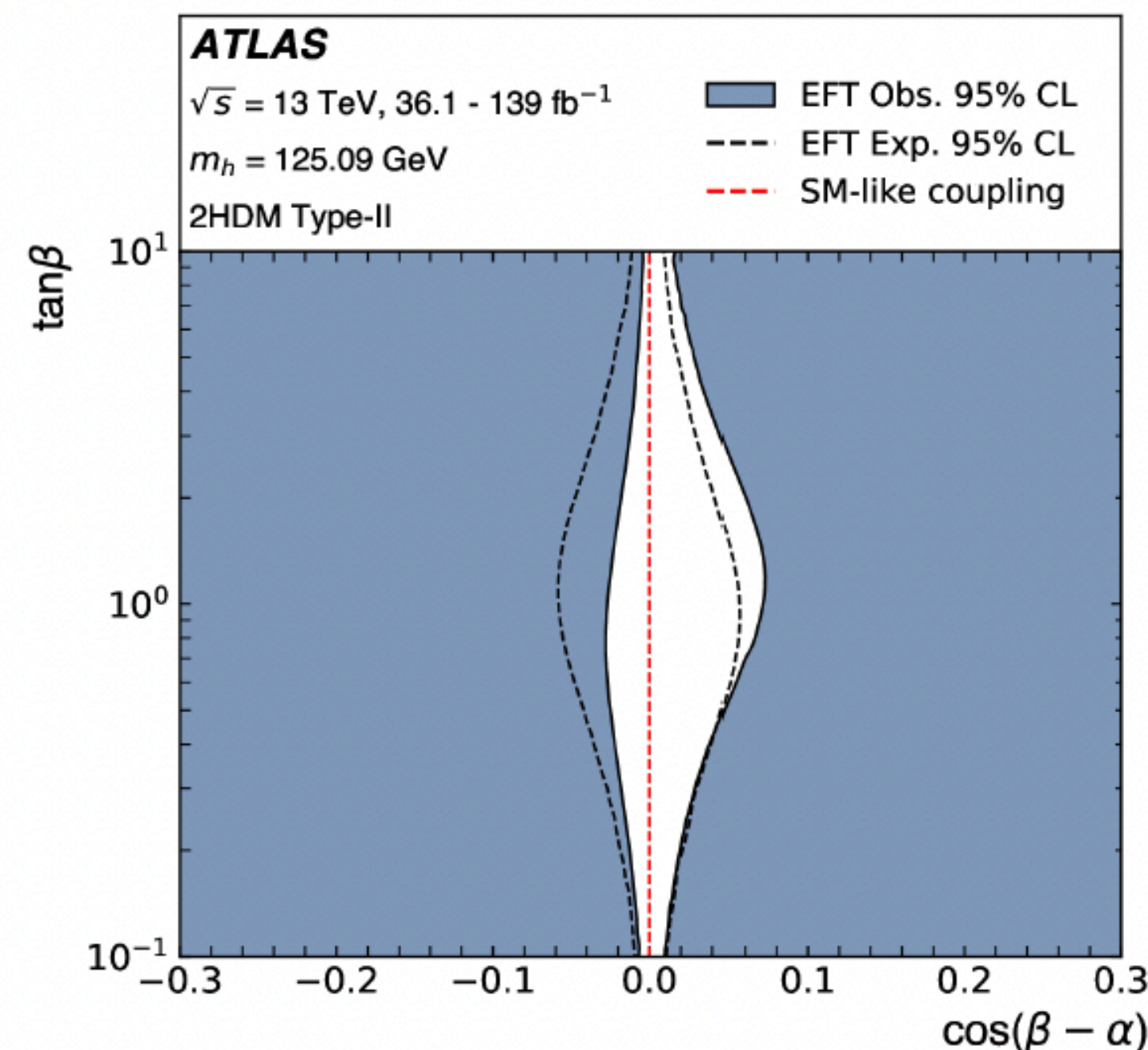
- Comes at the cost of losing generality, but can lead help us not to miss important features in the data.
- Requires matching models with EFTs.

arXiv:2112.10787v1

The leading IR/UV dictionary (tree-level, dimension 6 SMEFT) is already there since few years ago.

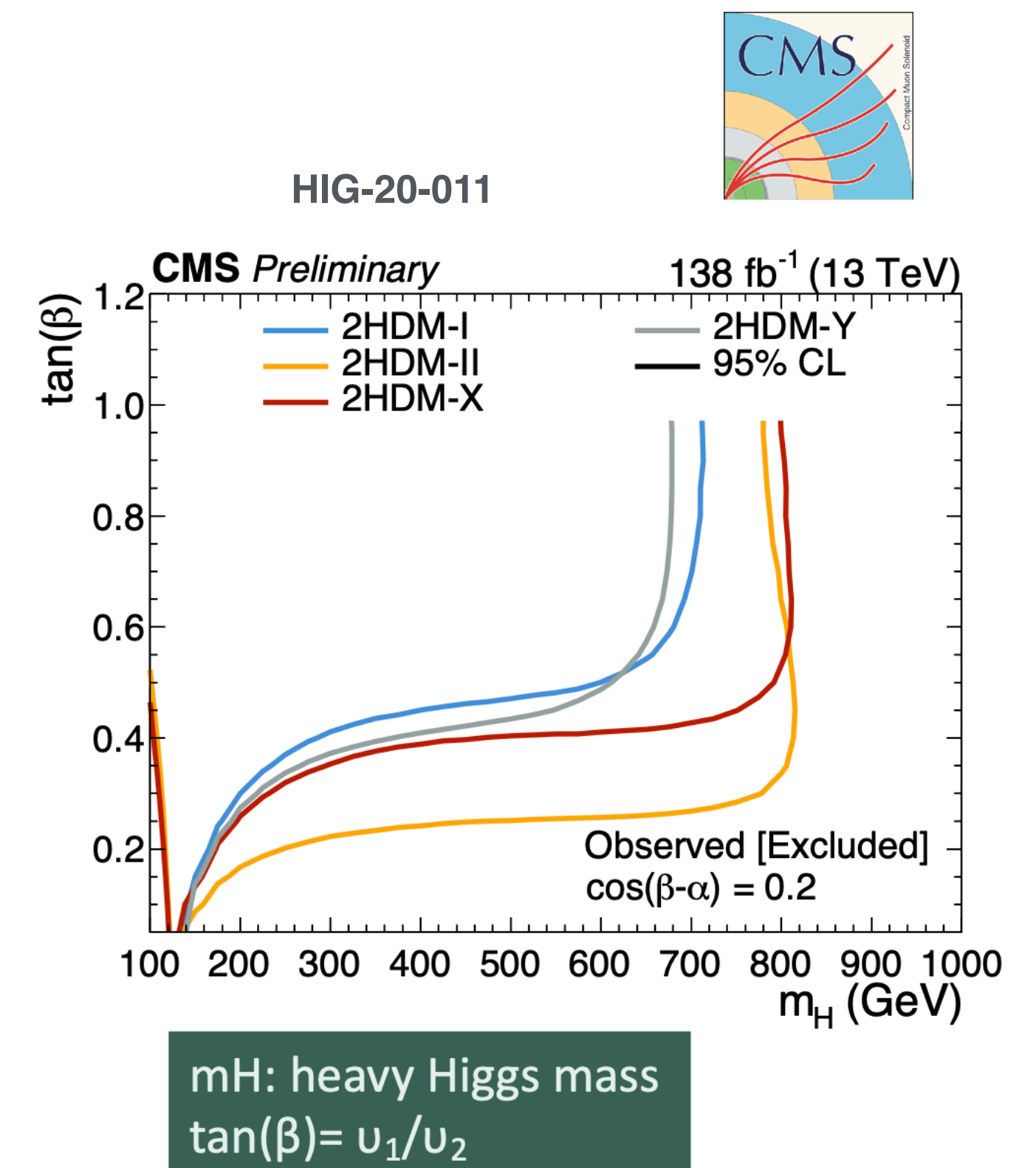
Example: The 2HDM Lagrangian can be written as a SMEFT expansion!

arXiv:2402.05742v



arXiv:2402.05742v2

concrete examples on SMEFT expansion used to
constrain a UV-complete model



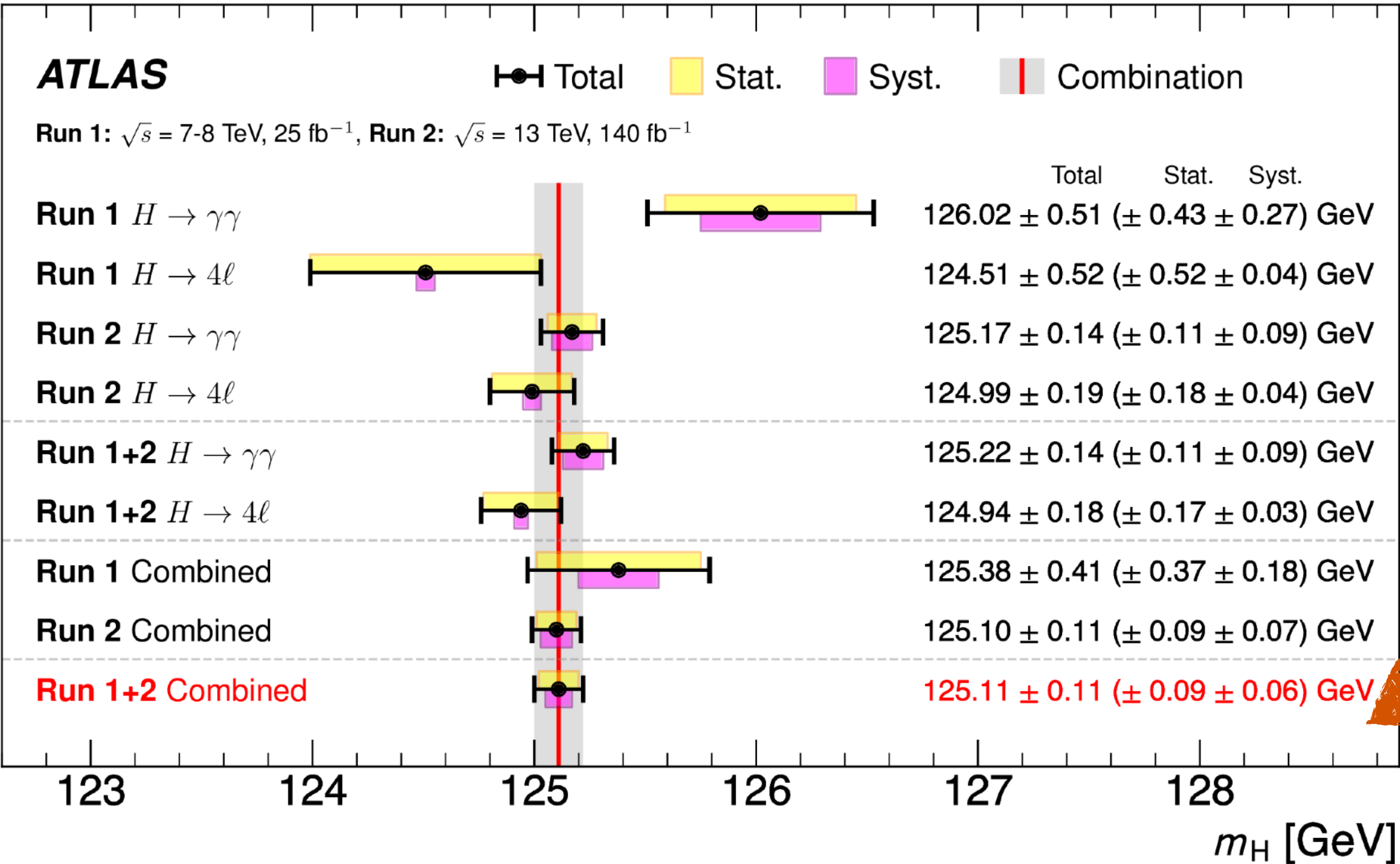
Lecture 2

Higgs mass

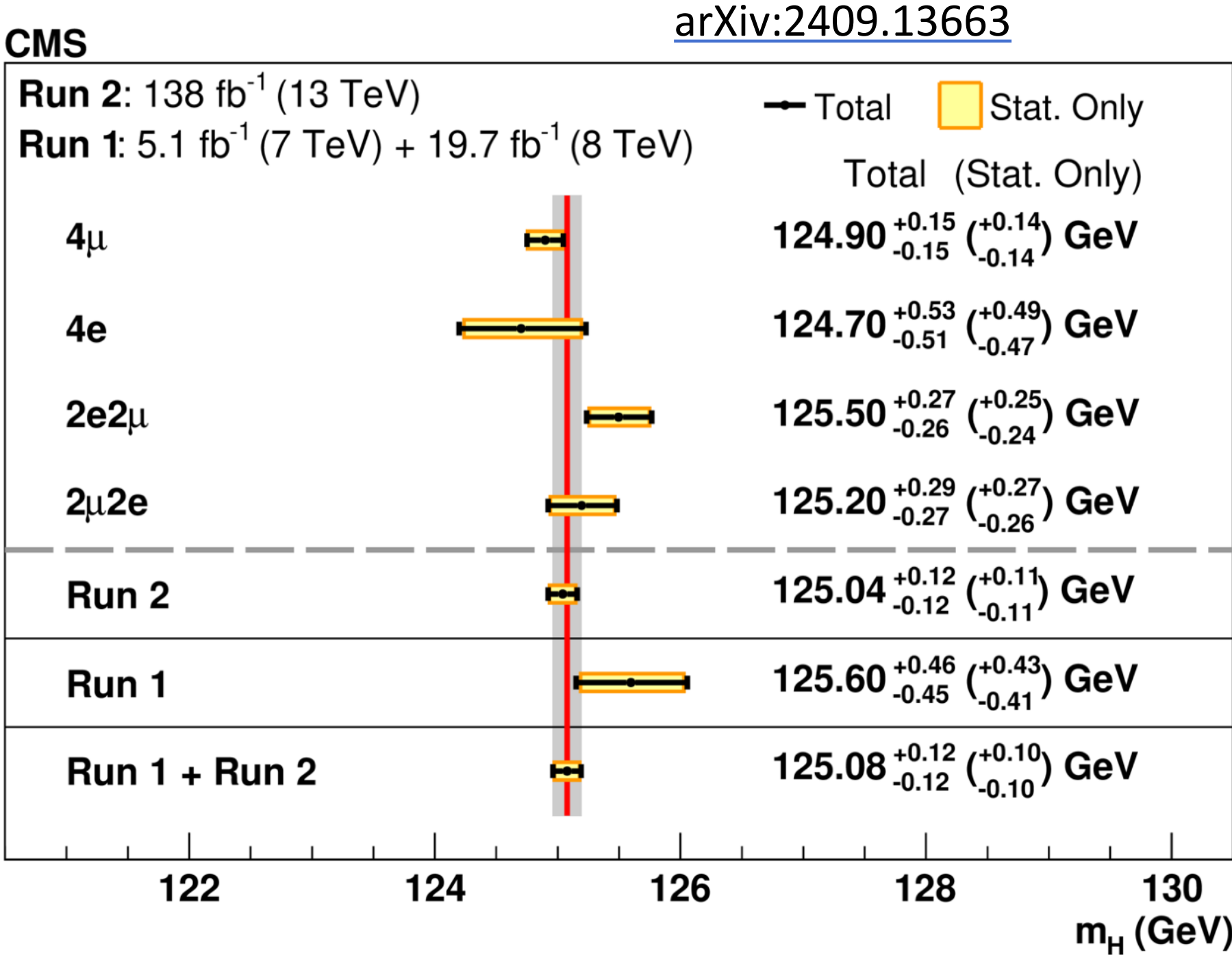
$m_H = 125.04 \pm 0.12$

$h \rightarrow ZZ$ Most precise single experiment measurement

Higgs mass precision is now at the 0.1% level for **both experiments**, was 0.2% after Run I.



PLB 847 (2023) 138315
PRL 131 (2023) 251802



ATLAS most precise m_H measurement at 0.09%

$m_H = 125.11 \pm 0.11$ GeV

Profits of various performance improvements:

- ~4x improvements in photon energy calibration!

➔ Reduces $H \rightarrow \gamma\gamma$ systematics by factor 3:

320 MeV $\rightarrow$ 80 MeV

Higgs width measurement $H^* \rightarrow ZZ \rightarrow 4\ell$

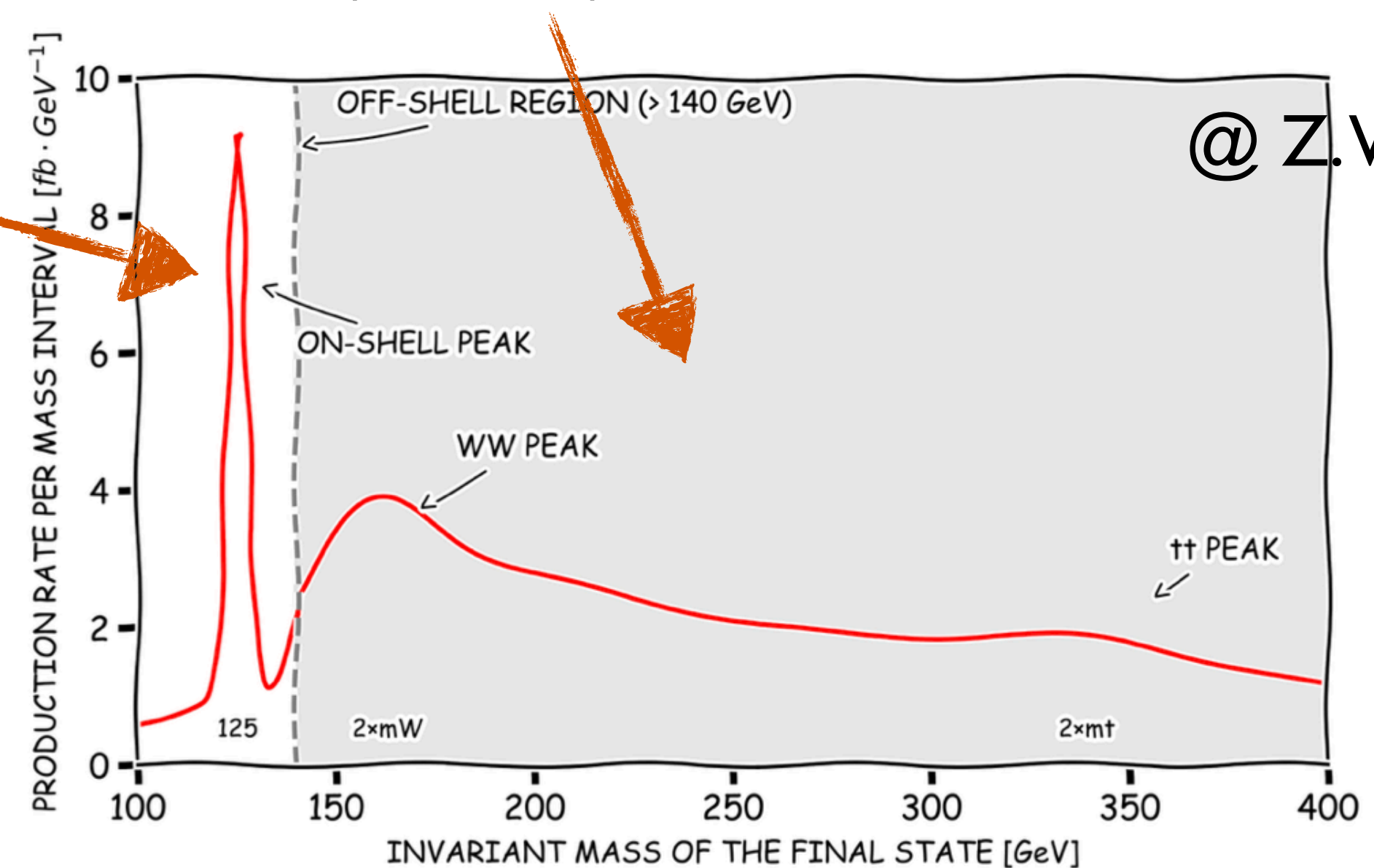
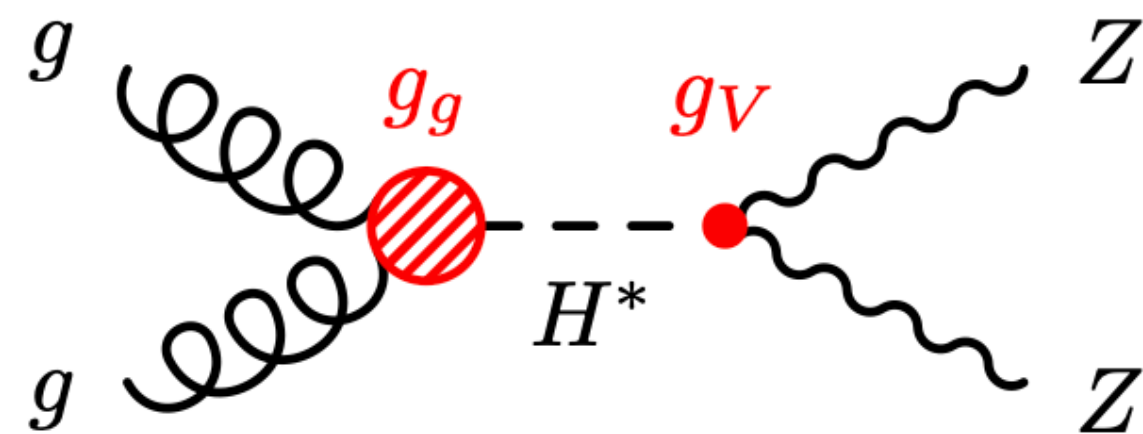
Measurement of the Higgs boson width is indirect and as such it is 3 orders of magnitude smaller than the detector mass resolution! (LHC was not supposed to measure it!)

$$\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{onshell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

$$\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{offshell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{M_{ZZ} - m_H}$$

$$\frac{\sigma_{\text{offshell}}}{\sigma_{\text{onshell}}} \propto \Gamma_H$$

It is measured from the region where $m_{ZZ} > m_H$ (offshell) vs $M_{ZZ} \sim M_H$ (onshell)



@ Z. Wolf

Higgs with measurement $H^* \rightarrow ZZ \rightarrow 4\ell$

$$\frac{\sigma_{\text{offshell}}}{\sigma_{\text{onshell}}} \propto \Gamma_H$$

New Idea: Neural networks used before in off shell analysis, but not ideal due to Signal (S) and Background (B) interference (I).



Now using Neural simulation-based inference.

ATLAS Innovative method using neural simulation based-inference (NSBI)
significance improved from 0.5 to 1.3σ .

NSBI handles high-dimensional parameter estimation without the need to bin data into low-dimensional summary histograms.

Statistical inference is the process of using data from a sample to make conclusions (inferences) about a larger population or about the underlying process that generated the data.

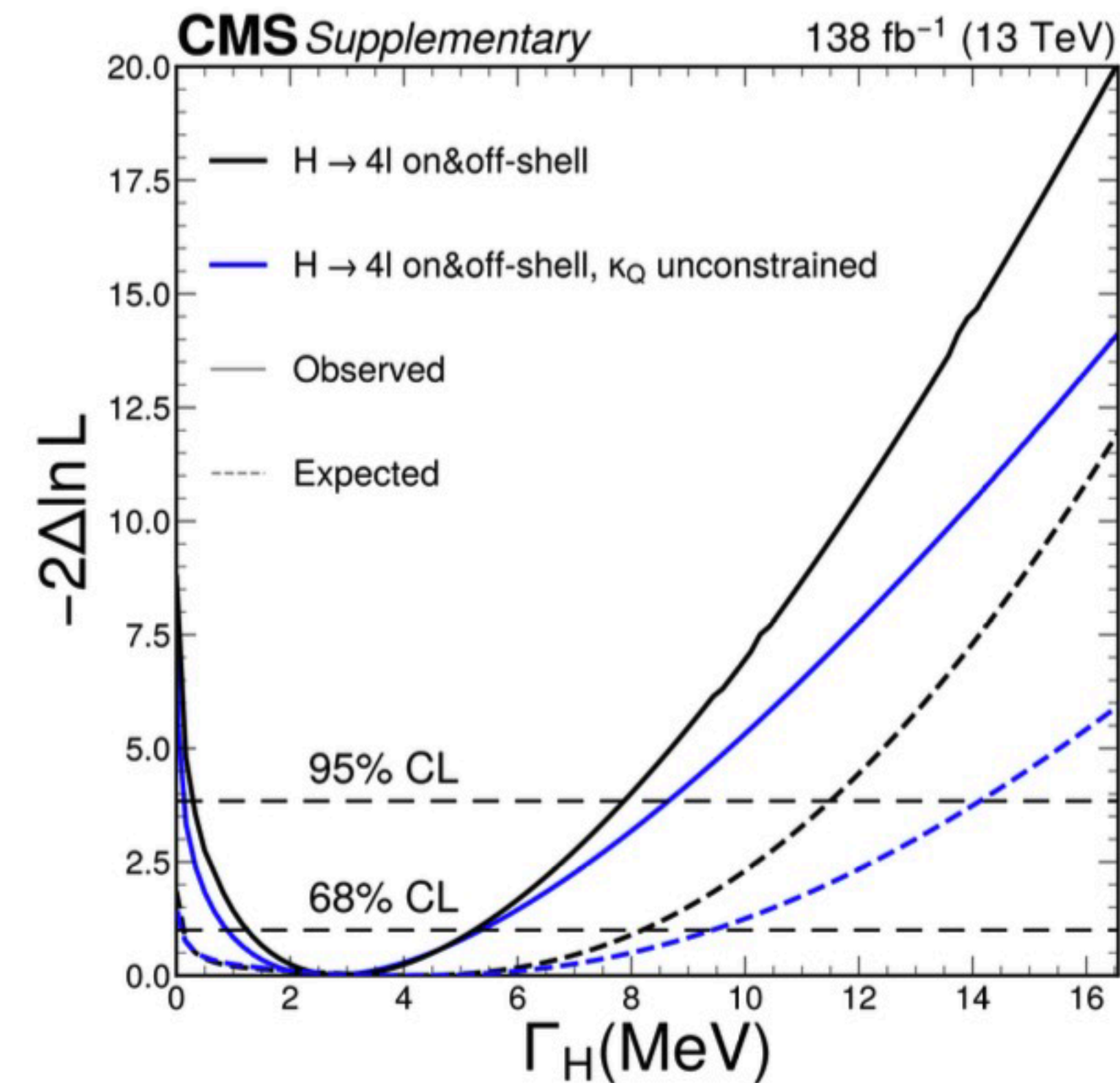
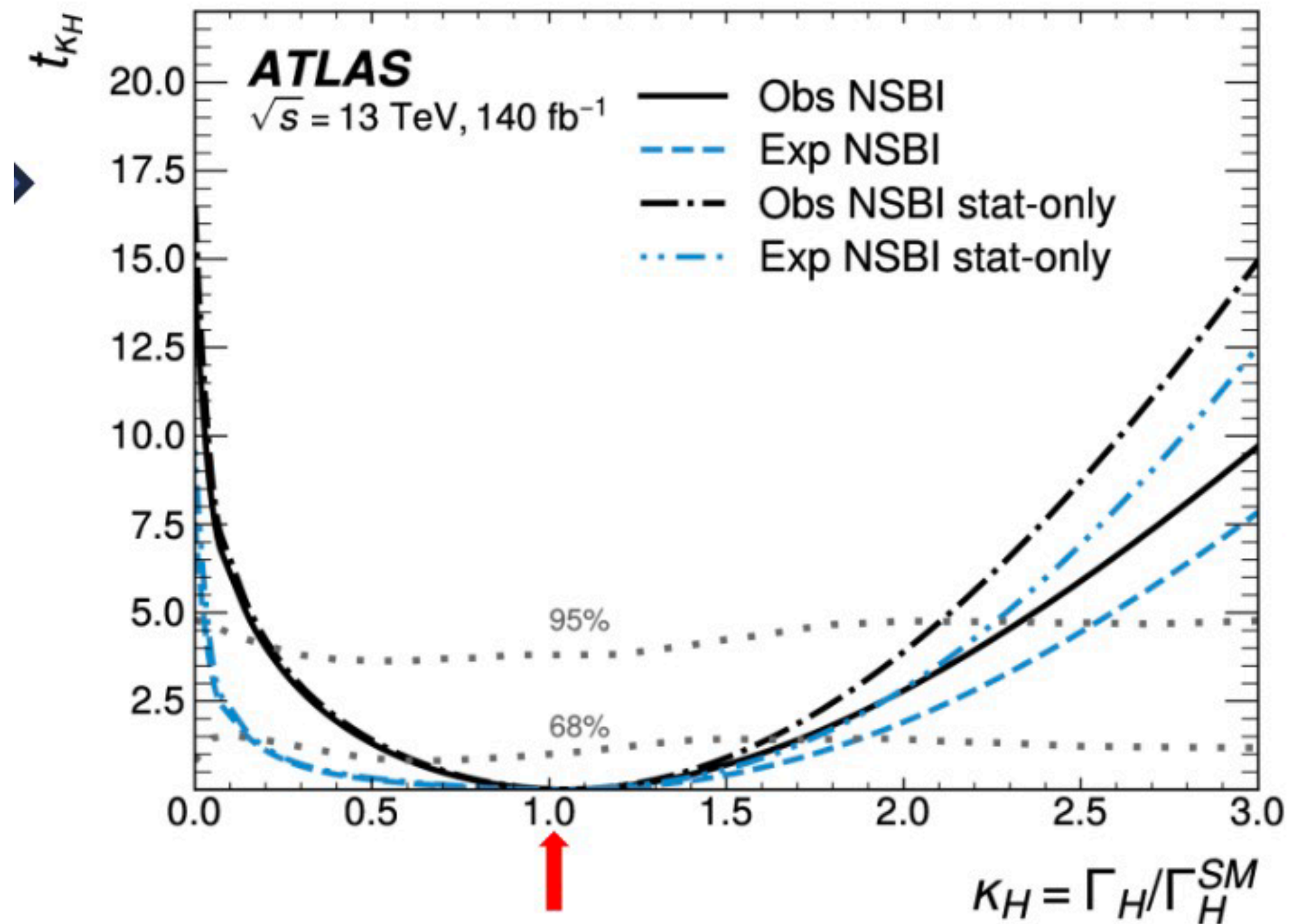
Higgs width

Log Likelihood tells you how compatible are the data with a certain hypothesis

In final state with $Z \rightarrow 4l / 2l2\nu$

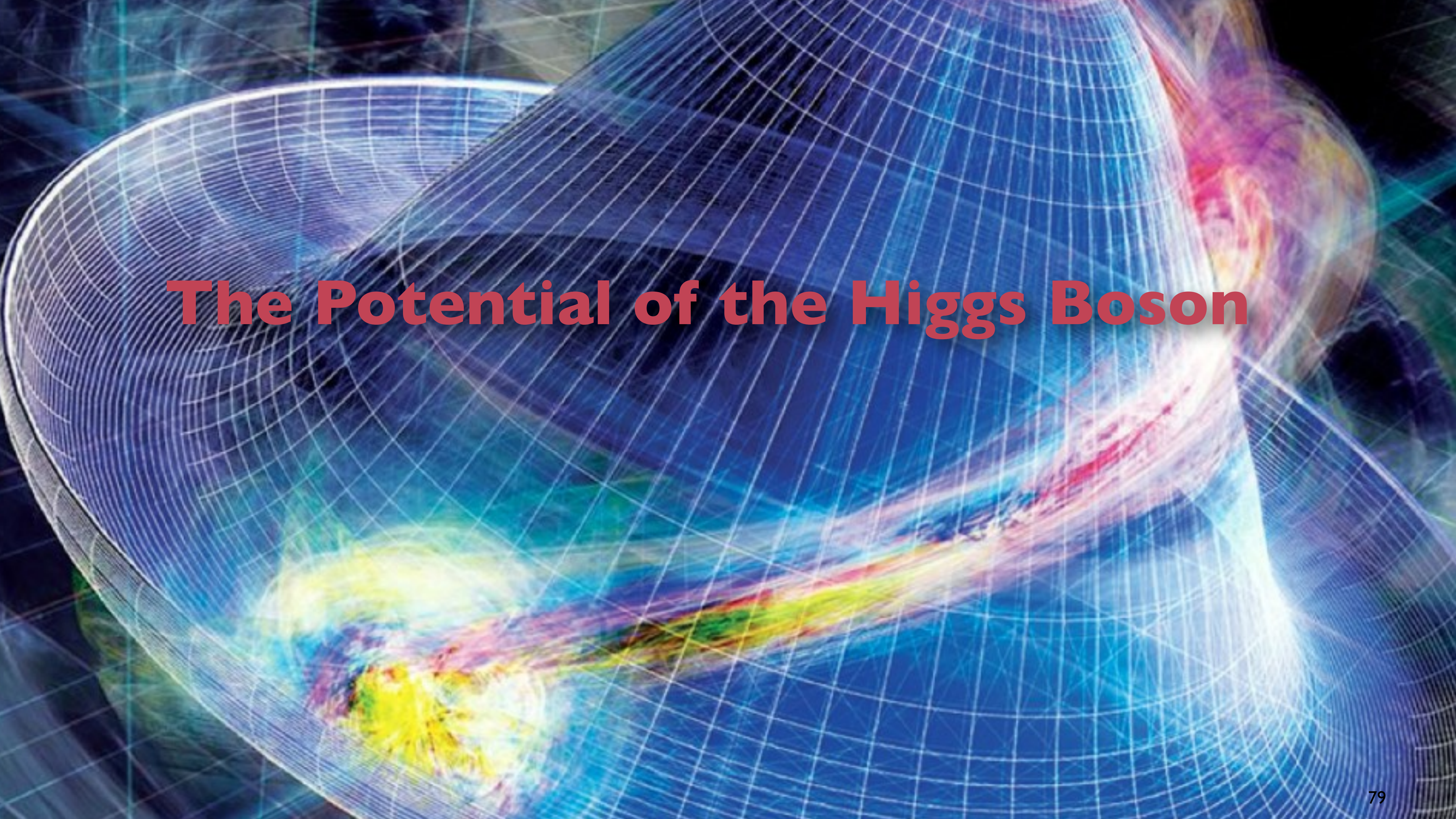
ATLAS
 $\Gamma_H = 4.3^{+2.7}_{-1.9} \text{ MeV}$

CMS
 $\Gamma_H = 3.0^{+2.0}_{-1.5} \text{ MeV}$



ATLAS Innovation NSBI

CMS Innovation include new physics in loops

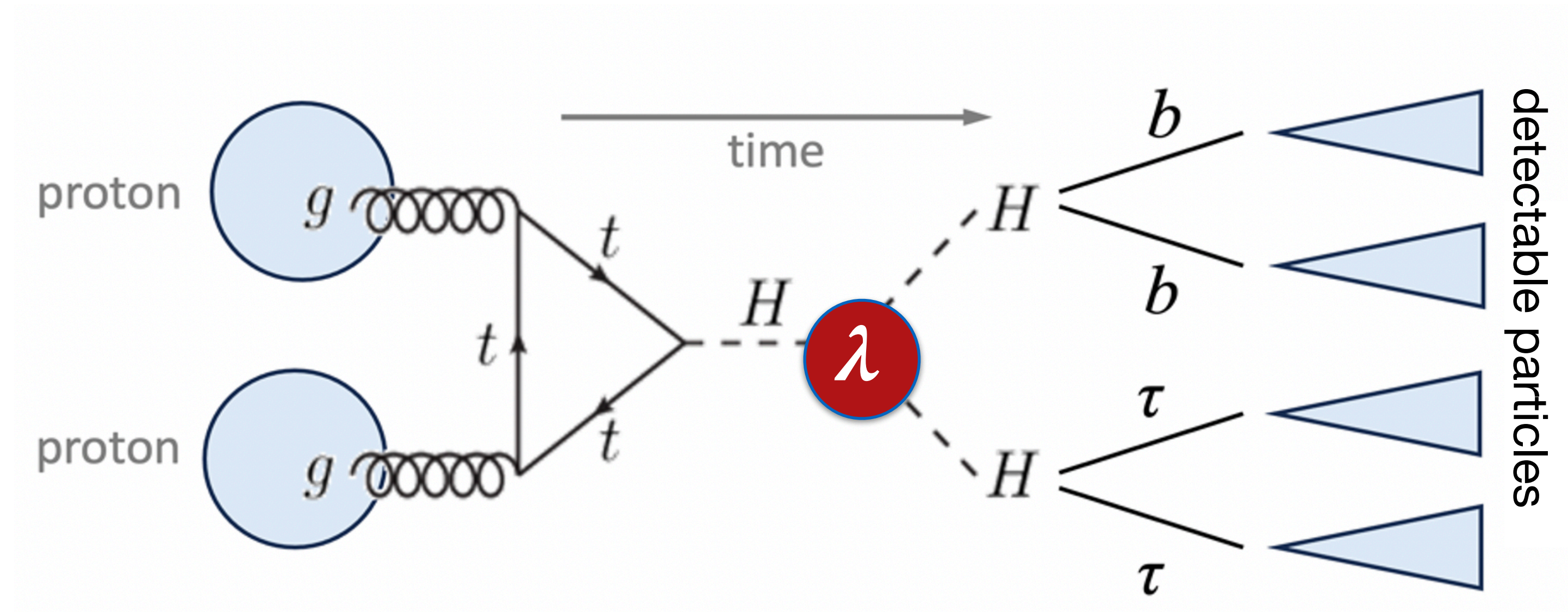
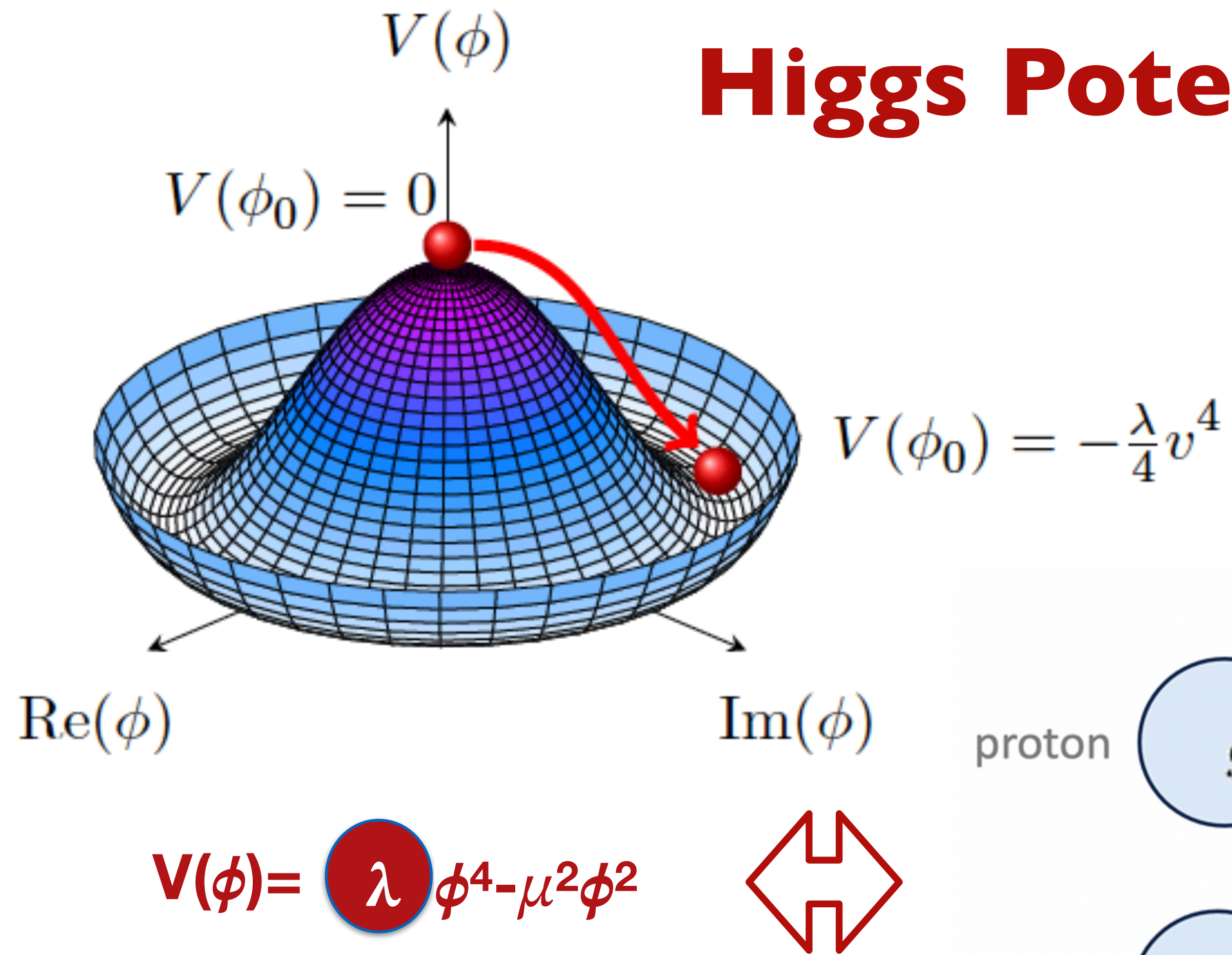
An abstract visualization of particle physics. It features a blue grid that curves and warps, creating a sense of depth and movement. A bright, multi-colored trail, resembling a particle's path or a burst of energy, streaks across the center of the image. The colors in the trail include yellow, green, blue, and red. The overall background is dark, making the grid and the colorful trail stand out.

The Potential of the Higgs Boson

2 Higgses

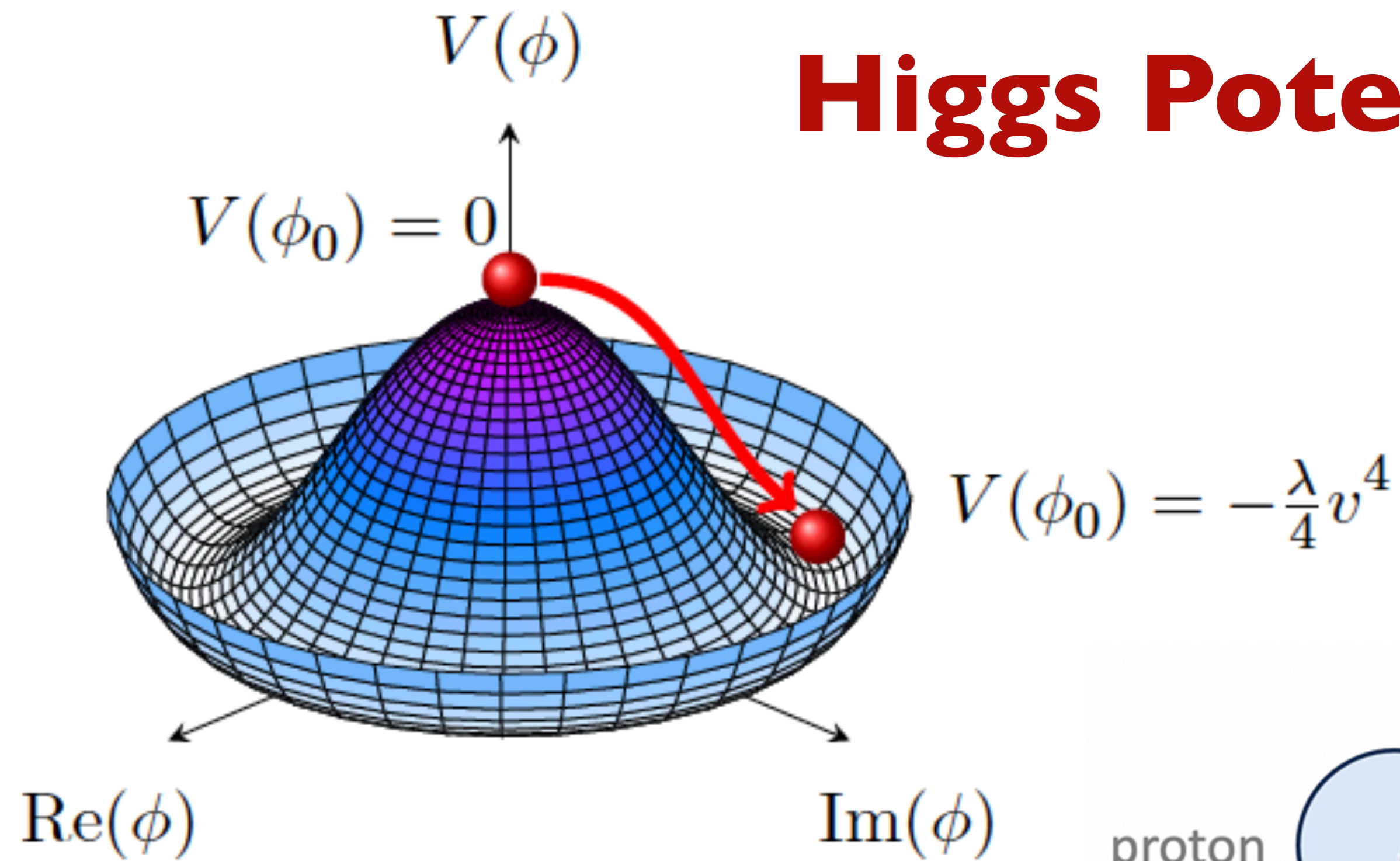


Higgs Potential and self-coupling

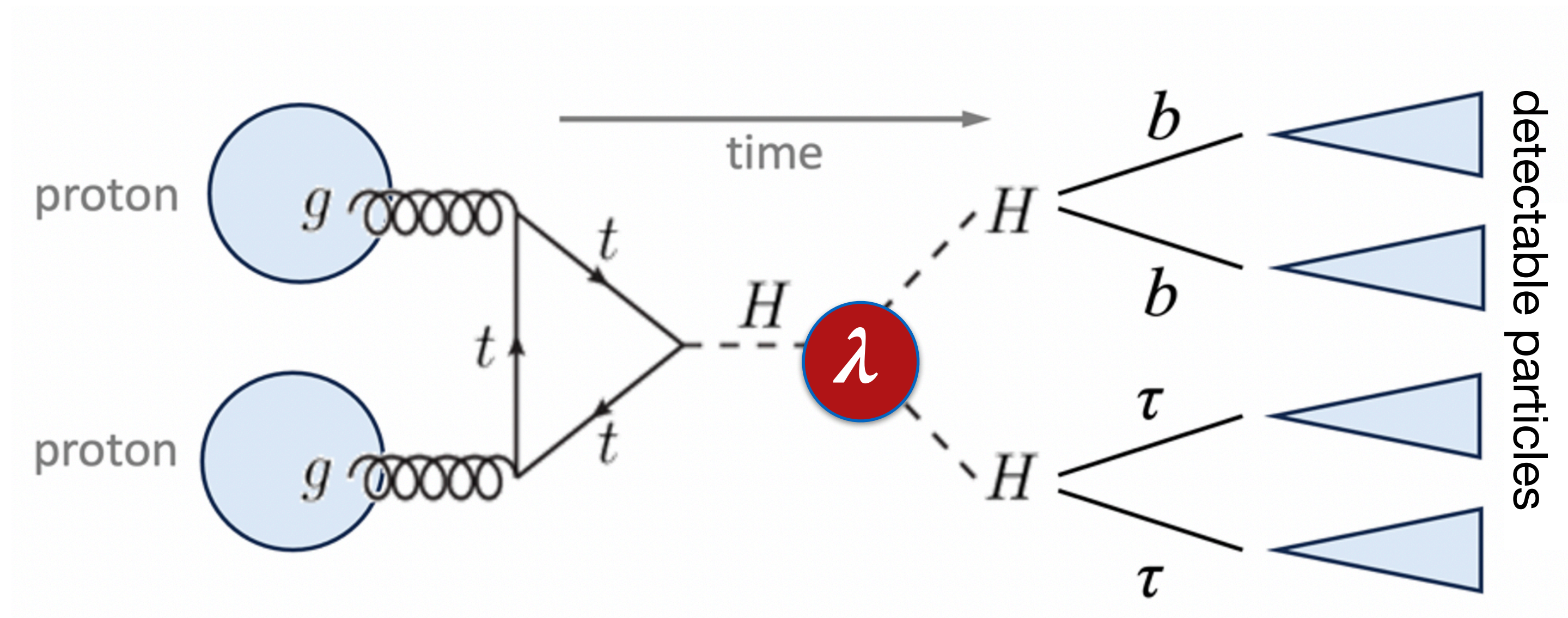
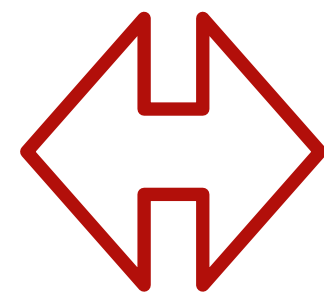


the Higgs potential determines di-Higgs occurrence rate in LHC collisions

Higgs Potential and self-coupling



$$V(\phi) = \lambda \phi^4 - \mu^2 \phi^2$$



for every di-Higgs event
we see a million events that look like it

Di-Higgs production has not been yet observed because it is very rare.

How difficult is it?

All recorded LHC events



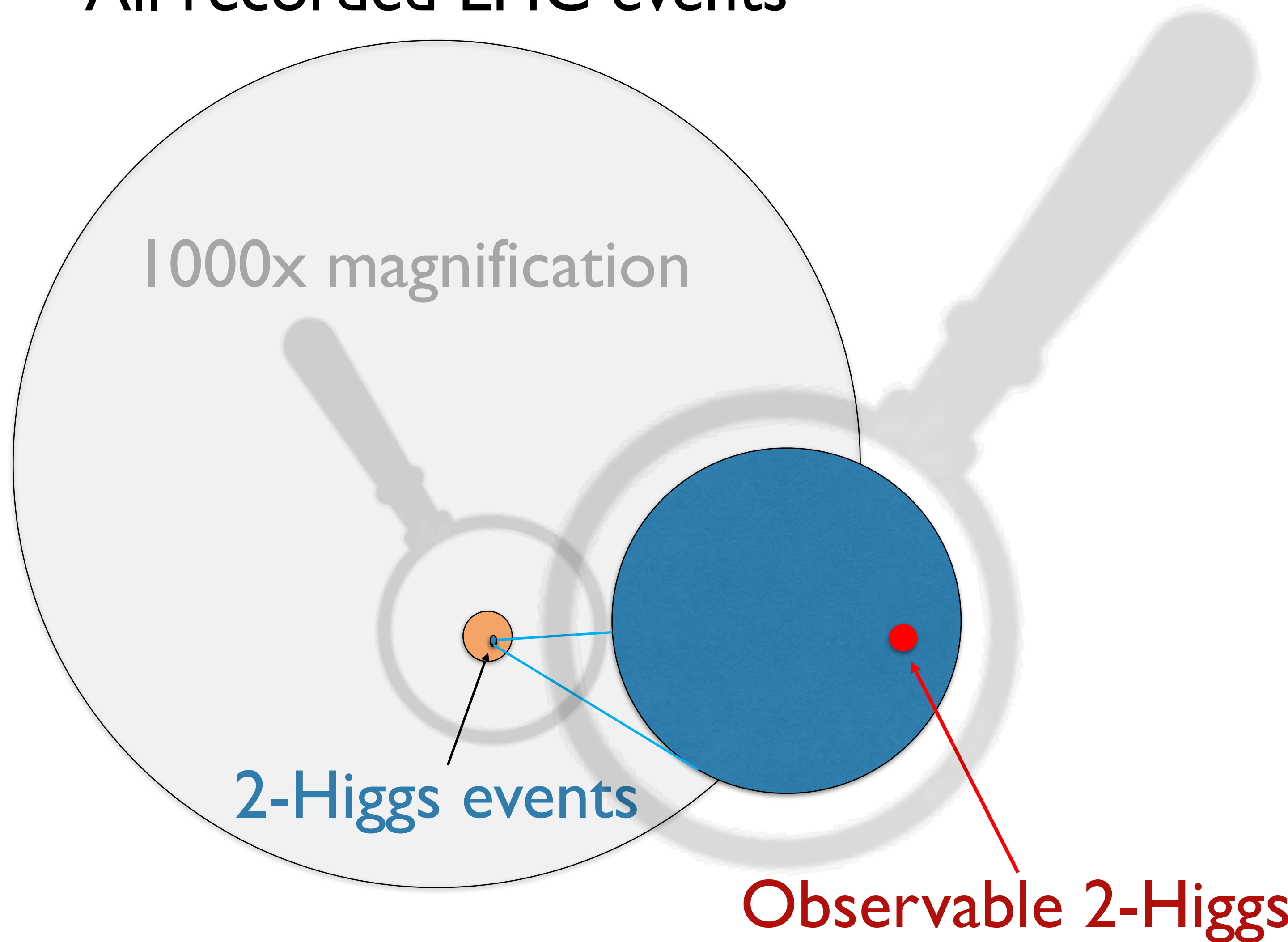
How difficult is it?

All recorded LHC events

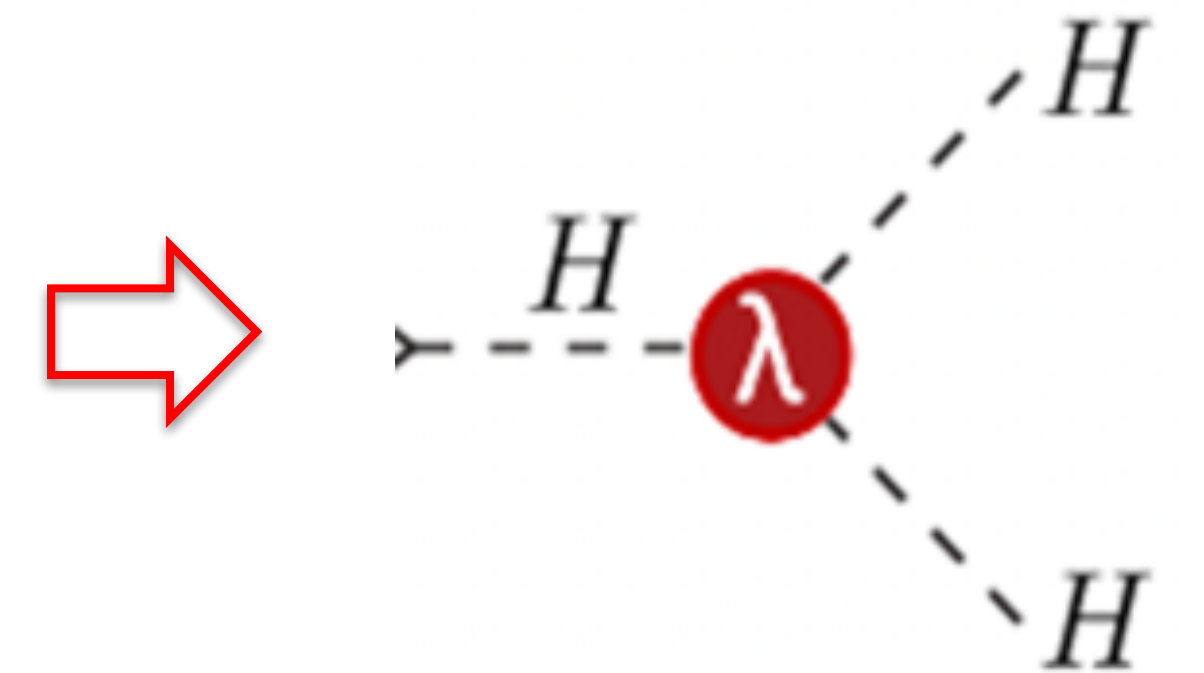


How difficult is it?

All recorded LHC events

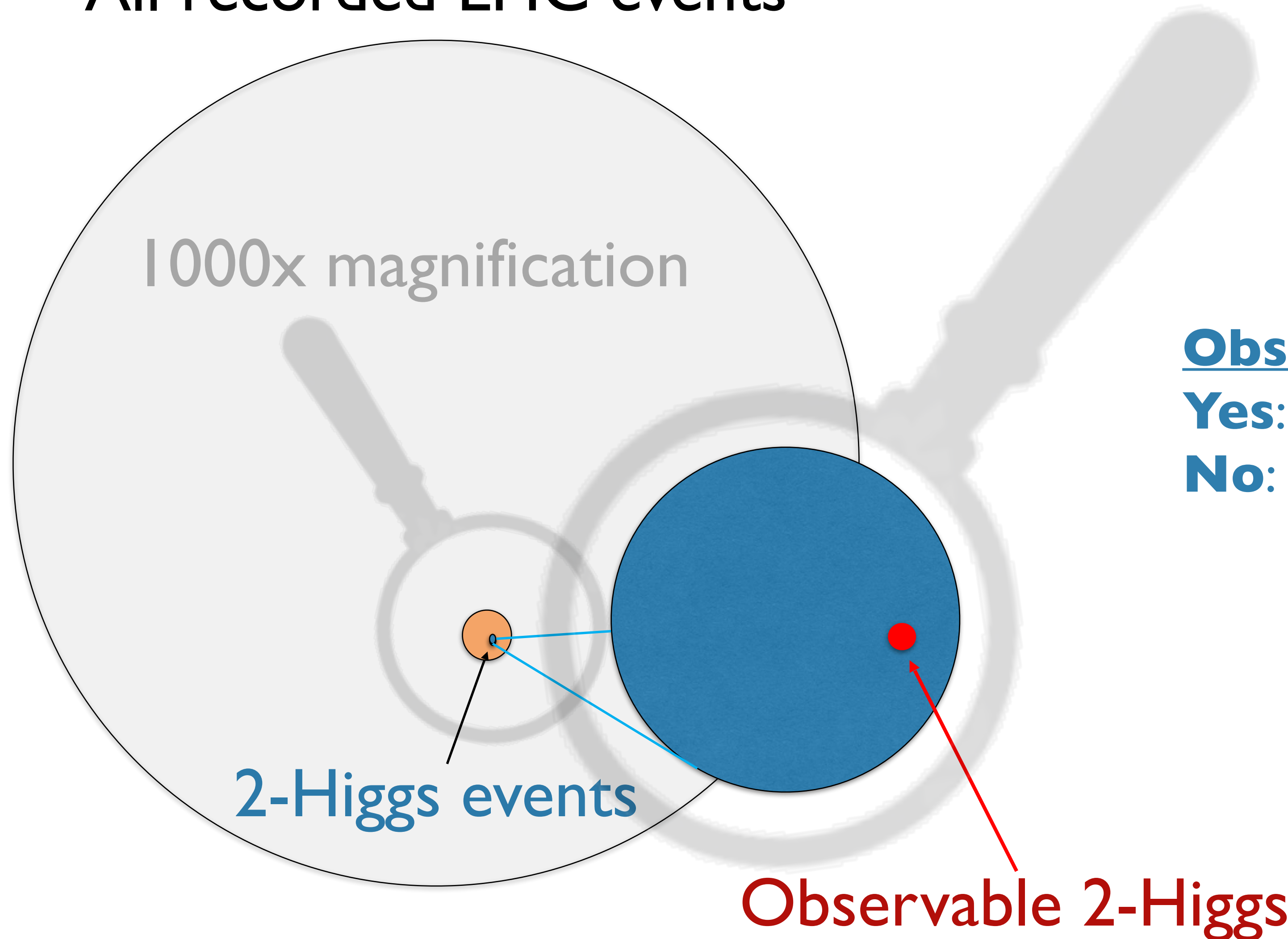


See this?



No evidence of di-Higgs production yet

All recorded LHC events

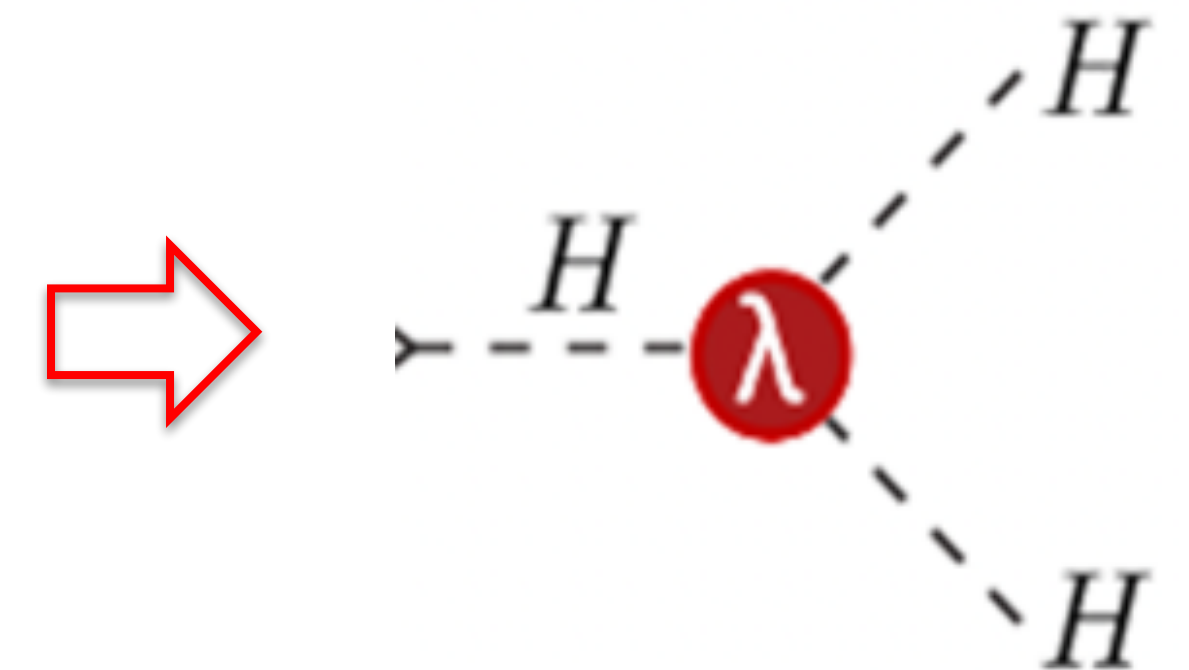


Observing 2 Higgs in Nature

Yes: Crucial proof 'Higgs mechanism'

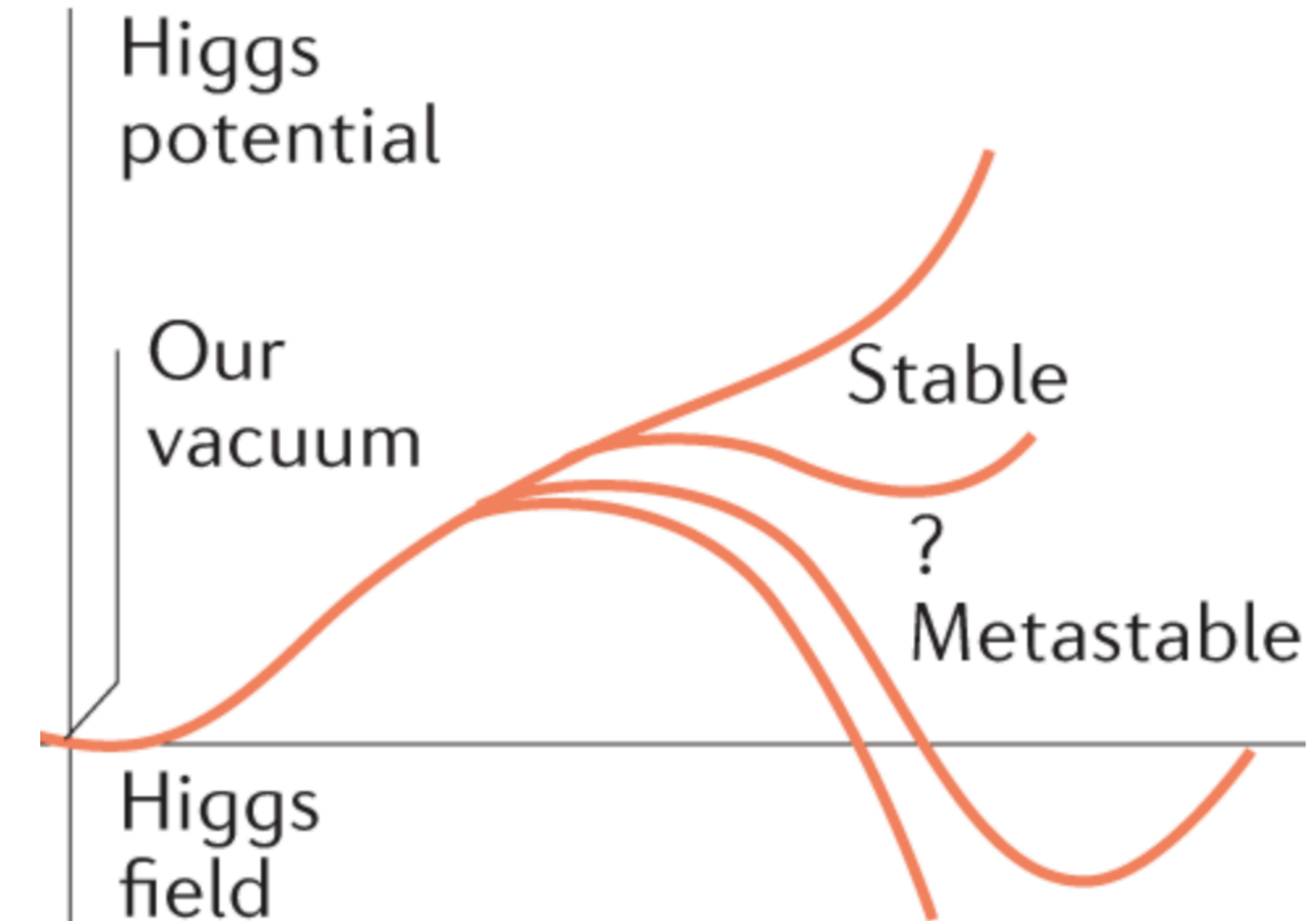
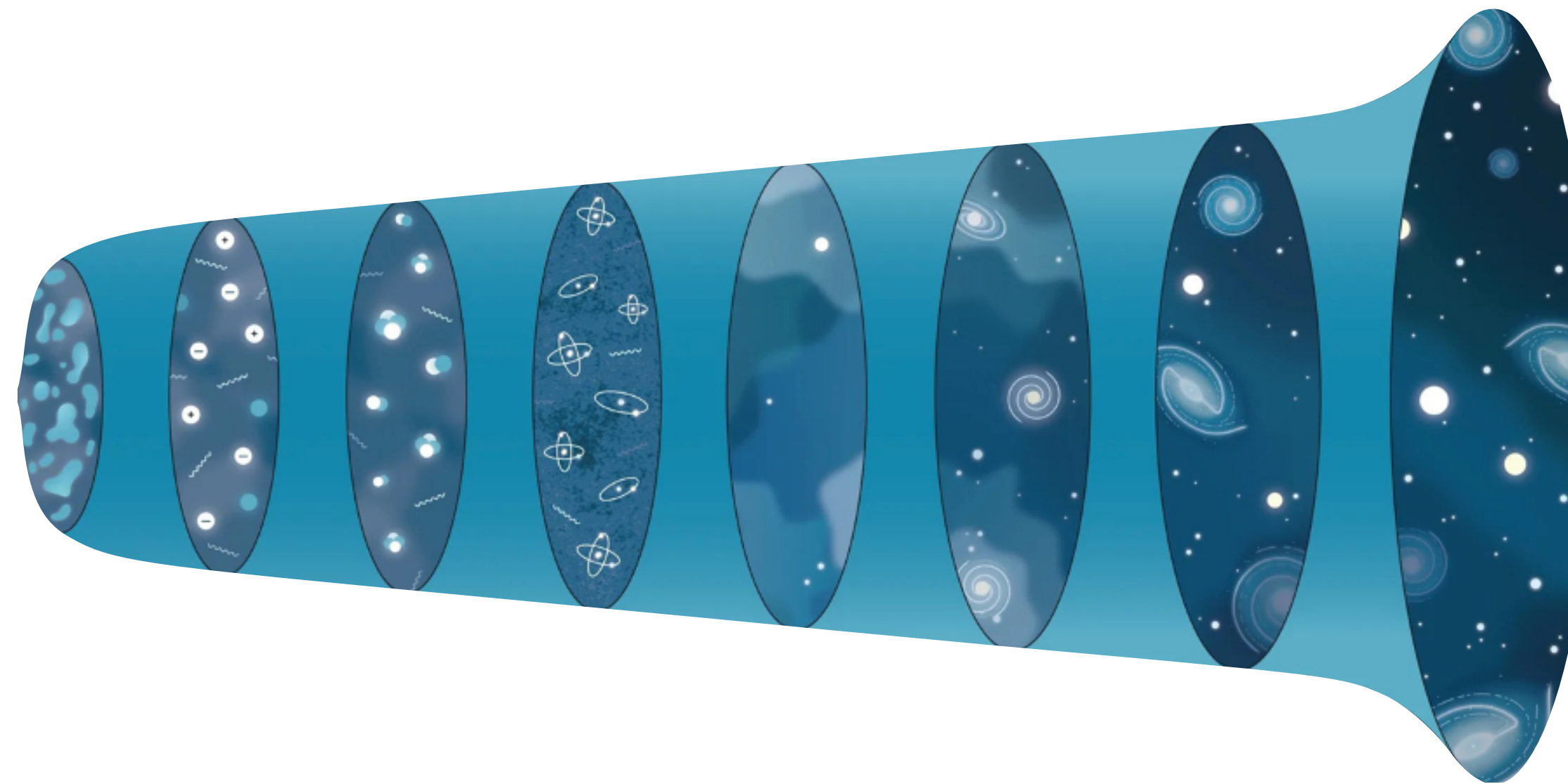
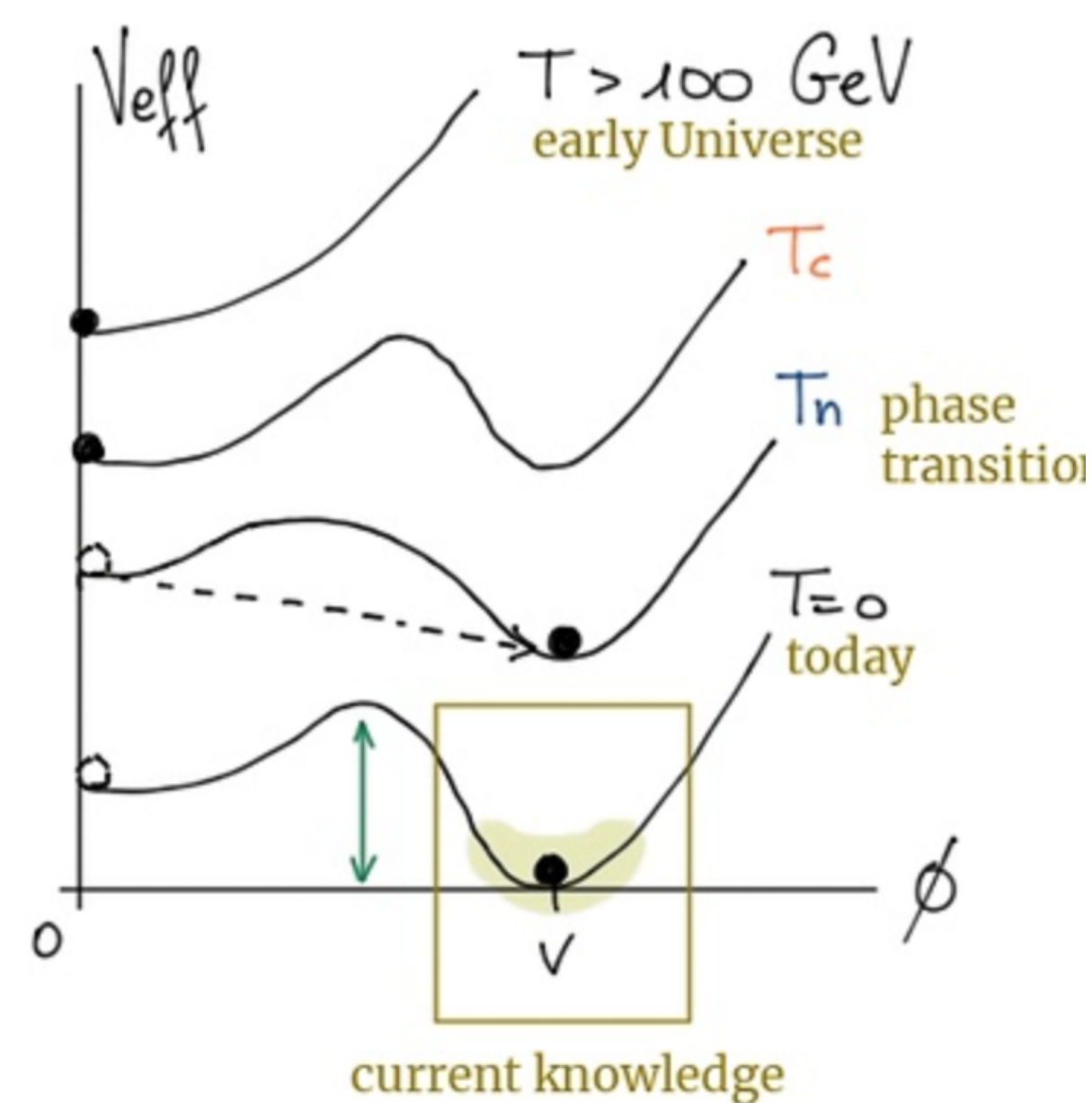
No: Our understanding of Nature is wrong

See this?



Impact of di-higgs observation

Tremendous impact on cosmology and theoretical physics



disappearance of anti-matter
in early universe

stability of universe

Understanding the beginning of Universe

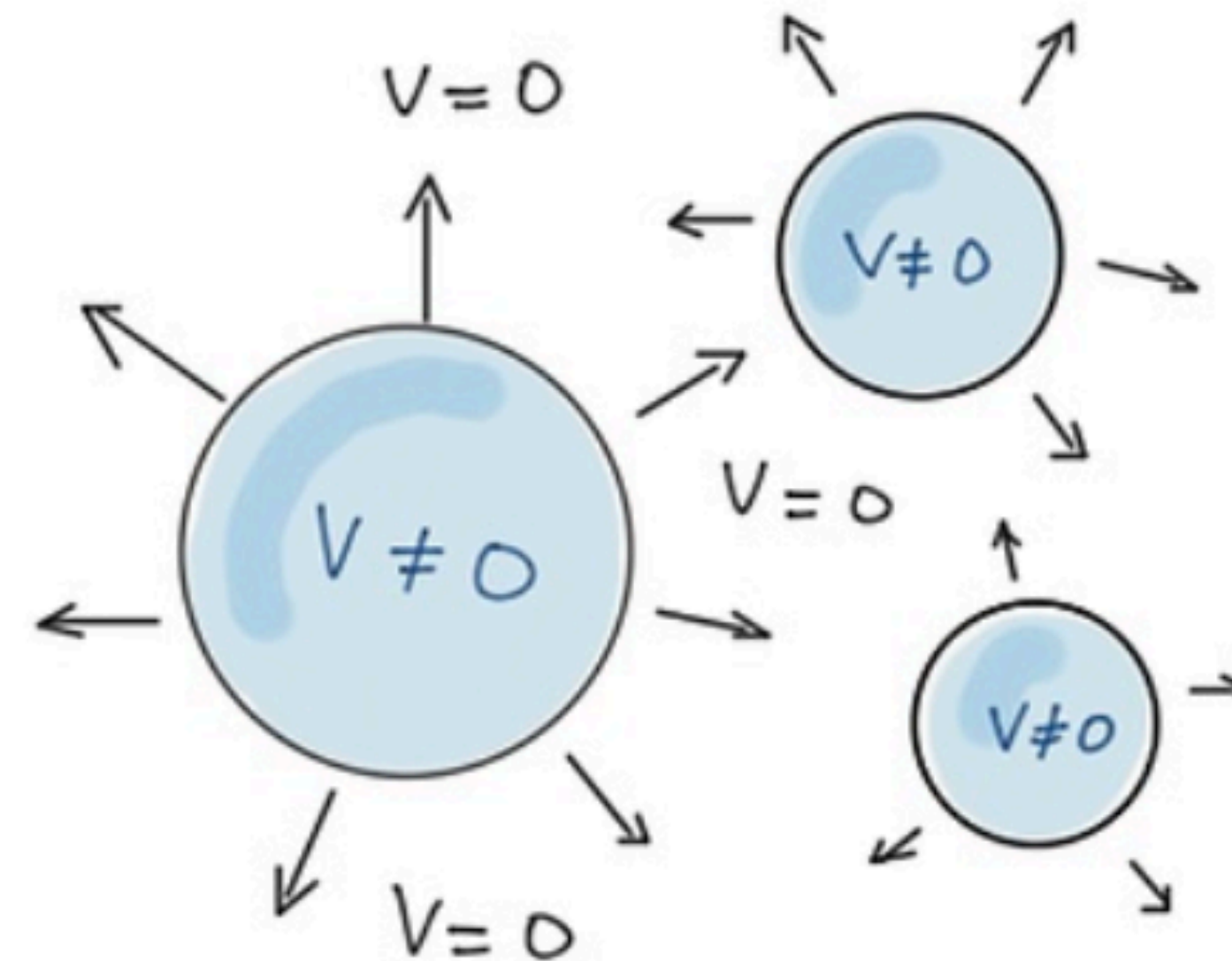
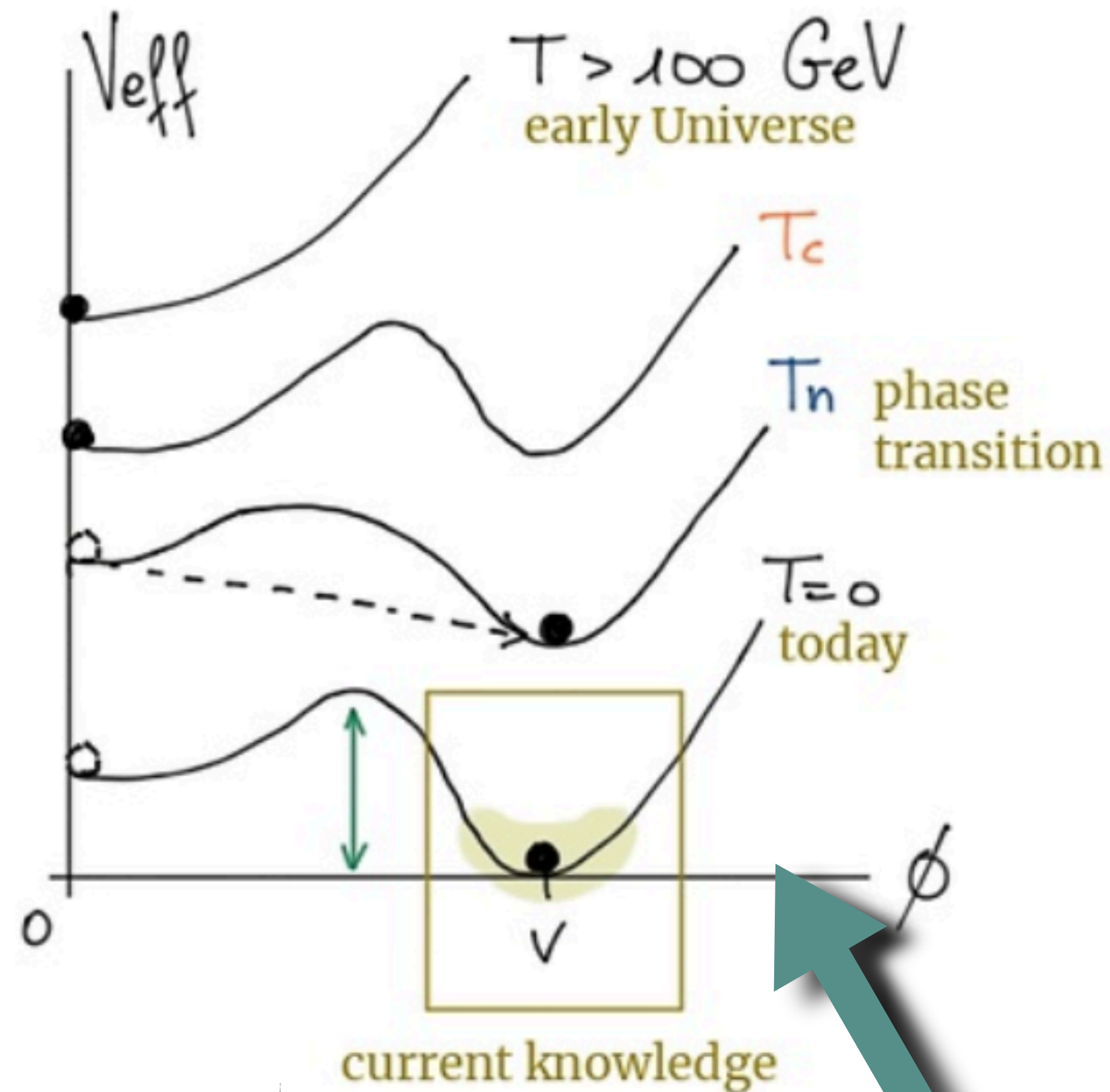
A violent EW symmetry breaking

First Order Phase Transition

(FOPT)



boiling universe

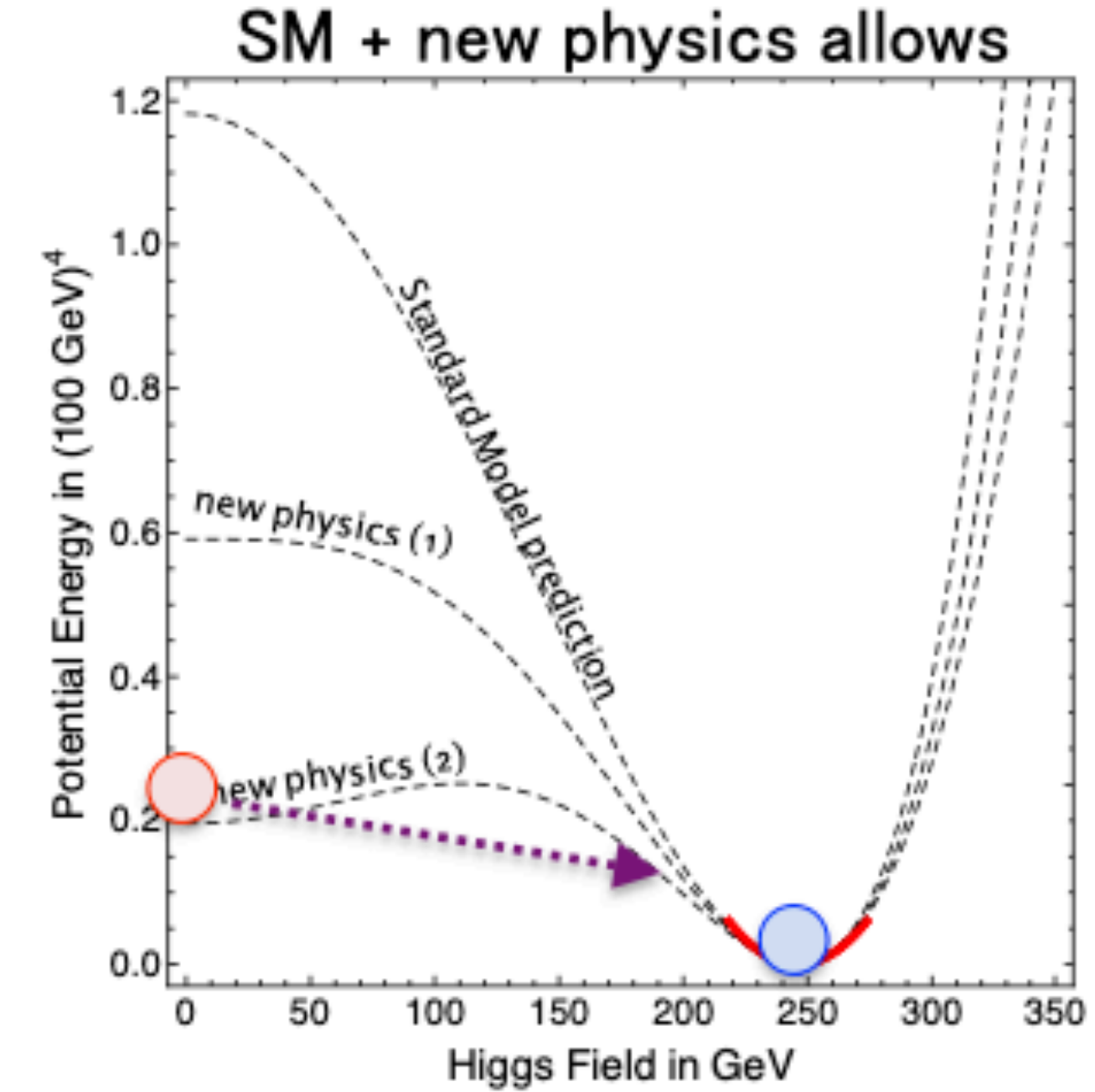
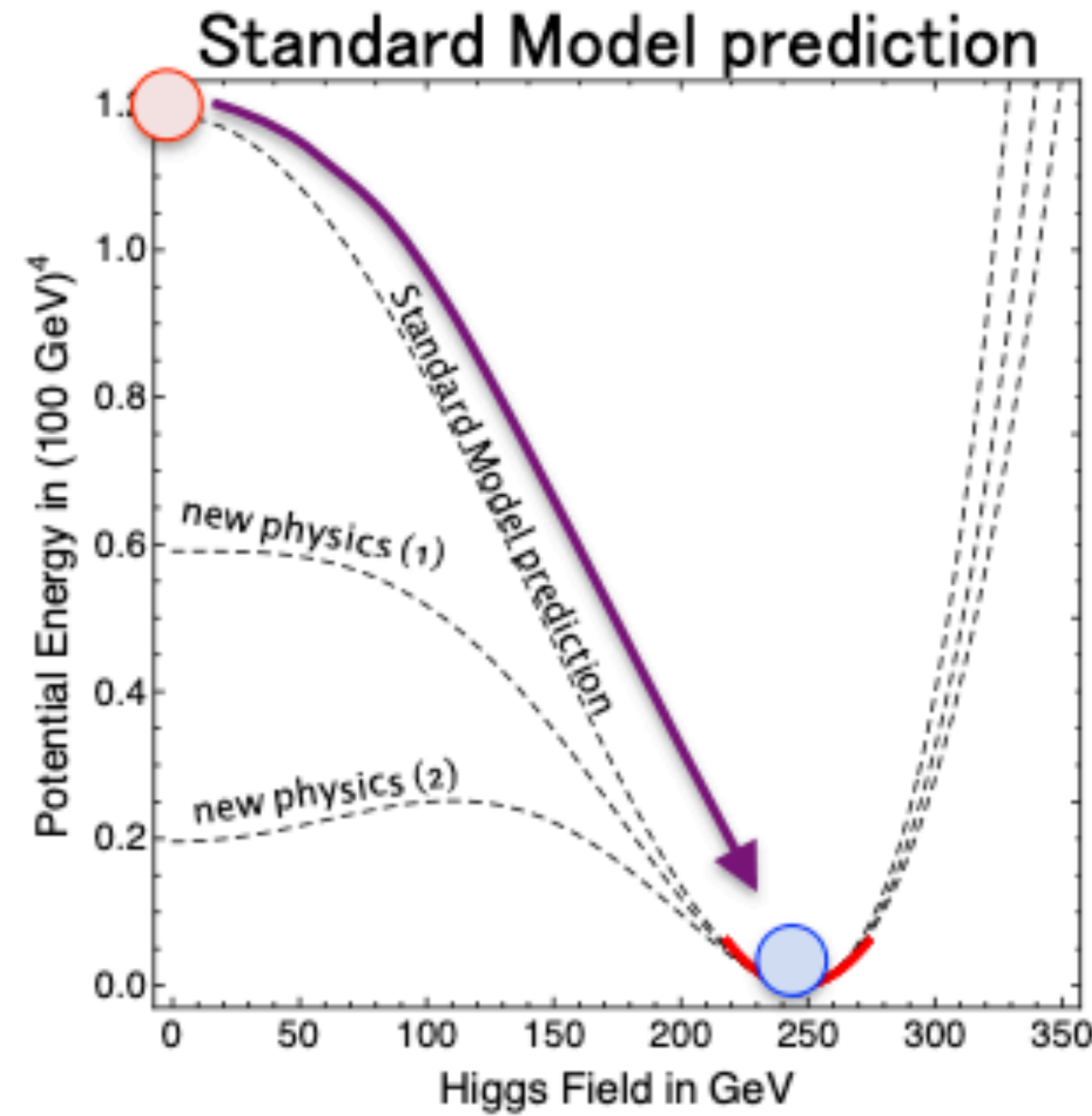


Why the Universe is made of matter?

The Higgs potential shape is crucial

ONLY a Strong FOPT can explain a boiling universe

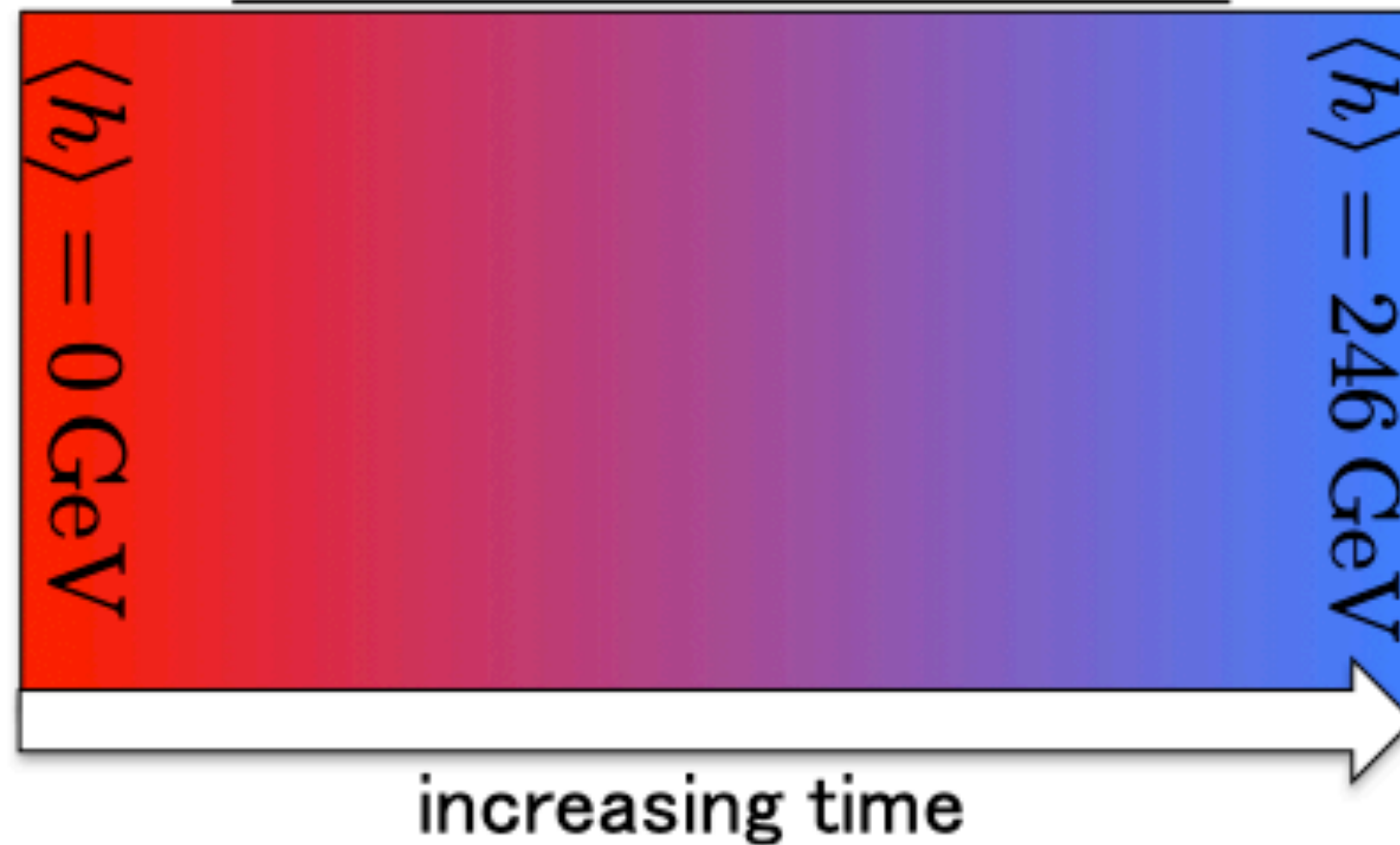
Understanding the beginning of Universe



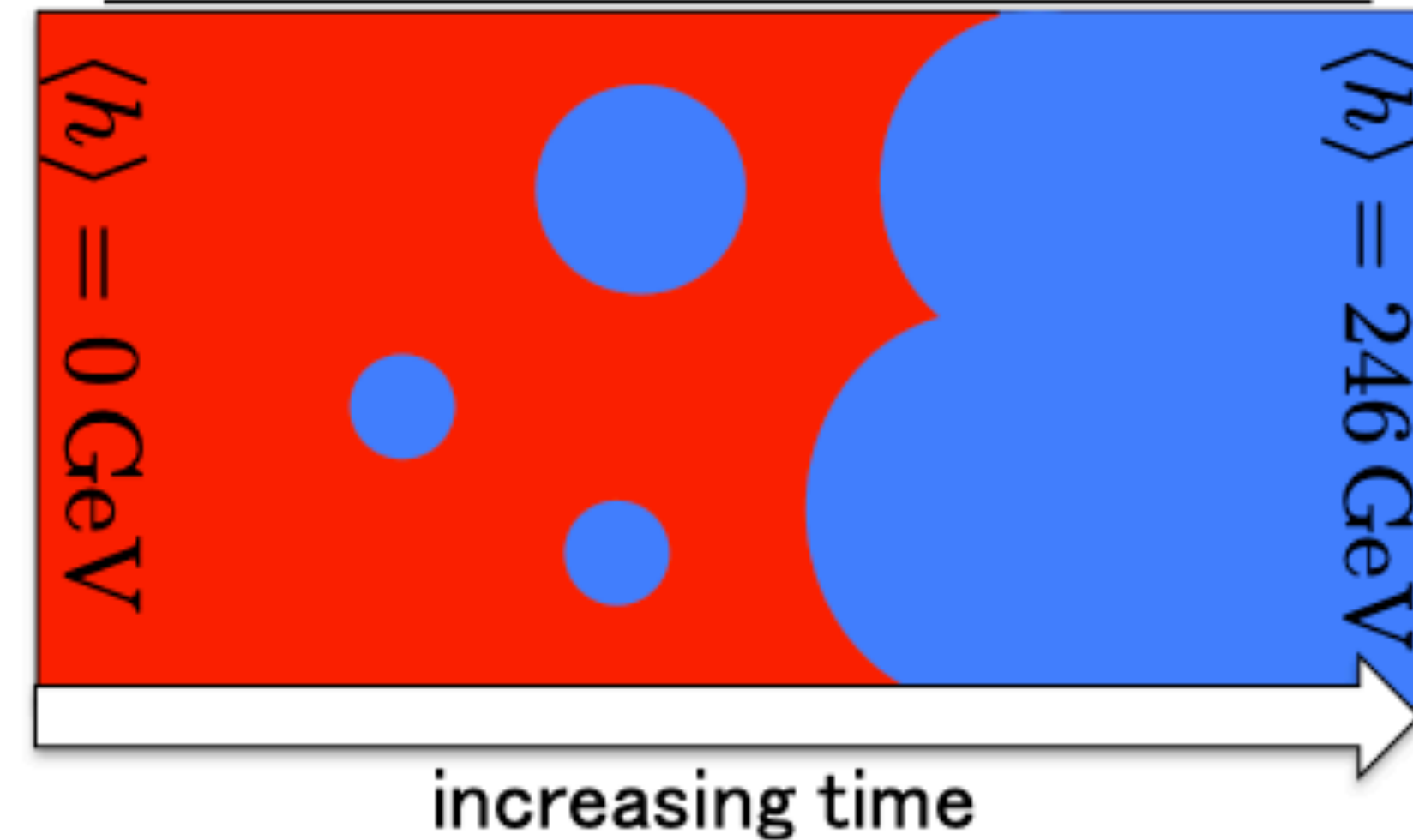
@L.Wang



Continuous Crossover



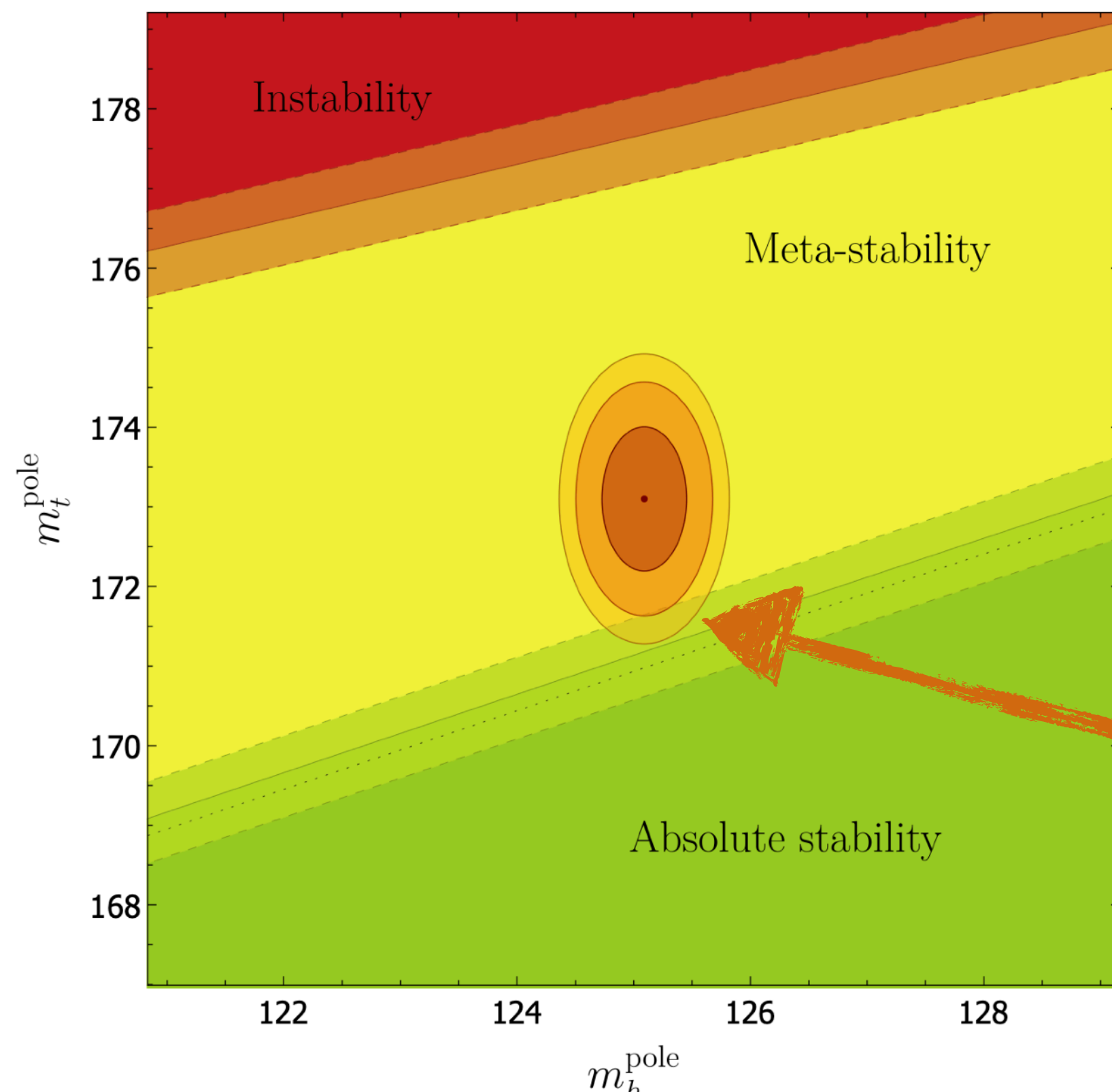
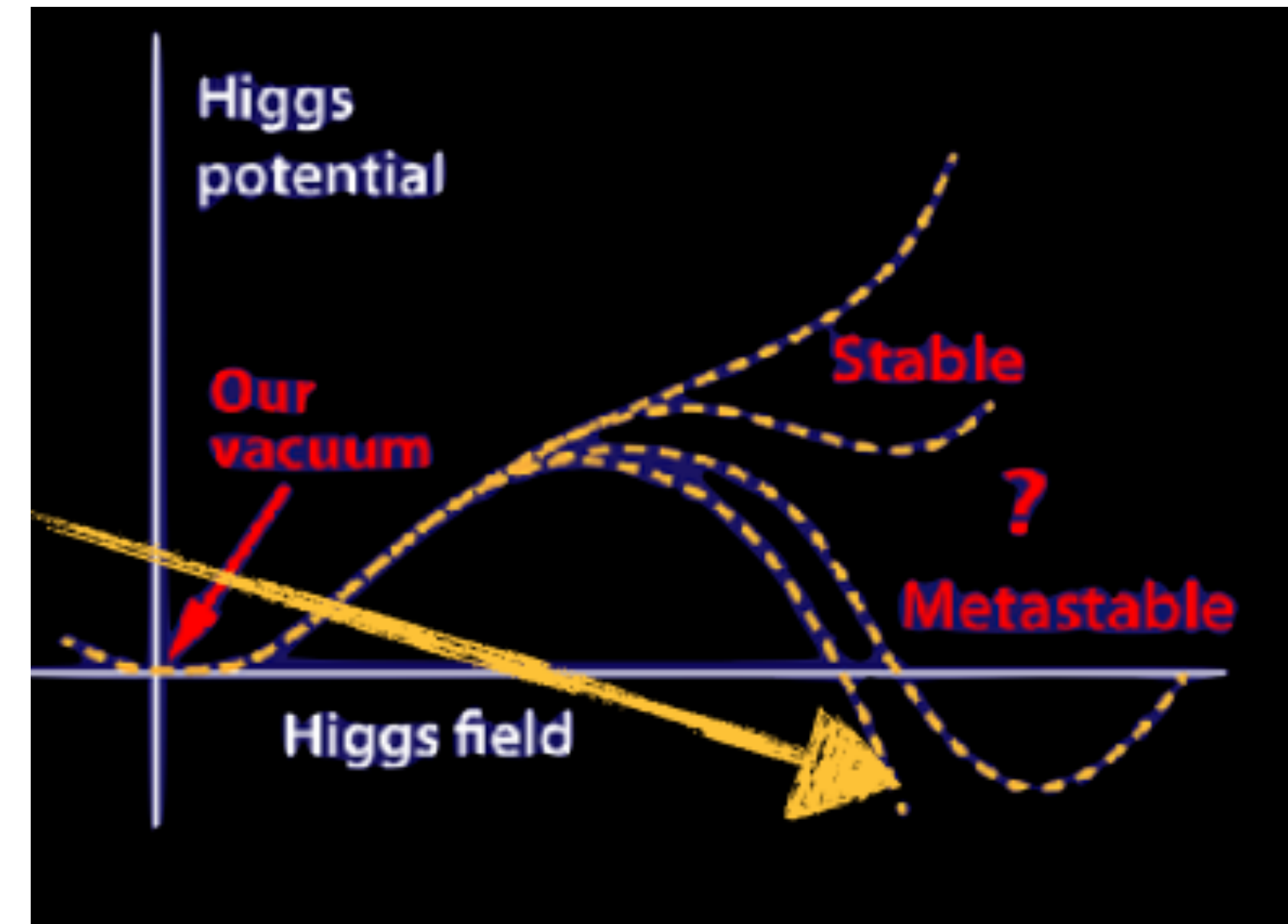
First Order Phase Transition



Understanding the fate of the Universe?

The Higgs field of the SM has a local minimum at a field value of $v = 246$ GeV.

However, it is possible that a second minimum develops at very large scalar field values



The SM parameters are linked together and from calculations using as input the Higgs mass, top quark mass and the strong coupling constant:

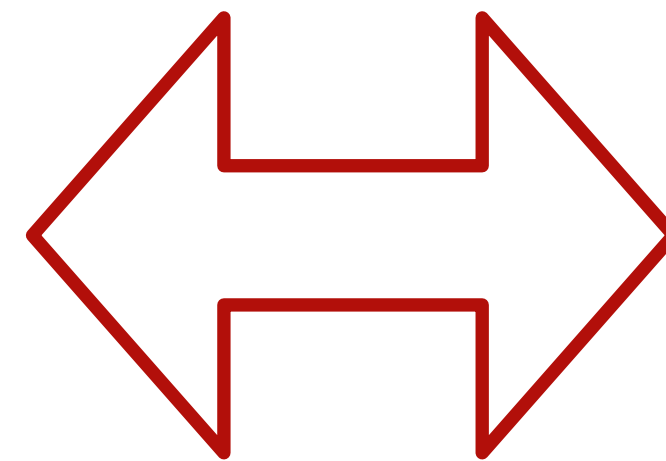
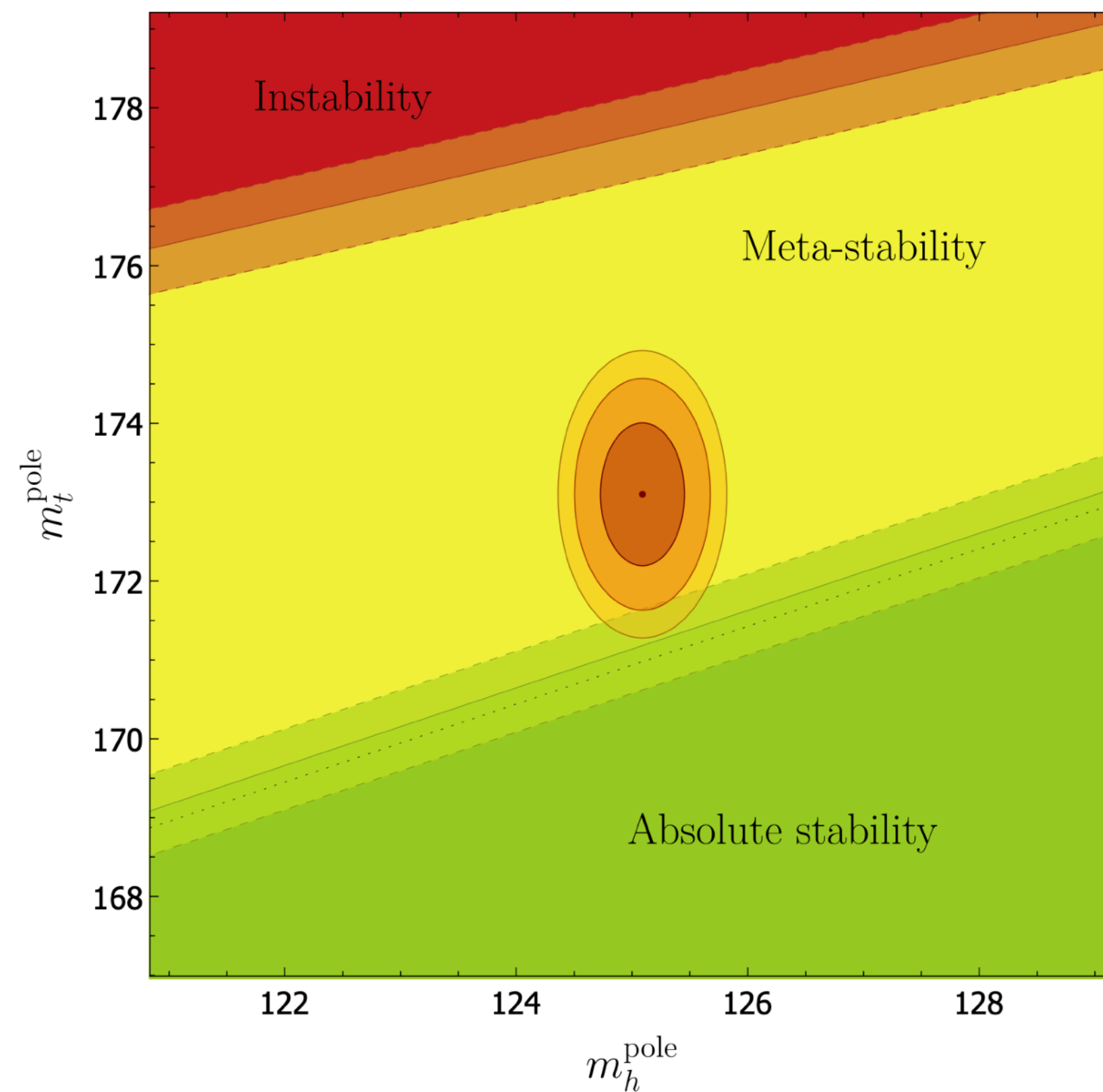


Our Universe appears to be metastable!
People often ask me what would happen then?

Understanding the fate of the Universe?

Luckily is the universe will endure a phase transition, this will be in a very distant future much longer than the present life of the universe.

I will be so old by then, that I would prefer this than having to move into a new flat!



di-Higgs candidate event

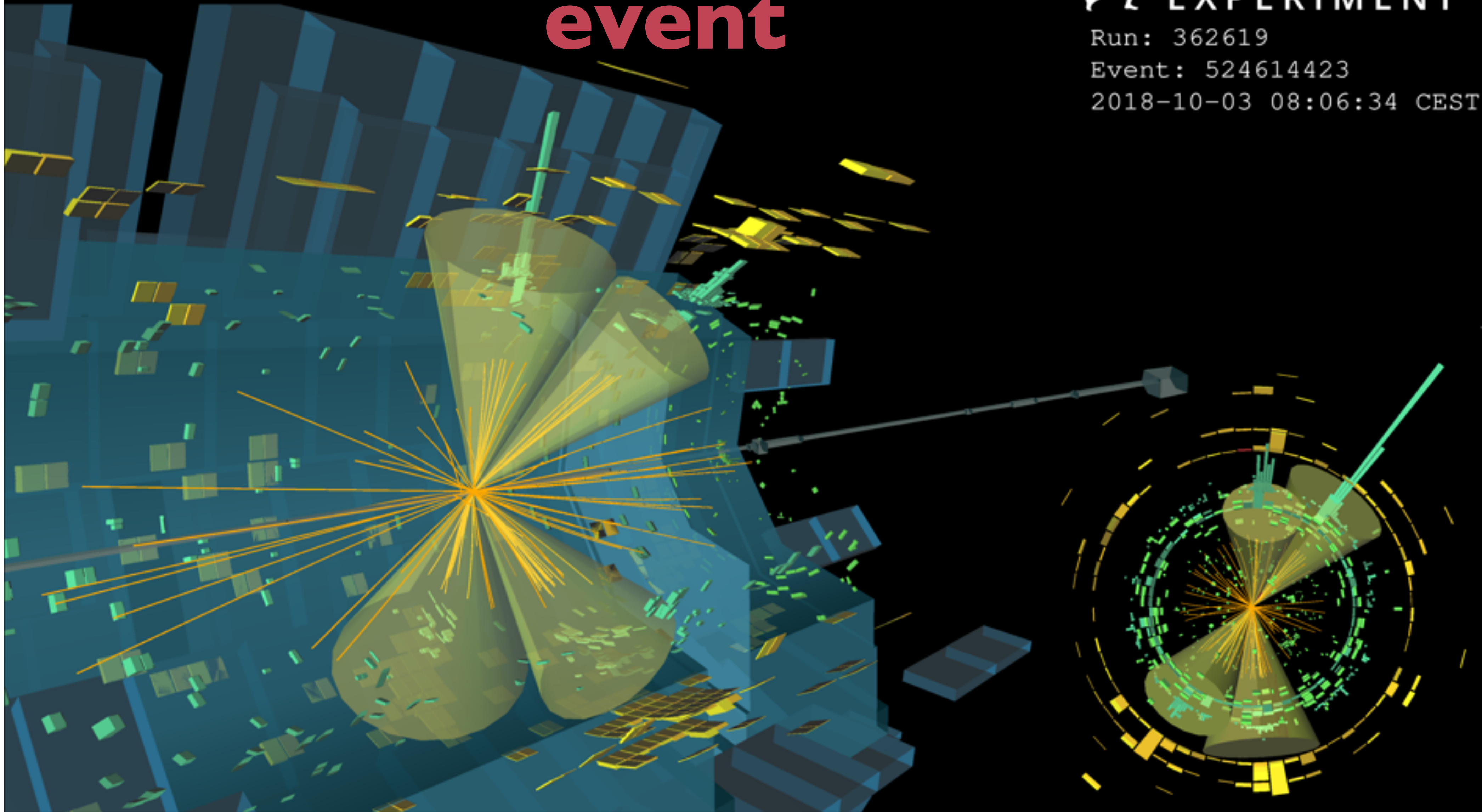


ATLAS
EXPERIMENT

Run: 362619

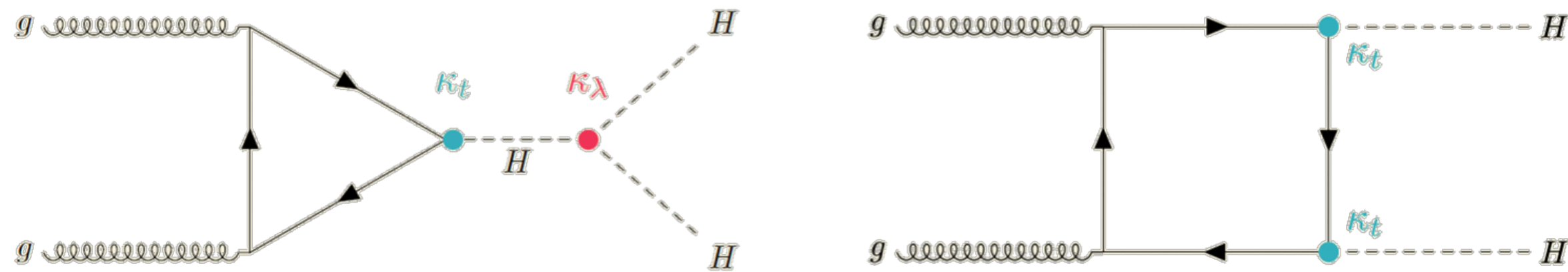
Event: 524614423

2018-10-03 08:06:34 CEST

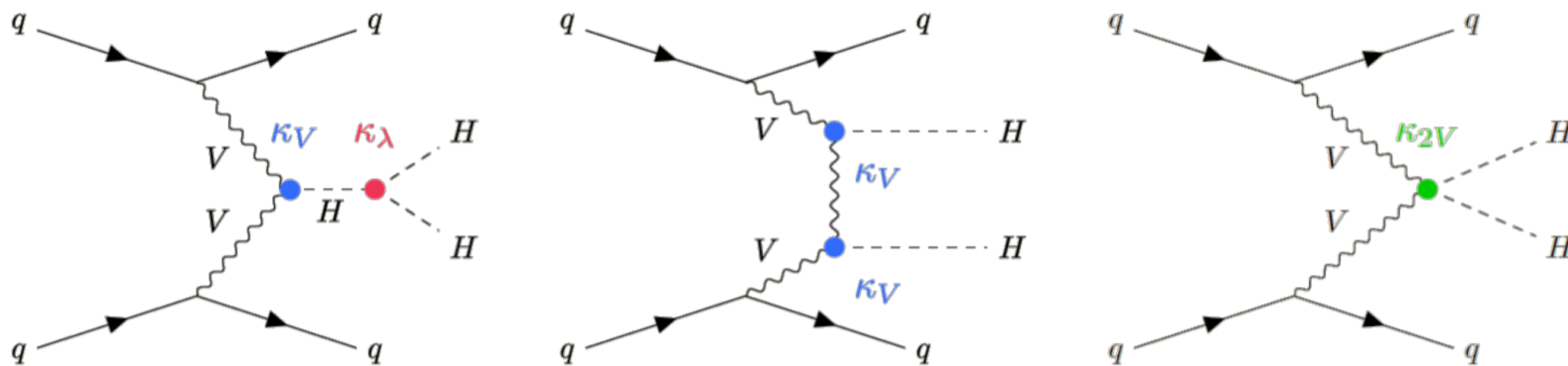


di-Higgs production at LHC

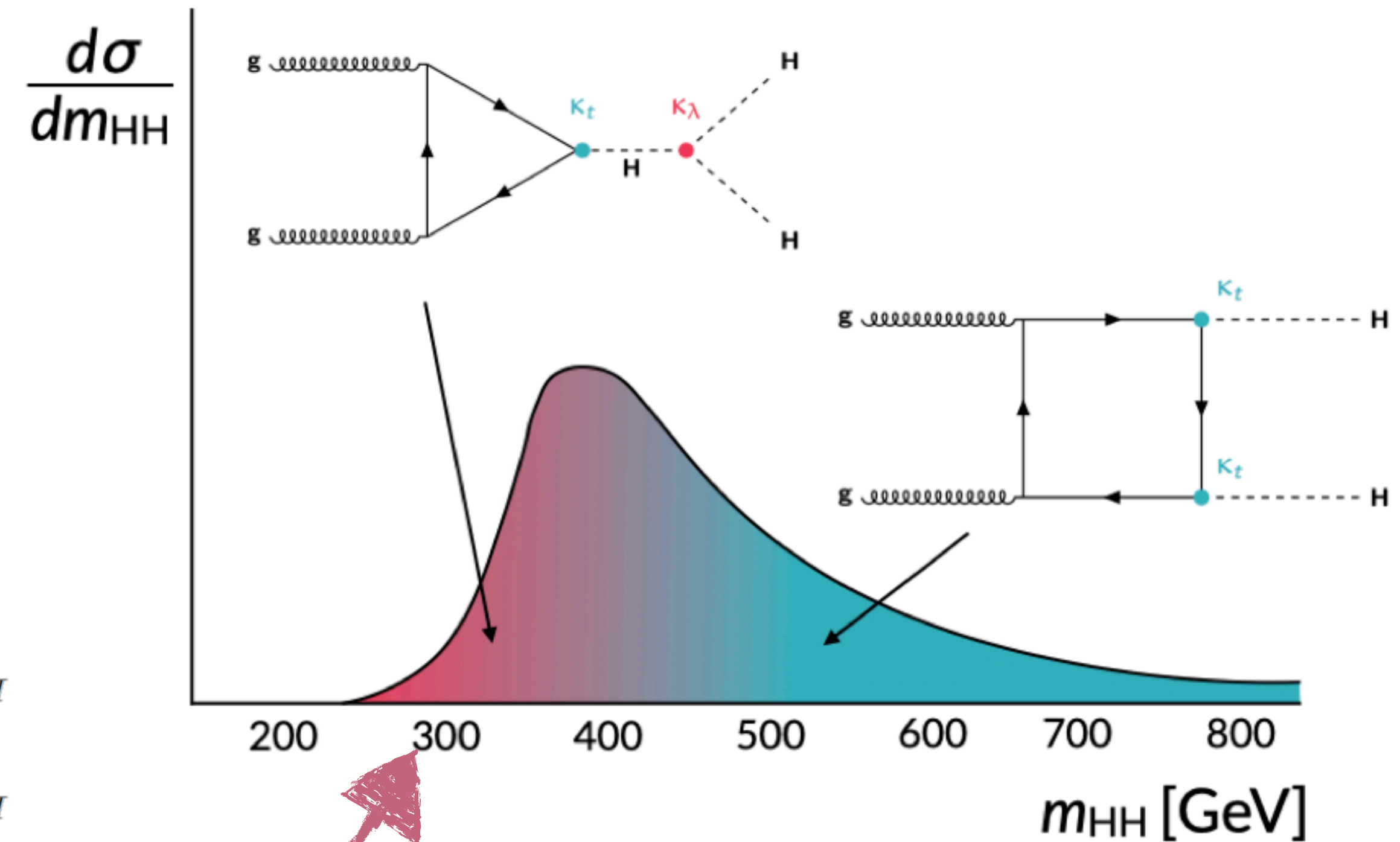
dominant production mode ggF
with 2 diagrams that have destructive interference



Vector-boson fusion is the second dominant mode



Associated productions, HHV HHtt have much smaller production cross-sections



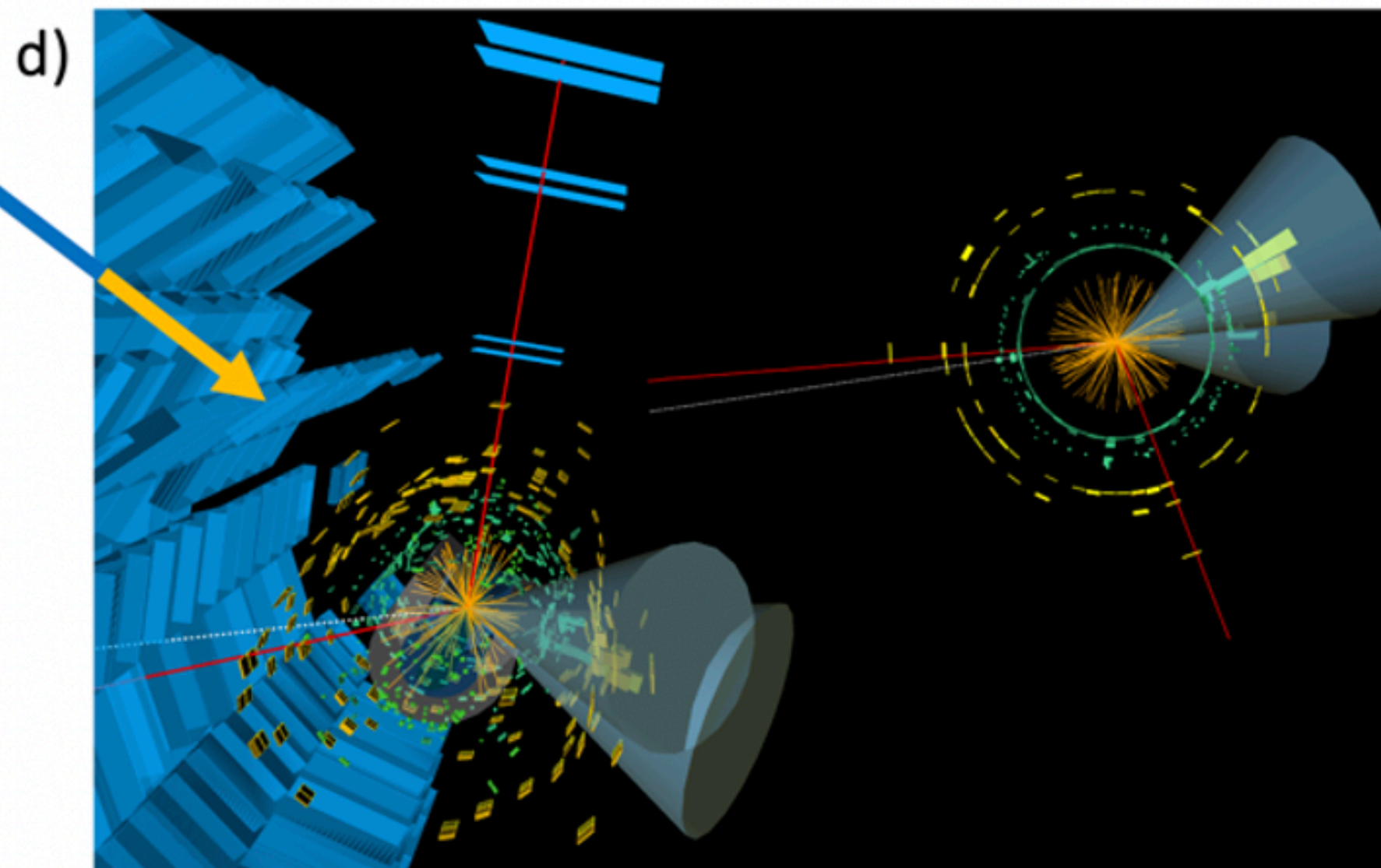
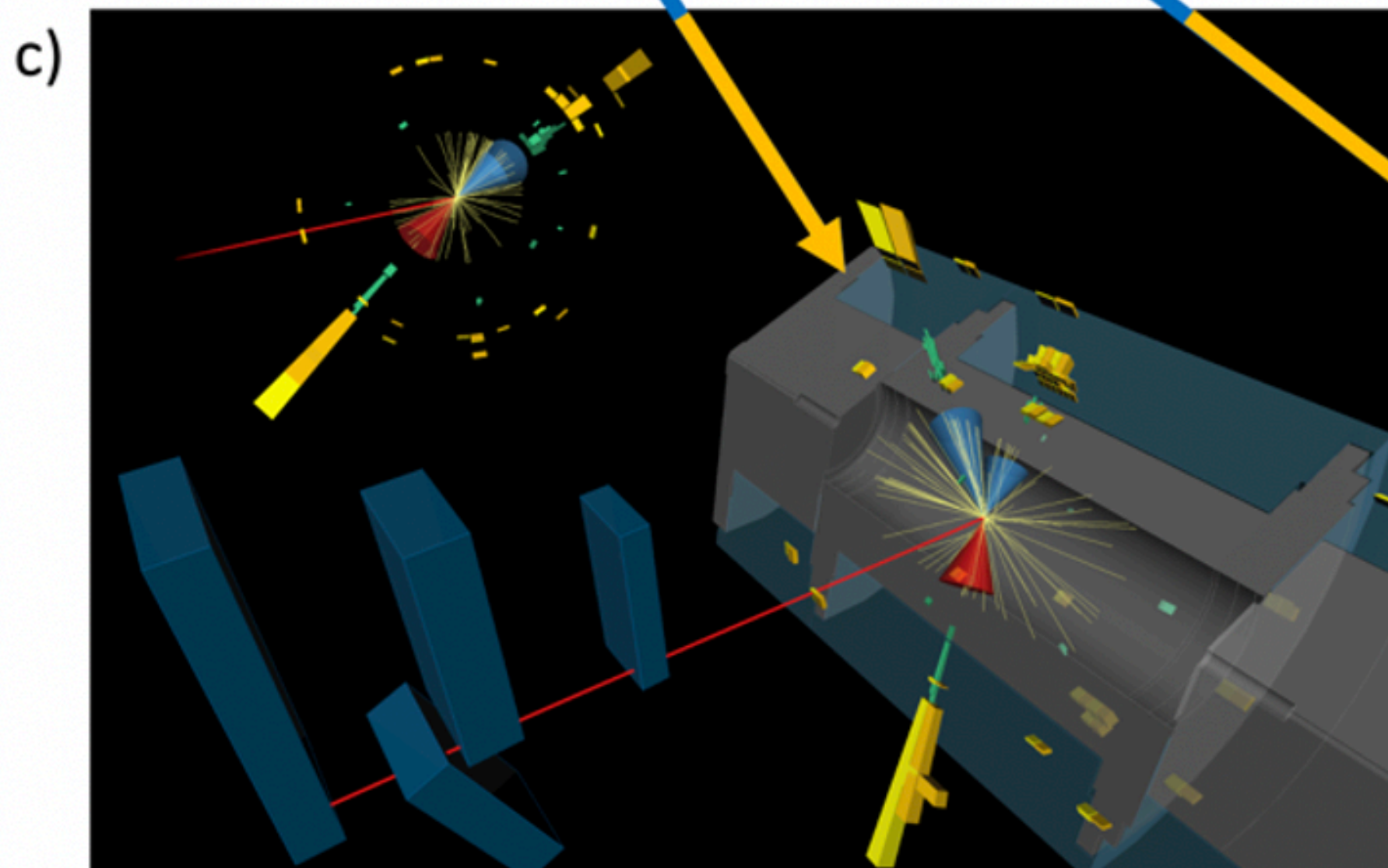
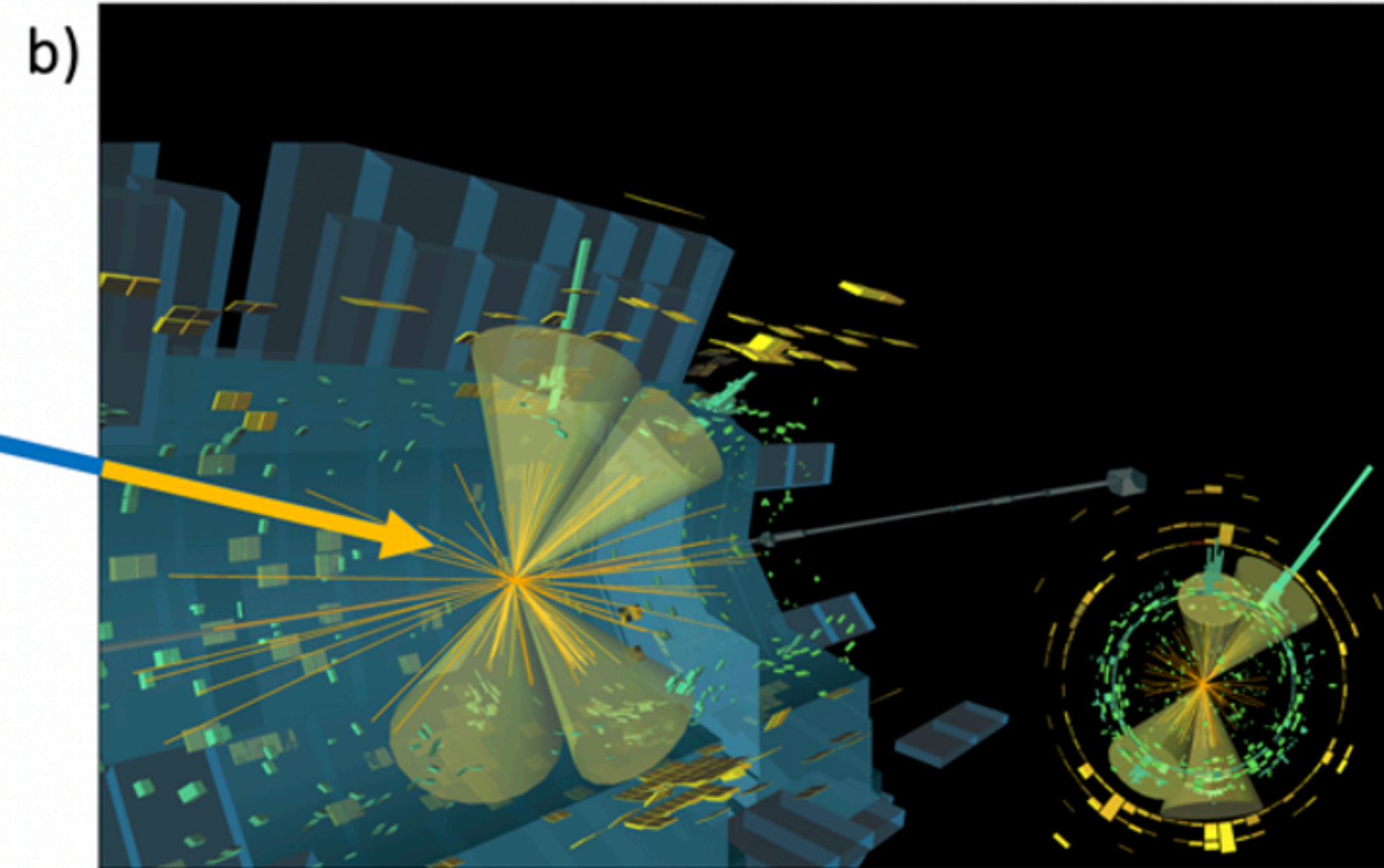
Triangle diagram contributes mostly at low m_{HH}

→ Analyses that contribute to that region are most sensitive to $\kappa_\lambda = \lambda / \lambda_{SM}$

Different final states investigated

a)

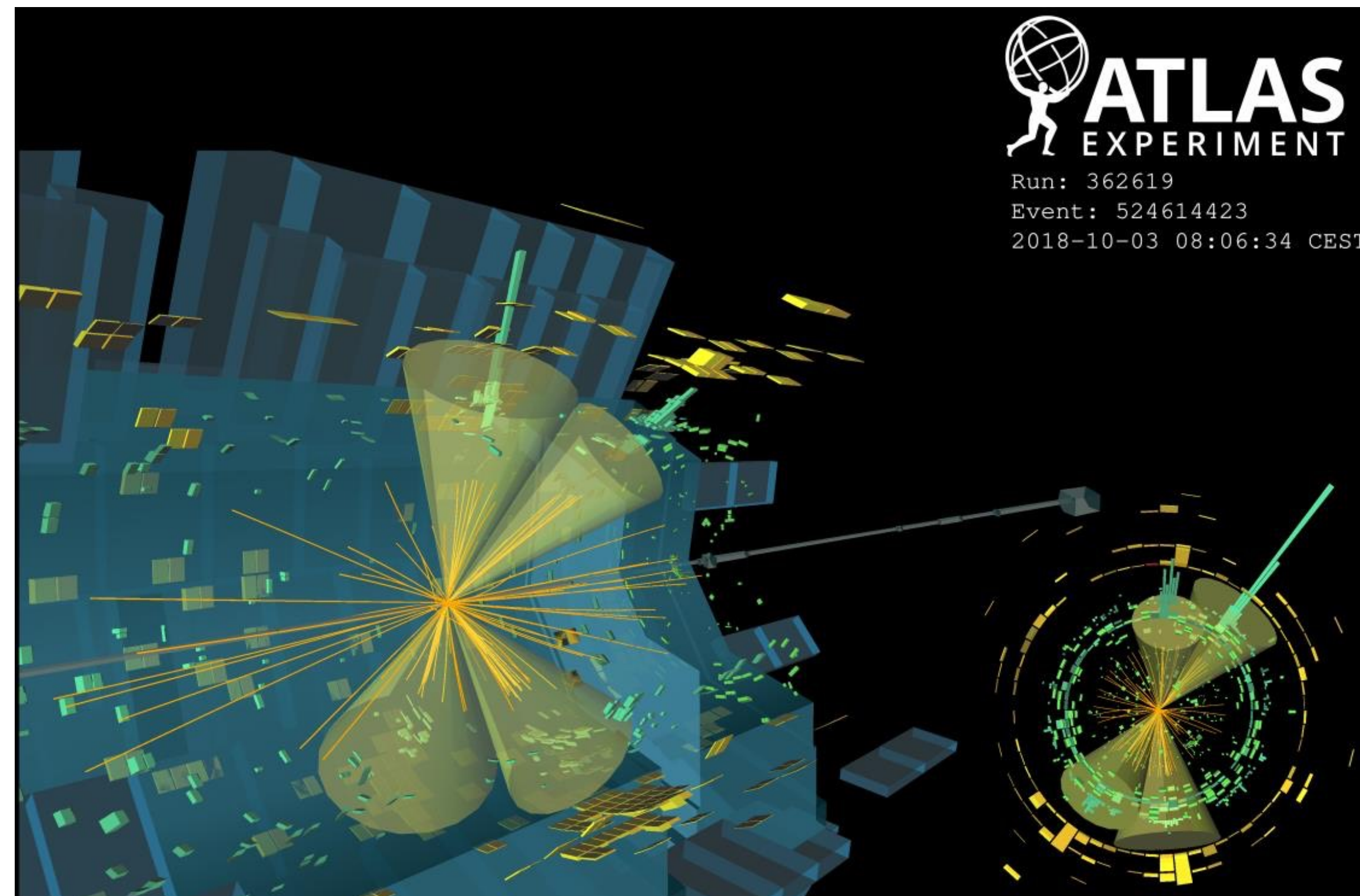
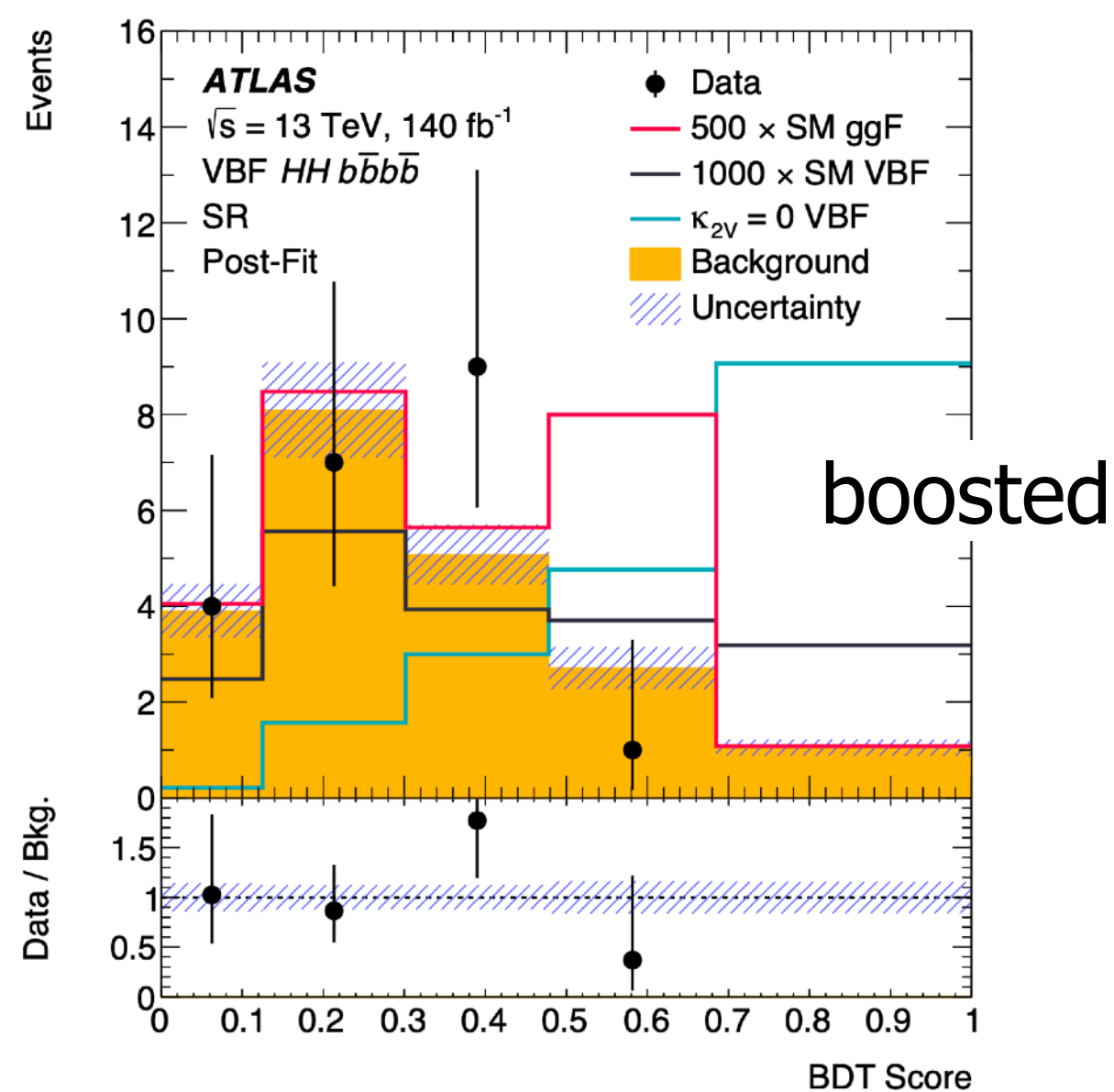
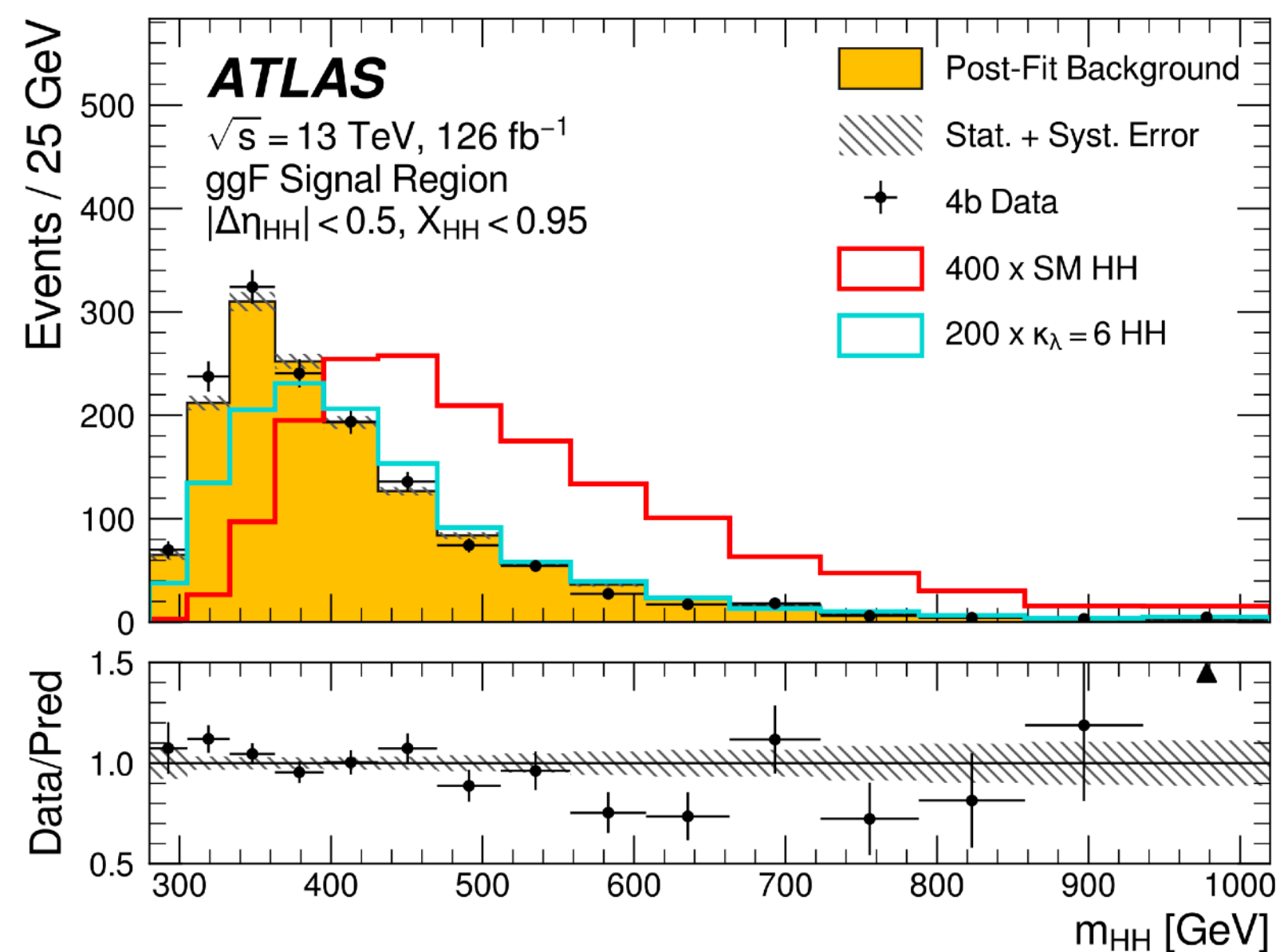
	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%



HH

 $HH \rightarrow bbbb$

resolved



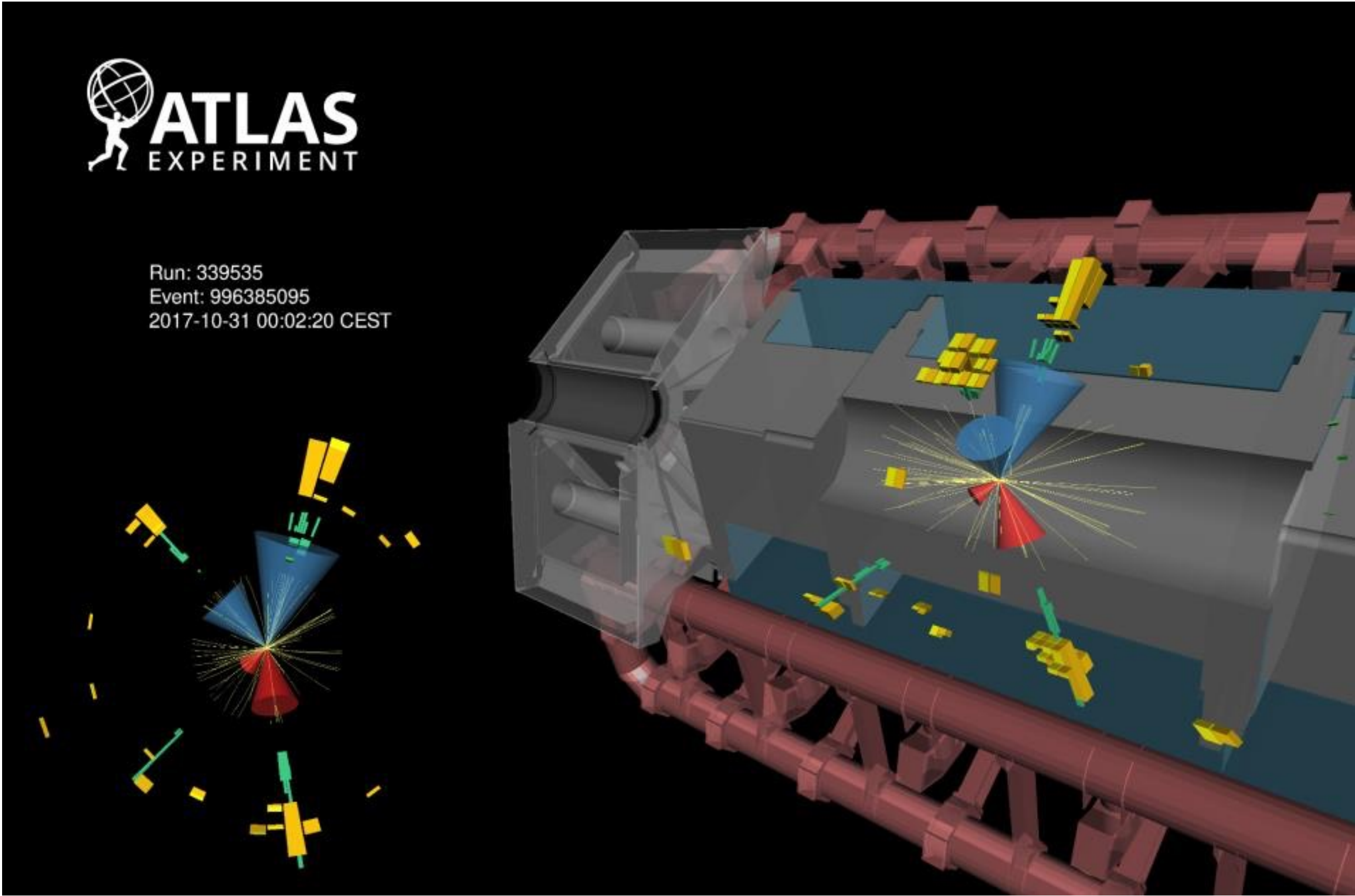
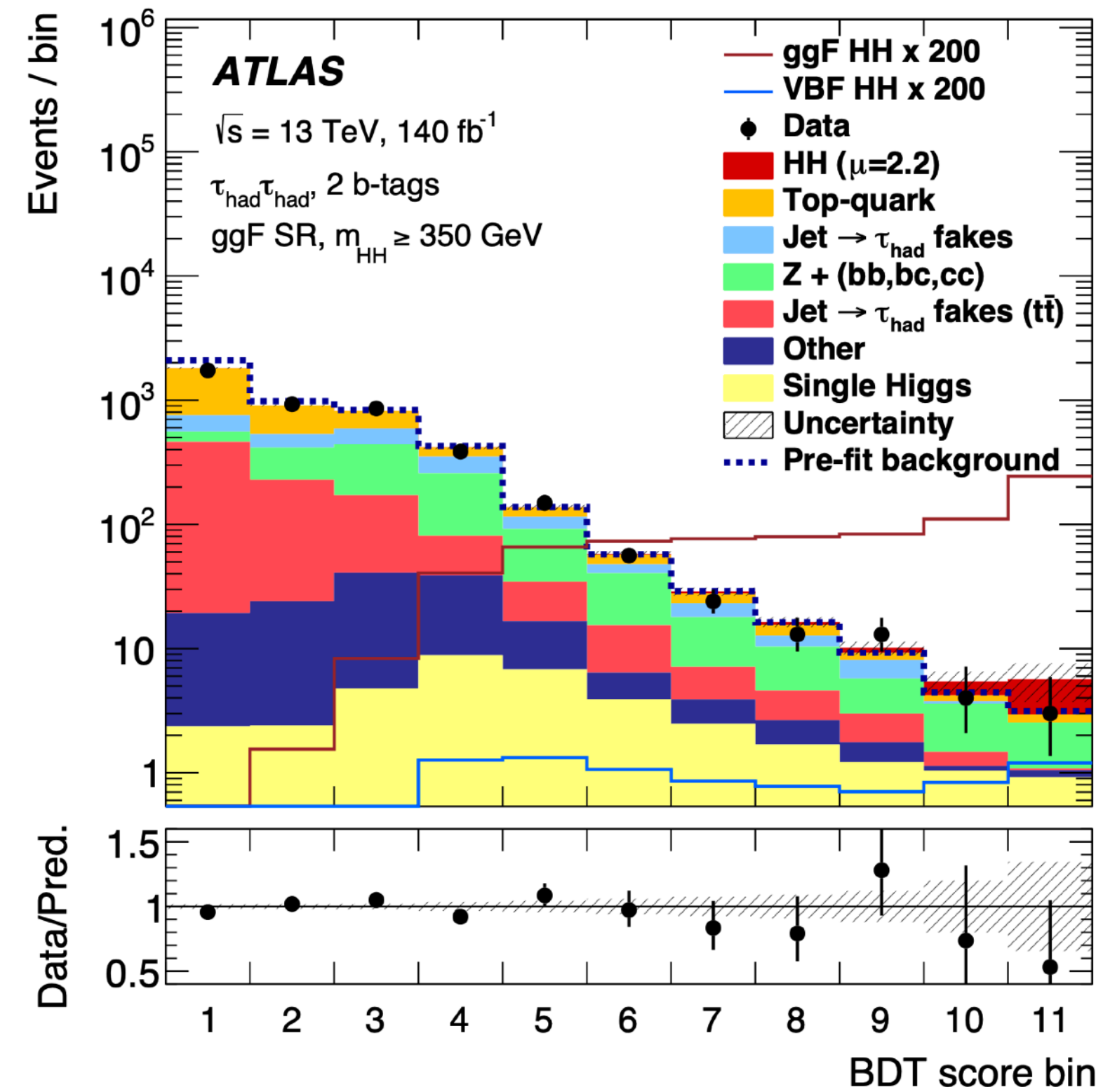
Highest BR, sensitive to high p_T of the Higgs

The sensitivity of the analyses is improved relative to previous iterations by using more sophisticated background modeling techniques, event categorization and improved jet reconstruction and flavor identification algorithms, in addition to the increased integrated luminosity of the analyzed data.

both in $T_{had}T_{had}$ and $T_{lep}T_{had}$ channel
and in ggF+VBF production

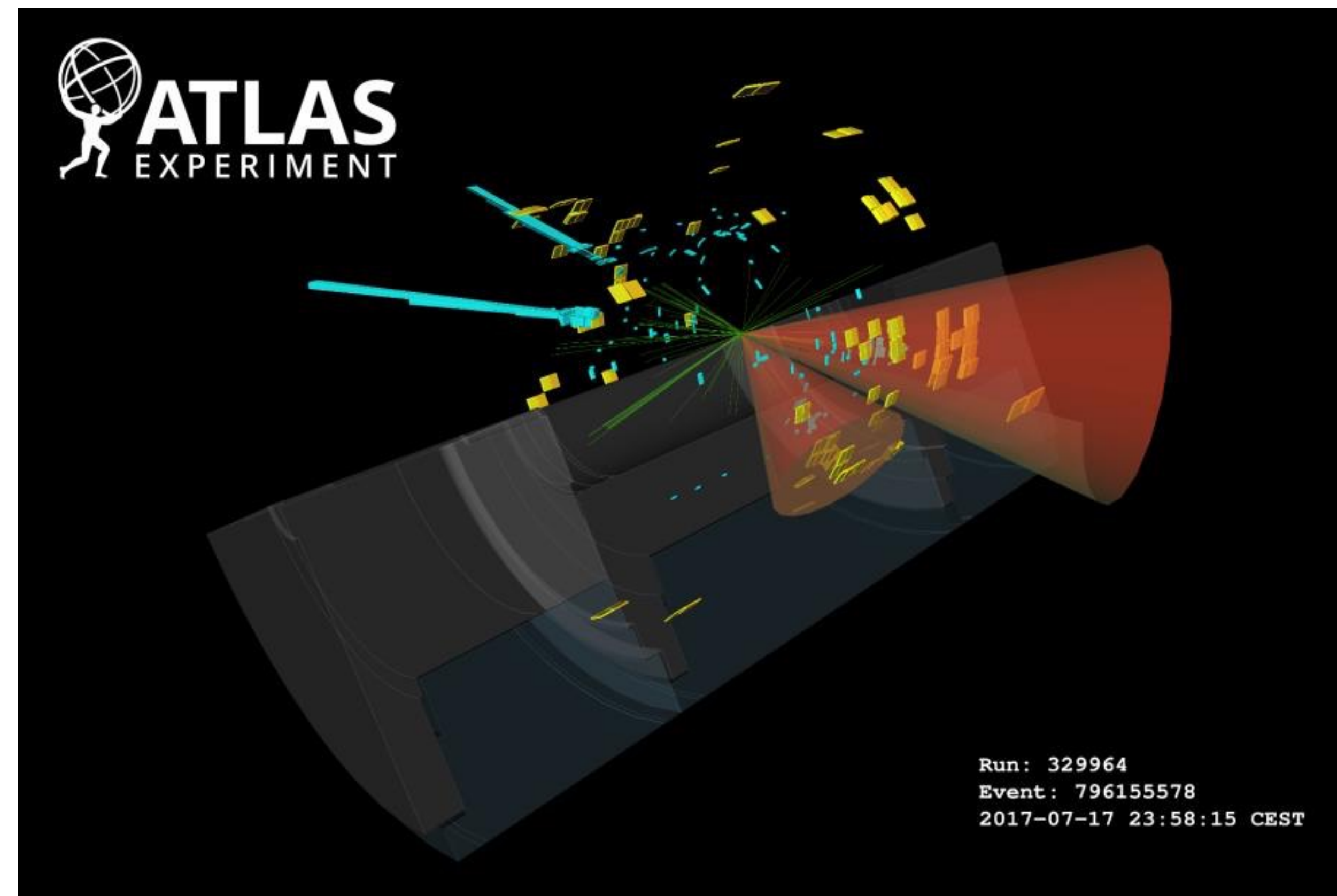
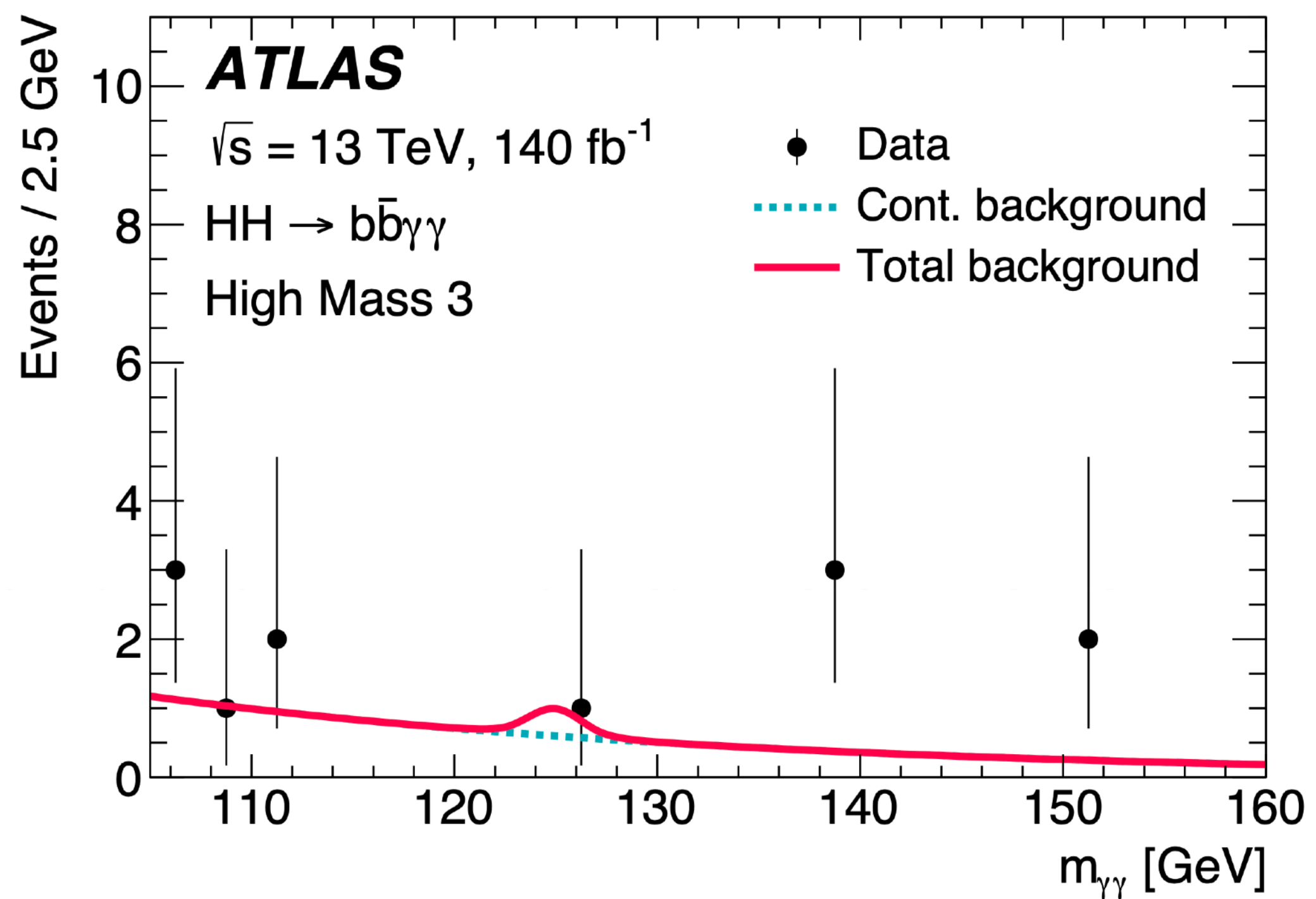
$HH \rightarrow bb\tau\tau$

[arXiv:2209.10910](https://arxiv.org/abs/2209.10910)



sensitivity gains due to significant improvements in the τ_{had} -vis and b -jet reconstruction and identification.

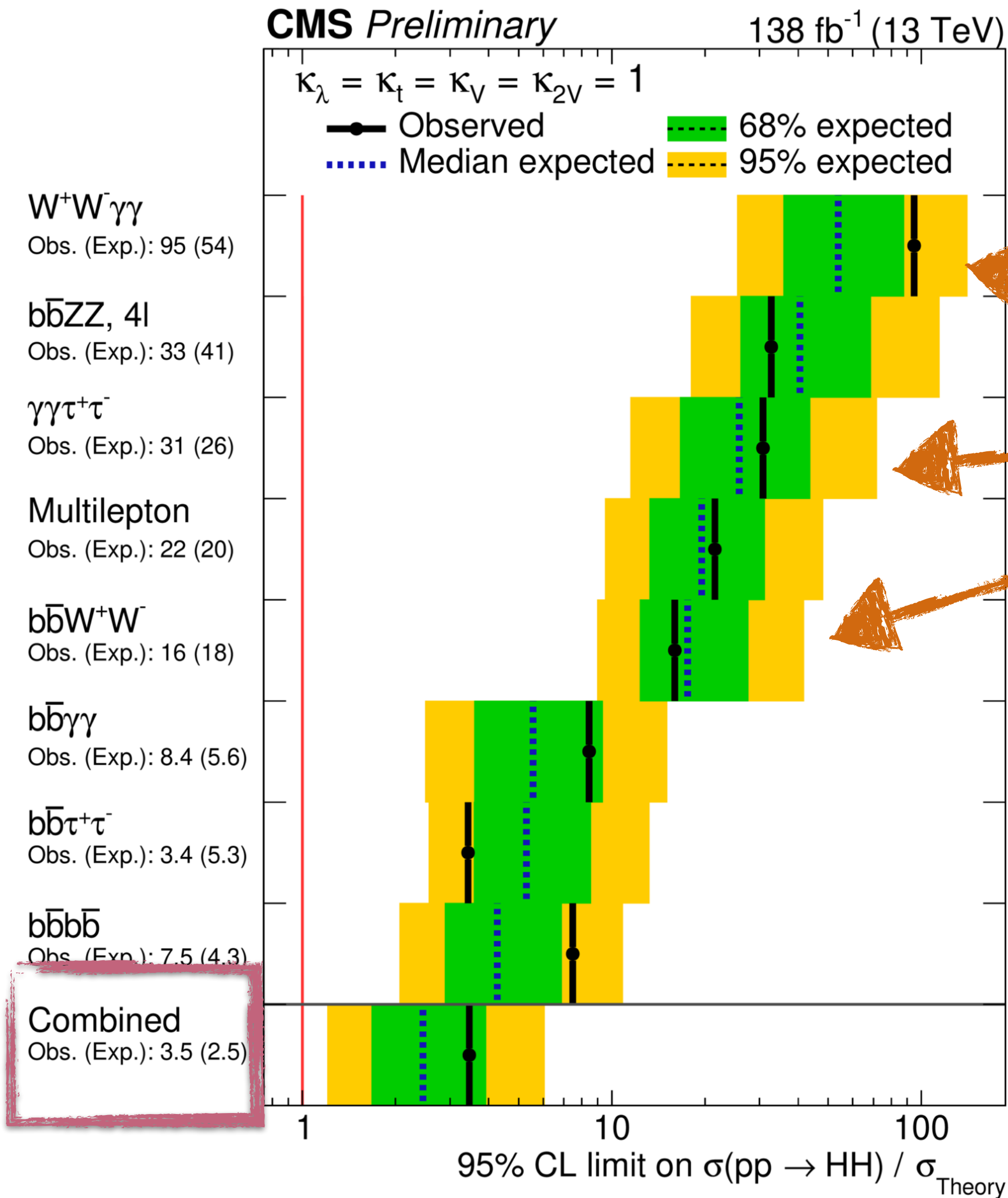
HH

 $HH \rightarrow bb\gamma\gamma$ 

incorporates a categorization based on $mbb\bar{\gamma}\gamma$ and multivariate event selections

di-Higgs in CMS

CMS-PAS-HIG-20-011



Inputs: bbbb resolved and boosted, bbττ, bbγγ

New wrt to Nature combination!

WWγγ

γγττ

bbWW the only existing analysis in this channel

Most complete HH combination @ CMS
 x-section sensitivity at 3.5 xSM (2.5 exp)

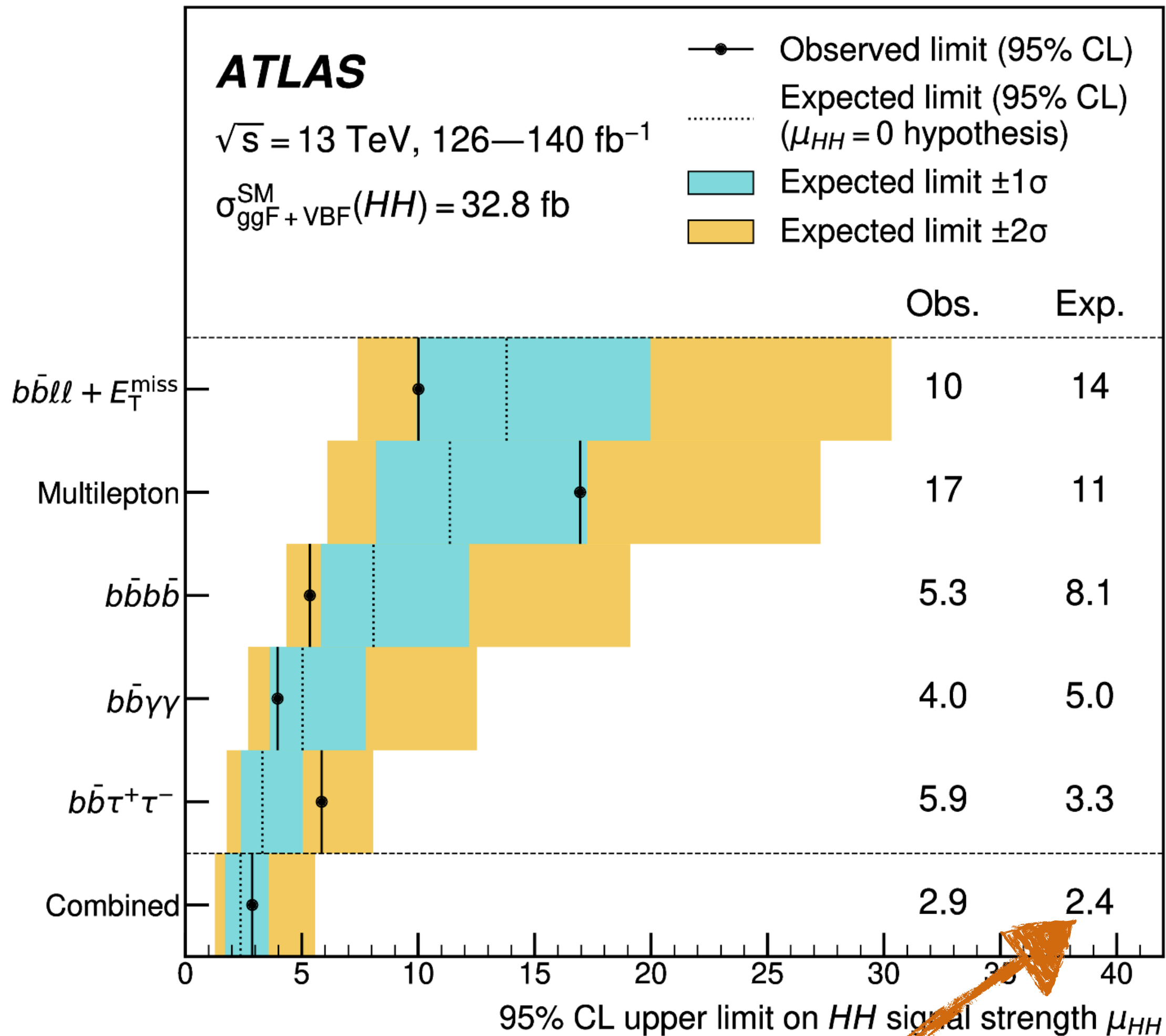
Observed : $\kappa_\lambda \in [-1.39, + 7.02]$

Expected $\kappa_\lambda \in [-1.02, + 7.19]$

di-Higgs ATLAS

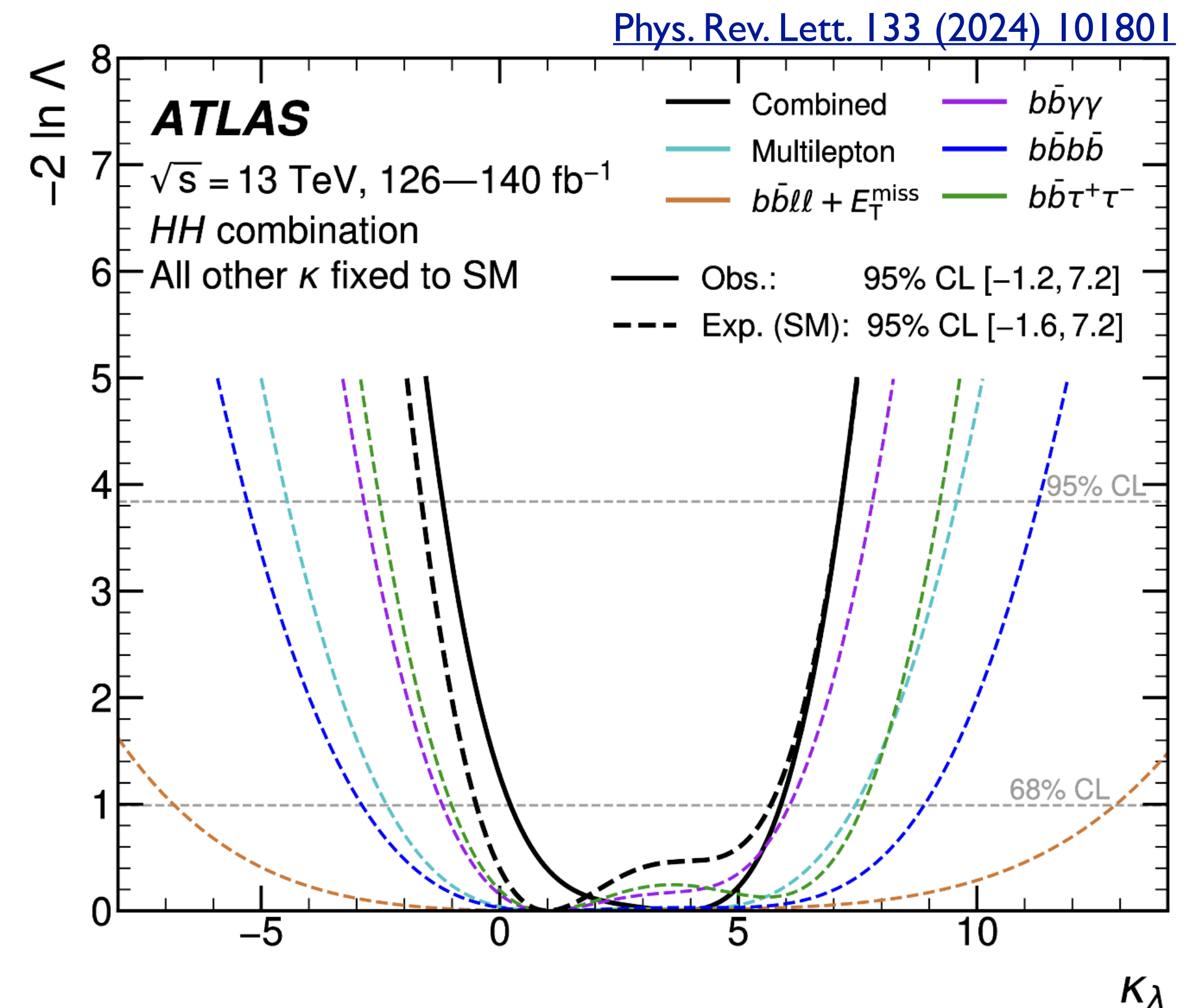
Observed : $\kappa_\lambda \in [-1.2, +7.2]$

Expected $\kappa_\lambda \in [-1.6, +7.2]$



best sensitivity to date

$b\bar{b}\gamma\gamma$
 $b\bar{b}\tau\tau$
 $b\bar{b}b\bar{b}$ (resolved jets)
 $b\bar{b}b\bar{b}$ (VBF w/ merged jets)
 $b\bar{b}l\bar{l}$ (+MET)
 Multilepton

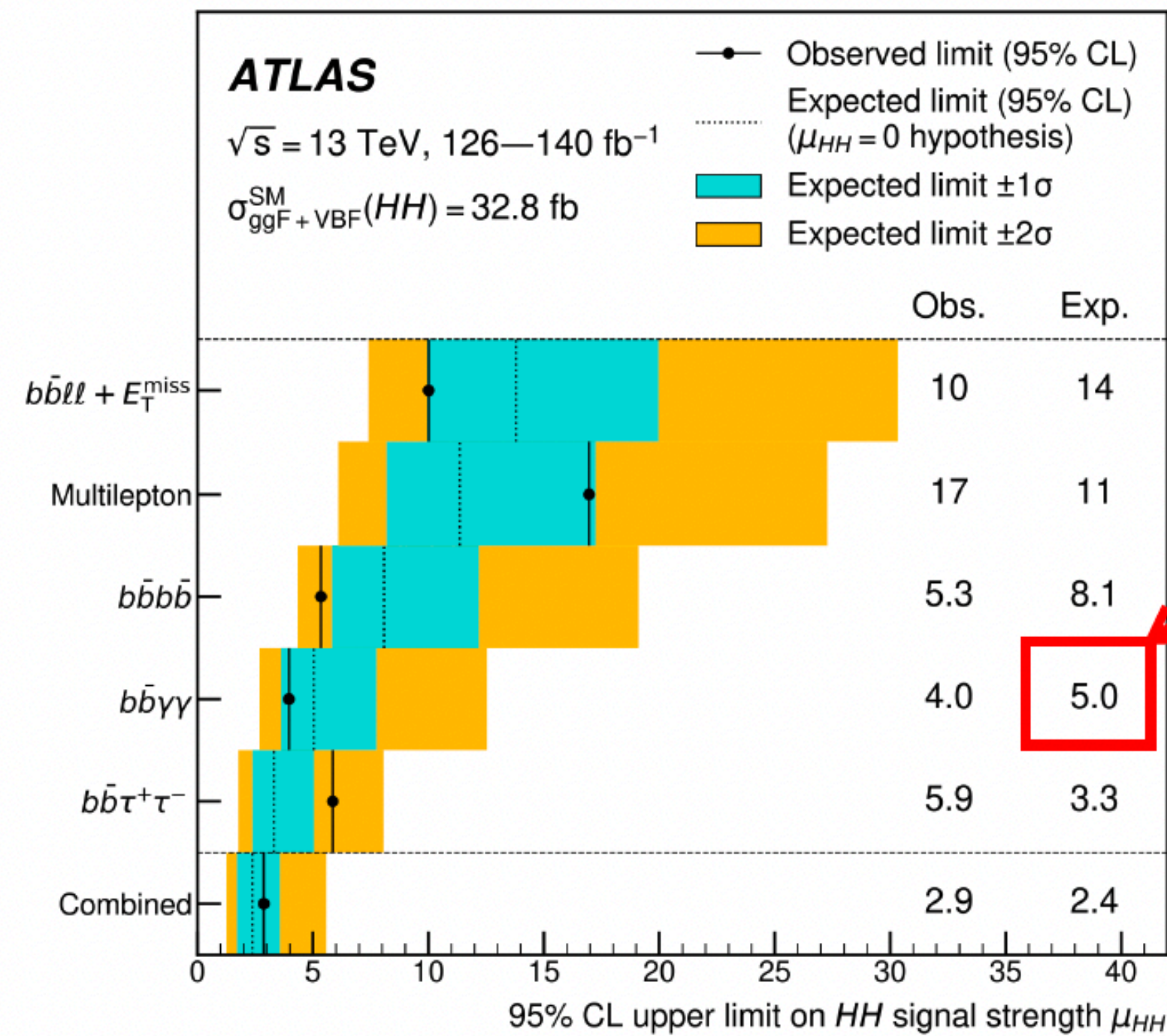
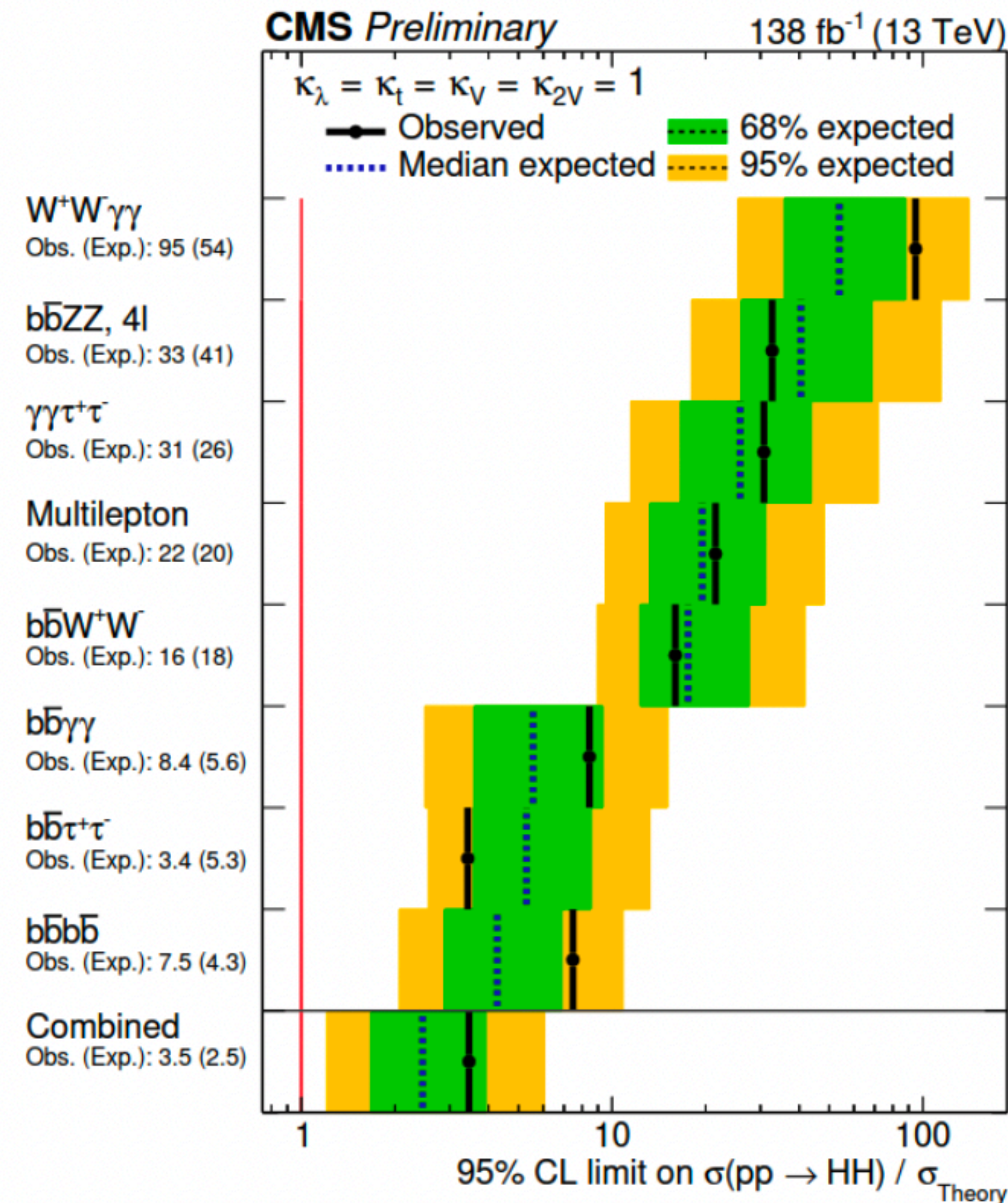


$b\bar{b}\gamma\gamma$ channel most sensitive, and $b\bar{b}\tau\tau$ at negative κ_λ

ATLAS+CMS

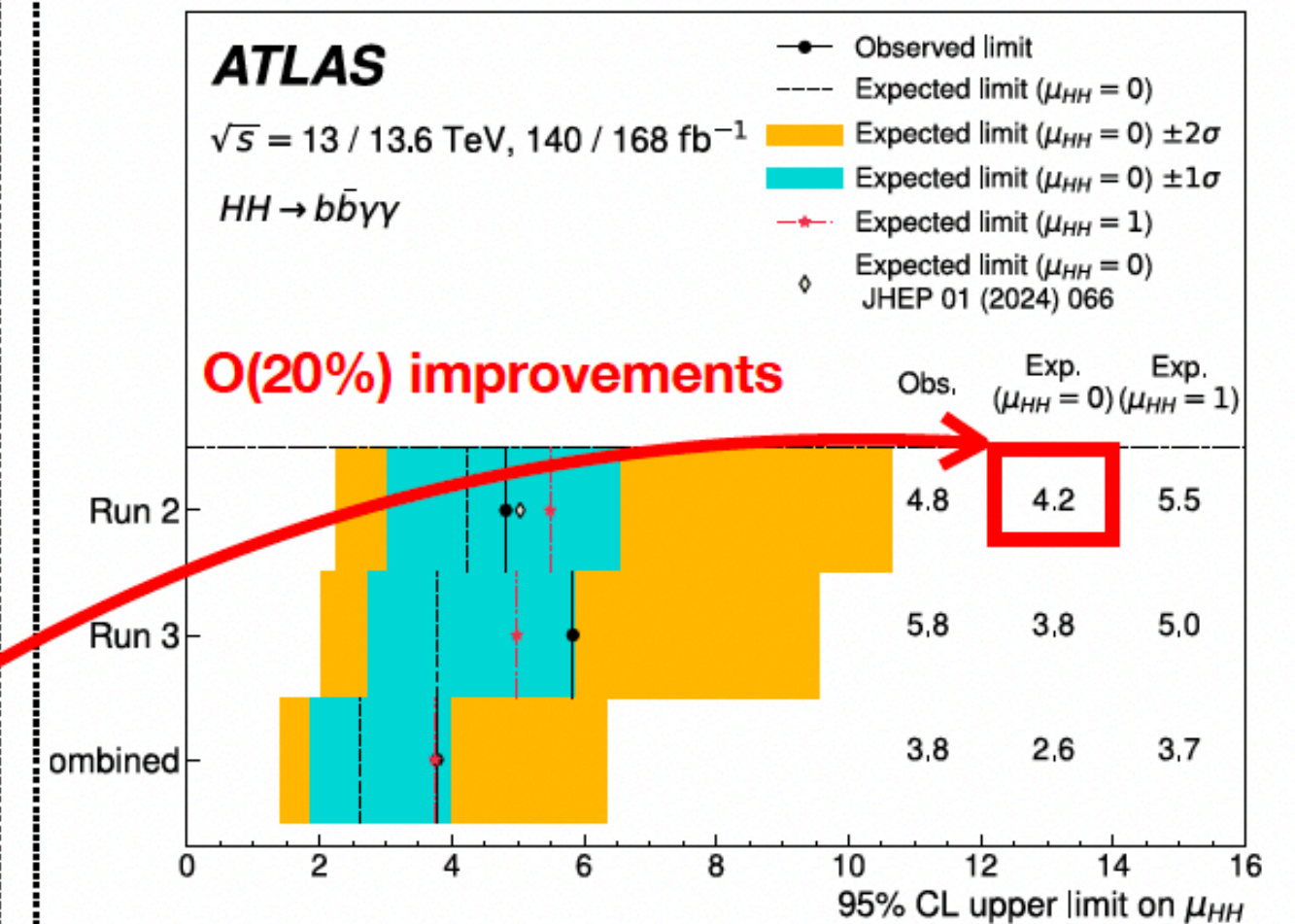
Run2

Similar sensitivity from ATLAS and CMS but different hierarchy across channels
Results are limited by stat. uncertainties



Run3 getting in the game

Opportunity to maximise the analysis sensitivity (data streams, triggers, object reconstruction, analysis techniques)

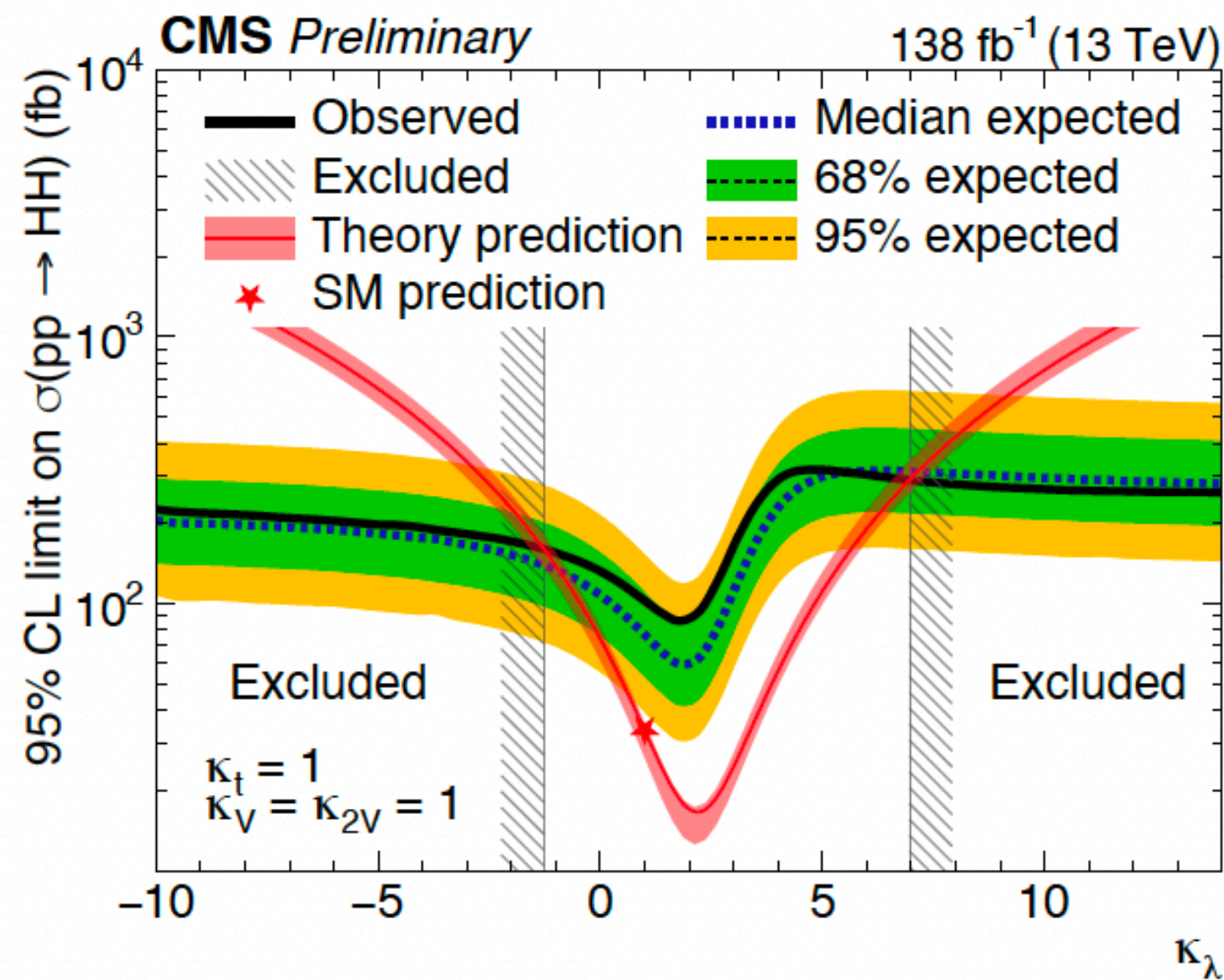


ATLAS - CMS combination (on-going) of Run2 analysis could be <1.7

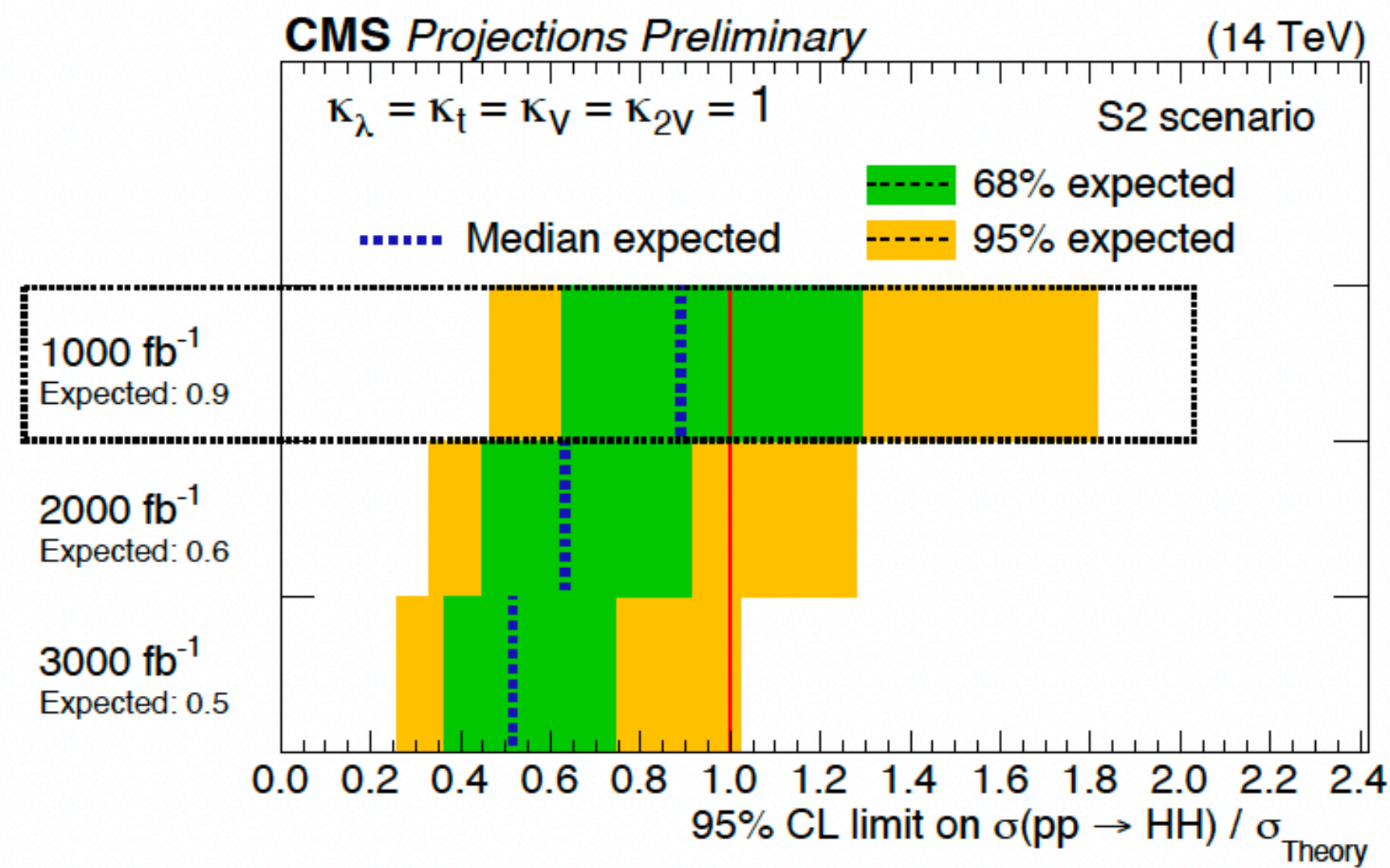
We can expect it to reach ~ 1 with **new improvements**, given 500/fb (Run1+Run2+Run3)

ATLAS+CMS

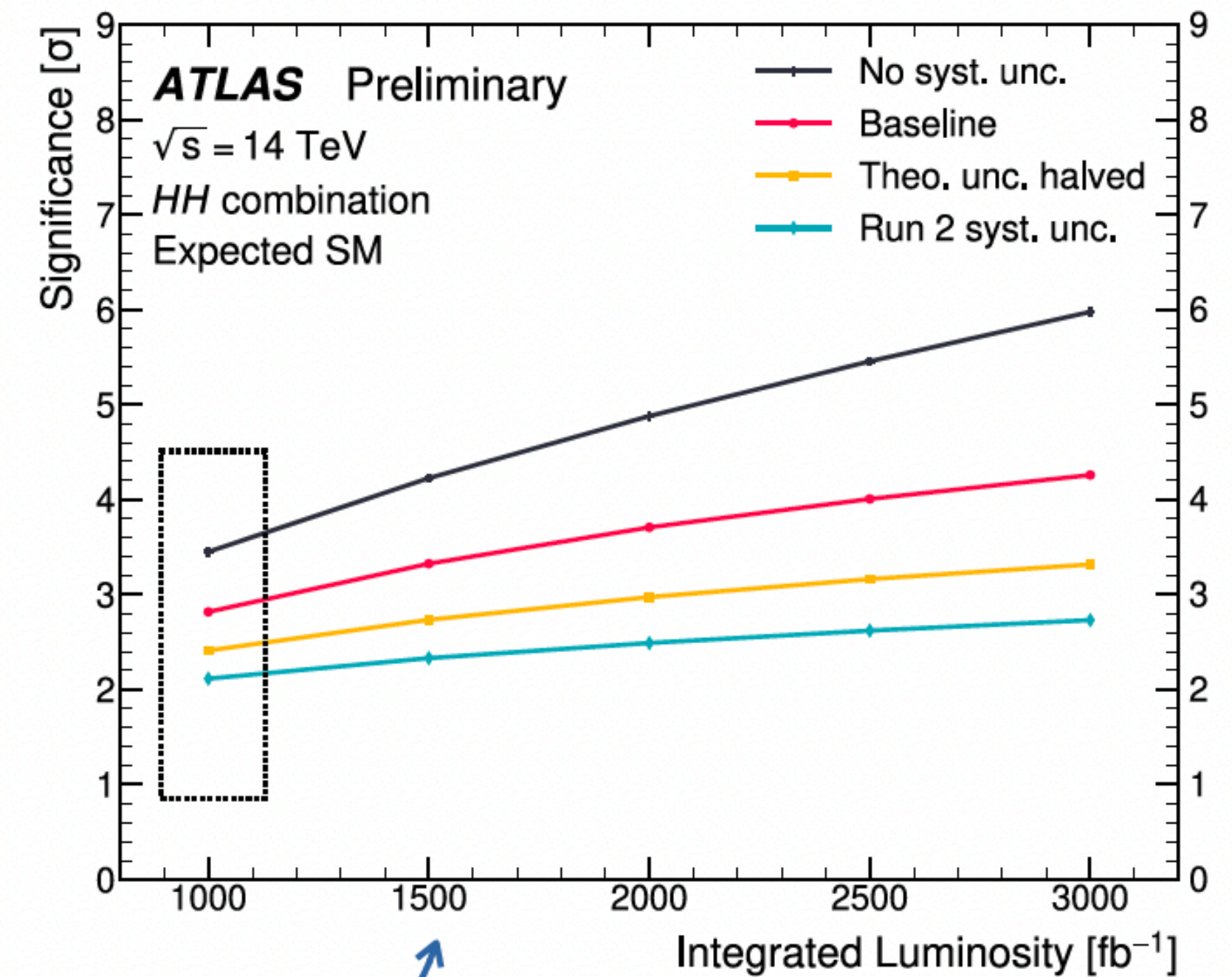
Sensitivity to exclude of $\lambda_{HHH} = 0$
by the the end of Run3



95% CL sensitivity for HH production
combining ATLAS and CMS.
Sensitivity with single experiment?



HH evidence at the end of Run3
combining ATLAS and CMS?

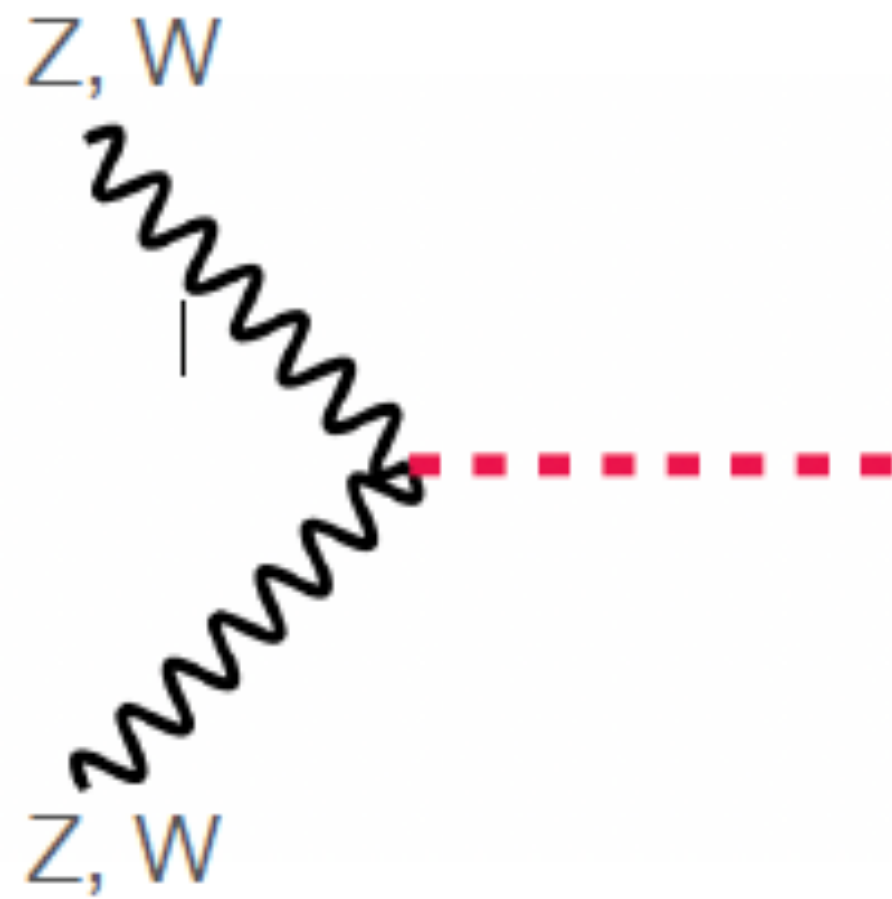


Single experiment 1000/fb projection as a gauge of two experiments combinations

Indirect determination of λ_3 (via single Higgs)

The determination of the Higgs self coupling can be made in a direct way, observing the di-Higgs process (which is the best way of assessing the presence of new physics deviations)

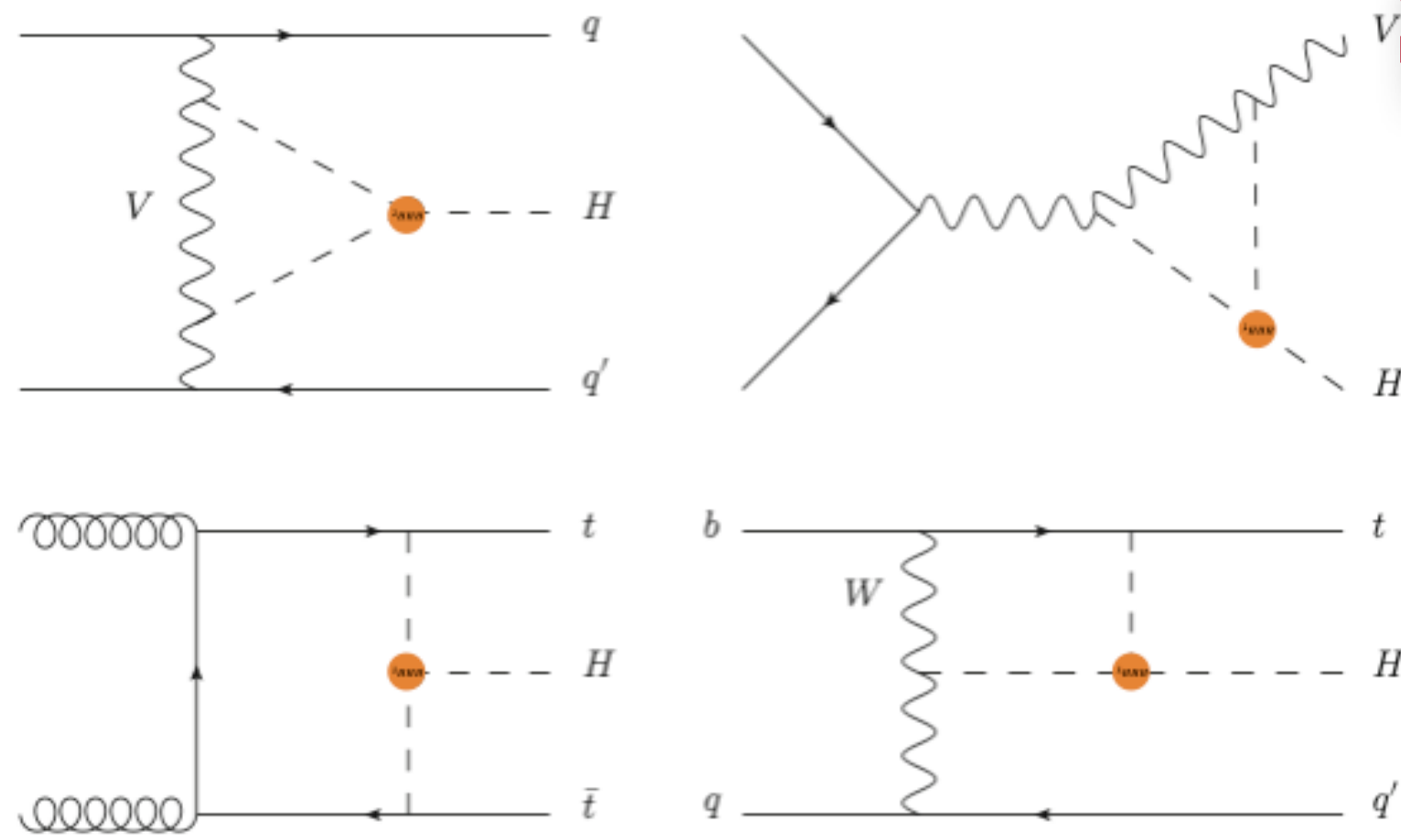
Or indirectly via single Higgs



New physics can often induce changes in the hZ coupling

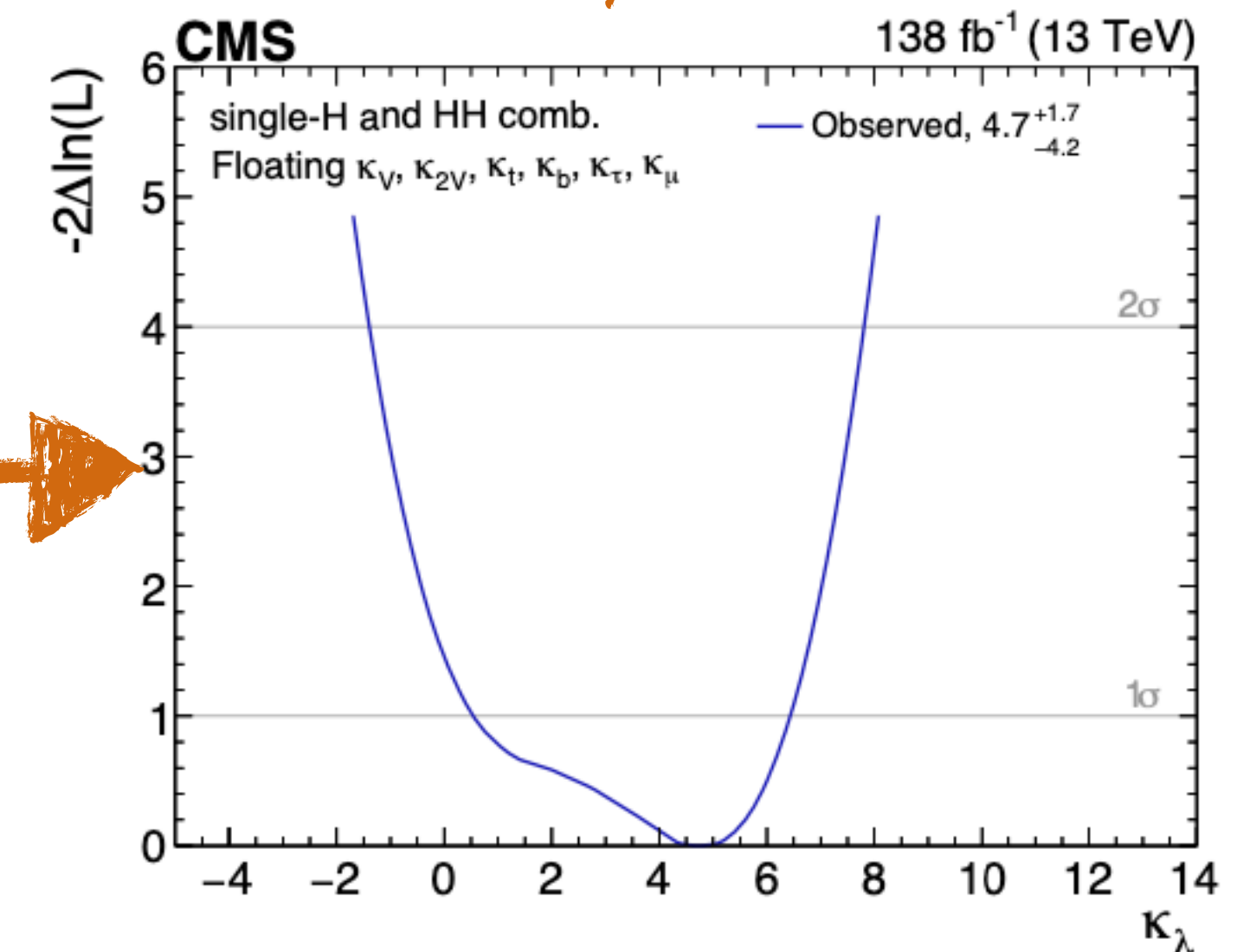
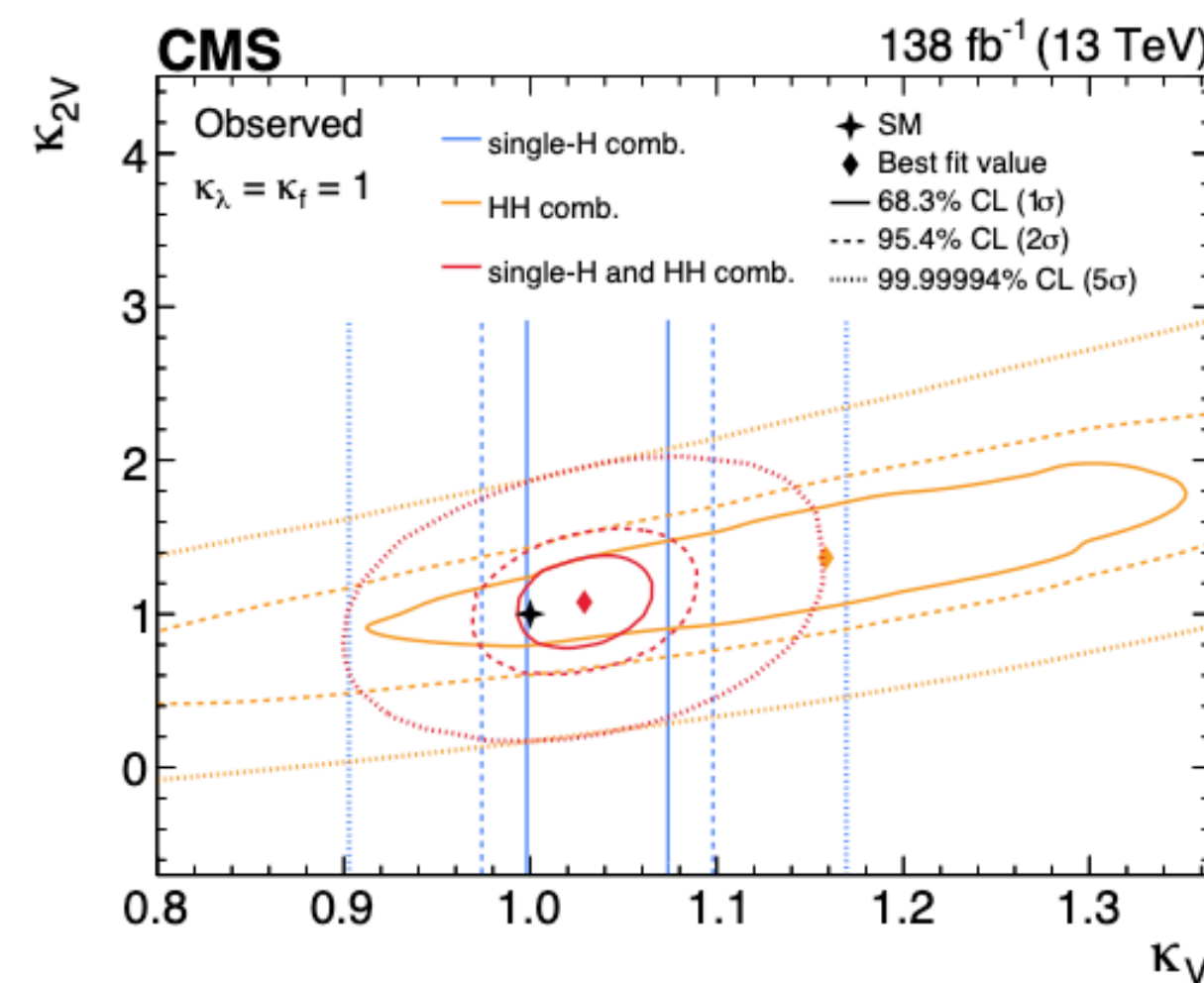
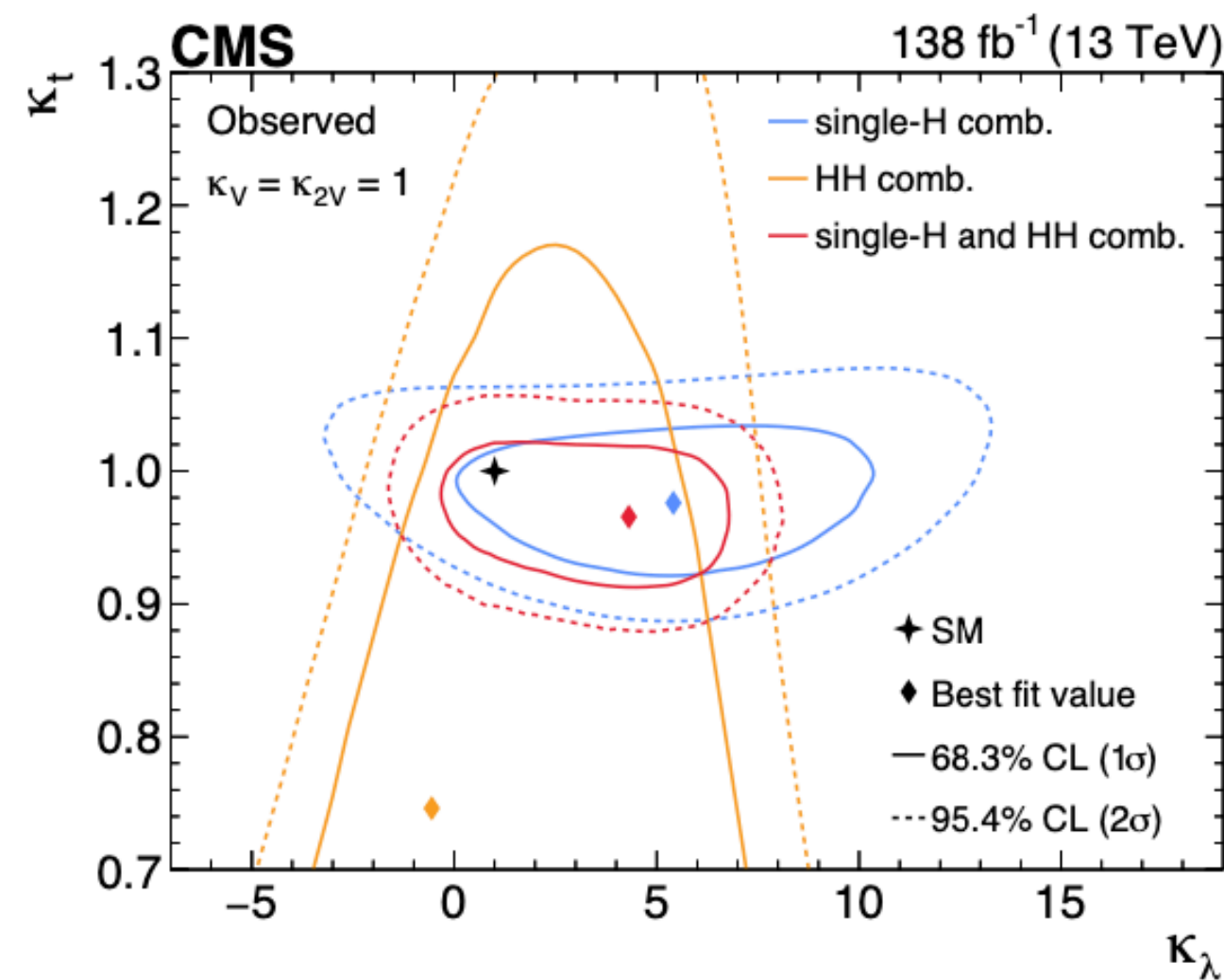
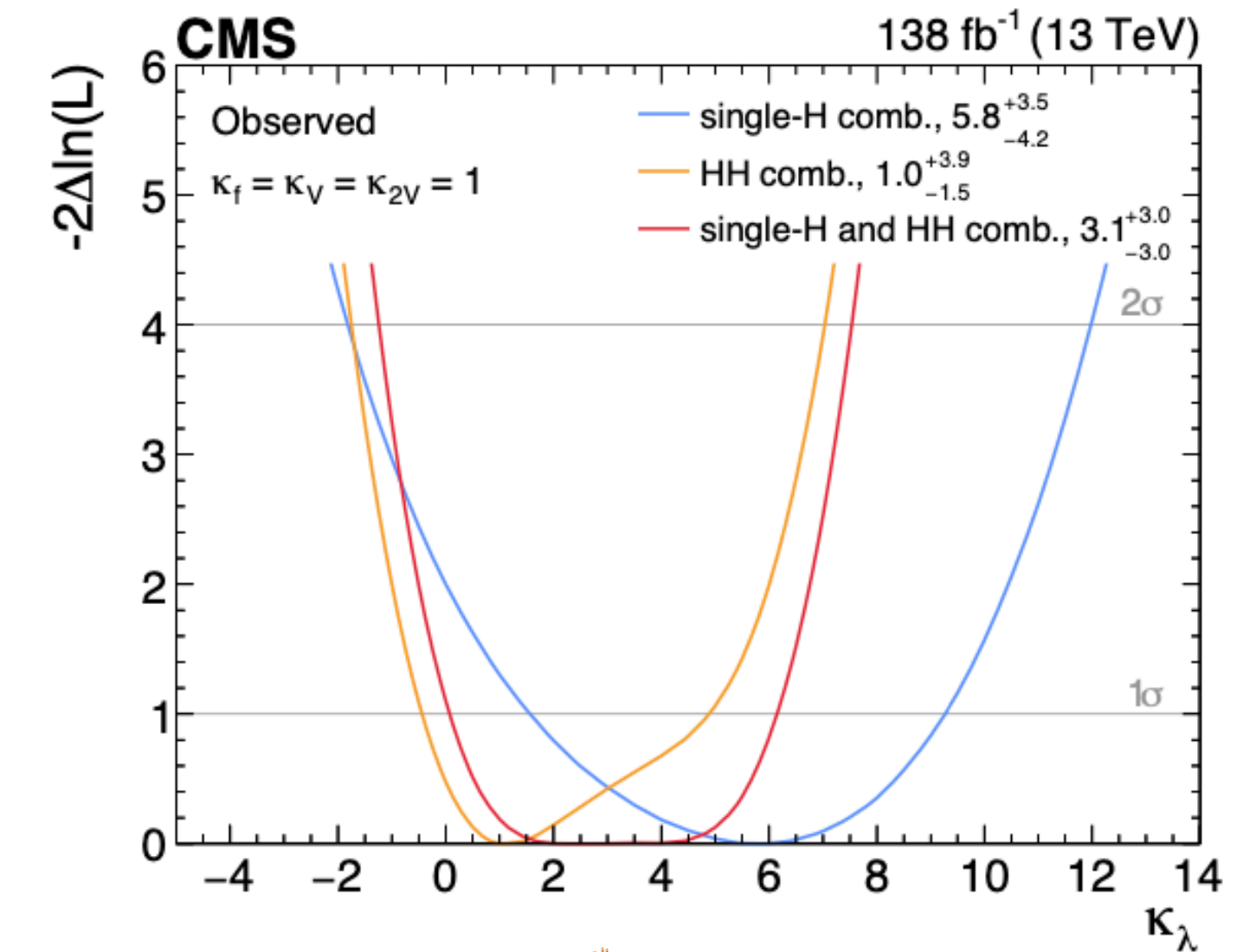
Single Higgs and di-higgs combination

arXiv:2407.13554



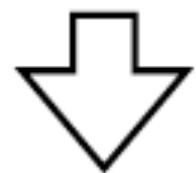
the single-H boson production includes processes sensitive to the higgs self couplings at the NLO EW correction level.

At the LHC, Single Higgs adds little on di-Higgs combination, but it helps because we can constrain the assumptions on κ_V , κ_{2V} , and κ_t in the fits



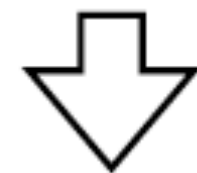
hZZ vs Higgs self-coupling

$$\frac{1}{\Lambda^2}(H^\dagger \partial H)^2$$



Modify H-Z coupling $\Rightarrow \delta_{Zh}$

$$\frac{1}{\Lambda^2}(H^\dagger H)^3$$



δ_{Zh}

Modify Higgs self-coupling $\Rightarrow \delta_{\lambda_3}$

However, $\delta_{Zh} \propto g_z$, while δ_{λ_3} is not related to $\lambda_{3,\text{SM}}$

With some tuning, one can find models in which $\delta_{\lambda_3} > \delta_{Zh}$

g_z = coupling strength of the Z boson to other particles.

$$g_z = \frac{g}{\cos \theta_W},$$

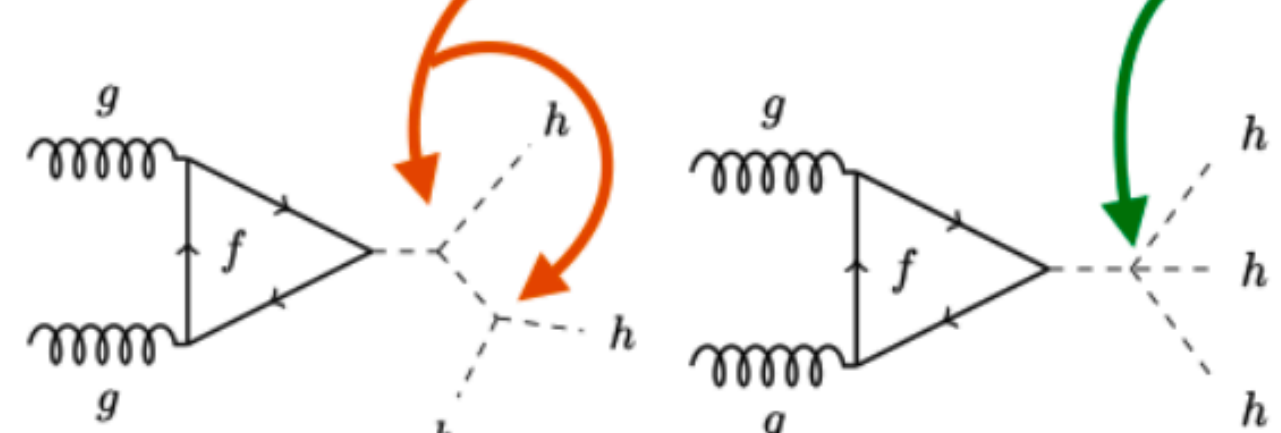
g is the weak isospin coupling (the $SU(2)_L$ coupling),
 θ_W is the weak mixing angle (Weinberg angle).

3 Higgses



Quartic Higgs couplings $HHH \rightarrow 6b$

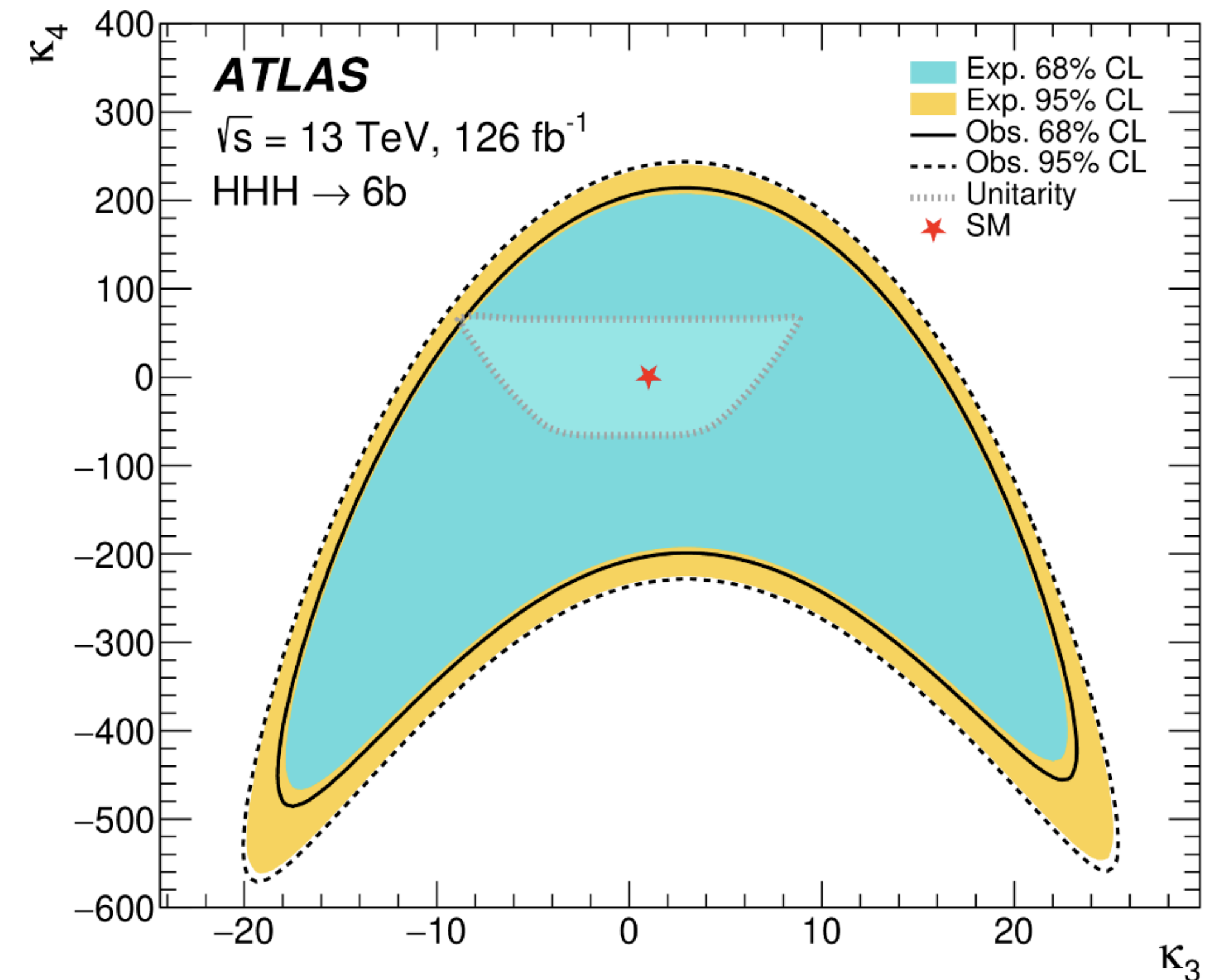
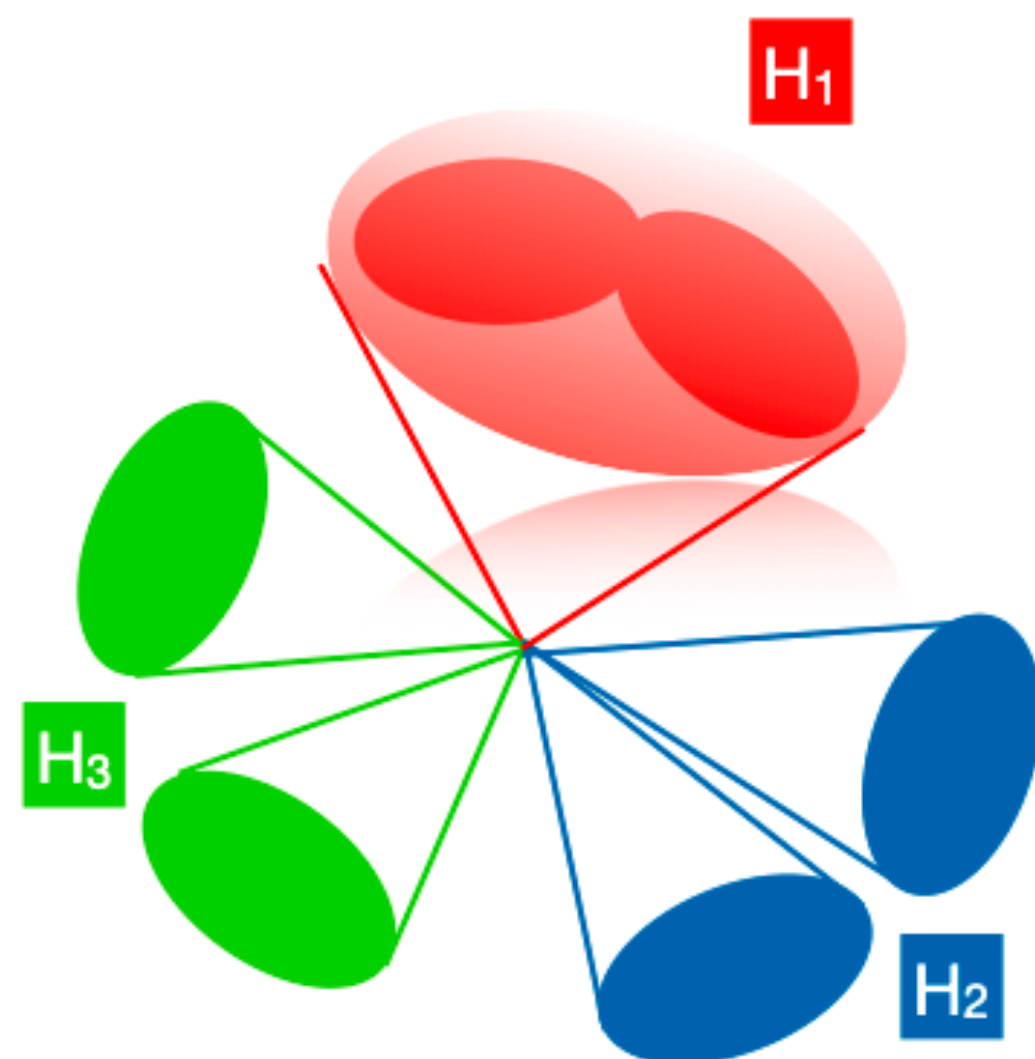
[arXiv:2411.02040](https://arxiv.org/abs/2411.02040)

$$V_h = \frac{1}{2}m_h^2 h^2 + (1 + \kappa_3)\lambda_{hhh} v h^3 + \frac{1}{4}(1 + \kappa_4)\lambda_{hhhh} h^4$$


Data consistent with SM.

$\sigma(\text{pp} \rightarrow HHH) < 59.4 \text{ fb @ 95\% CL}$
 $(\mu < 747)$

First time that the constraints are set on the quartic Higgs coupling.



Invisible Higgs

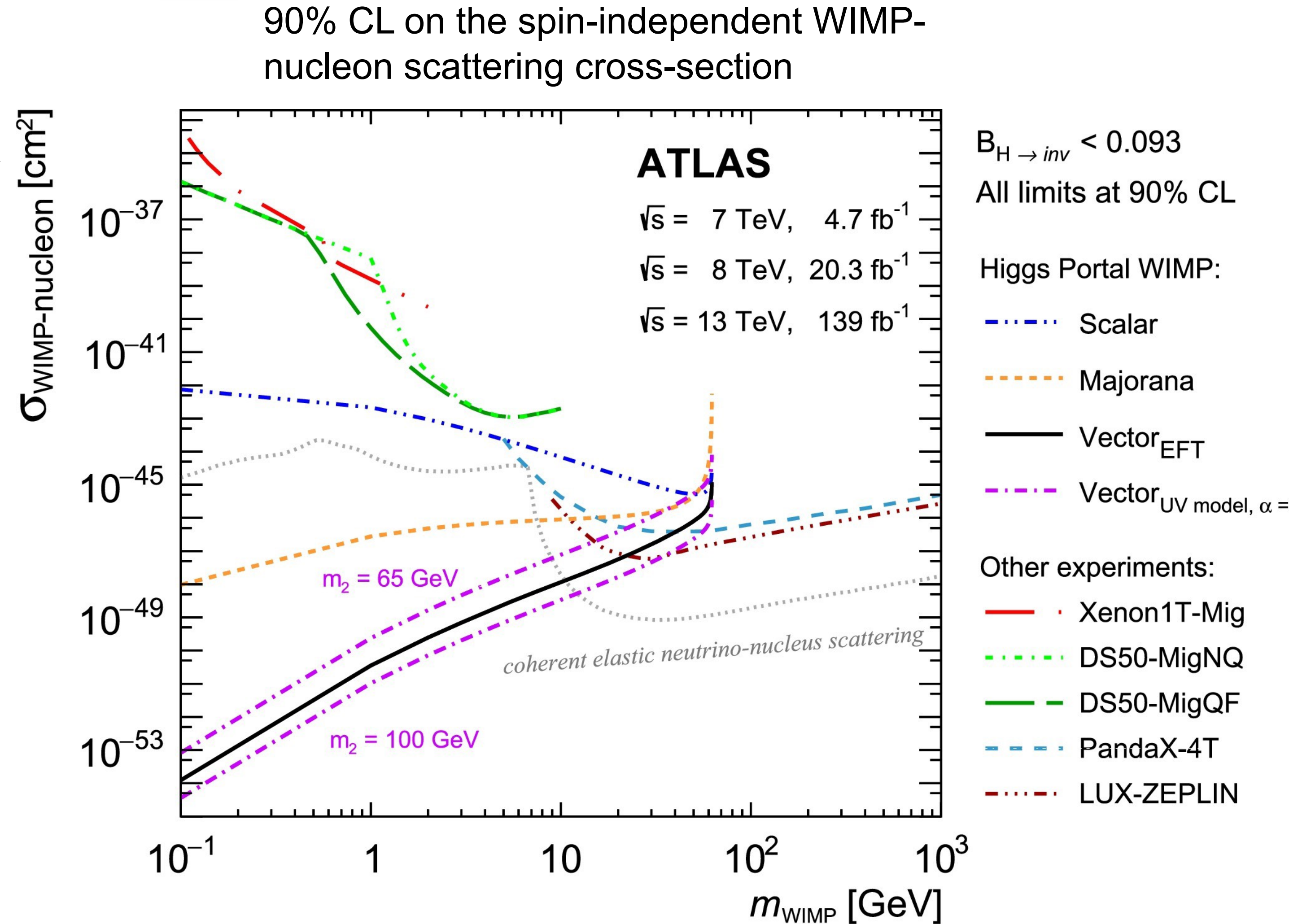


Invisible Higgs width

Phys. Lett. B 842 (2023) 137963

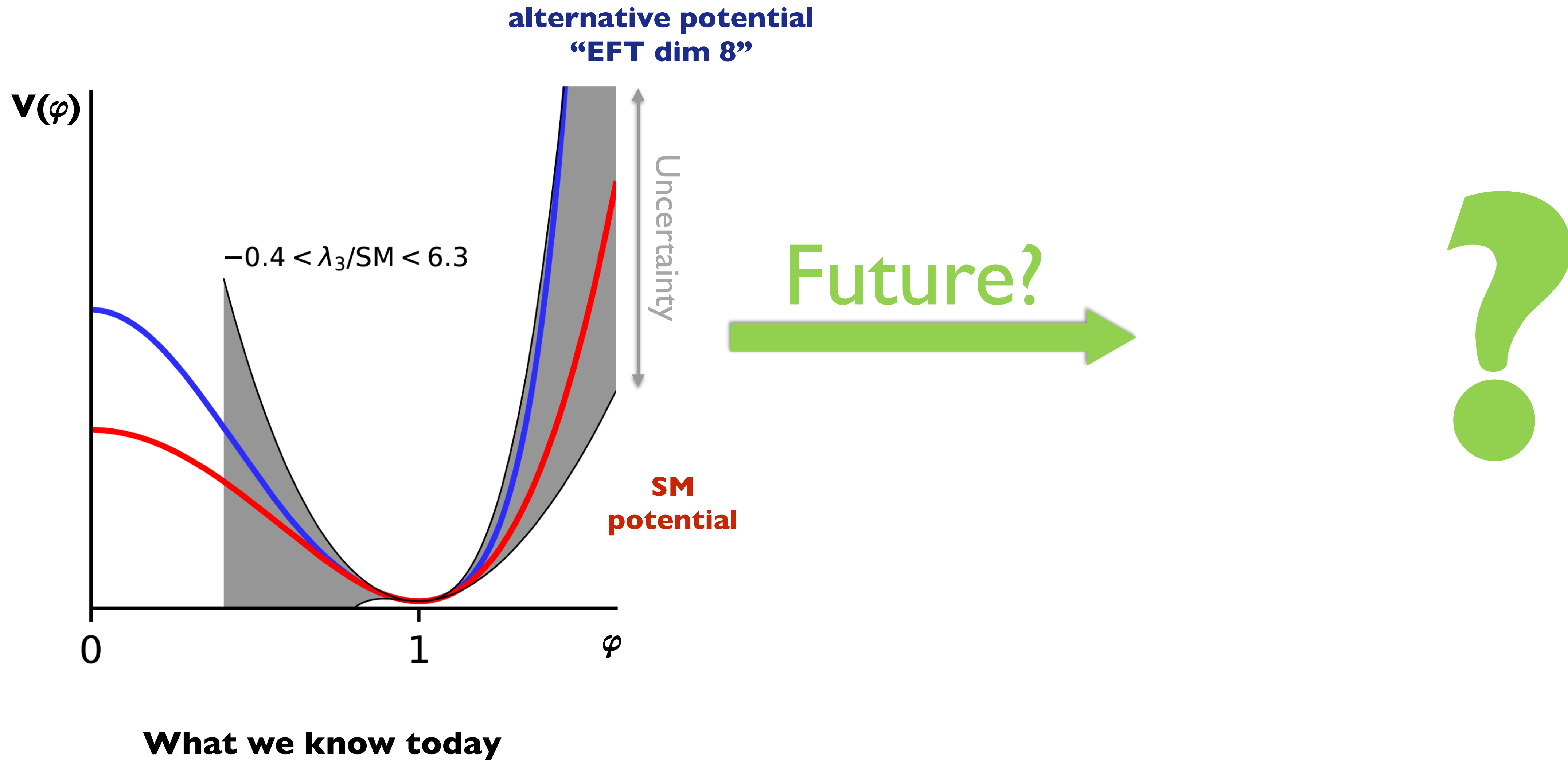
- SM particles get mass through the Higgs. Dark matter could behave the same way and be produced in Higgs decays
- SM Higgs invisible decays are $<0.1\%$
- **The analysis: $B(H \rightarrow \text{inv})_{\text{obs}} < 10.7\% \text{ @95\%CL}$**
 $B(H \rightarrow \text{inv})_{\text{exp}} < (7.7\%) \text{ @95\%CL}$

$$\text{BR}(H \rightarrow \text{inv}) = \frac{\Gamma(H \rightarrow \text{inv})}{\Gamma_{\text{total}}}$$



The regions above the limit contours are excluded

What's the future for the Higgs?



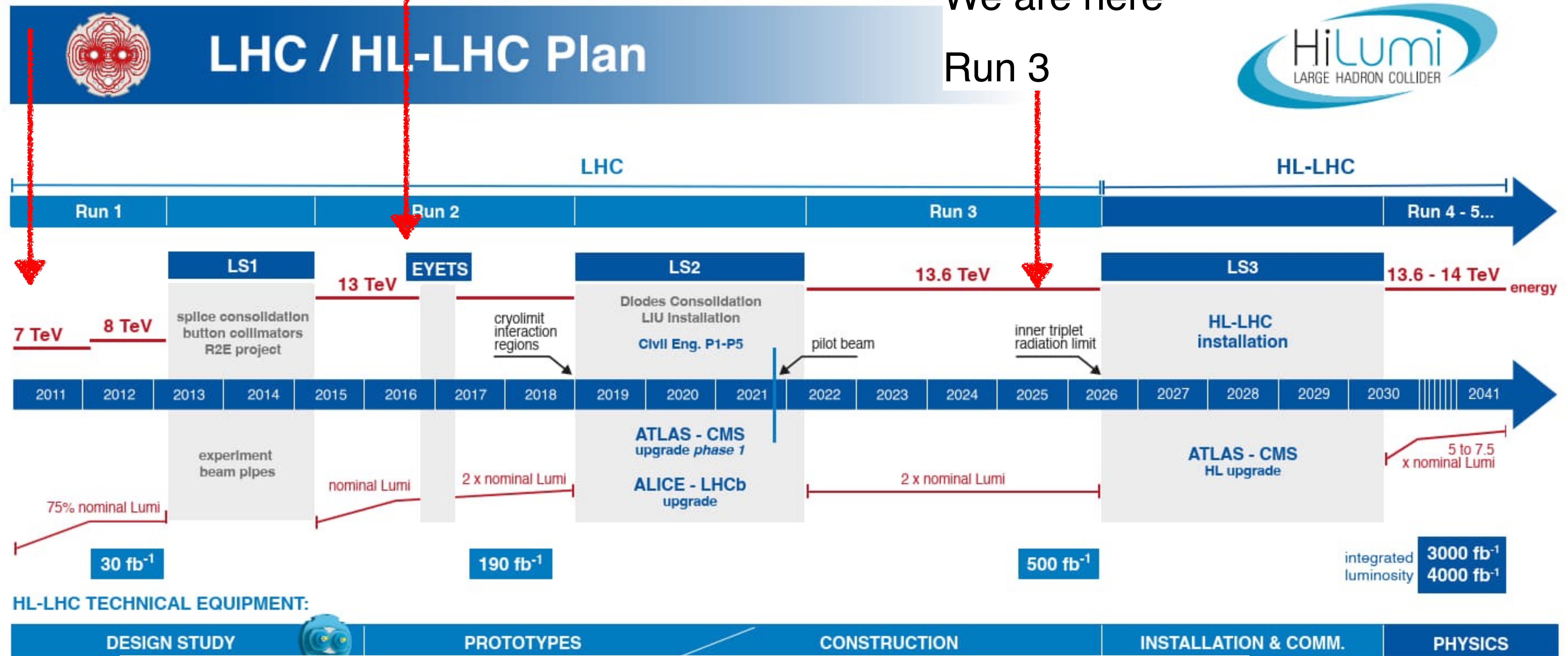
Run 1

Run 2

LHC Schedule

We are here

Run 3



HL-LHC will have a factor 5-7 more integrated luminosity



HL-LHC upgrade: The challenges

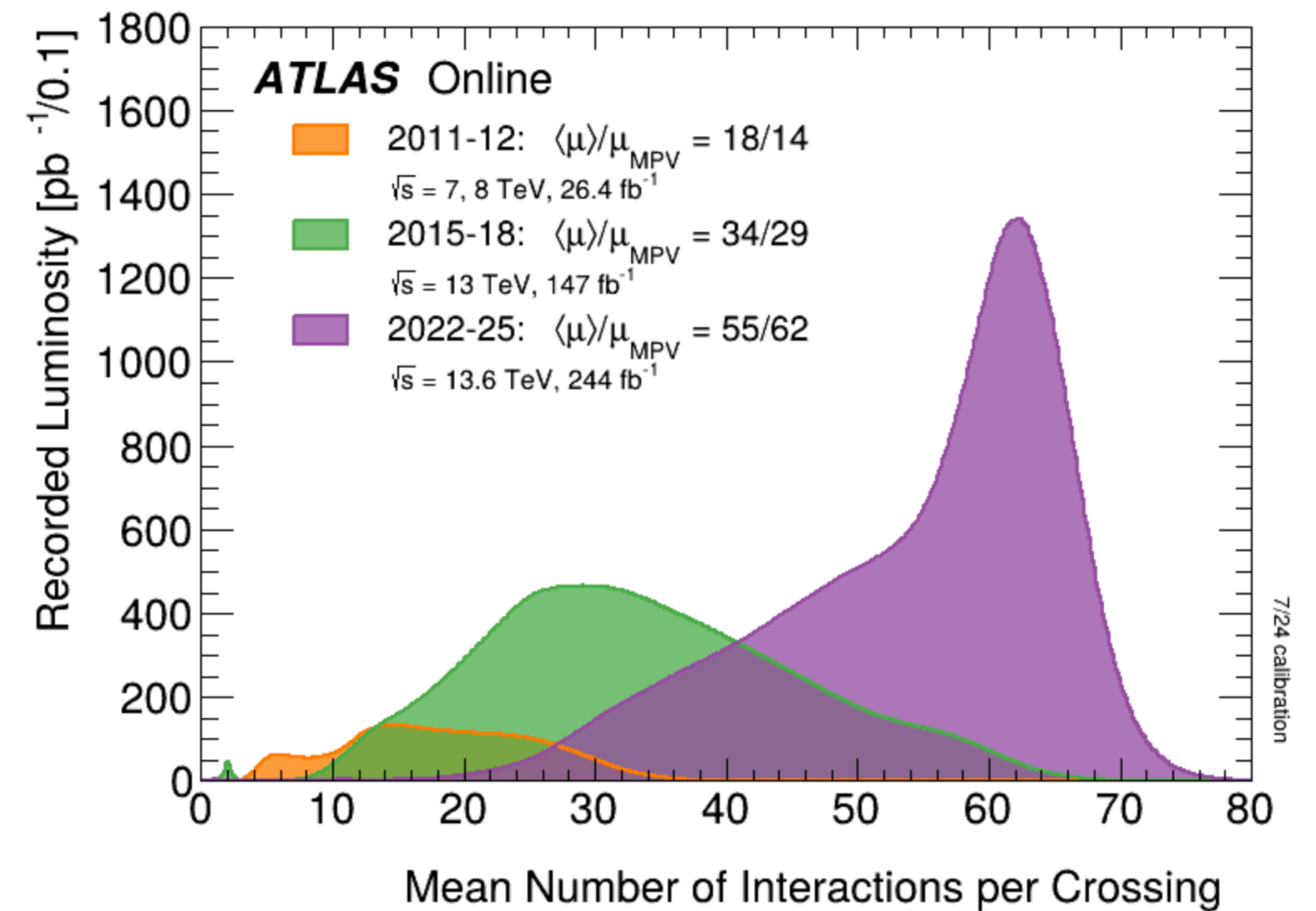
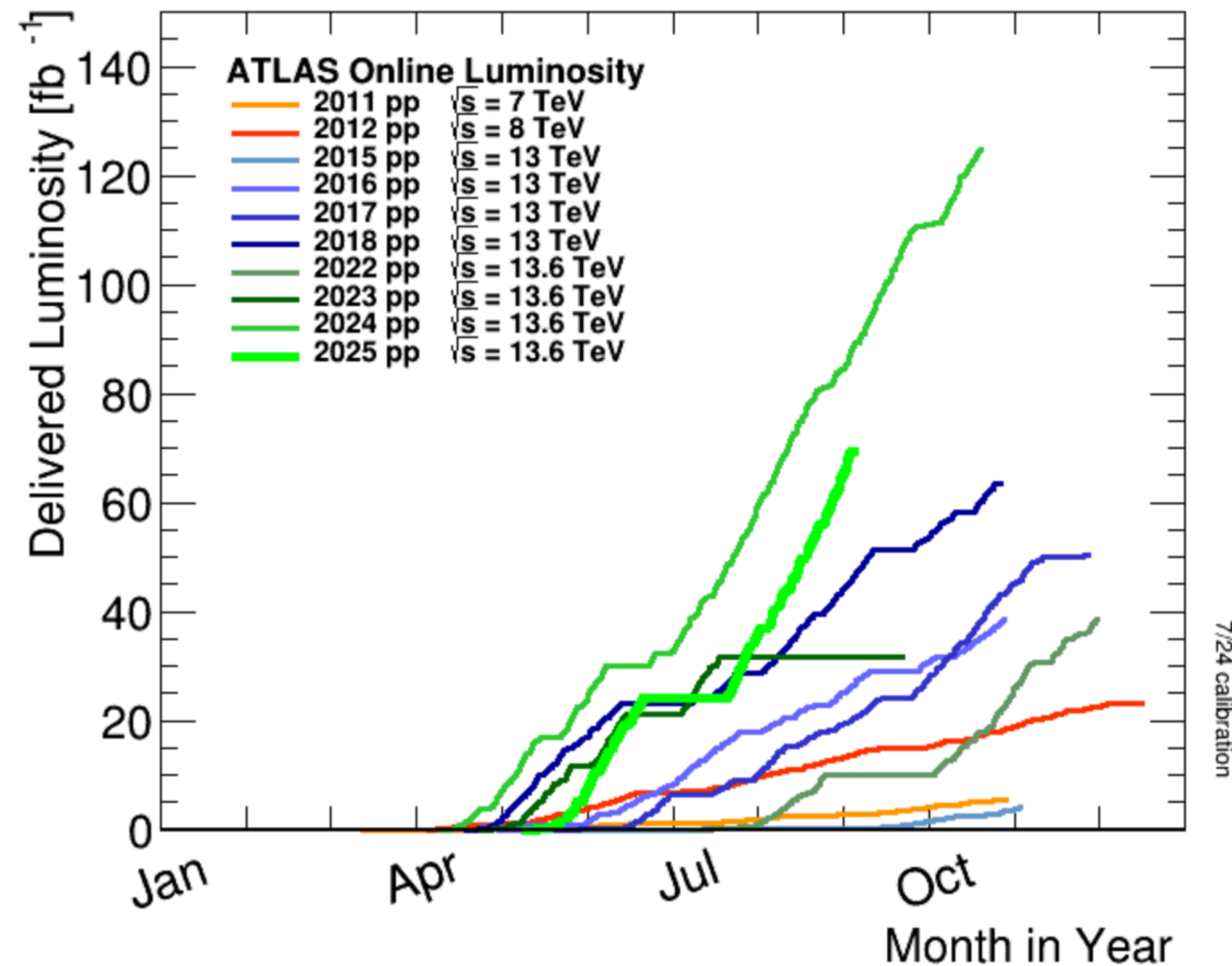
Unprecedented opportunities come with great challenges

- HL-LHC promises to provide 3000 fb⁻¹
- instantaneous luminosity a factor of 5-7 larger than LHC nominal value.
- Up to 200 p-p interactions per bunch crossing !

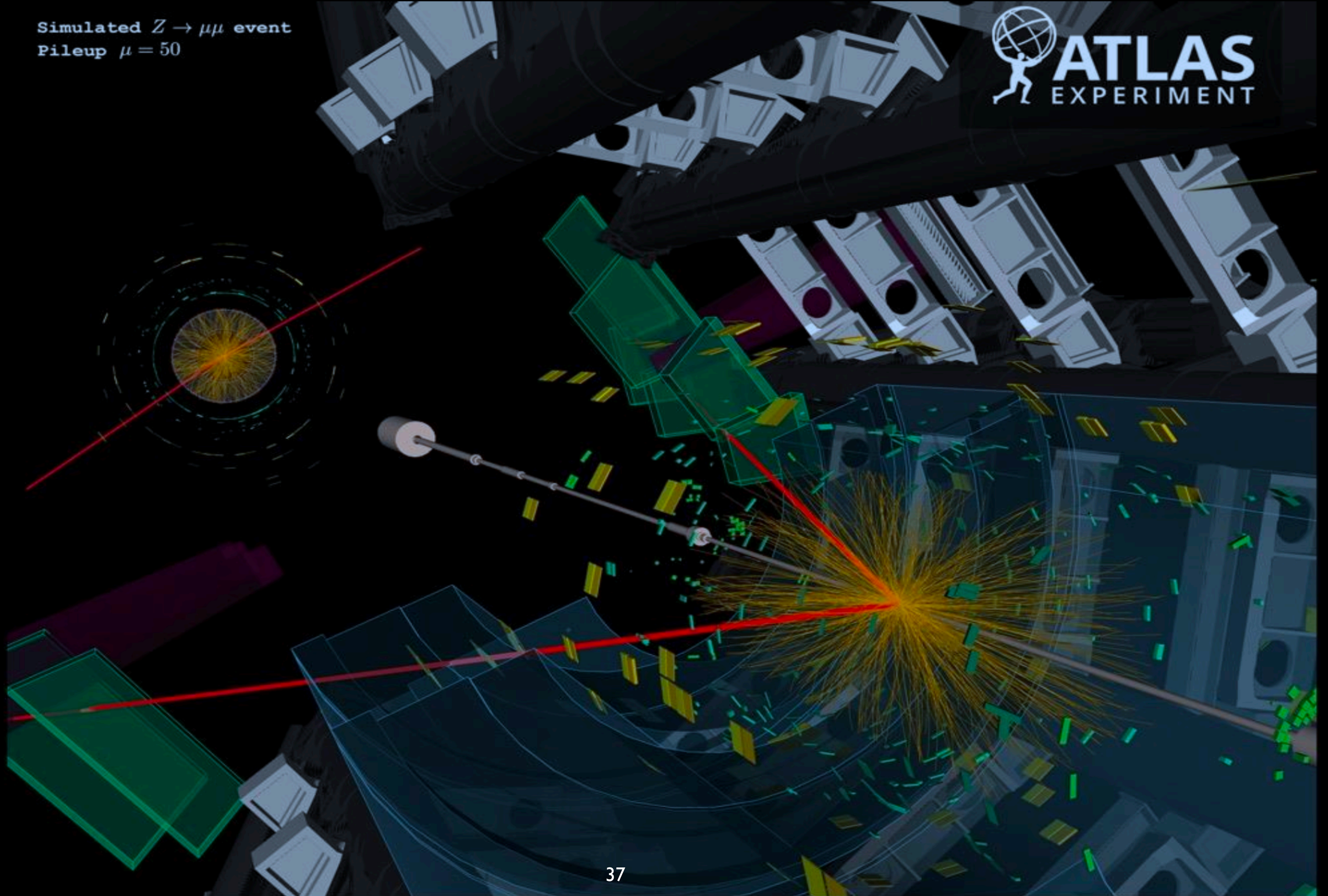
HL-LHC upgrade: The challenges

Luminosity-> delivered number of interactions
has never had such a steep rise!

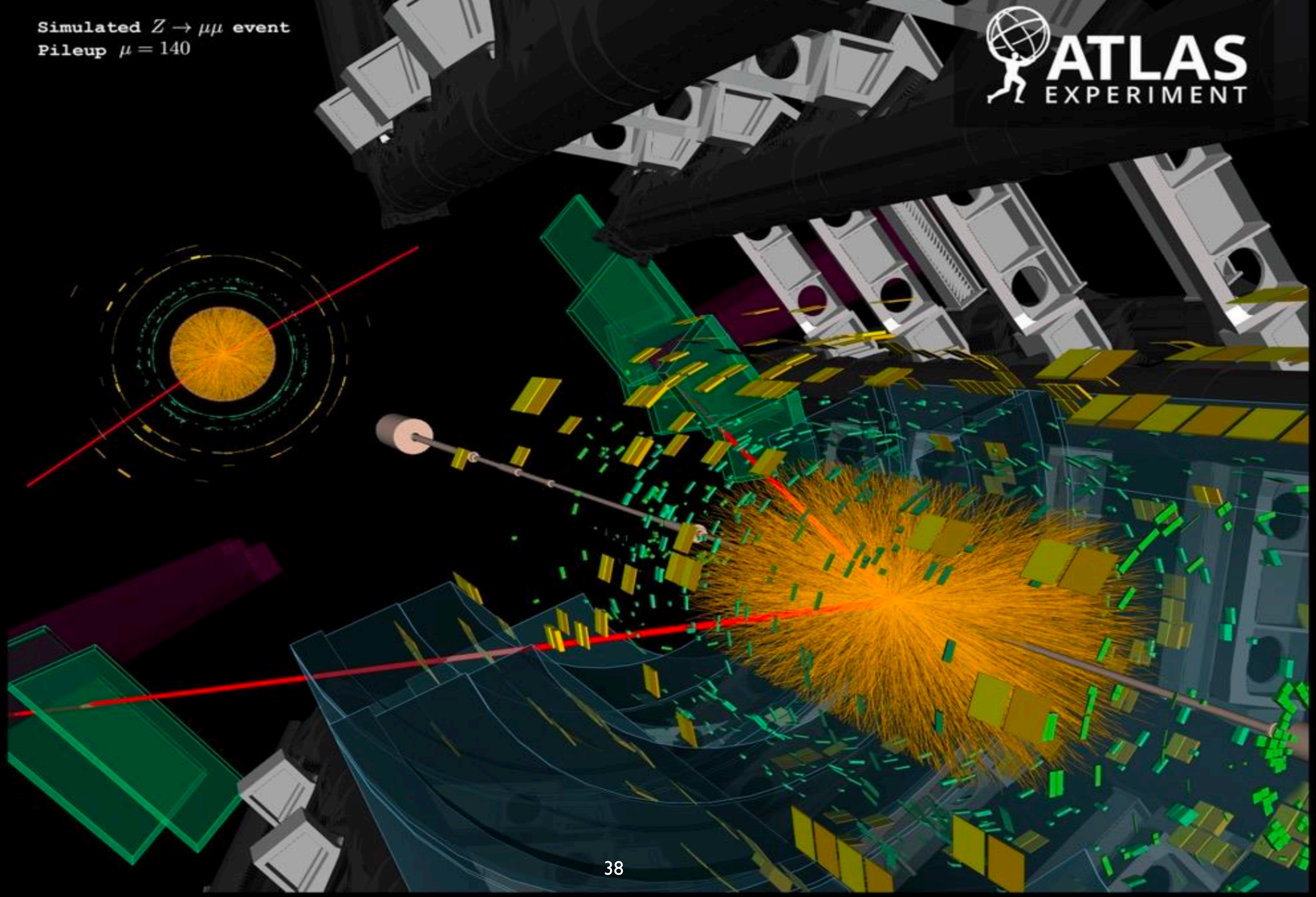
Luminosity->comes at the price of
increased number of interactions per bunch crossing
(that are a background). μ = number of interactions per
Crossing



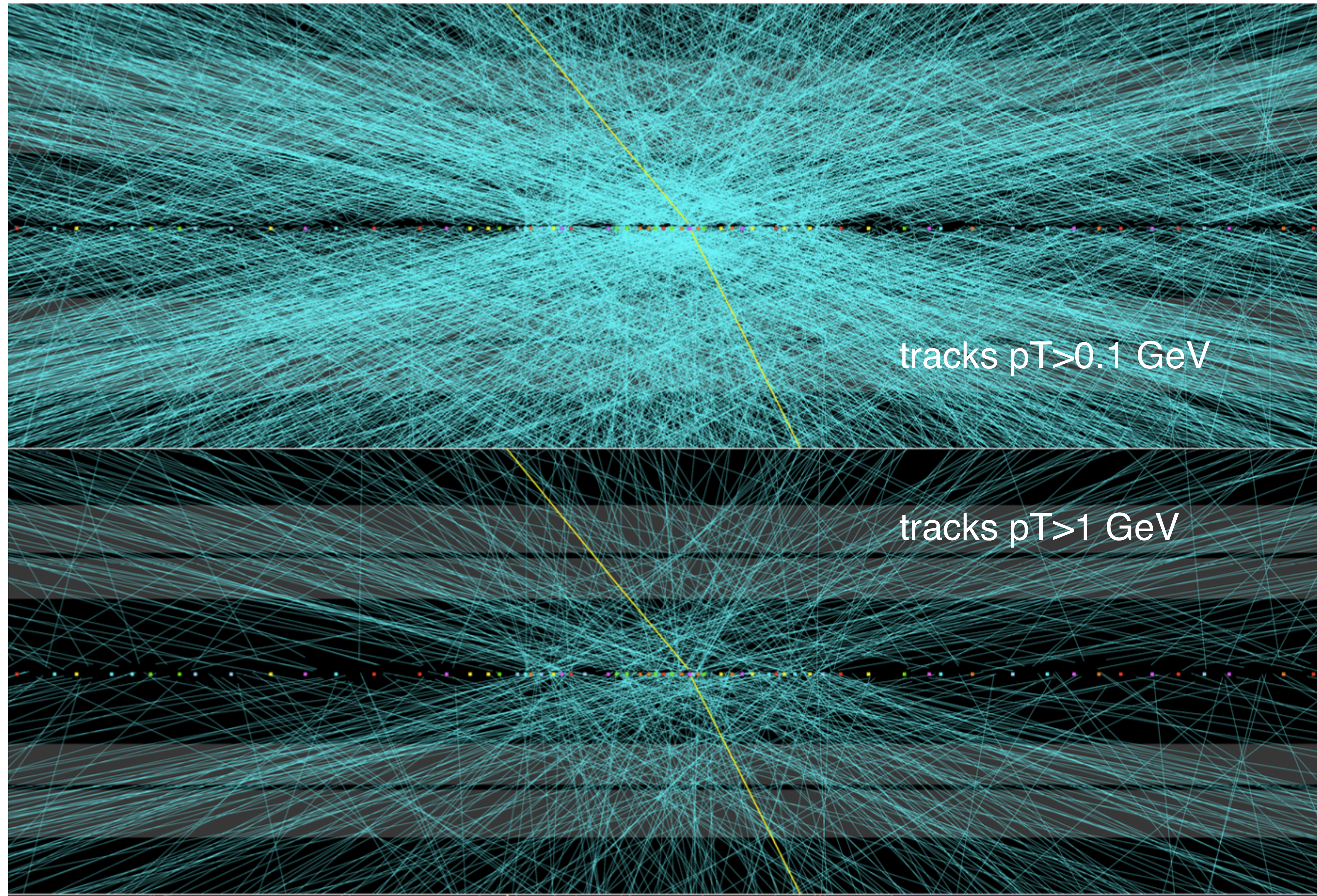
Simulated $Z \rightarrow \mu\mu$ event
Pileup $\mu = 50$



Simulated $Z \rightarrow \mu\mu$ event
Pileup $\mu = 140$



Pile-up



1) $Z \rightarrow \mu\mu$ event with 65
interaction vertices

HL-LHC upgrade

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

new and upgraded forward and luminosity detectors

Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz, Full-feature global trigger
Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

- LAr Calorimeter
- Tile Calorimeter
- Muon system

High Granularity Timing Detector (HGTD)

Forward region
($2.4 < |\eta| < 4.0$) to reduce
Pile-up

ITK: All silicon, up to $|\eta| = 4$

strongly augmented tracking acceptance,
50x present channels → to cope with high occupancy

Detectors
upgrades

CMS upgrade

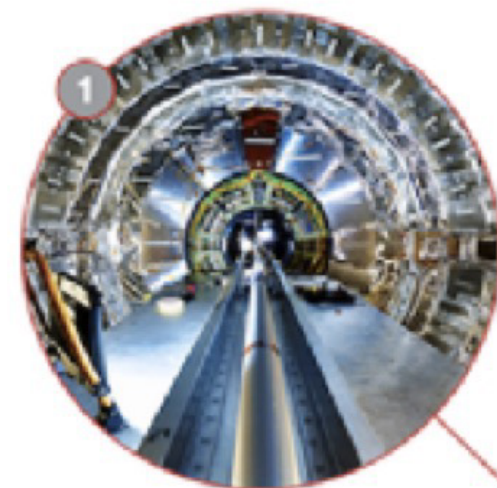
During Long Shutdown 2 (2018-2022), CMS completed the Phase 1 upgrades and started the Phase 2 upgrades. Some highlights :

- Phase 1: HCAL barrel readout, new barrel inner pixel (layer 1)
- Phase 2: First of GEM chambers installed, upgraded CSC electronics for HL-LHC, new beam pipe.
- GPU at HLT and transitioned to a hybrid CPU + GPU in trigger software (HLT nodes) : A Graphics Processing Unit (GPU) is a **programmable architecture**, offering large number of **parallel** independent streams of instructions, originally designed for image processing. **Accelerate online processing**

Detectors
upgrades

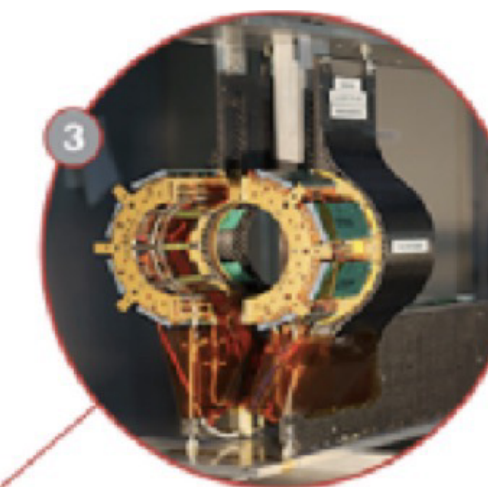
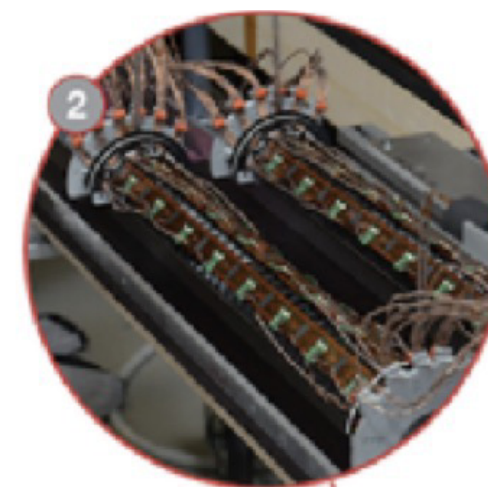
BEAM PIPE

Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.



PIXEL TRACKER

All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.



BRIL

New generation of detectors for monitoring LHC beam conditions and luminosity.



CATHODE STRIP CHAMBERS (CSC)

Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.

GAS ELECTRON MULTIPLIER (GEM) DETECTORS

An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.



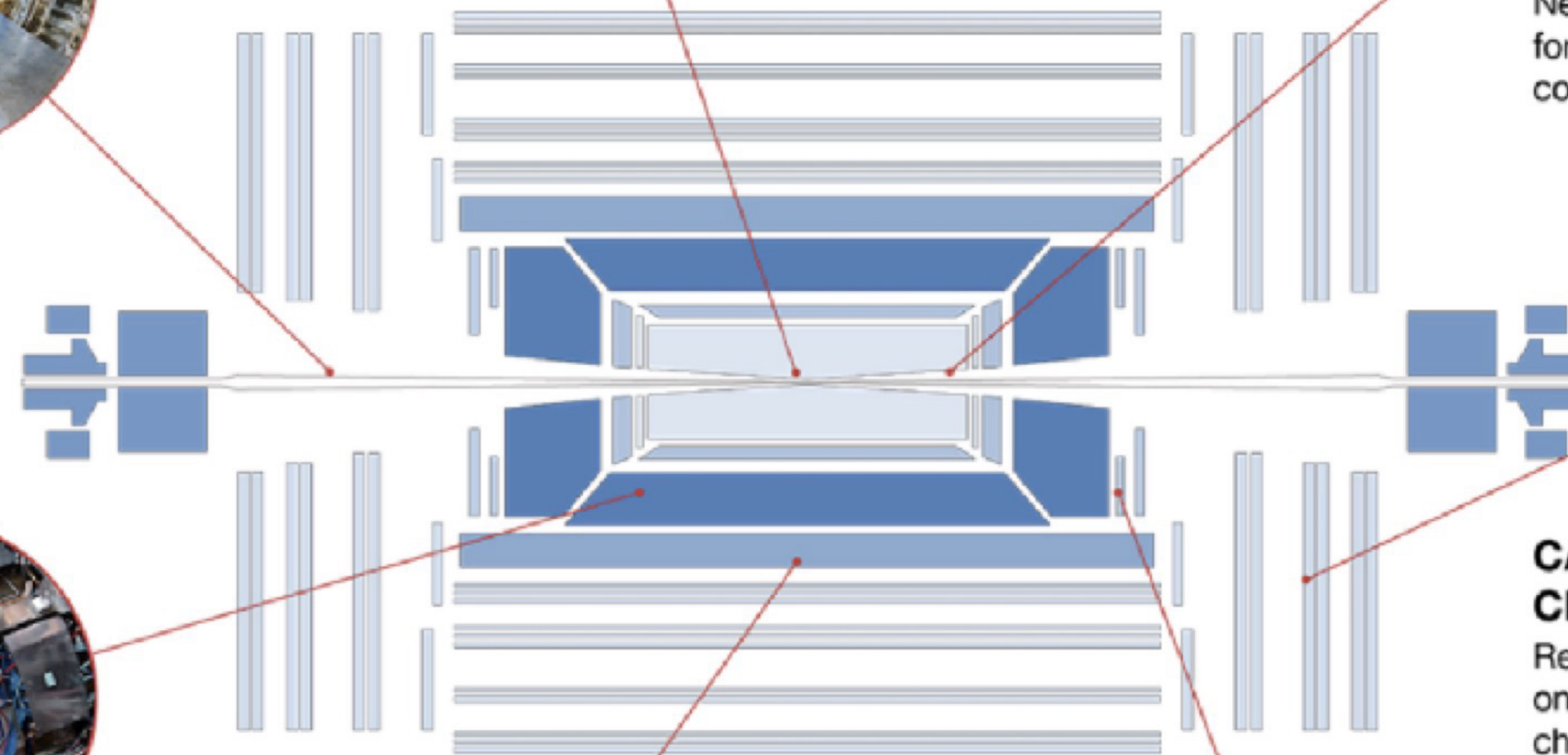
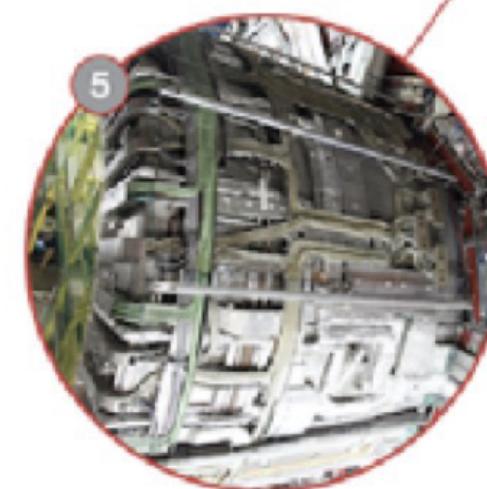
HADRON CALORIMETER

New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



SOLENOID MAGNET

New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.



Future Colliders after LHC

Future e⁺e⁻ Colliders in Asia

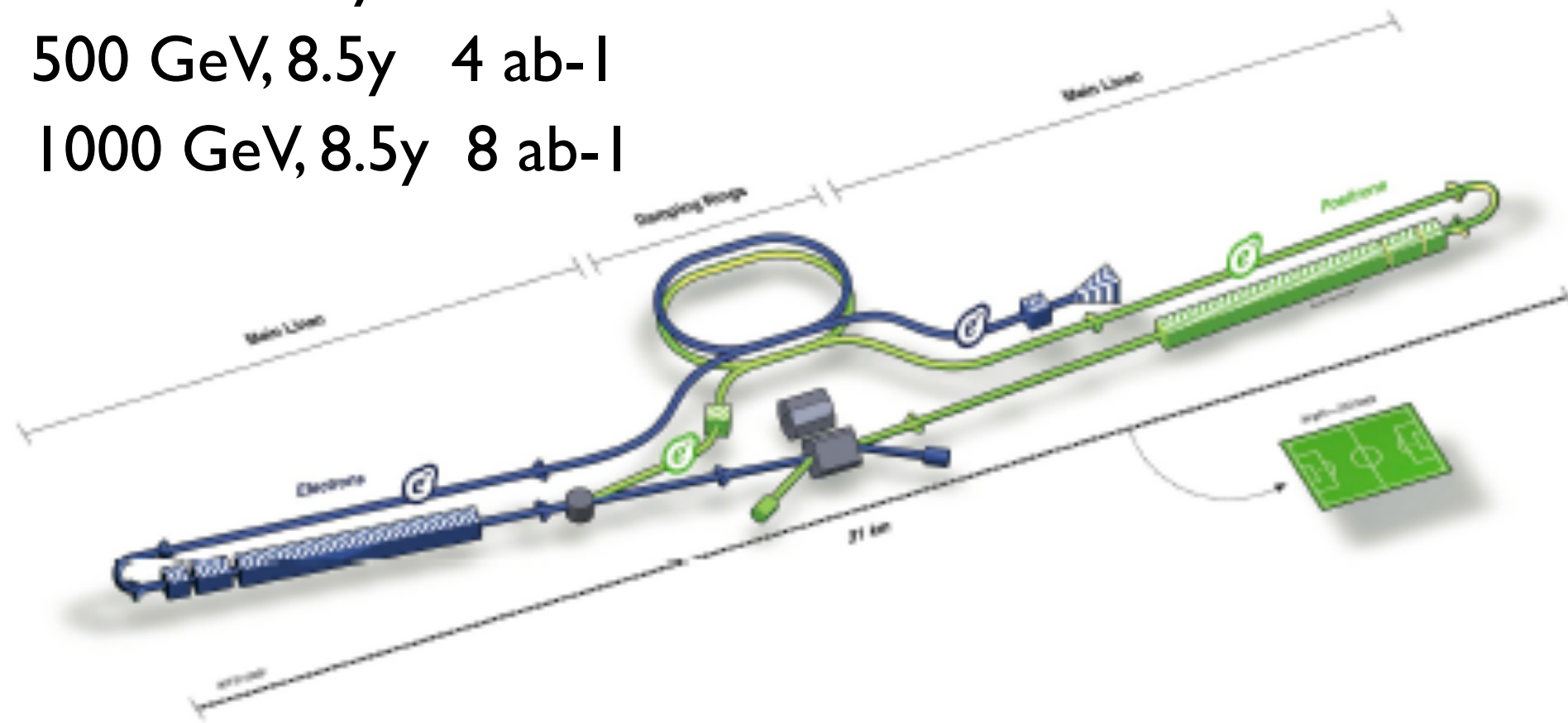
Linear e⁺e⁻

ILC Japan

250 GeV, 11y → 2 ab⁻¹

500 GeV, 8.5y 4 ab⁻¹

1000 GeV, 8.5y 8 ab⁻¹



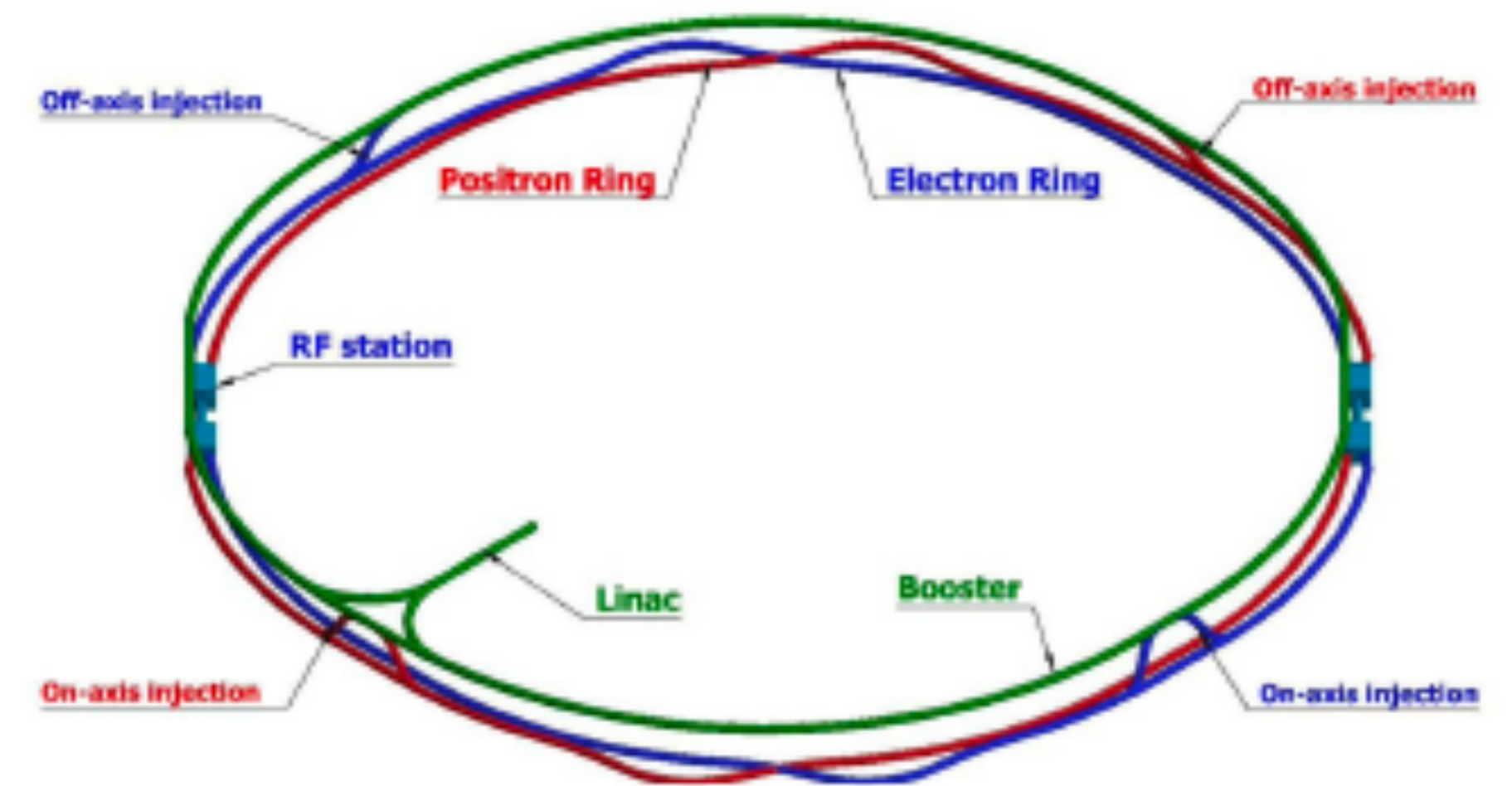
Circular e⁺e⁻

CEPC, China 100 Km tunnel

mZ, 2y → 16 ab⁻¹

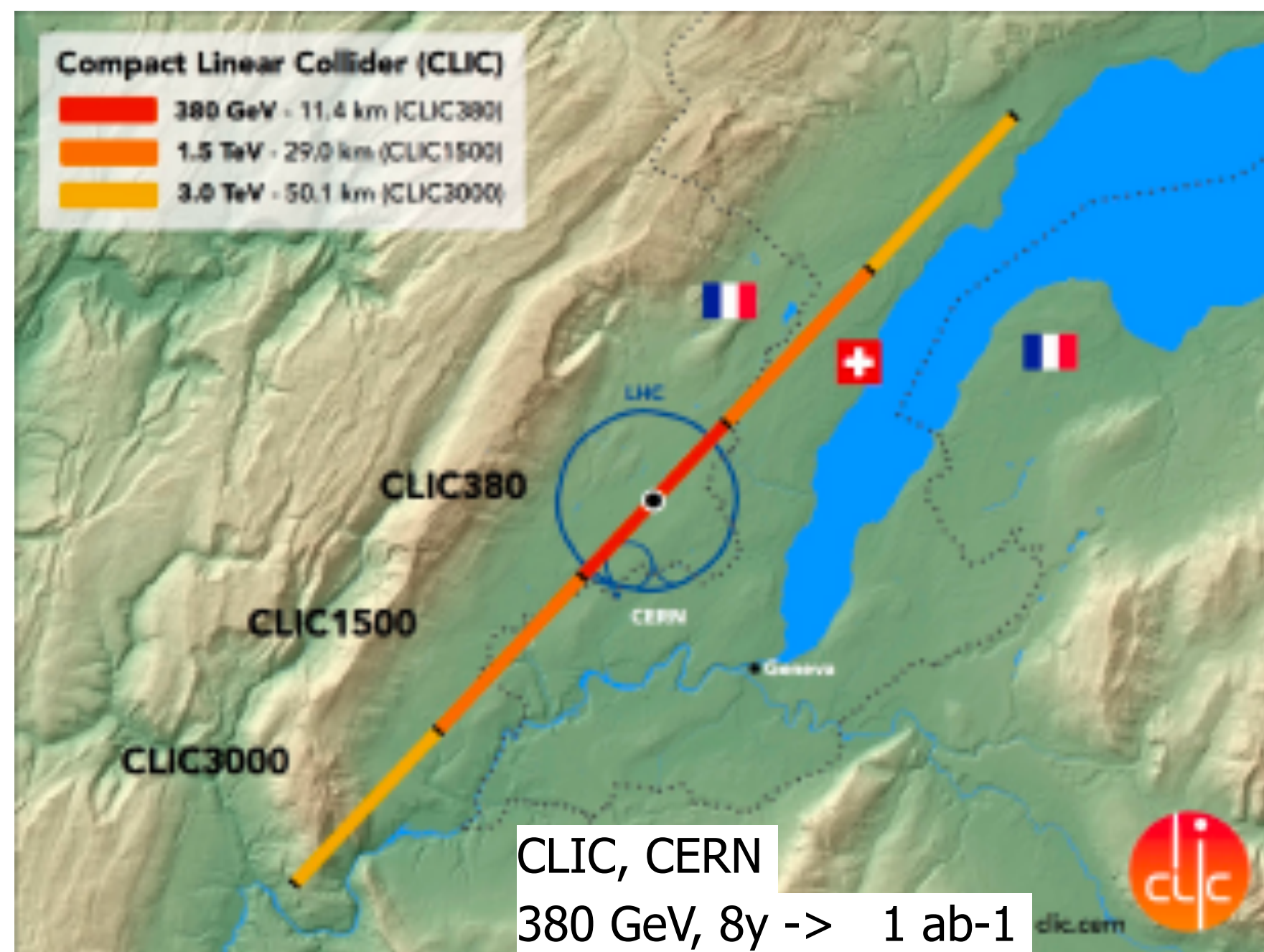
2 mW, 1y 2.6 ab⁻¹

240 GeV, 7y 5.6 ab⁻¹



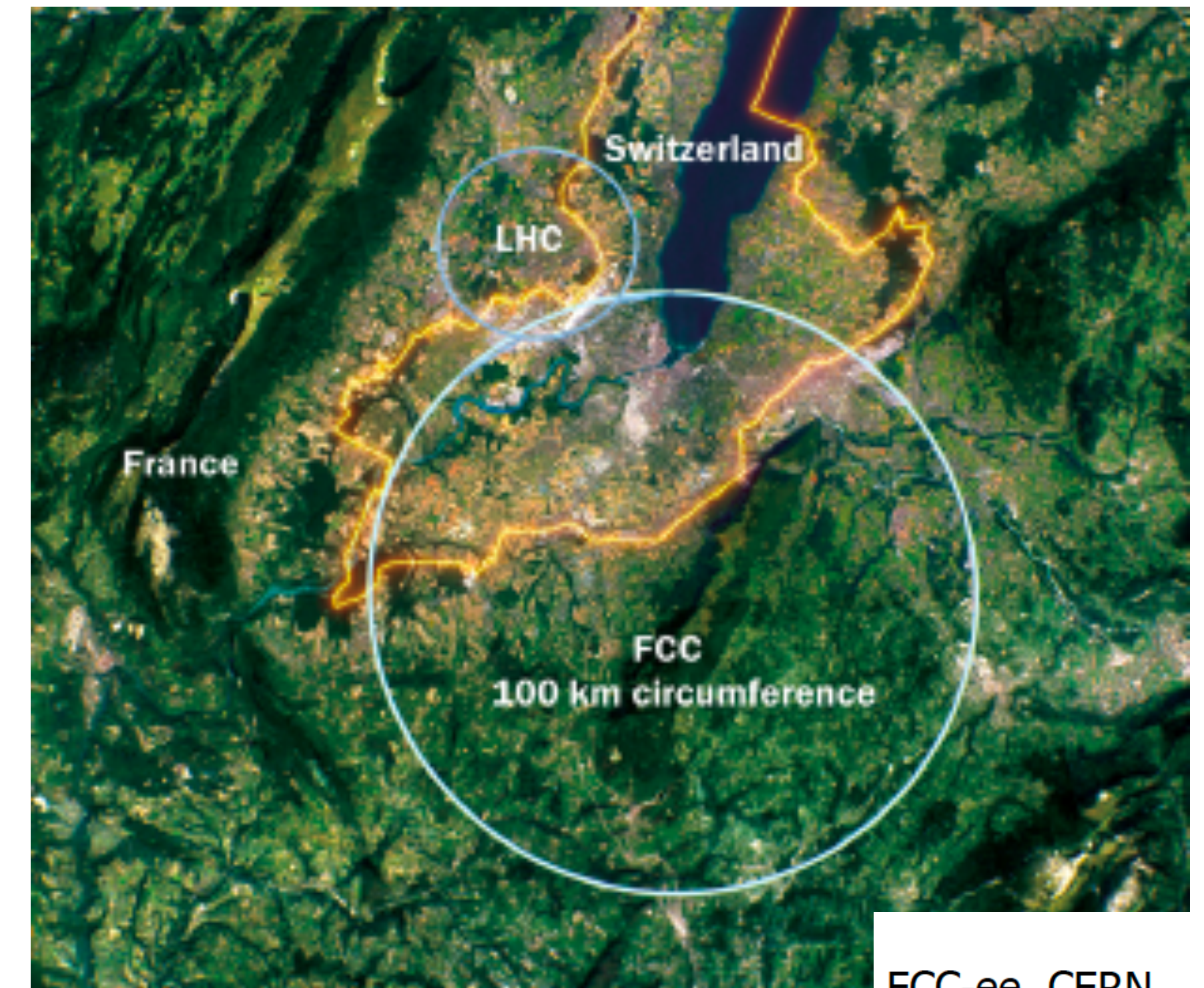
Future e⁺e⁻ Colliders in Europe

Linear e⁺e⁻: CLIC



380 GeV, 8y -> 1 ab⁻¹
1500 GeV, 7y 2.5 ab⁻¹
3000 GeV, 8.5y 5 ab⁻¹

Circular e⁺e⁻: FCC-ee



100 Km tunnel
in Geneva

FCC-ee, CERN
m_Z, 4y > 150 ab⁻¹
2 m_W, 1-2y 10 ab⁻¹
240 GeV, 3y 5 ab⁻¹
2 m_{top}, 5y 1.5 ab⁻¹

Can we reuse the LHC tunnel?

LEP3 e^+e^- machine in the
LHC tunnel

LEP3 (e^+e^- , circular, 91 – 230 GeV)



Contra: Lower centre of mass energy wrt to FCC-ee due to synchrotron radiation. Limited number of bunches (tens at most), constrained by RF power and beam–beam effects in the smaller ring.

Pros: Lower cost, Build new hadronic (p-p) machine in parallel.

Do we need an e^+e^- machine?

e^+e^- Could measure directly Higgs width and provide precision measurements as input to pp program that would increase the pp measurement precision

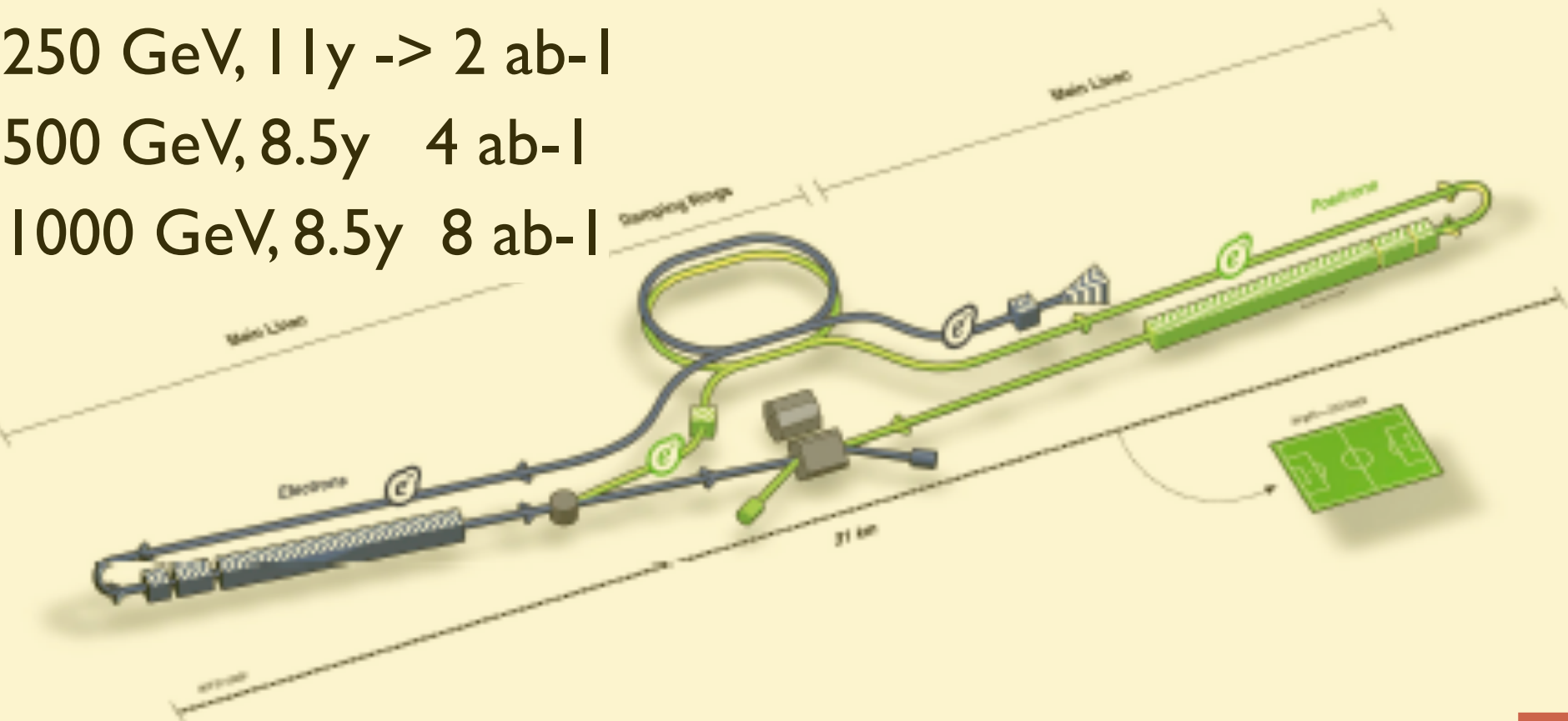
Future e+e- Colliders : Asia

ILC Japan

250 GeV, 11y -> 2 ab-1

500 GeV, 8.5y 4 ab-1

1000 GeV, 8.5y 8 ab-1

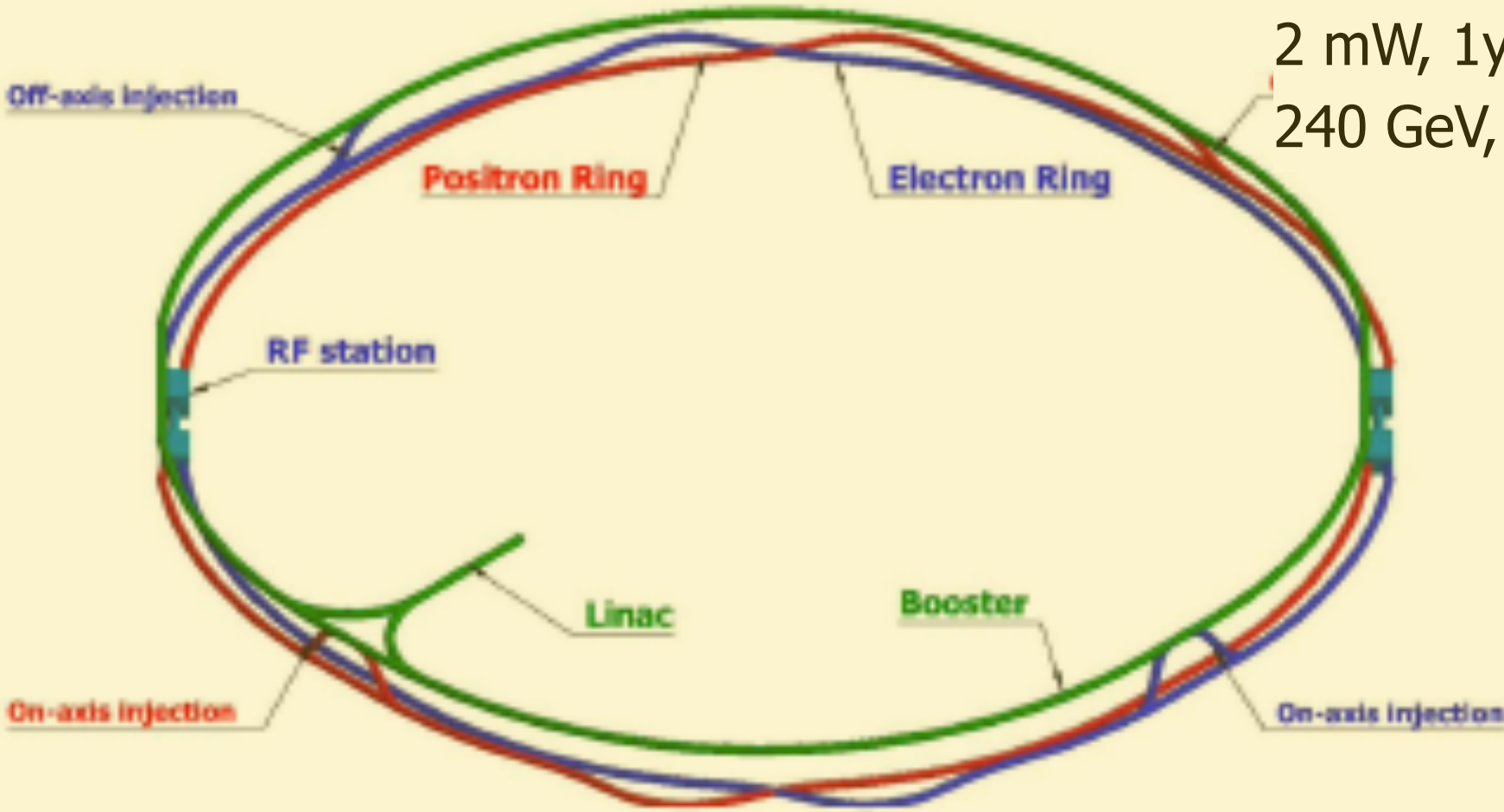


CEPC, China

mZ, 2y -> 16 ab-1

2 mW, 1y 2.6 ab-1

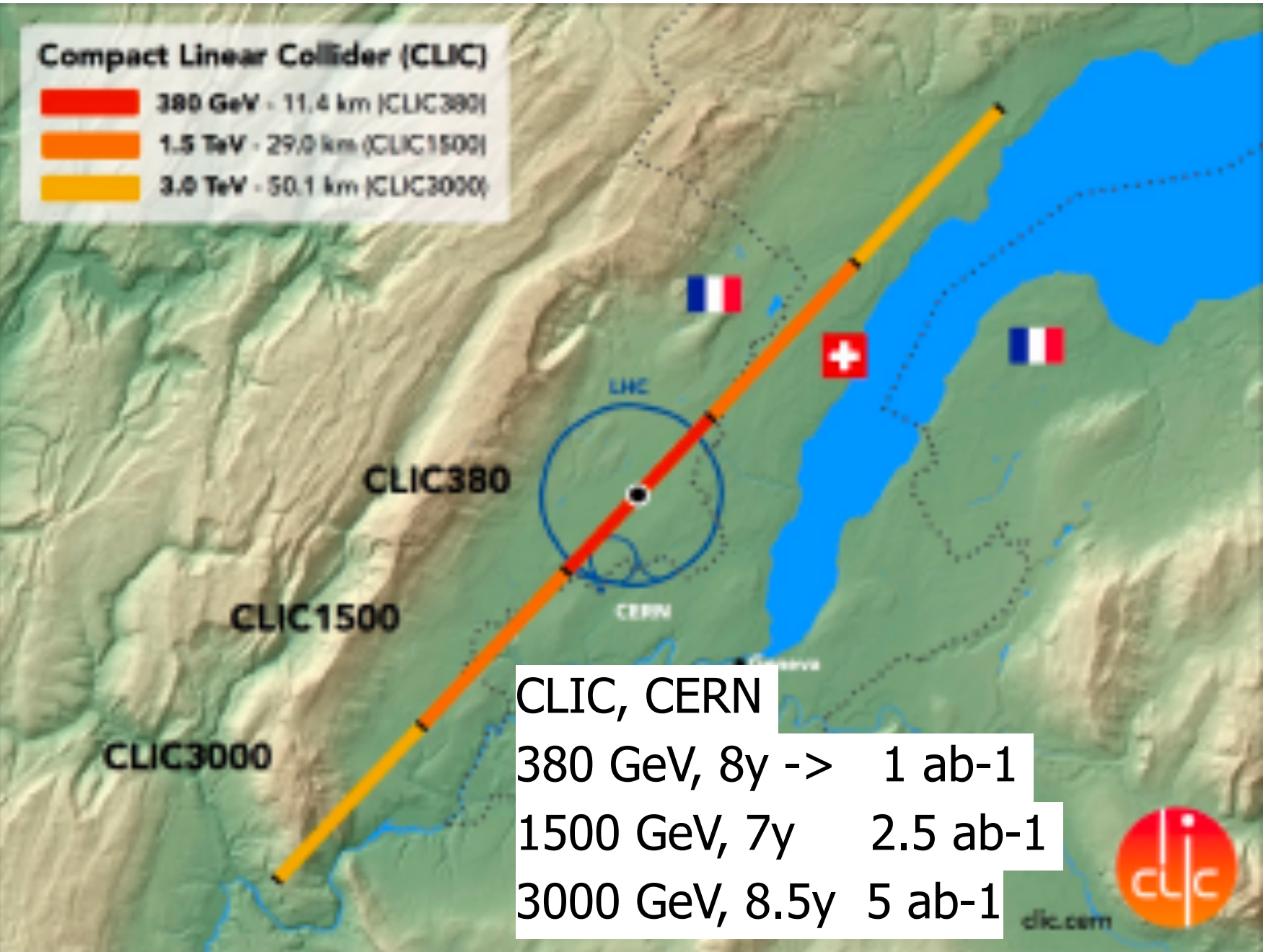
240 GeV, 7y 5.6 ab-1



Europe

LEP3 e+e- machine in the LHC tunnel

LEP3 (e+e-, circular, 91 – 230 GeV)



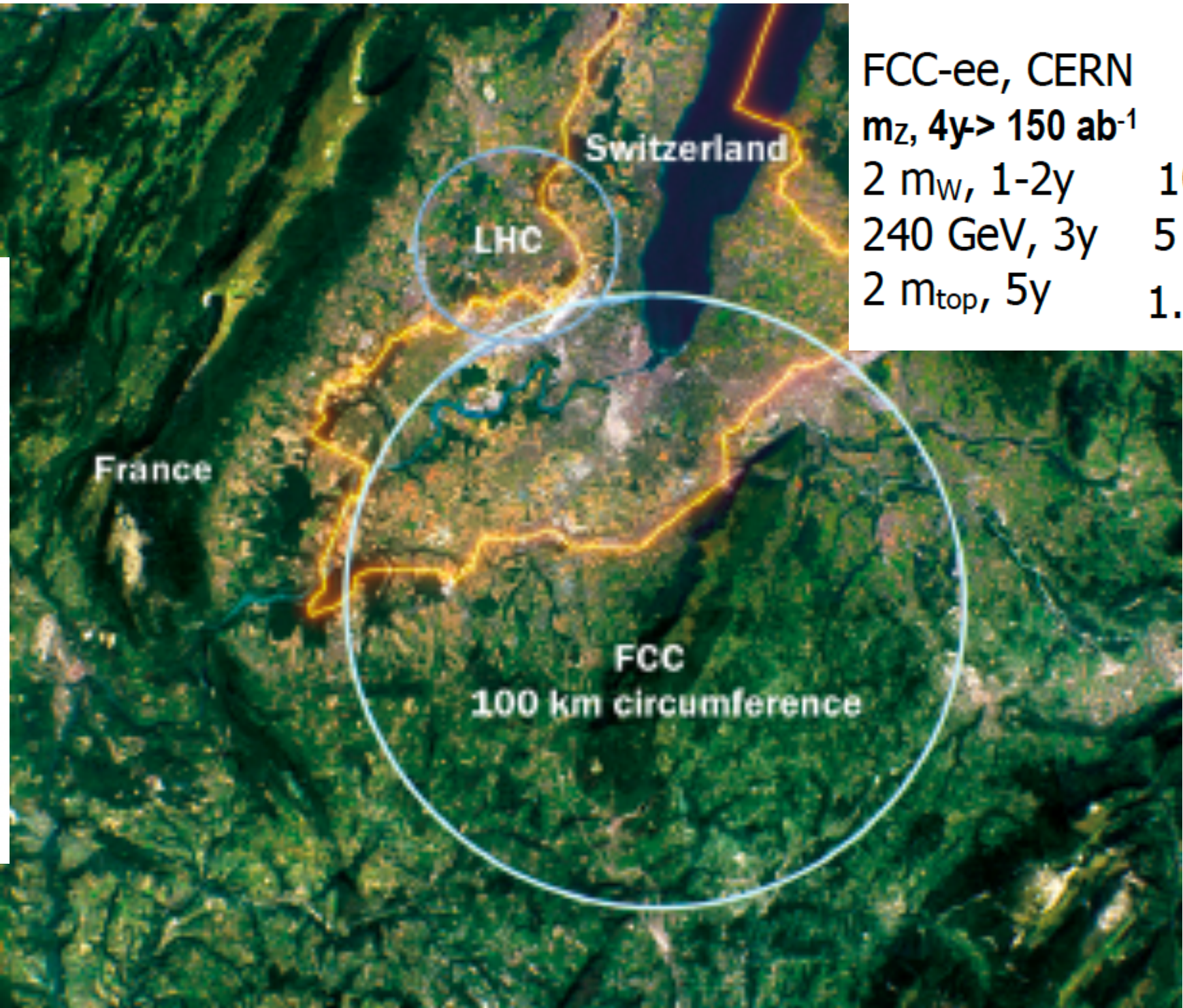
FCC-ee, CERN

mZ, 4y> 150 ab-1

2 mW, 1-2y 10 ab-1

240 GeV, 3y 5 ab-1

2 mtop, 5y 1.5 ab-1



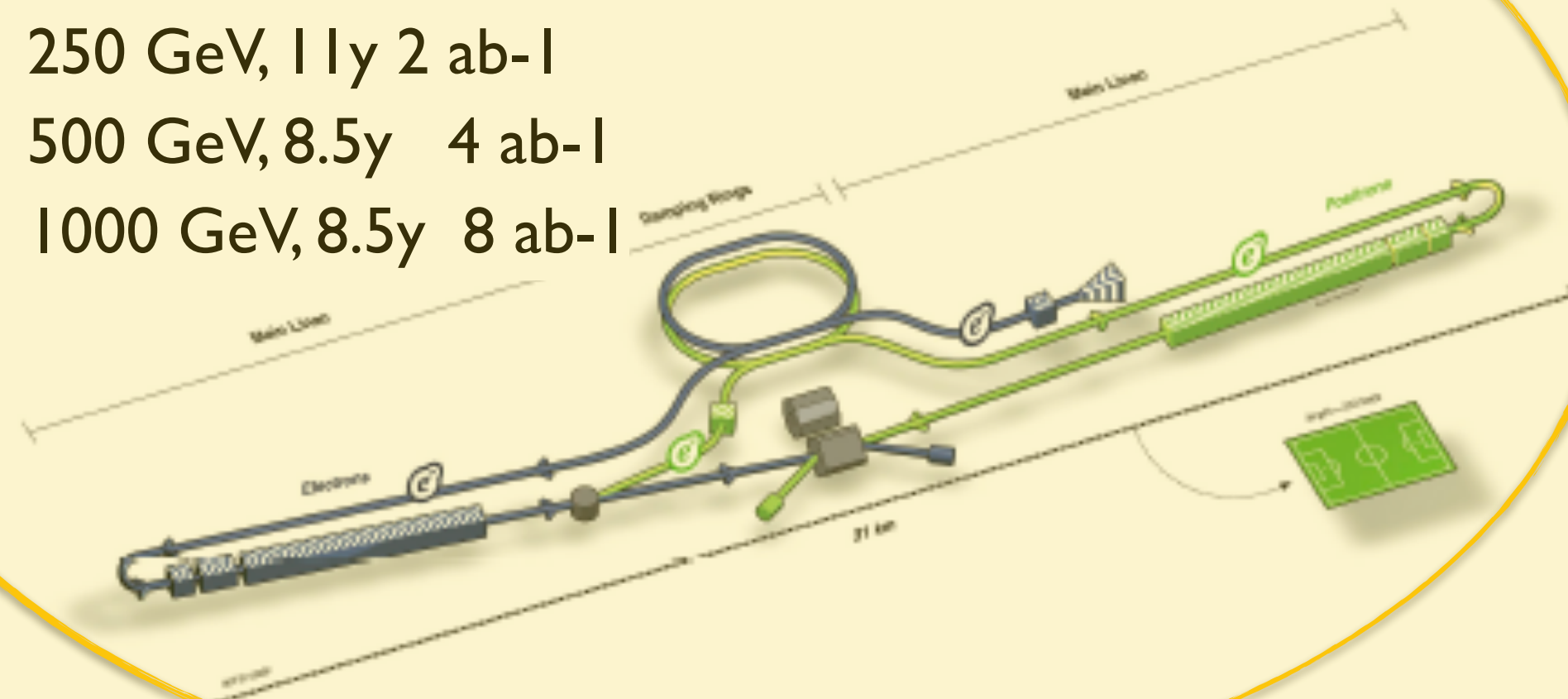
Hadron Colliders

ILC Japan

250 GeV, 11y 2 ab-1

500 GeV, 8.5y 4 ab-1

1000 GeV, 8.5y 8 ab-1



SPPC p-p machine
75 TeV intermediate
125 TeV goal -> ~20 ab-1



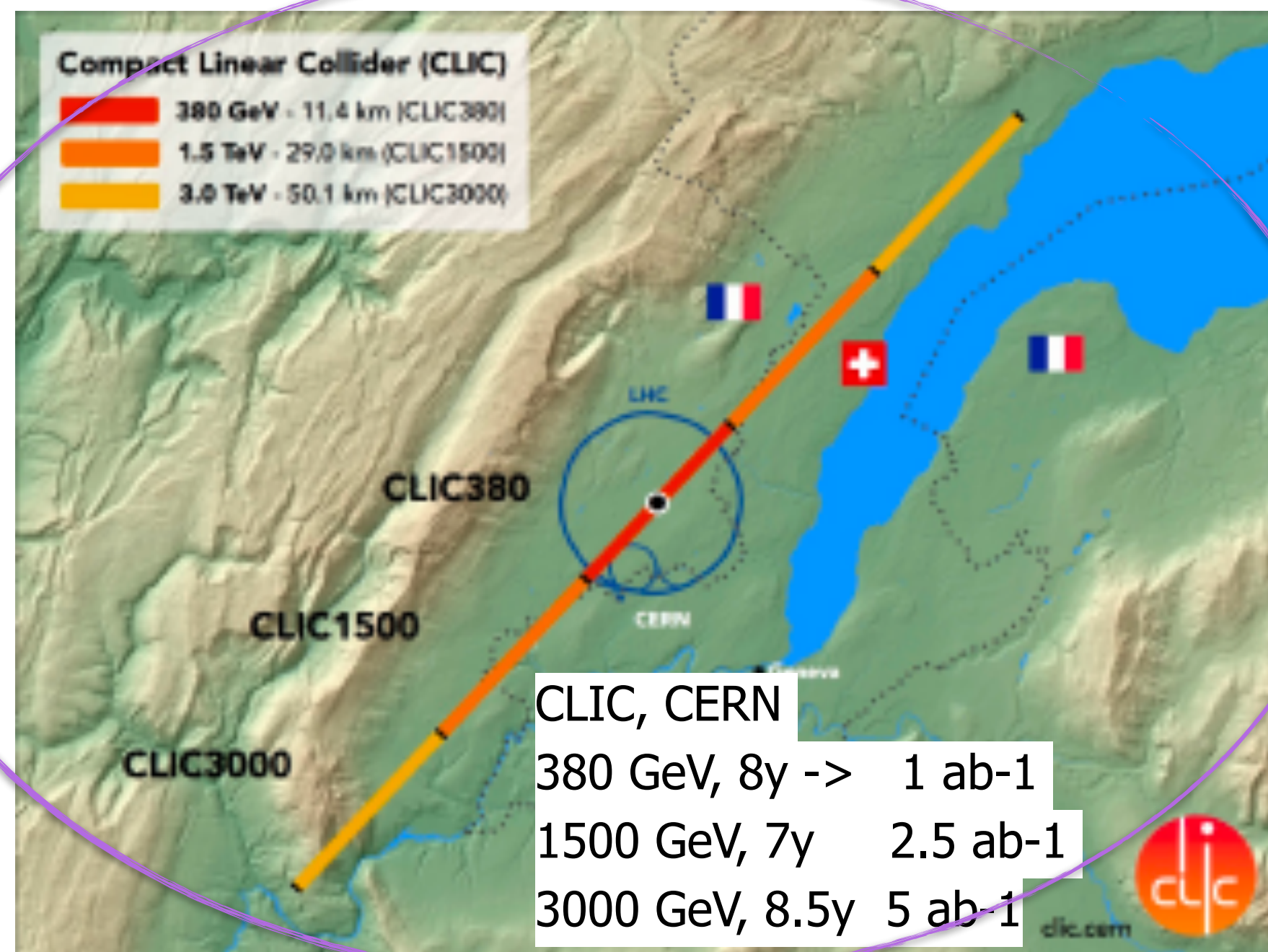
CEPC, China

mZ, 2y -> 16 ab-1

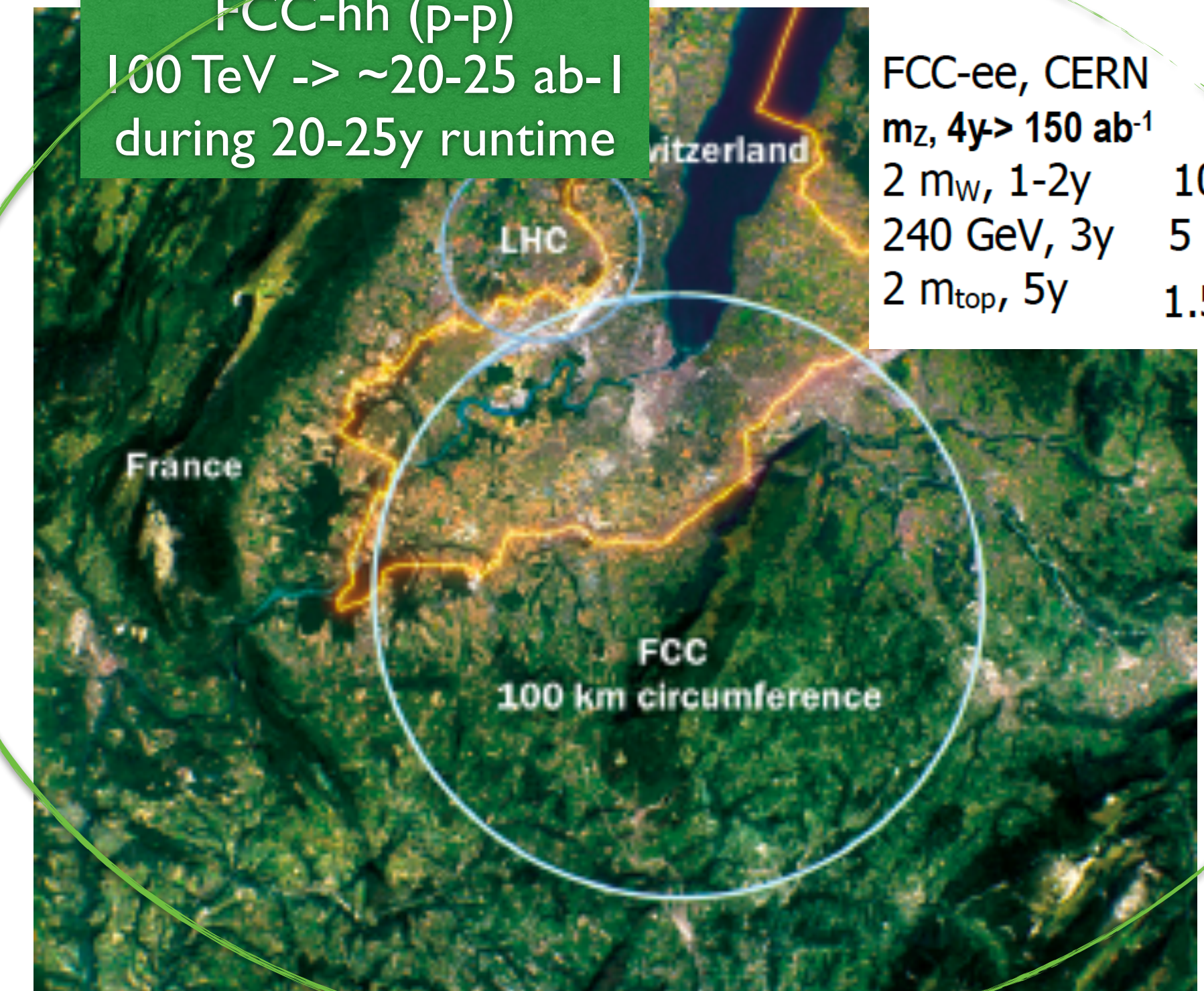
2 mW, 1y 2.6 ab-1

240 GeV, 7y 5.6 ab-1

p-p machines in the
100 km tunnels



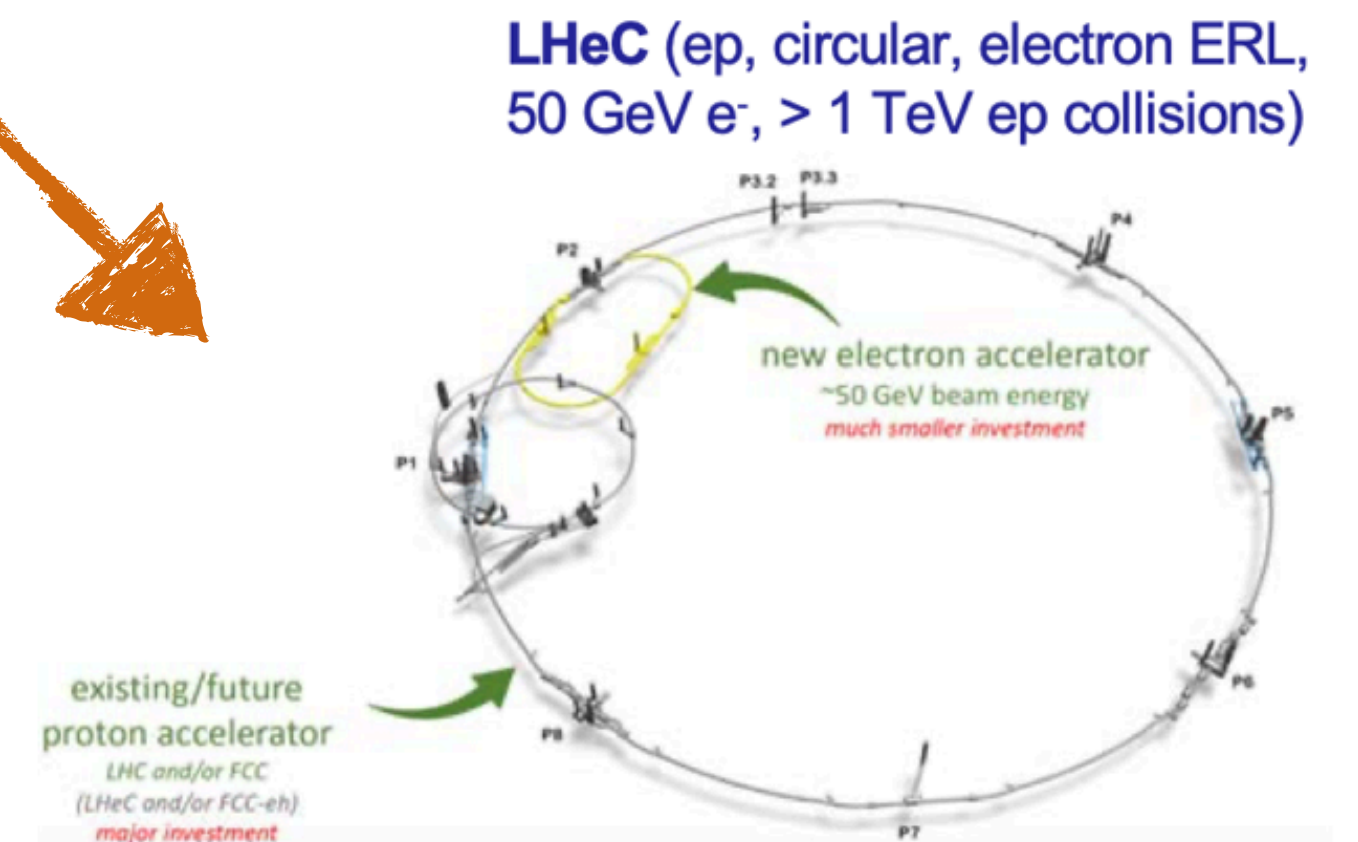
FCC-hh (p-p)
100 TeV -> ~20-25 ab-1
during 20-25y runtime



Do we need an e-p machine?

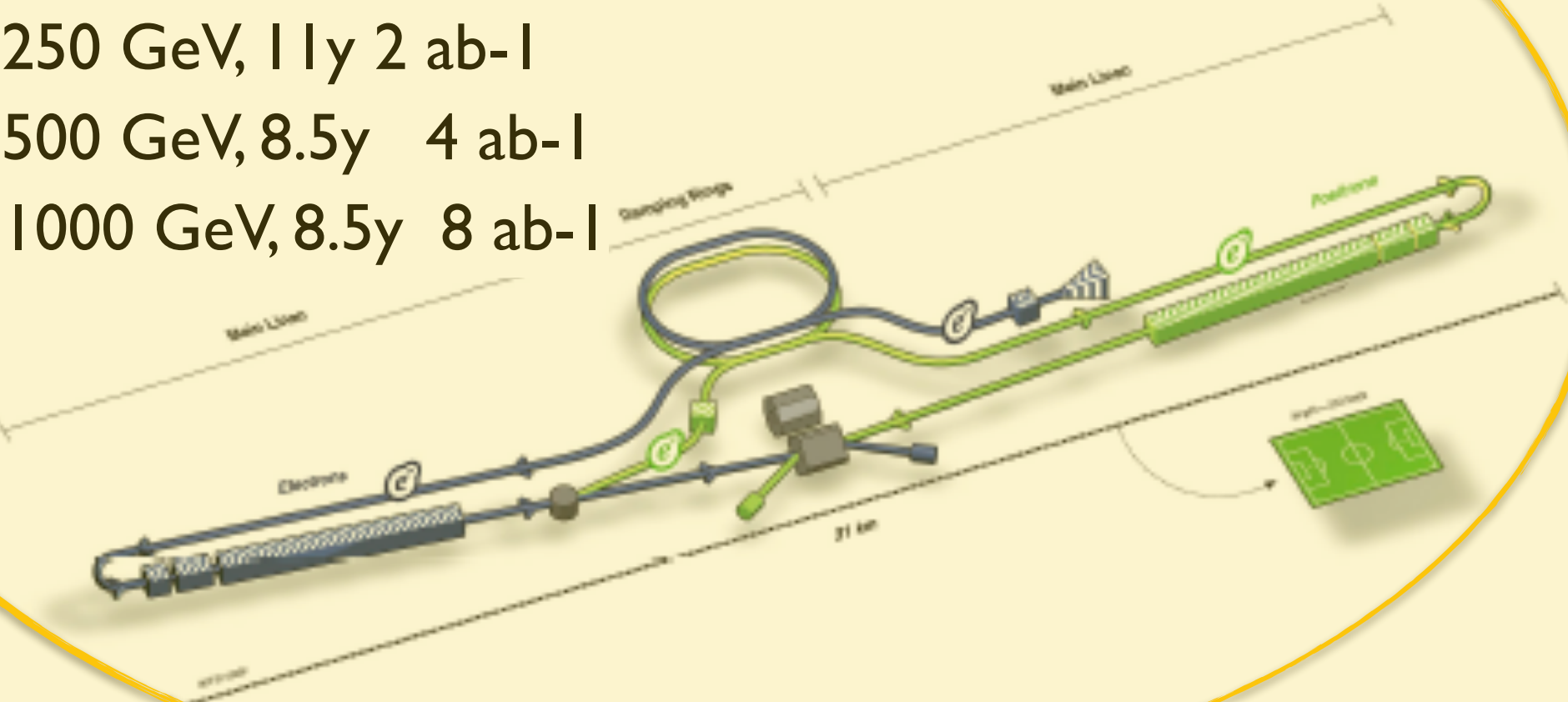
an electron proton accelerator could also be very useful as it would provide measurements of the PDFs of the proton, that are going to make errors smaller at a proton proton collider. There is an option called LHe-c, that could run in parallel to LHC, using its tunnel

e-p machine: LHeC 0.2-1.3 TeV
run together w/ HL-LHC
($\approx$ Run 5) $\rightarrow$ 1 ab⁻¹

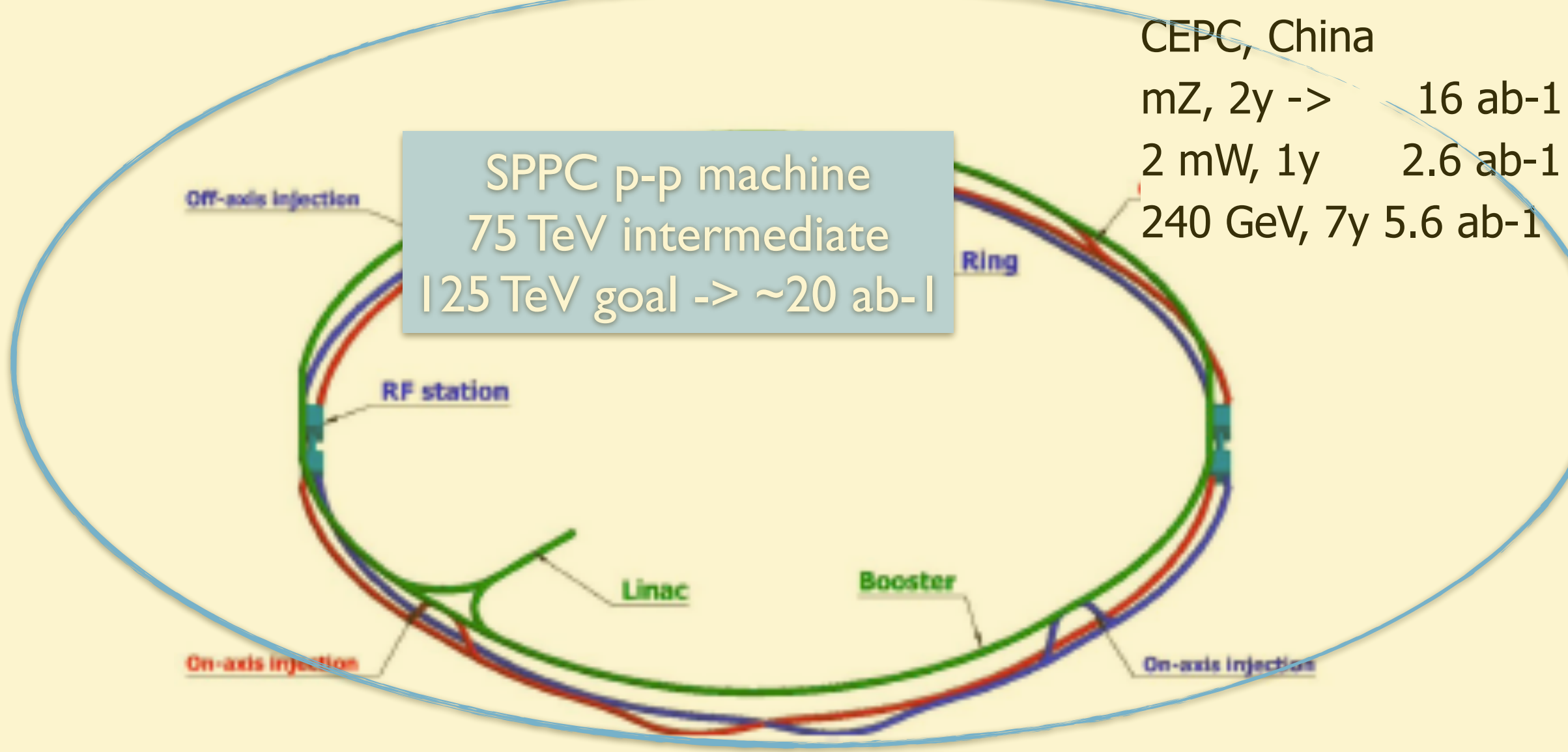


.....Colliders

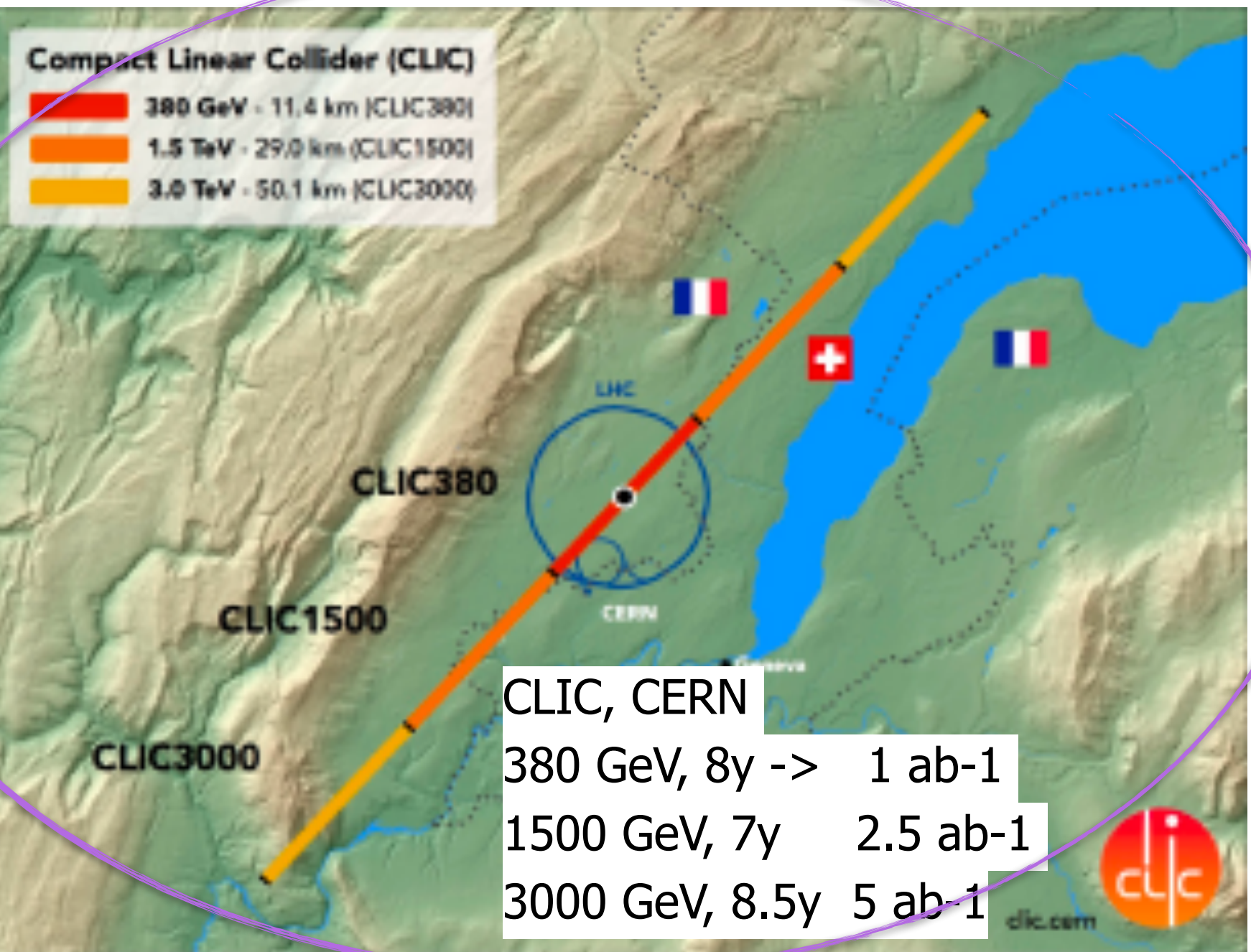
ILC Japan
250 GeV, 11y 2 ab-1
500 GeV, 8.5y 4 ab-1
1000 GeV, 8.5y 8 ab-1



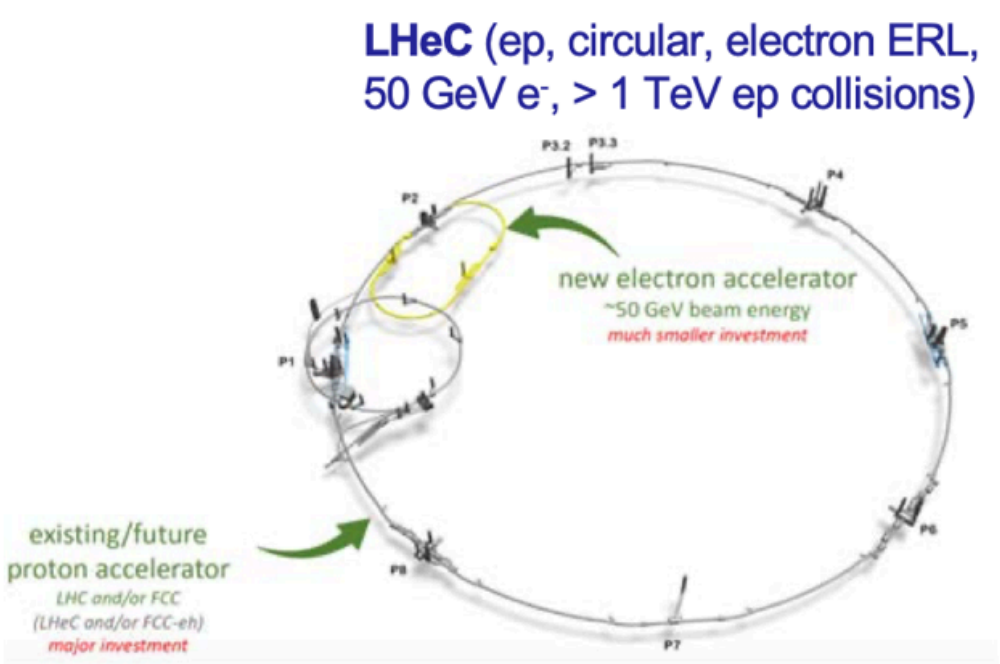
SPPC p-p machine
75 TeV intermediate
125 TeV goal -> ~20 ab-1



CEPC, China
mZ, 2y -> 16 ab-1
2 mW, 1y 2.6 ab-1
240 GeV, 7y 5.6 ab-1

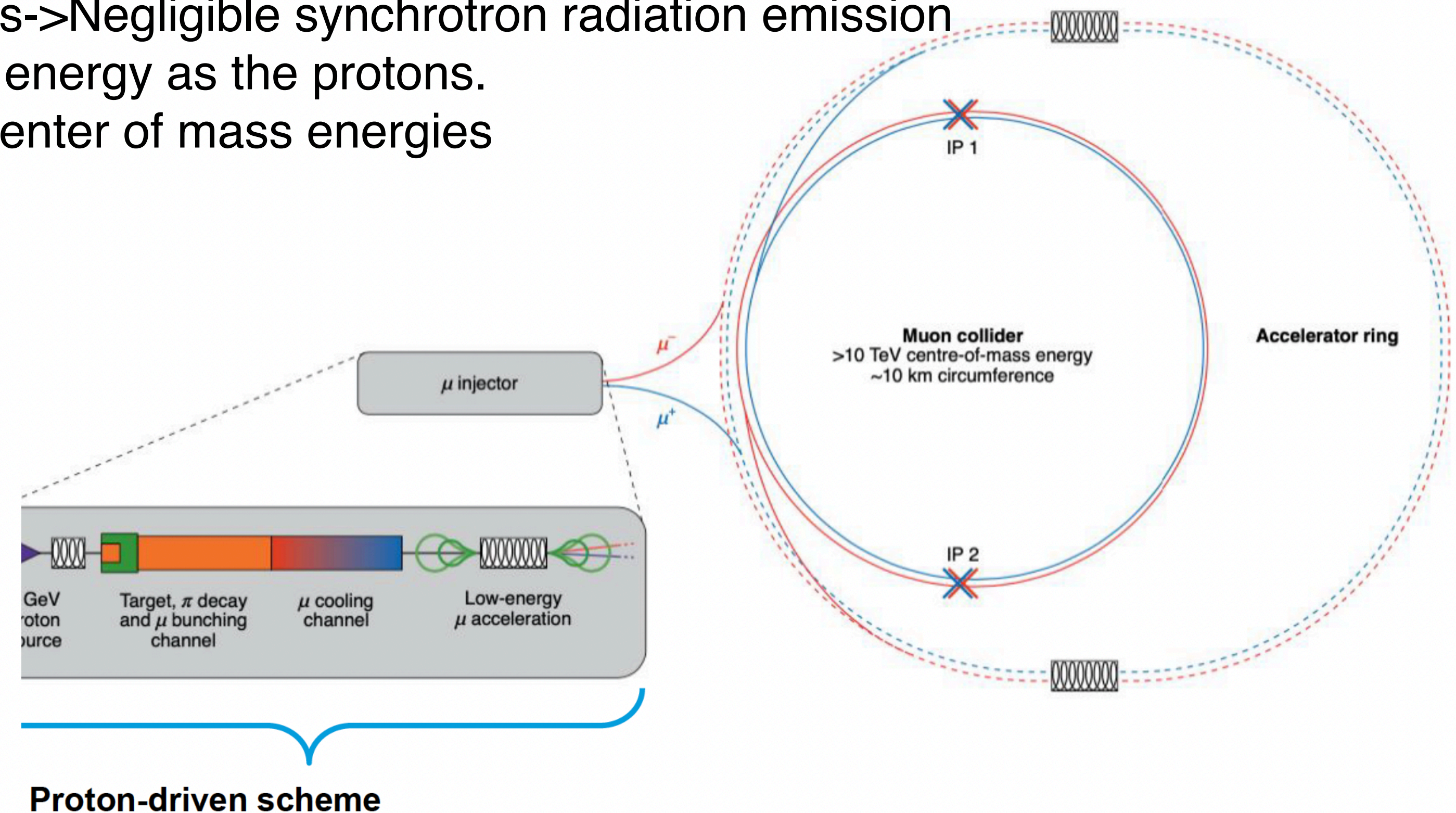
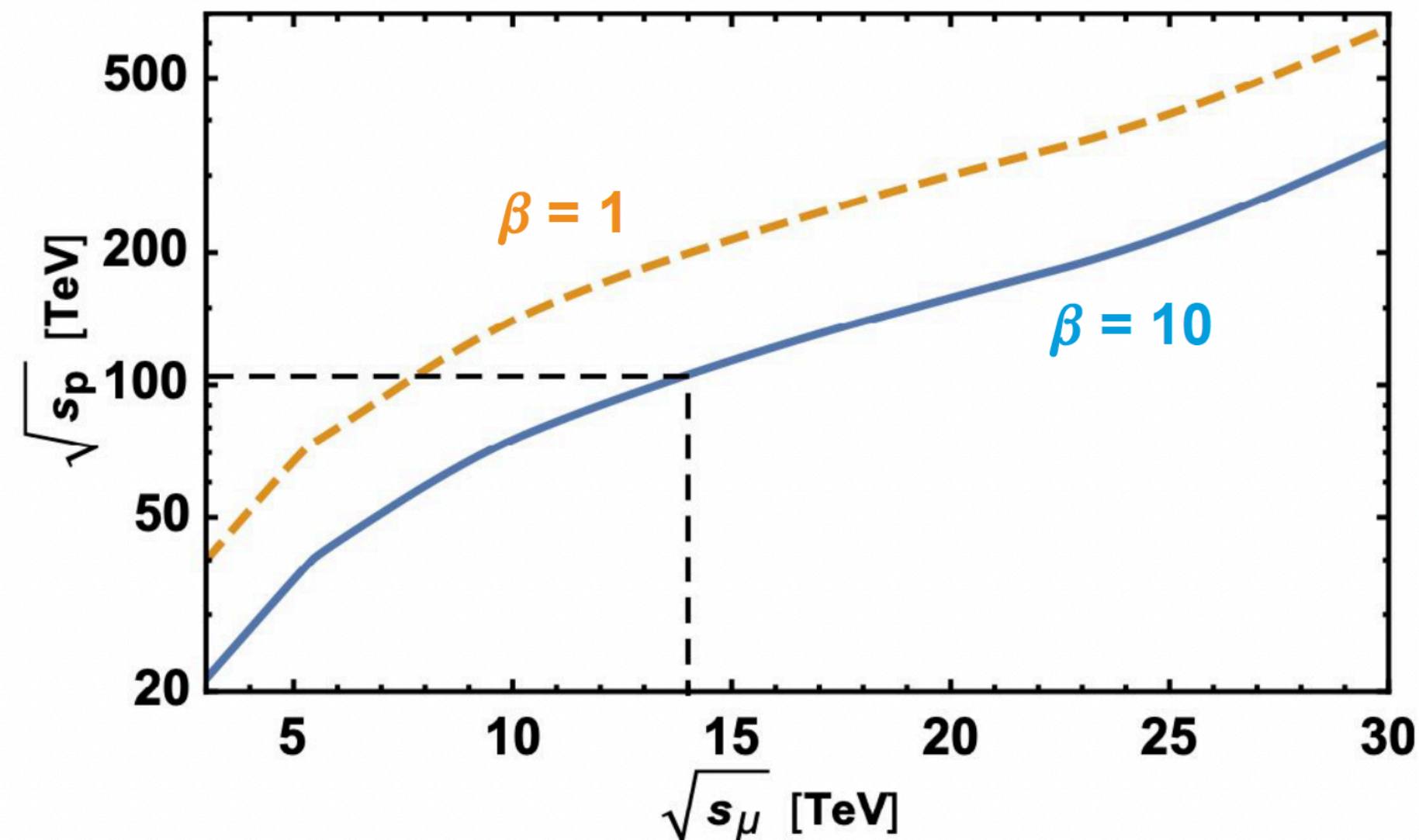


e-p machine: LHeC 0.2-1.3 TeV
run together w/ HL-LHC
(≈ Run 5) -> 1 ab-1



Do we need an $\mu^+\mu^-$ machine?

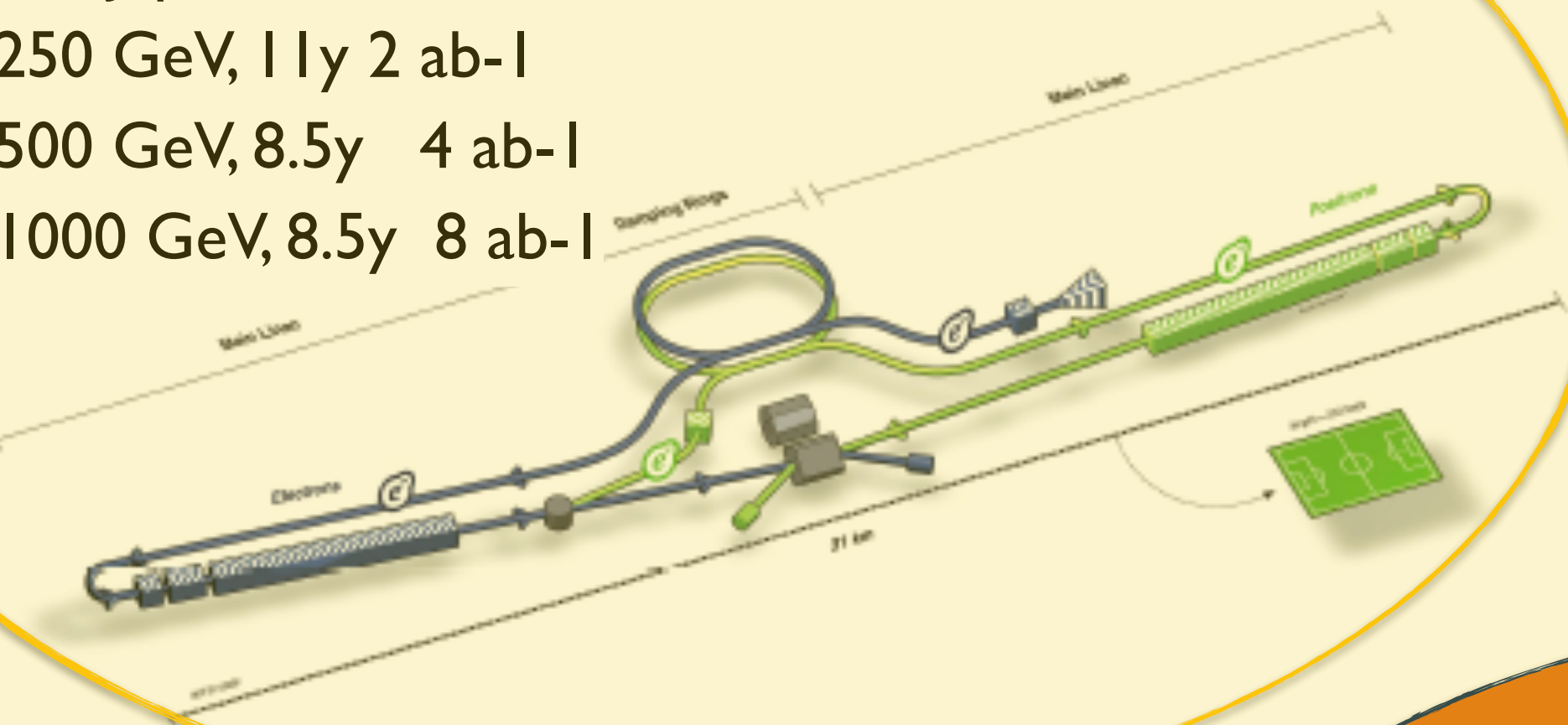
A muon Collider, is a new adventure. It combines the advantages of a hadron machine and a lepton machine. The muon mass is 207 times the electron mass $\rightarrow$ Negligible synchrotron radiation emission. It doesn't have PDFs (substructure) and loss of energy as the protons. It can probe precision physics at much lower center of mass energies.



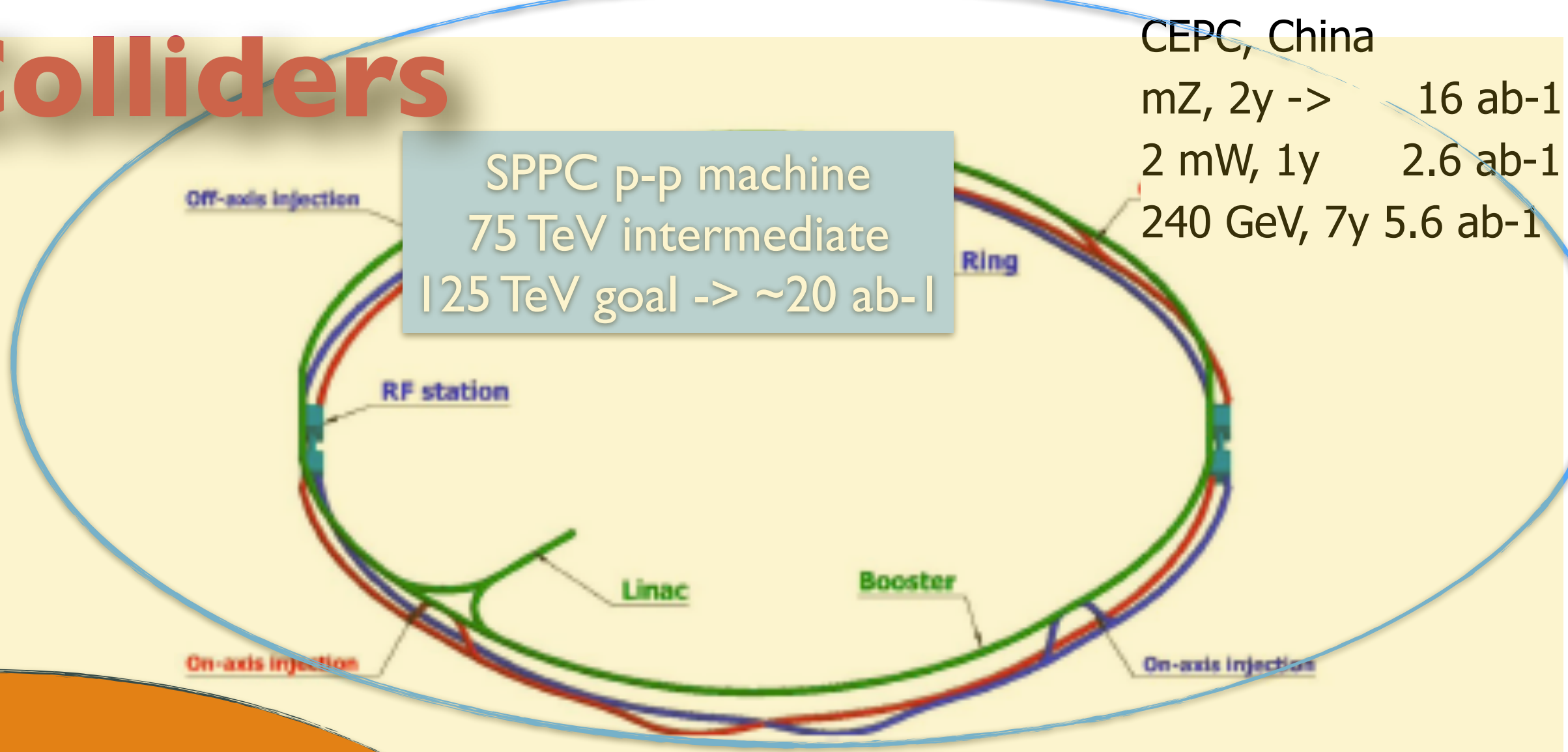
Challenge: muons have limited lifetime: $2.2 \mu\text{s}$ Technology challenge!

e^+e^- , hadron and muon Colliders

ILC Japan
250 GeV, 11y 2 ab-1
500 GeV, 8.5y 4 ab-1
1000 GeV, 8.5y 8 ab-1

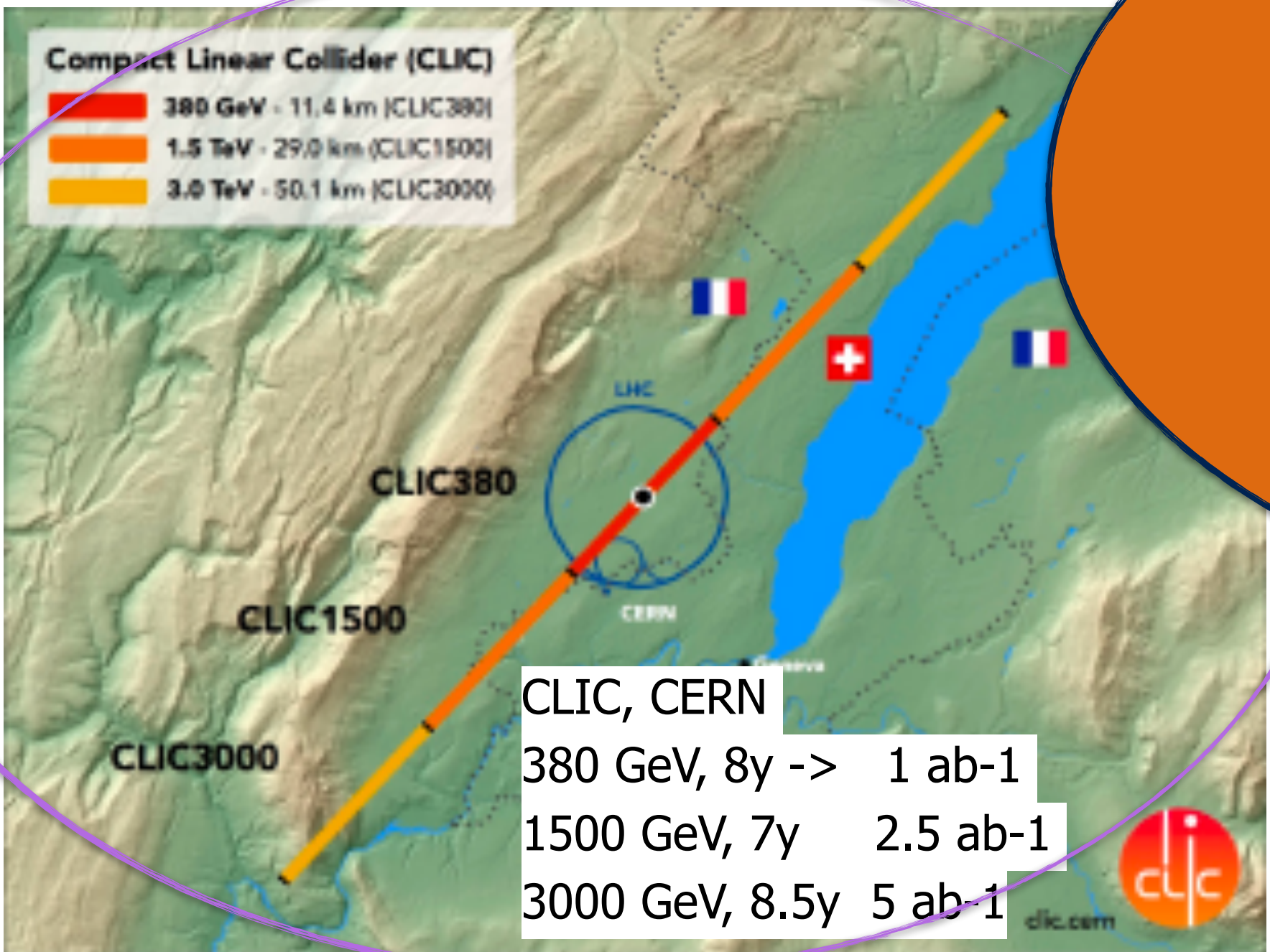


SPPC p-p machine
75 TeV intermediate
125 TeV goal -> ~20 ab-1

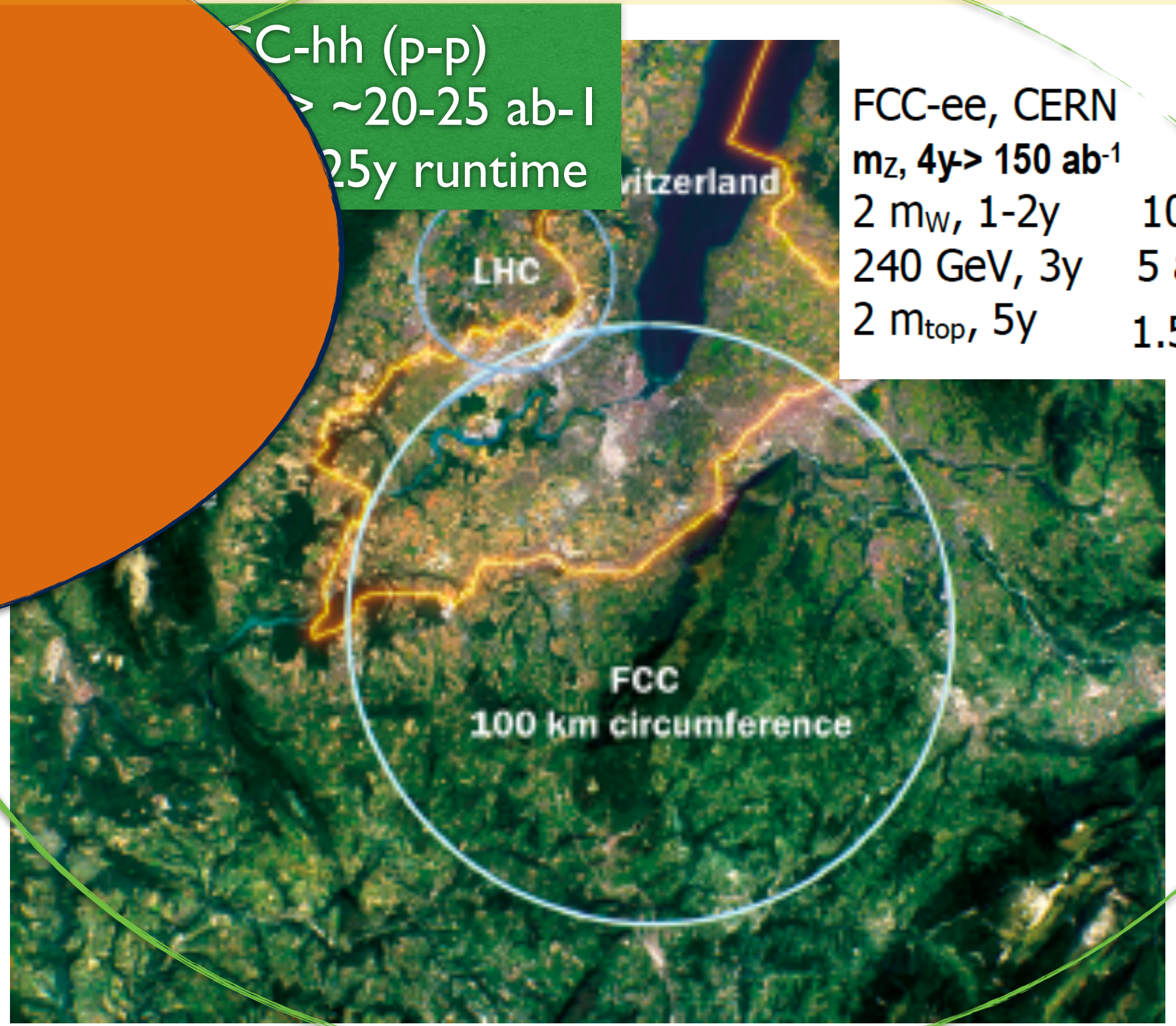


CEPC, China
mZ, 2y -> 16 ab-1
2 mW, 1y 2.6 ab-1
240 GeV, 7y 5.6 ab-1

Muon Collider
3 TeV 1 ab-1
10 TeV 10 ab-1
?



CLIC, CERN
380 GeV, 8y -> 1 ab-1
1500 GeV, 7y 2.5 ab-1
3000 GeV, 8.5y 5 ab-1

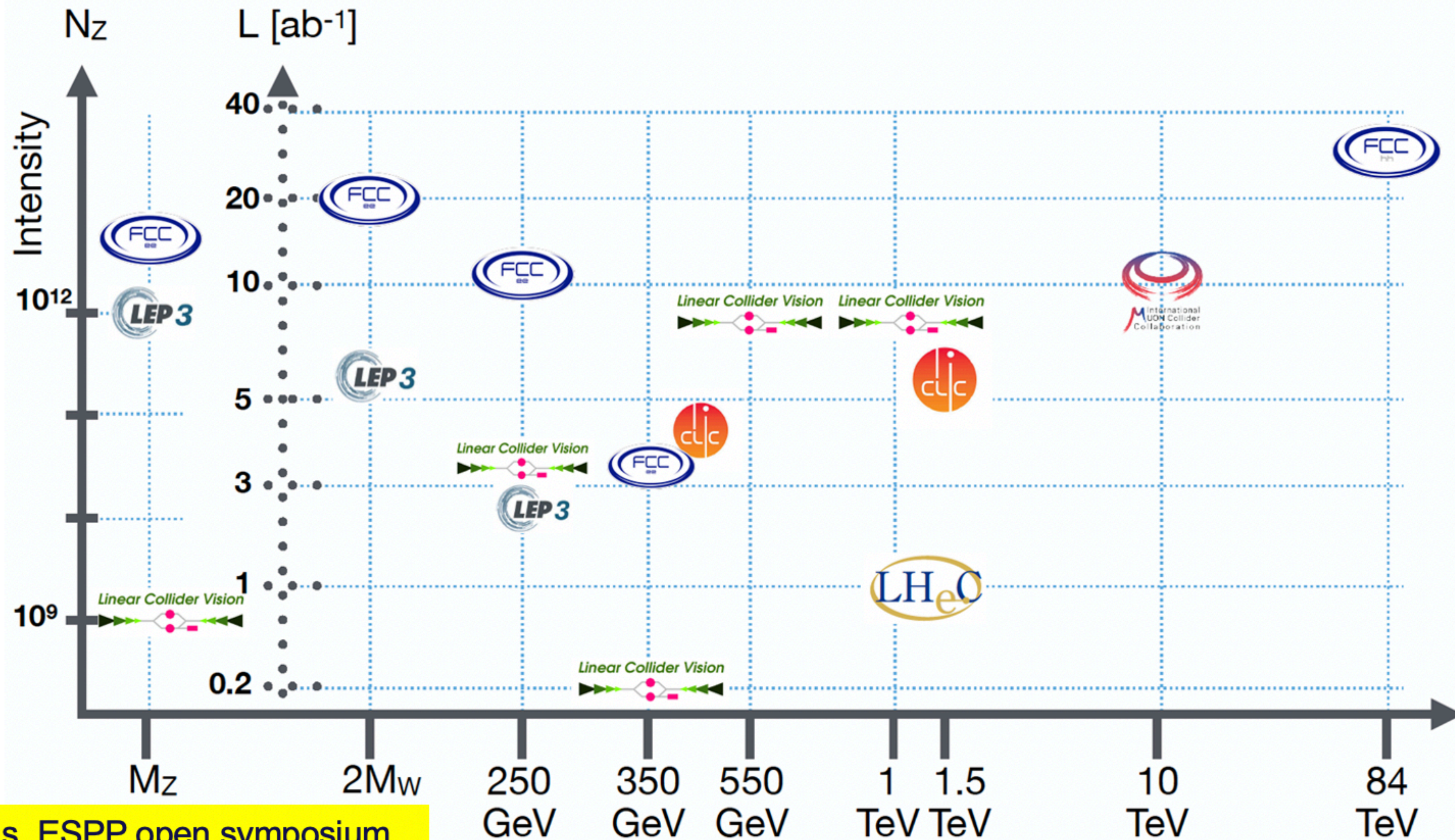


FCC-hh (p-p)
> ~20-25 ab-1
25y runtime

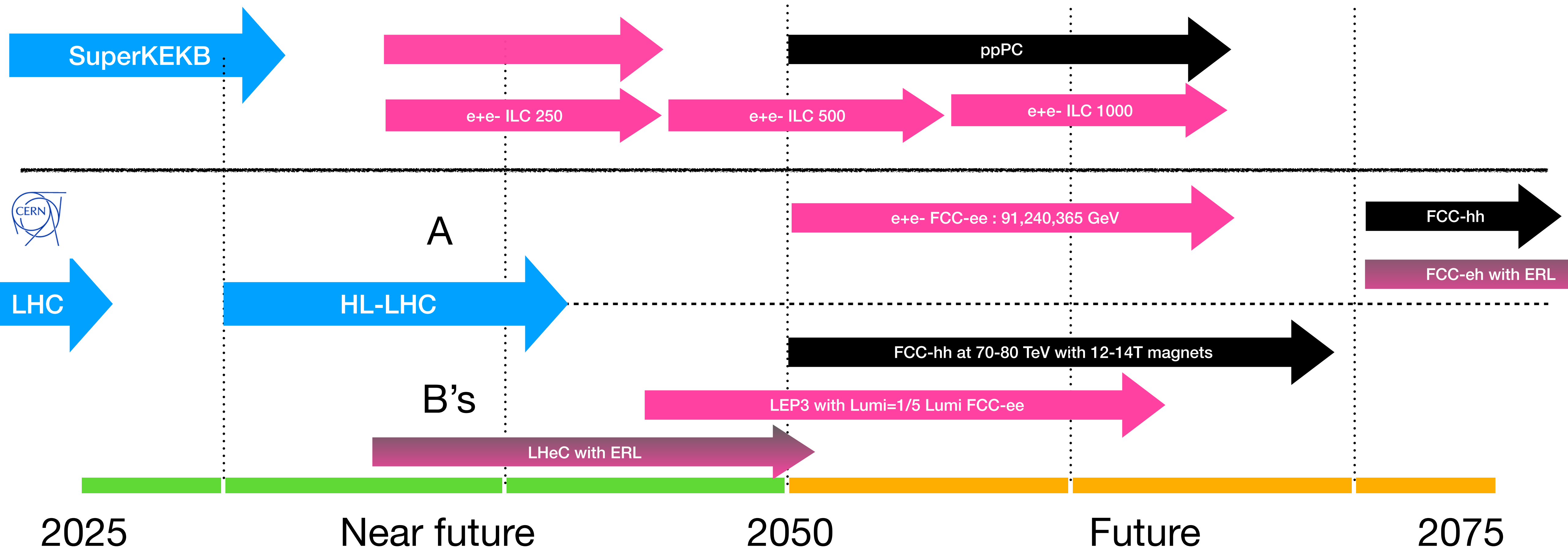
FCC-ee, CERN
mZ, 4y > 150 ab-1
2 mW, 1-2y 10 ab-1
240 GeV, 3y 5 ab-1
2 m_top, 5y 1.5 ab-1

Lecture 3: measurements in the future

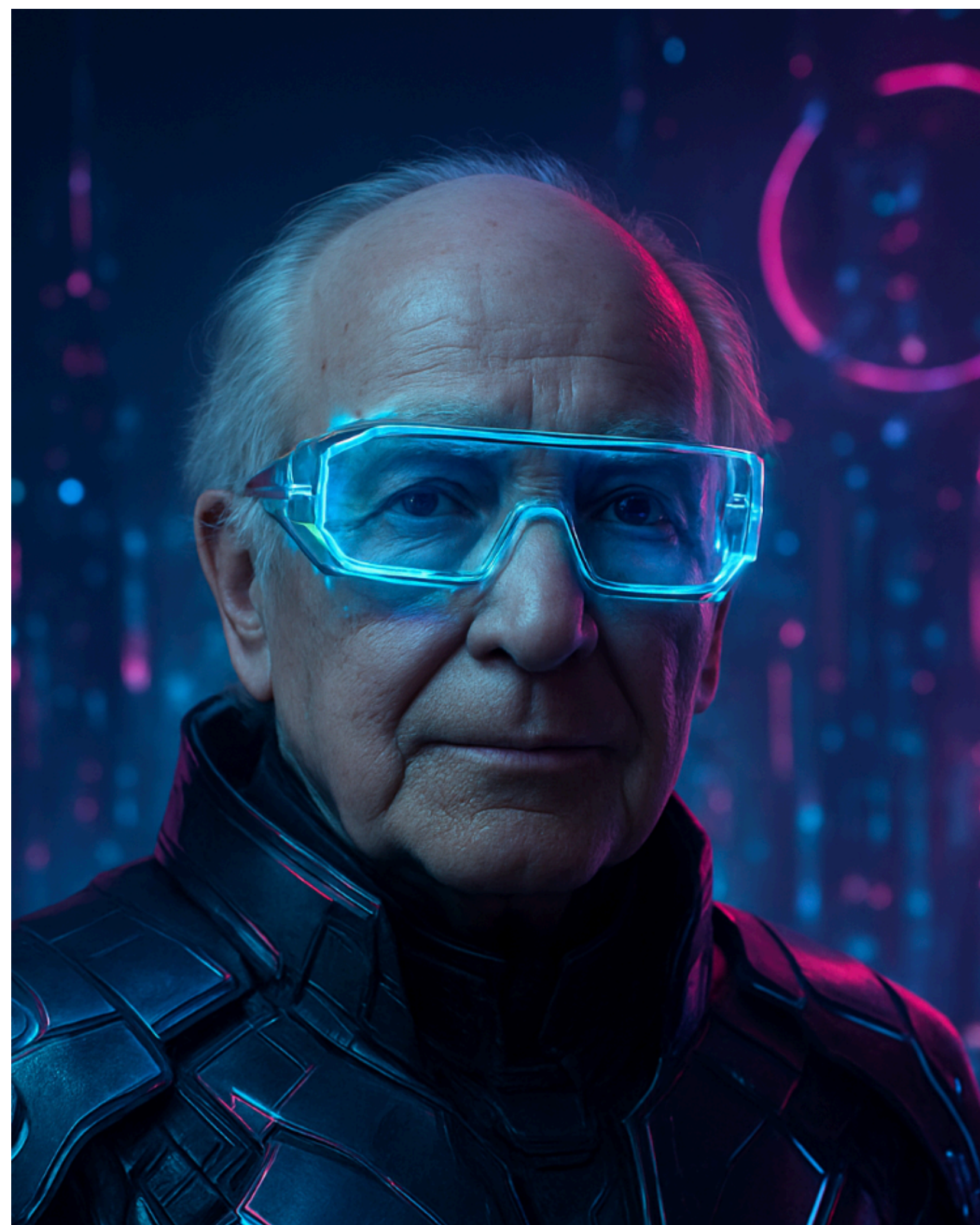
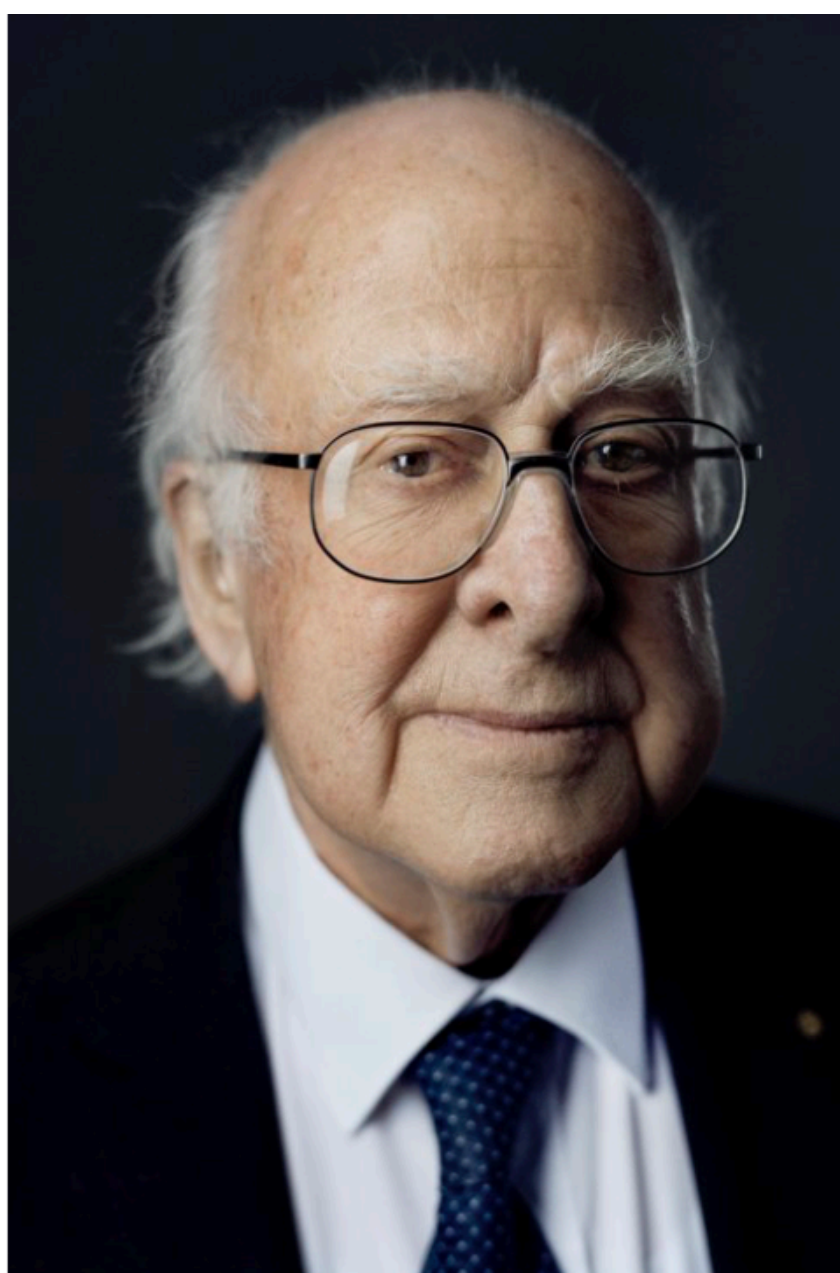
comparing future collider capabilities



Future experiments



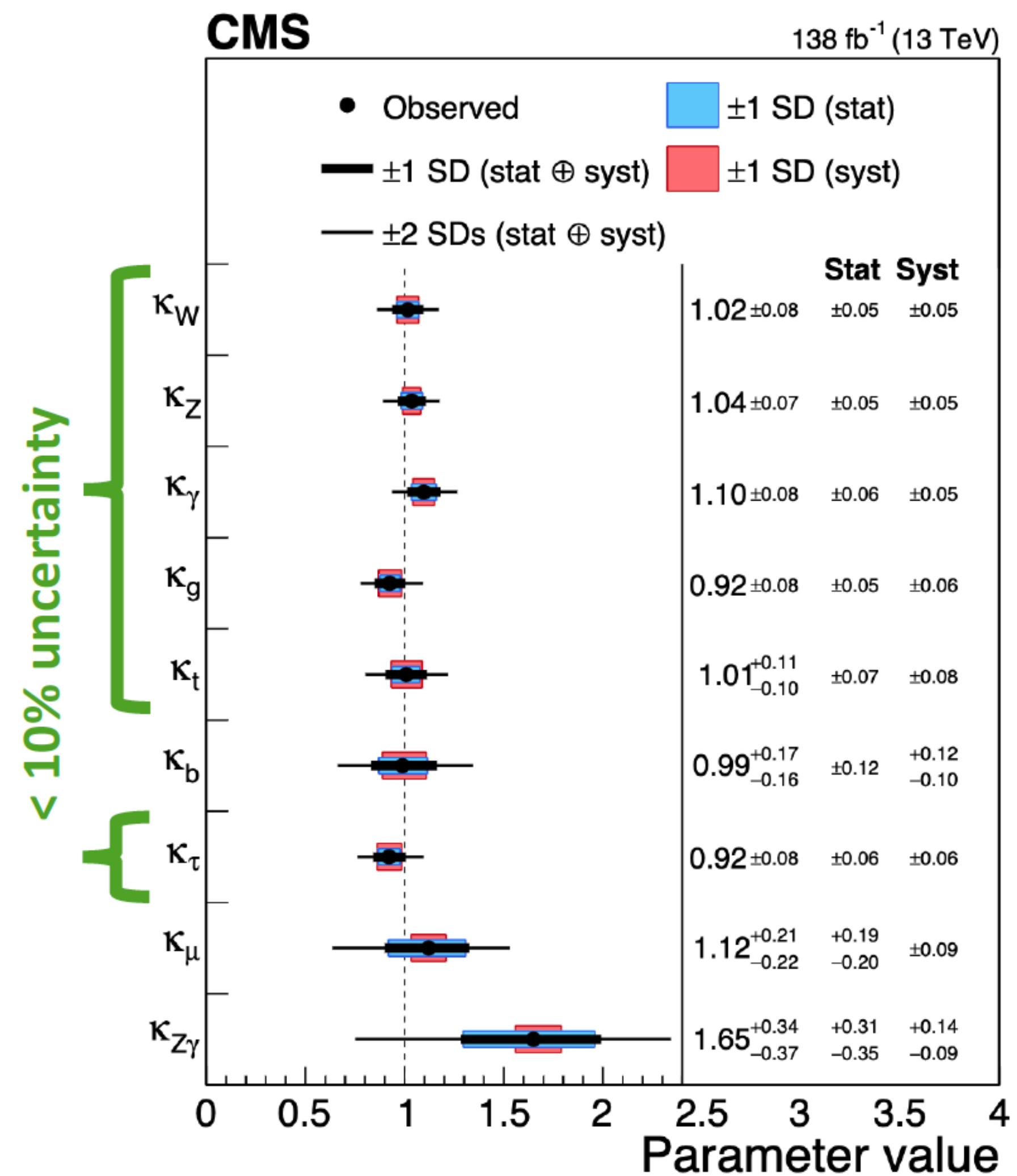
Single Higgs Future



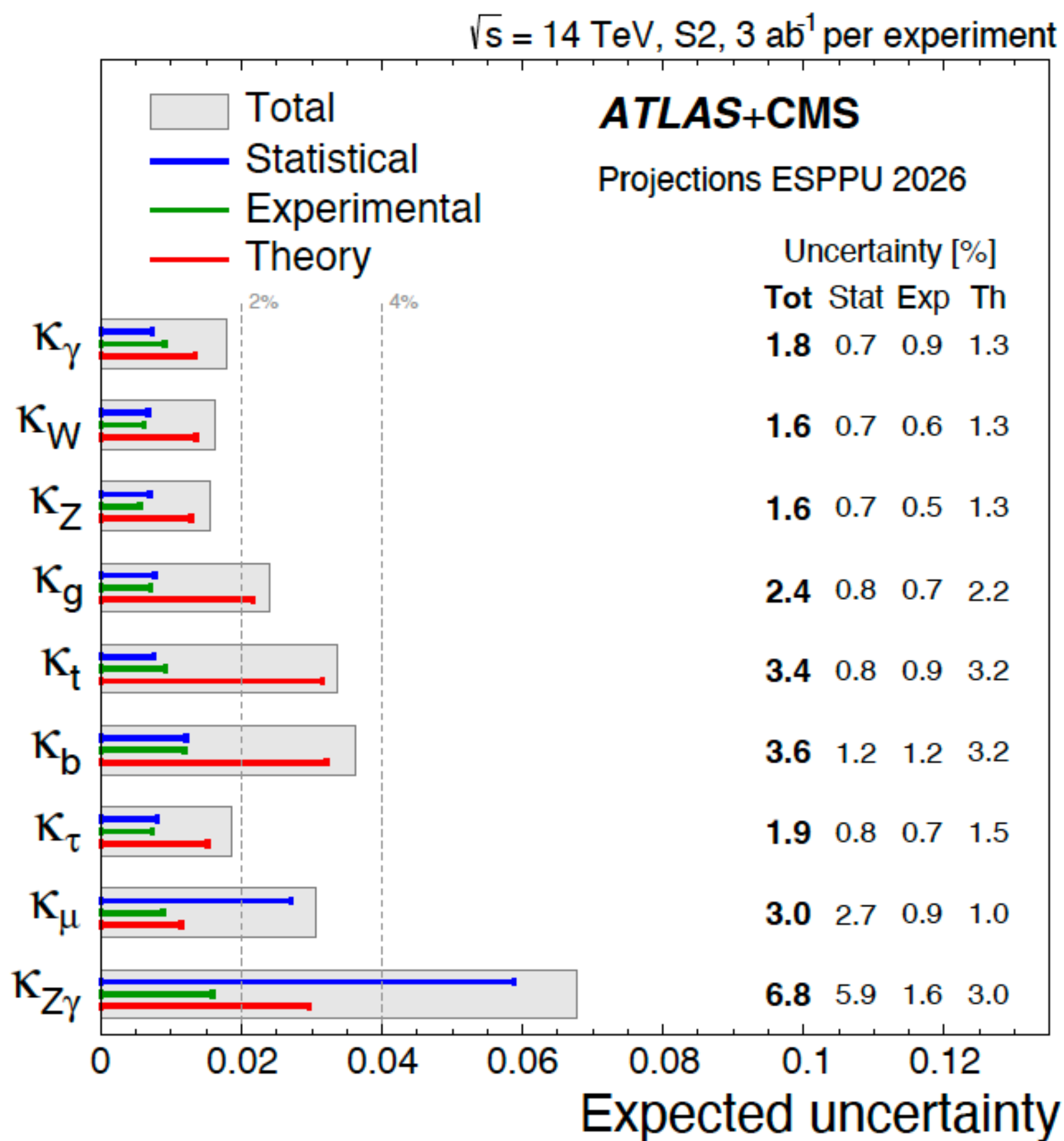
Higgs Couplings HL-LHC

run 2

HL-LHC

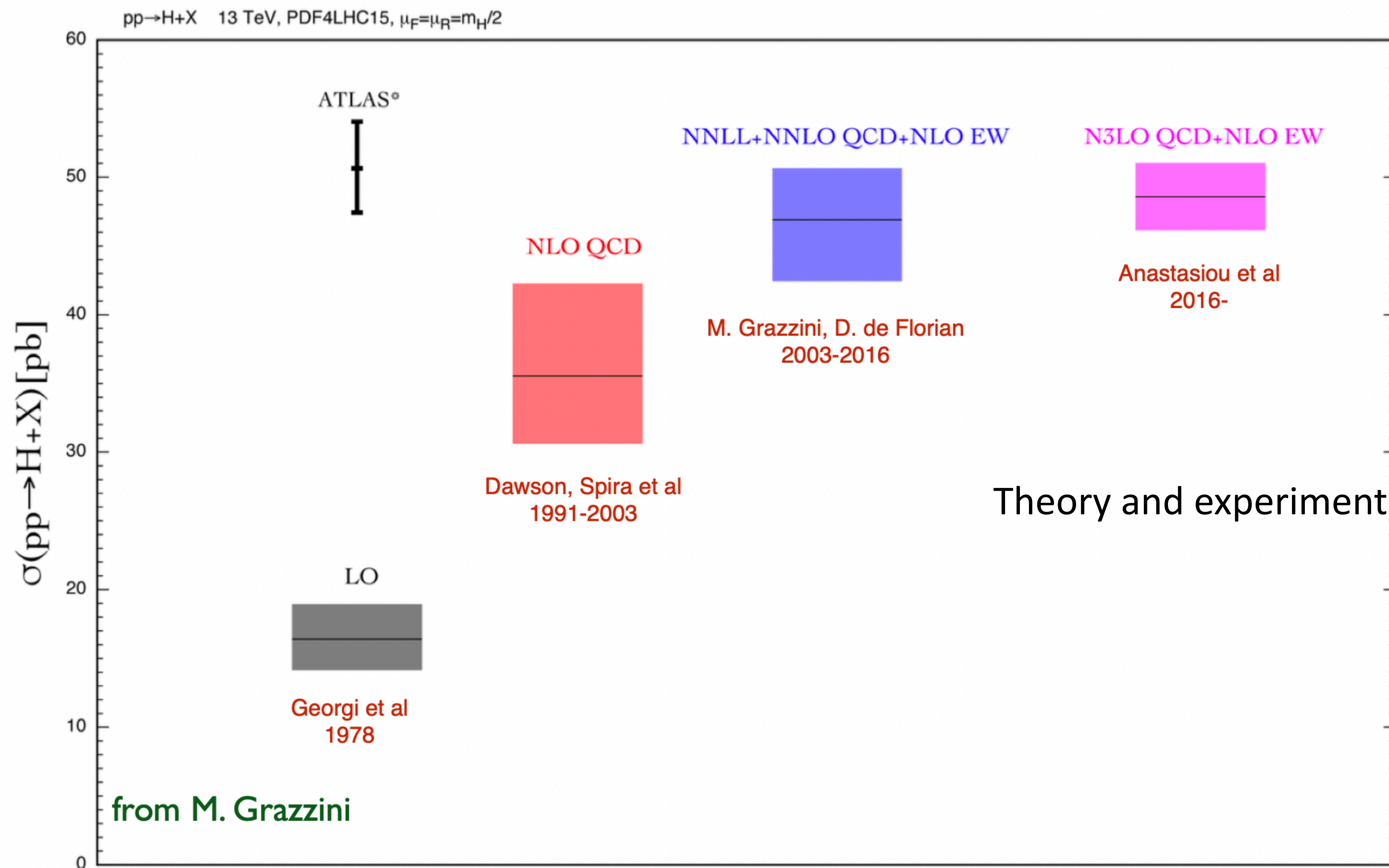


from ~10% to 2-3% precision

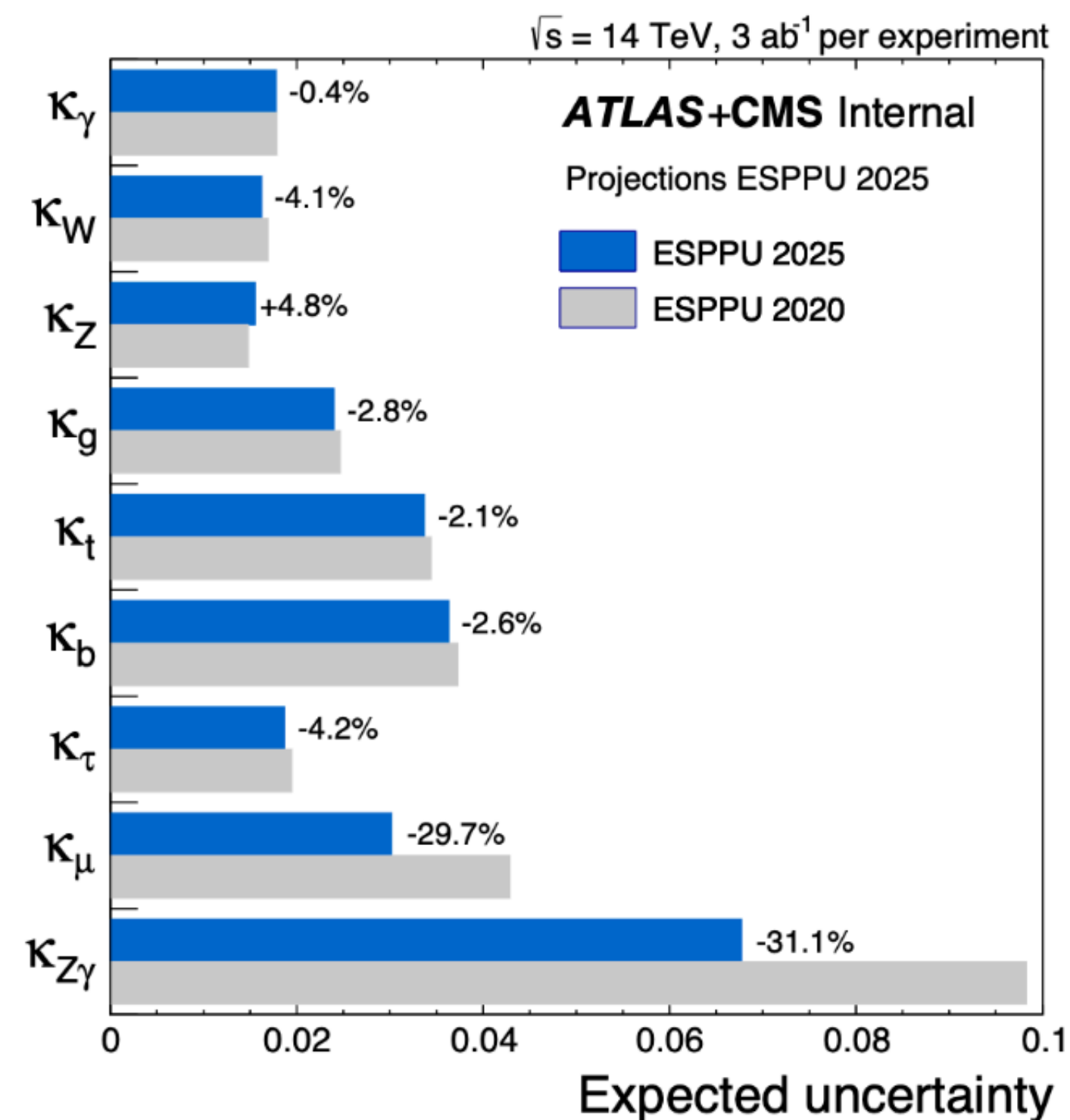
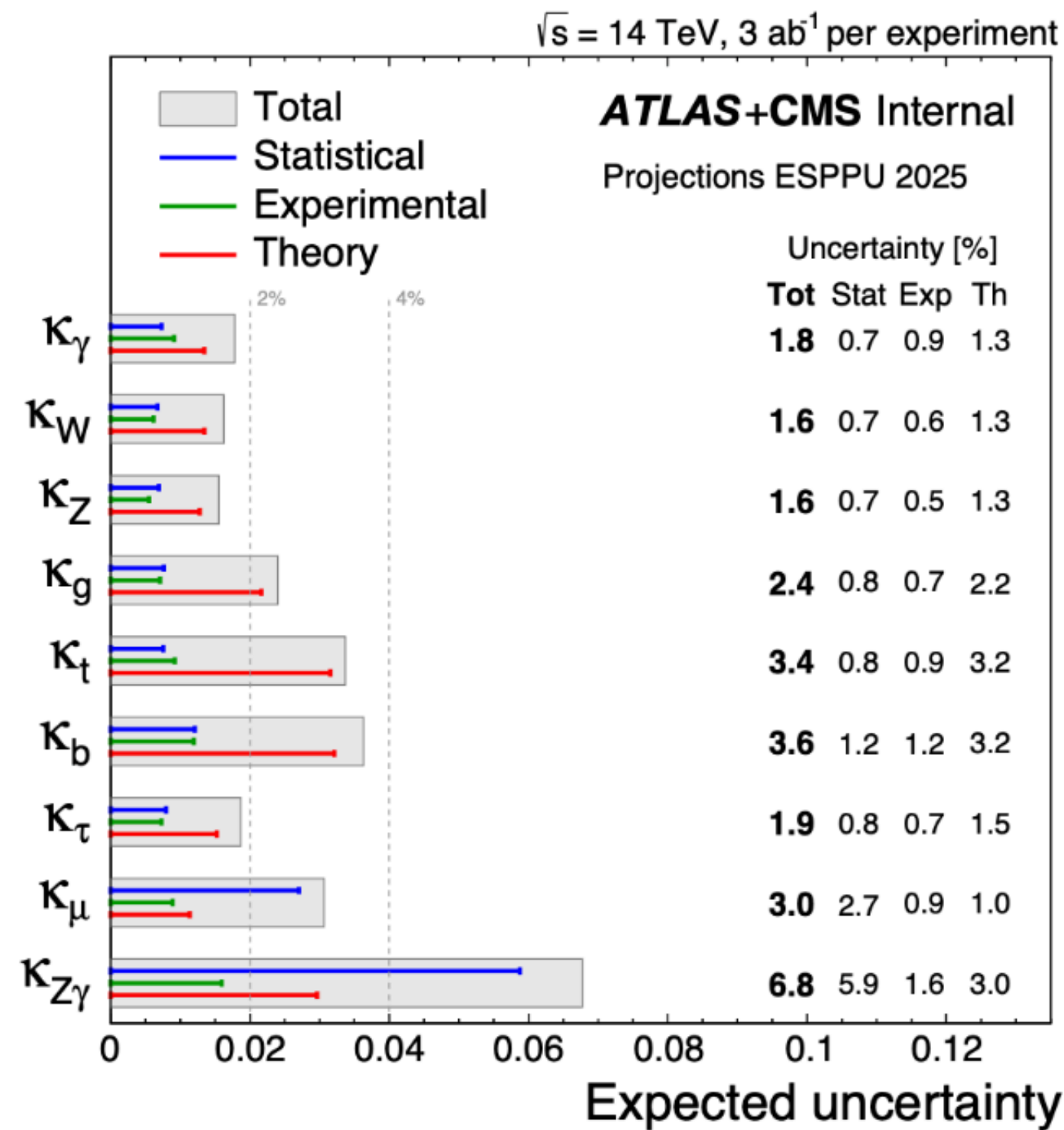


dominated by theory errors!

Inclusive Higgs x-section theoretical improvements



New Higgs Couplings Projection



ATLAS Combination,
using most recent Run-2 analyses for
 $H \rightarrow \gamma\gamma, Z\gamma, \mu\mu, VH \rightarrow bb, \tau\tau$
+ ESU 2020 projections for
 $H \rightarrow ZZ, WW, ttH \rightarrow bb, ttH \rightarrow \text{multileptons}$

CMS Combination from ESU2020
except κ_μ and $\kappa_{Z\gamma}$ recent Full Run2 results

κ_Z worse than ESU2020 due to refinement of ZH theory uncertainty

HL-LHC results will stay for years to come and some will be reference until Fcc-hh

[De Blas et al., 2020]

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2'	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98*	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	—	5.7	3.8	99*	86*	85*	120*	15	6.9	8.2	81*	75*	0.69
κ_c [%]	—	4.1	—	—	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	—	2.8	1.7	—	6.9	1.6	—	—	2.7	—	—	—	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	—	2.5	1.7	15	9.4	6.2	320*	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

κ_γ , κ_Z , $\kappa_{Z\gamma}$ will be the most precise measurements for a long time

New European Strategy numbers

<https://indico.cern.ch/event/1439855/contributions/6461657/>

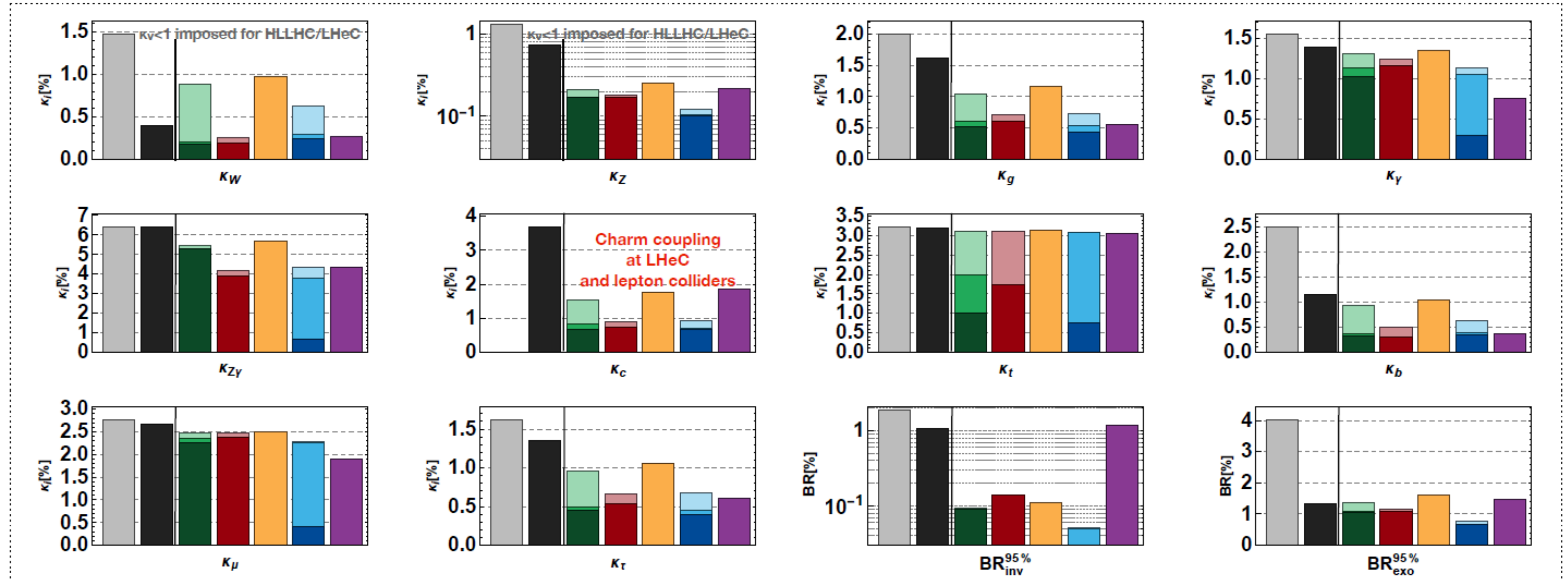
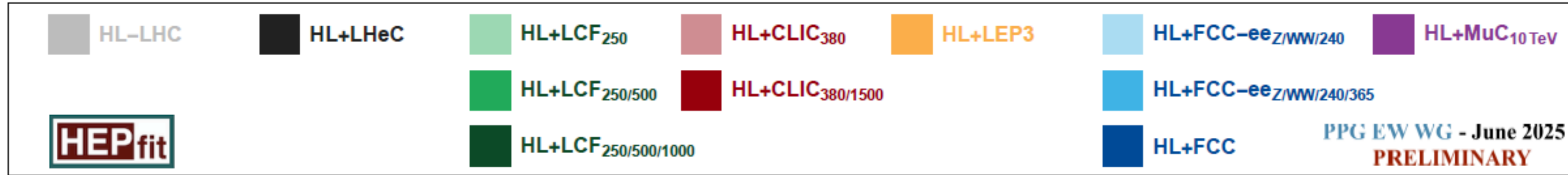
Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	—	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$ \kappa_s $ (%)	—	+29 -67
Γ_H (%)	—	0.78
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	1.9×10^{-2}	5×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}

The Fcc-ee projections include HL_LHC, difficult to understand...UNFAIR comparison

In addition results of 4 experiments are combined while only 2 are officially envisaged for the moment.

New European Strategy numbers

Kappa framework results



Higgs Couplings at Fcc-hh at lower energies

Mangano European Strategy kickoff meeting

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} (\%)$	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu} (\%)$	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma} (\%)$	0.9	1.0	0.8

- **A lower energy Fcc-hh can deliver results that are very close to baseline option**

rare Higgs Couplings HL-LHC projections

ATLAS+CMS

$\mathcal{L}$		$H \rightarrow Z\gamma$		$H \rightarrow \mu\mu$	
		$S1$	$S2$	$S1$	$S2$
		$\delta\mu[\%]$	$\delta\mu[\%]$	$\delta\mu[\%]$	$\delta\mu[\%]$
2 ab^{-1}	ATLAS	31	21	16	13
	CMS	24	23	9.8	8.4
	ATLAS+CMS	20	15	7.5	5.9
3 ab^{-1}	ATLAS	29	17	15	11
	CMS	20	19	8.5	7.0
	ATLAS+CMS	17	14	7.5	5.9

High pT bins statistically limited, new physics is likely to appear at high pT, large gains still with HL-LHC!

ATLAS+CMS $H \rightarrow \gamma\gamma$ $p_T > 650\text{ GeV}$

ATLASx2 $VH \rightarrow b\bar{b}$ $p_T > 600\text{ GeV}$

$\mathcal{L}$		$\delta\sigma_{\text{ggF } p_T^H > 650\text{ GeV}}^{\gamma\gamma}[\%]$		$\delta\sigma_{\text{WH } p_T^W > 600\text{ GeV}}^{b\bar{b}}[\%]$	$\delta\sigma_{\text{ZH } p_T^Z > 600\text{ GeV}}^{b\bar{b}}[\%]$
		$S1$	$S2$	$S1$	$S2$
2 ab^{-1}	ATLAS+CMS	1.2×10^2	97	-	-
3 ab^{-1}	ATLAS+CMS	1.0×10^2	79	19	22

Higgs Mass Future

HL-LHC: 21 MeV

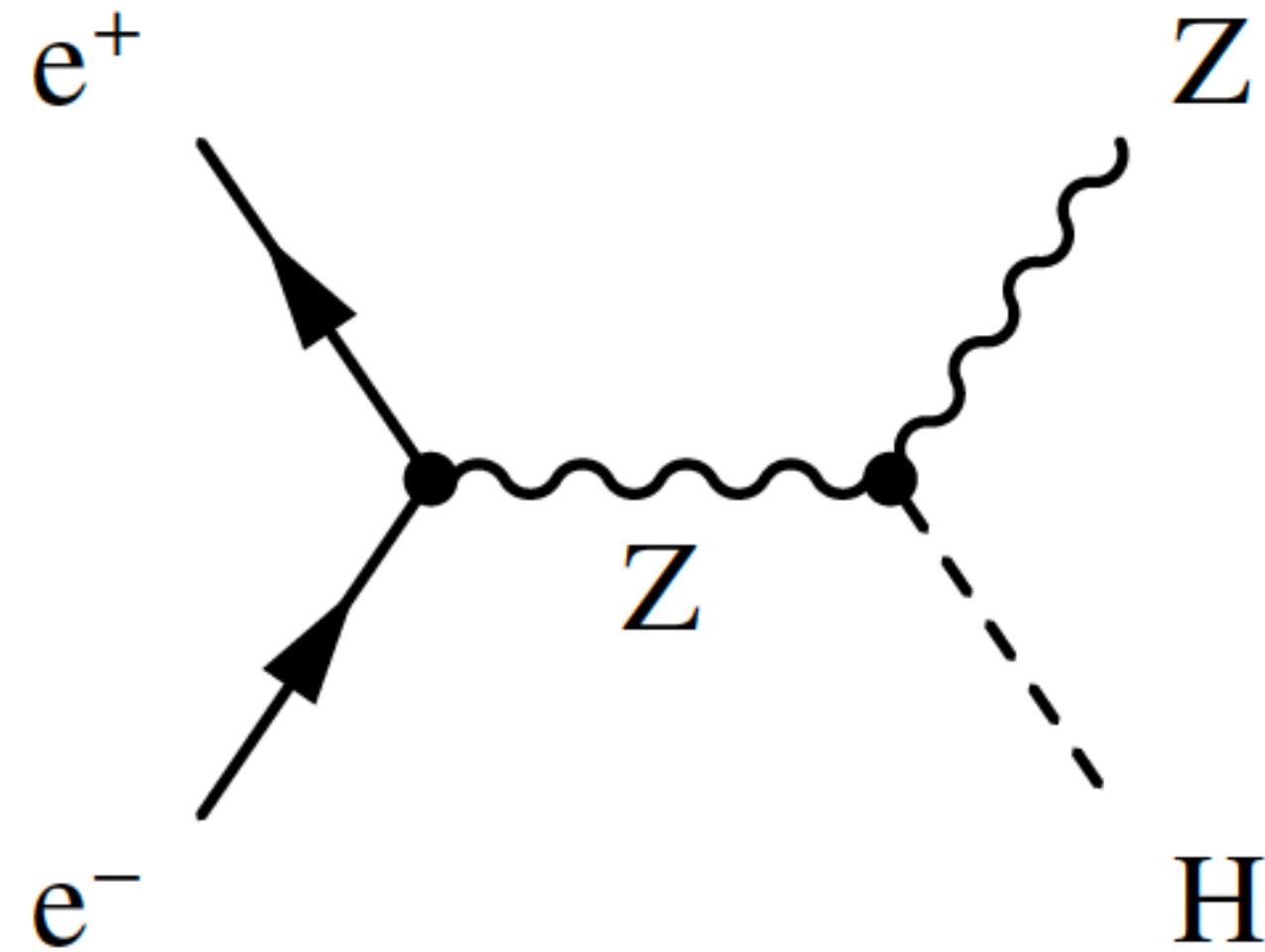
FCC-ee: 3 MeV

Linear collider: 12 MeV

LEP3: 15 MeV

Higgs mass estimates

Higgs Width @ e+e- Colliders



Measuring the inclusive production cross-section of the **ZH** process without presuming specific Higgs boson decay modes allows the determination of the absolute coupling between the Higgs and **Z** bosons. Combining this measurement with data on the **ZH**, **H → ZZ*** process, along with the **H → ZZ*** branching ratio, allows for the calculation of the total Higgs boson width without any additional theoretical assumptions:

Precision of Fcc-ee 4%
Precision of ILC(250)~11%
Precision of ILC(500) 5%
LEP3 (H->ZZ) 21%
LEP3(WW fusion) 12%

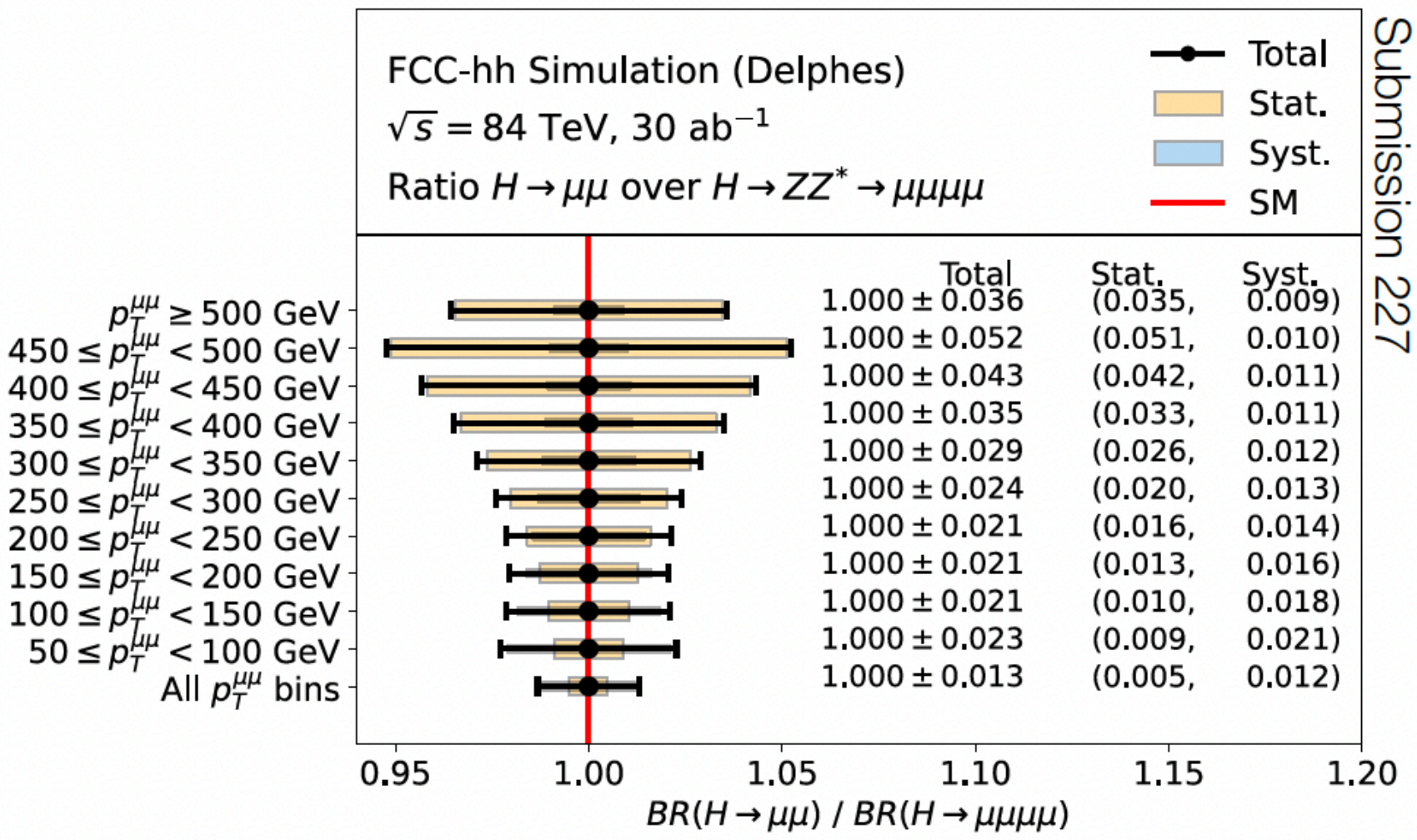
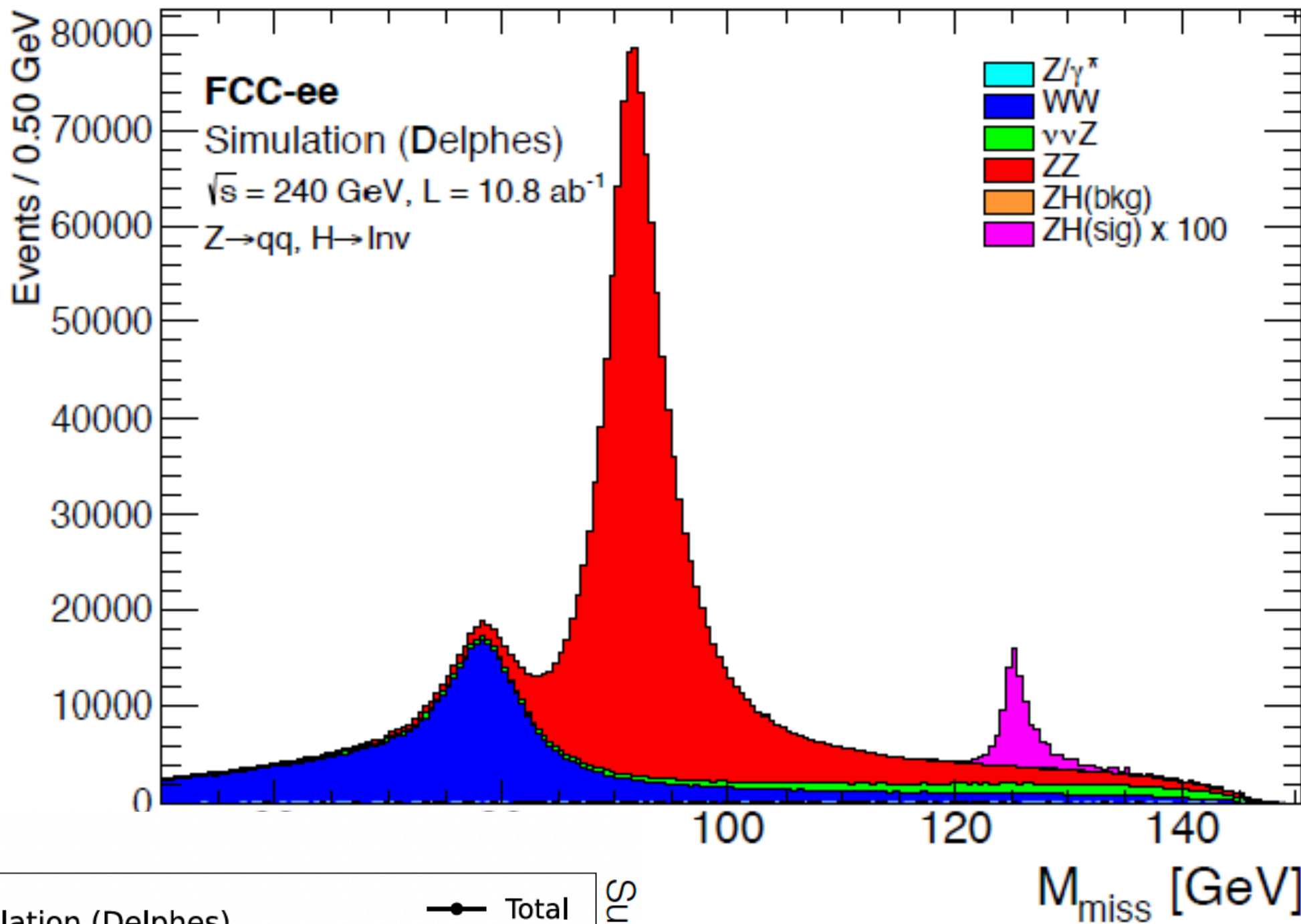
$$\Gamma_H \propto \frac{(\sigma_{e^+e^- \rightarrow ZH} \times BR_{H \rightarrow ZZ^*})^2}{\sigma_{e^+e^- \rightarrow ZH}}$$

Cannot be done at pp because of invisible decays (e.g. **Z** to neutrinos)

Higgs to invisible future

Fcc-ee gets to 0.05%-0.12% limit

Collider	Projected sensitivity (95% CL)
LHC (current)	~13%–19%
HL-LHC	2%
LEP3 / TLEP	~1% (exclude >2%)
FCC-ee / CEPC	≲ 0.1% (per mille level)
ILC (250 GeV)	~0.3%



Fcc-hh Higgs to invisible limit of 0.02%

Uses $H \rightarrow \mu\mu\mu\mu$ from FCCee to estimate cross section

2 Higgses Future



Example of improvements vs time:

ATLAS $HH \rightarrow b\bar{b}T\bar{T}$

ATL-PHYS-PUB-2024-016

2015 HL_LHC @3000 fb⁻¹
0.6 sigma

[ATL-PHYS-PUB-2015-046](#)

Table 9: Expected significance for several channel combinations, for a luminosity of 3 ab⁻¹, including the expected uncertainties quoted in the text, using the asymptotic approximation. This table only takes into account the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels.

Channel	Significance	Combined in channel	Total combined
$e + \text{jets}$	0.31	0.43	0.60
$\mu + \text{jets}$	0.30		
$\tau_{\text{had}}\tau_{\text{had}}$	0.41	0.41	

2021 HL_LHC @3000 fb⁻¹
2.8 sigma

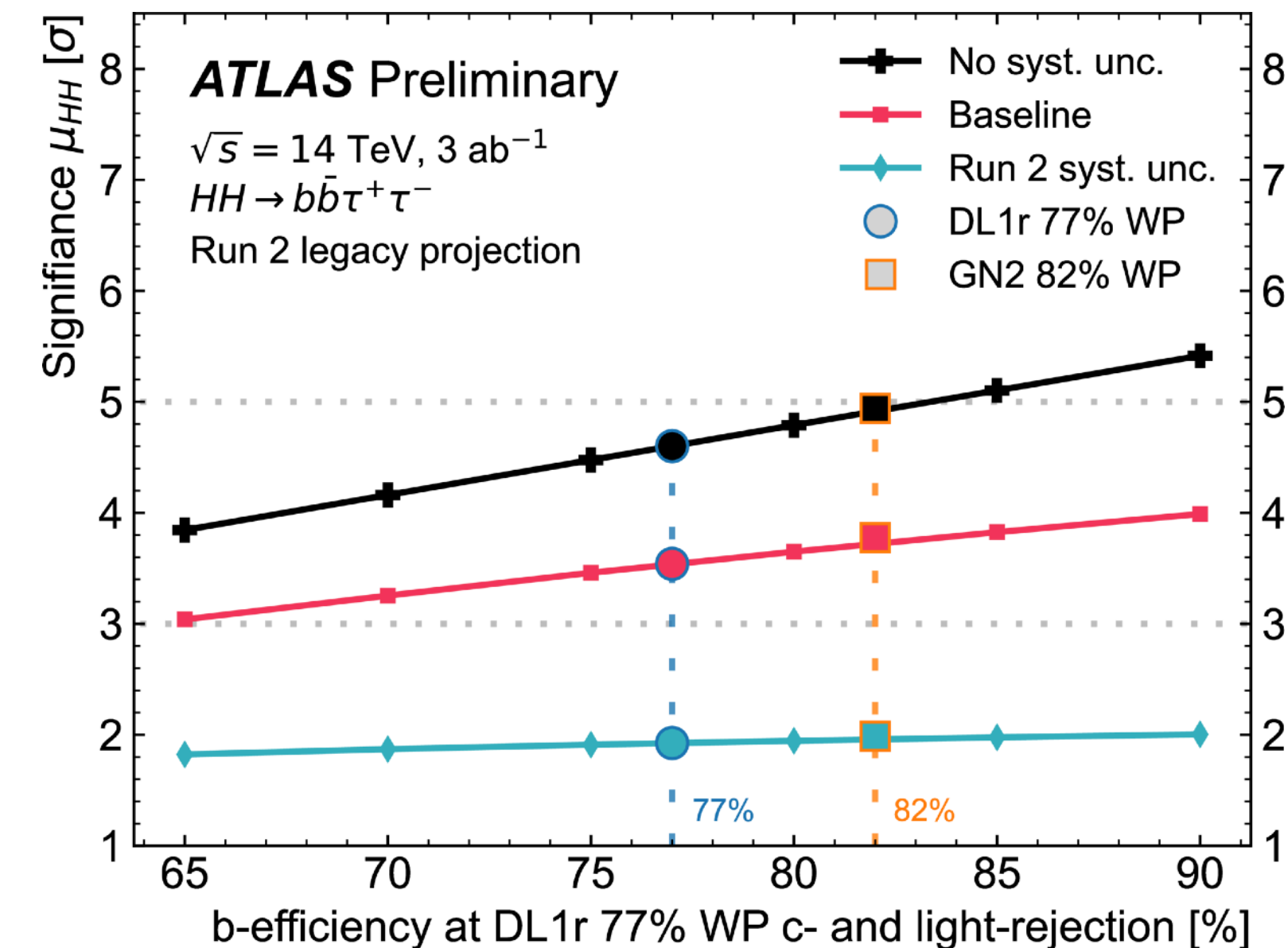
[ATL-PHYS-PUB-2021-044](#)

assuming SM kinematics for the signal, the 95% CL upper limit on the HH signal strength is projected to be at 0.71 times the SM prediction with respect to the background-only hypothesis assuming an integrated luminosity of 3000 fb⁻¹ and $\sqrt{s} = 14$ TeV. The signal significance is extrapolated to 2.8σ , and assuming a true value of $\kappa_\lambda = 1$, the self-coupling modifier is constrained to the 1σ CI $[0.3, 1.9] \cup [5.2, 6.7]$. If no HH

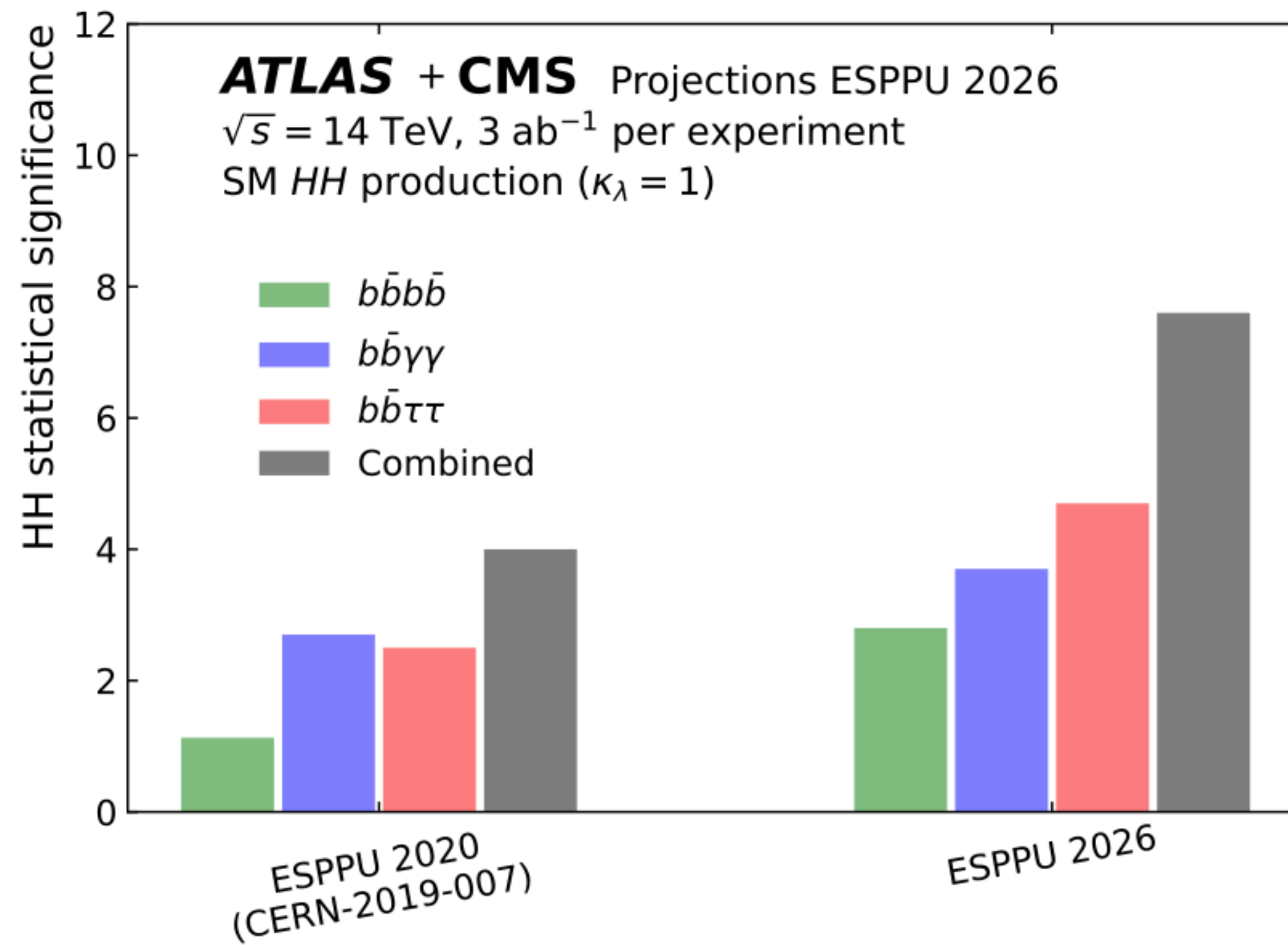
a variety of integrated luminosities ranging from 1000 to 3000 fb⁻¹. Assuming SM HH production, a signal significance of 3.5σ (4.6σ) is expected in the baseline (statistical only) extrapolation scenario for an integrated luminosity of 3000 fb⁻¹. This translates into expected

2024 HL_LHC @3000 fb⁻¹
3.5 sigma

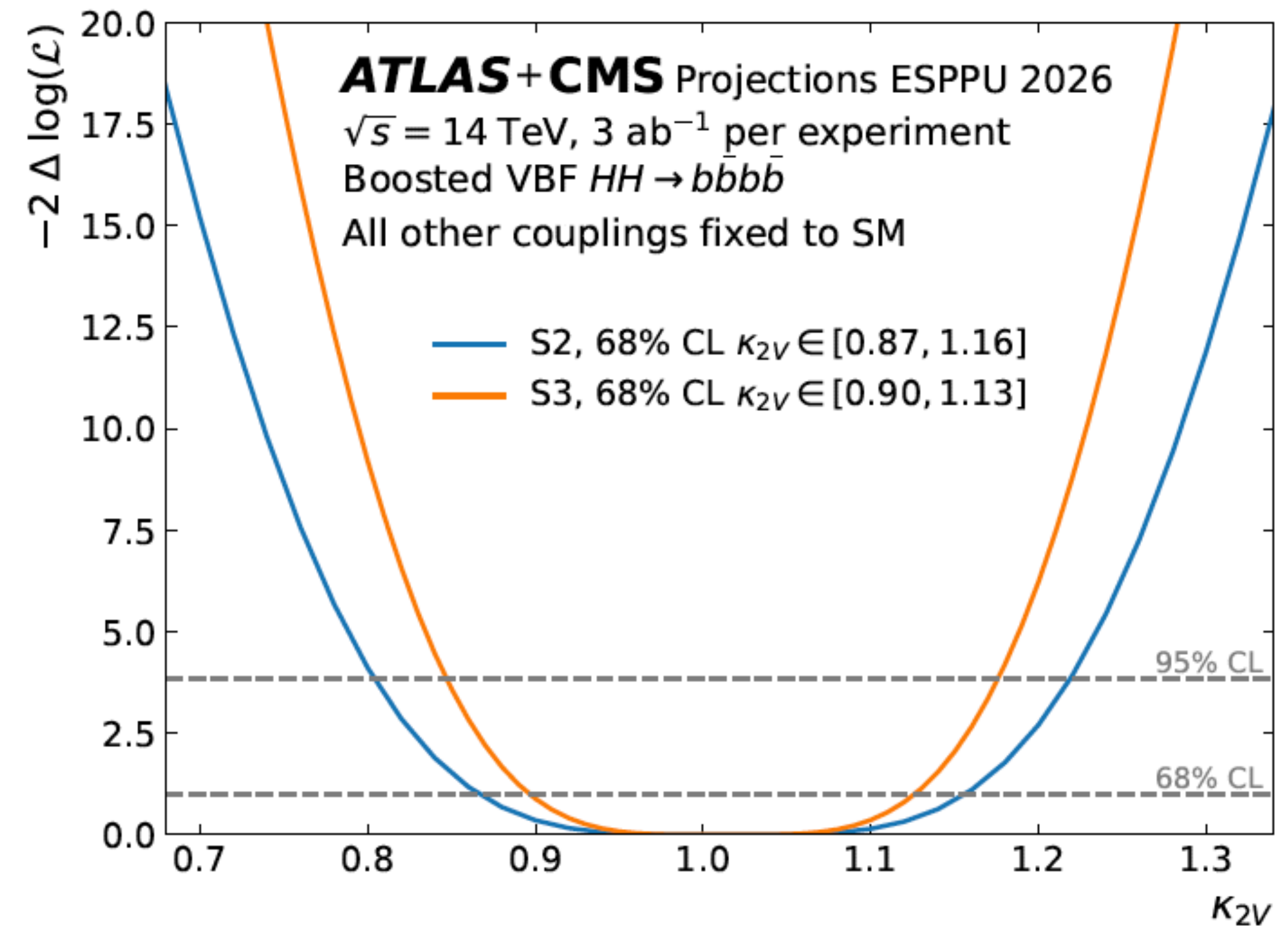
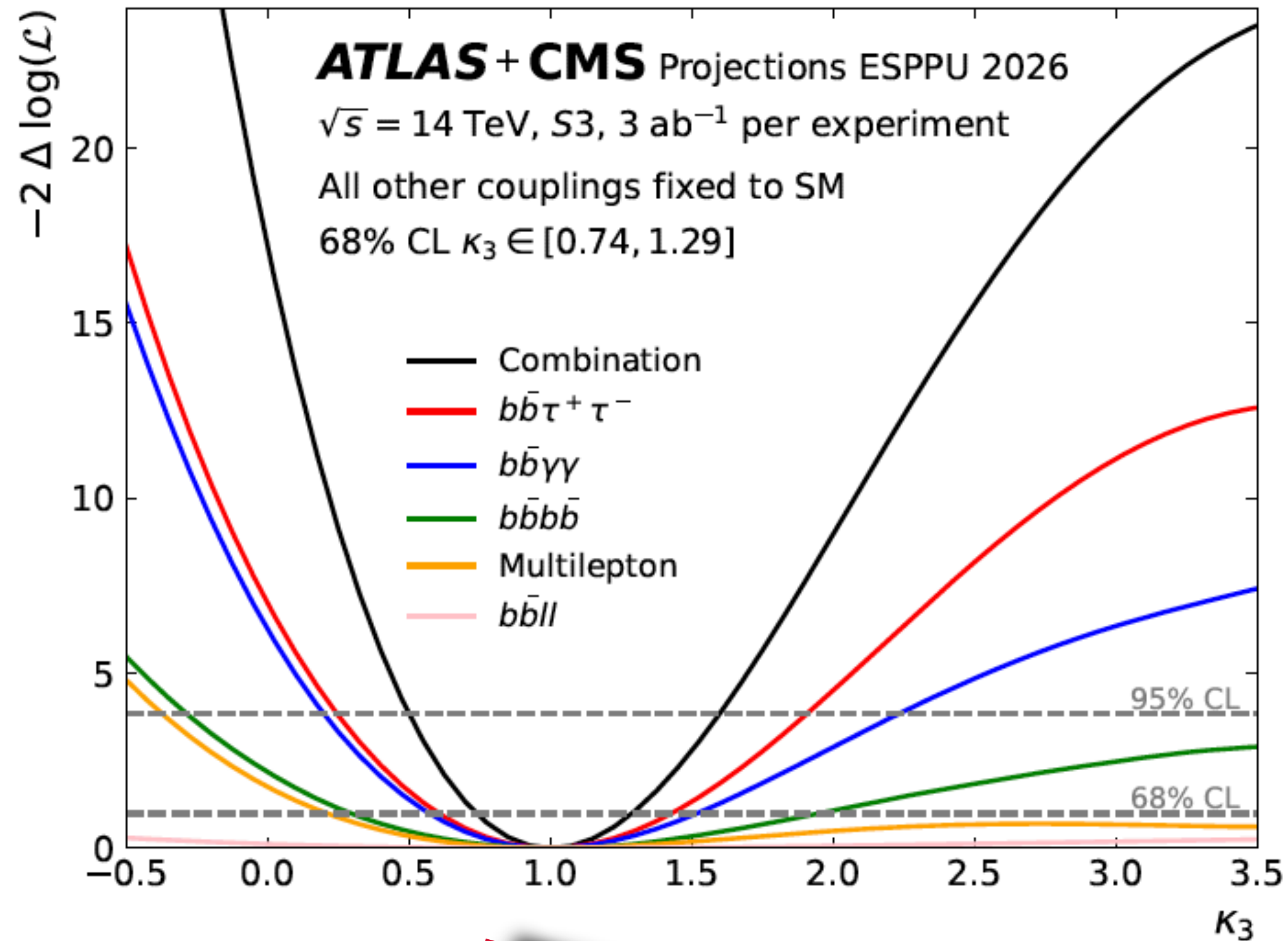
[ATL-PHYS-PUB-2024-016](#)



Improvements in projections since 2020



ATLAS+CMS HH combination



$HH \rightarrow b\bar{b}\gamma\gamma$ both ATLAS and CMS,
 $HH \rightarrow b\bar{b}\tau\tau$, $\rightarrow b\bar{b}l\bar{l}$, $\rightarrow$ multileptons ATLASx2
 $HH \rightarrow b\bar{b}b\bar{b}$ resolved and boosted CMSx2

Non-resonant HH combination

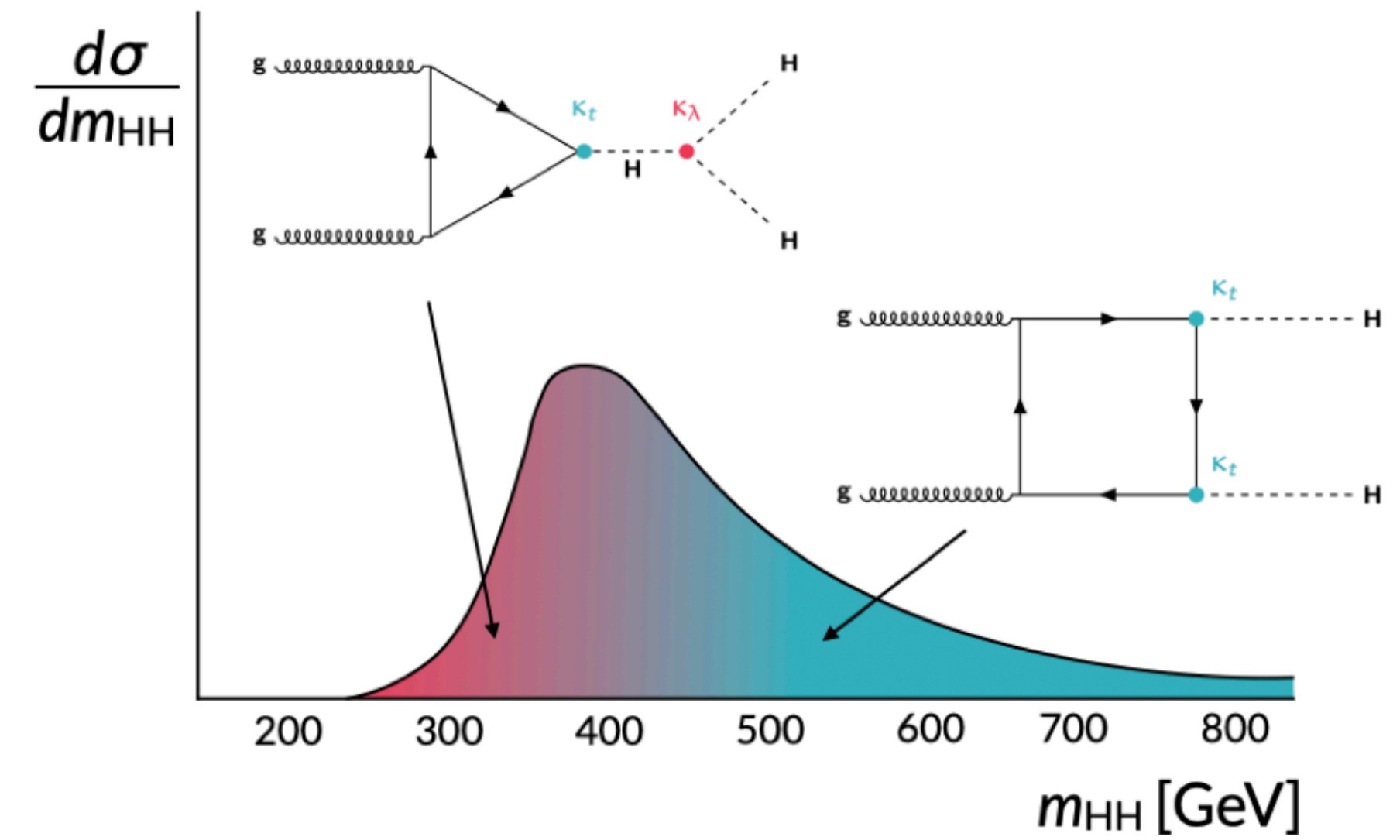
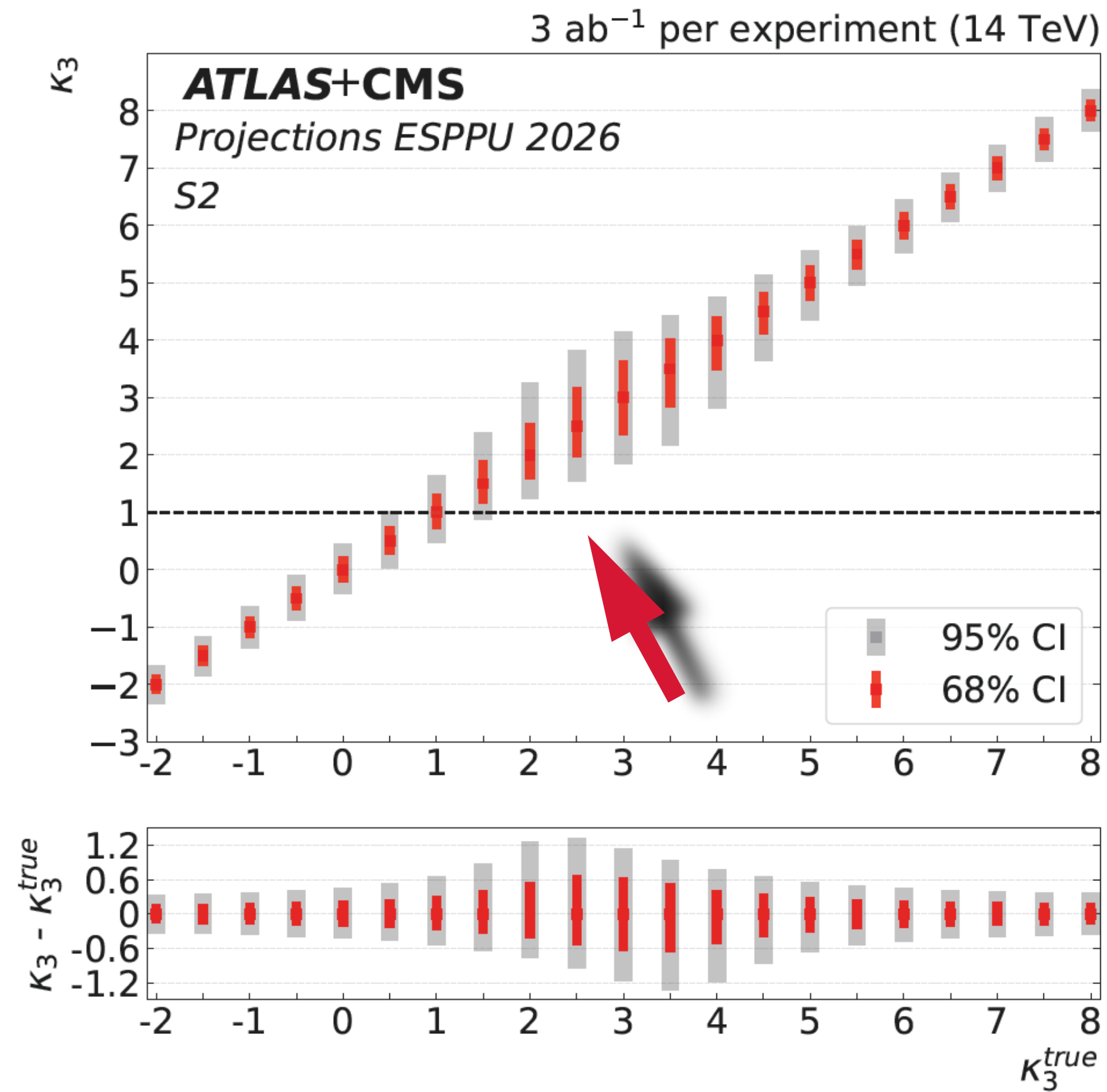
	2 ab ⁻¹ (S2)		3 ab ⁻¹ (S2)		3 ab ⁻¹ (S3)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
<i>HH</i> statistical significance						
<i>b</i> $\bar{b}$ $\tau^+\tau^-$	3.0 [†]	1.9	3.5 [†]	2.4	3.8[†]	2.7
<i>b</i> $\bar{b}$ $\gamma\gamma$	2.1 [†]	2.0 [†]	2.4 [†]	2.4 [†]	2.6[†]	2.6[†]
<i>b</i> $\bar{b}$ <i>b</i> $\bar{b}$ resolved	0.9	1.0 [†]	1.0	1.2 [†]	1.0	1.3[†]
<i>b</i> $\bar{b}$ <i>b</i> $\bar{b}$ boosted	—	1.8 [†]	—	2.2 [†]	—	2.2[†]
Multilepton	0.8 [†]	—	1.0 [†]	—	1.0[†]	—
<i>b</i> $\bar{b}$ $\ell^+\ell^-$	0.4 [†]	—	0.5 [†]	—	0.5[†]	—
Combination	3.7	3.5	4.3	4.2	4.5	4.5
ATLAS+CMS	6.0		7.2		7.6	
κ_3 68% confidence interval						
<i>b</i> $\bar{b}$ $\tau^+\tau^-$	[0.3, 1.8] [†]	[0.1, 3.0]	[0.4, 1.7] [†]	[0.2, 2.2]	[0.5, 1.6] [†]	[0.3, 2.0]
<i>b</i> $\bar{b}$ $\gamma\gamma$	[0.3, 2.0] [†]	[0.2, 2.3] [†]	[0.4, 1.8] [†]	[0.3, 2.0] [†]	[0.5, 1.7] [†]	[0.4, 1.9] [†]
<i>b</i> $\bar{b}$ <i>b</i> $\bar{b}$ resolved	[−0.7, 6.3]	[−0.6, 7.6] [†]	[−0.5, 6.1]	[−0.3, 7.3] [†]	[−0.5, 6.1]	[−0.3, 7.2] [†]
<i>b</i> $\bar{b}$ <i>b</i> $\bar{b}$ boosted	—	[−0.6, 8.5] [†]	—	[−0.4, 8.2] [†]	—	[−0.4, 8.2] [†]
Multilepton	[−0.2, 4.9] [†]	—	[−0.1, 4.7] [†]	—	[−0.1, 4.7] [†]	—
<i>b</i> $\bar{b}$ $\ell^+\ell^-$	[−2.4, 9.3] [†]	—	[−2.2, 9.2] [†]	—	[−2.1, 9.1] [†]	—
Combination	[0.6, 1.5]	[0.4, 1.7]	[0.6, 1.5]	[0.5, 1.6]	[0.6, 1.4]	[0.6, 1.5]
ATLAS+CMS uncertainty	−32% / +37%		−27% / +31%		−26% / +29%	
† used in the ATLAS+CMS combination						

Close to single experiment observation !

7.6σ ⇔ 4.0σ ESU2020

@3ab⁻¹ ATLAS and CMS will get to less than 30% accuracy on Higgs self couplings, with conservative assumptions!

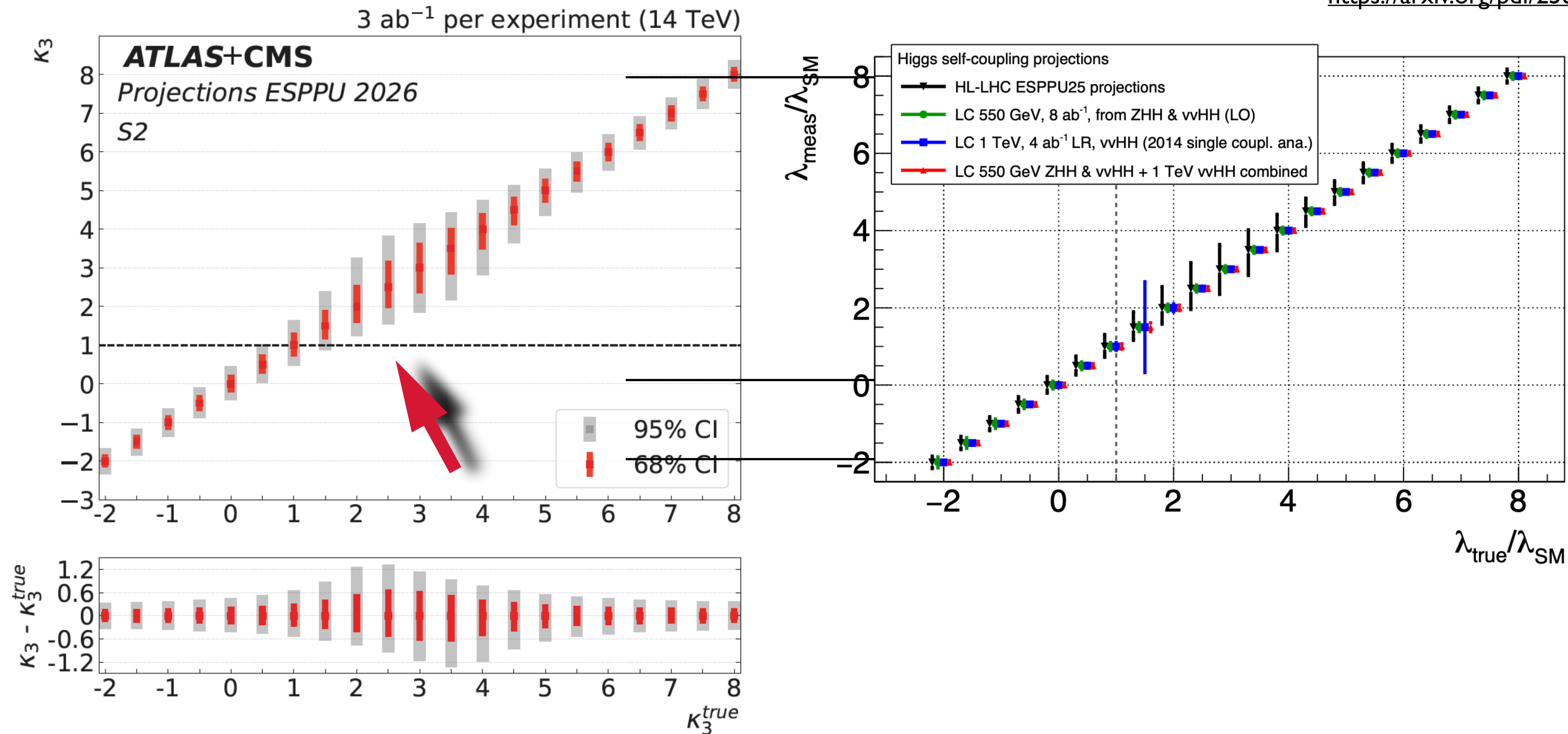
ATLAS+CMS Projections for non SM k_3



We can exclude at more than 2 sigma the $k_3=1$ around $k_3 \sim 2.5$, where we have maximal interference among box and triangle diagrams

ATLAS+CMS Projections for k_3

<https://arxiv.org/pdf/2503.19983v2>



Comparison
with Linear Collider

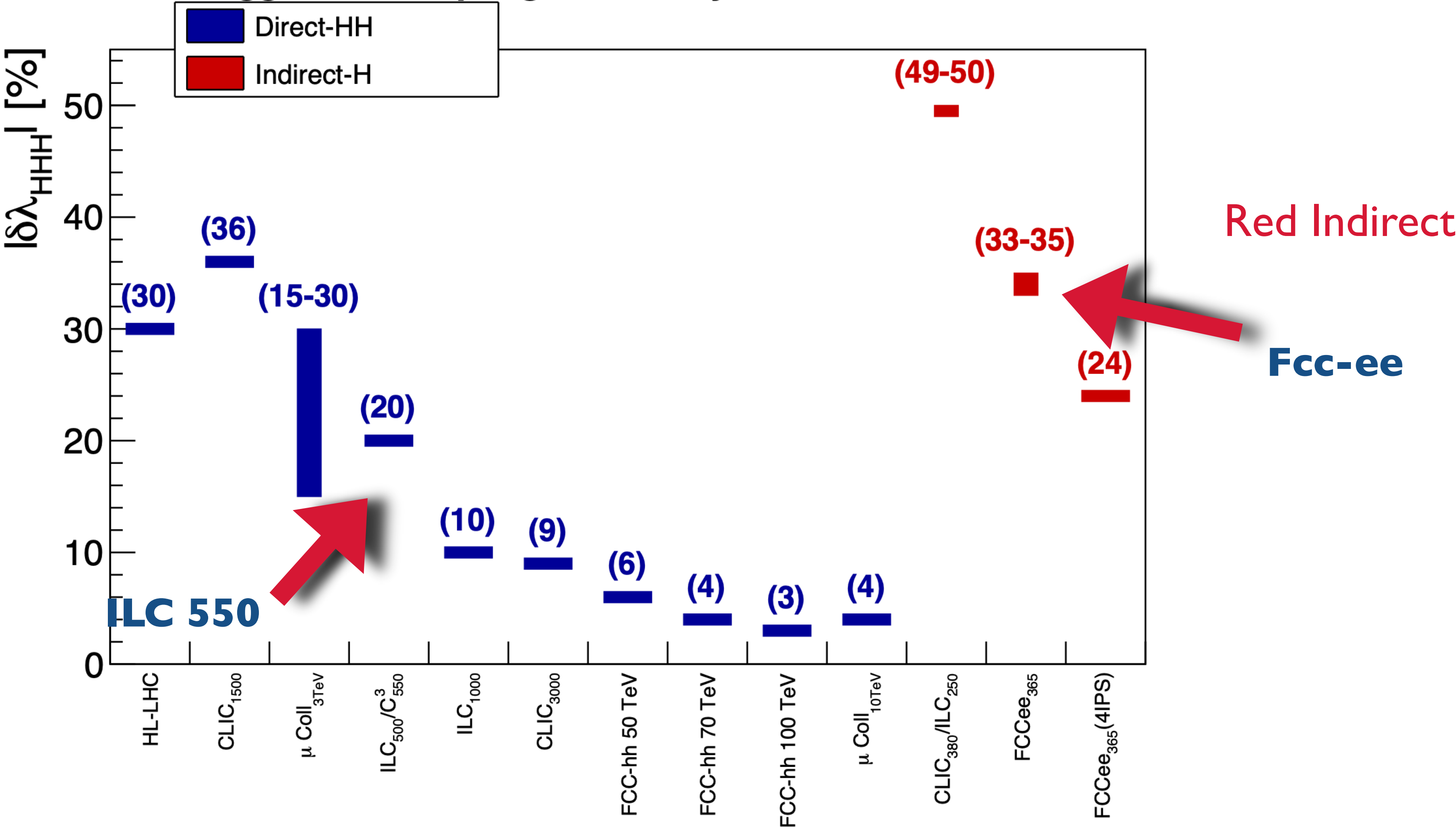
We can exclude at more than 2 sigma the $k_3=1$ around $k_3 \sim 2.5$,
where we have maximal interference among box and triangle diagrams

di-higgs precision European Strategy 2025

<https://indico.cern.ch/event/1439855/contributions/6461643/attachments/3046021/5381998/NearTermProtonCollider.pdf>

Higgs Self-Coupling Sensitivity at Future Colliders

Blue direct



Fcc-hh % precision on k_λ

- assuming $s = 100\text{TeV}$, $\mathcal{L}_{\text{int}} = 30\text{ ab}^{-1}$ @68%CL

Mangano,Ortona,Selvaggi,Eur. Phys. J. C80 (2020)]

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
syst	1.6	3.0	5.4
tot	3.4	5.1	7.8

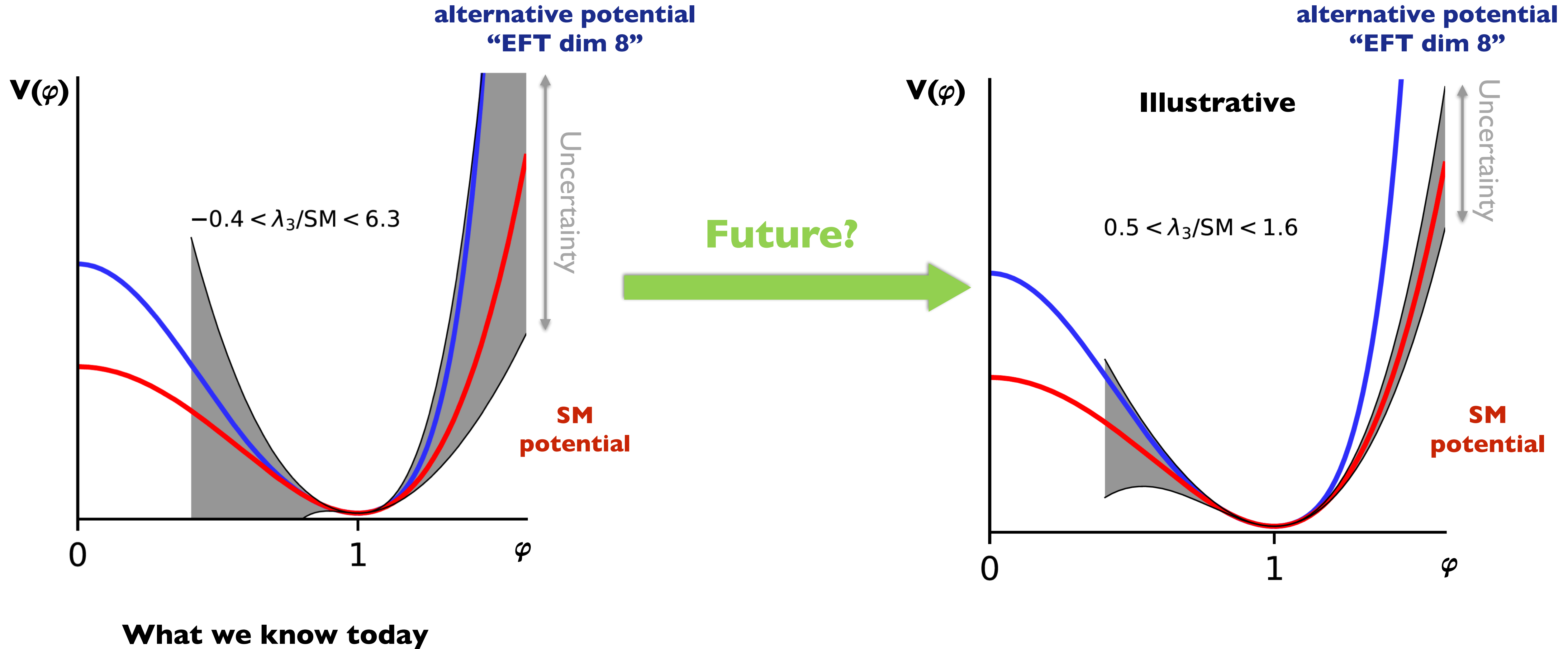
- Scenario I: Optimistic – target detector performance, similar to Run 2 LHC conditions.
- Scenario II: Realistic – intermediate detector performance.
- Scenario III: Conservative – pessimistic detector performance, assuming extrapolated HL-LHC performance using present-day algorithms.

Mangano,FCC-hhStudiesforNextEuropStrategyKick.off,9/24

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	3.8	5.6	8.4

- ➡ decreasing to 80 TeV the centre of mass energy.
- ➡ Interesting options also at 60 TeV
- ➡ both can be achieved with 12 Tesla existing magnet technology)

the Higgs Potential



Generic BSM potential & First Order Phase Transition (FOPT)

Consider a sufficiently general class of (non-SM) EWSB potentials, for which it is known whether they lead to a first-order phase transition, and determine their predictions for k_3 , the Higgs self coupling.

Effective Field Theories (EFT):

- EFT dim 6 (k_3 and k_4 are not independent)
- EFT dim 8 (k_3 and k_4 independent)

$$V_6^{\text{SMEFT}}(\phi) = \frac{1}{8} (\phi^2 - 1)^2 + \frac{k_3 - 1}{16} (\phi^2 - 1)^3,$$

$$V_8^{\text{SMEFT}}(\phi) = \frac{1}{8} (\phi^2 - 1)^2 + \frac{k_3 - 1}{16} (\phi^2 - 1)^3 + \frac{k_4 - 6k_3 + 5}{128} (\phi^2 - 1)^4.$$

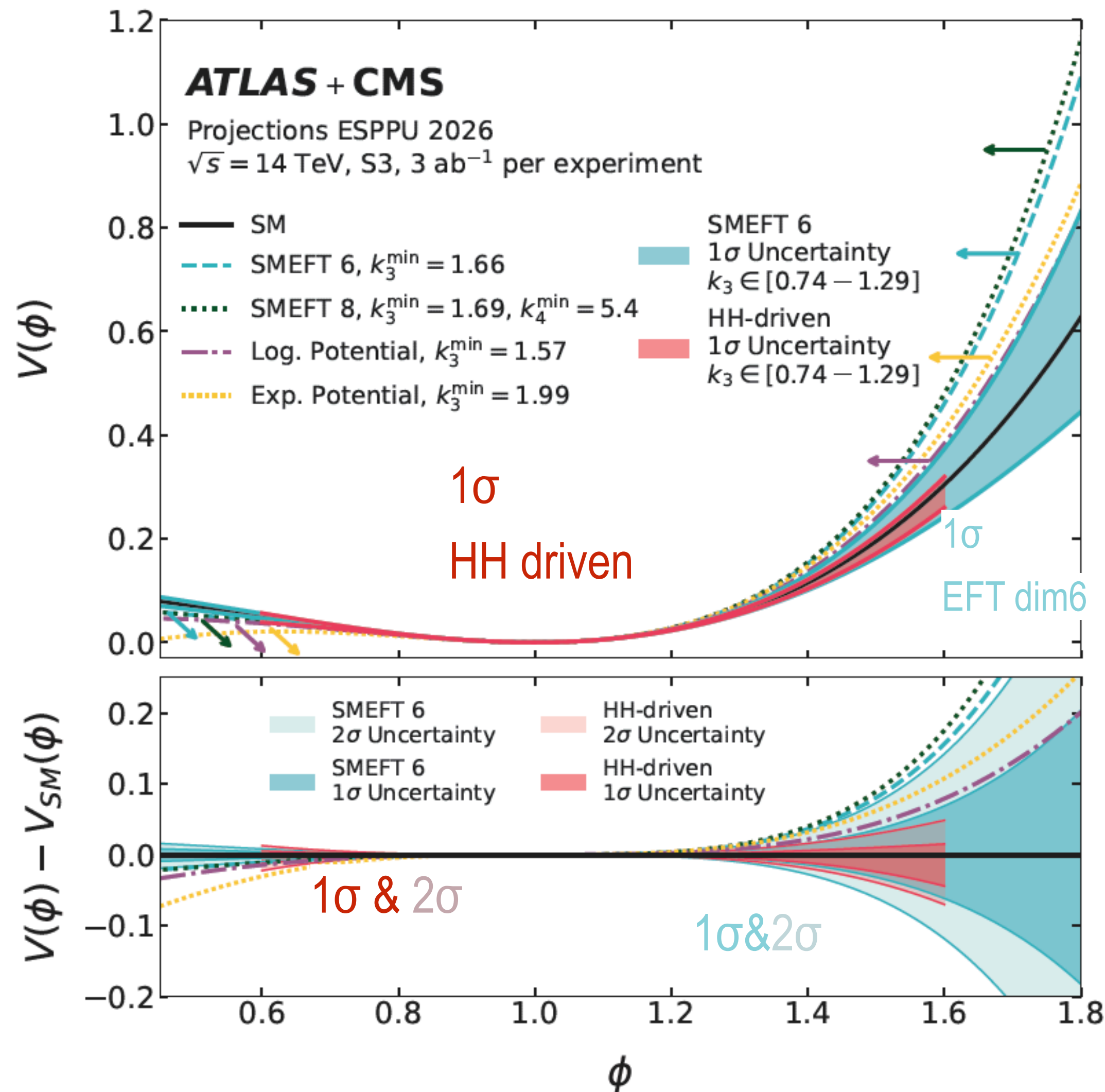
Logarithmic Potential

$$V^{\text{CW}}(\phi) = \frac{1}{8} (\phi^2 - 1)^2 + \frac{3}{8} (k_3 - 1) \left[\left(\frac{1}{2} \phi^4 - 1 \right) - \phi^2 \log \phi^2 \right].$$

Exponential Potential

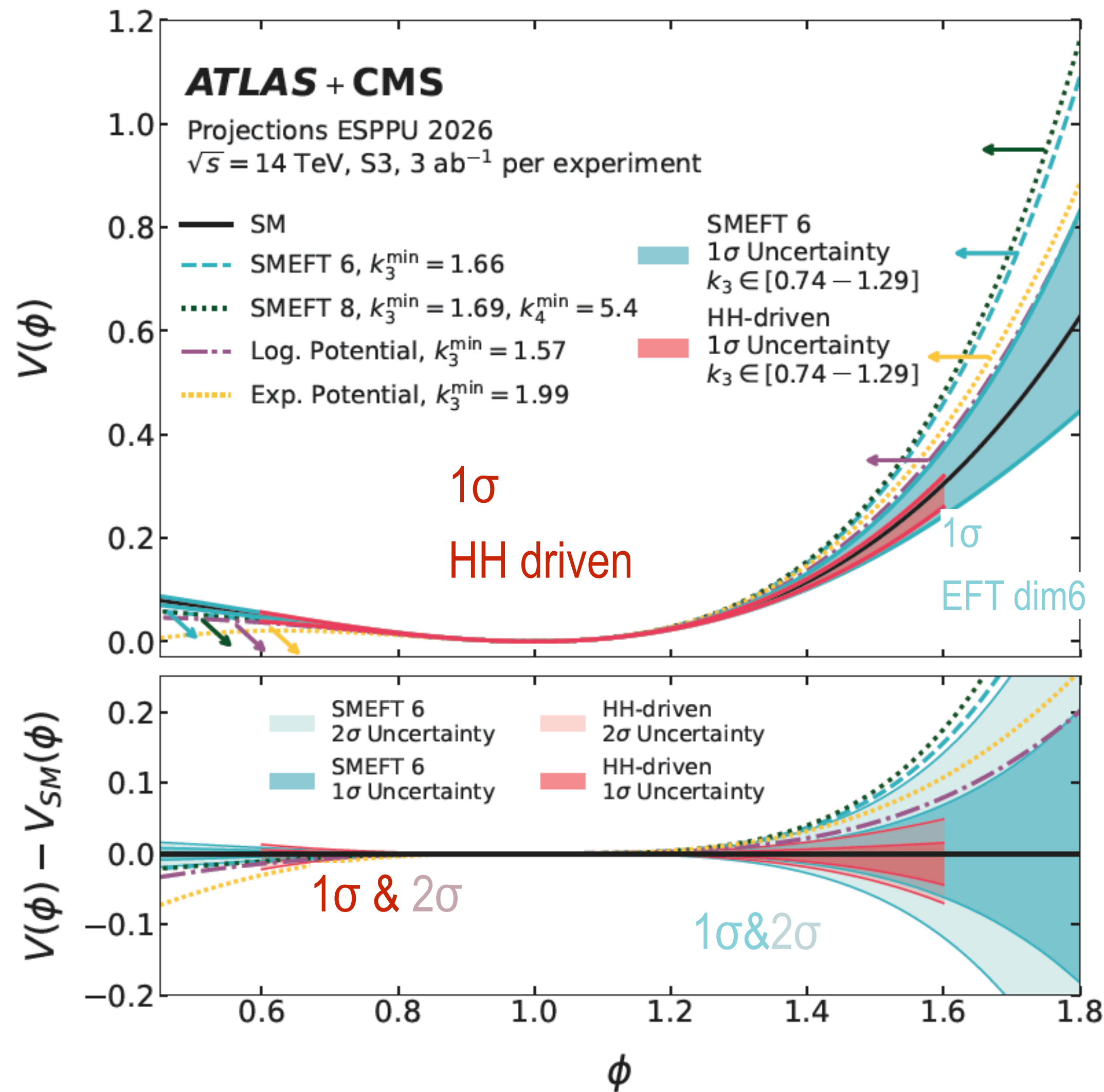
$$V^I(\phi) = \frac{1}{8} (\phi^2 - 1)^2 \pm \phi^4 e^{-\frac{2}{c_I \phi^2}} + \frac{e^{-2/c_I} \pm (-(c_I(c_I + 2) + 2)\phi^4 + 2(c_I + 2)\phi^2 - 2)}{c_I^2}$$

Higgs potential and generic model strong FOPT

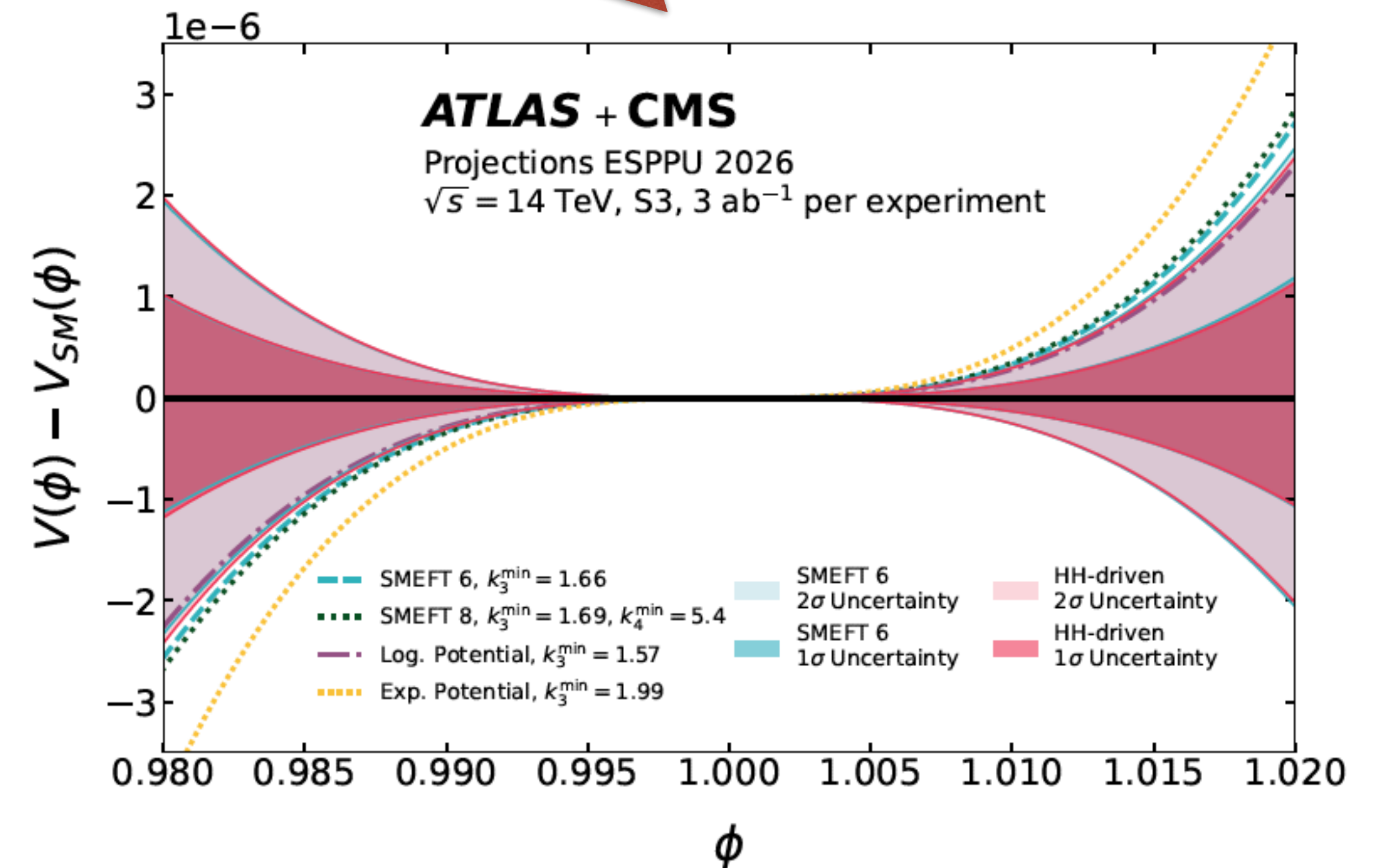


Around the minimum: all potentials coincide,
the HH driven curve is valid only around the minimum.
It is experimentally driven and agnostic of k_4 values

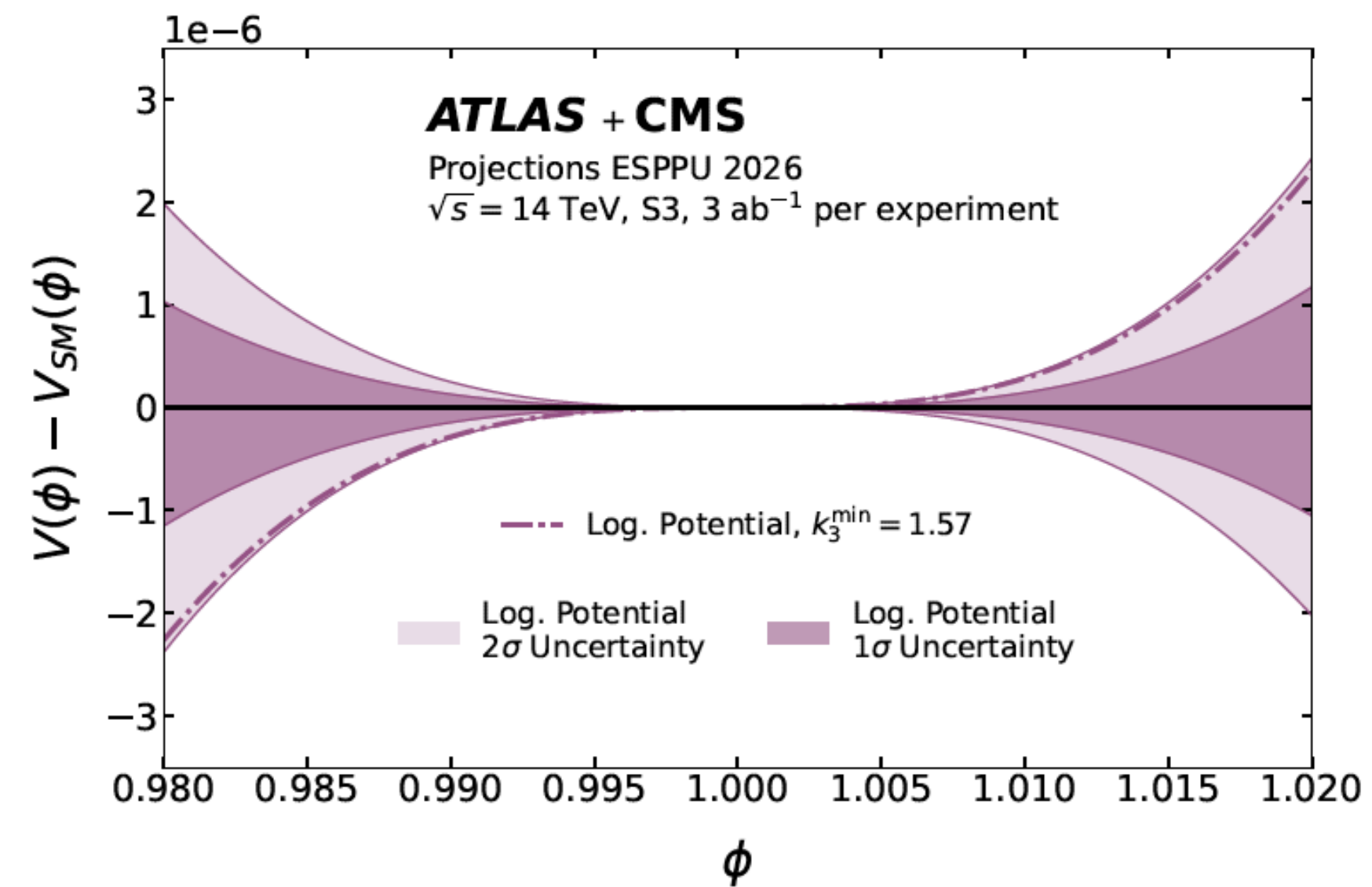
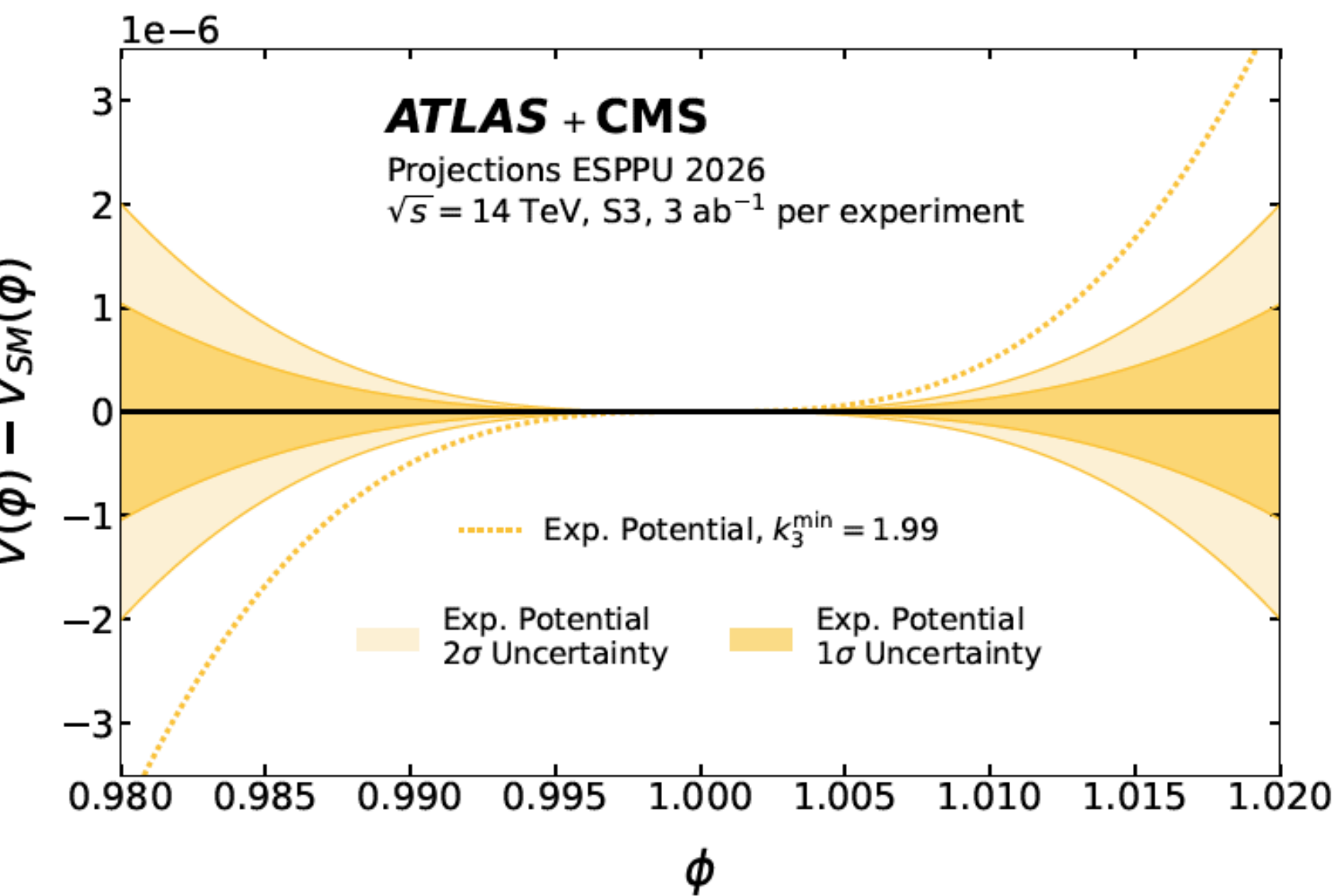
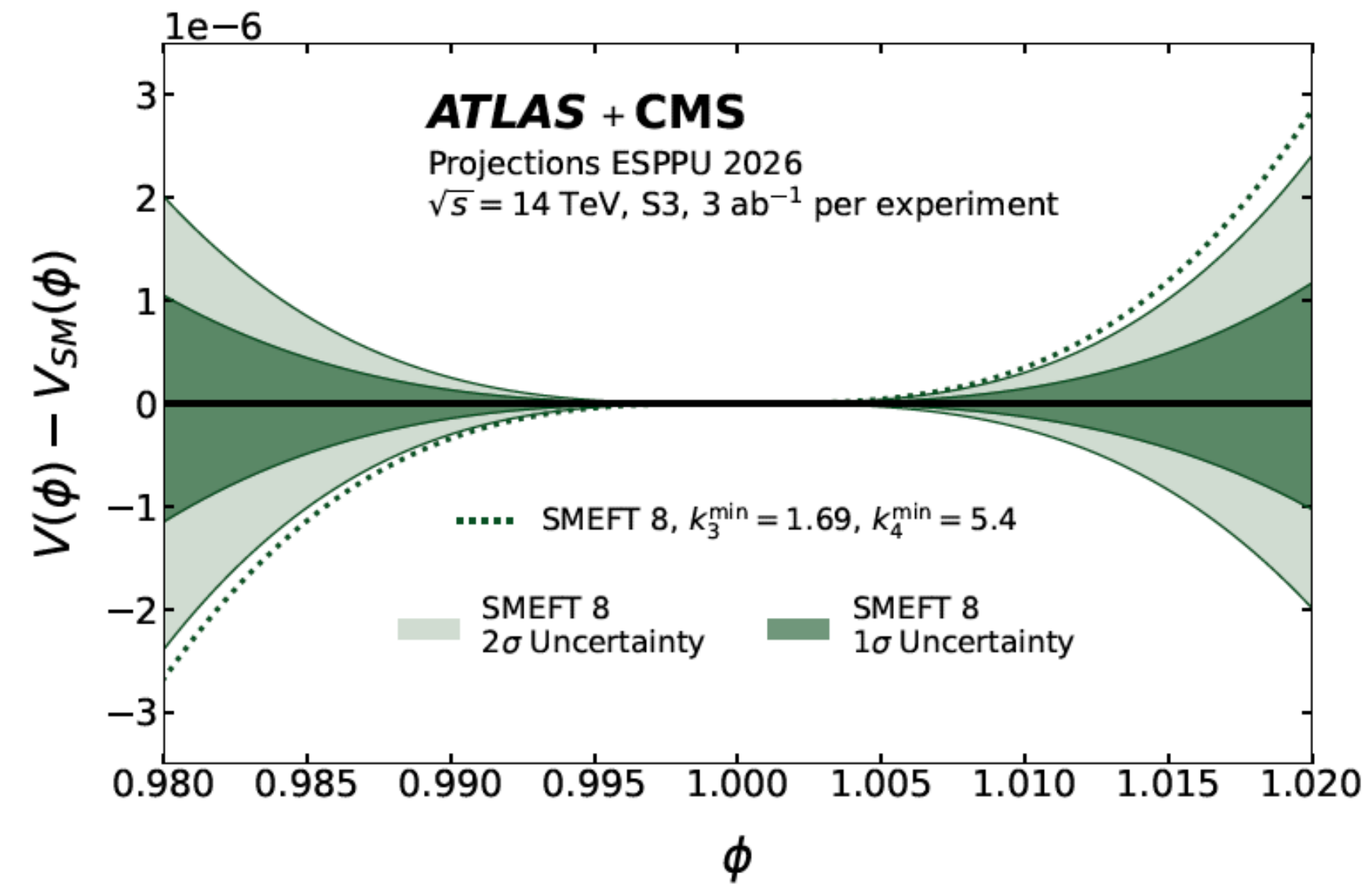
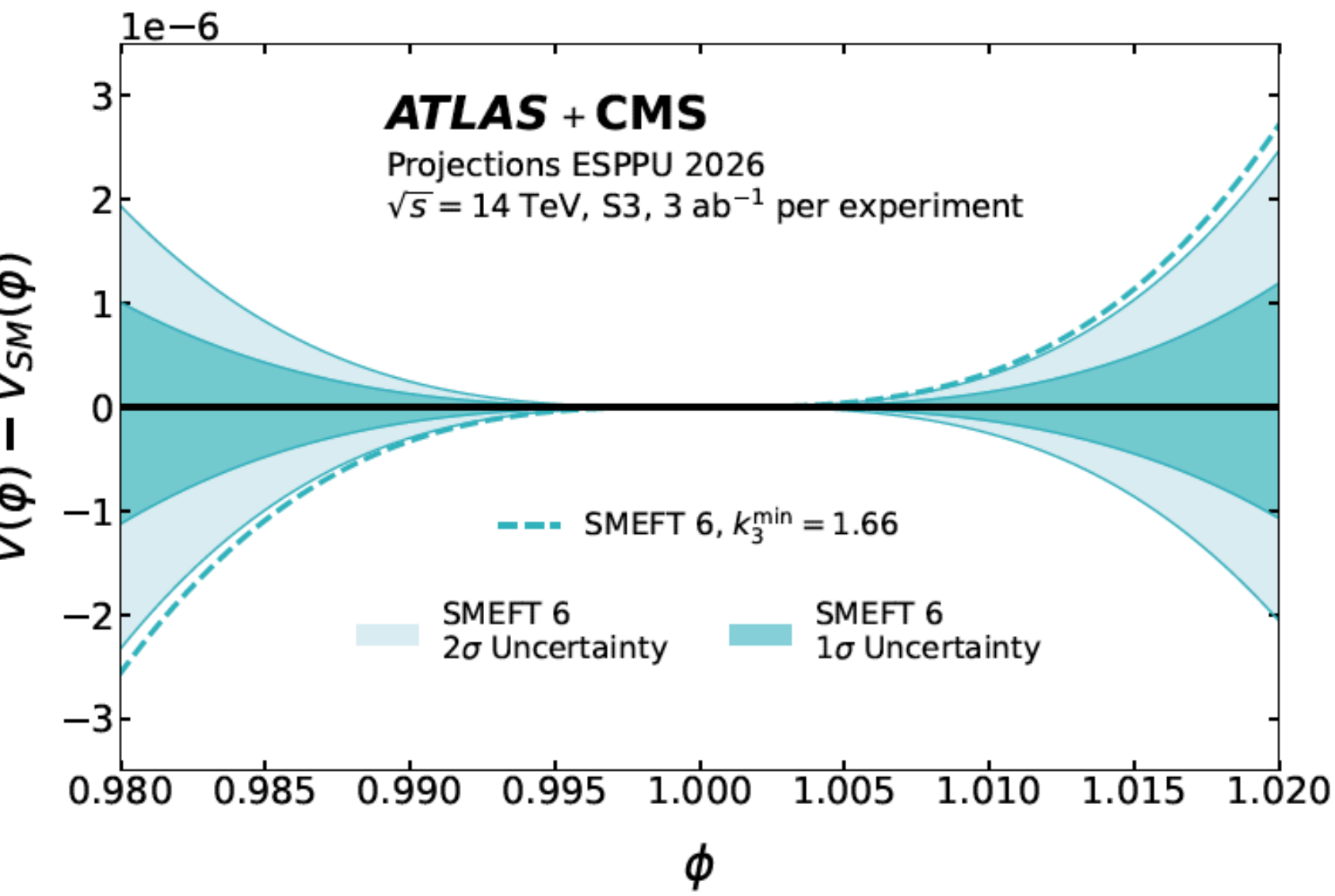
Higgs potential and generic model strong FOPT



Around the minimum: all potentials coincide,
Zoomed version shows that the red curve
that is data driven excludes fully all FOPT!



3 ab⁻¹ Strong FOPT

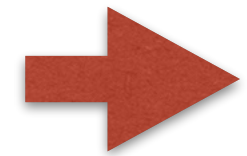


For the exclusion within each individual potential “model” we have to compare the dashed lines with the respective error band

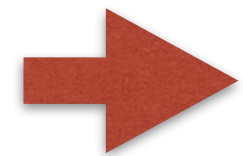
A specific model implementation

Scalar Singlet Model and FOPT

$$V(\Phi, S) = -\mu_H^2 |\Phi|^2 + \lambda_H |\Phi|^4 + b_1 S - \frac{\mu_S^2}{2} S^2 + \frac{b_4}{4} S^4 + \frac{a_2}{2} |\Phi|^2 S^2 + \frac{b_3}{3} S^3 + \frac{a_1}{2} |\Phi|^2 S.$$



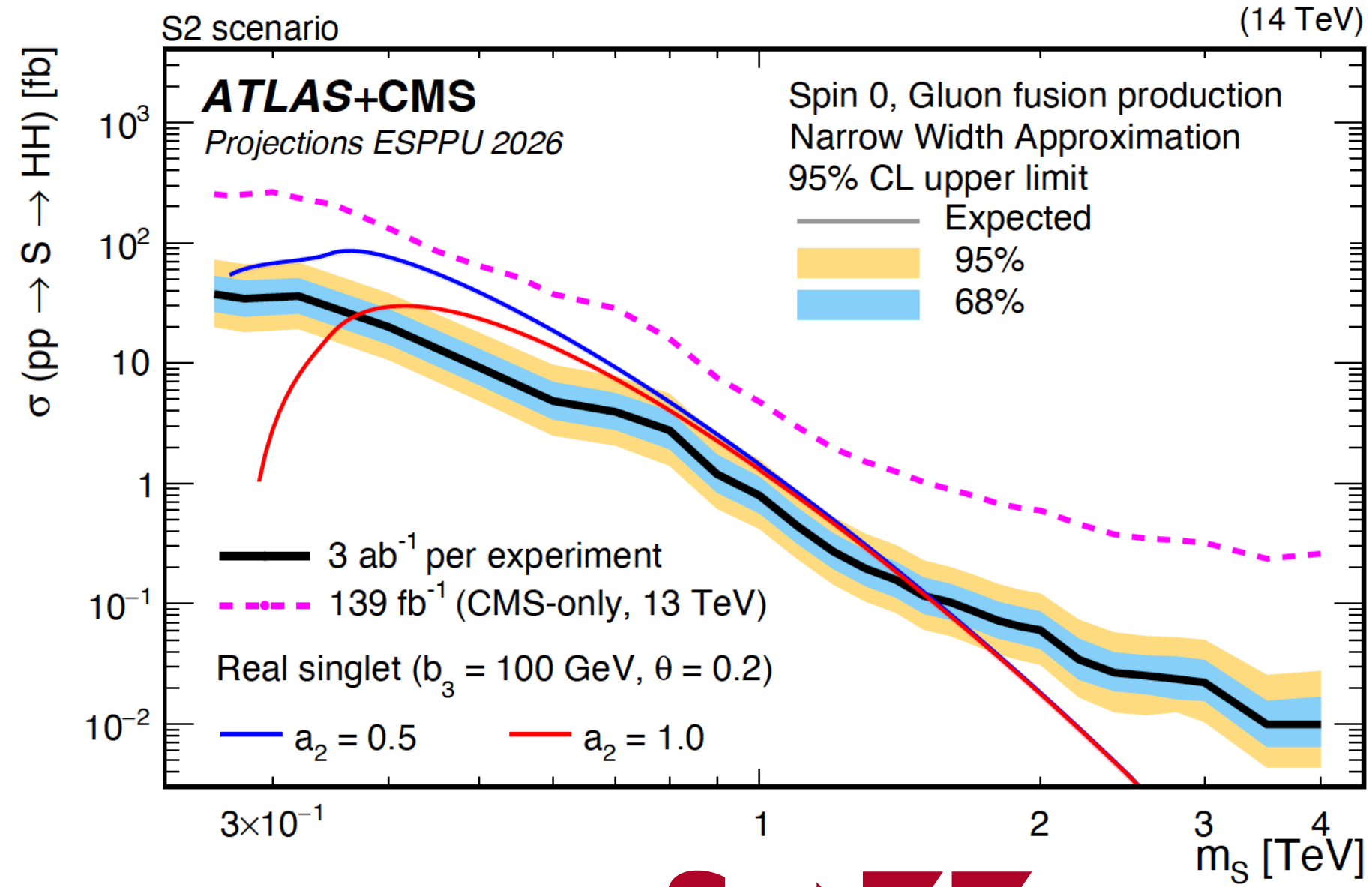
Specific model:
Consider generic model with addition Real Scalar singlet



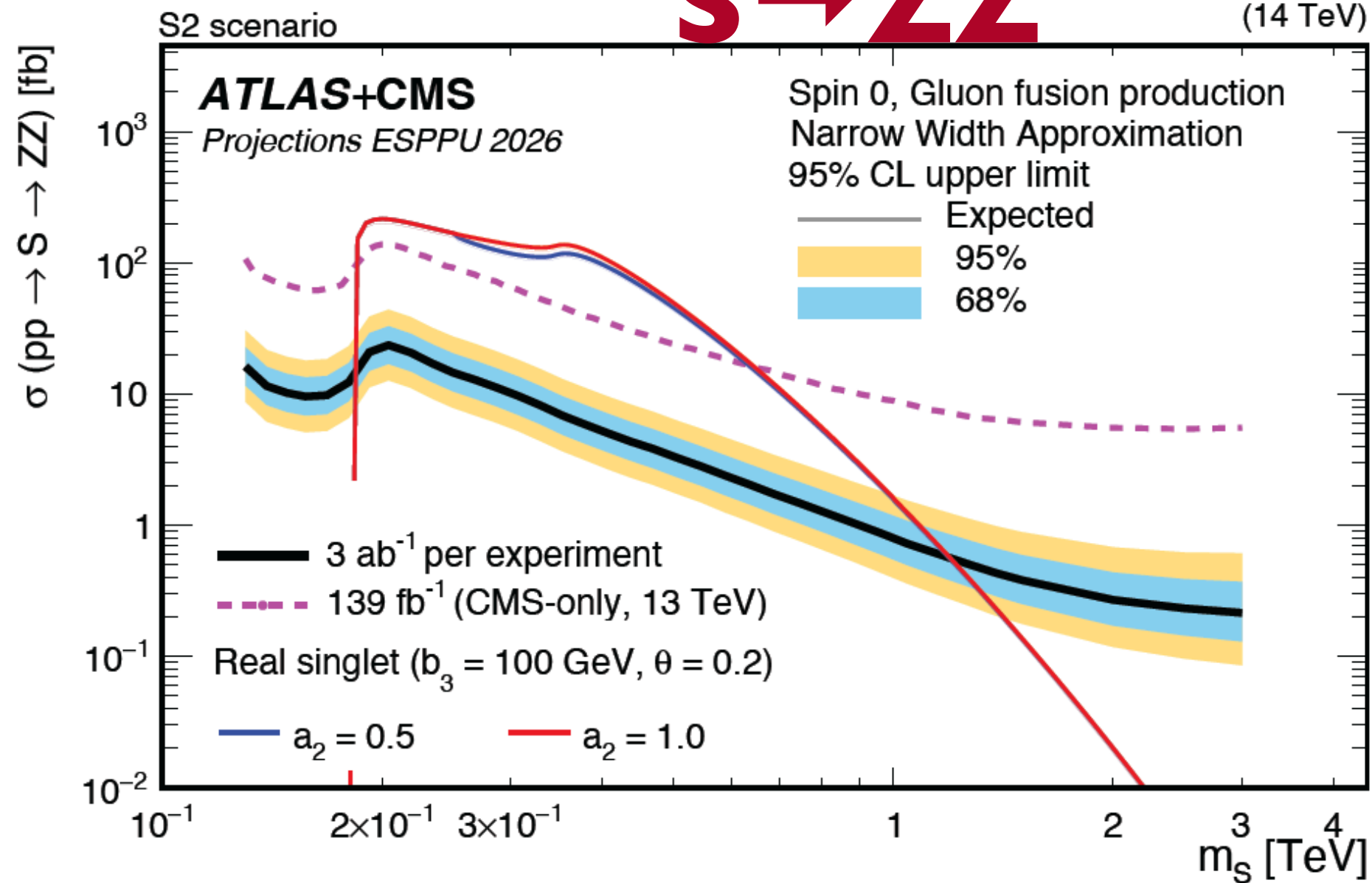
The singlet can decay to
 $S \rightarrow HH/ZZ, ttS \rightarrow tttt$

Scalar resonant searches $S \rightarrow HH/ZZ$, $ttS \rightarrow 4t$

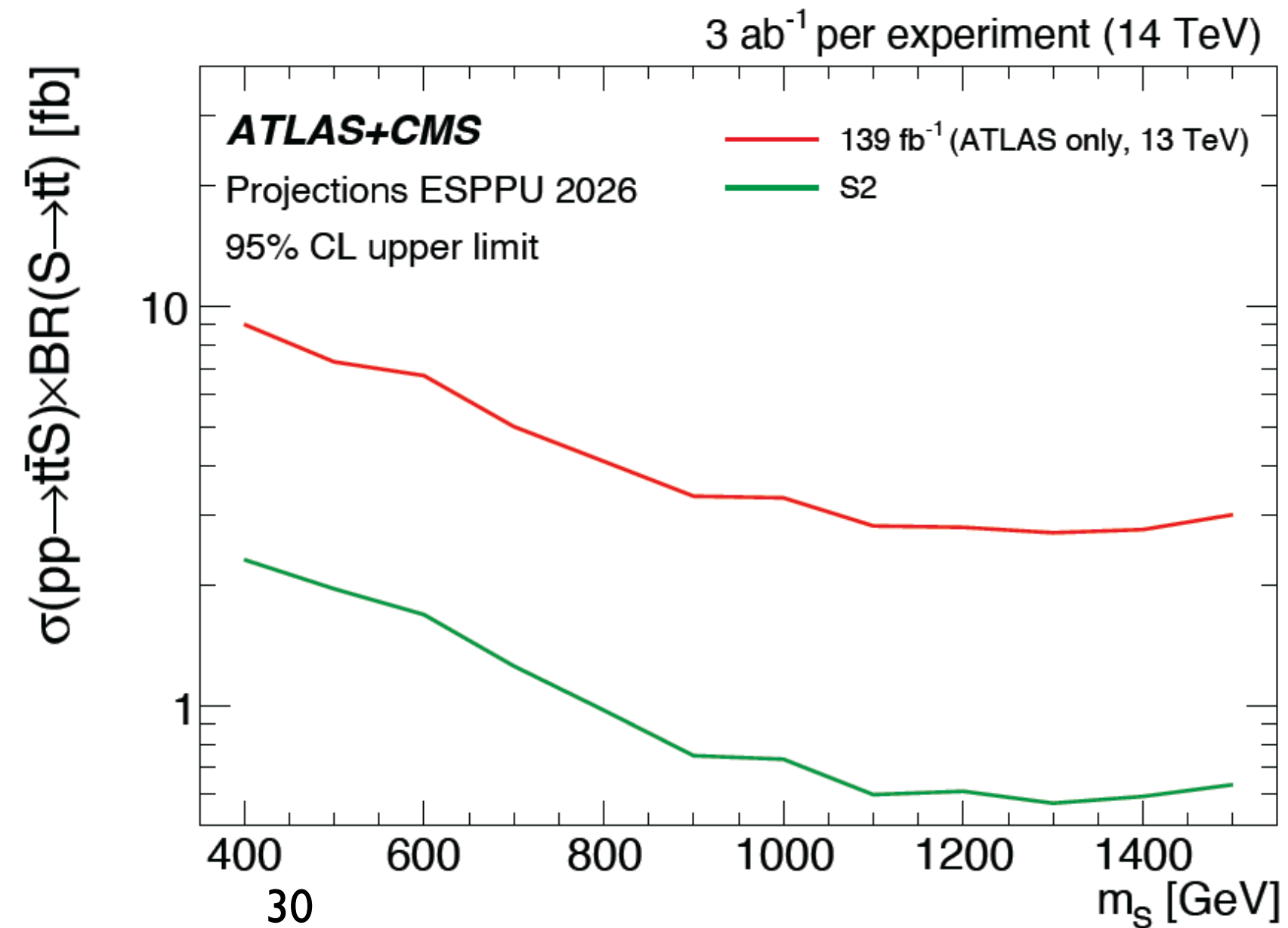
$S \rightarrow HH$



$S \rightarrow ZZ$

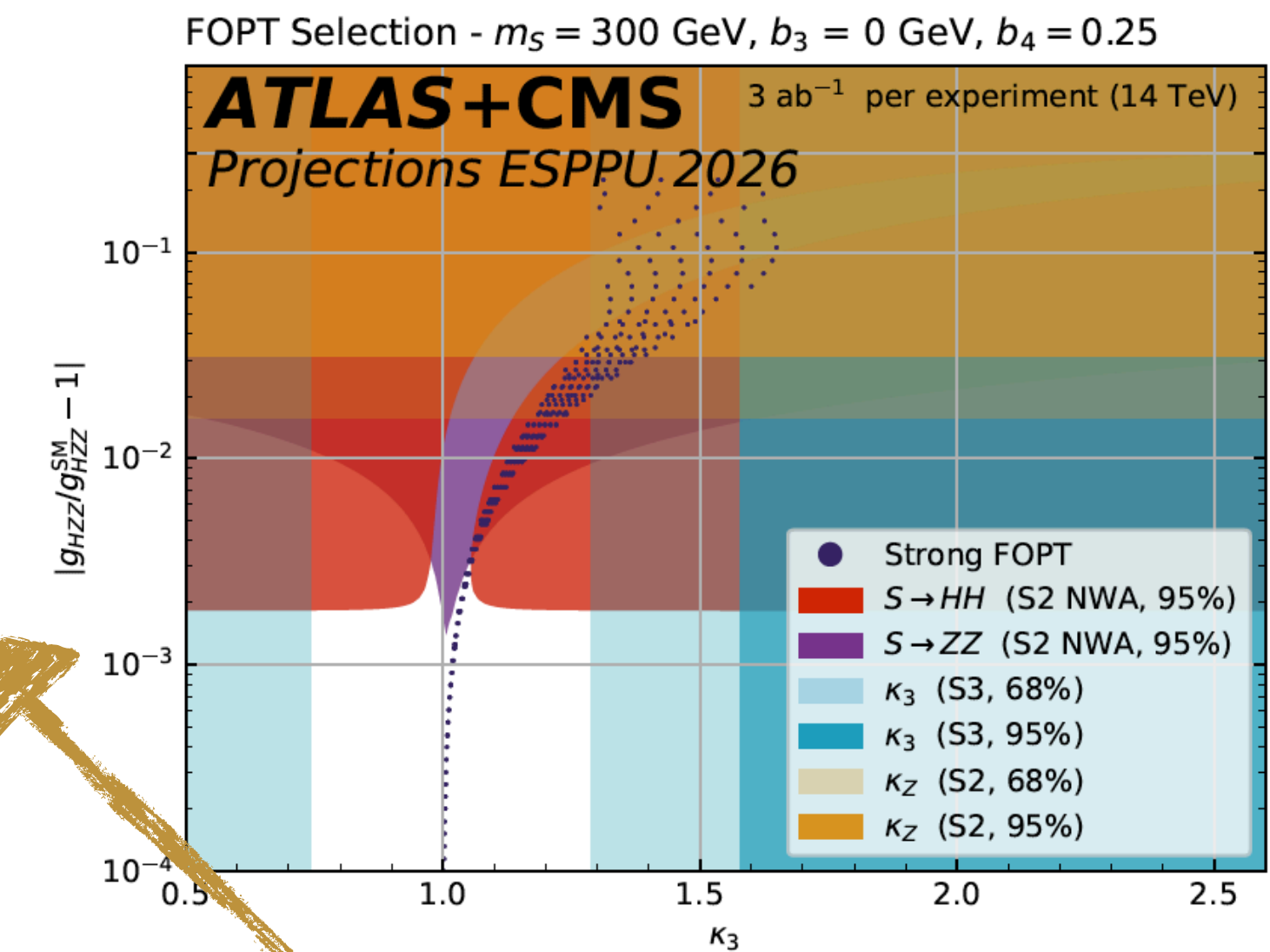
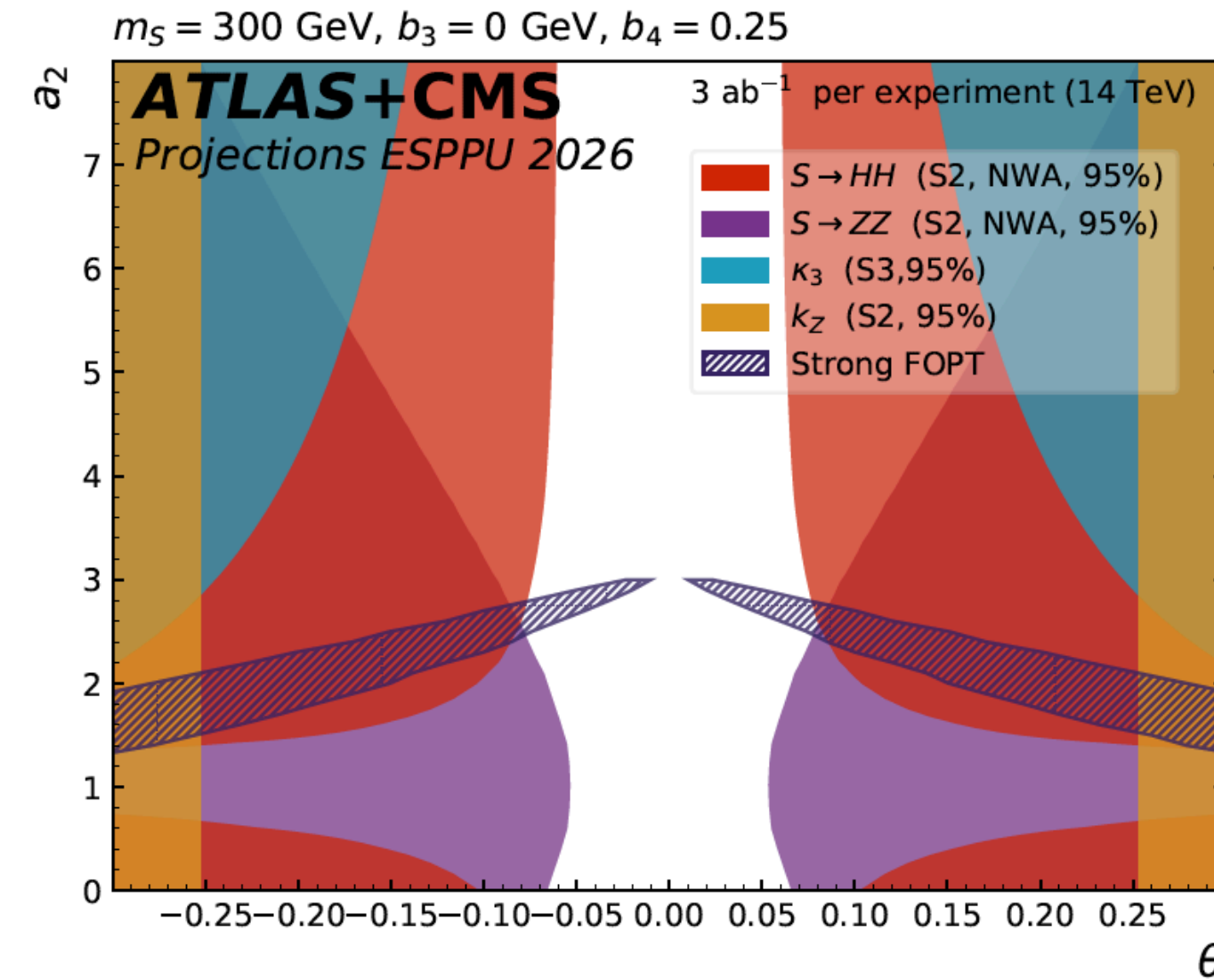


$ttS \rightarrow 4t$

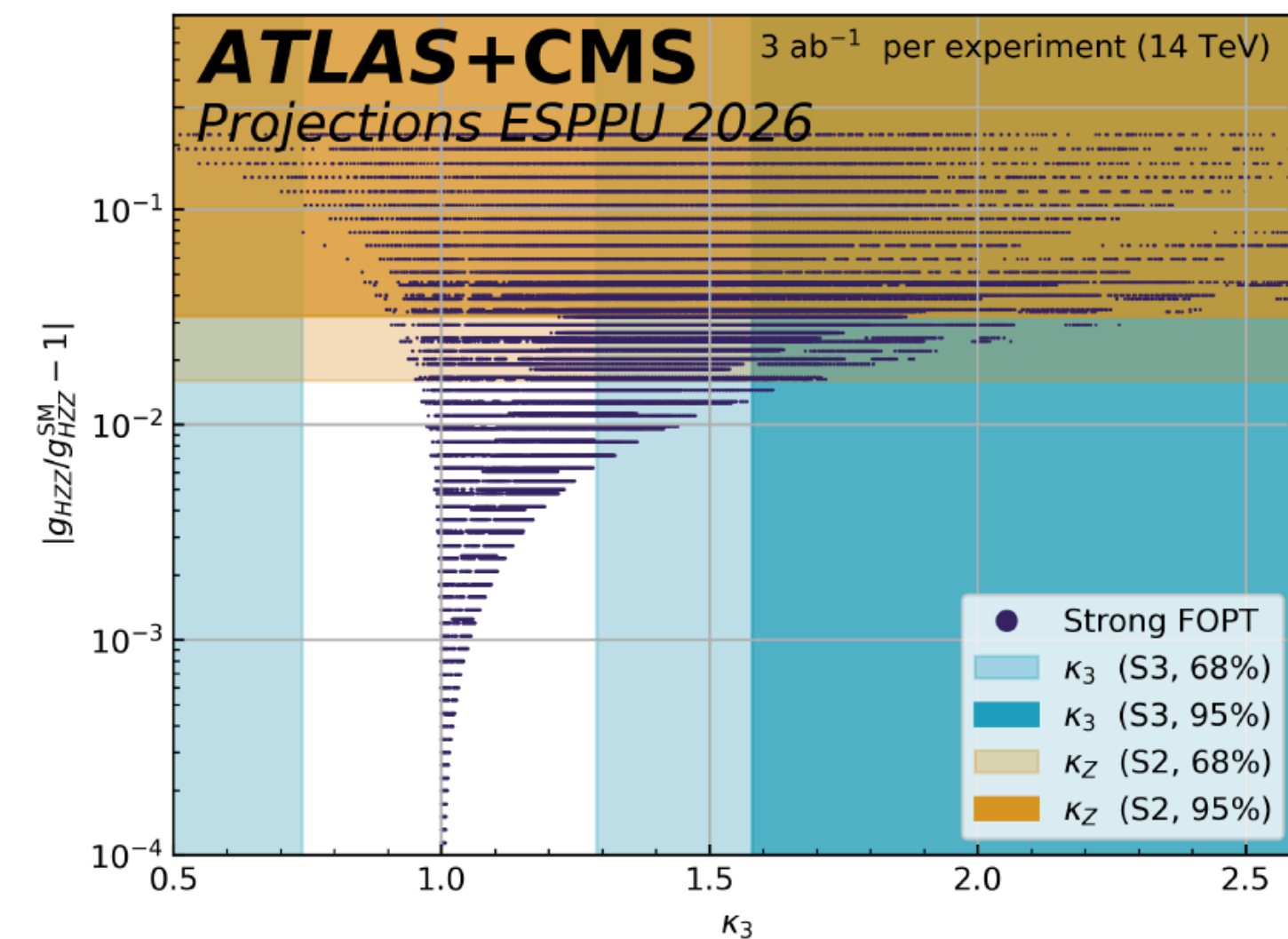


Scalar Singlet Model and FOPT

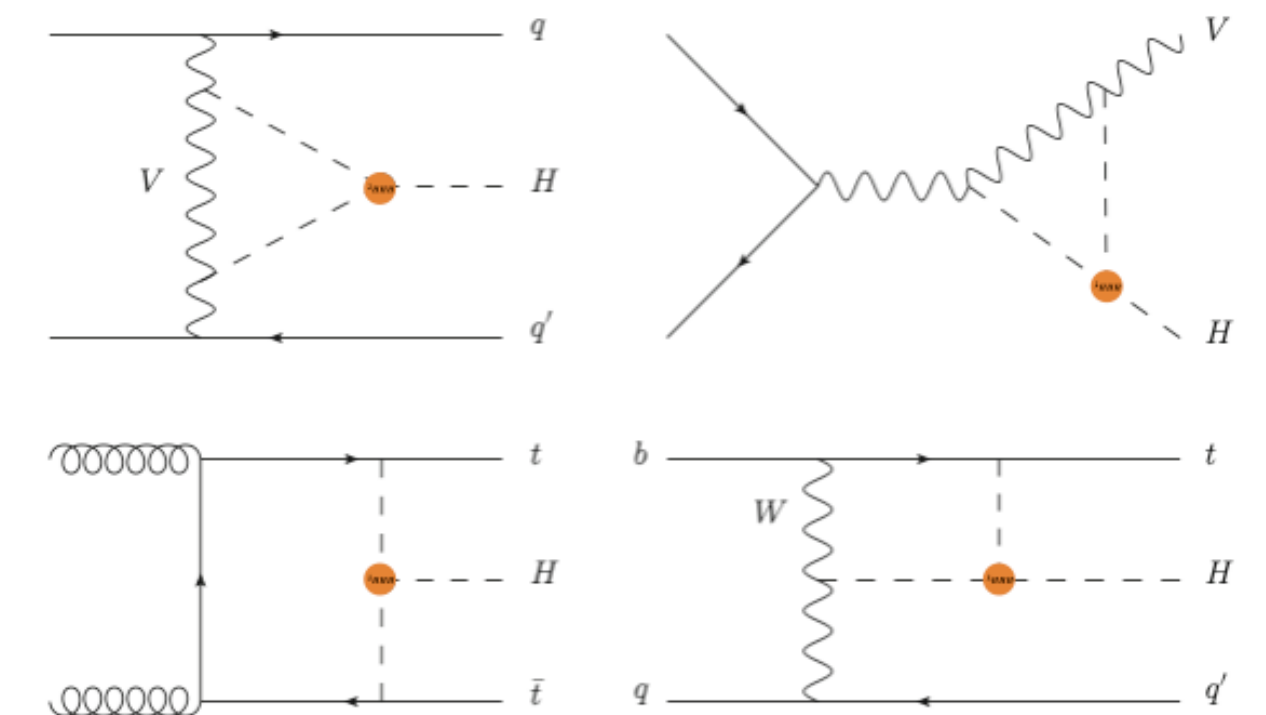
Conservative choice of model parameters



Full FOPT exclusion in other regions!



Single H boson production includes processes sensitive to the Higgs self couplings at NLO EW correction level. Constraint from κ_Z useful

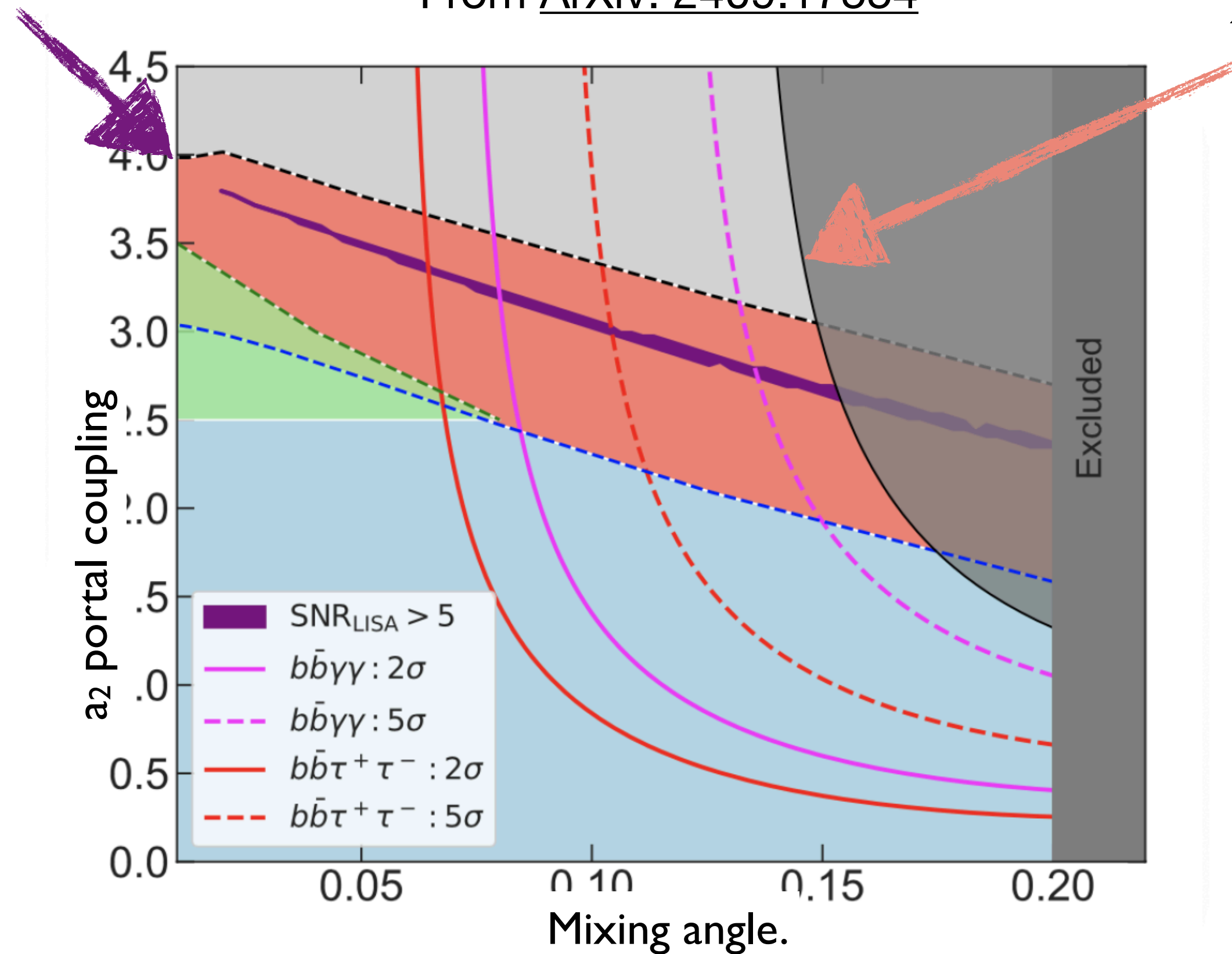


Comparison with Lisa sensitivity

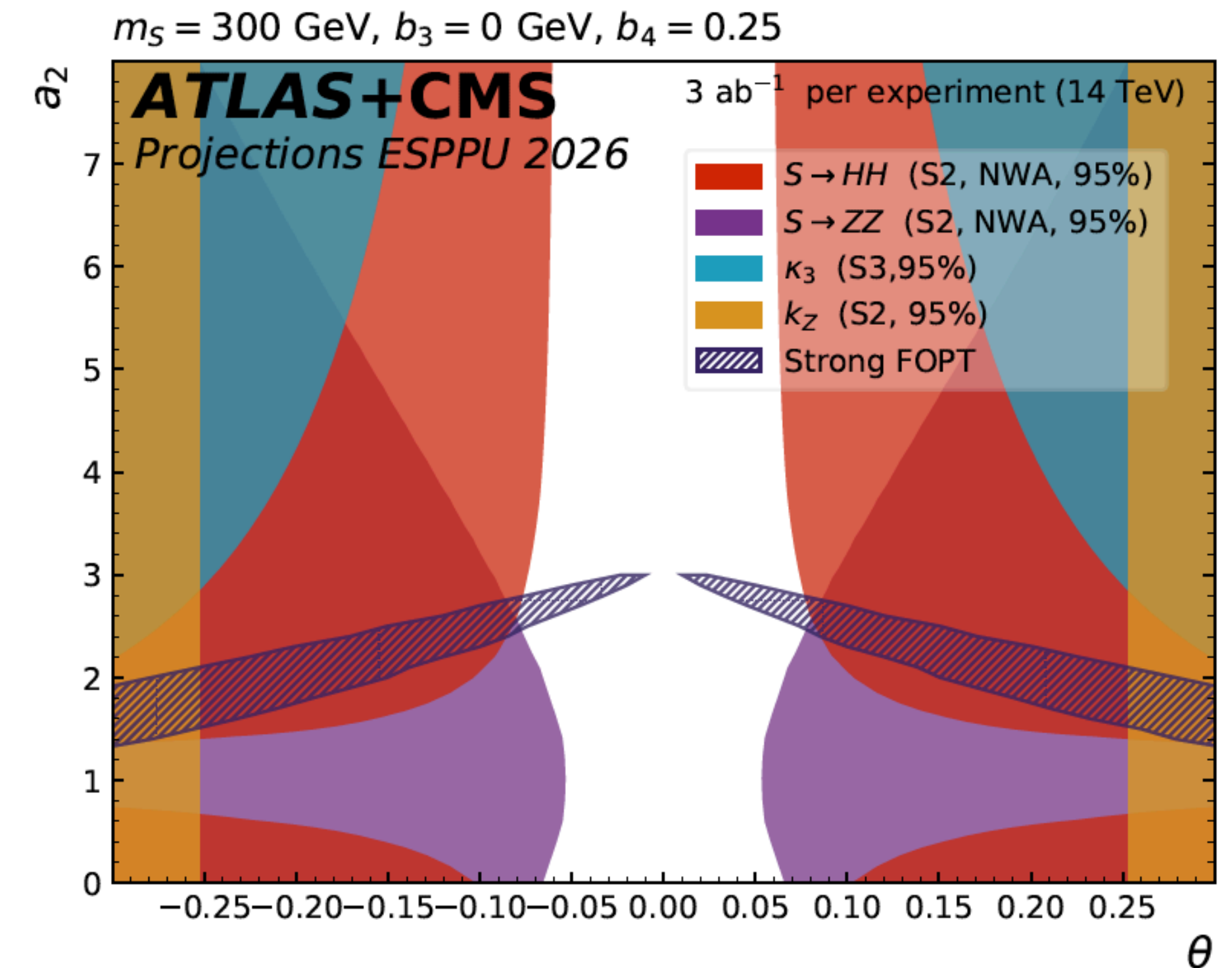
Gravitational waves experiment:

Lisa sensitivity

From [ArXiv: 2409.17554](#)

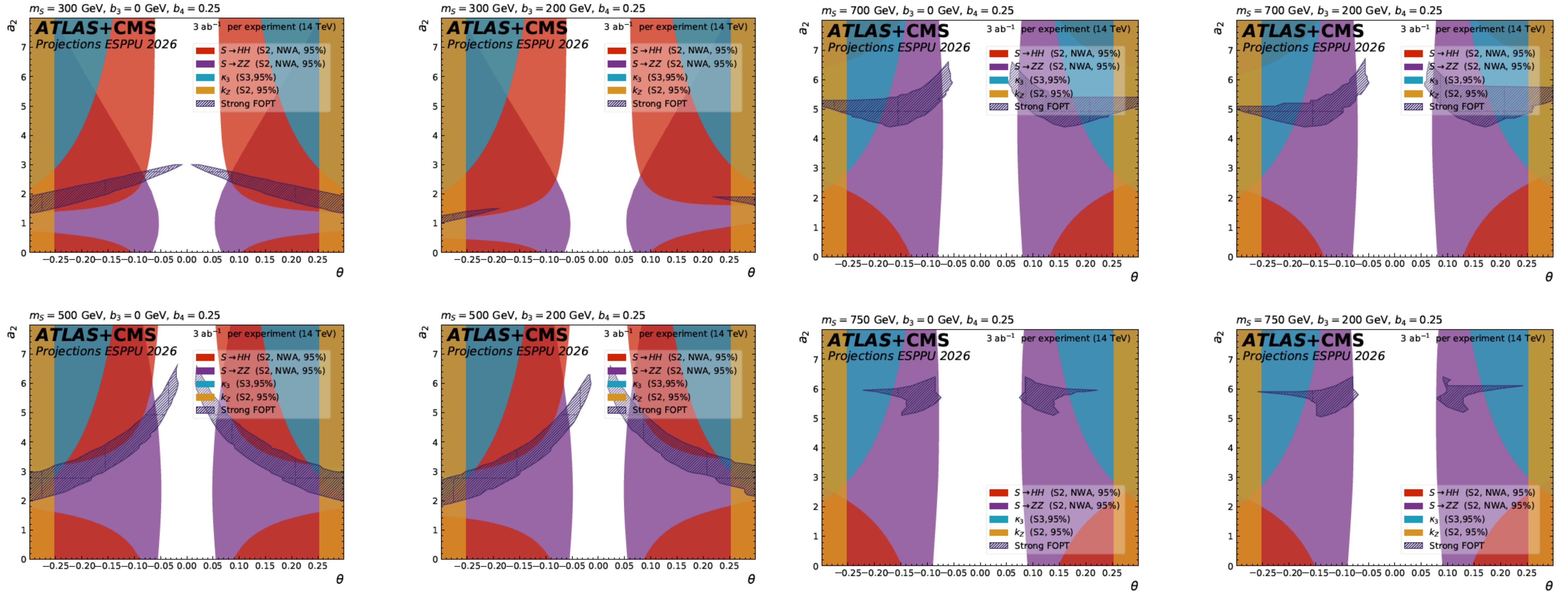


Models implying the existence of an additional scalar singlet that would imply a strong 1st order phase transition (orange region)



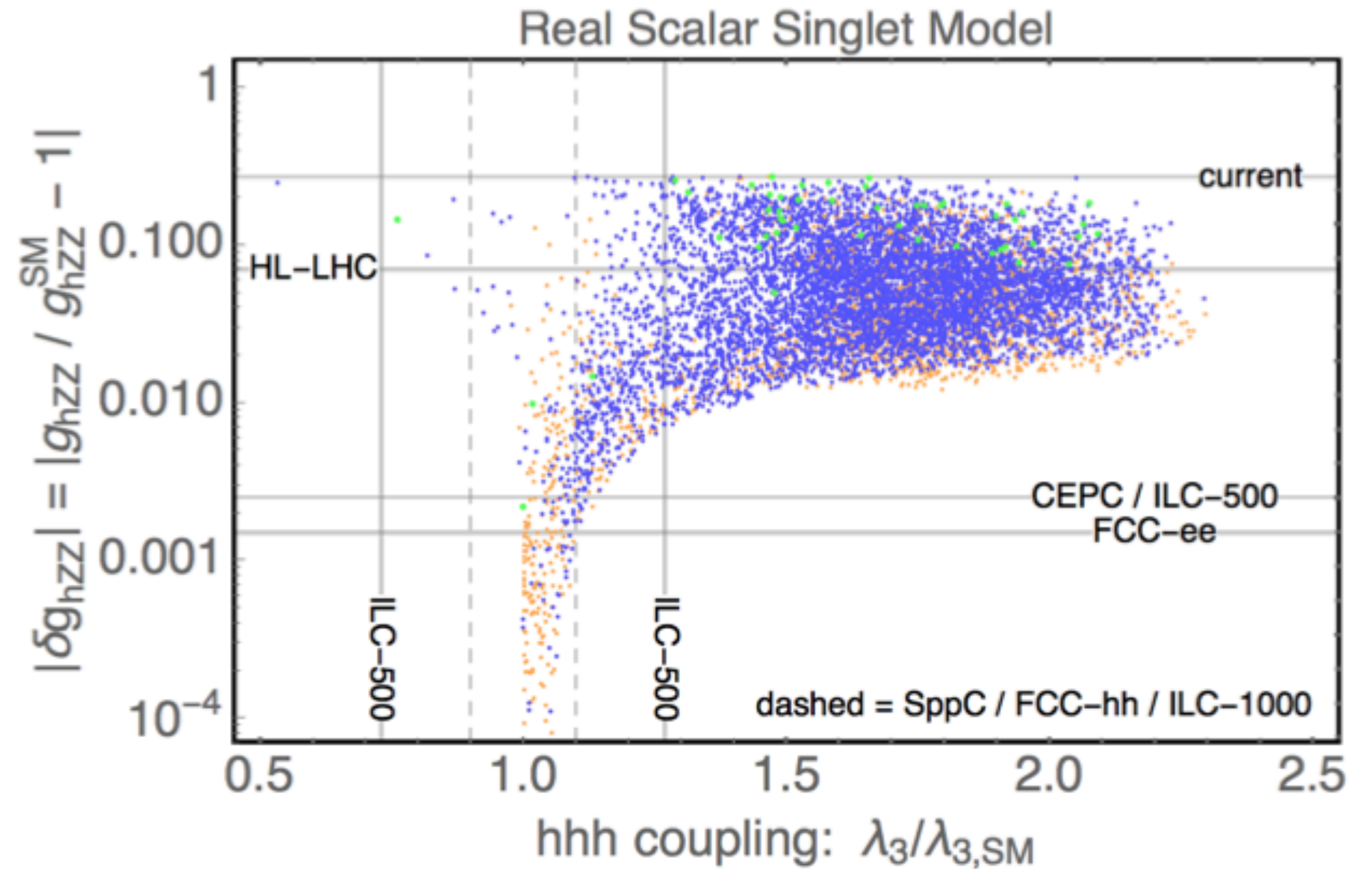
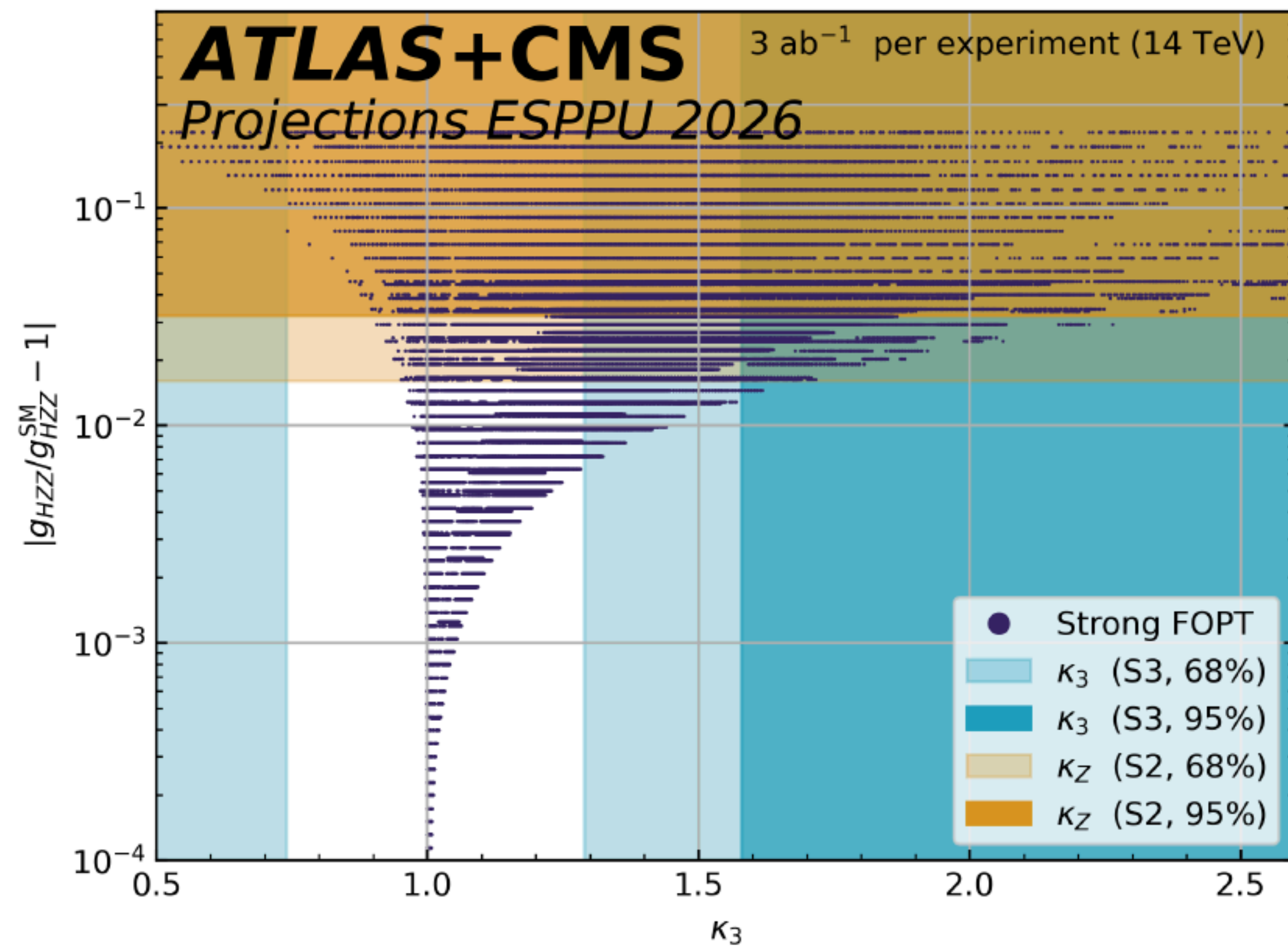
Nice complementarity with Gravitational Wave experiments

sample of different model parameters



Scalar Singlet FOPT exclusion by HZZ and k_3

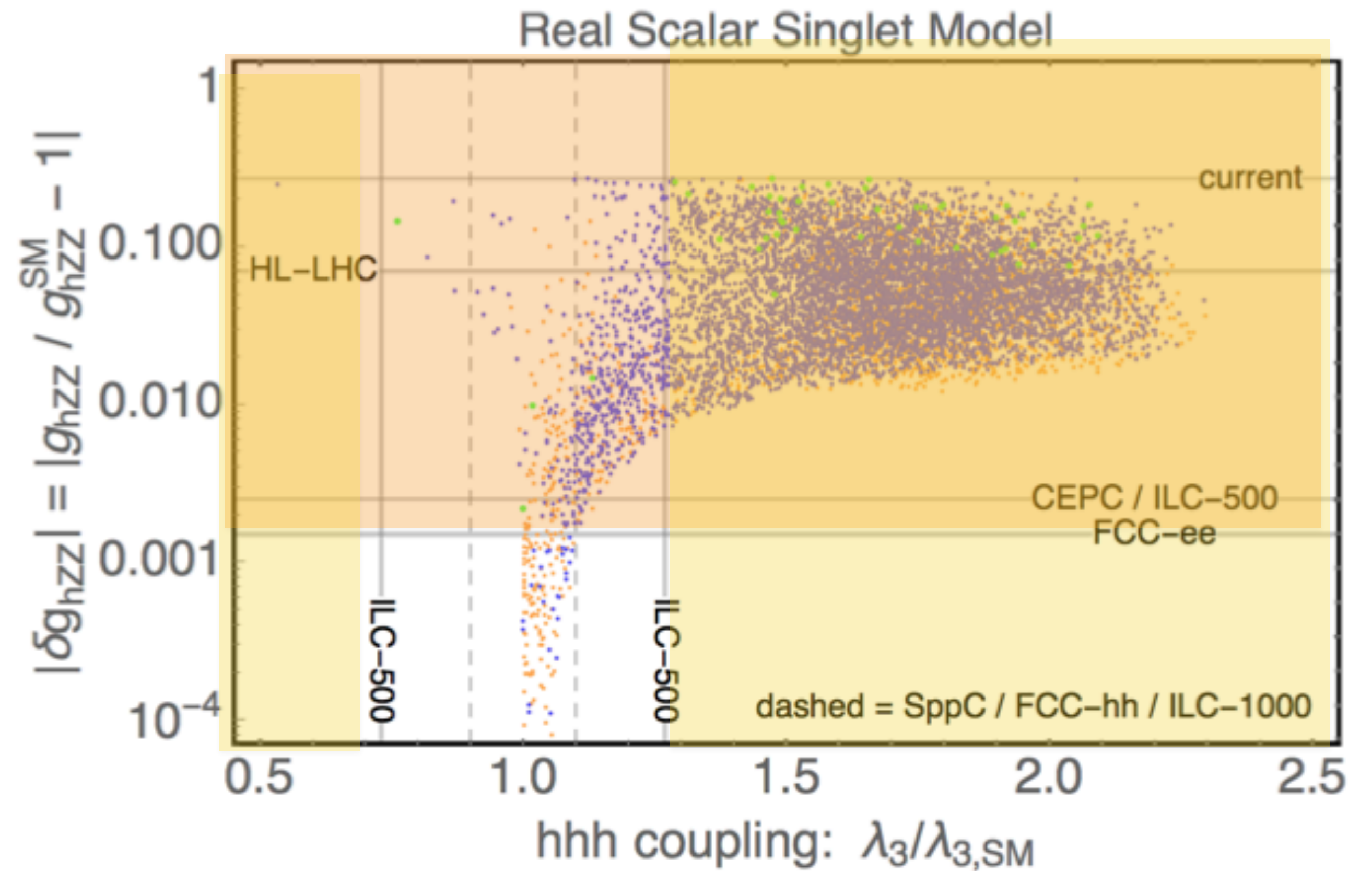
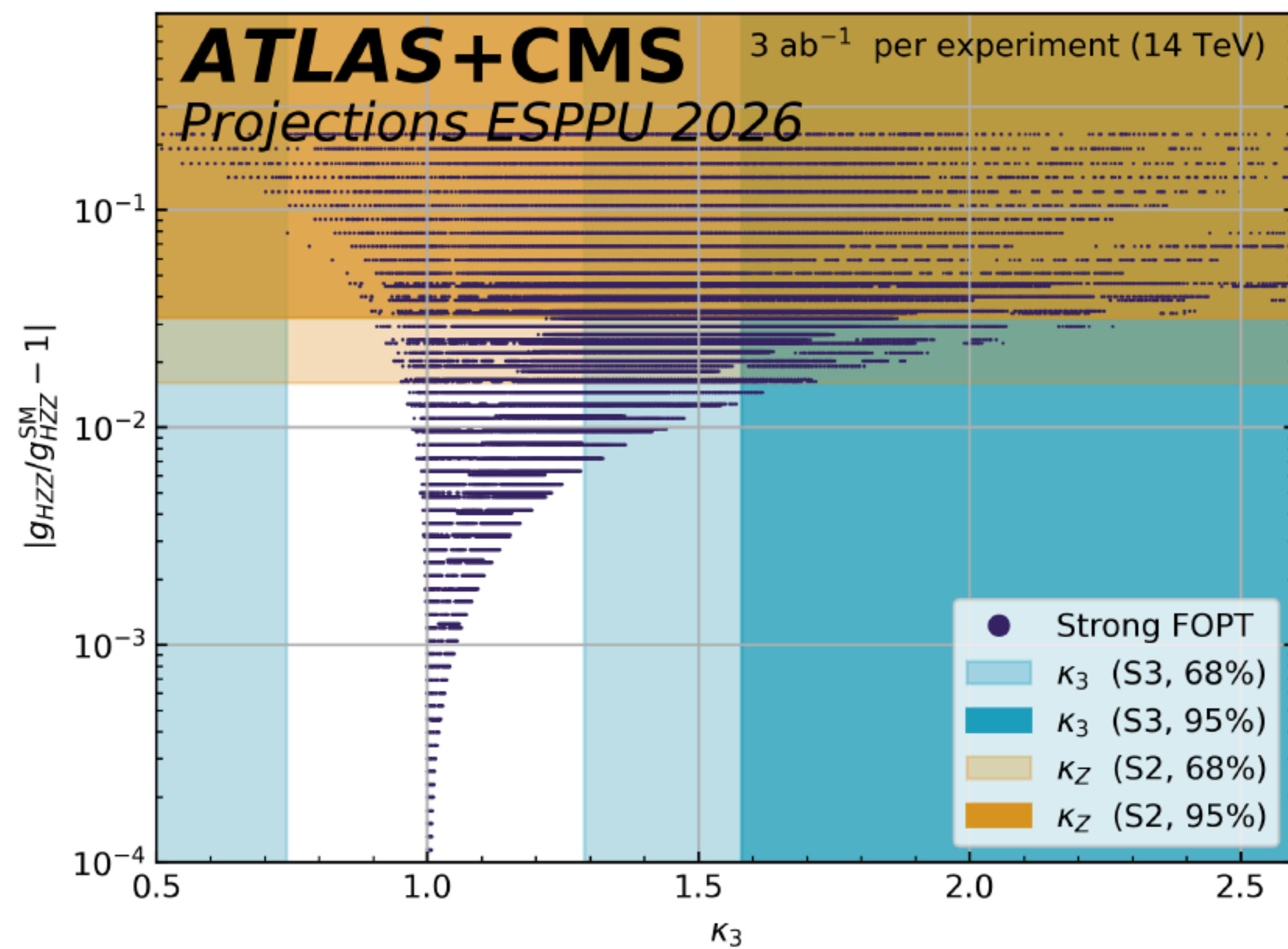
[arXiv:1608.06619](#)



Global exclusion, without constraint from resonances that depend on specific values of model parameters

Scalar Singlet FOPT exclusion by HZZ and k_3

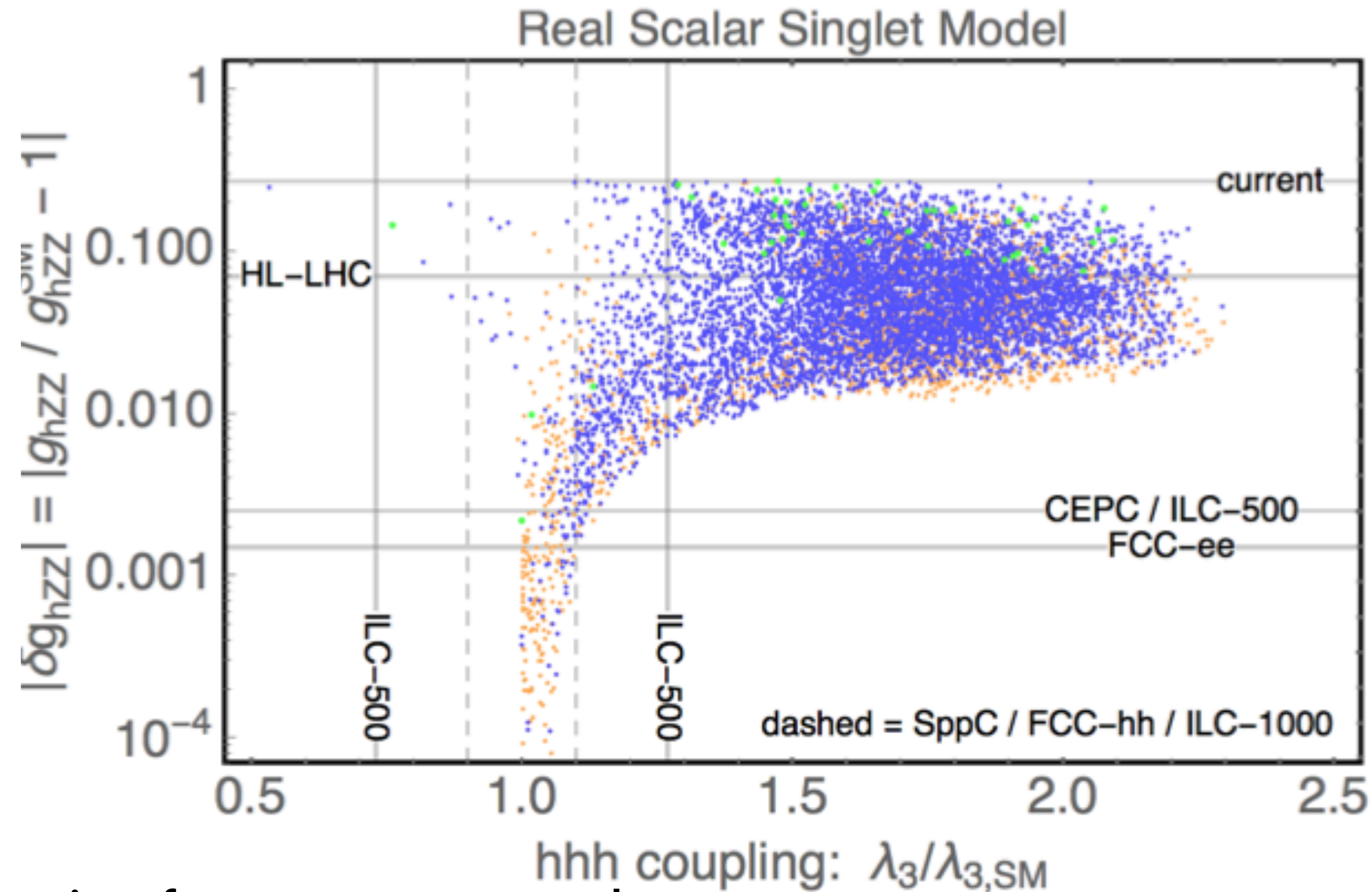
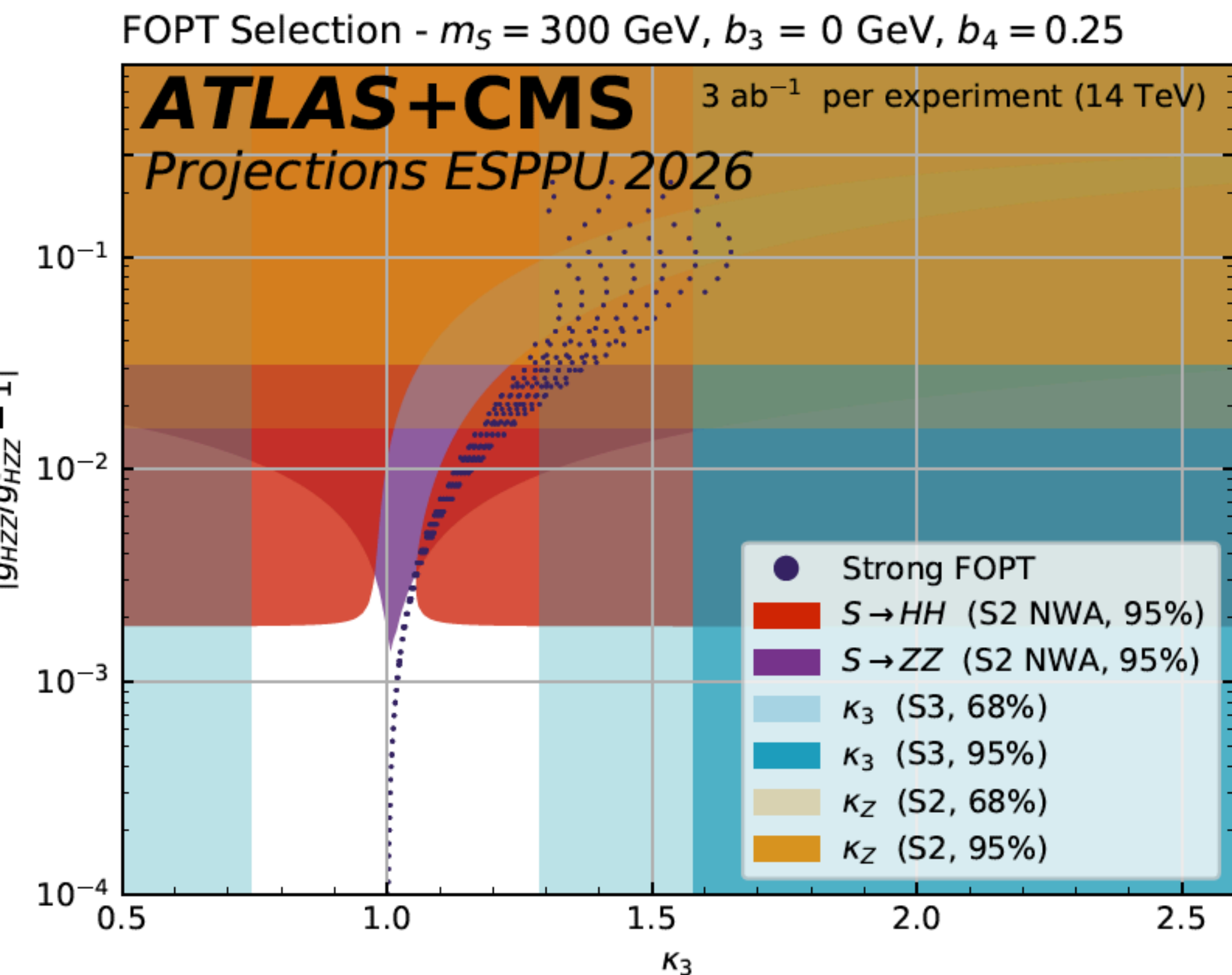
[arXiv1608.06619](#)



Global exclusion, without constraint from resonances that depend on specific values of model parameters

Scalar Singlet FOPT exclusion

arXiv:1608.06619

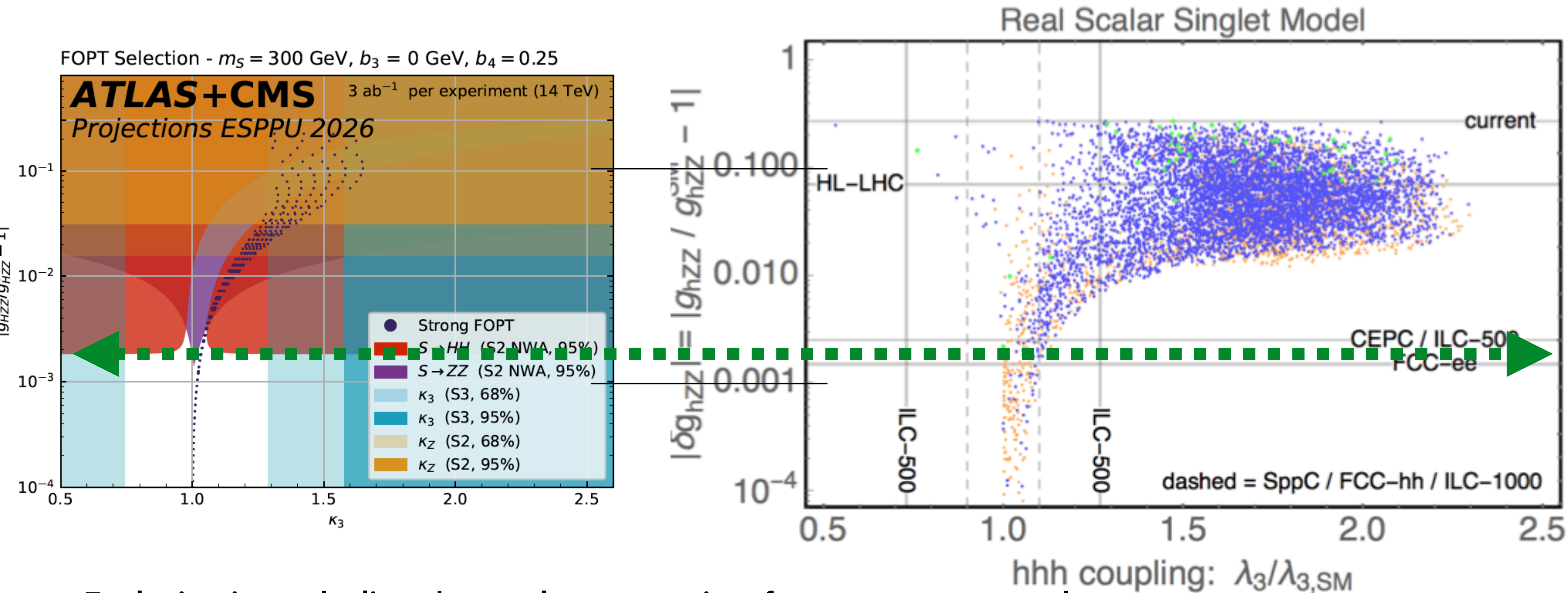


Exclusion in each slice shows also constraints from resonant searches

The exclusion is as strong as FCC-ee and ILC.

Scalar Singlet FOPT exclusion

arXiv:1608.06619

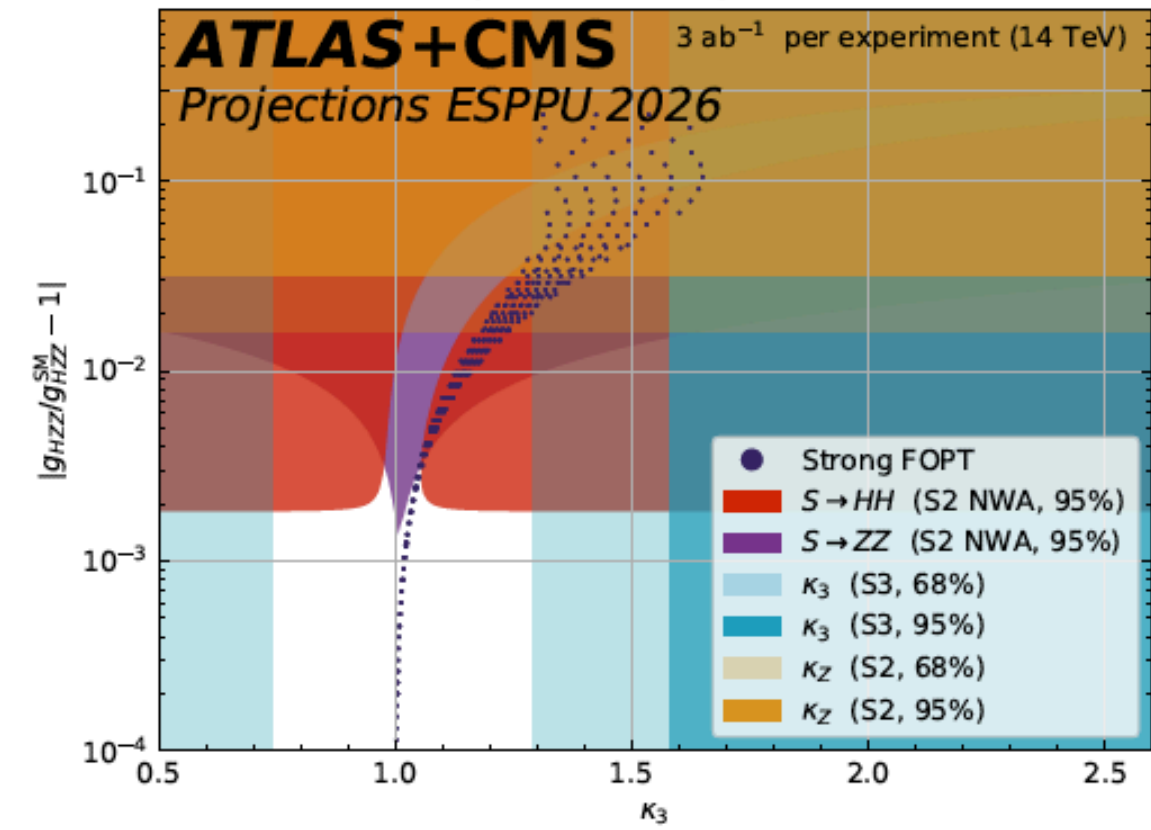


Exclusion in each slice shows also constraints from resonant searches

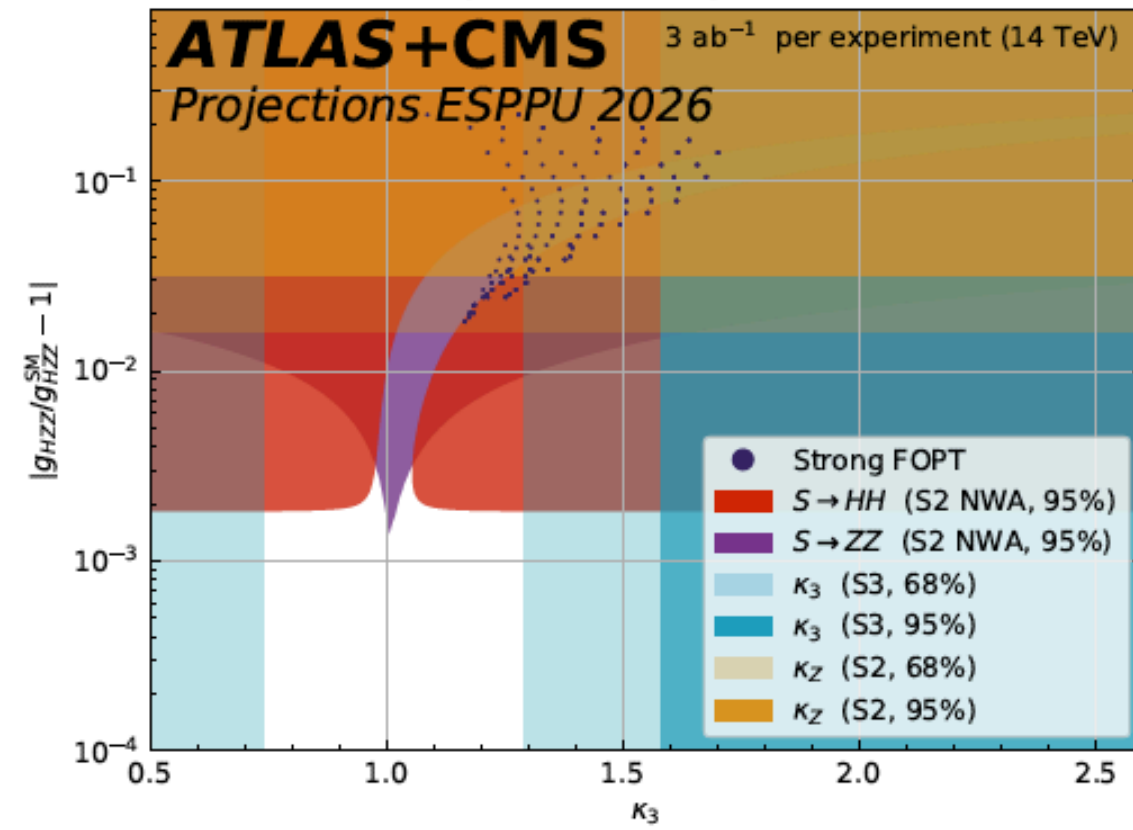
The exclusion ~ FCC-ee and ILC.

sample of different model parameters

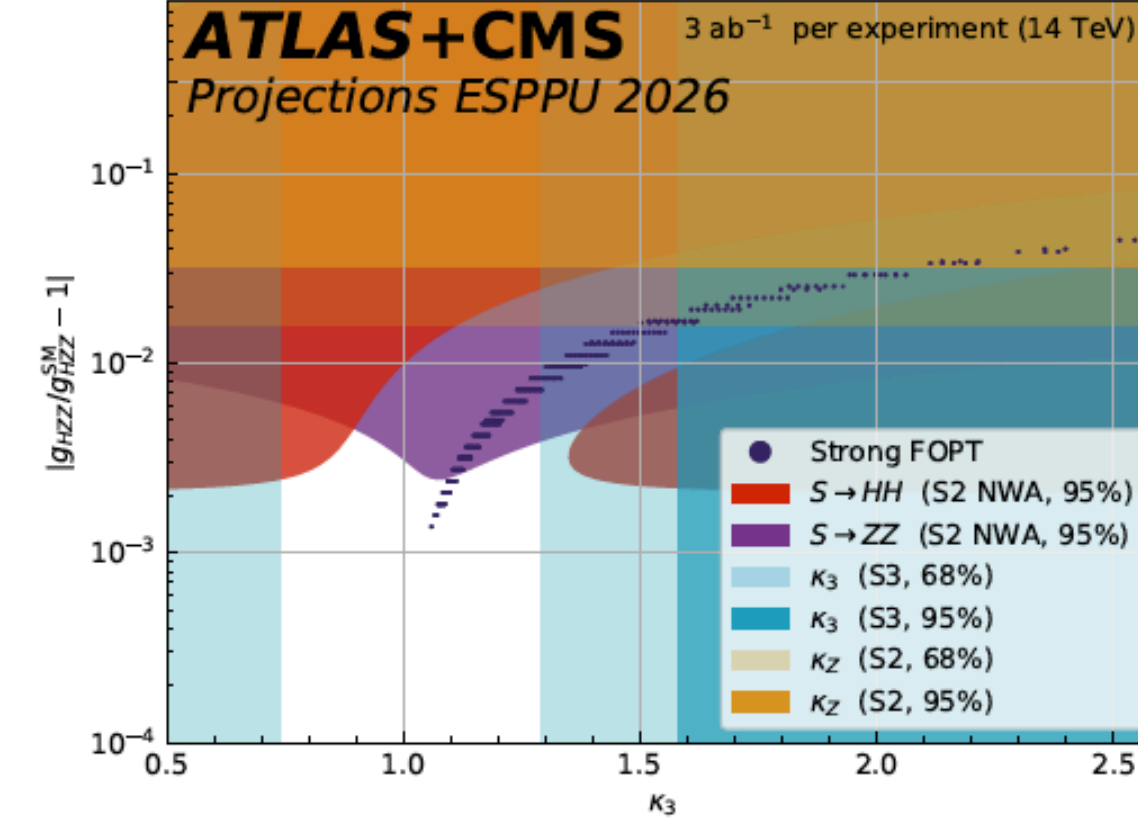
FOPT Selection - $m_S = 300$ GeV, $b_3 = 0$ GeV, $b_4 = 0.25$



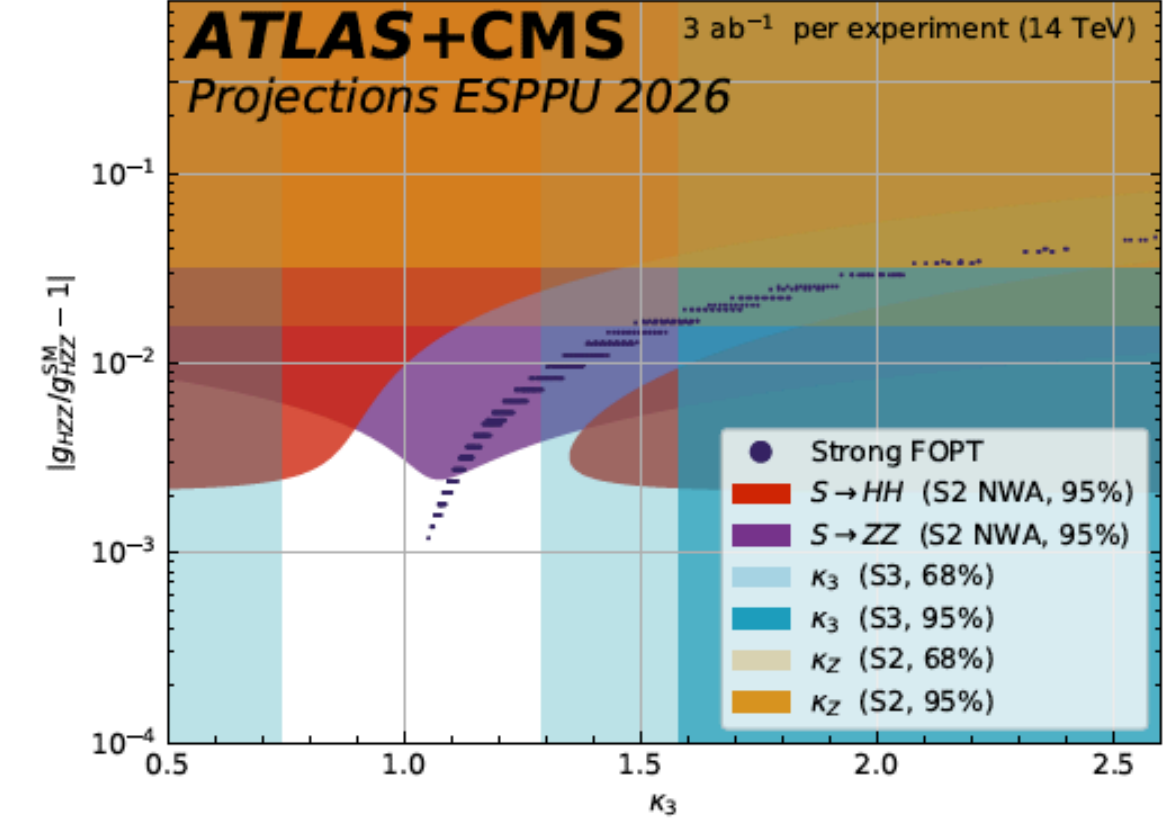
FOPT Selection - $m_S = 300$ GeV, $b_3 = 200$ GeV, $b_4 = 0.25$



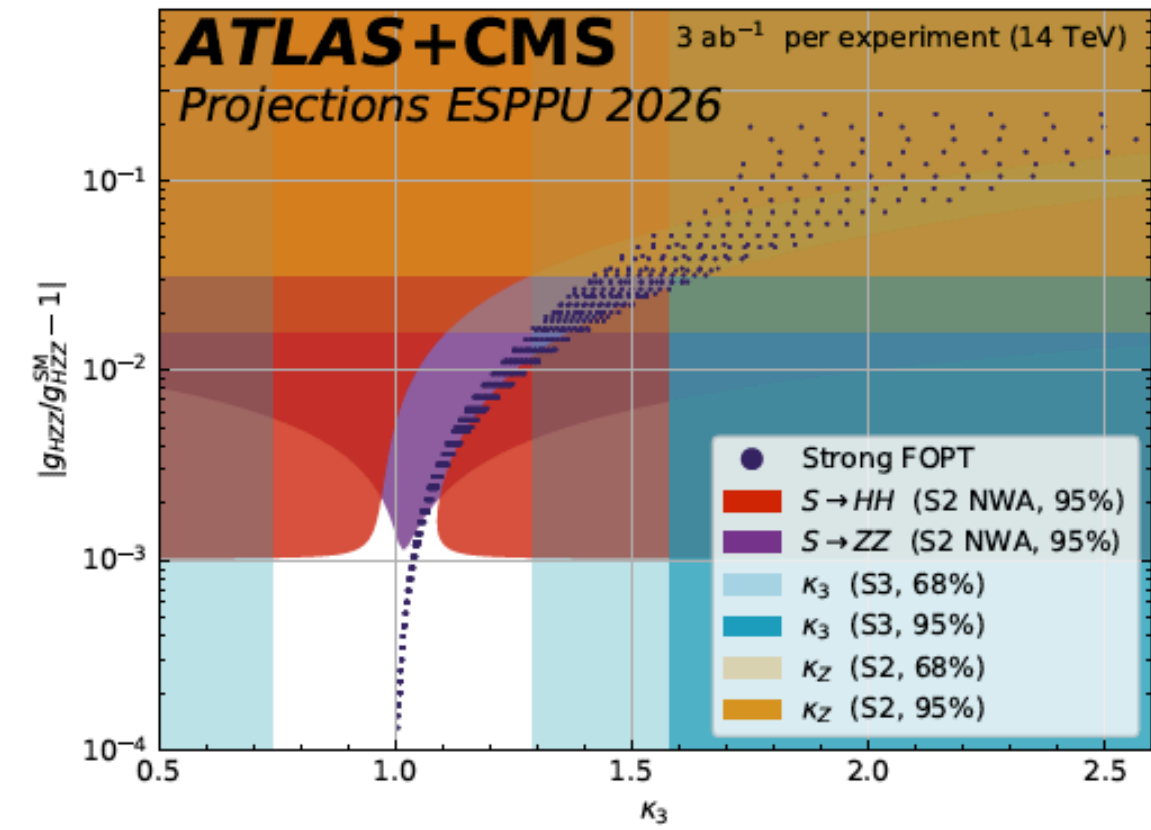
FOPT Selection - $m_S = 700$ GeV, $b_3 = 0$ GeV, $b_4 = 0.25$



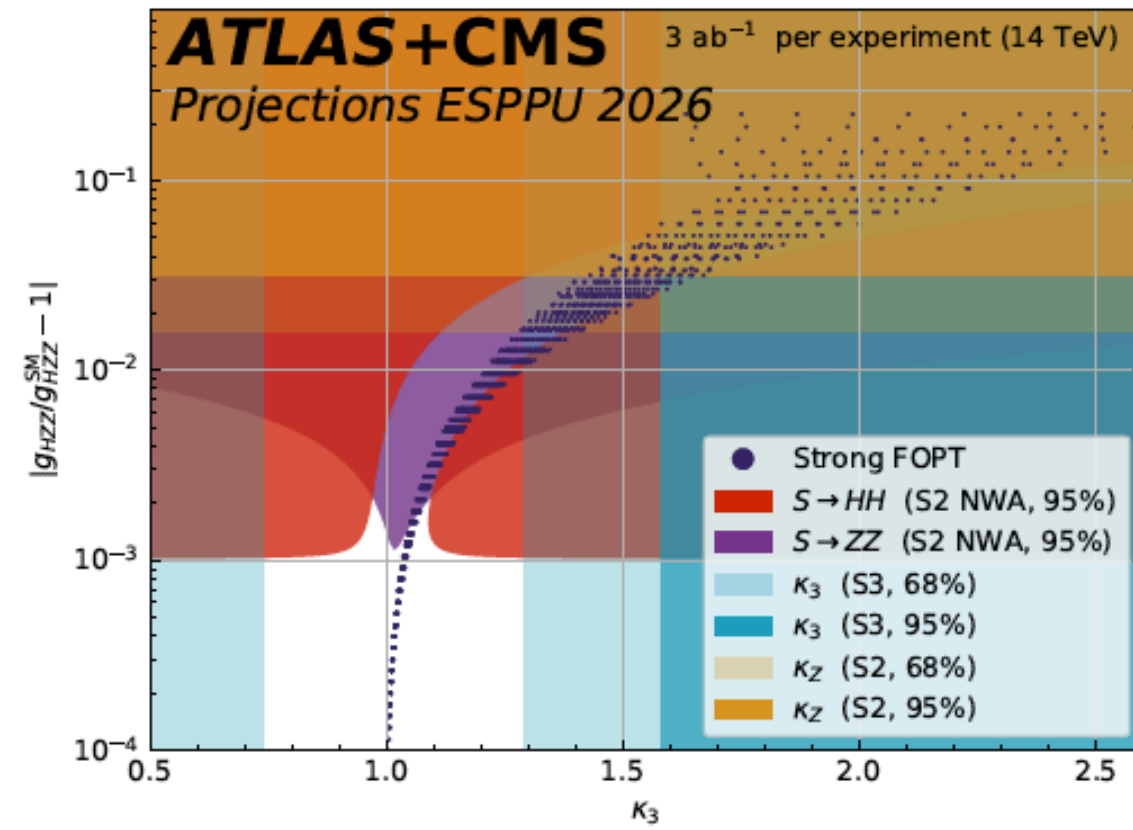
FOPT Selection - $m_S = 700$ GeV, $b_3 = 200$ GeV, $b_4 = 0.25$



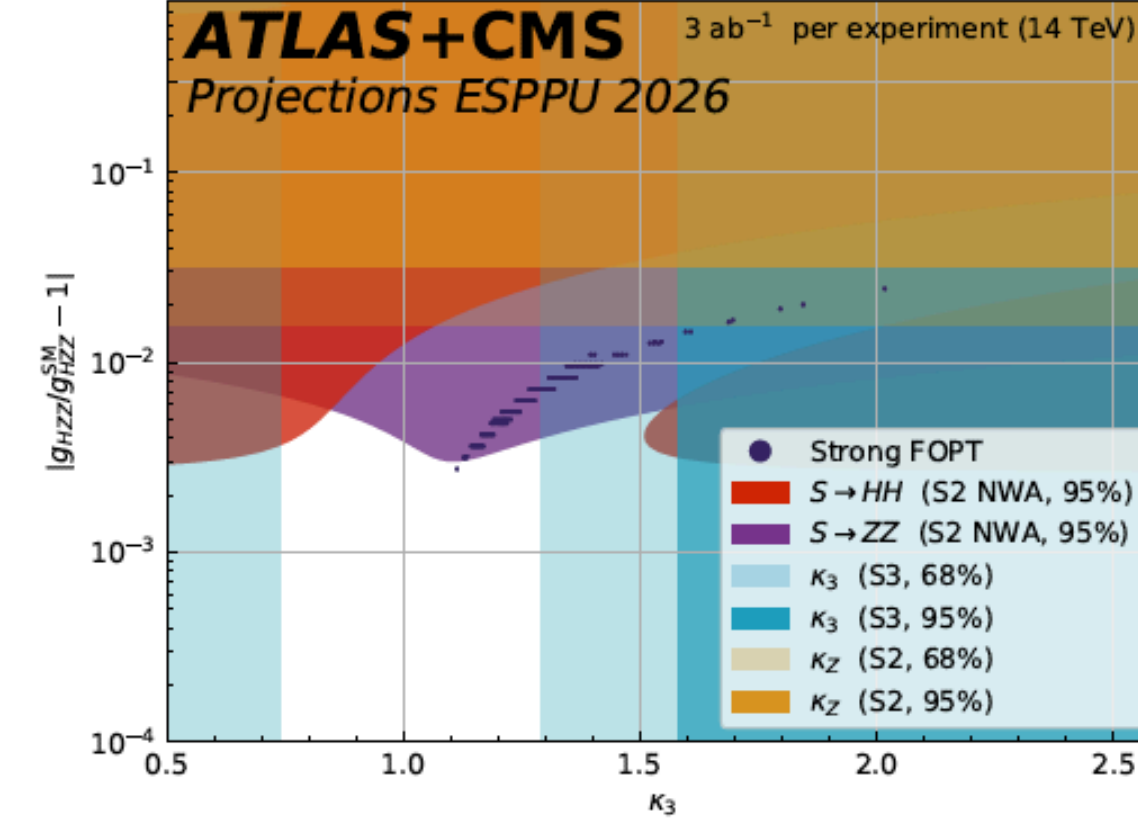
FOPT Selection - $m_S = 500$ GeV, $b_3 = 0$ GeV, $b_4 = 0.25$



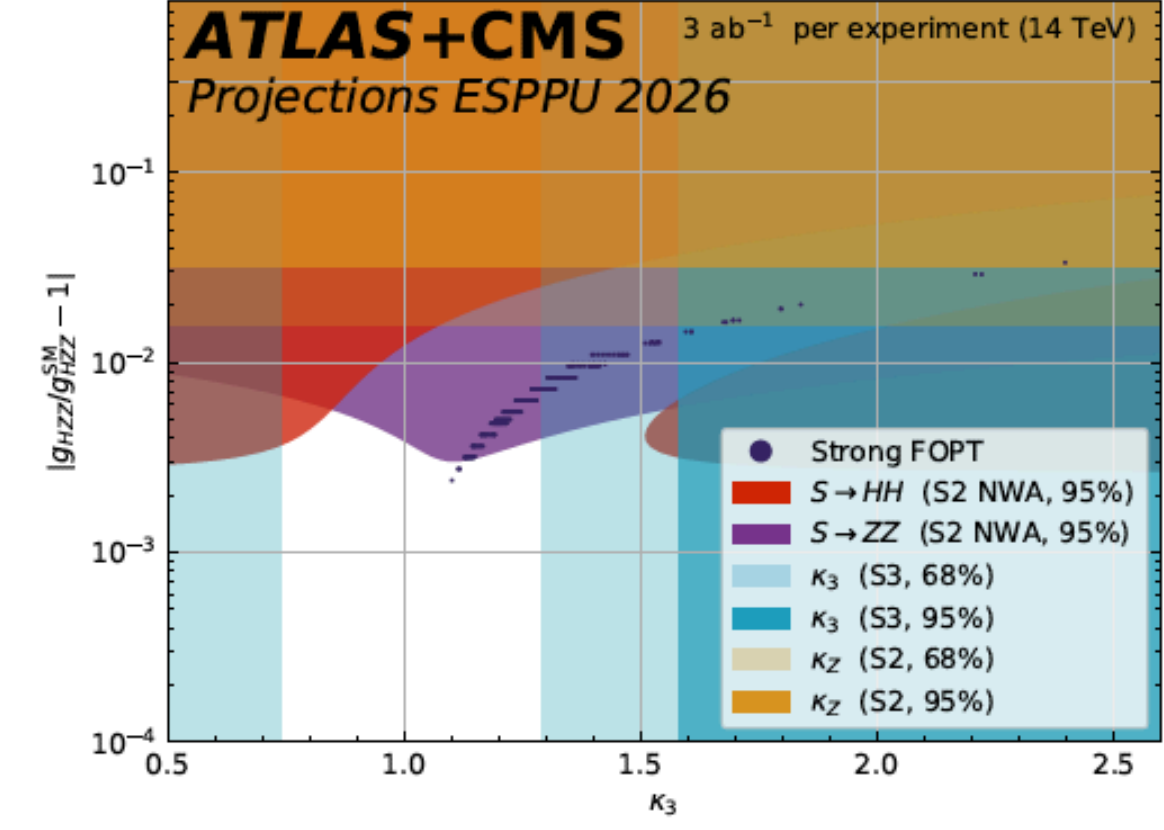
FOPT Selection - $m_S = 500$ GeV, $b_3 = 200$ GeV, $b_4 = 0.25$



FOPT Selection - $m_S = 750$ GeV, $b_3 = 0$ GeV, $b_4 = 0.25$



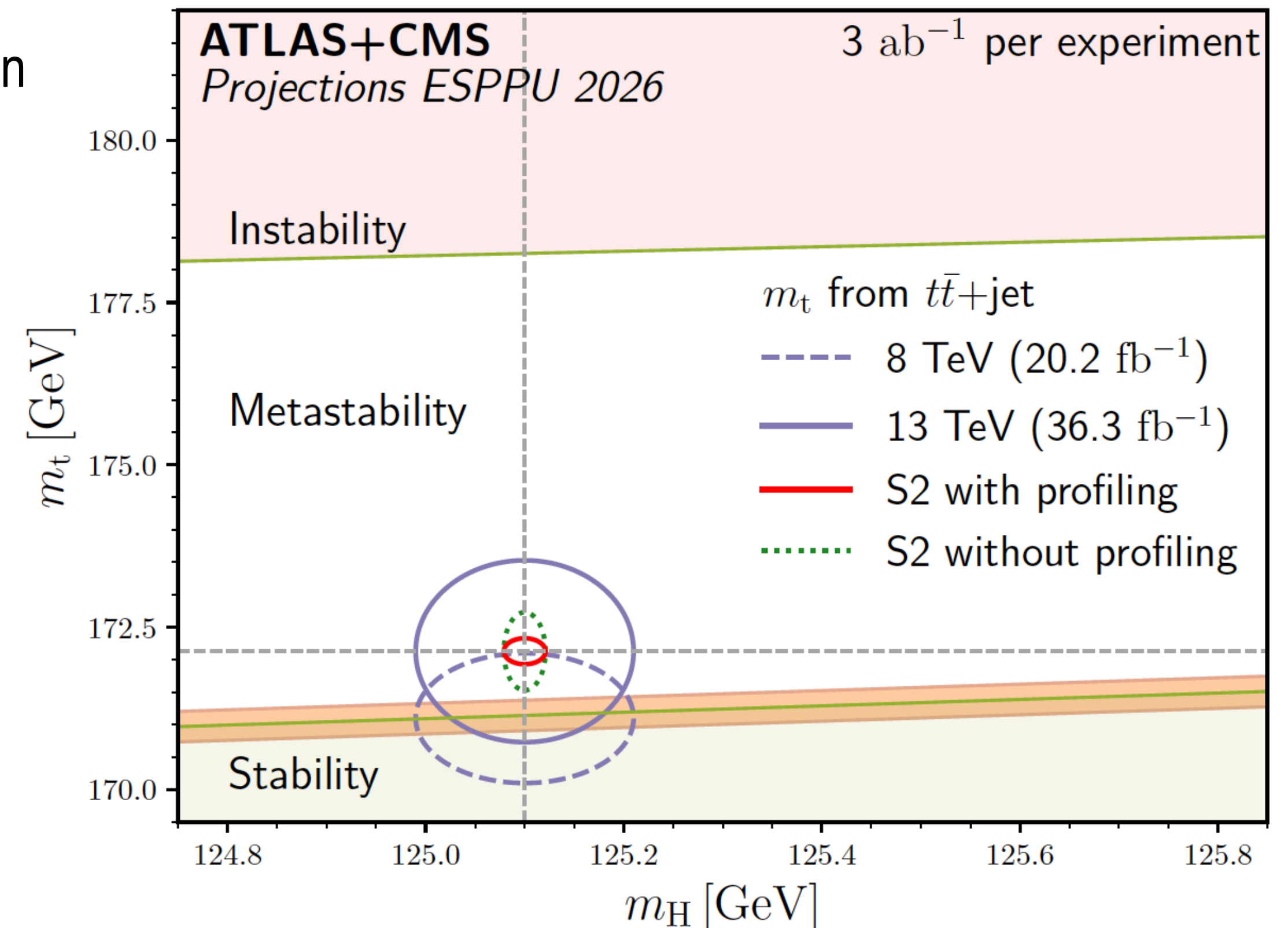
FOPT Selection - $m_S = 750$ GeV, $b_3 = 200$ GeV, $b_4 = 0.25$



EW Vacuum Stability

In case the SM is valid up to the Planck scale we have indirect indication that our Universe is metastable. This plots provides important information about tensions in the SM.

if central value stays where it is now, we will have more than 2σ exclusion of the Stability



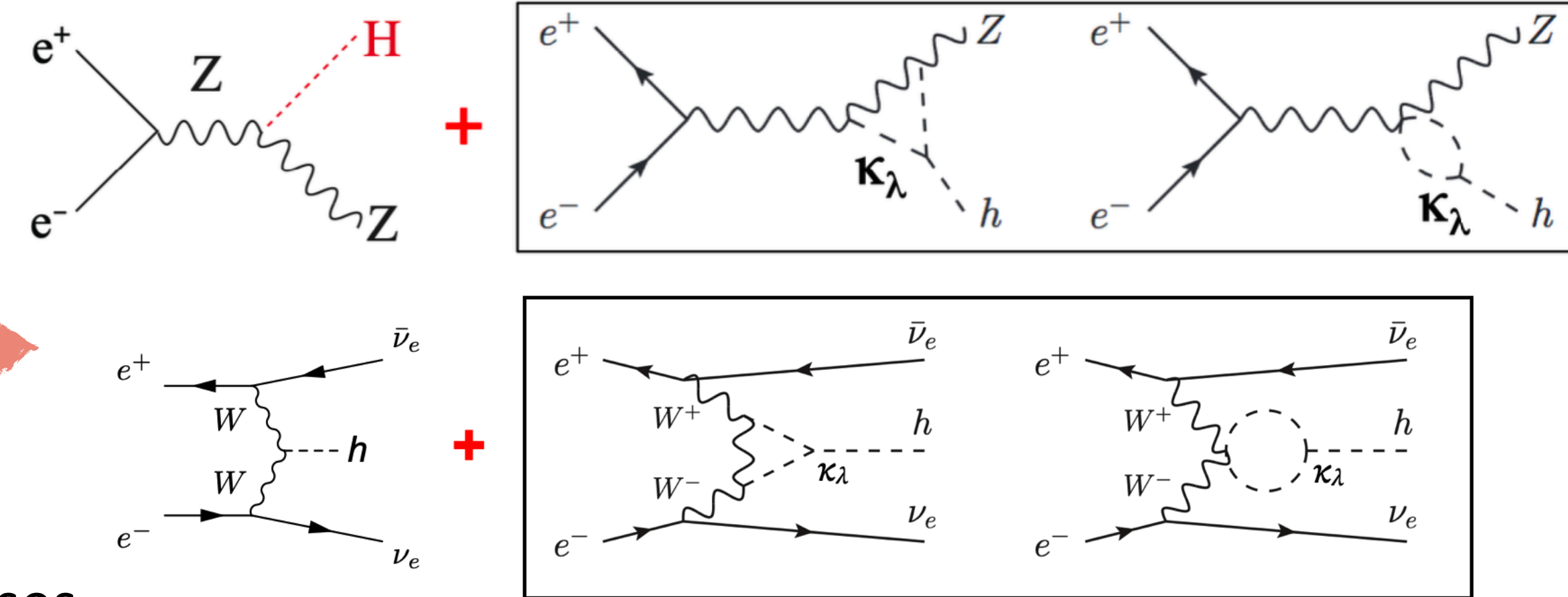
200 MeV precision from
 $t\bar{t} + \text{jets}$ 13 TeV by CMS
([link](#)) profiling

600 MeV precision from
 $t\bar{t} + 1\text{jets}$ 8 TeV by ATLAS
([link](#)) no profiling

$m_H^{ZZ} = \underline{\text{ATLAS}} + \underline{\text{CMS}}$ 21 MeV

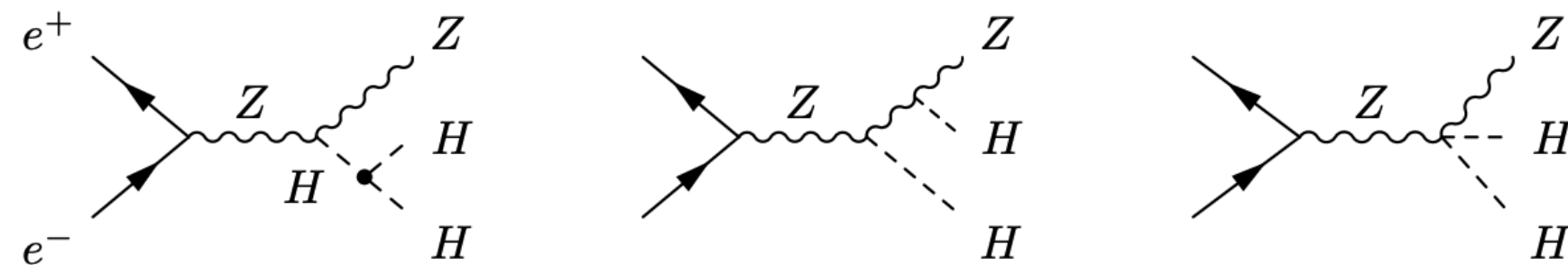
Higgs potential and κ_λ at e^+e^- Colliders

- At e^+e^- Colliders below di-Higgs threshold constraints on the Higgs potential come from indirect (or better at 1 loop) single Higgs production processes

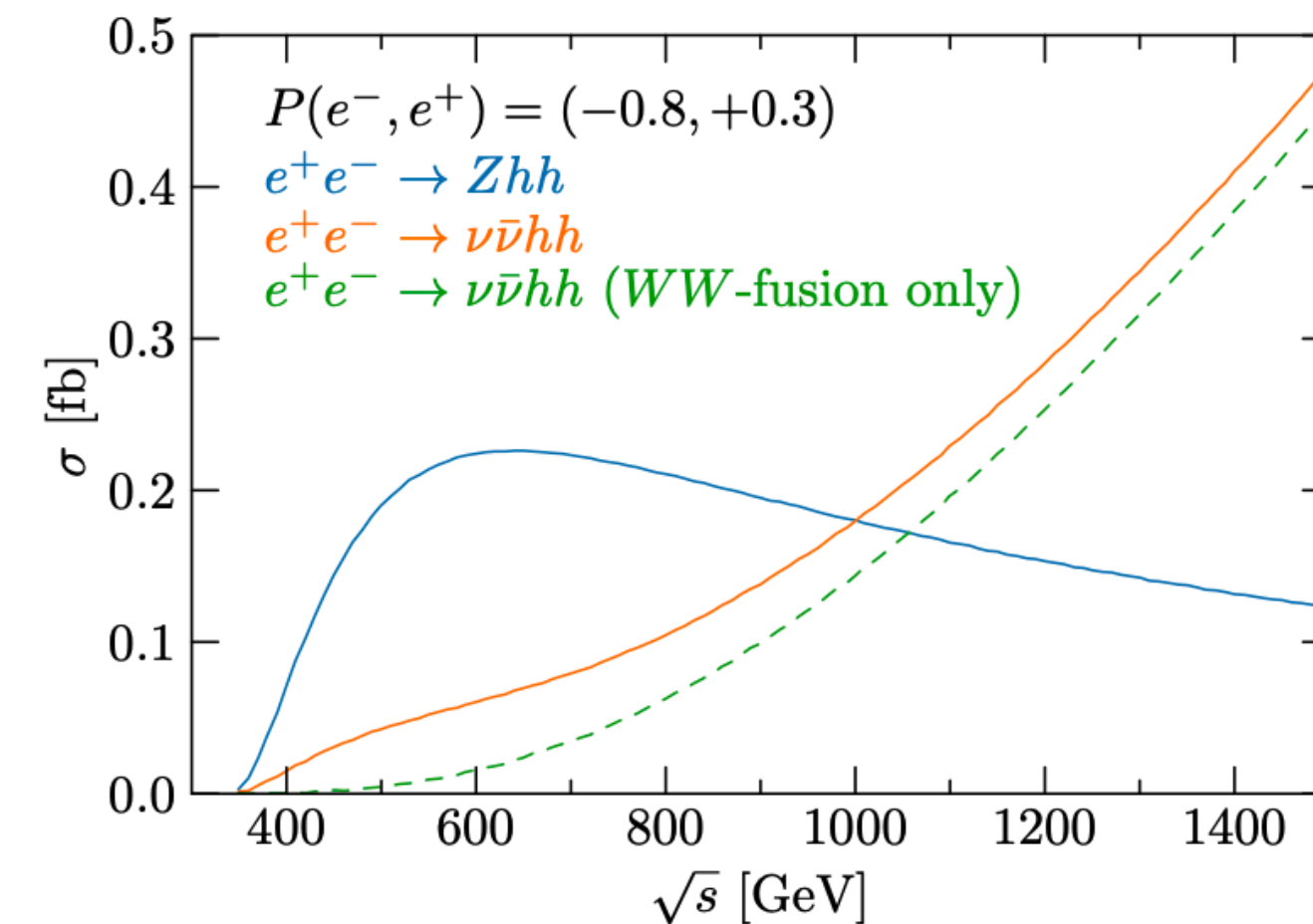
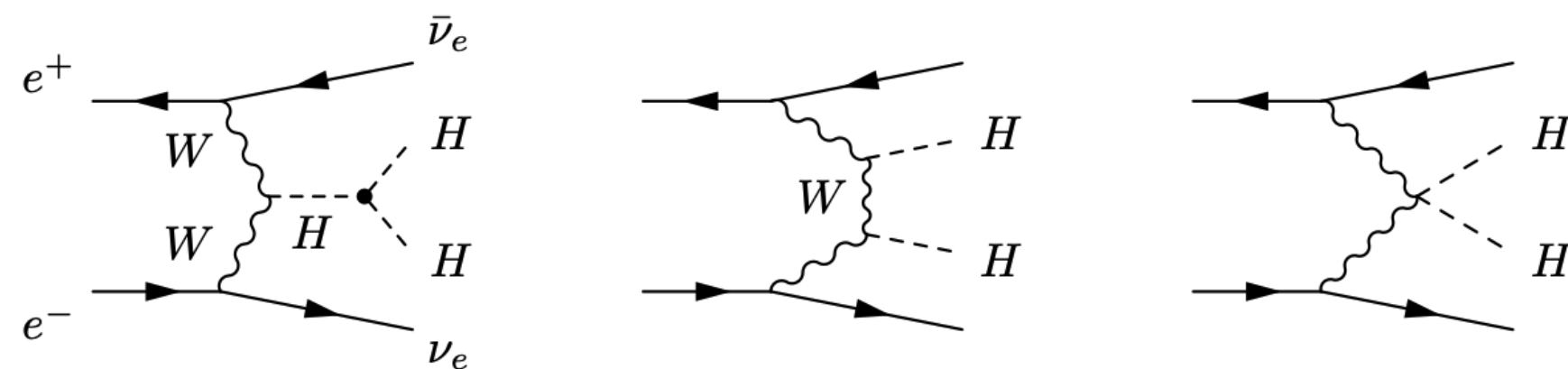


- At e^+e^- Colliders above di-Higgs threshold, direct di- Higgs processes

double Higgs-strahlung: $e^+e^- \rightarrow ZHH$



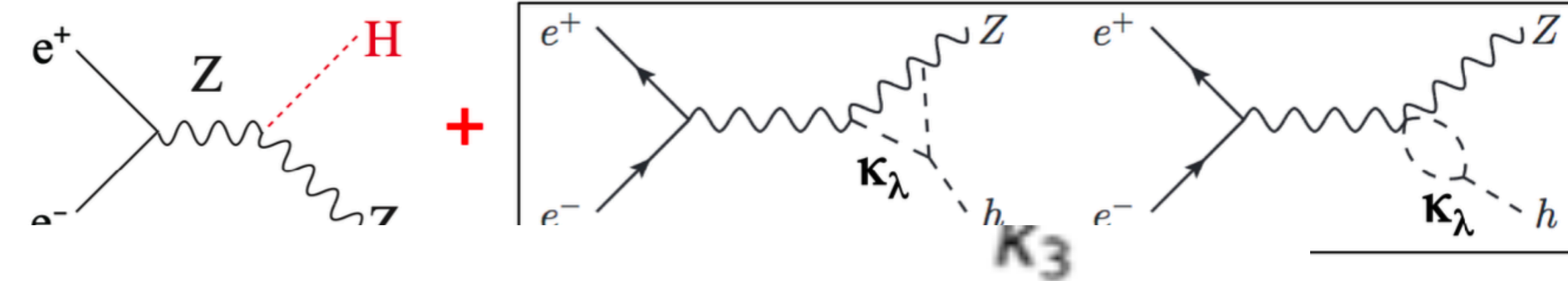
WW double-Higgs fusion: $e^+e^- \rightarrow \bar{\nu}_e \nu_e HH$



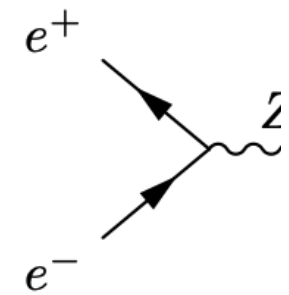
- Indirect sensitivity to limited by: experimental uncertainties on considered observables, on input parameters , theoretical uncertainties due to unknown Higher Order corrections

Higgs potential and κ_λ at e^+e^- Colliders

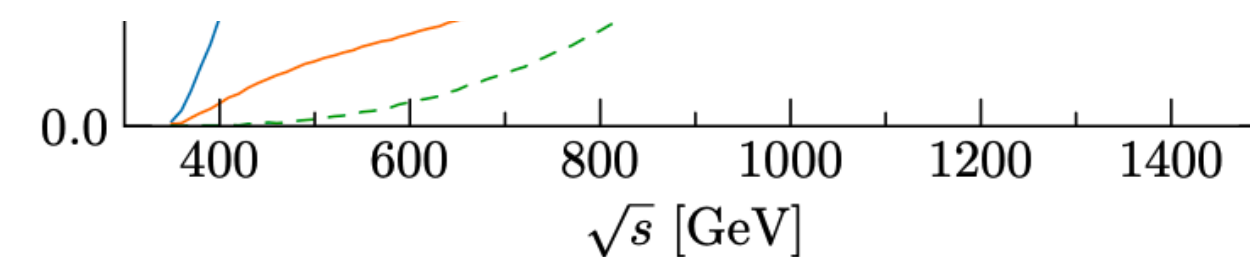
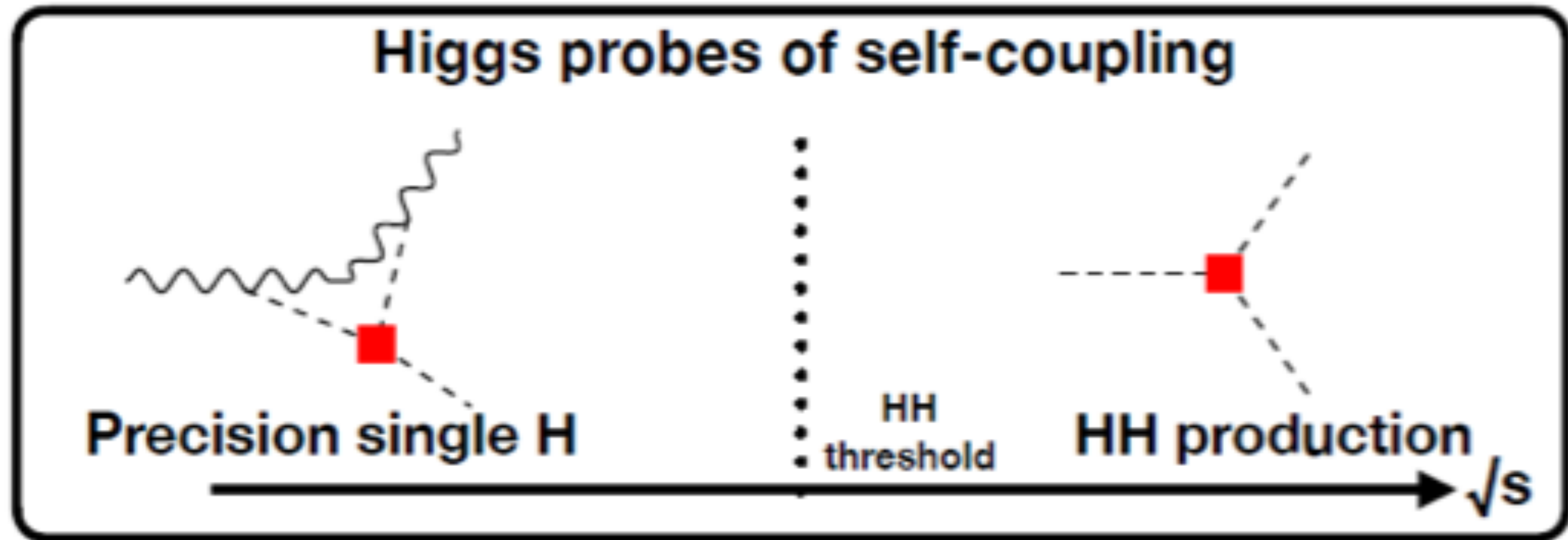
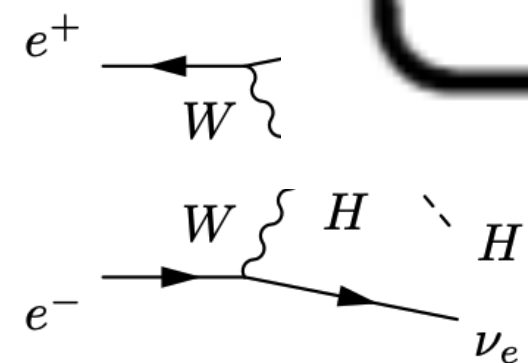
- At e^+e^- Colliders below di-Higgs threshold constraints on the Higgs pote
Higgs proc



- At e^+e^- Coll
double Higgs



WW double-



- Indirect sensitivity to limited by:** experimental uncertainties on considered observables, on input parameters , theoretical uncertainties due to unknown Higher Order corrections

Single&di-Higgs constraints on k_λ

single Higgs

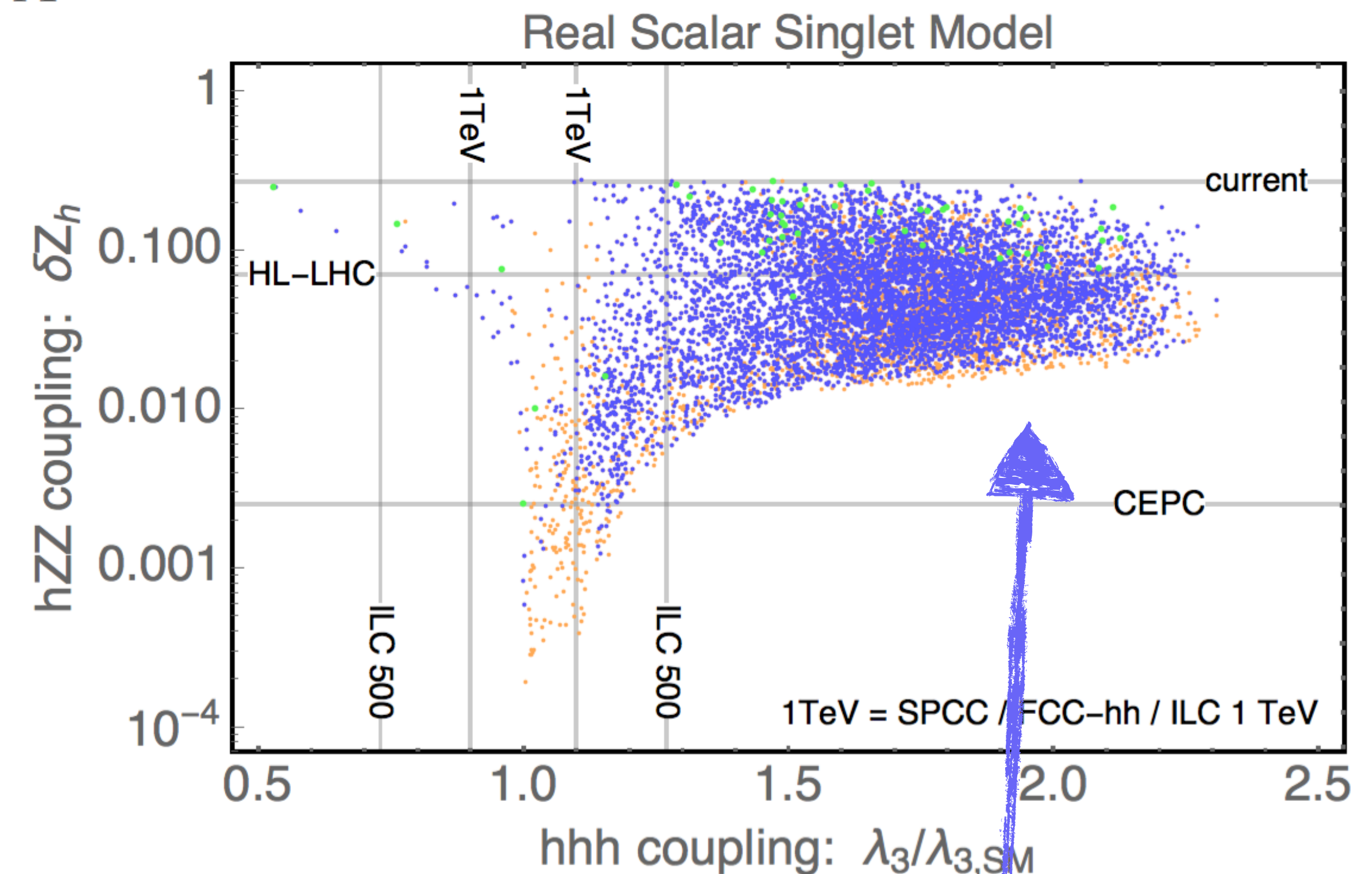


$$\frac{1}{\Lambda^2}(H^\dagger \partial H)^2 \quad \text{Modifies H-Z coupling} \Rightarrow \delta Z_h$$

- The HZ Coupling is better measured, but deviations in the Zh coupling (δZ_h) are proportional to g_Z (the Z SM coupling)
- deviations in λ ($\delta\lambda$) are not related to λ_{SM} . - There are Models iwhere $\delta\lambda \gg \delta Z_h$, notably the ones with a first order phase transition, with large self-interaction !

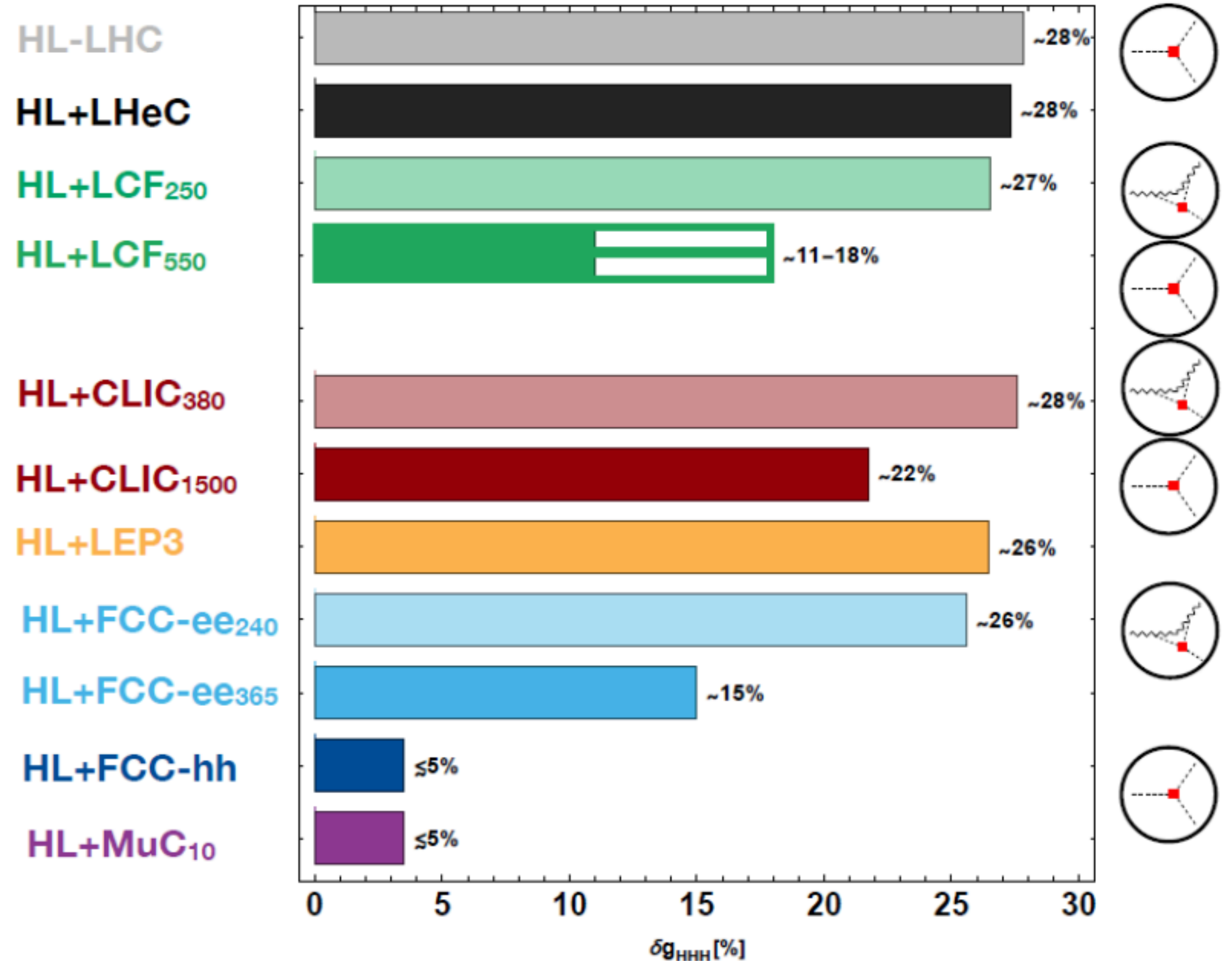
di-Higgs

$$\frac{1}{\Lambda^2}(H^\dagger H)^3 \quad \text{modifies Higgs self coupling} \quad \delta\lambda$$



k_λ and Future Colliders

At e^+e^- Colliders below HH threshold
come from indirect single Higgs
constraints



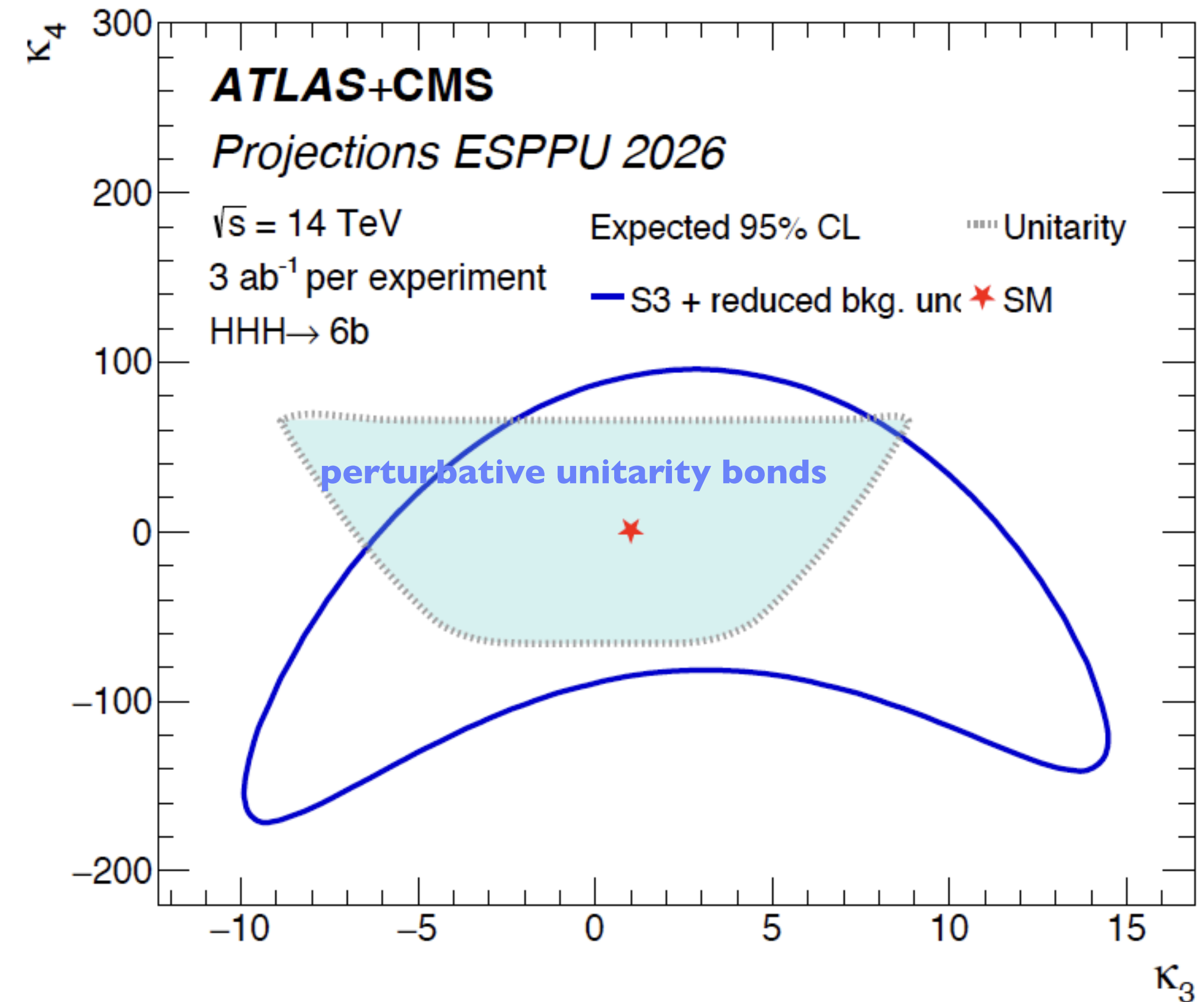
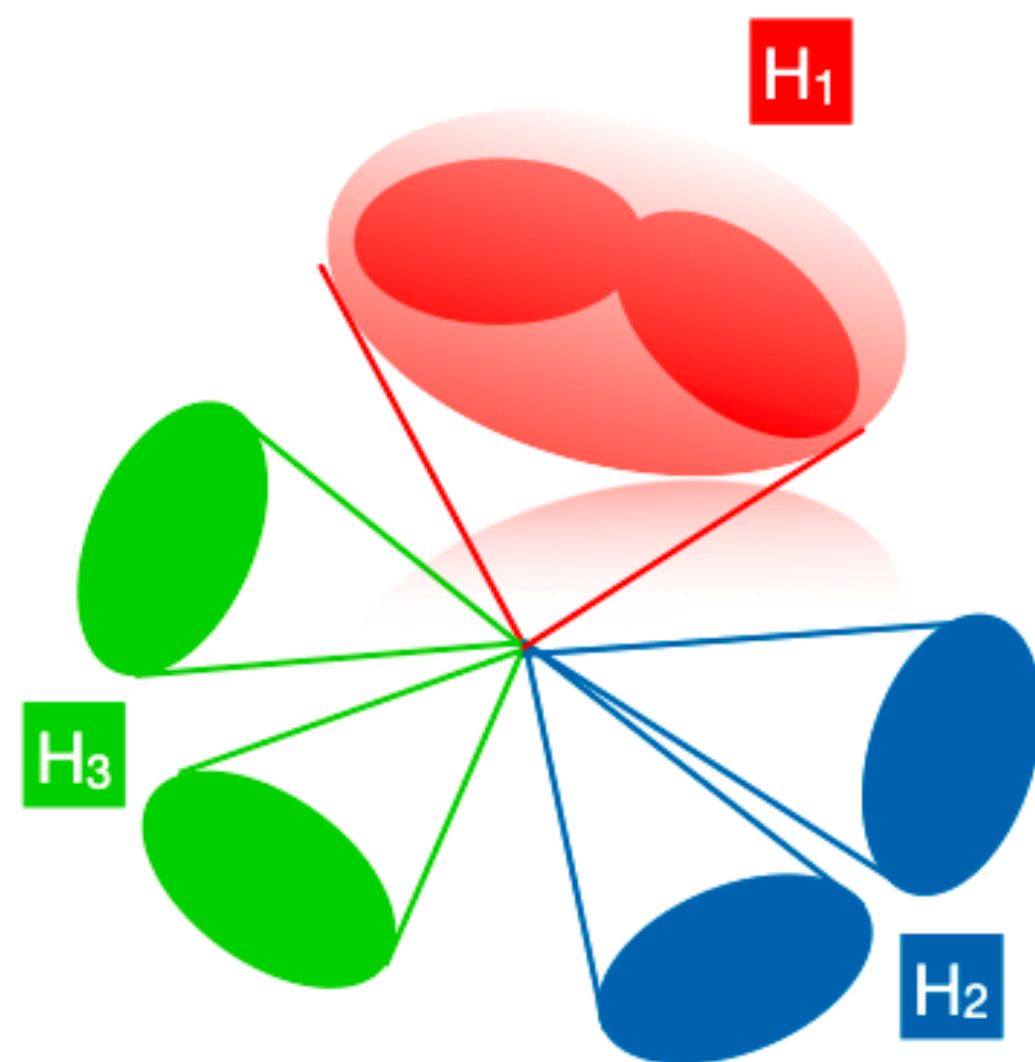
3 Higgses



Higgs quartic coupling

$$V_h = \frac{1}{2}m_h^2 h^2 + (1 + \kappa_3)\lambda_{hhh} v h^3 + \frac{1}{4}(1 + \kappa_4)\lambda_{hhhh} h^4$$

First time that the constraints are set on the quartic Higgs coupling.



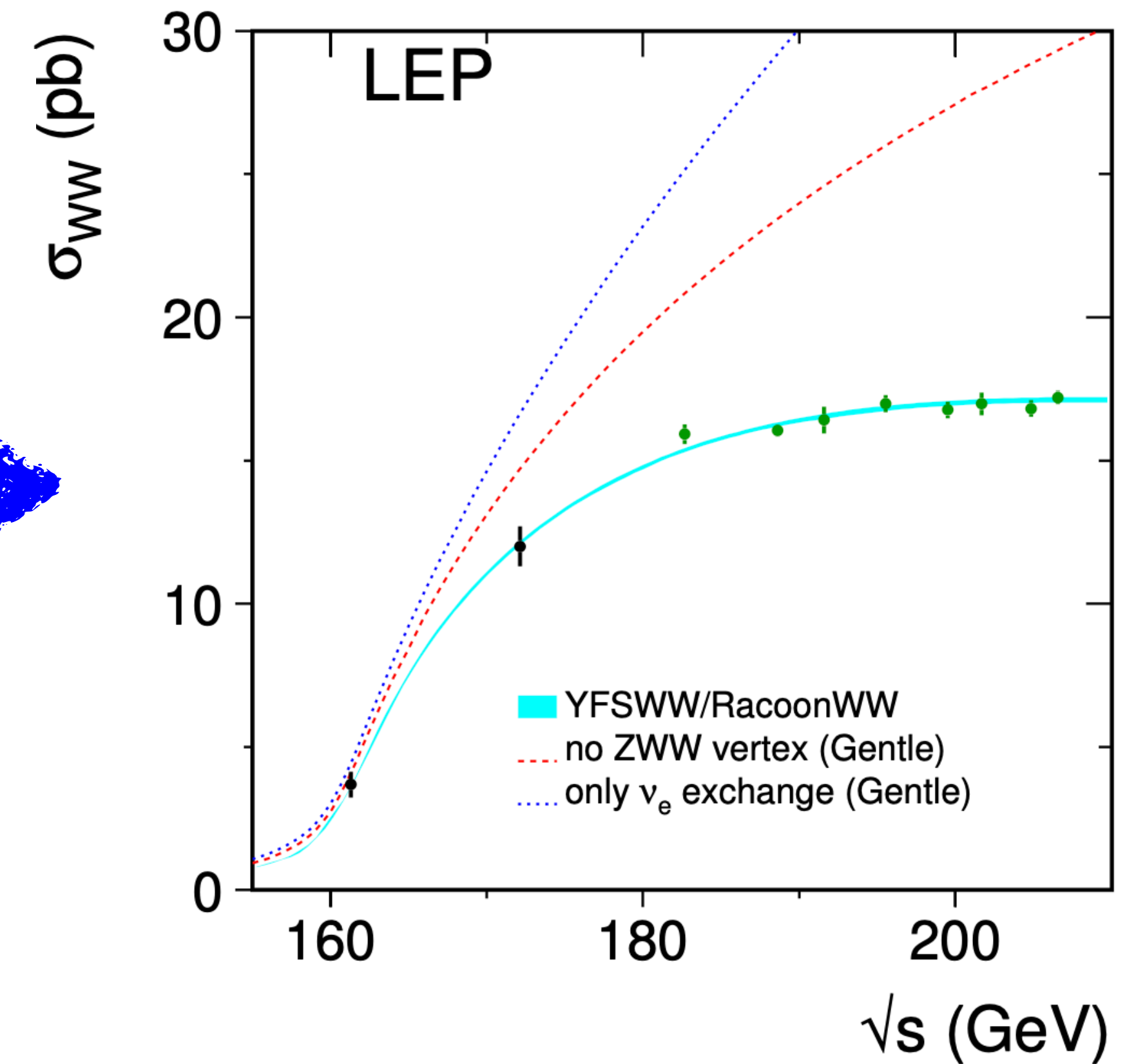
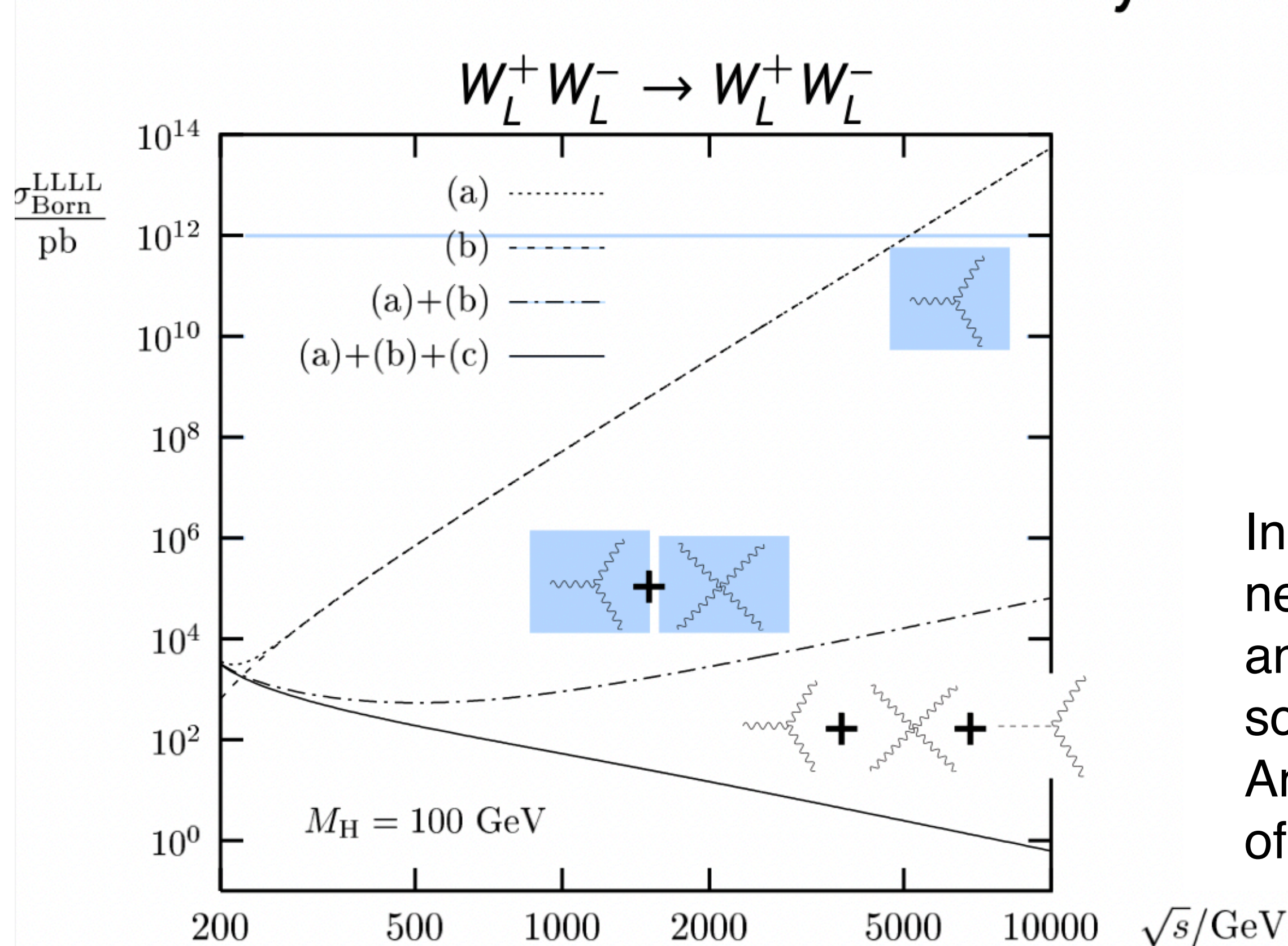
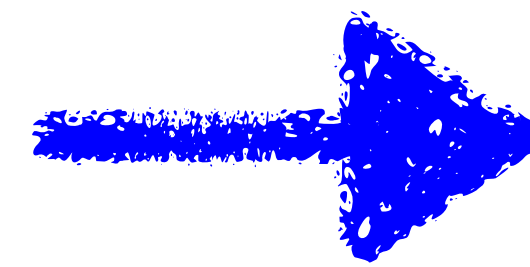
95% CL limit on cross-section < 109xSM
More channels will be added in the future!

Testing the Electroweak symmetry breaking via Vector Boson Scattering: Another approach

Electroweak symmetry breaking

Gauge-boson self interactions play a crucial role for the renormalisability of the electroweak theory

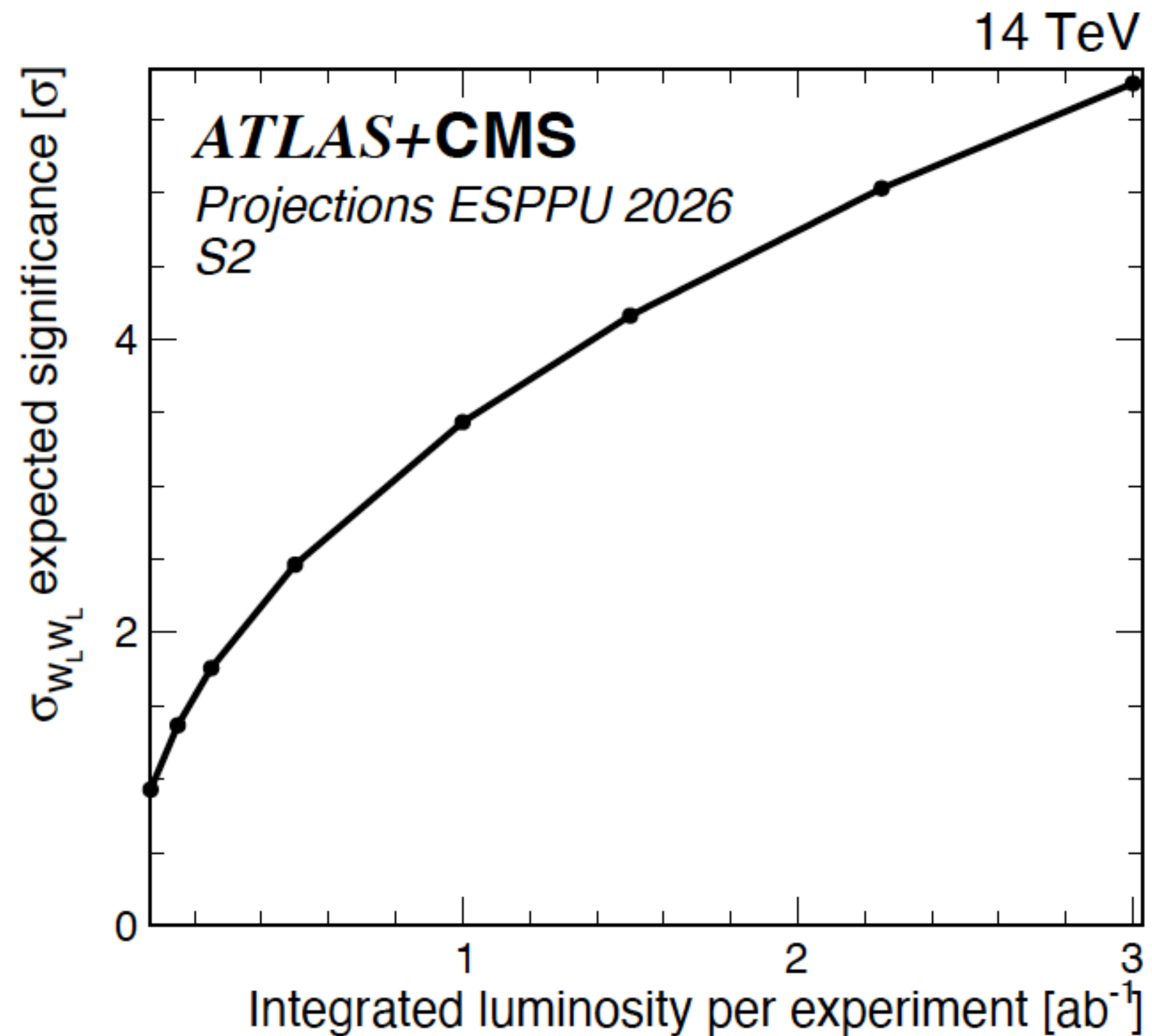
Large cancellations of divergences arising in individual diagrams are exact if couplings take the values of the SM



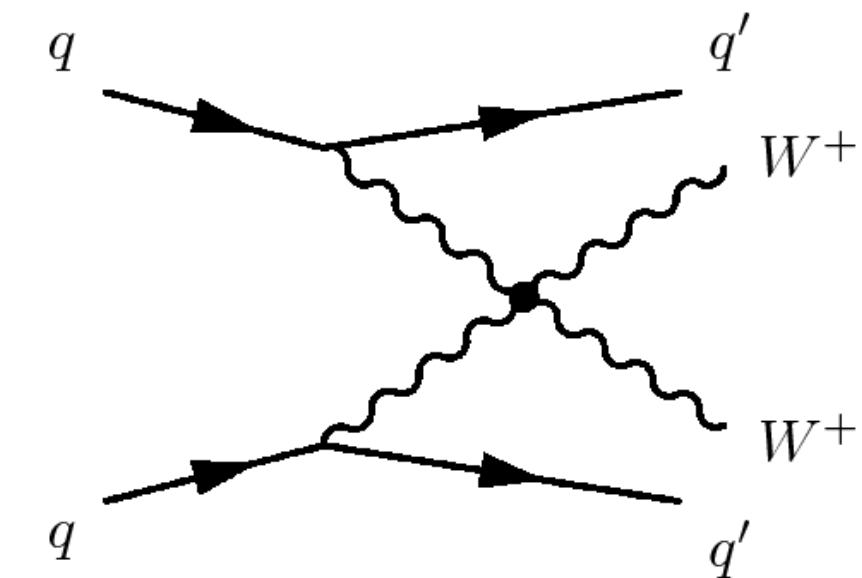
In vector boson scattering, the presence of the Higgs boson is needed to exactly cancel out the otherwise diverging scattering amplitudes at high energies and prevent unitarity violation at the TeV scale.

Any significant deviation from the predicted high-energy behaviour of vector boson scattering would point to new phenomena.

di-boson scattering: a complementary path



Observation of longitudinally polarised vector boson scattering $WLWL$ process with better than 20% precision



$V[H]$ Conclusions

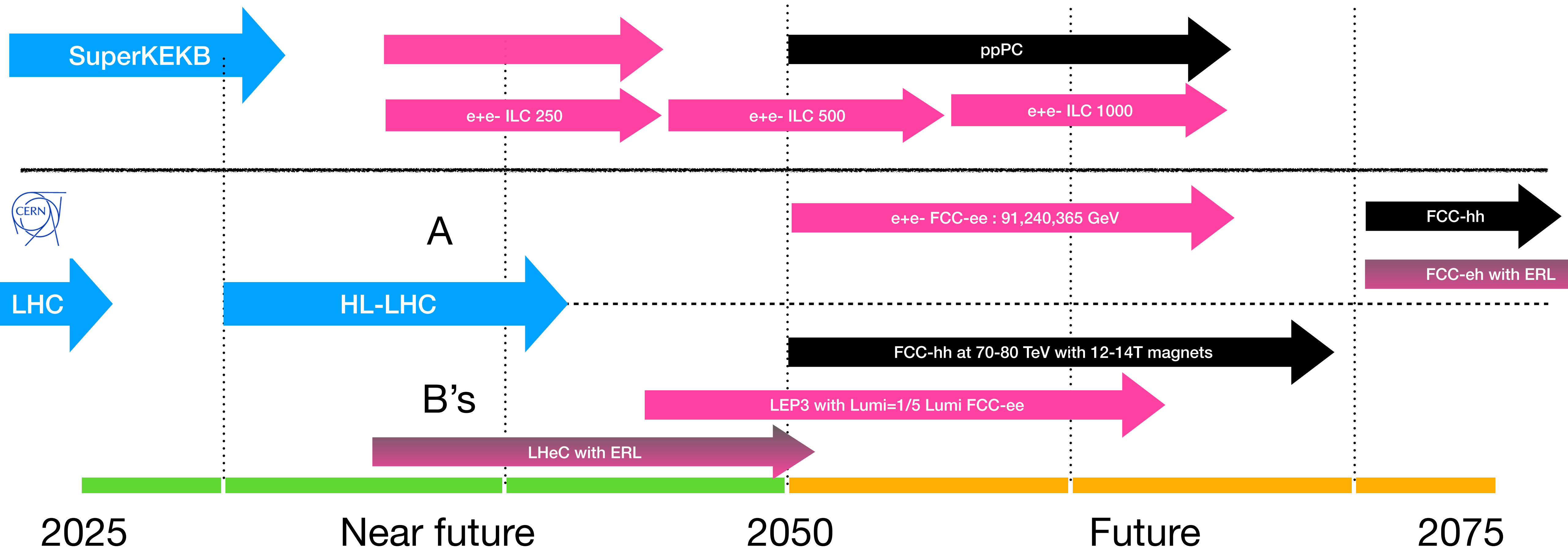
One of the most exciting phases of LHC for ATLAS and CMS is starting now, and will allow us to get information on the Higgs potential and on the fate of our universe and the presence of New Physics



We are continuously improving on our experimental techniques at an astonishing and unexpected rate!

The near future is going to be thrilling at the HL-LHC!

Going back from where we started.. are our opinions changed?



cost estimates

Fcc-ee +Fcc-hh 35 BCHF

Fcc-hh 27 BCHF

project	scenario / energy / details	cost	project	scenario	cost
FCC-ee	Z, WW, ZH, + 4 exp. CERN part	14.0 BCHF	LHeC	9 km new tunnel, 50 GeV e ⁻	2 BCHF
	+ 4 exp. non CERN part	+1.3 BCHF			
	+ upgrade to ttbar	+1.3 BCHF	Muon Collider	3.2 TeV at CERN	12.0 BCHF
FCC-hh	85 TeV pp, as second stage	+19.1 BCHF		7.6 TeV at CERN	17.0 BCHF
FCC-hh	85 TeV pp, standalone	27.3 BCHF		10 TeV green field	19 BCHF
LCF	250 GeV	8.5 BCHF	HALHF	e ⁻ 375 GeV, e ⁺ 41.7 GeV (250 GeV c.m.)	3.8 BCHF
	550 GeV	+5.5 BCHF		380 GeV	4.9 BCHF
CLIC	380 GeV	7.3 BCHF		550 GeV	6.3 BCHF
	1500 GeV	+7,1 BCHF	ALIVE	p-driven, 10 TeV	?
LEP3	ZH at 230 GeV + 2 exp CERN part	3.9 BCHF	ALEGRO	e ⁺ e ⁻ & $\gamma\gamma$, ≥ 10 TeV	?
	+ 2 exp non CERN part	+0.9 (0.3) BCHF			

The end.. or the beginning of a new journey



Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.

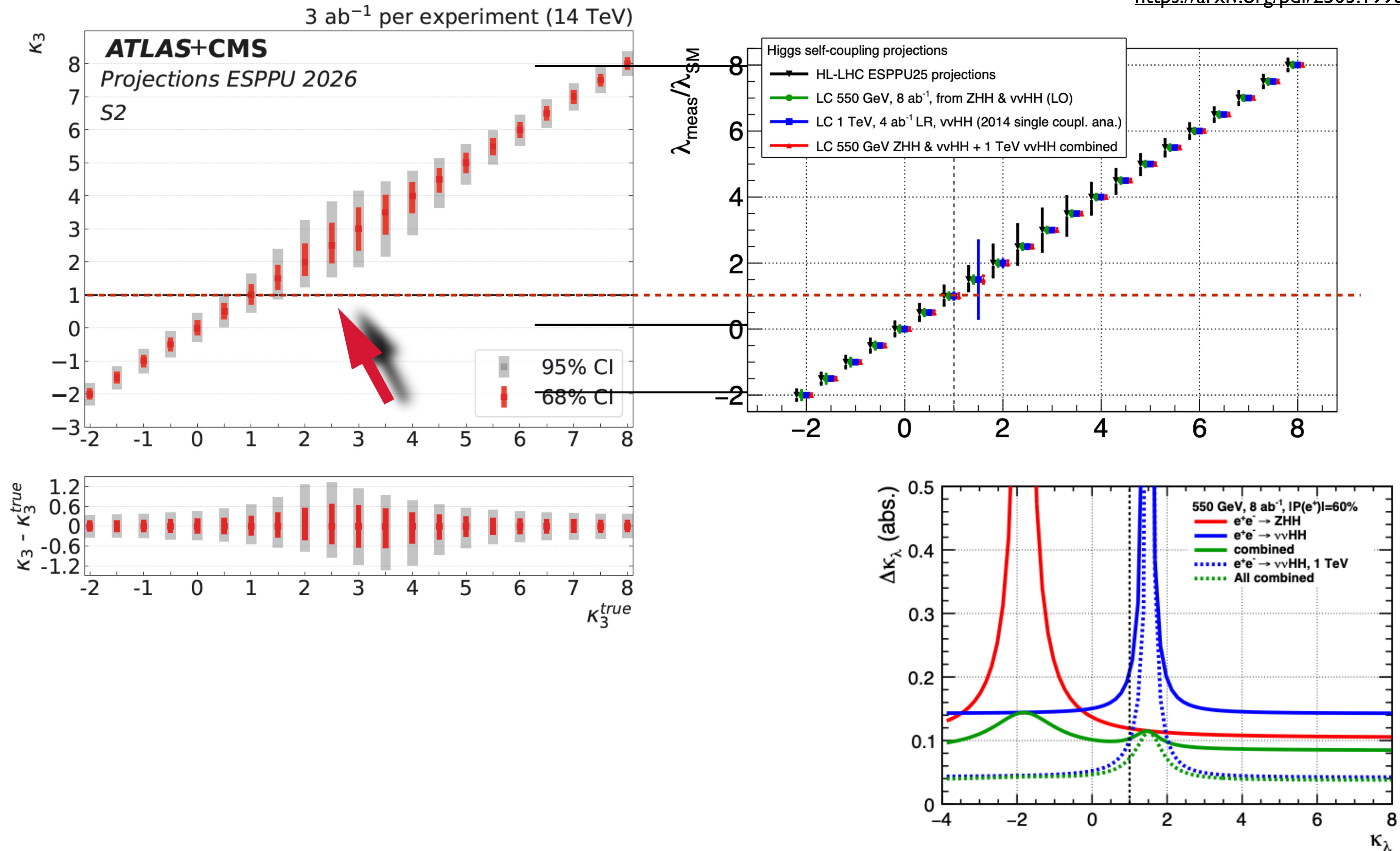
(Winston Churchill)

izquotes.com

BACK-UP

ATLAS+CMS Projections for κ_3

<https://arxiv.org/pdf/2503.19983v2>



Ratios of K's $\Rightarrow$ reduce theory systematics

