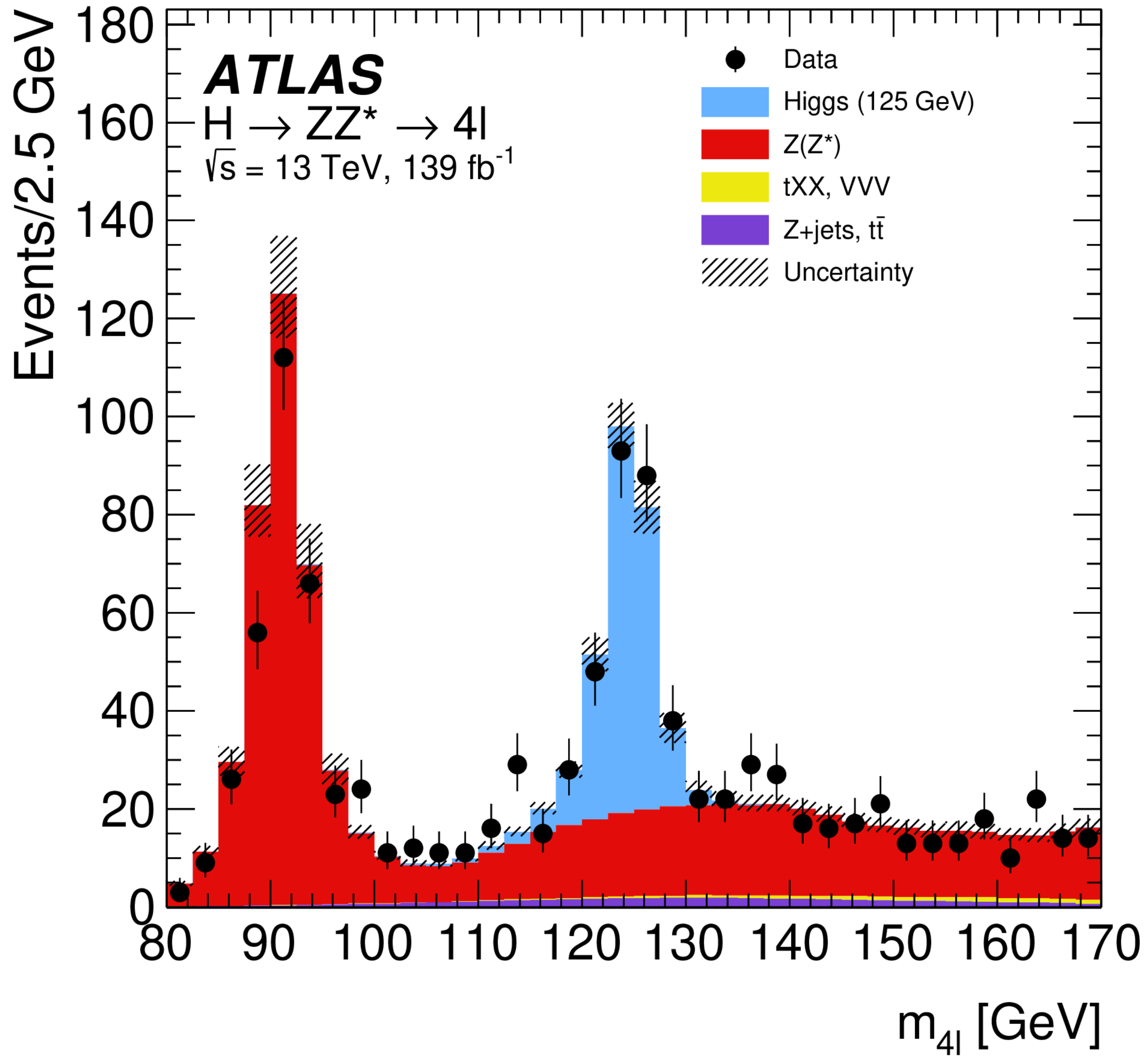
(Almost) 10 years of Higgs boson:

from discovery to the precision era

A panel at CERN collecting press titles after the July 4th announcement

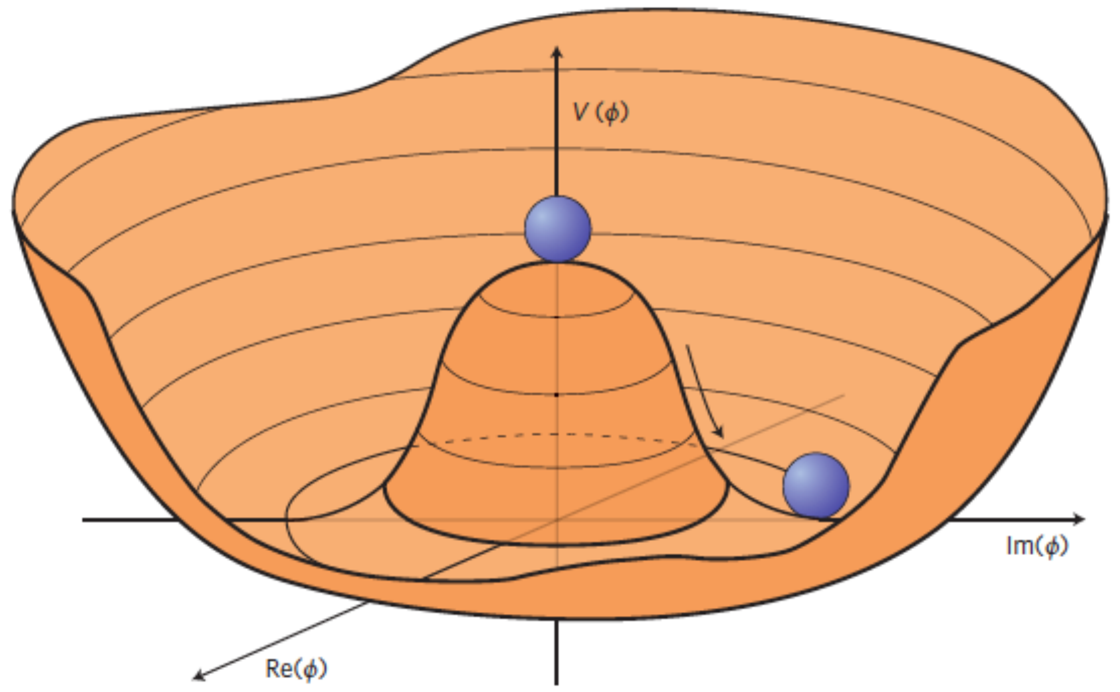


Giovanni Marchiori (APC)

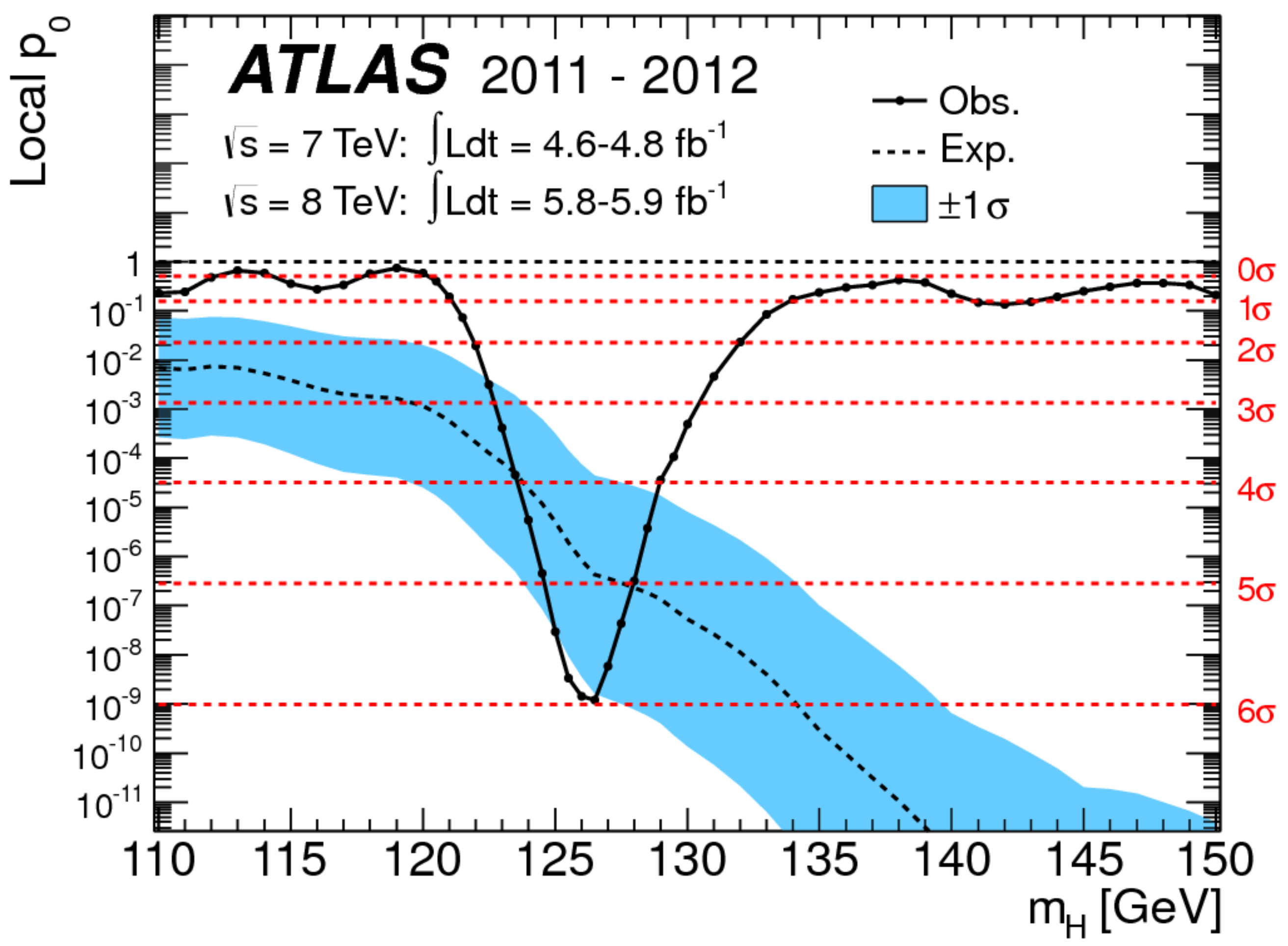
APC Seminar
21 January 2022

Outline

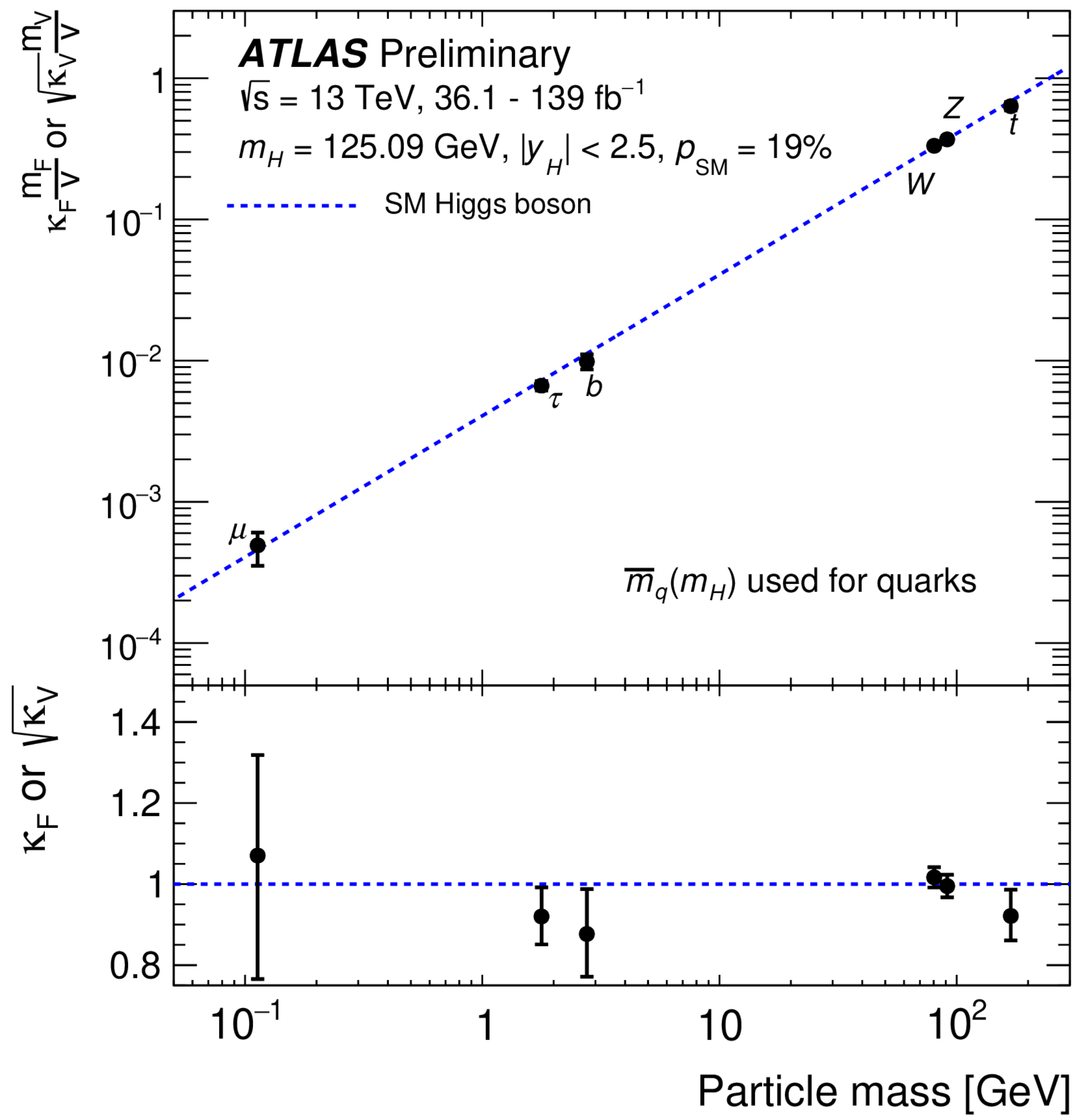
- The Standard Model of particle physics and the role of the Higgs field



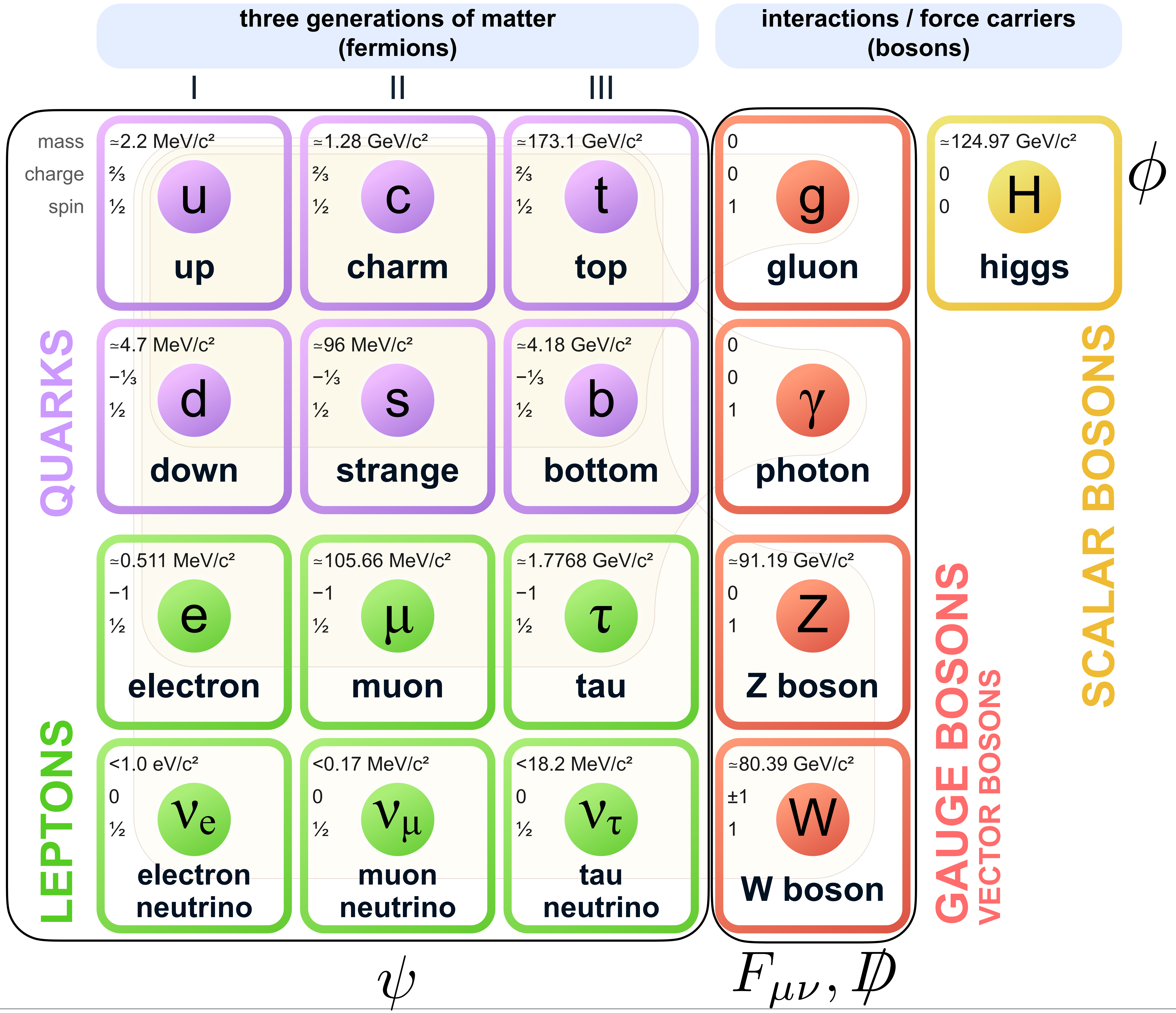
- The Higgs boson discovery in the LHC Run1

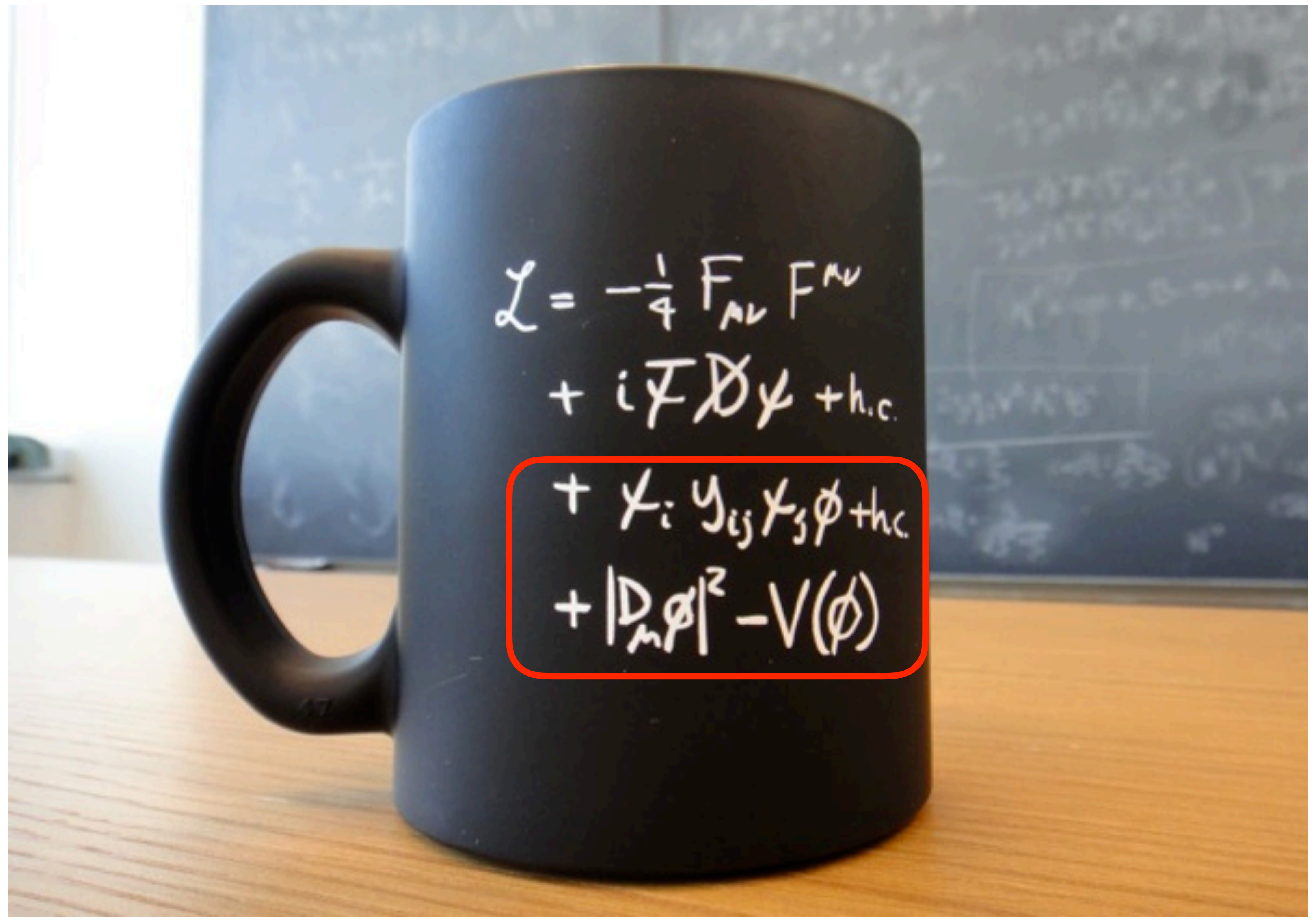


- Higgs Boson profiling with the LHC Run2 dataset



The Standard Model of particle physics





The Standard Model of particle physics

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L\equiv[\tfrac{1}{2}(1+\gamma_5)]\binom{\nu_e}{e} \quad (1)$$

and on a right-handed singlet

$$R\equiv[\tfrac{1}{2}(1-\gamma_5)]e. \quad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y\equiv N_R+\frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi=\binom{\varphi^0}{\varphi^-} \quad (3)$$

whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathfrak{L}=-\tfrac{1}{4}(\partial_\mu\vec{A}_\nu-\partial_\nu\vec{A}_\mu+g\vec{A}_\mu\times\vec{A}_\nu)^2-\tfrac{1}{4}(\partial_\mu B_\nu-\partial_\nu B_\mu)^2-\bar{R}\gamma^\mu(\partial_\mu-ig'B_\mu)R-L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu-i\tfrac{1}{2}g'B_\mu)L$$
$$-\tfrac{1}{2}|\partial_\mu\varphi-ig\vec{A}_\mu\cdot\vec{t}\varphi+i\tfrac{1}{2}g'B_\mu\varphi|^2-G_e(\bar{L}\varphi R+\bar{R}\varphi^\dagger L)-M_1{}^2\varphi^\dagger\varphi+h(\varphi^\dagger\varphi)^2. \quad (4)$$

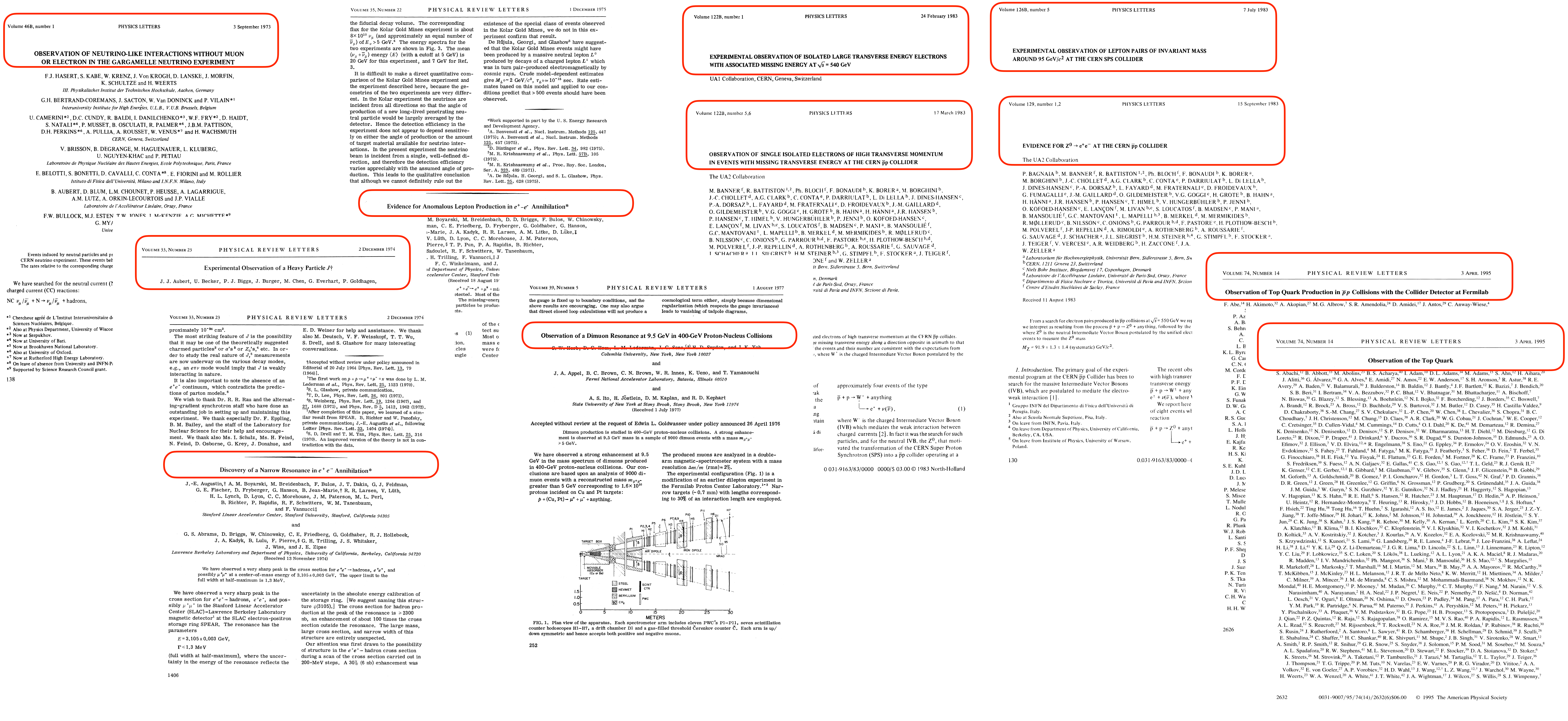
We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda\equiv\langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

- **Though its birthdate is usually referred to as the publication of Weinberg's 1967 paper "A model of leptons", the SM was built in the 60's and 70's as the result of the contributions of many brilliant theoretical physicists**

- These include (non-exhaustive list):
  - **1961-1964**: Glashow, Salam: SU(2) x U(1) model of electroweak interactions
  - **1964**: Gell-Mann and Zweig, quark model
  - **1964**: Higgs, Englert, Brout: spontaneous symmetry breaking
  - **1967**: Weinberg, Salam: coherent model of electroweak interactions AND spontaneous symmetry breaking. Prediction of a Higgs Boson
  - **1970**: Glashow, Iliopoulos, Maiani: prediction of 4th quark (charm) to solve strangeness-violating first-order weak interactions
  - **1971-72**: t'Hooft, Veltmann, Lee, Zinn-Justin: renormalisability of electroweak theory
  - **1973**: Fritzsch, Gell-Mann: QCD as SU(3) model of strong interactions
  - **1973-1974**: Gross, Wilczek, Politzer: asymptotic freedom of strong interactions
  - **1974**: Kobayashi, Maskawa: extend Cabibbo's theory (1963) of quark mixing to 3x3 complex matrix leading to CP violation in SM. Prediction of 3rd generation of quarks

Successes of the Standard Model

- **In the past 50+ years, many predictions of the SM concerning the phenomena of the microscopic world have been confirmed.**
  A few milestones:



Successes of the Standard Model

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  A few milestones:

1973: neutral weak currents (Gargamelle@CERN)

1974: 1st charm-quark resonance (BNL and Mark-I@SLAC)

1975: τ lepton (Mark-I@SLAC)

1977: 1st b-quark resonance (E288@Fermilab)

1983: W and Z bosons (UA1, UA2@CERN)

1995: top quark (CDF, D0@Fermilab)

2000s: CP violation in B mesons (BaBar@SLAC, Belle@KEK)

(+ a large wealth of results in neutrino physics..)

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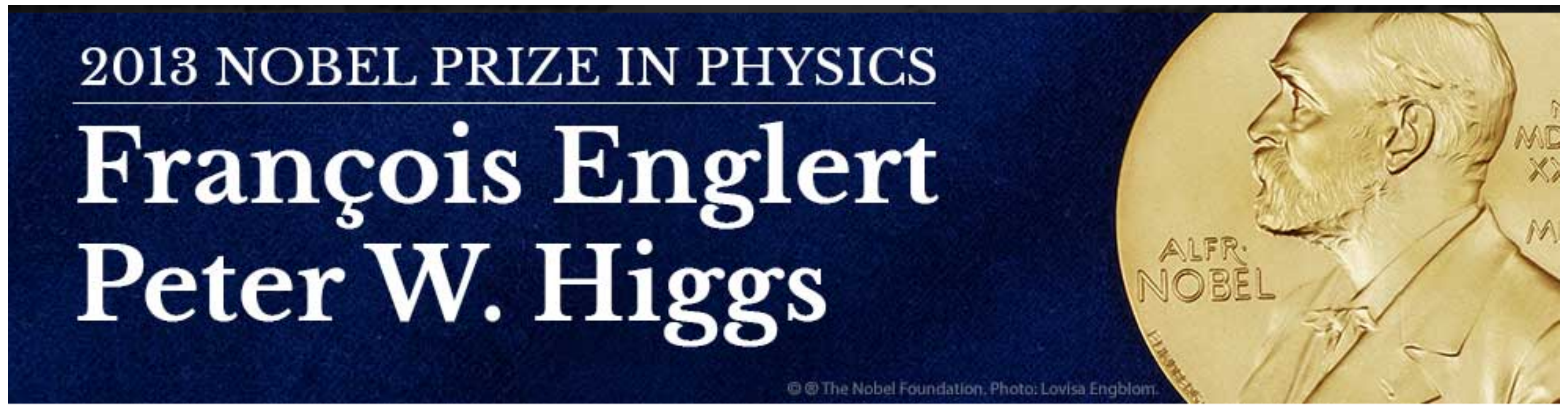
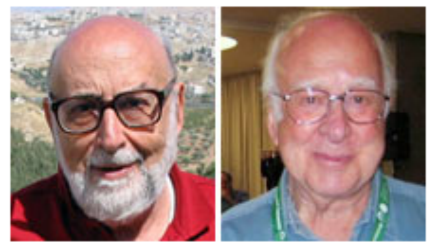
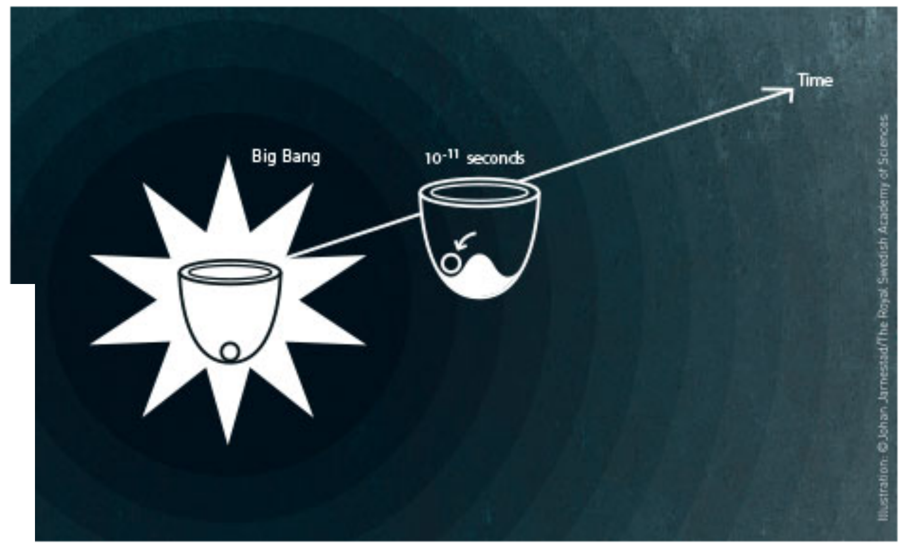


- **Crowning success of the SM: discovery of the Higgs boson in 2012**





Vhat Happened after the Big Bang?

Announcements of the 2013 Nobel Prizes

Physiology or Medicine:
Announced Monday 7 October

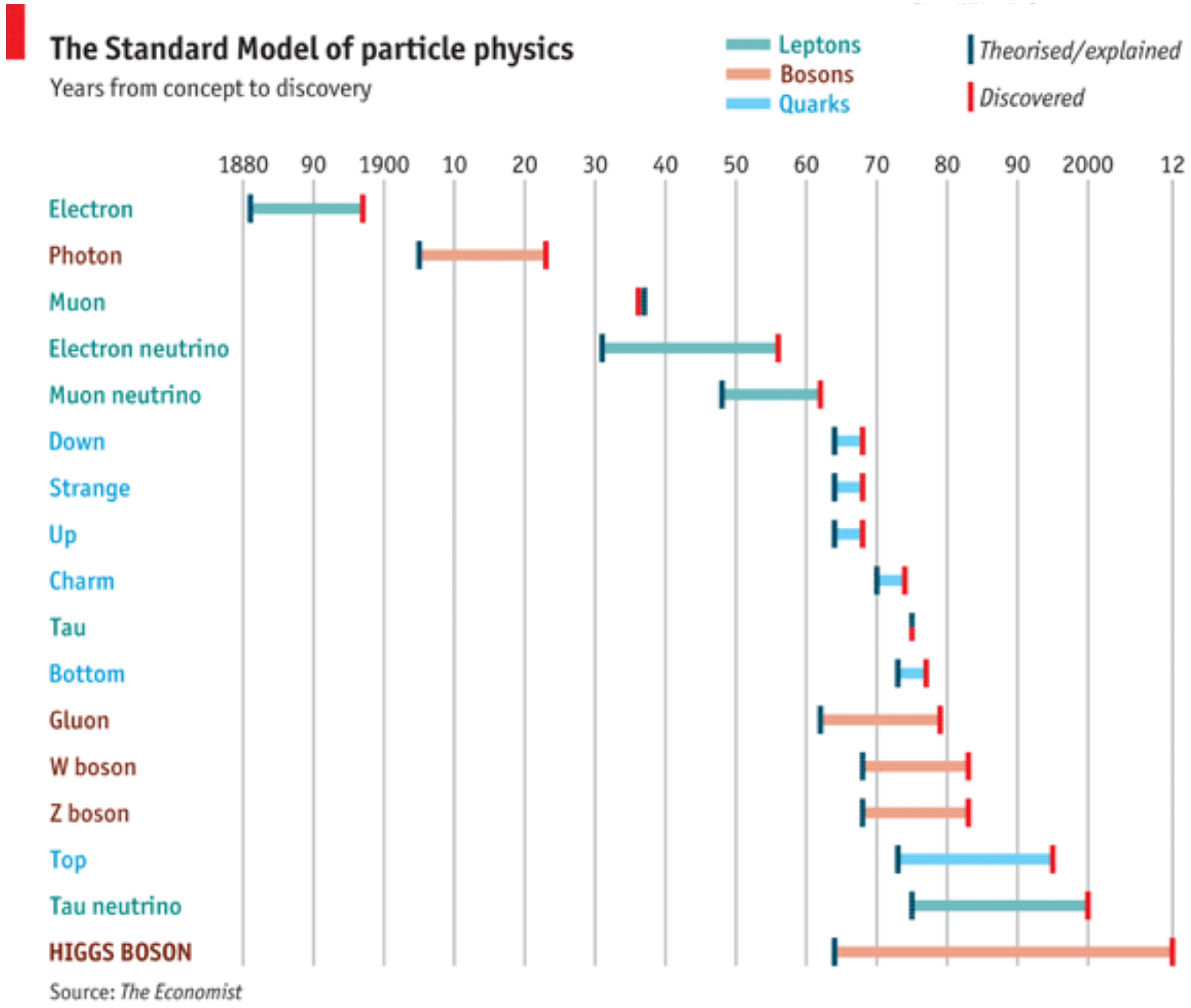
Physics:
Tuesday 8 October, 11:45 a.m. CET at the earliest

Chemistry:
Wednesday 9 October, 11:45 a.m. CET at the earliest

Literature:
Thursday 10 October 1.00 p.m. CET

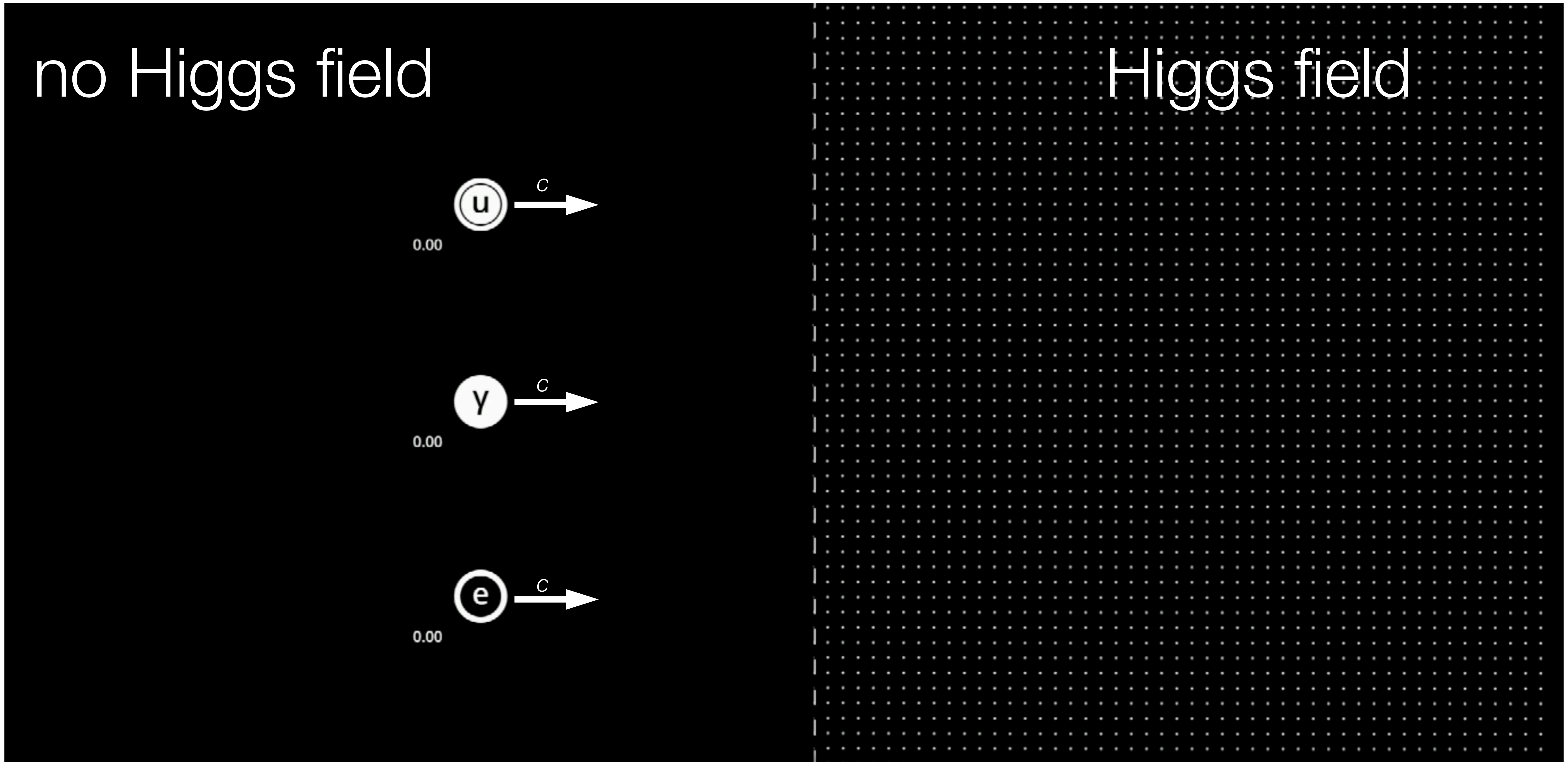
Peace:

- **What is so special about the Higgs boson?**
- **Why did it take so long to find it?**
- **What have we learnt about it so far?**



What is the Higgs boson?

- The **Higgs boson** is the particle corresponding to the quantum excitations of the Higgs field (as we shall se in the next slides..)
- The **Higgs field** is a scalar field that permeates all the universe since shortly after the Big Bang
- The interactions of the elementary particles with it give those particles their **masses**
    - The stronger the interaction, the larger the particle mass



From https://videos.cern.ch/record/2757407

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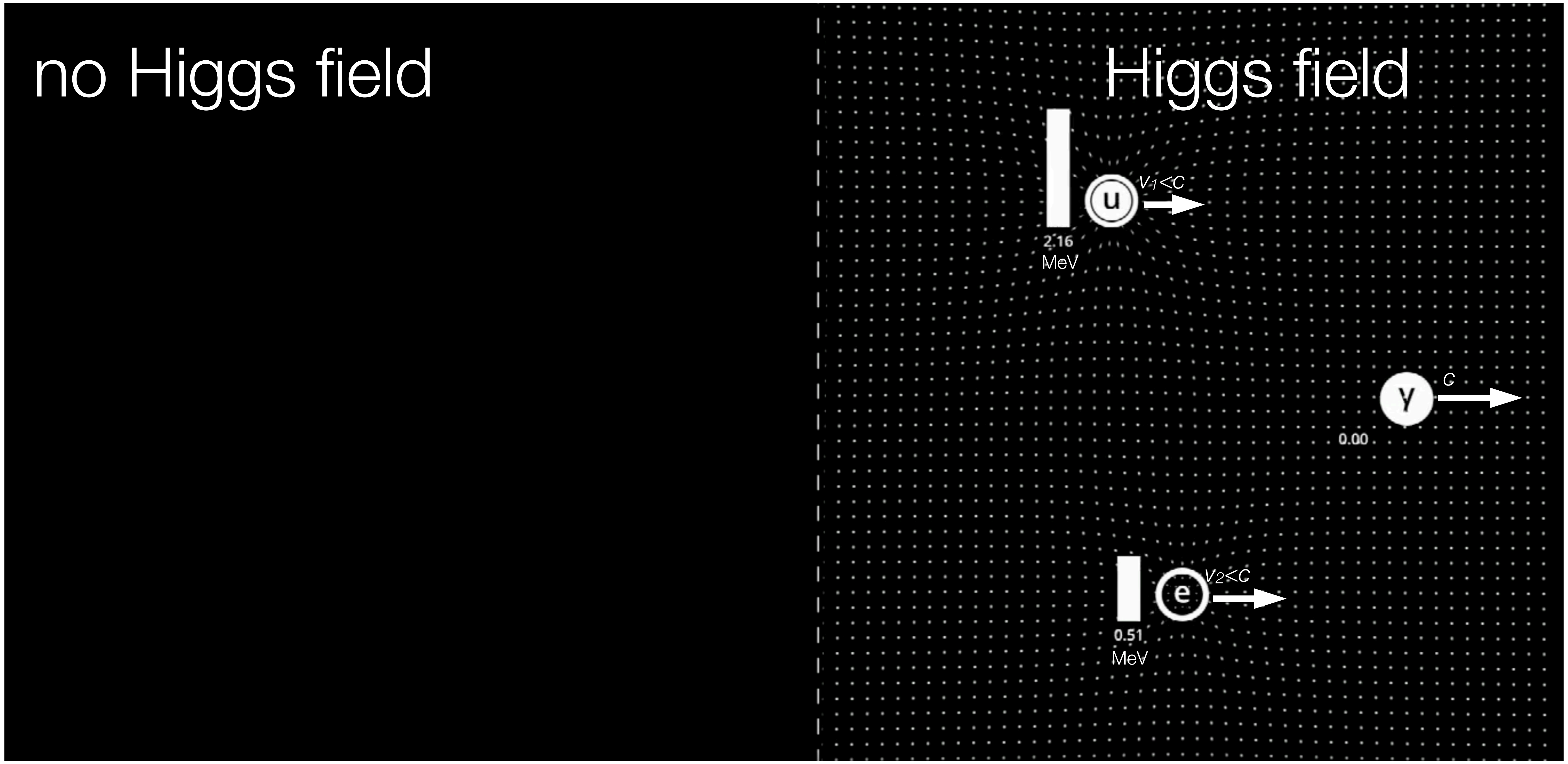
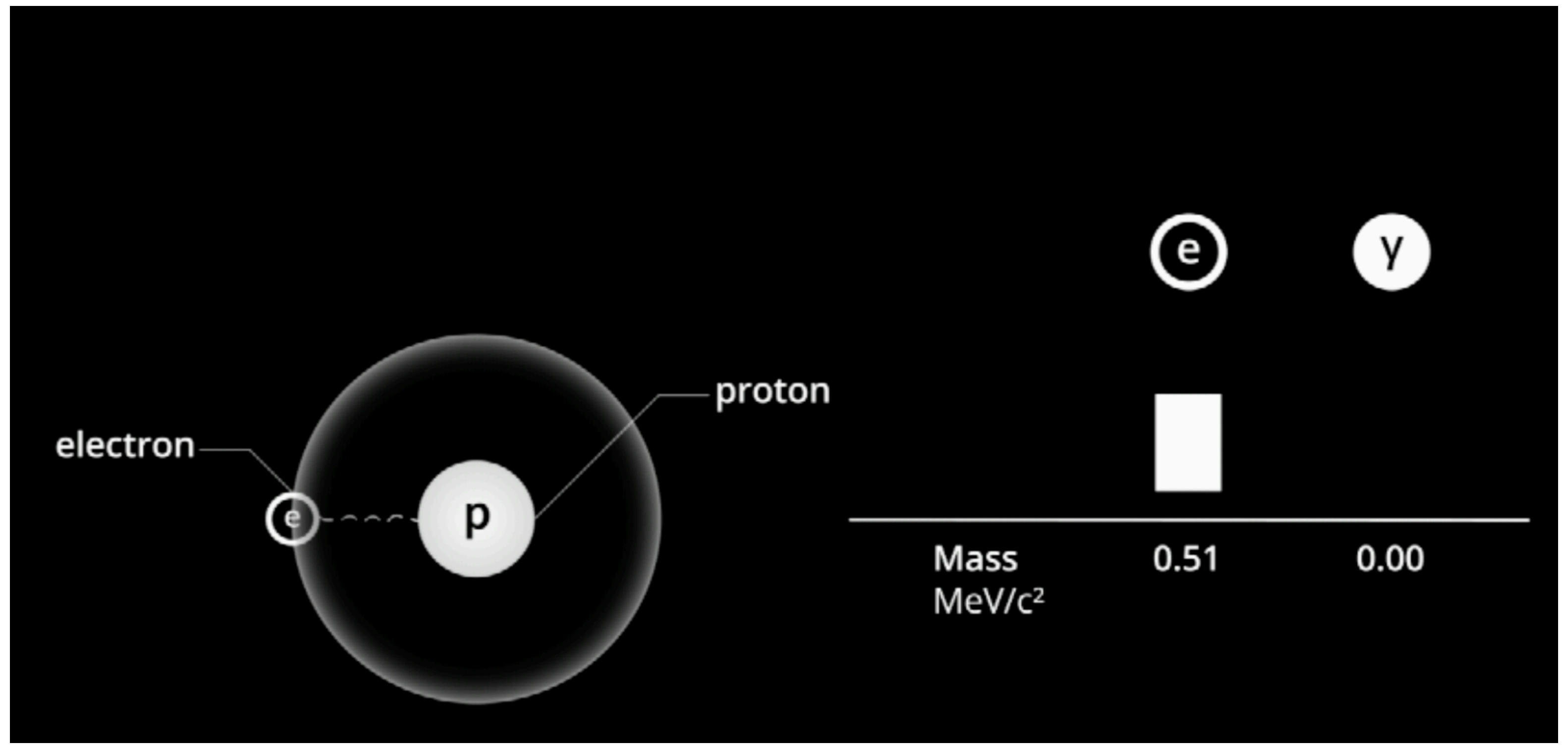


From https://videos.cern.ch/record/2757407

What would happen without the Higgs field?

- Without the interaction with the Higgs field giving the elementary particles their masses, our Universe would be much different:

Higgs → *hydrogen atoms*



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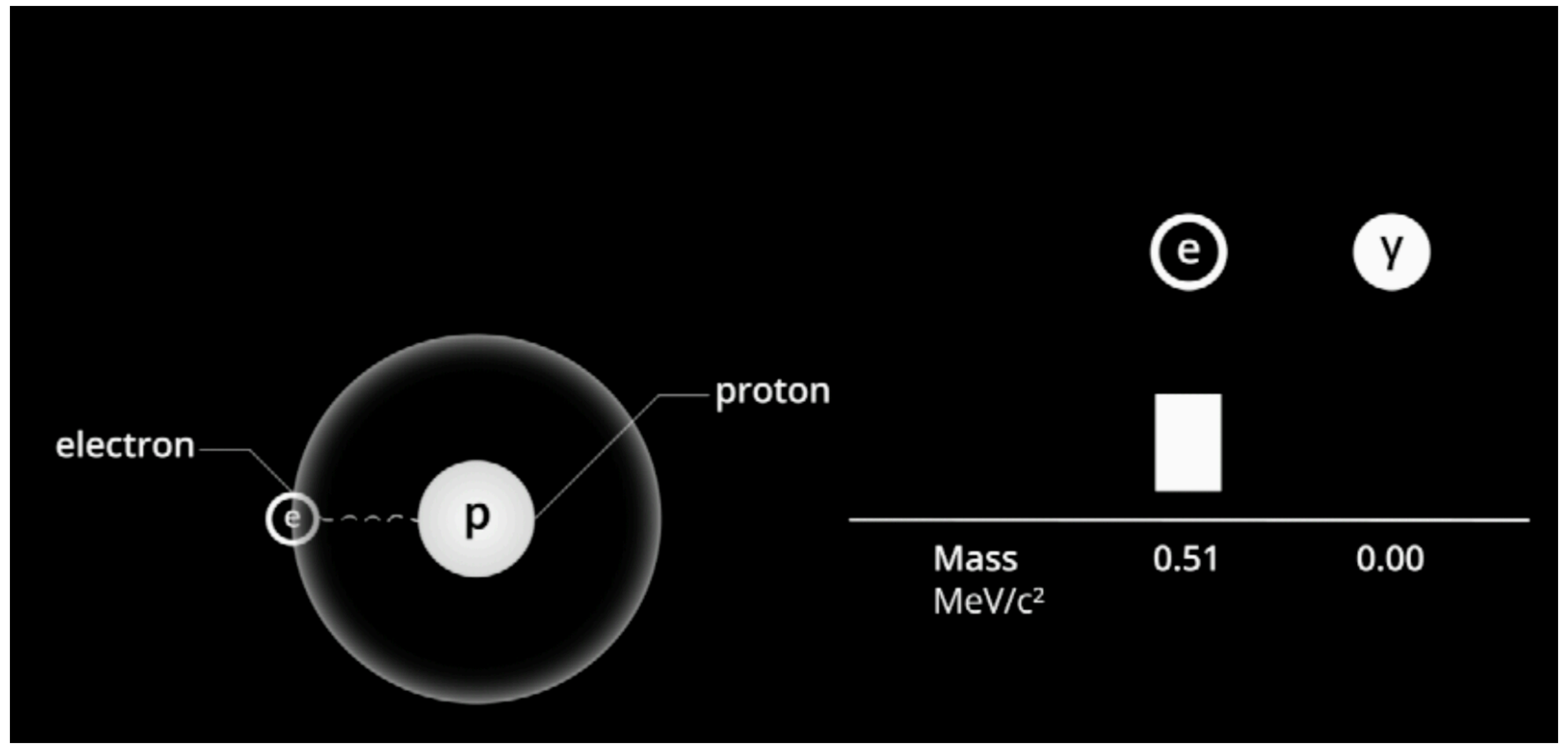
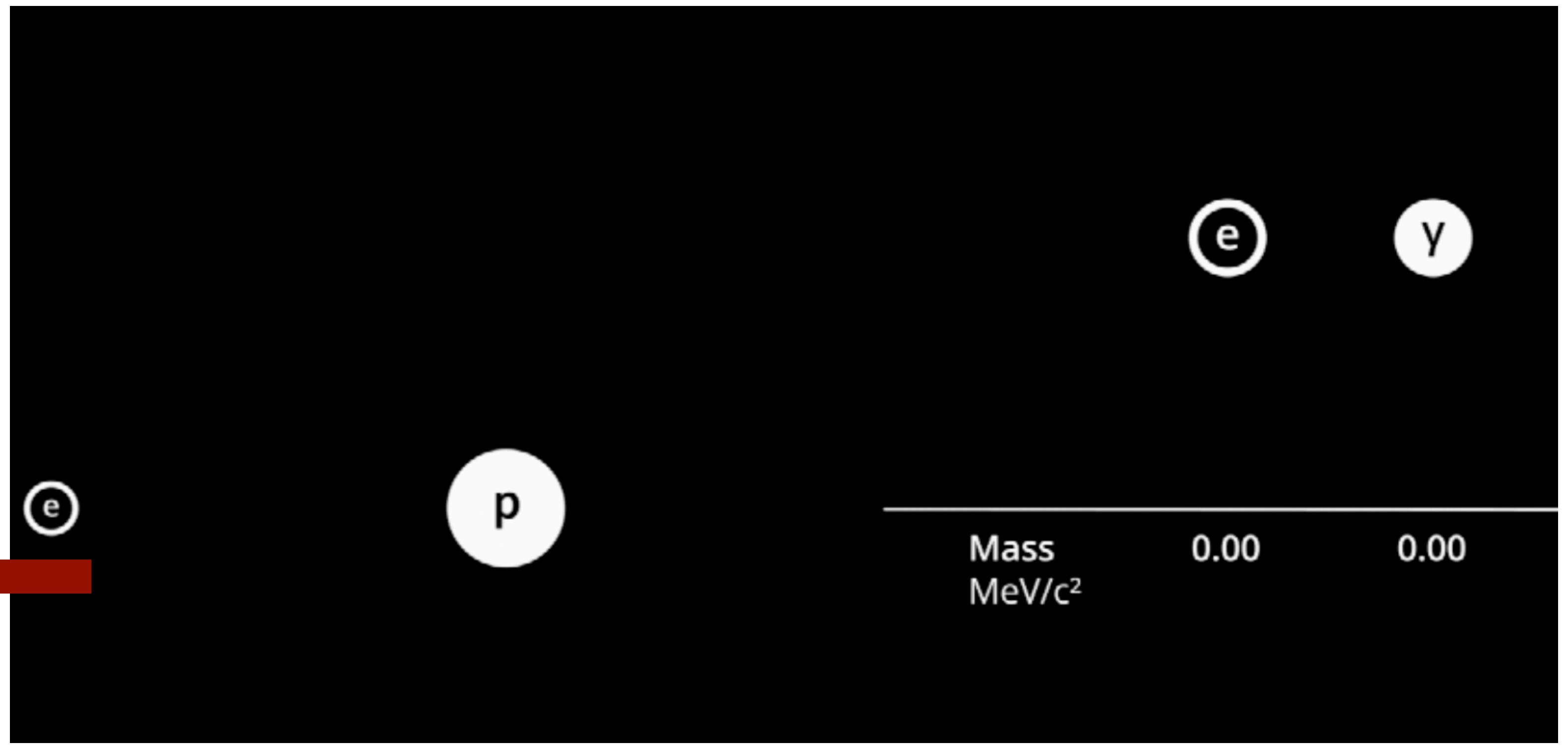
Higgs



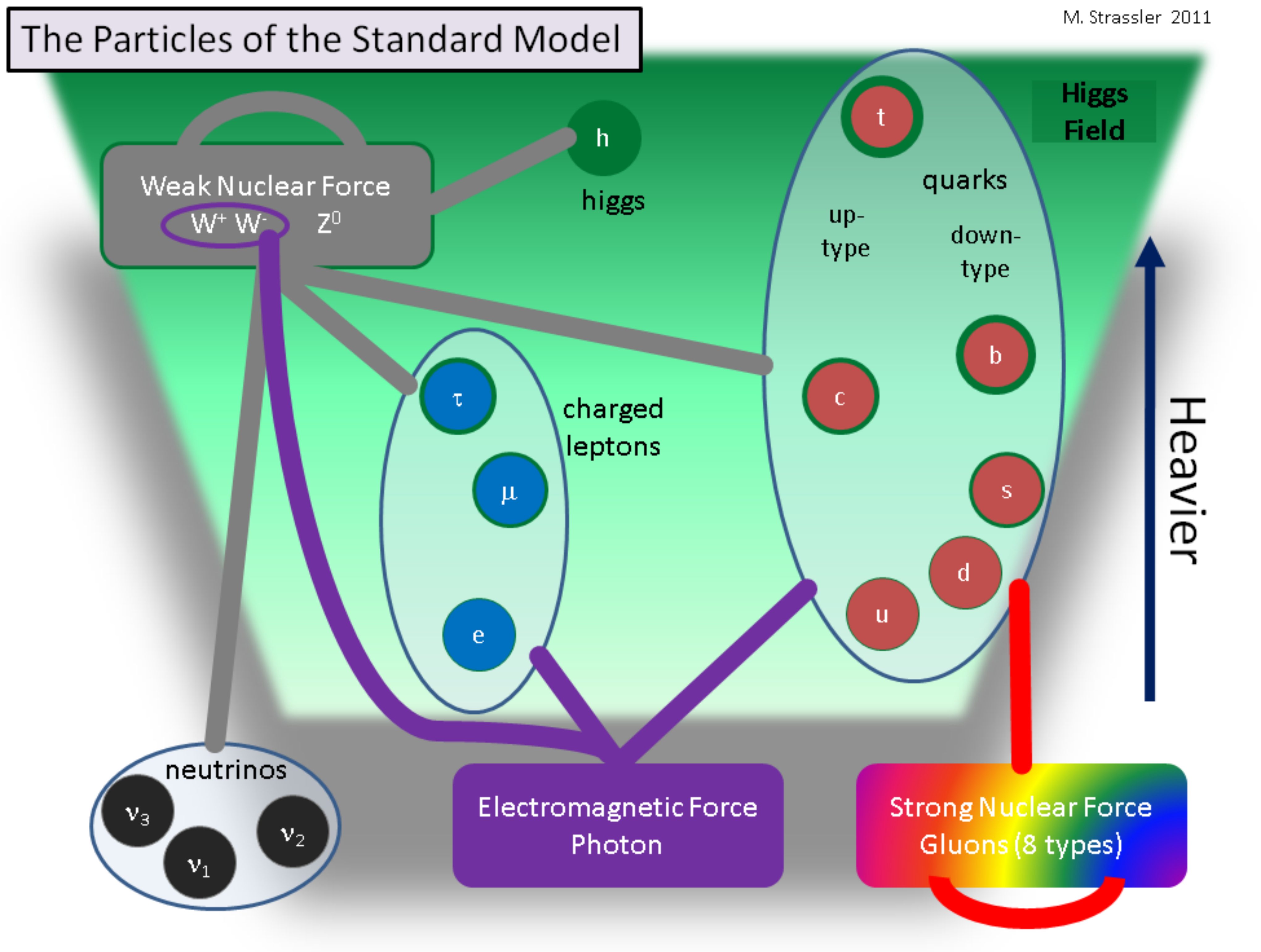
No Higgs

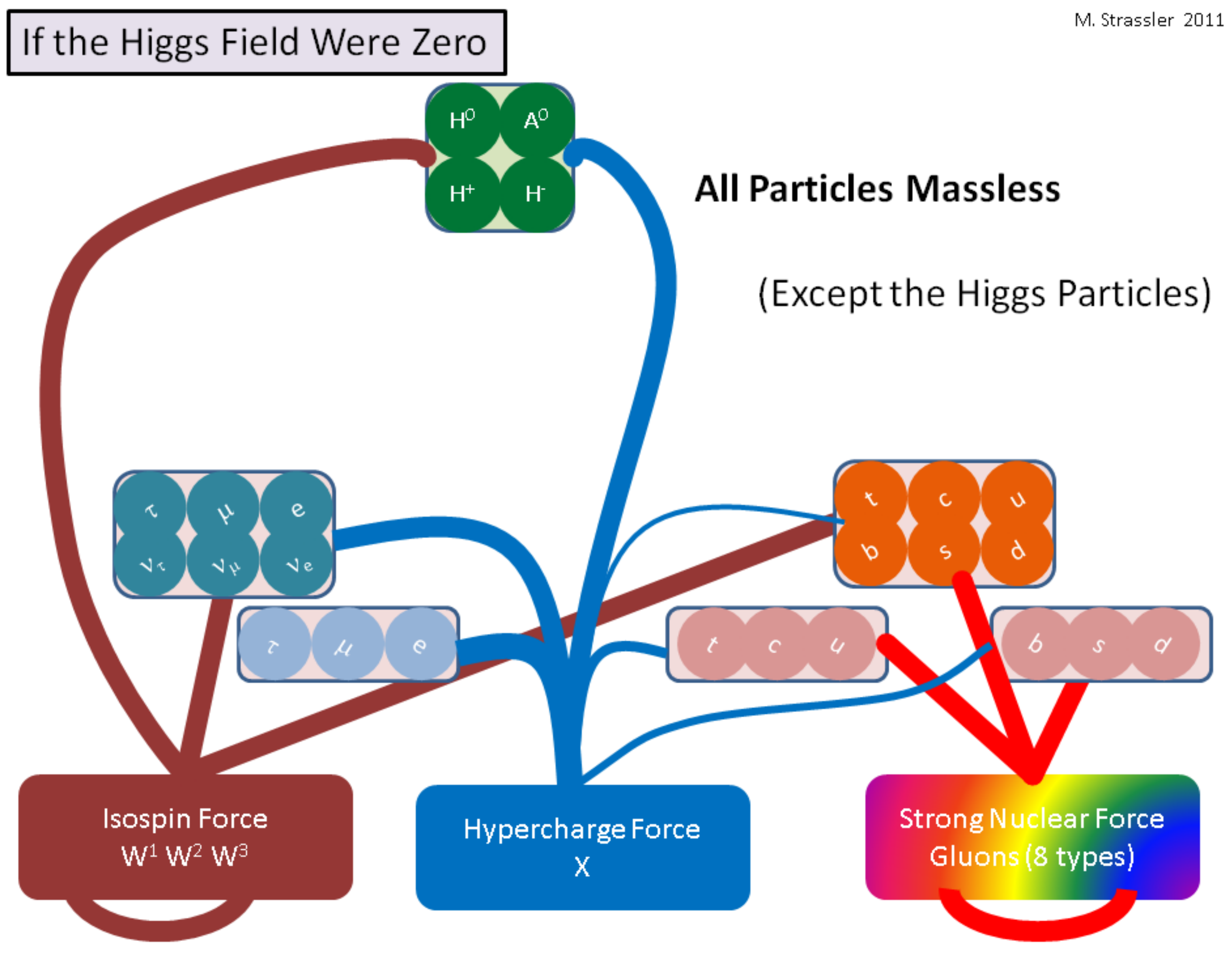


no hydrogen atoms

What would happen without the Higgs field?

- **Not only the elementary particles would be massless, but their interactions would be different from the one we know!**
  - Due to the SU(2)xU(1) gauge invariance of the SM Lagrangian (which is what forbids adding explicit mass terms!), weak interactions (mediated by massive gauge bosons) and electromagnetic interactions (mediated by the photon, affecting only charged fermions) would be replaced by a "isospin force" and a "hypercharge" force, both mediated by massless bosons, affecting both charged and neutral fermions
- Overall, the SM particle organisation would look quite different (and simpler):

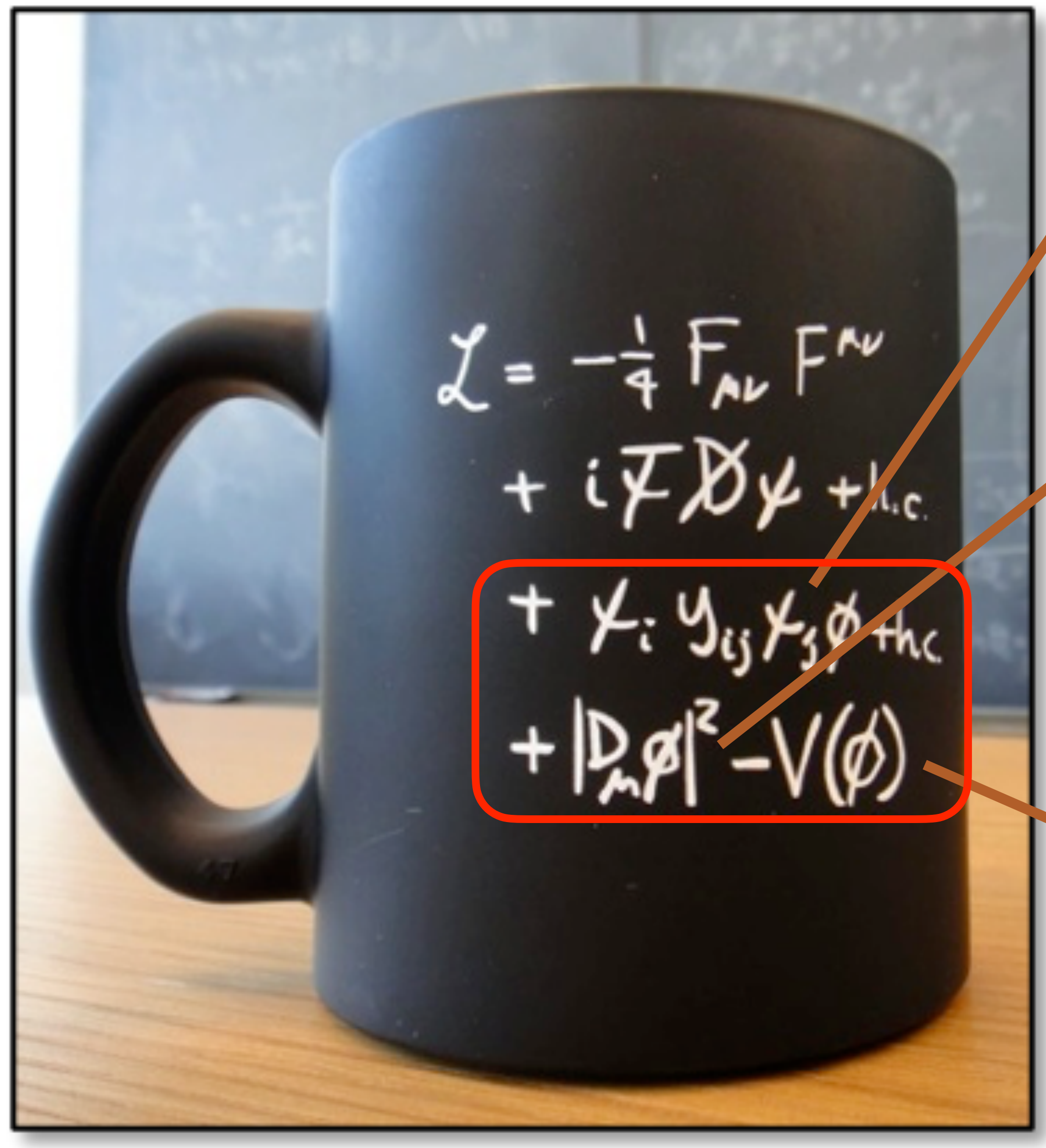




https://profmattstrassler.com/articles-and-posts/particle-physics-basics/the-known-apparently-elementary-particles/the-known-particles-if-the-higgs-field-were-zero/

The Brout-Englert-Higgs (BEH) mechanism

- A solution to both puzzles (particle masses+EW symmetry breaking) is provided by the **spontaneous symmetry breaking** mechanism
  - A **doublet of complex scalar fields ϕ** is added to the SM Lagrangian $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

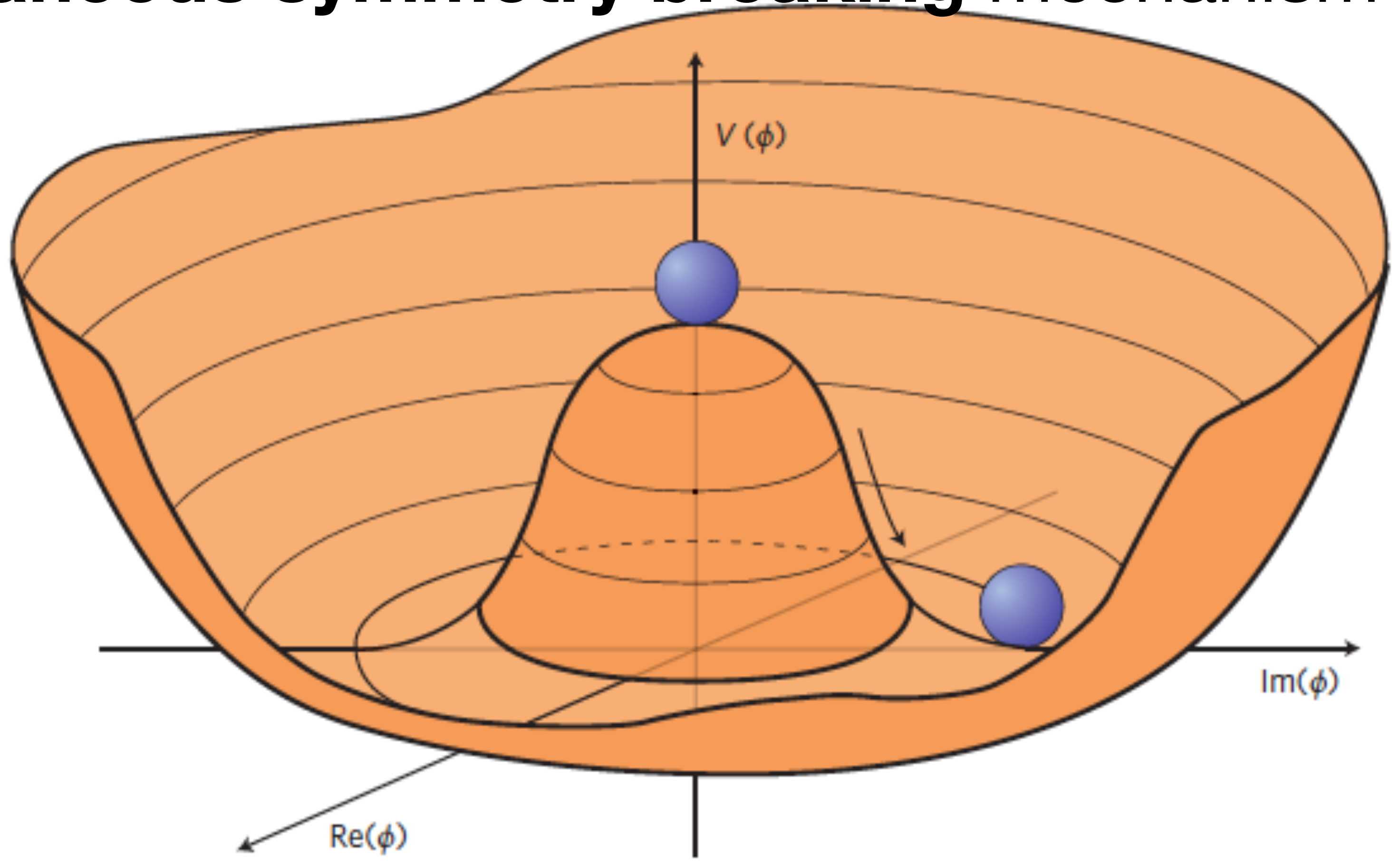


(Yukawa) interactions between the field and the fermions

Interactions between the field and the gauge bosons

Higgs field potential $\mu^2 < 0 \quad \lambda > 0$

$$V(\Phi) = \mu^2 \mid \Phi^\dagger \Phi \mid + \lambda \left(\mid \Phi^\dagger \Phi \mid \right)^2$$



infinite set of degenerate states with minimum energy, satisfying

$$|\langle 0 | \, \Phi \, | 0 \rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$$

$$v = \frac{|\mu|}{\sqrt{\lambda}} = \frac{2M_W}{g} = 246\text{GeV}$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- The Lagrangian density remains invariant under SU(2)xU(1), but the minimum (vacuum) is not
  - Spontaneous symmetry breaking!
- Expanding around the minimum, $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$, leads to the appearance of mass terms for fermions and weak gauge bosons, Higgs boson self-interactions, and precise relations between the particle masses and their couplings to the Higgs boson

The Brout-Englert-Higgs (BEH) mechanism

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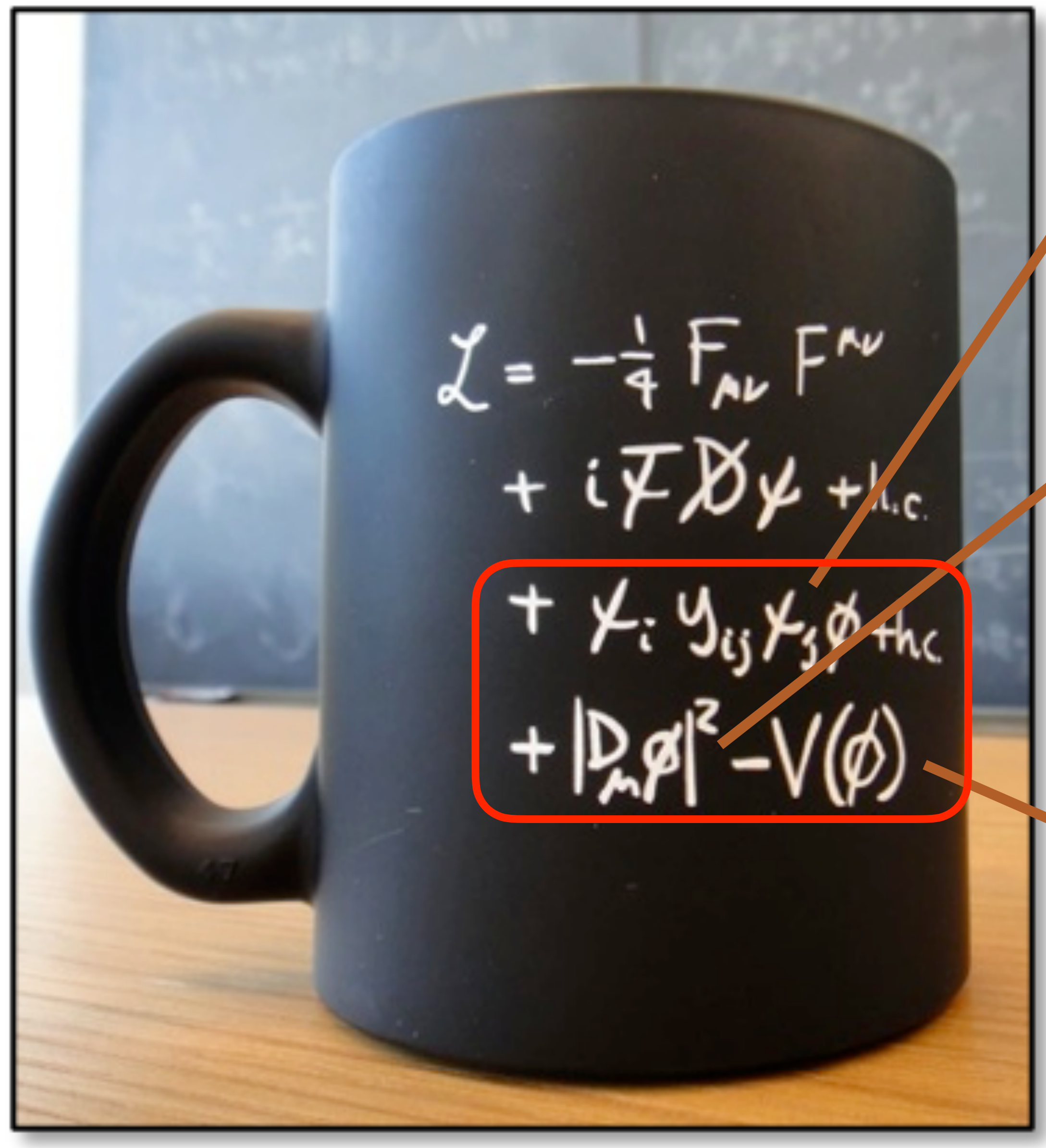
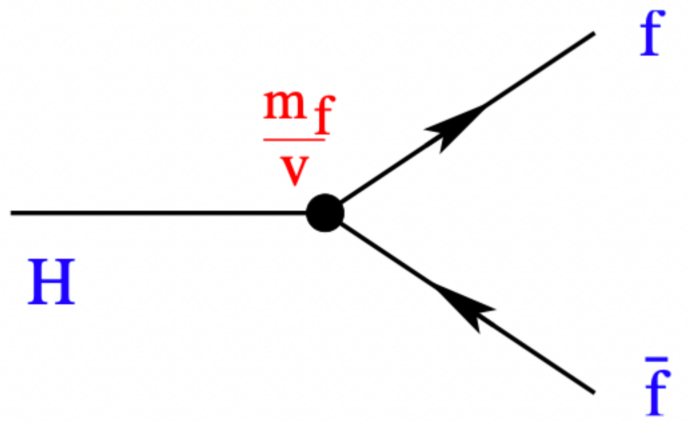


(Yukawa) interactions between the field and the fermions

Fermion masses + Higgs-fermion interactions

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \{m_d \bar{d}d + m_u \bar{u}u + m_e \bar{e}e\}$$

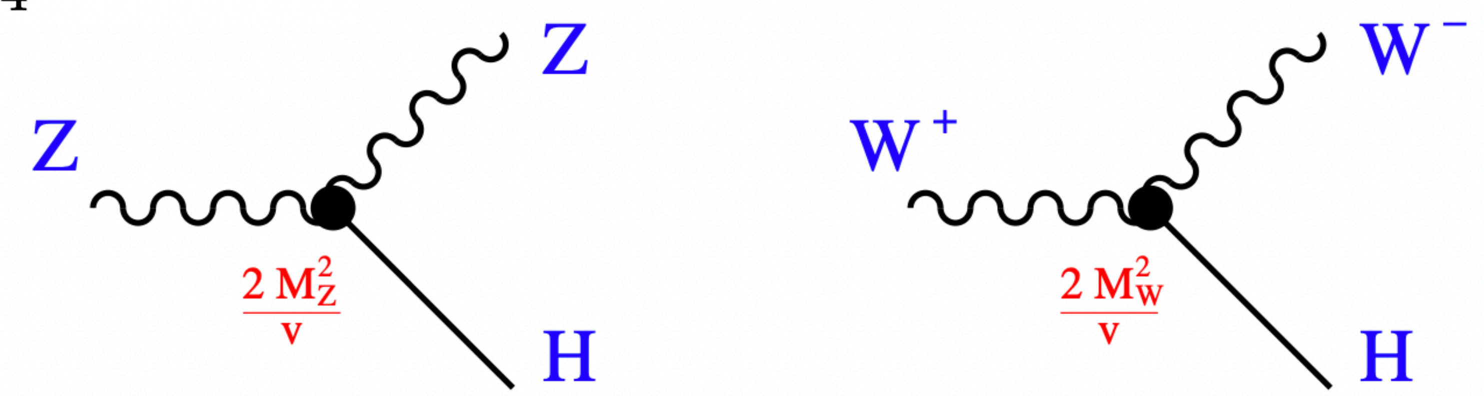


Interactions between the field and the gauge bosons

W, Z masses + W/Z-Higgs interactions

$$\mathcal{L}_{HG^2} = M_W^2 W_\mu^\dagger W^\mu \left\{1 + \frac{2}{v} H + \frac{H^2}{v^2}\right\} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \left\{1 + \frac{2}{v} H + \frac{H^2}{v^2}\right\}$$

$$M_W^2 = \frac{1}{4} g^2 v^2 \qquad M_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$$



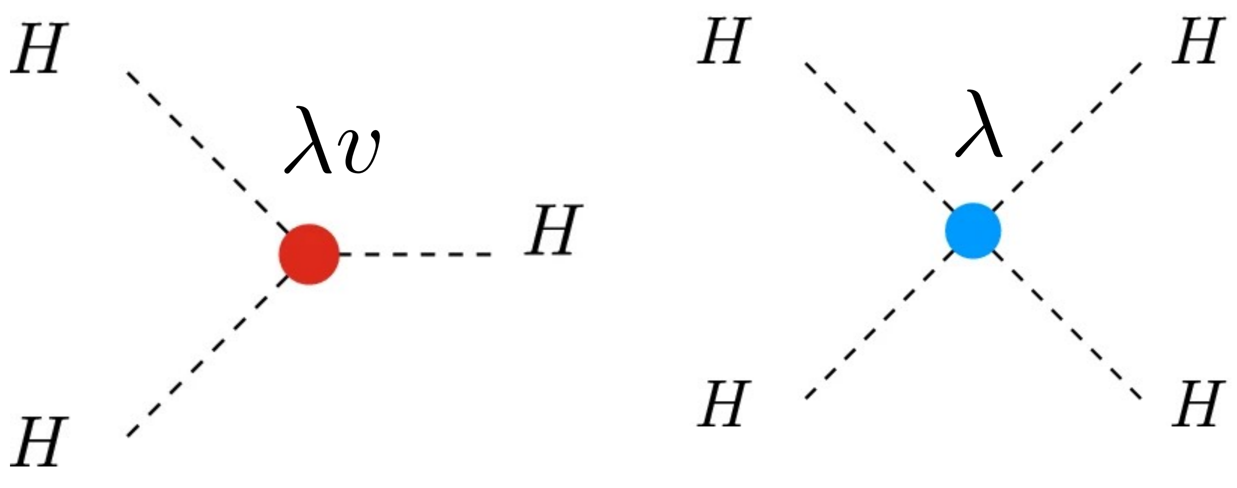
Higgs field potential $\mu^2 < 0 \quad \lambda > 0$

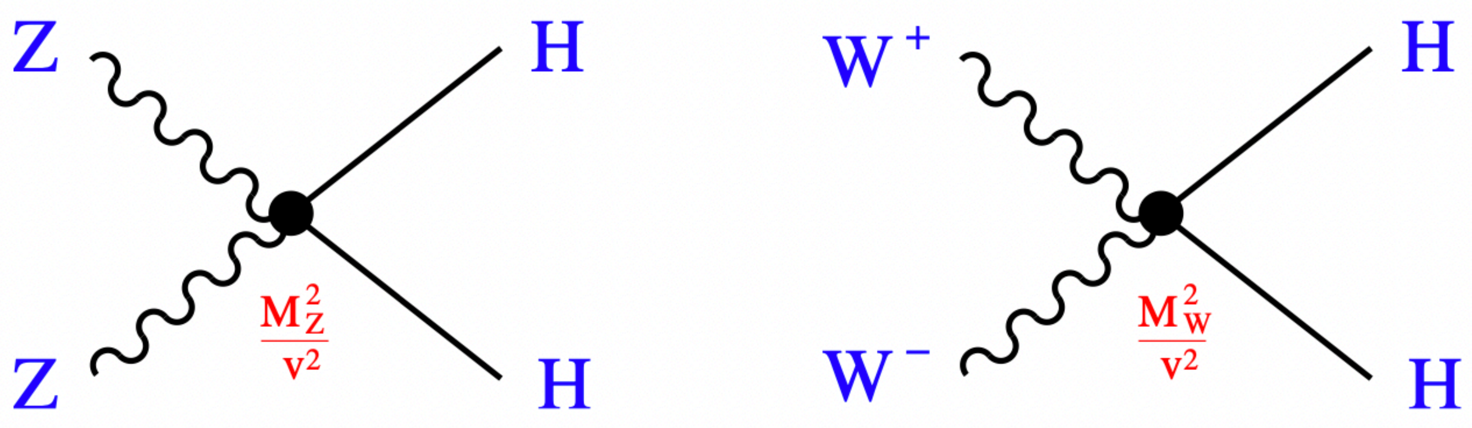
$$V(\Phi) = \mu^2 \,|\, \Phi^\dagger \Phi \,| + \lambda \left(|\, \Phi^\dagger \Phi \,| \right)^2$$

Higgs mass, and Higgs self interactions

$$\mathcal{L}_H = \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{1}{2} M_H^2 H^2 - \frac{M_H^2}{2v} H^3 - \frac{M_H^2}{8v^2} H^4$$
$$= \frac{1}{2} \partial_\mu H \partial^\mu H - \frac{1}{2} M_H^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

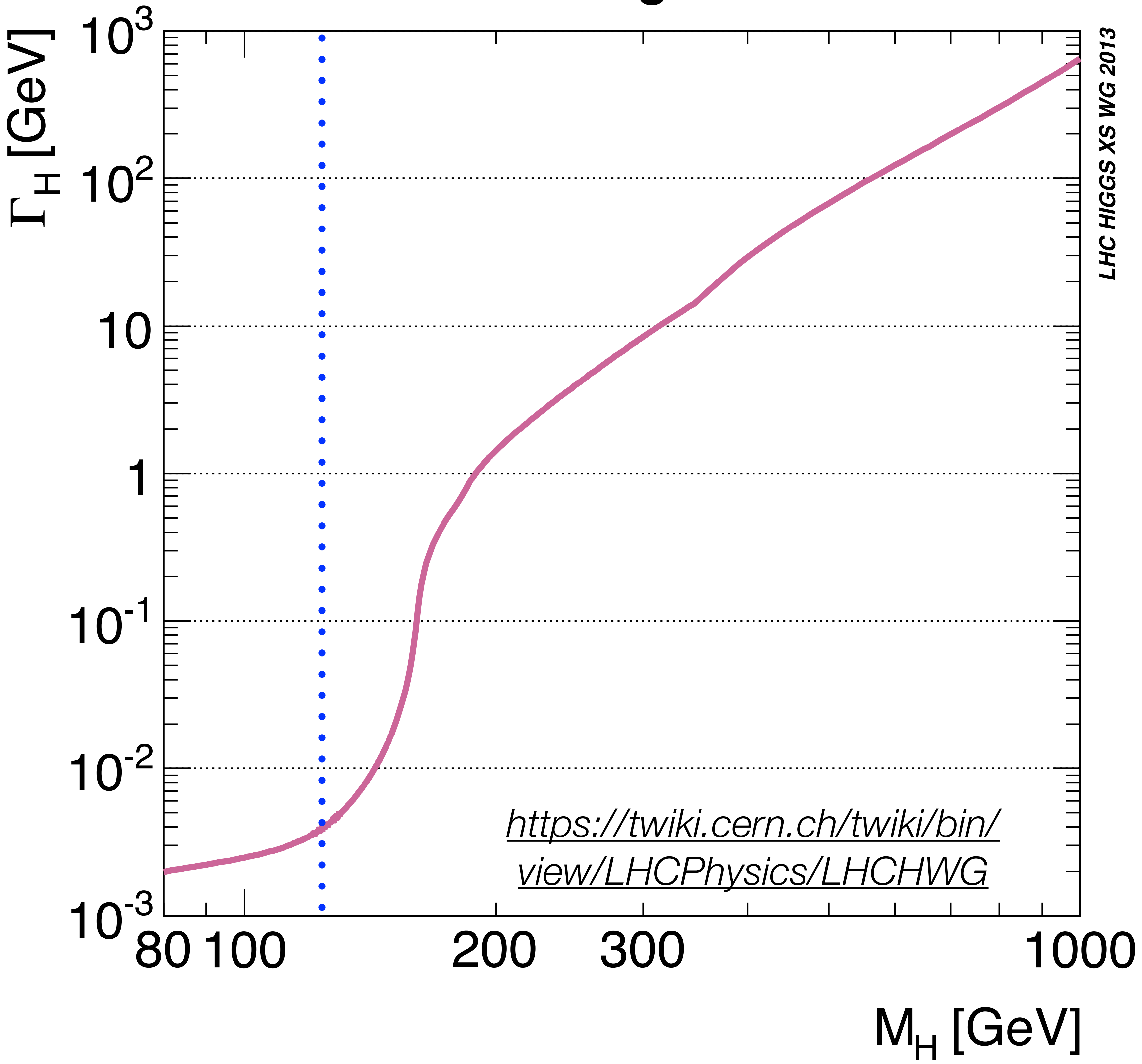
$$M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda} v$$





Predicted properties of the SM Higgs boson

- **Mass and self-coupling**: unknown
  - But related one each other through v: $M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}v$ $\quad v = \frac{|\mu|}{\sqrt{\lambda}} = \frac{2M_W}{g} = 246\text{GeV}$
- **Spin and parity**: 0+
- **Couplings to other particles**: all known
- **Partial and total widths**: can be determined from the couplings once the Higgs boson mass is fixed
- **Production cross sections and branching ratios** can also be deduced (see later)



$m_H = 125$ GeV

$\Rightarrow \Gamma_H = 4.2$ MeV

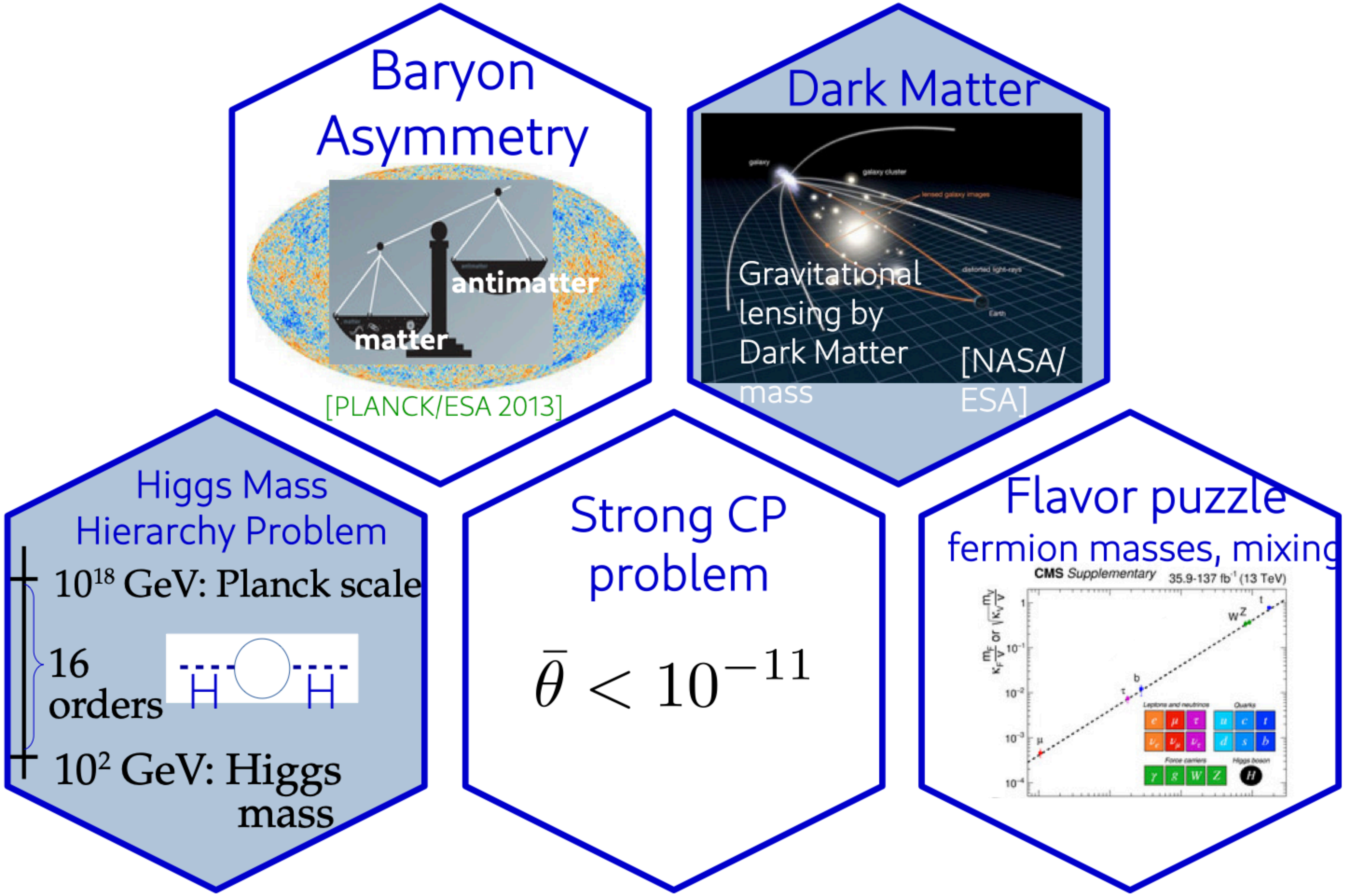
$\Rightarrow \tau = 1.6\ 10^{-22}$s

$\Rightarrow c\tau = 50$ fm

➡ We can only identify the Higgs boson by looking at its decay products

Could the Higgs tell us more about our Universe?

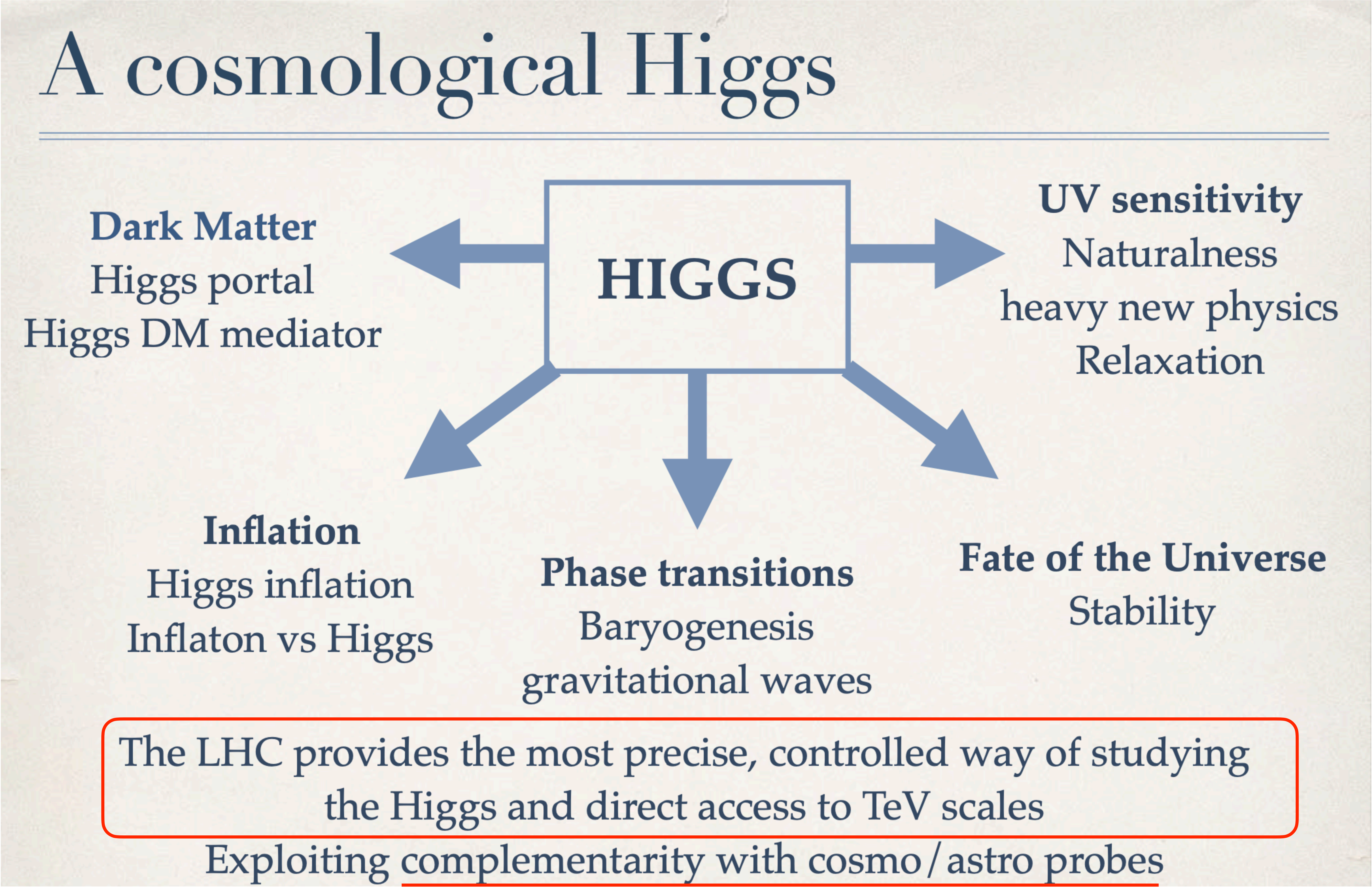
- Some open challenges in our understanding of the Universe:



E. Fuchs

Could the Higgs tell us more about our Universe?

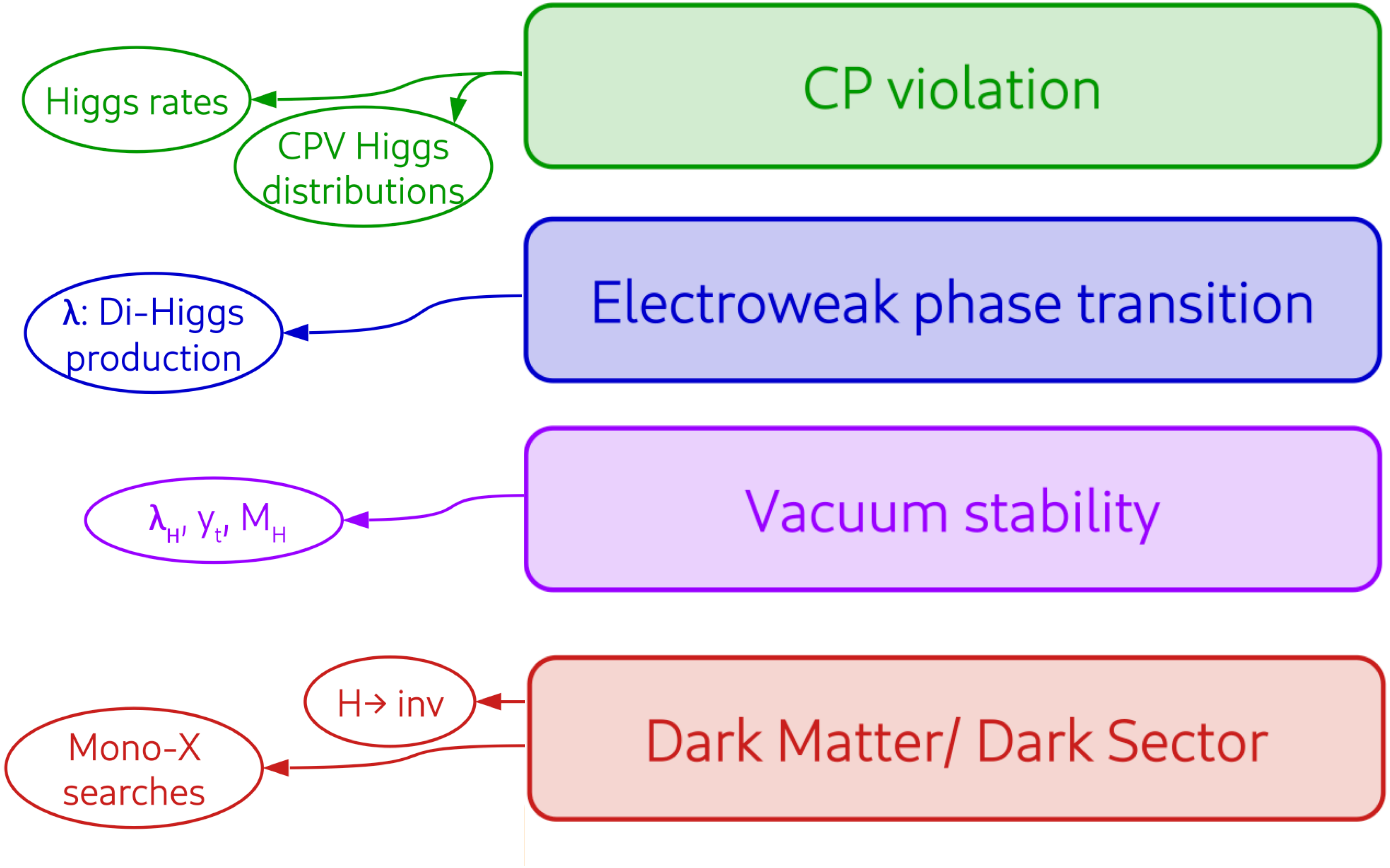
- The Higgs could be the key to solving (at least some of) these issues



V. Sanz

Could the Higgs tell us more about our Universe?

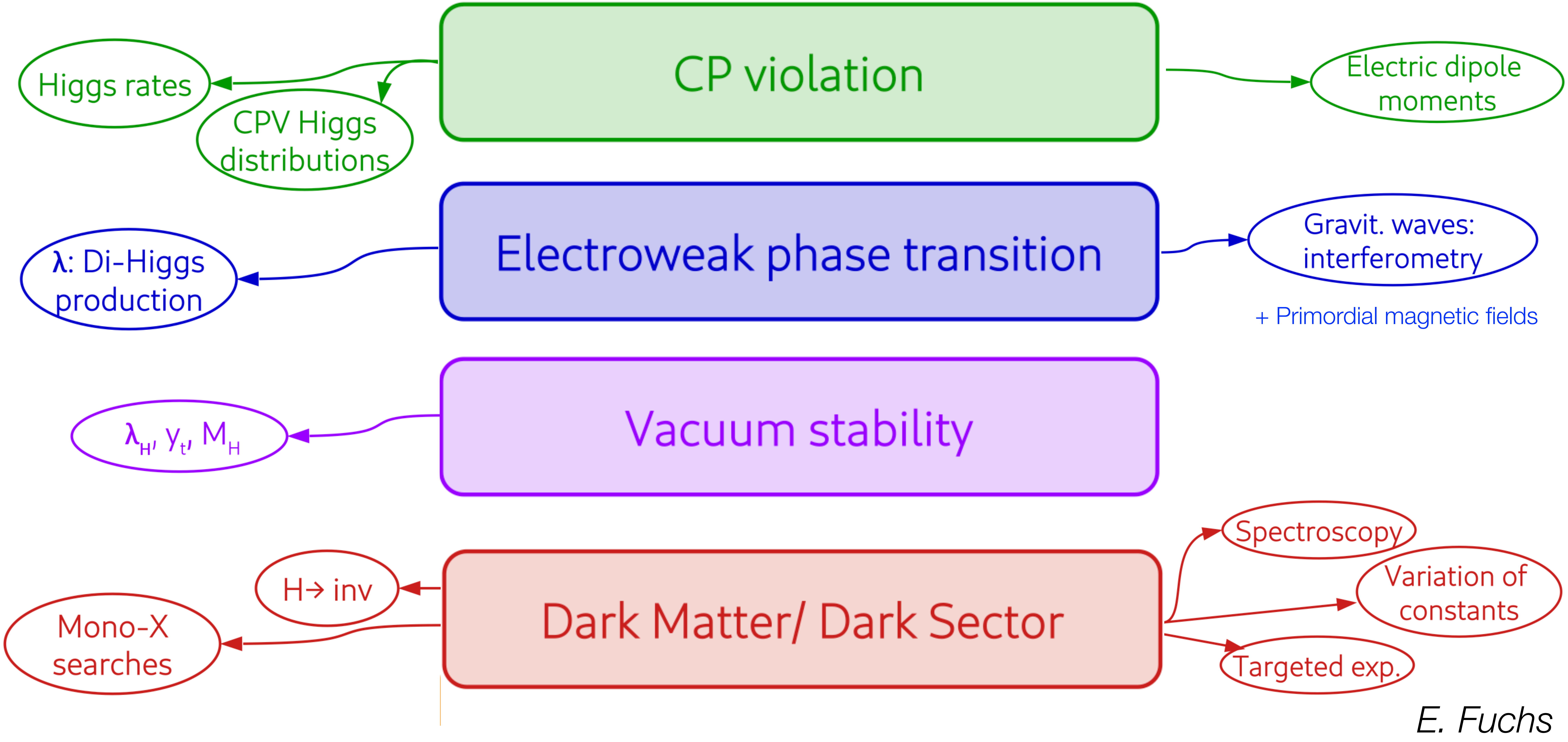
- Hopefully yes!



E. Fuchs

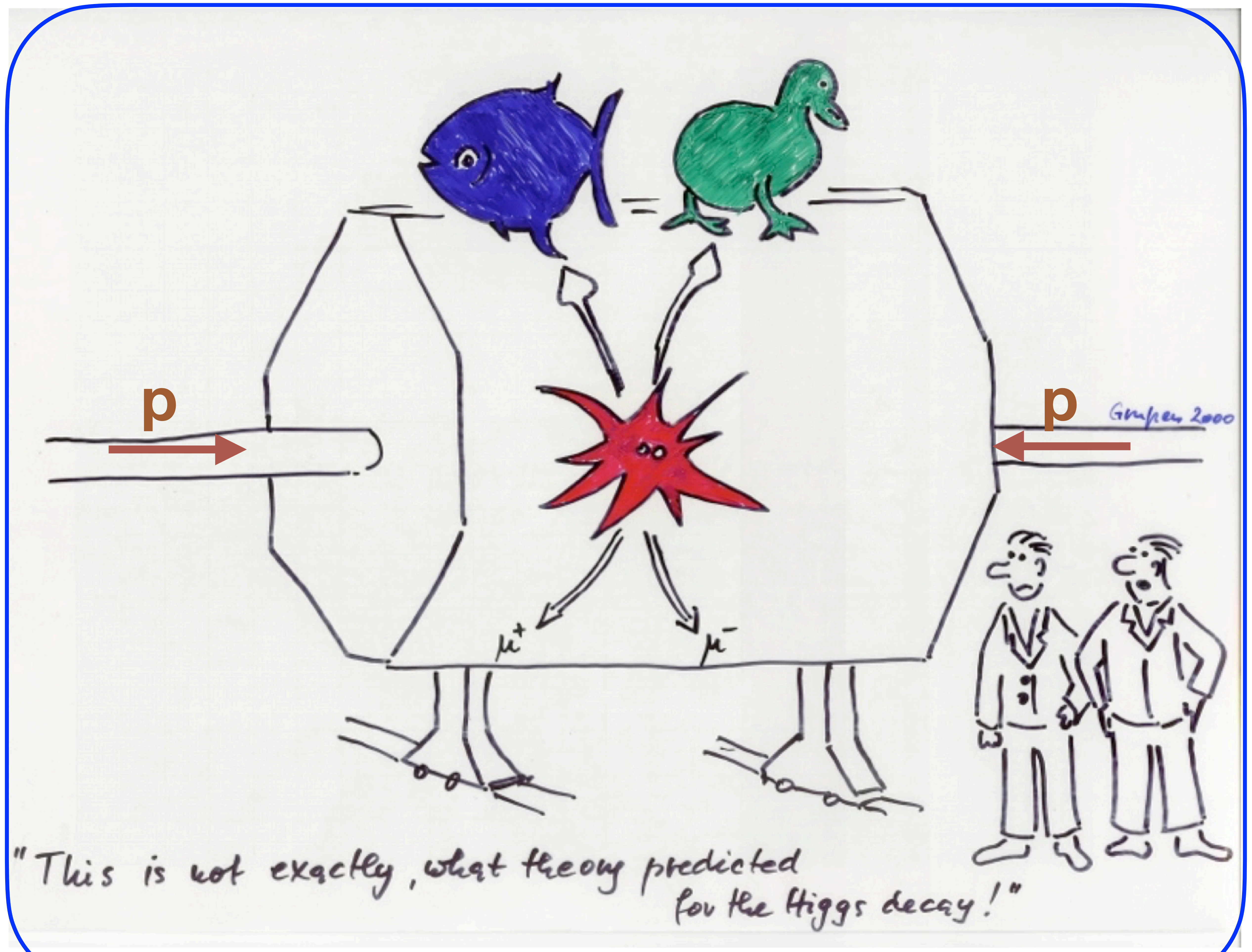
Could the Higgs tell us more about our Universe?

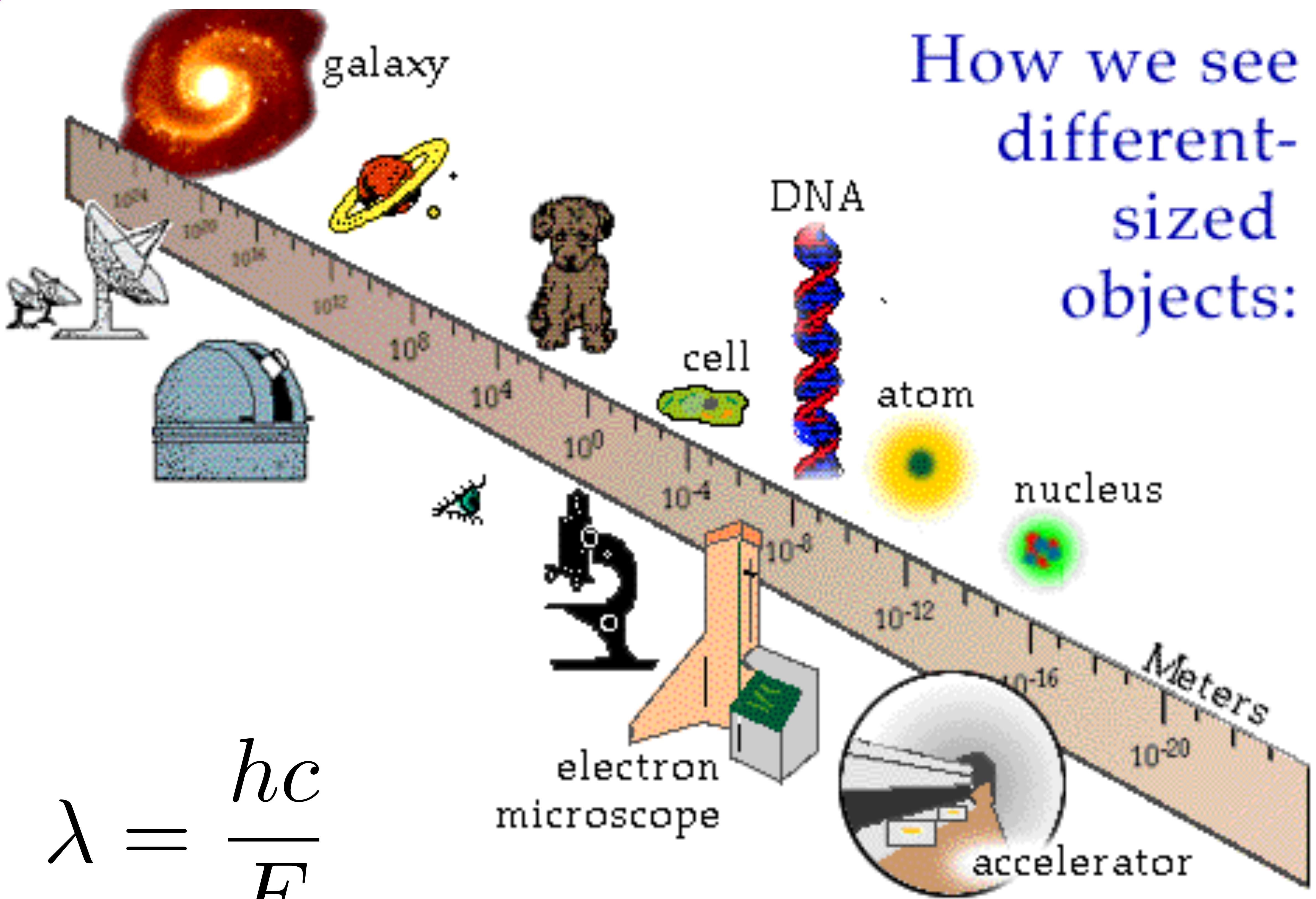
- Even more so in complementarity with other probes (astroparticles & DM / cosmology / gravitational waves / low energy observables)



Particle colliders

- Accelerate and collide particles to
  - convert their kinetic energy into mass of heavier, unstable particles ($E=mc^2$)
  - probe the internal structure of the target



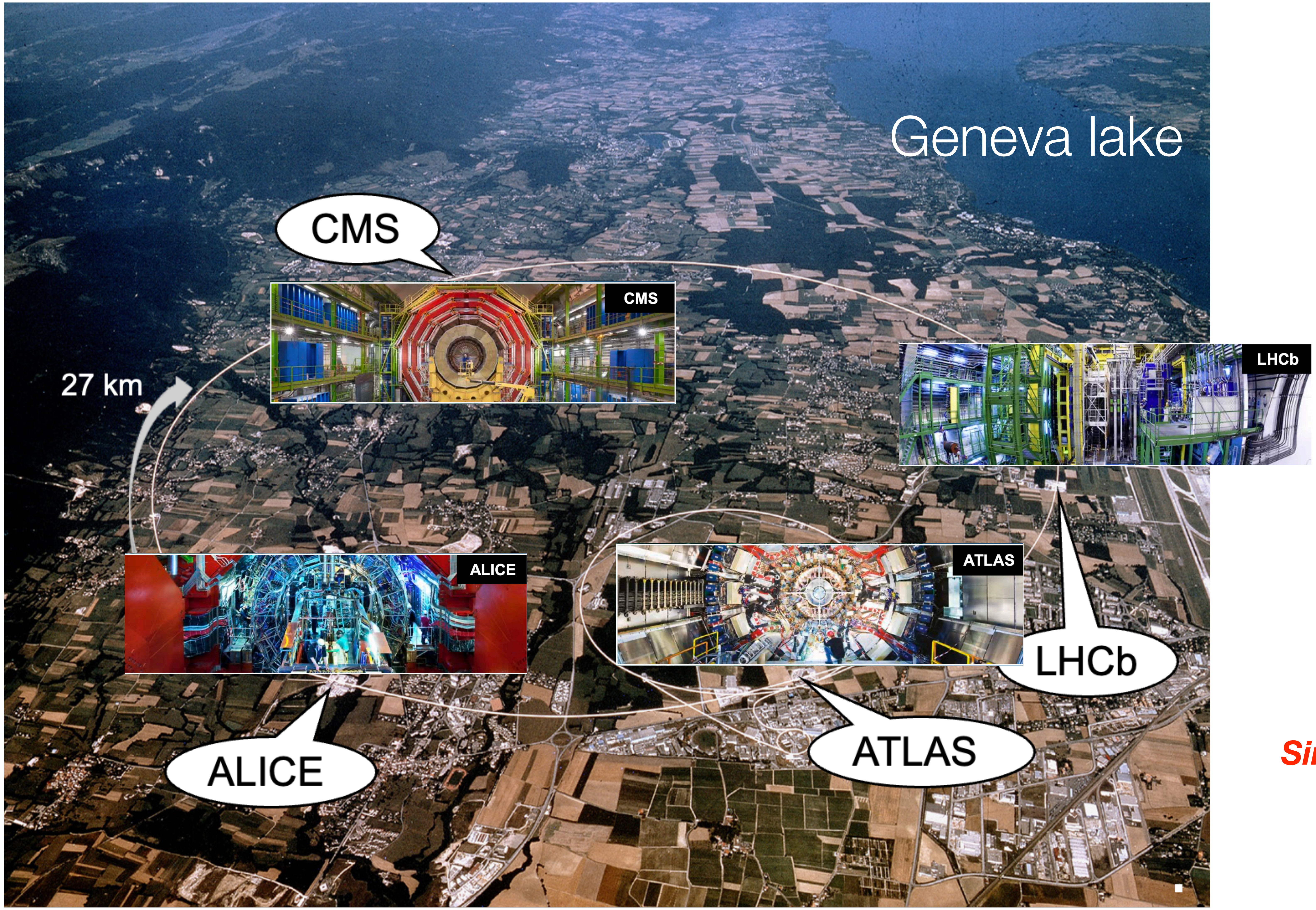


$$\lambda = \frac{hc}{E}$$

2 TeV => 10^{-19} m

The Large Hadron Collider (LHC) at CERN

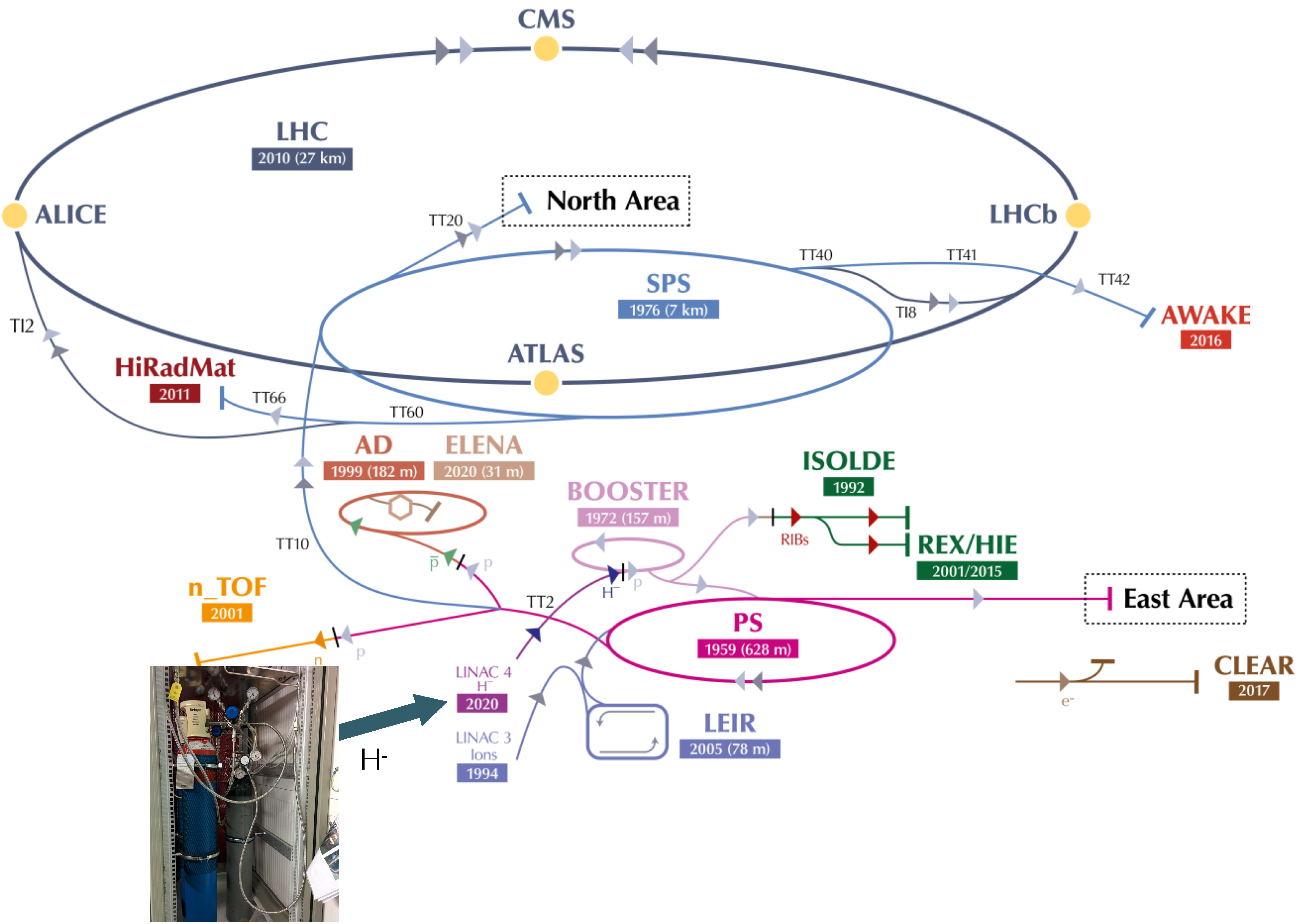
- The biggest and most energetic collider: 27 km long, ~100m underground at CERN near Geneva
- Protons (and heavy ions) accelerated to close to the speed of light by radiofrequency cavities and steered/focused by superconducting magnets
- Two beams of same energy E rotate in opposite directions and collide head-on ⇒ center-of-mass energy $\sqrt{s} = 2$ E



I will focus on the ATLAS detector and results

Similar results were obtained by the CMS experiment

The CERN accelerator complex



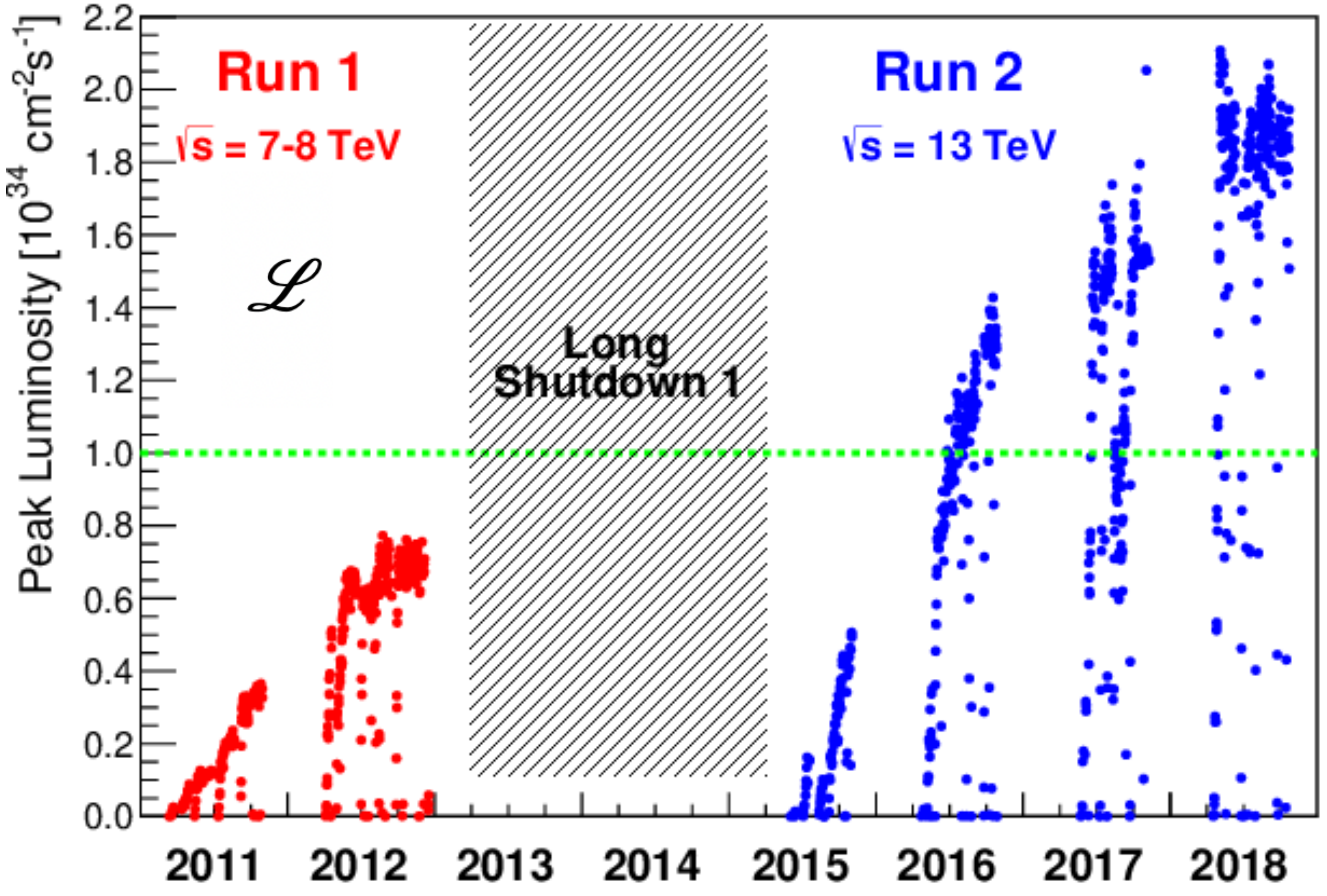
LHC fact sheet

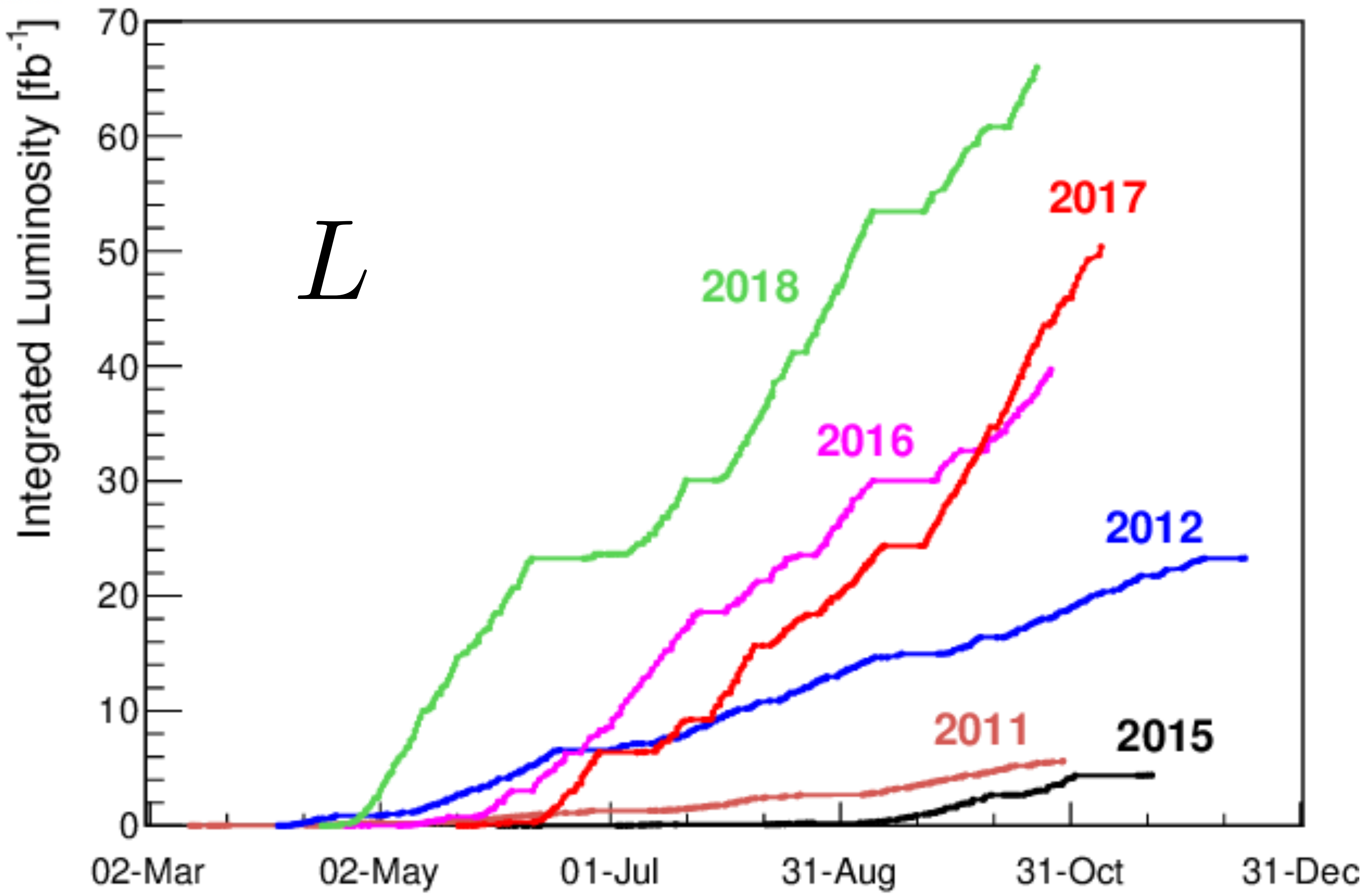
- (Very) brief history:
  - 1984: Proposal
  - 1994: Approval
  - 2008–2009: Startup
  - 2010–2012: Run 1 ($\sqrt{s_{pp}}$ = 7-8 TeV)
  - 2015–2018: Run 2 ($\sqrt{s_{pp}}$ = 13 TeV)
  - Near future (2022–2025): Run 3 ($\sqrt{s}$ = 13.6 TeV)
- Main parameters in Run2:

Quantity	Number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	6.5 TeV ⇒ 1-v/c ~ 1e-8
Nominal energy, ions	2.56 TeV/u (energy per nucleon)
Nominal energy, protons collisions $\sqrt{s}$	13 TeV (Design value: 14 TeV)
No. of bunches per proton beam	2808 ⇒ Bunches collide every 25 ns (40 MHz)
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11245
Number of collisions per second	1 billion ⇒ 25 collisions/bunch x-ing (or more..)

LHC luminosity

- Event yield = Integrated luminosity * cross section $N = L\sigma$
- L = integral over time of instantaneous luminosity, $\mathscr{L} = \dfrac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$

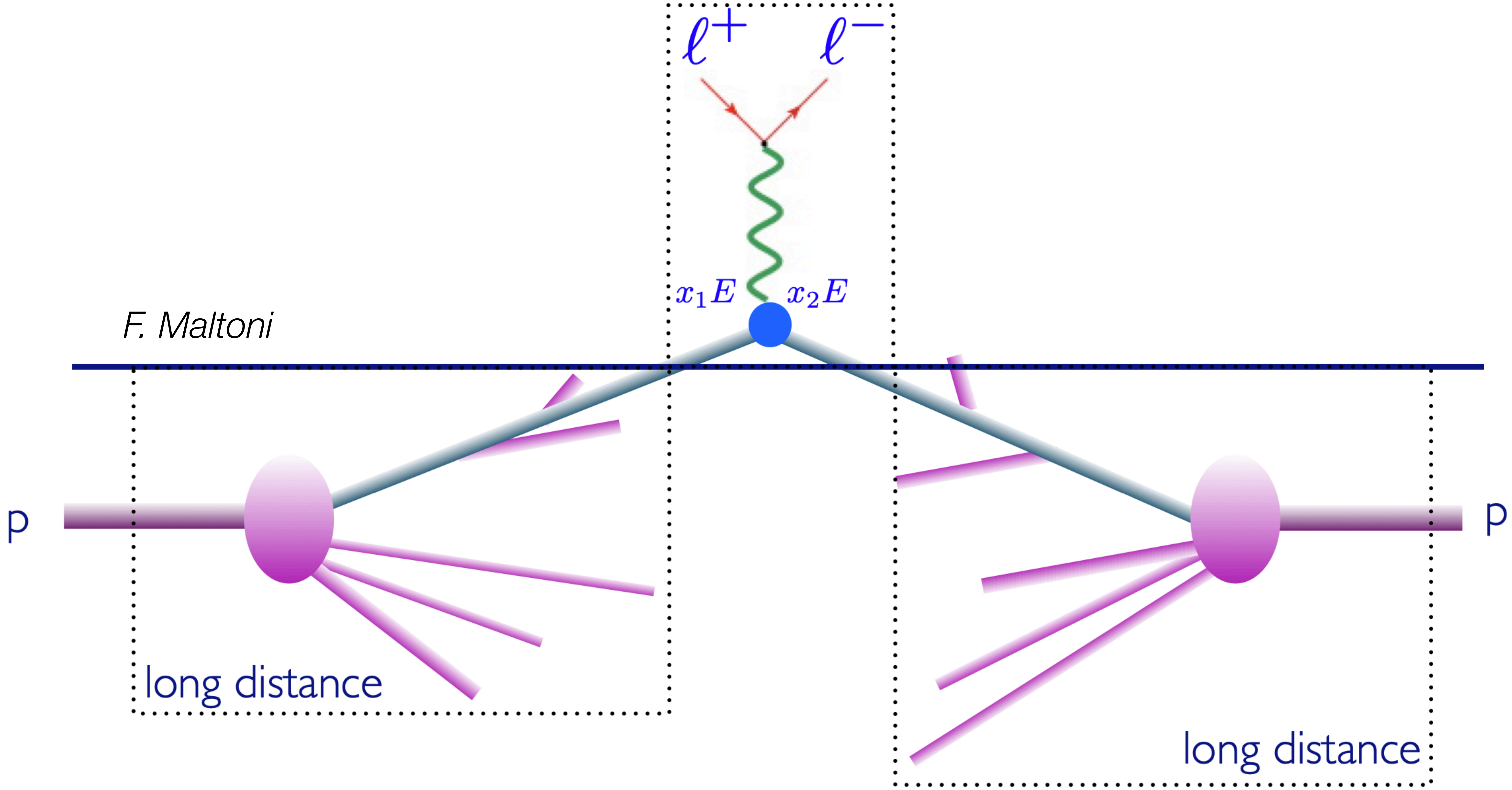


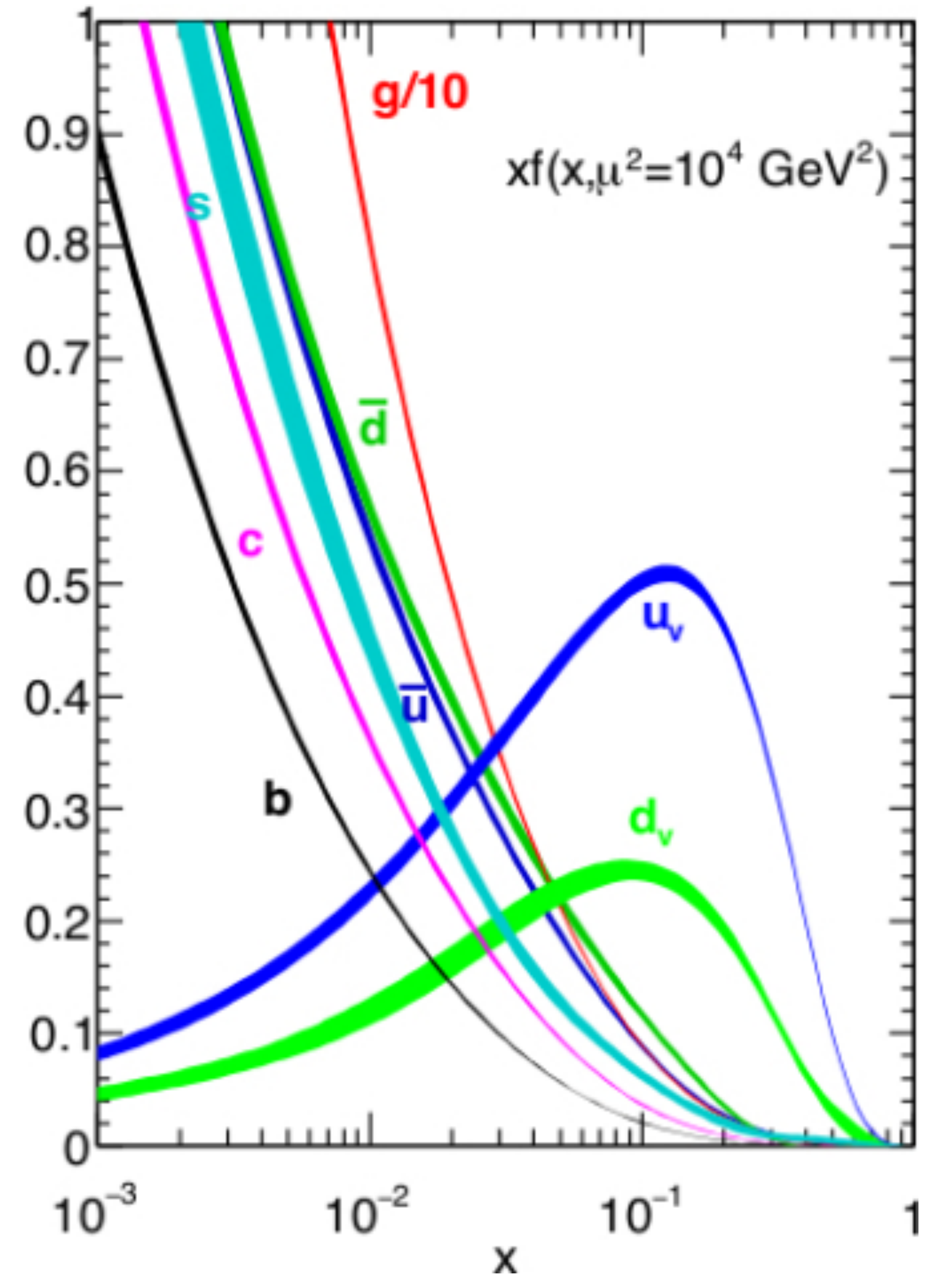


L = 25/fb at 7-8 TeV in Run1
L = 140/fb at 13 TeV in Run2
L ~ 350/fb in Run3 (expected)

(*) 1b = 10^{-28} m^2

The LHC master formula





$$\sigma_X = \sum_{a,b}\int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}\left(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

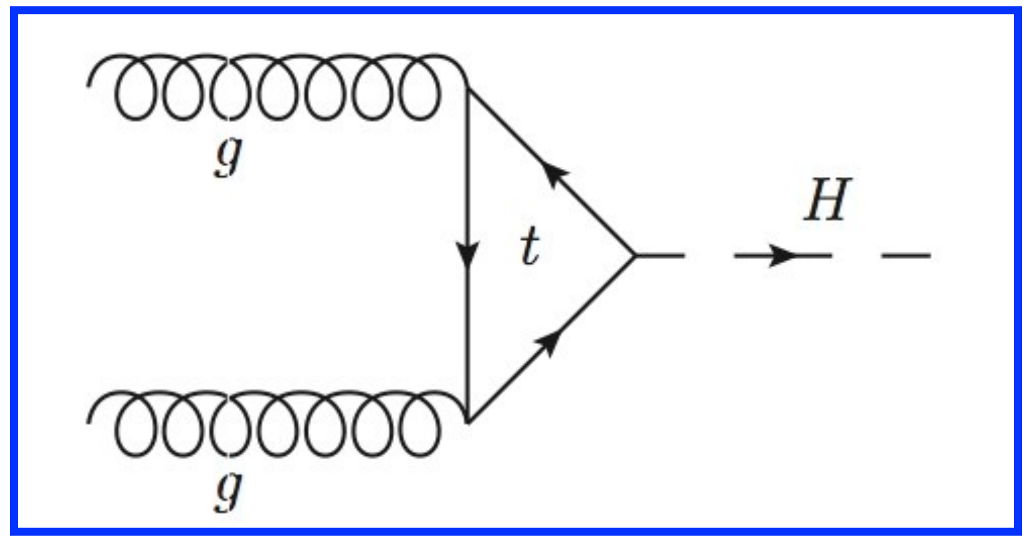
Parton Density Functions *Parton-level Cross Section*

- Gluons dominate at small x, valence quarks at x~1

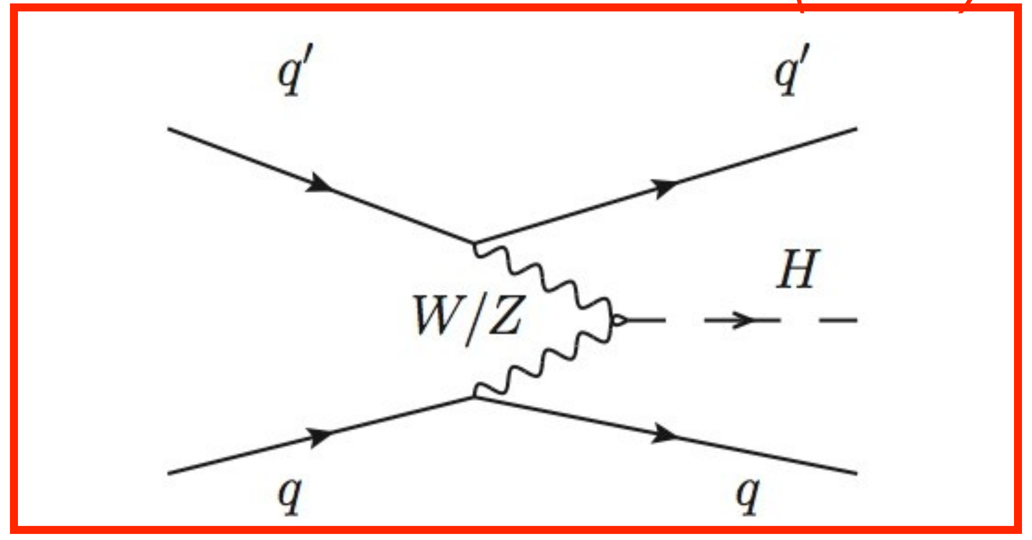
Producing a Higgs boson at the LHC

σ

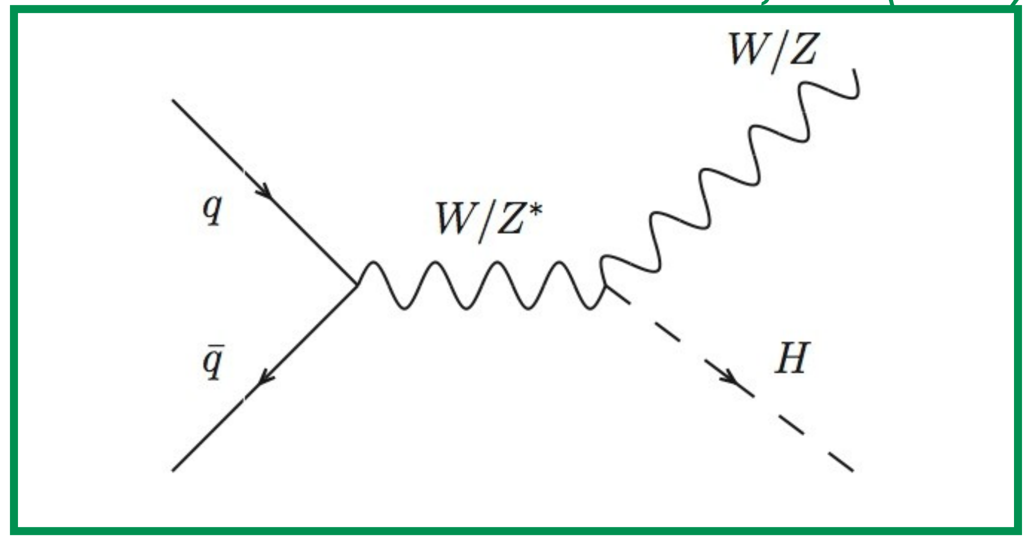
gluon-gluon fusion (ggF)



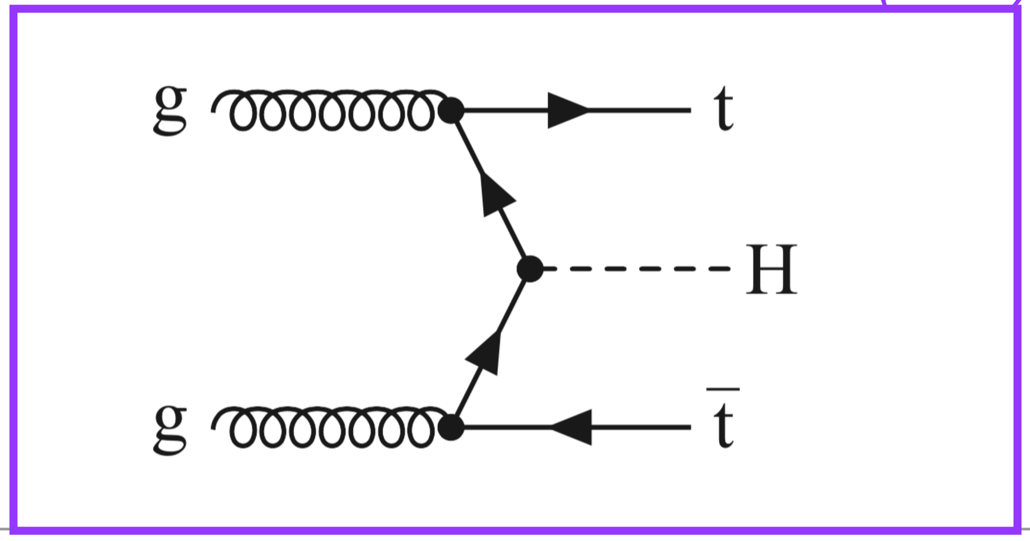
vector boson fusion (VBF)

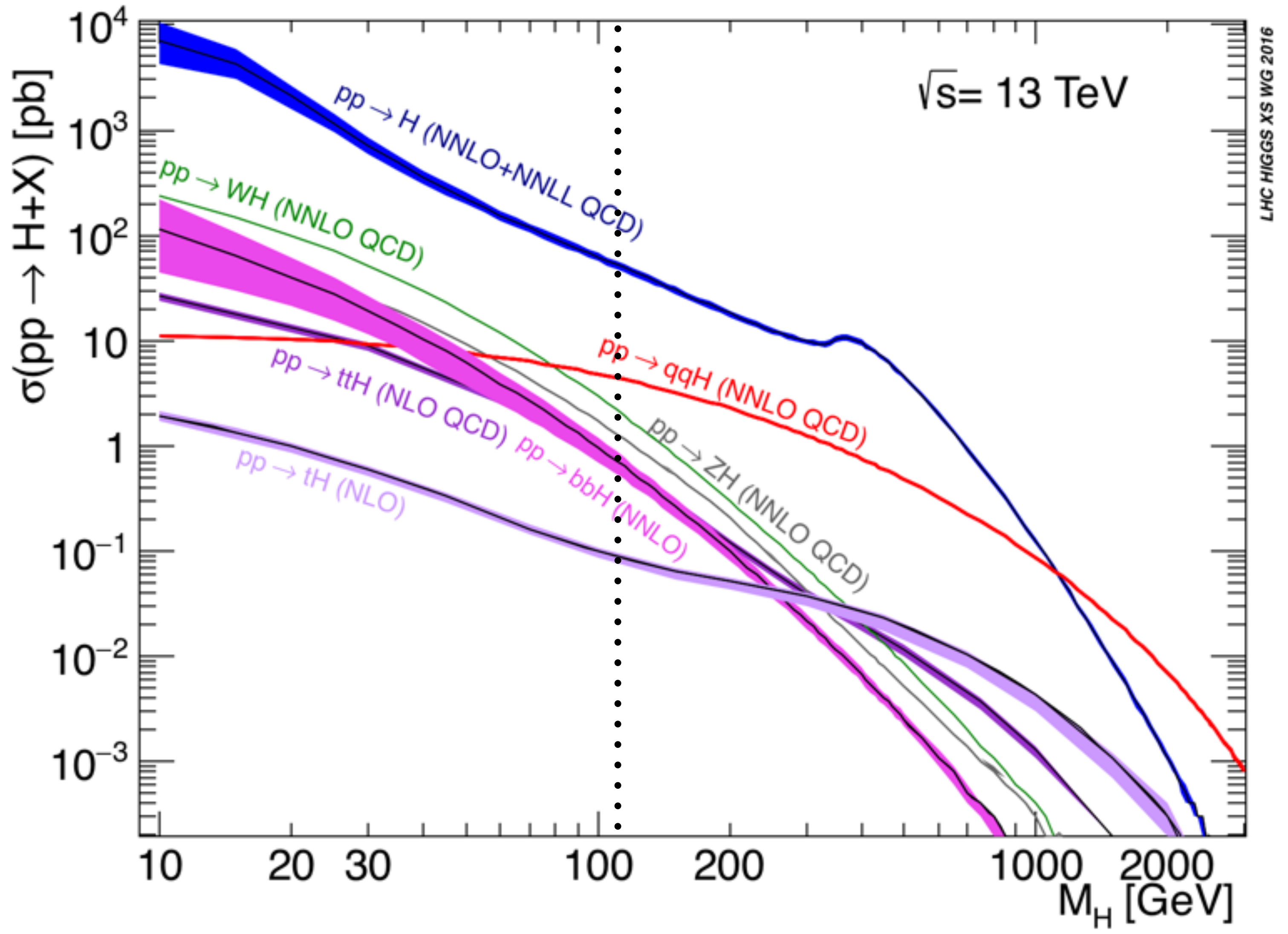


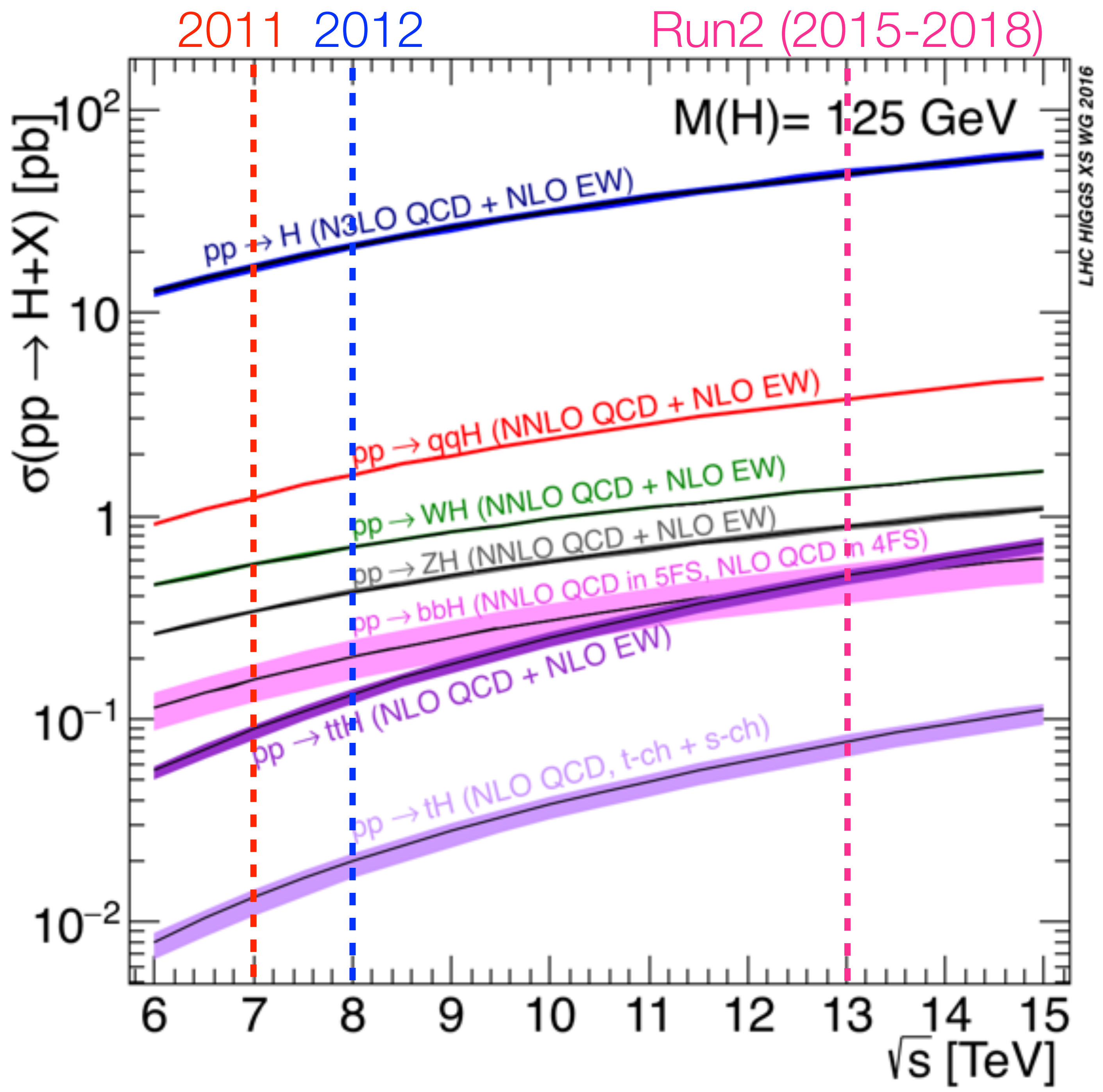
associated with V=W, Z (VH)



associated with ttbar (ttH)







	σ √s=13 TeV m=125 GeV	N(Higgs) in 140/fb
ggF	49 pb	6.9M
VBF	3.8 pb	530k
VH	2.3 pb	320k
ttH	0.5 pb	70k
TOTAL	**56 pb**	**7.8M**

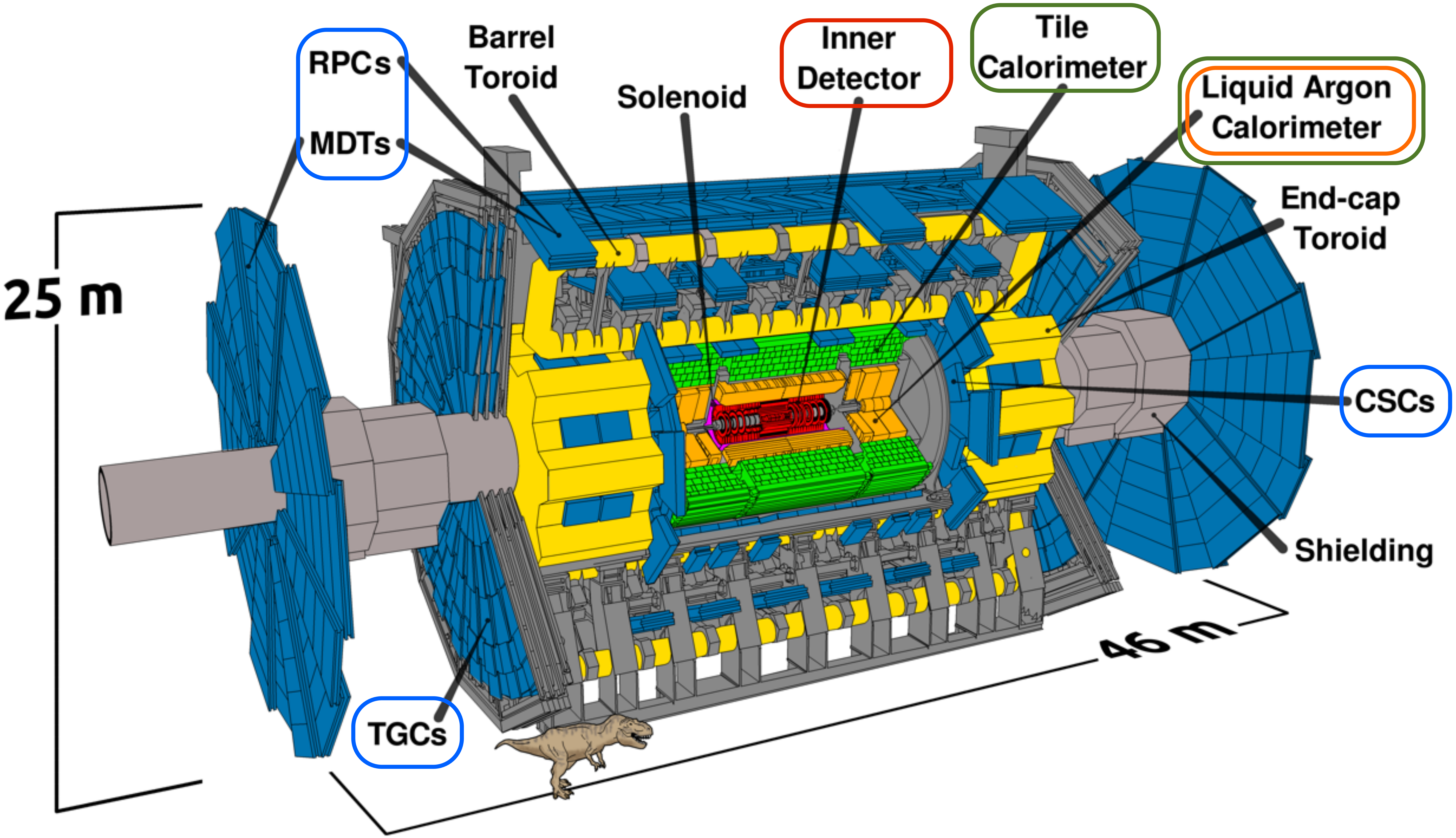
~8M Higgs bosons produced in Run2, ~600k in Run1

⇒ LHC = ‘Large Higgs Creator’!

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

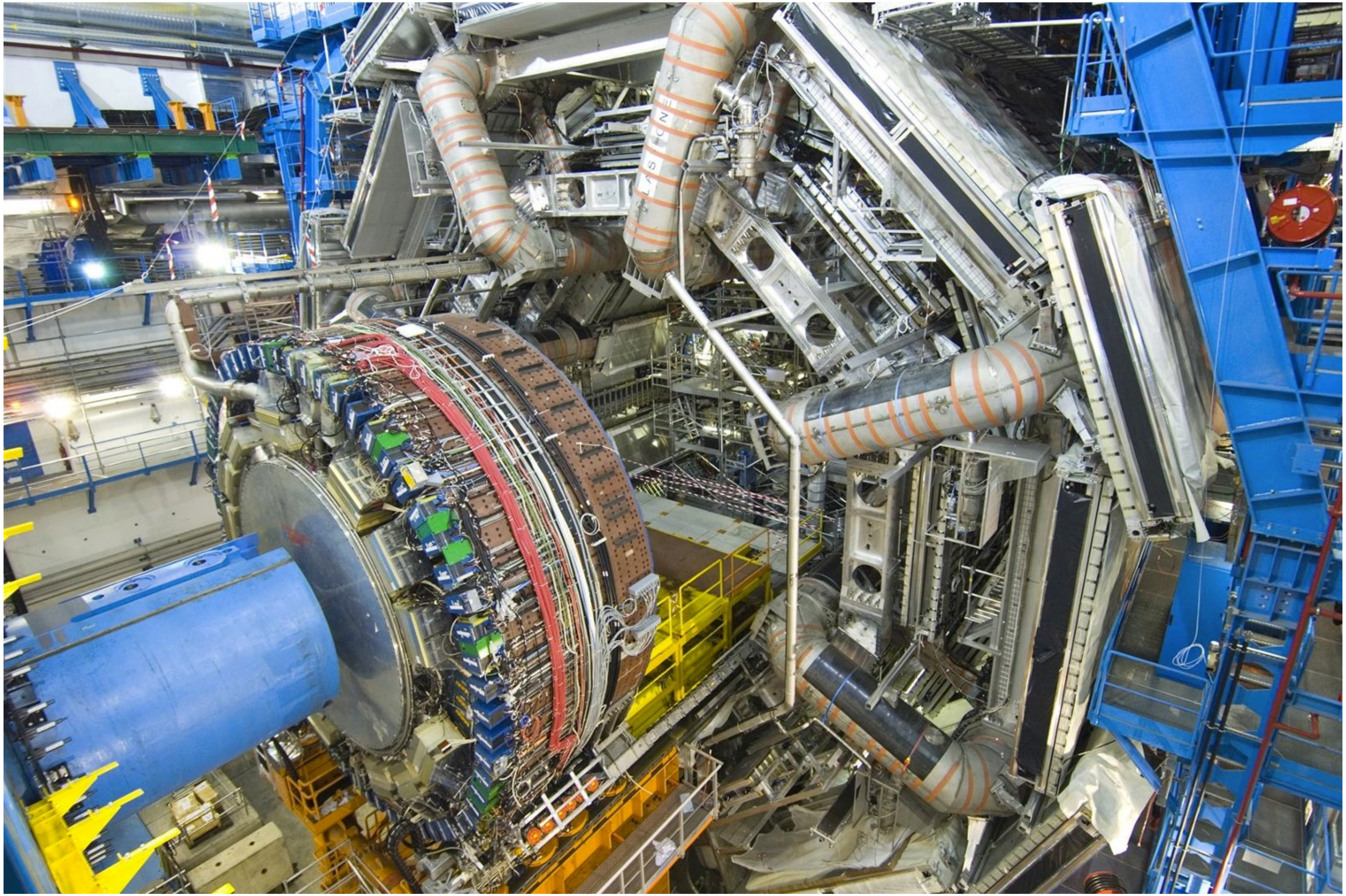
Detecting Higgs boson decays at the LHC: the ATLAS experiment

- ATLAS: a general-purpose, ~4π detector for multi-TeV pp and heavy-ion collisions



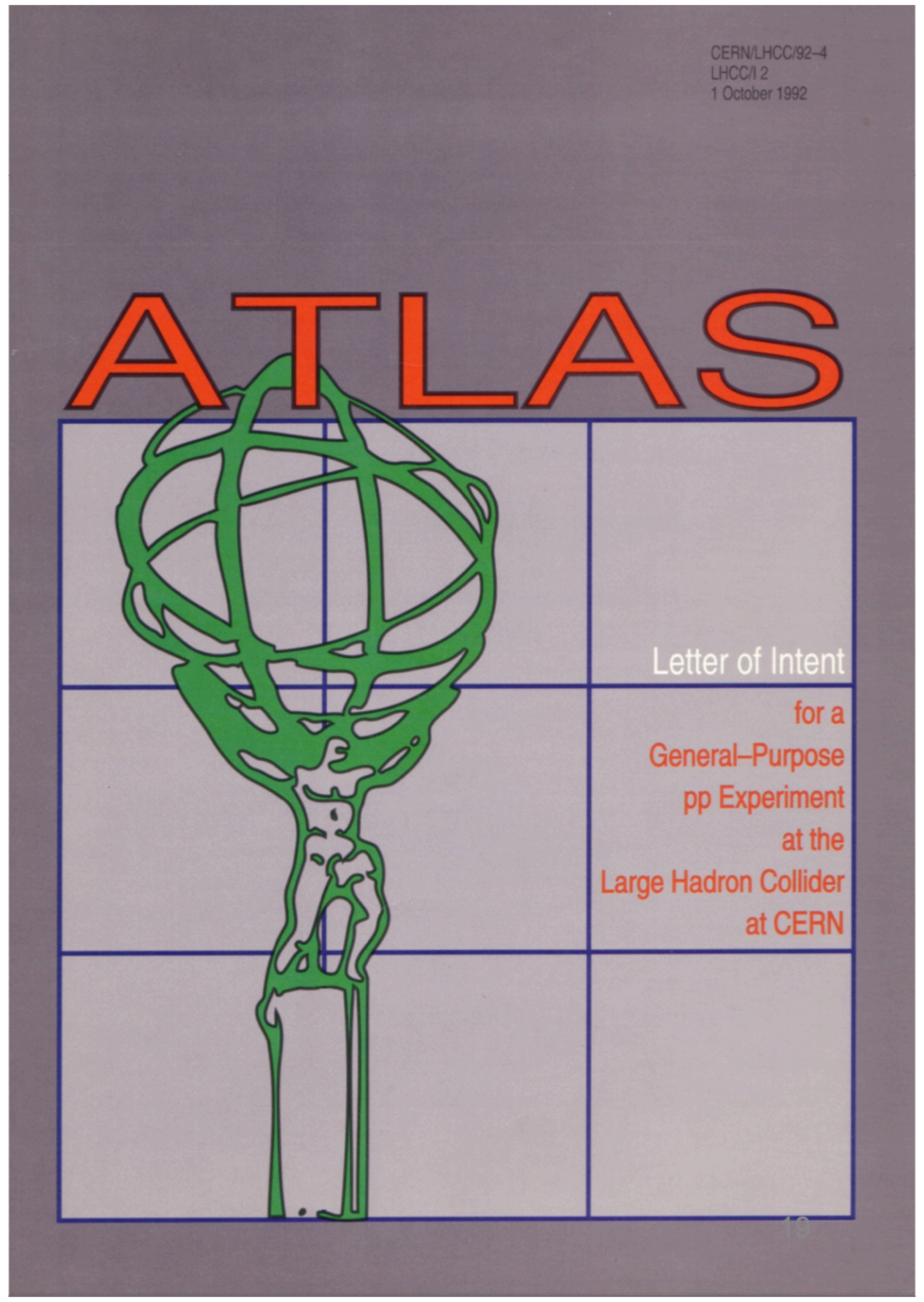
- **ID**: charged particle tracks, decay vertices
  - $|\eta|<2.5$
  - $\sigma_{p_T}/p_T \sim 0.05\% p_T \oplus 1\%$
- **ECAL**: e/γ energy and direction, hadron rejection
  - $|\eta|<3.2$
  - $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\%$ (barrel)
- **HCAL**: hadron (jet) energy/ direction
  - $|\eta|<4.9$
  - $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$ (barrel)
- **MS**: muon tracks
  - $|\eta|<2.7$
  - $\sigma_p/p<10\%$ up to 1 TeV

Detecting Higgs boson decays at the LHC: the ATLAS experiment

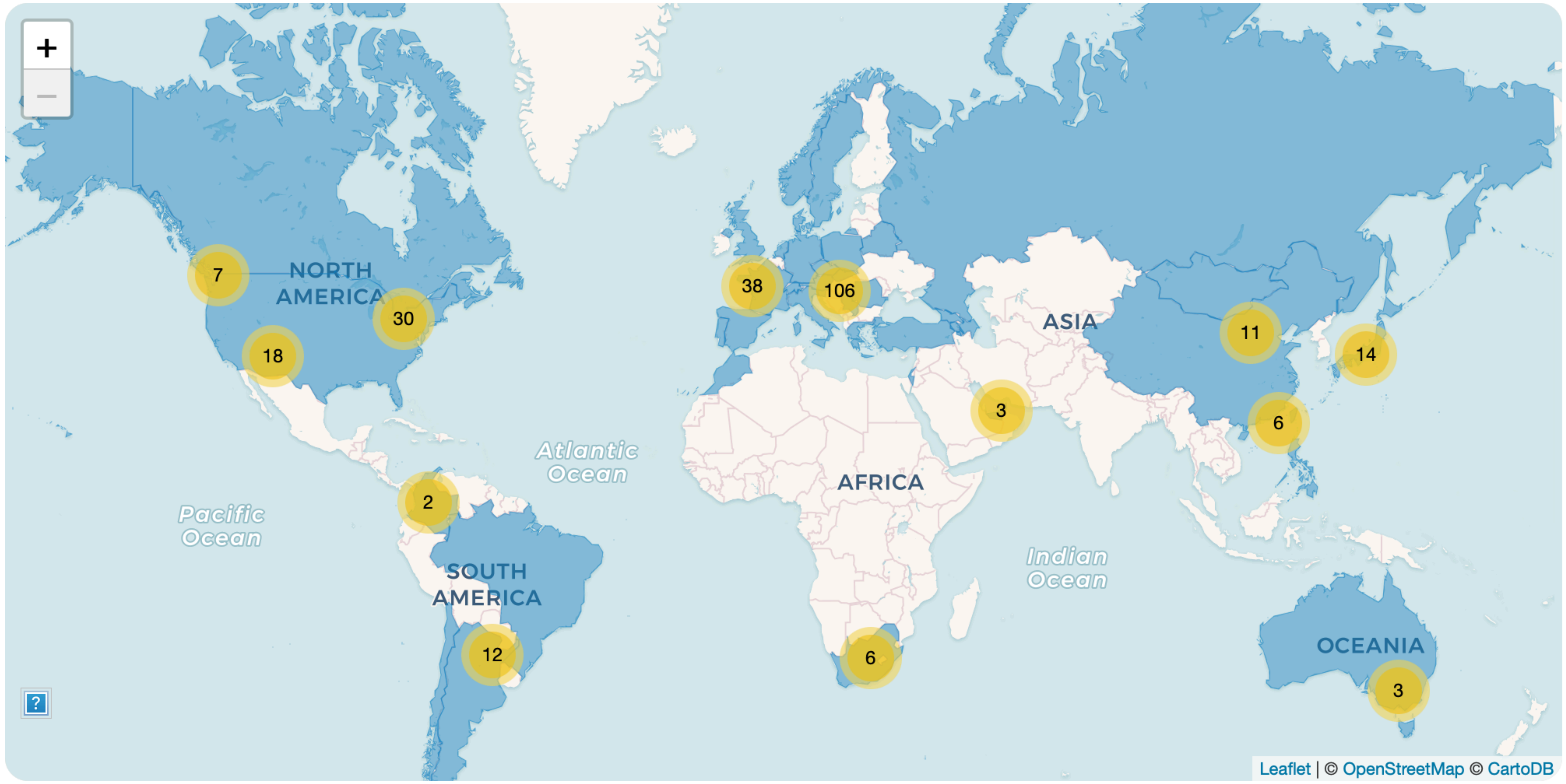


The ATLAS collaboration

- Formed in 1982 with Letter Of Intent for ATLAS experiment at LHC



3000	181	41	1200
Scientific authors	Institutions	Countries	Doctoral students



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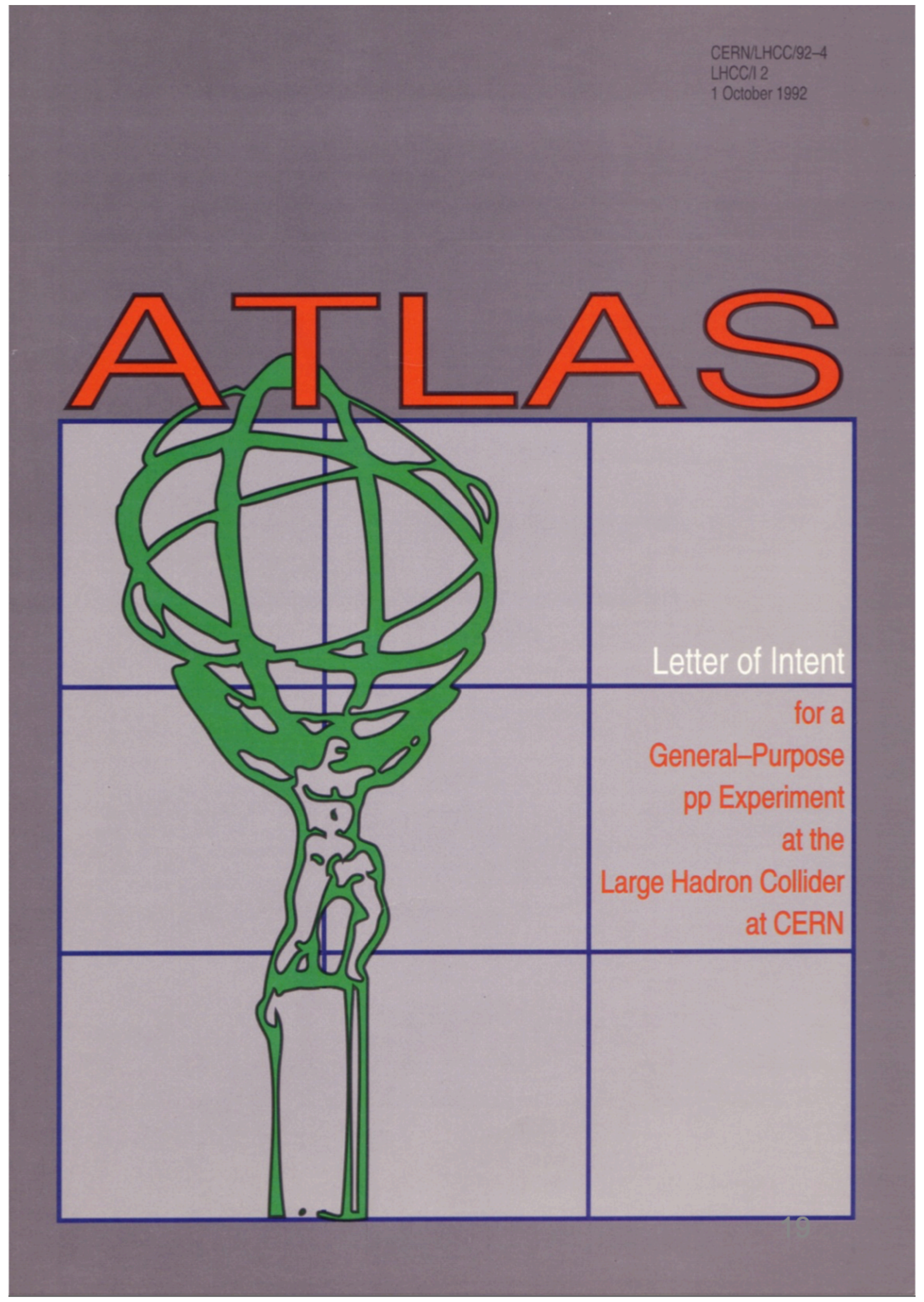
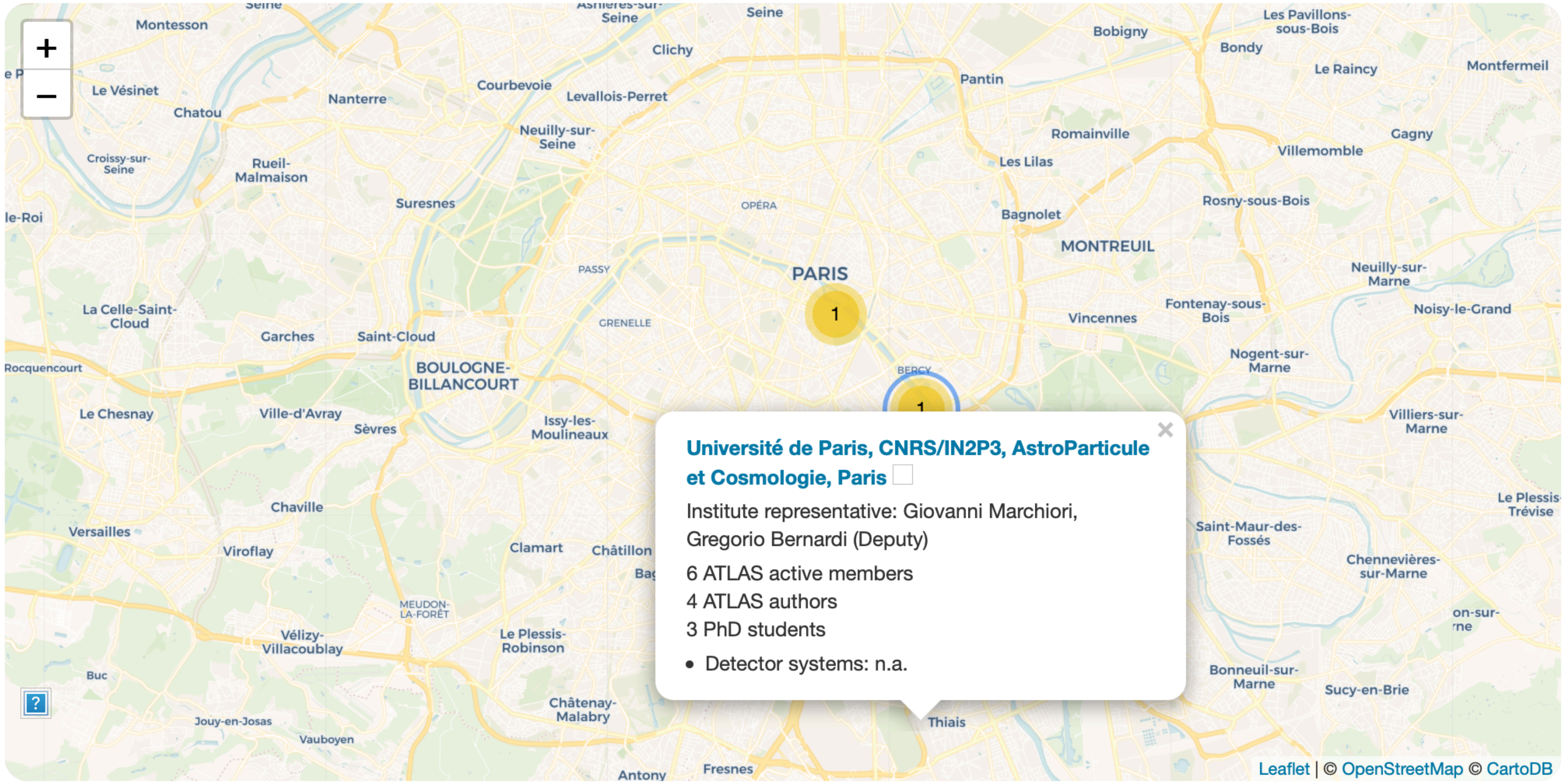
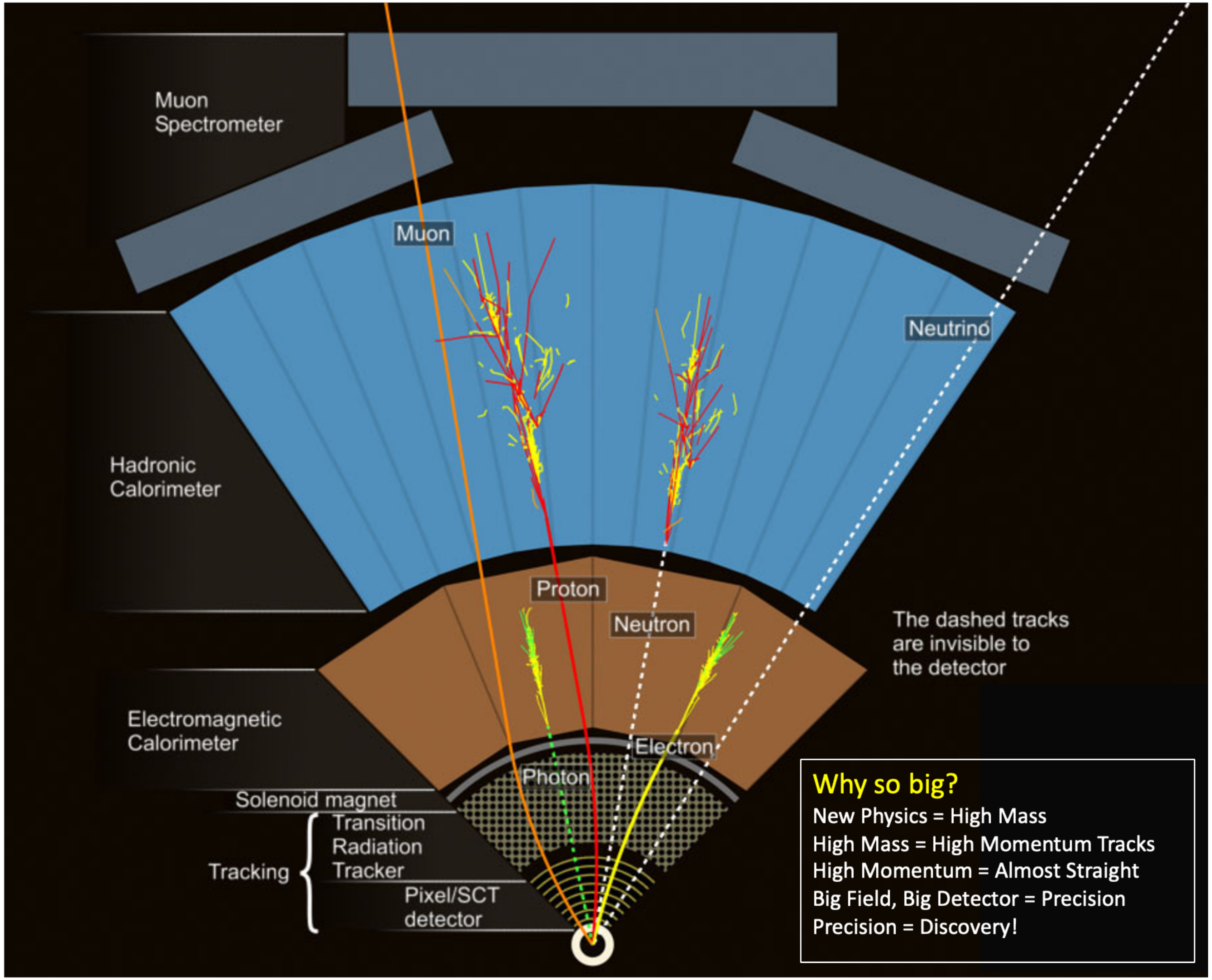


3000	181	41	1200
Scientific authors	Institutions	Countries	Doctoral students

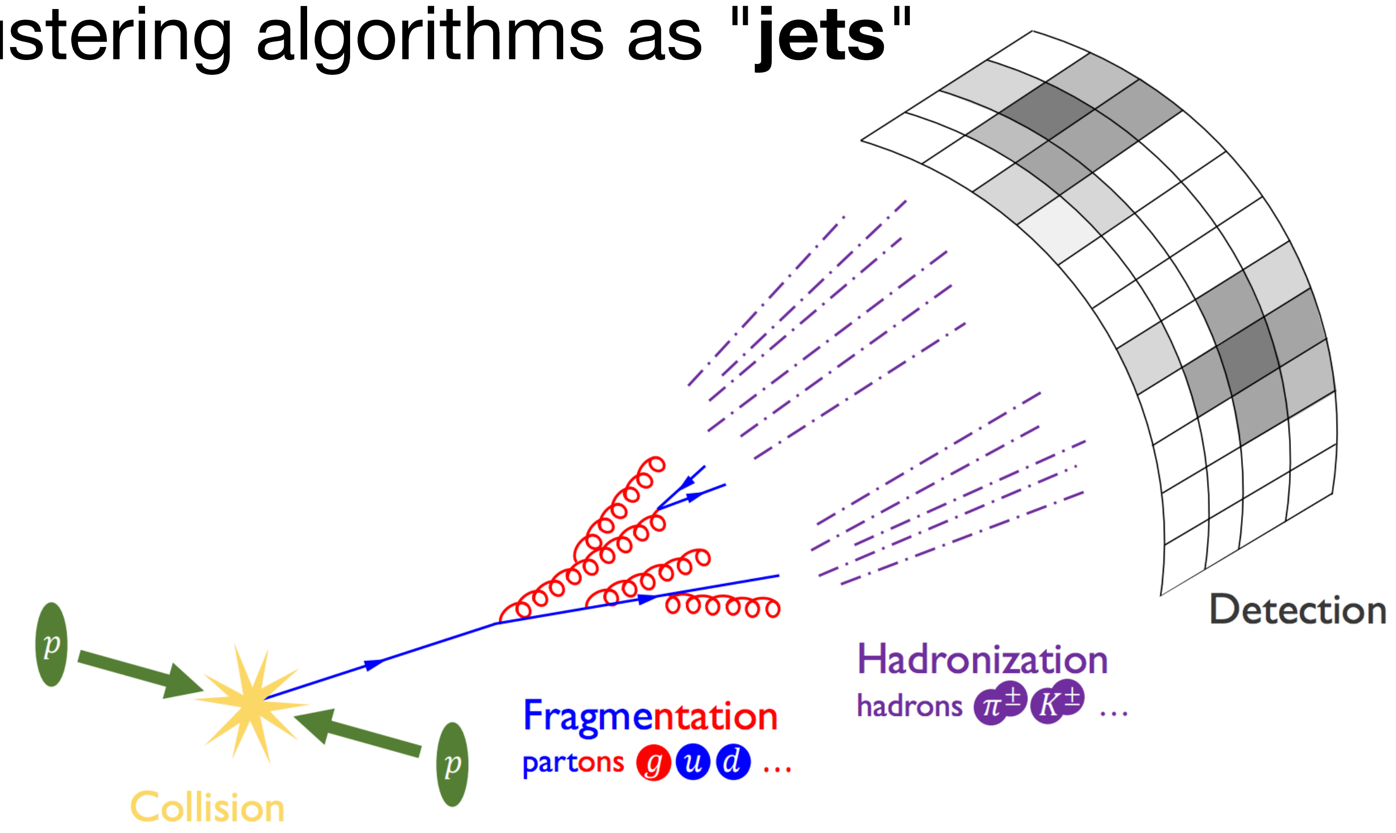
APC a full member since 15/10/2021



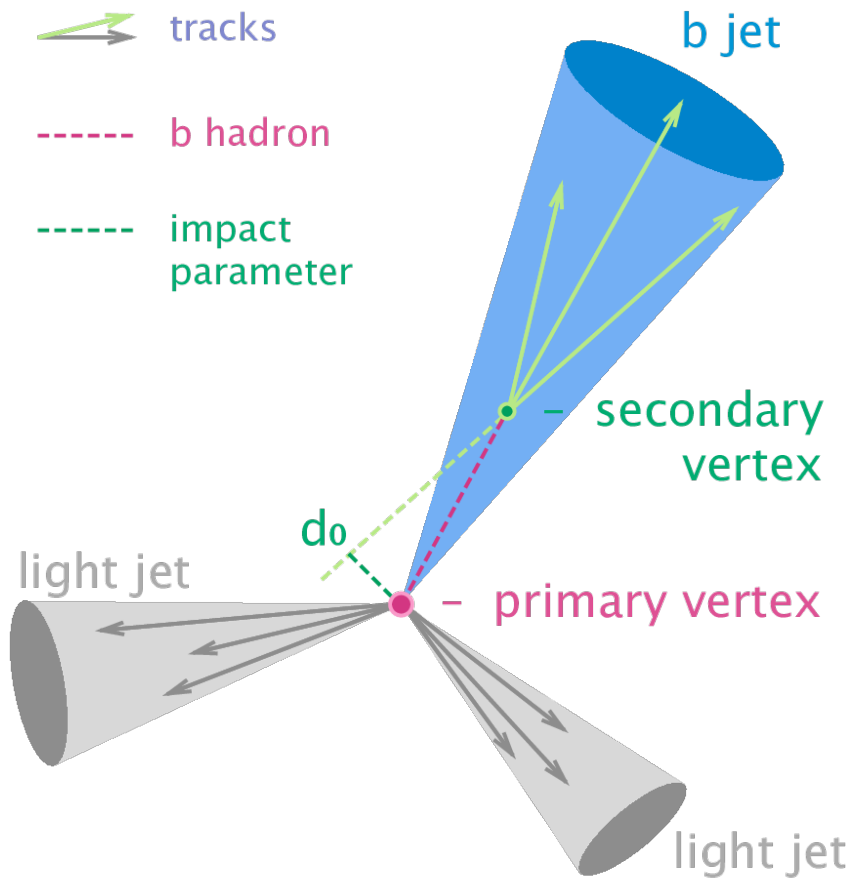
Identifying and measuring the properties of particles in ATLAS



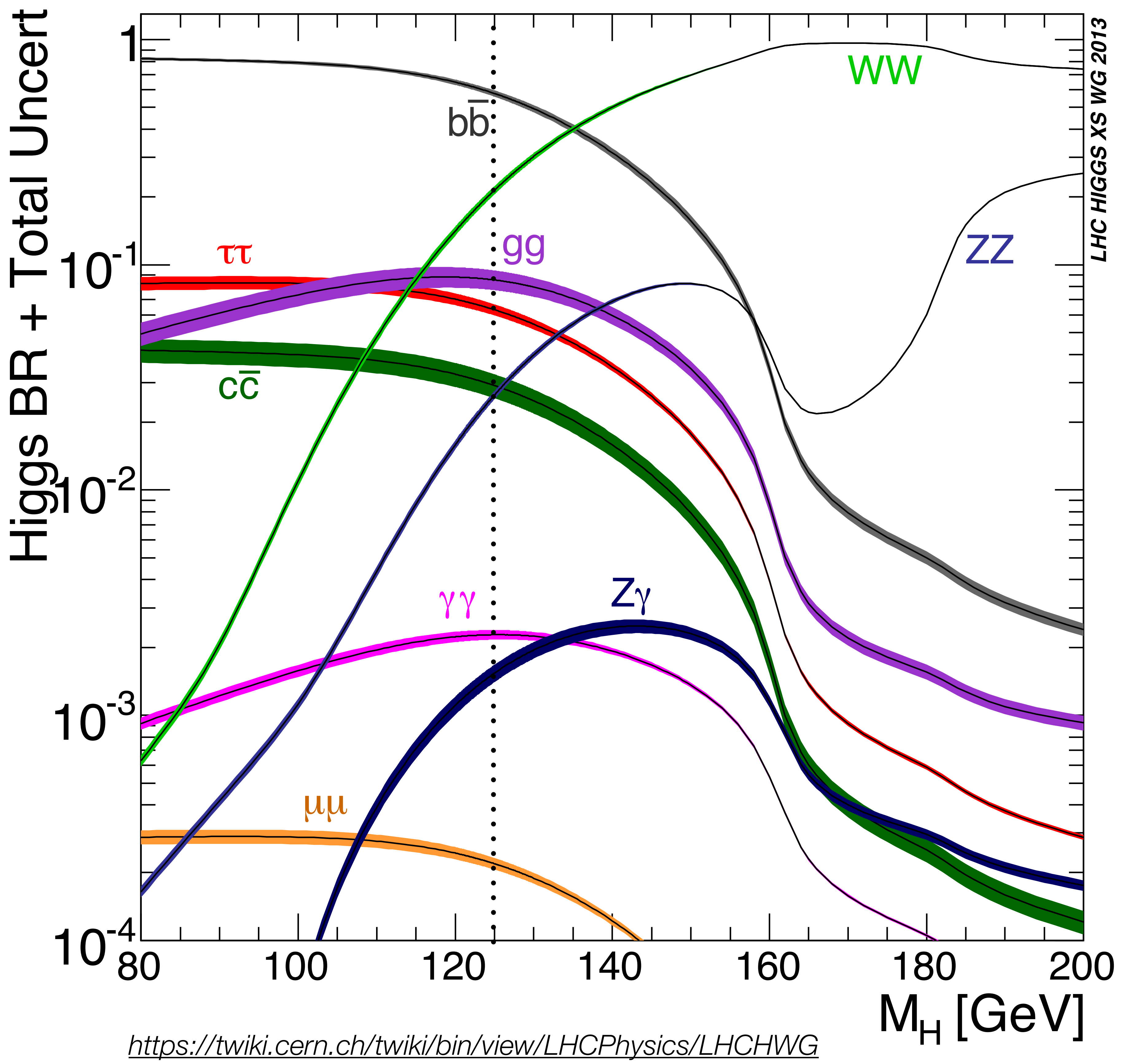
- Easiest particles to reconstruct: high-momentum electrons, muons and photons
- **Hadrons** are produced in clusters from quark/gluon hadronisation and reconstructed by clustering algorithms as "**jets**"



- High p_T jets can be efficiently reconstructed but with worse energy/direction resolution wrt γ, lep.
  - similarly/worse for ν (momentum conservation)
- **Flavour** of jets can be identified with good efficiency and low fake rate for b-quarks thanks to the long b-quark lifetime

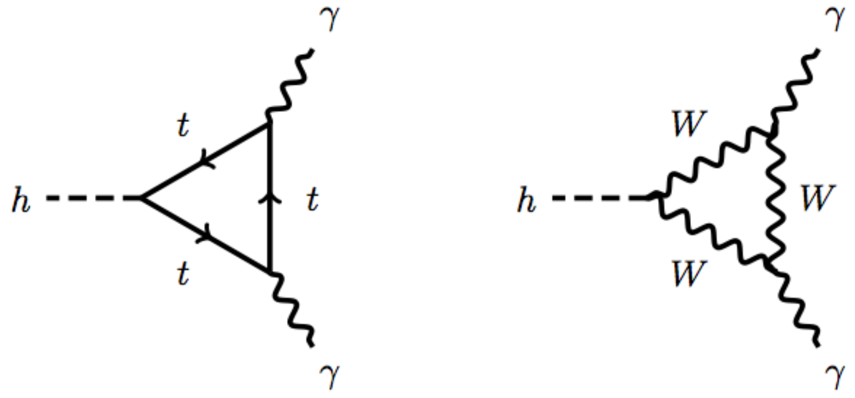


Higgs boson decays



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

Loop-induced effective photon coupling:



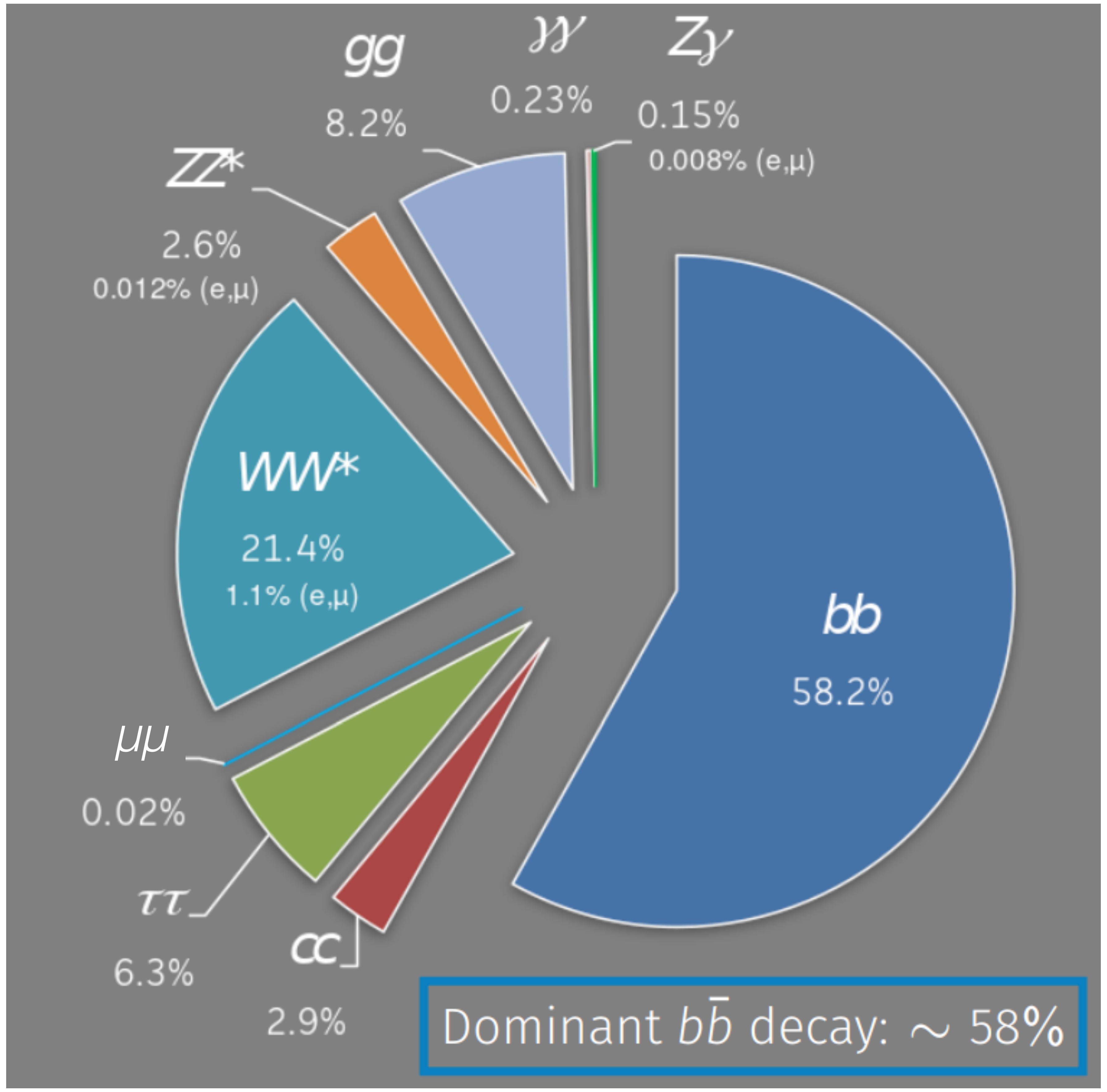
→4l

ZZ, **γγ**: high mass resolution channels mass and precise differential measurements

WW: High BR, but low mass resolution

μμ: very small BR, but access to coupling to 2nd generation fermions

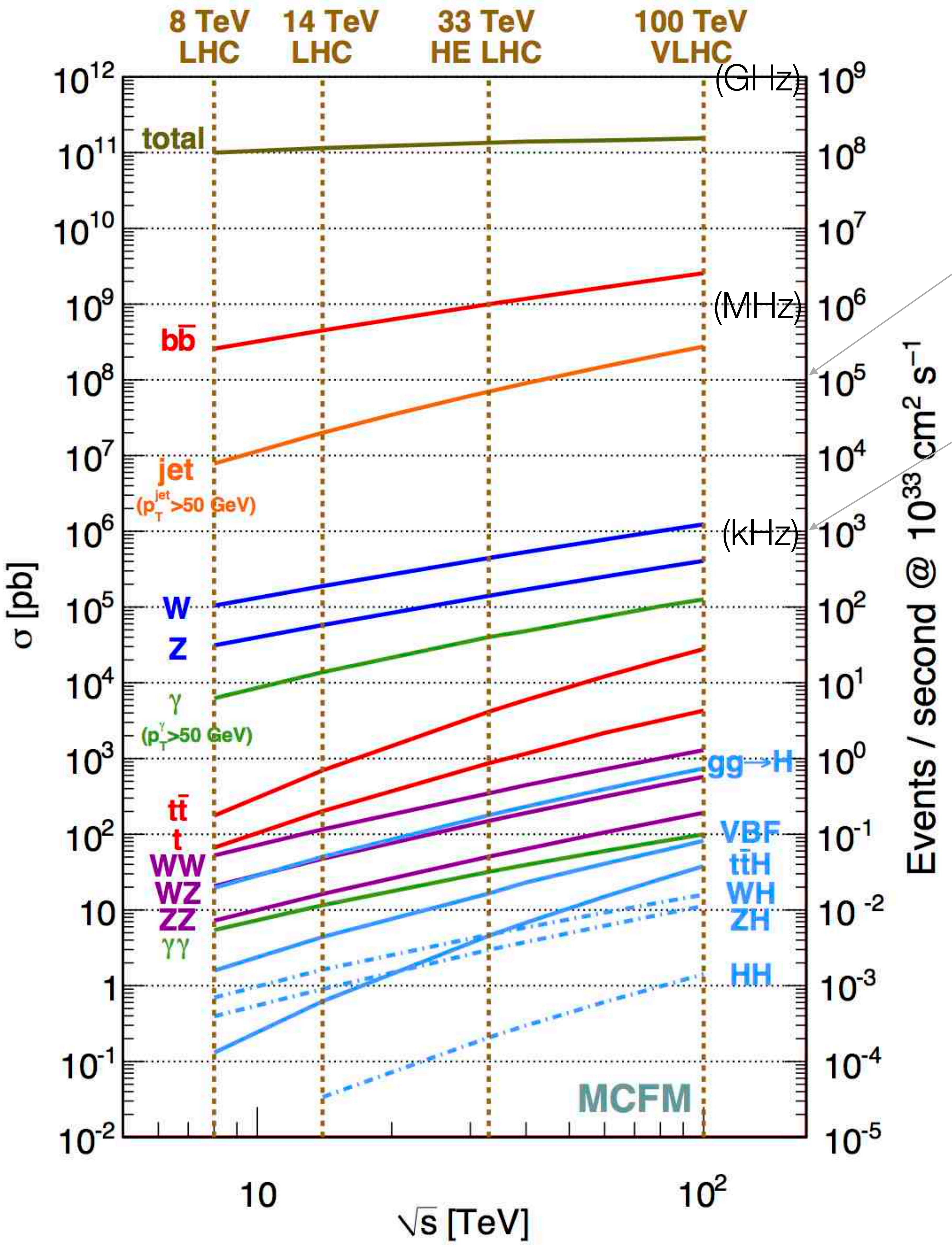
gg: high BR, but very poor q/g discrimination



cc: decent BR, but poor q,g rejection => challenging for coupling to 2nd gen fermions

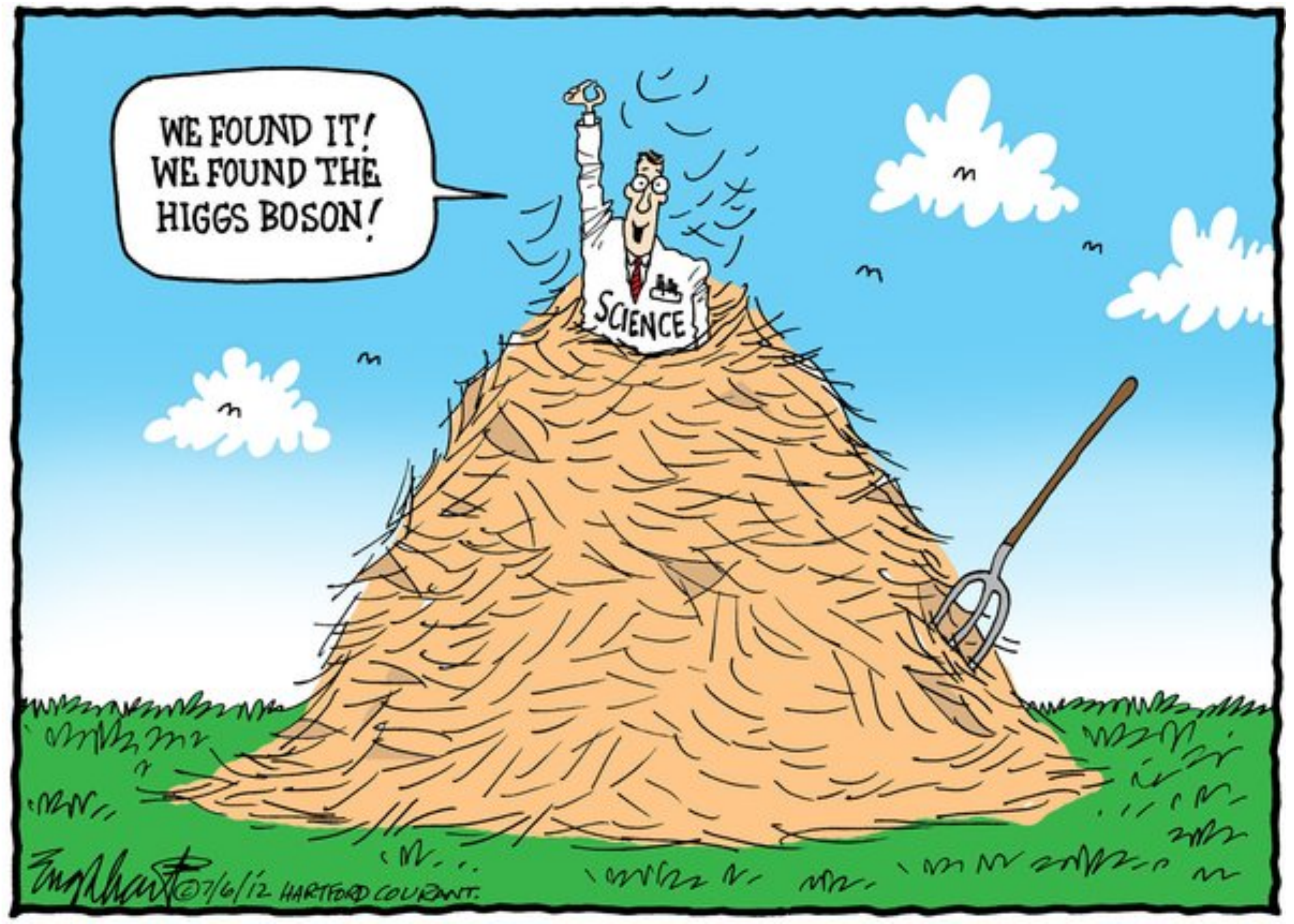
bb, **ττ**: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions

Backgrounds (and trigger) at the LHC



Level-1 trigger

High-level trigger



- SM non-Higgs processes much more likely to happen than Higgs
  - **Need selection with excellent background rejection => choose carefully the signatures under study**
    - (e.g: inclusive Higgs production with H->bb very difficult because of bb production is 10^7 times bigger!)
- Total xsection too big to keep everything on disk => **selective trigger**
- Even with a trigger with a rejection=10^6, we still have about 200 PB of data (and MC) to analyse => **distributed computing model** (GRID): data and CPUs are distributed throughout the world, analysis code can run wherever resources are available

Higgs boson selection efficiency

H(125 GeV) — approximate numbers

Channel	Produced		Selected	Mass resolution
$H \to \gamma\gamma$	18,200		6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$	210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$	5,880	20%
$H \to \tau\tau$	490,000		2,380	15%
$H \to bb$	4,480,000		9,240	10%

A. Hoecker, CERN

- Out of 8M Higgs boson events only about 20k are selected and used to study the properties of the Higgs boson!

The first tantalising signals

https://indico.cern.ch/event/164890/

CERN PUBLIC SEMINAR

Tuesday 13 Dec 2011, 14:00 → 16:00 Europe/Paris

500/1-001 - Main Auditorium (CERN)

Video in CDS

Webcast There is a live webcast for this event **Watch**

14:00 → 14:40 **Update on the Standard Model Higgs searches in ATLAS** 40m

Speaker: Fabiola Gianotti (CERN)

Slides

14:40 → 15:20 **Update on the Standard Model Higgs searches in CMS** 40m

Speaker: Guido Tonelli (Universita di Pisa and INFN Sezione di Pisa - CERN)

Slides

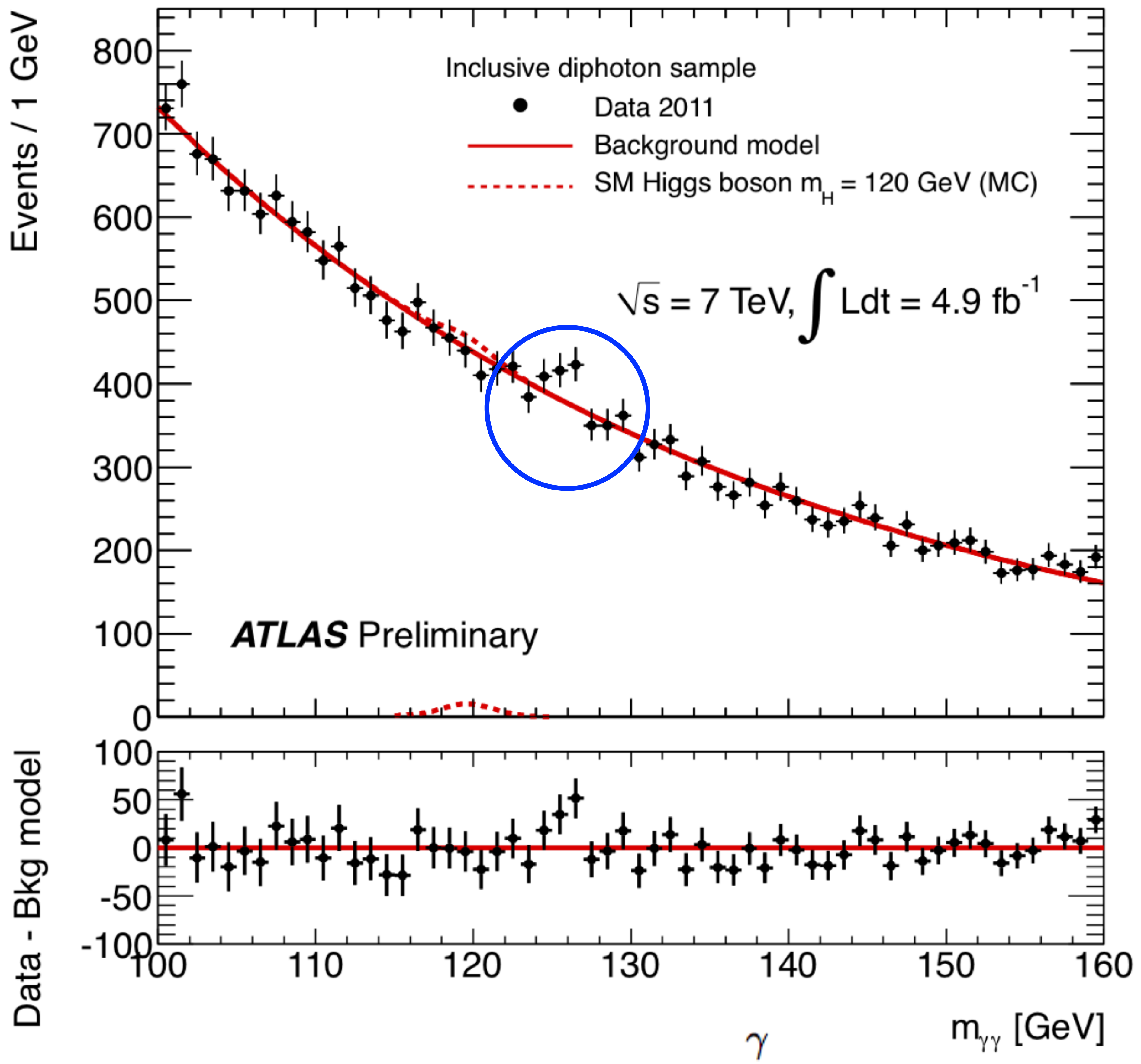
15:20 → 16:00 **Joint question session** 40m

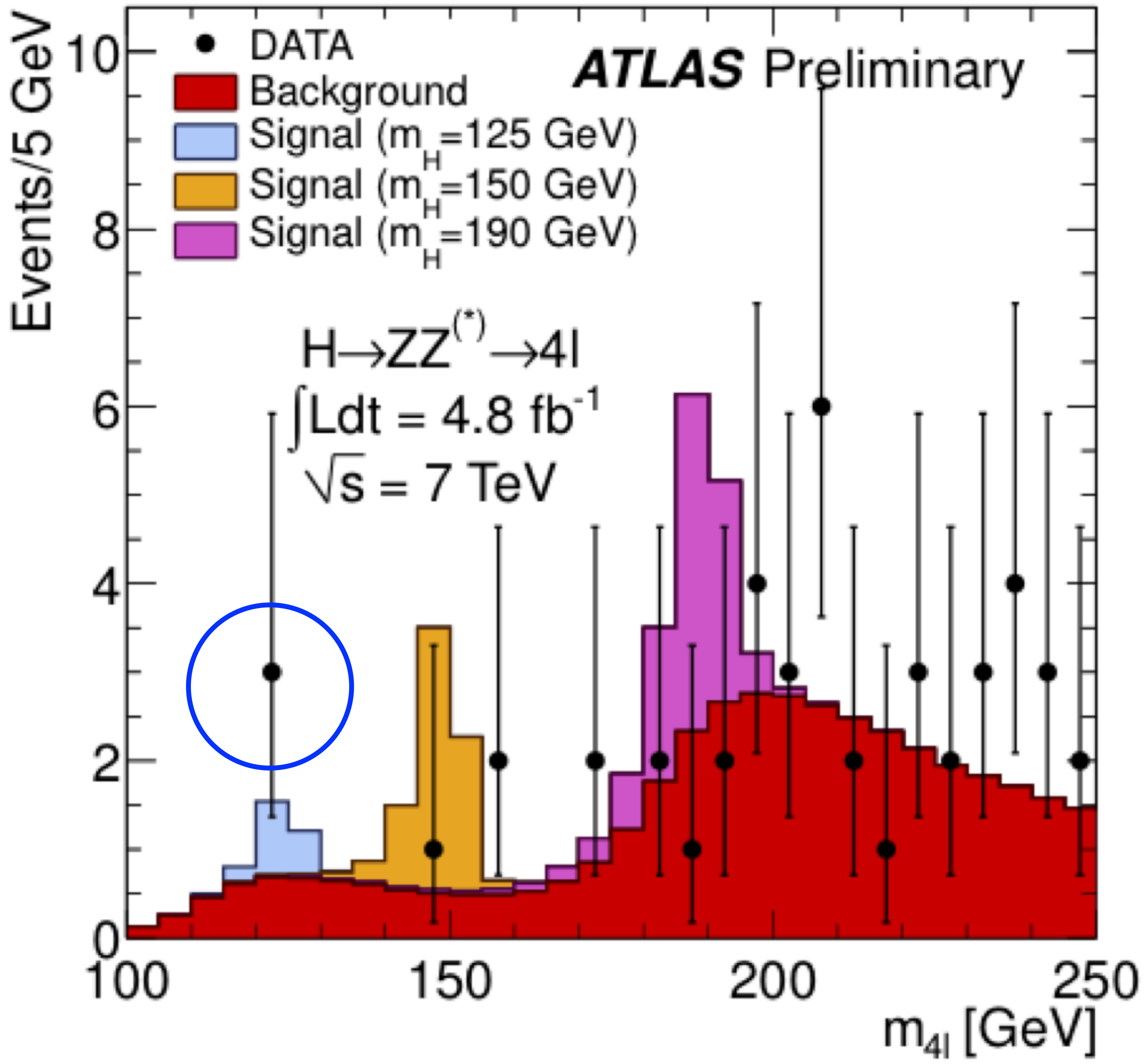
Analysis of up to 5/fb @ 7 TeV

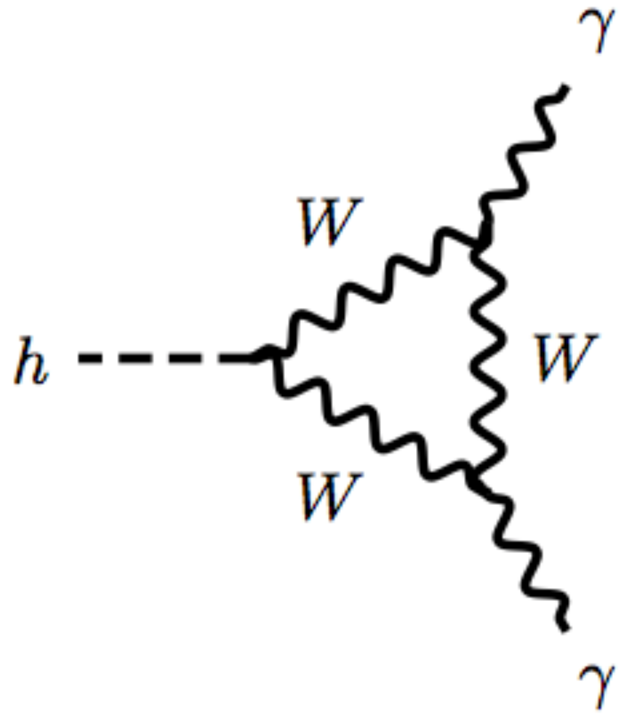
- $H\rightarrow\gamma\gamma$
- $H\rightarrow ZZ^{(*)}\rightarrow 4l$
- $H\rightarrow WW^{(*)}\rightarrow l\nu l\nu$

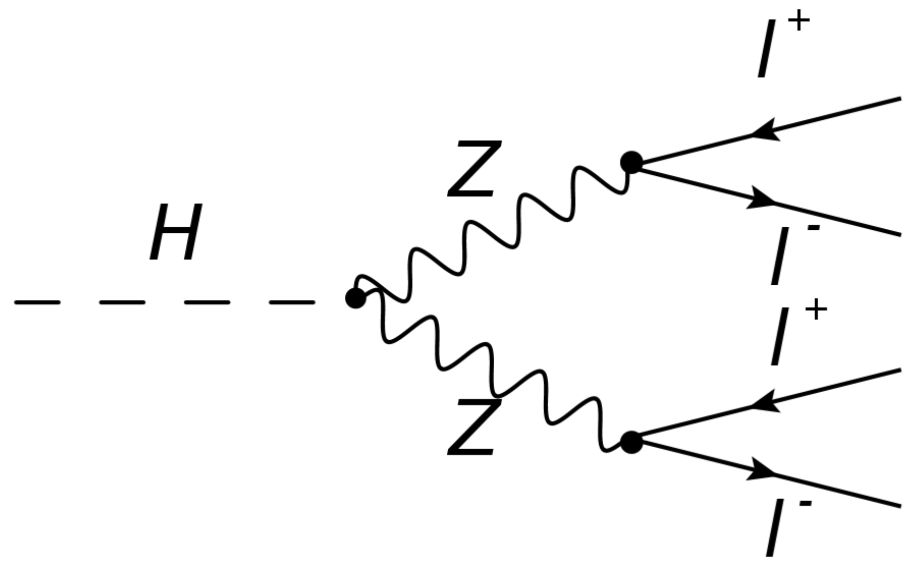
See also https://atlas.cern/updates/press-statement/atlas-experiment-presents-latest-higgs-search-status

The first tantalising signals

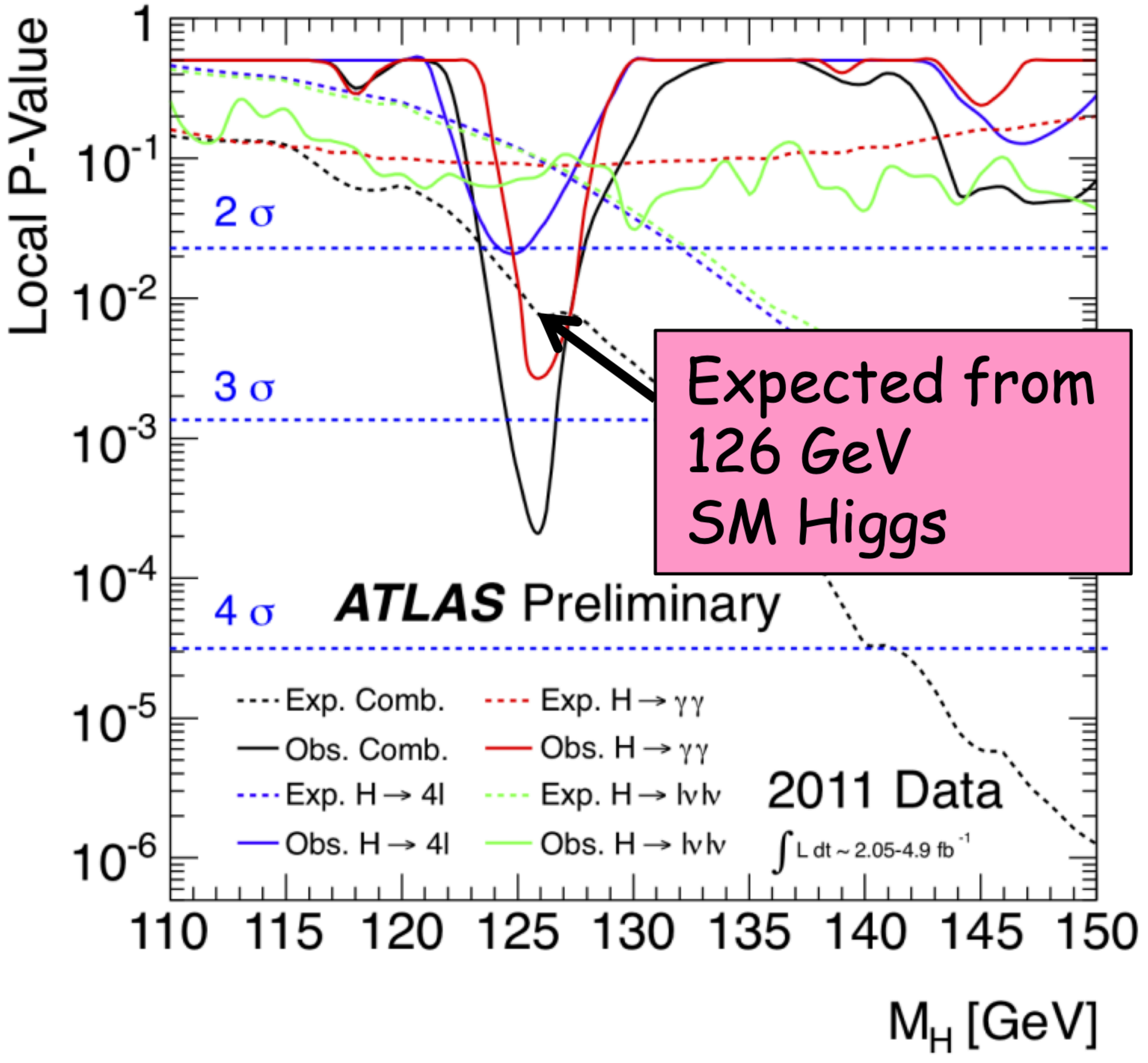


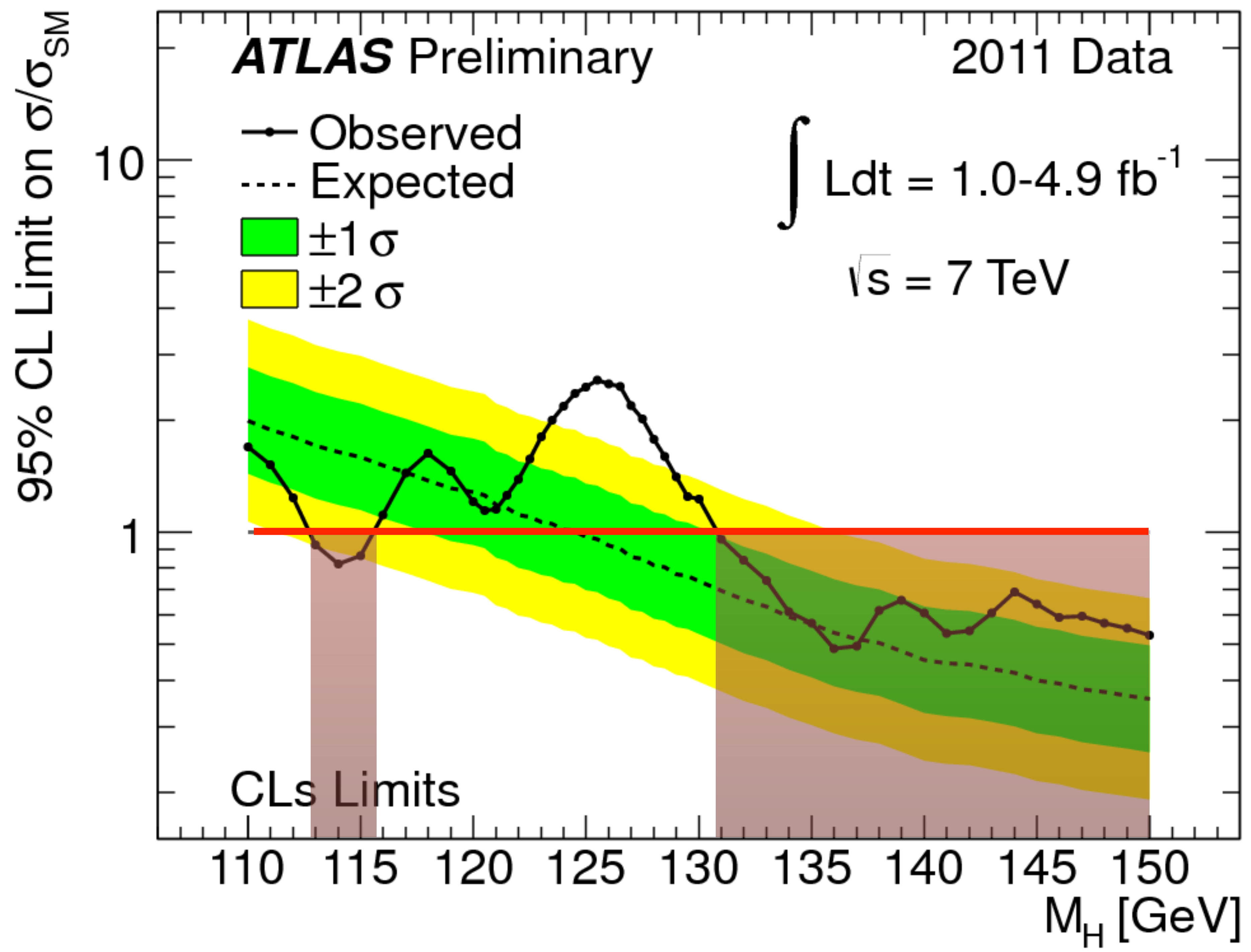






The first tantalising signals





We have looked for a SM Higgs boson
- over the mass region 110-600 GeV
- in 11 distinct channels
- using up to 4.9 fb^{-1} of integrated luminosity

→ We have restricted the most likely mass region (95% CL) to

115.5-131 GeV

We observe an excess of events around m_H~ 126 GeV:
- local significance 3.6 σ, with contributions from the $H \rightarrow \gamma\gamma$ (2.8 σ), $H \rightarrow ZZ^* \rightarrow 4l$ (2.1 σ), $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ (1.4 σ) analyses
- SM Higgs expectation: 2.4 σ local → observed excess compatible with signal strength within +1σ
- the global significance (taking into account Look-Elsewhere-Effect) is ~2.3σ

The Higgs boson discovery

- 4th July 2012 @CERN: (experimental) birth of the Higgs boson

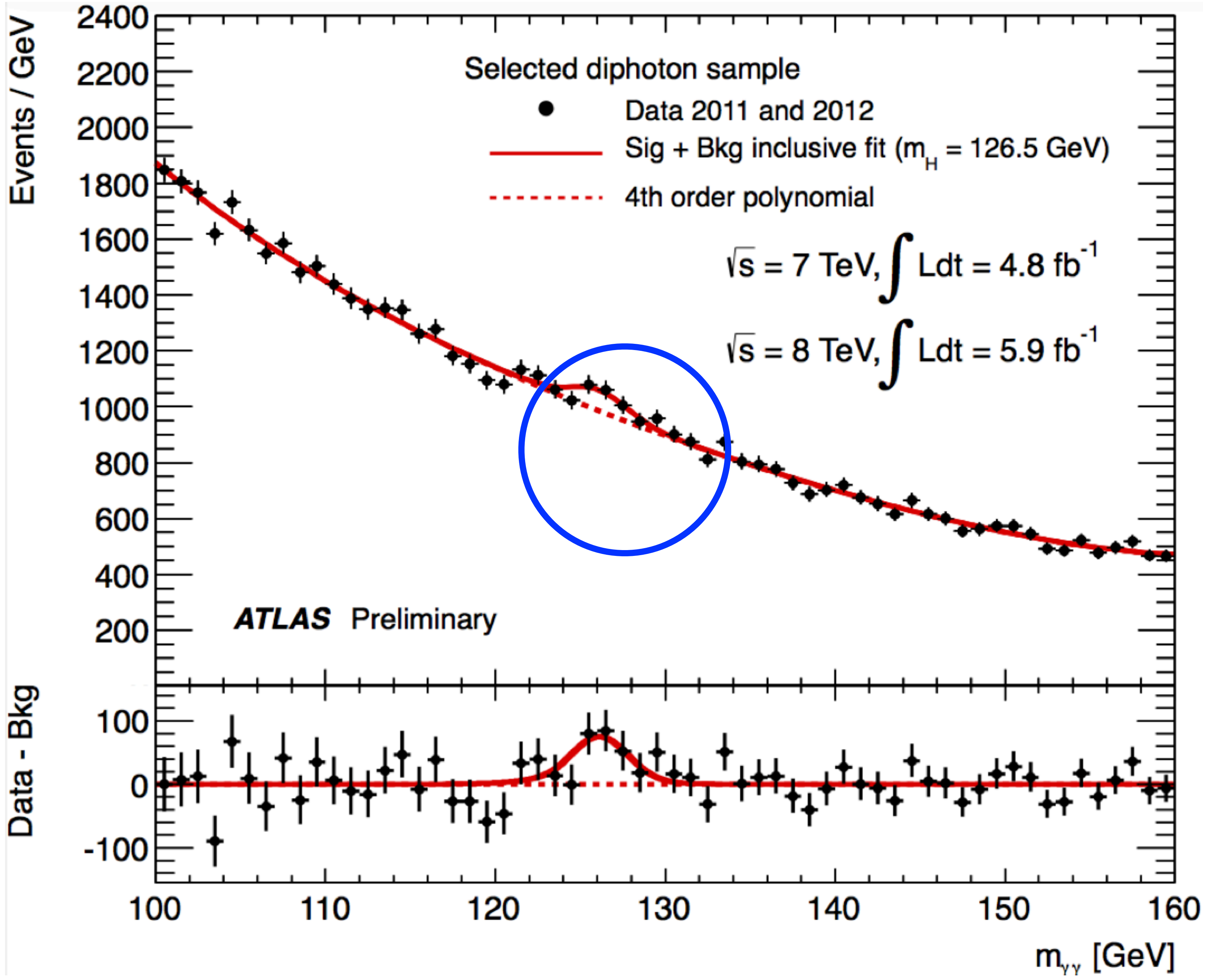
https://indico.cern.ch/event/197461/

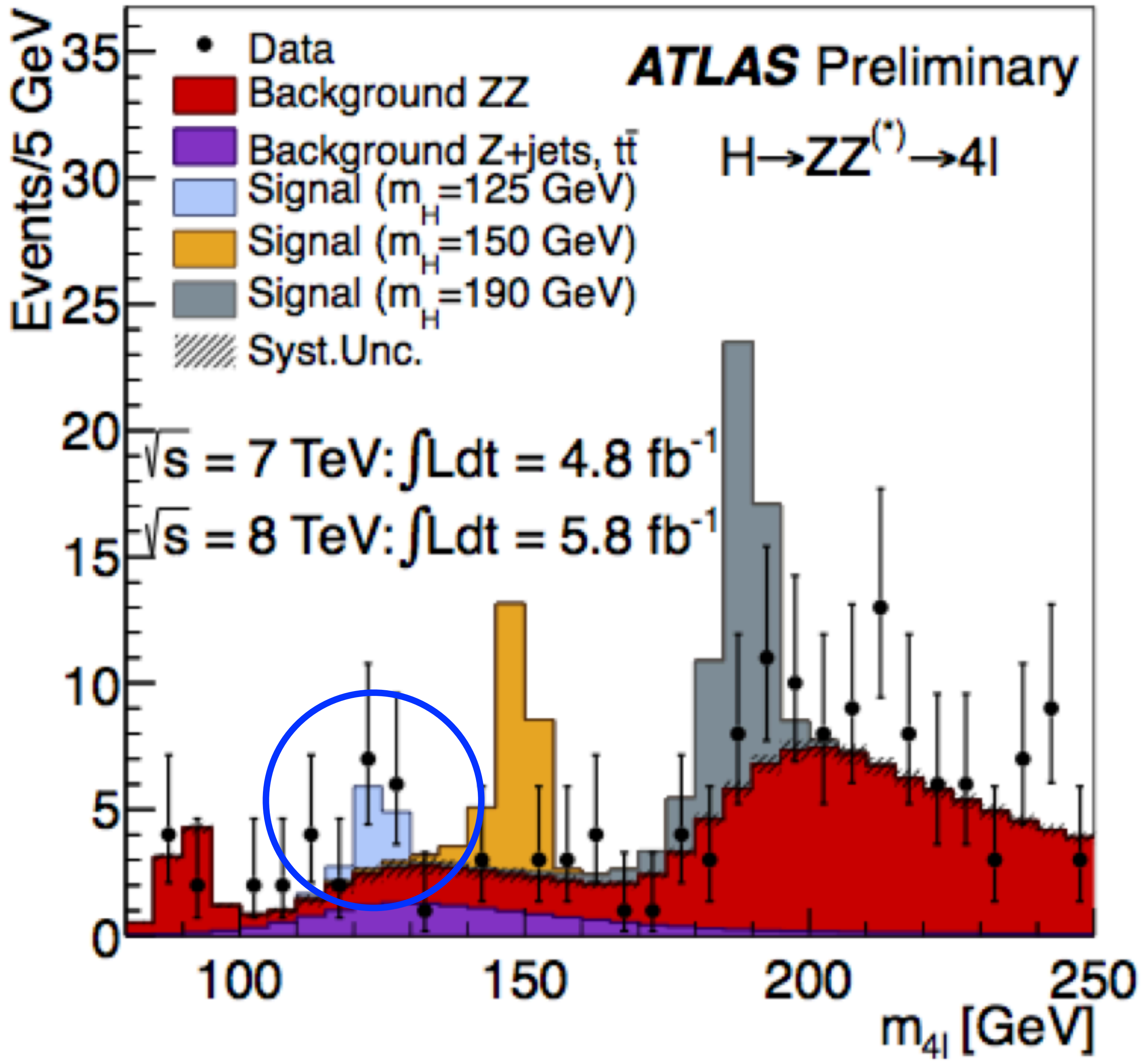
F. Gianotti (ATLAS) *R. Heuer (CERN)* *J. Incandela (CMS)*

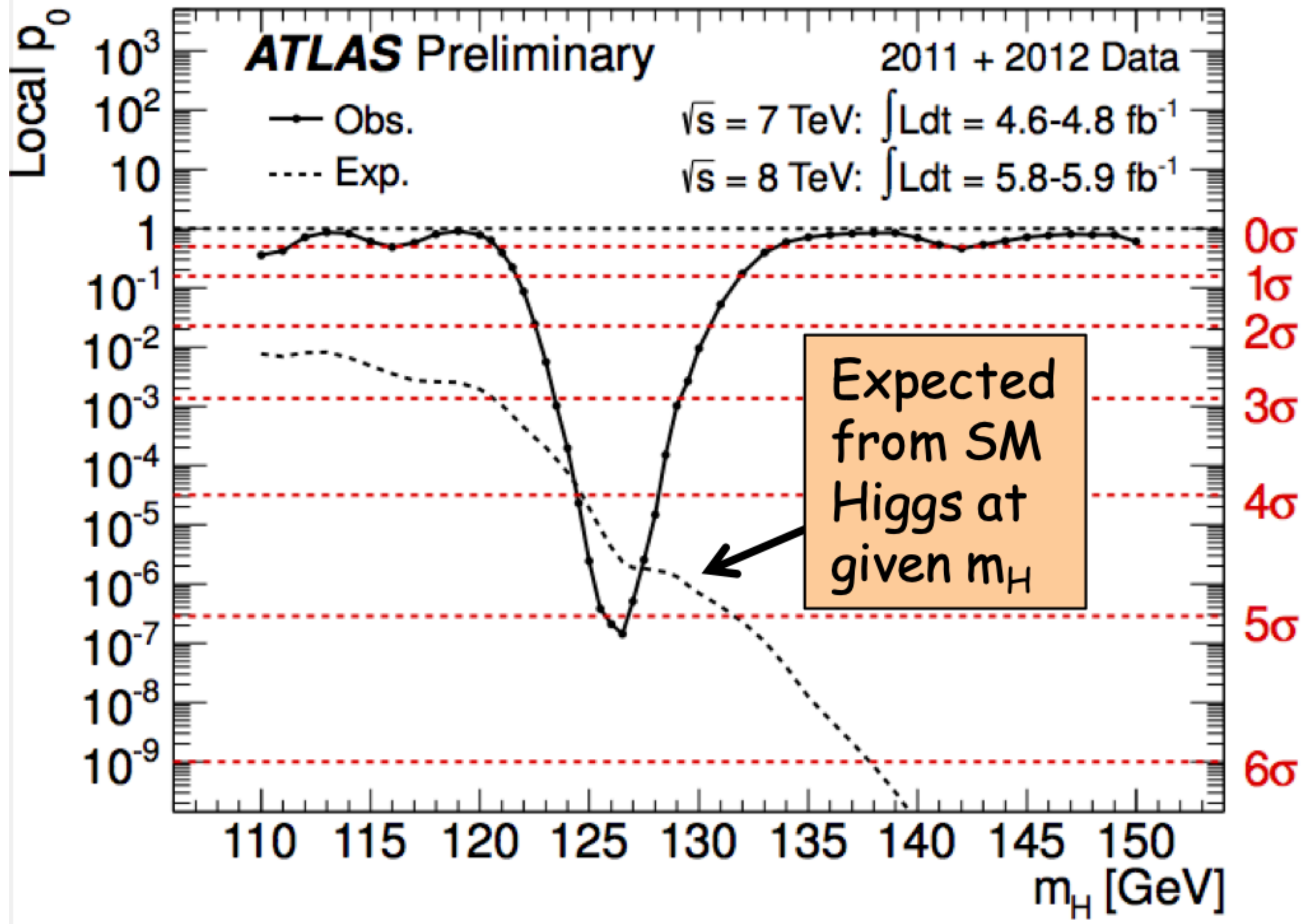
F. Englert *P. Higgs*

The Higgs boson discovery

- Analysis of up to 5/fb @ 7 TeV + 5/fb @ 8 TeV
- 5 final states considered:
  - The "easy" and cleanest ones: $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^{(*)}\rightarrow 4l$ (full dataset)
  - The more complex, less sensitive ones: $H\rightarrow WW^{(*)}\rightarrow l\nu l\nu$, $H\rightarrow\tau\tau$, $W/Z+H\rightarrow \nu l/\nu\nu/ll$ + bb (7 TeV data)
    - Lower reconstruction efficiency & resolution: missing energy from neutrinos, jets, flavour tagging, ..
- More data AND improved analyses (better reconstruction and identification of physics object, event categories targeting VBF production with better S/B..)







The Higgs boson discovery

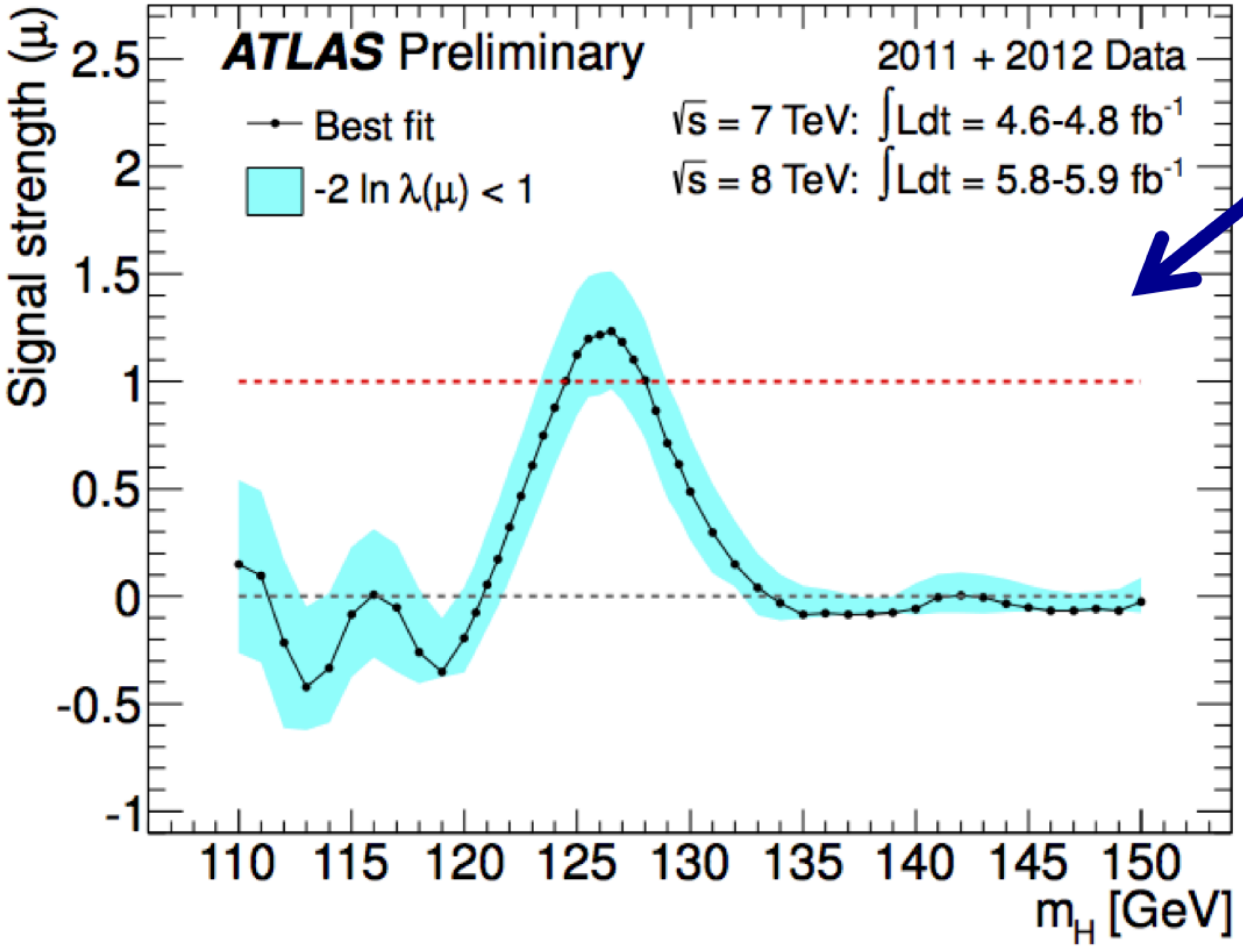
- Analysis of up to 5/fb @ 7 TeV + 5/fb @ 8 TeV
- 5 final states considered:
  - The “easy” and cleanest ones: H→γγ and H→ZZ$^{(*)}$→4l (full dataset)
  - The more complex, less sensitive ones: H→WW$^{(*)}$→lνlν, H→ττ, W/Z+H→νl/νν/ll+ bb (7 TeV data)
    - Lower reconstruction efficiency & resolution: missing energy from neutrinos, jets, flavour tagging, ..
  - Plus, some other H→WW/ZZ final states with lower sensitivity (e.g ZZ→llqq)

Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3 x 10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

The Higgs boson discovery

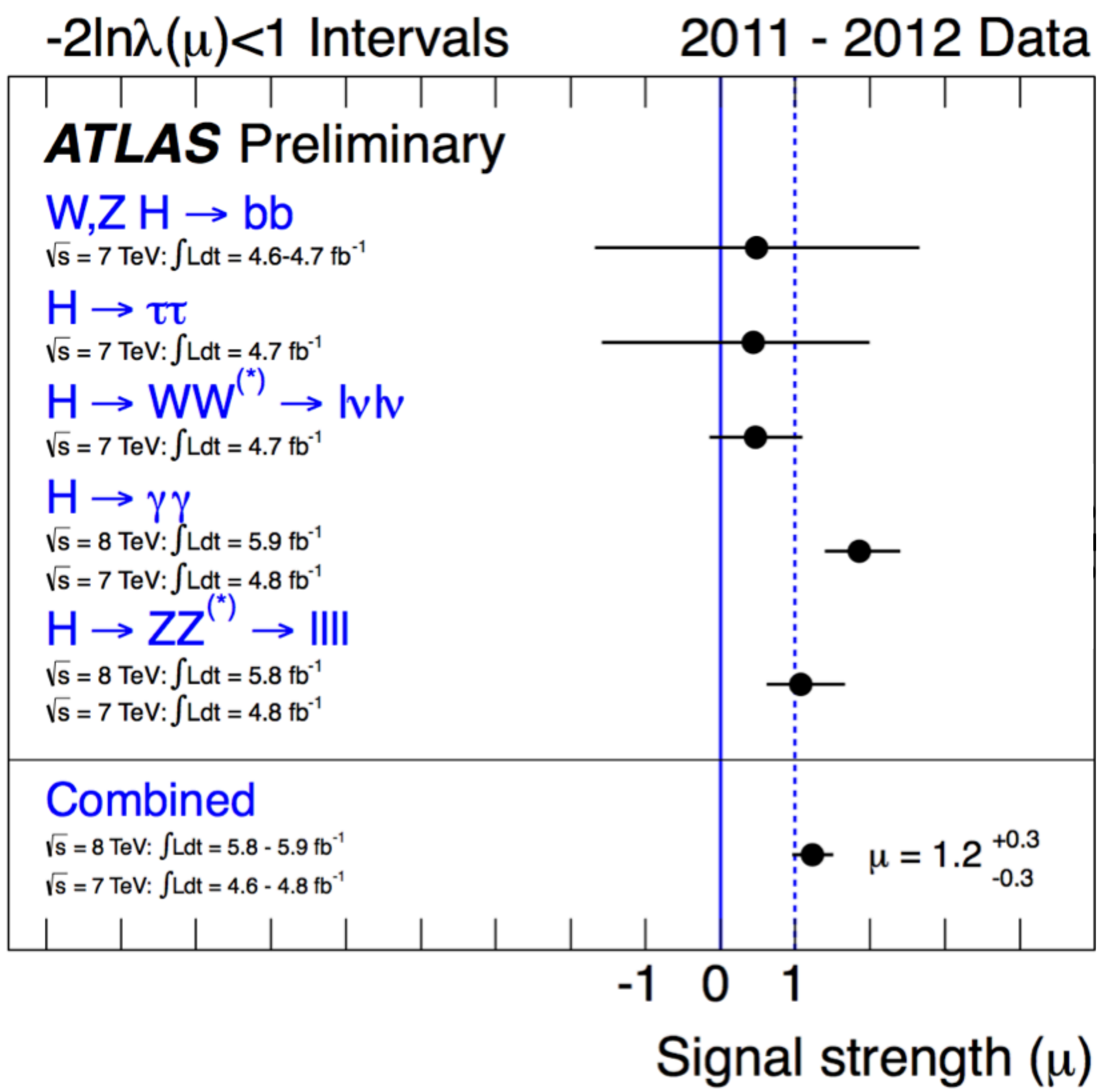
- Analysis of up to 5/fb @ 7 TeV + 5/fb @ 8 TeV
- 5 final states considered:
  - The "easy" and cleanest ones: H→γγ and H→ZZ$^{(*)}$→4l (full dataset)
  - The more complex, less sensitive ones: H→WW$^{(*)}$→lνlν, H→ττ, W/Z+H→νl/νν/ll+ bb (7 TeV data)
    - Lower reconstruction efficiency & resolution: missing energy from neutrinos, jets, flavour tagging, ..
  - Plus, some other H→WW/ZZ final states with lower sensitivity (e.g ZZ→llqq)



"signal strength"

Best-fit value at 126.5 GeV:
μ = 1.2 ± 0.3

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{obs}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$



What have we learnt since the Higgs boson discovery?

- In the past ~10 years we have measured or constrained many of its properties:
  - Mass
  - Width
  - Spin & parity
  - Main decay and production modes
  - Couplings to other particles
  - Differential cross sections
  - Rare decays
  - Self-coupling
  - beyond-SM interactions (anomalous couplings to SM particles, CP violation, coupling to dark matter sector..)

PDG 2012

Higgs Bosons — H^0 and $H^\pm$, Searches for

The July 2012 news about Higgs searches is described in the addendum to the Higgs review in the data listings, but is not reflected here.

The limits for H_1^0 and A^0 refer to the m_h^{max} benchmark scenario for the supersymmetric parameters.

H^0 Mass $m > 115.5$ and none 127–600 GeV, CL = 95%

H_1^0 in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)

Mass $m >$ 92.8 GeV, CL = 95%

PDG 2021

H^0 $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

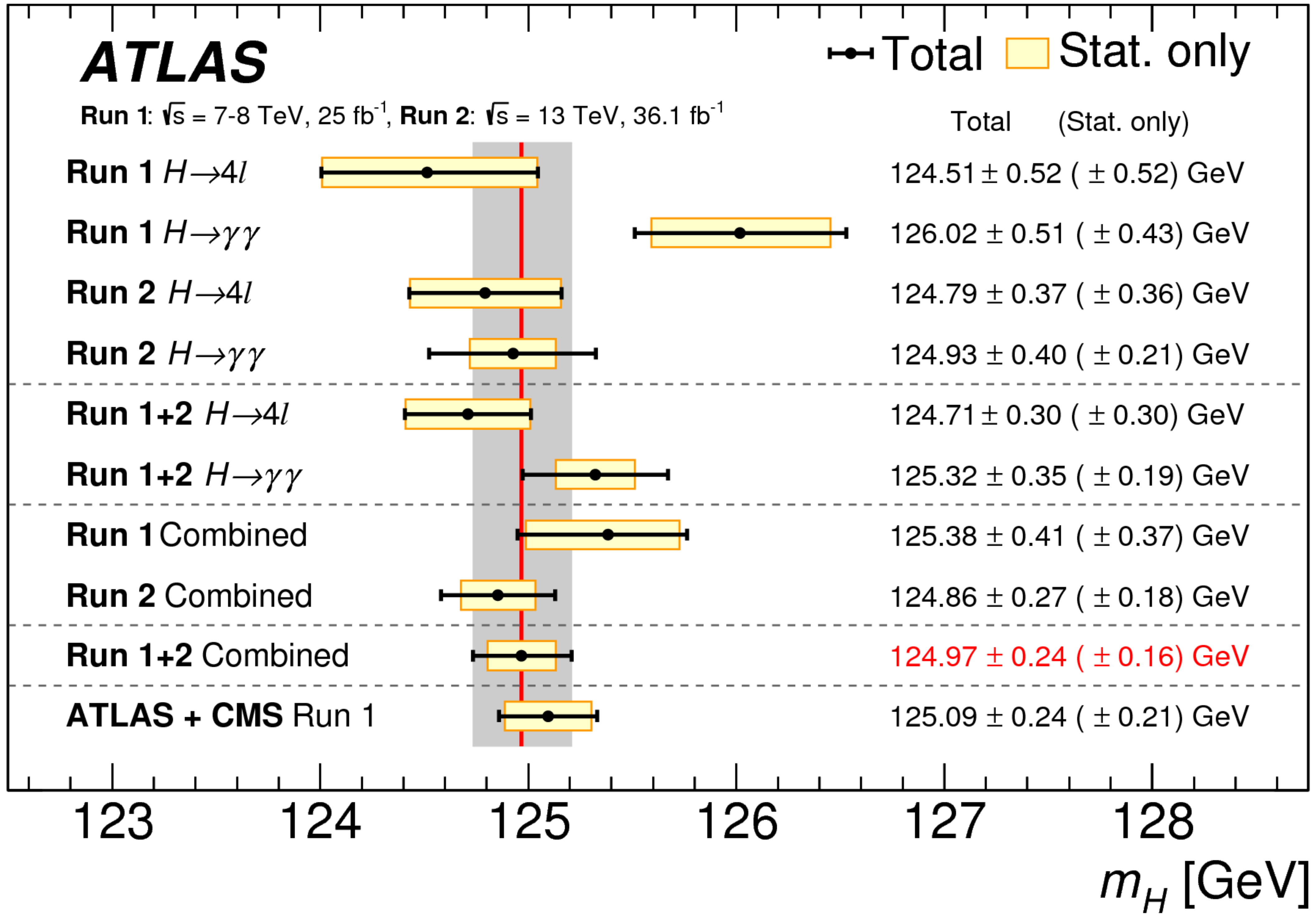
Combined Final States = 1.13 ± 0.06
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.06 \pm 0.09$
$\gamma\gamma = 1.11^{+0.10}_{-0.09}$
$c\bar{c}$ Final State = 37 ± 20
$b\bar{b} = 1.04 \pm 0.13$

...

Higgs boson mass

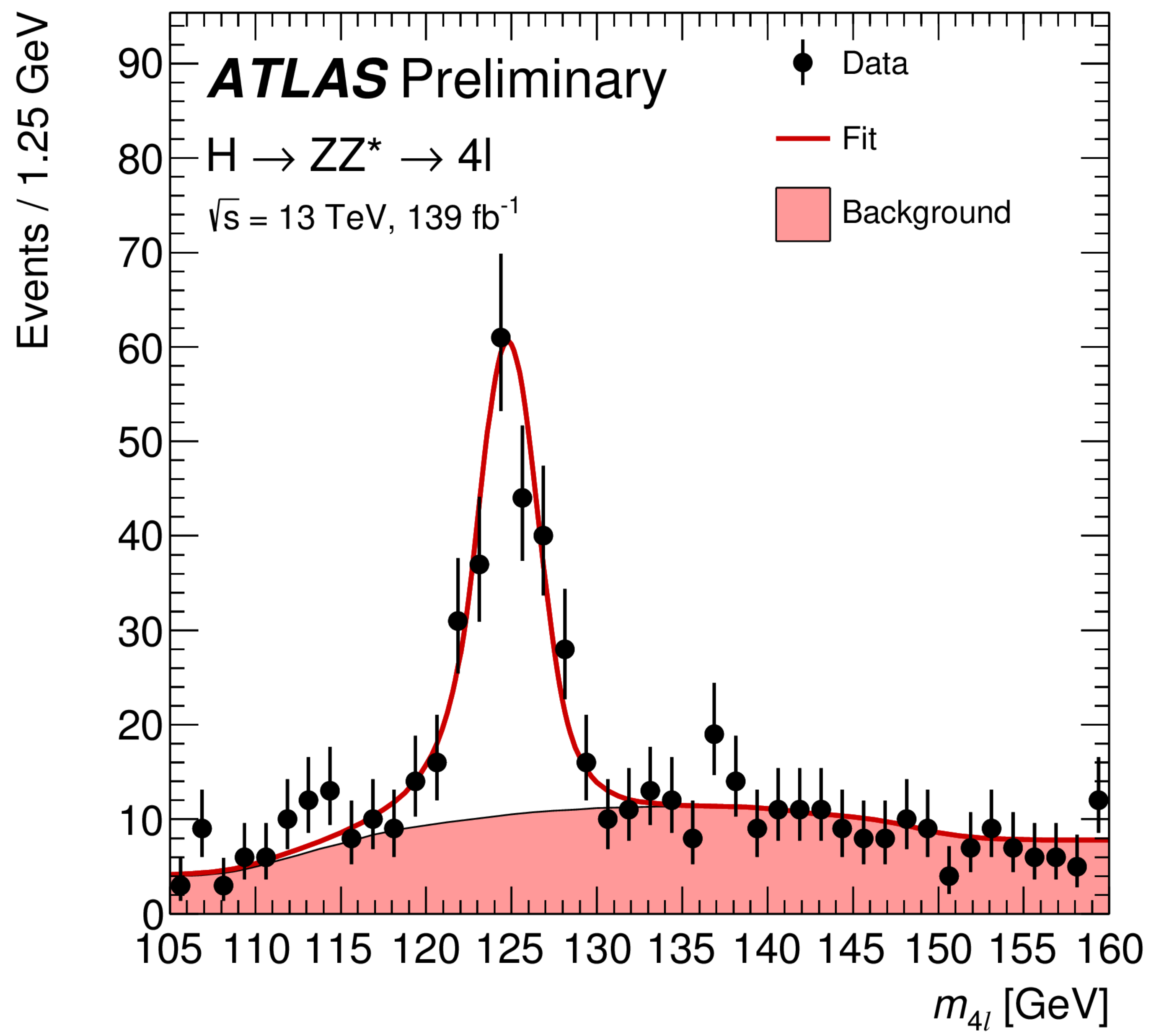
- Measured in high-resolution channels (γγ, ZZ→4l) from the position of the invariant mass peak
- Precision limited by statistical (ZZ) or experimental (γγ) systematic uncertainties
- Requires precise lepton and photon energy calibration (use control samples such as Z→ee, μμ)

H→ZZ→4l + H→γγ, 36/fb* [Phys. Lett. B 784 (2018) 345]



- **Run1 + partial Run2: 0.19% precision**

H→ZZ→4l, 139/fb* [ATLAS-CONF-2020-005]



$$m_H^{ZZ^*} = 124.92 \pm 0.19\ (\text{stat})^{+0.09}_{-0.06}\ (\text{syst})\ \text{GeV} = 124.92^{+0.21}_{-0.20}\ \text{GeV}$$

- **Full Run2: 0.16% precision**

One of the most precisely measured electroweak parameters!

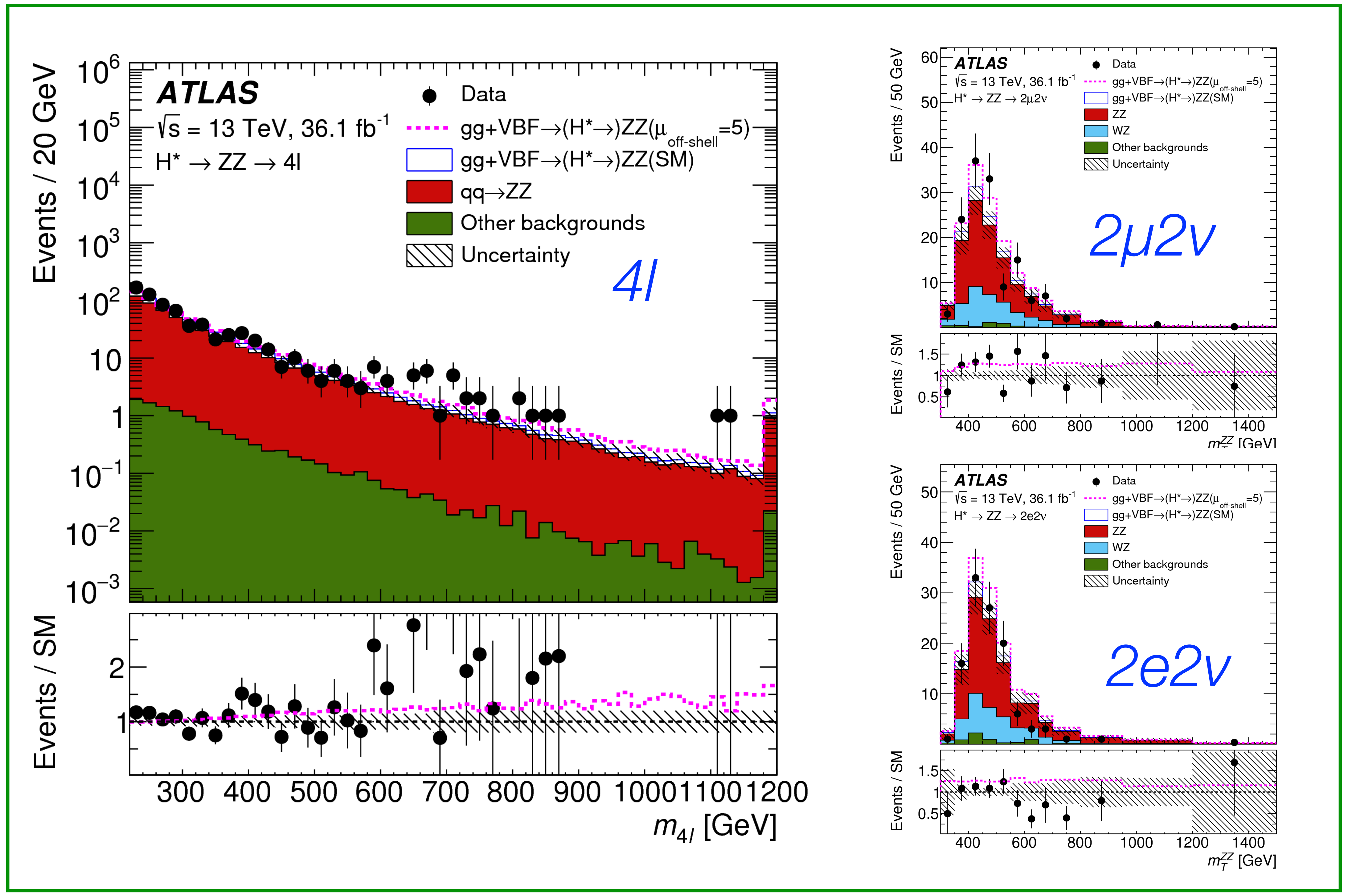
Higgs boson width

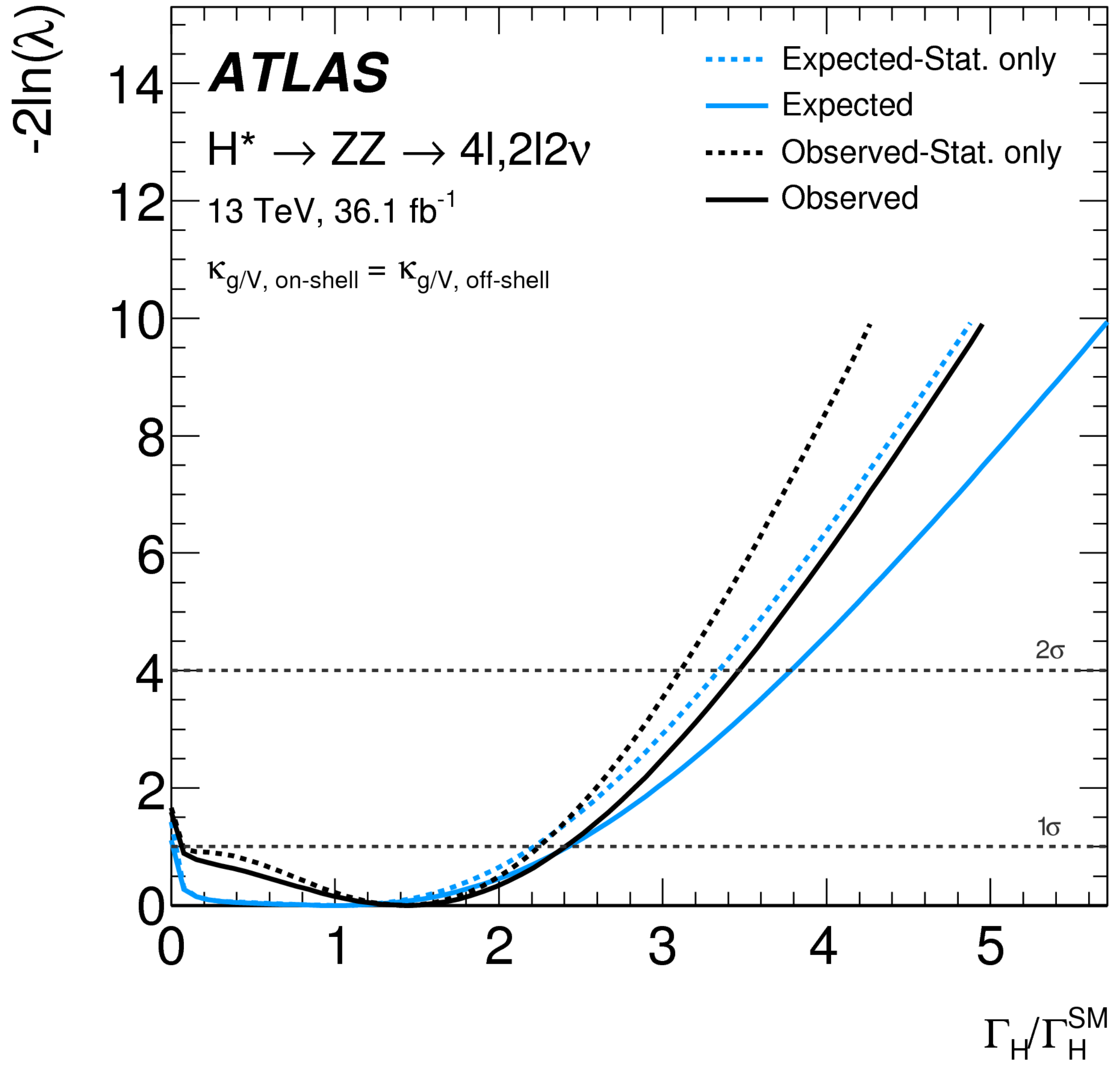
- SM Higgs boson **width (4.1 MeV) << experimental resolution (1–2 GeV) => too small** to be measured directly (direct limits ~ 1 GeV)
- Can be inferred **from ratio of off-shell/on-shell pp→H*→ZZ** (or WW) xsections

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}, \qquad \mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}},$$

with some **assumptions:**

- running of the couplings as in the SM: $\kappa_{\text{off-shell}} = \kappa_{\text{on-shell}}$
- no new signals in the search reason, apart from a possibly enhanced off-shell Higgs contribution





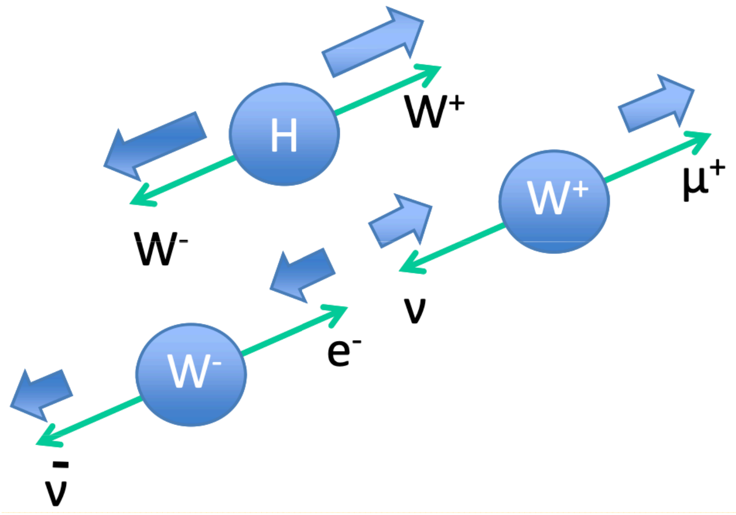
Phys. Lett. B 786 (2018) 223

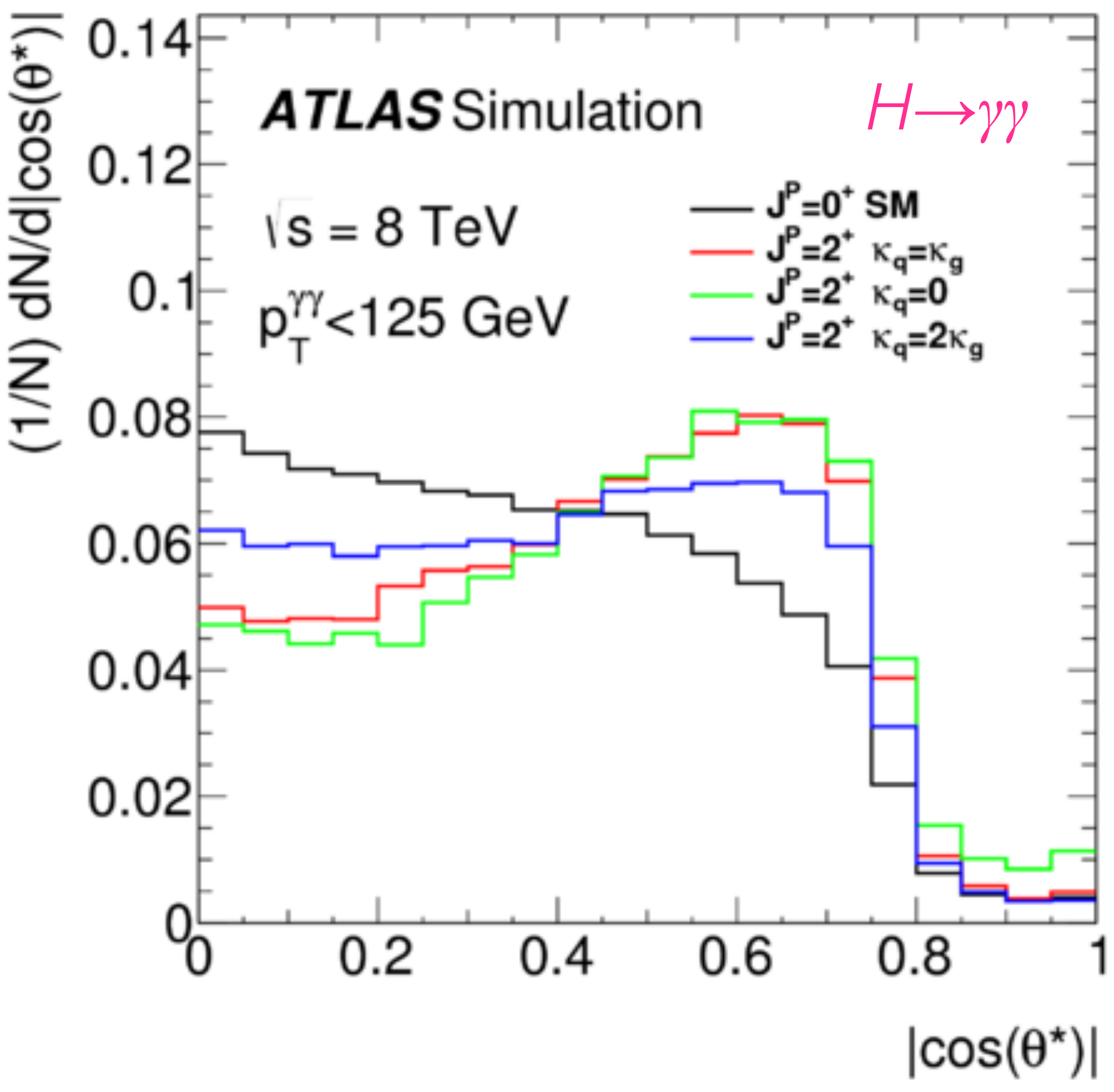
95% CL upper limits		Observed	Expected
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3
	$ZZ \to 2\ell 2\nu$ analysis	5.3	4.4
	Combined	3.8	3.4
$\Gamma_H/\Gamma_H^{\text{SM}}$	Combined	3.5	3.7

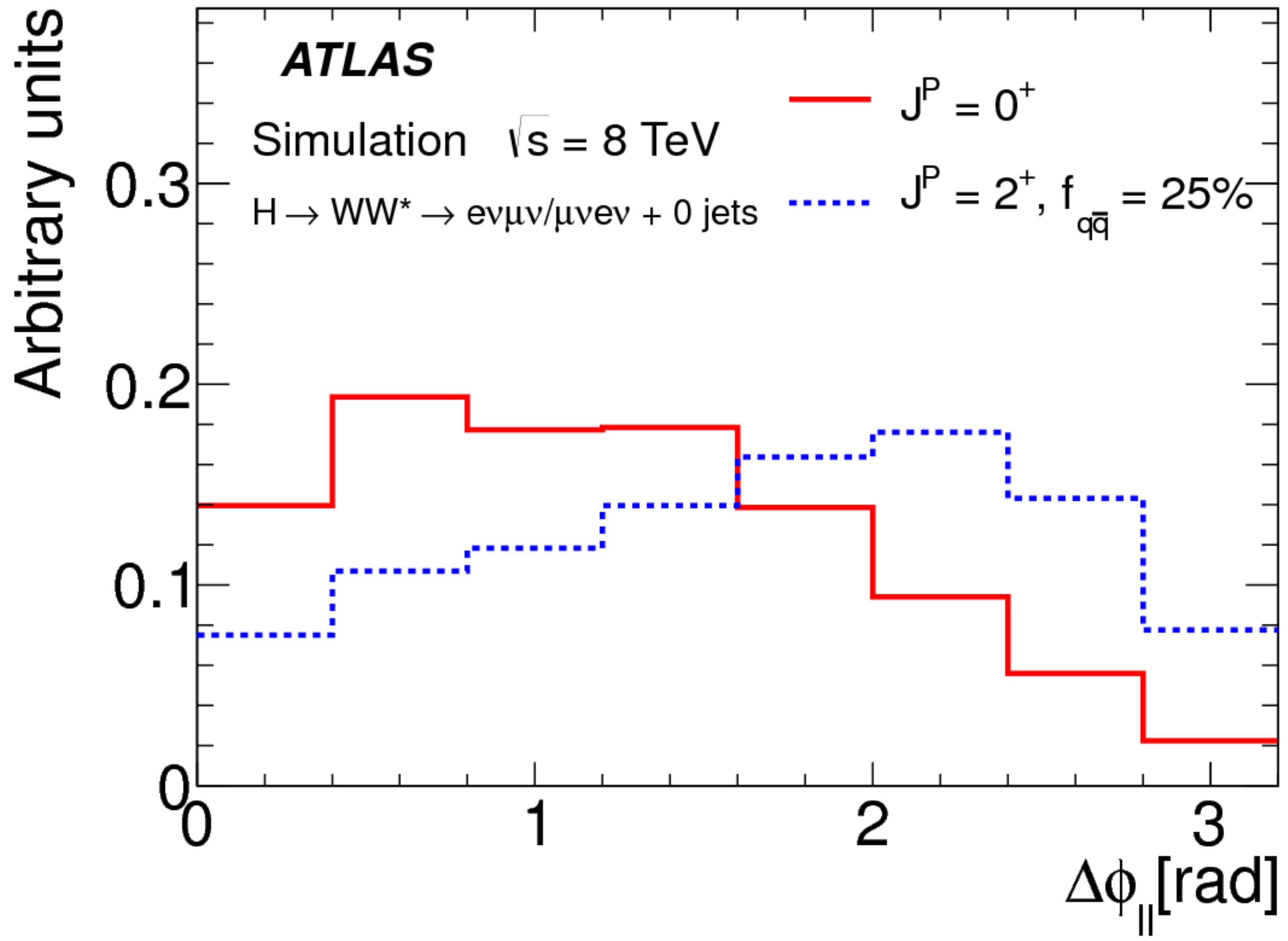
25% precision at HL-LHC… but model-dependent!

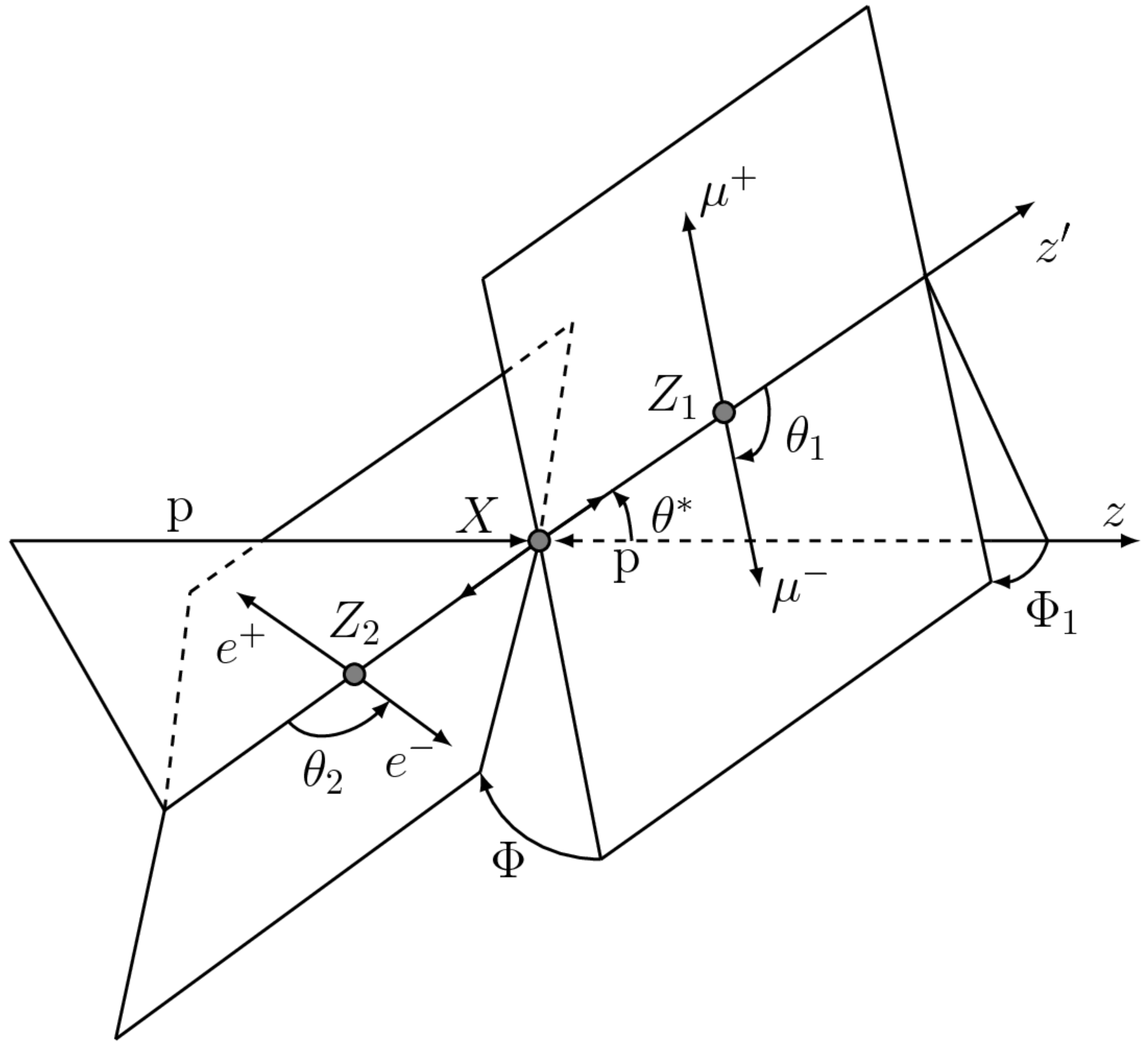
Higgs boson spin and parity

- **Spin 1 forbidden** by observation of H→γγ decay (Landau-Yang's theorem)
- **J^P = 0^-, 0^+ non-SM** (different tensor structure of the HVV couplings), and various graviton-like **2^+** scenarios are tested one-by-one against the SM 0^+ hypothesis exploiting angular distributions that are sensitive to J^P
  - Polar angle θ* of photon in γγ CM frame (flat for spin-0, quadratic in cosθ* for spin 2)
  - Azimuthal opening angle between two leptons in H→WW (small for spin-0, large for spin-2 due to W coupling to left-handed fermions)
  - Decay angles and dilepton invariant masses in H→ZZ→4l

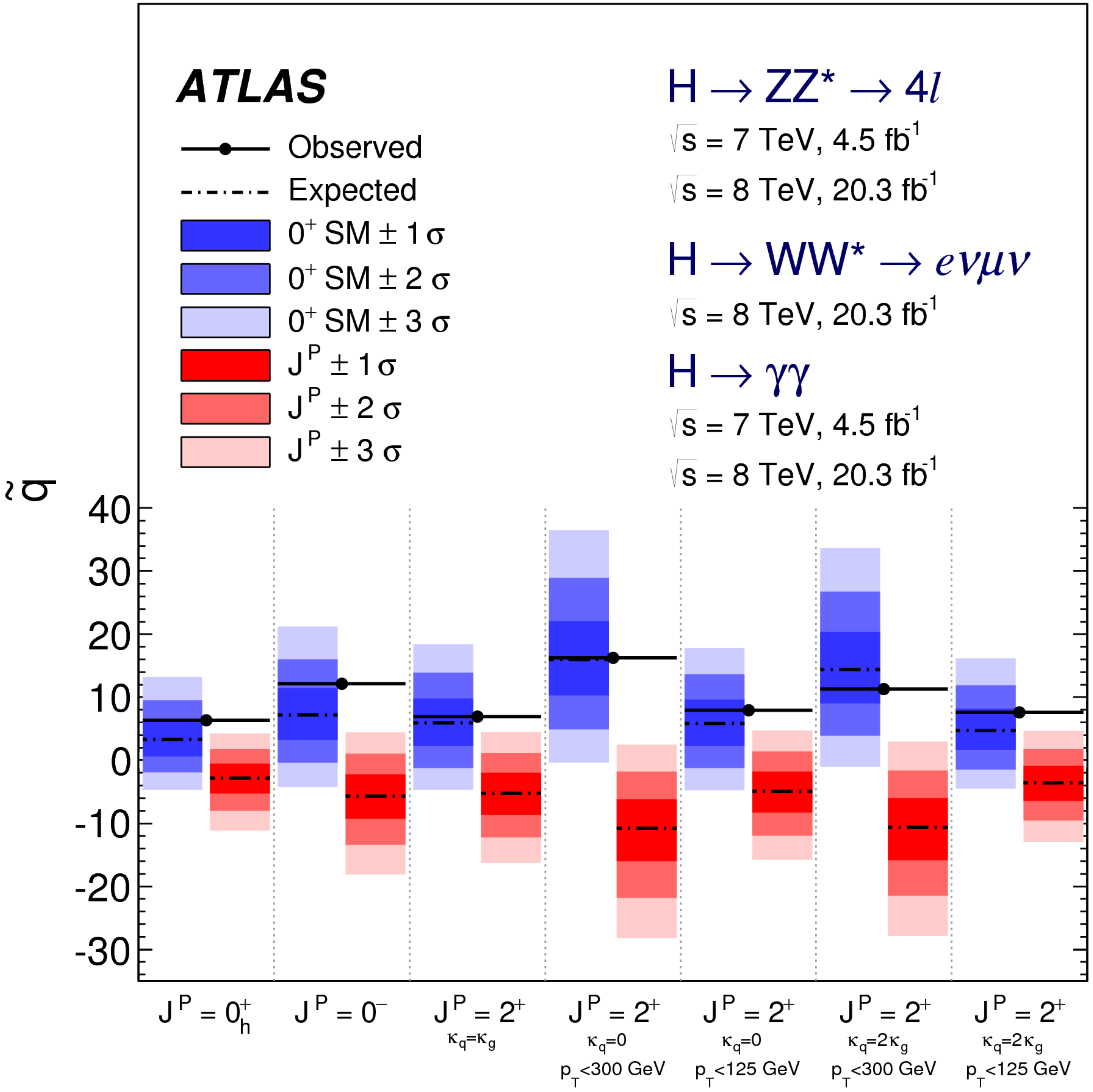








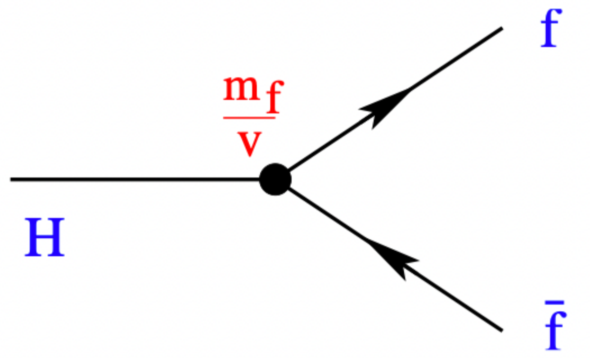
Higgs boson spin and parity



Eur. Phys. J. C75 (2015) 476

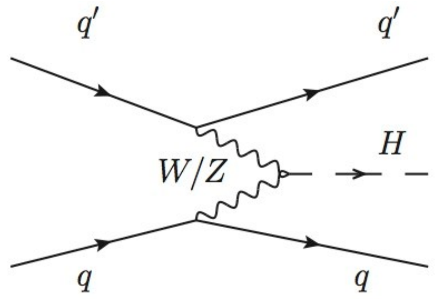
All alternative hypotheses disfavoured at > 3σ

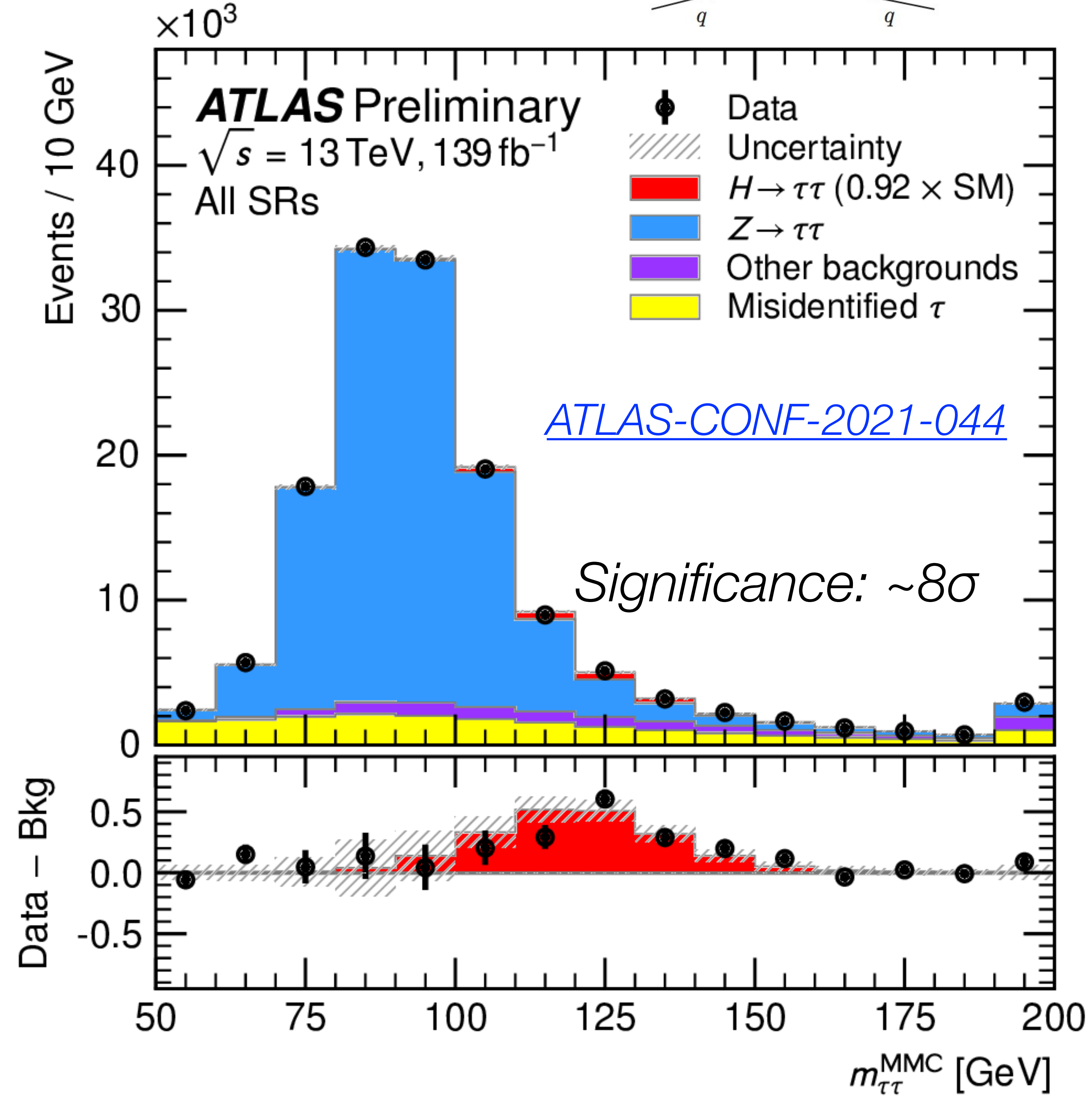
Observation of Higgs boson decays to τ-leptons and to b-quarks



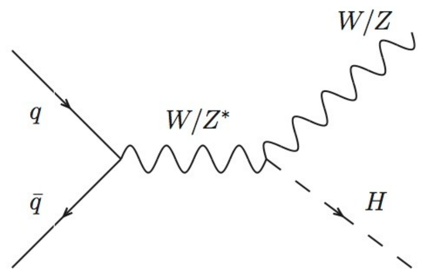
- First observation with partial Run2 datasets. More detailed studies performed with full dataset
- Best sensitivity provided by production modes with lower x-section but much better bkg rejection than gluon fusion
  - VBF (~8% of σ_H) for H→ττ, V(→leptons)H (~0.9% of σ_H) for H→bb
- Large sensitivity boost from use of multivariate techniques for object reconstruction and S/B discrimination in Run2 analyses

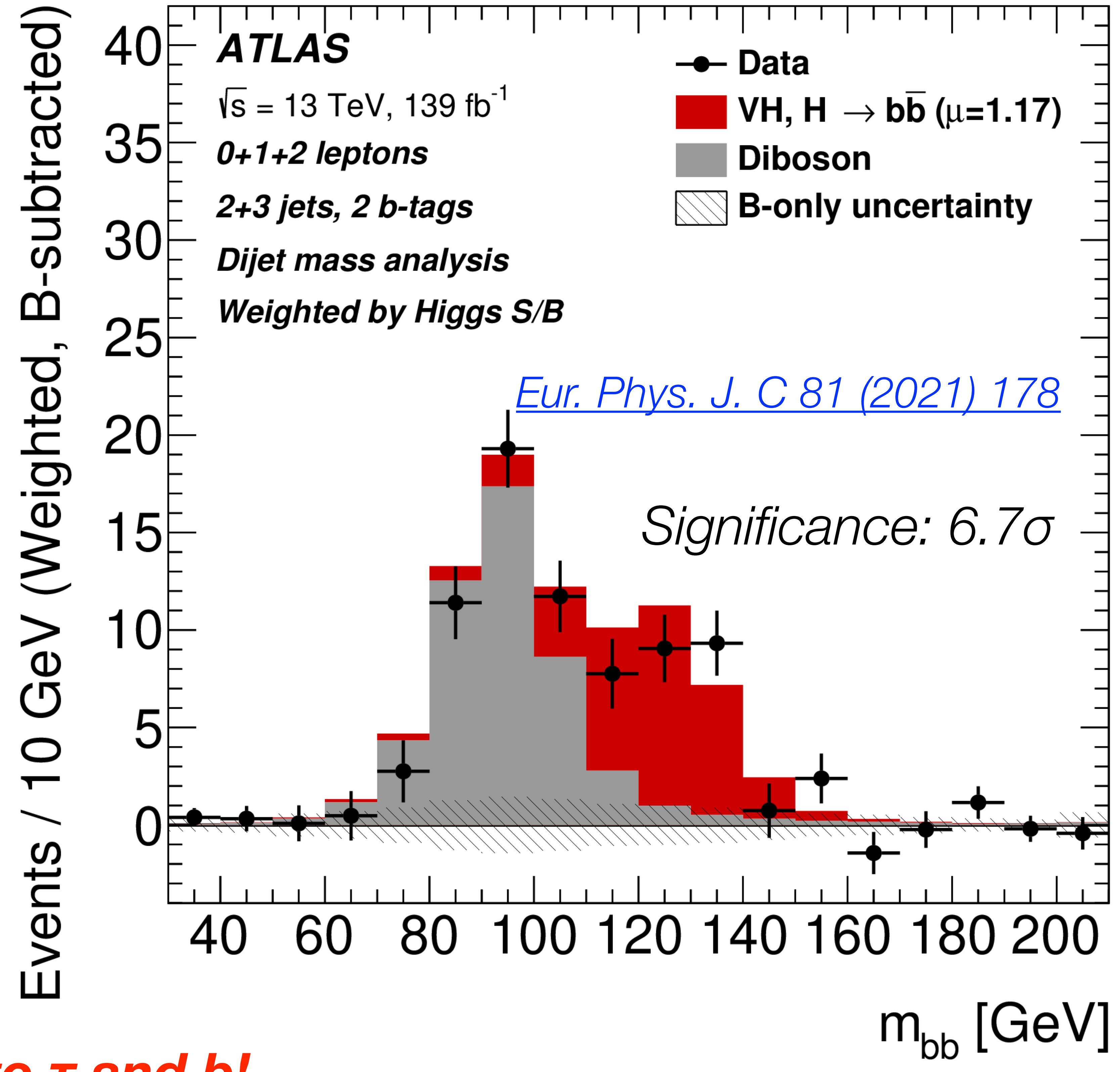
H→ττ





H→bb



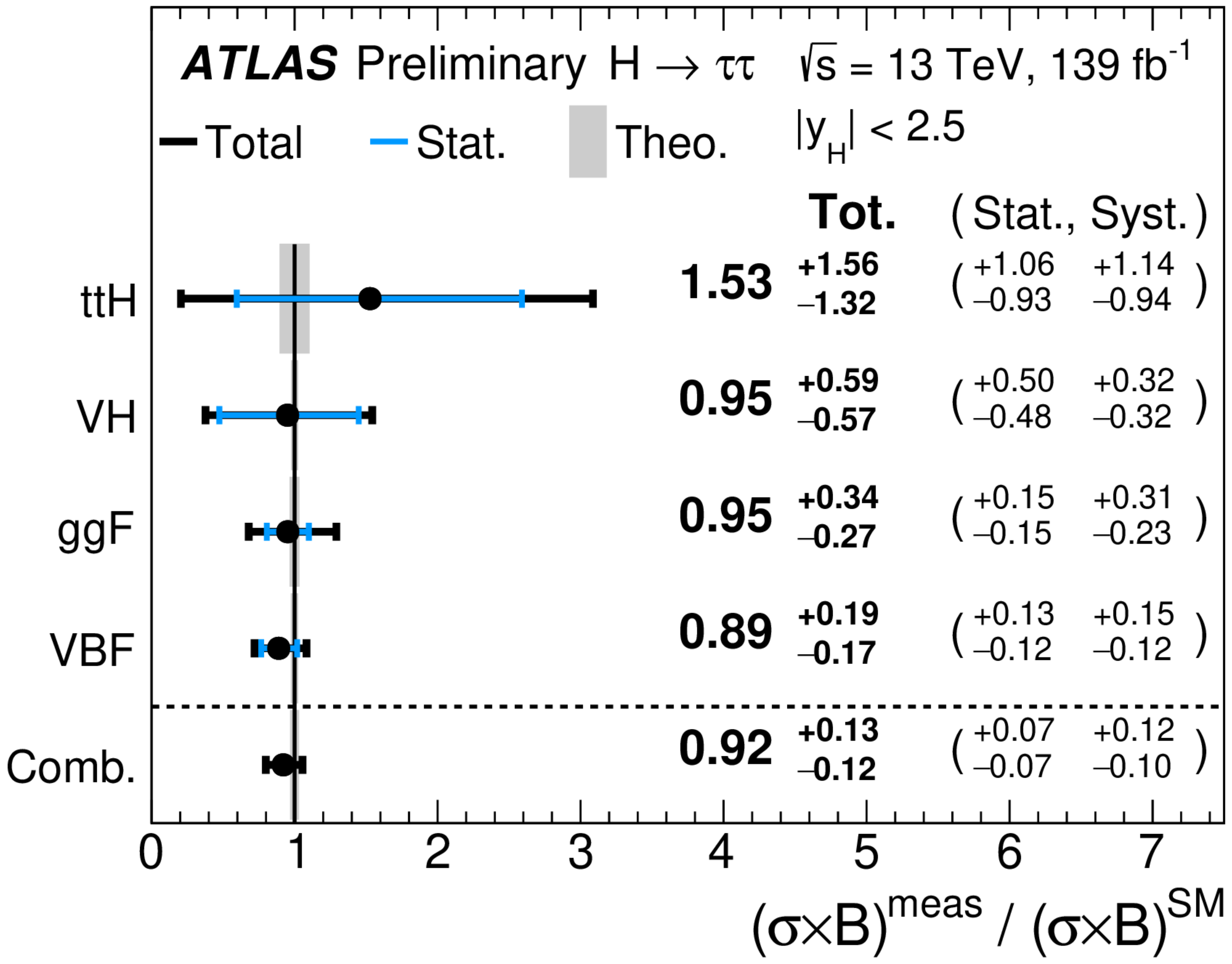


Evidence of Yukawa couplings to τ and b!

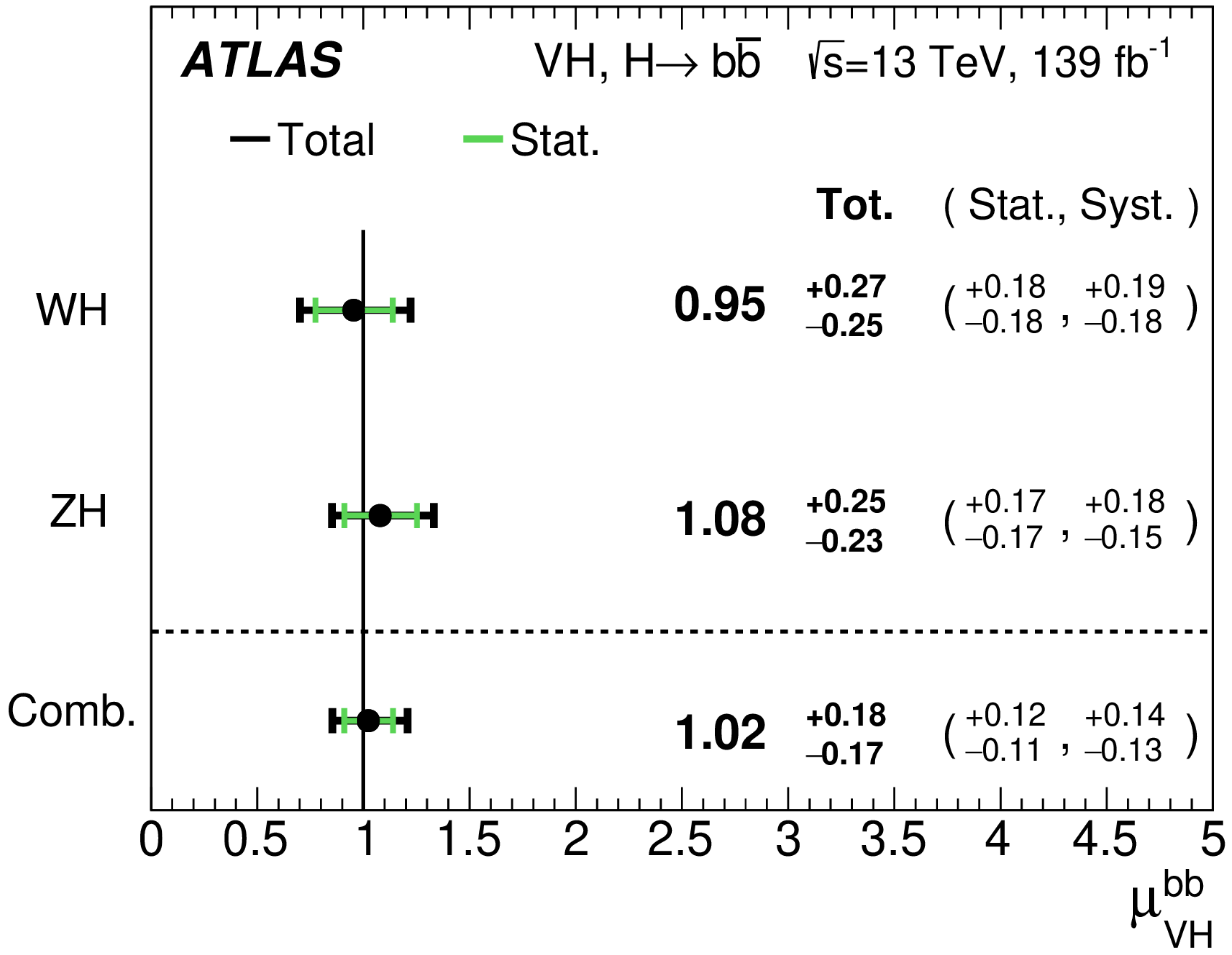
Observation of Higgs boson decays to τ-leptons and to b-quarks

- First observation with partial Run2 datasets. More detailed studies performed with full dataset
- Best sensitivity provided by production modes with lower x-section but much better bkg rejection than gluon fusion
  - VBF (~8% of σ_H) for H→ττ, V(→leptons)H (~0.9% of σ_H) for H→bb
- Large sensitivity boost from use of multivariate techniques for object reconstruction and S/B discrimination in Run2 analyses

H→ττ ATLAS-CONF-2021-044

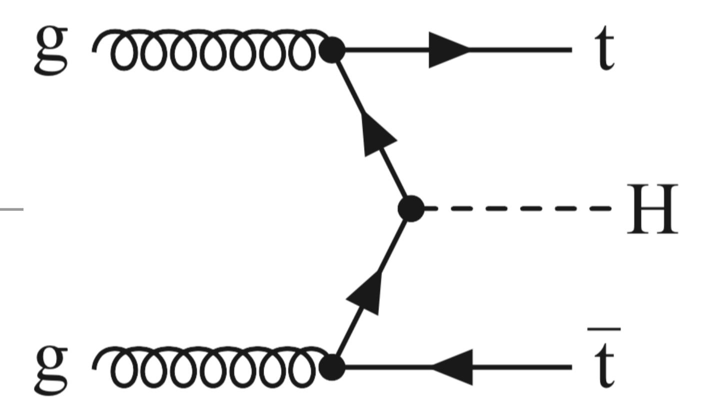


H→bb Eur. Phys. J. C 81 (2021) 178

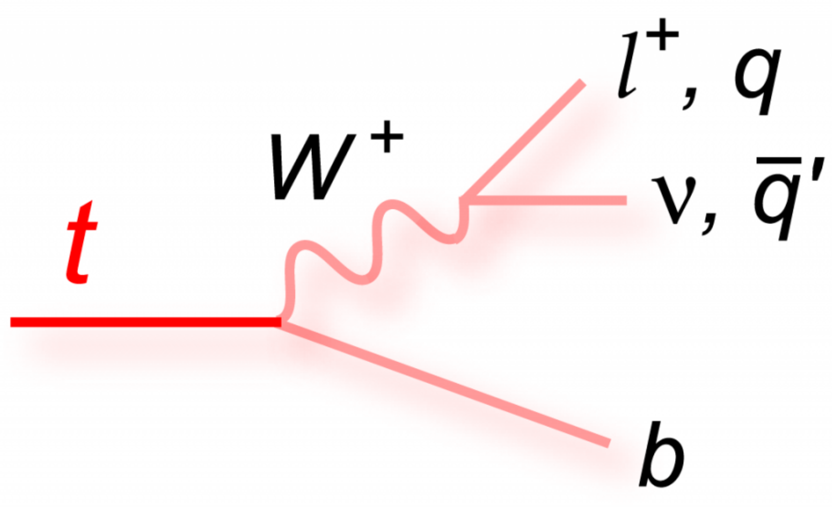


Good agreement with SM predictions

Observation of Higgs boson production with ttbar pairs



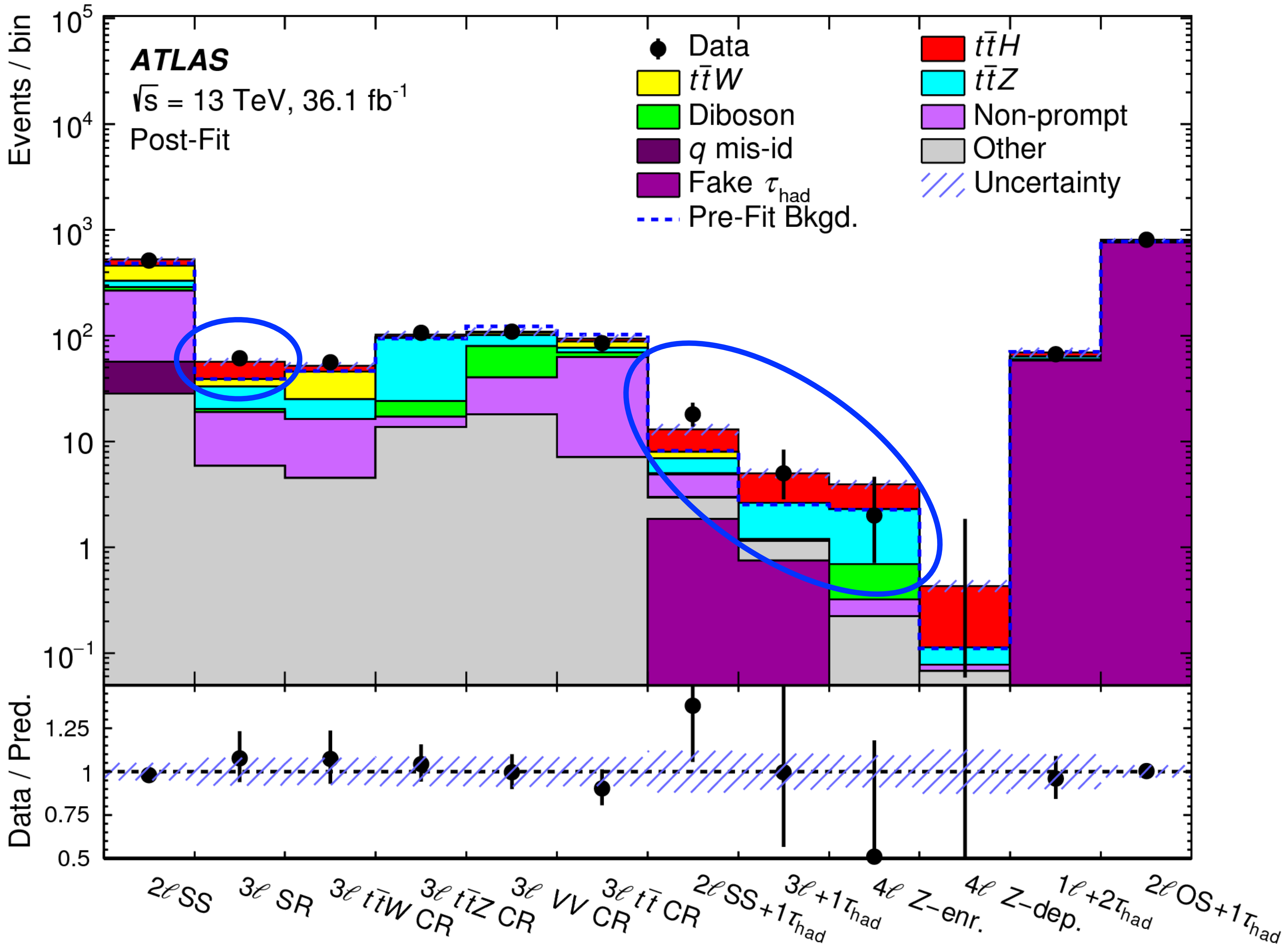
- ttbar pair identified by presence of b-jets, large jet multiplicity, possibly leptons and missing momentum
- Best sensitivity provided by decay modes with leptons (WW, ττ) or photons



Analysis	Integrated luminosity [fb^{-1}]	Expected significance	Observed significance
$H \to \gamma\gamma$	79.8	3.7 σ	4.1 σ
$H \to$ multilepton	36.1	2.8 σ	4.1 σ
$H \to b\bar{b}$	36.1	1.6 σ	1.4 σ
$H \to ZZ^* \to 4\ell$	79.8	1.2 σ	0 σ
Combined (13 TeV)	36.1−79.8	4.9 σ	5.8 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	5.1 σ	6.3 σ

Multileptons

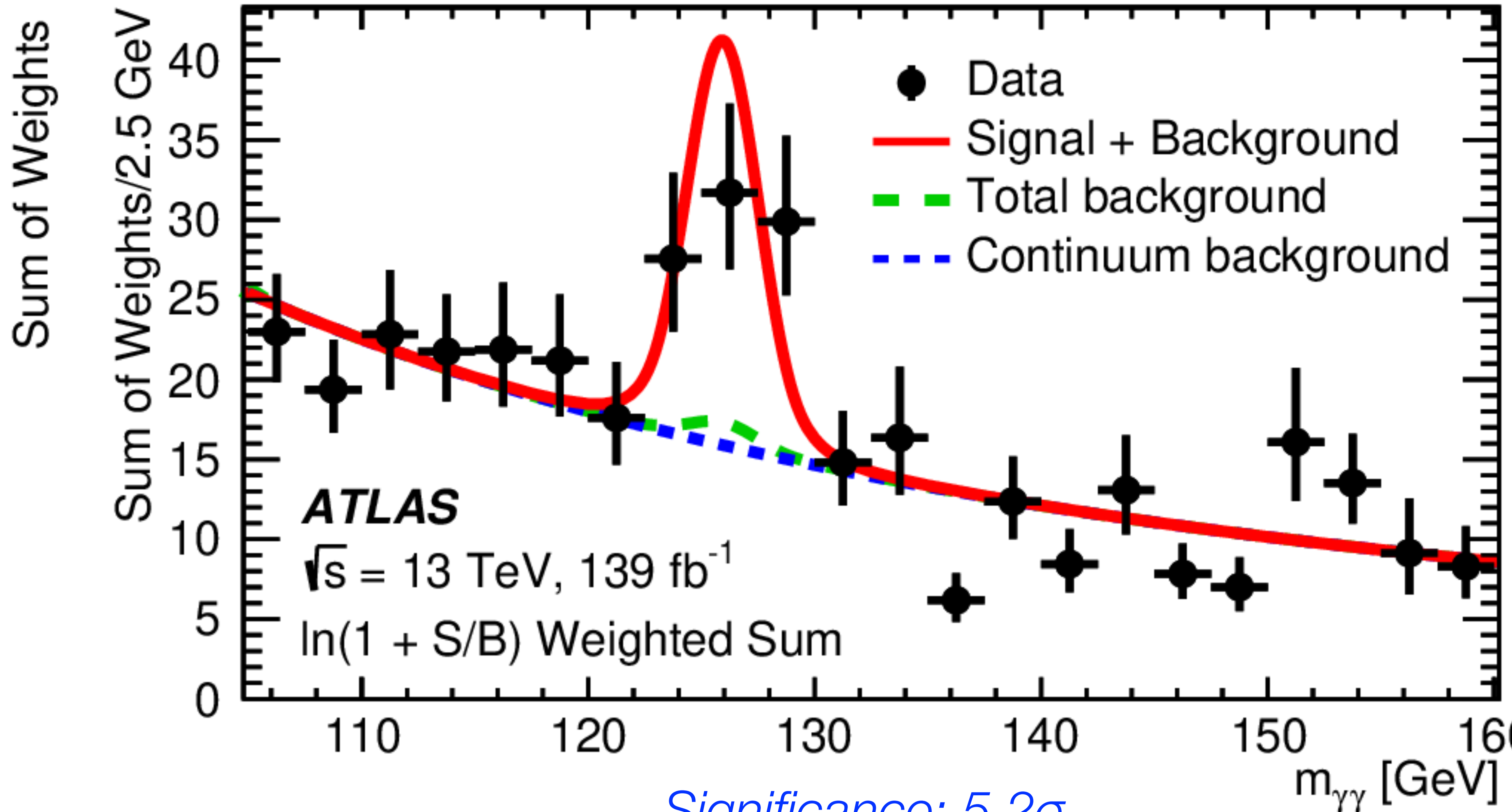
Phys. Rev. D 97 (2018) 072003



Significance: 4.1σ

H→γγ

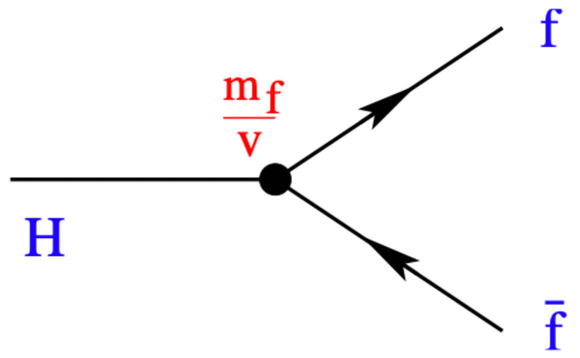
Phys. Rev. Lett. 125 (2020) 061802



Significance: 5.2σ

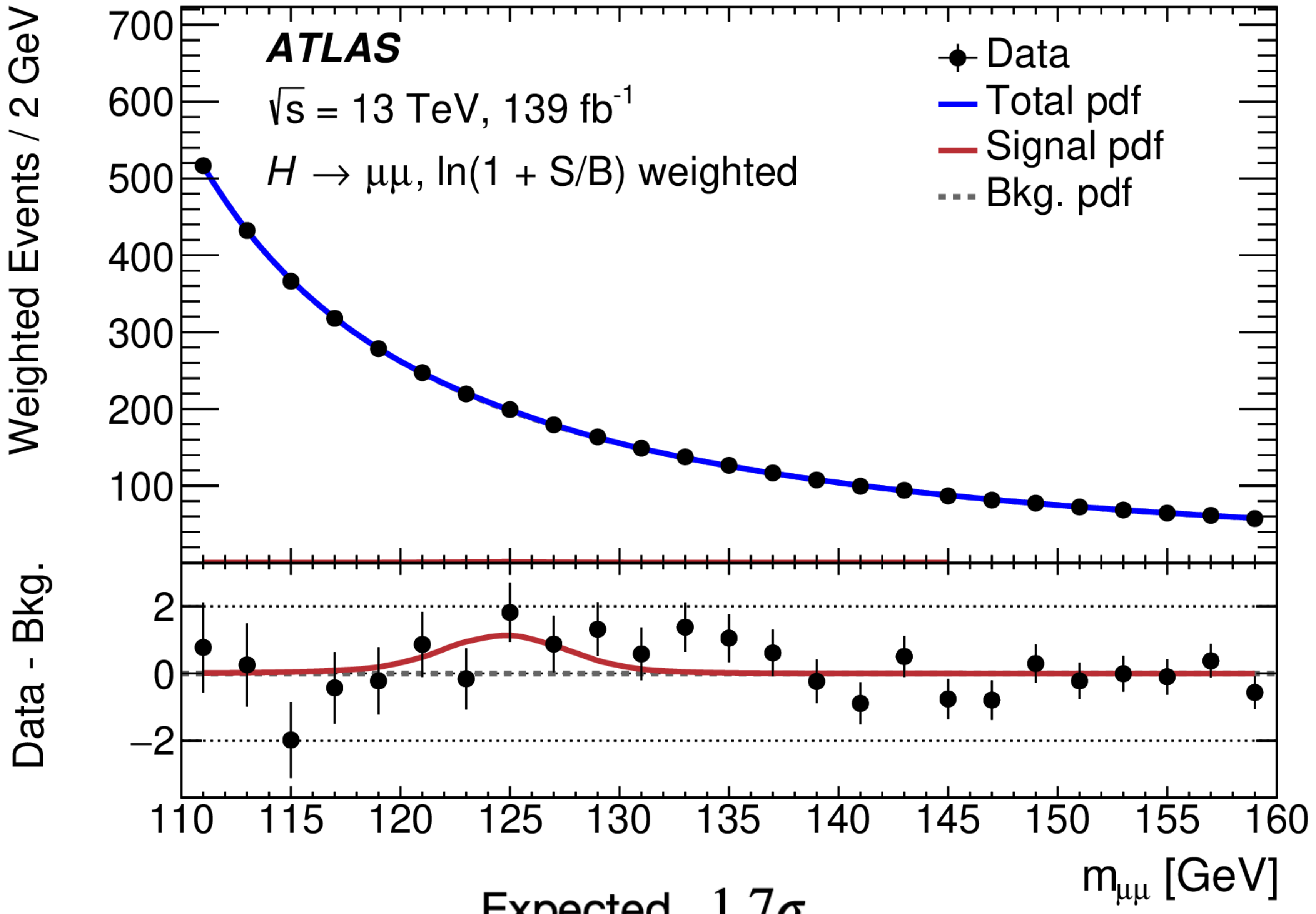
Direct evidence of Yukawa couplings to the top quark!

The challenging Yukawa couplings to 2nd-generation fermions



- $H \to \mu\mu$: very small BR (0.02%), important background from $Z^{(*)} \to \mu\mu$, but good resolution
- $H \to cc$: small BR (2%), poor resolution. Large bkg from QCD ⇒ search in V(→leptons)H. Poor c-tagging ⇒ bkg from H→bb

H→μμ [Phys. Lett. B 812 (2021) 135980]

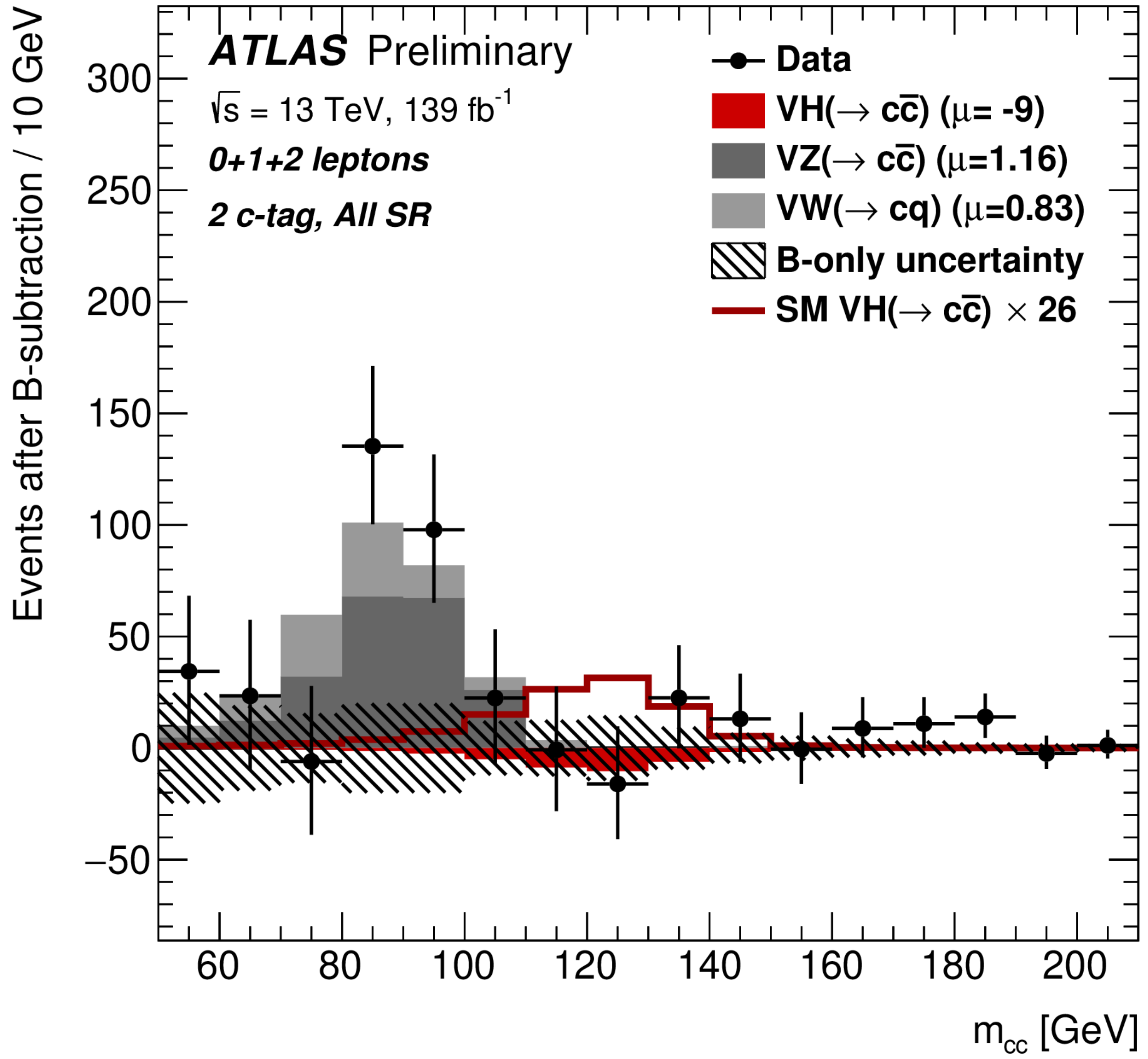


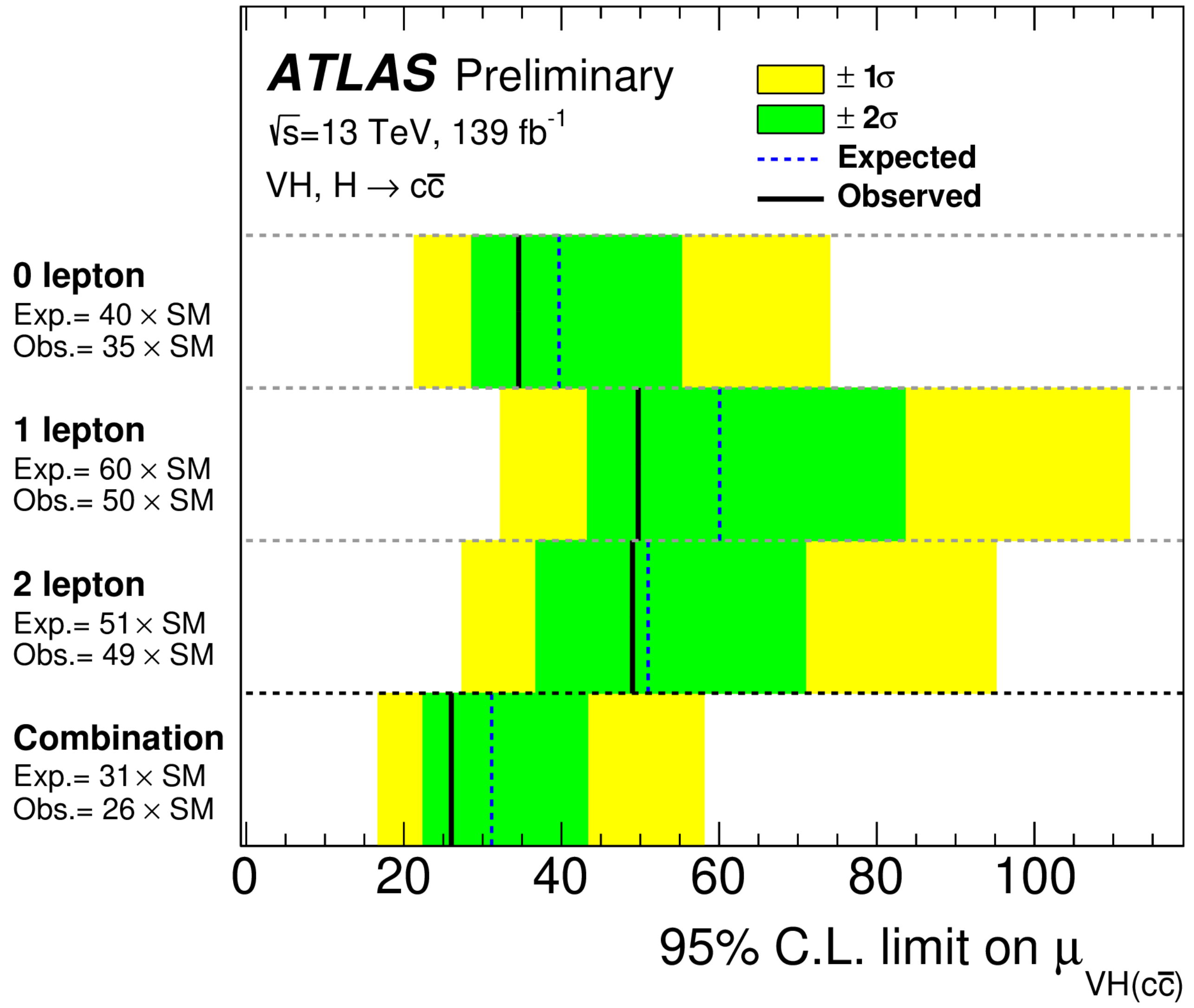
Expected 1.7σ

Observed 2.0σ

$\mu = 1.2 \pm 0.6$

H→cc [ATLAS-CONF-2021-021]





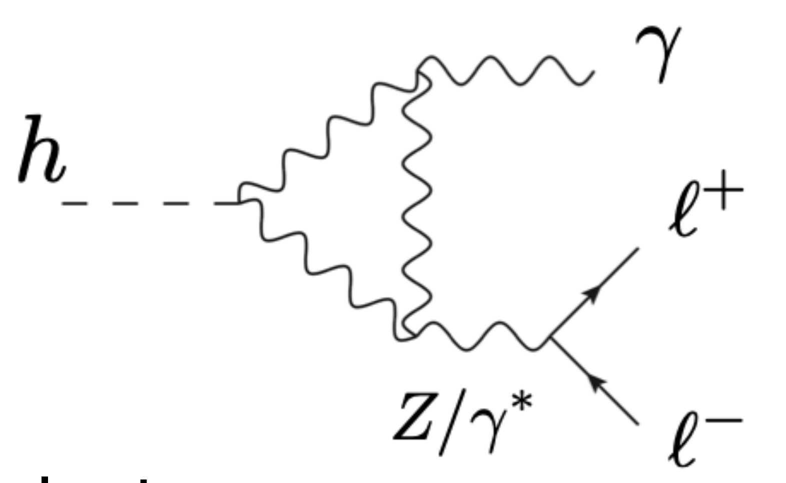
$|\kappa_c| < 8.5\ (12.4)$

3σ evidence in CMS! Expect observation in Run3

A long way before the observation… maybe at HL-LHC!

*(Decays to 1st generation fermions (ee) also searched for but no evidence found and UL set at 7*10⁴ the SM prediction of 5*10⁻⁹)*

Rare (resonant and non resonant) decays to $l^+l^-\gamma$

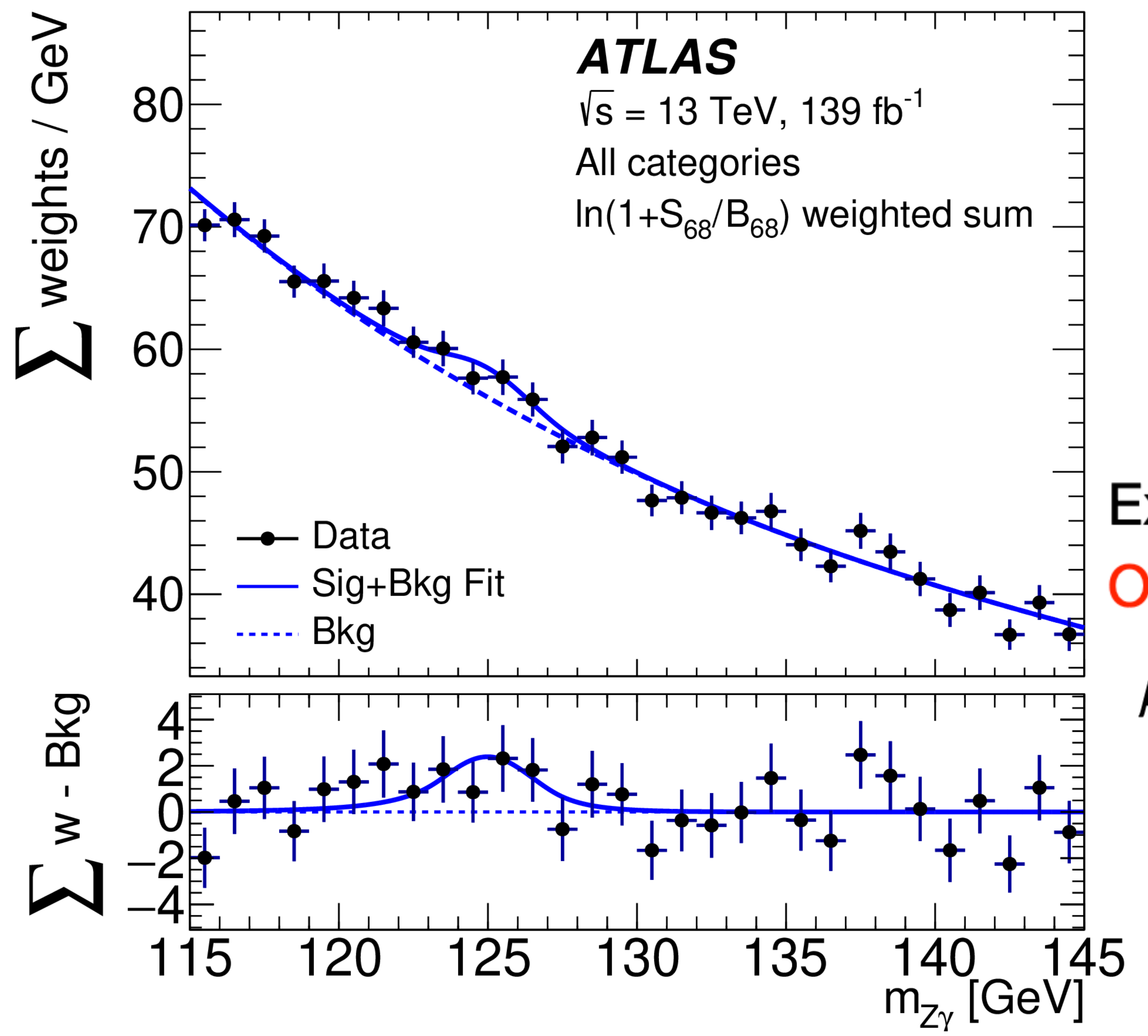


- $H \to Z\gamma \to ll\gamma$ (l=e,μ): ~4.4% of BR(γγ)
  - Tensor coupling, not measured yet: $|H^2| W^a_{\mu\nu} W^{\mu\nu a}$
  - Large Zγ background, low-momentum leptons and photons
- $H \to ll\gamma$ (l=e,μ), m_{ll}<30 GeV: ~5% of BR(γγ)
  - Dedicated reconstruction of very close-by electrons (EM showers partially overlapping in the calorimeter)

Potential BSM physics that could explain flavour anomalies could also modify these rates

H→Zγ→llγ

[Phys. Lett. B 809 (2020) 135754]



Expected 1.2σ

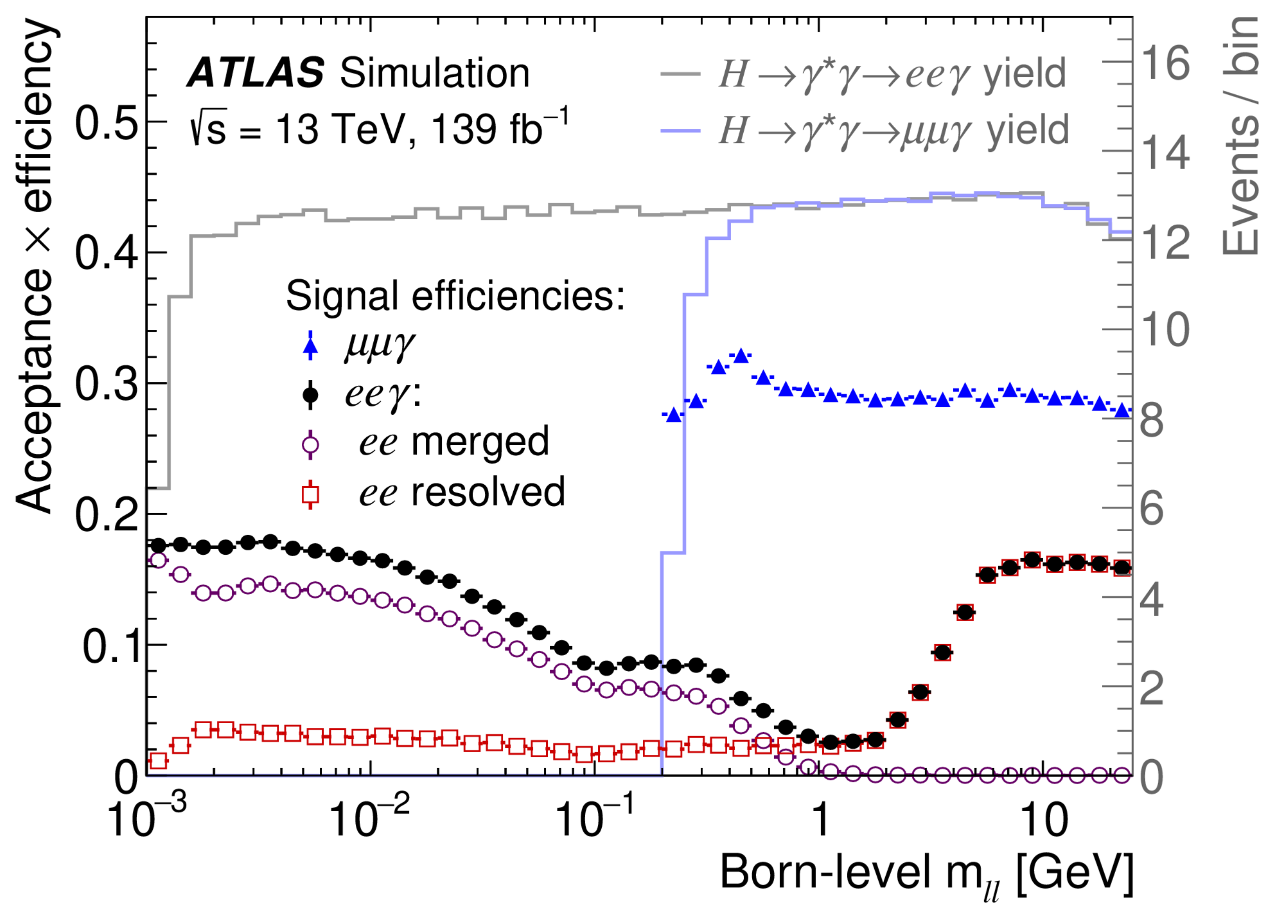
Observed 2.2σ

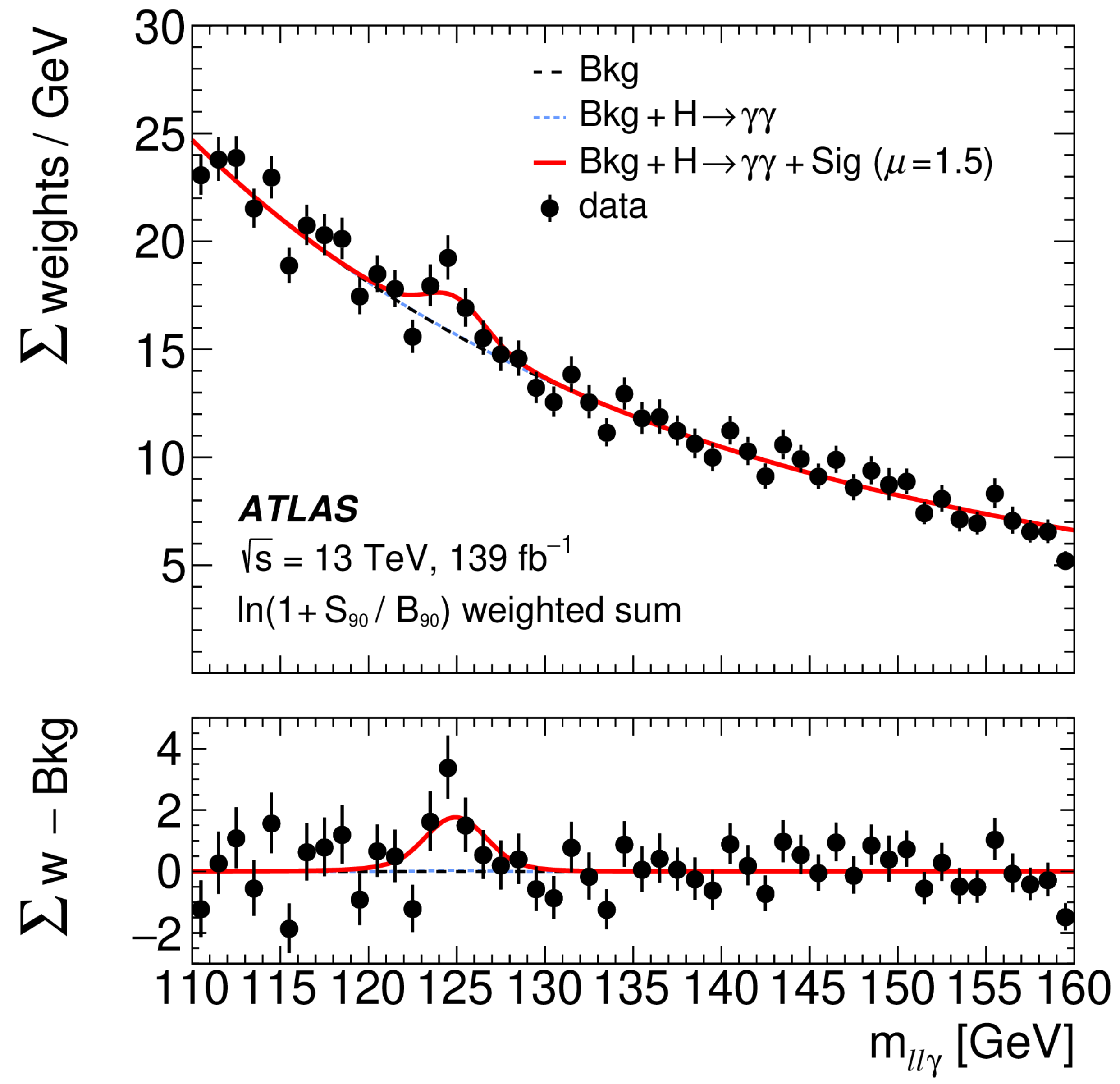
$\mu_{Z\gamma} = 2.0 \pm 0.9$

Similar excess in CMS.
Potential evidence in Run3?

*H→γ*γ→llγ*

[Phys. Lett. B 819 (2021) 136412]





Expected 2.1σ

Observed 3.2σ

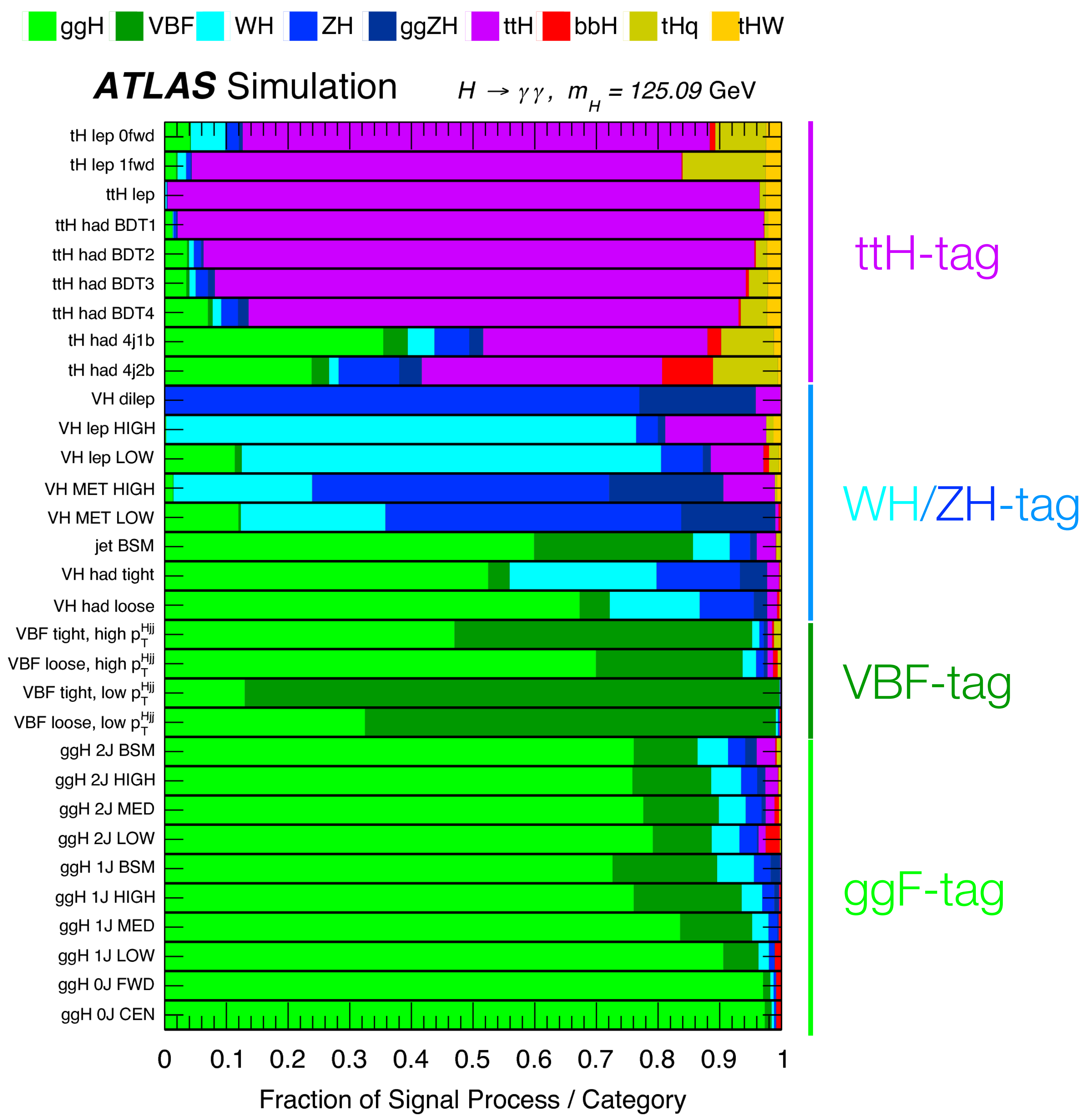
$\mu = 1.5 \pm 0.5$

First evidence! Keep watching with more data to look for SM deviations (compositeness, CP violation)

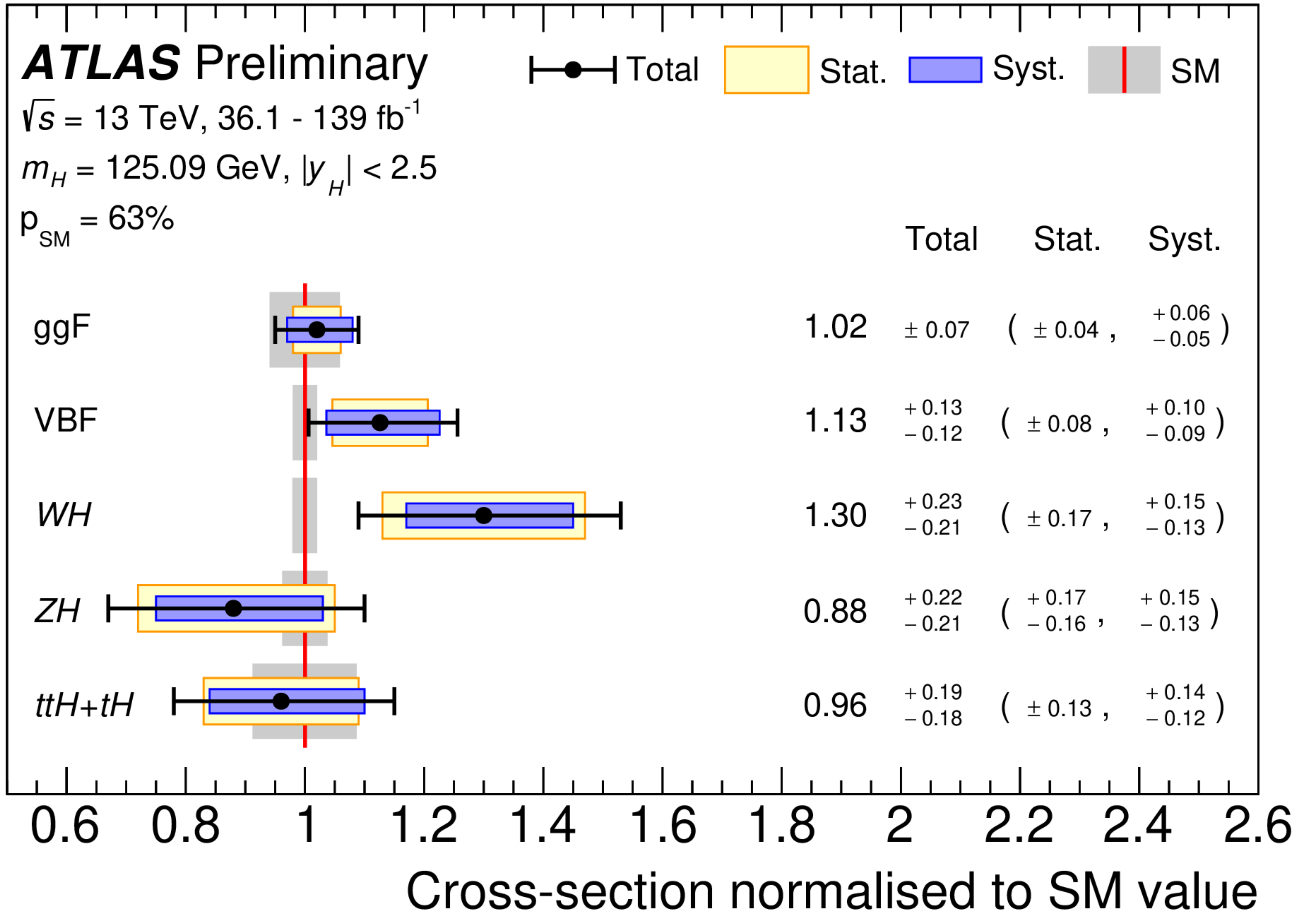
Observation of the main production modes

- Exploit different signatures of main production modes, define event categories enriched in one particular mode
- Simultaneous fit to event yields in various categories allows measurement of signal strengths for each production mode
- Assuming SM Higgs branching ratios (within TH uncertainties), different final states are combined to obtain x-section measurements

e.g. H→γγ (Phys. Rev. D 98 (2018) 052005)



ATLAS-CONF-2021-053



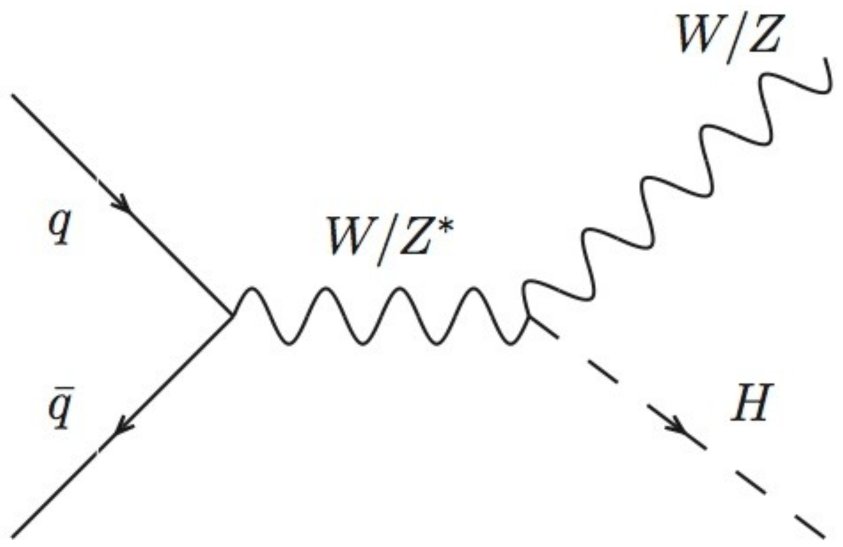
Rarer production modes not yet observed: tH, bbH (~0.5% of σ_H)

Higgs boson couplings to other particles: summary

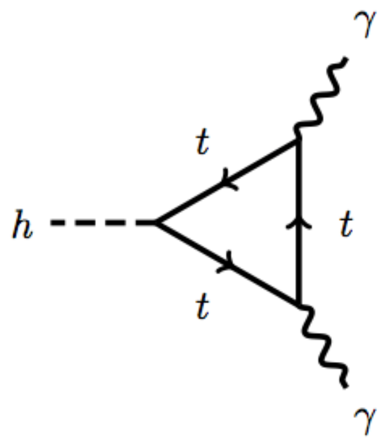
- Assuming that the signals in the different channels are due to a single, narrow, CP-even resonance, the signal strengths can be parametrised in terms of coupling scaling factors

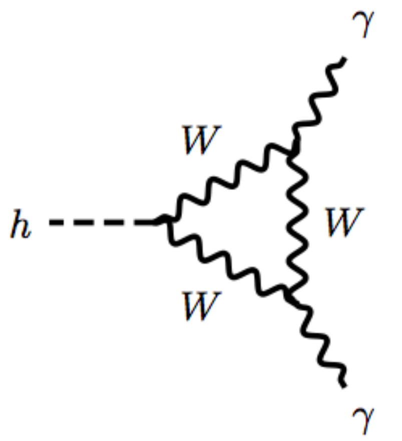
$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2}$$

- A couple of examples:



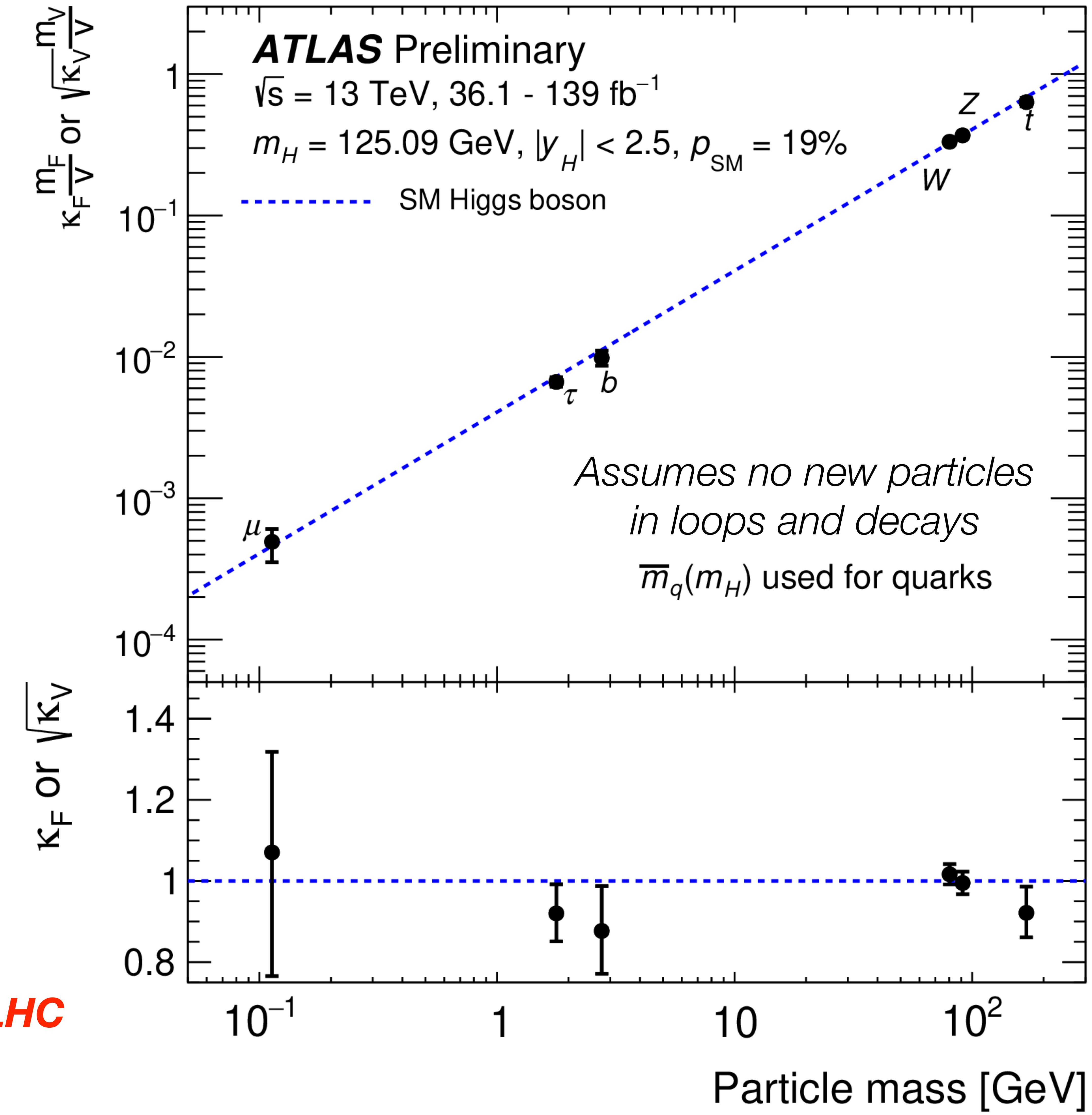
$$\sigma \propto \kappa_W^2,\ \kappa_Z^2$$





$$\Gamma_{\gamma\gamma} \propto\ 1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$$

ATLAS-CONF-2021-053



All measured couplings to fermions and bosons agree with the SM!

Current uncertainties (5-11%, 30% for μ) to be reduced by x3 at HL-LHC

Differential cross sections

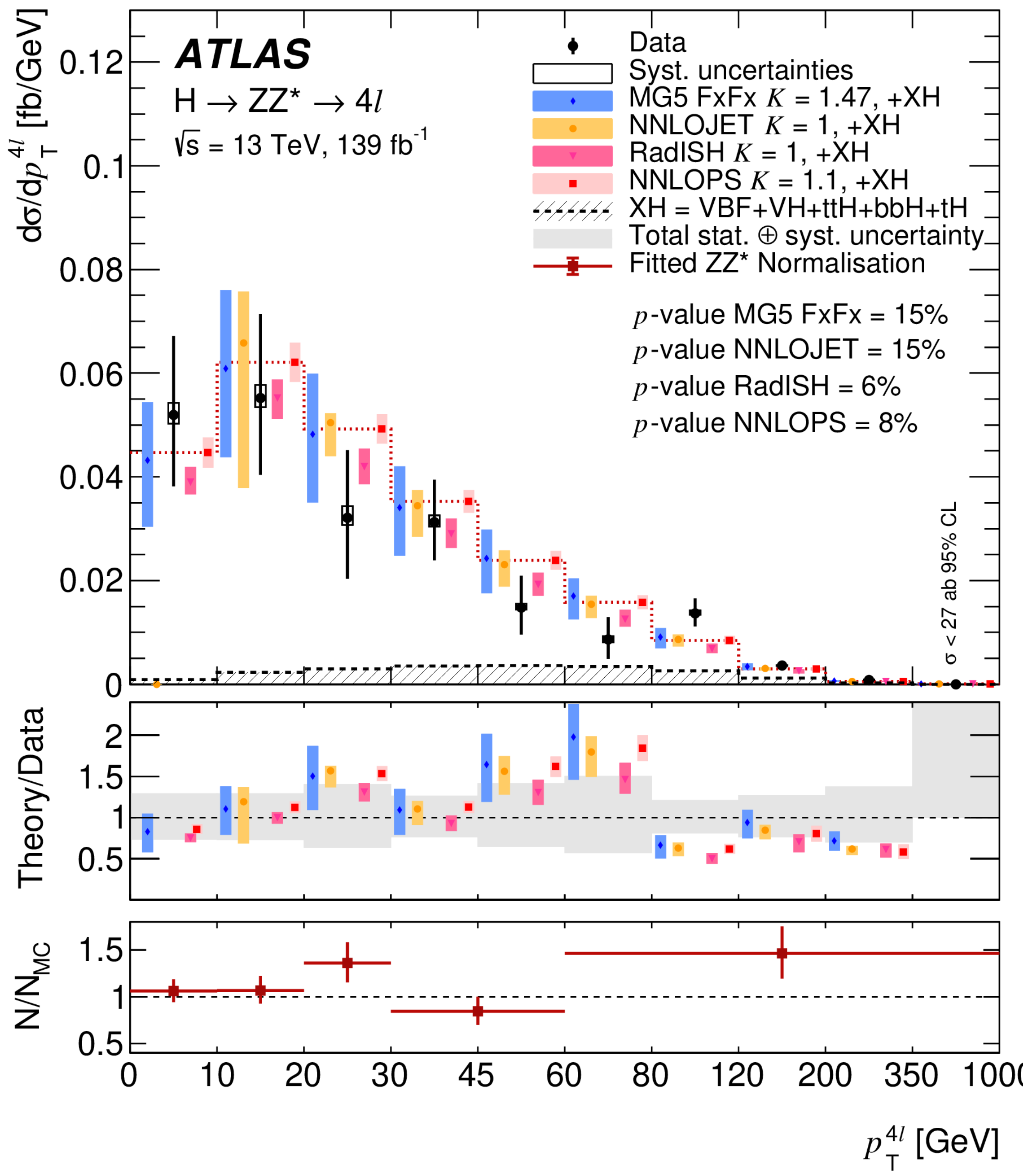
- More granular measurement as a function of several observables characterising the kinematics of Higgs boson production (Higgs p_T, N_{jets}, leading-jet p_T, invariant mass of leading and subleading jets (if present), …)

  ➡ Measured observables can be sensitive to production mode xsection ratios / spin / CP / Higgs Boson couplings ..

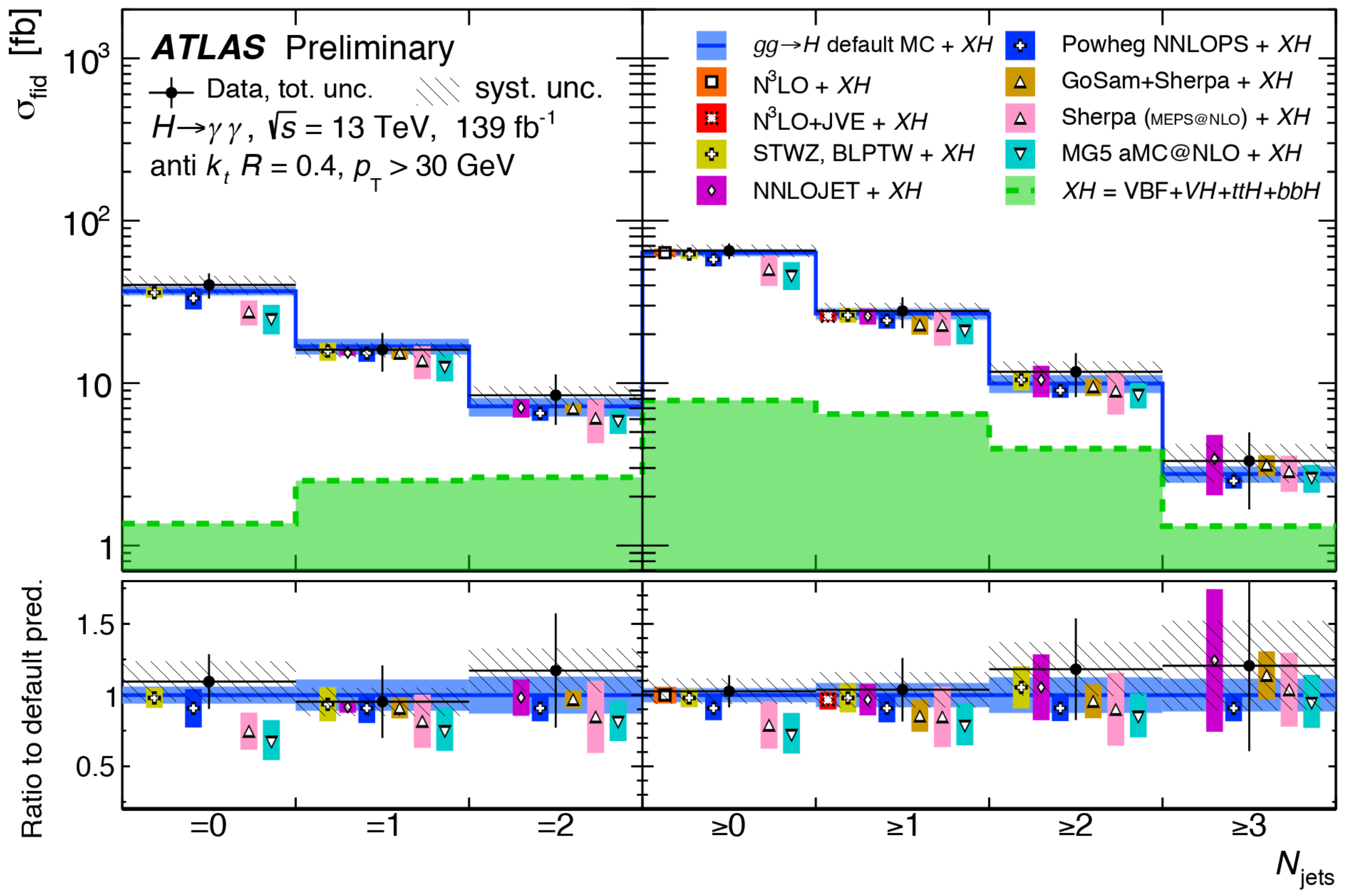
- In fiducial phase space, very close to experimental selection

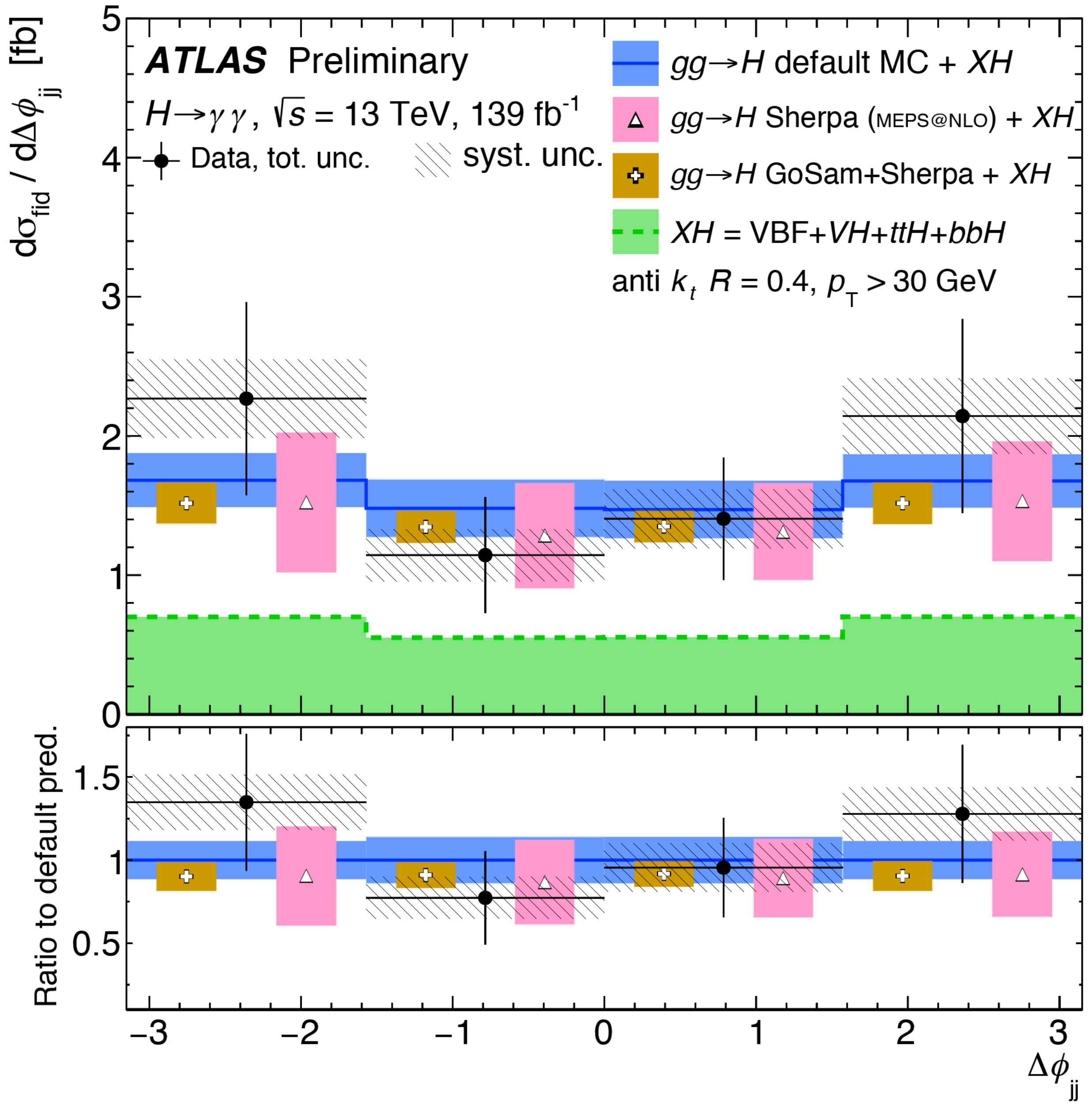
  ➡ Minimise model dependence from extrapolation from selected to full phase space; efficiency similar for all production modes

H→4l Eur. Phys. J. C 80 (2020) 942



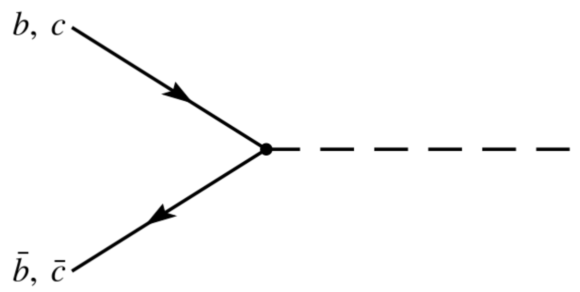
H→γγ ATLAS-CONF-2019-029

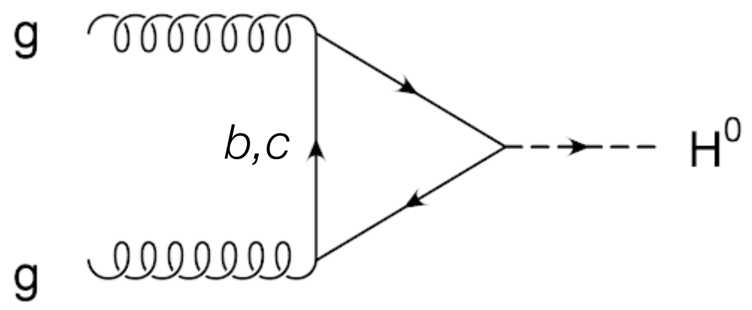




Differential cross sections

- Measurements allow constraining Higgs couplings indirectly
  - b, c couplings from $p_T(H)$





  - Anomalous (including CP-odd) couplings with gauge bosons, from various observables

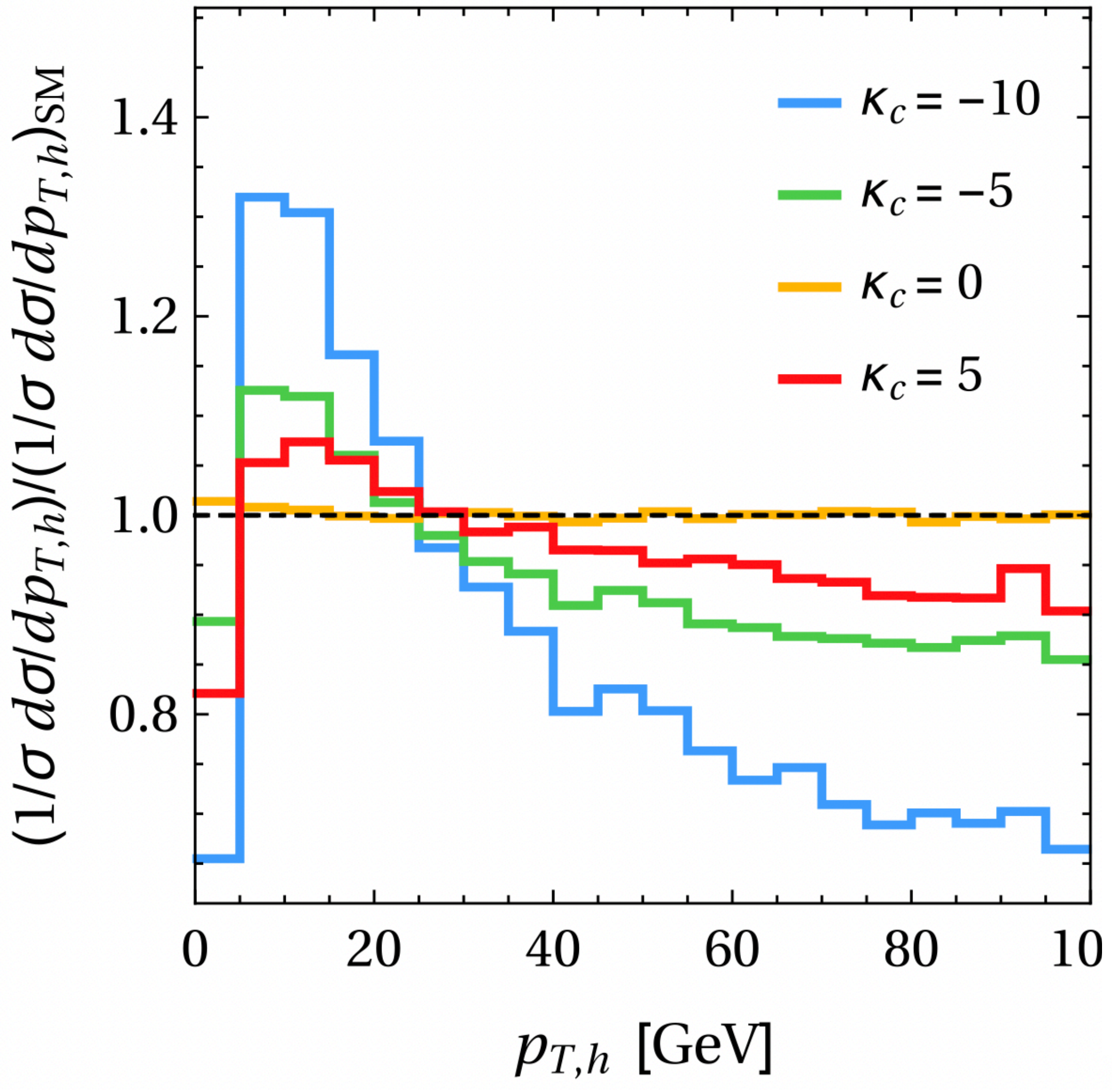
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \quad \text{for } d > 4.$$

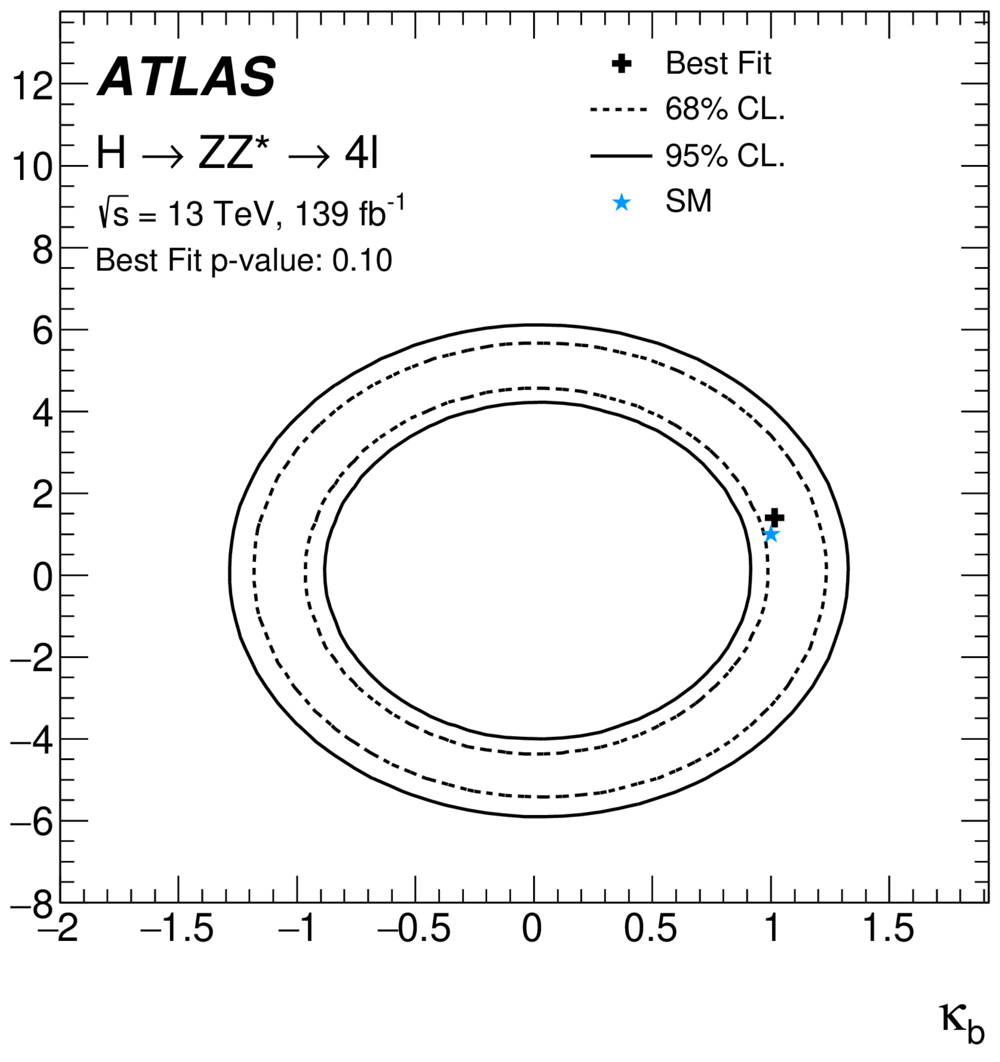
d=6, Λ=1 TeV

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\widetilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\widetilde{G}}$	$HH^\dagger \widetilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\widetilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\widetilde{B}}$	$HH^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

b, c Yukawa couplings

[Eur. Phys. J. C 80 (2020) 942]

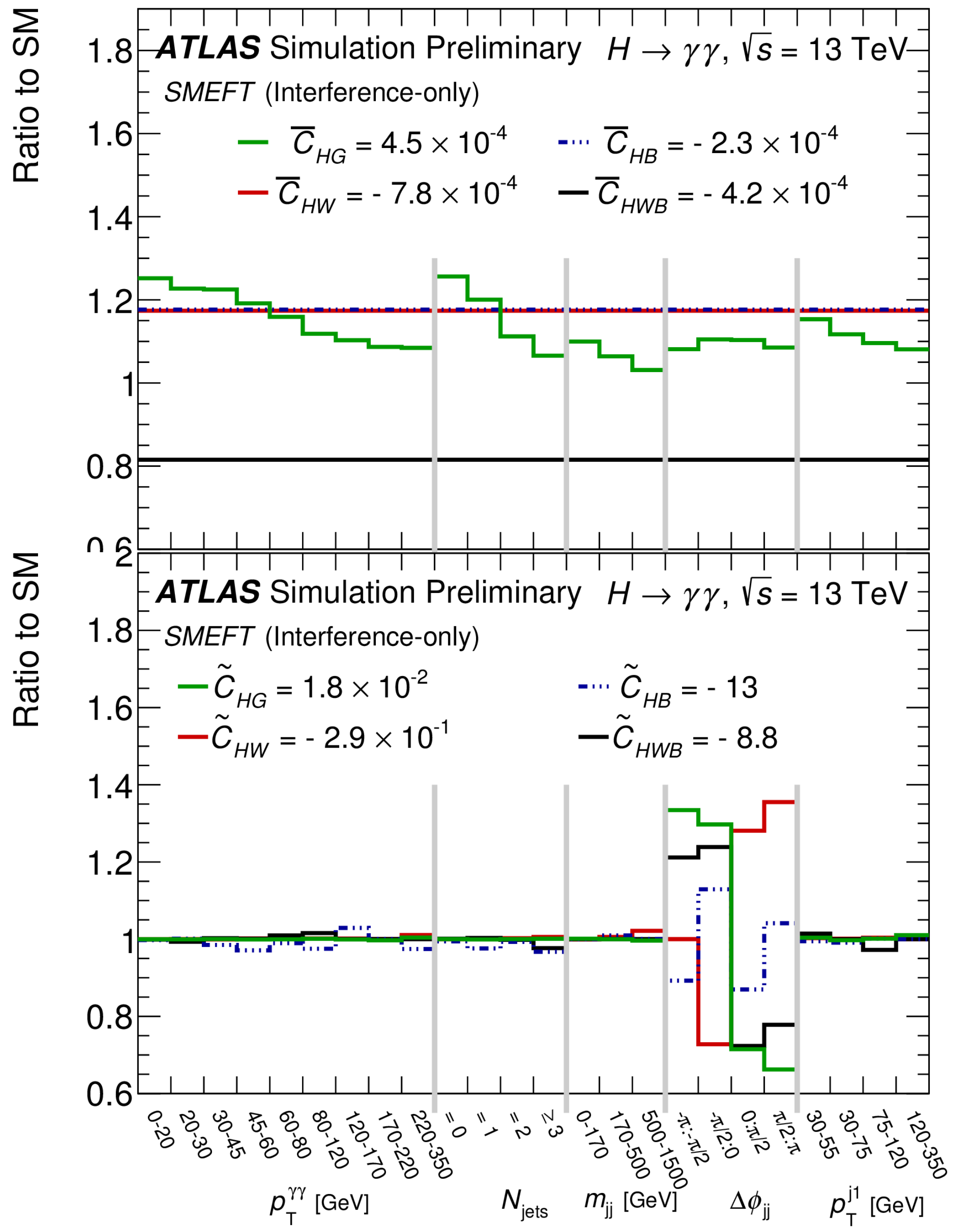


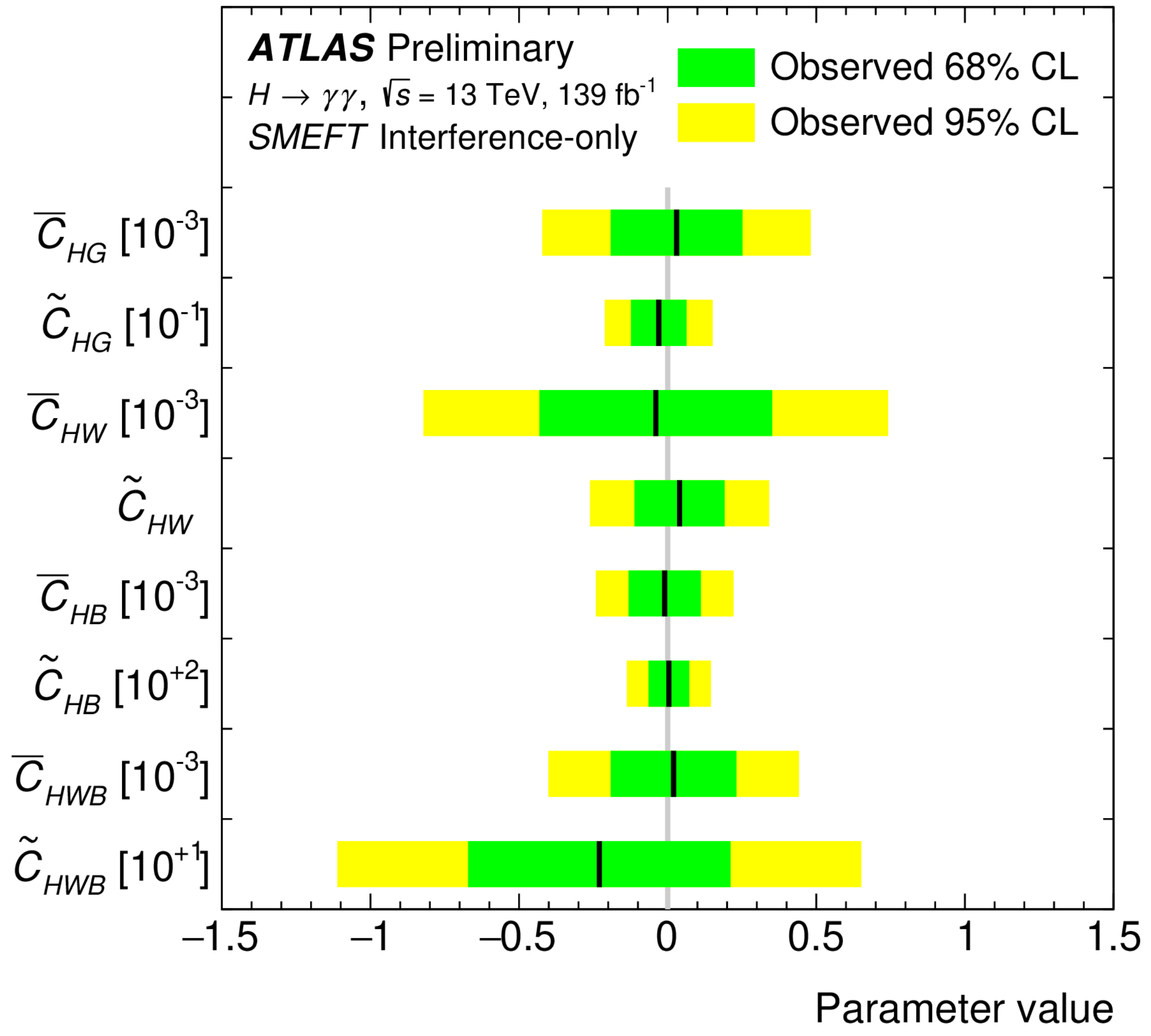


Constraints on κ_c similar to those from direct searches

anomalous couplings to gauge bosons

[ATLAS-CONF-2019-029]

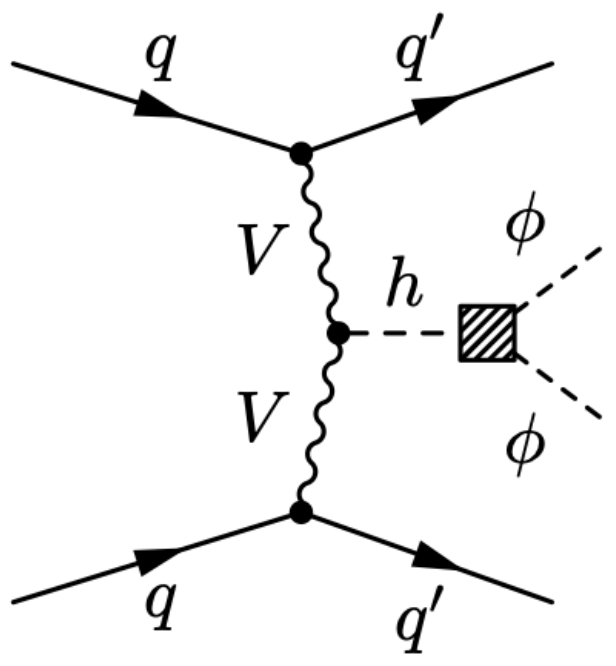




No evidence of CP-odd interactions

Higgs boson as a portal to dark matter?

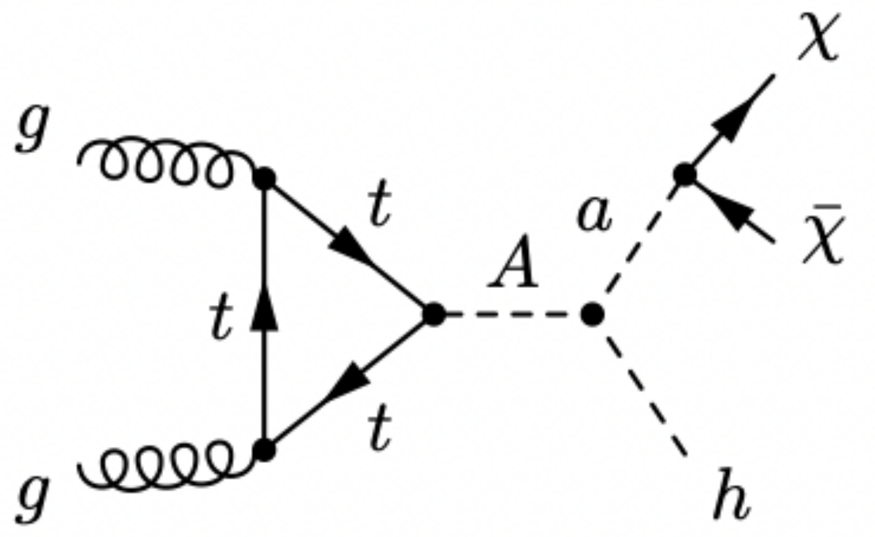
- IF dark matter is composed of neutral, weakly-interacting, massive particle (WIMP), and the dark sector is coupled to the Higgs, Higgs physics at collider experiments could shed light on it (for a review see e.g. https://arxiv.org/abs/2109.13597)



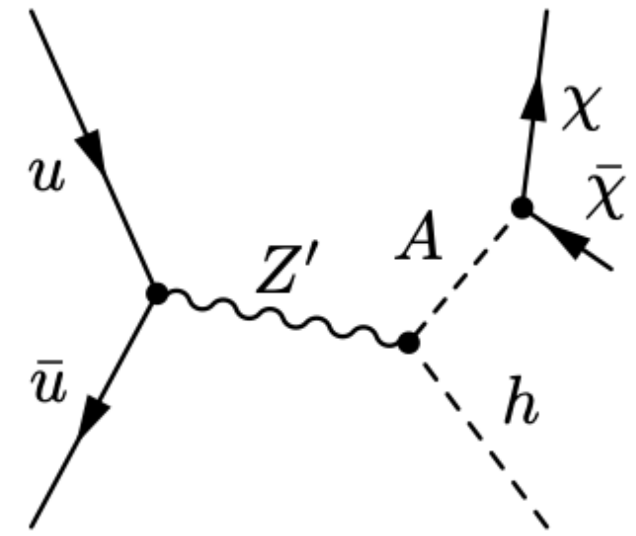
(a) Higgs portal ($m_{DM}<m_H/2$)

invisible Higgs decays

⇒ BR(H→invisible)



(b) Portals with extended Higgs sectors (e.g.: 2HDM+a)



(c) Portals with extended Higgs and gauge sectors (e.g.: 2HDM+Z')

"mono-Higgs": Higgs recoils against invisible particles (large missing momentum)

(+ searches for heavier Higgs bosons and Z' resonances)

mono-H(bb)

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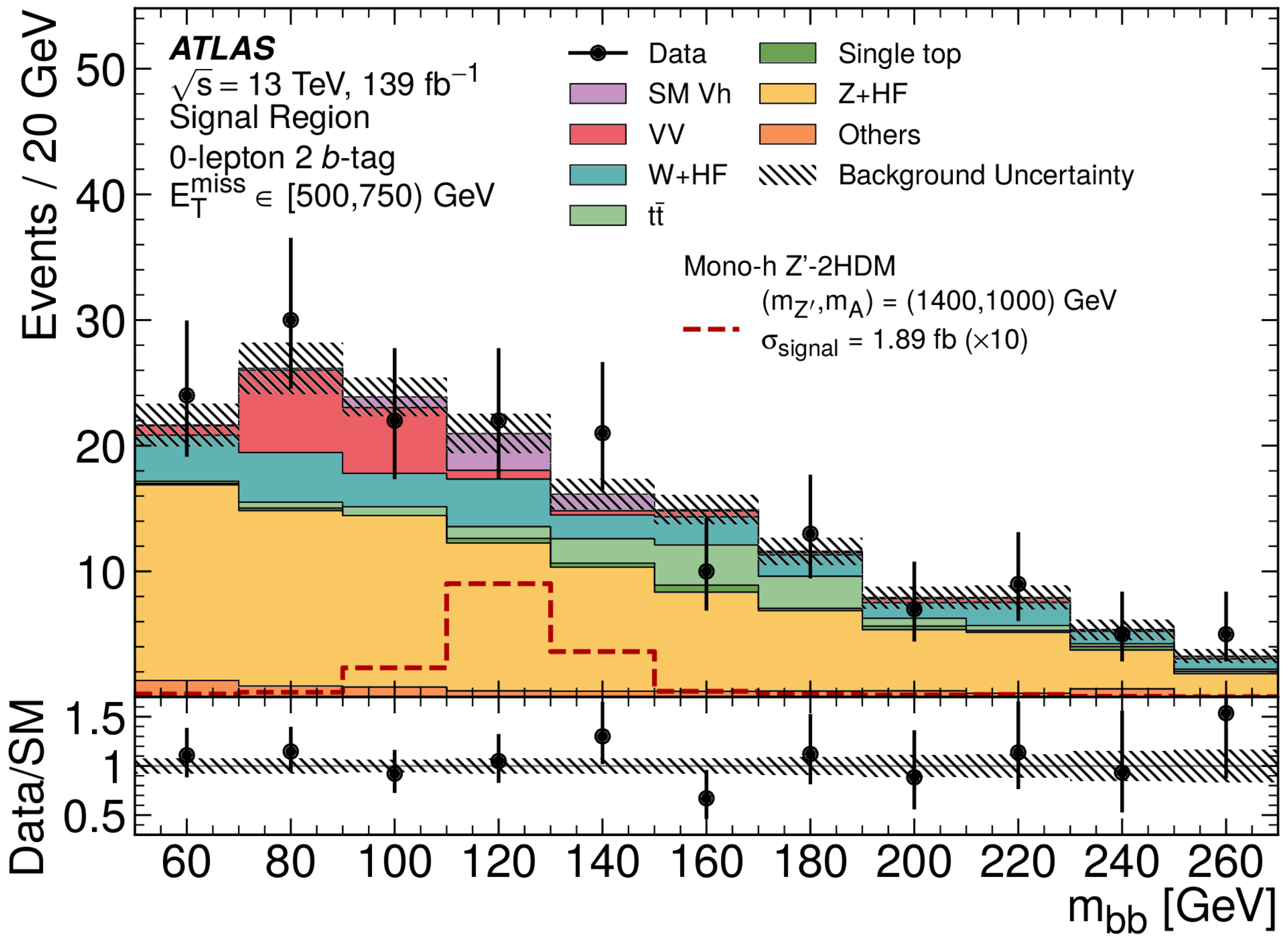
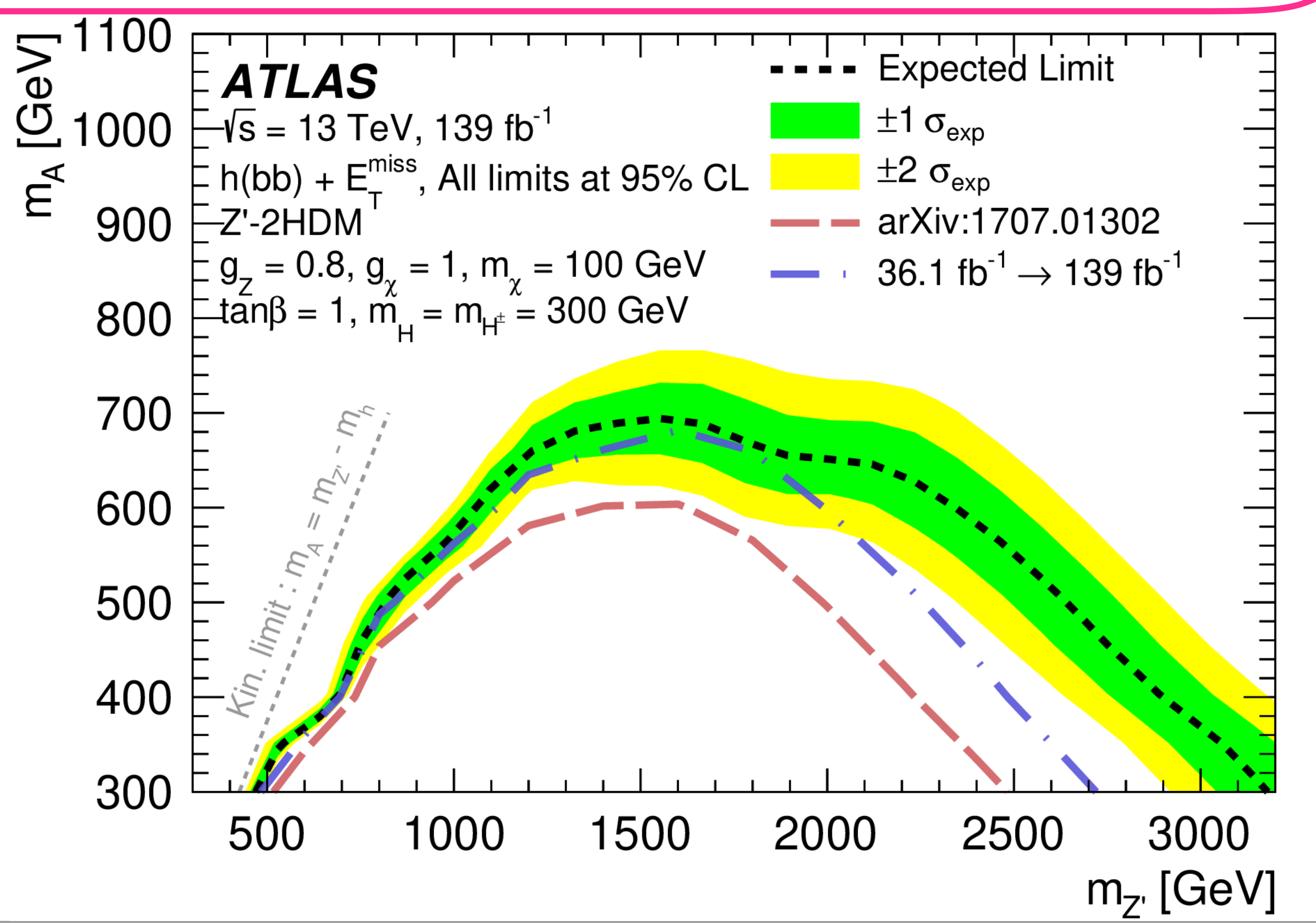
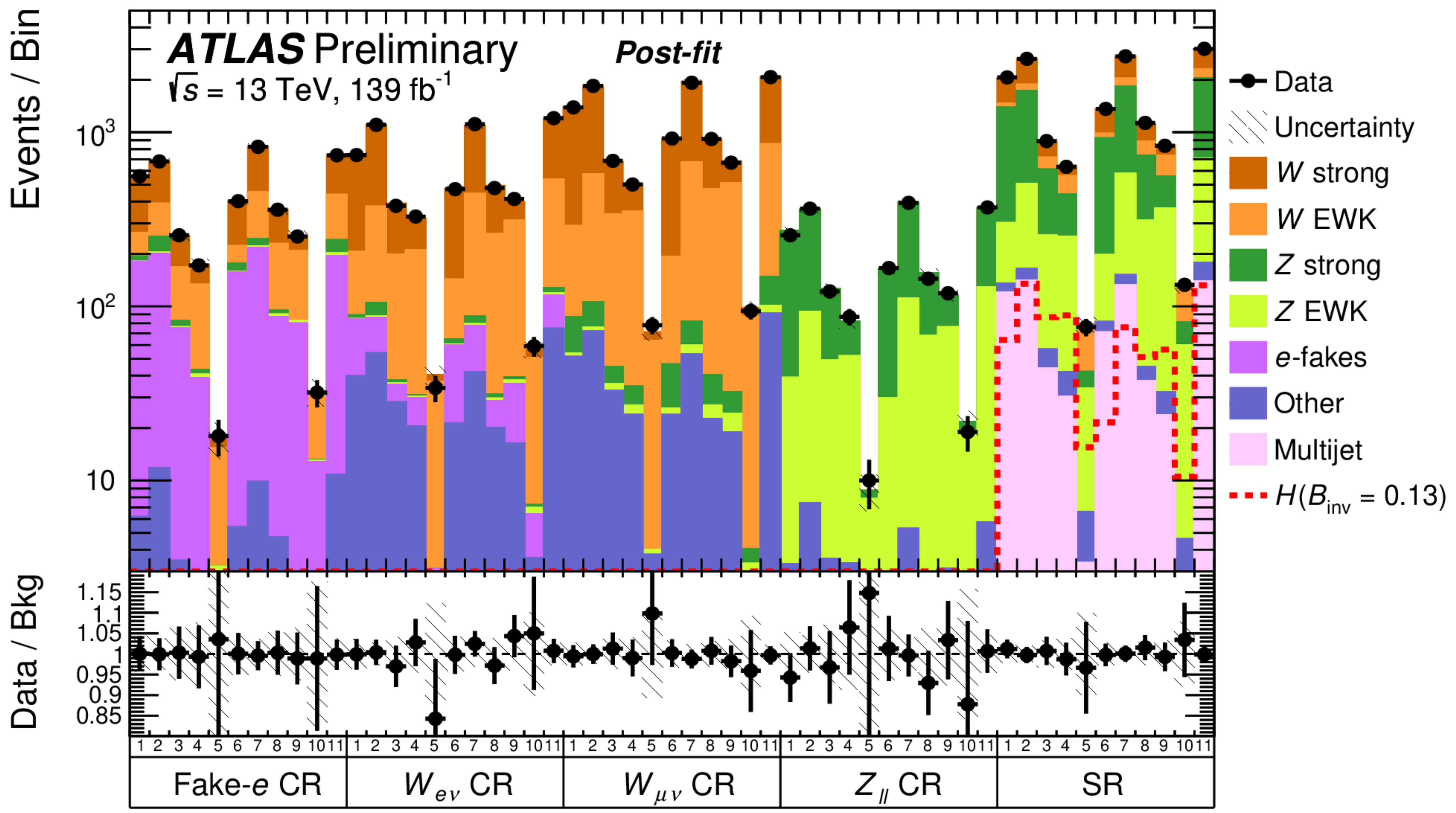




Higgs boson invisible decays

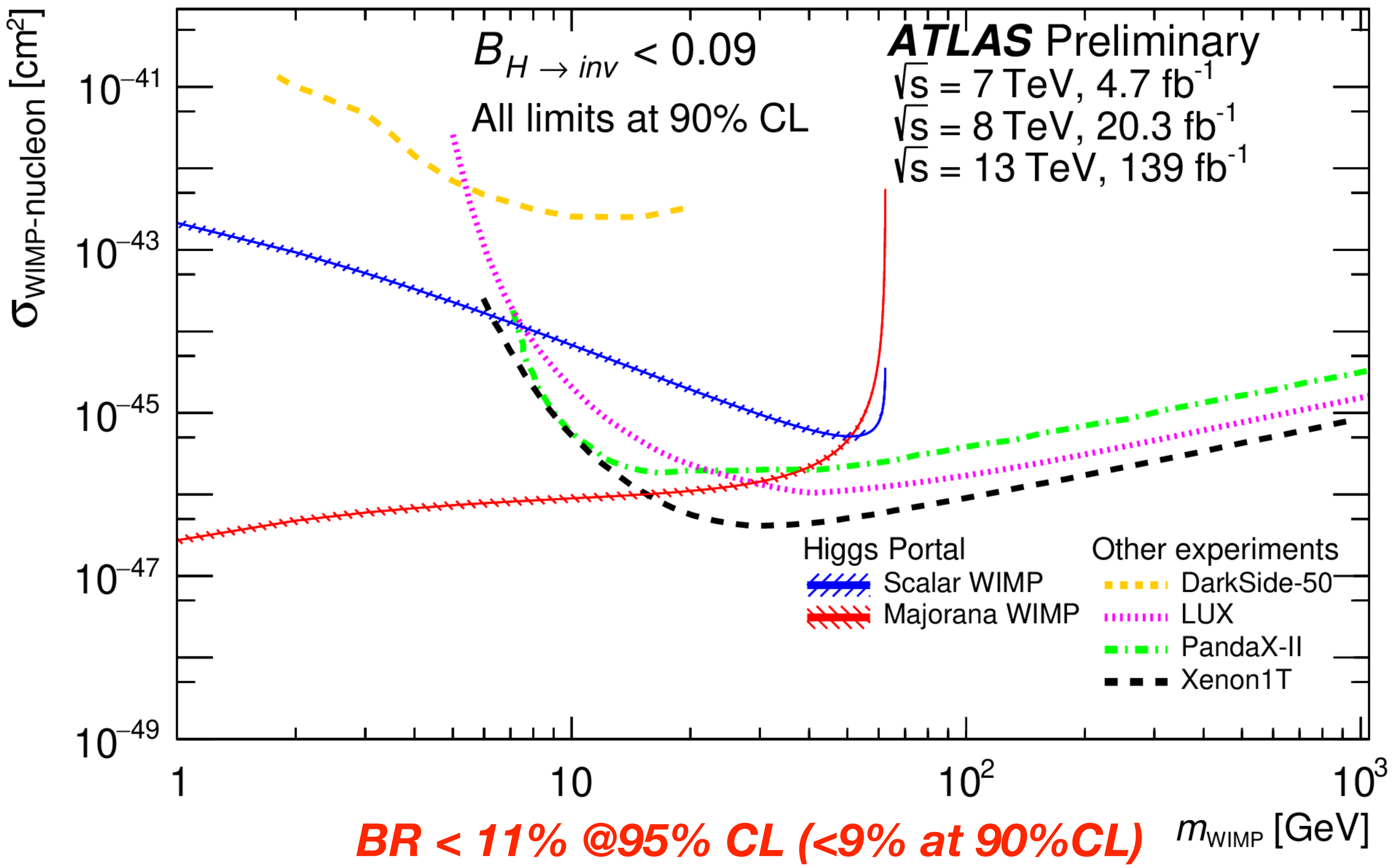
- BR(H→invisible) = 0.1% in SM ($H \to ZZ^{(*)} \to 4\nu$), too small for detection (poor missing momentum resolution, backgrounds from Z→νν)
- If Higgs decays to dark matter particles, BR(H→invisible) could be enhanced to a detectable level
- Most sensitive signature: VBF-tagged jets + large missing momentum
- Further combination with other searches (such as V(lep)H, V(had)H, ..)

VBF H→invisible (Run2) ATLAS-CONF-2020-008



BR(H→invisible)<13% @95%CL

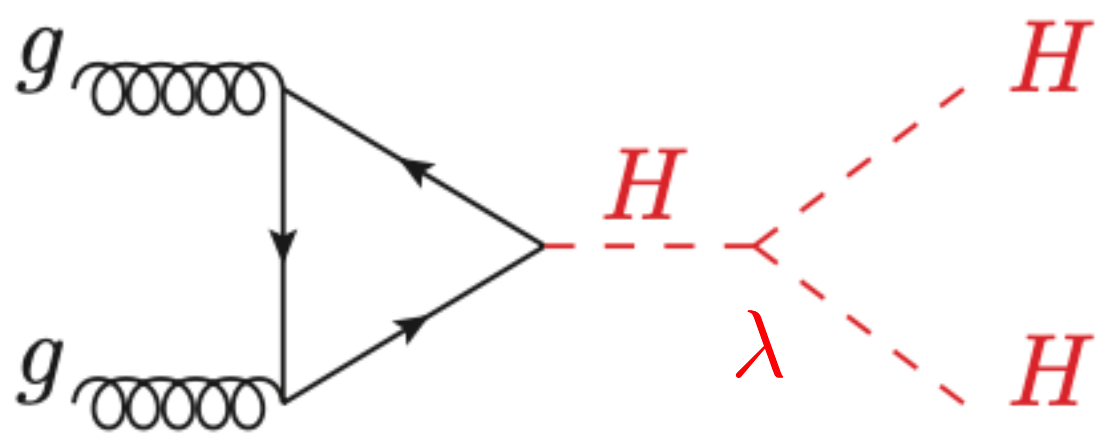
Combination ATLAS-CONF-2020-052



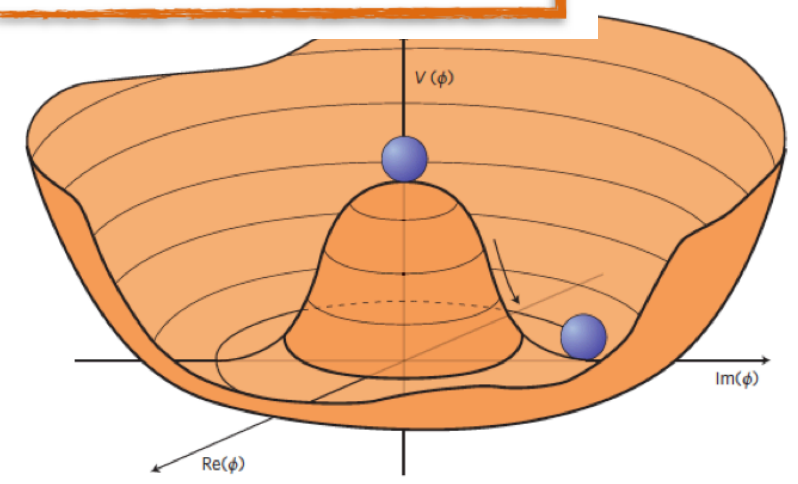
BR < 11% @95% CL (<9% at 90%CL)
Constraints on spin-independent WIMP-nucleon x-section complementary to direct searches

Higgs boson self-coupling

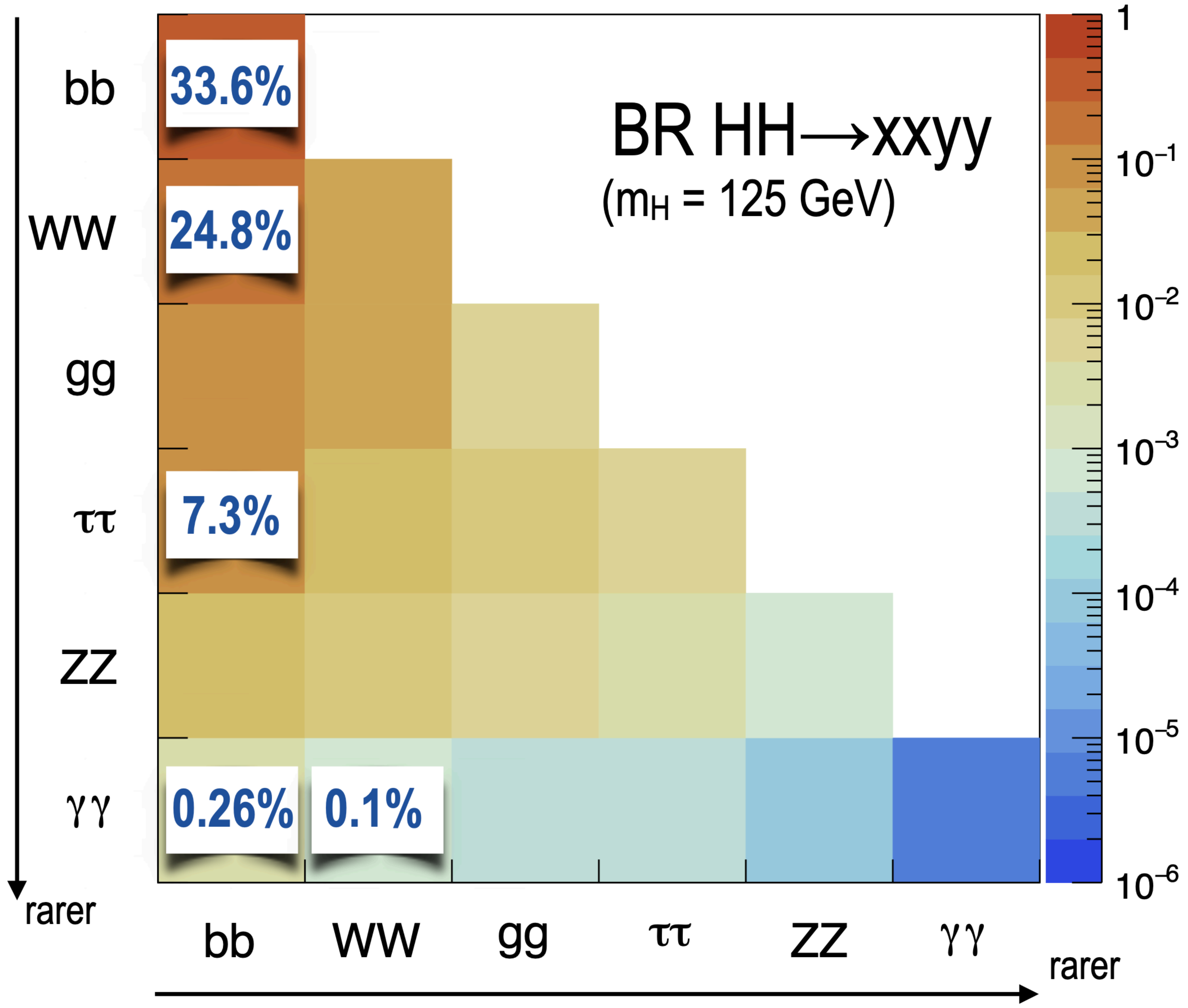
- Double-Higgs production = direct probe of Higgs self-coupling λ ⇒ **crucial for determining shape of Higgs field potential**



$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



- **Tiny cross section** ~1/1000 of Higgs production (33 fb at 13 TeV) ⇒ **extremely challenging!**
- **Multiple topologies investigated**. Analysis of full Run2 for most sensitive channels: bbγγ, bbττ. Analysis of other channels being finalised, combinations starting. No significant signal seen yet ⇒ upper limits!

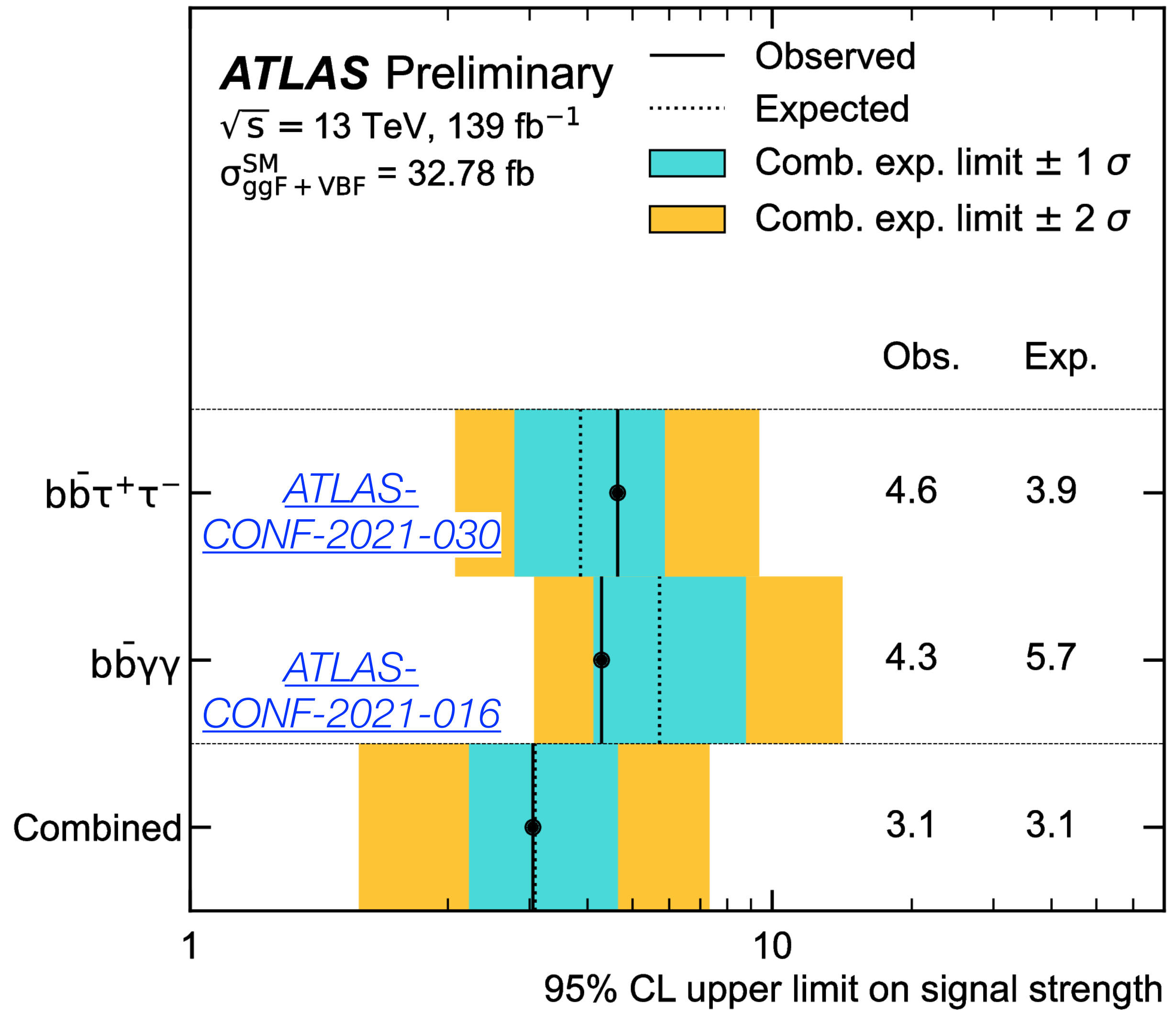


	WWγγ	bbγγ	bbττ	bbWW	bbbb
BR	0.1 %	0.26 %	7.4 %	25 %	33 %
95%CL upper limit on μ	<747 (386)	< 4.3 (5.7)	< 4.6 (3.9)	-	< 13 (21)

bbγγ, bbττ and combination

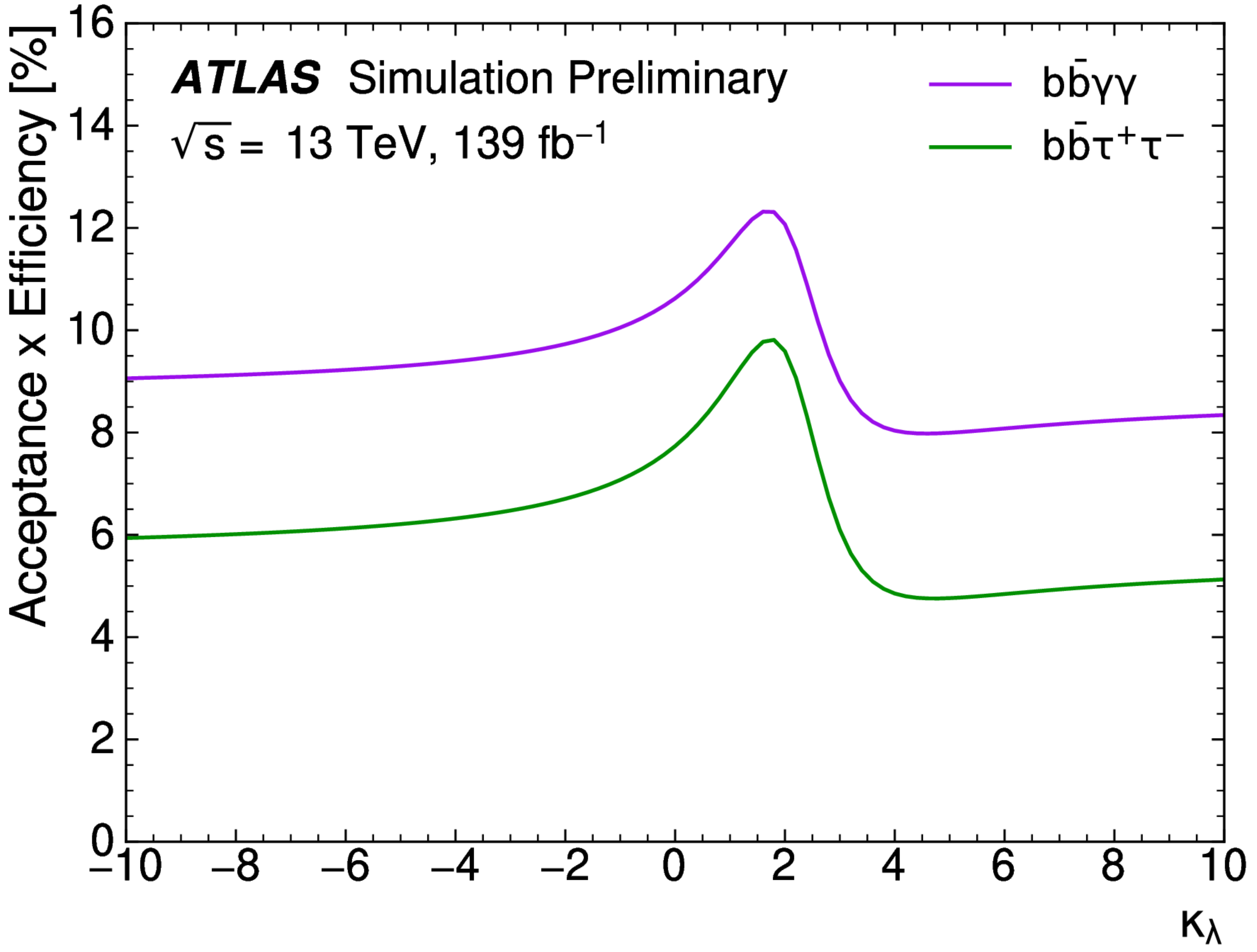
ATLAS-CONF-2021-052

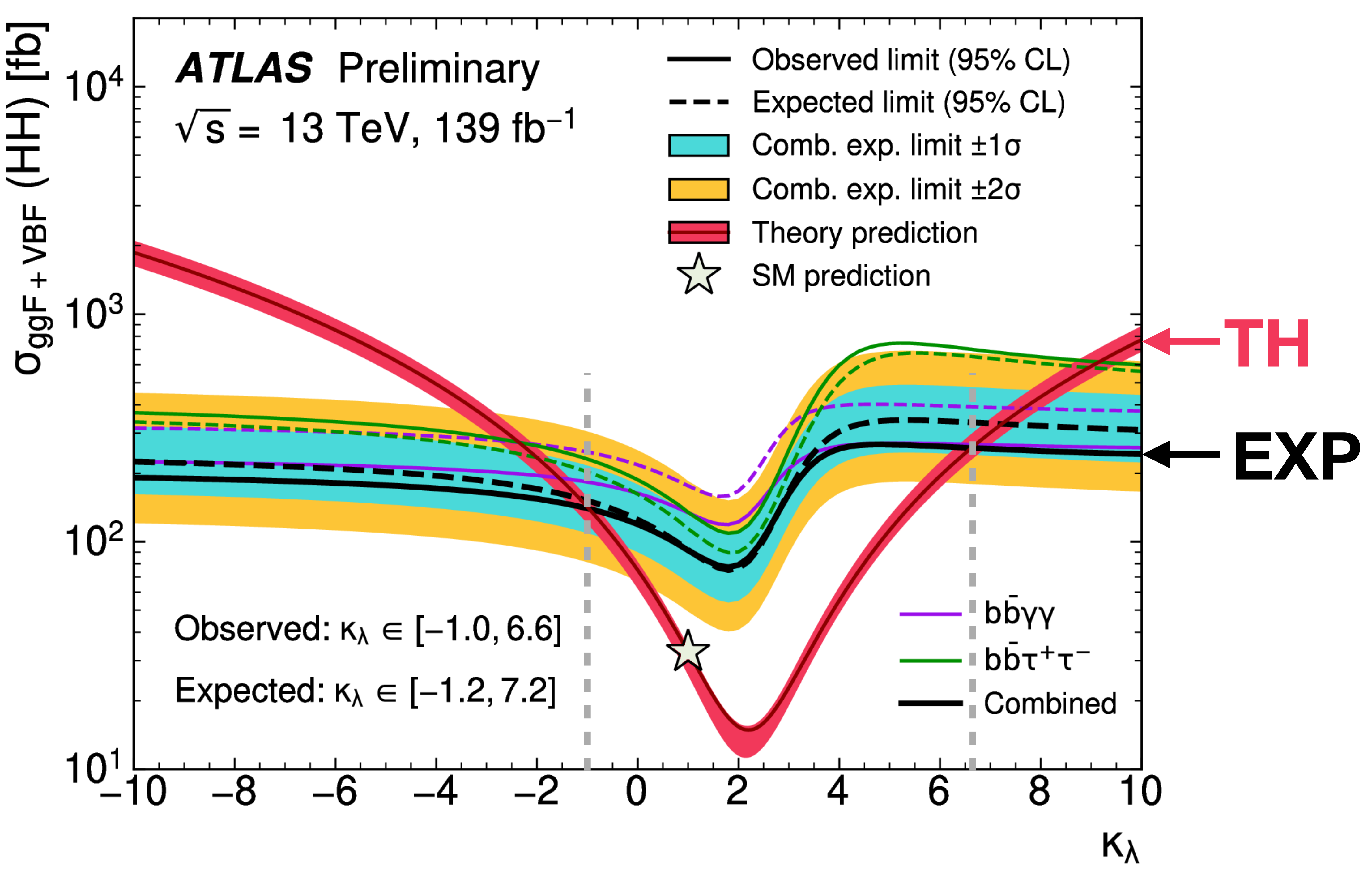
μ < 3.9



Higgs boson self-coupling

- Correcting the upper limit on the signal yields for the λ dependence of the acceptance*efficiency, limits on σ vs λ are determined
- The crossings with the theoretical prediction (assuming other couplings are SM-like) gives confidence intervals for λ





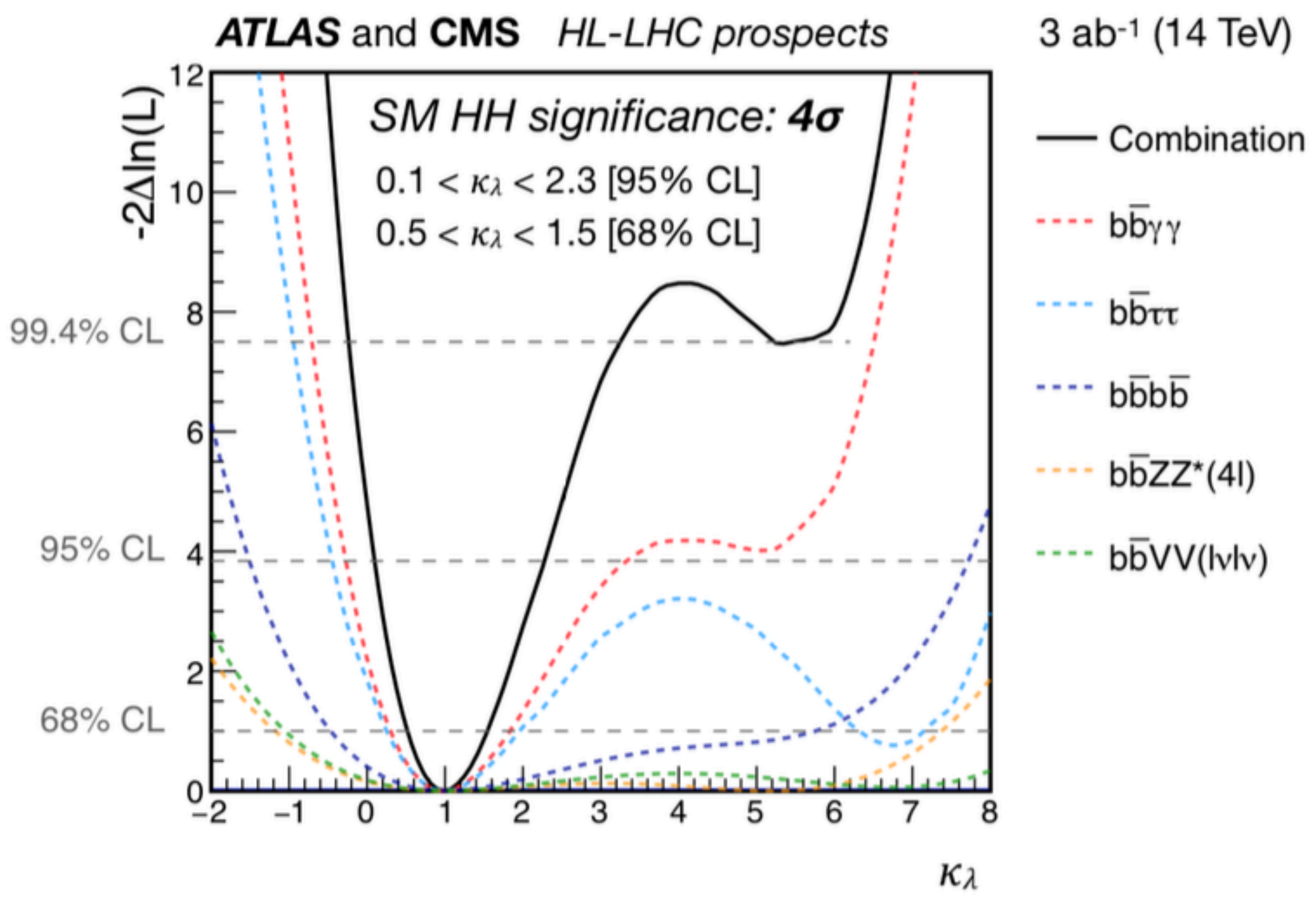
Observed: $\kappa_\lambda \in [-1.0, 6.6]$

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

With the other channels + full Run3 ATLAS+CMS could reach 2σ sensitivity on diHiggs production!

Higgs boson self-coupling

- HL-LHC projection (~2038, ~20x more data than Run2): $0.5 < \kappa_\lambda < 1.5$
  - could constrain models which predict strong first-order electroweak phase transitions
  - complementary to information provided by gravitational waves detected by space-based interferometers

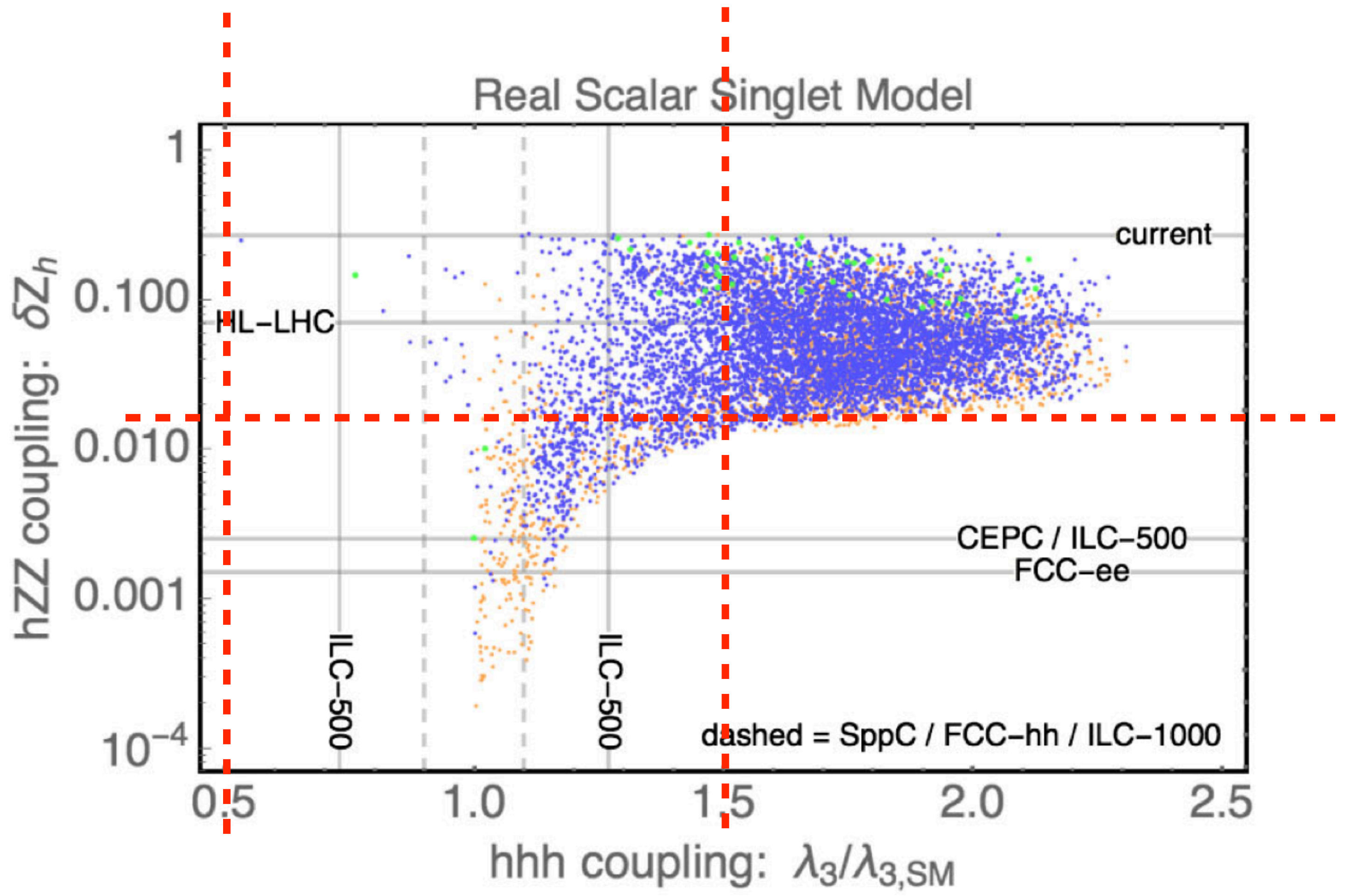


Phys. Rev. D 94 (2016) 7, 075008

PHYSICAL REVIEW D **94,** 075008 (2016)

Probing the electroweak phase transition with Higgs factories and gravitational waves

Peisi Huang,[1,2,*] Andrew J. Long,[1,†] and Lian-Tao Wang[1,3,‡]



1. Parameter space scan for the singlet model of II A. An orange point indicates a first-order phase transition, a blue point indicates a strongly first-order phase transition (3.4), and a green point indicates a very strong first-order phase transition with potentially detectable gravitational wave signal at eLISA. The right panels shows the predicted gravitational wave spectrum today along with the projected sensitivity of eLISA [2].

Conclusion

- (Almost) 10 year after its landmark discovery, the Higgs boson is now a grown-up kid
- Its characteristics resemble remarkably the SM predictions
  - Though accuracy of some measurement is still O(10%) or worse
- Our team has been deeply involved in several key measurements (discovery, mass and cross-section measurements with $H\to\gamma\gamma$; observation of $H\to bb$; searches for rare Higgs decays, HH production, and Higgs production with dark matter)
- The Higgs physics programme of ATLAS and the (HL)-LHC is only in its infancy
  - Expect 3x the current data in Run3 (2022-2025) and 20x by the end of the HL-LHC
  - Potential for further breakthrough discoveries possibly linked to open issues in HEP: CP violation in Higgs interactions, coupling to the dark sector, Higgs field potential, extended Higgs sector ….

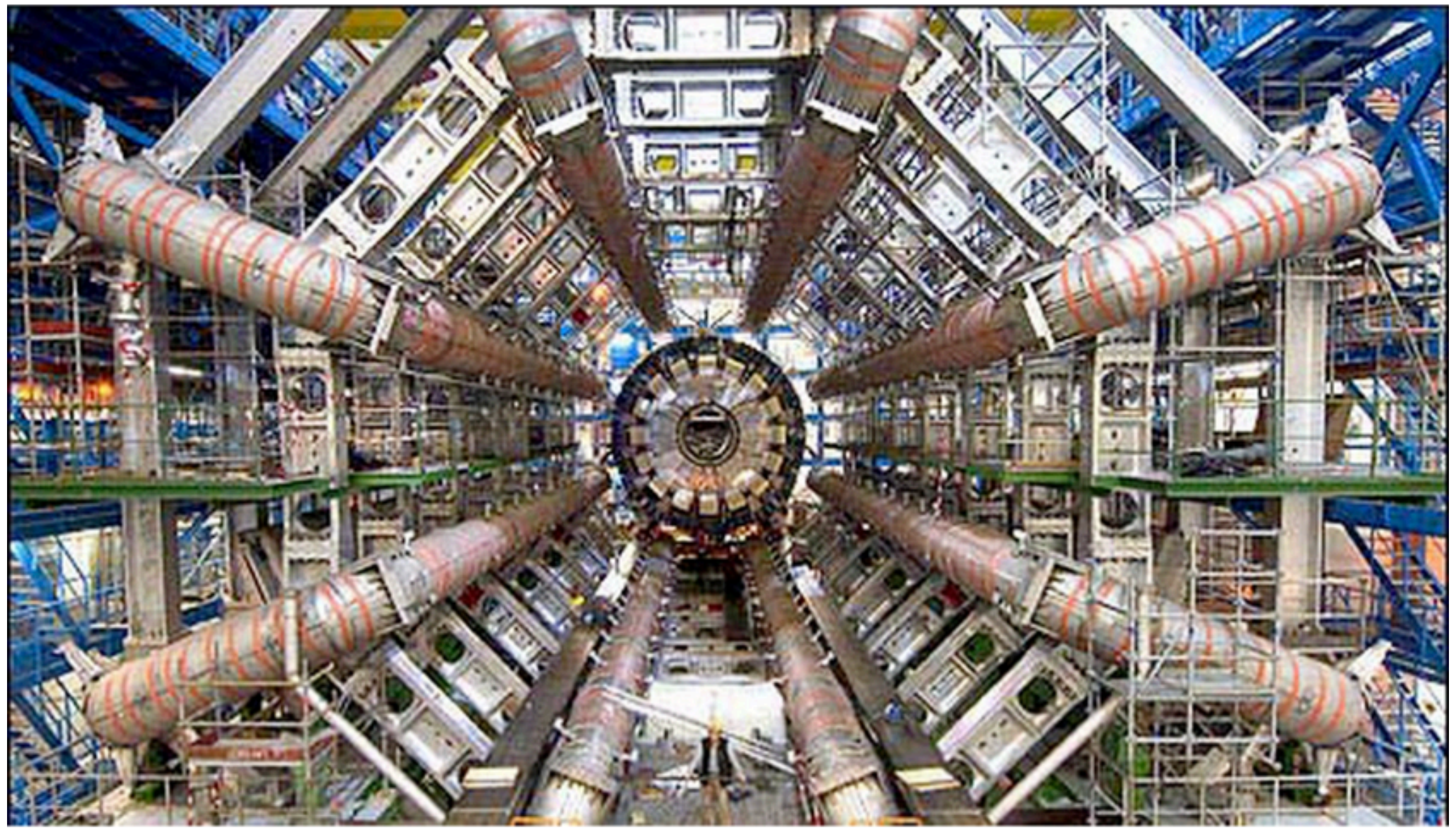
Thanks for listening and
many thanks to the organisers!

APC colloquium

Friday January 21
11am (on zoom)

Université de Paris

(Almost) 10 years of Higgs boson: from the discovery to the precision



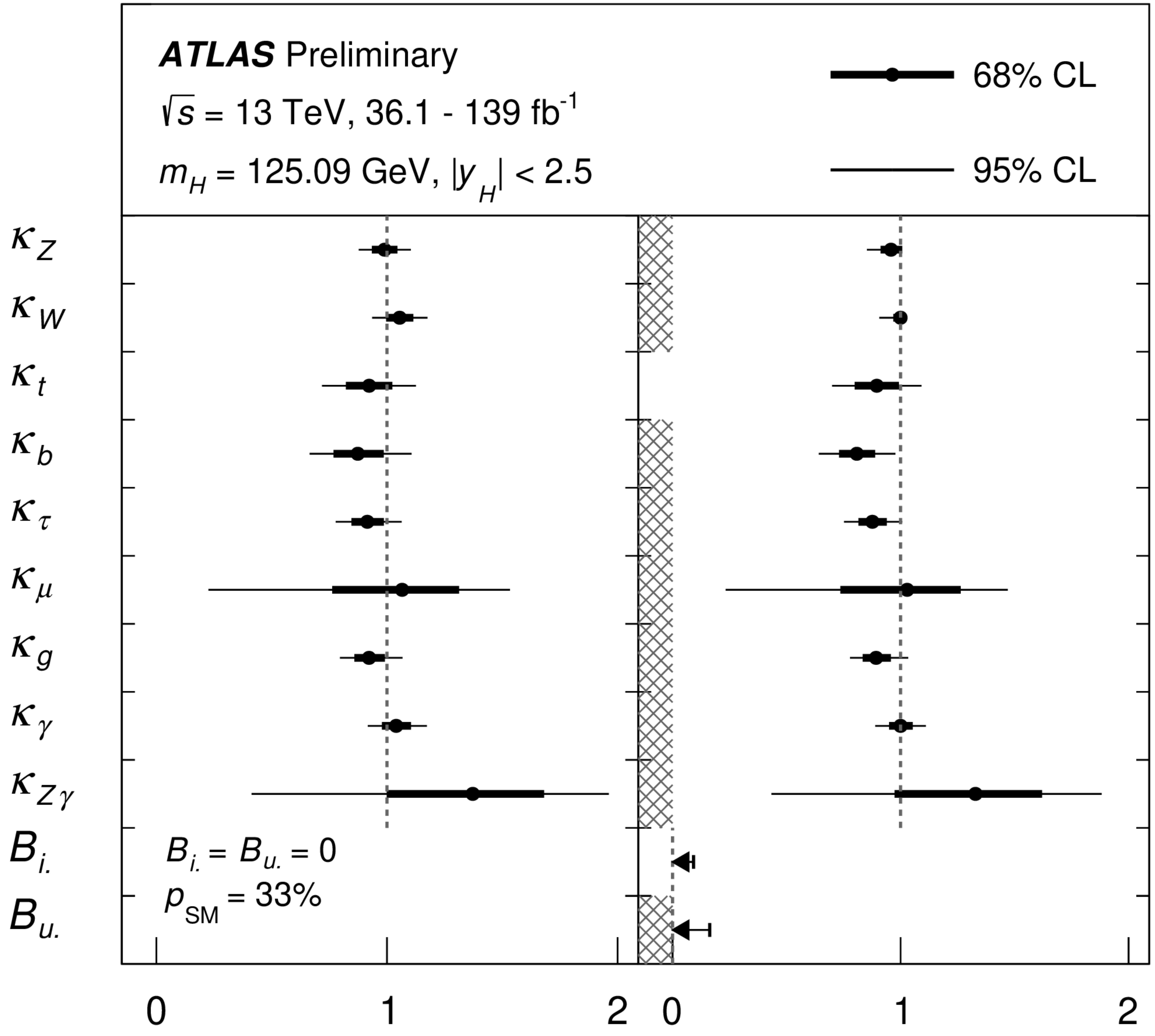
Giovanni Marchiori (APC)

The Higgs field and the associated scalar boson are the cornerstone of the Standard Model (SM) of particle physics. The Higgs field might also be the portal between the SM and the dark matter sector, and have cosmological implications.
After the first tantalising hints of its existence in December 2011, the discovery of the Higgs boson was officially announced by the ATLAS and CMS Collaborations at CERN on July 4th 2012.
In my talk I will review the role played by the Higgs boson in the SM, how it is produced and observed at the LHC, its discovery and its latest property measurements with the full dataset collected so far by the ATLAS experiment.

Extra material

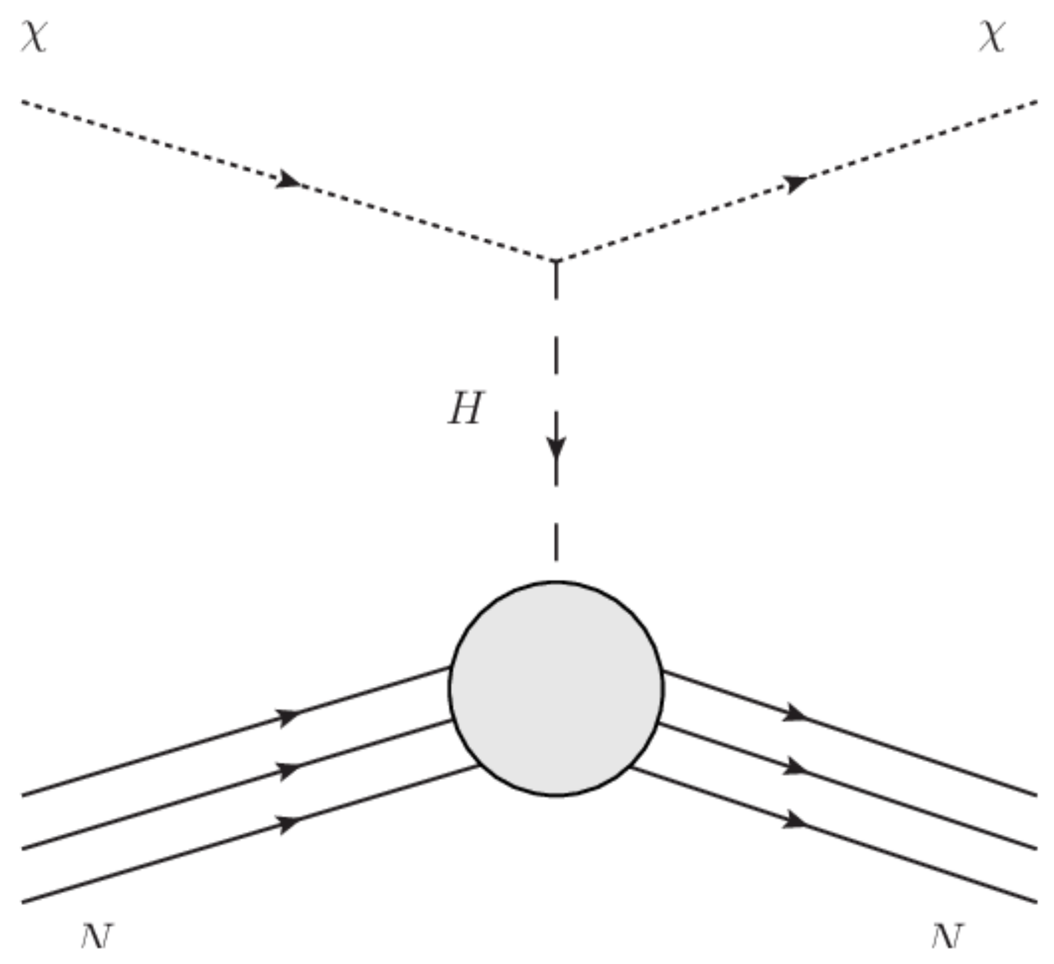
Higgs couplings fit in the presence of extra particles in loops or invisible decays

- Left: invisible/undetected BR fixed to zero
- Right: invisible/undetected BR floating
  - Use BR(inv) experimental upper limit
  - Assume κ_W, κ_Z<=1



Higgs invisible decays and WIMP-nucleon cross-section

Higgs portal model: the Higgs boson is assumed to be the only mediator in the WIMP–nucleon scattering



The upper limit on the invisible BR is converted to an upper limit on the partial width for the decay:

$$\Gamma_H^{\text{inv}} = \frac{\text{BF}(H \to \text{ invisible})}{1 - \text{BF}(H \to \text{ invisible})} \times \Gamma_H,$$

This in turn implies an upper limit on the Higgs-DM coupling λ:

$$\Gamma^{\text{inv}}_{H\to SS} = \frac{\lambda^2_{HSS} v^2 \beta_S}{64\pi m_H},$$

$$\Gamma^{\text{inv}}_{H\to VV} = \frac{\lambda^2_{HVV} v^2 m_H^3 \beta_V}{256\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4}\right),$$

$$\Gamma^{\text{inv}}_{H\to ff} = \frac{\lambda^2_{Hff} v^2 m_H \beta_f^3}{32\pi\Lambda^2},$$

$$\beta_\chi = \sqrt{1 - 4m_\chi^2/m_H^2}\ (\chi = S,\ V,\ f),$$

which can then be converted into a limit on the WIMP-proton cross-section:

$$\sigma^{\text{SI}}_{SN} = \frac{\lambda^2_{HSS}}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_S + m_N)^2},$$

$$\sigma^{\text{SI}}_{VN} = \frac{\lambda^2_{HVV}}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_V + m_N)^2},$$

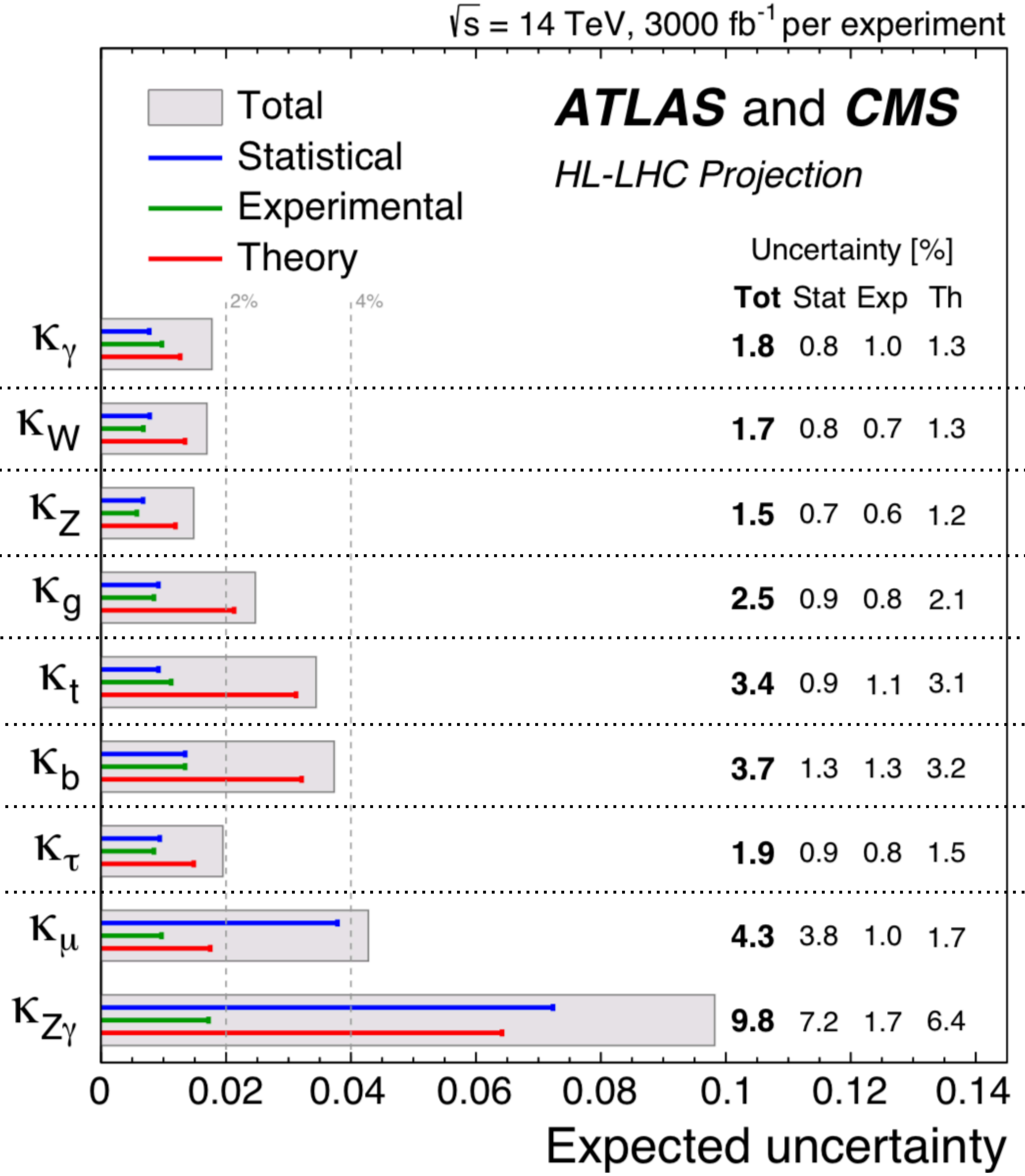
$$\sigma^{\text{SI}}_{fN} = \frac{\lambda^2_{Hff}}{4\pi\Lambda^2 m_H^4}\frac{m_N^4 m_f^2 f_N^2}{(m_f + m_N)^2},$$

Vacuum expectation value	$v/\sqrt{2}$	174 GeV
Higgs boson mass	m_H	125 GeV
Higgs boson width	Γ_H	4.07 MeV
Nucleon mass	m_N	939 MeV
Higgs–nucleon coupling form factor	f_N	$0.33^{+0.30}_{-0.07}$

HL-LHC Higgs couplings projections

M. Kado, *Higgs 2021*

	ATLAS - CMS Run 1 combination	NEW Higgs 2021 ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	$1.01^{+0.09}_{-0.14}$	6%
κ_W	11%	1.06 ± 0.06	$-1.11^{+0.14}_{-0.09}$	6%
κ_Z	11%	0.99 ± 0.06	0.96 ± 0.07	6%
κ_g	14%	$0.92^{+0.07}_{-0.06}$	$1.16^{+0.12}_{-0.11}$	7%
κ_t	30%	0.92 ± 0.10	1.01 ± 0.11	11%
κ_b	26%	0.87 ± 0.11	$1.18^{+0.19}_{-0.27}$	11%
κ_τ	15%	0.92 ± 0.07	0.94 ± 0.12	8%
	JHEP 08 (2016) 045	ATLAS-CONF-2021-53	CMS-PAS-HIG-19-005	



Measurements here assume no BSM in Higgs width

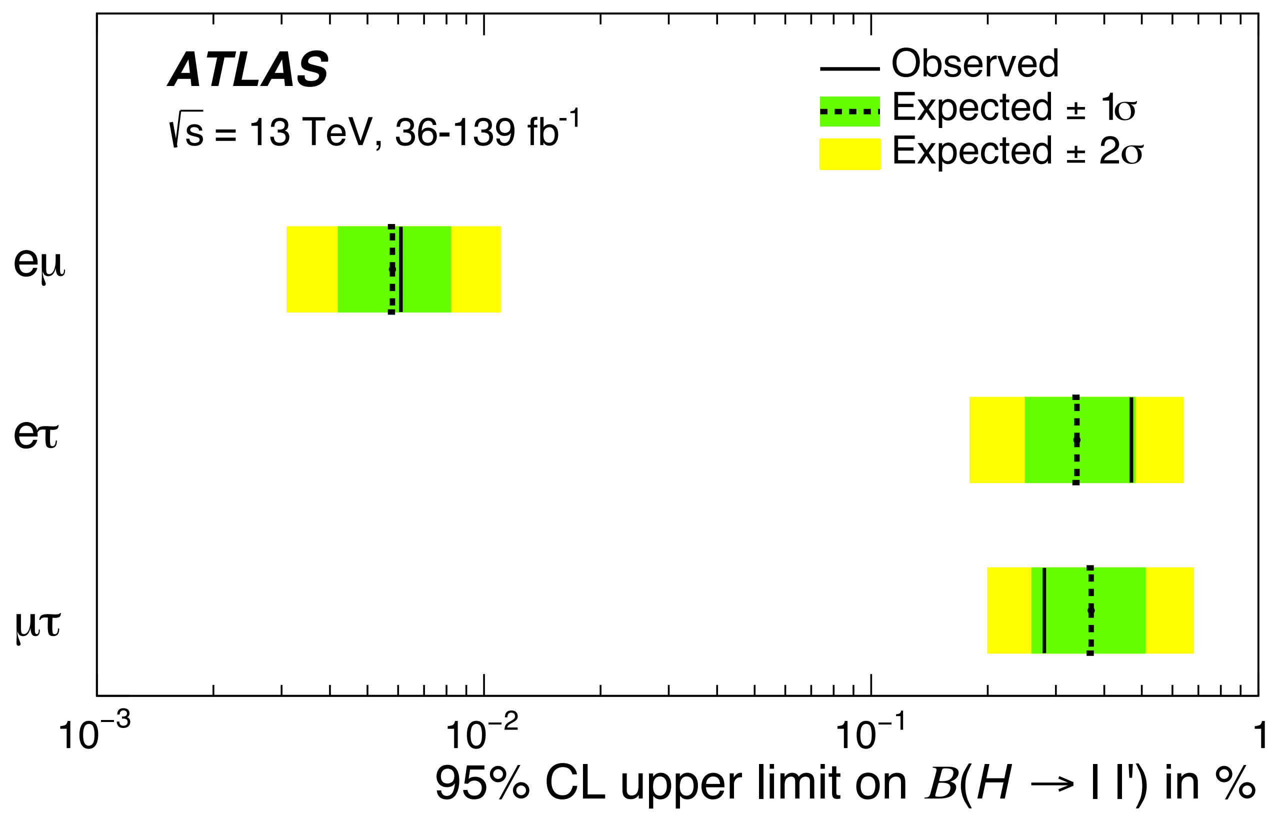
Still 25 times more data and reduction of a factor of 3 uncertainty!

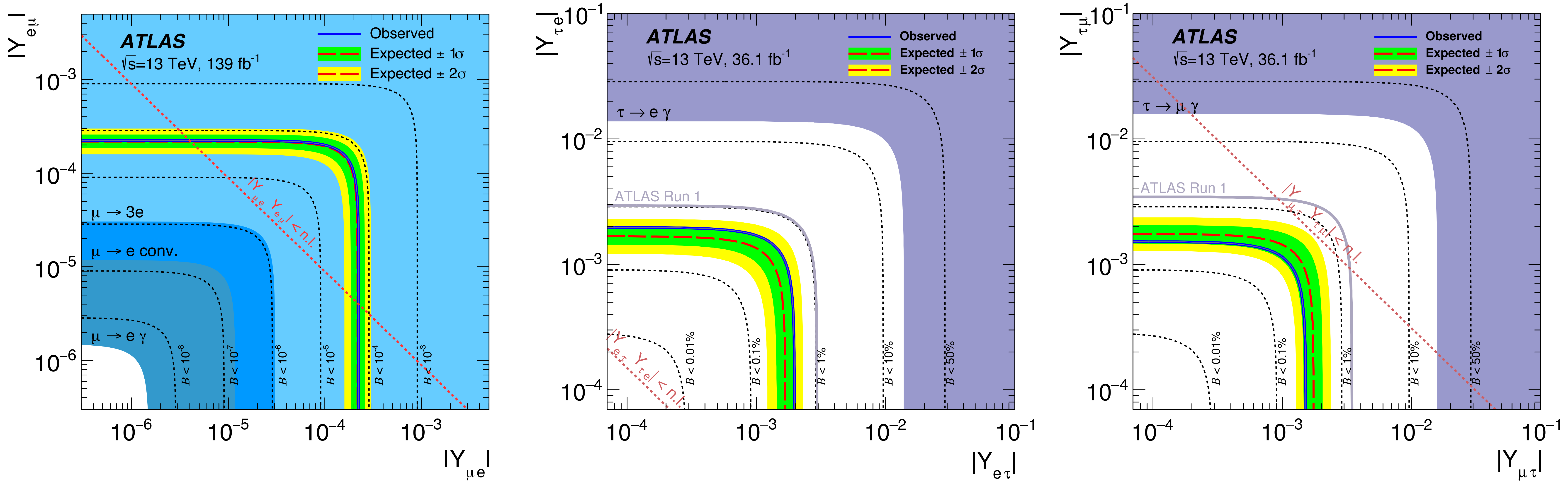
Lepton-flavor-violating Higgs boson decays

LFV Higgs decays ▸ Phys. Lett. B 801 (2020) 135148 ▸ Phys. Lett. B 800 (2020) 135069

T. Neep, *Higgs 2021*

- No significant excesses over the SM prediction are found
- Upper limits on the LFV Higgs branching fractions are set at 95% CL
  - $B(H \to e\mu) < 0.061\%$
  - $B(H \to e\tau) < 0.47\%$
  - $B(H \to \mu\tau) < 0.28\%$
- Branching fraction limits converted to limits on off-diagonal Yukawa couplings

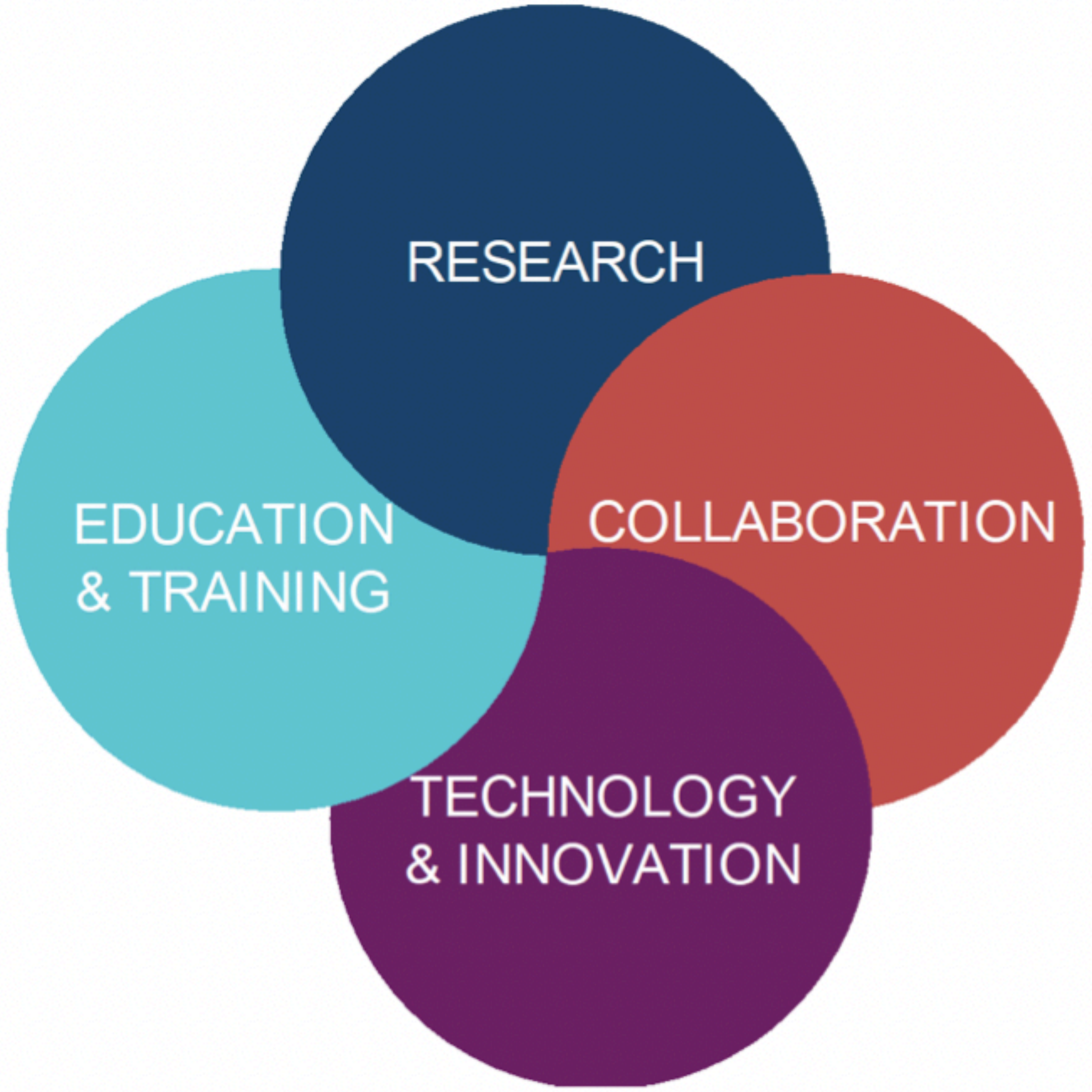




naturalness limit (denoted n.l.) $|Y_{\tau\ell}Y_{\ell\tau}| \lesssim \frac{m_\tau m_\ell}{v^2}$

CERN - a paradigm for European cooperation

- Created in the early 1950's, to build a powerful and competitive infrastructure for fundamental research in nuclear / particle physics in Europe
- Centered around four main pillars: scientific research / technological R&D / education and training of scientists and general public / collaboration
- Today's world's largest center for fundamental research



23 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Finland – France – Germany – Greece
Hungary – Israel – Italy – Netherlands – Norway
Poland – Portugal – Romania – Serbia – Slovakia
Spain – Sweden – Switzerland – United Kingdom

3 Associates Member States in the pre-stage to membership

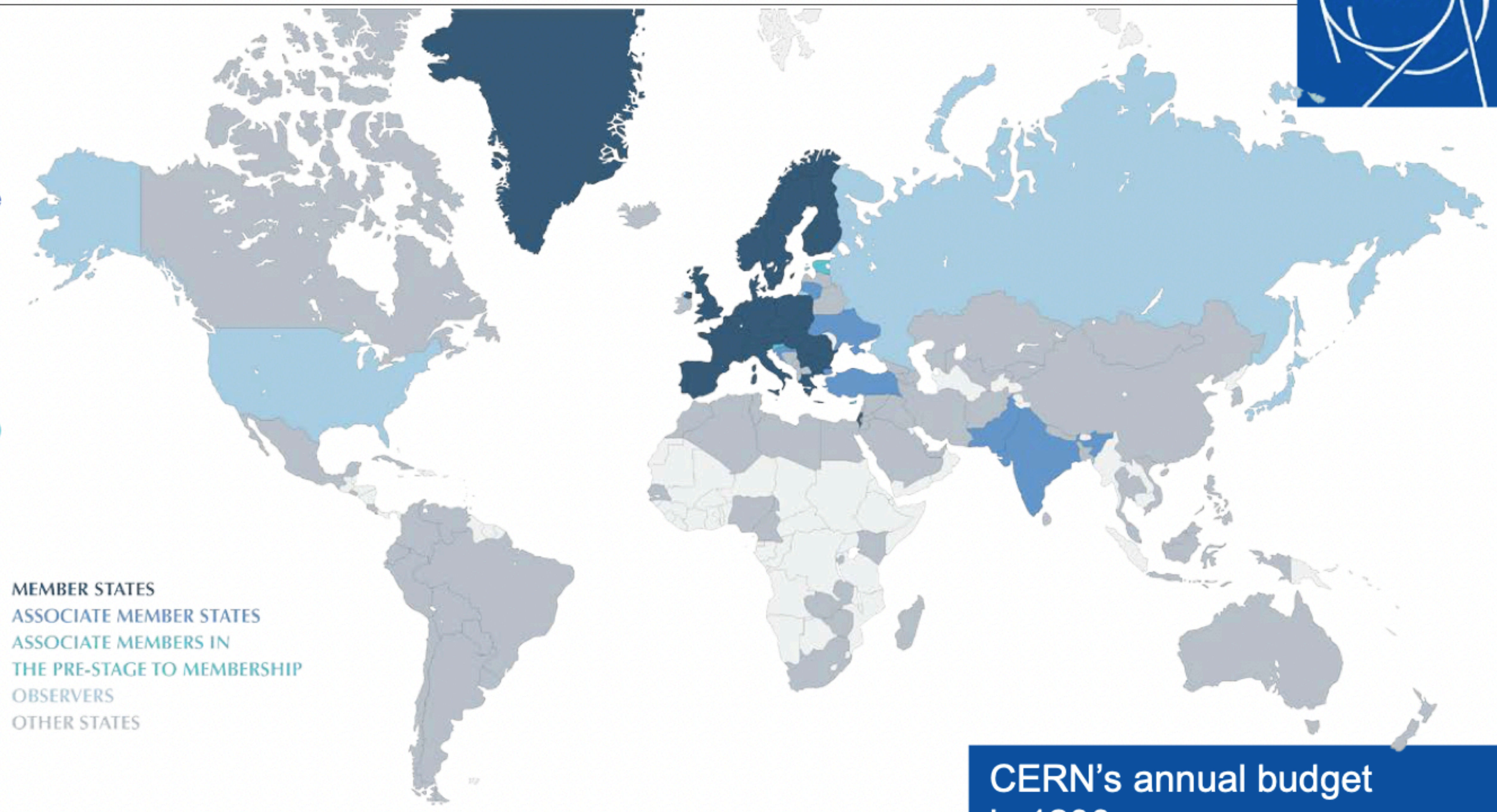
Cyprus – Estonia – Slovenia

7 Associate Member States

Croatia – India – Latvia - Lithuania – Pakistan – Turkey – Ukraine

6 Observers

Japan – Russia – USA
European Union – JINR – UNESCO



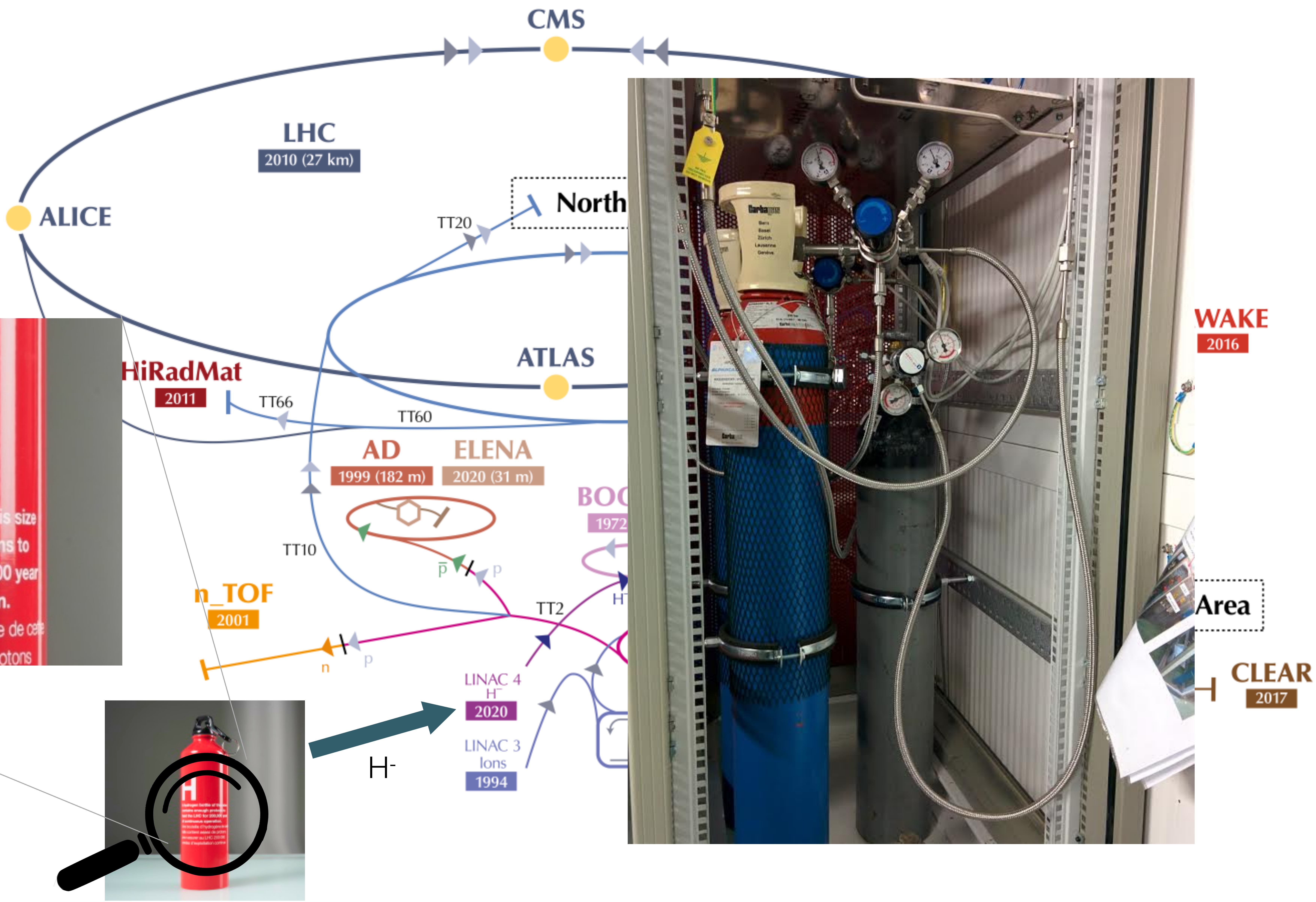
CERN's annual budget is 1200 MCHF (equivalent to a medium-sized European university)

More than 50 Cooperation Agreements with non-Member States and Territories

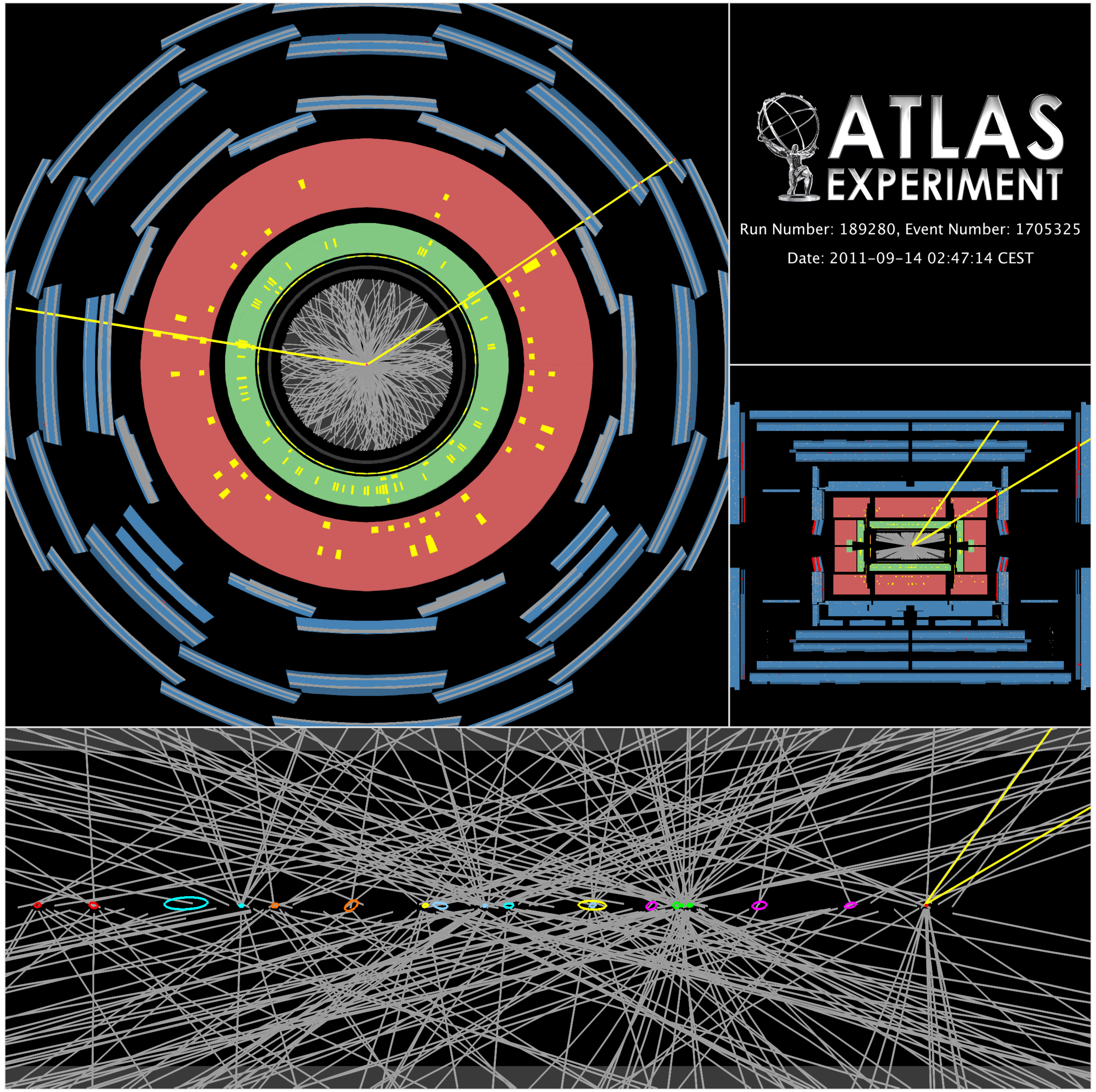
Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia
Bosnia and Herzegovina – Brazil – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Iceland
Iran – Japan - Jordan – Kazakhstan – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – Nepal
New Zealand – North Macedonia – Palestine – Paraguay – Peru – Philippines – Qatar - Republic of Korea – Russia
Saudi Arabia –South Africa - Sri Lanka – Thailand – Tunisia – United Arab Emirates – Unites States - Vietnam

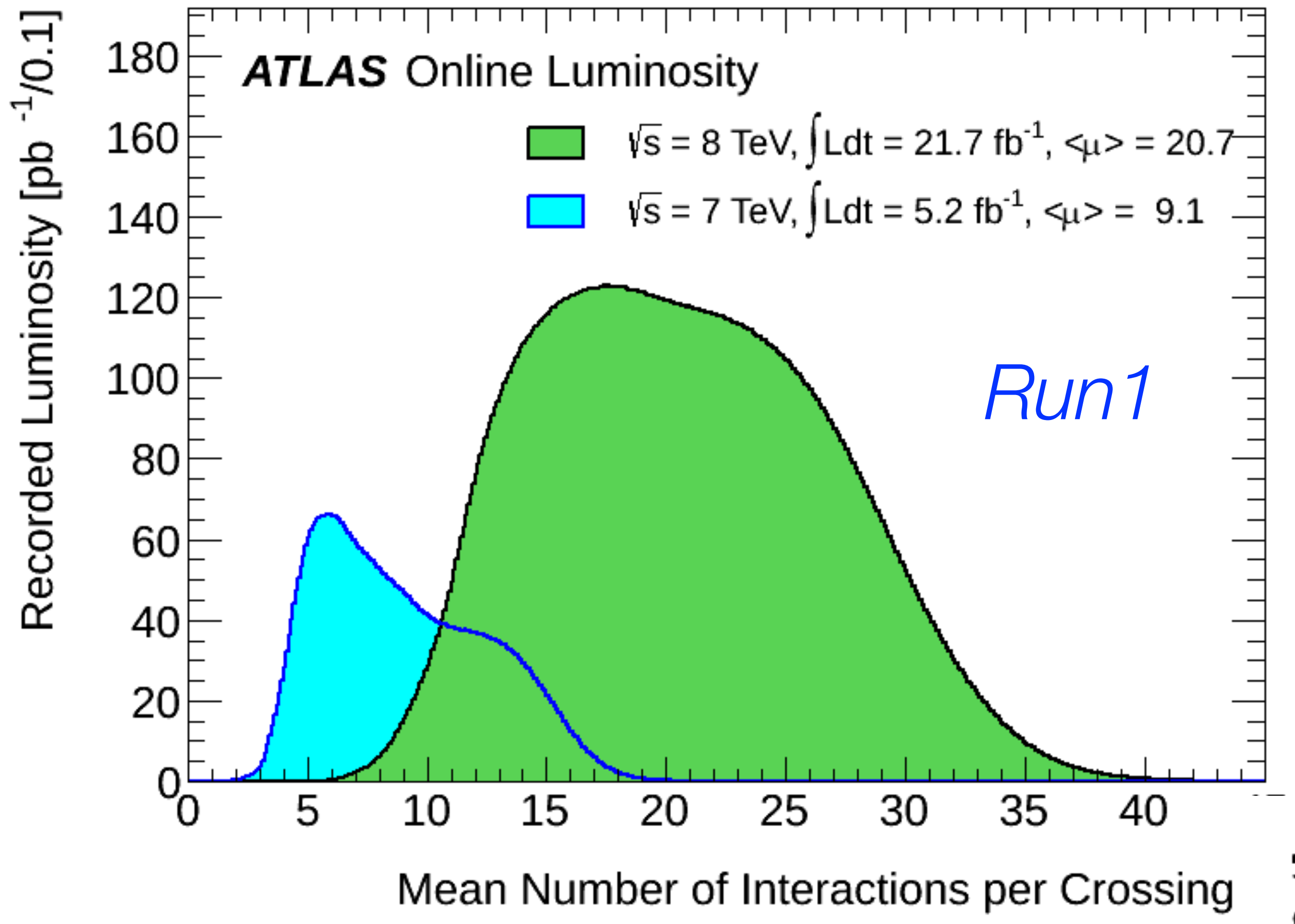
As of 31 December 2020:
Employees:
2635 staff, **756** fellows
Associates:
11399 users, **1687** others

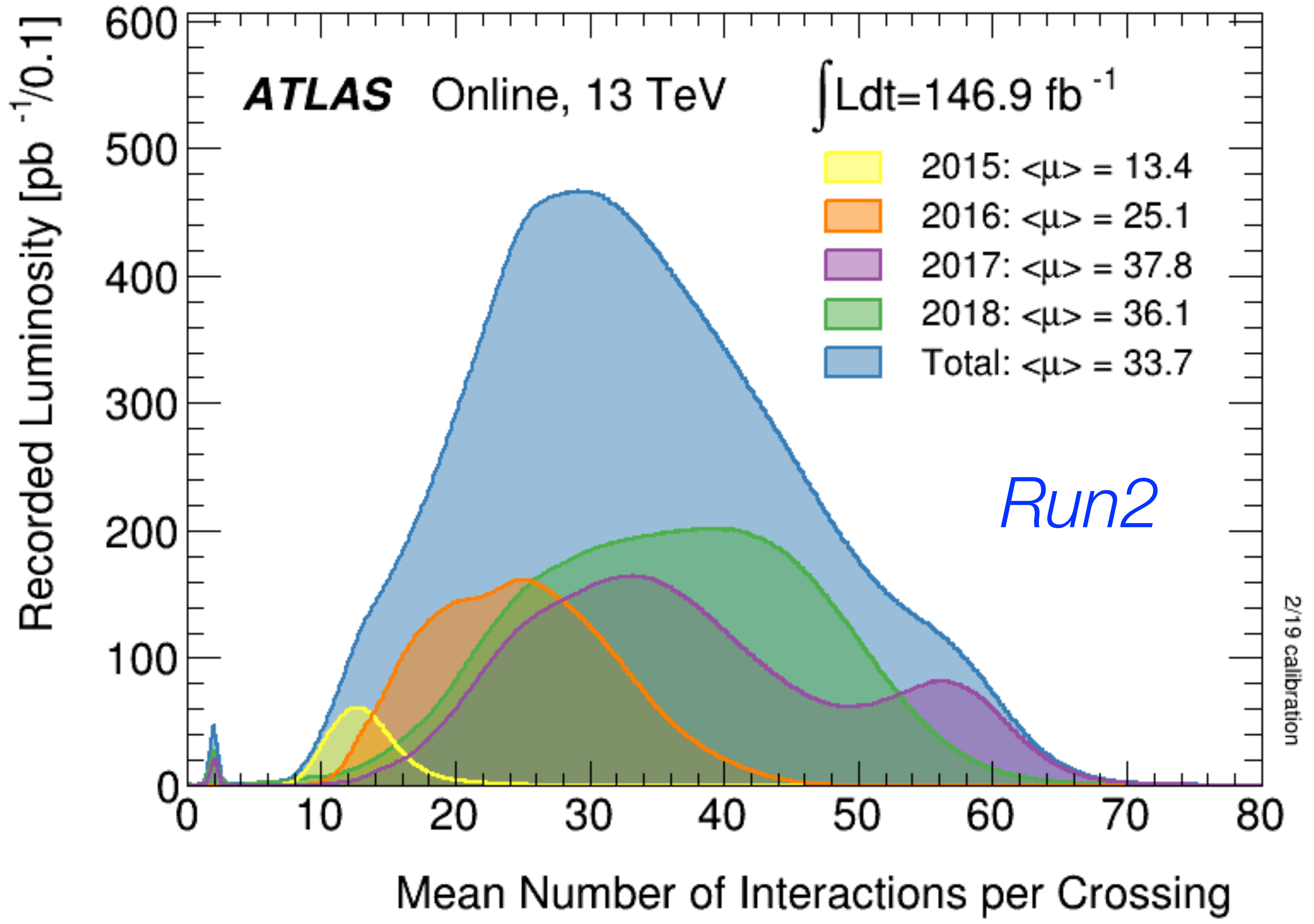
The CERN accelerator complex



Luminosity's dark side: pile-up

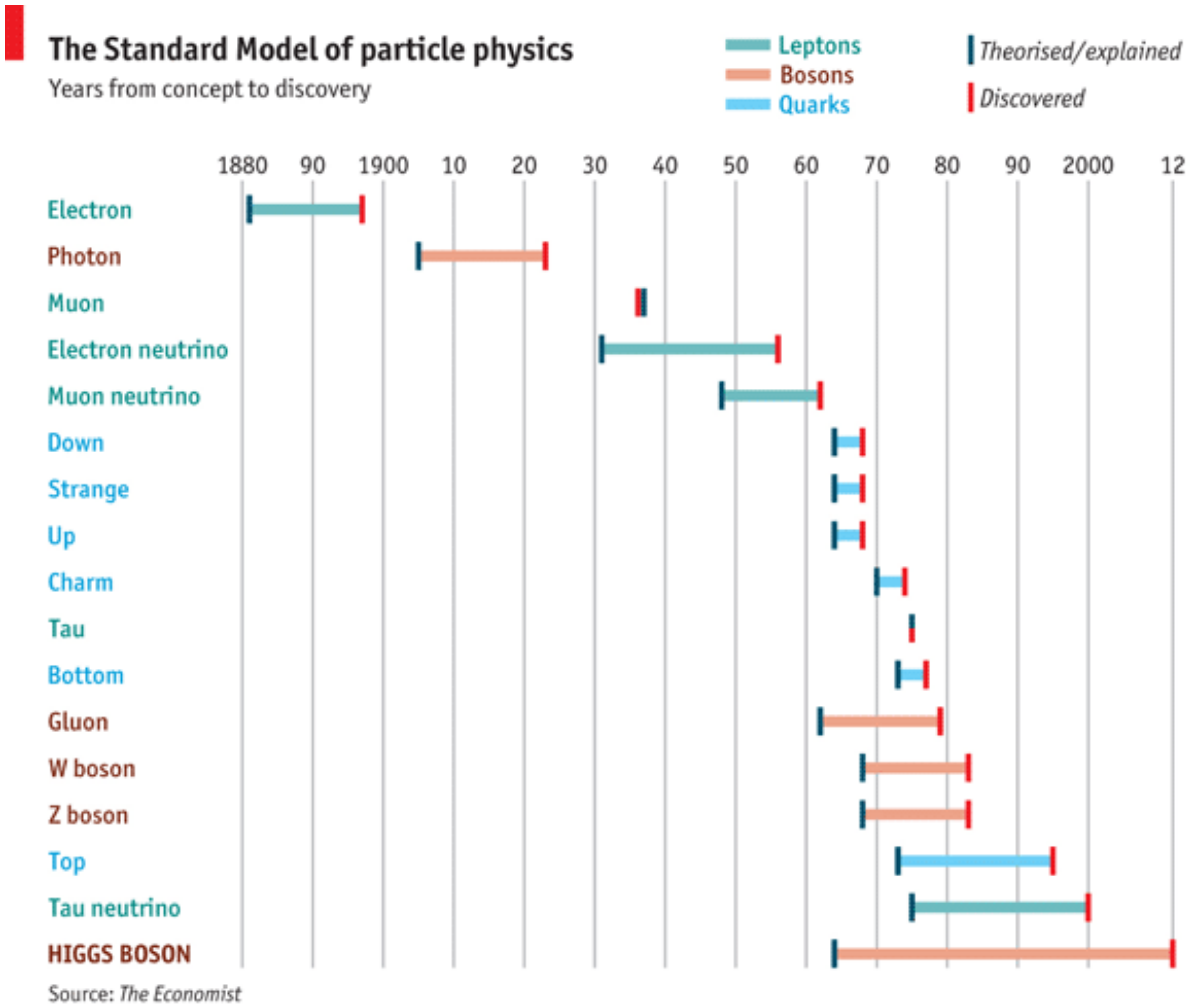




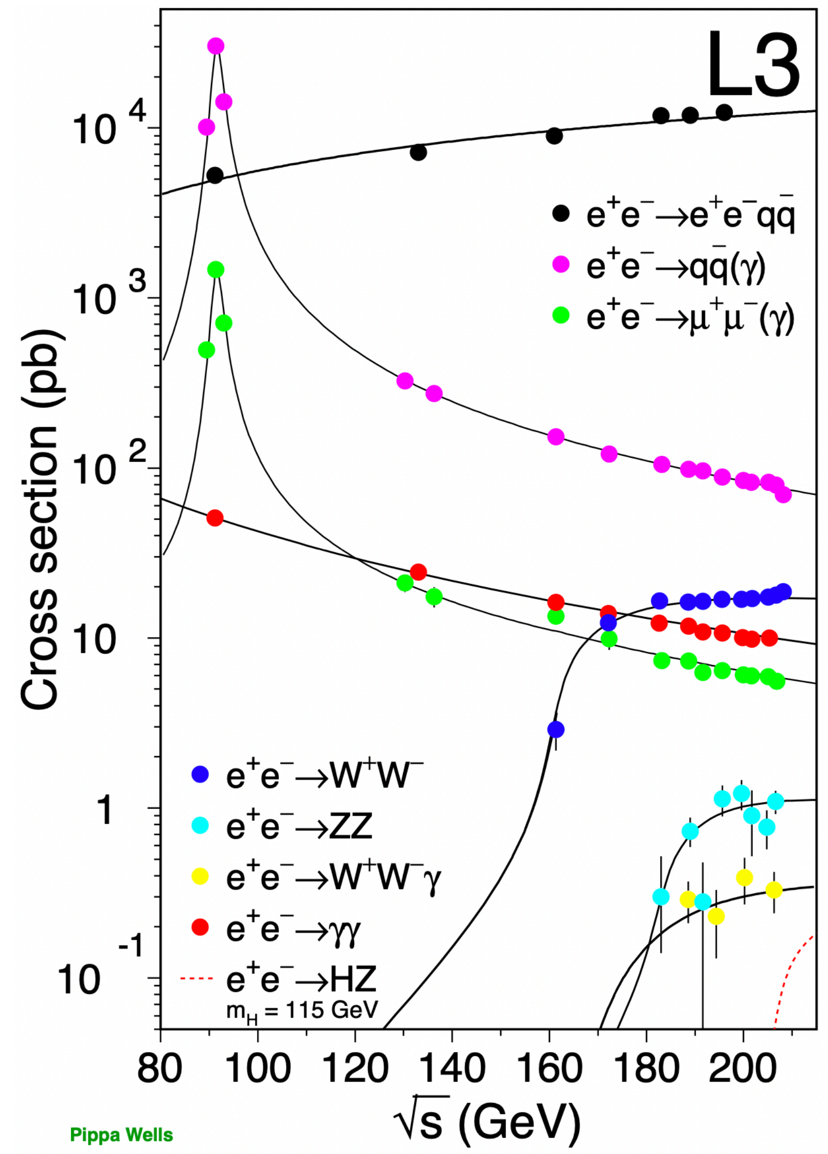


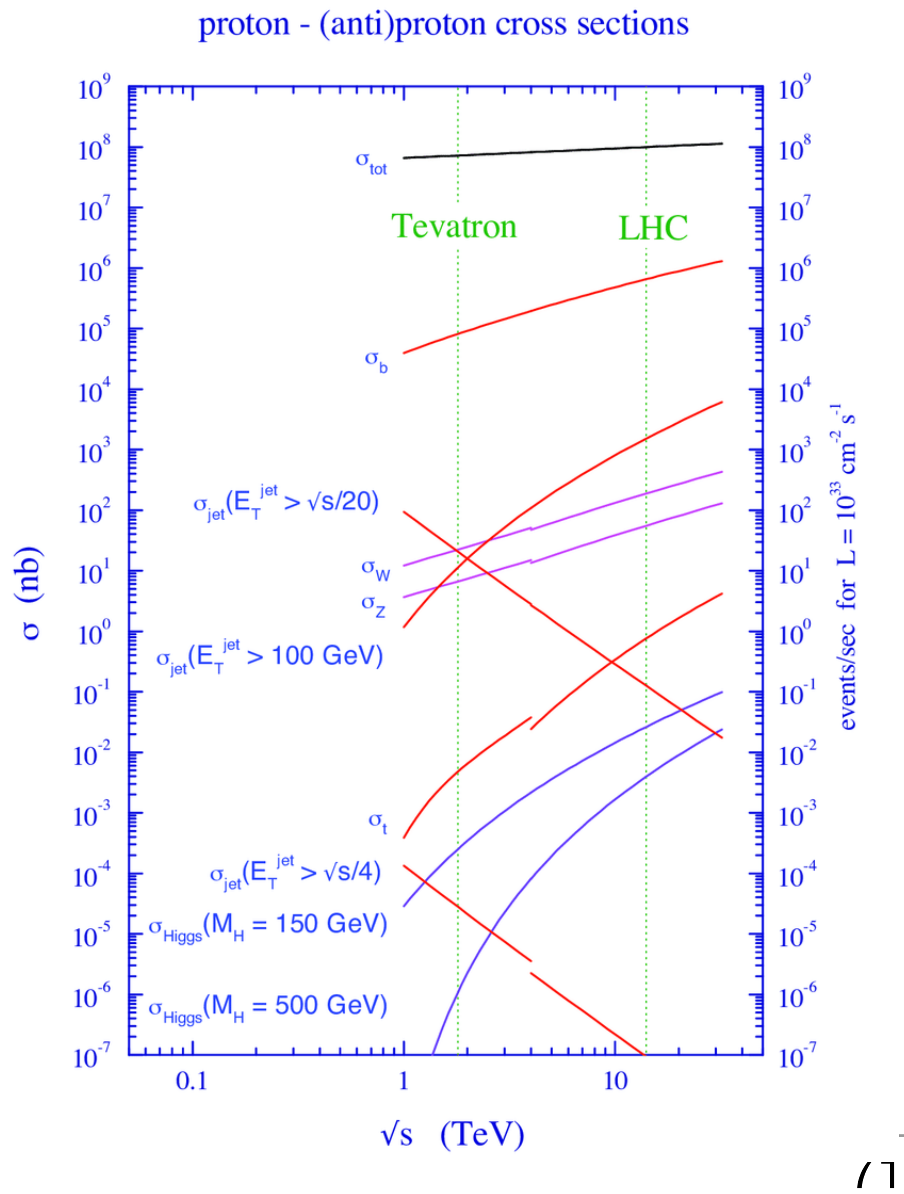
- Need detectors with excellent resolution to distinguish interaction vertices and discard signals associated to pile-up vertices

Why did it take so long to find the Higgs?



- The Higgs boson is quite massive (125 GeV) and its production x-section is small ⇒ **needs collider with sufficient energy & luminosity + optimised detectors**
  - LEP2 (e^+e^-, 4 experiments, ~700/pb at 189-206 GeV): σ~1 fb
    - too low luminosity => no events produced
  - Tevatron (ppbar, 2 experiments, 10/fb at 1.96 TeV): σ~1 pb
    - Cleanest channels (γγ, ZZ→4l..): no events produced
    - main decay mode among the others: bb (BR~60%)
      - BUT very large backgrounds from QCD bb production
    - ➡ Search for W(lν)H and Z(ll)H, l=e, μ: σ = 33fb, O(100) signal events selected, but poor resolution and large background from other processes (W/Z + jets, WZ(bb), ZZ(bb))





The Higgs boson discovery

- Final results published in [Phys. Lett. B 716 (2012) 1-29]
  - Including also H→WW→lνlν with 8 TeV data