Standard Model and Higgs Physics

Georg Weiglein, DESY

46. Herbstschule fuer Hochenergiephysik, Maria Laach, 09 / 2014

Outline

- Introduction: what's so special about a Higgs boson?
- The Brout-Englert-Higgs (BEH) mechanism
- Perturbative evaluation of quantum field theories (gauge theories)
- Top and electroweak physics
- Higgs phenomenology: Standard Model and beyond
- What do we know so far about the discovered signal and how can we interpret it?
- Conclusions

Many mportant topics will only briefly be covered or even not covered at all in this lecture

- Many important QCD aspects, jet physics, boosted topologies, Monte Carlo simulations (LO, NLO and beyond), matching with parton showers, ...
- High-precision predictions for Standard Model processes: signal + backgrounds
- Recent progress in NLO predictions (and beyond) for LHC processes
- Top physics beyond m_t determination
- Flavour physics in the quark and lepton sectors
- ...

Introduction: what's so special about a Higgs boson?

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Probing the fundamental laws of nature

Particle accelerators (Large Hadron Collider (LHC), . . .)

$\Rightarrow$ probe the TeV scale (Terascale)

What are the fundamental laws of nature?

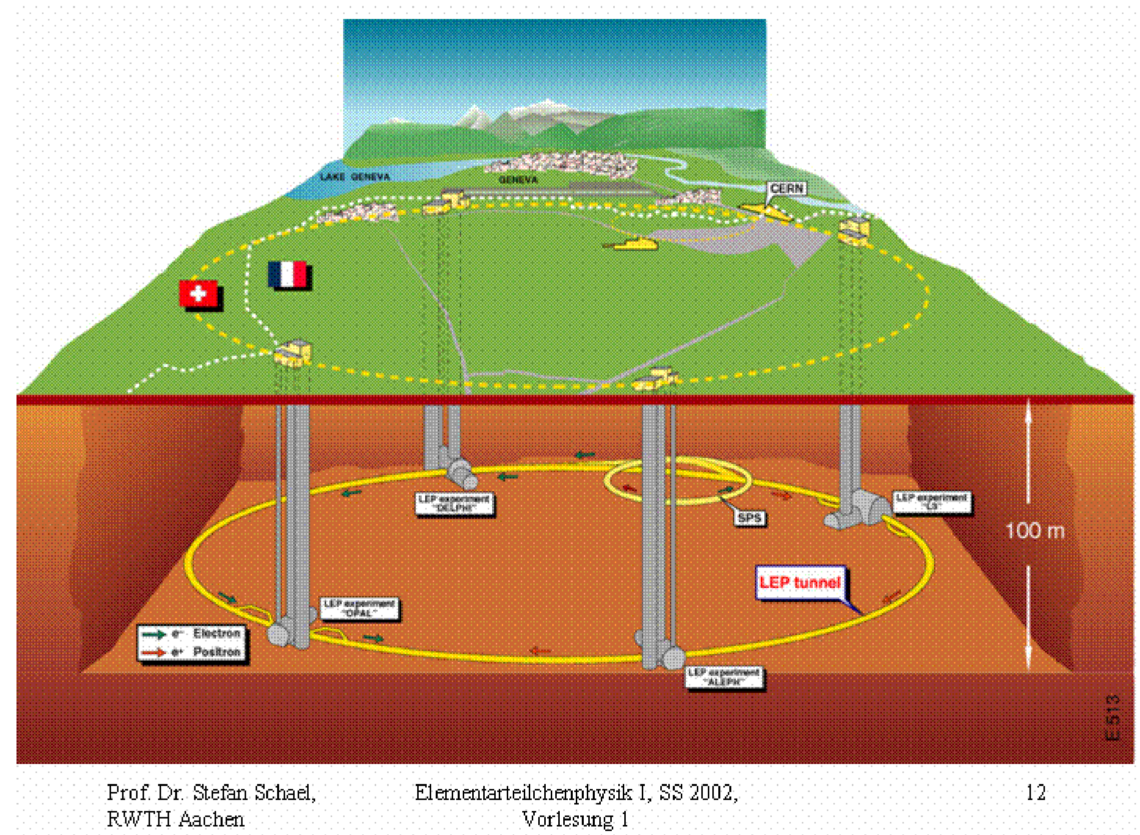
$\Rightarrow$ Study the fundamental forces (“interactions”) and the fundamental building blocks of matter (“elementary particles”)

Probing high energies and short distances $\Leftrightarrow$ viewing the early Universe

Linear and circular colliders

LEP (≤ 2000): e^+e^- collider, $E_{\mathrm{CM}} \lesssim 206\ \mathrm{GeV}$

circular accelerator, ≈ 28 km long



Energy loss due to synchrotron radiation: $\Delta E \sim \dfrac{E^4}{m^4\, r}$

Linear and circular colliders

$\Rightarrow$ High energy e^+e^- collider can only be realised as Linear Collider (LC): ILC, CLIC

Comparison: proposal for TLEP circular e^+e^- collider: 80–100 km long tunnel for $350\ \mathrm{GeV}$ machine

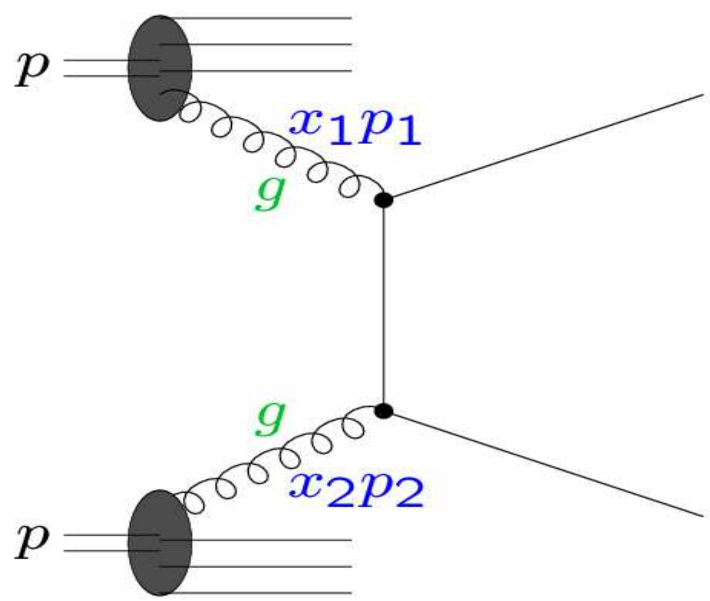
Synchrotron radiation loss smaller for proton by factor $(m_\mathrm{e}/m_\mathrm{p})^4 \approx 10^{-13}$

Tevatron, Run II (≤ 2011): circular $p\bar{p}$ collider, $E_\mathrm{CM} \approx 2\ \mathrm{TeV}$

LHC: circular pp collider (in LEP tunnel), $E_\mathrm{CM} \approx 14\ \mathrm{TeV}$

Physics at the LHC and the ILC (in a nutshell)

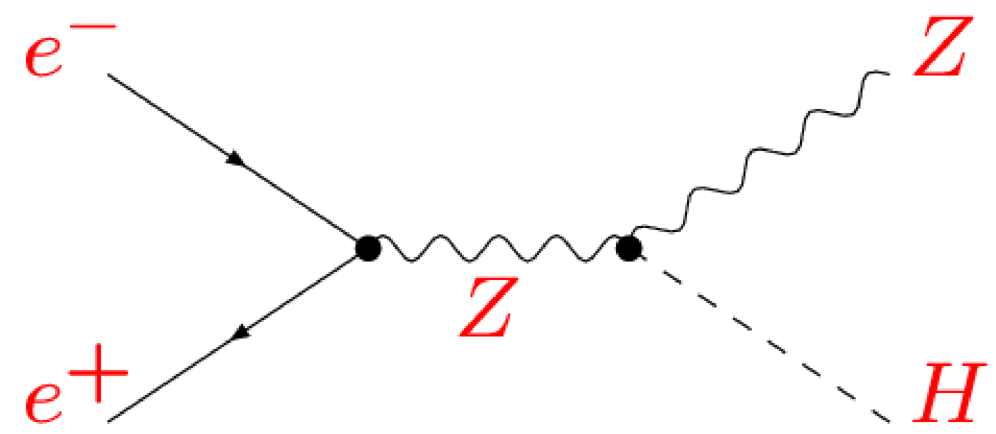
LHC: pp scattering
at $\lesssim 14$ TeV



Scattering process of proton constituents with energy up to several TeV,
strongly interacting

$\Rightarrow$ huge QCD backgrounds,
low signal–to–backgr. ratios

ILC: e^+e^- scattering
at $\lesssim$ 1 TeV

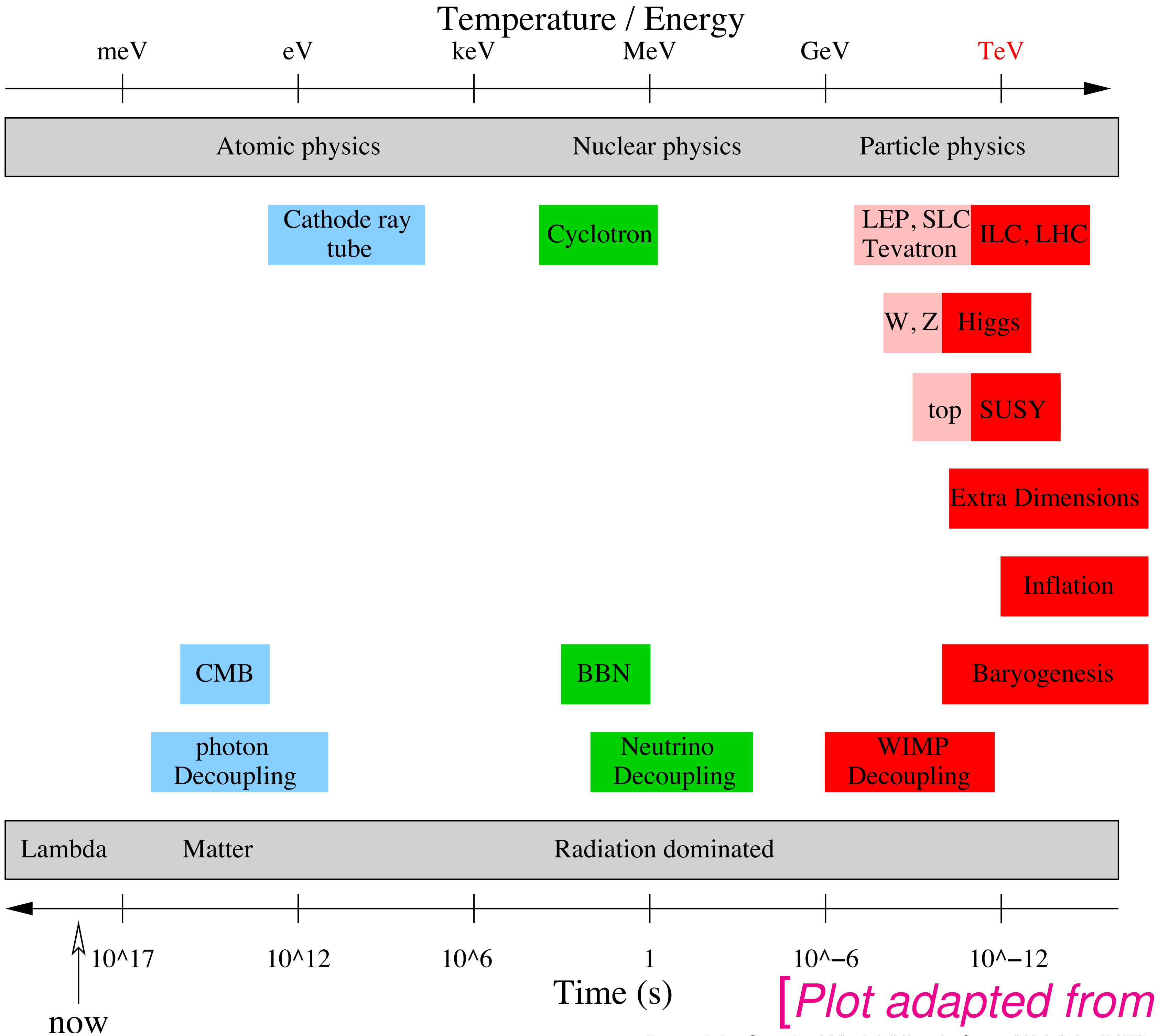


Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

$\Rightarrow$ rel. small backgrounds
high-precision physics

LHC physics: exploring the Terascale

$$1\ \mathrm{TeV} \approx 1000 \times m_{\mathrm{proton}} \Leftrightarrow 2 \times 10^{-19}\ \mathrm{m}$$



[Plot adapted from J. Feng ’05]

Particle accelerators: viewing the early Universe

Today's universe is cold and empty: only the stable relics and leftovers of the big bang remain

The unstable particles have decayed away with time, and the symmetries that shaped the early Universe have been broken as it has cooled

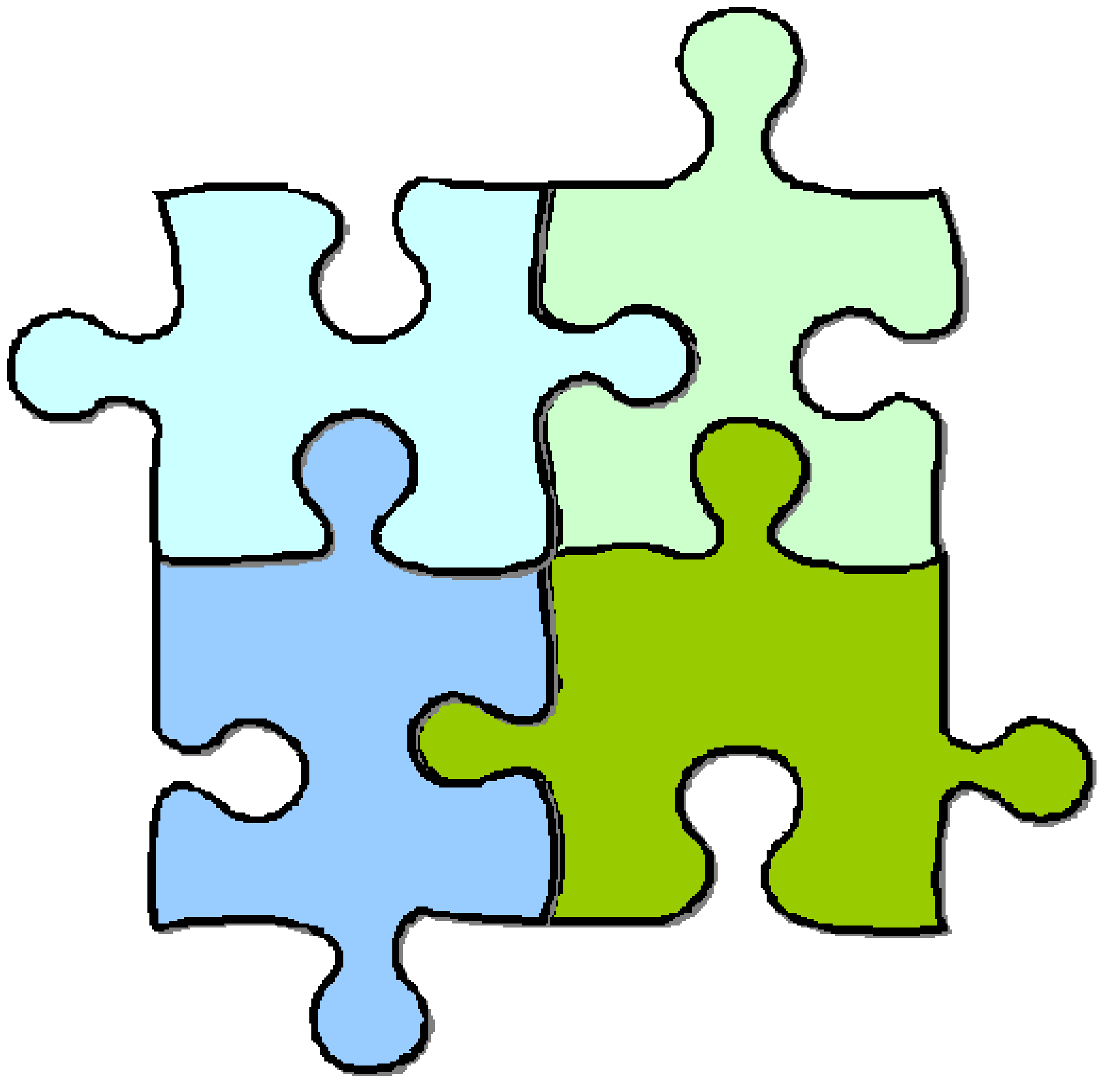
$\Rightarrow$ Use particle accelerators to pump sufficient energy into a point in space to re-create the short-lived particles and uncover the forces and symmetries that existed in the earliest Universe

$\Rightarrow$ Accelerators probe not only the structure of matter but also the structure of space-time, i.e. the fabric of the Universe itself

The Quantum Universe

Particle
Physics
Experiments
Accelerators
Underground

Quantum
Field
Theory
(Standard
Model)



Astronomy
Experiments
Telescopes
Satellites

Standard
Cosmology
Model

← 10^{-18} m

10^{26} m →

What can we learn from exploring the Terascale?

- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking? What is the role of the discovered particle at $\sim 126 \text{ GeV}$ in this context?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- What is dark matter? Can it be produced in the laboratory?
- Are there new sources of $\mathcal{CP}$-violation?
  Can they explain the asymmetry between matter and anti-matter in the Universe?

Fundamental interactions

- Electromagnetism (electricity + magnetism)
- Strong interaction (binds quarks within the proton and protons and neutrons within nuclei)
- Weak interaction (radioactivity, difference between matter and anti-matter, . . .)
- Gravity (solar system, . . .)

Interaction between two particles is mediated by a field

E.g.: atom, interaction between proton and electron: electromagnetic field

The Universe is a quantum world

The fields are quantised

Particles are quanta of fields

The photon is the quantum of the electromagnetic field

Fundamental interactions are mediated by the exchange of field quanta, i.e. particles

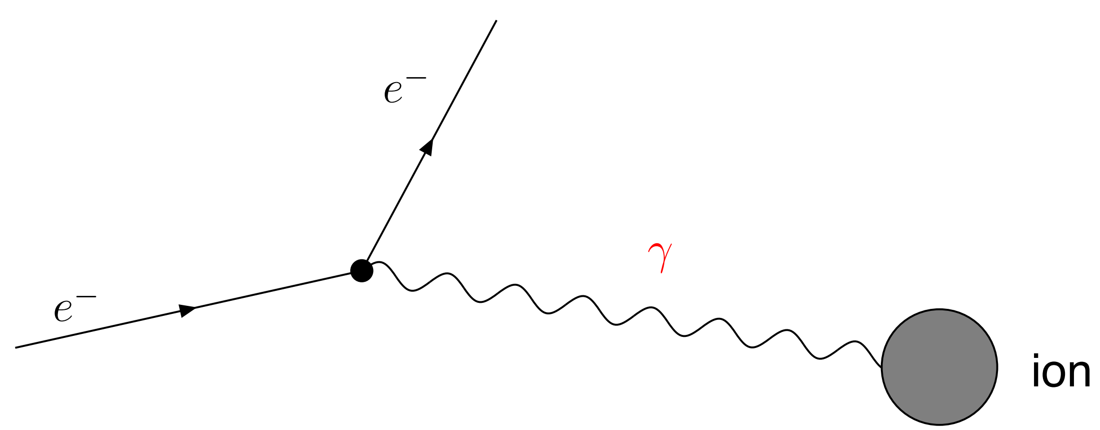
- Electromagnetic interaction: photon, γ
- Weak interaction: W, Z
- Strong interaction: gluon, g
- Gravity: graviton, G

Description of fundamental interactions with quantum field theories

Classical field theory (e.g. classical electrodynamics):

Quantum field theory (e.g. QED): field is quantised,

field quantum: photon



Interaction: exchange of field quanta

The Standard Model (SM): electroweak and strong interactions

Electroweak interaction:

Fermion fields: quarks: $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R,$ leptons: $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R$

3 generations:

$u, d, \quad s, c \quad t, b$

$\nu_e, e \quad \nu_\mu, \mu \quad \nu_\tau, \tau$

gauge bosons: γ, Z, W^+, W^-

Gauge group: $\mathrm{SU}(2)_\mathrm{I} \times \mathrm{U}(1)_\mathrm{Y} \supset \mathrm{U}(1)_\mathrm{em}$

Strong interaction: QCD

quarks: q_r, q_g, q_b, gauge bosons: $g_1, \ldots g_8$: gluons, $\mathrm{SU}(3)_\mathrm{C}$

All postulated fermions and gauge bosons experimentally verified

Construction principle of the SM: gauge invariance

Example:

Quantum electrodynamics (QED)

free electron field: $\mathcal{L}_{\mathrm{Dirac}} = i\overline{\Psi}\gamma_\mu\partial^\mu\Psi - m\overline{\Psi}\Psi$

invariant under global gauge transformation: $\Psi \to e^{i\theta}\Psi$

Requirement of local gauge invariance:

gauge field A_μ introduced, $\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$

gauge transformation: $\Psi \to e^{ie\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu\lambda(x)$

Construction of the QED Lagrangian

$\Rightarrow$ Lagrangian with interaction term:

$$\mathcal{L}_{\text{QED}} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{free photon field}} + \underbrace{\overline{\Psi}(i\gamma_\mu\partial^\mu - m)\Psi}_{\text{free electron field}} + \underbrace{\mathrm{e}\overline{\Psi}\gamma_\mu\Psi A^\mu}_{\text{interaction}}$$

free photon field free electron field interaction

invariant under local gauge transformations

mass term, $m^2 A^\mu A_\mu$: not gauge-invariant

$\Rightarrow$ A_μ: massless gauge field

How do elementary particles get mass?

- The fundamental interactions of elementary particles are described very successfully by quantum field theories that follow an underlying symmetry principle:
  "gauge invariance"

- This fundamental symmetry principle requires that all the elementary particles and force carriers should be massless

- However: W, Z, top, bottom, . . . , electron are massive, have widely differing masses

  explicit mass terms $\Leftrightarrow$ breaking of gauge invariance

How can elementary particles acquire mass without spoiling the fundamental symmetries of nature?

The Brout-Englert-Higgs (BEH) mechanism

$\Rightarrow$ Need additional concept:

Higgs mechanism, spontaneous electroweak symmetry breaking:

New field postulated that fills all of the space: the Higgs field

Higgs potential
$\Rightarrow$ non-trivial structure of the vacuum postulated!

Gauge-invariant mass terms from interaction with Higgs field

Spontaneous symmetry breaking: the interaction obeys the symmetry principle, but not the state of lowest energy

Very common in nature, e.g. ferromagnet

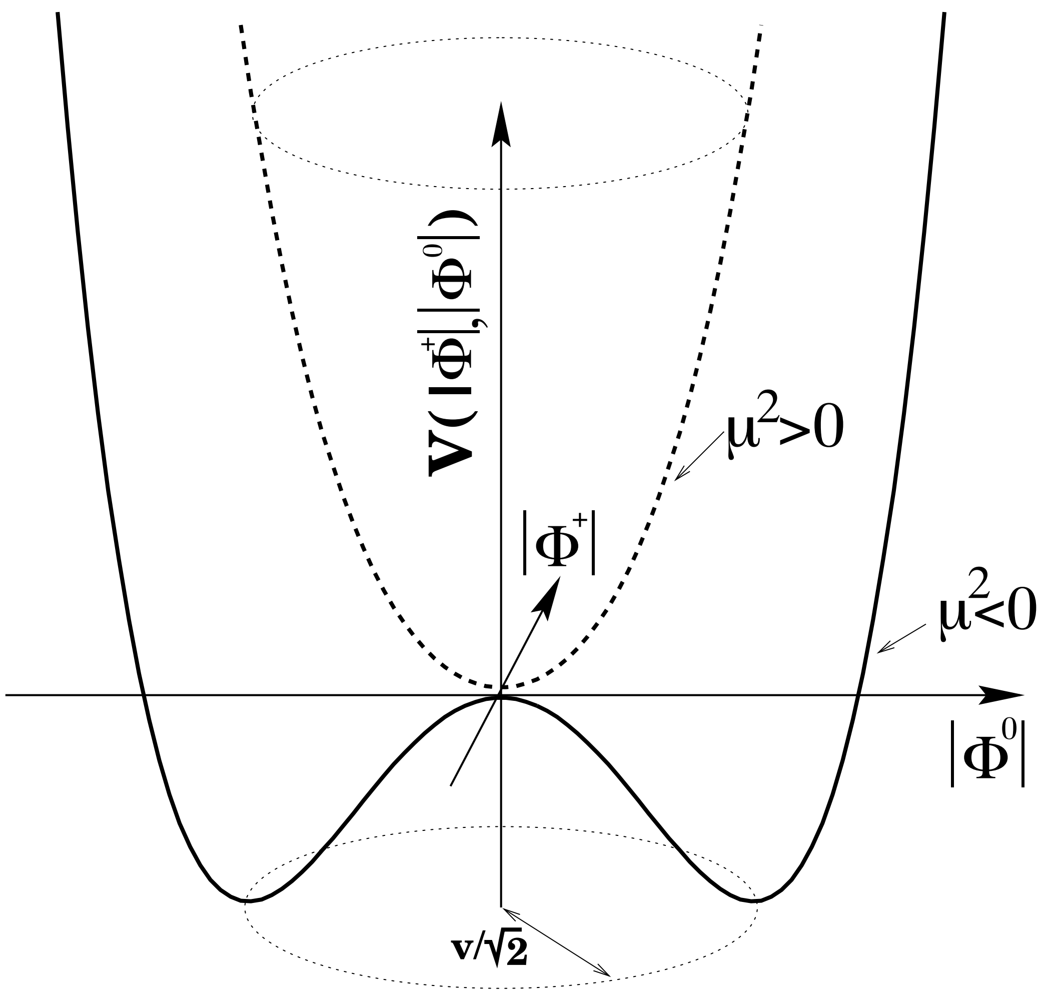
The BEH mechanism in the Standard Model (SM)

Postulated Higgs field: scalar SU(2) doublet $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential: $V(\Phi) = \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 + \mu^2\left(\Phi^\dagger\Phi\right), \quad \lambda > 0$

$\mu^2 < 0$

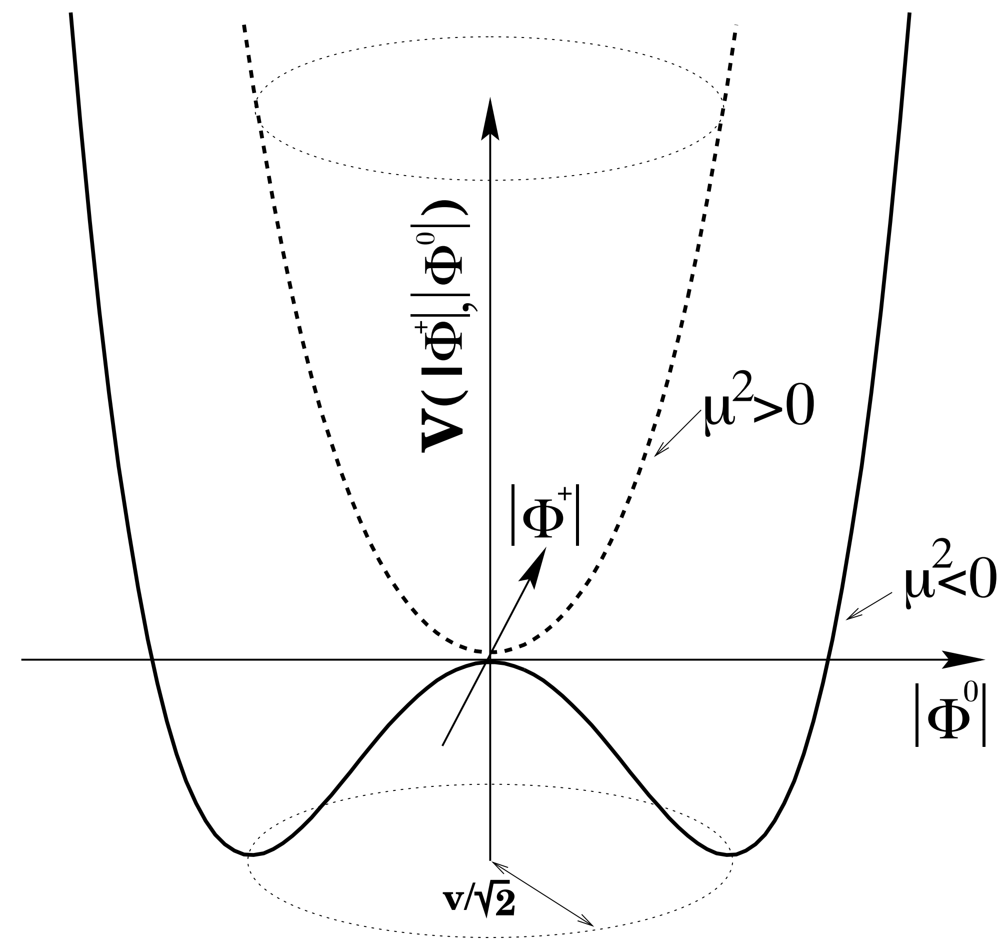
$\Rightarrow$ spontaneous symmetry breaking



The BEH mechanism in the Standard Model (SM)

Minimum of the potential at $\langle \Phi \rangle = \sqrt{\frac{-2\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$

The state of the lowest energy of the Higgs field (vacuum state) does not obey the underlying symmetry principle (gauge invariance)



$\Rightarrow$ Spontaneous breaking of the gauge symmetry

BEH mechanism $\Leftrightarrow$ non-trivial structure of the vacuum

The BEH mechanism sounds like a rather bold assumption to cure a theoretical / aesthetical problem

But: we know that there has to be new physics that is responsible for electroweak symmetry breaking

Otherwise our description breaks down at the TeV scale

$\Rightarrow$ Signatures of the physics of electroweak symmetry breaking must show up at the TeV scale

Possible alternatives to the Higgs mechanism:

- A new fundamental strong interaction ("strong electroweak symmetry breaking")
- New dimensions of space (electroweak symmetry breaking via boundary conditions for SM gauge bosons and fermions on "branes" in a higher-dimensional space)

The Higgs field and the Higgs boson

Higgs mechanism: fundamental particles obtain their masses from interacting with the Higgs field

Higgs boson(s): field quantum of the Higgs field

SM Higgs field: scalar SU(2) doublet, complex $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

$\Rightarrow$ 4 degrees of freedom

3 components of the Higgs doublet $\longrightarrow$ longitudinal components of W^+, W^-, Z

4th component: H: elementary scalar field, Higgs boson

Models with two Higgs doublets (e.g. MSSM)

$\Rightarrow$ prediction: 5 physical Higgses

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Standard Model and Higgs Physics, Lecture 2

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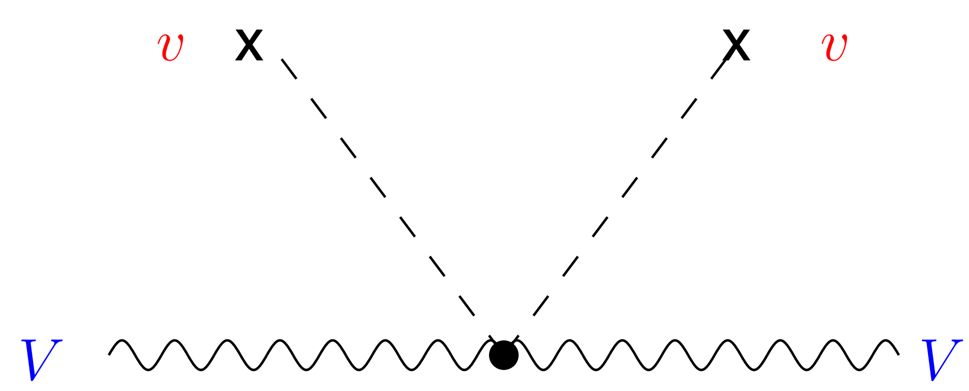
Gauge-invariant interaction with gauge fields

$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi);$ unitary gauge: $\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$

$VV\Phi\Phi$ coupling:



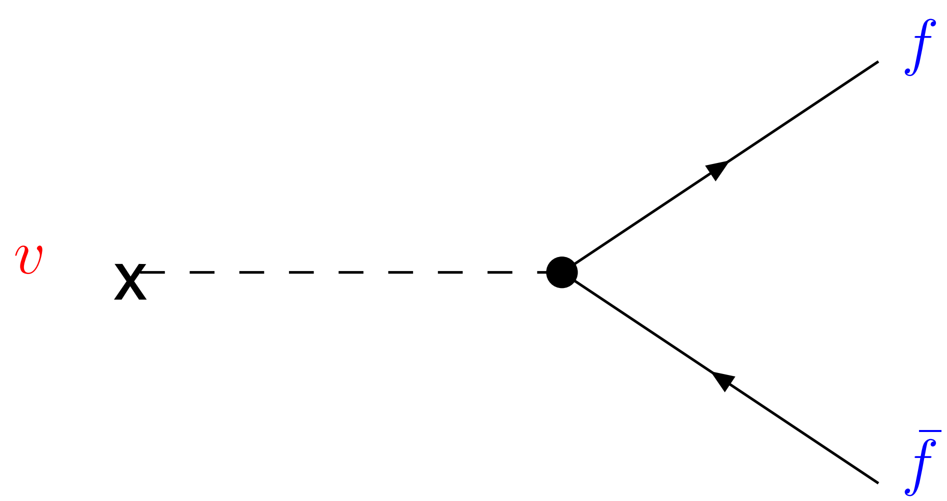
$\Rightarrow$ VV mass terms: $\frac{1}{2} g_2^2 v^2 \equiv M_{\text{W}}^2, \quad \frac{1}{2}(g_1^2 + g_2^2) v^2 \equiv M_{\text{Z}}^2$

WWH coupling: $g_{WWH} = g_2 \, M_{\text{W}}$

$\Rightarrow$ Higgs coupling to W bosons is proportional to the W mass

Fermion masses, Higgs mass

Fermion mass terms: Yukawa couplings

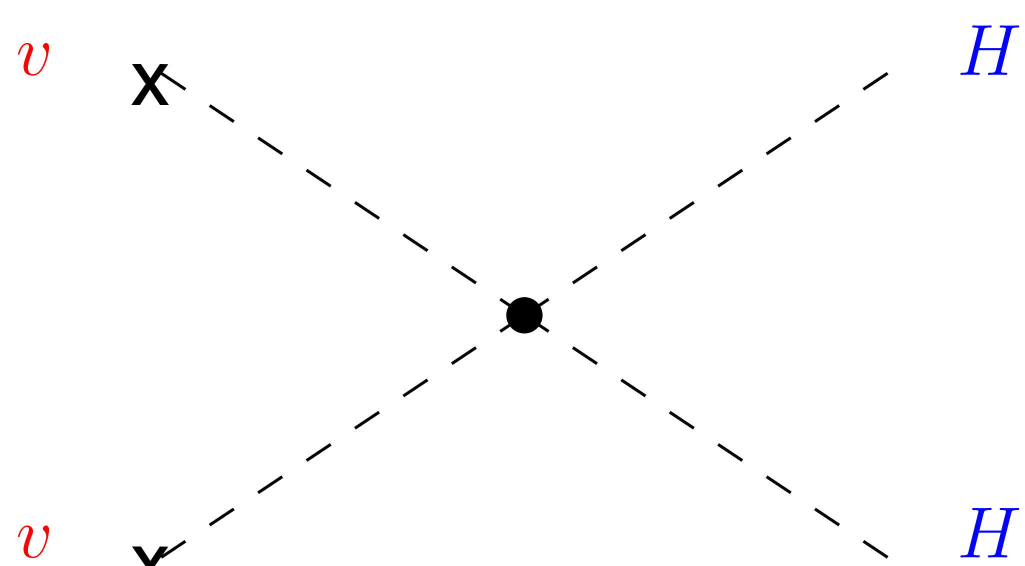


$$m_f = v\, g_f$$

free parameters

$\Rightarrow$ Higgs couplings are proportional to masses of the particles

Mass of the Higgs boson: self-interaction



$$M_{\mathrm{H}} = v\sqrt{\lambda}$$

free parameter

Higgs self-coupling $\Leftrightarrow$ access to Higgs potential

Fermion masses in the SM

Fermion mass terms in SM Lagrangian:

$$\mathcal{L}_{\mathrm{SM}} = \underbrace{m_d \bar{Q}_L H d_R}_{} + \underbrace{m_u \bar{Q}_L \tilde{H} u_R}_{}, \quad Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

d-quark mass u-quark mass

$\Rightarrow$ Would at first sight expect that two doublets are needed

“Trick” used in the SM:

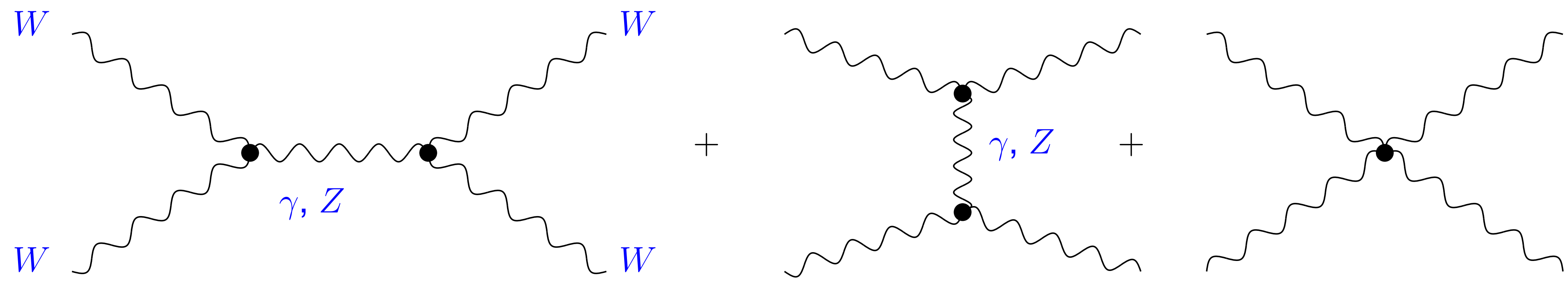
$$\tilde{H} = i\sigma_2 H^\dagger, \quad H \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{H} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$\Rightarrow$ One Higgs doublet sufficient to give mass to both up-type and down-type fermions

Unitarity cancellation in longitudinal gauge boson scattering

E.g.: WW scattering, longitudinally polarised: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$

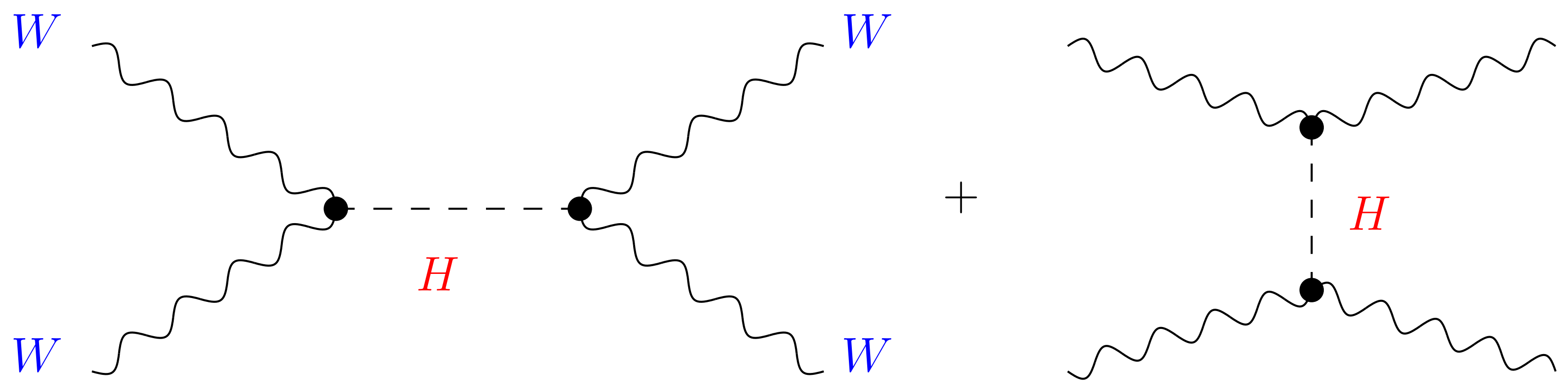


$= -g^2 \frac{E^2}{M_{\mathrm{W}}^2} + \mathcal{O}(1)$ for $E \gg M_{\mathrm{W}}$

$\Rightarrow$ violation of probability conservation

Compensated by Higgs contribution:

$\mathcal{M}_S =$



$= g_{WWH}^2 \frac{E^2}{M_{\mathrm{W}}^4} + \mathcal{O}(1)$ for $E \gg M_{\mathrm{W}}$, $g_{WWH} = g_2 \, M_{\mathrm{W}}$

Higgs physics beyond the SM

Standard Model: a single parameter determines the whole Higgs phenomenology: M_{H}

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite “natural”

$\Rightarrow$ Would result in several Higgs states

Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”

Consequence for gauge theories with spontaneous symmetry breaking (BEH mechanism): renormalisability

Standard Model Lagrangian as an example:

$$\mathcal{L}_{\mathrm{EW}}(\underbrace{g_2, g_1, v}_{M_{\mathrm{W}},\, M_{\mathrm{Z}},\, \alpha}, \underbrace{\lambda}_{M_{\mathrm{H}}}, \underbrace{g_f}_{m_f}) + \mathcal{L}_{\mathrm{QCD}}(\alpha_{\mathrm{s}})$$

Gauge invariance $\Rightarrow$ theory is renormalisable

[*G. 't Hooft '71*] [*G. 't Hooft, M. Veltman '72*] *Nobel prize '99*

$\Rightarrow$ theory can consistently been treated as a quantised field theory:

$\Rightarrow$ quantum effects can be evaluated

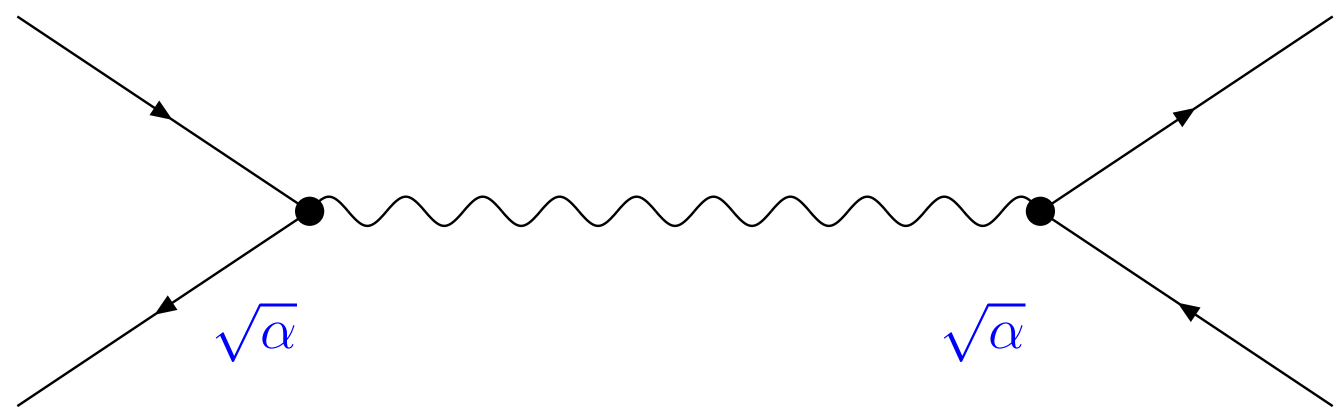
For non-renormalisable theory: need additional parameters in each loop order to compensate divergencies

Perturbative evaluation of quantum field theories (gauge theories)

Expansion in coupling constant: $\alpha \approx \frac{1}{137} \ll 1$

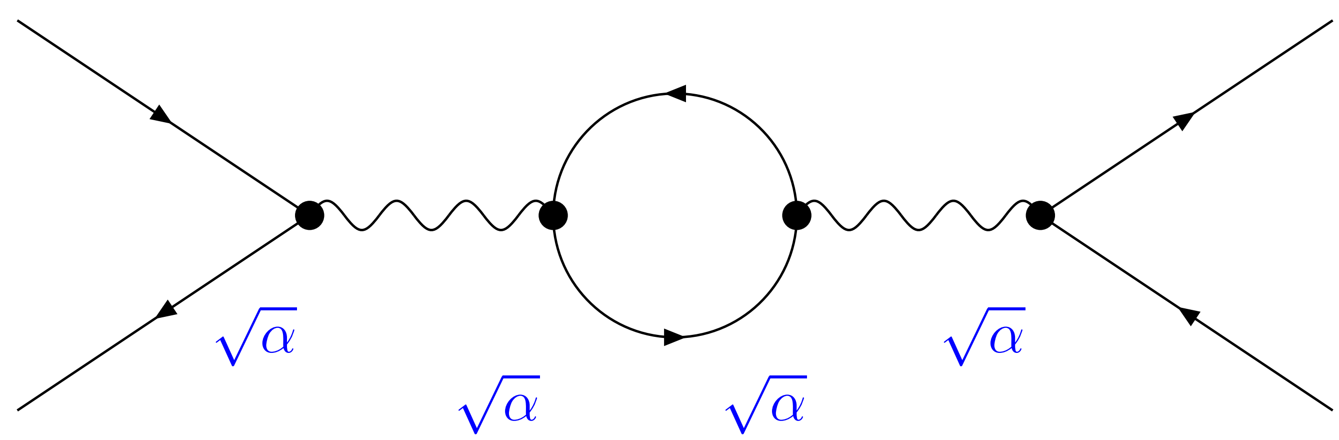
$\Leftrightarrow$ expansion about theory without interaction

lowest order,
classical limit



$\alpha \approx \frac{1}{137}$

quantum
corrections:
loop diagrams



$\mathcal{O}(\alpha)$ relative to lowest order

What can one learn from quantum corrections?

- Inclusion of quantum effects $\Leftrightarrow$ more accurate theoretical predictions

  Large loop corrections:

  - QCD corrections are often of $\mathcal{O}(100\%)$
  - EW enhancement factors: m_t^2, m_t^4, $\ldots$,
    large logarithms (involving two very different scales)
  - Per mille level corrections needed to match EW precision measurements

- Quantum effects provide sensitivity to the underlying structure of the theory

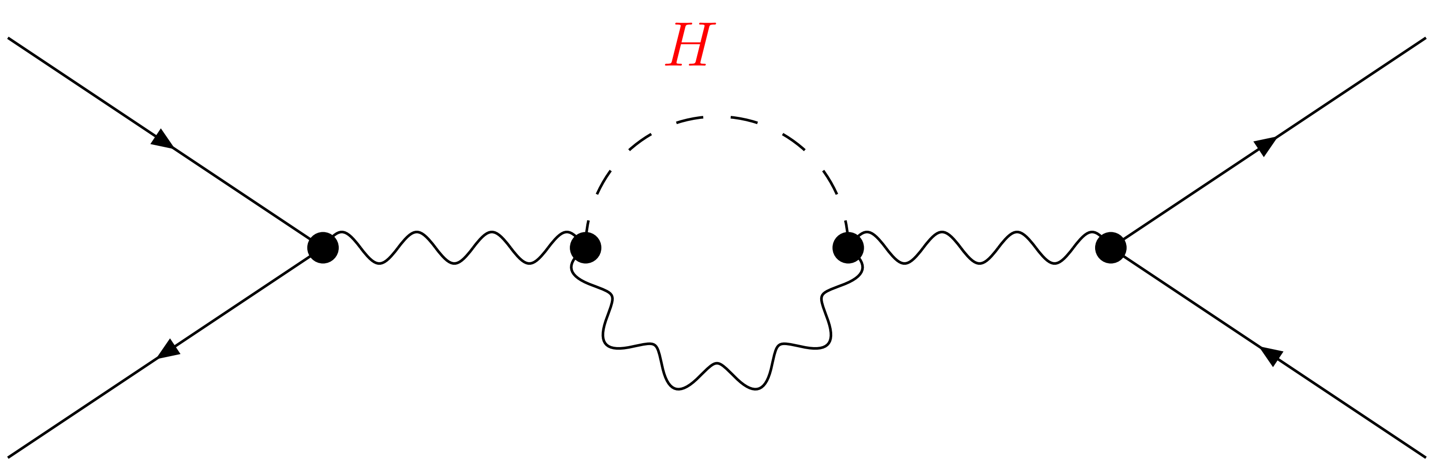
Electroweak precision physics: high-precision data vs. theory predictions

EW precision data:
$M_Z, M_W, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$

Theory:
SM, MSSM, ...

$\Downarrow$

Test of theory at quantum level: sensitivity to loop corrections



$\Downarrow$

Indirect constraints on unknown parameters: $M_{\mathrm{H}}, \ldots$

Effects of "new physics"?

Supersymmetry (SUSY)

SUSY: unique possibility to connect space–time symmetry (Lorentz invariance) with internal symmetries (gauge invariance):

Unique extension of the Poincaré group of symmetries of relativistic quantum field theories in $3+1$ dimensions

Local SUSY includes gravity, called “supergravity”

Lightest superpartner (LSP) is stable if “R parity” is conserved
$\Rightarrow$ Candidate for cold dark matter in the Universe

Gauge coupling unification, $M_{\mathrm{GUT}} \sim 10^{16}$ GeV
neutrino masses: see-saw scale $\sim .01$–$.1\, M_{\mathrm{GUT}}$

The minimal supersymmetric extension of the Standard Model (MSSM)

Superpartners for Standard Model particles:

$\left[u, d, c, s, t, b\right]_{L,R}$ $\left[e, \mu, \tau\right]_{L,R}$ $\left[\nu_{e,\mu,\tau}\right]_L$ Spin $\frac{1}{2}$

$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R}$ $\left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R}$ $\left[\tilde{\nu}_{e,\mu,\tau}\right]_L$ Spin 0

g $\underbrace{W^{\pm}, H^{\pm}}$ $\underbrace{\gamma, Z, H_1^0, H_2^0}$ Spin 1 / Spin 0

$\tilde{g}$ $\tilde{\chi}^{\pm}_{1,2}$ $\tilde{\chi}^0_{1,2,3,4}$ Spin $\frac{1}{2}$

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

Exact SUSY $\Leftrightarrow m_{\mathrm{e}} = m_{\tilde{\mathrm{e}}}, \ldots$

$\Rightarrow$ SUSY can only be realised as a broken symmetry

MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

High-precision physics

1978 Precise measurement of sinθ_W @ SLAC via polarized electrons $e^- D \to e^- X$
→ **Prediction of W and Z mass**

1983 Discovery of W and Z bosons at SppS

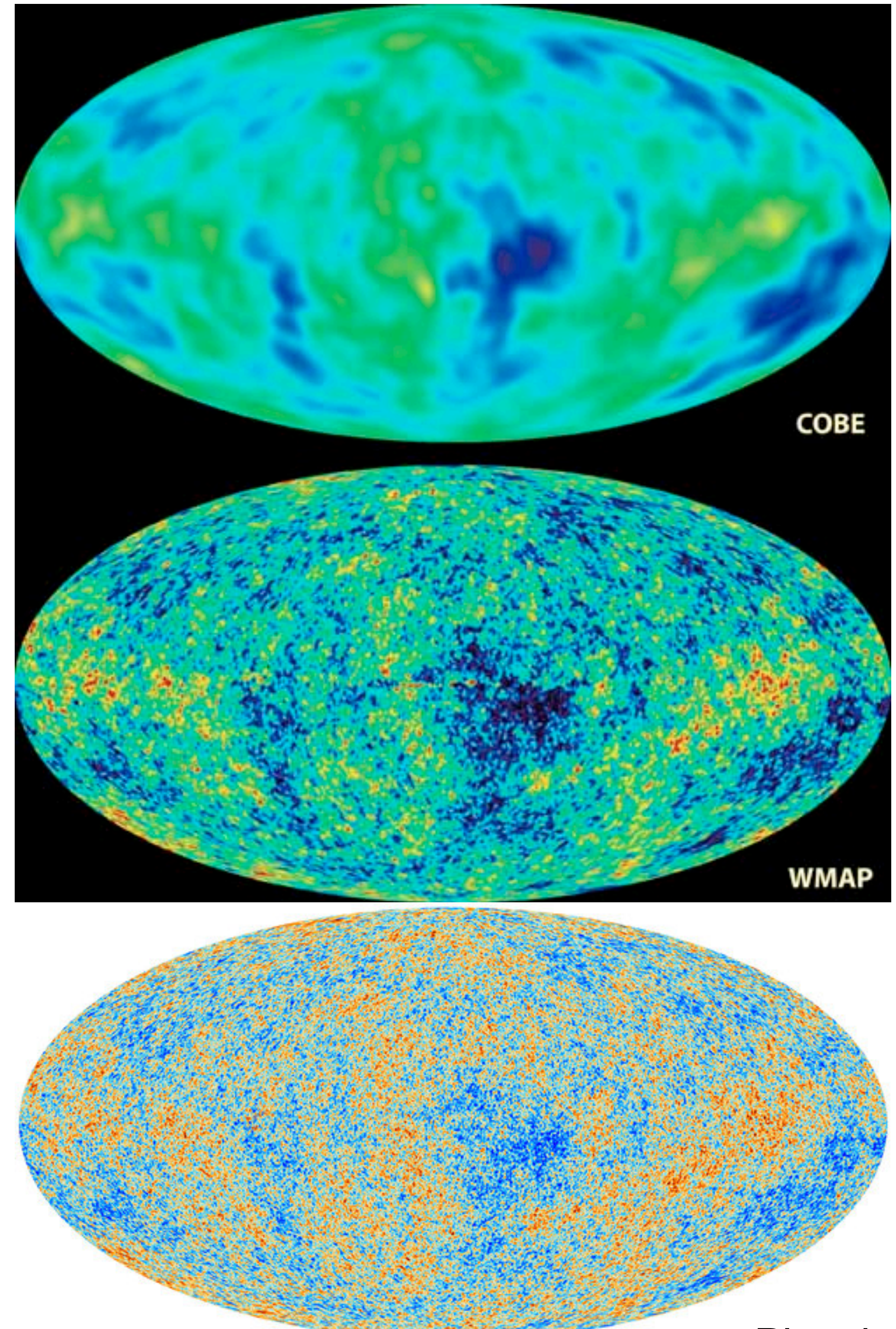
1989- Precise measurement of W and Z @ SLC/LEP → **Prediction of top mass**

1995 Discovery of top quark at Tevatron

Precise measurement of W, Z, top @ SLC/LEP/Tevatron → **Prediction of Higgs mass**

2012 Discovery of Higgs boson

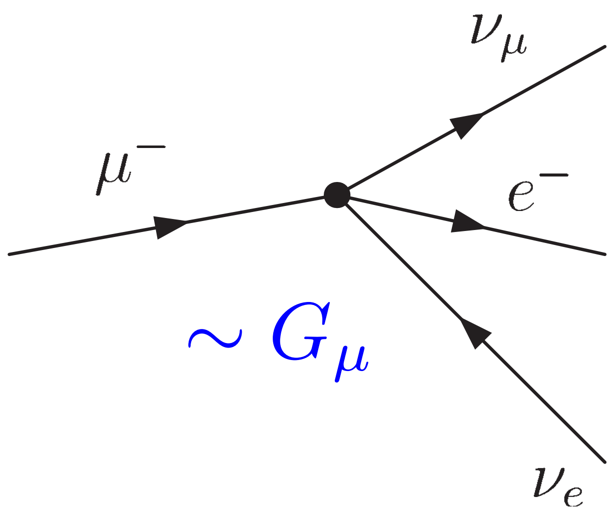
Precise measurement of W, Z, top, Higgs @ LHC/ILC → **Prediction of ???**

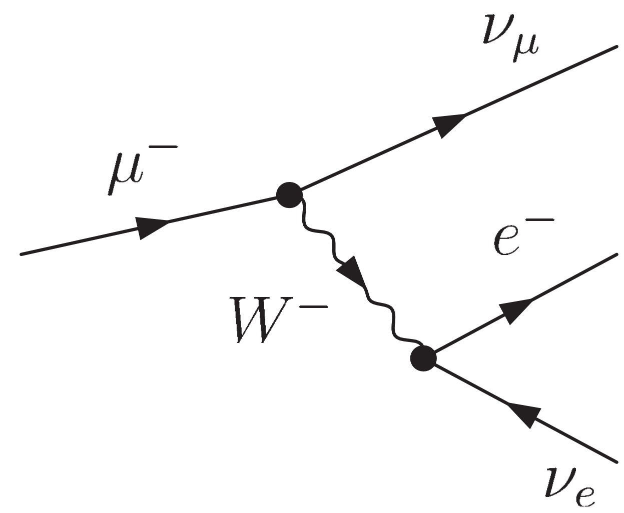


Planck

Example: prediction for the W-boson mass from muon decay

Fermi model





SM

M_W: Comparison of prediction for muon decay with experiment (Fermi constant G_μ)

$$\Rightarrow \quad M_\mathrm{W}^2 \left(1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu}\left(1 + \Delta r\right),$$

$\Updownarrow$

loop corrections

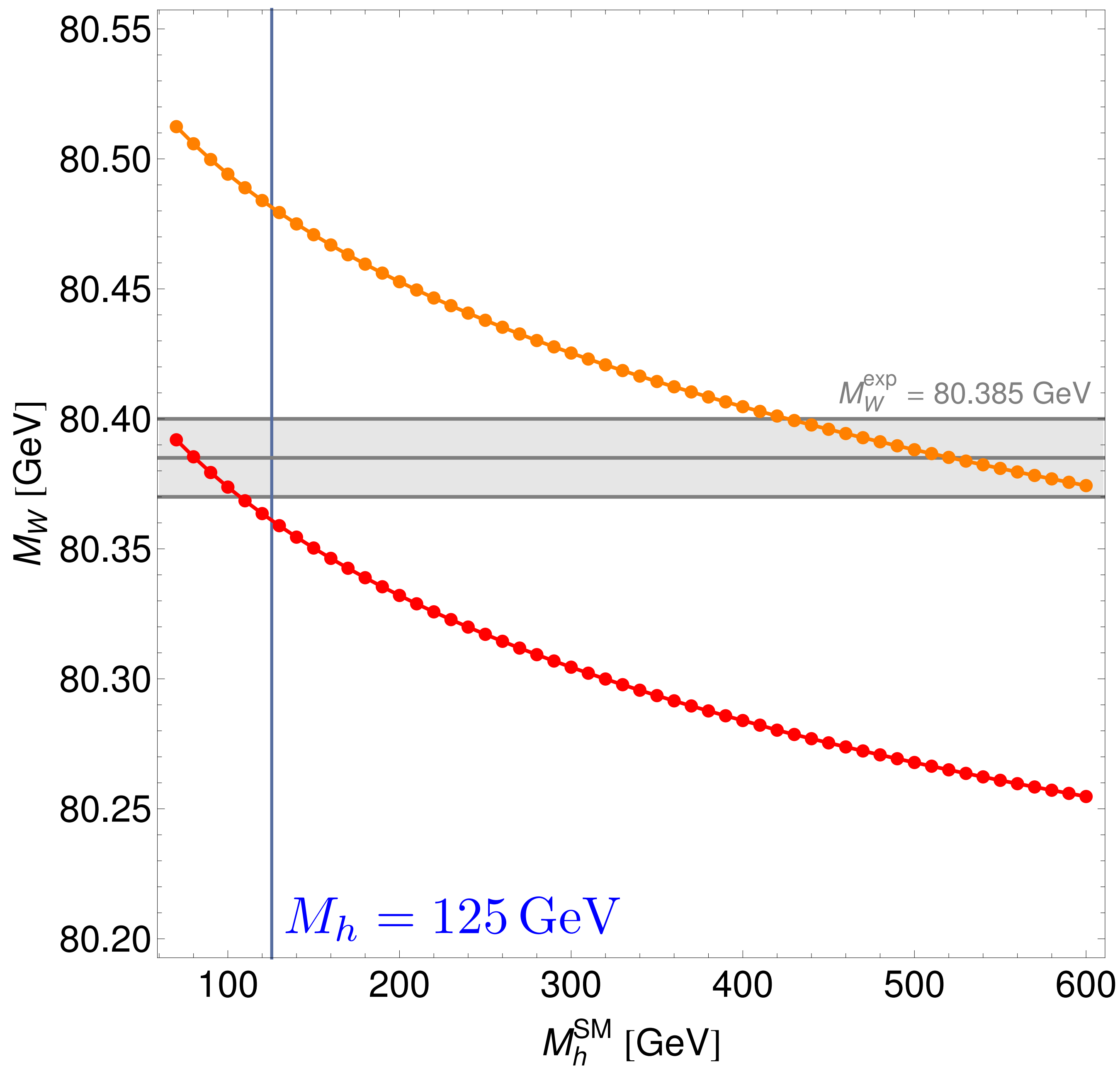
$\Rightarrow$ Theo. prediction for M_W in terms of M_Z, α, G_μ, $\Delta r(m_\mathrm{t}, m_{\tilde{\mathrm{t}}}, \ldots)$

Tree-level prediction: $M_\mathrm{W}^\mathrm{tree}$ = 80.939 GeV, $M_\mathrm{W}^\mathrm{exp}$ = 80.385 +- 0.015 GeV

⇒ off by > 30 σ (accuracy of 2×10^{-4})

W-mass prediction within the SM: one-loop result vs. state-of-the-art prediction

[L. Zeune, G. W. '14]



⇒ Pure one-loop result would imply preference for heavy Higgs, $M_h > 400$ GeV

Corrections beyond one-loop order are crucial for reliable prediction of M_W

Sources of theoretical uncertainties

- From experimental errors of the input parameters

$$\delta m_t = 0.9 \text{ GeV} \quad \Rightarrow \quad \Delta M_W^{\text{para}} \approx 5.4 \text{ MeV}, \; \Delta \sin^2 \theta_{\text{eff}}^{\text{para}} \approx 2.8 \times 10^{-5}$$

$$\delta(\Delta\alpha_{\text{had}}) = 0.00014 \quad \Rightarrow \quad \Delta M_W^{\text{para}} \approx 2.5 \text{ MeV}, \; \Delta \sin^2 \theta_{\text{eff}}^{\text{para}} \approx 4.8 \times 10^{-5}$$

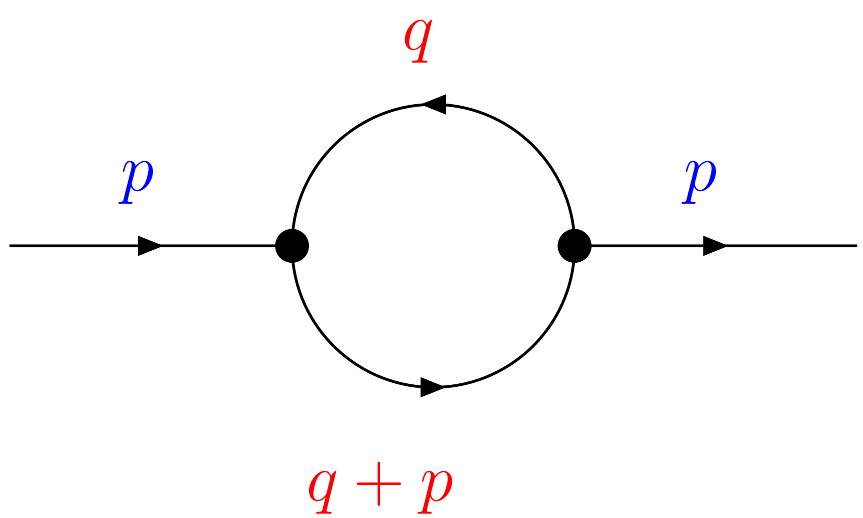
- From unknown higher-order corrections (“intrinsic”)

  SM: Complete 2-loop result $+$ leading higher-order corrections known for M_W and $\sin^2\theta_{\text{eff}}$

  $\Rightarrow$ Remaining uncertainties:
  [*M. Awramik, M. Czakon, A. Freitas, G.W. ’03, ’04*]
  [*M. Awramik, M. Czakon, A. Freitas ’06*]

$$\Delta M_W^{\text{intr}} \approx 4 \text{ MeV}, \quad \Delta \sin^2 \theta_{\text{eff}}^{\text{intr}} \approx 5 \times 10^{-5}$$

Quantum corrections: regularisation and renormalisation



$$\sim \int d^4q \frac{1}{(q^2 - m_1^2 + i\varepsilon)\left[(q+k)^2 - m_2^2 + i\varepsilon\right]}$$

$$q \to \infty: \quad \sim \int_0^\infty \frac{q^3 dq}{q^4} = \int_0^\infty \frac{dq}{q} \quad \to \infty$$

$\Rightarrow$ integral diverges for large q!

$\Rightarrow$ theory in this form not physically meaningful

$\Rightarrow$ further concept needed: renormalisation

Renormalisable theories: infinities can consistently be absorbed into parameters of theory

Two step procedure: regularisation

Regularisation:

theory modified such that expressions become mathematically meaningful

$\Rightarrow$ “regulator” introduced, removed at the end

e.g. cut-off in loop integral

$$\int_0^\infty d^4q \;\rightarrow\; \int_0^\Lambda d^4q; \quad \Lambda \rightarrow \infty \text{ at the end}$$

technically more convenient: dimensional regularisation

$$\int d^4q \;\rightarrow\; \int d^Dq, \quad D = 4 - \varepsilon; \quad D \rightarrow 4 \text{ at the end}$$

Two step procedure: renormalisation

Renormalisation:

original "bare" parameters replaced by renormalised parameters $+$ counterterms

reparametrization:

$$\underbrace{g_0}_{\text{bare parameter}} = \underbrace{g}_{\text{renormalised parameter}} + \underbrace{\delta g}_{\text{counterterm}}$$

Renormalisable theory:

divergences compensated by counterterms

Two aspects of renormalisation

- Absorption of divergences
- Determination of physical meaning of parameters order by order in perturbation theory

Why do parameters (and fields) have to be renormalised?

- The SM Lagrangian contains free parameters that are not predicted by the theory:

  α, M_W, M_Z, M_H $+$ fermion masses $+$ four parameters of the quark-mixing matrix ($+$ four parameters of the lepton-mixing matrix if right-handed neutrinos are included)

- The bare parameters appearing in the Lagrangian have no physical meaning

- One needs n physical observables (masses, cross sections, . . .) to fix n free parameters of the Lagrangian (further observables $\Leftrightarrow$ test of the theory)

Why do parameters (and fields) have to be renormalised?

- Only relations between observables are physically meaningful, not relations between observables and bare parameters

- Relations between physical observables include loop effects to all orders; one cannot "switch off" the interactions in nature

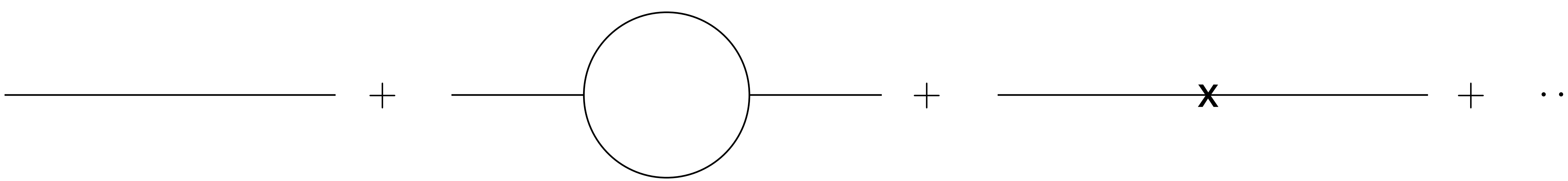
$\Rightarrow$ Need to define the meaning of the parameters in the Lagrangian in every loop order

Example: mass renormalisation (stable particle)

Renormalisation of the mass parameter: $m_0^2 = m^2 + \delta m^2$

Physical mass: pole of propagator

inverse propagator up to 1-loop order:



$p^2 - m^2$ $\qquad \Sigma(p^2)$ $\qquad -\delta m^2 + (p^2 - m^2)\delta Z_\Phi$

Pole of the propagator: $p^2 - m^2 + \Sigma(p^2) \; -\delta m^2 + (p^2 - m^2)\delta Z_\Phi = 0$

On-shell and MS renormalisation

"On-shell renormalisation": $\delta m^2 = \Sigma(p^2)\big|_{p^2=m^2}$

$\Rightarrow$ pole of propagator for $p^2 = m^2 \Rightarrow m$: "pole mass"

Counterterm contains divergence: expansion in $\varepsilon \equiv 4 - D$, 1-loop:

$$\delta m^2 = \underbrace{a\,\frac{1}{\varepsilon}}_{\substack{\text{divergent} \\ \text{for } D \to 4}} + \underbrace{b\,\varepsilon^0}_{\text{finite}} + \underbrace{c\,\varepsilon}_{\substack{\to 0 \\ \text{for } D \to 4}} + \ldots$$

Other renormalisation prescription:

$$\delta m^2 = a\frac{1}{\varepsilon}$$ "minimal subtraction" (MS)

On-shell and MS renormalisation

Slight variant of MS renormalisation: ``modified minimal subtraction”, $\overline{\mathrm{MS}}$

$\overline{\mathrm{MS}}$ and MS quantities depend on renormalisation scale μ (needs to be introduced for dimensional reasons)

$\overline{\mathrm{MS}}$ top quark mass: $m_t(\mu)$, ``running mass”

The difference between the pole mass and $m_t(m_t)$ from QCD corrections amounts to about 10 GeV!

The strong coupling is usually given as $\overline{\mathrm{MS}}$ quantity: $\alpha_{\mathrm{s}}(\mu)$, ``running coupling”

Mass renormalisation for unstable particles

For unstable particles: $\Sigma(p^2)\Big|_{p^2=m^2}$ is complex!

⇒ The pole of the propagator lies in the complex plane of p^2

How is the mass of an unstable particle related to the complex pole of the propagator?

The complex pole is gauge-invariant

⇒ Determine the mass from the real part of the complex pole:

$\mathcal{M}^2 = M^2 - iM\Gamma$, M: physical mass, Γ: decay width

What is the mass of an unstable particle?

Particle masses are not directly physical observables

Can only measure cross sections, branching ratios, kinematical distributions, . . .

$\Rightarrow$ masses are "pseudo-observables"

Need to define what is meant by M_{Z}, M_{W}, $m_{\mathrm{t}}, \ldots$:

$\overline{\mathrm{MS}}$ mass, pole mass (real pole, real part of complex pole, Breit–Wigner shape with running or constant width), . . .

$\Rightarrow$ Determination of M_{Z}, M_{W}, $m_{\mathrm{t}}, \ldots$ involves deconvolution procedure (unfolding)

Mass obtained from comparison data – Monte Carlo

$\Rightarrow$ M_{Z}, M_{W}, $m_{\mathrm{t}}, \ldots$ are not strictly model-independent

What is the mass of an unstable particle?

The experimental value of M_{Z} is (slightly) model-dependent

In the SM: Dependence on the value of the Higgs mass

$\delta M_{\mathrm{Z}} = \pm 0.2$ MeV for $100\ \mathrm{GeV} \leq M_{\mathrm{H}} \leq 1\ \mathrm{TeV}$

$\Rightarrow M_{\mathrm{Z}}^{\mathrm{SM}}$ (slightly) differs from $M_{\mathrm{Z}}^{\mathrm{MSSM}}$

Differences could be much bigger, in principle, for $\alpha_s(M_{\mathrm{Z}})$

Numerical differences between the various mass definitions for M_{W}, M_{Z} are relatively large

(Running / constant width in Breit–Wigner $\Rightarrow \Delta M_{\mathrm{W}} = 27\ \mathrm{MeV}$)

$\Rightarrow$ Important to always refer to the same definition

Expansion around the complex pole (example: M_Z)

Expansion of amplitude around complex pole:

$$\mathcal{A}(e^+e^- \to f\bar{f}) = \frac{R}{s - \mathcal{M}_\mathrm{Z}^2} + S + (s - \mathcal{M}_\mathrm{Z}^2)\, S' + \cdots$$

$$\mathcal{M}_\mathrm{Z}^2 = \overline{M}_\mathrm{Z}^2 - i\overline{M}_\mathrm{Z}\,\overline{\Gamma}_\mathrm{Z}$$

Expanding up to $\mathcal{O}(\alpha^2)$ using $\mathcal{O}(\overline{\Gamma}_\mathrm{Z}/\overline{M}_\mathrm{Z}) = \mathcal{O}(\alpha)$

From 2-loop order on:

real part of complex pole, $\overline{M}_\mathrm{Z} \neq$ pole of real part, $\widetilde{M}_\mathrm{Z}^2$

$$\delta\overline{M}^2_{(2)} = \delta\widetilde{M}^2_{(2)} + \underbrace{\mathrm{Im}\left\{\Sigma'_{\mathrm{T},(1)}(M^2)\right\}\ \mathrm{Im}\left\{\Sigma_{\mathrm{T},(1)}(M^2)\right\}}_{\text{gauge-parameter dependent!}}$$

Physical mass of unstable particles: real part of complex pole

$\Rightarrow$ Only the complex pole is gauge-invariant

Expansion around the complex pole leads to a Breit–Wigner shape with constant width

For historical reasons, the experimental values of M_{Z}, M_{W} are defined according to a Breit–Wigner shape with running width

$\Rightarrow$ Need to correct for the difference in definition when comparing theory with experiment

Standard Model and Higgs Physics, Lectures 3,4

Georg Weiglein, DESY

46. Herbstschule fuer Hochenergiephysik, Maria Laach, 09 / 2014

Top and electroweak physics

$\sin^2\theta_{\text{eff}}$, M_W, ...: Electroweak precision observables, high sensitivity to effects of new physics

$\Rightarrow$ test of the theory, discrimination between models

Top quark: By far the largest quark mass, largest mass of all known fundamental particles $\Rightarrow$ window to new physics?

$\Rightarrow$ large coupling to the Higgs boson

important for physics of flavour

prediction of m_t from underlying theory?

Loop corrections $\Rightarrow$ non-decoupling effects prop. to m_t^2, m_t^4

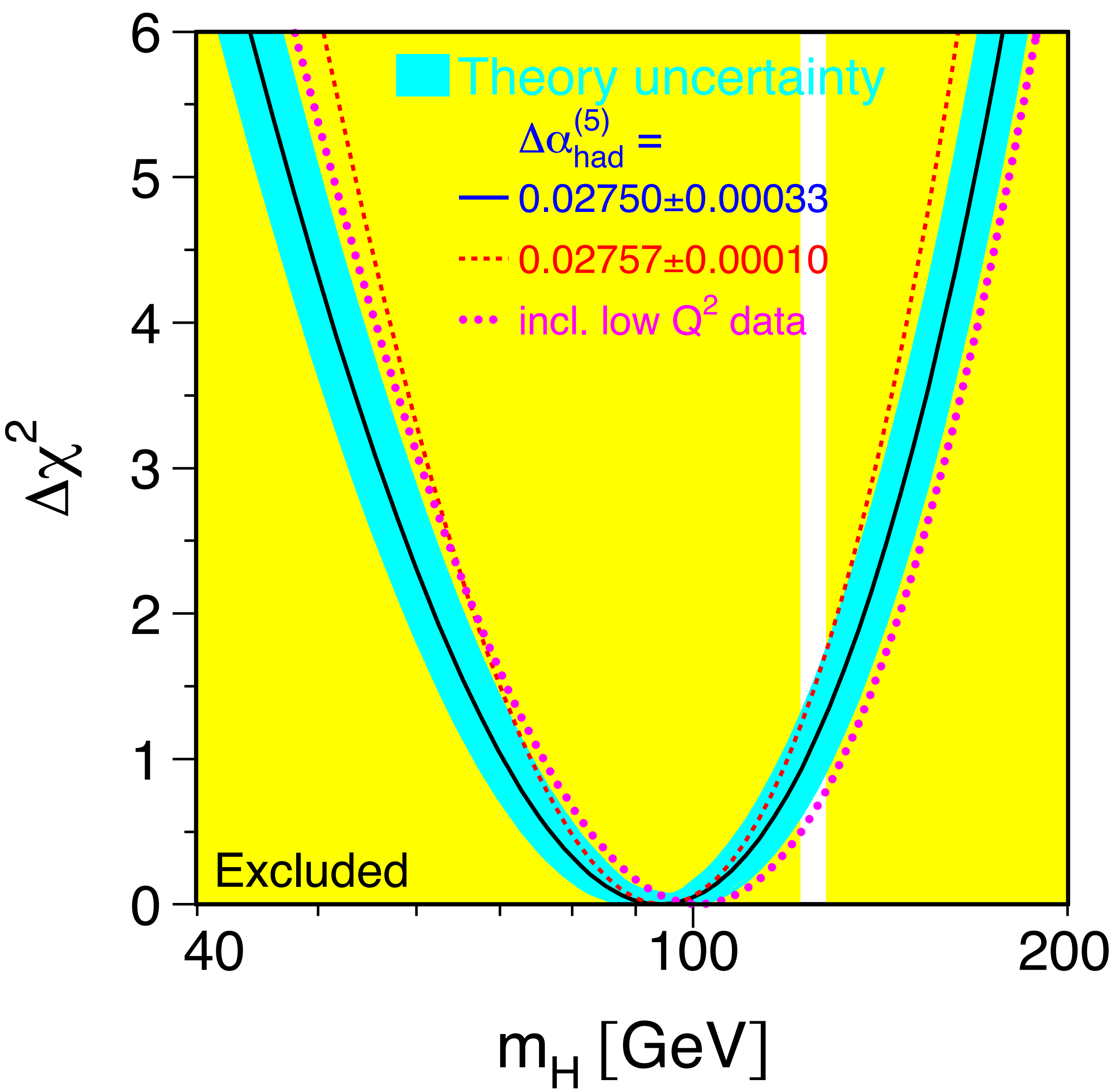
$\Rightarrow$ Need to know m_t very precisely in order to have sensitivity to new physics

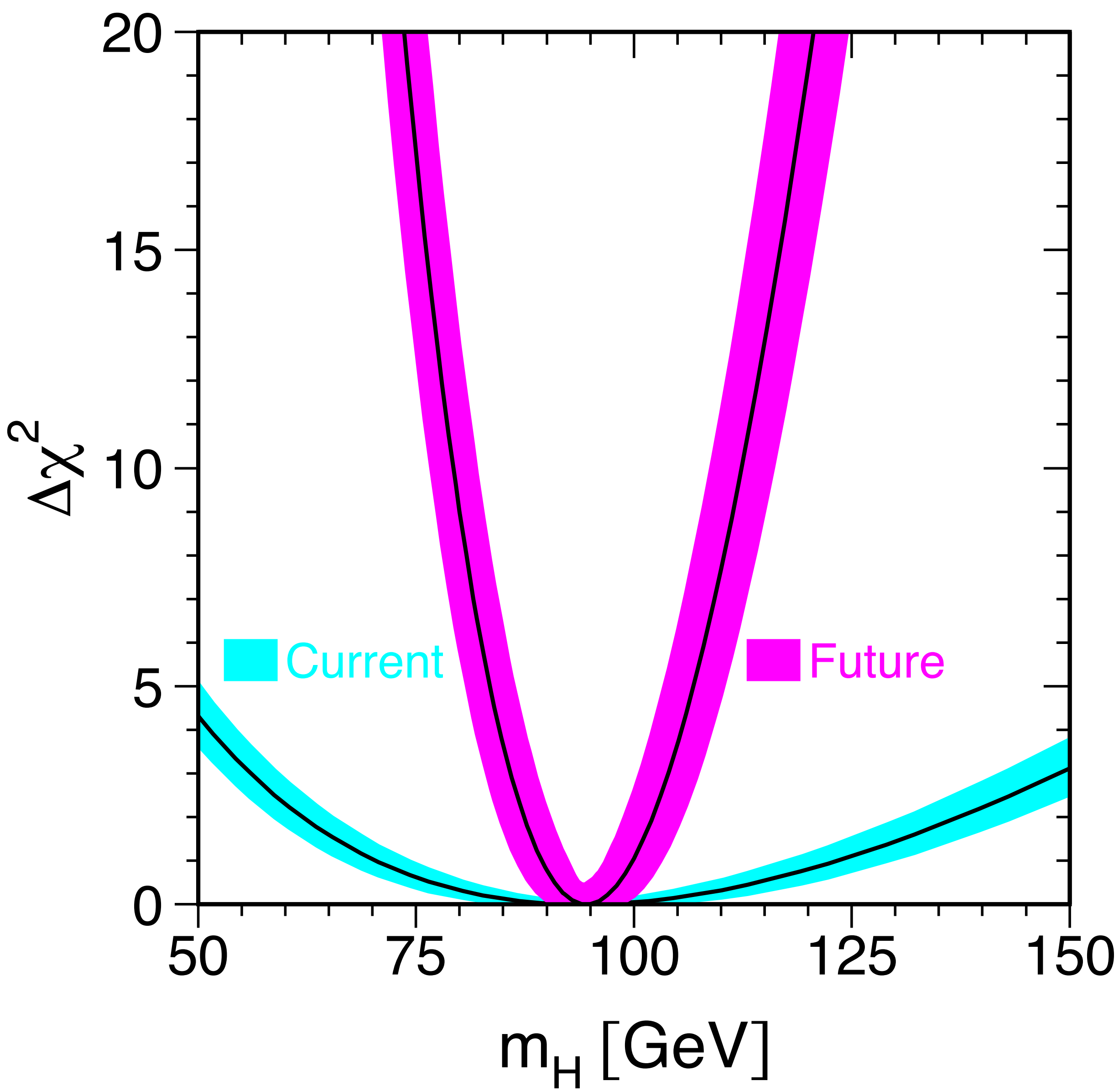
Higgs sector: indirect constraints on the Higgs mass within the SM, current situation vs. ILC (GigaZ)

Leading corrections to precision observables:

$\sim m_t^2$

$\sim \ln M_H$





⇒ Large increase in sensitivity, could lead to tension with exp. value

Precision top physics

Which mass is actually measured at the Tevatron and the LHC?

What is the mass of an unstable coloured particle?
Impact of higher-order effects?
The pole mass is not “IR safe”

ILC:

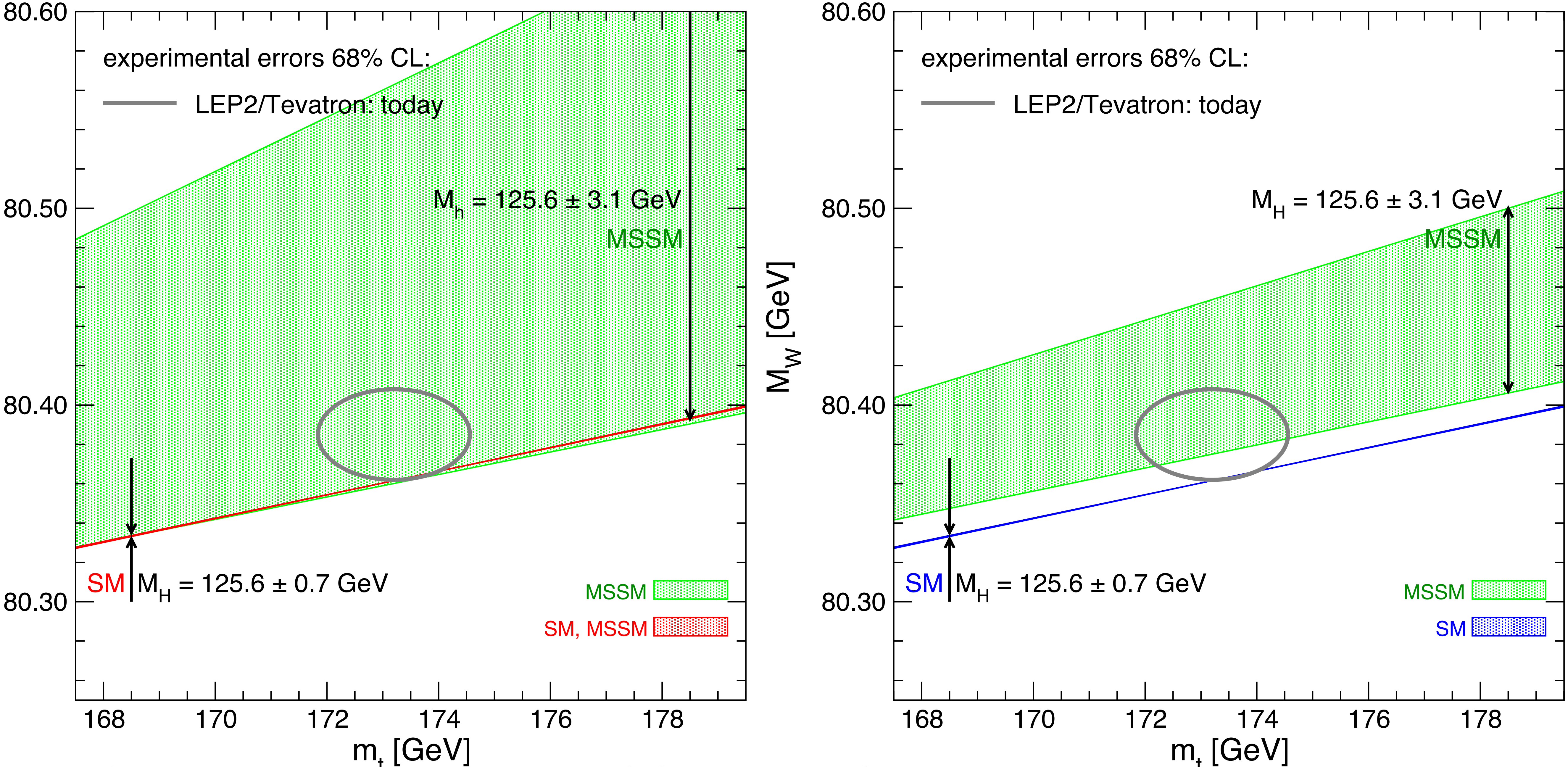
Measurement of ‘threshold mass’ with high precision:
$\lesssim 20\ \mathrm{MeV}$ + transition to suitably defined (short-distance) top-quark mass, e.g. $\overline{\mathrm{MS}}$ mass

ILC: $\delta m_{\mathrm{t}}^{\mathrm{exp}} \lesssim 100\ \mathrm{MeV}$ (dominated by theory uncertainty)

Prediction for M_W (parameter scan): SM vs. MSSM

Signal interpreted as light (left) / heavy (right) CP-even Higgs

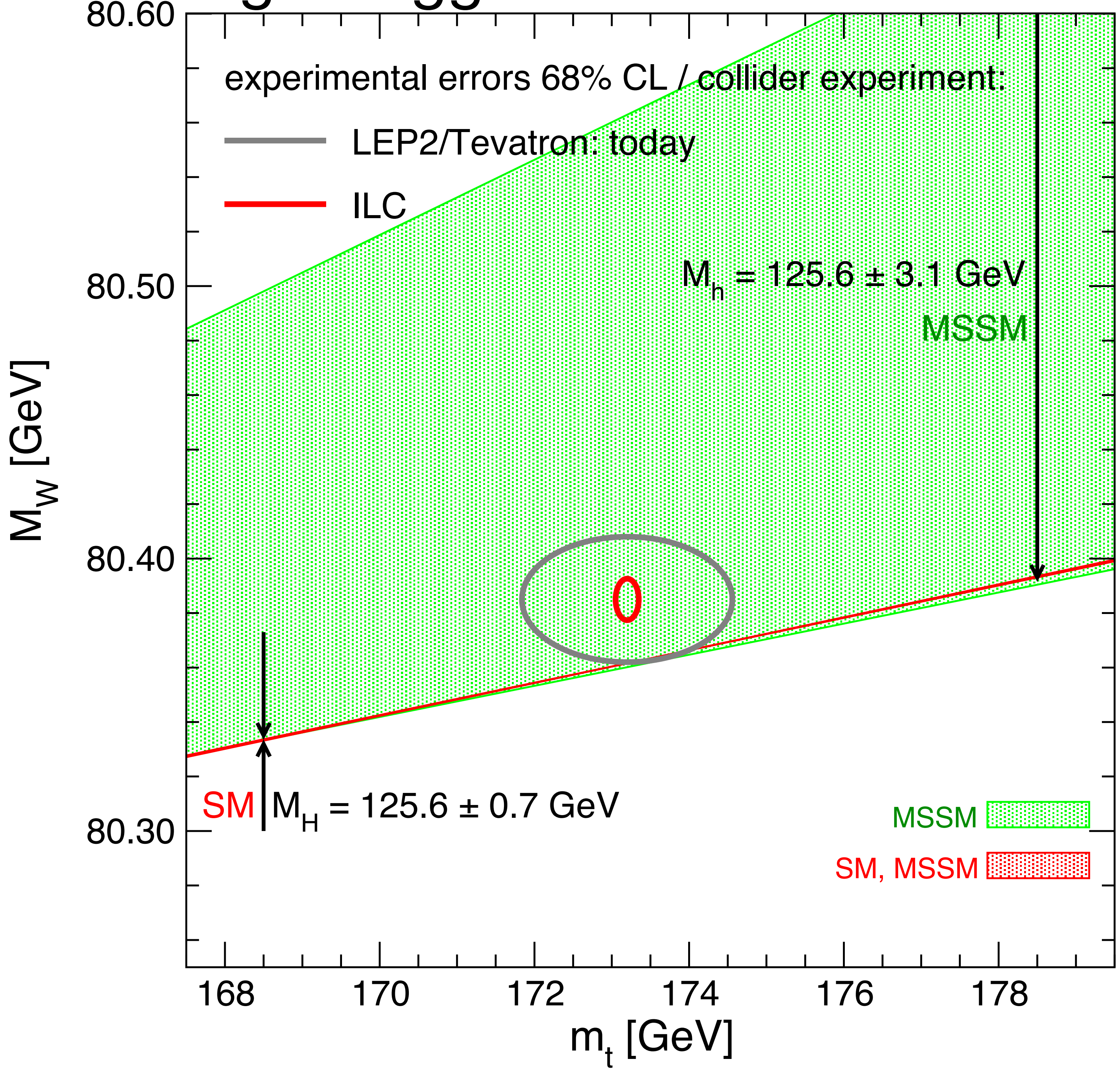
MSSM: SUSY parameters varied *[S. Heinemeyer, W. Hollik, G. W., L. Zeune '14]*



⇒ Slight preference for MSSM over SM

Prediction for M_W (parameter scan): SM vs. MSSM

Signal interpreted as light Higgs h *[S. Heinemeyer, W. Hollik, G. W., L. Zeune '14]*

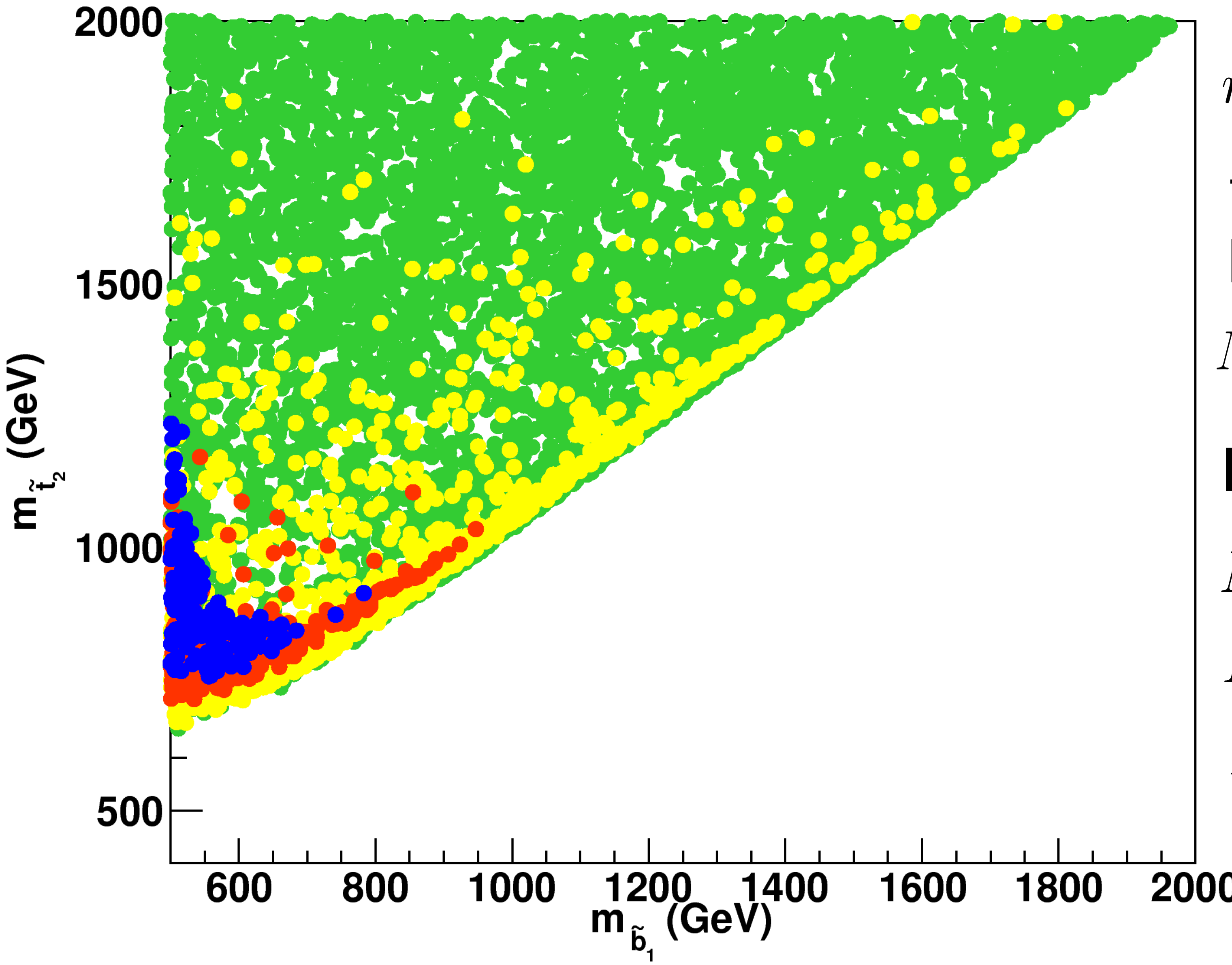


⇒Large improvement at the ILC, high sensitivity to new physics effects

Impact of high-precison measurements of m_t and M_W

Upper bounds on the heavier stop mass and the lighter sbottom mass in a hypothetical future scenario where the LHC has detected the lighter stop

Parameter scan: *[S. Heinemeyer, W. Hollik, G. W., L. Zeune '14]*



$$m_{\tilde{t}_1} = 400 \pm 40 \text{ GeV}$$

+ lower limits on other SUSY particles

$$M_h = 125.6 \pm 3.1 \text{ GeV}$$

Improved M_W precision:

$M_W = 80.375 \pm 0.005$ GeV (yellow)

$M_W = 80.385 \pm 0.005$ GeV (red)

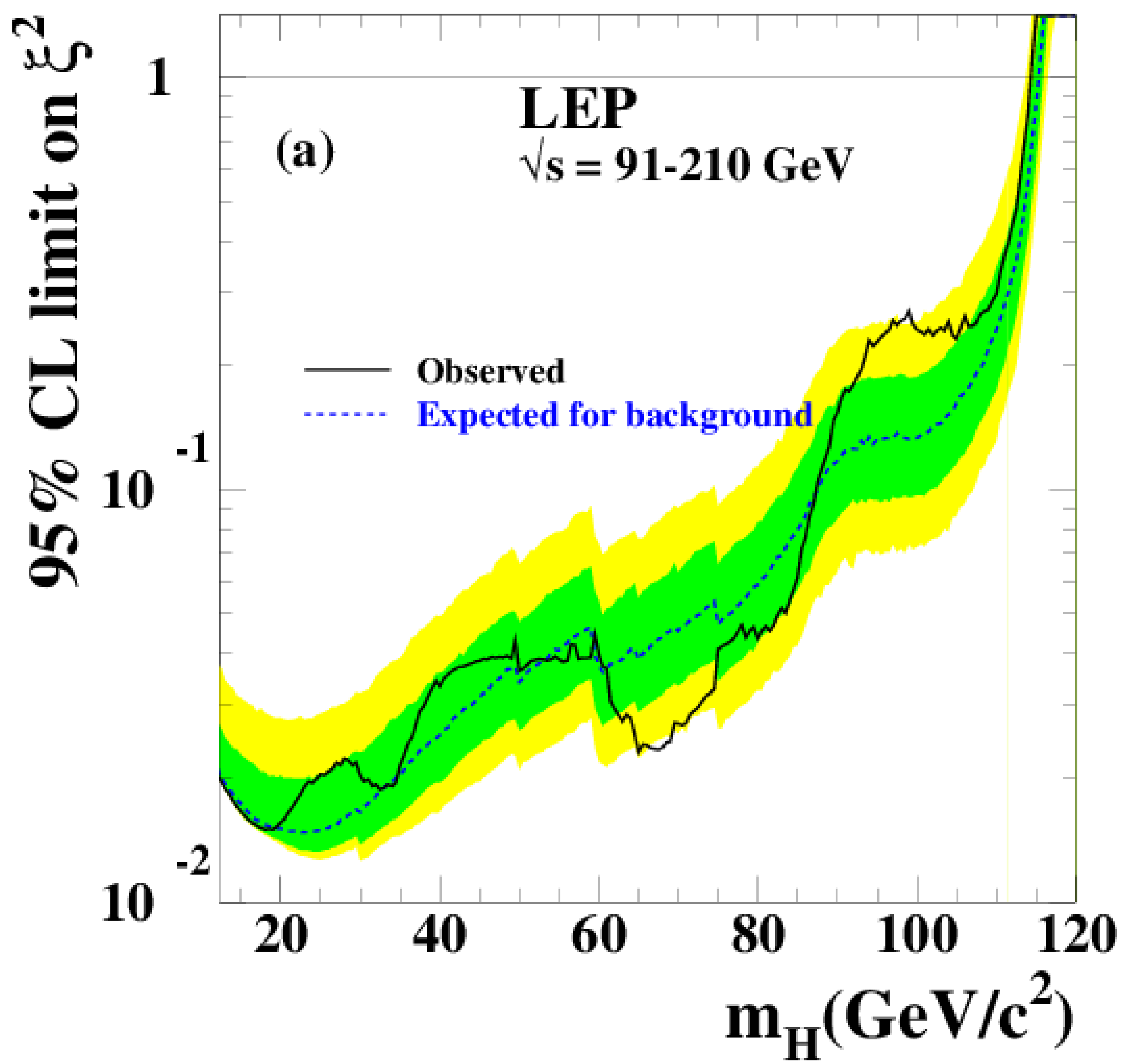
$M_W = 80.395 \pm 0.005$ GeV (blue)

⇒Precision observables provide constraints on undetected particles

Higgs phenomenology: Standard Model and beyond

Limits from the LEP Higgs searches: $e^+e^- \to ZH, H \to b\bar{b}$

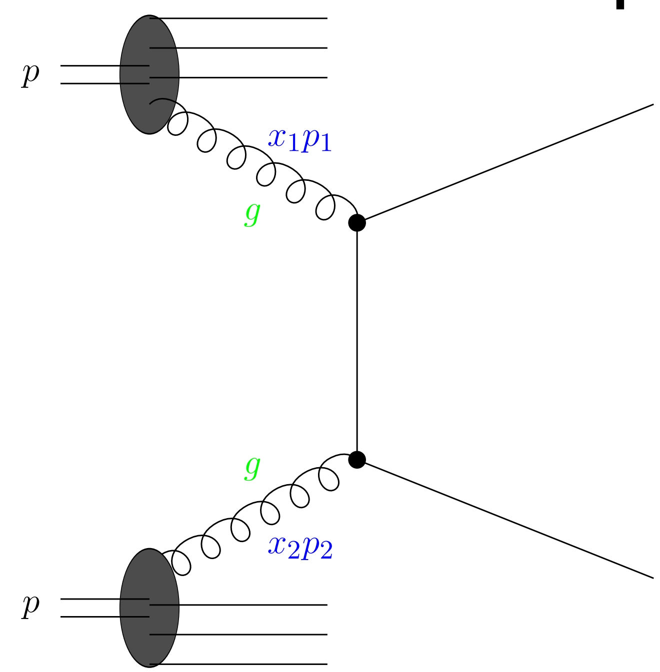
$$\left(\frac{g_{\mathrm{HZZ}}}{g_{\mathrm{HZZ}}^{\mathrm{SM}}}\right)^2$$



⇒ Limit for SM Higgs (ξ = 1): M_H > 114.4 GeV at 95% CL
No limit if the HZZ coupling is below 10% of the SM value

LHC: proton-proton scattering

pp scattering contains "hard" collision process of partons q, $\bar{q}$, g, e.g.:



[(over-) simplified parton-model picture]

$$\text{LHC: } \sigma(pp) = \int_0^1 \int_0^1 dx_1 dx_2 \sum_{q_i, q_j} q_i^p(x_1)\, q_j^p(x_2)\, \sigma(q_i q_j)$$

Available $(\text{energy})^2$ for partonic sub-process: $\hat{s} = x_1 x_2 s$

LHC: $\sqrt{s} = 14$ TeV; $\sqrt{\hat{s}}$ up to several TeV

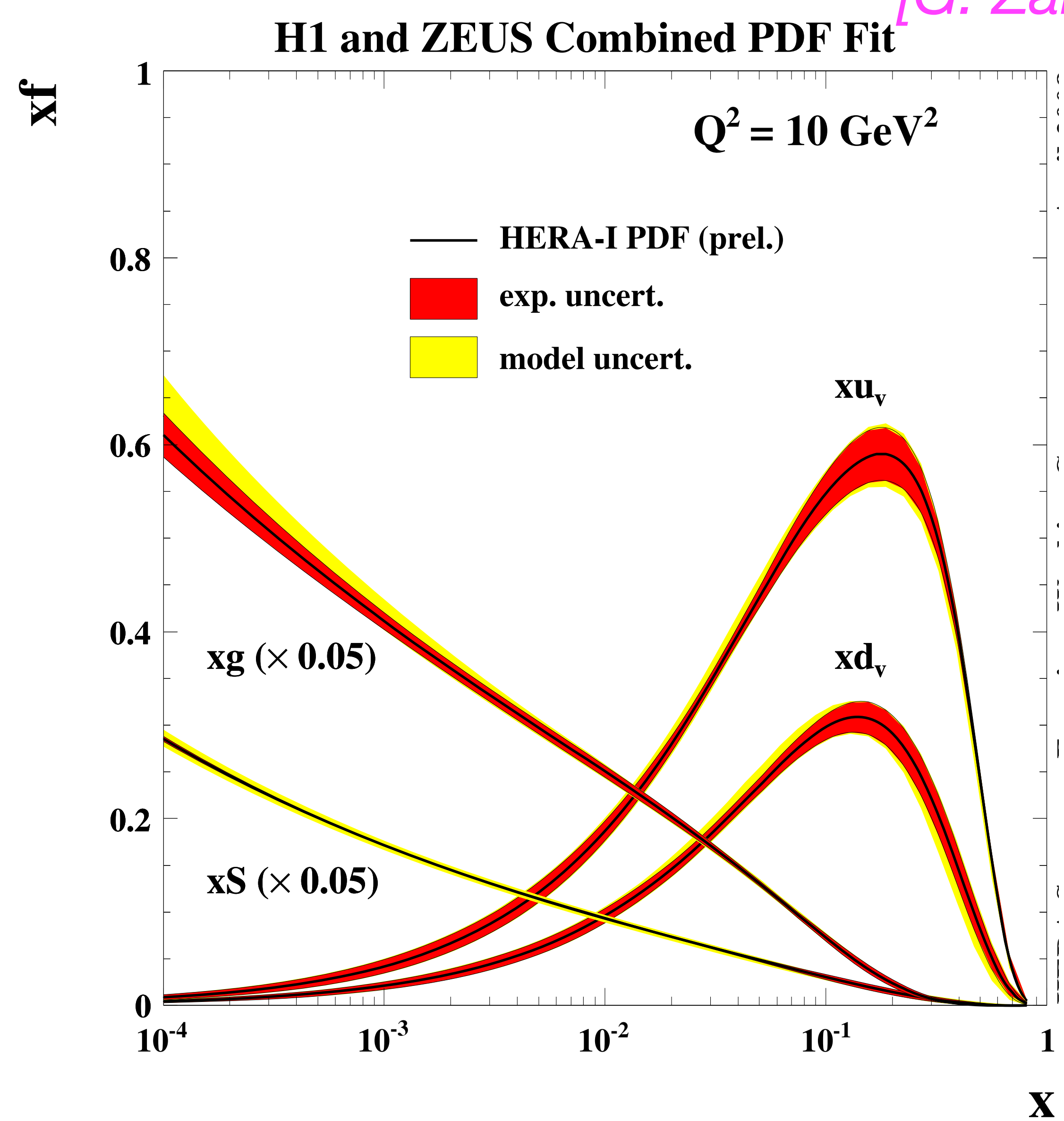
Proton remnant lost in beam pipe: can exploit only kinematics of transverse momenta

Typical features of pdf's

[G. Zanderighi '14]

Typical features:

- gluon distribution very large
- gluon and sea distributions grow at small x
- gluon dominates at small x
- valence distributions peak at x = 0.1 - 0.2
- largest uncertainties at very small or very large x



Crucial property: factorization!

PDFs extracted in DIS can be used at hadron colliders. This assumption can be checked against data (but often rigorous proof is missing)

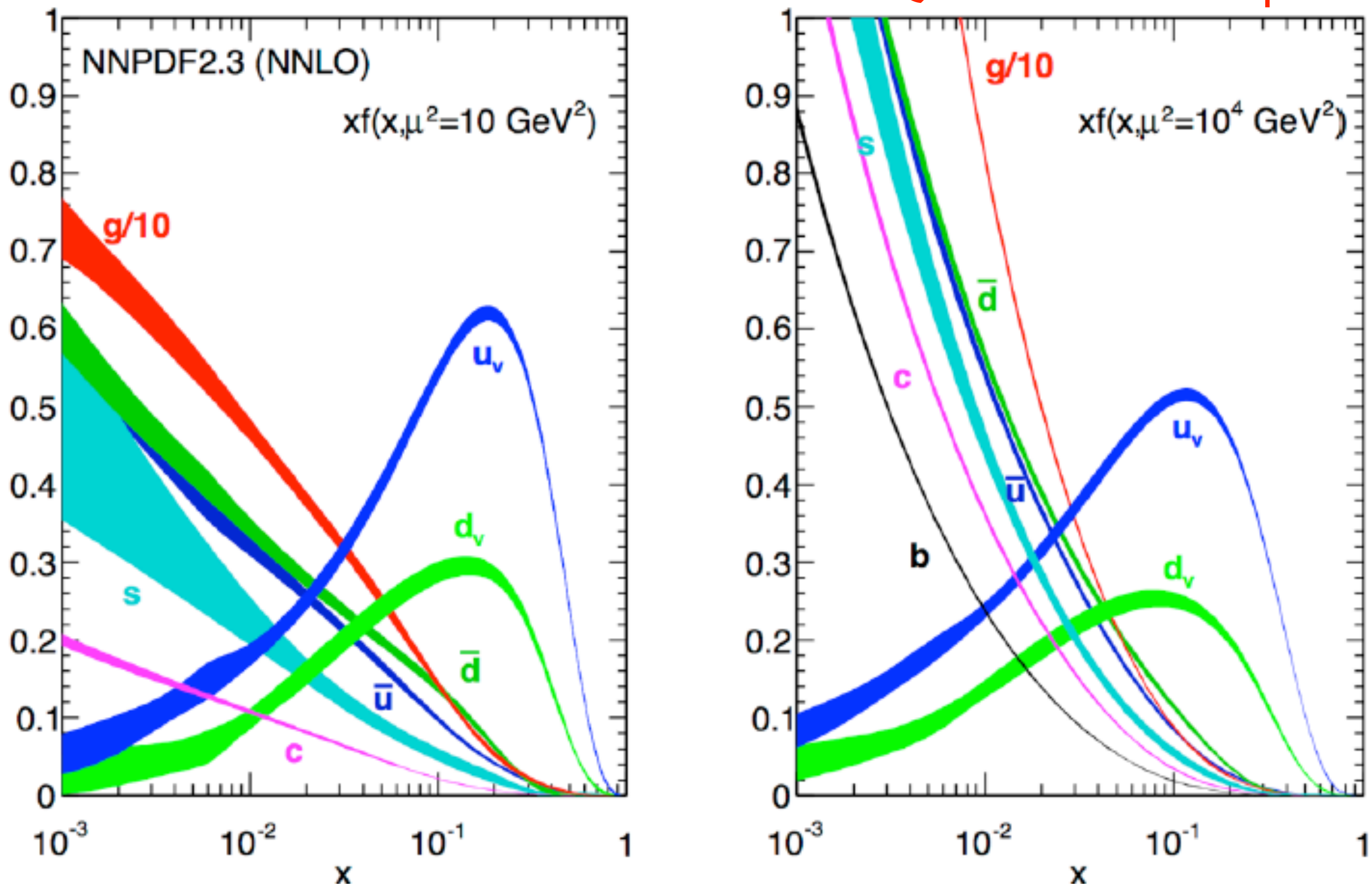
DGLAP evolution

[G. Zanderighi ’14]

The DGLAP evolution is a key to precision LHC phenomenology: it allows to measure PDFs at some scale (say in DIS) and evolve upwards to make LHC (7, 8, 13, 14, 33, 100.... TeV) predictions

Measure PDFs at 10 GeV

Evolve in Q^2 and make LHC predictions



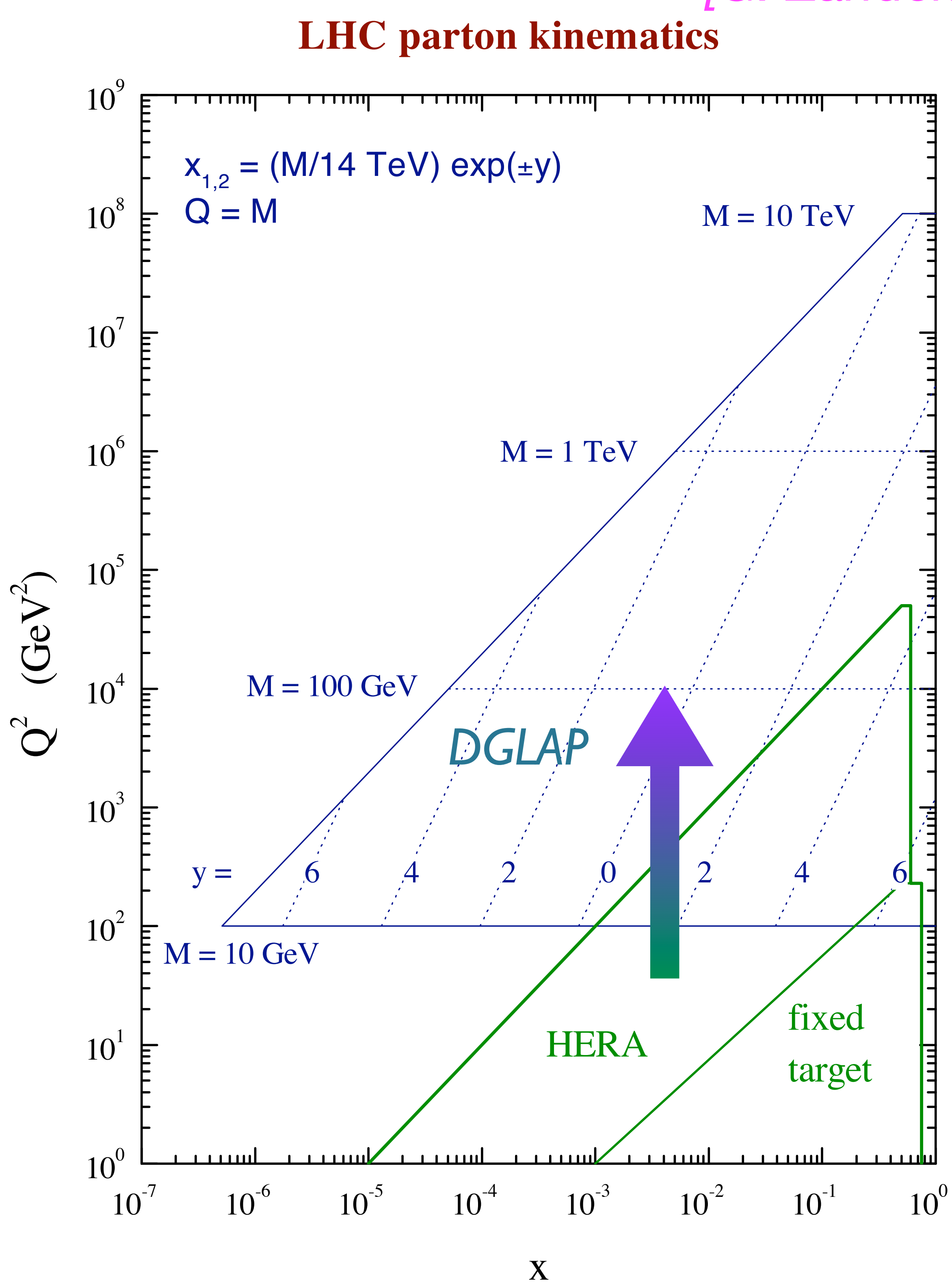
Different PDFs evolve in different ways (different equations + unitarity constraint)

⇒ The LHC is a ``gluon factory”

Parton density coverage

- most of the LHC x-range covered by Hera
- need 2-3 orders of magnitude Q^2-evolution
- rapidity distributions probe extreme x-values
- 100 GeV physics at LHC: small-x, sea partons
- TeV physics: large x

[G. Zanderighi ’14]



Precise predictions for LHC processes

Processes with many external legs are important for signal and background predictions, e.g. W + n jet production; scale uncertainty at leading order: 9% for n = 1, 28% for n = 2, 47% for n= 3, 64% for n = 4 (~ $\alpha_s(\mu)^4$), ...

$\Rightarrow$ Need NLO predictions to reduce theoretical uncertainty

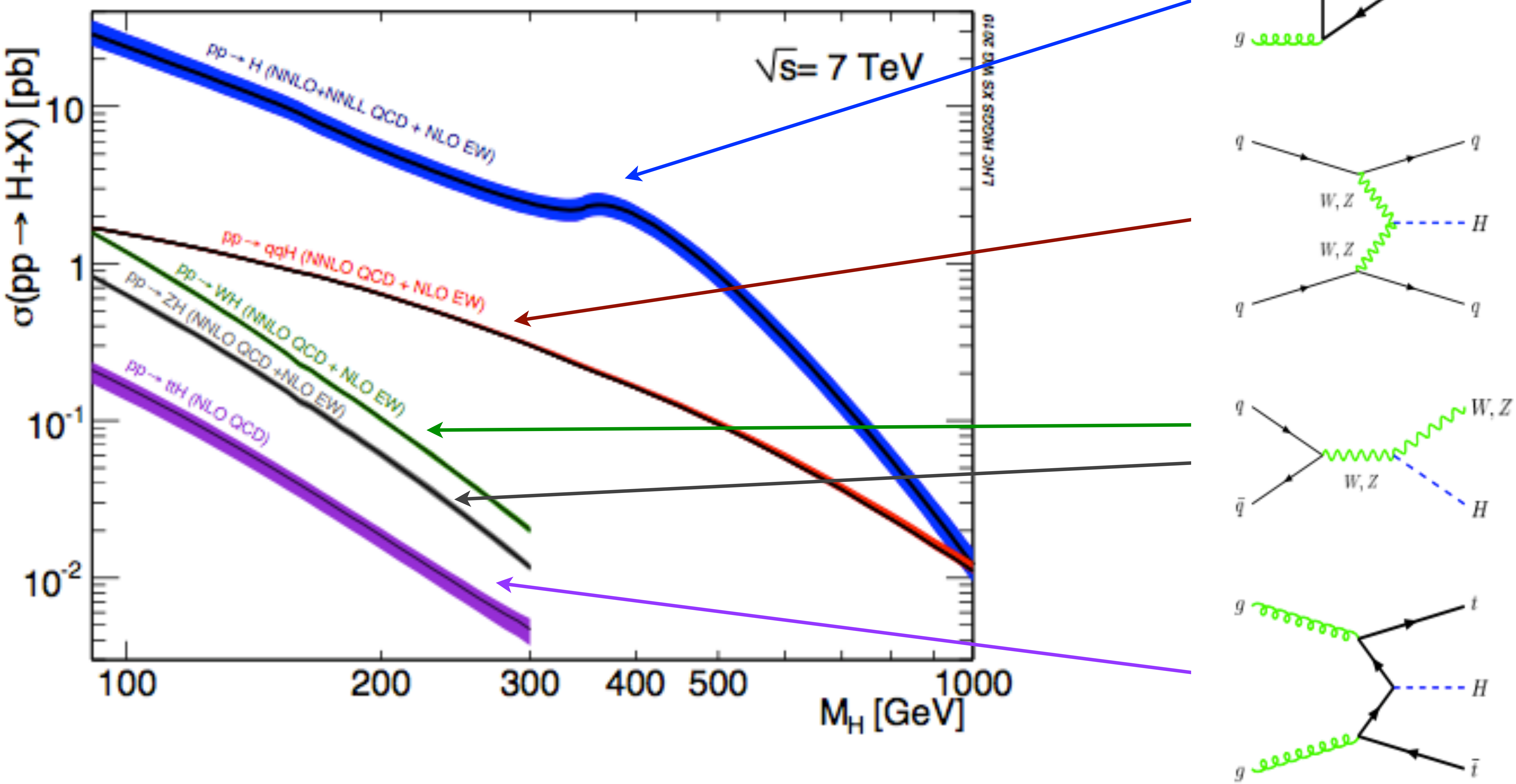
NLO predictions:

- Improve normalisation and shape of cross sections
- Improved description of hard jets
- ....

Difficult task for multi-leg processes

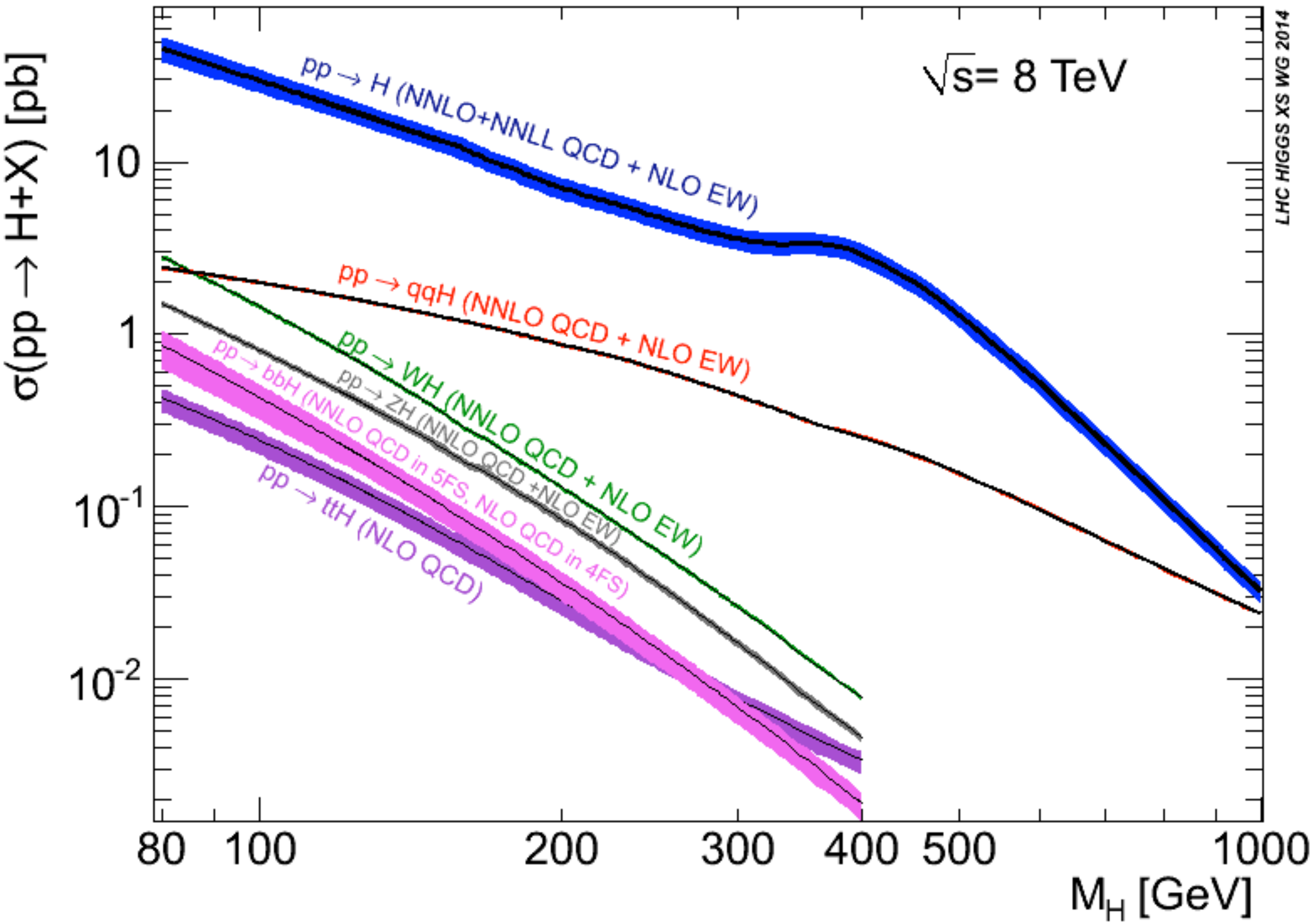
Production of a SM Higgs at the LHC

Production modes



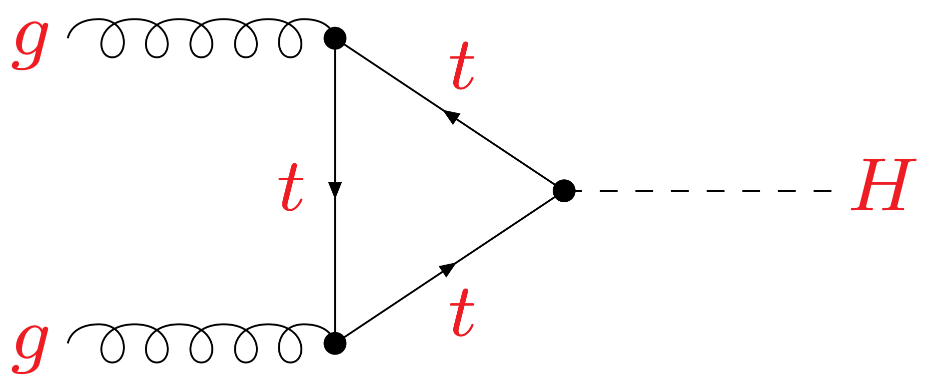
Production of a SM Higgs at the LHC

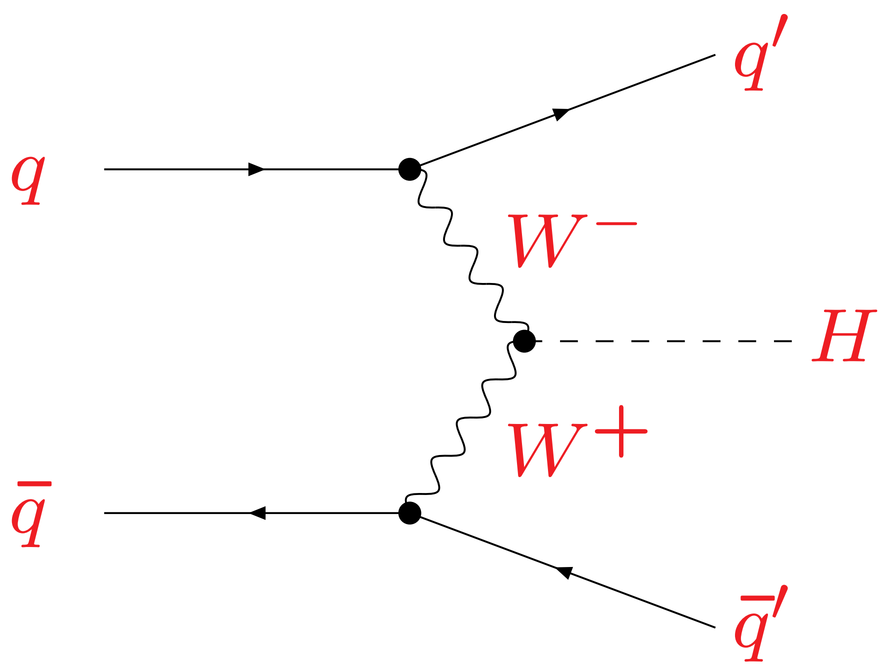
[LHC Higgs XS WG '14]



Dominant production processes for a SM-like Higgs

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$

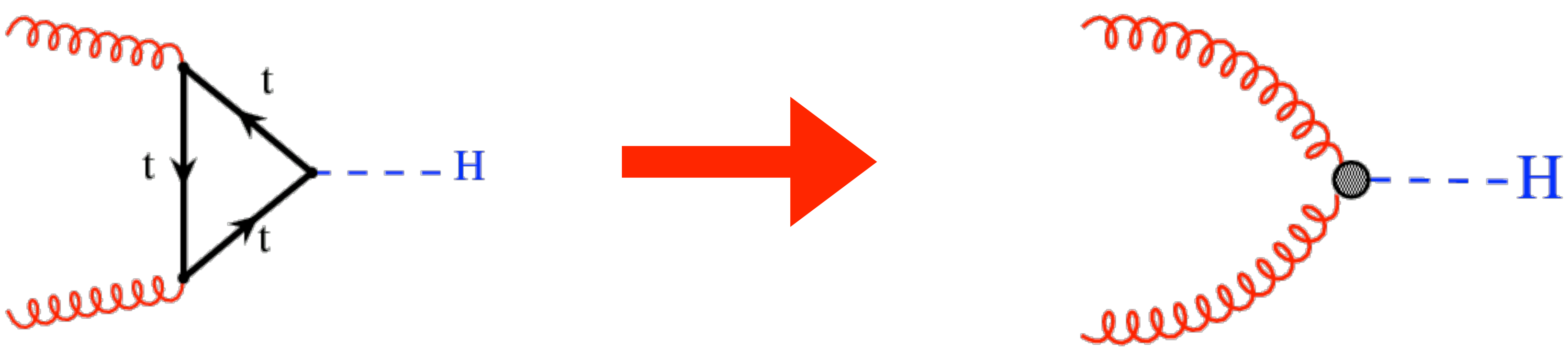




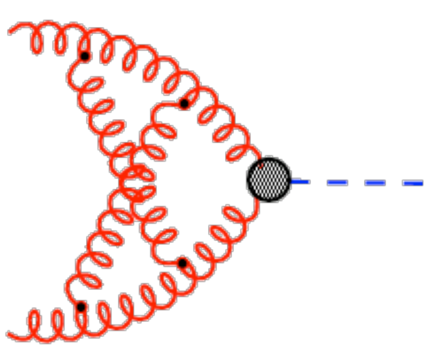
Prediction for Higgs production in gluon fusion

[G. Zanderighi ’14]

Inclusive Higgs production via gluon-gluon fusion in the large m_t-limit:

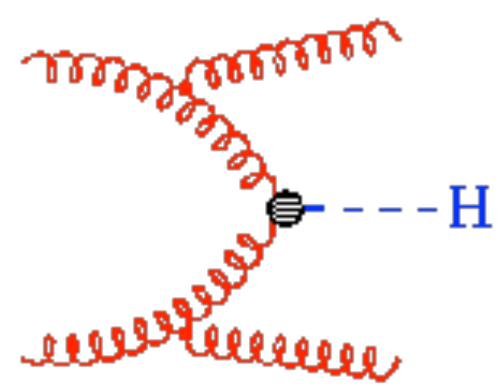


NNLO corrections known since many years now:



virtual-virtual

real-virtual



real-real

Prediction for Higgs production in gluon fusion

- Loop-induced process, can be affected by loops of BSM particles (do not have to compete with SM-type lowest-order contribution)

- Very large higher-order corrections, O(100%): the phase space for the leading-order contribution is essentially just a ``single point", $\hat{s} = M_{\mathrm{H}}^2$

$\Rightarrow$ Phase space opens up (production of additional gluon): $\hat{s} \geq M_{\mathrm{H}}^2$
sizable transverse Higgs momentum possible

- SM contribution can approximately be calculated in heavy top limit: loop correction ~ $1/m_{\mathrm{t}}$ cancels m_{t} term from Yukawa coupling

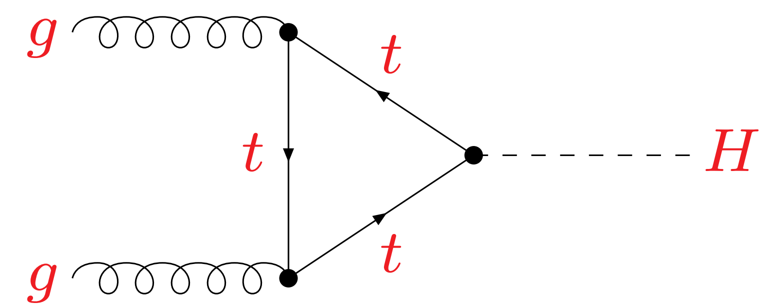
$\Rightarrow$ Non-decoupling effect of heavy particle

$\Rightarrow$ An additional fermion generation receiving their mass via the BEH mechanism would enhance the Higgs production rate in gluon fusion by about a factor 9!

$\Rightarrow$ Measured cross section puts strong constraints

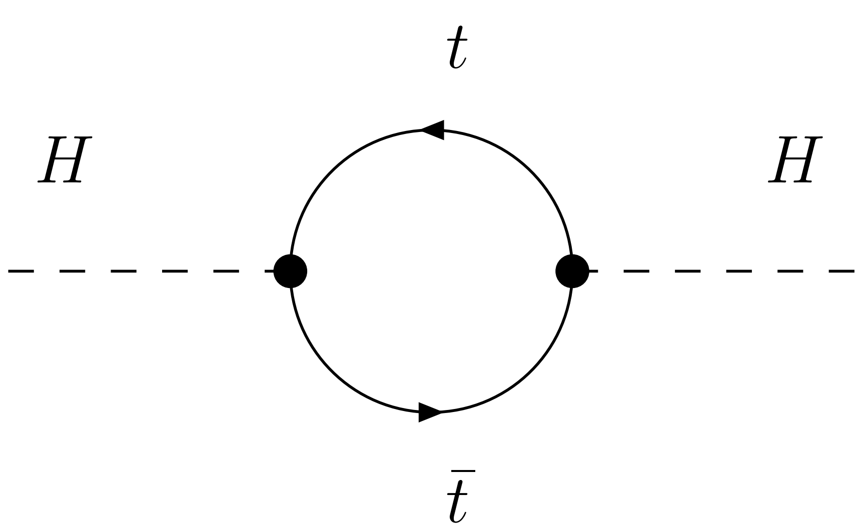
Importance of quantum corrections for Higgs physics, some examples

- Gluon fusion Higgs production: $\mathcal{O}(100\%)$ corrections



- Expect large higher-order corrections in the Higgs sector in every model which predicts the Higgs mass(es):

Large coupling of Higgs to top quark



One-loop correction $\Delta M_{\mathrm{h}}^2 \sim G_\mu m_{\mathrm{t}}^4$

- MSSM Higgs sector: large higher-order effects, sensitivity to splitting between top and stops

Most important decay channels

Good mass resolution:

- $H \to \gamma\gamma$ (loop induced)
- $H \to ZZ^* \to l^+l^-l^+l^-$, $l = e, \mu$

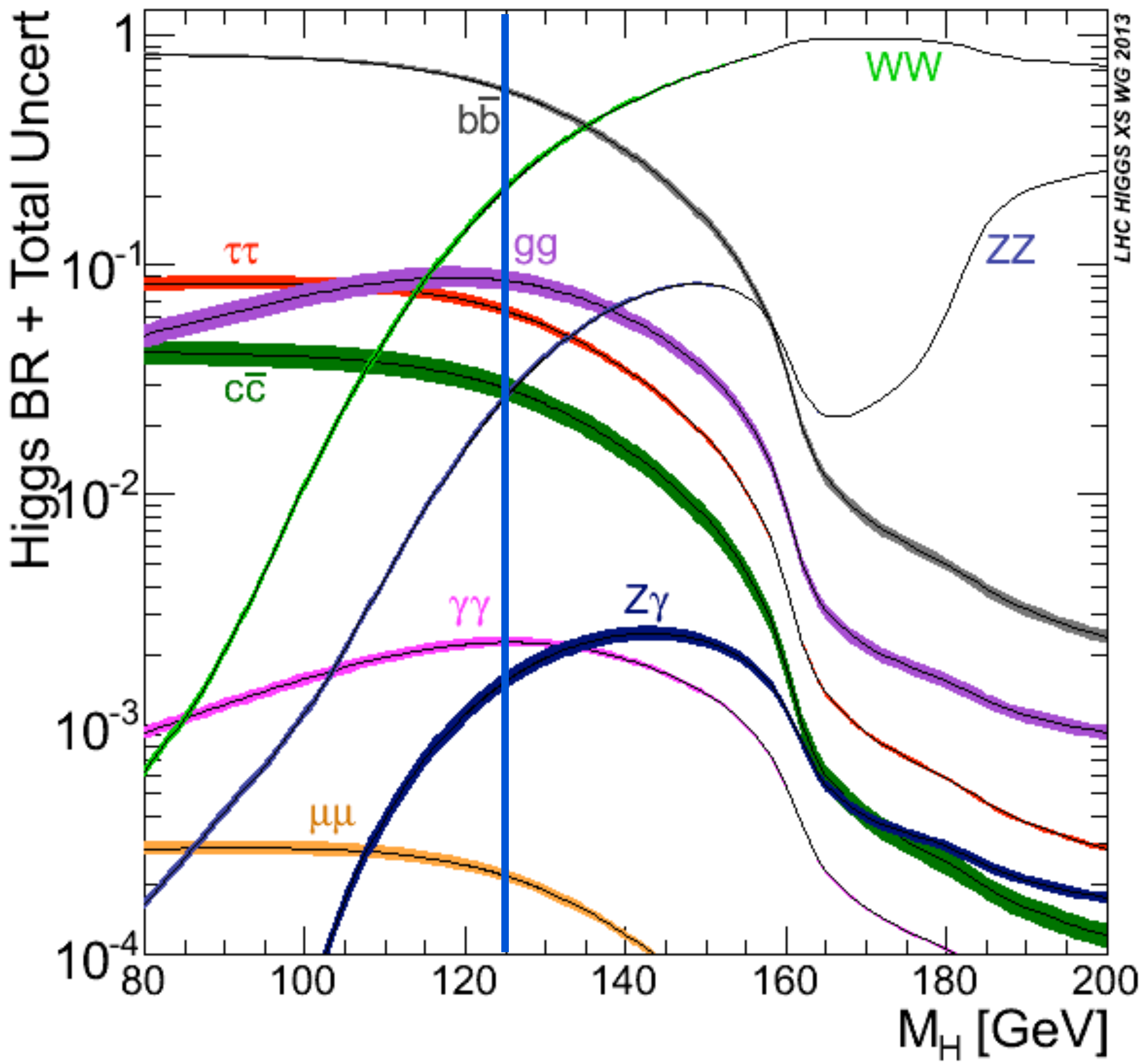
Poor mass resolution:

- $H \to WW^* \to \bar{\nu}l^-\nu l^+$, $l = e, \mu$
- $H \to \tau^+\tau^-$
- $H \to b\bar{b}$

SM Higgs branching fractions

$M_h = 125\,\mathrm{GeV}$

[LHC Higgs XS WG '14]



Extended Higgs sectors: possible deviations from the Standard Model

SUSY as a test case: well motivated, theory predictions have been worked out to high level of sophistication

“Simplest” extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

$\Rightarrow$ Two parameters instead of one: $\tan\beta \equiv \frac{v_u}{v_d}$, $\quad M_\mathrm{A}$ (or $M_{\mathrm{H}^\pm}$)

$\Rightarrow$ Upper bound on lightest Higgs mass, M_h:

Lowest order: $M_\mathrm{h} \leq M_\mathrm{Z}$

Including higher-order corrections: $M_\mathrm{h} \lesssim 135\,\mathrm{GeV}$

Interpretation of the signal at 125 GeV within the MSSM?

Higgs potential of the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$V = \left(|\mu|^2 + m^2_{H_u}\right)\left(|h^0_u|^2 + |h^+_u|^2\right) + \left(|\mu|^2 + m^2_{H_d}\right)\left(|h^0_d|^2 + |h^-_d|^2\right)$$

$$+ \left[b\left(h^+_u h^-_d - h^0_u h^0_d\right) + \text{h.c.}\right]$$

$$+ \underbrace{\frac{g^2 + g'^2}{8}}\left(|h^0_u|^2 + |h^+_u|^2 - |h^0_d|^2 - |h^-_d|^2\right)^2 + \underbrace{\frac{g'^2}{2}}\left|h^+_u h^{0*}_d + h^0_u h^{-*}_d\right|^2$$

gauge couplings, in contrast to the SM

Five physical states: $h^0, H^0, A^0, H^\pm$

$\Rightarrow$ Upper bound on lightest Higgs mass, M_h (*FeynHiggs*):
[*S. Heinemeyer, W. Hollik, G. W. '99*], [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

$M_\mathrm{h} \lesssim 135\,\mathrm{GeV}$ (for TeV-scale stop masses)

Higher-order corrections in the MSSM Higgs sector

- Quartic couplings in the Higgs sector are given by the gauge couplings, g_1, g_2 (SM: free parameter)

  $\Leftrightarrow$ Upper bound on the lightest Higgs mass

- Large higher-order corrections from Yukawa sector:

Yukawa couplings: $\frac{\mathrm{e}\, m_\mathrm{t}}{2 M_\mathrm{W} s_\mathrm{W}}, \frac{\mathrm{e}\, m_\mathrm{t}^2}{M_\mathrm{W} s_\mathrm{W}}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $G_\mu m_\mathrm{t}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_\mathrm{t}^2}\right), \quad \mathcal{O}(100\%)$!

$\Rightarrow$ Higher-order corrections are phenomenologically very important (constraints on parameter space from Higgs sector observables)
Can induce CP-violating effects

Search for non-standard heavy Higgses

"Typical" features of extended Higgs sectors:

- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons

$\Rightarrow$ • A signal could show up in $H \to ZZ \to 4\,l$ as a small bump, very far below the expectation for a SM-like Higgs (and with a much smaller width)

• Particularly important search channel: $H, A \to \tau\tau$

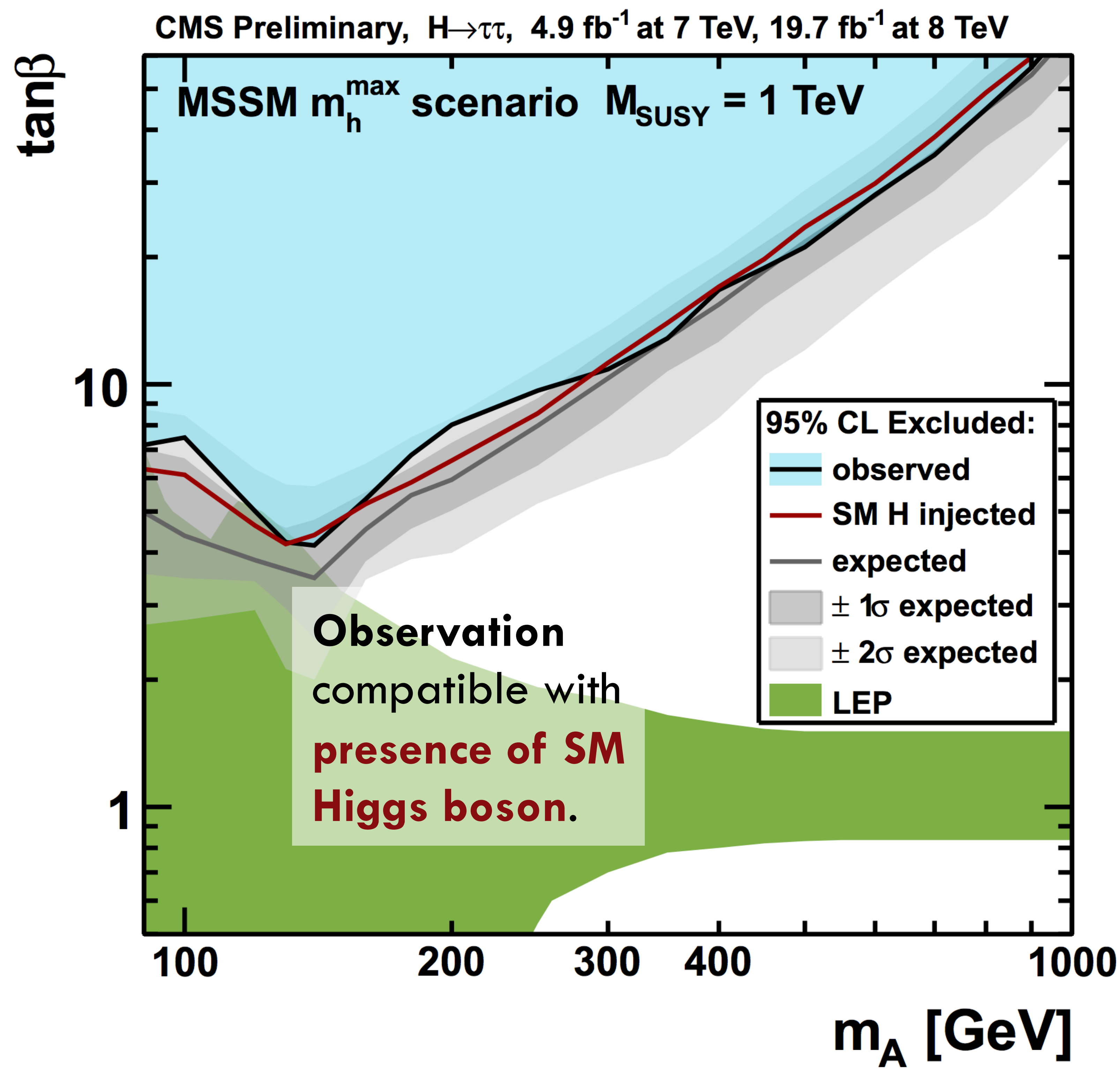
• Non-standard search channels can play an important role: $H \to hh$, $H, A \to \chi\chi$, ...

CMS result for h, H, A → ττ search

[CMS Collaboration '14]

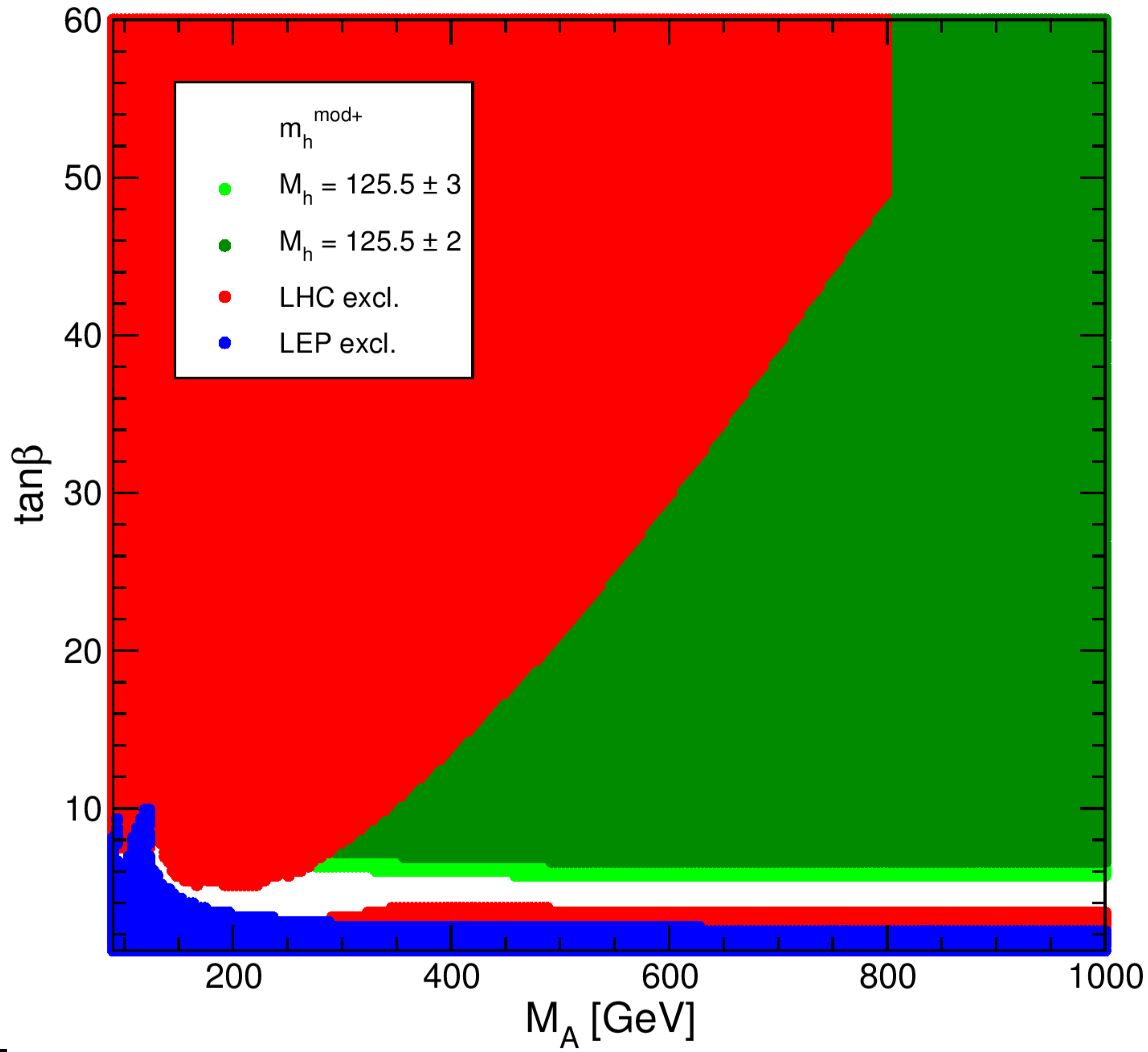
Analysis starts to become sensitive to the presence of the signal at 125 GeV

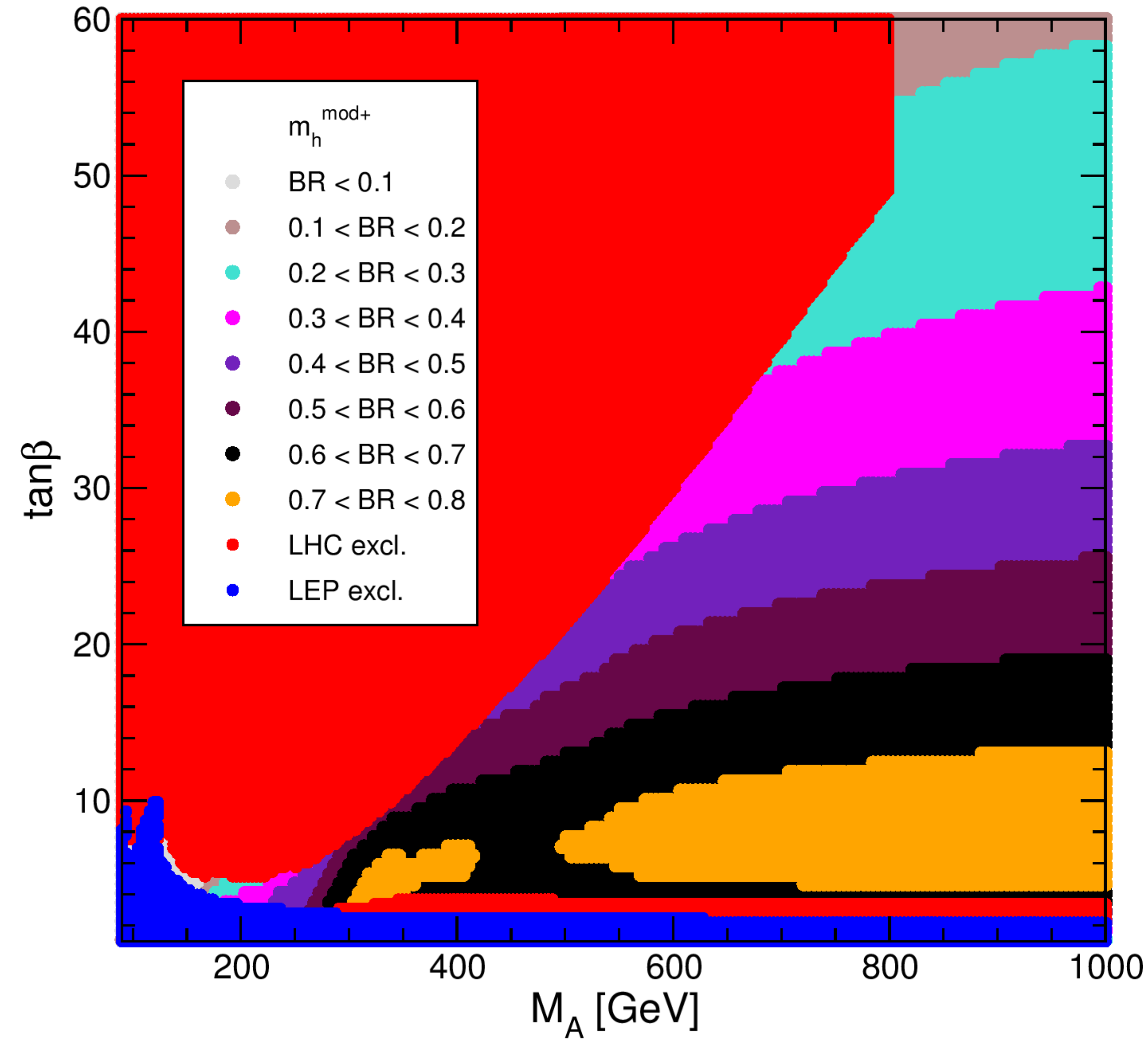
⇒ Searches for Higgs bosons of an extended Higgs sector need to test compatibility with the signal at 125 GeV (→ appropriate benchmark scenarios) and search for additional states



m_h^{mod} benchmark scenario

[M. Carena, S. Heinemeyer, O. Stål, C. Wagner, G. W. '14]





- Small modification of well-known m_h^{max} scenario where the light Higgs h can be interpreted as the signal at 125 GeV over a wide range of the parameter space

- Large branching ratios into SUSY particles (right plot) and sizable BR(H → hh) for rel. small tanβ possible

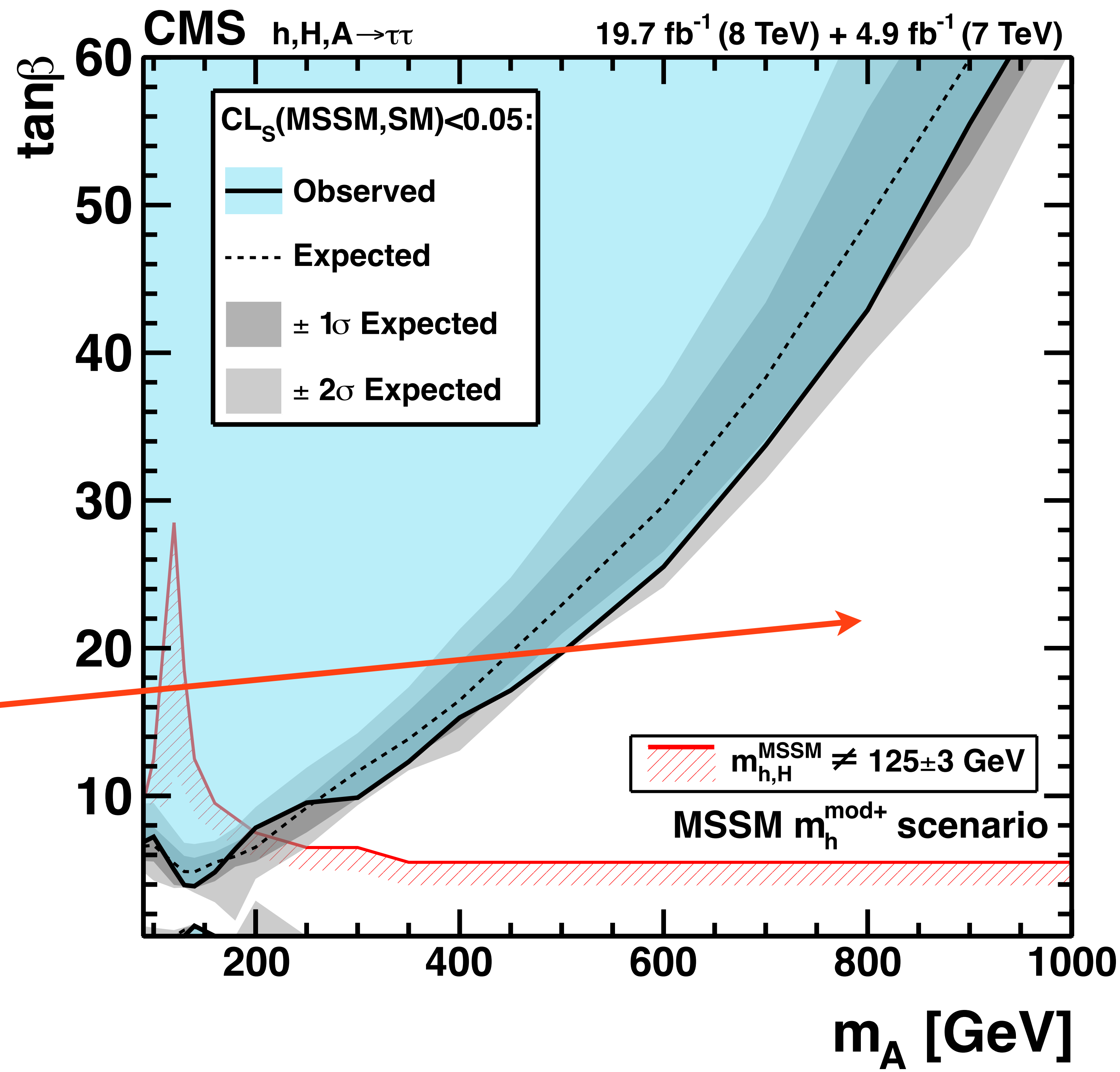
CMS result for h, H, A → $\tau\tau$ search

[CMS Collaboration '14]

m_h^{mod} benchmark scenario

Test of compatibility of the data to the signal of h, H, A (MSSM) compared to SM Higgs boson hypothesis

⇒ ``Wedge region'', where only h(125) can be detected; difficult to cover also with more luminosity



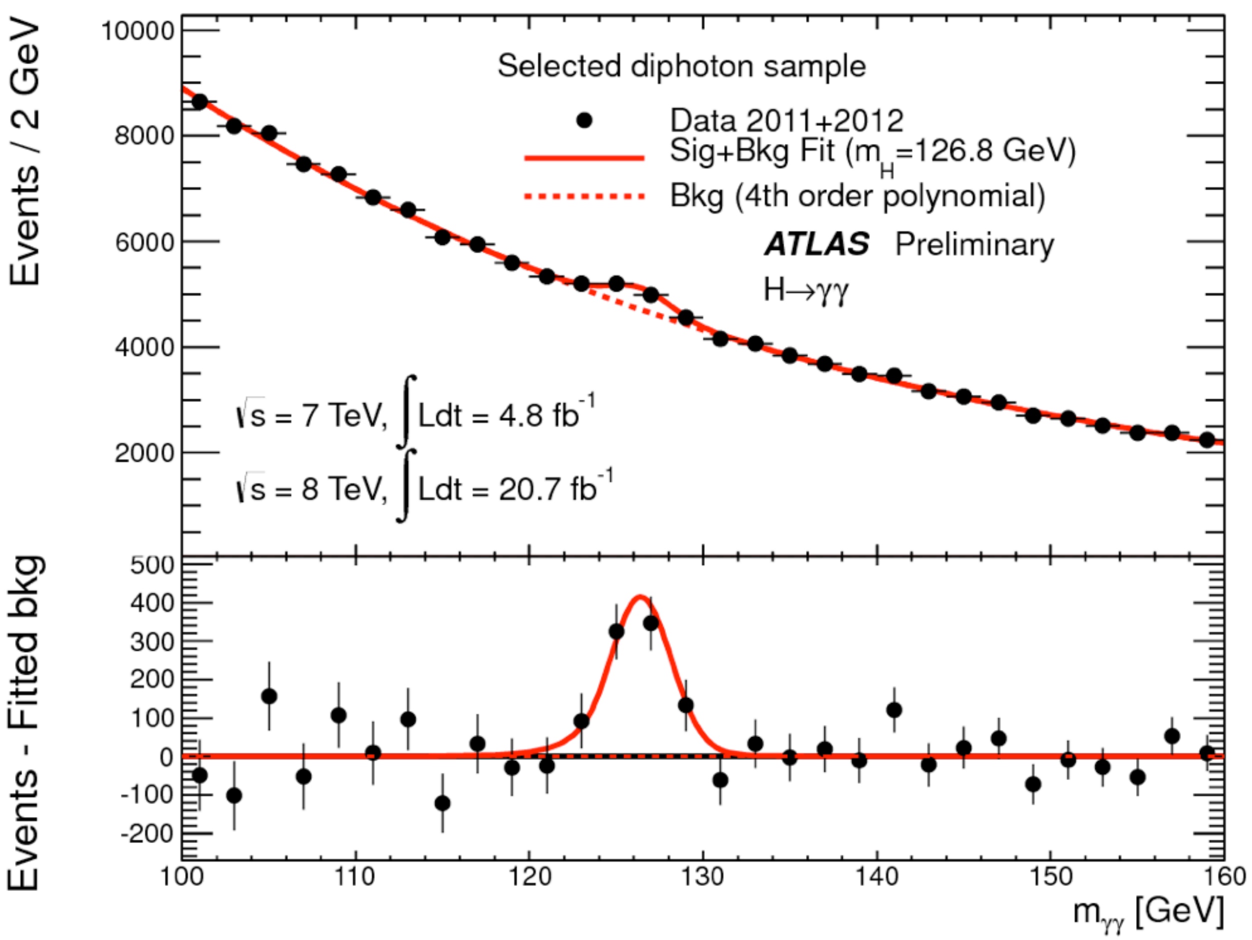
What about an additional light Higgs?

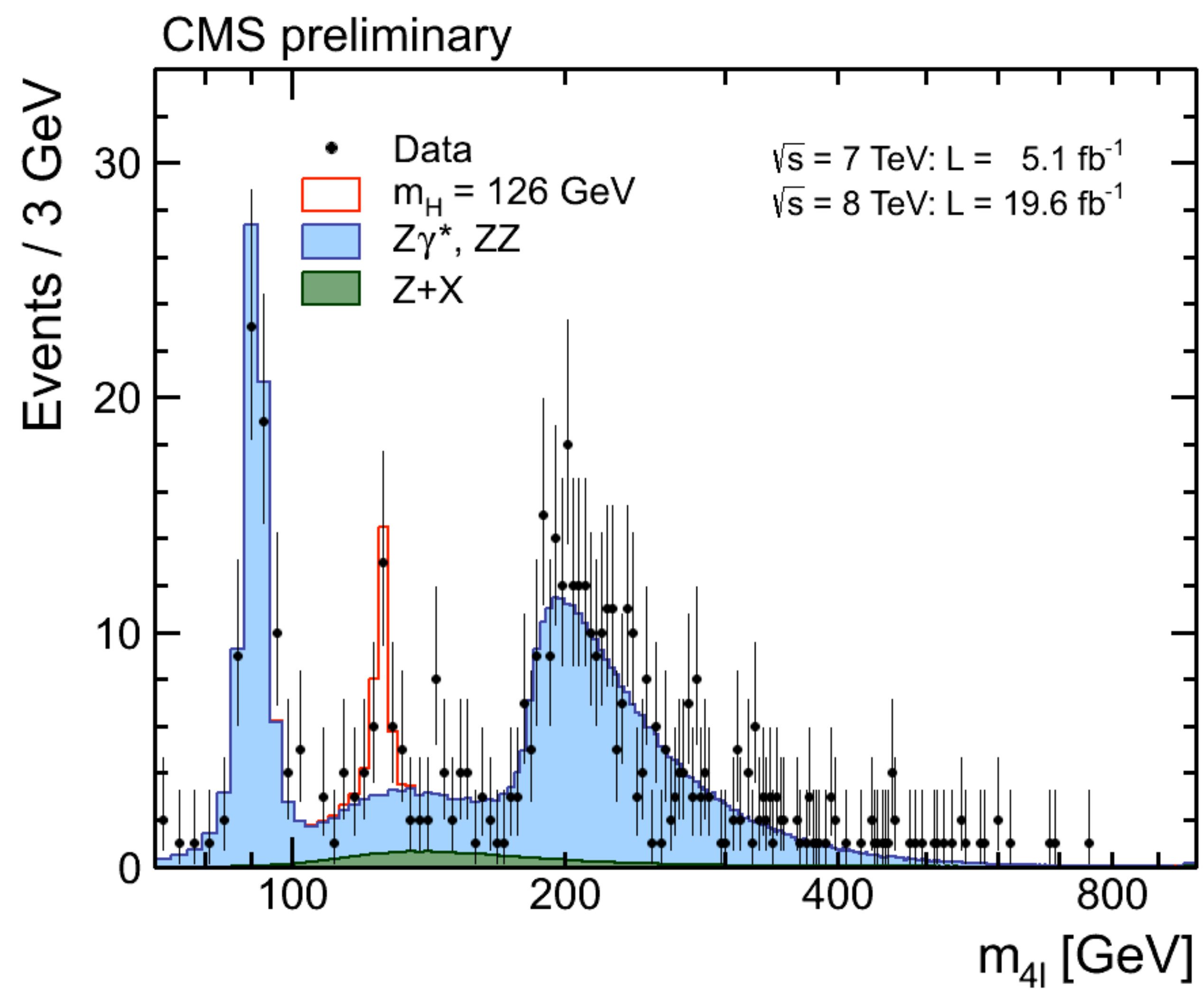
- The ``decoupling limit” type scenario of an extended Higgs sector is not the only possibility
- The signal at 125 GeV could also be a state of an extended Higgs sector that is not the lightest one
- This would imply the presence of at least one additional Higgs that is lighter than the one at 125 GeV (see below)

⇒ The best way of experimentally proving that the observed state at 126 GeV is not the SM Higgs would be to find in addition (at least one) non-SM like Higgs!

What do we know so far about the discovered signal and how can we interpret it?

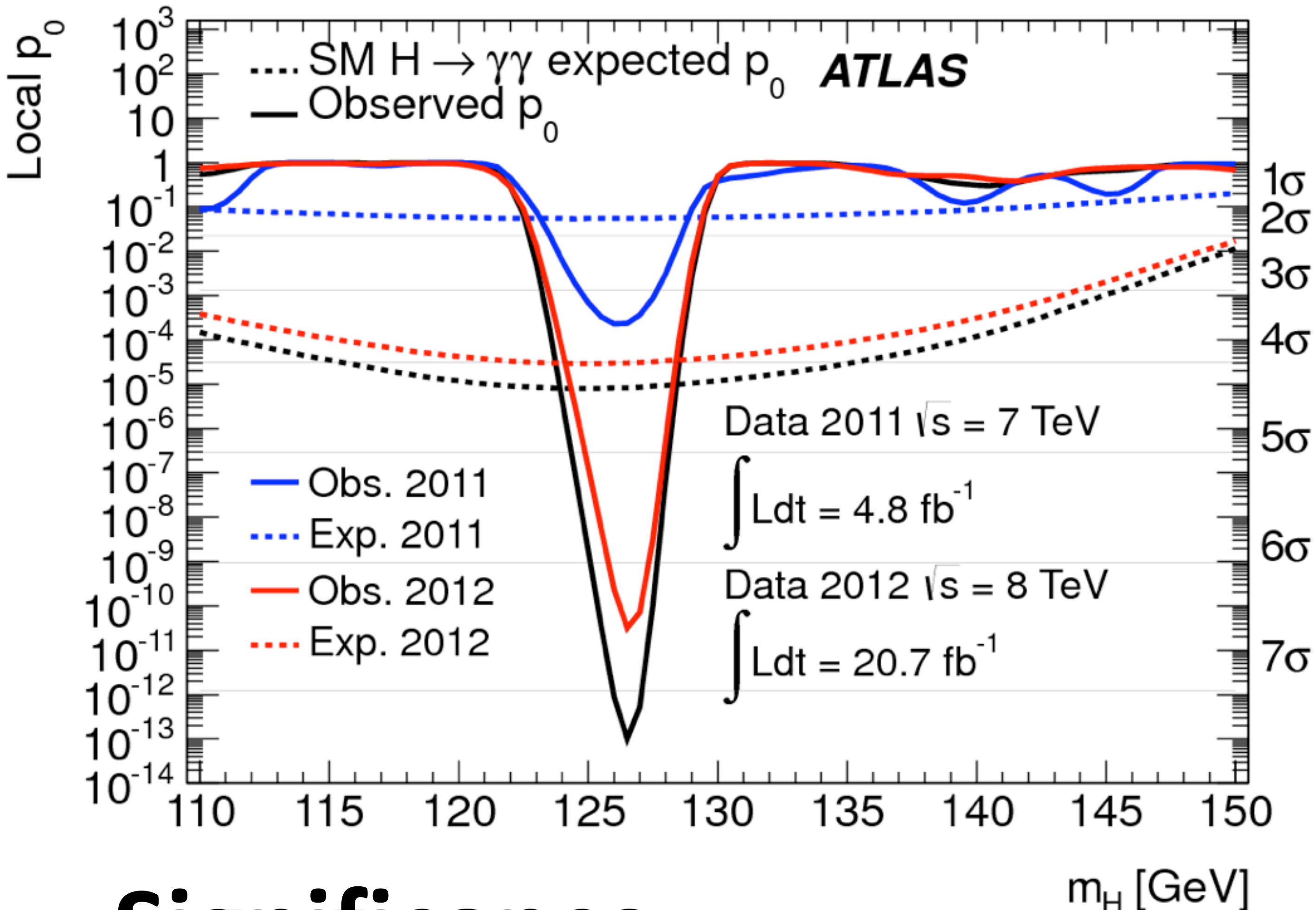
Discovery of a signal at about 125 GeV in the Higgs searches at ATLAS and CMS:

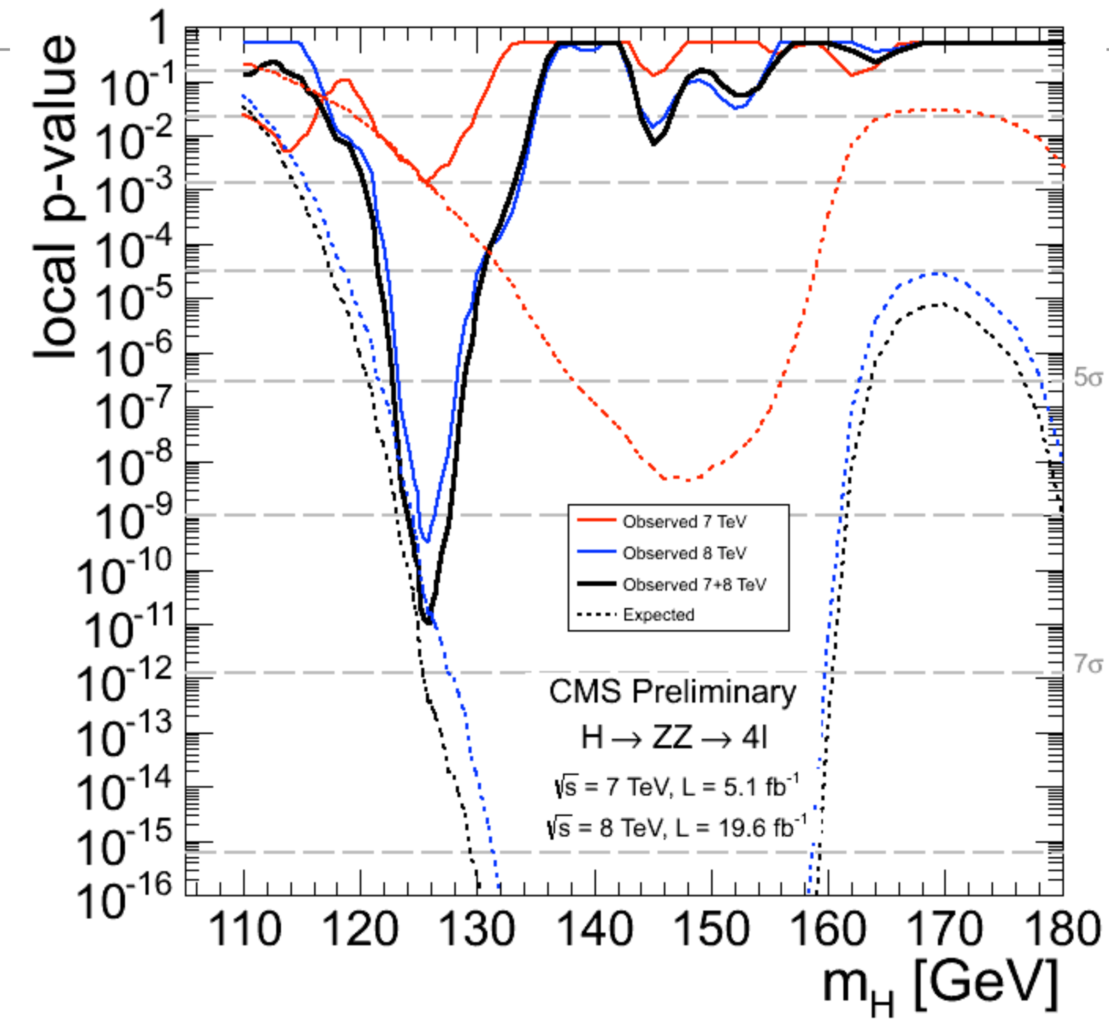




⇒ Discovery mainly based on the $\gamma\gamma$ and $ZZ^* \to 4\ l$ channels

Significance of the signal in ATLAS and CMS





Significance

$\sqrt{S}$ = 7 TeV, 8 TeV

5 fb^{-1} + 20 fb^{-1}

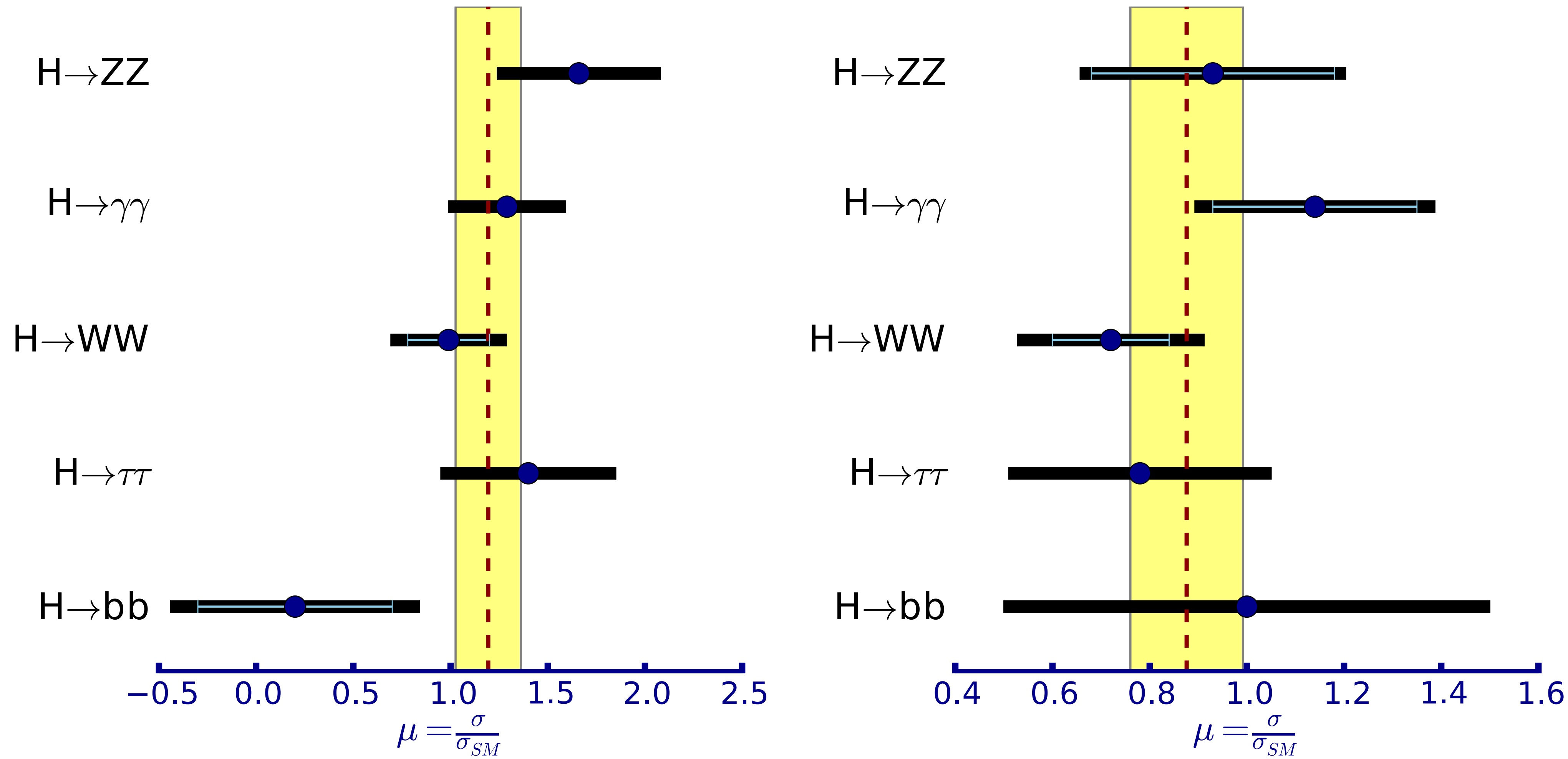
	ATLAS	
	Obs	Exp
$H \rightarrow \gamma\gamma$	7.4	4.3
$H \rightarrow ZZ$	6.6	4.4
$H \rightarrow WW$	3.8	3.8

CMS

Channel grouping	Significance (σ) Observed	Expected
$H \rightarrow ZZ$ tagged	6.5	6.3
$H \rightarrow \gamma\gamma$ tagged	5.6	5.3
$H \rightarrow WW$ tagged	4.7	5.4
Grouped as in Ref. [17]	*4.3*	*5.4*
$H \rightarrow \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [19]	*3.9*	*3.9*
$H \rightarrow bb$ tagged	2.0	2.3
Grouped as in Ref. [16]	*2.1*	*2.3*

Signal strength by channel for ATLAS and CMS

channel	signal strength ATLAS	CMS
H$\rightarrow ZZ$	$1.66^{+0.45}_{-0.38}$	$0.93^{+0.26}_{-0.23}(\text{stat})^{+0.13}_{-0.09}(\text{syst})$
H$\rightarrow \gamma\gamma$	1.29 ± 0.3	$1.14 \pm 0.21(\text{stat})^{+0.09}_{-0.05}(\text{syst})^{+0.13}_{-0.09}(\text{theo})$
H$\rightarrow W^+W^-$ (all)	$0.99 \pm 0.21(\text{stat}) \pm 0.21(\text{syst})$	$0.72^{+0.20}_{-0.18}$
H$\rightarrow \tau^+\tau^-$ (all)	$1.4^{+0.5}_{-0.4}$	0.78 ± 0.27
VH$\rightarrow$H$\rightarrow b\bar{b}$	$0.2 \pm 0.5 \pm 0.4$	1.0 ± 0.5



Properties of the discovered signal

Mass: statistical precision already remarkable with 2012 data

$\Rightarrow$ Need careful assessment of systematic effects for $\gamma\gamma$ and ZZ^* channels,

e.g. interference of signal and background, ...

Spin: Observation in $\gamma\gamma$ channel $\Rightarrow$ spin 0 or spin 2?

At which level of significance can the hypothesis spin $= 1$ be excluded (2 γ's vs. 4 γ's)?

Spin can in principle be determined by discriminating between distinct hypotheses for spin 0, (1), 2 $\Rightarrow$ spin 0 preferred

Discrimination against two overlapping signals?

Higgs mass measurement: the need for high precision

Measuring the mass of the discovered signal with high precision is of interest in its own right

But a high-precision measurement has also direct implications for probing Higgs physics

M_H: crucial input parameter for Higgs physics

BR($H \to ZZ^*$), BR($H \to WW^*$): highly sensitive to precise numerical value of M_H

A change in M_H of 0.2 GeV shifts BR($H \to ZZ^*$) by 2.5%!

$\Rightarrow$ Need high-precision determination of M_H to exploit the sensitivity of BR($H \to ZZ^*$), ... to test BSM physics

CP properties

$\mathcal{CP}$ properties: more difficult situation, observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables mainly used for investigaton of $\mathcal{CP}$-properties ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu\right] + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

SM, pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However: in many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

CP properties

⇒ Observables involving the *HVV* coupling provide only limited sensitivity to effects of a CP-odd component, even a rather large CP-admixture would not lead to detectable effects in the angular distributions of $H \to ZZ^* \to 4\,l$, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

However, there are only very weak bounds so far on an admixture of CP-even and CP-odd components

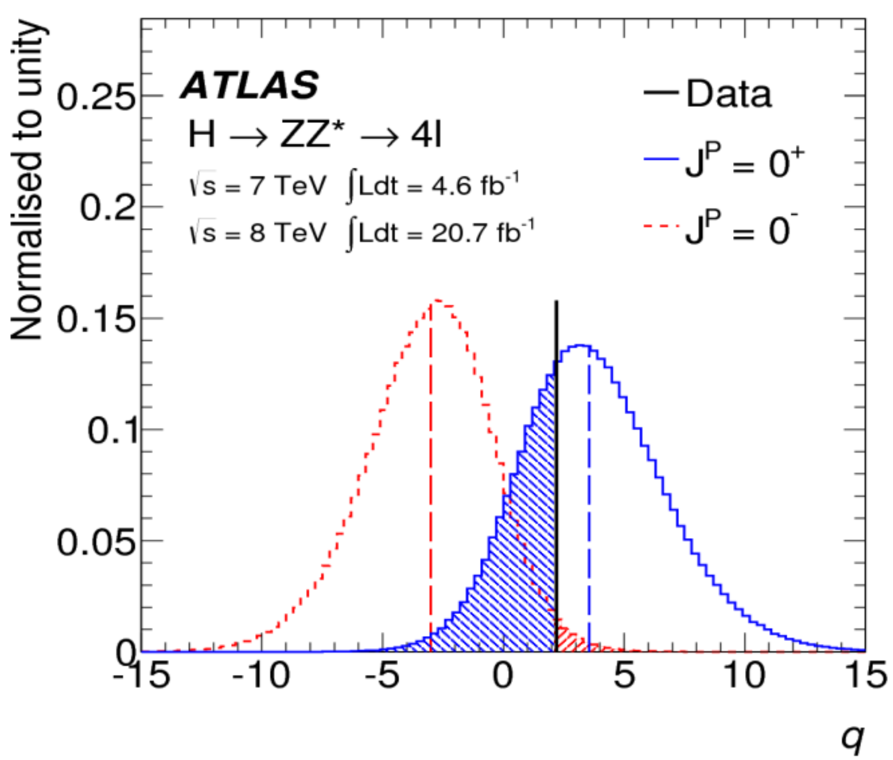
Channels involving only Higgs couplings to fermions could provide much higher sensitivity

Test of spin and CP hypotheses

[ATLAS Collaboration ’13]

The SM 0^+ has been tested against different J^P hypotheses using the three ATLAS discovery channels

0^+ against 0^-



0^+ against $1^{+/-}$

Combined H→ZZ and H→WW analysis excludes those hypotheses up to 99.7%

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$CL_s(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	0.62	$1.2 \cdot 10^{-4}$	$\boxed{3.0 \cdot 10^{-4}}$

- **1^+ hypothesis has been excluded at 99.97%**

Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$CL_s(J^P = 1^-)$
$H \to ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.33	$1.8 \cdot 10^{-3}$	$\boxed{2.7 \cdot 10^{-3}}$

- **1^- hypothesis has been excluded at 99.7%**

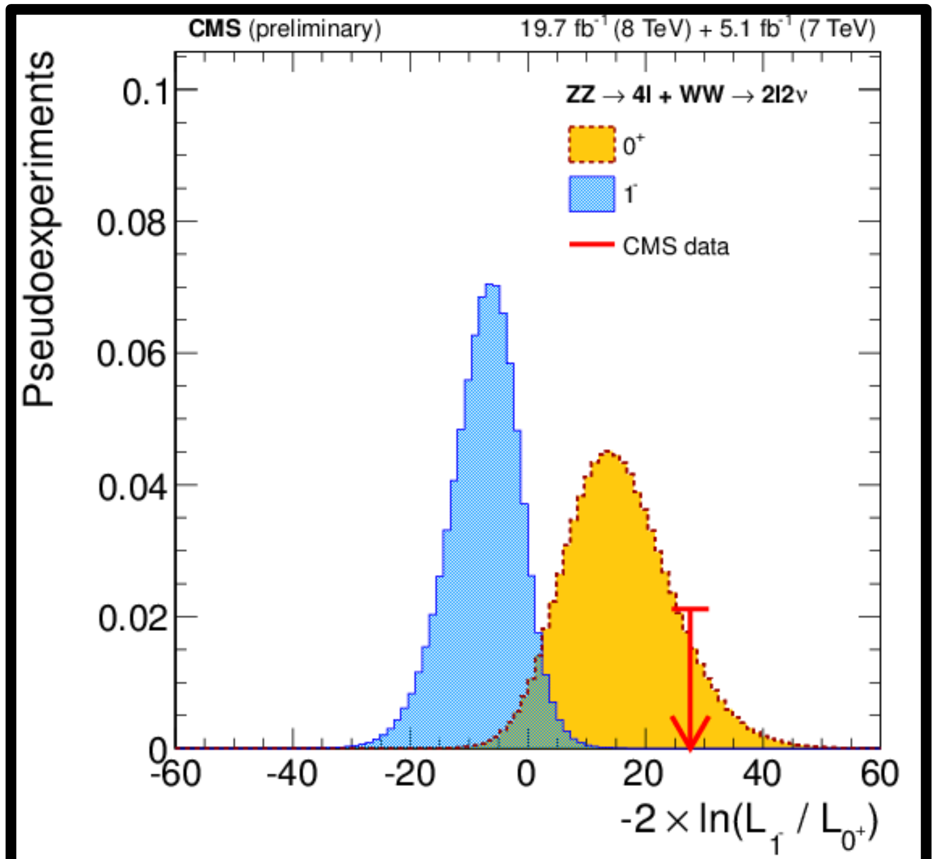
Channel	0^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 0^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 0^-)$	$CL_s(J^P = 0^-)$
$H \to ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022

H→ZZ analysis excludes the 0^- hypothesis at 97.8% CLs

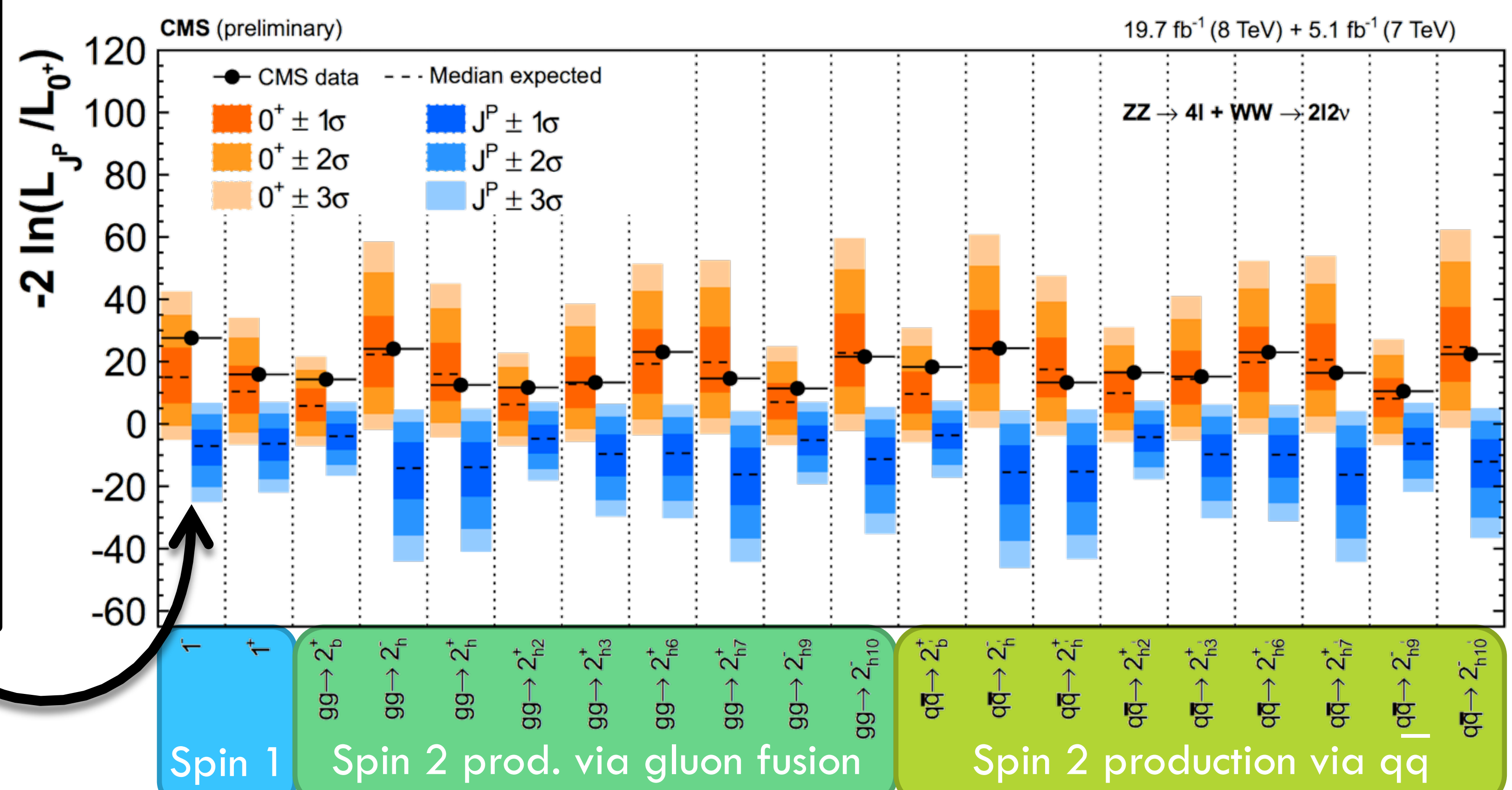
Test of spin and CP hypotheses

[CMS Collaboration '14]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CL_S.



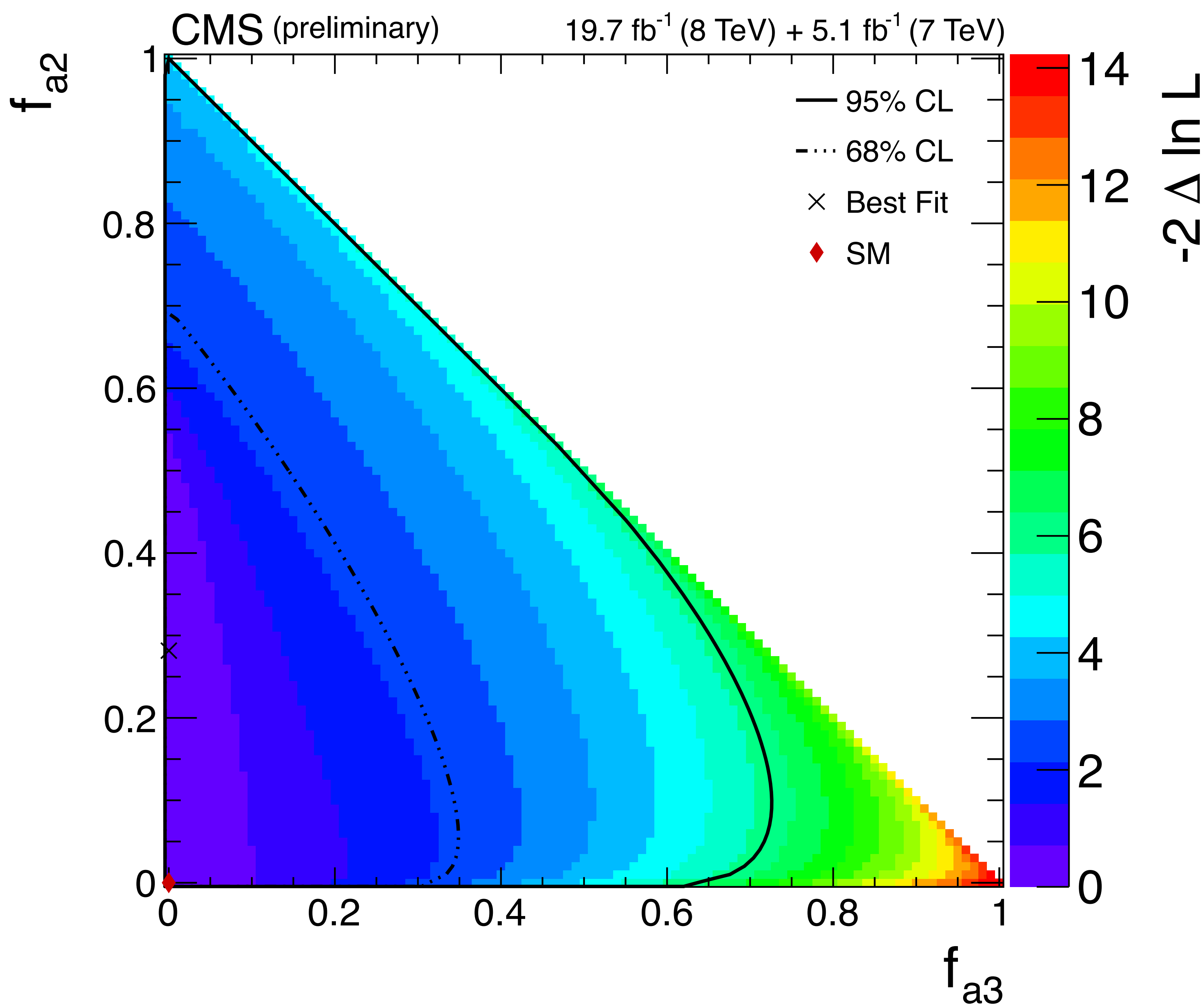
Hypothesis test for 0^+ vs. 1^-



Experimental analyses beyond the hypotheses of pure CP-even / CP-odd states

[CMS Collaboration '14]

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3}$$



Experimental analyses beyond the hypotheses of pure CP-even / CP-odd states

Loop suppression of a_3 in many BSM models

⇒ Even a rather large CP-admixture would result in only a very small effect in f_{a3}!

⇒ Extremely high precision in f_{a3} needed to probe possible deviations from the SM

The Snowmass report sets as a target that should be achieved for f_{a3} an accuracy of better than 10^{-5}!

Couplings

- What is meant by measuring a coupling?
  A coupling is not directly a physical observable; what is measured is $\sigma \times \mathrm{BR}$ (within acceptances), etc.
  $\Rightarrow$ Need to specify a Lagrangian in order to define the meaning of coupling parameters

- The experimental results that have been obtained for the various channels are not model-independent
  Properties of the SM Higgs have been used for discriminating between signal and background
  Need the SM to correct for acceptances and efficiencies

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\mathrm{prod,\,decay}} \sim g^2_{\mathrm{prod,\,decay}}$):

$$\sigma(H) \times \mathrm{BR}(H \to a + b) \sim \frac{\Gamma_{\mathrm{prod}} \Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}},$$

Total Higgs width cannot be determined without further assumptions

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

Total Higgs width: recent analyses from CMS and ATLAS

- Exploit different dependence of on-peak and off-peak contributions on the total width in Higgs decays to $ZZ^{(*)}$

- CMS quote an upper bound of $\Gamma/\Gamma_{\mathrm{SM}} < 5.4$ at 95% C.L., where 8.0 was expected, ATLAS: $\Gamma/\Gamma_{\mathrm{SM}} < 5.7$ at 95% C.L., 8.5 expect.
  [CMS Collaboration '14] *[ATLAS Collaboration '14]*

- Problem: equality of on-shell and far off-shell couplings assumed; relation can be severely affected by new physics contributions, in particular via threshold effects (note: effects of this kind may be needed to give rise to a Higgs-boson width that differs from the SM one by the currently probed amount)
  [C. Englert, M. Spannowsky '14]

$\Rightarrow$ SM consistency test rather than model-independent bound

Destructive interference between Higgs- and gauge-boson contributions (unitarity cancellations) $\Rightarrow$ difficult to reach $\Gamma/\Gamma_{\mathrm{SM}} \approx 1$ even for high statistics

Determination of couplings and CP properties need to be addressed together

Deviations from the SM: in general both the absolute value of the couplings and the tensor structure of the couplings (affects $\mathcal{CP}$ properties) will change

$\Rightarrow$ Determination of couplings and determination of $\mathcal{CP}$ properties can in general not be treated separately from each other

Deviations from the SM would in general change kinematic distributions

$\Rightarrow$ No simple rescaling of MC predictions possible

$\Rightarrow$ Not feasible for analysis of 2012 data set

$\Rightarrow$ LHC Higgs XS WG: Proposal of "interim framework"

``Interim framework” for analyses so far

Simplified framework for analysis of LHC data so far; deviations from SM parametrised by ``scale factors” $\varkappa_i$.

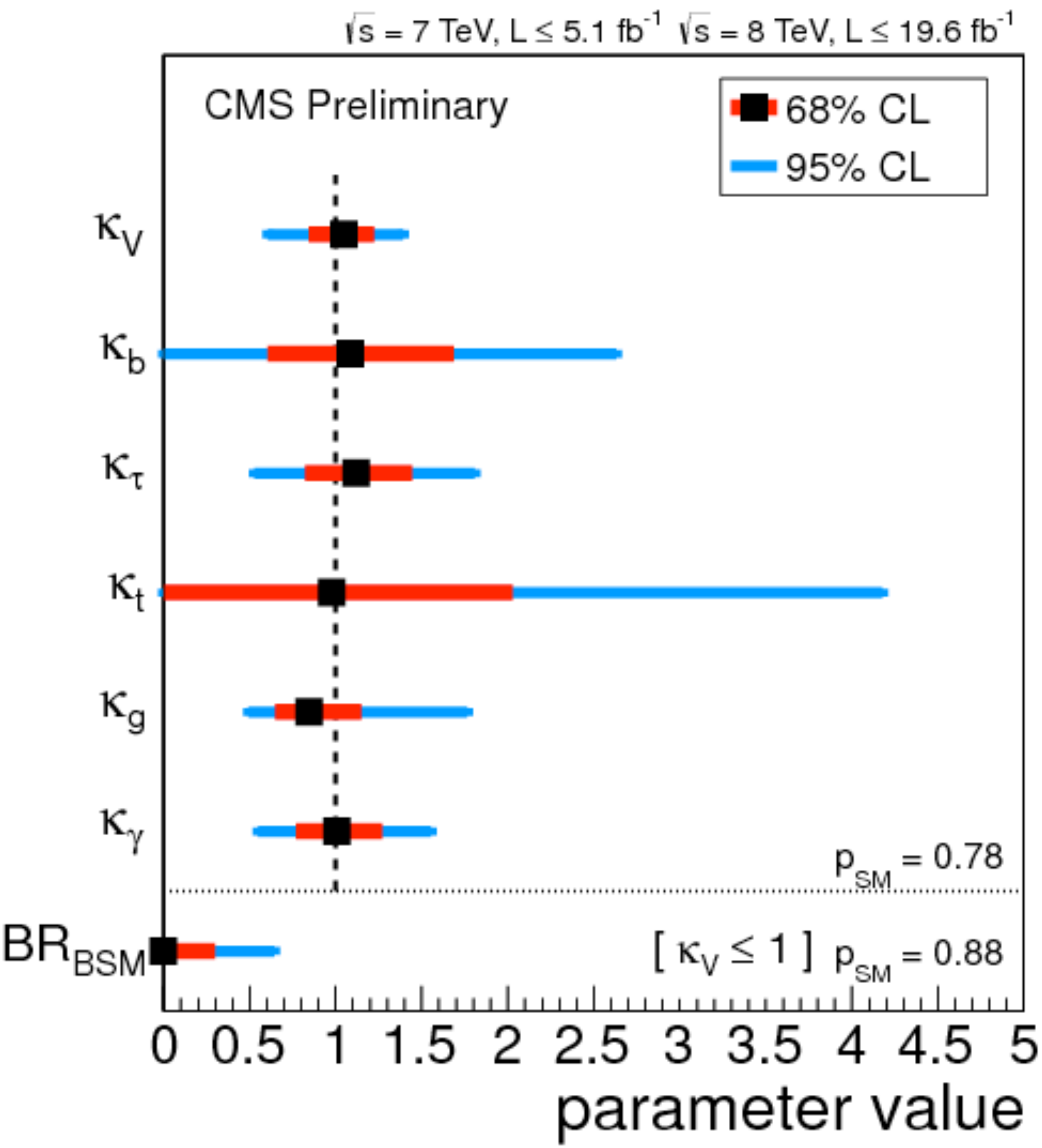
Assumptions:

- Signal corresponds to only one state, no overlapping resonances, etc.
- Zero-width approximation
- Only modifications of coupling strengths (absolute values of the couplings) are considered

⇒ Assume that the observed state is a CP-even scalar

Determination of coupling scale factors

[CMS Collaboration '13]



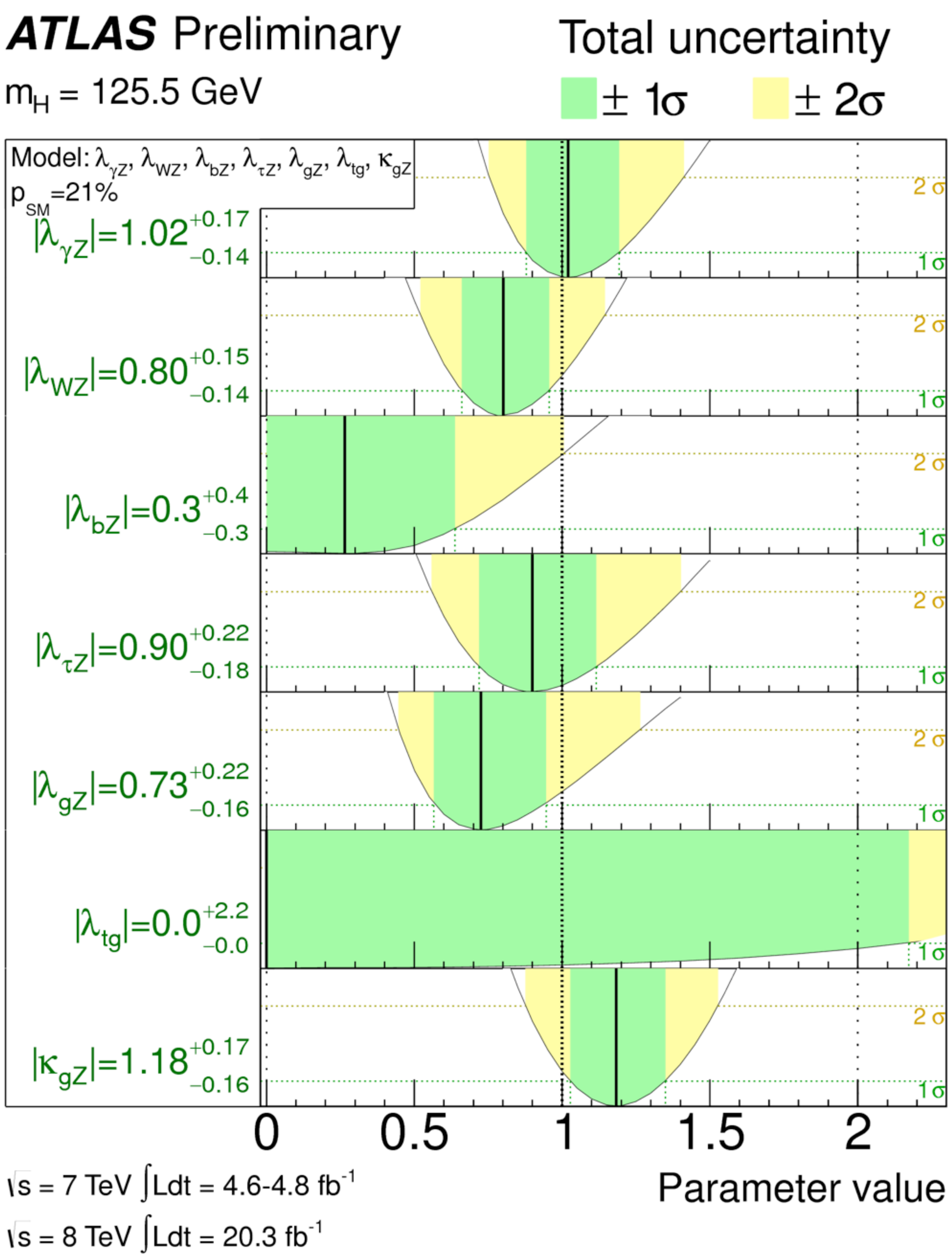
⇒ Compatible with the SM with rather large errors

Assumption $\varkappa_V \leqq 1$allows to set an upper bound on the total width

⇒ Upper limit on branching ratio into BSM particles: $BR_{BSM} \lesssim 0.6$ at 95% C.L.

Determination of coupling scale factors

[ATLAS Collaboration ’14]



⇒ Determination of ratios of coupling scale factors

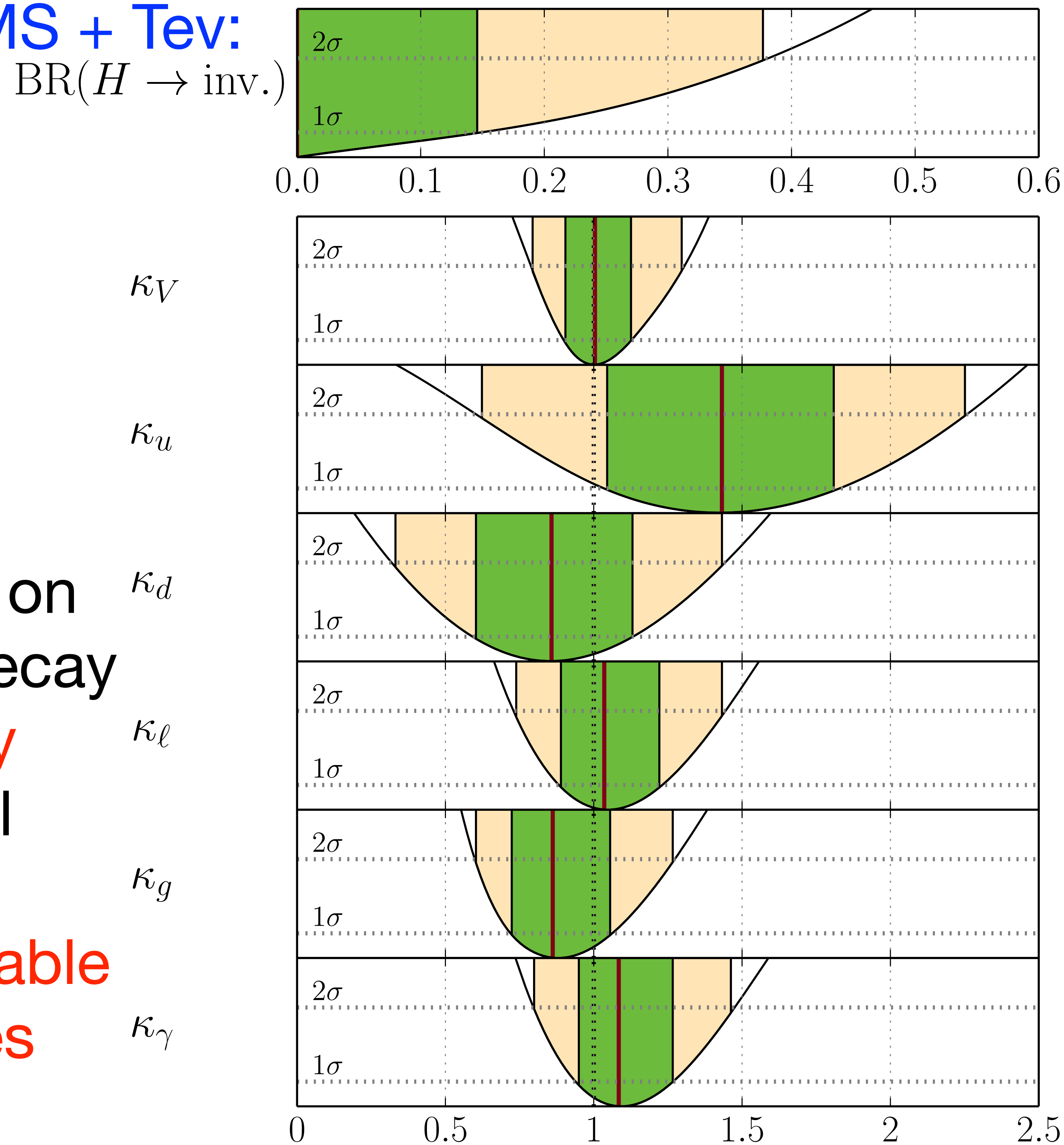
$$
\begin{aligned}
\lambda_{\gamma Z} &= \kappa_\gamma / \kappa_Z \\
\lambda_{WZ} &= \kappa_W / \kappa_Z \\
\lambda_{bZ} &= \kappa_b / \kappa_Z \\
\lambda_{\tau Z} &= \kappa_\tau / \kappa_Z \\
\lambda_{gZ} &= \kappa_g / \kappa_Z \\
\lambda_{tg} &= \kappa_t / \kappa_g \\
\kappa_{gZ} &= \kappa_g \cdot \kappa_Z / \kappa_H
\end{aligned}
$$

Constraints on coupling scale factors from ATLAS + CMS + Tevatron data

ATLAS + CMS + Tev:

Seven fit parameters

Assumption on additional decay modes: only invisible final states; no undetectable decay modes



HiggsSignals

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '14]

⇒ Significantly improved precision compared to ATLAS or CMS results alone

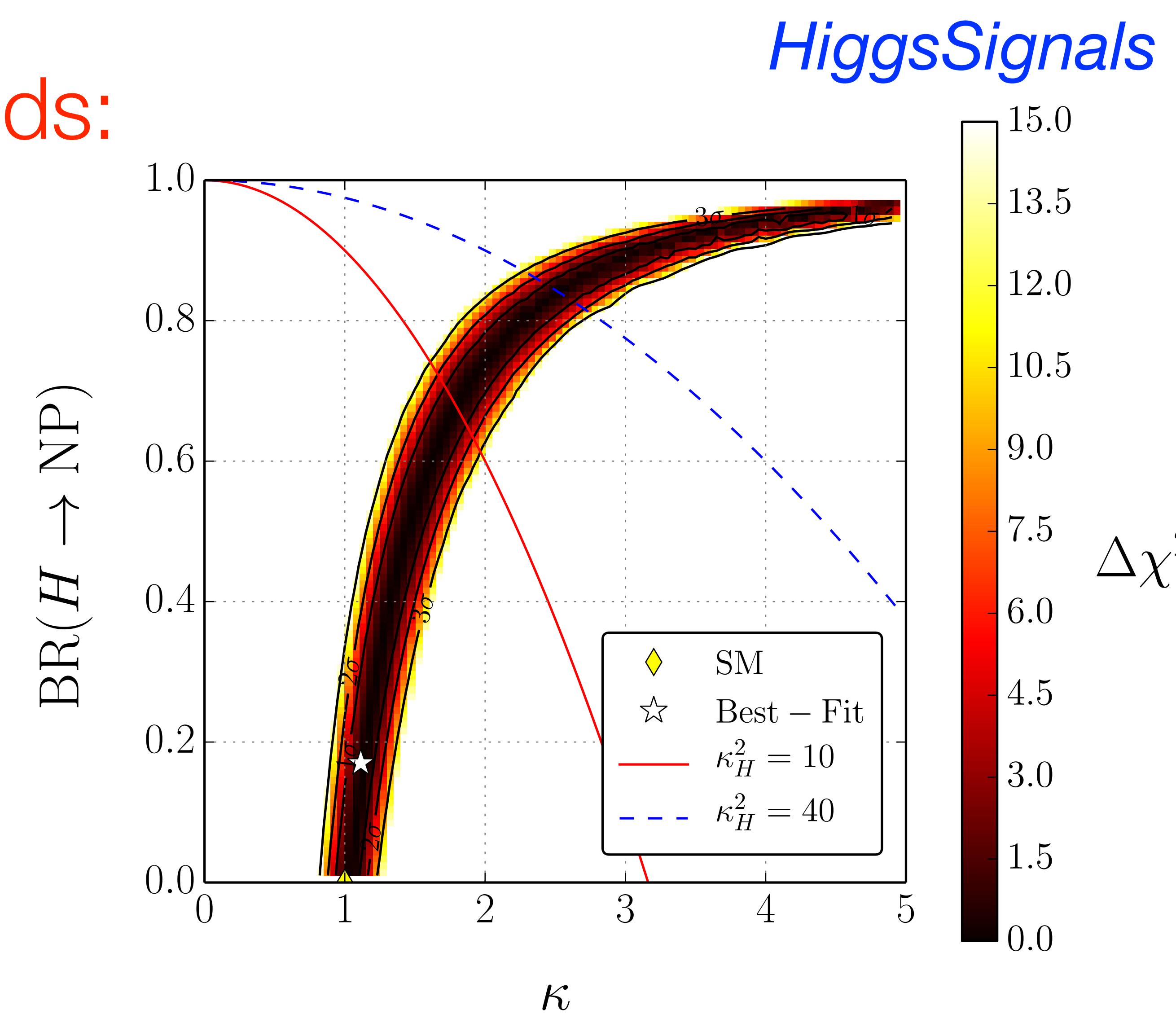
Simple example: common scale factor for all Higgs couplings, but no assumptions on undetectable / invisible decays

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '14]

ATLAS + CMS bounds:

Common scale factor ϰ for all Higgs couplings

No assumptions on undetectable / invisible decays



⇒ • Large range possible for scale factor ϰ and branching ratio into new physics final states without additional theoretical assumptions

• Constraints on total width, $\varkappa_H$, are crucial!

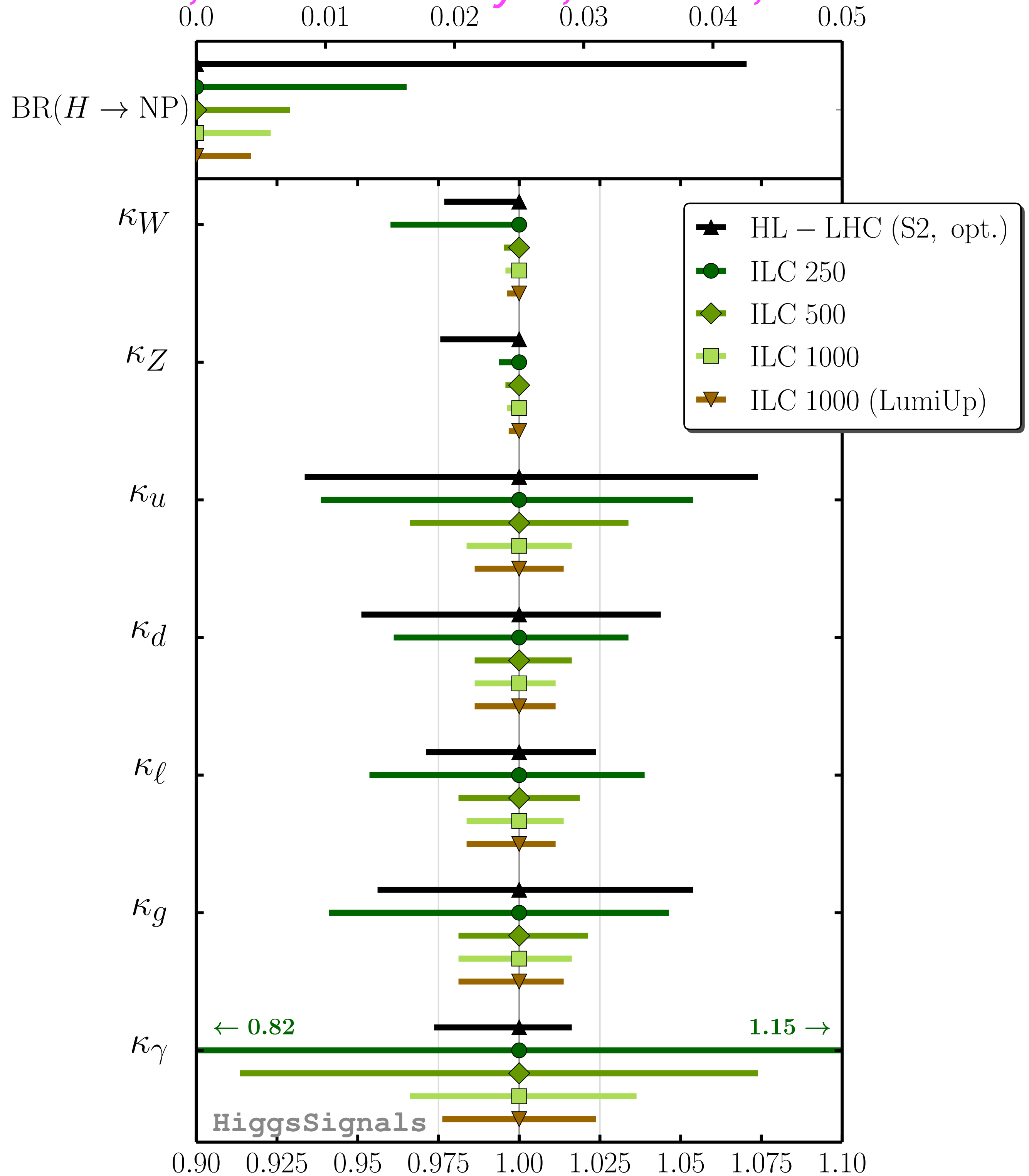
Prospects for Higgs-coupling determinations at HL-LHC and ILC: with theory assumption on $\varkappa_V$

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune ’14]

Assumed:

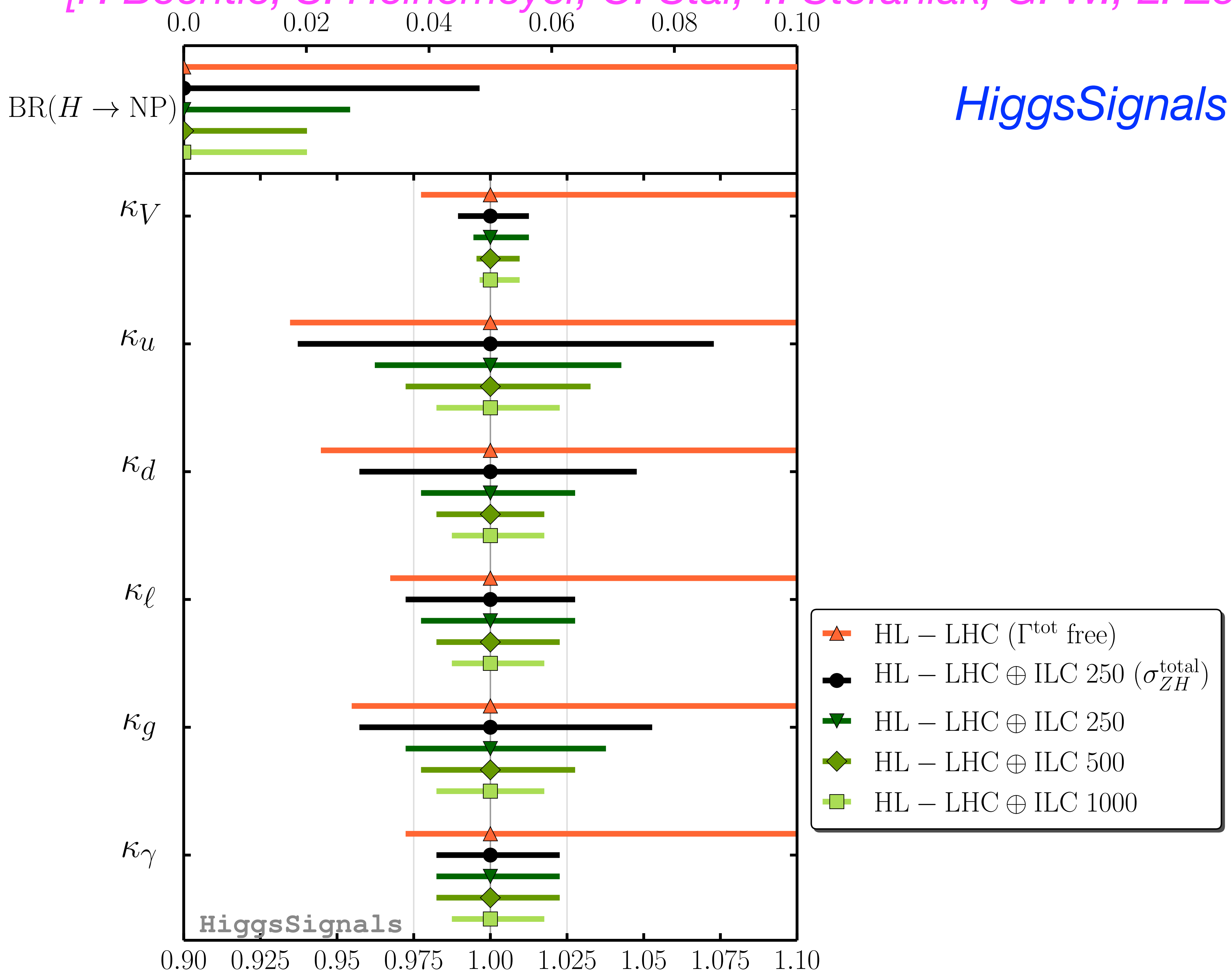
$\kappa_V \leq 1$

HiggsSignals



Prospects for Higgs-coupling determinations at HL-LHC and ILC: without theory assumption on $\varkappa_V$

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune ’14]



Future analyses of couplings and CP properties

Effective Lagrangian approach, obtained from integrating out heavy particles

Assumption: new physics appears only at a scale $\Lambda \gg M_\mathrm{h} \sim 126 \text{ GeV}$

Systematic approach: expansion in inverse powers of Λ; parametrises deviations of coupling strenghts and tensor structure

$$\Delta\mathcal{L} = \sum_i \frac{a_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{a_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

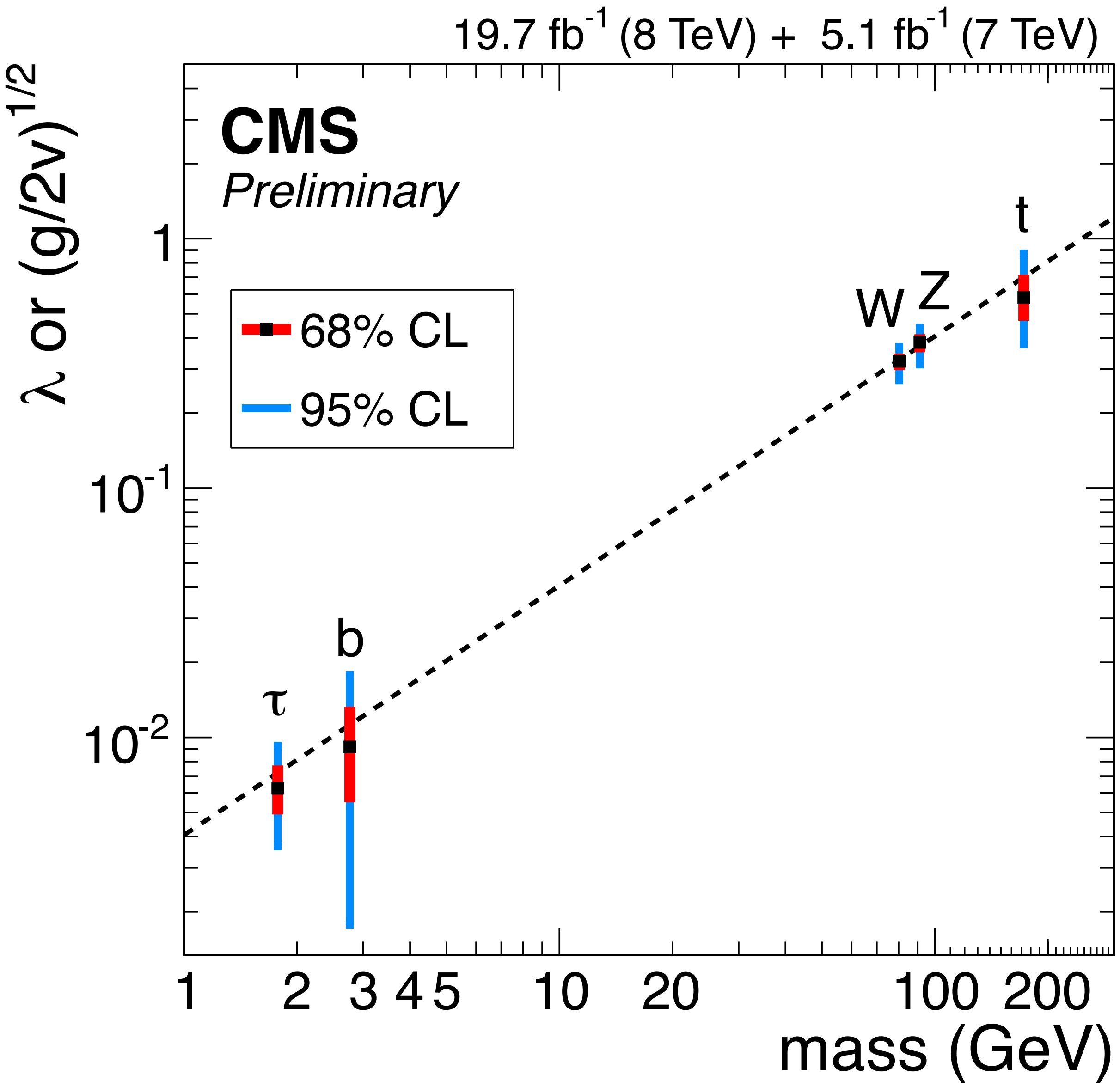
How about light BSM particles?

Difficult to incorporate in a generic way, need full structure of particular models

$\Rightarrow$ Analyses in terms of SM + effective Lagrangian and in specific BSM models: MSSM, . . . are complementary

Is the discovered signal the last missing ingredient of the Standard Model?

The properties of the signal determined so far are compatible with the predictions for the Higgs boson of the SM within the current experimental uncertainties



[CMS Collaboration '14]

Thus, is the discovered particle the Higgs boson of the SM?

Could it simply be the Higgs boson of the SM?

What does this actually mean?

The SM is necessarily incomplete (does not include gravity, . . .)

$\Rightarrow$ Interpretation in terms of "the" SM Higgs would imply that the low-energy limit of a more complete theory is just the SM $+$ nothing else

$\Rightarrow$ A logical possibility, but this would mean that the gauge hierarchy, dark matter, matter–anti-matter asymmetry in the universe, . . . , would all have origins that are not directly related to low-scale physics

Actually, the signal at 125 GeV poses a problem for the SM!

The hierarchy problem: the SM Higgs mass is affected by large corrections from physics at high scales

The Standard Model does not include gravity

$\Rightarrow$ breaks down at the latest at $M_{\mathrm{Planck}} \approx 10^{19}$ GeV

$\Rightarrow$ "effective theory", can only be valid up to cutoff scale Λ

Higgs mass in the SM is a free parameter

Expect that in more fundamental theory the Higgs mass can be predicted

$\Rightarrow$ Physical value of M_{H}^2 is obtained as the sum of lowest-order contribution $+$ higher-order corrections

$$M_{\mathrm{H}}^2 = M_{\mathrm{H},0}^2 + \Delta M_{\mathrm{H},1}^2 + \Delta M_{\mathrm{H},2}^2 + \ldots$$

$\Rightarrow$ Calculation of corrections to M_{H}^2 in SM with cutoff Λ

The hierarchy problem: the SM Higgs mass is affected by large corrections from physics at high scales

$$\Rightarrow \; \Delta M_H^2 \sim \Lambda^2$$

For $\Lambda = M_{\rm Planck}$: $\Delta M_{\rm H}^2 \sim M_{\rm Planck}^2 \Rightarrow \Delta M_{\rm H}^2 \approx 10^{30}\, M_{\rm H}^2$

$\Rightarrow$ Hierarchy problem, extreme fine-tuning necessary between $M_{\rm H,0}^2$ and $\Delta M_{\rm H}^2$ to get small $M_{\rm H}$, i.e. $M_{\rm H} \approx 126 \; {\rm GeV}$

Hierarchy problem: how can the Planck scale and the weak scale coexist?

There exists a Higgs-like state with a mass of $\sim 126\ \mathrm{GeV}$

But what protects its mass from physics at high scales?

This has implications also in a wider context:

- "Hierarchy problem": $M_{\mathrm{Planck}}/M_{\mathrm{weak}} \approx 10^{17}$

  How can two so different scales coexist in nature?

  Via quantum effects: physics at M_{weak} is affected by physics at M_{Planck}

  $\Rightarrow$ Instability of M_{weak}

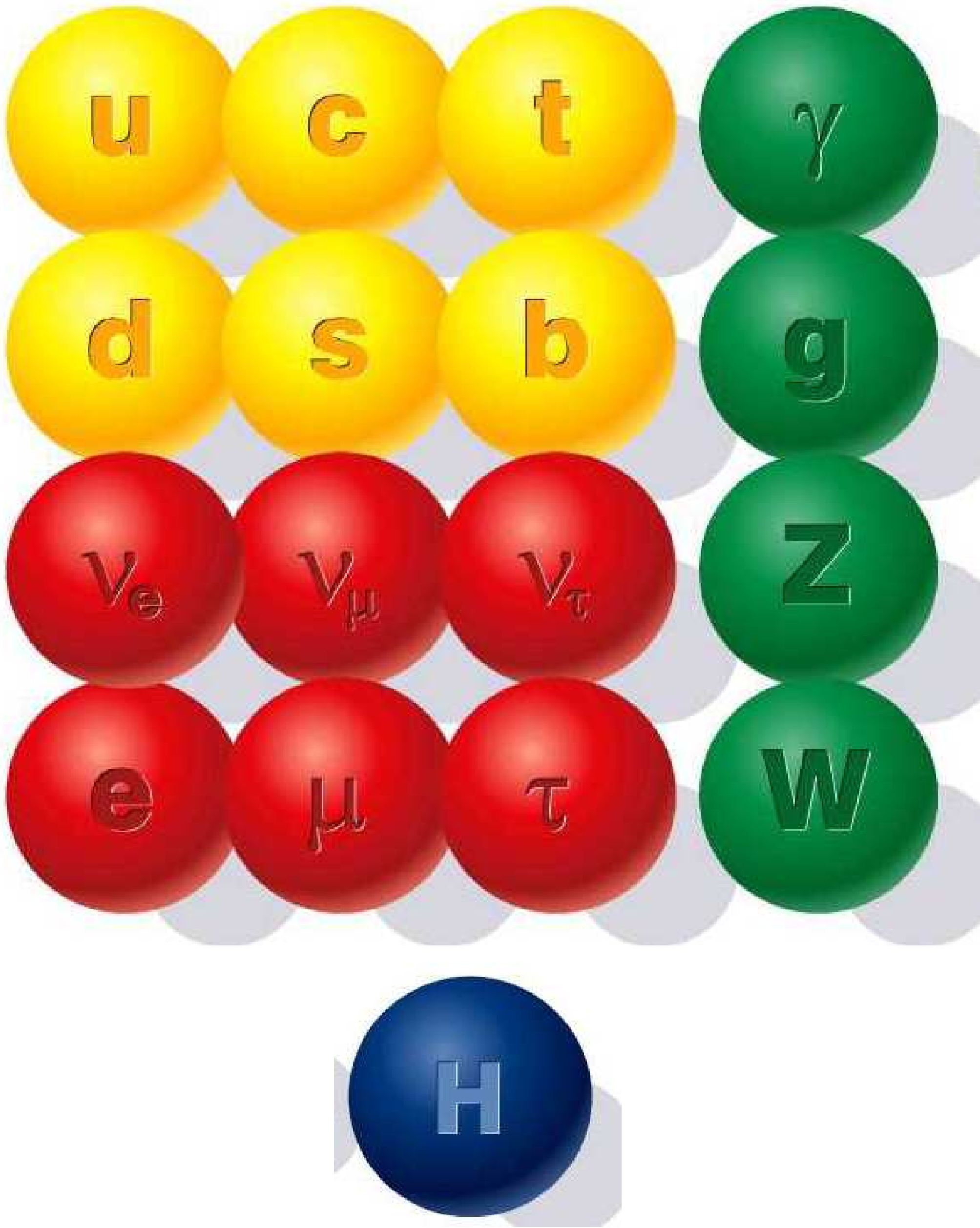
  $\Rightarrow$ Would expect that all physics is driven up to the Planck scale

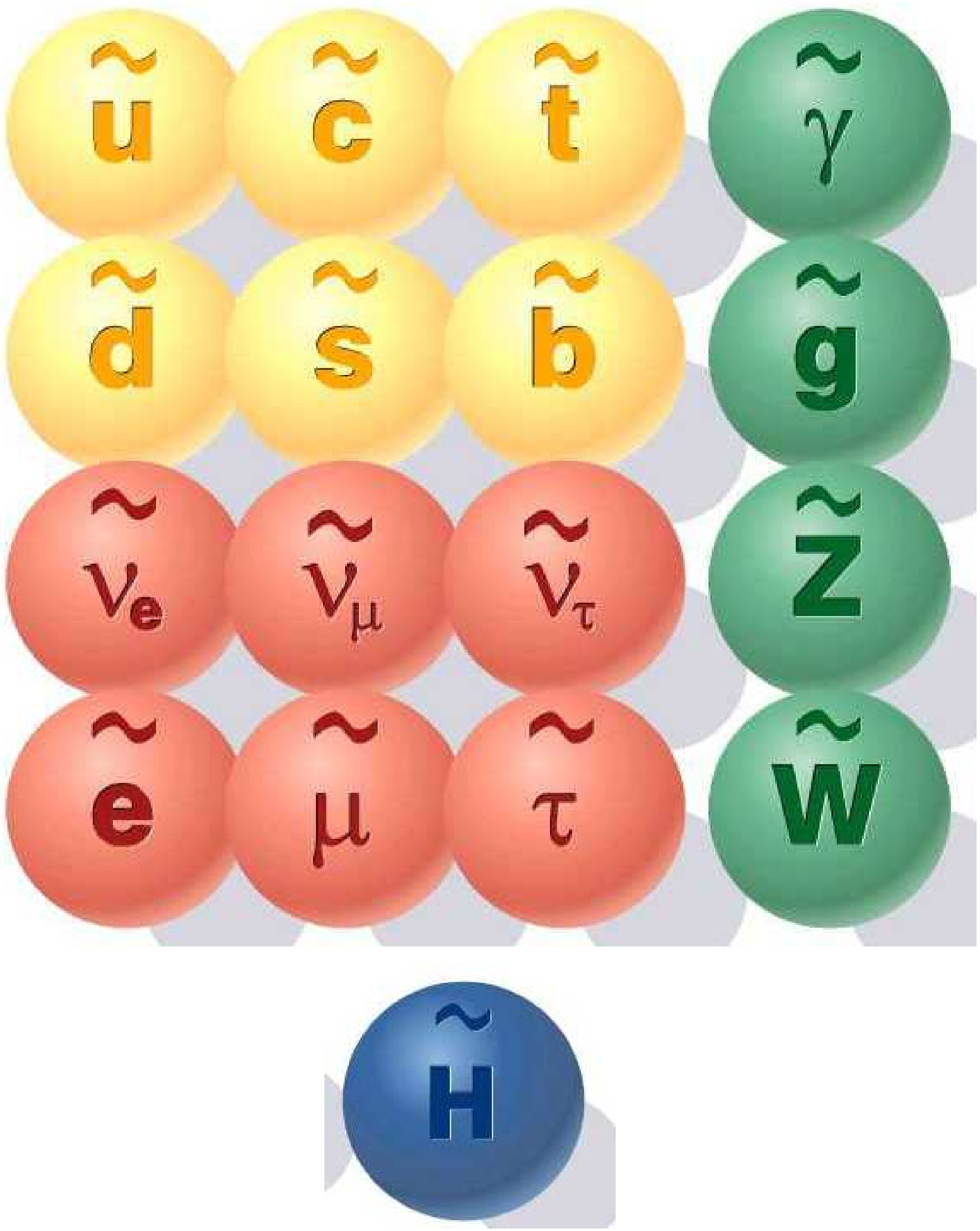
- Nature has found a way to prevent this

  The Standard Model provides no explanation

Strong motivation for BSM physics that stabilises the hierarchy

Supersymmetry: fermion $\longleftrightarrow$ boson symmetry,
leads to compensation of large quantum corrections





Interpretation of the signal in extended Higgs sectors (SUSY), case I: signal interpreted as light state h

- Most obvious interpretation: signal at about 125 GeV is interpreted as the lightest Higgs state h in the spectrum

- Additional Higgs states at higher masses

- Differences from the Standard Model (SM) could be detected via:

  - properties of h(125): deviations in the couplings, different decay modes, different CP properties, ...

  - detection of additional Higgs states: $H, A \to \tau\tau$, $H \to hh$, $H, A \to \chi\chi$, ...

Interpretation of the signal in terms of the light MSSM Higgs boson

- Detection of a SM-like Higgs with $M_H > 135$ GeV would have unambiguously ruled out the MSSM (with TeV-scale masses)

- Signal at 125 GeV is well compatible with MSSM prediction

- Observed mass value of the signal gives rise to lower bound on the mass of the CP-odd Higgs: $M_A > 200 \text{ GeV}$

- $\Rightarrow M_A \gg M_Z$: ``Decoupling region" of the MSSM, where the light Higgs h behaves SM-like

- $\Rightarrow$ Would not expect observable deviations from the SM at the present level of accuracy

The quest for identifying the underlying physics

In general 2HDM-type models one expects % level deviations from the SM couplings for BSM particles in the TeV range, e.g.

$$
\begin{aligned}
\frac{g_{hVV}}{g_{h_{\rm SM}VV}} &\simeq 1 - 0.3\% \left(\frac{200\ \rm GeV}{m_A}\right)^4 \\
\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} &\simeq 1 - 1.7\% \left(\frac{200\ \rm GeV}{m_A}\right)^2 \\
\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} &\simeq 1 + 40\% \left(\frac{200\ \rm GeV}{m_A}\right)^2 .
\end{aligned}
$$

⇒ Need very high precision for the couplings

Possibility of a sizable deviation even if the couplings to gauge bosons and SM fermions are very close to the SM case

- If dark matter consists of one or more particles with a mass below about 63 GeV, then the decay of the state at 125 GeV into a pair of dark matter particles is kinematically open

- The detection of an invisible decay mode of the state at 125 GeV could be a manifestation of BSM physics

  - Direct search for $H \to$ invisible

  - Suppression of all other branching ratios

SUSY interpretation of the observed Higgs signal: light Higgs h

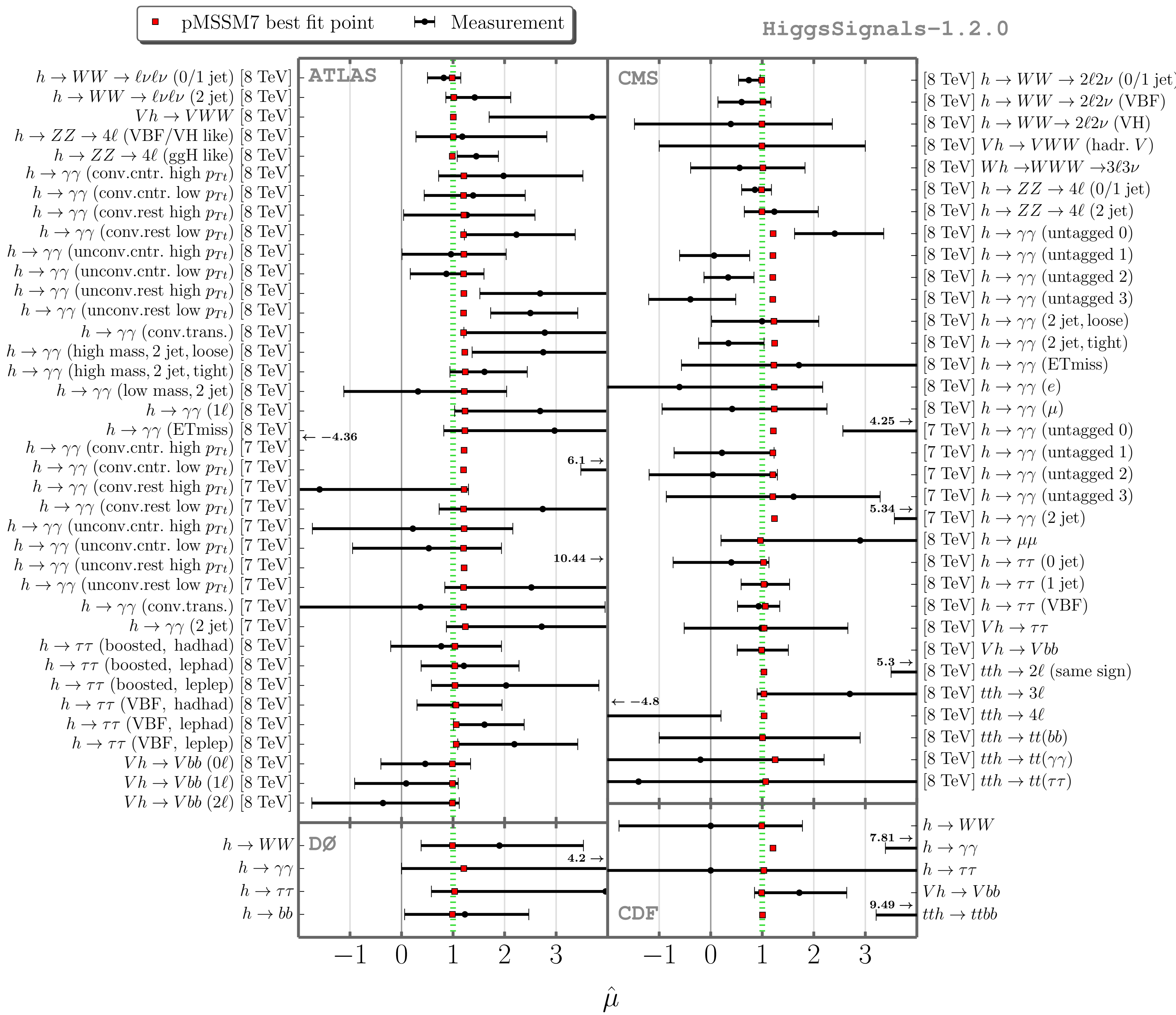
Fit to LHC data, Tevatron, precision observables: SM vs. MSSM

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '14]

Observables:

HiggsSignals

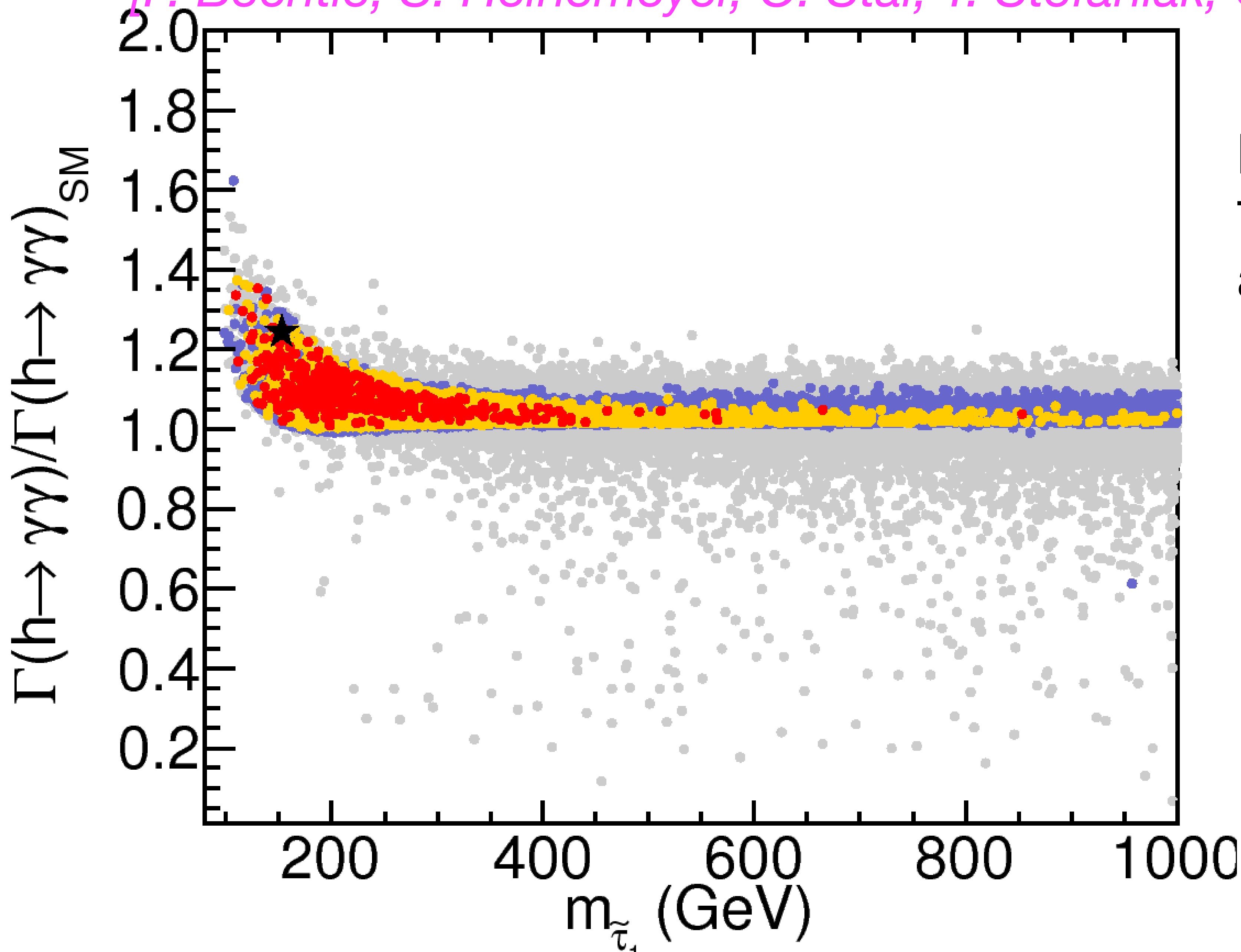
$$\mu_i = \frac{(\sigma \times \mathrm{BR})_i}{(\sigma \times \mathrm{BR})_i^{\mathrm{SM}}}$$



⇒ χ^2 reduced compared to the SM, (slightly) improved fit quality

Best fit prefers enhanced $\gamma\gamma$ rate from light staus

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '14]



pre-ICHEP data from ATLAS and CMS

$\Rightarrow$ ≈20% enhancement of partial width

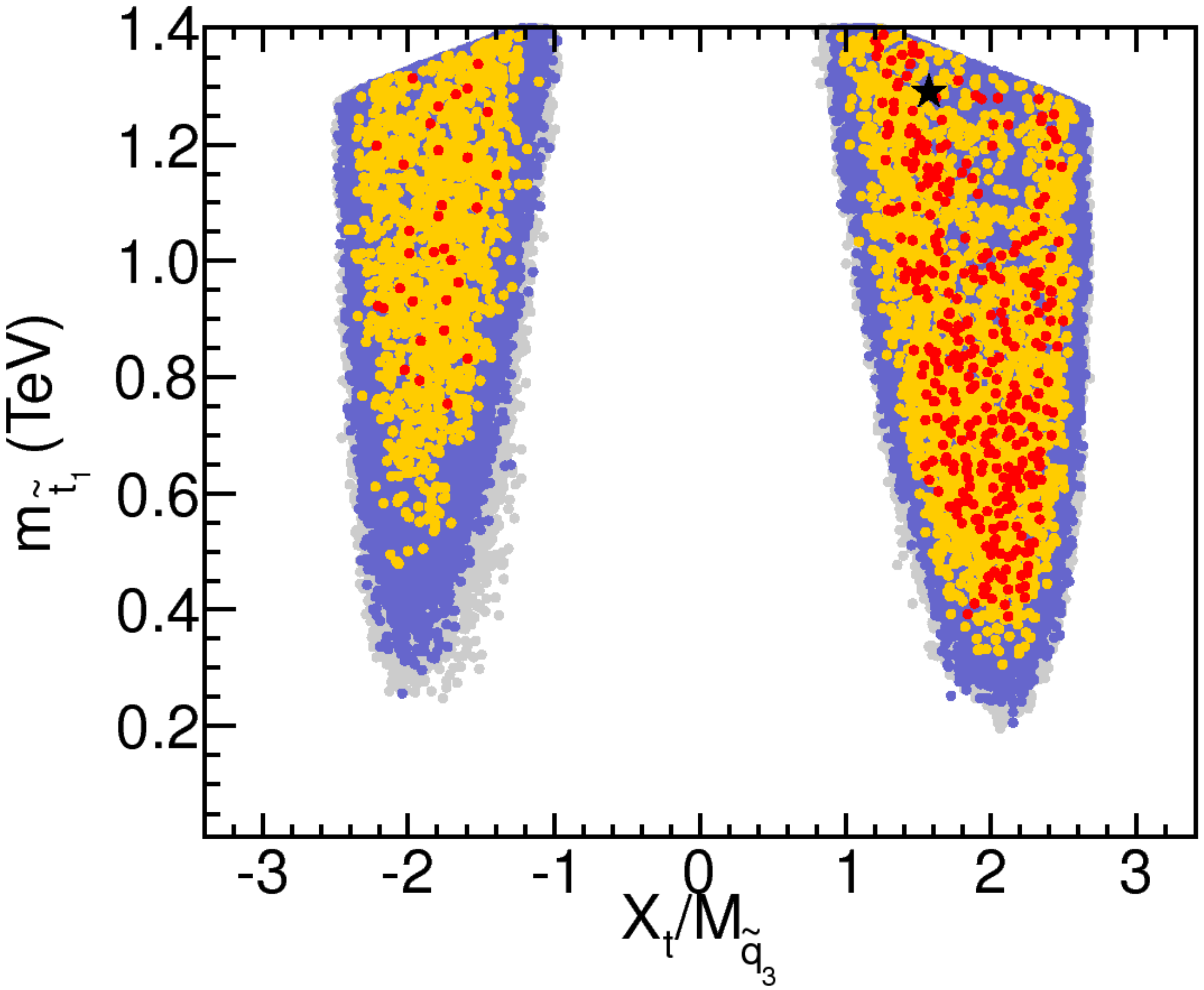
Fit assumes slepton mass universality: $M_{\tilde{E}_{1,2}} = M_{\tilde{L}_{1,2}} = M_{\tilde{l}_3}$

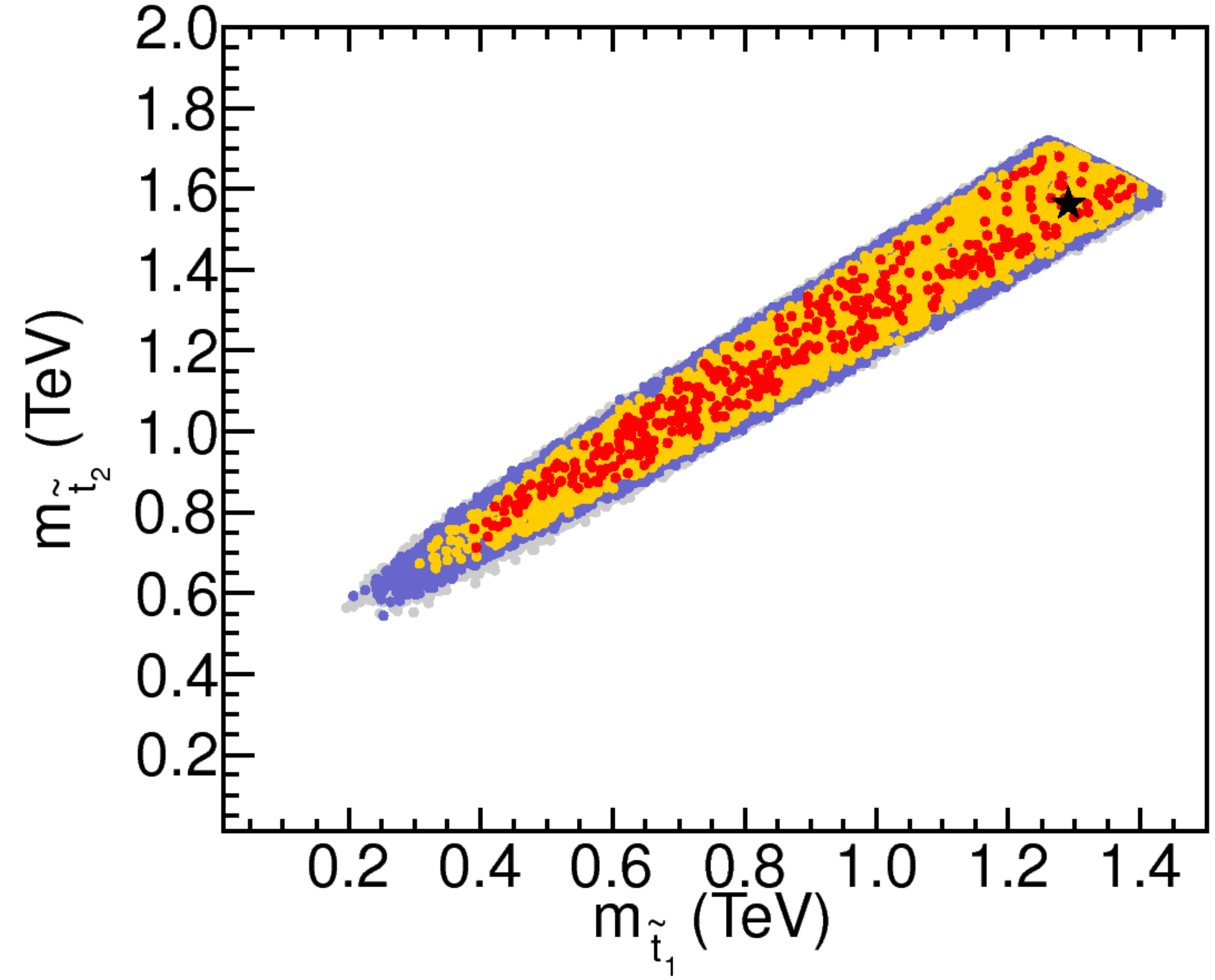
$\Leftrightarrow$ Also impact from $g_\mu - 2$

Interpretation of the signal at 125 GeV in terms of the light Higgs h of the MSSM

MSSM fit, preferred values for the stop masses:

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '14]





⇒ Large stop mixing required

Best fit prefers heavy stops beyond 1 TeV

But good fit also for light stop down to ≈300 GeV

Extended Higgs sectors, case II: signal interpreted as a state H of an extended Higgs sector that is not the lightest one

Extended Higgs sector where the second-lightest (or higher) Higgs has SM-like couplings to gauge bosons

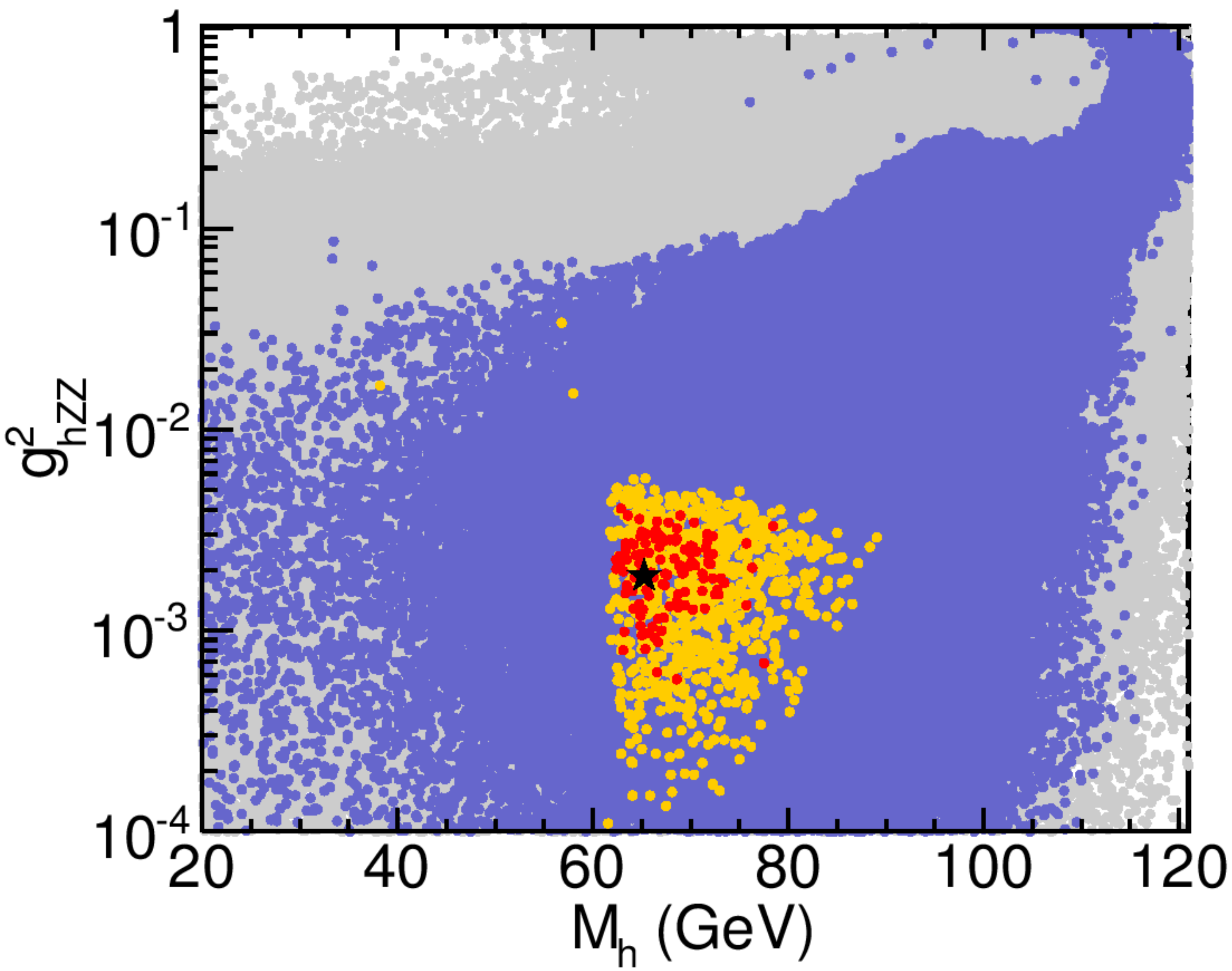
⇒ Lightest neutral Higgs with heavily suppressed couplings to gauge bosons, may have a mass below the LEP limit of 114.4 GeV for a SM-like Higgs (in agreement with LEP bounds)

Possible realisations: 2HDM, MSSM, NMSSM, ...

A light neutral Higgs in the mass range of about 60-100 GeV (above the threshold for the decay of the state at 125 GeV into hh) is a generic feature of this kind of scenario. The search for Higgses in this mass range has only recently been started at the LHC. Such a state could copiously be produced in SUSY cascades.

MSSM realisation: very exotic scenario, where all five Higgs states are light

Lightest Higgs: mass and couplings to gauge bosons (blue: *HiggsBounds*-allowed)
[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]

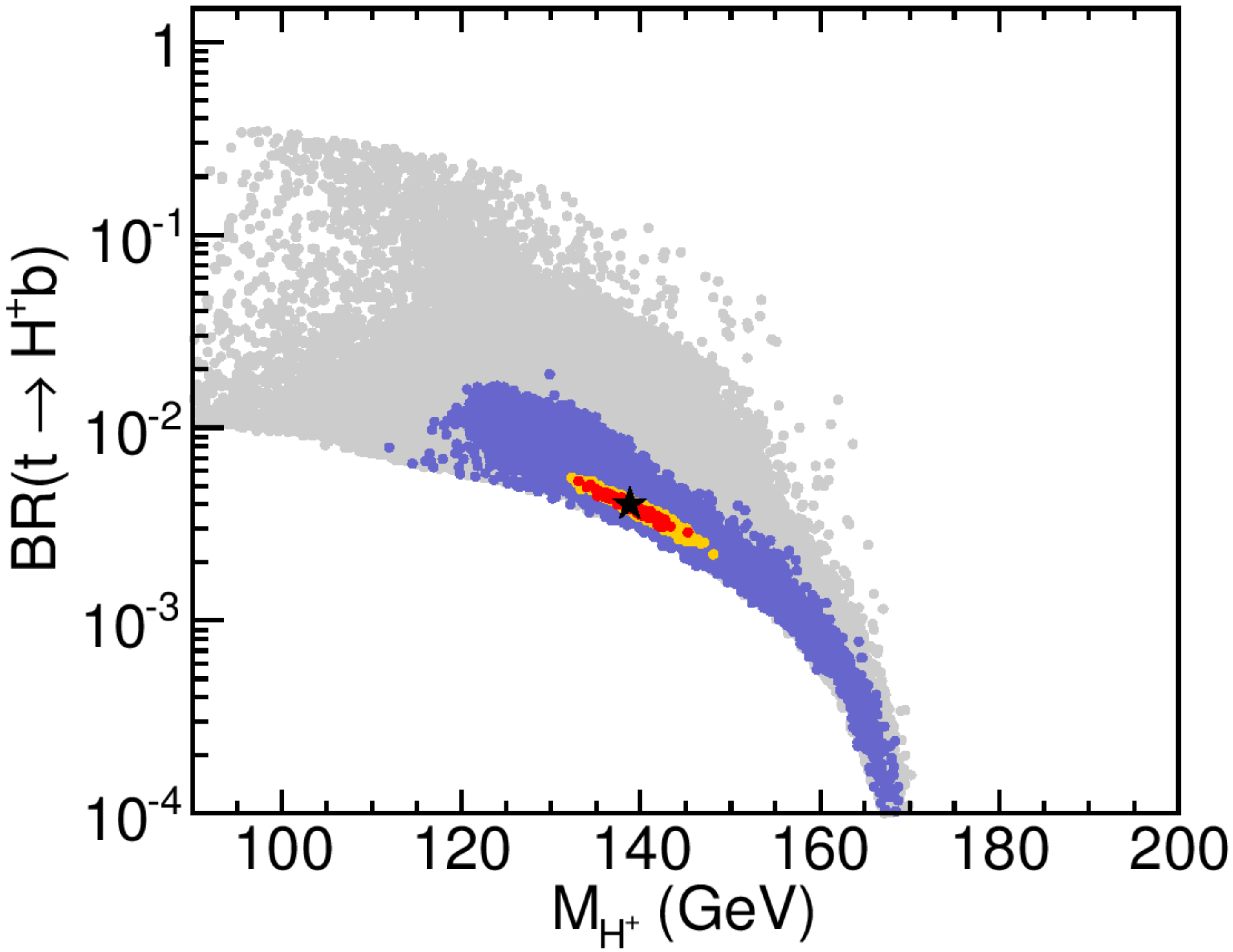


$\Rightarrow$ Light Higgs with $M_{\mathrm{h}} \approx 70\ \mathrm{GeV}$, in agreement with LEP limits

Before charged Higgs results from ATLAS: global fit yielded acceptable fit probability

MSSM scenario can directly be probed with charged Higgs searches

[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]



Low M_H scenario: dedicated benchmark scenario for charged Higgs searches

NMSSM: extension of the MSSM by a singlet + superpartner

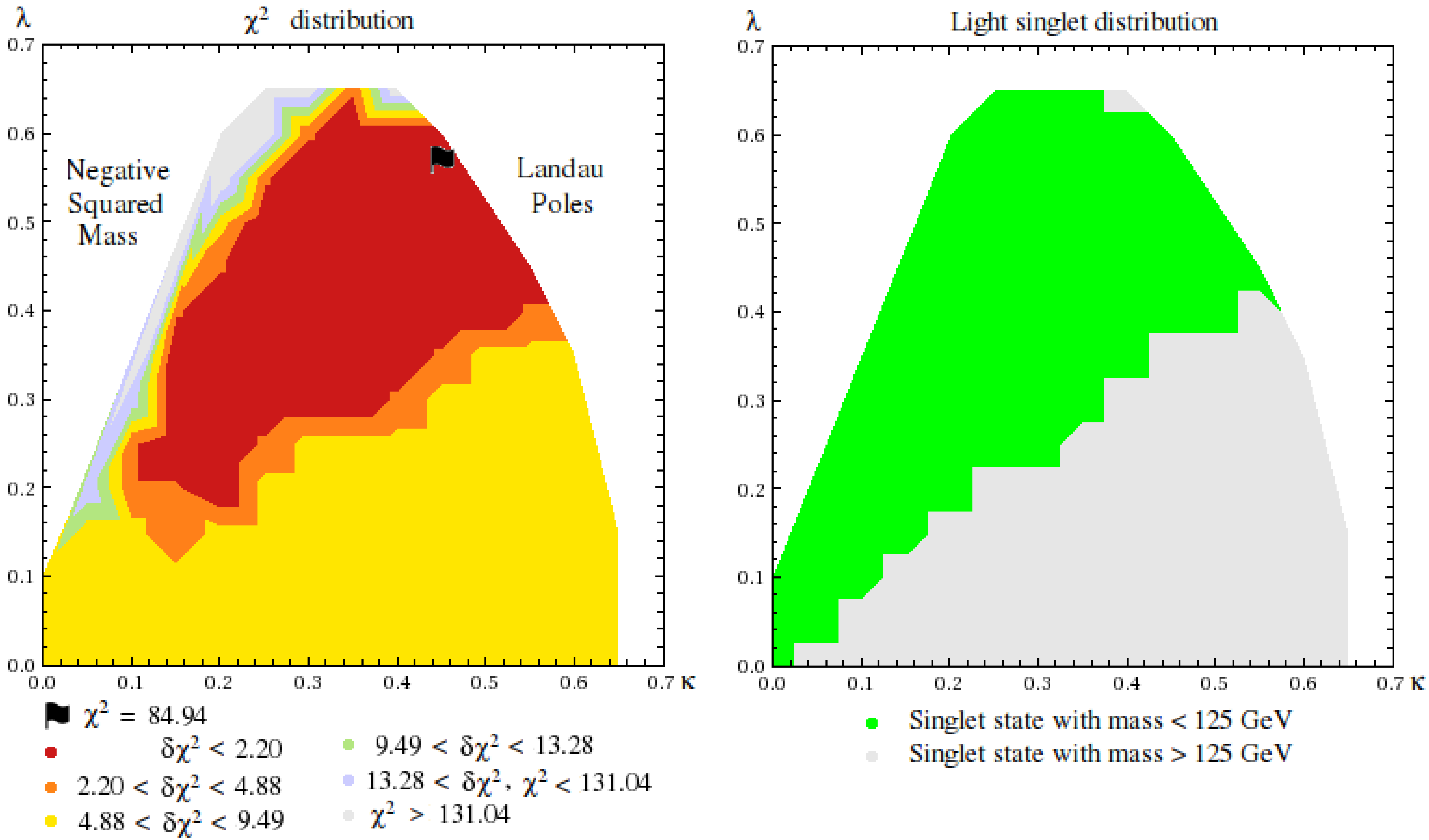
- The case that the signal at 125 GeV corresponds to a Higgs boson which is not the lightest one in the spectrum happens generically in the NMSSM if the singlet is light (singlet-doublet mixing → upward shift of the SM-like Higgs)

- Analysis of possible NMSSM phenomenology in view of the existing limits from the Higgs searches and the properties of the signal at 125 GeV (implemented via *HiggsBounds* and *HiggsSignals*) *[F. Domingo, G. W. '14]*

  Other work in this context: *[G. Belanger, U. Ellwanger, J. Gunion, Y. Jiang, S. Kraml, J. Schwarz '13], [M. Badziak, M. Olechowski, S. Pokorski '13], [J. Gunion, Y. Jiang, S. Kraml '12], [N. Christensen, T. Han, S. Su '13], ...*

Best fit point and preferred region in $\varkappa$ - λ plane

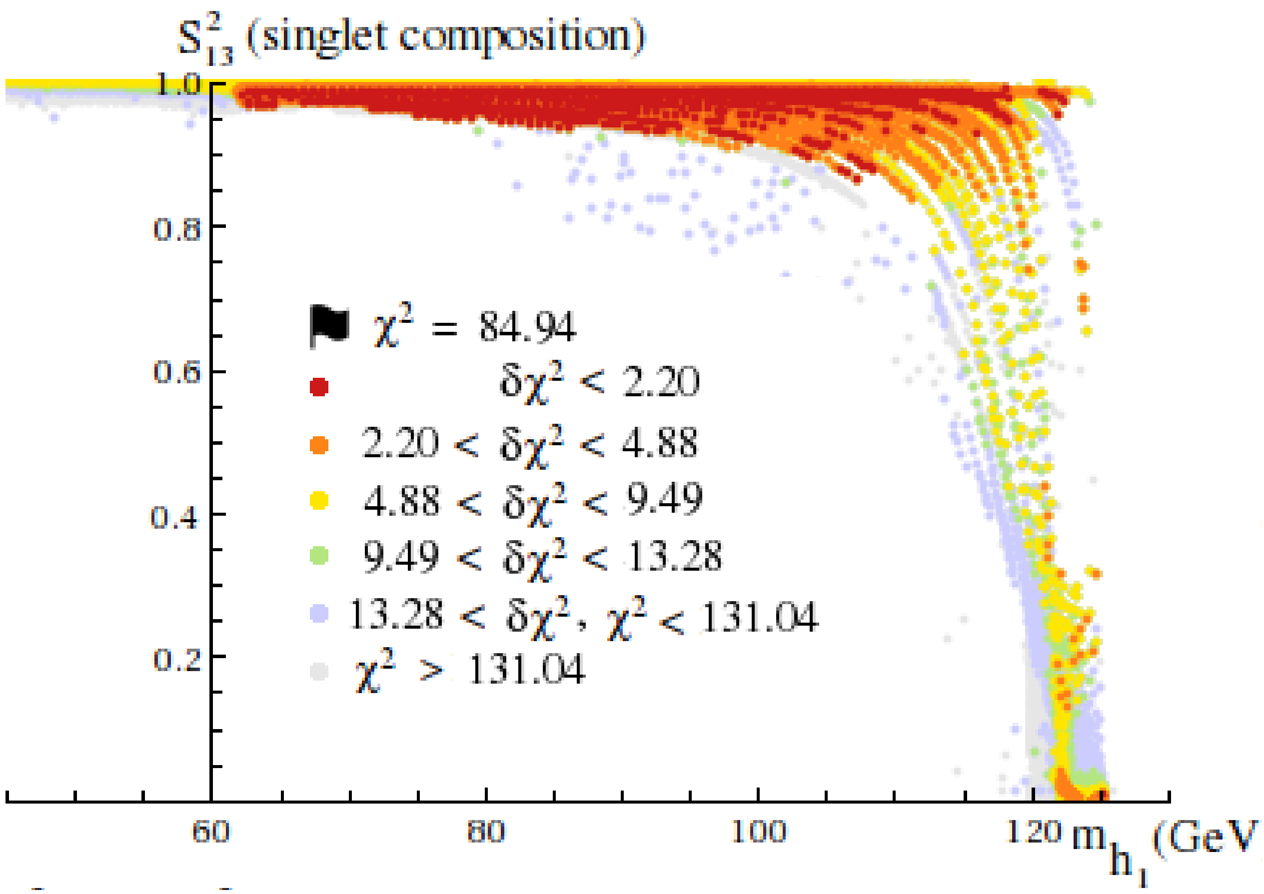
[F. Domingo, G. W. '14]

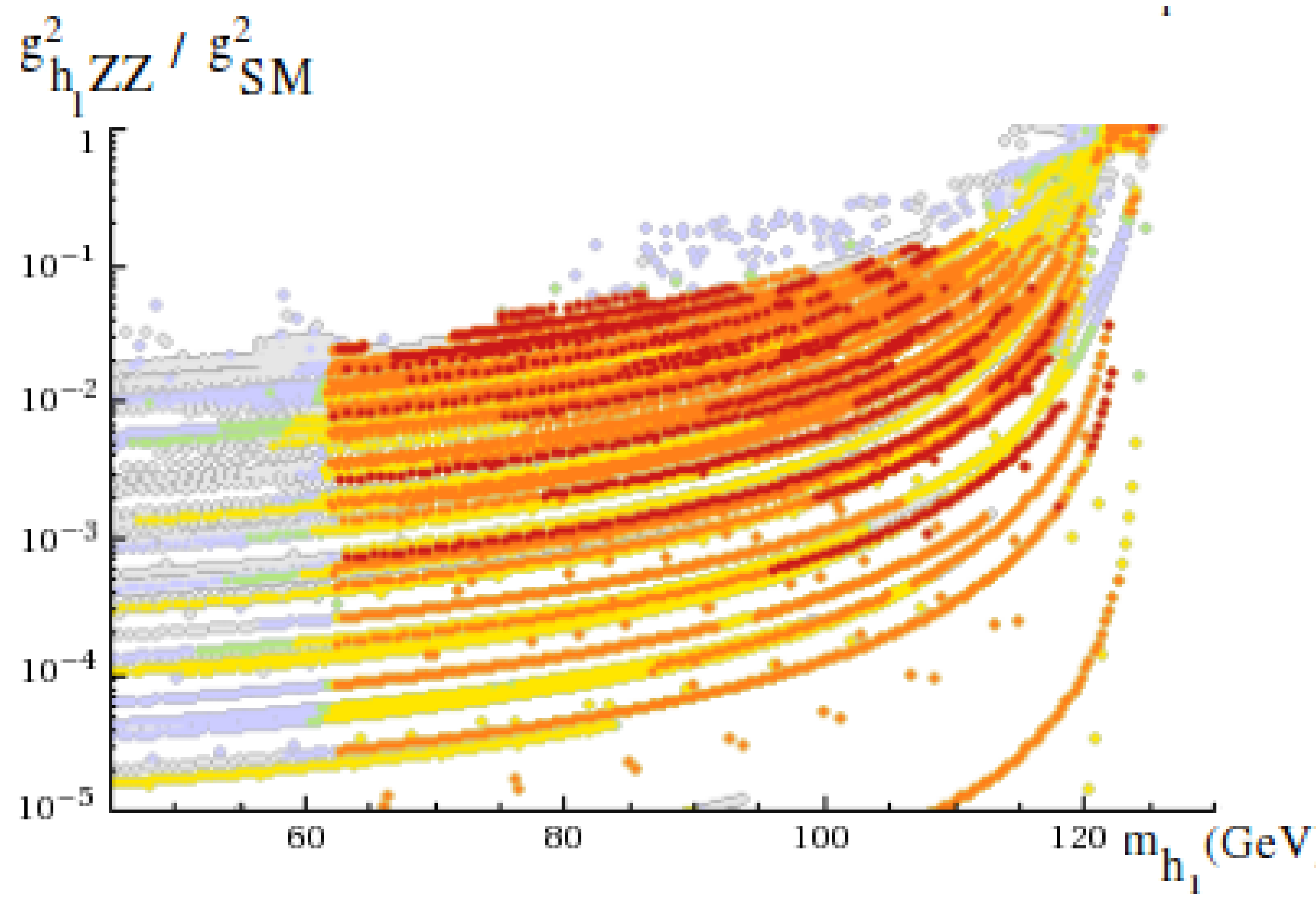


⇒ Preferred region spans over wide range of $\varkappa$ and λ, coincides largely with region where singlet mass is below 125 GeV

Composition of the lightest CP-even state

[F. Domingo, G. W. '14]





$\Rightarrow$ Large singlet component, strong suppression of the coupling to gauge bosons

Could it be a composite Higgs?

Composite "pseudo-Goldstone boson", like the pion in QCD $\Rightarrow$ Would imply new kind of strong interaction

Relation to weakly-coupled 5-dimensional model (AdS/CFT correspondence)

Discrimination from fundamental scalar

- Precision measurements of couplings ($\Rightarrow$ high sensitivity to compositeness scale), $\mathcal{CP}$ properties, ...
  Does the new state have the right properties to unitarize $W_L W_L$ scattering?
- Search for resonances
  (light Higgs $\Leftrightarrow$ light resonances?)

Present status

The properties of the signal are so far compatible with the predictions for the Higgs boson of the SM, but many other interpretations are possible, corresponding to very different underlying physics:

- Lightest or next-to-lightest state of an extended Higgs sector
- Pseudo-Goldstone boson, composite Higgs, ...
- Mixed state: Higgs-radion mixing, ...
- ...

⇒ Need to discriminate between the different possible options in order to identify the nature of electroweak symmetry breaking!

Conclusions

The spectacular discovery of a signal at ~125 GeV in the Higgs searches at LHC marks the start of a new era of particle physics

The discovered signal is so far compatible with a SM-like Higgs, but a variety of interpretations is possible, corresponding to very different underlying physics

Need high-precision measurements of the properties of the detected particle + searches for BSM states + precise theory predictions ⇒ direct / indirect sensitivity to physics at higher scales

⇒ Rich physics programme at LHC, HL-LHC and ILC

⇒ Exciting prospects: Higgs physics may be the key to revealing the physics behind the Standard Model!

Backup

Complementarity between benchmark scenarios and cross section limits

- Cross-section limits for different search topologies:
  Fairly model-independent ⇒ test of different models

  Exclusion bounds can be tested channel by channel; combination?

- Benchmark scenarios of specific models (in particular: models that have a Higgs state that is compatible with the signal at 125 GeV):
  full strength of experimental analysis can be exploited for specific benchmark scenario, combination of channels, etc., but difficult to interpret in other models or w.r.t. changes in the input parameters or the theoretical predictions

⇒ Analyses in benchmark scenarios are important for exploring possible Higgs phenomenology

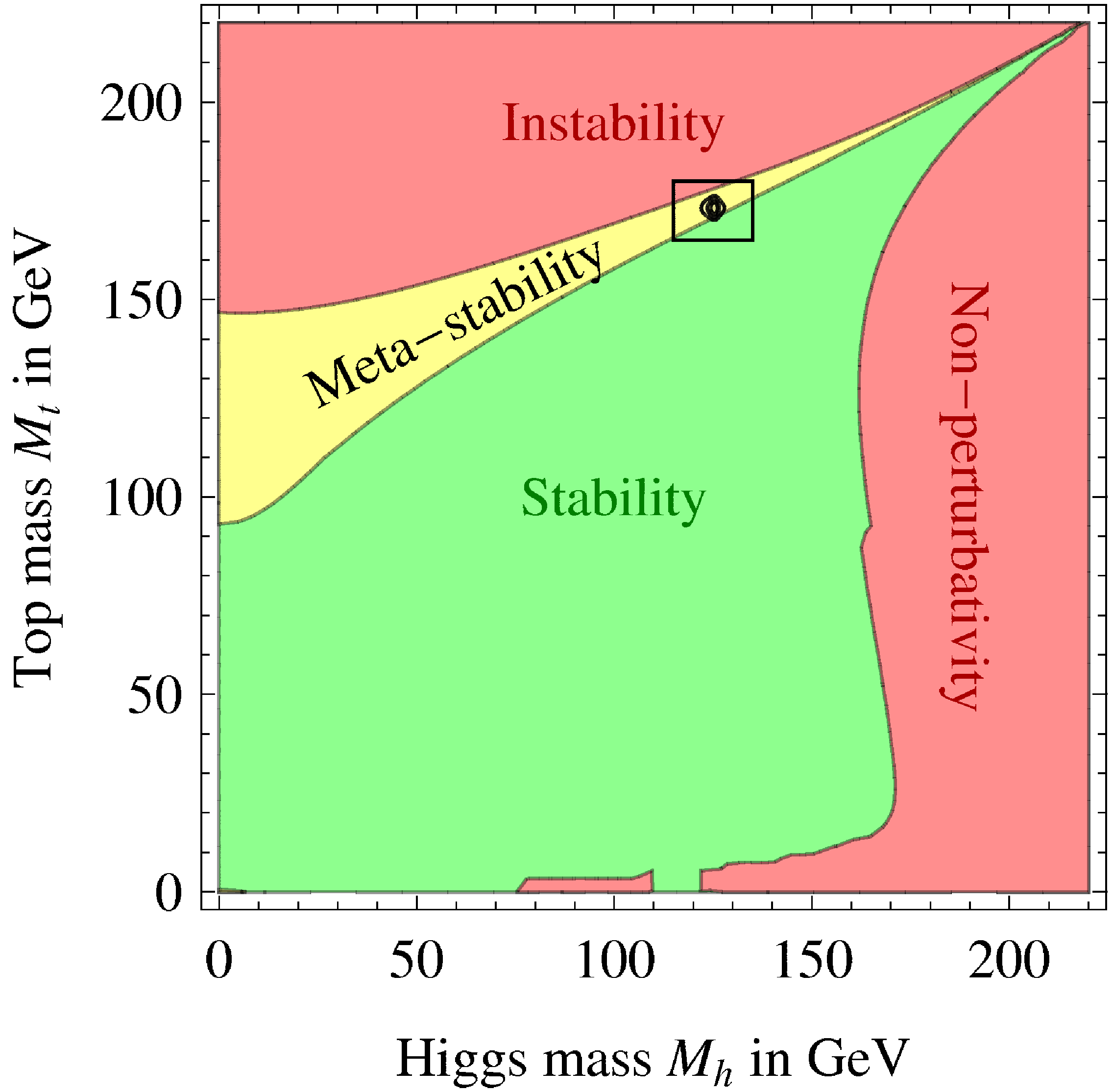
Benchmark results are crucial for validating implementation of cross section limits

Could the SM be valid all the way up to the Planck scale?

Yes, in principle, but . . .

Do we live in a metastable vacuum?

[*G. Degrassi et al. ’12*]



Extended Higgs sector: contributions of additional Higgs states stabilise the vacuum

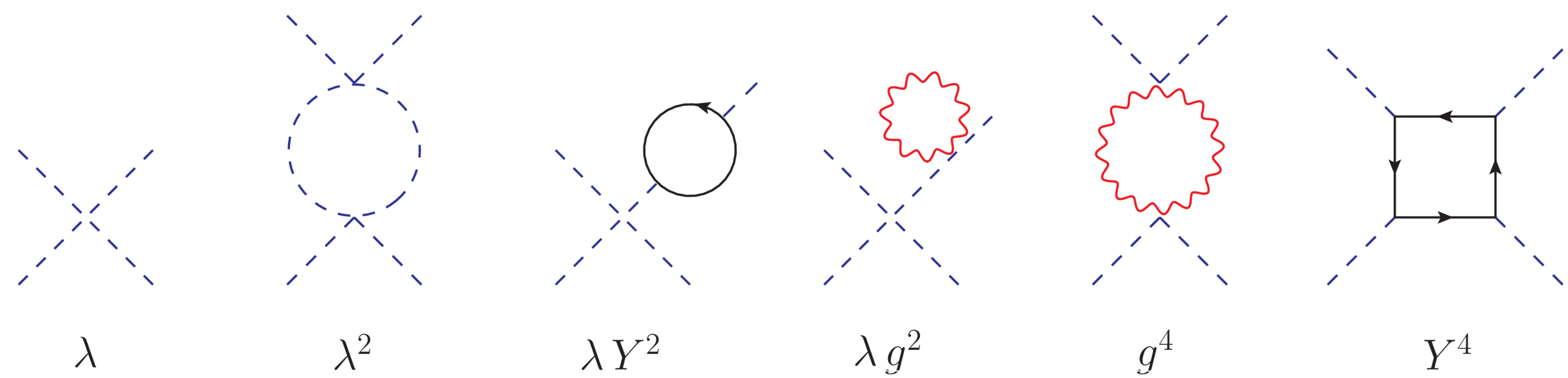
Could the SM be valid all the way up to the Planck scale? Is the vacuum stable in the SM?

Quantum corrections to the classical Higgs potential can modify its shape

$$V^{class}(\phi) = -\frac{1}{2}m^2\phi^2 + \lambda\phi^4 \longrightarrow V^{\text{eff}} \approx -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu) \sim \lambda(\mu)\phi^4(\mu)$$

$\phi \sim \mu \gg v$

λ runs



$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_cY_t - 9g^2 - 3g'^2\right) - 2N_cY_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2g'^2 + \ldots\right]$$

M_H large: λ^2 wins $\quad \lambda(M_t) \to \lambda(\mu) \gg 1 \quad$ non-perturbative regime, Landau pole

M_H small: $-Y_t^4$ wins $\quad \lambda(M_t) \to \lambda(\mu) \ll 1$

[G. Degrassi '13]