Rare Electroweak-type Higgs decays

[*Two-body Higgs decay with an on-shell Z or W + a light state*]

Gino Isidori

[*University of Zürich*]

- Introduction
- Light exotic states in h → 4μ
- The rare exclusive semi-hadronic Higgs decays
- Conclusions

Introduction

Despite all its successes, the SM is likely to be an *effective theory*, i.e. the limit
-*in the experimentally accessible range of energies and effective couplings*-
of a more fundamental theory, with new degrees of freedom

We need to search for New Physics with a broad spectrum perspective
given the lack of clear indications on the SM-EFT boundaries
(*both in terms of energies and effective couplings*)

Introduction

Despite all its successes, the SM is likely to be an *effective theory*, i.e. the limit -*in the experimentally accessible range of energies and effective couplings*- of a more fundamental theory, with new degrees of freedom

We need to search for New Physics with a broad spectrum perspective given the lack of clear indications on the SM-EFT boundaries (*both in terms of energies and effective couplings*)

"High-statistics" Higgs Physics

(*exploration of the Higgs properties with minimum theoretical bias*)

- *Ad hoc* sector of the SM, with several couplings not determined by symmetries
- First fundamental (?) scalar
- Natural "portal" toward possible "secluded sectors" with new particles/fields
- The vast majority of the allowed couplings of the Higgs are couplings to the SM fermions (still largely unexplored...) → large room for NP
- ...

Introduction

Despite all its successes, the SM is likely to be an *effective theory*, i.e. the limit -*in the experimentally accessible range of energies and effective couplings*- of a more fundamental theory, with new degrees of freedom

We need to search for New Physics with a broad spectrum perspective given the lack of clear indications on the SM-EFT boundaries (*both in terms of energies and effective couplings*)

"High-statistics" Higgs Physics

(*exploration of the Higgs properties with minimum theoretical bias*)

Precision measurements

Rare decays

(*more on Thursday...*)

Introduction

Rare Higgs decays are particularly interesting given the peculiar value of m_h (→ *WW & ZZ not allowed on-shell* → suppressed Higgs width & enhanced sensitivity to small couplings BSM)

Introduction

Rare Higgs decays are particularly interesting given the peculiar value of m_h (→ *WW & ZZ not allowed on-shell* → suppressed Higgs width & enhanced sensitivity to small couplings BSM)

In this talk I will concentrate on the following type of rare (two-body) Higgs decays:

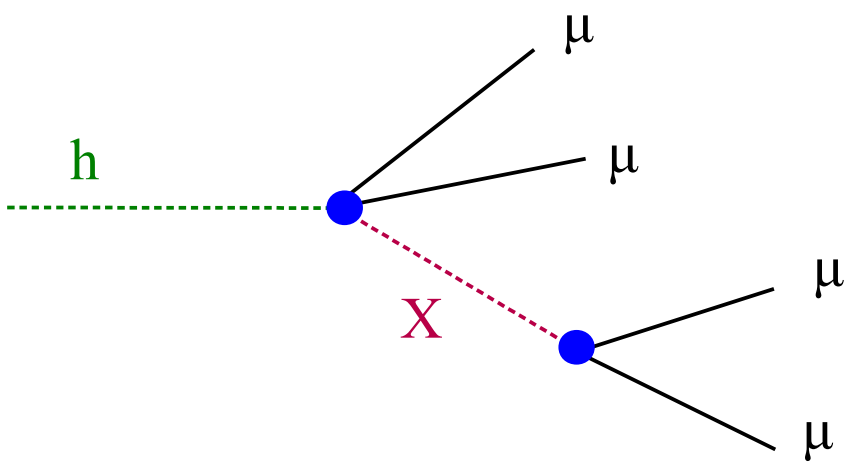
$h \to Z(W) + X$

I. Light exotic $X \to \mu\mu$

II. SM light meson ($X = \pi, \psi, \Upsilon, D, \ldots$)

- Clean experimental signature (*with II possible bkg. for I*)
- Unique window on specific NP models with light new states (I)
- Unique window on hV*ff* couplings, at low q^2, with *f=u,d,s,c,b* (II)

Light exotic states in h → 4l



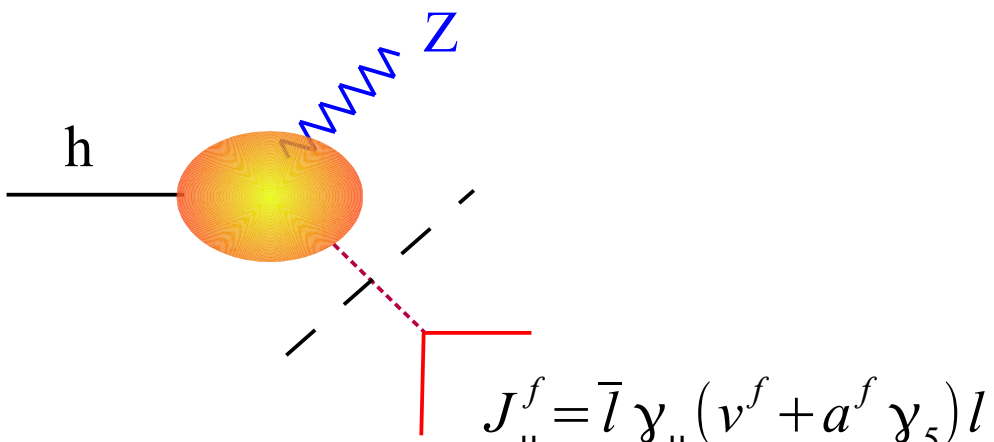
Light states in h → 4*l* *decays*

ATLAS and CMS have reported results about the h → ZZ* couplings

However, what has been observed in the experiments are the h → 4*l* decays (*l*=e,μ). With suitable cuts is possible to isolate the h →Z+*ll* amplitude but, in general,

$$A(h \to Z+ll) \neq A(h \to ZZ^*)$$

A(h →ZZ*) is not even a well-defined amplitude, if we do not specify the underlying theory....



$$J^f_\mu = \bar{l}\,\gamma_\mu (v^f + a^f \gamma_5)\, l$$

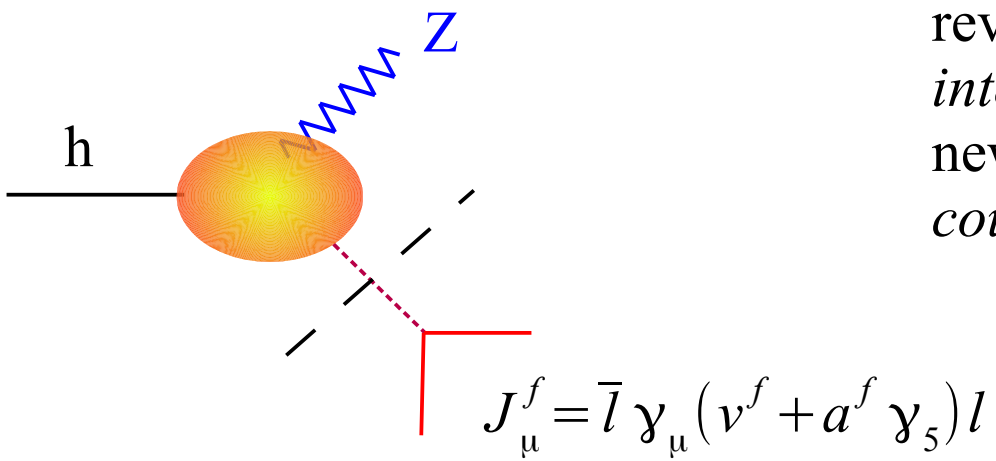
$$(2m_l)^2 < q^2 < (m_h - m_V)^2$$

Light states in h → 4*l* decays

ATLAS and CMS have reported results about the h → ZZ* couplings

However, what has been observed in the experiments are the h → 4*l* decays (*l*=e,μ). With suitable cuts is possible to isolate the h →Z+*ll* amplitude but, in general,

$$A(h \to Z+ll) \neq A(h \to ZZ^*)$$



$(2m_l)^2 < q^2 < (m_h - m_V)^2$

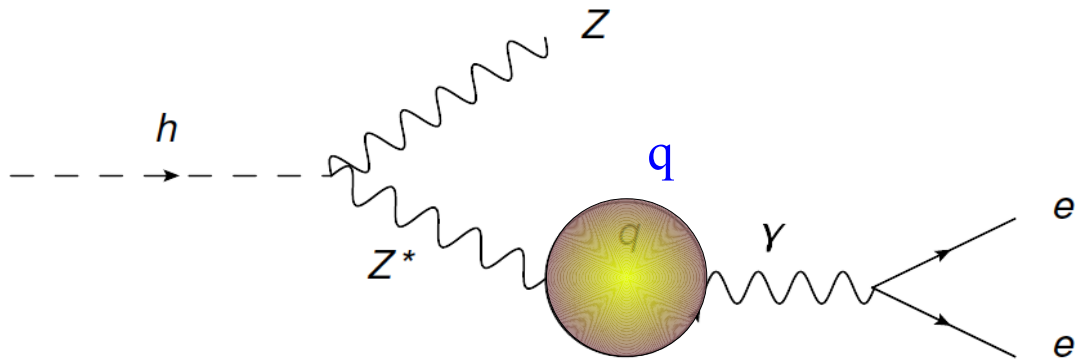
The "off-shellness" of the second lepton pair allows to probe a richer dynamical structure:

- We are far enough from the pole of the amplitude at $q^2 = m_Z^2$ (*dominant pole within the SM*)
- Measuring the q^2 dependence we could reveal new "distant poles" (↔ *contact interactions in the EFT*) or even new "light poles" (↔ *new light states coupled to h & fermions*)

GI, Manohar, Trott, 1305.0663
Curtin *et al.* 1312.4992,
Falkowski, Vega-Morales, 1405.1095
R. Dermisek, Raval, Shin, 1406.7018
Y. Chen *et al.* 1503.0585
M. Gonzalez-Alonso *et al.* 1504.04018, ...

Light states in h → 4*l* *decays*

The $d\Gamma/dm_{34}$ spectrum ($m_{34} = \sqrt{q^2}$ = lightest invariant mass pair) is the most interesting distribution to identify possible light-poles → *very precise SM distribution*, even at low m_{34}, including charmonium/bottomonium states:



$$\Pi^{Z\gamma}_{\mu\nu}(q) \equiv i \int d^4x e^{iqx} \langle 0|T J^Z_\mu(x) J^\gamma_\nu(0)|0\rangle$$

$$\approx \left(\frac{1}{2} - s^2_W\right) \Pi^{uds}_{\gamma\gamma}(q^2) + \left(\frac{3}{8} - s^2_W\right) \Pi^c_{\gamma\gamma}(q^2) + \left(\frac{3}{4} - s^2_W\right) \Pi^b_{\gamma\gamma}(q^2)$$

$$R(s) \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)}$$

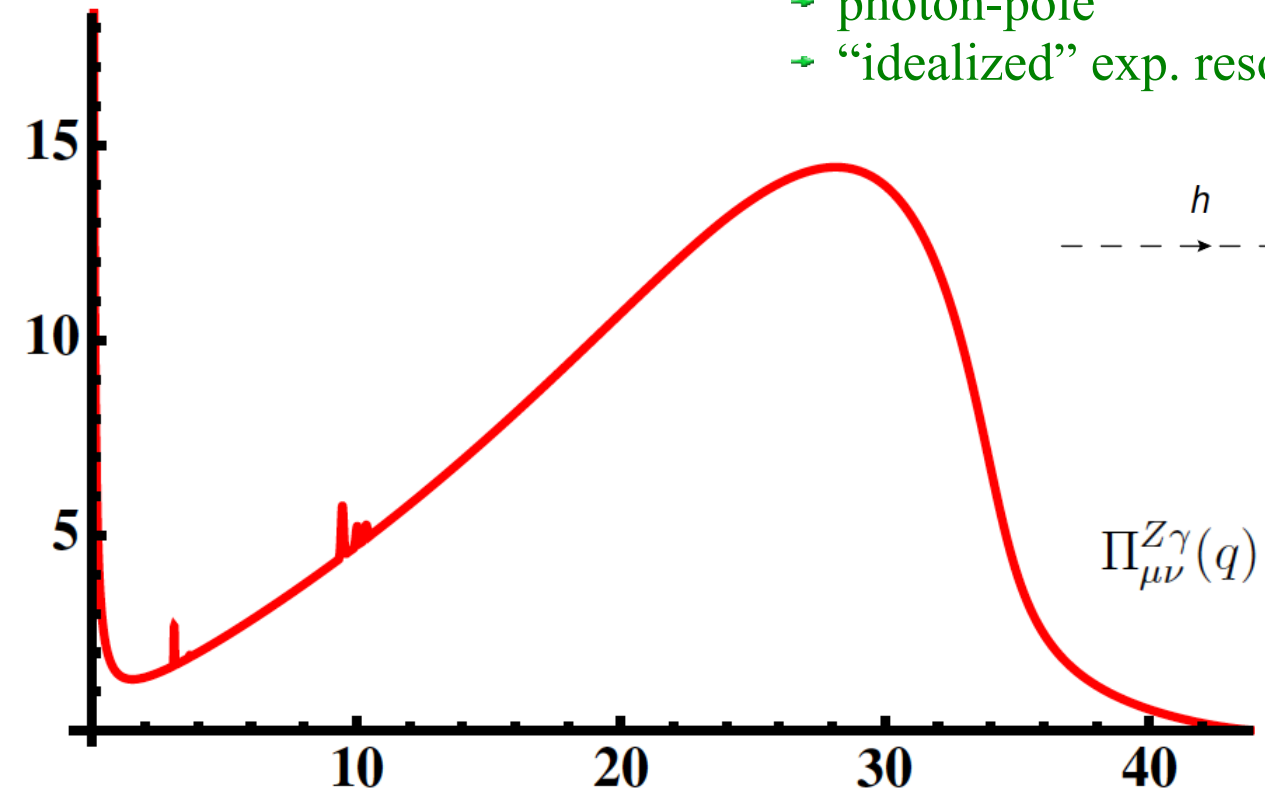
via dispersion relations

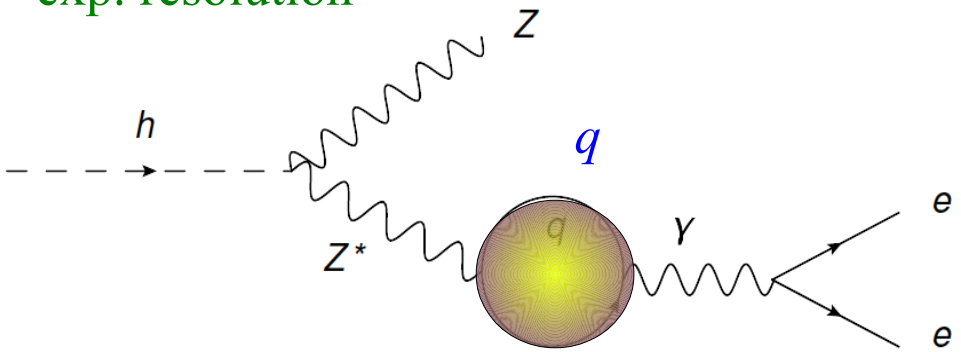
Gonzales-Alonso & GI, 1403.2648

Light states in h → 4*l* *decays*

The $d\Gamma/dm_{34}$ spectrum ($m_{34} = \sqrt{q^2}$ = lightest invariant mass pair) is the most interesting distribution to identify possible light-poles → *very precise SM distribution*, even at low m_{34}, including charmonium/bottomonium states:

- Heavy-quarkonia effects
- off-shell Z
- photon-pole
- "idealized" exp. resolution





$$\Pi^{Z\gamma}_{\mu\nu}(q) \equiv i \int d^4x e^{iqx} \langle 0|T J^Z_\mu(x) J^\gamma_\nu(0)|0\rangle$$

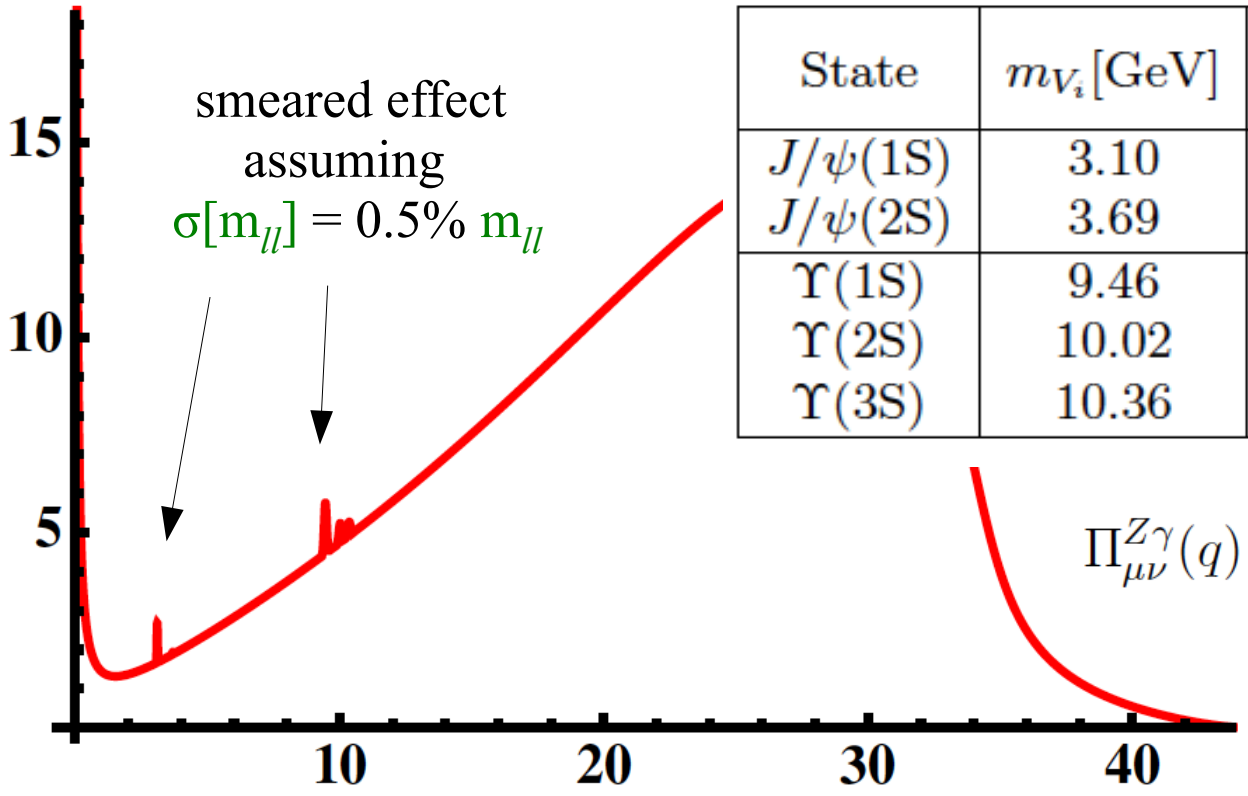
Gonzales-Alonso & GI, 1403.2648

Light states in h → 4*l* *decays*

The $d\Gamma/dm_{34}$ spectrum ($m_{34} = \sqrt{q^2}$ = lightest invariant mass pair) is the most interesting distribution to identify possible light-poles → *very precise SM distribution*, even at low m_{34}, including charmonium/bottomonium states:

- Heavy-quarkonia effects
- off-shell Z

$d\Gamma/dm_{34}$



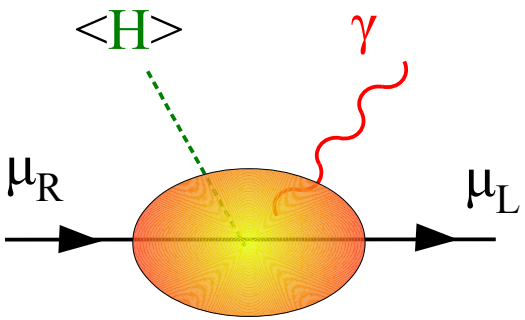
State	m_{V_i}[GeV]	$\mathcal{B}(h \to ZV_i)$	relative shift 1 GeV bin
$J/\psi(1S)$	3.10	2.3×10^{-6}	3.5%
$J/\psi(2S)$	3.69	1.1×10^{-6}	0.4%
$\Upsilon(1S)$	9.46	1.6×10^{-5}	3.1%
$\Upsilon(2S)$	10.02	8.2×10^{-6}	1.2%
$\Upsilon(3S)$	10.36	6.2×10^{-6}	0.9%

$$\Pi^{Z\gamma}_{\mu\nu}(q) \equiv i \int d^4x e^{iqx} \langle 0|T J^Z_\mu(x) J^\gamma_\nu(0)|0\rangle$$

SM resonance effects are small & under good th. control → *we can probe NP...*

Specific NP examples motivated by the $(g-2)_\mu$ anomaly

Since a long time the experimental determination of $a_\mu = (g-2)_\mu$ is not in good agreement with the SM prediction:

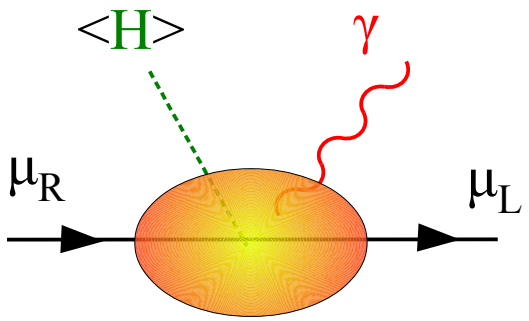


$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm th} = (2.9 \pm 0.9) \times 10^{-9}$$

The discrepancy is not extremely significant (~3σ), *but has survived a long list of scrutinies...*

Specific NP examples motivated by the $(g\text{-}2)_\mu$ *anomaly*

Since a long time the experimental determination of $a_\mu = (g\text{-}2)_\mu$ is not in good agreement with the SM prediction:



$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm th} = (2.9 \pm 0.9) \times 10^{-9}$$

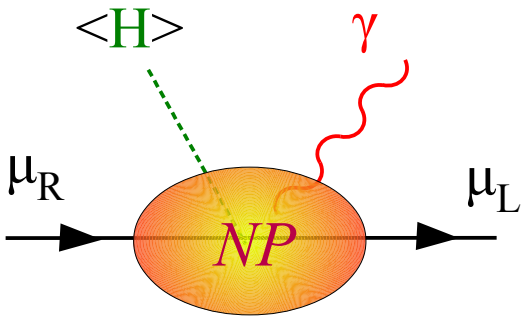
The discrepancy is not extremely significant (~3σ), *but has survived a long list of scrutinies...*

Solving the $(g\text{-}2)_\mu$ anomaly in terms of NP, requires the introduction of some new (*light or heavy...*) states coupled to muons.

In all cases there is a *natural connection* between NP effects in $(g\text{-}2)_\mu$ and $h \to 4l$

Specific NP examples motivated by the $(g\text{-}2)_\mu$ *anomaly*

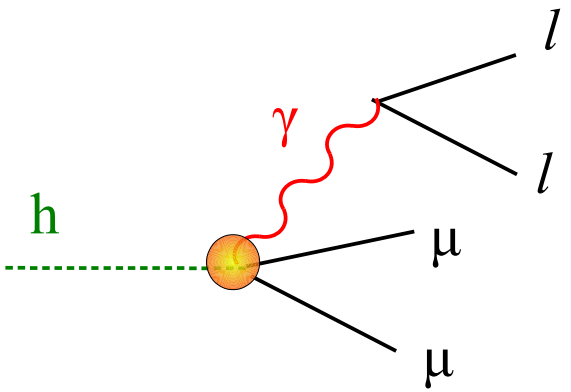
There is a *natural connection* between NP effects in $(g\text{-}2)_\mu$ and $h \to 4l$



$m_{NP} > m_h$

Tiny correction to $h \to 2\mu 2l$

unambiguous connection by means of EFT



$$\Delta\Gamma(h \to \mu^+\mu^-\gamma)^{(g-2)}_{\rm EFT} = -\frac{e^2 m_h^3 \Delta a_\mu}{128\pi^3 v^2}$$

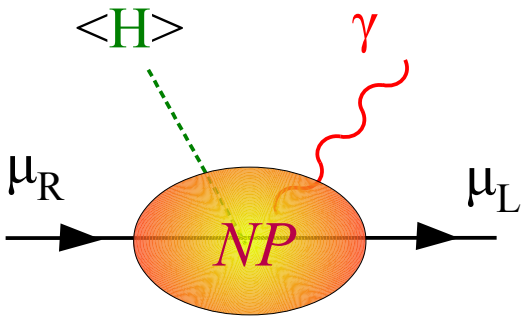
$O(10^{-4})$ correction with respect to $BR(h \to 2\mu\gamma)_{SM}$

unmeasurable even in the HL phase of LHC

Gonzales-Alonso & GI, 1403.2648

Specific NP examples motivated by the $(g-2)_\mu$ anomaly

There is a *natural connection* between NP effects in $(g-2)_\mu$ and $h \to 4l$



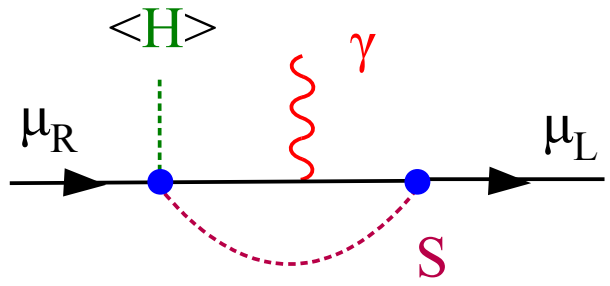
$m_{NP} > m_h$

Tiny correction to $h \to 2\mu 2l$

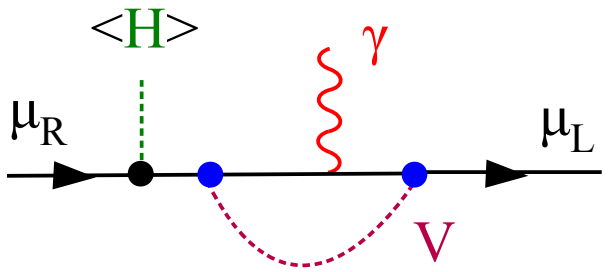
$2m_\mu < m_{NP} \ll m_h$

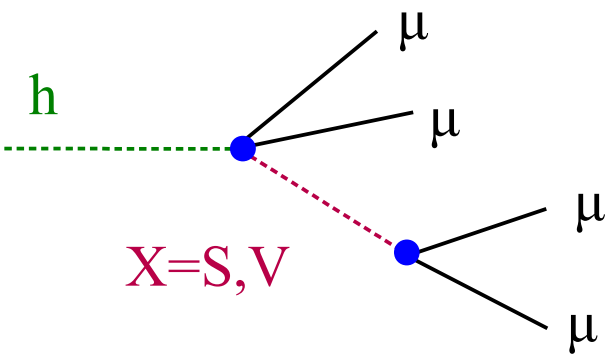
Possible "visible" non-standard peak in the $h \to 4\mu$ distribution

E.g.:



Pospelov, 0811.1030
Carone,1301.2027





Davoudials, Lee, Marciano, 1203.2947, 1304.4935
Curtin *et al.* 1312.4992, Gonzales-Alonso & GI, 1403.2648

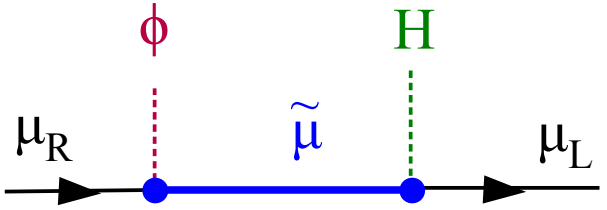
Specific NP examples motivated by the $(g\text{-}2)_\mu$ *anomaly*

A "minimalistic & concrete" set-up [*minimum set of free parameters*]:

- One light $SU(2)_L$-singlet scalar field, ϕ
- One effective coupling c_μ/Λ → Two parameter model (c_μ/Λ and m_ϕ):

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm kin}(\phi) + \left(\frac{c_\mu}{\Lambda}\,\bar{\mu}_L\,\mu_R\,H\,\phi + \text{h.c.}\right)$$

This $\mathscr{L}_{eff}$ *can be generated, for instance, introducing an heavy vector-like μ-partner*



- The ratio of the two free parameters is the fixed by $(g\text{-}2)_\mu$ anomaly:

$$\Delta a_\mu = \frac{|c_\mu|^2}{96\pi^2}\frac{v^2}{\Lambda^2}\frac{m_\mu^2}{m_\phi^2} \approx 6.4\times 10^{-9}\left|\frac{c_\mu/\Lambda}{(1\text{ TeV})^{-1}}\right|^2\left|\frac{10\text{ GeV}}{m_\phi}\right|^2$$

- For $m_\phi \gtrsim 1$ GeV the model is consistent with all known bounds.

Gonzales-Alonso & GI, 1403.2648

Specific NP examples motivated by the $(g\text{-}2)_\mu$ *anomaly*

A "minimalistic & concrete" set-up [*minimum set of free parameters*]:

- One light $SU(2)_L$-singlet scalar field, ϕ
- One effective coupling c_μ/Λ → Two parameter model (c_μ/Λ and m_ϕ)
- The ratio of the two free parameters is the fixed by $(g\text{-}2)_\mu$ anomaly

$$\frac{\mathcal{B}(h\to 4\mu)_{(\phi)}}{\mathcal{B}(h\to 4\mu)_{\rm SM}} \approx 150\left(\frac{\Delta a_\mu}{2.9\times 10^{-9}}\right)\left(\frac{m_\phi}{10\ {\rm GeV}}\right)^2 \mathcal{B}(\phi\to\mu^+\mu^-)$$

A potential huge effect !

A*lready ruled out by present data...*

...unless BR ($\phi \to \mu\mu$) << 1 → quite possible if there are additional (invisible) decay modes of ϕ (ν's, DM states, etc...).

Specific NP examples motivated by the $(g-2)_\mu$ *anomaly*

Going beyond this minimal set-up, we can state that

- If the $h \to X+\mu\mu$ on-shell decay is kinematically allowed
- If we fix the couplings of the X particle to have an impact on $(g-2)_\mu$

- Not difficult to satisfy all existing constraints, especially for $m_X \sim$ few GeV
- Sizable *local* deviations in $h \to 4\mu$ naturally expected

Specific NP examples motivated by the $(g-2)_\mu$ *anomaly*

Going beyond this minimal set-up, we can state that

- If the $h \to X+\mu\mu$ on-shell decay is kinematically allowed
- If we fix the couplings of the X particle to have an impact on $(g-2)_\mu$

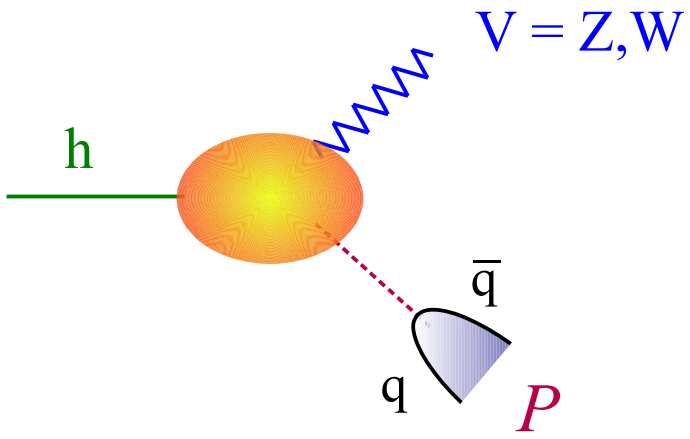
- Not difficult to satisfy all existing constraints, especially for $m_X \sim$ few GeV
- Sizable *local* deviations in $h \to 4\mu$ naturally expected

Note also that...

- Virtually in all models addressing the $(g-2)_\mu$ anomaly (with $X \to \mu\mu$), X is narrow & short-lived (*not true if we do not insist on g-2*)

- In the minimal "*dark-Z*" models [new U(1) & pure kinetic mixing with $U(1)_Y$] the region relevant for $(g-2)_\mu$ is already ruled-out, but it is easy to construct less minimal models [e.g. charging muons & not electrons under the new U(1)] where the region probed in $h \to 4\mu$ is relevant for $(g-2)_\mu$

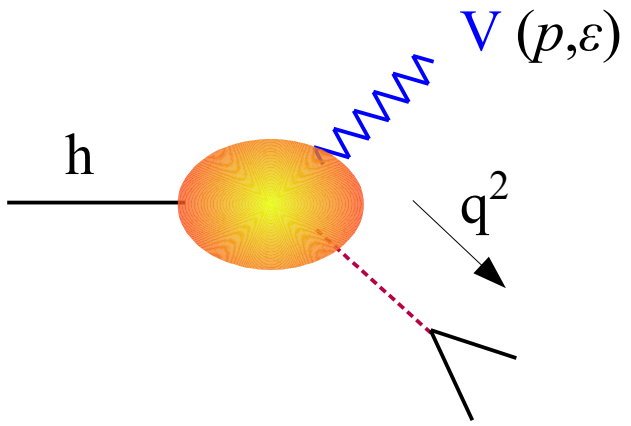
The rare exclusive semi-hadronic Higgs decays



The rare exclusive semi-hadronic Higgs decays

On general grounds, it is quite difficult to investigate the following aspects of the $h \to V ff$ amplitude:

- The $f = q$ case
- The $q^2 \to 0$ limit
- The terms relevant for $q_\mu J_\mu \neq 0$



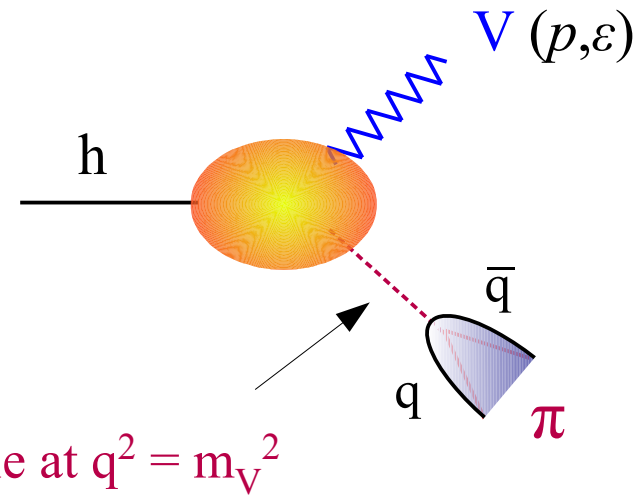
$$J^f_\mu = \bar{f}\,\gamma_\mu\,(v^f + a^f\,\gamma_5)\,f$$

A possible handle on all these aspects is provided by the rare $h \to VP$ decays, where P is a single hadron state and, in particular, a (quasi-)stable pseudo-scalar hadron

The rare exclusive semi-hadronic Higgs decays

On general grounds, it is quite difficult to investigate the following aspects of the $h \to V ff$ amplitude:

- The $f = q$ case
- The $q^2 \to 0$ limit
- The terms relevant for $q_\mu J_\mu \neq 0$



no pole at $q^2 = m_V^2$

A possible handle on all these aspects is provided by the rare $h \to VP$ decays, where P is a single hadron state and, in particular, a (quasi-)stable pseudo-scalar hadron

The pseudo-scalar case is particularly interesting and simple: in the $g \to 0$ limit it projects out the Goldstone-boson component of the amplitude

$$A^{\rm SM} \propto \frac{f_\pi}{v}$$

ratio of the two order parameters controlling the $SU(2)_L$ *breaking*

The rare exclusive semi-hadronic Higgs decays

Similar considerations holds if we replace the pseudo-scalar hadron with a light massive vector (amplitude dominated by the longitudinal polarization of the vector):

- BRs calculable with high precision within the SM:

$$\mathrm{B}(h \to Z\,\Upsilon)_{SM} = 1.5\times10^{-5} \qquad \mathrm{B}(h \to W^-\,D_s^*)_{SM} = 2.5\times10^{-5}$$
$$\mathrm{B}(h \to Z\,\eta_c)_{SM} = 1.4\times10^{-5} \qquad \mathrm{B}(h \to W^-\,D_s)_{SM} = 1.7\times10^{-5}$$
$$\mathrm{B}(h \to Z\,\psi)_{SM} = 2.3\times10^{-6} \qquad \mathrm{B}(h \to W^-\,\rho)_{SM} = 1.1\times10^{-5}$$
$$\ldots \qquad \mathrm{B}(h \to W^-\,\pi)_{SM} = 4.3\times10^{-6}$$
$$\ldots.$$

GI, Manohar, Trott, 1305.0663
Gao, 1406.7102
Alte, Konig, Neubert, 1609.0631

- Within SM, dominated by the tree-level amplitude [$D_\mu H^+ D_\mu H \leftrightarrow hZ^*Z$], except when suppressed

  → ~30% contrib. from $h \to \gamma^* Z$ for uu or cc hadrons (e.g. $h \to Z\psi$)

- Possible sizable modification in various BSM frameworks

The rare exclusive semi-hadronic Higgs decays

Possible BSM mechanisms leading to sizable enhancements:

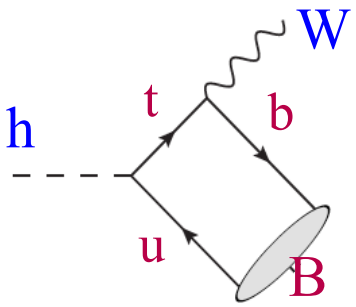
I. Enhanced $h \to \gamma^* Z$:

- One-order of magnitude enhancement for quarkonium modes with uu & cc components (ω, ρ, ψ), given present bounds on $h \to \gamma^* Z$
- Possibility to access the CP-structure of $h \to \gamma^* Z$

Alte, Konig, Neubert, 1609.0631

II. Flavor-changing $h \to tu$:

- One order of of magnitude for $h \to W B$



III. Non-standard $h \to Vqq$ amplitude [$h(U D_\mu U)\bar{\psi}_q \gamma^\mu \psi_q$]

- Sizable enhancement possible in several channels, provided h is not a pure $SU(2)_L$ doublet (→ evade EW constraints)

GI & Trott, 1307.4051

The rare exclusive semi-hadronic Higgs decays

- BRs calculable with high precision within the SM:

$B(h \to Z\,\Upsilon)_{SM} = 1.5\times10^{-5}$

$B(h \to Z\,\eta_c)_{SM} = 1.4\times10^{-5}$

$B(h \to Z\,\psi)_{SM} = 2.3\times10^{-6}$

...

$B(h \to W^-\,D_s^*)_{SM} = 2.5\times10^{-5}$

$B(h \to W^-\,D_s)_{SM} = 1.7\times10^{-5}$

$B(h \to W^-\,\rho)_{SM} = 1.1\times10^{-5}$

$B(h \to W^-\,\pi)_{SM} = 4.3\times10^{-6}$

....

$B(h \to W^\pm D_s^\mp(\gamma)) \approx 8\times10^{-5}$

$B[h \to (l^\mp l^\pm)_Z (l^\mp l^\pm)_\Upsilon] \approx 2.5\times10^{-8}$

$B[h \to (l^\pm \nu)_W (\pi^\mp K^\pm K^\mp)_{Ds}] \approx 1\times10^{-6}$

Conclusions

We need to search for New Physics

[*with a broad spectrum perspective given the lack of NP signal so far...*]

Exploration of the Higgs properties with "minimal theoretical bias"...

Rare Higgs decays

[*those discussed in this talk + many more...*]

provide a unique opportunity in this respect:

unexplored windows toward a large class of NP models