Theoretical considerations on Rare & Forbidden Higgs decays

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- Introduction
- Flavor-violating Higgs decays
- Decays into light exotic states
- Rare exclusive semi-hadronic 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*)

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↓

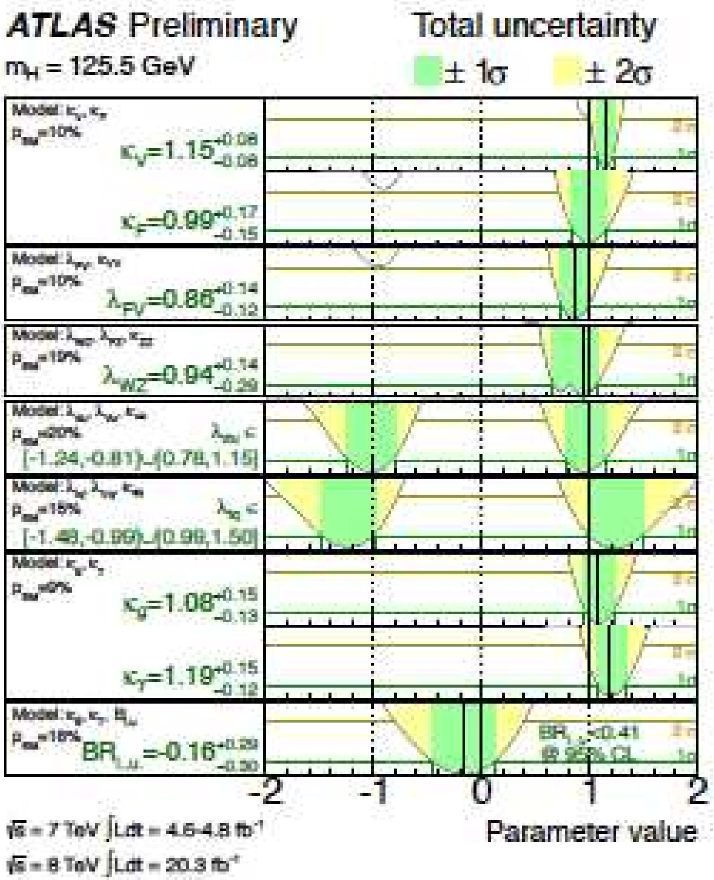
"High-statistics" Higgs Physics

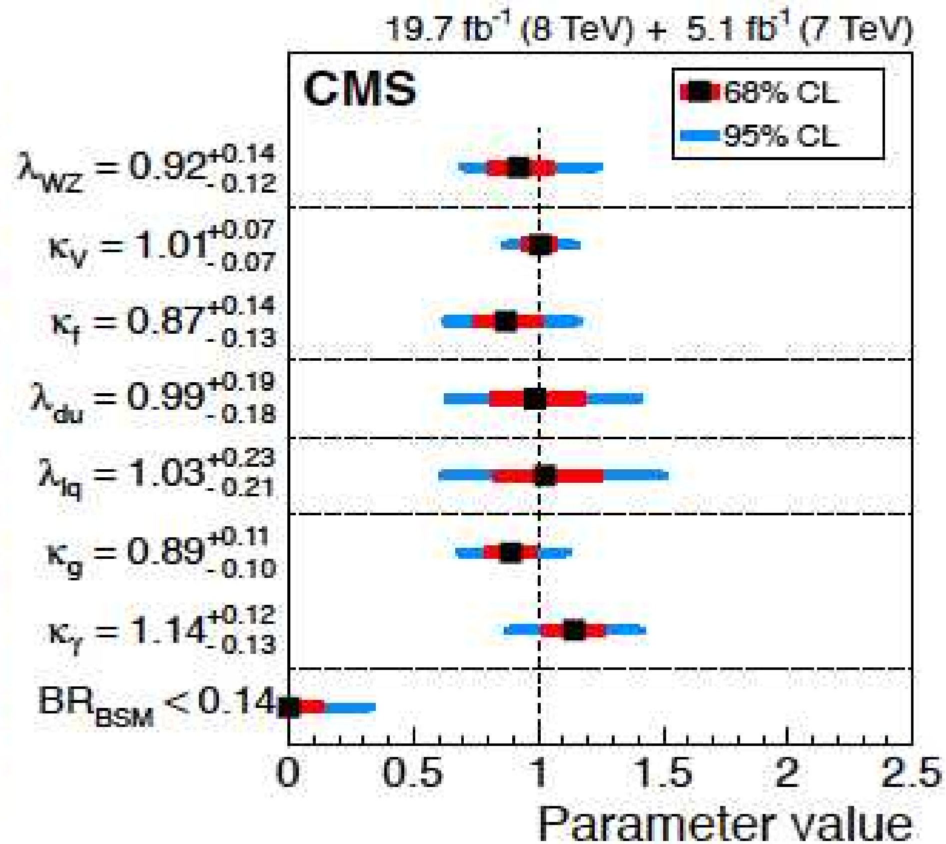
(*exploration of the Higgs properties with minimum theoretical bias*)

- *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

Some attempts in this direction have already started...





Introduction

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…but the peculiar value of m_h (→ *suppressed Higgs width*) offers many more interesting tests.

Precision measurements

Rare decays

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Precision measurements

Rare decays

On the TH side:

- Unique window on models where (light) NP couples directly (*effective tree-level coupling*) only to the Higgs field (*Higgs portal*, …)
- Large deviations from the SM less constrained by other observables (e.g. EWPO)

On the EXP side:

- Potential large room for improvement with increasing statistics vs. the (slow) improvement in measurements where we have already seen the SM signal...

Introduction

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…but the peculiar value of m_h ($\rightarrow$ *suppressed Higgs width*) offers many more interesting tests.

3 (almost) unexplored directions !

Rare decays

SM forbidden modes (LFV)

$h \rightarrow \tau\mu$
$h \rightarrow \tau e$
$h \rightarrow \mu e+\gamma$
$h \rightarrow bs$
…

decays to new light exotic states

$h \rightarrow X+\mu\mu \rightarrow 4\mu$
$h \rightarrow X+\gamma$
$h \rightarrow X+Y$
… [$\rightarrow$ Curtin *et al.* 1312.4992]

exclusive hadronic decays

$h \rightarrow D_{(s)} + W$
$h \rightarrow \Upsilon + Z$
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Flavor-violating Higgs decays

Flavor-violating Higgs decays

If we consider the SM as a low-energy effective theory, it is natural to include possible flavor-violating couplings of the physical Higgs boson.

h-mediated FCNCs are unavoidable in models with more Higgs doublets and, more generally, can be viewed as the effect of higher-dimensional operators (in the EFT approach):

Azatov, Toharia, Zhu, 0906.1990
Agashe & Contino, 0906.1542

$$Y^{ij}\, \psi_L{}^i \psi_R{}^j\, \phi + \varepsilon^{ij}\, \psi_L{}^i \psi_R{}^j\, \phi^3 + \ldots$$

$$\varepsilon^{ij} = \frac{c^{ij}}{\Lambda^2}$$

$$\Downarrow$$

$$\underbrace{(vY^{ij} + v^3\, \varepsilon^{ij})}_{vY_{\rm eff}}\, \psi_L{}^i \psi_R{}^j + (Y^{ij} + 3v^2\, \varepsilon^{ij})\, \psi_L{}^i \psi_R{}^j\, h + \ldots$$

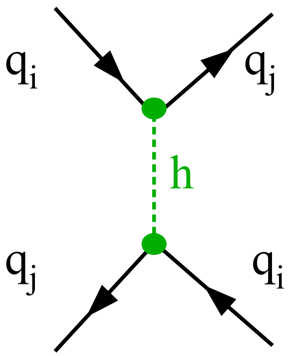
h FCNC couplings if $Y^{ij} \neq c\, \varepsilon^{ij}$

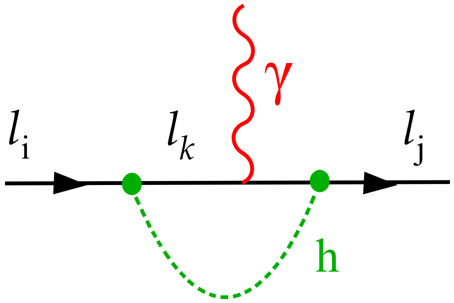
Flavor-violating Higgs decays

$$\mathcal{L}_{\rm eff} = \sum_{i,j=d,s,b\ (i\neq j)} c_{ij}\ \bar{d}_L^i d_R^j h + \sum_{i,j=u,c,t\ (i\neq j)} c_{ij}\ \bar{u}_L^i u_R^j h + \sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\ \bar{\ell}_L^i \ell_R^j h + {\rm H.c.}$$

(fermion mass-eigenstate basis)

Before looking at Higgs data, worth to explore the indirect bounds from the (*long list...*) of low-energy precision measurements:





▶ *Flavor-violating Higgs decays*

$$\mathcal{L}_{\rm eff} = \sum_{i,j=d,s,b~(i\neq j)} c_{ij}\, \bar d^i_L d^j_R h + \sum_{i,j=u,c,t~(i\neq j)} c_{ij}\, \bar u^i_L u^j_R h + \sum_{i,j=e,\mu,\tau~(i\neq j)} c_{ij}\, \bar \ell^i_L \ell^j_R h + \text{H.c.}$$

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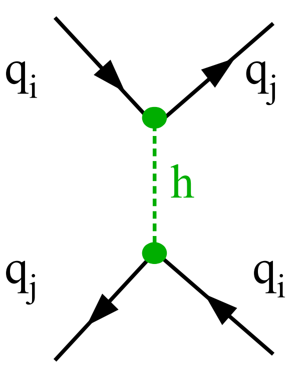
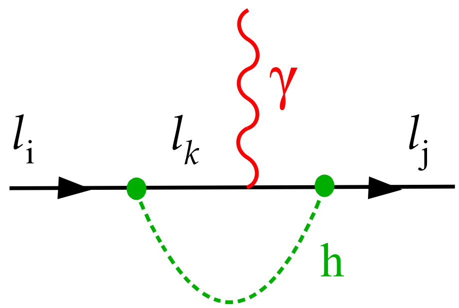


Severe bounds in the quark sector from $\Delta F=2$ processes

(except for terms involving the top)



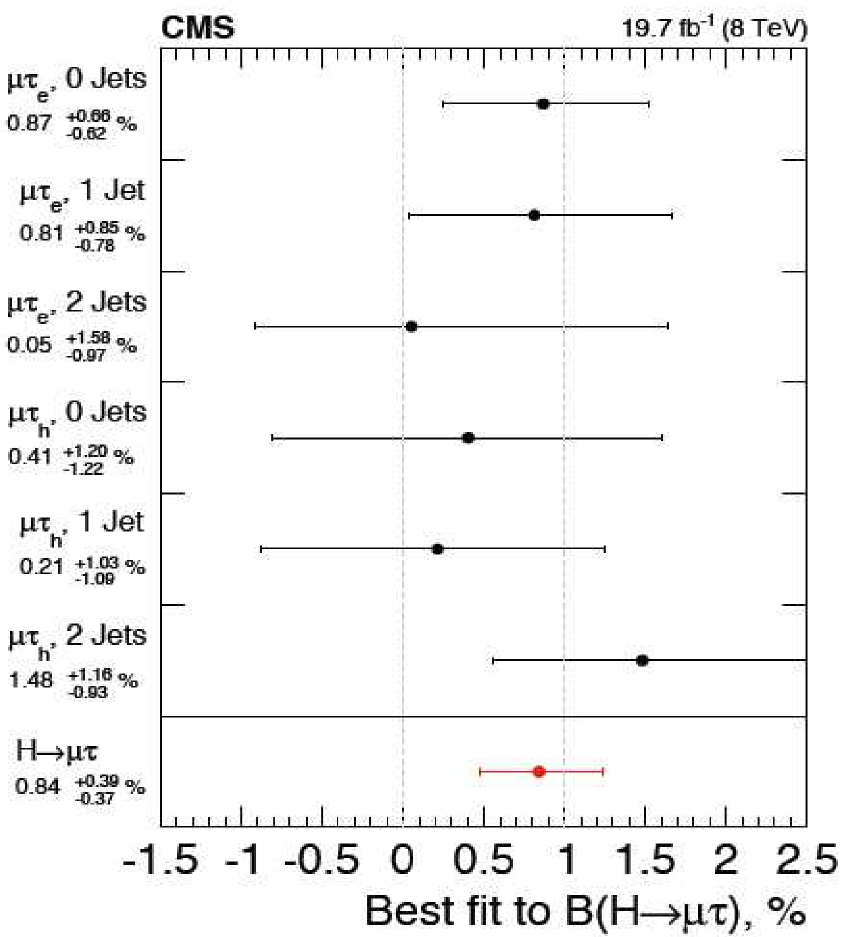
Bounds less severe in the lepton sector for the τμ and τe modes only

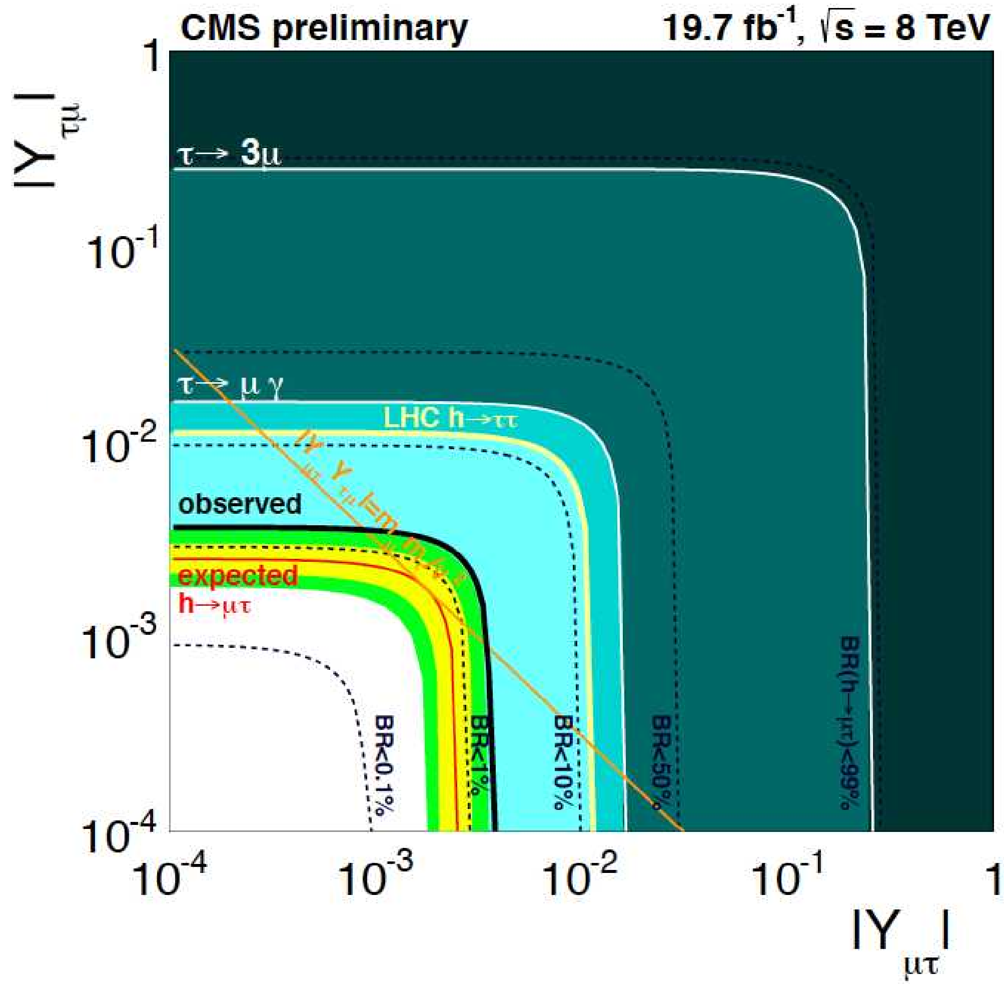
⬇

Indirect bounds imply $B(h \to \tau\mu, \tau e) \lesssim 10\%$

Blankenburg, Ellis, GI, 1202.5704
Harnik, Kopp, Zupan, 1209.1397
Davidson, Verdier, 1211.1248

Flavor-violating Higgs decays





2.4σ excess over bkg in the h → τμ search

Best-fit of the signal: $B(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$

CMS-HIG-14-005

Flavor-violating Higgs decays

Model-dependent considerations assuming the CMS result is a positive signal:

- Not easy (*but not impossible...*) to accommodate in realistic Yukawa models

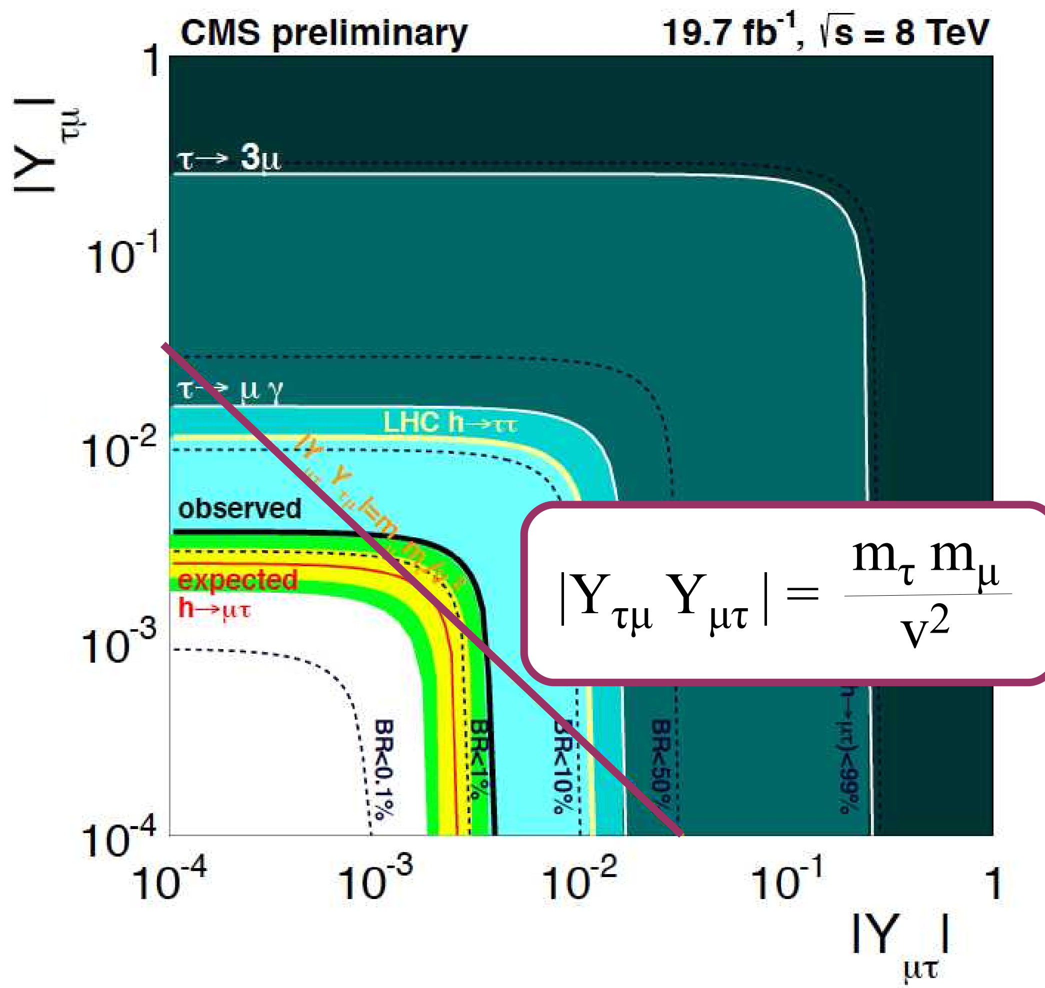
  Dery, Efrati, Nir, Soreq, Susic, 1408.1371

- The effect must appear at the tree-level, otherwise too-large $\tau \to \mu\gamma$ => *extended Higgs sector*

  Dorsner *et al.* 1502.07784

- Explicit model with L_μ-L_τ symmetry & connection to B-physics anomalies

  Crivellin, D'Ambrosio , Heeck, 1503.03477, 1501.00993



$$|Y_{\tau\mu} Y_{\mu\tau}| = \frac{m_\tau m_\mu}{v^2}$$

$$B(h \to \tau\mu) = (0.84\,^{+0.39}_{-0.37})\%$$

CMS-HIG-14-005

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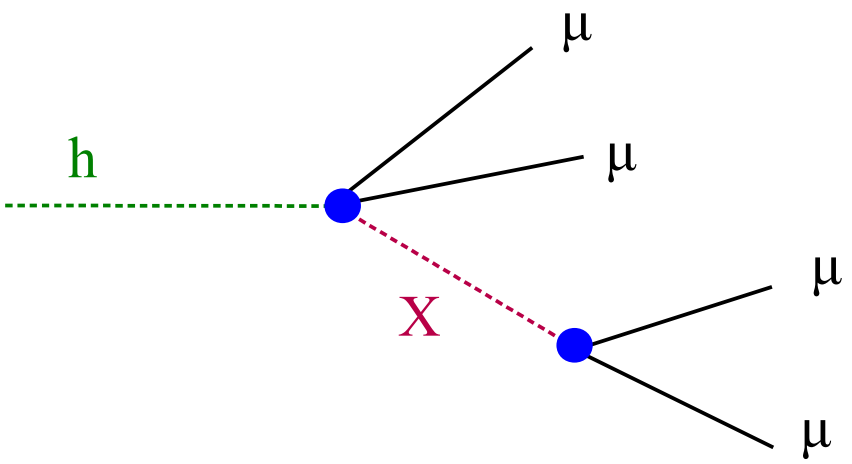
Main (long-term) messages:

- *Bottom-up (data driven) field*
- *Worth to improve the precision on* $h \to \tau\mu, \tau e$ *as much as possible (different model-building possibilities opens up at different BR levels)*

Light exotic states in $h \to 4l$

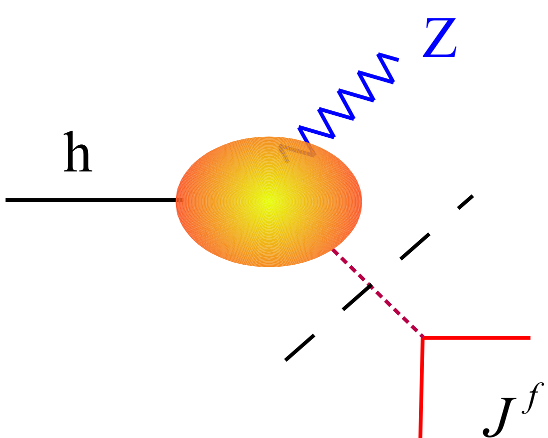


▶ Light states in $h \to 4l$ *decays*

ATLAS and CMS have reported results about the $h \to ZZ^*$ couplings

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

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



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

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

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 EFT*) or even new "light poles" (↔ *new light states coupled to h & fermions*)

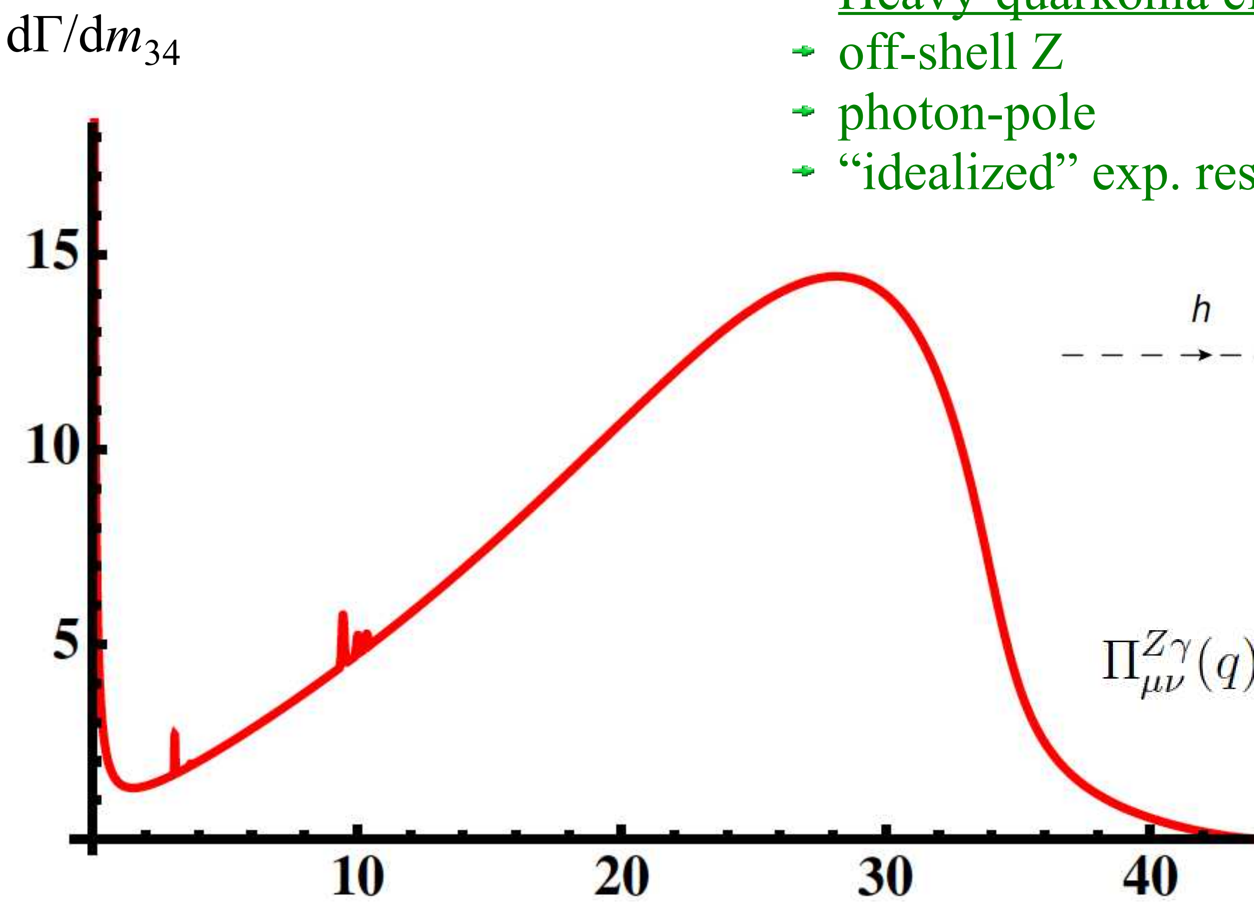
GI, Manohar, Trott, 1305.0663

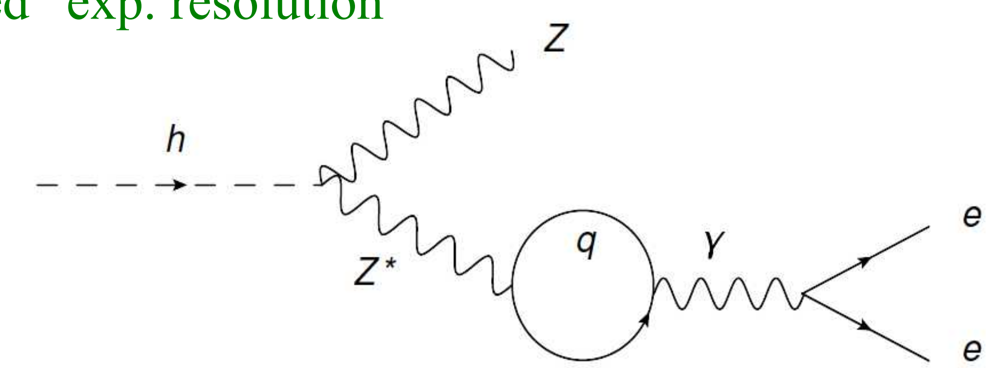
Curtin *et al.* 1312.4992,
Falkowski, Vega-Morales, 1405.1095
R. Dermisek, Raval, Shin, 1406.7018
Y. Chen *et al.* 1503.0585
M. Gonzalez-Alonso *et al.* 1504.04018, ...

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:

- 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*

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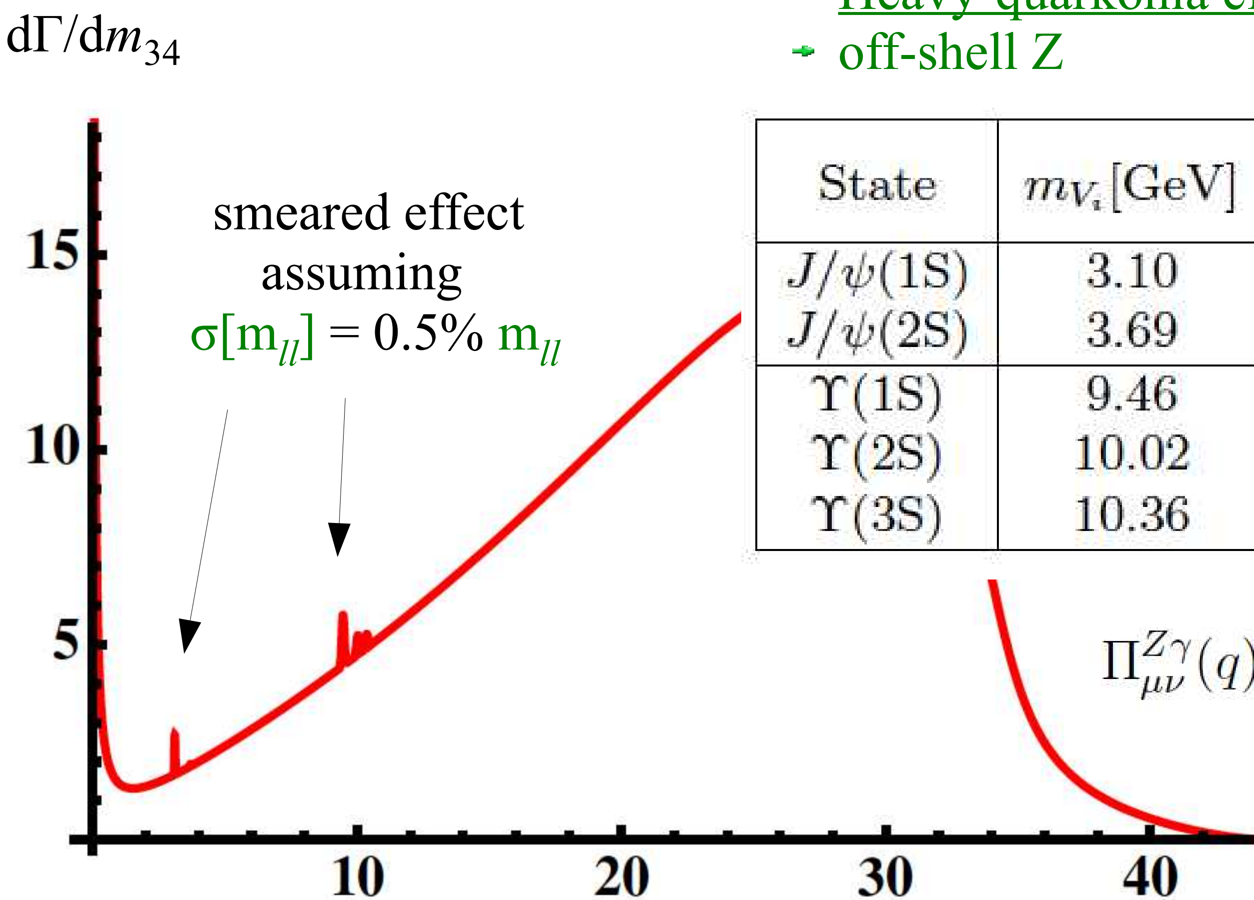


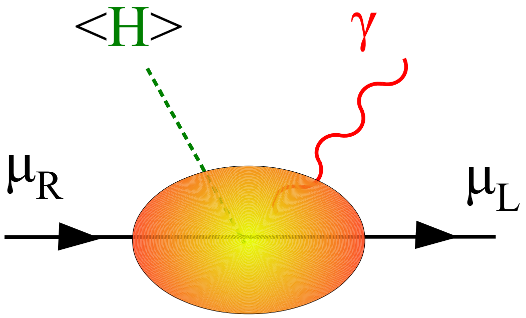
State	m_{V_i} [GeV]	$\mathcal{B}(h \to ZV_i)$	relative shift 1 GeV bin
$J/\psi(1S)$	3.10	3.2×10^{-6}	5.0%
$J/\psi(2S)$	3.69	1.5×10^{-6}	0.5%
$\Upsilon(1S)$	9.46	1.6×10^{-5}	3.1%
$\Upsilon(2S)$	10.02	8.2×10^{-6}	1.2%
$\Upsilon(3S)$	10.36	6.2×10^{-6}	0.9%

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

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...*

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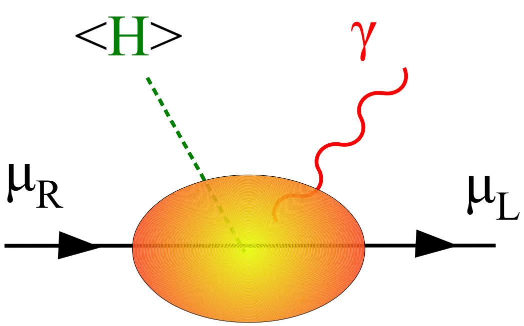

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↓

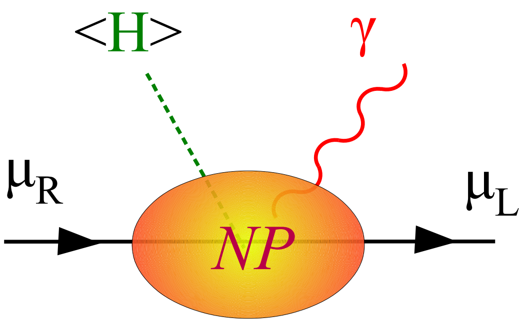
Solving the $(g\text{-}2)_\mu$ anomaly in terms of NP, requires the introduction of some new (*light or heavy...*) states coupled to muons.

↓

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

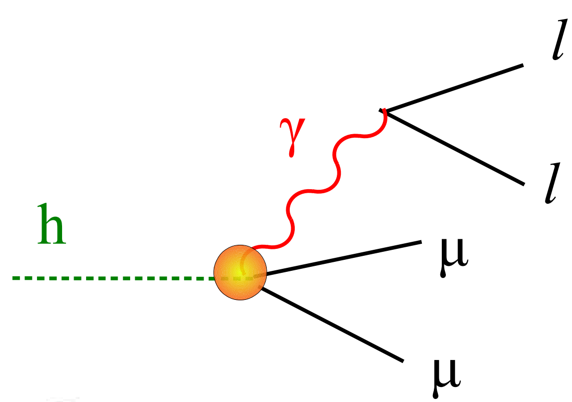
Specific NP examples motivated by the $(g\text{-}2)_\mu$ anomaly

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

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

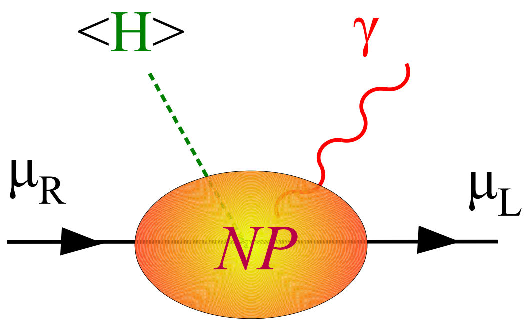
$O(10^{-4})$ correction with respect to $BR(h \to 2\mu\gamma)_{SM}$

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 $h \to 4l$



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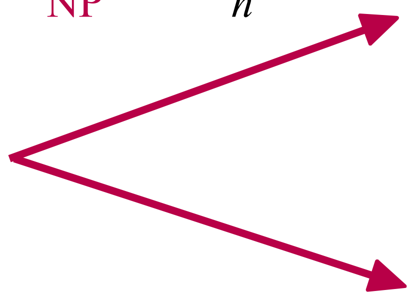
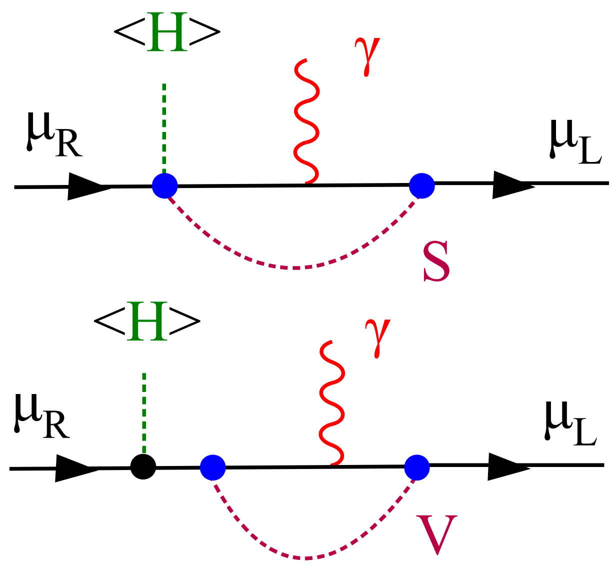


Tiny correction to h → 2μ2l

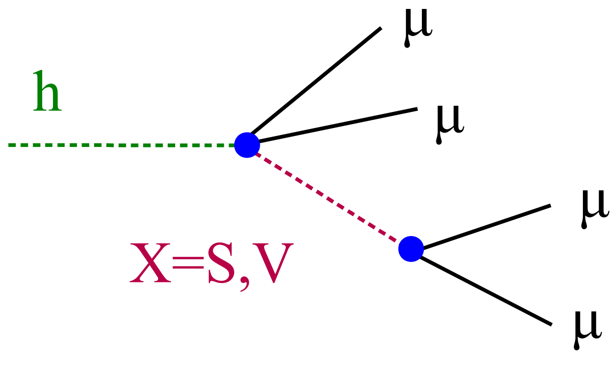
$2m_\mu < m_{NP} \ll m_h$

Possible "visible" non-standard peak in the h → 4μ 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

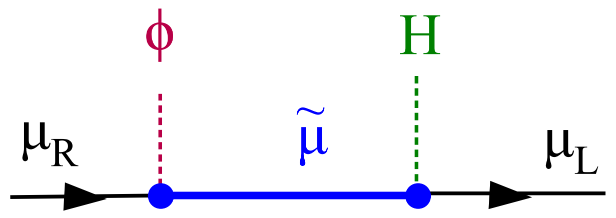
Specific NP examples motivated by the $(g-2)_\mu$ anomaly

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 $(g-2)_\mu$ 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 $(g-2)_\mu$ anomaly

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

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

A potential huge effect !

Already ruled out by present data...

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

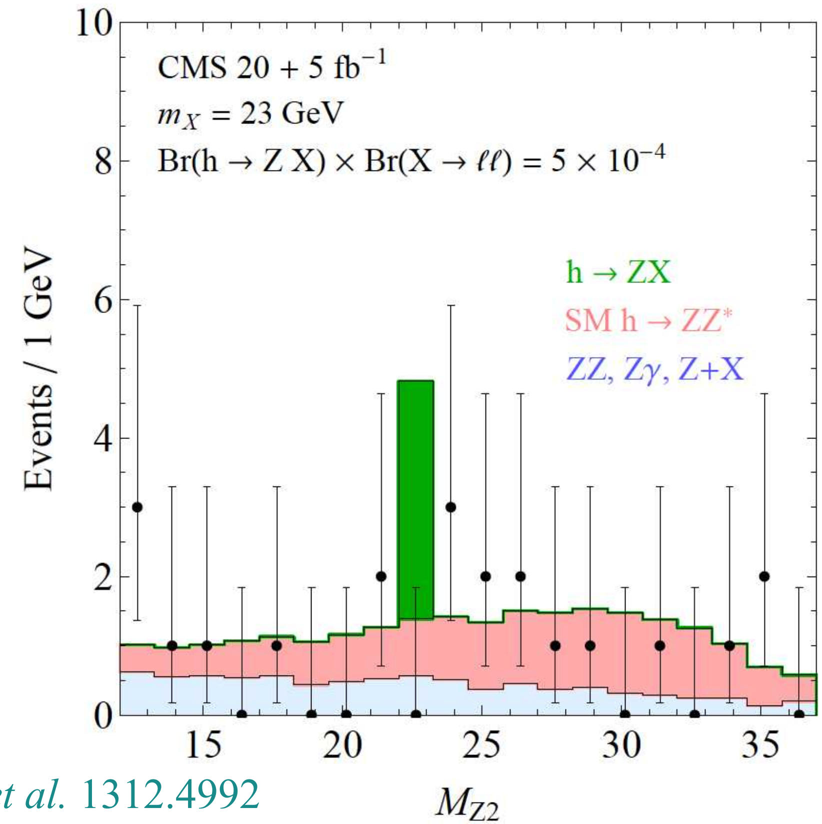
Specific NP examples motivated by the $(g-2)_\mu$ anomaly

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

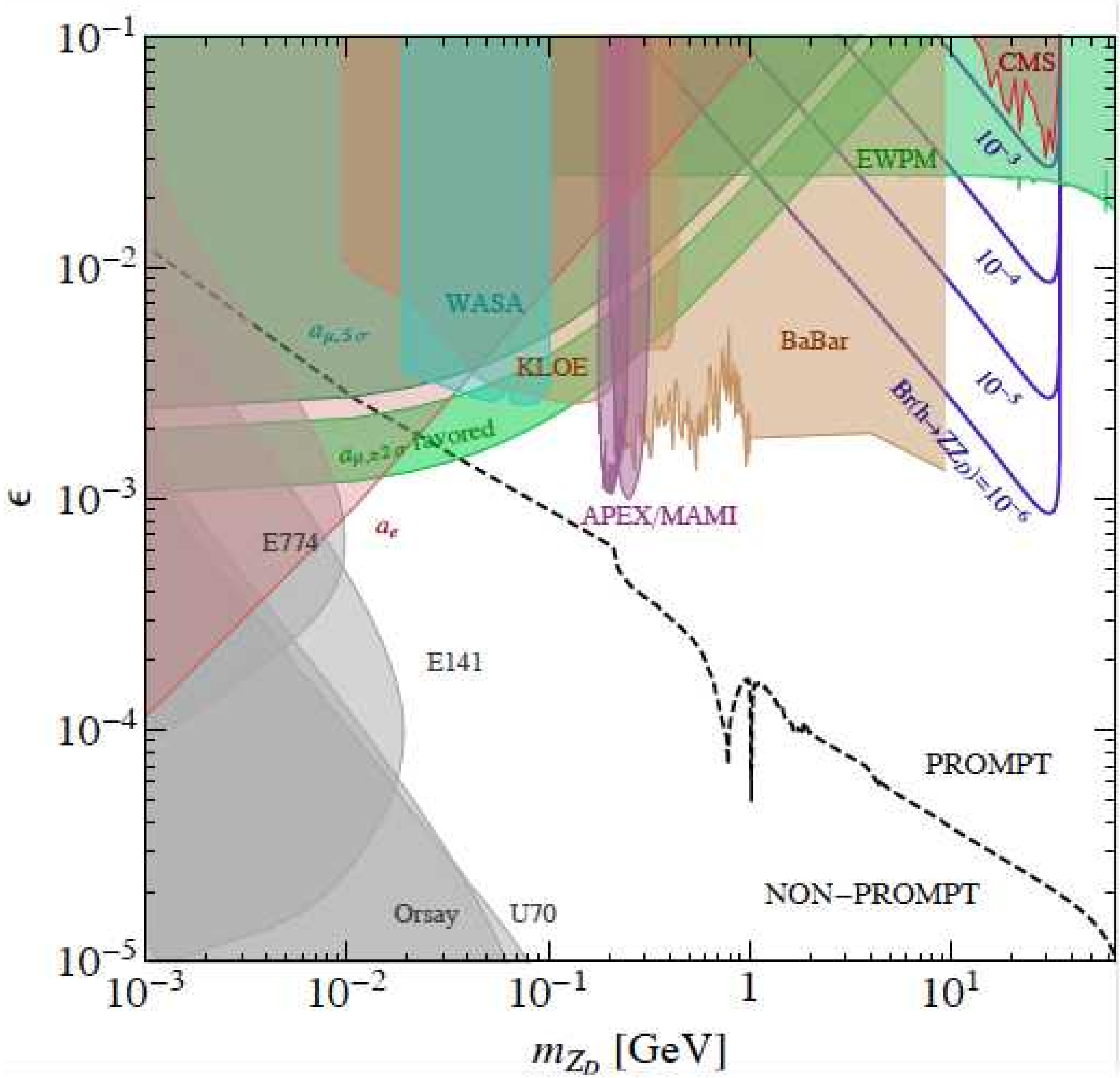


Curtin *et al.* 1312.4992

N.B.: In models addressing $(g-2)_\mu$ X is narrow and short-lived (*not necessarily true in general*)

N.B.: The light mass region ($1\ \mathrm{GeV} \lesssim m_X \lesssim 10\ \mathrm{GeV}$) is particularly motivated from the theoretical point of view ("*dark-Z*" models...)

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

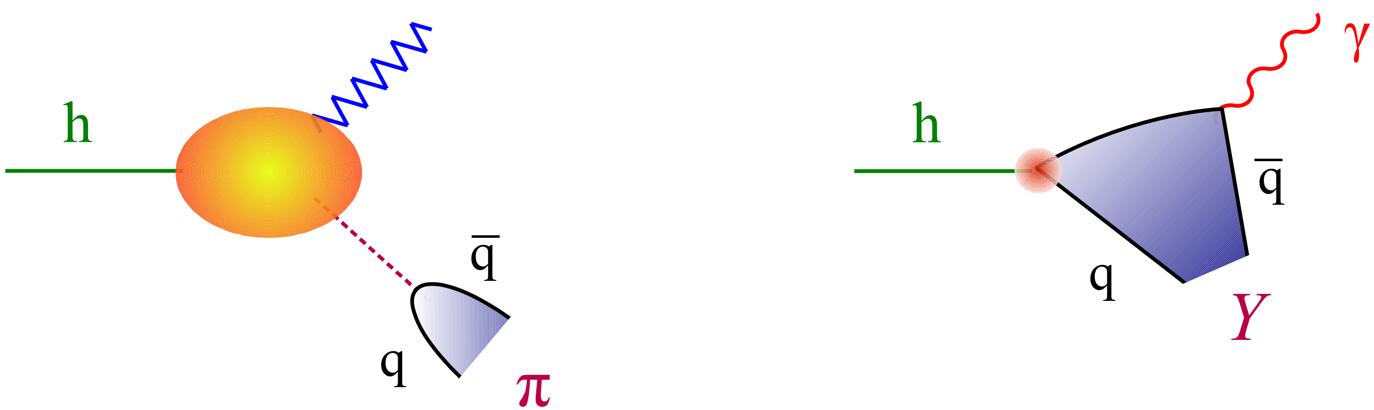


J. Shelton, talk at "Unlocking the Higgs Portal" (May, 2014)

In the minimal "*dark-Z*" models [new U(1) & pure kinetic mixing with $U(1)_Y$] the region relevant for $(g\text{-}2)_\mu$ is already ruled-out.

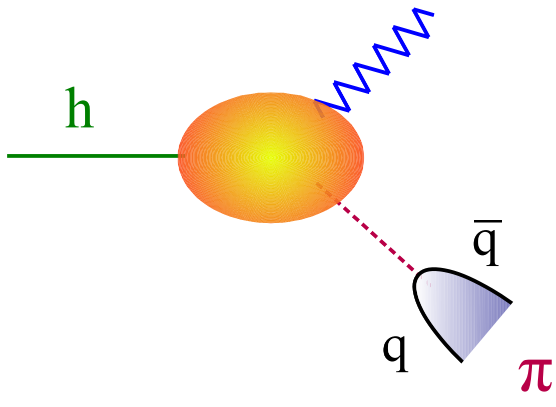
But it is easy to construct less minimal models [e.g. charging muons & not electrons under the new U(1)] where the region probed in $h \to 4\mu$ is relevant for $(g\text{-}2)_\mu$

Rare exclusive semi-hadronic Higgs decays



The rare exclusive semi-hadronic h decays

Rare $h \to V\,P$ decays, where P is a single hadron state (*pseudo-scalar* or *vector-meson*) and V=Z,W are a very interesting probe of the vacuum-structure of the theory



$$A^{SM} \propto \frac{f_P}{v}$$

GI, Manohar, Trott, 1305.0663

- Amplitude proportional to the ratio of the two order parameters controlling the $SU(2)_L$ breaking within the SM
- Pristine (unique) probe of the higgs-Goldstone-gauge coupling

▶ The rare exclusive semi-hadronic h decays

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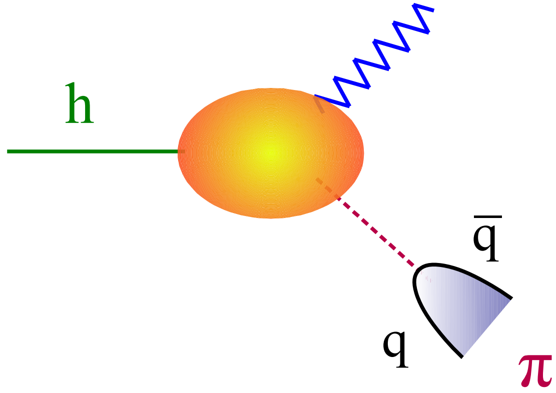


- BRs calculable with high precision within the SM:

$B(h \to Z\,\Upsilon)_{SM} = 1.6\times10^{-5}$
$B(h \to Z\,\eta_c)_{SM} = 1.4\times10^{-5}$
$B(h \to Z\,\psi)_{SM} = 3.2\times10^{-6}$
...

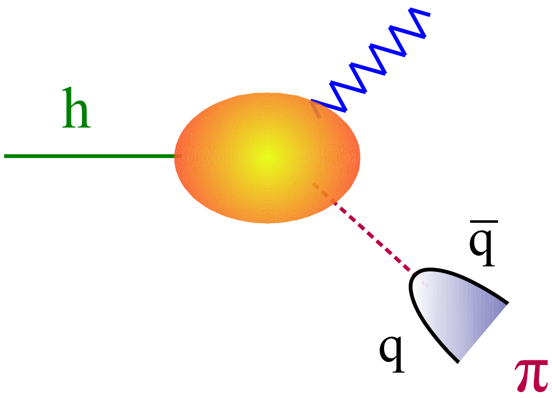
$B(h \to W^-\,D_s^*)_{SM} = 3.5\times10^{-5}$
$B(h \to W^-\,D_s)_{SM} = 2.1\times10^{-5}$
$B(h \to W^-\,\rho)_{SM} = 0.8\times10^{-5}$
$B(h \to W^-\,\pi)_{SM} = 0.6\times10^{-5}$
....

GI, Manohar, Trott, 1305.0663
Gao, 1406.7102

- Within SM, dominated by the tree-level amplitude [$D_\mu H^+ D_\mu H$], except when suppressed [e.g.: sizable contrib. from $h \to \gamma^*Z$ in $h \to \psi Z$]
- Possible sizable modification BSM, in presence of non standard couplings of h to fermion currents (V and A currents)

The rare exclusive semi-hadronic h decays

Rare $h \to V\, P$ decays, where P is a single hadron state (*pseudo-scalar* or *vector-meson*) and V=Z,W are a very interesting probe of the vacuum-structure of the theory



- BRs calculable with high precision within the SM:

$B(h \to Z\,\Upsilon)_{SM} = 1.6\times10^{-5}$
$B(h \to Z\,\eta_c)_{SM} = 1.4\times10^{-5}$
$B(h \to Z\,\psi)_{SM} = 3.2\times10^{-6}$
...

$B(h \to W^-\,D_s^*)_{SM} = 3.5\times10^{-5}$
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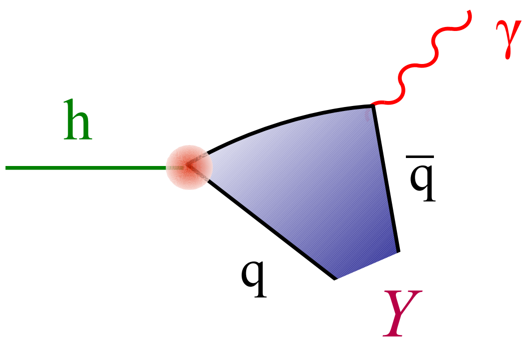
$B(h \to W^-\,\pi)_{SM} = 0.6\times10^{-5}$
....

$B(h \to W^\pm D_s^\mp(\gamma)) \approx 10^{-4}$

- Within SM, dominated by the tree-level amplitude $[D_\mu H^+ D_\mu H]$, except when suppressed [e.g.: sizable contrib. from $h \to \gamma^* Z$ in $h \to \psi Z$]
- Possible sizable modification BSM, in presence of non standard couplings of h to fermion currents (V and A currents)

▶ The rare exclusive semi-hadronic h decays

Radiative modes of the type $h \to \gamma Y$ where Y is a quarkonium state have similar/complementary properties:



- SM calculation more involved due to non-negligible contribution from hqq (Yukawa) couplings, but still under good th. Control

Bodwin, Petriello, Sonyev, Velasco,1306.5770
Kagan *et al.* 1406.1722

- Destructive interference between $h \to \gamma+(Z,\gamma)^*$ and Yukawa contributions → potential sensitive probe of modified Yukawa couplings

$B(h \to \gamma\, \psi)_{SM} = (2.5\pm0.3)\times10^{-6}$ $B(h \to \gamma\, \Upsilon)_{SM} \sim 10^{-8}$

(maximal destr. interf. → good SM null test !)

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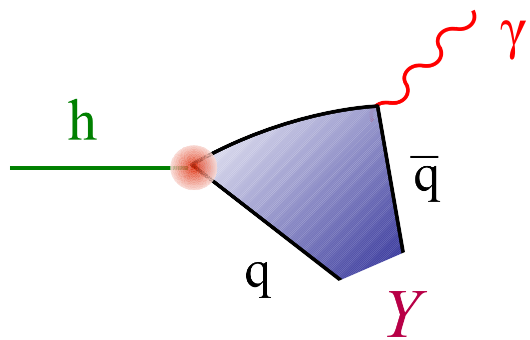

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Caveat: BSM effects may not come only from modified Yukawas
(e.g. modified coupl. to fermion currents, $h \to \gamma\gamma$, ...)

The rare exclusive semi-hadronic h decays

Beside these modes, for which we may hope to reach the SM signal, there is a long list of forbidden or more suppressed modes that would provide useful bounds on possible exotic couplings of the Higgs to fermion currents.

Worth to search for all the two-body modes of the type

$$h \to \{Z_{\text{leptonic}}, W_{\text{leptonic}}, \gamma\} + Mesons$$

- Good templates for (even more) exotic searches
- Part of a more extensive program of "exclusive hadronic tags" for the e.w. gauge boson in view of the HL-LHC program [Mangano & Melia, 1410.7475; Grossman, König, Neubert,1501.06569]

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


Backup

VP mode	$\mathcal{B}^{\rm SM}$	VP^* mode	$\mathcal{B}^{\rm SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}		

GI, Manohar, Trott, 1305.0663

Resonance	$\mathcal{B}(h\to ZV)$
$J/\Psi(1S)$	3.2×10^{-6}
$\Psi(2S)$	1.5×10^{-6}
$\Upsilon(1S)$	1.7×10^{-5}
$\Upsilon(2S)$	8.9×10^{-6}
$\Upsilon(3S)$	6.7×10^{-6}

Gao, 1406.7102

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar b}}=\frac{\kappa_\gamma\left[(3.0\pm0.13)\kappa_\gamma-0.78\bar\kappa_s\right]\cdot10^{-6}}{0.57\bar\kappa_b^2},$$

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar b}}=\frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma-0.24\bar\kappa_u-0.12\bar\kappa_d\right]\cdot10^{-5}}{0.57\bar\kappa_b^2}$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar b}}=\frac{\kappa_\gamma\left[(1.6\pm0.17)\kappa_\gamma-0.59\bar\kappa_u-0.29\bar\kappa_d\right]\cdot10^{-6}}{0.57\bar\kappa_b^2}$$

Kagan *et al.* 1406.1722