The h$\to Z\mu\mu$ spectrum at low q^2:
SM vs. light new physics

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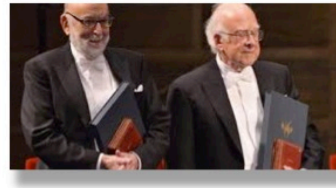
Outline

$h \to 4\ell$

- Introduction and motivation;
- SM prediction:
  - Tree-level result;
  - Locally important corrections;
- Connection with (g-2) anomaly:
  - Heavy d.o.f.
  - Light d.o.f.

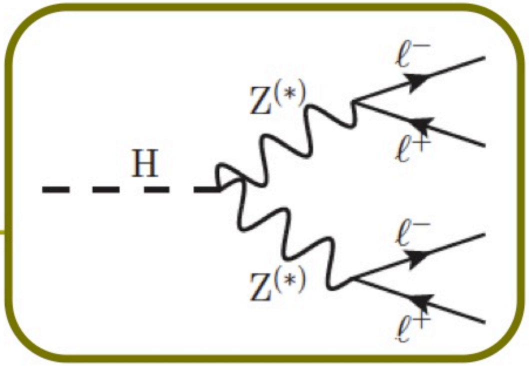
[MGA & G. Isidori, arXiv:1403.2648]

Introduction h!!!




- July 2012: ATLAS & CMS observed a ~125 GeV new particle with the properties of the Higgs boson.
- New phenomenology: properties of this new particle.
- Higgs decays:
  - Tiny higgs width! →
    - $f\bar{f}$ suppressed (coupling ~ mass);
    - gg, $\gamma\gamma$, $Z\gamma$ suppressed by loop;
    - WW*, ZZ* suppressed by multibody PS;
  - ➔ The exotic BR can be large even for small couplings.
  - O(500,000) Higgses produced at LHC7+LHC8!
  - ➔ Very small BR are detectable if the decay signature is clean.
  - BR(h➔BSM) could be as large as O(20-50%). *[Belanger et al'2013, Giardino et al'2013, Ellis & You'2013, Cheung et al'2013, Djouadi & Moreau'2013, …]*

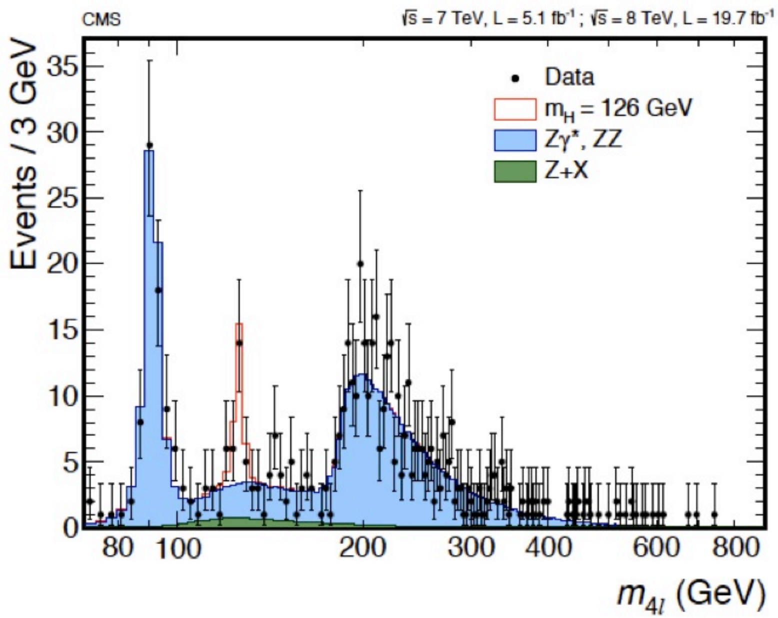
Introduction $h \rightarrow 4\ell$

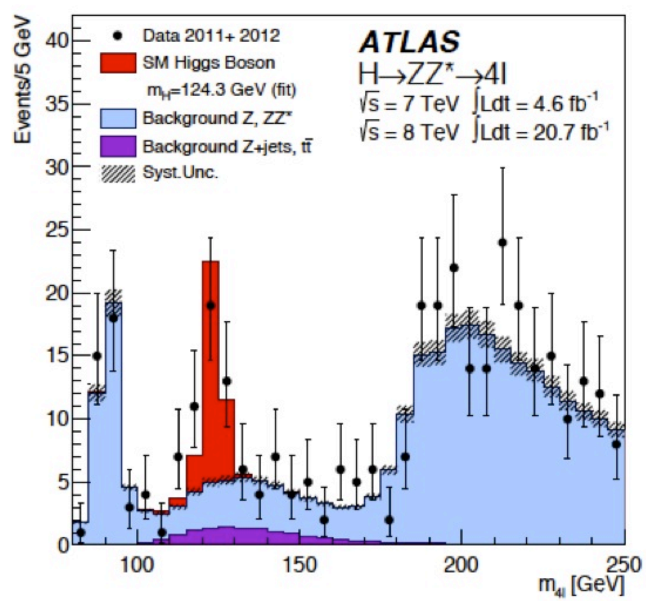


- Some features:
  - BR ~0.01% = ~60 events.
  - Clean signature;
  - Good S/B ratio: ~30 events (bkg ~10bkg) = 7σ!!

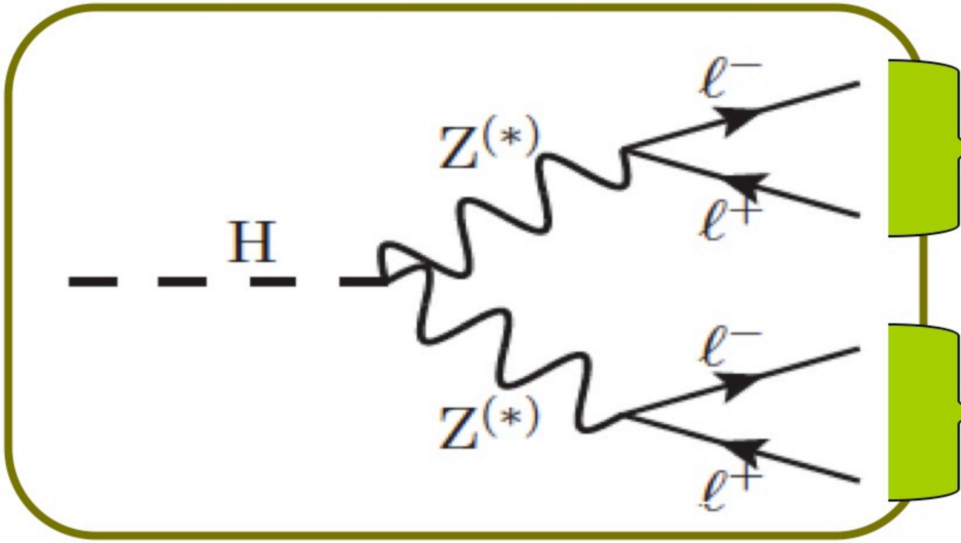
- Focus so far: total rate, mass & J^{CP} properties

  … but we know very little about the kinematic distribution.



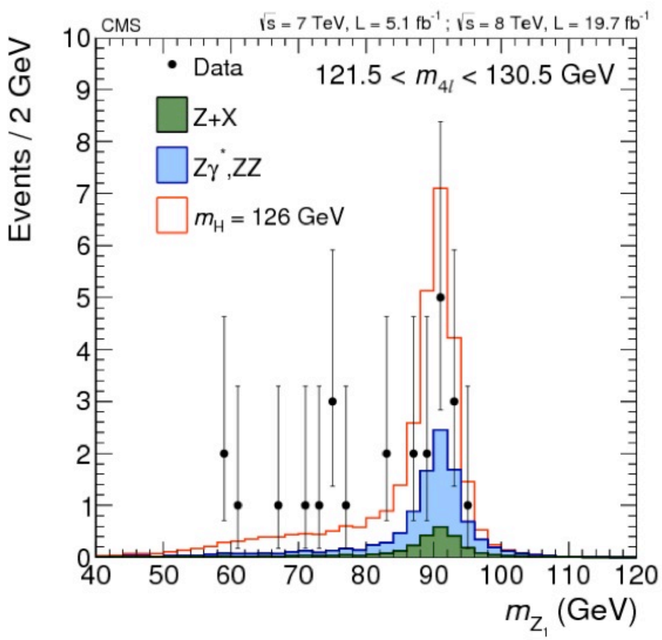


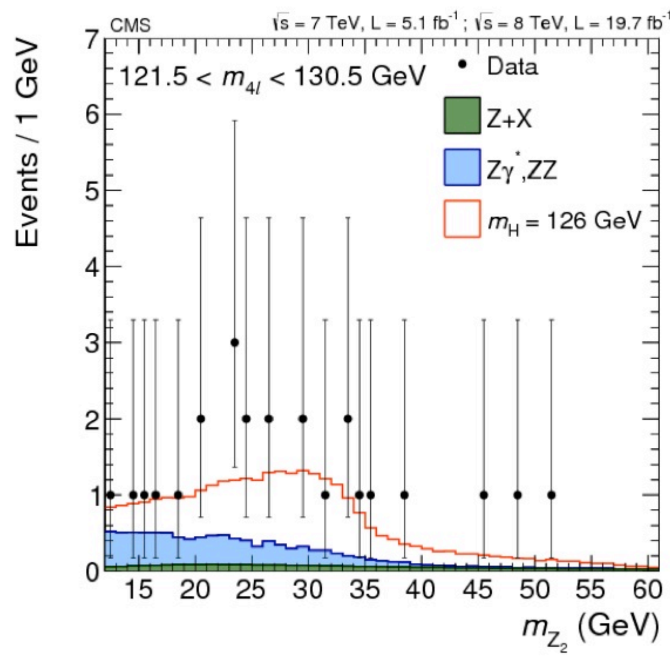
Introduction $h \to 4\ell$



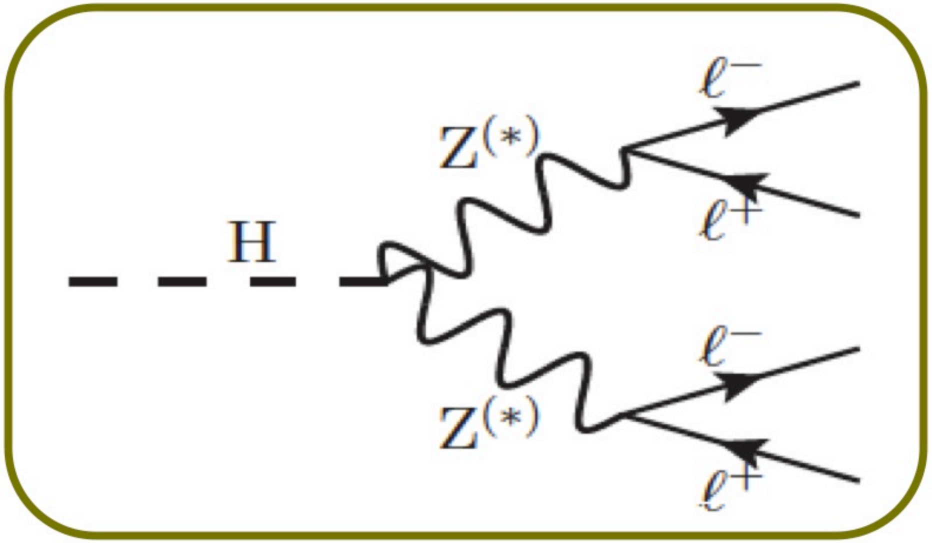
m_{12} (m_{Z1}) ~ M_Z

m_{34} (m_{Z2})





Introduction $h \to 4\ell$

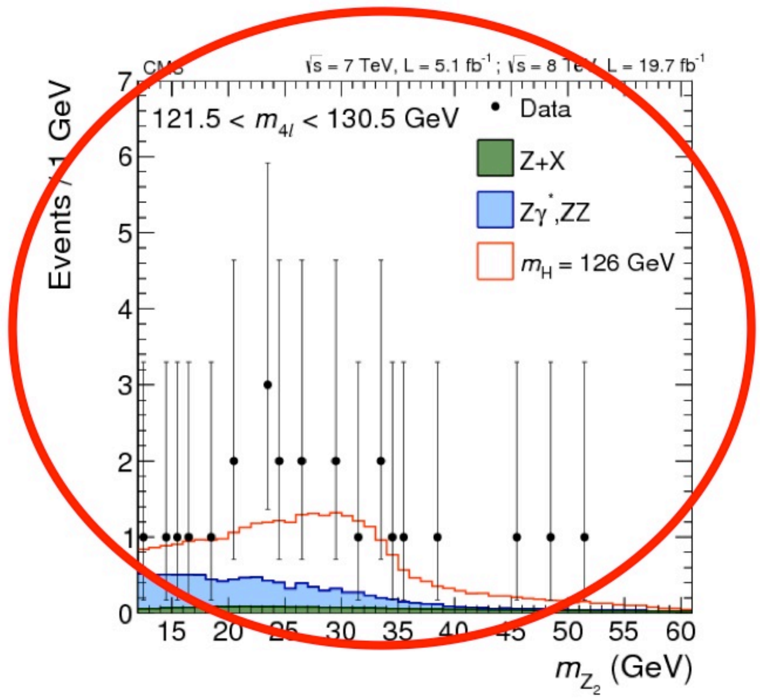


The q_{Z^*} distribution could reveal bSM effects!

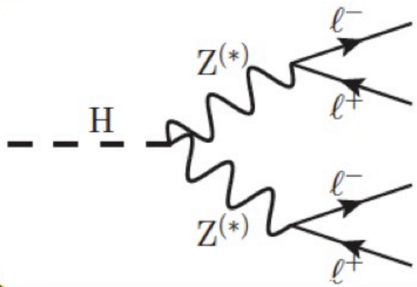
Heavy particles (EFT)
[Isidori et al.'2013, Grinstein et al.'2013]
Light particles
[Davoudiasl et al'2012, Curtin et al'2013, …]

SM: quarkonium contribution?

New light particles
➔ Natural connection with $(g\text{-}2)_\mu$.



SM prediction: tree-level



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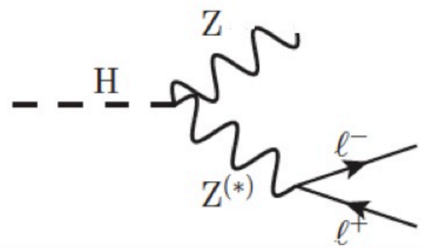
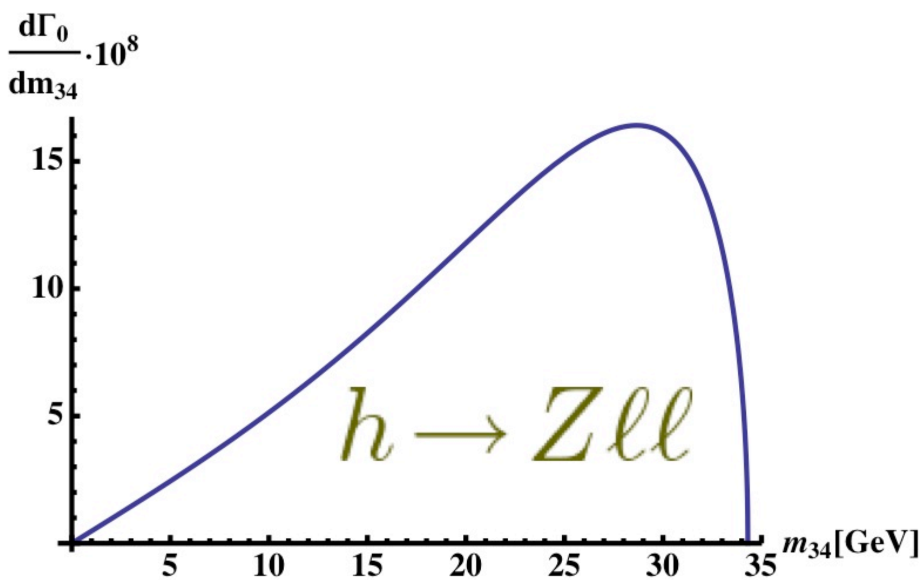
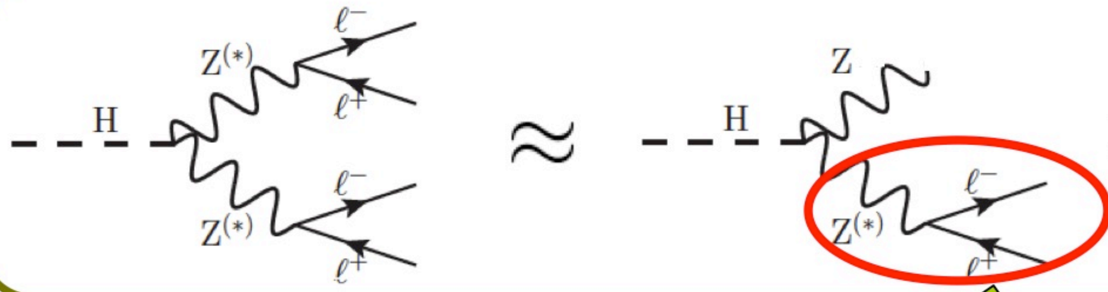


x $B\,(Z \to \ell\ell)$

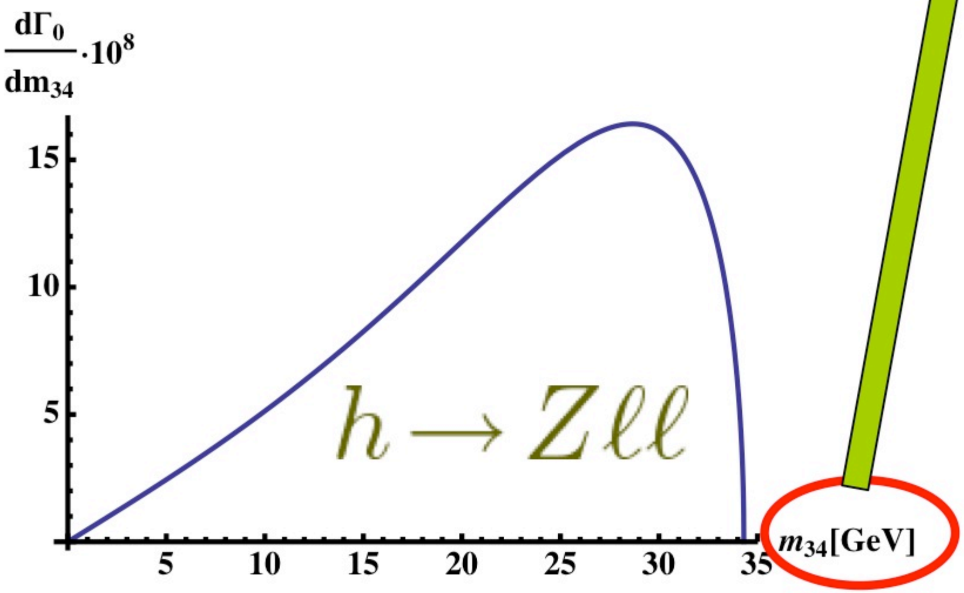


$$\frac{d\Gamma_0^{\rm SM}(h\to Z\ell^+\ell^-)}{dm_{34}^2} = \frac{m_Z^6}{8\pi^3 v^4 m_h}\left[(g_R^\ell)^2+(g_L^\ell)^2\right]\;\frac{\lambda(\hat{q}^2,\hat{\rho})}{(m_{34}^2-m_Z^2)^2}\left[m_{34}^2+\frac{m_h^4}{12m_Z^2}\,\lambda^2(\hat{q}^2,\hat{\rho})\right]$$

SM prediction: tree-level



x $B(Z\to\ell\ell)$

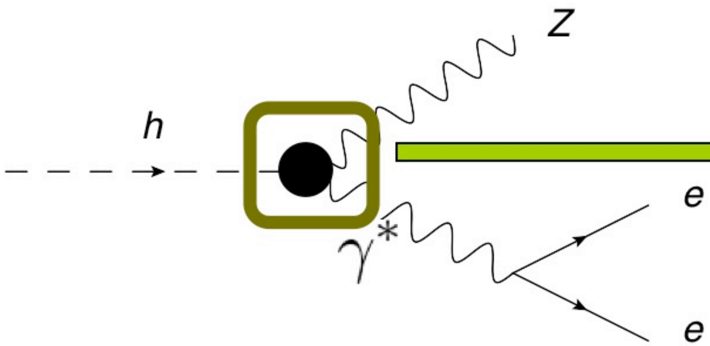


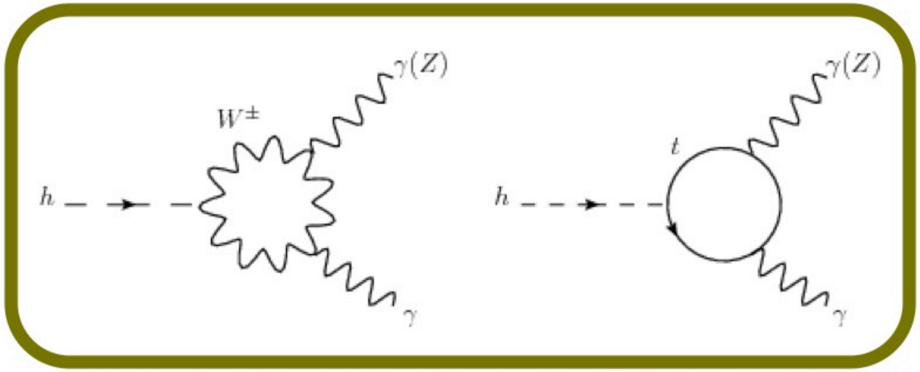
Locally significant corrections?

- Photon pole: $h\to Z\gamma^* \to Z\ell\ell$
- QCD resonances: $h\to ZV \to Z\ell\ell$

$$\frac{d\Gamma_0^{\rm SM}(h\to Z\ell^+\ell^-)}{dm_{34}^2} = \frac{m_Z^6}{8\pi^3 v^4 m_h}\left[(g_R^\ell)^2 + (g_L^\ell)^2\right]\ \frac{\lambda(\hat{q}^2,\hat{\rho})}{(m_{34}^2-m_Z^2)^2}\left[m_{34}^2 + \frac{m_h^4}{12m_Z^2}\,\lambda^2(\hat{q}^2,\hat{\rho})\right]$$

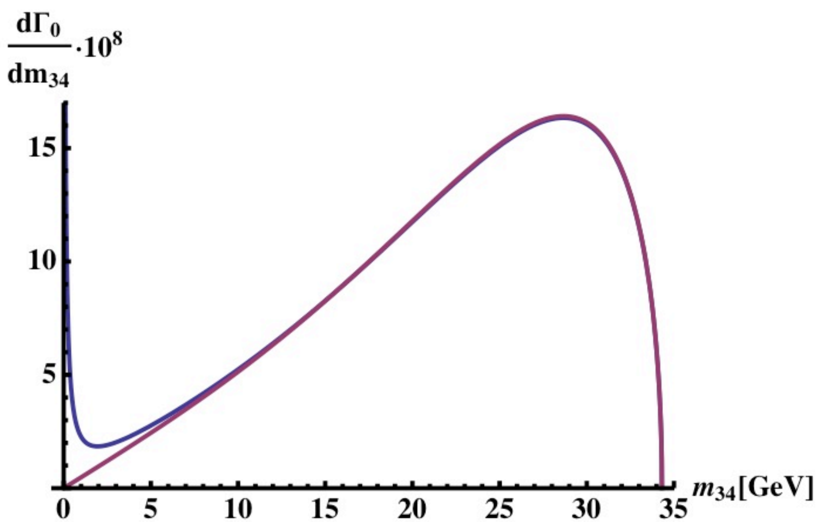
SM prediction: $h \to Z\gamma^* \to Z\ell\ell$

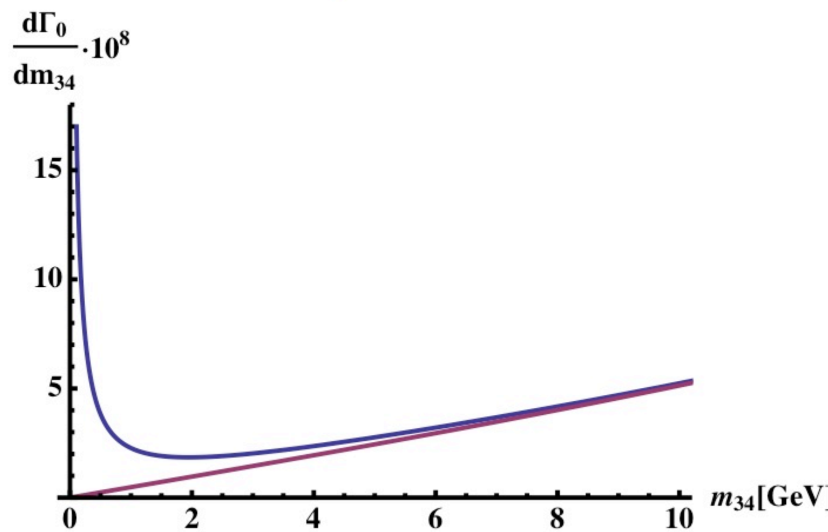




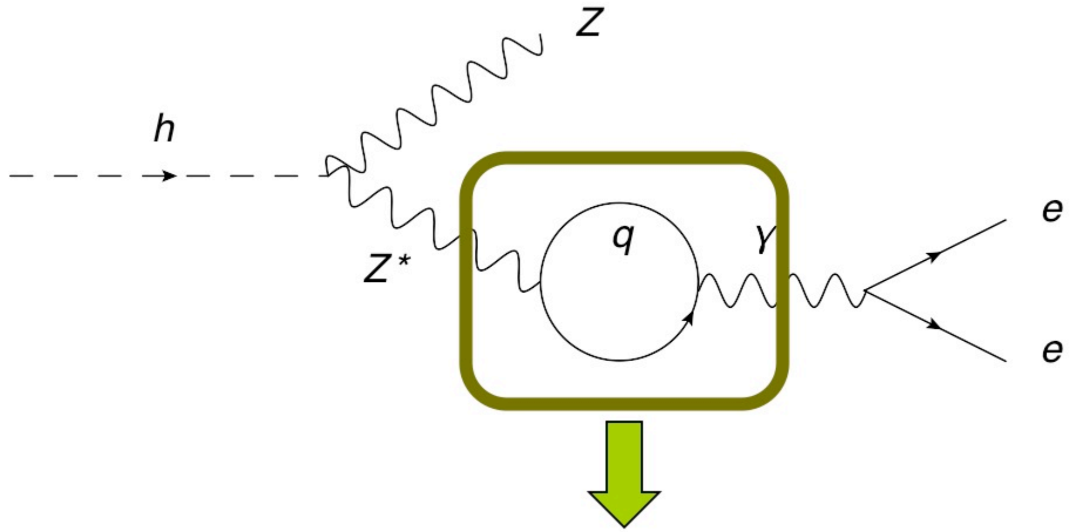
[Cahn et al. (1979), Bergstrom & Hulth (1985)]

$$\frac{d\Gamma_1^{\rm SM}(h\to Z\ell^+\ell^-)}{dq^2} = \frac{m_Z^6}{8\pi^3 v^4 m_h}\lambda(\hat{q}^2,\hat{\rho})\left\{-\frac{\alpha A_{Z\gamma}^{\rm SM}}{4\pi}\,\frac{Q_\ell(g_L^\ell+g_R^\ell)}{q^2-m_Z^2}\,\frac{m_h^2(1-\hat{q}^2-\rho)}{m_Z^2} + \left(\frac{\alpha A_{Z\gamma}^{\rm SM}}{4\pi}\right)^2\frac{Q_\ell^2}{q^2}\,\frac{m_h^4[3(1-\hat{q}^2-\rho)^2-\lambda(\hat{q}^2,\hat{\rho})^2]}{6m_Z^4}\right\},$$





SM prediction: QCD corrections



Long distance contributions are important!!

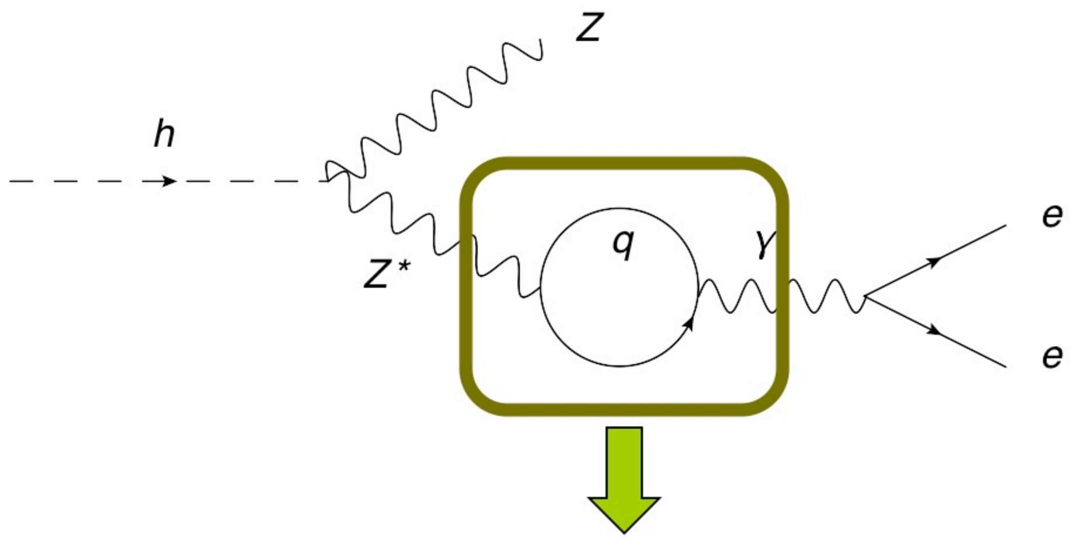
(hadronization)

$$\Pi^{Z\gamma}_{\mu\nu}(q) \equiv i \int d^4x e^{iqx} \langle 0|T J^Z_\mu(x) J^\gamma_\nu(0)|0\rangle = -\left(g^{\mu\nu}q^2 - q^\mu q^\nu\right)\Pi_{Z\gamma}(q^2)$$

$$\frac{d\Gamma_0^{\rm SM}(h\to Z\ell^+\ell^-)}{dm_{34}^2} = \frac{m_Z^6}{16\pi^3 v^4 m_h}\left[(g_A^\ell)^2 + (g_V^\ell)^2\right]\frac{\lambda(\hat{q}^2,\hat{\rho})}{(m_{34}^2 - m_Z^2)^2}\left[m_{34}^2 + \frac{m_h^4}{12 m_Z^2}\lambda^2(\hat{q}^2,\hat{\rho})\right]$$

$$g_V^\ell + 2e^2\Pi_{Z\gamma}(q^2)$$

SM prediction: QCD corrections



Long distance contributions are important!!

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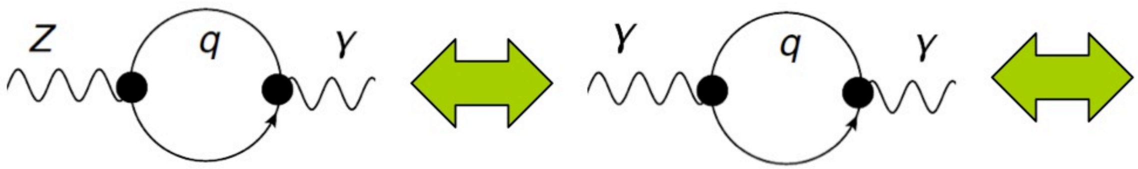
$$\Pi_{\mu\nu}^{Z\gamma}(q) \equiv i \int d^4x e^{iqx} \langle 0 | T J_\mu^Z(x) J_\nu^\gamma(0) | 0 \rangle = -\left(g^{\mu\nu} q^2 - q^\mu q^\nu\right) \Pi_{Z\gamma}(q^2)$$

- No 1st principles calculation;
- But it can be connected with R(s) data;
- Narrow resonance contribution is simpler: BW.

Higgs as a QCD lab!

SM prediction: QCD corrections



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

$$\Pi^{Z\gamma}_{\mu\nu}(q) \equiv i \int d^4x e^{iqx} \langle 0 | T J^Z_\mu(x) J^\gamma_\nu(0) | 0 \rangle = -\left(g^{\mu\nu} q^2 - q^\mu q^\nu\right) \Pi_{Z\gamma}(q^2)$$

It can be related with the hadronic photon vacuum polarization:

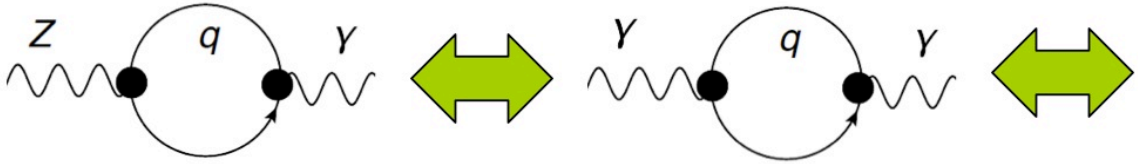
$$\Pi_{Z\gamma}(q^2) \approx \left(\frac{1}{2} - s_W^2\right) \Pi^{uds}_{\gamma\gamma}(q^2) + \left(\frac{3}{8} - s_W^2\right) \Pi^{c}_{\gamma\gamma}(q^2) + \left(\frac{3}{4} - s_W^2\right) \Pi^{b}_{\gamma\gamma}(q^2)$$

… which can be related to R(s) data:

$$\Pi_{\gamma\gamma}(q^2) - \Pi_{\gamma\gamma}(0) = \frac{q^2}{\pi} \int_0^\infty ds \frac{\text{Im}\Pi_{\gamma\gamma}(\text{s})}{s(s - q^2 - i\epsilon)} = \frac{q^2}{12\pi^2} \int_0^\infty ds \frac{R(s)}{s(s - q^2 - i\epsilon)}$$

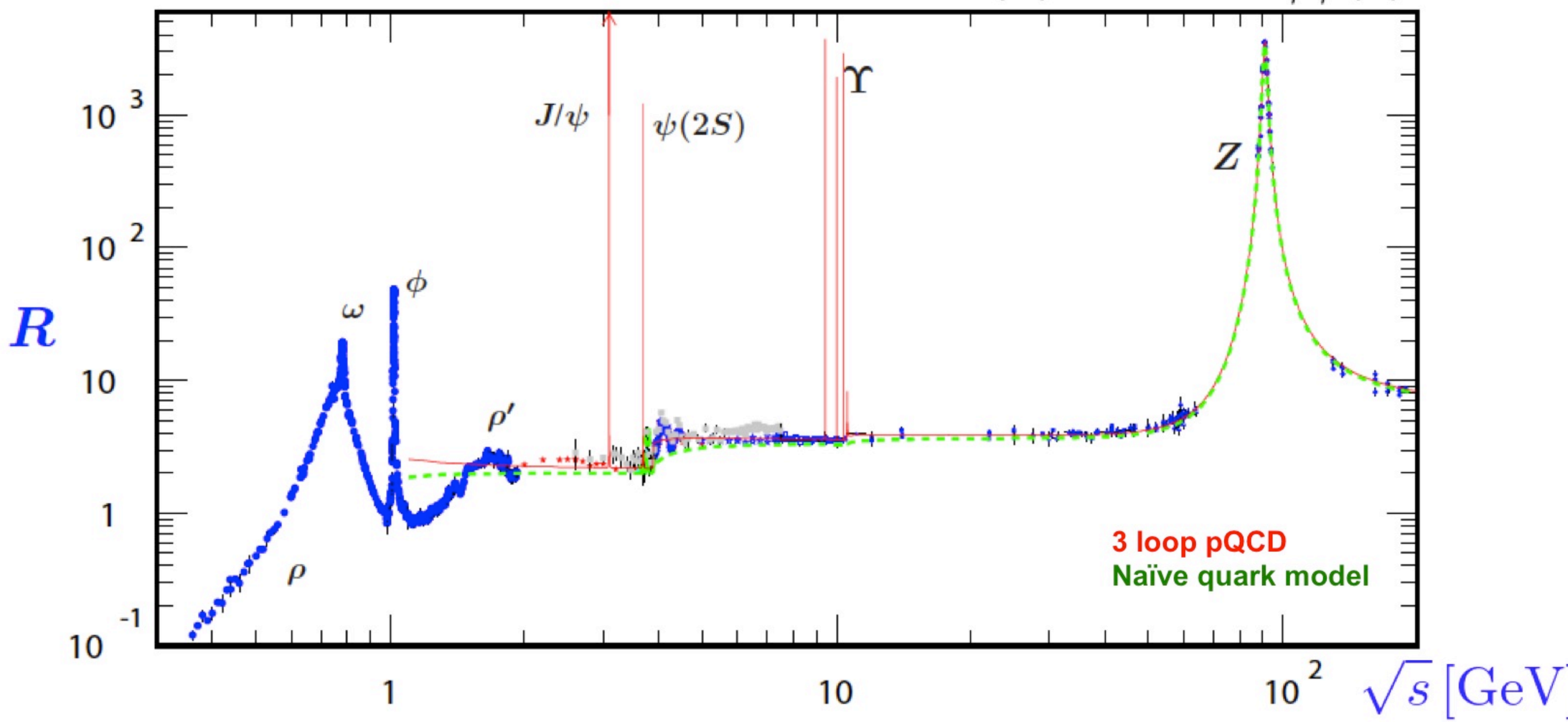
[Cabibbo & Gatto (1961), Jegerlehner (1986)]

SM prediction: QCD corrections



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

$$R(s) \sim \mathrm{Im}\Pi_{\gamma\gamma}(\mathrm{s})$$



SM prediction: QCD corrections

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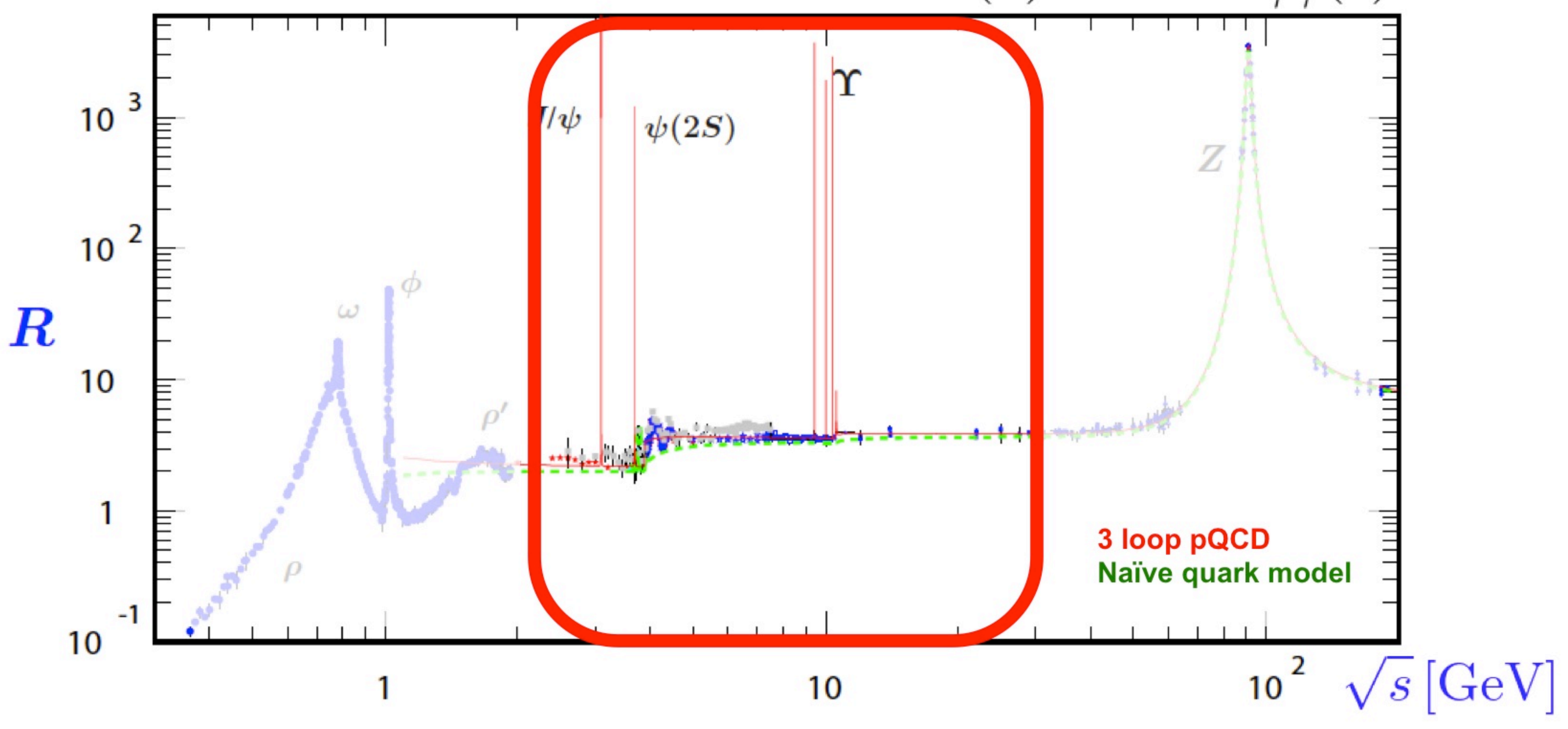
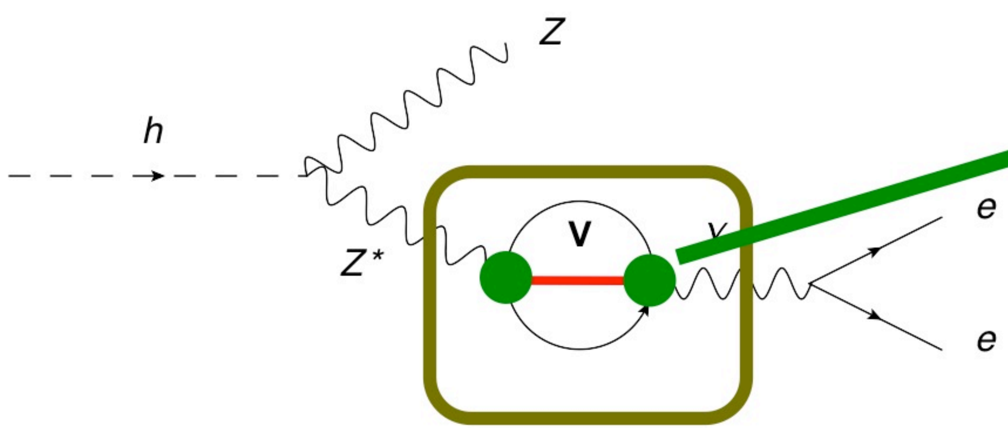


SM prediction: QCD corrections $q^2 > (2\ \mathrm{GeV})^2$



$$\langle 0|\bar{q}\gamma_\mu q|V_i(p,\epsilon)\rangle = f_{V_i} m_{V_i} \epsilon_\mu$$

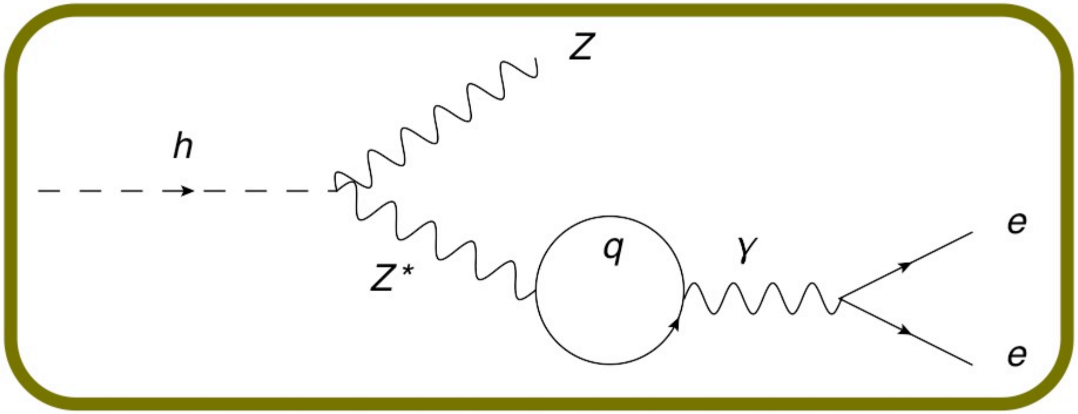
State	m_{V_i}[GeV]	f_{V_i}[MeV]
$J/\psi(1S)$	3.10	405
$J/\psi(2S)$	3.69	290
$\Upsilon(1S)$	9.46	680
$\Upsilon(2S)$	10.02	485
$\Upsilon(3S)$	10.36	420

f_V extracted from $V \to e^+e^-$:

$$\mathcal{B}(V_i \to \ell^+\ell^-) = \frac{4\pi Q_q^2}{3} \frac{\alpha^2 f_{V_i}^2}{m_{V_i}\Gamma_{V_i}}$$

$$\Pi_{Z\gamma}^q(q^2) = \frac{1}{2}\sum_i g_V^q Q_q \frac{q^2 f_{V_i}^2}{m_i^2(m_{V_i}^2 - q^2 - i\Gamma_{V_i} m_{V_i})}$$

SM prediction: QCD corrections



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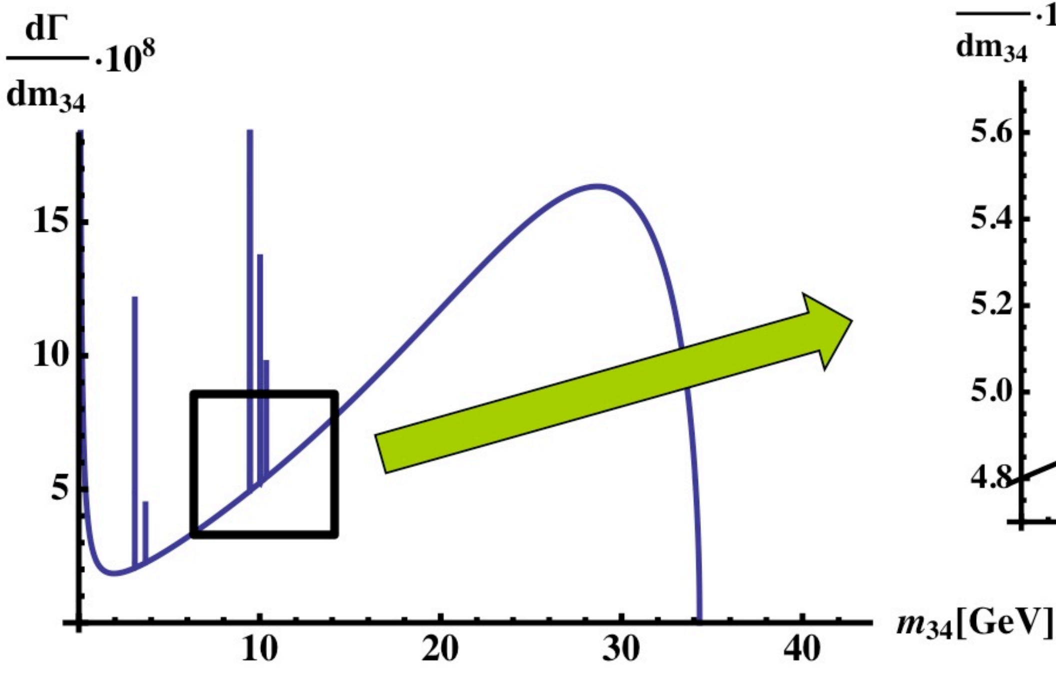
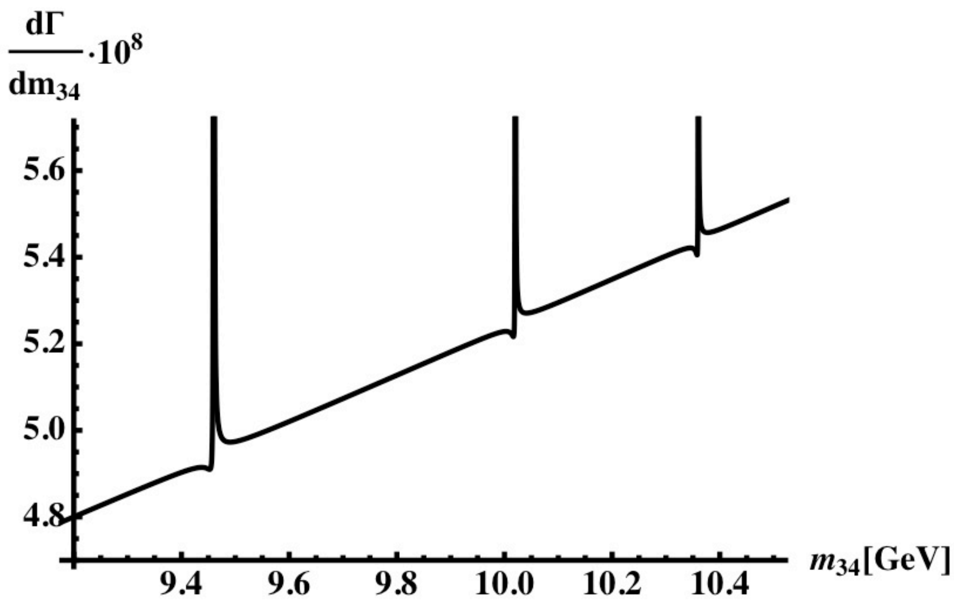
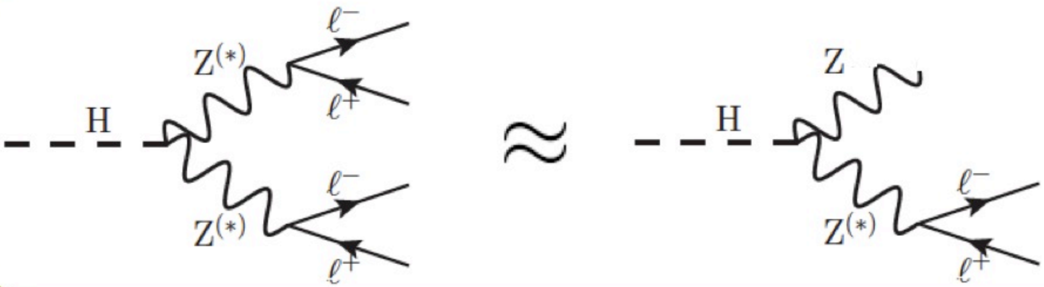




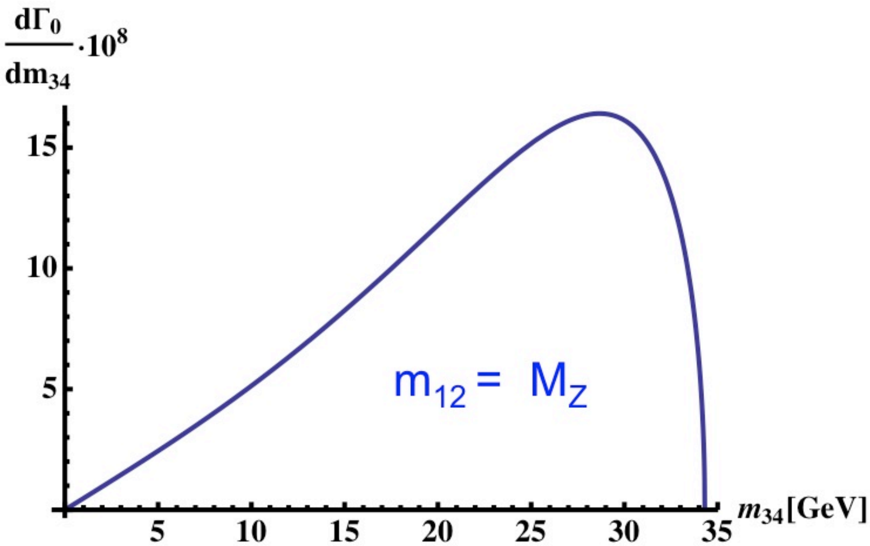
What does it mean that one Z is onshell?

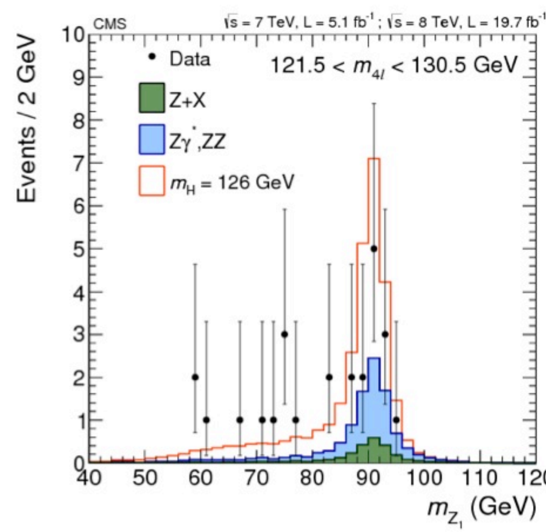


$\times\, B\,(Z \rightarrow \ell\ell)$

$$\frac{d\Gamma_0^{\rm SM}(h \to Z\ell^+\ell^-)}{dm_{34}^2} = \frac{m_Z^6}{8\pi^3 v^4 m_h}\left[(g_R^\ell)^2 + (g_L^\ell)^2\right]\,\frac{\lambda(\hat{q}^2,\hat{\rho})}{(m_{34}^2 - m_Z^2)^2}\left[m_{34}^2 + \frac{m_h^4}{12 m_Z^2}\,\lambda^2(\hat{q}^2,\hat{\rho})\right],$$

$$\hat{\rho} = m_Z^2/m_h^2$$





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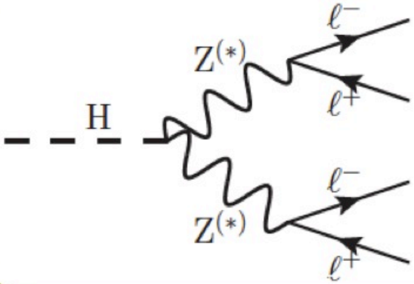

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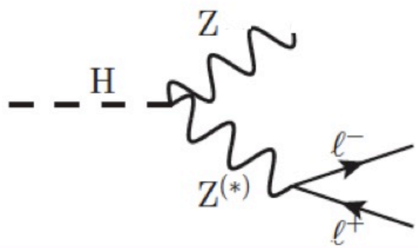
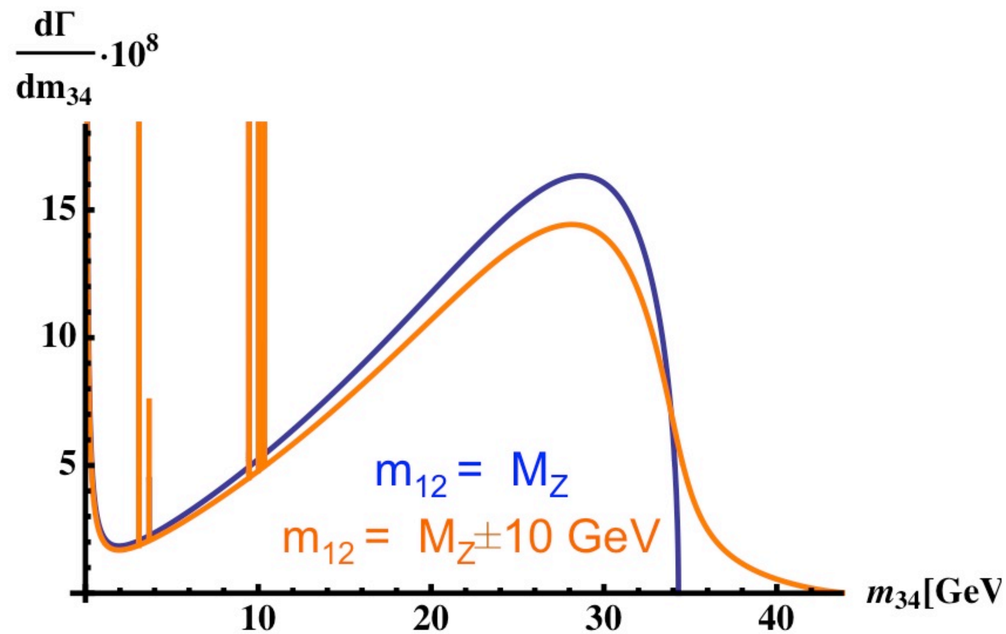


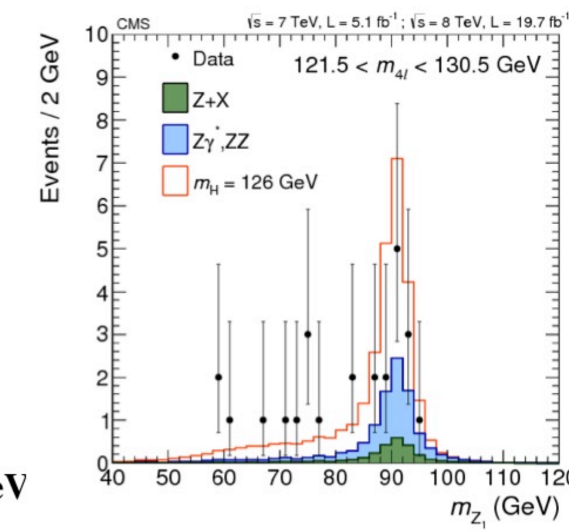
x $B\,(Z \to \ell\ell)\; dm_{12}^2 BW_{(M_Z,\Gamma_Z)}$

$$\frac{d\Gamma_0^{\rm SM}(h \to Z\ell^+\ell^-)}{dm_{34}^2} = \frac{m_Z^6}{8\pi^3 v^4 m_h}\left[(g_R^\ell)^2 + (g_L^\ell)^2\right]\; \frac{\lambda(\hat{q}^2,\hat{\rho})}{(m_{34}^2 - m_Z^2)^2}\left[m_{34}^2 + \frac{m_h^4}{12 m_Z^2}\,\lambda^2(\hat{q}^2,\hat{\rho})\right],$$

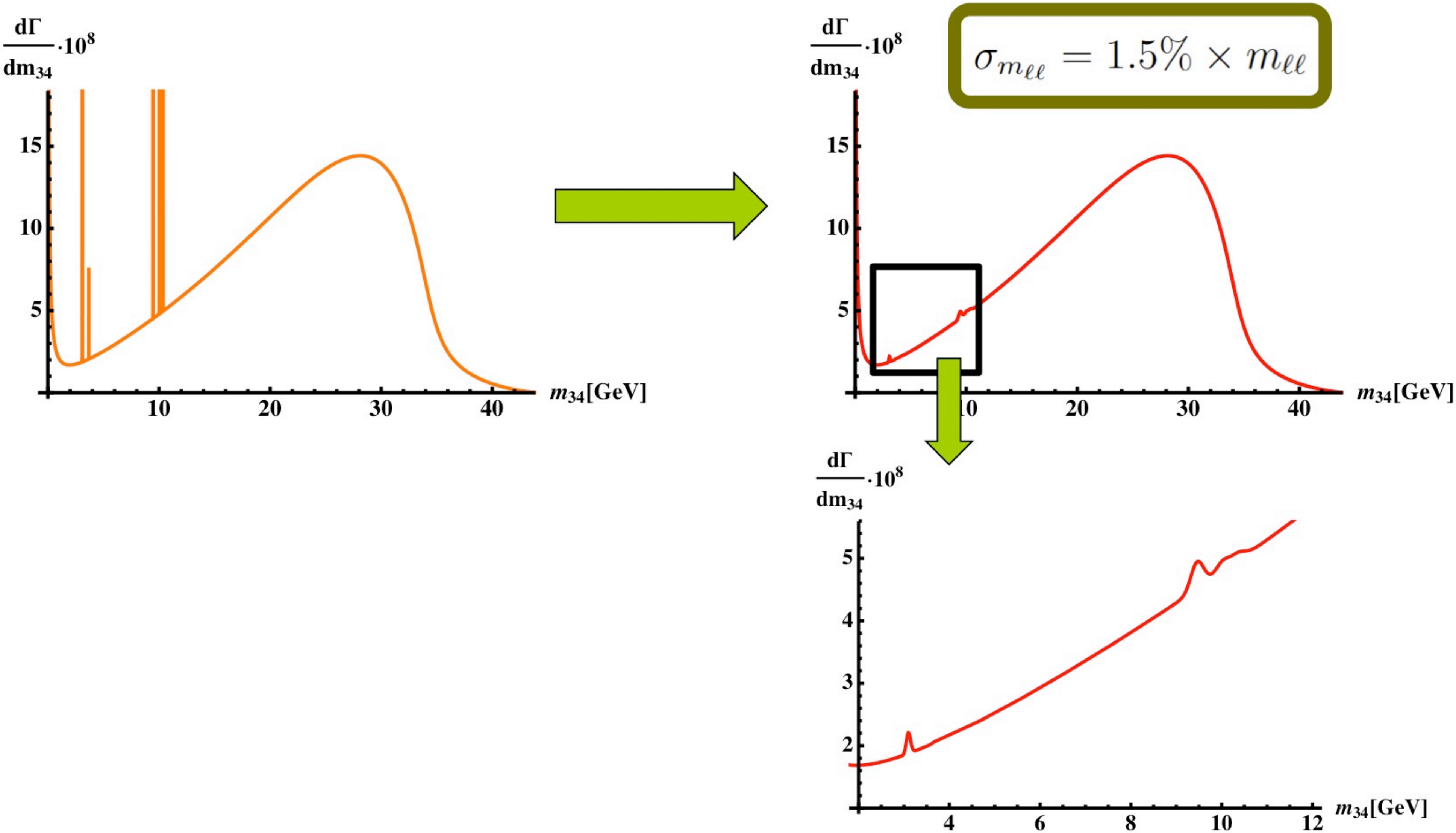
$$\hat{\rho} = m_Z^2/m_h^2$$

$m_Z^2 \Rightarrow m_{12}^2$





Smearing due to limited exp. resolution



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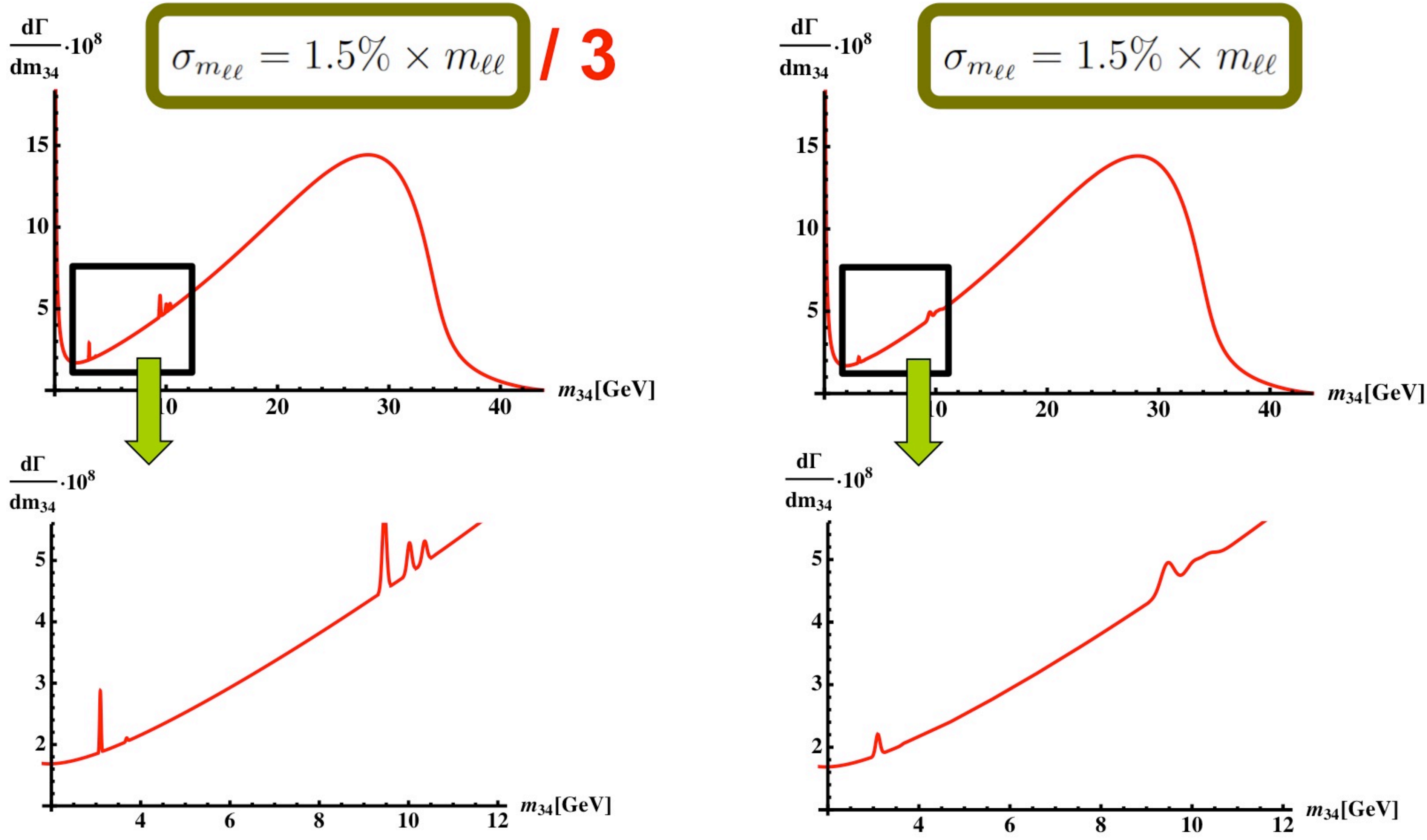
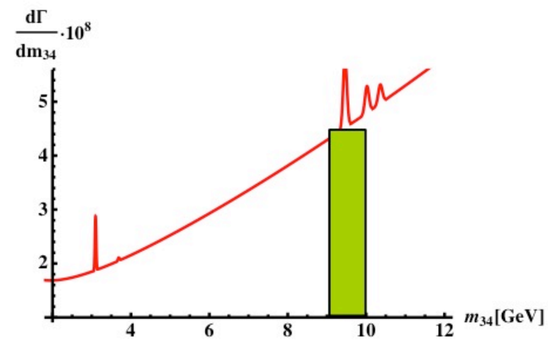


Effect on a single bin

- If the bin is much wider than the exp. resolution:

$$\Gamma(h \to ZV_i \to Z\ell^+\ell^-) \approx \Gamma(h \to ZV_i) \times \mathcal{B}(V_i \to \ell^+\ell^-)$$

$$\Gamma(h \to ZV_i) \;=\; \frac{(1-\hat{\rho})^3}{16\pi}\frac{m_h^3}{v^4}(g_V^q f_{V_i})^2.$$



State	m_{V_i}[GeV]	f_{V_i}[MeV]	$\mathcal{B}(h \to ZV_i)$	$\Delta[d\Gamma(h \to Z\ell\ell)/dm_{34}]_{[1\ \text{GeV bin}]}$
$J/\psi(1S)$	3.10	405	1.7×10^{-6}	2.6%
$J/\psi(2S)$	3.69	290	8.6×10^{-7}	0.2%
$\Upsilon(1S)$	9.46	680	1.6×10^{-5}	3.1%
$\Upsilon(2S)$	10.02	485	8.2×10^{-6}	1.2%
$\Upsilon(3S)$	10.36	420	6.2×10^{-6}	0.9%

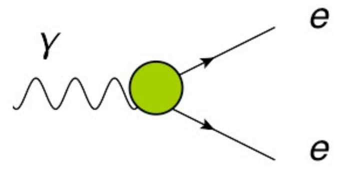
→ ~30%
[100 MeV bin]

PS: But, current cuts: m_{34} > 12 GeV (both CMS and ATLAS)

New Physics:

Could the NP behind $(g\text{-}2)_\mu$ affect Higgs decays?

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



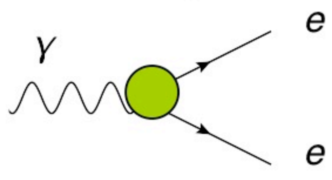
$$\mathcal{L}_{eff} \sim \frac{a_\mu}{m_\mu} \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

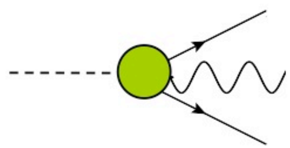
EFT approach

- Effective operator behind (g-2):

$$\mathcal{L}_{eff} \sim \frac{a_\mu}{m_\mu} \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

$$\mathcal{L}_{\rm EFT} = \frac{c_0}{\Lambda^2} \, \bar{L}_L^{(\mu)} \sigma^{\mu\nu} \mu_R F_{\mu\nu} H \, + \text{h.c.}$$





- However…

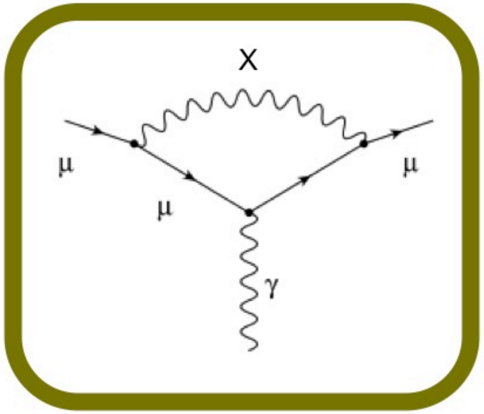
$$\Delta a_\mu = -\frac{c_0}{\Lambda^2} \frac{4 m_\mu v}{\sqrt{2} e} \approx -5 \times 10^{-9} \frac{c_0}{y_\mu} \left(\frac{5 \text{ TeV}}{\Lambda} \right)^2$$

$$\Rightarrow \quad B(h \to \mu^+ \mu^- \gamma)_{\rm EFT}^{(g-2)} = \frac{e^2 m_h^5 \left(\Delta a_\mu\right)^2}{12 (8\pi)^3 m_\mu^2 v^2 \Gamma_h} \sim \mathcal{O}\left(10^{-14}\right) \; ,$$

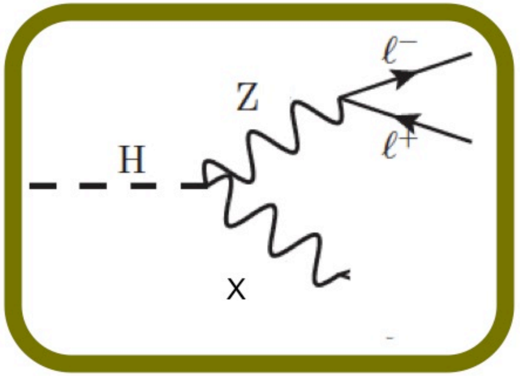
- Notes:
  - The relation can still happen (model-dependent).
  - The particles could be generated at the LHC.

Light states? $m_\mu \ll m_{\text{NP}} \ll m_h$

- $(g\text{-}2)_\mu$ can still be fine (with weaker couplings); [but not necessarily]

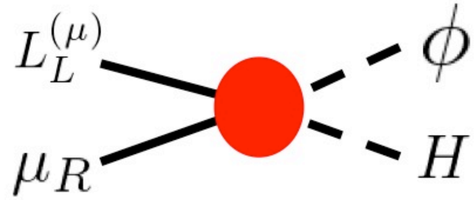


- Potential large effects in Higgs decay due to onshell production of the light states!

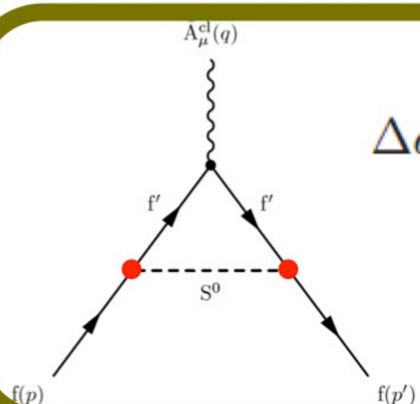


- Two examples:
  - SM + scalar
  - SM + vector

Light scalar

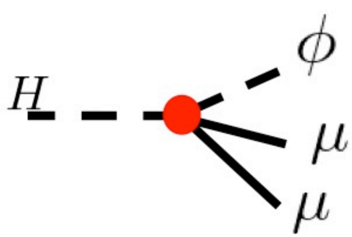


$$\mathcal{L}^{(1)} = \mathcal{L}_{\rm kin}^{(\phi)} + \left(\frac{c_{1\mu}}{\Lambda} \bar{L}_L^{(\mu)} \mu_R H \phi \; + \text{h.c.} \right) \,, \qquad \mathcal{L}_{\rm kin}^{(\phi)} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2$$



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

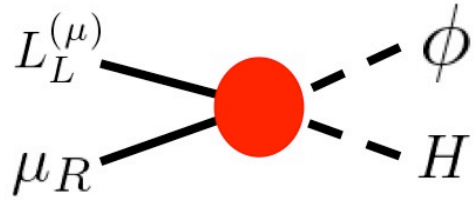
Correct sign!



$$\Gamma_\phi > \Gamma(\phi \to \mu\mu) = \frac{|c_{1\mu}|^2 v^2 m_\phi}{16\pi\Lambda^2} \approx (5.9 \text{ MeV}) \times \left(\frac{\Delta a_\mu}{2.9 \times 10^{-9}} \right) \left(\frac{m_\phi}{10 \text{ GeV}} \right)^3$$

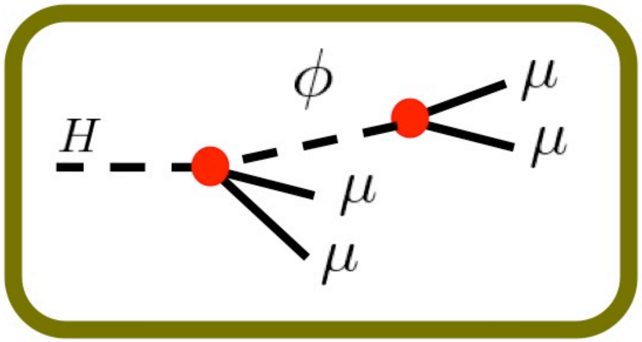
⇒ $h \to \phi\mu\mu \to 4\mu$

[Short-lived]



Light scalar

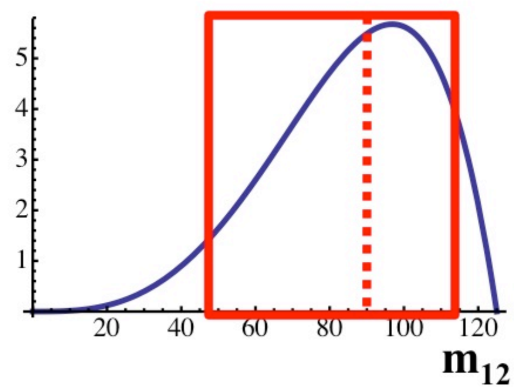
$$\mathcal{L}^{(1)} = \mathcal{L}_{\rm kin}^{(\phi)} + \left(\frac{c_{1\mu}}{\Lambda} \bar{L}_L^{(\mu)} \mu_R H \phi \ + \text{h.c.} \right)$$



Does the signal pass current m_{12} cut?

$40 < m_{12} < 120$ GeV (CMS)

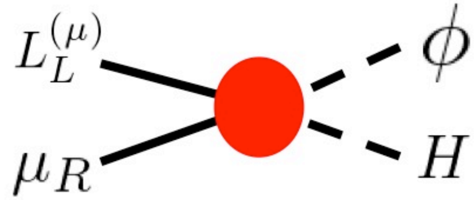
$50 < m_{12} < 106$ GeV (ATLAS)



$$\frac{d\Gamma(h \to \mu\mu\phi)}{dm_{12}} = \frac{|c_{1\mu}|^2}{128\pi^3 m_h^3 \Lambda^2} m_{12}^3 (m_h^2 - m_{12}^2)$$

$80 < m_{12} < 100$ GeV => $f = 0.35$

Light scalar



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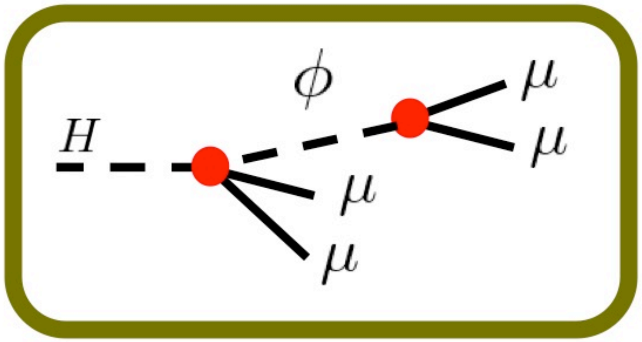
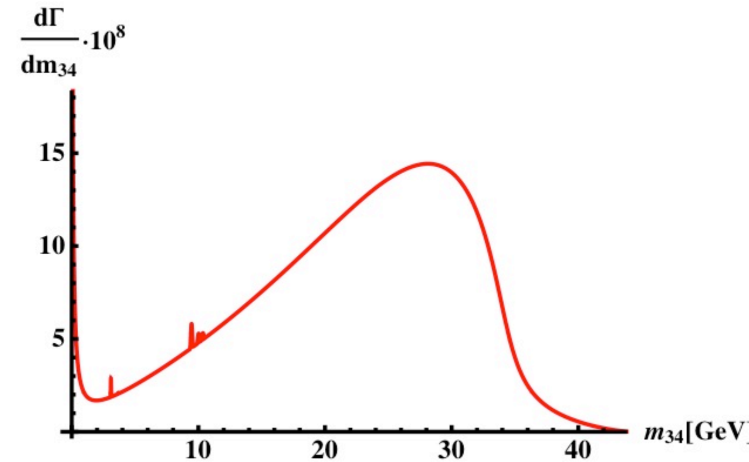


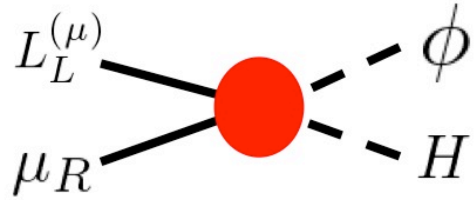


$$\frac{\mathcal{B}(h \to 4\mu)_{(\phi)}}{\mathcal{B}(h \to 4\mu)_{\rm SM}} \approx 150 \left(\frac{\Delta a_\mu}{2.9 \times 10^{-9}} \right) \left(\frac{m_\phi}{10 \text{ GeV}} \right)^2 \mathcal{B}(\phi \to \mu^+\mu^-)\, f \lesssim 0.5$$

A peak 900x larger than the Y(1s)!!

= 30x larger then SM [1 GeV bin]!!

Light scalar



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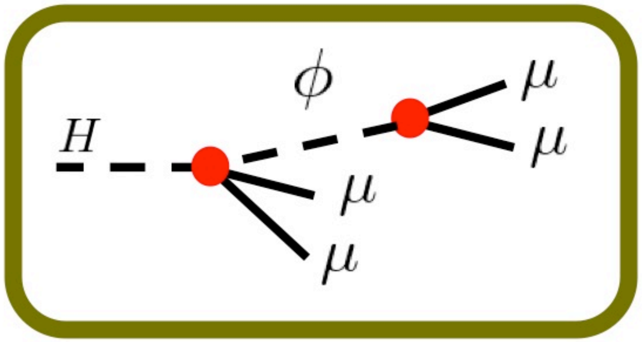

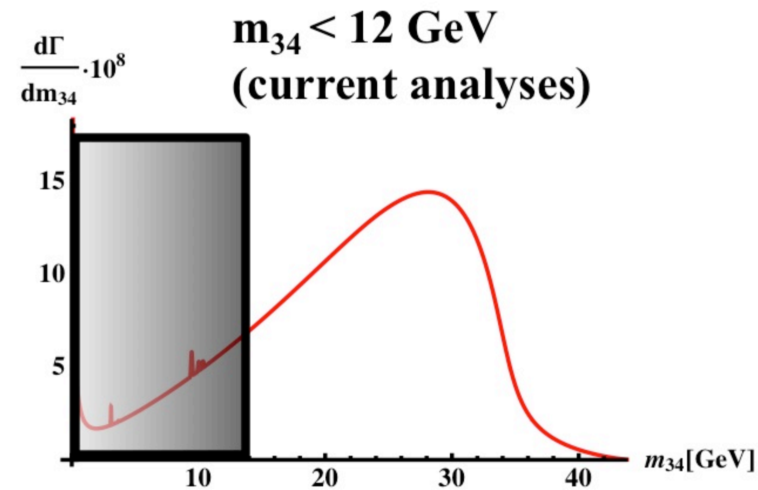

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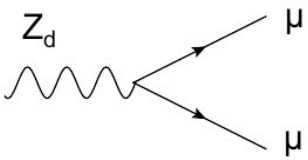
A peak 900x larger than the Y(1s)!!

= 30x larger then SM [1 GeV bin]!!

Light vector

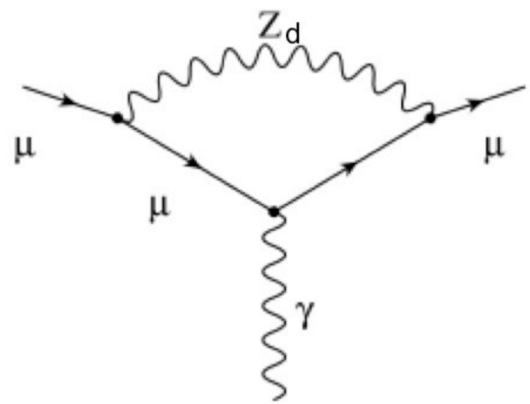
$$\mathcal{L}_{\text{int}}^{(2)} = -Z_d^{\mu}\left(c_L \bar{\mu}_L \gamma_\mu \mu_L \; + c_R \bar{\mu}_R \gamma_\mu \mu_R\right)$$



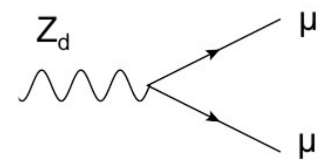
after EWSB (& diagonalization)

$$\Delta a_\mu = -\frac{1}{12\pi^2}\frac{m_\mu^2}{m_{Z_d}^2}\left(c_R^2 + c_L^2 - 3c_R c_L\right) \approx$$

$$\approx 2.3 \times 10^{-9}\left(\frac{10\ \text{GeV}}{m_{Z_d}}\right)^2 \frac{c_V^2 - 5c_A^2}{0.1^2}$$



Light vector



- Model realizations: dark photon

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu} - \epsilon_Z m_Z^2 Z_d^\mu Z_\mu$$

$$c_L = -e\,\epsilon - \frac{g}{2c_W}(1-2s_W^2)\epsilon_Z + g_d Q^d_{\mu_L}\,,$$

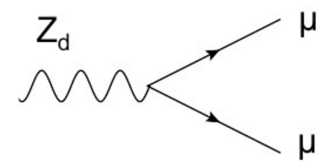
$$c_R = -e\,\epsilon + \frac{g}{c_W}s_W^2\epsilon_Z + g_d Q^d_{\mu_R}\,,$$

→ Right sign! $\Delta a_\mu > 0$ *[Fayet (2007), Pospelov (2009))]* **… but only allowed for very light masses.**

→ Wrong sign! $\Delta a_\mu < 0$

→ $U(1)_d$ charges could do the job.

Light vector



- Model realizations: dark photon

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$$\begin{aligned} c_L &= -e\,\epsilon - \frac{g}{2c_W}(1-2s_W^2)\epsilon_Z + g_d Q^d_{\mu_L} \,, \\ c_R &= -e\,\epsilon + \frac{g}{c_W}s_W^2\epsilon_Z + g_d Q^d_{\mu_R} \,, \end{aligned}$$

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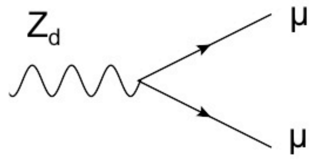

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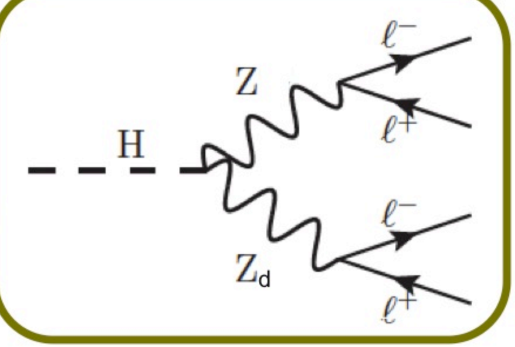


- Effect of Z_d in Higgs decay? $\Delta\mathcal{L}^{(2)}_{\rm int} = c_H\, v\, h Z^\mu_d Z_\mu$

$$\Gamma_{Z_d} \geq \Gamma(Z_d \to \mu^+\mu^-) = \frac{m_{Z_d}}{24\pi}\left(c_L^2 + c_R^2\right) \approx (1.3\ \text{MeV}) \times \frac{m_{Z_d}}{10\ \text{GeV}}\frac{c_L^2 + c_R^2}{0.1^2}$$

[Short-lived]

- Effect on the total BR:

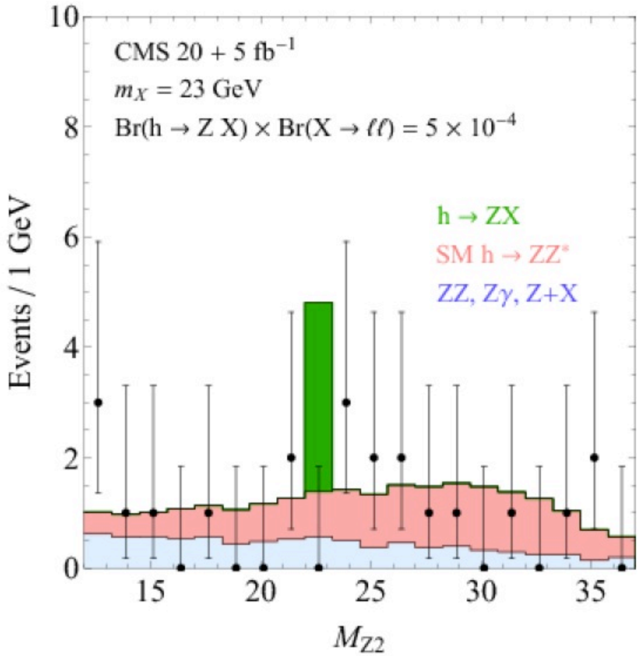
$$\frac{\mathcal{B}(h\to 4\mu)_{Z_d}}{\mathcal{B}(h\to 4\mu)_{\rm SM}} \approx 0.2\left(\frac{c_H}{10^{-4}}\frac{10\ \text{GeV}}{m_{Z_d}}\right)^2 \mathcal{B}(Z_d\to\mu^+\mu^-) \lesssim 0.5$$

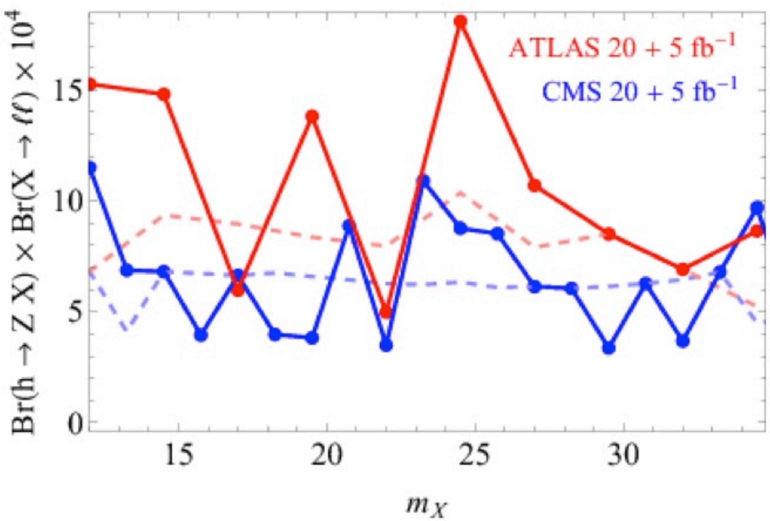
- Connection with dark photon/Z models: $c_H \approx 2\epsilon_Z \frac{m_Z^2}{v^2} + 2\epsilon \frac{m_{Z_d}^2}{v^2}\tan\theta_W$

Dark photon *[Curtin et al'2013]*
Dark Z *[Davoudiasl et al'2012]*

Light vector

- Once again, searching for a peak in the m_{34} spectrum is much better:





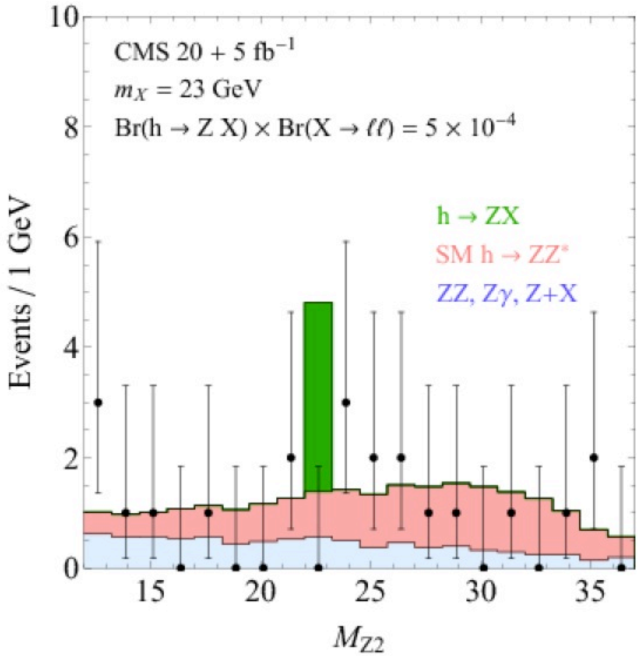
D. Curtin et al., arXiv:1312.4992

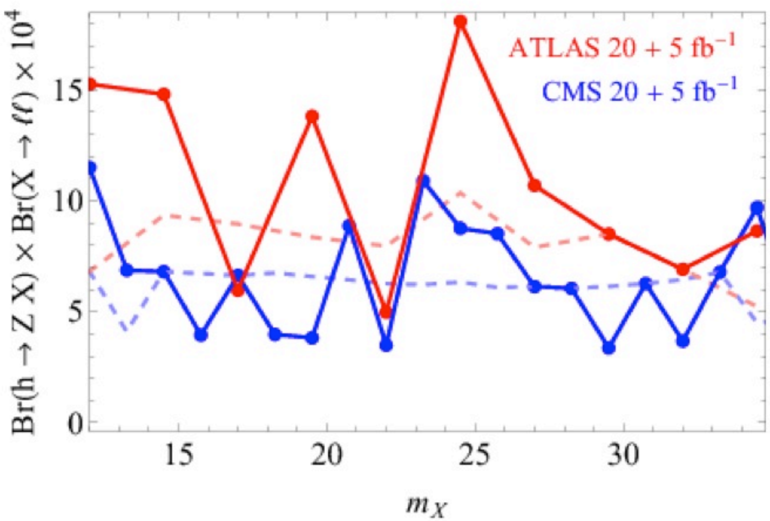
$$\mathcal{B}(h \to ZZ_d) \times \mathcal{B}(Z_d \to \mu\mu) \ < \ \kappa \times 10^{-4}$$

$$0 < \left(\frac{c_H}{10^{-4}}\right)^2 \frac{m_{Z_d}}{10 \text{ GeV}} \frac{\Gamma_h^{\text{SM}}}{\Gamma_{Z_d}} \frac{\Delta a_\mu}{2.9 \times 10^{-9}} \frac{c_V^2 + c_A^2}{c_V^2 - 5c_A^2} \ < \quad 3 \times \kappa$$

Light vector

- Once again, searching for a peak in the m_{34} spectrum is much better:





D. Curtin et al., arXiv:1312.4992

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$$0 < \left(\frac{c_H}{10^{-4}}\right)^2 \frac{m_{Z_d}}{10 \text{ GeV}} \frac{\Gamma_h^{SM}}{\Gamma_{Z_d}} \frac{\Delta a_\mu}{2.9 \times 10^{-9}} \frac{c_V^2 + c_A^2}{c_V^2 - 5c_A^2} < \quad 3 \times \kappa$$

Conclusions

- $\frac{d\Gamma(h \to 4\ell)}{dm_{34}}$ is a sensitive NP probe (heavy and light particles).

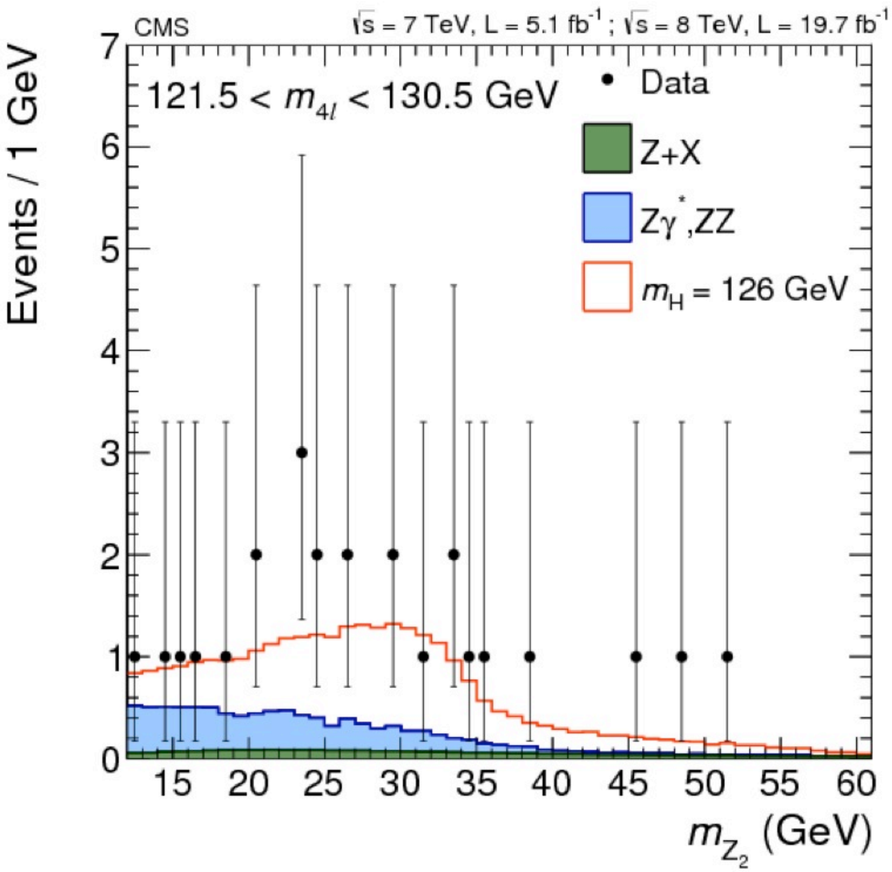
- Spectrum known with good theoretical accuracy.
  Quarkonium peaks quite small (~3% effect in a 1 GeV bin),
  but maybe visible in the high luminosity phase (~30% effect in a 0.1 GeV bin).

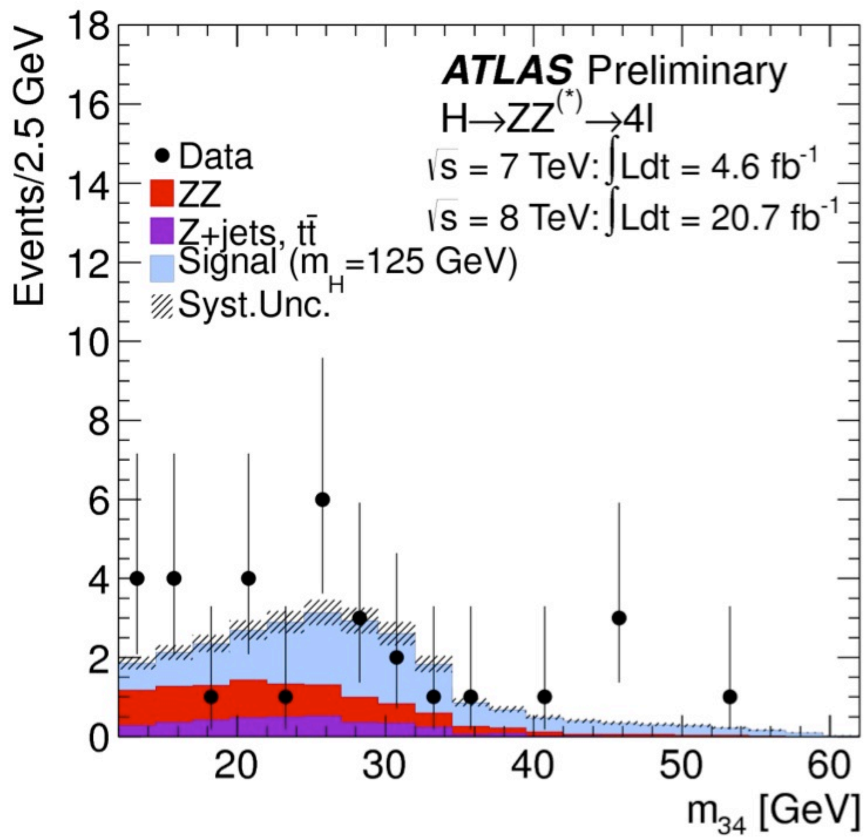
- NP examples: SM + light scalar/vector.
  The $(g-2)_\mu$ anomaly can be easily accommodated and visible consequences in the higgs decay are natural.

- Motivate dedicated searches for such light states (discovery potential).
  [m_{34} > 12 GeV cut]

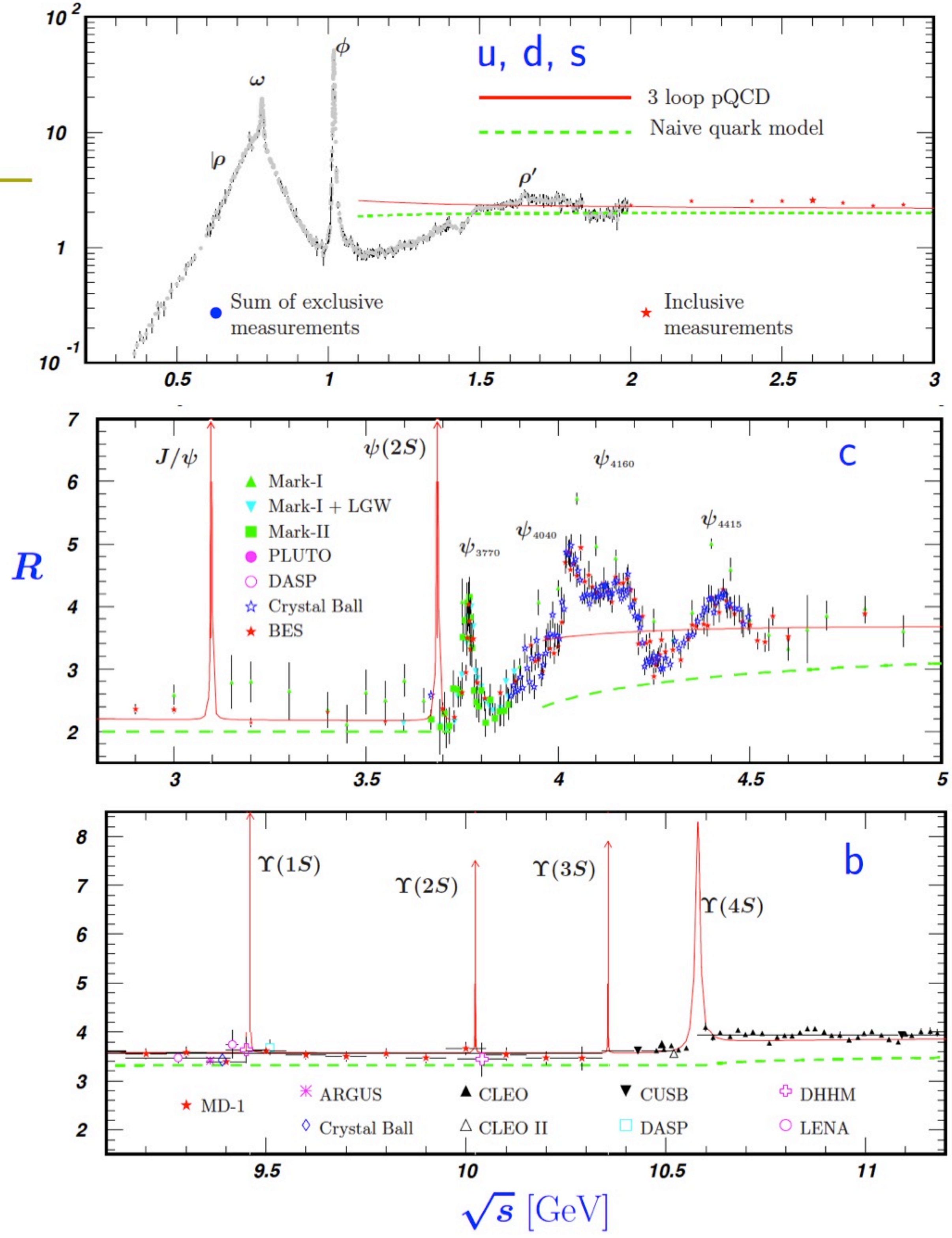
Backup slides

Introduction $h \to 4\ell$

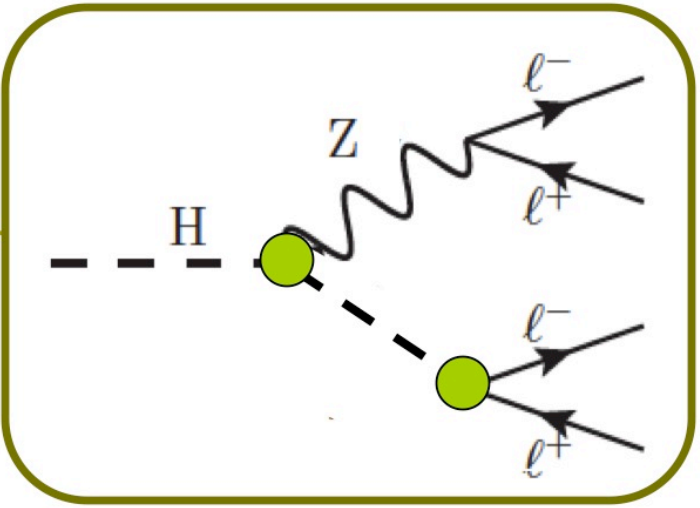




R(s) data


u, d, s
3 loop pQCD
Naive quark model
Sum of exclusive measurements
Inclusive measurements
c
J/ψ
ψ(2S)
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
R
b
Υ(1S)
Υ(2S)
Υ(3S)
Υ(4S)
MD-1
ARGUS
Crystal Ball
CLEO
CLEO II
CUSB
DASP
DHHM
LENA
√s [GeV]

Light scalar

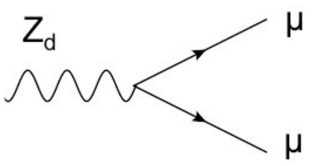


$$\Delta\mathcal{L}^{(1)} = \frac{c_{1h}}{2\Lambda}\left(iH^\dagger D_\mu H \partial^\mu \phi \; + \; \text{h.c.}\right)$$

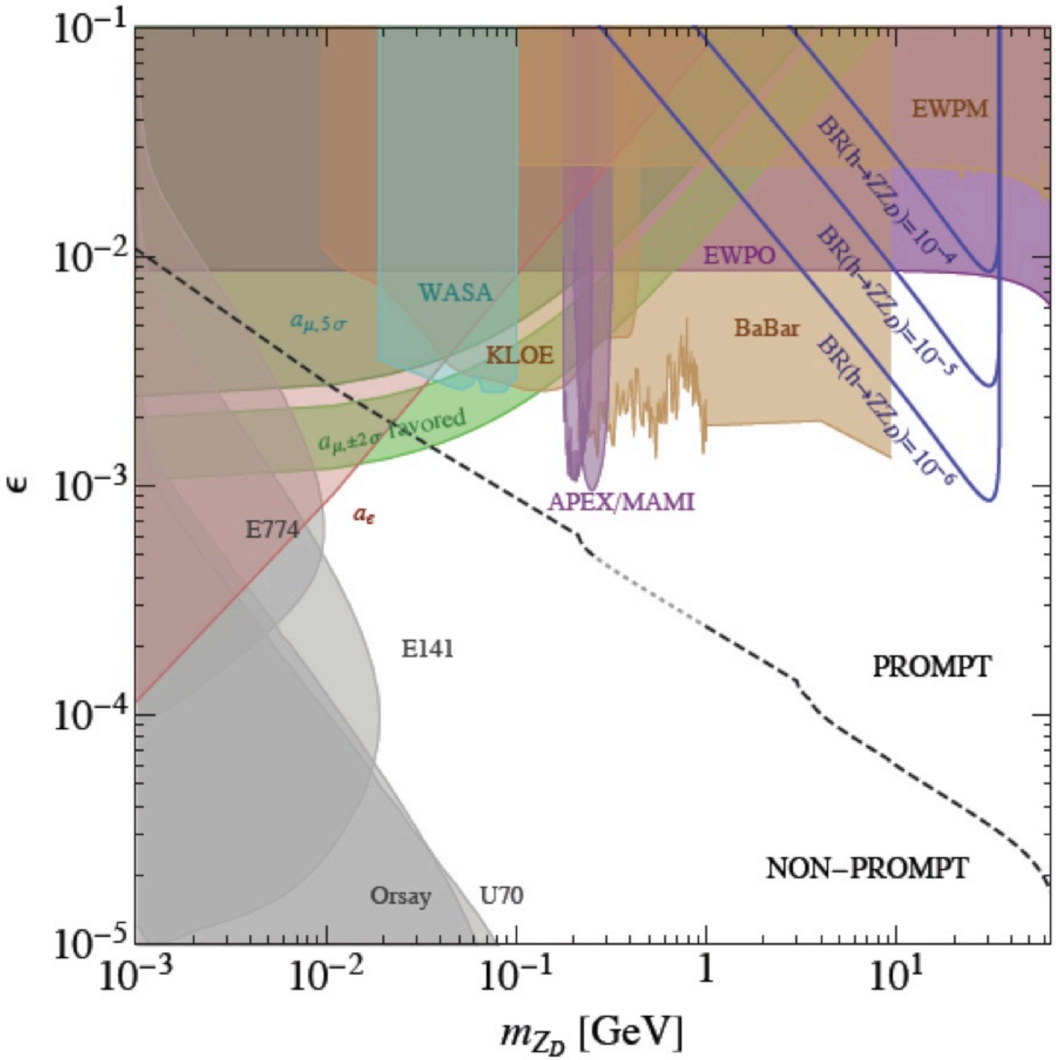
$$\Delta m_Z^2/m_Z^2 \approx c_{1h}^2/(32\pi^2) < 5 \times 10^{-4} \Longrightarrow |c_{1h}| < 0.4$$

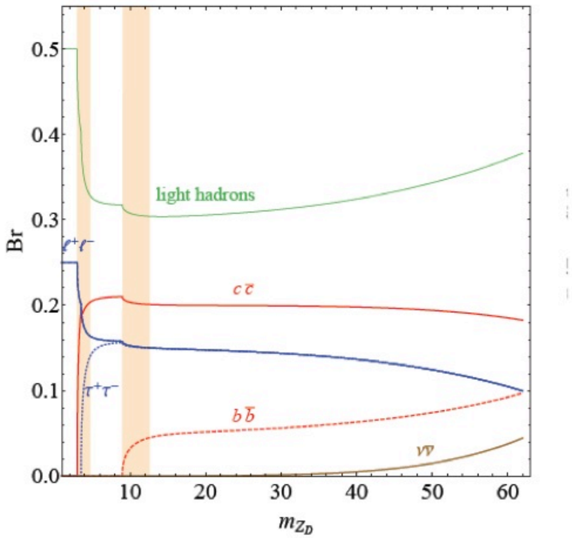
$$\frac{\mathcal{B}[h \to (2\ell)_Z (2\mu)_{(\phi)}]}{\mathcal{B}(h \to 2\ell 2\mu)_{\text{SM}}} \approx 160 \left|\frac{c_{1h}}{0.4}\right|^2 \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 \mathcal{B}(\phi \to \mu^+\mu^-)$$

Dark photon



$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu}$$





D. Curtin et al., arXiv:1312.4992