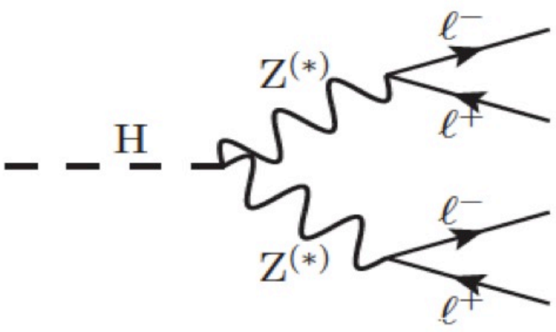
The $h \to 4\ell$ spectrum at low m_{ll}: SM vs. light new physics

Higgs Effective Field Theories 2014
[HEFT2014]

Madrid
September 29th, 2014

Martín González-Alonso

Institut de Physique Nucléaire de Lyon
(UCBL & CNRS/IN2P3)



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Introduction

- July 2012: ATLAS & CMS observed a ~125 GeV new particle with the properties of the Higgs boson.

- Room for New Physics?
  - Very heavy NP: (non)-linear EFT [or models]

    Small deviations

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i \mathcal{O}_i$$

  - Not so heavy: EFT breaks down...
    ... even lighter then the Higgs ➔ Exotic Higgs decays!

    More spectacular signals

[M. Strassler's talk (Tuesday)]

- Tiny Γ_h ➔ Large exotic BR 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, …]*
- Good exercise to keep in mind the limitations of the usual EFTs;
- Motivated by some anomalies (g-2, dark matter hints, ...).

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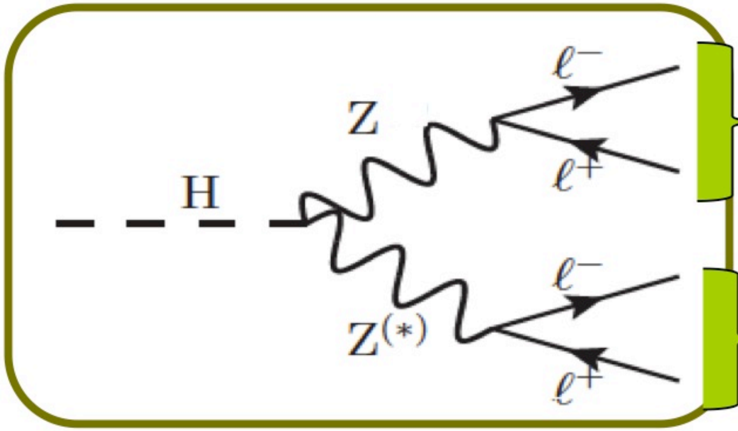
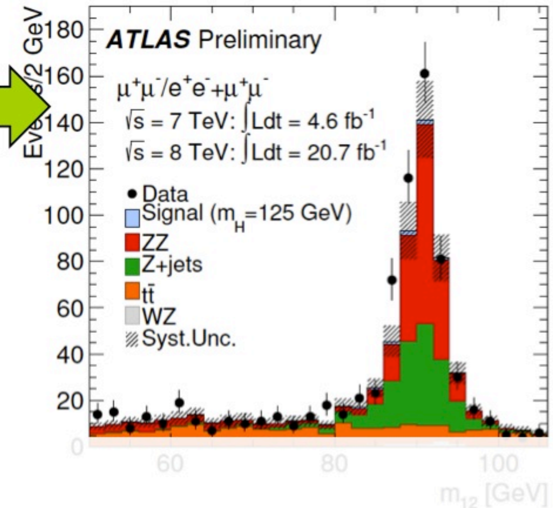


m_{12} (m_{Z1}) ~ M_Z

m_{34} (m_{Z2})



NP in the m_{34} distribution?

Heavy particles (EFT)
[Isidori et al.'2013, Grinstein et al.'2013, Pomarol-Riva'2013, ...]

Light particles
[Davoudiasl et al'2012-2013, Curtin et al'2013, …]

Questions:

QCD bkg? Quarkonia!

New light particles: connection with $(g\text{-}2)_\mu$?

[MGA & G. Isidori, arXiv:1403.2648]

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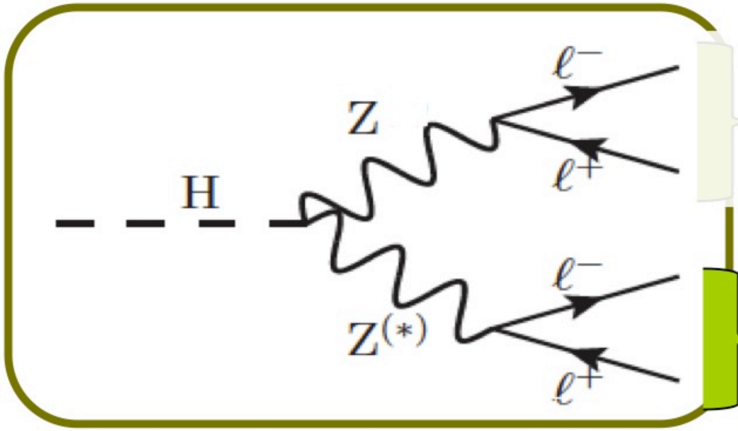

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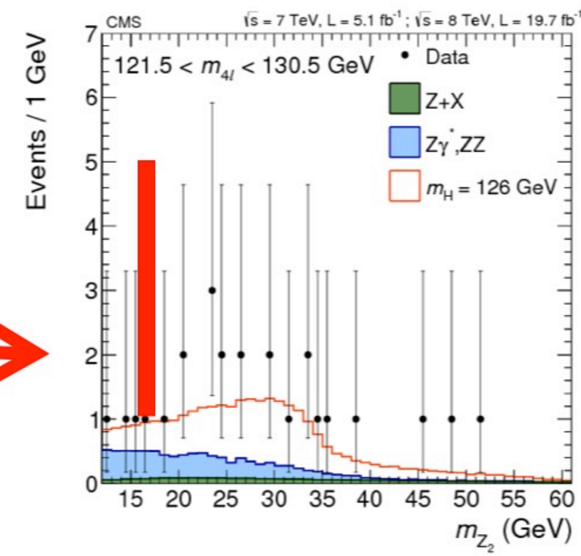

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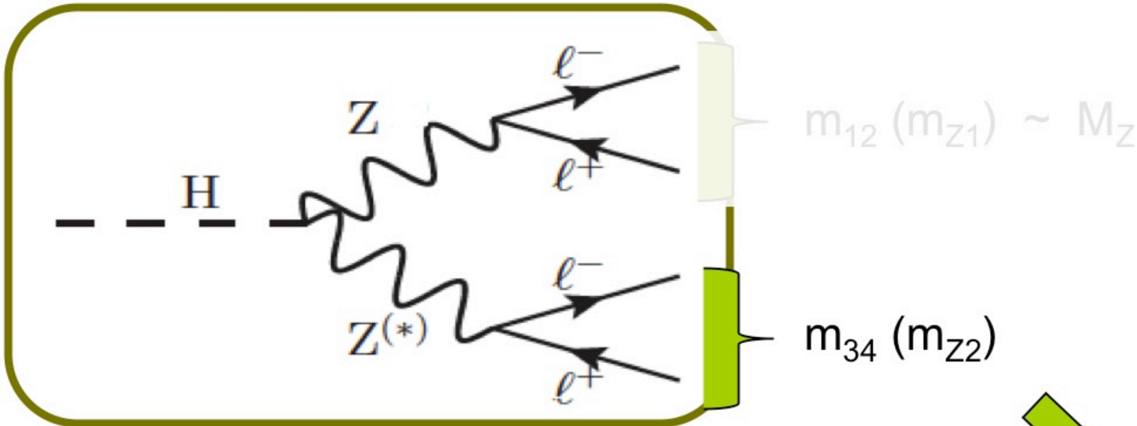

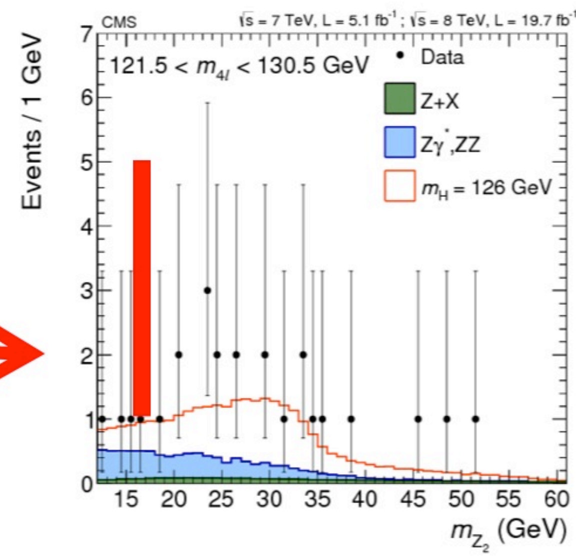

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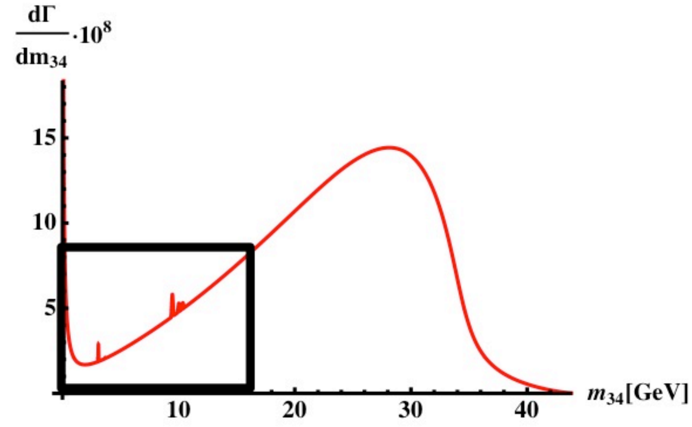
[MGA & G. Isidori, Phys.Lett. B733 (2014)]

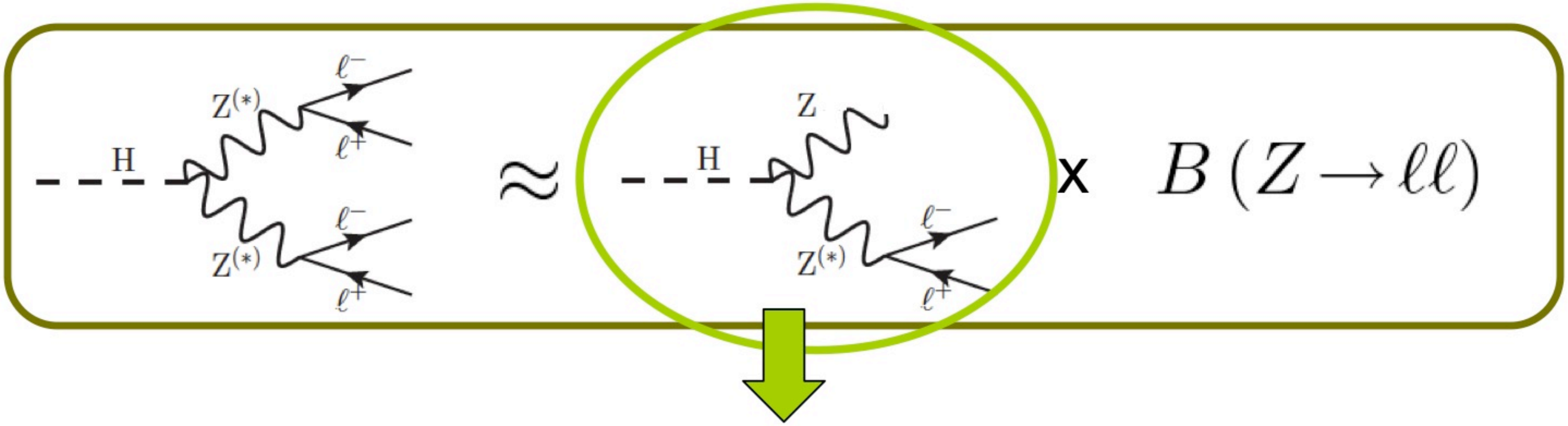
SM corrections:

Are locally important corrections under control?

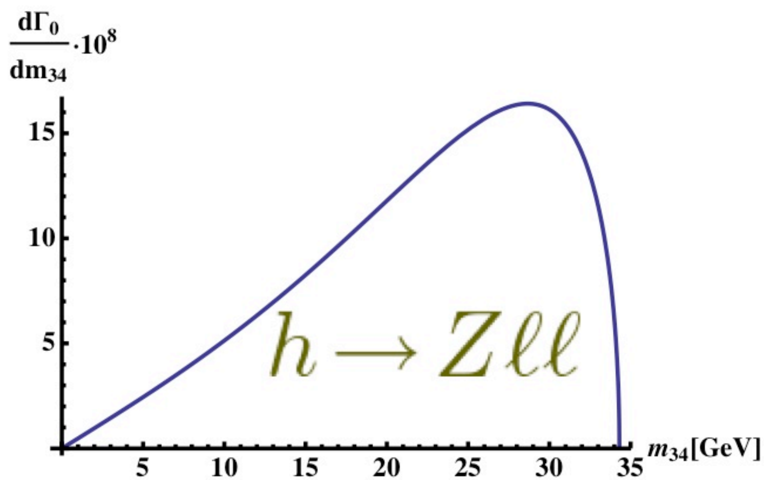
$$\frac{d\Gamma_0^{\mathrm{SM}}(h \to Z\ell^+\ell^-)}{dm_{34}^2} \quad ?$$



SM prediction: tree-level



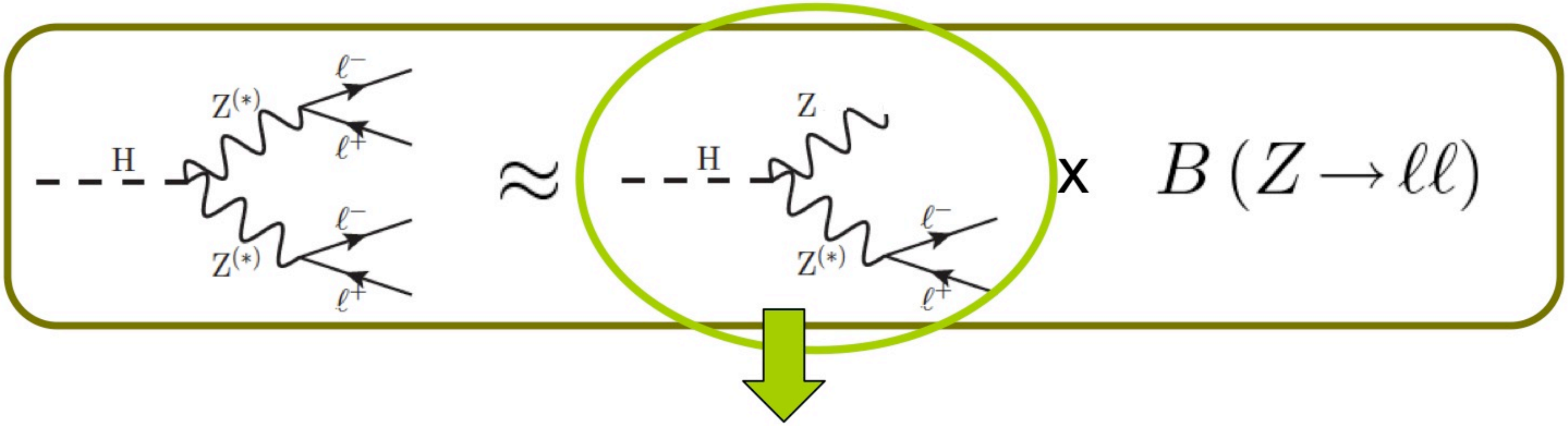
$$\frac{d\Gamma_0^{\rm SM}(h\to Z\ell^+\ell^-)}{dm_{34}^2} = \frac{m_Z^6}{8\pi^3 v^4 m_h}\left[(g_R^\ell)^2+(g_L^\ell)^2\right]\ \frac{\lambda(\hat{q}^2,\hat{\rho})}{(m_{34}^2-m_Z^2)^2}\left[m_{34}^2+\frac{m_h^4}{12m_Z^2}\ \lambda^2(\hat{q}^2,\hat{\rho})\right],$$



Locally imp. corrections?

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

SM prediction: tree-level



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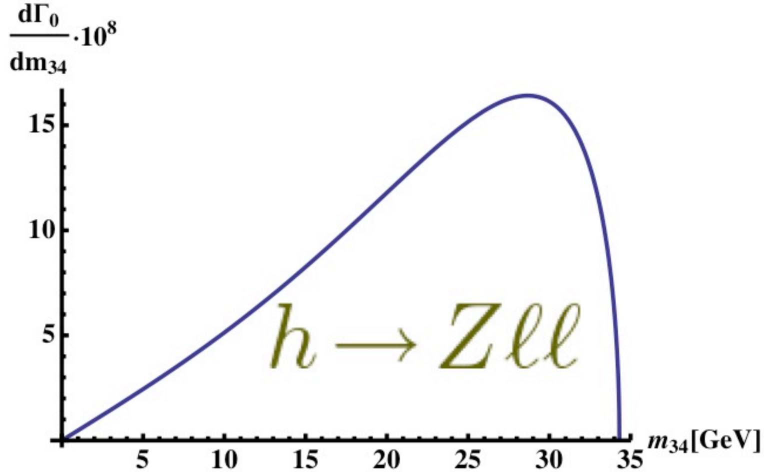
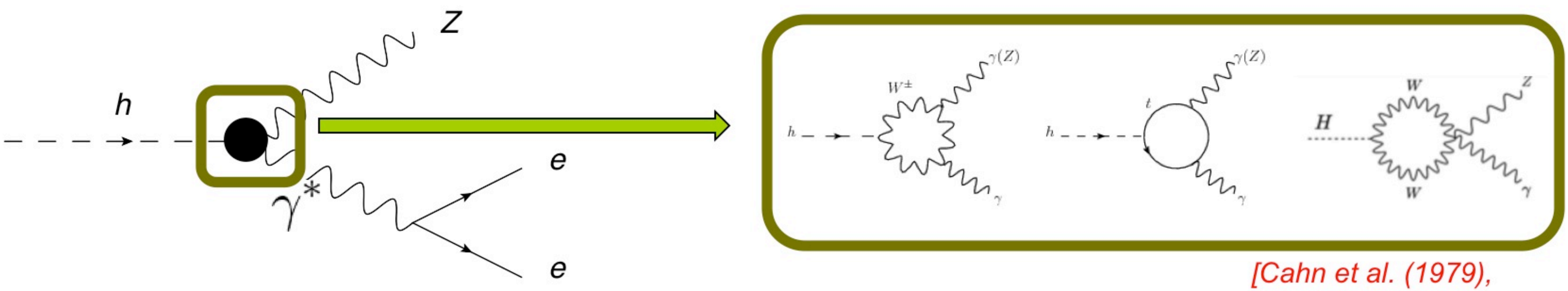


Locally imp. corrections?

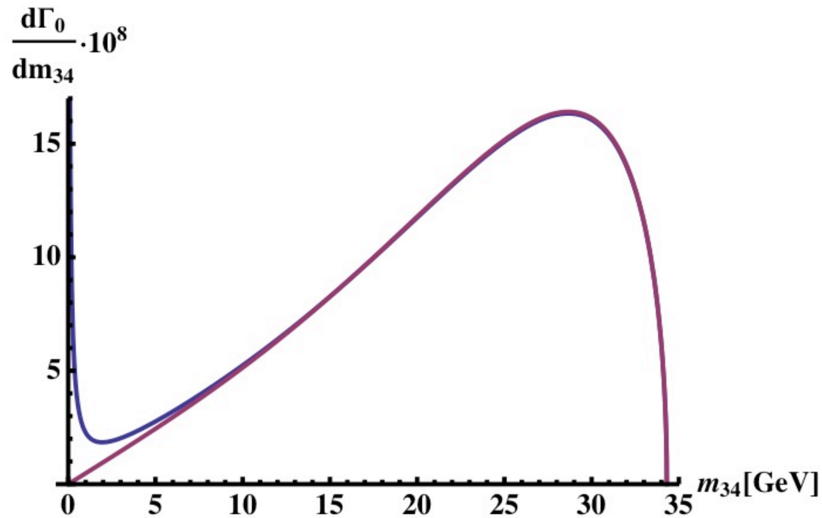
- **Photon pole:**
  $h\to Z\gamma^*\to Z\ell\ell$
- **QCD resonances:**
  $h\to ZV\to Z\ell\ell$

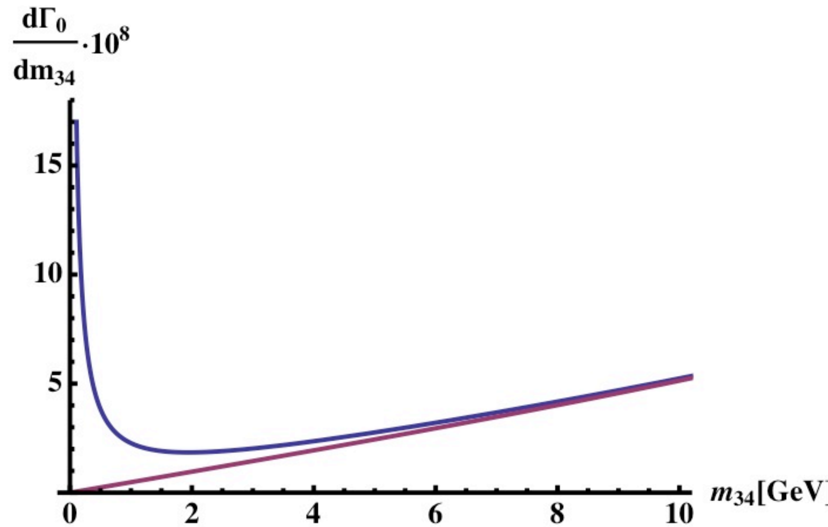
SM prediction: $h \to Z\gamma^* \to Z\ell\ell$



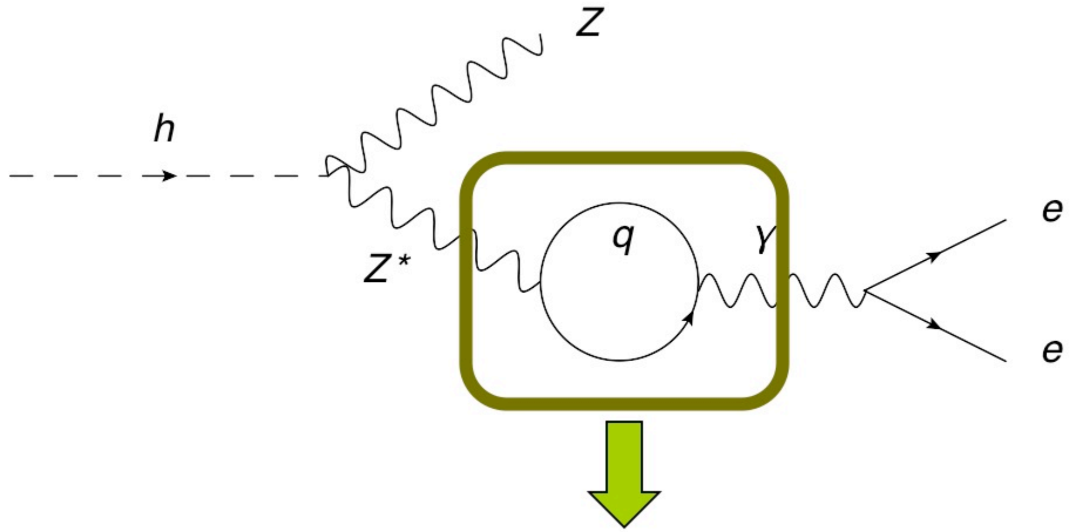
[Cahn et al. (1979), Bergstrom & Hulth (1985)]

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





SM prediction: QCD corrections



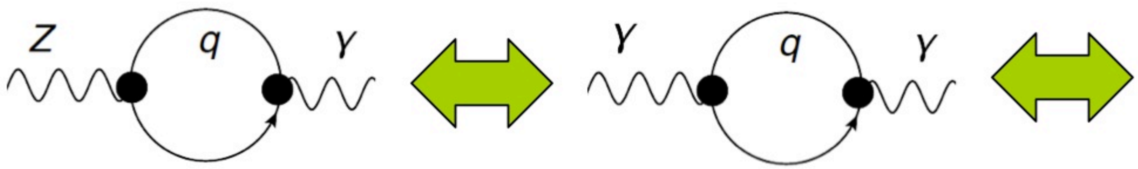
Long distance contributions are important (hadronization)

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

- No 1st principles calculation @ low q^2;
- It can be connected with $\Pi_{\gamma\gamma}$ ➔ R(s) data; [Jegerlehner'86] *Hadronic contributions to EW parameter shifts*
- Narrow resonance contribution is simpler: BW.

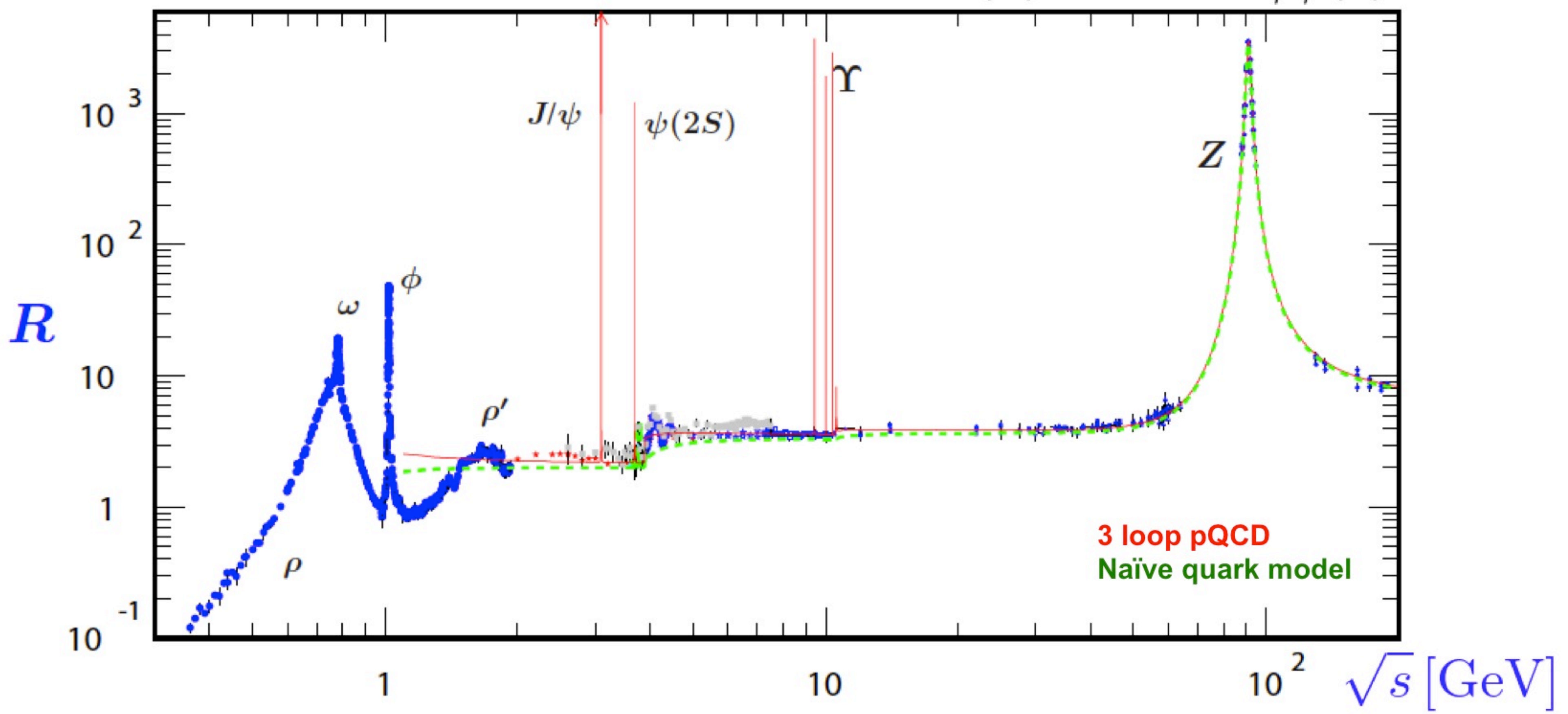
Higgs as a low-E QCD lab?

SM prediction: QCD corrections



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

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



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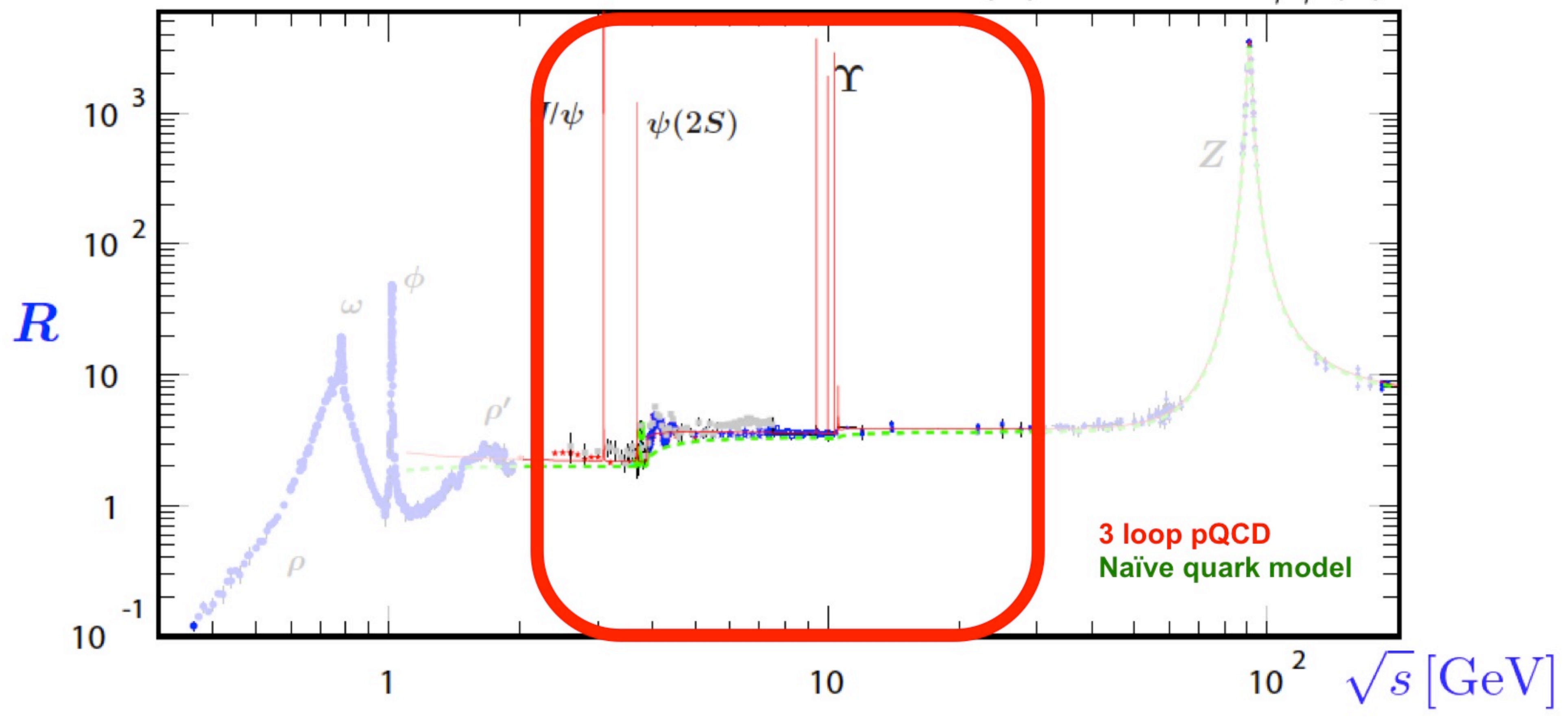
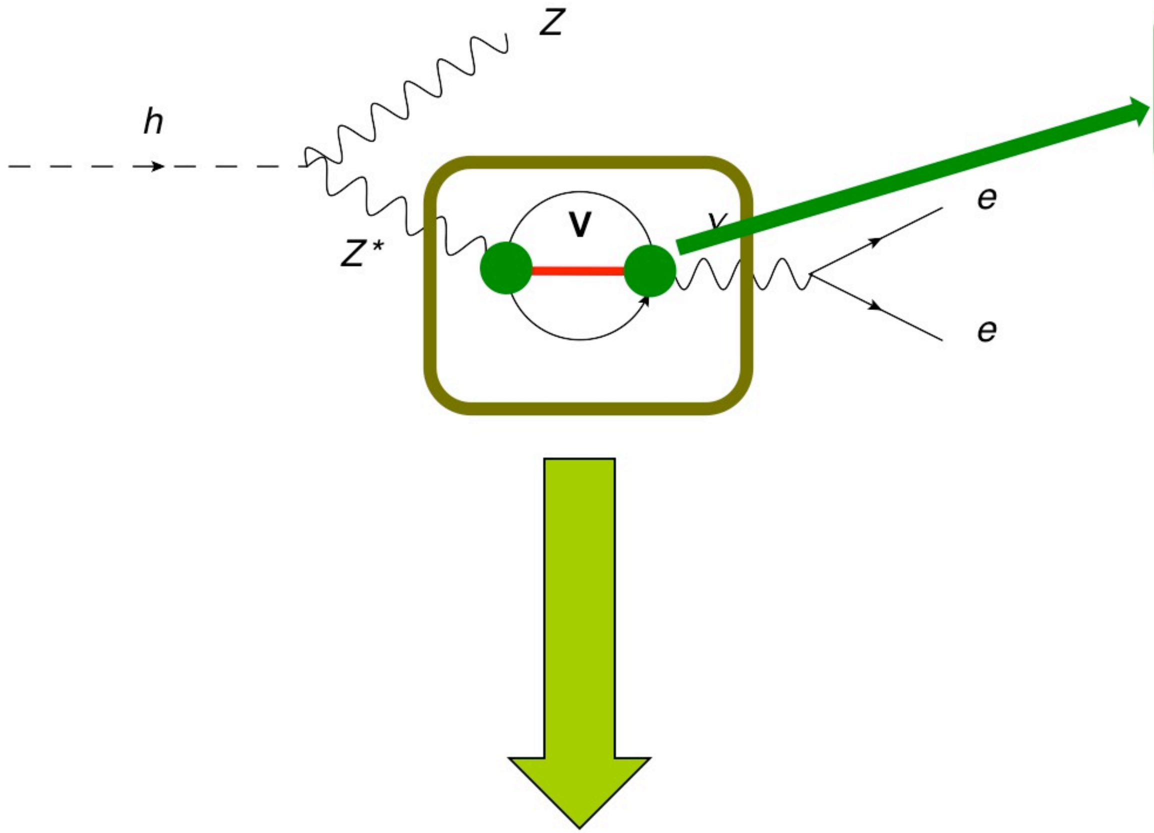


SM prediction: QCD corrections $q^2 > (2\ \mathrm{GeV})^2$



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

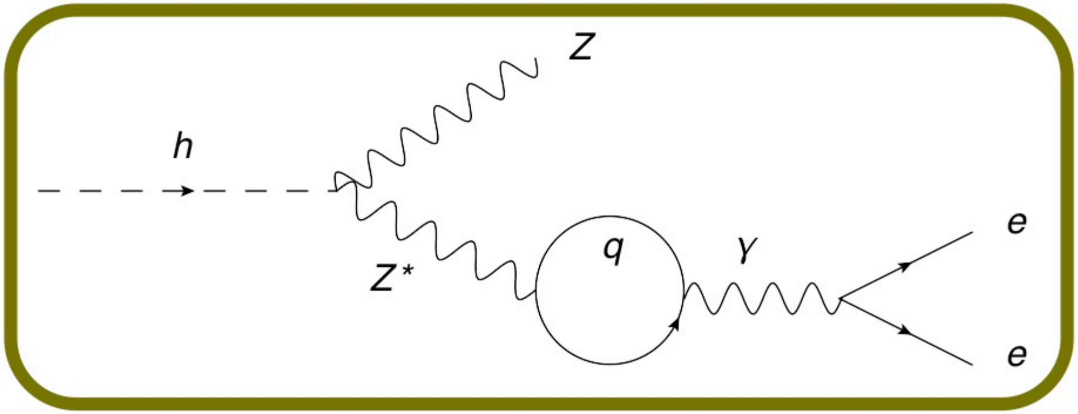
State	m_{V_i}[GeV]	f_{V_i}[MeV]
$J/\psi(1S)$	3.10	405
$J/\psi(2S)$	3.69	290
$\Upsilon(1S)$	9.46	680
$\Upsilon(2S)$	10.02	485
$\Upsilon(3S)$	10.36	420

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

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

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

SM prediction: QCD corrections



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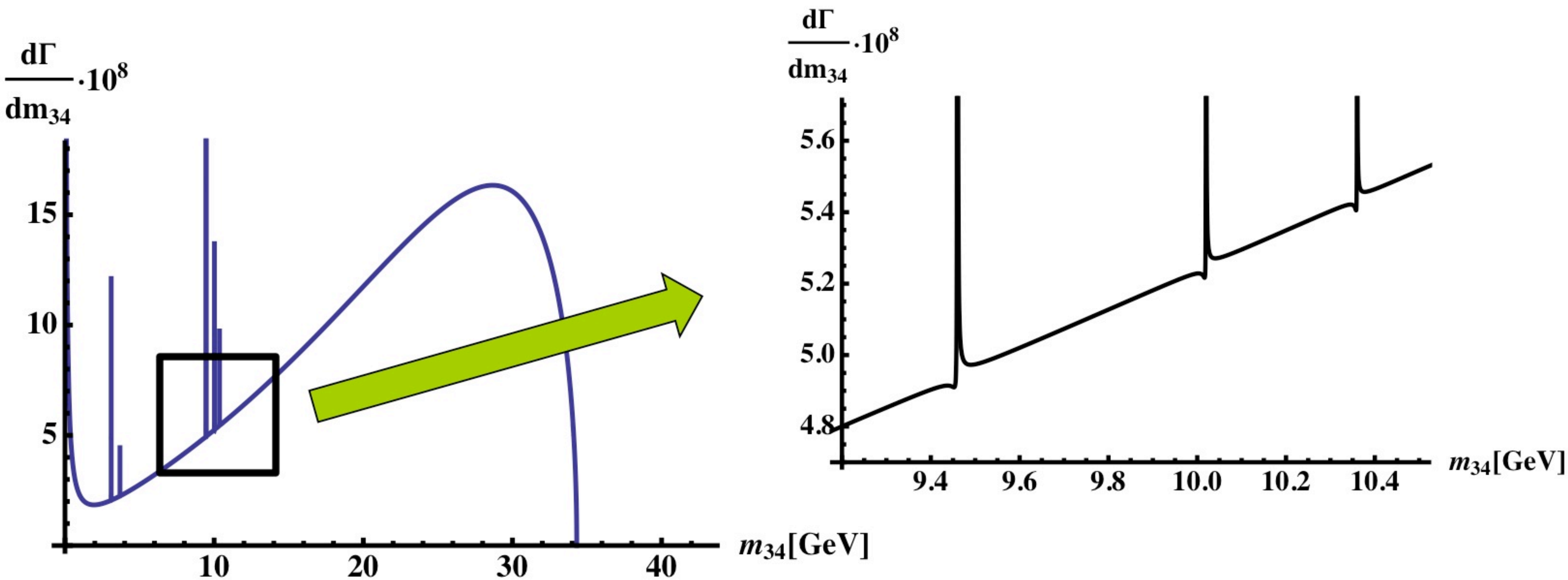
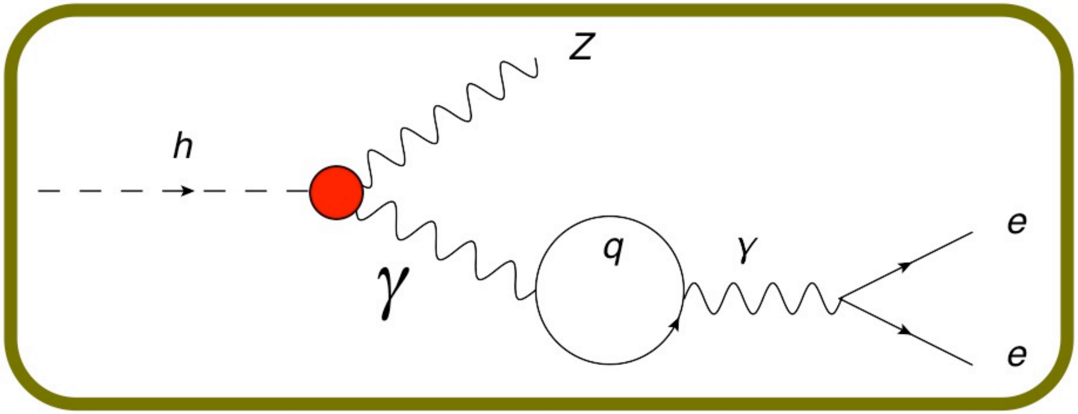


SM prediction: QCD corrections



$\Pi_{\gamma\gamma}(s)$

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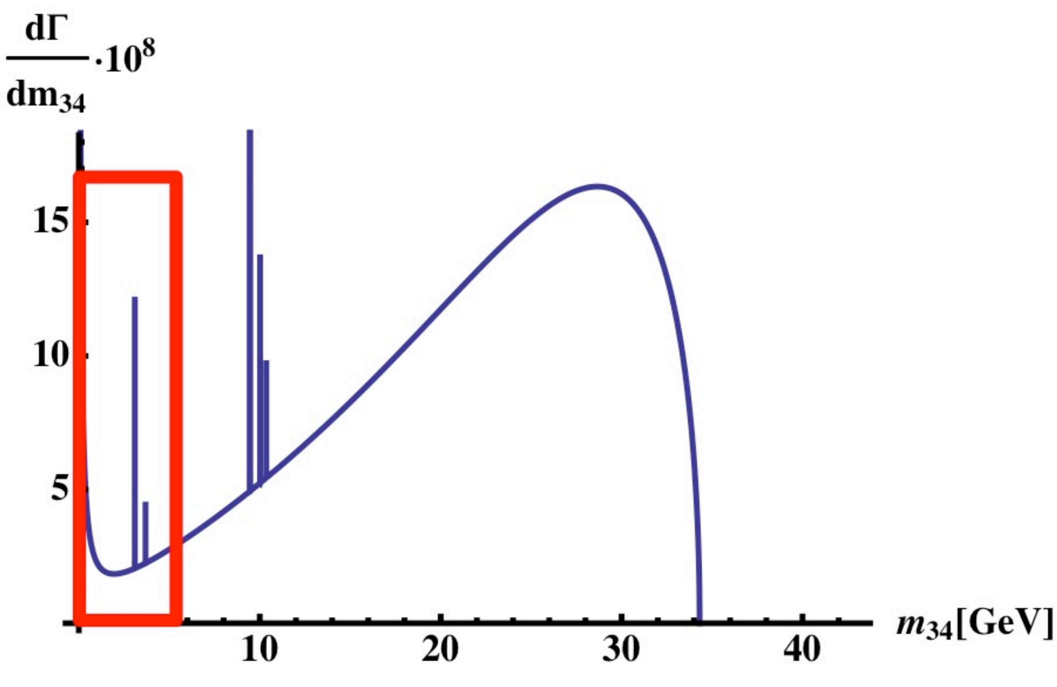
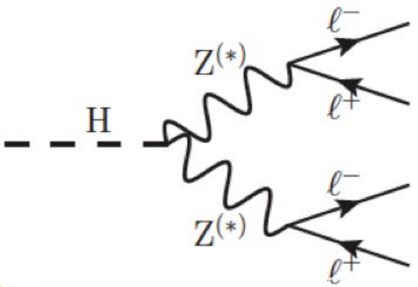
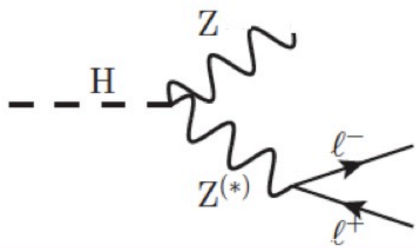


[D. Gao, Phys.Lett. B737 (2014)]

What does it mean that one Z is onshell?



$\approx$



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

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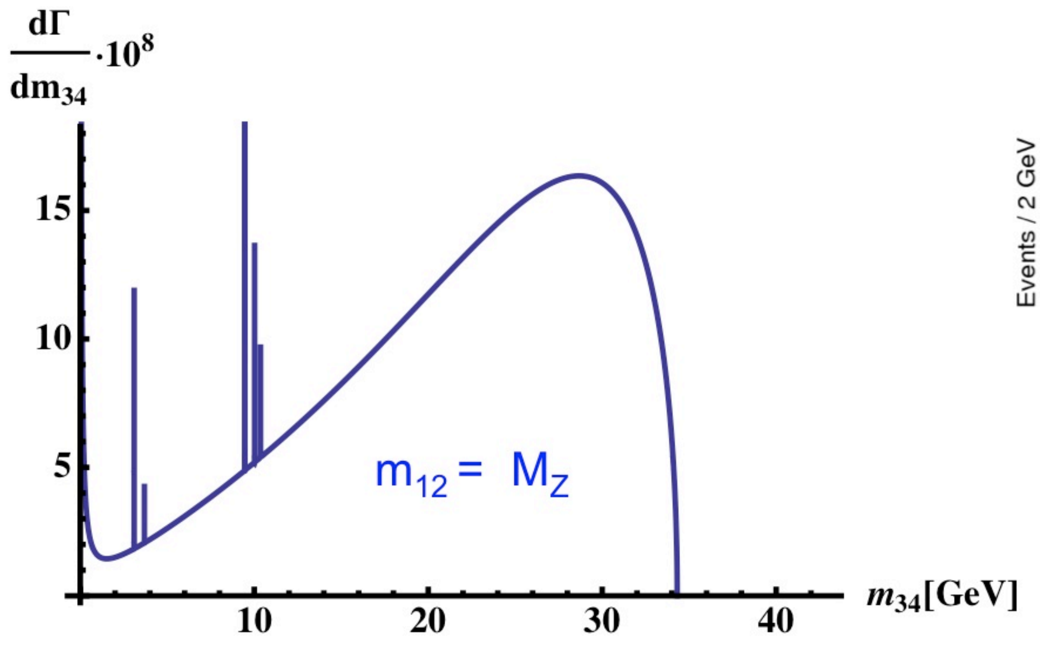

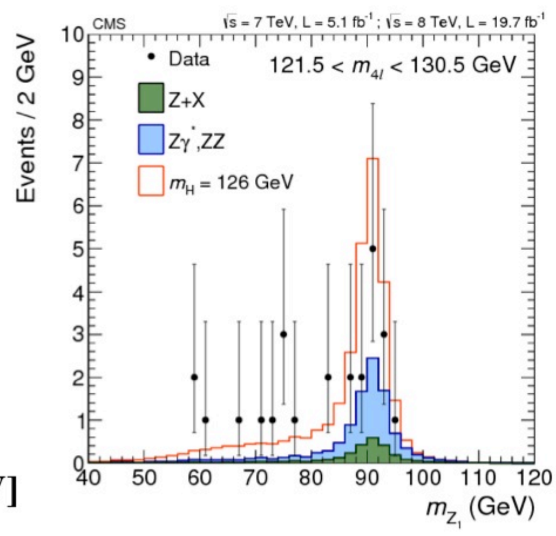

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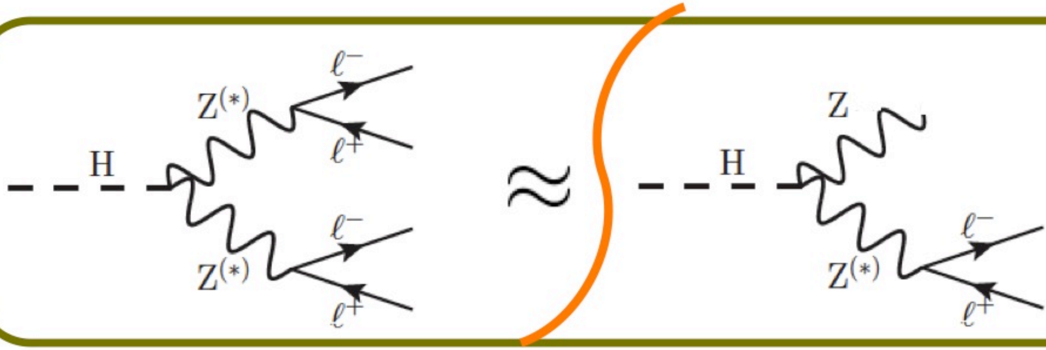

x $B\,(Z \to \ell\ell)\; dm_{12}^2 BW_{(M_Z,\Gamma_Z)}$

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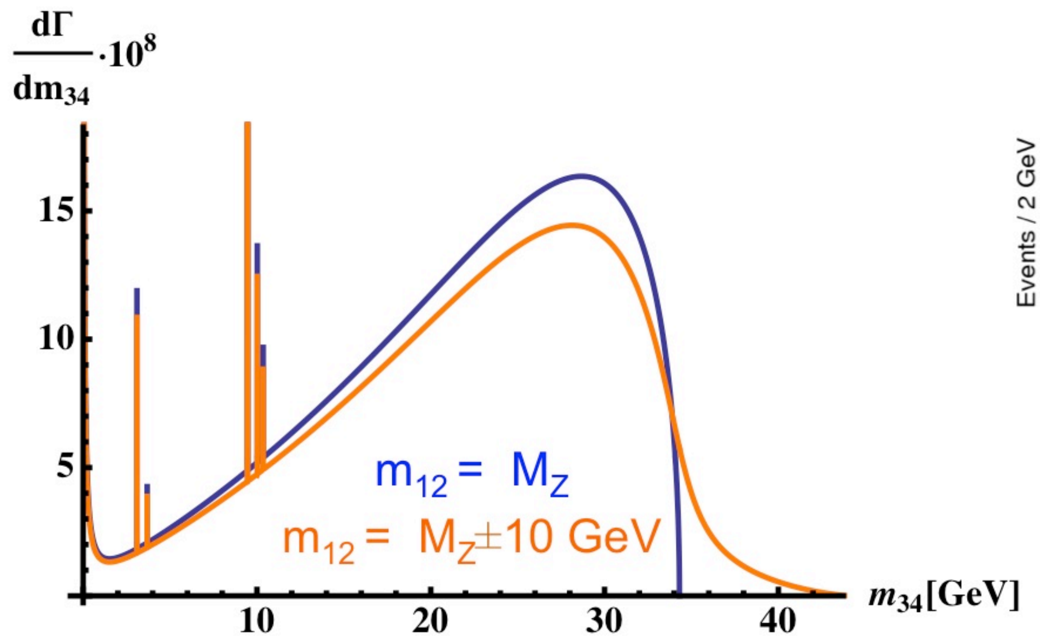
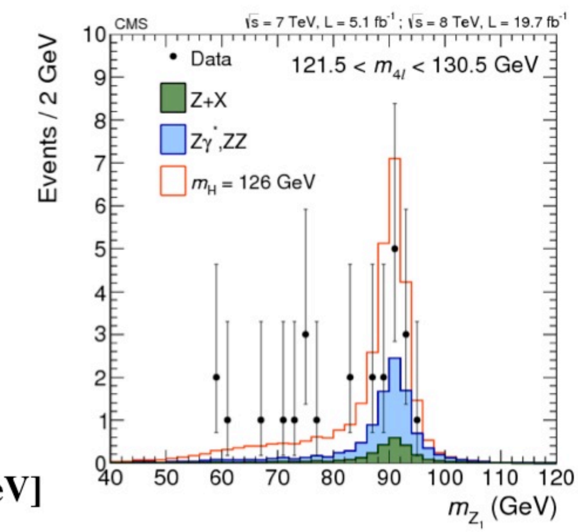
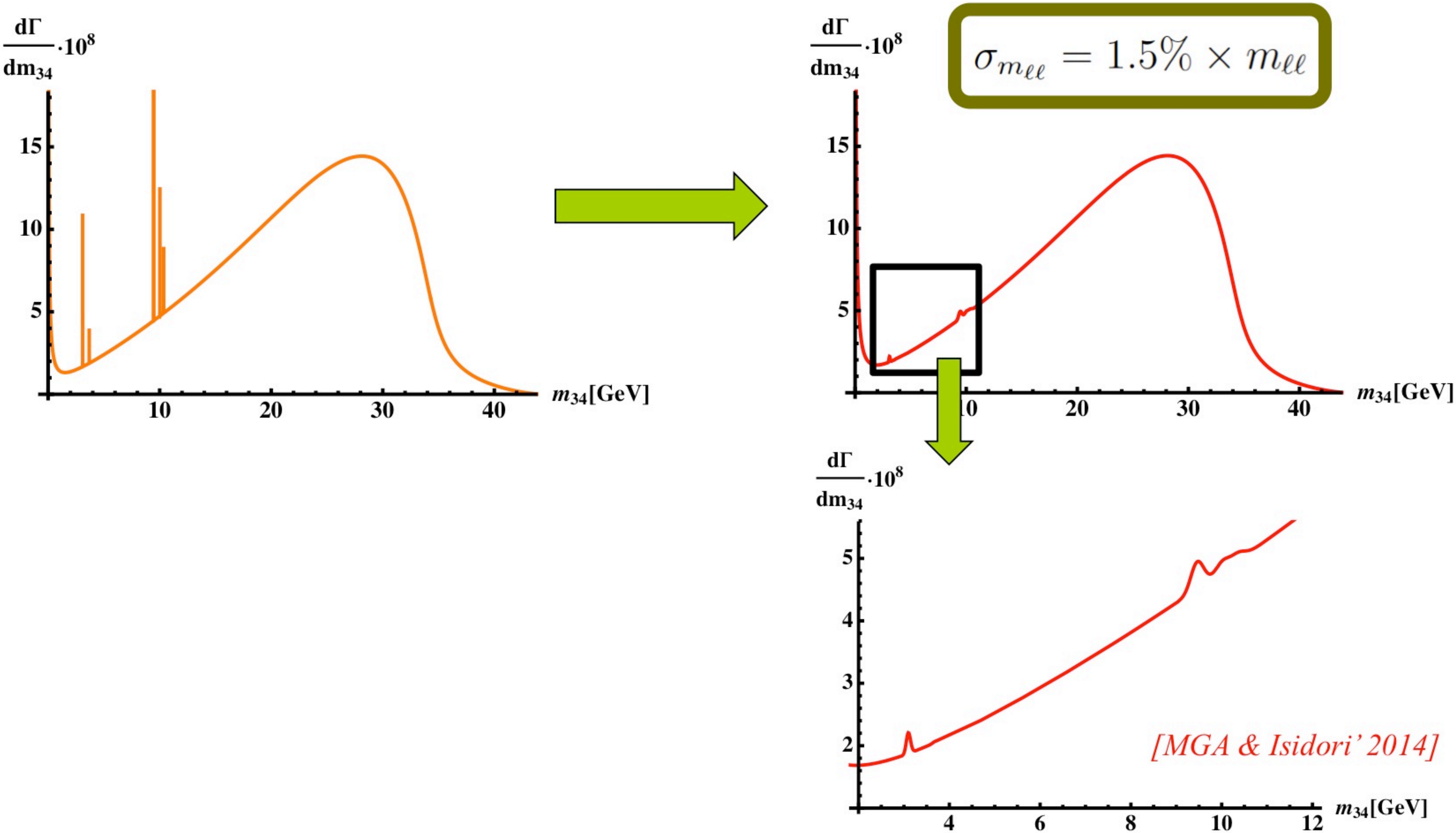
$$\hat{\rho} = m_Z^2/m_h^2$$

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





Smearing due to limited exp. resolution



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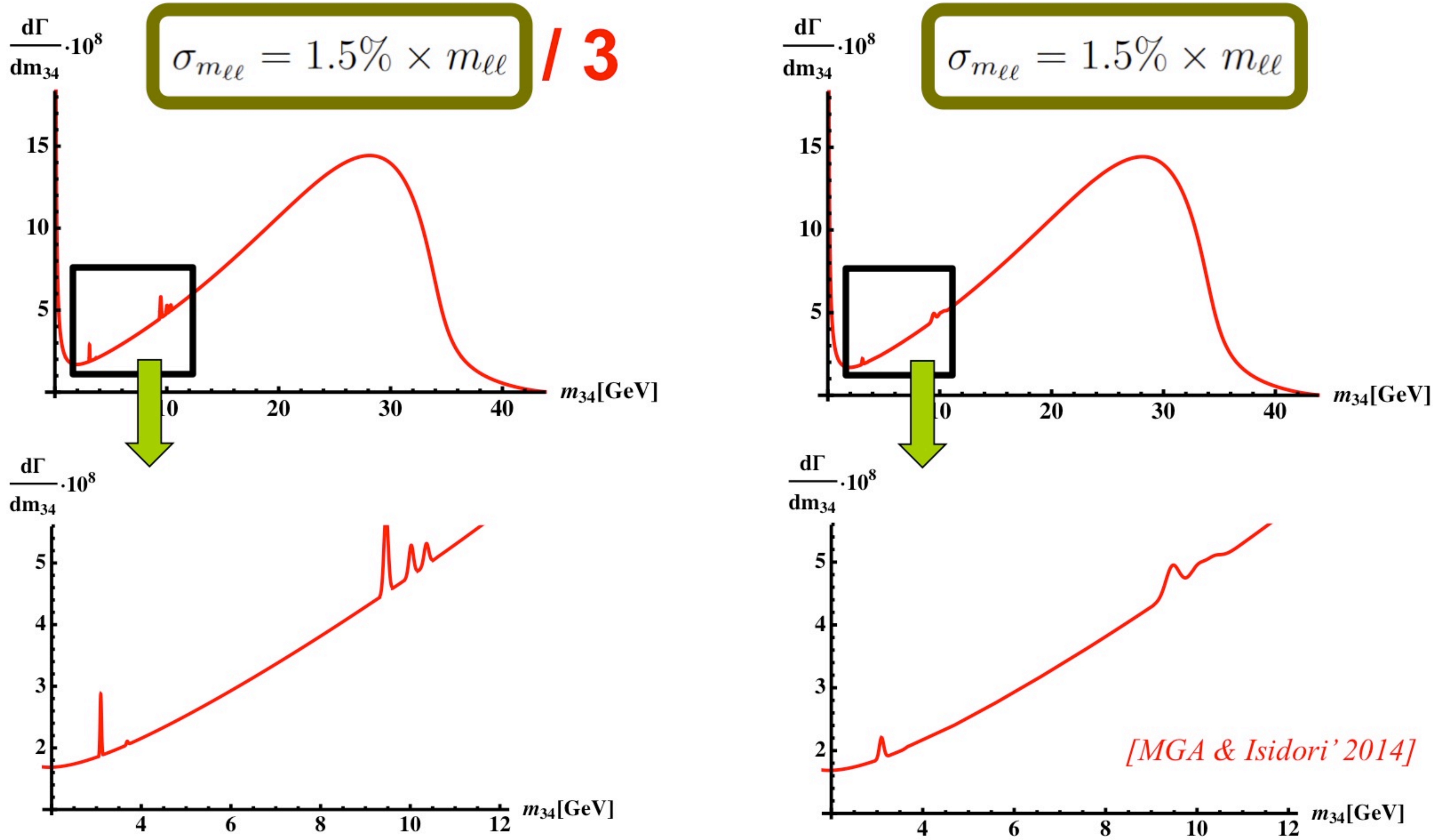
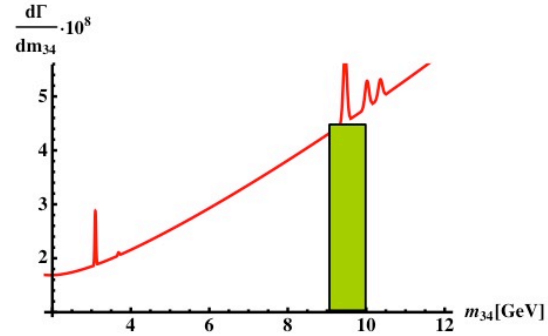


Effect on a single bin

- 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]	$\mathcal{B}(h \to ZV_i)$	$\Delta[d\Gamma(h \to Z\ell\ell)/dm_{34}]_{[1\ \mathrm{GeV\ bin}]}$
$J/\psi(1S)$	3.10	405	0.3×10^{-5}	5.0%
$J/\psi(2S)$	3.69	290	0.2×10^{-5}	0.4%
$\Upsilon(1S)$	9.46	680	1.7×10^{-5}	3.3% ⇨ ~30%
$\Upsilon(2S)$	10.02	485	0.9×10^{-5}	1.3% [100 MeV bin]
$\Upsilon(3S)$	10.36	420	0.7×10^{-5}	1.0%

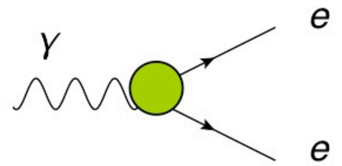
[MGA & Isidori' 2014, Gao'2014]

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?

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



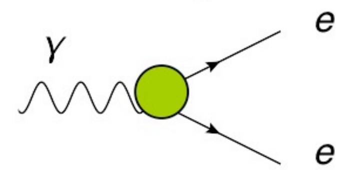
$$\mathcal{L}_{eff} \sim \frac{a_\mu}{m_\mu} \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

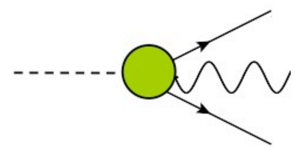
EFT approach

- 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…

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

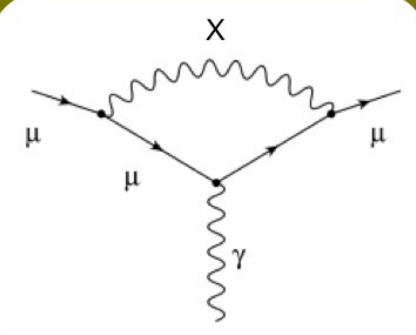
$$\Delta B(h\to\mu^+\mu^-\gamma)^{(g-2)}_{\rm EFT} = -\frac{e^2 m_h^3 \Delta a_\mu}{128\pi^3 v^2 \Gamma_h} + \frac{e^2 m_h^5 \left(\Delta a_\mu\right)^2}{12(8\pi)^3 m_\mu^2 v^2 \Gamma_h} \sim \mathcal{O}(10^{-10})$$

- Note: The relation can still happen (model-dependent).

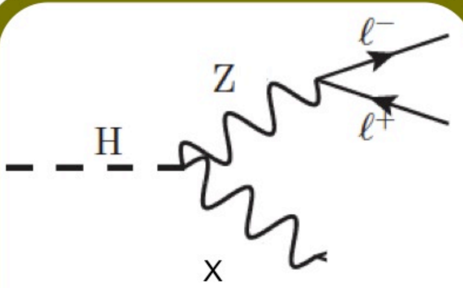
[MGA & Isidori' 2014]

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

- $(g\text{-}2)_\mu$ can still be fine (with weaker couplings);

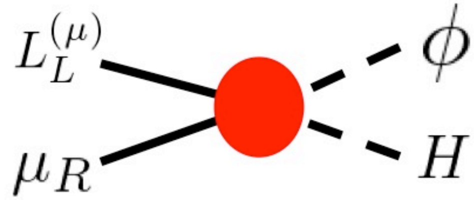


- Potential large effects in Higgs decay due to onshell production of the light states!

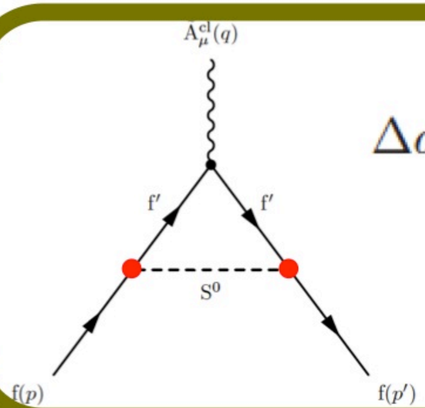


- Two examples:
  - SM + scalar
  - SM + vector

Light scalar

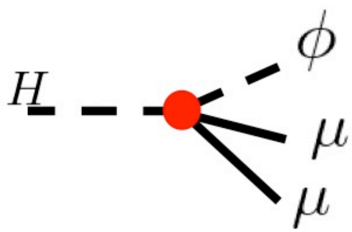


$$\mathcal{L}^{(1)} = \mathcal{L}_{\rm kin}^{(\phi)} + \left(\frac{c_{1\mu}}{\Lambda} \bar{L}_L^{(\mu)} \mu_R H \phi \ + \text{h.c.} \right) \ , \qquad \mathcal{L}_{\rm kin}^{(\phi)} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2$$



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

Correct sign!



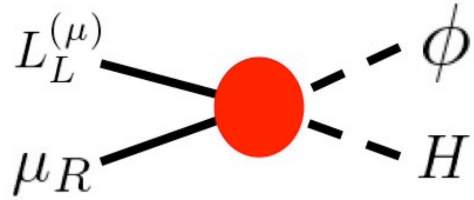
$$\Gamma_\phi > \Gamma(\phi \to \mu\mu) = \frac{|c_{1\mu}|^2 v^2 m_\phi}{16\pi\Lambda^2} \approx (5.9 \text{ MeV}) \times \left(\frac{\Delta a_\mu}{2.9 \times 10^{-9}} \right) \left(\frac{m_\phi}{10 \text{ GeV}} \right)^3$$

$$\Rightarrow \quad h \to \phi\mu\mu \to 4\mu$$

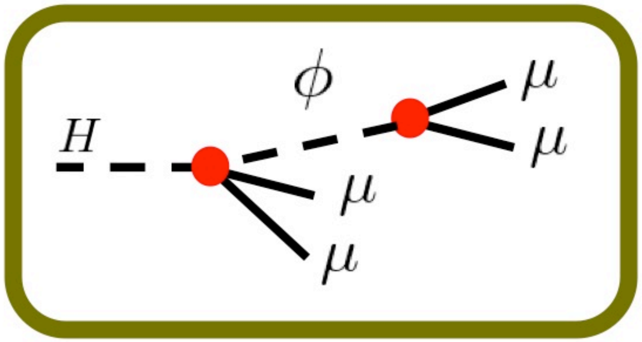
[Short-lived]

[MGA & Isidori' 2014]

Light scalar



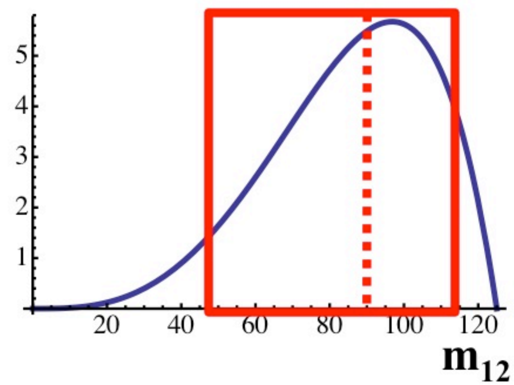
$$\mathcal{L}^{(1)} = \mathcal{L}^{(\phi)}_{\text{kin}} + \left(\frac{c_{1\mu}}{\Lambda} \bar{L}_L^{(\mu)} \mu_R H \phi \;+ \text{h.c.}\right)$$



Does the signal pass current m_{12} cut?

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

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

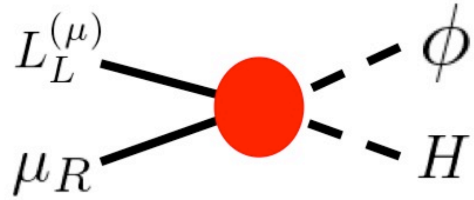


$$\frac{d\Gamma(h \to \mu\mu\phi)}{dm_{12}} = \frac{|c_{1\mu}|^2}{128\pi^3 m_h^3 \Lambda^2}\, m_{12}^3 (m_h^2 - m_{12}^2)$$

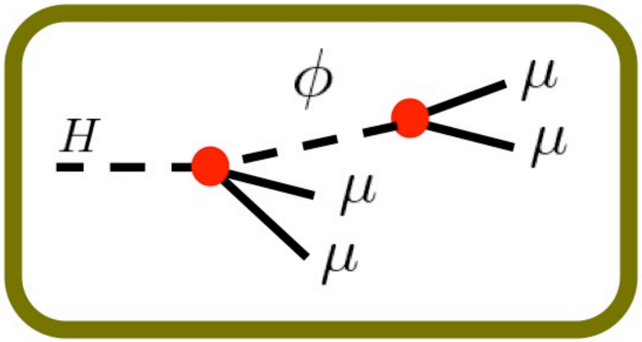
$80 < m_{12} < 100$ GeV ➔ $f = 0.35$

[MGA & Isidori' 2014]

Light scalar



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

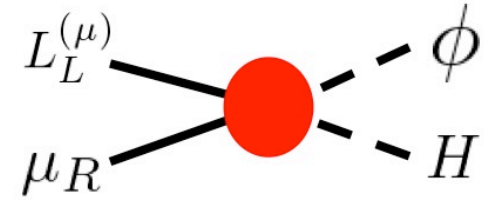


$$\frac{\mathcal{B}(h \to 4\mu)_{(\phi)}}{\mathcal{B}(h \to 4\mu)_{\text{SM}}} \lesssim 1$$

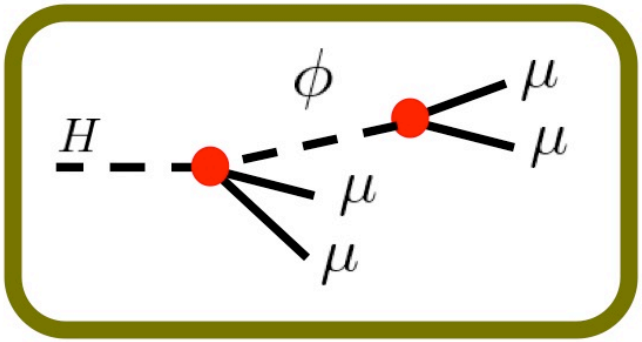
$$\left(\frac{\Delta a_\mu}{2.9 \times 10^{-9}} \right) \left(\frac{m_\phi}{10\ \text{GeV}} \right)^2 f\ \mathcal{B}(\phi \to \mu^+ \mu^-) \lesssim 0.007$$

[MGA & Isidori' 2014]

Light scalar



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



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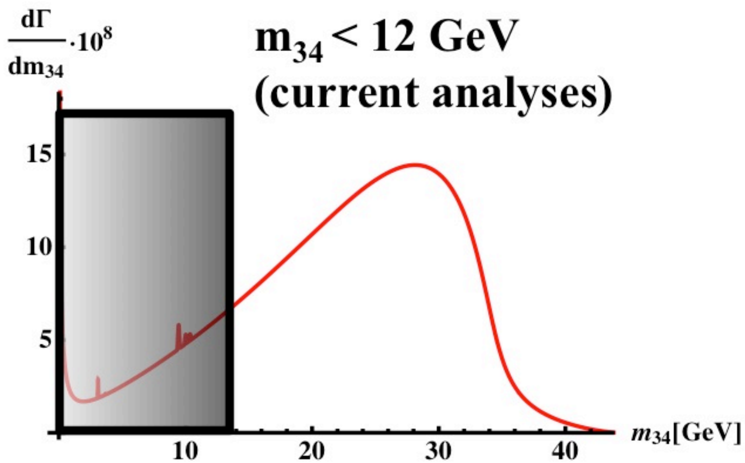


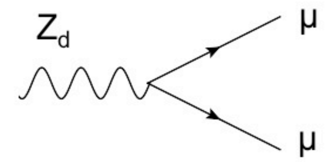
A peak 1500x ϒ(1s)!!

= 50x SM [1 GeV bin]!!

[MGA & Isidori' 2014]

Light vector

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

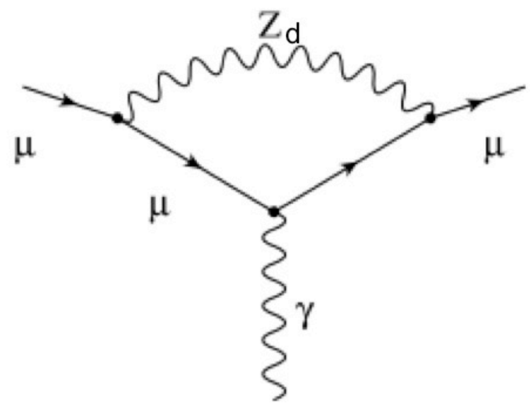


after EWSB (& diagonalization)

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

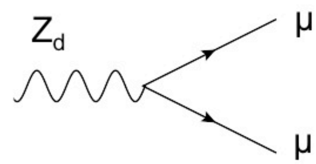
$$\approx 2.3\times 10^{-9}\left(\frac{10\ \mathrm{GeV}}{m_{Z_d}}\right)^2 \frac{c_V^2 - 5c_A^2}{0.1^2}$$

Sign!



HEFT 2014

Light vector



- Model realizations:

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

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

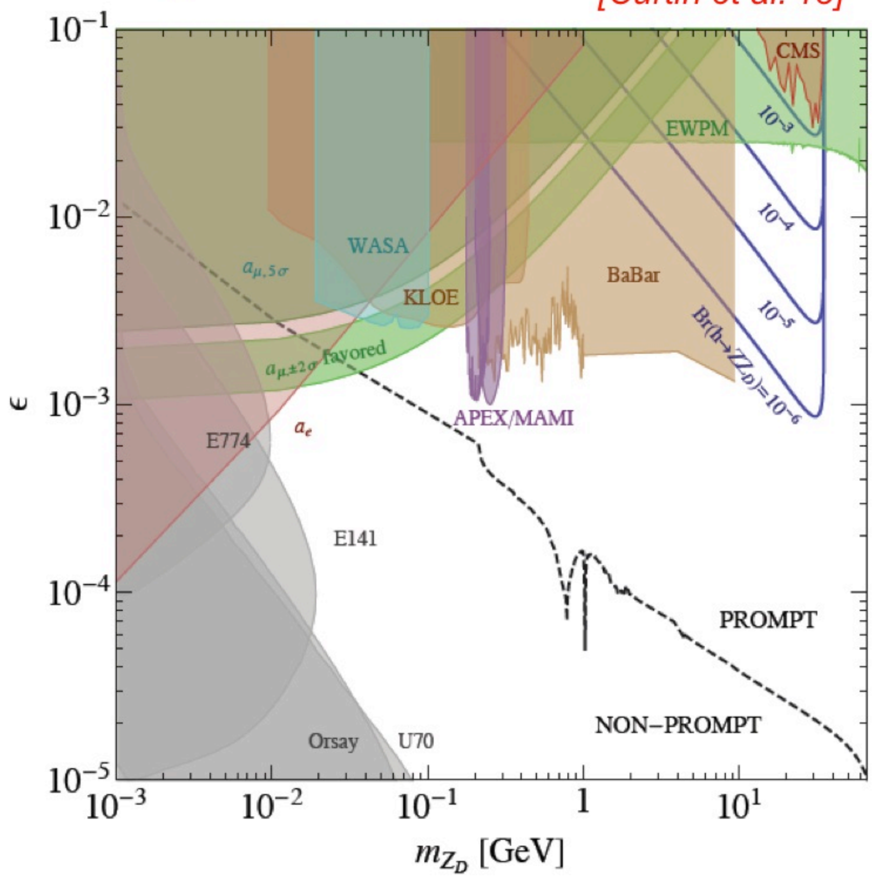
$$c_R = -e\,\epsilon + \frac{g}{c_W}s_W^2\epsilon_Z + g_d Q^d_{\mu_R}\,,$$

⇨ Right sign! $\Delta a_\mu > 0$

[Fayet'07, Pospelov'09]

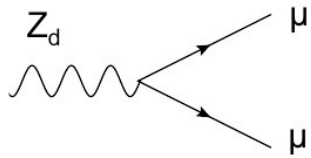
… but only allowed for very light Z_d.

[Curtin et al.'13]



HEFT 2014

Light vector



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[Davoudiasl et al'2012-2013]

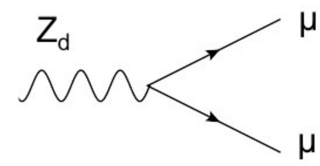
$$\begin{aligned} c_L &= -e\,\epsilon - \frac{g}{2c_W}(1-2s_W^2)\epsilon_Z + g_d Q^d_{\mu_L}\,, \\ c_R &= -e\,\epsilon + \frac{g}{c_W}s_W^2\epsilon_Z + g_d Q^d_{\mu_R}\,, \end{aligned}$$

➡ Right sign! $\Delta a_\mu > 0$ [Fayet'07, Pospelov'09)] … only allowed for very light Z_d.

➡ Wrong sign! $\Delta a_\mu < 0$

➡ $U(1)_d$ charges could do the job.

Light vector



- Model realizations:

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

[Davoudiasl et al'2012-2013]

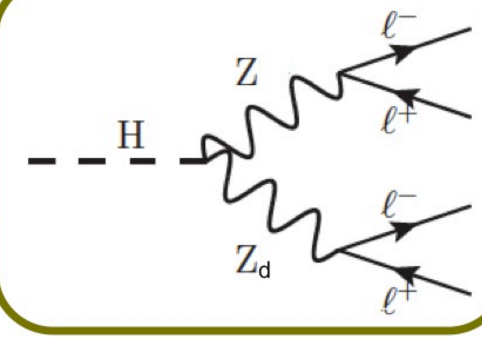
$$\begin{aligned} c_L &= -e\,\epsilon - \frac{g}{2c_W}(1-2s_W^2)\epsilon_Z + g_d Q^d_{\mu_L}\ , \\ c_R &= -e\,\epsilon + \frac{g}{c_W}s_W^2\epsilon_Z + g_d Q^d_{\mu_R}\ , \end{aligned}$$

➡ Right sign! $\Delta a_\mu > 0$ [Fayet'07, Pospelov'09)] … only allowed for very light Z_d.

➡ Wrong sign! $\Delta a_\mu < 0$

➡ $U(1)_d$ charges could do the job.

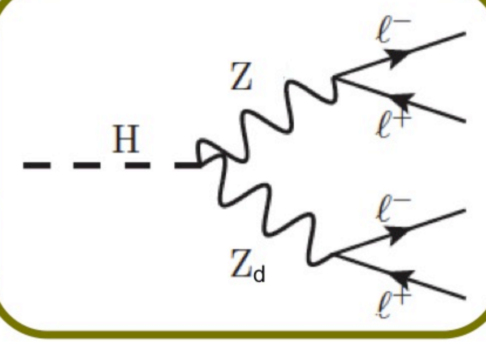
Light vector



- Effect of Z_d in Higgs decay? $\Delta\mathcal{L}^{(2)}_{\rm int} = c_H\, v\, h Z_d^\mu Z_\mu$
- Model-dep. connection with (g-2): $c_H \approx 2\epsilon_Z \frac{m_Z^2}{v^2} + 2\epsilon \frac{m_{Z_d}^2}{v^2} \tan\theta_W$
- BR(h ➔ 4l) data* give strong bounds on c_H $\left(\frac{c_H}{10^{-4}} \frac{10\ \text{GeV}}{m_{Z_d}}\right)^2 \frac{1}{5} B(Z_d \to \mu^+\mu^-) \leq 1$

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

Light vector



- Effect of Z_d in Higgs decay? $\Delta\mathcal{L}_{\rm int}^{(2)} = c_H\, v\, h Z_d^\mu Z_\mu$
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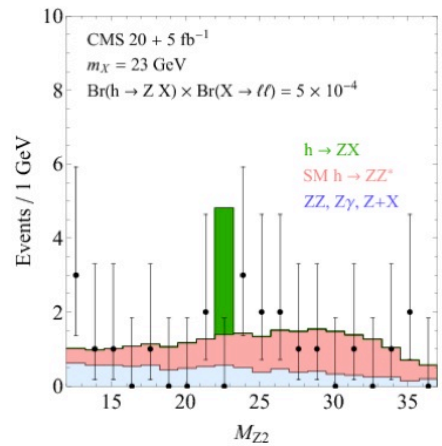
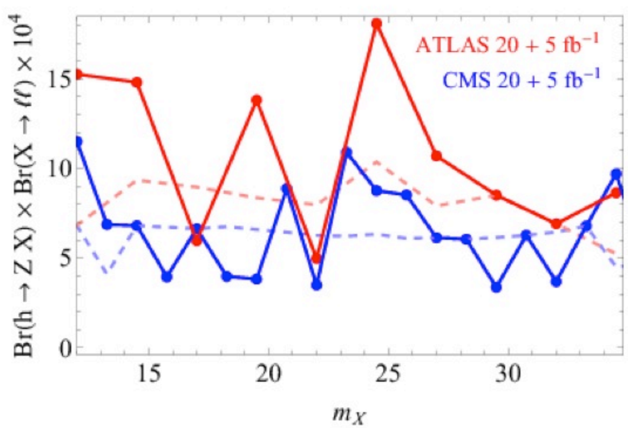
- BR(h ➔ 4l) data* give strong bounds on c_H

$$\left(\frac{c_H}{10^{-4}} \frac{10 \text{ GeV}}{m_{Z_d}}\right)^2 \frac{1}{5} B(Z_d \to \mu^+\mu^-) \leq 1$$

- Peak searching in $d\Gamma/dm_{34}$:
- Full diff. distribution recently studied.

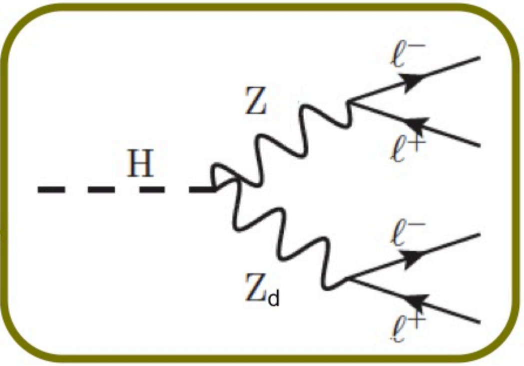
[Falkowski & Vega-Morales'14]



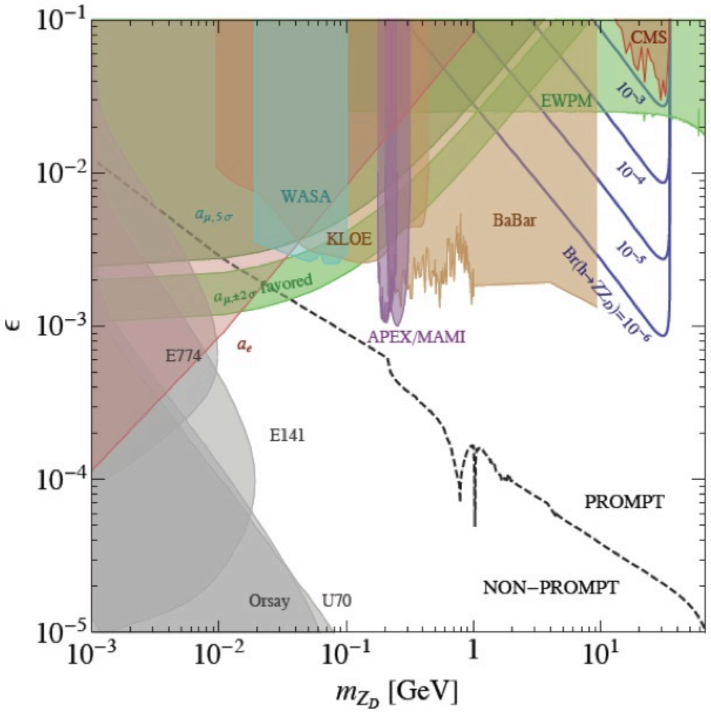


[Curtin et al.'13]

Light vector



- Competitive bounds:



Dark photon

[Curtin et al.'13]

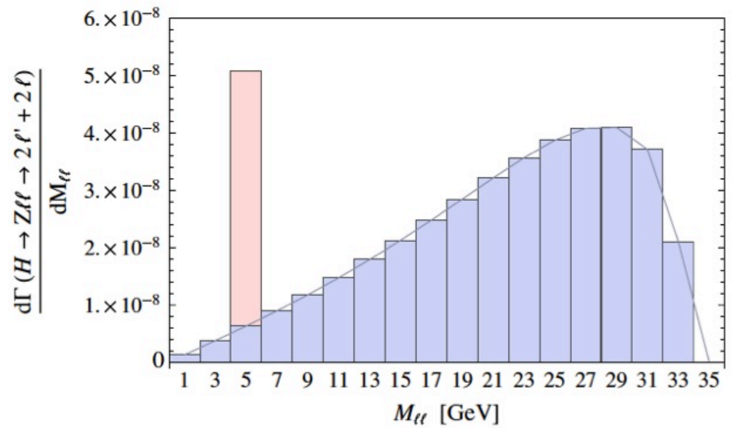


FIG. 3 (color online). Differential decay rate $H \to ZZ^* \to Z\ell^+\ell^- \to 4\ell$ vs $\ell^+\ell^-$ invariant mass with $m_H = 125$ GeV in the SM. For the illustration, $H \to ZZ_d \to Z\ell^+\ell^-$ with $m_{Z_d} =$ 5 GeV and $\delta^2 \mathrm{BR}(Z_d \to \ell^+\ell^-) = 10^{-5}$ (which would need $N_{\mathrm{Higgs}} \simeq 10^6$ for 3σ evidence) is also shown (spike at the 5 GeV bin). Bin size is selected to be 2 GeV.

Dark Z

[Davoudiasl et al'2012]

M. Strassler's talk (Tuesday)

Conclusions

- $\frac{d\Gamma(h \to 4\ell)}{dm_{34}}$ at low m_{34} as a probe of exotic Higgs decays.

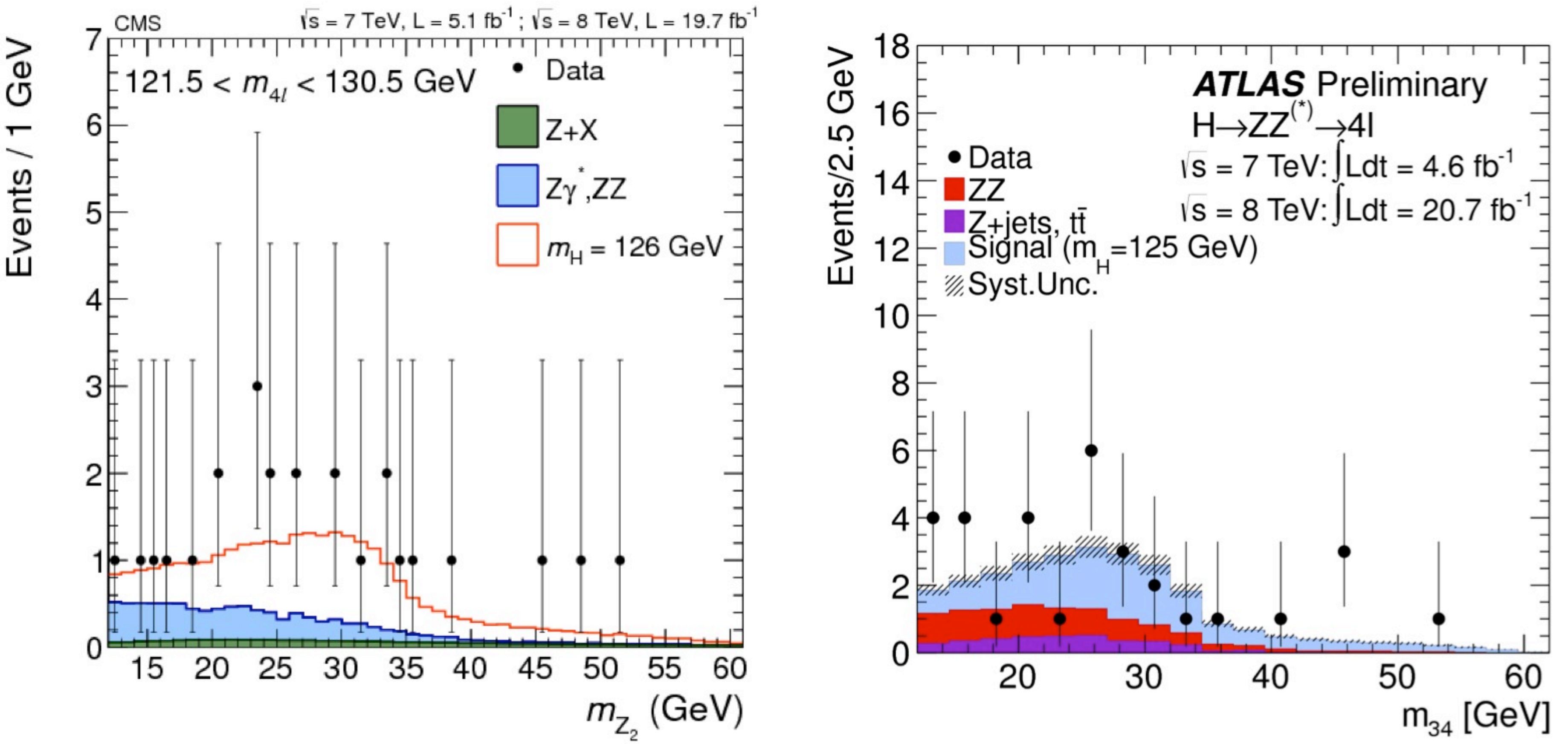
- Spectrum known with good theoretical accuracy.
  Υ(1s) peak: ~3% (30%) effect in a 1 GeV bin (0.1 GeV).

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

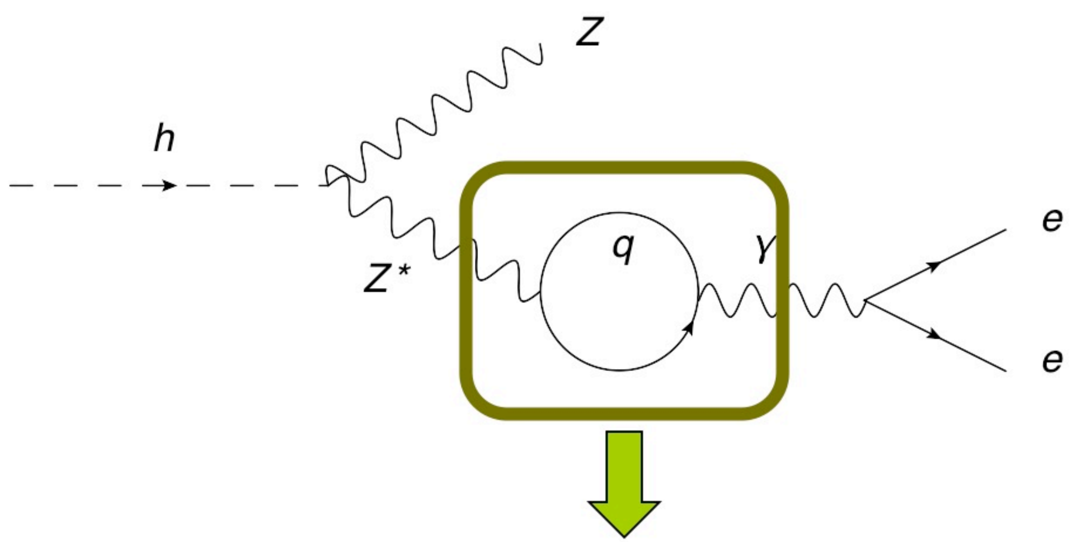
- Motivate dedicated searches for such light states (discovery potential).
  [m_{34} > 12 GeV cut] *[Davoudiasl et al'2012-2013, Curtin et al'2013, …]*
  [MGA & Isidori' 2014]

Backup slides

Introduction $h \to 4\ell$



SM prediction: QCD corrections



Long distance contributions are important

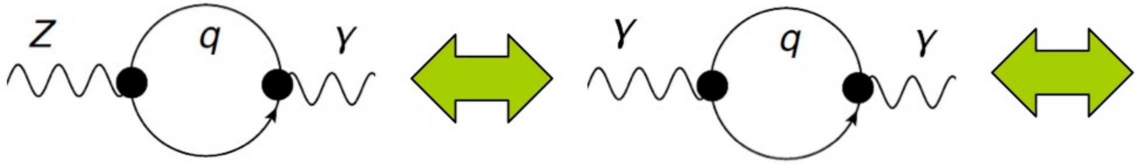
(hadronization)

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

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

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

SM prediction: QCD corrections



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

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

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:

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

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