

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

After the Discovery:
Hunting for a Non-Standard Higgs Sector

Benasque
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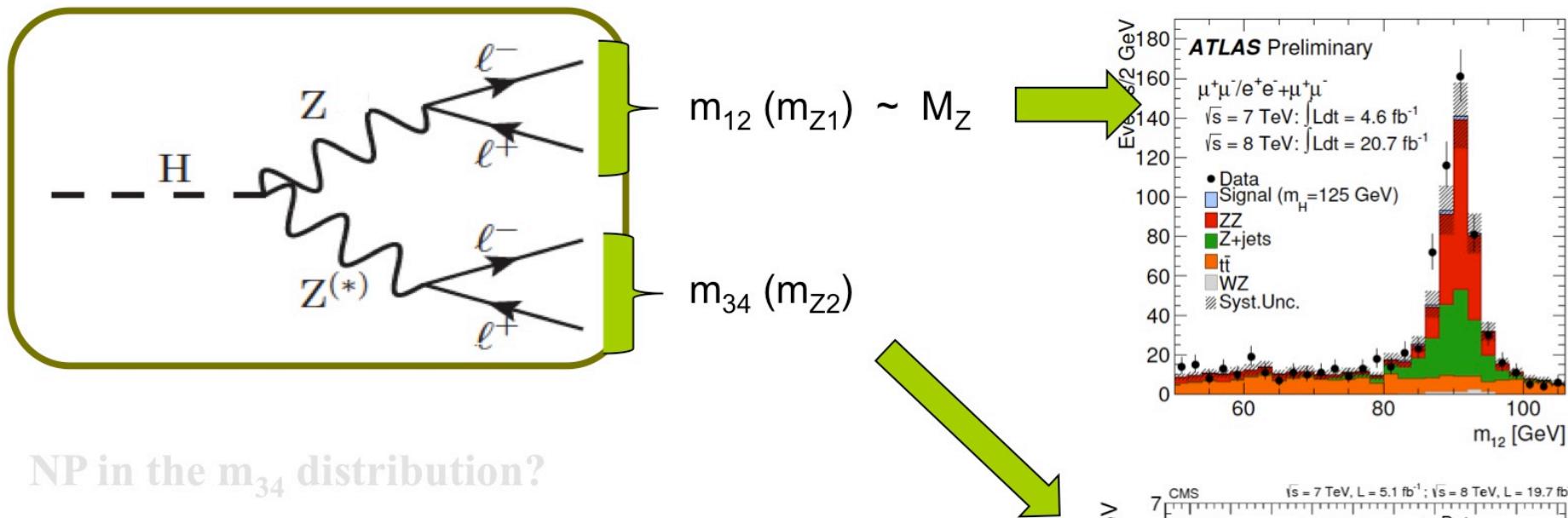


Introduction $h!!!$



- July 2012: ATLAS & CMS observed a ~ 125 GeV new particle with the properties of the Higgs boson.
- How much SM-like?
- Higgs decays:
 - Tiny higgs width!
 - ➔ 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.
 - $BR(h \rightarrow BSM)$ could be as large as $O(20\text{-}50\%)$. *[Belanger et al'2013, Giardino et al'2013, Ellis & You'2013, Cheung et al'2013, ...]*

Introduction $h \rightarrow 4\ell$



NP in the m_{34} distribution?

Heavy particles (EFT)

[Isidori et al.'2013, Grinstein et al.'2013, Pomarol-Riva'2013]

Light particles

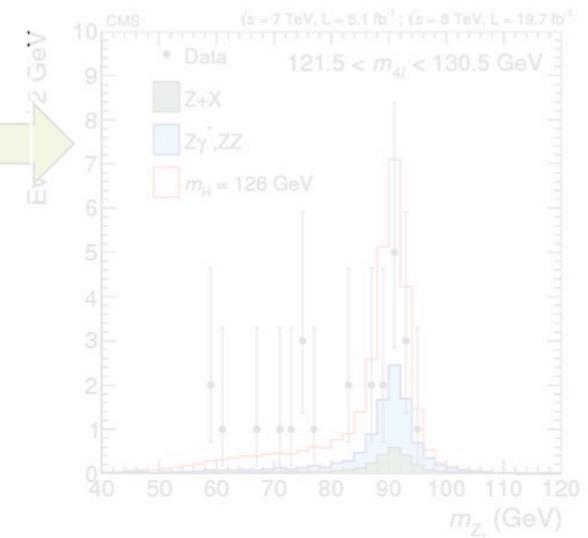
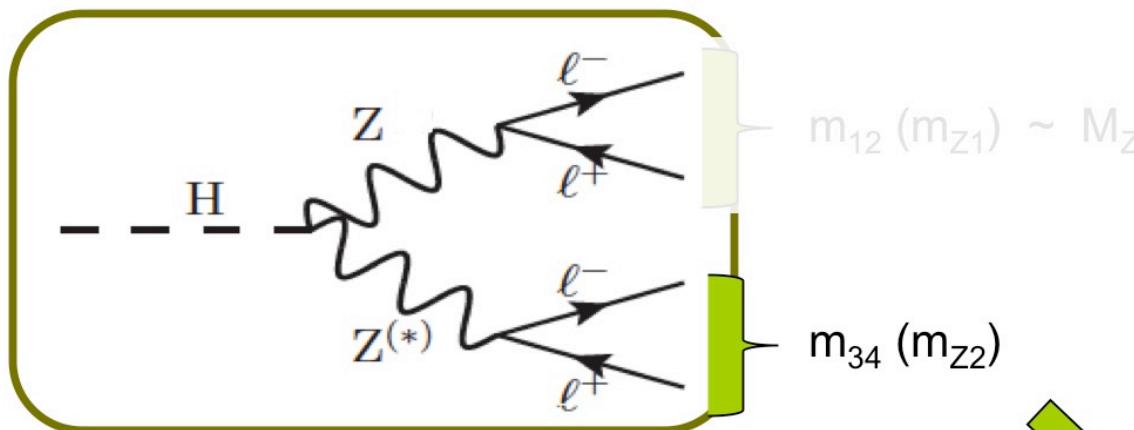
[Davoudiasl et al.'2012-2013, Curtin et al.'2013, ...]

Questions:

QCD bkg? Quarkonia!

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

Introduction $h \rightarrow 4\ell$



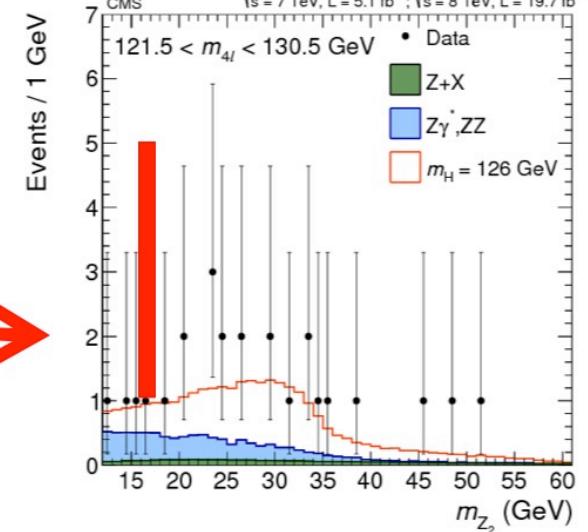
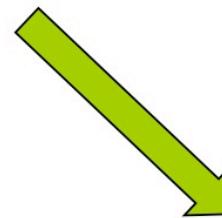
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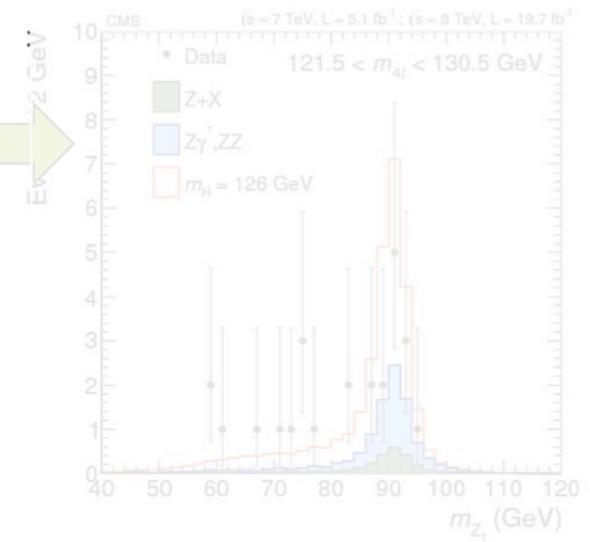
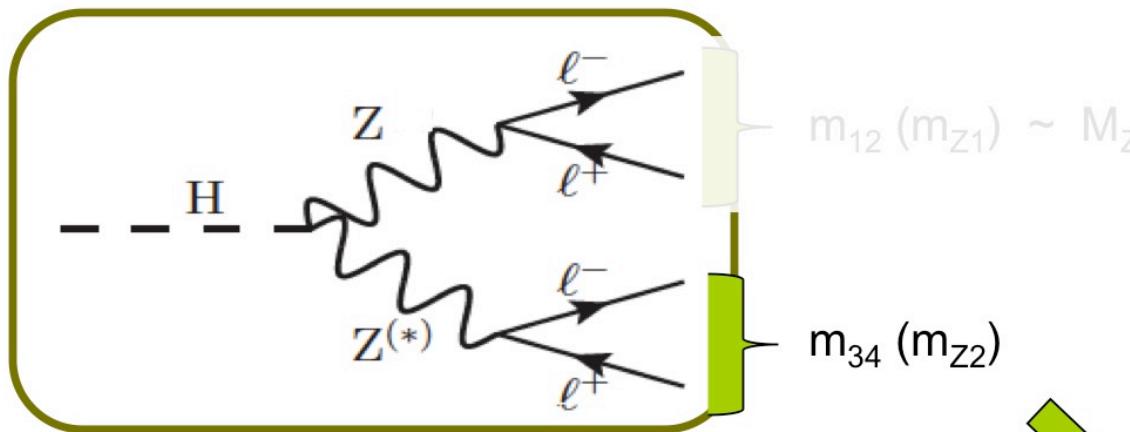


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Introduction $h \rightarrow 4\ell$



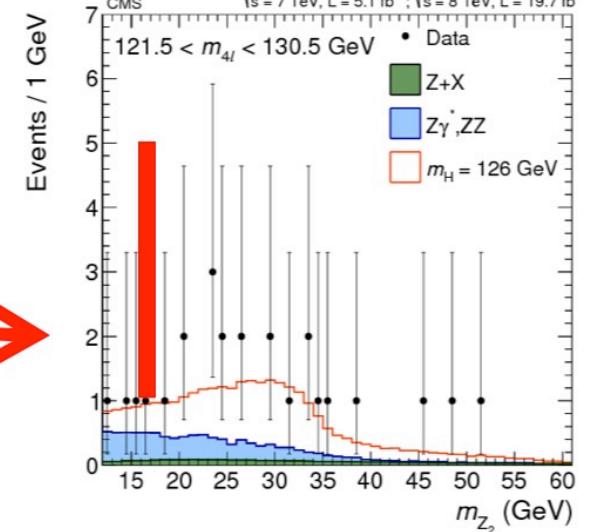
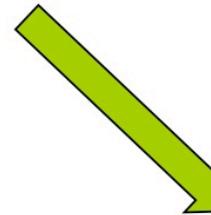
NP in the m_{34} distribution?

Heavy particles (EFT)

[Isidori et al.'2013, Grinstein et al.'2013, Pomarol-Riva'2013]

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Questions:

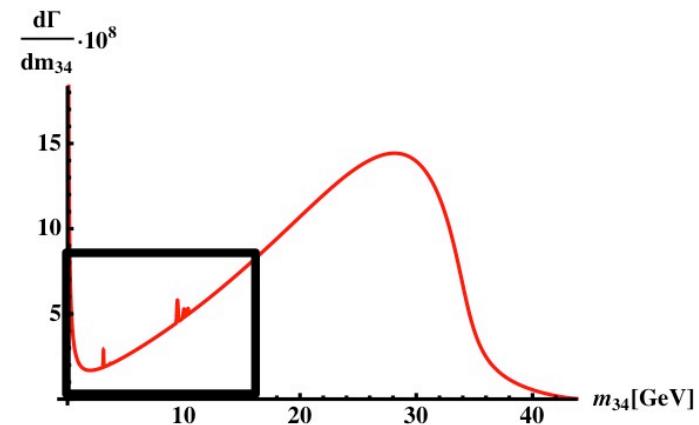
QCD bkg? Quarkonia!

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

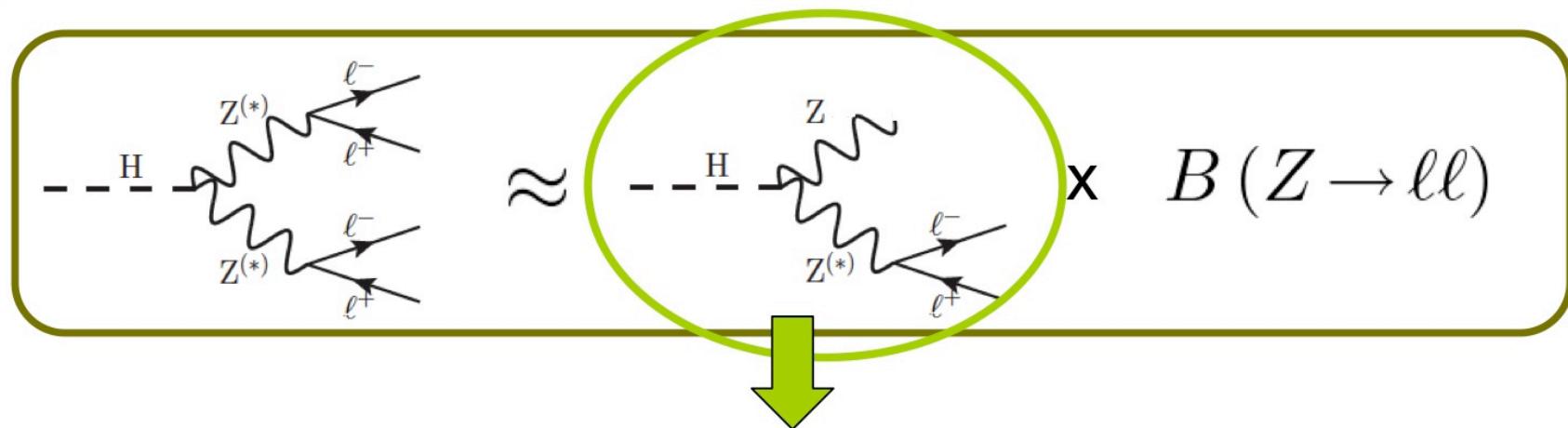
SM corrections:

Are locally important corrections under control?

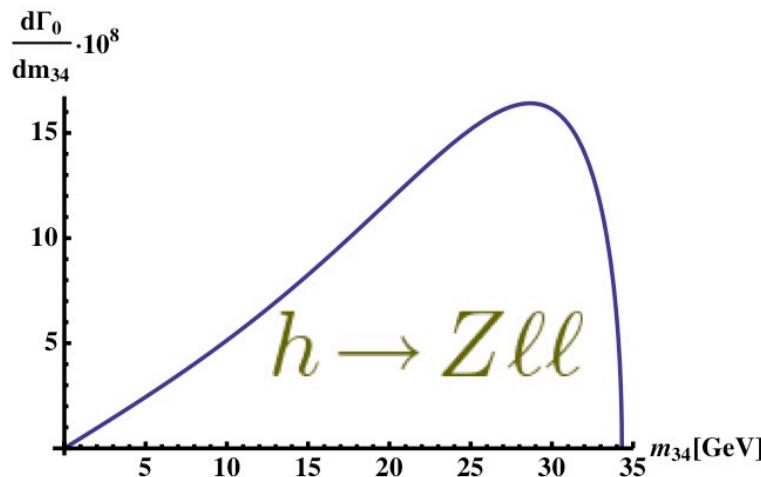
$$\frac{d\Gamma_0^{\text{SM}}(h \rightarrow Z\ell^+\ell^-)}{dm_{34}^2}$$
 ?



SM prediction: tree-level



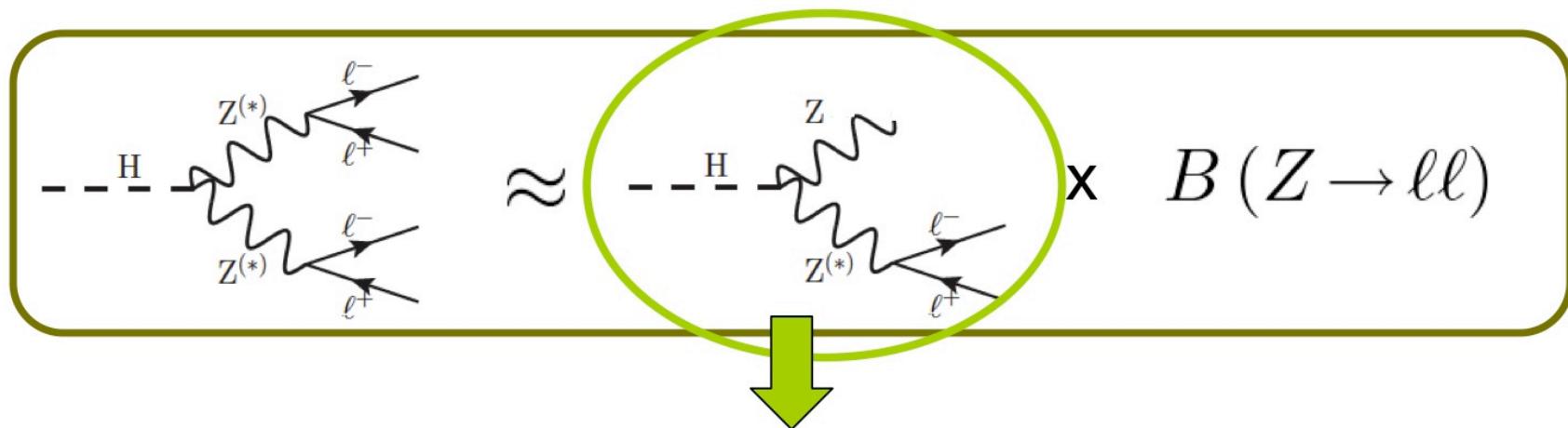
$$\frac{d\Gamma_0^{\text{SM}}(h \rightarrow Z\ell^+\ell^-)}{dm_{34}^2} = \frac{m_Z^6}{8\pi^3 v^4 m_h} [(g_R^\ell)^2 + (g_L^\ell)^2] \frac{\lambda(\hat{q}^2, \hat{\rho})}{(m_{34}^2 - m_Z^2)^2} \left[m_{34}^2 + \frac{m_h^4}{12m_Z^2} \lambda^2(\hat{q}^2, \hat{\rho}) \right],$$



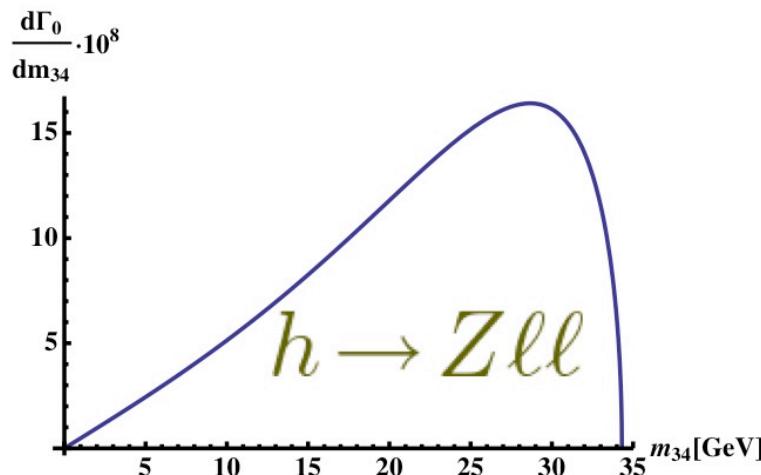
Locally imp. corrections?

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

SM prediction: tree-level



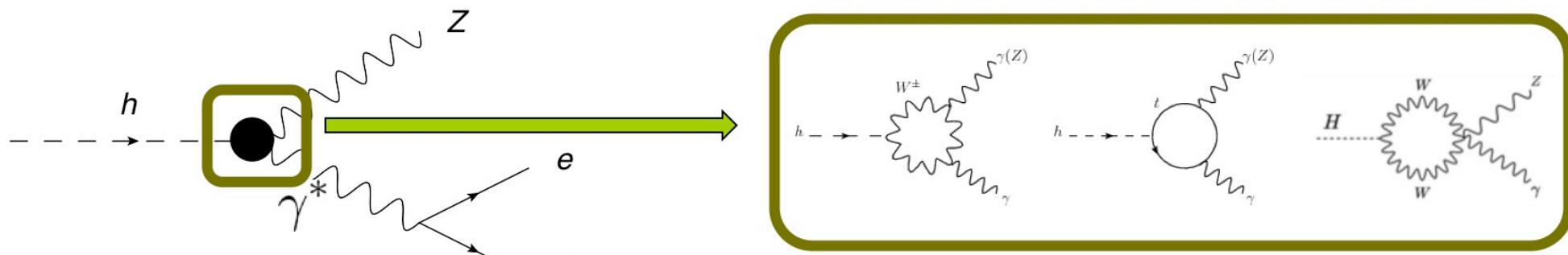
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Locally imp. corrections?

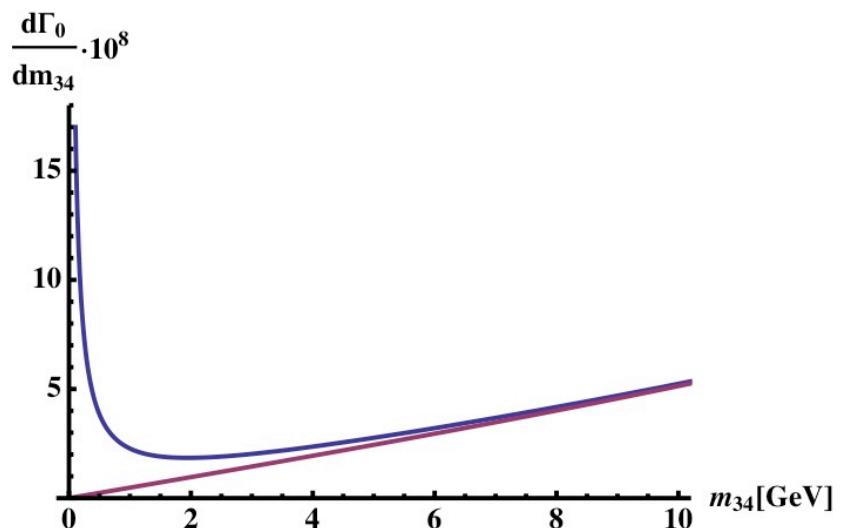
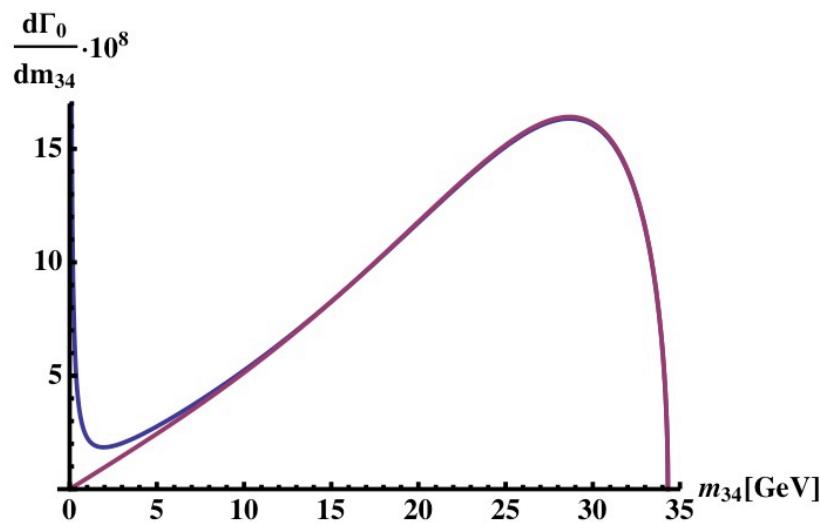
- **Photon pole:**
 $h \rightarrow Z\gamma^* \rightarrow Z\ell\ell$
- **QCD resonances:**
 $h \rightarrow ZV \rightarrow Z\ell\ell$

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

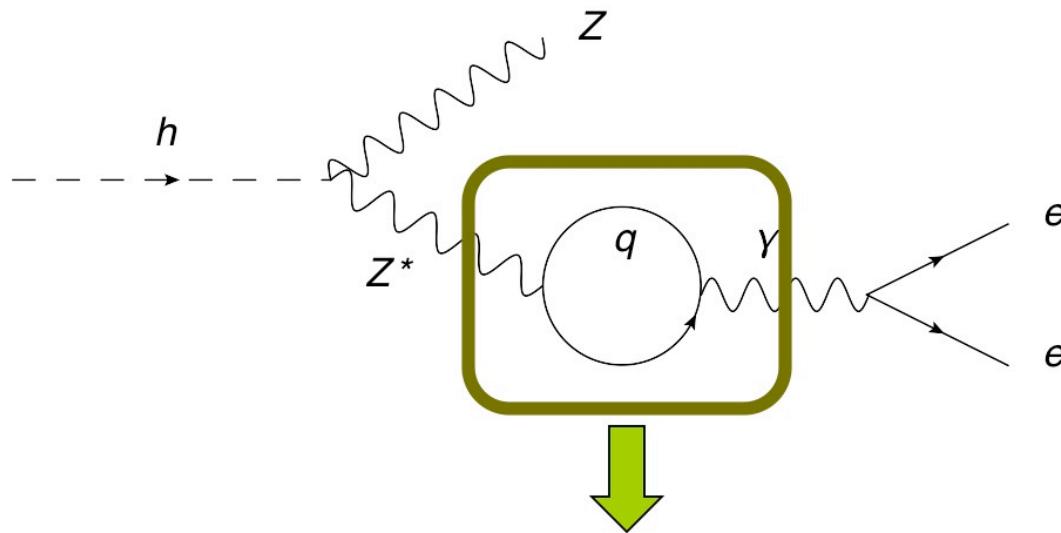


[Cahn et al. (1979),
Bergstrom & Hulth (1985)]

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



SM prediction: QCD corrections



Long distance
contributions are
important
(hadronization)

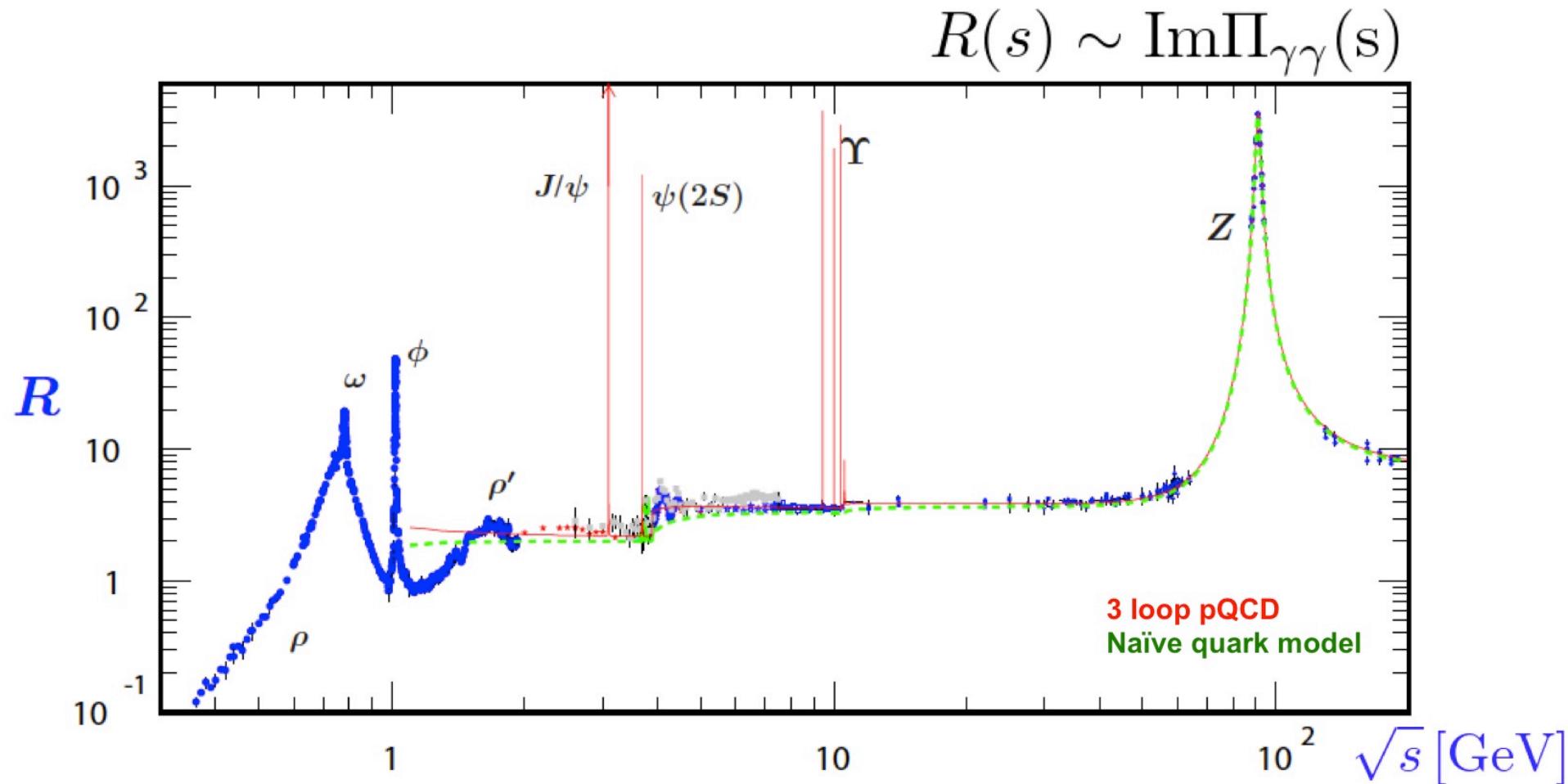
$$\Pi_{\mu\nu}^{Z\gamma}(q) \equiv i \int d^4x e^{iqx} \langle 0 | T J_\mu^Z(x) J_\nu^\gamma(0) | 0 \rangle = - (g^{\mu\nu} q^2 - q^\mu q^\nu) \Pi_{Z\gamma}(q^2)$$

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

Higgs as a
QCD lab?

SM prediction: QCD corrections

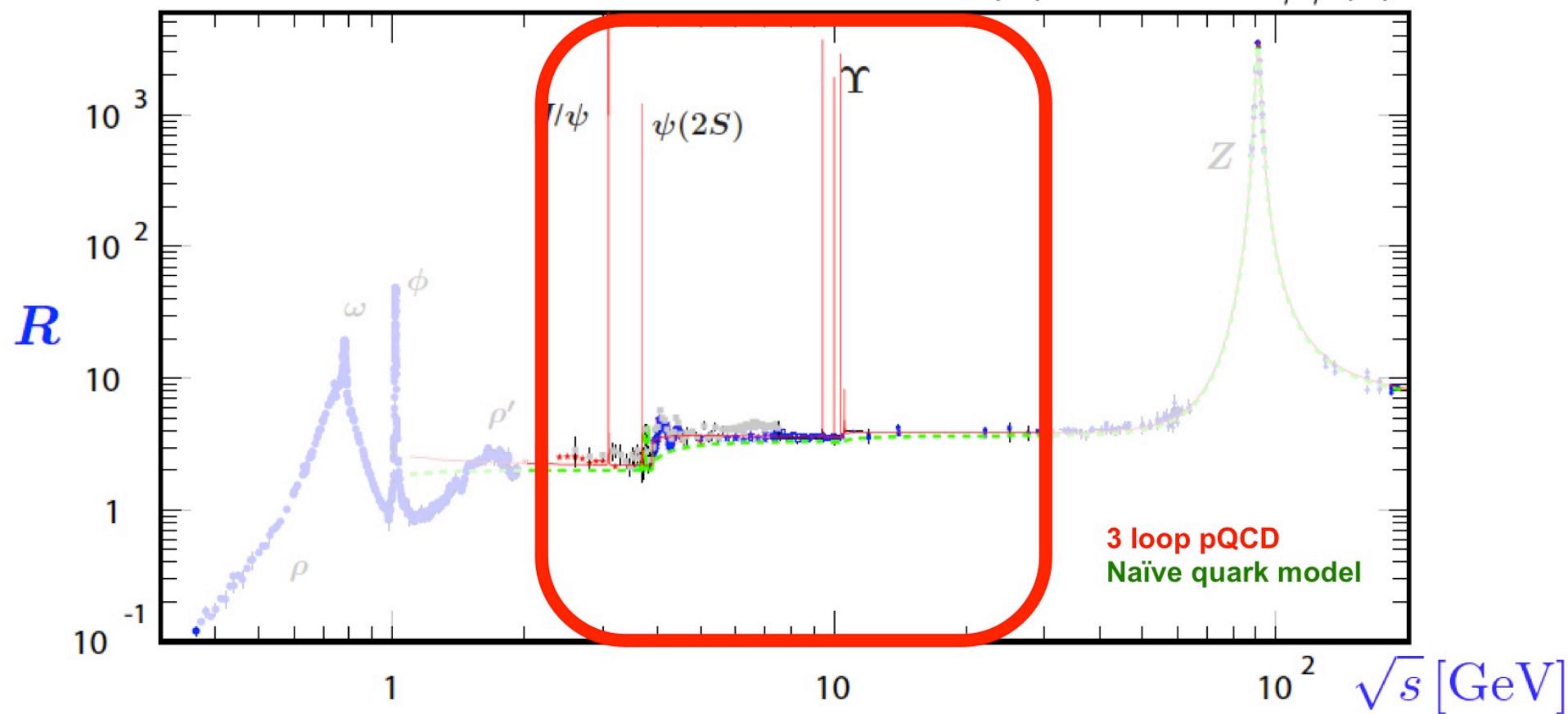
$$\text{Feynman diagram: } Z \rightarrow q\bar{q} \rightarrow \gamma\gamma \quad \leftrightarrow \quad \text{Feynman diagram: } \gamma \rightarrow q\bar{q} \rightarrow \gamma\gamma$$
$$R(s) \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma_0(e^+e^- \rightarrow \mu^+\mu^-)}$$



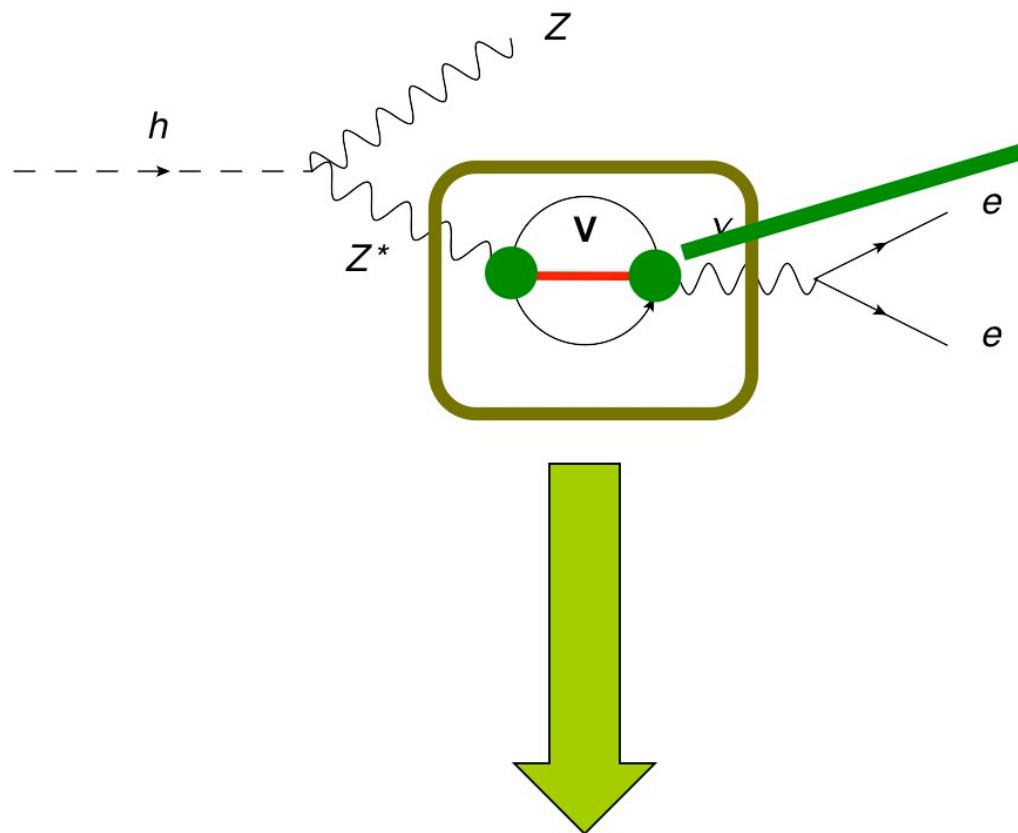
SM prediction: QCD corrections

$$\text{Diagram: } Z \rightarrow q\bar{q} \rightarrow \gamma\gamma \quad \leftrightarrow \quad \gamma \rightarrow q\bar{q} \rightarrow \gamma\gamma$$
$$R(s) \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma_0(e^+e^- \rightarrow \mu^+\mu^-)}$$

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



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



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

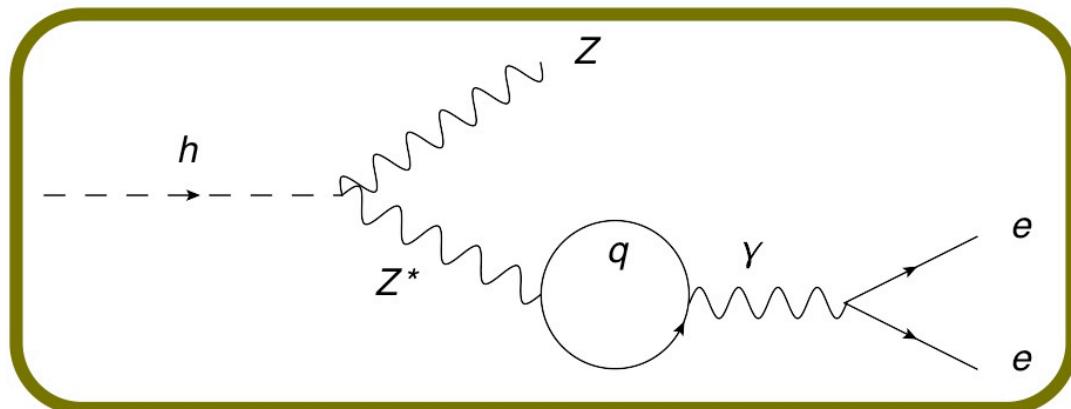
State	$m_{V_i} [\text{GeV}]$	$f_{V_i} [\text{MeV}]$
$J/\psi(1S)$	3.10	405
$J/\psi(2S)$	3.69	290
$\Upsilon(1S)$	9.46	680
$\Upsilon(2S)$	10.02	485
$\Upsilon(3S)$	10.36	420

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

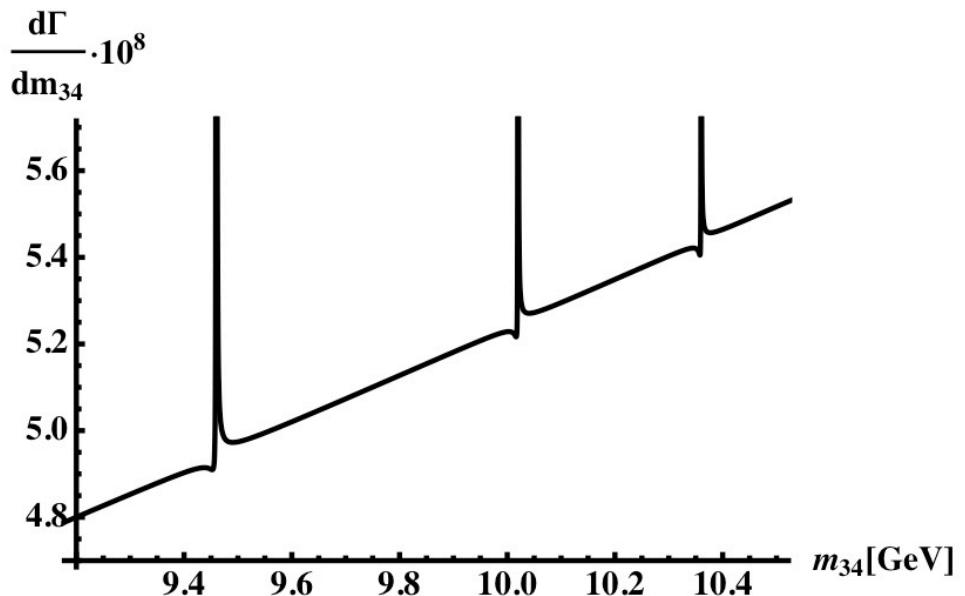
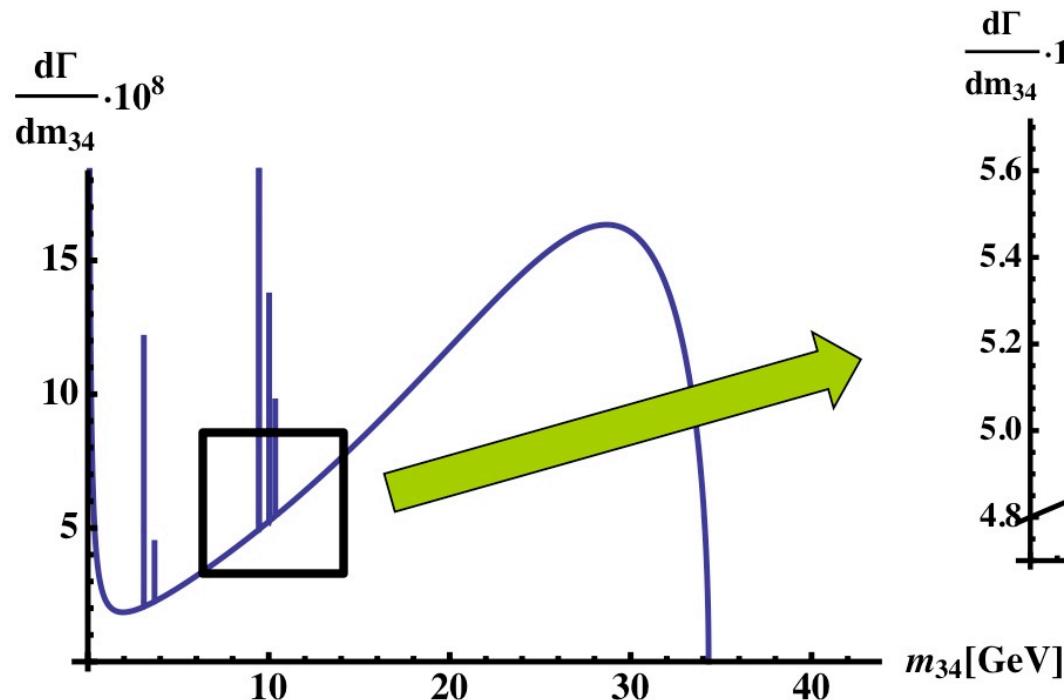
$$\mathcal{B}(V_i \rightarrow \ell^+ \ell^-) = \frac{4\pi Q_q^2}{3} \frac{\alpha^2 f_{V_i}^2}{m_{V_i} \Gamma_{V_i}}$$

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

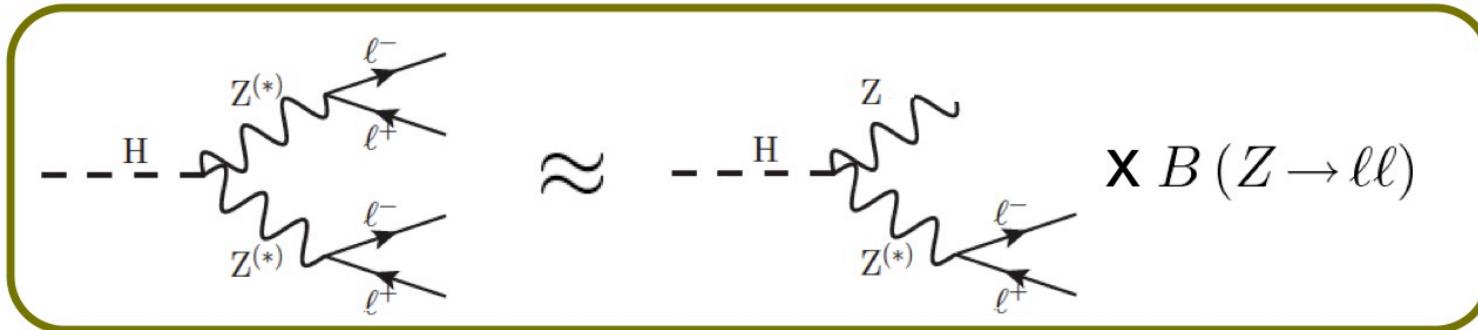
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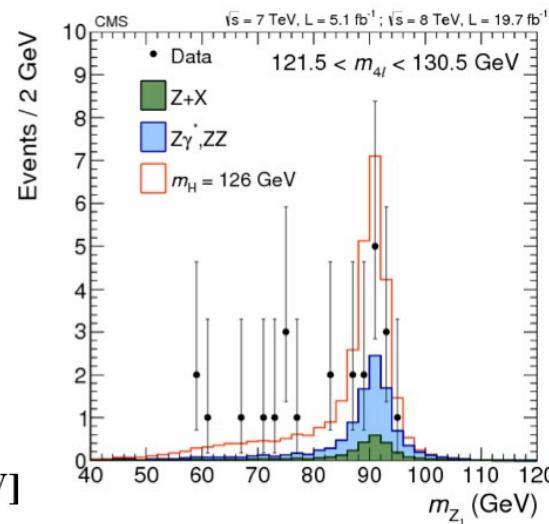
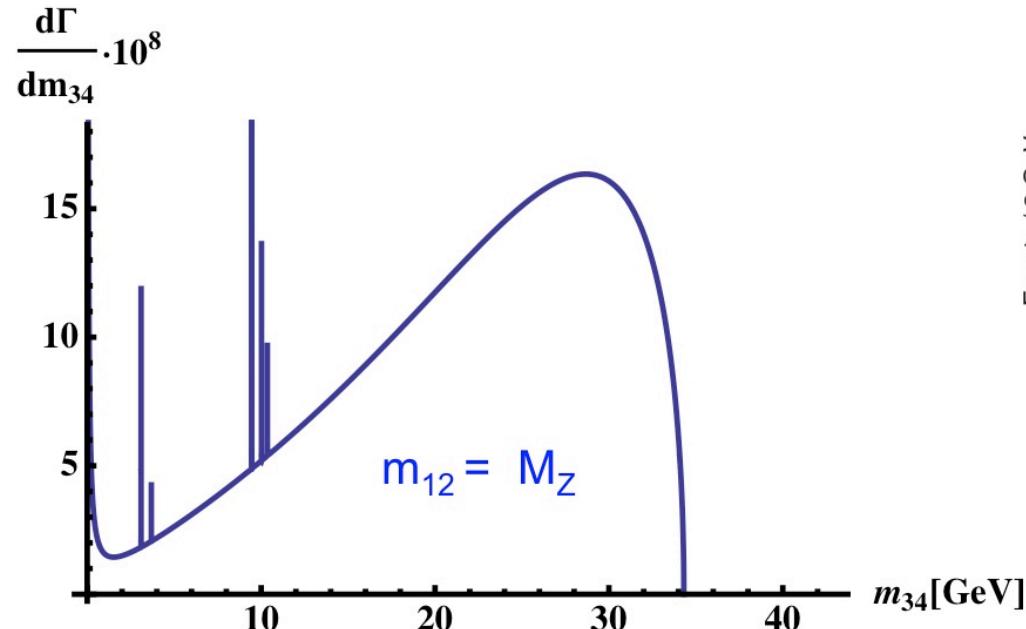


What does it mean that one Z is onshell?

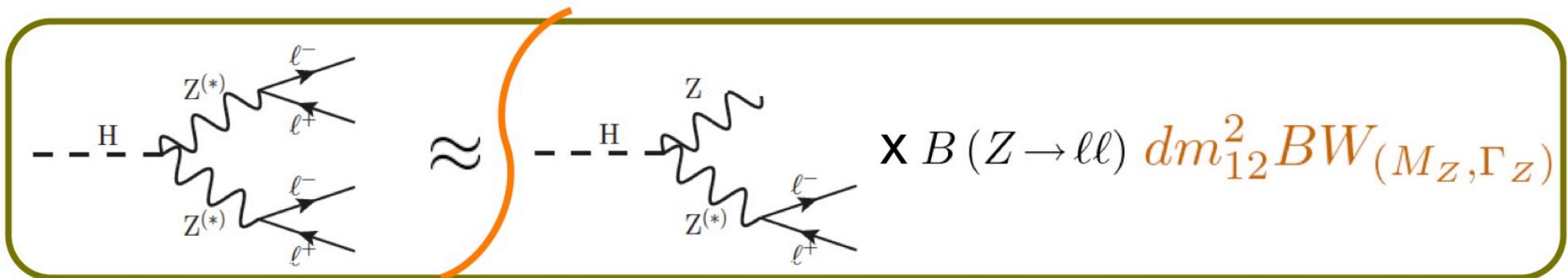


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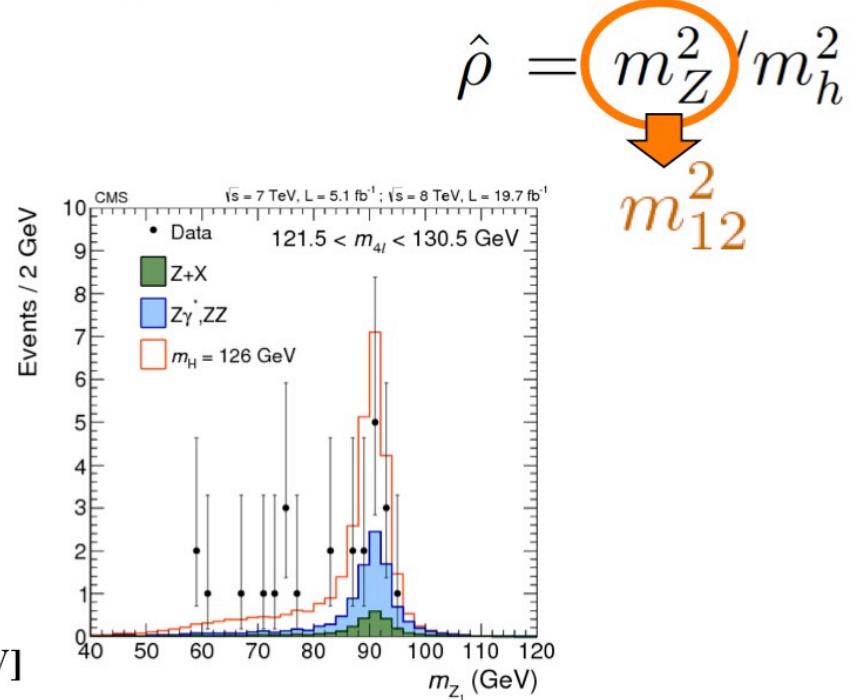
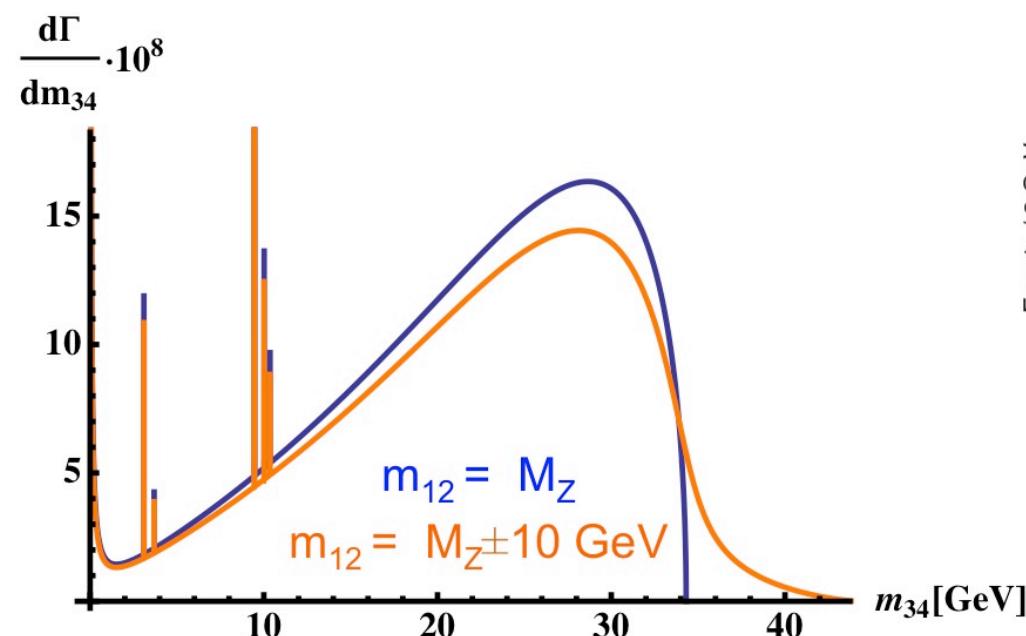
$$\hat{\rho} = m_Z^2/m_h^2$$



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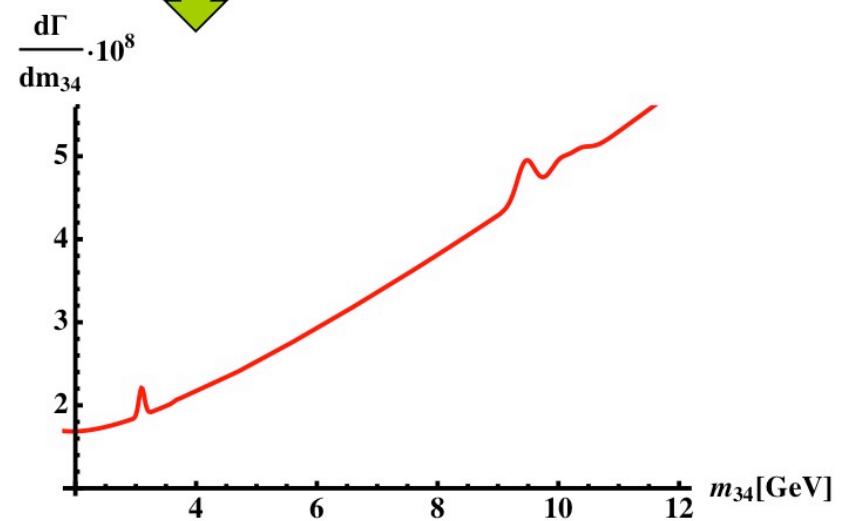
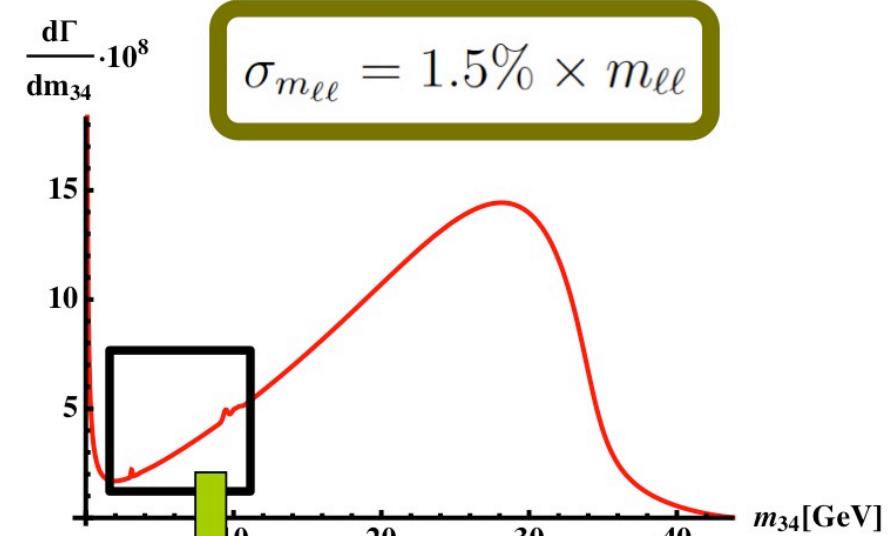
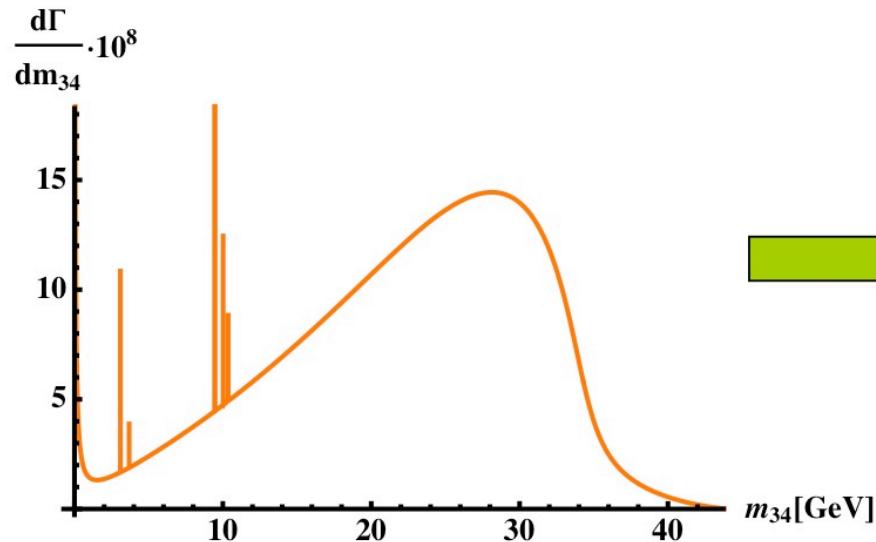


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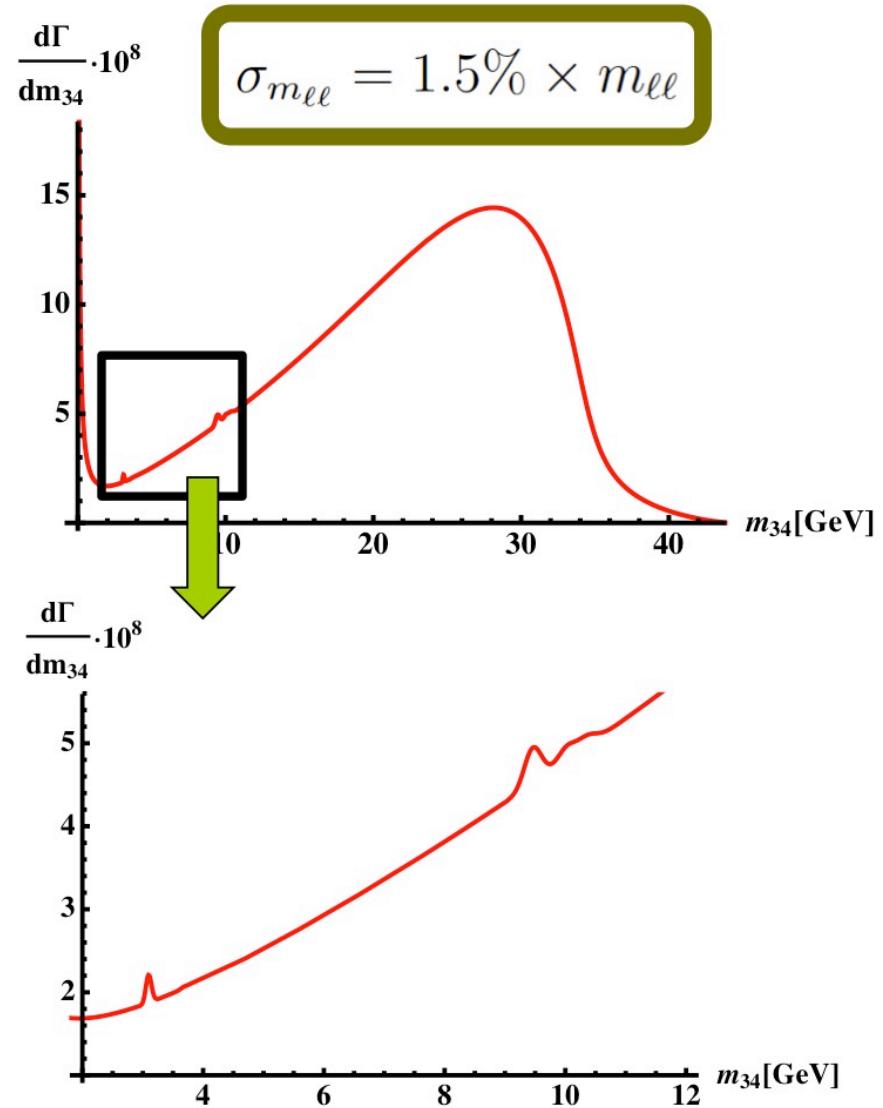
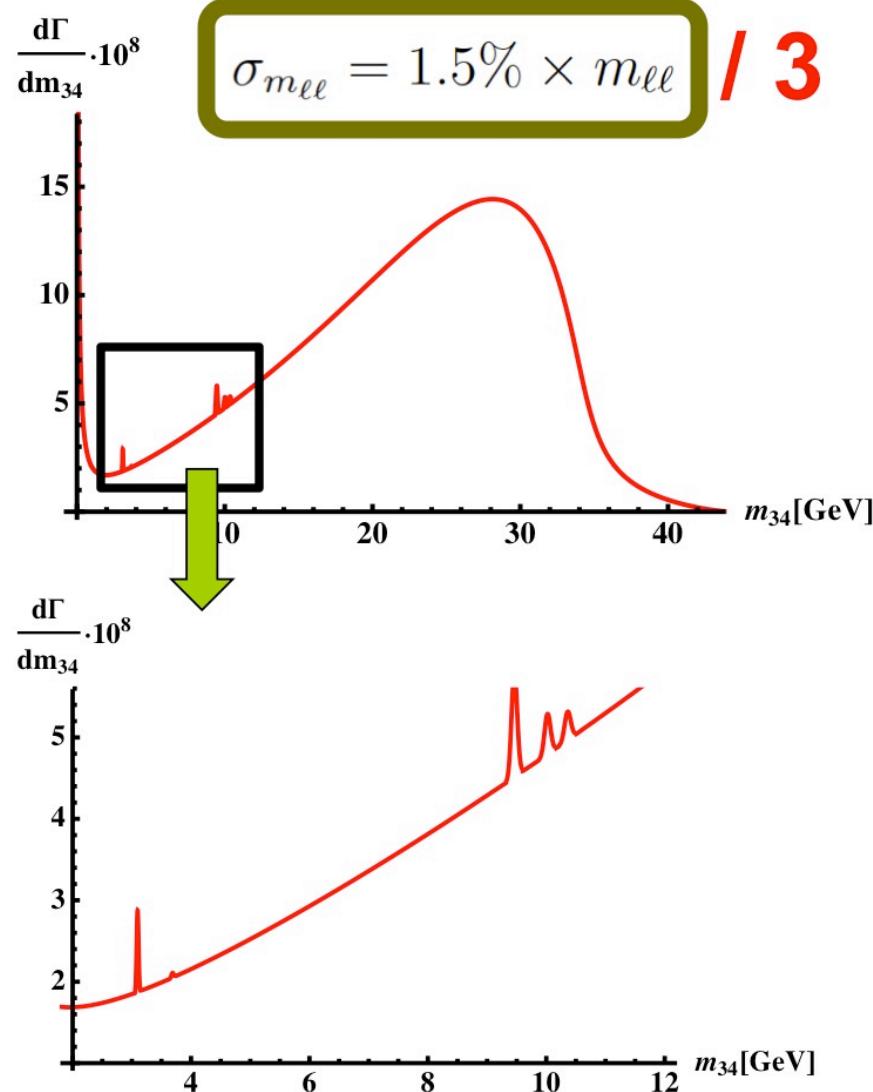


$$\hat{\rho} = \frac{m_Z^2}{m_h^2} / m_{12}^2$$

Smearing due to limited exp. resolution



Smearing due to limited exp. resolution

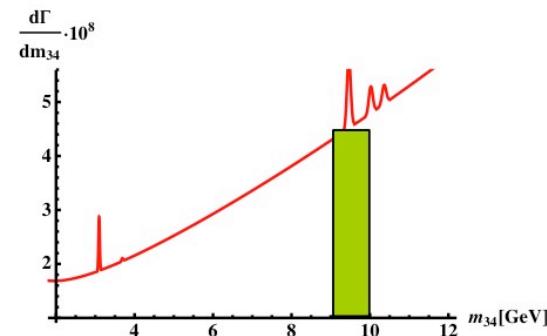


Effect on a single bin

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

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

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



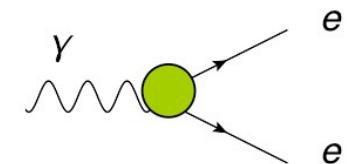
State	m_{V_i} [GeV]	f_{V_i} [MeV]	$\mathcal{B}(h \rightarrow ZV_i)$	$\Delta[d\Gamma(h \rightarrow Z\ell\ell)/dm_{34}]$ [1 GeV bin]
$J/\psi(1S)$	3.10	405	1.7×10^{-6}	2.6%
$J/\psi(2S)$	3.69	290	8.6×10^{-7}	0.2%
$\Upsilon(1S)$	9.46	680	1.6×10^{-5}	3.1% → ~30%
$\Upsilon(2S)$	10.02	485	8.2×10^{-6}	1.2% [100 MeV bin]
$\Upsilon(3S)$	10.36	420	6.2×10^{-6}	0.9%

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

New Physics:

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

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



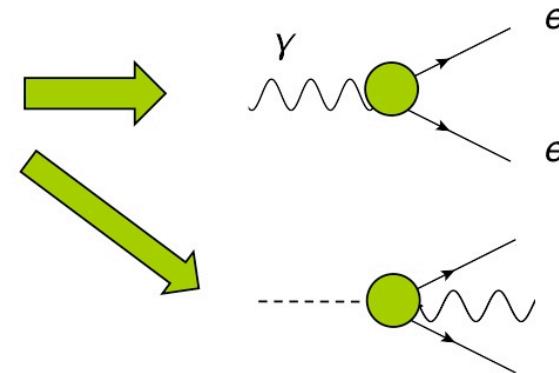
$$\mathcal{L}_{eff} \sim \frac{a_\mu}{m_\mu} \mu_L \sigma_{\mu\nu} \mu_R F^{\mu\nu}$$

EFT approach

- Effective operator behind (g-2):

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

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



- However...

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

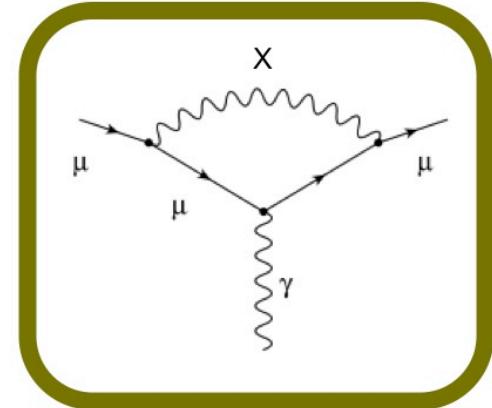
$$\rightarrow \Delta B(h \rightarrow \mu^+ \mu^- \gamma)_{\text{EFT}}^{(g-2)} = -\frac{e^2 m_h^3 \Delta a_\mu}{128 \pi^3 v^2 \Gamma_h} + \frac{e^2 m_h^5 (\Delta a_\mu)^2}{12 (8\pi)^3 m_\mu^2 v^2 \Gamma_h} \sim \mathcal{O}(10^{-10})$$

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

Light states?

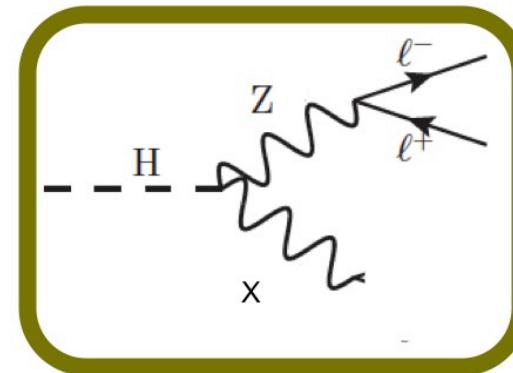
$$m_\mu \ll m_{\text{NP}} \ll m_h$$

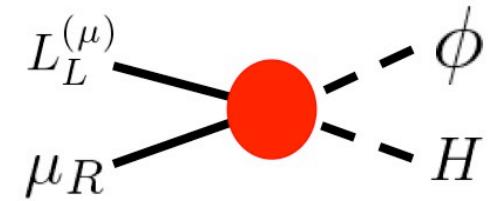
- $(g-2)_\mu$ can still be fine (with weaker couplings);



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

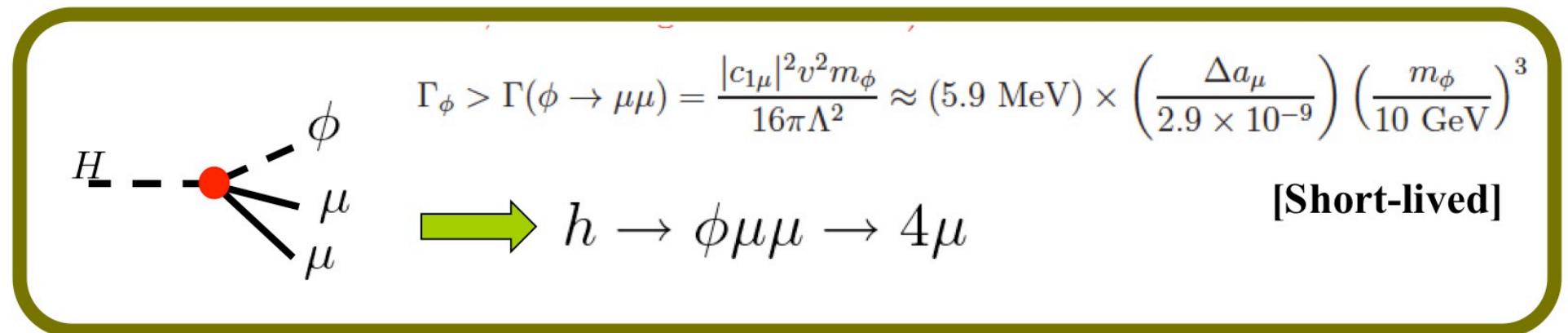
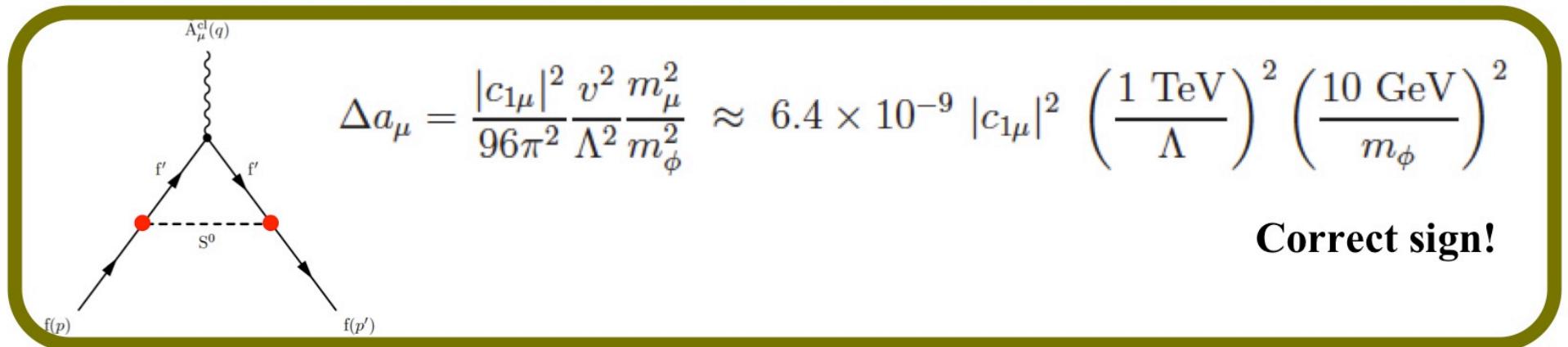
- Two examples:
 - SM + scalar
 - SM + vector



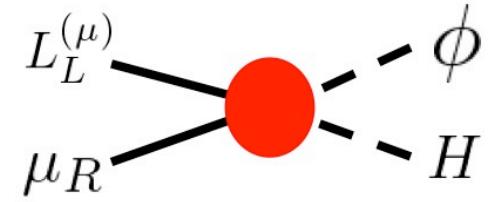


Light scalar

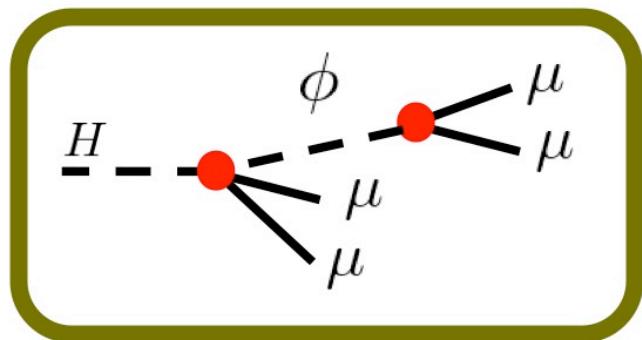
$$\mathcal{L}^{(1)} = \mathcal{L}_{\text{kin}}^{(\phi)} + \left(\frac{c_{1\mu}}{\Lambda} \bar{L}_L^{(\mu)} \mu_R H \phi + \text{h.c.} \right), \quad \mathcal{L}_{\text{kin}}^{(\phi)} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2$$



Light scalar



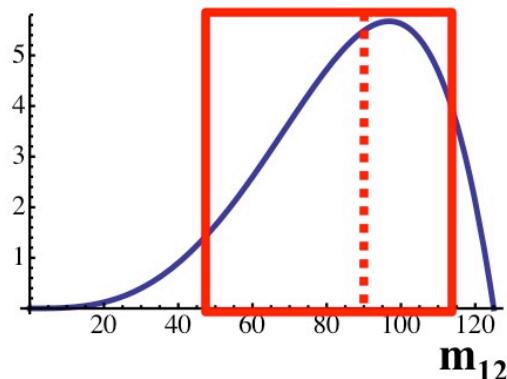
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Does the signal pass current m_{12} cut?

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

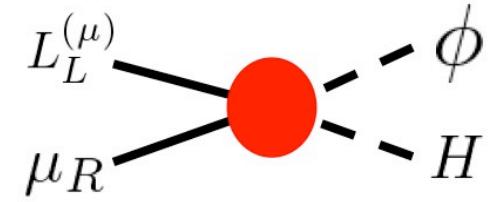
$50 < m_{12} < 106$ GeV (ATLAS)



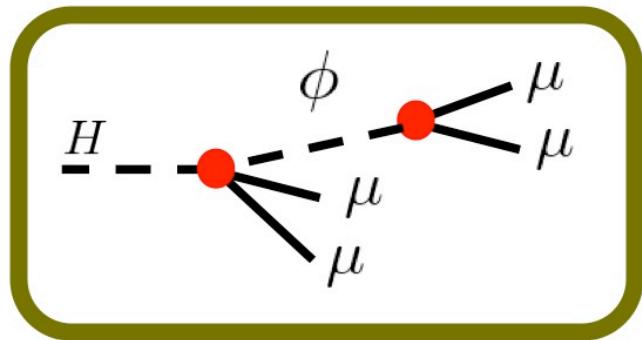
$$\frac{d\Gamma(h \rightarrow \mu\mu\phi)}{dm_{12}} = \frac{|c_{1\mu}|^2}{128\pi^3 m_h^3 \Lambda^2} m_{12}^3 (m_h^2 - m_{12}^2)$$

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

Light scalar



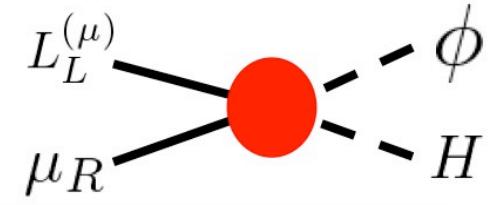
$$\mathcal{L}^{(1)} = \mathcal{L}_{\text{kin}}^{(\phi)} + \left(\frac{c_{1\mu}}{\Lambda} \bar{L}_L^{(\mu)} \mu_R H \phi + \text{h.c.} \right)$$



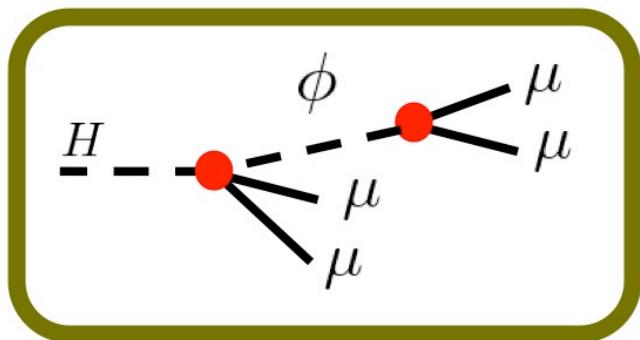
$$\frac{\mathcal{B}(h \rightarrow 4\mu)_{(\phi)}}{\mathcal{B}(h \rightarrow 4\mu)_{\text{SM}}} \lesssim 1$$

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

Light scalar

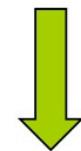
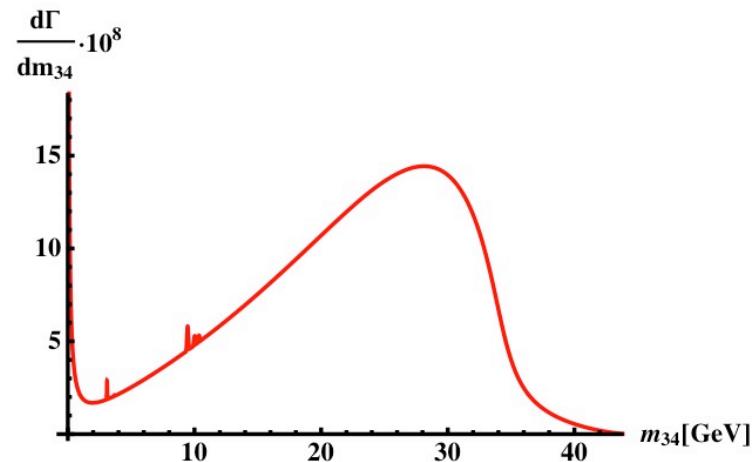


$$\mathcal{L}^{(1)} = \mathcal{L}_{\text{kin}}^{(\phi)} + \left(\frac{c_{1\mu}}{\Lambda} \bar{L}_L^{(\mu)} \mu_R H \phi + \text{h.c.} \right)$$



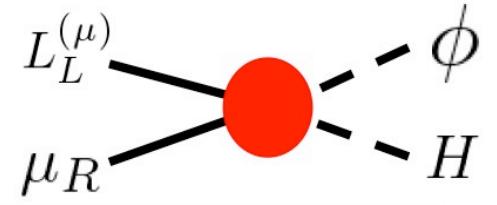
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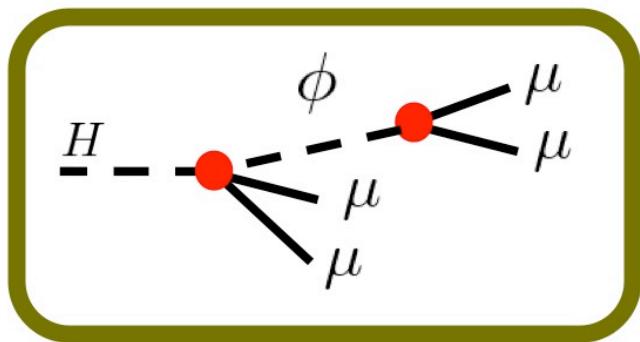


A peak **1500x** $\Upsilon(1s)!!$
= 50x SM [1 GeV bin]!!

Light scalar

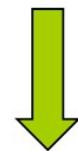
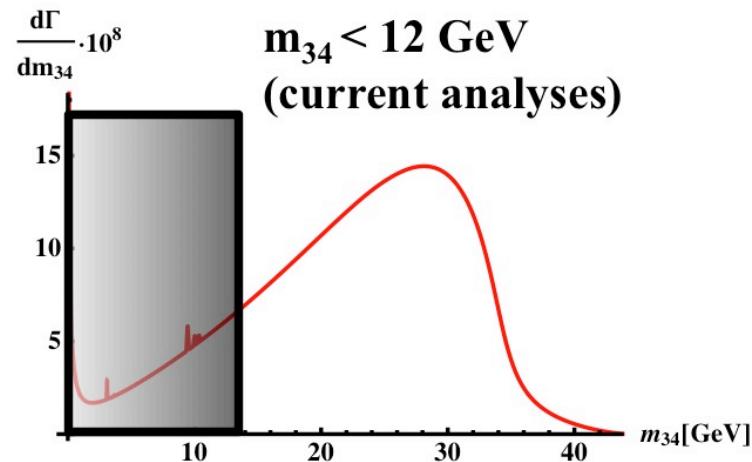


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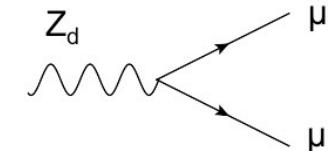


A peak **1500x** $\Upsilon(1s)!!$
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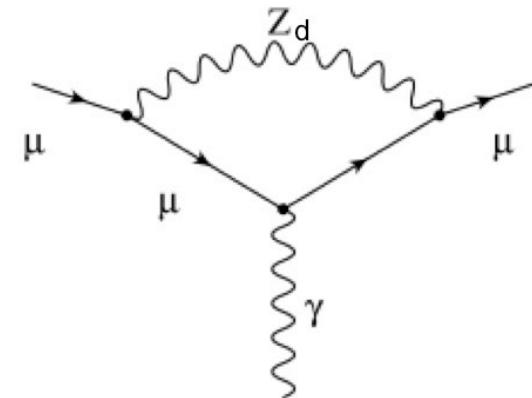
Light vector

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

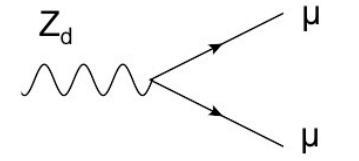
after EWSB (& diagonalization)



$$\begin{aligned}\Delta a_\mu &= -\frac{1}{12\pi^2} \frac{m_\mu^2}{m_{Z_d}^2} (c_R^2 + c_L^2 - 3c_R c_L) \approx \\ &\approx 2.3 \times 10^{-9} \left(\frac{10 \text{ GeV}}{m_{Z_d}} \right)^2 \frac{c_V^2 - 5c_A^2}{0.1^2} \text{ Sign!}\end{aligned}$$



Light vector



- Model realizations:

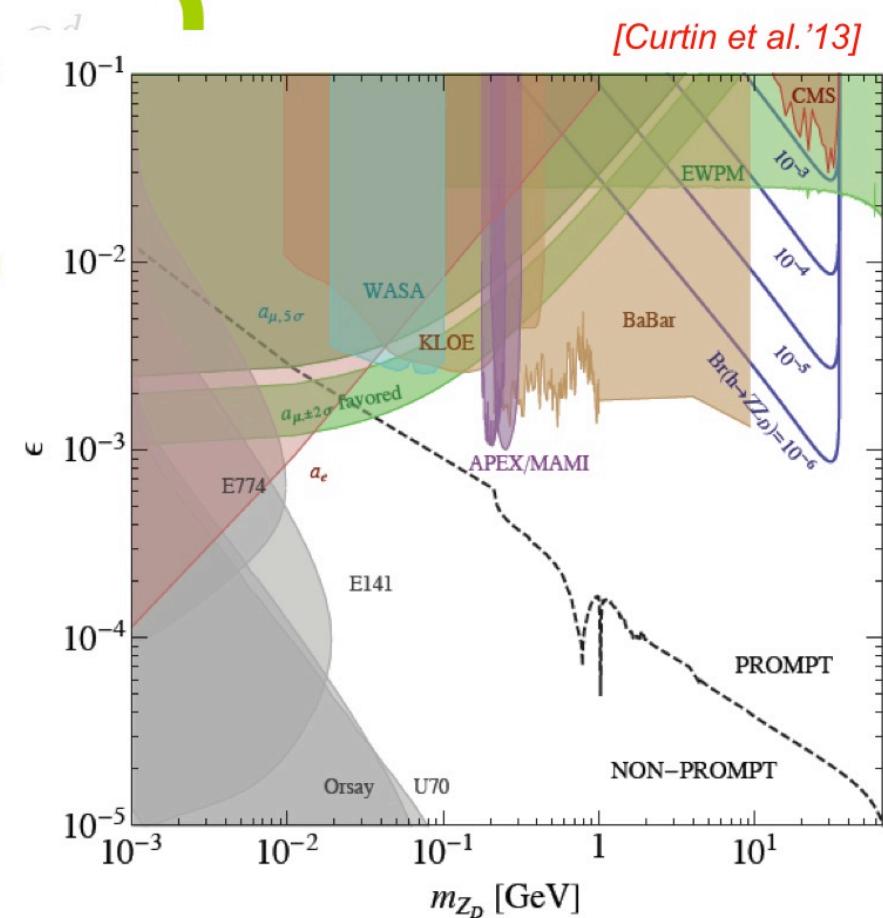
$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu} - \epsilon_Z m_Z^2 Z_d^\mu Z_\mu$$

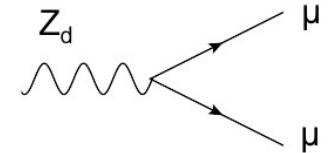
$$\begin{aligned} c_L &= -e\epsilon - \frac{g}{2c_W}(1-2s_W^2)\epsilon_Z + g_c \\ c_R &= -e\epsilon + \frac{g}{c_W}s_W^2\epsilon_Z + g_d Q_{\mu_R}^d, \end{aligned}$$

→ Right sign! $\Delta a_\mu > 0$

[Fayet'07, Pospelov'09]

... but only allowed for very light Z_d .





Light vector

- Model realizations:

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

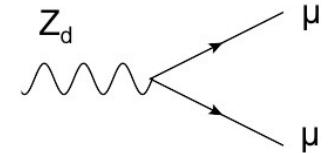
[Davoudiasl et al'2012-2013]

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

→ 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:

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

[Davoudiasl et al'2012-2013]

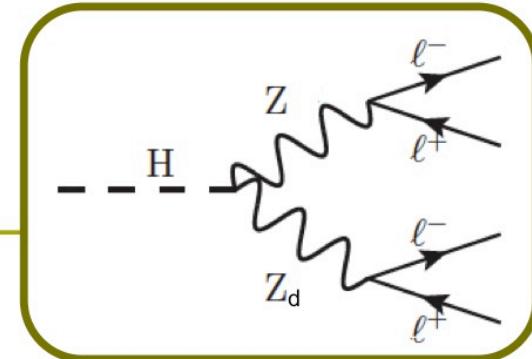
$$\begin{aligned} c_L &= -e\epsilon - \frac{g}{2c_W}(1 - 2s_W^2)\epsilon_Z + g_d Q_{\mu_L}^d , \\ c_R &= -e\epsilon + \frac{g}{c_W}s_W^2\epsilon_Z + g_d Q_{\mu_R}^d , \end{aligned}$$

→ Right sign! $\Delta a_\mu > 0$ [Fayet'07,
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Light vector

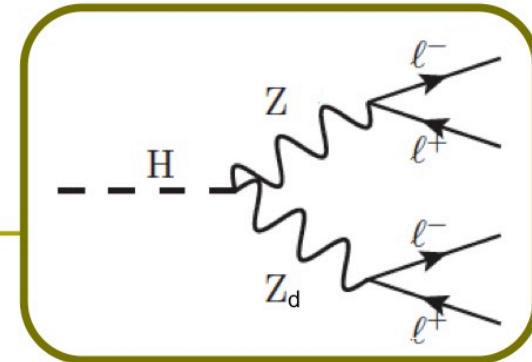


- Effect of Z_d in Higgs decay? $\Delta\mathcal{L}_{\text{int}}^{(2)} = c_H v h Z_d^\mu Z_\mu$
- Model-dependent connection with (g-2): $c_H \approx 2\epsilon_Z \frac{m_Z^2}{v^2} + 2\epsilon \frac{m_{Z_d}^2}{v^2} \tan \theta_W$
- BR($h \rightarrow 4l$) data* give strong bounds on c_H

$$\frac{c_H}{10^{-4}} \frac{m_{Z_d}}{10 \text{ GeV}} \lesssim \mathcal{O}(1)$$

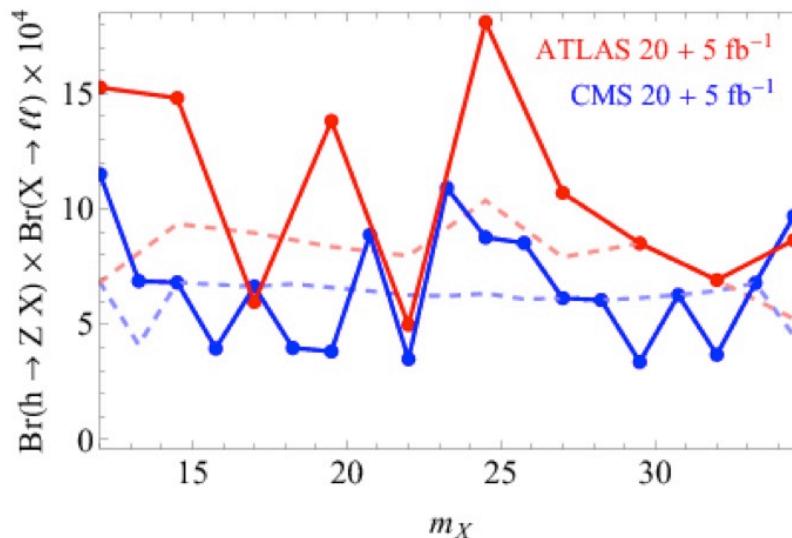
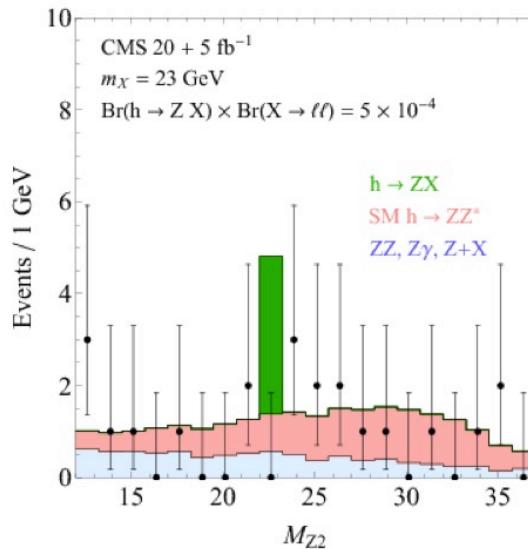
* Short-lived Z_d $\Gamma_{Z_d} \geq \Gamma(Z_d \rightarrow \mu^+ \mu^-) = \frac{m_{Z_d}}{24\pi} (c_L^2 + c_R^2) \approx (1.3 \text{ MeV}) \times \frac{m_{Z_d}}{10 \text{ GeV}} \frac{c_L^2 + c_R^2}{0.1^2}$

Light vector



- Effect of Z_d in Higgs decay? $\Delta\mathcal{L}_{\text{int}}^{(2)} = c_H v h Z_d^\mu Z_\mu$
- Model-dependent 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($h \rightarrow 4l$) data* give strong bounds on c_H
- Peak searching in $d\Gamma/dm_{34}$:

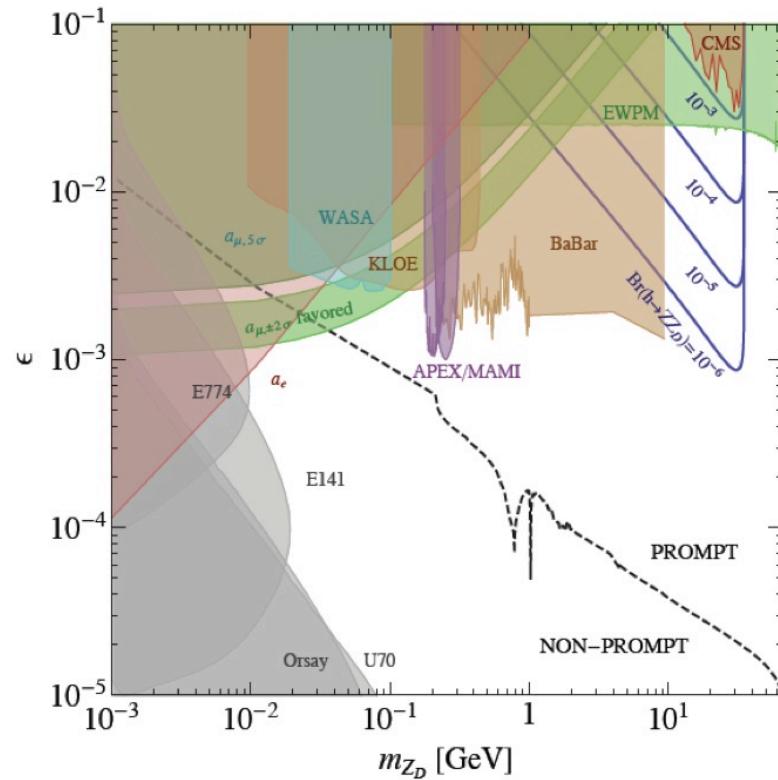
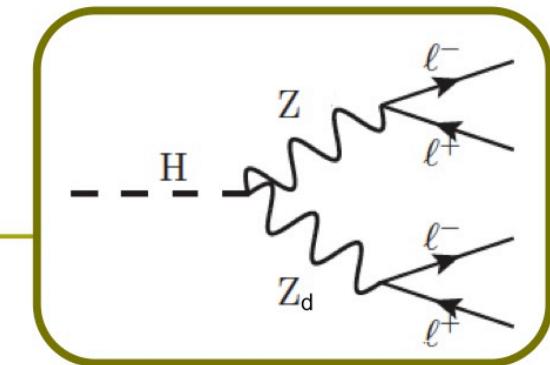
$$\frac{c_H}{10^{-4}} \frac{m_{Z_d}}{10 \text{ GeV}} \lesssim \mathcal{O}(1)$$



[Curtin et al.'13]

Light vector

- Competitive bounds:



Dark photon
[Curtin et al.'13]

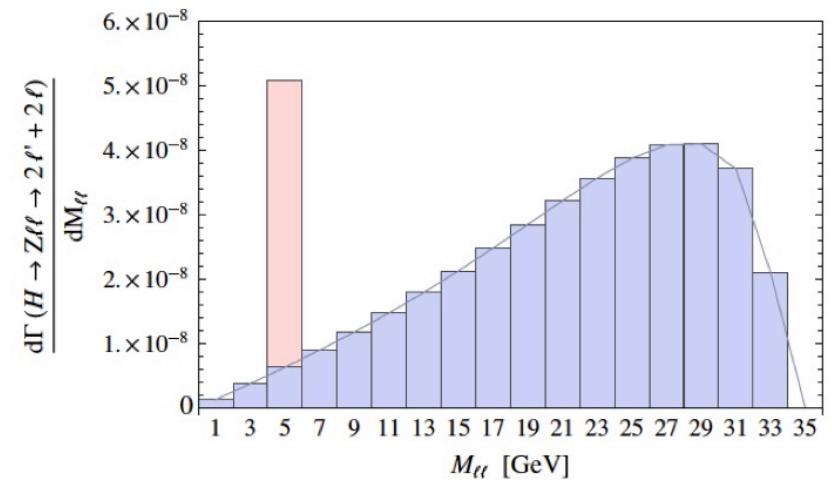


FIG. 3 (color online). Differential decay rate $H \rightarrow ZZ^* \rightarrow Z\ell^+\ell^- \rightarrow 4\ell$ vs $\ell^+\ell^-$ invariant mass with $m_H = 125$ GeV in the SM. For the illustration, $H \rightarrow ZZ_d \rightarrow Z\ell^+\ell^-$ with $m_{Z_d} = 5$ GeV and $\delta^2\text{BR}(Z_d \rightarrow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

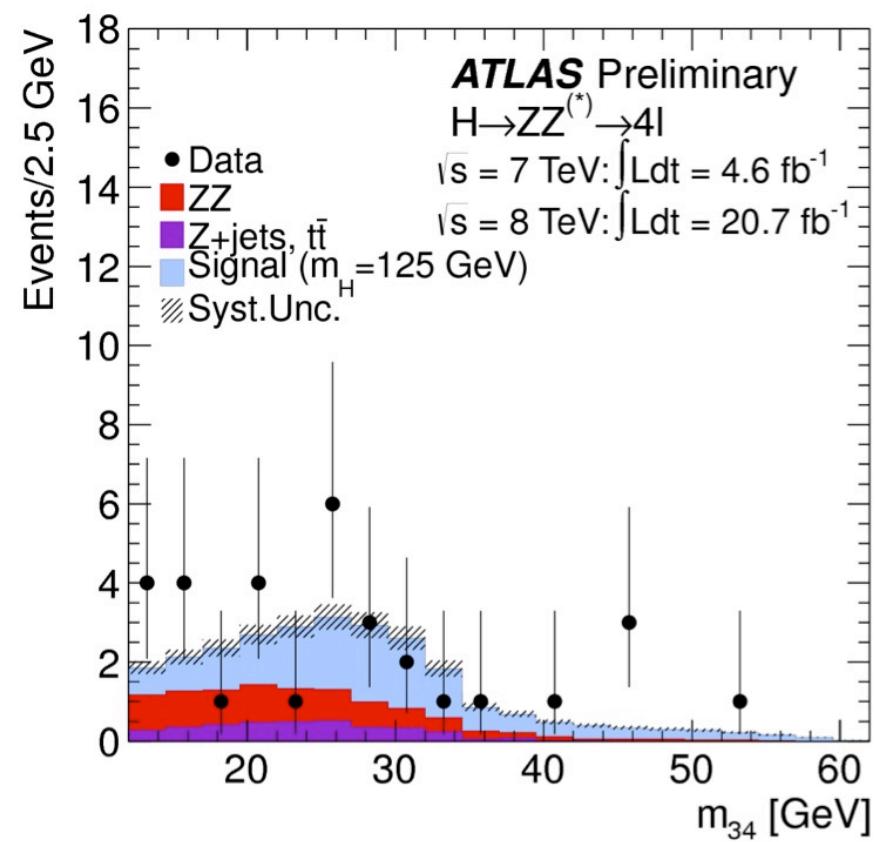
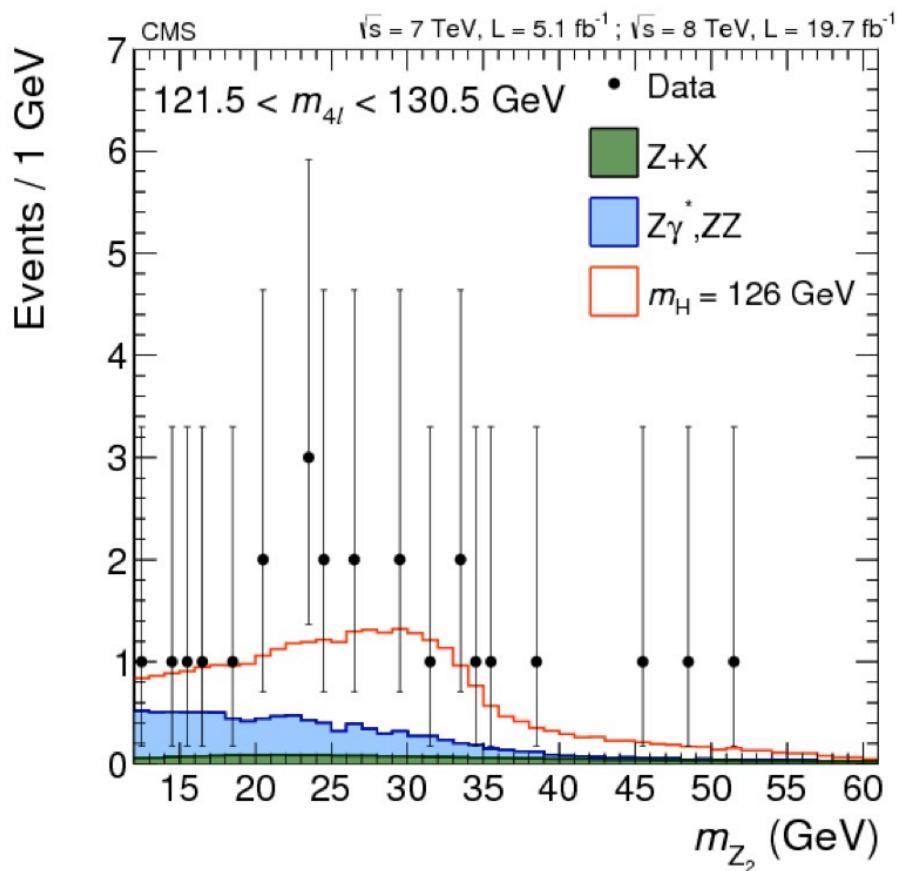
Dark Z
[Davoudiasl et al'2012]

Conclusions

- $\frac{d\Gamma(h \rightarrow 4\ell)}{dm_{34}}$ is a sensitive NP probe (heavy and light particles).
- Spectrum known with good theoretical accuracy.
Quarkonium peaks: $\sim 3\%$ (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).
 $[m_{34} > 12 \text{ GeV cut}]$ *[Davoudiasl et al'2012-2013, Curtin et al'2013, ...]*

Backup slides

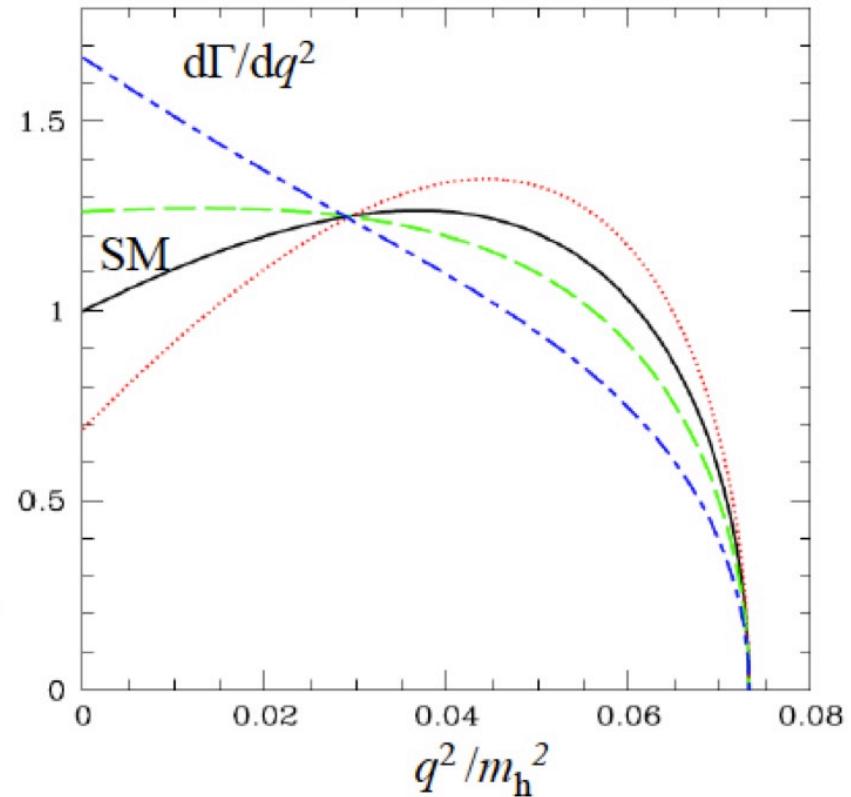
Introduction $h \rightarrow 4\ell$



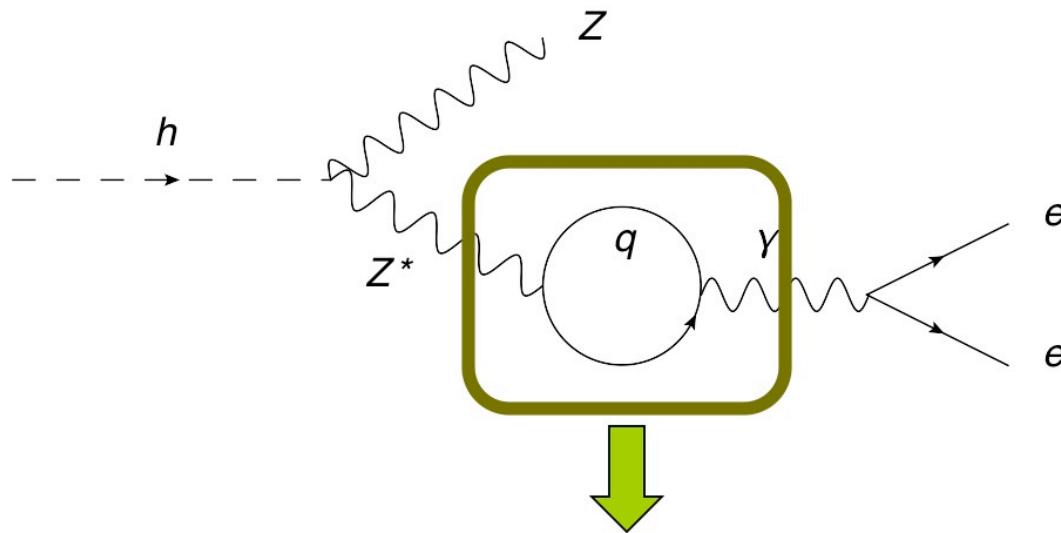
Introduction

- Generic 1 TeV NP can give an OK total rate and significant deviations in the spectrum. *[Isidori et al.'2013, Grinstein et al.'2013]*
- Significant constraints from EWPO. *[Ciuchini et al., Pomarol & Riva'2013]*
- Testing if these constraints are verified
tests if h is indeed part of an SU(2) doublet.

[Isidori & Trott'2013]



SM prediction: QCD corrections



Long distance
contributions are
important
(hadronization)

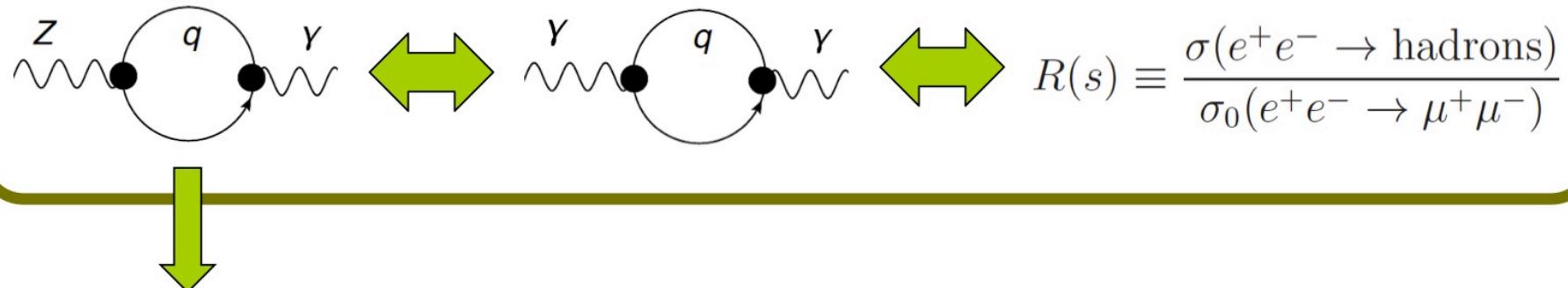
$$\Pi_{\mu\nu}^{Z\gamma}(q) \equiv i \int d^4x e^{iqx} \langle 0 | T J_\mu^Z(x) J_\nu^\gamma(0) | 0 \rangle = - (g^{\mu\nu} q^2 - q^\mu q^\nu) \Pi_{Z\gamma}(q^2)$$

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



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

SM prediction: QCD corrections



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

It can be related with the hadronic photon vacuum polarization:

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

... which can be related to $R(s)$ data:

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

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

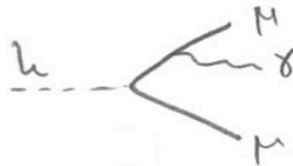
EFT approach

- Effective operator behind (g-2):

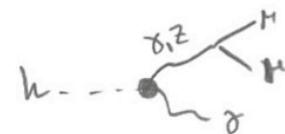
$$\mathcal{L}_{\text{EFT}} = \frac{c_0}{\Lambda^2} \bar{L}_L^{(\mu)} \sigma^{\mu\nu} \mu_R F_{\mu\nu} H + \text{h.c.}$$



- Interference with SM...



NOTE: Interference with...



Is loop & yukawa suppressed.

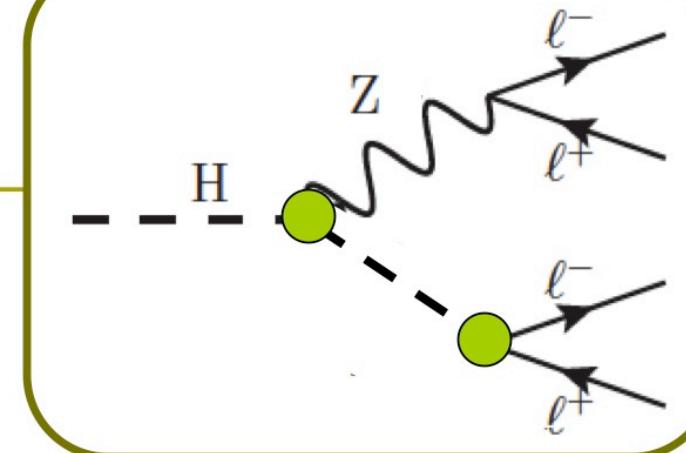
- Final result:

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

Four orders of magnitude
smaller than the SM
contributions

Light scalar

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



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

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