Interference effects in Vector boson pair production

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Rescaling properties of the cross section on the peak

- In the narrow width approximation

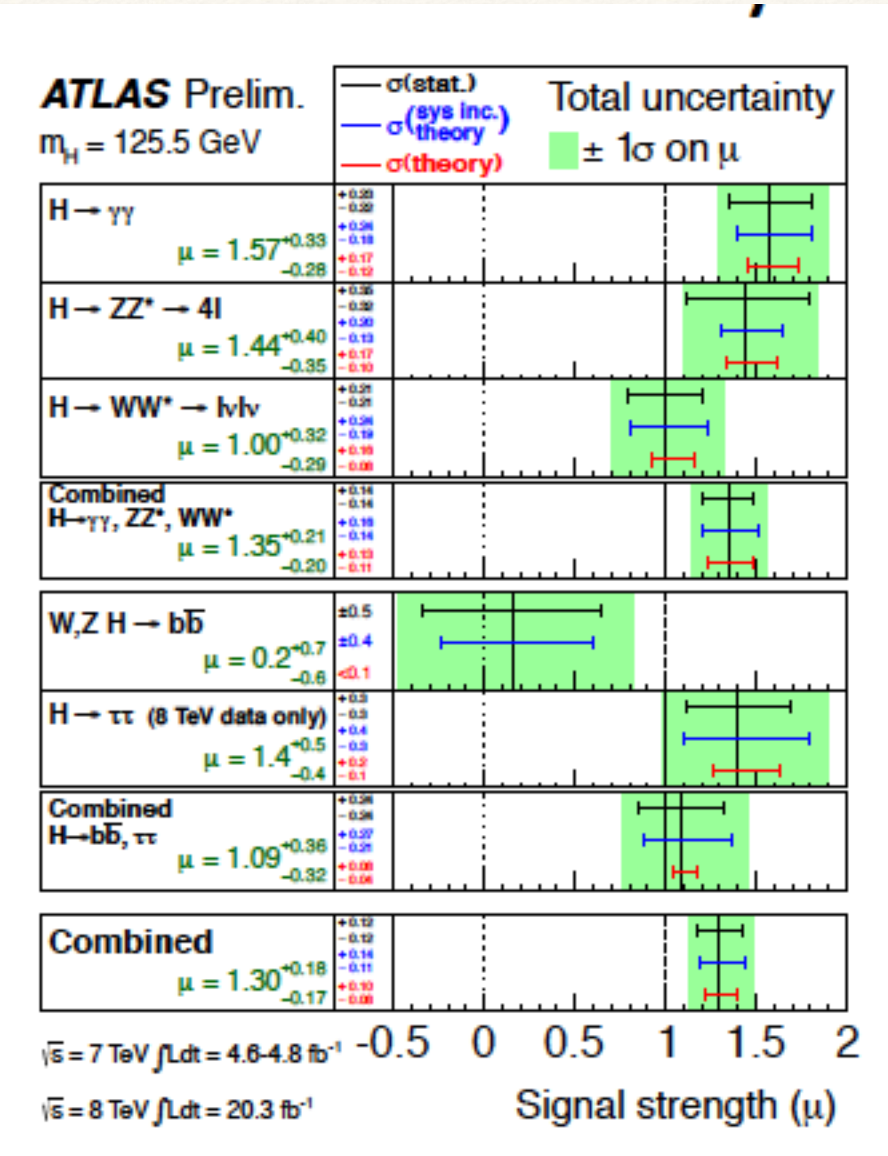
$$\sigma(i \to H) \times BR(H \to X) = |M(i \to h)|^2 \frac{\Gamma(h \to X)}{\Gamma_h} \sim \frac{g_i^2 g_f^2}{\Gamma_h}$$

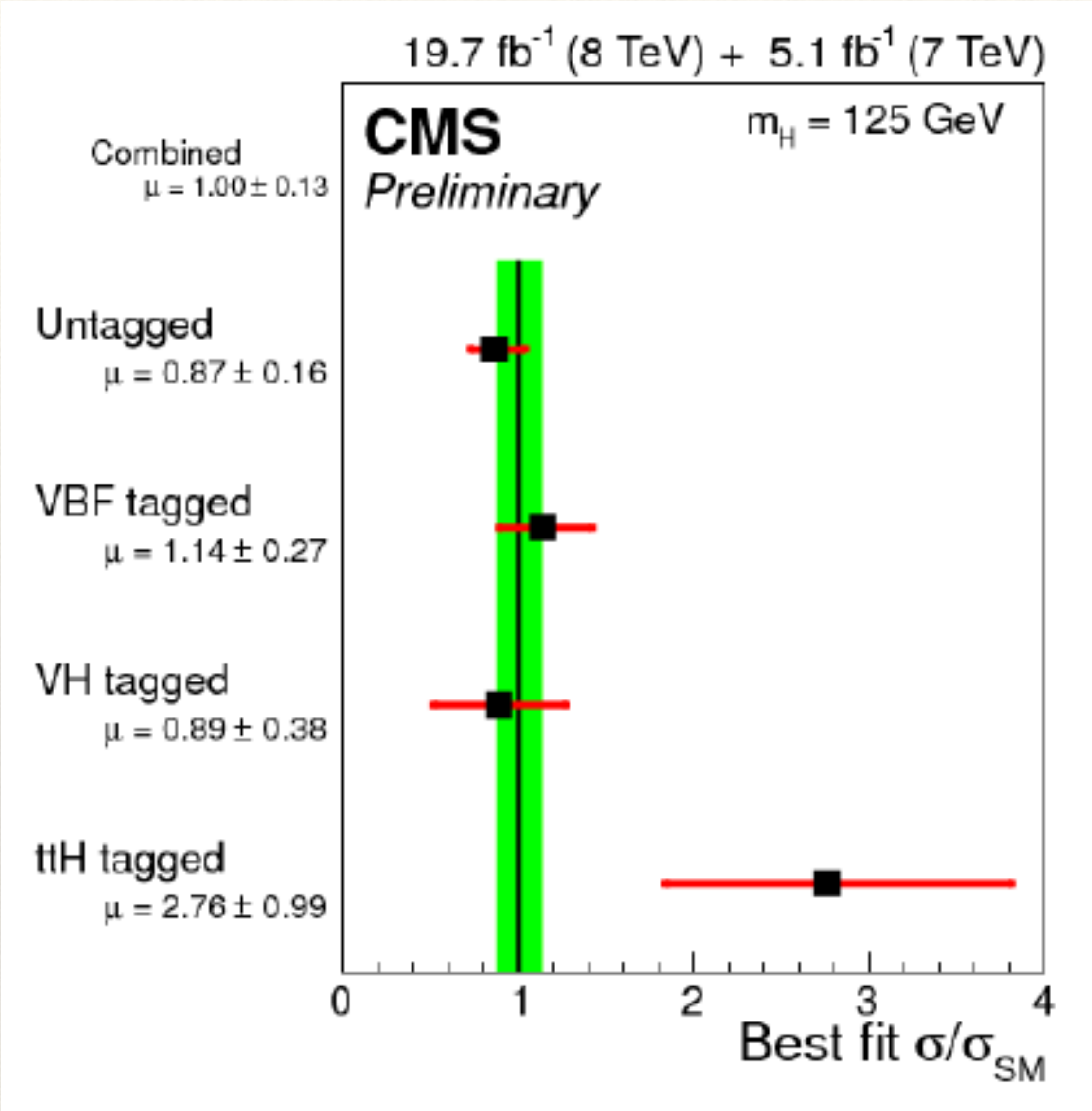
- Measurements on the Higgs peak, are only sensitive to the ratio, $\frac{g_i^2 g_f^2}{\Gamma_h}$

- Performing the rescaling by κ leaves the on-shell rate unchanged.

$$g_i \to \kappa g_i$$
$$g_f \to \kappa g_f$$
$$\Gamma_H \to \kappa^4 \Gamma_H$$

Signal strength measurements





- Signal strength measurements, (that assume a value for the total width), confirm that $g_i^2 g_f^2/\Gamma_h$ is close to its standard model value (with ~20% errors)

Narrow width approximation for Higgs production

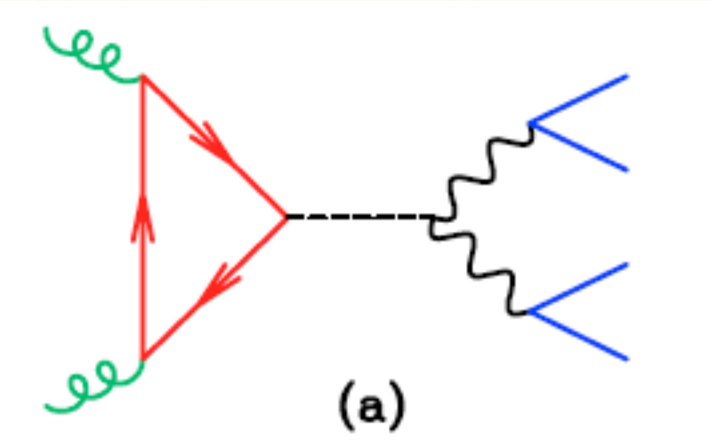
- In the limit $\Gamma/M_h \to 0$ we may replace the Breit-Wigner distribution by a delta function.

$$\frac{1}{(\hat{s}-M_h^2)^2+M_h^2\Gamma_h^2} \approx \frac{\pi}{M_h\Gamma_h}\,\delta(\hat{s}-M_h^2)\,.$$

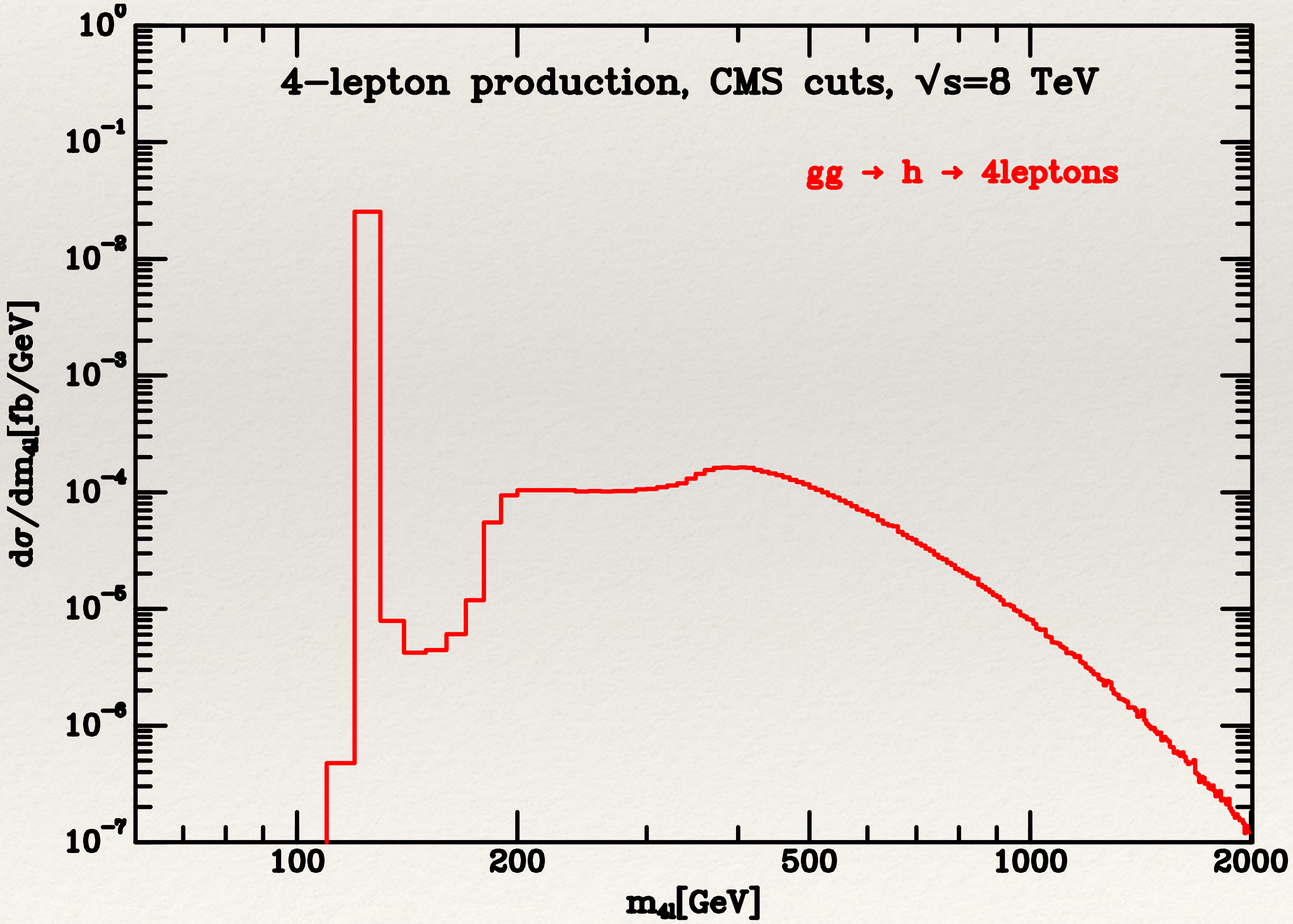
- For the standard model Higgs, $\Gamma/M_h = 1/30{,}000$ so narrow width approximation should apply…..

Narrow width approximation for Higgs boson

- How can it fail?
  - $\Gamma_H \,/\, M_H = 1/30{,}000$



- It fails spectacularly for $gg \to H \to ZZ^{(*)} \to e^- e^+ \mu^- \mu^+$.



- At least 10% of the cross section comes from m_{4l}>130GeV.

  Kauer, Passarino,arXiv:1206.4803

- Similar tail for H→WW.

Interference in pp→ZZ→e⁻e⁺μ⁻μ⁺

$$
\begin{array}{l}
p + p \to H \to ZZ \\
\qquad\qquad\qquad\quad \hookrightarrow \mu^- + \mu^+ \\
\qquad\qquad\qquad \hookrightarrow e^- + e^+ \,.
\end{array}
$$

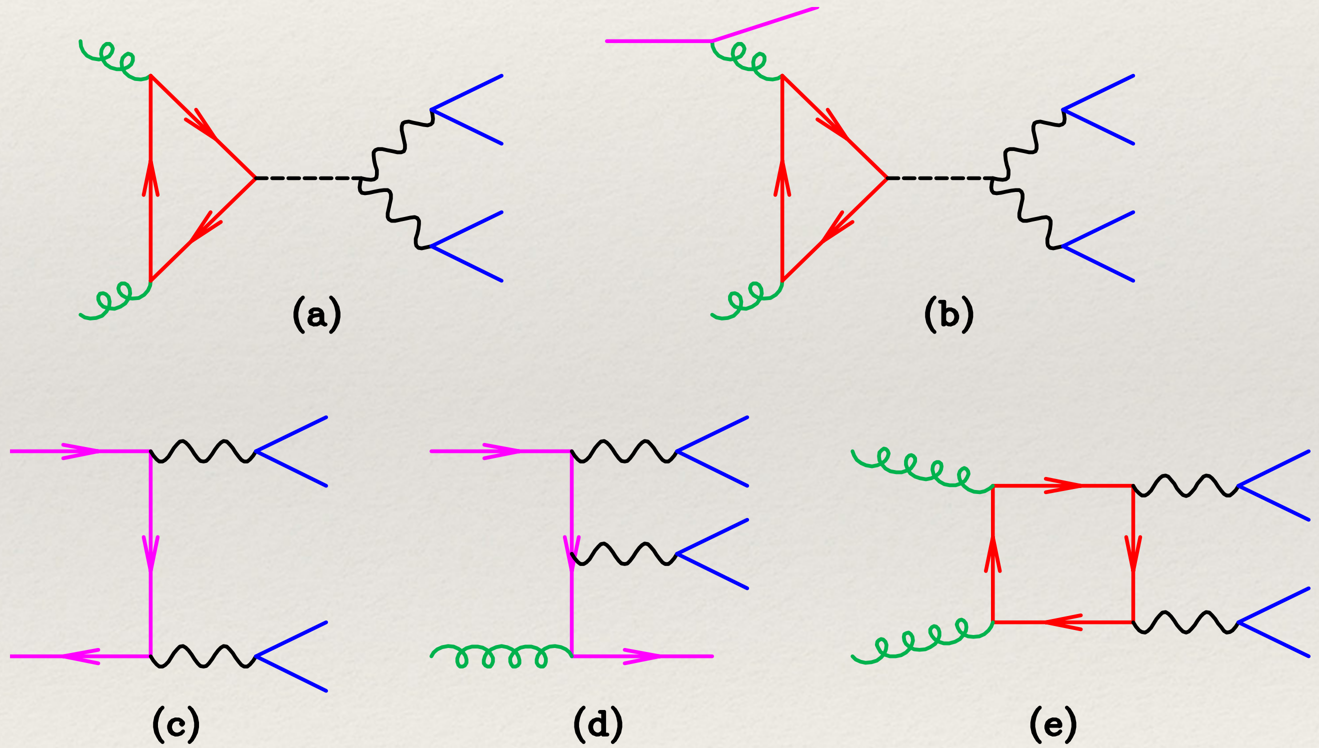
$$
\begin{array}{l}
p + p \to Z/\gamma^* + Z/\gamma^* \\
\qquad\qquad\qquad\qquad \hookrightarrow \mu^- + \mu^+ \\
\qquad\qquad\quad \hookrightarrow e^- + e^+
\end{array}
$$

- We cannot consider the Higgs process alone.
- Both interfering and non-interfering backgrounds.

pp→e⁻e⁺μ⁻μ⁺ in the standard model

$(a) : g(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$
$(b) : q(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s^3 e^4)$
$(c) : q(-p_1) + \bar{q}(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(e^4)$
$(d) : q(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s e^4)$
$(e) : g(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$

- Mishmash of orders in perturbation their
- Representative diagrams are:-
- (a) and (e), (b) and (d) can interfere.
- (b-d) interference does not overwhelm (a-e)



Caola-Melnikov 1307.4935

Caola-Melnikov method for Higgs width

- Higgs cross section under the peak, section depends on ratio of couplings and width.

$$\sigma_{\rm peak} \propto \frac{g_i^2 g_f^2}{\Gamma}$$

- Measurements at the peak cannot untangle couplings and width.
- Off-peak cross section is independent of the width, but still depends on $g_i^2 g_f^2$ (modulo interference, see later).

$$\sigma_{\rm off} \propto g_i^2 g_f^2$$

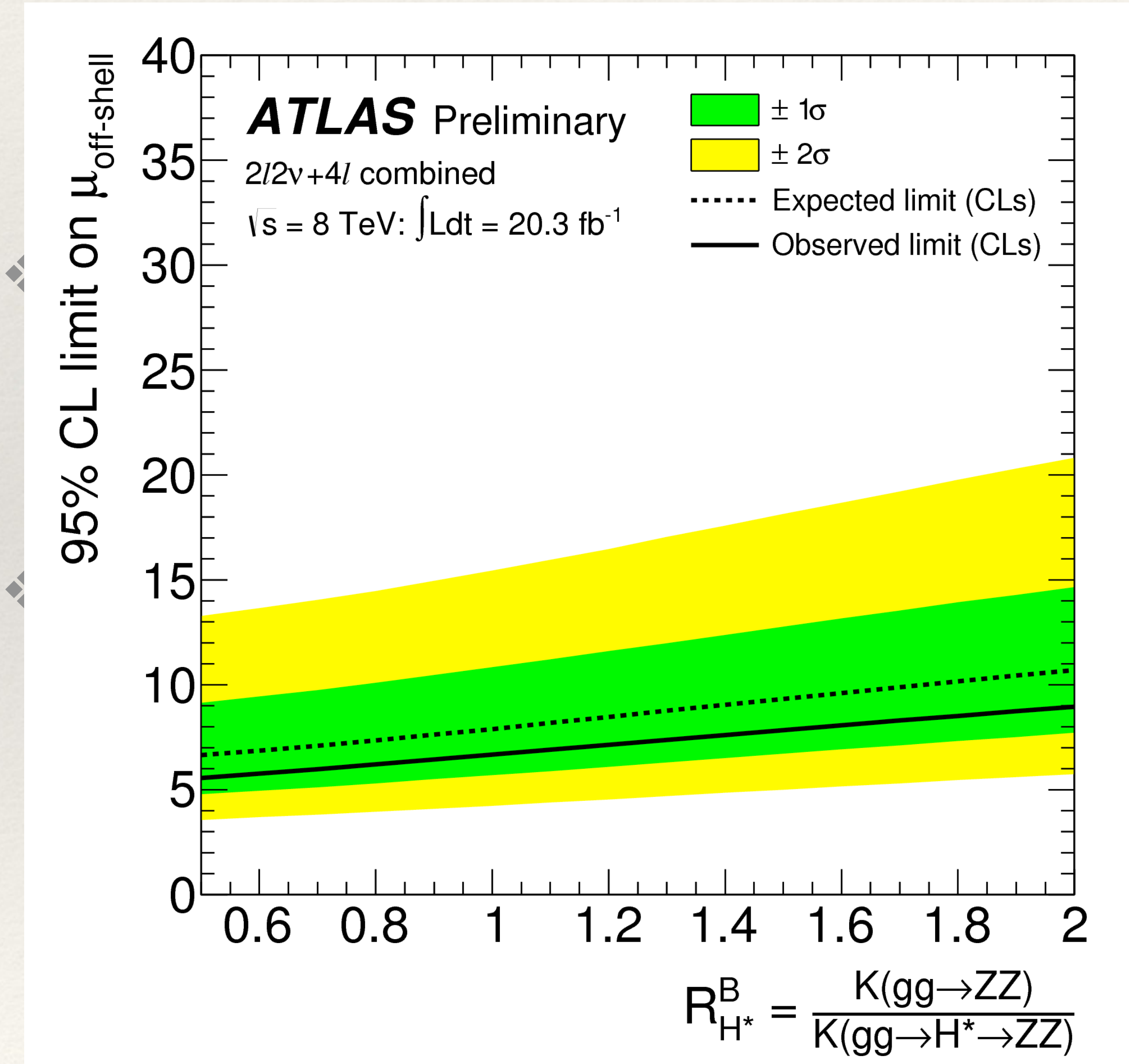
- Assuming $g_i^2 g_f^2$ is the same on-shell as off-shell, we have

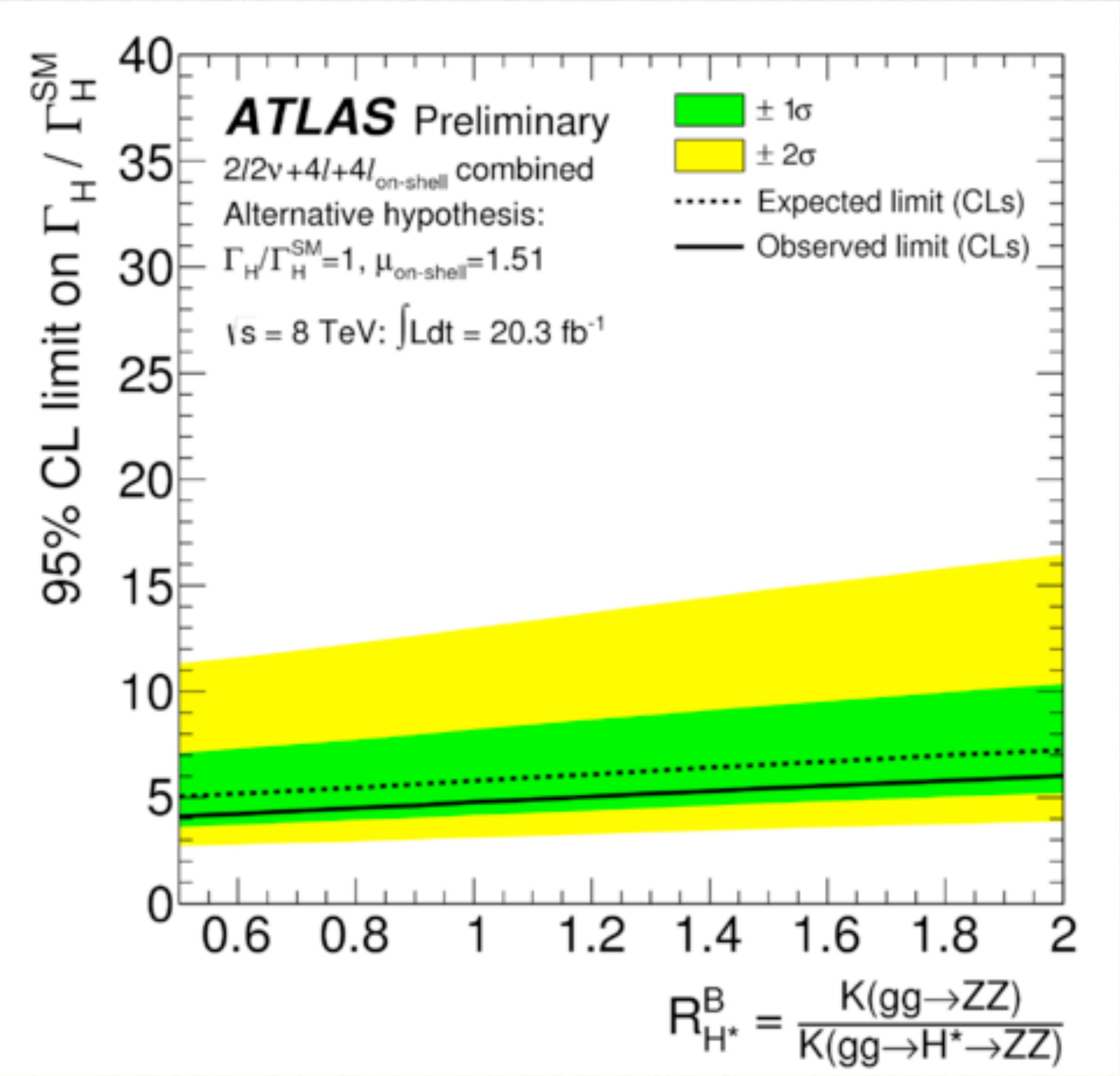
$$\frac{\left(\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}\right)_{\rm experimental\ gg}}{\left(\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}\right)_{\rm theoretical\ SM}} = \frac{\Gamma}{\Gamma^{\rm SM}}$$

ATLAS result

ATLAS-CONF-2014-042

- Presented as a function of the unknown relative K factor between "signal" and "background".

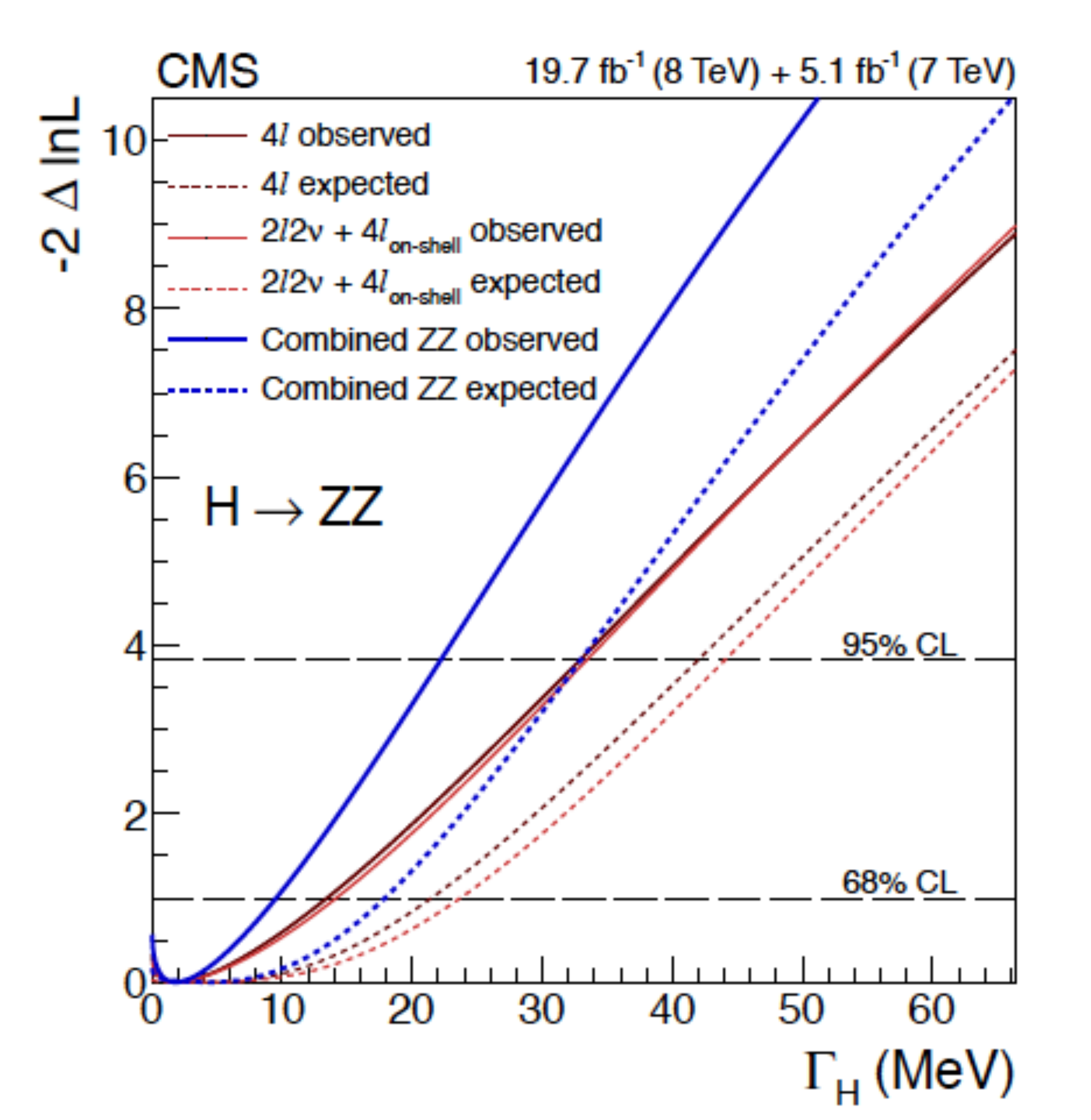




CMS result

arXiv:1405.3455

- Γ_H/Γ_H^{SM}=5.4 at 95%cl



- Results are at least 2 orders of magnitude better than previous limit from direct observation of the final state.

Model-dependence of Higgs width bound.

- The bound on the Higgs width holds under the assumption that the coupling constants remain the same over a large span of energy $\sqrt{s}$=126→~500 GeV.
- If new phenomena are present, this will not always be true.
- In all cases there is great interest in the measurement of the gluon induced 4-lepton cross section away from the Higgs peak.
- If there is a large scale separation between the new phenomena and the off-shellness probed, this can be treated using an effective operator formulation.

$$\mu^{\mathrm{on}}_{ZZ} \equiv \frac{\sigma_h \times \mathrm{BR}(h \to ZZ \to 4\ell)}{[\sigma_h \times \mathrm{BR}(h \to ZZ \to 4\ell)]_{\mathrm{SM}}} \sim \frac{\kappa^2_{ggh}\,\kappa^2_{hZZ}}{\Gamma_h/\Gamma_h^{\mathrm{SM}}}\,,$$

$$\mu^{\mathrm{off}}_{ZZ} \equiv \frac{\mathrm{d}\overline{\sigma}_h}{[\mathrm{d}\overline{\sigma}_h]_{\mathrm{SM}}} \sim \kappa^2_{ggh}(\hat{s})\,\kappa^2_{hZZ}(\hat{s})\,,$$

Englert and Spannowsky, 1405.0285

Cacciapaglia et al, 1406.1757
Azatov et al, 1406.6338
Gaines et al, 1403.4951

Theoretical predictions for Vector Boson Fusion

Campbell, RKE 1502.02990

Diagrams for pp → jet+jet+e⁻e⁺μ⁻μ⁺

- Off-shell behaviour for VBF subject of much theoretical study.
- Jet cuts

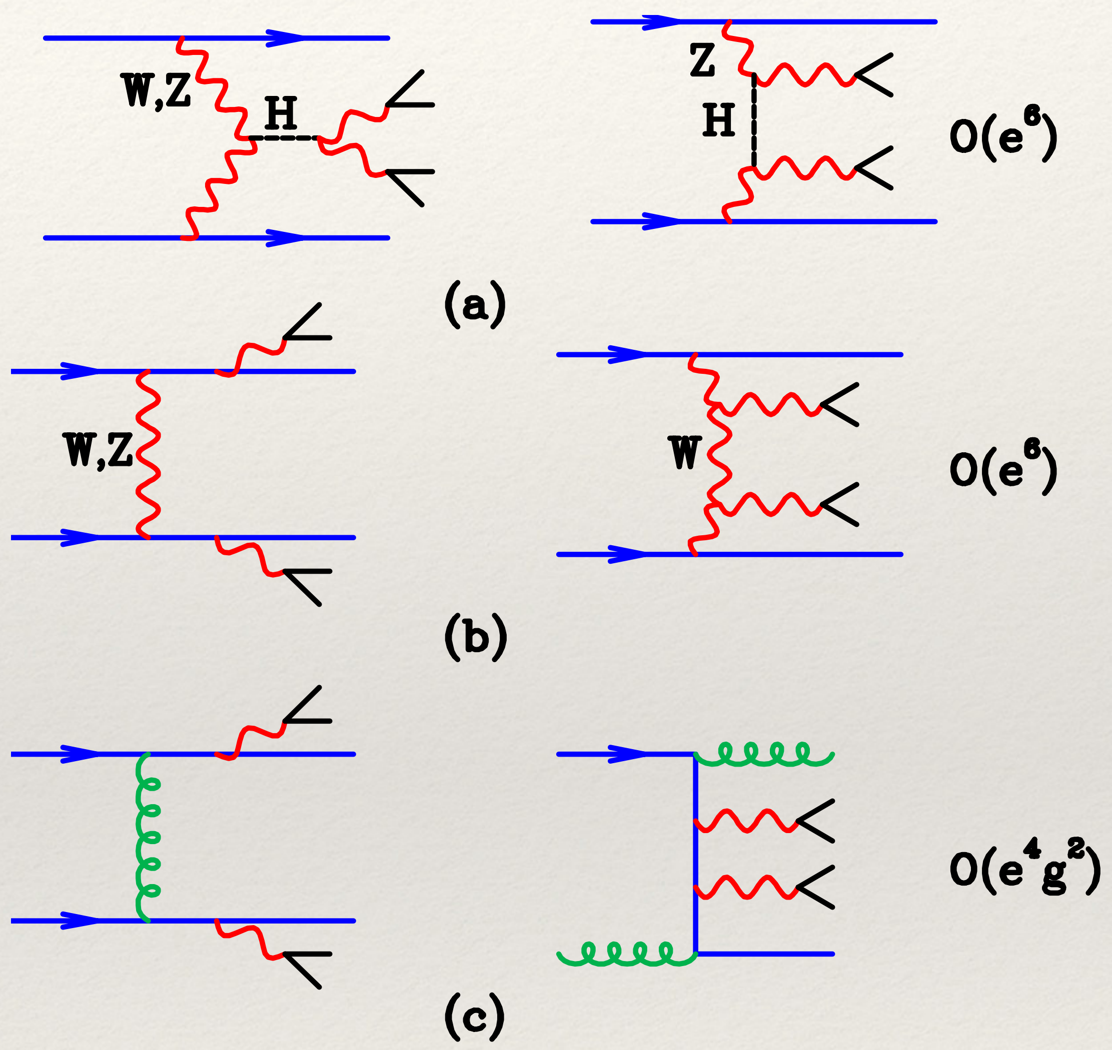
$$p_{T,J} > 30 \text{ GeV}\,, |\eta_J| < 4.5\,, R = 0.4$$

- CMS lepton cuts

$$\begin{aligned} p_{T,\mu} &> 5 \text{ GeV}\,,\ |\eta_\mu| < 2.4\,, \\ p_{T,e} &> 7 \text{ GeV}\,,\ |\eta_e| < 2.5\,, \\ m_{ll} &> 4 \text{ GeV}\,,\ m_{4\ell} > 100 \text{ GeV}\,. \end{aligned}$$

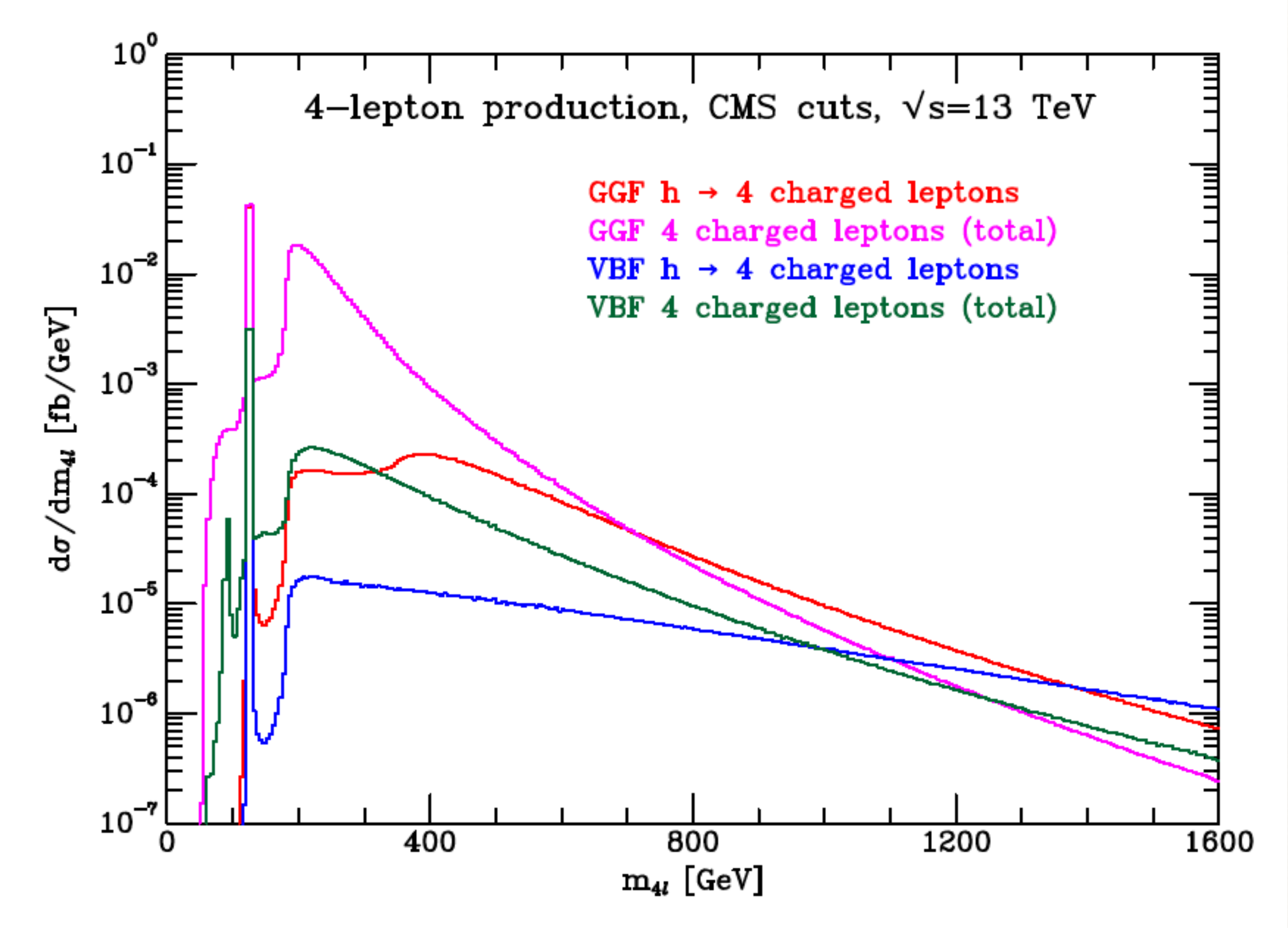
- Additional VBF cuts

$$\begin{aligned} y_{gap} &> 2.4 \\ \eta_1 \times \eta_2 &< 0 \\ m_{j_1 j_2} &> 500 \text{ GeV} \end{aligned}$$



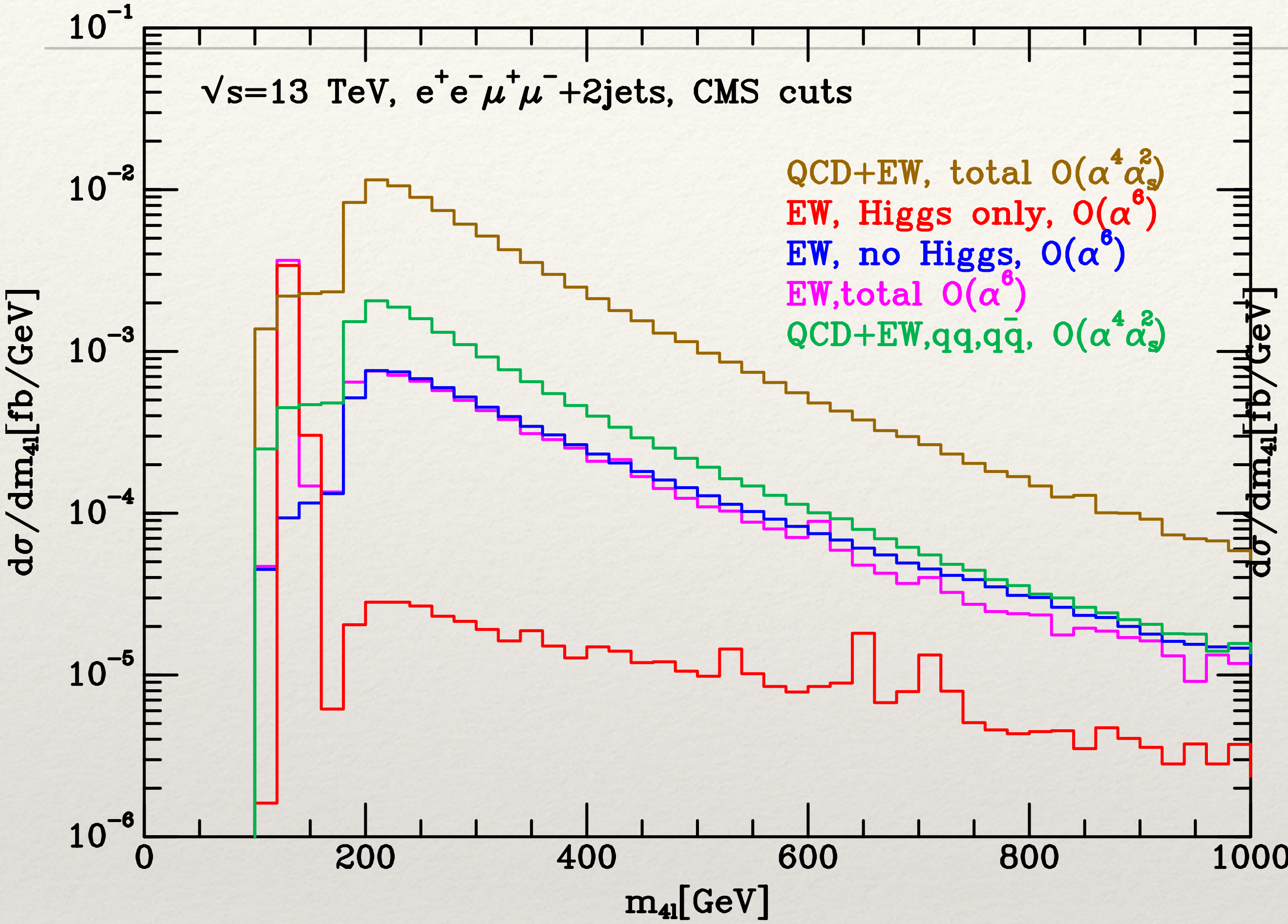
Gluon-gluon fusion vs Vector boson fusion

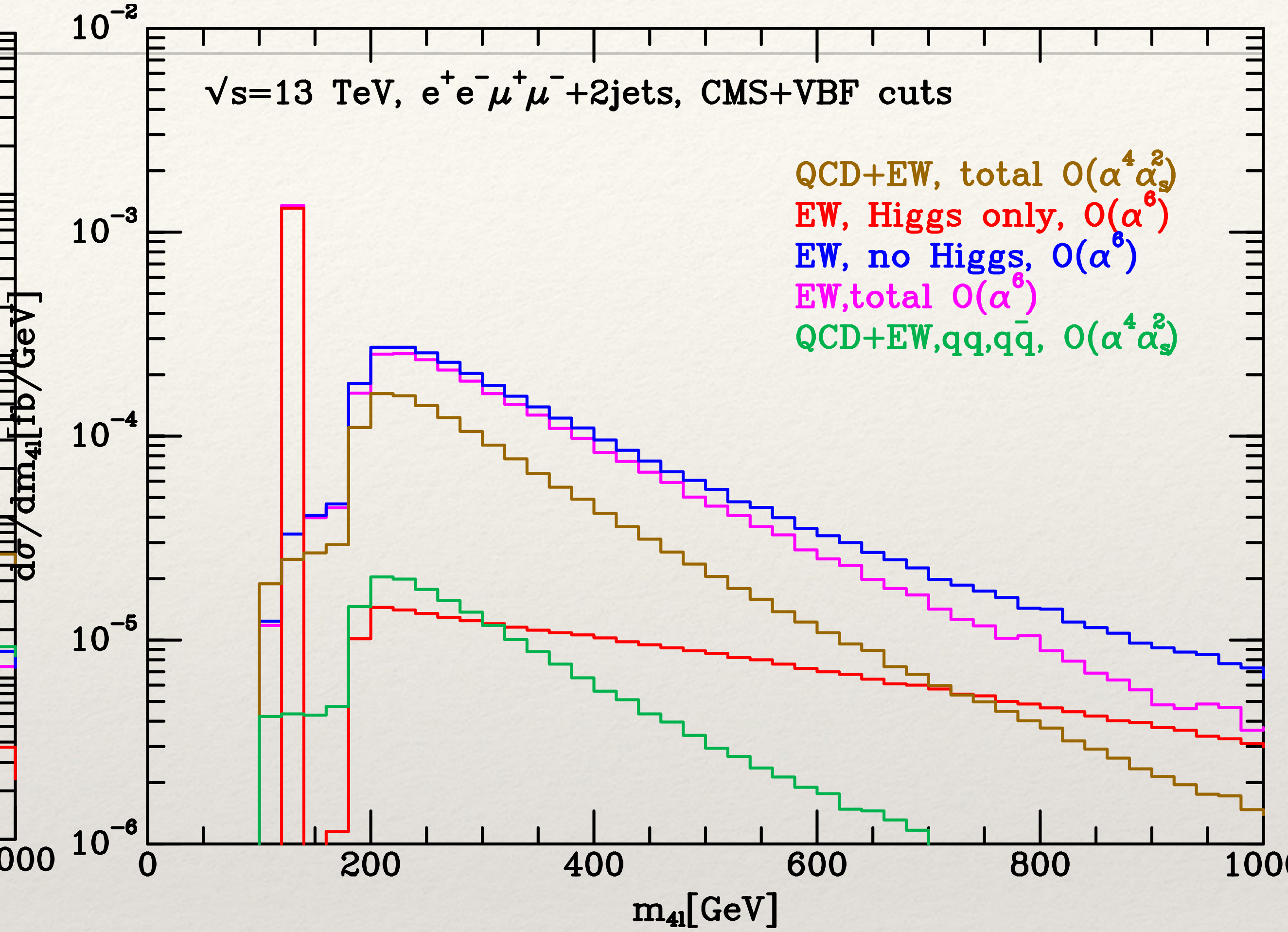
- $(pp \rightarrow e^- e^+ \mu^- \mu^+)$ vs $(pp \rightarrow jet+jet+e^- e^+ \mu^- \mu^+$ with VBF cuts)



- EW cross section for Higgs ~10% of gg fusion (before VBF cuts)
- Higgs tail relatively more important in $pp \rightarrow jet+jet+e^- e^+ \mu^- \mu^+$
- Different slope for VBF tail.

VBF cuts @ 13 TeV

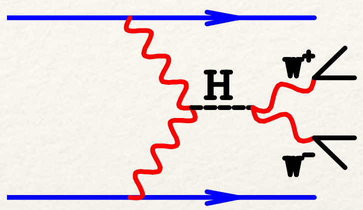




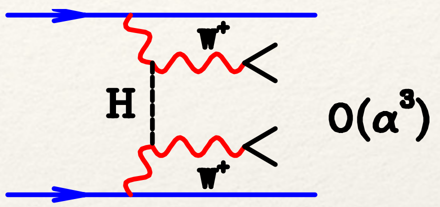
- Run II will give us access to VBF
- VBF cuts reduce the strong background, $O(\alpha^4\ \alpha_s^2)$, but $gq \to gq\ e^-e^+\mu^-\mu^+$ still significant.
- This same statement holds for $W^+W^-, W^\pm Z, ZZ$

New idea

Most useful channel is W^+W^- vs W^+W^+



W^+W^- On-shell



W^+W^+ Off-shell

- In the first instance, we work in the effective coupling framework, where standard couplings are rescaled by κ_V.
- At $\sqrt{s}$=8TeV, SM prediction displays a dependence on κ_V

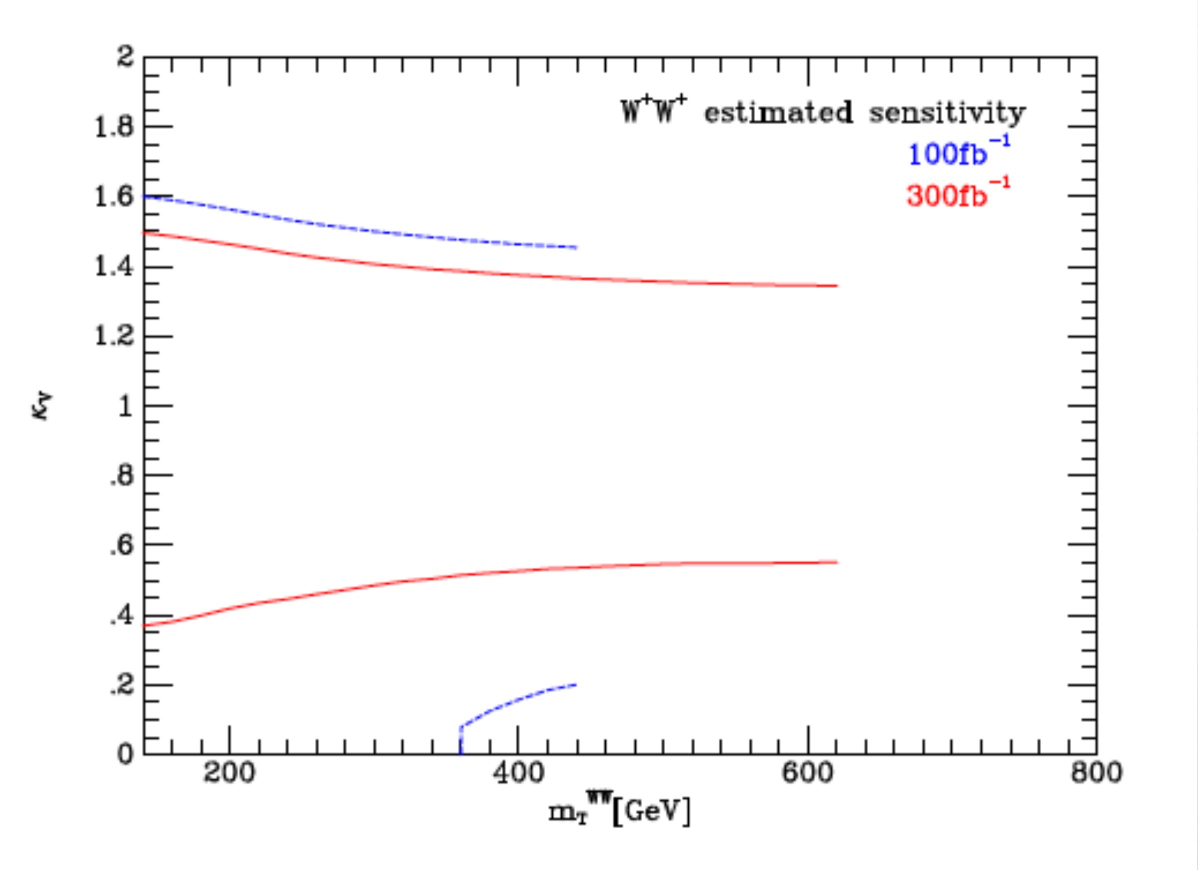
$$\sigma^{same-sign}_{fiducial} = 1.015 - 0.106\,\kappa_V^2 + 0.040\,\kappa_V^4 \text{ fb}\,.$$

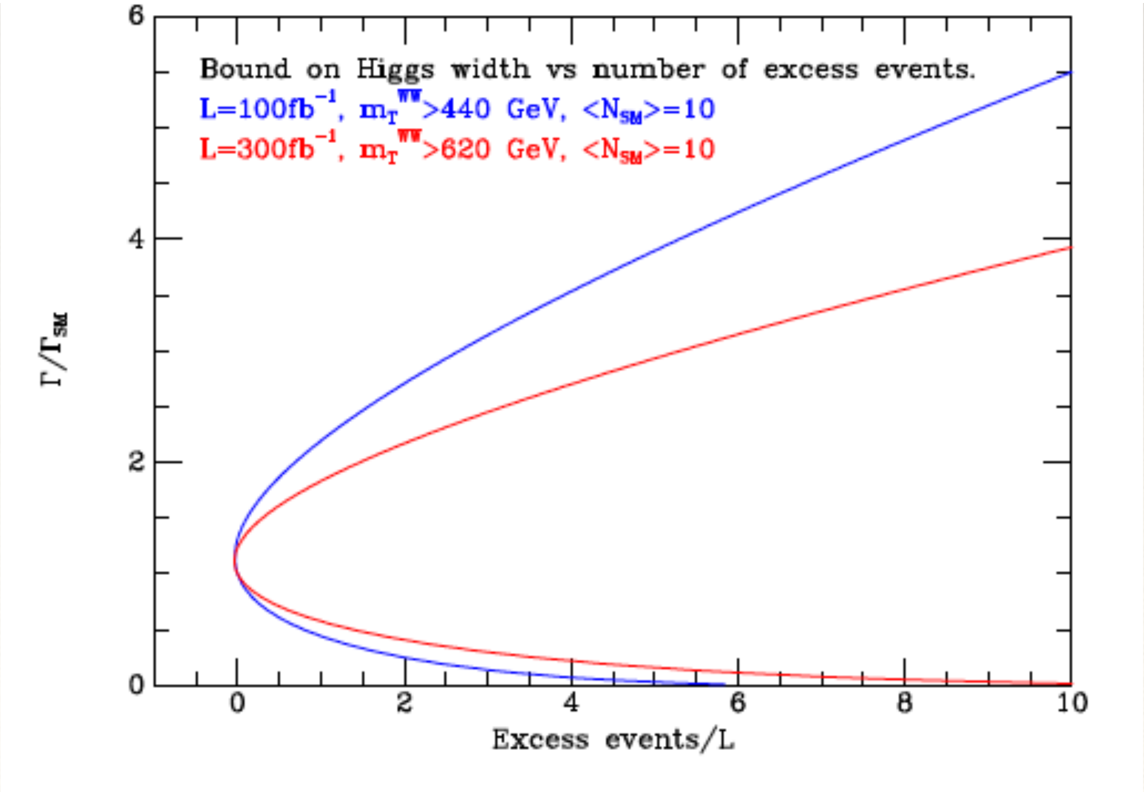
- ATLAS on-shell signal-strength $\mu^{ATLAS}_{VBF} = 1.27^{+0.53}_{-0.45}$
- ATLAS W^+W^+ measurement $\sigma^{measured} = 1.3 \pm 0.4(stat) \pm 0.2(syst)\text{ fb}\,.$
- Bound is $\kappa_V < 7.8\,.$
- current notional width bound $\Gamma_H < 60.8 \times \Gamma_H^{SM}\,.$

Current result

Improvement with 100, 300fb^{-1} at $\sqrt{s}$=13TeV

- Expected upper and lower bounds on κ_V obtained from W^+W^+ events as a function of the transverse mass.
- Bounds are cut off when SM prediction falls below 10 events.
- In all cases the best bounds are achieved, taking the highest possible cut on the transverse mass.
- Possible width bounds with (100, 300fb^{-1}) are similar to those currently obtained from gg fusion (20fb^{-1}).





Effective coupling dependence of other processes

- $\sqrt{s}$=13TeV in 100fb^{-1}
- $M_{(T)}$>300GeV
- Note that numbers are not so different for $\boldsymbol{\kappa}_V$=0 (no Higgs) and $\boldsymbol{\kappa}_V$=1 (SM)
- For this energy and luminosity we cannot place the cut sufficiently high that the non-cancelling terms dominate.

Signal

$$
\begin{aligned}
l^-l^+\nu\bar{\nu}: &\quad N^{\text{off}} = 127.9 - 42.8\,\kappa_V^2 + 20.8\,\kappa_V^4 \\
l^+l^+\nu\nu: &\quad N^{\text{off}} = 37.2 - 18.3\,\kappa_V^2 + 8.3\,\kappa_V^4 \\
l^-l^-\bar{\nu}\bar{\nu}: &\quad N^{\text{off}} = 11.0 - 4.1\,\kappa_V^2 + 1.8\,\kappa_V^4 \\
l^+l^-l^+\nu: &\quad N^{\text{off}} = 23.5 - 6.8\,\kappa_V^2 + 3.2\,\kappa_V^4 \\
l^+l^-l^-\bar{\nu}: &\quad N^{\text{off}} = 11.3 - 3.3\,\kappa_V^2 + 1.6\,\kappa_V^4 \\
l^-l^+l^-l^+: &\quad N^{\text{off}} = 6.0 - 3.0\,\kappa_V^2 + 1.5\,\kappa_V^4
\end{aligned}
$$

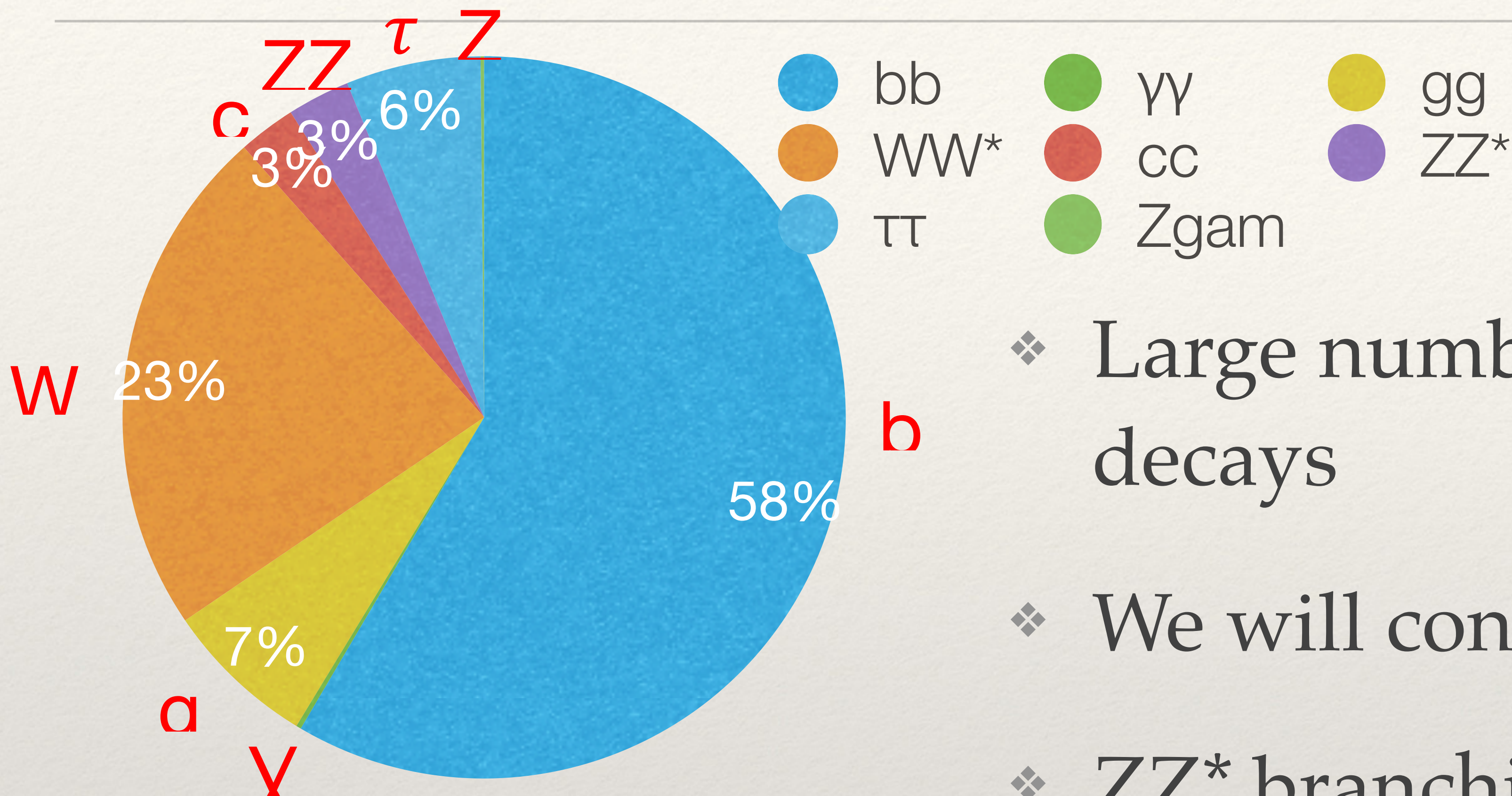
Signal + Background

$$
\begin{aligned}
l^-l^+\nu\bar{\nu}: &\quad N^{\text{off}} = 224.8 - 42.8\,\kappa_V^2 + 20.8\,\kappa_V^4 \\
l^+l^+\nu\nu: &\quad N^{\text{off}} = 38.8 - 18.3\,\kappa_V^2 + 8.3\,\kappa_V^4 \\
l^-l^-\bar{\nu}\bar{\nu}: &\quad N^{\text{off}} = 11.5 - 4.1\,\kappa_V^2 + 1.8\,\kappa_V^4 \\
l^+l^-l^+\nu: &\quad N^{\text{off}} = 60.1 - 6.8\,\kappa_V^2 + 3.2\,\kappa_V^4 \\
l^+l^-l^-\bar{\nu}: &\quad N^{\text{off}} = 29.5 - 3.3\,\kappa_V^2 + 1.6\,\kappa_V^4 \\
l^-l^+l^-l^+: &\quad N^{\text{off}} = 9.0 - 3.0\,\kappa_V^2 + 1.5\,\kappa_V^4
\end{aligned}
$$

Conclusions

- Sensitivity to κ_V decreases as the standard model value $\kappa_V = 1$ is approached.
- With samples of order $100 fb^{-1}$ we can reach similar bounds on the Higgs boson width from VBF, as we currently have with gluon fusion, but with different theoretical systematics.

How can we probe a 4 MeV width for the Higgs?



- Large number of observable SM Higgs decays
- We will consider ZZ*,WW*.
- ZZ* branching ratio is 3%, (but before BR to observable mode).
- $_H^{SM}$≈4 MeV, c.f. jet resolution ~ 1GeV.
- re there other contributions to the tota idth?

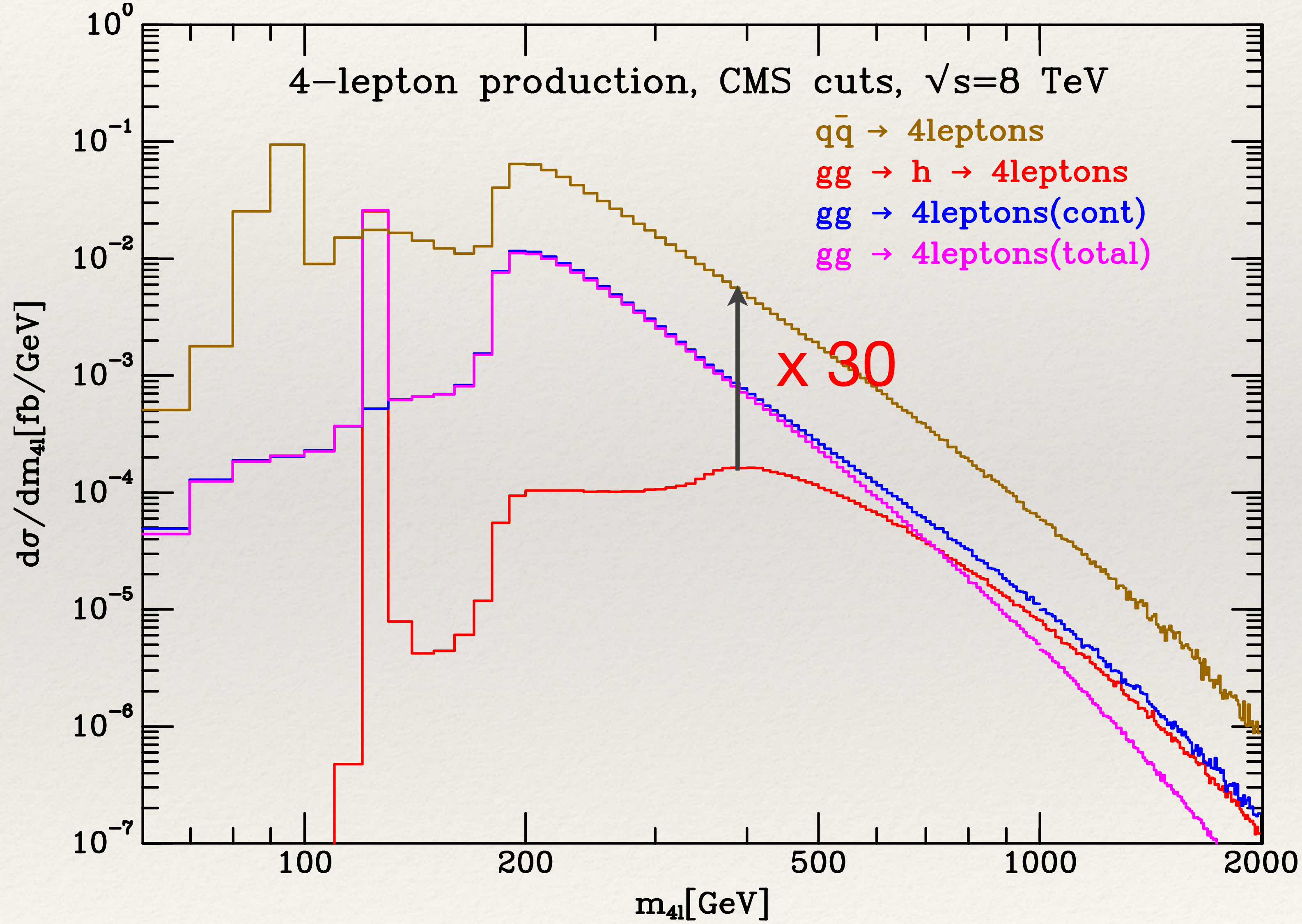
Particle	Width[MeV]	Lifetime[s]
t	$\sim 1,300$	$\sim 5 \times 10^{-25}$
W	$\sim 2,000$	$\sim 3 \times 10^{-25}$
Z	$\sim 2,500$	$\sim 2.6 \times 10^{-25}$
h	4.21 ± 0.16	$\sim 1.65 \times 10^{-22}$
b	4.4×10^{-10}	$\sim 1.5 \times 10^{-12}$

The big picture @ 8TeV

- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect off-resonance.
- Destructive at large mass, as expected.
- With the standard model width, Γ_H, challenging to see enhancement / deficit due to Higgs channel.
- 3 phenomena happening in the tail.

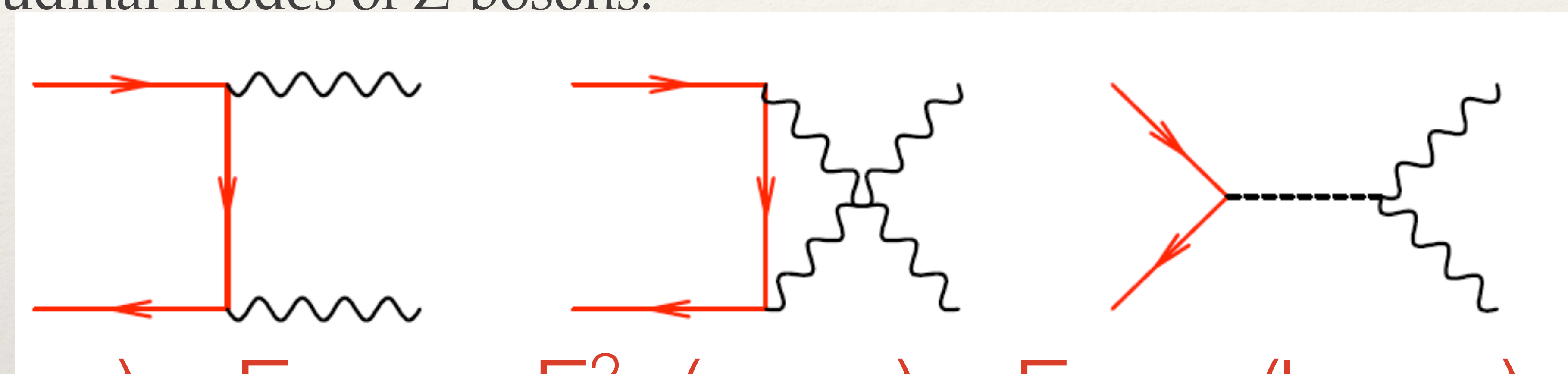
$$p_{T,\mu} > 5 \text{ GeV}\,, \quad |\eta_\mu| < 2.4\,,$$
$$p_{T,e} > 7 \text{ GeV}\,, \quad |\eta_e| < 2.5\,,$$
$$m_{ll} > 4 \text{ GeV}\,, \quad m_{4\ell} > 100 \text{ GeV}\,.$$

CMS cuts
CMS PAS HIG-13-002



Higgs being Higgs

- Consider right hand side of gluon-gluon initiated diagrams.
- tt → ZZ, longitudinal modes of Z-bosons.

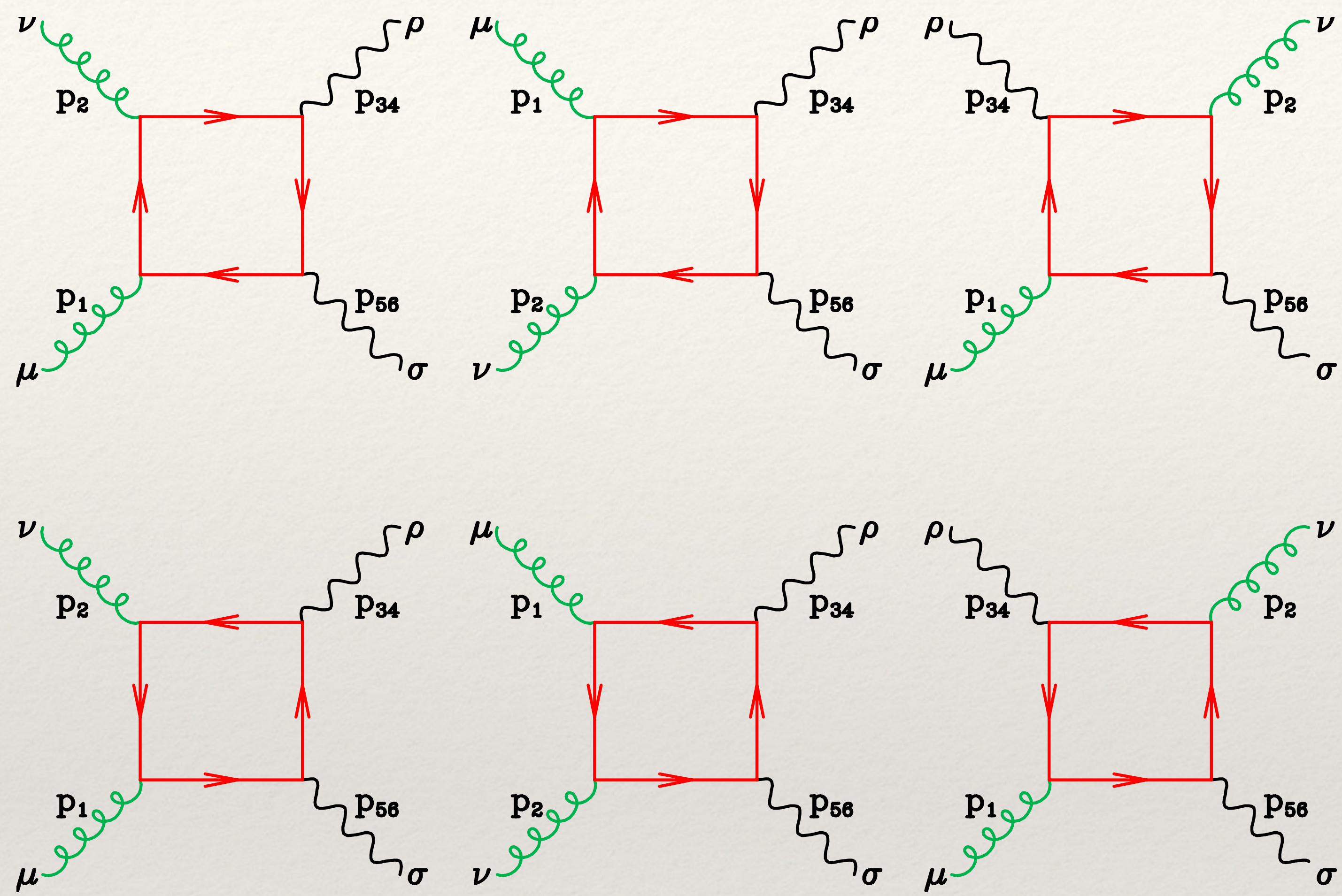


$a_2E^2+(b_1+a_1)m_tE$ $\quad$ $-a_2E^2+(c_1-a_1)m_tE$ $\quad$ $-(b_1+c_1)\, m_tE$

- Higgs tail has to be there to cancel bad high energy behavior of continuum diagrams.
- Observation of this cancellation, (if possible) is as interesting as longitudinal WW,ZZ scattering.

- First cancellation due to the gauge structure
- Second cancellation requires the Higgs
- c.f Lee, Quigg and Thacker

Diagrams for gg→Z/g* +Z/g* (background)



- We perform a stable, analytic calculation of these diagrams and their interference with the Higgs diagrams.
- Obtaining numerical stability is challenging for automatic procedures. Human intervention required.