Higgs constraints from vector boson fusion and scattering

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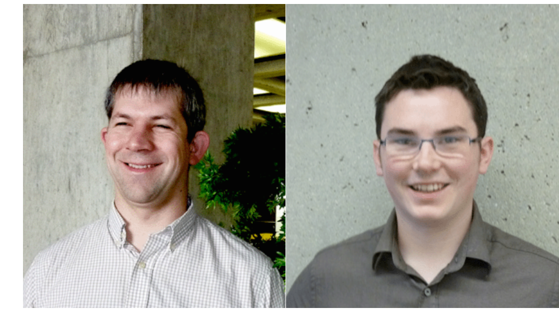
- MCFM v7.0
- Off-shell behavior in $gg \to ZZ$
- Rates for vector boson scattering.
- The importance of W^+W^+
- Prospects for coupling and width measurement.

- Campbell, RKE, Giele, 1503.06182, Campbell, RKE, 1502.02990,
- Campbell, RKE,Furlan,Rontsch, 1409.1897, Campbell, RKE, Williams, 1312.1628,1311.3589

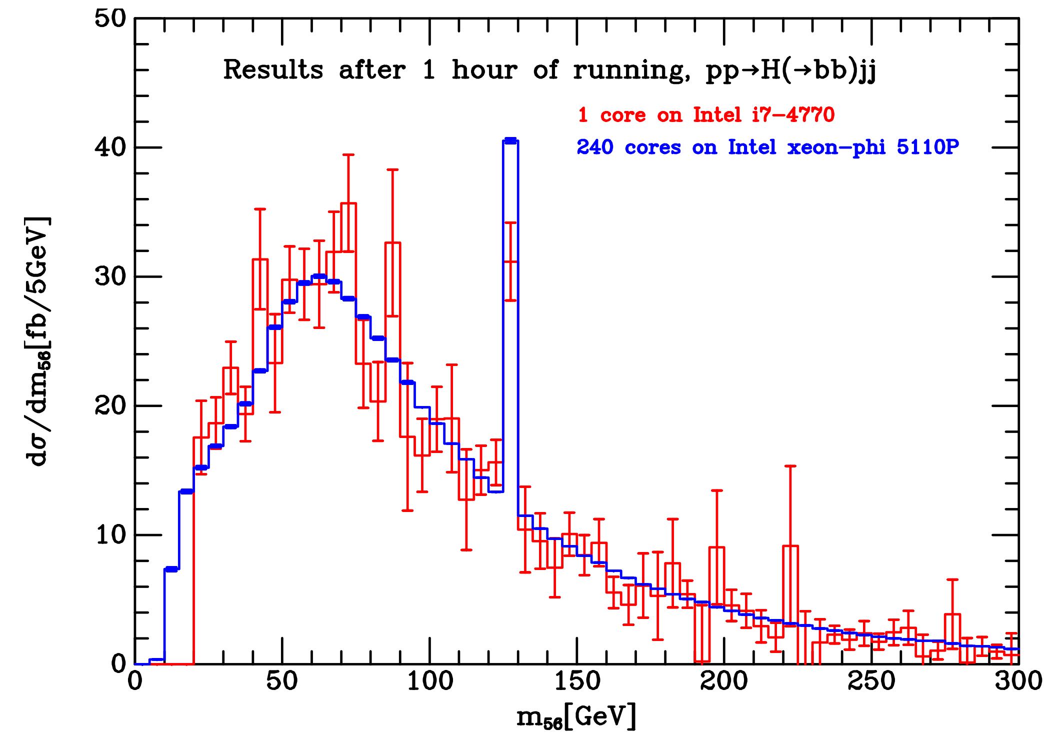
MCFM (Monte Carlo for FeMtobarn processes)



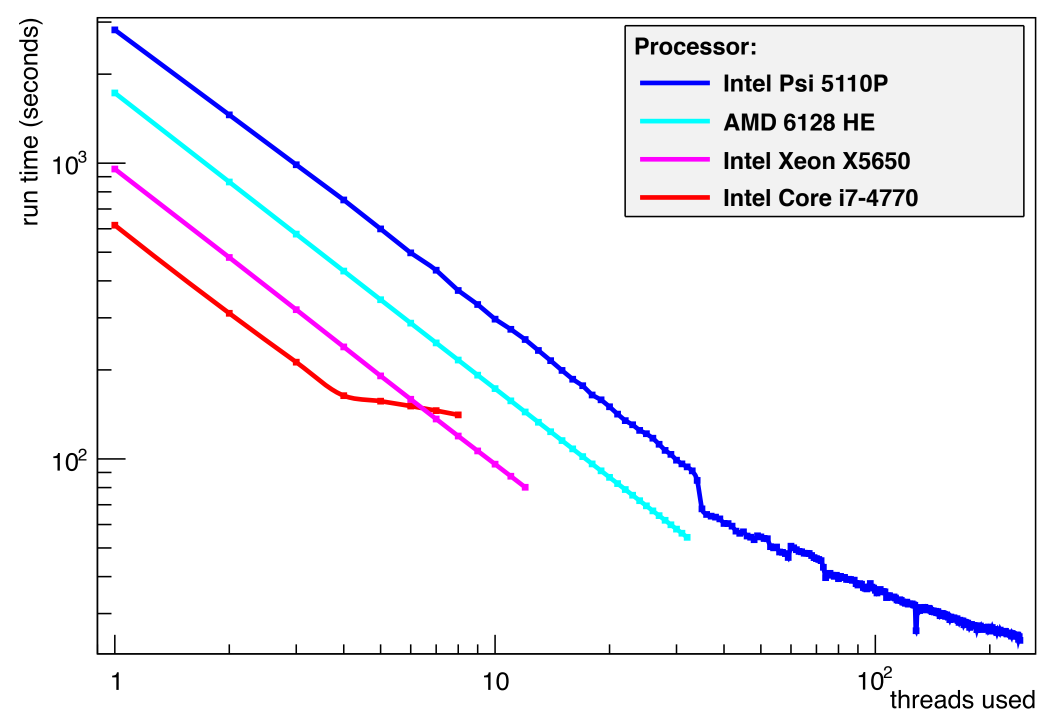
- MCFM is a parton-level Monte Carlo program that computes hadron-collider cross sections at NLO [Campbell, RKE, Williams]
- Gives access to explicit final states, distributions.
- Implements analytic results for matrix elements, so fast and numerically stable.
- Flexible, freely distributed code, widely used in the community
- Theoretical predictions for more than 300 processes, (extensive use at Tevatron and LHC, (cited by > 650 experimental papers).
- Significant role as a catalyst for other theoretical efforts.
- Eight updates to the code in the last eight years.
- OpenMP version of MCFM v7.0 in March 2015.

MCFM and Open Multi-processing

- OpenMP offers standardized way of exploiting multi-threading.
- e.g. standard option for gfortran and intel compilers.
- Automatically uses all available threads
- Non destructive of the single thread code, (compiler directives are interpreted as comments, if compiled without openMP flag).
- Full statistics contributes to the adaptation of the VEGAS grid.
- It is our intention that the only thing that user is aware of is code speed-up.



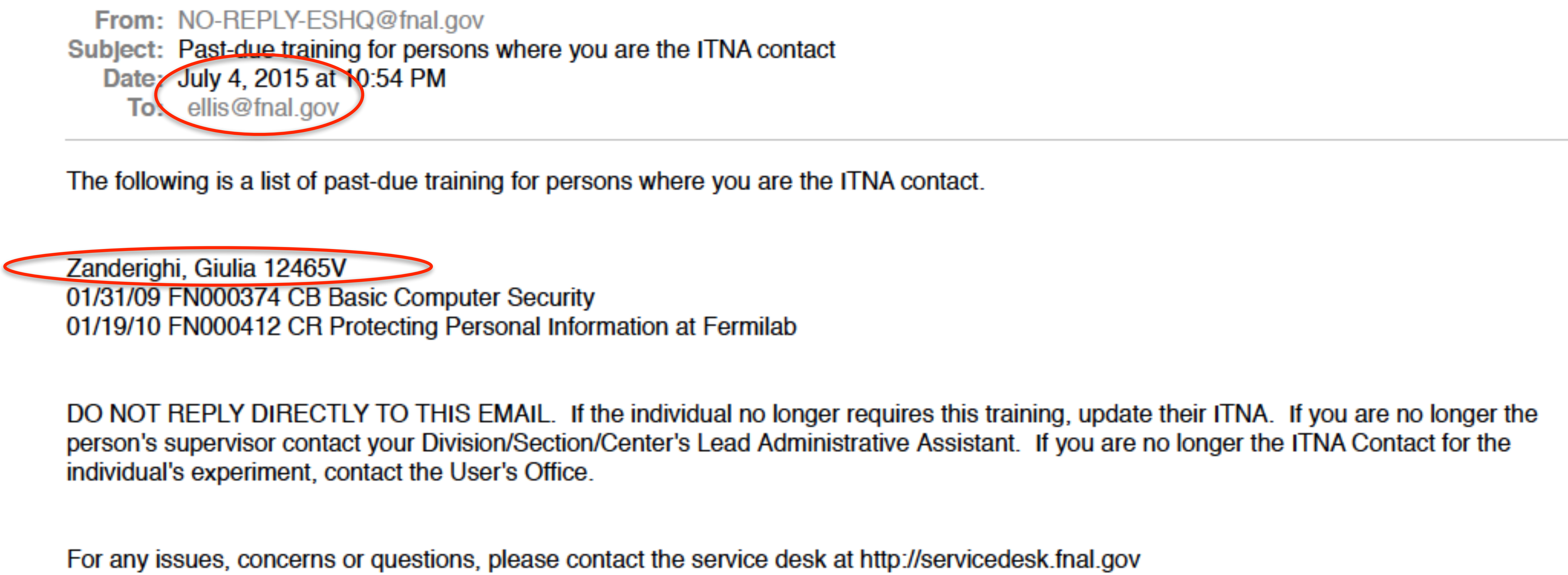
PP-> H(->bb)+ 2 jets @ NLO (140,000 events)



Speedup of 98x with 128 cores

MCFM7.0 is available for download (by properly trained individuals)

* mcfm.fnal.gov
* OpenMP version of MCFM v7.0 in March 2015.


From: NO-REPLY-ESHQ@fnal.gov
Subject: Past-due training for persons where you are the ITNA contact
Date: July 4, 2015 at 10:54 PM
To: ellis@fnal.gov

The following is a list of past-due training for persons where you are the ITNA contact.

Zanderighi, Giulia 12465V
01/31/09 FN000374 CB Basic Computer Security
01/19/10 FN000412 CR Protecting Personal Information at Fermilab

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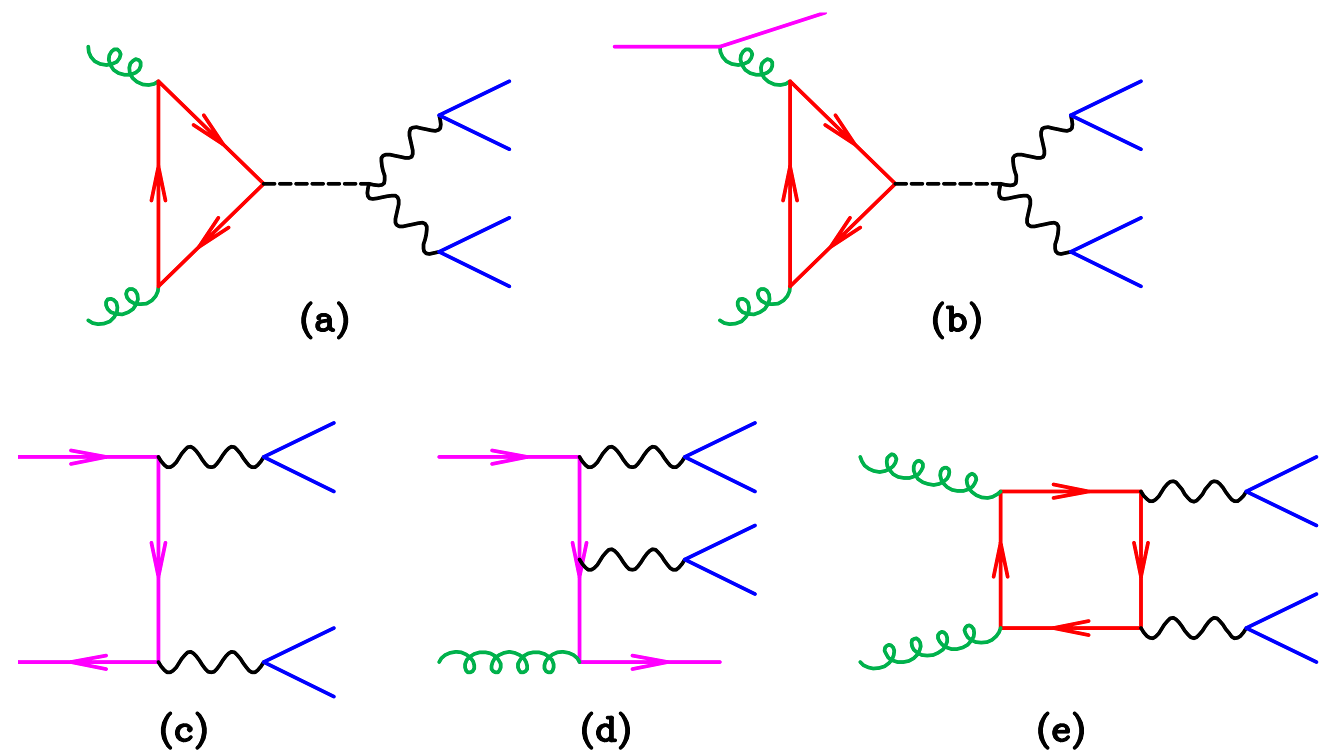
Higgs constraints from gluon-gluon fusion

pp→e⁻e⁺μ⁻μ⁺ in the standard model

- Mishmash of orders in perturbation theory

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

- Representative diagrams are:-
- (a) and (e), (b) and (d) can interfere.
- (b-d) interference does not overwhelm (a-e).



Higgs couplings and width

- Off-shell tail is a valuable source of information about the Higgs production and decay couplings $\sigma_{\text{off}} \propto g_i^2 g_f^2$
- Higgs cross section under the peak depends on ratio of couplings and width.

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

- So 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).
- Taking ratio $$\frac{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{experimental gg}}}{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{theoretical SM}}} = \frac{\Gamma}{\Gamma^{\text{SM}}}$$
- Ratio depends linearly on the Higgs boson width, (but see later).

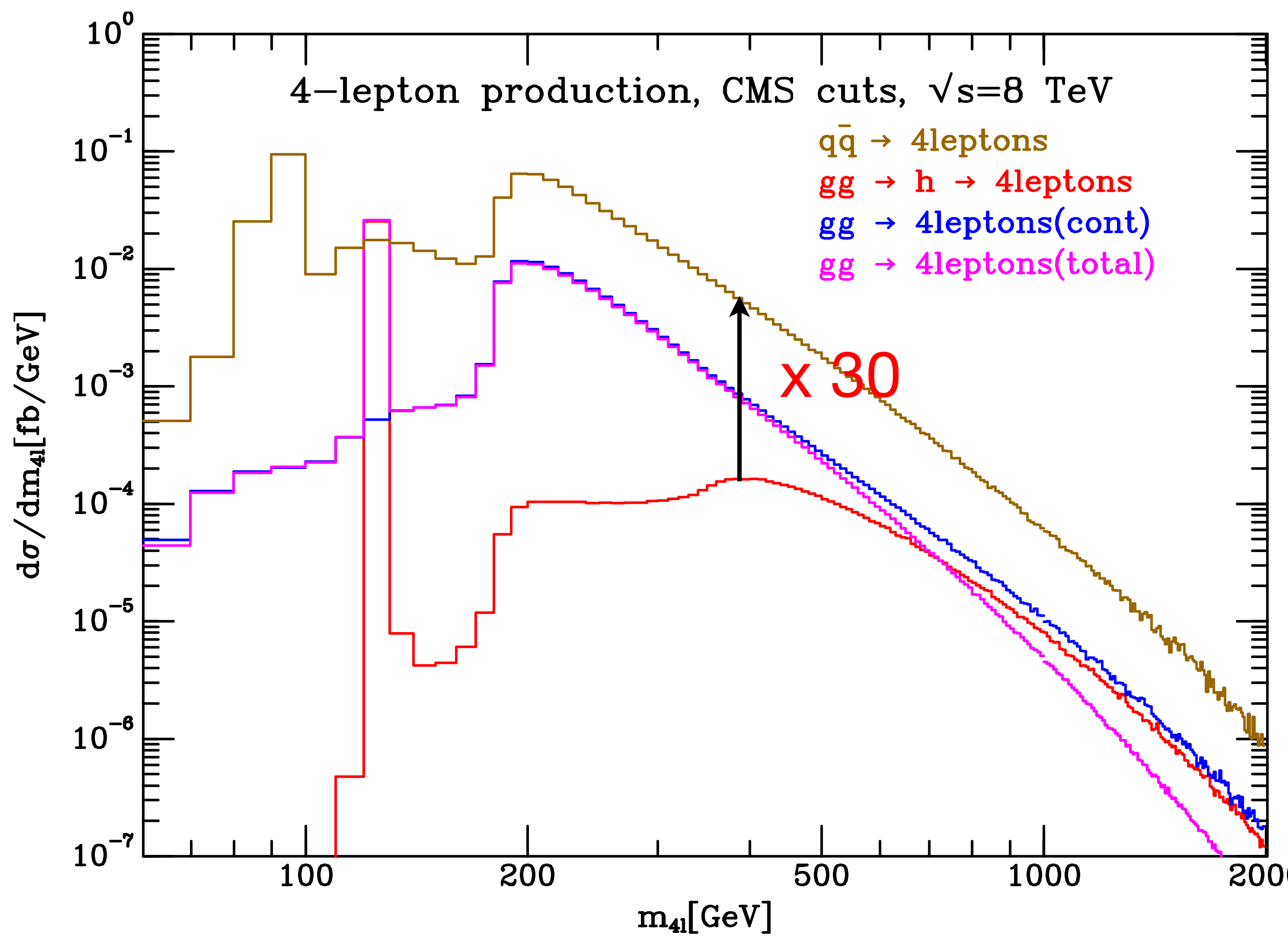
Caola-Melnikov 1307.4935

The big picture @ 8TeV

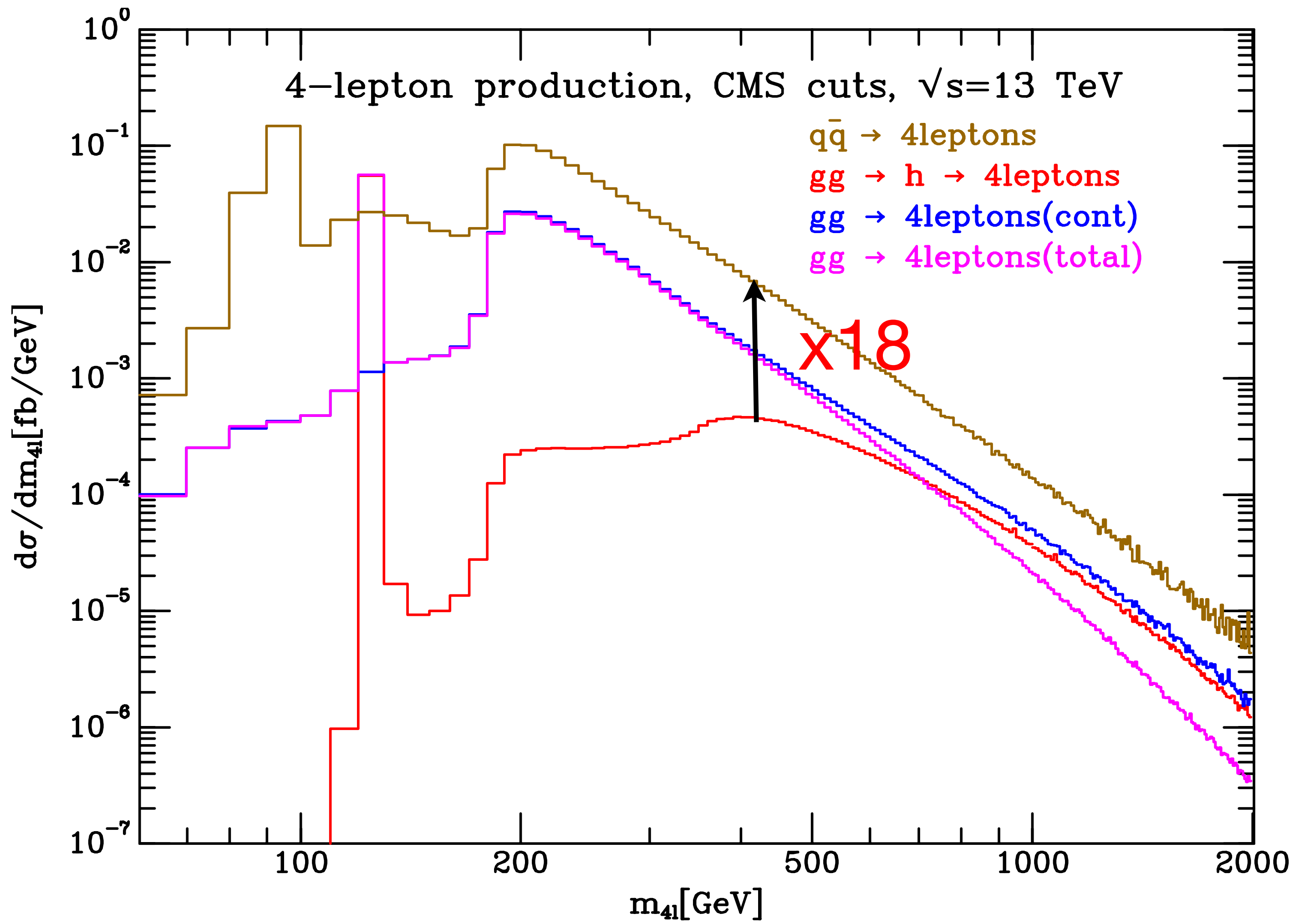
- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect off-resonance.
- Destructive at large mass, as expected.
- With the standard model width, Γ_H, challenging to see enhancement/ deficit due to Higgs channel.
- 3 phenomena happening in the tail.

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

CMS cuts
CMS PAS HIG-13-002



The big picture @ 13 TeV



- σ_{qqb} (m_{4l}=400)/σ^{H}_{gg} (m_{4l}=400) ≈ 18 at √s=13 TeV
- (c.f. ~30 at √s=8 TeV).
- Higgs off-shell contribution is relatively bigger at higher energy.

Criticisms of the CM method

- The CM method relies on the assumption that the on-shell (at m_{4l}=125 GeV) and off-shell couplings (at m_{4l}≈400 GeV) are the same. Englert et al, 1410.5440,1405.0285

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

- K-factor of interference of background and signal only approximately known. Melnikov, 1503.0127,Li et al, 1504.02388

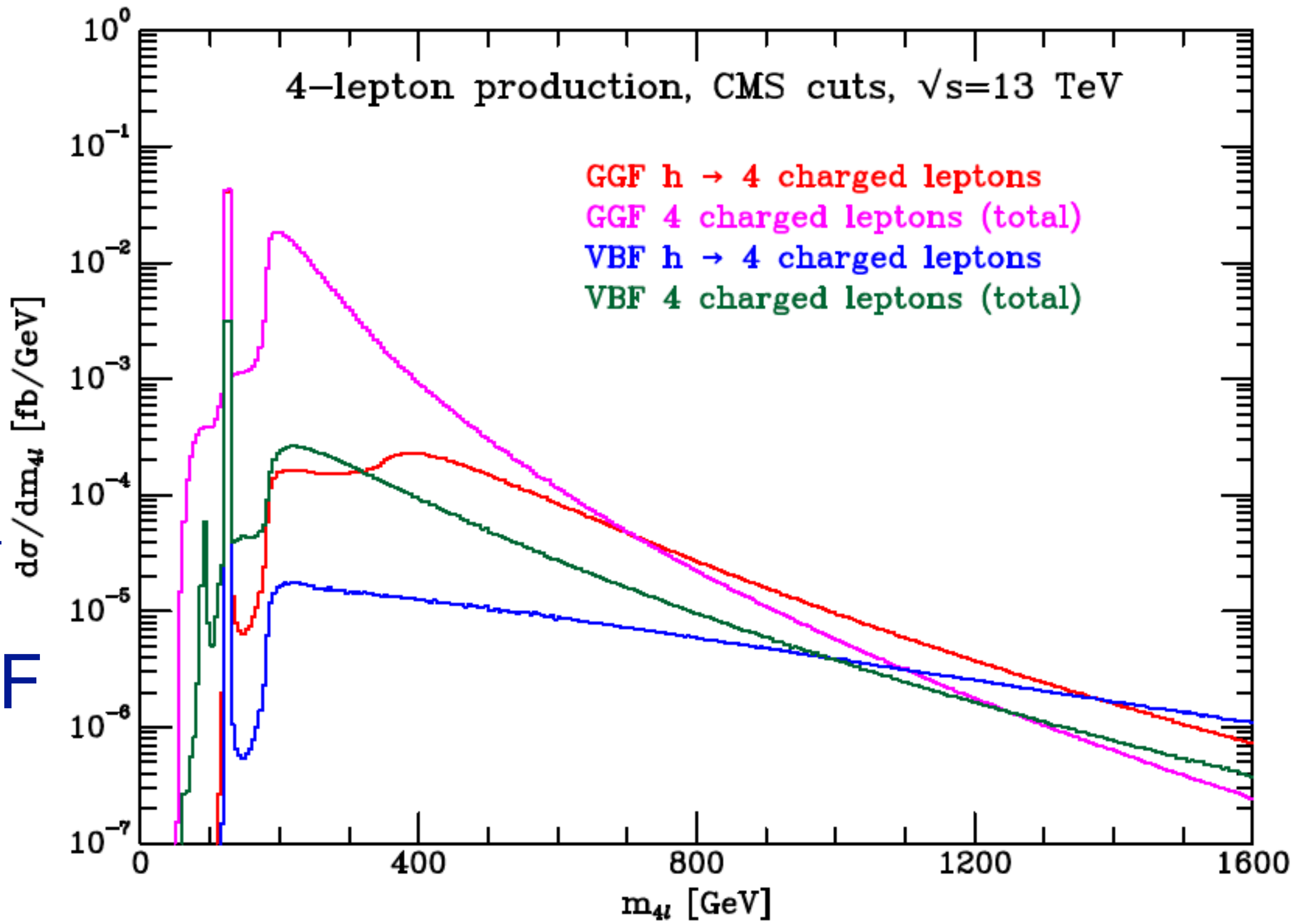
- We will therefore investigate the same method in VBF Higgs production which has a different theoretical "systematic".

- VBF starts at tree graph level.

Gluon-gluon fusion vs Vector boson fusion

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

- EW cross section for Higgs ~10% of gg fusion.
- Higgs tail relatively more important in pp → jet+jet+$e^-e^+\mu^-\mu^+$
- Different slope for VBF Higgs tail (E^2 vs E).



Diagrams for pp → jet+jet+$e^-e^+\mu^-\mu^+$

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

$$p_{T,J} > 20 \text{ GeV}\,, |\eta_J| < 4.5\,, R = 0.4\,.$$

- CMS lepton cuts

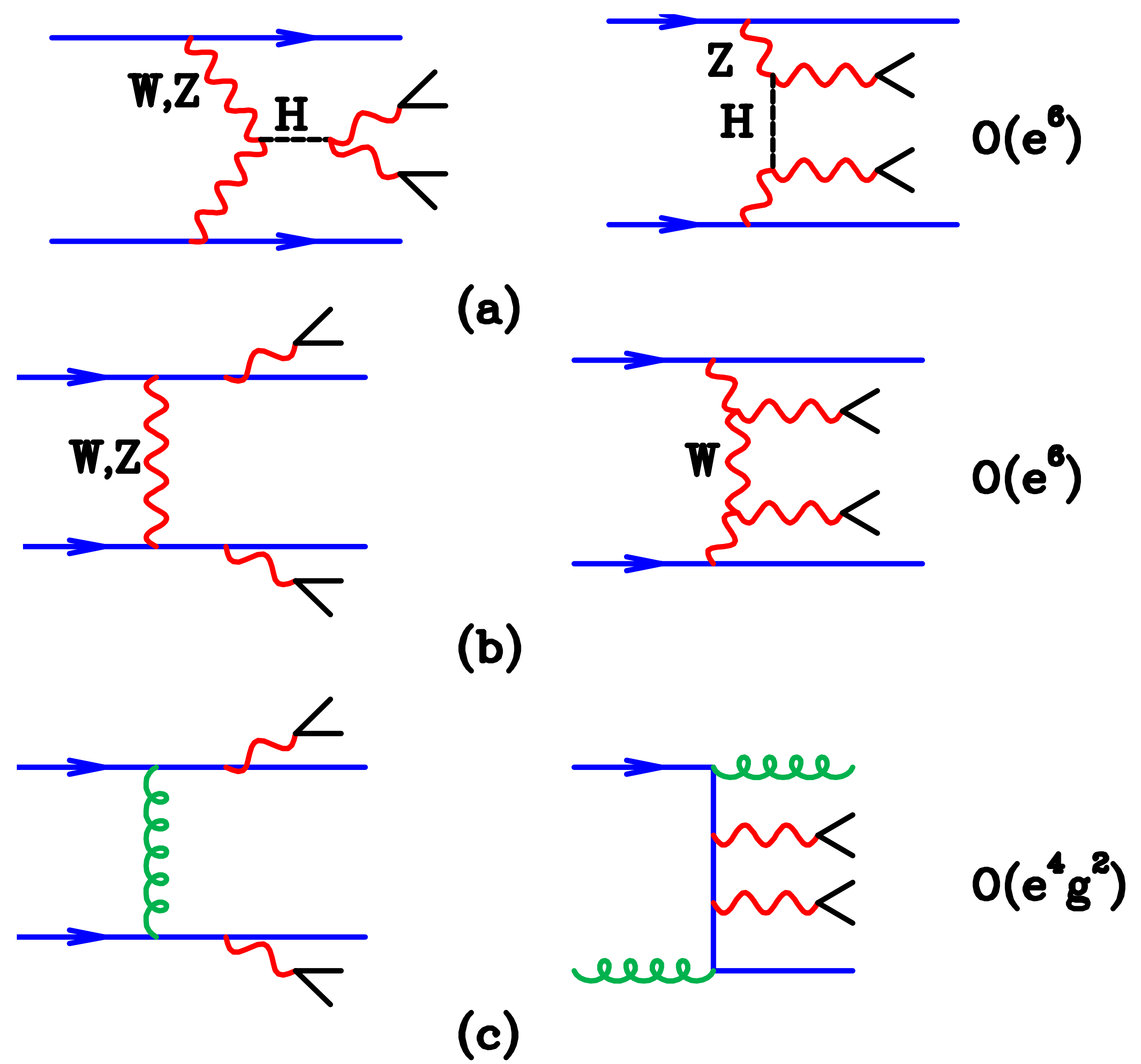
$$p_{T,\ell} > 20 \text{ GeV}\,,\quad |\eta_\ell| < 2.5\,,$$
$$m_{ll} > 10 \text{ GeV}\,,\quad \text{for all charged lepton combinations.}$$

$$\not{E}_T > 40 \text{ GeV}\,.$$

- Additional VBF cuts

$$y_{gap} > 2.5,\quad \eta_1 \times \eta_2 < 0,\quad m_{j_1 j_2} > 500 \text{ GeV}.$$

$$\eta_J^{min} < \eta_\ell < \eta_J^{max}\,.$$



Shorthand notation, WW,WZ,ZZ

- Processes referred to as $W^-W^+, W^\pm W^\pm, W^\pm Z, ZZ$
- This is a short-hand for all doubly-resonant, singly-resonant and non-resonant contributions that lead to the same four lepton final state.
- e.g. the doubly resonant processes are:-

$$q+q \to W^+ + W^- + q + q$$
$$\hookrightarrow \mu^- + \nu_\mu$$
$$\hookrightarrow \nu_e + e^+$$

$$q+q \to W^+ + W^+ + q + q$$
$$\hookrightarrow \nu_\mu + \mu^+ \tag{1.3}$$
$$\hookrightarrow \nu_e + e^+$$

$$q+q \to W^- + W^- + q + q$$
$$\hookrightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e$$

$$q+q \to W^+ + Z/\gamma + q + q$$
$$\hookrightarrow \mu^- + \mu^+ \tag{1.5}$$
$$\hookrightarrow \nu_e + e^+$$

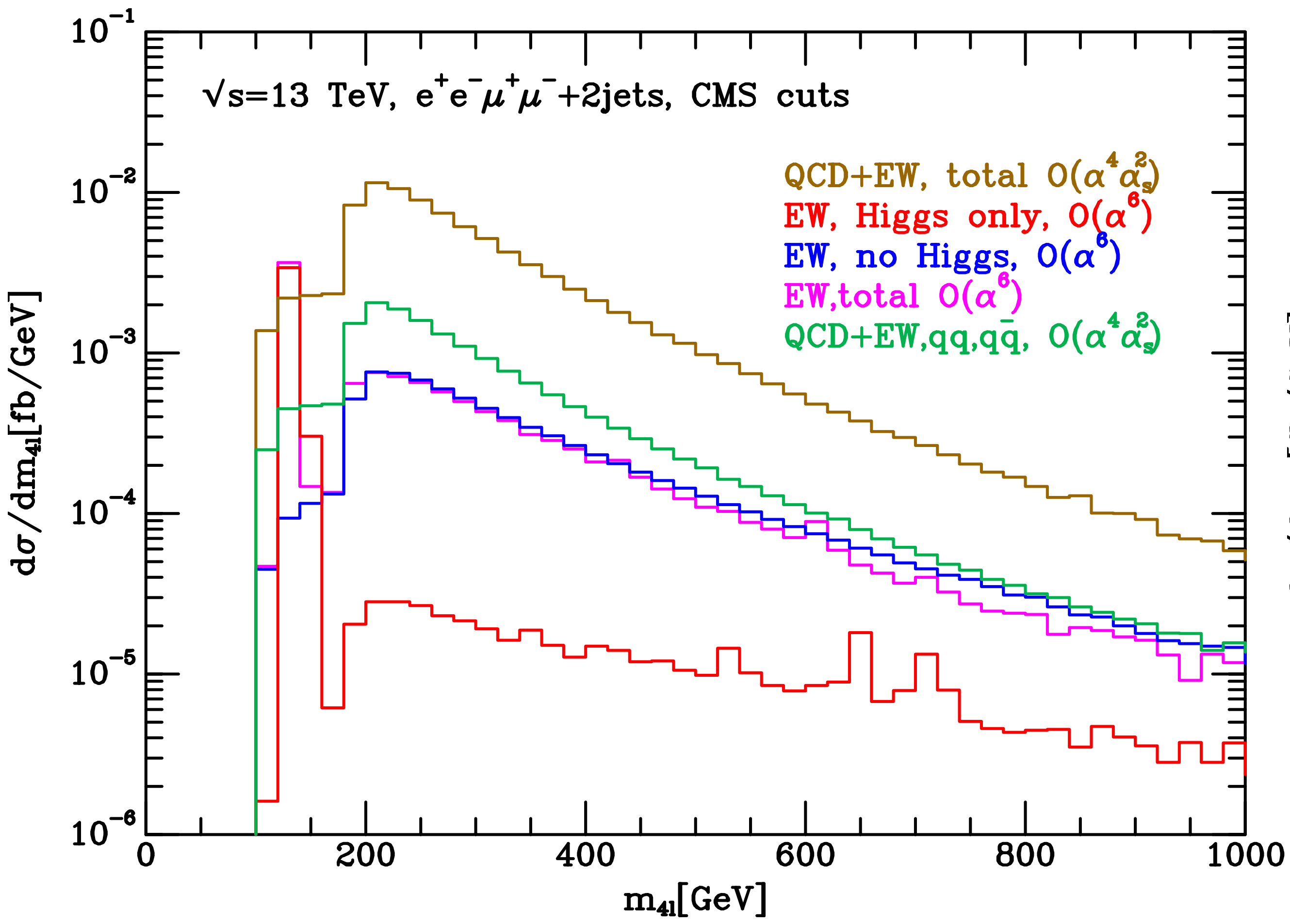
$$q+q \to W^- + Z/\gamma + q + q$$
$$\hookrightarrow \mu^- + \mu^+$$
$$\hookrightarrow e^- + \nu_e$$

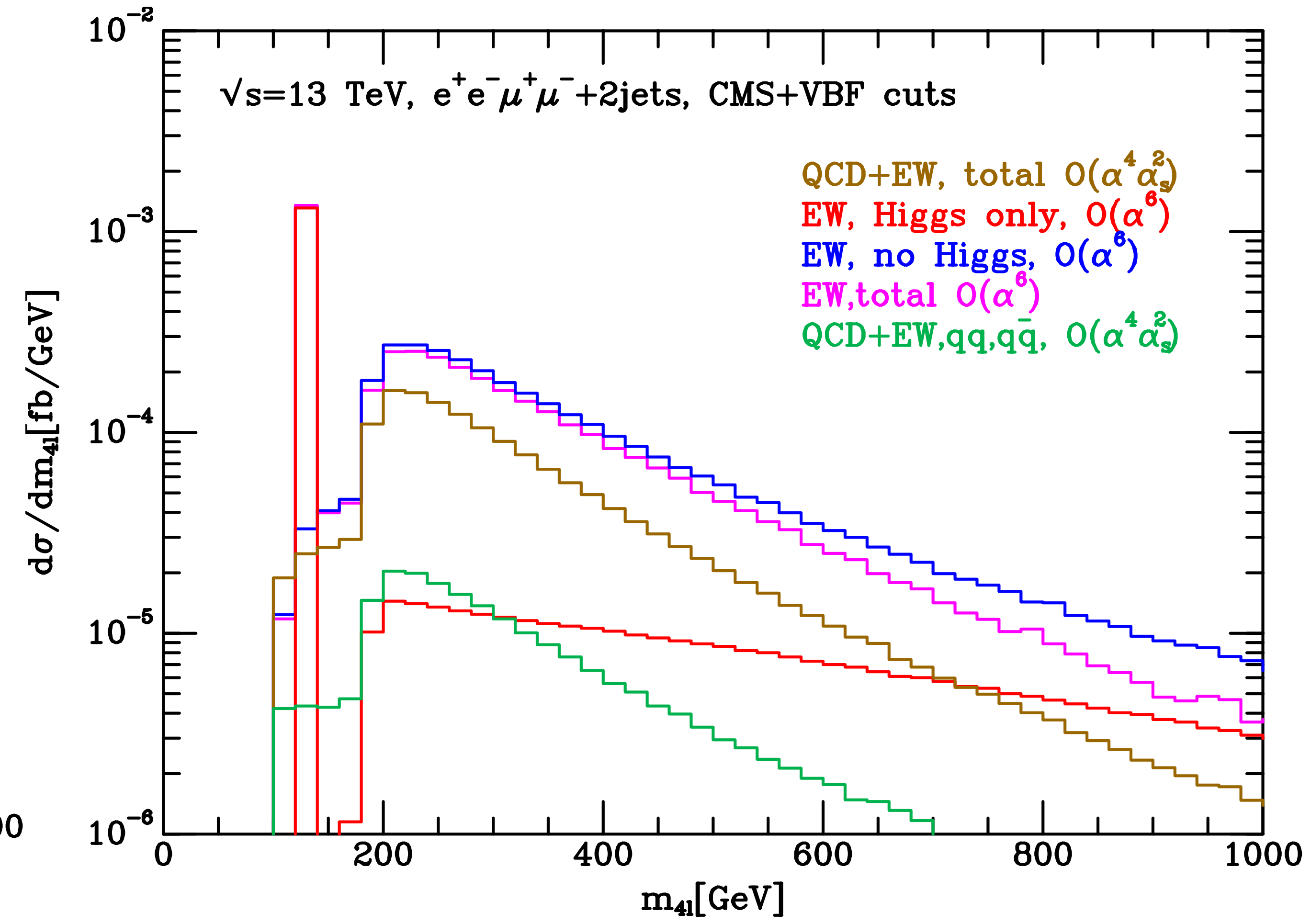
$$q+q \to Z/\gamma + Z/\gamma + q + q$$
$$\hookrightarrow \mu^- + \mu^+ \tag{1.7}$$
$$\hookrightarrow e^- + e^+$$

$$q+q \to Z/\gamma + Z + q + q$$
$$\hookrightarrow \nu_\mu + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + e^+$$

VBF cuts @ 13 TeV

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





Rates for signal and background

Signal, O(α^6)

Process	Nominal process	Cut	σ [fb] $O(\alpha^6)$	Factor	Events in 100 fb^{-1}
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e jj$	W^-W^+	$m_T^{WW} > 300$ GeV	0.2378	x4	95
$pp \to \nu_e e^+\nu_\mu\mu^+ jj$	W^+W^+	$m_T^{WW} > 300$ GeV	0.1358	x2	27
$pp \to e^-\bar{\nu}_e\mu^-\bar{\nu}_\mu jj$	W^-W^-	$m_T^{WW} > 300$ GeV	0.0440	x2	9
$pp \to \nu_e e^+\mu^-\mu^+\mu^+ jj$	W^+Z	$m_T^{WZ} > 300$ GeV	0.0492	x4	20
$pp \to e^-\bar{\nu}_e\mu^-\mu^+ jj$	W^-Z	$m_T^{WZ} > 300$ GeV	0.0242	x4	10
$pp \to l^-l^+\nu_l\bar{\nu}_l jj$	ZZ	$m_T^{ZZ} > 300$ GeV	0.0225	x6	14
$pp \to l^-l^+\nu_l\bar{\nu}_l jj$	ZZ	$m_T^{WW} > 300$ GeV	0.0181	x6	11
$pp \to e^-e^+\mu^-\mu^+ jj$	ZZ	$m_{4l} > 300$ GeV	0.0218	x2	4

W$^+$W$^+$

Table 3. Electroweak ($\mathcal{O}(\alpha^6)$) cross sections at $\sqrt{s} = 13$ TeV, under the cuts given in Eqs. (2.2)–(2.6) and the off-shell definition specified in the table. The factor gives the approximate number by which the result shown for specific lepton flavours must be multiplied to account for two flavours of charged leptons, e, μ and three flavours of neutral leptons, ν_e, ν_μ, ν_τ.

Factor takes into account sum over e,μ and ν_e,ν_μ,ν_τ

c.f. ttbar 254 events

Background, O(α^{4}α$_s$^{2})

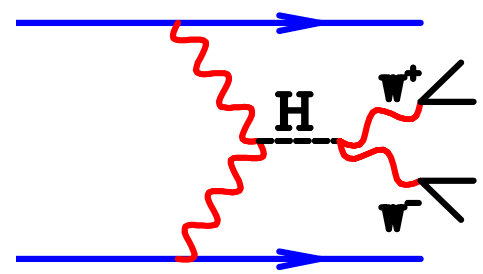
Process	Nominal process	Cut	σ [fb] $O(\alpha^4\alpha_s^2)$	Factor	Events in 100 fb^{-1}
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e jj$	W^-W^+	$m_T^{WW} > 300$ GeV	0.2227	x4	89
$pp \to \nu_e e^+\nu_\mu\mu^+ jj$	W^+W^+	$m_T^{WW} > 300$ GeV	0.0079	x2	2
$pp \to e^-\bar{\nu}_e\mu^-\bar{\nu}_\mu jj$	W^-W^-	$m_T^{WW} > 300$ GeV	0.0025	x2	0
$pp \to \nu_e e^+\mu^-\mu^+\mu^+ jj$	W^+Z	$m_T^{WZ} > 300$ GeV	0.0916	x4	37
$pp \to e^-\bar{\nu}_e\mu^-\mu^+ jj$	W^-Z	$m_T^{WZ} > 300$ GeV	0.0454	x4	18
$pp \to l^-l^+\nu_l\bar{\nu}_l jj$	ZZ	$m_T^{ZZ} > 300$ GeV	0.0143	x6	9
$pp \to l^-l^+\nu_l\bar{\nu}_l jj$	ZZ	$m_T^{WW} > 300$ GeV	0.0118	x6	7
$pp \to e^-e^+\mu^-\mu^+ jj$	ZZ	$m_{4l} > 300$ GeV	0.0147	x2	3

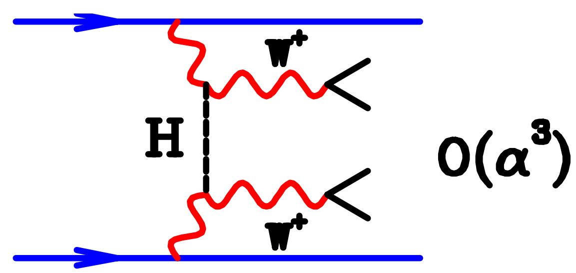
W$^+$W$^+$

Table 4. Mixed QCD-electroweak ($\mathcal{O}(\alpha^4\alpha_s^2)$) cross sections at $\sqrt{s} = 13$ TeV, under the cuts given in Eqs. (2.2)–(2.6) and the off-shell definition specified in the table.

Ignore other sources of background, W+jet, QCD…..

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 $\Gamma_H < 60.8 \times \Gamma_H^{SM} .$

Suitability of effective operator formalism.

- First consider interim framework with (same) rescaled SM Higgs couplings to W and Z

$$\frac{\Gamma_{WW}}{\Gamma_{WW}^{SM}} = \kappa_V^2, \quad \frac{\Gamma_{ZZ}}{\Gamma_{ZZ}^{SM}} = \kappa_V^2 \ .$$

- We now also consider a higher dimension operator formalism, e.g.

$$\mathcal{L}_{HD} = F_{HD} \ \mathrm{tr}\left[\mathbf{H}^\dagger \mathbf{H} - \frac{v^2}{4}\right] \cdot \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right]$$

- With operator we find Feynman rules

$$hW_\mu^+ W_\nu^- : \qquad i g M_W g_{\mu\nu} \frac{v^2 F_{HD}}{2} \,,$$

$$hZ_\mu Z_\nu : \qquad i g \frac{M_W}{\cos^2\theta_W} g_{\mu\nu} \frac{v^2 F_{HD}}{2}$$

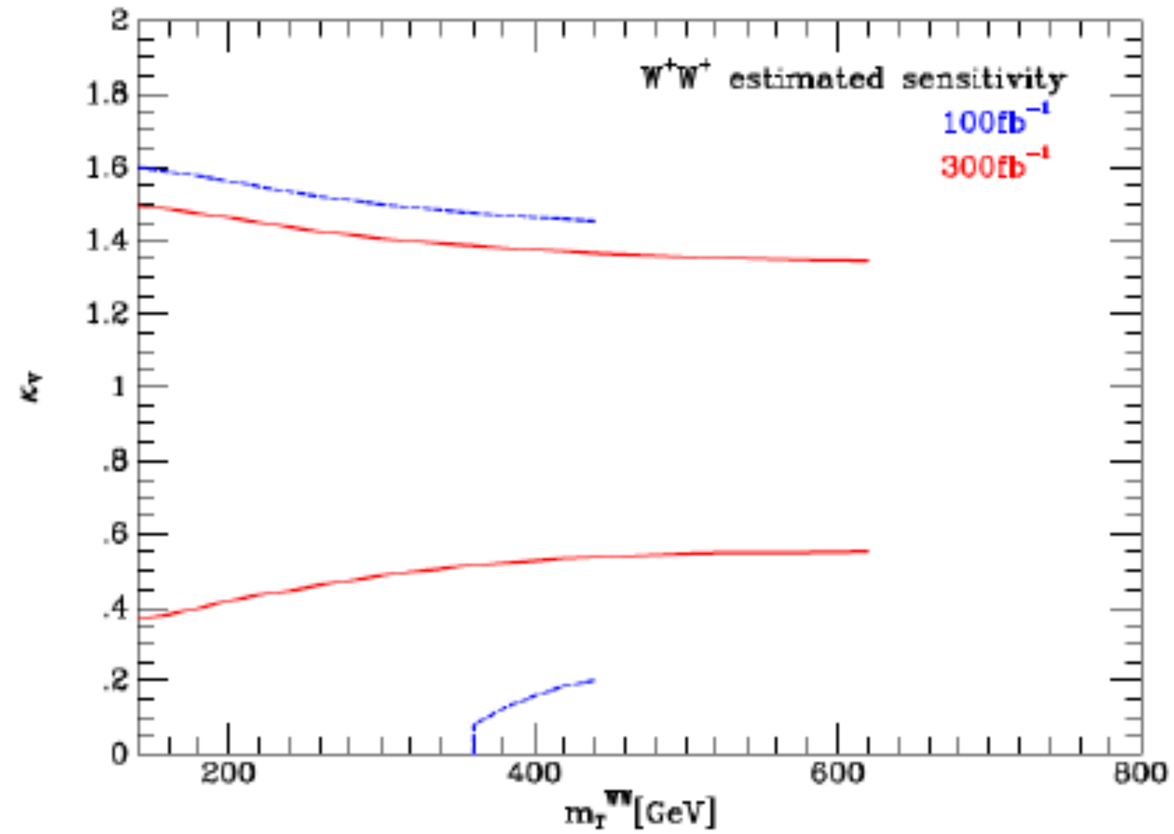
$$\kappa_V = 1 + F_{HD} \frac{v^2}{2}$$

- To probe scales higher that 1TeV will require sensitivity to κ_V at the 3% level.

- Premature to consider operator formalism.

Limits from runs 2 and 3

- Perform a simple analysis to determine optimal cut m_{cut} to isolate the off-shell tail.
- Define a statistical uncertainty $\delta=\sqrt{N}$. What values of κ_V can be excluded at 95%c.l. by an observation of N+2δ events?
- In all case ensure that m_{cut} corresponds to a SM prediction of at least 10 events.
- Only W^+W^+ provides a lower bound



- For $100fb^{-1}$ at $m_{cut=}$ 440 GeV, we find $0.20< \kappa_V <1.45$
- For $300fb^{-1}$ the best lower limit corresponds to saturating the 10 event limit at m_{cut}=620 GeV, we find $0.55< \kappa_V <1.34$

Effective coupling dependence of other processes

- $\sqrt{s}$=13TeV
- Note that numbers are not so different for κ_V=0 (no Higgs) and κ_V=1(SM).
- For this energy and luminosity we cannot place the cut sufficiently high that non-cancelling terms dominate.

Signal

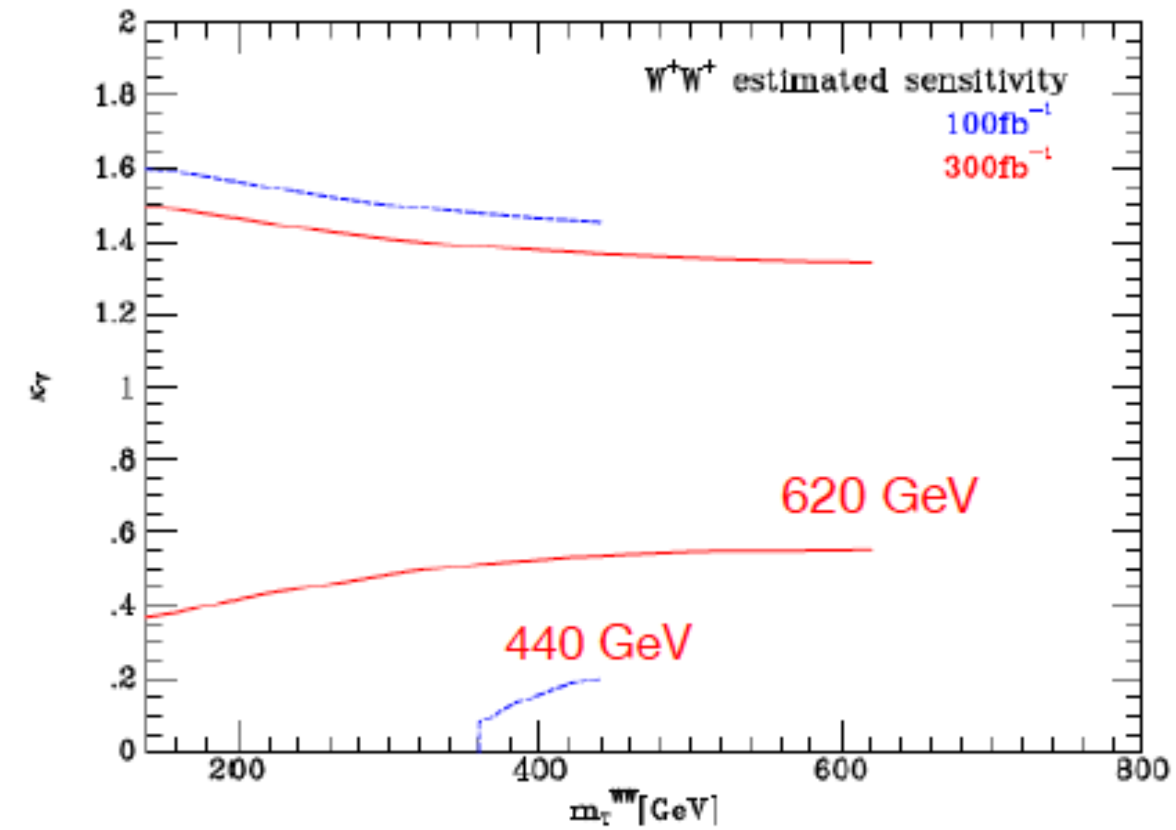
$$l^-l^+\nu\bar{\nu}: \quad N^{\rm off} = 127.9 - 42.8\,\kappa_V^2 + 20.8\,\kappa_V^4$$
$$l^+l^+\nu\nu: \quad N^{\rm off} = 37.2 - 18.3\,\kappa_V^2 + 8.3\,\kappa_V^4$$
$$l^-l^-\bar{\nu}\bar{\nu}: \quad N^{\rm off} = 11.0 - 4.1\,\kappa_V^2 + 1.8\,\kappa_V^4$$
$$l^+l^-l^+\nu: \quad N^{\rm off} = 23.5 -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

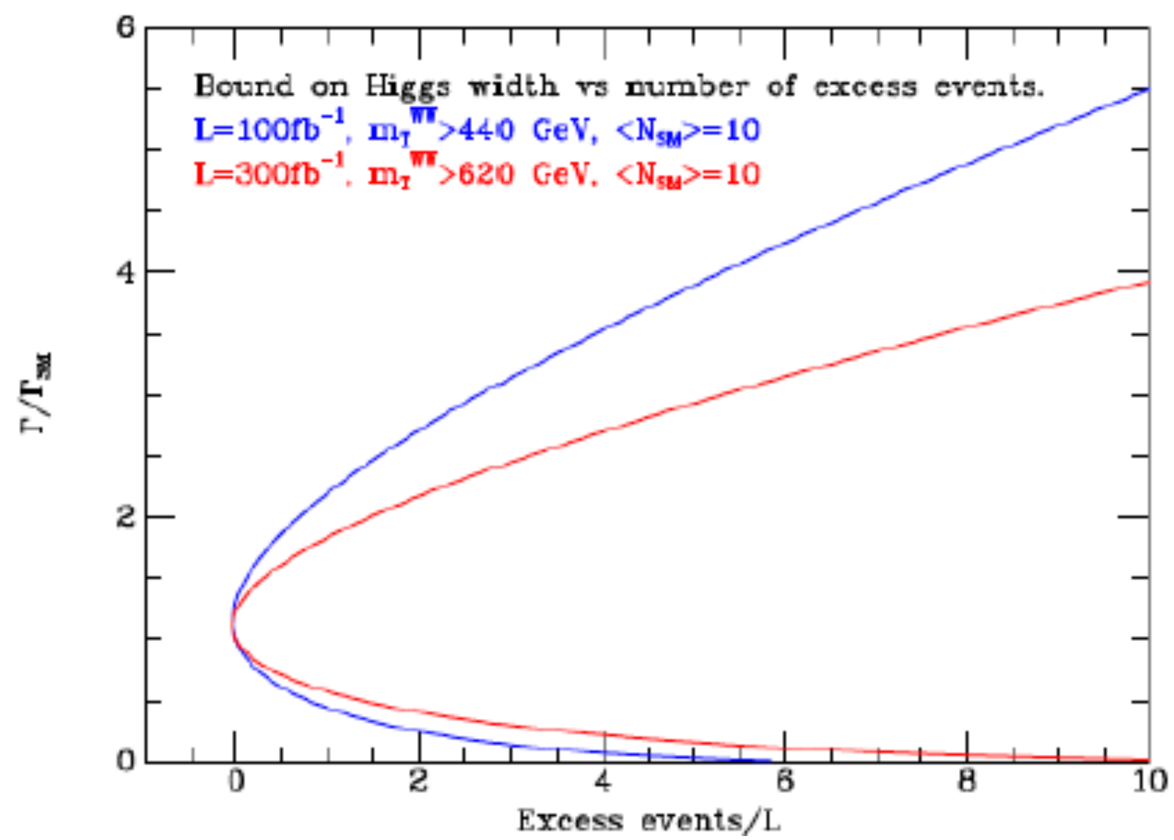
Signal +B'ground

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

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

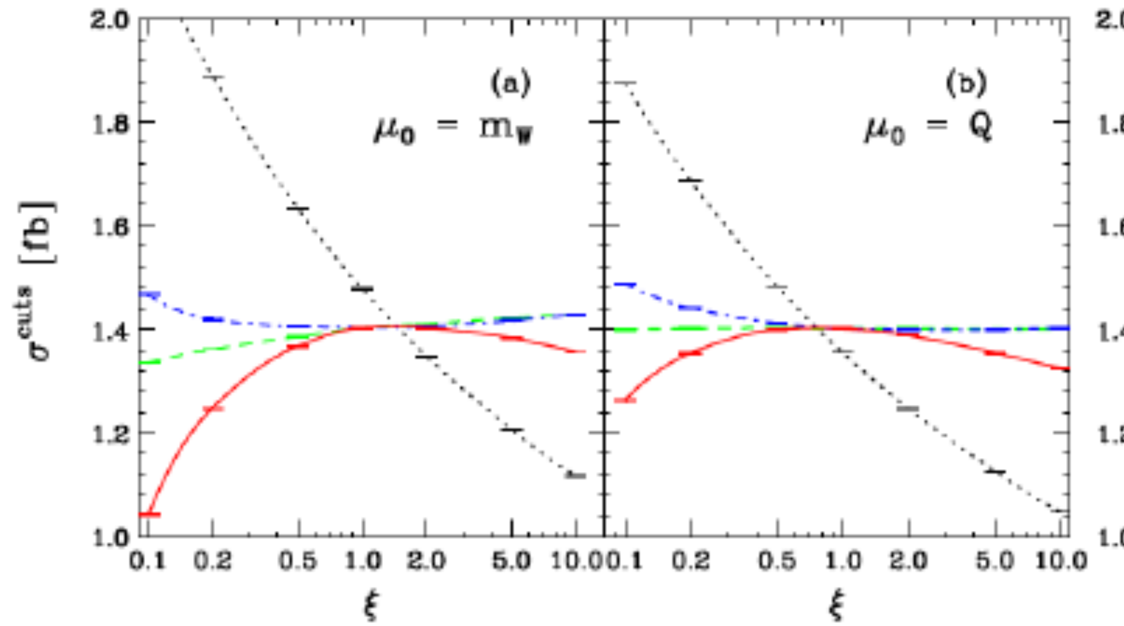
- Expected upper and lower bounds on κ_V obtained from W^+W^+ events as a function of the transverse mass.
- Bounds are cut off when SM prediction falls below 10 events.
- In all cases the best bounds are achieved, taking the highest possible cut on the transverse mass.
- Possible width bounds with (100,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





W^+W^+ at NLO

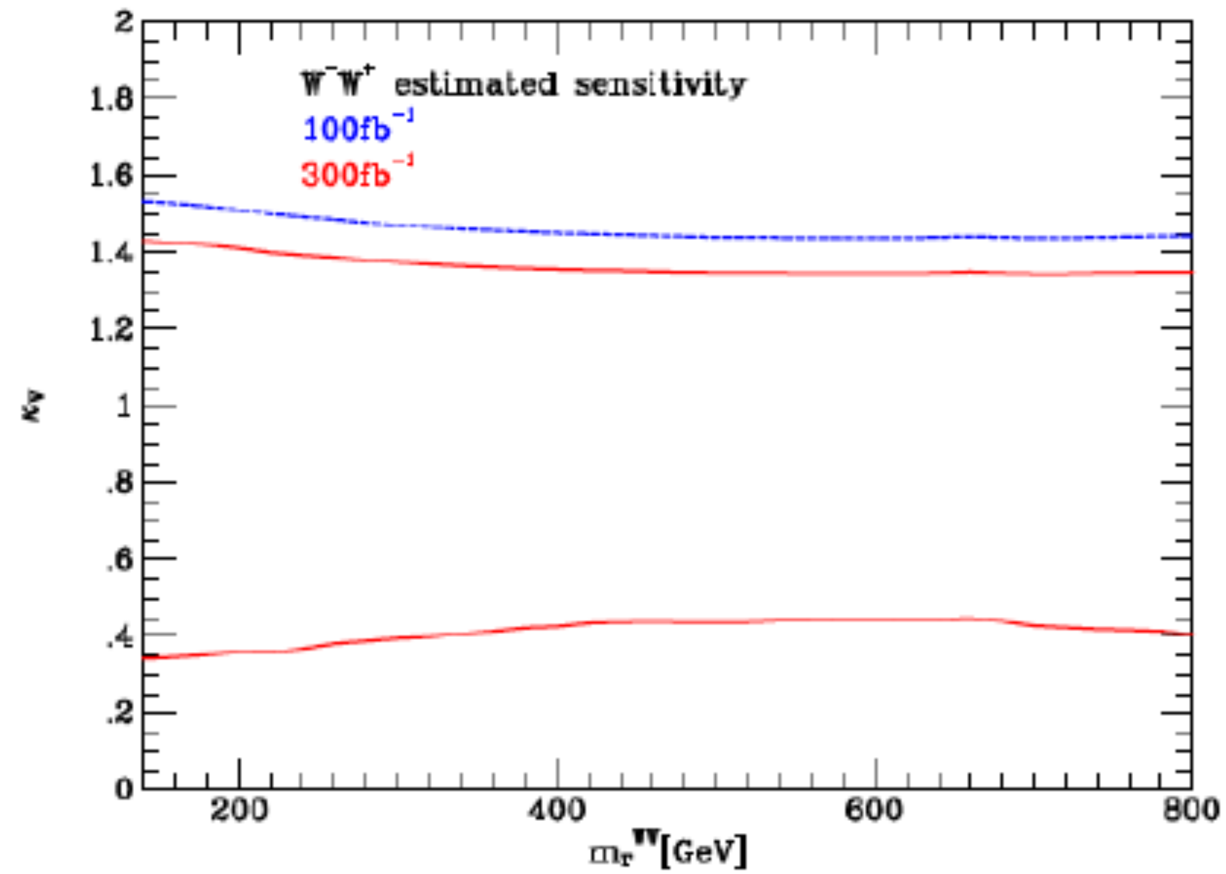
- NLO Corrections are known to both the $O(\alpha^6)$ and $O(\alpha^4\alpha_s^2)$ processes.
- NLO corrections to $O(\alpha^6)$ process are small. Jäger et, 0907.0580
- NLO Corrections to the $O(\alpha^4\alpha_s^2)$ processes are <20% with VBF cuts.
- Interference between the two (at LO) is small (<3% for tight VBF cuts)
- NLO corrections are completely known, unlike gg-fusion case, where there are partial results.



Melia et al, 1007.5313,
Campanario et al, 1311.6738

Bounds from on κ_V from W^-W^+ at $\sqrt{s}$=13TeV

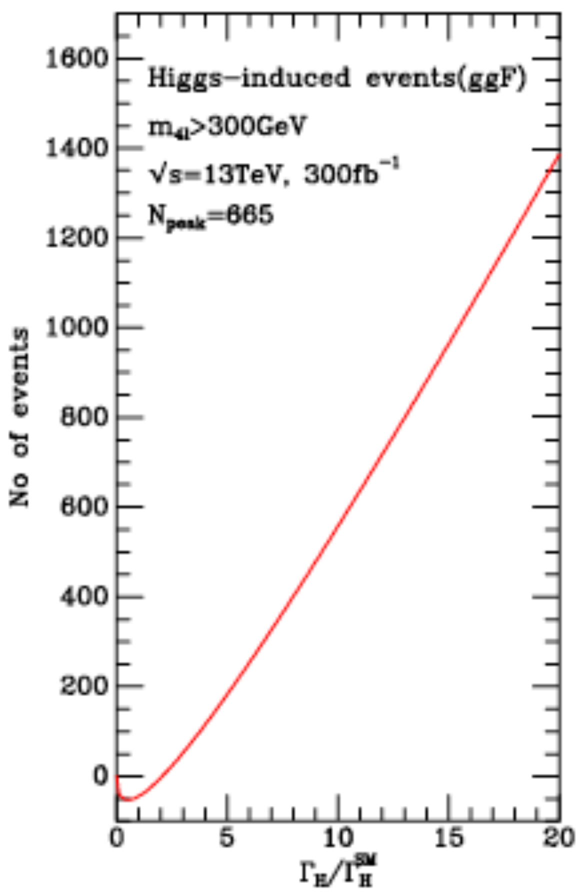
- With a bigger data set 300fb^{-1} we can also obtain lower bounds from the W^-W^+ process.
- Tradeoff between decreasing statistics and increasing sensitivity.

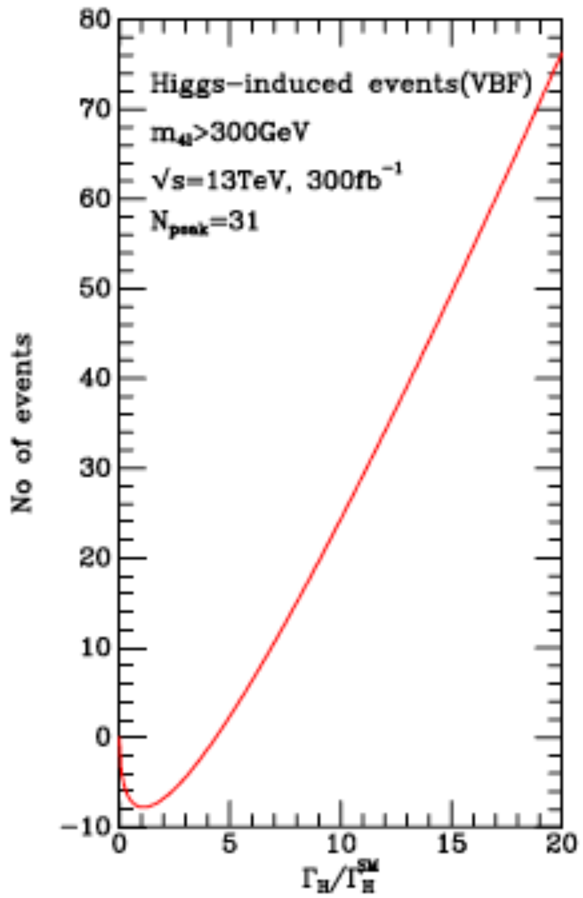


$$0.45 < \kappa_V < 1.35\,, \qquad W^-W^+\ (m_T^{WW} > 660\ \text{GeV})\,.$$

Bounds on the Higgs width

* Best VBF bounds on the Higgs width come from the W^+W^+ channel.
* NLO corrections completely known for this channel.
* VBF has a similar dependence as ggF on ratio of widths.
* Rate is for VBF is ~21 times smaller than for ggF, but rate is insensitive to Γ_H, exactly for Γ_H~1





Summary

- OpenMP leads to significant improvement in performance for MCFM. (MPI/quadruple precision will also be available soon).
- Measurement of off-shell couplings of the Higgs boson is of great interest.
- In view of large backgrounds in VBF processes, useful to consider W^+W^+ process for off-shell coupling measurement.
- W^+W^+ channel will achieve similar sensitivity to current gluon fusion results with $300 fb^{-1}$.
- Assuming off-shell and on-shell couplings are the same, this measurement can be used to bound the Higgs boson width using VBF.
- This measurement is of great interest because of different theoretical "systematics" than gluon fusion.