Signal-background interference in $gg \to H \to VV$

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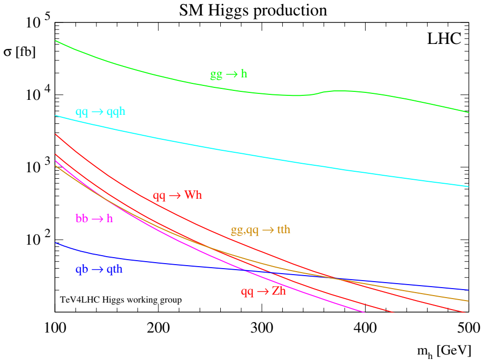
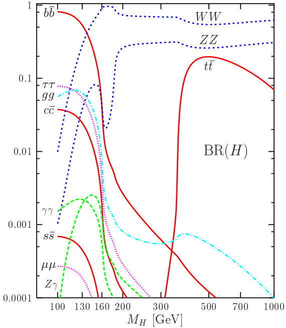
Outline

- SM Higgs $\rightarrow VV$ search at the LHC
- Gluon-induced VV background
- Signal-background interference
- Intermediate Higgs mass range
- Heavy Higgs
- Conclusion

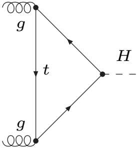
Higgs boson production and decay at the LHC





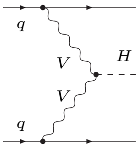
Gluon fusion:

$(gg \to H)$



Vector boson fusion:

$(qq \to Hqq,\ V = W, Z)$



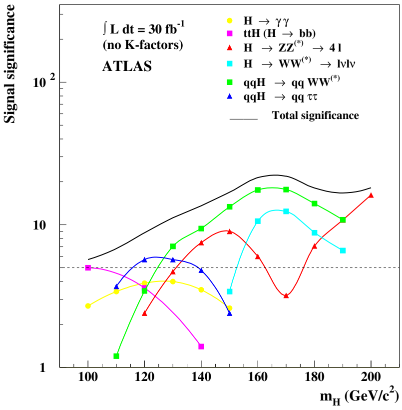
Dominant decay modes:

$H \to b\bar{b}$ for $M_H < 135$ GeV

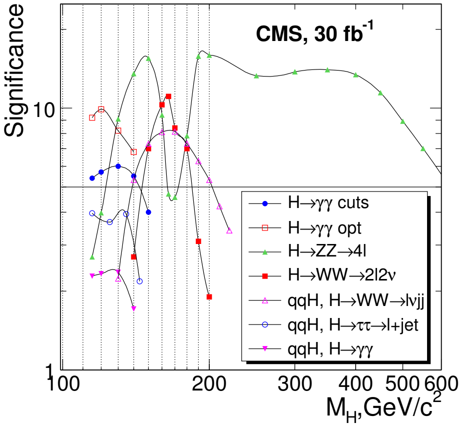
$H \to WW, ZZ$ for $M_H > 135$ GeV

source: Tevatron-for-LHC Higgs Report (2007), Djouadi (2005)

LHC discovery potential for the SM Higgs boson



ATLAS



CMS

LEP: $M_H > 114.4$ GeV, $M_H = 89^{+35}_{-26}$ $(< 158, 185)$ GeV

Tevatron: $M_H \notin [158, 175]$ GeV

Discoveries at the LHC

Discovery convention

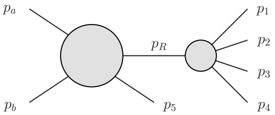
S = nr. of signal events, B = nr. of background events,

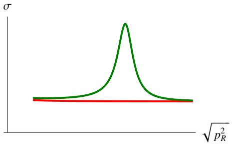
Observation significance: $\sigma = S/\sqrt{B+S}$

Discovery if $\sigma \geq 5 \quad \rightarrow \quad P(\text{background fluctuation}) \leq \; 2.85 \times 10^{-7}$

Discoveries require the accurate determination of rates *and uncertainties* for signals *and backgrounds*

The experimentally ideal case: a new, reconstructible mass peak





p_1, p_2, p_3, p_4 measurable $\rightarrow$ $p_R = p_1 + p_2 + p_3 + p_4$

$\rightarrow$ invariant mass distribution from experimental data ($\rightarrow$ resonance mass and width)

$\rightarrow$ background via sideband interpolation ($\rightarrow$ signal)

but: neutrinos and dark matter candidates not detectable at the LHC

Gluon-induced WW and ZZ backgrounds to Higgs searches

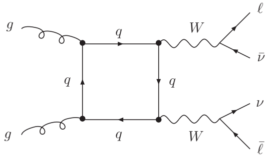
$pp \to WW/ZZ \to \ell, \nu$ at $\mathcal{O}(\alpha_s^2)$

Why partial NNLO calculation? New subprocess $gg \to WW/ZZ$!

enhanced by

- large gluon-gluon flux at the LHC
- experimental selection cuts: boost of VV system only in $q\bar{q}$ scattering

+ 5% correction without cuts



+ 30% correction to NLO with Higgs search cuts

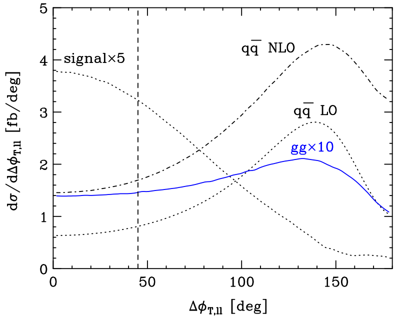
Binoth, Ciccolini, Kauer, Krämer, JHEP 0503 (2005) 065, JHEP 12 (2006) 046

14-dim. integration, amplitude representation $\sim$ 100000 terms, *quadruple precision*

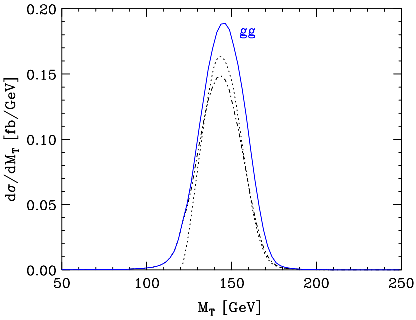
GG2WW event generator tool $\rightarrow$ used by several ATLAS and CMS groups

Drollinger, Binoth, Ciccolini, Dührssen, Kauer, CERN-CMS-NOTE-2005-024,
Mellado, Quayle, Wu, Les Houches Physics at TeV Colliders 2005 Proceedings,
Davatz, Dittmar, Giolo-Nicollerat, CERN-CMS-NOTE-2006-047,
Giolo-Nicollerat, CERN-CMS-CR-2006-038

WW background



$p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{E}_T > 25$ GeV



Higgs search cuts $\longrightarrow$ gg: dominant higher order correction

Higgs search cuts = standard cuts (left) and $\Delta\phi_{T,\ell\ell} < 45^\circ$, $m_{\ell\ell} < 35$ GeV, jet veto: $p_{Tj} > 20$ GeV and $|\eta_j| < 3$, 35 GeV $< p_{T\ell,\text{max}} < 50$ GeV, 25 GeV $< p_{T\ell,\text{min}}$ Davatz, Dissertori, Dittmar, Grazzini, Pauss, JHEP 0405 (2004) 009

ZZ background

$gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ $\longrightarrow$ **+ 15% correction to NLO**

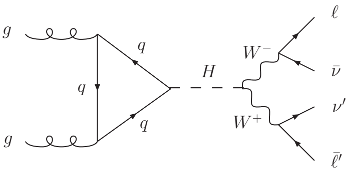
Binoth, Kauer, Mertsch, DIS 2008 and Les Houches Physics at TeV Colliders 2007 Proceedings

GG2ZZ event generator tool $\rightarrow$ used by several ATLAS and CMS groups

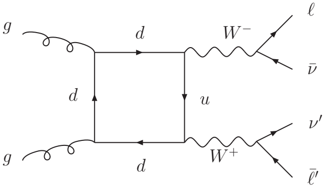
Mellado, Mir, Wu; Rebuzzi ($\rightarrow$ **ATLAS Book**); Rosati, Solfaroli (ATLAS), Giordano, Nikitenko (CMS)

$gg \to VV$ signal-background interference

representative Feynman graphs ($V = W$):



signal (sig) amplitude



continuum (cont) amplitude

Signal-background interference for $M_H = 140, 170, 200$ GeV

	$\sigma[gg(\to H) \to WW \to \ell\bar{\nu}\bar{\ell}'\nu']$ [fb]					
Selection	**no cuts**			**Higgs search cuts**		
$\lvert\mathcal{M}_{cont(gg:1,2)}\rvert^2$	53.64(1)			1.3837(3)		
$\lvert\mathcal{M}_{cont(gg:3)}\rvert^2$	2.859(3)			0.00377(2)		
$\lvert\mathcal{M}_{cont(gg:1,2,3)}\rvert^2$	60.00(1)			1.4153(3)		
$\frac{\lvert\mathcal{M}_{cont(gg:1,2,3)}\rvert^2}{\lvert\mathcal{M}_{cont(gg:1,2)}\rvert^2+\lvert\mathcal{M}_{cont(gg:3)}\rvert^2}$	1.06			1.02		
M_H [GeV]	**140**	**170**	**200**	**140**	**170**	**200**
$\lvert\mathcal{M}_{sig}\rvert^2$	79.83(2)	116.23(3)	75.40(2)	1.8852(5)	12.974(2)	1.6663(7)
$\lvert\mathcal{M}_{sig+cont(gg:1,2,3)}\rvert^2$	132.50(5)	174.58(9)	134.46(5)	3.174(2)	15.287(6)	3.413(2)
$\frac{\lvert\mathcal{M}_{sig+cont(gg:1,2,3)}\rvert^2}{\lvert\mathcal{M}_{sig}\rvert^2+\lvert\mathcal{M}_{cont(gg:1,2,3)}\rvert^2}$	**0.948**	0.991	0.993	**0.962**	**1.062**	**1.108**

details: see hep-ph/0611170

Signal-background interference for $M_H = 400$ GeV
Settings and cuts

$\mu_R = \mu_F = M_H/2 = 200$ GeV, $\Gamma_H = 29.16$ GeV
MSTW2008LO (68% C.L.), other: LHC Higgs Cross Section WG, arXiv:1101.0593 [hep-ph], App. A (with G_μ scheme)

***WW* standard cuts**:

$p_{T\ell} > 20$ GeV , $|\eta_\ell| < 2.5$

$\not{p}_T > 30$ GeV , $M_{\ell\bar{\ell}'} > 12$ GeV

***WW* Higgs search cuts** ($M_H = 400$ GeV):

standard cuts and

$p_{T\ell\text{min}} > 25$ GeV , $p_{T\ell\text{max}} > 90$ GeV

$M_{\ell\bar{\ell}'} < 300$ GeV , $\Delta\phi_{\ell\bar{\ell}'} < 175°$

***ZZ* standard cuts**:

$p_{T\ell} > 20$ GeV , $|\eta_\ell| < 2.5$

76 GeV $< M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} < 106$ GeV

Signal-background interference for $M_H = 400$ GeV
Results

$gg \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$, LHC, 7 TeV, standard cuts:

$\sigma(|\mathcal{M}_{\rm sig} + \mathcal{M}_{\rm cont}|^2) = 10.5817$ MC: $\pm 0.0063(\pm 0.059\%)$ scale($\times$2): $-2.5573(-24\%) + 3.6967(+35\%)$ PDF: $-0.2723(-2.6\%) + 0.2382(+2.3\%)$ fb, sym. scale error: $\pm 28\%$, sym. PDF error: $\pm 2.4\%$

$\sigma(|\mathcal{M}_{\rm sig}|^2) = 4.3611$ MC: $\pm 0.0021(\pm 0.048\%)$ scale($\times$2): $-1.1500(-26\%) + 1.7227(+40\%)$ PDF: $-0.1318(-3\%) + 0.1261(+2.9\%)$ fb, sym. scale error: $\pm 31\%$, sym. PDF error: $\pm 3\%$

$\sigma(|\mathcal{M}_{\rm cont}|^2) = 6.3506$ MC: $\pm 0.0039(\pm 0.062\%)$ scale($\times$2): $-1.4583(-23\%) + 2.0621(+32\%)$ PDF: $-0.1526(-2.4\%) + 0.1243(+2\%)$ fb, sym. scale error: $\pm 26\%$, sym. PDF error: $\pm 2.2\%$

$$\frac{\sigma(|\mathcal{M}_{\rm sig} + \mathcal{M}_{\rm cont}|^2)}{\sigma(|\mathcal{M}_{\rm sig}|^2) + \sigma(|\mathcal{M}_{\rm cont}|^2)} = 0.9879(8) \quad \text{(at 14 TeV: } 0.9680(8))$$

Signal-background interference for $M_H = 400$ GeV

$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}'\nu_{\ell'}$, **LHC, 7 TeV, Higgs search cuts**:

$\sigma(|\mathcal{M}_{\rm sig} + \mathcal{M}_{\rm cont}|^2) = 3.007$ MC: $\pm 0.003(\pm 0.1\%)$ scale($\times$2): $-0.782(-26\%) + 1.164(+39\%)$ PDF: $-0.088(-2.9\%) + 0.084(+2.8\%)$ fb, sym. scale error: $\pm 30\%$, sym. PDF error: $\pm 2.9\%$

$\sigma(|\mathcal{M}_{\rm sig}|^2) = 2.502$ MC: $\pm 0.002(\pm 0.081\%)$ scale($\times$2): $-0.660(-26\%) + 0.989(+40\%)$ PDF: $-0.076(-3\%) + 0.073(+2.9\%)$ fb, sym. scale error: $\pm 31\%$, sym. PDF error: $\pm 3\%$

$\sigma(|\mathcal{M}_{\rm cont}|^2) = 0.633$ MC: $\pm 0.001(\pm 0.15\%)$ scale($\times$2): $-0.161(-25\%) + 0.237(+38\%)$ PDF: $-0.018(-2.8\%) + 0.017(+2.6\%)$ fb, sym. scale error: $\pm 30\%$, sym. PDF error: $\pm 2.7\%$

$$\frac{\sigma(|\mathcal{M}_{\rm sig} + \mathcal{M}_{\rm cont}|^2)}{\sigma(|\mathcal{M}_{\rm sig}|^2) + \sigma(|\mathcal{M}_{\rm cont}|^2)} = 0.959(2) \quad \text{(at 14 TeV: } 0.940(2)\text{)}$$

Signal-background interference for $M_H = 400$ GeV

$gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$**, LHC, 7 TeV, standard cuts**:

$\sigma(|\mathcal{M}_{\text{sig}} + \mathcal{M}_{\text{cont}}|^2) = 0.6875$ MC: $\pm 0.0009(\pm 0.12\%)$ scale($\times$2): $-0.1696(-25\%) + 0.2470(+36\%)$ PDF: $-0.0185(-2.7\%) + 0.0163(+2.4\%)$ fb, sym. scale error: $\pm 29\%$, sym. PDF error: $\pm 2.5\%$

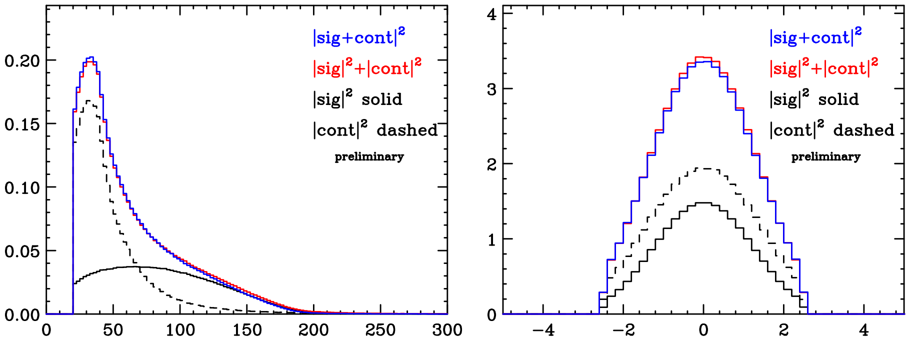
$\sigma(|\mathcal{M}_{\text{sig}}|^2) = 0.3658$ MC: $\pm 0.0004(\pm 0.11\%)$ scale($\times$2):$-0.0961(-26\%) + 0.1437(+39\%)$ PDF: $-0.0110(-3\%) + 0.0104(+2.8\%)$ fb, sym. scale error: $\pm 31\%$, sym. PDF error: $\pm 2.9\%$

$\sigma(|\mathcal{M}_{\text{cont}}|^2) = 0.3332$ MC: $\pm 0.0004(\pm 0.1\%)$ scale($\times$2):$-0.0774(-23\%) + 0.1099(+33\%)$ PDF: $-0.0083(-2.5\%) + 0.0068(+2\%)$ fb, sym. scale error: $\pm 27\%$, sym. PDF error: $\pm 2.3\%$

$$\frac{\sigma(|\mathcal{M}_{\text{sig}} + \mathcal{M}_{\text{cont}}|^2)}{\sigma(|\mathcal{M}_{\text{sig}}|^2) + \sigma(|\mathcal{M}_{\text{cont}}|^2)} = 0.984(2)$$

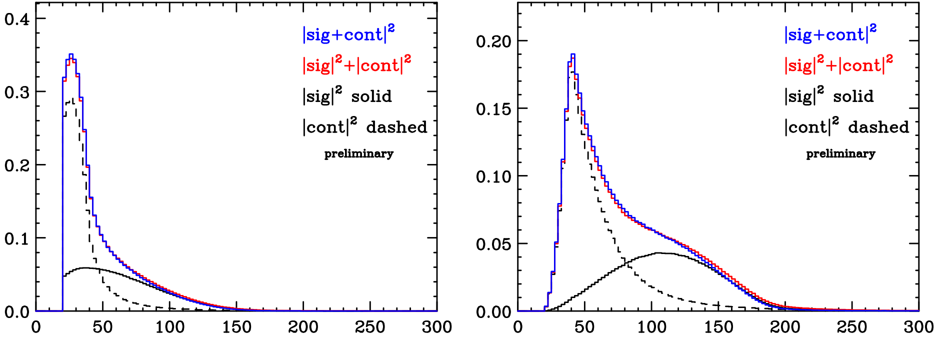
$gg \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ distributions (LHC, 7 TeV, standard cuts)

$p_{T\ell}$ and η_ℓ distributions ([GeV,] fb)



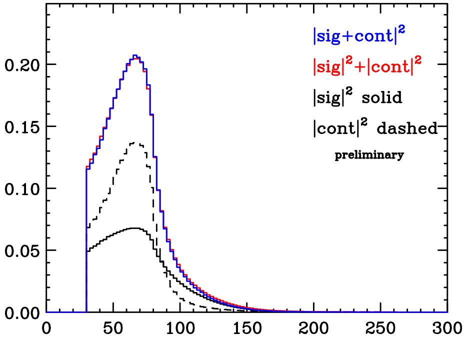
$gg \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ distributions (LHC, 7 TeV, standard cuts)

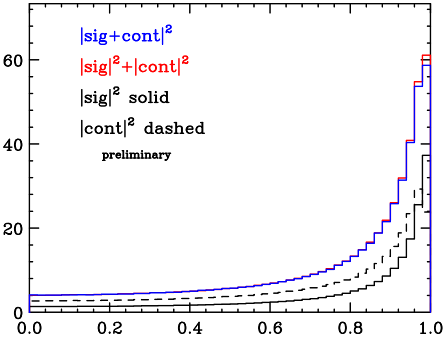
$p_{T\ell\mathrm{min}}$ and $p_{T\ell\mathrm{max}}$ distributions ([GeV,] fb)



$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}' \nu_{\ell'}$ distributions (LHC, 7 TeV, standard cuts)

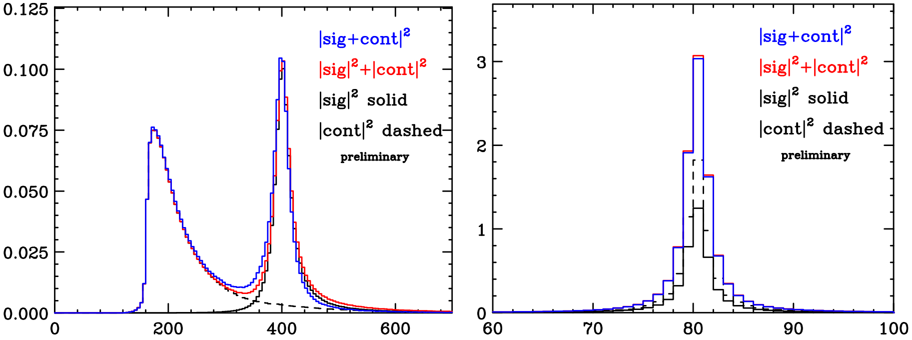
$\not{p}_T$ and $|\cos\theta_{\ell\bar{\ell}',\text{beam}}|$ distributions ([GeV,] fb)





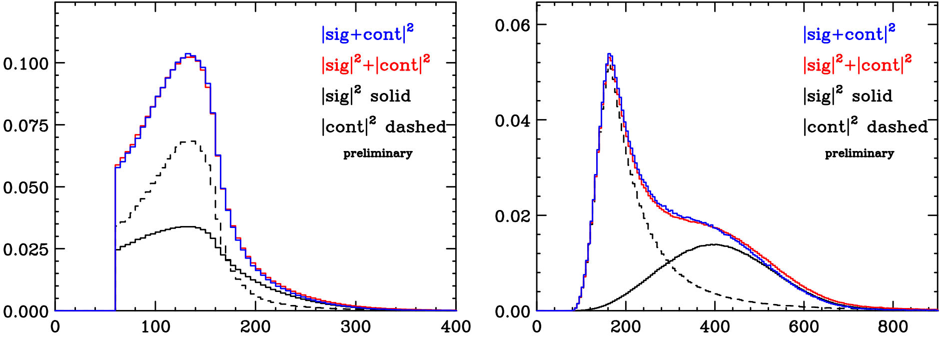
$gg \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ distributions (LHC, 7 TeV, standard cuts)

M_{WW} and $M_{\ell\bar{\nu}_\ell}$ distributions ([GeV,] fb)



$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}' \nu_{\ell'}$ distributions (LHC, 7 TeV, standard cuts)

$M_T(WW)$ distributions ([GeV,] fb)

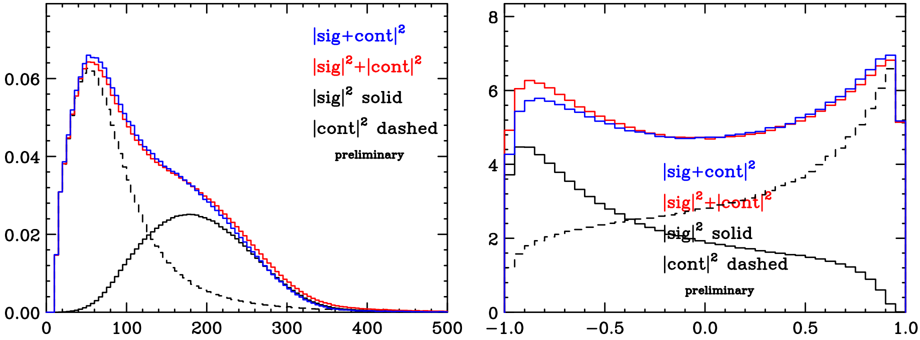


left: $M_T = \sqrt{2\, p_{T\ell\bar{\ell}'}\, \not{p}_T (1 - \cos \Delta\phi_{\ell\bar{\ell}',\text{miss}})}$

right: $M_T = \sqrt{(E_{T,\ell\bar{\ell}'} + \not{E}_T)^2 - (\vec{p}_{T,\ell\bar{\ell}'} + \vec{\not{p}}_T)^2}\,,\ E_{T,\ell\bar{\ell}'} = \sqrt{p^2_{T,\ell\bar{\ell}'} + m^2_{\ell\bar{\ell}'}}\,,\ \not{E}_T = \sqrt{\not{p}^2_T + m^2_{\ell\bar{\ell}'}}$

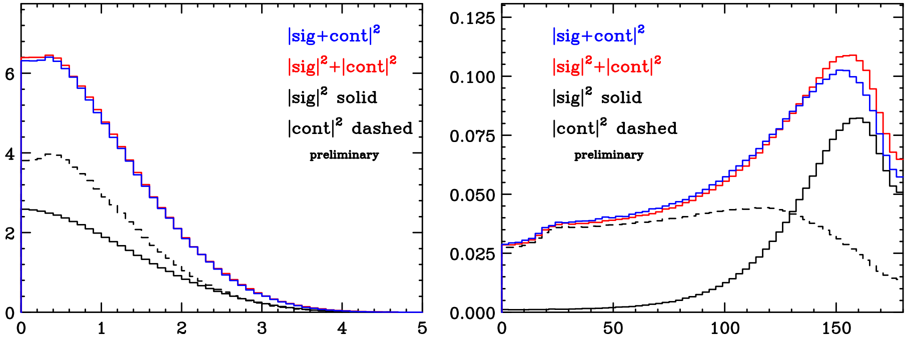
$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}' \nu_{\ell'}$ distributions (LHC, 7 TeV, standard cuts)

$M_{\ell\bar{\ell}'}$ and $\cos\theta_{\ell\bar{\ell}'}$ distributions ([GeV,] fb)



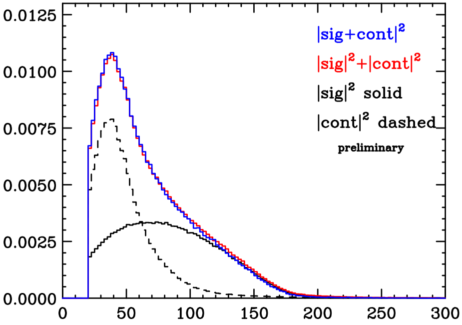
$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}' \nu_{\ell'}$ distributions (LHC, 7 TeV, standard cuts)

$|\eta_\ell - \eta_{\bar{\ell}}|$ and $\Delta\phi_{\ell\bar{\ell}'}$ distributions (0-180 degrees, fb)



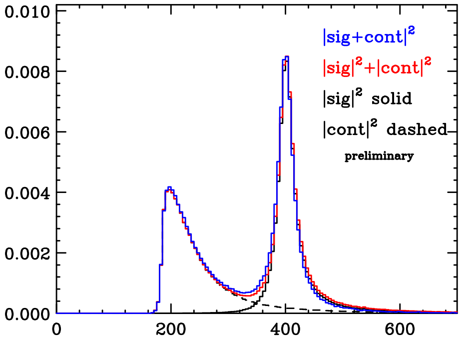
$gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ distributions (LHC, 7 TeV, standard cuts)

$p_{T\ell}$ and η_ℓ distributions ([GeV,] fb)



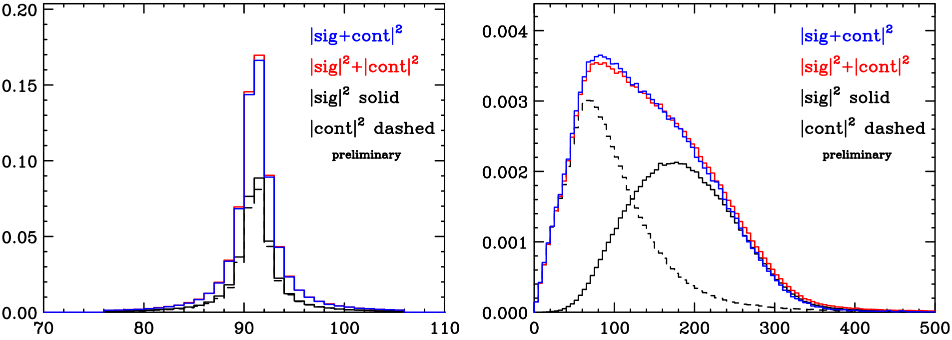
$gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ distributions (LHC, 7 TeV, standard cuts)

$M_{\ell\bar{\ell}\ell'\bar{\ell}'}$ distribution ([GeV,] fb)



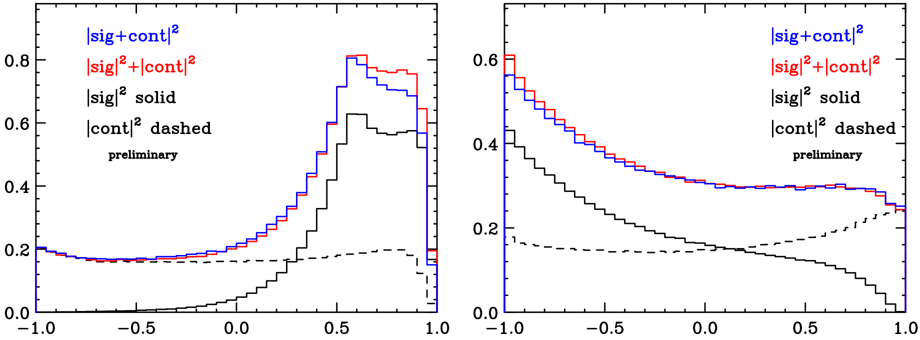
$gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ distributions (LHC, 7 TeV, standard cuts)

$M_{\ell\bar{\ell}}$ and $M_{\ell\ell'}$ distributions ([GeV,] fb)



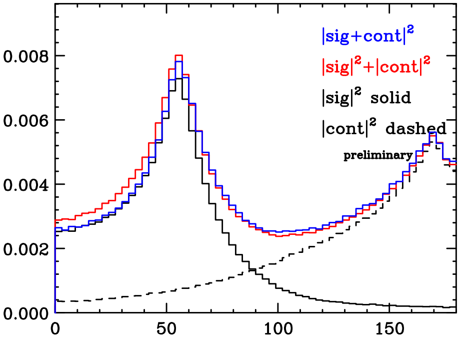
$gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ distributions (LHC, 7 TeV, standard cuts)

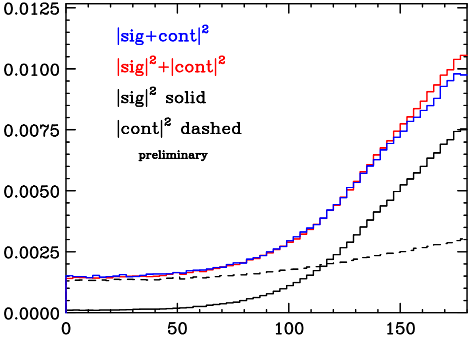
$\cos\theta_{\ell\bar{\ell}}$ and $\cos\theta_{\ell\ell'}$ distributions ([GeV,] fb)



$gg \to Z(\gamma^*)Z(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ distributions (LHC, 7 TeV, standard cuts)

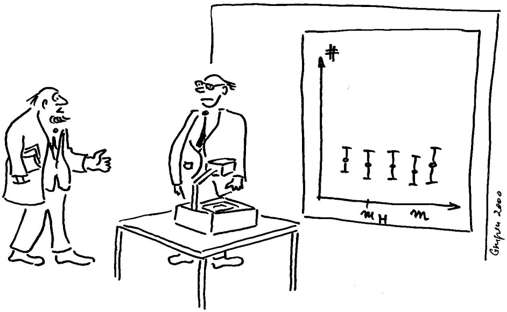
$\Delta\phi_{\ell\bar{\ell}}$ and $\Delta\phi_{\ell\ell'}$ distributions ([GeV,] fb)





Conclusion

Interference effects are not suppressed and can be as large as 5-10% when Higgs search selection cuts are applied or for $M_H \ll 2M_V$.

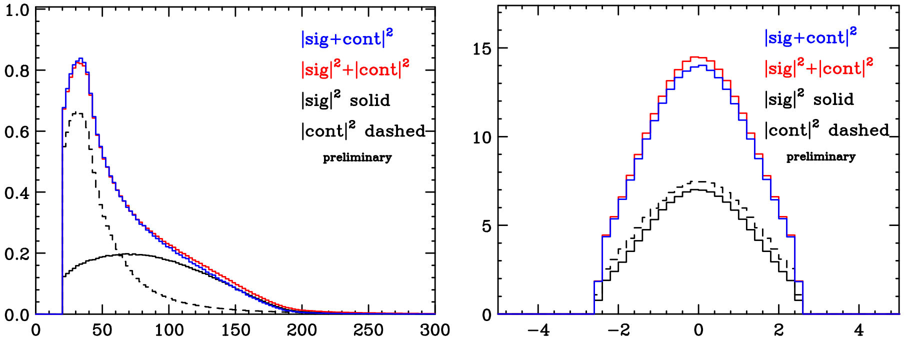


"You call this evidence for the Higgs?"
"Yes! Zero lifetime and infinite width!"

Backup Slides

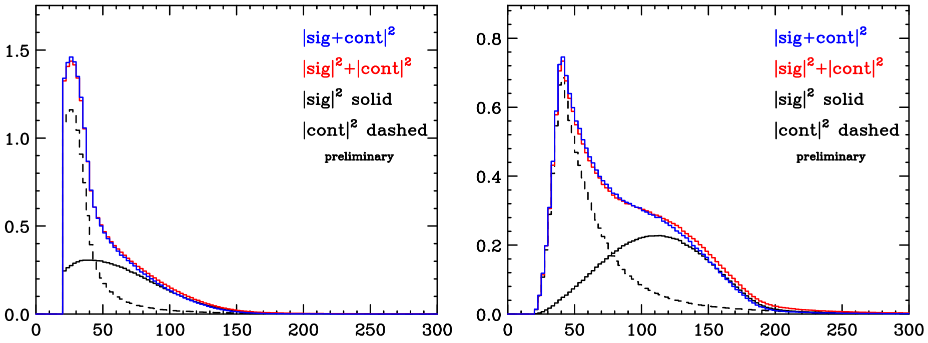
$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}' \nu_{\ell'}$ distributions (LHC, 14 TeV, standard cuts)

$p_{T\ell}$ and η_ℓ distributions ([GeV,] fb)



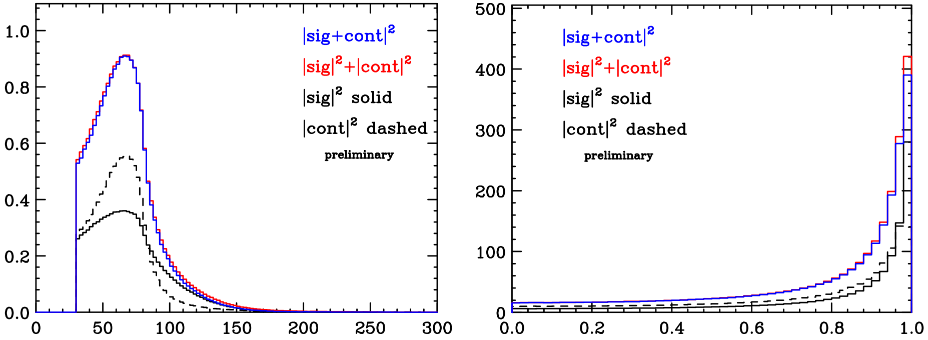
$gg \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ distributions (LHC, 14 TeV, standard cuts)

$p_{T\ell\text{min}}$ and $p_{T\ell\text{max}}$ distributions ([GeV,] fb)



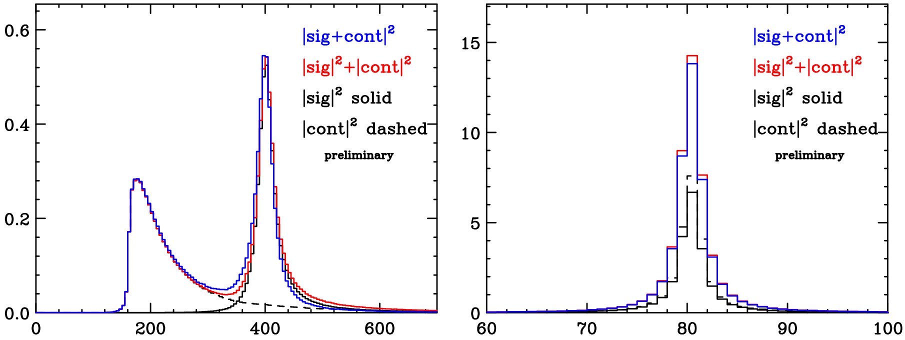
$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}'\nu_{\ell'}$ distributions (LHC, 14 TeV, standard cuts)

$\not{p}_T$ and $|\cos\theta_{\ell\bar{\ell}',\text{beam}}|$ distributions ([GeV,] fb)



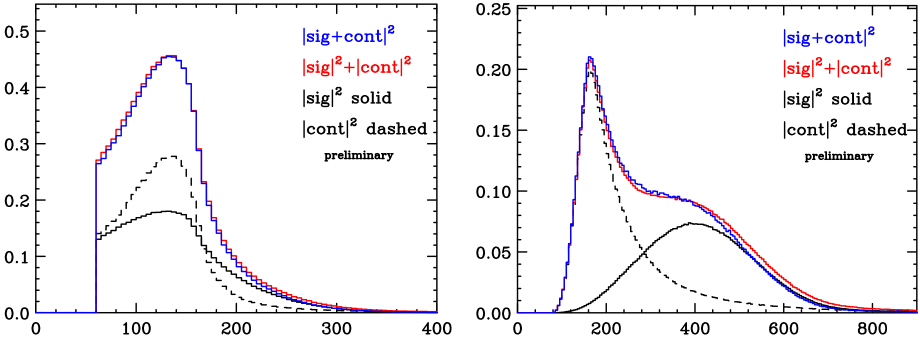
$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}'\nu_{\ell'}$ distributions (LHC, 14 TeV, standard cuts)

M_{WW} and $M_{\ell\bar{\nu}_\ell}$ distributions ([GeV,] fb)



$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}' \nu_{\ell'}$ distributions (LHC, 14 TeV, standard cuts)

$M_T(WW)$ distributions ([GeV,] fb)

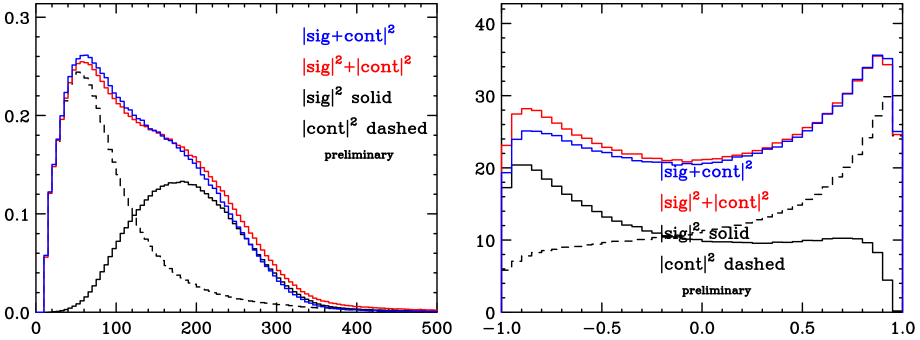


left: $M_T = \sqrt{2\, p_{T\ell\bar{\ell}'}\, \not{p}_T (1 - \cos \Delta\phi_{\ell\bar{\ell}',\text{miss}})}$

right: $M_T = \sqrt{(E_{T,\ell\bar{\ell}'} + \not{E}_T)^2 - (\vec{p}_{T,\ell\bar{\ell}'} + \vec{\not{p}}_T)^2}\,,\ E_{T,\ell\bar{\ell}'} = \sqrt{p^2_{T,\ell\bar{\ell}'} + m^2_{\ell\bar{\ell}'}}\,,\ \not{E}_T = \sqrt{\not{p}^2_T + m^2_{\ell\bar{\ell}'}}$

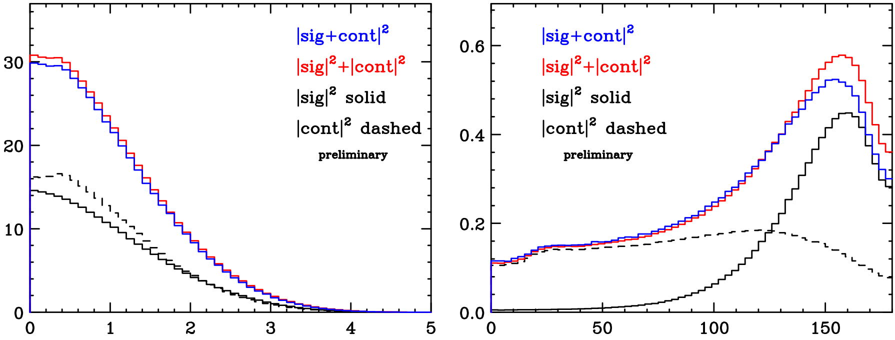
$gg \to WW \to \ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$ distributions (LHC, 14 TeV, standard cuts)

$M_{\ell\bar{\ell}'}$ and $\cos\theta_{\ell\bar{\ell}'}$ distributions ([GeV,] fb)



$gg \to WW \to \ell\bar{\nu}_\ell \bar{\ell}'\nu_{\ell'}$ distributions (LHC, 14 TeV, standard cuts)

$|\eta_\ell - \eta_{\bar{\ell}}|$ and $\Delta\phi_{\ell\bar{\ell}'}$ distributions (0-180 degrees, fb)



	$\sigma(pp \to W^*W^* \to \ell\bar{\nu}\bar{\ell}'\nu')$ [fb], LHC, $M_W/2 \le \mu_{\mathrm{ren,fac}} \le 2M_W$					
	$q\bar{q}$		gg	$\frac{\sigma_{gg,3gen}}{\sigma_{gg,2gen}}$	$\frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}}$	$\frac{\sigma_{\mathrm{NLO}+gg}}{\sigma_{\mathrm{NLO}}}$
	LO	NLO	NNLO			
σ_{tot}	$875.8(1)^{+54.9}_{-67.5}$	$1373(1)^{+71}_{-79}$	60.00(1) $53.64(1)^{+14.0}_{-10.8}$	1.12	1.57	1.04 1.04
σ_{std}	$270.5(1)^{+20.0}_{-23.8}$	$491.8(1)^{+27.5}_{-32.7}$	29.79(2) $25.89(1)^{+6.85}_{-5.29}$	1.15	1.82	1.06 1.05
σ_{bkg}	$4.583(2)^{+0.42}_{-0.48}$	$4.79(3)^{+0.01}_{-0.13}$	1.4153(3) $1.3837(3)^{+0.40}_{-0.31}$	1.02	1.05	1.30 1.29

2 massless generations, 3 generations

$\sigma(pp \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}')$ [fb]				
gg	$q\bar{q}$		$\frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}}$	$\frac{\sigma_{{\rm NLO}+gg}}{\sigma_{\rm NLO}}$
	LO	NLO		
$16.3(1)$	$105.2(1)$	$118.9(2)$	1.13	1.14