ZH associated production via gluon fusion in the SM and the 2HDM

Benoît Hespel, Fabio Maltoni and Eleni Vryonidou

Centre for Cosmology, Particle Physics and Phenomenology

ERC Miniworkshop, June 1, 2015

Based on ArXiv:1503.01656

Contents

Introduction to ZH production

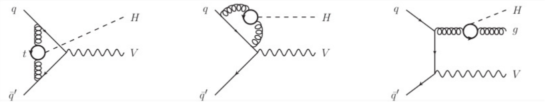
ZH associated production, really?

- Suppressed in the SM wrt gluon fusion and VBF :(
- **BUT** very interesting from an experimental point of view :)

Experimental motivation

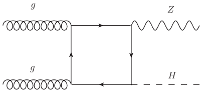
- Discovery of the Higgs at LHC in 2012
- Upcoming LHC run II with $\sqrt{\hat{s}} = 13$ TeV and larger luminosity
- Presence of a vector boson $\Rightarrow$ possible leptons coming from its decay!
- This can help to access the challenging $H \to b\bar{b}$ decay mode where CMS and ATLAS reported small excess

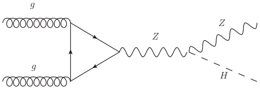
Introduction



Theoretical motivation

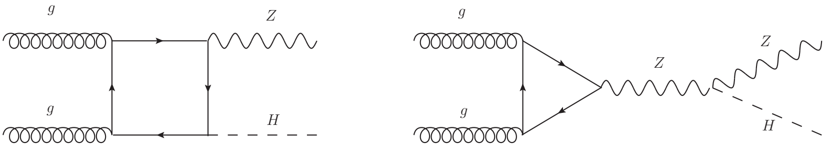
- Drell-Yan *ZH* production known at NNLO in QCD and NLO EW
- NNLO includes Drell-Yan type terms of $\mathcal{O}(\alpha_w^2\alpha_s^2)$ + purely virtual gluon fusion $gg \to ZH$ (increased wrt other NNLO contributions due to large gluon-gluon luminosity at small Bjorken x)
- $gg \to ZH$ differential distributions can be of vital importance for experimentalists in boosted Higgs searches to tame the large QCD background





Contents

$gg \to ZH$



- Gauge invariant, IR and UV finite
- Accounts for 10% of the total NNLO cross section at 14 TeV
- Massive t and b quark in the box, all quarks in the triangle
- Only the axial part of the quark to Z boson coupling contributes
- Box and triangle interfere destructively like in HH production

Technical setup

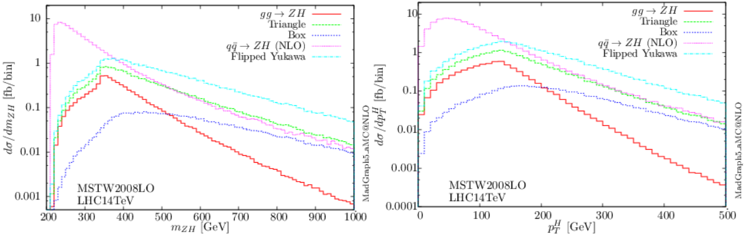
Event Generation

- MadGraph5_aMC@NLO framework (one-loop amplitude got via MadLoop using OPP integrand-reduction method)
- Reweighting procedure: tree-level generation with EFT and then $wgt \to (\mathcal{M}^2_{loop}/\mathcal{M}^2_{EFT}) * wgt$
- Need this because loop-induced processes **were not yet** automatically handled by MadGraph5_aMC@NLO
- Advantage: better statistics at high p_T

Parameters

$m_t = 173$ GeV, $m_b = 4.75$ GeV $m_H = 125$ GeV,
pdf=MSTW2008LO, $\mu_R = \mu_F = \mu_0 = m_{ZH}$,

Partonic differential results



Observations

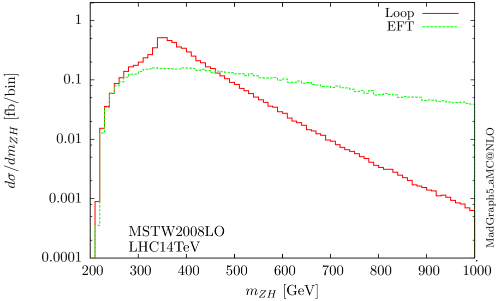
- Presence of the $2m_t$ threshold with important rise in the invariant mass distribution
- Different shapes for gluon induced and Drell-Yan
- Cancellation between box and triangle nearly exact at high energy
- Huge dependence on the relative phase between HZZ and $t\bar{t}H$ couplings ⇒ cross section increases by factor 5

$gg \to ZH$

σ[fb]	8 TeV	14 TeV
Total	386	885
Drell-Yan	364	801
Gluon-fusion	**17.6**	**70.6**
Top-induced	4.93	13.0

- $gg \to ZH$ is essentially LO and introduces large scale dependance on the NNLO result ($\mathcal{O}$(30%))
- NLO $gg \to ZH$ would impact the N^3LO cross section and would include 2 loop topologies, which are out of current technology
- $\Rightarrow$ only known in EFT ($m_t \to \infty$) $\Rightarrow$ unreliable at the diffential level

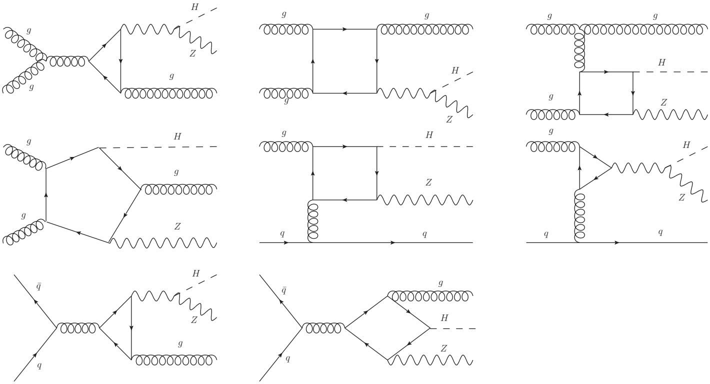
$gg \to ZH$ in the EFT ?



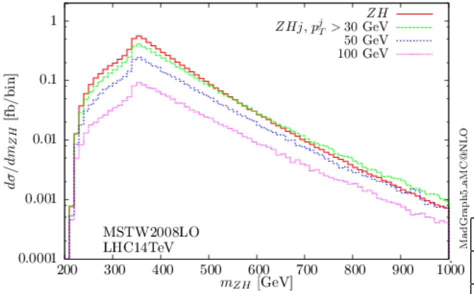
And multiscale 2 loop amplitudes results are not availble ...
What can we do ?

$gg \to ZHg$, $qg \to ZHq$, $q\bar{q} \to ZHg$

To improve predictions, let's consider also $2 \to 3$: new channels $gg \to ZHg$, $qg \to ZHq$ and $q\bar{q} \to ZHg$



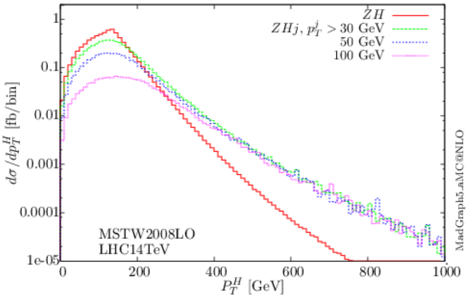
$2 \to 3$ invariant mass distributions



Cut	$\sigma(gg \to Zhj)$
30 GeV	57.9 fb
50 GeV	35.3 fb
100 GeV	14.5 fb

- Bulk of the cross-section is still at $2m_t$
- $2 \to 3$ contribution is not as much suppressed as expected (compared to $2 \to 2$)

$2 \to 3$ differential distributions



p_T^H spectrum

- $2 \to 3$ gives a harder tail
- High p_T^H insensitive to p_T^j cut $\Rightarrow$ hard ISR dominates
- New preferred configuration is when a **hard jet** recoils against the Higgs (with soft Z)

Merging-matching setup

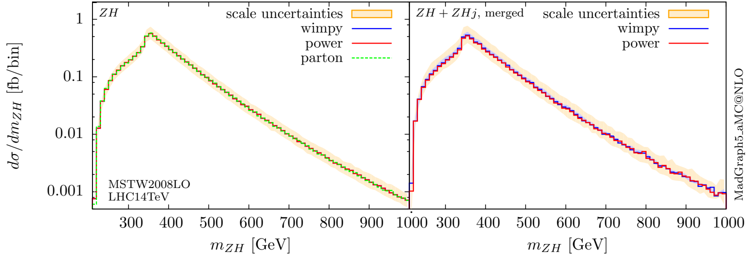
Why?

- As we saw, the additionnal jet can modify dramatically the shape of the distribution. So it has to be taken into account
- In the following we will use merged sample up to 1 jet matched to the PS

Technicalities

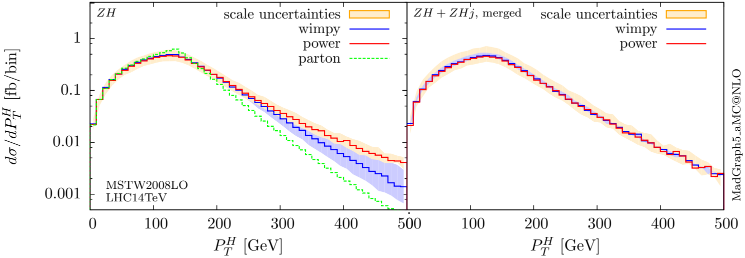
- Idea: Matrix element describes well hard jet, while PS describes better soft jet ⇒ Need to define a region for both and avoid double counting
- We employed the LML shower-k_T scheme as implemented in MadGraph5_aMC@NLO.
- Then merged samples are passed through PYTHIA8 for matching to PS

Merged Results



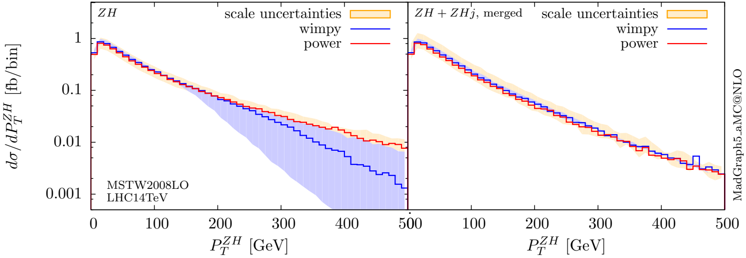
- Shower scale: $\mu_f = m_{ZH}$ (*wimpy-shower*) or $\mu_f = \sqrt{\hat{s}}/2$ (*power-shower*)
- MLM shower-KT with QCut = 30 GeV
- Invariant mass is **insensitive** to shower/merging

Merged Results



- p_T^H spectrum is harder whatever the shower scale choice
- Shower scale variation: $\mu_f/2 < \mu_{PS} < 2\mu_f$
- Merged results are stable while non-merged have large shower uncertainties $\Rightarrow$ ME+PS predictions are more accurate and predictive than PS alone

Merged Results



- **Highly sensitive** to shower

Contents

CP-conserving 2HDM

5 Physical states

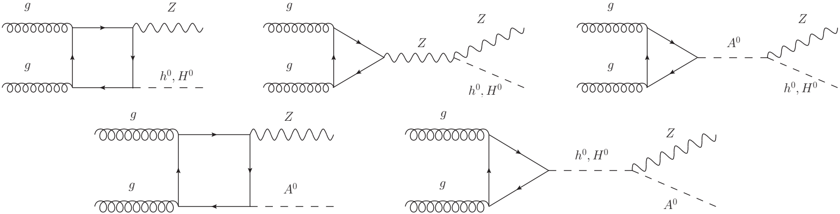
There are 2 Higgs doublets Φ_1, Φ_2 leading to 5 physical states after EWSB:

- 2 CP-even scalar particles: light h^0 and heavy H^0
- 1 CP-odd pseudo-scalar particle: A^0
- 2 Charged Higgses: $H^\pm$

Parametrization

- 7 independant parameters : $\tan\beta, \sin\alpha, m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm}, m_{12}^2$
- In the following we will set $m_{h^0} = 125$ GeV (SM-like)
- We will only consider the first 2 Yukawa types: **type I** wher all fermions couple to only one doublet and **type II** where up-type (down) quarks couple to Φ_2 (Φ_1)

New processes, new diagrams!



$gg \to Z(h^0/H^0/A^0)$

- New contribution coming from the pseudoscalar A^0 s-channel exchange.
- Resonance effect will depend on mass hierarchy between neutral particles

Z boson couplings to Higgses

$$\hat{g}_{ZZ}^{h^0} = \sin(\beta - \alpha), \quad \hat{g}_{ZZ}^{H^0} = \cos(\beta - \alpha), \quad \hat{g}_{ZZ}^{A^0} = 0,$$

$$g_Z^{A^0 h^0} \propto \cos(\beta - \alpha), \quad g_Z^{A^0 H^0} \propto -\sin(\beta - \alpha)$$

- Experimental constraints as well as theoretical requirements (vacuum stability, unitarity, etc.) impose $sin(\beta - \alpha) \simeq 1$.
- $\Rightarrow g_{ZZ}^{H^0} \simeq g_Z^{A^0 h^0} \ll 1$

Calculation setup

- Same as before: MadGraph5_aMC@NLO + ME+PS shower-k_T
- Relies on the 2HDM@NLO model obtained from NLOCT package

Non-excluded benchmark points

- **Benchmark B1**: Type II scenario with moderate mass hierarchy $m_{h^0} < m_{H^0} \lesssim m_{A^0} \simeq m_{H^\pm}$
- **Benchmark B2**: Type I scenario with light Heavy Higgs H^0 and much heavier pseudoscalar A^0: $m_{h^0} \lesssim m_{H^0} \ll m_{A^0} \simeq m_{H^\pm}$
- **Benchmark B3**: Type II scenario with inverted mass hierarchy: $m_{h^0} < m_{A^0} < m_{H^0} \simeq m_{H^\pm}$

Only allows $\mathcal{O}($ 10%) modification of the Yukawas

	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.1872	300	441	442	38300
B2	1.20	-0.1760	200	500	500	-60000
B3	1.70	-0.1757	350	250	350	12000

2DHM Total rates

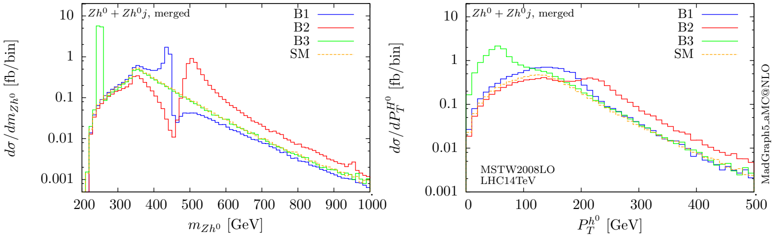
	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.1872	**300**	**441**	442	38300
B2	1.20	-0.1760	**200**	**500**	500	-60000
B3	1.70	-0.1757	**350**	**250**	350	12000

	$gg \to Zh^0$	$gg \to ZH^0$	$gg \to ZA^0$
B1	$113\ ^{+30\%}_{-21\%}$	$\mathbf{686}\ ^{+30\%}_{-22\%}$	$0.622\ ^{+32\%}_{-23\%}$
B2	$85.8\ ^{+30.1\%}_{-21\%}$	$\mathbf{1544}\ ^{+30\%}_{-22\%}$	$0.869\ ^{+34\%}_{-23\%}$
B3	$167\ ^{+31\%}_{-19\%}$	$0.891\ ^{+33\%}_{-21\%}$	$\mathbf{1325}\ ^{+28\%}_{-21\%}$

Features

- Zh^0 cross section can be significantly enhanced (factor 2 in B3) due to the A^0 new resonnance (whose effect is however suppressed by $\cos(\beta-\alpha)$)
- ZH^0 or ZA^0 can become very large in the resonnant case (it reaches the Pb level) with light mass

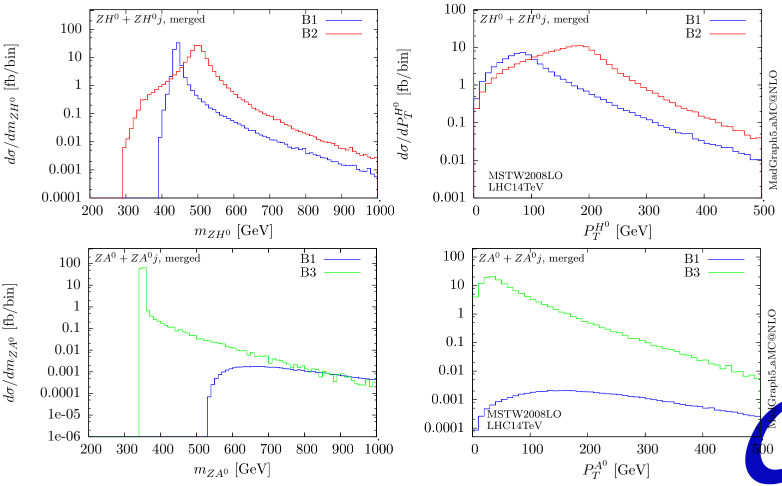
2DHM Differential distributions



Remarks

- Resonant peak at m_{A^0}. The sharpness varies as $m_{A^0} \nearrow \Rightarrow \Gamma_{A^0} \nearrow$
- B1, B2: interesting interference patterns with SM-like diagram. Sign of Zh^0A^0 is different in B1 and B2 $\Rightarrow$ dip appears before or after the peak
- Values of top Yukawas explains the behaviour at high energy as the box becomes important

2DHM Differential distributions



Contents

Summary

Conclusion

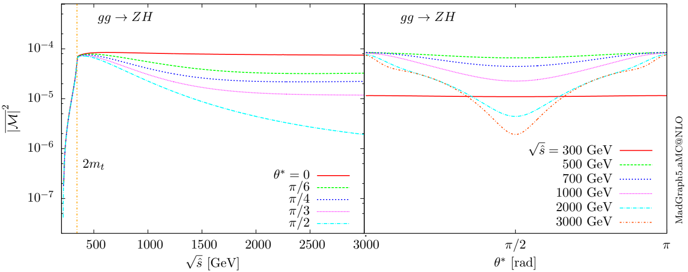
- Gluon induced ZH associated production should be considered in **boosted regimes searches** at the lHC
- **Merged samples** up to 1 jet give more **accurate and predictive results** which should be taken into account at least for differential distribution
- In the 2HDM large cross sections have been found for ZH^0 and ZA^0 production when a **resonnance** is kinematically allowed.
- Small enhancement of the Zh^0 total rate can also be expected and interesting **interference** patterns can be observed at the differential level

Thanks for you attention

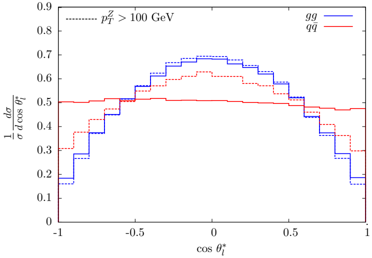
Partonic results

Matrix element squared

- No angular dependence at low energy ($\sqrt{\hat{s}} < 2m_t$), but varies largely at high energy
- Forward and backward direction preferred at high energy
- This behaviour is linked to the box and triangle interference



Leptons angular distribution



Polarization of the Z boson

- The difference in p_T shape is also visible in the p_T of the leptons coming from the Z
- $\theta^* =$ angle between lepton and Z direction in the Z rest frame
- The shape without any p_t^Z cut is very different from Drell-Yan to gluon fusion
- After the cut mostly longitudinal Z polarization remains

Z boson polarisation fractions

Process	f_0 (%)	f_L (%)	f_R (%)
$gg \to ZH$	82.2	8.9	8.9
$gg \to ZH$, $p_T^Z > 100$ GeV	86.3	6.9	6.8
$q\bar{q} \to ZH$	35.6	32.4	32.0
$q\bar{q} \to ZH$, $p_T^Z > 100$ GeV	62.6	18.8	18.6