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

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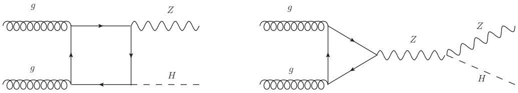
28th Rencontres de Blois on "Particle Physics and Cosmology"
May 31, 2016

Based on ArXiv:1503.01656

Introduction to ZH production



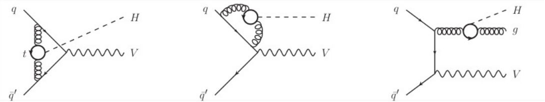
ZH associated production, really?

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

Experimental motivation

- LHC run II with $\sqrt{s} = 13$ 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

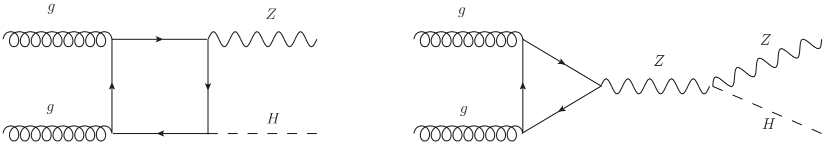
Introduction



Theoretical motivation

- Drell-Yan ZH production known at NNLO in QCD and NLO EW (Hamberg Neerven, Matsuura, '91, Harlander, Kilgore, '02, Brein, Djouadi, Harlander, '04, Brein, Harlander, Zirke '12)
- 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

$gg \to ZH$



- 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
- Box and triangle interfere destructively like in HH production

Technical setup

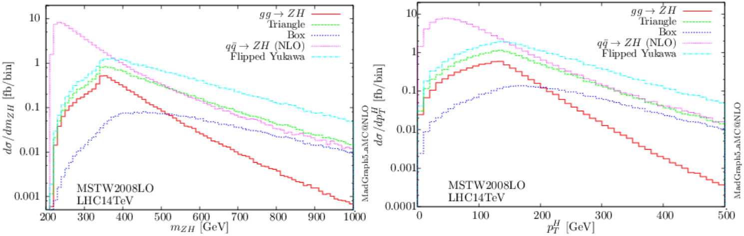
Event Generation

- MadGraph5_aMC@NLO framework (one-loop amplitude got via MadLoop using OPP integrand-reduction method)
- **Reweighting procedure**: tree-level generation with EFT and then $wgt \to (\mathcal{M}^2_{loop}/\mathcal{M}^2_{EFT}) * wgt$
- Needed this because loop-induced processes **were not yet** automatically handled by MadGraph5_aMC@NLO
- Automated event generation for loop-induced processes available since July 2015 (Hirschi, Mattelaer)

Parameters

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

Parton-level 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 ZZH and $t\bar{t}H$ couplings $\Rightarrow$ cross section increases by factor 5

$gg \to ZH$

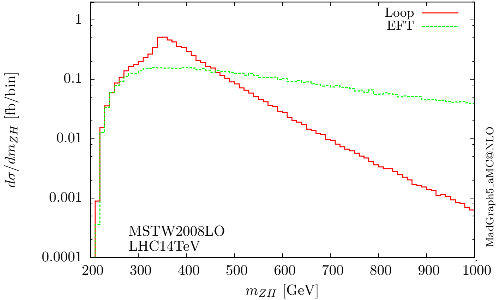
Contribution [fb]	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 14$ TeV
$gg \to ZH$ (LO)	$17.4\ ^{+34\%}_{-24\%}$	$58.5\ ^{+30\%}_{-21\%}$	$70.7\ ^{+29\%}_{-21\%}$
$pp \to ZH$ (NNLO[1])	$387\ ^{+2.2\%}_{-1.6\%}$	$795\ ^{+3.2\%}_{-2.0\%}$	$886\ ^{+3.2\%}_{-2.3\%}$

- $gg \to ZH$ 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 multiscale 2-loop topologies, which are out of current technology
- NLO K-factors known in EFT (L. Altenkamp et al '13) but EFT is unreliable at the diffential level

[1] vh@nnlo (Brein, Harlander, Zirke, '12)

$gg \to ZH$ in the EFT ?

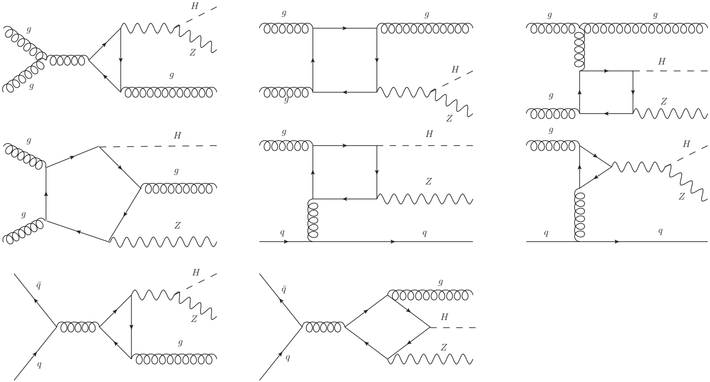
EFT: $m_t \to \infty$



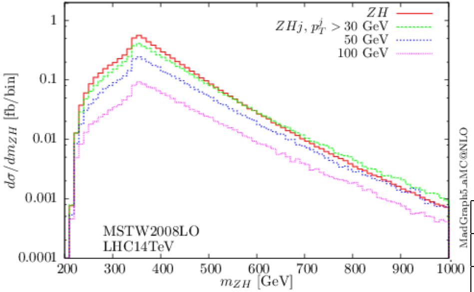
Without the multiscale 2-loop amplitude result what can we do ?

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

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



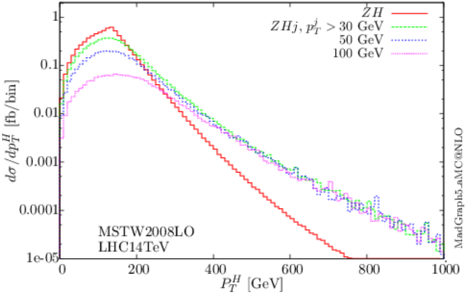
$2 \to 3$ invariant mass distributions

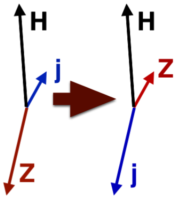


Cut	$\sigma(gg \to ZHj)$
no cut	70.7 fb
30 GeV	57.9 fb
50 GeV	35.3 fb
100 GeV	14.5 fb

- 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 distribution





p_T^H spectrum

- $2 \to 3$ gives a harder tail (takes over the 0-jet above 300 GeV)
- 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

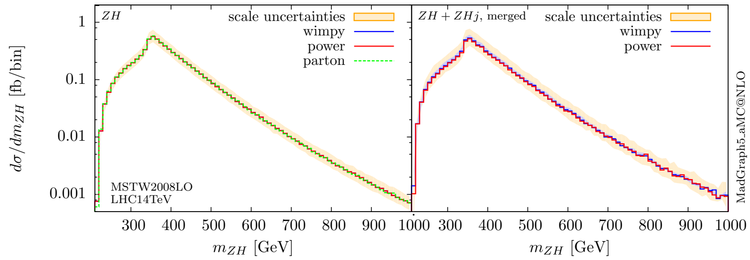
Why?

- 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 (See also Goncalves, Krauss, '15)

Technicalities

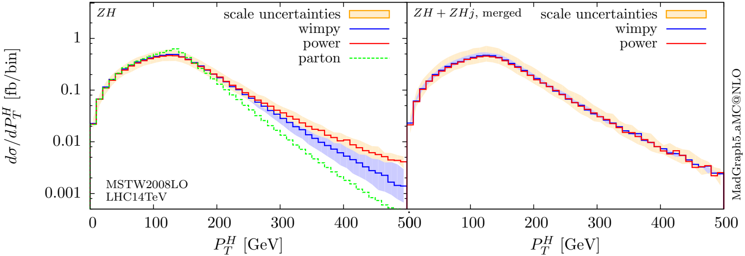
- Idea: Matrix element describes well hard jet, while PS describes better soft jet $\Rightarrow$ Need to define a region for both and avoid double counting
- We employed the shower-k_T scheme as implemented in MadGraph5_aMC@NLO.
- Then merged samples are passed through PYTHIA8 for matching to PS

Merged Results



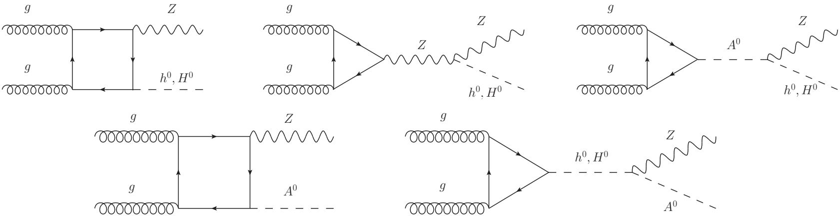
- Shower scale: $\mu_f = m_{ZH}$ (*wimpy-shower*) or $\mu_f = \sqrt{\hat{s}}/2$ (*power-shower*)
- MLM shower-KT with QCut = 30 GeV
- Invariant mass is **insensitive** to shower/merging

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

$Z\Phi$ prodution in the CP-conserving 2HDM



- 2 Higgs doublets Φ_1, Φ_2 leading to 5 physical states after EWSB:
- New contribution for $gg \to Zh^0$ coming from the pseudoscalar A^0 s-channel exchange.
- Resonance effect will depend on mass hierarchy between neutral particles for $gg \to ZH^0/ZA^0$

See also Harlander, Liebler, Zirke, '14

Z boson couplings to Higgses

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

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

$$\hat{g}^{A^0}_{ZZ} = 0,$$

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

Calculation setup

- Same as before: MadGraph5_aMC@NLO + ME+PS shower-k_T
- Relies on the 2HDM@NLO model obtained from NLOCT package (Degrande '14)

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: $m_{h^0} < m_{A^0} < m_{H^0} \simeq m_{H^\pm}$

Low $\tan\beta$ only allows $\mathcal{O}($ 10%) modification of the h^0 Yukawa

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

2DHM Total rates

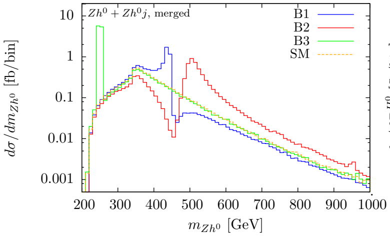
	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$
B1	1.75	-0.1872	**300**	**441**	442
B2	1.20	-0.1760	**200**	**500**	500
B3	1.70	-0.1757	**350**	**250**	350

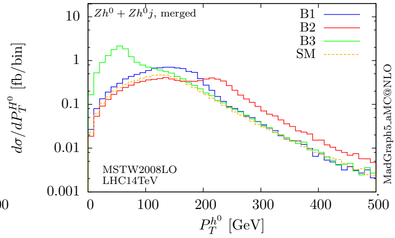
	$gg \to Zh^0$	$gg \to ZH^0$	$gg \to ZA^0$
B1	$113\ ^{+30\%}_{-21\%}$	$\mathbf{686}\ ^{+30\%}_{-22\%}$	$0.622\ ^{+32\%}_{-23\%}$
B2	$85.8\ ^{+30.1\%}_{-21\%}$	$\mathbf{1544}\ ^{+30\%}_{-22\%}$	$0.869\ ^{+34\%}_{-23\%}$
B3	$167\ ^{+31\%}_{-19\%}$	$0.891\ ^{+33\%}_{-21\%}$	$\mathbf{1325}\ ^{+28\%}_{-21\%}$

Features

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

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

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 for differential distribution
- In the 2HDM large cross sections have been found for ZH^0 and ZA^0 production when a **resonance** 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

Thank you for your attention

2HDM couplings of interest

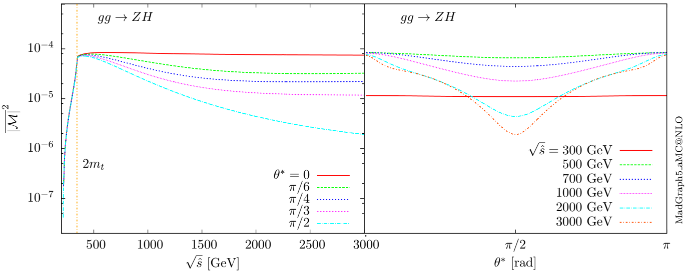
	$\hat{g}_{h^0tt}$	$\hat{g}_{h^0bb}$	$\hat{g}_{H^0tt}$	$\hat{g}_{H^0bb}$	$\hat{g}_{A^0tt}$	$\hat{g}_{A^0bb}$	$g_{A^0Zh^0}$	$g_{A^0ZH^0}$	$\hat{g}_{ZZH^0}$	$\hat{g}_{ZZh^0}$
B1	0.958	1.118	-0.639	1.677	0.571	1.75	-0.069	-0.998	-0.0689	0.998
B2	1.108	1.108	-0.684	-0.684	0.833	-0.833	0.141	-0.990	0.141	0.990
B3	0.987	1.034	-0.608	1.679	0.588	1.700	-0.020	-1.000	-0.020	1.000

Coupling	type-I	type-II
$\hat{g}_u^{h^0}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
$\hat{g}_d^{h^0}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
$\hat{g}_u^{H^0}$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
$\hat{g}_d^{H^0}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
$\hat{g}_u^{A^0}$	$\cot\beta$	$\cot\beta$
$\hat{g}_d^{A^0}$	$-\cot\beta$	$\tan\beta$

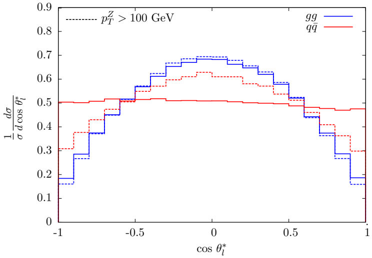
Partonic results

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



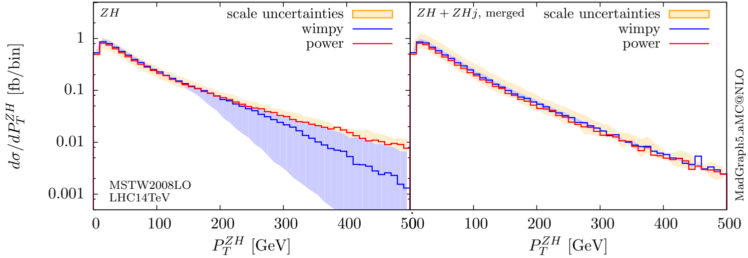
Polarization of the Z boson

- 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

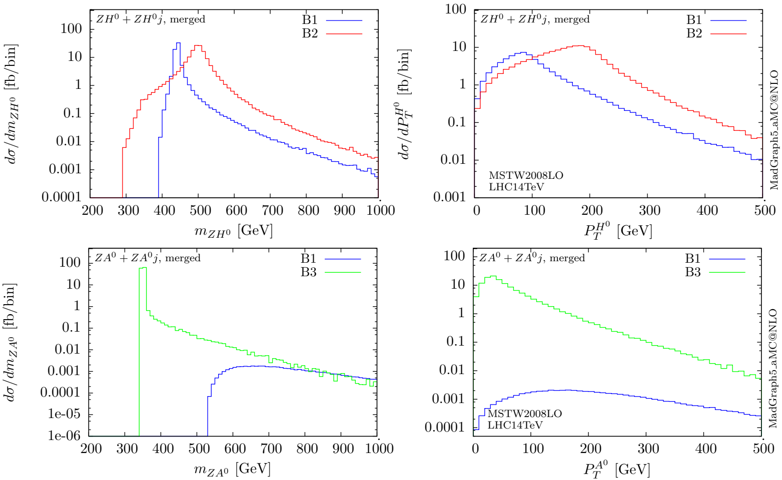
Process	f_0 (%)	f_L (%)	f_R (%)
$gg \to ZH$	82.2	8.9	8.9
$gg \to ZH$, $p_T^Z > 100$ GeV	86.3	6.9	6.8
$q\bar{q} \to ZH$	35.6	32.4	32.0
$q\bar{q} \to ZH$, $p_T^Z > 100$ GeV	62.6	18.8	18.6

Merged Results



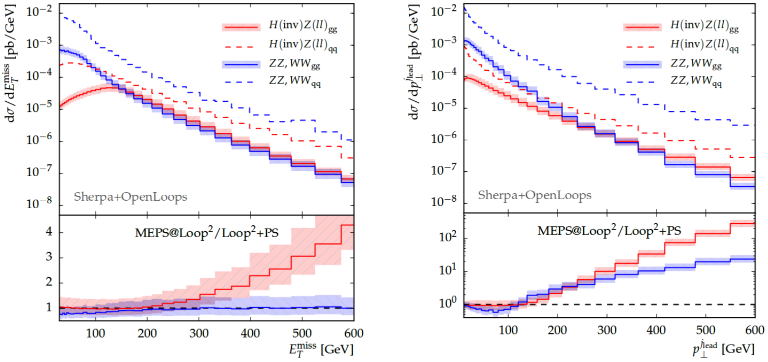
- **Highly sensitive** to shower

2DHM Differential distributions



Fraction of gg contribution

Gonçalves, Krauss, '16



Importance of merging results in $H(inv)Z(ll)$

Gonçalves, Krauss, '16