VH cross section working group
Theory status and plans

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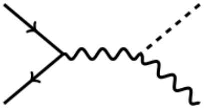
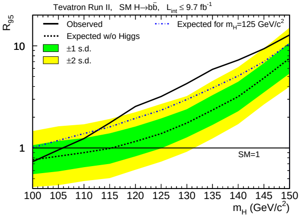
G. Piacquadio (ATLAS -*CERN*), **A. Rizzi** (CMS - *Pisa U.*)

Collaborators: **M. Grazzini, R. Harlander, D. Lopez Mateos, A. Mueck, J. Nielsen, M. Sanders, F. Tramontano**

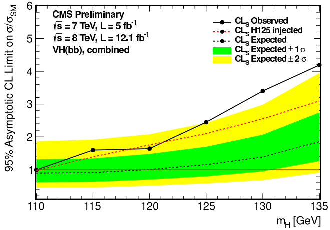


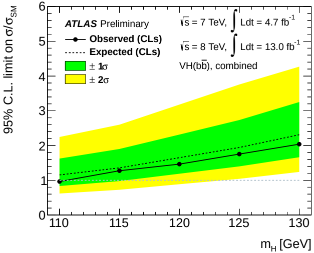
VII LHC Higgs Cross Section Workin Group Workshop
CERN – Dec. 5th 2012

SM Higgs production via $VH(\to b\bar{b})$: very interesting new results



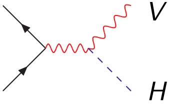
- Tevatron excess of events ($\sim 3\sigma$) in the mass range 120-135 GeV arXiv:1207.6436.
- LHC is approaching the SM limit. CMS excess of events ($\sim 2\sigma$) around 130 GeV HIG-12-044-pas.





Inclusive cross sections

Associated *VH* production: total cross section



Relevant channel at LHC with a boosted analysis: [Butterworth et al.('08)].

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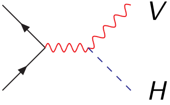

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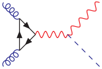

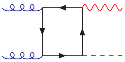

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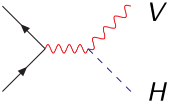

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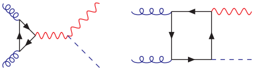

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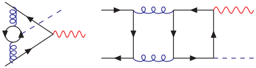

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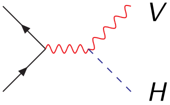

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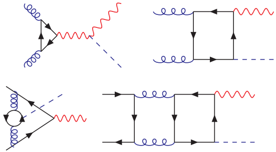

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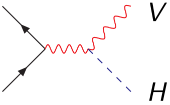

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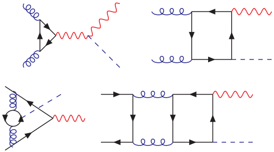

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Combination of NNLO QCD and NLO EW corrections for $\sigma_{\rm tot}$

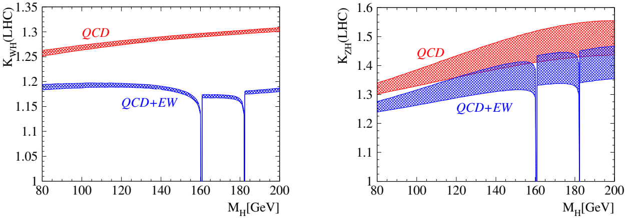
Brein et al. & Ciccolini et al. '04

$$\sigma_{\rm WH} = \sigma_{\rm WH}^{\rm VH@NNLO} \times (1 + \delta_{\rm WH,EW})$$

$$\sigma_{\rm ZH} = \sigma_{\rm ZH}^{\rm VH@NNLO} \times (1 + \delta_{\rm ZH,EW}) + \sigma_{\rm gg\to ZH}$$

Note:
$\delta_{\rm VH,EW}$ insensitive to PDFs !

K factors for $\rm pp \to VH + X$ @ $\sqrt{s} = 14\,\rm TeV$:

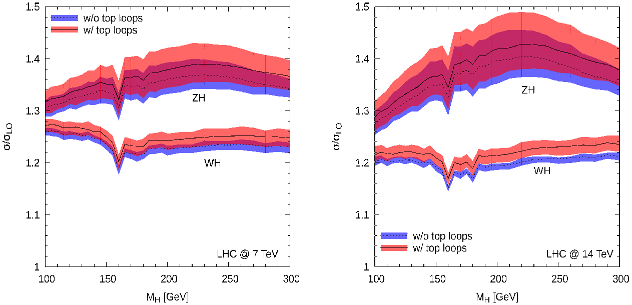


- typical size of corrections: $\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha) \sim 5{-}10\%$
- spikes at $M_{\rm H} = 2M_{\rm W}$ and $M_{\rm H} = 2M_{\rm Z}$
  = perturbative artifacts from WW/ZZ threshold
  $\hookrightarrow$ require inclusion of W/Z decays (see below)

from S. Dittmaier

Impact of non-DY-like corrections on total cross sections

Brein, Harlander, Wiesemann, Zirke '11



blue: LHC Higgs XS Group prediction

red: + non-DY-like corrections

For $M_{\mathrm{H}} < 200\,\mathrm{GeV}$: corrections $\sim 1{-}2\% \sim$ remaining theory uncertainty

$\hookrightarrow$ contribution relevant

from S. Dittmaier

Impact on total cross section

Altenkamp, S.D., Harlander, Rzehak, Zirke '12

Situation and result similar to $gg \to H$ (where exact NLO result known!)

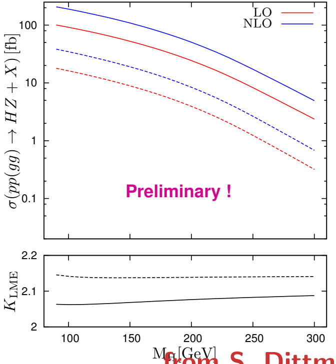
- take only K-factor in large-mass expansion (LME) !

$$\sigma^{\mathrm{NLO,approx}}_{gg\to ZH} = \sigma^{\mathrm{LO,full}}_{gg\to ZH} \times K_{\mathrm{LME}}$$

- numerical result:

  (dashed/solid: $\sqrt{s} = 7/14\,\mathrm{TeV}$)

  $K_{\mathrm{LME}} \sim 2.1$



$\Rightarrow$ gg contribution to σ_{tot} rises from LO $\to$ NLO by

$4\% \to 8\%$ for $\sqrt{s} = 7\,\mathrm{TeV}$

$8\% \to 17\%$ for $\sqrt{s} = 14\,\mathrm{TeV}$

(numbers for $M_H = 120\,\mathrm{GeV}$)

Note:

scale uncertainty of gg part $\sim 30\%$

(scale variation by factor 3)

from S. Dittmaier

Differential cross sections

Associated VH production: differential distributions

- Fully differential NNLO QCD corrections for WH (Drell-Yan like contributions), including tree-level $H \to b\bar{b}$ and $W \to l\nu$ decays with spin correlations [G.F,Grazzini,Tramontano('11)].
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Combination of NNLO QCD and NLO EW corrections for $\mathrm{d}\sigma$

LHC Higgs XS report
CERN-2012-002, arXiv:1201.3084 [hep-ph]

$$\mathrm{d}\sigma_{\mathrm{WH}} = \mathrm{d}\sigma_{\mathrm{WH}}^{\mathrm{VH@NNLO(DY)}} \times (1 + \delta_{\mathrm{WH,EW}})$$

$$\mathrm{d}\sigma_{\mathrm{ZH}} = \mathrm{d}\sigma_{\mathrm{ZH}}^{\mathrm{VH@NLO}} \times (1 + \delta_{\mathrm{ZH,EW}})$$

Again:
$\delta_{\mathrm{VH,EW}}$ insensitive to PDFs !

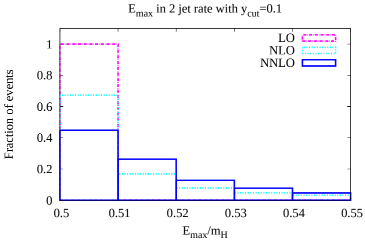
Features:

- NNLO QCD for WH in Drell–Yan-like approximation (ZH in progress)
  Ferrera, Grazzini, Tramontano '11
- NLO EW (+QCD) calculated with HAWK
  Denner, S.D., Kallweit, Mück '11
- size of corrections and TH uncertainties larger than for σ_{tot}

channel	$\mathrm{Hl}^+\nu_\mathrm{l}$	$\mathrm{Hl}^-\bar{\nu}_\mathrm{l}$	$\mathrm{Hl}^+\mathrm{l}^-$	$\mathrm{H}\nu_\mathrm{l}\bar{\nu}_\mathrm{l}$
$\delta_{\mathrm{EW}}^{\mathrm{bare}}/\%$	-14	-14	-11	-7
$\Delta_{\mathrm{PDF}}/\%$	±5	±5	±5	±5
$\Delta_{\mathrm{scale}}/\%$	±2	±2	±2	±2
$\Delta_{\mathrm{HO}}/\%$	±1	±1	±7	±7

from S. Dittmaier

QCD correction to $H \to bb$ decay



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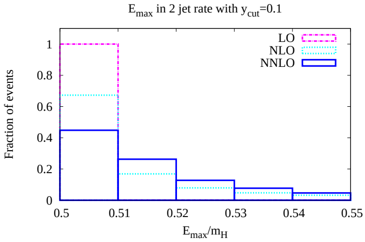

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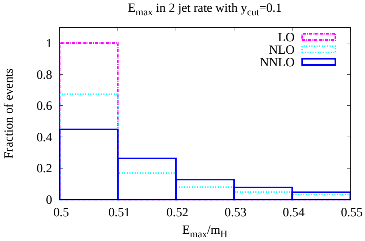

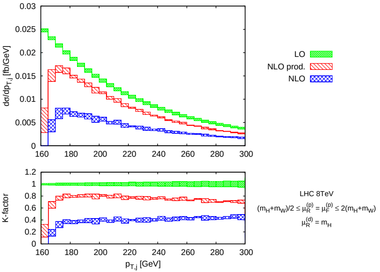

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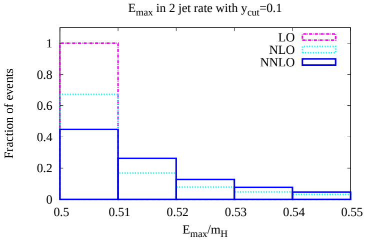

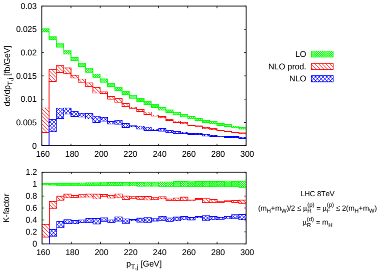

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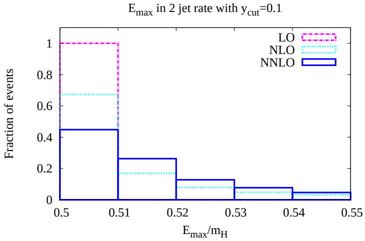
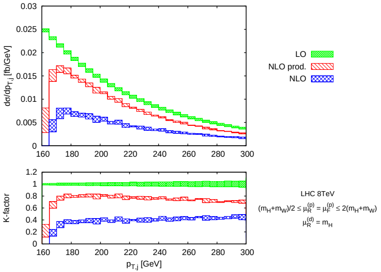
QCD correction to $H \to bb$ decay



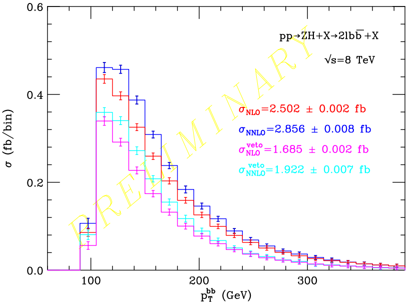


- [Anastasiou,Herzog,Lazopoulos('12)]:
  Fully differential $H \to b\bar{b}$ at NNLO QCD (but in the $m_b = 0$ approx.).
  Energy spectrum of the leading jet (JADE alg., $ycut = 0.1$).

- [Banfi,Cancino('12)]: $pp \to HW$ phenomenological analysis with NLO QCD correction both to production and to ($H \to b\bar{b}$) decay [Drees,Hikasa('90)].
  Boosted analysis at 14 TeV: stable with respect to NLO correction to decay.
  CMS analysis at 8 TeV: NLO corrections to decay important (especially when a extra-jet veto is applied).
  $p_T^{b\bar{b}}$ distribution up to NLO.

NEW: associated ZH production at NNLO:

G.F., Grazzini, Tramontano (in preparation)



$pp \to ZH(\to 2l\, b\bar{b})$
p_T spectra of the $b\bar{b}$ system at the LHC for $m_H = 125\,GeV$ at NLO and NNLO with and without the jet veto.

- $gg \to HZ$ top-loop $\sim g^2\lambda_t^2\alpha_S^2$ (non DY-like) corrections included.
- Cuts (we follow CMS analysis):
  Leptons: $p_T^l > 20\,GeV$, $|\eta^l| < 2.5$,
  $75 < m_{ll} < 105\,GeV$, $p_T^{ll} > 100\,GeV$.
  Jets: anti-k_T algorithm with R=0.5.
  Two b-jets (with $p_T > 20\,GeV$, $|\eta| < 2.5$ and $p_T^{bb} > 100\,GeV$).
  Jet veto: extra jet radiation is vetoed if $p_T > 20\,GeV$ and $|\eta| < 2.5$.
- Higher-order corrections: NLO (NNLO) effects: without jet-veto +20% (+14%); with jet-veto −20% (+14%).
  Effect of the jet-veto: −33% both at NLO and NNLO.

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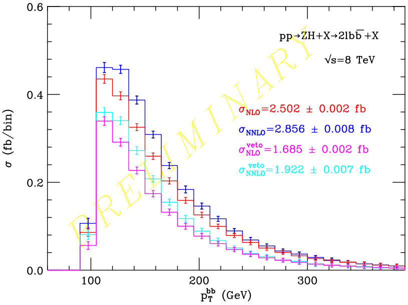

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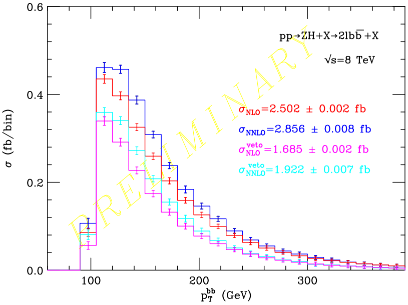

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Theoretical status...

VH production cross-sections known with high precision through NNLO QCD + NLO EW.

Inclusive cross-sections:

- Known at NNLO QCD (DY-like) + NLO EW
- Recent results: NNLO QCD (not DY-like); $gg \to HZ$ at NLO.

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...and plans:

- Fully-differential NNLO QCD results for *VH* to be combined with NLO EW (including $H \to WW/ZZ$ decays).
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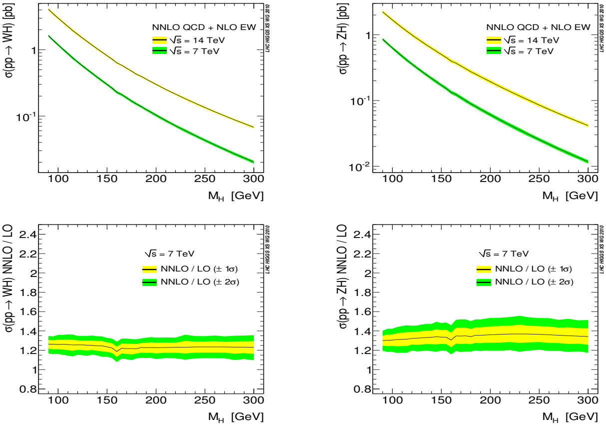
Back up slides

Recent update for σ_{tot} @ LHC (7 and $14\,\mathrm{TeV}$) in LHC Higgs XS report

CERN-2011-002
arXiv:1101.0593 [hep-ph]

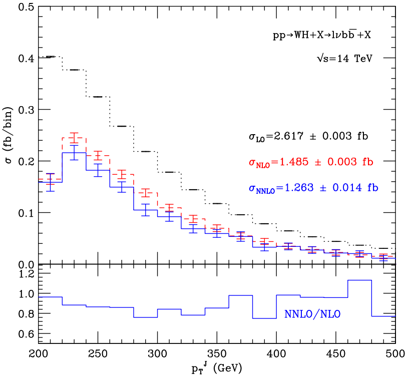


Uncertainties @ $7\,\mathrm{TeV}$: WH: PDF $\sim$ 3–4%, scale $\sim$ 1%
ZH: PDF $\sim$ 3–4%, scale $\sim$ 1–2%

from S. Dittmaier

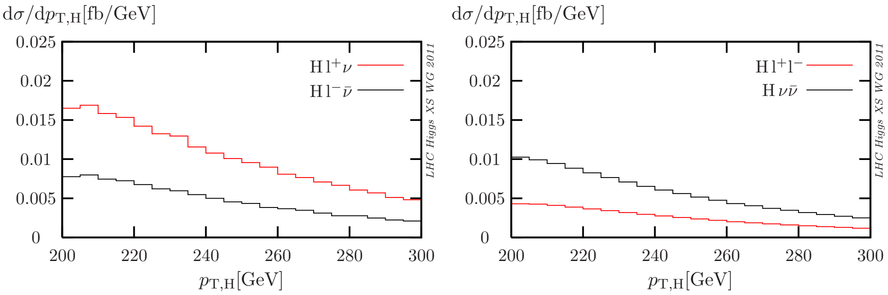
Physikalisches Institut
Fakultät für Mathematik und Physik
Albert-Ludwigs Universität Freiburg

Stefan Dittmaier, *NLO QCD & EW corrections to Higgs strahlung off W/Z bosons with HAWK* EPS11, Grenoble, 2011 – 8



p_T spectra of the fat jet at the LHC for $m_H = 120 GeV$ at LO (dots), NLO (dashes) and NNLO (solid) [G.F.,Grazzini,Tramontano('11)].

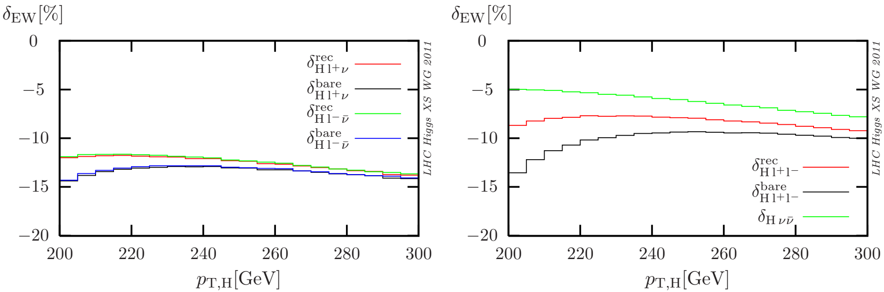
- Selection strategy of [Butterworth et al.('08)]: search a large-p_T Higgs boson thorough a collimated $b\bar{b}$ pair decay.
  Cuts:
  Leptons: $p_T^l > 30 GeV$, $|\eta^l| < 2.5$,
  $p_T^{miss} > 30 GeV$, $p_T^W > 200 GeV$.
  Jets: Cambridge/Aachen algorithm with R=1.2.
  Fat jet (contain the $b\bar{b}$) $p_T^J > 200 GeV$, $|\eta^J| < 2.5$
  Jet veto: No other jets with $p_T > 20 GeV$ and $|\eta| < 5$.
- Large negative higher-order corrections: NLO (NNLO) effects -52%/-36% (-6%/-19%), depending on the scale choice ($\mu_F = \mu_R = m_W + m_H$).
- Jet veto strongly affect the higher order corrections ⇒ stability of fixed order calculation challenged.



Yellow Report II:arXiv:1201.3084

Distributions in $p_{T,H}$ for $pp \to WH \to l\nu H$ (NNLO QCD + NLO EW) and for $pp \to ZH \to ll/\nu\nu H$ (NLO QCD + NLO EW).
Boosted setup: $|\eta_l| < 2.5$, $p_{T,l} > 20$ GeV, $p_{T,\nu} > 25$ GeV, $p_{T,H} > 200$ GeV, $p_{T,W/Z} > 190$ GeV.

We produced similar results at 8 TeV (soon available).



Yellow Report II:arXiv:1201.3084

Size of higher-order corrections increase in the high $p_{T,H}$ region. Relative effect of NLO EW corrections for $p_{T,H}$ for $pp \to WH \to l\nu H$ and for $pp \to ZH \to ll/\nu\nu H$.

Boosted setup: $|\eta_l| < 2.5$, $p_{T,l} > 20$ GeV, $p_{T,\nu} > 25$ GeV, $p_{T,H} > 200$ GeV, $p_{T,W/Z} > 190$ GeV.

Present theory uncertainties in the ATLAS VH → bb analyses

Bin	$ZH \to \ell^+\ell^- b\bar{b}$ p_T^Z [GeV] 0-50	50-100	100-200	>200	$WH \to \ell\nu b\bar{b}$ p_T^W [GeV] 0-50	50-100	100-200	>200	$ZH \to \nu\bar{\nu}b\bar{b}$ E_T^{miss} [GeV] 120-160	160-200	>200
Components of the Background Systematic Uncertainties											
b-tag Eff	1.4%	1.0%	0.3%	4.8%	0.9%	1.3%	0.9%	7.2%	4.5%	4.8%	5.3%
Bkg Norm	3.6%	3.4%	3.6%	3.8%	2.7%	1.8%	1.8%	4.5%	3.2%	3.2%	2.9%
JES/MET	2.1%	1.2%	2.7%	5.1%	1.5%	1.4%	2.1%	9.5%	8.0%	9.2%	11.8%
Leptons	0.2%	0.3%	1.1%	3.4%	0.1%	0.2%	0.2%	1.7%	0.0%	0.0%	0.0%
Luminosity	0.2%	0.1%	0.2%	0.4%	0.1%	0.1%	0.1%	0.2%	0.2%	0.5%	0.7%
Pileup	0.9%	1.6%	0.5%	1.3%	0.1%	0.2%	0.8%	0.5%	1.9%	3.2%	2.8%
Theory	5.2%	1.3%	4.7%	14.9%	2.3%	0.4%	1.6%	14.8%	3.9%	4.4%	7.8%
Total Bkg	6.9%	4.3%	6.6%	17.3%	3.9%	2.7%	3.4%	19.6%	10.7%	12.2%	15.6%
Components of the Signal Systematic Uncertainties											
b-tag Eff	6.4%	6.4%	7.0%	13.7%	6.4%	6.4%	7.0%	12.1%	7.1%	8.2%	9.2%
JES/MET	4.9%	3.2%	3.5%	5.5%	6.6%	5.5%	4.8%	4.4%	7.9%	6.0%	6.9%
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Theory	4.6%	3.6%	3.3%	5.3%	4.4%	4.7%	5.0%	8.0%	3.3%	3.3%	5.6%
Total Signal	10.1%	9.1%	9.6%	16.5%	11.4%	10.8%	11.0%	16.0%	11.8%	11.4%	13.4%

- VH/ZH theory signal uncertainty:
  - 30-50% of total uncertainty
- Background theory uncertainty (mainly Vbb):
  - Leading uncertainty, in particular in the high pT bins with the best sensitivity.

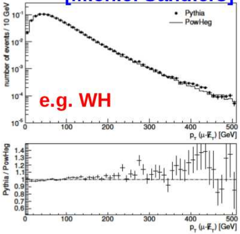
from G. Piacquadio ATLAS

Signal uncertainties considered (II)

- Presently we only finally consider the difference between Pythia and Powheg+Herwig.

[Michiel Sanders]

	p_T(V)	*WH*	*ZH* ($Z \to \ell\ell$)
NLO QCD	[0, 50]	−4.5%	−4.9%
	[50, 100]	−4.9%	−2.3%
	[100, 200]	−4.7%	−0.7%
	[200, ∞]	−5.9%	−4.5%



- This is added to the uncertainty due to the NLO EW correction:

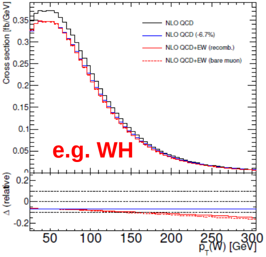
	p_T(V)	*WH*	*ZH* ($Z \to \ell\ell$)
Uncertainty	[0, 50]	4.5%	4.9%
	[50, 100]	5.0%	2.8%
	[100, 200]	5.7%	1.8%
	[200, ∞]	10.4%	6.2%

- These „acceptance“ or „differential“ uncertainties dominate over the inclusive parton level uncertainties.
- We need more effort to disentangle the differences we see, in order to finally reduce the systematic uncertainty.

from G. Piacquadio

NLO EW differential corrections

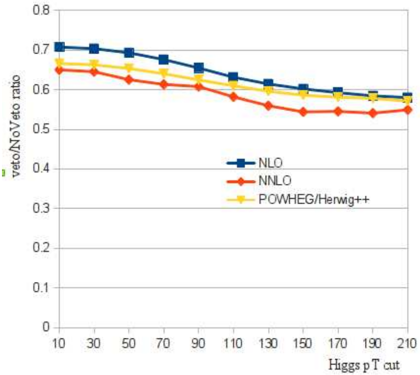
- Obtained by **Alexander Mueck** from the HAWK team (~YR II) and expressed as a function of pT(W) for WH and pT(Z) for ZH.
- Correction derived with respect to inclusive correction and applied to reweight events as a function of pT(W) or pT(Z).



$WH \to \ell\nu bb$	[0, 50]	[50, 100]	[100 – 200]	[200 – ∞]
Δ_{EW}	−6.8%	−7.5%	−9.8%	−14.7%
δ_{EW}	−0.1%	−0.8%	−3.3%	−8.6%
$ZH \to \ell\ell bb$	[0, 50]	[50, 100]	[100 – 200]	[200 – ∞]
Δ_{EW}	−5.7%	−6.6%	−6.7%	−9.2%
δ_{EW}	−0.7%	−1.6%	−1.7%	−4.3%
$ZH \to \nu\nu bb$	[0, 50]	[50, 100]	[100 – 200]	[200 – ∞]
Δ_{EW}	−3.9%	−4.3%	−4.2%	−6.4%
δ_{EW}	+1.3%	+0.8%	+1.0%	−1.4%
$ZH \to \nu\nu b\bar{b}$	–	[120 – 160]	160 – 200	[200 – ∞]
Δ_{EW}	–	−4.0%	−4.1%	−6.4%
δ_{EW}	–	+1.1%	+1.1%	−1.4%
$WH \to \ell\nu bb$	–	[120 – 160]	160 – 200	[200 – ∞]
Δ_{EW}	–	−9.1%	−10.3%	−13.3%
δ_{EW}	–	−2.5%	−3.9%	−7.0%

- Applied in ATLAS. Significantly reduces signal cross section at high pT!

from G. Piacquadio ATLAS

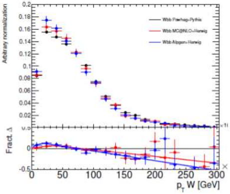


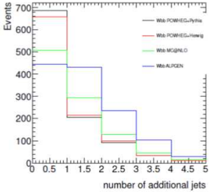
from A. Rizzi CMS

Jet veto efficiency predicted by NNLO QCD and NLO+PS function Higgs pT-cut. In the high p_T cut region, NNLO corrections are relevant.

W+bb background comparison (II)

- The overall normalization is derived from data (m(bb) sidebands).
- From the difference between generators, a systematic uncertainty on m(bb) and pT(W) is derived (presently dominated by statistical uncertainties).
- Difference in number of jets presently overcome by normalizing W+bb+0 jets and W+bb+1 jets separately in data.
- Presently one of the leading uncertainties of the analysis.
- Additional 2012 statistics will not improve analysis if we don't solve this!





from G. Piacquadio