Report on the VH subgroup activities (Theory part)

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VH subgroup conveners:
John Campbell, Carlo Pandini, Luca Perrozzi and FT

The 13th Workshop of the LHC Higgs Cross Section Working Group - CERN, 13-14 July 2017

Outline

- NNLOPS
- NLOPS QCD+EW corrections
- VH(bb)@NNLO
- ggZH@NLO

NNLO+PS MATCHING:
ASSOCIATED HIGGS PRODUCTION

Wojciech Bizoń
(University of Oxford)

in collaboration with:
William Astill, Emanuele Re, Giulia Zanderighi

LHC HXSWG – WG1 meeting (29/06/2017)

- Already in YR4 NNLOPS for HW: in a nutshell

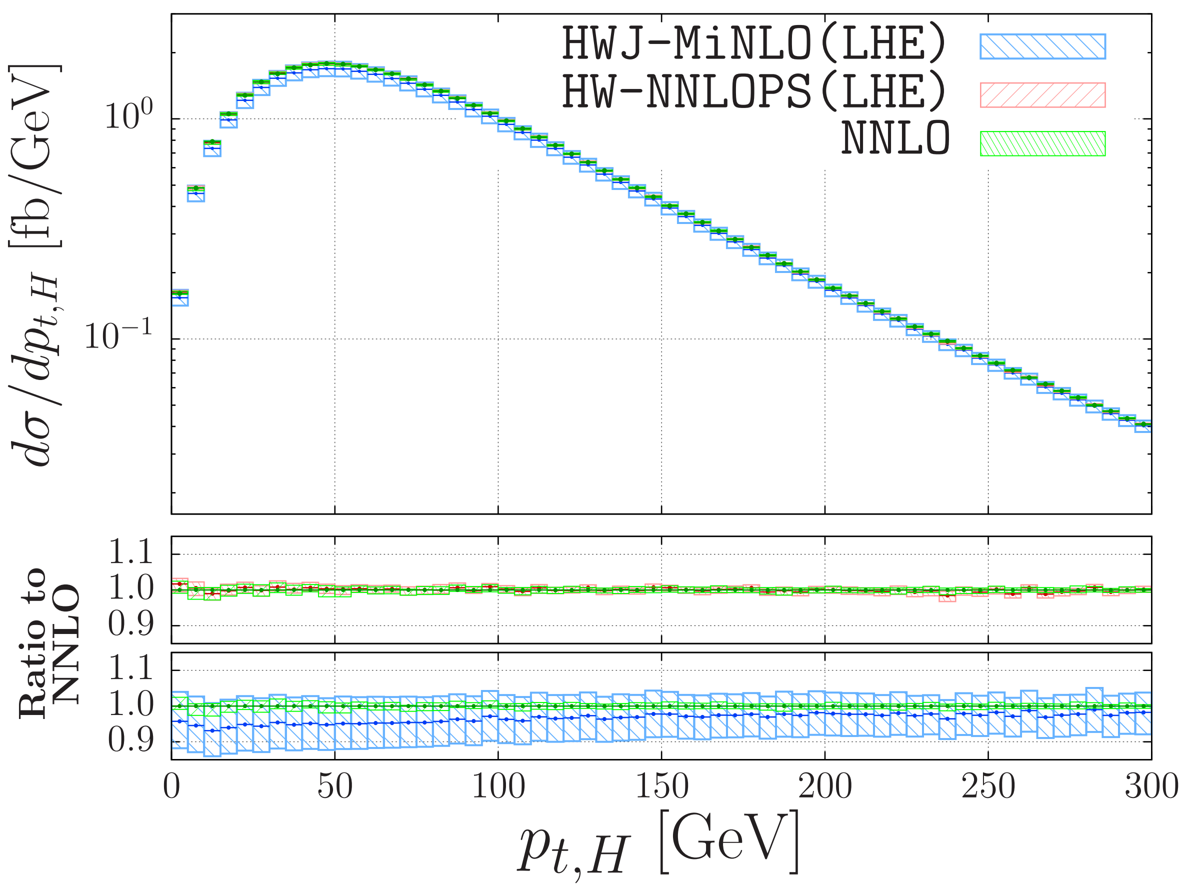
Starting from the VHJ generator:

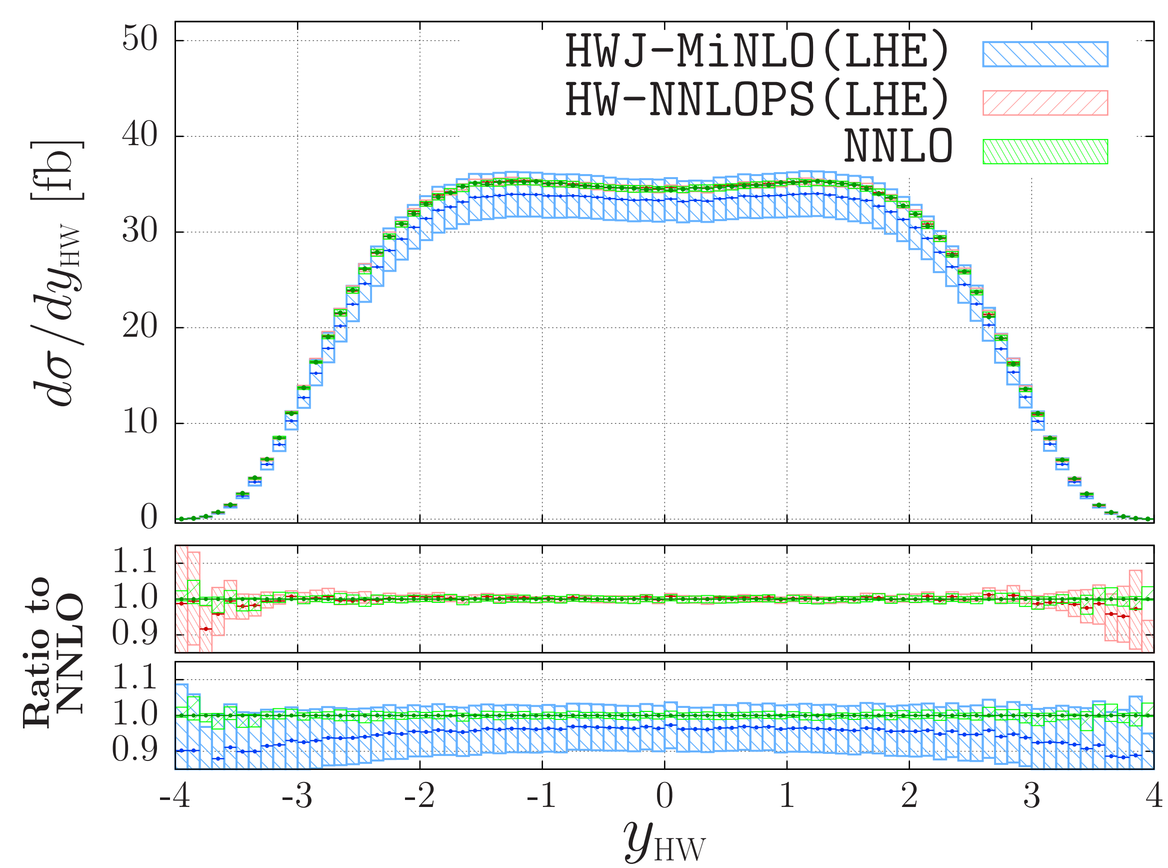
- $$\tilde{B}_{\mathtt{MiNLO}} = \alpha_s(q_T)\Delta^2(q_T,\bar{\mu}_R)\left[B\left(1-2\Delta^{(1)}(q_T,\bar{\mu}_R)\right)+\alpha_s(\bar{\mu}_R)\left(V(\bar{\mu}_R)+\int d\Phi_r R\right)\right]$$

Preserve NLO⁰ accuracy for VH

- $$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathtt{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathtt{MiNLO}}} = \frac{d\sigma^{(0)}+d\sigma^{(1)}\alpha_s+d\sigma^{(2)}\alpha_s{}^2}{d\sigma^{(0)}+d\sigma^{(1)}\alpha_s+d\tilde{\sigma}^{(2)}\alpha_s{}^2} = 1+\frac{d\sigma^{(2)}-d\tilde{\sigma}^{(2)}}{d\sigma^{(0)}}\alpha_s{}^2+\mathcal{O}(\alpha_s{}^3)$$

Preserve NLO accuracy for VHJ production





GROWING COMPLEXITY

- Easy to imagine: with bigger phase-space (formally simple) procedure becomes computationally involving…

  (a) Higgs production (ggH): 1-dim 1 variable (1D histogram = 25 bins)

  (b) Drell-Yan production: 3-dim 3 variables (3D histogram = 15 625 bins)

  (c) VH production: 6-dim 6 variables (6D histogram = ??? [244M bins])

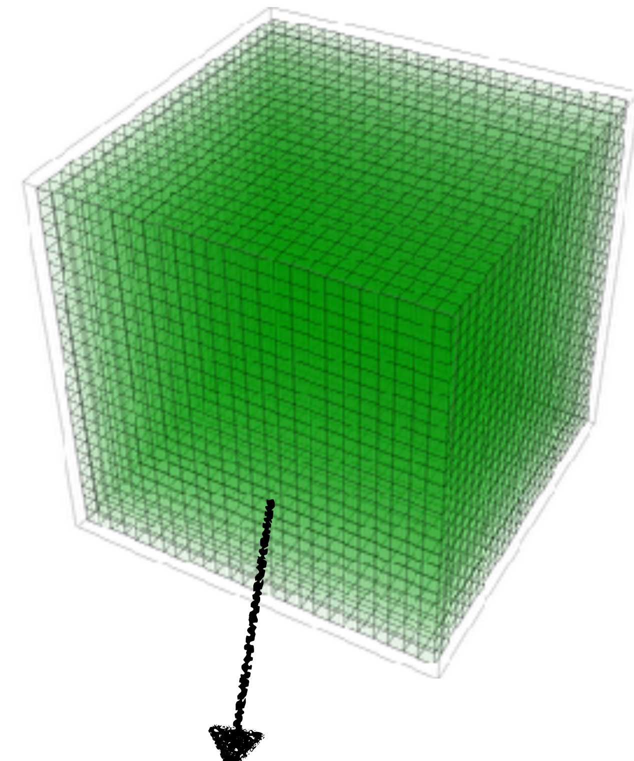
- phase-space parametrisation:

1	2	3	4	5	6
y_{VH}	$p_{t,H}$	Δy	θ^*	ϕ^*	$m_{\ell\bar{\ell}'}$

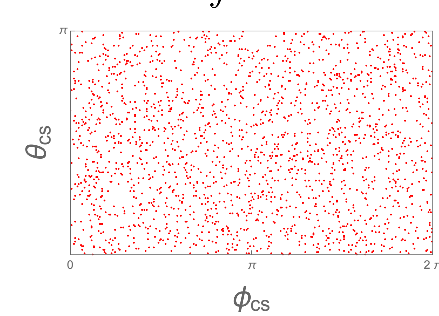
- cross-section in terms of Collins-Soper angles:

$$\frac{d\sigma}{d(\cos\theta^*)d\phi^*} = \frac{3\,\sigma}{16\pi}\Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin 2\theta^*\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos 2\phi^* + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin\theta^*\sin\phi^* + A_6\sin 2\theta^*\sin\phi^* + A_7\sin^2\theta^*\sin 2\phi^*\Big]$$

- neglect dependence on $m_{\ell\bar{\ell}'}$ (validated)



$$< A_i >= \int d\phi^* d\theta^* \ldots$$



FINALLY:

– one 3D histogram for each A-coefficient (8+1 tables)

– still numerically challenging as each bin is an integral over 2-dim phase-space

REWEIGHTING UNCERTAINTY (HZ)

- large phase-space ==> computationally heavy task
- HW@NNLOPS: “smooth” enough distributions required very long runs (~1month x 300cores)
- Is it essential to have that long runs?

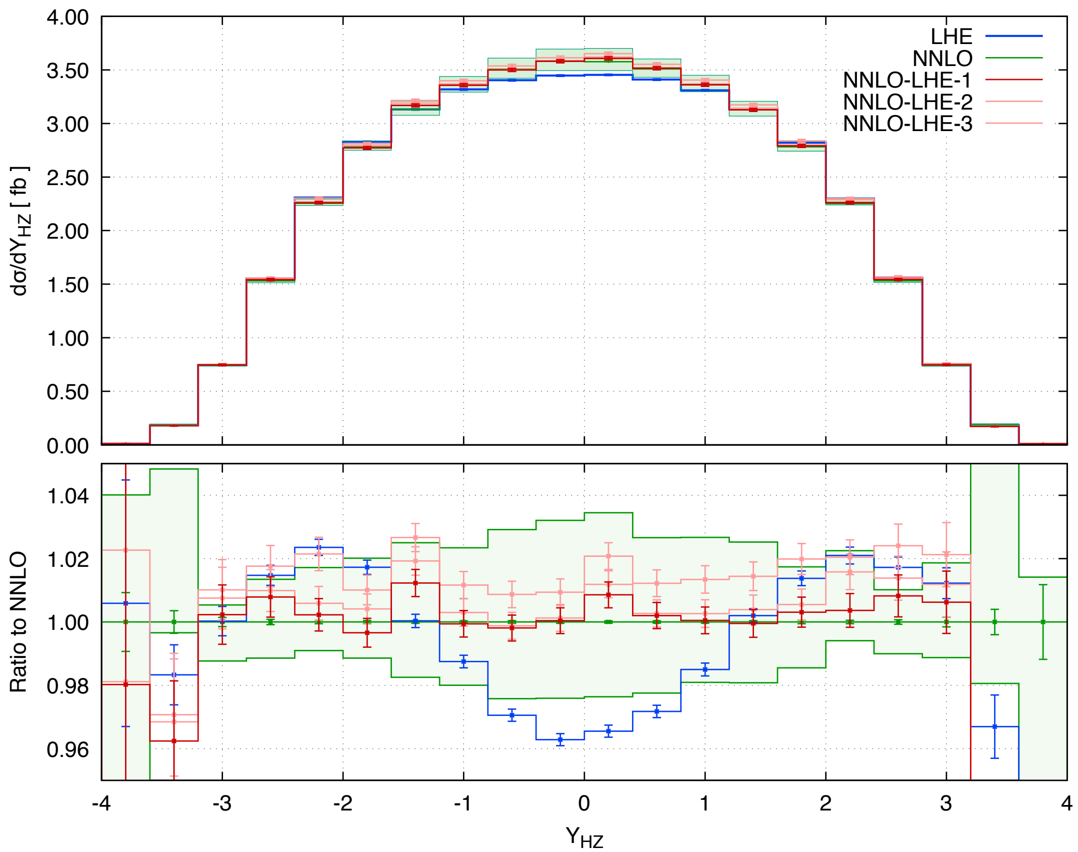
  – results below (HZ) were prepared with NNLO runs (~2 days x 2000cores) and 12.5M HZJ events

  – we have used various setups:

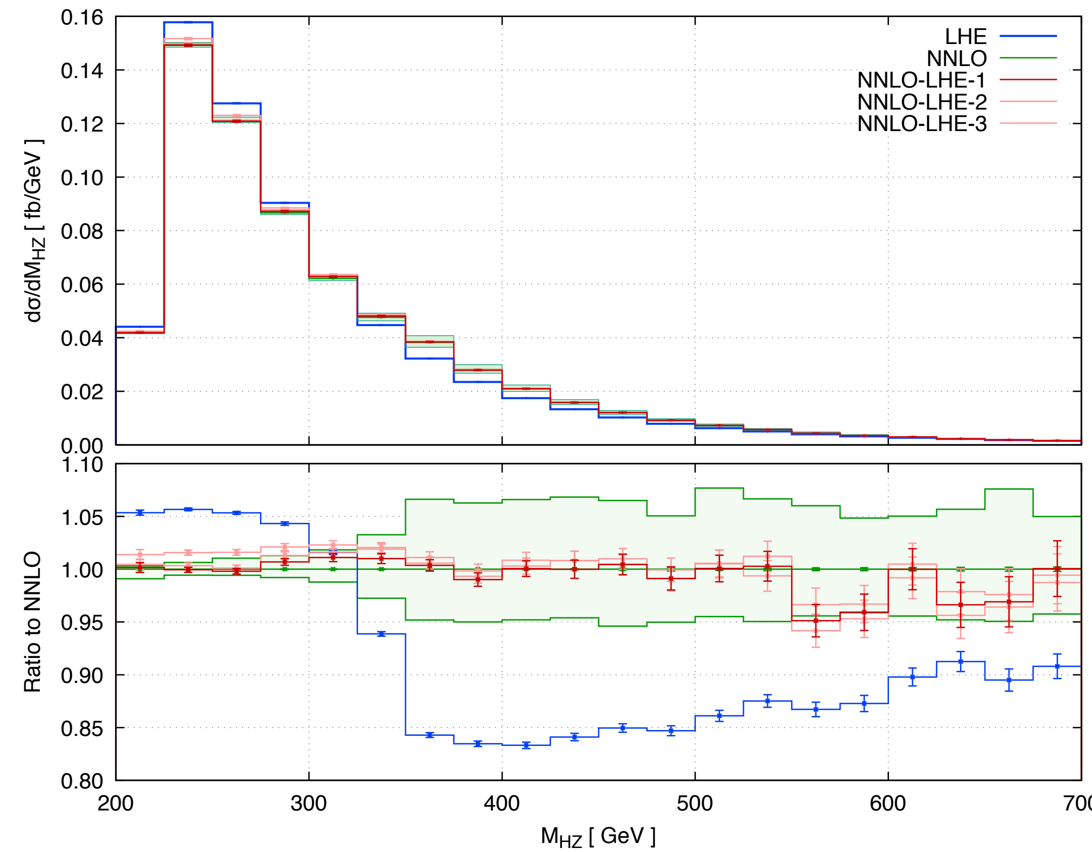
  (a) reweight only with three basic variables (neglect Collins-Soper angles: A(i)=0)

  (b) neglect A(i) coefficients with large uncertainties (stat.err > 200%, stat.err > 50%)

  => use less precise histograms for reweighting but assign an error associated with this procedure



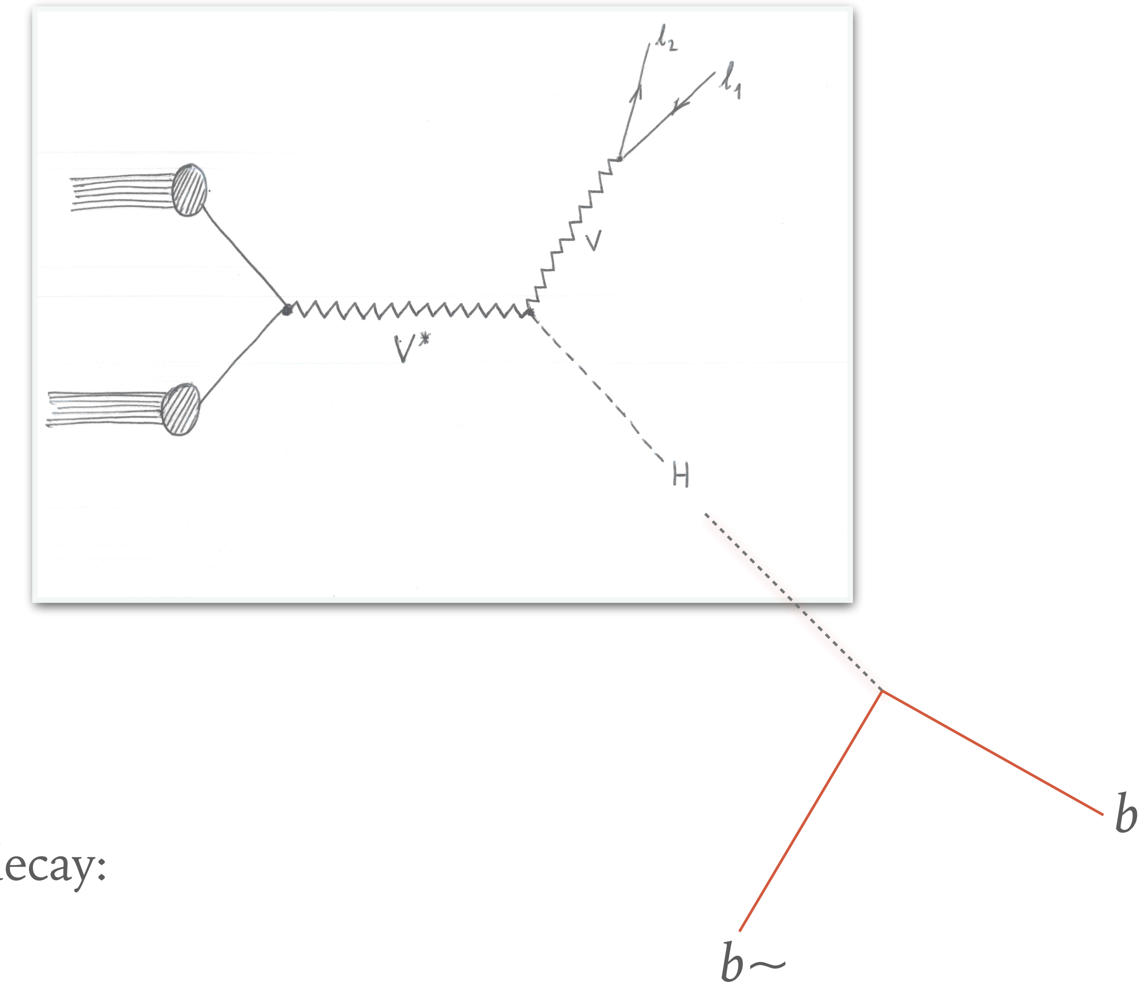
PRELIMINARY!



PRELIMINARY!

INCORPORATING HBB DECAY AT NLO

- **Hbb** – largest SM Branching Ratio (~60%)
- Allows for "precision" measurements in non-primary H-production channels



REWEIGHTING: TREATMENT OF THE DECAY

- in narrow width approximation phase-space split into production/decay:

$$d\Phi_{Vb\bar{b}} = d\Phi_{VH} \times d\Phi_{(H \to b\bar{b})}$$

- NNLO reweighting performed using Born kinematics hence we can use the same setup as without Higgs decay (we are actually changing setup but purely for practical purposes).
- This approach secures NNLO accuracy in production stage.
- NNLO-LHE: Hbb decay is treated at NLO within POWHEG (i.e. virtual corrections + some events contain real emission from bb-pair) which enables probing decay observables at NLO.

[170x.xxxxx; W.Astill, WB, E.Re, G.Zanderighi]

USING THE CODE

- VH Reweighting requires two sources of input

  (1) HWJ / HZJ @POWHEG+MiNLO

  (2) HW / HZ @NNLO

- our code contains:

  – patches (analysis, identical physical parameters, …) to produce compatible results

  – `hv_minnlo`: program for reweighting event files using multidimensional histograms

- for HW(NNLOPS) we have used `HVNNLO` code:
  [1107.1164; G.Ferrera, M.Grazzini, F.Tramontano], [1407.4747; G.Ferrera, M.Grazzini, F.Tramontano]

- for HZ(NNLOPS) we are using `MCFM-8.0` for NNLO distributions:
  [1601.00658; J.Campbell, R.K.Ellis, C.Williams]

- we are planning to release the full code with detailed manual shortly after HZ publication

- for the time being, we are able to provide multidimensional HW distributions used in first paper [1603.01620], disadvantage: fixed settings

Should other NNLO codes become available in the meantime,

we can help interested users to interface it with our NNLO-reweighter!

NLO QCD+EW corrections for HV and HV+jet in the POWHEG BOX RES

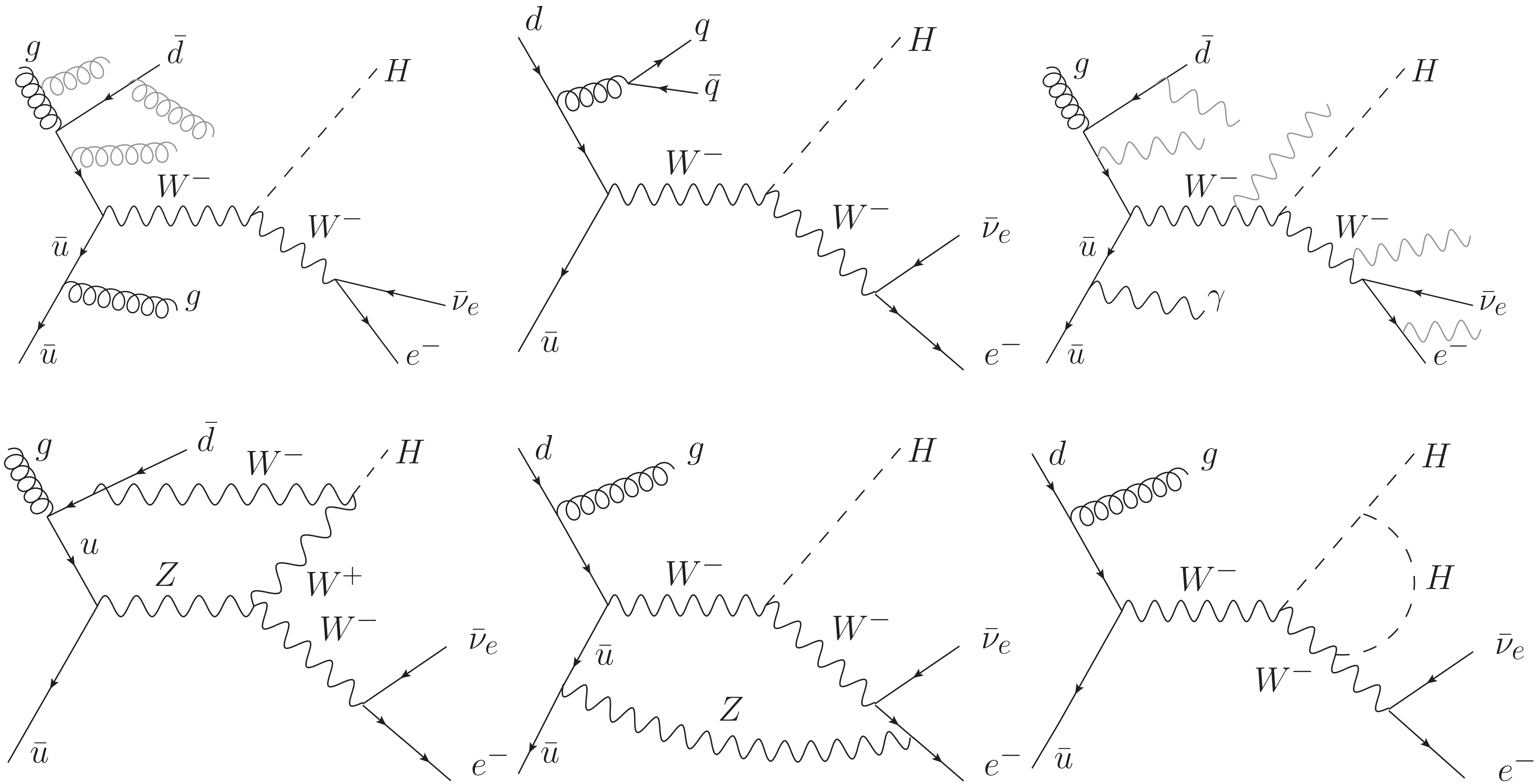
Carlo Oleari
Università di Milano-Bicocca, Milan

29 June 2017

In collaboration with: F. Granata, J. Lindert and S. Pozzorini
arXiv:1706.03522

- ✗ NLO QCD+EW HV and HVj production
- ✗ Resonances and the `POWHEG BOX RES` code
- ✗ HVj+ `MiNLO`
- ✗ A few results
- ✗ Conclusions

QCD+EW corrections to HVj



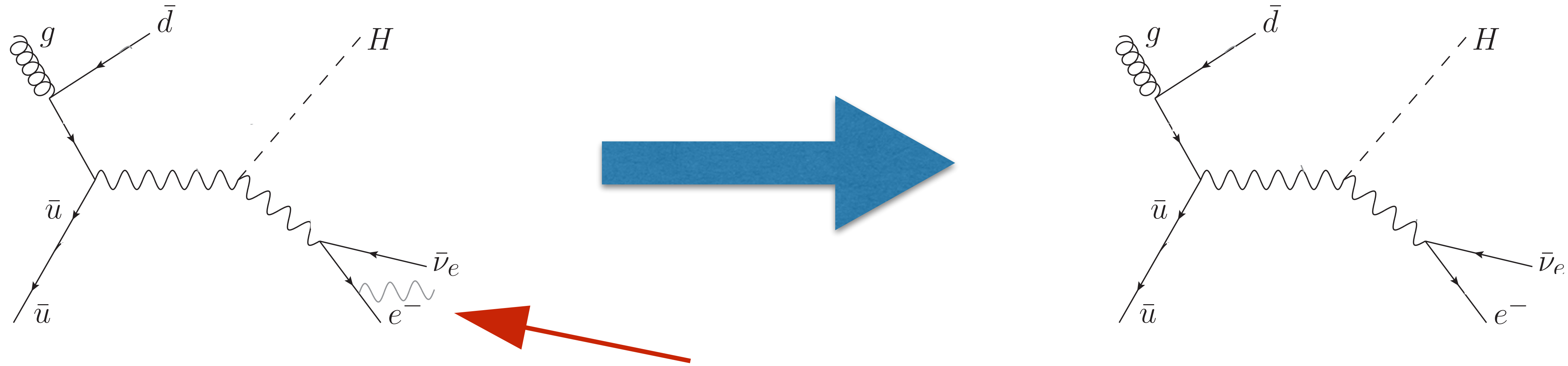
Born: $\mathcal{O}\left(\alpha_S\, \alpha_{EM}^3\right)$ QCD real+virtual: $\mathcal{O}\left(\alpha_S^2\, \alpha_{EM}^3\right)$ EW real+virtual: $\mathcal{O}\left(\alpha_S\, \alpha_{EM}^4\right)$

Sensitive to the trilinear Higgs boson coupling.

All EW amplitudes computed with OpenLoops that recently achieved automation also for EW corrections

Resonances

When dealing with resonances whose decay products can radiate, we have two technical problems to tackle. Consider for example $e^- \bar{\nu}_e \mu^+ \nu_\mu b \bar{b}$



1. **mismatch of resonance virtuality among real and subtractions in the NLO computation**
2. **more seriously this mismatch affect the R/B in POWHEG event generation**

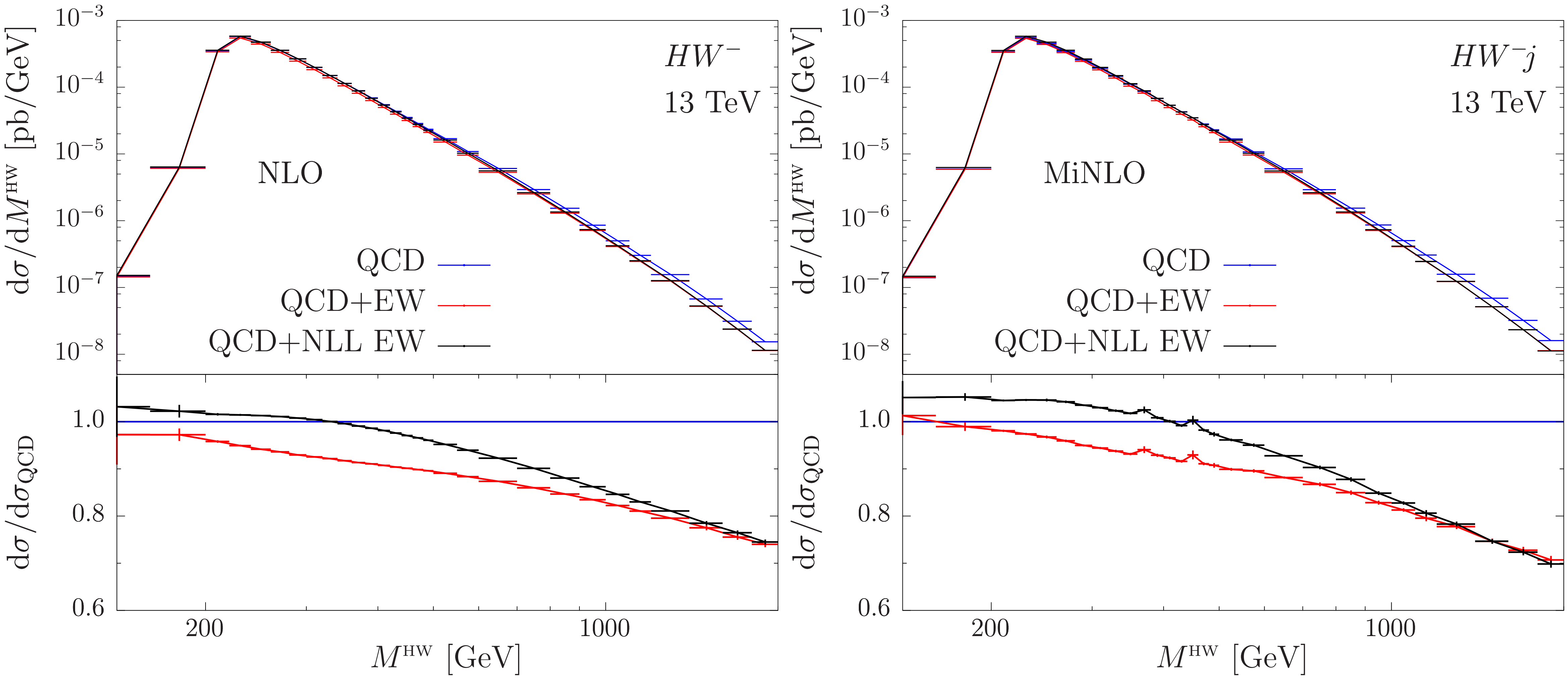
The `POWHEG BOX RES`

The solutions have been discussed in Jezo, Nason, arXiv:1509.09071. The output of this has been a major revision of the `POWHEG BOX V2` code: the `POWHEG BOX RES`.

- For each flavour structure, the code automatically finds all the possible resonance histories compatible with the partonic process at hand and keeps track of them, while generating radiation from each resonance, preserving the virtuality of the resonances.

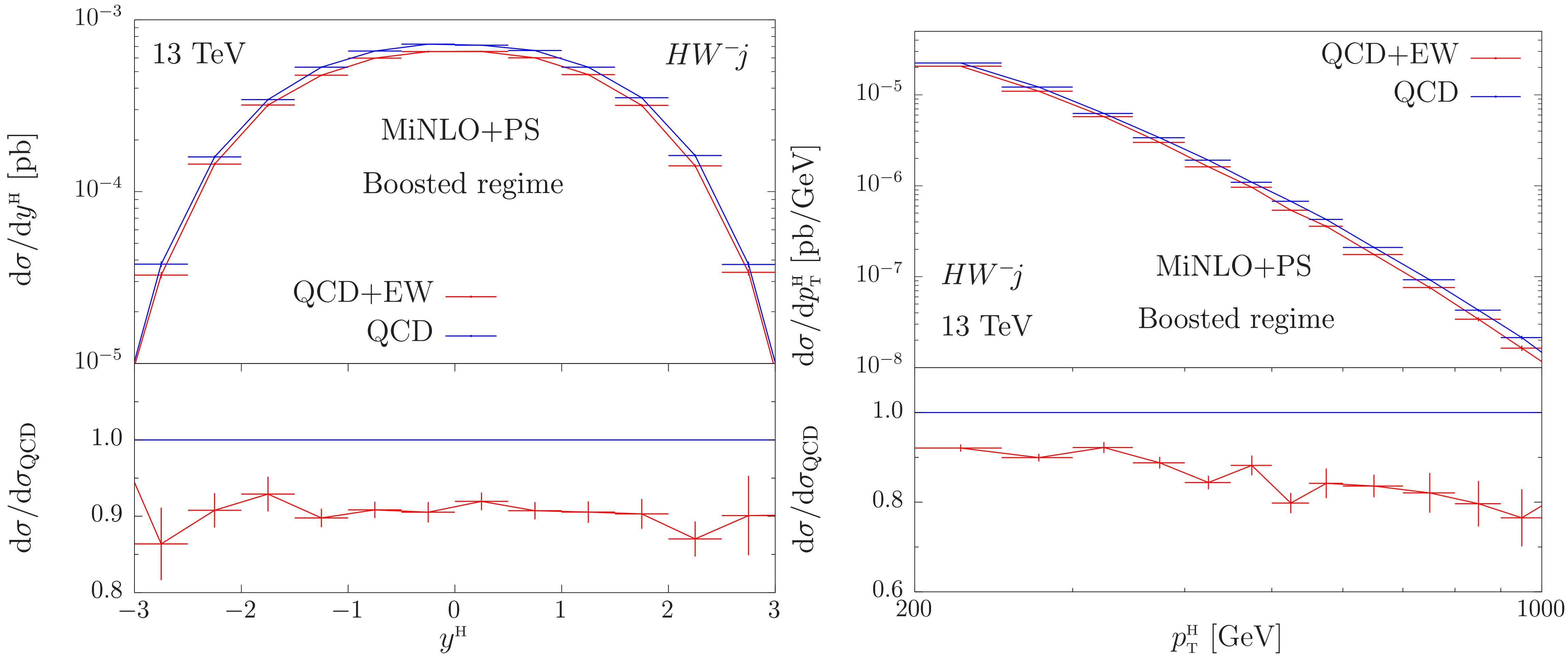
Applied now to HV and HVj production, where the virtuality of the V boson is preserved when photon radiation is produced.

NLO results at fixed order for HW^- and HW^-j production



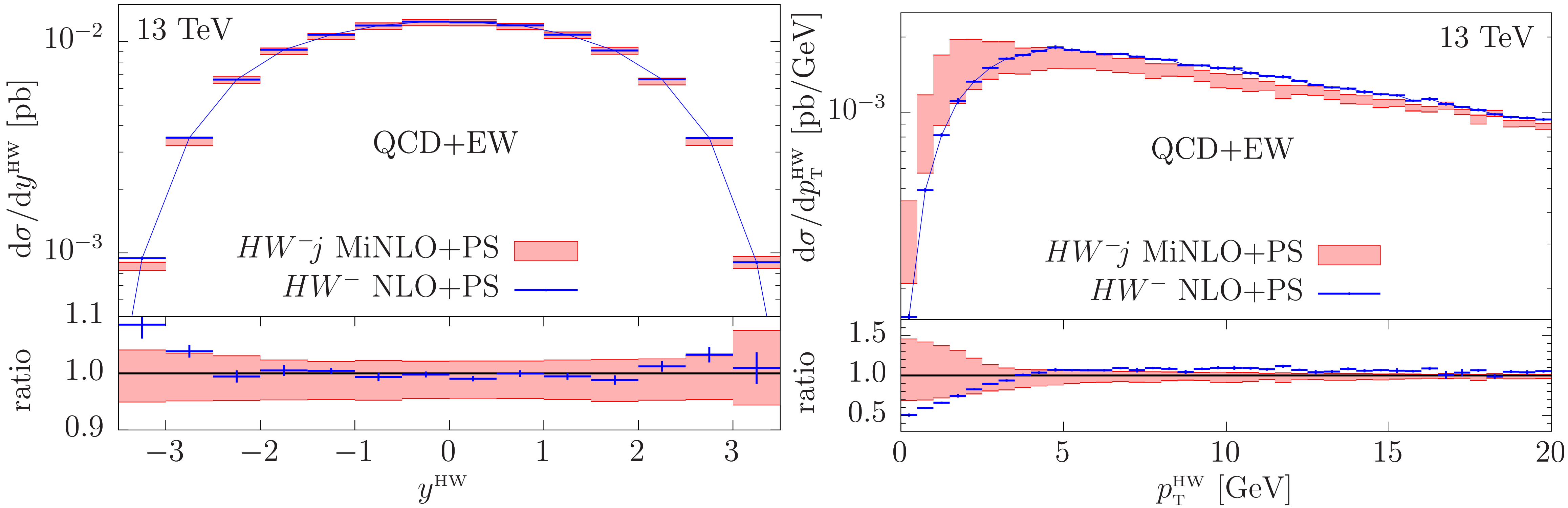
- EW corrections can largely exceed the ten percent level in the high-energy regions, where Sudakov logarithms become dominant.
- An example is the invariant mass of the HV pair in HV and HVj production, where the EW corrections reach -30% around 2 TeV.

MiNLO + Parton Shower results for HW^-j production



- These results closely agree with the corresponding ones for HW^- production.
- This supports the fact that the `MiNLO` predictions for HVj should preserve NLO QCD+EW accuracy for inclusive (with respect to the jet) quantities.

HV vs. *HVj* generators



- Scale variation bands (details in arXiv:1706.03522)
- With MiNLO, the y^{HW} and p_T^{HW} distributions computed with the HWj generator are finite and agree with the results for HW.
- y^{HW} has NLO accuracy both in HV and with HVj.
  p_T^{HW} has LO accuracy for HV and NLO accuracy for HVj.

Possible recipe for QCD@NNLOPS+EW@NLOPS (C. Oleari)

In principle one could get distributions with the highest achievable accuracy combining 3 event samples as follows:

1) event sample with QCD @ NNLOPS
2) event sample with EW @ NLOPS
3) event sample with LO PS

QCD NNLO + EW NLO + PS = 1 + 2 - 3

VH production with $H \to b\bar{b}$ decay in full NNLO QCD

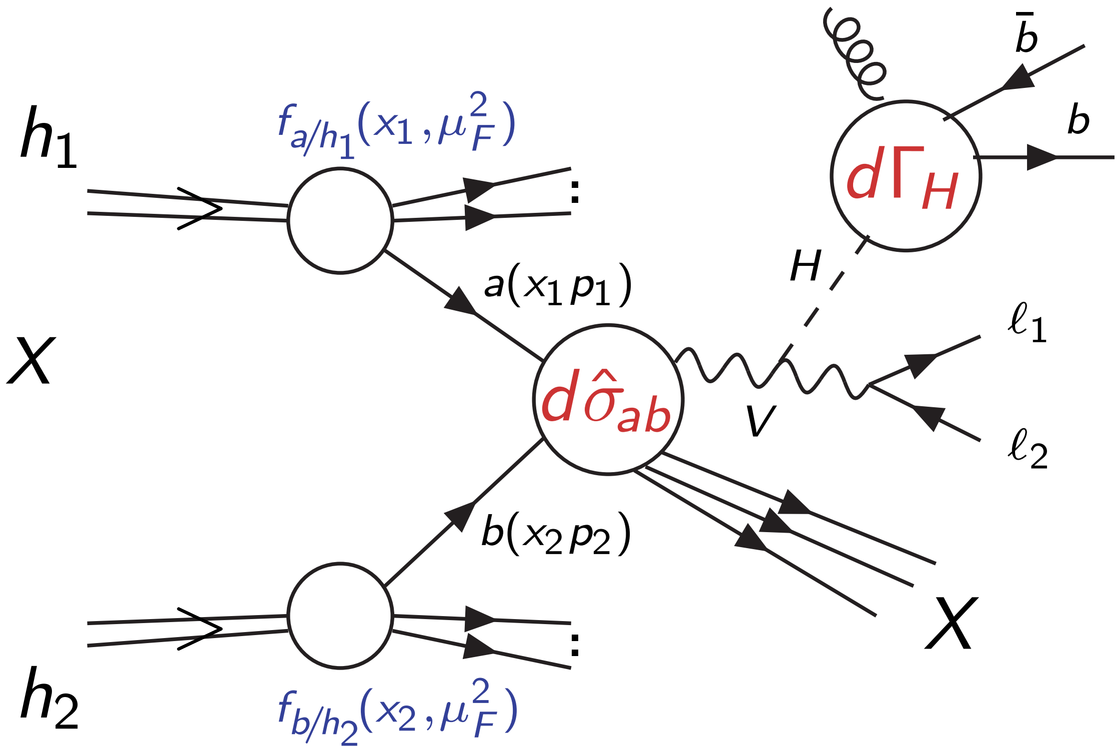
Giancarlo Ferrera

Università di Milano & INFN Milano

LHC Higgs Cross Section Working Group
VH subgroup – June 29th 2017

In collaboration with: M. Grazzini, G. Somogyi & F. Tramontano

Associated VH production with H $\to b\bar{b}$ decay



$$h_1(p_1) + h_2(p_2) \;\to\; V + H + X \;\to\; \ell_1\ell_2 + b\bar{b} + X$$

where $\quad V = Z^0, W^\pm \quad$ and $\quad \ell_1\ell_2 = \ell^+\ell^-, \ell\nu_\ell$

QCD factorization formula

$$d\sigma = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1, \mu_F^2)\, f_{b/h_2}(x_2, \mu_F^2)\, d\hat{\sigma}_{ab}(x_1 p_1, x_2 p_2; \mu_F^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^p$$

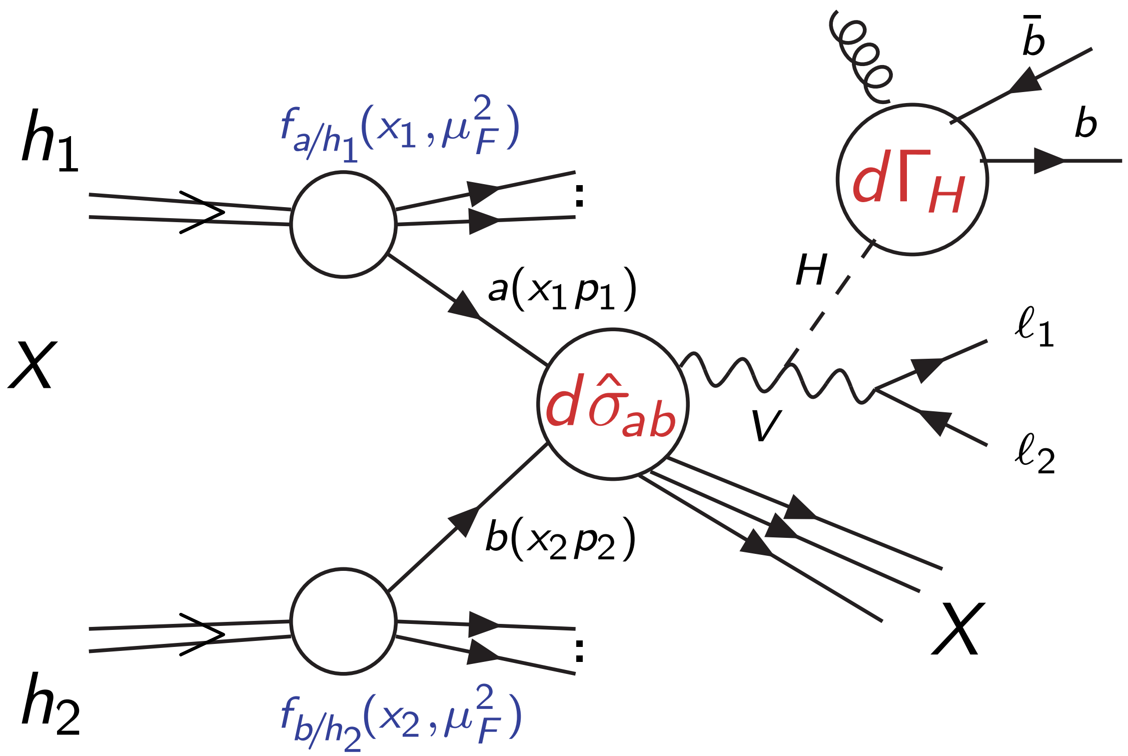
- By using the zero width approximation ($\Gamma_H \ll m_H$)

$$d\sigma_{VH\to Vb\bar{b}} = d\sigma_{VH} \times \frac{d\Gamma_{H\to b\bar{b}}}{\Gamma_H} = d\sigma_{VH} \times \frac{d\Gamma_{H\to b\bar{b}}}{\Gamma_{H\to b\bar{b}}} \times \mathrm{Br}(H \to b\bar{b})\,,$$

- Perturbative expansion gives

$$d\sigma^{NNLO+nlo}_{VH\to Vb\bar{b}} = \left[d\sigma^{(0)}_{VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} + \left(d\sigma^{(1)}_{VH} + d\sigma^{(2)}_{VH}\right) \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}} \right] \times \mathrm{Br}(H \to b\bar{b})\,,$$

Associated VH production with H $\to$ b$\bar{\text{b}}$ decay



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- Perturbative expansion gives

$$d\sigma^{full\ NNLO}_{VH\to Vb\bar{b}} = \left[d\sigma^{(0)}_{VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}} + d\Gamma^{(2)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}} + \Gamma^{(2)}_{H\to b\bar{b}}} + d\sigma^{(1)}_{VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(2)}_{H\to b\bar{b}}} + d\sigma^{(2)}_{VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}} \right] \times \mathrm{Br}(H \to b\bar{b}),$$

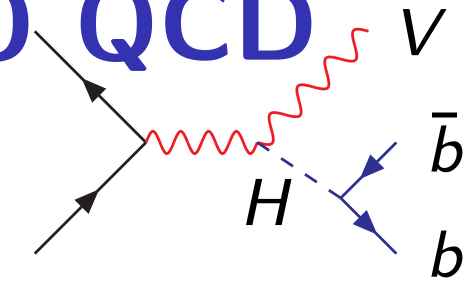
VH production and decay in full NNLO QCD

G.F.,Somogyi,Tramontano arXiv:1705.0304

Fully differential NNLO calculation for VH production including $H \to b\bar{b}$ at NNLO and $V \to l_1 l_2$ decays with spin correlations.

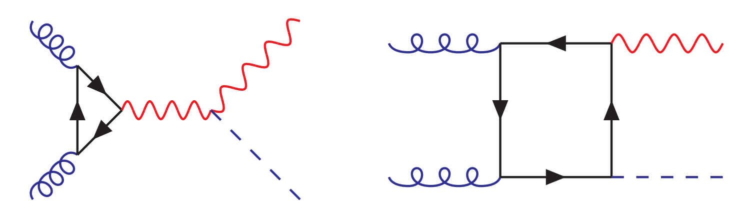
- NNLO calculation for $h_1 h_2 \to VH + X$ production calculated in [G.F.,Grazzini,Tramontano('11,'15)] within the q_T-subtraction formalism [Catani, Grazzini('07)] requires:
  - Up to $d\sigma_{NLO}^{VH+\mathrm{jets}}$.
  - $\mathcal{H}^{VH(1)}$ and $\mathcal{H}^{VH(2)}$ [Catani,Cieri,de Florian,G.F.,Grazzini('09,'12)]: contains the finite-part of the one- and two-loops amplitude $c\bar{c} \to VH$.
  - Up to $d\sigma_{NLO}^{CT}$: depends by the (universal) q_T-resummation coefficients [Bozzi,Catani,de Florian,Grazzini('09,'12)].
- $H \to b\bar{b}$ decay at NNLO calculated by [Del Duca,Duhr,Somogyi,Tramontano, Trocsanyi('15)] with CoLoRFulNNLO method [Del Duca,Somogyi,Trocsanyi ('07)].
- Fully inclusive QCD effects in the H decay taken into account by normalizing the $Hb\bar{b}$ branching fraction to the LHCHXSWG-YR result.

VH production and decay in full NNLO QCD

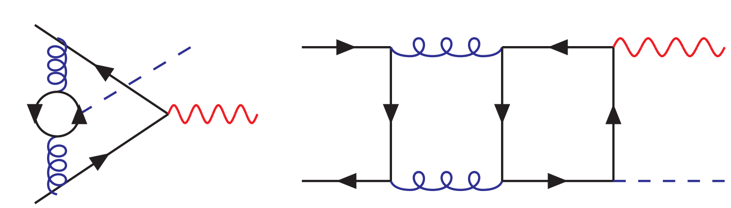


Our fully differential calculation implemented in the parton level code HVNNLO.
For VH prod. we have consistently included:

- NNLO DY-like QCD corrections
  (bulk of NNLO correction for WH)
  [Van Neerven et al.('91)]
- $gg \to HZ$ top-loop $\sim g^2 \lambda_t^2 \alpha_S^2$
  (non DY-like) corrections [Kniehl('90)]
  (important at the LHC due to large
  gg luminosity).



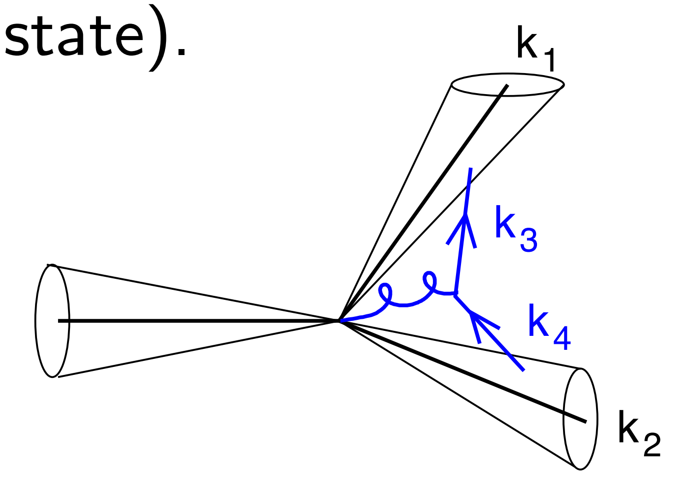
- NNLO top-mediated contributions
  $\sim g^3 \lambda_t \alpha_S^2$ to VH
  [Brein,Harlander,Wiesemann,Zirke('11)]
  (we included only the terms calculated
  with the full m_t dependence)



b-quark jets identification

We are interested in the identification of the b-quark jet which originate from the Higgs boson (b-quark treated in massless approximation).

- We consistently include b-quark emissions from initial and final state partons (at NNLO up to four b-quarks in the final state).
- Standard jet alg. not infrared and collinear safe definition of flavoured jets: splitting of a gluon in a soft or collinear (massless) $b\bar{b}$ pair affect the flavour of a jet.



- Collinear unsafety removed by defining "b-jet" if contains $N(b) - N(\bar{b}) \neq 0$.
- Infrared unsafety removed by using the "flavour-k_T" algorithm [Banfi,Salam,Zanderighi('06)]

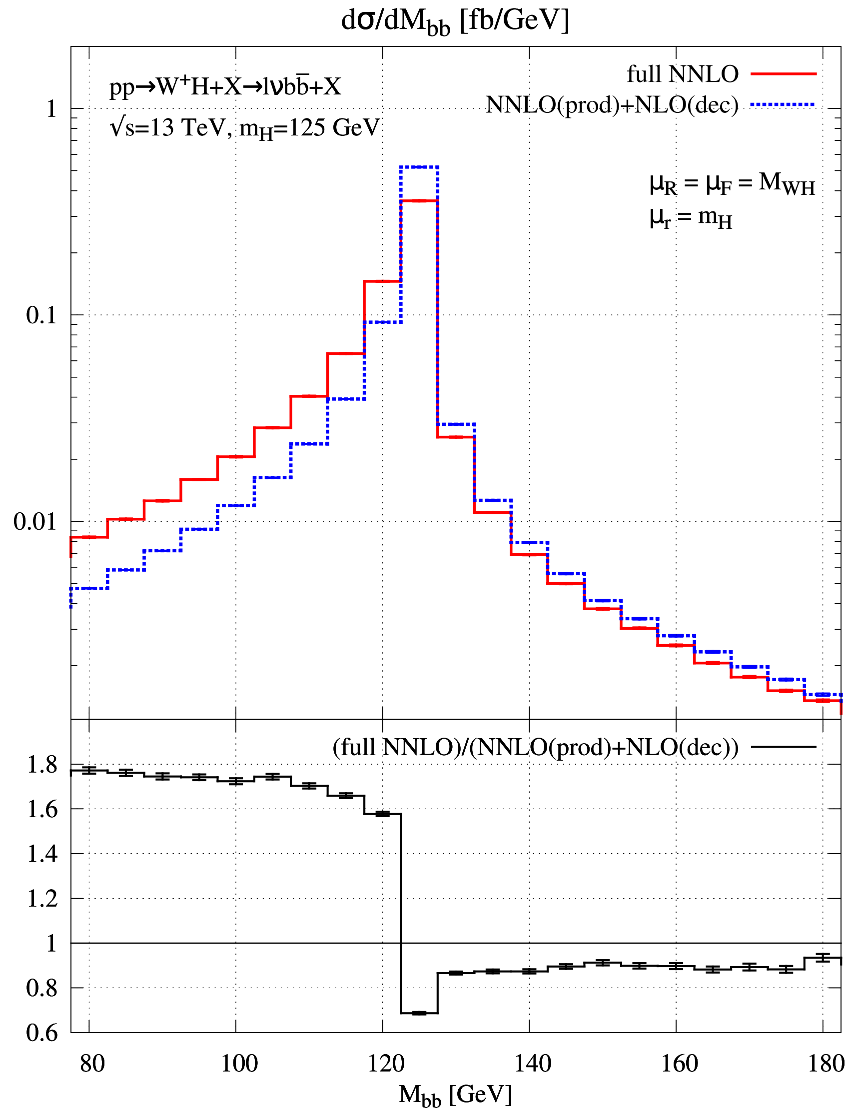
$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavoured} \\ \min(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavourless} \end{cases}$$

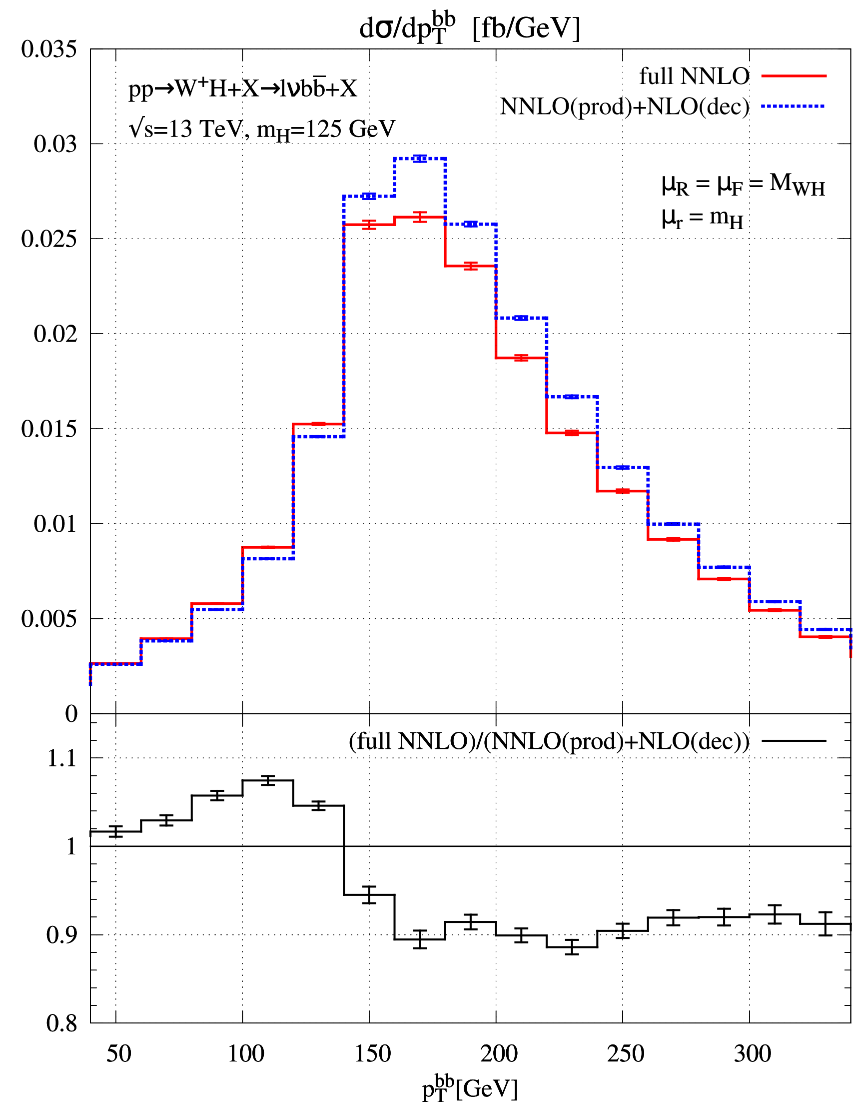
(numerical difference with respect to standard alg. small in our case).

NEW: production at full NNLO of WH(bb)

σ (fb)	NNLO(prod)+NLO(dec)	full NNLO
W^+H	4.23 ± 0.02	3.96 ± 0.02

$K_{fact} \sim -6.5\%$





LHC13 analysis: $p_T^l > 15\ GeV$, $|\eta_l| < 2.5$, $p_T^W > 150\ GeV$, 2 *b-jets* $p_T^b > 25 GeV$, $|\eta_b| < 2.5$, flavour-k_T $R = 0.5$.

Left panel: M_{bb} spectrum of the *b*-jets pair. Right panel: p_T^{bb} spectrum of the *b*-jets pair. Lower panels: spectra normalized to the NNLO+nlo results.

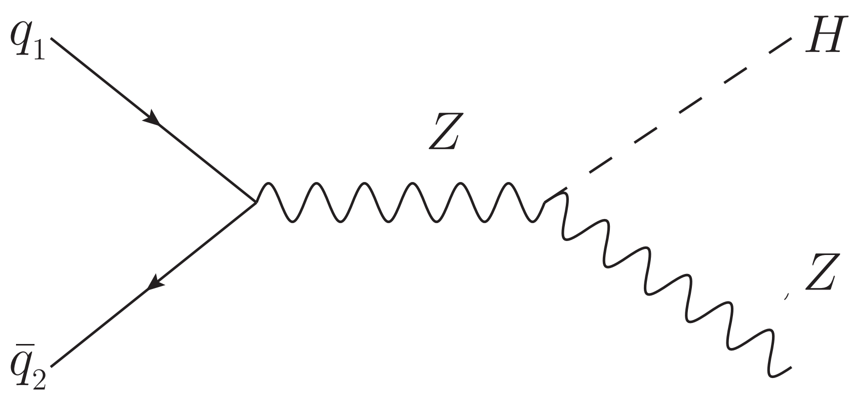
Hurdles towards gg->ZH @ NLO

Sophia Borowka (CERN)

HXSWG VH subgroup meeting, 29th June 2017

Why the gg channel is interesting

- LO process is Higgs-Strahlung



- Drell-Yan component known up to NNLO

Hamberg, Neerven, Matsuura ’91, Harlander, Kilgore ’02, Brein, Djouadi,Harlander ’04

- LO gg channel enters at NNLO with ~10% Brein, Harlander, Zirke ’12
- gluon fusion scale uncertainty large (~30%), dominates overall pp->ZH uncertainty at NNLO
- gg->ZH @NLO with full top-mass dependence

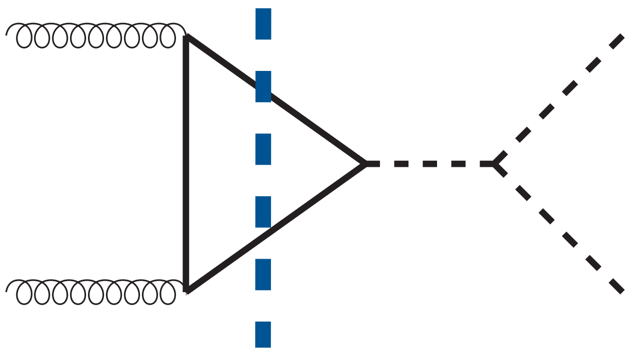
Computation available in the large mass expansion finding large K-factor for the inclusive cross section and strong hints for a large k-facort also at differential level

[Altenkamp, Dittmaier, Harlander, Rzehak Zaire 2013]

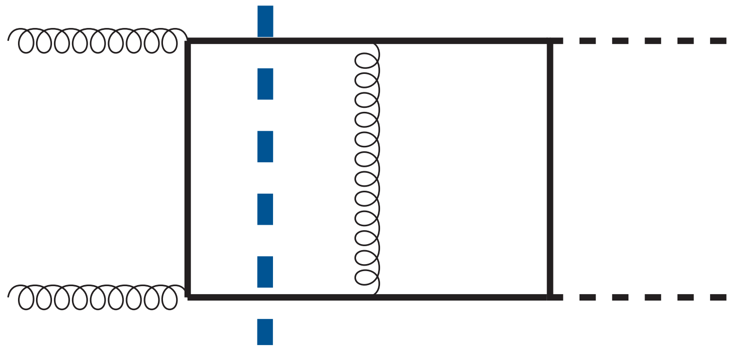
HH: Differences between SM and HEFT

➡ what happens in the exact Standard Model

➡ threshold effects can show up



$m_{hh} = 2\, m_t$



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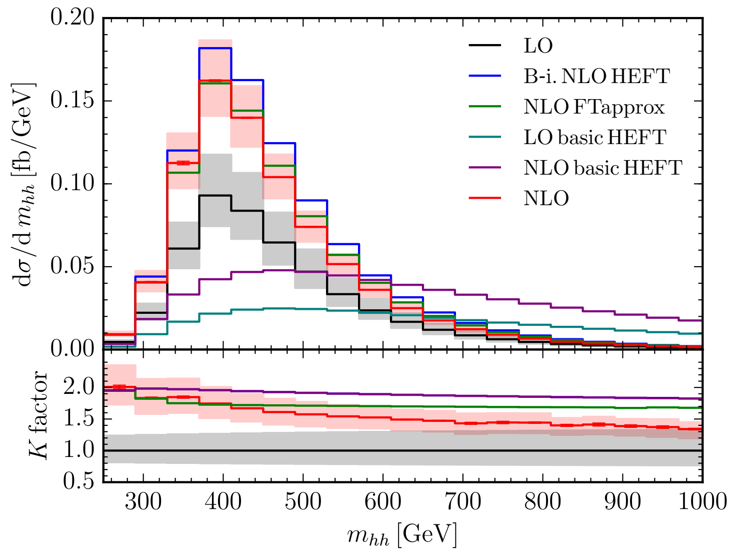
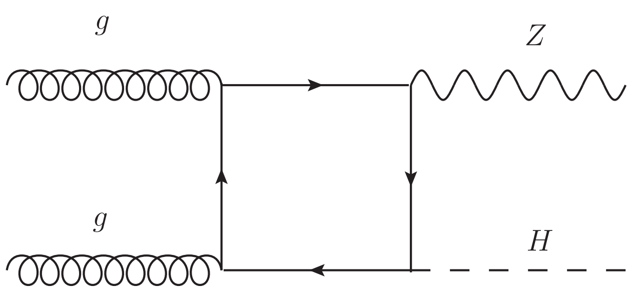
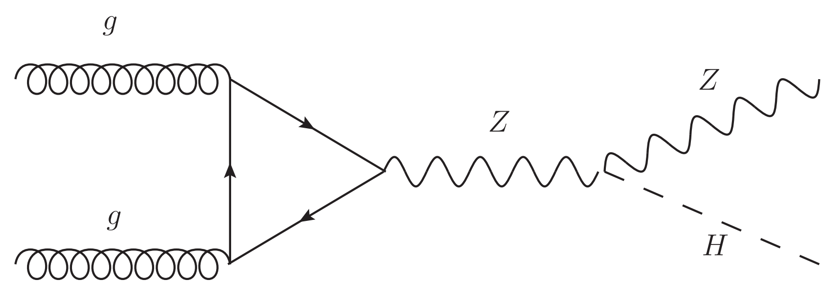


SB, N. Greiner, G. Heinrich, S.P. Jones,
M. Kerner, J. Schlenk, U. Schubert, T. Zirke '16

gg->ZH diagrams

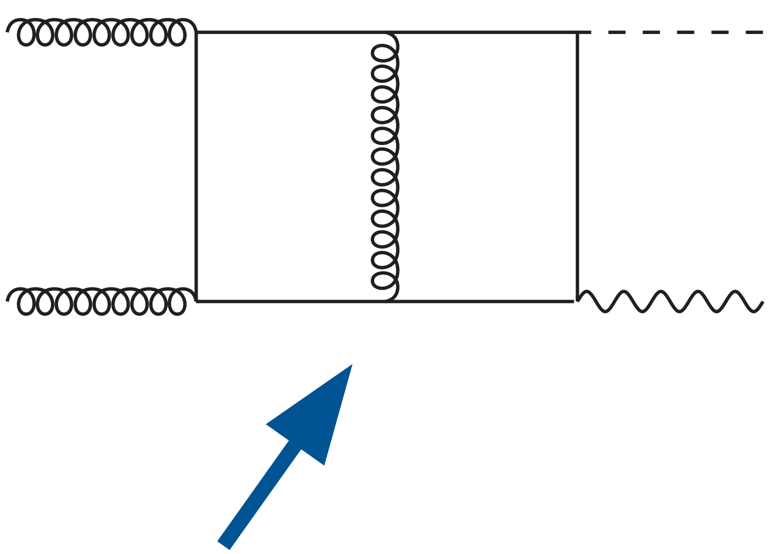
Leading Order:



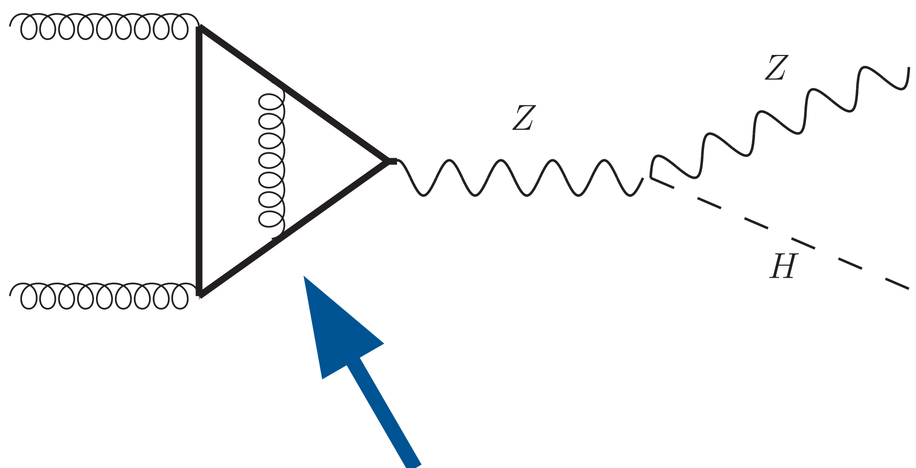


Dicus, Kao '88; Kniehl '90

Exact virtual NLO part:



not known yet



master integrals known from
Gehrmann, Huber,Maitre '05

Exact real radiation for NLO by: Hespel, Maltoni, Vryonidou '15

Schematic gg->HH setup (virtual NLO)

generation of diagrams for amplitude → reduction of amplitude to set of master integrals → computation of master integrals

- reduction programs:
FIRE, KIRA, LiteRed, REDUZE
Smirnov '15; Maierhöfer, Usovitsch, Uwer '17; Lee '13; von Manteuffel, Studerus '12

- REDUZE can generate quasi-finite basis

SB, G. Heinrich, S. Jahn, S.P. Jones, M. Kerner, J. Schlenk, T. Zirke '17

Important for success:

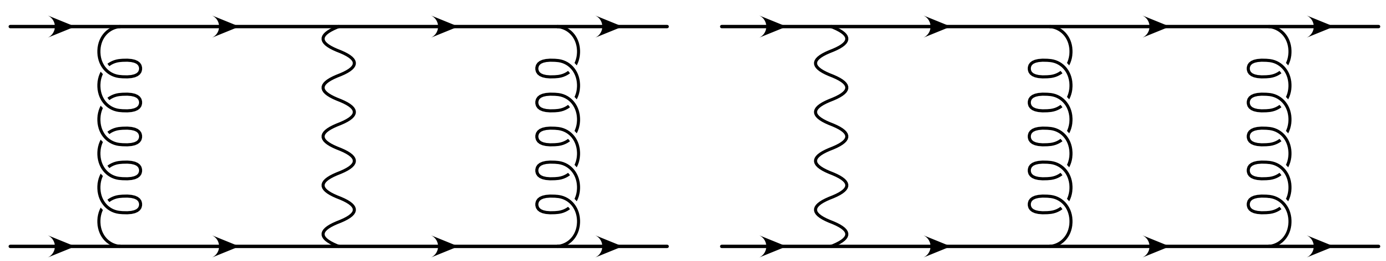
+ use quasi-finite basis Panzer '14; von Manteuffel, Panzer, Schabinger '14
+ use QMC Dick, Kuo, Sloan '13; Li, Wang, Zan, Zhao '15;
+ only integrate up to necessary accuracy
(2 form factors for HH, 3% for one form factor, ≈10% for the other, depending on the ratio of the two)

Problems that may occur in gg->ZH

- additional mass scale makes reduction much more involved
- if reduction not available no transformation into quasi-finite basis possible
- if double-box integrals are not finite, numerical convergence significantly worse
- form factors may may be of similar importance (high accuracy also needed for most complicated integrals)
- numerical convergence in general slower the more scales are involved

A possible recipe that might help in the reduction to master integrals

- The number of scales is the limiting factor for the reduction program to work
- numerics might help to reduce the complexity of the reduction algorithms
  - Example: t-channel single top at NNLO



[Assadsolimani, Kant, Tausk, Uwer 2014]

  - reduction of double box diagrams successfully achieved exploiting the relation:

$$m_t^2 \approx \frac{14}{3} m_W^2 \qquad m_W = 80.385 \pm 0.015\,\mathrm{GeV}/c^2 \longrightarrow m_t \approx 173.65\,\mathrm{GeV}/c^2$$

$$m_t = 173.34 \pm 0.27\,(\mathrm{stat}) \pm 0.71\,(\mathrm{syst})\,\mathrm{GeV}/c^2$$

- for HZ one could use for example: $m_z : m_H : m_t \approx 8 : 11 : 15$

91.1876 : 125 : 173.3 → 91.1876 : 125.4 : 171.0

leading to O(1%) error on the correction

Conclusion

- Since the publication of YR4 there has been substantial progress
- Event generation will be available including NNLOPS QCD effects for both WH and ZH
- NLO EW corrections available at the level of NLOPS for both VH and VHJ(-MINLO) processes
- At least at the level of distributions the improvements of the last two items could be combined
- VH(bb)@NNLO computed including higher order corrections for the decay and the product of nlo corrections from production and decay, substantial effects, comparison with MC expectation needed.
- Still no progress on ggZH@NLO, Sophia and collaborators has shown that numerics offers a possible road, but needs of big efforts…