Higgs boson decay to bottom quarks in VH associated production at the LHC

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Based on:

- G. Ferrera, M. Grazzini, FT [Phys. Rev. Lett. 2011, JHEP 2014, Phys. Lett. B 2015]
- G. Luisoni, P. Nason, C. Oleari, FT [JHEP 2013]
- V. Del Duca, C. Duhr, G. Somogyi, FT, Z. Trocsanyi [JHEP 2015]
- G. Ferrera, G. Somogyi, FT [Phis. Lett. B 2018]
- and others

Indian Institute of Technology Hyderabad - Web seminar - 22 March 2018

Outline

* Motivation

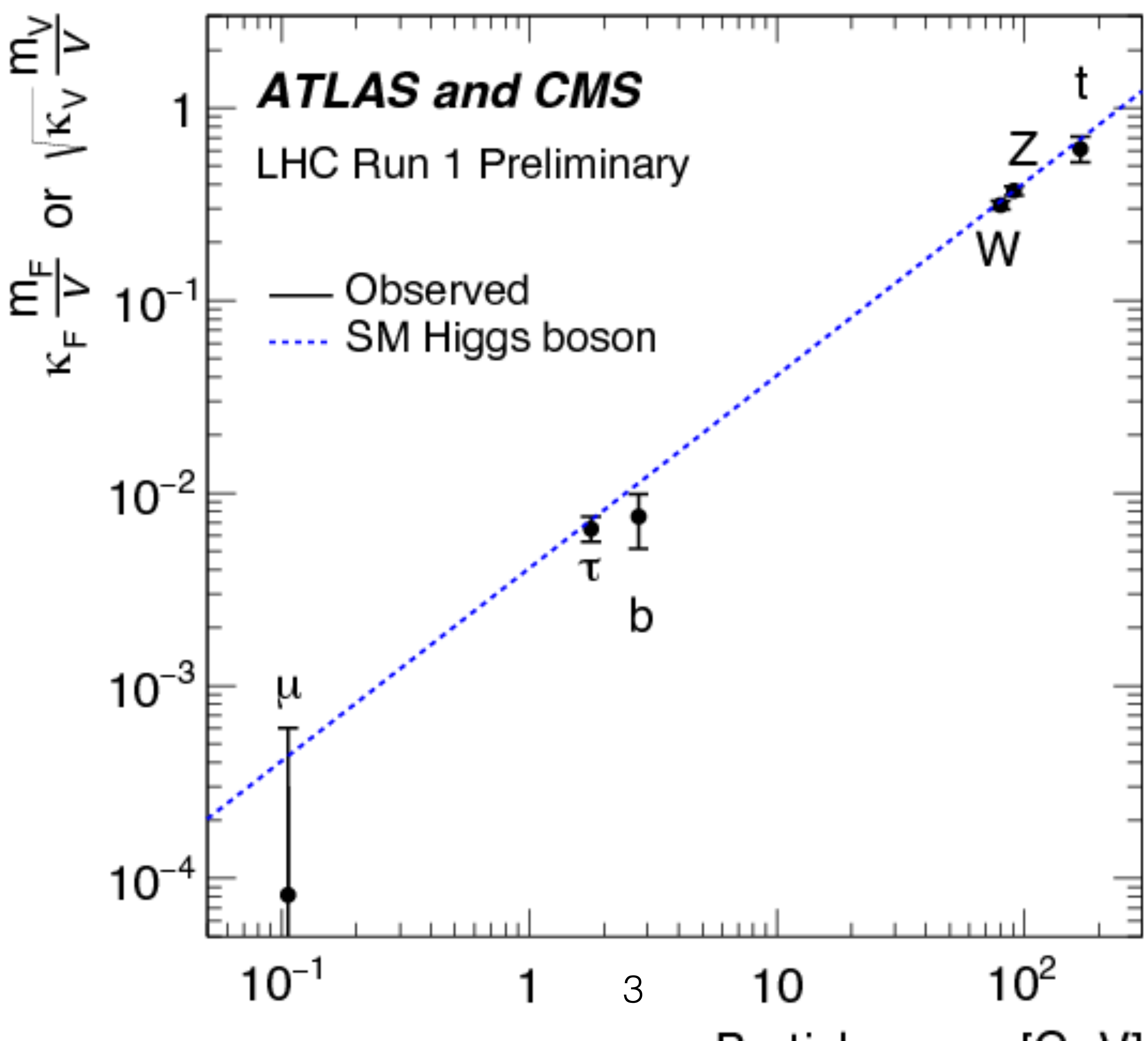
* Higher order corrections

* Results

* Conclusion/Outlook

Higgs particle @ ATLAS and CMS

- VH(bb) allows to measure Higgs coupling to beauty
- Deviation from the SM still possible
- Need of precise fully differential predictions



Higgs particle @ ATLAS and CMS

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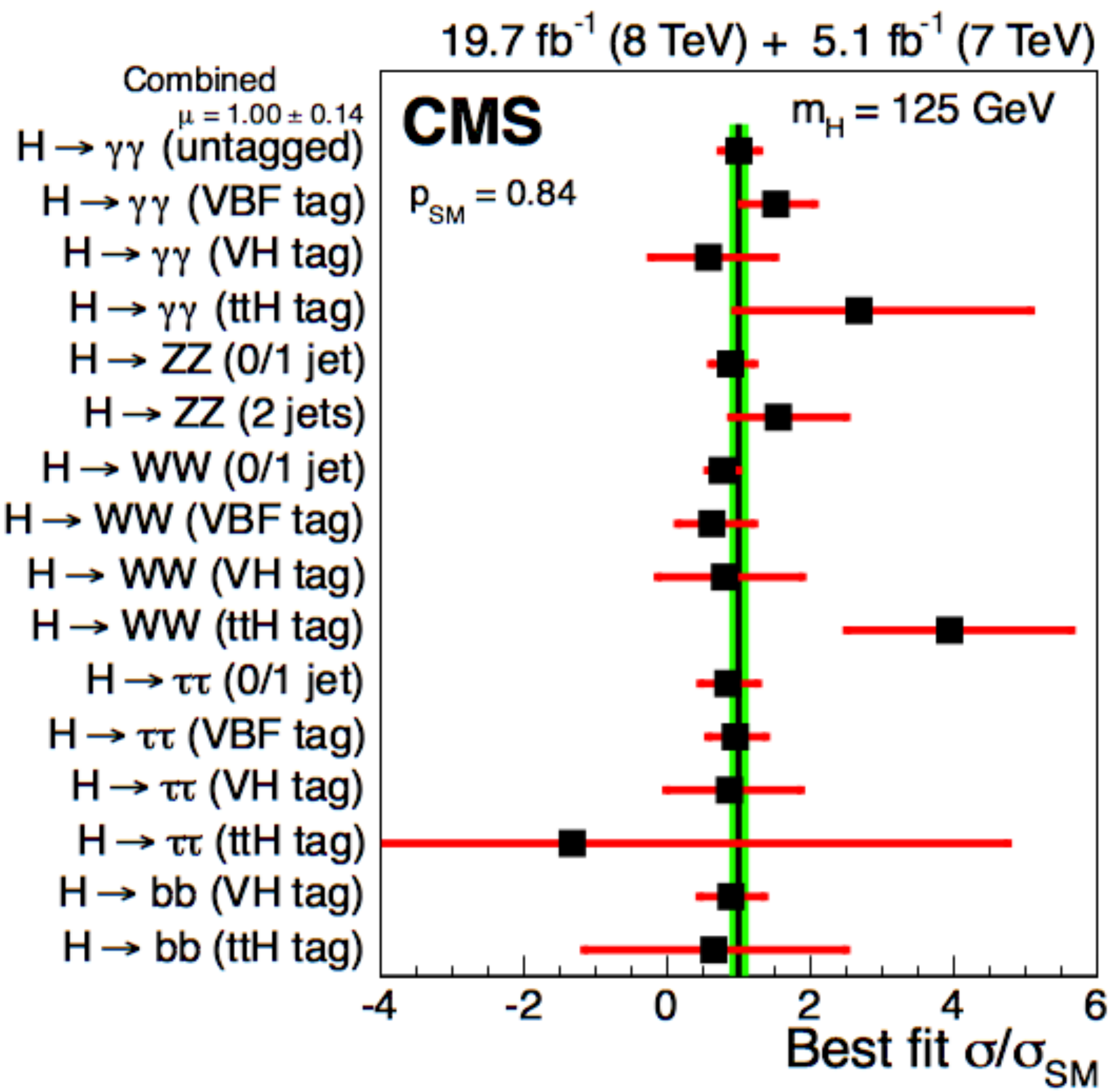
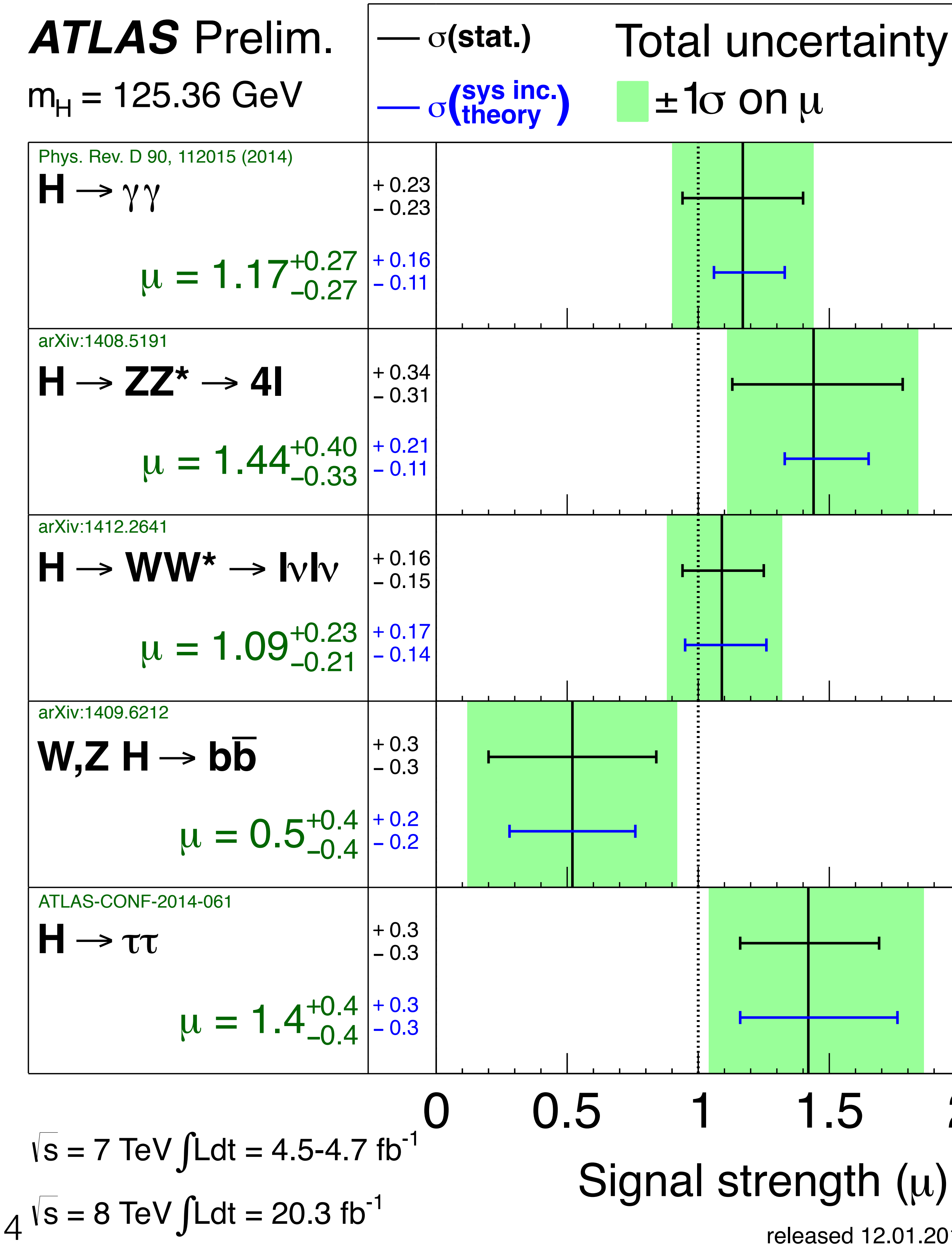
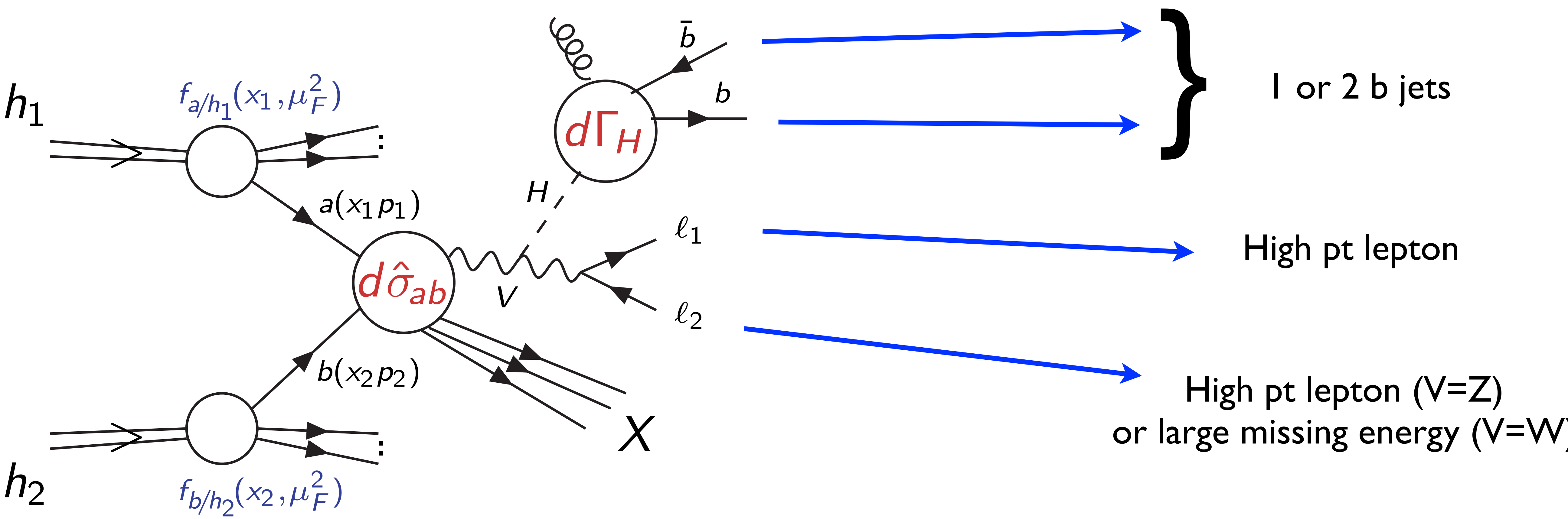




VH(bb) signal phenomenology



- Large sources of backgrounds from V+bb, V+b, V+jets, tt, VV

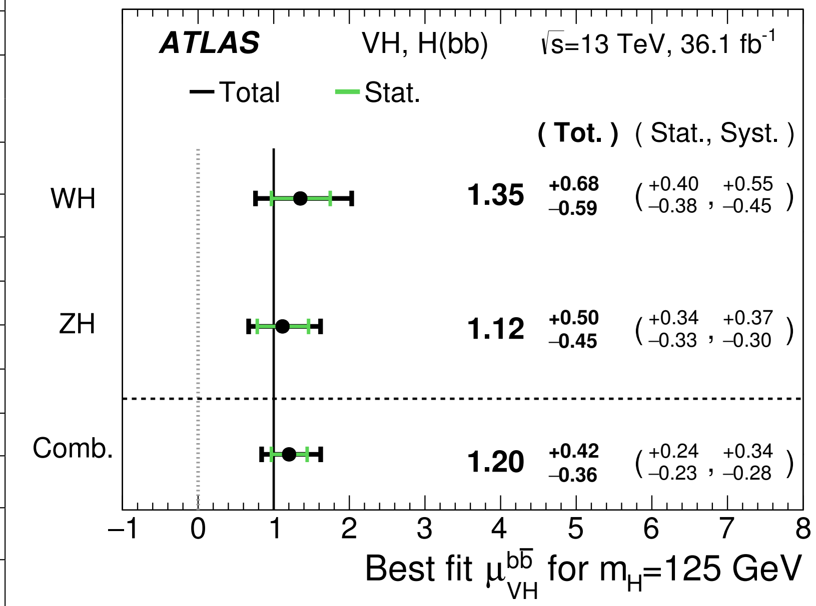
- For boosted events S/B ratio improve considerably and allows detection at the LHC
[Butterworth, Davison, Rubin, Salam 2008]

- Search strategy for VH production important to asses the relevance of the corrections to the decay process

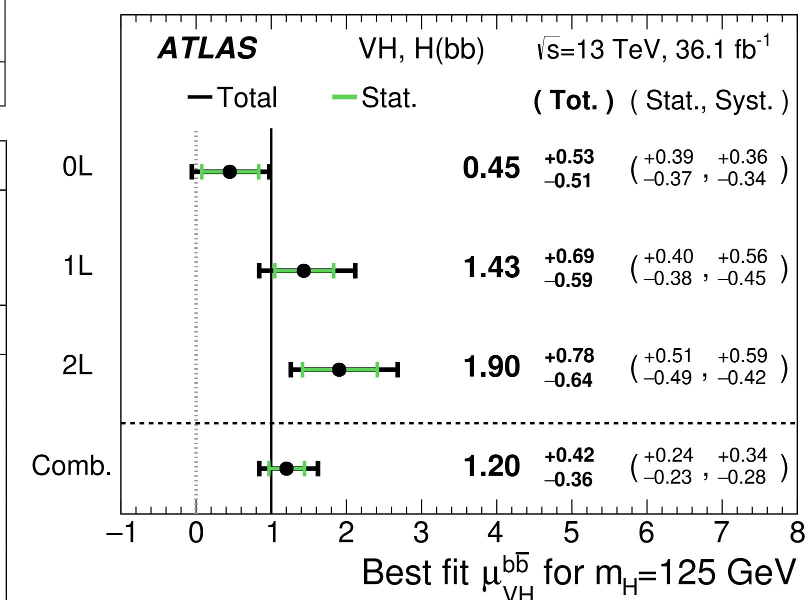
$$R_{bb} \gtrsim 2\frac{m_H}{p_T} \qquad (p_T \gg m_H)$$

Evidence for the $H \to b\bar{b}$ decay with the ATLAS detector

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 loose leptons with $p_{\mathrm{T}} > 7\,\mathrm{GeV}$	1 tight electron $p_{\mathrm{T}} > 27\,\mathrm{GeV}$	1 medium muon $p_{\mathrm{T}} > 25\,\mathrm{GeV}$	2 loose leptons with $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ ≥ 1 lepton with $p_{\mathrm{T}} > 27\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	—	—
$m_{\ell\ell}$	—	—		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_{T}	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), >150 GeV (3 jets)	—		—
$\min[\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{jets})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	—		—
$\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{bb})$	$> 120^\circ$	—		—
$\Delta\phi(\boldsymbol{b}_1, \boldsymbol{b}_2)$	$< 140^\circ$	—		—
$\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{E}_{\mathrm{T,trk}}^{\mathrm{miss}})$	$< 90^\circ$	—		—
p_{T}^{V} regions	$> 150\,\mathrm{GeV}$			(75, 150] GeV, $> 150\,\mathrm{GeV}$
Signal regions	✓	$m_{bb} \geq 75\,\mathrm{GeV}$ or $m_{\mathrm{top}} \leq 225\,\mathrm{GeV}$		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	—	$m_{bb} < 75\,\mathrm{GeV}$ and $m_{\mathrm{top}} > 225\,\mathrm{GeV}$		Different-flavour leptons



Signal regions	0-lepton: $p_{\mathrm{T}}^{V} > 150\,\mathrm{GeV}$, 2-$b$-tag		1-lepton: $p_{\mathrm{T}}^{V} > 150\,\mathrm{GeV}$, 2-$b$-tag		2-lepton: $75\,\mathrm{GeV} < p_{\mathrm{T}}^{V} < 150\,\mathrm{GeV}$, 2-$b$-tag		2-lepton: $p_{\mathrm{T}}^{V} > 150\,\mathrm{GeV}$, 2-$b$-tag	
Sample	2-jet	3-jet	2-jet	3-jet	2-jet	$\geq$3-jet	2-jet	$\geq$3-jet
$Z + ll$	9.0 ± 5.1	15.5 ± 8.1	< 1	—	9.2 ± 5.4	35 ± 19	1.9 ± 1.1	16.4 ± 9.3
$Z + cl$	21.4 ± 7.7	42 ± 14	2.2 ± 0.1	4.2 ± 0.1	25.3 ± 9.5	105 ± 39	5.3 ± 1.9	46 ± 17
Z + HF	2198 ± 84	3270 ± 170	86.5 ± 6.1	186 ± 13	3449 ± 79	8270 ± 150	651 ± 20	3052 ± 66
$W + ll$	9.8 ± 5.6	17.9 ± 9.9	22 ± 10	47 ± 22	< 1	< 1	< 1	< 1
$W + cl$	19.9 ± 8.8	41 ± 18	70 ± 27	138 ± 53	< 1	< 1	< 1	< 1
W + HF	460 ± 51	1120 ± 120	1280 ± 160	3140 ± 420	3.0 ± 0.4	5.9 ± 0.7	< 1	2.2 ± 0.2
Single top quark	145 ± 22	536 ± 98	830 ± 120	3700 ± 670	53 ± 16	134 ± 46	5.9 ± 1.9	30 ± 10
$t\bar{t}$	463 ± 42	3390 ± 200	2650 ± 170	20640 ± 680	1453 ± 46	4904 ± 91	49.6 ± 2.9	430 ± 22
Diboson	116 ± 26	119 ± 36	79 ± 23	135 ± 47	73 ± 19	149 ± 32	24.4 ± 6.2	87 ± 19
Multi-jet e sub-ch.	—	—	102 ± 66	27 ± 68	—	—	—	—
Multi-jet μ sub-ch.	—	—	133 ± 99	90 ± 130	—	—	—	—
Total bkg.	3443 ± 57	8560 ± 91	5255 ± 80	28110 ± 170	5065 ± 66	13600 ± 110	738 ± 19	3664 ± 56
Signal (fit)	58 ± 17	60 ± 19	63 ± 19	65 ± 21	25.6 ± 7.8	46 ± 15	13.6 ± 4.1	35 ± 11
Data	3520	8634	5307	28168	5113	13640	724	3708



CMS: Evidence for the Higgs boson decay to a bottom quark-antiquark pair

Variable	0-lepton	1-lepton	2-lepton
$p_T(V)$	>170	>100	$[50,150], >150$
$M(\ell\ell)$	—	—	$[75,105]$
p_T^{ℓ}	—	$(>25, >30)$	>20
$p_T(j_1)$	>60	>25	>20
$p_T(j_2)$	>35	>25	>20
$p_T(jj)$	>120	>100	—
$M(jj)$	$[60,160]$	$[90,150]$	$[90,150]$
$\Delta\phi(V, jj)$	>2.0	>2.5	>2.5
$CMVA_{max}$	$>CMVA_T$	$>CMVA_T$	$>CMVA_L$
$CMVA_{min}$	$>CMVA_L$	$>CMVA_L$	$>CMVA_L$
N_{aj}	<2	<2	—
$N_{a\ell}$	$=0$	$=0$	—
p_T^{miss}	>170	—	—
$\Delta\phi(\vec{p}_T^{miss}, j)$	>0.5	—	—
$\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{miss}(trk))$	<0.5	—	—
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	—	<2.0	—
Lepton isolation	—	<0.06	$(<0.25, <0.15)$
Event BDT	>-0.8	>0.3	>-0.8

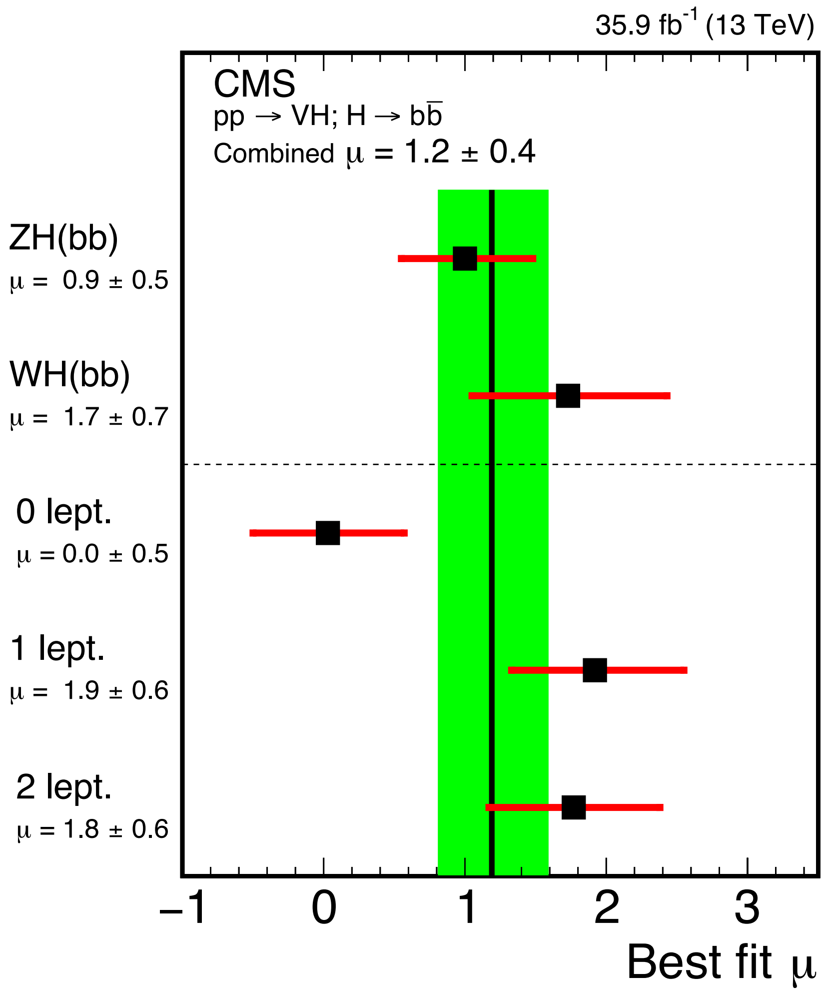
Process	0-lepton	1-lepton	2-lepton low-$p_T(V)$	2-lepton high-$p_T(V)$
Vbb	216.8	102.5	617.5	113.9
Vb	31.8	20.0	141.1	17.2
V+udscg	10.2	9.8	58.4	4.1
$t\bar{t}$	34.7	98.0	157.7	3.2
Single top quark	11.8	44.6	2.3	0.0
VV(udscg)	0.5	1.5	6.6	0.5
VZ(bb)	9.9	6.9	22.9	3.8
Total background	315.7	283.3	1006.5	142.7
VH	38.3	33.5	33.7	22.1
Data	334	320	1030	179
S/B	0.12	0.12	0.033	0.15

$$VH(H \to b\bar{b})$$

Channels	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
Combined	2.8	3.3

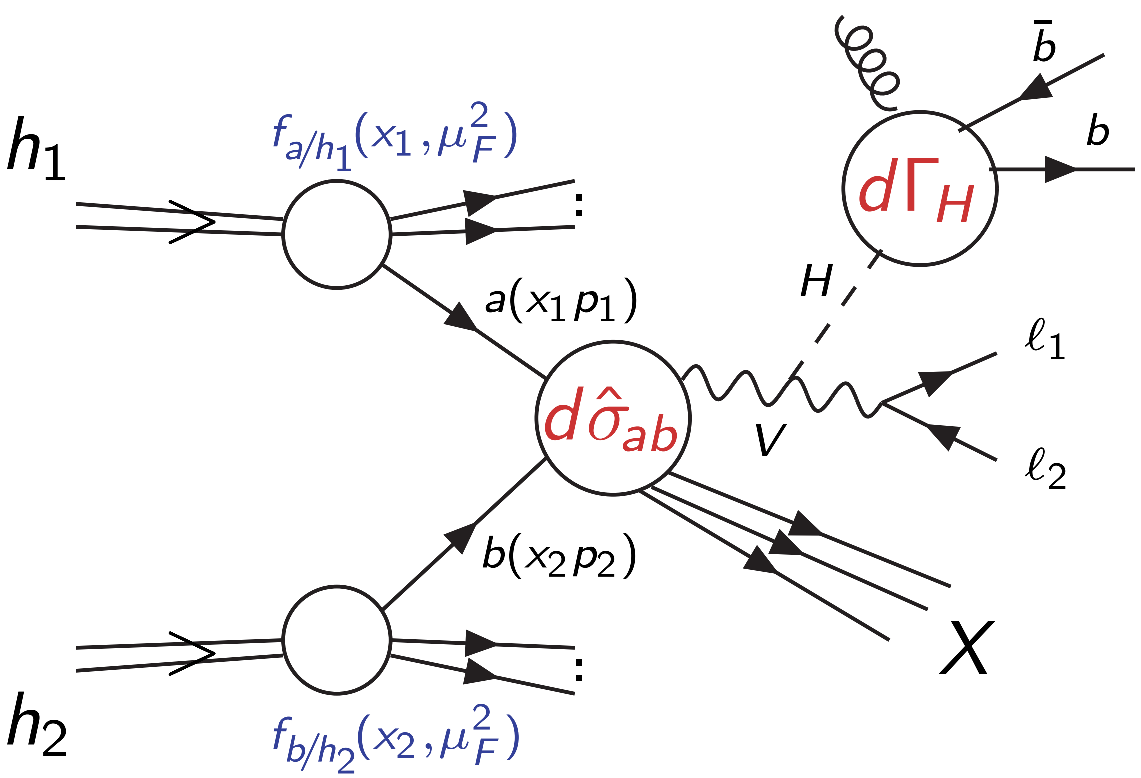
$$VZ(Z \to b\bar{b})$$

Channels	Significance expected	Significance observed	Signal strength observed
0-lepton	3.1	2.0	0.57 ± 0.32
1-lepton	2.6	3.7	1.67 ± 0.47
2-lepton	3.2	4.5	1.33 ± 0.34
Combined	4.9	5.0	1.02 ± 0.22



* Higher order corrections

VH higher order Corrections (QCD)
(parton level)



QCD corrections (inclusive)

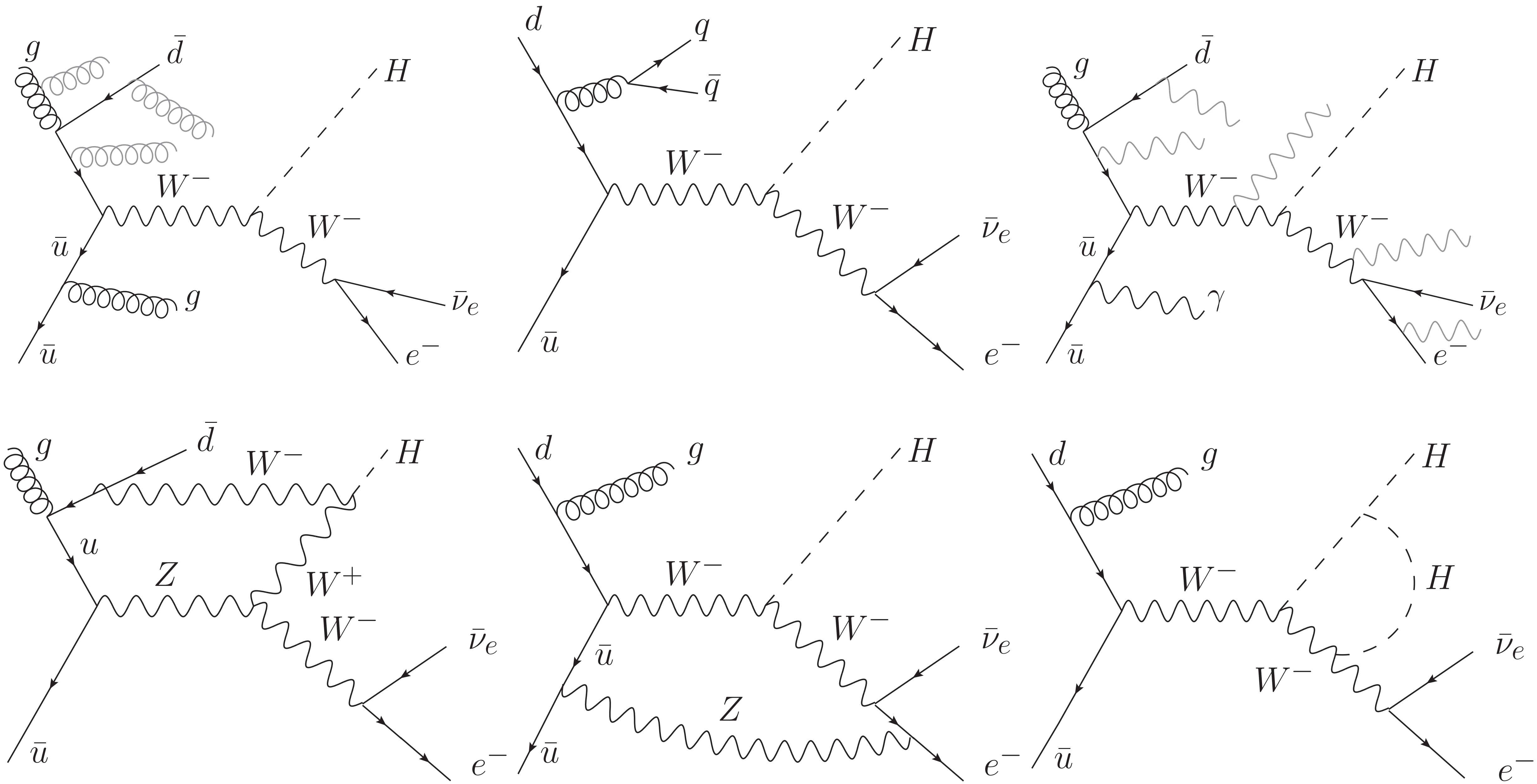
- NNLO QCD corrections for VH are basically the same of DY (1~3% at the LHC) [Van Neerven et al 1991, Brein, Harlander, Djouadi 2000]
- For ZH there is also gg->ZH top-loop, the most accurate prediction covers gg->ZH @ NLO QCD in the heavy-top limit (5% at the LHC) [Altenkamp, Dittmaier, Harlander, Rzehak, Zirke 2012]
- NNLO top-mediated contribution (1~2% at the LHC) [Brei, Harlander, Wiesemann, Zirke 2011]
- N3LO threshold corrections computed [Kumal, Mandal, Ravindran (2014)]
- The inclusive H → bb decay rate is known up to fourth order in QCD (0.1%) [Baikov,Chetyrkin,Kuhn('05)] (and up to NLO EW (1~2%) [Dabelstein, Hollik; Kniehl (1992)])

QCD corrections (differential)

- Fully differential NNLO QCD corrections for VH, including leptonic V decays with spin correlations and NLO H decay HVNNLO [Ferrera, Grazzini, FT (2011, 2014)] (qT subtraction method) MCFM [Campbell, Ellis, Giele, Williams (2016)] (N-jettiness method) + top-loop contributions from [Brein et al (2011)]
- NNLO fully-differential decay rate H → bb computed through new non-linear mapping method [Anastasiou,Herzog,Lazopoulos(2012)] and the Colourful (dipole) method [Del Duca,Duhr,Somogyi,FT,Trocsanyi (2015)]
- Resummation of jet-veto and transverse-momentum logarithms performed [Y.Li,Liu(2014)][Shao,C.S.Li,H.T.Li(2013)], [Dawson,Han,Lai,Leibovich,Lewis(2012)]

* Event generators

QCD+EW corrections to HVj



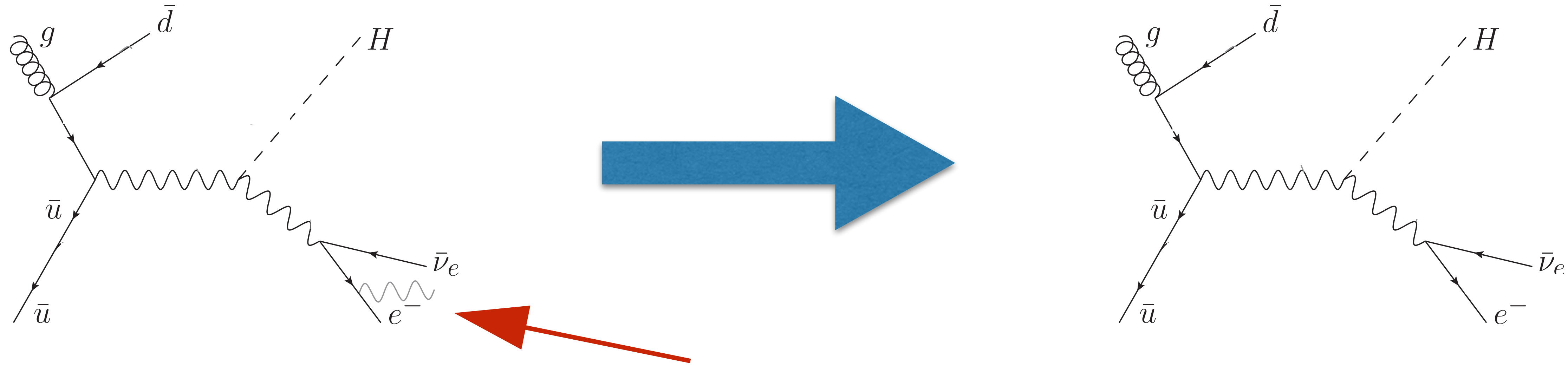
Born: $\mathcal{O}\left(\alpha_S\,\alpha_{EM}^3\right)$ QCD real+virtual: $\mathcal{O}\left(\alpha_S^2\,\alpha_{EM}^3\right)$ EW real+virtual: $\mathcal{O}\left(\alpha_S\,\alpha_{EM}^4\right)$

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**

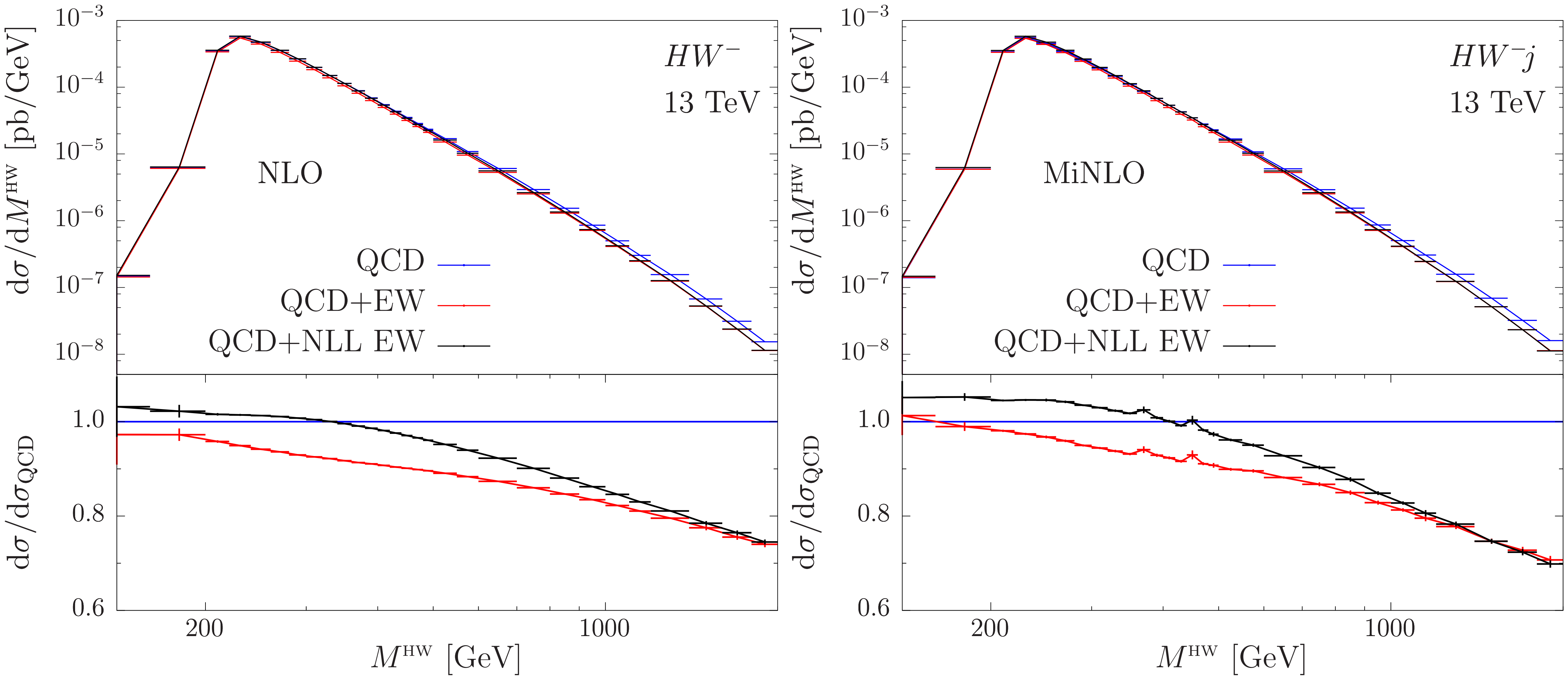
The POWHEG BOX RES

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.

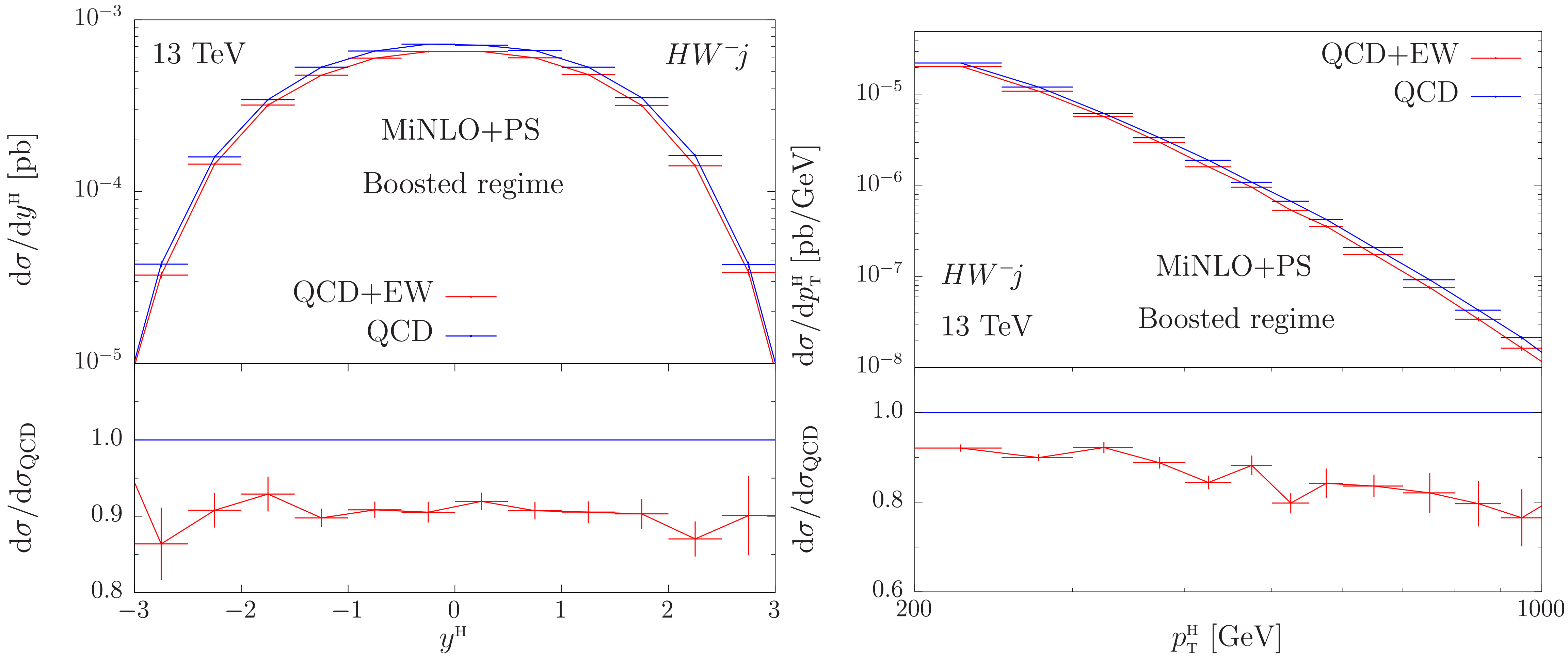
Applied now to HV and HVj production, where the virtuality of the V boson is preserved when photon radiation is produced.

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



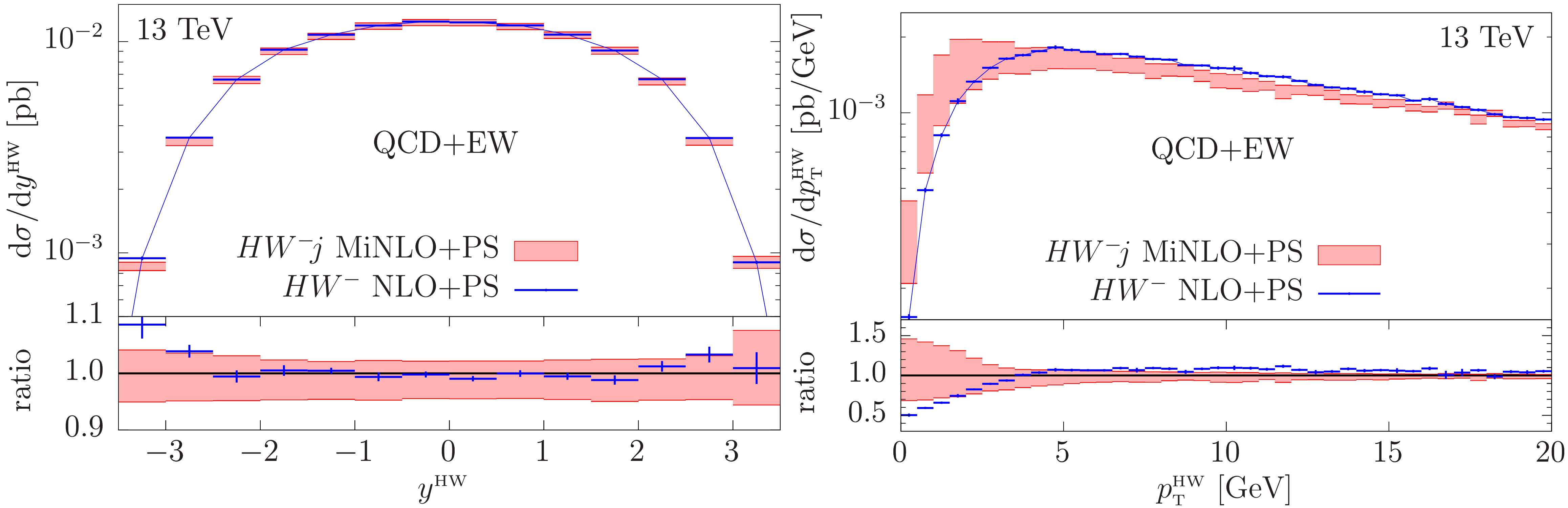
- EW corrections can largely exceed the ten percent level in the high-energy regions, where Sudakov logarithms become dominant.
- An example is the invariant mass of the HV pair in HV and HVj production, where the EW corrections reach -30% around 2 TeV.

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.

- Already in YR4 NNLOPS for HW: in a nutshell

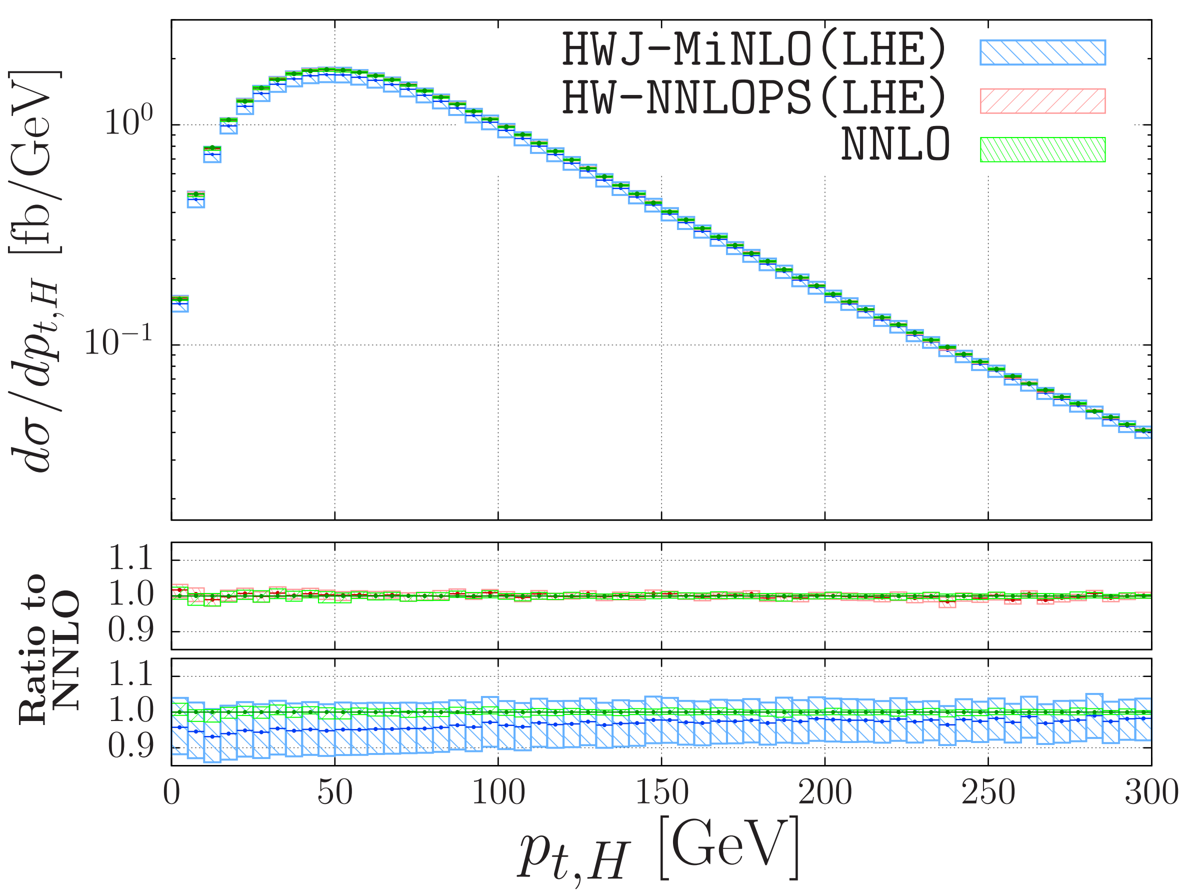
Starting from the VHJ generator:

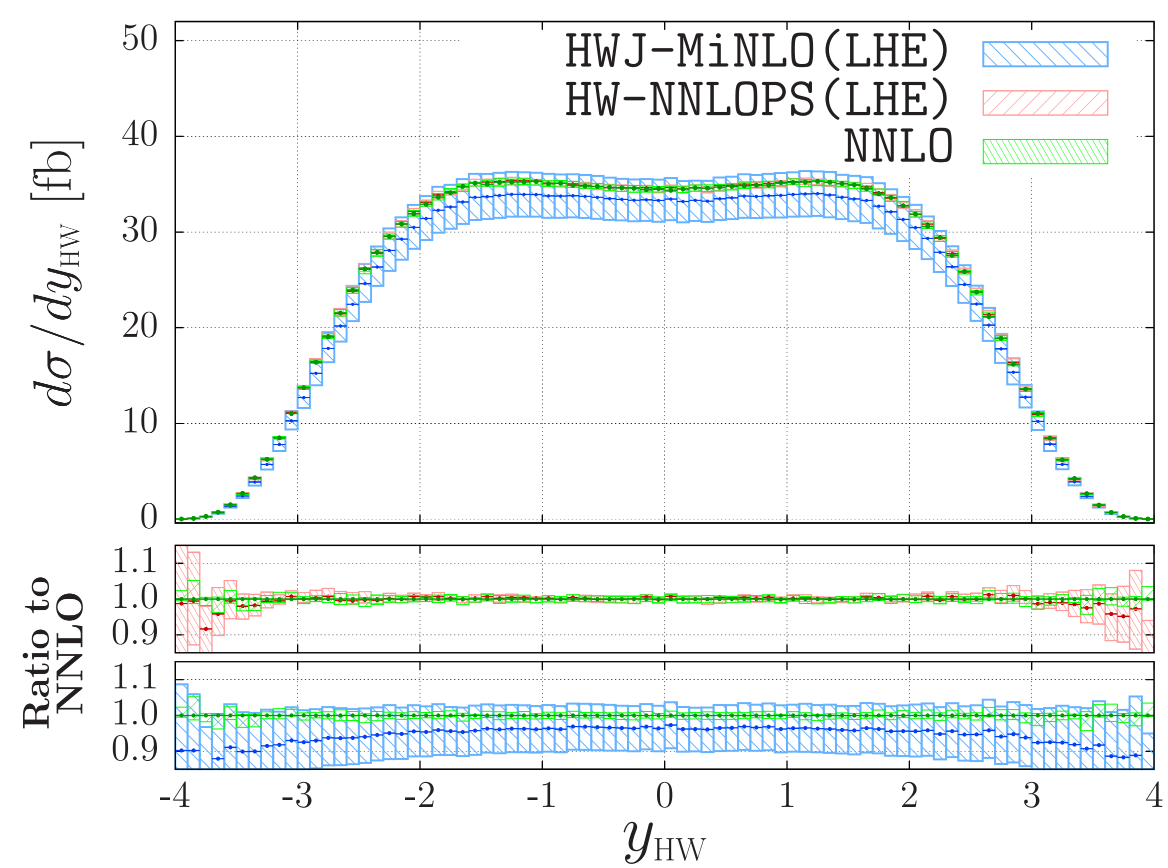
- $\tilde{B}_{\texttt{MiNLO}} = \alpha_s(q_T)\Delta^2(q_T,\bar{\mu}_R)\left[B\left(1-2\Delta^{(1)}(q_T,\bar{\mu}_R)\right)+\alpha_s(\bar{\mu}_R)\left(V(\bar{\mu}_R)+\int d\Phi_r R\right)\right]$

Preserve NLO⁰ accuracy for VH

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

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])

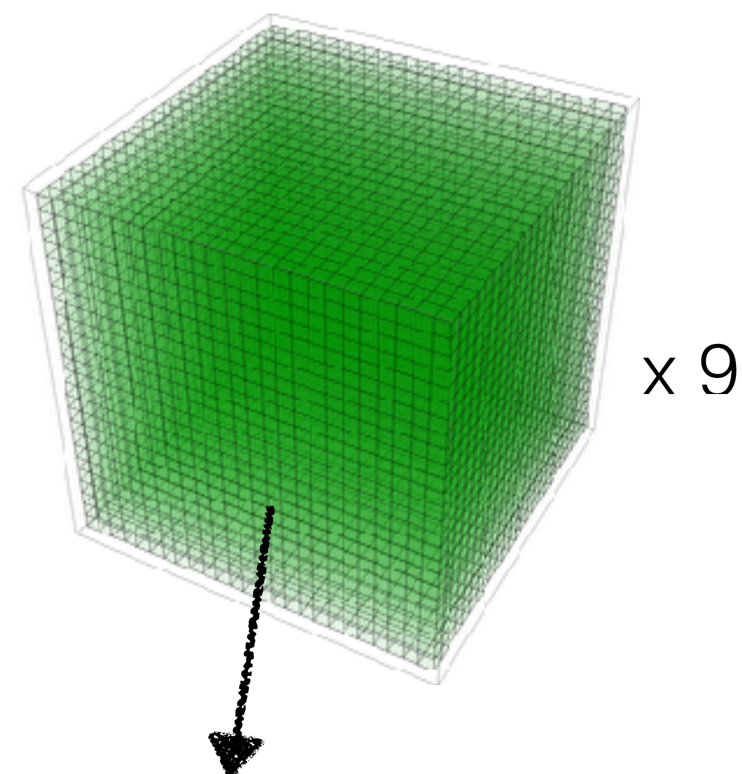
- phase-space parametrisation:

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

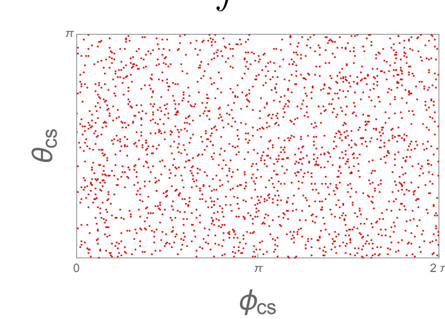
- cross-section in terms of Collins-Soper angles:

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

- 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

Possible recipe for QCD@NNLOPS+EW@NLOPS

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

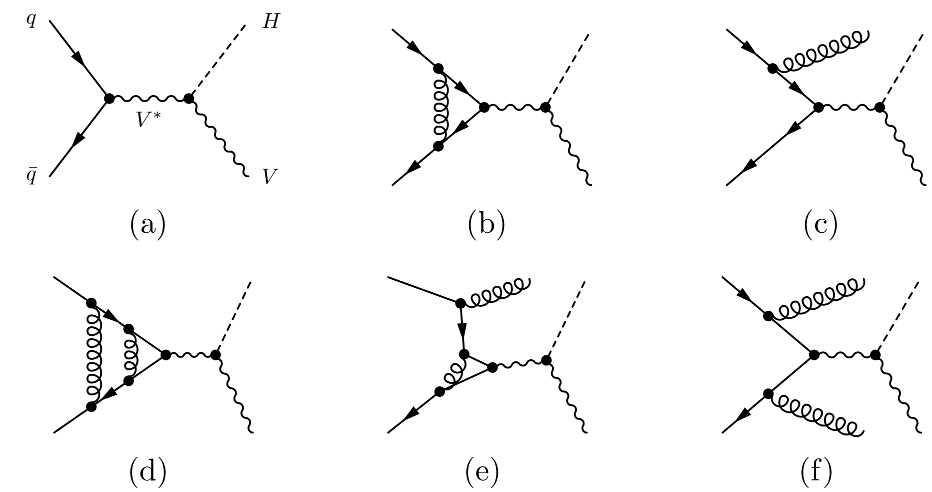
1) event sample with QCD @ NNLOPS
2) event sample with EW @ NLOPS
3) event sample with LO PS

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

* A closer look at the radiative corrections: production

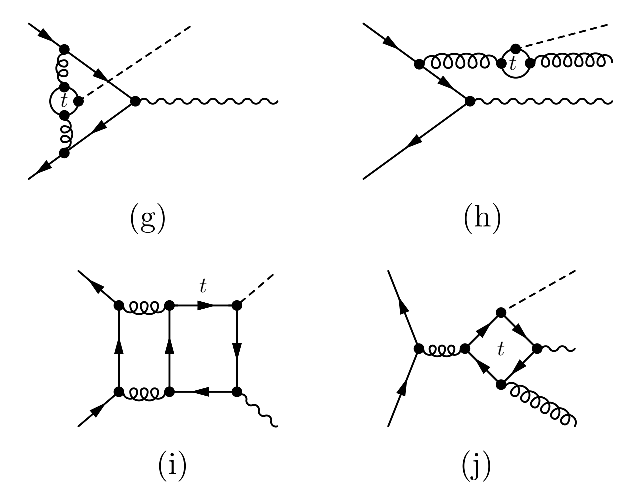
Higgs boson associated production

- Drell–Yan type contribution
- They contribute to the cross section at order $g^4 \alpha_s^n$ (n = 0, 1, 2)
- increase the cross section by about 30% with respect to LO

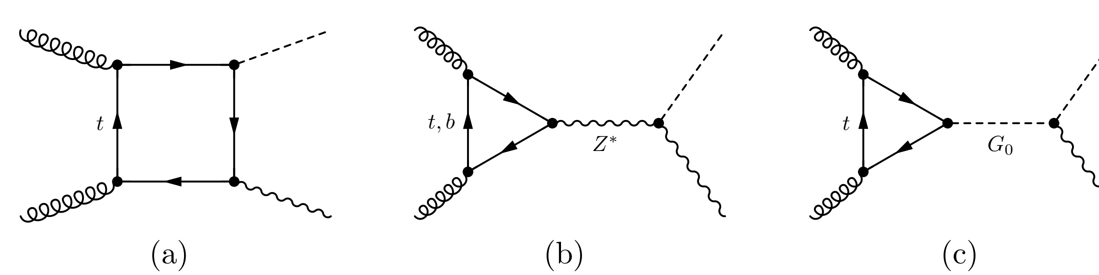


- top-loop-induced contributions
- Interference with the LO and the real-emission

  NLO amplitude is of order $y_t \, g^3 \, \alpha_s^2$
- numerical impact is at the percent level.



- Contributes to the cross section at order $y_t^2 \, g^2 \, \alpha_s^2$
- At one-loop order it amounts to about 4% (6%) of the total Higgs strahlung cross section at the LHC with 8TeV (14TeV)
- Rather strong renormalisation and factorisation scale dependence of about 30%
  - increase the theoretical uncertainty of the HZ relative to the WH process



Production: qT subtraction method [Catani, Grazzini 2007]

$$h_1\, h_2 \to F$$ a colorless system

- qT is the transverse momentum of the colorless system (F), it is exactly zero at the leading order

- for qT.ne.0 there can be only divergences from single unresolved parton configurations

  ✓ can be treated with NLO subtraction methods like CS dipoles

- double unres. singularities are **all** associated with qT = 0 configurations

  ✓ can be treated by an additional subtraction defined exploiting the knowledge of the logarithmically enhanced contributions from the qT resummation formalism [Catani, De Florian, Grazzini 2000]

$$d\sigma^F_{N^nLO} \stackrel{q_T\to 0}{\longrightarrow} d\sigma^F_{LO}\otimes\Sigma(q_T/M)dq_T^2 = d\sigma^F_{LO}\otimes\sum_{n=1}^{\infty}\sum_{k=1}^{2n}\left(\frac{\alpha_S}{\pi}\right)^n \Sigma^{(n,k)}\frac{M^2}{q_T^2}\ln^{k-1}\frac{M^2}{q_T^2}\,dq_T^2$$

$$d\sigma^{CT} \stackrel{q_T\to 0}{\longrightarrow} d\sigma^F_{LO}\otimes\Sigma(q_T/M)dq_T^2$$

Production: qT subtraction method [Catani, Grazzini 2007]

Fully differential cross section: $d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}\right]$

$$\textit{where} \quad \mathcal{H}^{F}_{NNLO} = \left[1 + \frac{\alpha_S}{\pi}\mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)}\right]$$

- the choice of the counter term (CT) has arbitrariness but the qT→0 limit behavior is universal

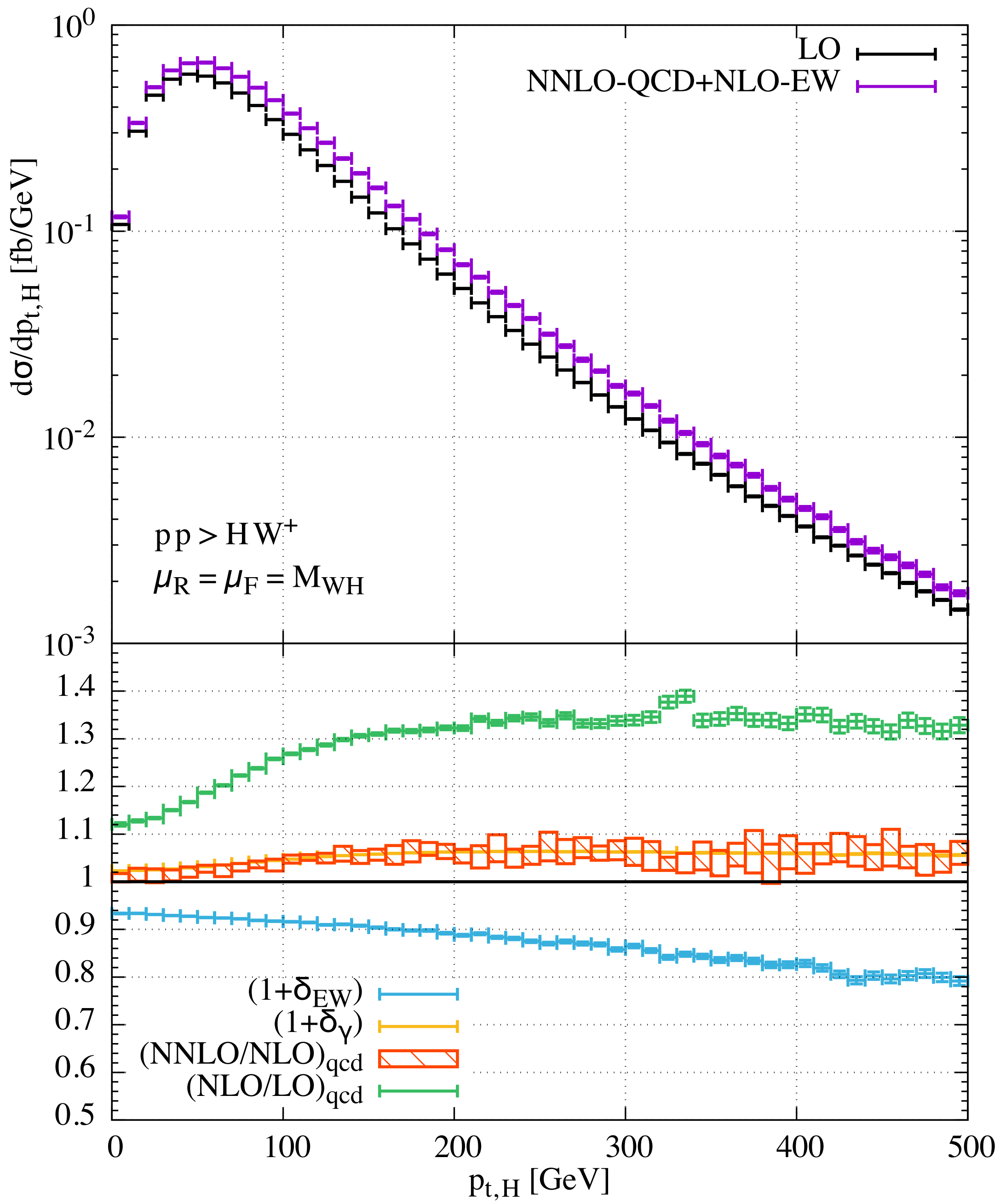
- CT regularize simultaneously the real-virtual and the double real integration that have to be run together

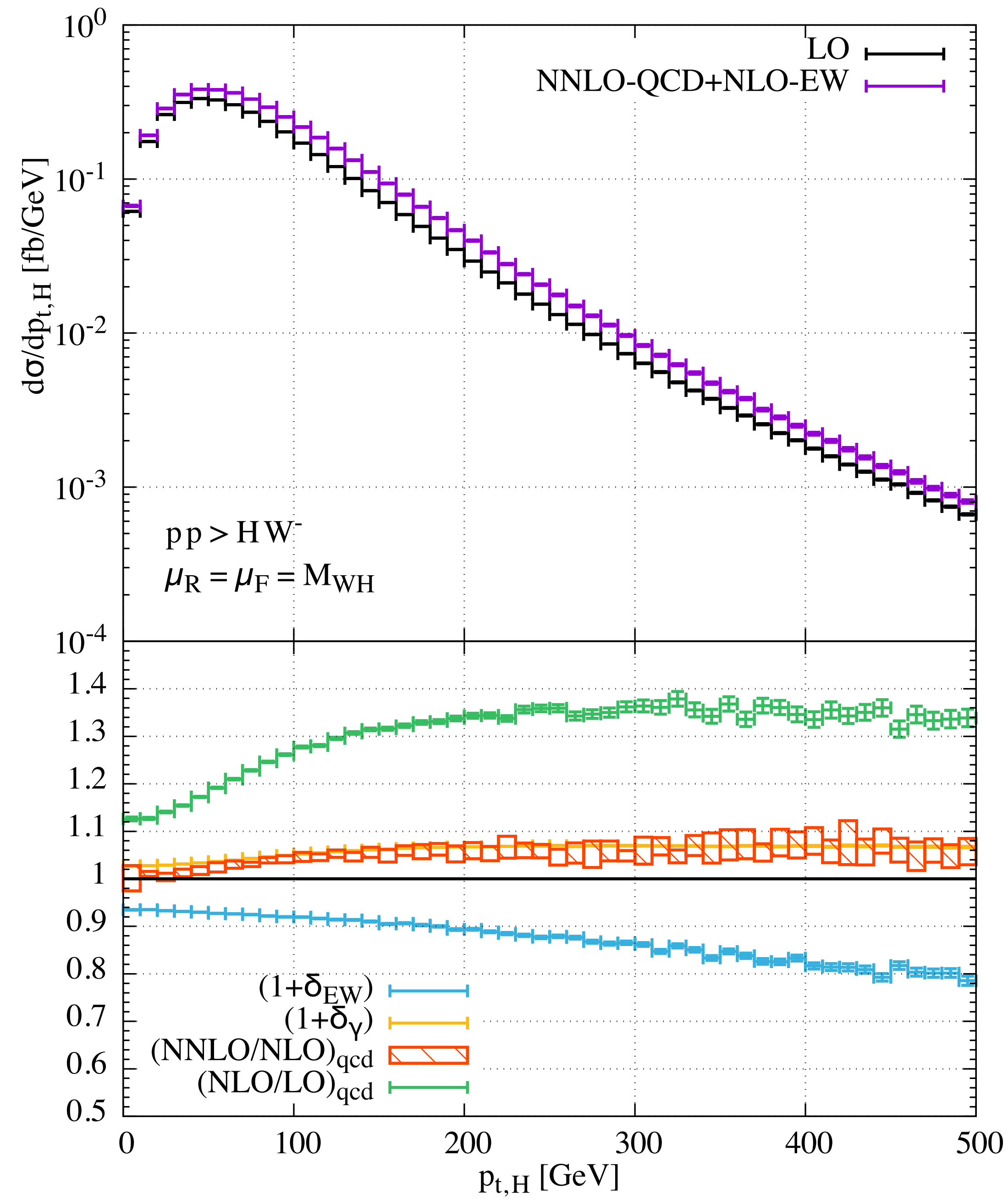
- the Hard function H contains both the double virtual amplitude and the integral of the CT

  ✓ its process dependent part can be obtained by the virtual amplitude via a universal process independent factorisation formula
  [Catani, Cieri, De Florian, Ferrera, Grazzini 2009]

- the method has been used for:
  ggF Higgs production [Catani, Grazzini 2007],
  DY and **Diphoton** [Catani, Cieri, De Florian, Ferrera, Grazzini 2009],
  VV' production [Grazzini,Kallweit,Rathlev,Torre 2013] and
  [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi 2014]

WH higher order corrections (YR4)
(parton level)





$$\delta_{EW} = \sigma_{EW}/\sigma_{LO}$$

$$\delta_\gamma = \sigma_\gamma/\sigma_{LO}$$

- LHC13
- anti-kt with R=0.4

$p_{\mathrm{T}l} > 15\ \mathrm{GeV}, \qquad |y_l| < 2.5\,.$

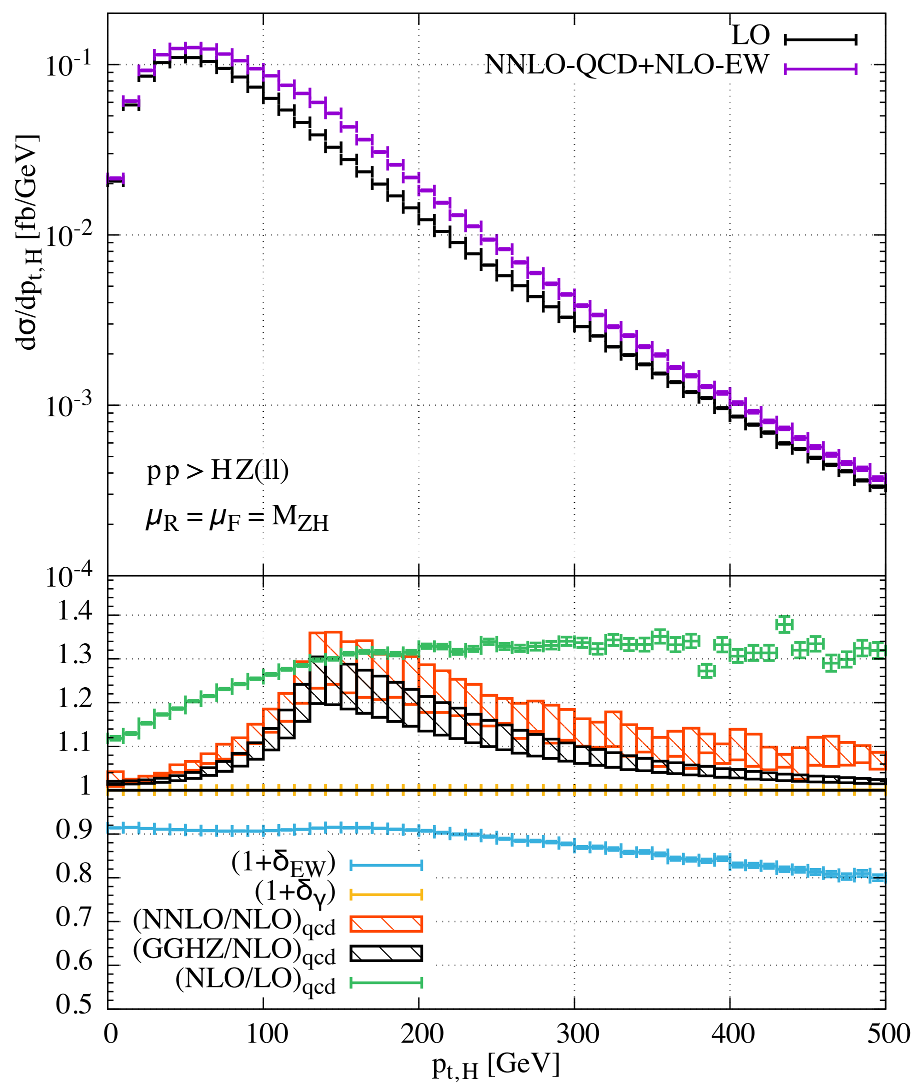
ZH associated production

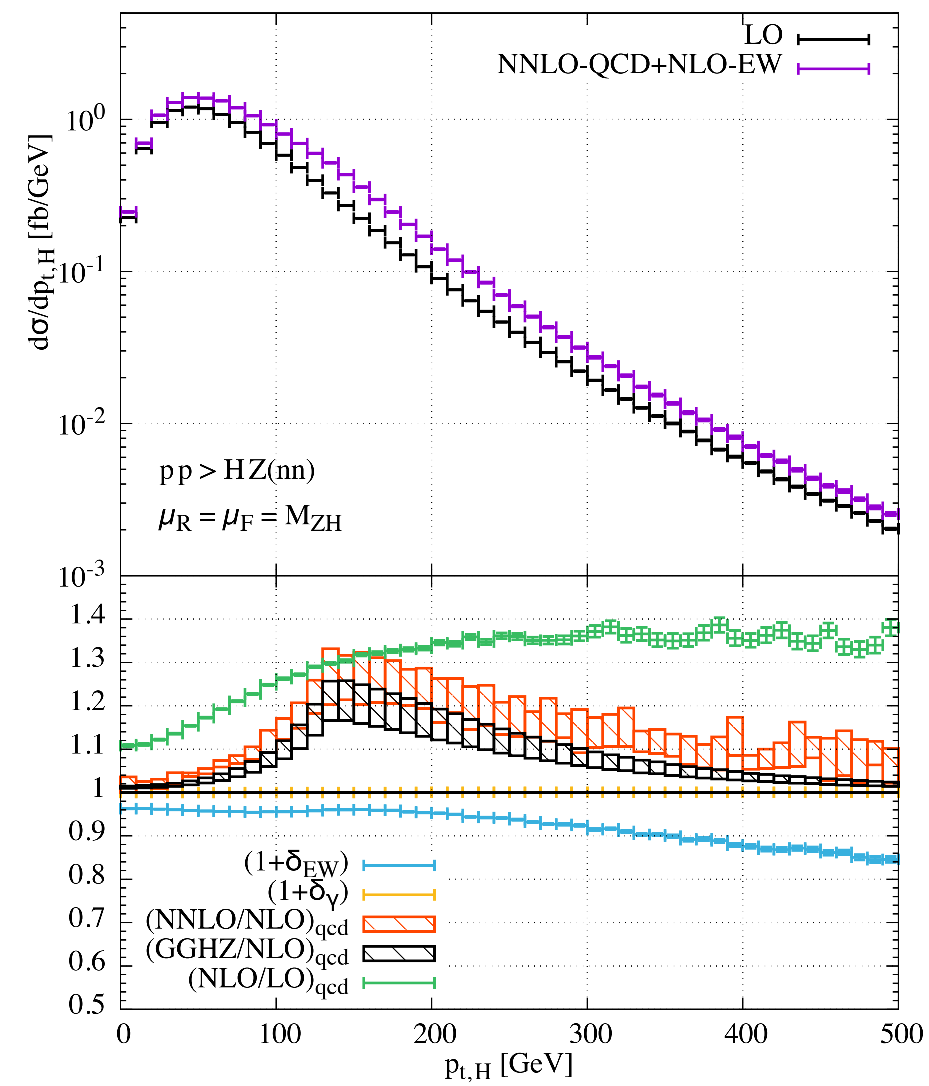
Inclusive Cross Section

$\sqrt{s}$[GeV]	σ[fb]	Δ_{scale}[%]	$\Delta_{\text{PDF}/\alpha_s/\text{PDF}\oplus\alpha_s}$[%]	$\sigma^{\text{DY}}_{\text{NNLOQCD}}$[fb]	$\sigma^{\text{ggZH}}_{\text{NLO+NLL}}$[fb]	$\sigma_{\text{t-loop}}$[fb]	δ_{EW}[%]	σ_γ[fb]
7	11.43	$^{+2.6}_{-2.4}$	$\pm1.6/\pm0.7/\pm1.7$	10.91	0.94	0.11	-5.2	$0.03^{+0.04}_{-0.00}$
8	14.18	$^{+2.9}_{-2.4}$	$\pm1.5/\pm0.8/\pm1.7$	13.36	1.33	0.14	-5.2	$0.04^{+0.05}_{-0.00}$
13	29.82	$^{+3.8}_{-3.1}$	$\pm1.3/\pm0.9/\pm1.6$	26.66	4.14	0.31	-5.3	$0.11^{+0.12}_{-0.01}$
14	33.27	$^{+3.8}_{-3.3}$	$\pm1.3/\pm1.0/\pm1.6$	29.47	4.87	0.36	-5.3	$0.12^{+0.13}_{-0.01}$

Differential Cross Section

$75\text{ GeV} < M_{ll} < 105\text{ GeV}.$

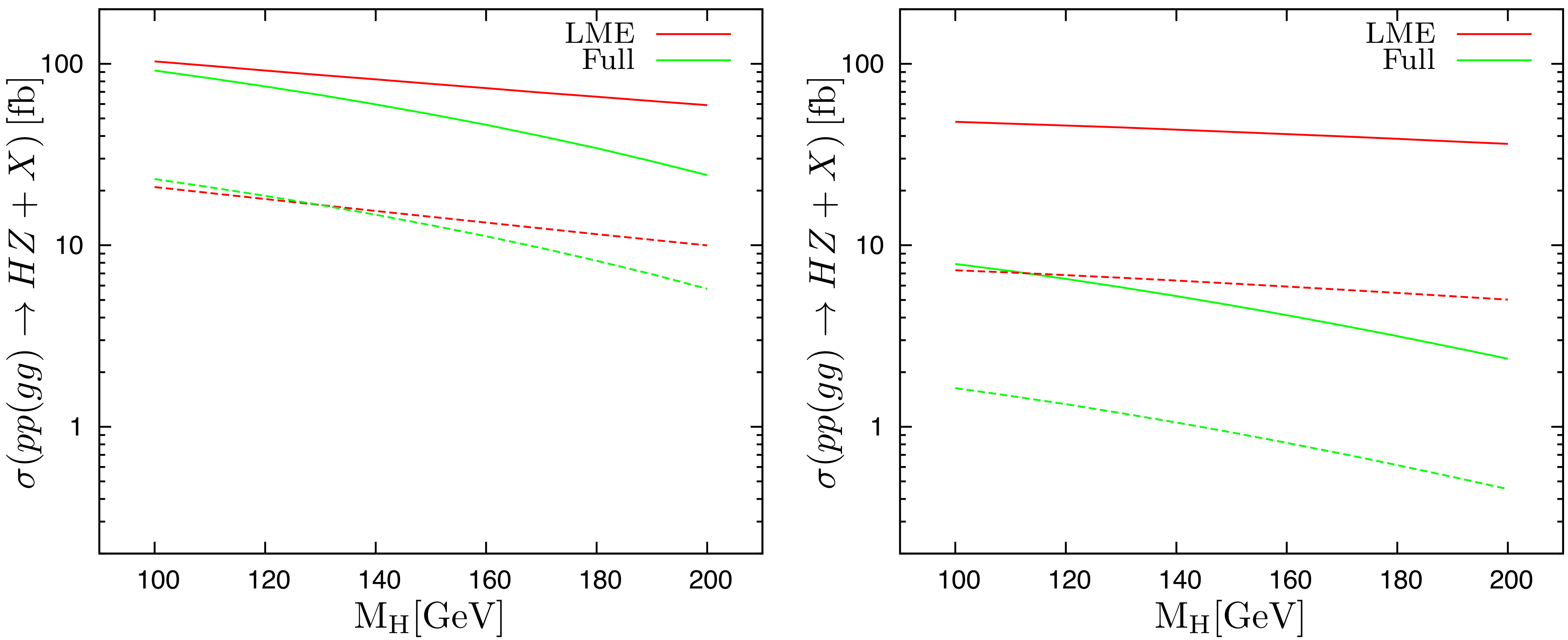




Higgs cross section working group

ggZH contribution to the associated production

$\sqrt{s}$ = 8 TeV (dashed) and 14 TeV (solid)



(a) Inclusive cross section

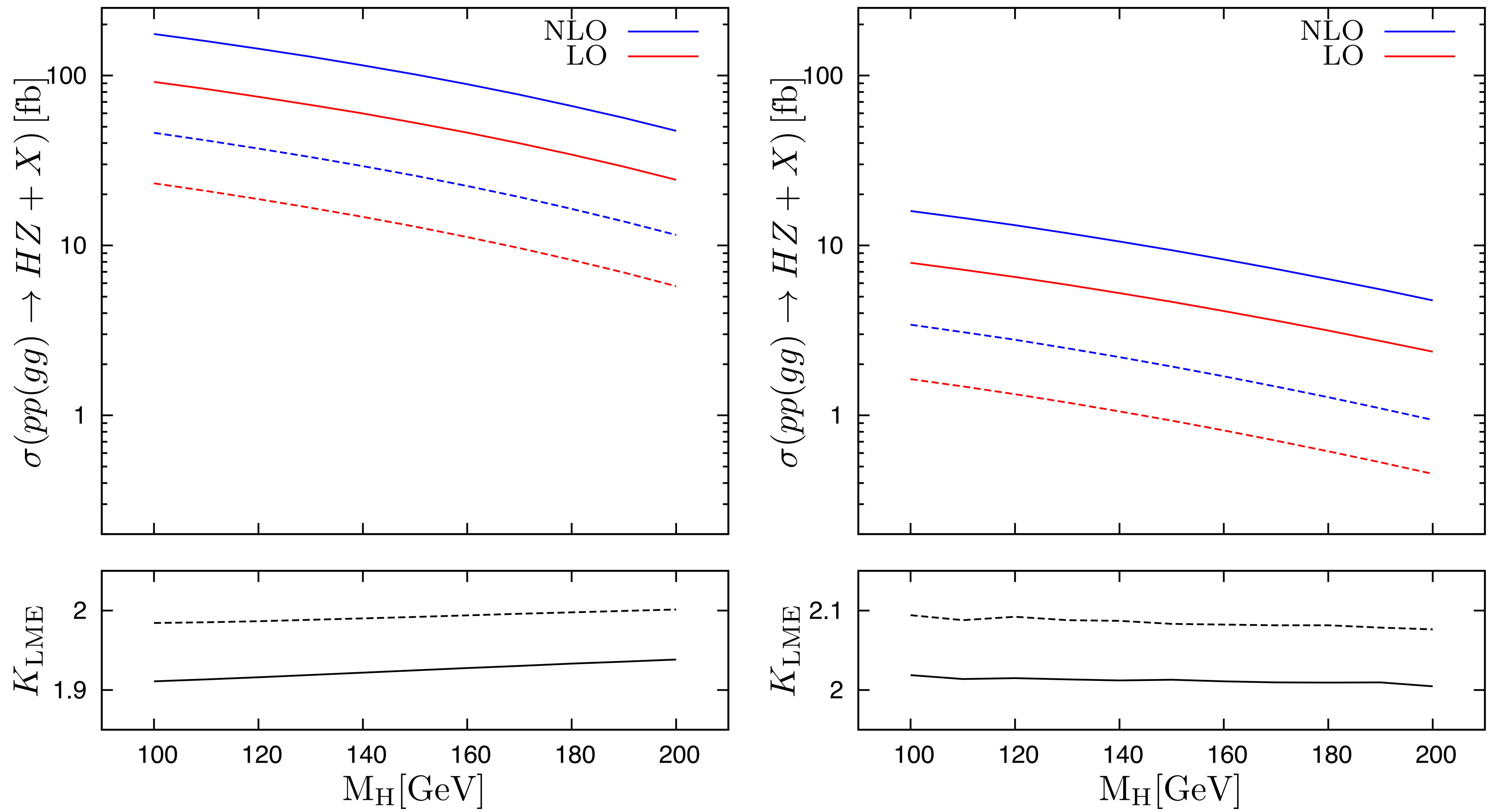
(b) $p_{T,H} > 200$ GeV

Large Mass Expansion for the LO

[Altenkamp, Dittmaier, Harlander, Rzehak, Zirke 2012]

ggZH contribution to the associated production

$\sqrt{s}$ = 8 TeV (dashed) and 14 TeV (solid)



(a) Inclusive cross section (b) $p_{T,H} > 200$ GeV

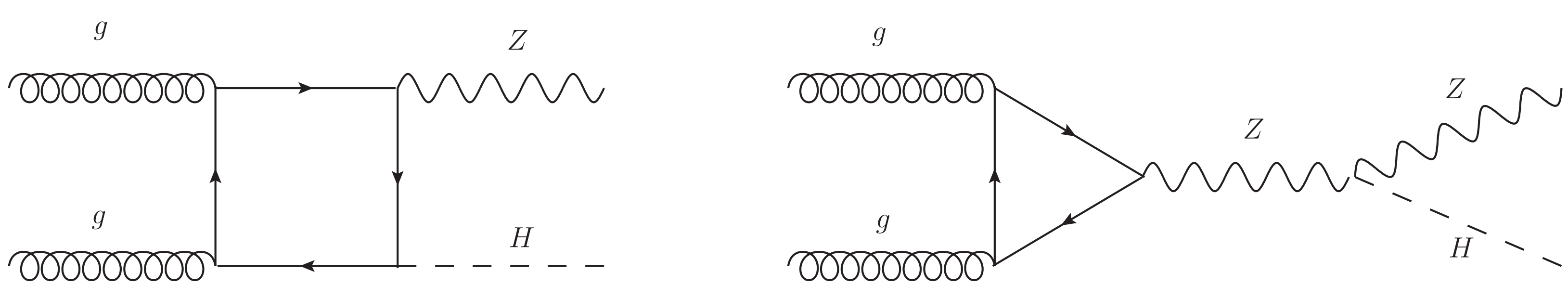
$$\sigma^{\rm NLO}_{\rm approx}(m_t, m_b) = \sigma^{\rm LO}(m_t, m_b) K(m_t \to \infty, m_b = 0)$$

$$= \frac{\sigma^{\rm LO}(m_t, m_b)}{\sigma^{\rm LO}(m_t \to \infty, m_b = 0)} \sigma^{\rm NLO}(m_t \to \infty, m_b = 0)$$

[Altenkamp, Dittmaier, Harlander, Rzehak, Zirke 2012]

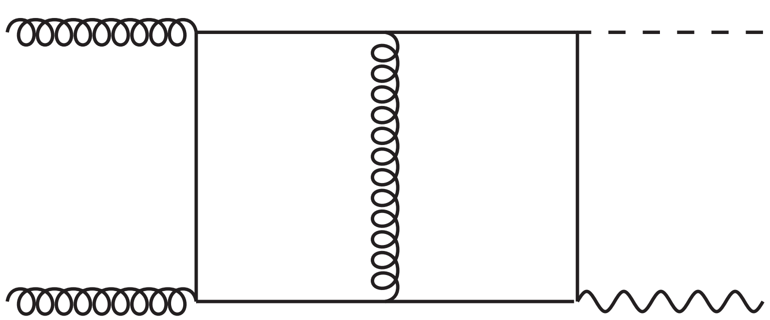
gg->ZH diagrams

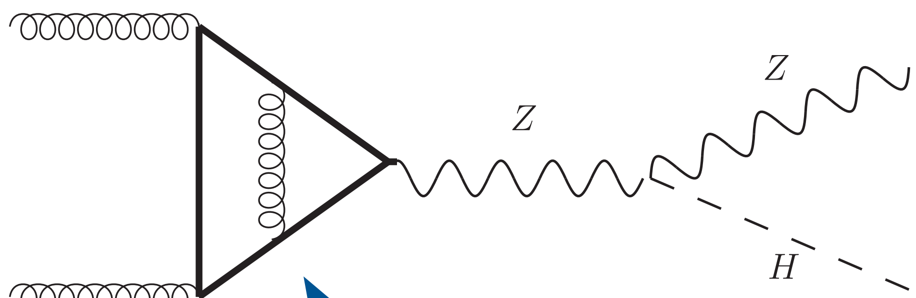
Leading Order:

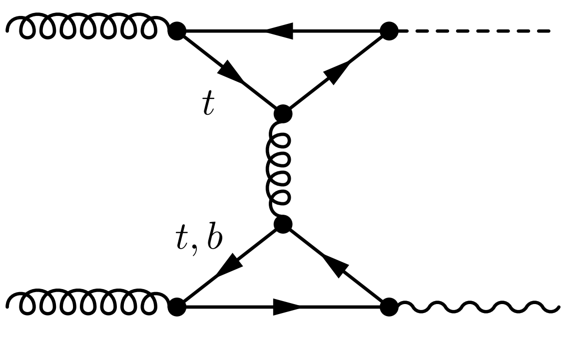


Dicus, Kao '88; Kniehl '90

Exact virtual NLO part:







not known yet

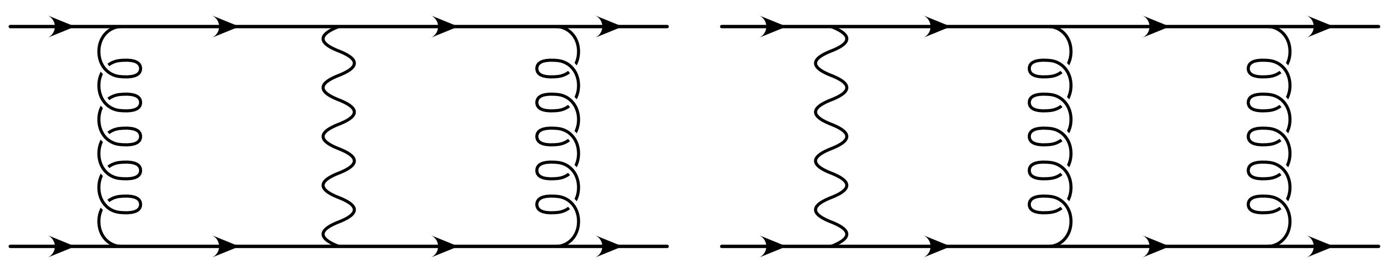
master integrals known from Gehrmann, Huber,Maitre '05

easy

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

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

* A closer look at the radiative corrections: decay

Decay: Colourful method [Del Duca, Somogyi and Trocsanyi 2007, 2009]

- completely local method
- based on the universal infrared factorization of QCD squared matrix elements
- local subtraction terms for regulating the singularities
- Phase space factorization
- O(300) integrals to account of the final state singularities

$$\mathrm{d}\sigma_{m+2}^{\mathrm{NNLO}} = \left\{\mathrm{d}\sigma_{m+2}^{\mathrm{RR}} J_{m+2} - \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_2}} J_m - \left[\mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_1}} J_{m+1} - \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_{12}}} J_m\right]\right\}_{\epsilon=0},$$

$$\mathrm{d}\sigma_{m+1}^{\mathrm{NNLO}} = \left\{\left[\mathrm{d}\sigma_{m+1}^{\mathrm{RV}} + \int_1 \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_1}}\right] J_{m+1} - \left[\mathrm{d}\sigma_{m+1}^{\mathrm{RV,A_1}} + \left(\int_1 \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_1}}\right)^{\mathrm{A_1}}\right] J_m\right\}_{\epsilon=0},$$

$$\mathrm{d}\sigma_{m}^{\mathrm{NNLO}} = \left\{\mathrm{d}\sigma_{m}^{\mathrm{VV}} + \int_2 \left[\mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_2}} - \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_{12}}}\right] + \int_1 \left[\mathrm{d}\sigma_{m+1}^{\mathrm{RV,A_1}} + \left(\int_1 \mathrm{d}\sigma_{m+2}^{\mathrm{RR,A_1}}\right)^{\mathrm{A_1}}\right]\right\}_{\epsilon=0} J_m .$$

Status of (287) integrals

Int	status
$\mathcal{I}^{(k)}_{1\mathcal{C},0}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},1}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},2}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},3}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},4}$	✔
$\mathcal{I}^{(k,l)}_{1\mathcal{C},5}$	✔
$\mathcal{I}^{(k,l)}_{1\mathcal{C},6}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{C},7}$	✔
$\mathcal{I}_{1\mathcal{C},8}$	✔

Int	status
$\mathcal{I}_{1\mathcal{S},0}$	✔
$\mathcal{I}_{1\mathcal{S},1}$	✔
$\mathcal{I}_{1\mathcal{S},2}$	$(m > 3)$ ✔
$\mathcal{I}^{(k)}_{1\mathcal{S},3}$	✔
$\mathcal{I}_{1\mathcal{S},4}$	✔
$\mathcal{I}_{1\mathcal{S},5}$	✔
$\mathcal{I}_{1\mathcal{S},6}$	✔
$\mathcal{I}_{1\mathcal{S},7}$	✔

Int	status
$\mathcal{I}_{1\mathcal{CS},0}$	✔
$\mathcal{I}_{1\mathcal{CS},1}$	✔
$\mathcal{I}^{(k)}_{1\mathcal{CS},2}$	✔
$\mathcal{I}_{1\mathcal{CS},3}$	✔
$\mathcal{I}_{1\mathcal{CS},4}$	✔

Int	status
$\mathcal{I}^{(k,l)}_{12\mathcal{C},1}$	✔
$\mathcal{I}^{(k,l)}_{12\mathcal{C},2}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},3}$	✔
$\mathcal{I}^{(k,l)}_{12\mathcal{C},4}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},5}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},6}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},7}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},8}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},9}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{C},10}$	✔

Int	status
$\mathcal{I}_{2\mathcal{S},1}$	✔
$\mathcal{I}_{2\mathcal{S},2}$	✔
$\mathcal{I}_{2\mathcal{S},3}$	✔
$\mathcal{I}_{2\mathcal{S},4}$	✔
$\mathcal{I}_{2\mathcal{S},5}$	✔
$\mathcal{I}_{2\mathcal{S},6}$	✔
$\mathcal{I}_{2\mathcal{S},7}$	✔
$\mathcal{I}_{2\mathcal{S},8}$	✔
$\mathcal{I}_{2\mathcal{S},9}$	✔
$\mathcal{I}_{2\mathcal{S},10}$	✔
$\mathcal{I}_{2\mathcal{S},11}$	✔
$\mathcal{I}_{2\mathcal{S},12}$	✔
$\mathcal{I}_{2\mathcal{S},13}$	✔
$\mathcal{I}_{2\mathcal{S},14}$	✔
$\mathcal{I}_{2\mathcal{S},15}$	✔
$\mathcal{I}_{2\mathcal{S},16}$	✔
$\mathcal{I}_{2\mathcal{S},17}$	✔
$\mathcal{I}_{2\mathcal{S},18}$	✔
$\mathcal{I}_{2\mathcal{S},19}$	✔
$\mathcal{I}_{2\mathcal{S},20}$	✔
$\mathcal{I}_{2\mathcal{S},21}$	✔
$\mathcal{I}_{2\mathcal{S},22}$	✔
$\mathcal{I}_{2\mathcal{S},23}$	✔

Int	status
$\mathcal{I}^{(k)}_{12\mathcal{S},1}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},2}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},3}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},4}$	✔
$\mathcal{I}^{(k)}_{12\mathcal{S},5}$	✔
$\mathcal{I}_{12\mathcal{S},6}$	✔
$\mathcal{I}_{12\mathcal{S},7}$	✔
$\mathcal{I}_{12\mathcal{S},8}$	✔
$\mathcal{I}_{12\mathcal{S},9}$	✔
$\mathcal{I}_{12\mathcal{S},10}$	✔
$\mathcal{I}_{12\mathcal{S},11}$	✔
$\mathcal{I}_{12\mathcal{S},12}$	✔
$\mathcal{I}_{12\mathcal{S},13}$	✔

Int	status
$\mathcal{I}^{(k)}_{12\mathcal{CS},1}$	✔
$\mathcal{I}_{12\mathcal{CS},2}$	✔
$\mathcal{I}_{12\mathcal{CS},3}$	✔

Int	status	Int	status
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},1}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},1}$	✔
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},2}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},2}$	✔
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},3}$	✔	$\mathcal{I}^{(2)}_{2\mathcal{CS},2}$	✔
$\mathcal{I}^{(j,k,l,m)}_{2\mathcal{C},4}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},3}$	✔
$\mathcal{I}^{(-1,-1,-1,-1)}_{2\mathcal{C},5}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},4}$	✔
$\mathcal{I}^{(k,l)}_{2\mathcal{C},6}$	✔	$\mathcal{I}^{(k)}_{2\mathcal{CS},5}$	✔

✓: pole coefficients are known analytically, finite numerically, in some cases analytically

| | page 0

Fully analytic determination of all the singularities for $H \to b\bar{b}$

$$\sigma_m^{\rm NNLO} = \int_m \left\{ {\rm d}\sigma_m^{\rm VV} + \int_2 \left[{\rm d}\sigma_{m+2}^{\rm RR,A_2} - {\rm d}\sigma_{m+2}^{\rm RR,A_{12}} \right] + \int_1 \left[{\rm d}\sigma_{m+1}^{\rm RV,A_1} + \left(\int_1 {\rm d}\sigma_{m+2}^{\rm RR,A_1} \right)^{\rm A_1} \right] \right\} J_m$$

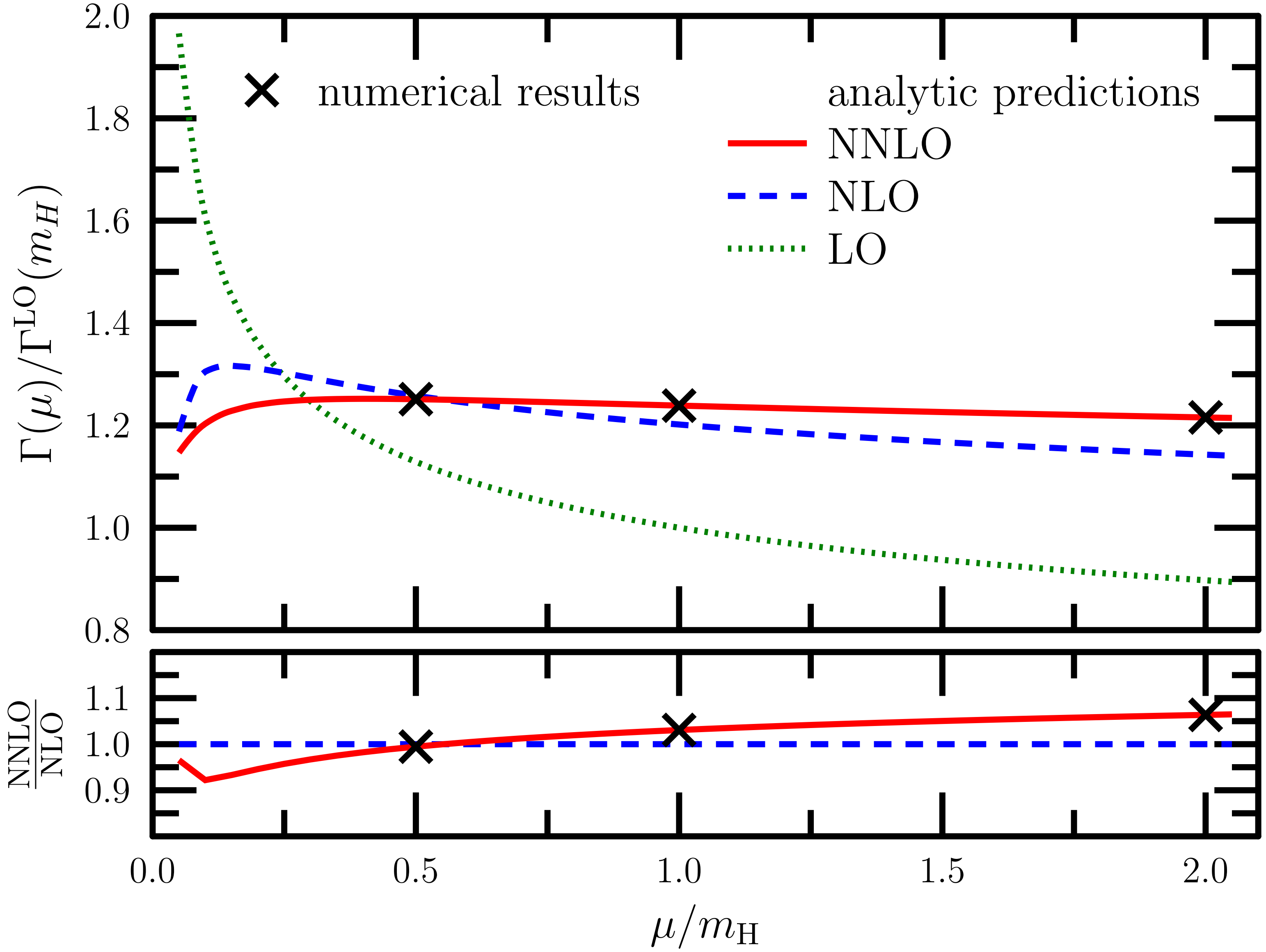
$$\begin{aligned} {\rm d}\sigma_{H\to b\bar{b}}^{\rm VV} = \left(\frac{\alpha_{\rm s}(\mu^2)}{2\pi}\right)^2 {\rm d}\sigma_{H\to b\bar{b}}^{\rm B} \Bigg\{ &+ \frac{2C_{\rm F}^2}{\epsilon^4} + \left(\frac{11 C_{\rm A} C_{\rm F}}{4} + 6 C_{\rm F}^2 - \frac{C_{\rm F} n_{\rm f}}{2} \right) \frac{1}{\epsilon^3} \\ &+ \left[\left(\frac{8}{9} + \frac{\pi^2}{12} \right) C_{\rm A} C_{\rm F} + \left(\frac{17}{2} - 2\pi^2 \right) C_{\rm F}^2 - \frac{2 C_{\rm F} n_{\rm f}}{9} \right] \frac{1}{\epsilon^2} \\ &+ \left[\left(-\frac{961}{216} + \frac{13\zeta_3}{2} \right) C_{\rm A} C_{\rm F} + \left(\frac{109}{8} - 2\pi^2 - 14\zeta_3 \right) C_{\rm F}^2 + \frac{65 C_{\rm F} n_{\rm f}}{108} \right] \frac{1}{\epsilon} \Bigg\} \end{aligned}$$

C. Anastasiou, F. Herzog, A. Lazopoulos, arXiv:0111.2368

$$\begin{aligned} \sum \int {\rm d}\sigma^{\rm A} = \left(\frac{\alpha_{\rm s}(\mu^2)}{2\pi}\right)^2 {\rm d}\sigma_{H\to b\bar{b}}^{\rm B} \Bigg\{ &- \frac{2C_{\rm F}^2}{\epsilon^4} - \left(\frac{11 C_{\rm A} C_{\rm F}}{4} + 6 C_{\rm F}^2 + \frac{C_{\rm F} n_{\rm f}}{2} \right) \frac{1}{\epsilon^3} \\ &- \left[\left(\frac{8}{9} + \frac{\pi^2}{12} \right) C_{\rm A} C_{\rm F} + \left(\frac{17}{2} - 2\pi^2 \right) C_{\rm F}^2 - \frac{2 C_{\rm F} n_{\rm f}}{9} \right] \frac{1}{\epsilon^2} \\ &- \left[\left(-\frac{961}{216} + \frac{13\zeta_3}{2} \right) C_{\rm A} C_{\rm F} + \left(\frac{109}{8} - 2\pi^2 - 14\zeta_3 \right) C_{\rm F}^2 + \frac{65 C_{\rm F} n_{\rm f}}{108} \right] \frac{1}{\epsilon} \Bigg\} \end{aligned}$$

V. Del Duca, C. Duhr, G. Somogyi, FT, Z. Trocsanyi, arXiv:1501.07226

Inclusive result



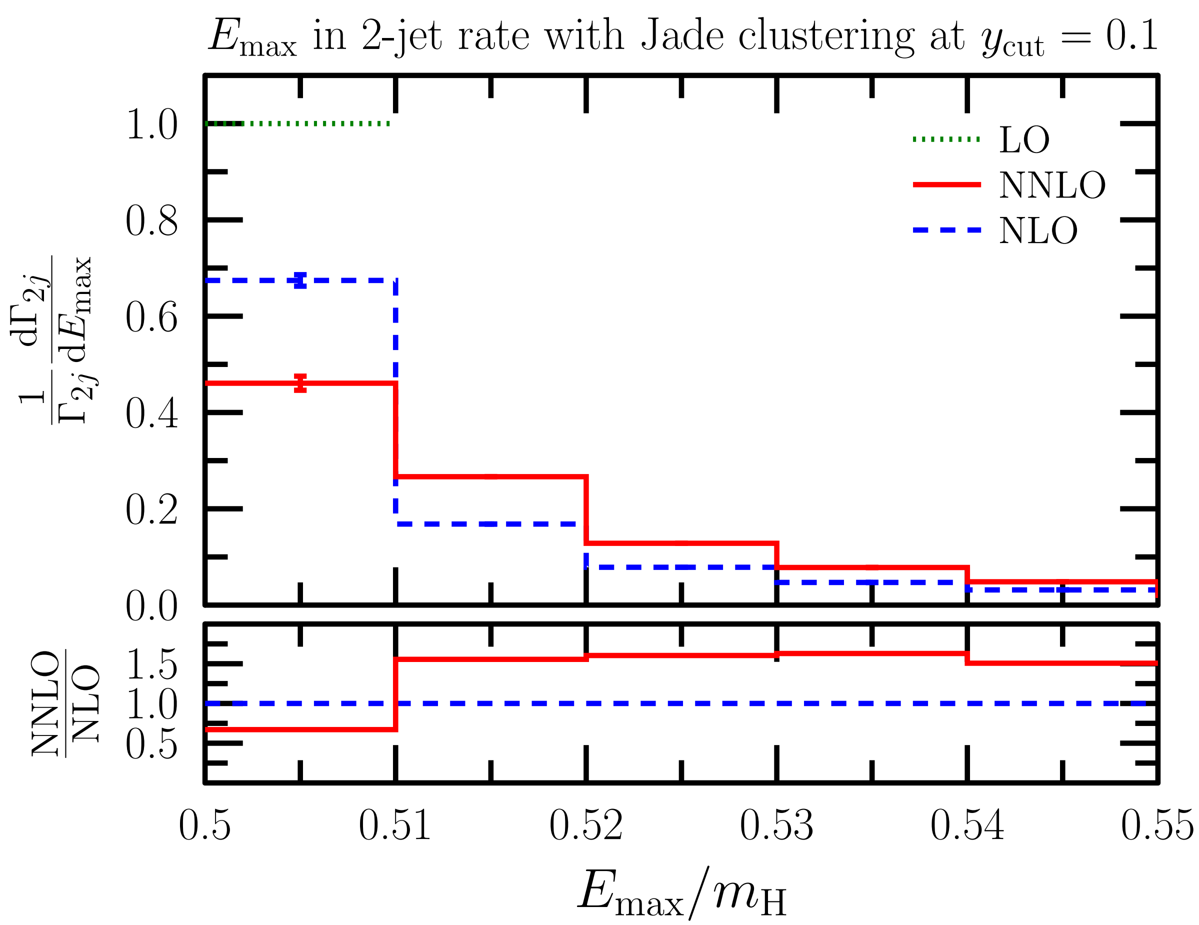
In perfect agreement with:

[Gorishnii, Kataev, Larin, Surguladze 1990]

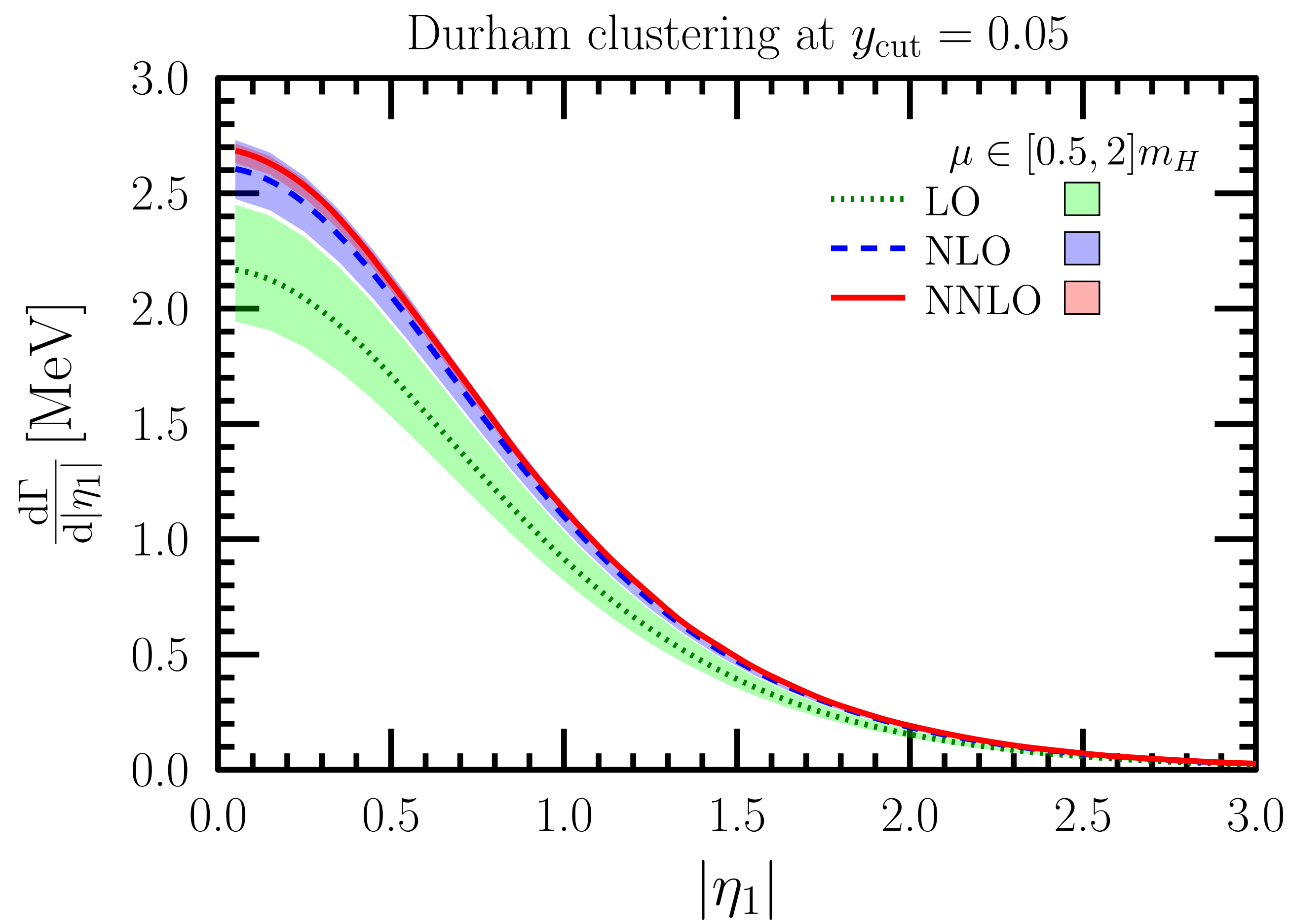
[Baikov, Chetyrkin, Kuhn 2006]

[Del Duca, Duhr, Somogyi, FT, Trocsanyi 2015]

Differential results



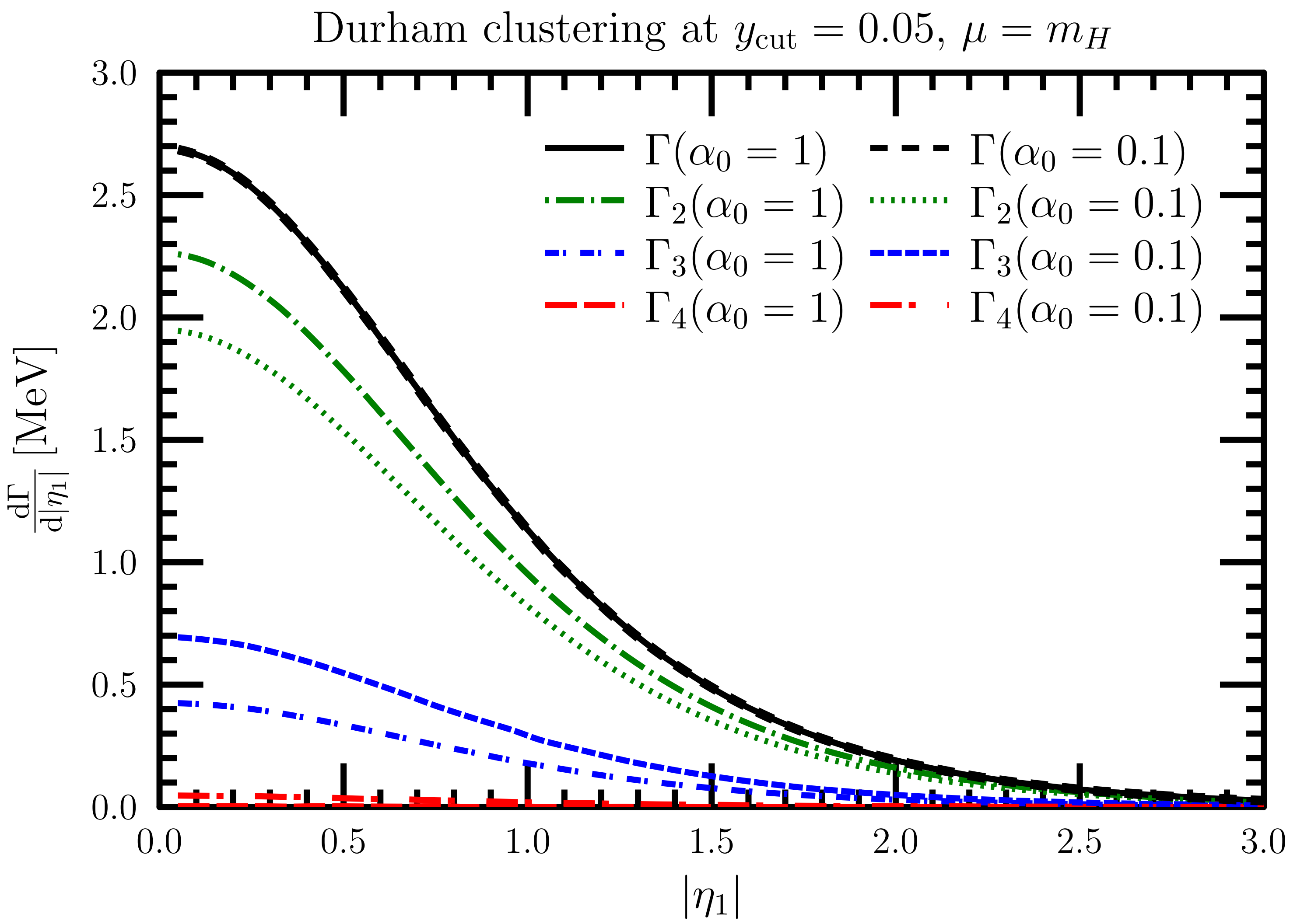
Energy spectrum of the leading jet in the rest frame of the Higgs boson for 2j events.
Excellent agreement with
[Anastasiou, Herzog, Lazopoulos '12]



Absolute value of the pseudorapidity of the leading jet in the rest frame of the Higgs boson

[Del Duca, Duhr, Somogyi, FT, Trocsanyi 2015]

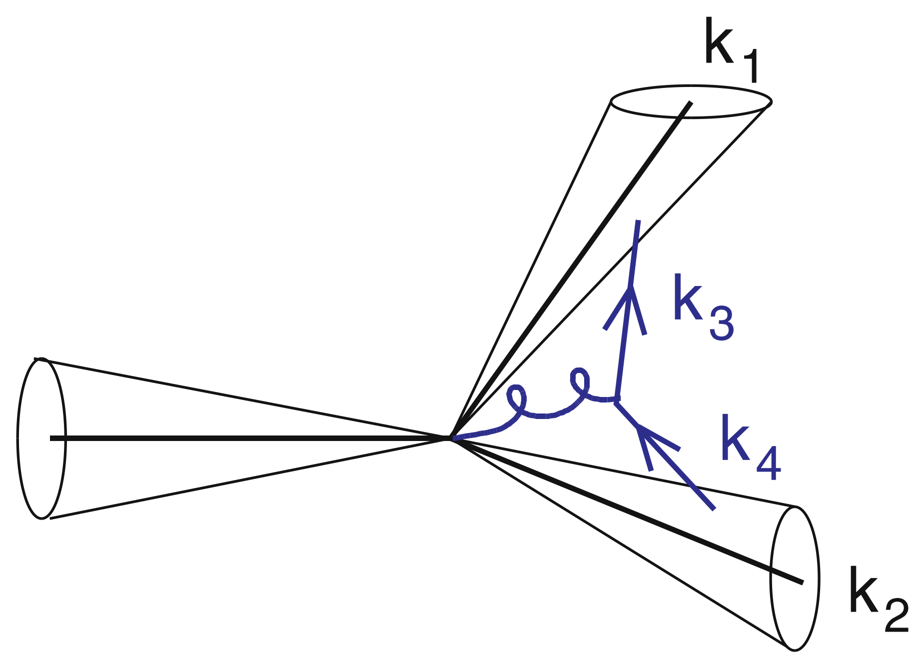
Differential results



[Del Duca, Duhr, Somogyi, FT, Trocsanyi 2015]

* Caveat

Jet algorithm



Flavor-kT provides an IRC safe definition of jet flavour

[Banfi, Salam, Zanderighi 2006]

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

$$d_{iB}^{(F)} = \begin{cases} \max(k_{ti}^2, k_{tB}^2)\,, & i \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tB}^2)\,, & i \text{ is flavourless.} \end{cases}$$

$$k_{tB}(\eta) = \sum_i k_{ti}\left(\Theta(\eta_i - \eta) + \Theta(\eta - \eta_i)e^{\eta_i - \eta}\right)$$

$$k_{t\bar{B}}(\eta) = \sum_i k_{ti}\left(\Theta(\eta - \eta_i) + \Theta(\eta_i - \eta)e^{\eta - \eta_i}\right)$$

* A closer look at the radiative corrections: combination

$(pp \to VH) \otimes (H \to bb)$

QCD corrections in the Narrow Width Approximation

$$d\sigma_{pp\to VH+X\to Vb\bar{b}+X} = \left[\sum_{k=0}^{\infty} d\sigma^{(k)}_{pp\to VH+X}\right] \times \left[\frac{\sum_{k=0}^{\infty} d\Gamma^{(k)}_{H\to b\bar{b}}}{\sum_{k=0}^{\infty} \Gamma^{(k)}_{H\to b\bar{b}}}\right] \times Br(H\to b\bar{b})$$

Precise knowledge from YR1

Including up to NLO corrections

$$d\sigma^{\mathrm{NLO(prod)+NLO(dec)}}_{pp\to VH+X\to Vb\bar{b}+X} = \left[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} + d\sigma^{(1)}_{pp\to VH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}}\right] \times Br(H\to b\bar{b})$$

Including up to NNLO corrections for the production and up to NLO for the decay

$$d\sigma^{\mathrm{NNLO(prod)+NLO(dec)}}_{pp\to VH+X\to l\nu b\bar{b}+X} = \left[d\sigma^{(0)}_{pp\to VH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} + \left(d\sigma^{(1)}_{pp\to VH+X} + d\sigma^{(2)}_{pp\to VH+X}\right) \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}}\right] \times Br(H\to b\bar{b})$$

Including up to NNLO corrections for both the Higgs production and its decay

$$
\begin{aligned}
d\sigma^{\mathrm{NNLO(prod)+NNLO(dec)}}_{pp\to WH+X\to l\nu b\bar{b}+X} = \Bigg[& d\sigma^{(0)}_{pp\to WH} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}} + d\Gamma^{(2)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}} + \Gamma^{(2)}_{H\to b\bar{b}}} \\
& + d\sigma^{(1)}_{pp\to WH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}} + d\Gamma^{(1)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}} + \Gamma^{(1)}_{H\to b\bar{b}}} \\
& + d\sigma^{(2)}_{pp\to WH+X} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{\Gamma^{(0)}_{H\to b\bar{b}}} \Bigg] \times Br(H\to b\bar{b})
\end{aligned}
$$

- combine NNLO in the production and nnlo in the decay stages
- inclusion of NLO(prod) x NLO(dec) contribution relevant

* Results

Setup and fiducial cross sections at LHC13

$G_F = 1.1663787\,10^{-5}\text{GeV}^{-2}$

$m_Z = 91.1876\text{GeV}$

$m_W = 80.385\text{GeV}$

$w_Z = 2.4952\text{GeV}$

$w_W = 2.085\text{GeV}$

$m_t = 172\text{GeV}$

$m_H = 125\text{GeV}$

$Br(H \to b\bar{b}) = 0.578$

jet-algorithm: $\text{flavor}_{\text{kt}}(0.5)$

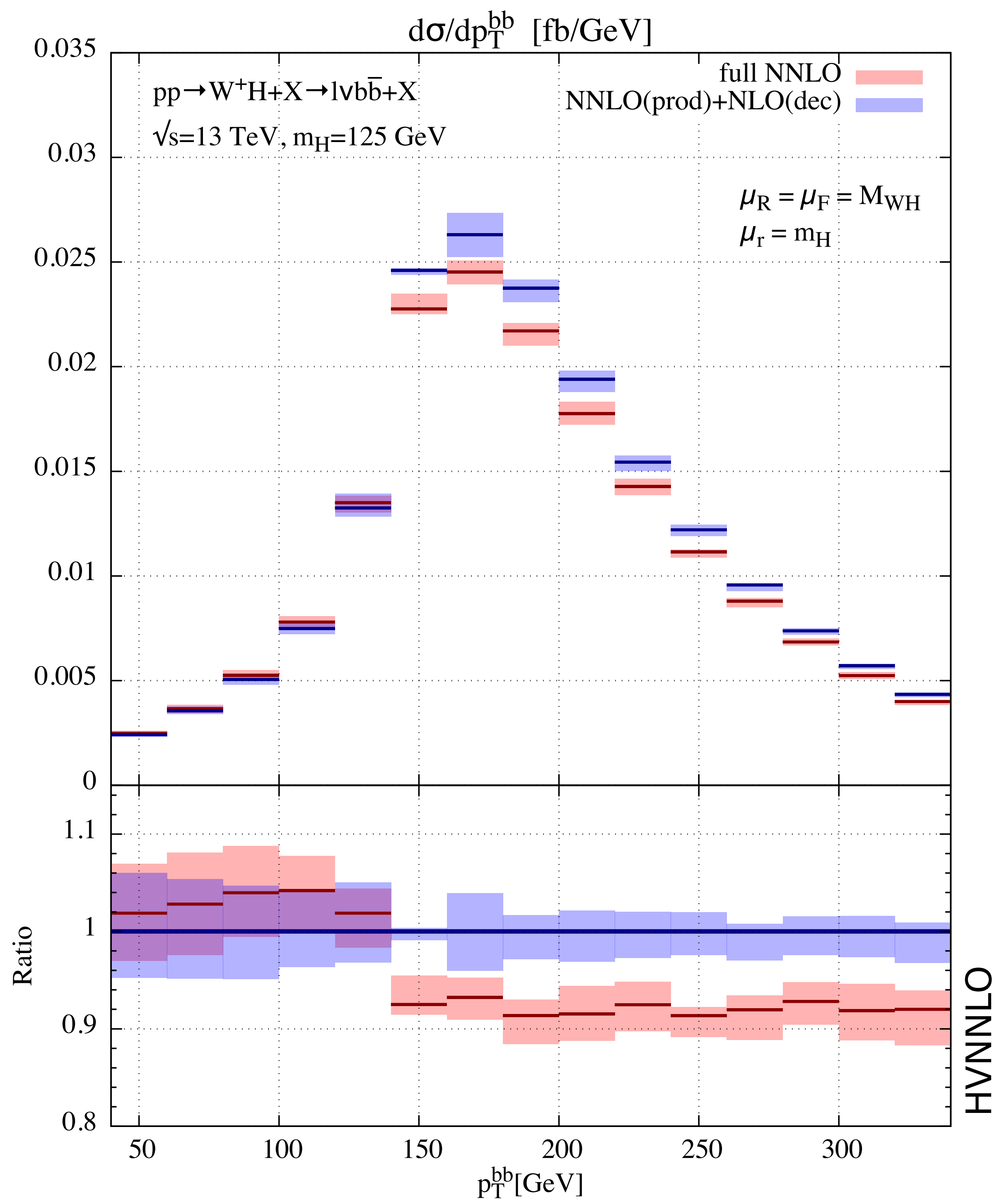
W^+	$Z(\nu\nu)$
at least 2 b jets	
$p_T^l > 15\text{GeV}$ $\lvert\eta_l\rvert < 2.5$ $E_T^{miss} > 30\text{GeV}$ $p_T^W > 150\text{GeV}$ $p_T^b > 25\text{GeV}$ $\lvert\eta_b\rvert < 2.5$	$E_T^{miss} > 150\text{GeV}$ $p_T^b > 25\text{GeV}$ $\lvert\eta_b\rvert < 2.5$

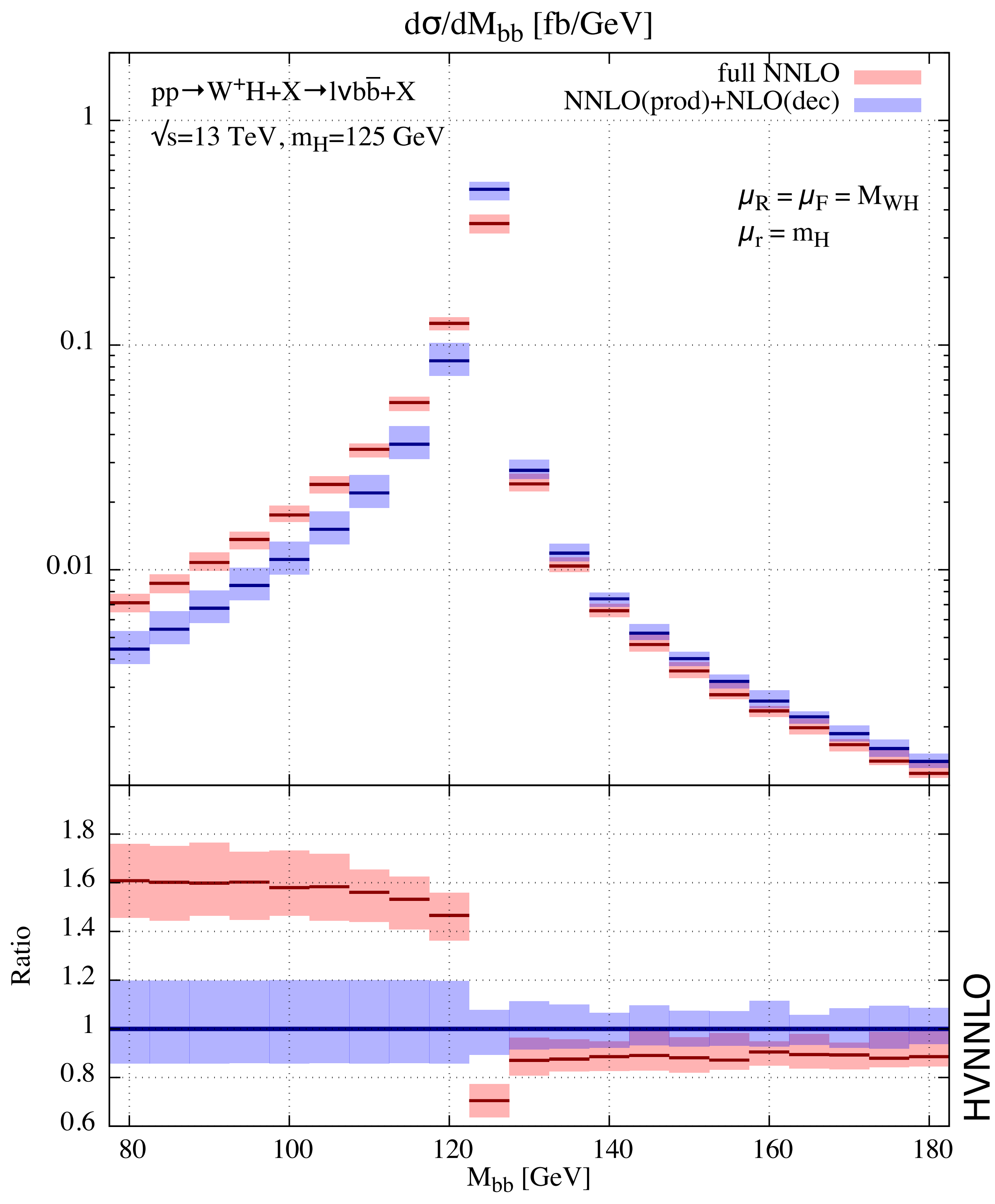
scale variation is the convolution of:

$$\begin{cases} M_{VH}/2 \leq \{\mu_R, \mu_F\} \leq 2M_{VH},\; \mu_r = m_H, 1/2 \leq \mu_R/\mu_F \leq 2 \\ \mu_R = \mu_F = M_{VH},\; m_H/2 \leq \mu_r \leq 2m_H \end{cases}$$

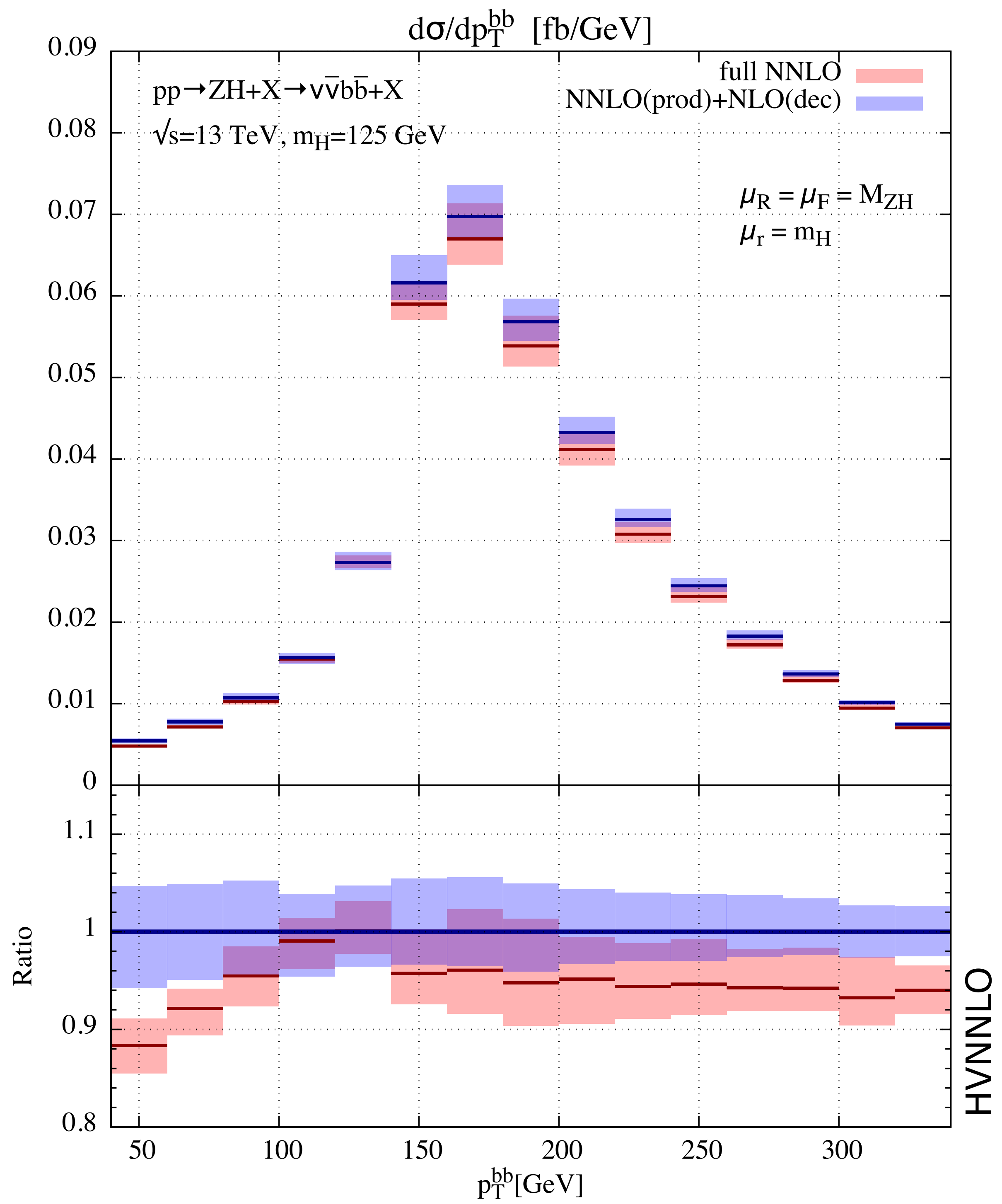
σ (fb)	NNLO(prod)+NLO(dec)	full NNLO
$pp \to W^+H + X \to l\nu_l b\bar{b} + X$	$3.94^{+1\%}_{-1.5\%}$	$3.70^{+1.5\%}_{-1.5\%}$
$pp \to ZH + X \to \nu\nu b\bar{b} + X$	$8.65^{+4.5\%}_{-3.5\%}$	$8.24^{+4.5\%}_{-3.5\%}$

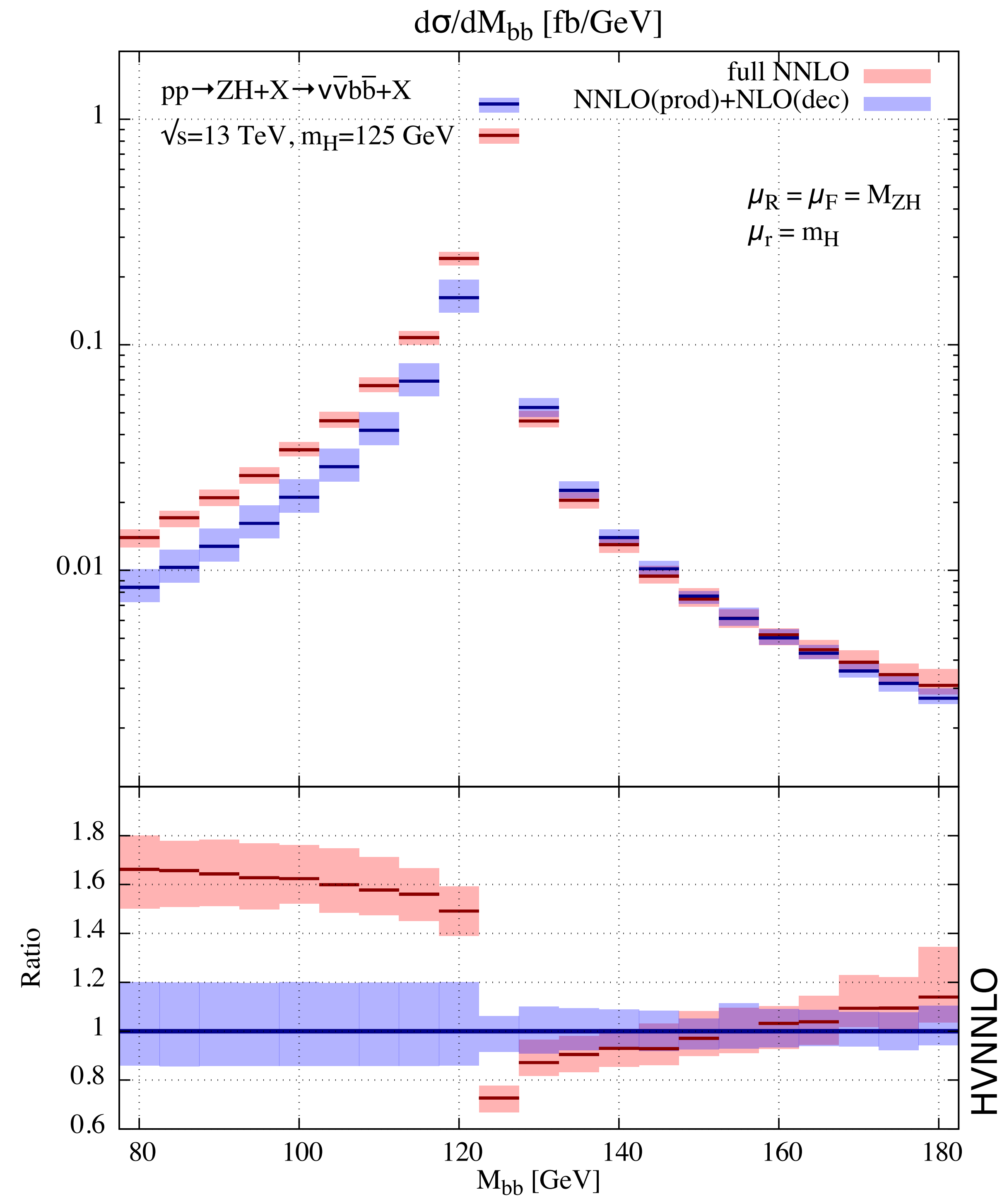
$W^+H(bb)$ differential cross sections at LHC13





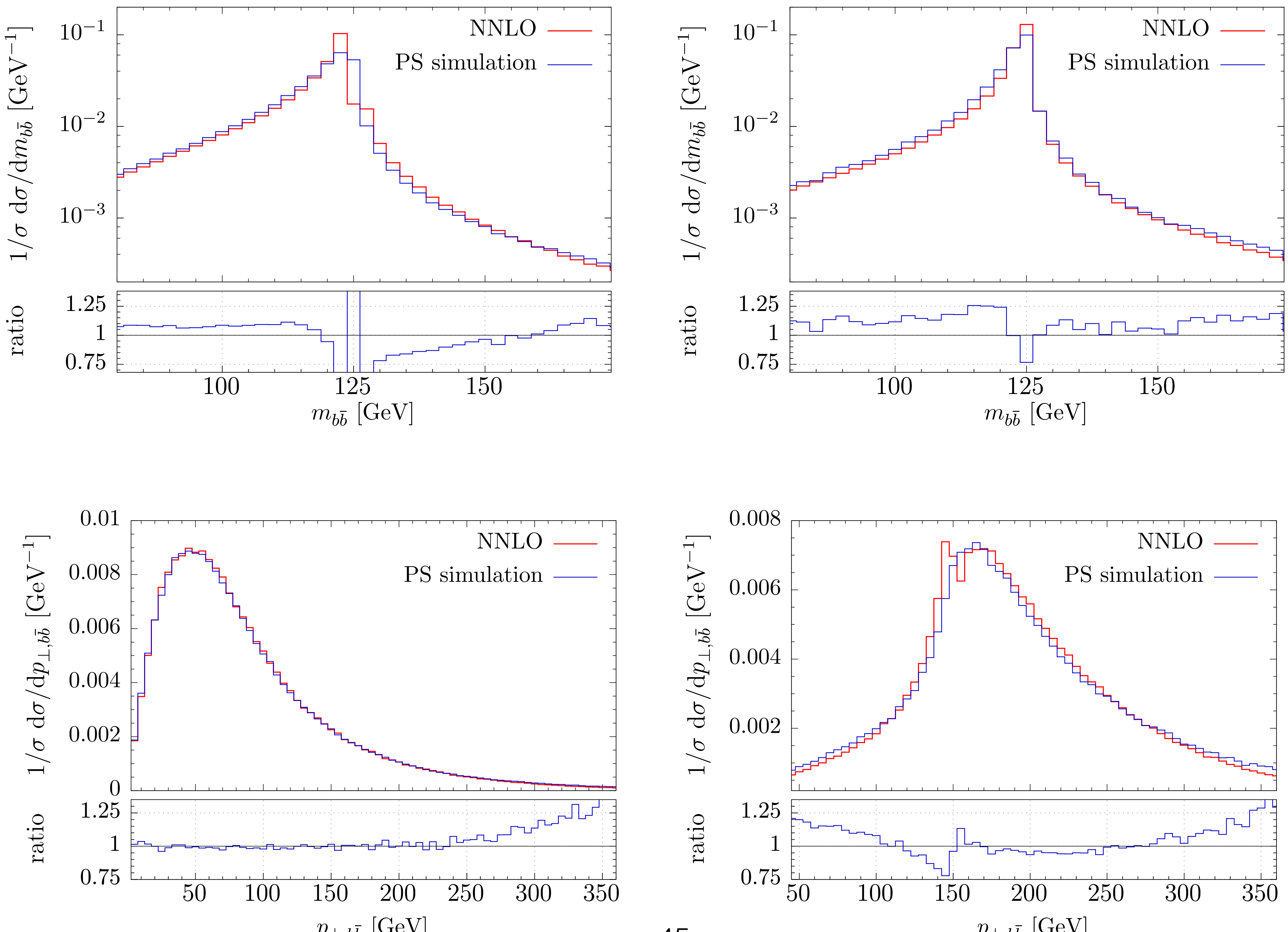
Z(vv)H(bb) differential cross sections at LHC13





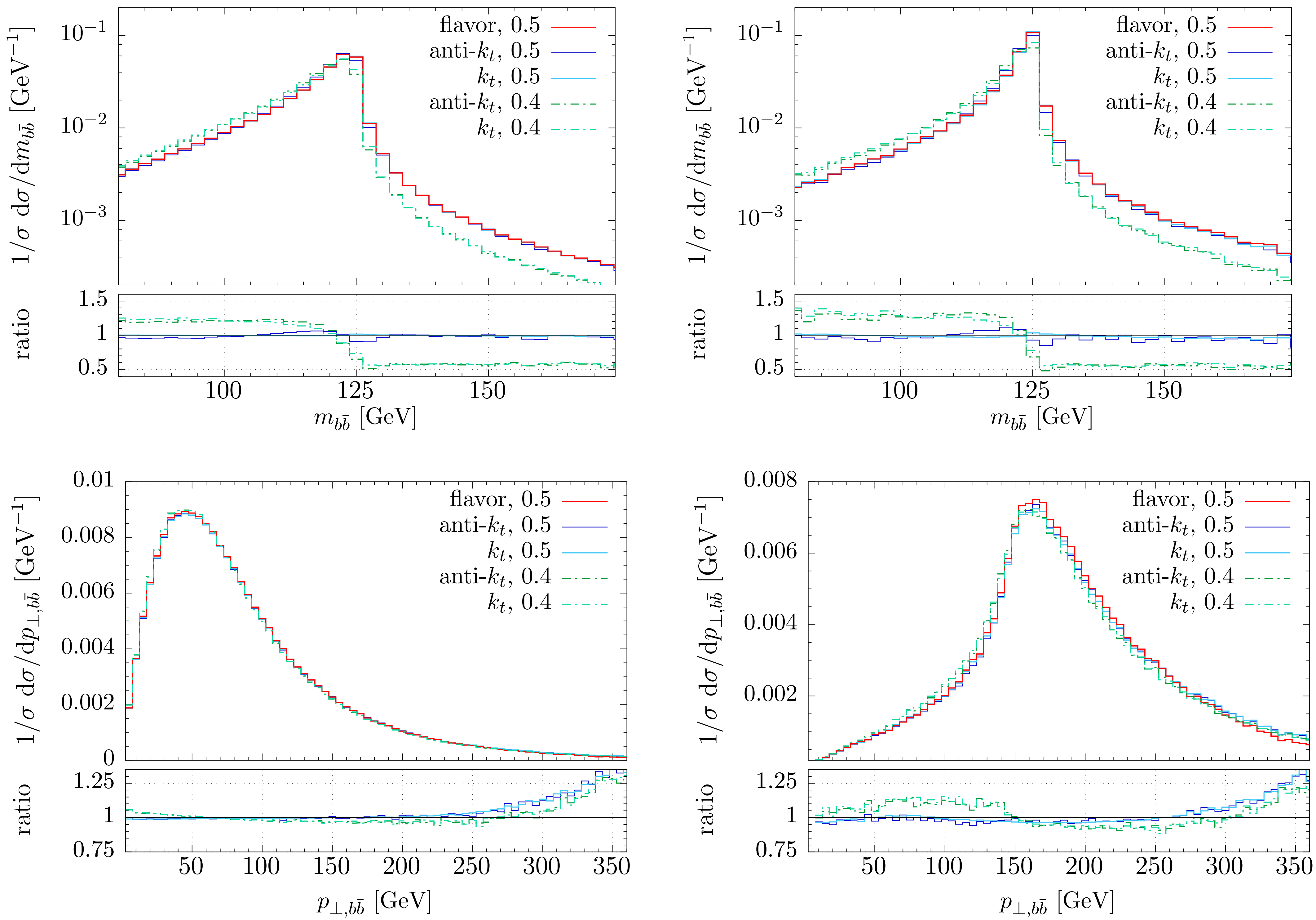
$W^-H(b\bar{b})$ differential cross sections at LHC13 also studied in [Caola,Luisoni, Melnikov, Röntsch 2017]

- Comparison with Shower Monte Carlo



$W^{-}H(bb)$ differential cross sections at LHC13 also studied in [Caola,Luisoni, Melnikov, Röntsch 2017]

- study of the impact of the jet algorithm



Conclusion

- ✳ Event generation in good shape: NNLO+nloPS in the making, NLOQCD+EW+PS available
- ✳ Although still not real progress on ggZH@NLO
- ✳ Calculation of NNLO QCD corrections to VH production with nnlo QCD H → bb decay in hadron collision included in a fully-exclusive parton level Monte Carlo code [Ferrera, Somogyi, Tramontano 1705.10304]
- ✳ Independent computation with totally different techniques recently completed and excellent agreement found [Caola,Luisoni, Melnikov, Röntsch 1712.06954]
- ✳ first reliable estimate of perturbative uncertainty available

Outlook/Work in progress

- ✳ Public release of the HVNNLO parton-level numerical code
- ✳ Inclusion of other Higgs boson decay channels, es. H → WW/ZZ → 2l2v/4l decay
- ✳ Extension to the case of Higgs decay to massive b quarks @NNLO