Karlsruhe Institute of Technology

Higgs decays into b-quarks…

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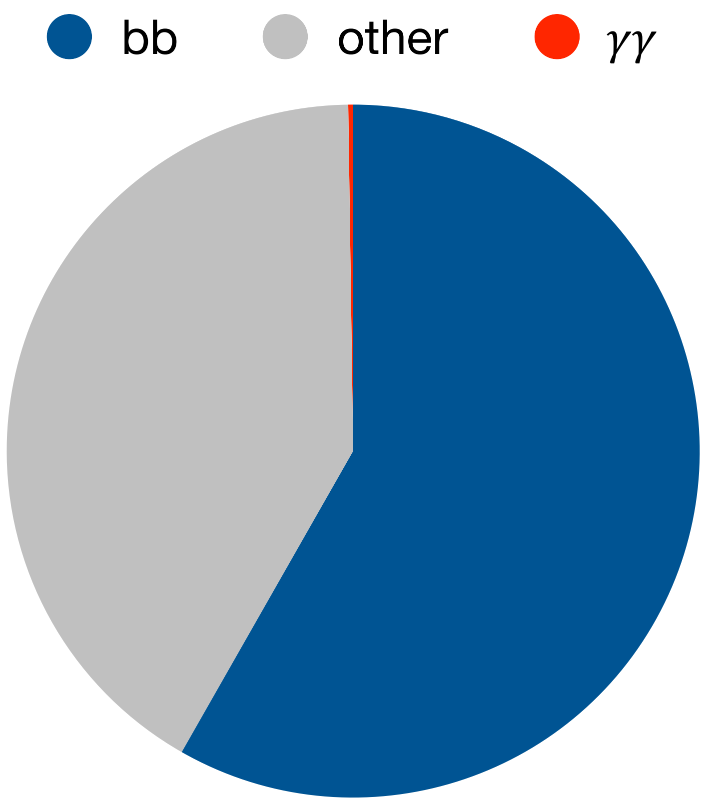
Outline

- Higgs decay into b-quarks
- NNLO+PS using MiNLO
- NNLO with massive b-quarks
- Summary

Higgs decay to b-quarks

- most common decay channel of the Higgs boson (MH=125 GeV)
- very challenging due to overwhelming QCD backgrounds
- observed by both **ATLAS** & **CMS** [1808.08238, 1808.08242]
- important for exotic searches which benefit from the large Hbb branching ratio



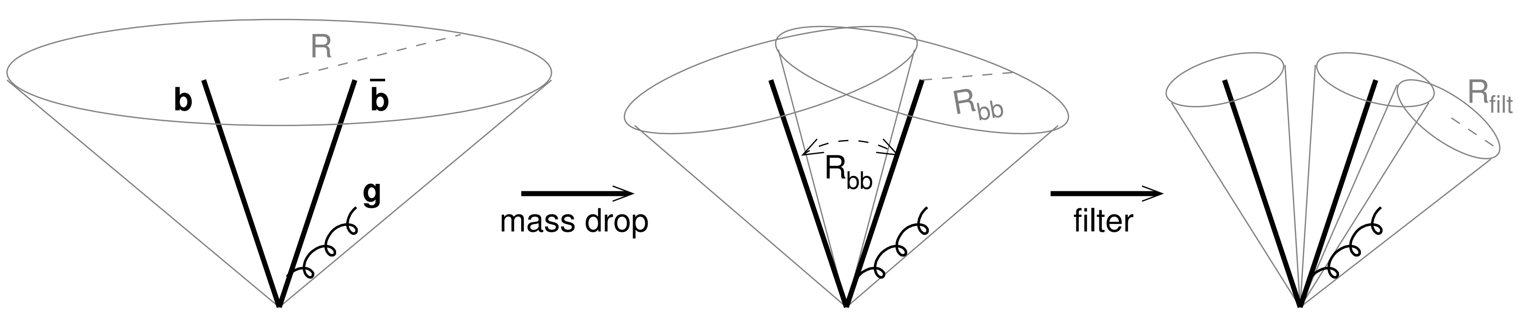
- NLO: solved a long time ago [Phys.Rev.D22(1980),715], …
  NNLO with mb=0: multiple results in the literature [1110.2368], [1501.07226], [1712.06954], [1907.05836]
  NNLO with finite mb: this talk… [1805.06658] and [1911.11524]
  N3LO: first results appearing [1904.08960]

Finding b-jets from Higgs decays

- b-quarks confined inside B-hadrons

- b-jets classified as decay products of the Higgs boson based on the jet properties (M_{bb}, ΔR_{bb}, …)

- sophisticated techniques developed to improve signal-to-background ratio
  eg. boosted region [Butterworth, Davison, Rubin, Salam, 0802.2470] and references thereto



- precise theoretical description might be helpful for sharpening various tools needed for precision Higgs phenomenology

NNLO+PS using MiNLO

[WB, E.Re, G.Zanderighi, 1912.09982]

NNLO+PS: why and how?

- what do we want?

  Goal 1: transition from limited multiplicity to a realistic picture of an event with O(100) particles in a final state
  Solution: a parton shower algorithm based on knowledge of soft/collinear QCD evolution

  Goal 2: improve accuracy of event generators
  Solution: include as much information as possible from higher-order perturbative QCD

- plan of action:

  1. construct an NLO-accurate Hbbg event generator in POWHEG
     (NLO description of exclusive bb+1jet observables)

  2. upgrade the Hbbg event generator with MiNLO
     (improve accuracy of the Sudakov form factor responsible for damping soft/collinear emissions,
     as a result all bb+0jet and bb+1jet observables are described with NLO accuracy)

  3. perform reweighting of events such that bb+0jet observables are NNLO accurate

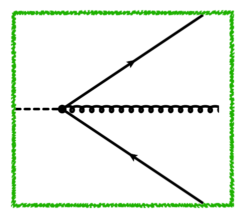
MiNLO: building a generator

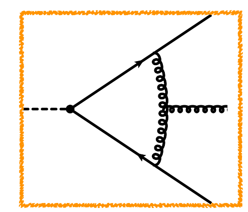
- for simplicity we work in the Higgs rest frame

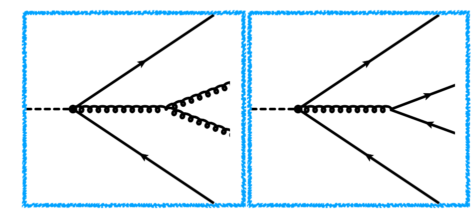
- the main POWHEG function that is being integrated is the B-bar function which contains all necessary ingredients

$$\bar{B}(\Phi_{bbg}) = \underline{\alpha_s(q_t^2)\Delta^2(y_3)}\left[\underline{B_{H\to bbg}}\cdot\left(1-2\Delta^{(1)}(y_3)\right)+\underline{V_{H\to bbg}}+\int d\Phi_r \underline{R_{H\to bbg}}\right]$$

Sudakov Form Factor



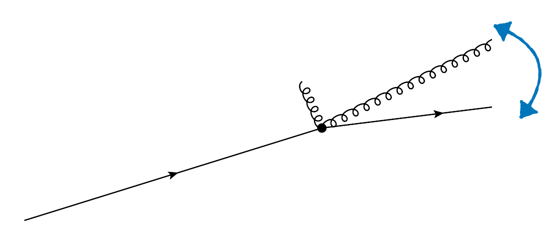




- MiNLO:
  - ☞ Sudakov FF needs to contain terms A_1, A_2, B_1, B_2
  - ☞ strong coupling should be evaluated at scale q_t

- y_3 = three-jet resolution parameter
  - ☞ separates between two- and three-jet configurations within a clustering algorithm
  - ☞ we use C/A algorithm for simplicity:

$$v_{ij} = 2(1-\cos\theta_{ij}) \qquad\qquad y_{ij} = v_{ij}\cdot\frac{\min(E_i,E_j)^2}{M_H^2}$$



  - ☞ configurations with small y_3 parameter are suppressed by vanishing Sudakov FF
  - ☞ NNLL resummation performed in [Banfi, McAslan, Monni, Zanderighi,1607.03111]

MiNLO: verification

- Hbbg_MiNLO generator constructed within POWHEG framework, upgraded with MiNLO
- Higgs decay → no partons in initial state → no PDFs required → we can perform small-α_s limit to verify an NLO accuracy of the Hbbg_MiNLO generator
- we consider the Hbb decay width and compare it with the analytical result

$$\delta(\alpha_s) \equiv \frac{1}{\alpha_s^2} \cdot \frac{\Gamma^{\mathtt{MiNLO}}_{H\to b\bar{b}} - \Gamma^{\mathrm{NLO}}_{H\to b\bar{b}}}{\Gamma^{\mathrm{LO}}_{H\to b\bar{b}}}$$

- if the Hbbg_MiNLO generator yields a correct NLO decay width, the difference should approach a constant in the small-α_s limit
- challenge: for small values of α_s the Sudakov peak moves to lower and lower y_3 values (calculation in quadruple precision required)
- all three curves approach constant value in the $\alpha_s \to 0$ limit
  ☞ the difference between MiNLO and NLO results is at most O(α_s^2)

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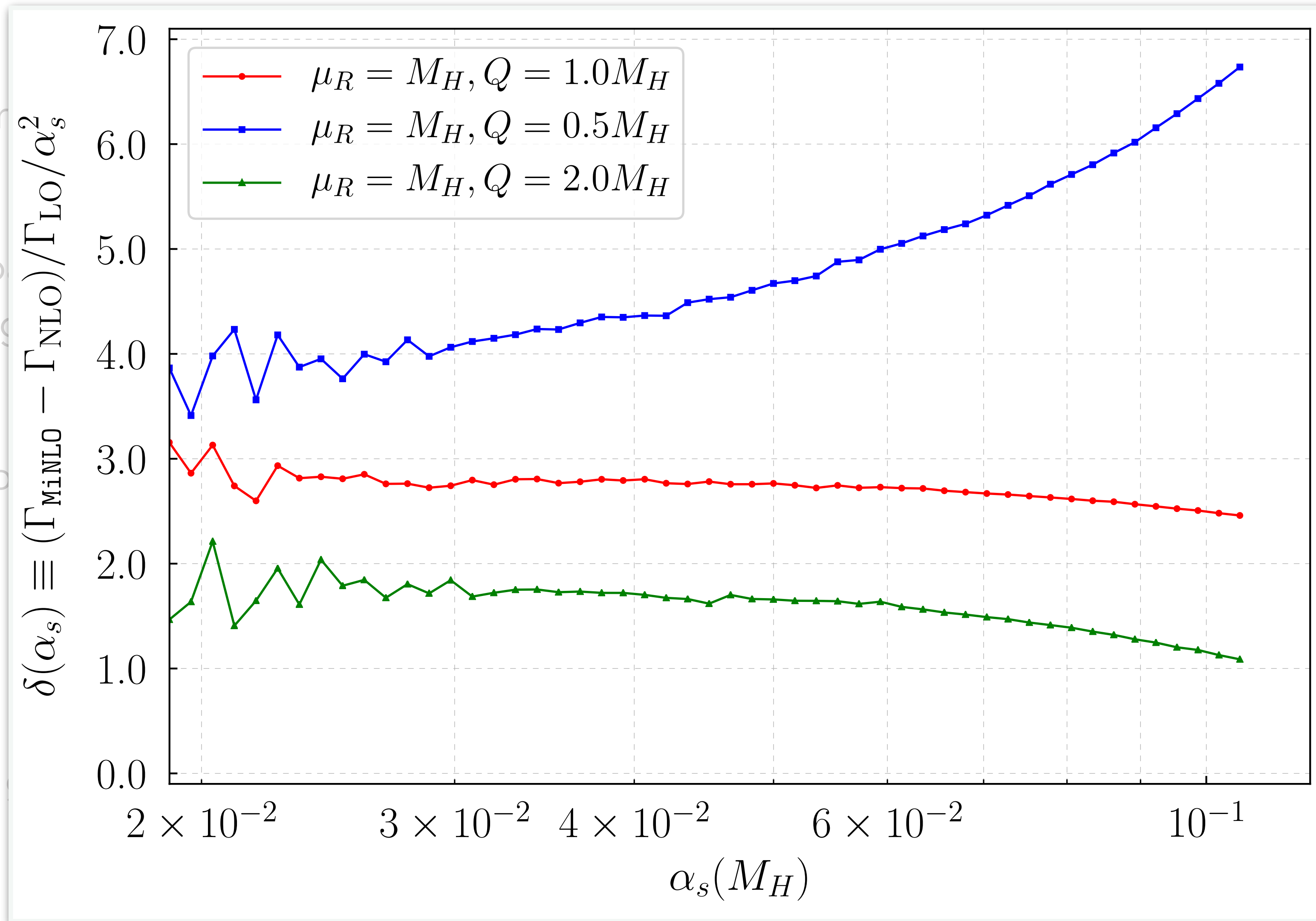

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NNLO+PS: reweighting

- the Hbbg_MiNLO results can be further improved to reproduce the exact NNLO decay width
  ☞ this can be achieved by reweighting the Hbbg_MiNLO events by a factor

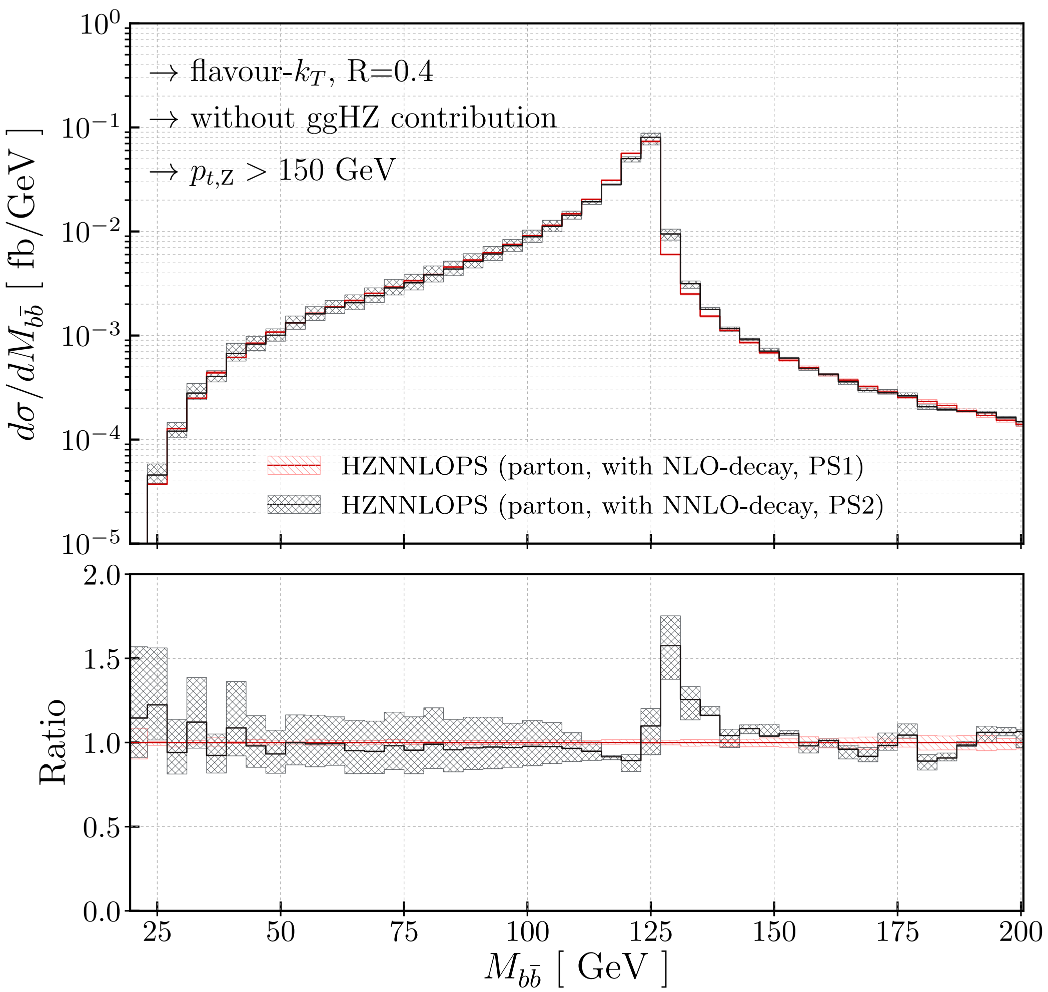
$$\mathcal{W} = \frac{\Gamma^{\mathrm{NNLO}}_{H\to b\bar{b}}}{\Gamma^{\mathtt{MiNLO}}_{H\to b\bar{b}}}$$

- the resulting events can be easily interfaced with any Higgs production mode

- the amalgamated events can be showered with a kt-ordered parton shower
  ☞ there are two veto scales (`scalup_prod` and `scalup_dec`)
  ☞ veto is separately applied to production and decay evolution

NNLO+PS: example

- example: decay events interfaced with associated Higgs production
  ☞ **pp → HZ → (bb)(e+e-) @13TeV**
- results compared to the ones presented in
  [Astill,WB,Re,Zanderighi, 1804.08141]
  ☞ production described at NNLO
  ☞ decay described at NLO(red) / NNLO(black)
- parton shower interface:
  ☞ PS1: whole production/decay event generated by POWHEG,
  single veto scale for production/decay
  ☞ PS2: production/decay separately generated,
  two veto scales (`scalup_prod` and `scalup_dec`)
- better scale uncertainty estimation by NNLO decay events (left of the Higgs boson peak)
- changes around the peak: related to b-quark mass
  ☞ NLO-decay: massive b-quarks
  ☞ NNLO-decay: massless b-quarks



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  ☞ production described at NNLO

  ☞ decay described at NLO(red) / NNLO(black)

- parton shower interface:
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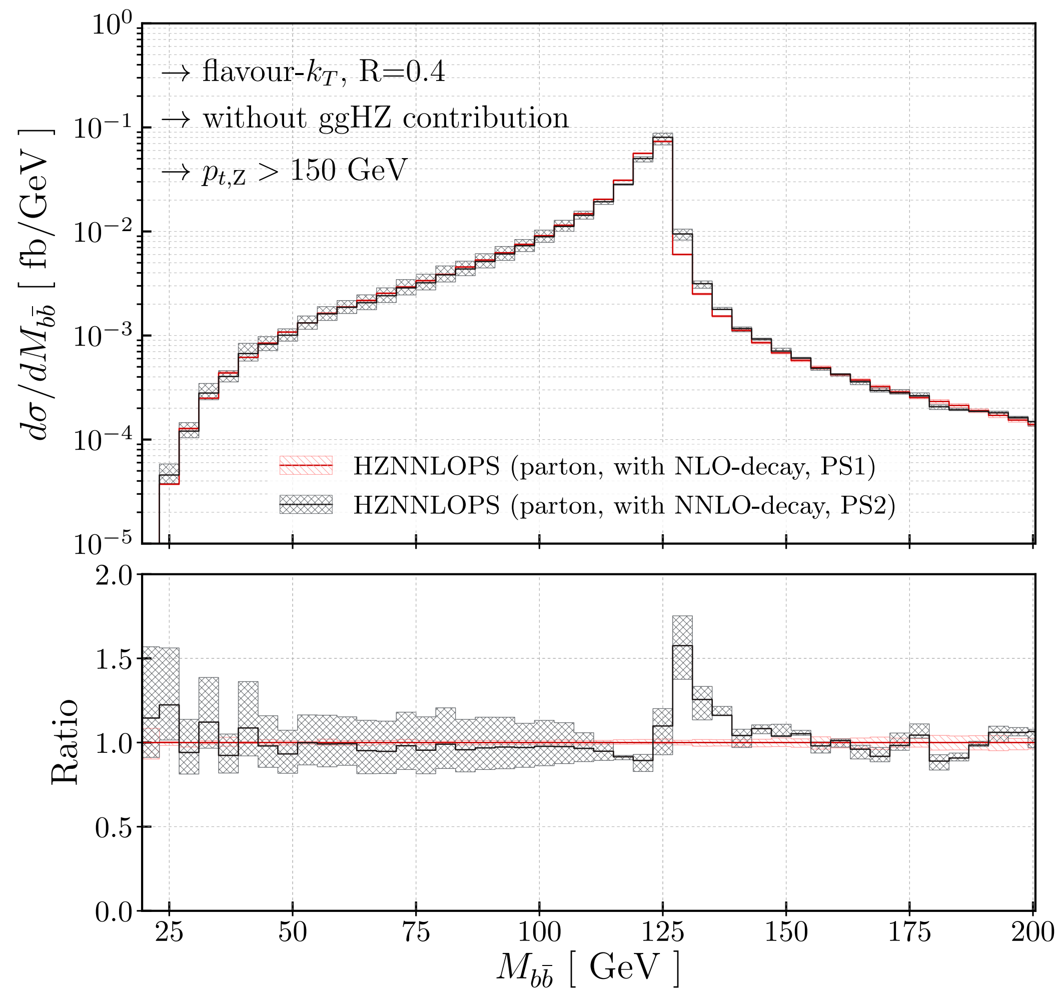

☞ `h_bbg` process available in POWHEG-BOX-V2

☞ 60M ready to use decay events available at https://cernbox.cern.ch/index.php/s/v1qxYyICeL66InO

NNLO+PS using MiNLO

NNLO with massive b-quarks

[A.Behring, WB, 1911.11524]

Overview

- need of high-precision Standard Model predictions requires consideration of many effects: masses of b-quarks [Bernreuther, Chen, Si, 1805.06658] and [Behring, WB, 1911.11524]

- structure of an NNLO calculation:
  - ☞ **double-virtual corrections (VV):** two-loop H→bb amplitudes, explicit 1/ϵ poles ← VV obtained using heavy-quark form factor [Bernreuther et al., hep-ph/0508254] [Ablinger et al., 1712.09889]
  - ☞ **real-virtual corrections (RV):** one-loop H→bbg amplitudes, explicit 1/ϵ poles, divergences in soft limit
  - ☞ **double-real corrections (RR):** tree-level H→bb{gg,qq} amplitudes, divergences in soft/collinear limits

- soft/collinear divergences regulated using **nested soft-collinear subtraction scheme**

- additionally:
  - ☞ **four b-quarks contribution:** tree-level H→bbbb, UV&IR finite
  - ☞ **top-quark mediated contribution:** two-loop H→bb(y_t) and one-loop H→bbg(y_t), UV&IR finite

approx. tot. dec: [Chetyrkin,Kwiatkowski, hep-ph/9505358] & [Larin,Ritbergen,Vermaseren, hep-ph/9506465]
exact & differential: [Primo,Sasso,Somogyi,Tramontano, 1812.07811]

Soft/collinear divergences

- singularities of QCD amplitudes in soft/collinear limits are **generic and independent of a hard process**
- soft/collinear divergences in **RR** and **RV** contributions:
  - ☞ RV, single-soft: H→bb(g)
  - ☞ RR, single-soft: H→bbg(g)
  - ☞ RR, single-coll: H→bb[gg]
  - ☞ RR, double-soft: H→bb(gg) & H→bb(qq)
- **nested soft-collinear subtractions**
  - ☞ the real-virtual case H(q₁) ⟶ b(q₂) + b(q₃) + g(q₄) @one-loop is regulated then as

$$2\mathrm{Re}\langle\mathcal{M}^{(0)}_{bbg}|\mathcal{M}^{(1)}_{bbg}\rangle \mathrm{d}\Phi_{bbg} = \Big[(I-S_4)+S_4\Big]2\mathrm{Re}\langle\mathcal{M}^{(0)}_{bbg}|\mathcal{M}^{(1)}_{bbg}\rangle \mathrm{d}\Phi_{bbg}$$

  - ☞ the double-real case $H(q_1) \longrightarrow b(q_2) + b(q_3) + g(q_4) + g(q_5)$ is regulated then as

$$F_{LM}(bbgg) = (I-S_5)(I-S_{45})(I-C_{45})F_{LM}(bbgg)$$ ← fully-regulated term

$$+\Big[S_5(I-S_{45})(I-C_{45})+(I-S_5)(I-S_{45})C_{45}+S_5(I-S_{45})C_{45}\Big]F_{LM}(bbg)[dg_5]$$ ← single-unresolved term

$$+S_{45}F_{LM}(bb)[dg_4][dg_5]$$ ← double-unresolved term

with $F_{LM}(bbX) = \mathrm{d}\Phi_{bbX}\,|\mathcal{M}^{\mathrm{tree}}_{bbX}|^2\,\mathcal{F}_{\mathrm{obs}}(bbX)$

the $[dg_i]$ being the usual real-emission phase-space and ***S***,***C*** denoting the soft/collinear operators

- single- and double-unresolved terms feature 1/ϵ poles that appear after integration over the unresolved phase space ☞ **next slide**

Integrated subtraction terms: RR

- RR, single-unresolved subtraction terms:
  - ☞ computed long time ago as part of the FKS subtraction scheme at NLO

    compendium of formulae: [Alioli,Nason,Oleari,Re,1002.2581]

- RR, double-unresolved subtraction terms:
  - ☞ factorisation formula

$$S_{45}|\mathcal{M}^{\rm tree}_{bbgg}|^2 = g_s^4\,{\rm DSoft}^{(0)}_{gg}(q_2,q_3;q_4,q_5)\,|\mathcal{M}^{\rm tree}_{bb}|^2$$

  - ☞ split phase space into energy ordered configurations: $1 == \Theta(E_4 - E_5) + \Theta(E_5 - E_4)$
  - ☞ in the double-soft limit momenta q_2 and q_3 are in back-to-back configuration
  - ☞ the integrated double-soft subtraction term is (integrated numerically)

$$\begin{aligned}{\rm DSoft}^{(0)}_{gg,{\rm int}}(q_2,q_3) &= \int [dg_4][dg_5]\,{\rm DSoft}^{(0)}_{gg}(q_2,q_3;q_4,q_5)\\ &= \frac{1}{(4\pi)^2}\left(\frac{\mu_R}{E_{\rm max}}\right)^{4\epsilon}\left[\frac{C^{(-3)}_{gg}}{\epsilon^3}+\frac{C^{(-2)}_{gg}}{\epsilon^2}+\frac{C^{(-1)}_{gg}}{\epsilon}+C^{(0)}_{gg}\right]\end{aligned}$$

with $E_{max} = (M_H^2 - 4m_b^2)/2$

Integrated subtraction terms: RV

- soft-limit of one-loop amplitudes with massive quarks studied previously [Mitov,Moch, hep-ph/0612149] and [Bierenbaum,Czakon,Mitov, 1107.4384]

eikonal-factors

$$S_{ij,k} = \frac{(q_i \cdot q_j)}{(q_i \cdot q_k)(q_j \cdot q_k)}$$

$$S_4 2\mathrm{Re}\langle \mathcal{M}^{(0)}_{bbg} | \mathcal{M}^{(1)}_{bbg} \rangle = -\, g_s^2 C_F \left(S^{(0)}_{22,4} = 2S^{(0)}_{23,4} + S^{(0)}_{33,4} \right) \times \left[2\mathrm{Re}\langle \mathcal{M}^{(0)}_{bb} | \mathcal{M}^{(1)}_{bb} \rangle + \left(\underbrace{\mathcal{R}^{(1)}_{23,4}}_{\text{one-loop soft function}} + \underbrace{Z^{(1)}_{\alpha_s} + Z^{(1)}_{A}}_{\text{renormalisation constants}} \right) |\mathcal{M}^{(0)}_{bb}|^2 \right]$$

- in the soft limit momenta q_2 and q_3 are in back-to-back configuration

- **one-loop soft function:** the integration over soft-gluon phase space reduces to
  - ☞ an energy integral (dE_4): overall scaling only → trivial integration
  - ☞ angular integral ($d(cos\theta)$):
    - ✔ (a) numerically very simple
    - ✔ (b) performed also analytically, result in terms of HPLs [using Mathematica, HarmonicSums]

Pole cancellation

- integrated subtraction terms allow to trade soft/collinear divergences for 1/ϵ poles
- since singularities of QCD amplitudes in soft/collinear limits are generic and independent of a hard process, pole cancellation can be demonstrated without referring to exact form of matrix elements
- single-unresolved configuration (RR + RV)

$$\mathrm{d}\Gamma^{\mathrm{SU}}_{\mathrm{RR}}(bbgg+bbqq)+\mathrm{d}\Gamma^{\mathrm{SU}}_{\mathrm{RV}}(bbg)=\left[\frac{\#}{\epsilon^2}+\frac{\#}{\epsilon}+\cdots\right](I-S_4)F_{LM}(bbg)$$

$$F_{LM}(bbg)=\mathrm{d}\Phi_{bbg}\,|\mathcal{M}^{(0)}_{bbg}|^2\,\mathcal{F}_{\mathrm{obs}}(bbg)$$

☞ **cancellation shown analytically**

- fully-unresolved configuration (RR + RV + VV)

(a) part proportional to one-loop H→bb matrix element

$$\mathrm{d}\Gamma^{\mathrm{FR}}_{\mathrm{RV}}(bbg)+\mathrm{d}\Gamma^{\mathrm{FR}}_{\mathrm{VV}}(bb)=\left[\frac{\#}{\epsilon}+\cdots\right]F^{\mathrm{fin}}_{LV}(bb)$$

$$F^{\mathrm{fin}}_{LV}(bb)=\mathrm{d}\Phi_{bb}\,2\mathrm{Re}\langle\mathcal{M}^{(0)}_{bb}|\mathcal{M}^{(1)}_{bb}\rangle\,\mathcal{F}_{\mathrm{obs}}(bb)$$

☞ **cancellation shown analytically**

(b) part proportional to tree-level H→bb matrix element

$$\mathrm{d}\Gamma^{\mathrm{DU}}_{\mathrm{RR+RV+VV}}=\left[\frac{\#}{\epsilon^3}+\frac{\#}{\epsilon^2}+\frac{\#}{\epsilon}+\cdots\right]F_{LM}(bb)$$

☞ **cancellation shown numerically** (since integrated double-soft function computed only numerically)

Results: verification

- approximate analytical result in heavy-scalar decay into quark-antiquark pair
  [Harlander, Steinhauser, hep-ph/9704436]

- expand the NNLO width as

$$\Gamma^{\mathrm{NNLO}}_{H\to b\bar{b}} = \Gamma^{\mathrm{LO}}_{H\to b\bar{b}} \cdot \left[1 + \left(\frac{\alpha_s}{\pi}\right)\gamma_1 + \left(\frac{\alpha_s}{\pi}\right)^2 \gamma_2\right]$$

  with further breakdown into colour structures

$$\gamma_1 = C_F \cdot \gamma_1^{C_F}$$
$$\gamma_2 = C_F^2 \cdot \gamma_2^{C_F^2} + C_F C_A \cdot \gamma_2^{C_F C_A} + C_F T_F n_l \cdot \gamma_2^{C_F T_F n_l} + C_F T_F \cdot \gamma_2^{C_F T_F}$$

- compare our result to analytical prediction (MH=125.09 GeV, mb=4.78 GeV)

	$\gamma_1^{C_F}$	$\gamma_2^{C_F^2}$	$\gamma_2^{C_F C_A}$	$\gamma_2^{C_F T_F n_l}$	$\gamma_2^{C_F T_F}$
HS '97	-7.446648	$+19.4192$	-53.5558	$+18.6286$	$+14.7946$
Our result	$-7.446648(7)$	$+19.4199(10)$	$-53.5557(20)$	$+18.6283(2)$	$+14.7945(1)$

- very good agreement down to a few digits (thanks to mb/MH << 1)

Summary

- $H \to bb$ decay process is an important channel that is already being explored at the LHC, measurements during the HL-LHC programme will offer many more $H \to bb$ events

- full exploitation of such data will benefit from better theoretical understanding

- NNLO QCD calculation of the $H \to bb$ decay successfully combined with parton shower (massless b-quarks)
  ☞ tool available in the POWHEG repository of processes (`h_bbg` process)

- calculation of b-quark mass effects at NNLO QCD completed within the nested soft-collinear subtraction scheme

- good position to perform thorough phenomenological studies…

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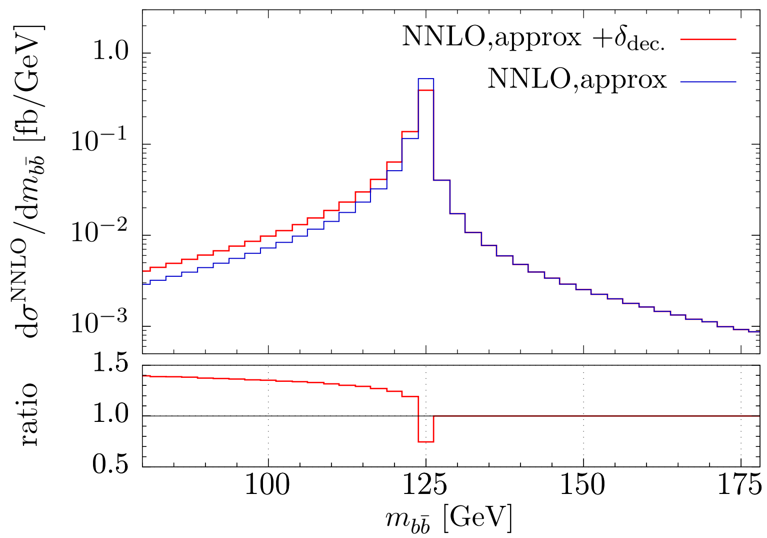
THANK YOU!

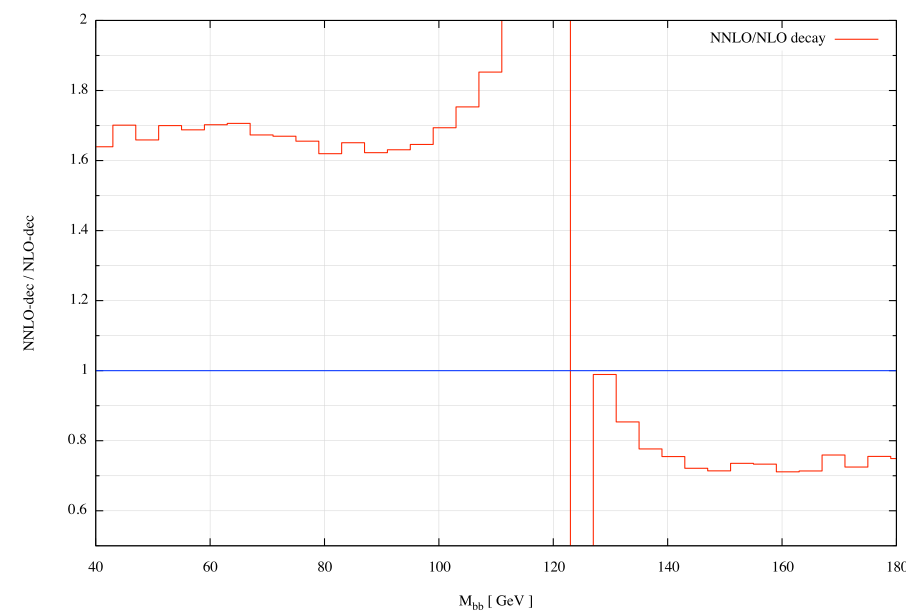
Backup

[WB,Re,Zanderighi, 1912.09982]

NNLO+PS: M_{bb}

- invariant mass of the b-jets (M_{bb})
- NNLO/NLO K-factor agrees with fixed-order predictions





Plot for HW production
[Caola,Luisoni,Melnikov,Rontsch, 1712.06954]

[A.Behring, WB, 1911.11524]

NNLO: Pole cancellation (1)

- single-unresolved

$$2M_H \langle \mathrm{d}\Gamma^{\mathrm{FR}}_{\mathrm{RV}}(b\bar{b}g)\rangle = \frac{1}{\epsilon}\left[\left(\frac{\alpha_s}{4\pi}\right) 4C_F \left[1+\frac{1+\beta^2}{2\beta}\log\left(\frac{1-\beta}{1+\beta}\right)\right]\langle F^{\mathrm{fin}}_{LV}(b\bar{b})\rangle\right] + \mathcal{O}\left(\epsilon^0\right) , \tag{4.22}$$

and the explicit expansion of the double-virtual contribution, Eq. (4.20), yields

$$2M_H \langle \mathrm{d}\Gamma^{\mathrm{FR}}_{\mathrm{VV}}(b\bar{b})\rangle = -\frac{1}{\epsilon}\left[\left(\frac{\alpha_s}{4\pi}\right) 4C_F \left[1+\frac{1+\beta^2}{2\beta}\log\left(\frac{1-\beta}{1+\beta}\right)\right]\langle F^{\mathrm{fin}}_{LV}(b\bar{b})\rangle\right] , \tag{4.23}$$

- fully-unresolved (proportional to one-loop H→bb matrix element)

$$\begin{aligned} &2M_H \langle \mathrm{d}\Gamma^{\mathrm{SU}}_{\mathrm{RR}}(b\bar{b}gg + b\bar{b}q\bar{q})\rangle \\ &= \left\langle \left(\frac{\alpha_s}{4\pi}\right)\left[\frac{2C_A}{\epsilon^2} + \frac{1}{\epsilon}\left[4C_F + \beta_0(n_l) + \frac{C_A - 2C_F}{v_{23}}\log\left(\frac{1+v_{23}}{1-v_{23}}\right)\right.\right.\right. \\ &\quad \left.\left.\left. + 2C_A\log\left(\frac{m_b\mu_R}{2(q_2\cdot q_4)}\right) + 2C_A\log\left(\frac{m_b\mu_R}{2(q_3\cdot q_4)}\right)\right]\right](I-S_4)F_{LM}(b\bar{b}g)\right\rangle + \mathcal{O}\left(\epsilon^0\right) . \end{aligned} \tag{4.24}$$

A similar expansion holds for the real-virtual single-unresolved contribution, Eq. (4.14),

$$\begin{aligned} &2M_H \langle \mathrm{d}\Gamma^{\mathrm{SU}}_{\mathrm{RV}}(b\bar{b}g)\rangle \\ &= \left\langle \left(\frac{\alpha_s}{4\pi}\right)\left[-\frac{2C_A}{\epsilon^2} - \frac{1}{\epsilon}\left[4C_F + \beta_0(n_l) + \frac{C_A - 2C_F}{v_{23}}\log\left(\frac{1+v_{23}}{1-v_{23}}\right)\right.\right.\right. \\ &\quad \left.\left.\left. + 2C_A\log\left(\frac{m_b\mu_R}{2(q_2\cdot q_4)}\right) + 2C_A\log\left(\frac{m_b\mu_R}{2(q_3\cdot q_4)}\right)\right]\right](I-S_4)F_{LM}(b\bar{b}g)\right\rangle . \end{aligned} \tag{4.25}$$

[A.Behring, WB, 1911.11524]

NNLO: Pole cancellation (2)

- fully-unresolved (proportional to one-loop H→bb matrix element)
  ☞ cancellation of at least 7-digits

	$\mathcal{C}^{\mathrm{DU},(-3)}_{C_F C_A}$	$\mathcal{C}^{\mathrm{DU},(-2)}_{C_F C_A}$	$\mathcal{C}^{\mathrm{DU},(-2)}_{C_F^2}$	$\mathcal{C}^{\mathrm{DU},(-2)}_{C_F T_F n_l}$	$\mathcal{C}^{\mathrm{DU},(-1)}_{C_F C_A}$	$\mathcal{C}^{\mathrm{DU},(-1)}_{C_F^2}$	$\mathcal{C}^{\mathrm{DU},(-1)}_{C_F T_F n_l}$	$\mathcal{C}^{\mathrm{DU},(-1)}_{C_F T_F}$
RR	-22.11	-279.75	$+244.32$	$+14.74$	-1777.55	$+2672.58$	$+185.77$	0
RV	$+22.11$	$+320.28$	-488.64	-29.47	$+1732.44$	-2672.58	-161.20	$+257.20$
VV	0	-40.53	$+244.32$	$+14.74$	$+45.11$	0	-24.56	-257.20
Sum	10^{-13}	10^{-10}	10^{-8}	10^{-11}	10^{-6}	10^{-6}	10^{-5}	0
Rel. canc.	10^{-14}	10^{-13}	10^{-11}	10^{-13}	10^{-10}	10^{-9}	10^{-7}	0

Table 1: Numerical values of the pole coefficients of the double-unresovled term as defined in Eq. (4.27). The numerical values correspond to $m_b = 4.78$ GeV, $M_H = 125.09$ GeV and the renormalisation scale is $\mu_R = 3M_H$. Each column corresponds to a particular colour structure of a given ϵ pole. The three rows correspond to the double-real, real-virtual, and double-virtual contributions. In the last two rows, we report the absolute and relative level of cancellation after adding up RR + RV + VV contributions. The last row is normalised to the largest value of each column.

[A.Behring, WB, 1911.11524]

NNLO: Results

- Expansion coefficients and H→bb decay width in the MS-bar scheme

μ_R	$\frac{1}{2}M_H$	M_H	$2M_H$
$\overline{\gamma}_1^{b\bar{b}}$ (our res.)	+3.023597(10)	+5.796203(15)	+8.568783(11)
$\overline{\gamma}_1^{b\bar{b}}$ (Ref. [20])	+3.024	+5.798	+8.569
$\overline{\gamma}_1^{b\bar{b}}$ (Ref. [71], $m_b = 0$)	+2.8941	+5.6667	+8.4393
$\overline{\gamma}_2^{b\bar{b}}$ (our res., w/o $y_b y_t$)	−3.2466(31)	+30.4376(33)	+79.1755(38)
$\overline{\gamma}_2^{b\bar{b}}$ (our res., with $y_b y_t$)	+3.7123(31)	+37.3965(33)	+86.1345(38)
$\overline{\gamma}_2^{b\bar{b}}$ (Ref. [20], with $y_b y_t$)	+3.685	+37.371	+86.112
$\overline{\gamma}_2^{b\bar{b}}$ (Ref. [71], $m_b = 0$)	−3.8368	+29.1467	+77.1844
$\overline{\Gamma}_{\mathrm{LO}}^{b\bar{b}}$ [MeV]	+2.17005	+1.92702	+1.73274
$\overline{\Gamma}_{\mathrm{NLO}}^{b\bar{b}}$ [MeV]	+2.43161	+2.32781	+2.21731
$\overline{\Gamma}_{\mathrm{NNLO}}^{b\bar{b}}$ [MeV] (w/o $y_b y_t$)	+2.42041(1)	+2.40333(1)	+2.36344(1)
$\overline{\Gamma}_{\mathrm{NNLO}}^{b\bar{b}}$ [MeV] (with $y_b y_t$)	+2.44441(1)	+2.42059(1)	+2.37628(1)

Table 3: The results for the LO, NLO and NNLO total decay width. The total width is calculated using our results for the expansion coefficients, $\overline{\gamma}_1^{b\bar{b}}$ and $\overline{\gamma}_2^{b\bar{b}}$. For comparison we include corresponding results from Ref. [20]. We also provide results in the limit of massless b-quarks from Ref. [71], which do not contain the $y_b y_t$ contribution. The uncertainties quoted for our results correspond to errors from numerical integration.