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Precise predictions for Higgsstrahlung at future colliders

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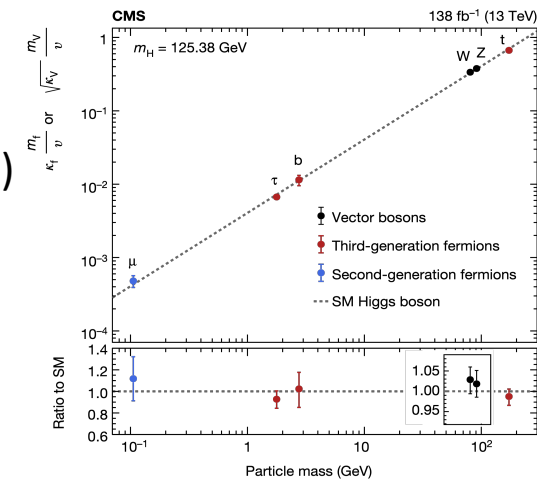
Outline

- Introduction: Precision Higgs physics
- Part I: Higgsstrahlung at hadron colliders: LHC and HL-LHC
 - WH@N³LO [M. Marcoli et al; 2606.31286]
- Part II: Higgsstrahlung at FCC-ee
 - Jet rates and event shapes: Hadronic Higgs decays
[E. Fox et al; 2502.17333, 2508.14282]
 - jet observables in ZH@NNLO
[S. Caletti et al; 2510.20485]
- Summary and outlook

Introduction: Precision Higgs Physics

- Higgs boson H: prediction of Brout-Englert-Higgs mechanism (1964, Nobel Prize 2013)
- Discovered in 2012 in the $H \rightarrow \gamma\gamma$ channel [ATLAS: 1207.7214, CMS:1207.7235]
- Present LHC data compatible with a scalar and even parity particle of mass $m_H \sim 125.2 \text{ GeV}$, as predicted by the Standard Model (SM)
- Couplings
 - fermions (f): $g_{Hff} \sim m_f/v$ (largest for top-quarks)
 - EW gauge bosons (V): $g_{HVV} \sim m_V^2/v^2$ (no direct γ -coupling)
 - Higgs (H): $g_{HHH} \sim m_H^2/v$, $g_{HHHH} \sim m_H^2/v$ (Ultimate test of Higgs mechanism)
- Couplings probed in multiple Higgs production or decay modes
- No deviation from SM predictions observed so far at LHC

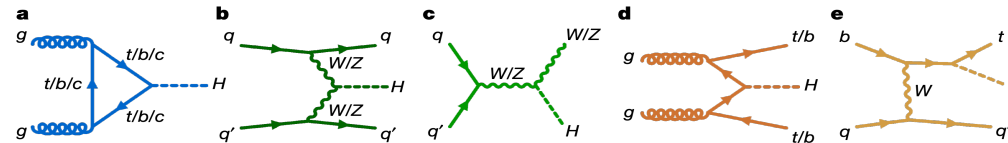
CMS Nature (2022)
2207.00043



Part I : Higgsstrahlung at hadron colliders

Higgs production at hadron colliders

- Production modes:



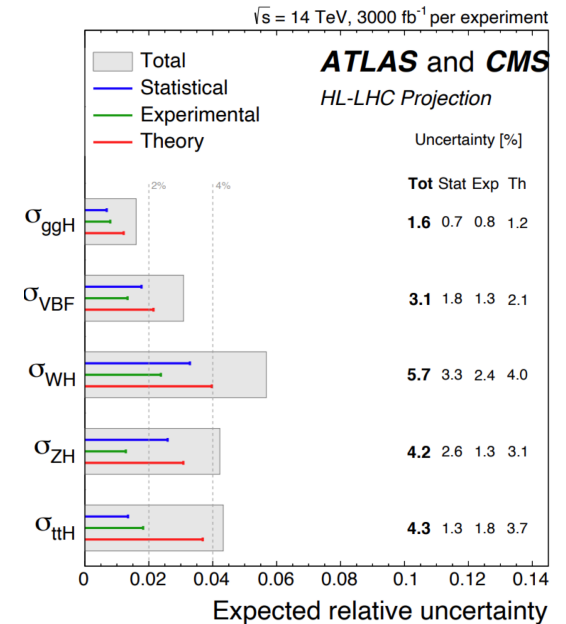
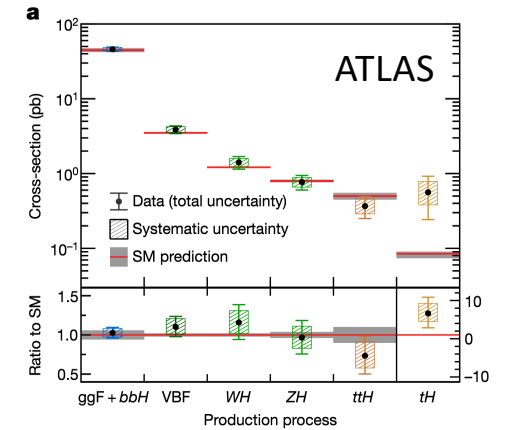
- Present: Good agreement between theory and experiment

[ATLAS Nature (2022): 2207.00092; theory: Higgs Working Group 1610.07922]

- Future: HL-LHC experimental precision on production channels expected to go down to O(2%) [HL-LHC report 1902.00134]

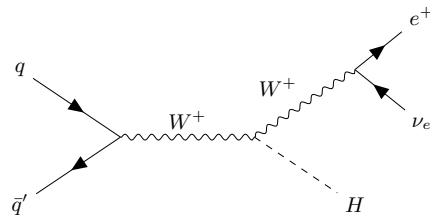
- Close interplay experiment – theory needed for coupling determinations
 - Require precise theory with higher orders in QCD and full event properties

- Focus: Higgs-strahlung off a W-boson at large transverse momentum
 - High p_T kinematics: enhanced sensitivity to HWW coupling at HL-LHC

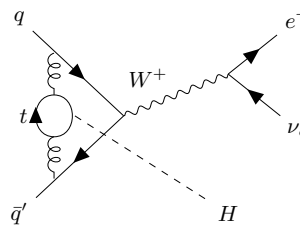


WH production: Theory status beyond NNLO

- WH production related to $pp \rightarrow W^+(\rightarrow e^+\nu_e)H$ with on-shell Higgs
- Total cross section known up to N^3 LO [J.Baglio et al; 2209.06138] (DY: H couples to off shell W only)
- Differential cross sections known up to NNLO
[G. Ferrera et al; 1705.10304, F. Caola et al; 1712.06554, R. Gauld et al; 1907.05836]
- Two separate Higgs production categories at order α_s^2



Higgsstrahlung at Born level:
Higgs couples to off-shell W



$O(y_t)$ qq induced top-quark-loop:
contributions at $O(\alpha_s^2)$ are UV and IR finite

WH@N³LO : Methodology

- Fiducial N³LO obtained from NNLO : using q_T slicing [S. Catani et al; 0703012]

$$d\sigma = \int_{q_T < q_T^{\text{cut}}} d\sigma^{\text{singular}} + \int_{q_T > q_T^{\text{cut}}} d\sigma^{\text{regular}} \quad q_T^{\text{cut}} \text{ applied on } q_T \text{ of colour-singlet system (WH)}$$

- $d\sigma^{\text{singular}}$: N³LO expansion of transverse momentum resummation:

Code: **RadISH** [P. Monni et al; 1604.02191, 1705.09127]

- $d\sigma^{\text{regular}}$: higher multiplicity fixed order computation: WH +Jet @NNLO
[R. Gauld et al; 2009.14209, 2110.12992]

Code: **NNLOJET** [A. Huss et al; 2503.22804]

- Slicing procedure only applied @ N³LO:

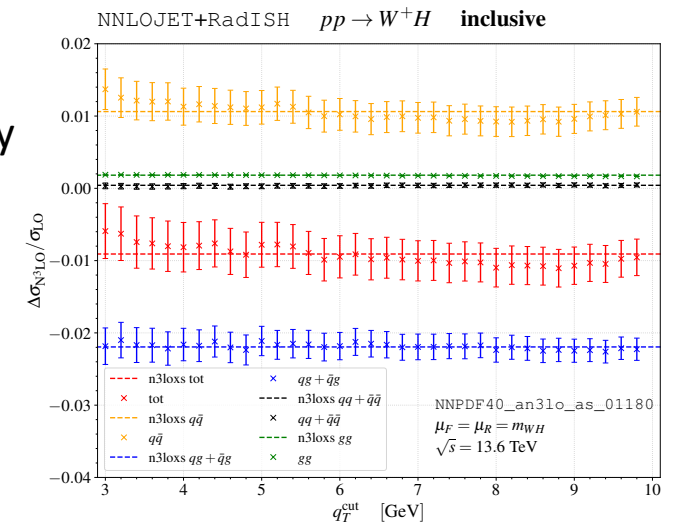
- Up to NNLO: use fixed order WH computation (both Higgs categories)

[R. Gauld et al; 1907.05836] (NNLOJET)

- Same strategy applied for fiducial Drell-Yan @N³LO [X. Chen et al; 2203.01565]

Validation: Inclusive $W^+ H$ production

- Testing slicing procedure for on-shell W^+
Compare N³LO corrections with **n3loxs** [J.Baglio et al; 2209.06138]
 - Finding excellent agreement for all partonic channels individually
- Allow to identify the optimal range for q_T^{cut} values:
Result stable for $3 \text{ GeV} < q_T^{\text{cut}} < 10 \text{ GeV}$
 - choose $q_T^{\text{cut}} = 5 \text{ GeV}$ avoiding instabilities
for above-cut computation: VH +jet @NNLO (**NNLOJET**)



Fiducial cross sections: boosted Higgs

- Corrections up to N³LO

- Quantify uncertainty through 7-point scale variation for central scale : $\mu_R=\mu_F=M_{\text{HW}}$
- up to NNLO: poor perturbative convergence
- at N³LO: +1.5% increase within NNLO uncertainty
- N³LO result with residual scale uncertainty below 1%

- Result at N³LO with fiducial cuts

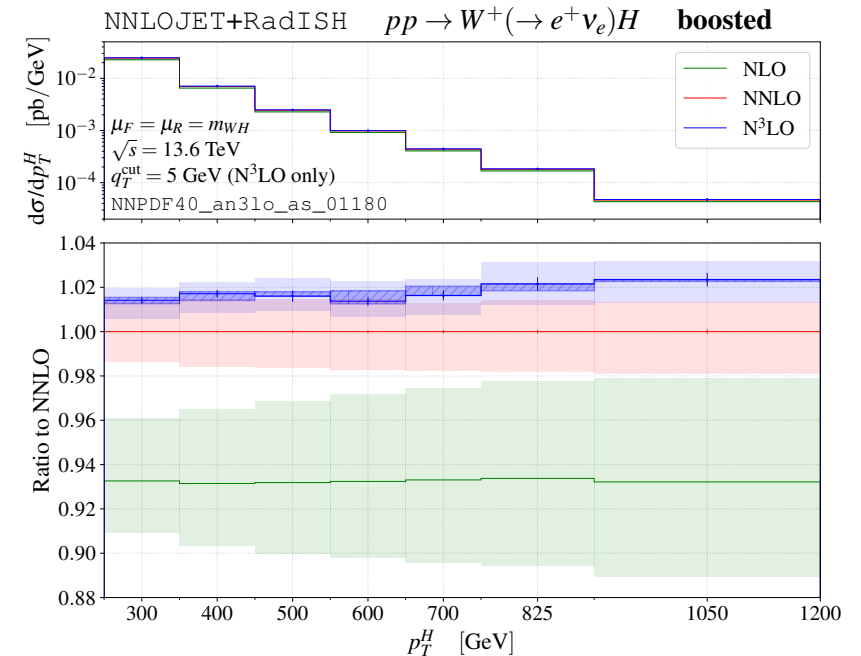
- can not be inferred from inclusive case [J.Baglio et al; 2209.06138]
- Inclusive N³LO corrections are negative (-1%) and show no reduction in the scale uncertainty wrt. to NNLO

σ [pb]	Boosted
	$p_T^H \geq 250$ GeV
LO	$2.457^{+2.5\%}_{-2.5\%}$
NLO	$3.324^{+3.3\%}_{-2.8\%}$
NNLO	$3.564^{+1.4\%}_{-1.4\%}$
N ³ LO	$(3.62 \pm 0.01)^{+0.5\%}_{-0.8\%}$

p_T^H spectrum : Boosted Higgs

- Size of N³LO corrections

- Increase over NNLO result : +1.5%-2%
- stable for whole p_T^H range
- residual scale uncertainty at N³LO
 - 1% for $p_T^H \cong 300$ GeV and up to 2% in the tail
- slicing cut variation: Excellent numerical control
 - uncertainty band (dark blue) with ($4\text{GeV} < q_T^{\text{cut}} < 6\text{GeV}$) considerably smaller than scale uncertainty band



Part II: Higgs strahlung at FCC-ee: $e^+e^- \rightarrow ZH$

Higgs-strahlung at FCC-ee

- FCC-ee: Higgs factory at ZH production threshold

expect: $O(10^6)$ events at $\sqrt{s}=240$ GeV

- Number of Higgs bosons produced: comparable to the number of Z-bosons at LEP

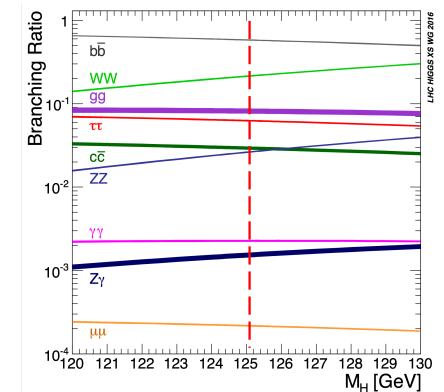
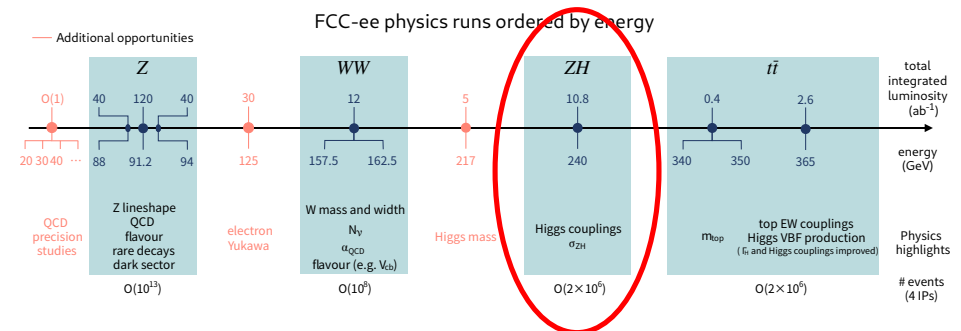
- $e^+e^- \rightarrow ZH$ (leptonic Z-decays): Ideal for precision studies of Higgs properties and couplings

- clean environment : free from QCD initial state radiation
- New at FCC-ee: Expect model-independent Higgs couplings @per-mille level

- Require precise theory

- computations in perturbative QCD with higher order corrections
- Focus on jet observables in ZH for dominant hadronic decay channels

$H \rightarrow bb$ (or: $H \rightarrow cc$) and $H \rightarrow gg$



Hadronic Higgs decay observables: Theory status beyond NLO

- Inclusive branching fractions: known analytically @N⁴LO

[F.Herzog et al; 1707.01044]

- $H \rightarrow bb$ for $m_q=0$ (except in y_b)
- $H \rightarrow gg$ in EFT with infinite top mass limit

- Exclusive observables in the Higgs rest-frame

- Jet rates: ($H \rightarrow bb$ decay mode)
 - $H \rightarrow bb$: known @N³LO [R.Mondini et al; 1904.08960] (MCFM)
 - $H \rightarrow bb + \text{jet}$: known @NNLO [R.Mondini et al; 1904.08961] (MCFM)
- Jet rates and event-shapes @NNLO for $H \rightarrow bb + \text{jet}$ and $H \rightarrow gg + \text{jet}$
[E.Fox et al; 2502.17333, 2508.14282] (NNLOJET)

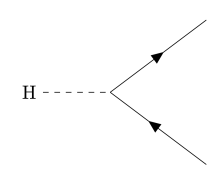
- Here: NNLO jet observables in $e^+e^- \rightarrow ZH \rightarrow l^+l^- bb (gg)$ at $\sqrt{s}=240$ GeV

- in the collider frame: with $H \rightarrow 2$ jets (boosted kinematics for final states)
- new implementation in parton-level event generator: (NNLOJET)

Hadronic Higgs decays: Main modes

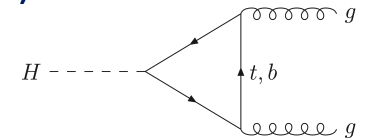
- $H \rightarrow b\bar{b}$: main Higgs decay channel

- essential for precise determination of Γ_H
- already accessible at LHC via ZH production and leptonic Z-decay
- direct (Yukawa induced) coupling at α_s^0 : $y_b(\mu_R) = \sqrt{2}m_b(\mu_R)/v$



- $H \rightarrow gg$: accessible only at lepton colliders (fixed energy, low QCD background)

- no direct coupling: loop induced coupling at α_s^1



- Both processes included in NNLOJET using $\mathcal{L}_{\text{Higgs}} = -\frac{\lambda(M_t, \mu_R)}{4} H G_{\mu\nu}^a G^{a, \mu\nu} + \frac{y_b(\mu_R)}{\sqrt{2}} H \bar{\psi}_b \psi_b$

- with $H \rightarrow gg$ decay computed in HEFT with an effective Hgg coupling:
 - top quark Wilson coefficient $C(M_t)$ known to four-loops

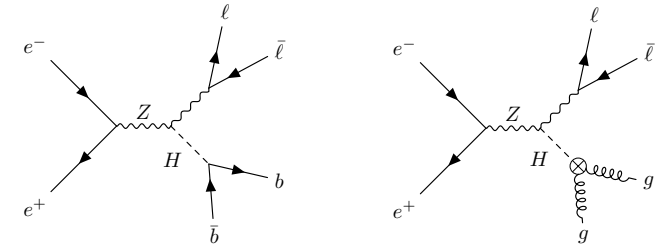
- no interference between both categories for $m_q=0$ (except in y_b)

$$\lambda(M_t, \mu_R) = -\frac{\alpha_S(\mu_R) C(M_t, \mu_R)}{3\pi v}$$

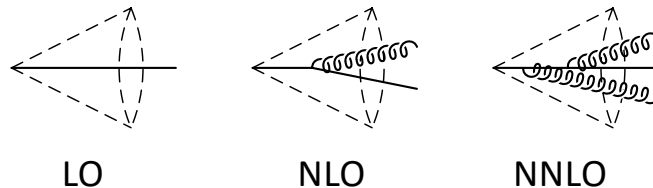
Jet observables: Higgsstrahlung off a Z-boson

- Cross section in factorised form

$$d\sigma_X^{\text{N}^k\text{LO}} = \sum_{i=0}^k \int dq^2 d\sigma_{ZH} \times \frac{1}{(q^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} \times d\Gamma_{H \rightarrow X}^{(i)}, \quad \text{with } X = b\bar{b}, gg$$



- Jets defined with the IR-safe k_T algorithm: partons i, j clustered if $y_{ij} < y_{\text{cut}}$

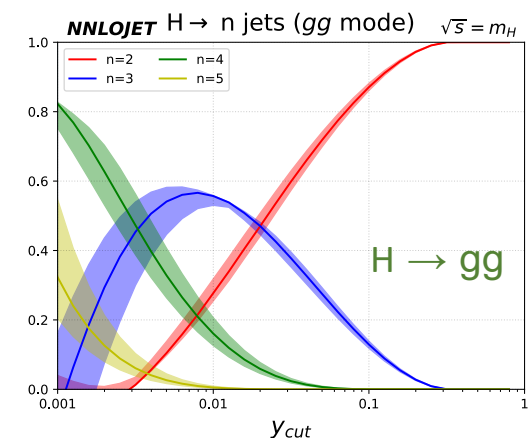
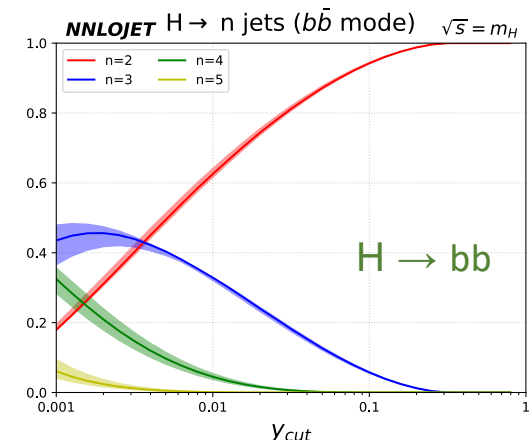


$$y_{ij} = \frac{2(1 - \cos \theta_{ij})}{E_{\text{tot}}^2} \min(E_i^2, E_j^2)$$

- Fraction of n-jet events are frame-dependent: collider vs. Higgs rest frame

n-jet Higgs decay rates at order α_s^2

- Hadronic n-jet fractions in Higgs rest frame:
 - 5-jets@LO, 4-jets @NLO, 3-jets@NNLO, 2-jets@N³LO
- y_{cut} dependence:
 - Large y_{cut} : dominated by 2-jet rate (for $y_{\text{cut}} > 1/3$)
 - Lowering y_{cut} : opening of higher multiplicity channels
 - with visible shape changes and larger scale uncertainty bands
 - clear differences between decay modes
 - $H \rightarrow b\bar{b}$: similar as for Z-decay to jets: colour singlet to fermion pairs with identical infrared structure of QCD corrections
 - $H \rightarrow gg$: larger fraction of high-multiplicity jet final states
 - Intersection between 2 and 3 jet curves: at larger y_{cut}
 - New derivation and implementation in **NNLOJET**

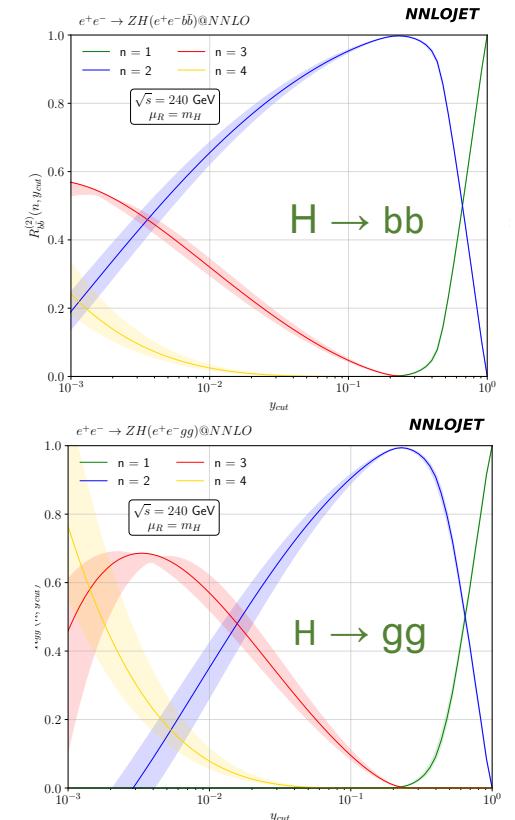


n-jet cross sections: Higgsstrahlung at order α_s^2

- n-jet fractions:

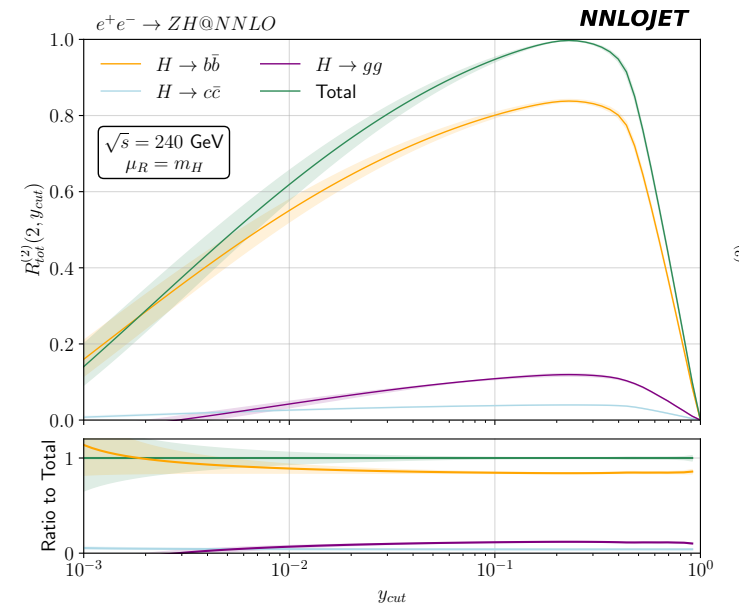
$$R_X^{(k)}(n, y_{\text{cut}}) = \frac{\sigma_X^{(k)}(n, y_{\text{cut}})}{\sigma_X^{(k)}}, \text{ with } X = gg, b\bar{b}$$

- Perturbative QCD at work: 4-jets@LO, 3-jets@NLO, 2-jets@NNLO and 1-jet@NNLO: only possible in collider frame
- y_{cut} dependence
 - Large y_{cut} : dominated by 1 and 2-jet rates
 - peak at $y_{\text{cut}} \cong 0.2$ for 2-jet
 - Lowering y_{cut} : opening of 3- and 4-jet rates
 - with visible shape changes, larger theory uncertainties
 - Hbb vs Hgg: Intersection point for 2 vs. 3 jet rates: 5 times larger in Hgg
($H \rightarrow b\bar{b}$ at $y_{\text{cut}} \cong 0.003$ and $H \rightarrow gg$ at $y_{\text{cut}} \cong 0.015$)



Individual decay channels for 2-jet rate @NNLO

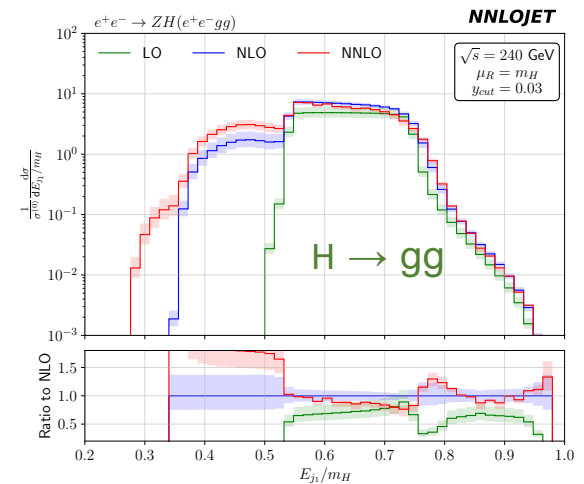
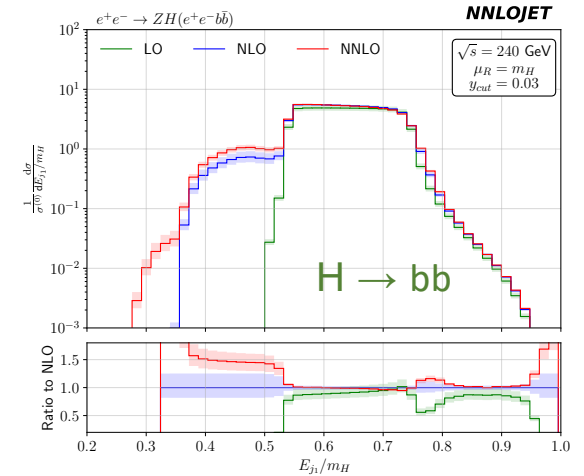
- Shape and size: dominated by $H \rightarrow b\bar{b}$
 - in accordance with inclusive hadronic branching fractions (85% for $H \rightarrow b\bar{b}$, 11% for $H \rightarrow gg$, 4% for $H \rightarrow c\bar{c}$)
 - Fraction of $H \rightarrow gg$ events enhanced at large y_{cut}
 - Results in line with H decay in Higgs rest frame [E.Fox et al; 2502.17333, 2508.14282] (NNLOJET)
- Choice of $y_{\text{cut}} \in [0.01, 0.1]$ for reliable predictions
 - to veto one-jet and high-multiplicity n-jet configurations
 - resummation needed at small y_{cut}



Leading-jet energy distribution

- Bulk region dominated by 2-jet events: LO boundaries
 - Jets boosted in laboratory frame

$$\min(E_{j1}/m_H) \cong 0.54, \max(E_{j1}/m_H) \cong 0.75$$
- Decay channels $H \rightarrow bb$: vs. $H \rightarrow gg$: distinct signatures
 - **Bulk region**: good perturbative convergence
 - $H \rightarrow bb$: small corrections, percent level left-over uncertainty @NNLO
 - $H \rightarrow gg$: sizeable higher order corrections ($\cong 10\%$ left over uncertainty @NNLO)
 - **Low energy**: opening of 3- and 4-jet contributions : forbidden at LO
 - visible shape changes and large scale uncertainty bands
 - **High energy**: Sharp decrease of distribution
 - larger corrections and uncertainties (more pronounced for $H \rightarrow gg$)



Summary and Outlook

- Precise predictions for Higgsstrahlung processes at future hadron and lepton colliders
 - Part I: differential WH@N3LO for boosted Higgs @LHC using **RadiSH+NNLOJET** (q_T slicing)
 - N³LO corrections crucial for fiducial cross sections and Higgs p_T spectrum :
as sizeable as NNLO result; scale uncertainties only reduced at N³LO to percent level
 - Part II: ZH @ FCC-ee: with $H \rightarrow 2$ jets up to NNLO, in collider frame
 - Distinct signatures for $H \rightarrow b\bar{b}$ vs. $H \rightarrow g\bar{g}$ for jet observables
- Outlook: Study B-hadron production for ZH @ FCC-ee
 - with b-quark or gluons from Higgs decays hadronizing into B-hadrons,
using parton-to-hadron fragmentation functions in computations : ($b \rightarrow B$, $g \rightarrow B$)
→ See talk by Francesco Merlotti (Thursday afternoon)

Thank you !