Precision Phenomenology for Hadronic Higgs Decays at Future Colliders

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IP3

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Work in collaboration with
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Thomas Gehrmann, Nigel Glover, Christian T. Preuss

Overview

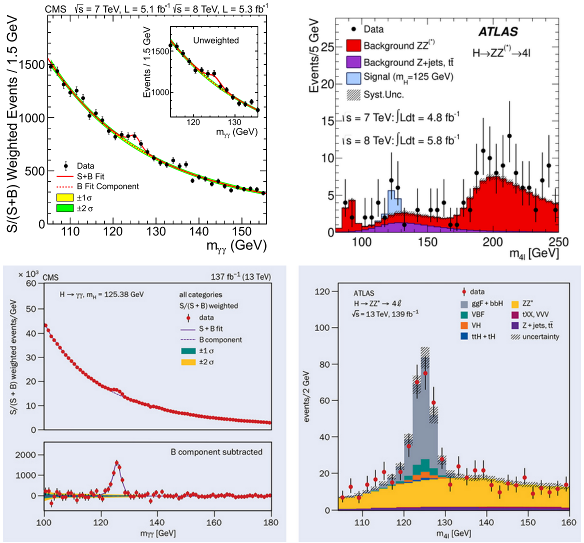
- Introduction
- Jet rates in hadronic Higgs decays
- Event shapes in hadronic Higgs decays
- Jet observables in $e^+e^-\to ZH$
- Summary and outlook

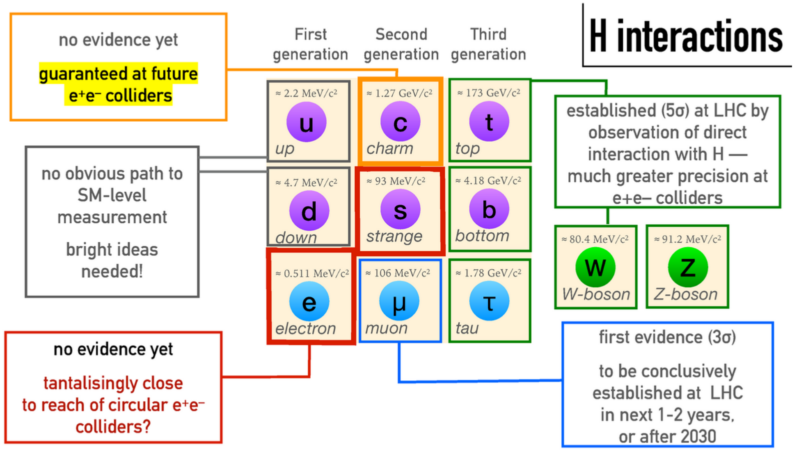
INTRODUCTION

Higgs boson: from discovery to precision

The precision Higgs physics era started right after its discovery:

- Higgs boson properties (mass, width, …)
- Higgs boson interaction with other SM particles
- Higgs boson self interaction





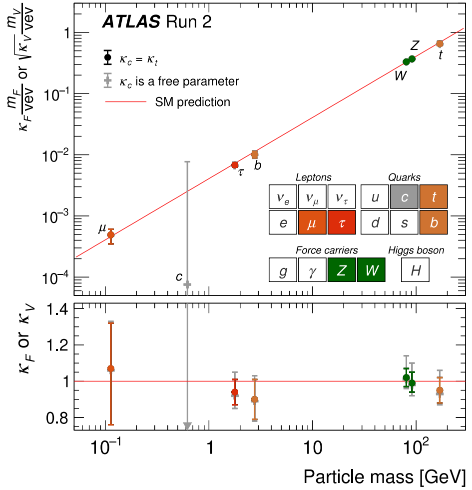
[Slide from Gavin Salam]

Bottom:

- Observed (2019) and precisely measured at the LHC
- Crucial role of machine learning in b-jet tagging

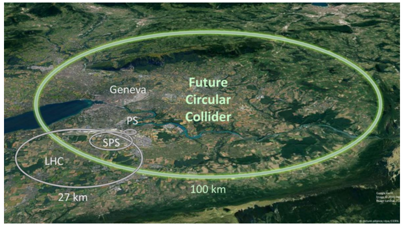
Charm:

- Very promising recent results thanks to machine learning
- Potential for observation at the LHC in the near future



Higgs factories at future colliders

Future electron-positron colliders will operate as **Higgs factories**, enabling high-precision measurements of the Higgs boson properties and couplings.

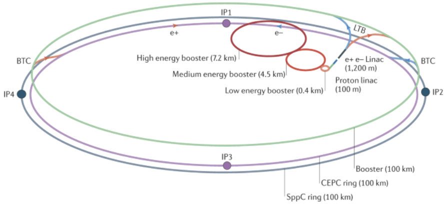


FCC

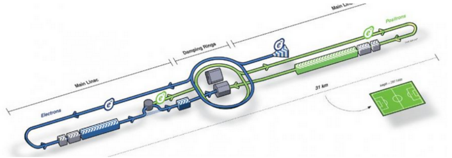
Baseline physics programme at FCC-ee.

[Monni, d' Enterria FCC:QCD physics, ESPPU 2025-2026]

Run	Z	WW	ZH	$\mathrm{t\bar{t}}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
time (years)	4	2	3	1	4
$\mathcal{L}_{\mathrm{int}}$ (ab^{-1})	205	19.2	10.8	0.42	2.70
$\mathrm{e^+e^- \to Z,\ WW,\ ZH,\ t\bar{t}}$					
N_{evts} (Z, W, H, top)	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH	2×10^{6} $\mathrm{t\bar{t}}$	
N_{evts} (HFS decays)	4.2×10^{12}	1.1×10^{8}	1.2×10^{6}	0.9×10^{6}	
N_{partons} (HFS decays)	≥ 2	≥ 4	≥ 4	≥ 6	
E_{j} (max. jet scale probed)	45 GeV	40 GeV	45, 65 GeV	125 GeV	
$\mathrm{e^+e^- \to Z^{(*)} \to q\bar{q}}$					
σ	32.5 nb	40 pb	13.5 pb	5.3 pb	
N_{evts} (HFS)	4.2×10^{12}	7.7×10^{8}	1.5×10^{8}	1.7×10^{7}	
E_{j} (max. jet scale probed)	45 GeV	80 GeV	120 GeV	180 GeV	



CEPC



ILC

O(10^6) clean Higgs boson production events: same ballpark of all events at LEP!

Higgs boson decays to hadrons

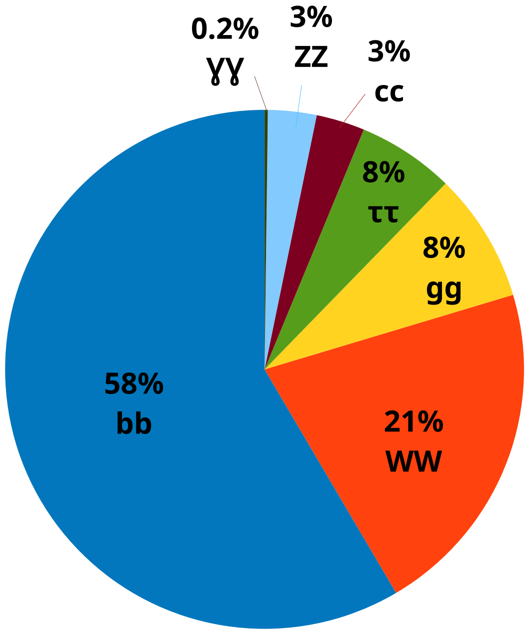
Study hadronic decays of the Higgs boson to extract Yukawa couplings.

Direct hadronic decays: bb, gg, cc.

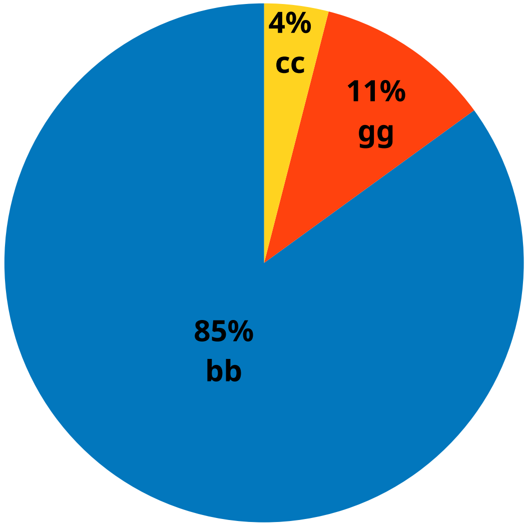
Full or semi-hadronic decays also from: $W^* W$, $Z^* Z$, $\tau\,\tau$.

Peculiar kinematic features (invariant mass, missing energy). Neglected in the following.

Higgs branching ratios (all decays)



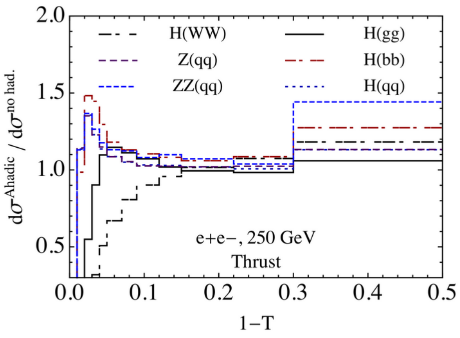
Higgs branching ratios (only direct hadronic decays)



Higgs: colour singlet decaying both to quarks and gluons.

Interesting for **quark/gluon jet tagging** and **QCD dynamics.**

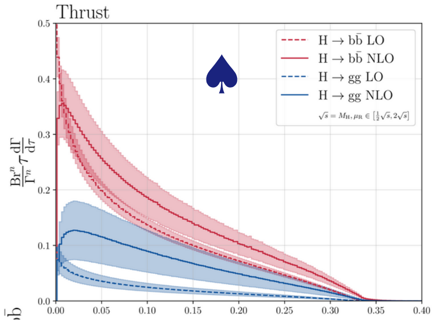
Idea: distinguish different Higgs decays from the **dynamics of the hadronic final state**



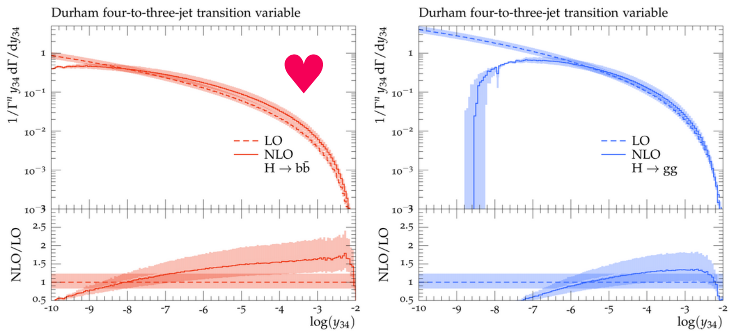
[Gao 1608.01746]

Sensitivity to light quark Yuakwas from hadronic event shapes in e+e-→ZH

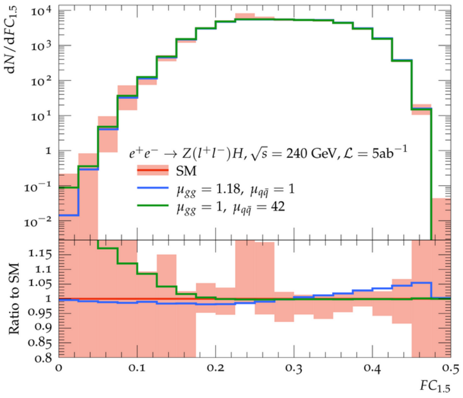
[Coloretti, Gehrmann-De Ridder, Preuss 2202.07333]



[Gehrmann-De Ridder, Preuss, Williams 2310.09354]

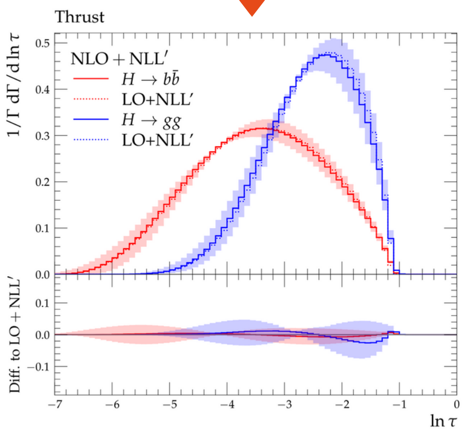


[Knobbe, Krauss, Reichelt, Schumann 2306.03682]



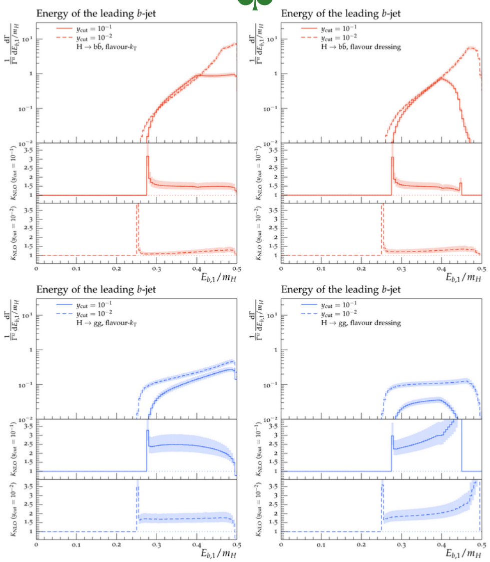
Measuring hadronic Higgs boson BRs at future lepton colliders

Expose differences between Higgs decay to bottom quarks or gluons via:



[Gehrmann-De Ridder, Preuss, Reichelt, Schumann 2403.06929]

- H→ 3 jet NLO
- H→ 4 jet NLO
- flavour-jet algorithms
- resummation and matching to fixed-order (NLO+NLL')



[Campillo Aveleira, Gehrmann-De Ridder, Preuss 2402.17379]

JET RATES
IN HADRONIC HIGGS DECAYS

work with Elliot Fox, Aude Gehrmann-De Ridder, Thomas Gehrmann, Nigel Glover, Christian T. Preuss

Phys.Rev.Lett. 134 (2025) 25, 251905, arXiv: 2502.17333

Jet rates in electron-positron annihilation

Let's consider e^+e^- annihilation to hadrons and the Durham jet reconstruction algorithm:

- for each pair (i,j) of jet candidates compute the distance:

[Catani, Dokshitzer, Olsson, Turnock, Webber *Phys. Lett*. B 269 (1991)]
[Brown, Stirling *Phys. Lett*. B 252 (1990)]

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

invariant mass of all hadronic particles

- if $y_{ij}^D < y_{\rm cut}$, cluster i and j together,
- Repeat;

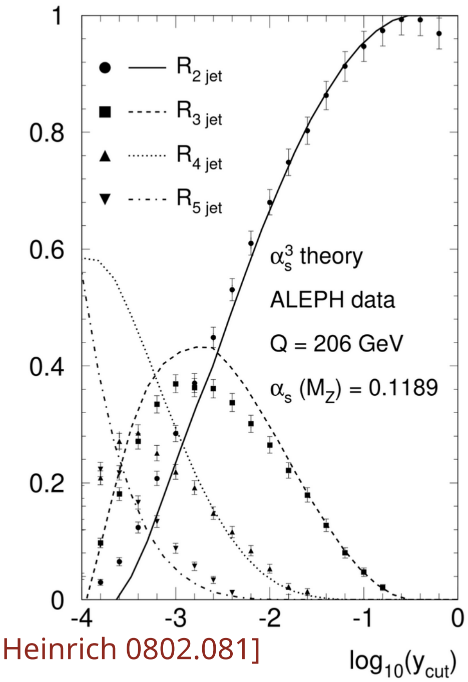
jet resolution parameter

The algorithm stops when all $y_{ij}^D > y_{\rm cut}$ and events are classified as 2, 3, 4, … -jet events.

n-jet rate $R(n, y_{\rm cut})$: fraction of events classified as n-jet events.

Jet rates are precision observables (NNLO and N^{3}LO).

Jet rates at LEP

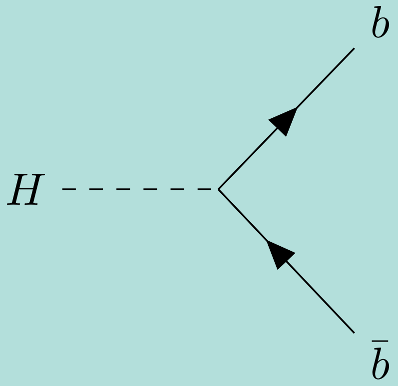


[Gehrmann-De Ridder, Gehrmann, Glover, Heinrich 0802.081]

Jet rates in the hadronic decays of a Higgs boson

We consider a Higgs boson at rest (neglect production mode) decaying hadronically.

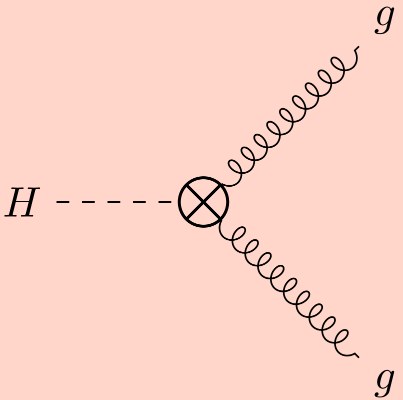
Yuakawa mode



$$\Gamma^{(0)}_{H\to b\bar{b}} = \frac{m_b^2(\mu_R) m_H N_c}{8\pi v^2}$$

- massless b (apart from Yuakwa interaction) ***
- analogous contribution from charm

Gluonic mode



$$\Gamma^{(0)}_{H\to gg} = \frac{\alpha_s^2(\mu_R) m_H^3 (N_c^2-1)}{576\pi^3 v^2}$$

- effective vertex: infinite top mass limit
- finite t, b and c mass and EW vertex corrections included by rescaling

Inclusive decay widths at order k in QCD:

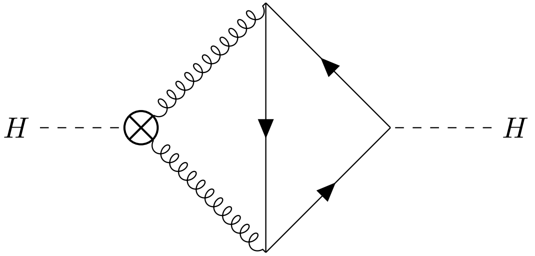
$$\Gamma^{(k)}_{H\to b\bar{b}} = \Gamma^{(0)}_{H\to b\bar{b}} \left(1 + \sum_{n=1}^{k} \alpha_s^n(\mu_R) C^{(n)}_{b\bar{b}}\right)$$

$$\Gamma^{(k)}_{H\to gg} = \Gamma^{(0)}_{H\to gg} \left(1 + \sum_{n=1}^{k} \alpha_s^n(\mu_R) C^{(n)}_{gg}\right)$$

Expansion coefficients know up to k=4

[Herzog, Ruijl, Ueda, Vermaseren, Vogt 1707.01044]

*** The interference between the two modes vanishes. We verified that it is anyway negligible for the observables we consider.



= 0

Setup of the calculations

We compute the decay of a Higgs boson into three jets **H→ j j j** up to NNLO in QCD;

$$R_X^{(k)}(n, y_{\mathrm{cut}}) = \frac{\Gamma^{(k)}_{H\to X}(n, y_{\mathrm{cut}})}{\Gamma^{(k)}_{H\to X}}$$

$$\sum_{n=2}^{k+2} R_X^{(k)}(n, y_{\mathrm{cut}}) = 1$$

Form this we can extract the **3-jet rate at NNLO and the 2-jet rate at N^{3}LO**;

Previous calculation in the Yukawa mode. **Novel results in the gluonic mode**.

[Mondini, Williams 1904.08961]

[Mondini, Schiavi, Williams 1904.08960]

Physical parameters: $m_H = 125.09\,\mathrm{GeV} \quad m_Z = 91.200\,\mathrm{GeV}$

$v = 246.22\,\mathrm{GeV} \quad \alpha_s(m_Z) = 0.11800 \quad m_t(m_H) = 166.48\,\mathrm{GeV}$

$y_b(m_H) = m_b(m_H)/v = 0.011309 \quad y_c(m_H) = m_c(m_H)/v = 0.0024629$

[Gehrmann-De Ridder, Gehrmann, Glover 0505111]

We rely on the **antenna subtraction method** for the removal of **infrared singularities** up to NNLO.

[Fox, Glover, MM 2410.12904]

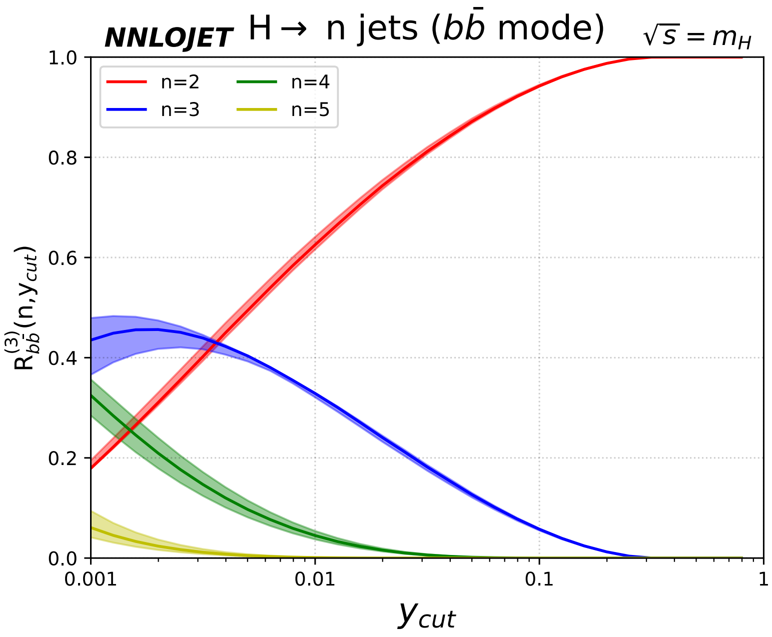
In particular on the **generalised antenna functions** we recently computed, which provide improved convergence and a significant computational speedup.

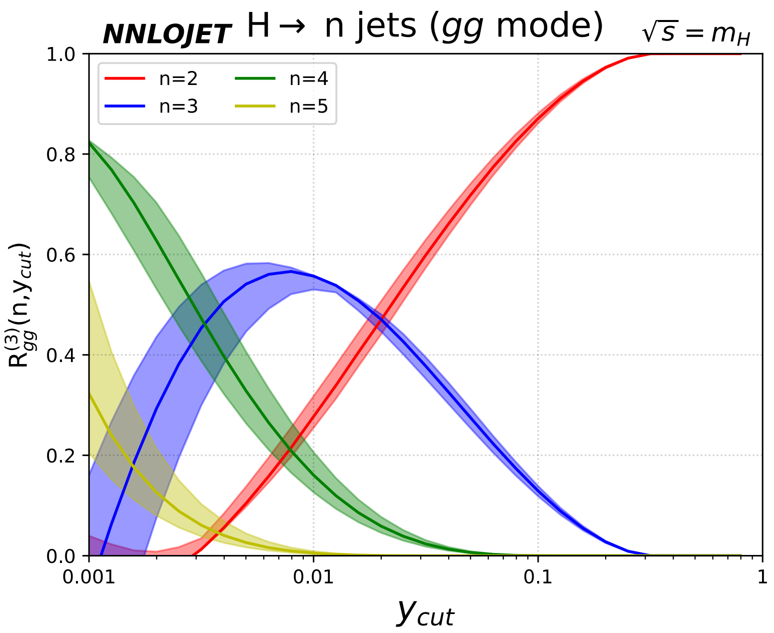
[NNLOJET Collaboration, A. Huss *et al.* 2503.22804]

The computation is performed within the ***NNLOJET*** parton-level event generator.

Jet rates in the hadronic decays of a Higgs boson

- Hbb mode follows jet rates in electron-positron annihilation (quark radiators);
- Higher multiplicity rates arise earlier for Hgg;
- Breakdown of fixed-order calculations when jet-rates turn negative;
- Breakdown happens earlier for for Hgg ($y_{cut} = 0.001$)

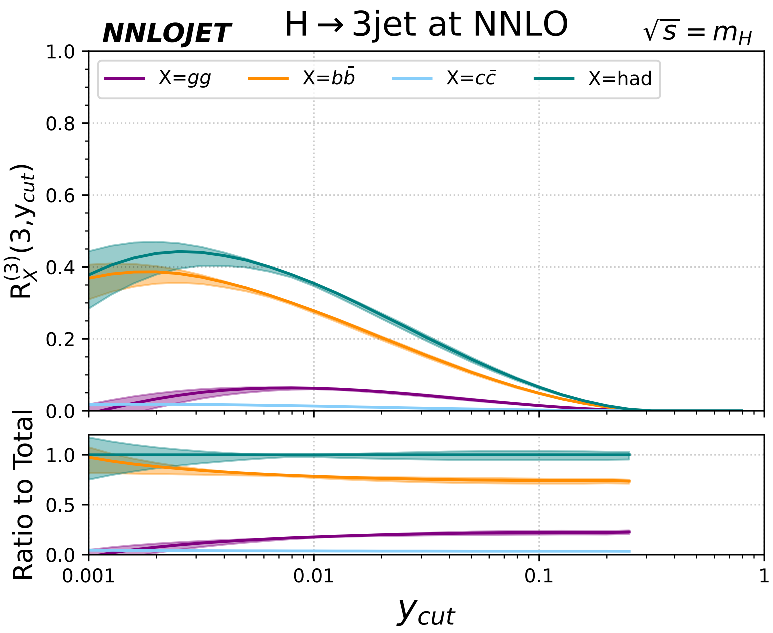


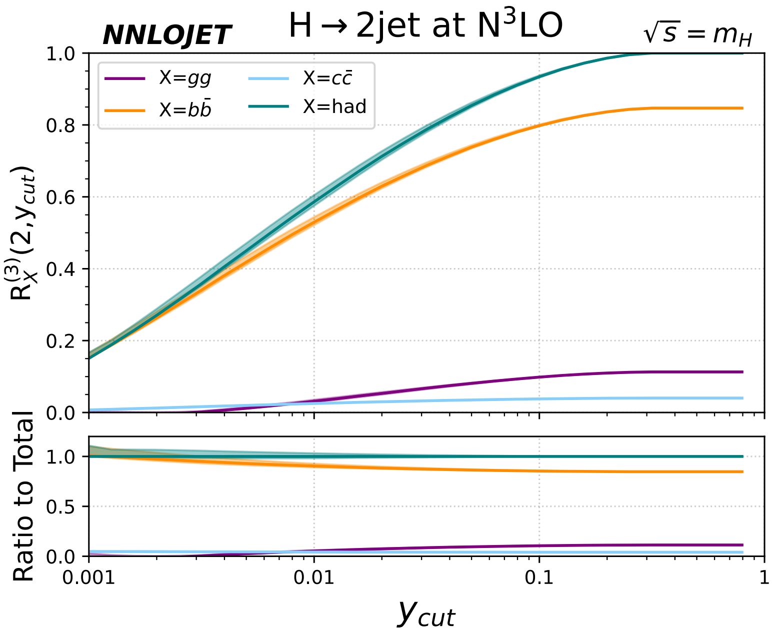


[Fox, Gehrmann-De Ridder, Gehrmann, Glover, MM, Preuss 2502.17333]

Jet rates in the hadronic decays of a Higgs boson

- Enhanced gluonic fraction in the hard three-jet region: from 11% (inclusive) to ~25%;
- Pure Yuakwa mode in two-jet events at low y_{cut};
- At large y_{cut}, relative fraction reach inclusive ones (85%, 11%, 4%) as expected;





[Fox, Gehrmann-De Ridder, Gehrmann, Glover, MM, Preuss 2502.17333]

EVENT SHAPES
IN HADRONIC HIGGS DECAYS

work with Elliot Fox, Aude Gehrmann-De Ridder, Thomas Gehrmann, Nigel Glover, Christian T. Preuss

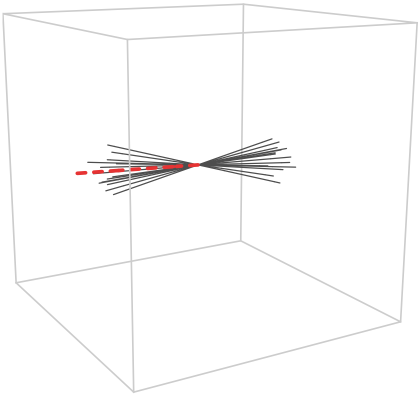
arXiv: 2508.14282

Event shapes in the hadronic decays of a Higgs boson

Event shapes are an alternative to jet cross-sections. They measure the geometric distribution of radiation. Classic example: the **thrust**.

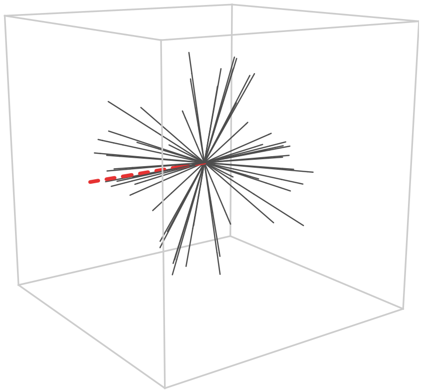
$$T = \max_{\vec{n}} \left(\frac{\sum_i \vec{p}_i \cdot \vec{n}}{\sum_i \vec{p}_i} \right)$$

$$\tau \equiv 1 - T = \min_{\vec{n}} \left(1 - \frac{\sum_i \vec{p}_i \cdot \vec{n}}{\sum_i \vec{p}_i} \right)$$



$$T = 0.998\,, \quad \tau = 0.002$$

pencil-like
back to back



$$T = 0.65\,, \quad \tau = 0.35$$

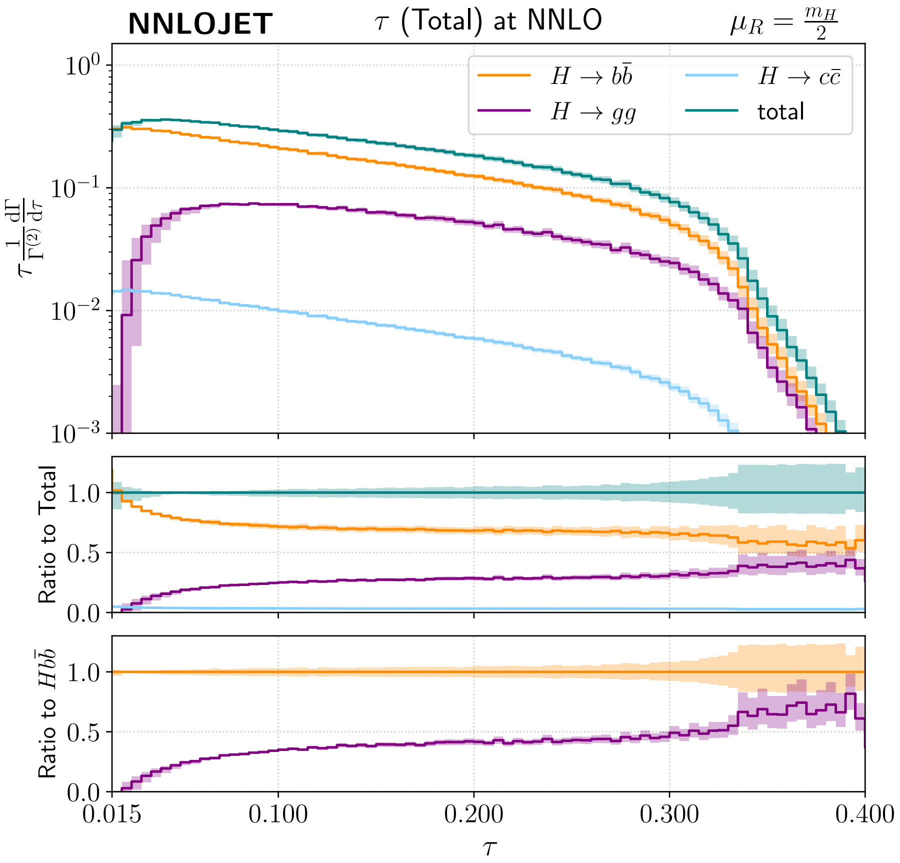
spherical
isotropic

We consider the same setup as before and compute **NNLO**-accurate predictions for **event shapes in hadronic Higgs decays** for the two modes.

Thrust distribution

[Fox, Gehrmann-De Ridder, Gehrmann, Glover, MM, Preuss 2508.14282]

- Also here, Hgg fraction enhanced (>40%) in the high-multiplicity hard region;
- Perturbative predictions for the gluonic mode breaks down earlier than for the Yukawa one;
- All-order resummation effects are important when τ→ 0 (back-to-back region);
- Resummation more important for the gluonic mode.

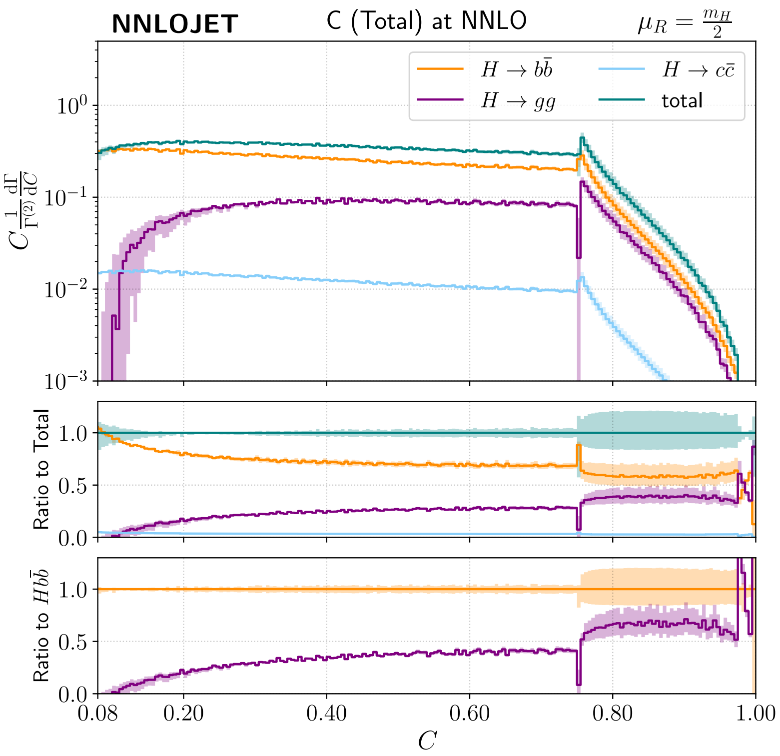


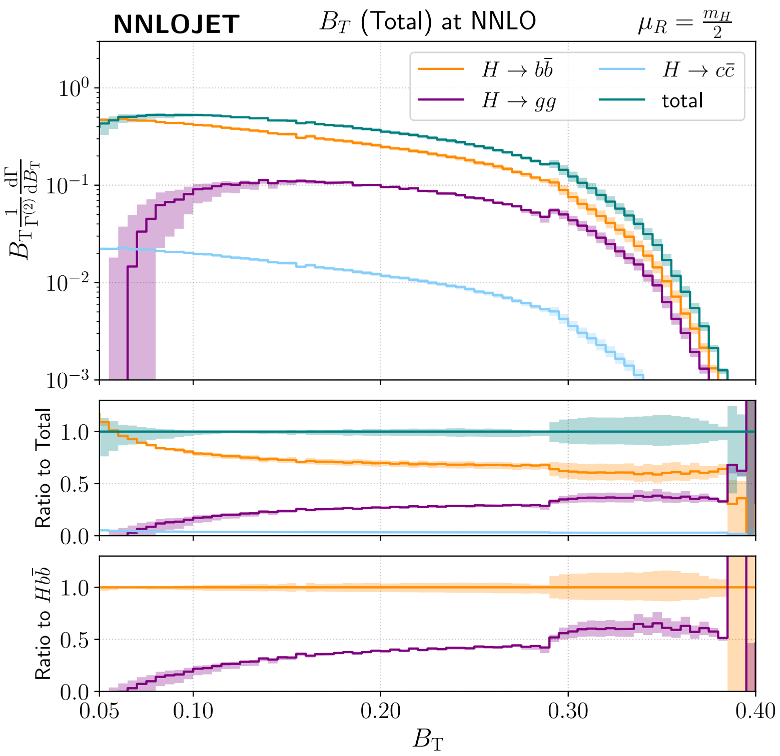
pencil-like
back to back

spherical
isotropic

Thrust distribution and more

Similar observations for other event shapes too: C-parameter and total jet broadening.





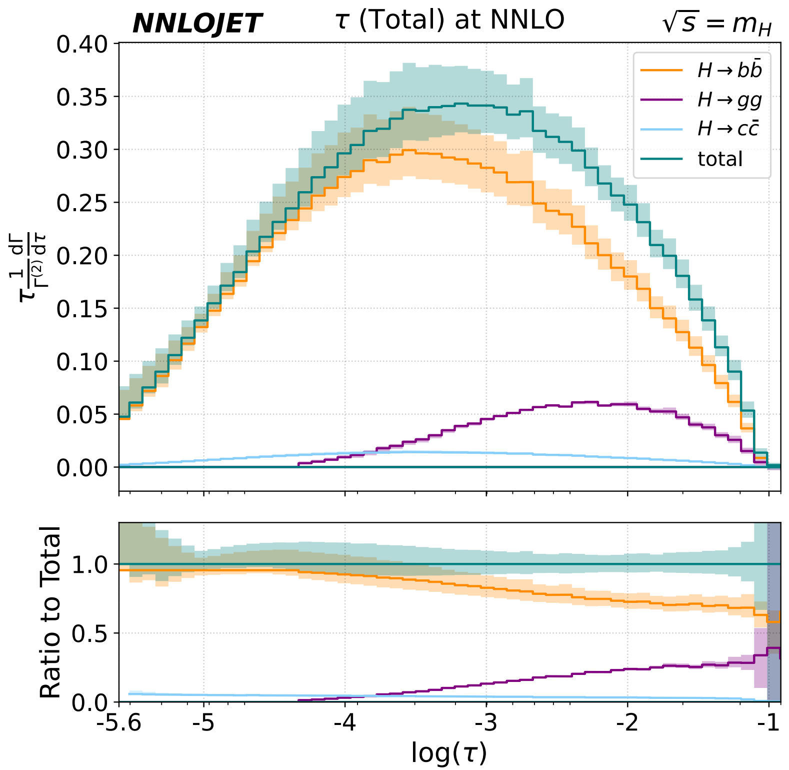
[Fox, Gehrmann-De Ridder, Gehrmann, Glover, MM, Preuss 2508.14282]

Thrust resummation

Does resummation change the story close to the back-to-back region?

PRELIMINARY

- Matched resummation and fixed order calculation for thrust at **NNLO+NNLL**;
- The gluonic mode fraction still vanishes as τ→ 0;
- Around τ=0.015 the **charm** contribution becomes more important than the gluonic one.



JET OBSERVABLES IN $e^+e^-\to ZH$

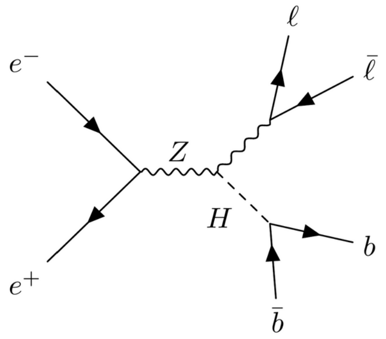
work in preparation with Simone Caletti and Aude Gehrmann-De Ridder

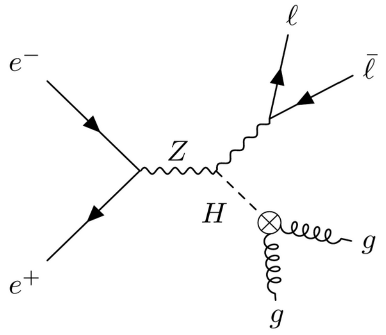
Not only decay: e+e- → ZH at future colliders

We consider the **ZH production** process at lepton colliders, with the (off-shell) Z boson decaying **leptonically**.

Again, we compare the **Yukawa** and **gluonic** mode for the (off-shell) Higgs decay at **NNLO**.

In this process, the hadronic cluster is **not** in the c.o.m. of the collision any more.





$$\sqrt{s} = 240.00\,\mathrm{GeV} \qquad m_H = 125.09\,\mathrm{GeV} \qquad m_Z = 91.188\,\mathrm{GeV}$$

The Higgs boson is boosted with respect to the c.o.m. of the collision:

$$\gamma = \frac{E_H}{m_H} = \frac{s + m_H^2 - m_Z^2}{2 m_H \sqrt{s}} \approx 1.08 \qquad \beta = \sqrt{1 - \frac{1}{\gamma^2}} \approx 0.38$$

numbers correct for on-shell Z and H

Leading and sub-leading jet energies

$$\frac{E_{\pm}^{lab}}{m_H} = \frac{1}{2}\left(\gamma \pm \sqrt{\gamma^2 - 1}|\cos\theta|\right)$$

at LO, with
on-shell Z and H

angle w.r.t. Higgs direction

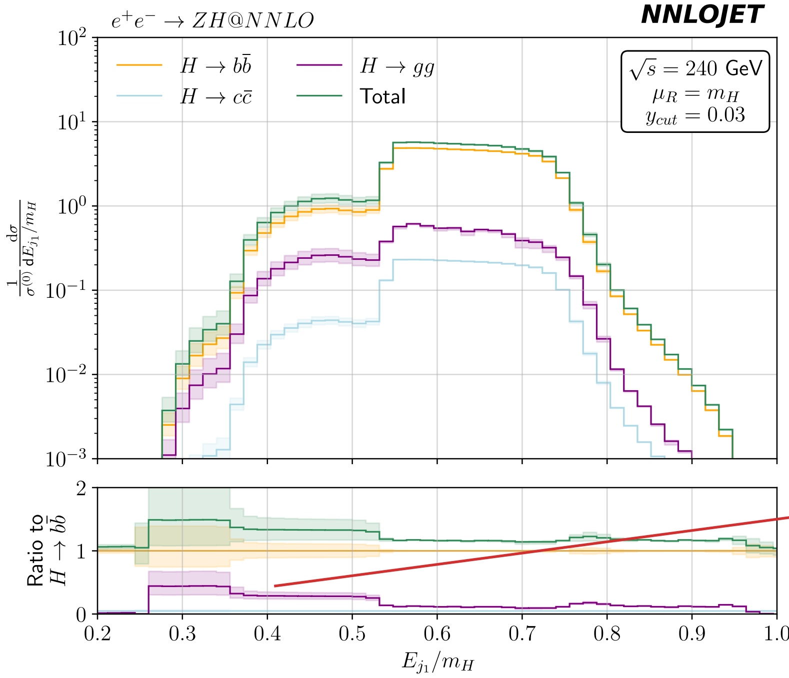
leading jet: $\max\left(\frac{E_+^{lab}}{m_H}\right) \approx 0.74\,, \quad \min\left(\frac{E_+^{lab}}{m_H}\right) \approx 0.54$

subleading jet: $\max\left(\frac{E_-^{lab}}{m_H}\right) \approx 0.54\,, \quad \min\left(\frac{E_-^{lab}}{m_H}\right) \approx 0.33$

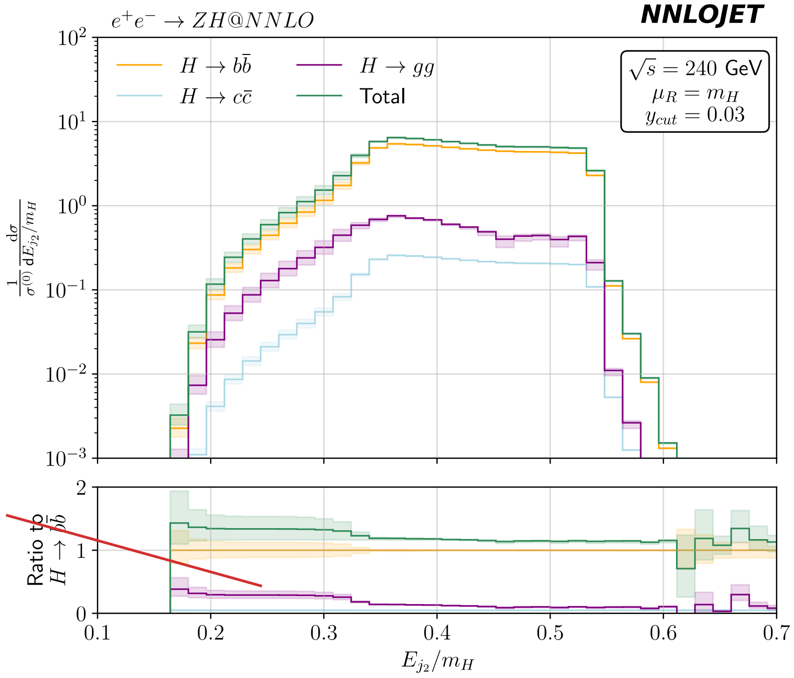
Leading-jet energy

PRELIMINARY

Sub-leading-jet energy



enhanced gluonic fraction



Angle between jets

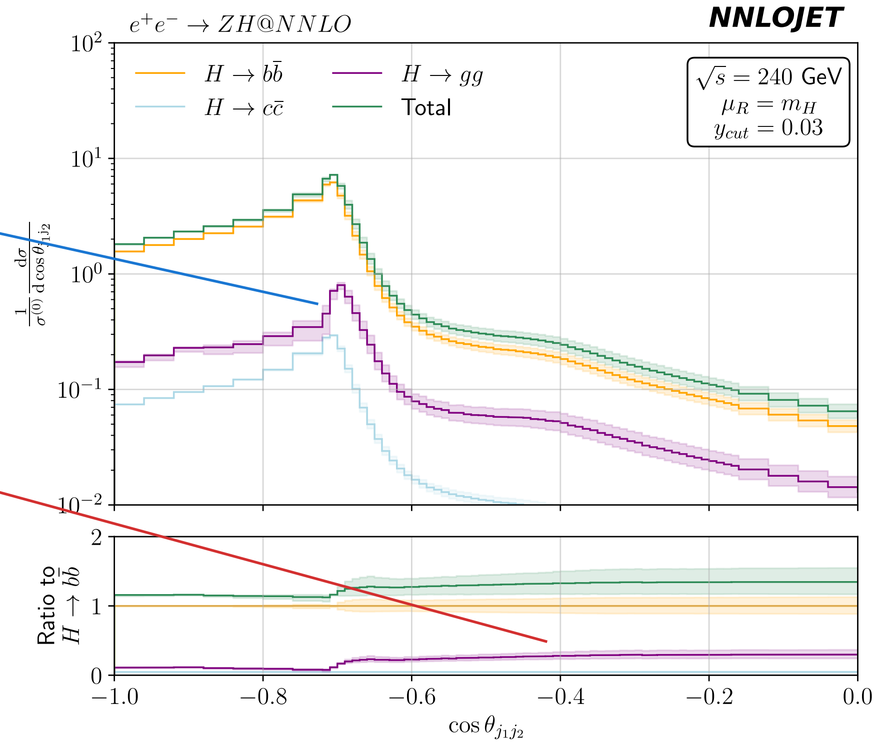
$$\cos\theta_{j_1 j_2} = \left.\frac{p_1 \cdot p_2}{|p_1||p_2|}\right|_{lab} = -1 + 2\beta^2 \approx -1 + 2(0.38)^2 \approx -0.71$$

at LO, with
on-shell Z and H

different peak position

enhanced gluonic fraction

PRELIMINARY



SUMMARY AND OUTLOOK

Summary:

- The **hadronic decays of a Higgs boson** offer opportunities for the extraction of Yukawa couplings, as well as the study of QCD dynamics (quark/gluon jets);
- We presented the **NNLO**-accurate predictions for **jet rates**, **event shapes** (with **resummation**) in hadronic Higgs decays and for jet observables in **ZH production at lepton colliders**;
- Several observables can be used to improve the sensitivity to different decay modes. In general, gluonic decays are enhanced in the **multi-jet region** and suppressed in the **back-to-back limit**;

Outlook:

- Inclusion of quark mass effects, exact top-mass dependence in gluonic mode;
- Impact of $H \to V^*V \to$ hadrons;
- Higher multiplicity at NNLO: decay to 4-jet, event shapes in e+e- → ZH;
- Hadronically decaying Z in e+e- → ZH: study the interplay between the two hadronic clusters;

Thank you for your attention!