Recent Developments in Higgs Boson Theory

Thomas Gehrmann

Universität Zürich

Higgs Hunting 2025

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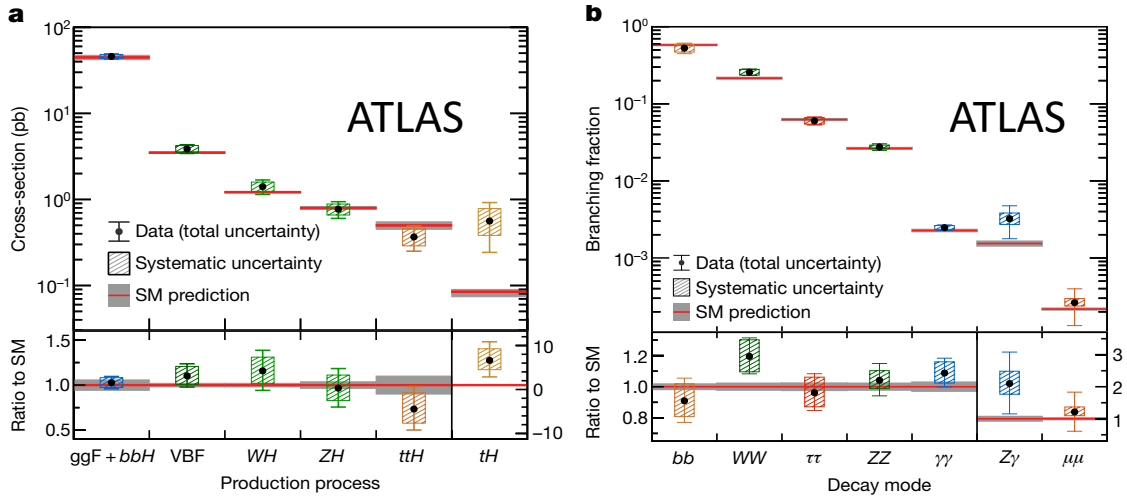
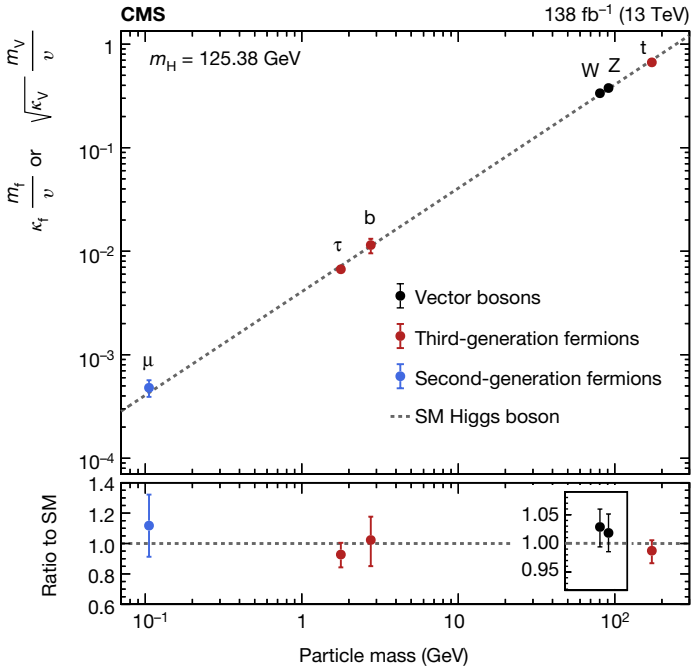
Precision Higgs physics

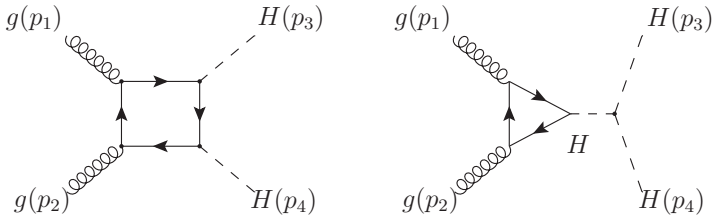
- LHC discovered and established Standard Model Higgs boson
  - multiple production and decay modes
- HL-LHC: turning to precision studies
  - precision measurements of couplings
  - search for BSM physics in Higgs sector
- Probing Higgs mechanism
  - measure Higgs boson self-coupling
  - reconstruct Higgs potential
- Close interplay experiment-theory





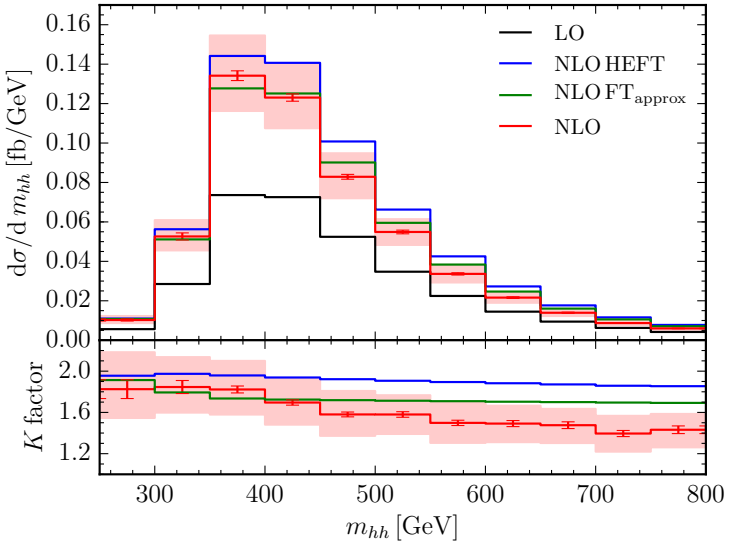
Higgs pair production

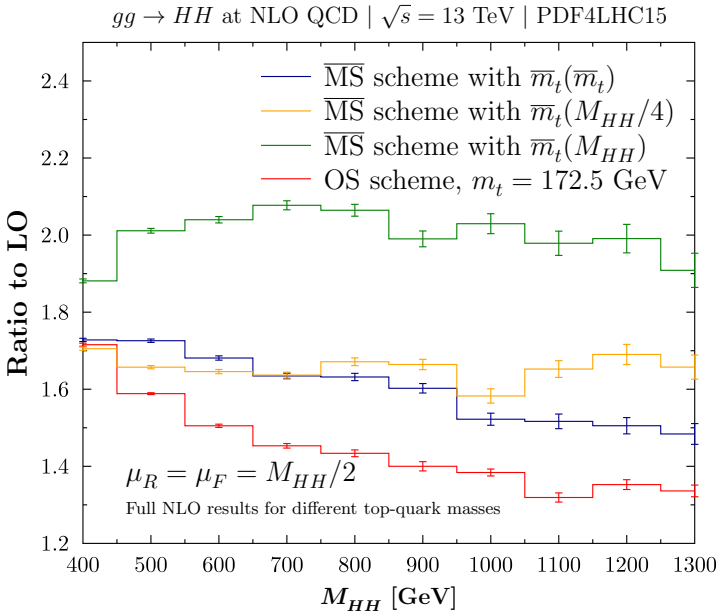
- probe Higgs self-interaction: gg ⟶ HH



  - sensitivity to v_{HHH}
  - destructive subprocess interference
  - small cross section: $\sigma(HH) \sim 10^{-3}\,\sigma(H)$
  - HL-LHC measurement: combine multiple final states

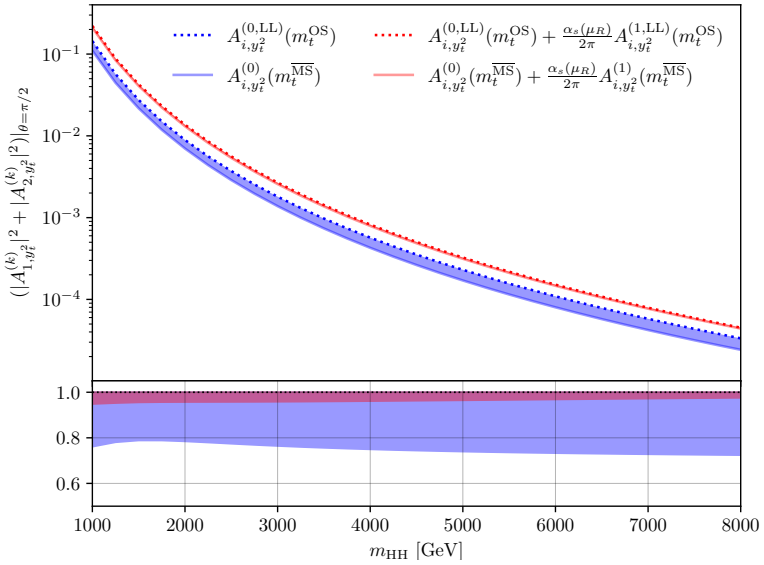
- sizable NLO corrections
  (S.Borowka, N.Greiner, G.Heinrich, S.Jones, M.Kerner, J.Schlenk, T.Zirke)
  - sensitive on top quark mass scheme: OS versus MS
    (J.Baglio, F.Campanario, S.Glaus, M.Mühlleitner, J.Ronca, M.Spira, J.Streicher)
  - precision extraction of v_{HHH} questionable

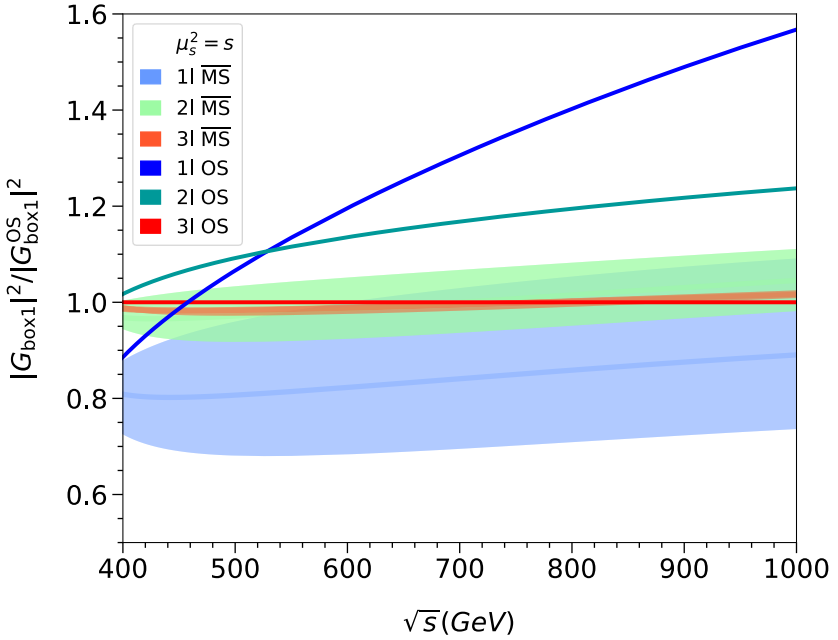




Higgs pair production

- method-of-regions analysis of gg → HH amplitudes up to three loops
  (S.Jaskiewicz, S.Jones, R.Szafron, Y.Ullrich)
  - identify large leading-logarithmic corrections in OS scheme → resummation
- computation of forward three-loop gg → HH amplitudes (J.Davies, K.Schönwald, M.Steinhauser)
  - larger corrections in OS scheme
  - reduced scheme-dependence
  - results converge towards MS result
- amplitude-level results
  - awaiting phenomenological studies



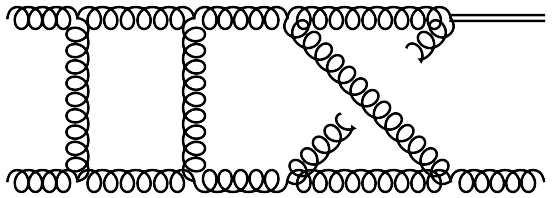


Multi-loop amplitudes

- Higgs boson processes demand technically challenging loop amplitudes
  - gluon fusion: large higher-order corrections
  - several internal and external mass scales (m_H,m_t,m_b,...)
  - high-multiplicity final states (ttH, VBF, VH)
- Driver of technical innovation in multi-loop amplitudes
  - first-ever N3LO QCD result for hadron colliders: gluon fusion cross section (C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger)
  - two-loop top quark mass effects in HH and H+jet gluon fusion amplitudes
    - pySecDec (S.Borowka, N.Greiner, G.Heinrich, S.Jones, M.Kerner, G.Luisoni, J.Schlenk, T.Zirke)
    - numerical loop integration (J.Baglio, F.Campanario, S.Glaus, M.Mühlleitner, J.Ronca, M.Spira, J.Streicher)
    - DiffExp (R.Bonciani, V.Del Duca, H.Frellevig, M.Hidding, V.Hirschi, F.Moriello, G.Salvatori, G.Somogyi, F.Tramontano)
  - eikonal expansion for non-factorizable QCD corrections in VBF (K.Asteriadis, C.Bronnum-Hansen, M.M.Long, J.Quarroz, K.Melnikov, A.Penin)

Multi-loop amplitudes

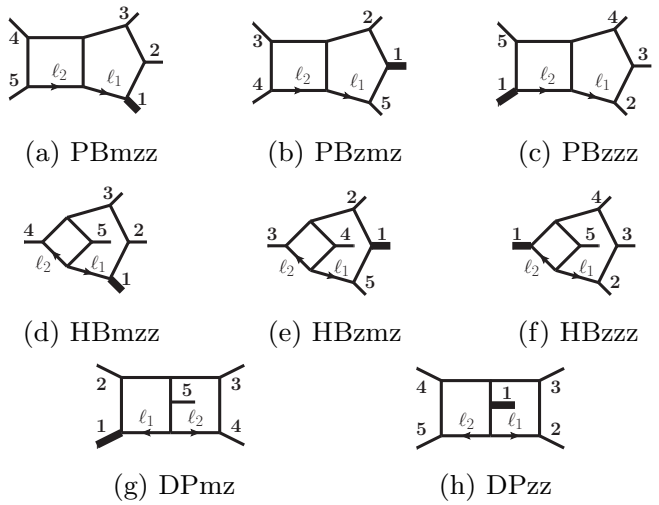
- Current frontier: Higgs boson p_T distribution at N3LO
  - ingredients: two-loop H+2jet (2→3) and three-loop H+1jet (2→2) amplitudes



- Current frontier: NNLO QCD corrections to ttH production
  - missing ingredient: two-loop ttH (2→3) amplitudes
- Workflow
  - algebraic reduction of amplitudes to small set (1000's) of master integrals
  - computation of master integrals from their differential equations
- Challenges
  - algebraic complexity: system and expression size in integral reduction
  - analytic complexity: function space and evaluation of master integrals

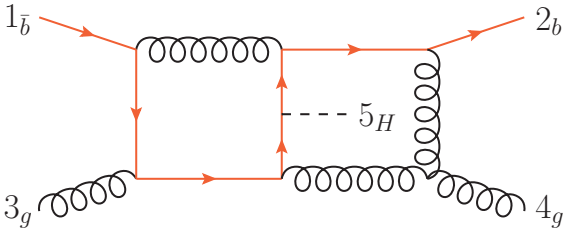
Computer algebra for multi-loop amplitudes

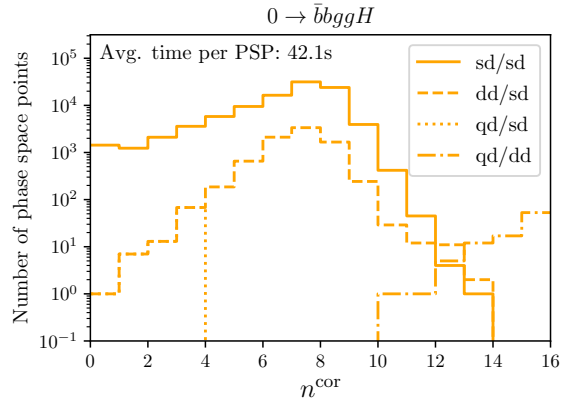
- Innovations in integral reduction
  - reconstruct coefficients from numerical samples over finite prime number field
    (FinRed: A.von Manteuffel, R.Schabinger; FiniteFlow: T.Peraro)
  - trimming of linear systems (Kira: F.Lange, J.Usovitsch, Z.Wu; Blade: X.Guan, X.Liu, Y.Q.Ma, W.H.Wu)
  - optimization of integral basis for reconstruction (G.De Laurentis, H.Ita, B.Page, V.Sotnikov)
- Innovations in integral computation
  - numerical computation from series expansion
    (AMFlow: X.Liu, Y.Q.Ma)
  - optimized analytical function basis
    - two-loop pentagon functions
      (S.Abreu, D.Chicherin, H.Ita, B.Page, V.Sotnikov, W.Tschernow, S.Zoia)
    - three-loop graded transcendental functions
      (J.Henn, P.Jakubcik, J.Lim, C.Mella, N.Syrrakos, L.Tancredi, W.Torres Bobadilla, TG)

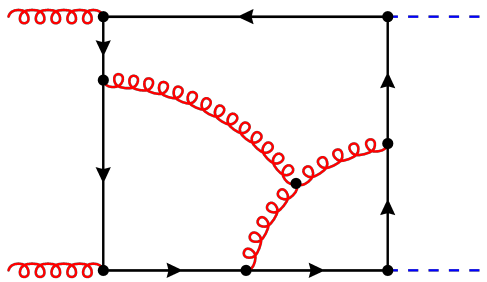


Multi-loop amplitude results

- Two-loop amplitudes for qqH production
  - closed fermion loop contributions to qq⟶ttH
    (B.Agarwal, G.Heinrich, S.Jones, M.Kerner, S.Klein, J.Lang, V.Magerya, A.Olsson; F.Febres Cordero, G.Figueiredo, M.Kraus, B.Page, L.Reina)
  - full amplitudes for qq⟶bbH and gg⟶bbH (m_b=0)
    (S.Badger, H.Bayu Hartanto, R.Poncelet, Z.Wu, Y.Zhang, S.Zoia)
  - test-case for ML surrogate approximations
    (V.Breso, G.Heinrich, V.Mageyra, A.Olsson)
- Three-loop amplitudes for H+jet production
  - leading colour amplitudes for gg ⟶Hg and gq ⟶Hq
    (X.Chen, X.Guan, B.Mistlberger)
- Three-loop amplitudes for HH production
  - expansion in masses or transverse momenta for gg⟶HH
    (J.Davies, K.Schönwald, M.Steinhauser)

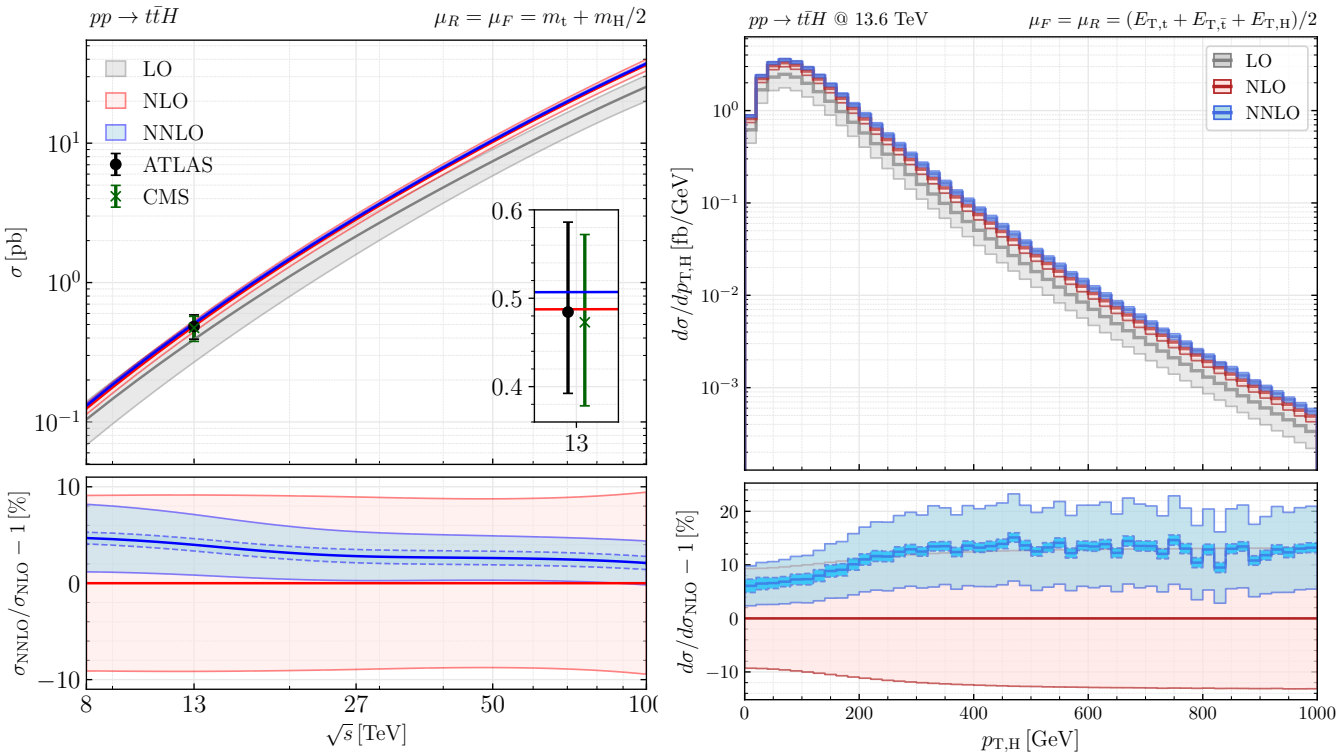






ttH production: NNLO QCD corrections

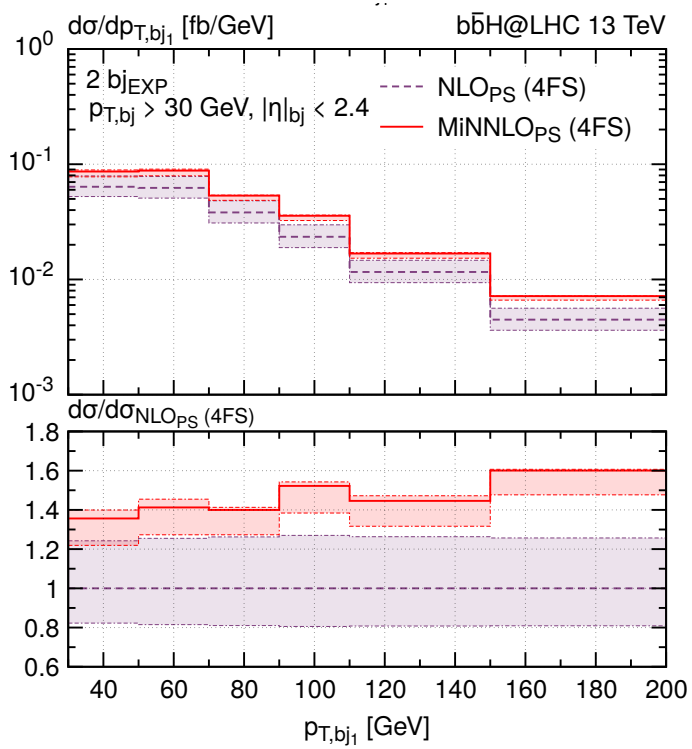
- enable precision ttH studies at HL-LHC
  - top quark Yukawa coupling
  - new physics searches
- use approximation to two-loop amplitude
  - genuine (IR-subtracted) two-loop finite remainder small
  - estimate from expansions and assign error



(S.Devoto, M.Grazzini, S.Kallweit, J.Mazzitelli, C.Savoini)

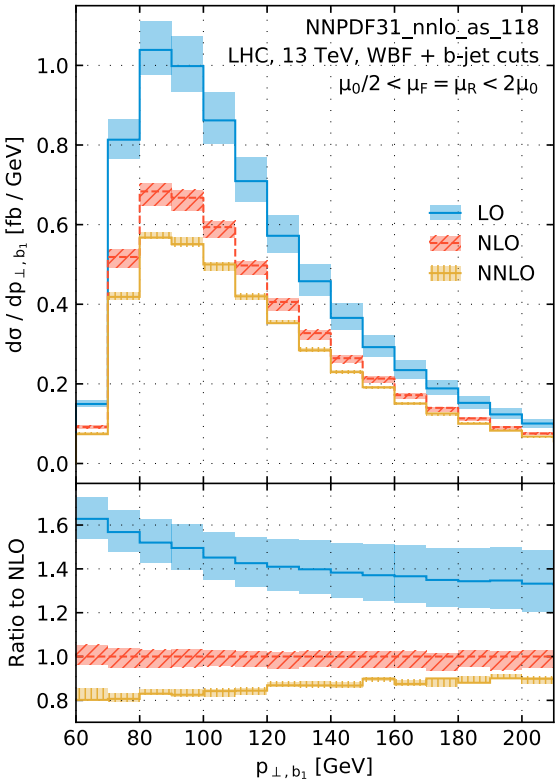
bbH production: NNLO+PS

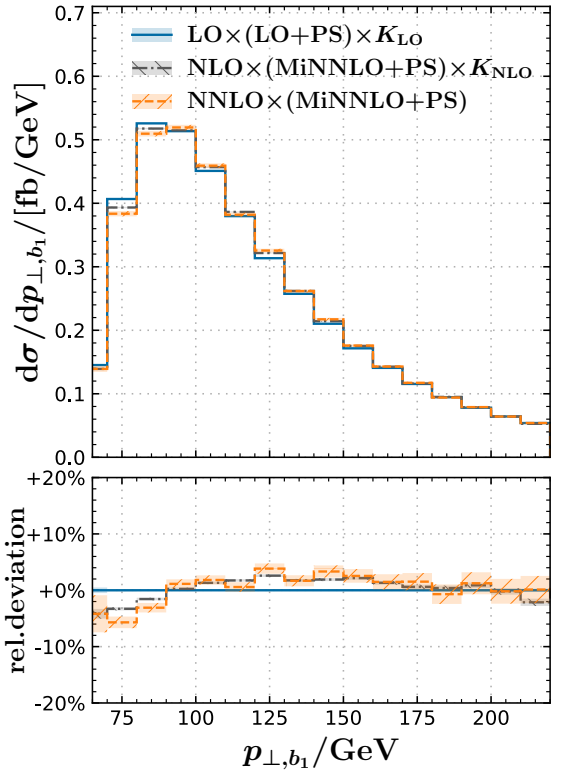
- associated Higgs production with bottom quark pair
  - production rate at LHC comparable to ttH, experimentally challenging
  - background to HH searches
  - enhanced in BSM scenarios
- NNLO+PS computation (C.Biello, J.Mazzitelli, A.Sankar, M.Wiesemann, G.Zanderighi)
  - in 4FNS (massive b-quarks)
  - massification of massless two-loop amplitude
    (S.Badger, H.Bayu Hartanto, R.Poncelet, Z.Wu, Y.Zhang, S.Zoia)
  - using MiNNLOPS for parton shower matching
  - NLO+PS discrepancy 4FNS/5FNS substantially reduced



Vector boson fusion

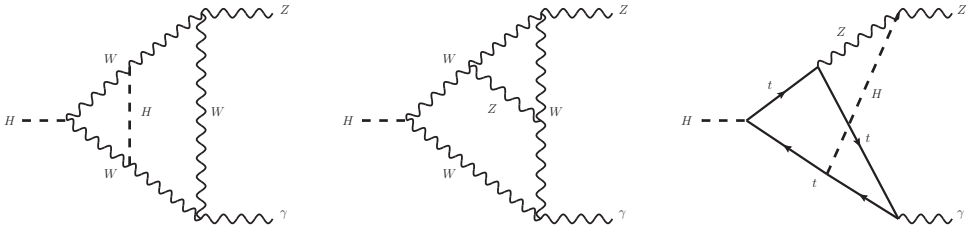
- detection of VBF Higgs production in $H \longrightarrow bb$ channel
  - requires stringent cuts (e.g. ATLAS: $p_{T,bjet}$>65 GeV)
  - cuts induce large perturbative corrections
    (K.Asteriadis, A. Behring, K.Melnikov, I.Novikov, R.Röntsch)
- fixed-order description insufficient
  - dominant effects from final-state radiation off b-quarks
  - match to parton shower
    (A.Behring, K.Melnikov, I.Novikov, G.Zanderighi)



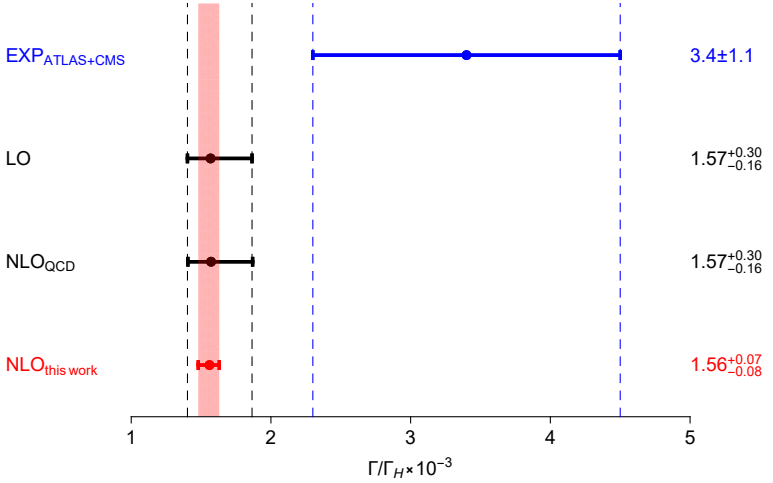


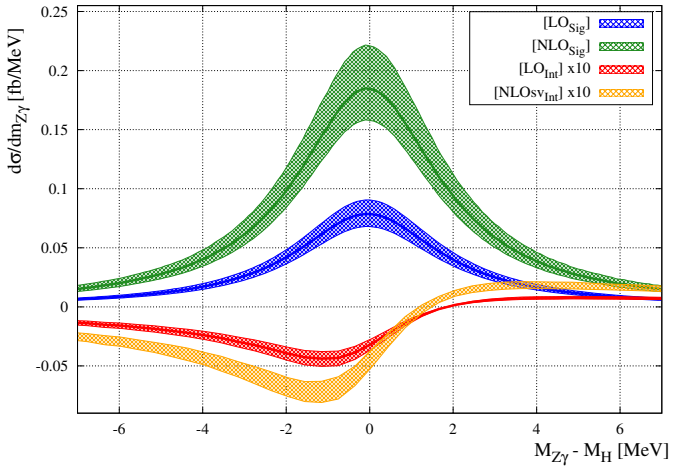
Dalitz decays: $H \to l^+l^-\gamma$

- dominated by loop-induced $H \to Z\gamma$
- NLO electroweak corrections
  - small effect, reduce theory uncertainty
    (Z.Q.Chen, L.B.Chen, C.F.Qiao, R.Zhu)



- signal-background interference
  (F.Buccioni, F.Devoto, A.Djouadi, J.Ellis, J.Quevillon, L.Tancredi)
  - small distortion of distributions
  - negligible effect on mass peak





Decay interferometry

- Higgs boson decays to weak gauge bosons

  $H \longrightarrow ZZ^* \longrightarrow e^+e^-\mu^+\mu^-$ and $H \longrightarrow WW^* \longrightarrow l^+\nu l^-\nu$

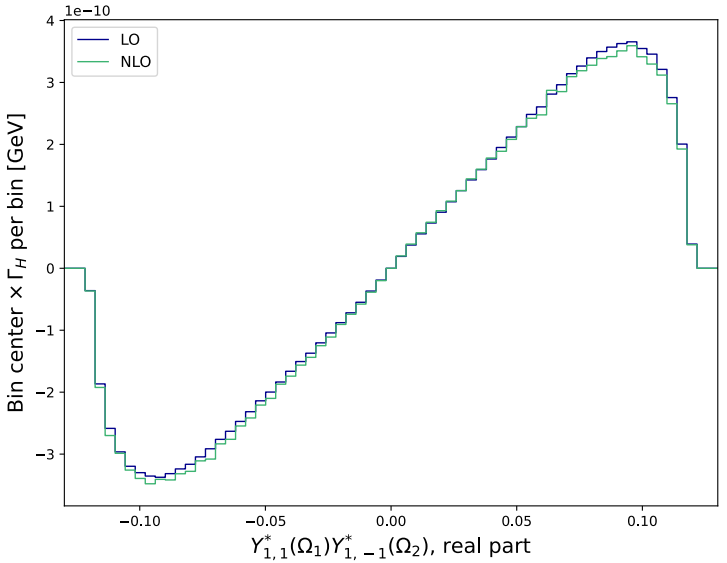
  - form an entangled two-qutrit state (A.Barr)
  - lepton and neutrino helicity unmeasurable: event-by-event test of entanglement not feasible
  - reconstruct spin-density matrix of diboson system (quantum tomography) (J.Aguilar-Saavedra, J.Bernal, J.Casas, J.Moreno)
  - uses decomposition of final-state lepton distribution in spherical harmonics
  - most promising channel $H \longrightarrow ZZ^* \longrightarrow e^+e^-\mu^+\mu^-$
  - simple spin-density matrix at LO

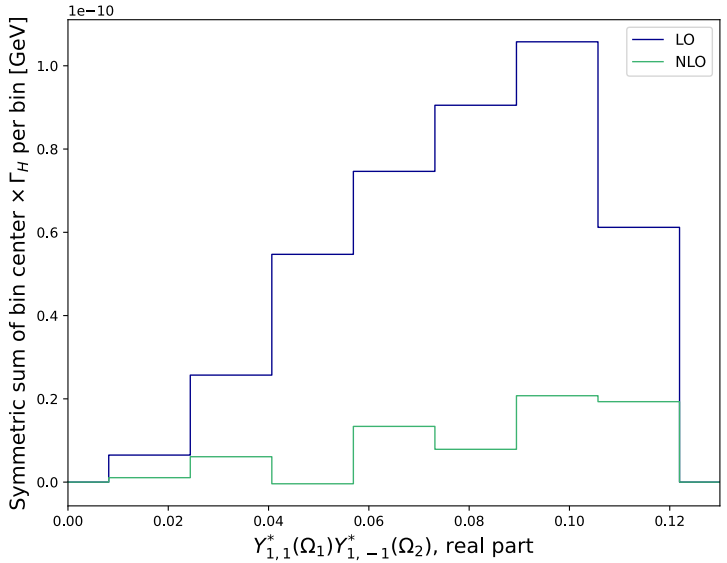
$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}\left(1-\sqrt{2}A^1_{2,0}\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Decay interferometry

- precision study of spin-density matrix of $H \longrightarrow ZZ^* \longrightarrow e^+e^-\mu^+\mu^-$
  - partial wave coefficients very sensitive to NLO EW corrections
    (M.Del Gratta, F.Fabbri, P.Lamba, F.Maltoni, D.Pagani; D.Goncalves, A.Kaladharan, F.Krauss, A.Navarro)
  - Bell-inequality tests require careful selection of reference frame, observables and cuts

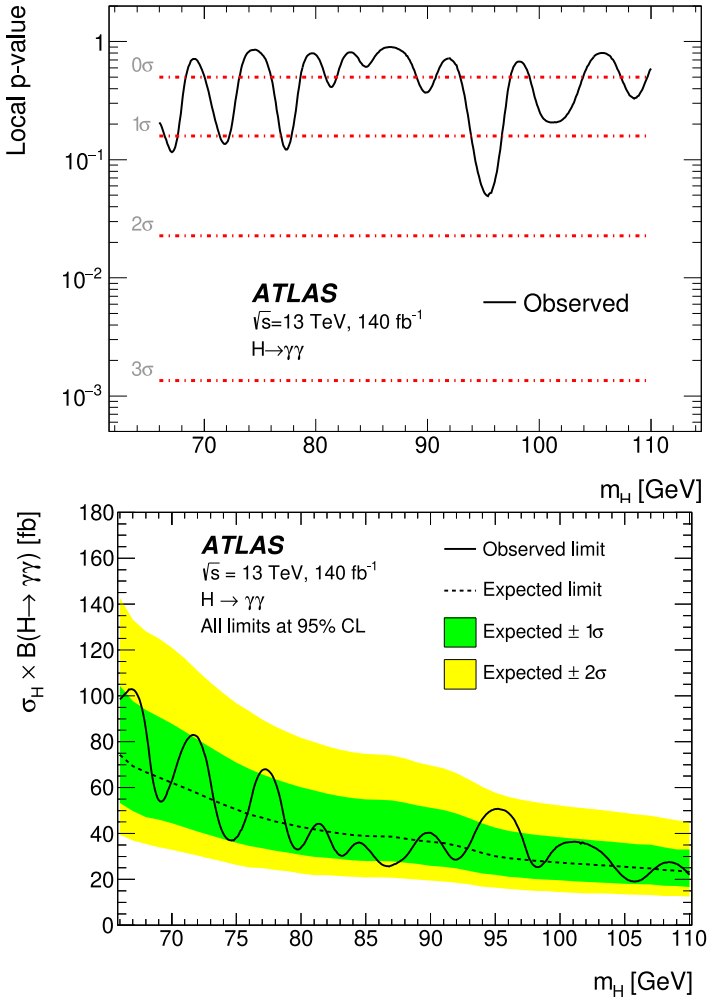
	LO	NLO	NLO / LO
$A^1_{2,0}$	$-0.592(1)$	$-0.509(2)$	$0.860(2)$
$A^2_{2,0}$	$-0.591(1)$	$-0.565(2)$	$0.956(2)$
$C_{2,1,2,-1}$	$-0.937(2)$	$-0.943(4)$	$1.006(3)$
$-C_{1,1,1,-1}$	$-0.94(1)$	$-0.16(2)$	$0.17(2)$
$A^1_{2,0}/\sqrt{2}+1$	$0.5817(7)$	$0.640(1)$	$1.101(2)$
$C_{2,2,2,-2}$	$0.581(3)$	$0.568(4)$	$0.977(6)$
$-C_{1,0,1,0}$	$0.59(1)$	$0.03(2)$	$0.06(4)$
$C_{2,0,2,0}$	$1.418(3)$	$1.400(5)$	$0.987(3)$
$C_{1,0,1,0}+2$	$1.41(1)$	$1.97(2)$	$1.39(1)$





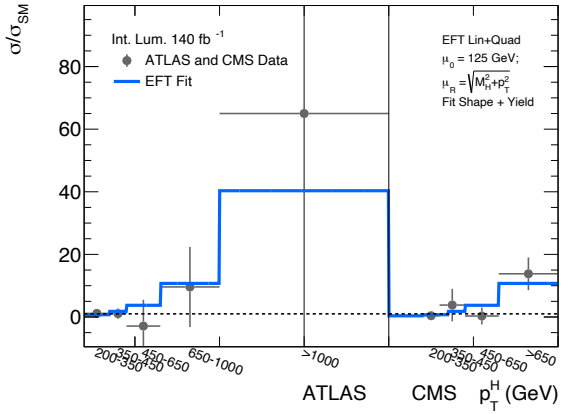
New physics searches in the Higgs sector

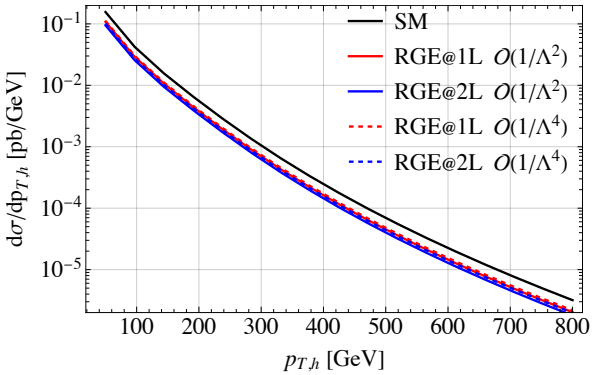
- Another Higgs boson decaying to γγ at 95 GeV?
  - ATLAS and CMS report ~2σ excess at same mass value
- Triggered substantial theory activity
  - 2HDM and its extensions (U.Haisch, A.Malinauskas; D.Azevedo, T.Biekötter, P.Ferreira; T.Biekötter, S.Heinemeyer, G.Weiglein)
  - triplet scalar (S.Ashanujjaman, S.Banik, G.Coloretti, A.Crivellin, B.Mellado, A.T.Mulaudzi)
  - NMSSM (J.Cao, X.Jia, Y.Yue, H.Zhou, P.Zhu)
  - Georgi-Machacek model (T.K.Chen, C.W.Chiang, S.Heinemeyer, G.Weiglein)
  - MRSSM (J.Kalinowski, W.Kotlarski)
  - Left-right symmetric models (P.Bhupal Dev, R.N.Mohapatra, Y.Zhang)
- Usually predicting other light states

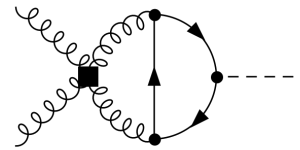


Anomalous couplings: SMEFT

- Model-independent framework to quantify BSM effects
- Important constraints from Higgs observables
  - e.g. transverse momentum distribution
    (M.Battaglia, M.Grazzini, M.Spira, M.Wiesemann)
- Consistent treatment: SMEFT renormalization group
  - global one-loop analysis
    (F.Maltoni, G.Ventura, E.Vryonidou; J.ter Hoeve, L.Mantani, J.Rojo, A.Rossia, E.Vryonidou)
  - two-loop analysis in Higgs sector (S.Di Noi, R.Gröber, M.Mandal)
- Two-loop SMEFT computations in progress
  - field renomalization (C.Duhr, A.Vasquez, G.Ventura, E.Vryonidou)
  - two-loop matching and impact on Higgs production (U.Haisch)

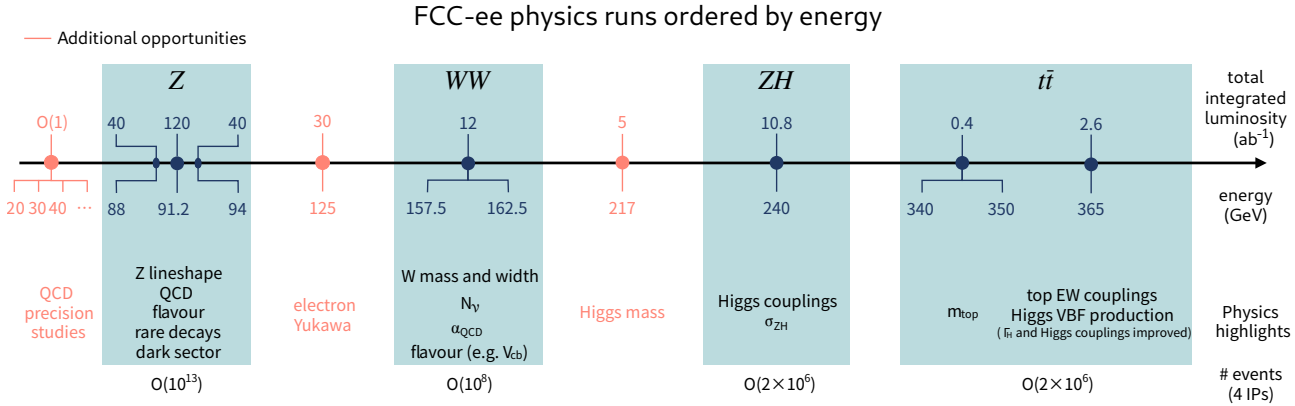


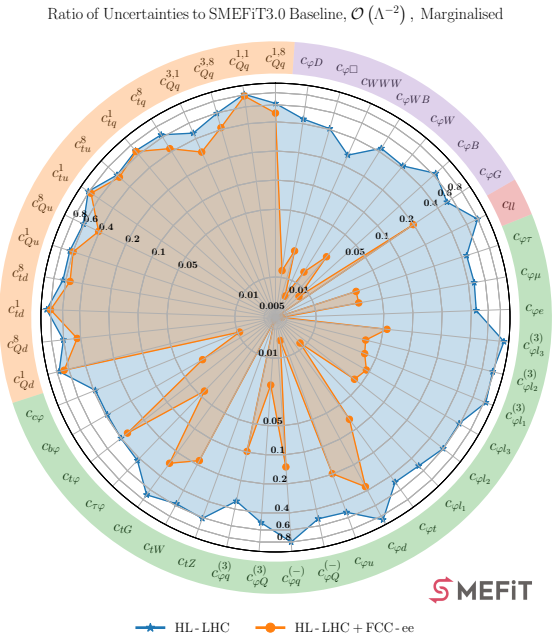




FCC-ee as Higgs boson factory

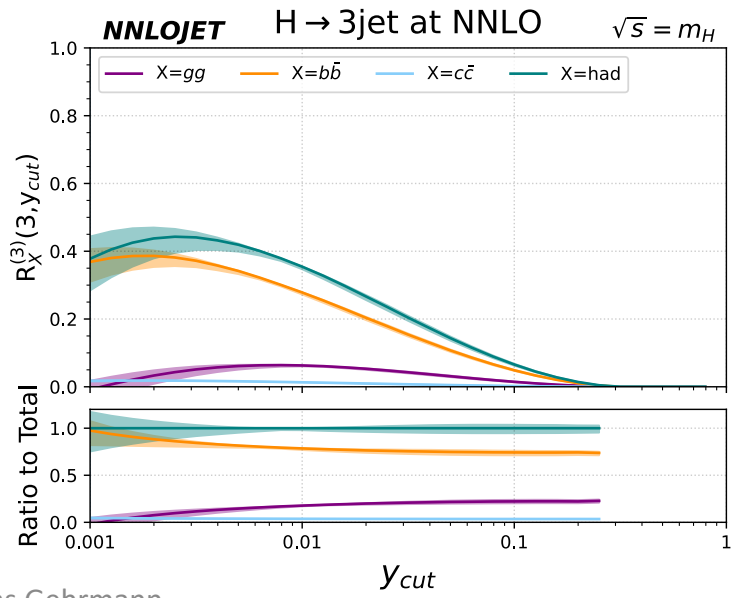
- FCC-ee project at CERN
  - ultrahigh-luminosity e^+e^- collider
  - under consideration
  - start of operation ~2045
- Unique Higgs boson precision studies
  - produce 2M Higgs bosons
  - reconstruct all decay channels
  - tightly constrain SMEFT operators
    (E.Celada, T.Gianni, J.ter Hoeve, L.Mantani, J.Rojo, A.Rossia, M.Thomas, E.Vryonidou)
  - including Higgs self-coupling (V.Maura, B.Stefanek, T.You)
- Require new level of precision theory

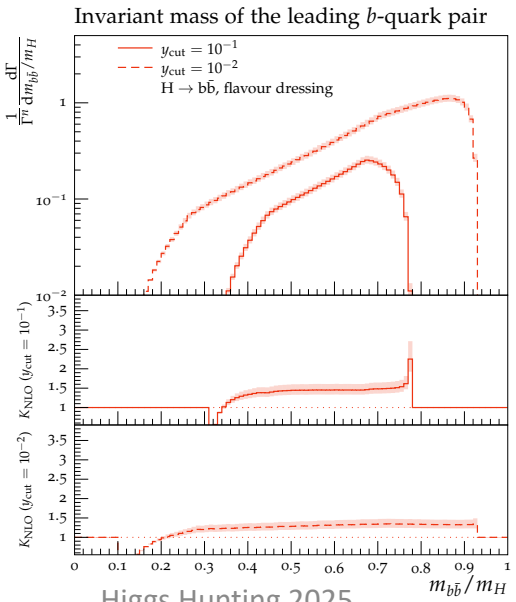


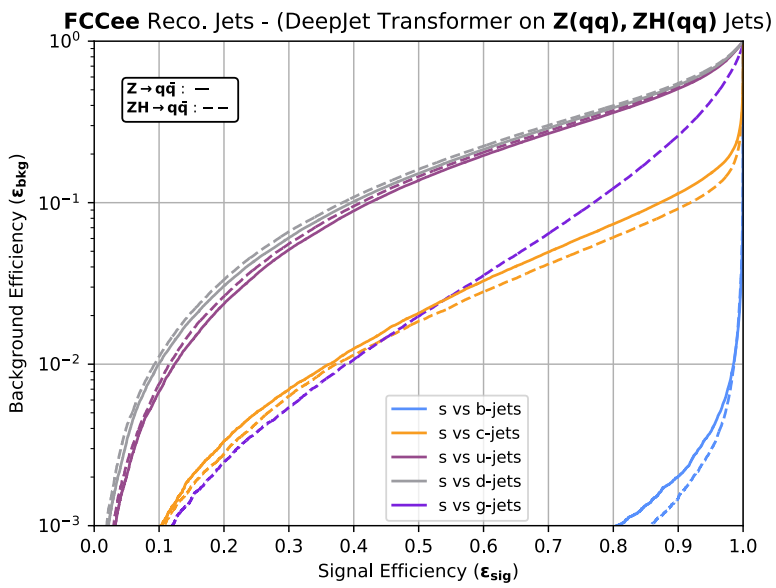


QCD Higgs physics at FCC-ee

- Hadronic Higgs decays at FCC-ee
  - dominant contributions from H ⟶ bb, H ⟶ cc, H ⟶ gg
  - discriminate decay modes through jet rates, event shape distributions and flavour tagging (B.Campillo Aveleira, E.Fox, A.Gehrmann-De Ridder, N.Glover, M.Marcoli, C.Preuss, TG)
  - possibly resolve H ⟶ ss using transformer-based neural networks (F.Blekman, F.Canelli, A.De Moor, K.Gautam, A.Ilg, A.Macchiolo, E.Ploerer)







Outlook

- Theory and experiment prepare for precision Higgs physics program
- Important progress on precision theory predictions
  - Predictions for increasingly complex final states
  - Resolving long-standing issues and puzzles
  - Higgs physics is driver of innovation in multi-loop amplitude technology
- Exciting opportunities ahead
  - Quantum information in Higgs decay
  - Model independent new physics searches in SMEFT
  - Precision Higgs physics at FCC-ee
- Looking forward to an exciting Higgs Hunting 2025