Higgs boson decay into four bottom quarks in the SM and beyond

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July 2, 2019

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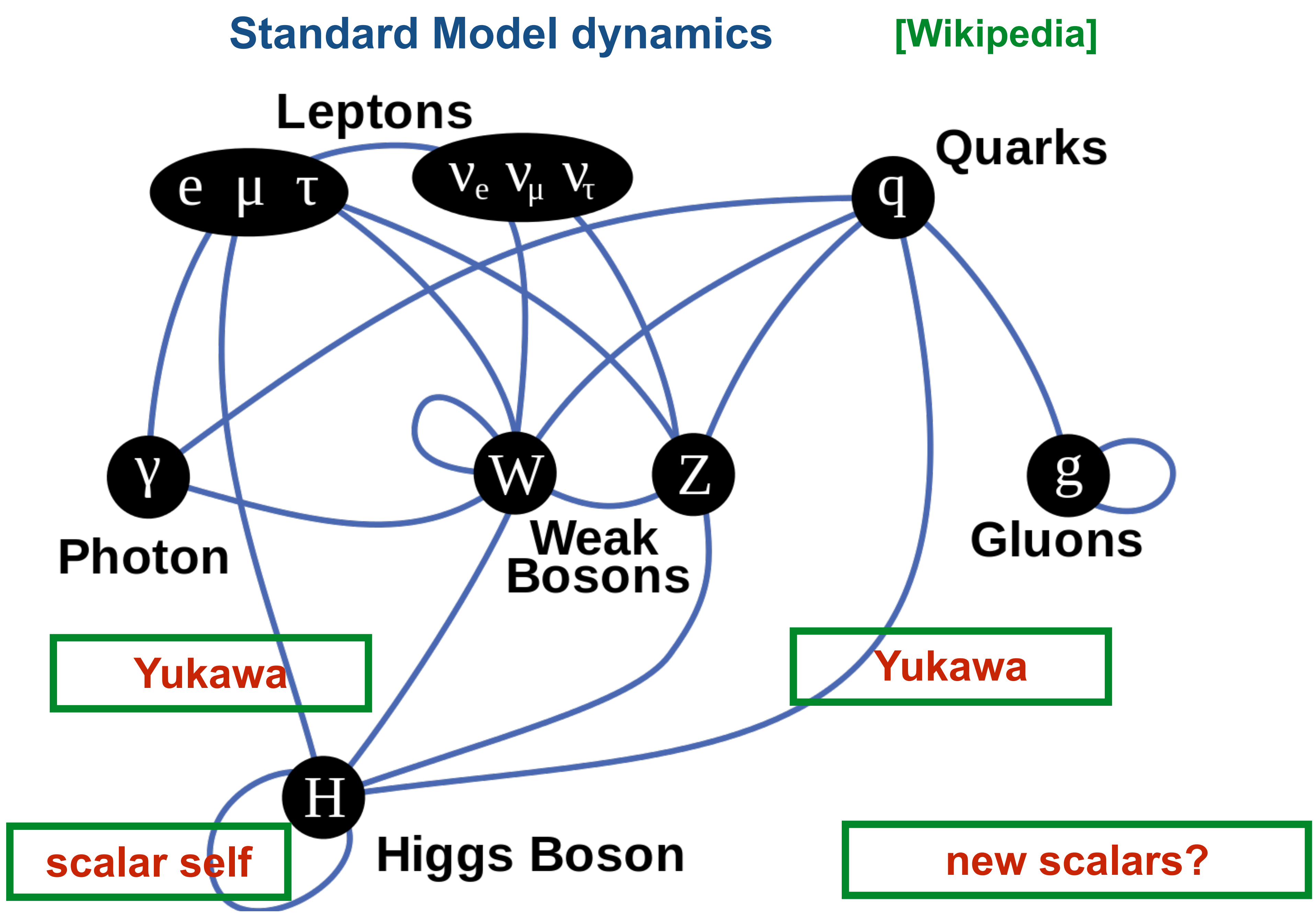
Post Higgs boson Era

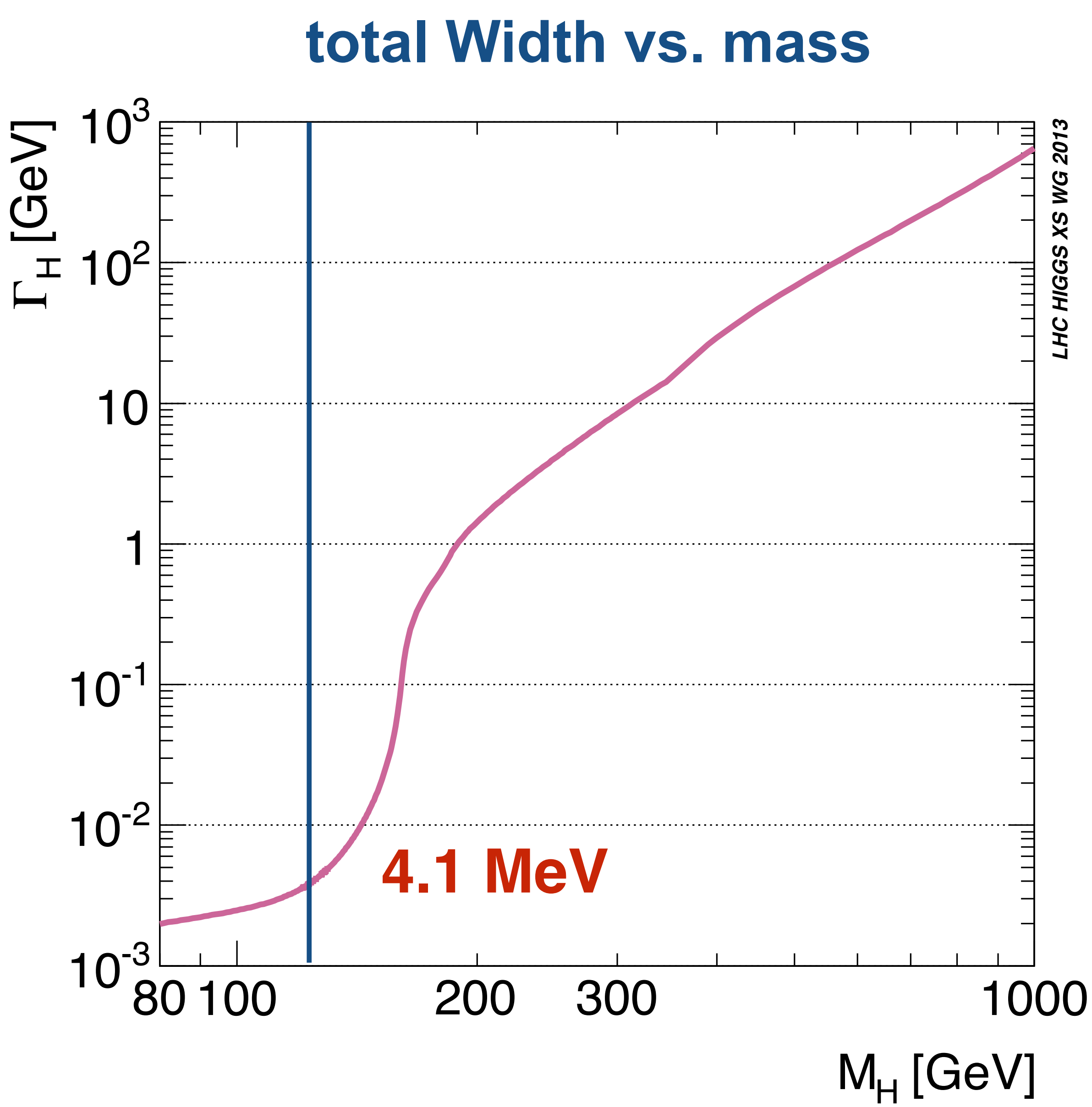
- Study on properties of the Higgs boson including looking for further extensions has been one of the high priority in the next few decades

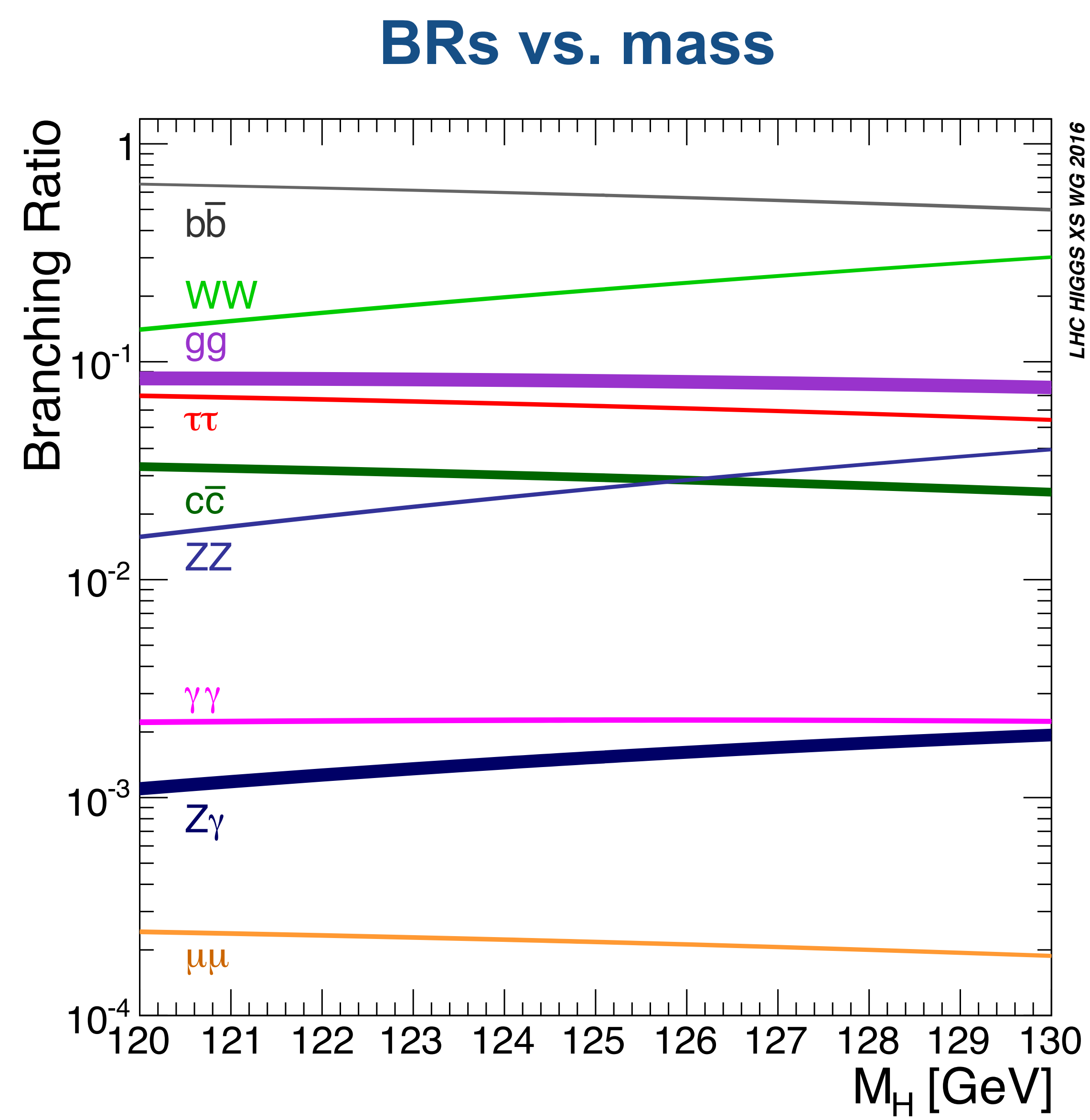


- Higgs boson introduces new phenomenas for study of elementary particles, spin-0 particle, scalar self interactions, Yukawa interactions

Decays of the Higgs boson

- Higgs boson with a mass of 125 GeV decays dominantly to bottom quark pair via Yukawa y_b~0.01 resulting in small width Γ/m~3×10^{-5}





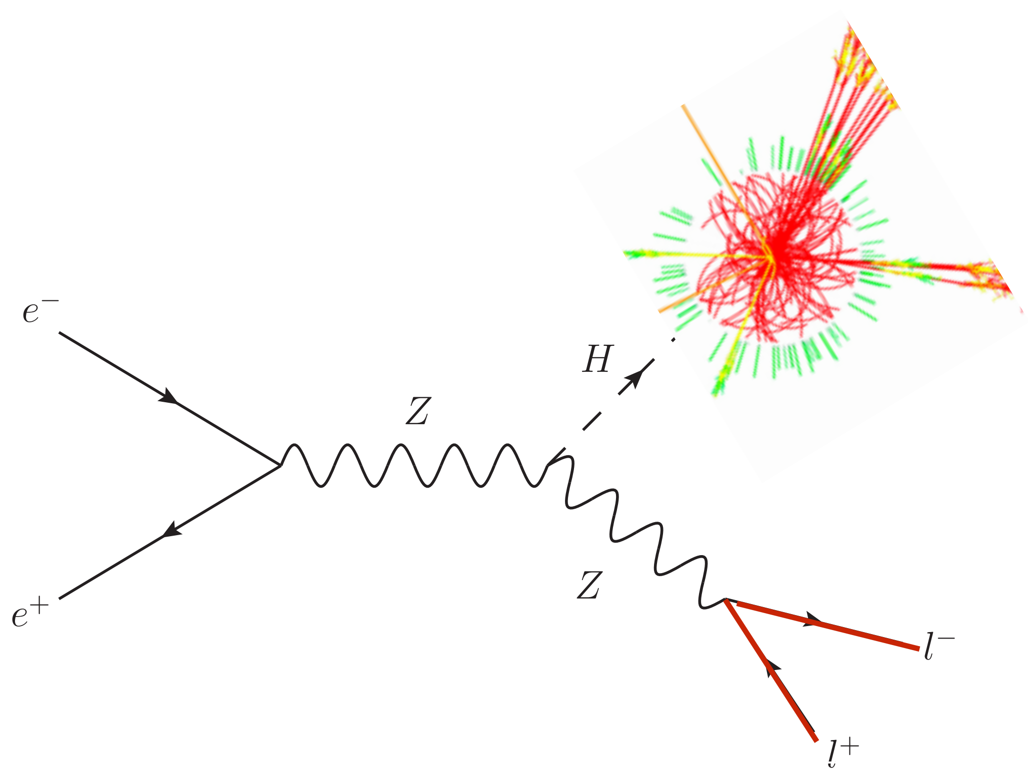
Hadronic decays of the Higgs boson

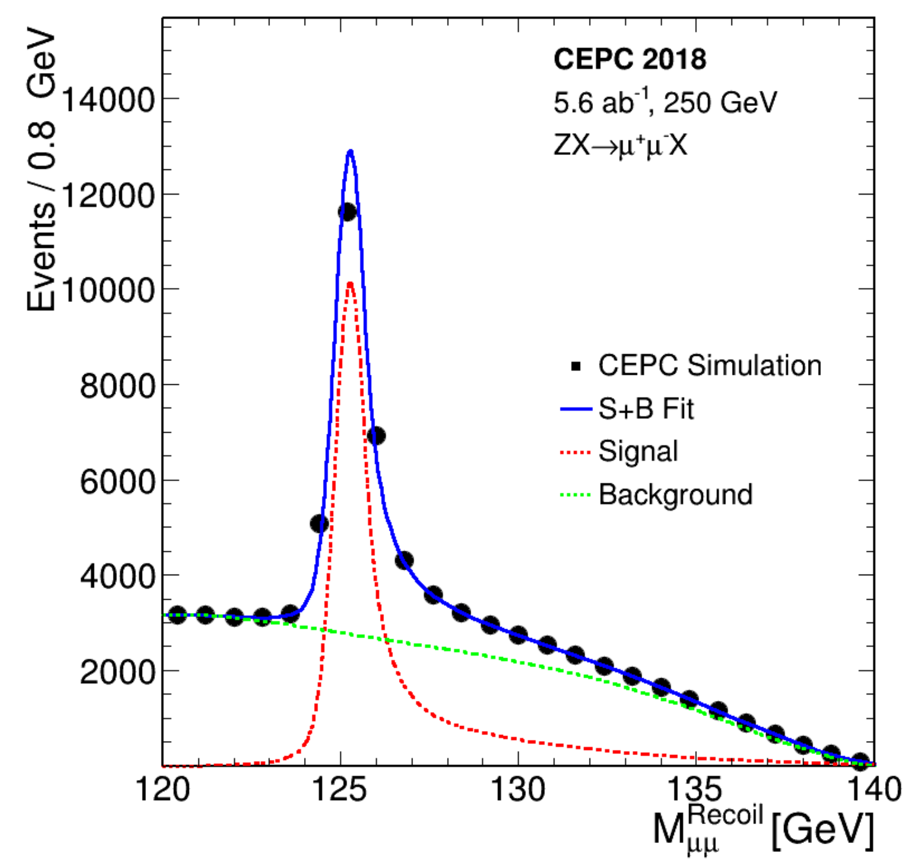
- Higgs boson event of hadronic decays can be selected based on the recoil mass and be fully reconstructed

SM event numbers assuming 250 GeV, 5 ab^{-1} and Z to electrons and muons

$Z(l^+l^-)H(X)$	gg	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
BR [%]	8.6	57.7	2.9	9.5	1.3	~ 0.02
N_{event}	6140	41170	2070	6780	930	14

$$m^2_{\rm recoil} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$





- full kinematic information allowing measurement of event shapes in Higgs rest frame

[An + for CEPC, 2018]

Higgs measurements at CEPC

- CEPC Higgs factory can provide percent-level precision with model-independent measurement of various Higgs couplings

	Estimated Precision	
Property	CEPC-v1 (250 GeV, 5.6 ab^{-1})	CEPC-v4 (240 GeV)
m_H	5.9 MeV	5.9 MeV
Γ_H	2.7%	2.8%
$\sigma(ZH)$	0.5%	0.5%
$\sigma(\nu\bar{\nu}H)$	3.0%	3.2%

Decay mode	$\sigma \times$ BR	BR	$\sigma \times$ BR	BR
$H \to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H \to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H \to gg$	1.2%	1.3%	1.3%	1.4%
$H \to WW^*$	0.9%	1.1%	1.0%	1.1%
$H \to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H \to \gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H \to Z\gamma$	13%	13%	16%	16%
$H \to \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H \to \mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–	$< 0.28\%$	–	$< 0.30\%$

[An + for CEPC, 2018]

- different hadronic channels can be separated through jet identifications, e.g., heavy-flavor tagging, quark-gluon jet discrimination

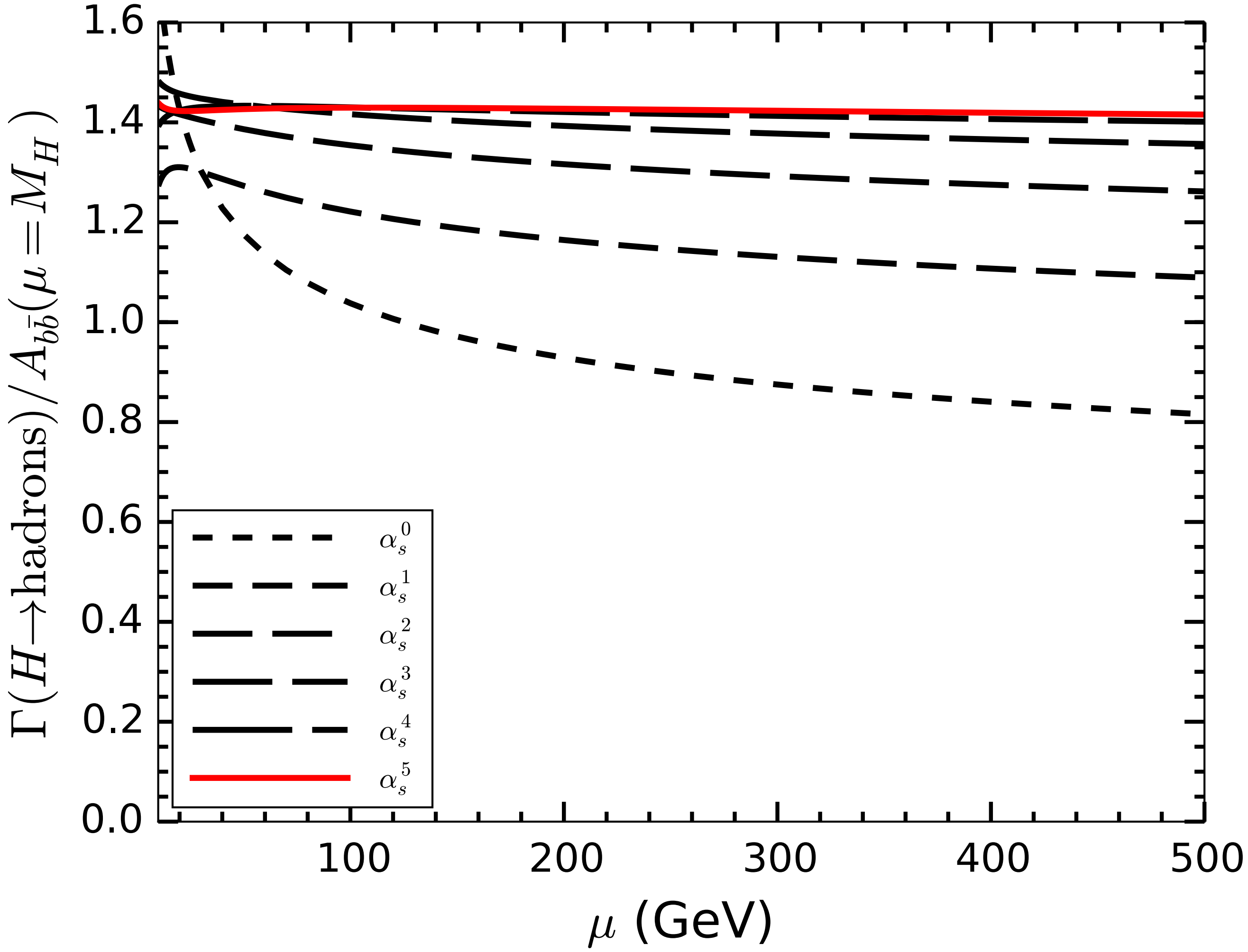
Total hadronic decay width

- High precision theoretical predictions exist, full results known at O(as^4); even higher order results exist for individual channels

Higgs effective theory

$$\mathcal{L}_{\rm eff} = -\frac{H^0}{v^0}\left(C_1[\mathcal{O}'_1] + C_2[\mathcal{O}'_2]\right) + \mathcal{L}'_{\rm QCD} \qquad \mathcal{O}'_1 = \left(G^{0\prime}_{a,\mu\nu}\right)^2 , \quad \mathcal{O}'_2 = m_b^{0\prime}\bar{b}^{0\prime}b^{0\prime}$$

$$\Gamma(H \to \text{hadrons}) = A_{b\bar{b}}\left[(C_2)^2(1+\Delta_{22}) + C_1C_2\Delta_{12}\right] + A_{gg}\,(C_1)^2\,\Delta_{11}$$



[Davies, Steinhauser, Wellmann, 2017]

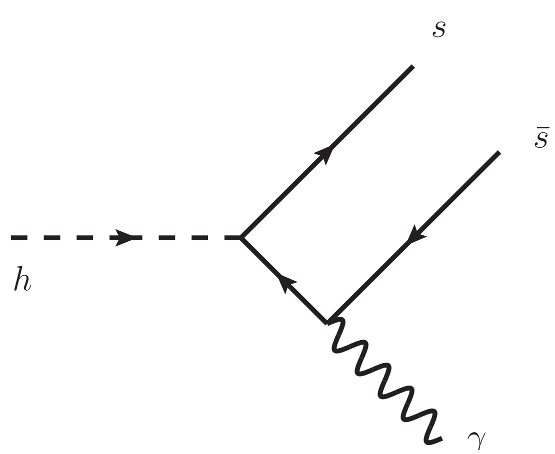
[Herzog, Ruijl, Ueda, Vermaseren, Vogt, 2017]

Exclusive hadronic decays

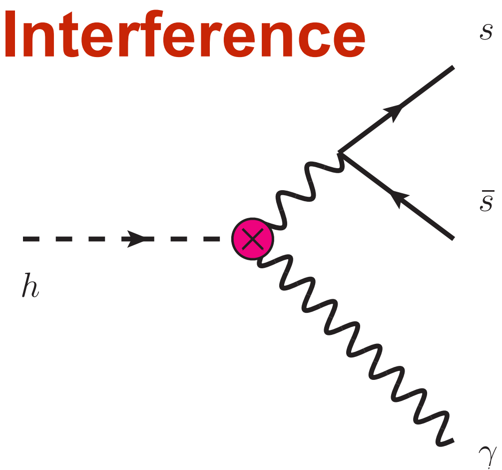
- Measuring Yukawa couplings of light-quarks at LHC are particularly challenging due to their smallness, **$y_s/y_b \sim 2\%$**, and huge QCD Bks

exotic decays (BR~10^{-6})

$$h \to \phi\gamma$$



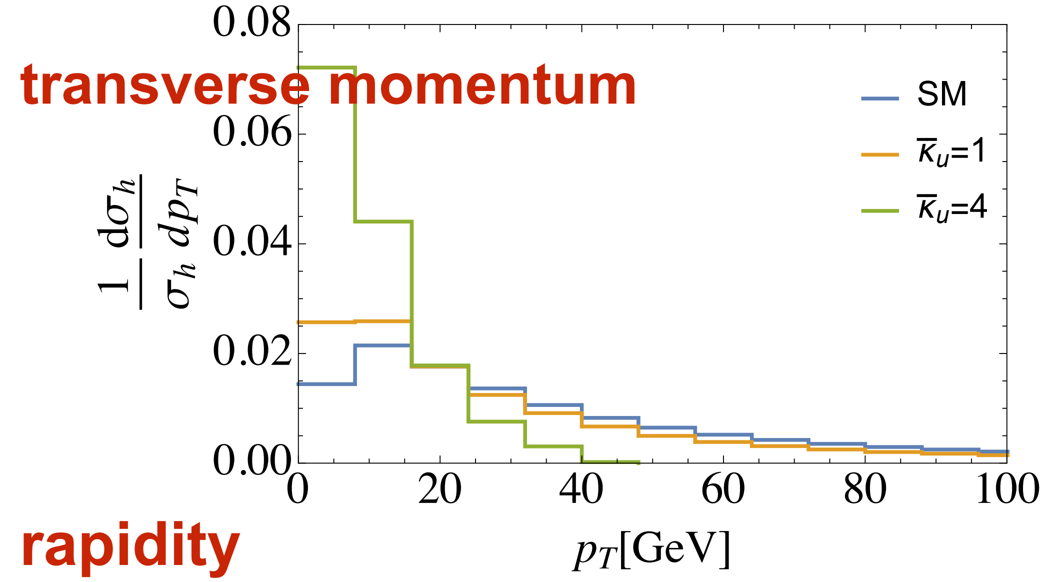
Interference



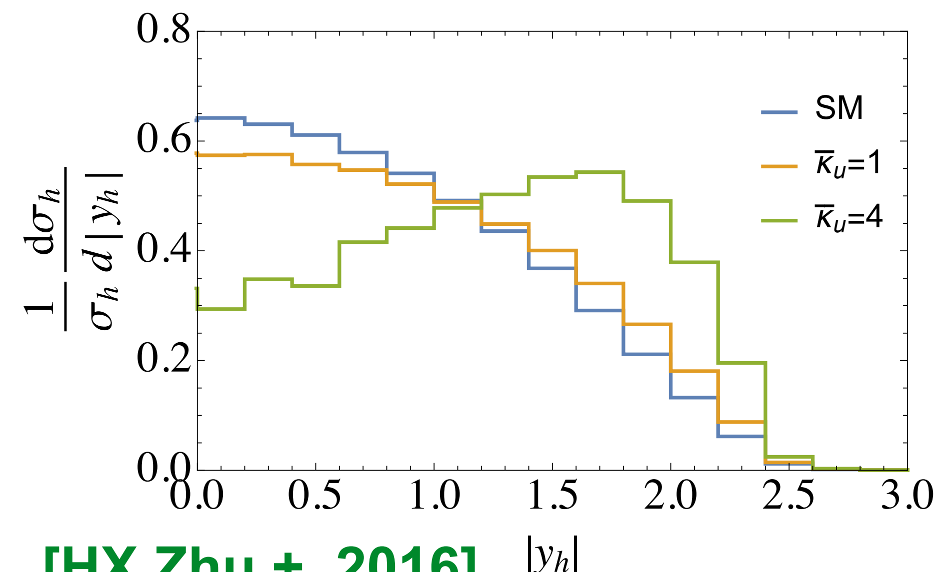
[Kagan +, 2014, 2016]

- low sensitivity due to huge hadronic backgrounds

Higgs kinematics



rapidity

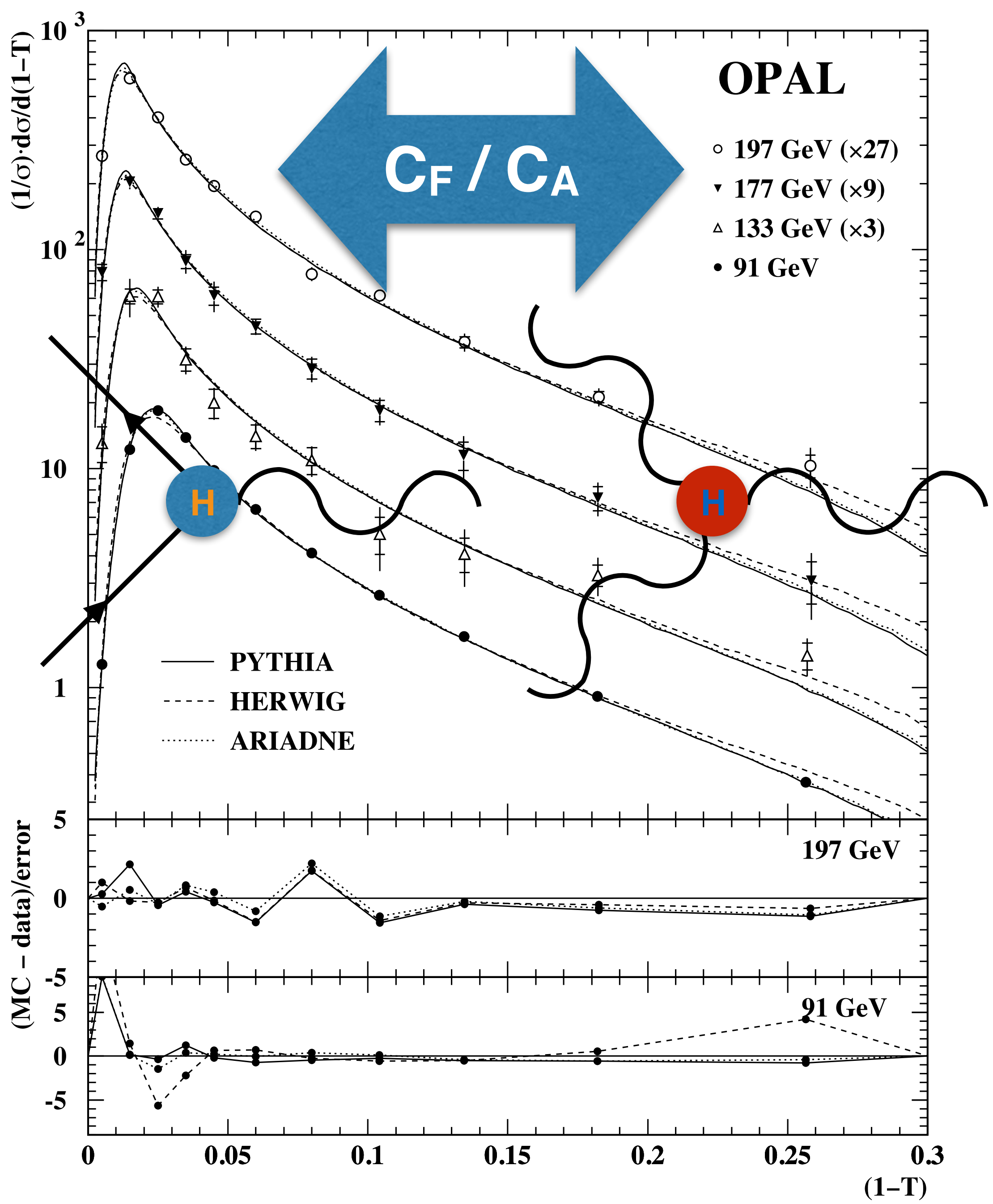


[HX Zhu +, 2016]

- LHC/HL-LHC can probe Yukawa of u/d quarks to ~$0.3y_b$

Exclusive hadronic decays

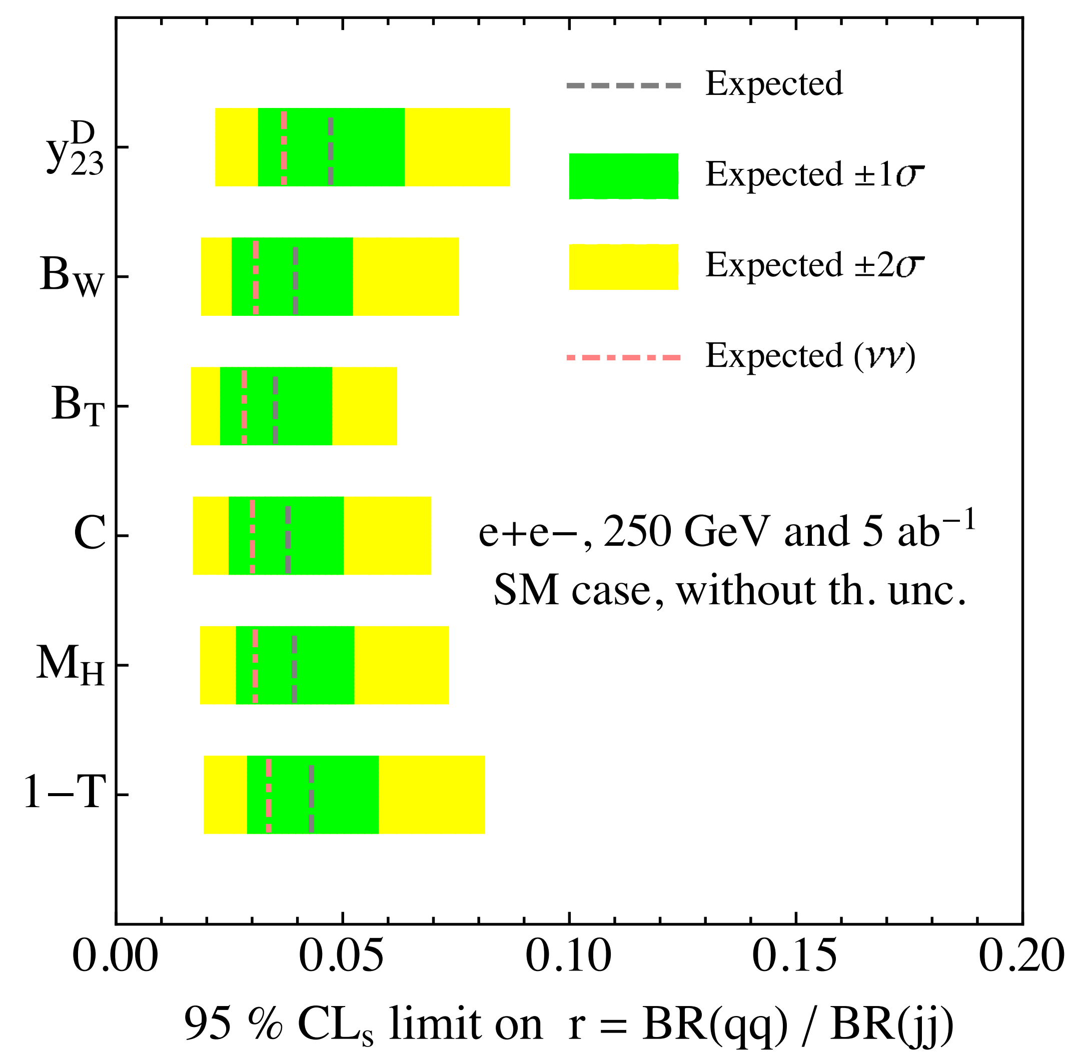
- Using hadronic event shapes to look for light-quark decay modes and Yukawa couplings; projected sensitivity for 250 GeV run with 5 ab^{-1}



[OPAL, 2005]

expected exclusion limit

[JG, 1608.01746]

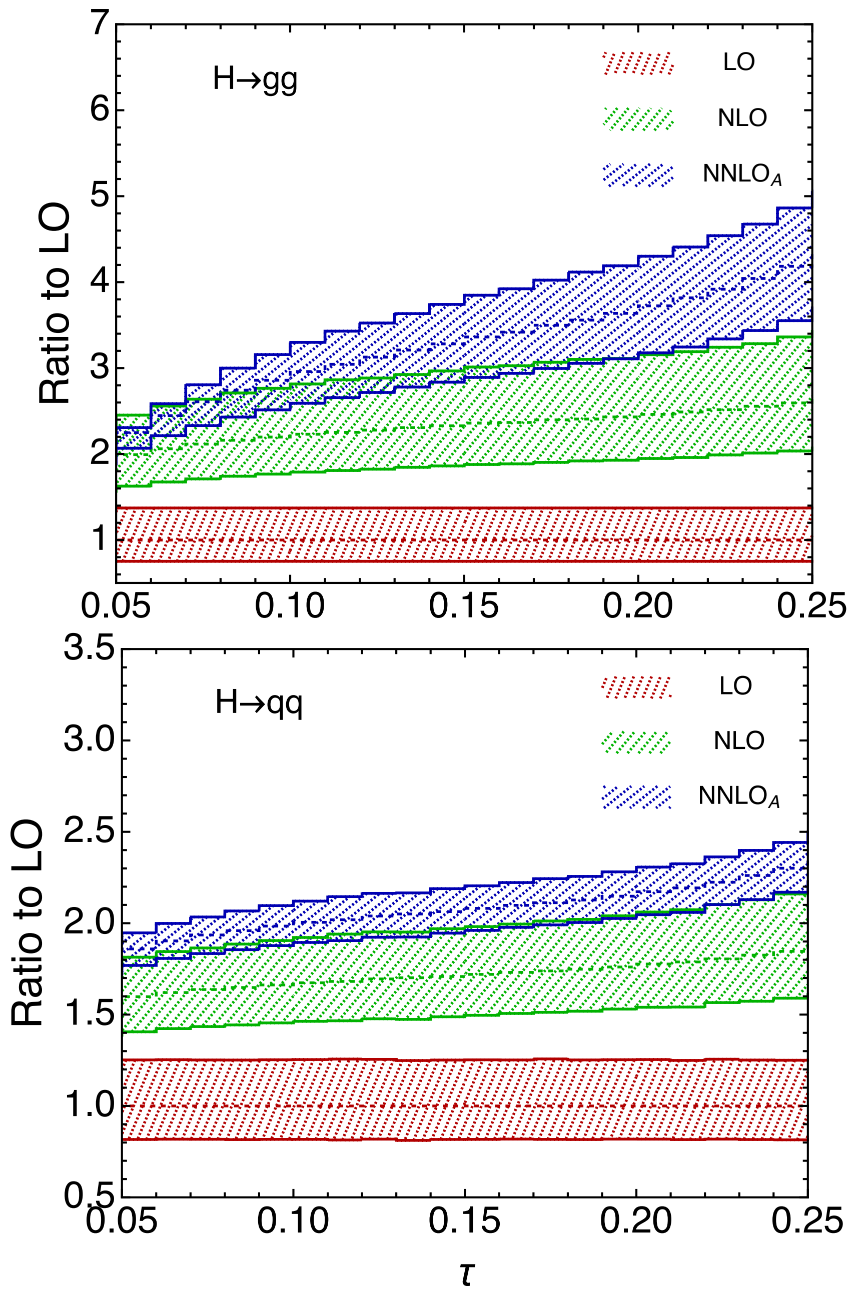


from various event shapes

Improving theoretical prediction

- Works are in progress on improving theoretical predictions on event shapes in Higgs decay, NLO and beyond **[JG, Gong, Ju, Yang, 2019]**

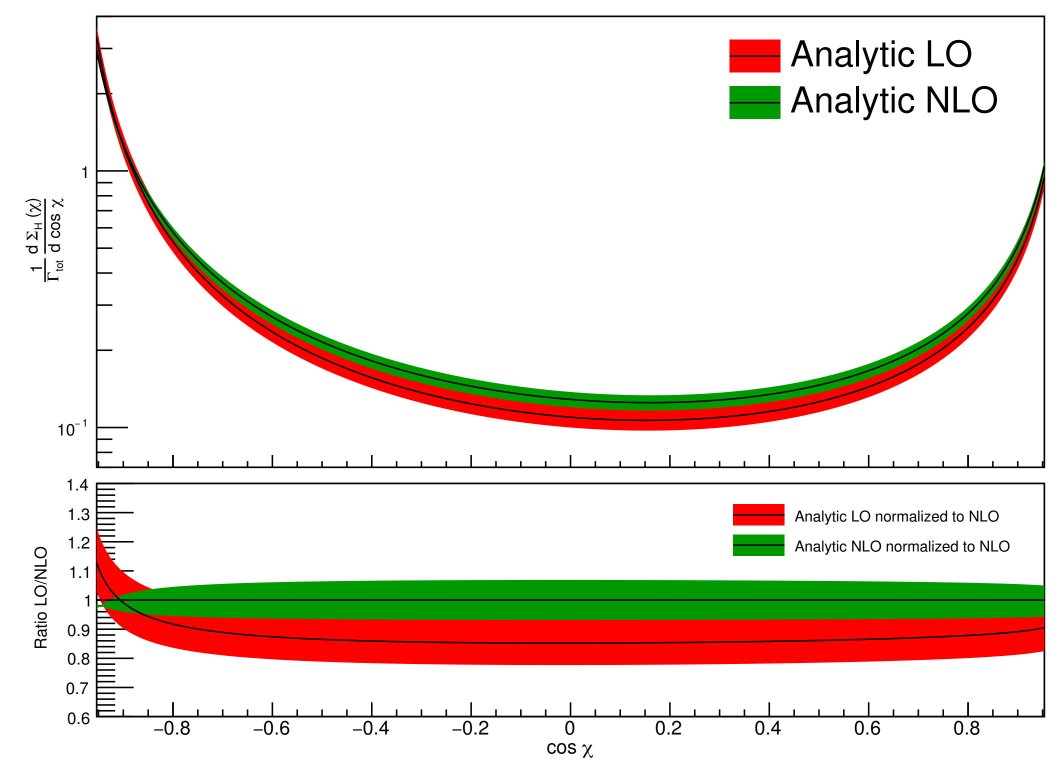
thrust distribution



- ☆ large QCD corrections similar to the inclusive decay

energy-energy correlations

$$\frac{1}{\Gamma_{\rm tot}}\frac{d\Sigma_H(\chi)}{d\cos\chi} = \sum_{a,b}\int \frac{2E_aE_b}{m_H^2}\,\delta(\cos\theta_{ab}-\cos\chi)\,d\Gamma_{a+b+X}$$



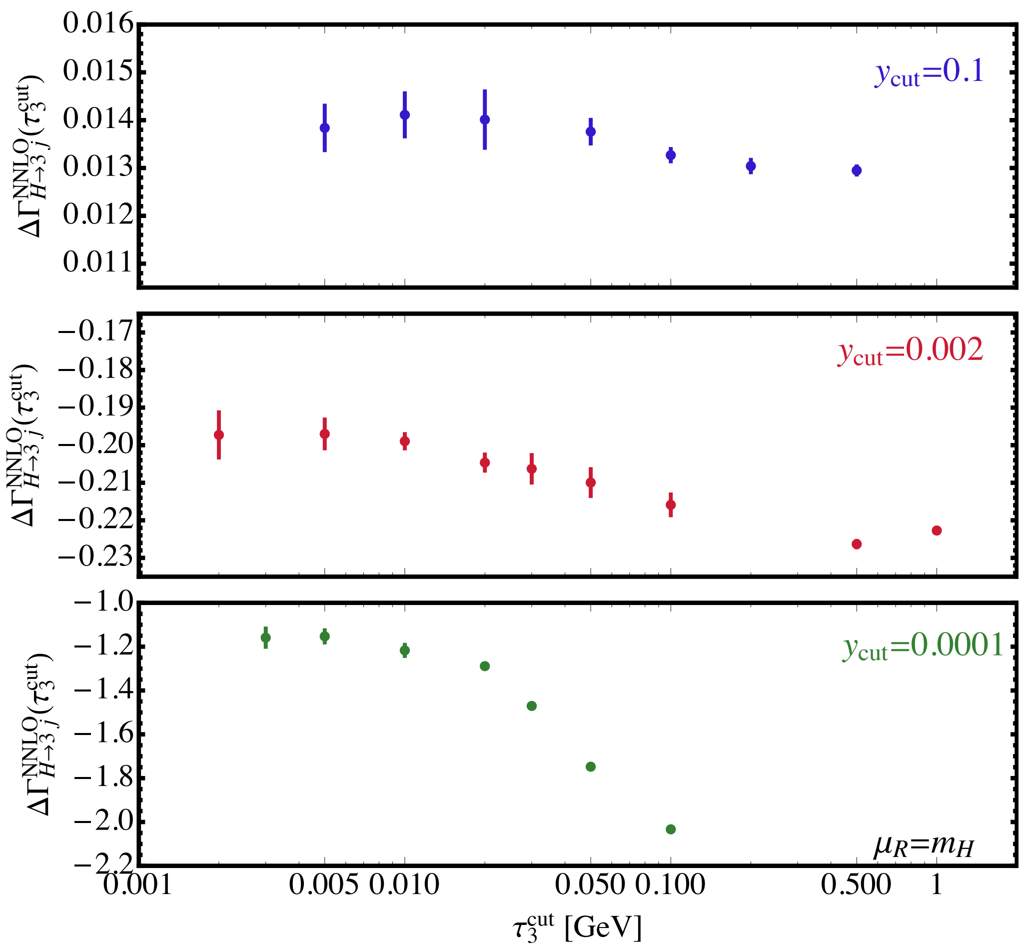
[Luo, Shtabovenko, Yang, Zhu, 2019]

- ☆ NLO predictions in a compact analytic form, only di-gluon channel yet

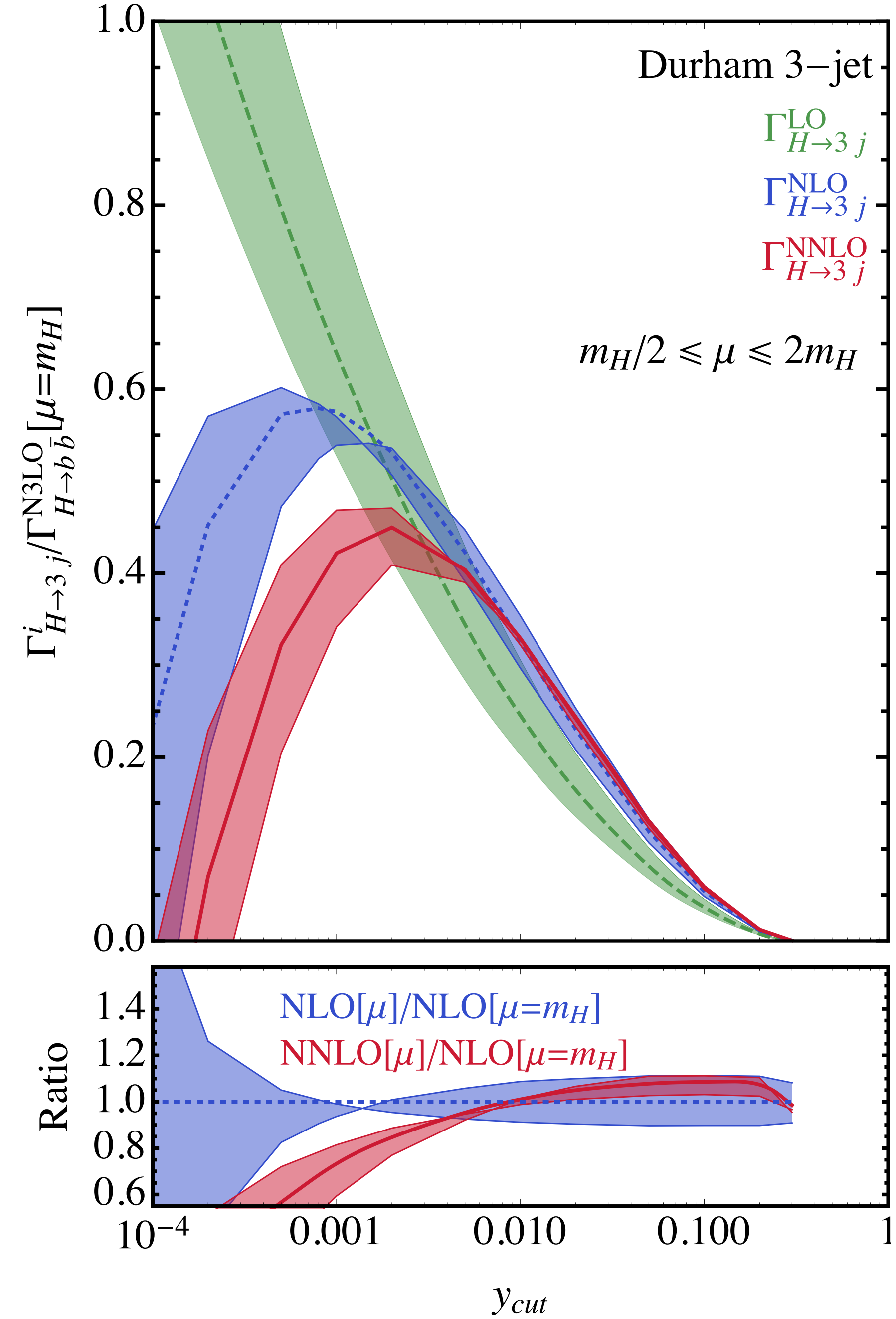
Improving theoretical prediction

✦ Exact NNLO QCD corrections have been recently carried out for Higgs decaying into three-jet for the (massless) bottom quark channel

3-jettiness for slicing



[Mondini, Williams, 2019]



☆ phase space slicing method is now widely used for NNLO calculations in QCD

[Catani, Grazzini, 2007]

[JG, Li, Zhu, 2012]

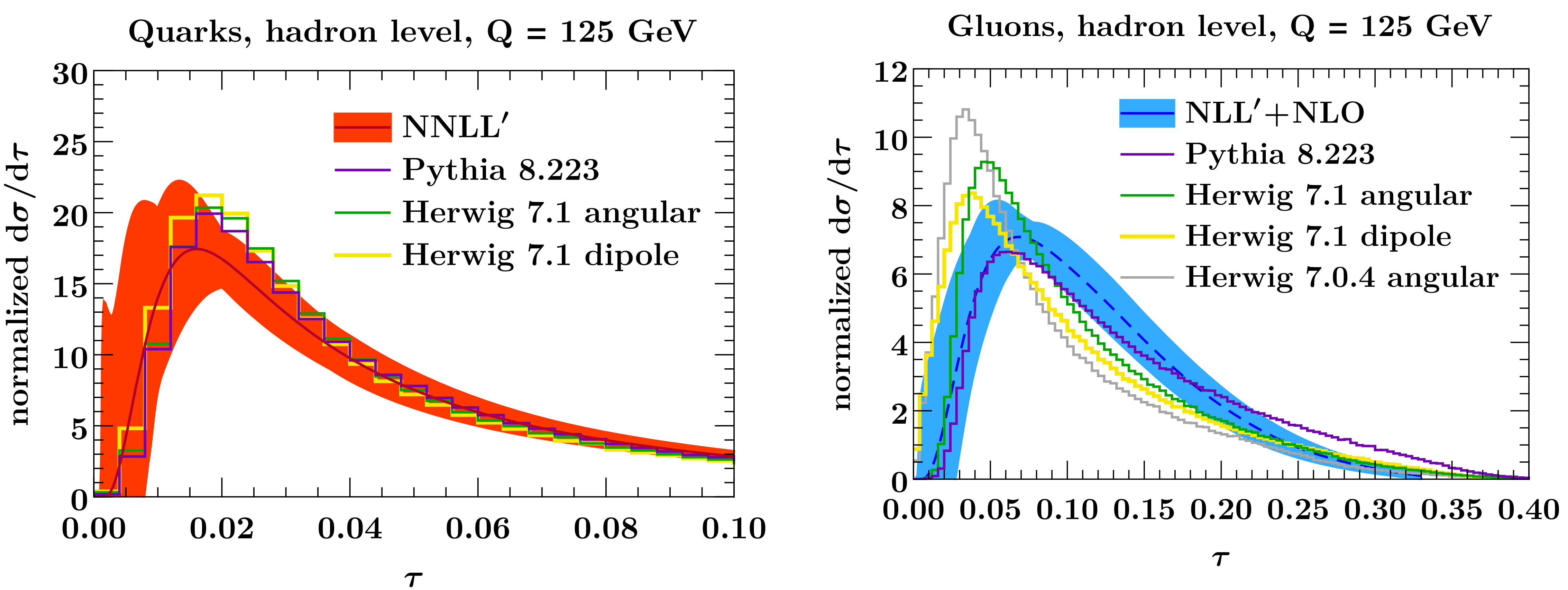
[Boughezal, Focke, Liu, Petriello, 2015]

☆ scale variations largely reduced at NNLO

Improving theoretical prediction

✦ Dependence of the event shape distributions on hadronization effects via either MC or analytic models

[Mo, Tackmann, Waalewijn, 2017]



thrust distribution (hadron level)

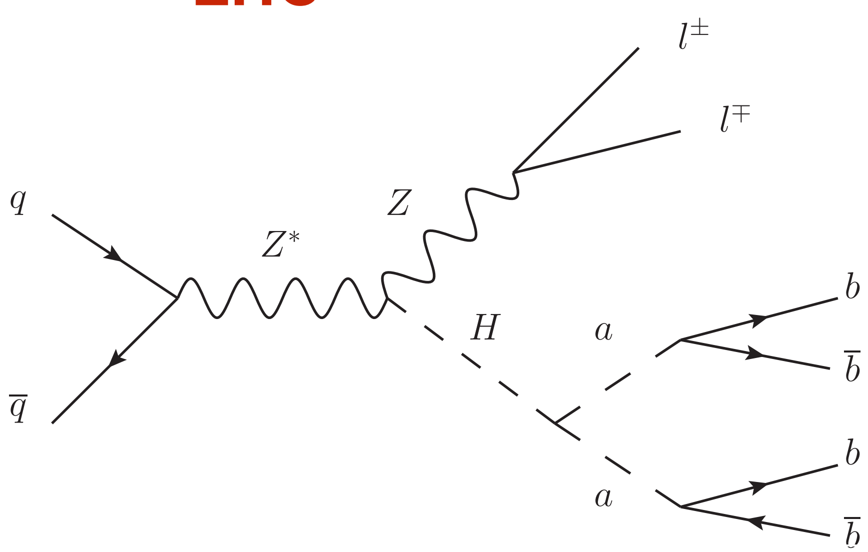
⭐ Non-perturbative corrections are not well understood in general for case of quark-gluon jet discrimination

Exotic hadronic decays

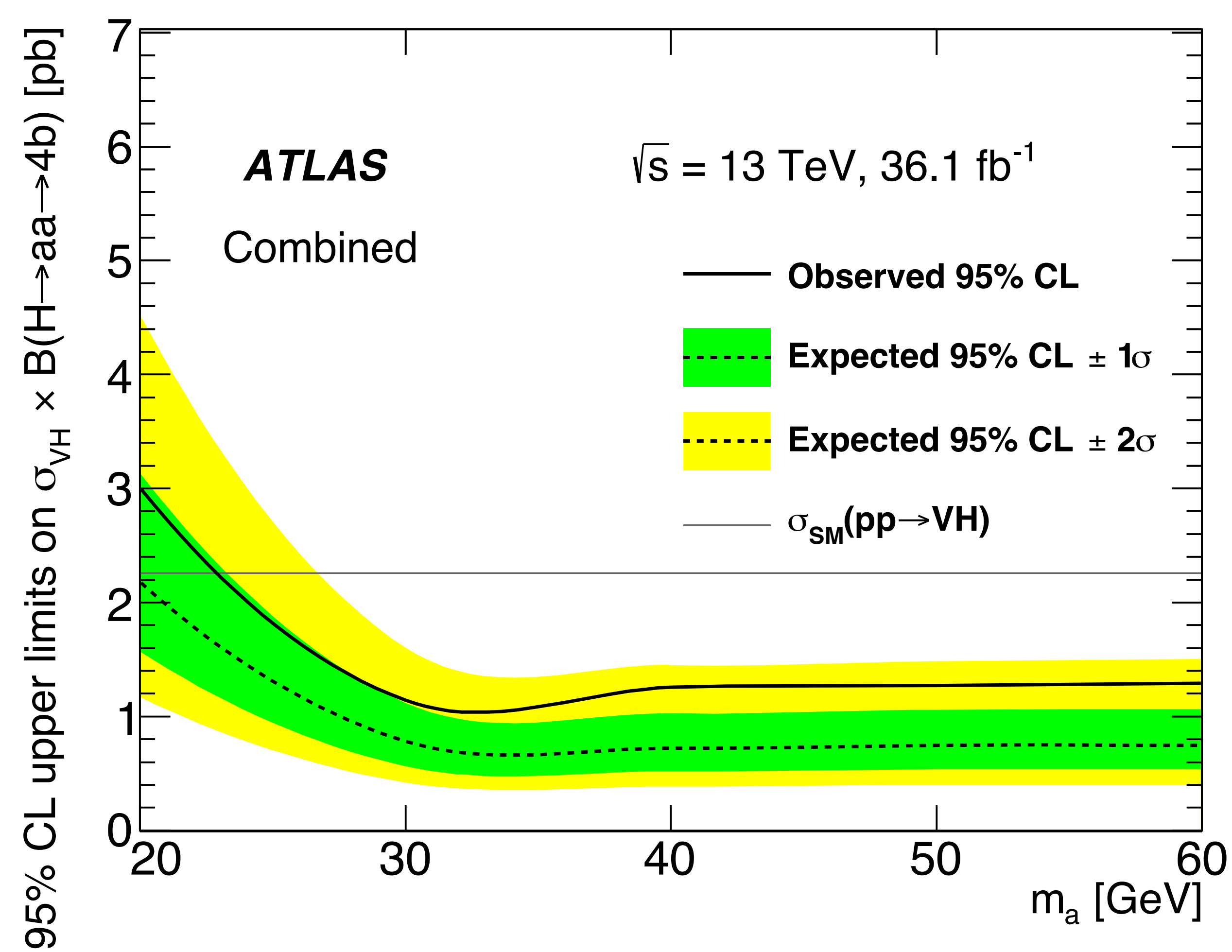
- Exotic hadronic decay modes can be explored directly at future electron-positron colliders, e.g., Higgs boson to four bottom quarks

direct search of new light scalars

LHC



[ATLAS, 1806.07355]



- current LHC limit on BRs (H→aa→4b) at ~50%

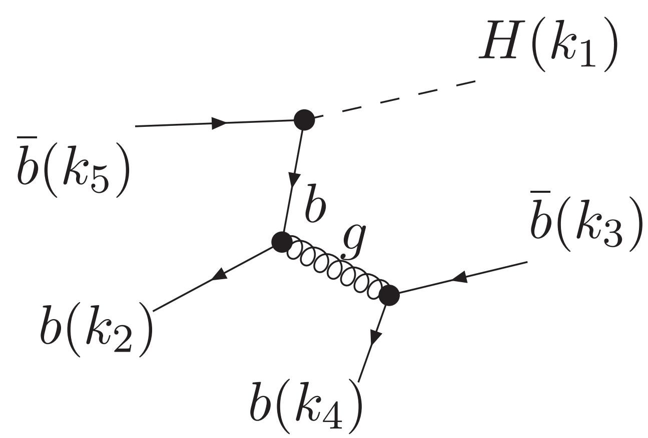
Higgs boson to four bottom quarks in SM

- A complete next-to-leading order calculation including both Yukawa and EW couplings with full bottom quark mass dependences

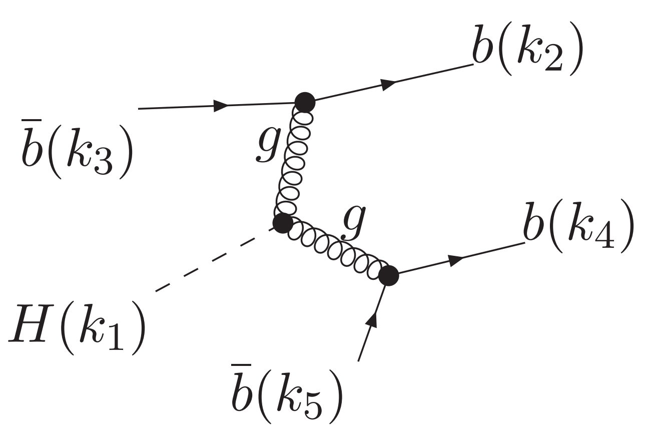
exotic decay in the SM **[JG, 1905.04865]**

Yukawa

$$\Gamma_{4b,yuk} = \left(\frac{\alpha_S(\mu)}{2\pi}\right)^2 \Big\{ A_{b\bar{b}}[\Delta_{b\bar{b}}(x)(1+\delta_{b\bar{b}}(x))C_2^2 + \Delta_{bg}(x)(1+\delta_{bg}(x))C_1C_2] + A_{gg}[\Delta_{gg}(x)(1+\delta_{gg}(x))C_1^2] \Big\},$$



$$A_{b\bar{b}} = \frac{3M_H}{8\pi v^2}\overline{m}_b^2(\mu), \qquad A_{gg} = \frac{4M_H^3}{2\pi v^2}, \qquad x = m_b^2/M_H^2,$$



$$\begin{aligned}
\delta_{b\bar{b}}(x) &= \frac{\alpha_S(\mu)}{2\pi}\left[(2\beta_0 + 3C_F)\ln(4\mu^2/M_H^2) + a_{b\bar{b}}(x)\right], \\
\delta_{bg}(x) &= \frac{\alpha_S(\mu)}{2\pi}\left[(3\beta_0 + 3C_F)\ln(4\mu^2/M_H^2) + a_{bg}(x)\right], \\
\delta_{gg}(x) &= \frac{\alpha_S(\mu)}{2\pi}\left[(4\beta_0)\ln(4\mu^2/M_H^2) + a_{gg}(x)\right].
\end{aligned}$$

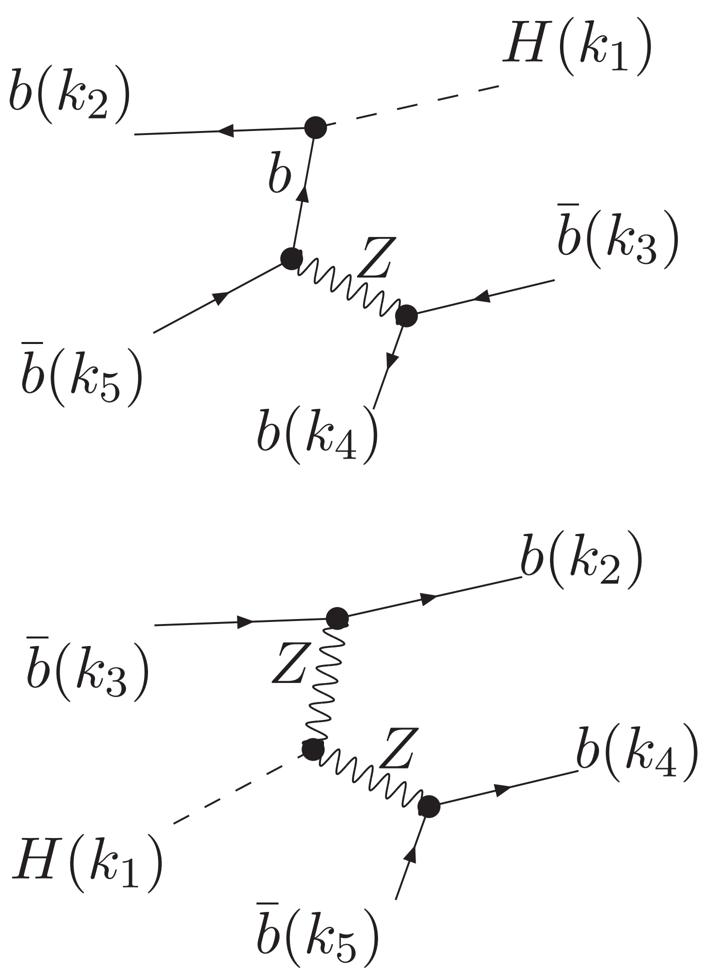
- mixing of operator O_1 and O_2

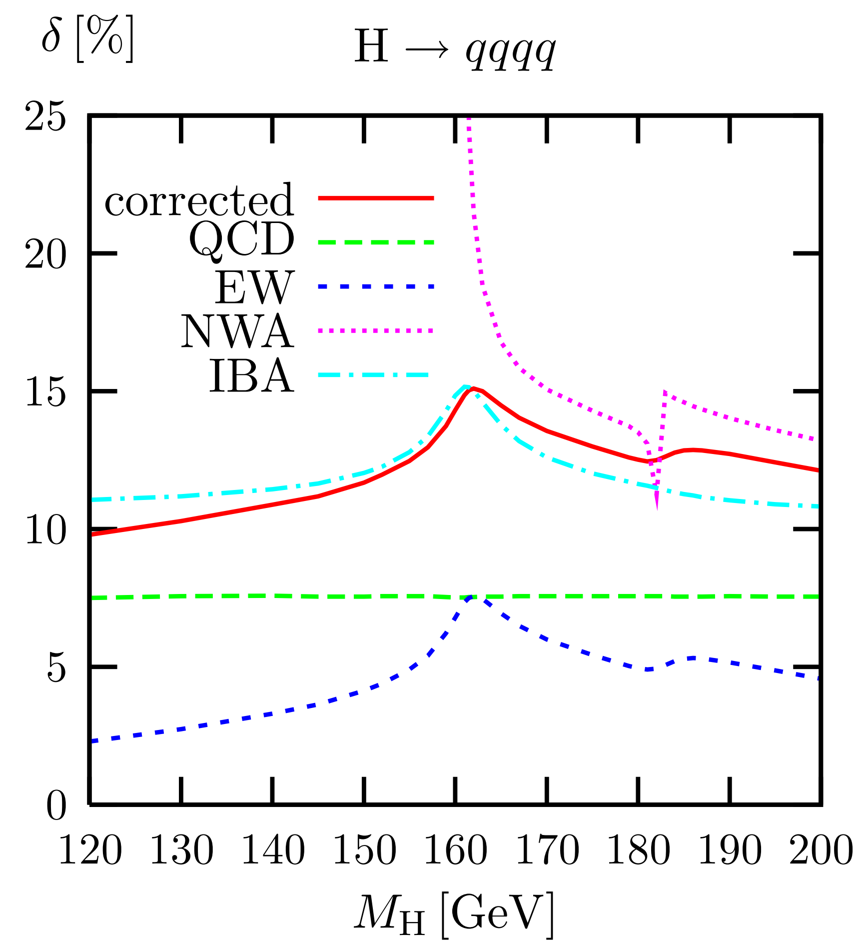
Higgs boson to four bottom quarks in SM

- A complete next-to-leading order calculation including both Yukawa and EW couplings with full bottom quark mass dependences

exotic decay in the SM **[JG, 1905.04865]**

EW $$\Gamma_{4b,ew} = A_{ZZ}\Delta_{ZZ}(x)(1+\delta_{ZZ}(x)), \quad A_{ZZ} = \frac{32 M_Z^4 M_H}{\pi^3 v^4}, \qquad \delta_{ZZ} = \frac{\alpha_S(\mu)}{2\pi}[a_{ZZ}(x)]$$





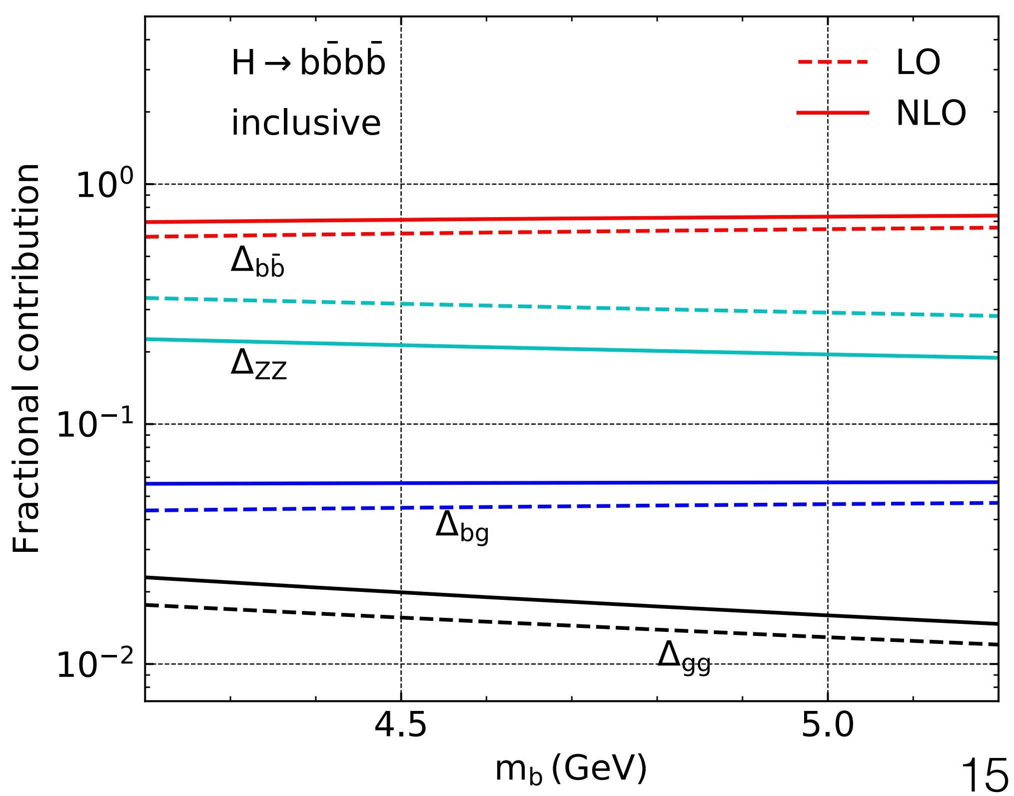
- complex mass scheme **[Denner, Dittmaier+, 2005]**
- NLO QCD correction for massless quarks from PROPHECY4F **[Denner, Dittmaier+, 2006]**

Higgs boson to four bottom quarks in SM

- A complete next-to-leading order calculation including both Yukawa and EW couplings with full bottom quark mass dependences

m_b (GeV)	$x\,(10^{-3})$	$\Delta_{b\bar{b}}$	Δ_{bg}	Δ_{gg}	$a_{b\bar{b}}$	a_{bg}	a_{gg}	Δ_{ZZ}	a_{ZZ}
4.2	1.129	7.32	-144.0	1.160	45.2	56.9	57.8	0.1222	5.64
4.4	1.239	6.80	-133.3	1.094	45.2	56.0	56.7	0.1205	5.80
4.6	1.354	6.32	-123.4	1.032	45.1	55.2	55.7	0.1188	5.97
4.8	1.474	5.89	-114.7	0.976	45.0	54.5	54.8	0.1170	6.14
5.0	1.600	5.49	-106.7	0.922	44.9	53.8	53.9	0.1152	6.32
5.2	1.730	5.13	-99.4	0.873	44.9	53.2	53.2	0.1133	6.50

- Bottom mass (pole) dependence, at LO and for the NLO QCD corrections

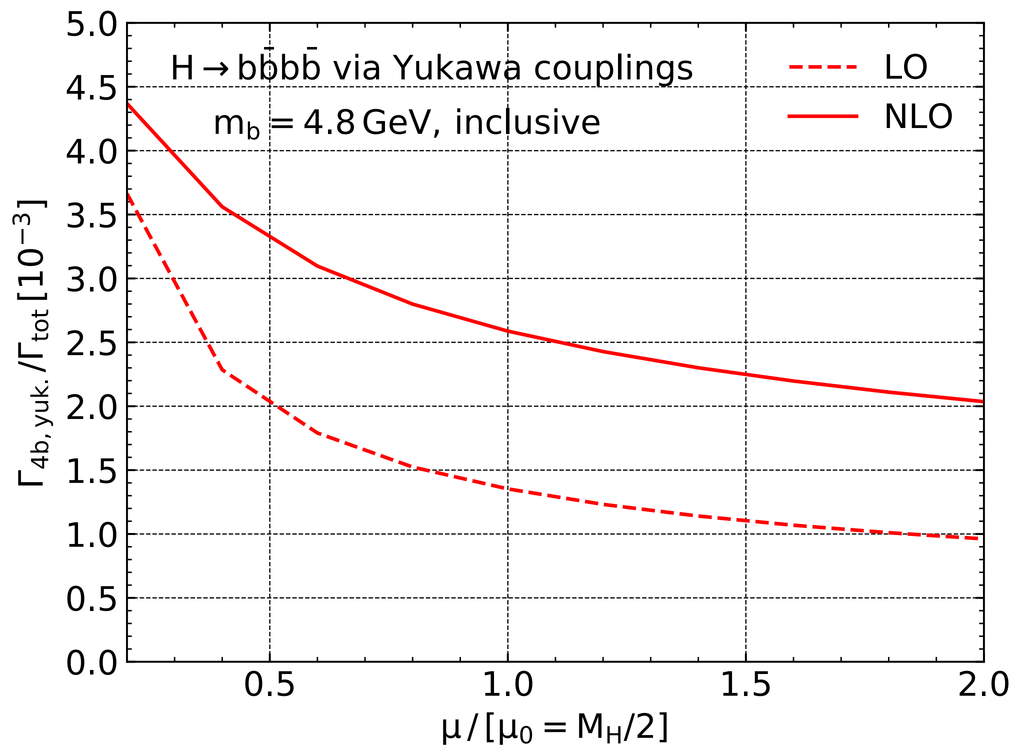


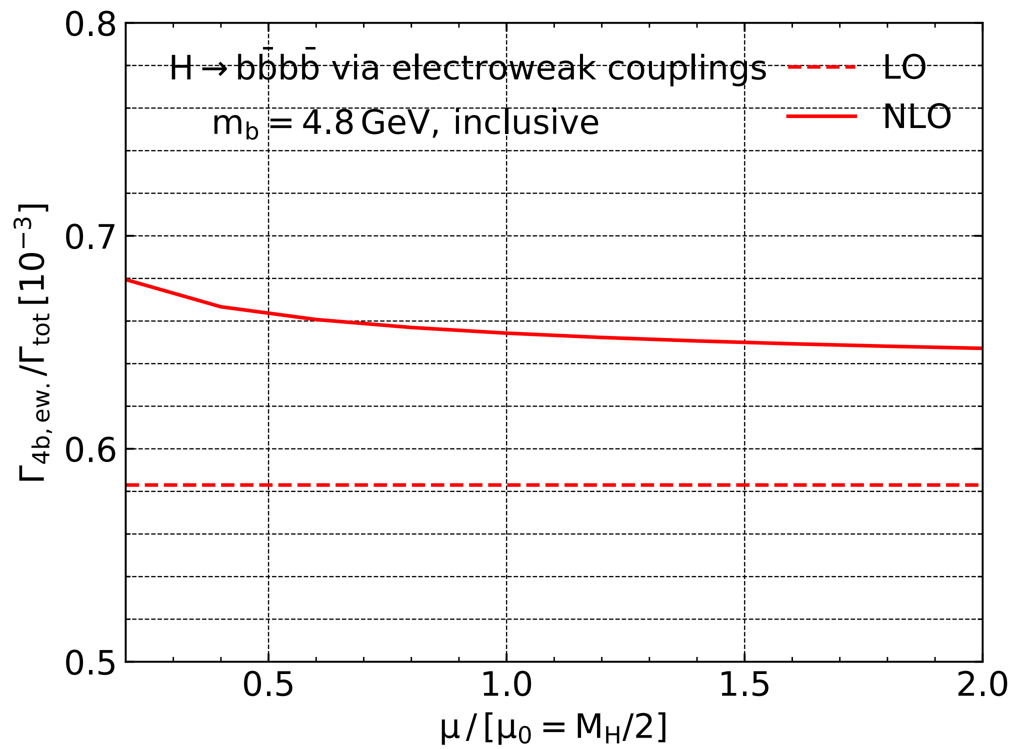
- SM predictions on BRs(H→4b) at ~0.3% with large QCD corrections; and dominated by Yukawa interactions

Higgs boson to four bottom quarks in SM

- A complete next-to-leading order calculation including both Yukawa and EW couplings with full bottom quark mass dependences

QCD scale variations



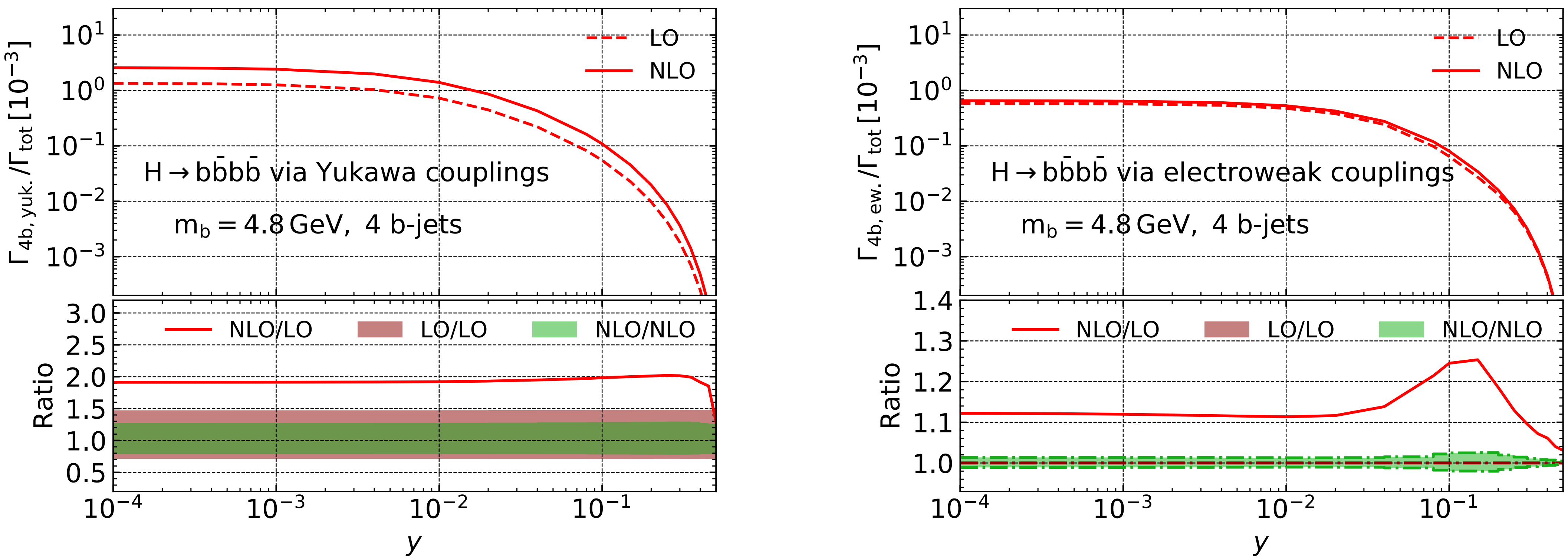


- QCD scale dependence is reduced though still significant for decay via Yukawa interactions,~25%

Jet cross sections

- Jet cross sections by requiring at least four b-tagged jets in the final state with e+e- k_T algorithm

k_T algorithm $$d_{ij} = \frac{2\min(E_i^2, E_j^2)}{Q^2}(1-\cos\theta_{ij}) \qquad Q^2 = M_H^2/4$$

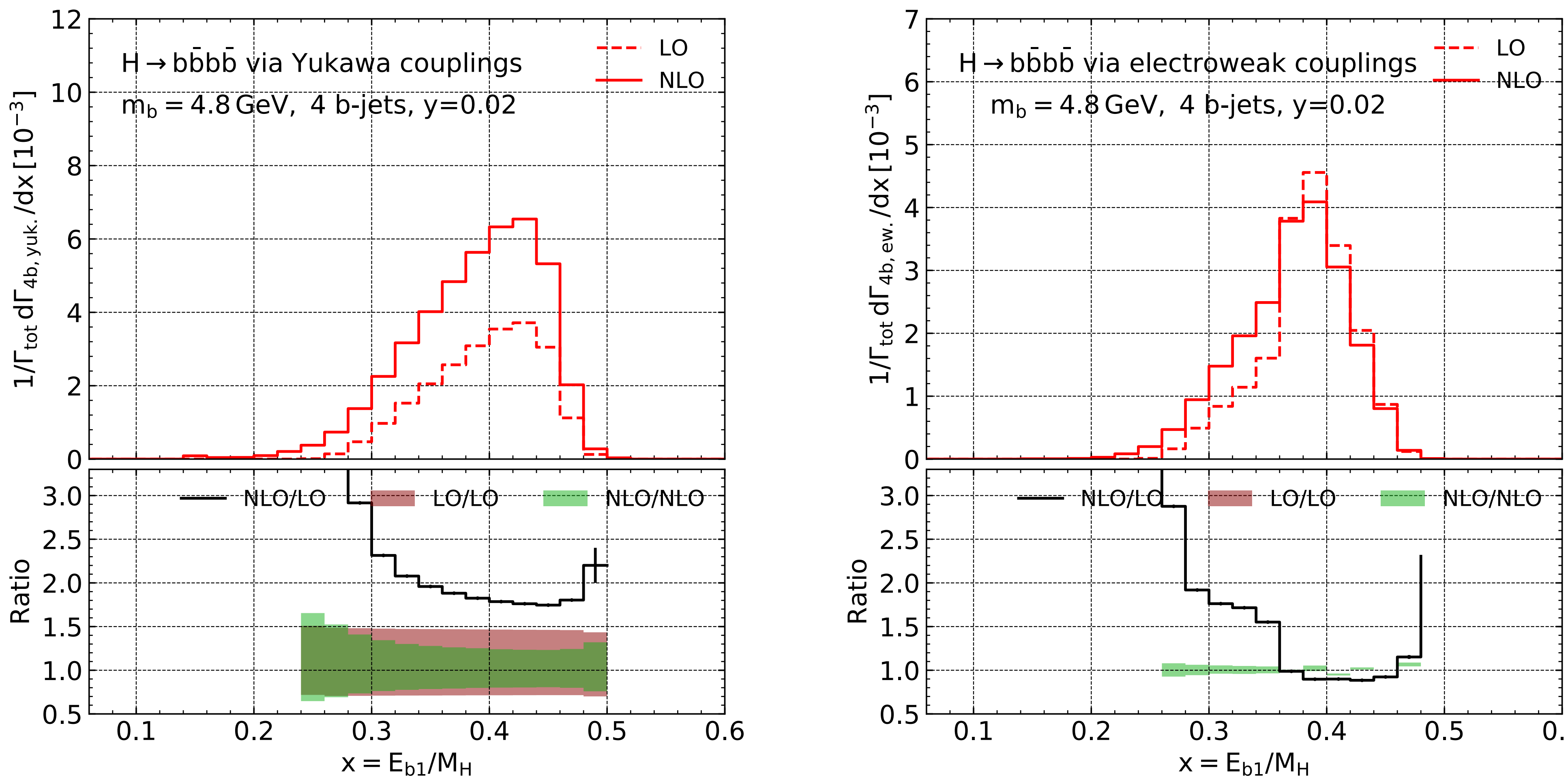


- partial width as a function of the jet resolution parameter y; y=0.02 corresponds to an opening angle of about 0.3(17 degrees)

Event topology

- Four b-jets are ordered by energy; kinematic distributions are constructed for individual jet and jet pairs

energy of the leading b-jet

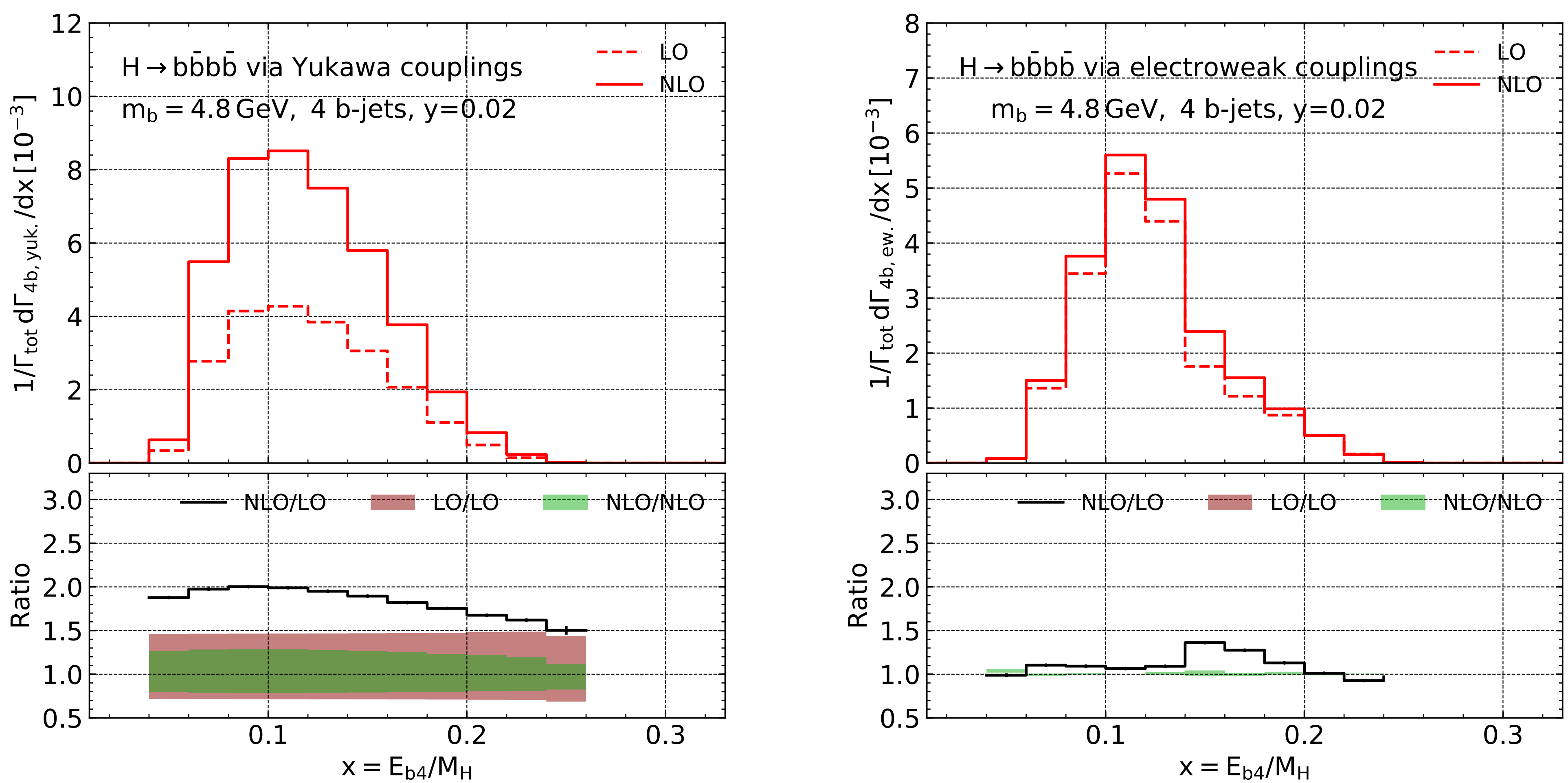


- spectrum are harder and broader for decay via Yukawa couplings; QCD corrections change the shapes in different ways

Event topology

- Four b-jets are ordered by energy; kinematic distributions are constructed for individual jet and jet pairs

energy of the softest b-jet

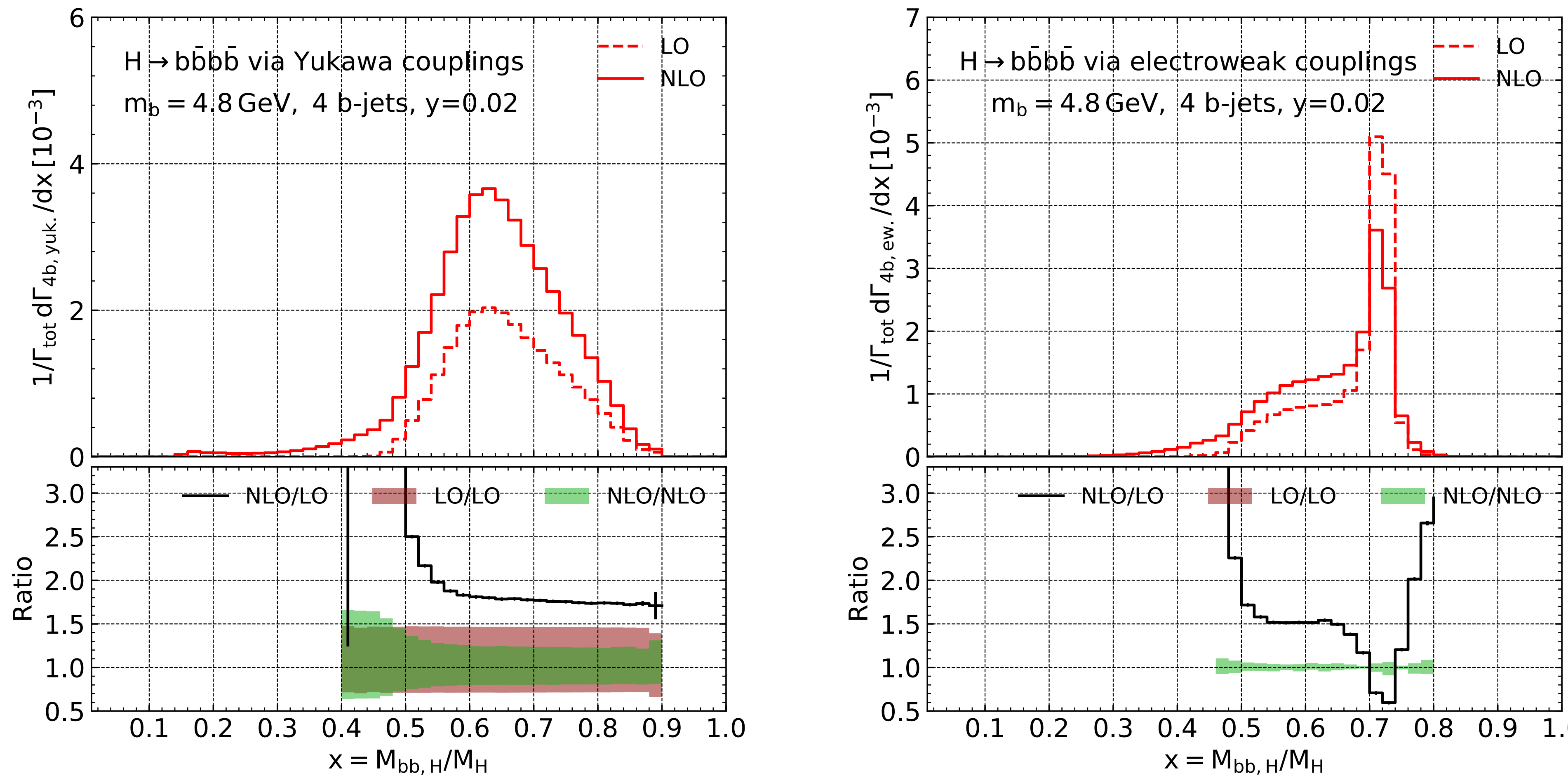


- softest b-jet peaked at E~15 GeV and are broader for decay via Yukawa couplings; QCD corrections show less dependence on energy

Event topology

- Four b-jets are ordered by energy; kinematic distributions are constructed for individual jet and jet pairs

highest b-jet pair invariant mass

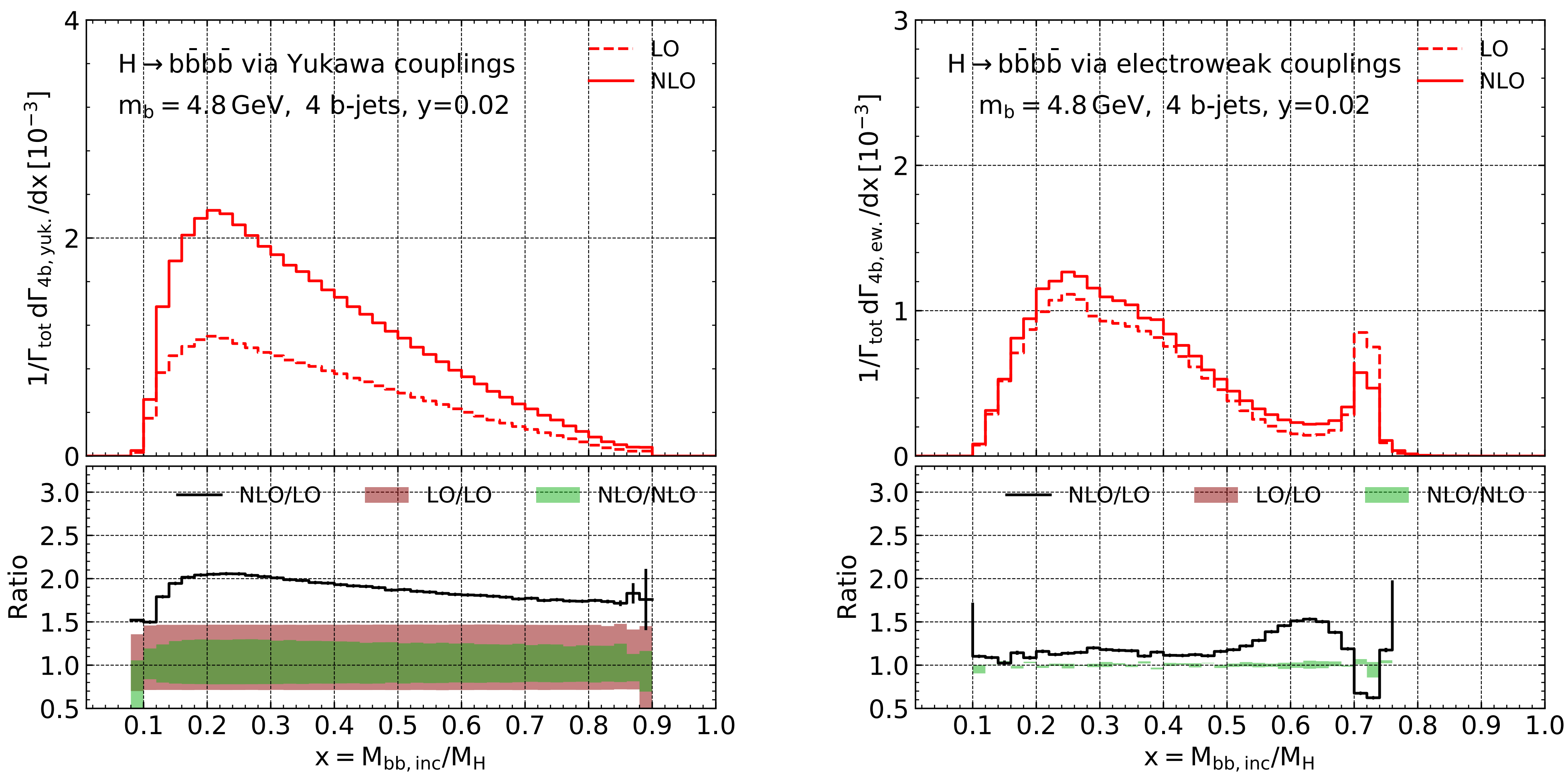


- clear Z mass peak in decay via EW coupling, while much broader for decay via Yukawa couplings; QCD corrections are quite different in two cases

Event topology

- ✦ Four b-jets are ordered by energy; kinematic distributions are constructed for individual jet and jet pairs

inclusive b-jet pair invariant mass

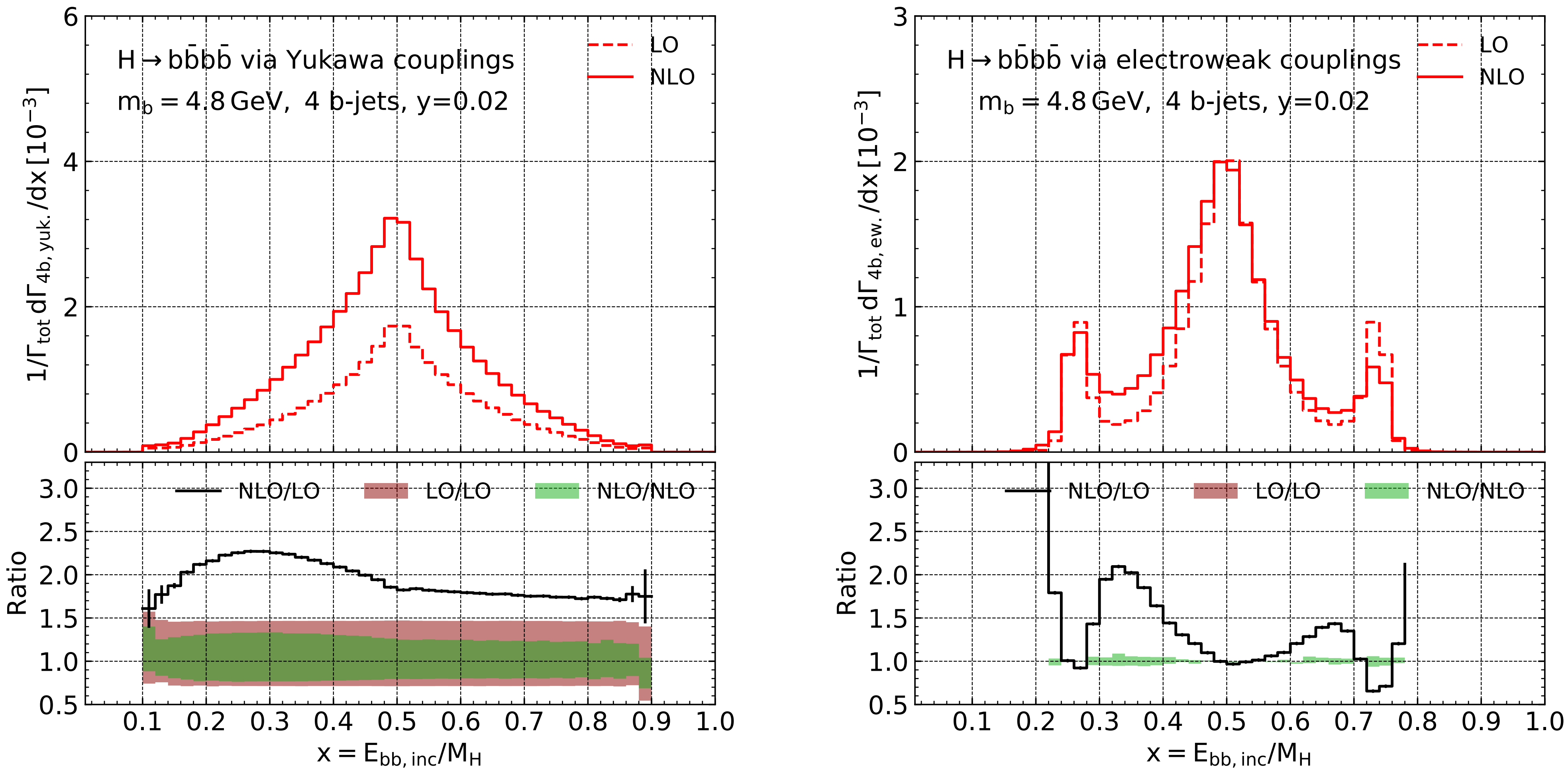


- ☆ Z mass peak is diluted for decay via EW coupling and another peak arises for $M \sim 0.2 M_H$; QCD corrections are almost flat except close to Z mass region

Event topology

- Four b-jets are ordered by energy; kinematic distributions are constructed for individual jet and jet pairs

inclusive b-jet pair energy

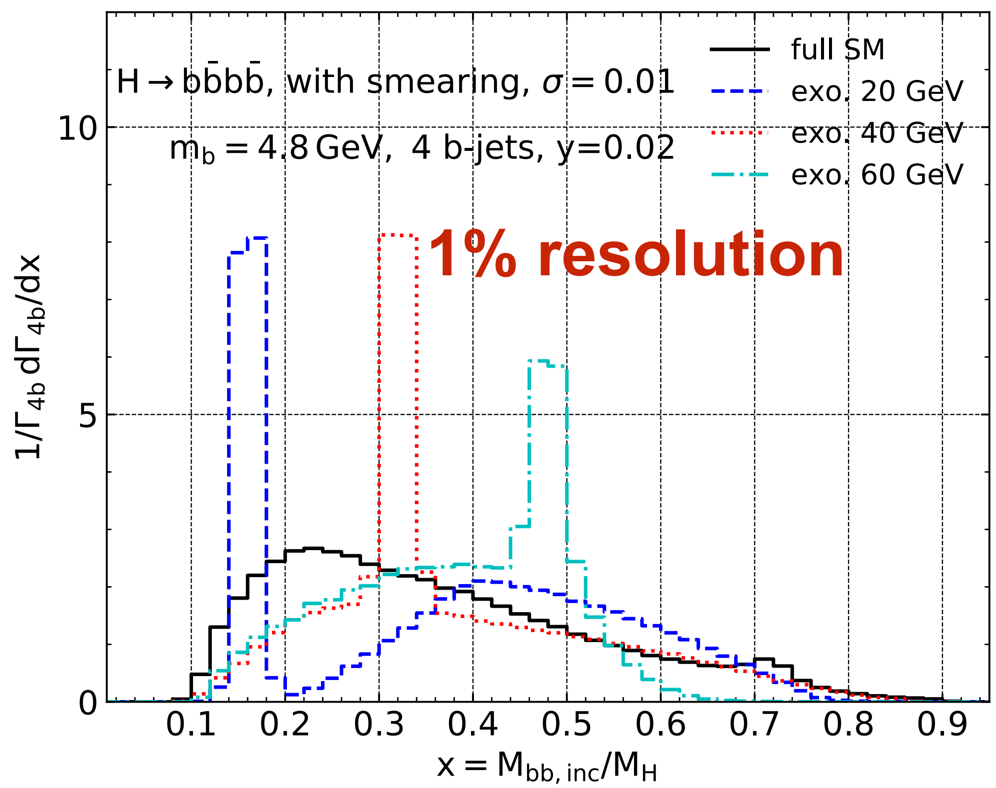


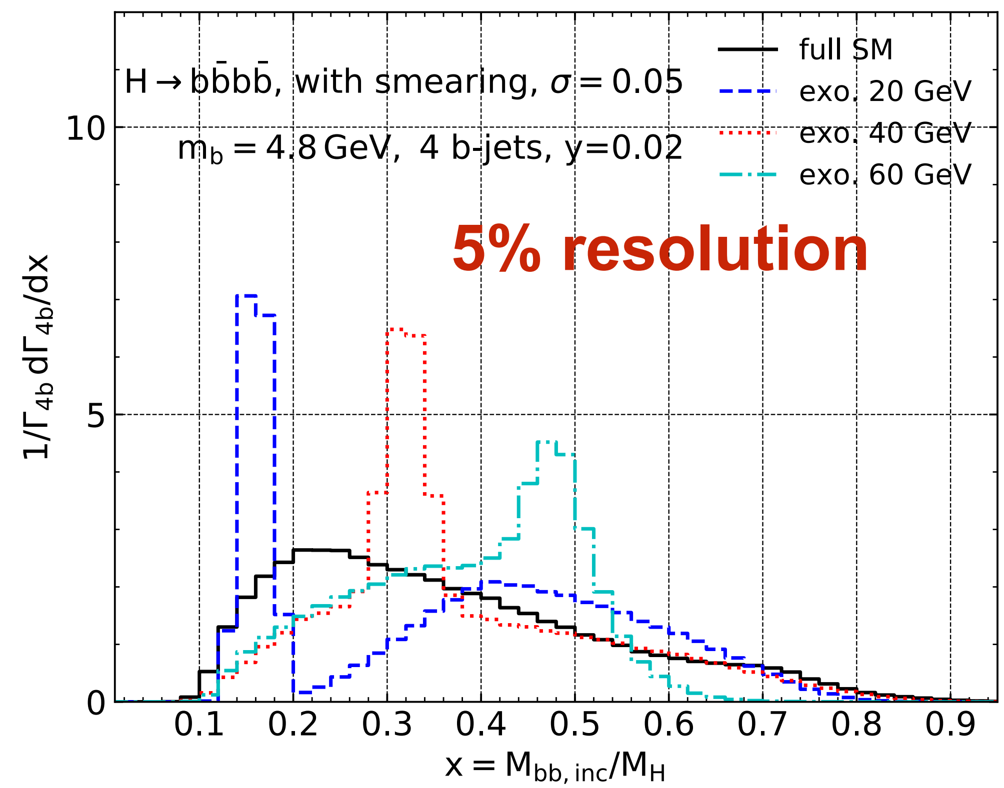
- Symmetric at LO, asymmetries driven by unclustered gluon in QCD real radiations; triple peak structure expected for decay via EW couplings

SM vs BSM to four bottom quarks

- A comparison of the four bottom quark decay mode in SM and induced by two light scalars for normalized distributions

inclusive b-jet pair mass





- all calculated at NLO in QCD and assuming narrow width case for the light scalars; Gaussian smearing are applied with different energy resolutions

Summary

- Precision test of the Higgs couplings will be one of the most imperative task in the next few decades

- Better understanding on hadronic decays of the Higgs boson, on both perturbative and non-perturbative QCD aspects, will be important for extraction of the relevant Higgs couplings

- Rare or exotic hadronic decay modes can also be explored at future Higgs factory, for instance, decay to light quarks or to multiple heavy-quarks

Summary

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Thank you for your attention!