Triple Higgs production
A window on SM and BSM physics

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HHH workshop

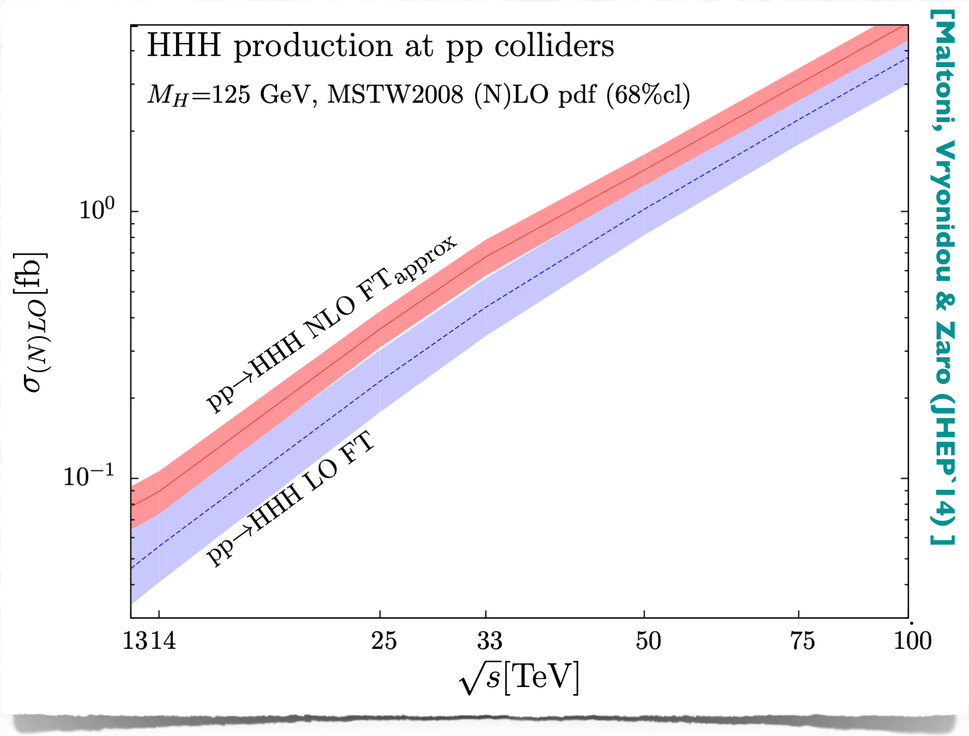
Dubrovnik, 14-16 July 2023

Triple Higgs production at colliders – a growing interest

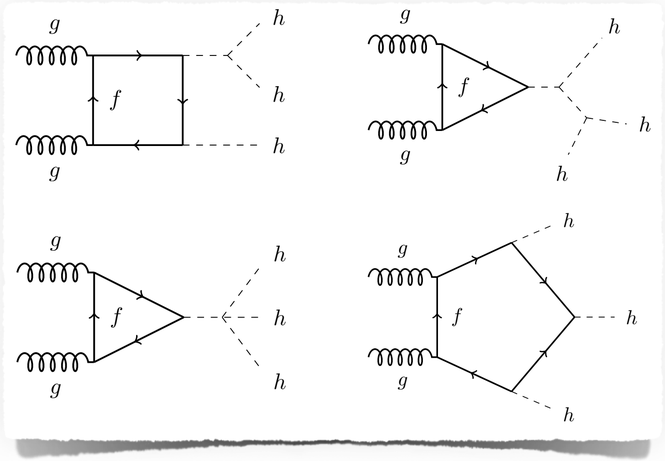
Modern studies of *hhh* production at hadron colliders

- Pioneering works in the early 2000s
  - ➙ SM prospects rather bleak [Plehn & Rauch (PRD`05)]
  - ➙ BSM rates more appealing [Binoth, Karg, Kauer & Rückl (PRD`06)]

- SM rates between 100 ab @ 13 TeV to a few fb at 100 TeV
  - ➙ NLO corrections in the full theory approximation
  - ➙ K-factors of 1.5 – 2



[Maltoni, Vryonidou & Zaro (JHEP`14)]



FCC working group studies

- Large rates in many models ≡ wealth of possibilities
  - ➙ Extra resonant contributions
  - ➙ Coupling modifiers
- Precision predictions available — See talk by Zanderighi
- The Higgs discovery
  - ➙ Multiple Higgs production crucial for the Higgs potential

$$V_h = \frac{1}{2}m_h^2 h^2 + \lambda_{hhh} v h^3 + \frac{1}{4}\lambda_{hhhh} h^4$$

On the way to the Higgs potential

The Higgs potential in the SM - very few freedoms

- The Higgs mass and vev the (known) keys

$$V_h = \frac{1}{2}m_h^2 h^2 + \lambda_{hhh} v h^3 + \frac{1}{4}\lambda_{hhhh} h^4$$

with $\lambda_{hhh} = \lambda_{hhhh} = \frac{m_h^2}{2v^2}$

- Higgs self-couplings: *direct* verification in order
  - ➙ Better knowledge of EWSB
  - ➙ Access to an extended scalar sector
  - ➙ Nature of the electroweak phase transition

See talk by Karkout & du Pree

Simplest new physics parameterisation

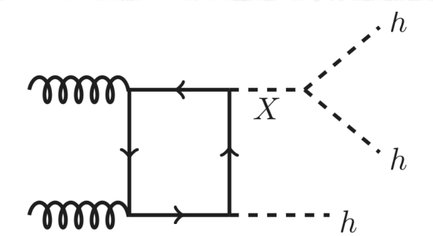
- SM coupling modifiers

$$V_h = \frac{1}{2}m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh} h^4$$

- In the SM $\kappa = 0$
  - ➙ Experimental constraints at the LHC and beyond
  - ➙ Requires multi-Higgs production

More involved parameterisation

- Extended scalar sector
  - ➙ xSM, 2HDM, 3HDM, *etc.*
- Resonant enhancement in multi-Higgs production



$$\begin{aligned} V_0(\phi_1,\phi_2,\phi_3) \;=\; & \mu_1^2\left(\phi_1^\dagger\phi_1\right) + \mu_2^2\left(\phi_2^\dagger\phi_2\right) + \mu_3^2\left(\phi_3^\dagger\phi_3\right) + \lambda_1\left(\phi_1^\dagger\phi_1\right)^2 \\ & + \lambda_2\left(\phi_2^\dagger\phi_2\right)^2 + \lambda_3\left(\phi_3^\dagger\phi_3\right)^2 + \lambda_4\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_5\left(\phi_1^\dagger\phi_1\right)\left(\phi_3^\dagger\phi_3\right) \\ & + \lambda_6\left(\phi_2^\dagger\phi_2\right)\left(\phi_3^\dagger\phi_3\right) + \lambda_7\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) \\ & + \lambda_8\left(\phi_1^\dagger\phi_3\right)\left(\phi_3^\dagger\phi_1\right) + \lambda_9\left(\phi_2^\dagger\phi_3\right)\left(\phi_3^\dagger\phi_2\right) \end{aligned}$$

See talks by Pasechnik, Papaefstathiou & Robens

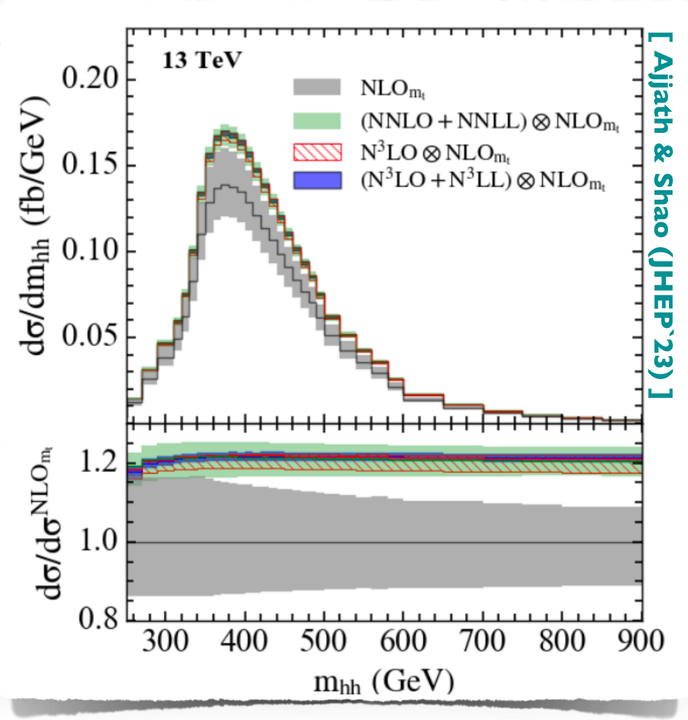
Cornering EWSB step 1 – The trilinear self-coupling

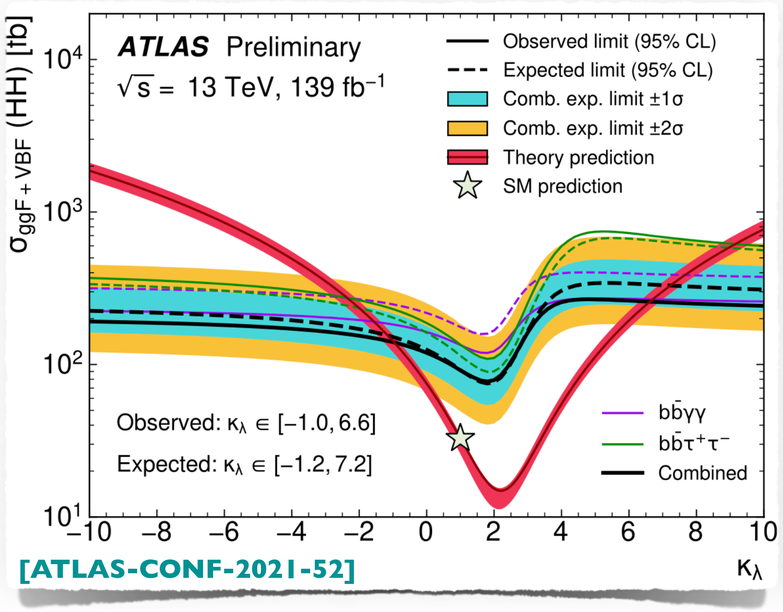
The trilinear coupling λ_{hhh} – a HL goal for the LHC

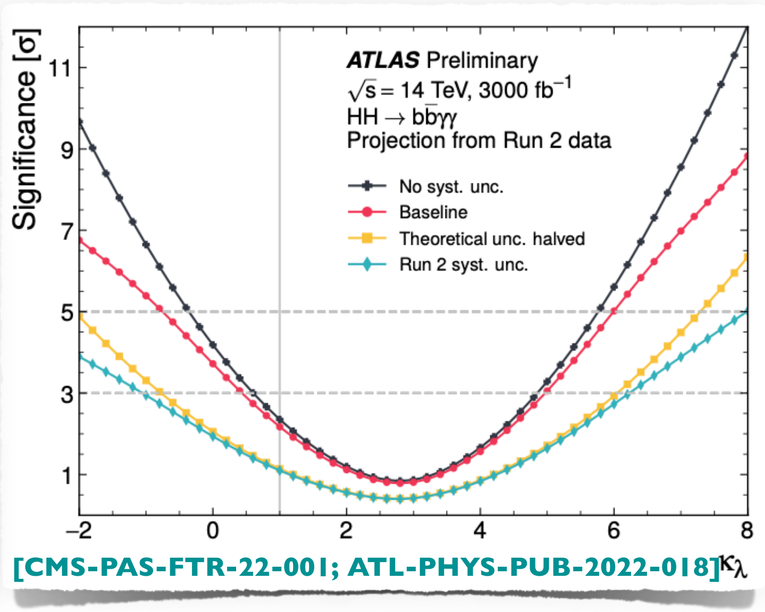
- Parametrisation adopted for LHC studies

$$V_h = \frac{1}{2} m_h^2 h^2 + \kappa_\lambda \lambda_{hhh} v h^3 + \dots$$

- Cornering κ_λ with *hh* production (bb$\gamma\gamma$, bb$\tau\tau$, *etc.*)
  - ➙ Hard due to small cross section (at least in the SM)
  - ➙ Precise measurements challenging, but doable (4σ in the SM)
  - ➙ N3LO+N3LL predictions with small scale uncertainties







See talk by Stamenkovic

Paving the way to the production of more Higgses

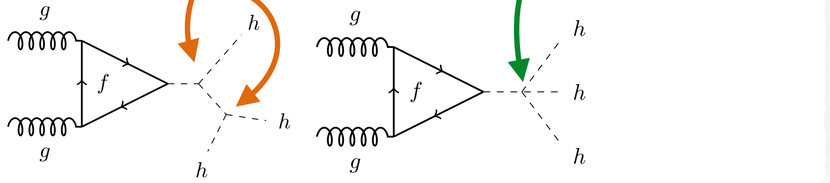
➙ Topic of this workshop!

Cornering EWSB step 2 – The quartic self-coupling

The quartic coupling λ_{hhhh} requires *hhh* production (at leading order)

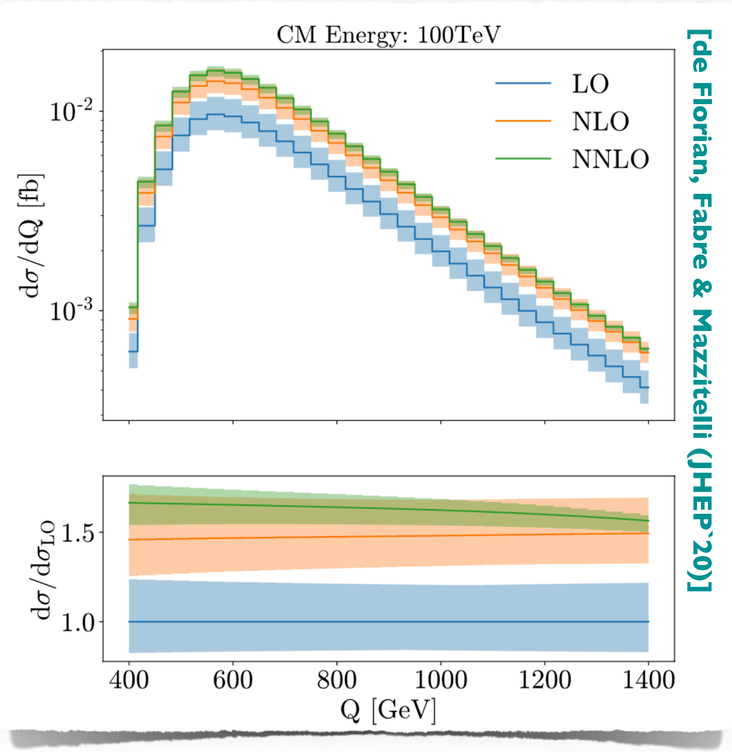
- Cannot be probed independently of λ_{hhh}
- Small SM cross sections ($\kappa = 0$)
  - → σ (14 TeV) ≃ 0.1 fb (NNLO-FT)
  - → σ (100 TeV) ≃ 5 fb (NNLO-FT)

$$V_h = \frac{1}{2}m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh} h^4$$



Theory predictions under good control

- LO rates used in the first FCC studies
- NNLO-dBi corrections obtained recently
  - → K_{NNLO} (14 TeV) = 1.70
  - → K_{NNLO} (100 TeV) = 1.43
  - → Scale uncertainties of 5−10 %
- ⚠ Predictions = approximations in the heavy top limit (HTL) (but state of the art)
  - → NLO-FT: virtuals in the HTL
  - → NNLO-dBi: form factors for operators in the HTL
- M_{hhh} (=Q) differential distributions known

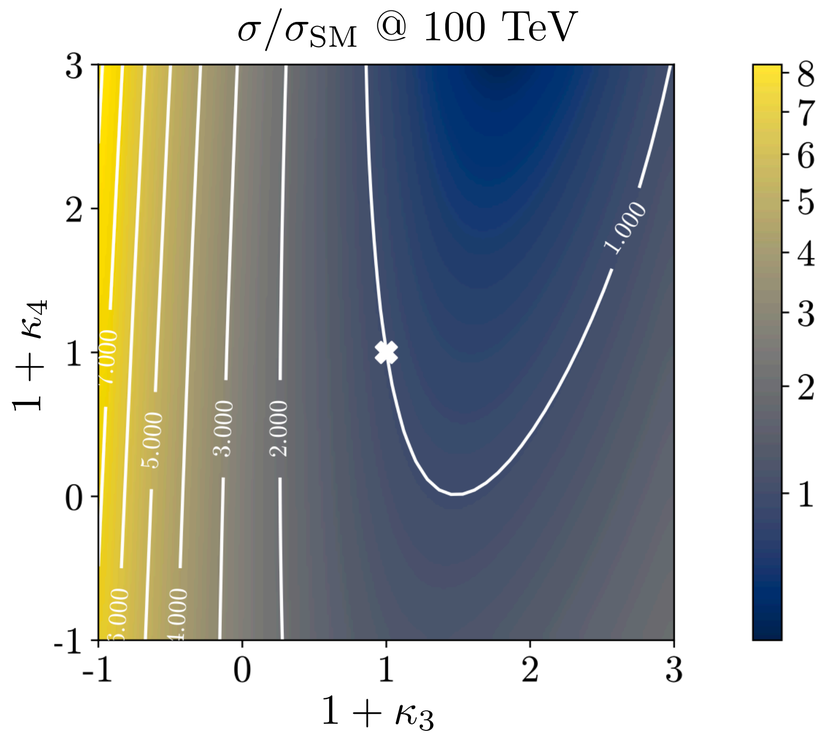


BSM effects in *hhh* production

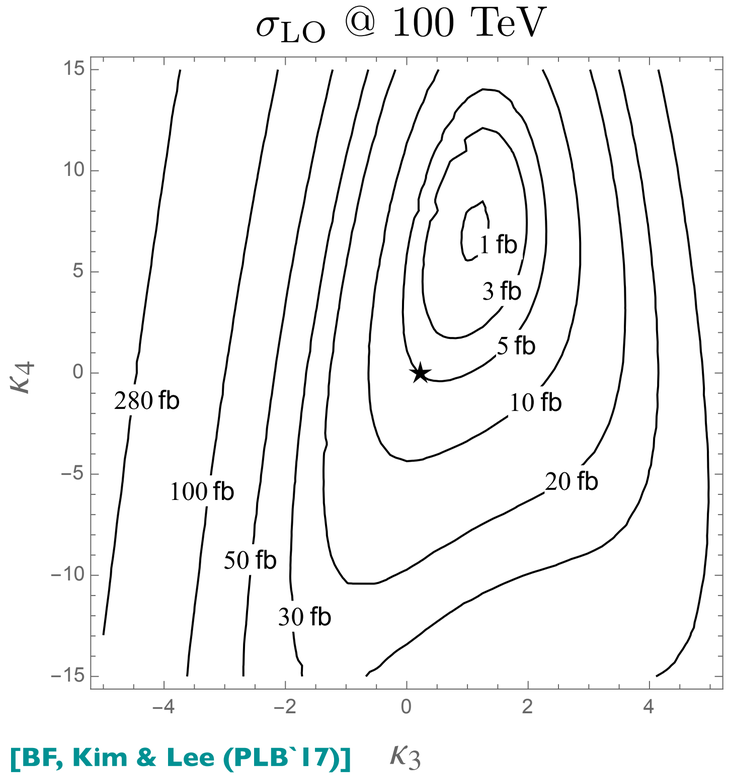
BSM effects on *hhh* production in the κ framework

- Strong dependence on κ_3
  - ➞ sign crucial (constructive or destructive interference)
  - ➞ negative κ_3 ≡ large rate increase (factor of 10 for $\kappa_3 = -2$)

- Generally mild dependence on κ_4 for a fixed κ_3 value
  - ➞ κ_4 parameter possibly very hard to probe!
- Worst case situation $\kappa_{3,4} > 0$
  - ➞ smaller rates than in the SM



[de Florian, Fabre & Mazzitelli (JHEP`20)]



[BF, Kim & Lee (PLB`17)]

Convention:

$$V_h = \frac{1}{2}m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh} h^4$$

Rates not everything…

- Impact on fiducial regions?

κ parameters not the whole story

- UV-complete models?

Signatures of triple Higgs production

Signatures and the triple-Higgs decay table

- Main channels ≡ at least 100 events with 30 ab^{-1} @ 100 TeV
  ➞ control of the background also crucial
- Many modes probed

$hhh \to$ final state	BR (%)	σ (ab)	$N_{30\text{ab}^{-1}}$
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21	1110.338	33310
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.204	416.41	12492
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.312	364.853	10945
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
$(b\bar{b})(b\bar{b})(ZZ_{2\ell})$	0.331	19.131	573
$(b\bar{b})(WW_{2\ell})(WW_{1\ell})$	0.244	14.105	423
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.228	13.162	394
$(b\bar{b})(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(b\bar{b})(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(b\bar{b})(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125

[Papaefstathiou & Sakurai (JHEP`16)]

The golden (clean) *4b2γ* mode

See talks by BF & Sakurai

- Extremely efficient *b*-tagging desirable
- Good photon resolution
- Forward detector coverage desirable
- 2σ reachable in the SM

[Papaefstathiou & Sakurai (JHEP`16)]
[BF, Kim & Lee (PRD`16)]
[Chen, Yan, Zhao, Zhao & Zhong (PRD`16)]

The *2b2ℓ4j + MET* mode

[Kilian, Sun, Yan, Zhao & Zhao (JHEP`17)]

- High-level variables (like M_{T2})
- Challenging for the SM, potentially powerful for BSM

The *4b2τ* mode

[BF, Kim & Lee (PLB`17)]

- Exploiting boosted Higgses and high-level variables
- Good double-tau tagging crucial
- 2σ reachable in the SM

See talk by BF

The *6b* mode

- Kinematic fit from 6 *b*-jets
- Good *b*-tagging crucial
- 2σ reachable in the SM
- Excellent probe of BSM

See talks by Papaefstathiou & Robens

[Papaefstathiou, Tetlalmatzi-Xolocotzi & Zaro (EPJC`19)]
[Papaefstathiou, Robens & Tetlalmatzi-Xolocotzi (JHEP`21)]

Motivation towards *hhh* studies @ LHC

Triple Higgs production ➙ good prospects in the SM and beyond

- Four signatures studied phenomenologically
  - ➙ Good *b*-tagging crucial
  - ➙ High-level variables often necessary
- Excellent prospects
  - ➙ 2σ reach in the SM for three of them
  - ➙ Potential for a combination

Strong motivation for experimental investigations

See talks by Balunas & Lansberg

- At the FCC, but also at the LHC
  - ➙ Relying on existing and future colliders
  - ➙ Exploiting lessons learned from *hh* production
- A lot of challenges (signal and background modelling, interpretations)
  - ➙ Keep LHC recasting in mind (future reinterpretations in other models)

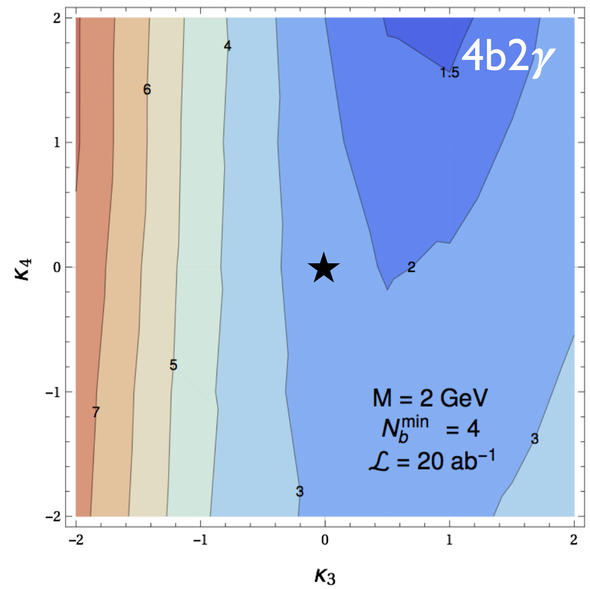
[Les Houches Recommendations (EPJC'12)]

[ReInterpretation Forum (SciPost`20)]

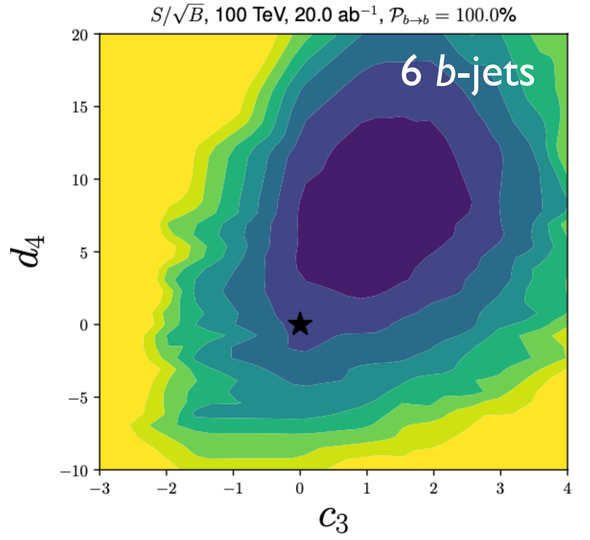
Combination of *hh* and *hhh* searches

See talk by Moser, Arnold & Stamenkovic

- Improvement of the experimental precision



[BF, Kim & Lee (PRD`16)]



[Papaefstathiou et al. (EPJC`19)]

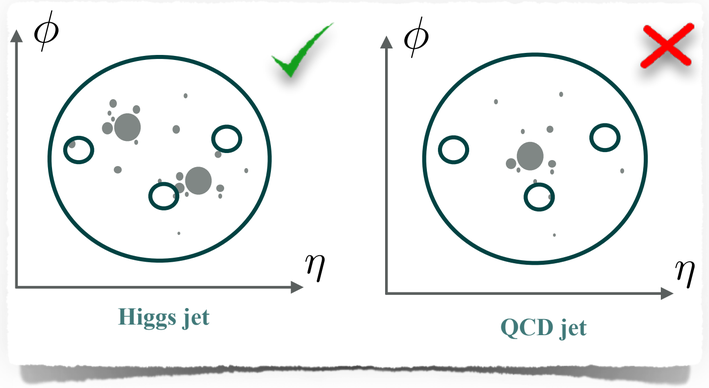
The experimental agenda of the workshop

b-jets in all studied channels

- *b*-tagging efficiencies usually very high (> 80 %)
- Boosted and resolved Higgs reconstruction
  - ➙ Double *b*-tags relevant
  - ➙ Machine-learning-based methods
  - ➙ Single method for both regimes
- Lessons taken from *hh* searches

See talks by Kolosova, Liu & Chen

See talks by Karkout, Li & Stamenkovic



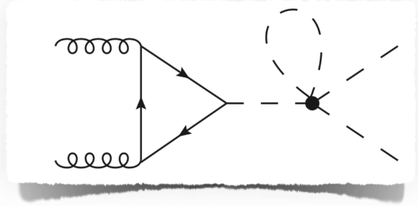
Exploitation of machine learning methods

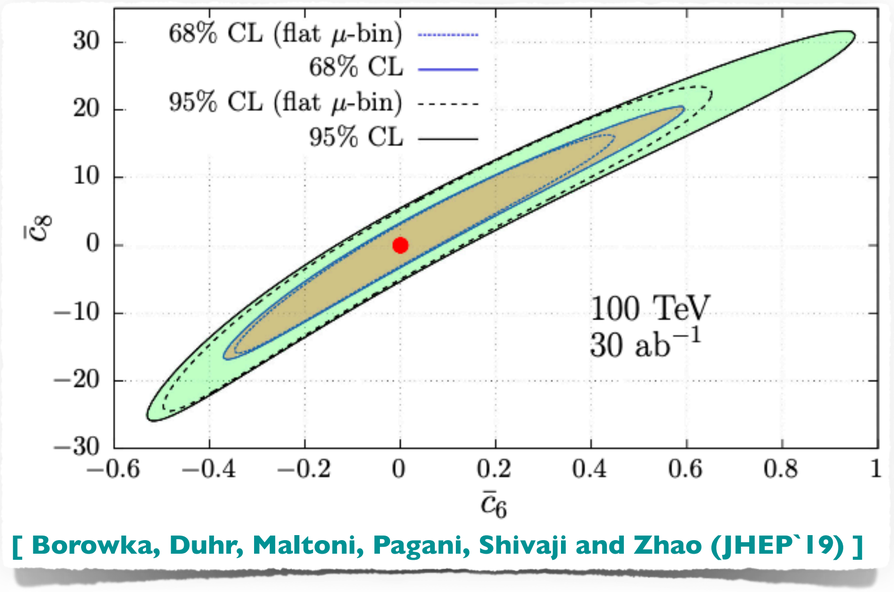
- Tests in *hh* production in the *2b4j* channel
- Application to *hhh*

See talks by Stylianou, Diaz, Duarte & Ganguly

Few remarks

- Not so much on photons and taus (why?)
- *hh*/*hhh* connection has some potential
  - ➙ sensitivity to κ_4 via loop corrections to *hh*





[Borowka, Duhr, Maltoni, Pagani, Shivaji and Zhao (JHEP`19)]

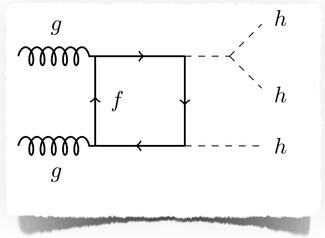
Summary

(Modern) triple Higgs studies are seven years old

- Promising channel to corner the Higgs potential
- Good phenomenological prospects… at 100 TeV
- The LHC ≡ good preparation for this
  ➙ especially experimentally speaking

Questions from my side

- What about photon resolution and tau-tagging
  ➙ Not addressed during this workshop (?)
- Revisiting older studies
  ➙ Modern (ML) techniques
  ➙ More accurate (TH and EXP) modelling
- New modes so far untouched?
  ➙ Fully hadronic
  ➙ Channels with taus and leptons



I am looking forward to the nice workshop