Complementing constraints of the Higgs potential shape with triple Higgs searches at the LHC

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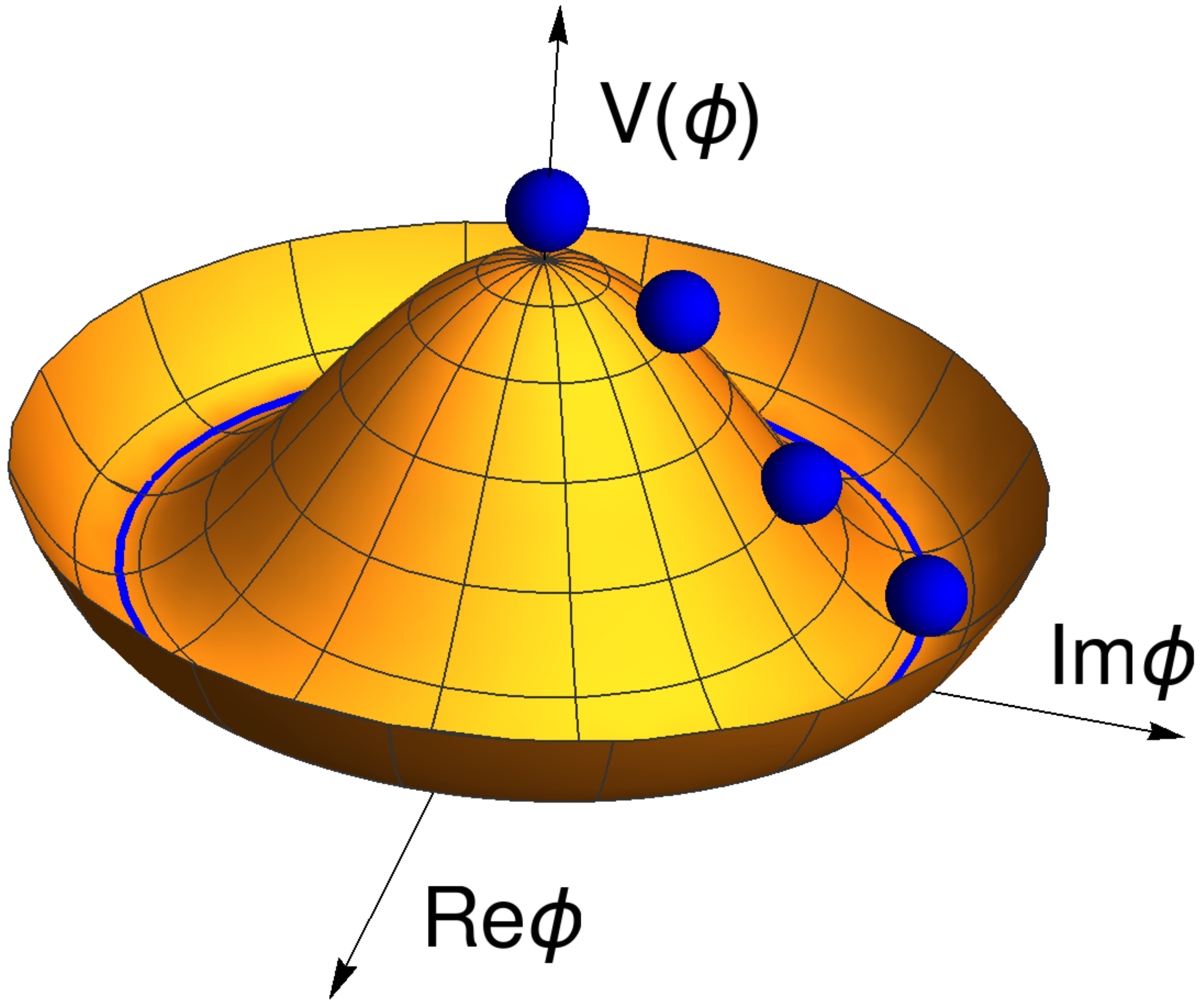
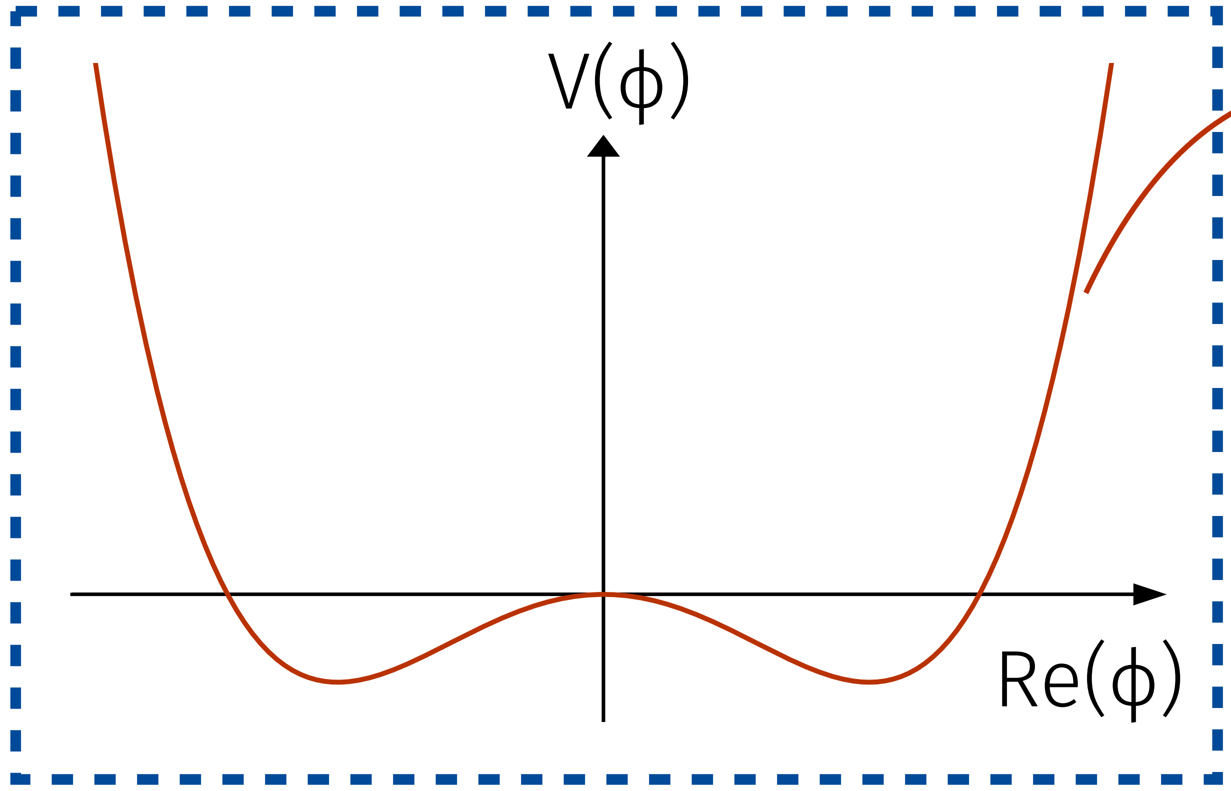


Setting the stage: the Higgs potential

highest term needs to be even, else any other polynomial would do

$$\begin{aligned}\mathcal{L}_{\rm SM} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\psi}\not{D}\psi \\ \text{experim. accessible since 2012} & \begin{cases} + |D_\mu\phi|^2 \boxed{- \overset{\text{arbitrary}}{\mu^2}(\phi^\dagger\phi) - \overset{> 0}{\lambda}(\phi^\dagger\phi)^2} \\ + y_{ij}\psi_i\phi\psi_j + \text{h.c.} \end{cases}\end{aligned}$$



Where does this potential come from?

Why is it Mexican-hat shaped?

- The Higgs potential is **introduced ad-hoc** to the SM and has a high degree of arbitrariness attached to it → no fundamental explanation for its form (Mexican-hat is an assumption)
- We need to measure the form of the potential in order to know it, experiment will have the final word

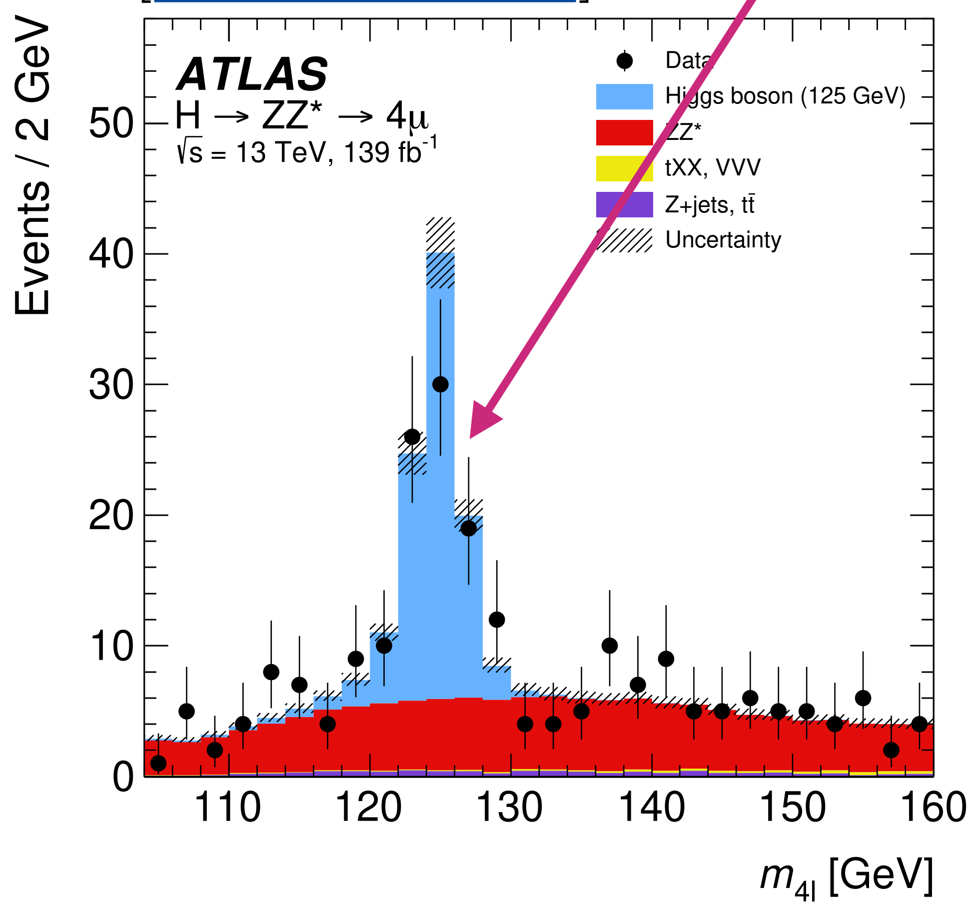
Constraining V(H) - how?

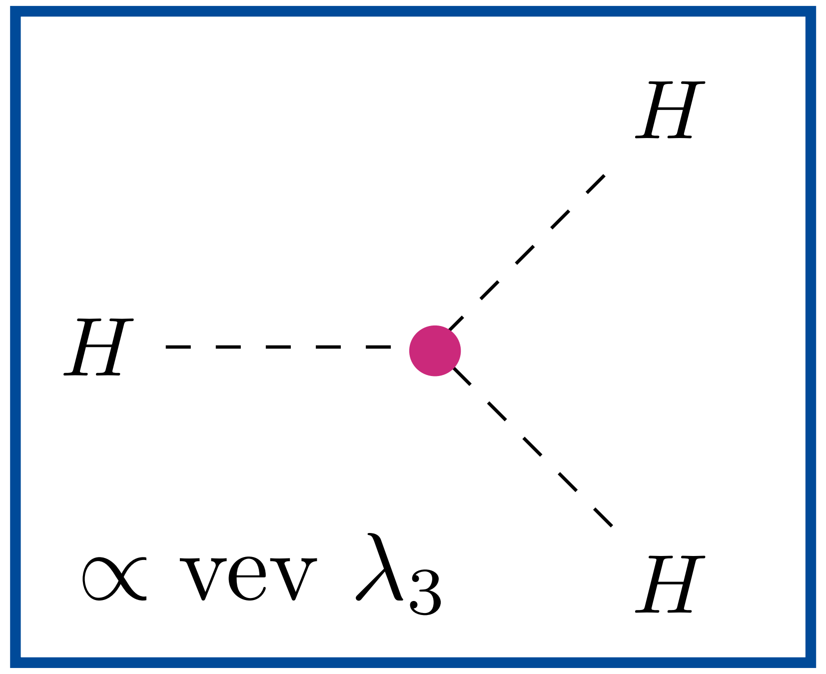
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3\ \mathrm{vev}\ H^3 + \frac{1}{4}\lambda_4 H^4$$

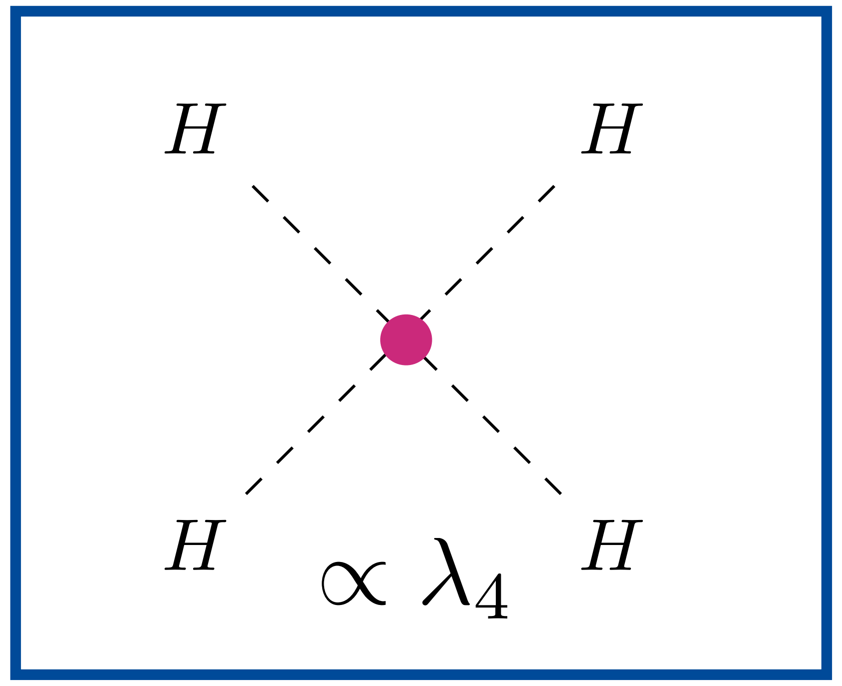
In SM:

$$\lambda_3 = \lambda_4 = \lambda = \frac{m_H}{2v^2} \sim \frac{1}{8}$$

[CERN-EP-2022-135]







Parameterize:

$$\kappa_3 = \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}}$$

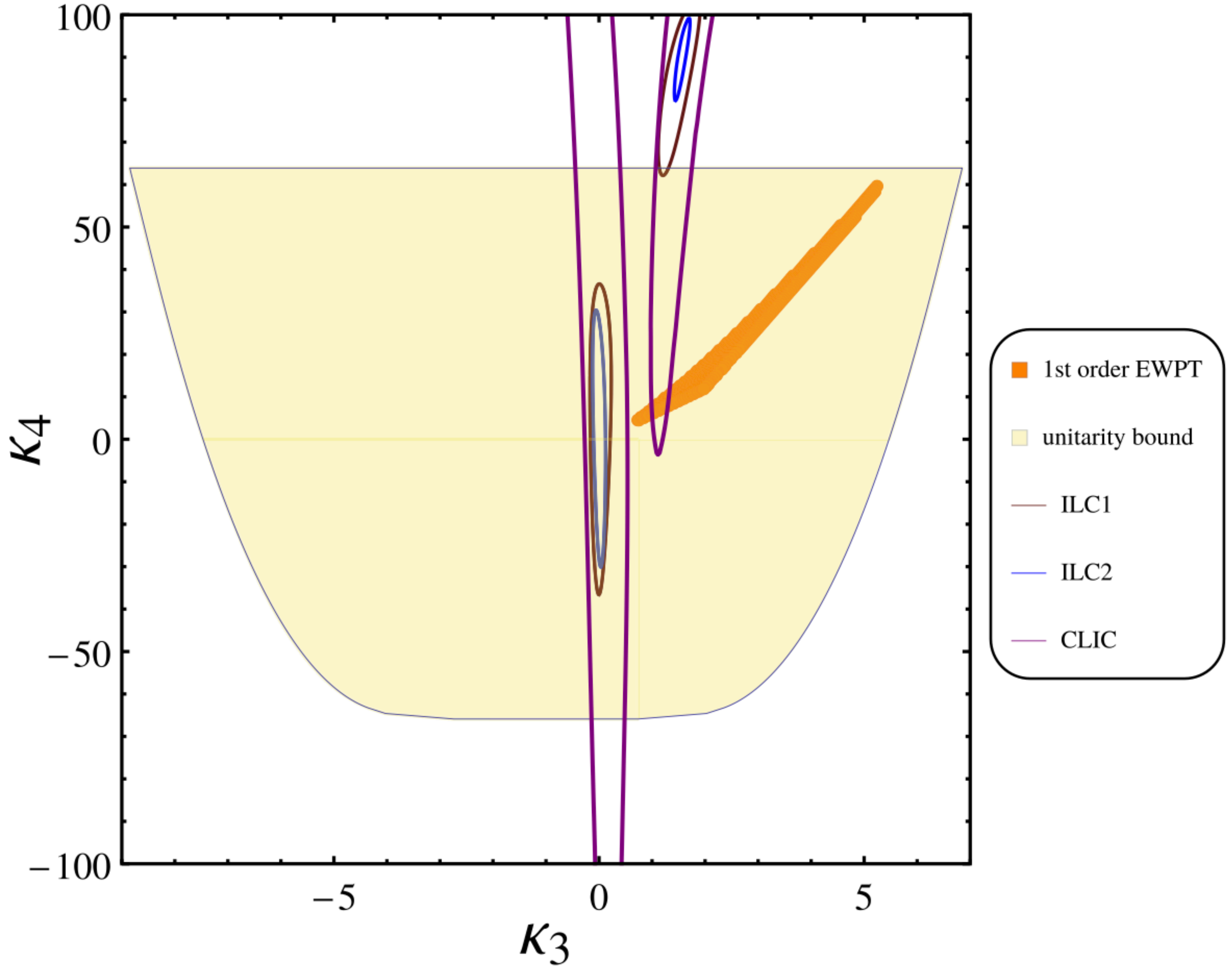
$$\kappa_4 = \frac{\lambda_4}{\lambda_4^{\mathrm{SM}}}$$

[with SM = κ_3 = κ_4 = 1]

- To constrain the shape of V(H) we need to measure **multi Higgs production**
- Large effort ongoing to search for di-Higgs production (HH)
- Little effort so far on triple-Higgs production (HHH)

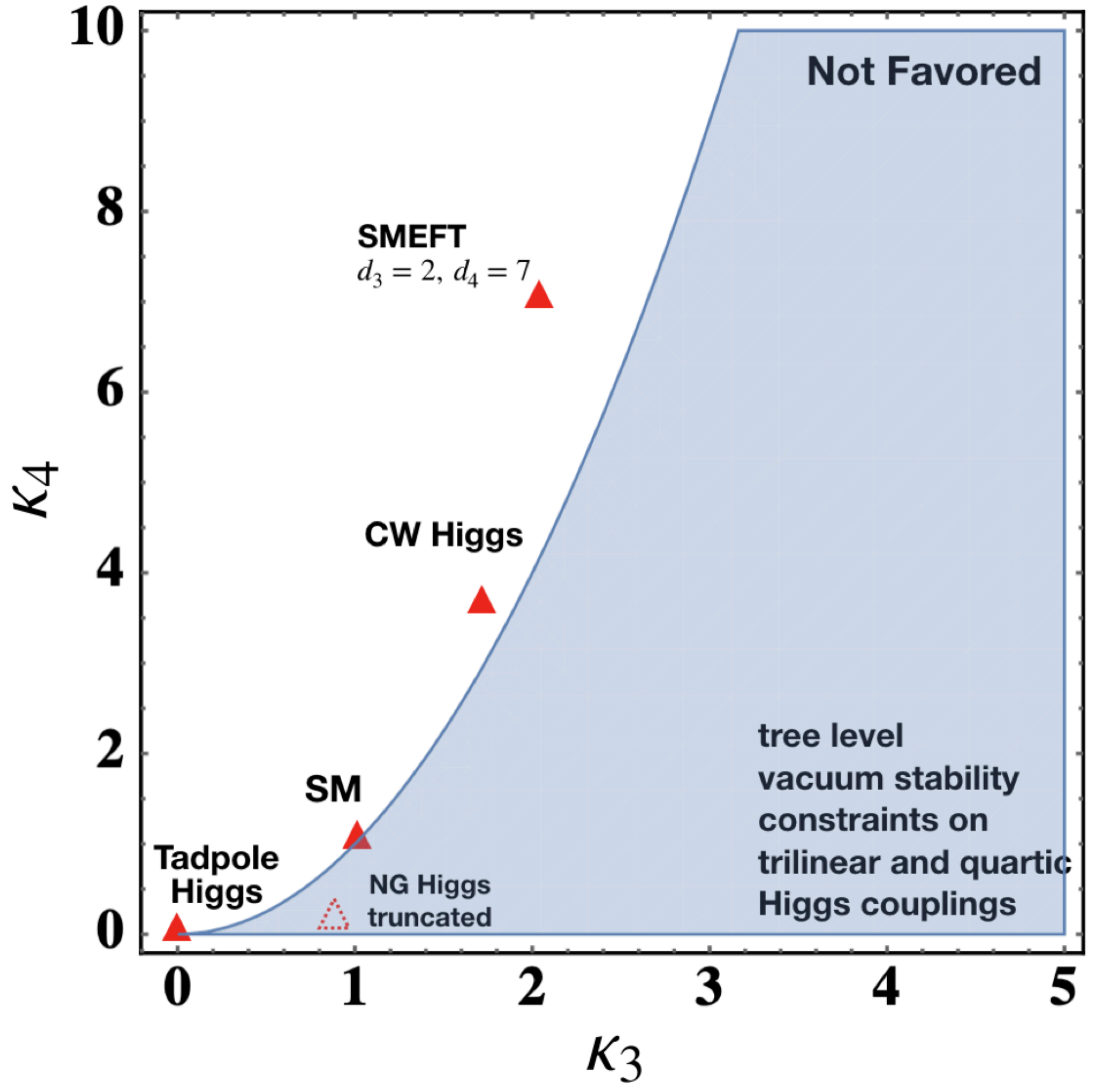
Bounds from theory on κ3 and κ4

[Liu, Lyu, Ren, Zhu - 2018 - PRD 98 093004]



$|\kappa_3| \lesssim 6$ and $|\kappa_4| \lesssim 60$
from unitarity bounds

[Agrawal, Saha, Zu, Yu, Yuan - 2020 - PRD 101 075-23]



vacuum stability poses conditions on the relationship between κ3 and κ4*

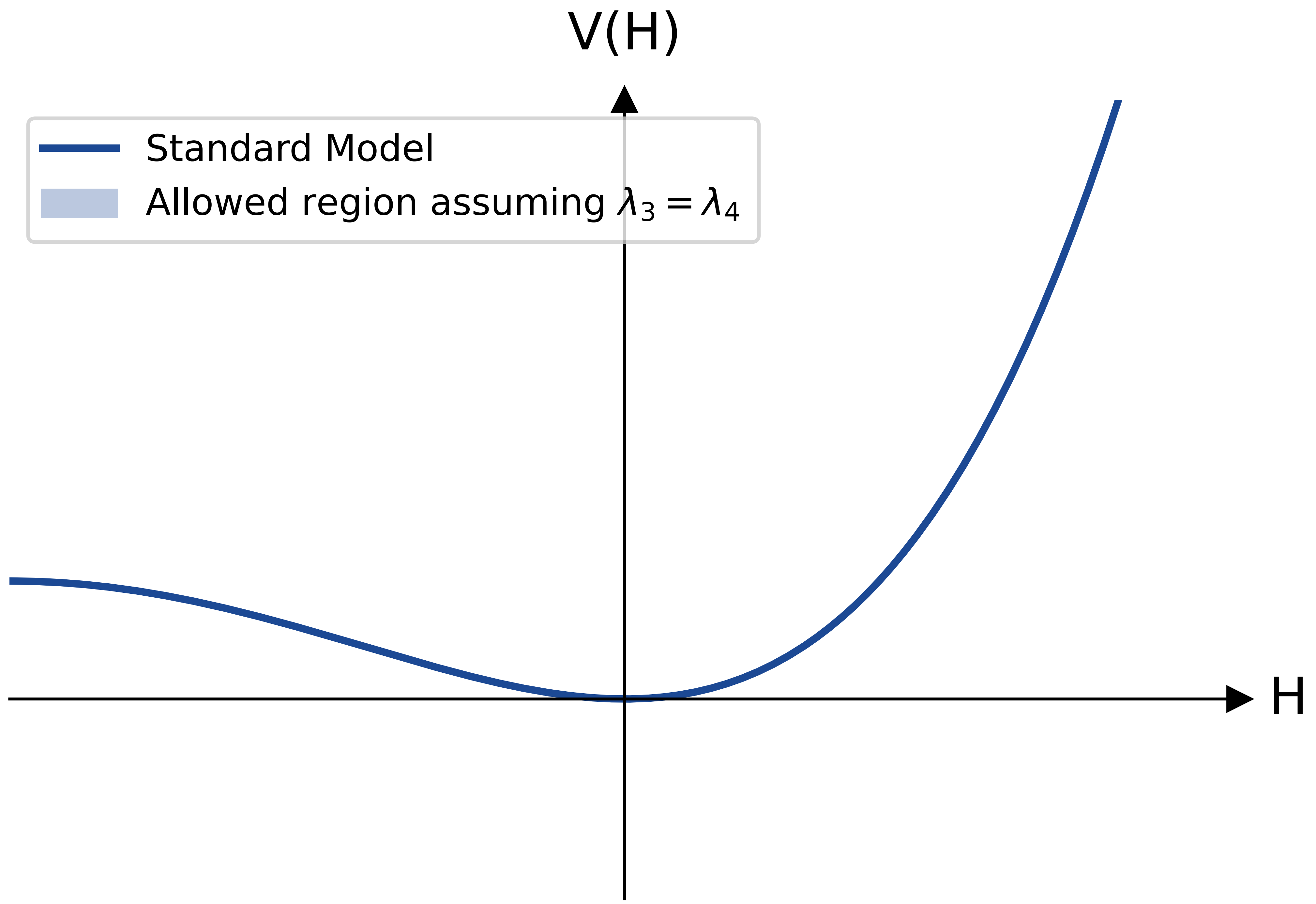
$$\kappa_4 \geq \frac{9}{8}\kappa_3^2$$

*beware of the assumptions

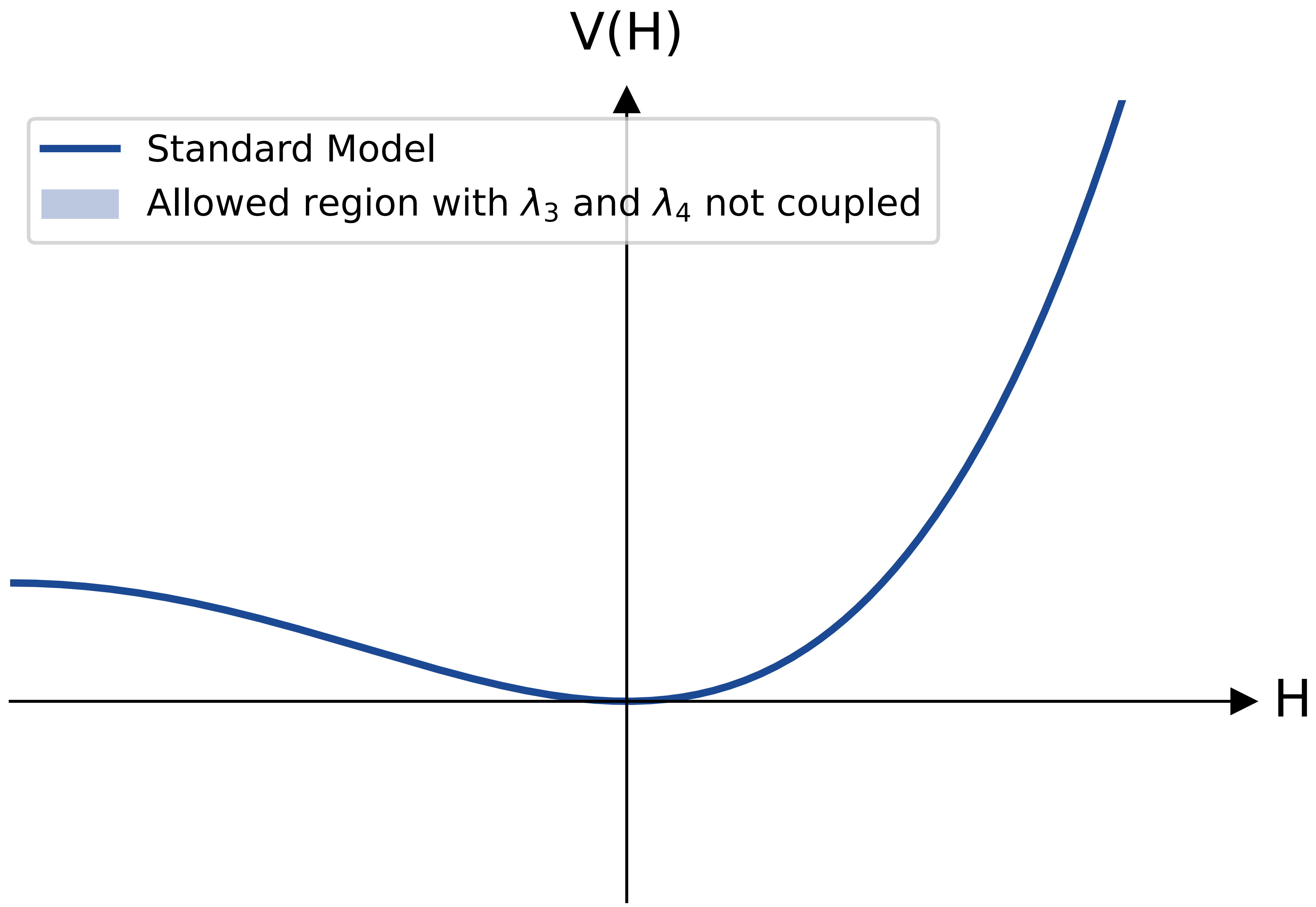
Constraining V(H) - where do we stand?

[using Run 2 ATLAS constraints from Phys. Lett. B 843 (2023) 137745]

Assuming 1 free parameter $\lambda_3 = \lambda_4 = \lambda$



Assuming 2 free parameters λ_3 and λ_4



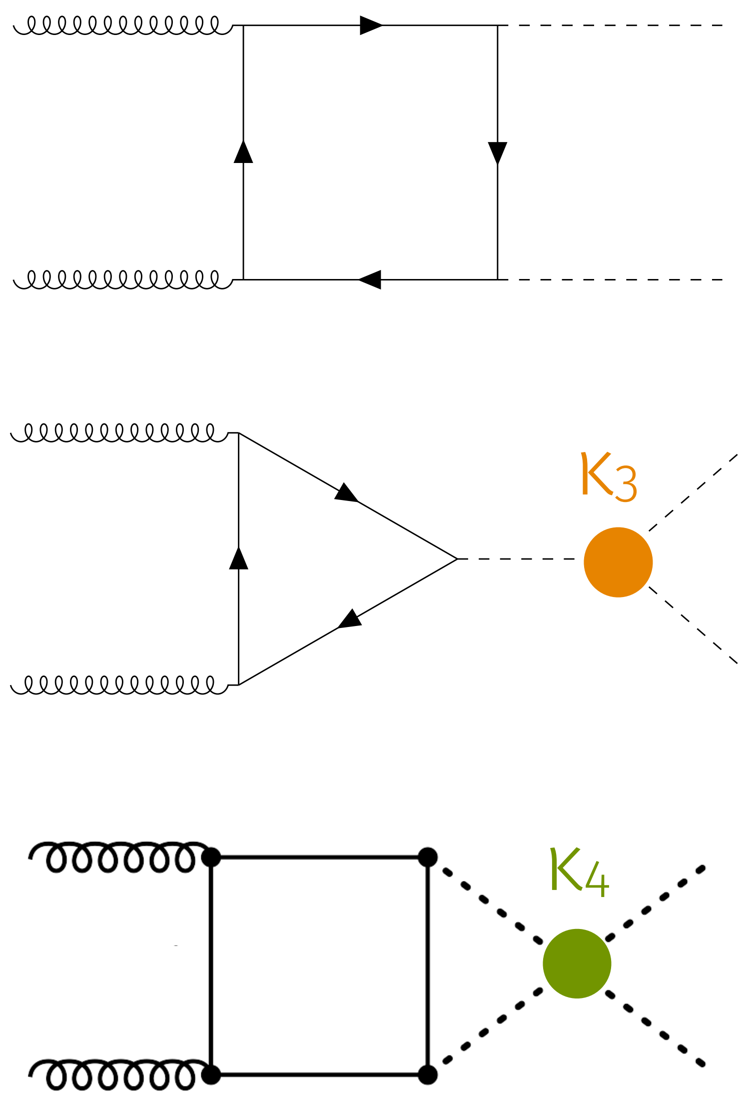
[plot style inspired by Nathaniel Craig]

- Current experimental constraints on the shape of V(H) are very weak
- They become even weaker when dropping the assumption that $\lambda_3 = \lambda_4 = \lambda$

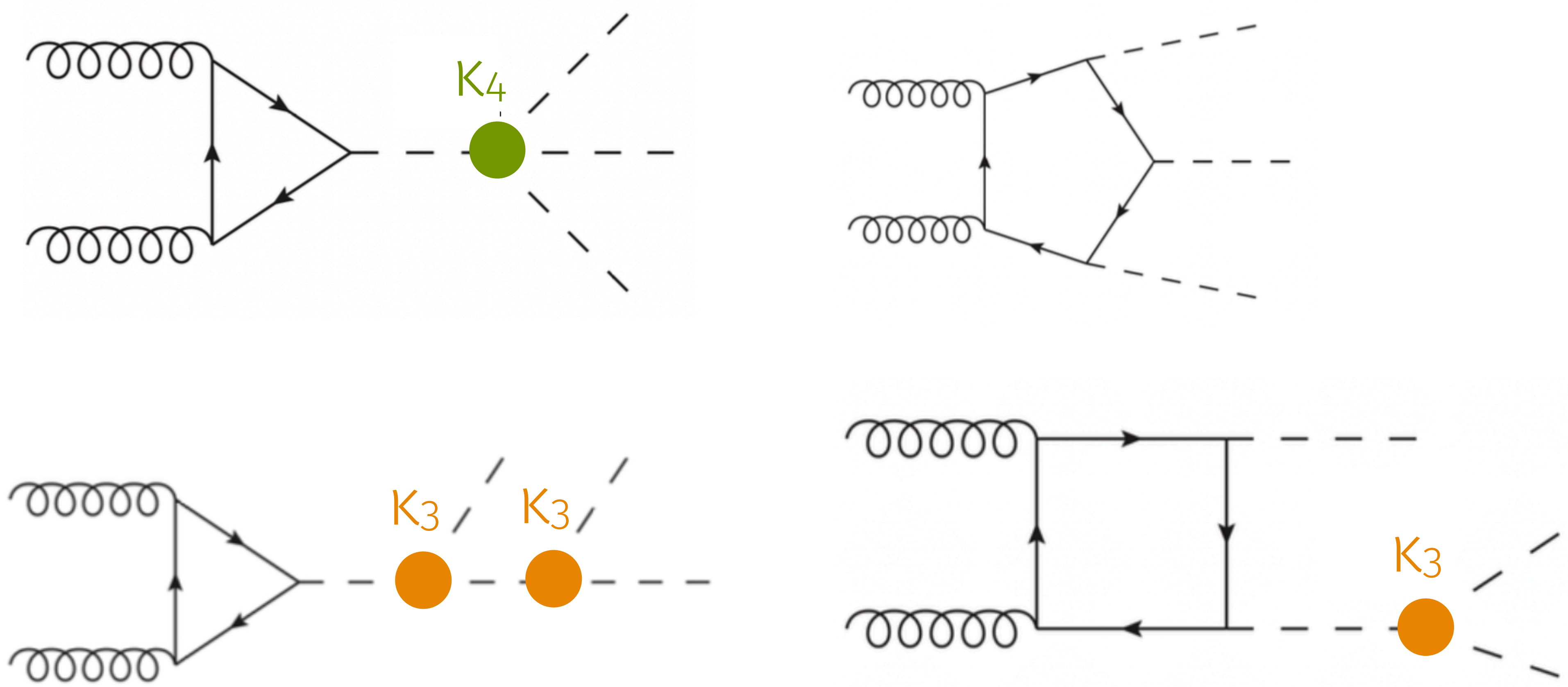
On multi Higgs production

- Multi Higgs boson production rates are extremely low compared to single Higgs production, which itself is already low [h/hh ~ 1800, hh/hhh ~ 450 @ LHC]
- To add to the complexity, the connection between final state multiplicity and contributing coupling modifiers is not trivial

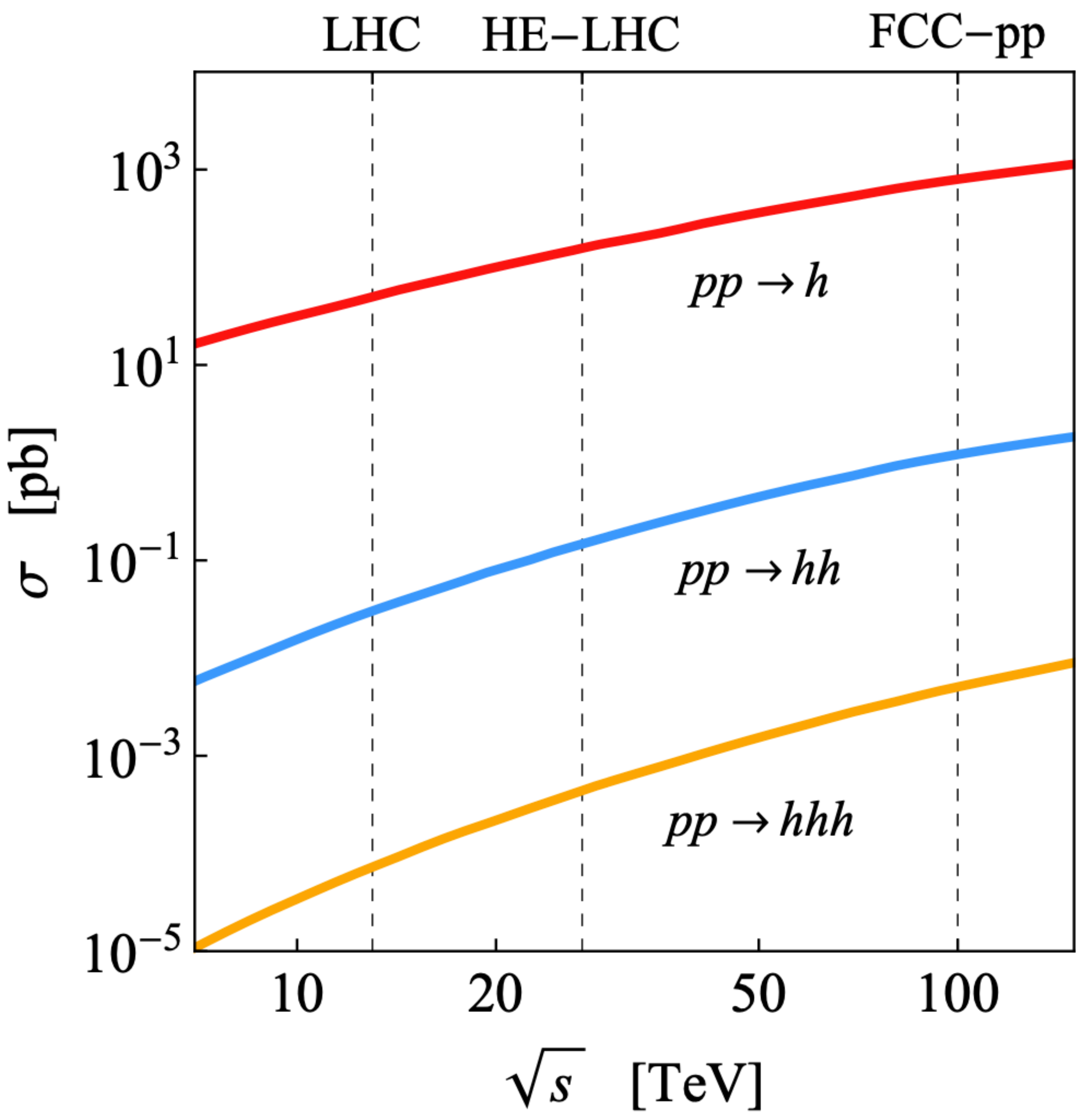
pp→HH:



pp→HHH:



[Bizon, Haisch, Rottoli JHEP 10 (2019) 267]

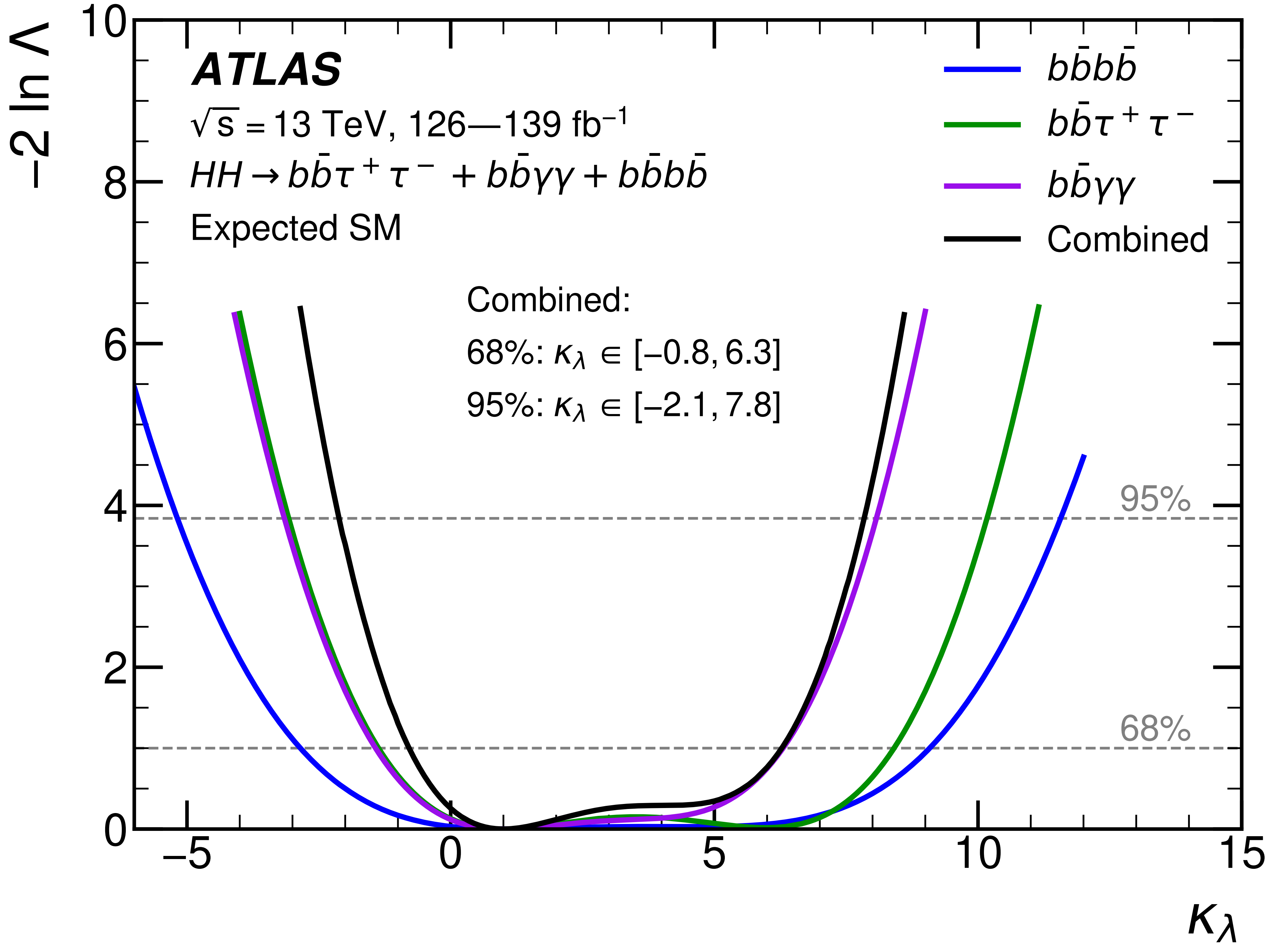


Run 2 expected yields:

pp→HH: ~ 4500 events

pp→HHH: ~ 13 events

Constraints from HH searches



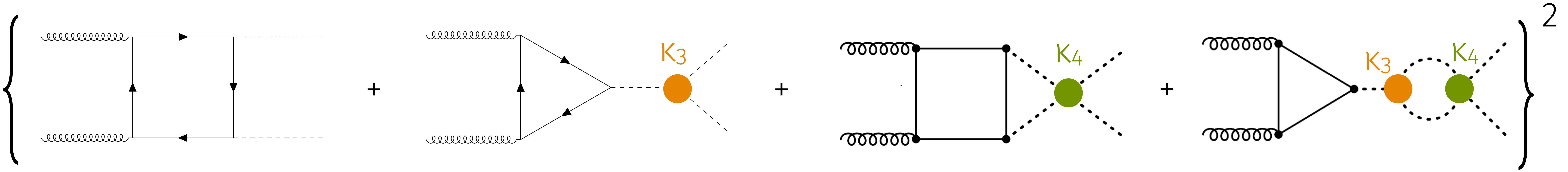
- The three “golden” HH channels are used to set the leading constraints on κ$_3$ [on the lower side we are already setting meaningful constraints, upper bound still slightly larger than unitarity constraints]
- These constraints are done without considering $\mathcal{O}(\kappa_4)$ contributions to the HH cross-section

The impact of κ₄ on HH production

[collaboration with Franziska Rauscher]

- Has been estimated by Bizon, Haisch and Rottoli [JHEP 10 (2019) 267] for HE-LHC and FCC-pp
- Derived LHC parameterization of the HH signal strength μ with the help of Luca Rottoli (many thanks) at LO

$$\sigma(pp \to HH) \sim$$



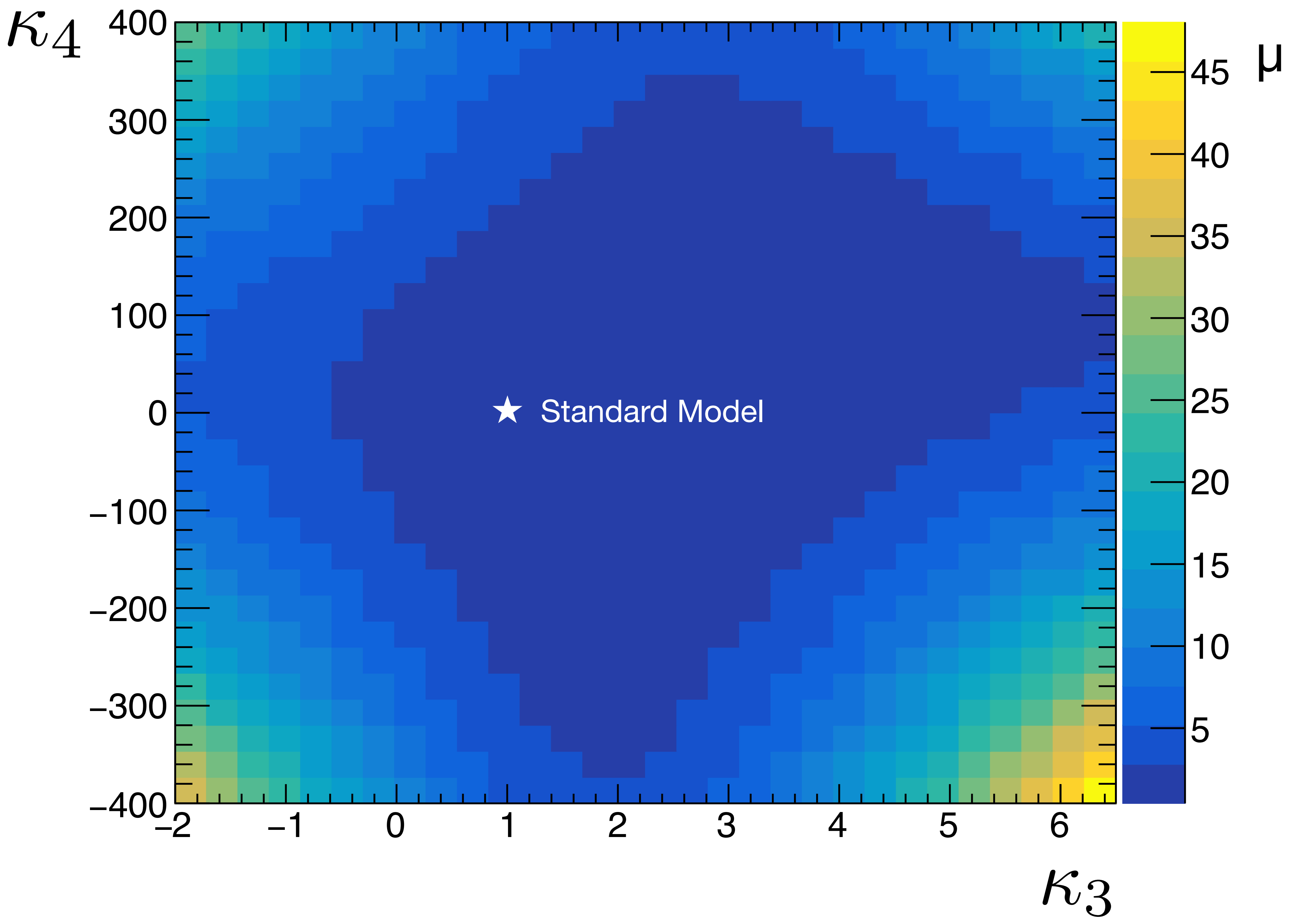
$$\sim\ p_0 + p_1\ \kappa_3 + p_2\ \kappa_4 + p_3\ \kappa_3^2 + p_4\ \kappa_3\kappa_4 + p_5\ \kappa_4^2 + p_6\ \kappa_3^2\kappa_4 + p_7\ \kappa_3\kappa_4^2 + p_8\ \kappa_3^2\kappa_4^2$$

- Neither shape nor acceptance effects included in the following, but current HH analyses are also not very sensitive to either of them ….

The impact of κ₄ on HH production

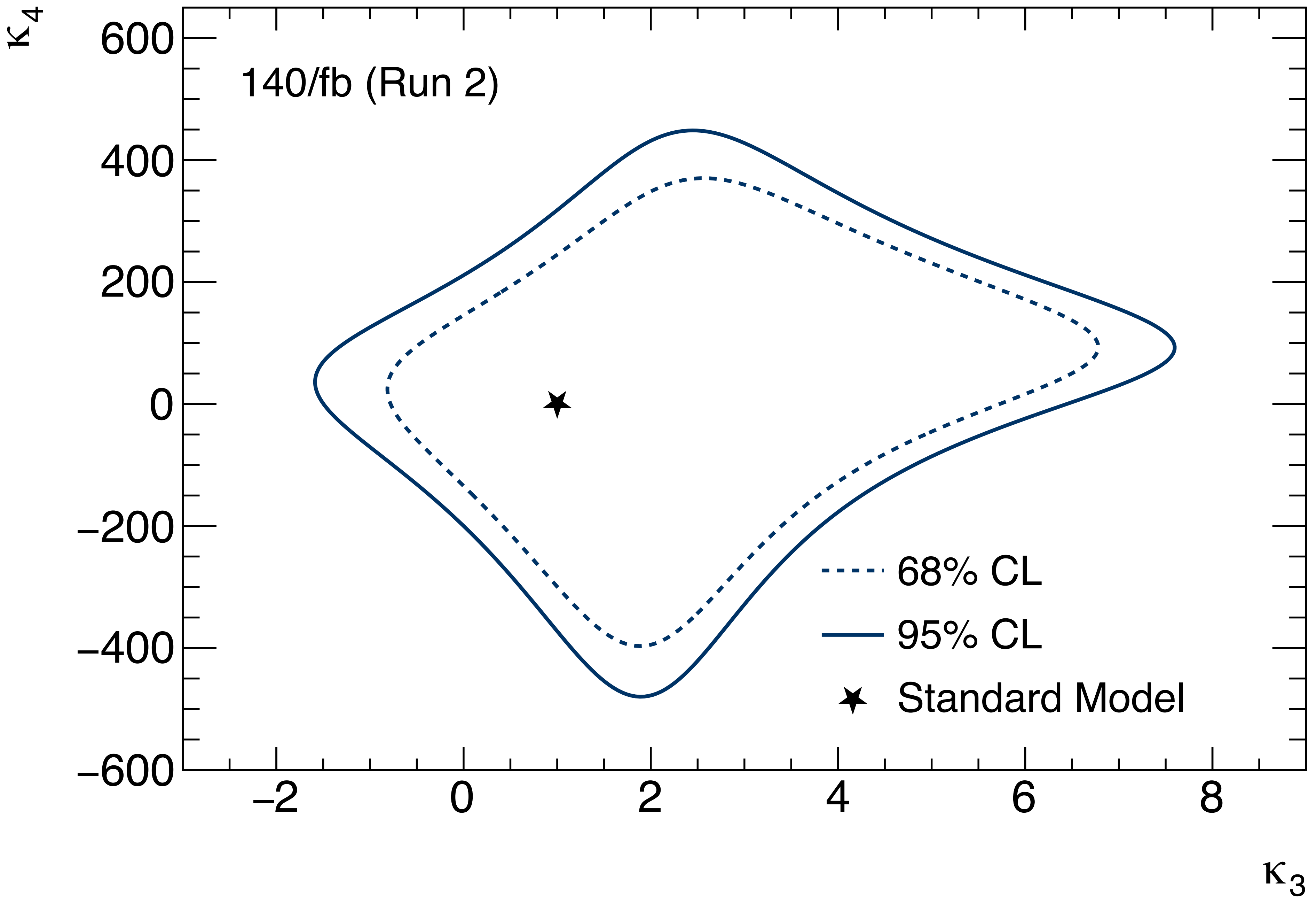
[collaboration with Franziska Rauscher]

Impact of κ_3 and κ_4 on $\mu(pp \to HH)$:



Constraints assuming $\mu_{expected} < 2.9$ @ 95%CL:

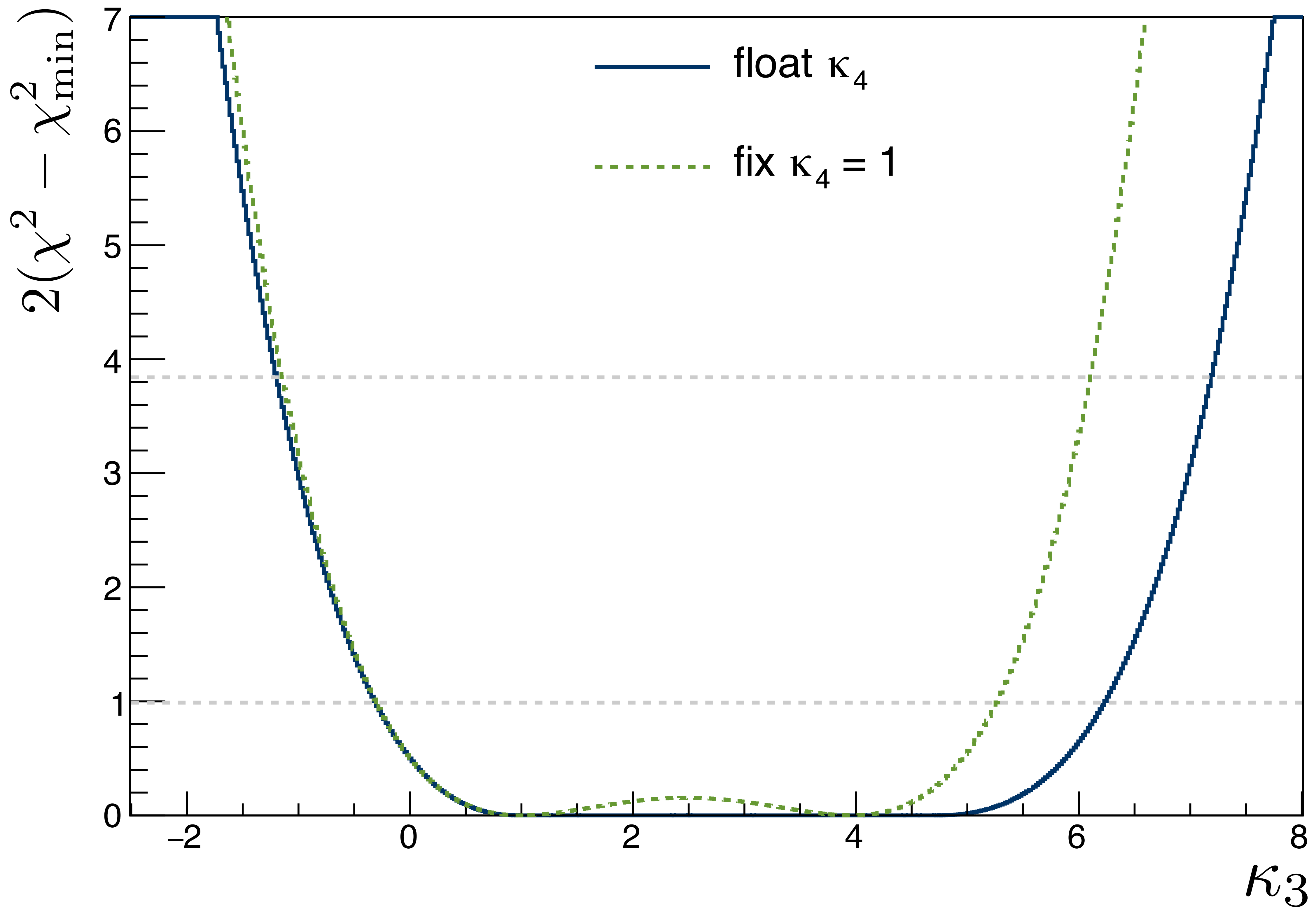
[Run 2 ATLAS, Phys. Lett. B 843 (2023) 137745]



- As expected, HH cross-section only depends weakly on κ4 → can constrain only values that are anyway beyond unitarity bounds
- No complete degeneracy, not all values of κ_3 can be compensated by a non-SM κ_4

HH constraints on κ3 w/o κ4 profiled

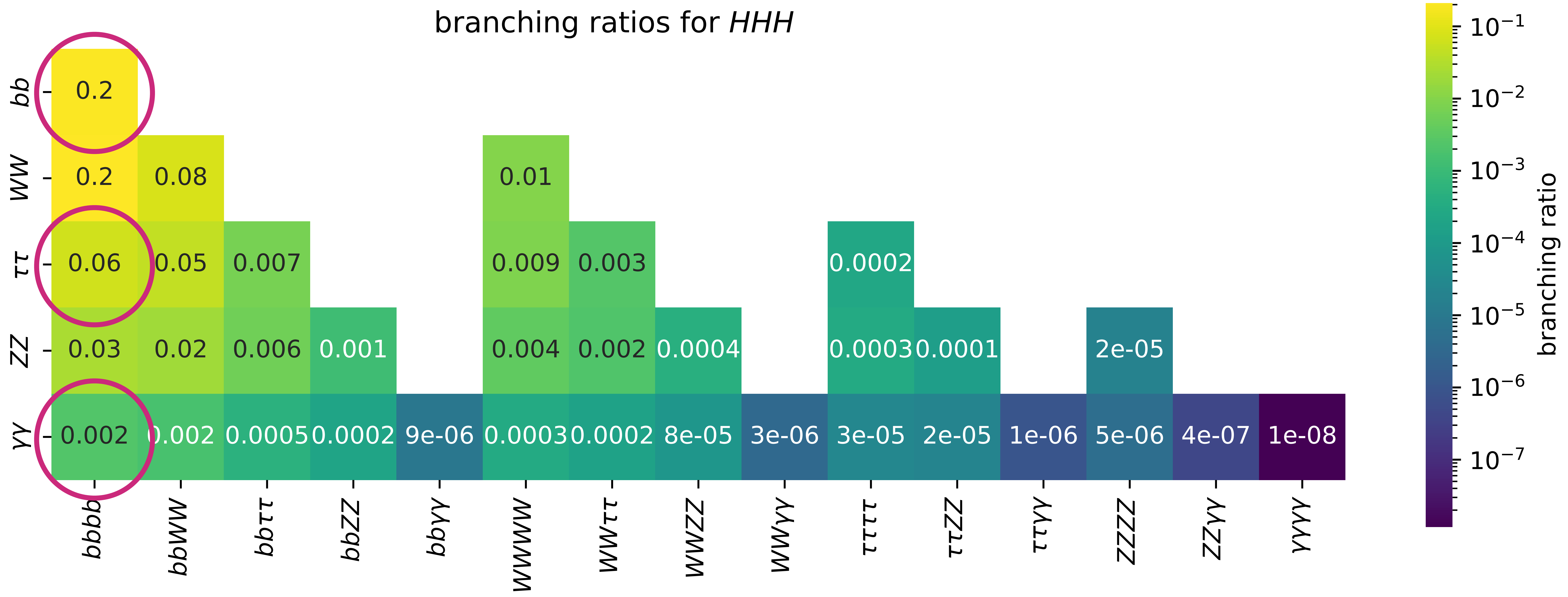
[collaboration with Franziska Rauscher]



- Can set limits on κ3 without implicit assumptions on κ4 in HH measurements
- Limits for high κ3 get ~ 20% worse but gain model independence

Searches for HHH production

[plot by Katharina Häußler]



- No analyses published yet → need to do some “by-hand” extrapolation
- Focusing only on the following final states: **6b**, **4b2τ** and **4b2ɣ**
- **Pheno studies** for a future 100 TeV pp collider exist
  [Chen, Yan, Zhao, Zhao, Zhong - PRD 93 013007] and [Fuks, Kim, Lee - PRD 93 035026]
  → use this combined with ATLAS/CMS HH numbers as the starting point for our estimation

Searches for HHH production

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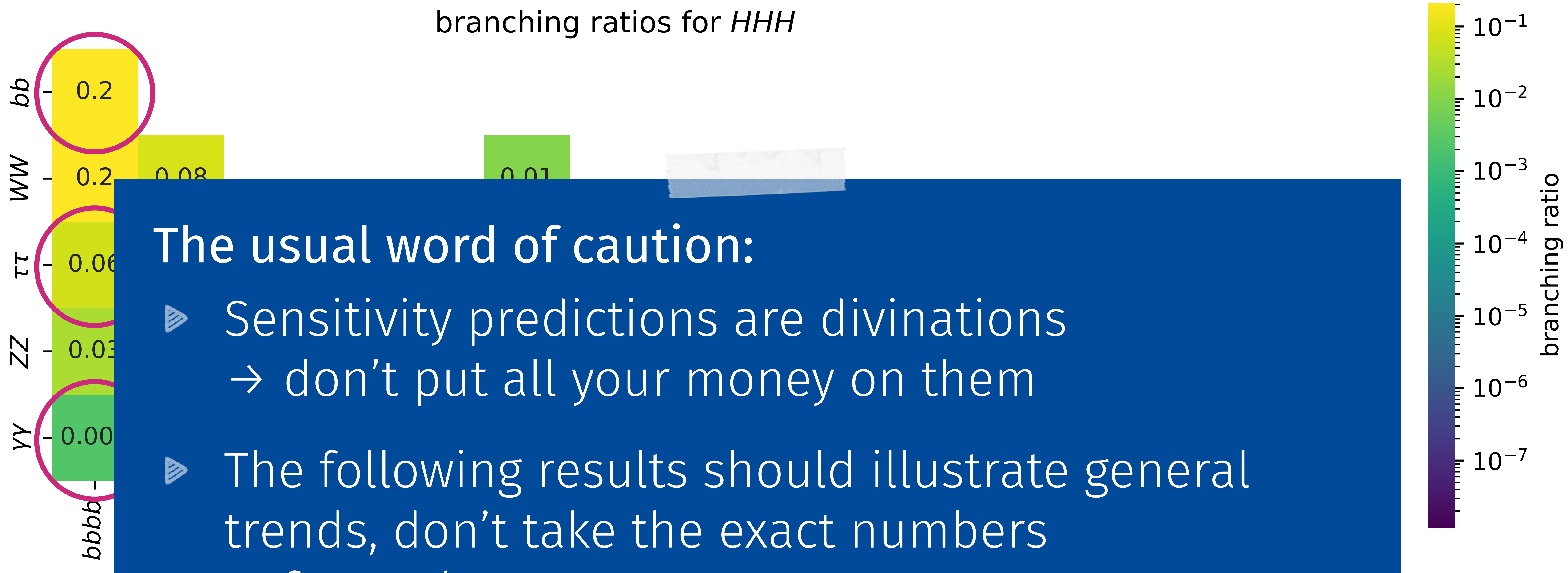

The usual word of caution:

- Sensitivity predictions are divinations
  → don't put all your money on them
- The following results should illustrate general trends, don't take the exact numbers at face value

- No analyses published yet → need to do some "by-hand" extrapolation
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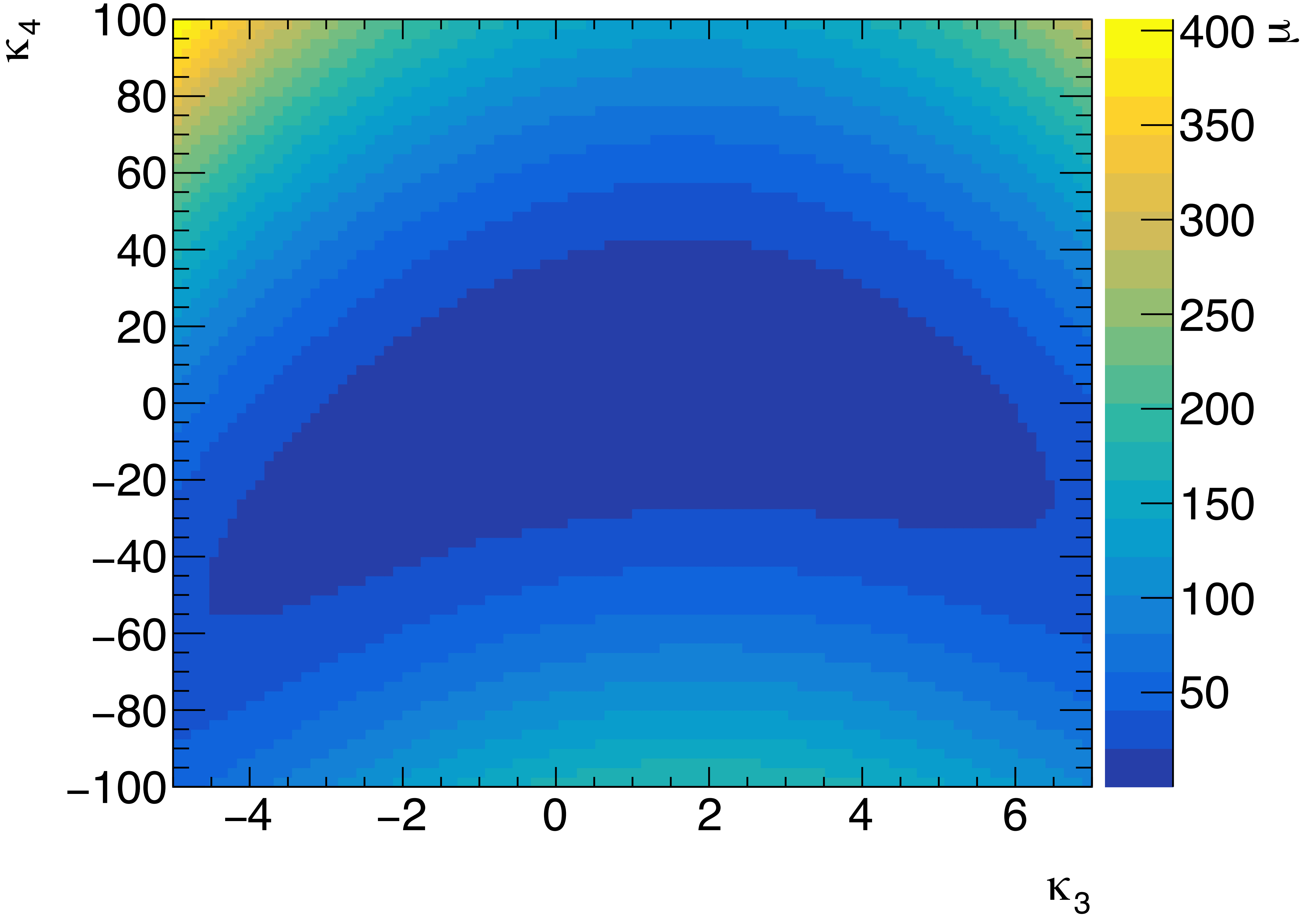
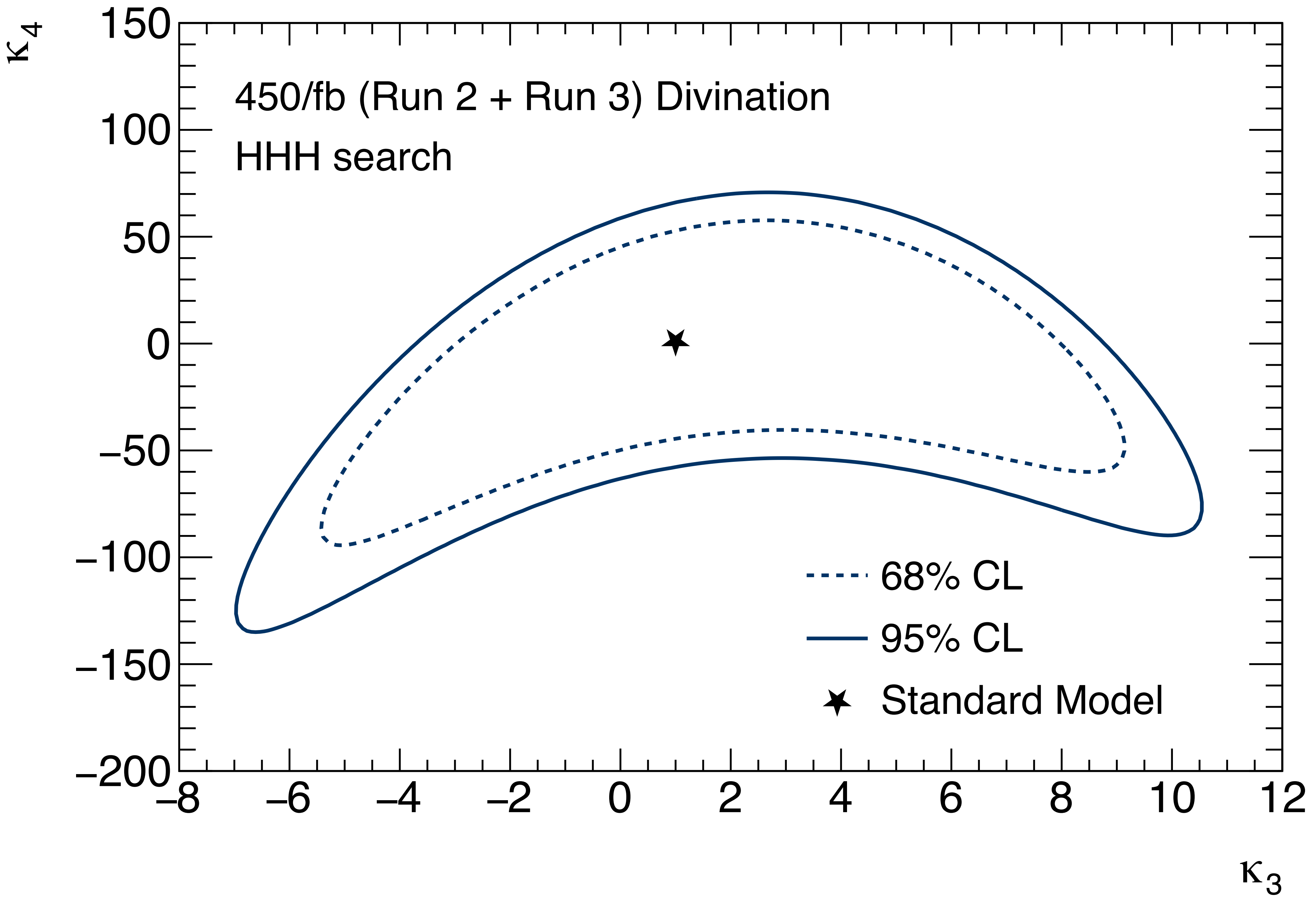
The dependence of the HHH XS on κ₃ and κ₄

- Using the HE-LHC values from Bizon, Haisch and Rottoli [JHEP 10 (2019) 267]
  (μ parameterization doesn't show a large energy dependence between HE-LHC and FCC-hh]

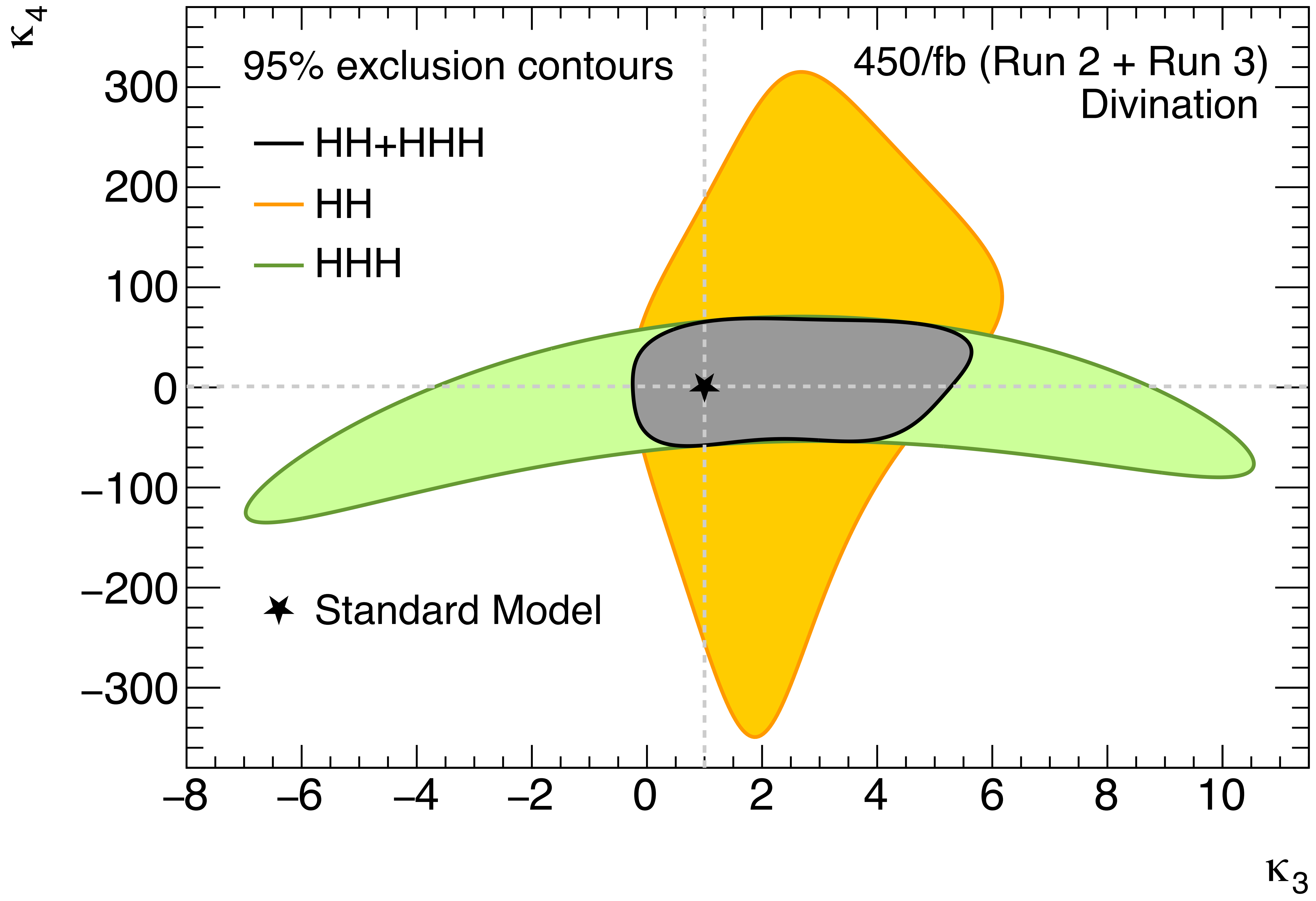
Impact of κ₃ and κ₄ on μ(pp→HHH):



Constraints assuming $\mu_{HHH} < 50$ @ 95%CL:
[rough estimation for Run 2 and Run 3]

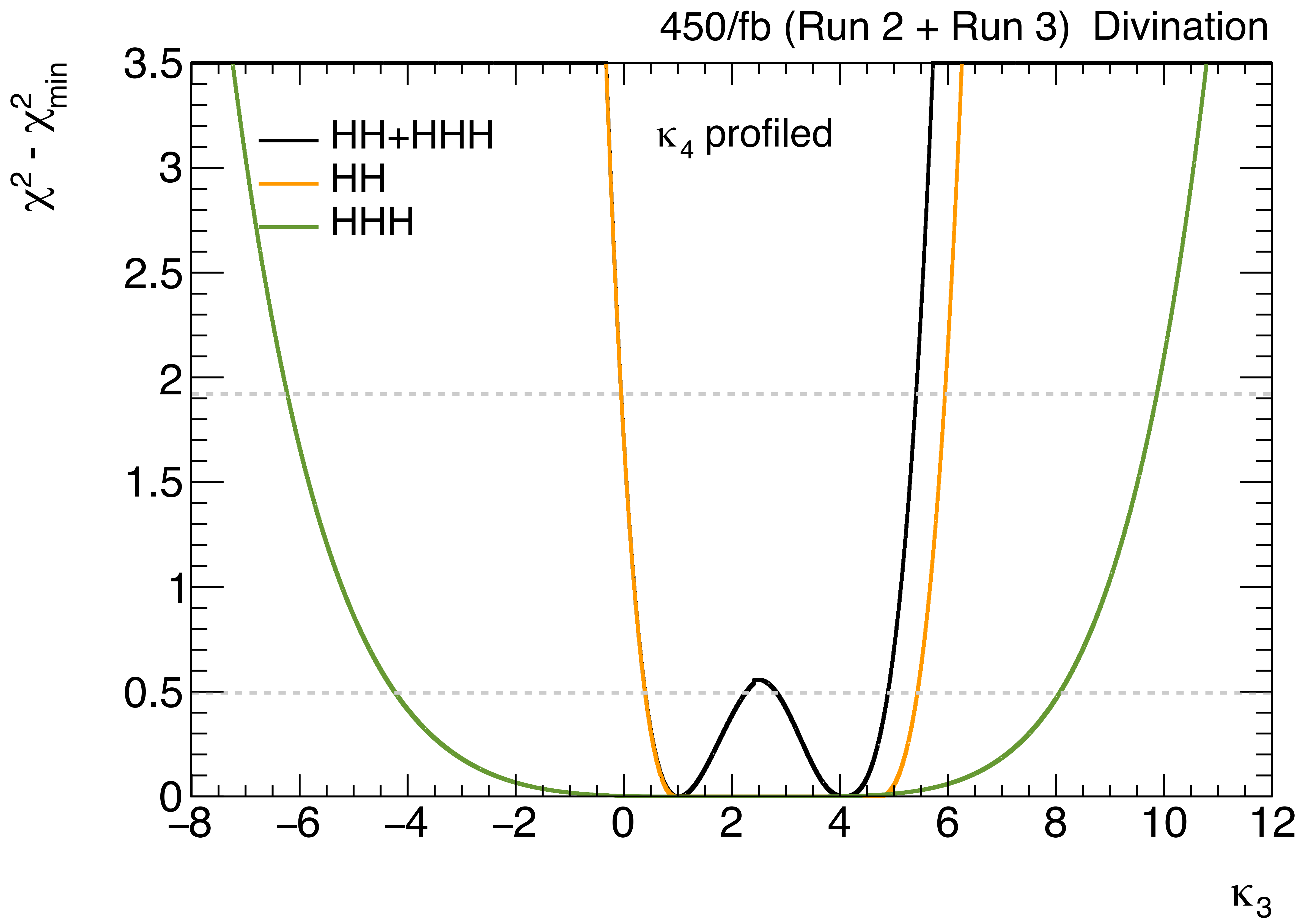


The complementarity of HH and HHH



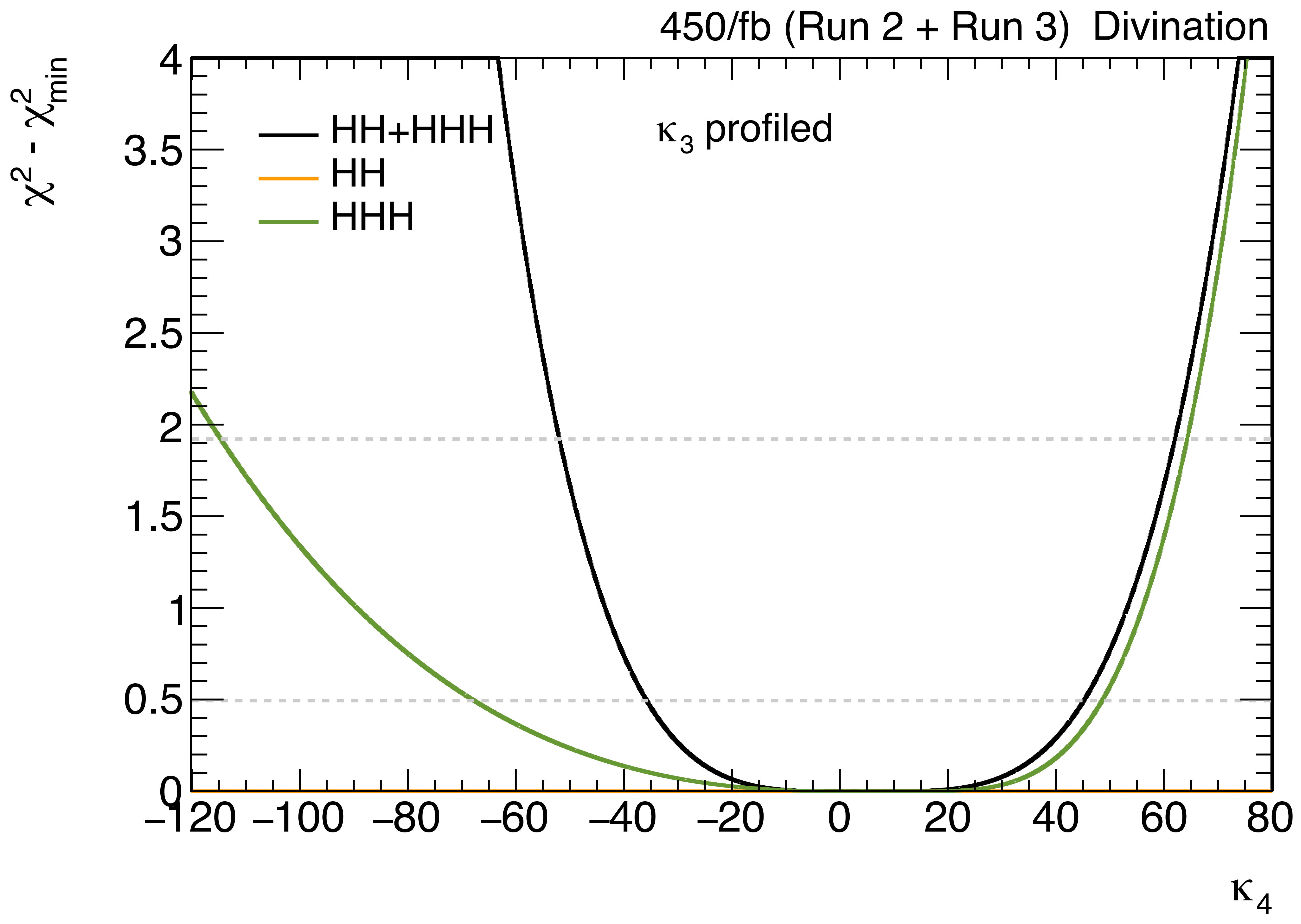
- Constraints on κ_3 and κ_4 from HH and HHH analyses are nicely complementary
- With the combined Run 2 and Run 3 dataset we might already be getting close to the unitarity threshold for κ_4 → simple extrapolation based only on inclusive yields, we can do better than this!

HH + HHH: constraints on κ_3



- Main constraint on κ_3 is coming from the HH analysis
- Combination with HHH helps at high κ_3 and in the region between the two minima

HH + HHH: constraints on κ₄

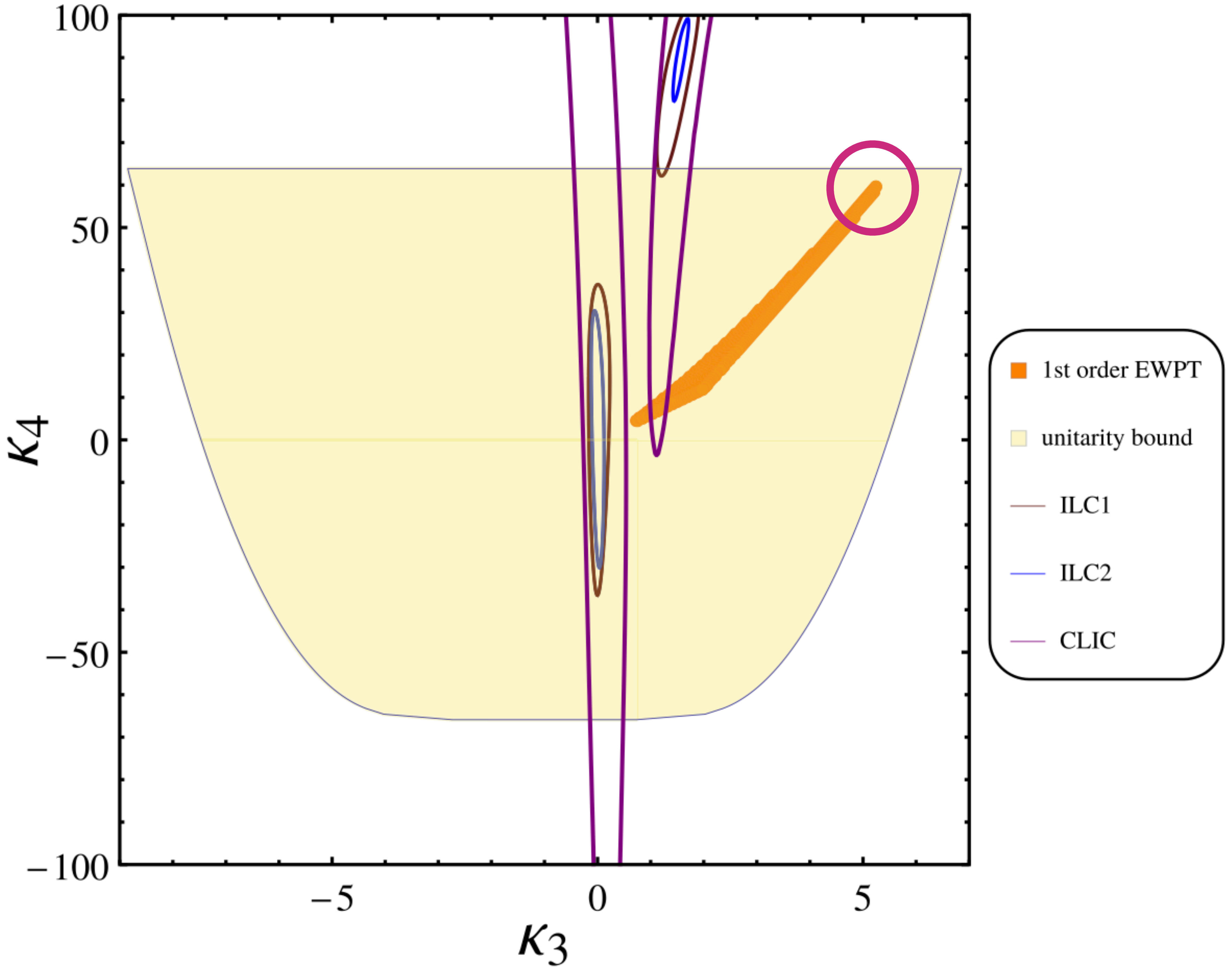


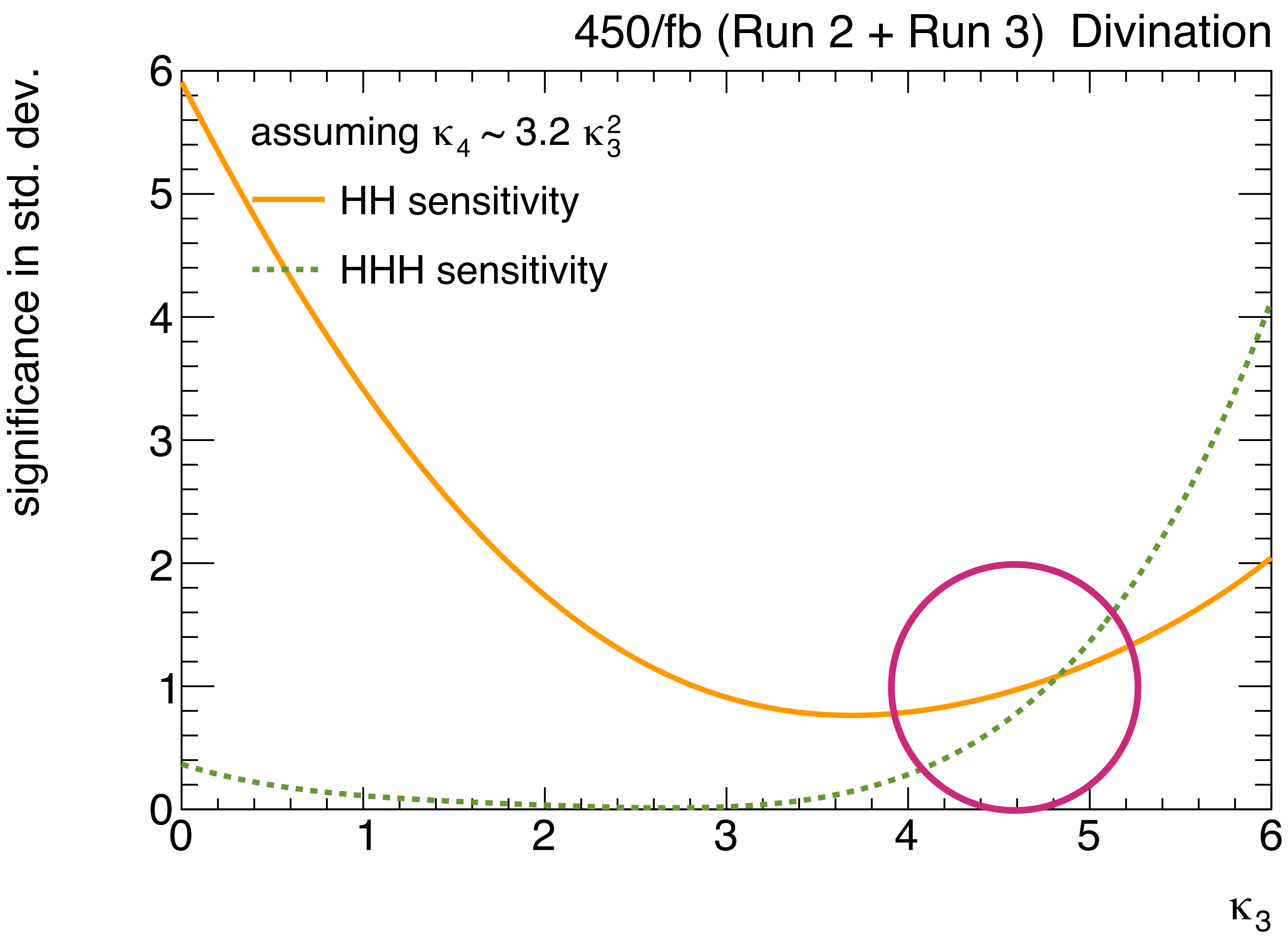
- Main constraint on κ₄ is coming from the HHH analysis
- Combination with HH helps significantly for negative κ₄

Sensitivity to new physics

[many thanks to Wouter Verkerke for the plot suggestion]

[Liu, Lyu, Ren, Zhu - 2018 - PRD 98 093004]



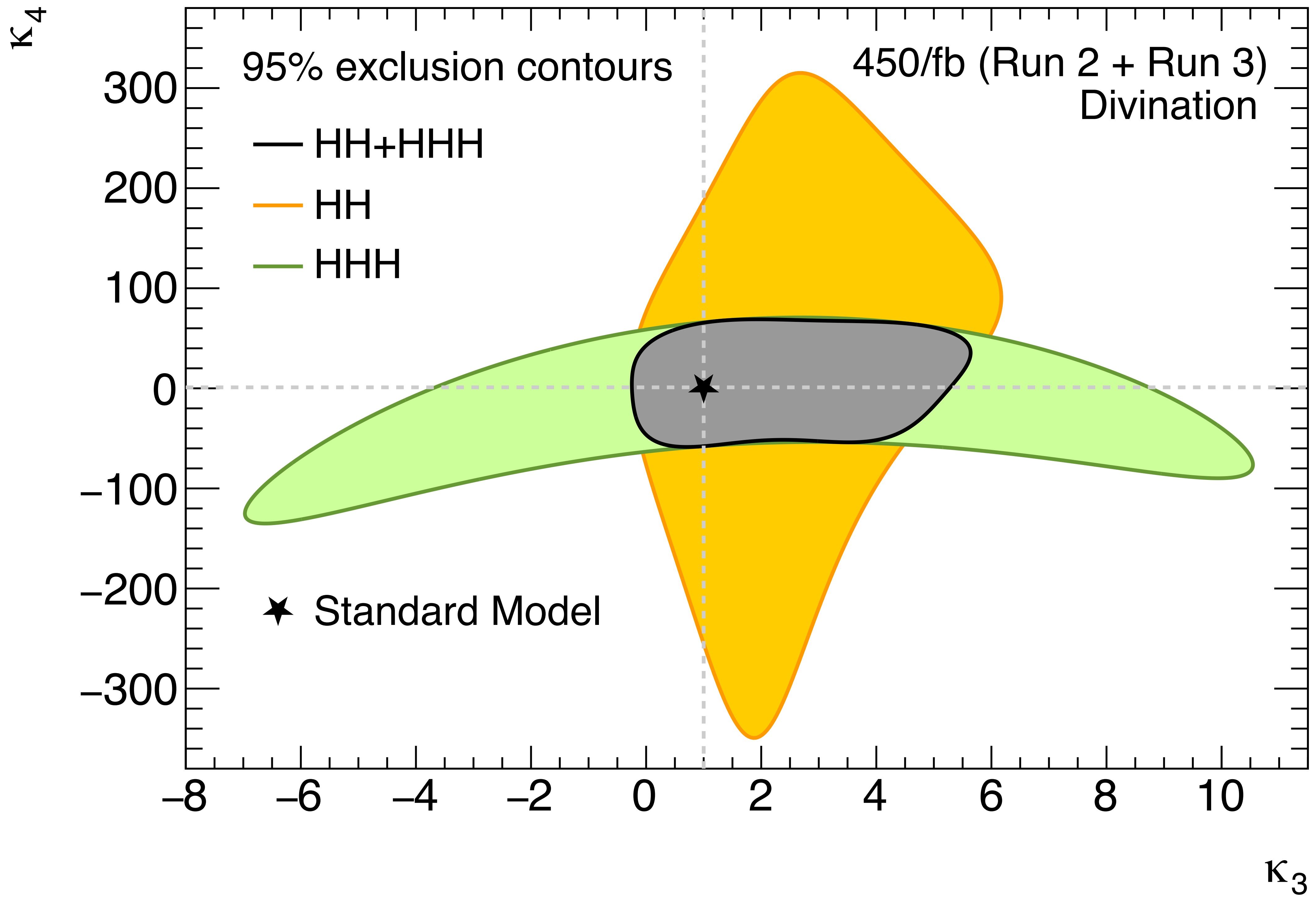


- Let’s assume a correlation between κ_3 and κ_4 and check the sensitivity of the HH and HHH analyses to the signal as a function of κ_3

- In this scenario, a search for HHH would be equally sensitive to the new physics as the HH search for larger values of κ_3

Summary and outlook

- Measurements of HHH production can nicely complement the ongoing HH program to constrain the shape of the Higgs potential
- It would be great if theorists could guide us towards interesting values of κ_3 and κ_4
- For us experimentalists: now is the time to sit down and do the actual measurements
- This will also give us a better starting point for more accurate extrapolations into the future



Let's discuss!

Backup