Search for non-resonant triple Higgs boson production in the six b quark final state in proton-proton collisions at CMS

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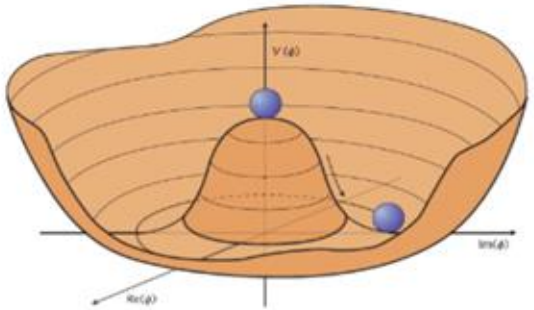
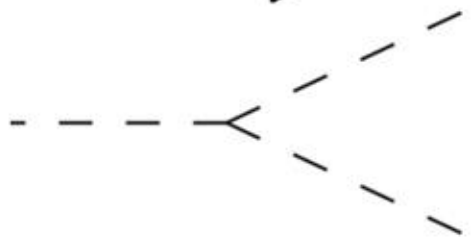
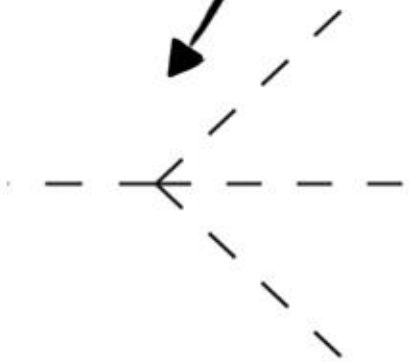
Motivation: measuring the Higgs potential

arXiv:2607.05145

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







In the Standard Model: the Higgs potential is responsible for the masses of all particles

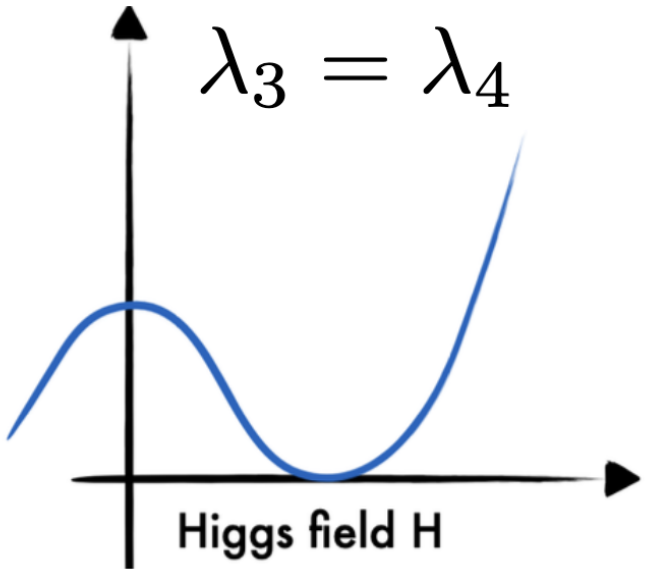
- Directly responsible for the interaction of the Higgs boson with itself
  - Trilinear coupling: responsible for di-Higgs production
  - Quartic coupling: responsible for triple-Higgs production
- Higgs self-coupling: one of the most important properties of the Higgs boson that is not measured yet

Motivation: measuring the Higgs potential

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

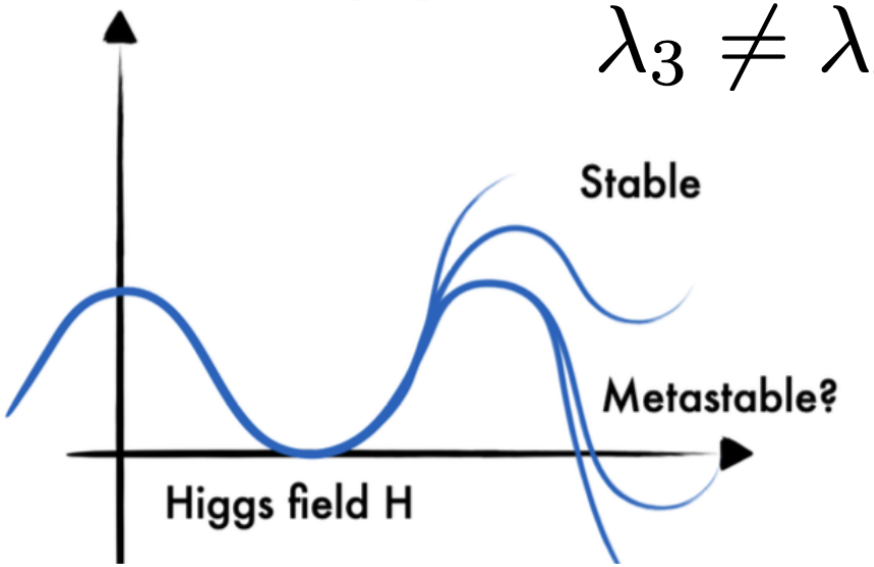
Standard Model

$\lambda_3 = \lambda_4$



New physics

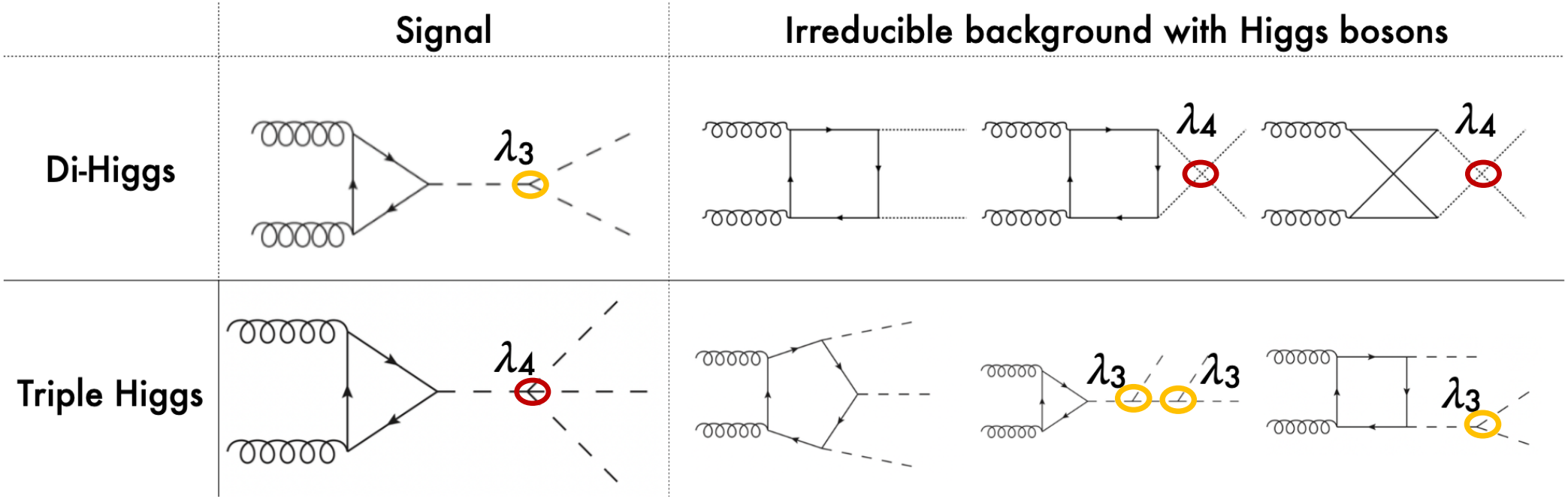
$\lambda_3 \neq \lambda_4$



In the Standard Model: $\lambda_3 = \lambda_4$

- Not given for a fact, needs to be measured
- New physics can affect the shape of the Higgs potential → large consequences for the Universe

Probing self-interaction di-Higgs and triple Higgs



Probing the Higgs self-coupling possible through di-Higgs and triple Higgs measurements:

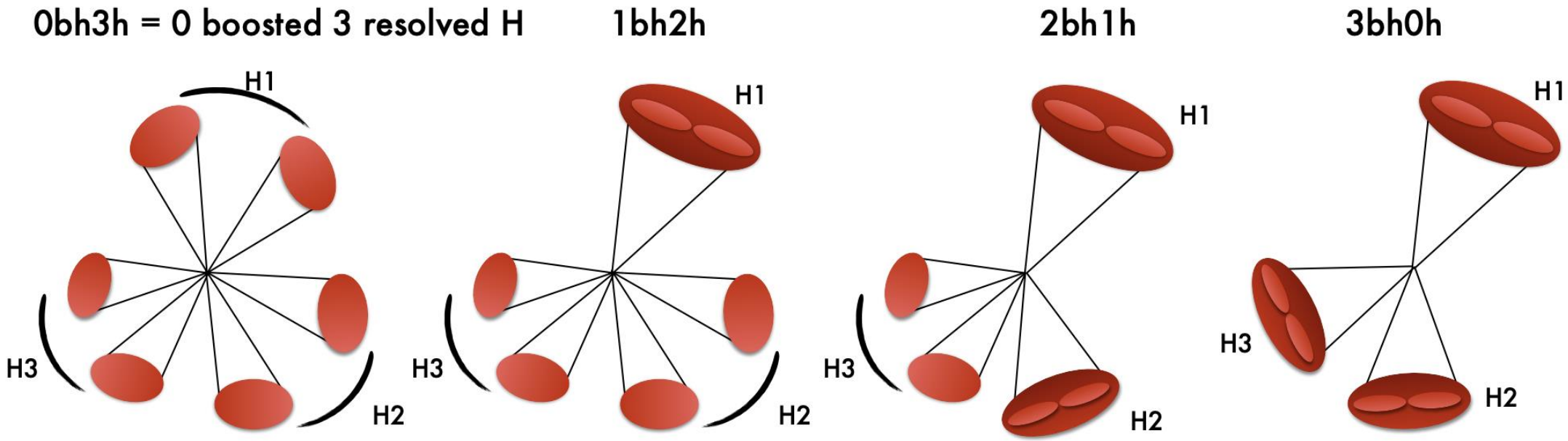
- Di-Higgs: nearly exclusively sensitive to λ_3 coupling (very small contribution from $\lambda 4$)
- Triple Higgs: sensitive to both λ_3 and λ_4 coupling

  → Full determination of the Higgs potential only possible through combined measurement!

Sensitivity:

- Di-Higgs: current sensitivity < 2.5 x SM @ 95% CL → expect evidences at HL-LHC
- HHH6b ATLAS: < 750 x SM @ 95% CL
- HHH4b2y CMS: < 2000 x SM @ 95% CL

Signal topology



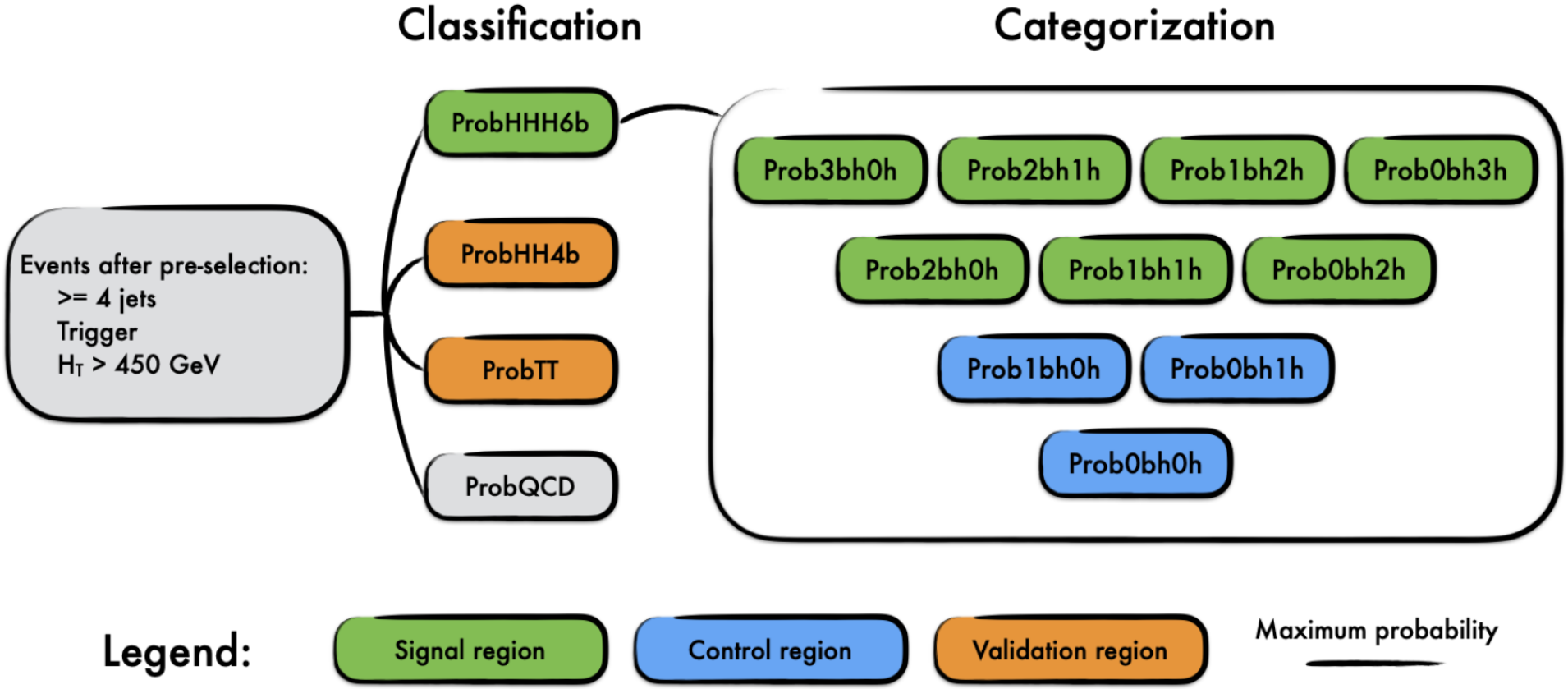
HHH: cross-section = 0.08 fb-1

- About 14 events produced in Run 2, Rare process = every event counts
  - Topology definition: 0bh3h = 0 boosted Higgs 3 resolved Higgs, …

From truth matching study: match b-quark to AK4 jets and Higgs to AK8 jets

- 3 reconstructible Higgs: **25% of HHH** events with 6 b-quarks in the acceptance of detector
  - Mostly 0 boosted 3 resolved Higgs, 1 boosted 2 resolved Higgs
  - Main reason: one b-quark outside tracker acceptance (eta > 2.5)
- 2 reconstructible Higgs: **50% of HHH**
- 1 and 0 reconstructible Higgs: **about 25% of HHH**

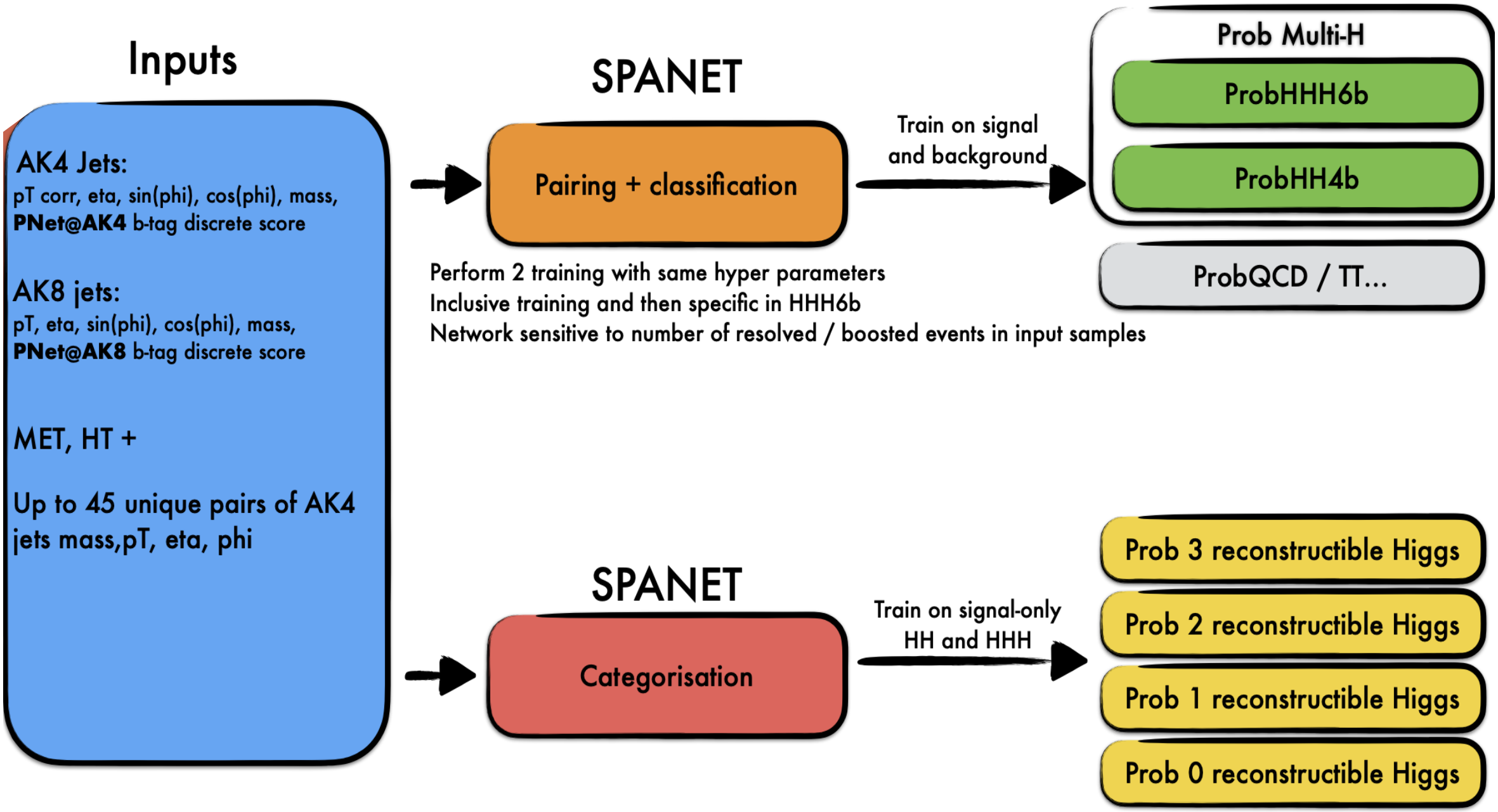
Analysis strategy



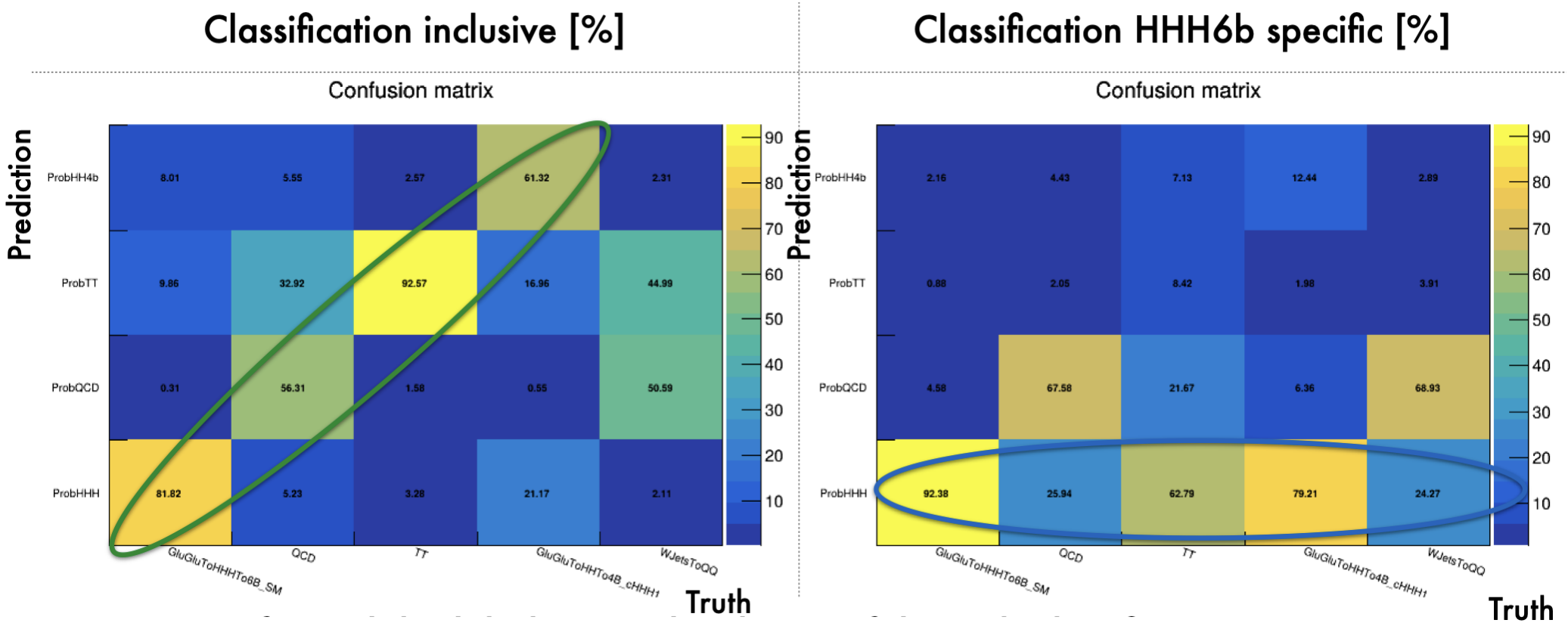
Dominant background: QCD (95%) and ttbar (5%)
Train two networks using SPANET

- Multi-classifier: HHH6b vs HH4b vs QCD vs ttbar → Effectively vetoing HH4b events
  - Use HH4b-like events to validate background model, use ttbar node to validate Data / MC
- Multi-categorization: trained on HHH6b and HH4b predict categories based on truth matching

SPANET multi classifier



Classification

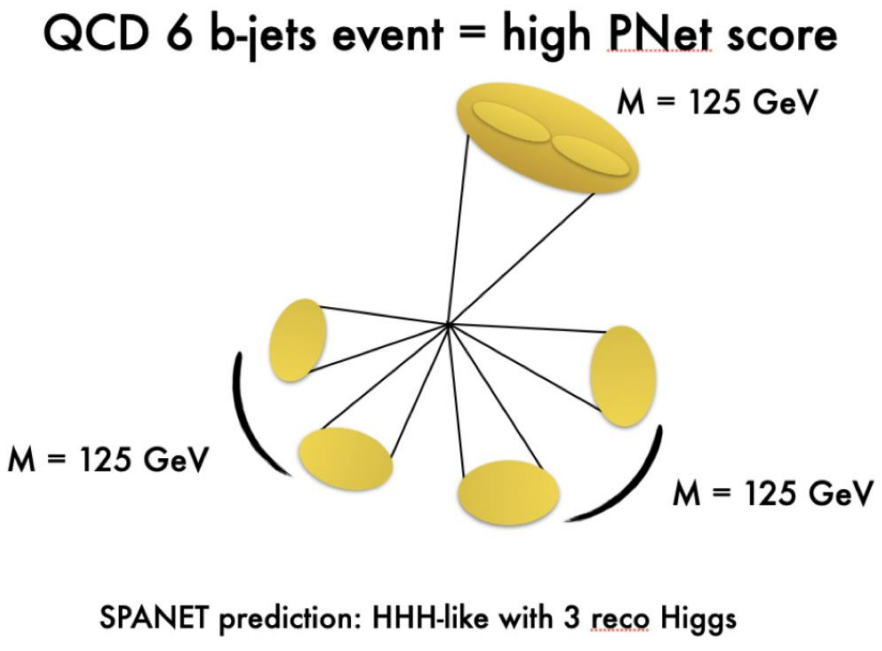


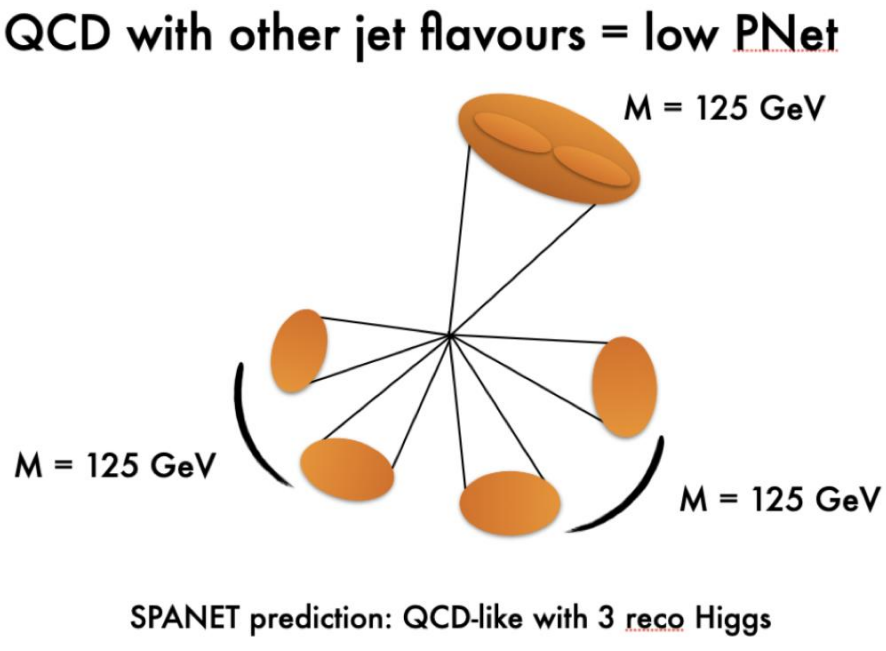
Two trainings performed: both balancing the classes of the multi-classifier

- First inclusive training right after event selection: acts as pre-selection
- Second training on HHH6b-specific events: found to bring additional separation
- Reduce QCD background by x4 in second training
- Battery of overtraining tests performed, as well as sensitivity comparison

All indicate improvement is consistent with observed confusion matrix

Background model

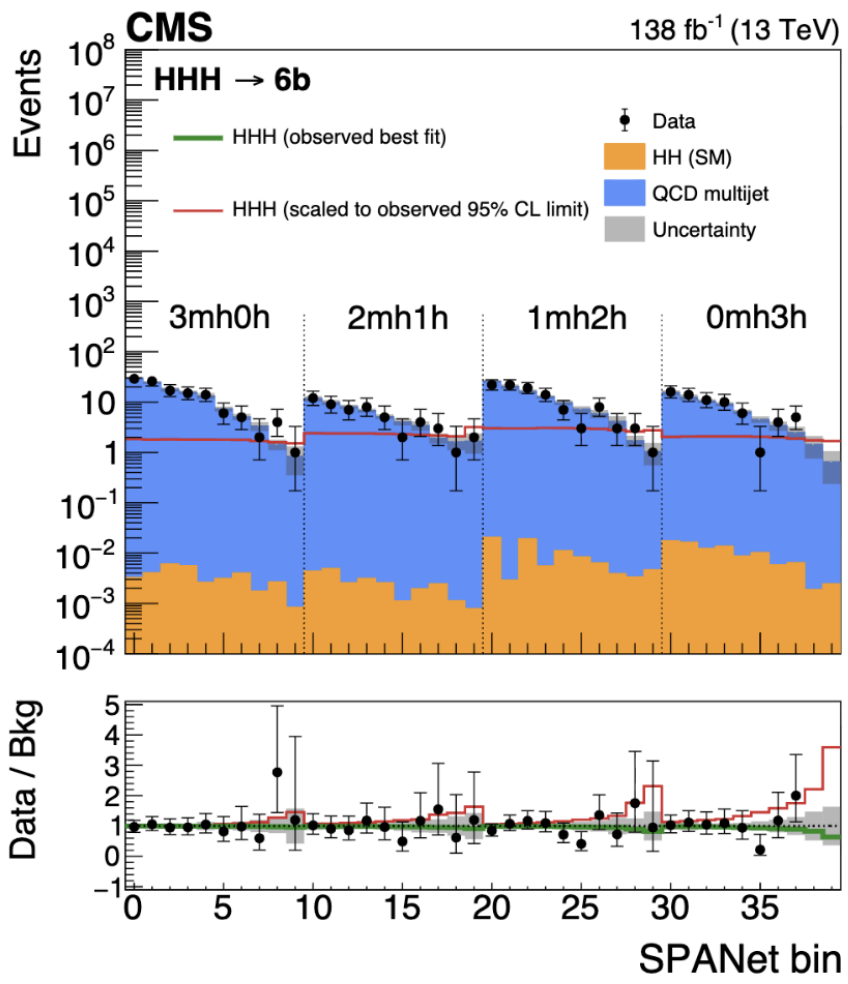


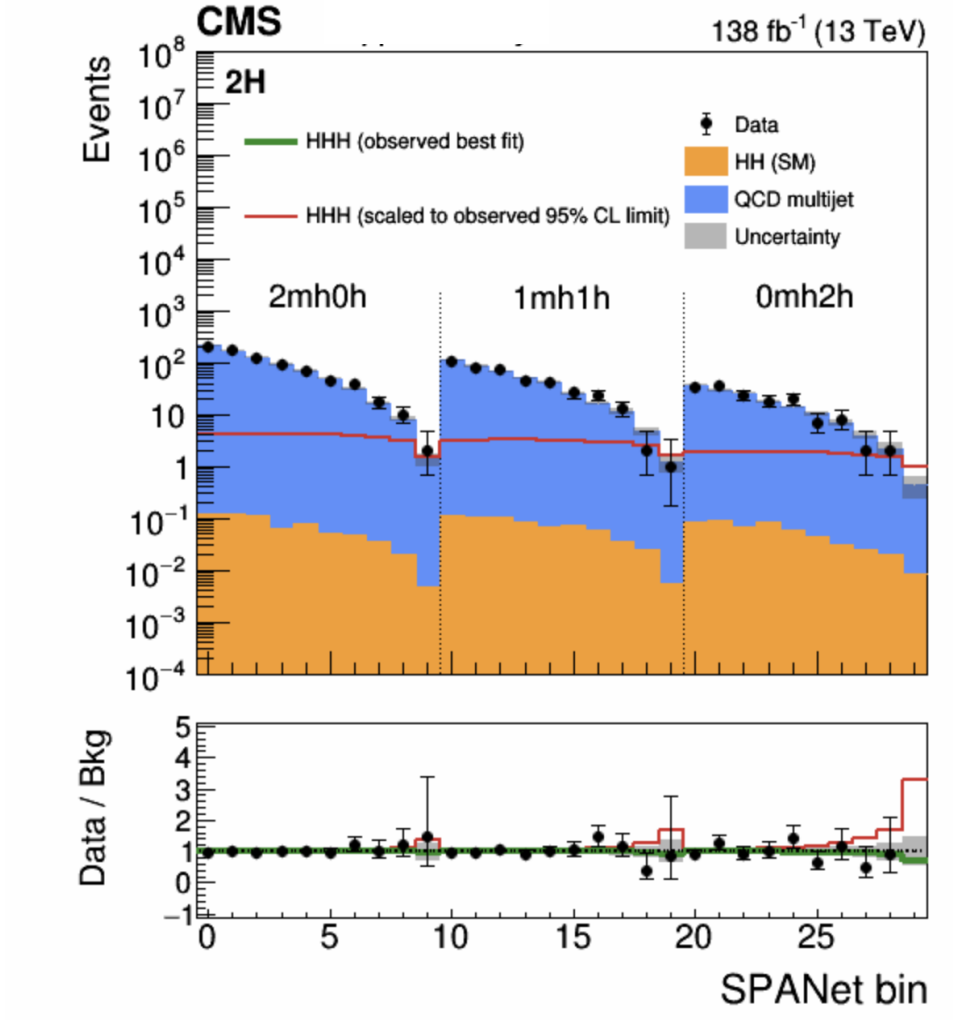


Proposal: use data events failing the HHH-like classification for background modelling

- Use background-like events and replace the PNet score of all AK4 and AK8 jets with signal-like events
- Re-run inference and let SPANET classify and categorise these events
- Assumptions: very low signal yield in background like events - verified with the confusion matrices
- Advantages: no systematics on object / trigger for the background given that it's data

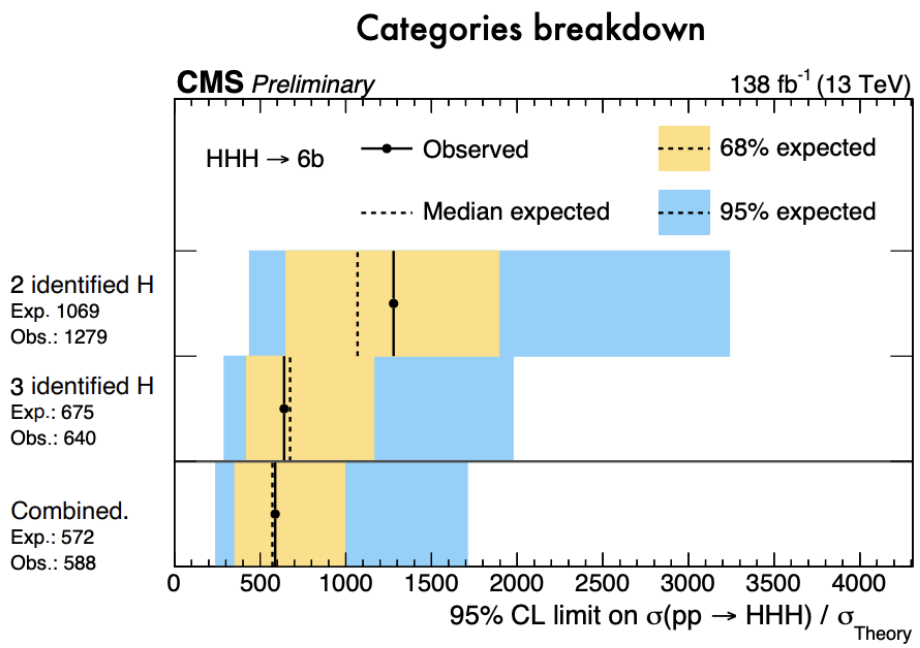
Data/MC distribution

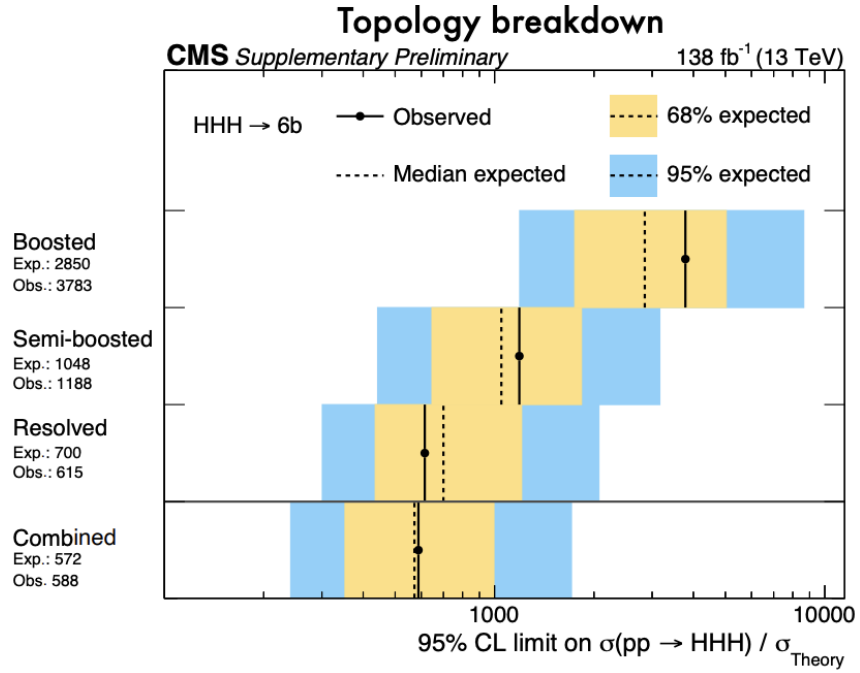




Data/MC in good agreement under uncertainties

Results: Upper limits

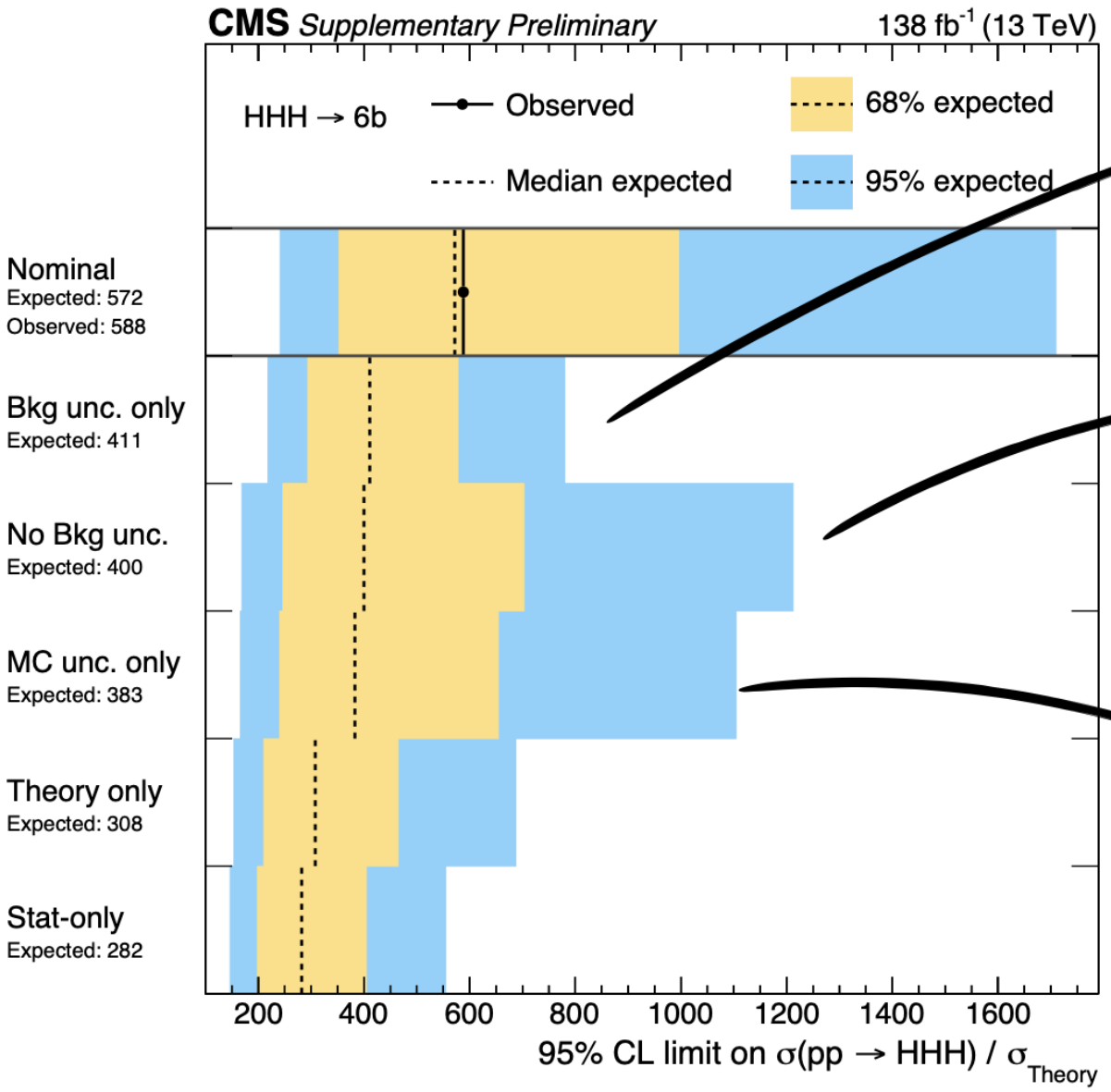




Result: observed (expected) limit of $\mu < 588\ (572)$ x the SM at 95% CL

- 3 reconstructed Higgs category drives the sensitivity
- **+18% sensitivity** achieved thanks to **2Higgs categories**!
- Resolved categories drive the sensitivity
- **+20% sensitivity** achieved thanks to **semi-boosted and boosted categories**!

Results: Upper limits

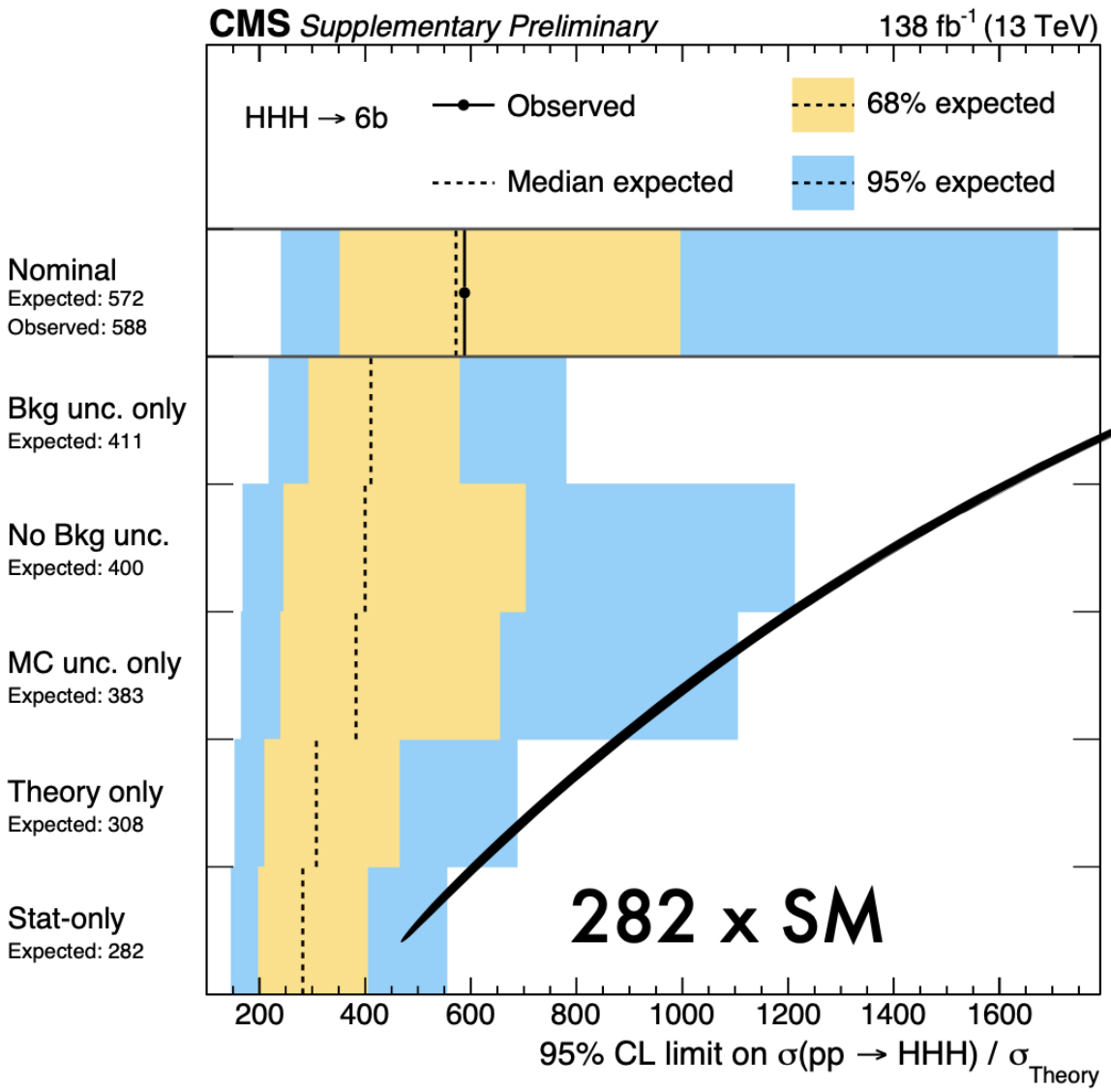


Dominant uncertainty:
background modeling
shape uncertainty

Signal uncertainties:
AK4 and AK8 jet tagging,
JES, JER, JMR
Theory uncertainty (scale)

Bin-wise background model
uncertainty

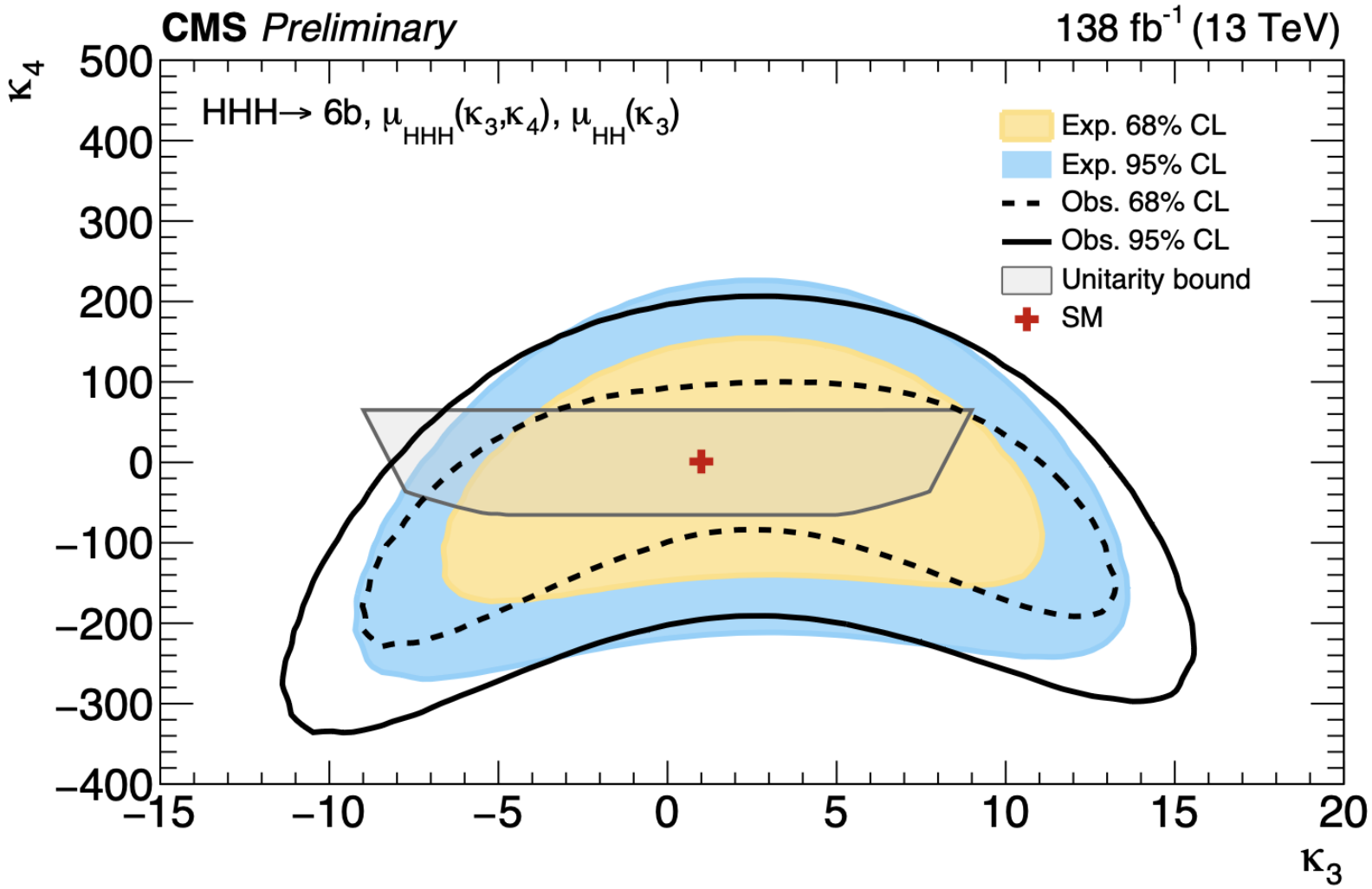
Results: Upper limits



Compared to 2023 estimate

Pessimistic: 285x SM with Run 2
Extrapolated from FCC-hh
Spot on (that counts)
(If we had no systematics)

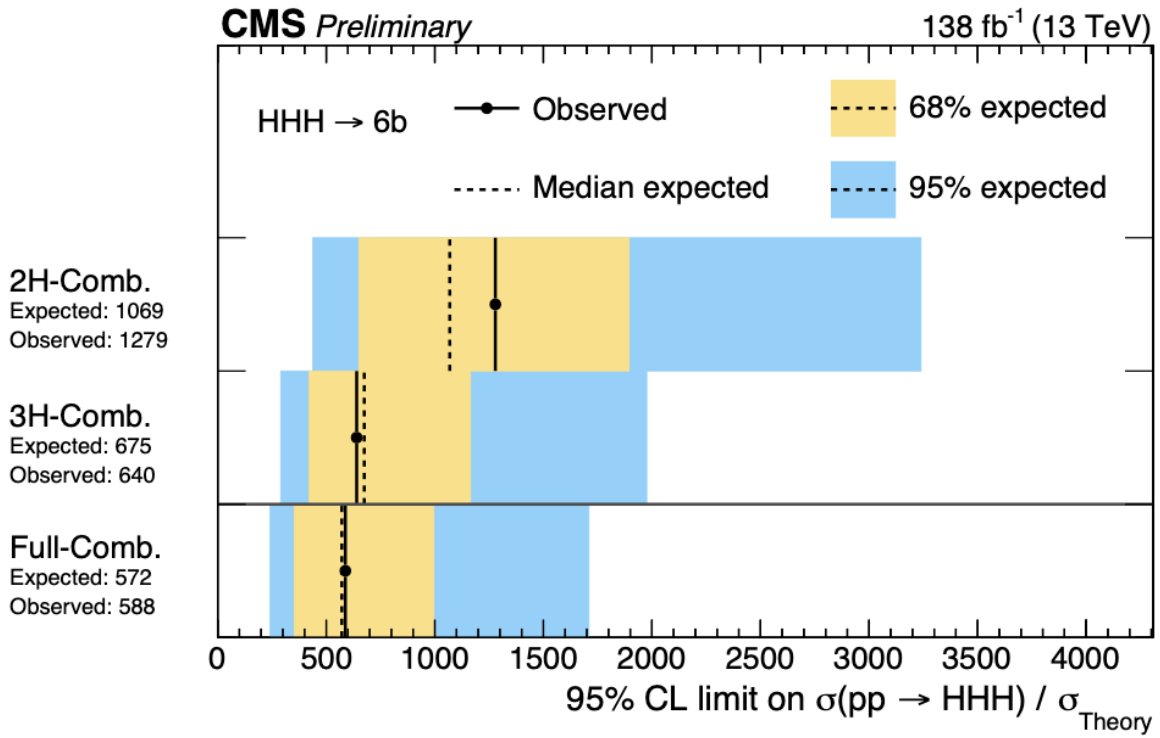
Coupling constraint

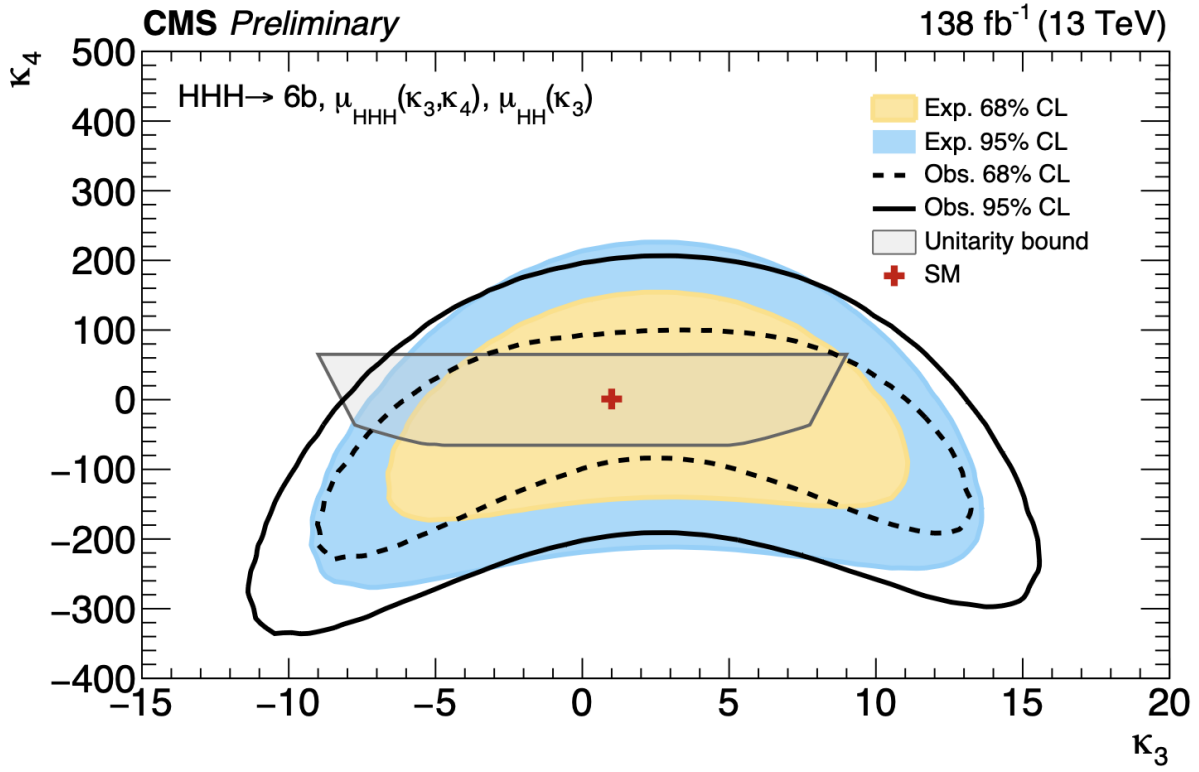


Interpretation: normalization effects of κ_3 and κ_4 on HHH and κ_3 on HH

First exclusion at 95% CL within the perturbative-unitarity-allowed (κ_3 , κ_4) region !

Conclusion



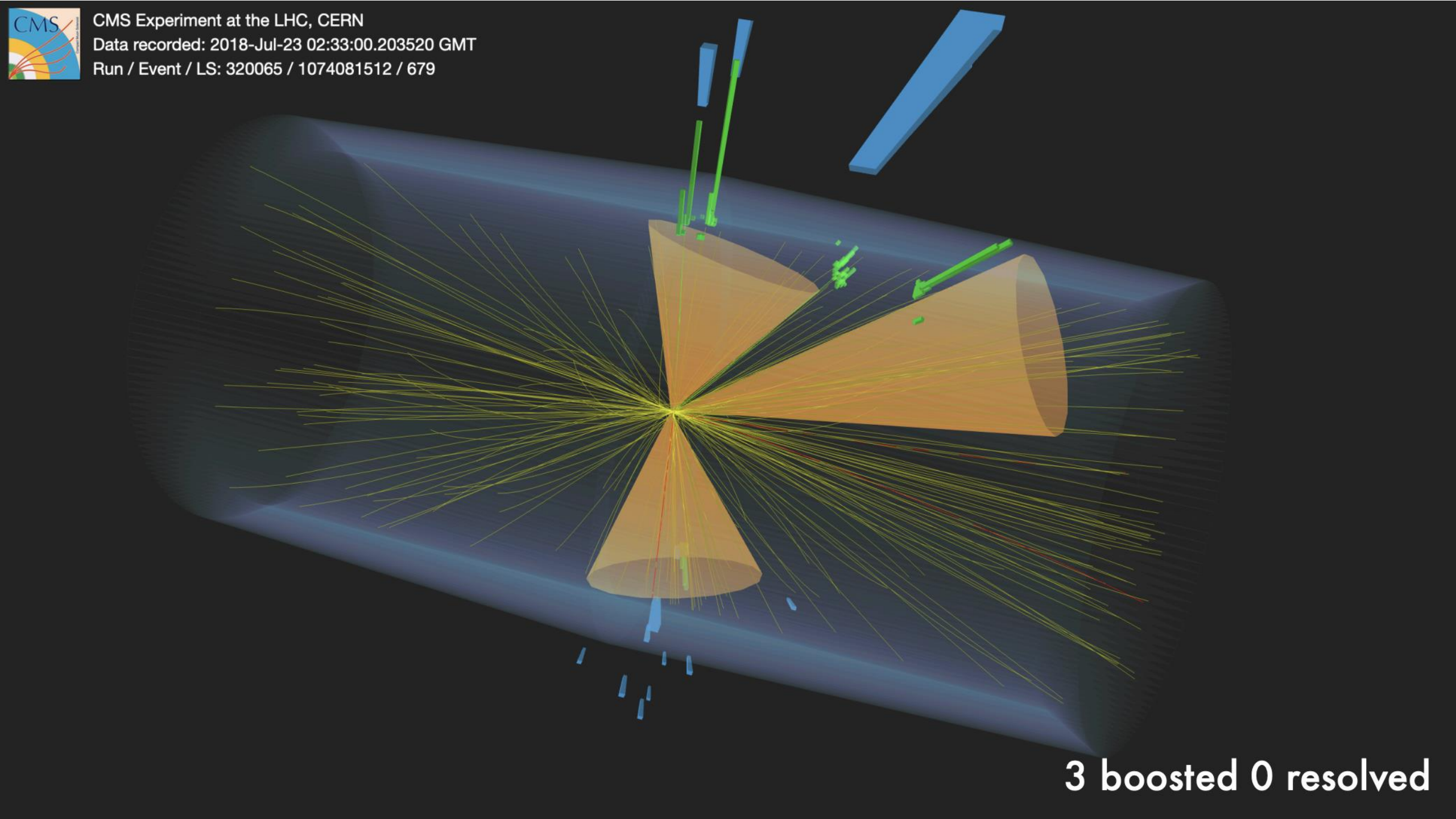


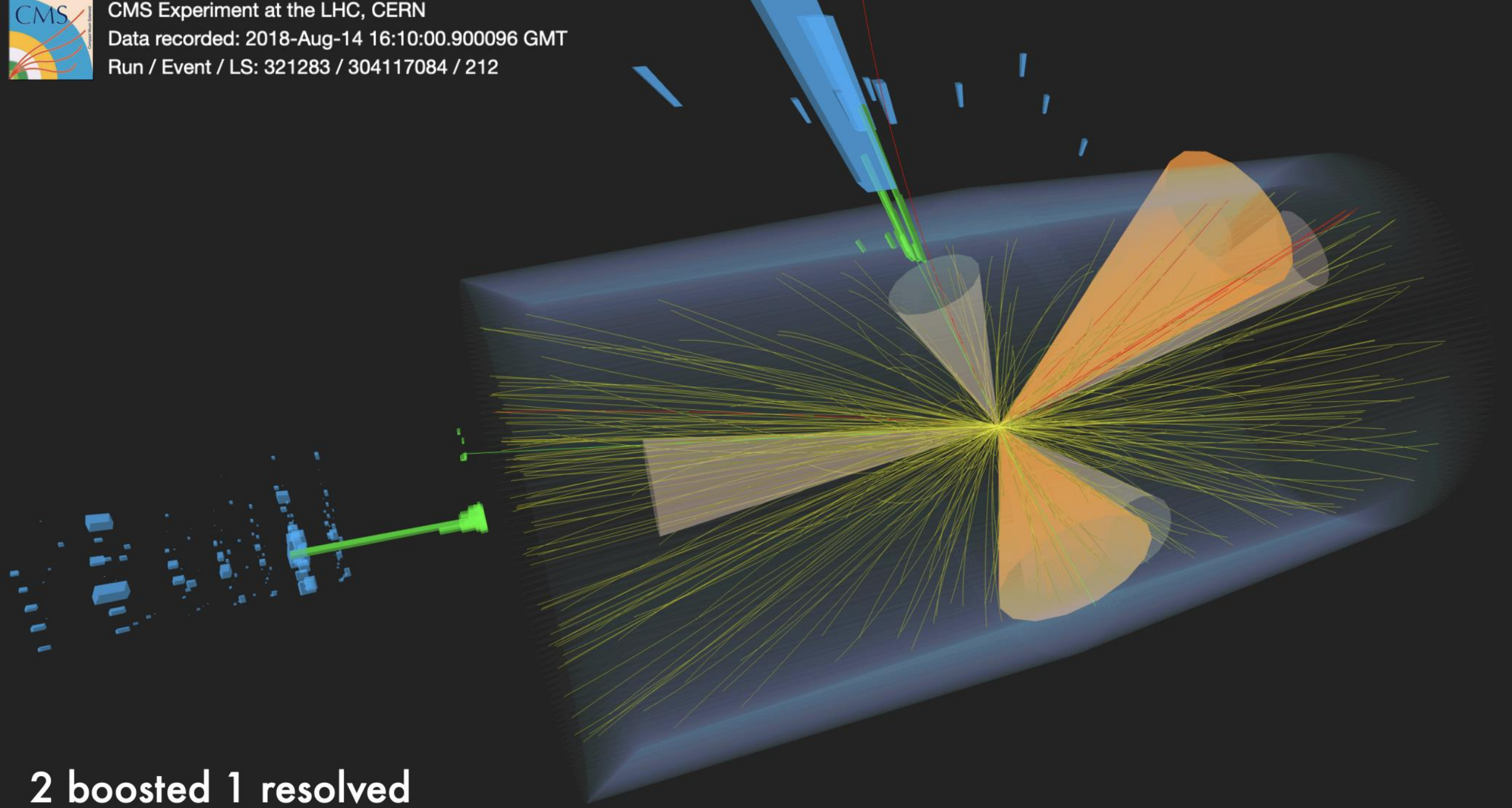
Non-resonant : *HHH → 6b* μ < 588 (572)

First exclusion at 95% CL within the perturbative-unitarity-allowed (κ_3 , κ_4) region !

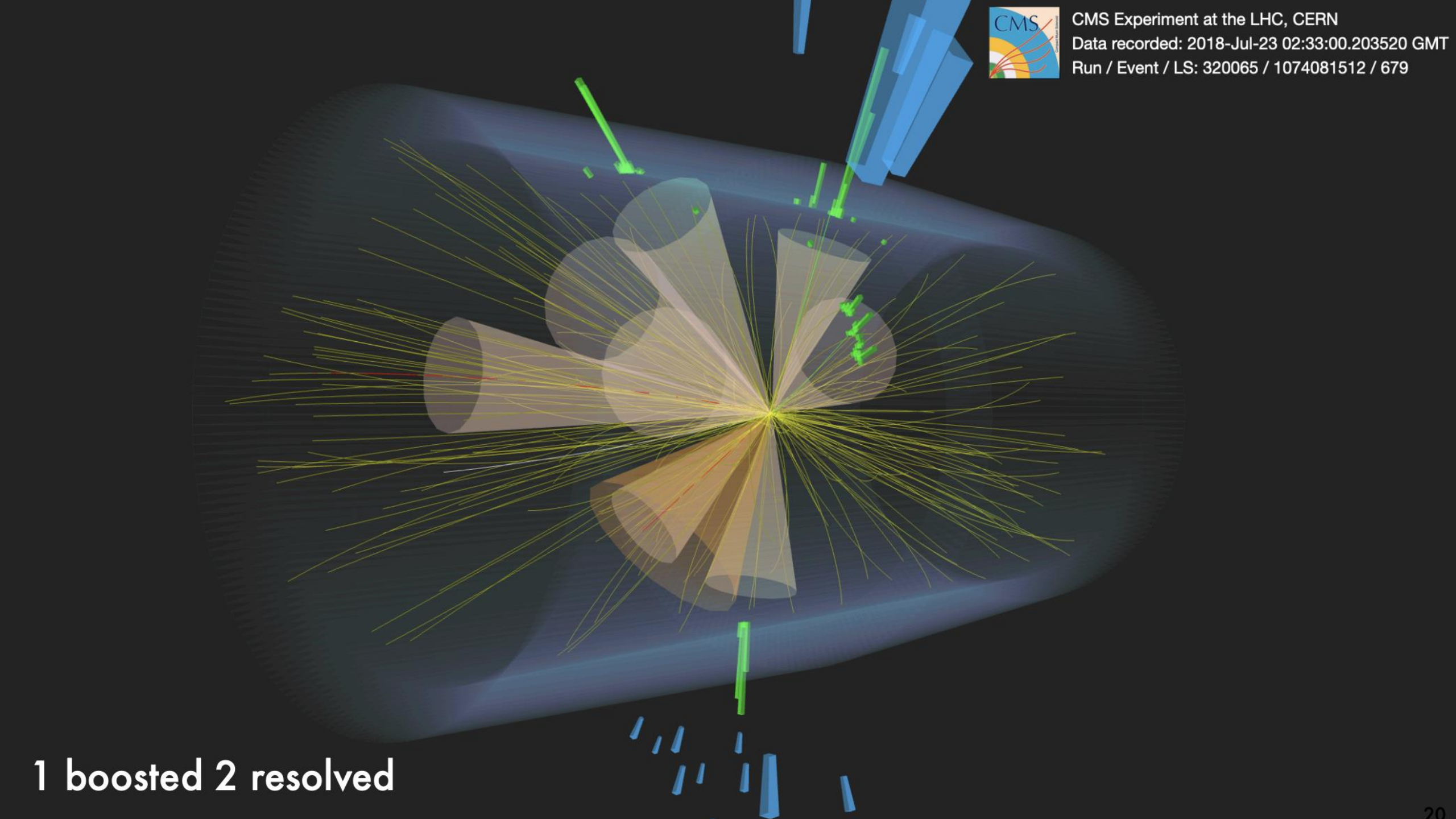
Boosted topologies improve sensitivity by around 30%

- QCD combinatorics remains challenging, while background-modelling uncertainties dominate the sensitivity.
- Challenges faced in HHH motivate developments of new tools: i.e jet-charge tagger


CMS Experiment at the LHC, CERN
Data recorded: 2018-Jul-23 02:33:00.203520 GMT
Run / Event / LS: 320065 / 1074081512 / 679
3 boosted 0 resolved

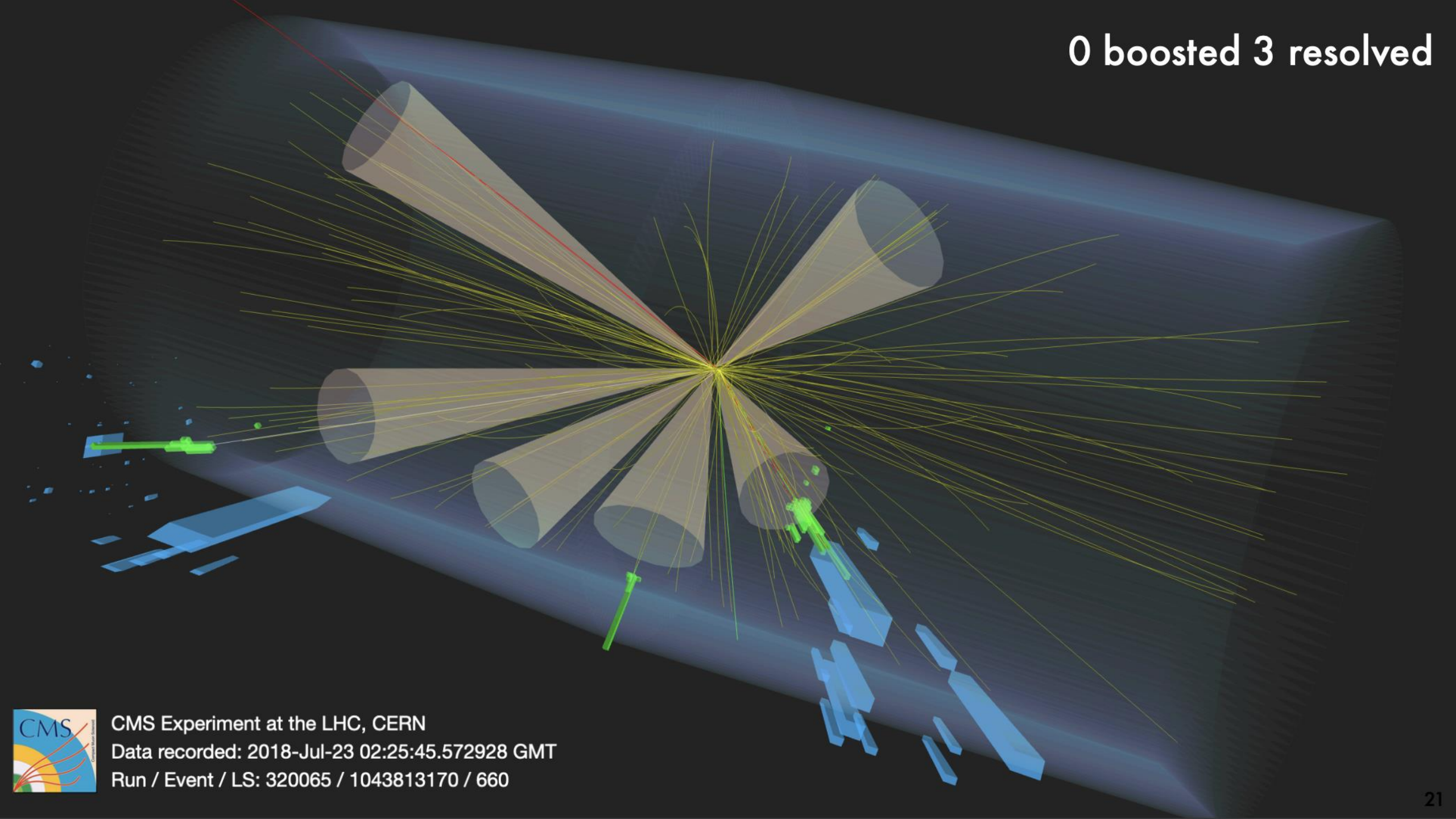


2 boosted 1 resolved



1 boosted 2 resolved

0 boosted 3 resolved



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Thanks For Listening!

Event pre-selection and object definition

Dataset	JetHT in 2016, 2016APV and 2018, BTagCSV in 2017
Trigger	2018: HT > 330 GeV, 4 jets pT 75,60,45,40 GeV, 3 b-tag with DeepCSV
	2017: HT > 300 GeV, 4 jets pT 75,60,45,40 GeV, 3 b-tag with DeepCSV
	2016: HT > 450 GeV, **6 jets**, pT > 40 GeV, 1 b-tag with DeepCSV
	HT > 400 GeV, 6 jets, pT > 30 GeV, 2 b-tag with DeepCSV
Event pre-selection	>= 4 AK4 jets with pT > 25 GeV, 0 isolated leptons (e, mu)

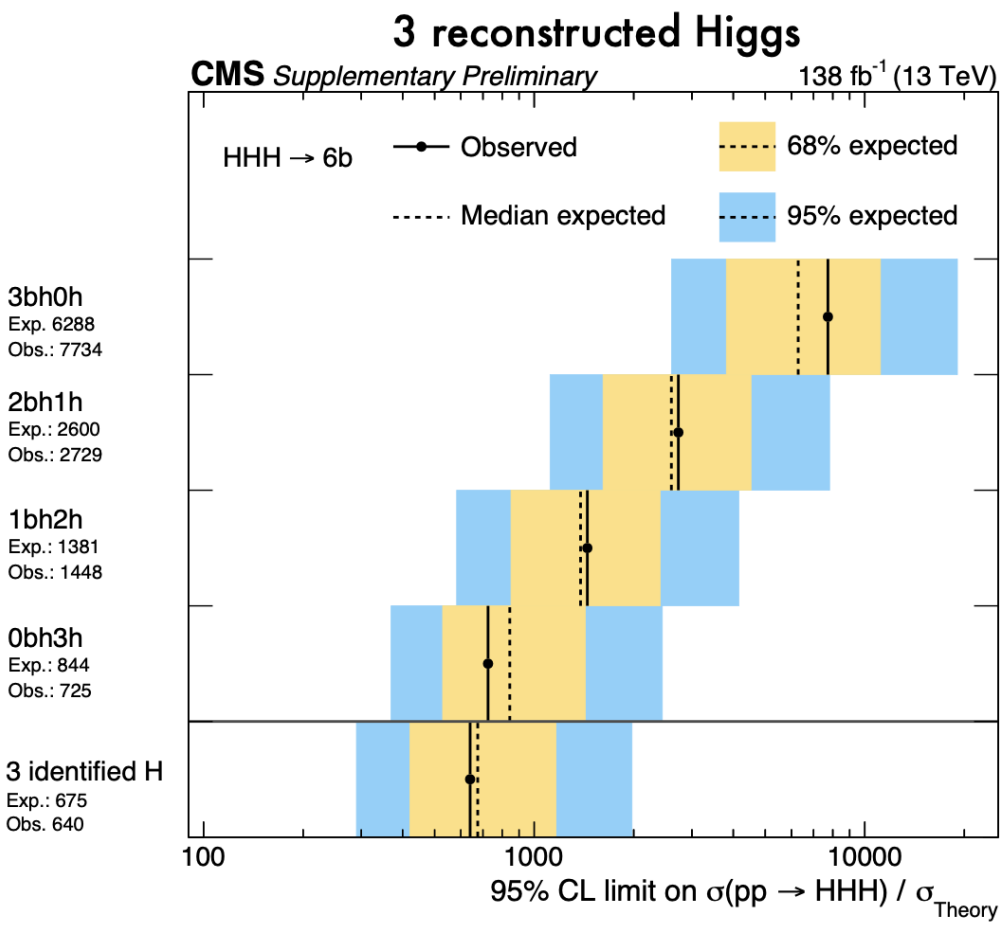
AK8 jets	**pT > 300 GeV**, discretised **PNet@AK8** score (see back-up)
AK4 jets	**pT > 25 GeV**, discretised **PNet@AK4** score (see back-up) PNet about 5% better b-jet efficiency than DeepJet

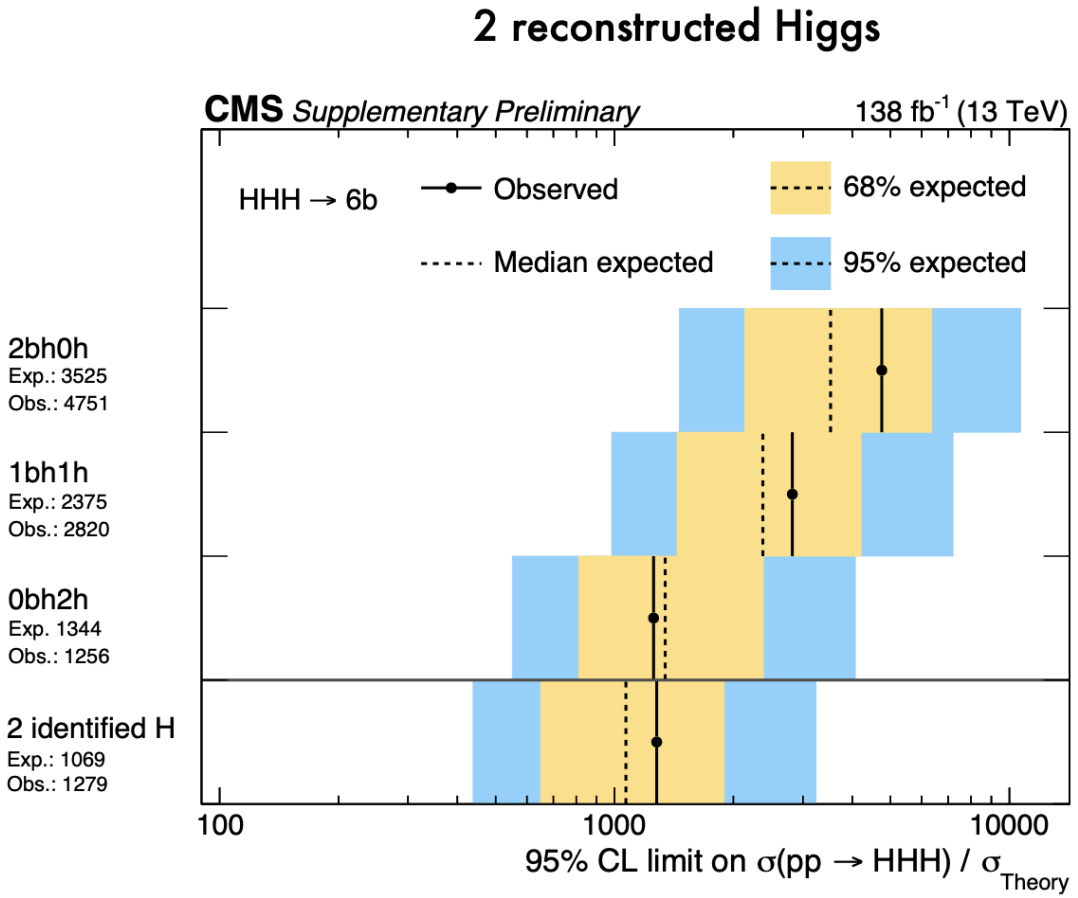
List of signal and backgrounds

Process	Generator	Accuracy	σ order	$\sigma_{13\ \mathrm{TeV}}$ [pb]
ggF HHH	MADGRAPH5_aMC@NLO	LO	NNLO	0.000079
ggF HH	POWHEG 2.0	NLO	NNLO	0.031
$t\bar{t}HH$	MADGRAPH5_aMC@NLO	LO	NLO	0.0007
VHH	MADGRAPH5_aMC@NLO	LO	NLO	0.0008
ggF H	POWHEG (MiNLO)	NLO	N^3LO	48.6
WH	POWHEG 2.0	NLO	NNLO	1.37
$qq \to ZH$	POWHEG 2.0	NLO	NNLO	0.88
$gg \to ZH$	POWHEG 2.0	LO	NLO	0.086
$t\bar{t}H$	POWHEG 2.0	LO	NLO	0.507
QCD	MADGRAPH5_aMC@NLO	LO	LO	1 918 063
$t\bar{t}$	POWHEG 2.0	NLO	NNLO	832
$W \to qq'$+jets	MADGRAPH5_aMC@NLO	LO	NLO	2 913
$Z \to qq$+jets	MADGRAPH5_aMC@NLO	LO	NLO	1 164
$VV \to qqqq$	POWHEG 2.0	NLO	NNLO	63
$VVV \to qqqqqq$	MADGRAPH5_aMC@NLO	NLO	NLO	0.44

Signal HHH: cross-section about 0.1 fb, 14 events produced in Run 2 with 20% to 6b
Dominant backgrounds are QCD, TT

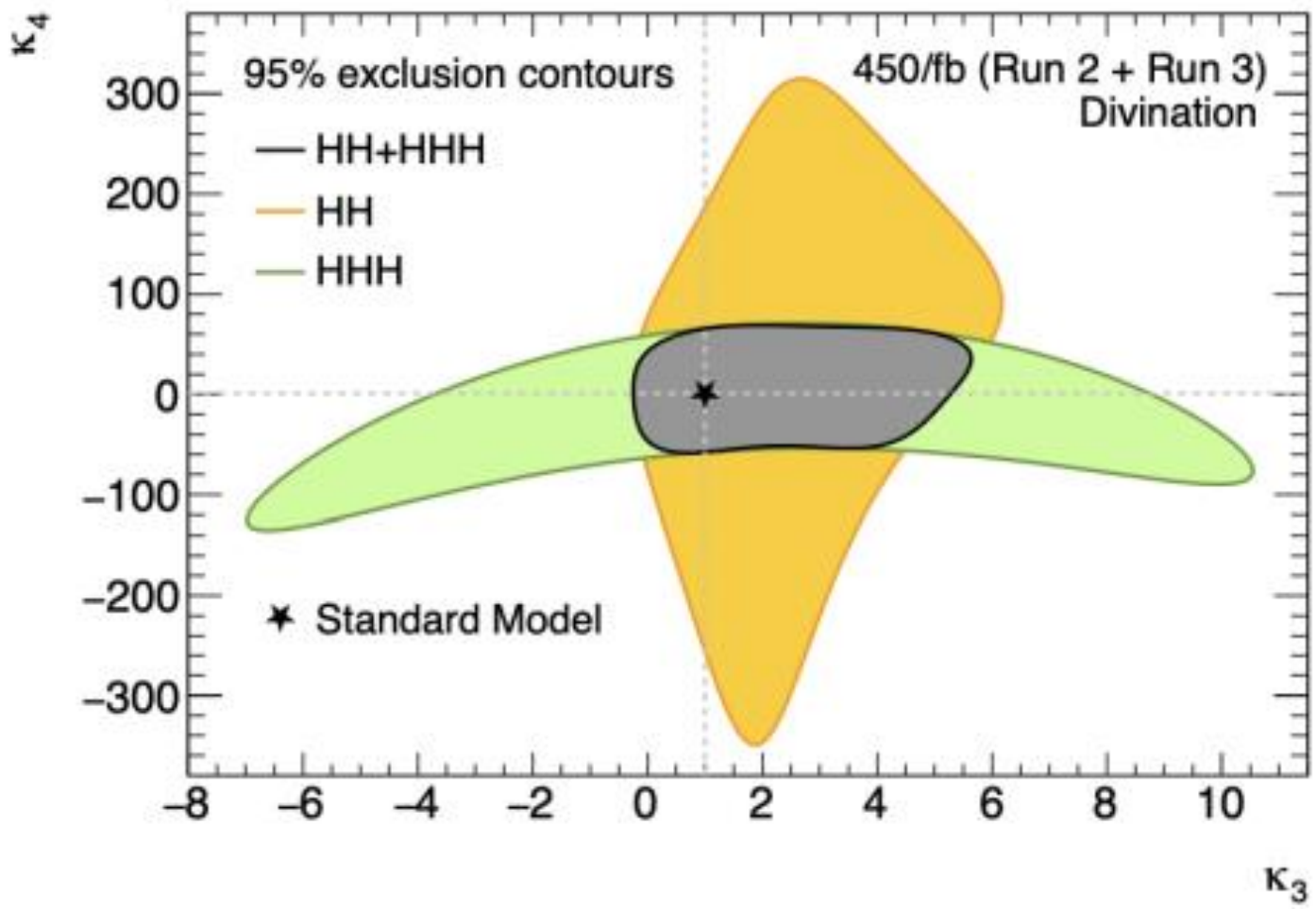
Results: Upper limits





Sensitivity dominated **by fully resolved 0bh3h category**

- Followed by 1bh2h and 0bh2h
- Slight **excess in 2Higgs**, **slight deficit in 3Higgs**
- Inclusive strategy targeting all the final states!


95% exclusion contours
450/fb (Run 2 + Run 3)
Divination
HH+HHH
HH
HHH
Standard Model
κ4
κ3
300
200
100
0
−100
−200
−300
−8
−6
−4
−2
0
2
4
6
8
10