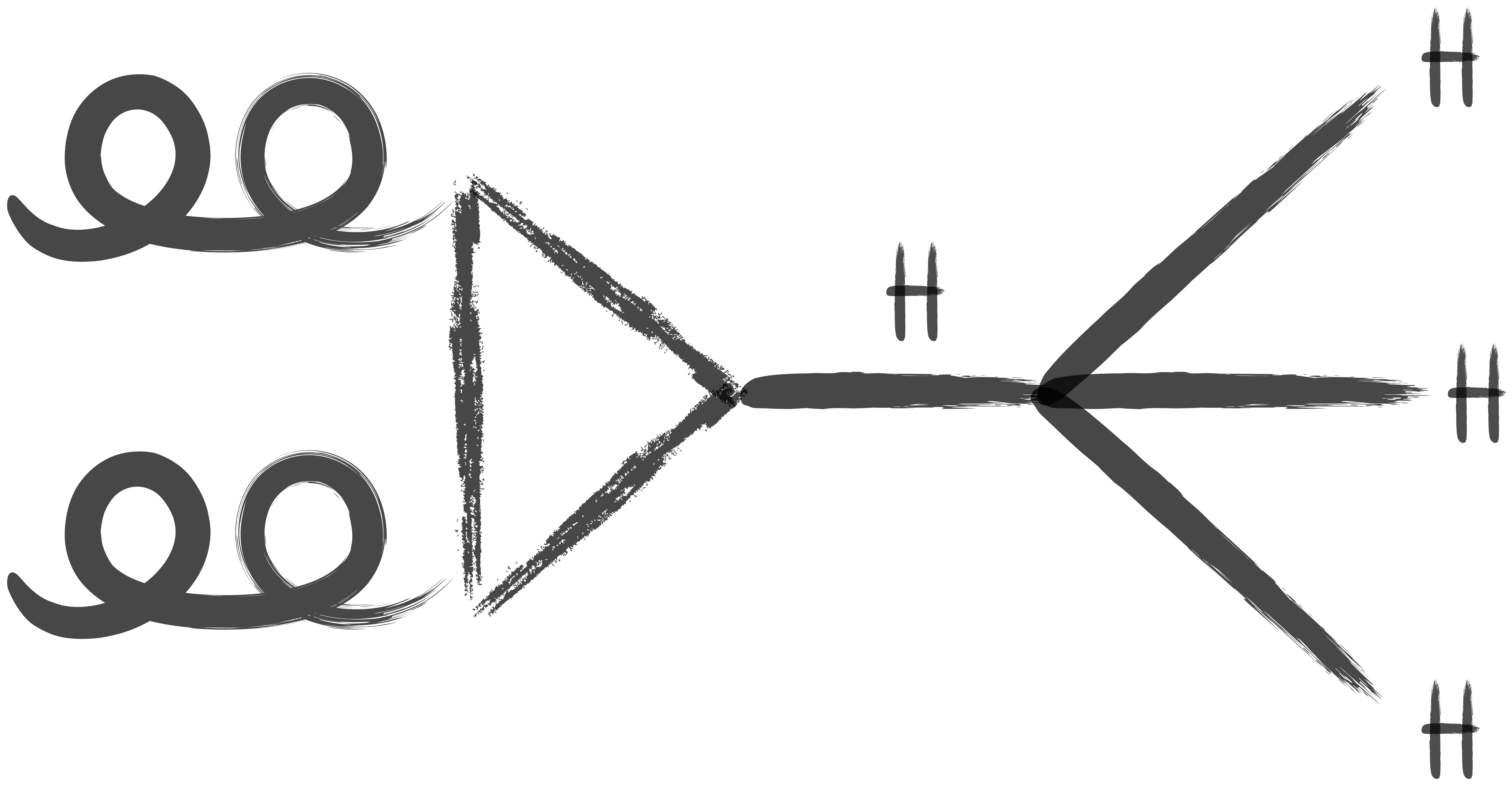
Overview of HHH physics at the LHC and summary of HHH workshop in Dubrovnik

BROWN

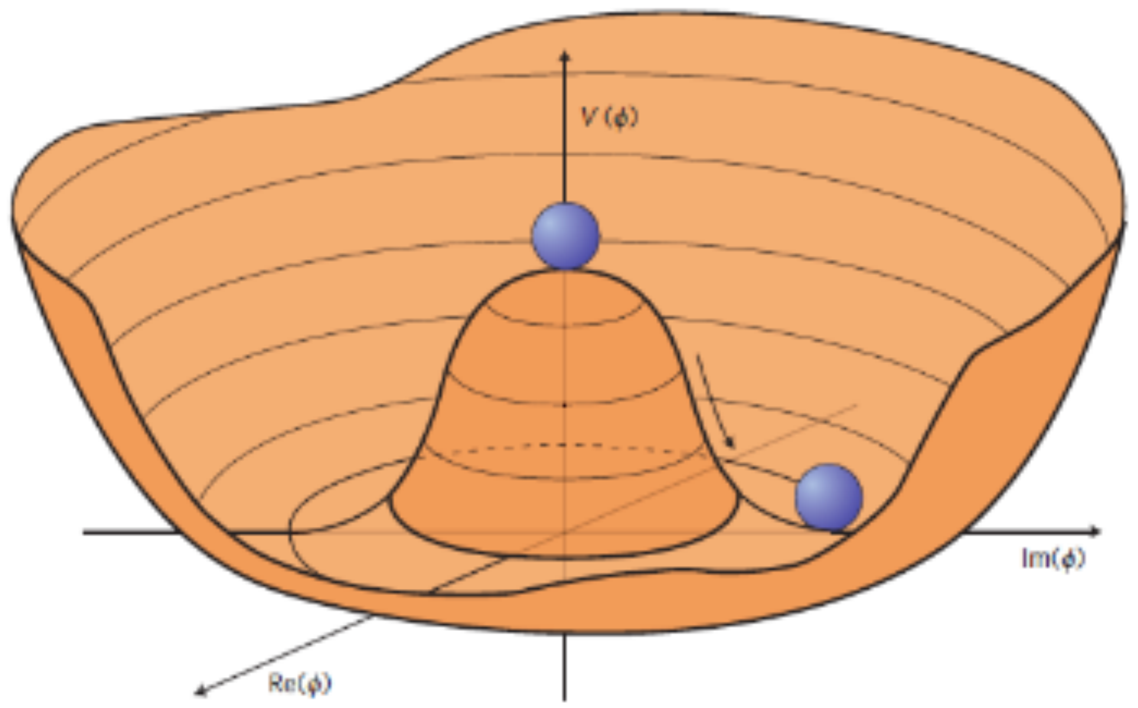


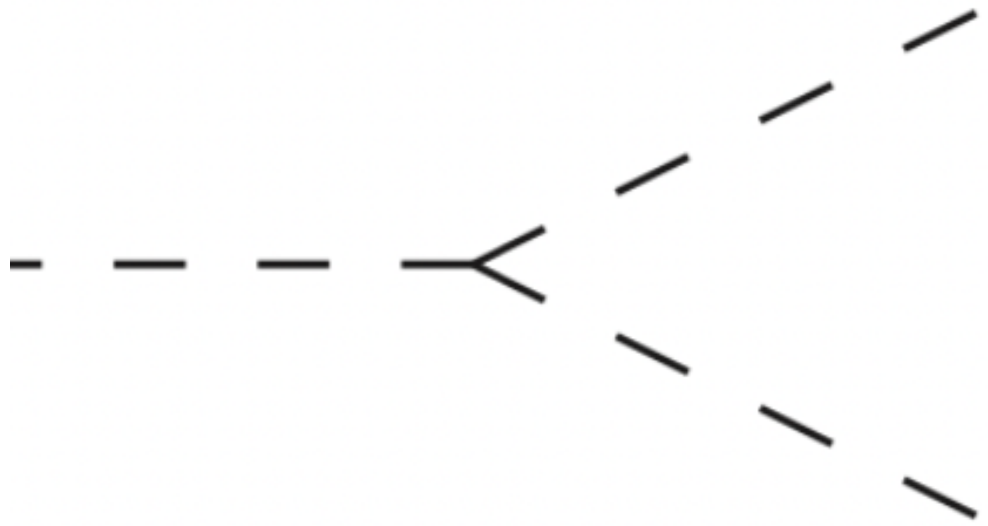
15th of November 2023

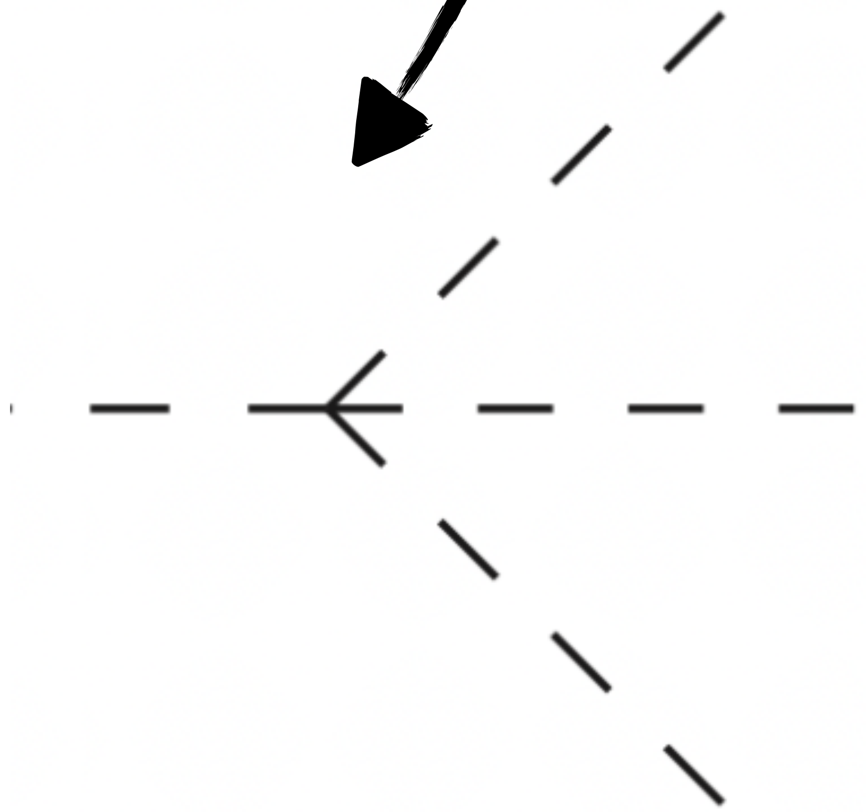
Marko Stamenkovic

Measuring the Higgs potential: motivation

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







Higgs self-coupling: one of the most important properties of the Higgs boson that is not measured yet

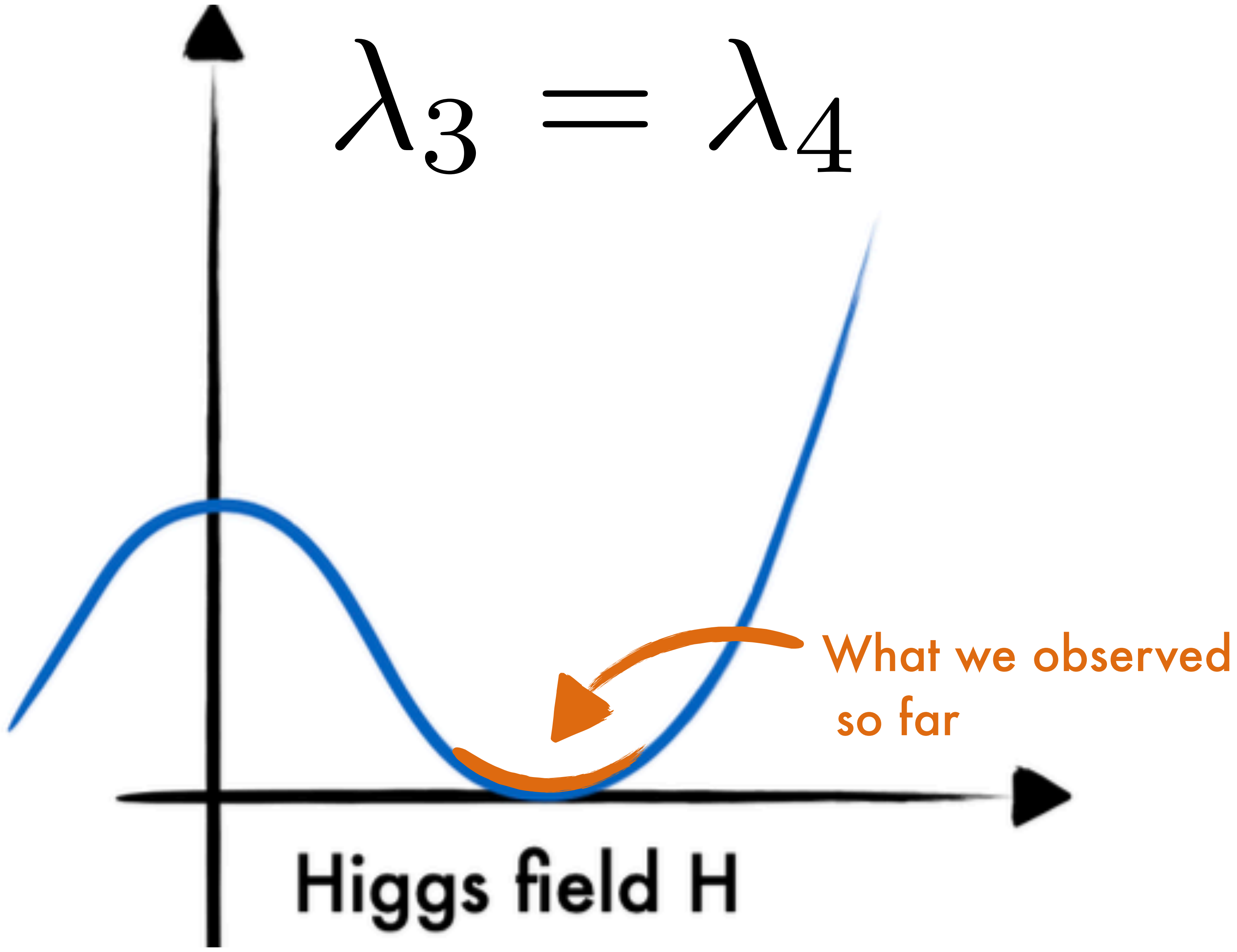
In the Standard Model: the Higgs potential is responsible for the masses of all particles

- 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

Measuring the Higgs potential: motivation

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

Standard Model



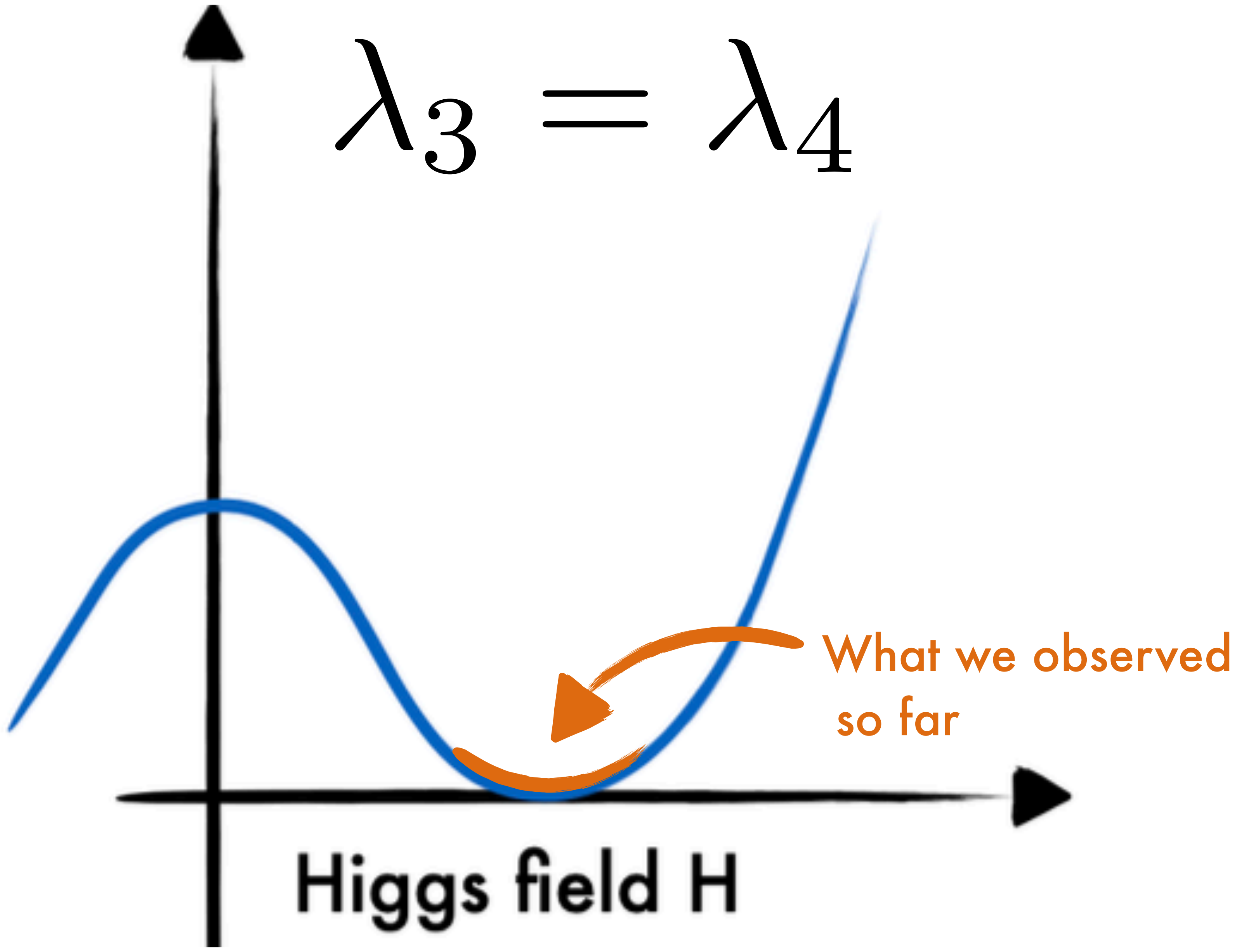
In the Standard Model: $\lambda_3 = \lambda_4$

Measuring the Higgs potential: motivation

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

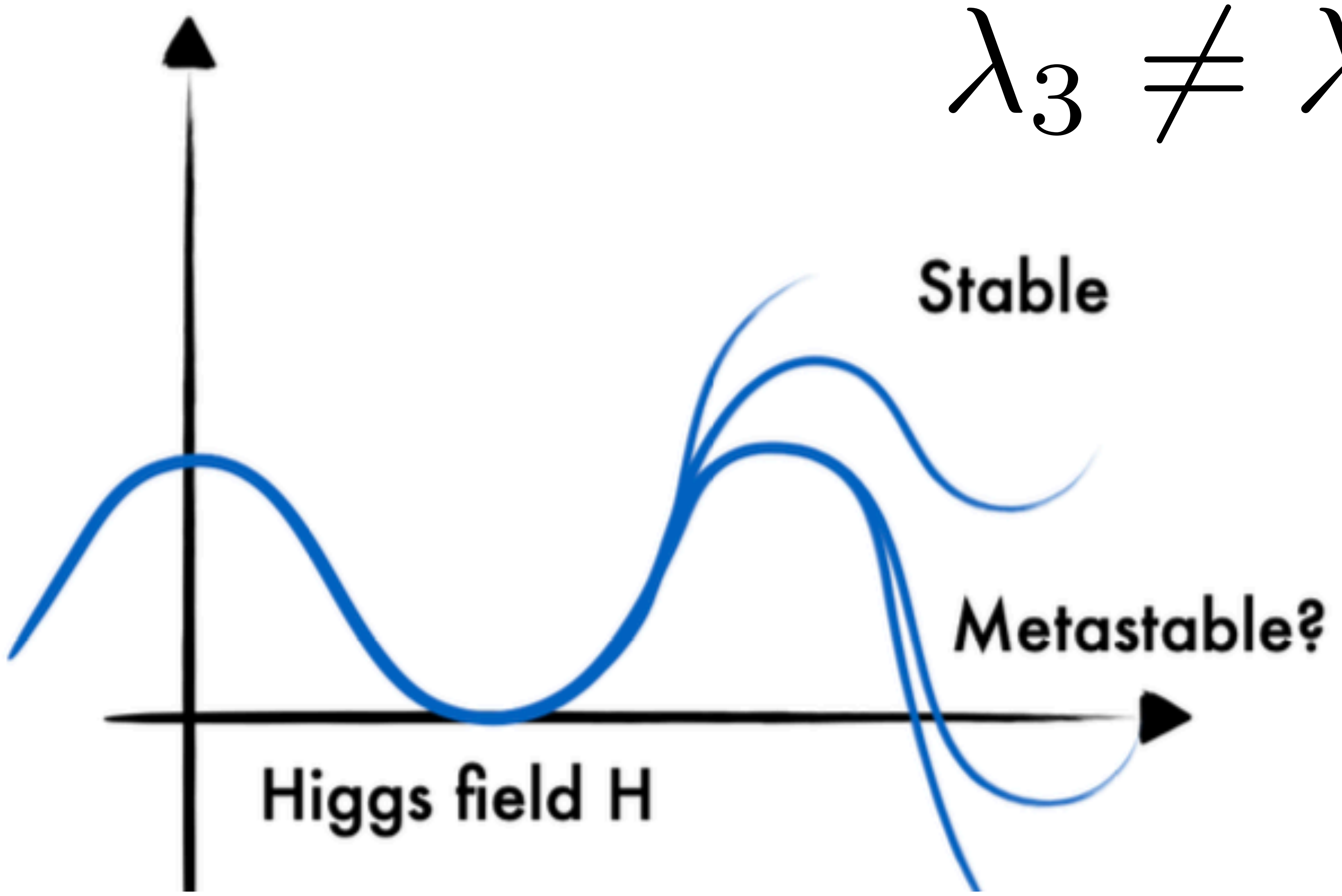
Standard Model

$\lambda_3 = \lambda_4$



New physics

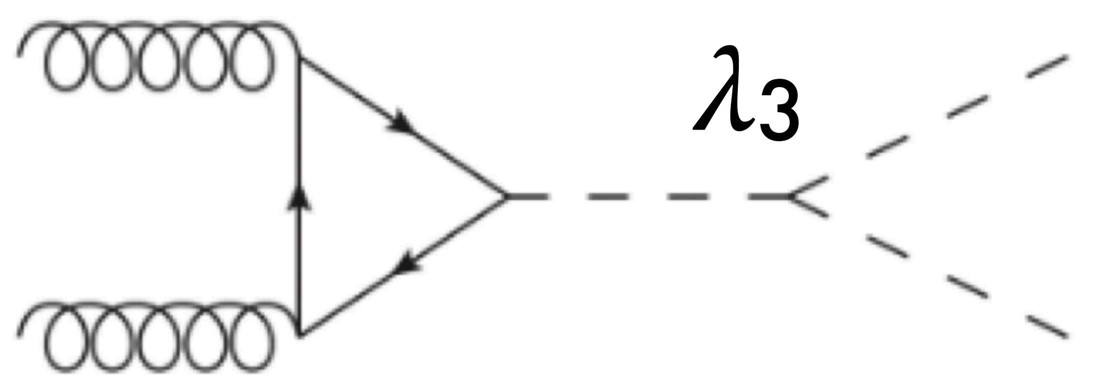
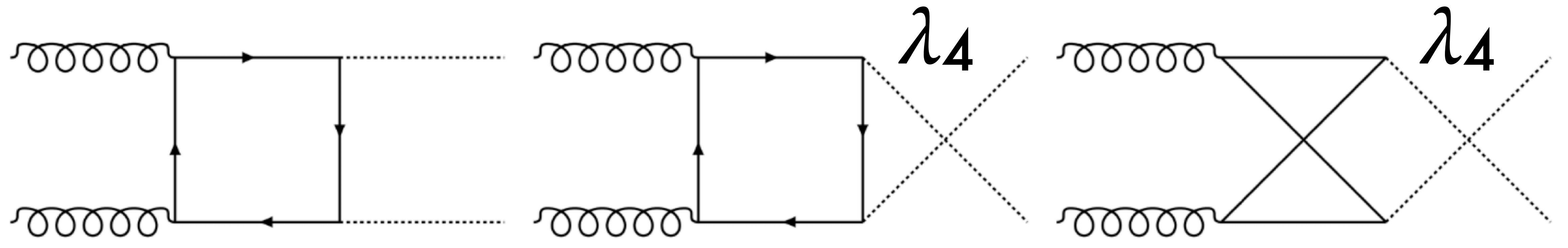
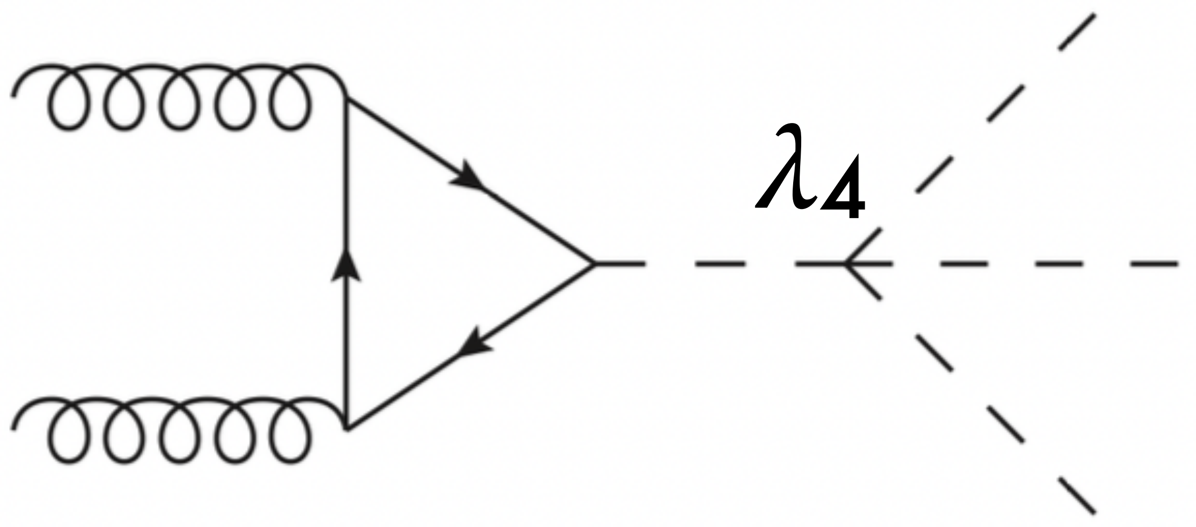
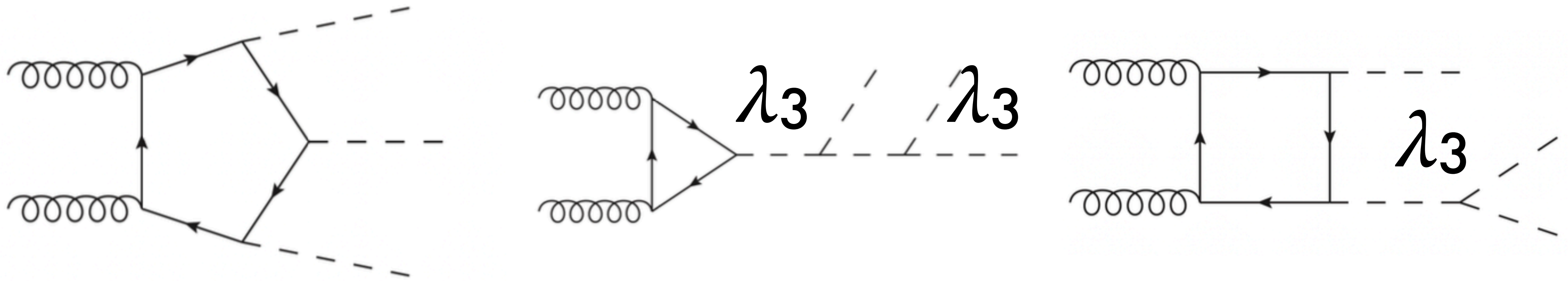
$\lambda_3 \neq \lambda_4$



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

	Signal	Irreducible background with Higgs bosons
Di-Higgs		
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 λ_4)
- Triple Higgs: sensitive to both λ_3 and λ_4 coupling

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

Sensitivity:

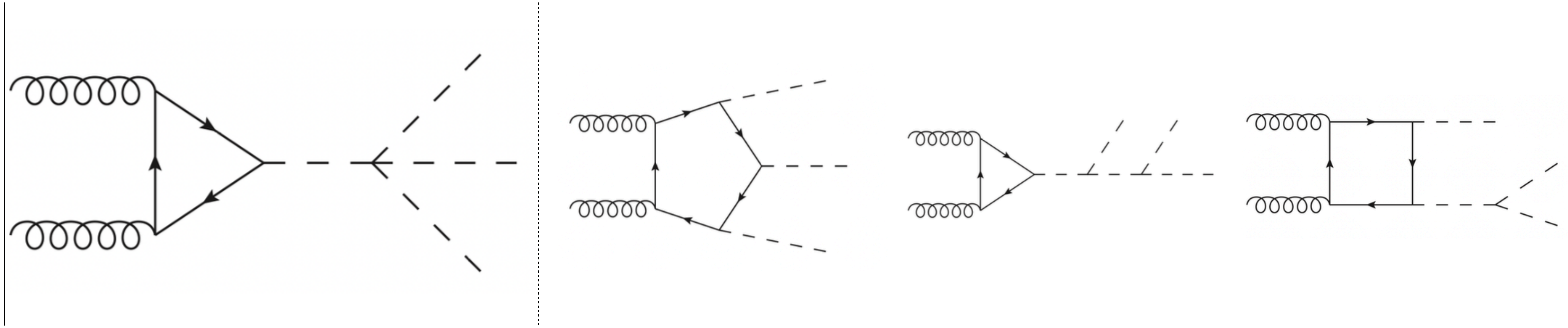
- Di-Higgs: current sensitivity < 2.5 x SM @ 95% CL → expect evidences at HL-LHC
- Triple Higgs: considered impossible to measure at LHC → No estimated results so far!

Extrapolating HHH sensitivities from FCC to LHC

Triple Higgs projections @ FCC-hh

Main Feynman diagrams of triple Higgs production

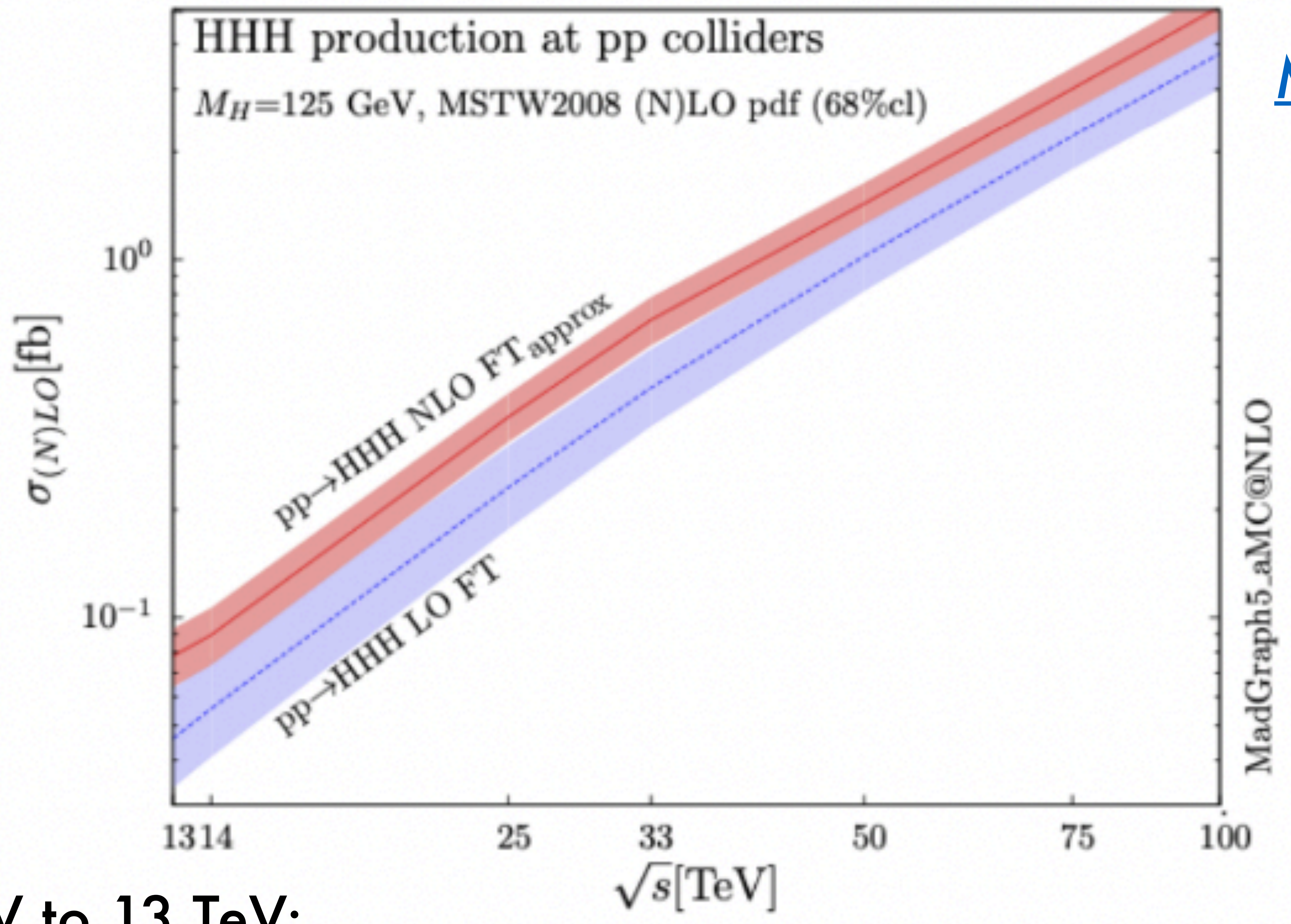
Triple Higgs



Different diagrams with three Higgs in the final state: involving both cubic and quartic coupling

- Case study: focus on three decay modes based on **theory papers at 100 TeV**
- HHH→ (bb) (bb) (bb) [Eur. Phys. J. C (2019) 79:947]: largest branching fraction + large background
- HHH → (bb) (bb) (γγ) [arXiv:1606.09408v1] : low branching ratio but clean signature with photons
- HHH → (bb) (bb) (ττ) [Phys. Lett. B771 (2017) 354-358] : trade off branching ratio vs background
  - Also very sensitive channel in di-Higgs

Cross-sections



Maltoni, Vryonidu, Zaro

Extrapolation from 100 TeV to 13 TeV:

- σ(HHH)$_{13TeV}$ / σ(HHH)$_{100TeV}$ = 1 / 60
- σ(QCD 6-bjets)$_{13TeV}$ / σ(QCD 6 b-jets)$_{100TeV}$ = 1 / 10 (taken from this paper)
- Assume 2 different scenarios:
  1. Optimistic scaling: both signal and background scale with 1 / 60
  2. Pessimistic scaling: signal 1/60 and background 1/10 (more accurate for HHH→6b)
     - 'Pessimistic' in the sense that these theory papers are mostly simple cunt and count, not optimised

Estimated result at LHC @ 13 TeV

Channel	$\mathcal{L}$ at 100 TeV	Significance	$\mathcal{L}$ at 13 TeV	Pessimistic	Optimistic
$HHH \to b\bar{b}b\bar{b}b\bar{b}$ [28]	20 ab^{-1}	1.6σ	139 fb^{-1}	$285\times$ SM	$120\times$ SM
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$ [29]	20 ab^{-1}	2.1σ	139 fb^{-1}	$220\times$ SM	$90\times$ SM
$HHH \to b\bar{b}b\bar{b}\tau^+\tau^-$ [30]	30 ab^{-1}	2.0σ	139 fb^{-1}	$280\times$ SM	$115\times$ SM
Combination	20 ab^{-1}	2.9σ	139 fb^{-1}	$150\times$ SM	$64\times$ SM

$\mathcal{L}$ at 13 TeV	Pessimistic	Optimistic
139 fb^{-1}	$150\times$ SM	$64\times$ SM
300 fb^{-1}	$100\times$ SM	$40\times$ SM
500 fb^{-1}	$80\times$ SM	$35\times$ SM
3000 fb^{-1}	$30\times$ SM	$15\times$ SM

Estimated results: 60-150x SM prediction for triple Higgs productions with 139/fb

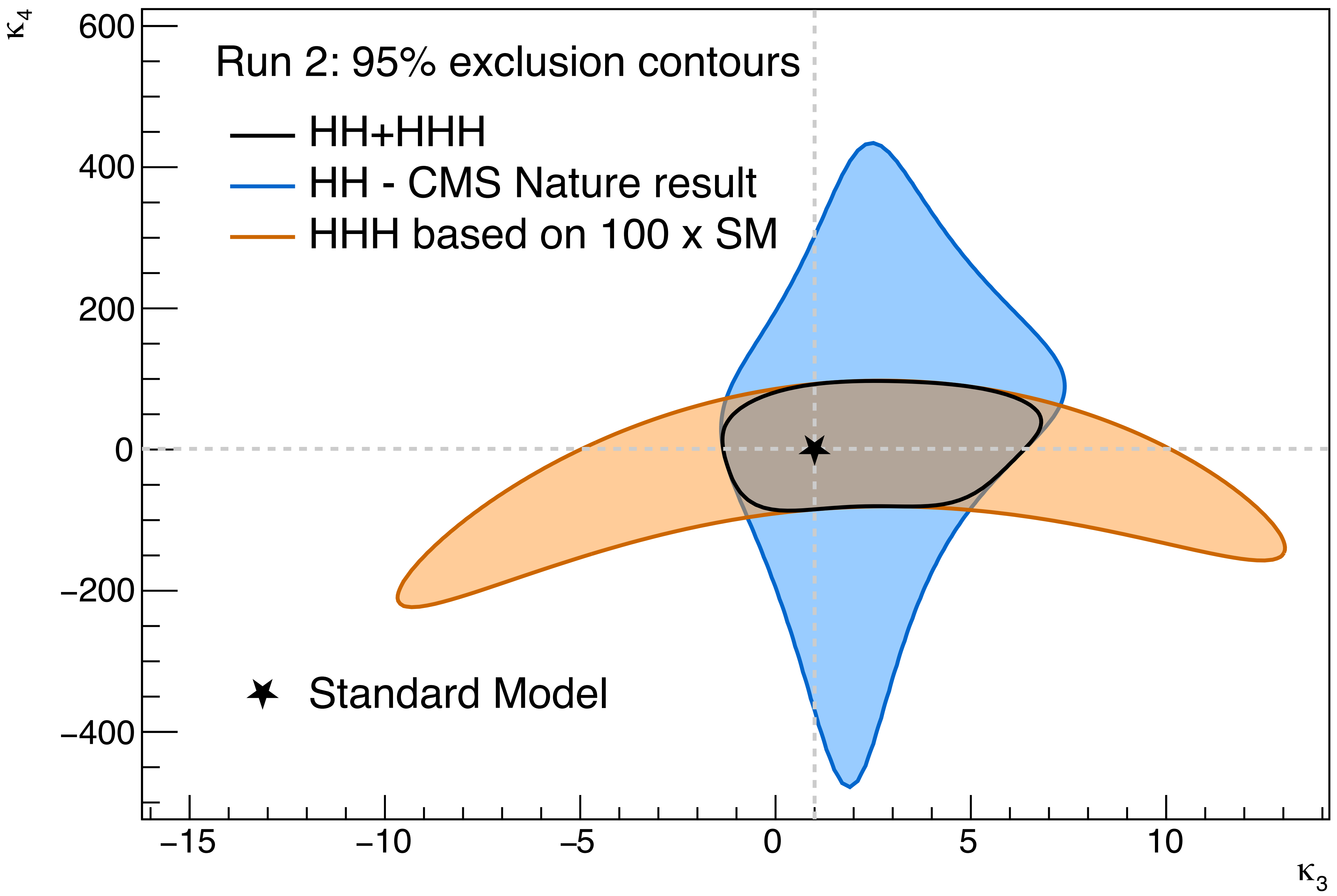
- Note: **back of the envelope estimate** based on simple theory projections
  - Missing crucial components such as detector resolutions, systematics, object reconstruction
  - Object identification performance: optimistically
- Need to test this experimentally with a dedicated analysis at the LHC

Estimating the sensitivity to the self-coupling

Probing self-interaction di-Higgs and triple Higgs

Based on
arXiv:1810.04665v3

Simulating κ_3 and κ_4 coupling modifications



HH and HHH parametrisation with trilinear κ_3 and κ_4 quartic coupling modifiers

- Current HH analyses: neglect κ_4 coupling modifier → additional assumption
  - Relax assumption $\lambda_3 = \lambda_4$ in combined HH and HHH measurement

Probing self-interaction di-Higgs and triple Higgs

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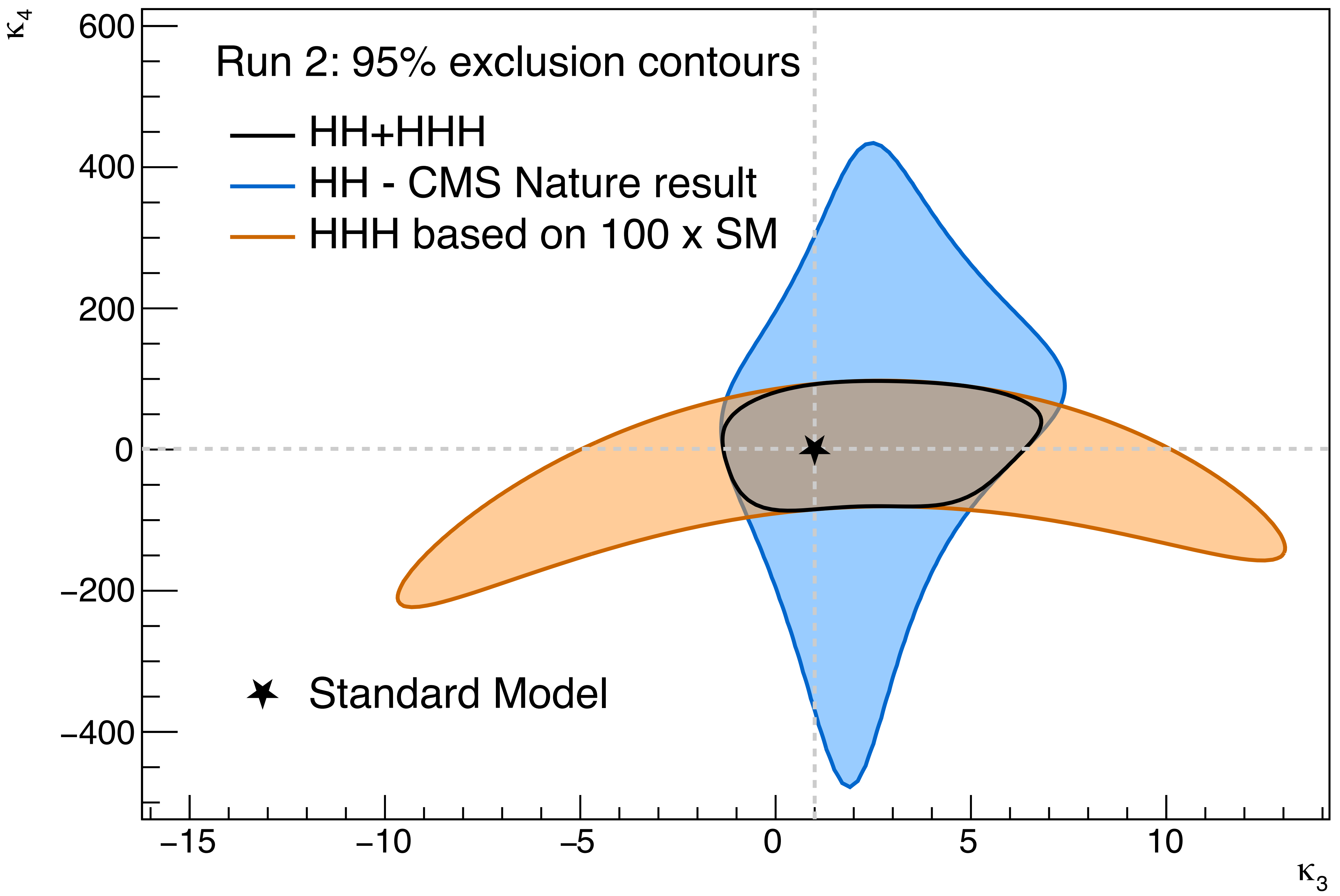


CMS searches	Limit at 95% CL
HH→bbbb (boosted)	$-9.9 < \kappa_3 < 16.9$
HH→bbbb (resolved)	$-2.3 < \kappa_3 < 9.4$
HH→bbττ	$-3.0 < \kappa_3 < 9.0$
HH→bbγγ	$-3.3 < \kappa_3 < 8.5$
HH combination (Nature paper)	$-1.2 < \kappa_3 < 6.5$
Projection for HHH assuming μ_{HHH} < 100x SM (Normalisation only)	**$-5 < \kappa_3 < 10$**

HH and HHH parametrisation with trilinear κ_3 and κ_4 quartic coupling modifiers

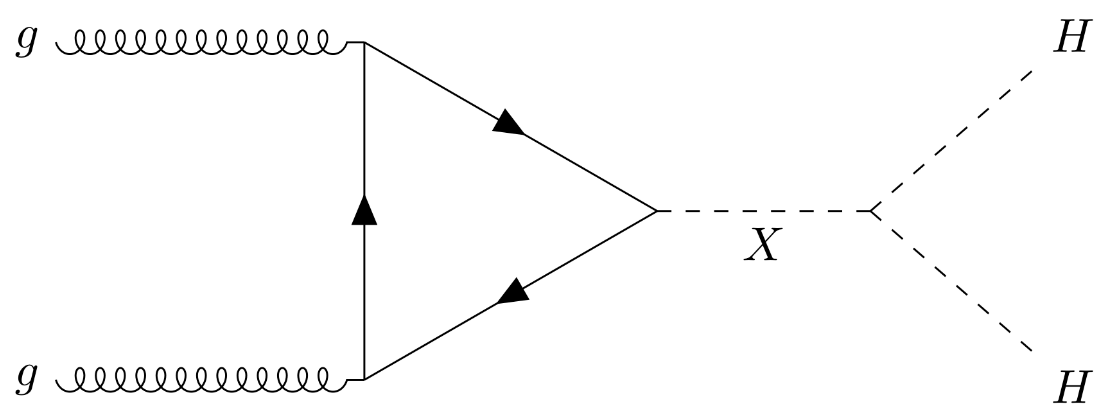
- Current HH analyses: neglect κ_4 coupling modifier → additional assumption
  - Relax assumption $\lambda_3 = \lambda_4$ in combined HH and HHH measurement
- Assuming HHH sensitivity about 100x SM: competitive limit on κ_3 possible w.r.t HH channels

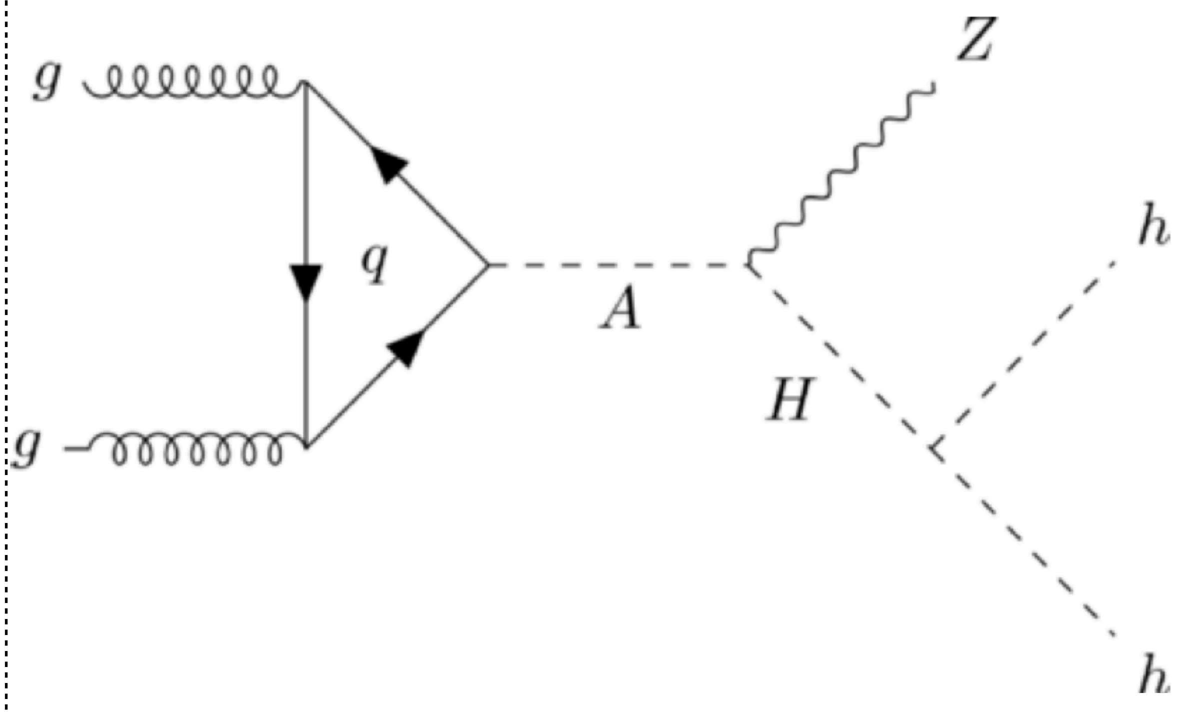
→ Can we reach 100x SM HHH sensitivity with Run 2?

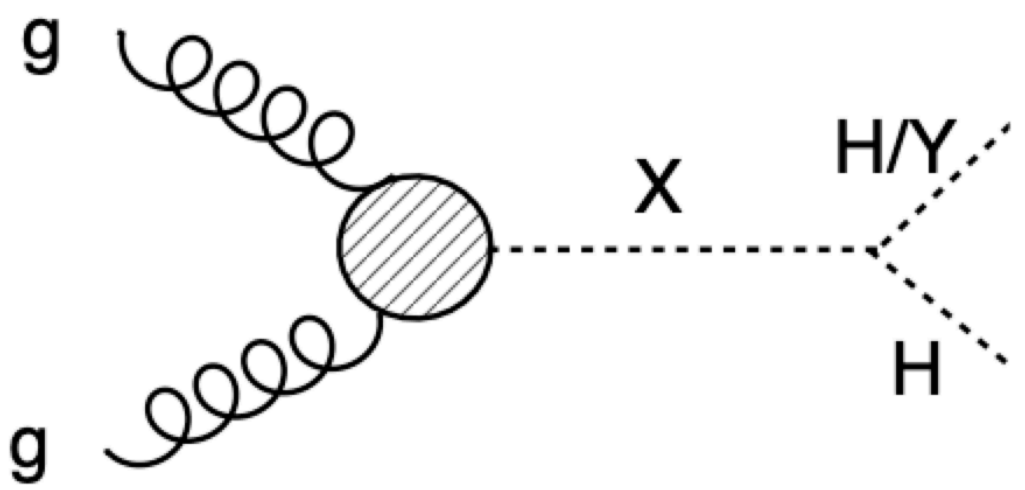
HH and HHH: probe for BSM

Eur. Phys. J. C 80, 151 (2020)
JHEP 05 (2021) 193
Phys. Rev. D 103, 115005 (2021)
Eur. Phys. J. C 80, 884 (2020)

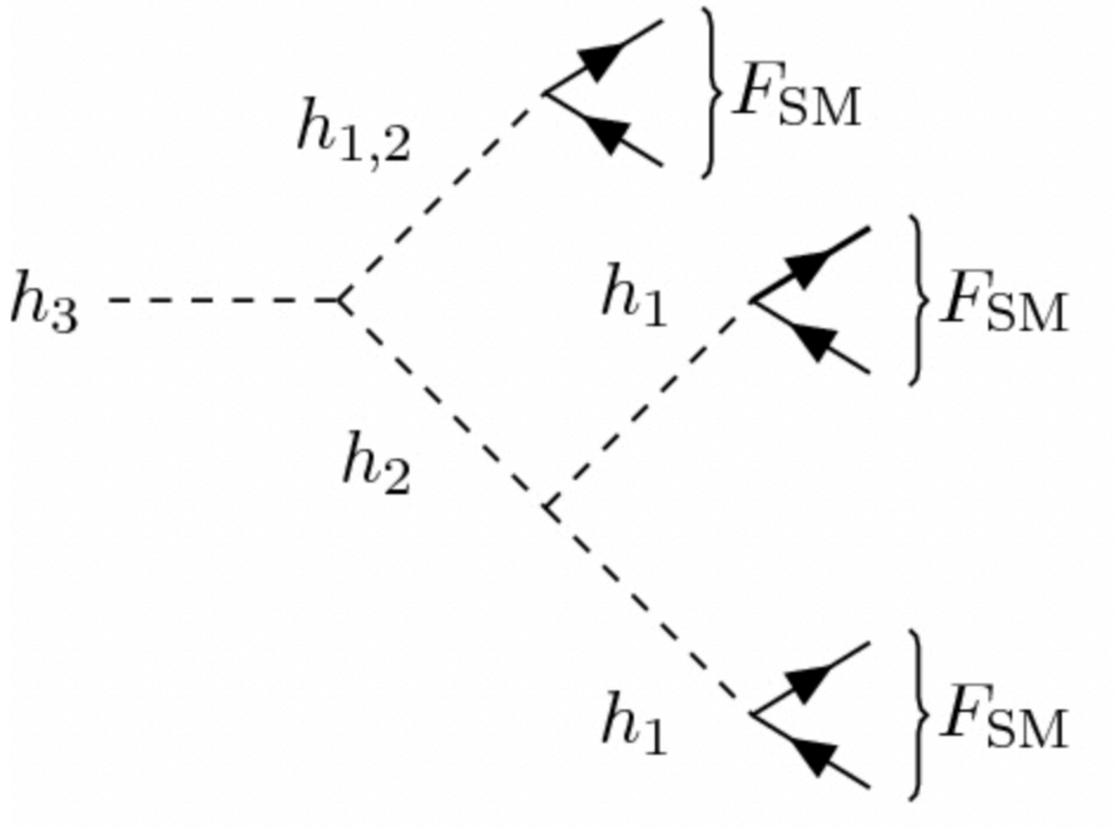
BSM HH

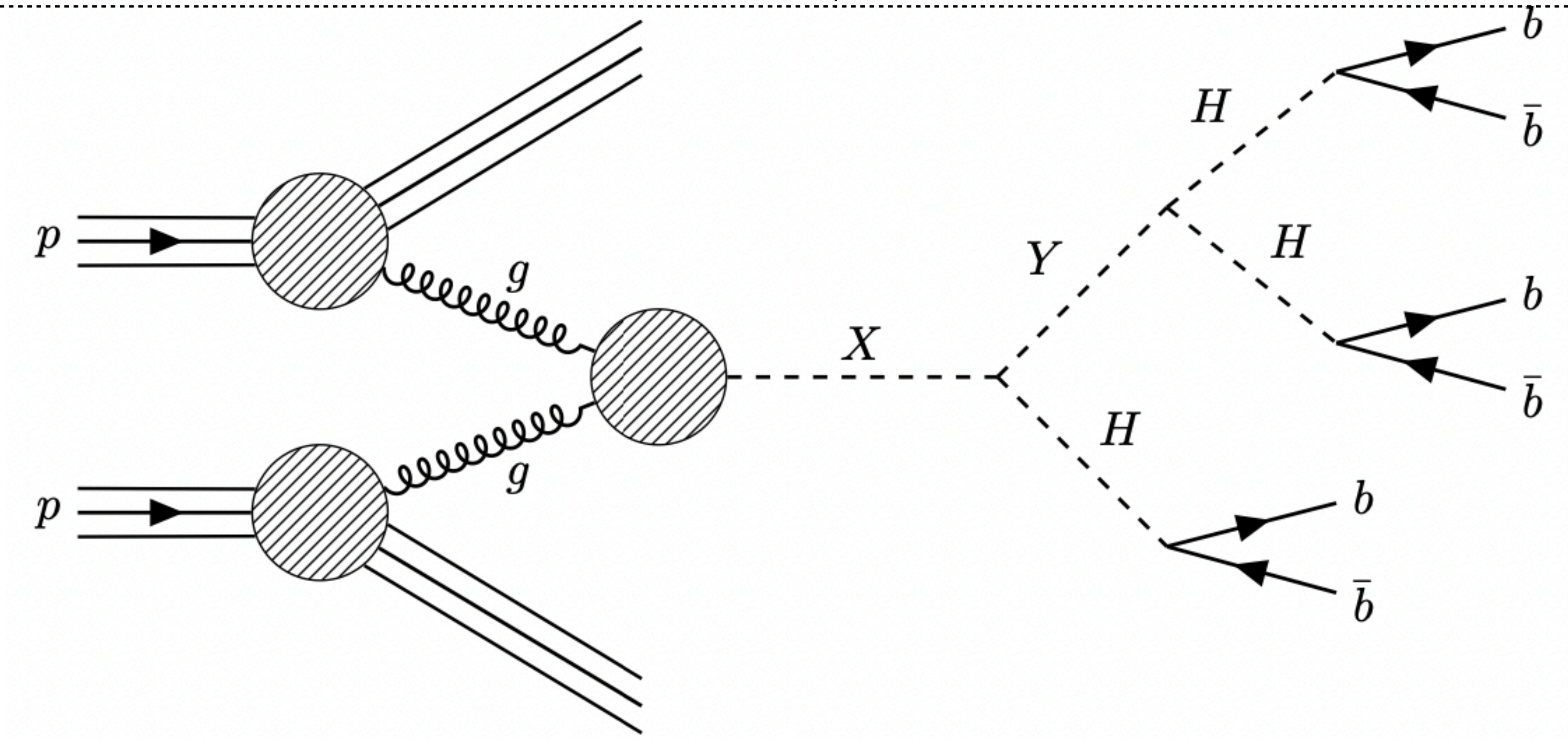






BSM HHH





HH and HHH sensitive to new physics:

- New resonances with spin0, spin2, two Higgs doublet, new scalars
- Any enhancement of HH and HHH production = sign of new physics!

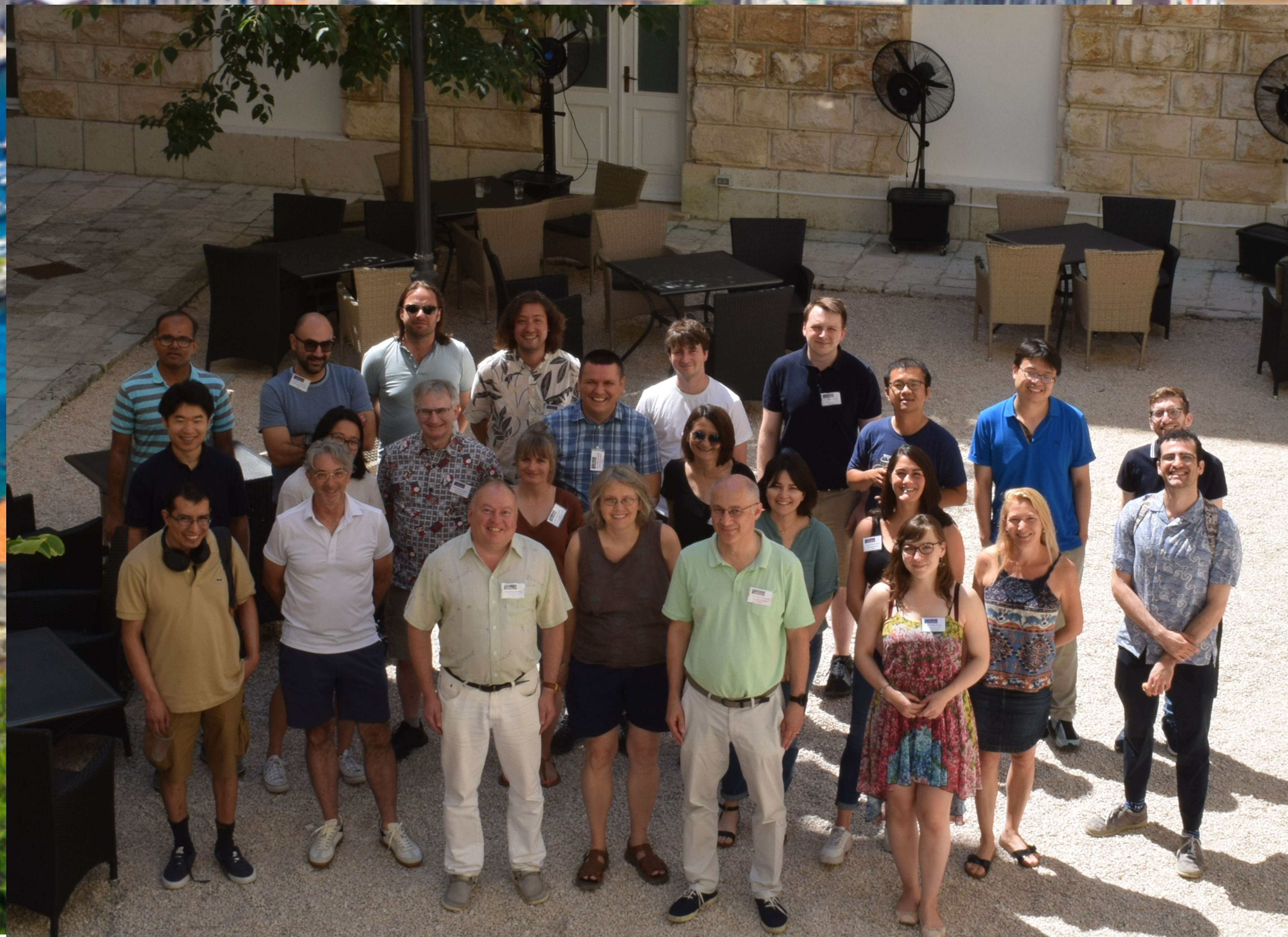
HHH workshop

14-16th of July 2023 Dubrovnik / Croatia

Organising committee

Vuko Brigljević, Ruđer Bošković Institute
Dinko Ferenček, Ruđer Bošković Institute
Greg Landsberg, Brown University
Tania Robens, Ruđer Bošković Institute
Marko Stamenkovic, Brown University
Tatjana Šuša, Ruđer Bošković Institute

https://indico.cern.ch/e/hhh2023



HHH workshop overview

Day 1	Day 2	Day 3
HHH theory **Lessons from ATLAS and CMS HH**	**ATLAS vs CMS** **Flavour tagging** **Trigger**	**BSM enhancements in HH and HHH** **FCC projections** **Overview**
ML for HHH **+** **HHH phenomenology**	**BSM HHH** **3HDMs** **Experimental thoughts**	Excursion

Successful 3 days workshop with theorists and experimentalists from both ATLAS and CMS

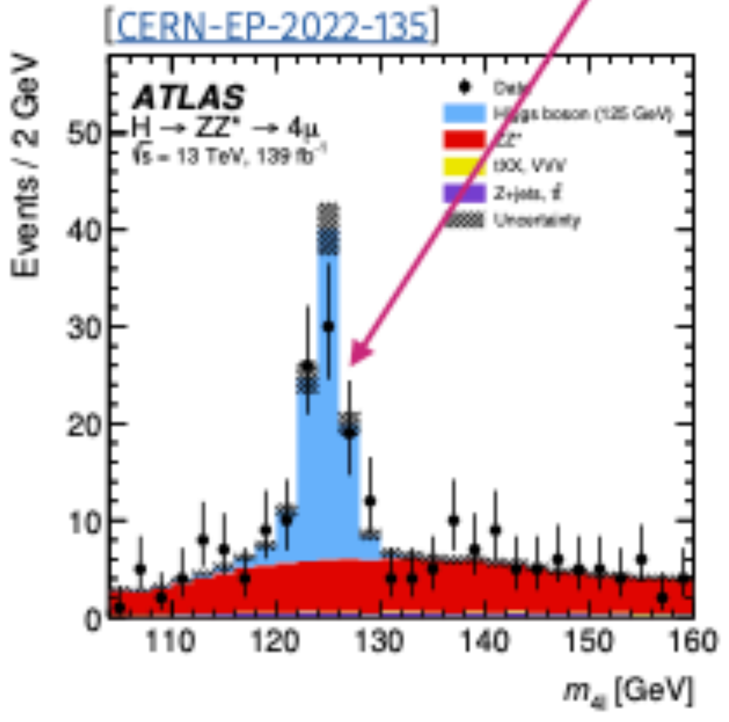
- A lot of interesting discussions, summarised non-exhaustively in the next few slides
- All the presentations available on the indico: [HHH 2023 workshop in Dubrovnik]

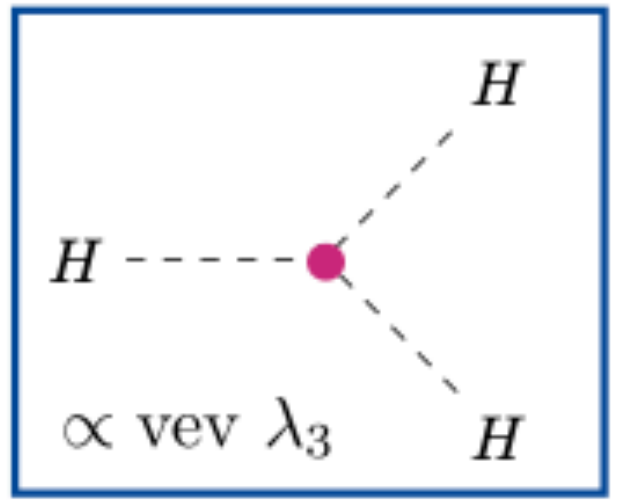
Higgs trilinear and quartic coupling

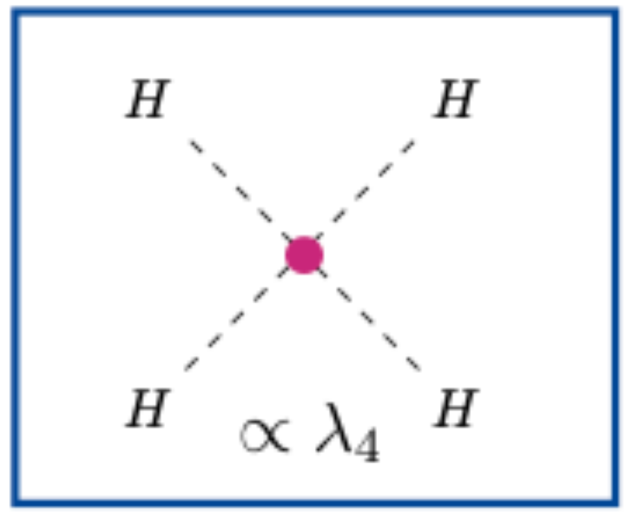
B. Moser

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

[CERN-EP-2022-135]







In SM:

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

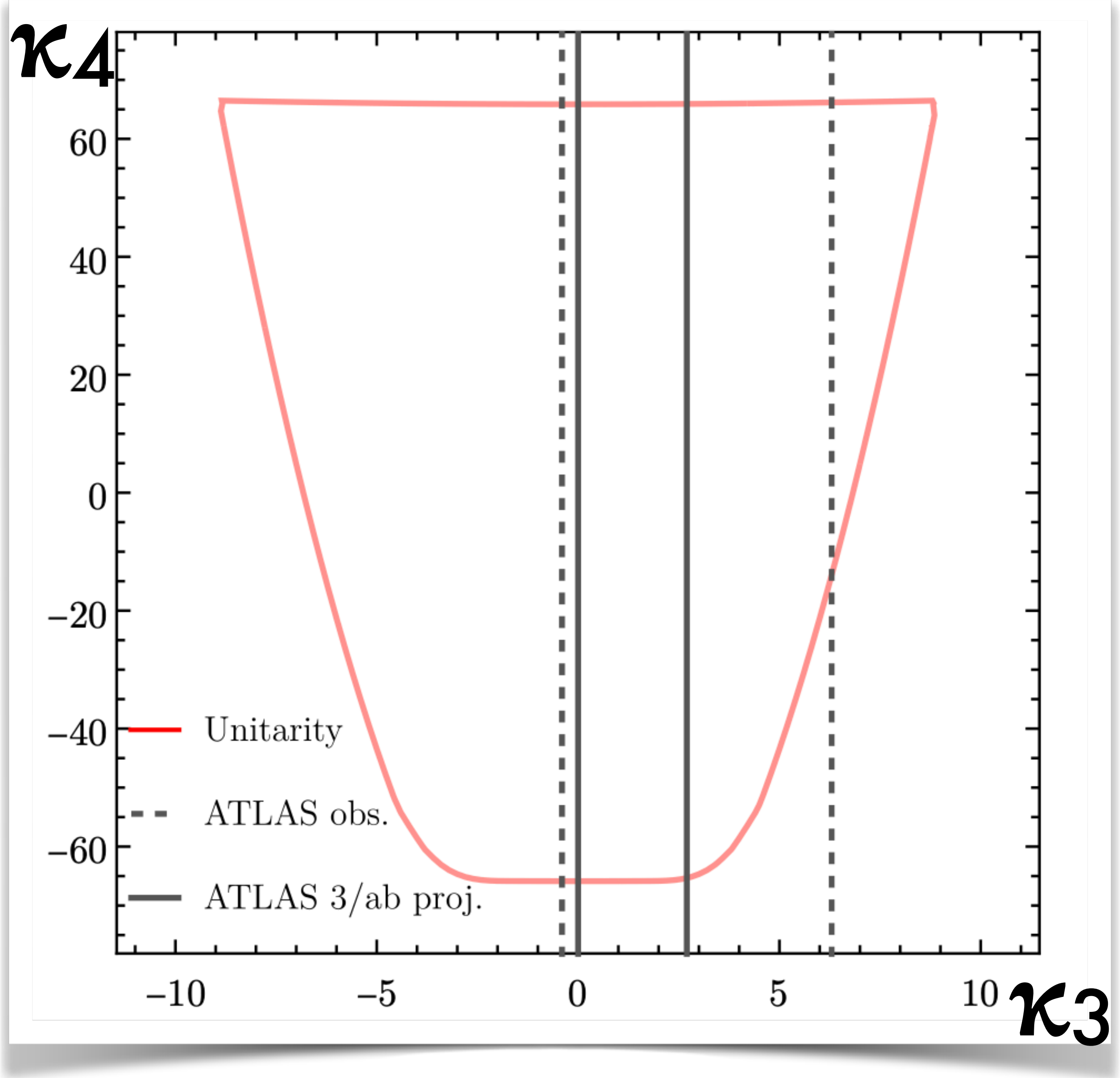
Parameterize:

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

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

[with SM = κ_3 = κ_4 = 1]

P. Stylianou



Higgs potential: responsible for self-coupling of the Higgs

- Measuring multi-Higgs production = critical probe of the SM
- No explanation for the shape of the Higgs potential
- Sensitive to new physics

Unitarity constraints: provide some constraints on λ_3 and λ_4

- HH combination: scratching κ_3 values not excluded by unitarity
  - With some assumptions on the quartic coupling
- LHC is the only machine in the world capable of probing λ_4 ?

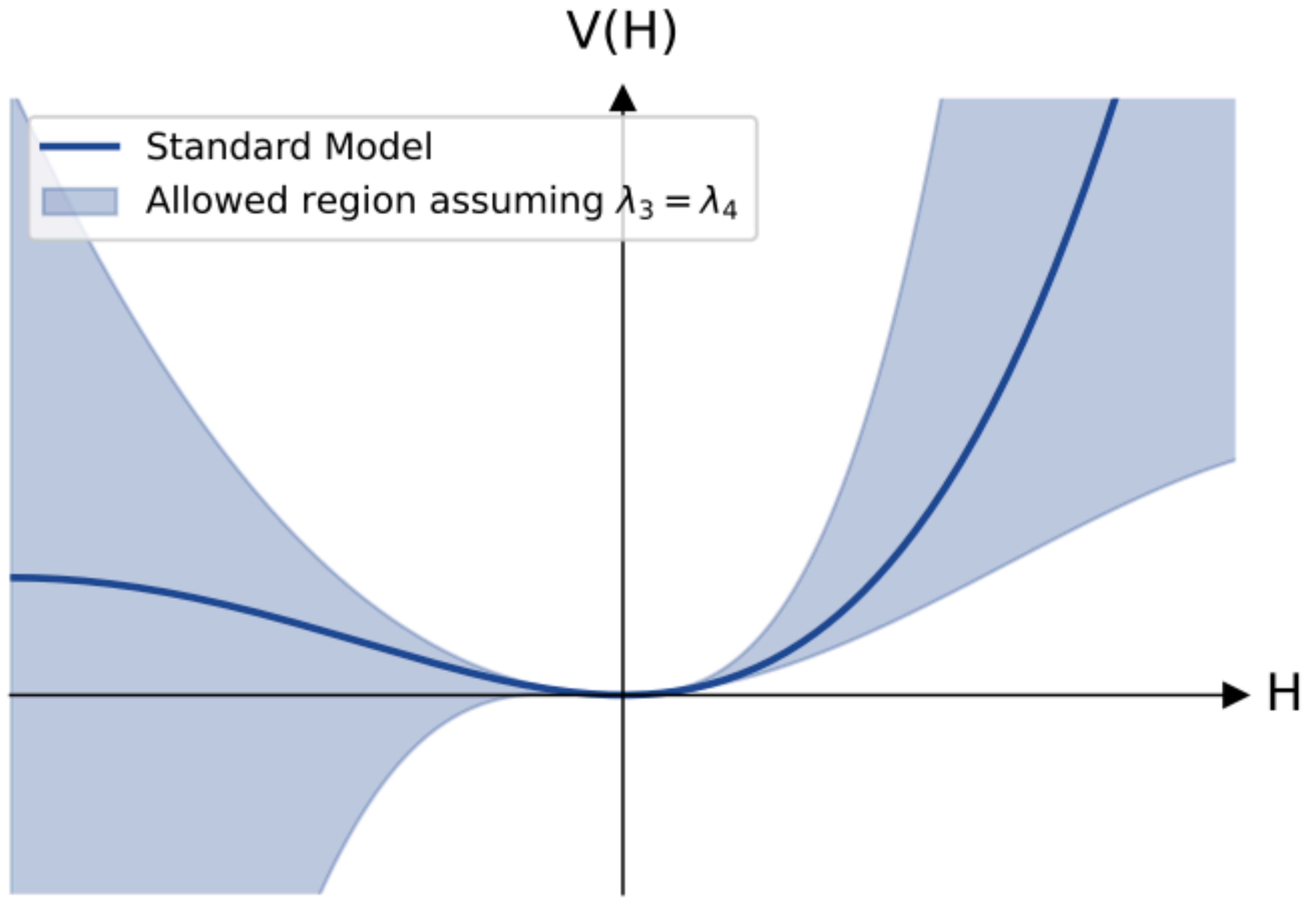
Higgs potential V(H)

B. Moser

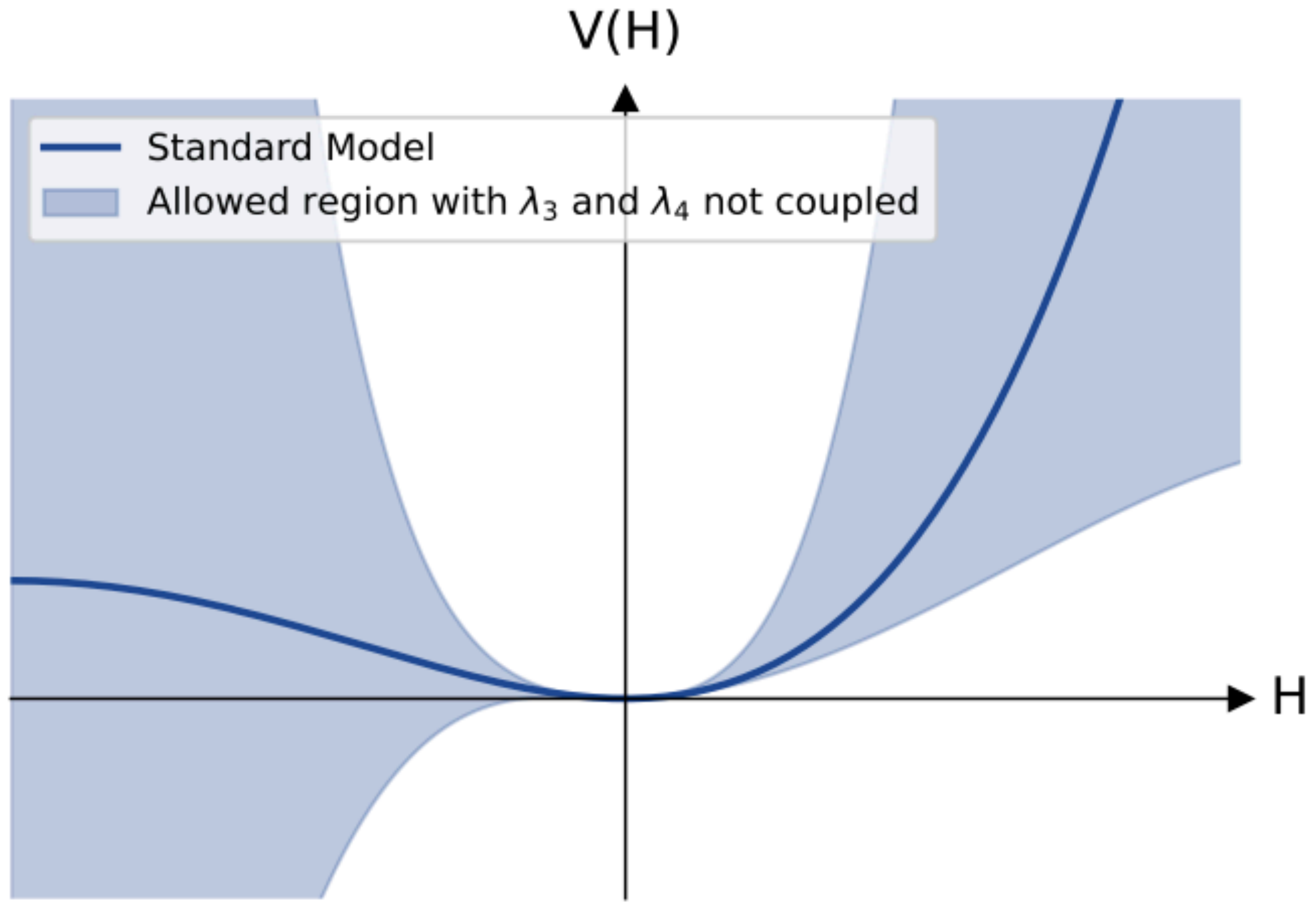
Constraining V(H) - where do we stand?

[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]

Measuring the Higgs potential:

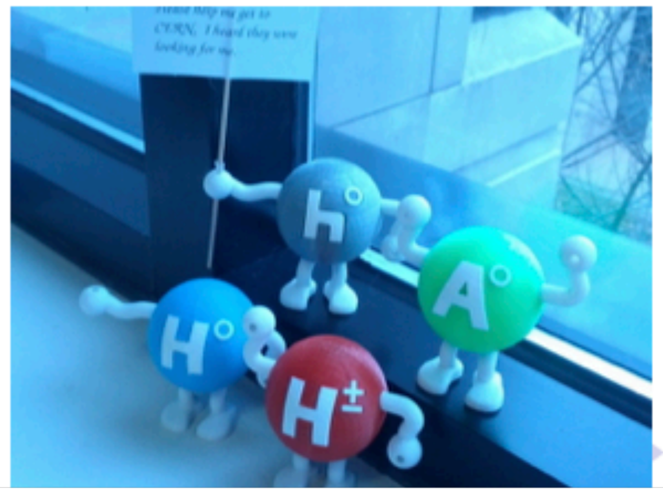
- Current knowledge → large amount of shapes still allowed, with different minima still allowed
  - Experimentally establishing the Higgs potential is one of the highest priority of the LHC program
  - With as little approximations / hypotheses possible

New physics in HHH

T. Robens

- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\text{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - can **push vacuum breakdown to higher scales**
  - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
  - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...

  $\Rightarrow$ **new scalar states** $\Leftarrow$



- 3 scalar states h_1, h_2, h_3 that mix

concentrate on
$p\,p \to h_3 \to h_2\,h_1 \to h_1\,h_1\,h_1 \to b\,\bar{b}\,b\,\bar{b}\,b\,\bar{b}$

(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{3000\text{fb}^{-1}}$
(255, 504)	32.40	6.40	2.92	9.23
(263, 455)	50.36	9.95	4.78	15.11
(287, 502)	39.61	7.82	4.01	12.68
(290, 454)	49.00	9.68	5.02	15.86
(320, 503)	35.88	7.09	3.76	11.88
(264, 504)	37.67	7.44	3.56	11.27
(280, 455)	51.00	10.07	5.18	16.39
(300, 475)	43.92	8.68	4.64	14.68
(310, 500)	37.90	7.49	4.09	12.94
(280, 500)	40.26	7.95	4.00	12.65

discovery, exclusion

$\Rightarrow$ **at HL-LHC, all points within reach** $\Leftarrow$

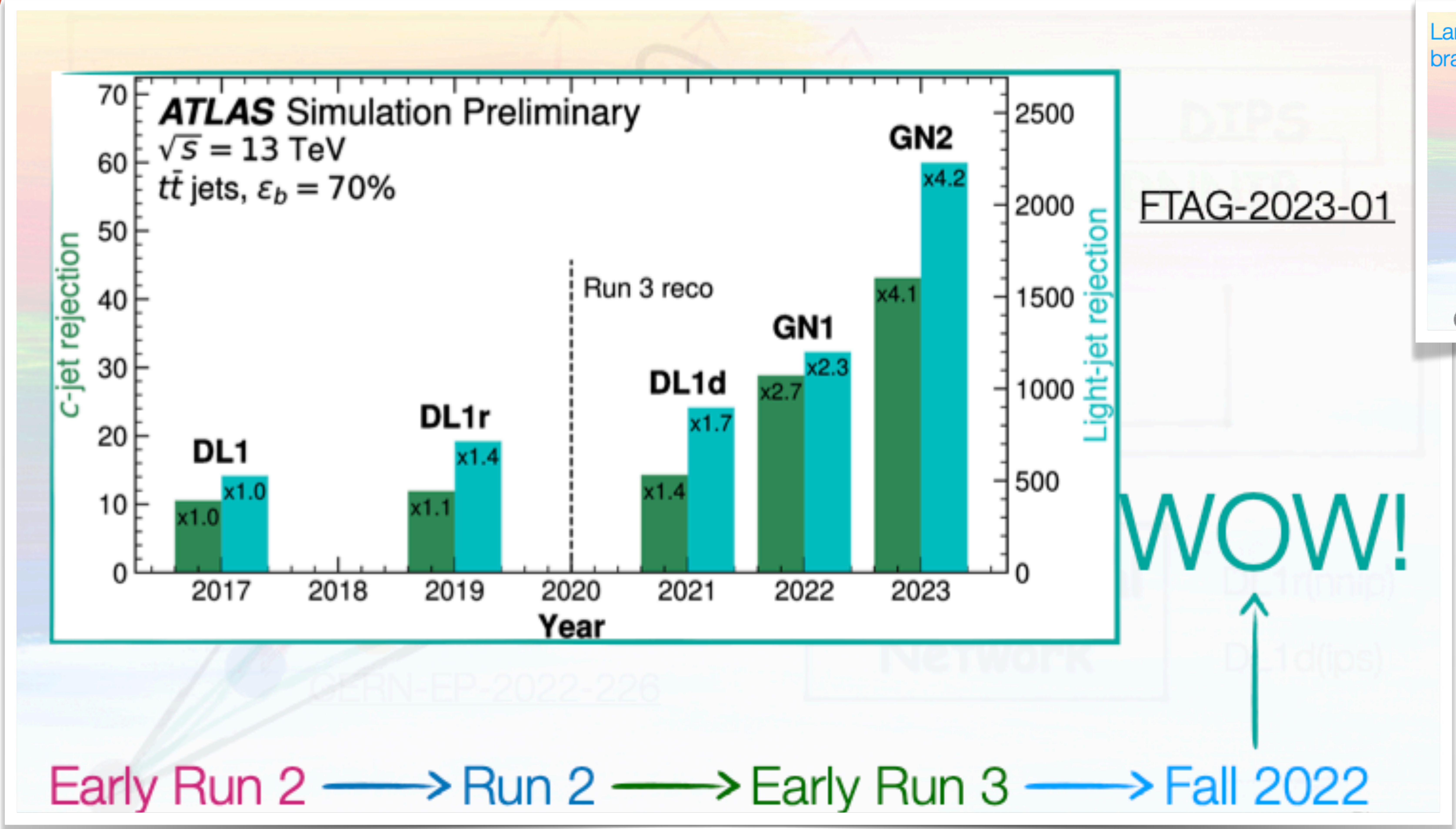
HHH: rich phenomenology

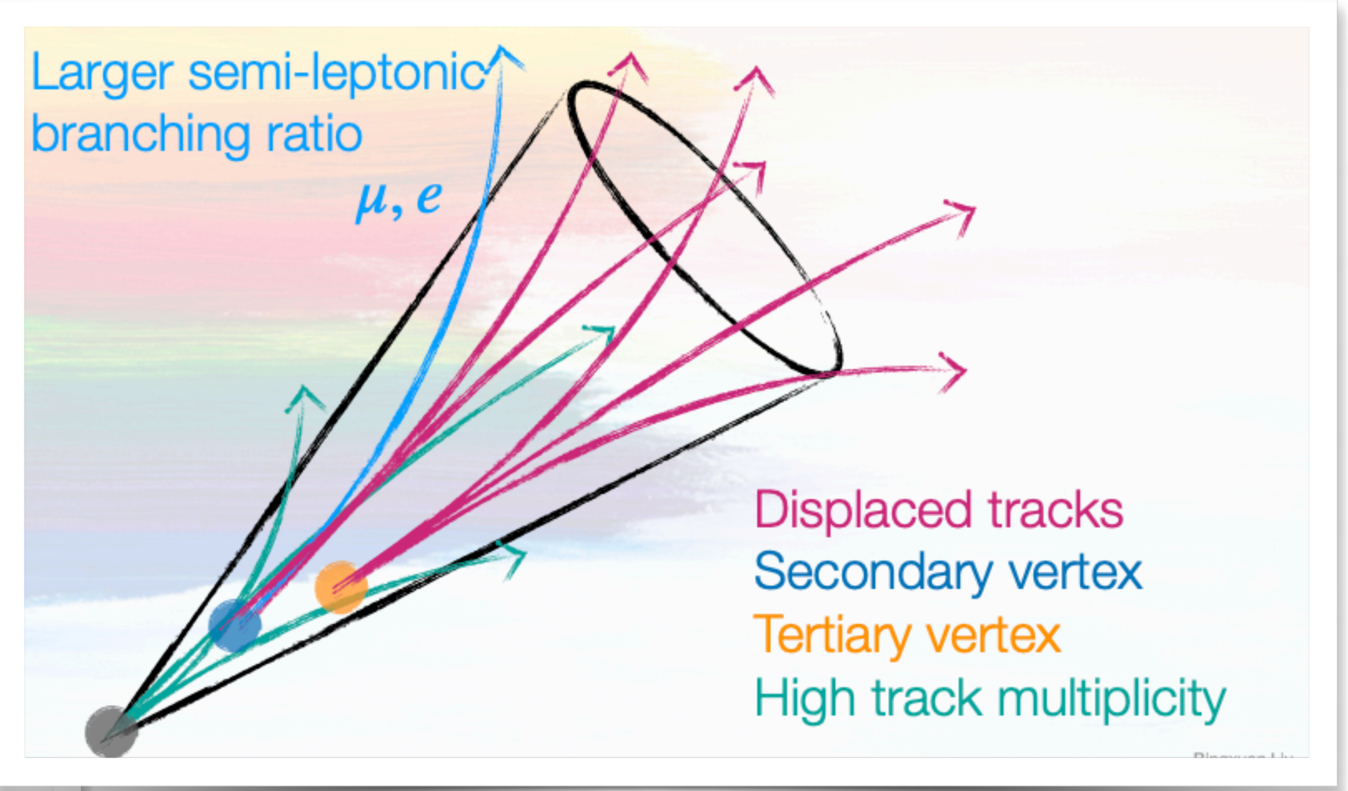
- Capable of probing various BSM scenarios
- Including extended sectors with scalars, 3HDMs

Experimental overview

B. Liu

Flavour tagging



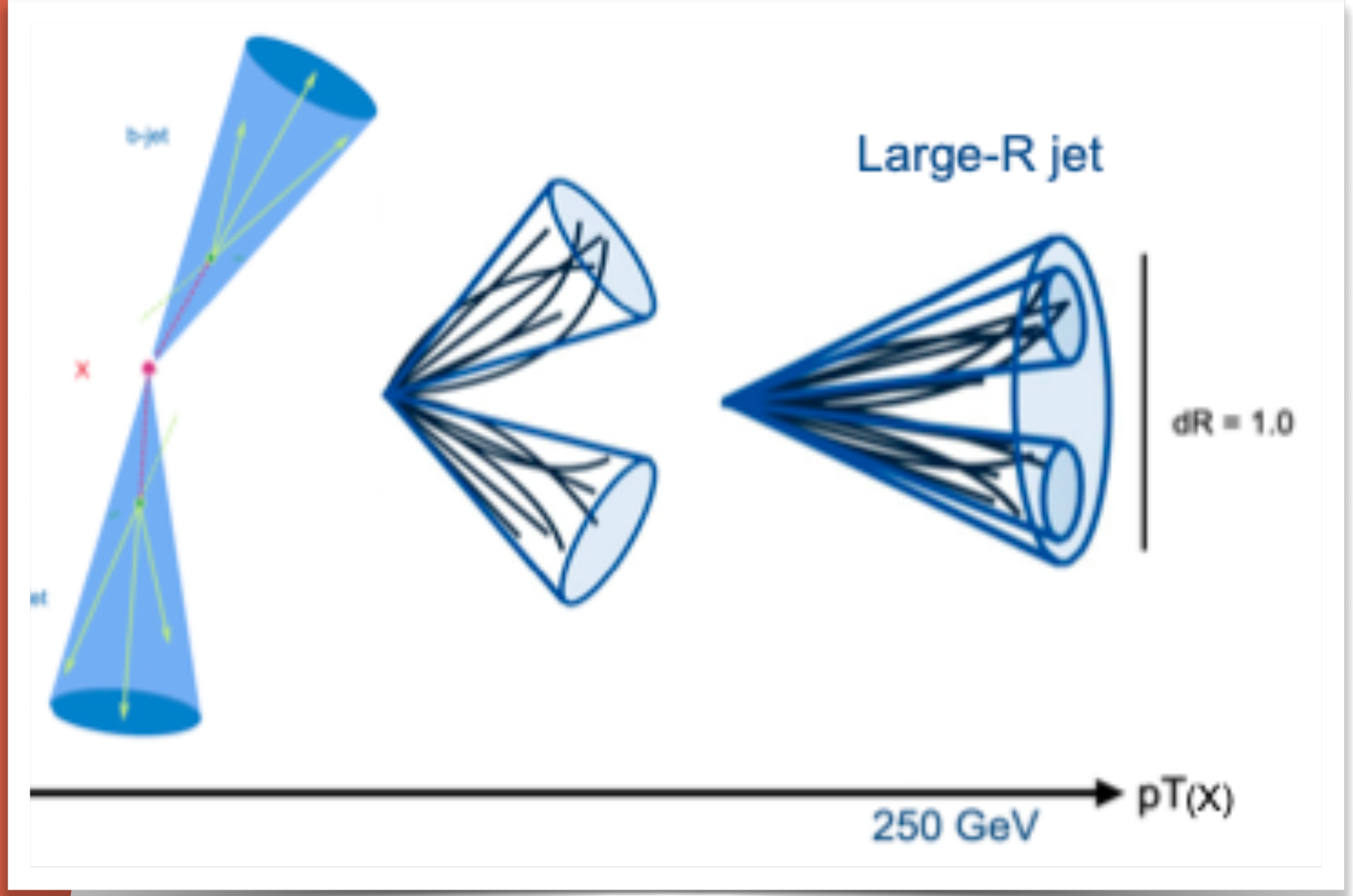


Experimentally: extraordinary progress achieved every year

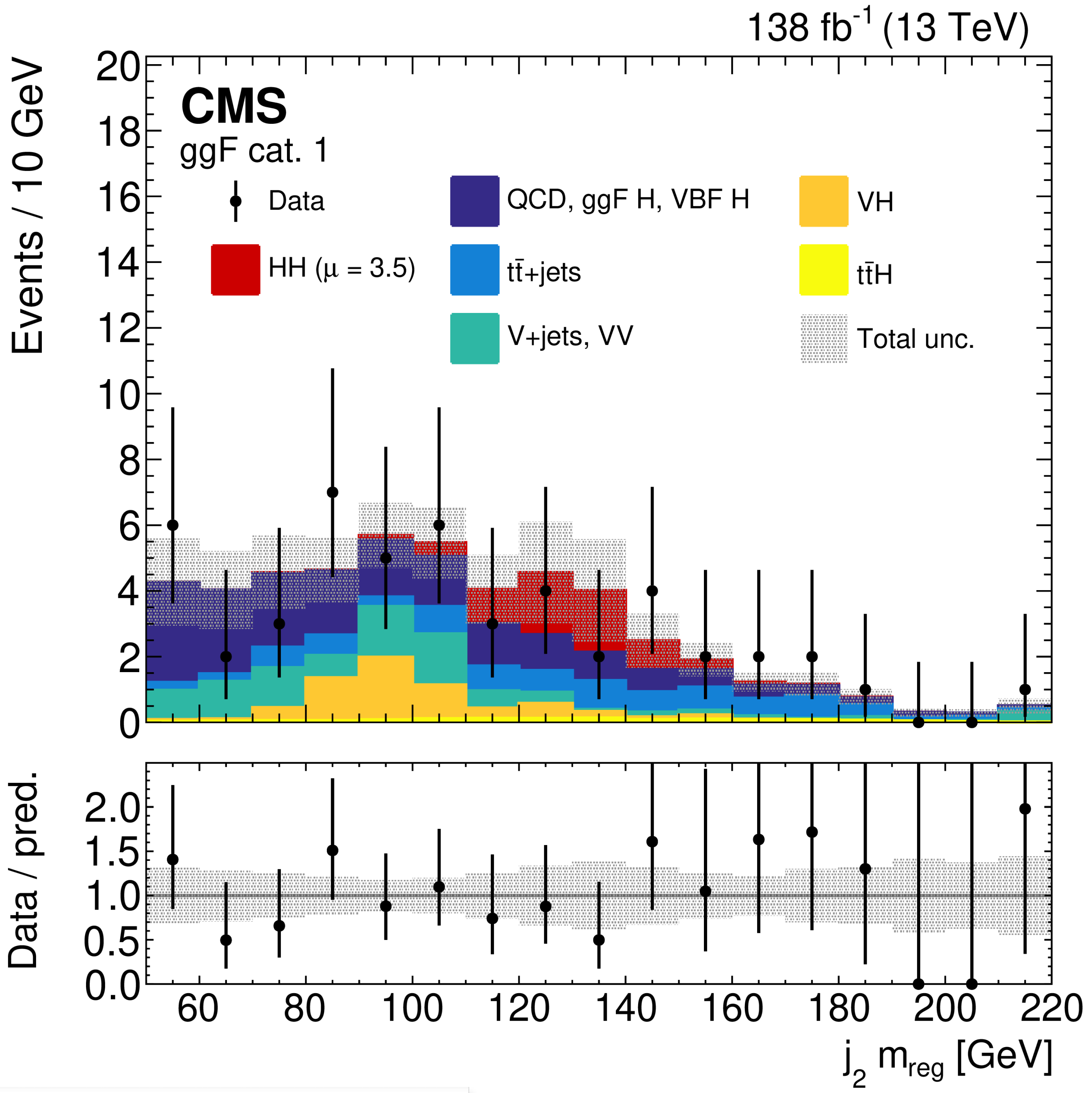
- Flavour tagging to identify b-jets in the detector: improved by a factor 4 in the span of 6 years!
- For the same identification of b-jets: remove 4x more background than before!
- Similar progress in both ATLAS and CMS: crucial for HH and HHH!

Boosted Higgs tagging

O. Karkout

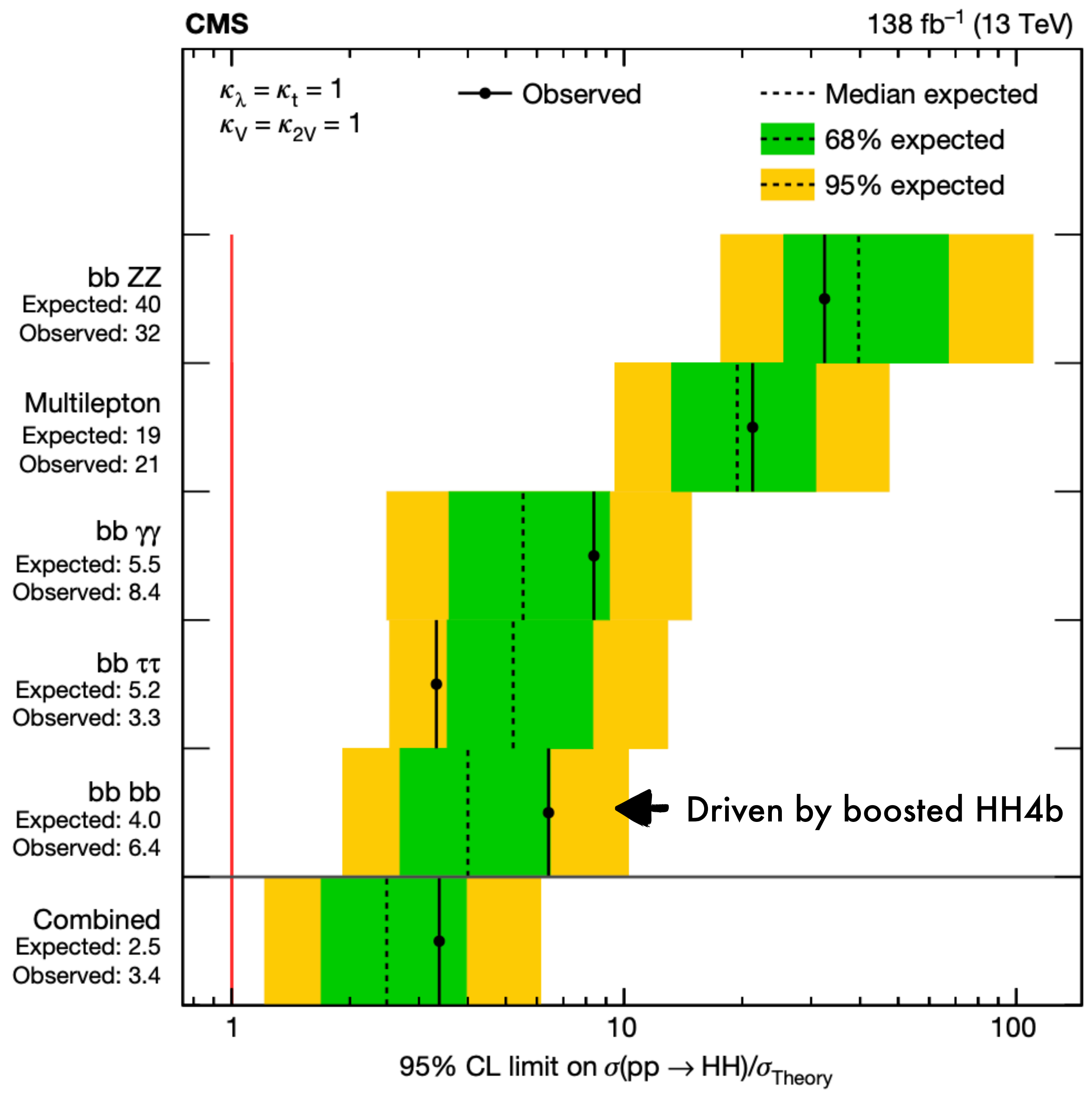


Boosted HH4b

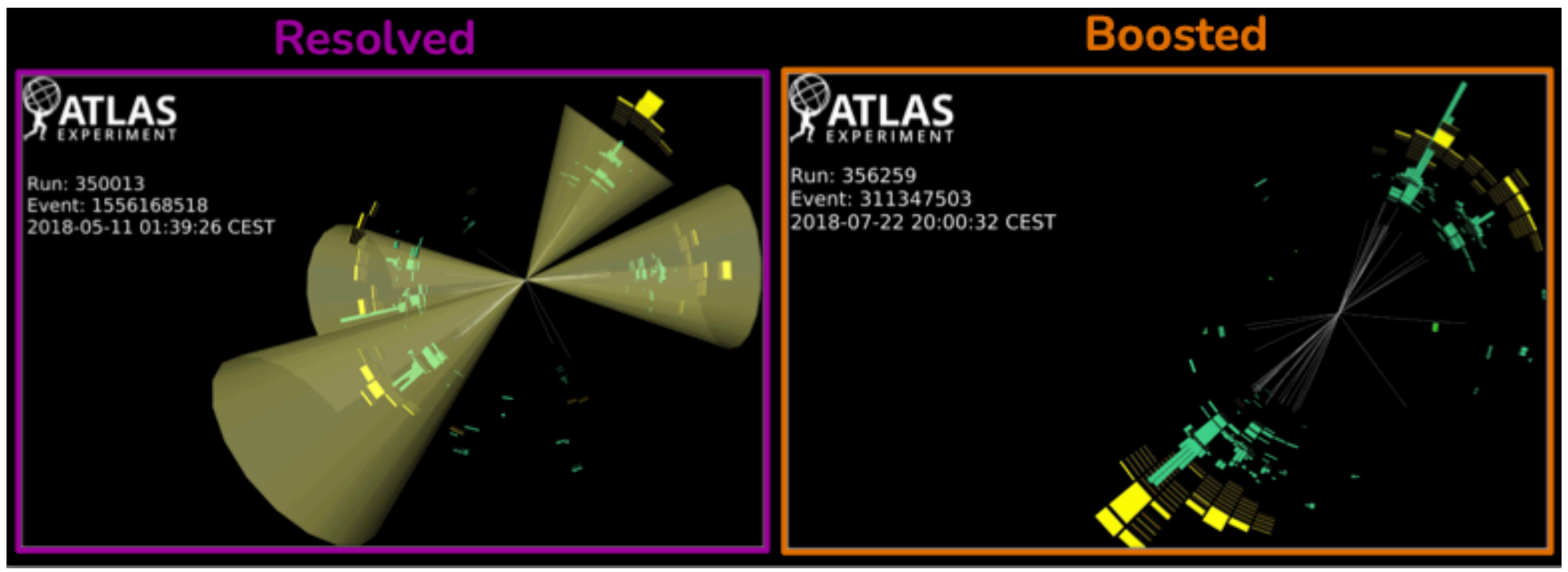


HH combination

MS



W. Balunas



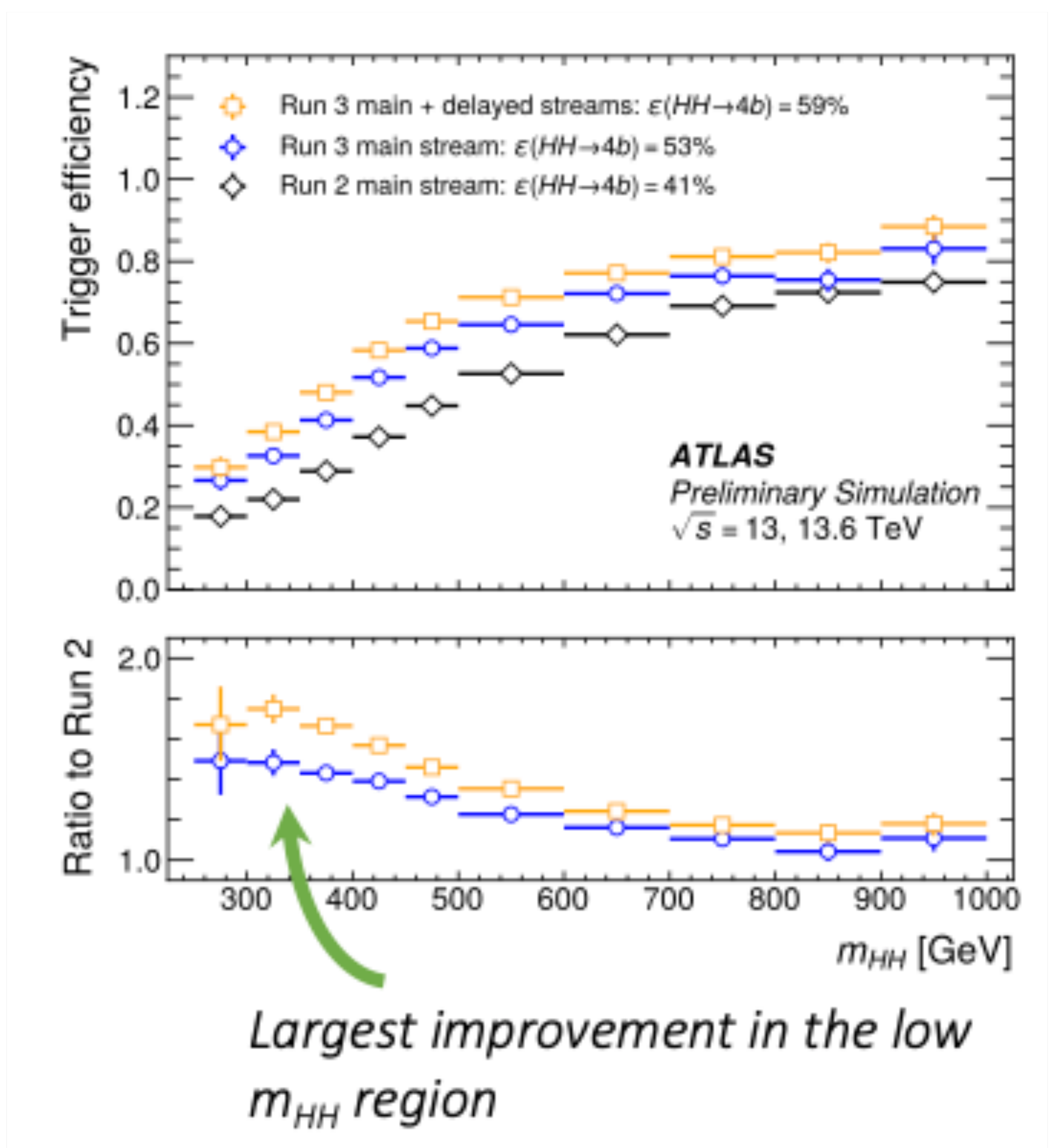
Extraordinary progress in Hbb tagging:

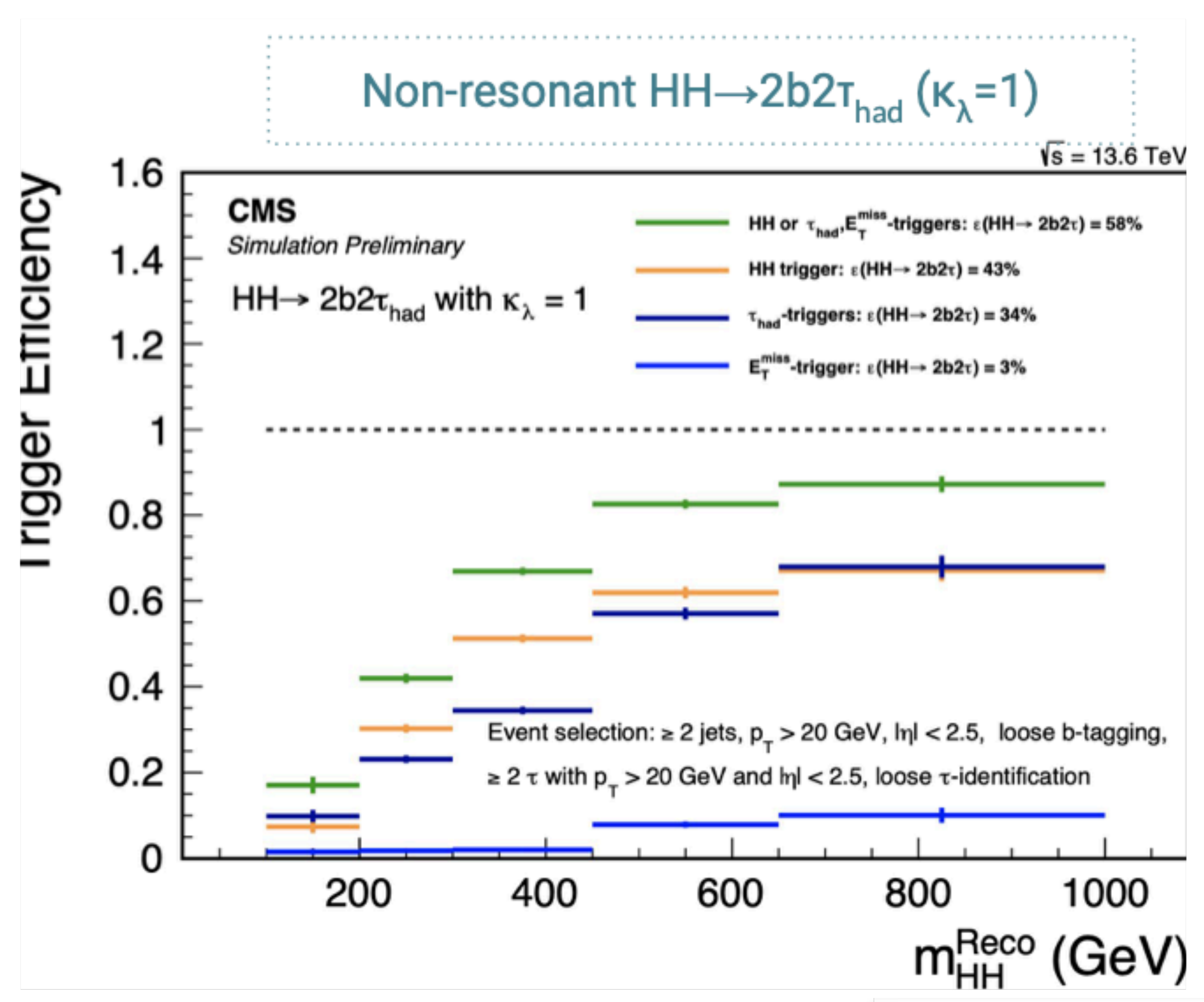
- Boosted Higgs identification crucial for HH
  - Lower background
  - Better Higgs identification, resolution
  - Less combinatorial background
- Will play a crucial role in HHH too!

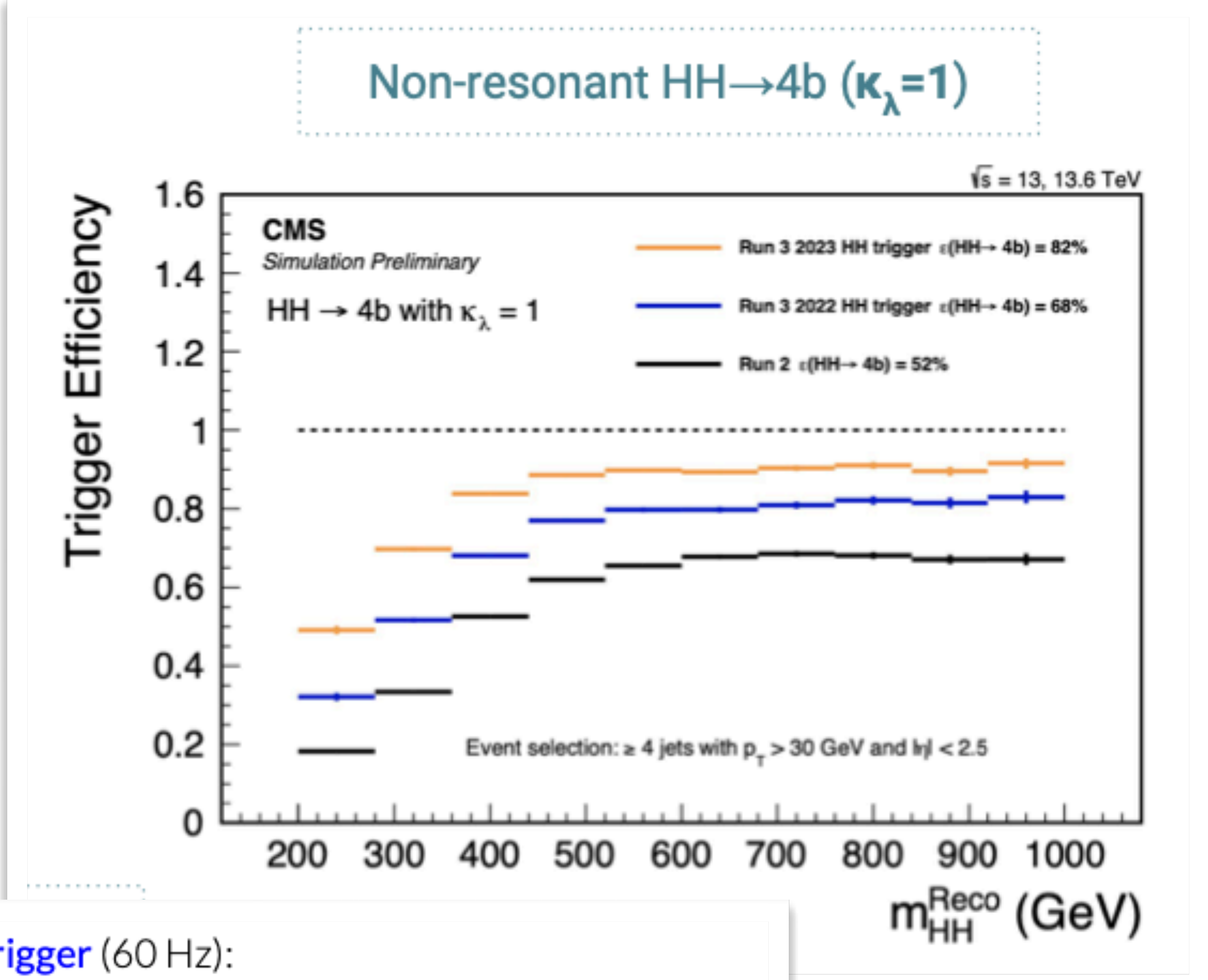
Triggers for Run 3

M. Chen

M. Kolosova







Run 3 2022 HH trigger (60 Hz):

- L1 H_T > 360 GeV
- ≥ 4 jets with p_T > 70, 50, 40, 35 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.65

Run 3 2023 HH trigger (180 Hz):

Data Parking

- L1 H_T > 280 GeV
- ≥ 4 jets with p_T > 30 GeV
- 2 leading-in-**ParticleNet** jets have average b-disc > 0.55

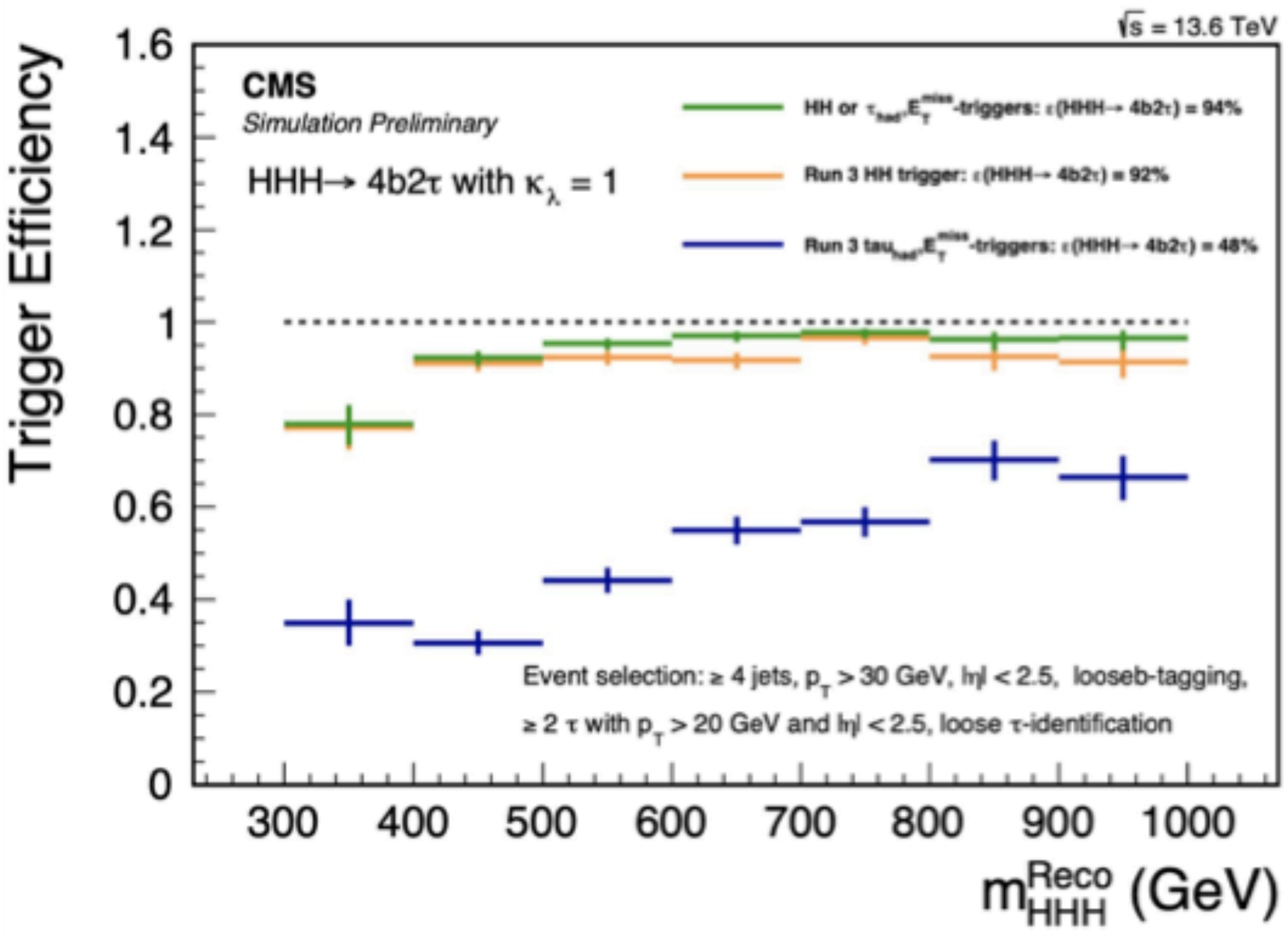
Extraordinary work on trigger by both ATLAS and CMS

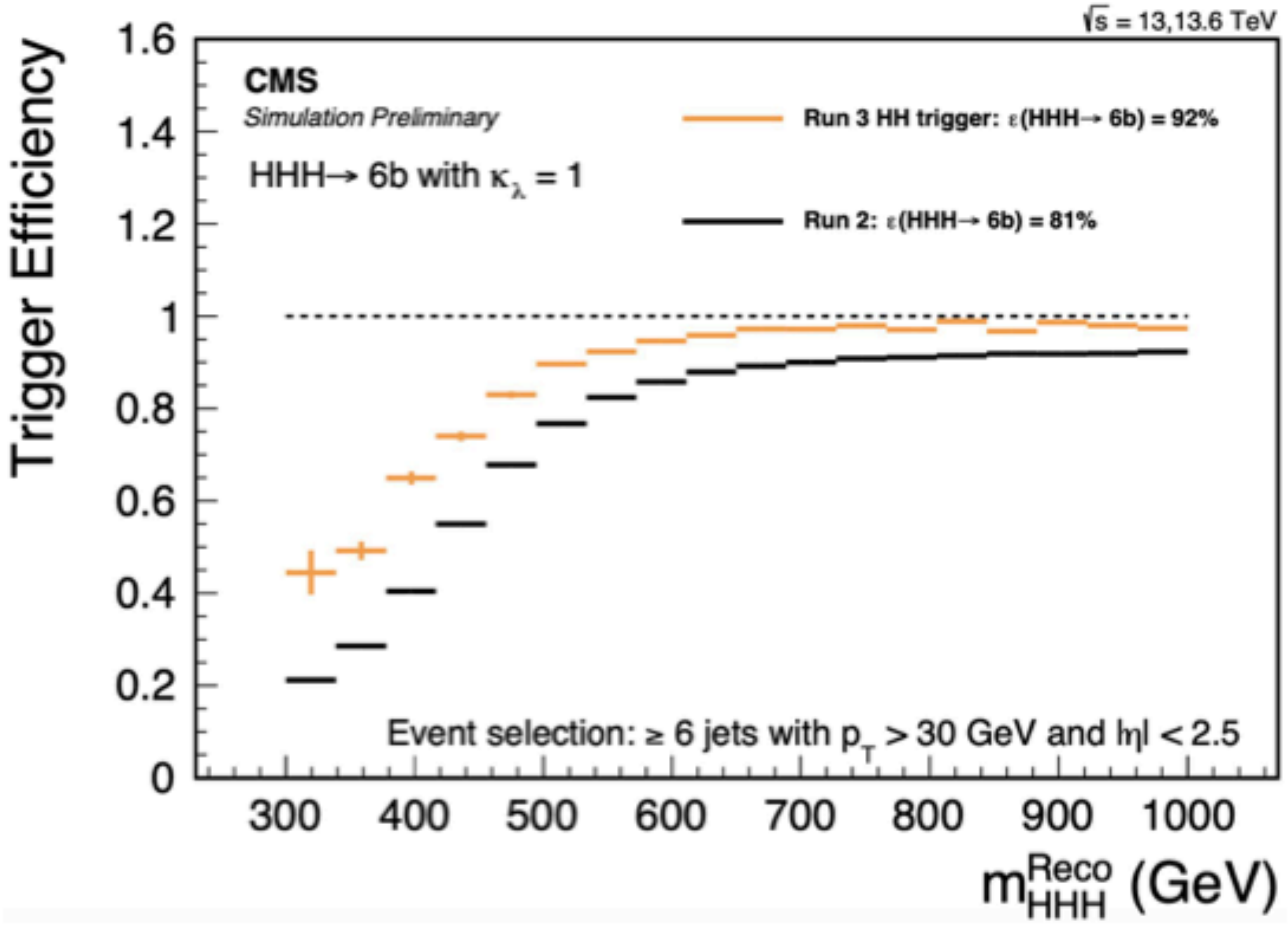
- In 2018: only 50% of HH4b events produced recorded
- With latest improvements in taggers:
  - Up to 80-90% of events will recorded in all channels!

Triggers for Run 3: targeting HHH too

M. Kolosova

Same trigger(s) can be used in the search for triple Higgs production in the **4b2τ_{had}** and **6b** final states, achieving **94%** and **92%** overall efficiency, respectively!



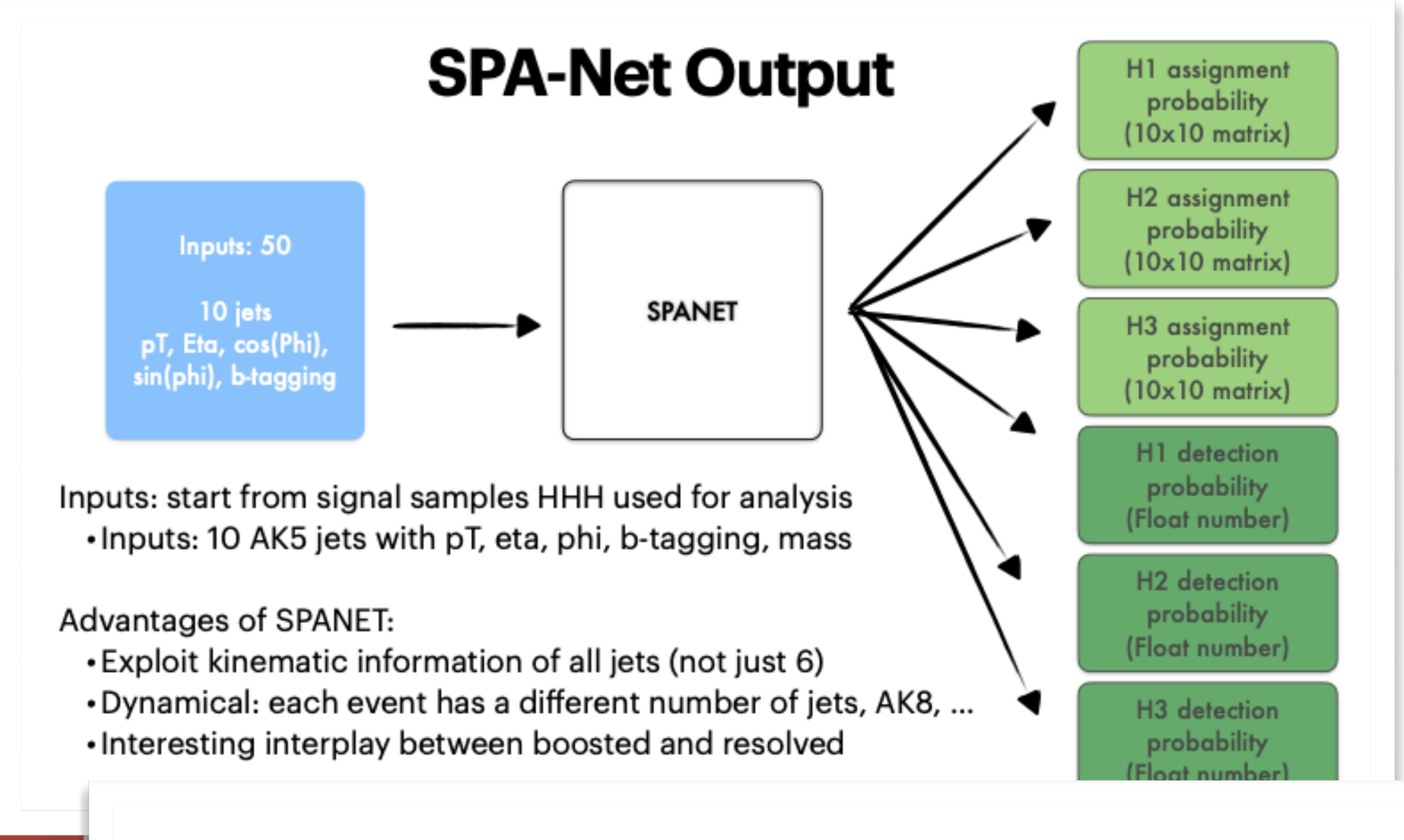


New trigger strategy benefitting from taggers and additional HLT rate: highly optimal for HHH

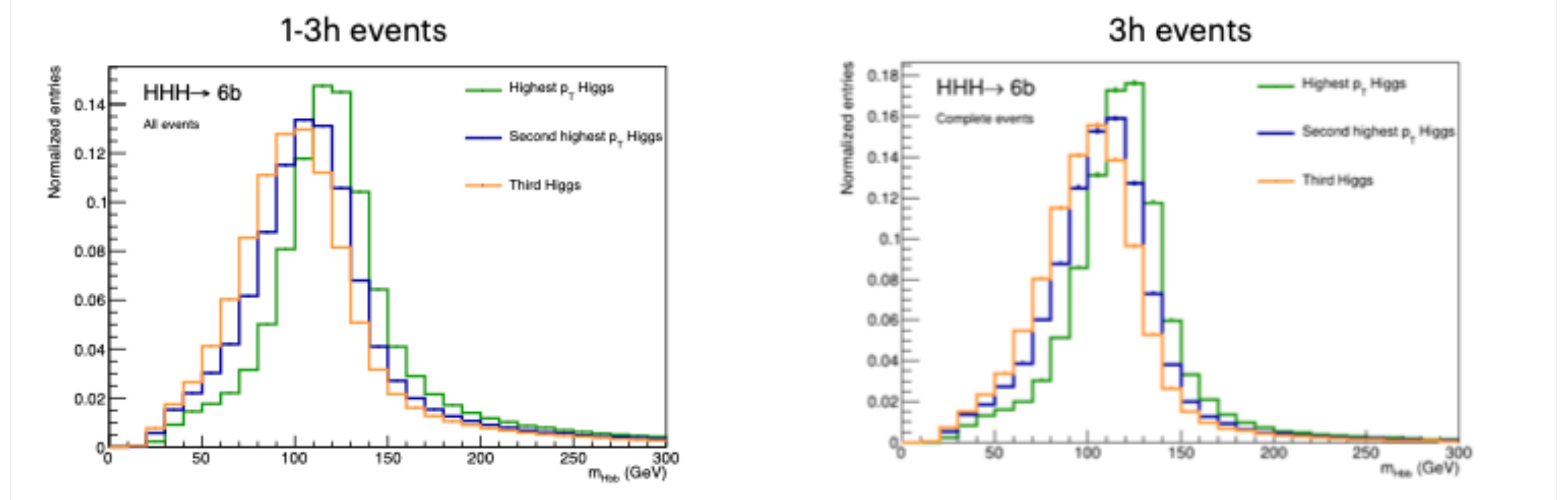
HHH reconstruction

MS

Attention networks



H purity	1-3h		3h	
	Chi2 baseline	SPA-Net	Chi2 baseline	SPA-Net
6 jets	46.3%	53.4% (**+15%**)	64.1%	67.8% (**+6%**)
7 jets	40.2%	53.3% (**+33%**)	47.0%	61.9% (**+32%**)
>= 8 jets	33.8%	49.8% (**+47%**)	36.4%	54.2% (**+49%**)
Full	38.6%	51.7% (**+33%**)	43.1%	58.2% (**+35%**)



HH4b: combinatorially easy

HHH6b:

- 3 Higgses with same mass!
- However, can we reconstruct them?

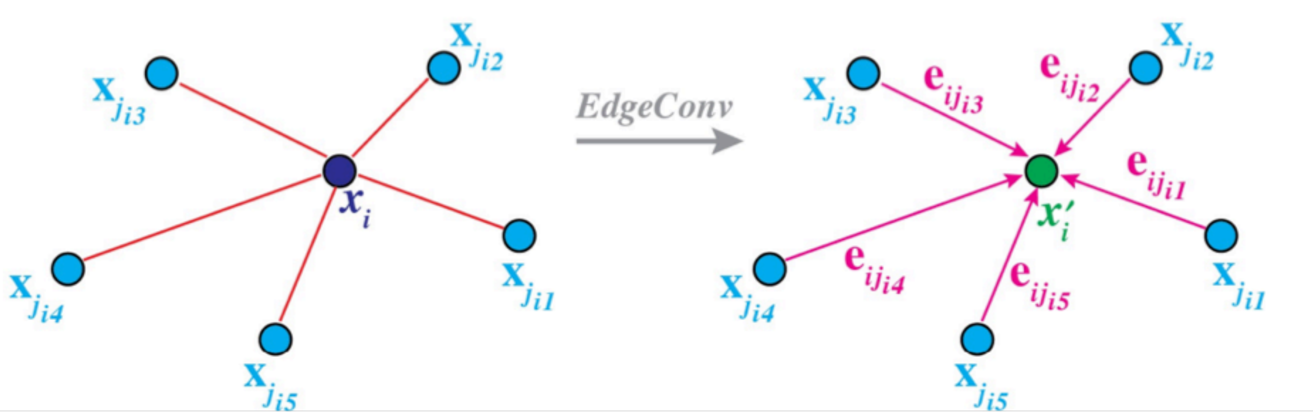
Graph networks

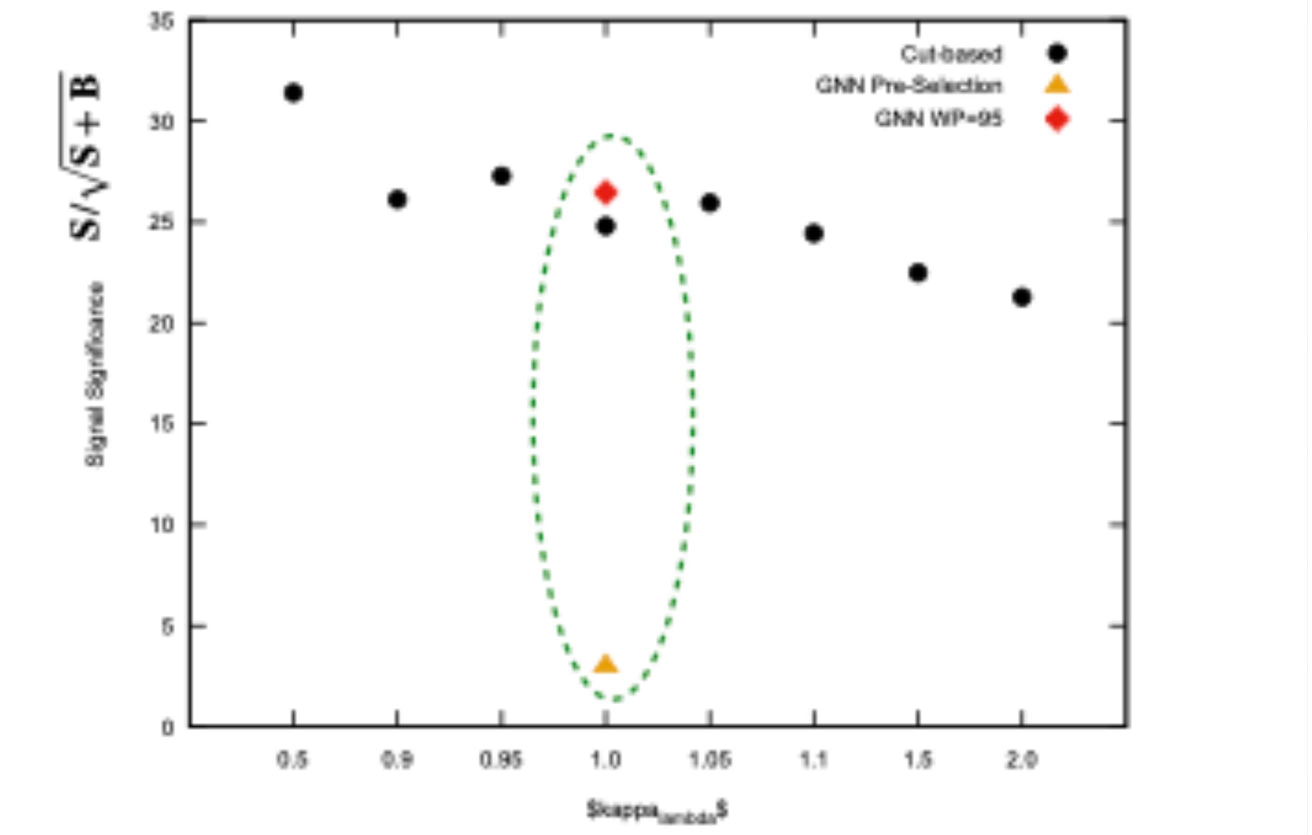
S. Ganguly

In a graph, each node can "learn" about the state of neighboring node through message passing operation

$$(x')_i^{l+1} = max_{j\in\mathcal{N}(i)}\ \Theta_x(x_j^l - x_i^l) + \Phi_x(x_i^l)$$

$$(e')_i^{l+1} = mean_{j\in\mathcal{N}(i)}\ \Theta_e(e_j^l - e_i^l) + \Phi_e(e_i^l)$$





- ☑ For multi-b final states event level classifiers are capable of increasing sensitivity
- ☑ These preliminary studies (for FCC-hh) are generalizable across hh or hhh searches
- ☑ Compared two different GNN models : probably a general GNN will do the required job.
- ☑ The individual tagging score and pairing scores should improve the sensitivity.

Strategy discussions

Branching Fractions

G. Landsberg

- H(bb) = 58.1%, H(ττ) = 6.26%, H(WW) = 21.5%, H(gg) = 8.18%, H(ZZ) = 2.6%, H(γγ) = 0.23%
- σ_{HHH}(14 TeV, NNLO) = 0.1fb
- Aim at σ^{95} = 100 x σ_{HHH} = 10 fb; Run 2 x σ^{95} ~ 1000 events; Run 2 x σ^{95} x ε ~100 events
- To set a limit, need expected yield of 3 signal events: do not consider Br < 3% for now
- **HHH → 6b: 19.5%**
- **HHH → bbbbττ: 6.3%; bbbb$\tau_h\tau_h$: 2.7%**
- **HHH → bbbbWW → 4b4j: 9.9%**
- **HHH → bbbbgg → 4b2j: 8.3%**
- HHH → bbbbWW → 4b2jℓν: 5.9%
- ~~HHH → bbττWW → 2b2τ4j: 2.1%~~
- ~~HHH → bbbbWW → 4b2ℓ2ν: 0.9%~~
- ~~HHH → bbττττ: 0.68%~~
- ~~HHH → bbbbγγ: 0.23%~~

41% - Focus on these topologies: 4b + jets

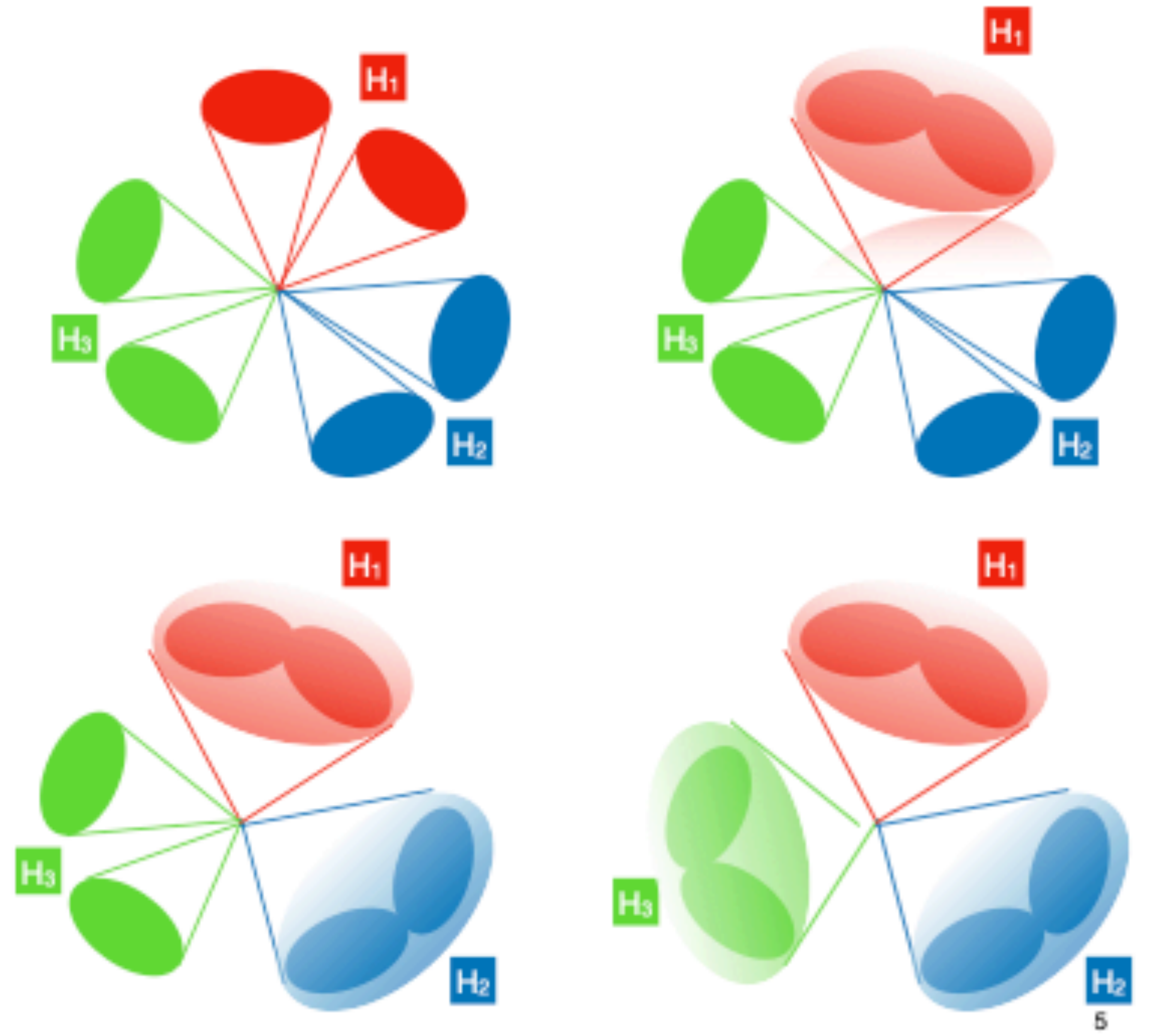
N.B.1: this is SIMPLER than HH → 4b
All the techniques developed for that analysis can be reused if desired
Backgrounds by construction are order of magnitude or more lower

N.B.2: WW → lvjj, while promising, doesn't have a mass peak

HHH:
- 41% of the cross-section accessible via fully hadronic decays
- 4b + jets

Exploit boosted topologies
- Focus on 2 Hbb to maximise the sensitivity
- Use large radius jets to simplify the pairing

Toward Merged Topologies



- Our experience: merged jet topologies offer better performance than resolved ones
  - Smaller combinatorics
  - Substructure variables are apparently more powerful than what we use in the resolved case
- Idea: why bother with resolved, fully merged, and partially merged topologies?
  - Work with CA1.5-2.0 jets and have at least two out of three Higgs boson decays merged!
  - No combinatorics, and the advantage of using jet substructure techniques!

5

Summary of the workshop / HHH at LHC

J. Konigsberg

Final remarks

- HHH SM prospects @ LHC
  - Bleak, dim, hopeless?
  - But H=>bb was thought of the same… done and done → Hbb observed in 2018!
  - So was HH… and we'll get to it - promise! → ATLAS and CMS improving tools to accelerate the discovery
- We are doing the right thing here in figuring out how
  - Our knowledge & tools evolve continuously
  - Workshops catalyze the process
- There is anyway [earlier/good] hope for BSM HHH
  - Many opportunities for discovery
- Also, experimentally, we should just search. period.

Summary of the workshop / HHH at LHC

J. Konigsberg

Final remarks

- HHH SM prospects @ LHC
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What's next ?

2024 ?

*City of Dubrovnik interested in HHHH workshop, please get in touch

Mark the date: HHH workshop 2024

had a very nice *HHH* workshop in Dubrovnik this year

[https://indico.cern.ch/event/1232581/]

⇒ da capo next year (by popular demand): ⇐
IUC, Dubrovnik, 29.-31.7.2024

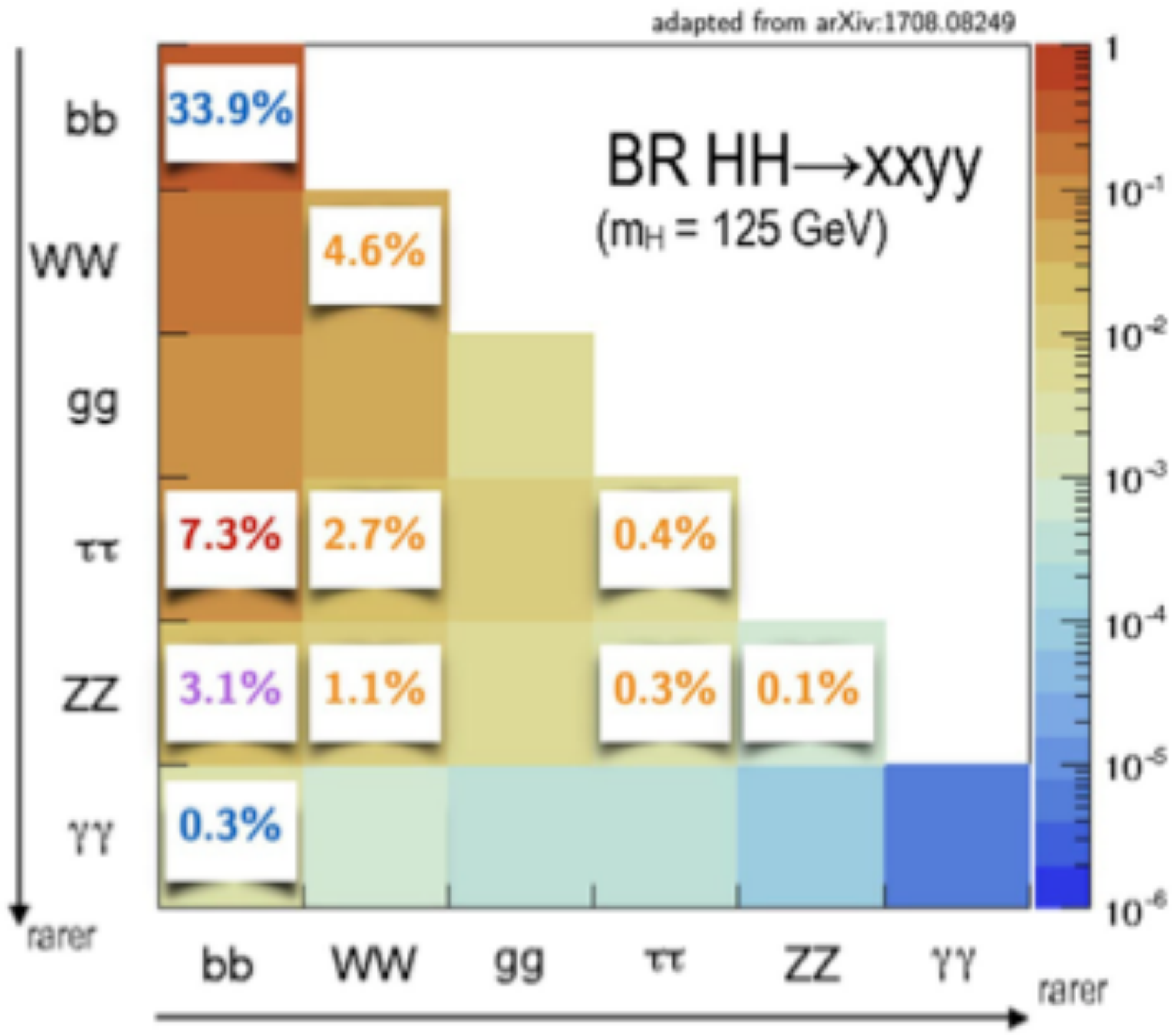
! Save the date !

Back-up

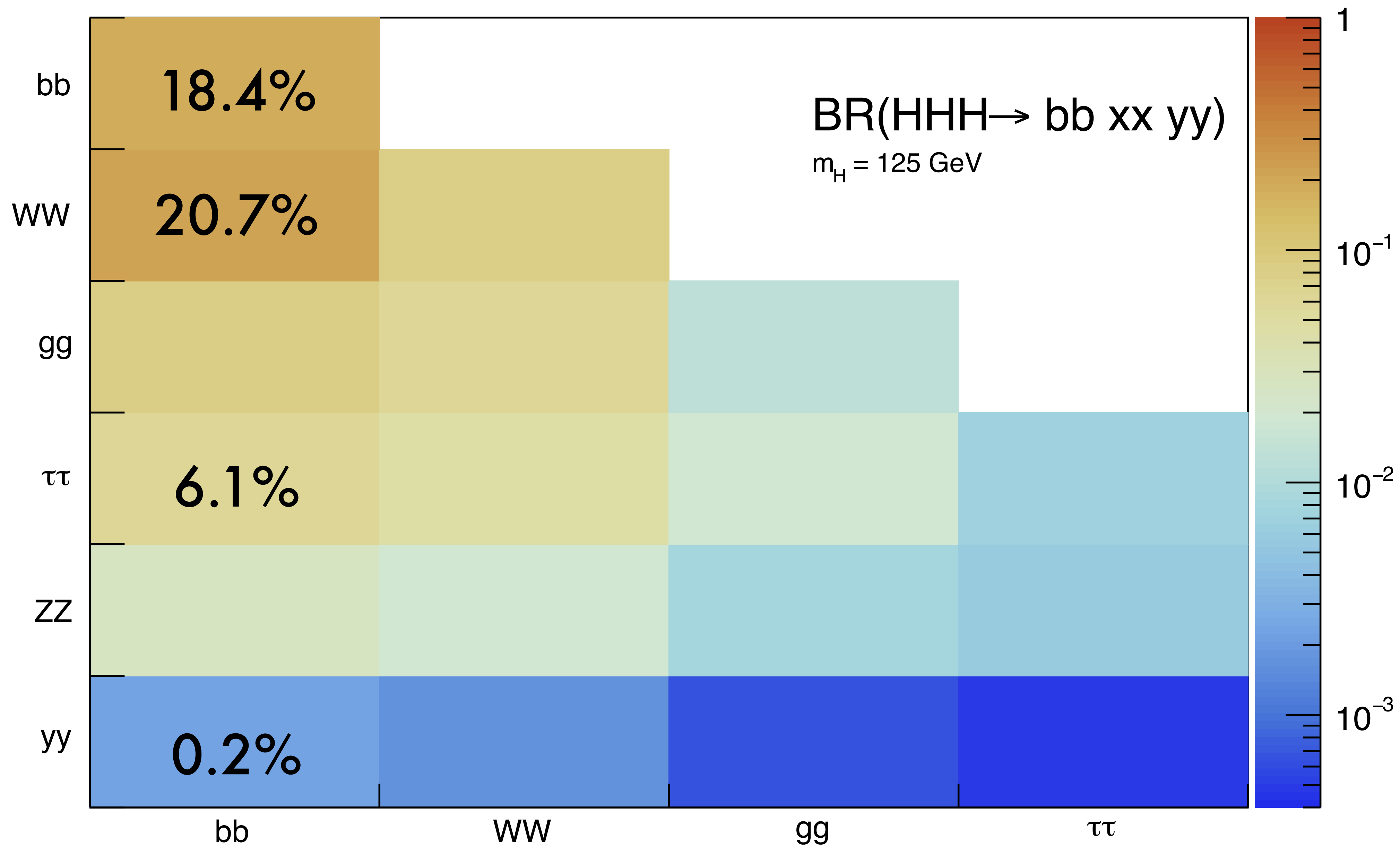
Phenomenology

Phenomenology of HH and HHH

HH branching ratio



HHH→bb XX YY branching ratio



Main HH decay modes experimentally accessible:

- HH→4b ⇒ largest branching ratio, challenging due to high b-jet multiplicity and QCD background
- HH→2b2τ ⇒ sizeable branching ratio, lower QCD background
- HH→2b2γ ⇒ rare process however clean signature due to photons

HHH→6b, HHH→4b2τ and HHH→4b2W: approximately 45% of total cross-section!

- Similar challenges as HH with large b-jets multiplicity, what are the lessons from HH useful for HHH?
- Will focus on non-resonant HH, however main challenges and lessons similar to resonant HH

HHH6b: analysis strategy

Non-resonant HHH6b process: σ(HHH) x BR(HHH→6b) ~ 0.1 fb x 20%

- Complex mixing between resolved and boosted reconstruction
- Interesting mixing of resolved versus boosted topologies
  - Exploit kinematics