Di-Higgs measurements at the HL-LHC and future colliders

Physics Potential of Future Colliders workshop, Sep 18-20 2024

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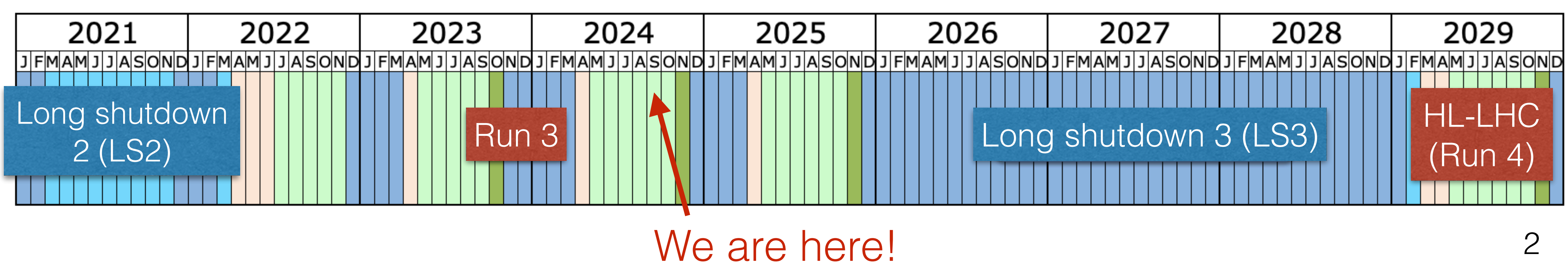
Introduction

Di-Higgs and High Luminosity LHC (HL-LHC)

- Already seen in previous talks the **importance of Higgs physics** at future particle colliders.
- What will I try to do here?
  - **Focus on di-Higgs (HH) production**, in particular **at the HL-LHC** expected to start in 2029.
  - HL-LHC: upgrade of the LHC that will increase the collider luminosity by at least a factor of 5.
    - This will bring **more data but also unprecedented detector challenges** due to the high number of simultaneous pp collisions ($\langle \mu \rangle = 200$).
- Some questions I will try to answer:
  - Why are future HH measurements crucial?
  - What can be achieved with the HL-LHC dataset? And after this?
  - What are the limitations for the future?



Why are HH measurements interesting?

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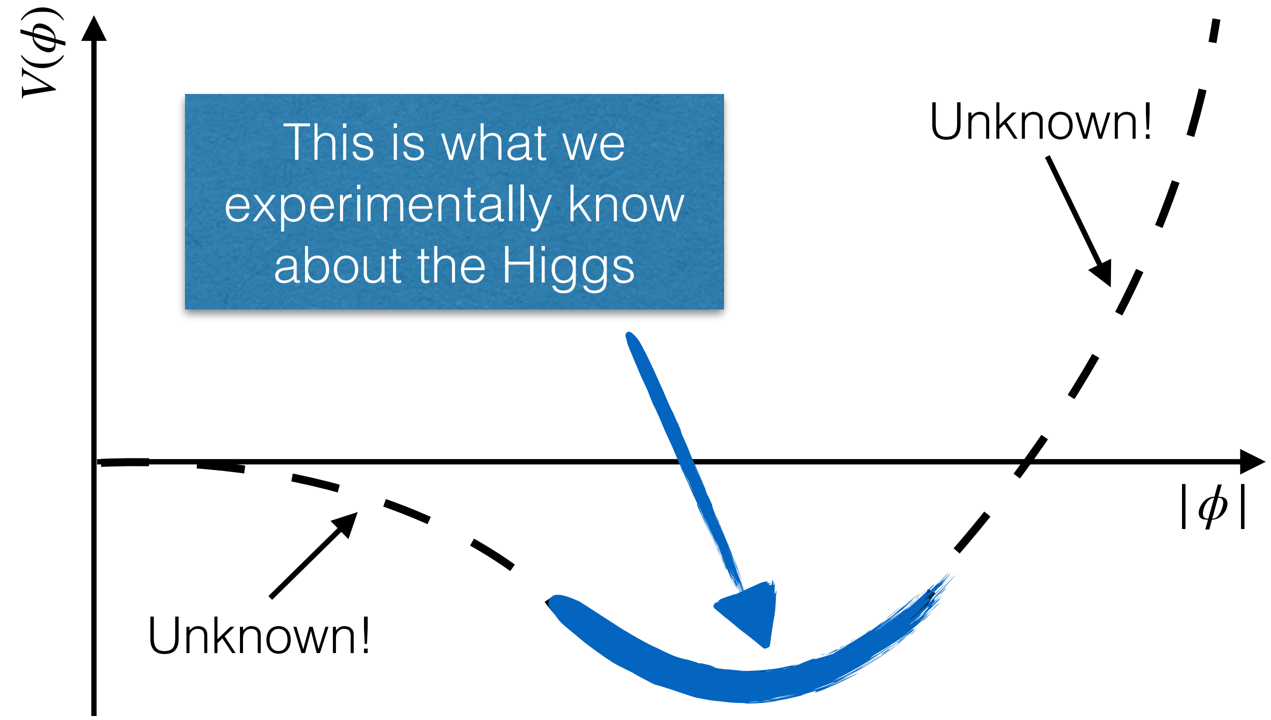
The Higgs potential

What is still unknown?

- In the Standard Model, Higgs potential represented by: $V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$
- So far, we only **established where the minimum of the Higgs potential is**.



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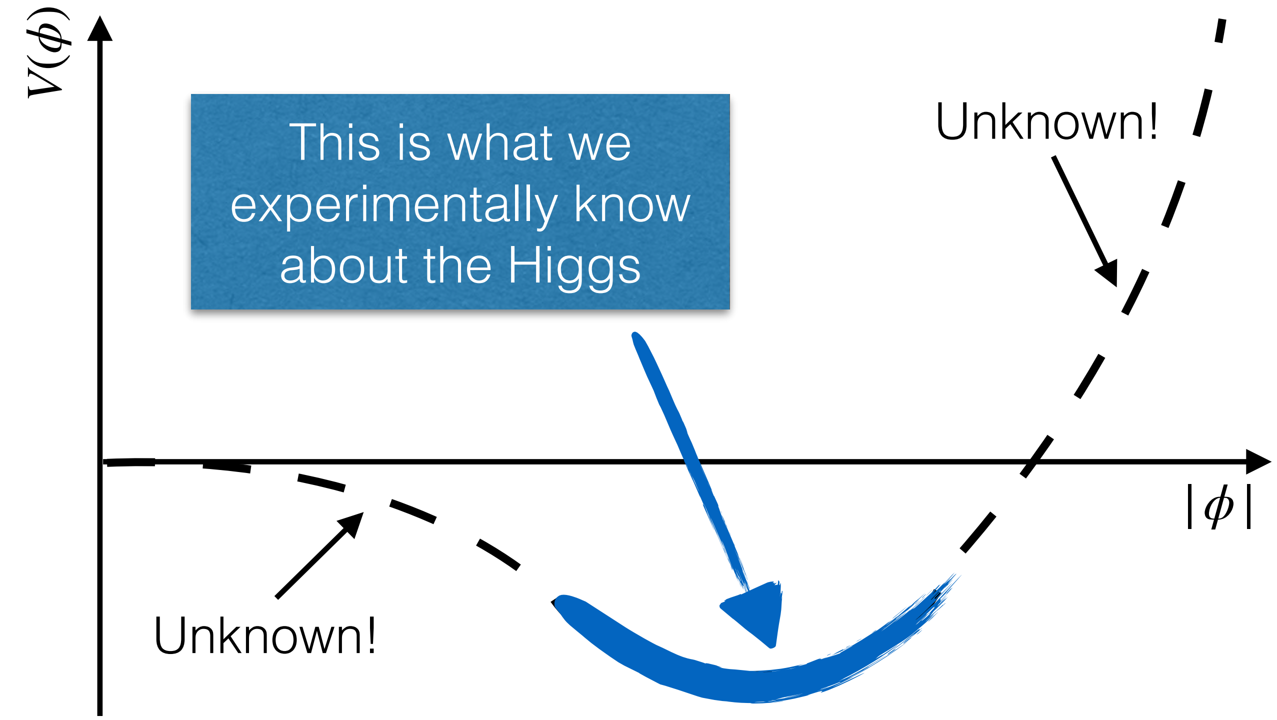
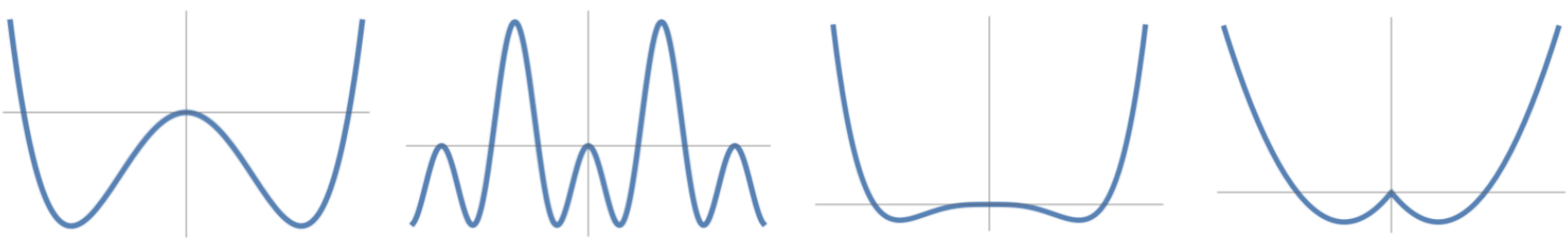


Different potential shapes could explain the same physics we see now!

arxiv:1907.02078

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda(H^\dagger H)^2 + \frac{c_6\lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a\sin^2(\sqrt{H^\dagger H}/f) + b\sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda(H^\dagger H)^2 + \epsilon(H^\dagger H)^2 \log\frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3\sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$



Landau-Ginzburg Higgs | Nambu-Goldstone Higgs | Coleman-Weinberg Higgs | Tadpole-Induced Higgs

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How to measure the Higgs potential?

Multiple-Higgs events

We **need to access the λ parameter** of the Higgs potential.

$$V(h) = -\mu^2|\phi|^2 + \lambda|\phi|^4 \simeq \frac{1}{2}m_h^2h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

ATLAS EXPERIMENT

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Tells us where the minimum of the potential is

$\Rightarrow m_H = \sqrt{2\lambda}v \approx 125$ GeV means $\lambda_{SM} \approx 0.13$

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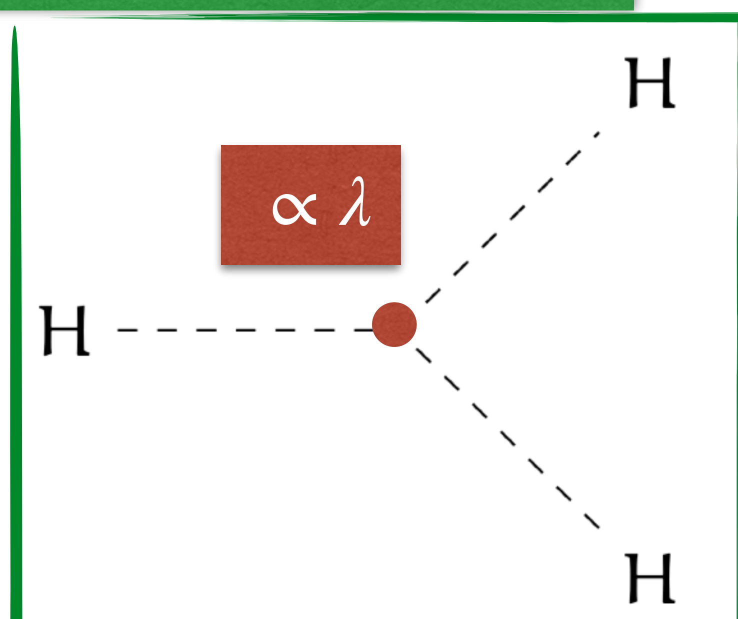
Trilinear Higgs self-coupling



Access to λ through **3-Higgs interactions. Possible to access for the first time at HL-LHC**

We generally look more at κ_λ rather than λ directly

$$\kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}}$$

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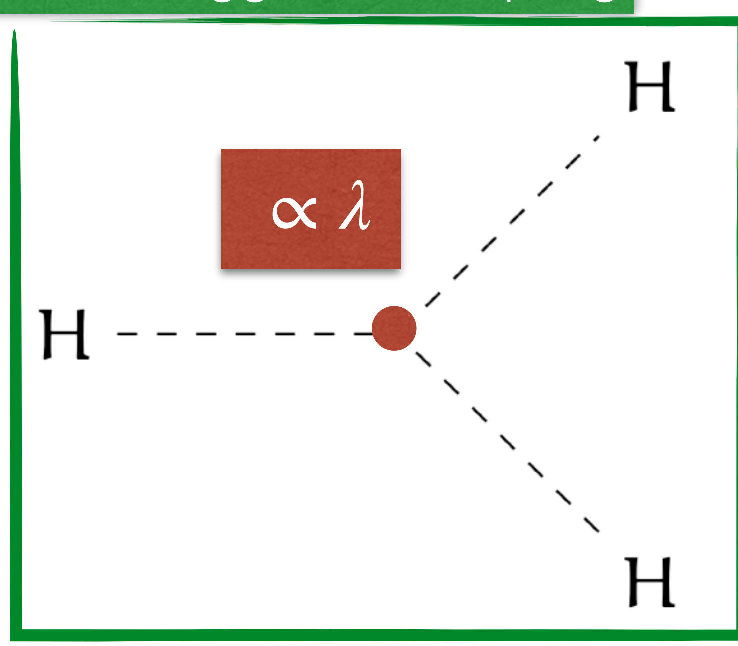
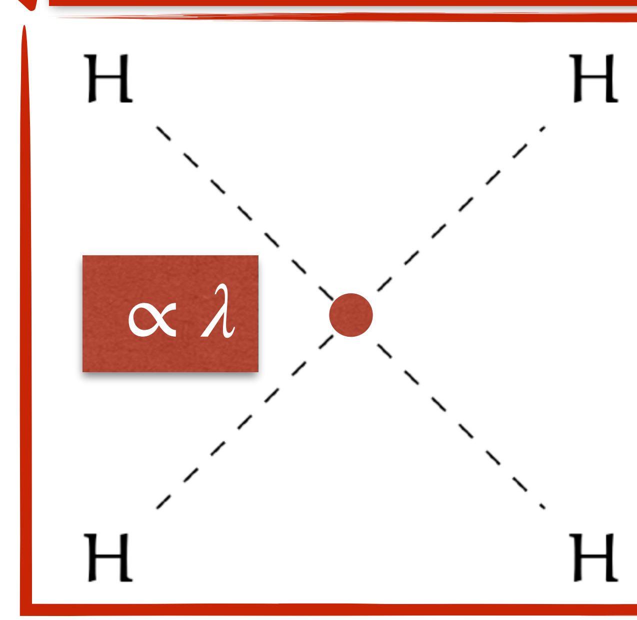


Access to λ through **3-Higgs interactions. Possible to access for the first time at HL-LHC**

Quadrilinear Higgs self-coupling



Out of the reach of HL-LHC and most of the future collider scenarios.

We generally look more at κ_λ rather than λ directly

$$\kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}}$$

HH production at the HL-LHC

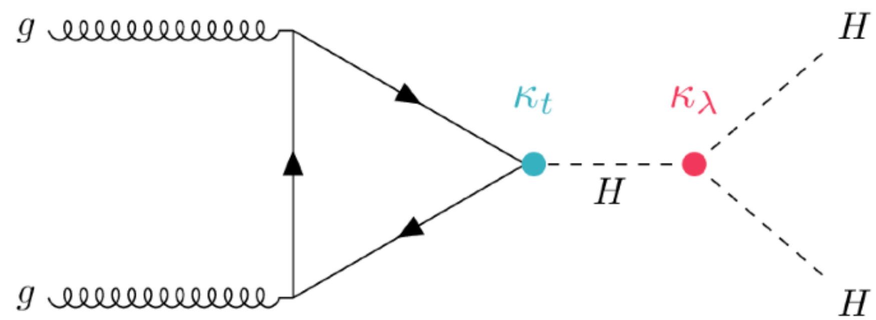
Non-resonant HH production

Gluon-gluon fusion (ggF)

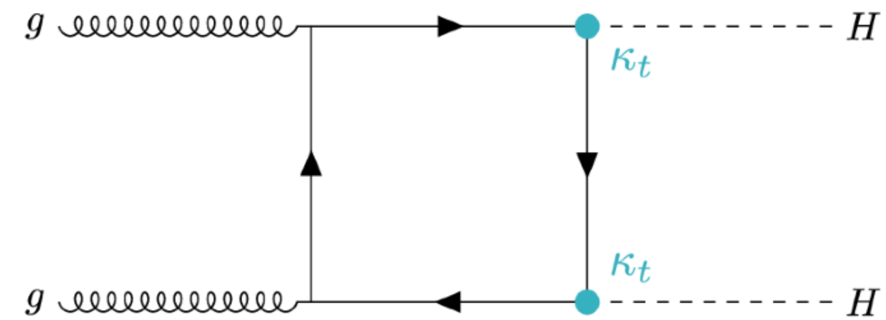
- Destructive interference leads to small cross-section:

$\sigma_{\text{ggF}} = 36.4$ fb

Triangle diagram



Box diagram

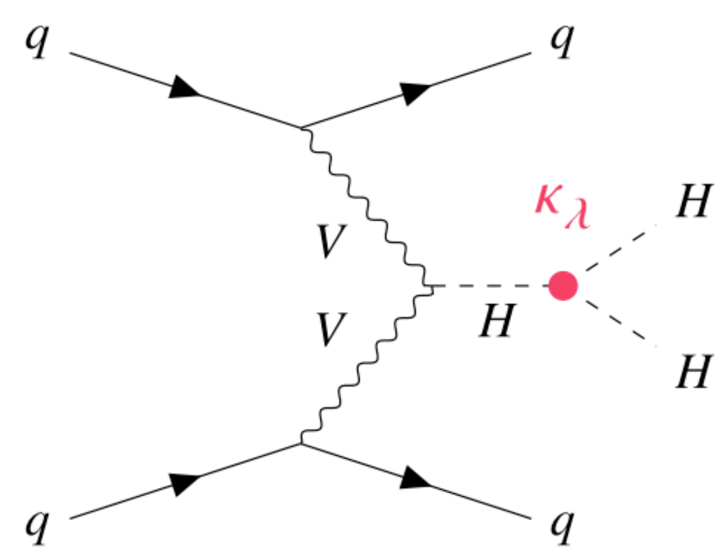


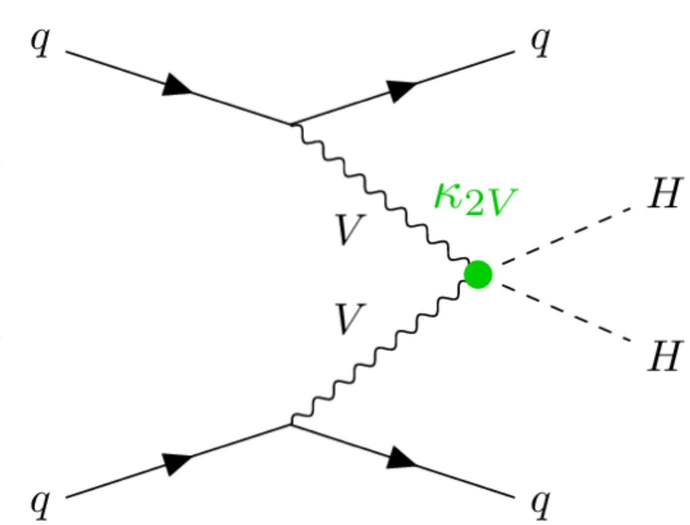
1 HH event every 1000 single-H events!

Vector-boson fusion (VBF)

- Signature: 2 Higgs + 2 quarks close to the LHC proton beams.
- Access to κ_λ, but also to **VVHH process** (never measured!) which could provide test **of SM unitarity via measurement of** k_{2V}.
- **Very tiny** cross-section:

$\sigma_{\text{VBF}} = 2.0$ fb





$$\kappa_{2V} \equiv \frac{c_{2V}}{c_{2V}^{SM}}$$

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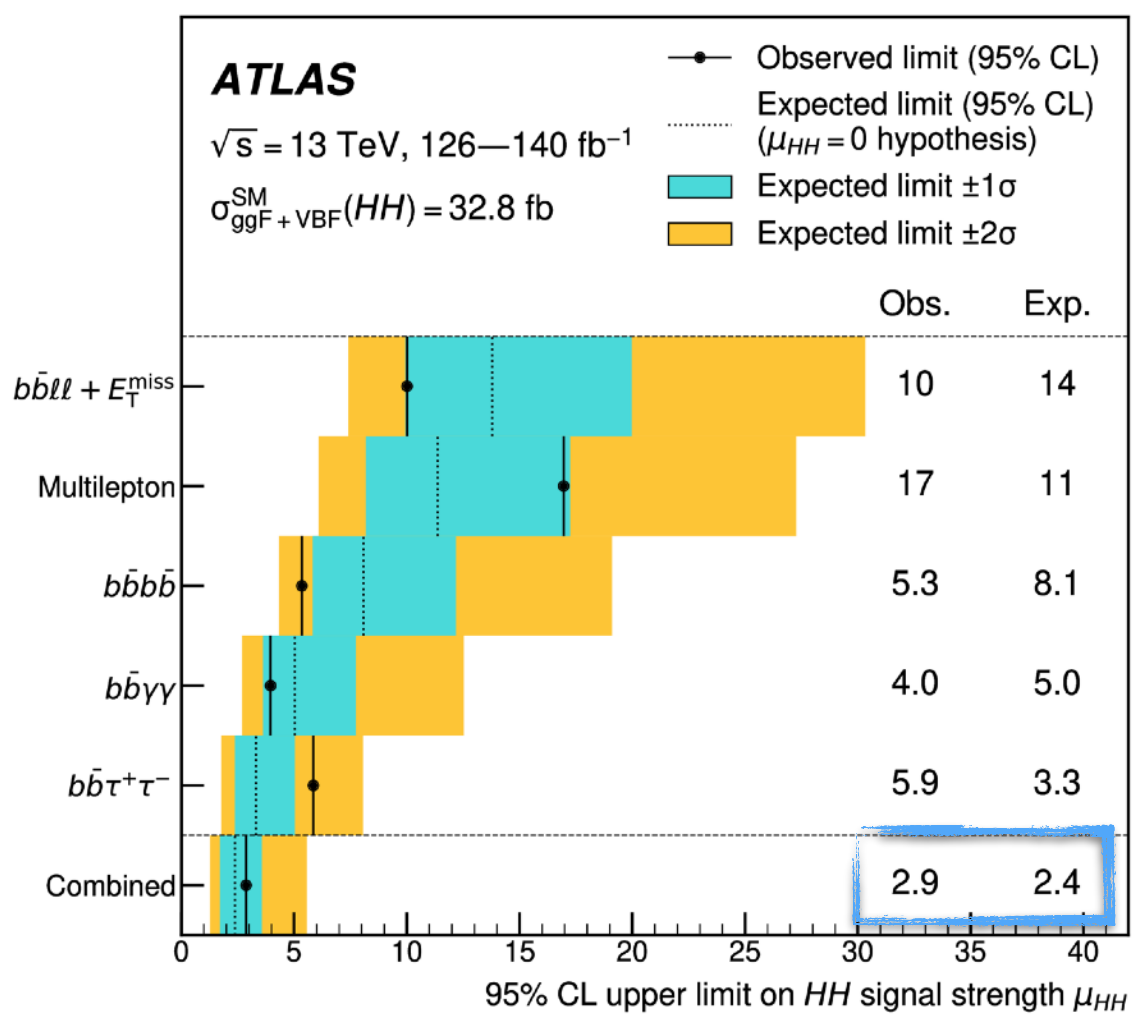
What have we achieved so far?

Latest ATLAS Run 2 results

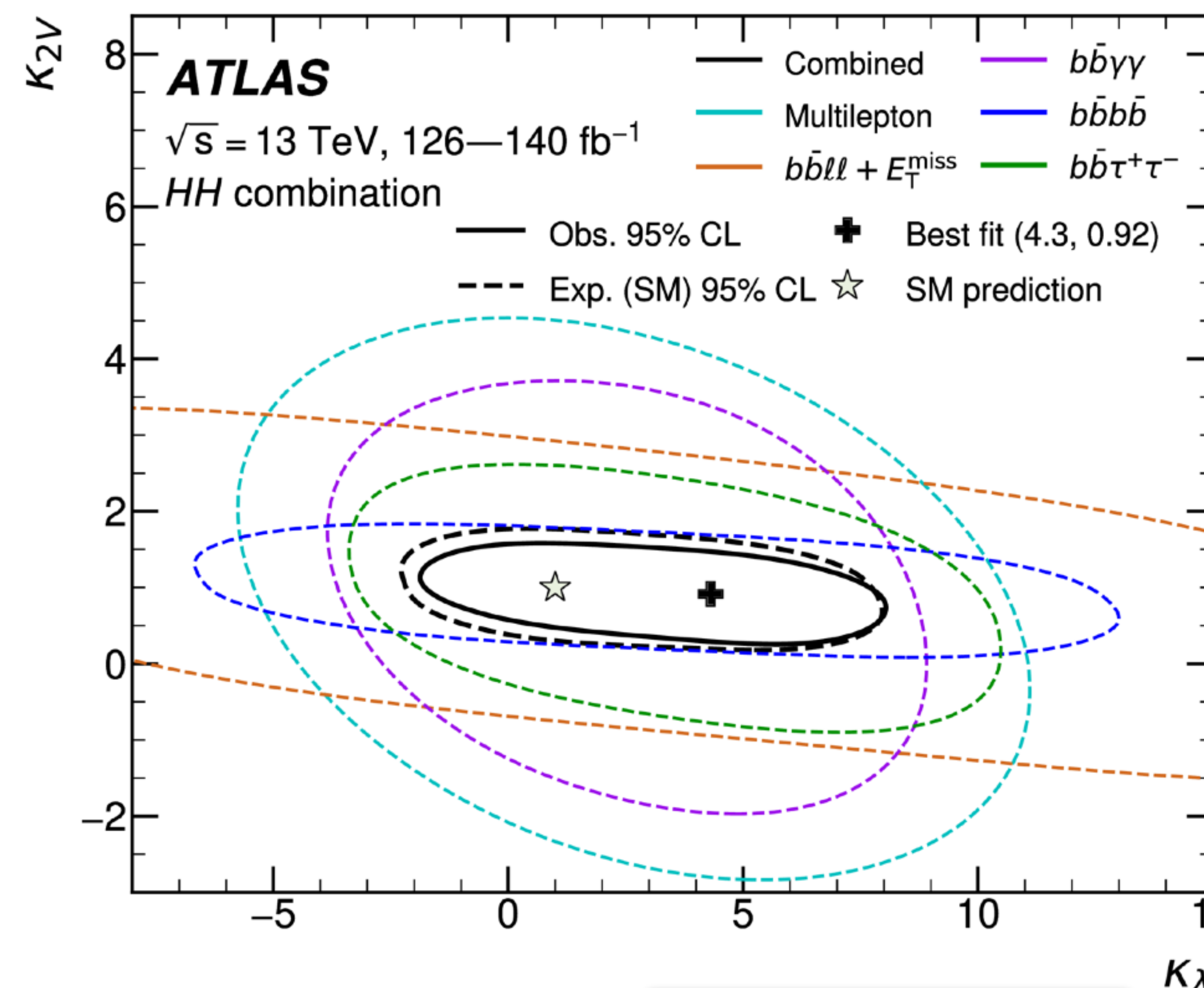
SM signal strength 95% CL upper limits

- **No signal observed**, but we are **getting very close!** Maximal sensitivity is obtained through combination of different HH decay channels.
    - Observed 95% CL upper limit is $2.9 \times \sigma_{HH}(SM)$!
    - **SM hypothesis** $(\kappa_\lambda, \kappa_{2V}) = (1.0,\ 1.0)$ **still compatible with observation at 95% CL.**
    - CMS has very similar numbers 🙂
- Dominant uncertainty: **statistical! Adding more data will help a lot!**

Phys. Rev. Lett. 133 (2024) 101801



4.0x better than 36 fb^{-1} combination



$\kappa_\lambda \in [-1.2, 7.2]$

$\kappa_{2V} \in [0.6, 1.5]$

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What can we achieve at the HL-LHC?

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Di-Higgs at the HL-LHC

Some caveats…

- This is a nice question, but **it is not so simple to answer.** 🙂

Can certainly extrapolate the previous Run 2 results with HL-LHC luminosity ($3000\ \mathrm{fb}^{-1}$)

- However, many important questions remain:
  1. When are we going to hit the **systematics wall?**
  2. **Can we reduce systematics** in the next years? **By how much?**
  3. How much are the detector upgrades going to improve performance?
- **ATLAS and CMS will need to be upgraded** to cope with **large radiation doses**, **high data flows**, and **challenging reconstruction conditions** (200 simultaneous pp collisions).

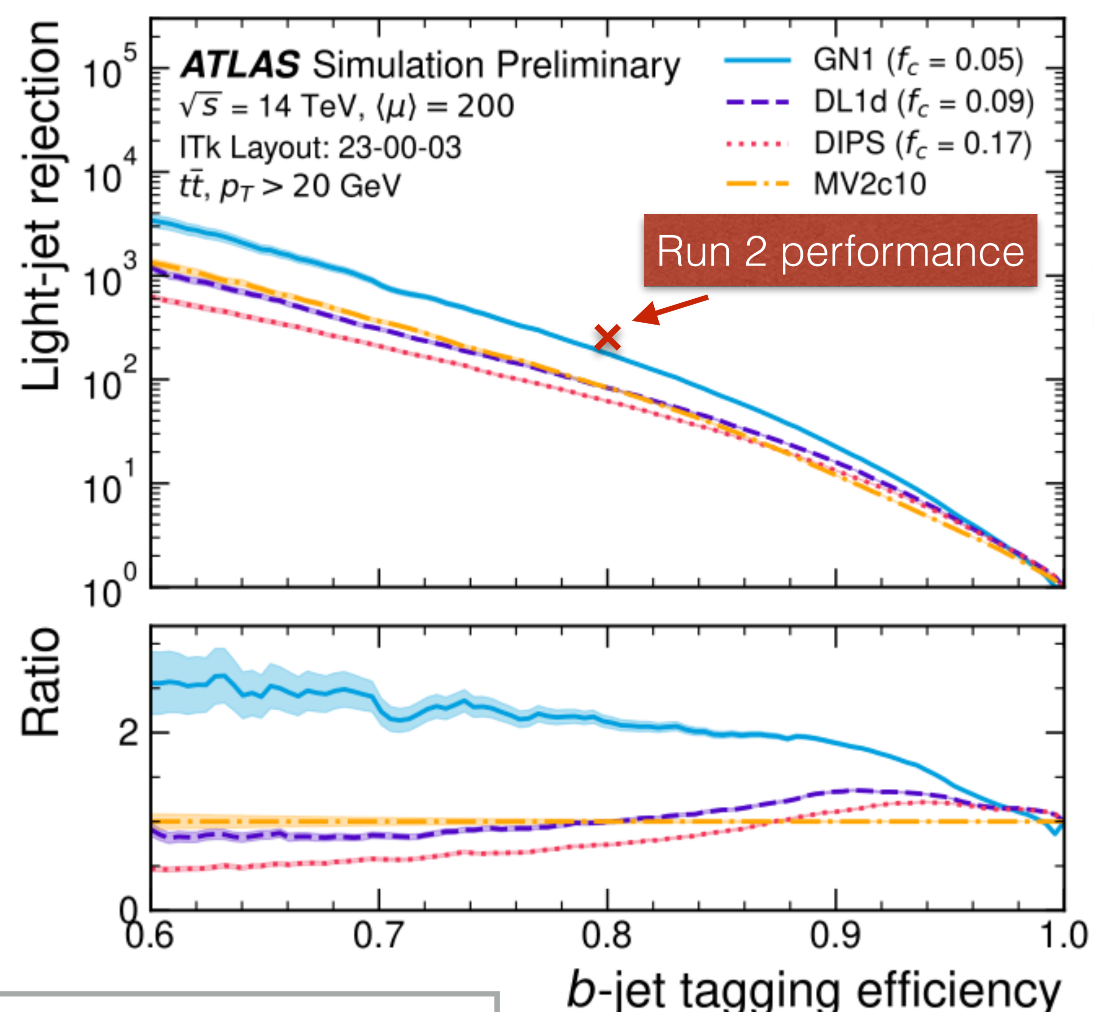
	ATLAS upgrades	CMS upgrades
Inner detector	**Brand new** and fully made of silicon!	
Timing detectors	**Yes!** Forward region only (2.4 < |η| < 4.0)	**Yes!** Full eta coverage.
Calorimeter	**New readout** electronics	**New readout** electronics. **New end-cap calorimeter** (5D shower reconstruction)
Trigger	Brand new! L1/HLT output rates: **1MHz/10kHz**	Brand new! L1/HLT output rates: **650kHz/7.5kHz**
Muon chambers	New Small Wheel (installed), upgraded barrel RPCs, new TGC chambers, new MDT electronics	**Extend eta gaps and increase redundancy** with new technologies

HL-LHC reconstruction performance

Are detector upgrades enough to cope with the higher pileup conditions?

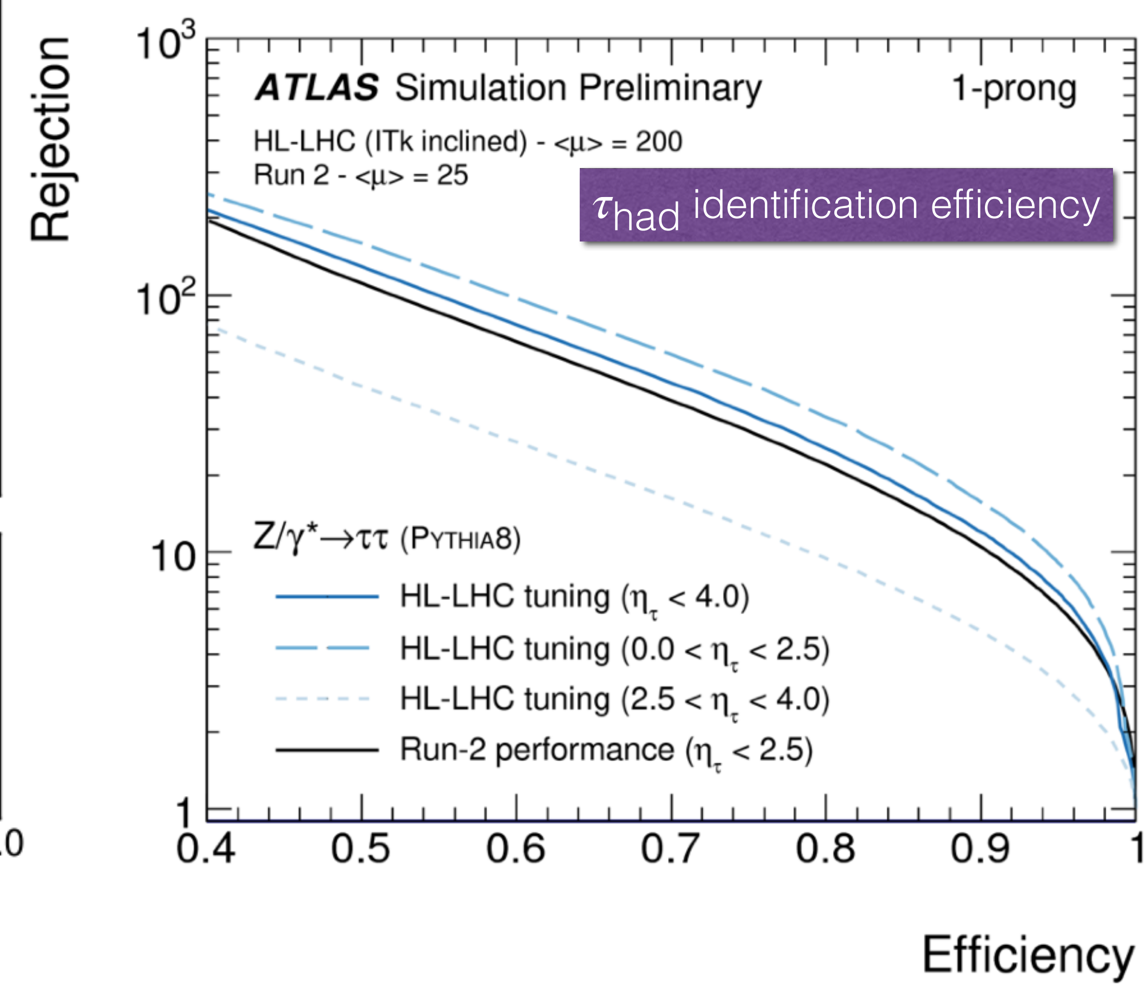
- For HH, crucial point is the **reconstruction performance of b-jets, τ_{had}, photons, and leptons** (e and μ).
- Current HL-LHC simulations show **comparable (or better) reconstruction performance** between Run 2 and HL-LHC thanks to upgraded detectors!

An **extrapolation from Run 2 analyses should give a realistic idea of the expected H-LHC sensitivity for HH!**



ATL-PHYS-PUB-2022-047

ATL-PHYS-PUB-2019-005



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A history of Run 2 extrapolations

- A little bit of history:
  - Projections for CERN Yellow-Report (2019): based on **partial Run 2 analyses** ($36\ \mathrm{fb}^{-1}$)
  - Snowmass process (2021): based on **first round of complete Run 2 analyses** ($139\ \mathrm{fb}^{-1}$).
  - European Strategy update for particle physics: soon in 2025!

CERN Yellow Reports: Monographs CERN-2019-007

CERN yellow report (2019)

Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC

Editors:
Andrea Dainese
Michelangelo Mangano
Andreas B. Meyer
Aleandro Nisati
Gavin Salam
Mika Anton Vesterinen

CERN

arXiv:1902.10229

Snowmass EF report (2022)

1

The Future of US Particle Physics

The Energy Frontier Report

2021 US Community Study
on the Future of Particle Physics

organized by
the APS Division of Particles and Fields

*In memory of Meenakshi Narain,
a friend and a colleague, who passed away on January 1, 2023.
This report will be one of her enduring legacies,
and a result of her guidance, leadership and vision.
We will miss her.*

arXiv:2211.11084v3 [hep-ex] 4 Jan 2023

Community Planning Exercise: Snowmass 2021

arXiv:2211.11084

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ATLAS + CMS projections (2019)

A simple extrapolation…

- CERN Yellow Report extrapolation **based of partial Run 2 ATLAS and CMS results (36 fb^{-1})** with expected reduction systematic uncertainties.
  - **Combined significance:** 4.0σ (4.5σ) with and without systematic uncertainties.
    - Scenario without systematics give best possible case.
  - **Precision on κ_λ modifier:** $\sim 50\,\%$

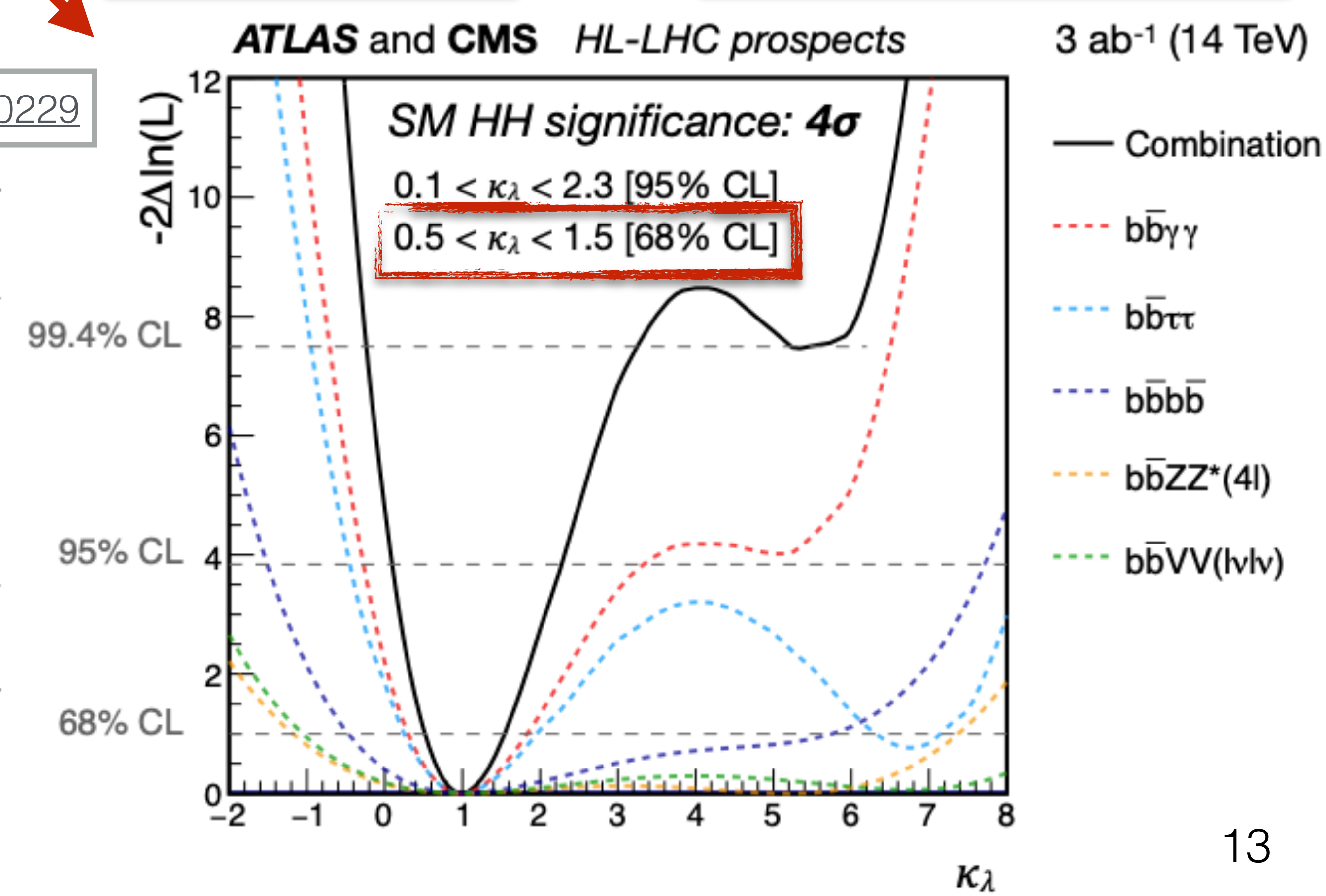
$$\mathcal{L}_{\text{comb}} = \prod_{\text{analysis}} \mathcal{L}_a \rightarrow \log(\mathcal{L}_{\text{comb}}) = \sum_{\text{analysis}} \log(\mathcal{L}_a)$$

$$Z_{\text{comb}} = \sqrt{\sum_{\text{analysis}} Z_a^2}$$

arXiv:1902.10229

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

Statistical significance (Z)



Are these numbers still realistic?

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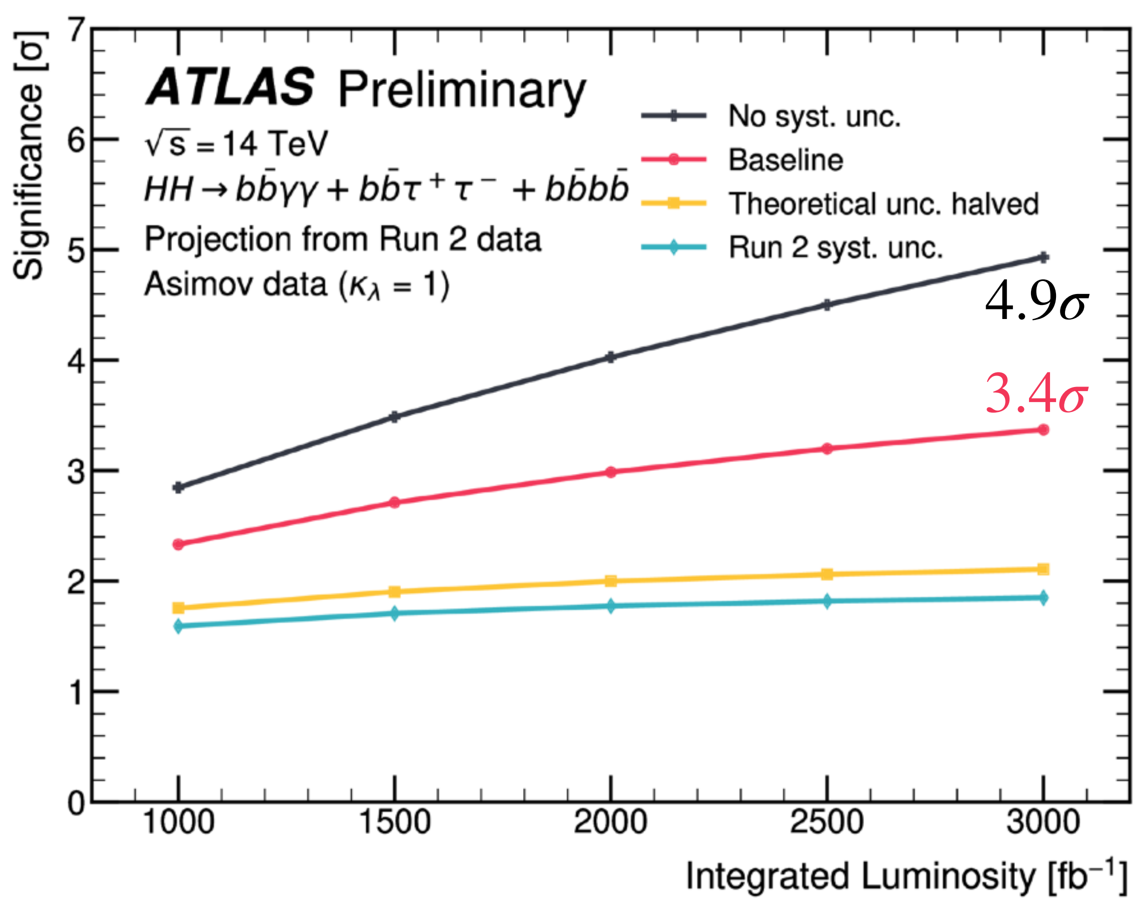
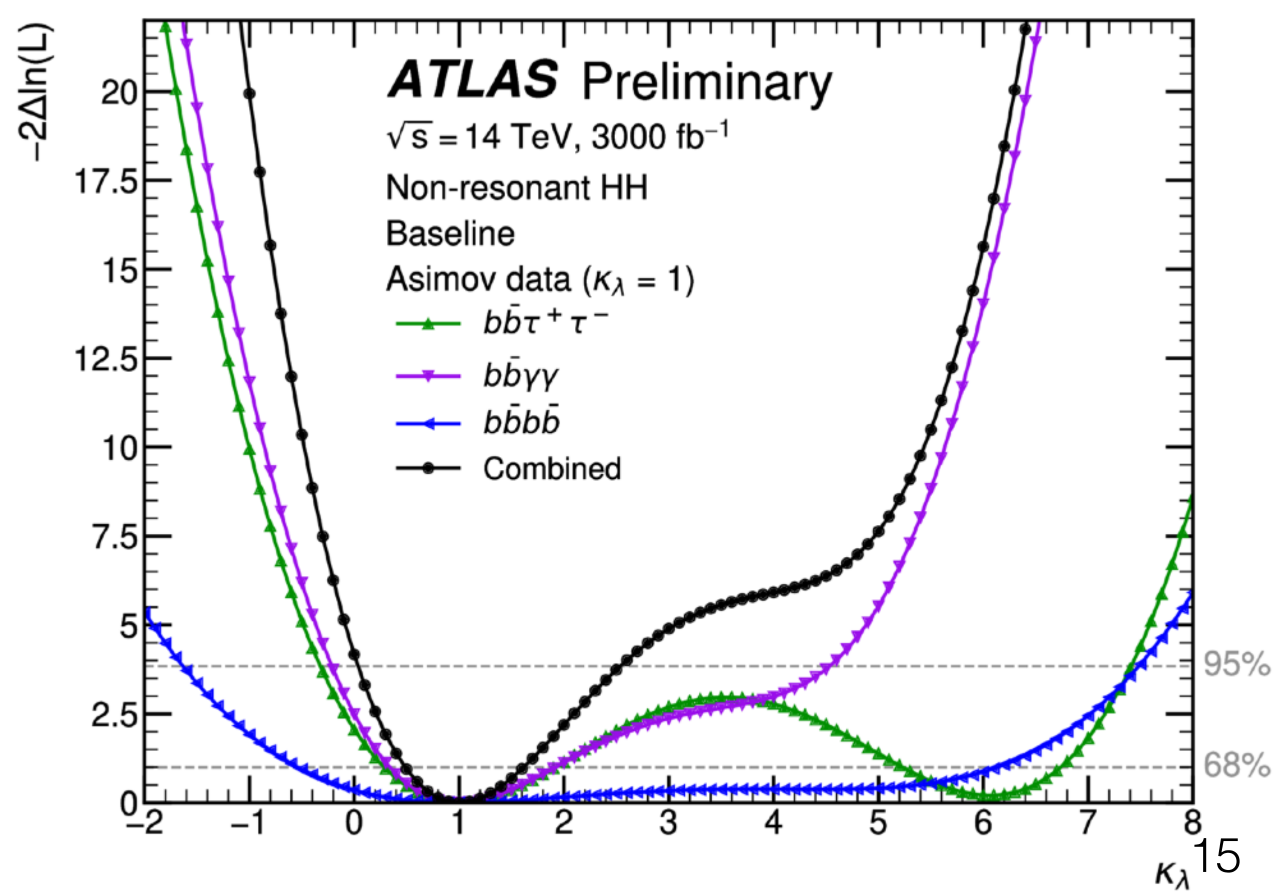
ATLAS Snowmass projections (2022)

New ATLAS projections

- **Only ATLAS projections were updated** with new Run 2 analyses ($139\ \mathrm{fb}^{-1}$)
  - Statistical significance: 3.4σ (4.9σ) with (without) systematic uncertainties.
  - 68% CL κ_λ range (with systematics): **[0.5,1.6]**
- Achieved **almost the same expected sensitivity ATLAS+CMS with ATLAS-only!**
  - Previous CERN Yellow report ATLAS-only κ_λ range: [0.25,1.9]
- **This means that ATLAS+CMS should be much better than 4.0σ and 50% precision** on κ_λ quoted in many documents. 🙂

ATLAS-PHYS-PUB-2022-053





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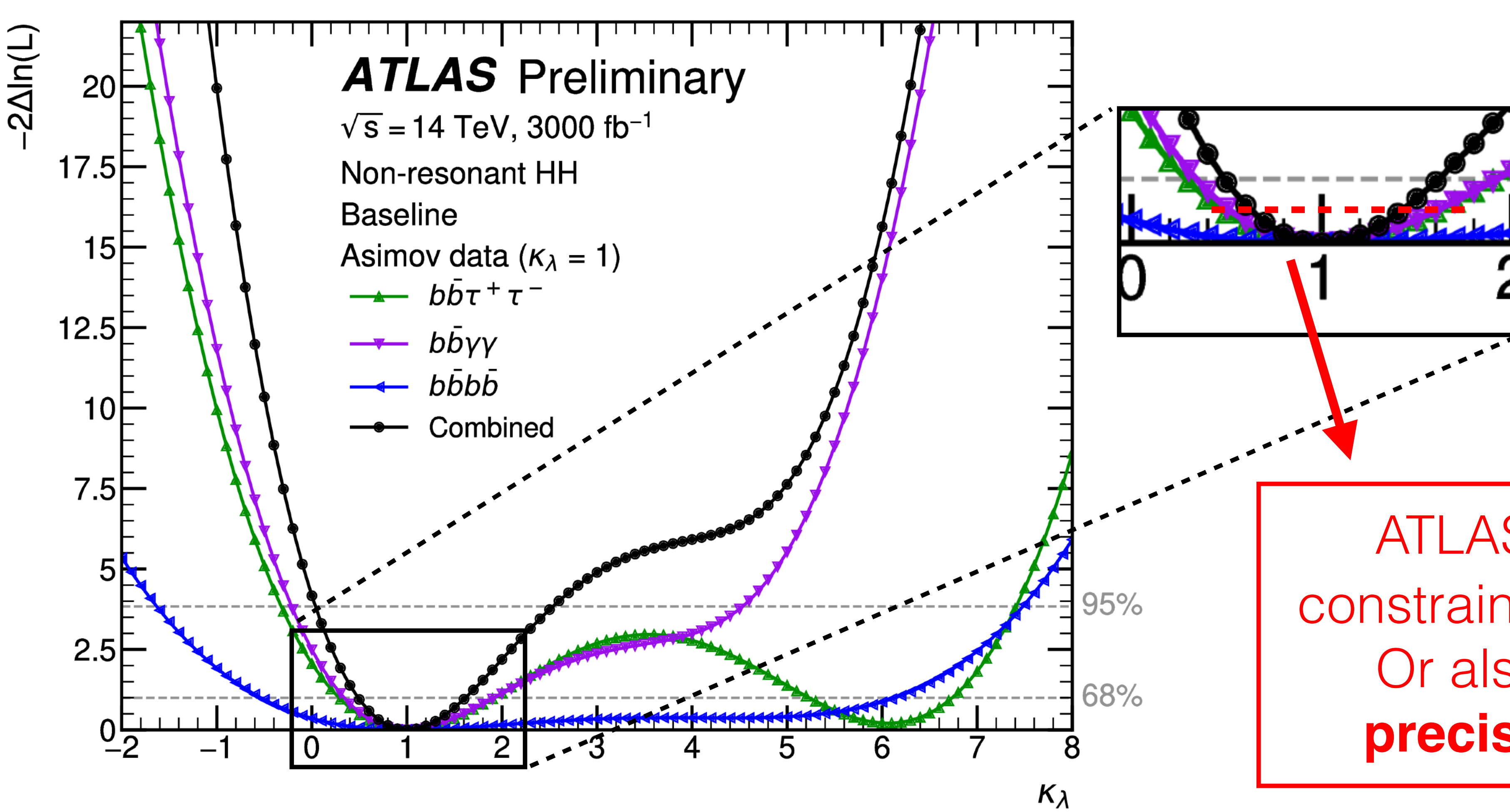
My personal ATLAS+CMS estimation

Speculations...

- **Let's assume that ATLAS and CMS will have identical sensitivity** to HH. Not very far from reality if you look at the latest CMS results 😉.
- This means that:
  - Significance: $Z_{\text{ATLAS+CMS}} \approx \sqrt{Z^2_{\text{ATLAS}} + Z^2_{\text{ATLAS}}} = \sqrt{2} \cdot Z_{\text{ATLAS}}$

$Z_{\text{ATLAS+CMS}} \approx 4.8\sigma\ (6.9\sigma)$ with (without) systematics

  - κ_λ precision: $\log(\mathscr{L}_{\text{ATLAS+CMS}}) \approx \log_{\text{ATLAS}}(\mathscr{L}) + \log_{\text{ATLAS}}(\mathscr{L}) = 2 \cdot \log_{\text{ATLAS}}(\mathscr{L})$



ATLAS+CMS κ_λ constraint ~[0.65,1.3]. Or also **30-35% precision on κ_λ**.

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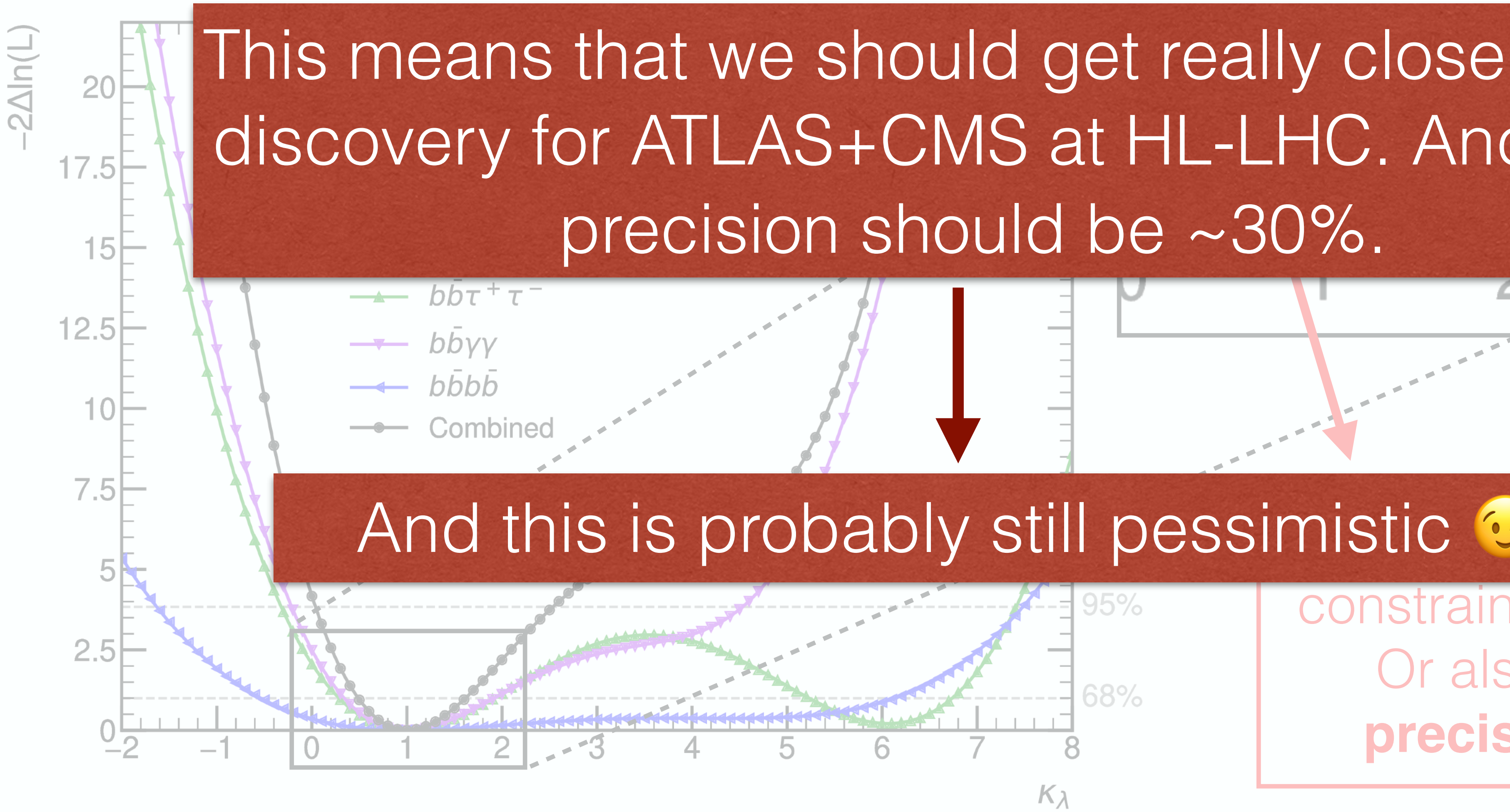

This means that we should get really close to a 5σ discovery for ATLAS+CMS at HL-LHC. And the κ_λ precision should be ~30%.

And this is probably still pessimistic 😉

…MS κ_λ constraint ~[0.65,1.3]. Or also **30-35% precision on κ_λ**.

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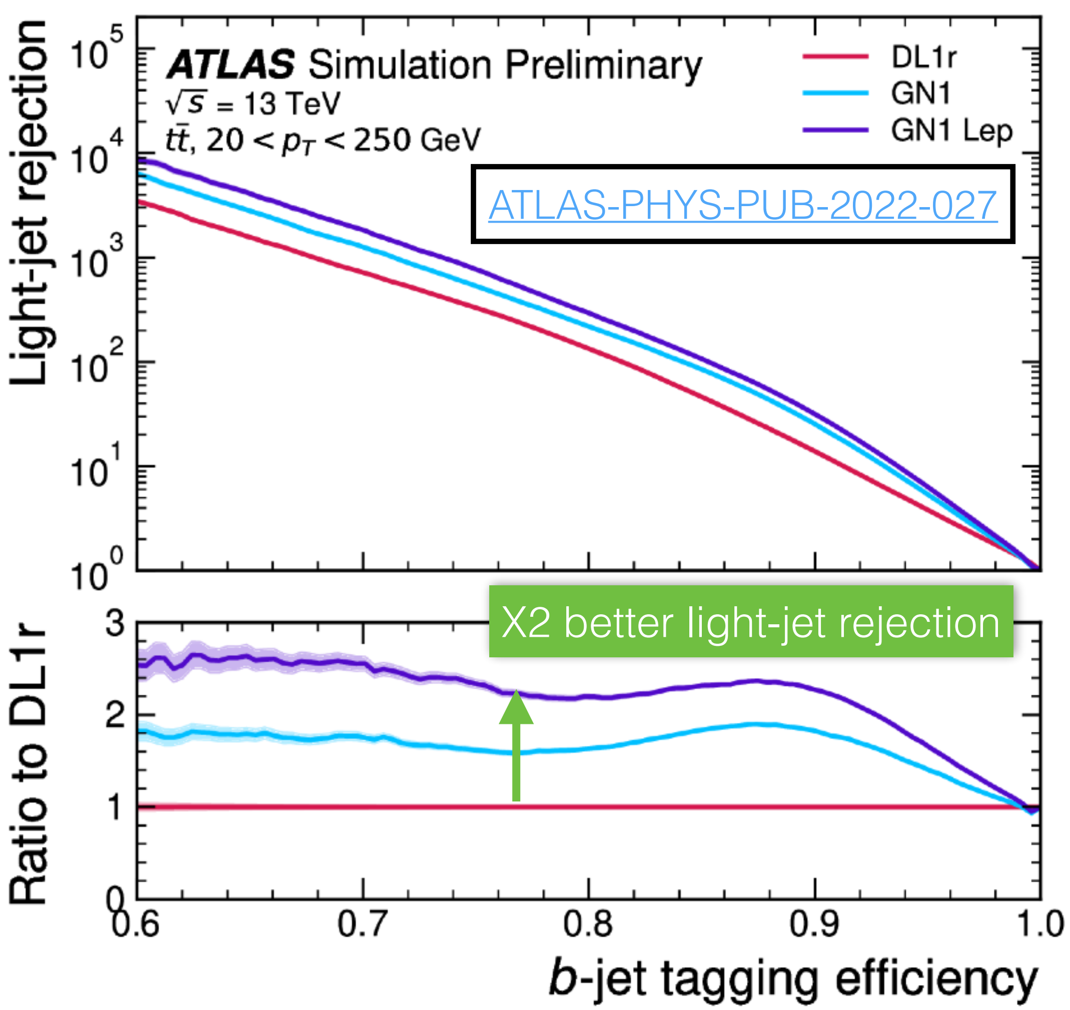
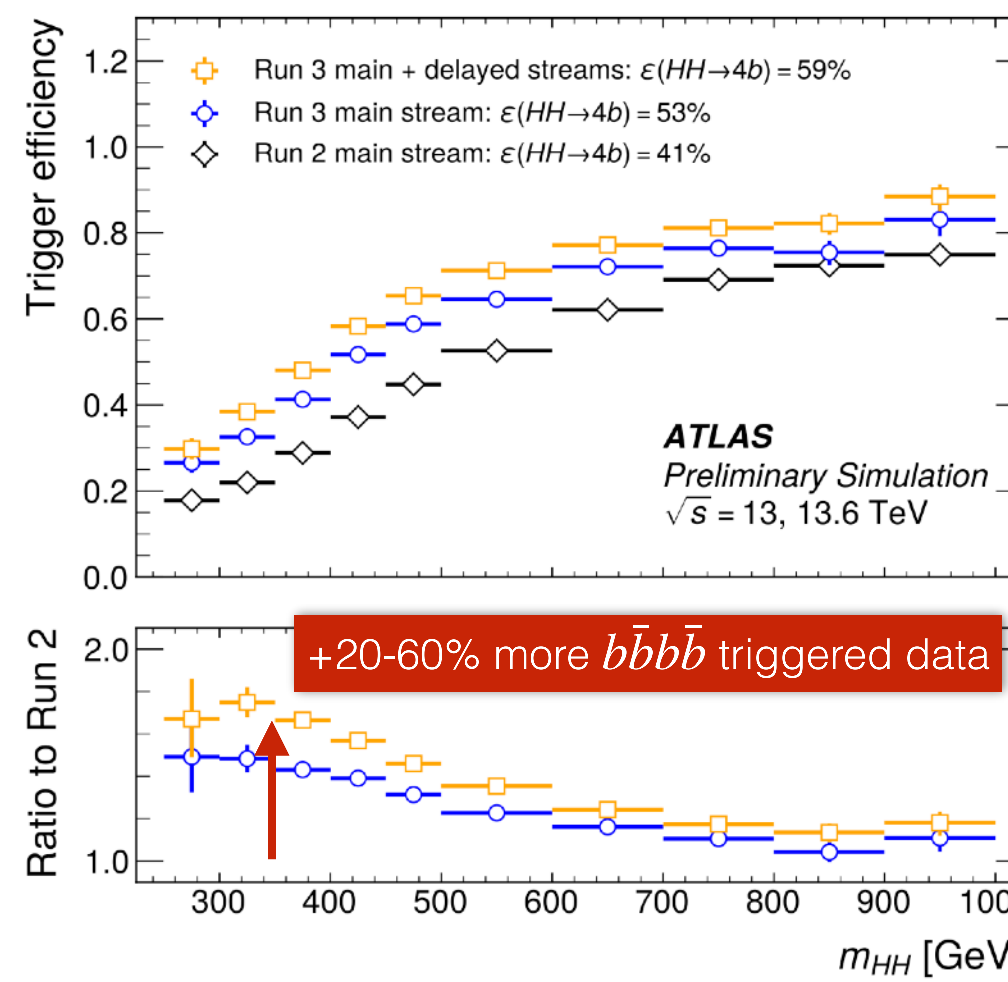
Run 3 ATLAS improvements

More data, better reconstruction and triggers

- We **already achieved plenty of improvements in Run 3** for reconstruction and triggers. And these will be all propagated to HL-LHC! 😉
- Some examples:
  - **b-tagging largely improved** with Graph Neural Networks (GN1)!
  - **Triggers significantly improved** (e.g. asymmetric $HH \rightarrow b\bar{b}b\bar{b}$ triggers)!
- So, 4.8σ **and 30%** κ_λ **precision is probably still pessimistic** (we can do more!)



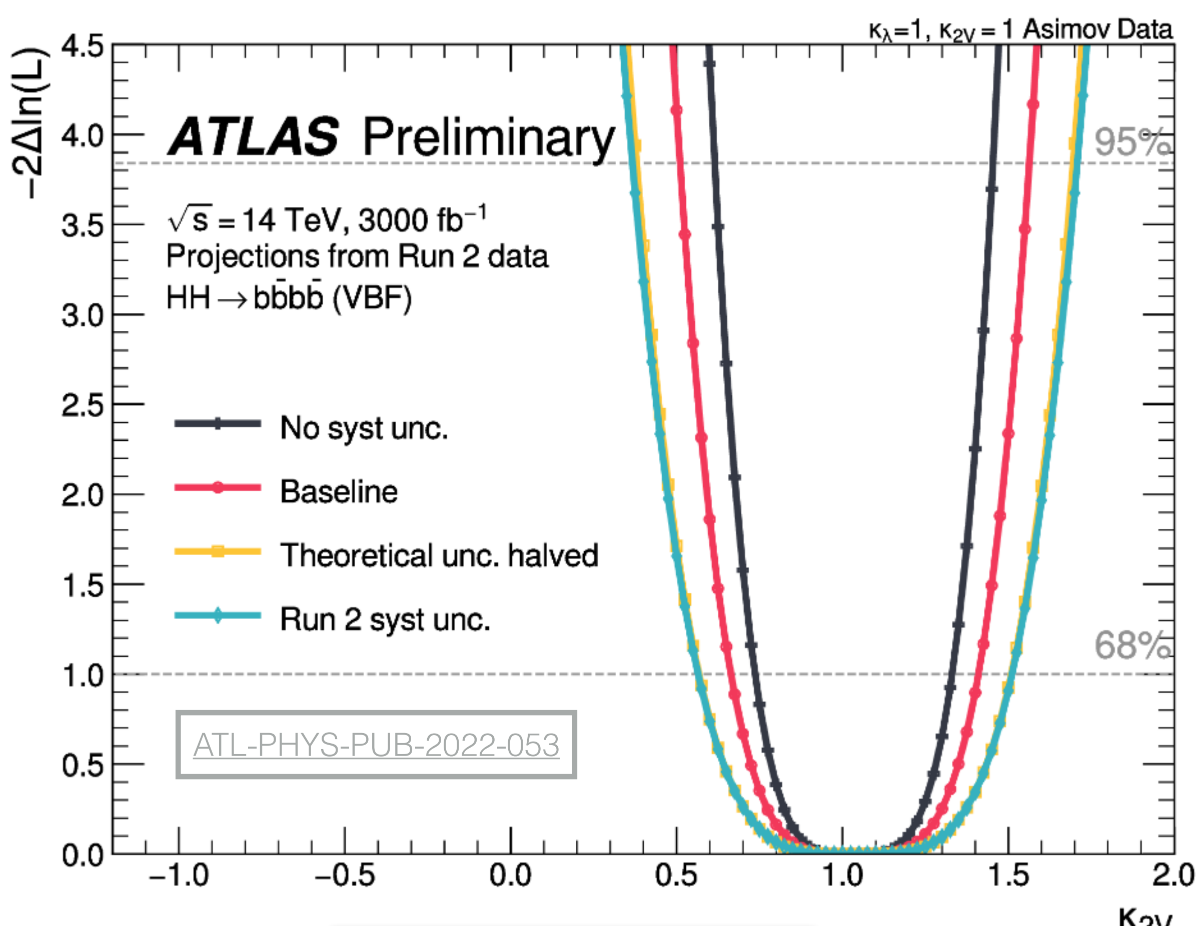


Boosted VBF $HH \to b\bar{b}b\bar{b}$ (2024)

k2V limits

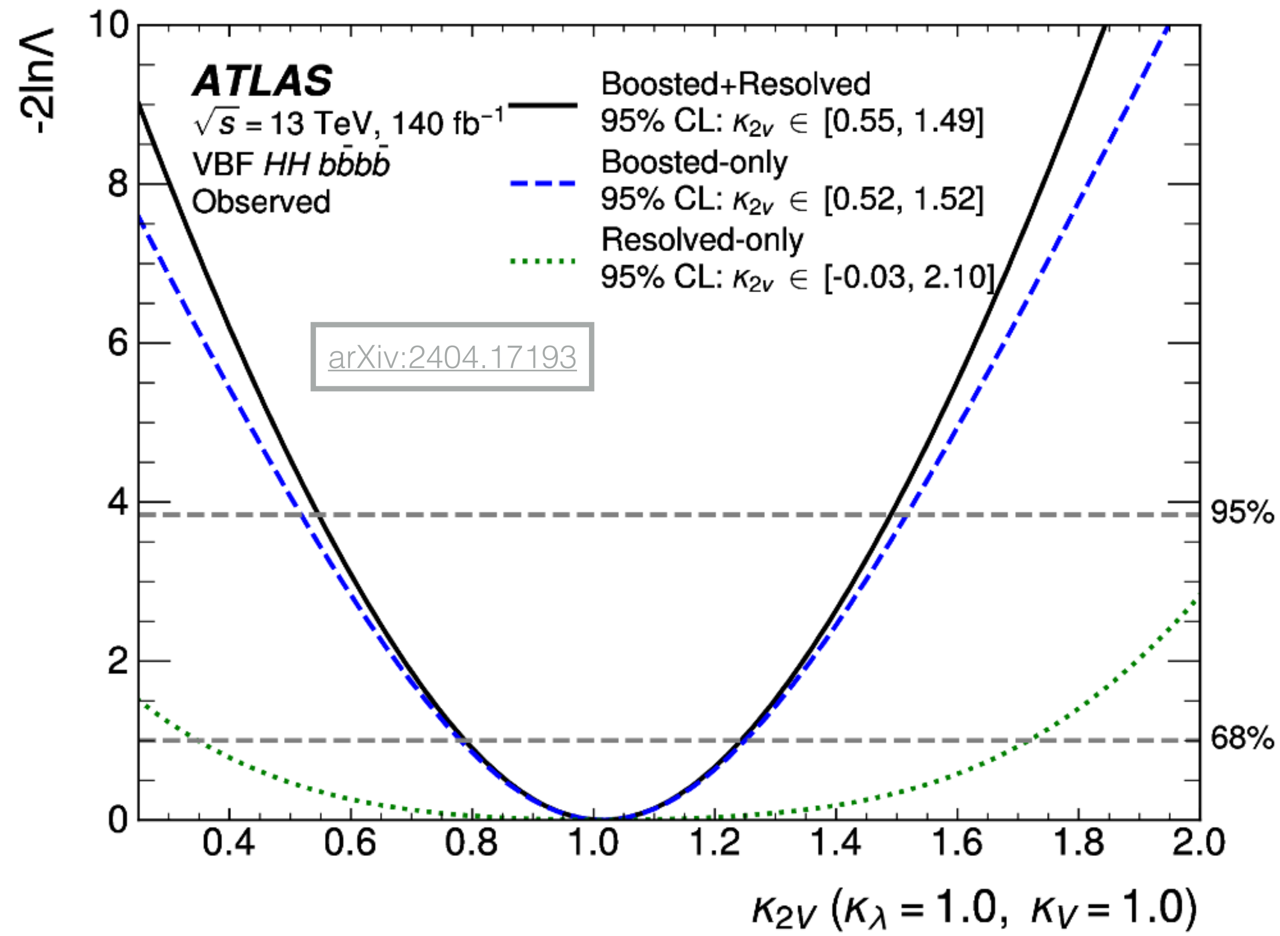
- At 95% CL, expected $\kappa_{2V} \in [0.5, 1.6]$ at HL-LHC.
- Recently published (2024) a new Run 2 search ($140\ \mathrm{fb}^{-1}$) allowing to already beat HL-LHC limit! **A huge step forward in just 2 years!**
- It isn't hard to believe that all these numbers are still pessimistic!

Resolved $HH \to b\bar{b}b\bar{b}$ at HL-LHC ($3000\ \mathrm{fb}^{-1}$)



$k_{2V} \in [0.5, 1.6]$

Boosted VBF $HH \to b\bar{b}b\bar{b}$ ($140\ \mathrm{fb}^{-1}$)



$k_{2V} \in [0.55, 1.49]$

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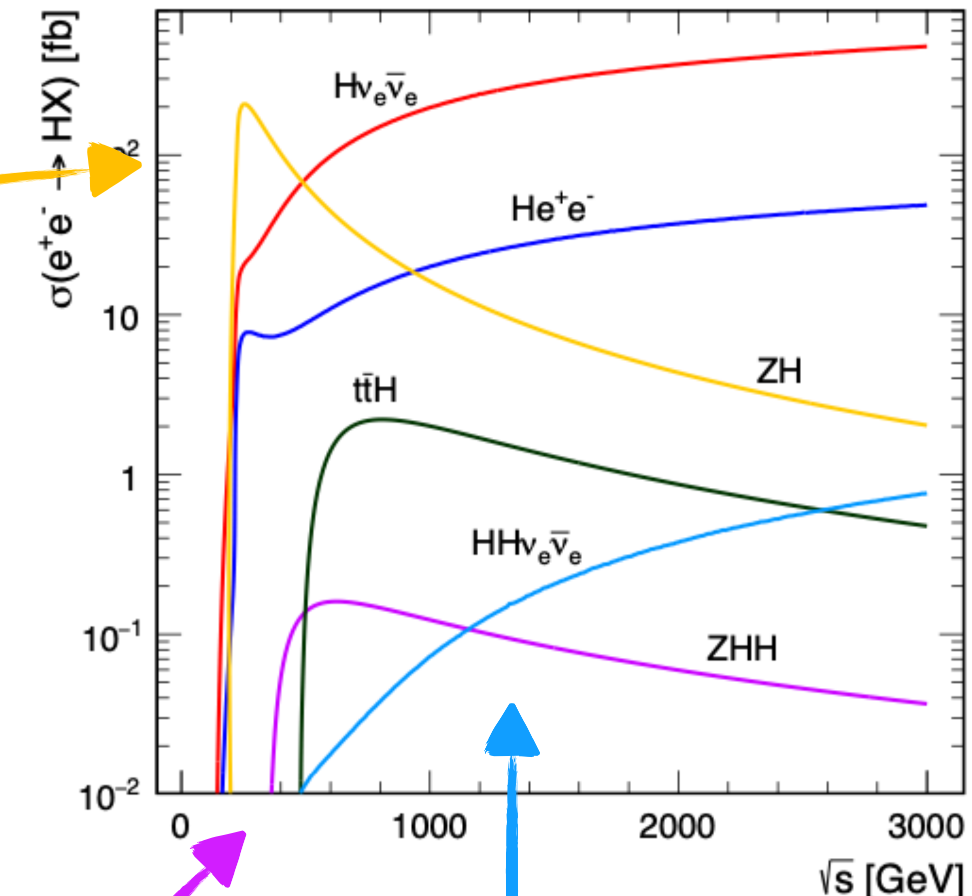
What can we achieve beyond HL-LHC?

HH production at future Higgs factories

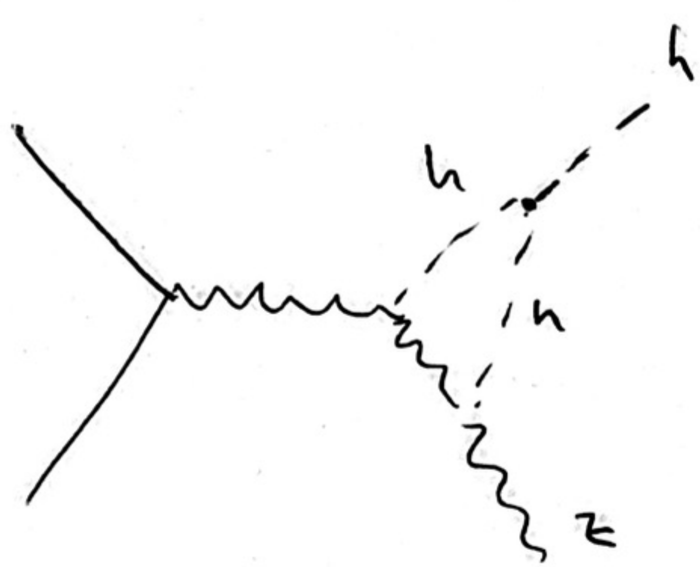
- **Two ways to constrain** self-coupling modifier κ_λ at Higgs factories:
  - Indirect constraint (ZH): no access to HH
    - **Dominant at circular e^+e^- colliders** (FCC-ee,CEPC) and **low-energy linear colliders** (ILC250, etc.)
    - **Requires good knowledge of other Higgs couplings** ($e\,.\,g\,.\,\kappa_V, \kappa_\gamma$) to measure κ_λ precisely.
  - Direct constraint (ZHH, $\nu\nu HH$): access to HH
    - **Dominant at high-energy lepton colliders** (ILC, CLIC, C3, Muon Collider).

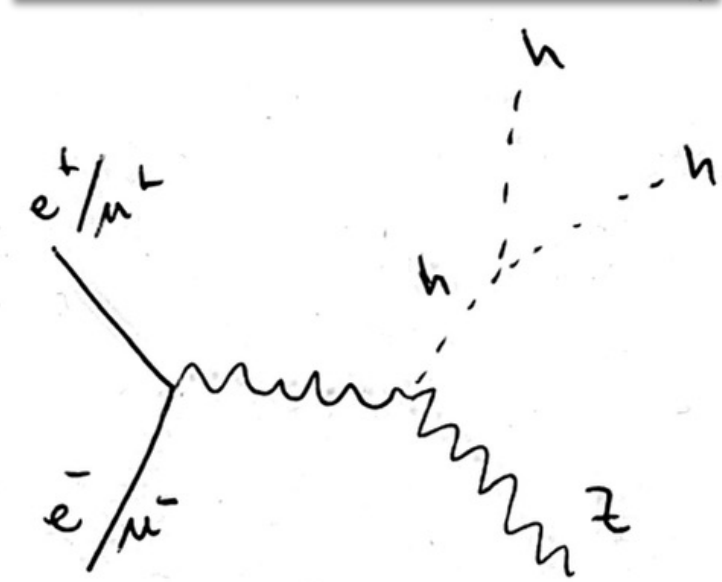


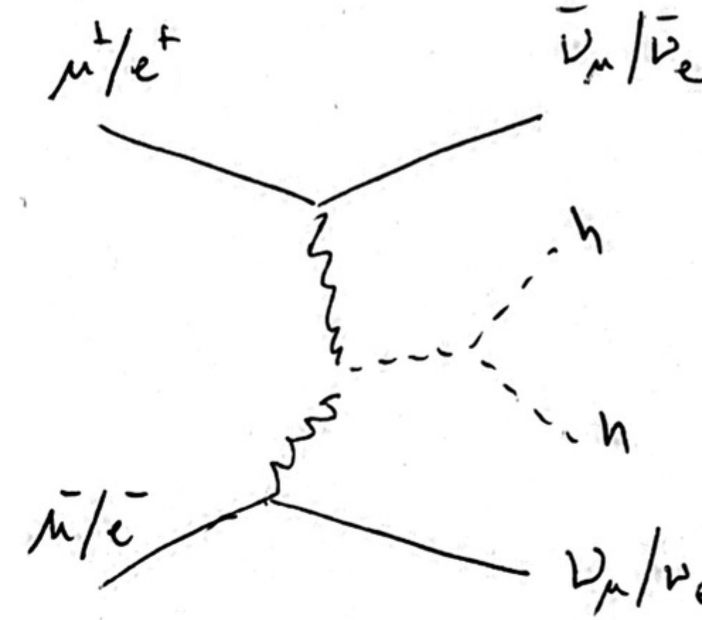
$\sqrt{s} \approx m_Z + m_h \sim 250$ GeV

$\sqrt{s} \approx m_Z + 2 \cdot m_h \sim 500$ GeV

$\sqrt{s} \gg m_Z + 2 \cdot m_h$







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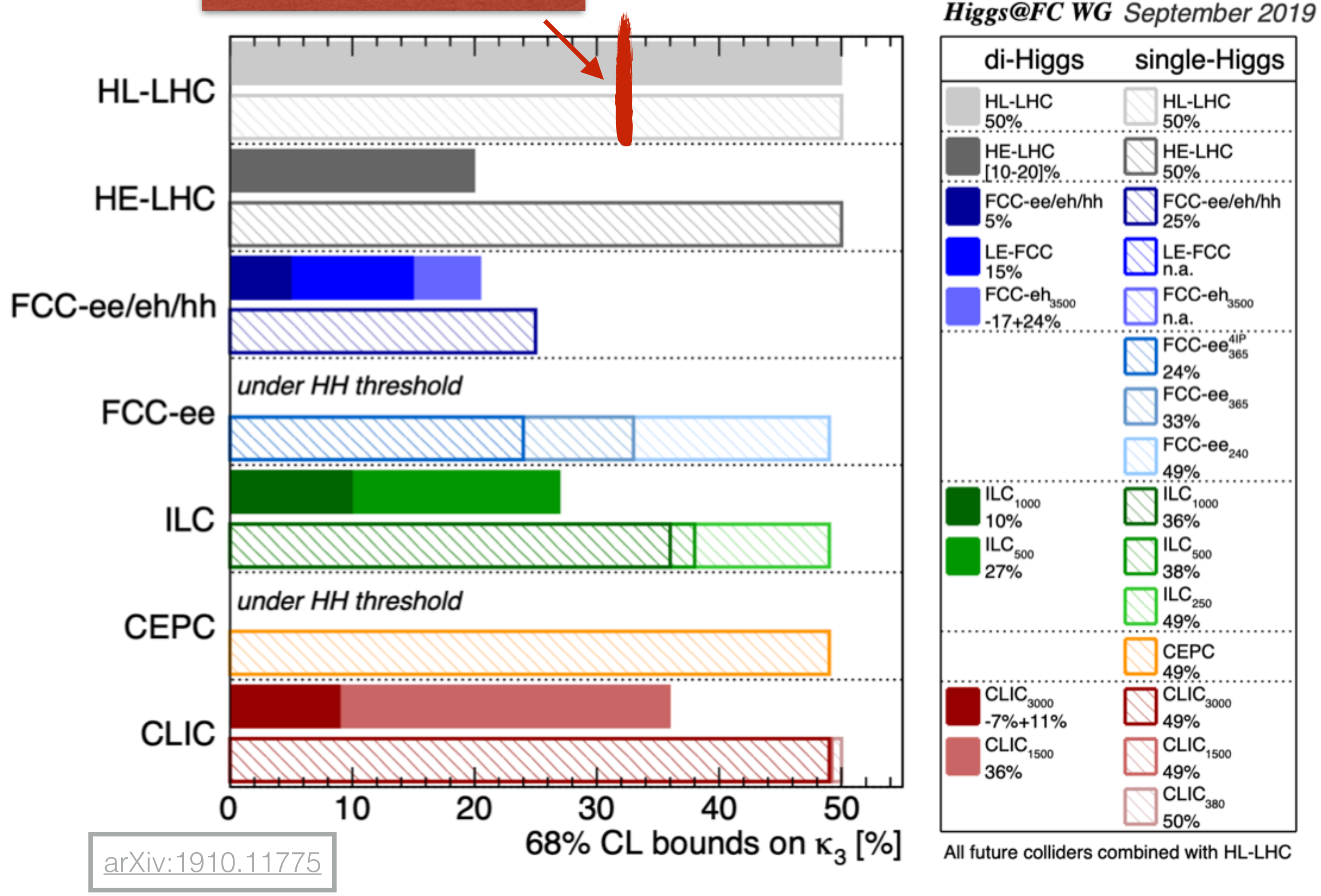
ATLAS EXPERIMENT

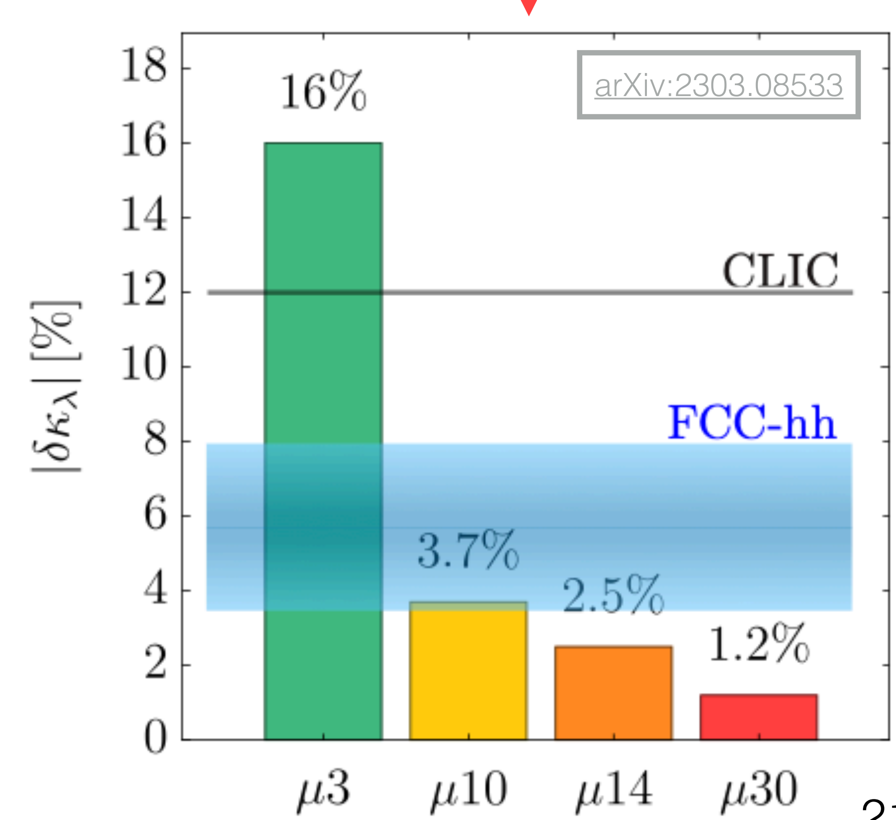
Comparison of future colliders

- Circular e^+e^- colliders **(FCC-ee, CLIC) could get κ_λ precision down to 25-50%** with indirect ZH measurements.
  - O(1%) **knowledge of other Higgs couplings is expected to be good enough**!
- Possible to achieve:
  - **~10% precision with high-energy linear colliders (ILC1000, CLIC3000, etc.)**
  - ~**5% precision with high-energy hadron colliders (FCC-hh)**

Personal estimation 🙂



Want more? You need a 30 TeV Muon Collider ($\nu\nu HH$)!



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ATLAS EXPERIMENT

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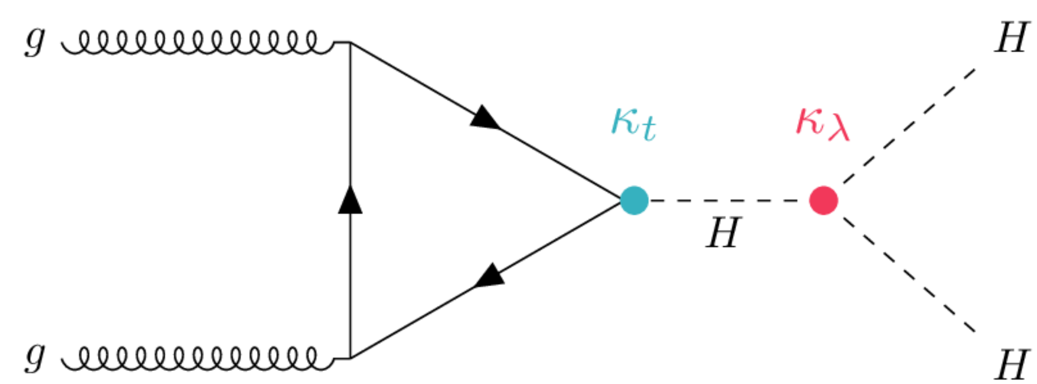
Conclusion and outlook

- The Higgs sector is **UNIQUE** and still **largely unexplored**!
  - Shape of the **Higgs potential is essential** to fully understand EWSB!
  - **HH searches at HL-LHC will give first measurement** of potential shape via measurement of κ_λ.
- **Some personal HL-LHC estimations:**
  - ⚠️ **Unofficial, please use with caution!**
  - 5σ **discovery should be well within reach!** Especially considering how quickly we are improving things.
- **For better precision: future e^+e^- and hadron-hadron colliders**
  - Want better? Then you need a ≥15 TeV Muon Collider ($\sigma(\kappa_\lambda) \sim 1\,\%$).



	Personal HL-LHC projection
Significance Z	**4.8σ (6.9σ)** with and without systematics
Precision κ_λ	**~30%** with systs
Precision κ_{2V}	**~50%** with systs

Already better than this with Run 2 dataset!

	Precision on κ_λ
Circular e+e- (FCC-ee/CEPC)	~ 25-50%
FCC-hh	~5%
High-energy linear colliders	~10%

Backup

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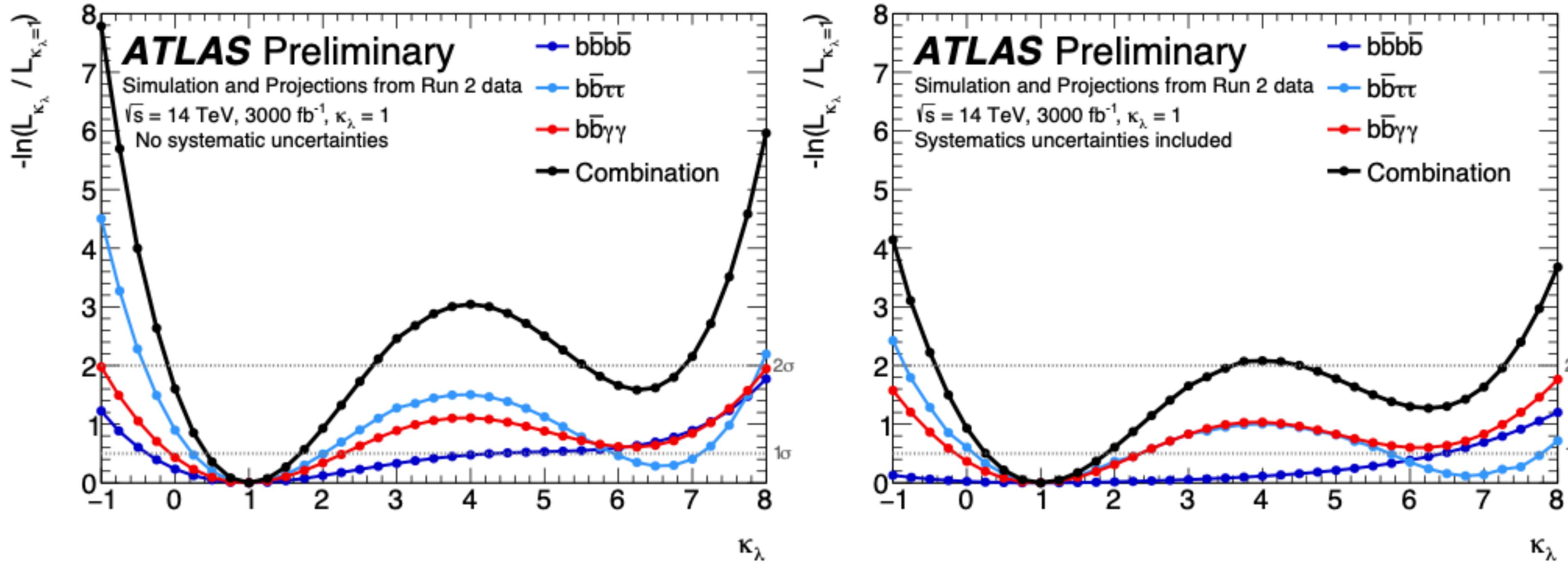
HL-LHC systematic uncertainties and cross-sections

Source	Scale factor	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$
Experimental Uncertainties			
Luminosity	0.6	*	*
b-jet tagging efficiency	0.5	*	*
c-jet tagging efficiency	0.5	*	*
Light-jet tagging efficiency	1.0	*	*
Jet energy scale and resolution, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.0	*	*
κ_λ reweighting	0.0	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*	
Photon energy scale and resolution	1.0	*	
Spurious signal	0.0	*	
Value of m_H	0.08	*	
τ_{had} efficiency (statistical)	0.0		*
τ_{had} efficiency (systematic)	1.0		*
τ_{had} energy scale	1.0		*
Fake-τ_{had} estimation	1.0		*
MC statistical uncertainties	0.0		*
Theoretical Uncertainties	0.5	*	*

Process	Scale factor
Signals	
ggF HH	1.18
VBF HH	1.19
Backgrounds	
ggF H	1.13
VBF H	1.13
WH	1.10
ZH	1.12
$t\bar{t}H$	1.21
Others	1.18

ATLAS CERN Yellow report



(a) Statistical uncertainties only

(b) Statistical + systematic uncertainties

The combined minimum negative-log-likelihoods are shown in Figure 66. The 68% Confidence Intervals for κ_λ are $0.52 \leq \kappa_\lambda \leq 1.5$ and $0.57 \leq \kappa_\lambda \leq 1.5$ with and without systematic uncertainties respectively. The second minimum of the likelihood is excluded at 99.4% CL. A summary of the 68% CI for each channel in each experiment, as well as the combination are shown in Figure 66b.

Table 54: 68% Confidence Intervals for κ_λ, estimated for an Asimov dataset containing the backgrounds plus SM signal.

	Statistical-only	**Statistical + Systematic**
$HH \to b\bar{b}b\bar{b}$	$-0.4 \leq \kappa_\lambda \leq 4.3$	$-2.3 \leq \kappa_\lambda \leq 6.4$
$HH \to b\bar{b}\tau\tau$	$0.2 \leq \kappa_\lambda \leq 2.0 \cup 5.9 \leq \kappa_\lambda \leq 7.2$	$0.1 \leq \kappa_\lambda \leq 2.3 \cup 5.7 \leq \kappa_\lambda \leq 7.8$
$HH \to b\bar{b}\gamma\gamma$	$-0.1 \leq \kappa_\lambda \leq 2.4$	$-0.2 \leq \kappa_\lambda \leq 2.5$
combined	$0.4 \leq \kappa_\lambda \leq 1.7$	$0.25 \leq \kappa_\lambda \leq 1.9$

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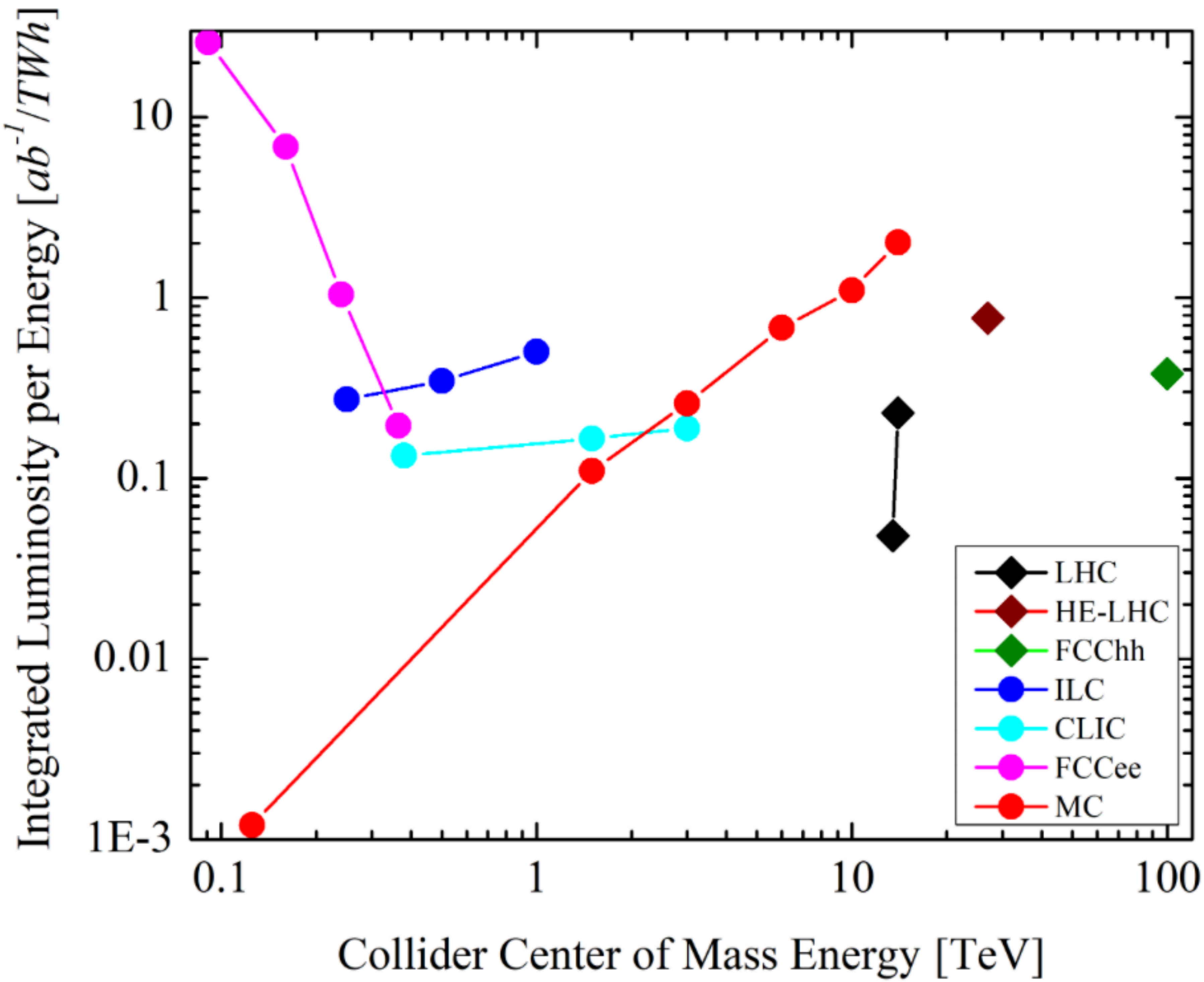
Future colliders luminosities



HH measurements at HL-LHC and future colliders

Potential of Future Colliders workshop [2024]

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