Measuring the Higgs Self-Coupling with Di- and Single-Higgs Processes

ICHEP 2020

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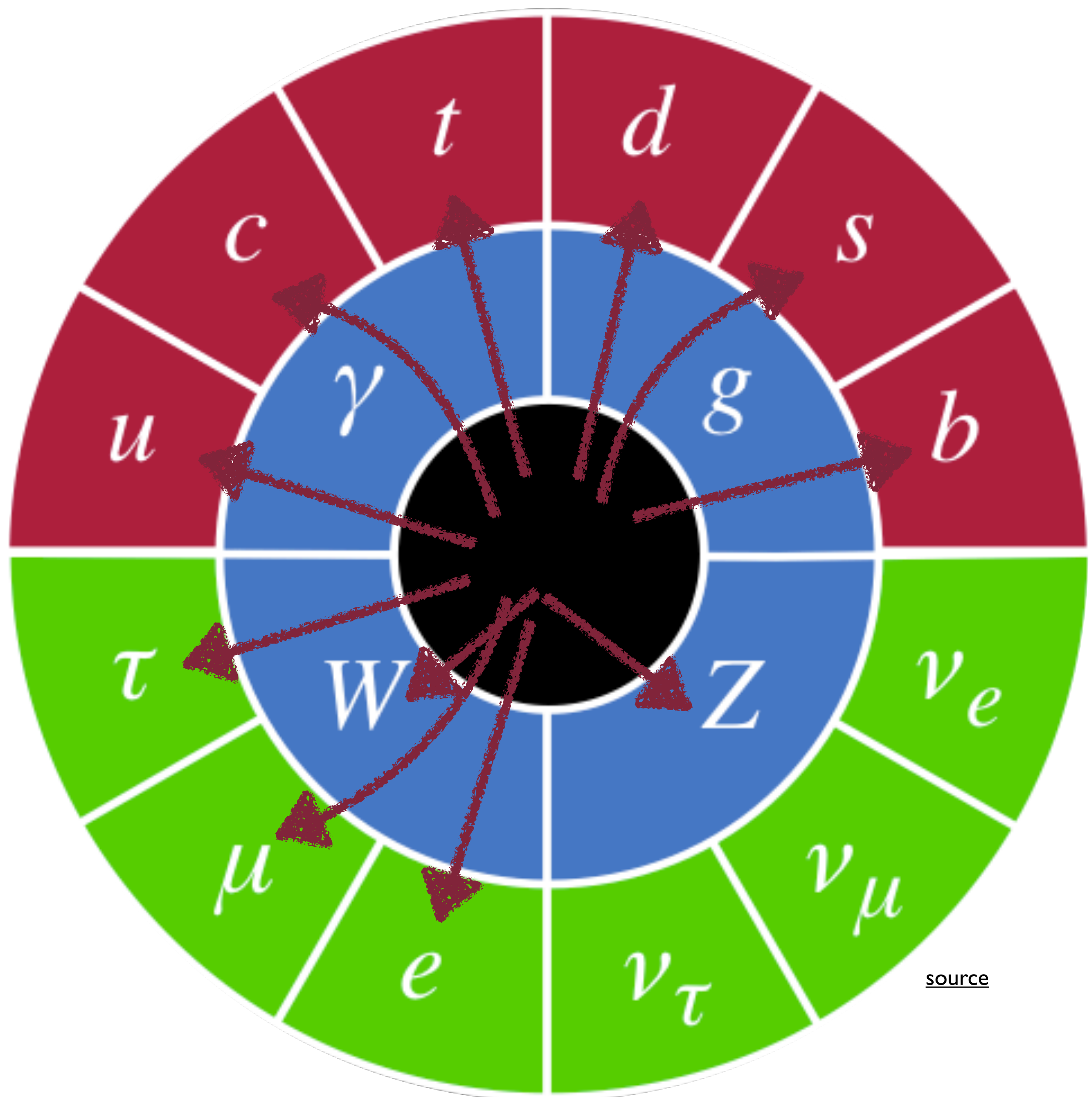
On behalf of ATLAS
TRIUMF

Results from ATLAS-CONF-2019-049

ATLAS
EXPERIMENT

The Higgs is the Center



The Higgs is the center of the Standard Model

The process of Electroweak Symmetry Breaking creates massive gauge bosons

The Higgs field gives masses to all the fermions

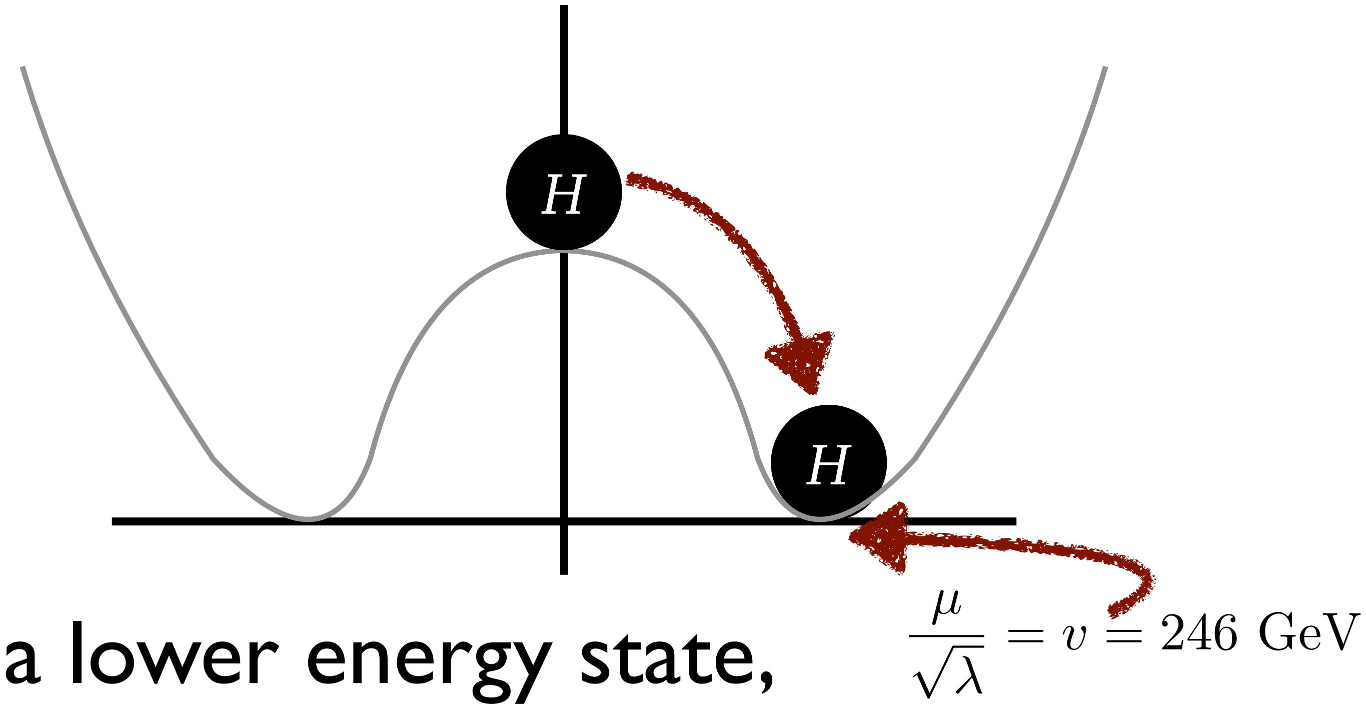
The SM doesn't make sense without the Higgs

Understanding the Higgs is key to Understanding the SM, and physics beyond

The Mystery of the Potential

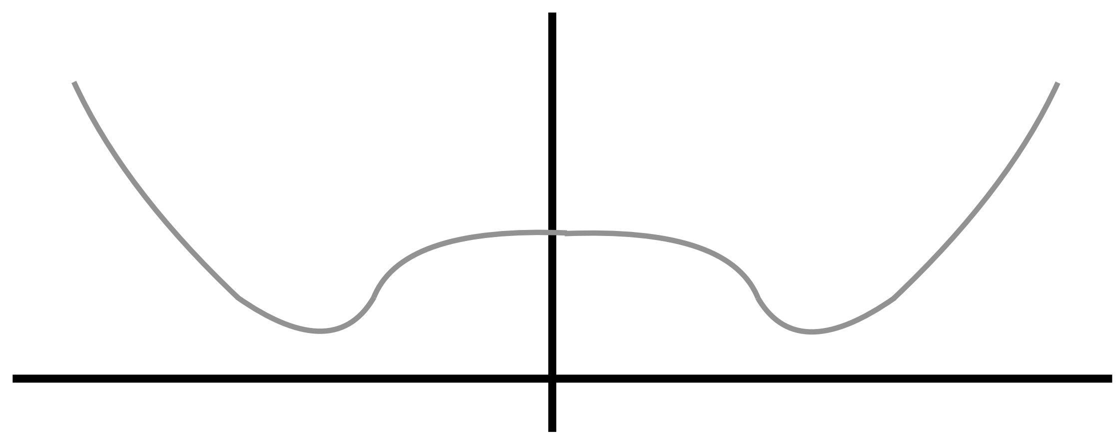
The SM Higgs potential is:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



The field "rolls" into a lower energy state, the initial symmetry is broken, the field acquires a non-zero vacuum expectation value

But many other shapes could have caused the same physics



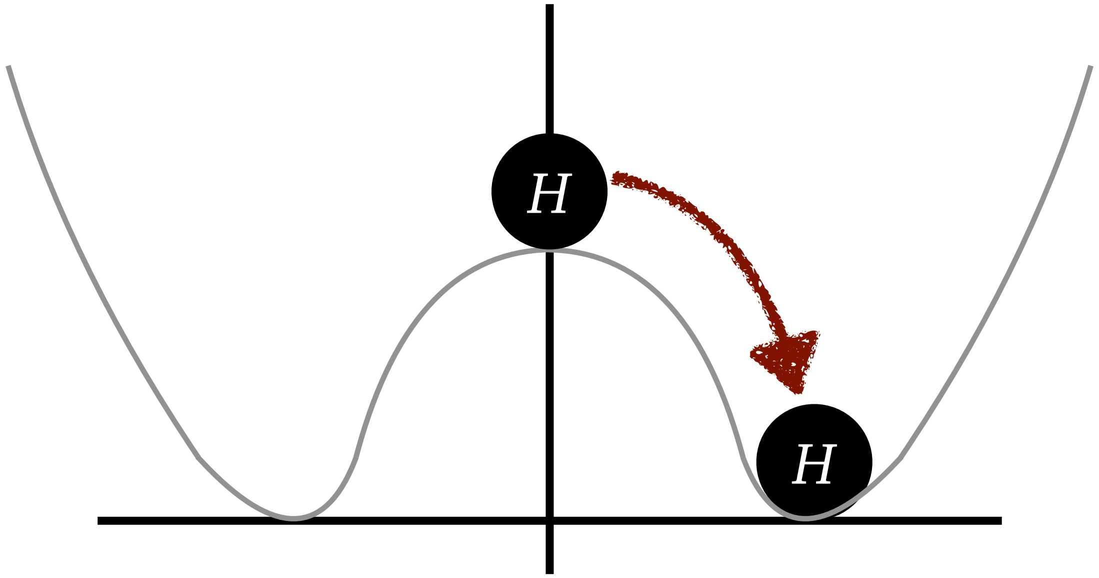
We have no knowledge of the actual shape: just some of its properties

Why does this matter?

Why Measure the Potential?

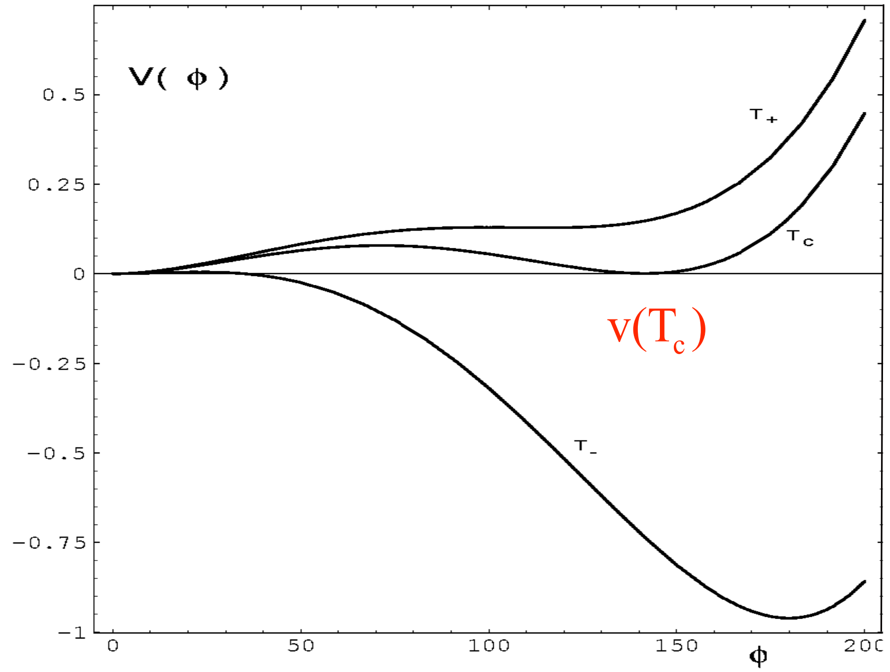
Many models alter the Higgs potential

Models of "electroweak baryogenesis" have the Higgs potential undergo a phase transition, which could explain matter-antimatter asymmetry



This phase transition requires modifications to the SM potential!

And generically: it's hard to alter only the potential, and not change any other Higgs couplings!

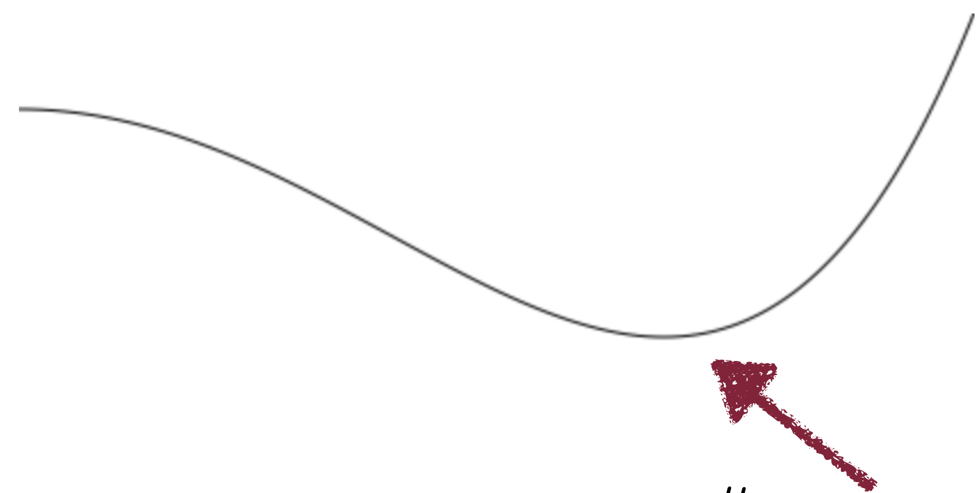


If we can measure the shape of the potential, we can find hints of fundamental, critical new physics!

How to Measure the Potential

The SM Higgs potential is:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



$$\frac{\mu}{\sqrt{\lambda}} = v = 246 \text{ GeV}$$

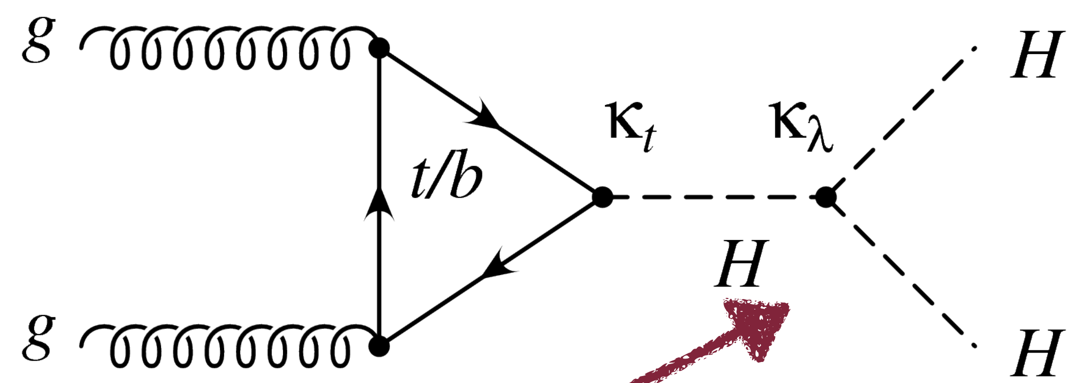
Expand around the minimum, get:

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \ldots$$

$$= V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \ldots$$

This is the mass: well measured

This term is the Higgs self-coupling



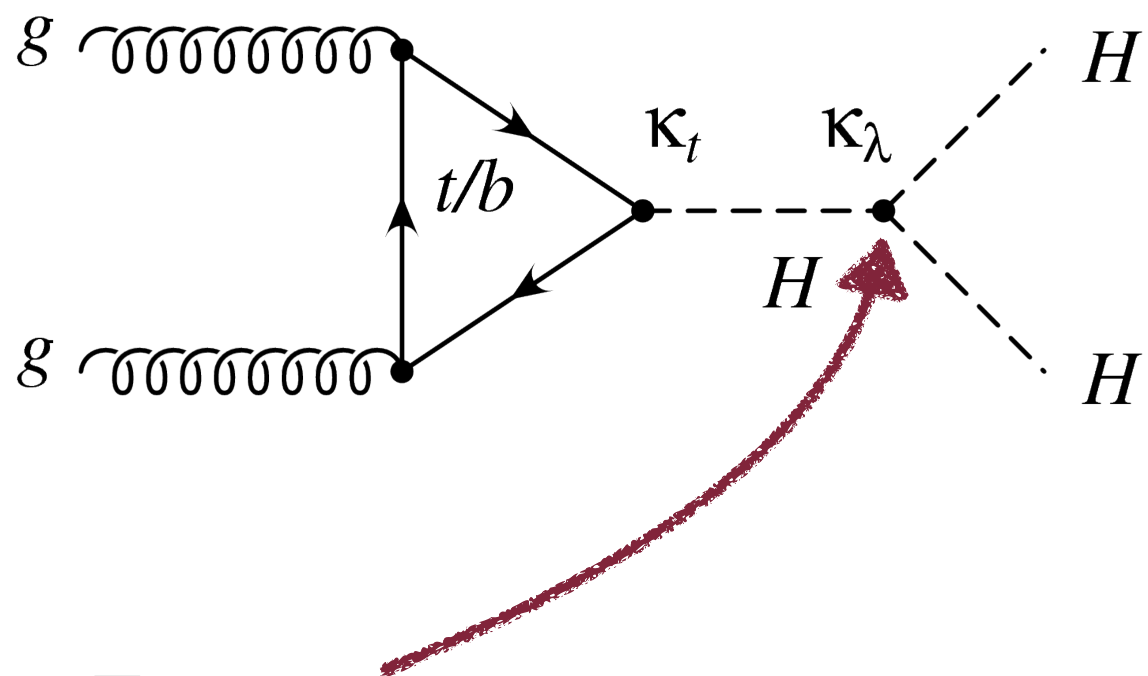
The SM predicts di-Higgs production

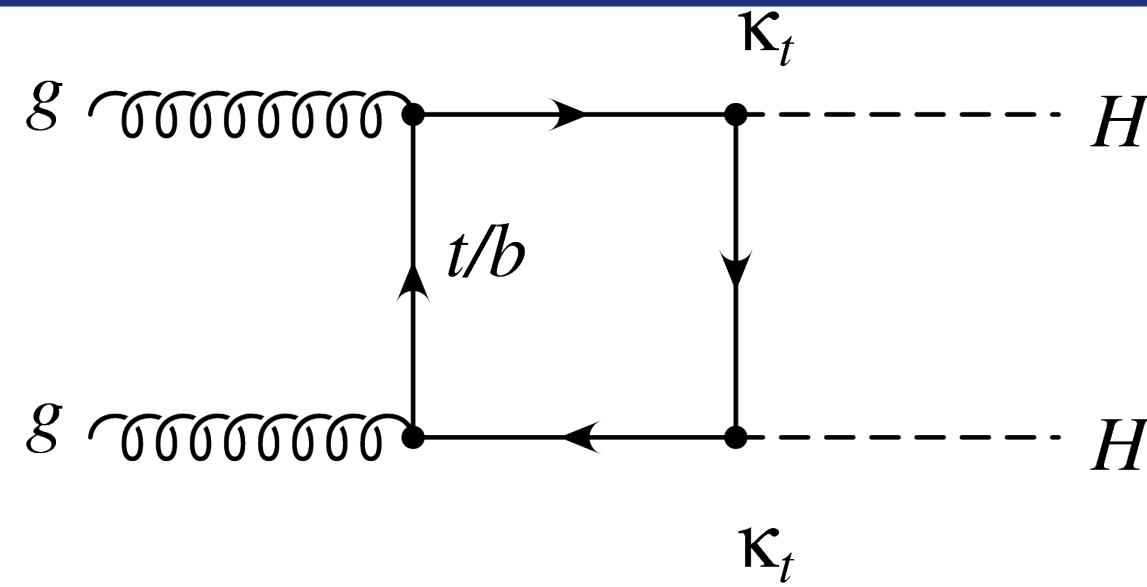
$$\lambda_{HHH}^{SM} = \frac{m_h^2}{2v^2}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

This higher-order term tells us more about the shape of the potential!

Self-Coupling with Di-Higgs





This coupling is what we want to measure

This tells us about the shape of the Higgs potential

This process has the same final state, but κ_λ doesn't appear: no information about the Higgs potential

These two processes destructively interfere in the SM, leading to **very low cross section**

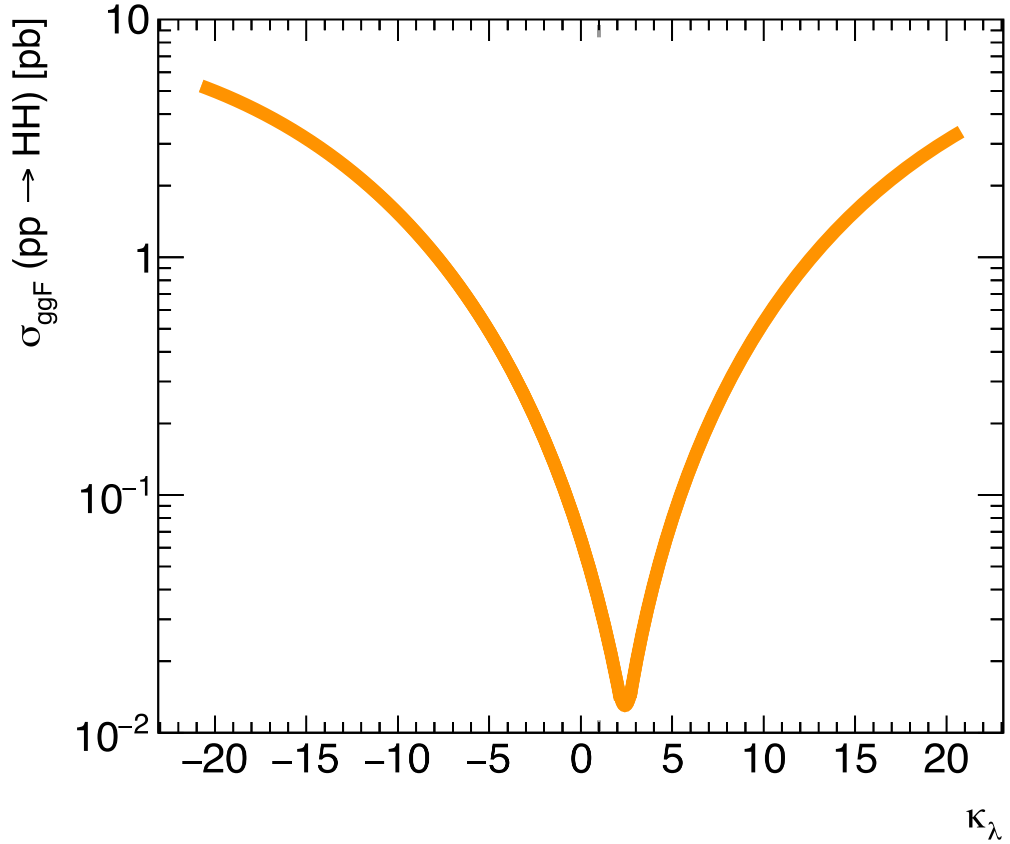
Also important: κ_λ always appears with κ_t: sensitivity can change if κ_t allowed to float

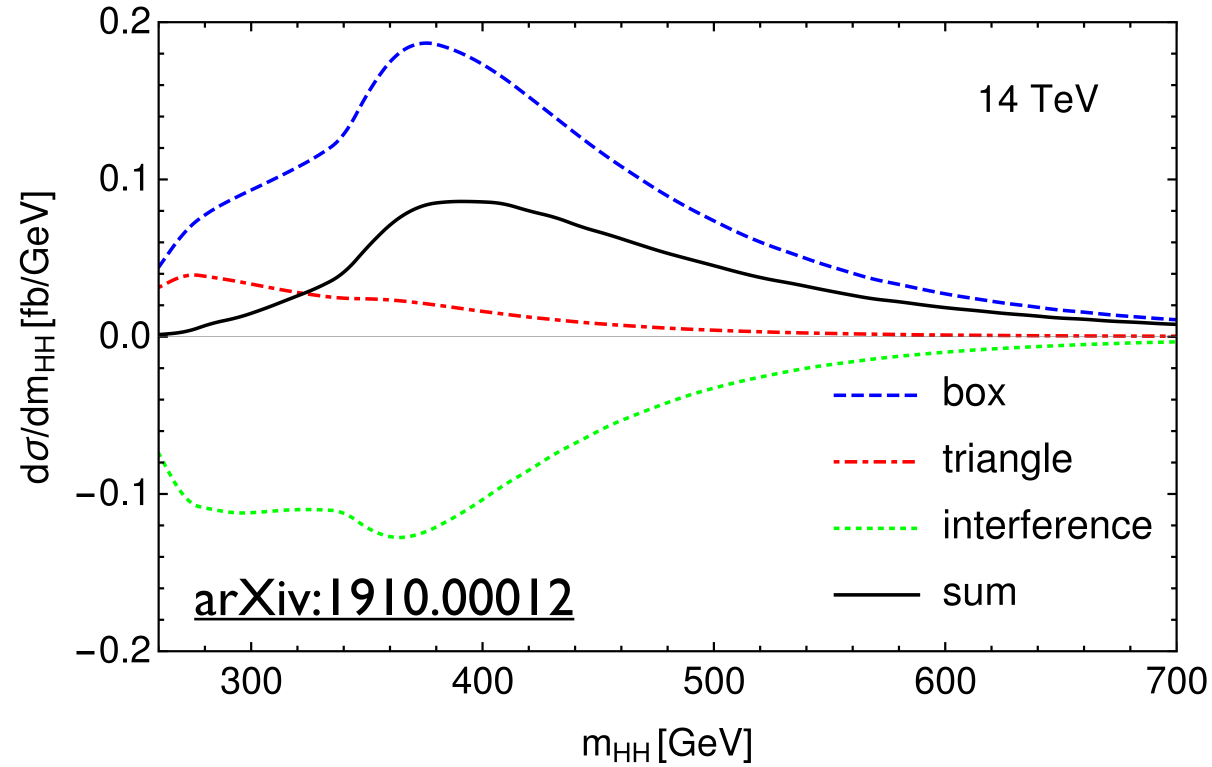
Measuring with Di-Higgs

If κ_λ isn't the SM value interference diminishes: larger cross section!

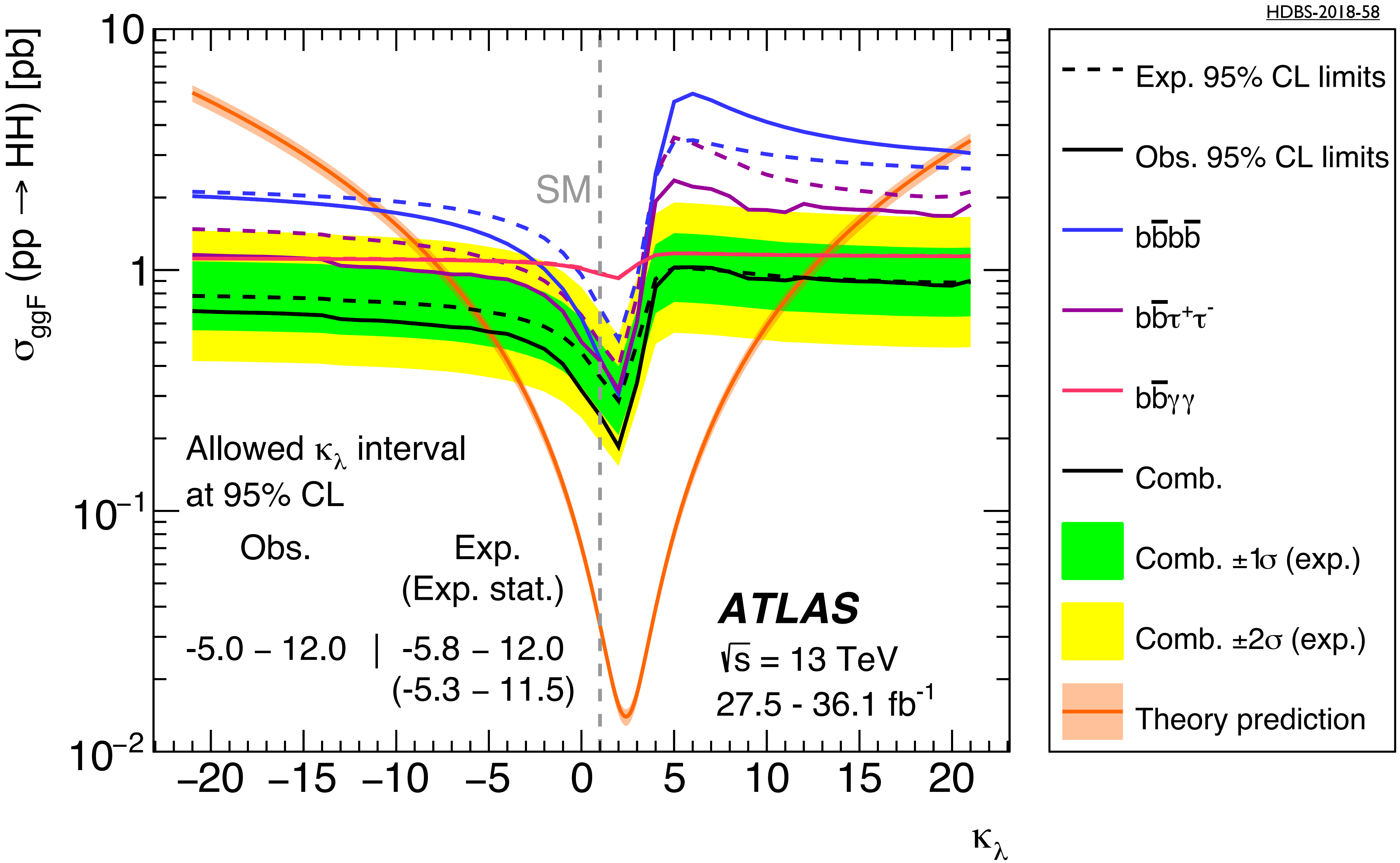
But while the cross section can increase, the **lowest m_{HH} component** is what is most enhanced

Measuring κ_λ is challenging: need both rate and shape information for best constraints





Di-Higgs Results

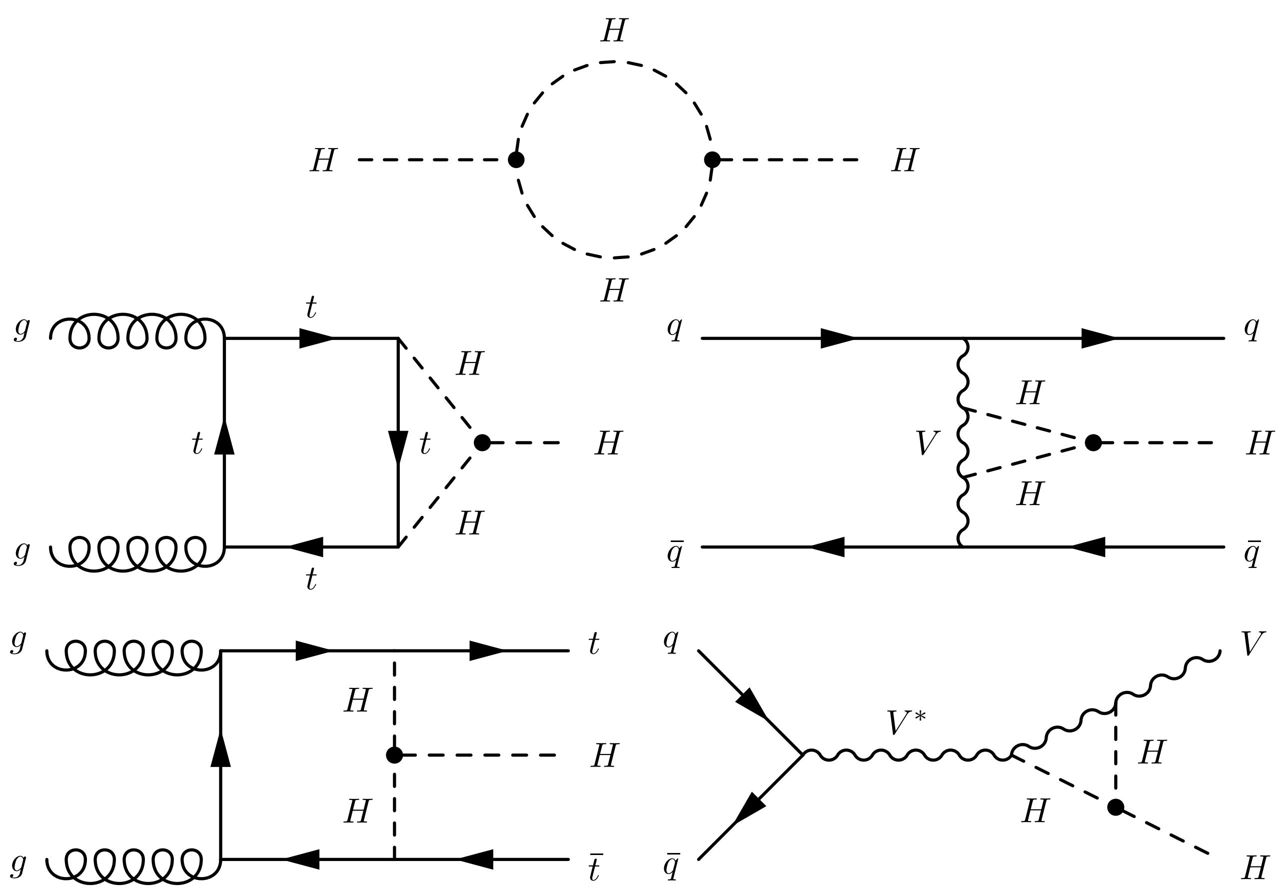


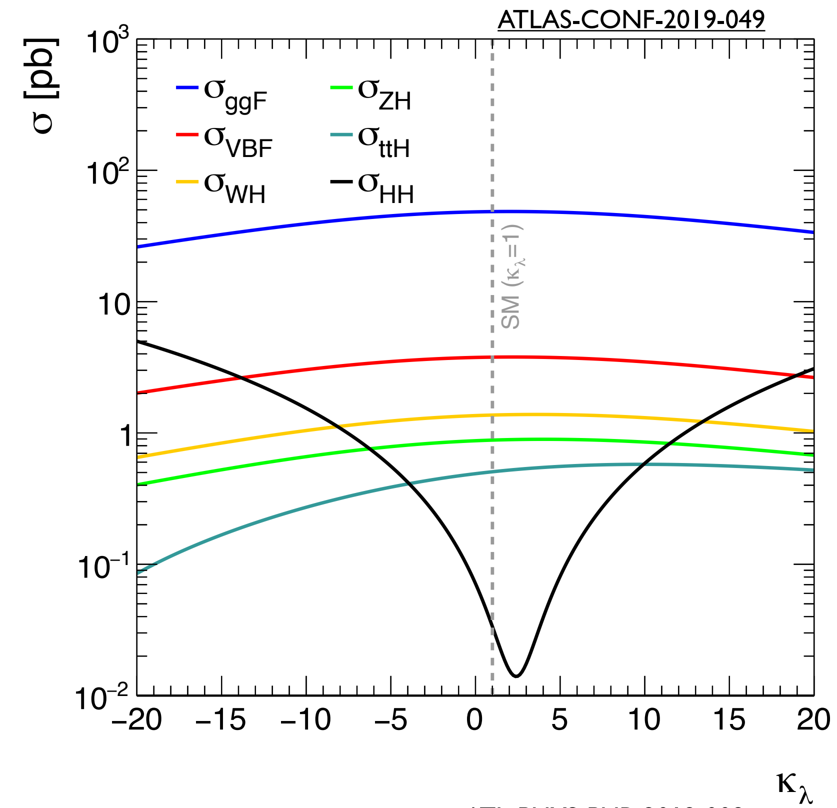
Di-Higgs searches set strong constraints on κλ

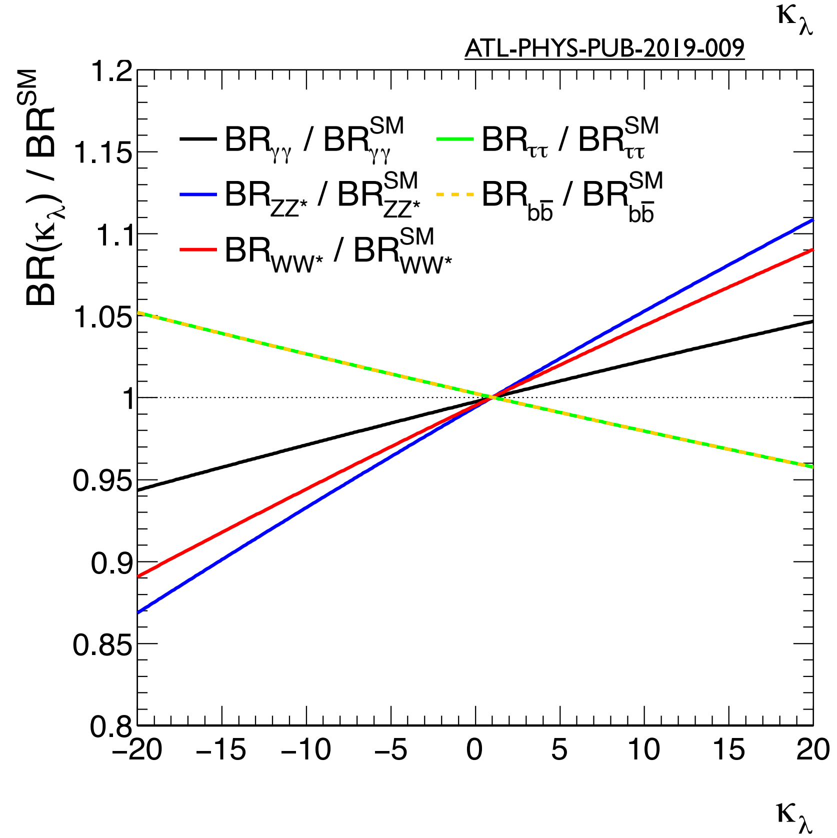
But this **assumes only new physics is κλ…**

Can we say anything else?

Measuring with Single Higgs







Single Higgs final states can also be sensitive to κ_λ

NLO EW corrections give Higgs cross-section, branching ratios, and kinematics dependence on κ_λ

Combining Single and Double

Analysis	Integrated luminosity (fb^{-1})	Ref.	
$H \to \gamma\gamma$ (excluding $t\bar{t}H$, $H \to \gamma\gamma$)	79.8	[21,22]	21, 22
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8	[23,24]	23, 24
$H \to WW^* \to e\nu\mu\nu$	36.1	[25]	25
$H \to \tau^+\tau^-$	36.1	[26]	26
VH, $H \to b\bar{b}$	79.8	[27,28]	27, 28
$t\bar{t}H$, $H \to b\bar{b}$	36.1	[29]	29
$t\bar{t}H$, $H \to$ multilepton	36.1	[30]	30
$HH \to b\bar{b}b\bar{b}$	27.5	[31]	31
$HH \to b\bar{b}\tau^+\tau^-$	36.1	[32]	32
$HH \to b\bar{b}\gamma\gamma$	36.1	[33]	33

Can perform a combined analysis, using single and double Higgs!

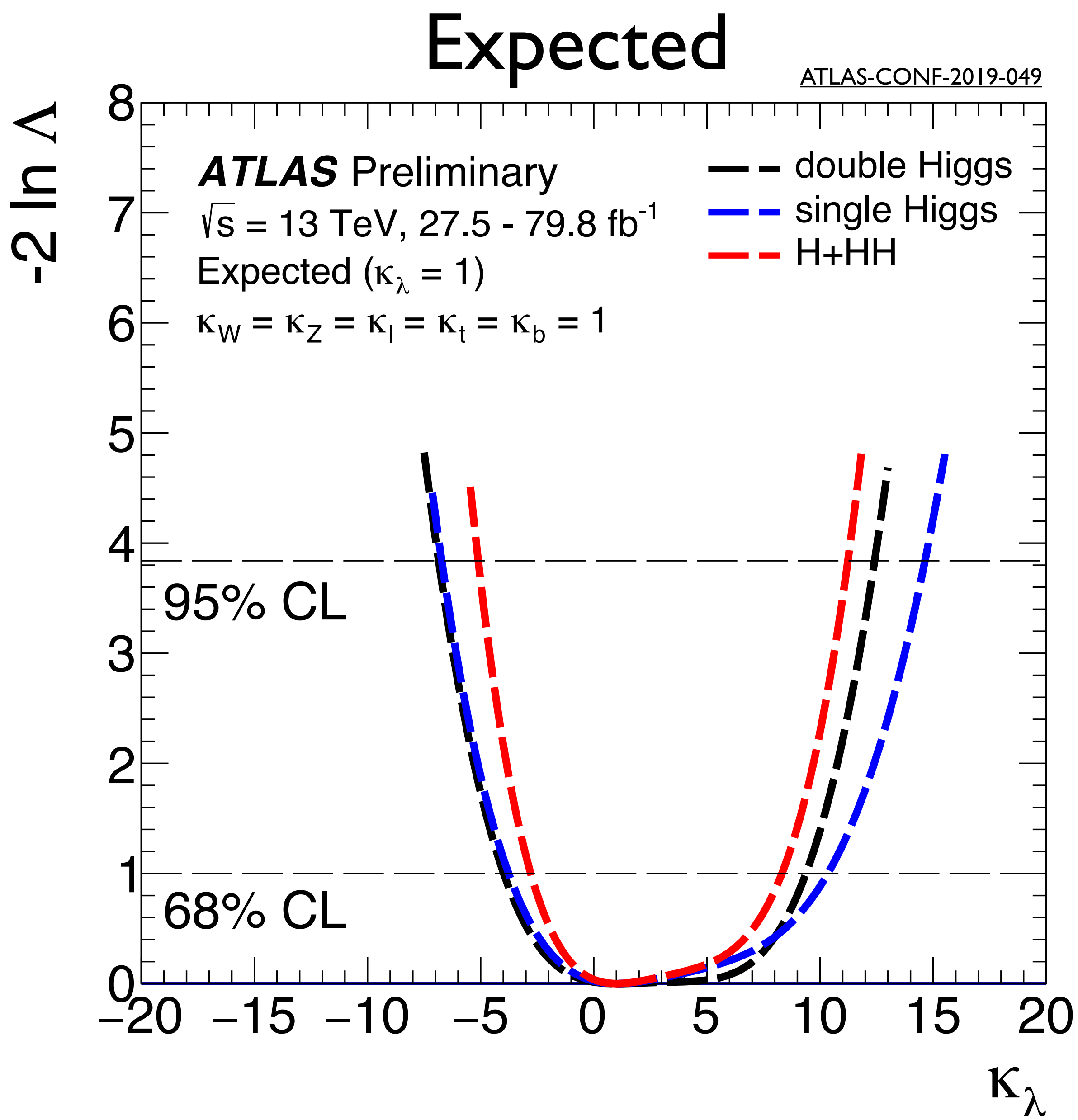
Single Higgs analysis use STXS template fits
for VBF and VH measurements

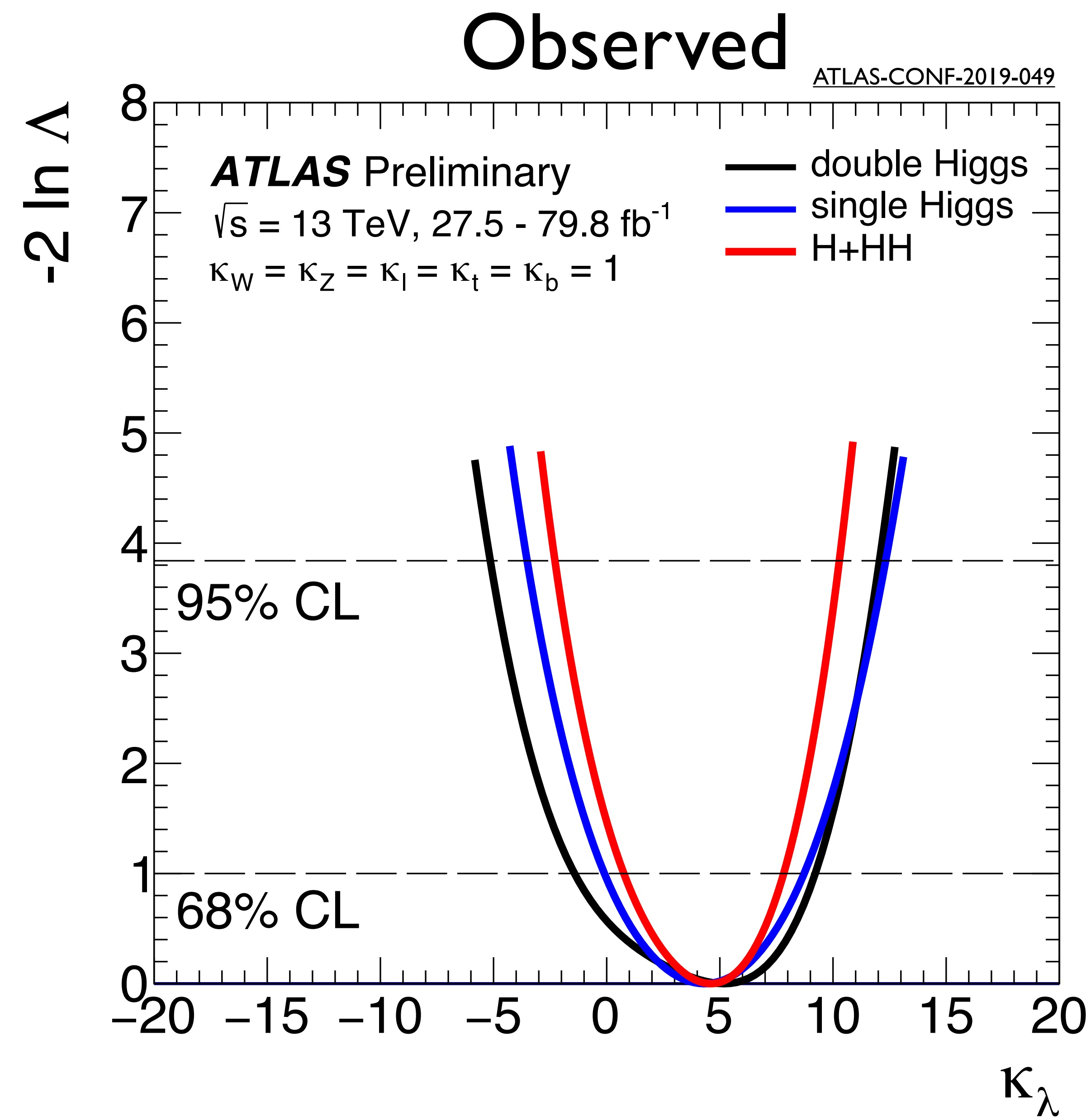
Explicit checks for overlap: remove ttH→γγ due to bbγγ overlap

Perform two types of interpretations:

1. New physics only in κ_λ
2. New physics in any κ coupling

Results: κλ



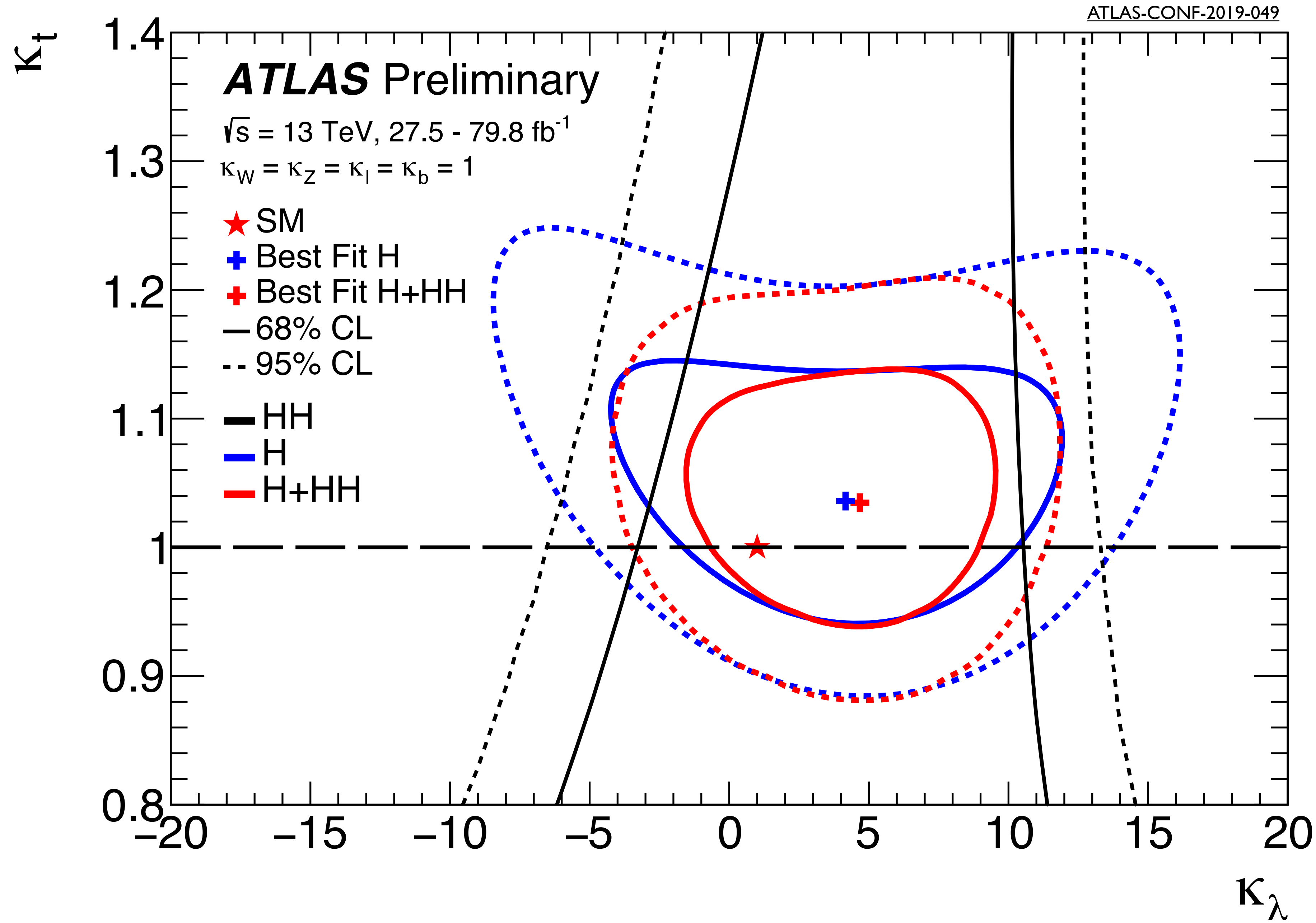


Di-Higgs and **Single-Higgs** provide similar limits on κλ!

NB: single Higgs has ~2x larger luminosity for many channels

Combination provides strongest limits

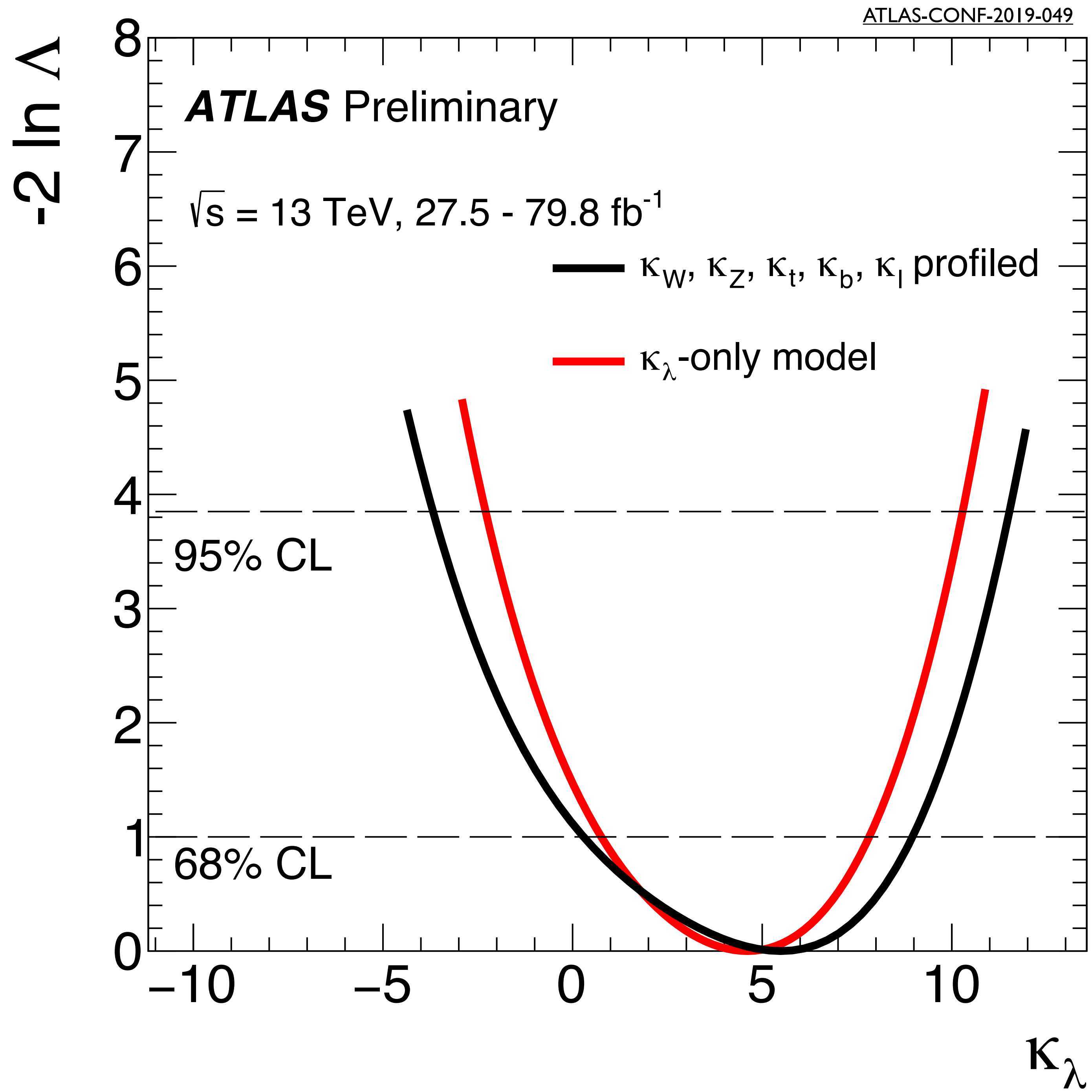
Relaxing Constraints



Di-Higgs measurements cannot simultaneously constrain κ_λ and κ_t

Single Higgs allows the **Combinations** to be sensitive to variations in both parameters

Even Fewer Constraints



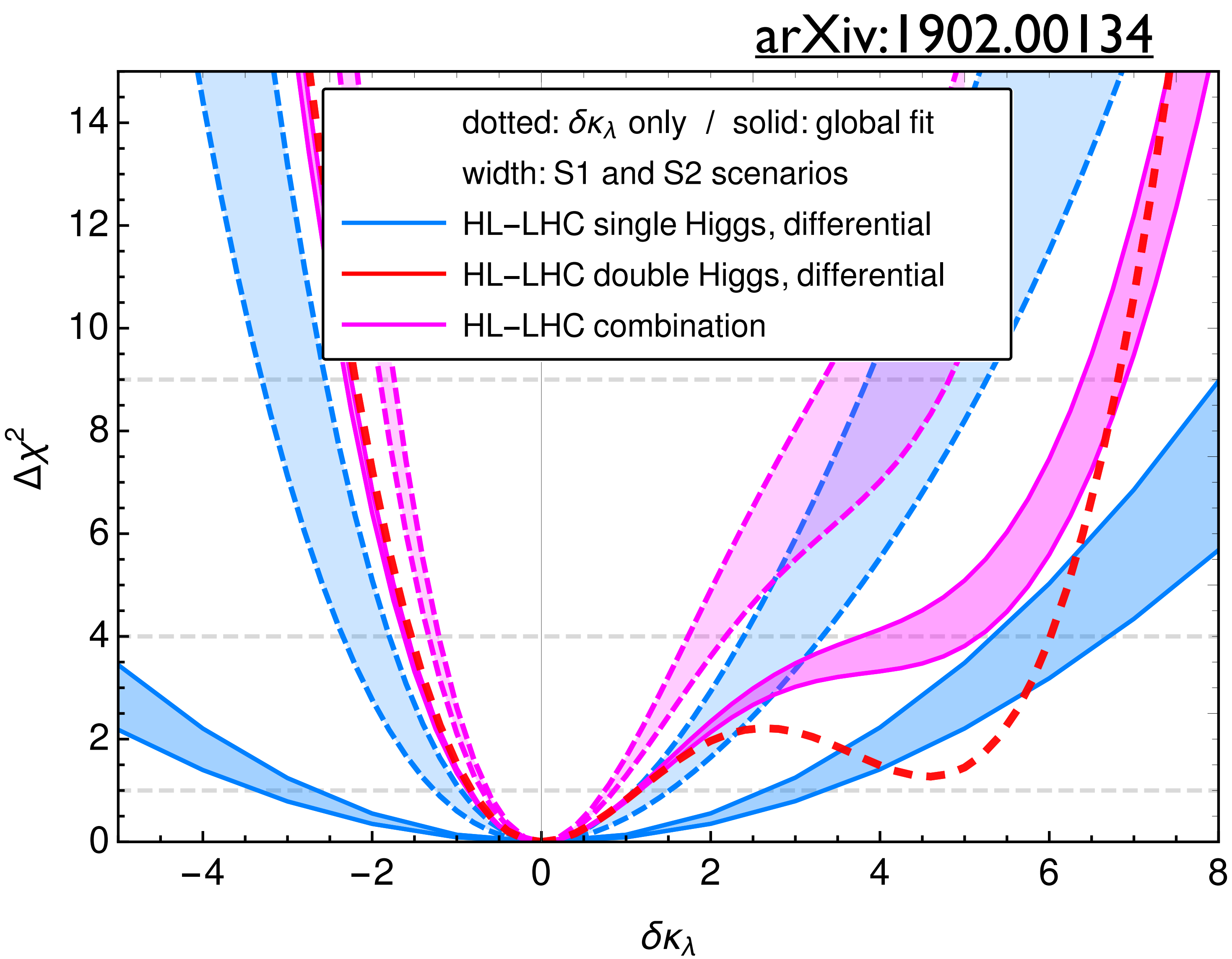
Can also directly **fit to best κ** value, **as well as κλ**

More degrees of freedom: Weaker constraints on κλ

New physics could affect couplings beyond κλ!

Important to consider most general constraints: difficult without single Higgs

What Next?

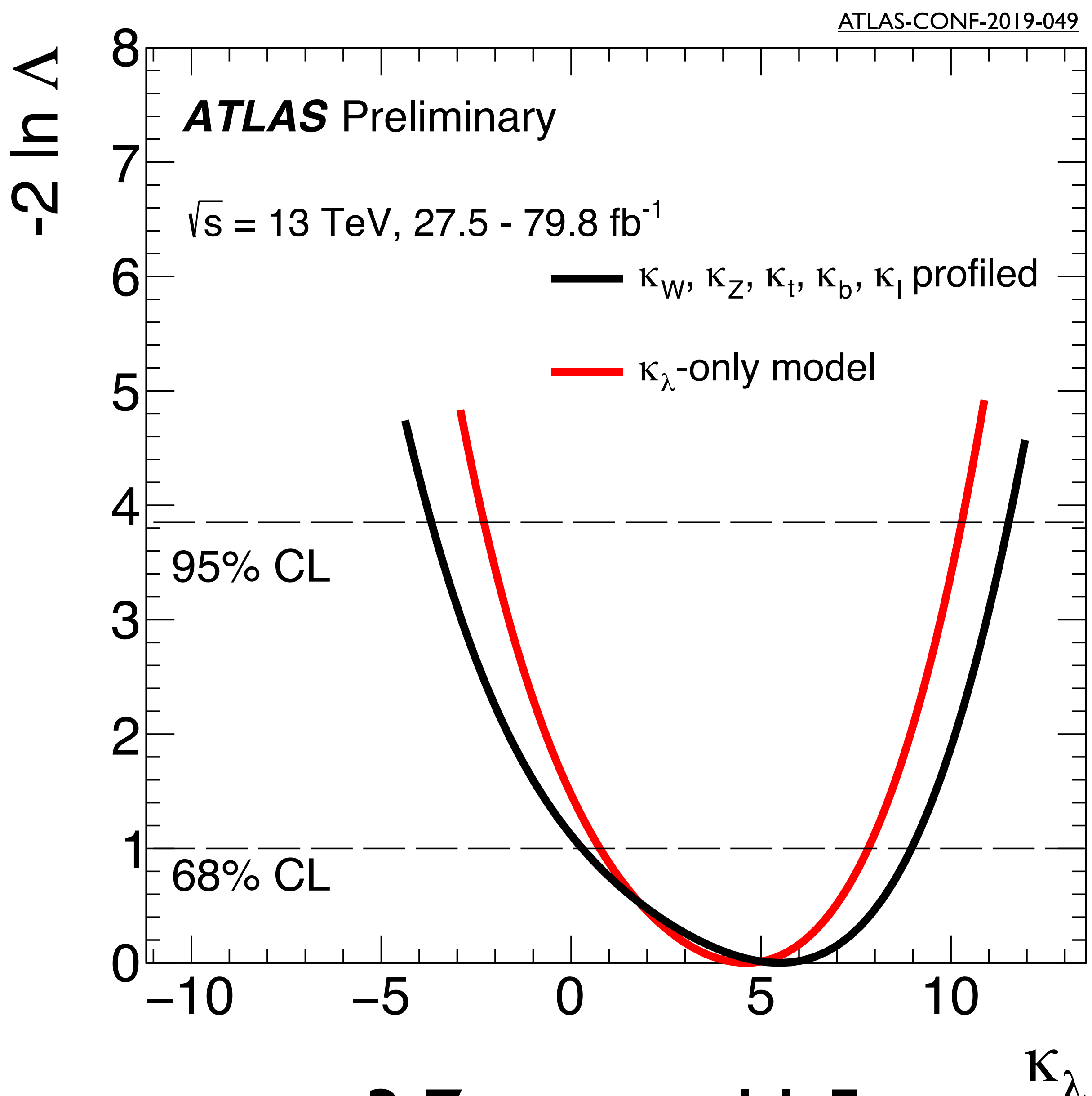


Prospects are good for measuring κλ via **HH processes**!

But adding **single Higgs** can only help constrain κλ, especially in **combinations**

… and will help reduce assumptions: can expand to EFT models with even fewer constraints

Conclusions



$-3.7 < \kappa_\lambda < 11.5$

$-2.3 < \kappa_\lambda < 10.3$

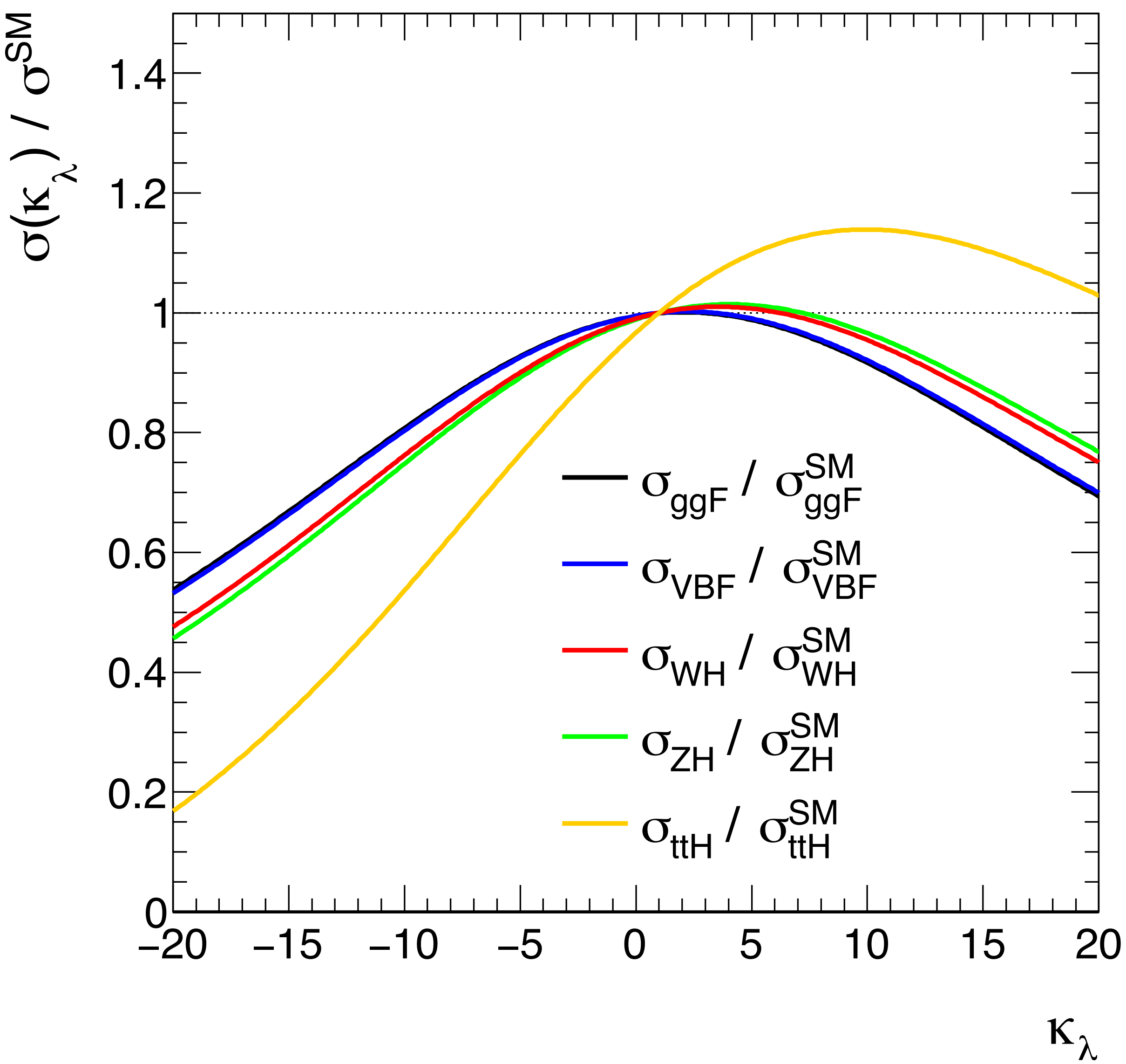
ATLAS has performed a unique, new measurement combining single and di-Higgs final states to measure the Higgs self-coupling

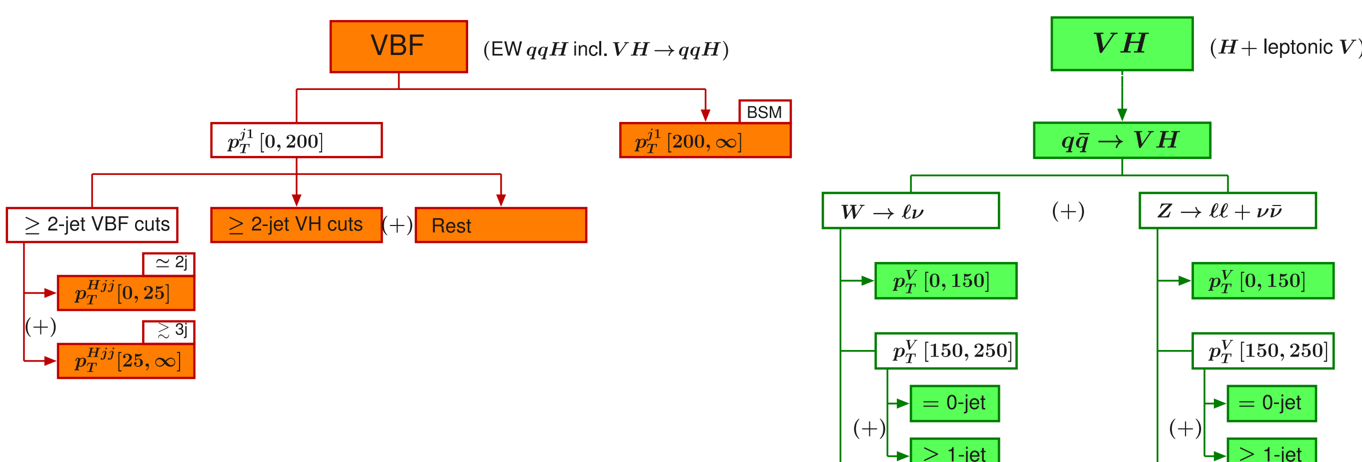
With more physics constraints, we can relax the model assumptions and test more 'realistic' deviations from the SM

This combination provides the **most precise**, and **most general**, constraints on the Higgs self-coupling

Thank You!

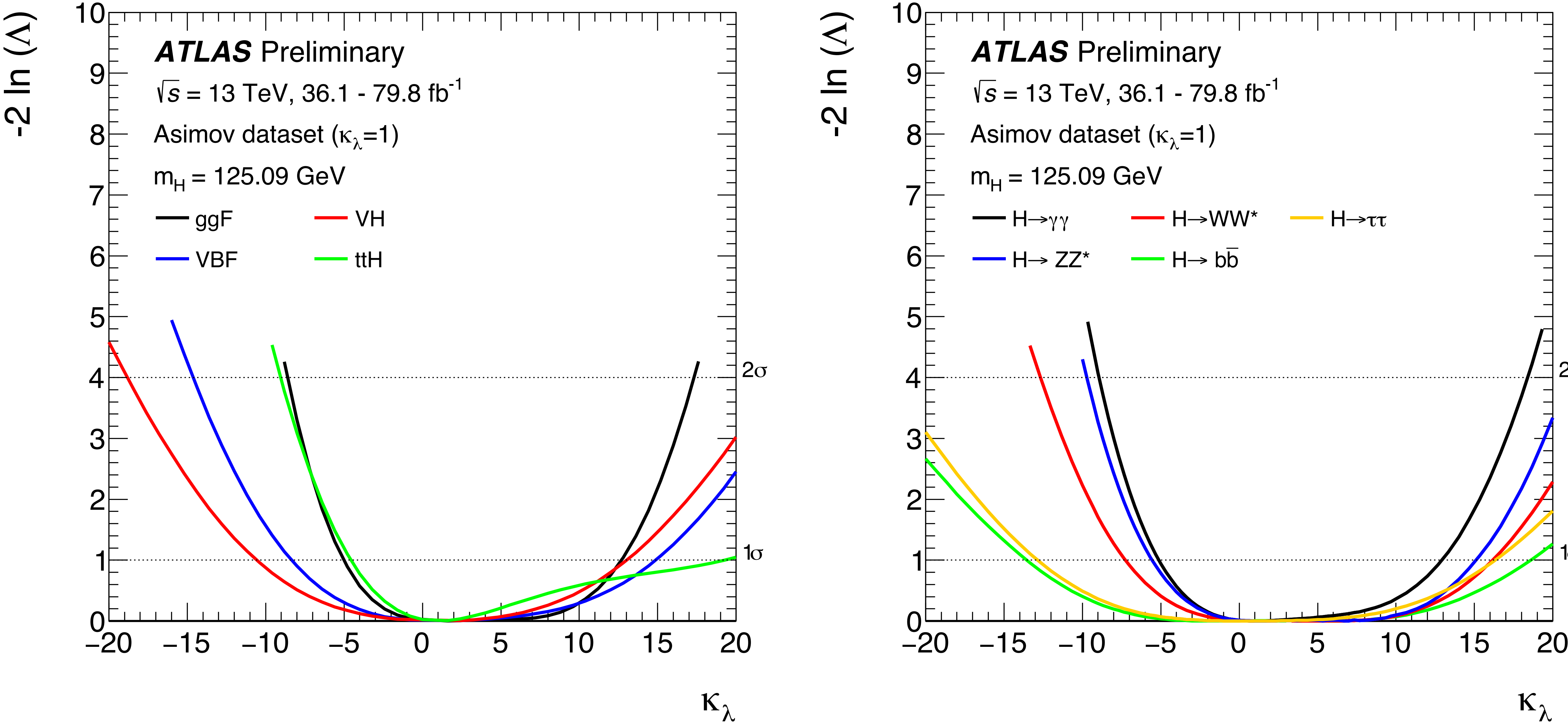
More on Single Higgs





Constructed from figures in arXiv:1610.07922

More on Single Higgs



More on Combination