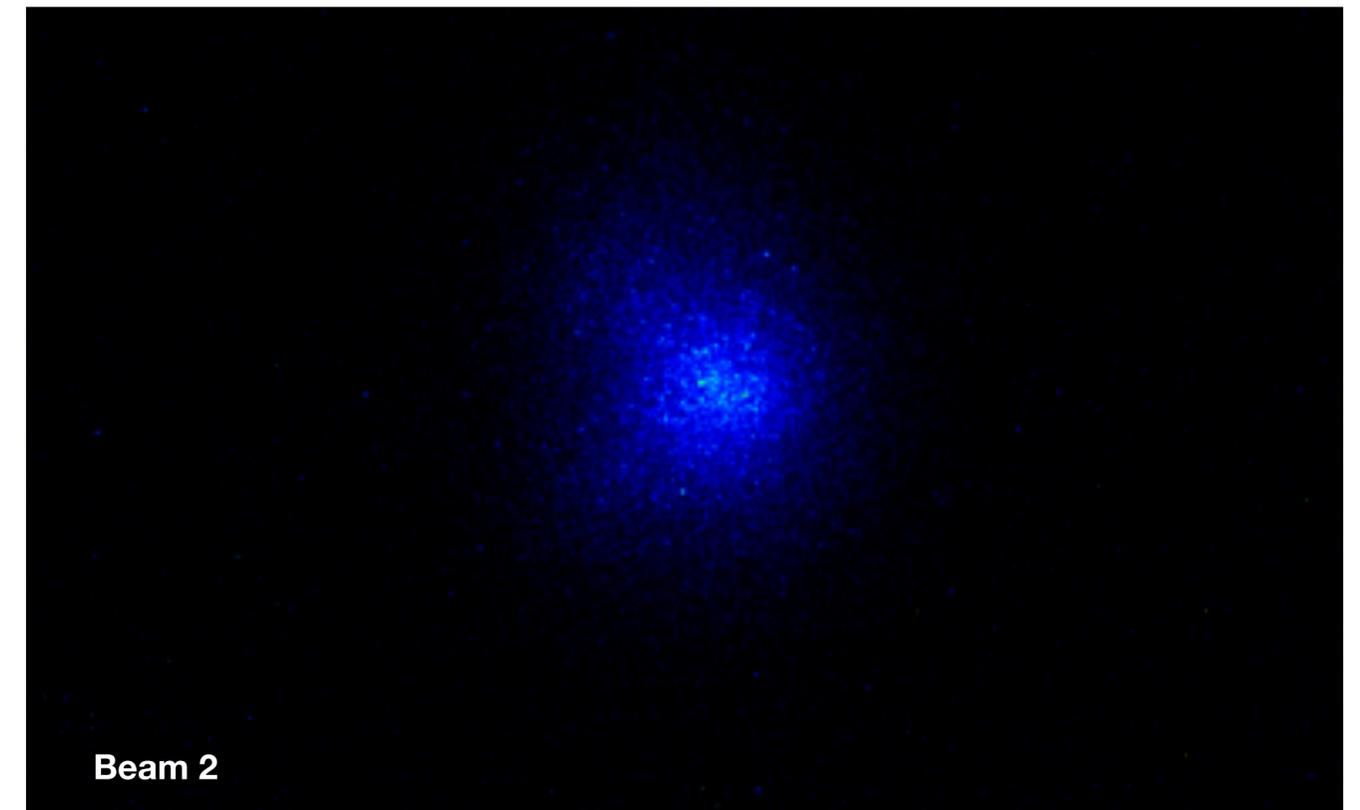
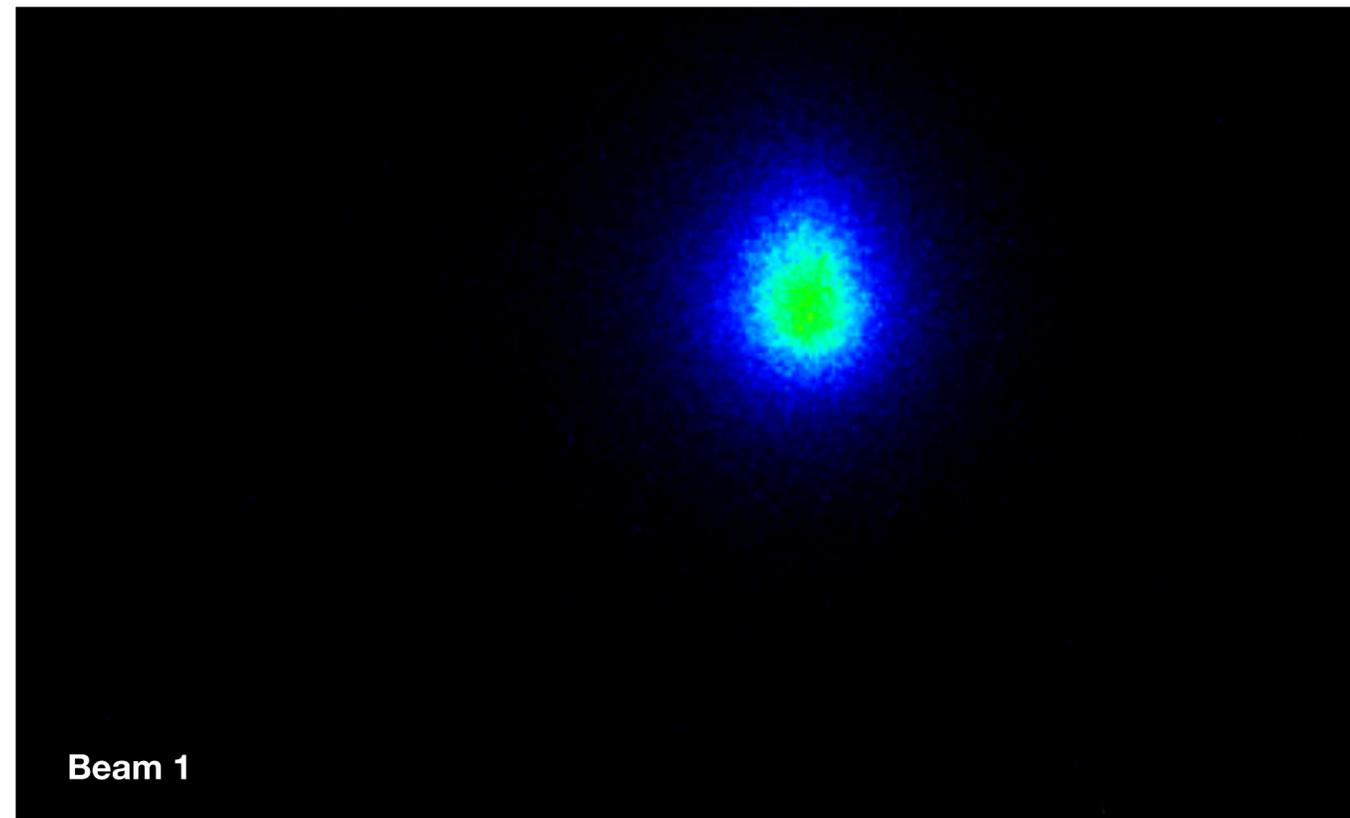


# Higgs physics in the light of Run 2 at Run 3 and Beyond\*!

**Selected topics** - Challenges and opportunities

**HIGGS 2021** - Stonybrook University and BNL October 18-22 2021

Beams are back in the LHC! (Pilot beam run)



Courtesy of M. Lamont, J. Wenninger and the CERN Control Center Team

# Scope and Disclaimer

**Focus on few recent results** to discuss **challenges** and **opportunities** at Run 3 and beyond at HL-LHC

Many apologies, only cover very few selected topics! Does not do justice to the extensive work done and the immense scope of the field!

## Precision

- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS
- Off Shell couplings and width
- Interferometry
- SMEFT

## Rare Production

- tH (single top and Higgs)
- FCNC top decays
- Di-Higgs production (and trilinear couplings)

## The Higgs particle



$$J = 0$$

In the following  $H^0$  refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of  $H^0$  and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ( $H^\pm$  and  $H^{\pm\pm}$ )", respectively.

### $H^0$ MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
<b>125.18 ± 0.16 OUR AVERAGE</b>			
125.26 ± 0.20 ± 0.08	<sup>1</sup> SIRUNYAN	17AV CMS	$pp$ , 13 TeV, $Z Z^* \rightarrow 4\ell$
125.09 ± 0.21 ± 0.11	<sup>2,3</sup> AAD	15B LHC	$pp$ , 7, 8 TeV

PDG Listing entry for the Higgs boson

## Rare decays

- $Z\gamma, \gamma\gamma^*, \text{Muons } \mu^+\mu^-$
- LFV  $\mu\tau, e\tau$
- $J/\Psi\gamma, Z\Upsilon, WD, \phi\gamma, \rho\gamma$

## Non minimal Higgs sectors

- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

## Tool for discovery

- Portal to DM (invisible Higgs)
- Portal to hidden/BSM sectors
- Portal to BSM physics with  $H^0$  in the final state ( $ZH^0, WH^0, H^0H^0$ )

\*Subjects partially discussed in this talk!



CERN-LPCC-2018-04  
March 20, 2019

## Higgs Physics at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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Huang<sup>120</sup>, A. Huss<sup>1</sup>, S. Jézéquel<sup>28</sup>, Sa. Jain<sup>69</sup>, S.P. Jones<sup>1</sup>, K. Köneke<sup>25</sup>, J. Kalinowski<sup>121</sup>, J.F. Kamenik<sup>122,123</sup>, M. Kaplan<sup>100</sup>, A. Karlberg<sup>61</sup>, M. Kaur<sup>60</sup>, P. Keicher<sup>86</sup>, M. Kerner<sup>61</sup>, A. Khanov<sup>124</sup>, J. Kieseler<sup>1</sup>, J.H. Kim<sup>125</sup>, M. Kim<sup>126</sup>, T. Klijsma<sup>43</sup>, F. Kling<sup>127</sup>, M. Klute<sup>100</sup>, J.R. Komaragiri<sup>128</sup>, K. Kong<sup>125</sup>, J. Kozaczuk<sup>129</sup>, P. Kozow<sup>121</sup>, C. Krause<sup>45</sup>, S. Lai<sup>33</sup>, J. Langford<sup>58</sup>, B. Le<sup>21</sup>, L. Lechner<sup>93</sup>, W.A. Leight<sup>130</sup>, K.J.C. Leney<sup>131</sup>, T. Lenz<sup>24</sup>, C.-Q. Li<sup>132</sup>, H. Li<sup>83</sup>, Q. Li<sup>133</sup>, S. Liebler<sup>134</sup>, J. Linder<sup>20</sup>, D. Liu<sup>135</sup>, J. Liu<sup>136</sup>, Y. Liu<sup>137</sup>, Z. Liu<sup>138,45</sup>, D. Lombardo<sup>8</sup>, A. Long<sup>139</sup>, K. Long<sup>41</sup>, I. Low<sup>140,135</sup>, G. Luisoni<sup>46</sup>, L.L. Ma<sup>83</sup>, A.-M. Magnan<sup>58</sup>, D. Majumder<sup>125</sup>, A. Malinauskas<sup>19</sup>, F. Maltoni<sup>141</sup>, M.L. Mangano<sup>1</sup>, G. Marchiori<sup>67,67</sup>, A.C. Marini<sup>100</sup>, A. Martin<sup>77</sup>, S. Marzani<sup>142,99</sup>, A. Massironi<sup>1</sup>, K.T. Matchev<sup>40,143</sup>, R.D. Matheus<sup>23</sup>, K. Mazumdar<sup>69</sup>, J. Mazzitelli<sup>61</sup>, A.E. Mcdougall<sup>21</sup>, P. Meade<sup>119</sup>, P. Meridiani<sup>6</sup>, A.B. Meyer<sup>15</sup>, E. Michielin<sup>18</sup>, P. Milenovic<sup>1,144</sup>, V. Milosevic<sup>58</sup>, K. Mimasu<sup>141</sup>, B. Mistlberger<sup>145</sup>, M. Mlynarikova<sup>146</sup>, M. Mondragon<sup>147</sup>, P.F. Monni<sup>1</sup>, G. Montagna<sup>148,48</sup>, F. Monti<sup>26,13</sup>, M. Moreno Llacer<sup>1</sup>, A. Mueck<sup>149</sup>, P.C. Muiño<sup>27</sup>, C. Murphy<sup>150</sup>, W.J.

Outcome of the 2013 European Strategy: HL-LHC!

European Strategy 2012-2013 [Recommendations](#)

Outcome of the 2020 European Strategy:

European Strategy 2018-2020 [Recommendations](#)

**“...HL-LHC should be the focal point of European Particle Physics...”**

**HL-LHC is a Higgs factory** ~160 M Higgs events

In comparison Future ee up to ~1.3 M Higgs Events, [but much cleaner and « usable » events](#)

Review of challenges and opportunities: recent HL/HE-LHC CERN [Yellow Report](#)

Most of the work done in 2018! **A lot happened since...**

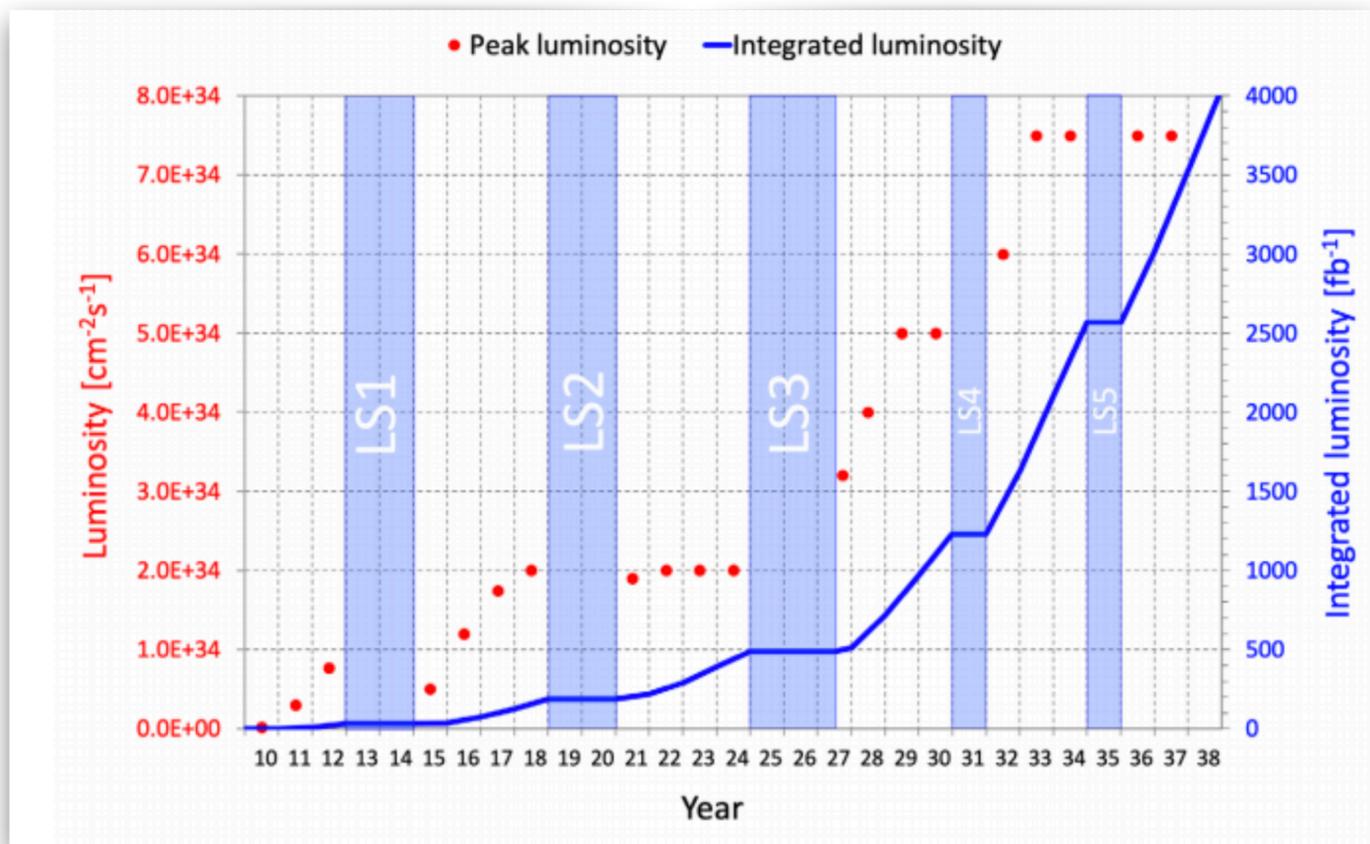
**Snowmass 2021**

EW Physics - [Higgs Boson properties and couplings](#)

EW Physics - [Higgs Boson portal to new physics](#)



# HL-LHC Roadmap



## Imminent Run 3 $500 \text{ fb}^{-1}$

- Starting spring 2022
- Centre-of-mass energy of 13.6 TeV (decided after two LHC sector warm ups for one dipole change and a diode repair as well as a risk assessment)
- Reaching an instantaneous luminosity of  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  (luminosity reached in 2018)
- Total integrated luminosity of  $300 \text{ fb}^{-1}$  to reach a total of  $500 \text{ fb}^{-1}$
- With luminosity levelling to optimise integrated luminosity versus risk and mitigate PU: 50 PU events expected. Conditions similar to 2018 (not huge change w.r.t. Run 2)

Process	ggF	HH	ttH
<b>13.6 TeV / 13 TeV</b>	<b>7%</b>	<b>11%</b>	<b>13%</b>
14 TeV / 13.6 TeV	6%	7%	7%

## Large jump in 2026-27 for Run 4 (then Run 5 and 6)

- Attempt to ramp to nominal 14 TeV
- Reaching an instantaneous luminosity of  $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  (luminosity reached in 2018)
- Total integrated luminosity should reach  $2.5 \text{ ab}^{-1}$
- Specific running conditions to be determined PU up to 140-200 possibly.

## Beyond Run 4 (full HL-LHC)

- Reaching an instantaneous luminosity of  $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Total integrated luminosity should reach  $3 - 4 \text{ ab}^{-1}$
- Up to PU of 200 possibly.

# Setting our Goals

## Main assumptions for the projections

- TH systematic uncertainties on the Higgs signals **divided by a factor of 2** w.r.t. 2018 values according to the foreseen improvements in Perturbative corrections PDFs,  $\alpha_S$
- Experimental systematic uncertainties reappraised in view of the larger dataset (many systematics dependent on data driven calibrations)
- Many uncertainties will also be reduced by the profiling (~equivalent to using control regions with higher statistics).
- MC statistics taken as negligible.

# 1 %

## Luminosity

*"Reduction down to 1% by a better understanding of the calibration methods and their stability employed in its determination, and making use of the new capabilities of the upgraded detectors."*

**Dominant uncertainties:** Calibration transfer (from VdM to entire period), scan-to-scan reproducibility, non factorisation effects and analytic fit model. See for instance ATLAS Run 2 [Pub Note](#).

**Nothing is granted!**

# Progress in TH Prediction (in a tiny nutshell)

Gavin Salam

## the master formula

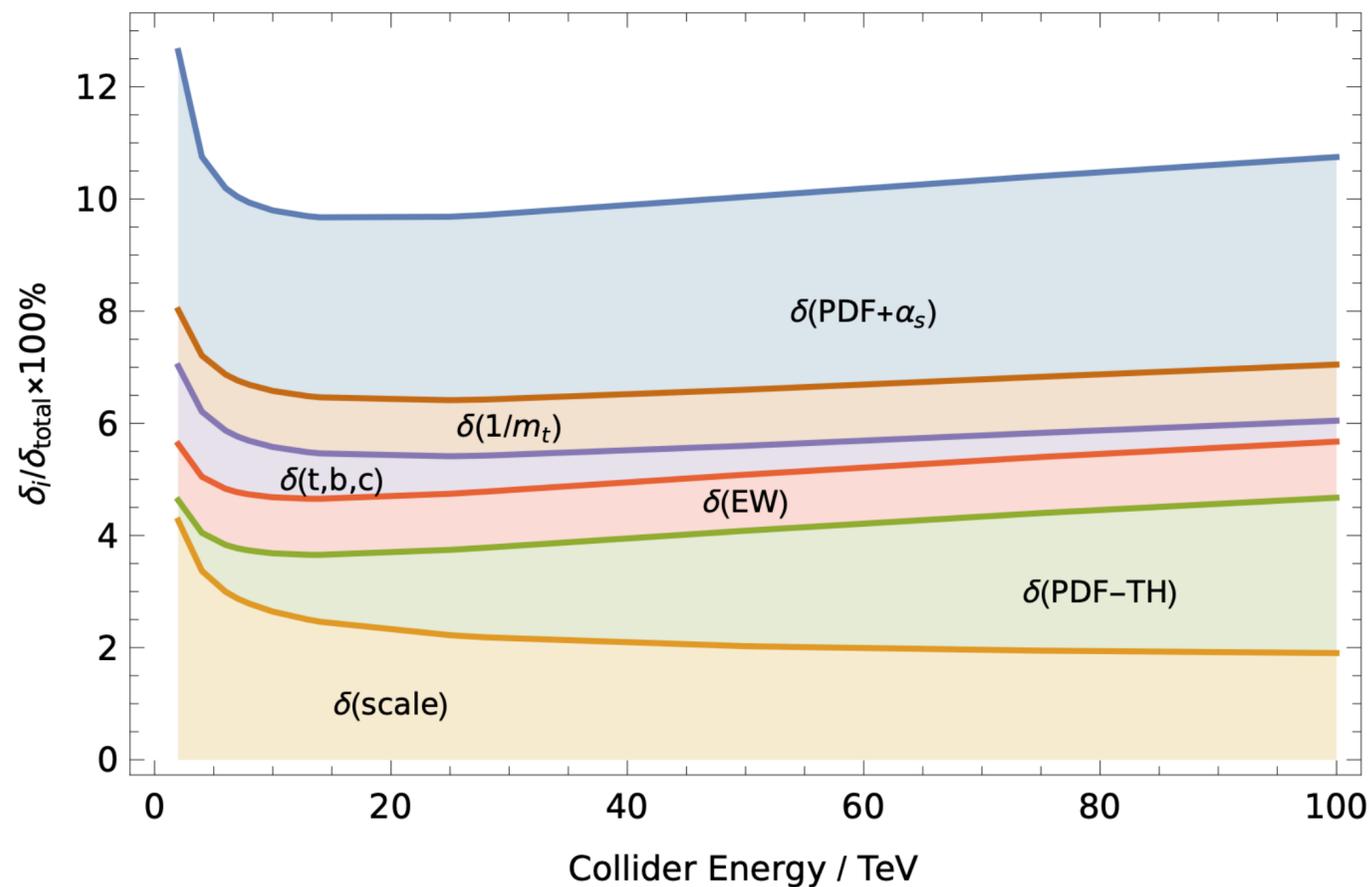
$$\sigma = \sum_{ij} \int dx_1 dx_2 f_{i/p}(x_1) f_{j/p}(x_2) \hat{\sigma}(x_1 x_2 s) \times [1 + \mathcal{O}(\Lambda/M)^p]$$

$\alpha_s$  Improvements in precision from the Lattice (until FCC-ee Z hadronic)

$$\sigma_{ggF} = 48.68 \pm 3.9 \text{ (scales)} \pm 1.9 \text{ (PDF)} \pm 2.6 \text{ } (\alpha_s) \text{ Pb}$$

PDFs already at 1% (CT18 - NNPDF)  
Discussions ongoing

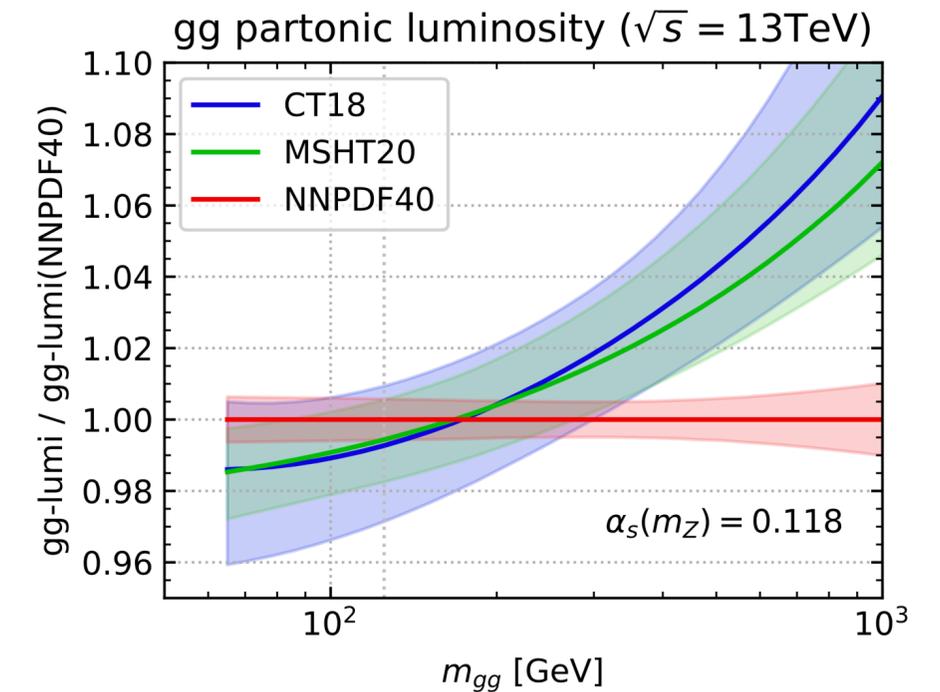
Gavin Salam



Alexander Huss

- PDF and  $\alpha_s$
- Finite quark masses effects
- Missing EW and mixed EW-QCD corrections
- Mismatch in the PDF (NNLO) and perturbative order N3LO
- Missing HO beyond N3LO

Many more signal processes!



Modelling of signal and background key!

- NLO QCD and EW predictions matched to PS
- NNLO PS matching
- CPU time challenge

Simon Plätzer  
Frank Siegert

# Performance Achievements and Challenges

- Run 1 and Run 2: So far excellent trigger and object reconstruction performance in **increasing levels of PU**. Trigger Thresholds kept relatively stable throughout.
- The gain in acceptance and in performance with new detectors (to improve PU mitigation), new algorithms and new computing capabilities is expected to at least match current experimental performance.
  - Keeping Trigger thresholds at similar levels
  - Object reconstruction performance (efficiency vs rejection and energy scale and resolution) at stable levels.
  - Challenge to come: improve calibrations not only with more data to come but also improved strategies.

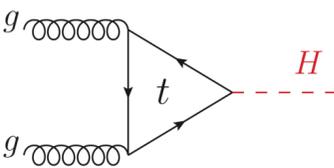
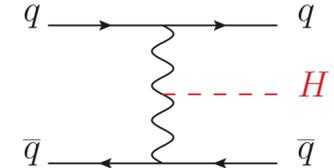
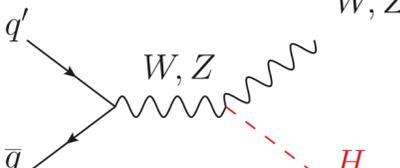
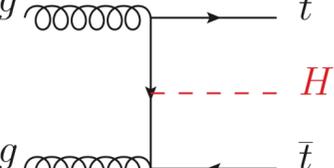
## Menus at LHC and for HL-LHC

Signature	Run 1	Run 2	HL-LHC
Single e (isolated)	25	27	22 / 27
Single photon	120	140	120*
HT	700	700	375 / 350
MET	150	200	200

- Increase readout rate 750-1000 kHz (currently 100 kHz).
- Increased latency and higher granularity.
- Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz).

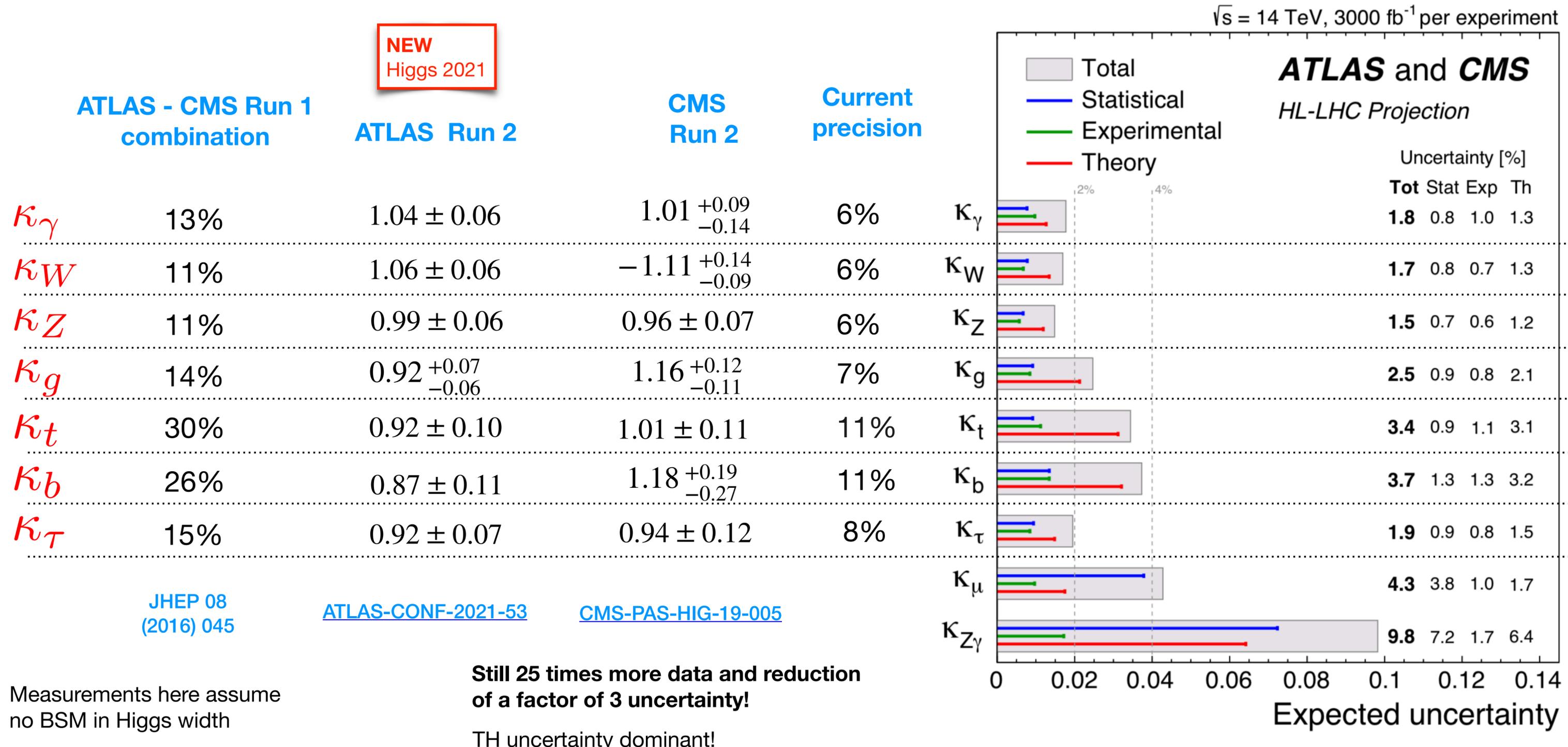
# Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 5% (~140 fb<sup>-1</sup>) of full HL-LHC dataset!

Channel categories	Br	ggF  ~4 M vets produced	VBF  ~300 k vets produced	VH  ~200 k vets produced	ttH  ~40 k evts produced	
Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb	
Observed modes	$\gamma\gamma$	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	$\tau\tau$	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Z $\gamma$ and $\gamma\gamma^*$	0.2 %	✓	✓	✓	✓
	$\mu\mu$	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

\*N3LO

# Where do we Stand in Coupling Properties Measurements?



# Measurement of the Higgs Boson Mass

10

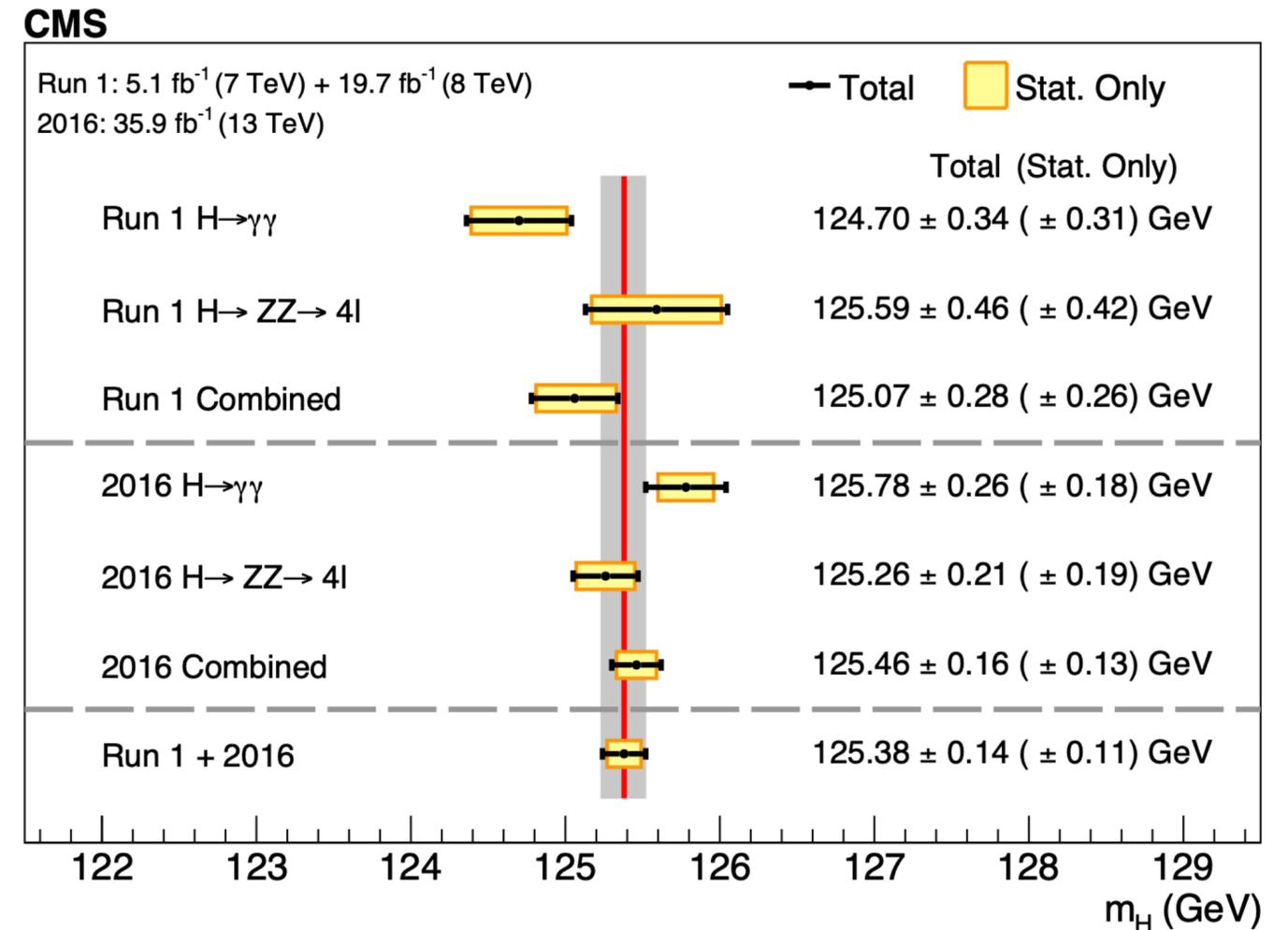
## Higgs boson mass measurement

- Measurement done exclusively in the diphoton and 4-leptons channel.
- Measurement precision dominated by statistics and **experimental** systematic uncertainties!
- Requires specific and most precise calibration!

Precision is driven by **statistics** but photon, electron and muon scale and resolution systematics will soon become limiting!

**at HL-LHC:** Goal to achieve ~10-20 MeV precision

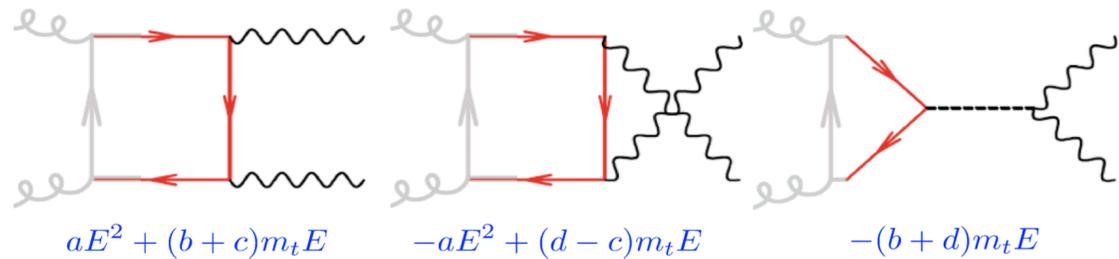
Latest (and most precise) measurement from [CMS](#):



Precision mass measurements could also lead to constraints on the Higgs width through mass shifts from the interference between signal and continuum in the diphoton channel (see backup)

# Off Shell HVV Couplings and Width

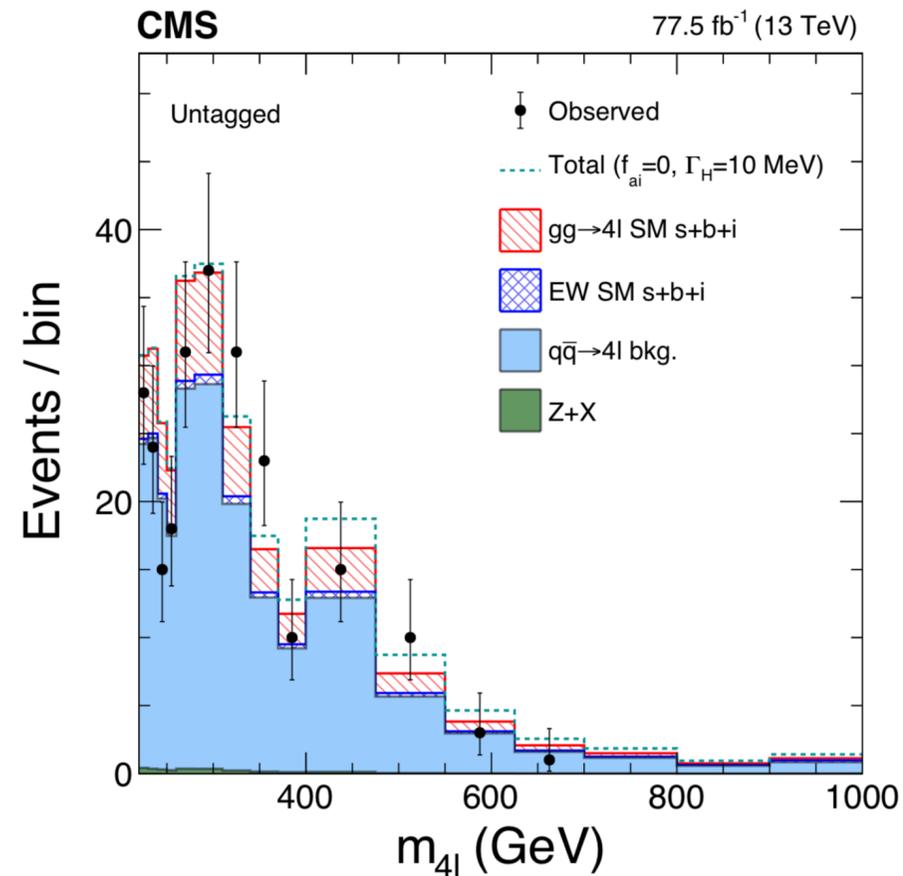
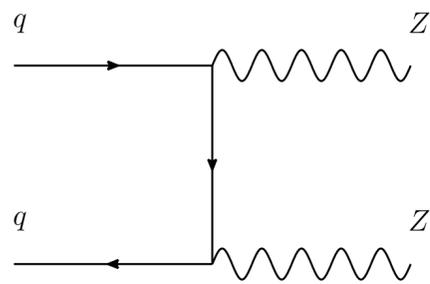
**Higgs as a propagator:** Without the s-channel Higgs unitarity problem!



From J. Campbell

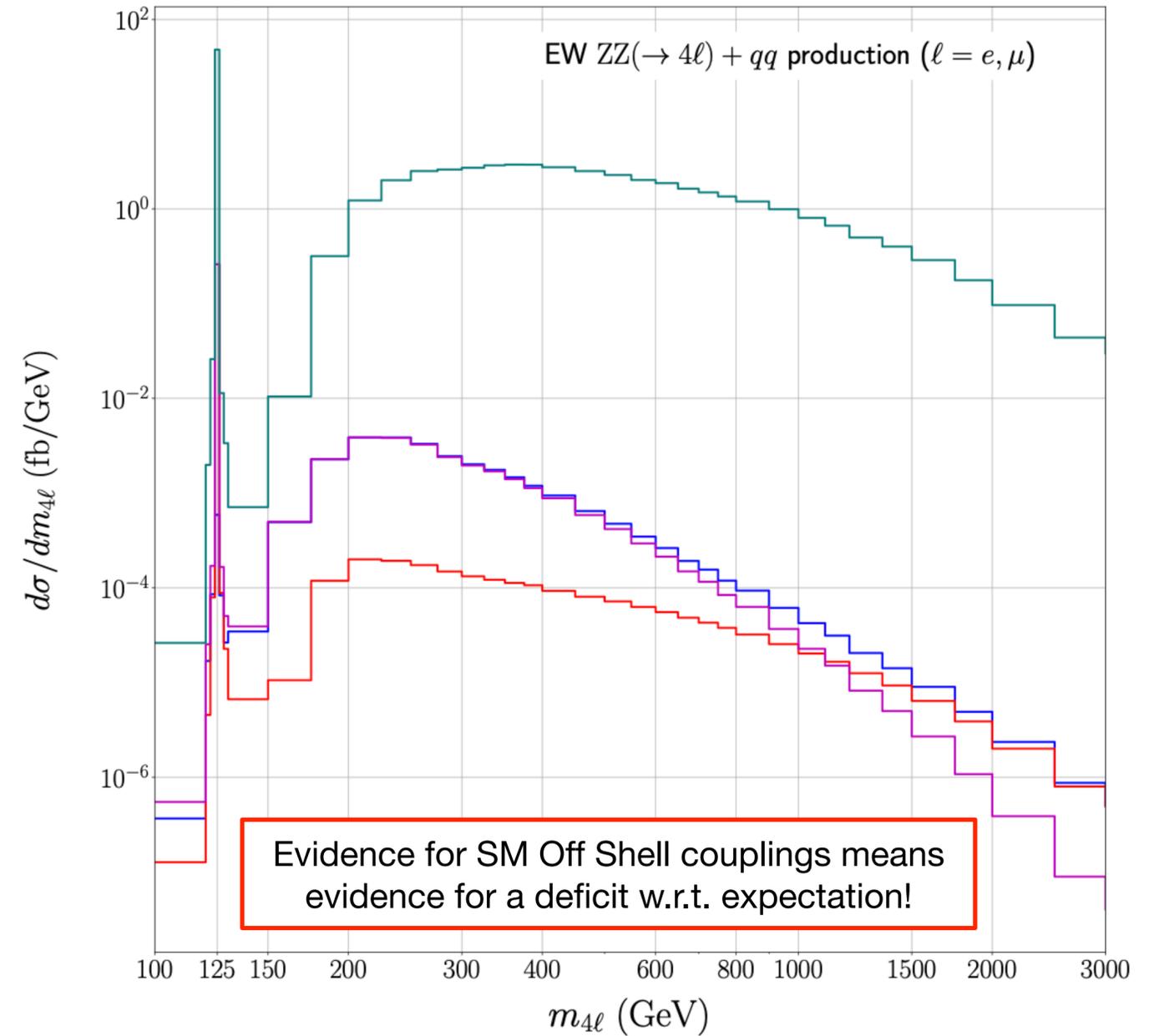
Negative interference Higgs signal and  $gg \rightarrow VV$  background

Highly non trivial also due to large other backgrounds:



**CMS Simulation**

13 TeV



Evidence for SM Off Shell couplings means evidence for a deficit w.r.t. expectation!

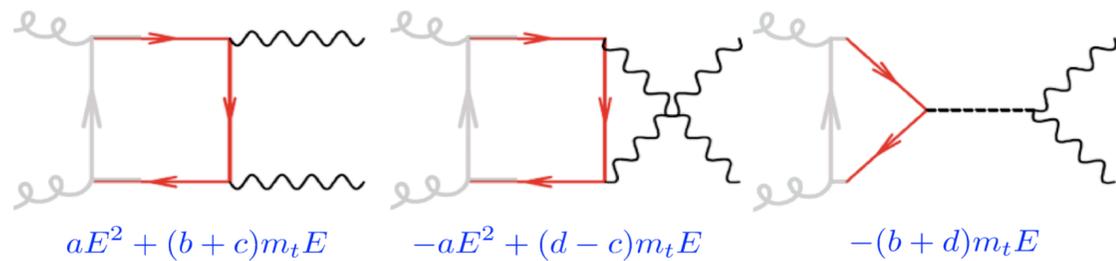
Constraint:

$$\mu_{sig}^{on-shell}(gg \rightarrow H \rightarrow ZZ \rightarrow 2e2\mu) = 1$$

- SM H signal
- SM contin.
- Total SM
- Total PS

# Off Shell HVV Couplings and Width

**Higgs as a propagator:** Without the s-channel Higgs unitarity problem!



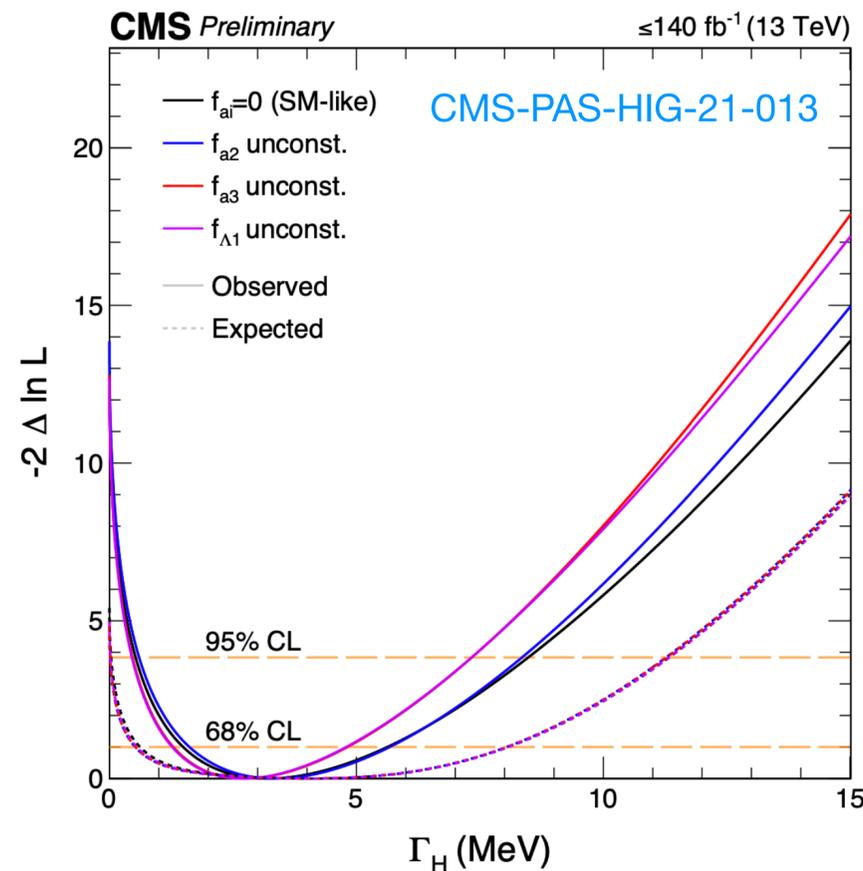
From J. Campbell

Extraction of the width using ratio between Off Shell and On Shell couplings  
Assuming that these couplings run as in the Standard Model and measuring them **on shell** allows for a measurement of the width of the Higgs boson!

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \quad (\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

## CMS Combination $4\ell$ with $2\ell 2\nu$

**NEW**  
Higgs 2021



See talks by Keti Kaadze, Savas Kyriacou and Mostafa Mahdavihorrami

**Partial Run 2 dataset!** [PRD 99](#) (2019):

$$\Gamma_H = 3.2^{+2.8}_{-2.2} \text{ MeV}$$

Expected sensitivity:  $\Gamma_H = 4.1^{+5.0}_{-4.0} \text{ MeV}$

**Combination with  $ZZ \rightarrow 2\ell 2\nu$**

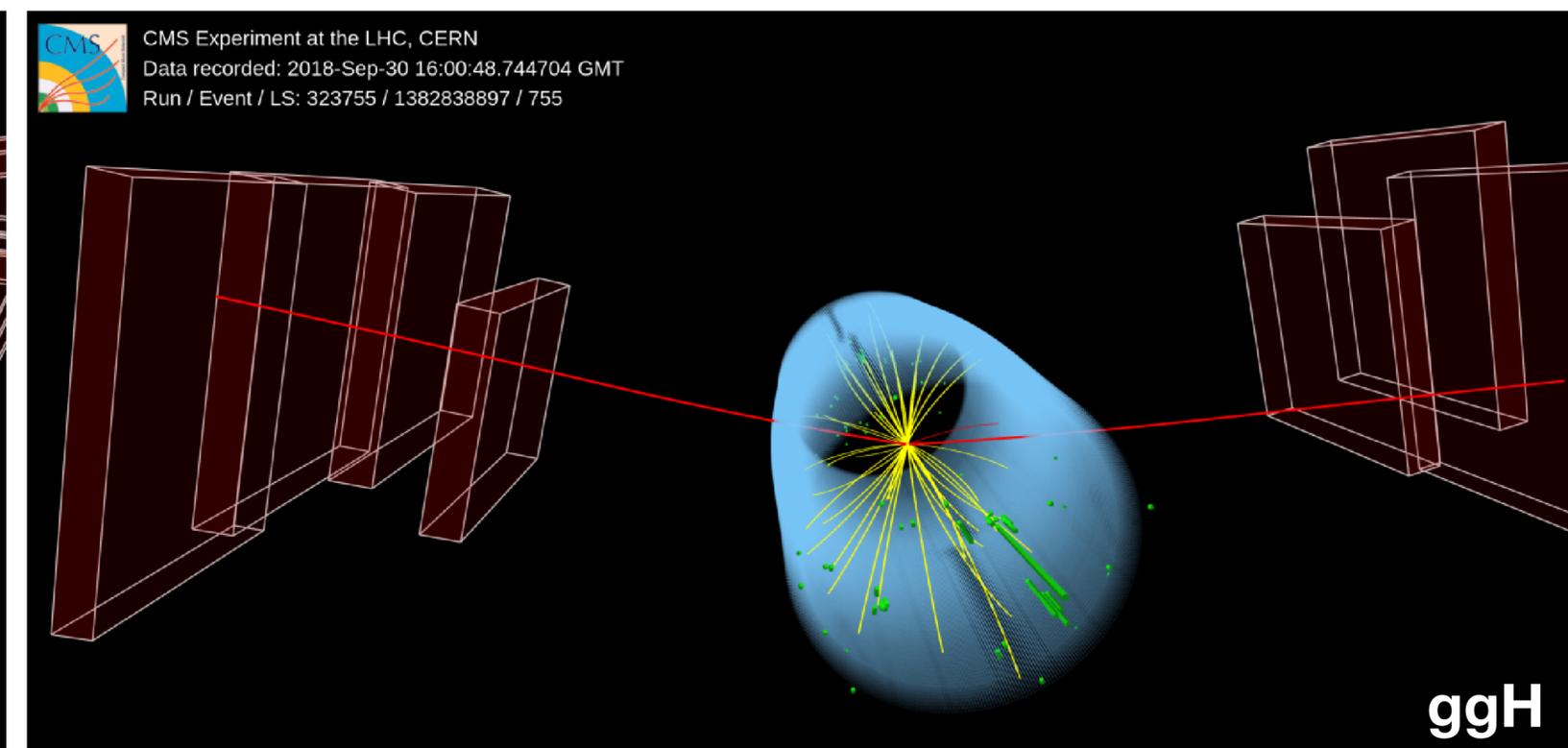
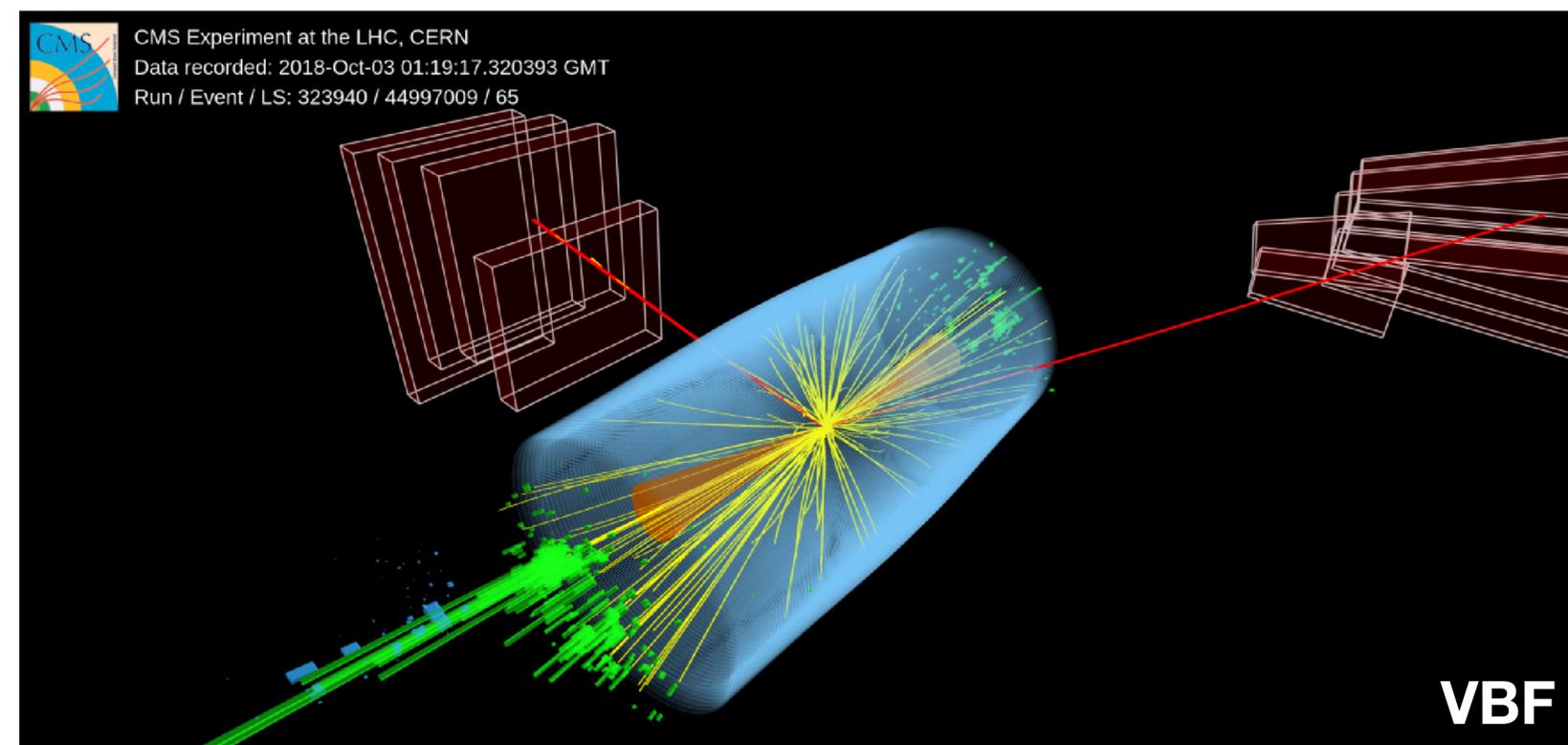
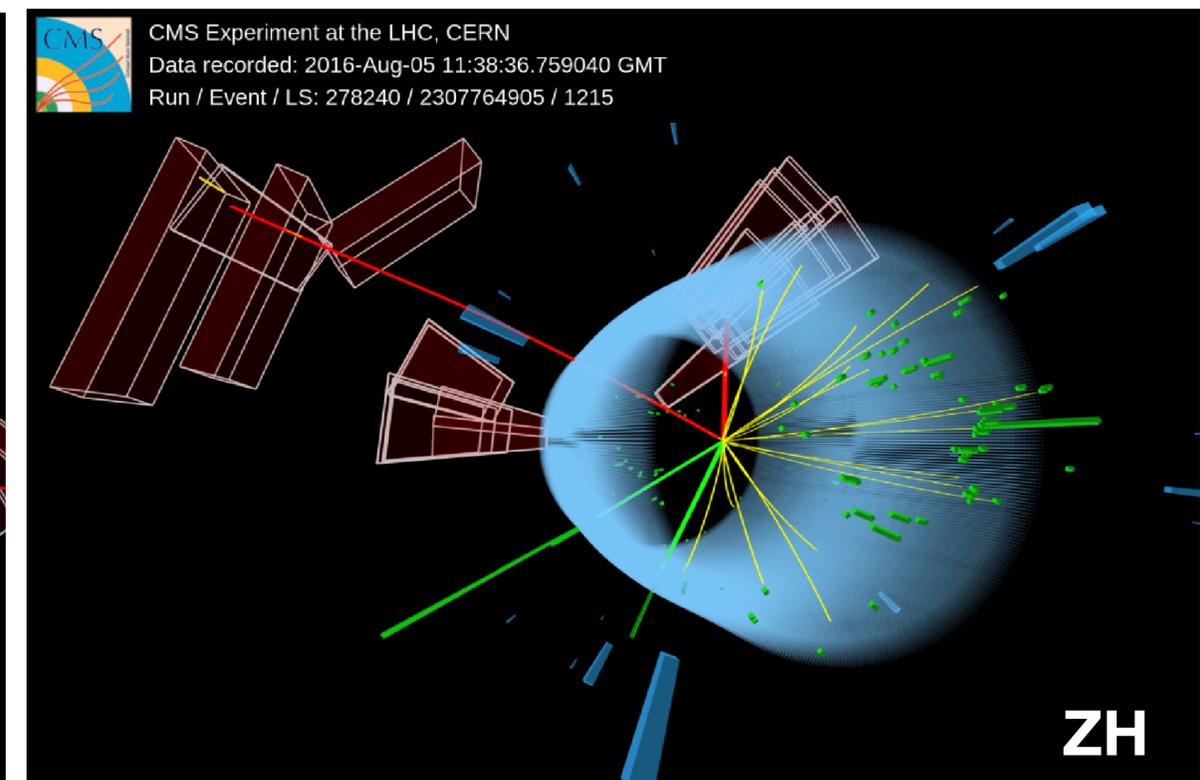
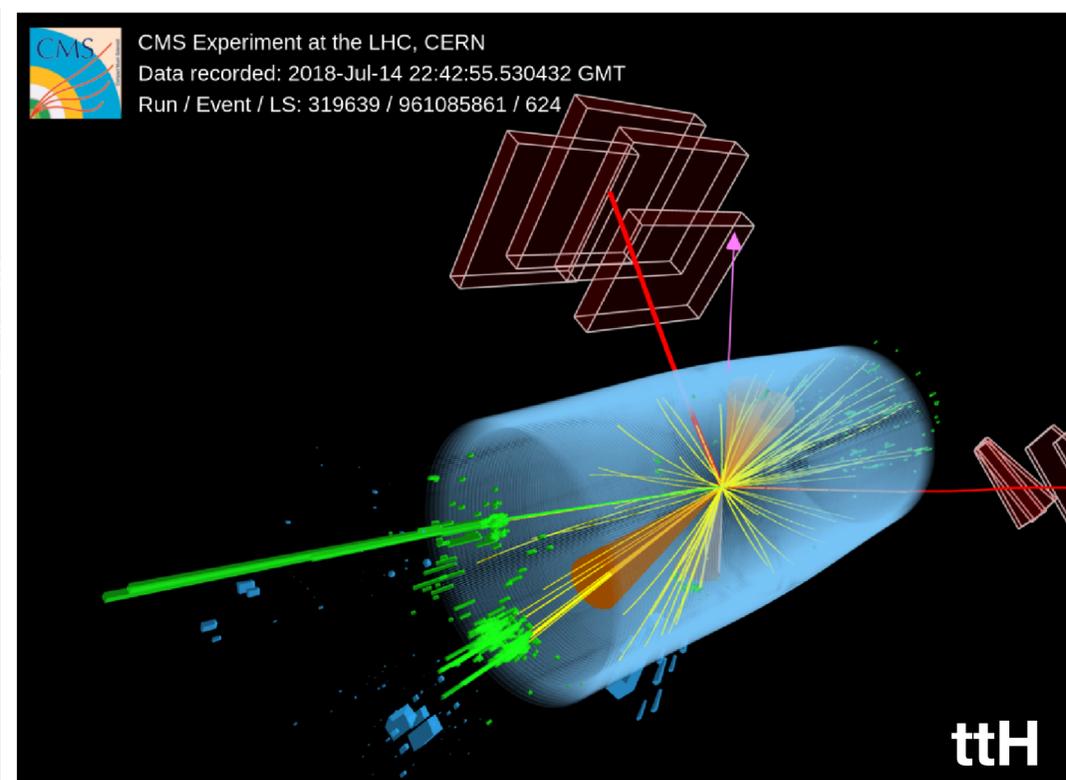
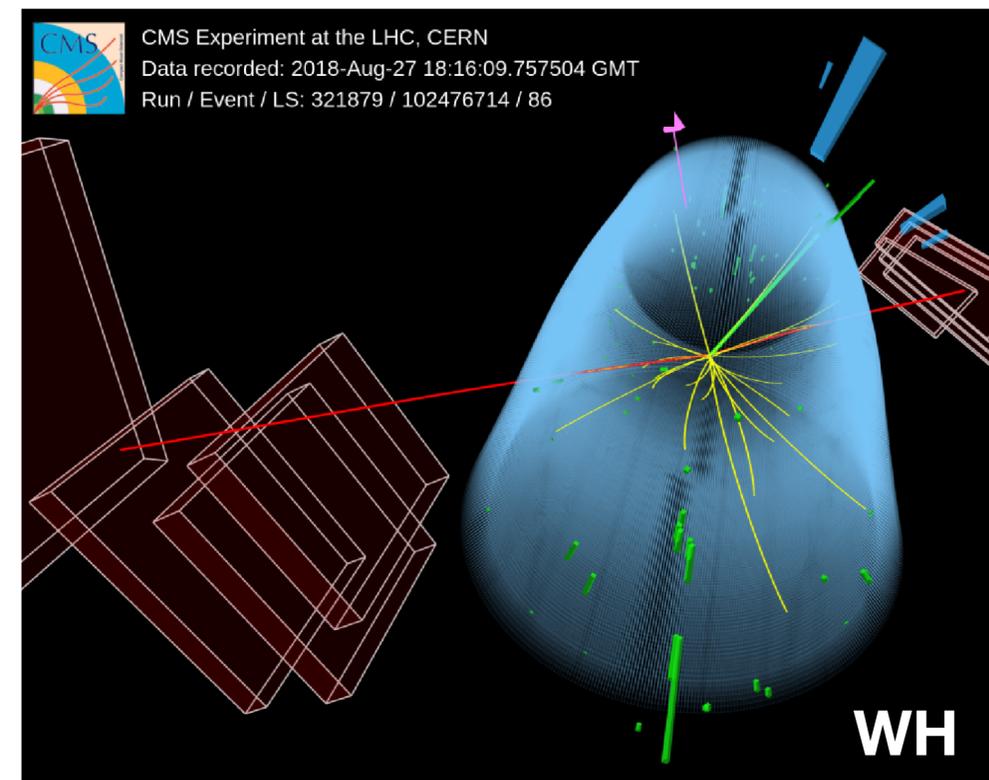
$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$$

Evidence for Off-Shell production at  $3.6\sigma$

**at HL-LHC:**  $\Gamma_H = 4.1^{+1.0}_{-1.1}$  Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with  $3 \text{ ab}^{-1}$

**Remarkable result to follow closely at Run 3!**  
**How much better can be done at HL-LHC?**

# Evidence for $H \rightarrow \mu^+ \mu^-$



# Evidence for Second Generation Yukawa Coupling

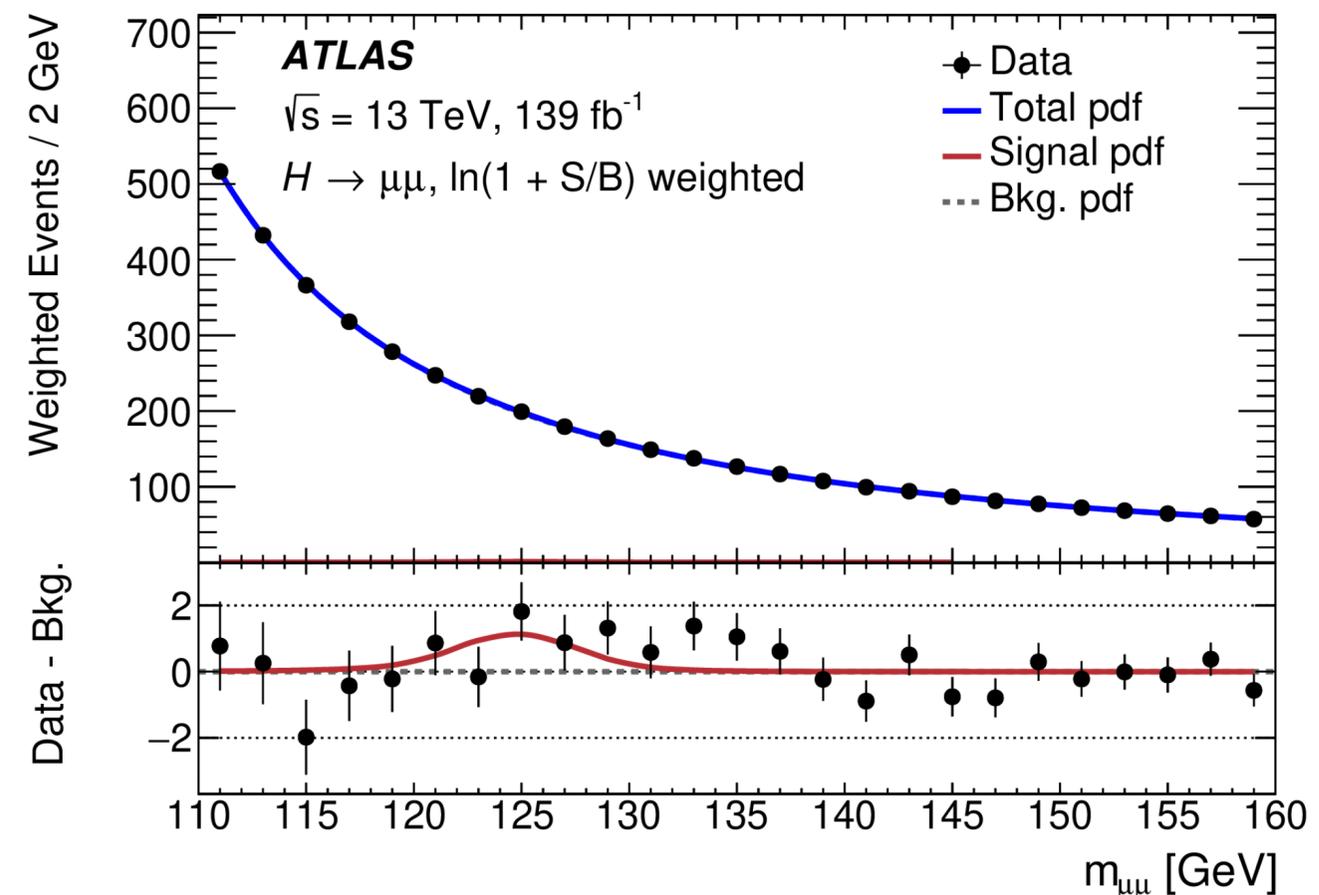
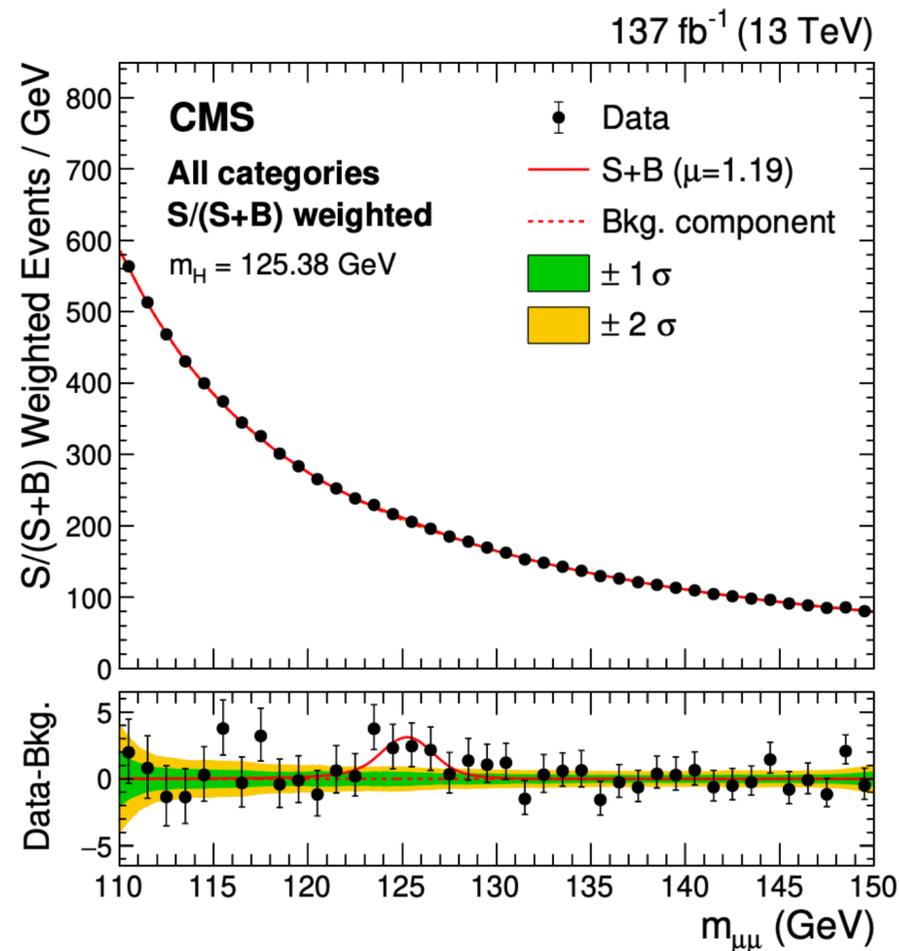
## Very challenging channel!

- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity through the separation in production modes.

## Analysis overview

- All production modes ggF, VBF, VH, ttH
- Improvements in mass resolution through Brem recovery
- DNN/BDT discriminants in all categories / Sideband region used to control backgrounds

**Summary of all categories** Estimate the background parameters through a fit of an analytical form!



# Evidence for Second Generation Yukawa Coupling

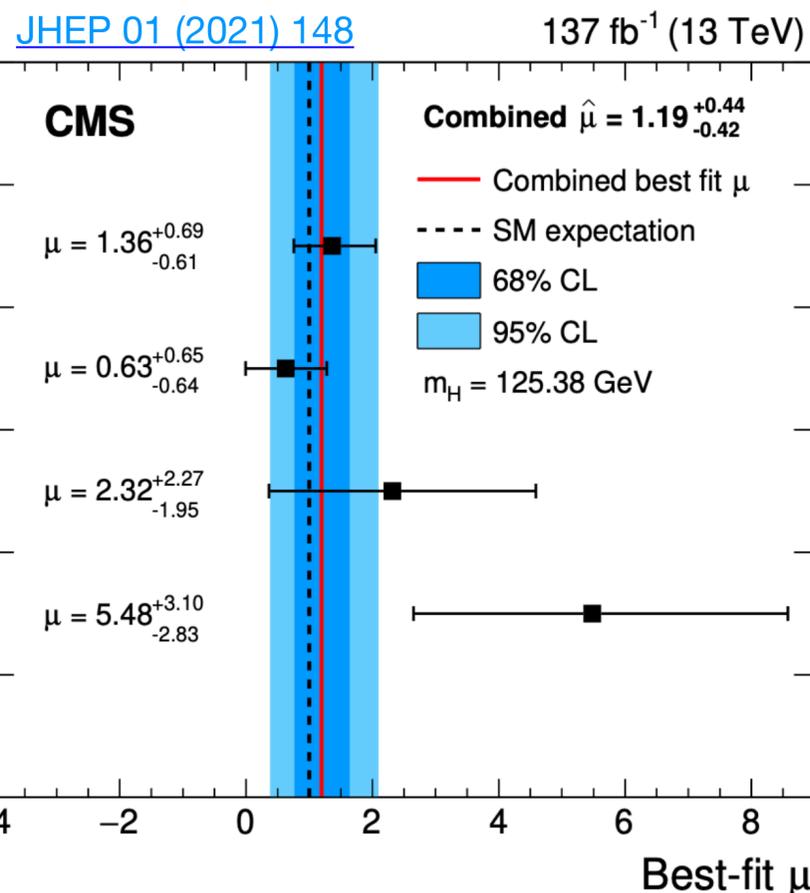
## Very challenging channel!

- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity through the separation in production modes.

## Analysis overview

- All production modes ggF, VBF, VH, ttH
- Improvements in mass resolution through Brem recovery
- DNN/BDT discriminants in all categories / Sideband region used to control backgrounds

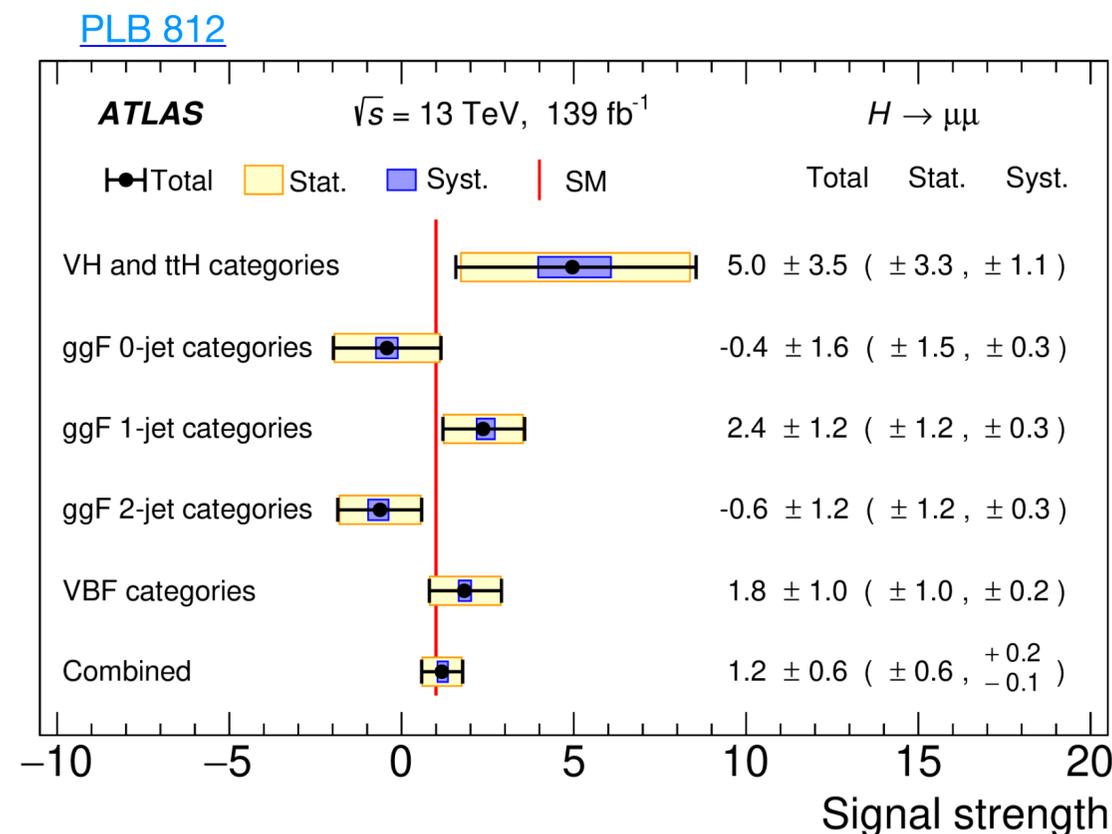
**Summary of all categories** Estimate the background parameters through a fit of an analytical form!



## CMS Result

Expected  $2.5\sigma$   
 Observed  $3.0\sigma$

$$\mu = 1.19 \pm 0.43$$



## ATLAS Result

Expected  $1.7\sigma$   
 Observed  $2.0\sigma$

$$\mu = 1.2 \pm 0.6$$

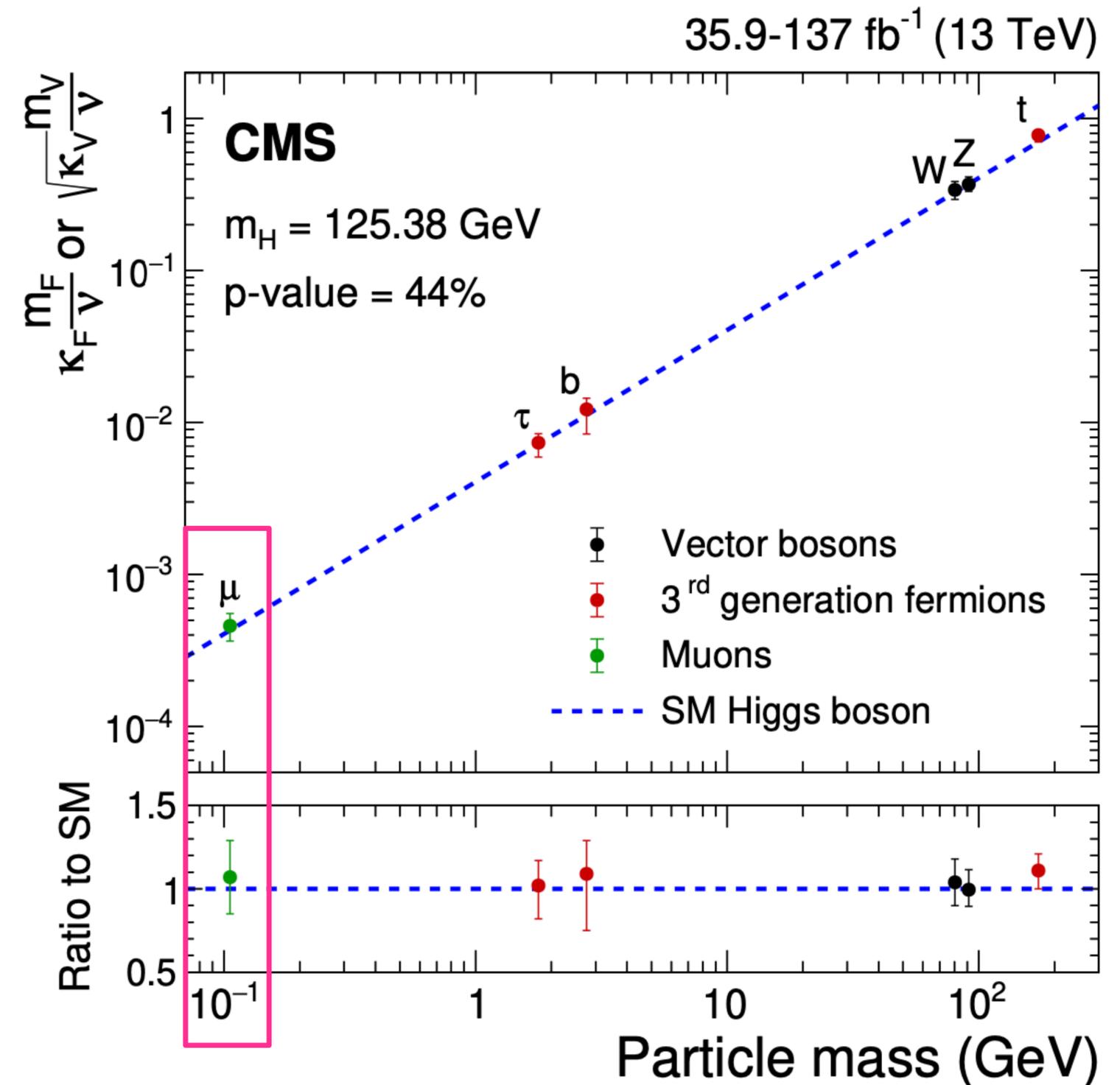
Result dominated by statistical uncertainty, but watch systematics!

# Evidence for Second Generation Yukawa Coupling

## Superb achievement!

- With 300 fb<sup>-1</sup> Additional, combined significance should nearly reach **observation sensitivity!**
- Foreseen precision at **HL-LHC 4.3%**
- With new analysis should be able to reach **~3%** level.
- Control of background modelling systematic uncertainty need to be better than 5% of the signal meaning better than O(0.5) permil of the background!

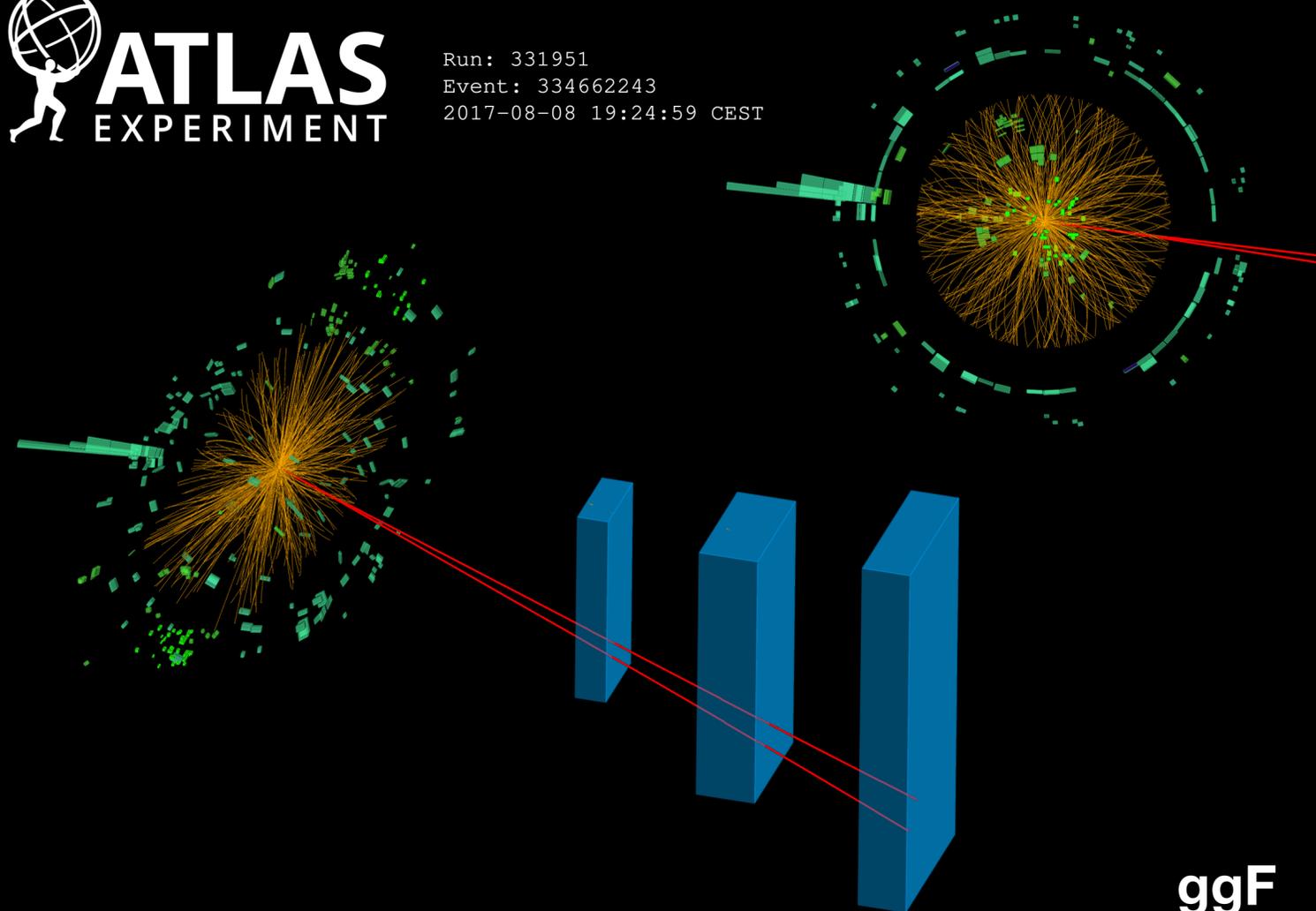
Spurious signal type background modelling uncertainties will not scale down with the data statistics but with the MC!



# Evidence for $H \rightarrow \gamma \ell^+ \ell^-$

 **ATLAS**  
EXPERIMENT

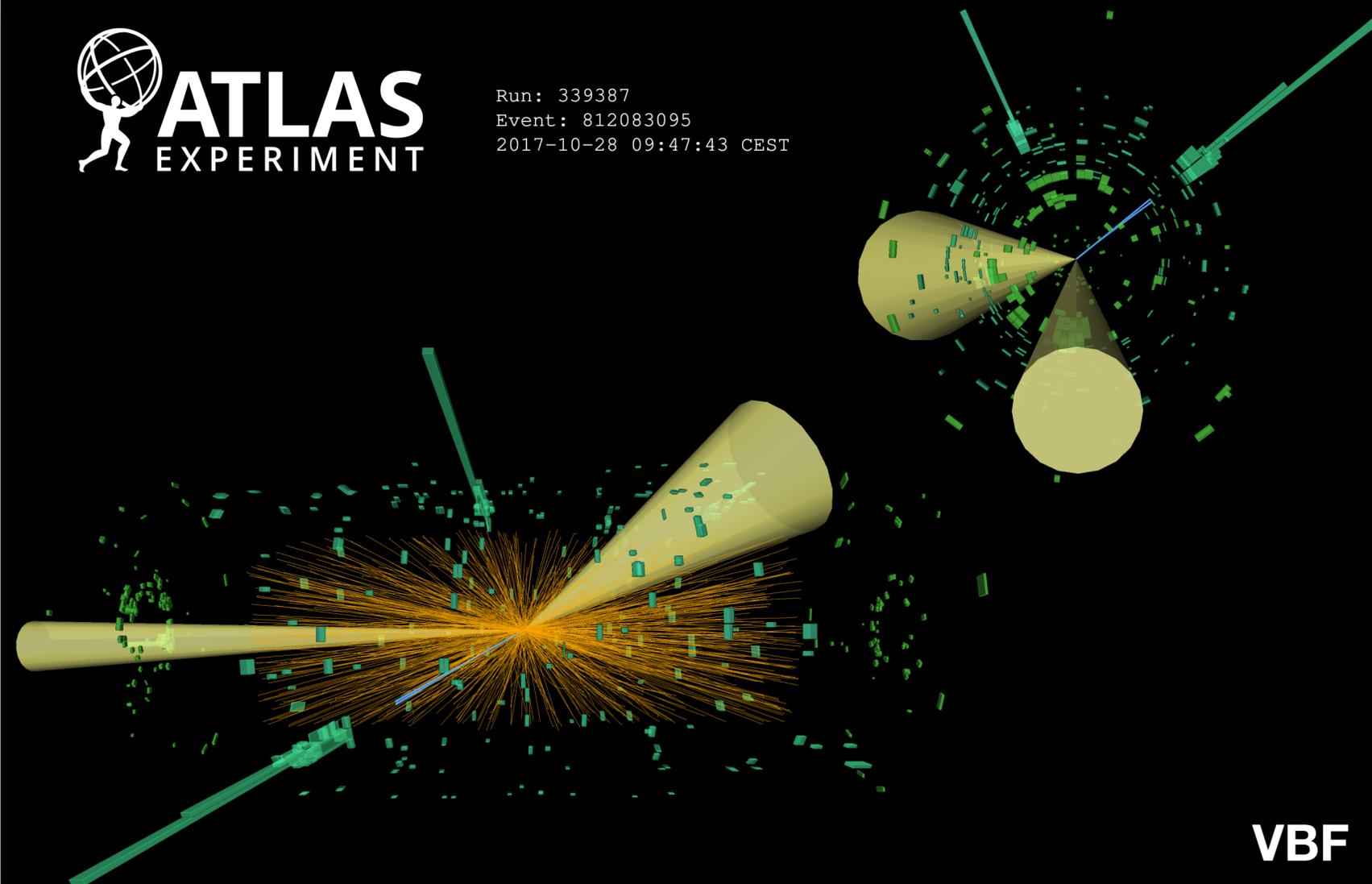
Run: 331951  
Event: 334662243  
2017-08-08 19:24:59 CEST



ggF

 **ATLAS**  
EXPERIMENT

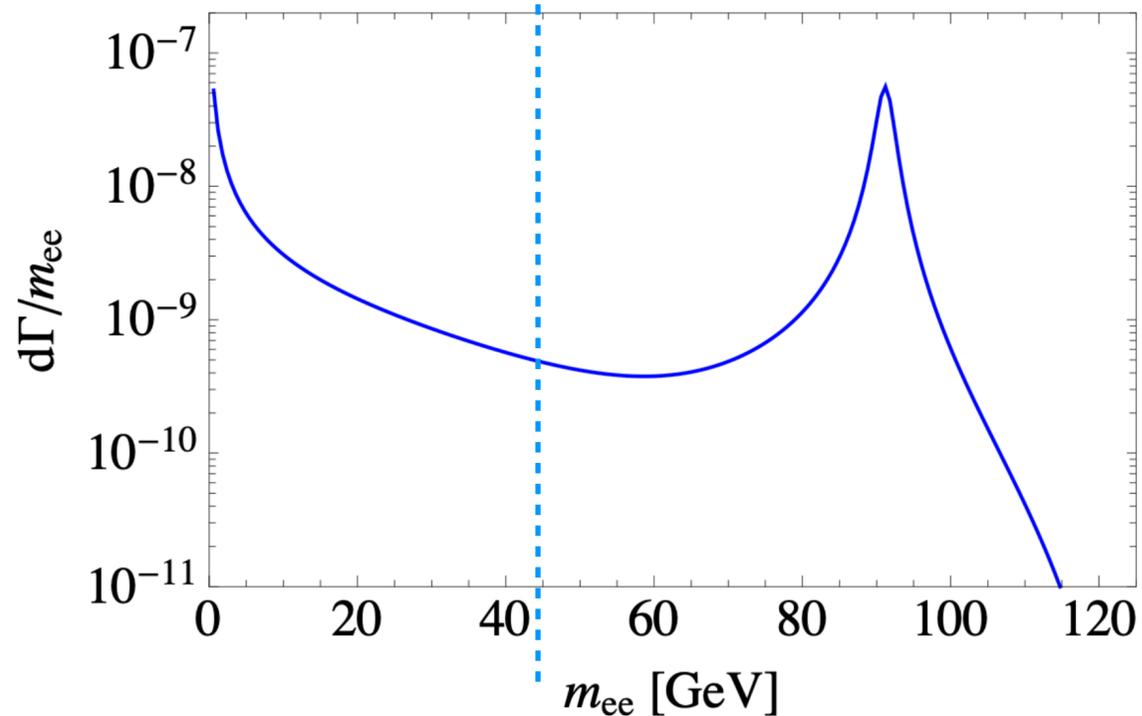
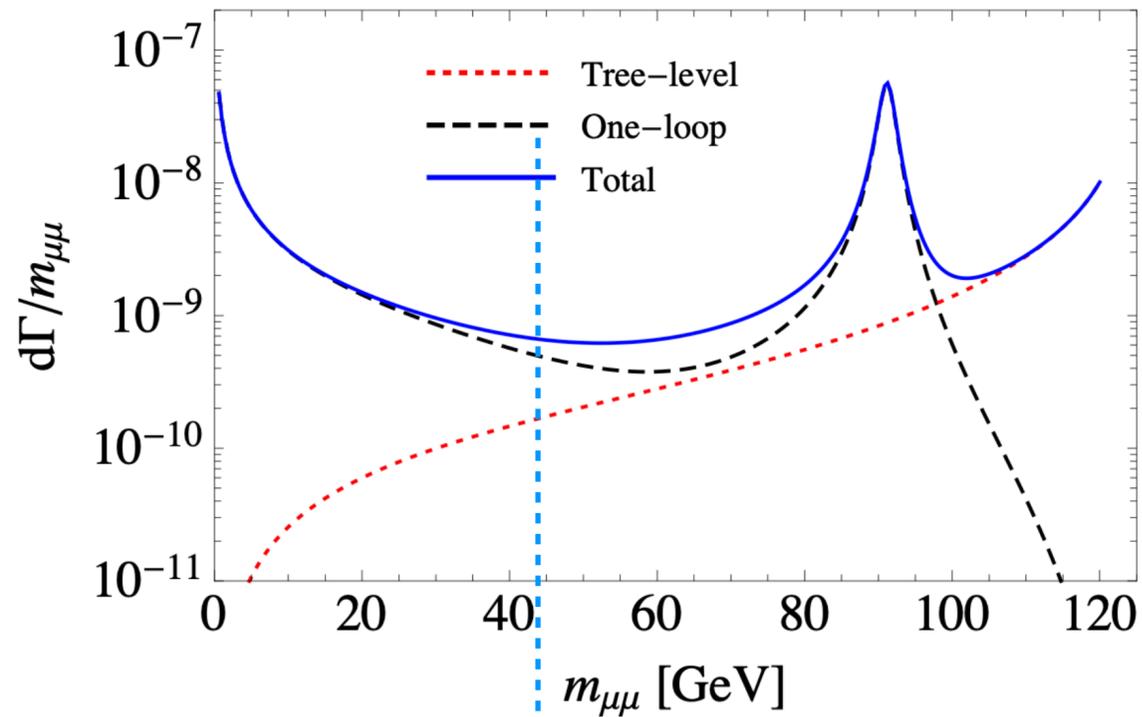
Run: 339387  
Event: 812083095  
2017-10-28 09:47:43 CEST



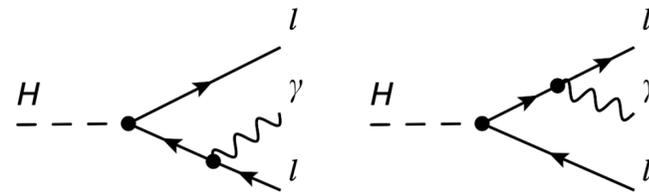
VBF

# Evidence for $H \rightarrow \gamma \ell^+ \ell^-$

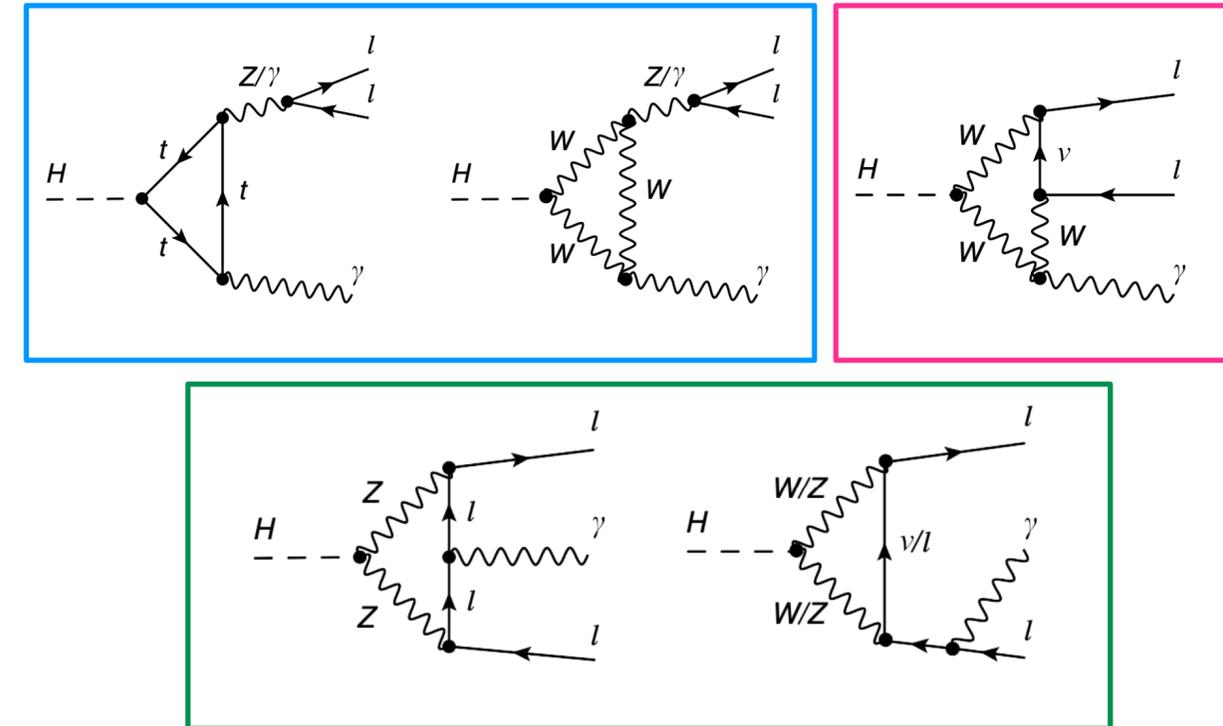
[Phys. Rev. D 101, 073003 \(2020\)](#)



Tree level (visible only for muons)



Loop level diagrams different types of contributions



A very interesting channel studied in two regimes, at the Z resonance ( $Z\gamma$ ) often referred to as  $\gamma^*\gamma$  but this neglects important contributions to the  $\gamma \ell \ell$  decay!

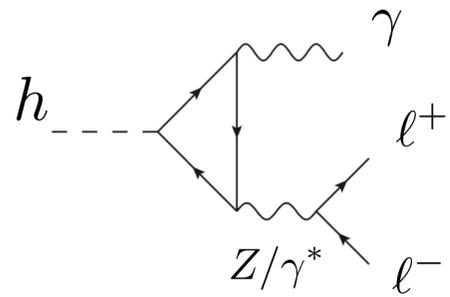
Underlying BSM dynamics that could affect the  $R_{K^*}$  ratio could also affect the  $\ell \ell \gamma$  rate

$$R_{K^*} \equiv \frac{\text{Br}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\text{Br}(B \rightarrow K^{(*)} e^+ e^-)}$$

Interesting decay observable as a Forward-Backward asymmetry of the lepton w.r.t. flight direction, sensitive to **CP violation** in the interference between the  $Z\gamma$  and  $\gamma^{(*)}\gamma$  couplings.

# Evidence for $H \rightarrow \gamma \ell^+ \ell^-$

[Phys. Lett. B 819 \(2021\) 136412](#)



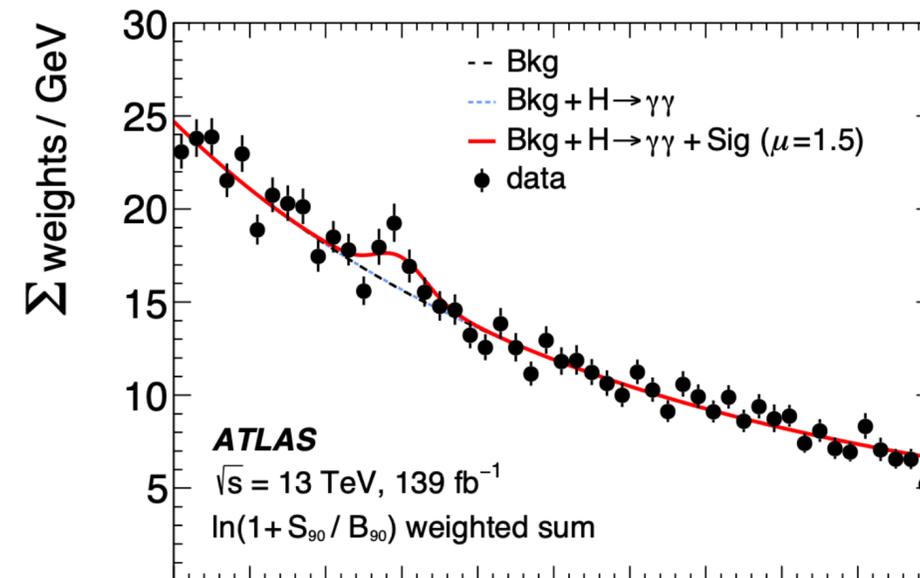
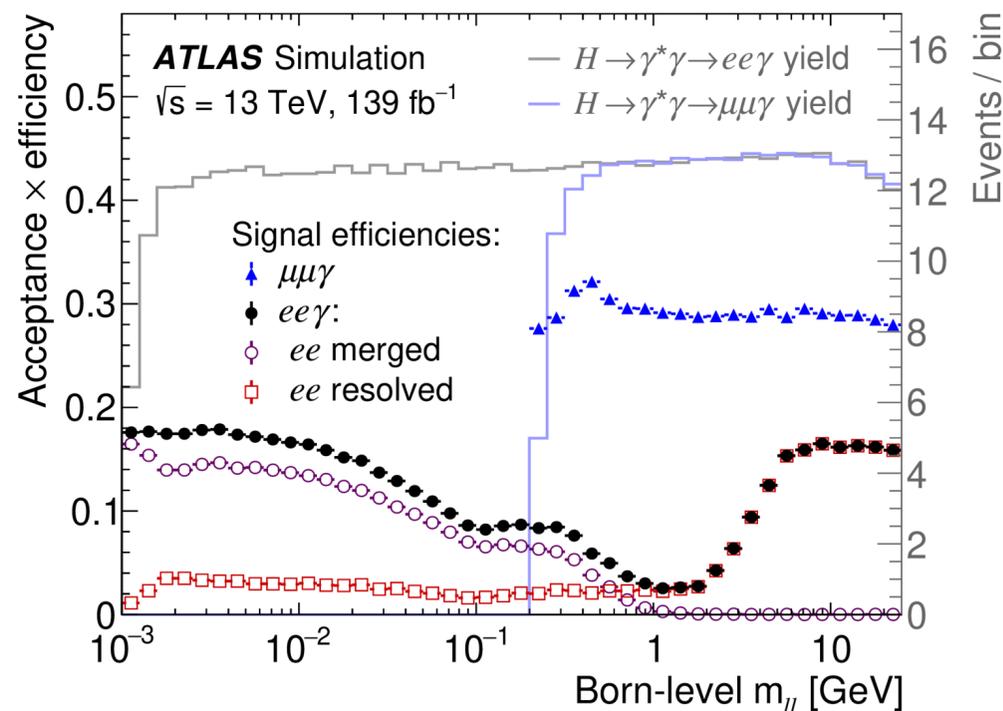
Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

$$\sim 1.7\% \text{ of } Br(\gamma\gamma)$$

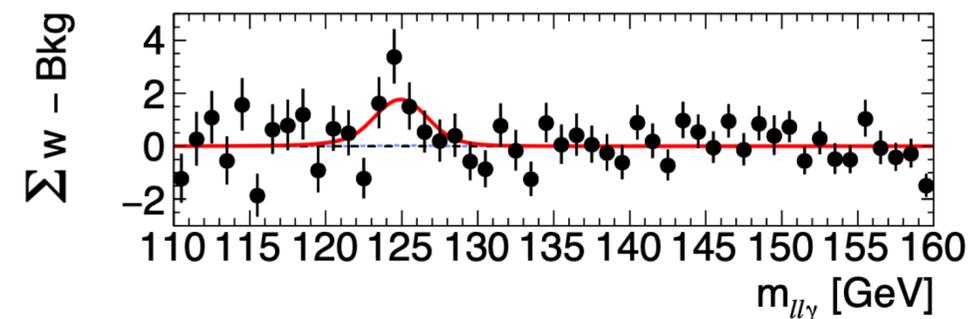
$$m_{\ell^+\ell^-} < 50 \text{ GeV}$$

Key experimental challenge is to go to low dilepton mass this required a **new reconstruction technique**:

Merged electron reconstruction where a calorimeter (electron-like) cluster is associated to two tracks and conversions are carefully rejected!



- 3 x 3 categories (VBF, high pT ggF, low pT ggF) ⊗ (ee resolved, ee merged,  $\mu\mu$ )
- Contributions from  $J/\psi$  are removed with a mass cut



$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5 \text{ (stat.) }^{+0.2}_{-0.1} \text{ (syst.)}$$

Expected  $2.1\sigma$

$$\mu_{\text{exp}} = 1.0 \pm 0.5 = 1.0 \pm 0.5 \text{ (stat.) }^{+0.2}_{-0.1} \text{ (syst.)}$$

Observed  $3.2\sigma$

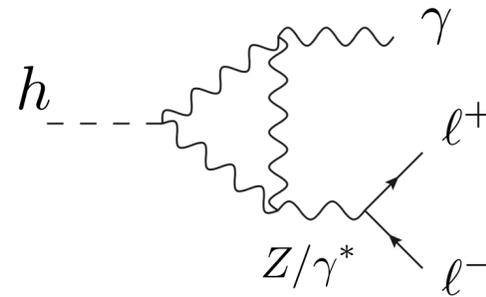
In this case the **HL-LHC** **O(3%)**

**Highlights importance of further developing our reconstruction techniques!**

# Searches for the $H \rightarrow Z\gamma$ Decay Mode

**Z-photon**  $|H^2|W_{\mu\nu}^a W^{\mu\nu a}$

Field tensor coupling not measured yet!



$\sim 2.3\%$  of  $Br(\gamma\gamma)$

A priori straightforward similar search for a leptonic (electrons and muons) decaying Z and a photon.

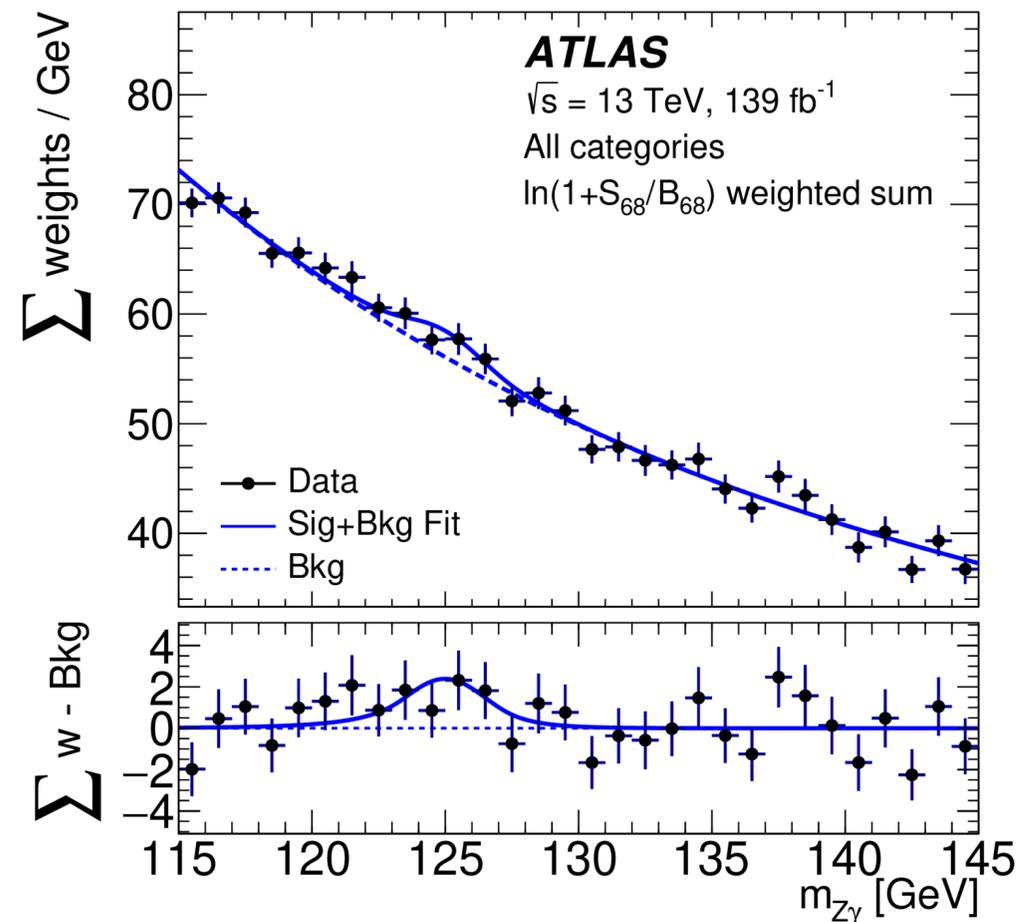
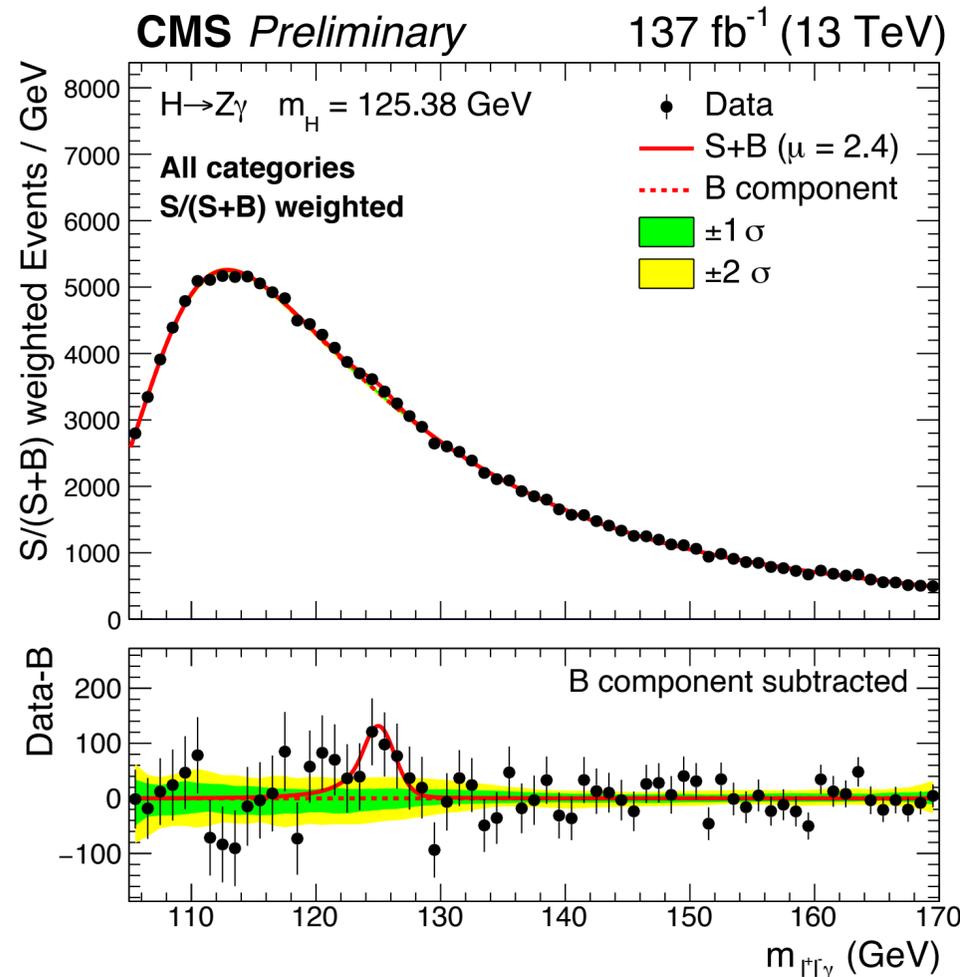
**NEW**  
Higgs 2021

## CMS Result

ggF, VBF, VH and ttH enriched channels

$$\mu_{Z\gamma} = 2.4 \pm 0.9$$

Expected  $1.2\sigma$   
Observed  $2.7\sigma$



## ATLAS Result

ggF and VBF enriched channels

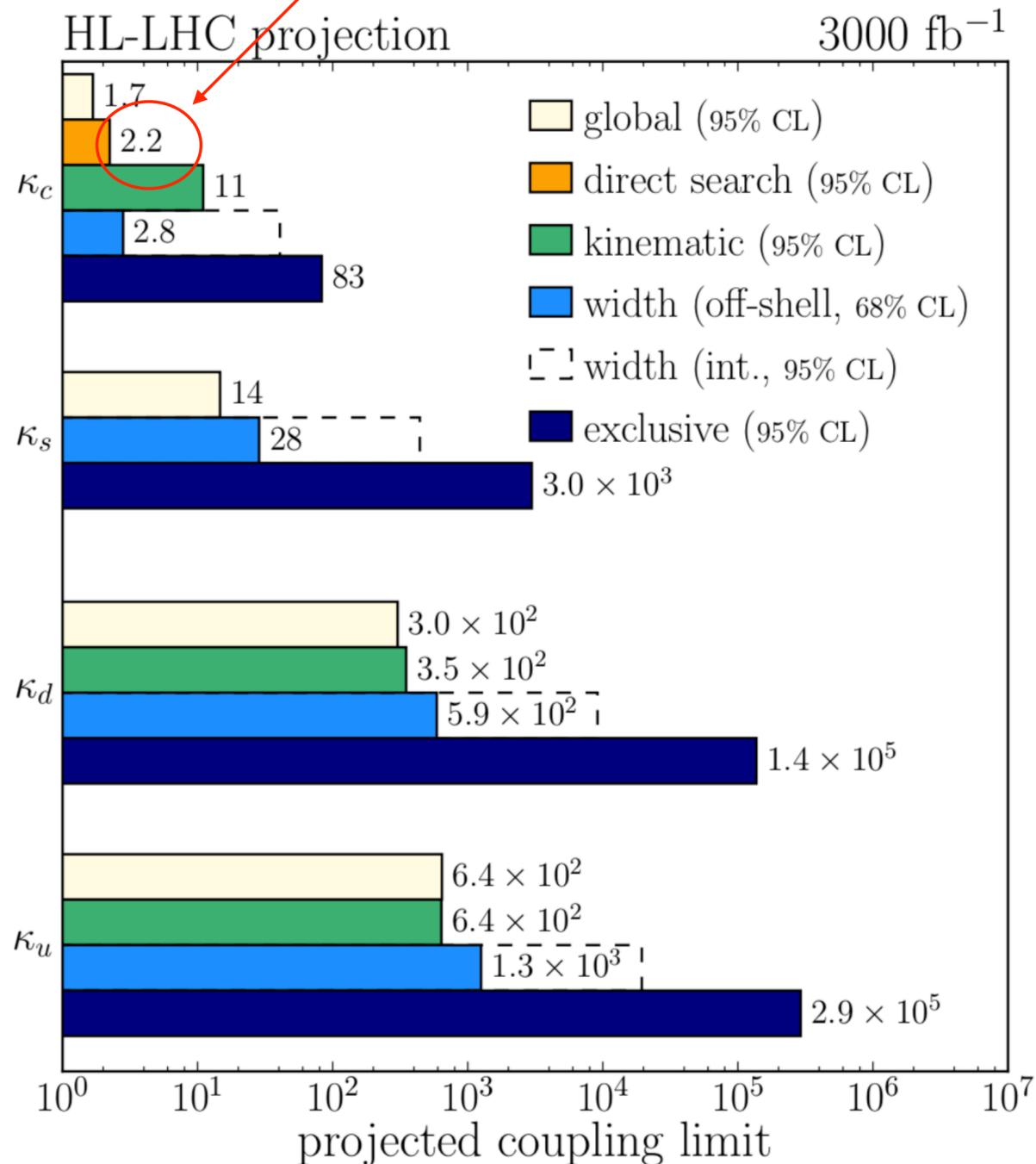
$$\mu_{Z\gamma} = 2.0 \pm 0.9$$

Expected  $1.2\sigma$   
Observed  $2.2\sigma$

To follow closely at Run 3 for first evidence!

Already significantly better sensitivity than analysis used for the YR projection **HL-LHC**  $\sim 10\%$

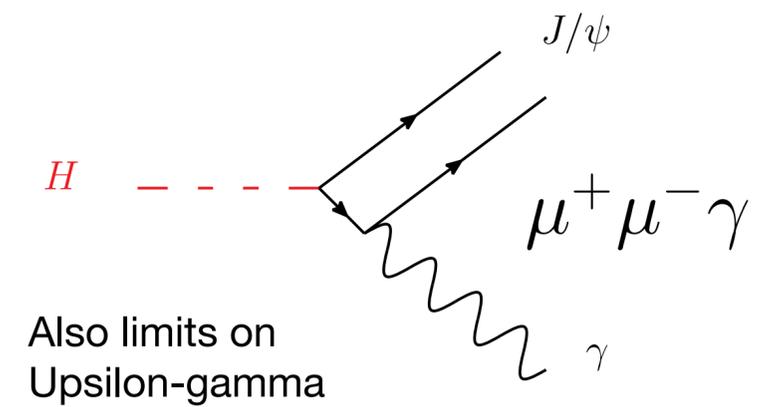
Includes (approximately)  
projection from LHCb analysis



## First and Second generation Yukawas

- Most stringent constraint coming from the couplings fit assuming no BSM width.
- For the charm Yukawa direct search (using charm tagging) is not far behind!
- Then coupling combination through width offshell.
- Exclusive searches still only marginally sensitive.
- New emerging ideas to be explored with such large datasets.

Potentially sensitive to charm Yukawa



Sensitivity to gamma-gamma\* (top loop) and interference

HL-LHC

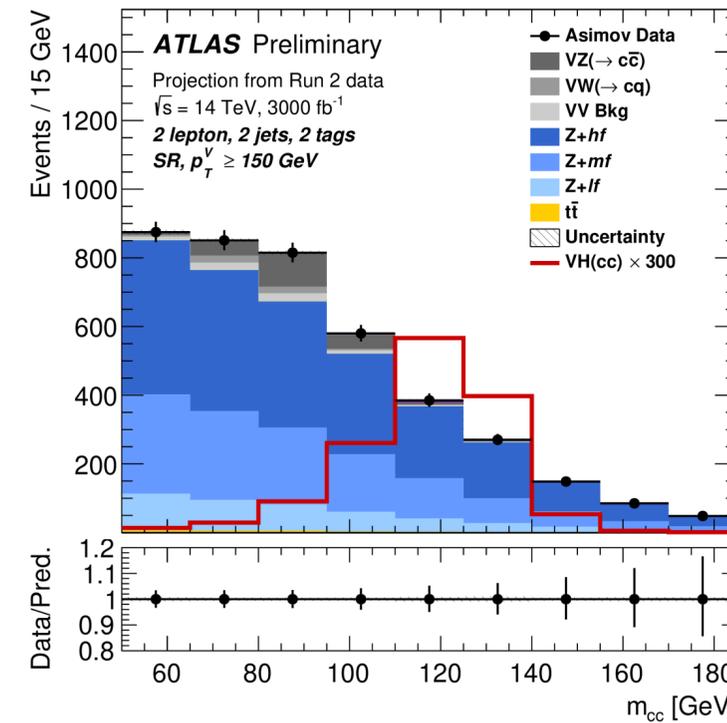
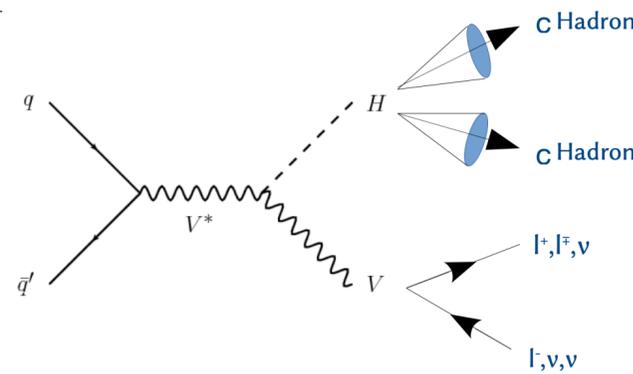
<15xSM

# The challenging Yukawa coupling to charm

NEW  
Higgs 2021

[ATL-PHYS-PUB-2021-039](https://arxiv.org/abs/2103.03917)

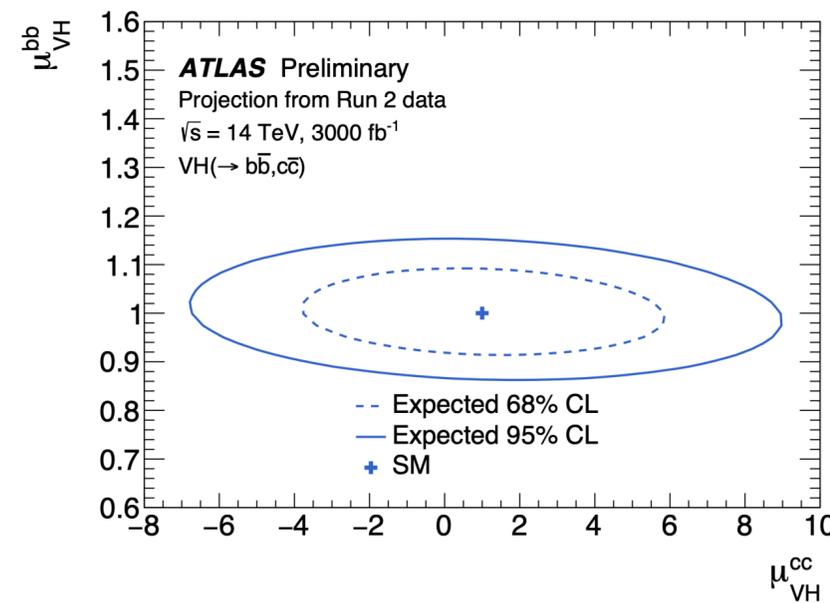
Analysis of the VH(bb) and VH(cc) simultaneous with charm tagging!



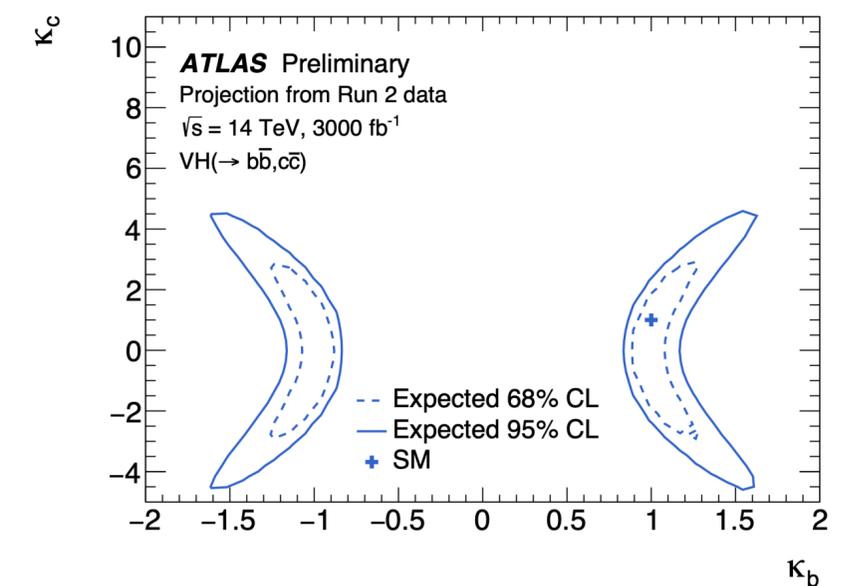
$$\mu_{VH}^{b\bar{b}} = 1.00 \pm 0.06,$$

$$\mu_{VH}^{c\bar{c}} = 1.00 \pm 3.20$$

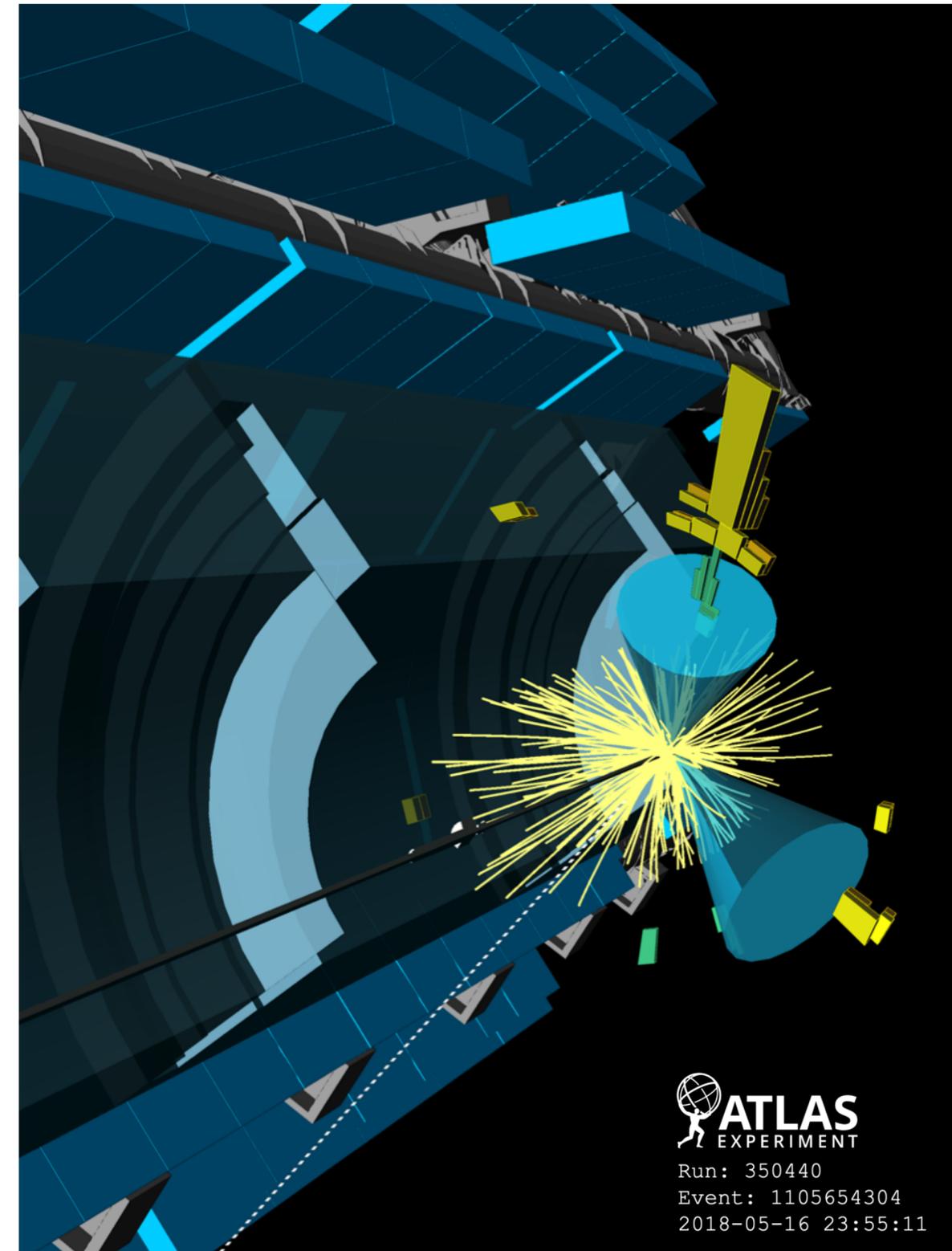
Done in combination between VH(bb) and VH(cc)!



Moderate correlation of **-11%**



$$|\kappa_c| < 3.0 \quad |\kappa_c/\kappa_b| < 2.7$$



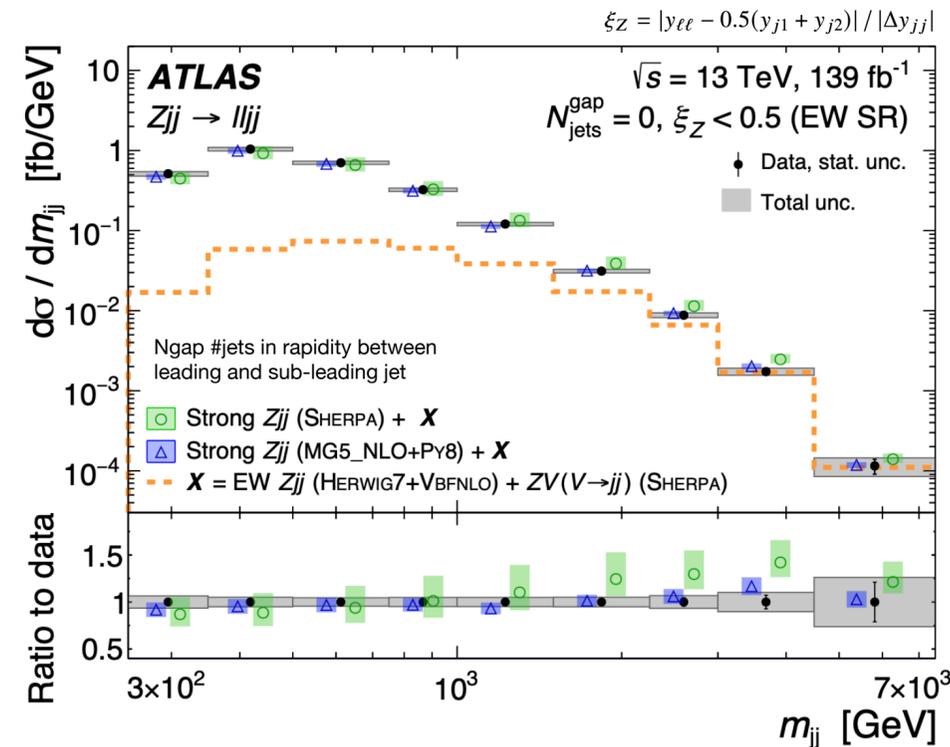
ATLAS  
EXPERIMENT

Run: 350440  
Event: 1105654304  
2018-05-16 23:55:11

# The challenging Yukawa coupling to charm

Source of uncertainty	$\Delta\mu_{VH}^{c\bar{c}}$
Total	3.21
Statistical	1.97
Systematics	2.53
Statistical uncertainties	
Data statistics only	1.59
Floating normalisations	0.95
Theoretical and modelling uncertainties	
$VH, H \rightarrow c\bar{c}$	0.27
<b>Z+jets</b>	<b>1.77</b>
Top-quark	0.96
W+jets	0.84
Diboson	0.34
$VH, H \rightarrow b\bar{b}$	0.29
Multi-Jet	0.09
Experimental uncertainties	
Jets	0.59
Leptons	0.20
$E_T^{\text{miss}}$	0.18
Pile-up and luminosity	0.19
Flavour tagging	
c-jets	0.61
b-jets	0.16
light-jets	0.51
$\tau$ -jets	0.19

## V+jets production



## ME accuracy

SHERPA 2.2.1      NLO (0-2j), LO (3-4j)

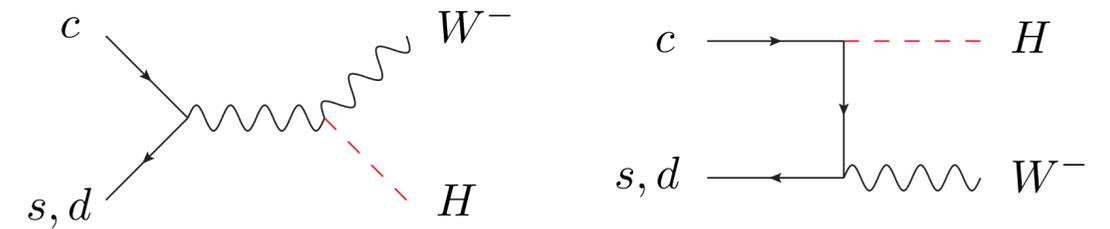
MADGRAPH5\_aMC@NLO      NLO (0-2j), LO (3-4j)

Frank Siegert    Simon Plätzer

## Highlights importance of:

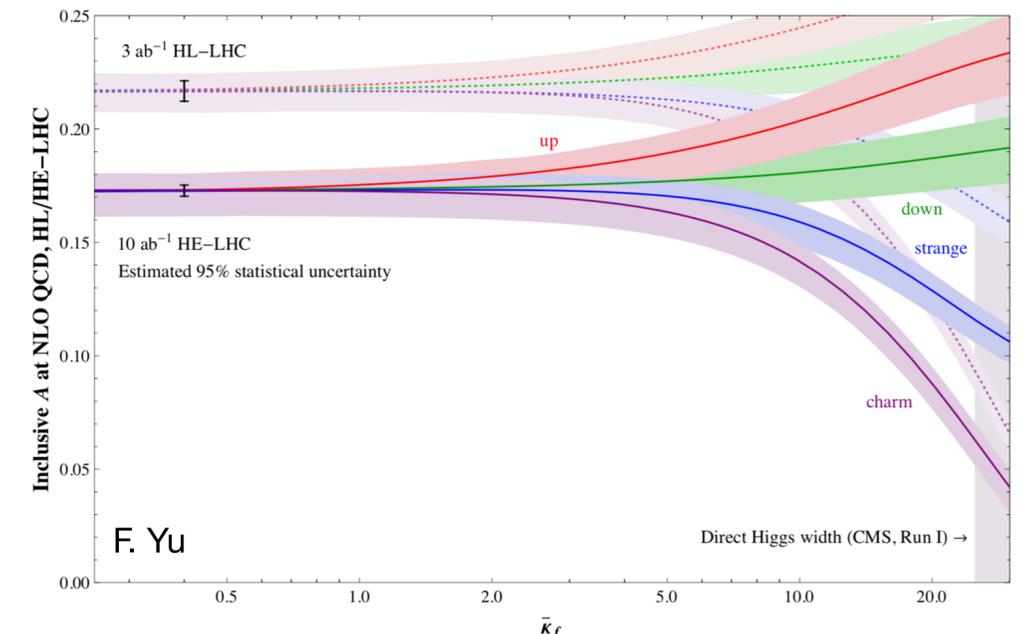
- State-of-the-art prediction
- Ancillary measurements
- Fiducial measurements and their ratios

## VH(bb) fiducial measurements and ratios can also help constraining $Y_c$ !



Based on d anti-d asymmetry in the PDFs

$$A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}$$

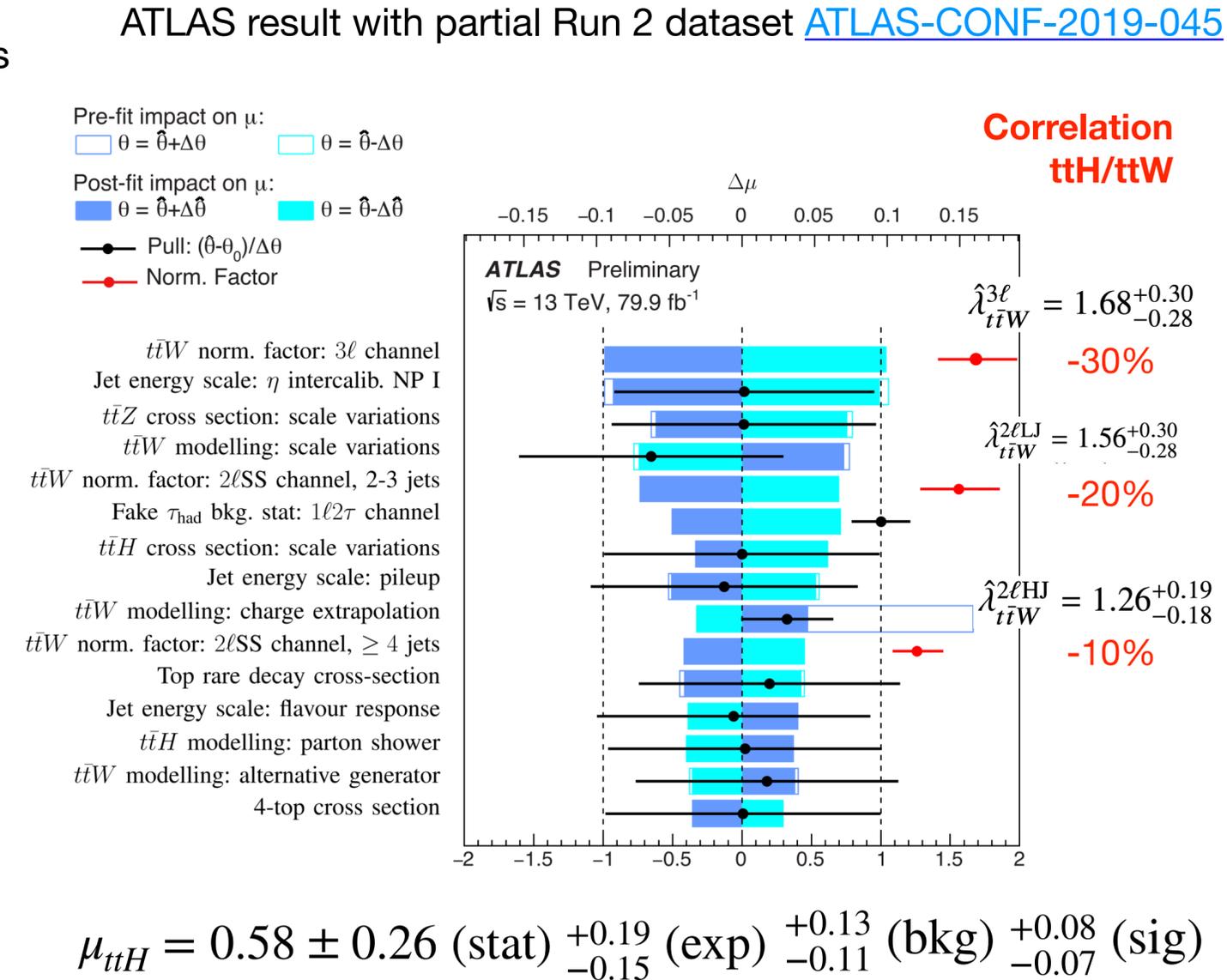
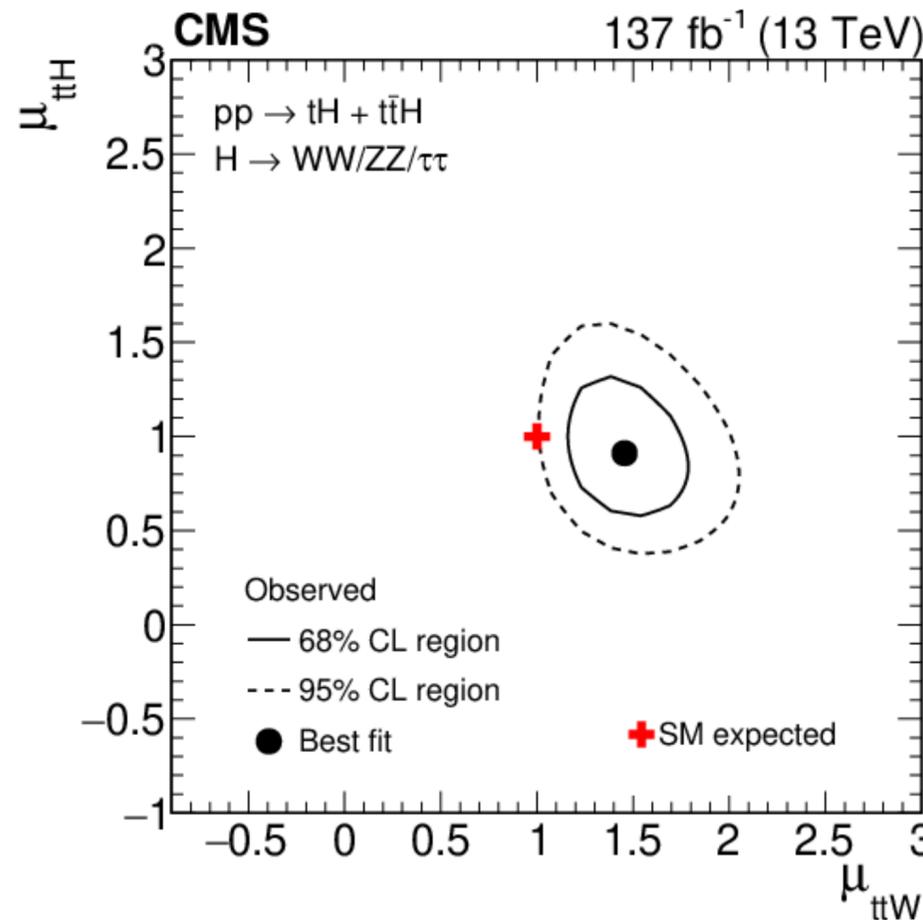
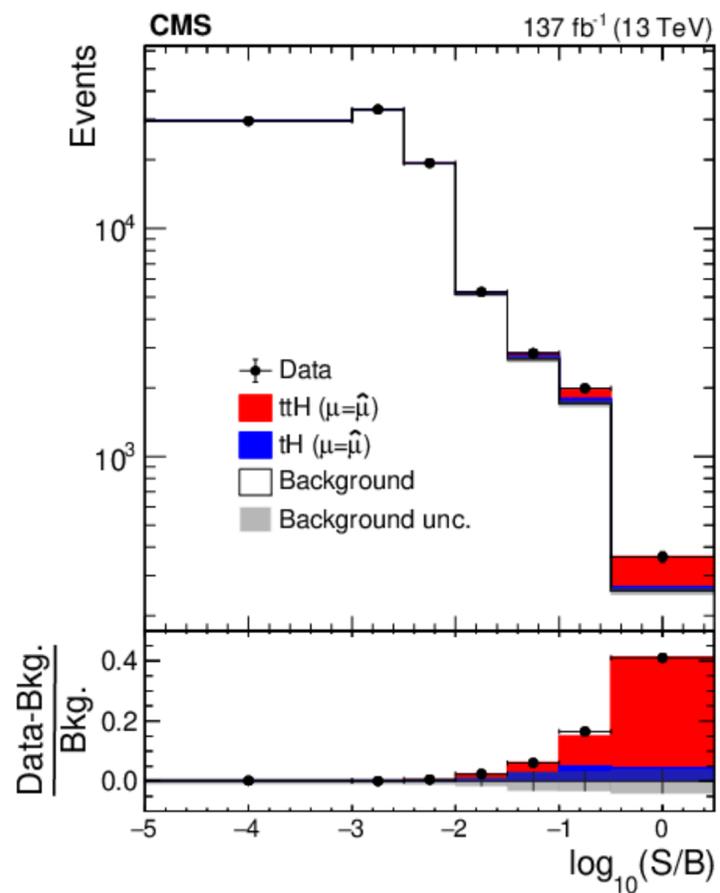


Many TH uncertainties will cancel, of course in this case sensitive to PDFs.

# Probe of the top Yukawa coupling - the ML Case

**ML** Due to the large multiplicity of final states, inclusive approach (still) with 10 channels including 1L, 2L-SS, and 3L as well as 0-, 1- and 2-hadronically decaying taus

[EPJC \(2021\) 81](#)



Moderate but visible anti-correlation between ttH and ttW

$$\mu_{ttH} = 0.92 \pm 0.19 \text{ (stat)} \text{ }^{+0.17}_{-0.13} \text{ (syst)}$$

$$\mu_{ttW} = 1.43 \pm 0.21 \text{ Most sensitive channel (but even STAT/SYST)}$$

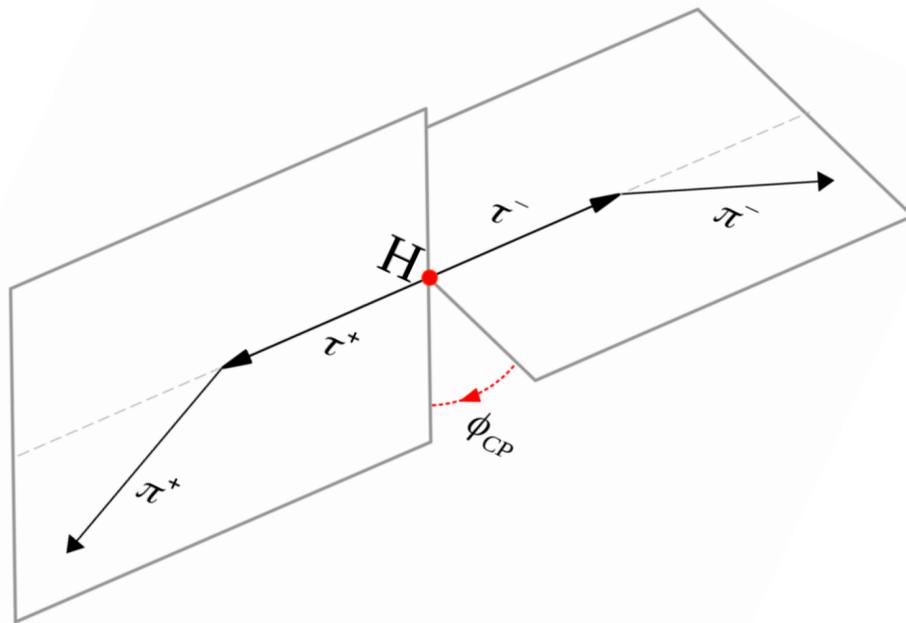
- Highlights importance of state-of-the-art MC (ttW) with latest QCD and EW corrections
- Perform ancillary measurements of ttW (in remote regions of phase space)
- Sharpen tools to remove backgrounds (fake leptons) - DL techniques

# CP properties of the Tau Yukawa

Through polarisation sensitive variable

[CMS PAS HIG-20-006](#)

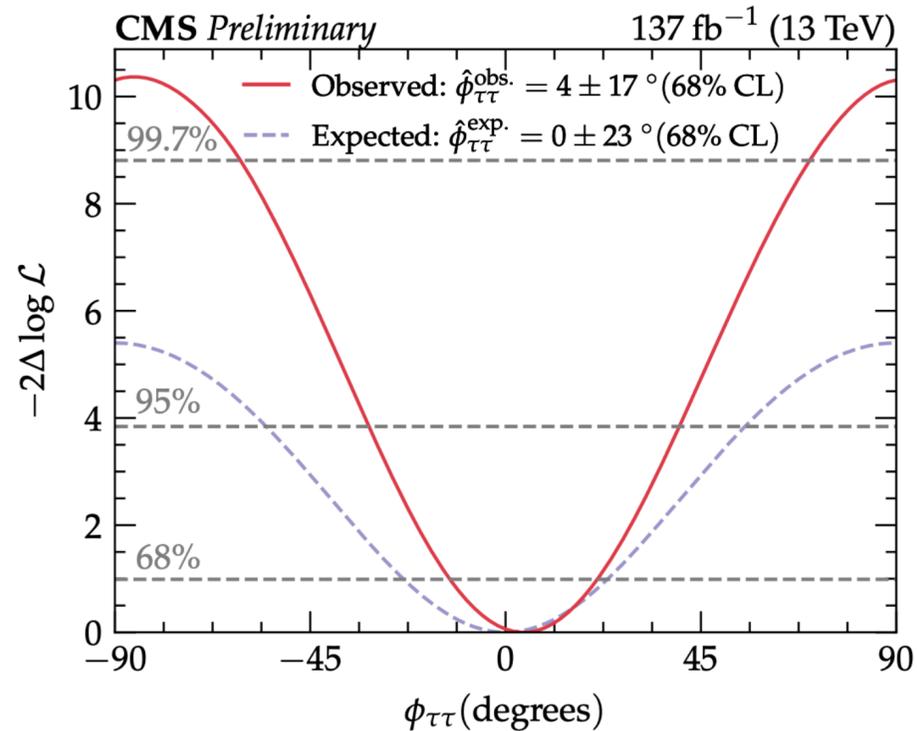
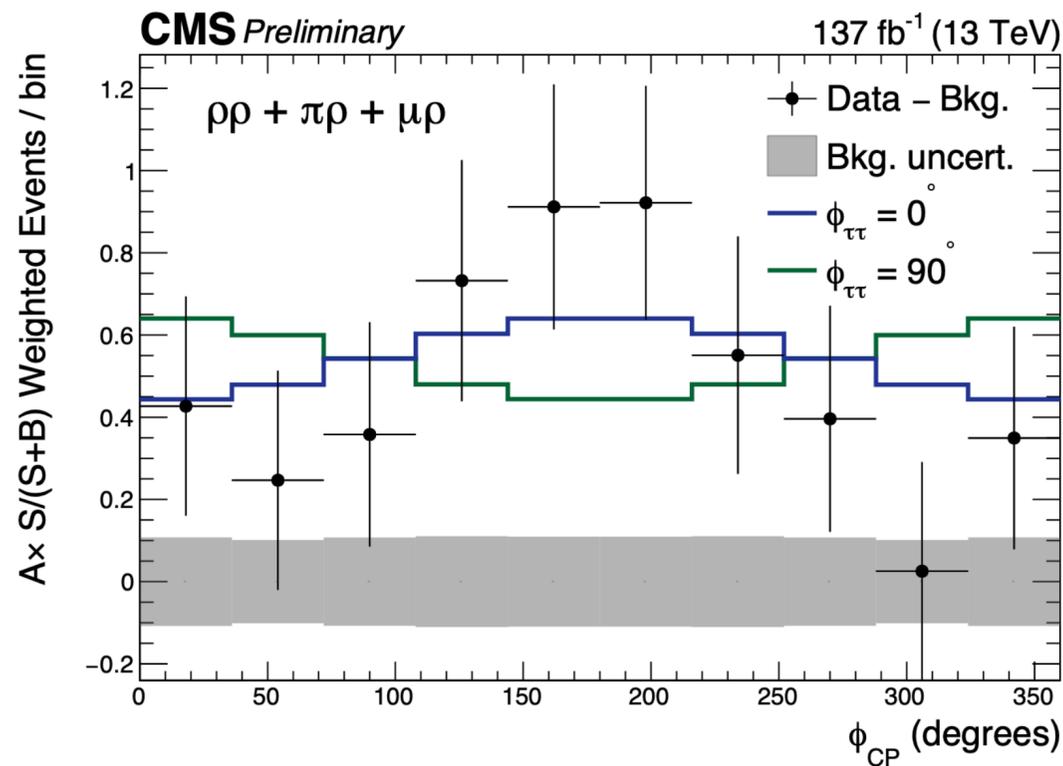
Uses either impact parameter direction for single-prong taus ( $\pi^\pm$ ) only or using the  $\pi^0$  momentum for the  $\tau \rightarrow \pi^\pm \pi^0 [\rho(770 \text{ MeV})] \nu_\tau$



Tau decays are selected with a BDT and the  $\phi_{CP}$  distribution is considered in different bins of this BDT score

$$\mathcal{L}_Y = -\frac{m_\tau H}{v} (\kappa_\tau \bar{\tau} \tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau) \quad \tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

Overall weighted distribution for all channels:



$$\phi_{\tau\tau} = 4 \pm 17^\circ (23^\circ \text{ exp.})$$

CP-even preferred vs CP-Odd at  $\sim 3\sigma$  level

Projected (statistical) precision between 18 and 30 degrees!

ATLAS HL-LHC [projection](#)

Developing PU robust experimental methods to reconstruct exclusive tau decay modes (using substructure and DL techniques) will be key!

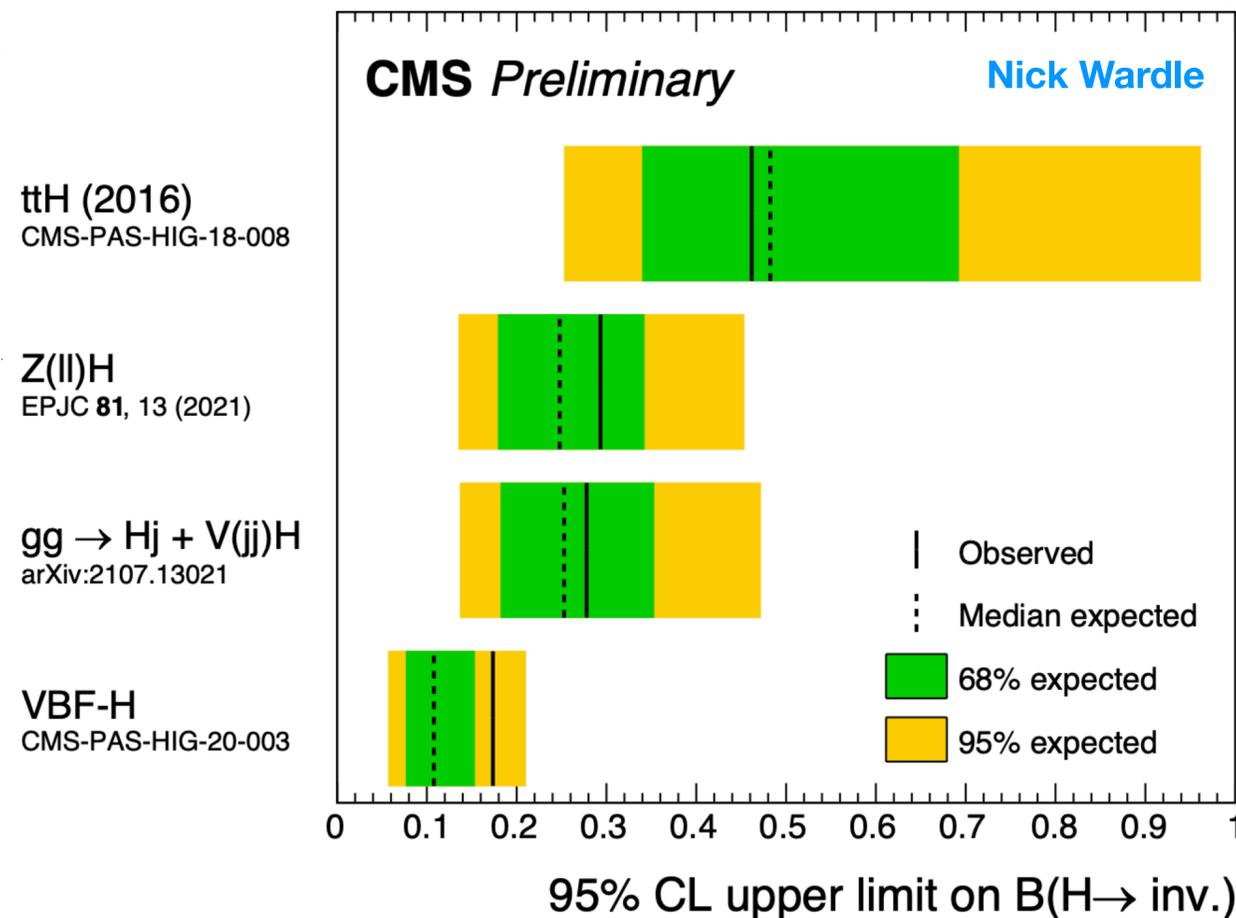
# Invisible decays of the Higgs boson

**NEW**  
Higgs 2021

## CMS New VBF

$$Br(inv.) < 0.17 \text{ (0.11)}$$

CMS-PAS-HIG-20-003 35.9-138 fb<sup>-1</sup> (13 TeV)



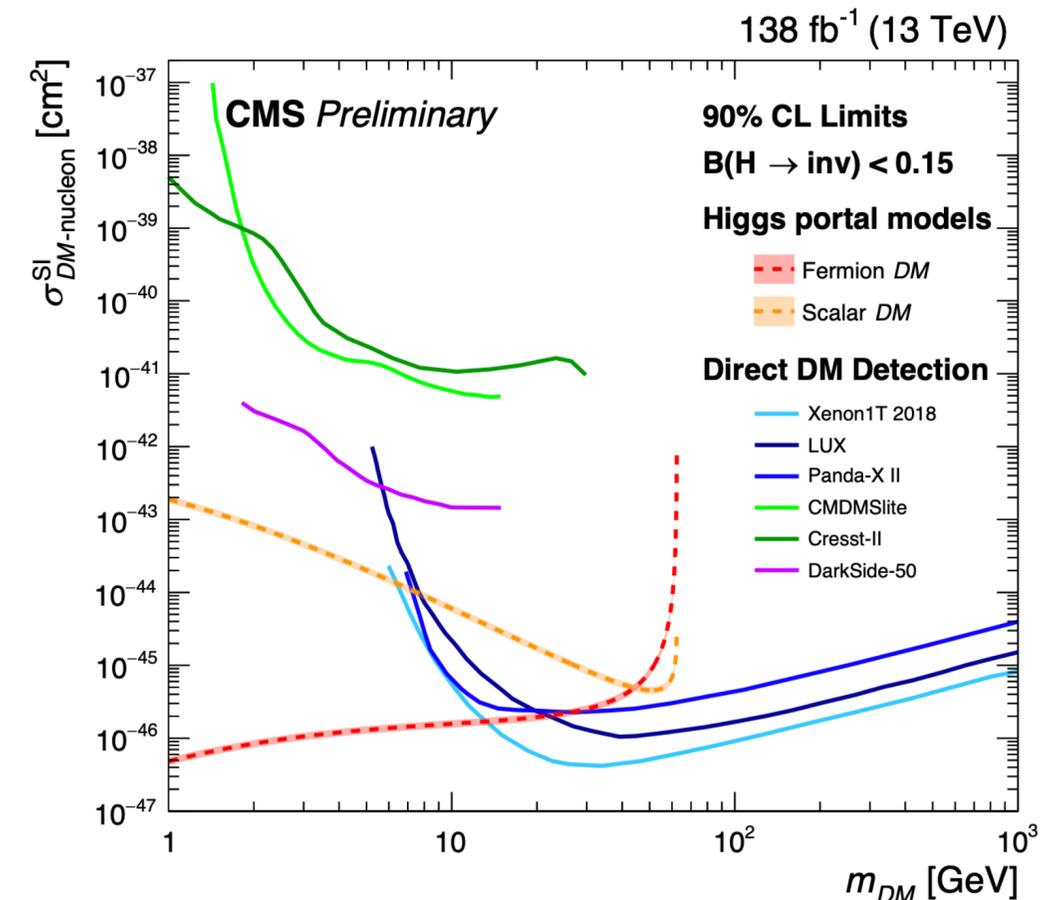
Overall major background is  $z \rightarrow \nu\bar{\nu}$  (with jets) major challenge to control, but also interesting new measurements from it:

Precision measurement of the invisible Z width from [CMS-PAS-CMP-18-014](#)

[ATLAS-CONF-2020-052](#)

Limits are now below **9%** on invisible branching at 90% CL

Interpretation in terms of WIMP-Nucleon cross section limits: very nice complementarity with direct searches!



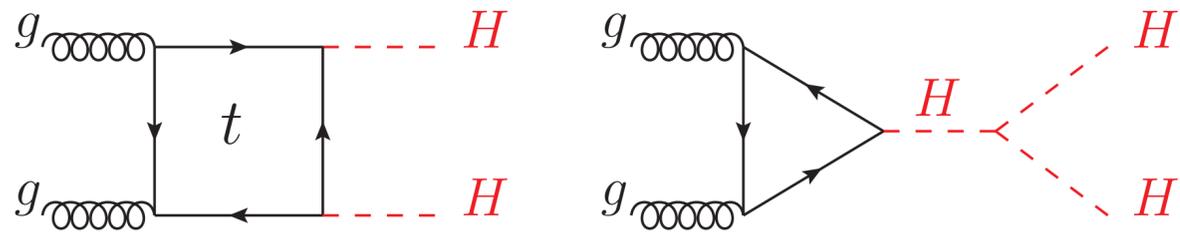
HL-LHC projection  $(\mu_{VBF, VH} \cdot BR_{inv})^{HL-LHC} \leq 2.5\%$

- Control of backgrounds
- Precision on MET and Jet reconstruction and trigger are key!

# Higgs boson self coupling

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The Higgs self coupling is also key to the HL-LHC program!

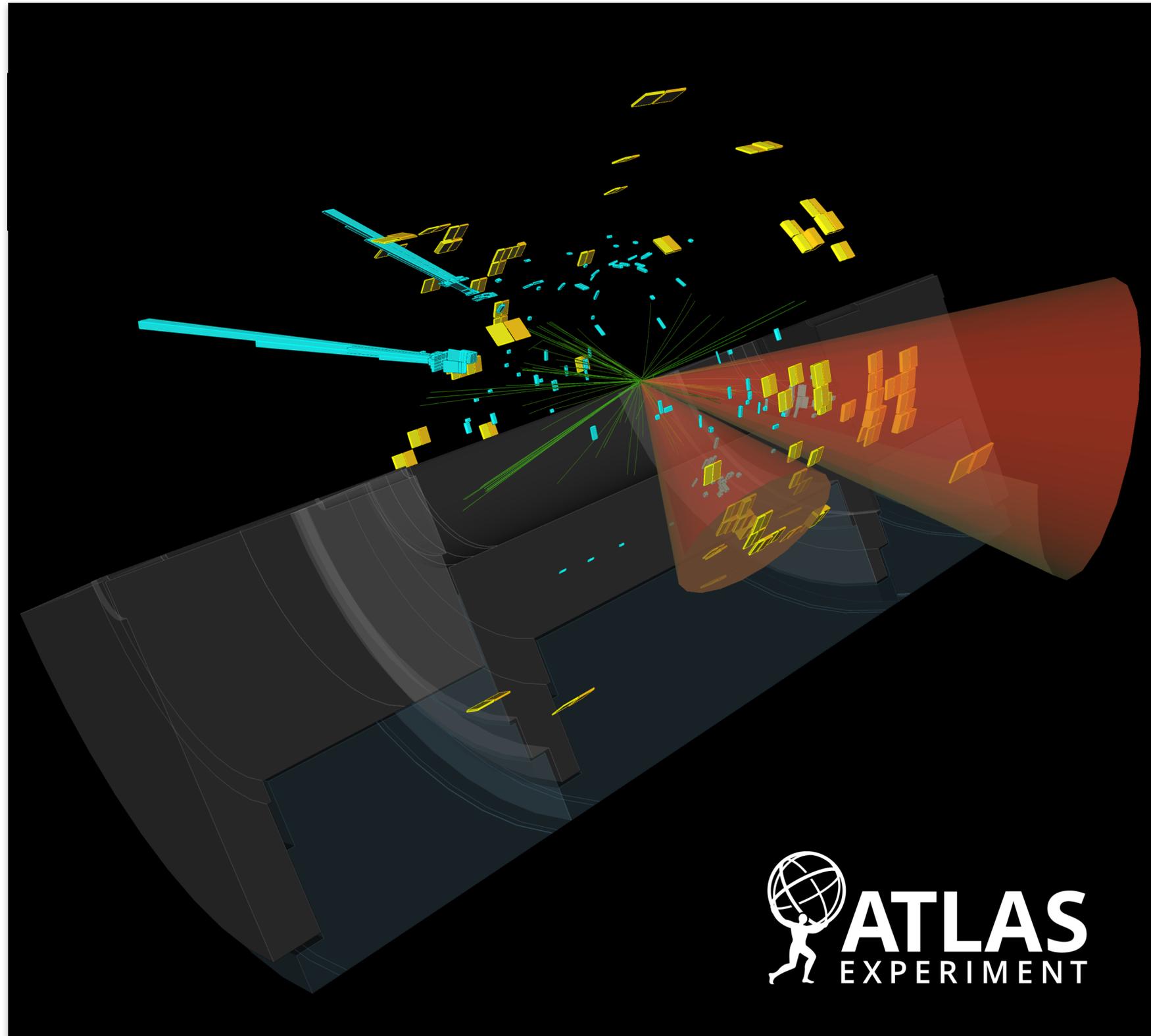


Very similar analysis as the Off-shell Higgs couplings!

Incredibly small cross section  $\sim 1000$  times smaller than Higgs production!

**Huge challenge!** but still more than 100k event will be produced at HL-LHC!

**Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!



# Towards a Measurement of the Higgs Self Coupling

**Summary** in terms of limits on HH production

exp.	WW $\gamma\gamma$	bb $\gamma\gamma$	bb $\tau\tau$	bbWW	bbbb	bb4l
$\sigma \times \text{Br}$	0.1 %	0.26 %	7%	25%	34%	1.5%*
ATLAS	<747 (386)	<4.1 (5.5)	<4.7 (3.9)	-	<12.9 (21)	-
CMS	-	<7.7 (5.2)	<30 (25)	<79 (89)	<3.7 (7.3)	30 (37)

\*without the Z leptonic branching of 3.3% ~4 events expected at HL-LHC high s/b ~ 5

**NEW**  
Higgs 2021

**ATLAS**  
Combination of  
 $b\bar{b}\tau\tau$  and  $b\bar{b}\gamma\gamma$

Observed constraint on trilinear coupling at 95% CL:

$$-1.0 < \kappa_\lambda < 6.6$$

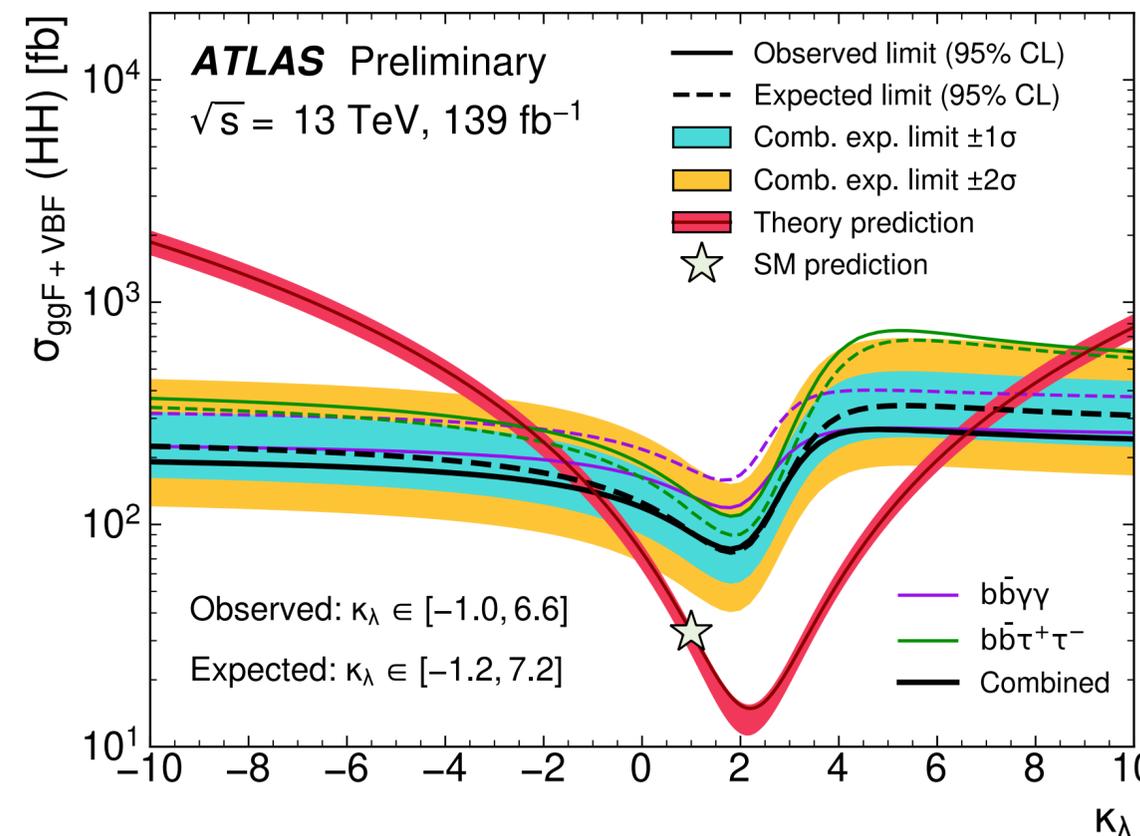
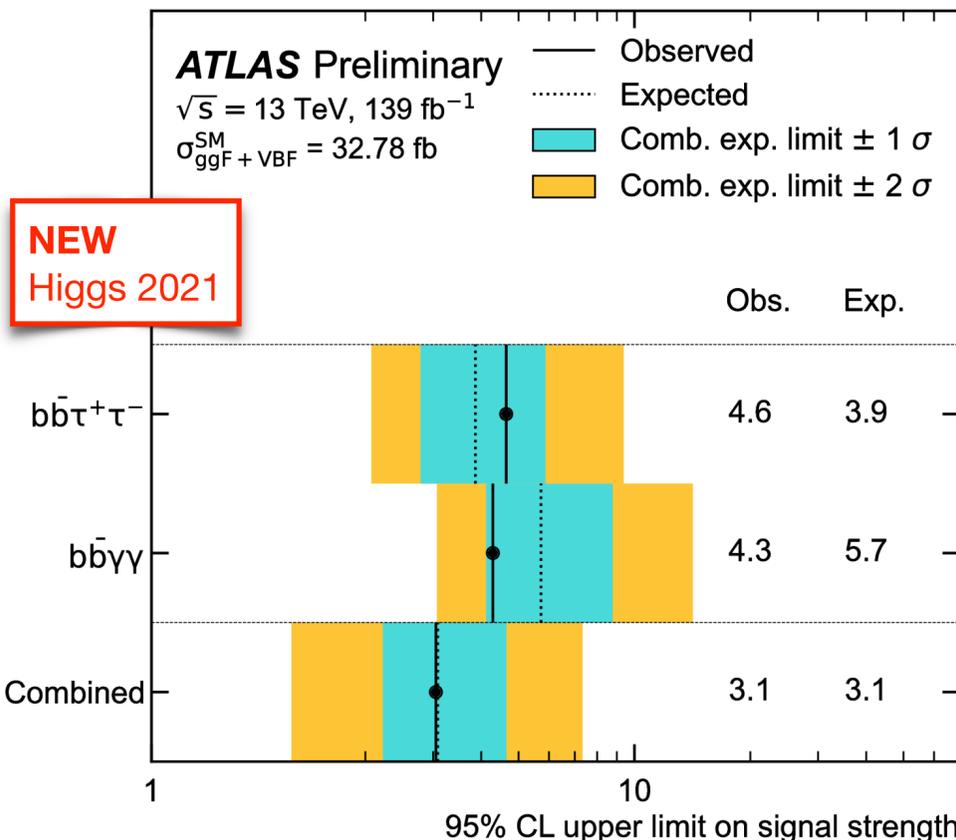
Expected range:

$$-1.2 < \kappa_\lambda < 7.2$$

With the improvement of the full Run 2 dataset analyses Back of the envelope calculation with  $0.5 \text{ ab}^{-1}$  should get close to  $2\sigma$  sensitivity (ATLAS and CMS combined)!

**Major and exciting challenge for Run 3!**

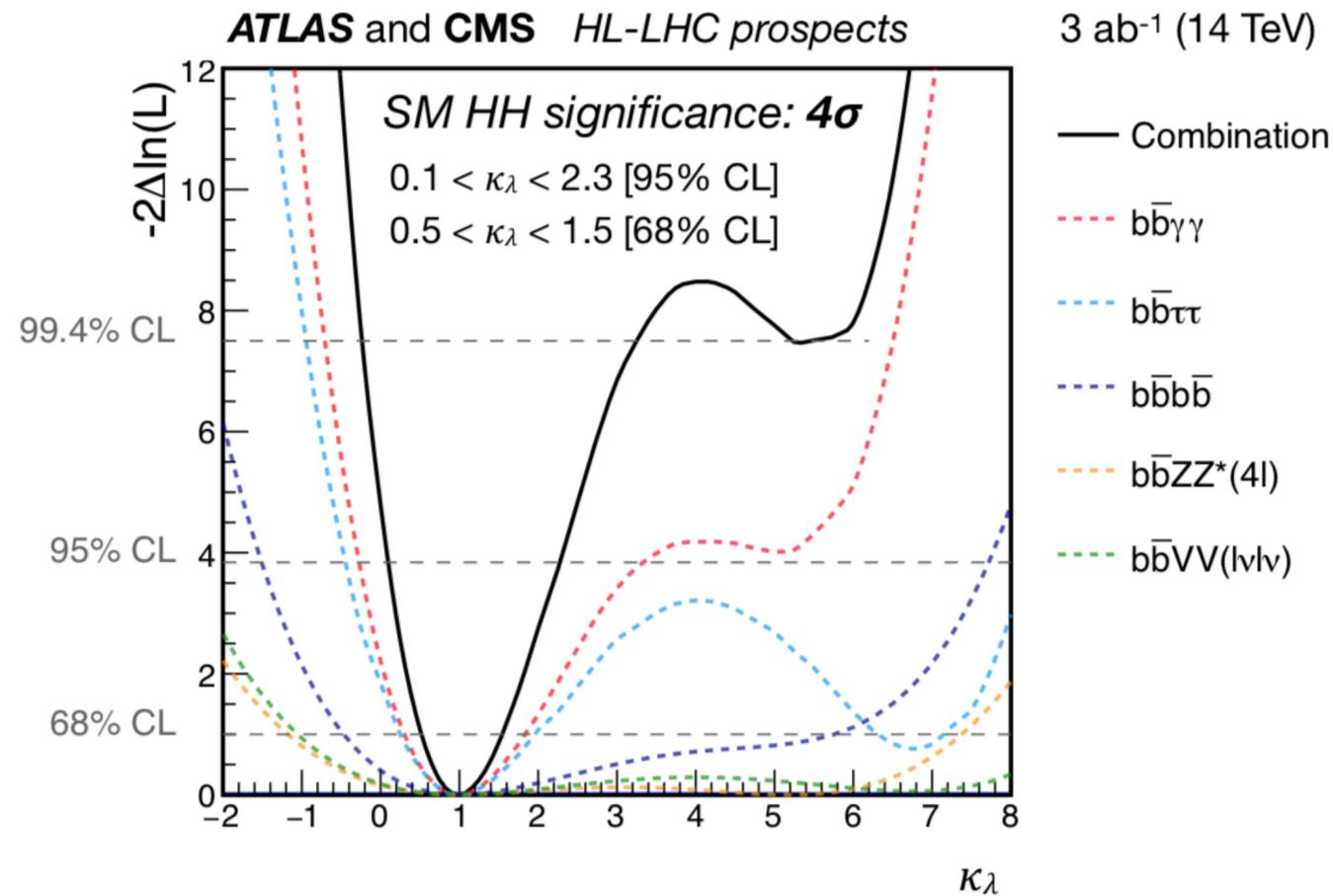
Full data results in all channels are being finalised and combinations starting!



# Towards a Measurement of the Higgs Self Coupling

From [P. Huang, A. Long and L.-T. Wang](#)

## At HL-LHC



Current estimates yield an observation of an HH signal at 4σ

50% level constraints on the Higgs boson self coupling!

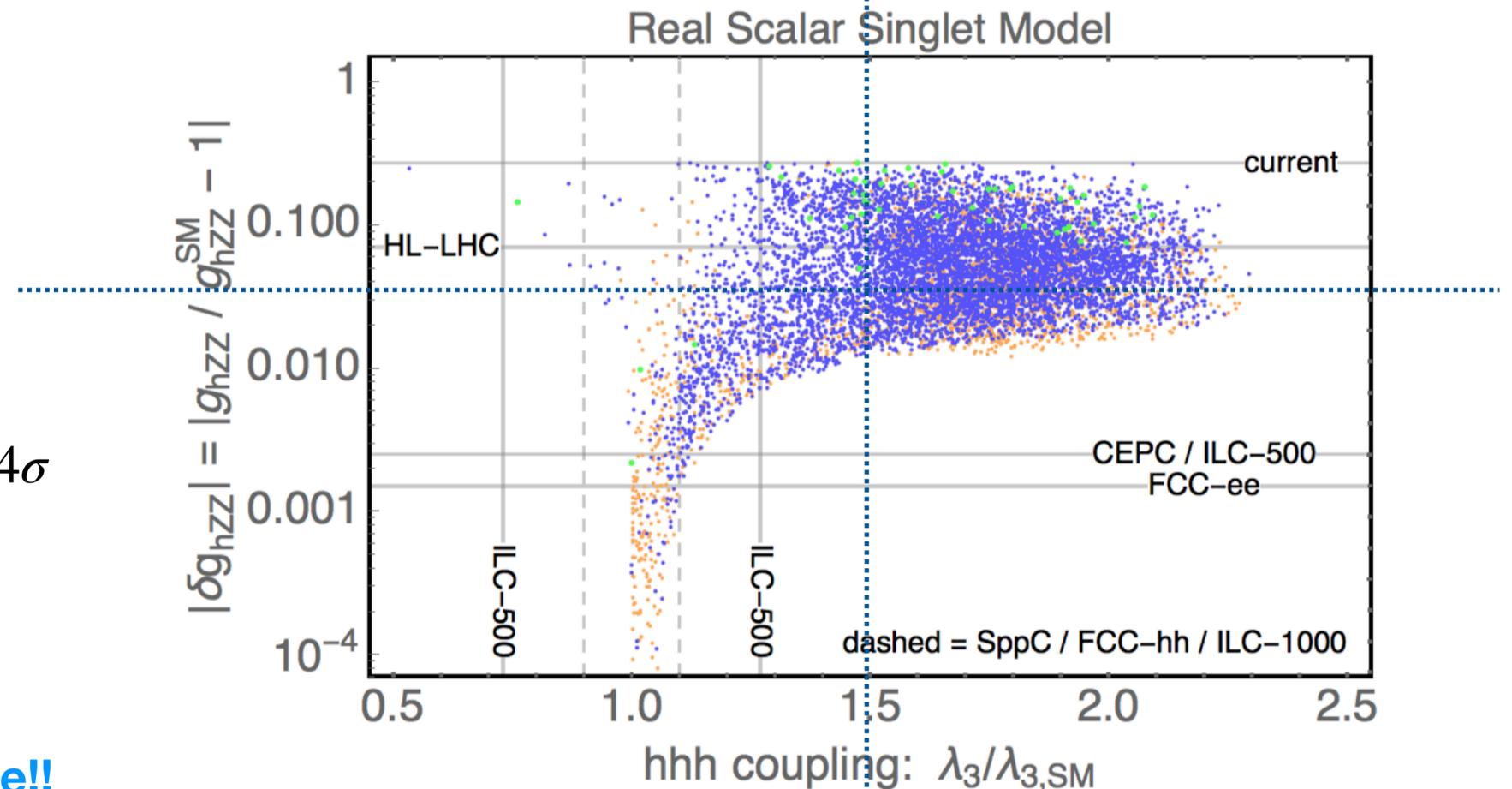
$$0.5 < \kappa_\lambda < 1.5$$

Already impressive, must try all we can to improve!!

## Probing 1st order phase transition and GW signals

The sensitivity of HL-LHC to the trilinear coupling could constrain models which would predict strongly first order EW phase transition!

In these cases, signals of stochastic background (e.g. collisions of bubbles) in the phase transition could potentially be detected by next generation interferometers like eLISA\*)



\*eLISA: evolved LISA

# Conclusions and Outlook

30

- The LHC will very soon have collisions (Spring 2022) and Run 3 is about to start at centre-of-mass energy of 13.6 TeV and 500 fb<sup>-1</sup> expected for the Run 3 per experiments.
- Several landmark results expected, many milestones and outstanding goals for Higgs physics at Run 3.
- Latest results show that many HL-LHC projections of 2018 were conservative.
- The HL-LHC Higgs physics program is outstanding and has surpassed by far what was thought to be possible at a hadron collider - **Entering the precision era!**
- There are however still many fronts to battle simultaneously:
  - Progress on HO perturbative calculations in QCD and EW and HO MC and PS
  - Pursue development of global interpretation SMEFT framework
  - Perform ancillary measurements
  - Seek optimal fiducial regions, ratios, STXSs and perform the measurements!
  - Further develop reconstruction tools
  - Push limits of searches for extended Higgs sector
  - Optimise analyses and try new ideas!!
- Impressive progress on all fronts shown at this conference!

Superb conference with many exciting new results, excellent talks and plenty of time for discussion!

**Many THANKS and CONGRATULATIONS  
the the Higgs 2021 organising teams!!**