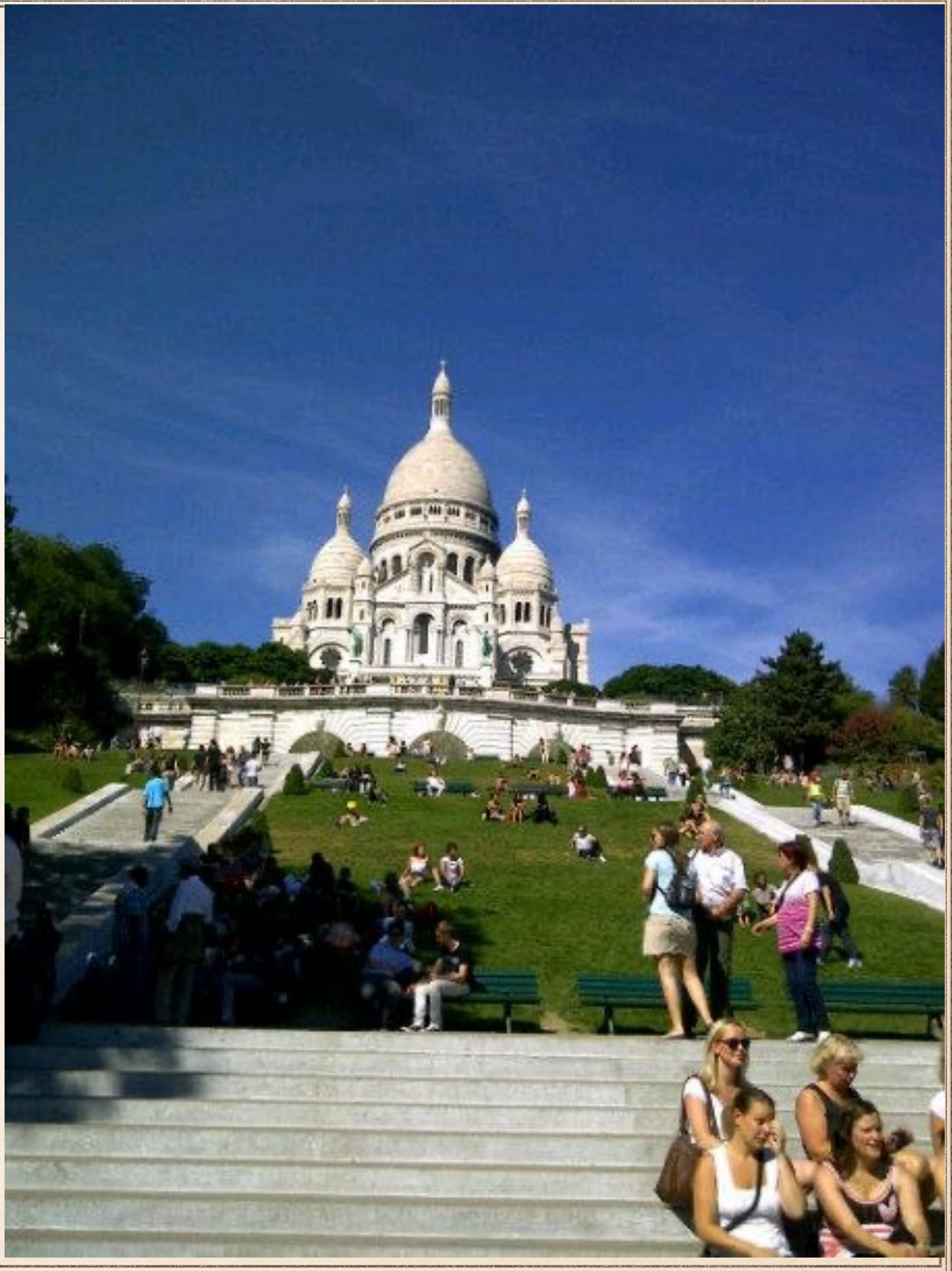
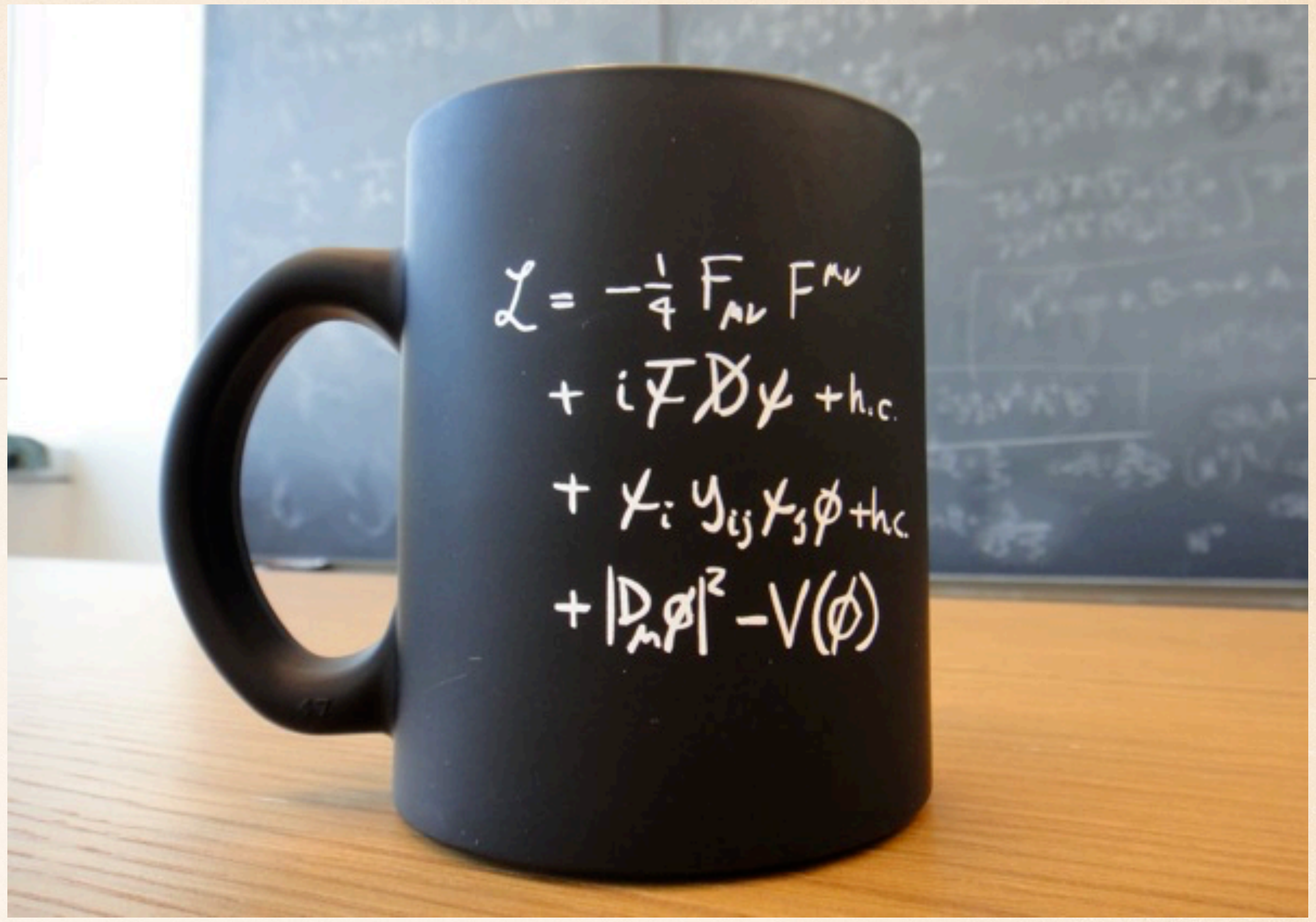
HIGGS SELF COUPLINGS

Lidija Živković on behalf of the ATLAS collaboration

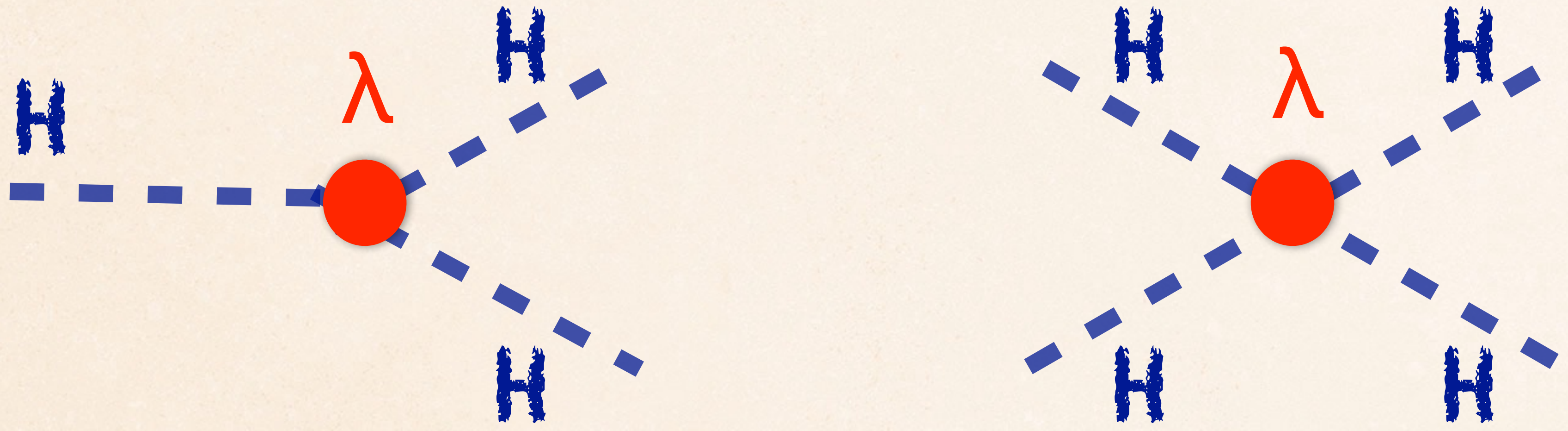
Institute of Physics Belgrade



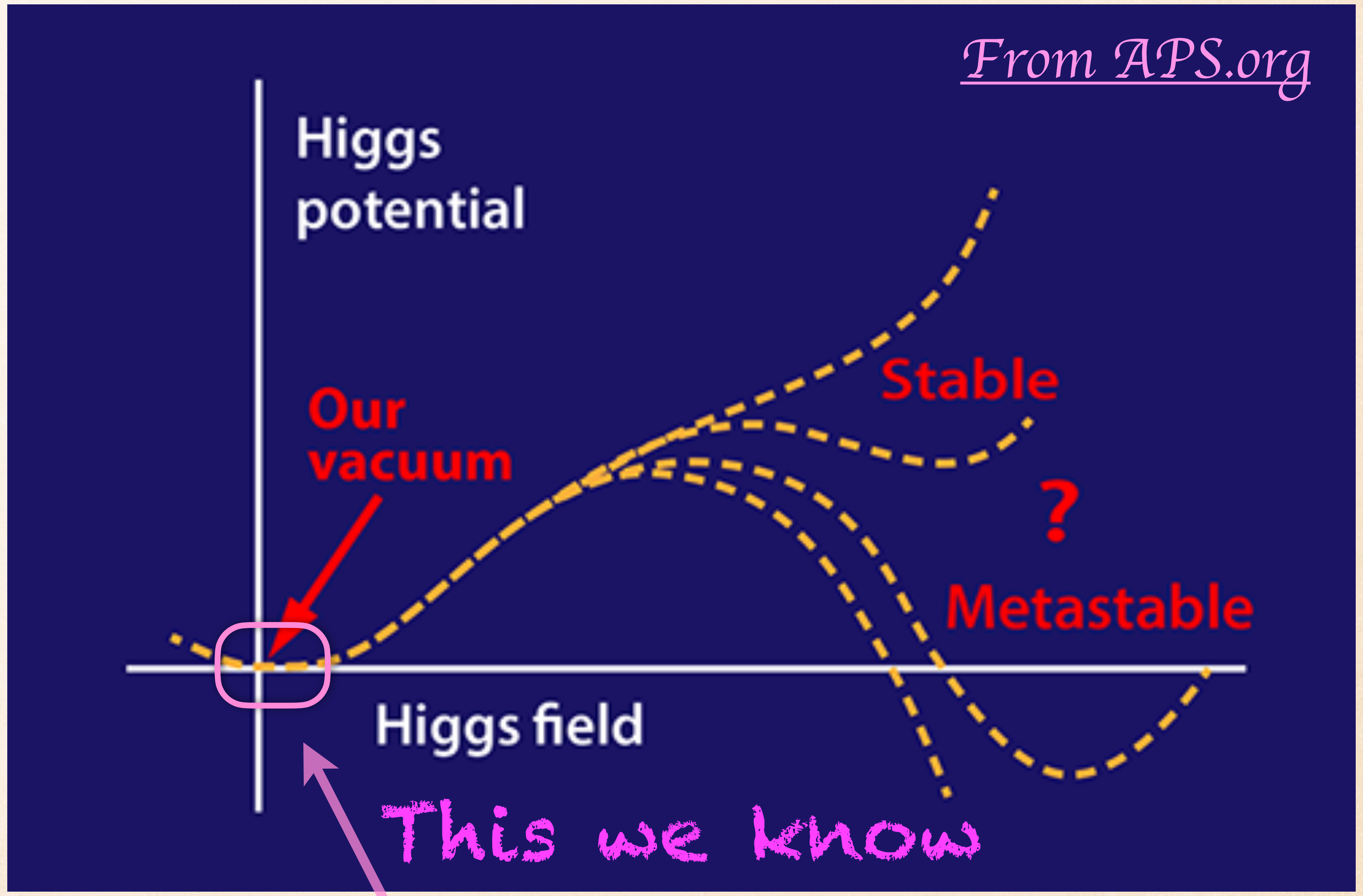
MOTIVATION



- Higgs potential
  $V(\phi^{\dagger}\phi) = \mu(\phi^{\dagger}\phi) + \lambda(\phi^{\dagger}\phi)^2 \rightarrow$
  $V(H) = \lambda v^2 H^2 + \lambda v H^3 + (1/4)\lambda H^4; M_H^2 = 2\lambda v^2$



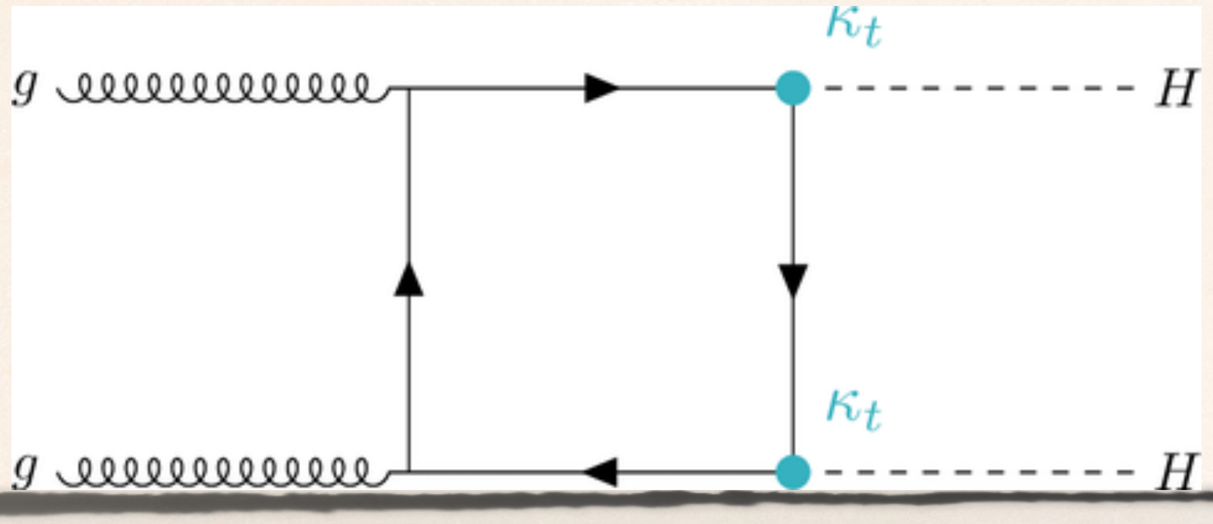
- Investigating the HH production allows for direct measurement of the Higgs self-coupling
  - Probe the shape of the Higgs potential

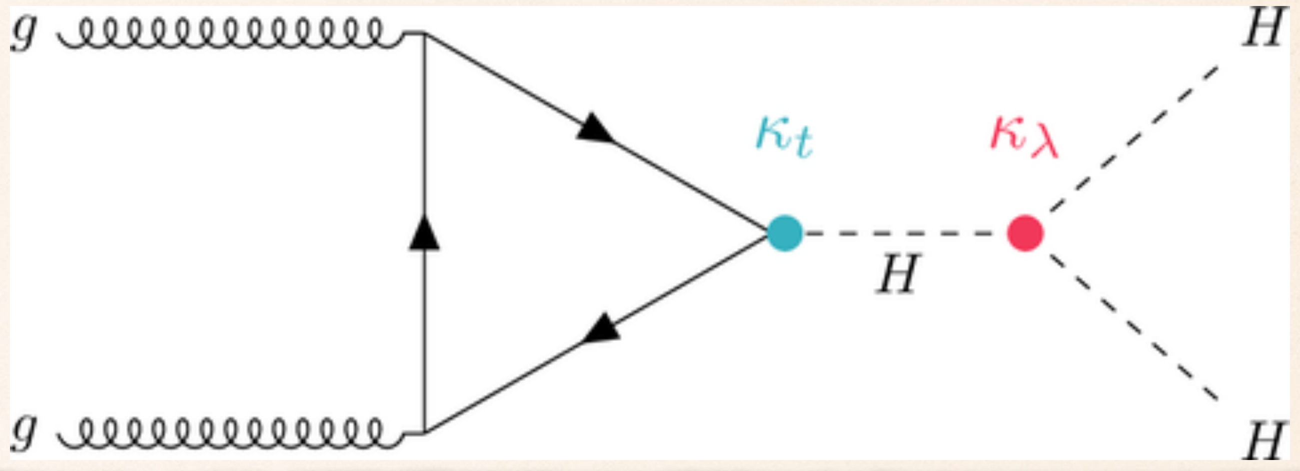


PRODUCTION

$$\kappa_X = \frac{c_{HX}^{exp}}{c_{HX}^{SM}}$$

Gluon Fusion: Destructive interference - small SM $\sigma_{HH}^{ggF} \sim 31\ fb @ 13TeV$

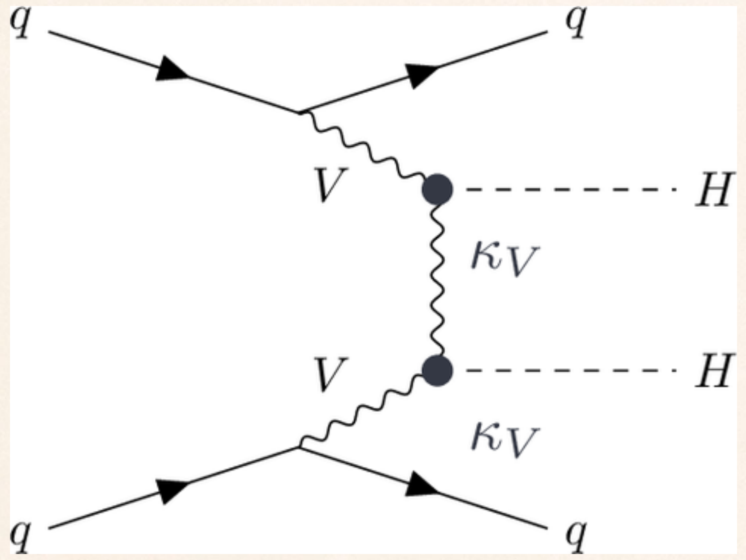


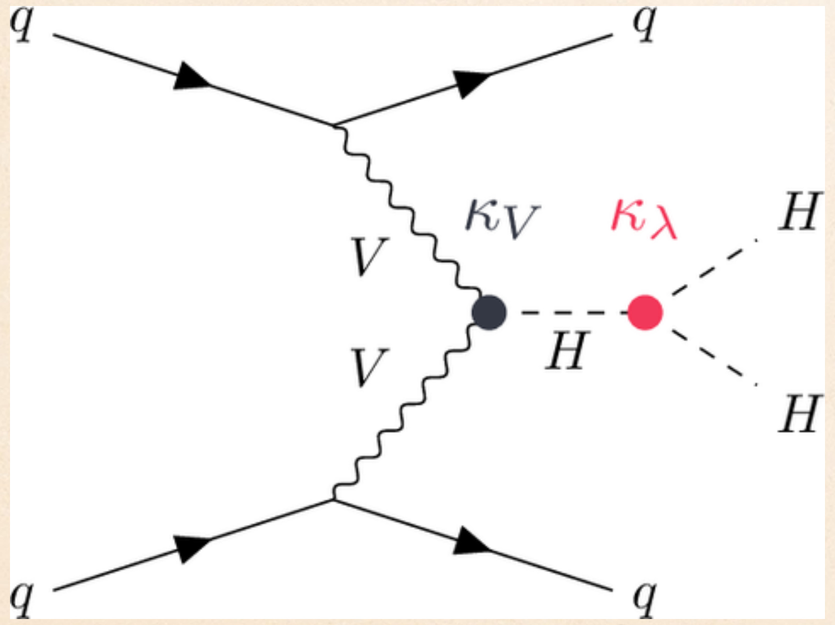


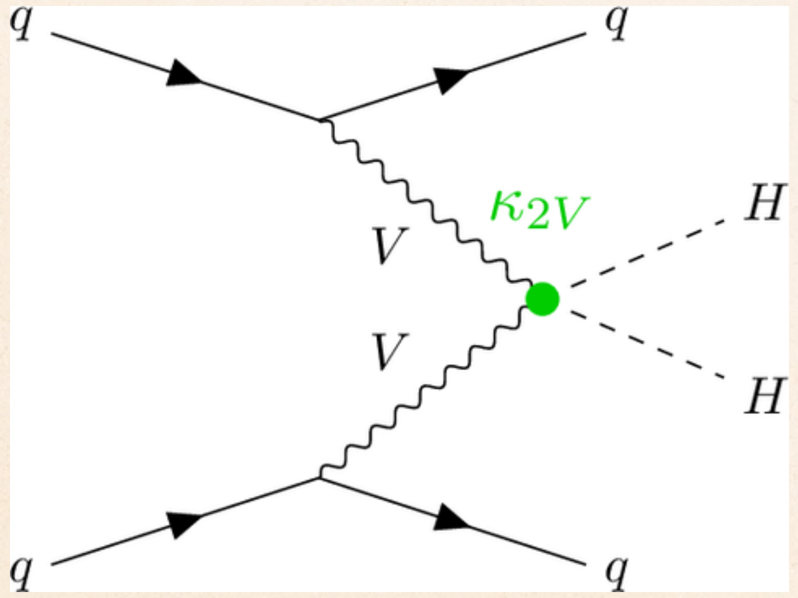
$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

VBF:

$\sigma_{HH}^{VBF} \sim 1.72\ fb @ 13TeV$



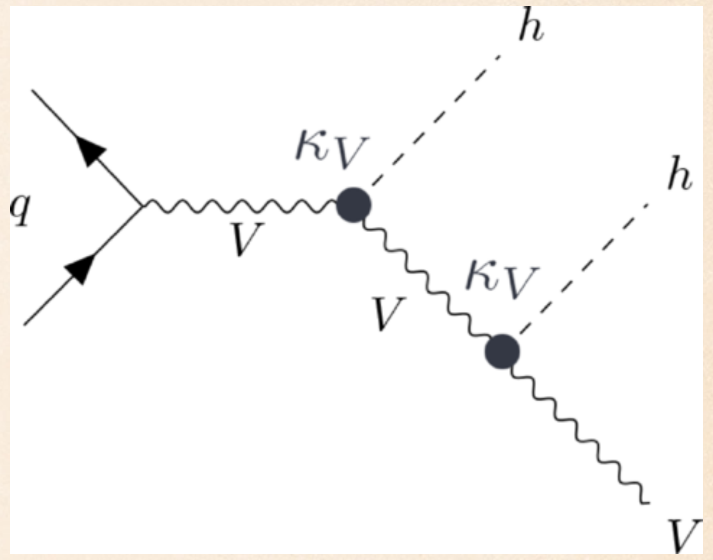


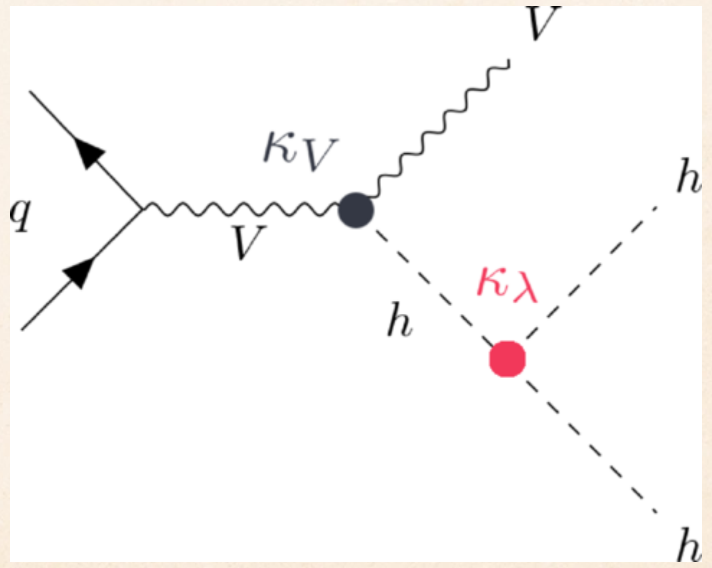


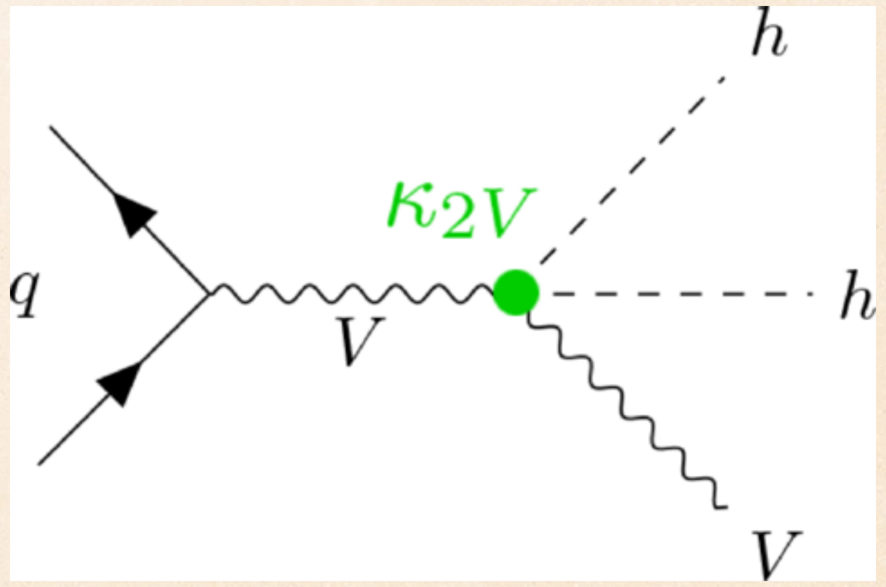
$$\kappa_{2V} = \frac{\lambda_{HHVV}}{\lambda_{HHVV}^{SM}}$$

Associated production:

$\sigma_{VHH}^{ggF} \sim 0.86\ fb @ 13TeV$



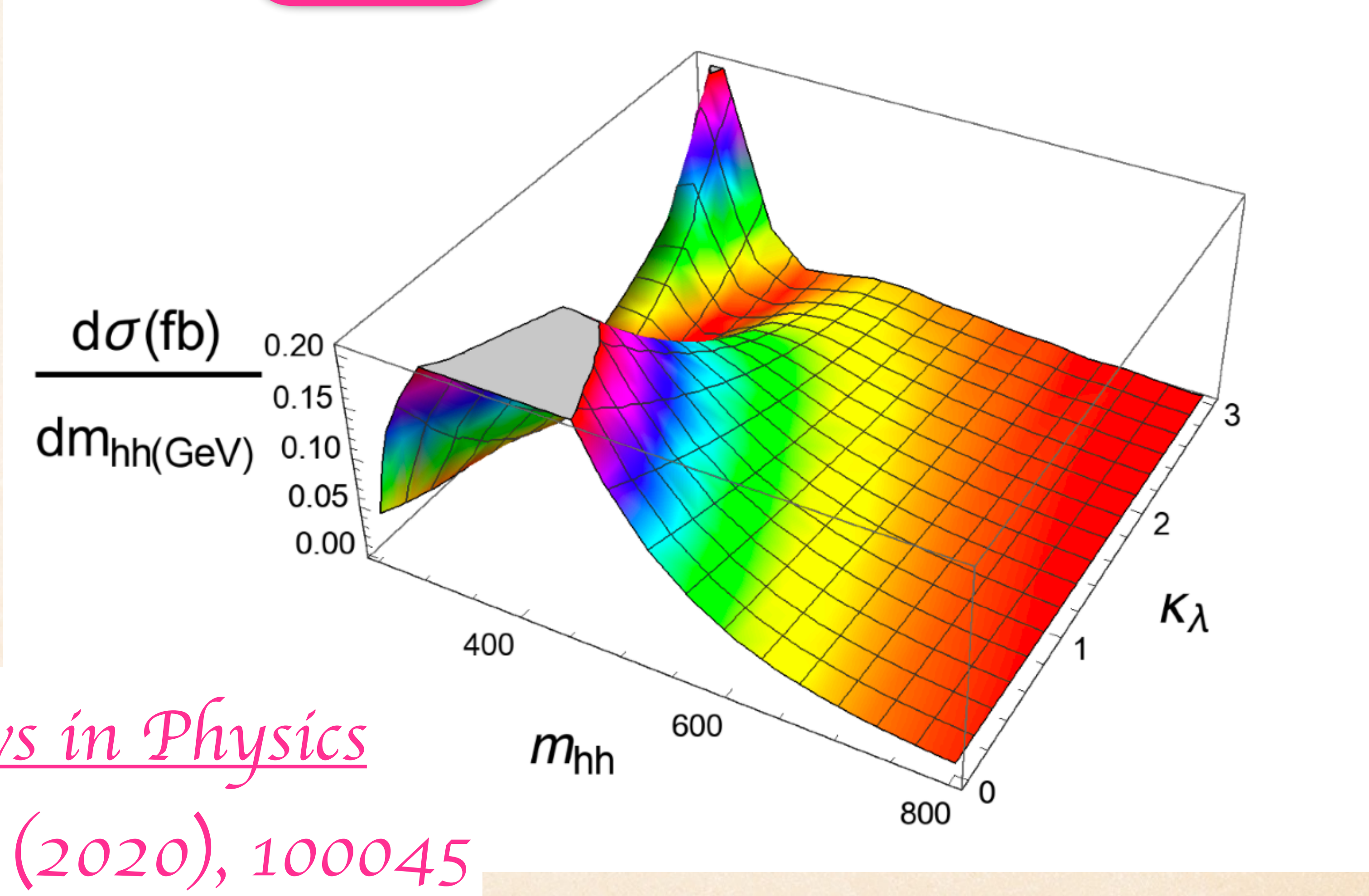




HH DECAY MODE AND SEARCHES

- Due to large $\mathscr{B}(H \to bb)$ at least one bb decay is required in most cases
  - Excellent b-jet identification might be crucial for observation
- Cross sections, branching ratios and kinematics depend on κ_λ
  - Optimisation of analyses strategies are important

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

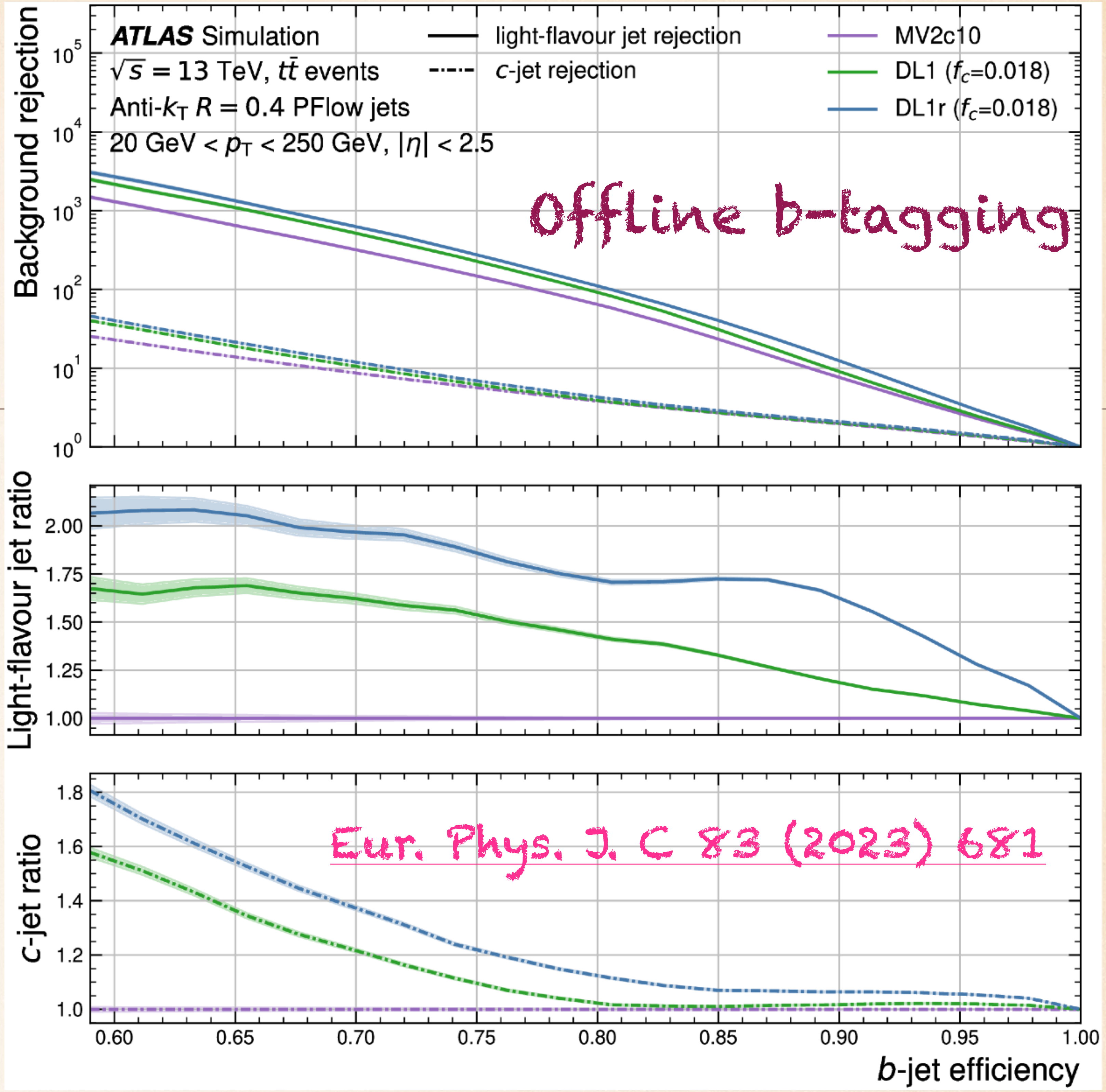


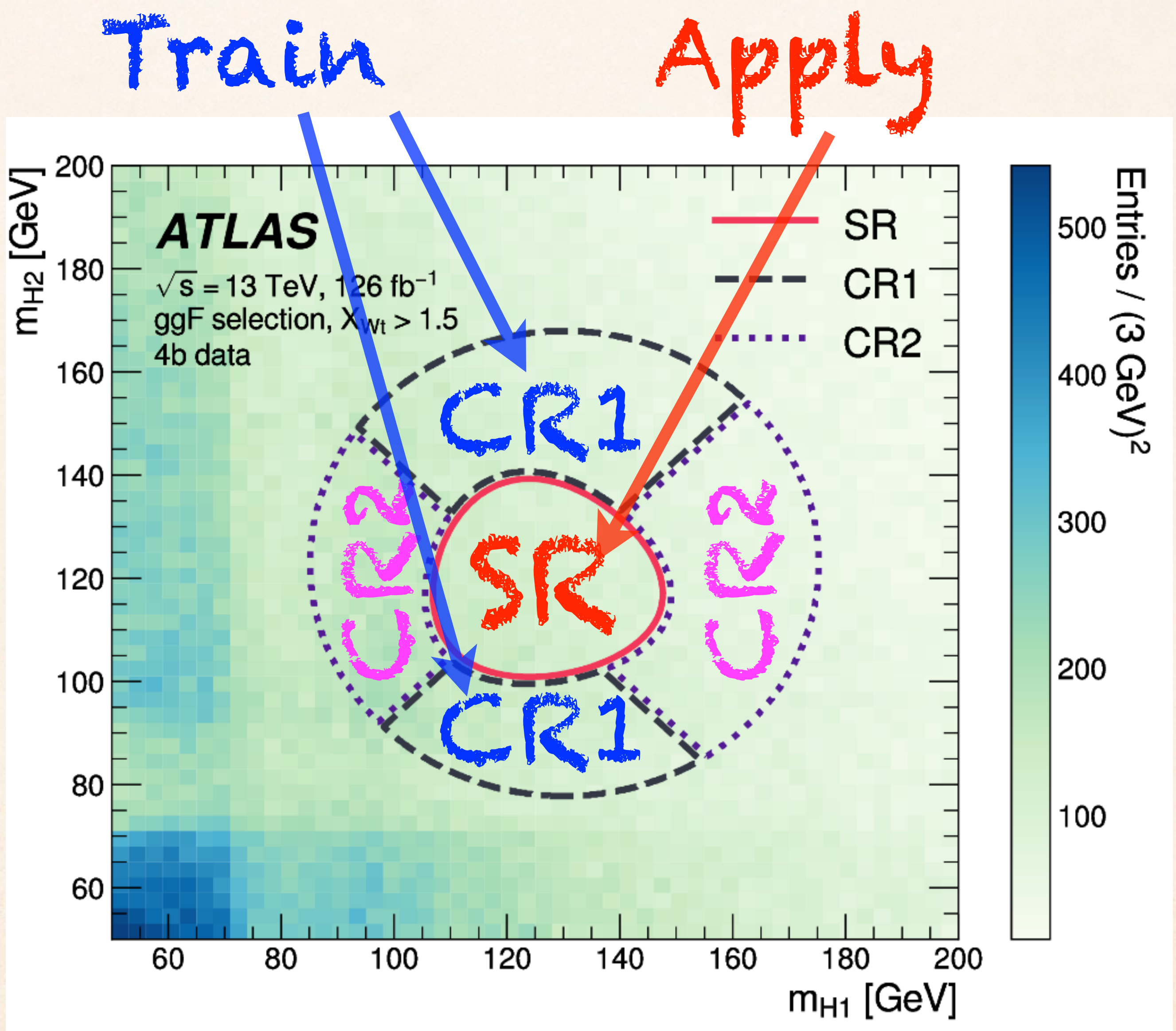
Reviews in Physics Volume 5, (2020), 100045

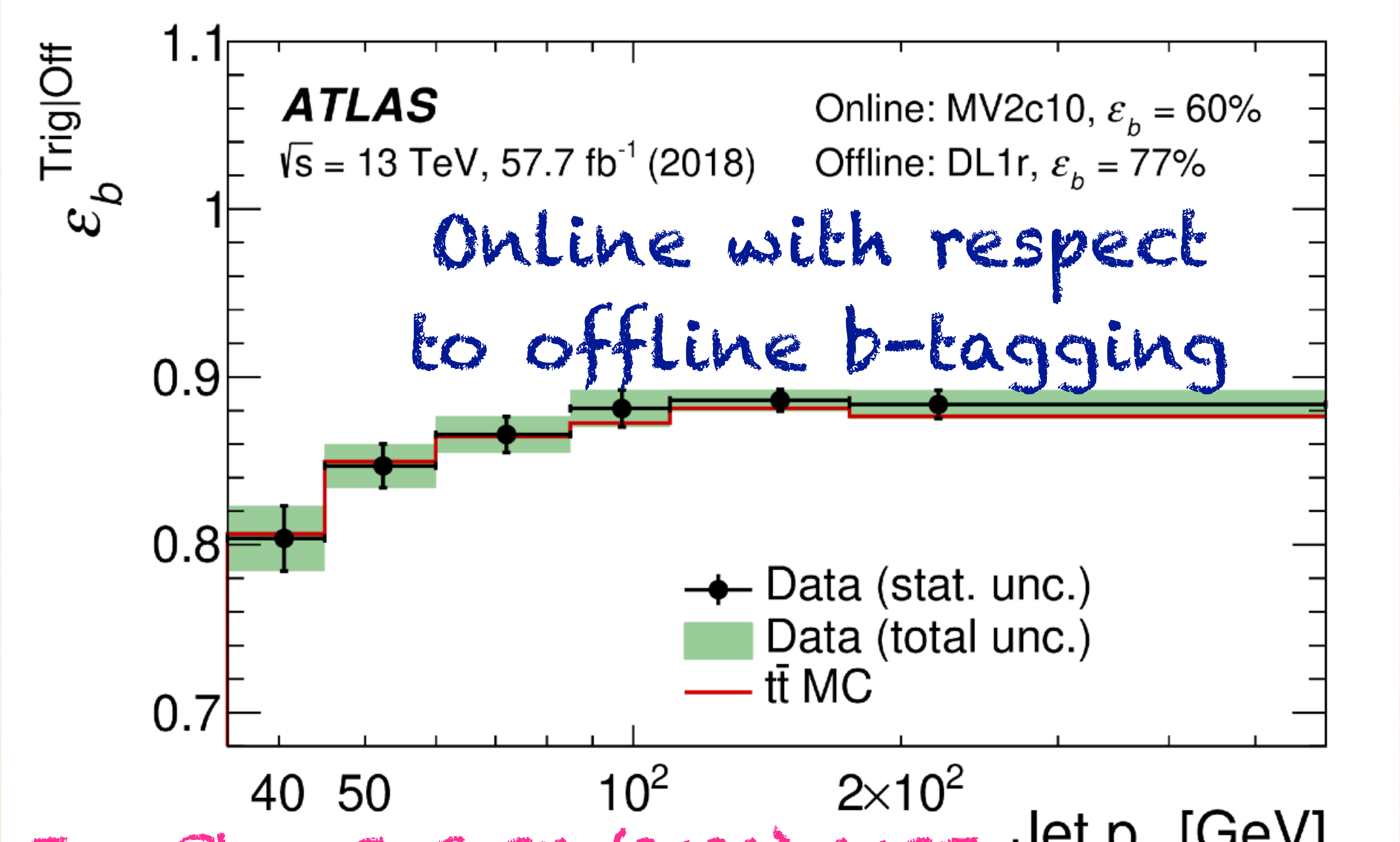
$HH \to bbbb$

Phys. Rev. D 108 (2023) 052003

- Highest BR, but also large background
  - 4 central jets fulfilling b-jet tagging (DL1r)
    - b-jets used in trigger as well (MV2c10)
  - To separate VBF production – 2 forward jets
- Background estimation – 90% of the background events come from multijet processes
  - Fully data-driven technique based on sample with exactly 2 b-jets
  - Reweight 2 b-jet data to 4 b-jet in CR1 using an NN
    - CR2 used for systematics on the method



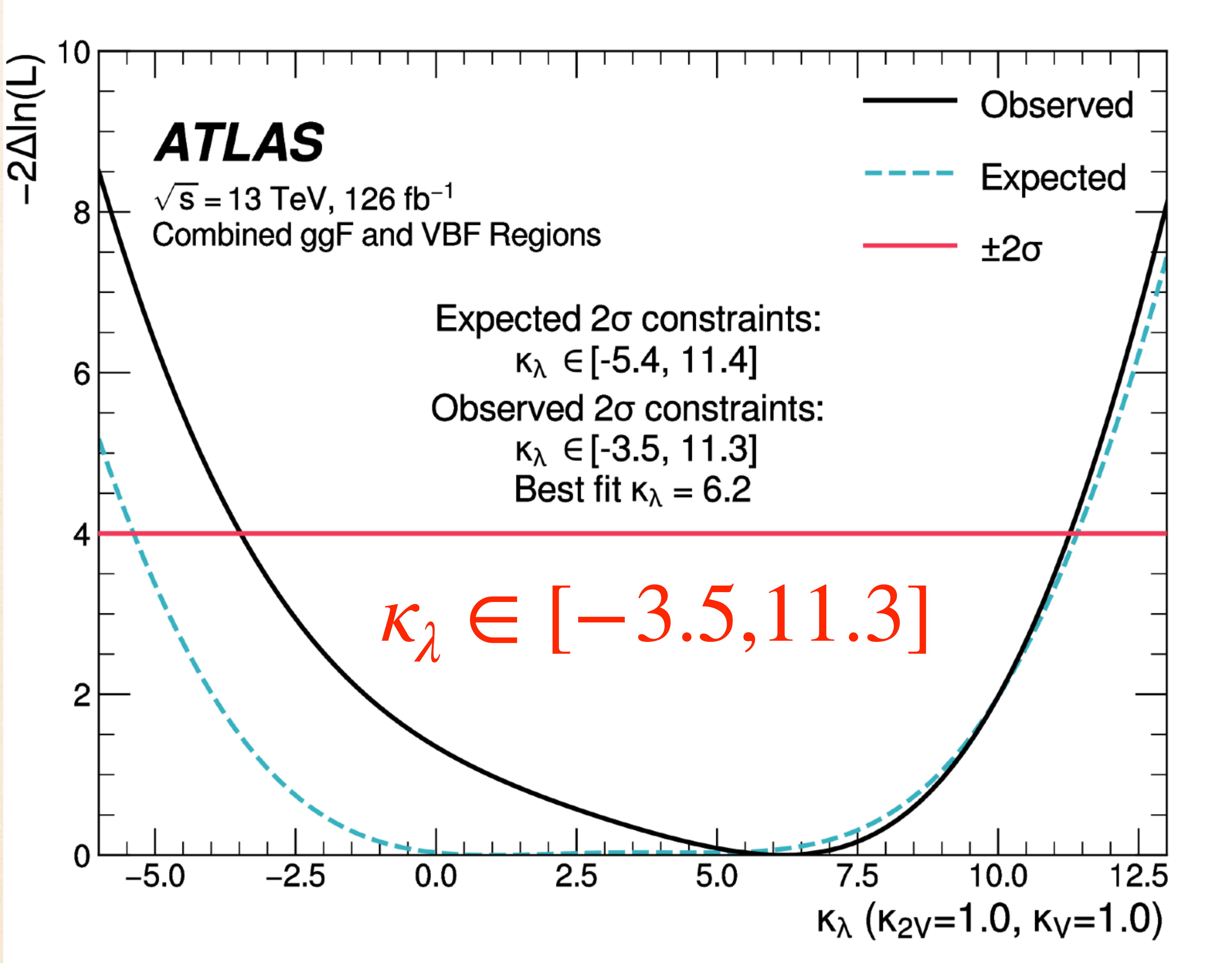




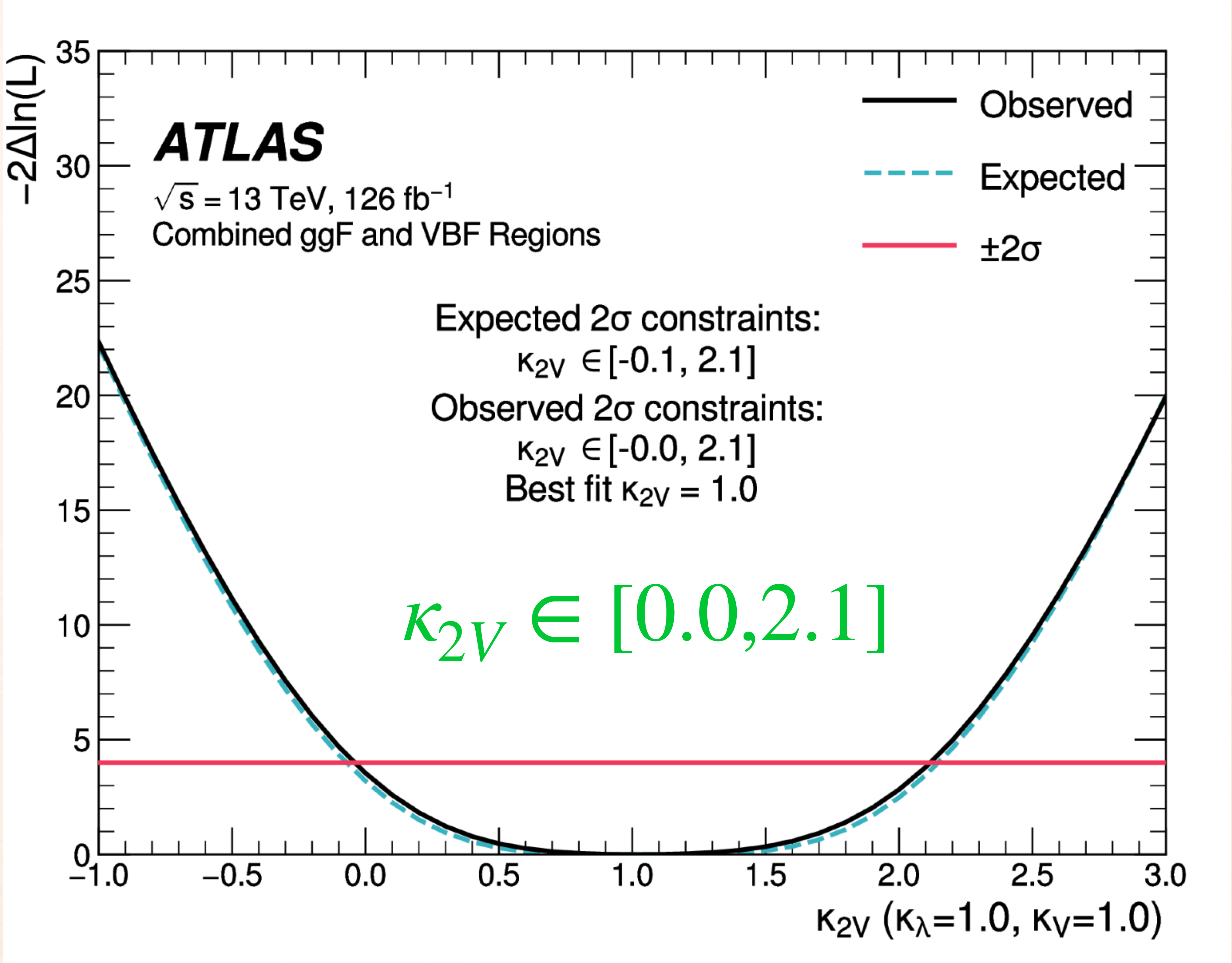
$HH \rightarrow bbbb$

Phys. Rev. D 108 (2023) 052003

- Likelihood scans on the κ_λ and κ_{2V} parameters



$\kappa_\lambda \in [-3.5, 11.3]$



$\kappa_{2V} \in [0.0, 2.1]$

ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

$HH \to bb\tau\tau$

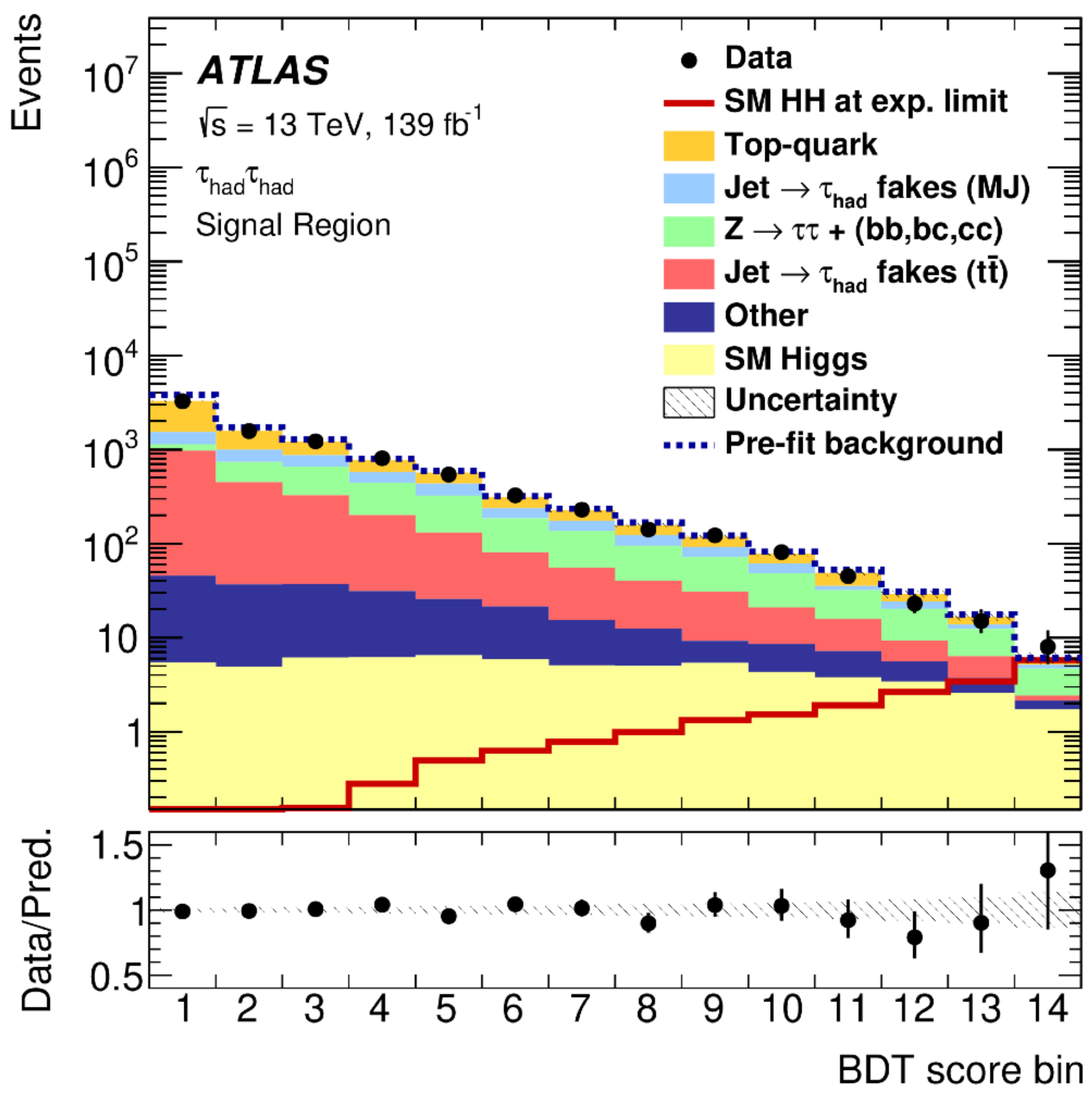
JHEP 07 (2023) 040

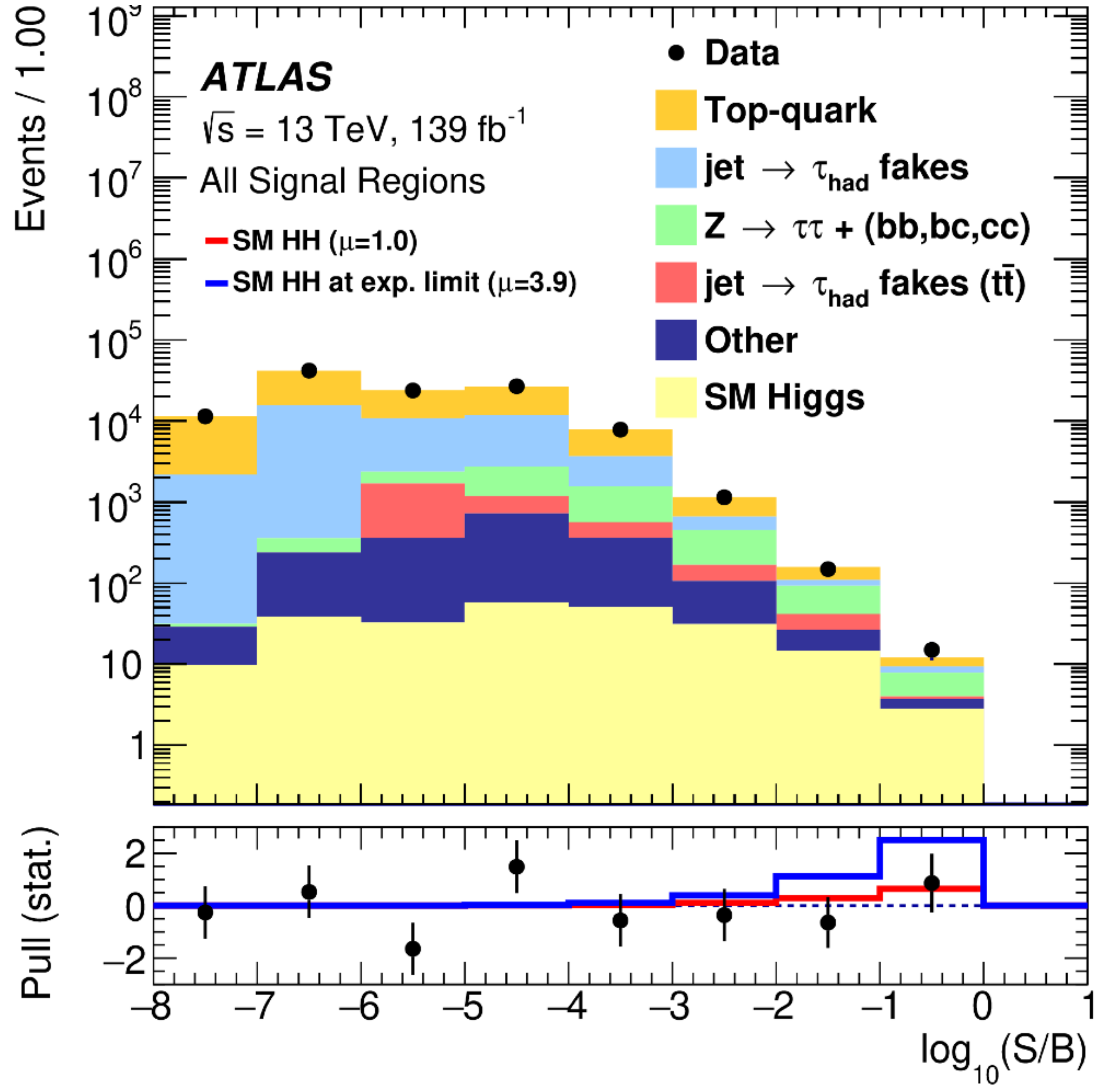
- Select 2 b-jets and
  - Either 2 hadronic τ-jets with opposite charge
  - Single- and Di τ-Triggers (Combined) - one signal category
  - Or 1 hadronic τ-jet and 1 lepton with opposite charge
  - Single lepton trigger and l+τ-Trigger - two signal categories

BDT

NN

- Dominant backgrounds
  - Real τ-jets from ttbar and $Z \to \tau\tau$ + heavy flavor jets
  - Fake τ-jets from multijet and ttbar production
- Signal extraction by combining 3 MVA outputs in bins of $\log_{10}(S/B)$
- The observed (expected) upper limit on the non-resonant diHiggs production @95% CL, is 4.7 (3.9) times the SM
- Observed (Expected): $\kappa_\lambda \in [-2.4, 9.2]([-2., 9.])$



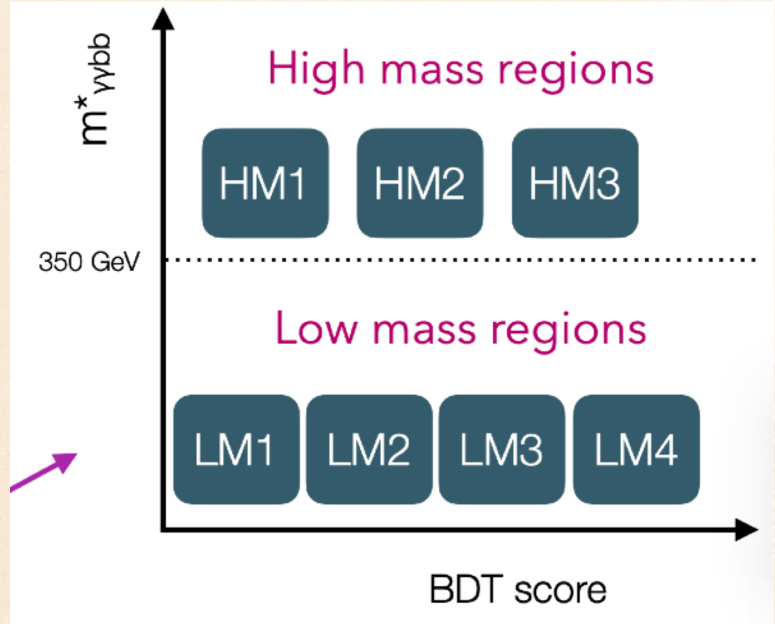


$HH \to bb\gamma\gamma$

ATLAS-CONF-2023-050

New

- Reoptimised analysis to probe anomalous values of the κ_λ and of the κ_{2V}

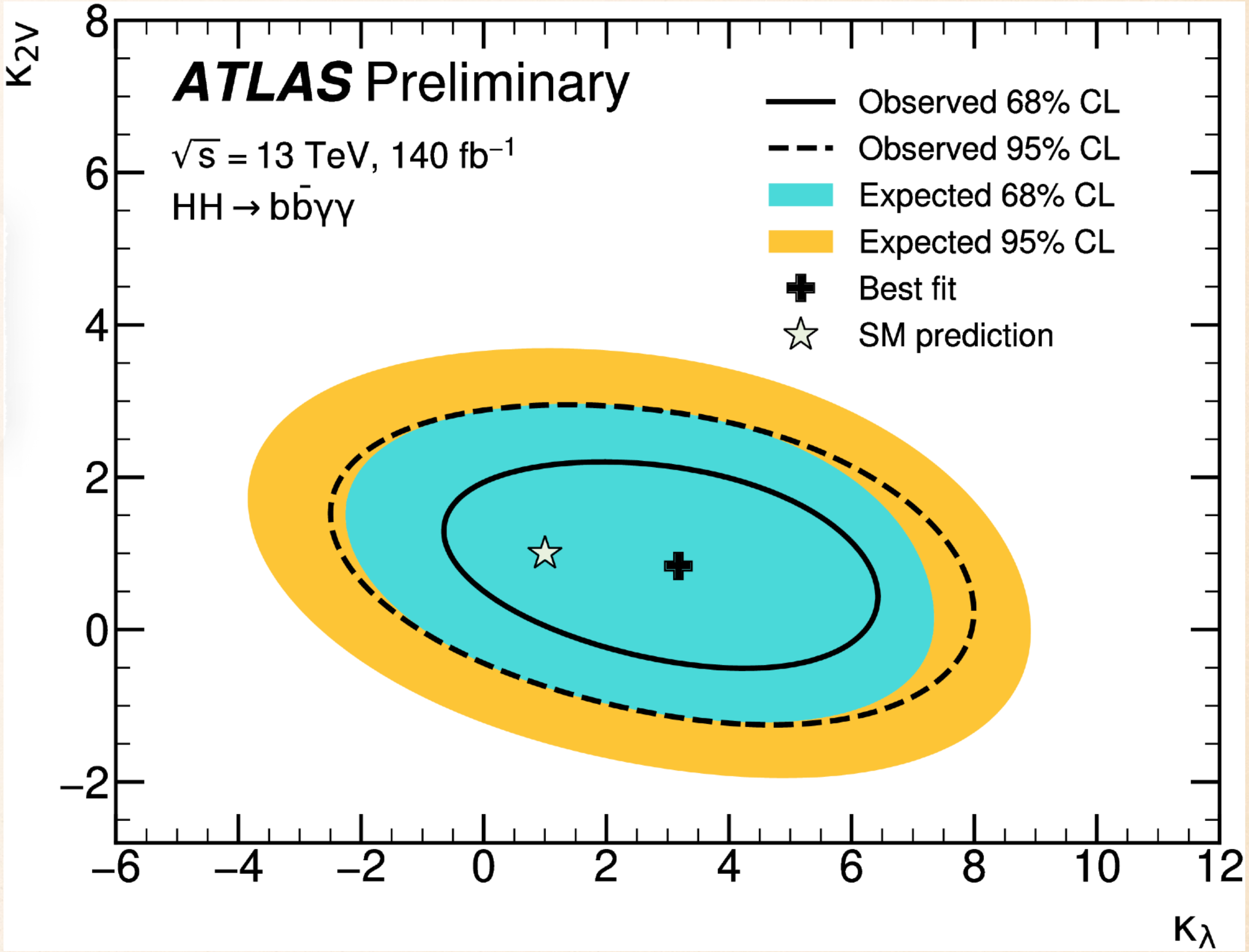


7 categories (from 4 previously)

+ improved BDT

$m_{\gamma\gamma}$ discriminant in each category

- Observed (expected) upper limit on
  - μ_{HH}: 4.0(5.0)
  - $\kappa_\lambda \in [-1.4,6.9]([-2.8,7.8])$and $\kappa_{2V} \in [-0.5,2.7]([-1.1,3.3])$
- More details this afternoon by Tom Ingebretsen Carlson



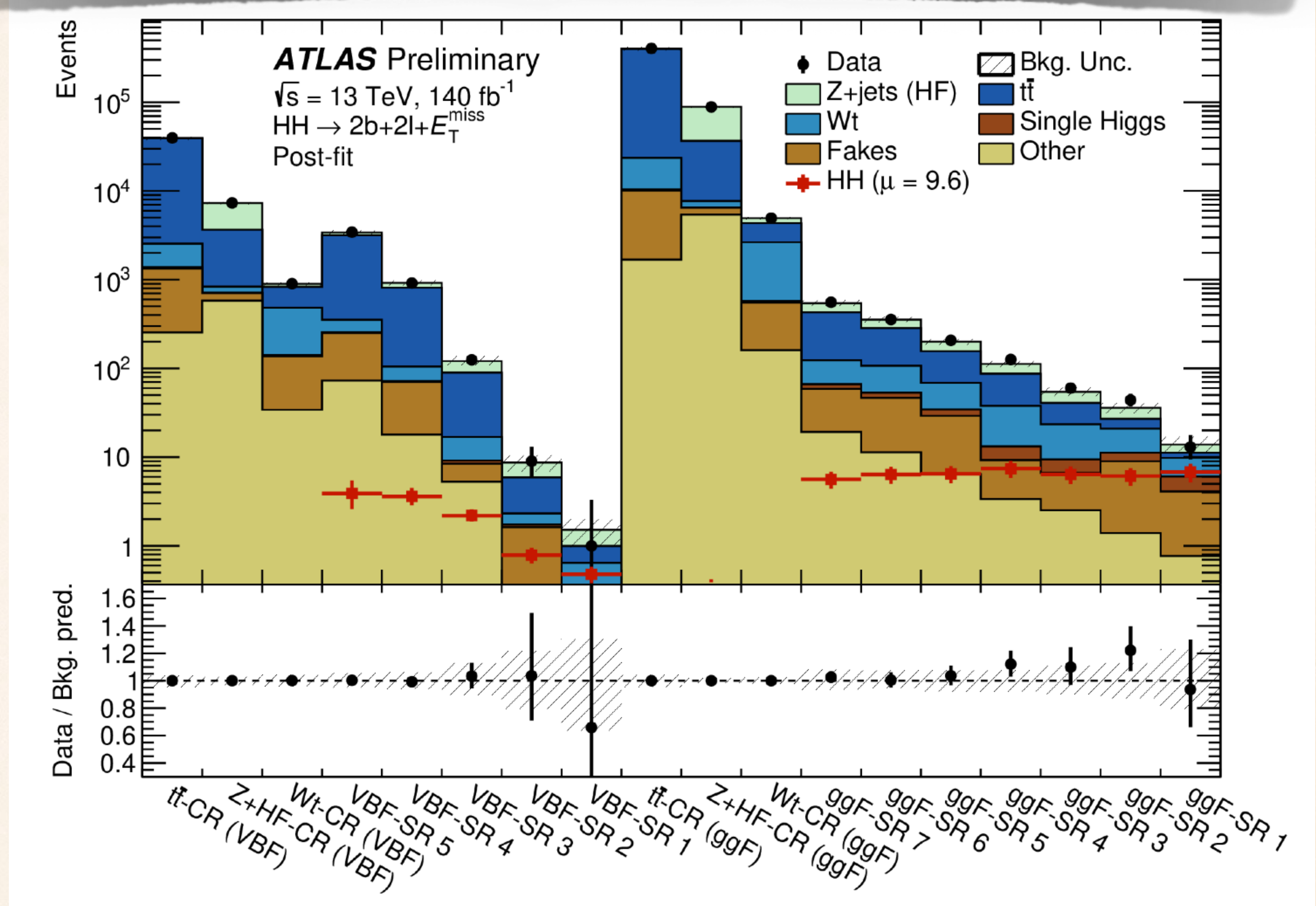
ATLAS-CONF-2023-064

New

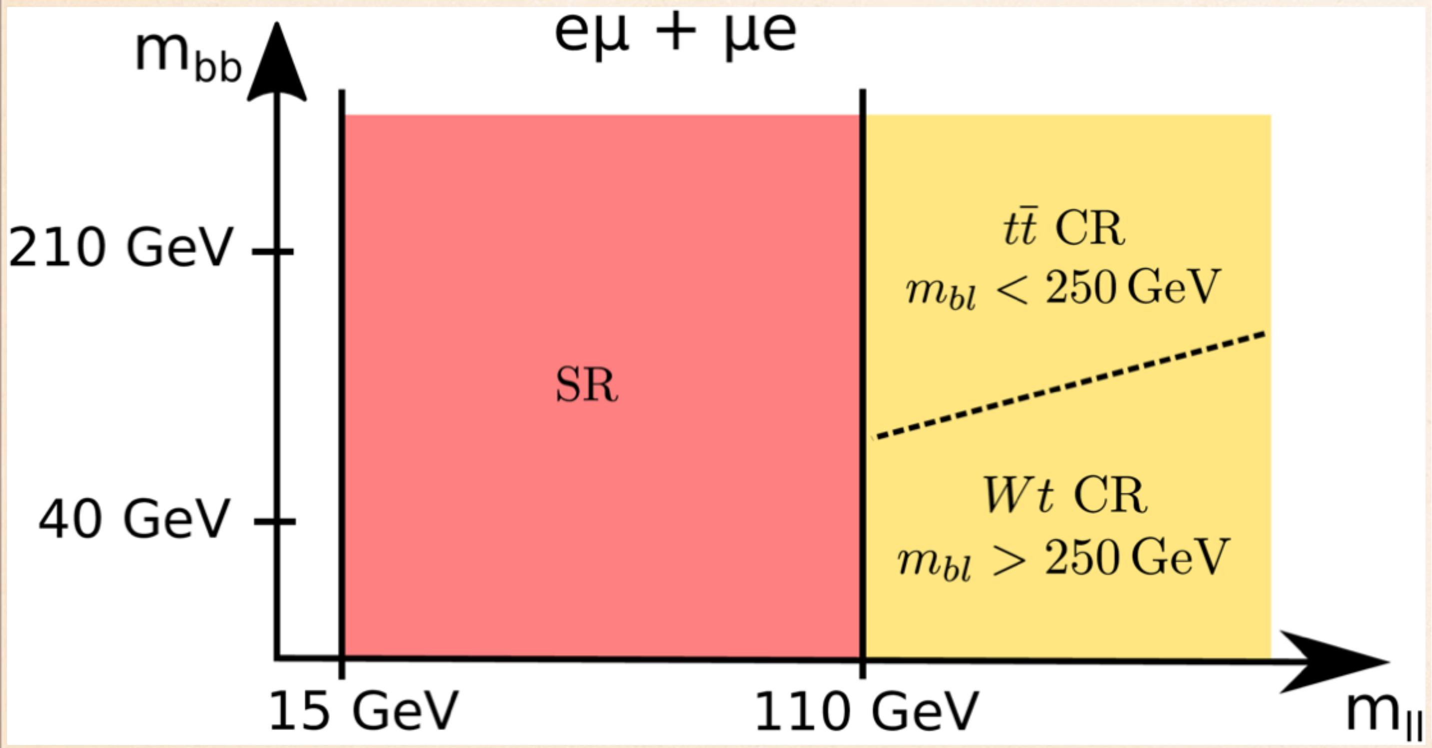
$HH \rightarrow bb + W^+W^-/ZZ/\tau^+\tau^- \rightarrow bb + l^+l^- + \text{neutrinos}$

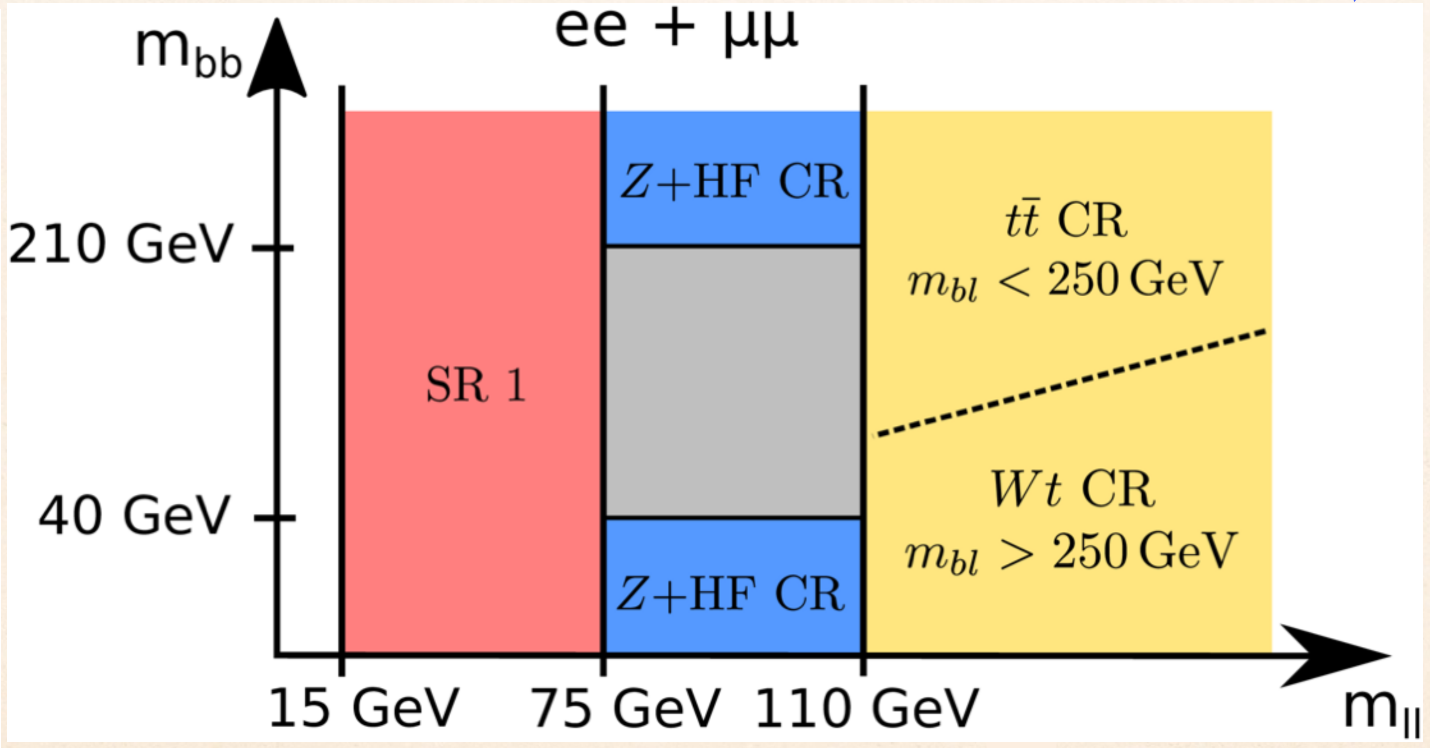
- Select: 2 b-jets, two opposite charge leptons, E_T^{miss}
- Dominant background from top quark processes and Z + heavy flavour - estimated from simulation (shape) with normalization being constrained from data
- Signal and control regions defined by topology
- MVA used to separate signal and background events and set limits

Yields in CR and highest score bins of MVA



- Observed (expected) 95% CL upper limit on $\frac{\sigma_{pp\rightarrow HH}}{\sigma^{SM}_{pp\rightarrow HH}}$ 9.6 (16.2)
  - significant improvement (previous 40(29))



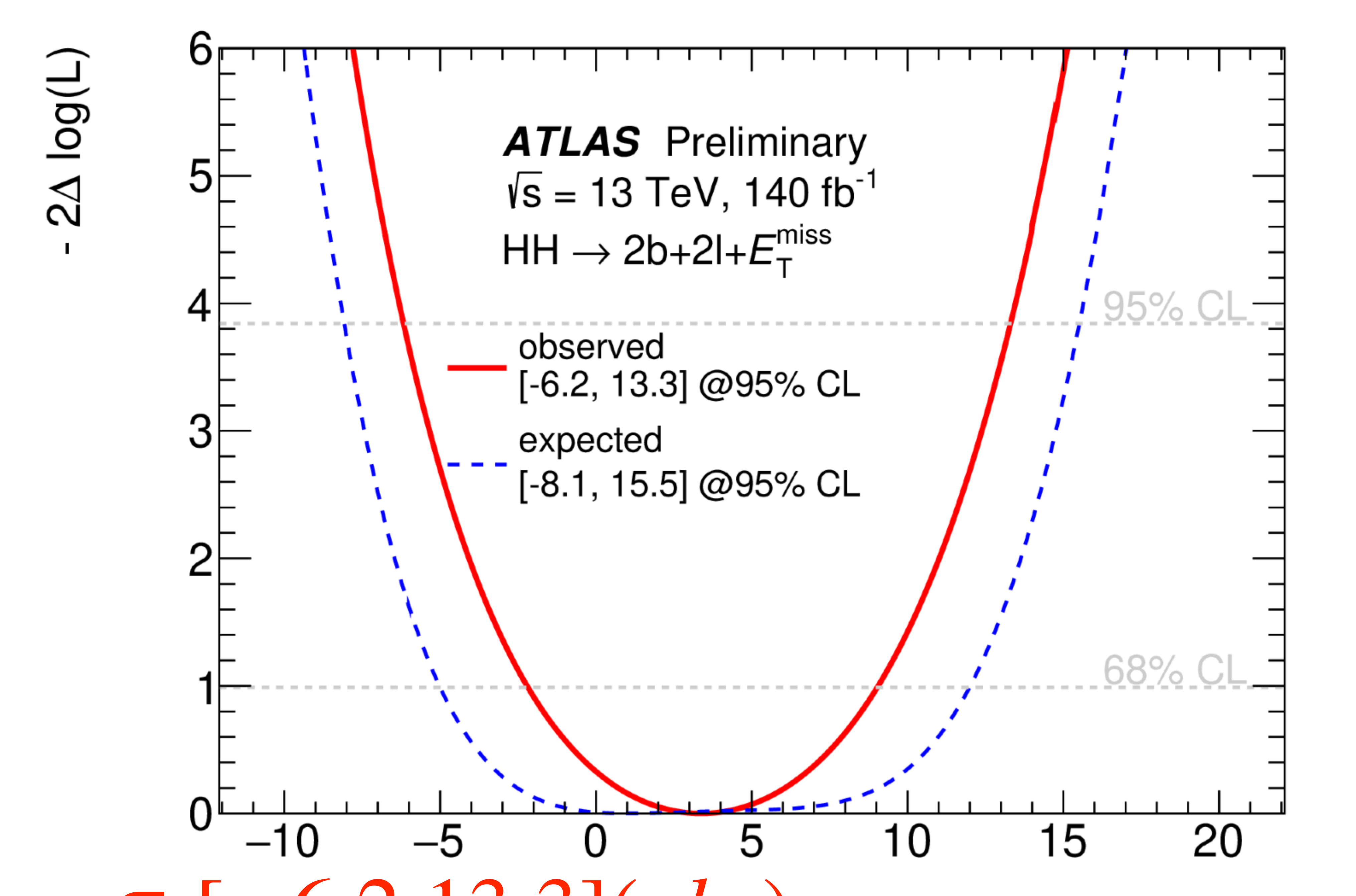


ATLAS-CONF-2023-064

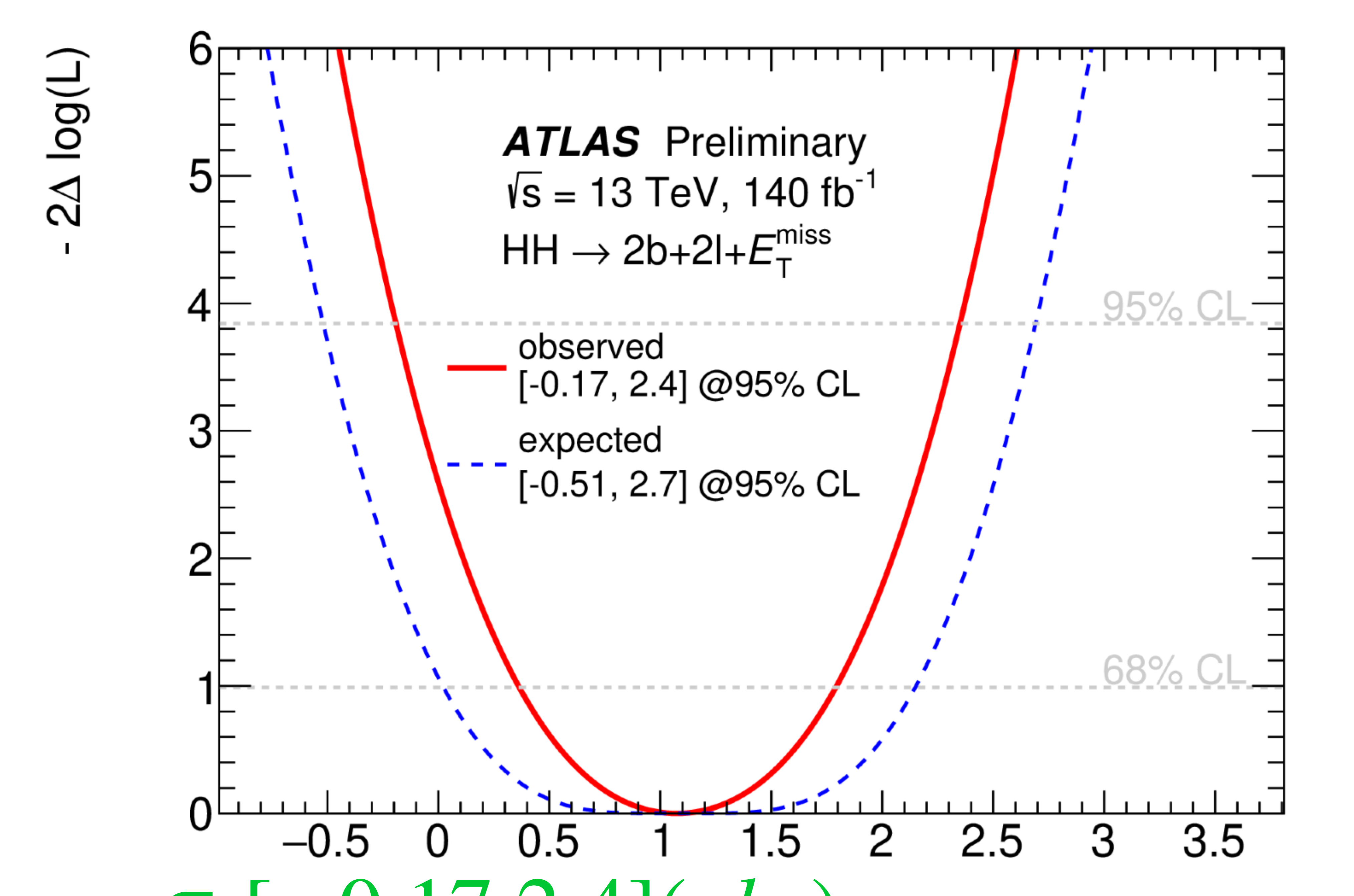
New

$HH \to bb + W^+W^-/ZZ/\tau^+\tau^- \to bb + l^+l^- + \text{neutrinos}$

- Likelihood scans on the κ_λ and κ_{2V} parameters
  - All other modifiers set to SM values, i.e. $\kappa_t = 1$ and also $\kappa_{2V}(\kappa_\lambda)$ in respective fits



$\kappa_\lambda \in [-6.2, 13.3](obs)$

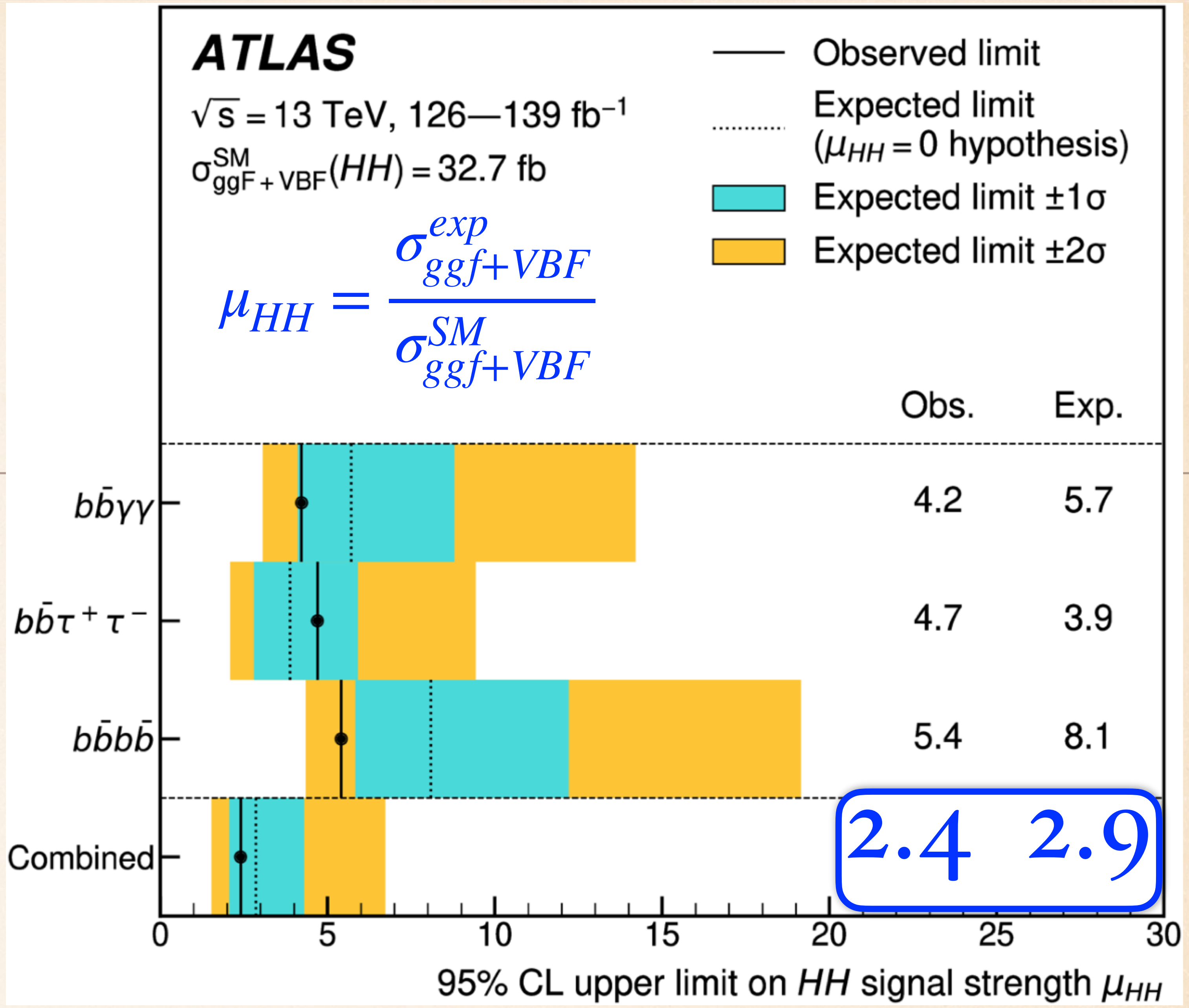


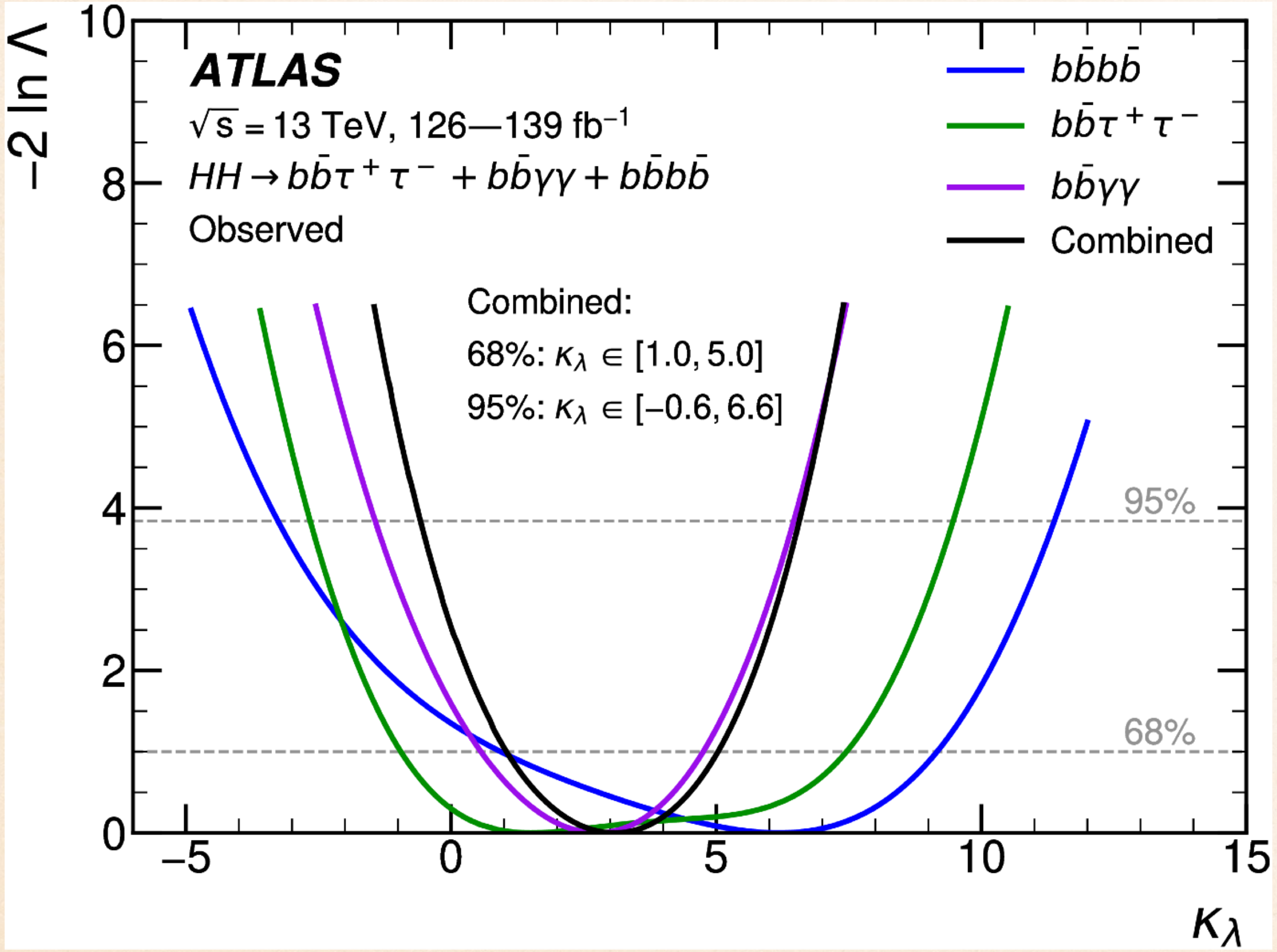
$\kappa_{2V} \in [-0.17, 2.4](obs)$

Phys. Lett. B 843 (2023) 137745

COMBINATION - HH

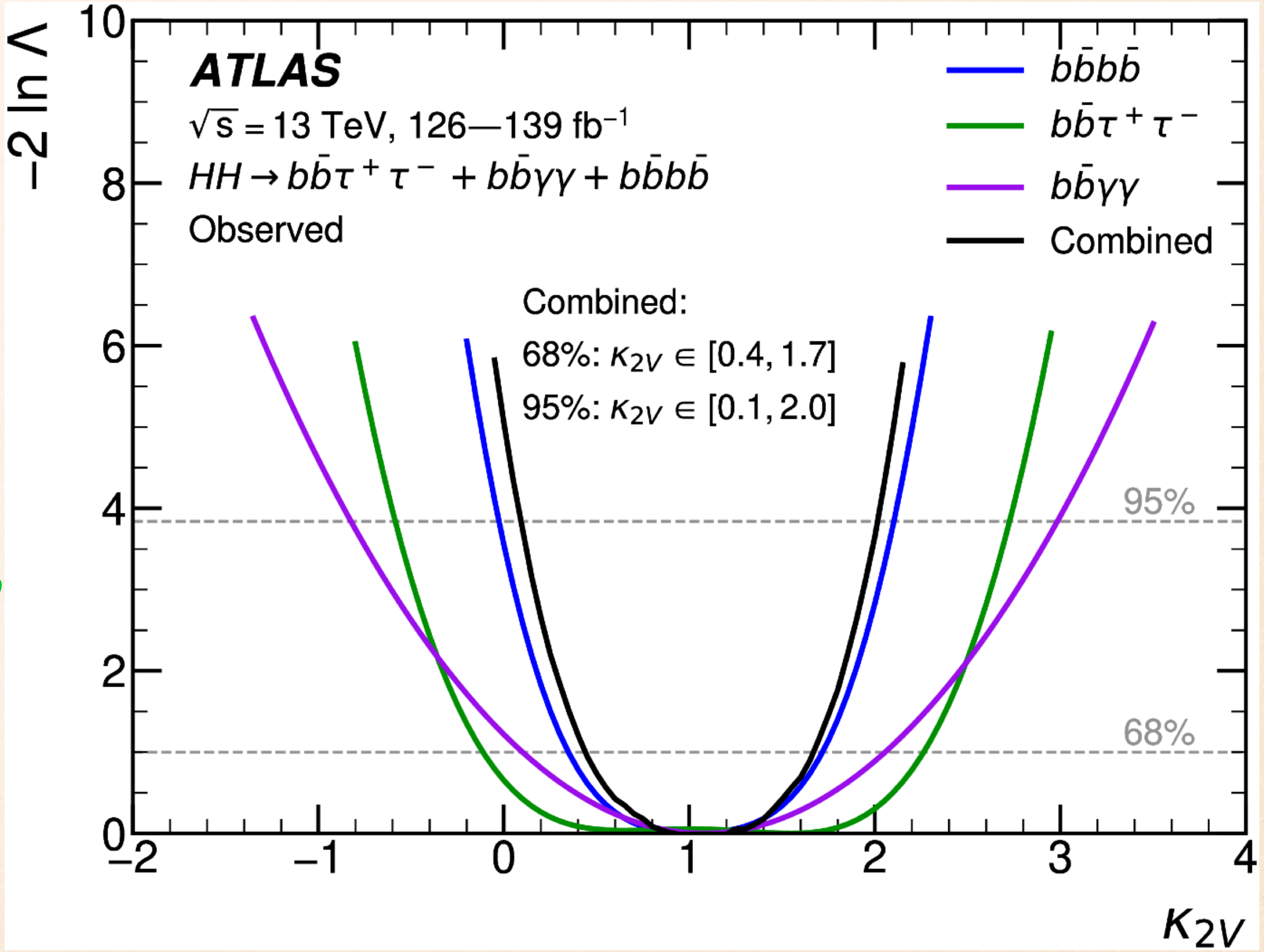
- The ggF process is sensitive to the relative sign between κ_λ and κ_t
- The VBF process is sensitive to the relative sign between κ_{2V} and κ_V
- Combine $bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$ (old)





$\kappa_\lambda \in (-0.6, 6.6)^{obs}$
$(-2.1, 7.8)^{exp}$

$\kappa_{2V} \in (0.1, 2.0)^{obs}$
$(0.0, 2.1)^{exp}$

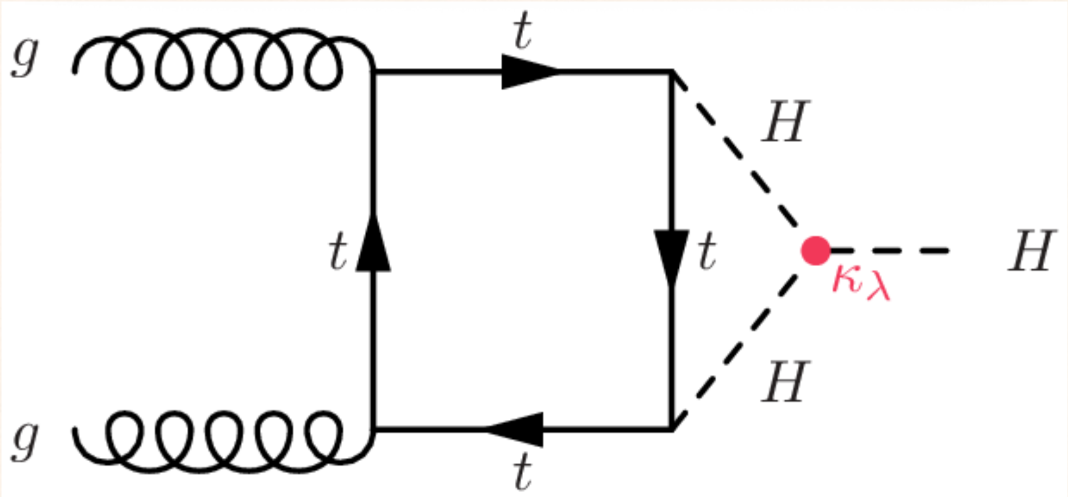


Phys. Lett. B 843 (2023) 137745

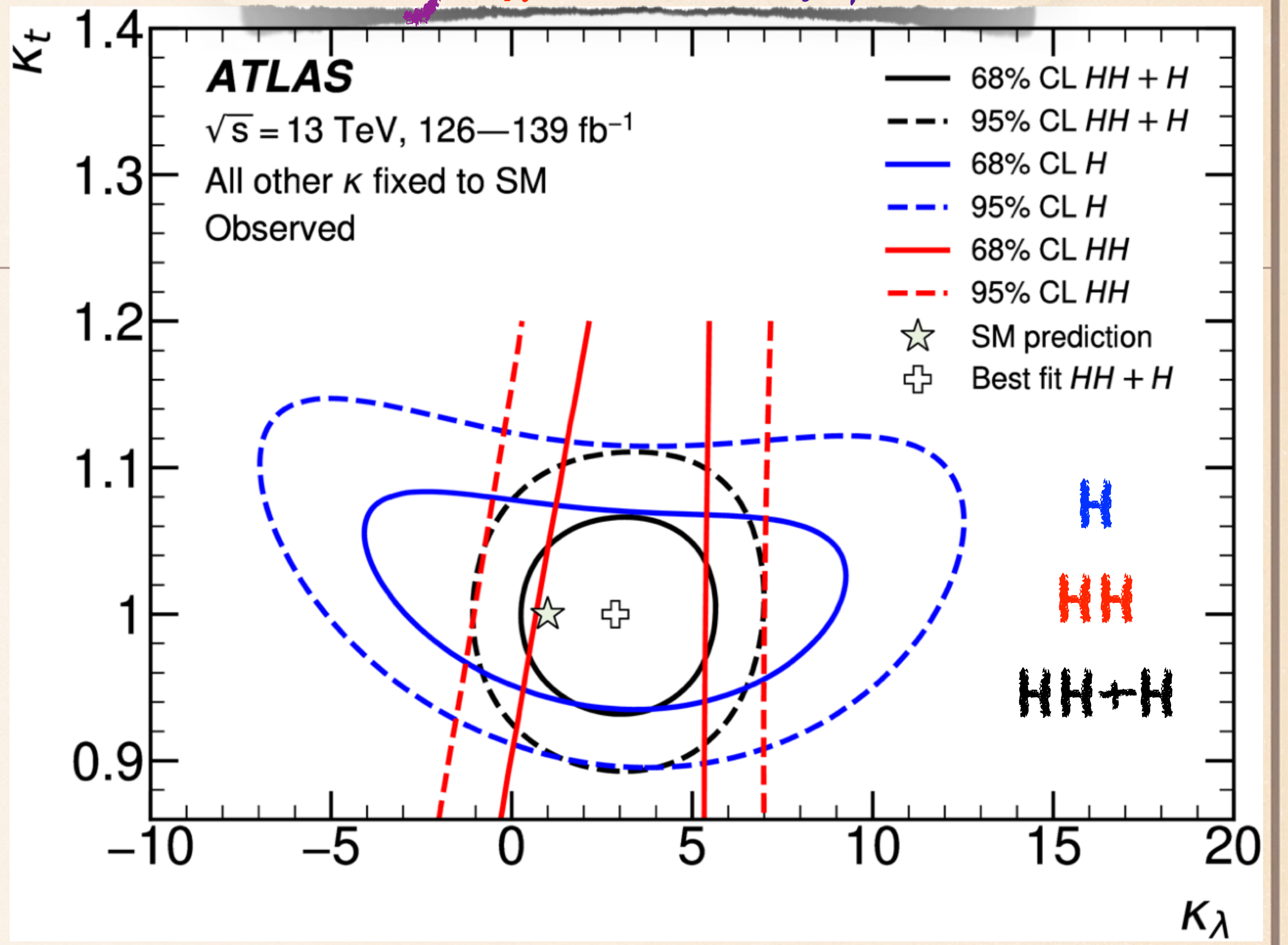
COMBINATION - H+HH

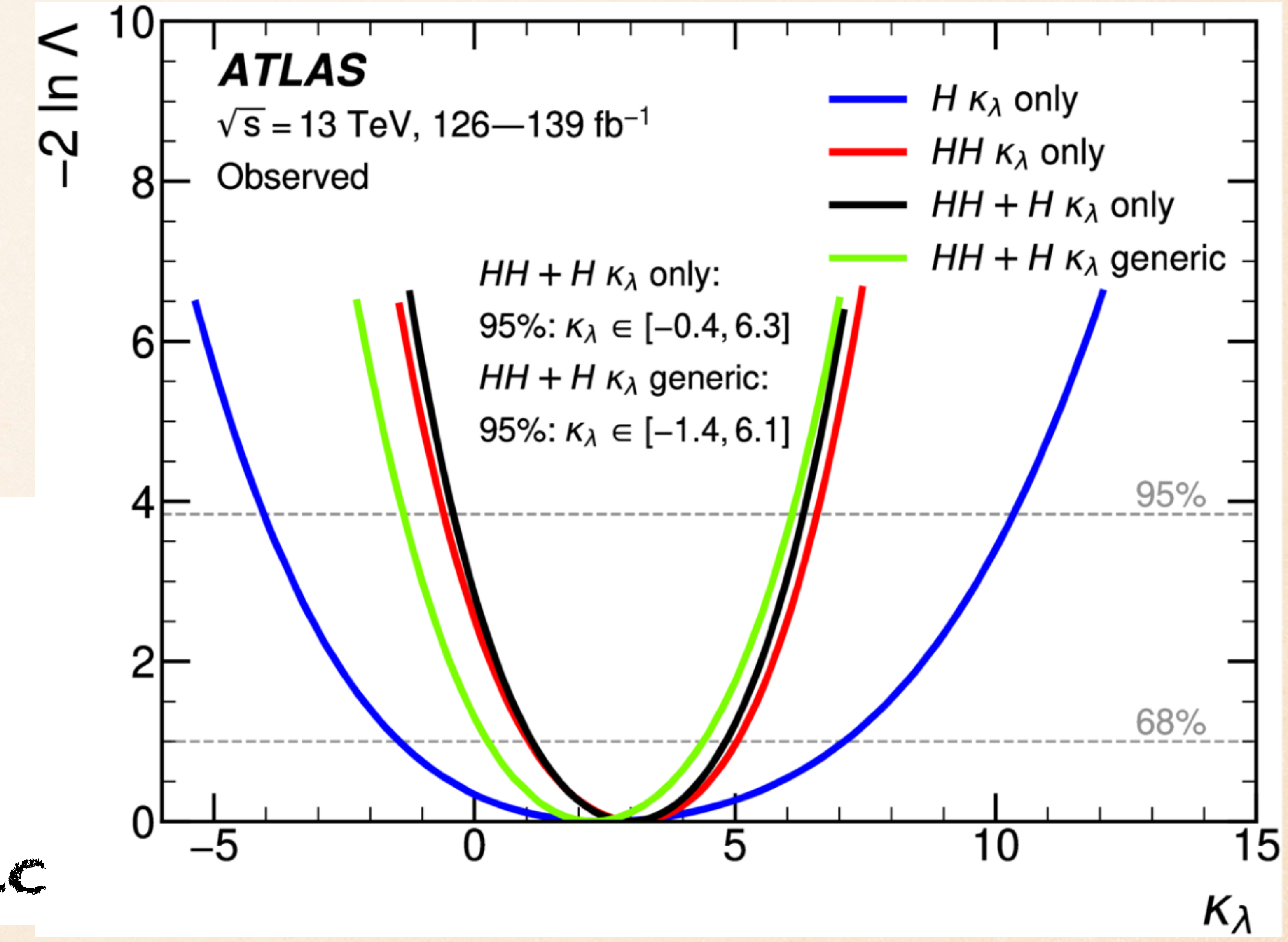
- Single Higgs production does not depend on κ_λ at LO, but it contributes to the calculation @NLO(EW)
  - an indirect constraint on κ_λ can be extracted
- Two approaches
  - Consider only departure of the κ_λ from the SM, all other as predicted
  - All of the coupling modifiers except κ_{2V} to float freely in the fit

ttH is the most sensitive to κ_λ



Only κ_λ and κ_t free

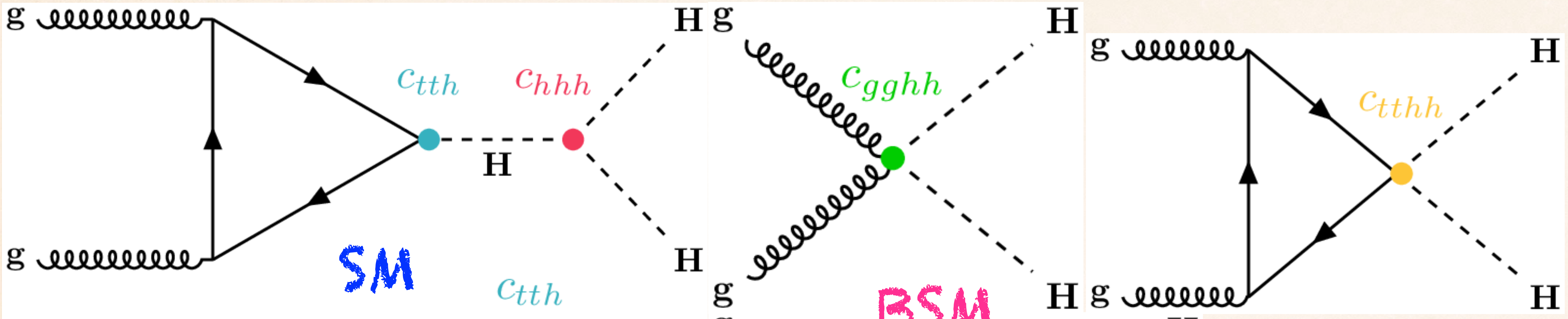


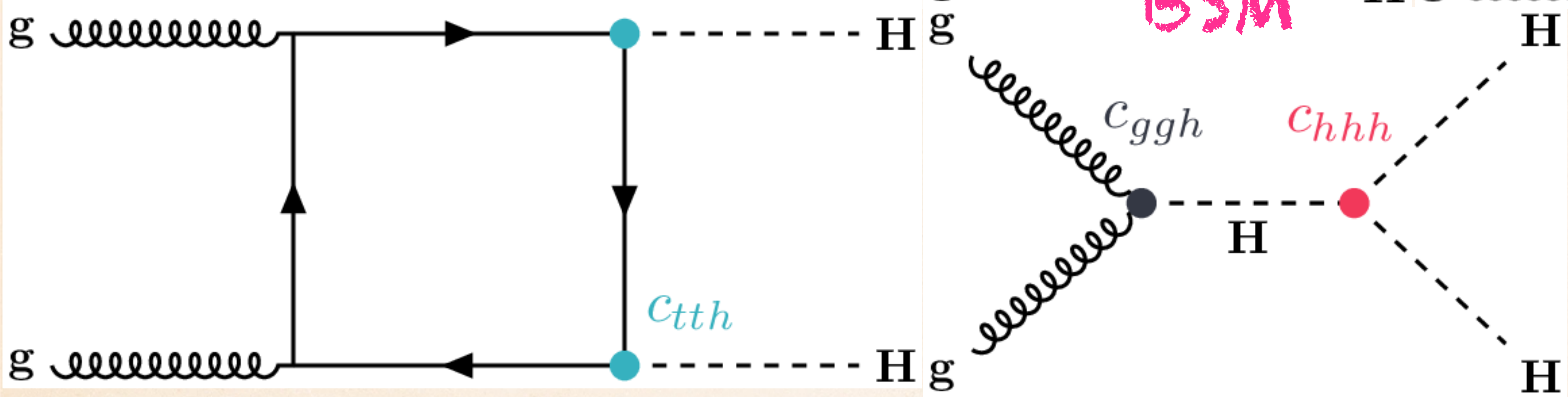


H κ_λ only
HH κ_λ only
HH+H κ_λ only
HH+H κ_λ generic

EFFECTIVE FIELD THEORIES

*Jay Sandesara about other results from EFT
*Tom Ingebretsen Carlson about EFT in $bb\gamma\gamma$

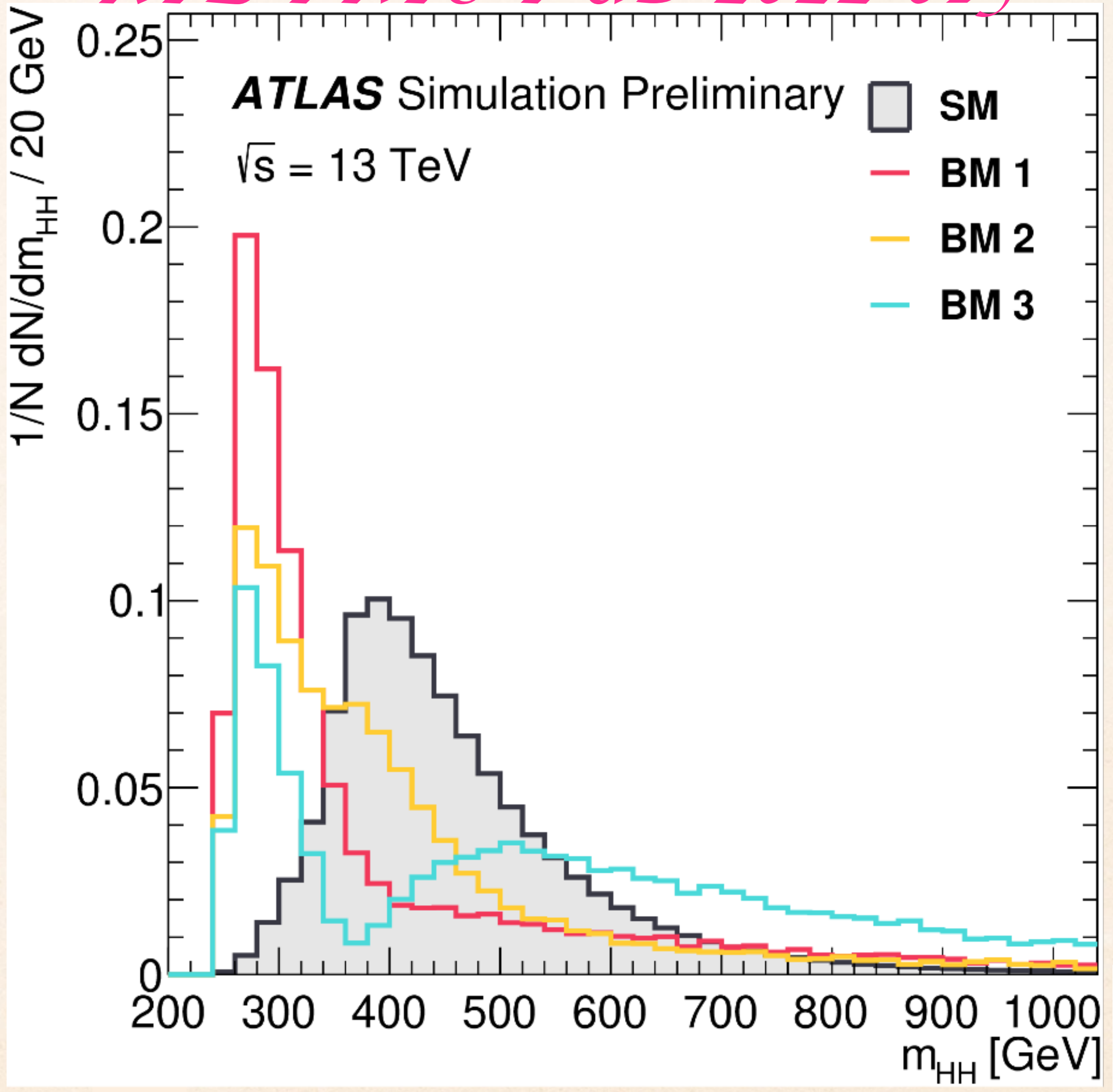


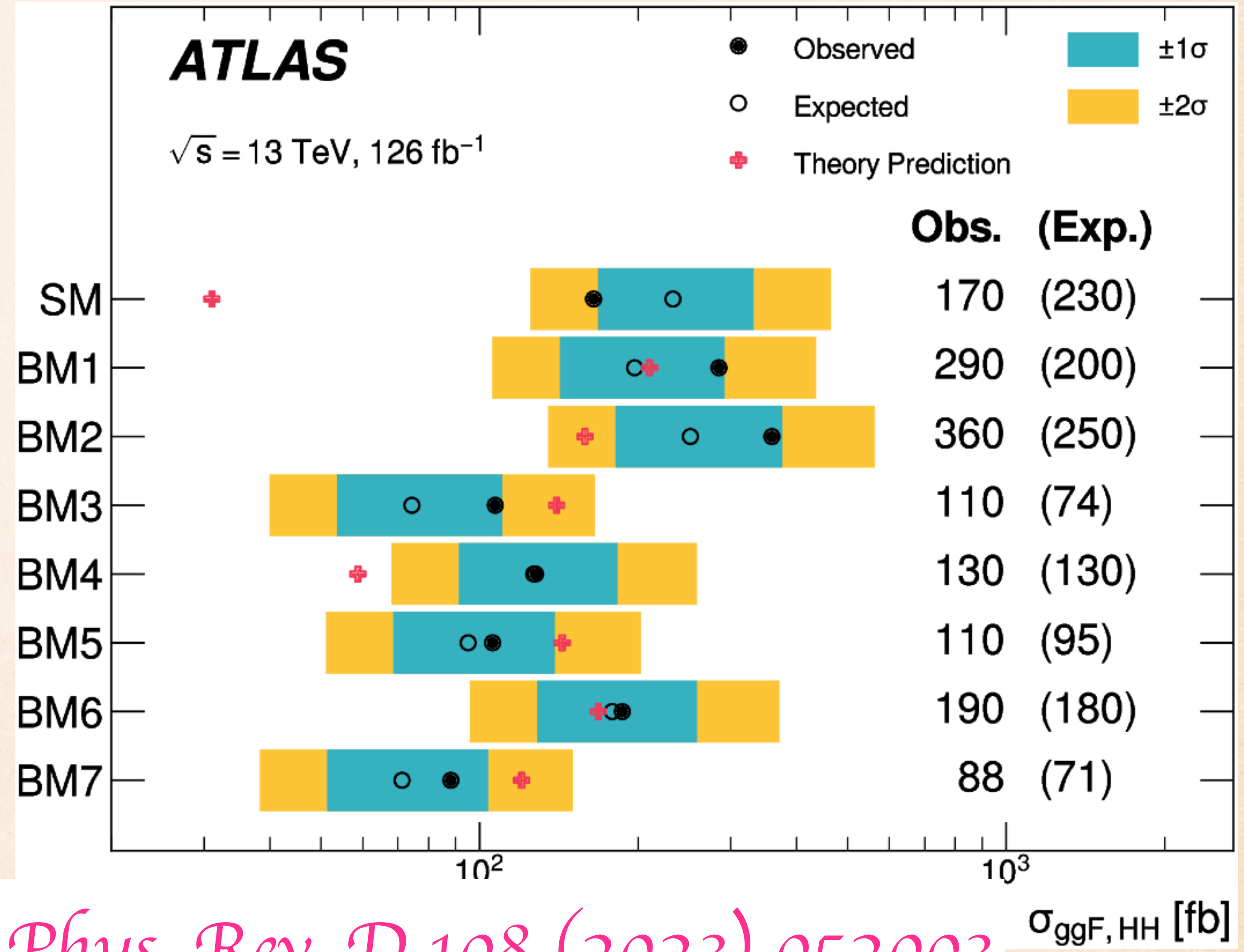


- Effective Field Theories (EFT) – indirect probe of new physics
  - H(iggs)EFT – physical Higgs boson
- BSM benchmarks based on impact on m_{HH}

Benchmark Model	c_{HHH}	c_{ttH}	c_{ggH}	c_{ggHH}	c_{ttHH}
SM	1	1	0	0	0
BM1	3.94	0.94	1/2	1/3	−1/3
BM2	6.84	0.61	0.0	−1/3	1/3
BM3	2.21	1.05	1/2	1/2	−1/3
BM4	2.79	0.61	−1/2	1/6	1/3
BM5	3.95	1.17	1/6	−1/2	−1/3
BM6	5.68	0.83	−1/2	1/3	1/3
BM7	−0.10	0.94	1/6	−1/6	1

ATL-PHYS-PUB-2022-019

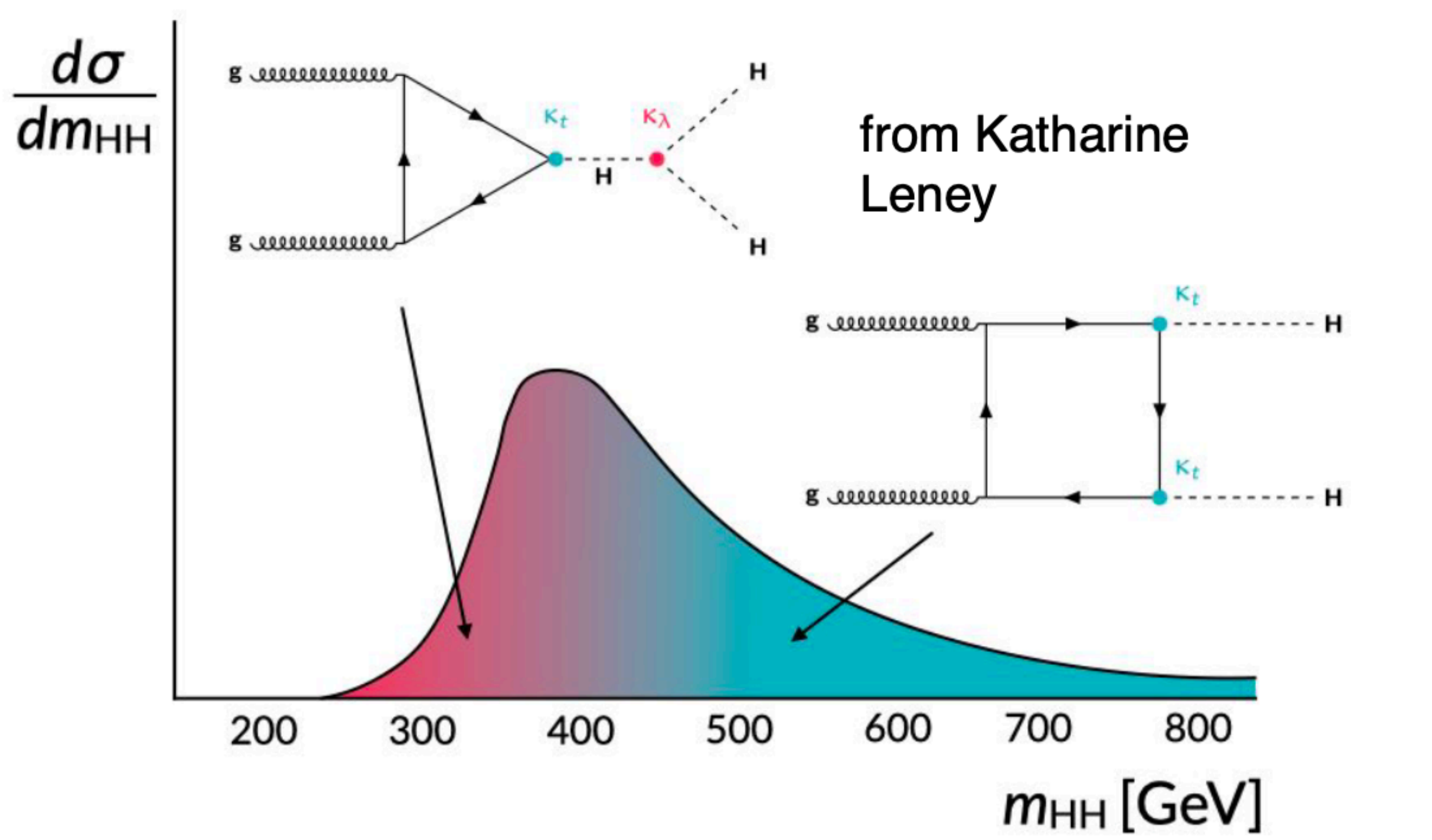




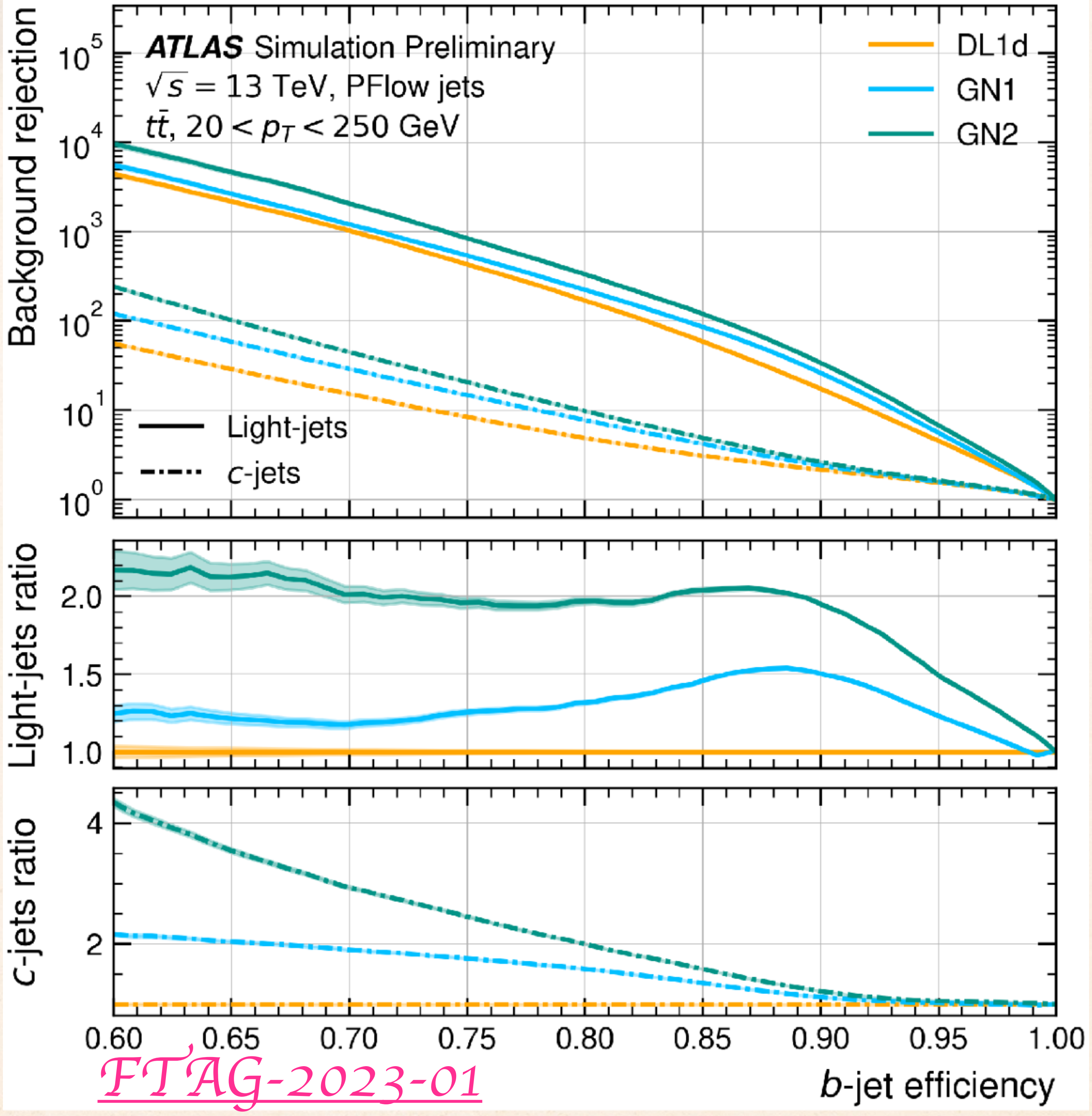
Phys. Rev. D 108 (2023) 052003

FUTURE IS HERE

- LHC Run 3 is ongoing
- Low m_{HH} is crucial to constrain κ_λ

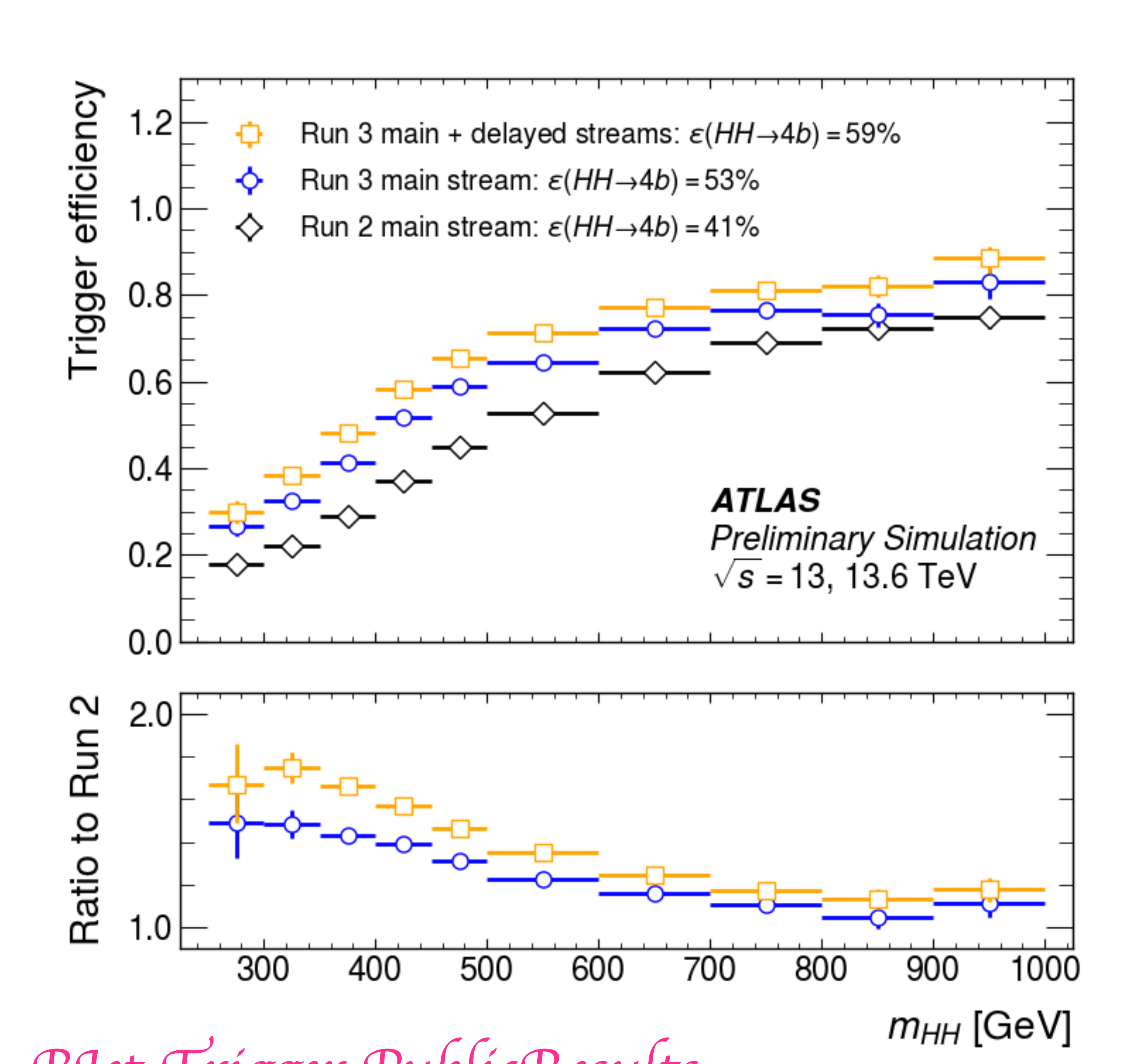


Better b-tagging



[FTAG-2023-01]

Smarter triggering

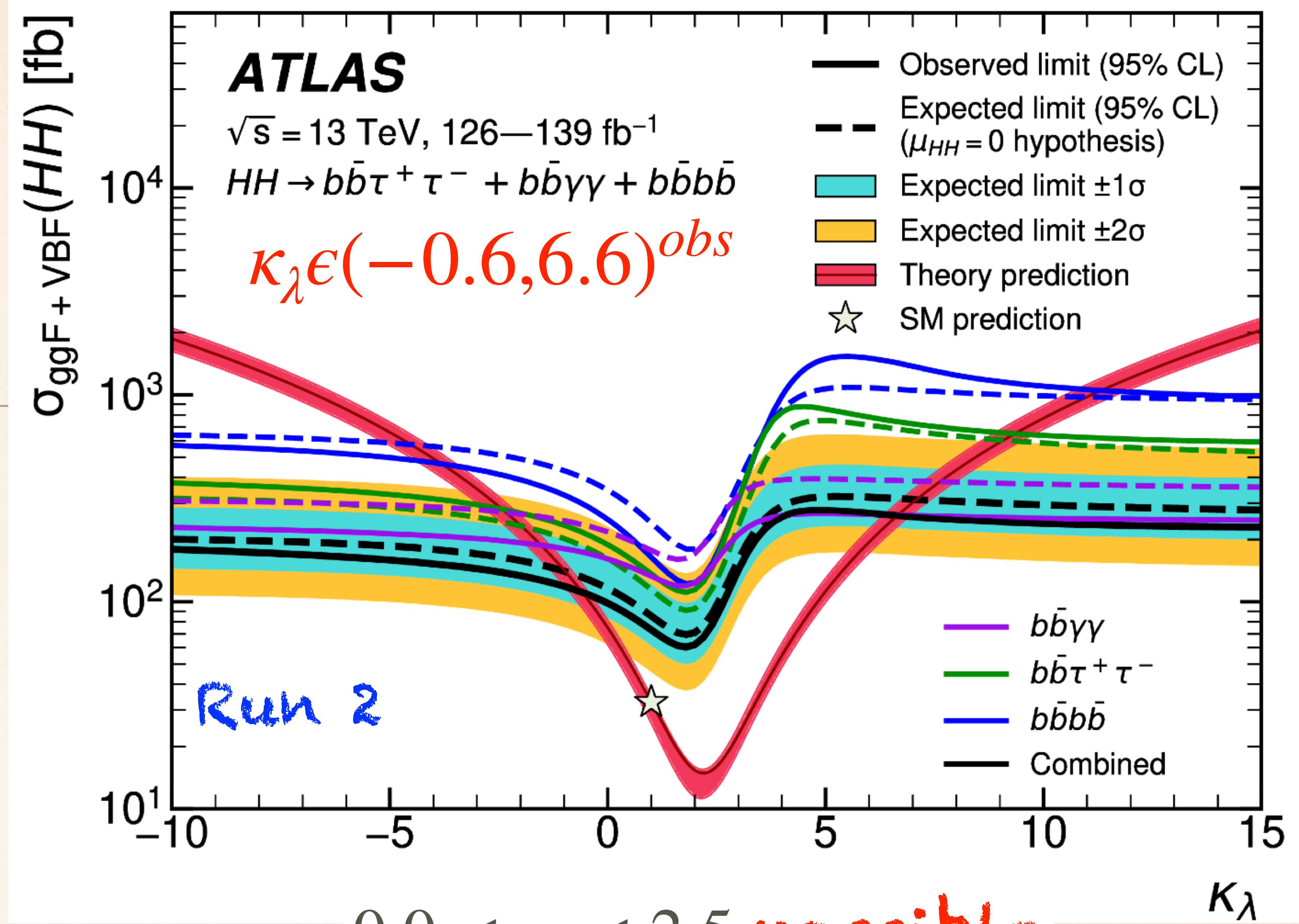


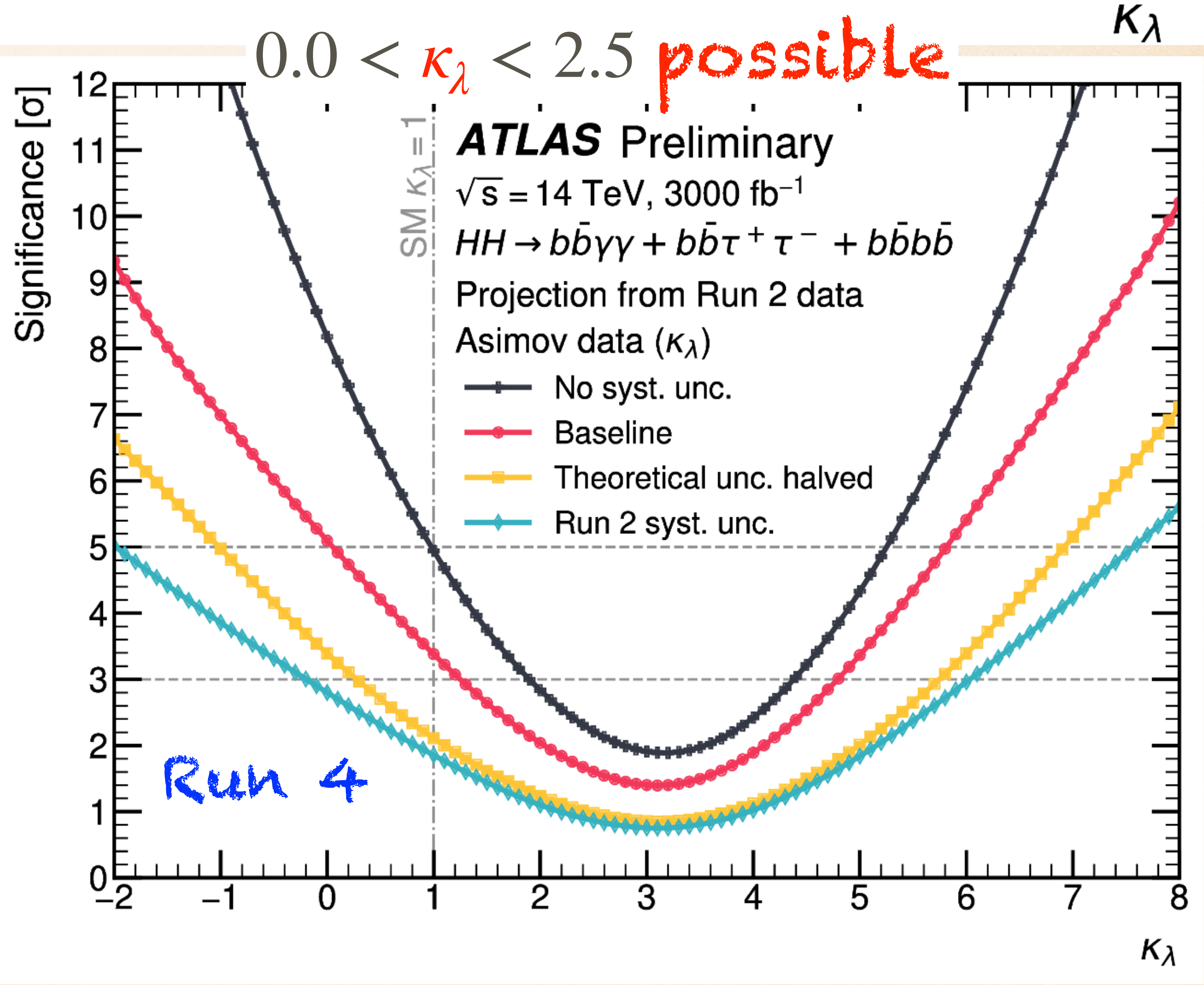
[BJet Trigger PublicResults]

SUMMARY

- Many improvements in experimental devices and techniques lead us to fantastic results
- With run 3 we will double the data
- We go further: Projections for HL-LHC:
  - ATLAS – 3.4σ significance; 5σ possible combining with CMS

Public results





TO MEENAKSHI

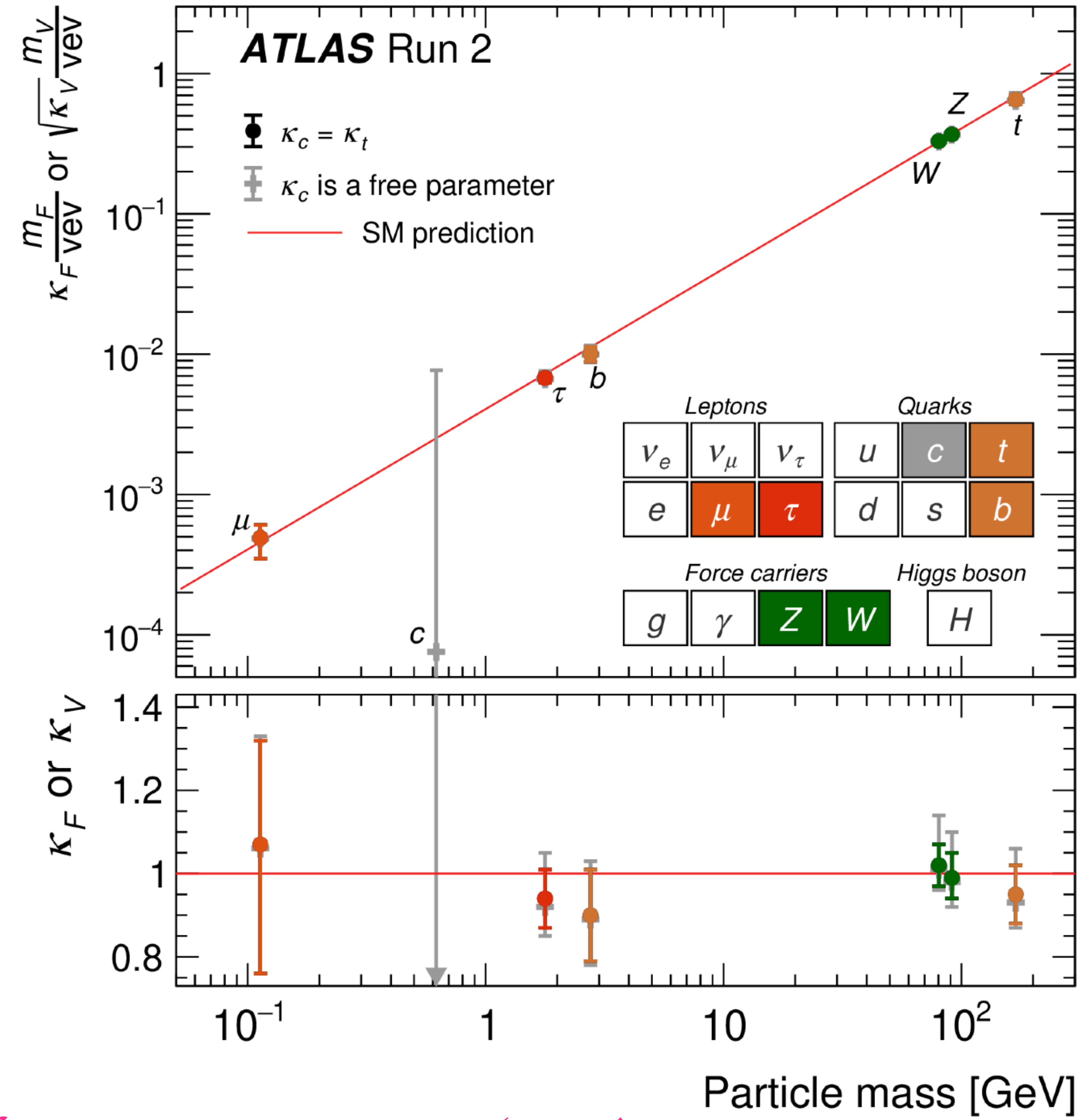
- In early 2000's $VH \rightarrow Vbb$ was impossible to think of at that time future LHC
  - DiHiggs analyses were wild dreams
- People like Meenakshi made it possible

BACKUP

MOTIVATION

- In 2012 a new particle with properties consistent with those predicted for the Higgs boson of the standard model was discovered
- Precision era in Higgs physics points to SM-like particle
  - The coupling between the Higgs boson and a given particle is fully defined by the particle's mass and type.
- Missing Higgs self coupling, explanation of EWK symmetry breaking

$$\kappa_X = \frac{c_{HX}^{exp}}{c_{HX}^{SM}}$$



Nature 607, pages 52-59 (2022)

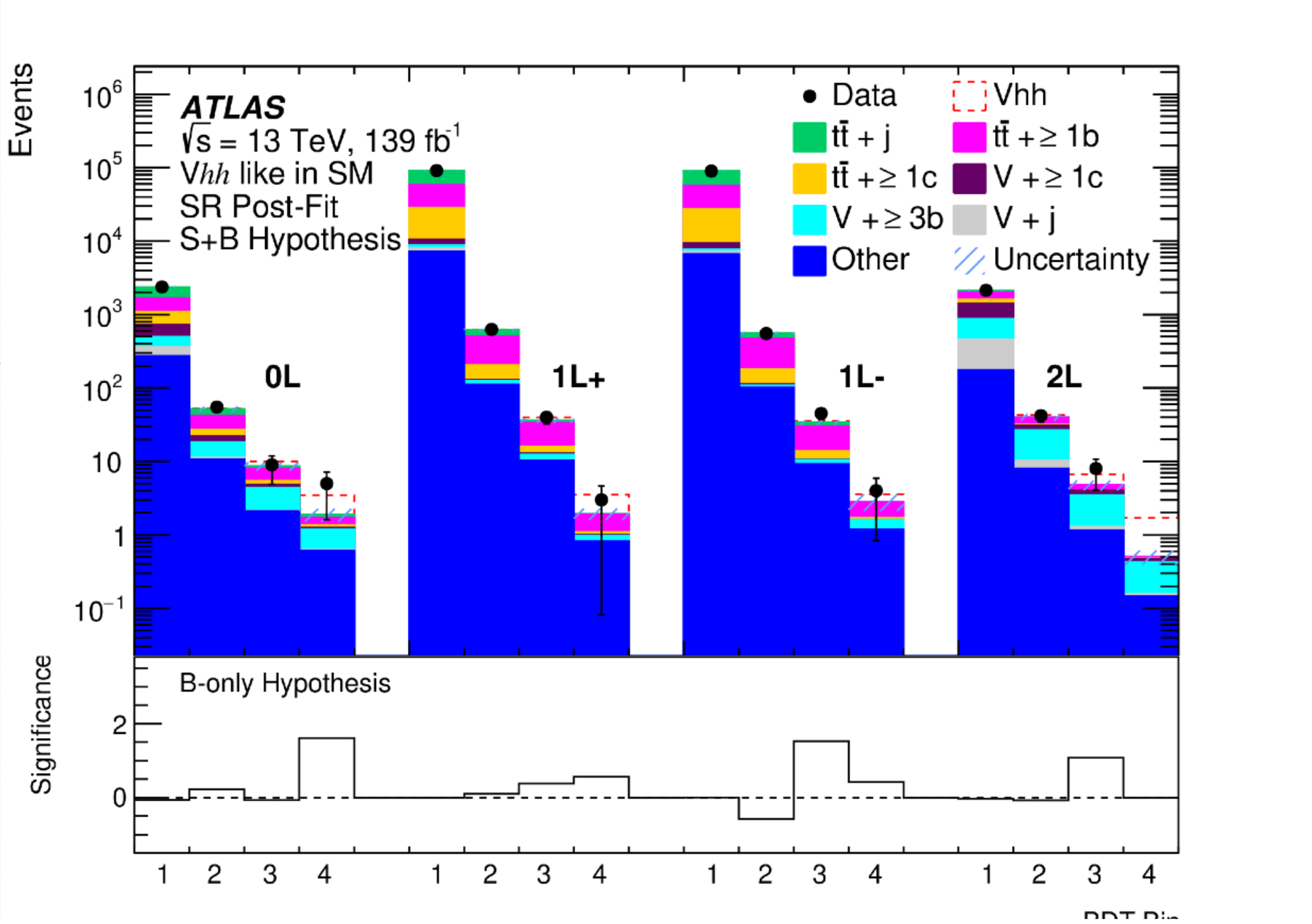
VHH PRODUCTION

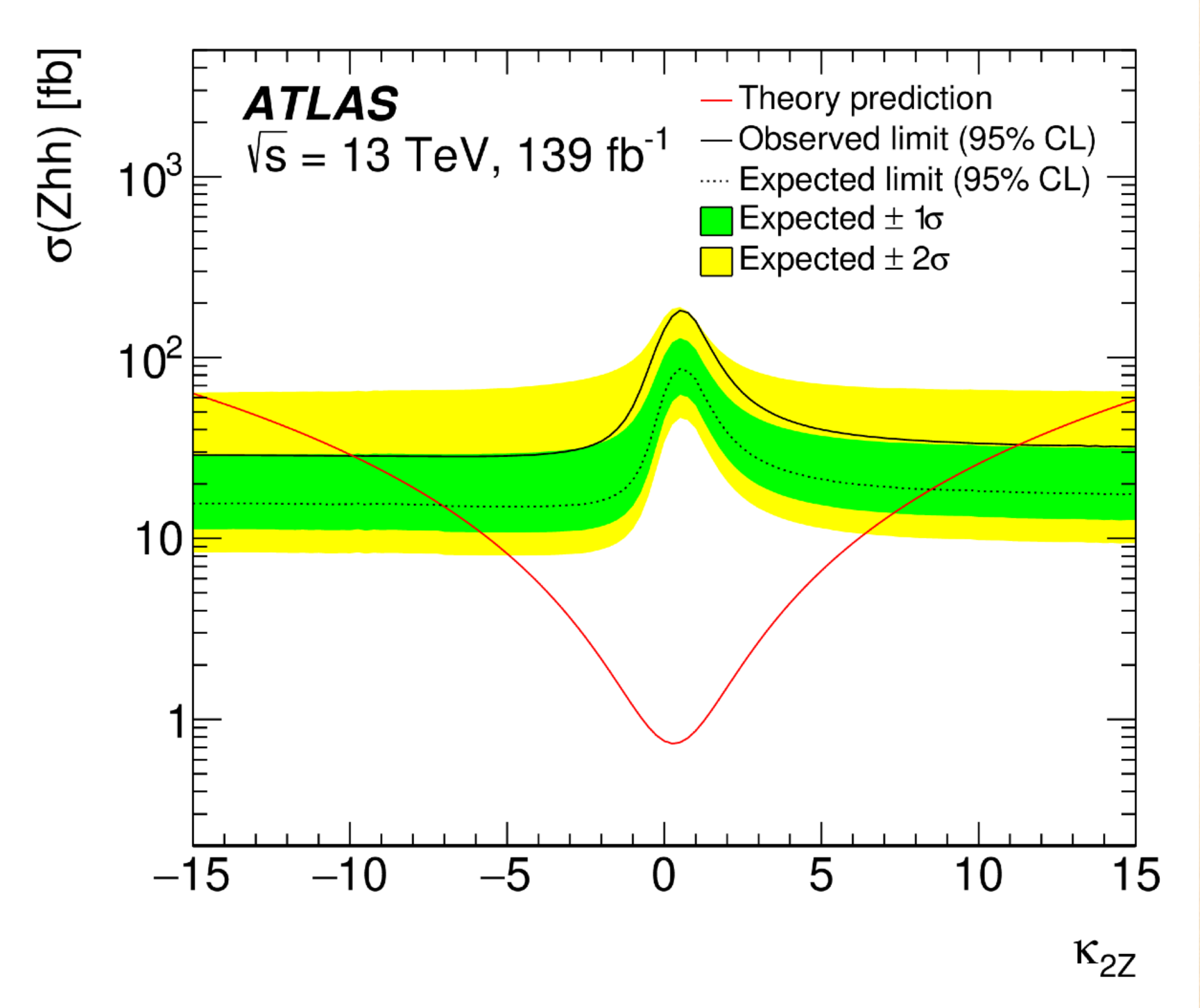
[EPJC 83 (2023) 519]

- Unlikely VBF it can probe separately WWHH (κ_{2W}) and ZZHH (κ_{2Z}) interactions
- $HH \to bbbb$ and leptonic decays of V: $Z \to \nu\nu$ (0L), $W \to l\nu$ (1L) and $Z \to ll$ (2L)
- Extract signal with simultaneous fit to BDT distributions
- Results interreted in three different scenarios:
  - "SM" - SM kinematics but with its cross-section scaled by a signal-strength parameter μ
  - κ_λ - tests for an anomalous tri-linear hhh coupling, assuming SM couplings for the rest
  - κ_{2V} - tests for an anomalous quartic hhVV coupling

$$-34.4 < \kappa_\lambda < 33.3 \qquad -12.3 < \kappa_{2W} < 13.5$$

$$-8.6 < \kappa_{2V} < 10.0 \qquad -9.9 < \kappa_{2Z} < 11.3$$





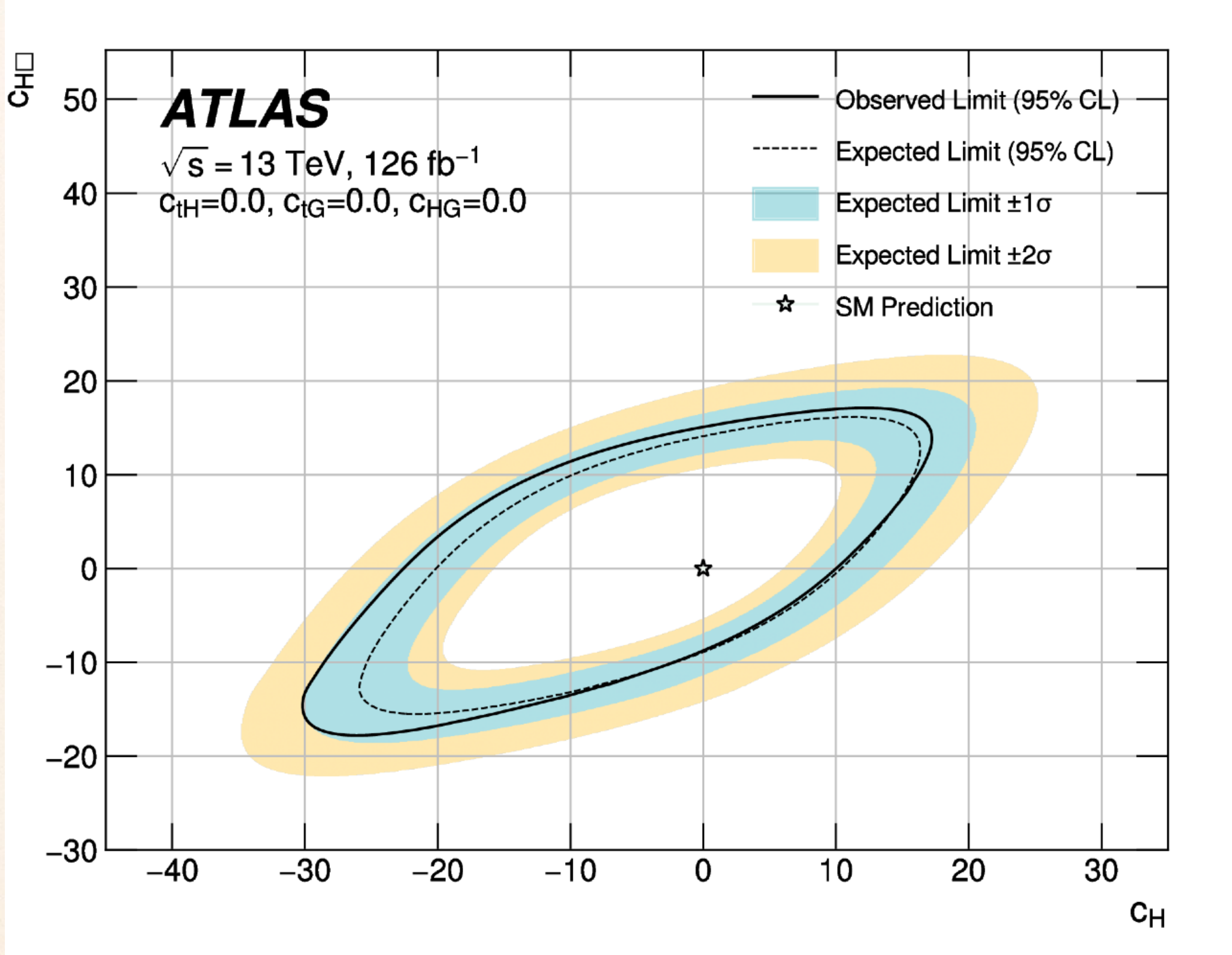
EFFECTIVE FIELD THEORIES

*In dedicated session Jay Sandesara will talk about other results from EFT

*Tom Ingebretsen Carlson will talk about EFT in $bb\gamma\gamma$ later today

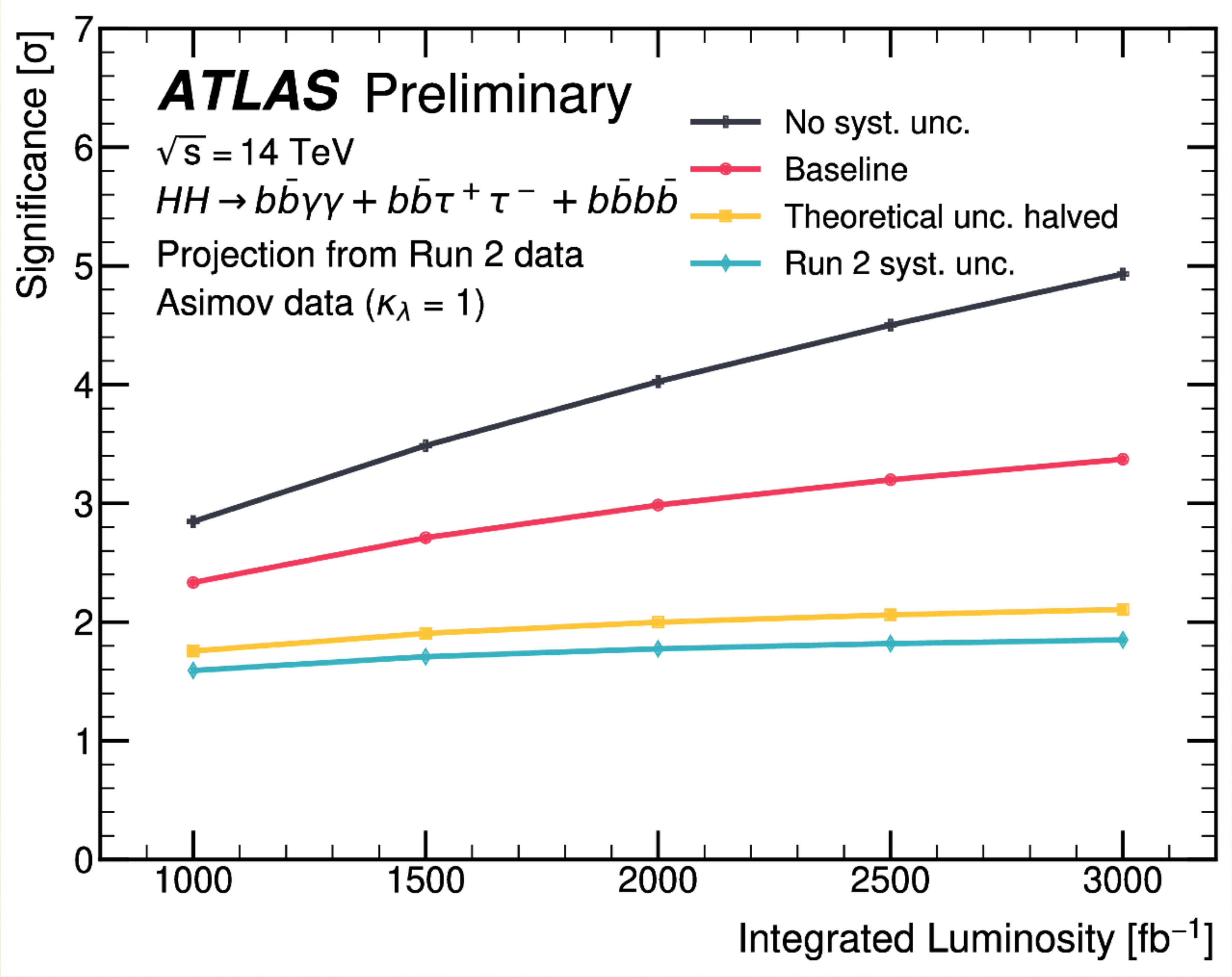
- Effective Field Theories (EFT) - indirect probe of new physics
  - SMEFT: $\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + (1/\Lambda^2) \sum c_k^{(6)} O_k^{(6)}$

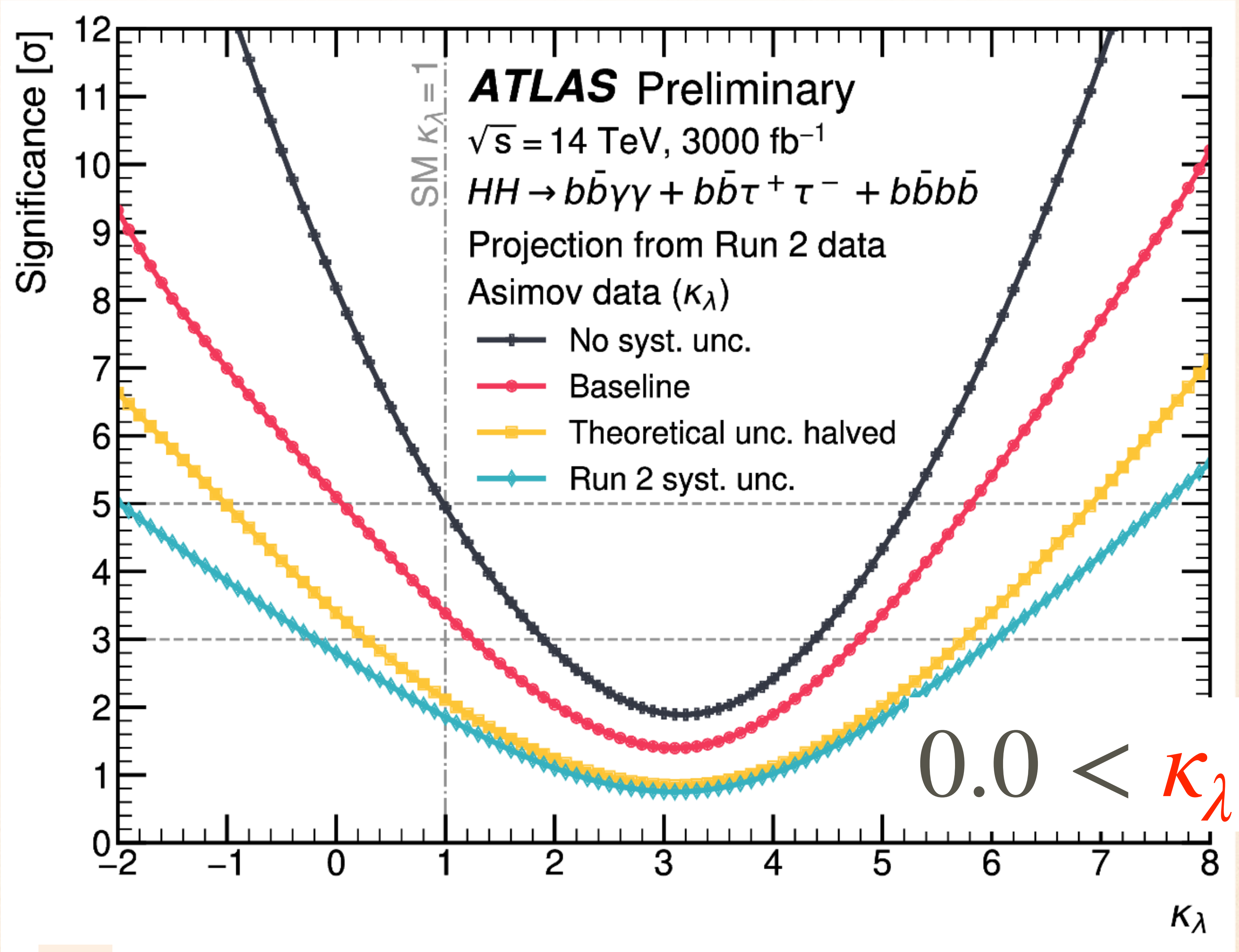
Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$



FURTHER IN FUTURE - HL-LHC

- Four systematic uncertainty scenarios probed - baseline accounts for expected improvements
- ATLAS - 3.4σ significance; 5σ possible combining with CMS
- Improvement of the results from further work on trigger, object reconstruction, analyses techniques





$0.0 < \kappa_\lambda < 2.5$ possible

FURTHER IN FUTURE - HL-LHC

- Four systematic uncertainty scenarios probed - baseline accounts for expected improvements
-

	Significance [σ]				Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

IMPROVEMENTS

- Run2 vs run 3 taggers