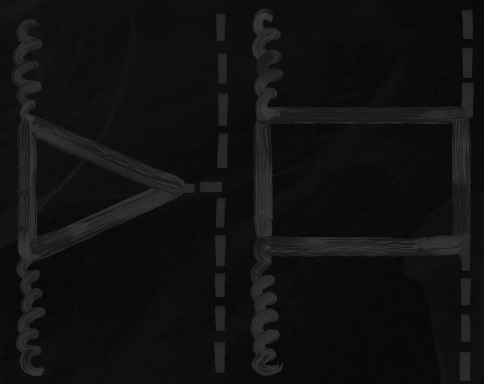
# Higgs pairs at colliders

## Present and Prospects

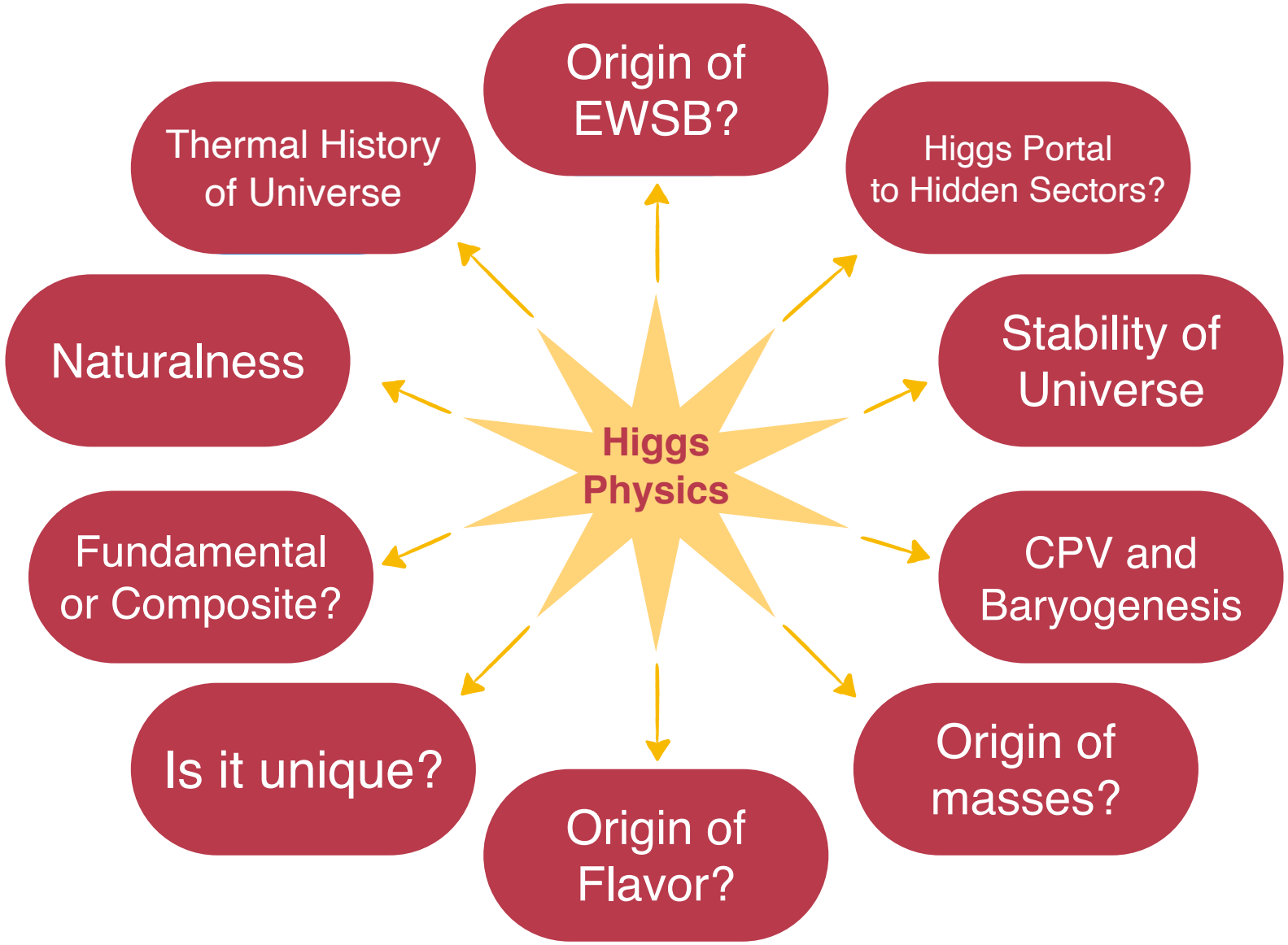


Caterina Vernieri

HEP Seminar · Imperial College London

October 14, 2026

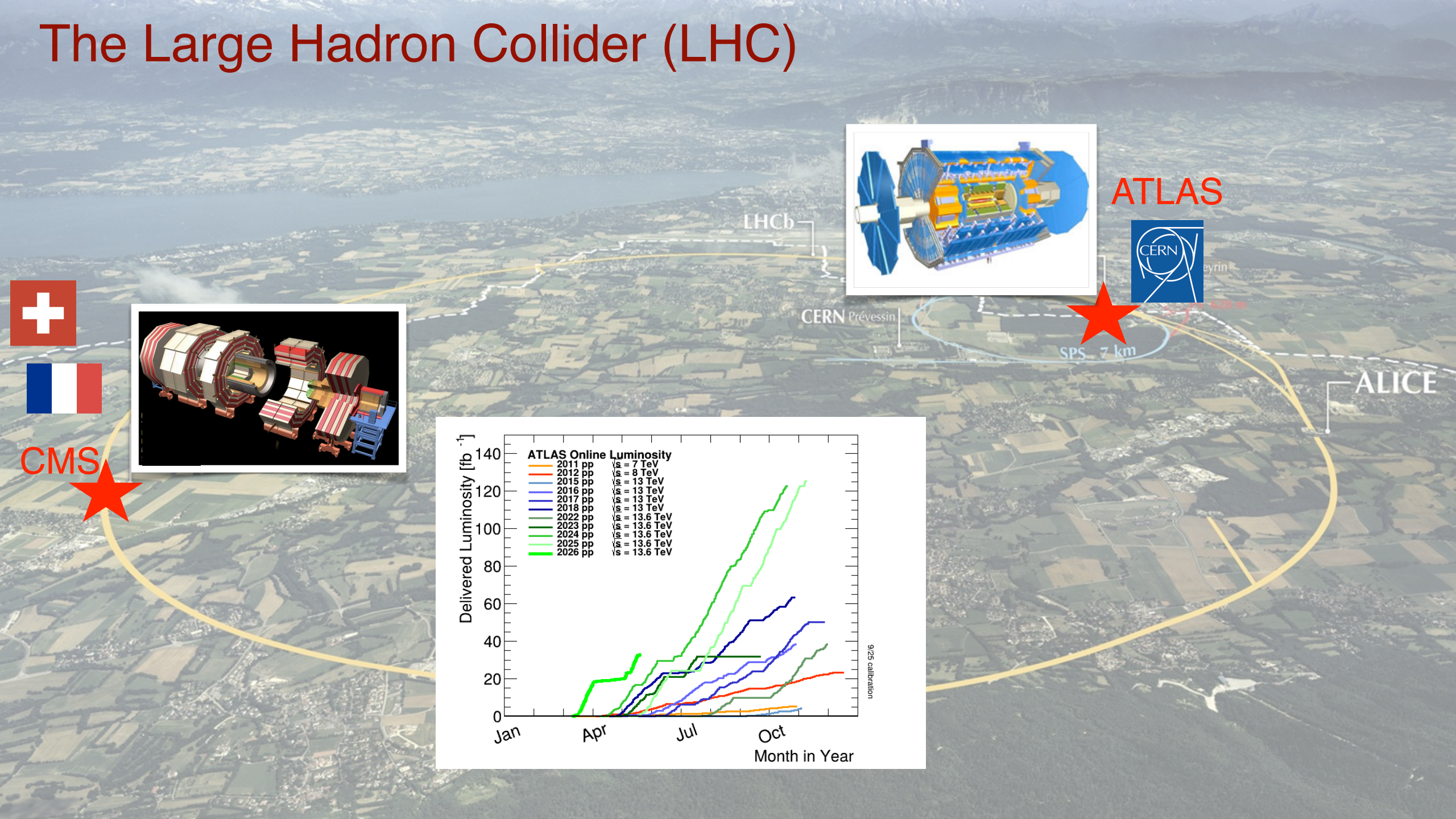
SLAC





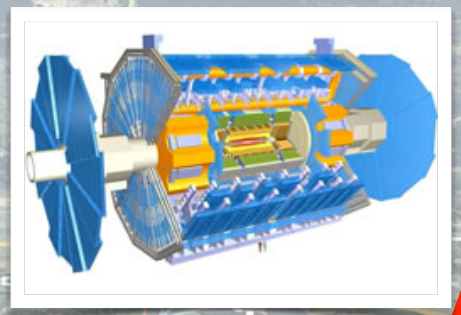

The Energy Frontier 2021 Snowmass Report

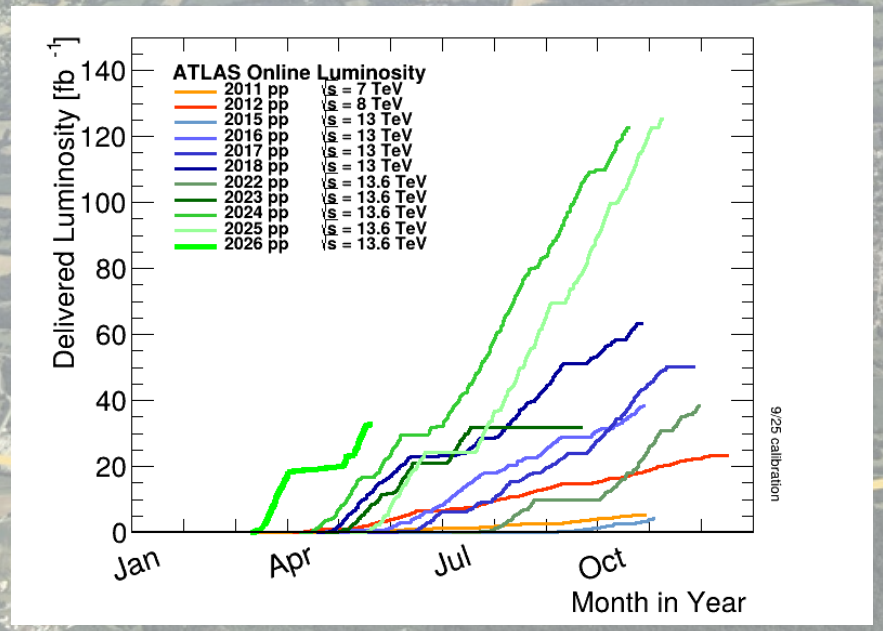
# The Large Hadron Collider (LHC)



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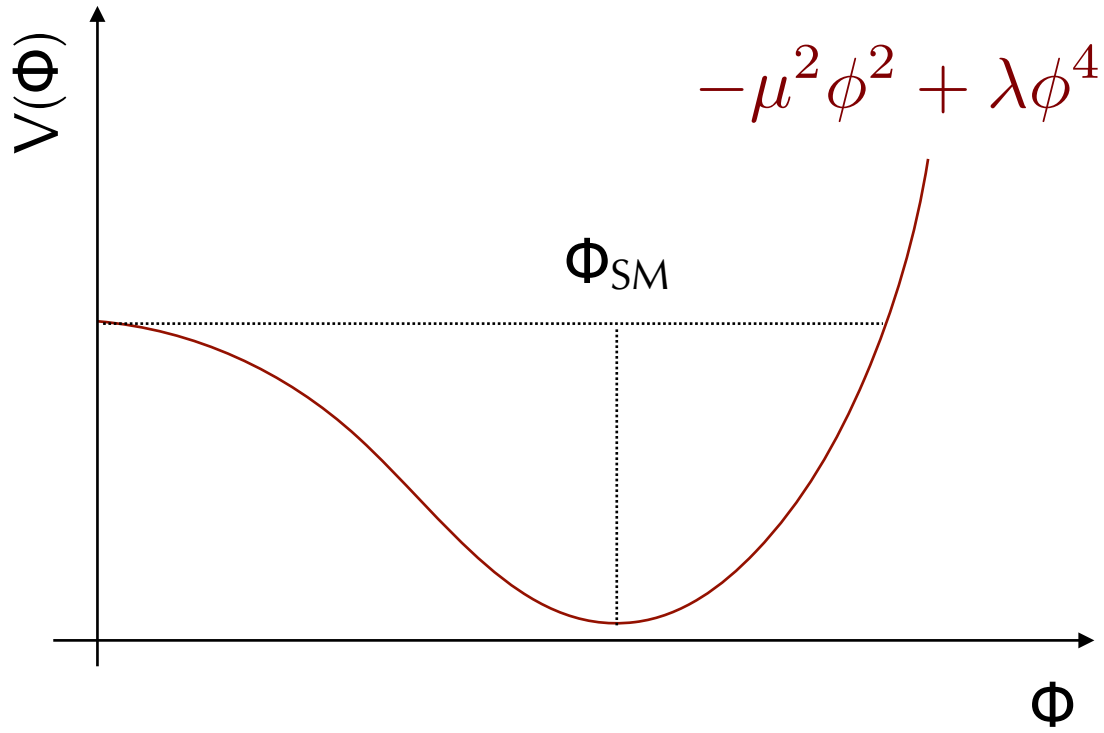




***~ 0.5/ab delivered***

*A factor ~**50x** more data than at the time of the Higgs discovery*

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - \boxed{V(\phi)} = -\mu^2 \phi^2 + \lambda \phi^4$$

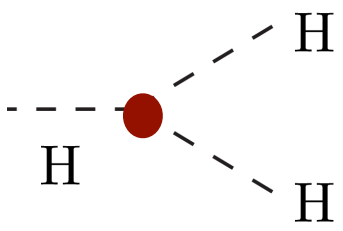



**Probing this Higgs Boson potential**

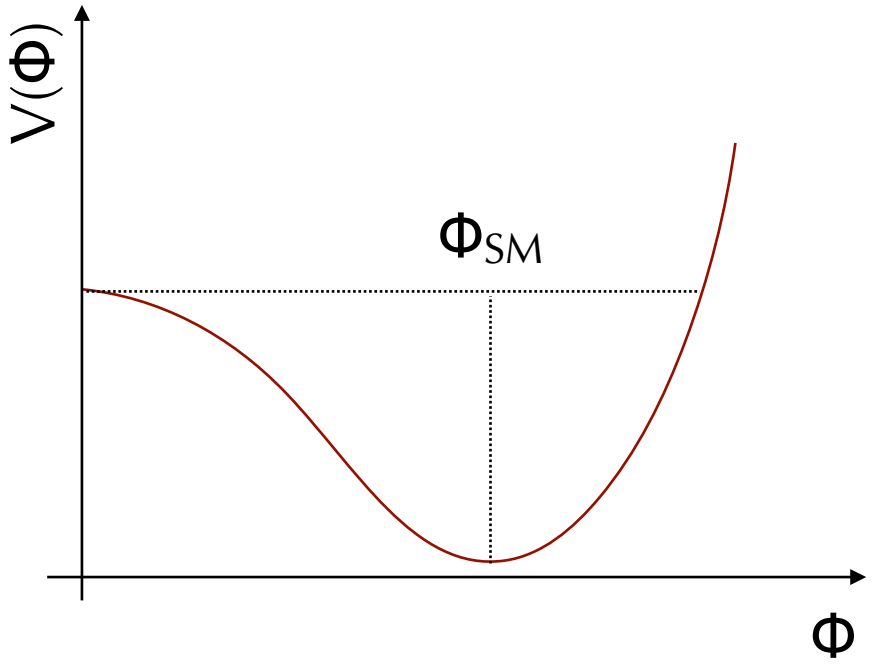
# Testing the shape

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

$$V(v+h) = V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$



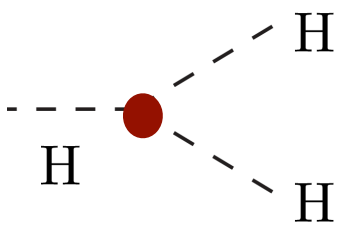

$$\lambda = \frac{m_h^2}{2v^2} = 0.13$$



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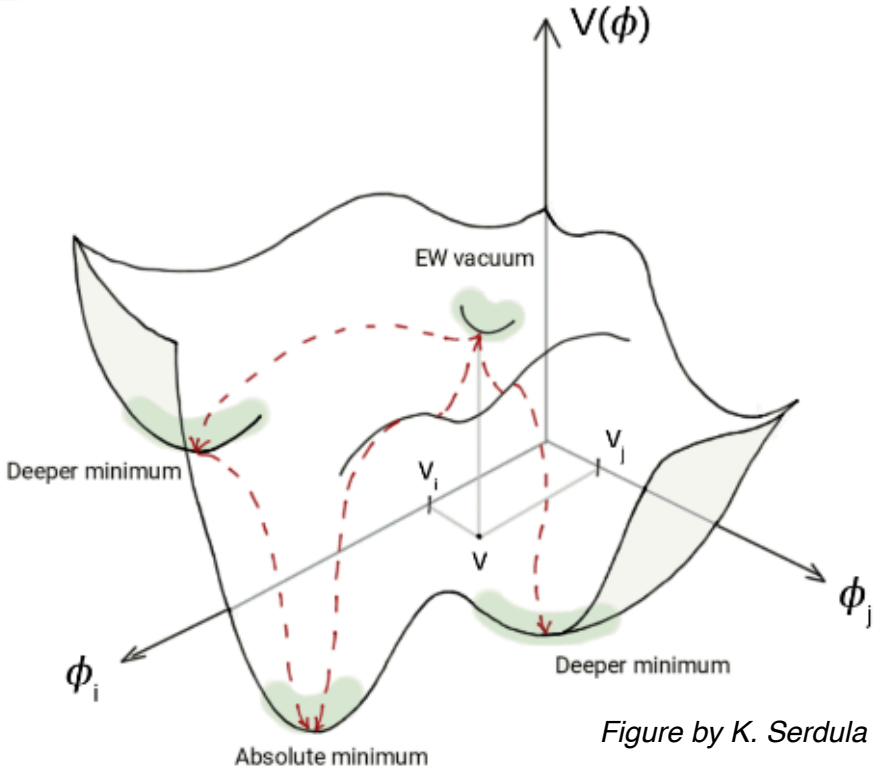
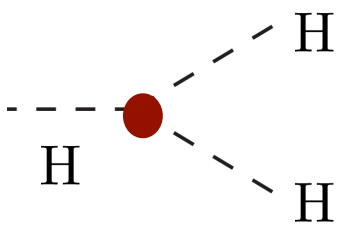



*Figure by K. Serdula*

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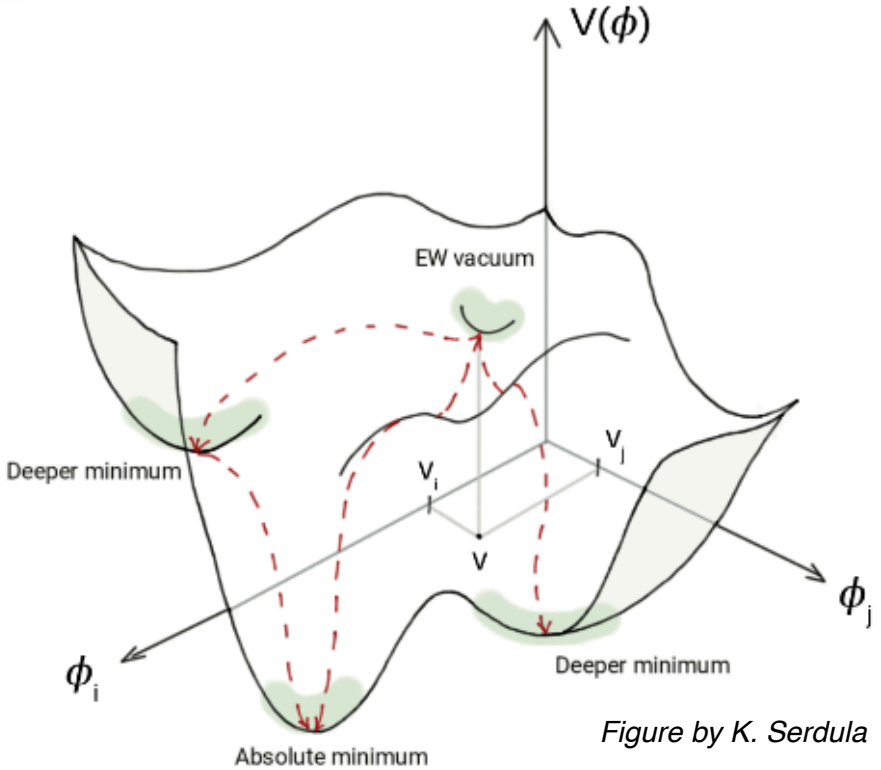
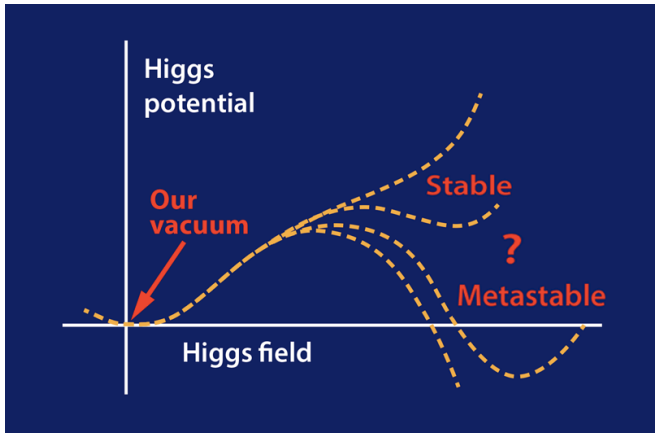


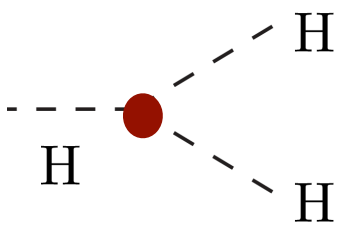

*Figure by K. Serdula*



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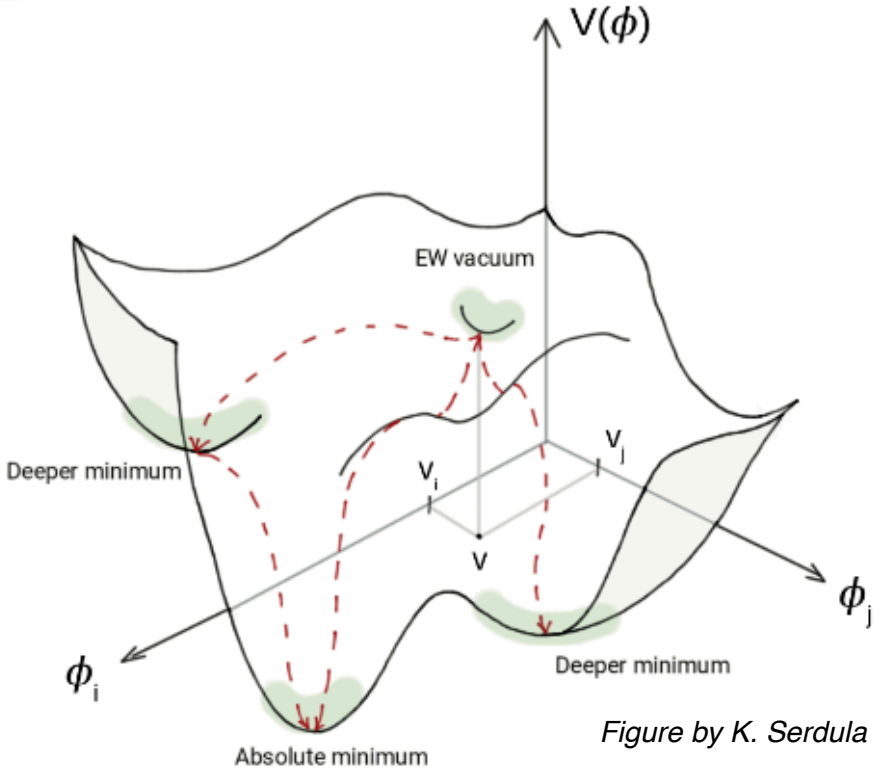
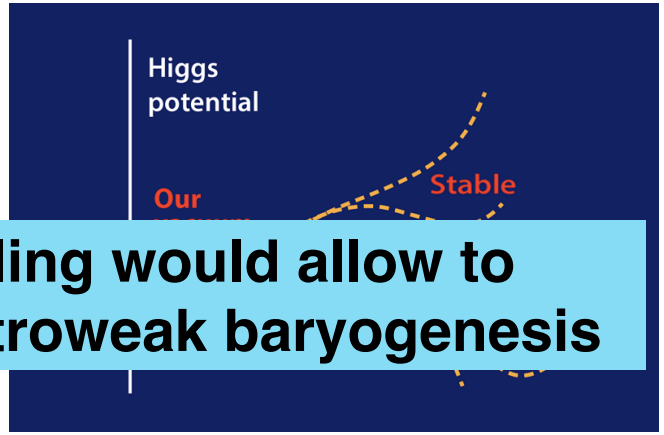



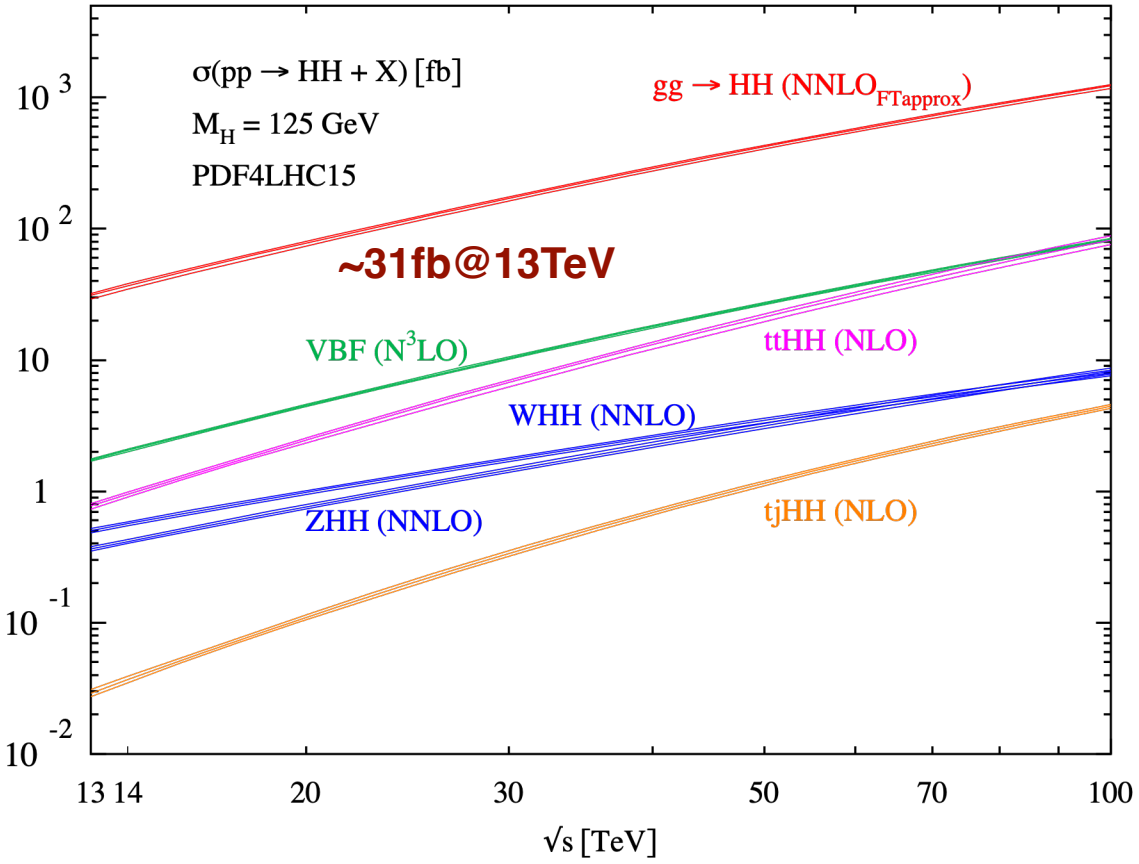

*Figure by K. Serdula*



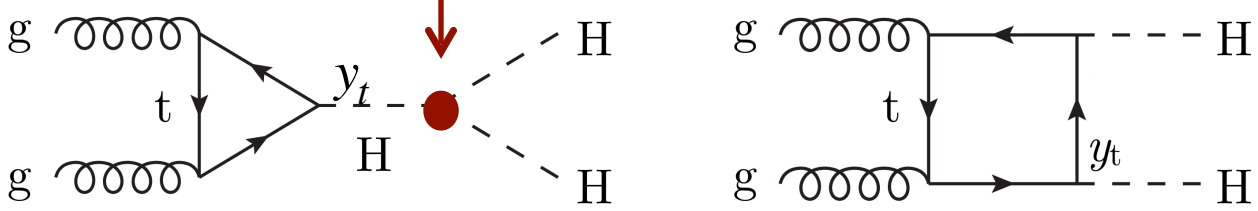

**O(20%) precision on the Higgs self-coupling would allow to exclude/demonstrate at 5σ models of electroweak baryogenesis**

# Higgs boson self-coupling

Review in Physics (2020) 100045




$$\lambda = \frac{m_H^2}{2v^2} = 0.13$$

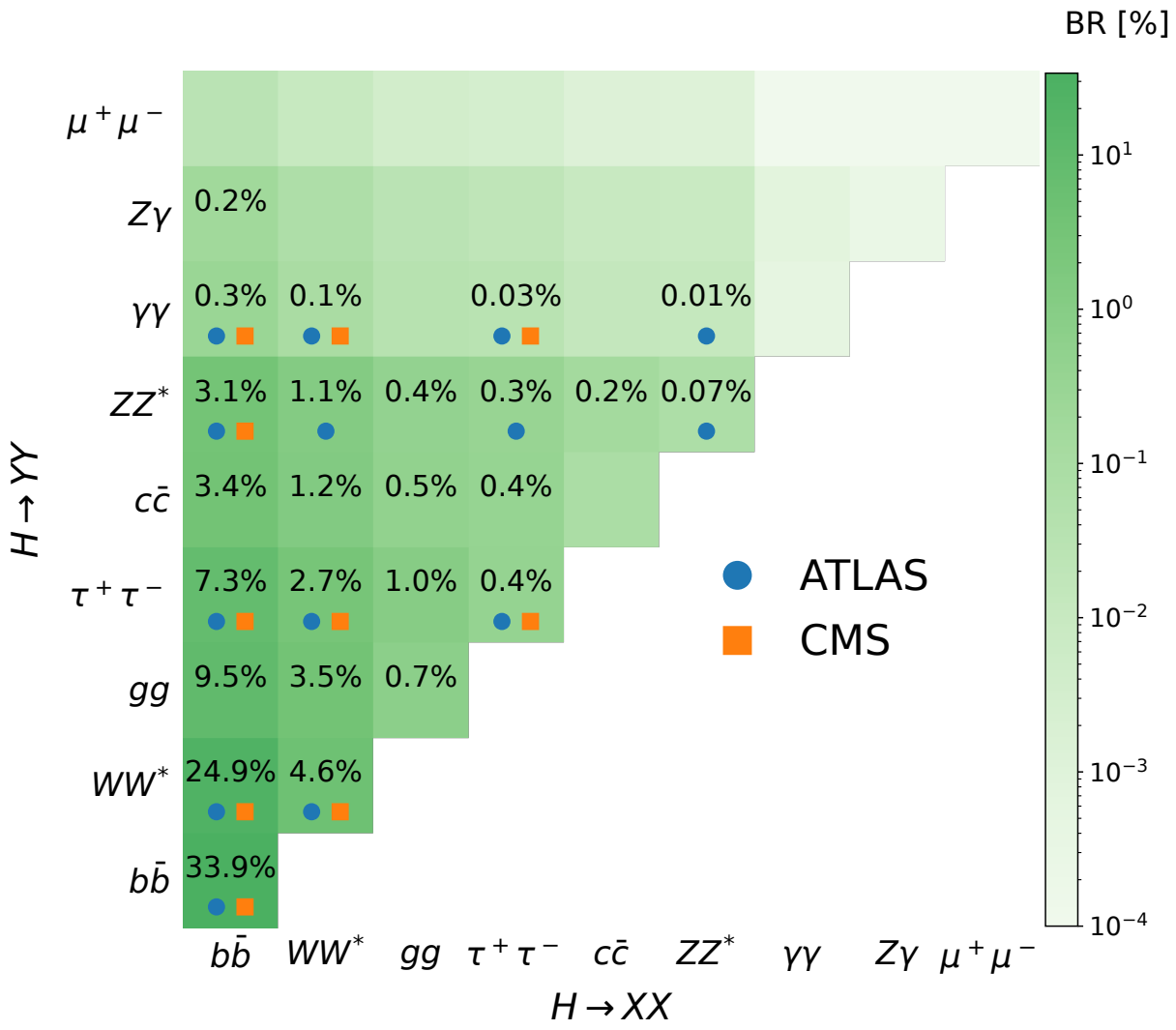



@13.6 TeV **34.1 fb** +6.5% / –23.2%

**HH production allows to probe the self-coupling:** $\Delta\sigma/\sigma \sim \Delta\lambda/\lambda$ **if** $\lambda \sim \lambda_{SM}$

Extremely challenging measurement at the LHC, but **it can be sensitive to large deviations from BSM**: $\kappa_\lambda = \lambda/\lambda_{SM}$

# HH, a variety of final states




**H(bb̄)** is a key element in the exploration of HH

**highest BR**

good b-jets identification performance: 70%

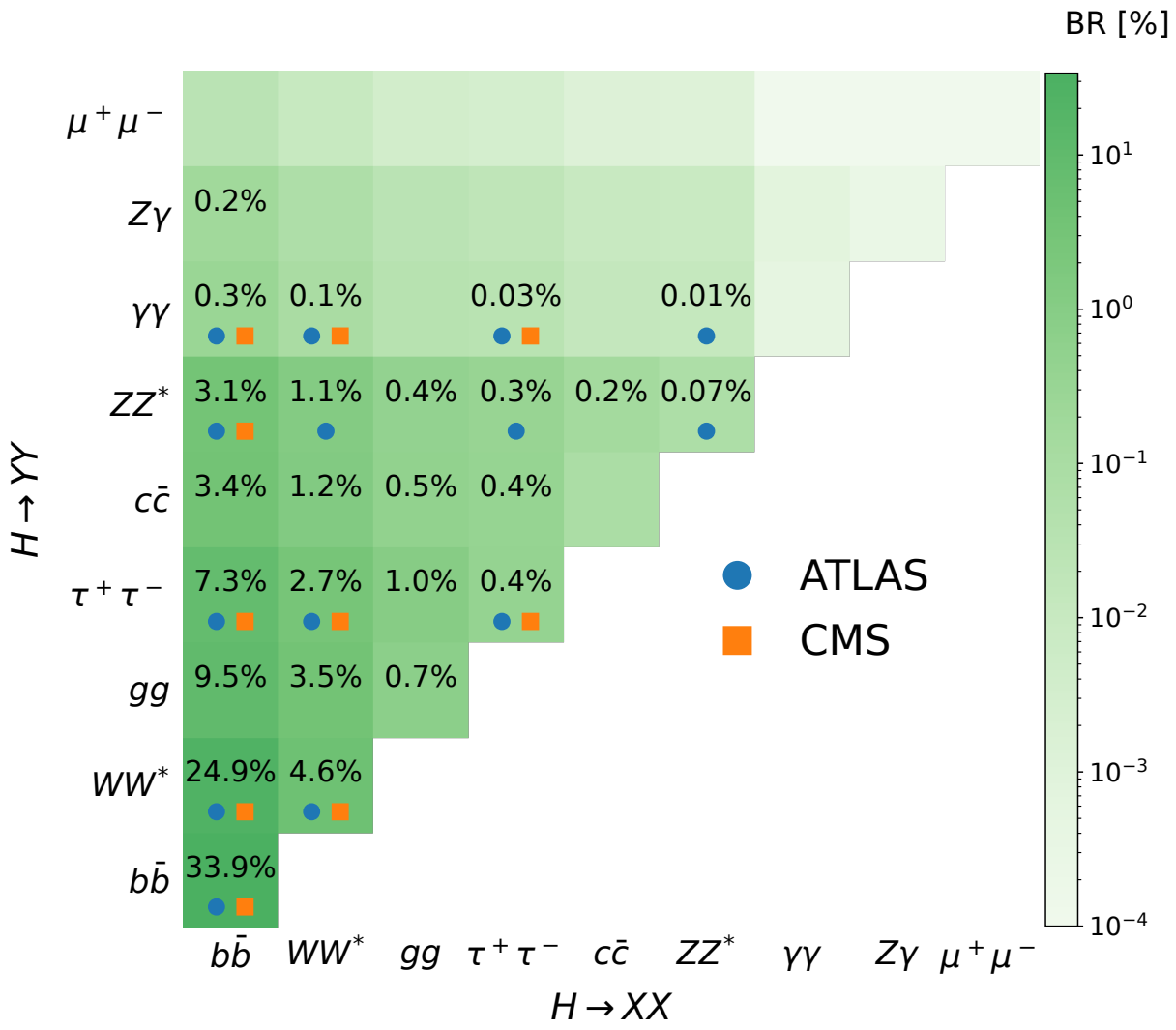
efficiency at 0.3-1% q/g mistag probability

**H(γγ)**

clean final state

**excellent mass resolution**, ~1%

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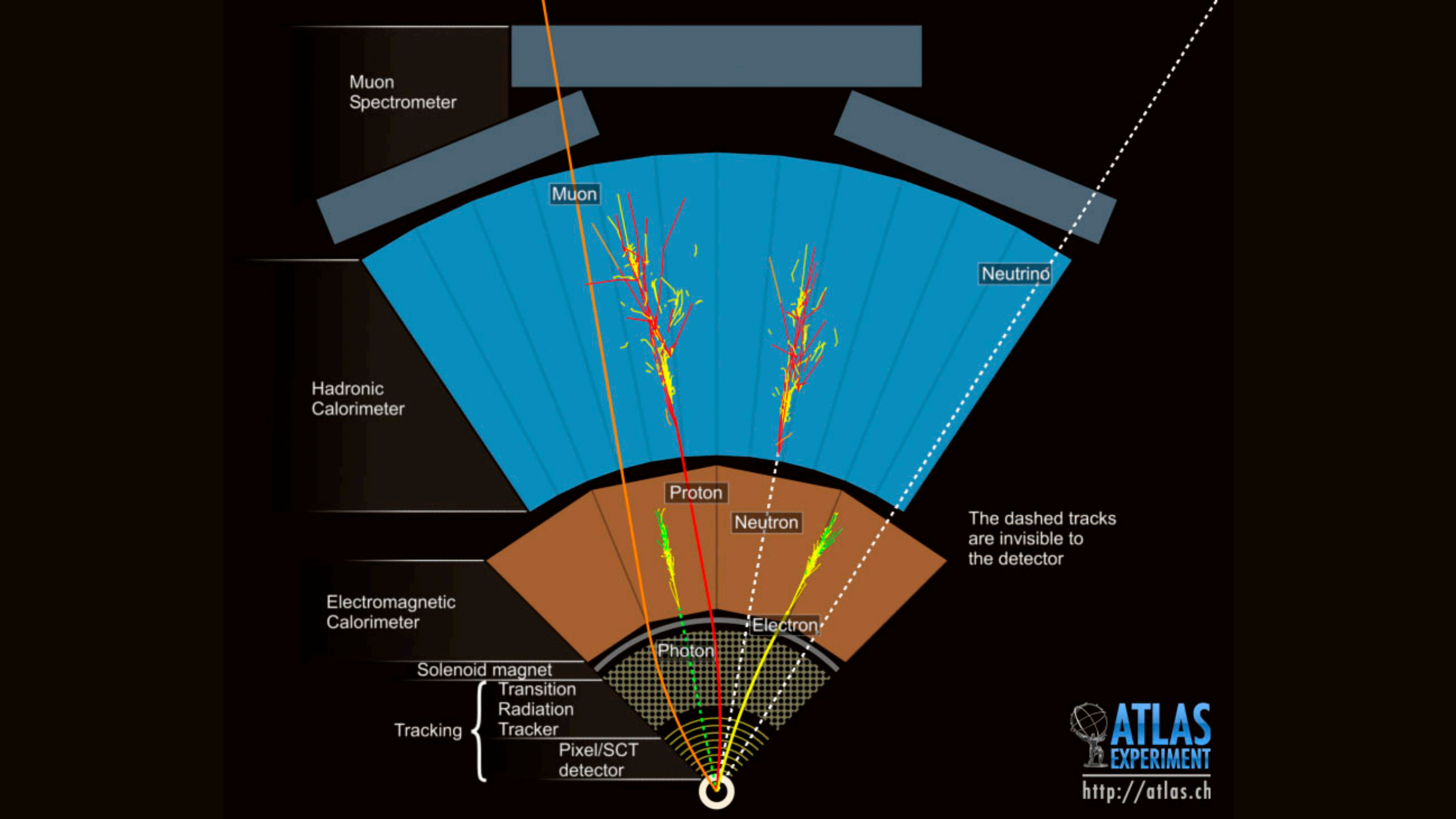
**H(γγ)**

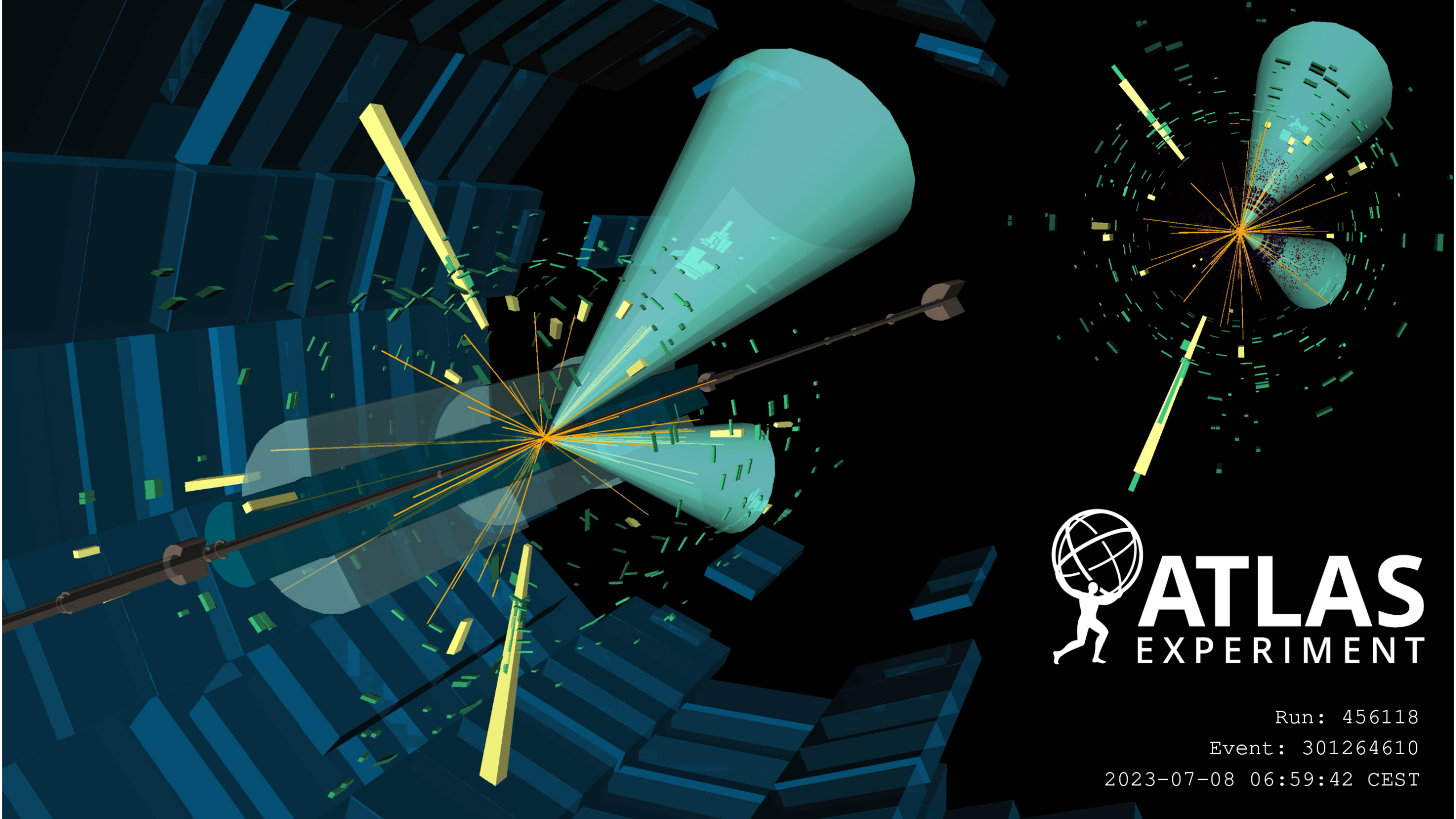
clean final state

**excellent mass resolution**, ~1%

Several channels have been investigated:

- Similar sensitivity to SM HH
- Different coverage on $m_{HH}$

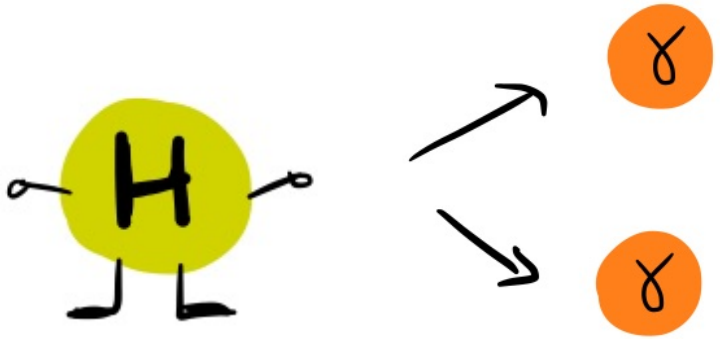

Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

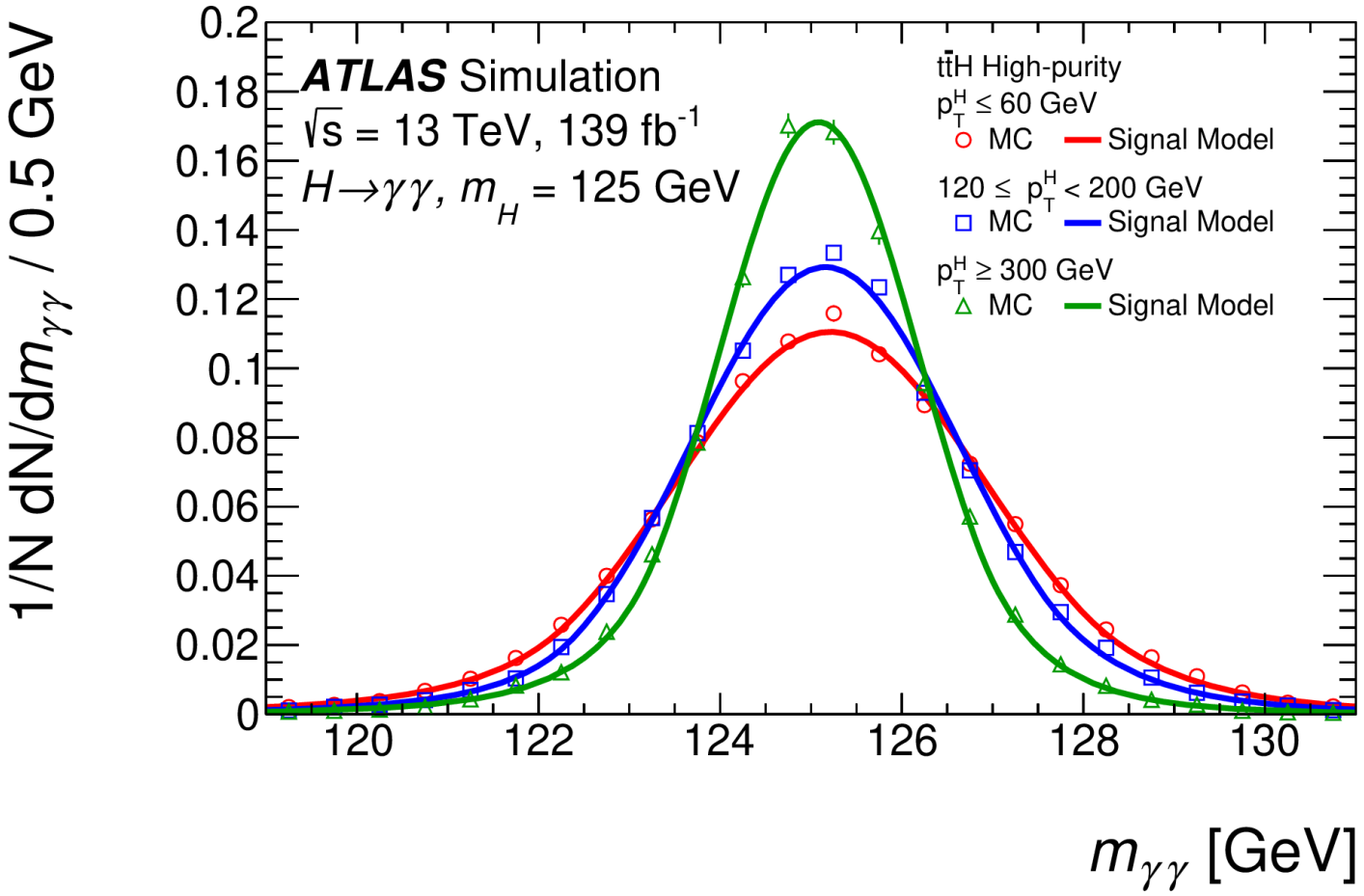

ATLAS
EXPERIMENT
Run: 456118
Event: 301264610
2023-07-08 06:59:42 CEST

# H(γγ)

ATLAS-JHEP 07 (2023) 088

**Excellent diphoton mass resolution, ~0.2%**

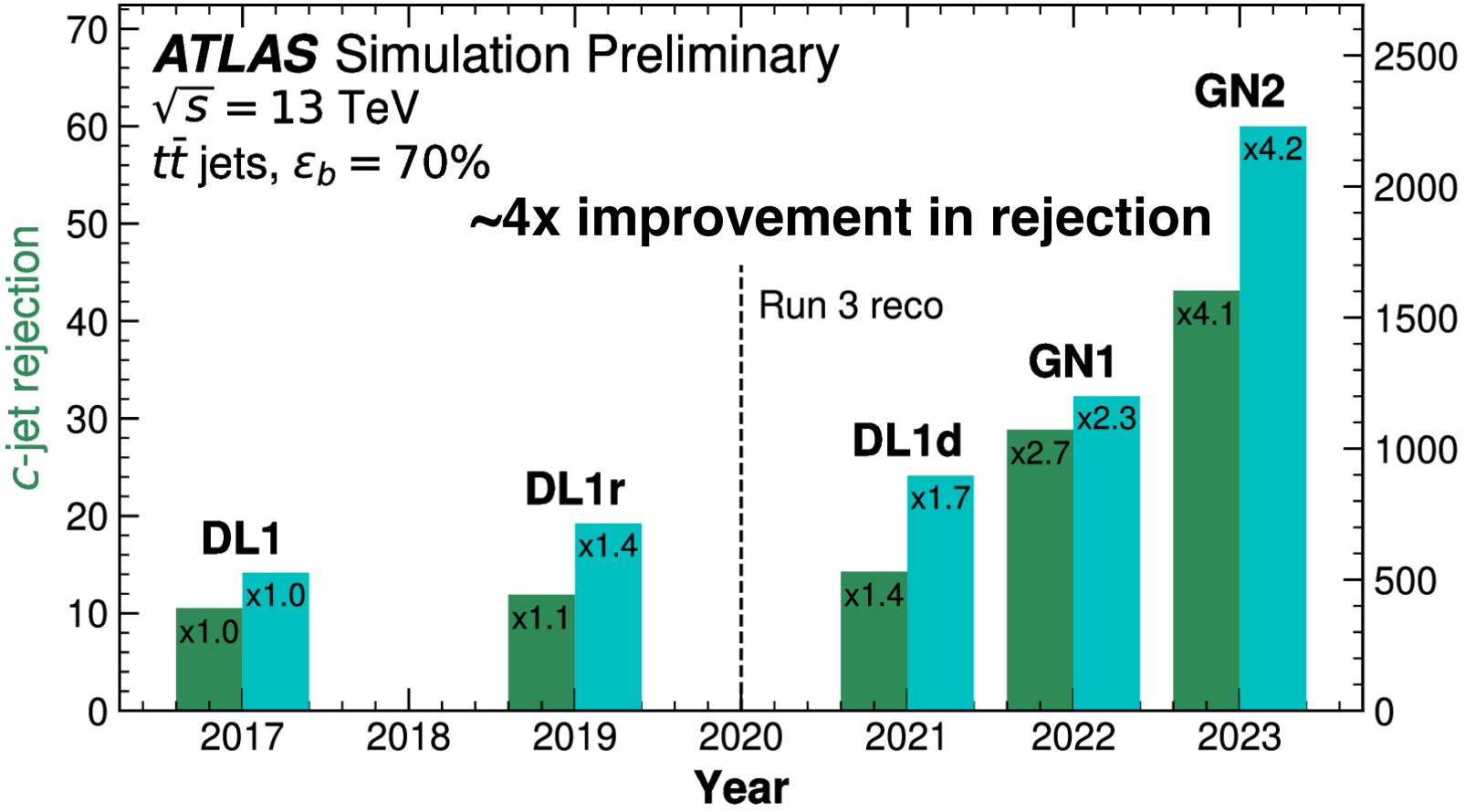


# Incredible progress in flavor tagging

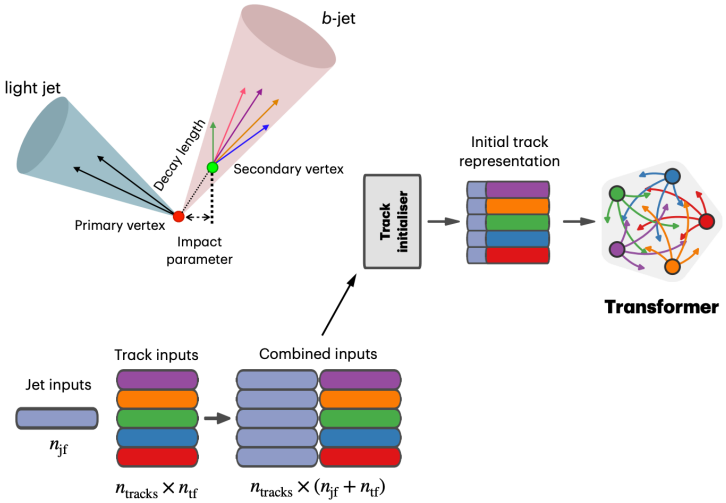
ATLAS-FTAG-23-05
ATLAS-FTAG-23-01

## Low level algorithms replaced by complex models




70% b-jet efficiency: c (light) jet rejection increase by factor 3 (1.5)

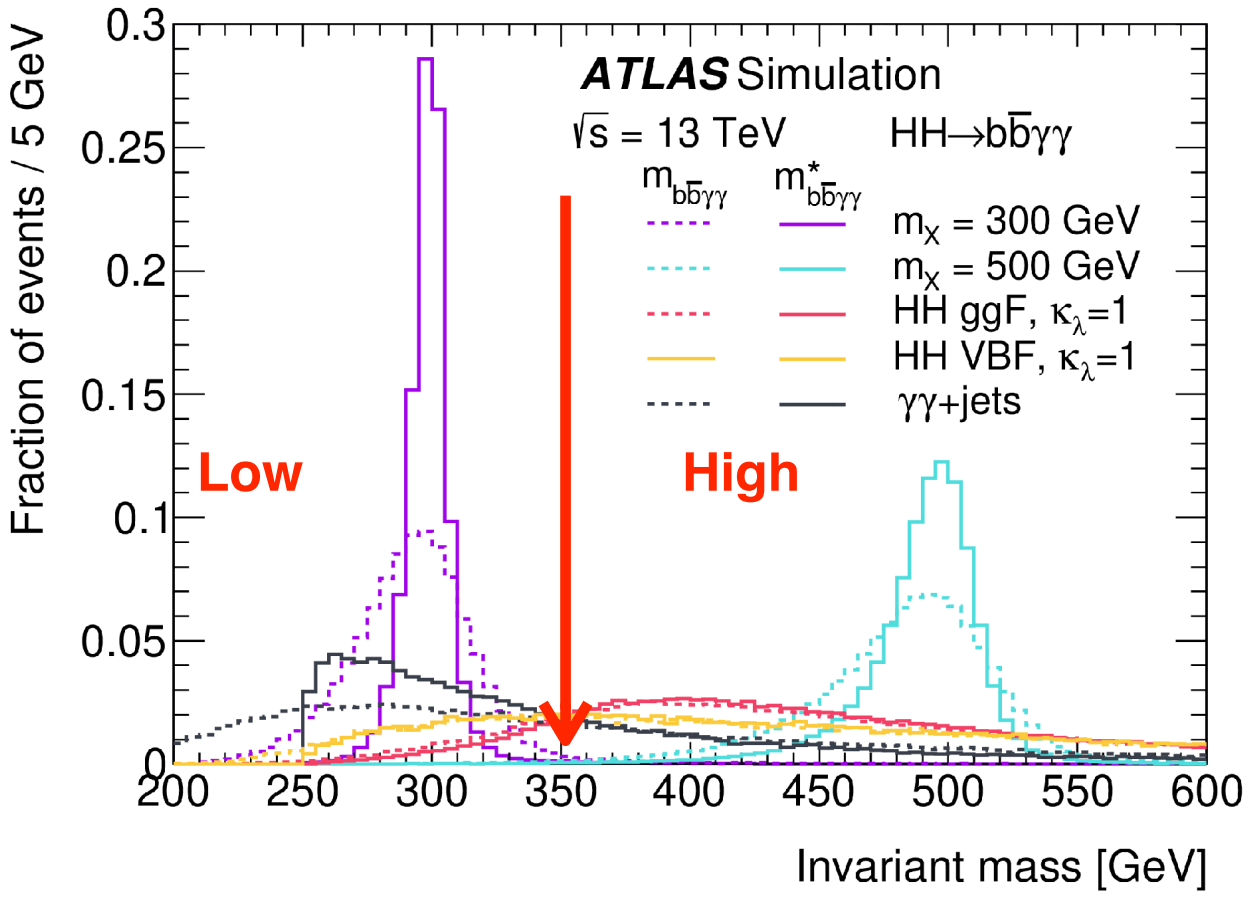
- improvements over the entire jet $p_T$ range




WP: 85% efficiency, 1% mis-tag rate for lights

# HH to bb̄γγ - the strategy

ATLAS-Phys. Rev. D 106, 052001
ATLAS-PLB 876 (2026) 140280

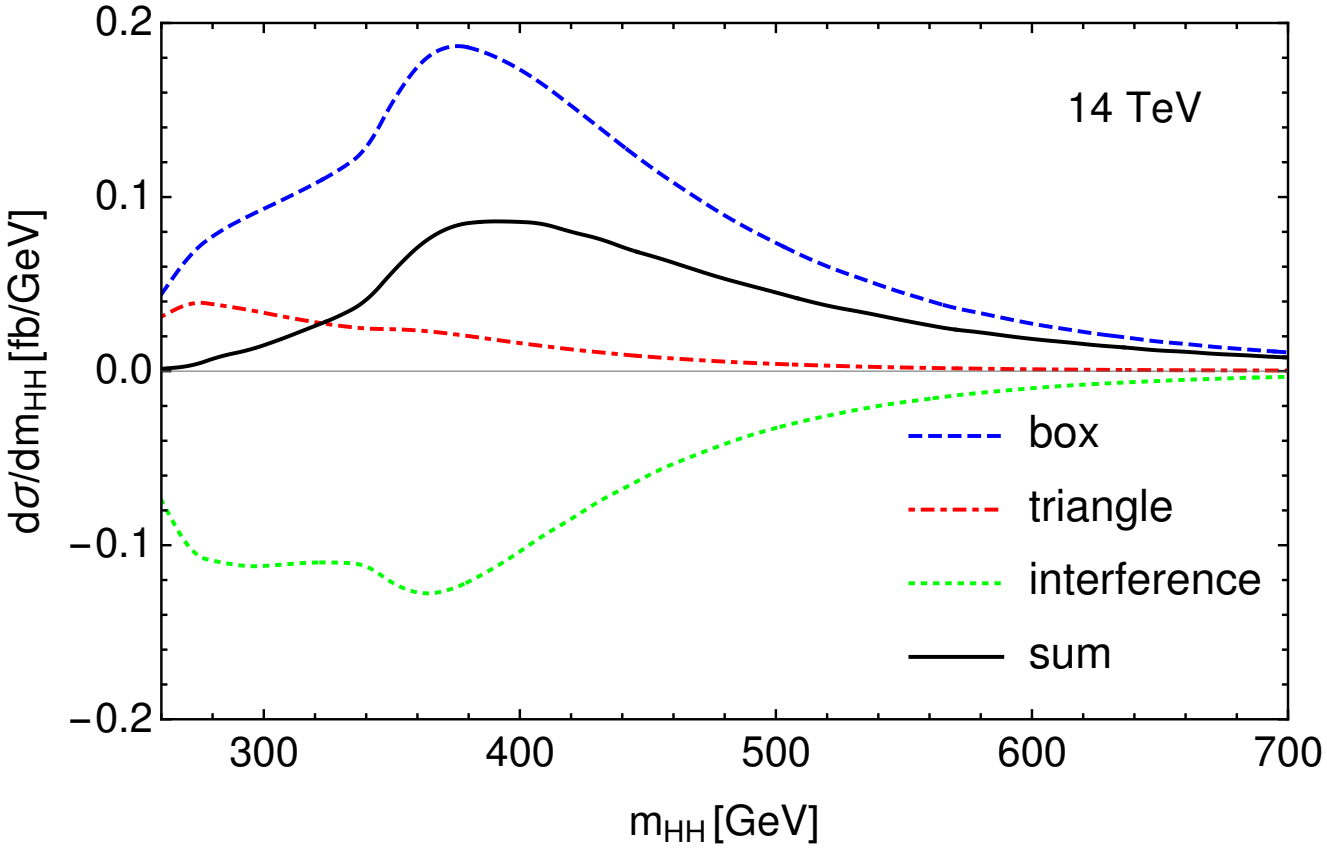



$m^*_{\gamma\gamma b\bar{b}} = m_{\gamma\gamma b\bar{b}} - (m_{b\bar{b}} - m_H) - (m_{\gamma\gamma} - m_H)$

- Photon selection similar to H(γγ) measurements
  - $m_{\gamma\gamma}$ and $m_{b\bar{b}}$ compatible with the Higgs boson mass
- $m^*_{\gamma\gamma b\bar{b}}$ resolution improves by up to 10% due to the cancellation of detector resolution effects
- $m^*_{\gamma\gamma b\bar{b}}$ and **BDT (includes angular correlations)** used to categorize events
  - Fit $m_{\gamma\gamma}$ distribution in 7 regions per run period based on BDT score
- **Sensitivity to Low/High** $m_{\gamma\gamma b\bar{b}}$

# HH to bb̄γγ - the strategy

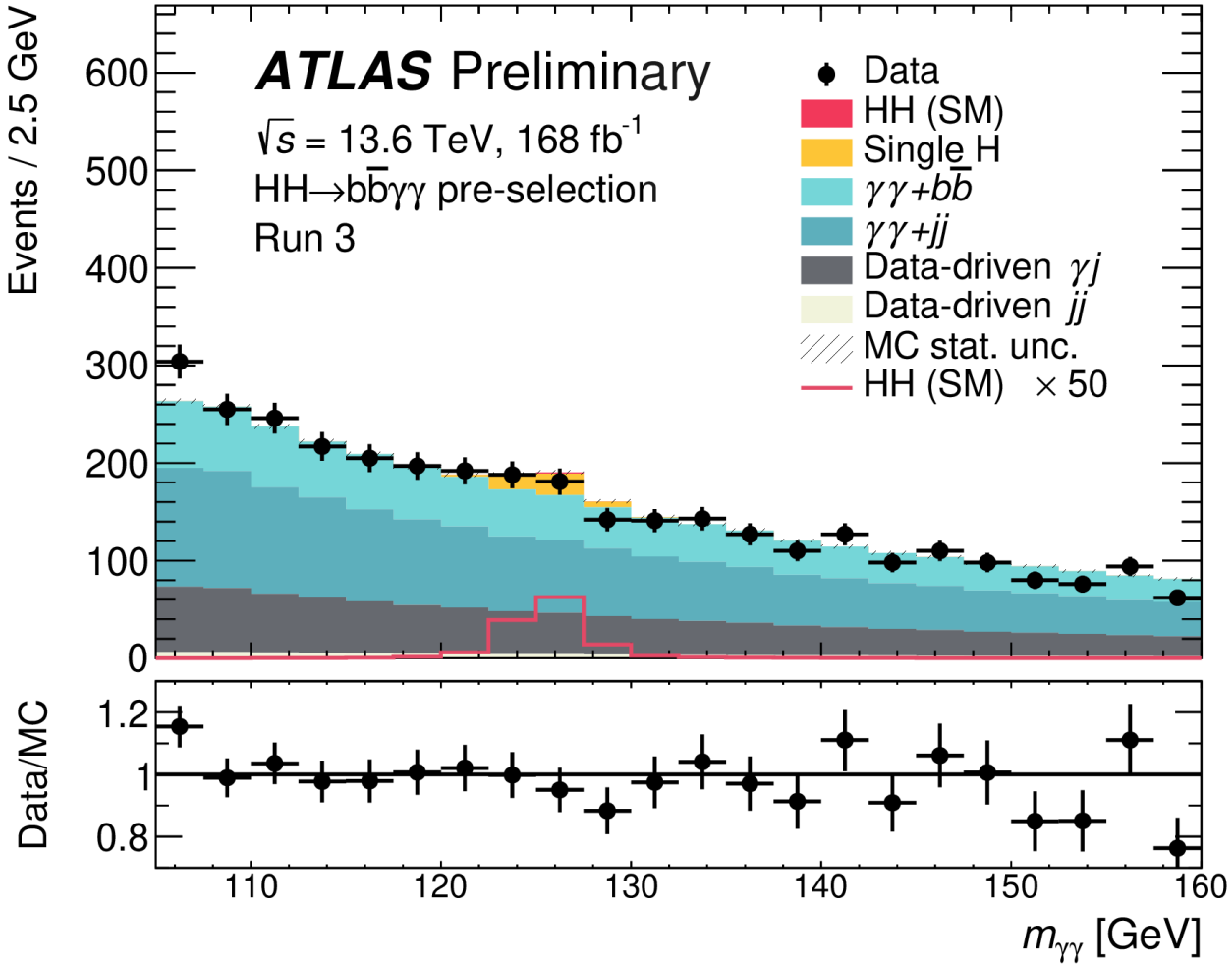
ATLAS-Phys. Rev. D 106, 052001
ATLAS-PLB 876 (2026) 140280




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# HH to $b\bar{b}\gamma\gamma$ - backgrounds

ATLAS-Phys. Rev. D 106, 052001
ATLAS-PLB 876 (2026) 140280

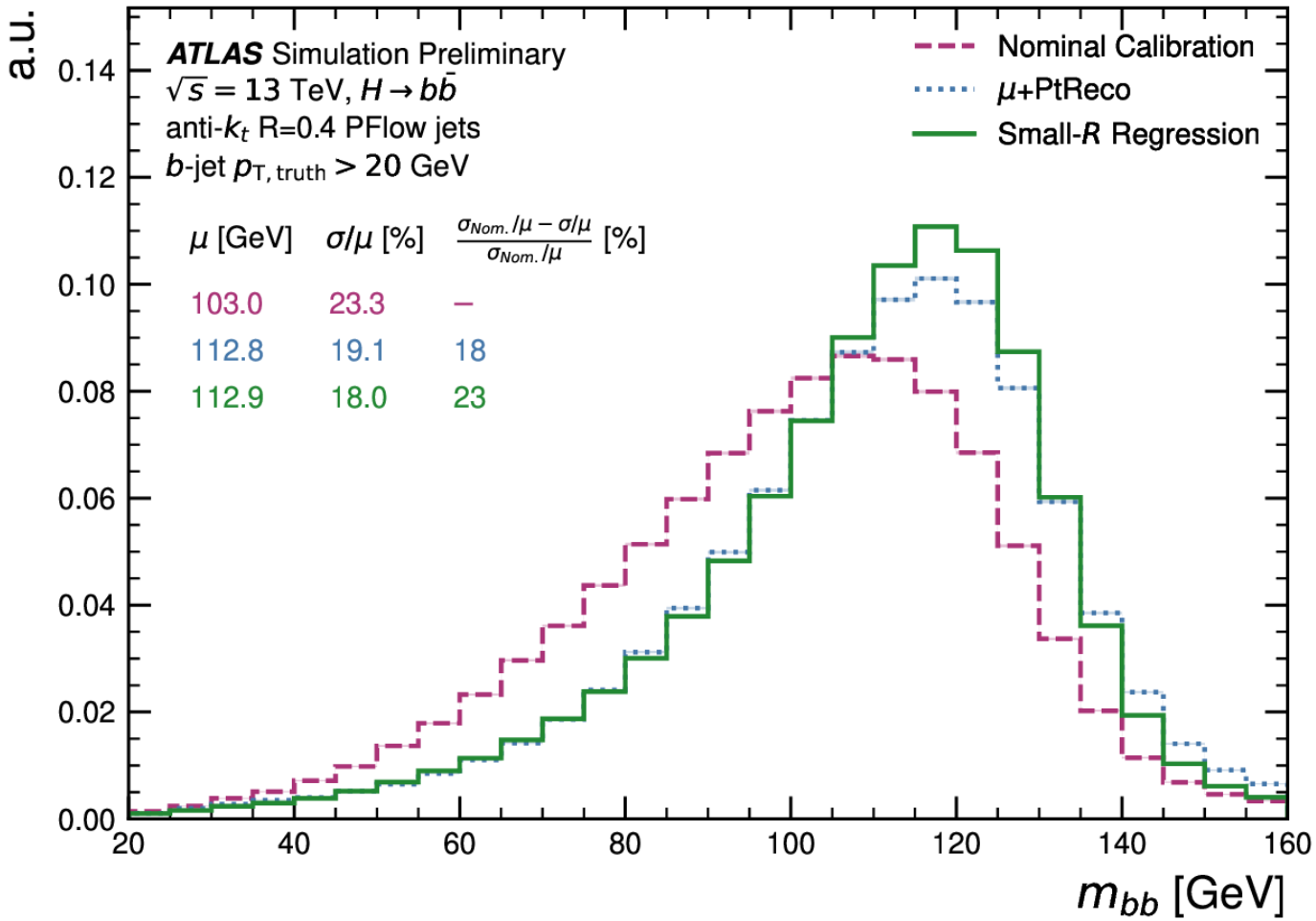



- Main **backgrounds** are:
  - **γγ+jets** (prompt or jets misidentified as γ)
  - **SM single Higgs** modeled from simulation
- Fake γj and jj (2%) background processes estimated in data from sidebands
- The dominant γγ-continuum background modeled using exponential function and tested in data sidebands

ATLAS-Phys. Rev. D 106, 052001
ATLAS-PLB 876 (2026) 140280
ATL-PHYS-PUB-2024-015

# Improving the b-jet resolution

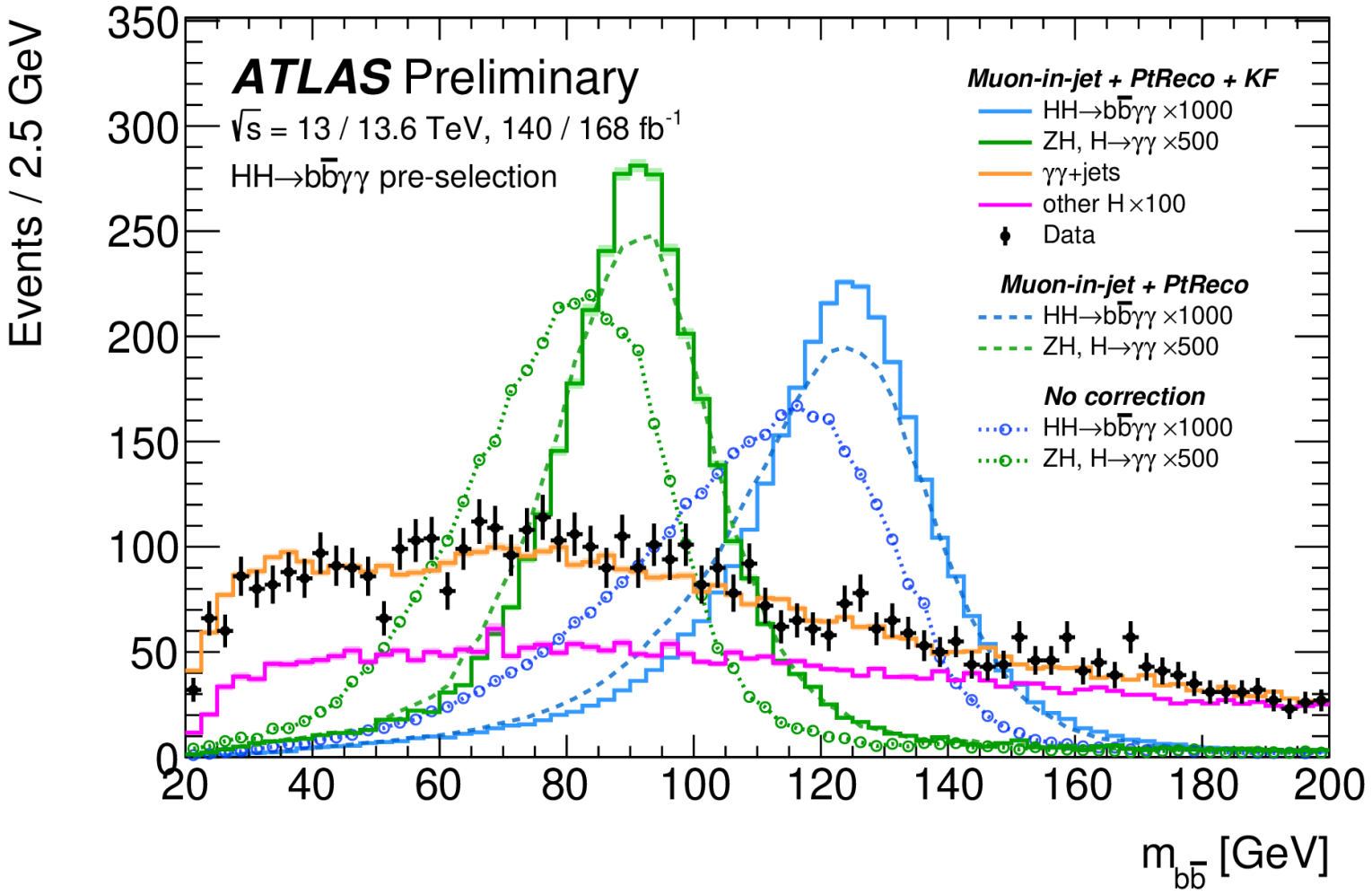
Multidimensional calibration targeting the truth jet $p_T$ to account also for the missing neutrino energy



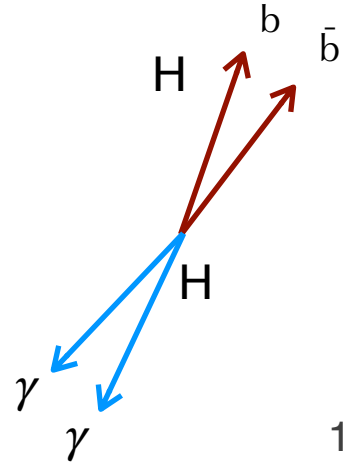

- Muons originating from semileptonic B hadrons decays (Muon-in-jet correction)
- Undetected energy from neutrinos and out-of-cone effects (PtReco correction)
  - **$m_{b\bar{b}}$ resolution improves up to 17%**
- ***Future***: transformer-based **regression** to correct reconstructed jet properties to the true values.
  - Improvement with respect to the nominal calibration between up to 30%

# Improving the b-jet resolution

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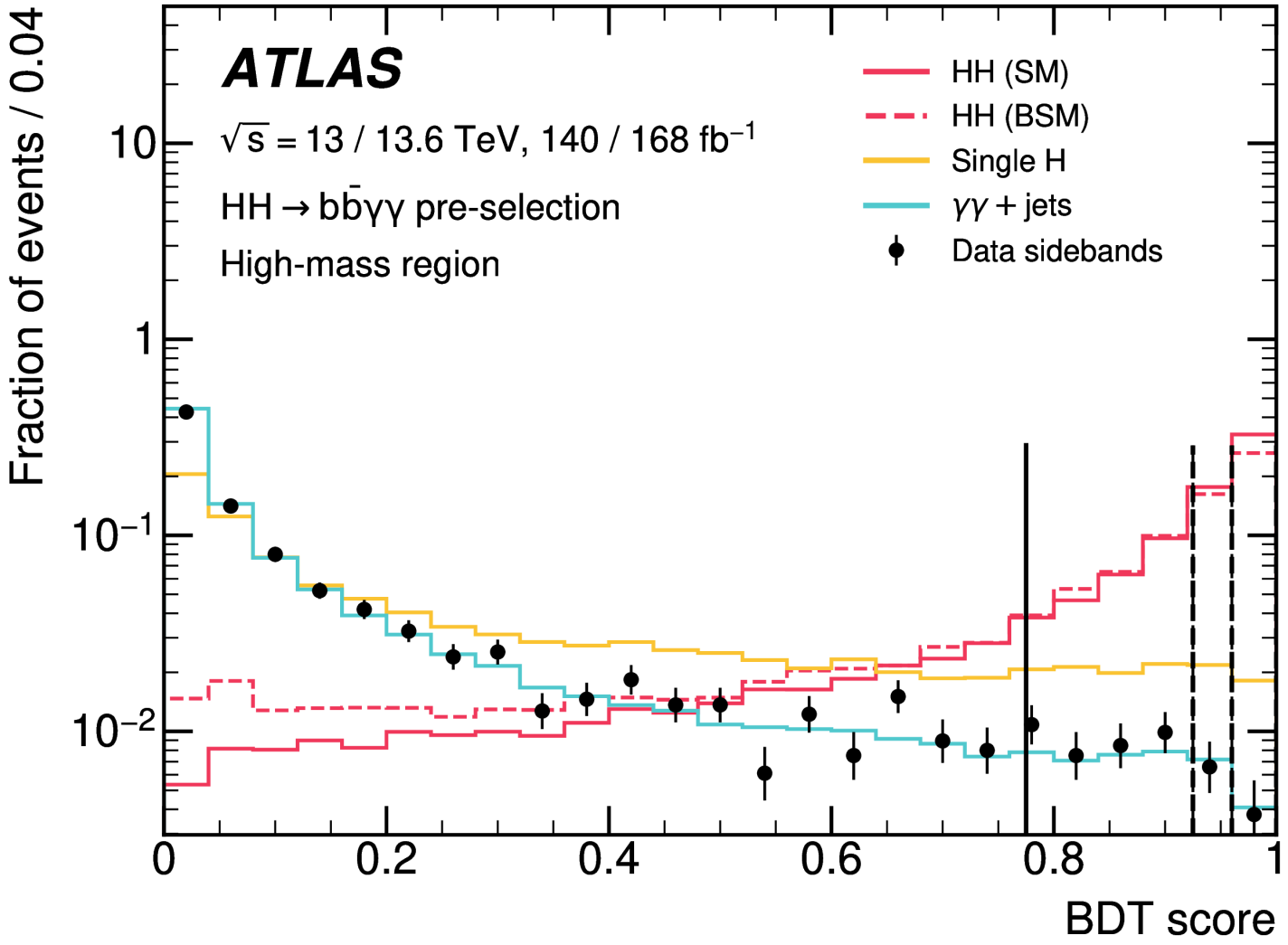



- Kinematic fit to constraint the $p_T$ balance of the dijet and the diphoton systems
  - Jet momentum varied within experimental resolution
- **$m_{b\bar{b}}$ resolution improves by 27%**
- When $m_{b\bar{b}}$ is constrained to 125 GeV $m_{HH}$ resolution improves by 46%
  - **5% improvement on expected significance**



# HH to $b\bar{b}\gamma\gamma$ - categories

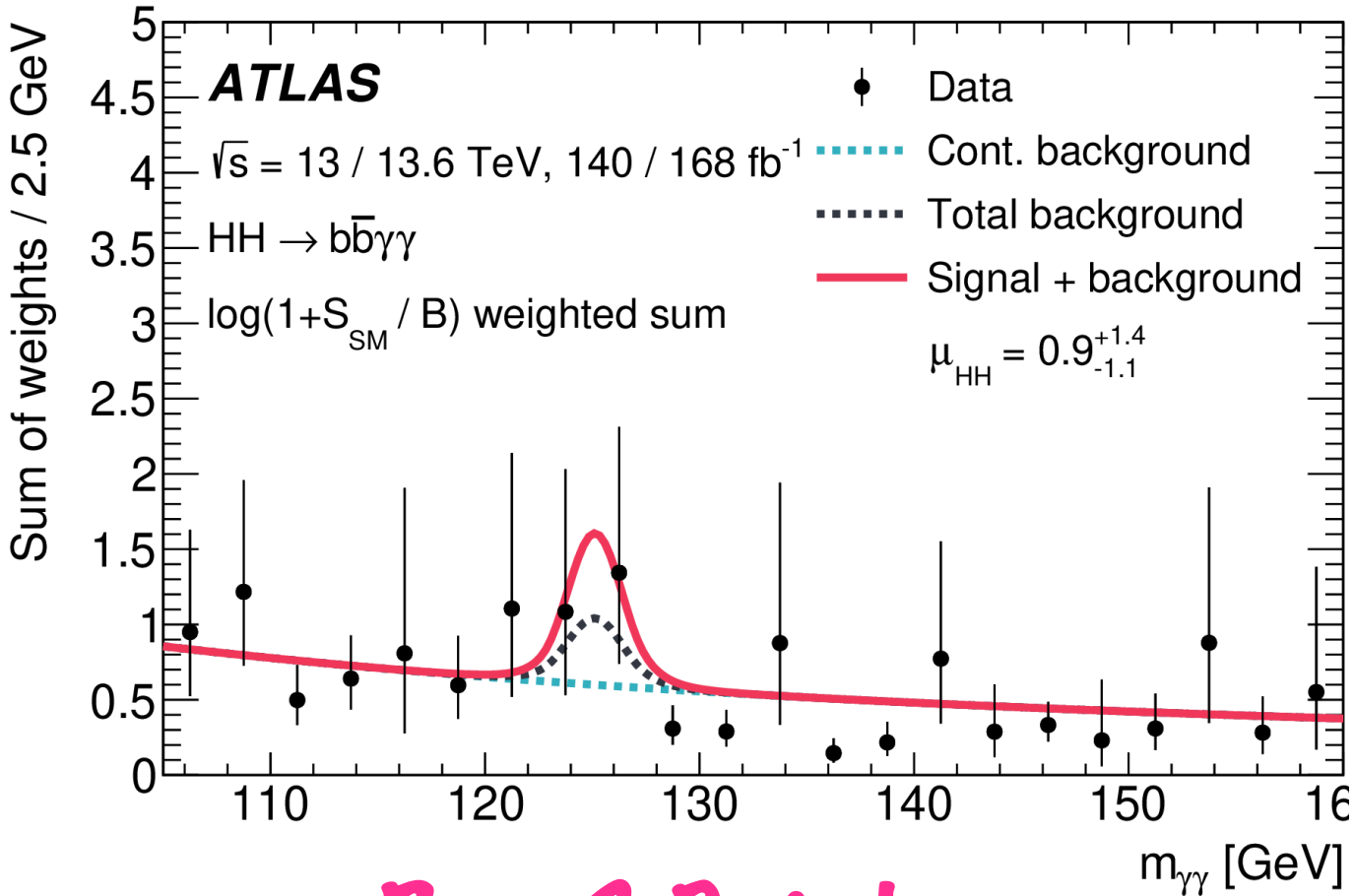
ATLAS-PLB 876 (2026) 140280




- Low and high $m_{HH}$ regions retain sensitivity to different $\kappa_\lambda$ values
- BDTs use event kinematics and angular correlations
  - 4 low-mass and 3 high-mass categories in each run period
  - 14 $m_{\gamma\gamma}$ distributions enter the simultaneous fit

# HH to $b\bar{b}\gamma\gamma$ - results

ATLAS-PLB 876 (2026) 140280




Run 3 Data!

- Fit $m_{\gamma\gamma}$ in 7 signal regions per run period.

  **Observed significance of SM HH: 0.8σ**
  **Expected significance: 1.0σ**

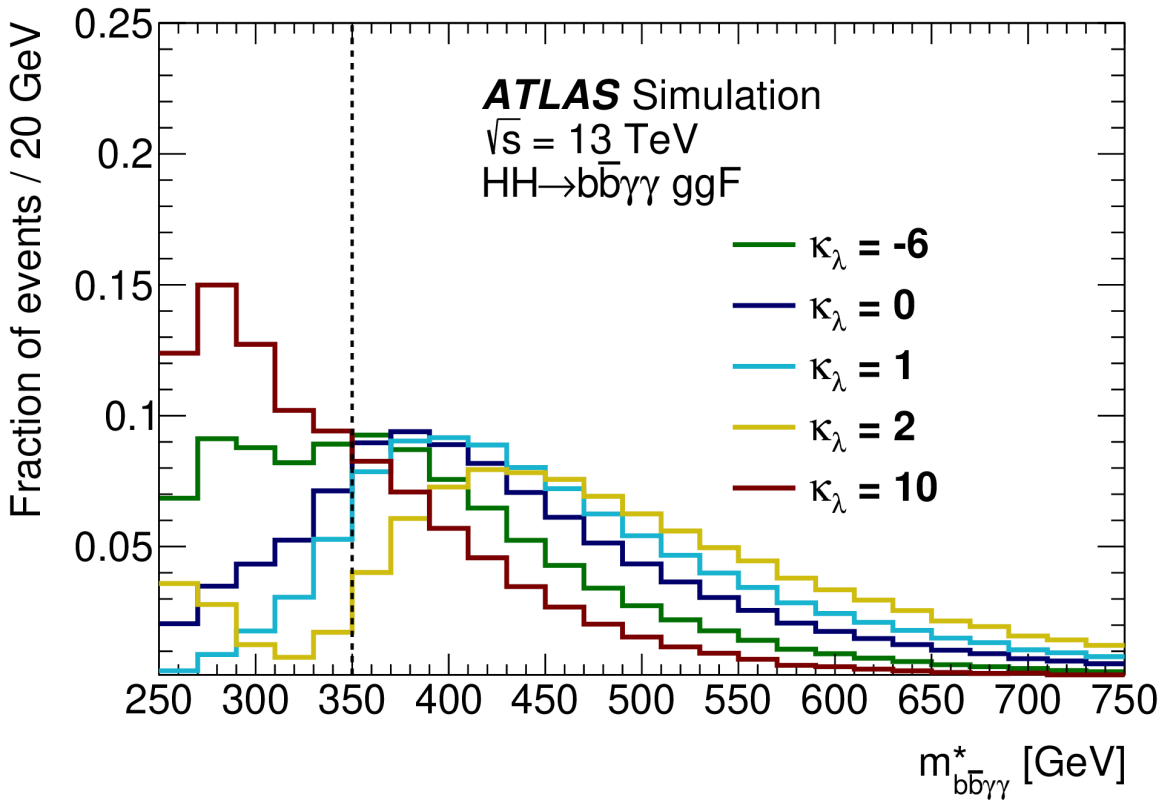
- 95% CL limits on HH production observed (expected) at 3.7 (2.6) times the SM prediction

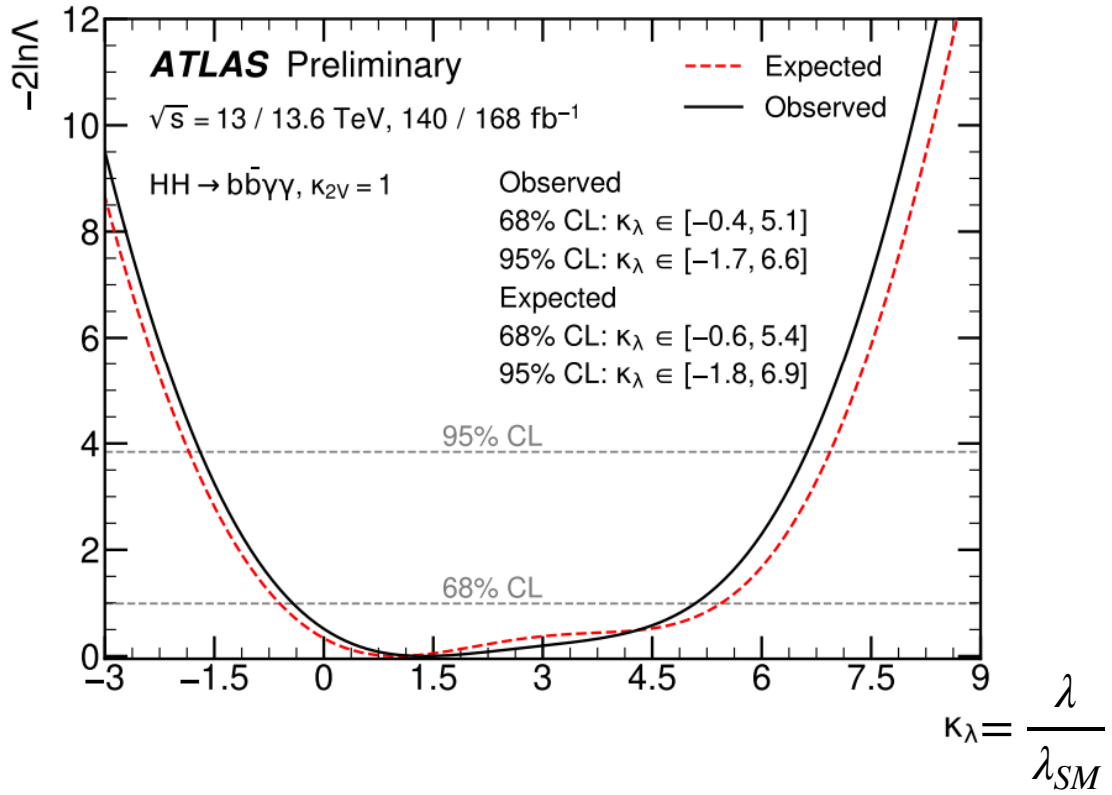
  **5x improvement over previous result and current best available limits**

  - 5% from improved resolution with kinematic fit
  - 20% from improved b-tagging
  - 60% from additional data

# Constraints on $\kappa_\lambda$ from $b\bar{b}\gamma\gamma$

ATLAS-Phys. Rev. D 106, 052001
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**$\kappa_\lambda \in$ [-1.7, 6.6]**
**assuming SM top-H coupling**

# HH to $b\bar{b}\gamma\gamma$ - uncertainties

ATLAS-PLB 876 (2026) 140280

| Source of systematic uncertainty | Relative impact [%] Up | Down |
|---|---|---|
| **Experimental** | | |
| Photon energy scale | +22 | −34 |
| Photon energy resolution | +14 | −7.5 |
| Photon efficiency | +13 | −2.5 |
| Jet | +10 | −6.9 |
| Luminosity | +6.7 | −1.2 |
| **Theory** | | |
| QCD scale + $m_{\text{top}}$, PDF+$\alpha_S$ | +35 | −5.2 |
| $\mathcal{B}(H \to \gamma\gamma, b\bar{b})$ | +10 | −2.1 |
| Parton showering model | ±15 | |
| Heavy-flavour content | ±30 | |
| **Background model** | | |
| Spurious signal | ±7.2 | |

- Still statistically limited:

$\Delta\mu_{HH}$(stat.) = +1.3 / −1.0

$\Delta\mu_{HH}$(syst.) = ±0.5

- Leading systematics: HH theory, photon energy calibration and single-Higgs + heavy flavor

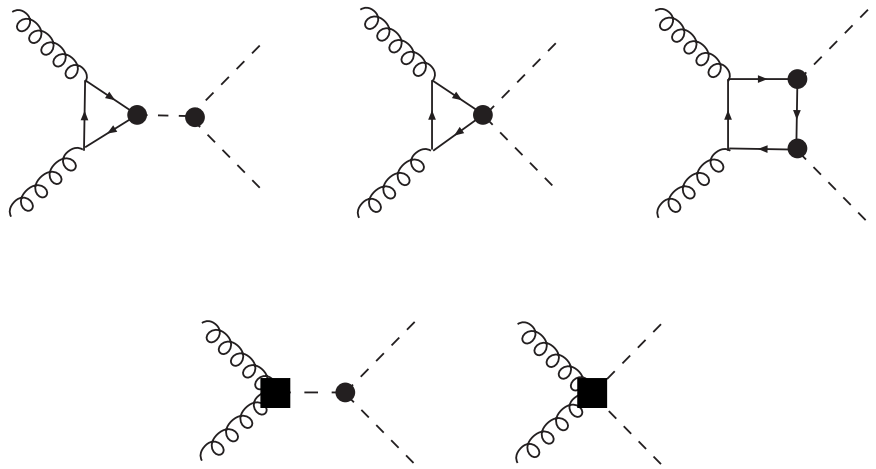
# Towards an (SM)EFT analysis for the self-coupling

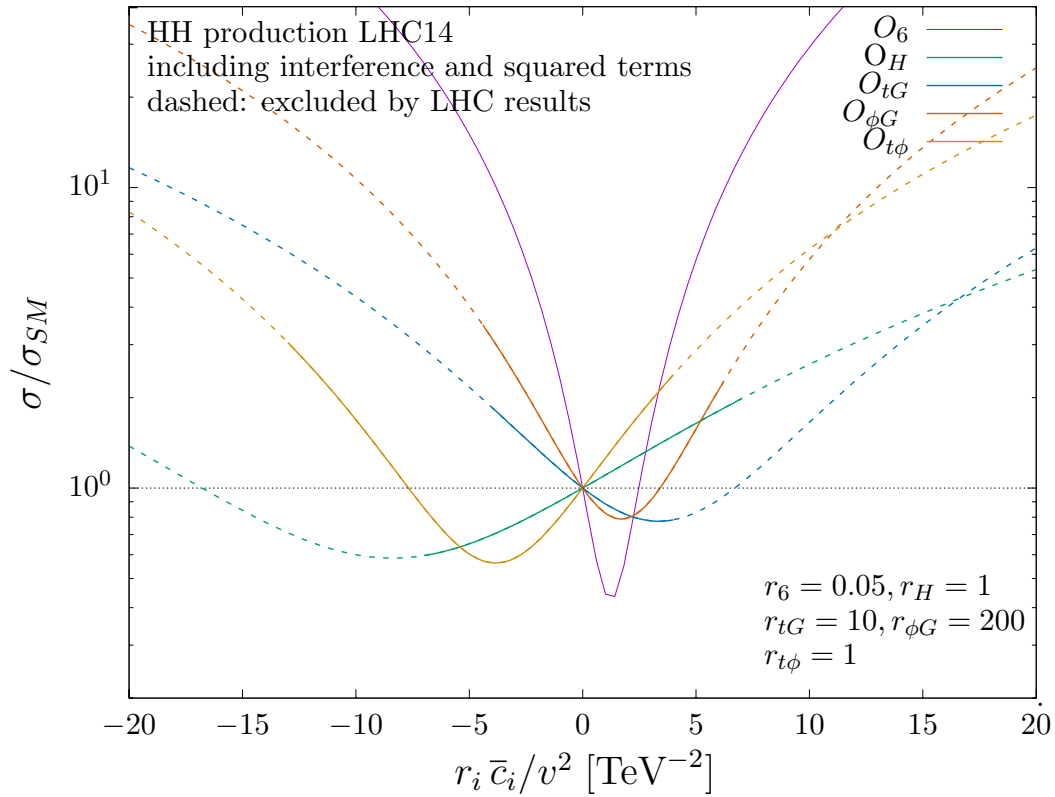
The EFT formalism summarizes deviations that might appear in a very wide class of models beyond the SM

**The most general set of BSM perturbations will modify other interactions and not just $\lambda$**

BSM contributions to HH production cross sections are at most of size $E^2/M^2$, if E~$m_H$ and M~ O(TeV):

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{\hat{c}_i}{M^2}\mathcal{O}_i + \cdots$$



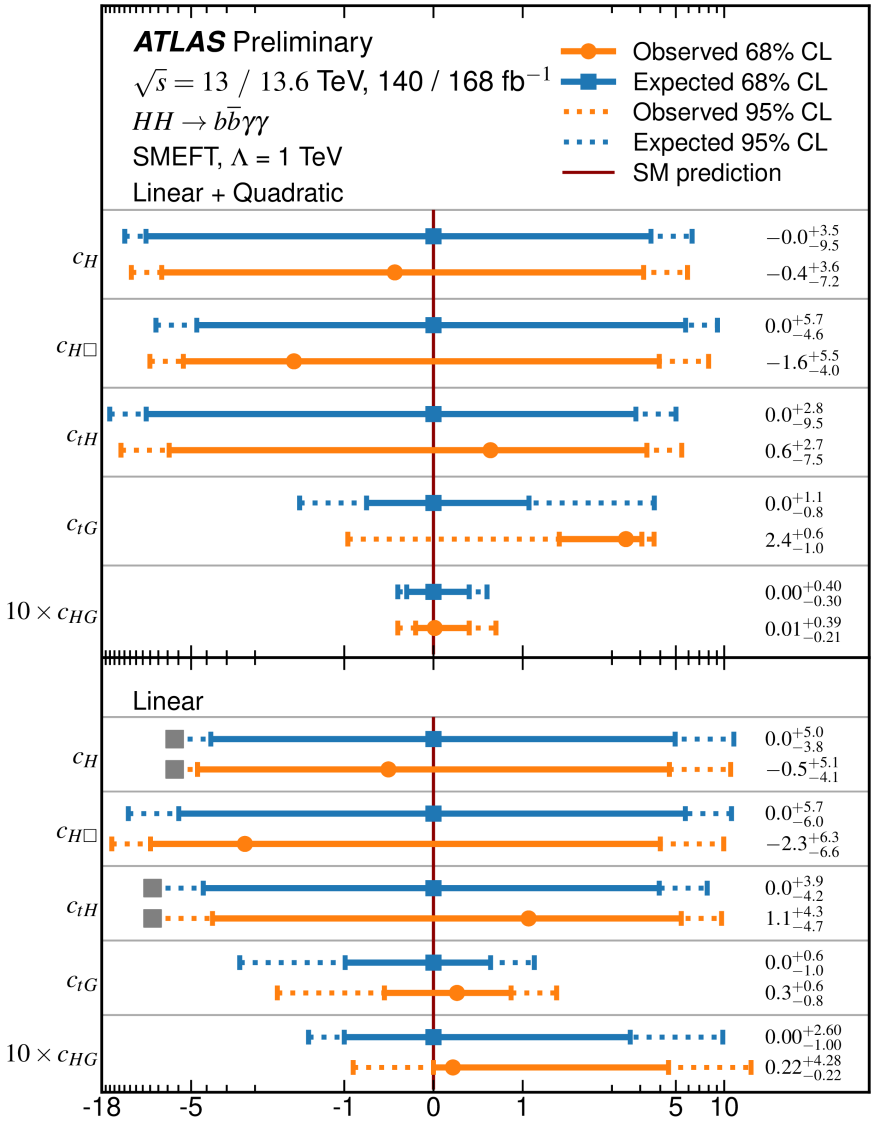



**5 operators contribute** to the HH process at LO

- if CP conserved

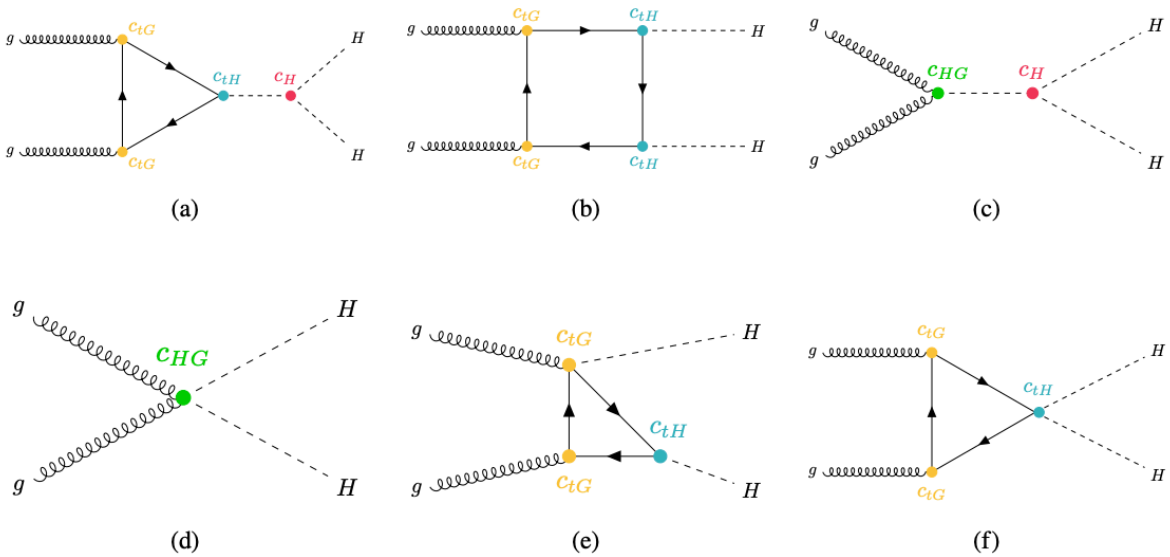
# Beyond $\kappa_\lambda$

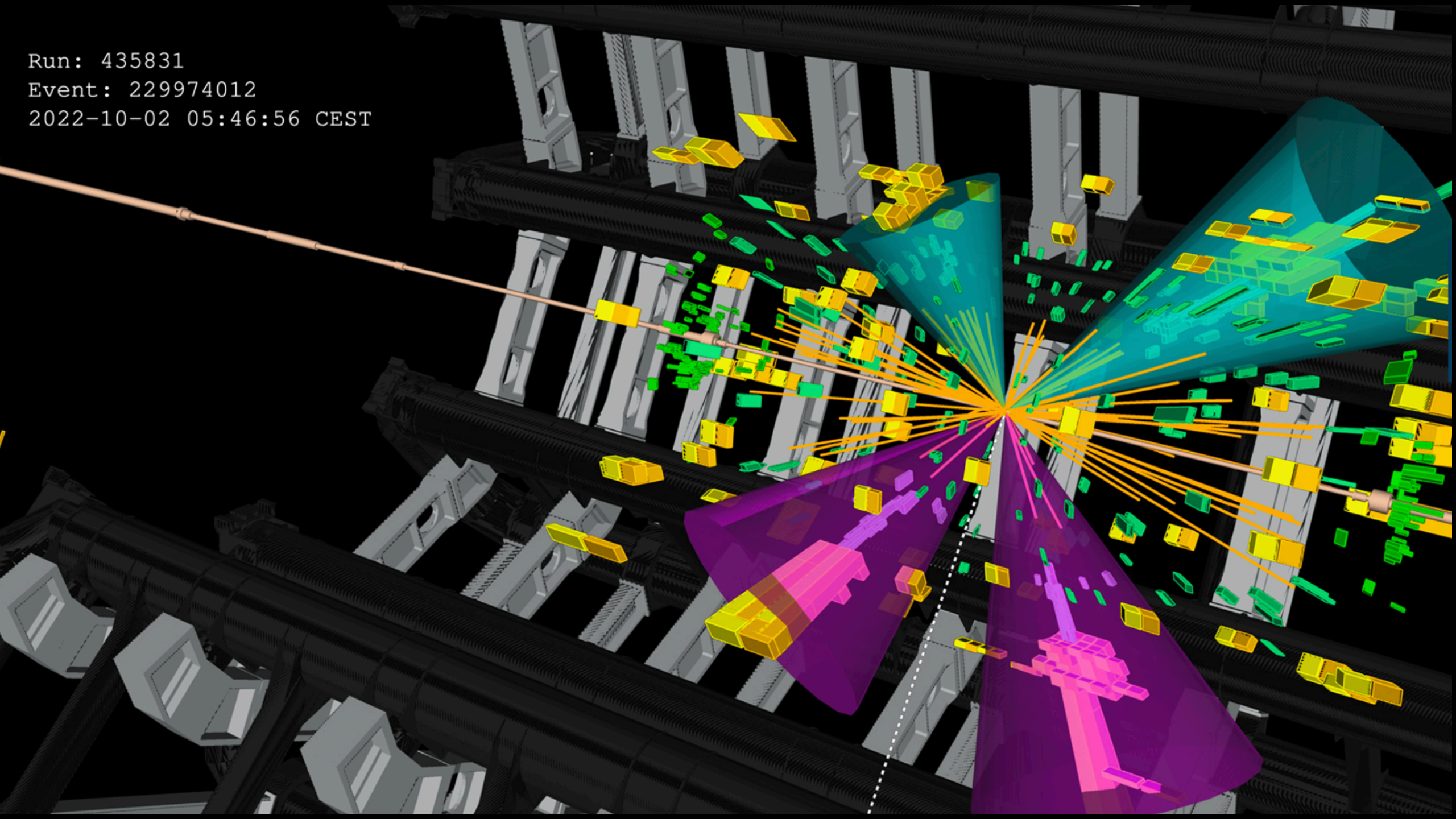
ATL-PHYS-PUB-2025-034




**HH only**

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



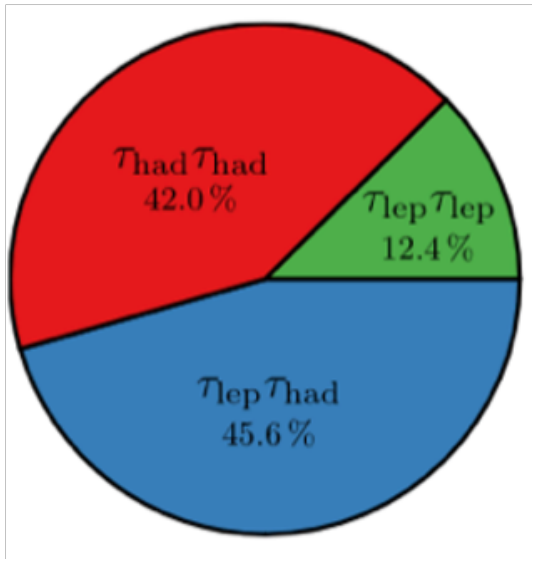

Run: 435831
Event: 229974012
2022-10-02 05:46:56 CEST

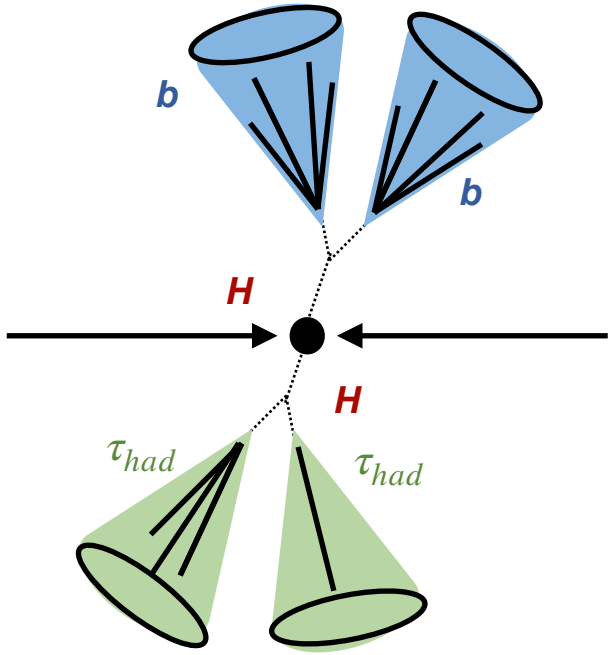
# HH to bb̄ττ

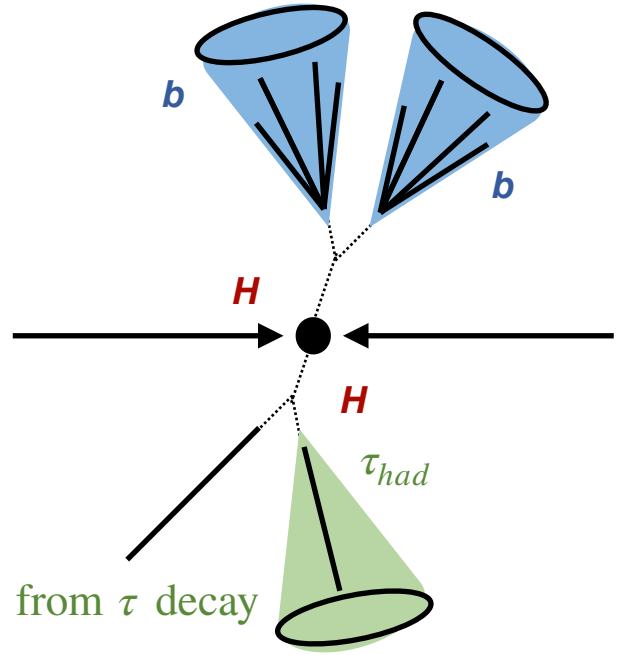
7.3% of all $HH$ decays and a good compromise between expected signal yield and purity.

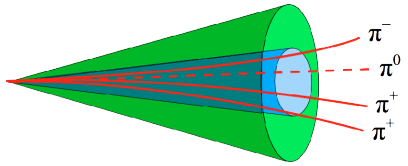
Lepton, τ and b-jet triggers extend acceptance across the HH phase space

Based on tau decay mode, analysis two channels: had-had & lep-had




90% efficiency with > 3 prongs

80% efficiency with > 1 prong

# HH to $b\bar{b}\tau\tau$ - the strategy

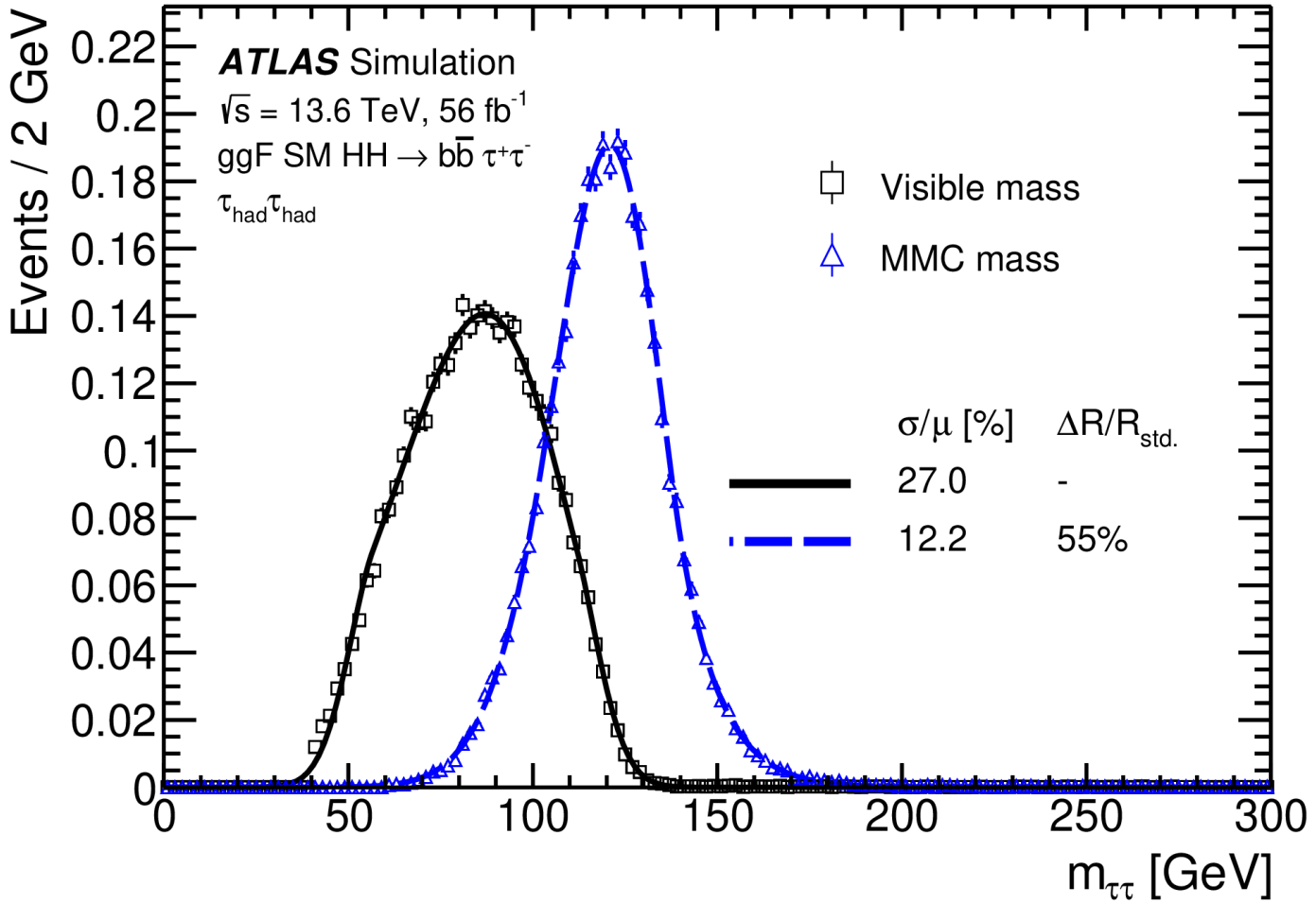
arXiv:2607.26879

- All tau decay contains at least one neutrino
- Additional complexity in estimating kinematics of di-tau system
- Missing Mass Calculator is used to reconstruct the $\tau\tau$ system
  - visible $\tau$ decay products and missing transverse momentum
  - $\tau$-decay constraints give a likelihood estimate of the $\tau\tau$ mass

# HH to bb̄ττ - the strategy

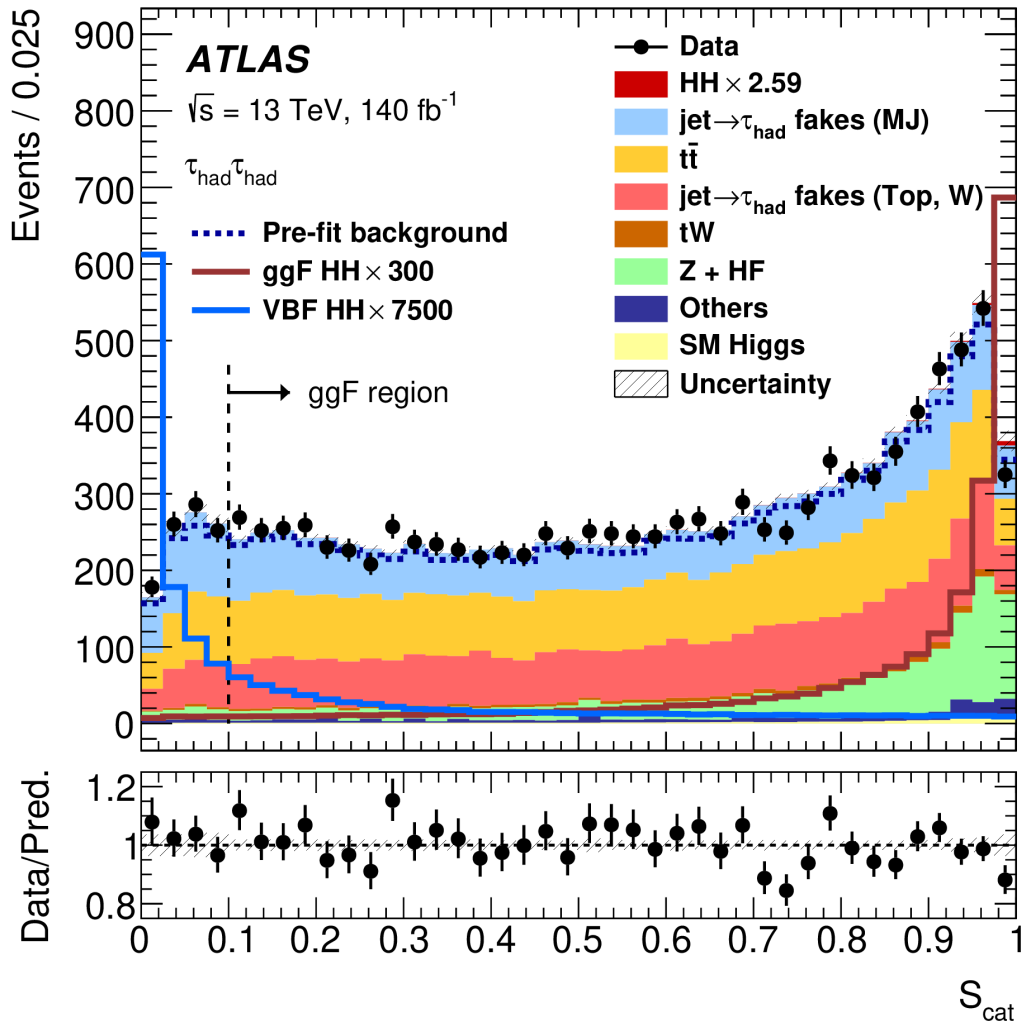
arXiv:2607.26879

- All tau decay contains at least one neutrino
- Additional complexity in estimating kinematics of di-tau system
- Missing Mass Calculator is used to reconstruct the ττ system
  - visible τ decay products and missing transverse momentum
  - τ-decay constraints give a likelihood estimate of the ττ mass



# HH to bb̄ττ - backgrounds

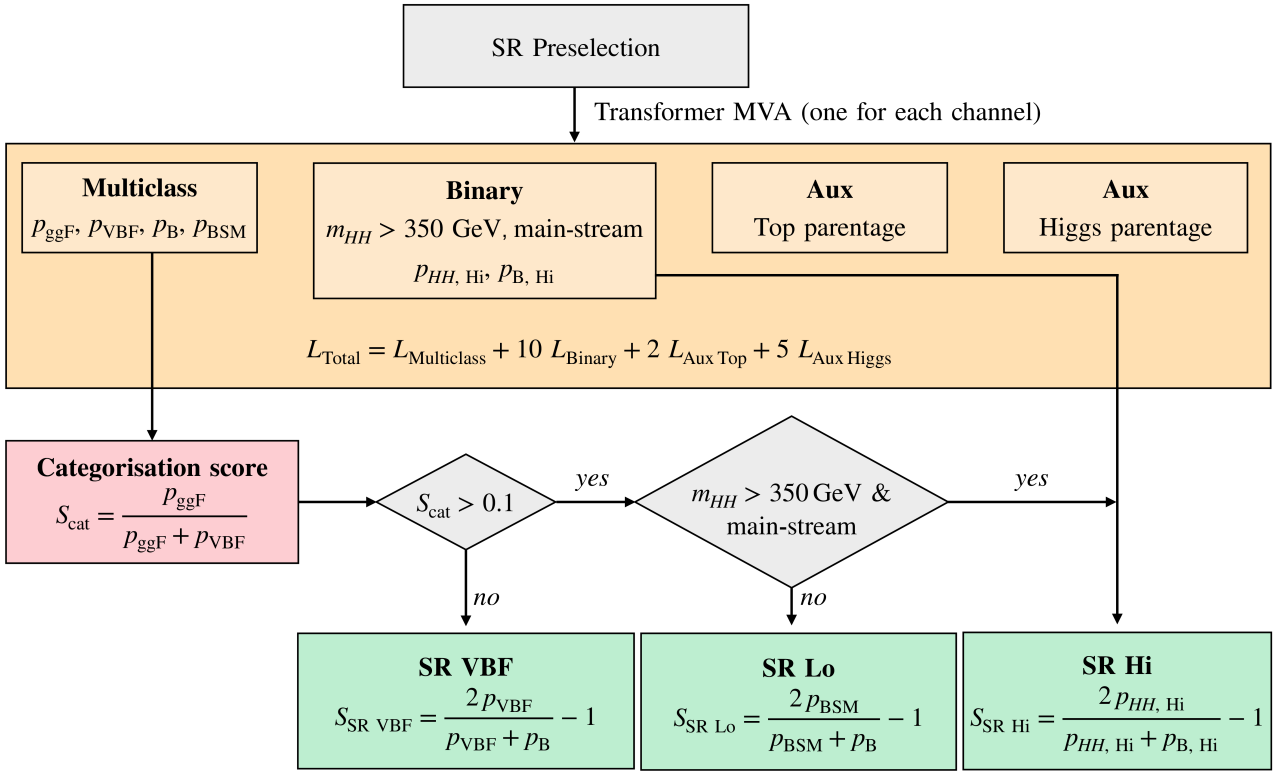
arXiv:2607.26879




- tt̄ is one of the dominant background for both lep-had and had-had channel (45 & 60%)
  - Simulation with correction from data
- Z+heavy flavour is irreducible and estimated directly from data
- tW is subdominant but tW–tt̄ interference becomes important in the most signal-like bins
  - Estimated in a dedicated control region in data
- Multijet events, jets misidentified as τhad, are also estimated in data

# HH to $b\bar{b}\tau\tau$ - multivariate analysis

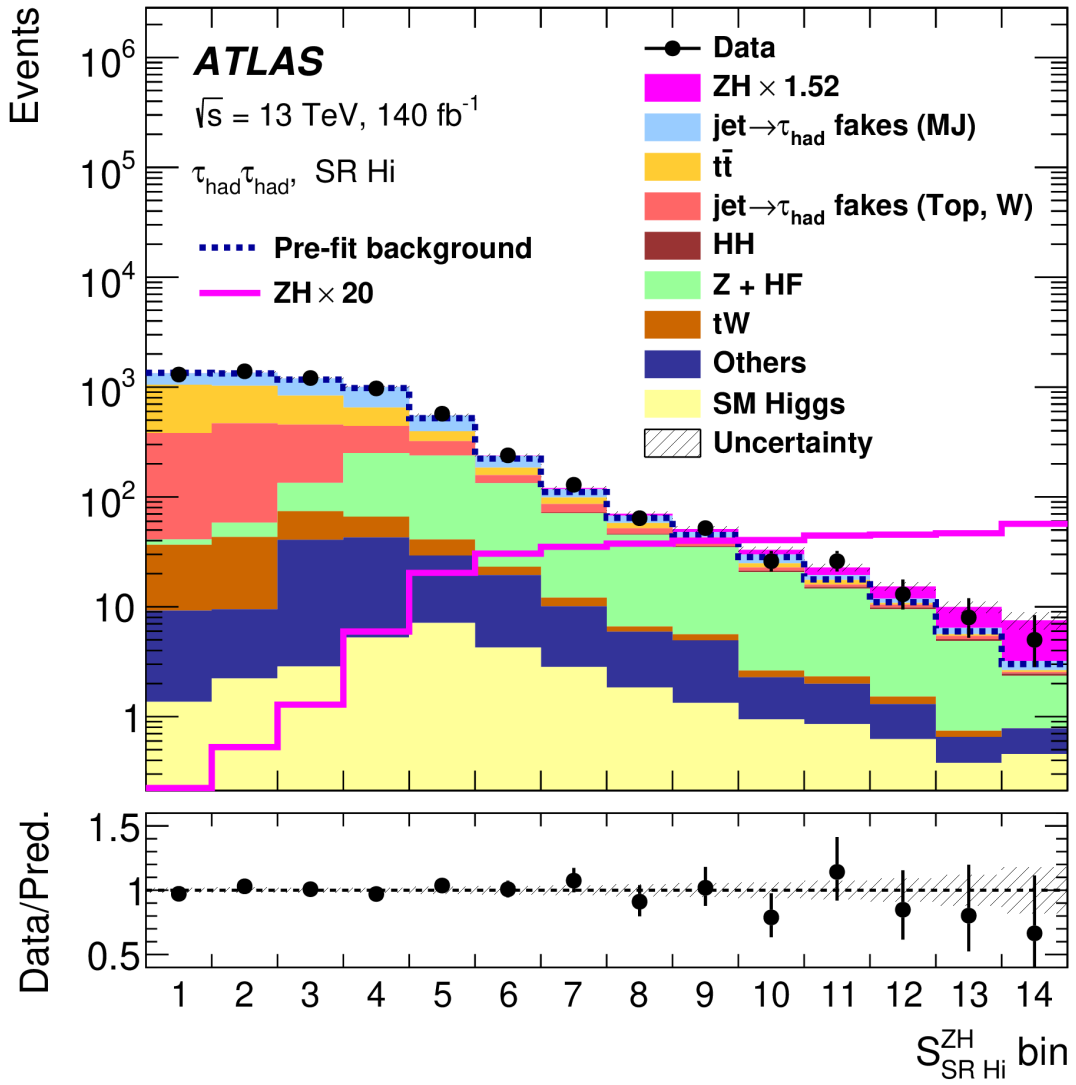
arXiv:2607.26879




- Total: 12 discriminant distribution + 4 control region distributions used for final fit
  - 3 models per Run period per τ decay channel
- Object information together with event kinematics
  - Multiclass outputs for ggF, VBF, BSM-like signal and backgrounds
  - Auxiliary tasks identify objects from Higgs and top decays
  - Dedicated high-$m_{HH}$ classifier targets SM HH

# Validating the $b\bar{b}\tau\tau$ analysis with ZH

arXiv:2607.26879

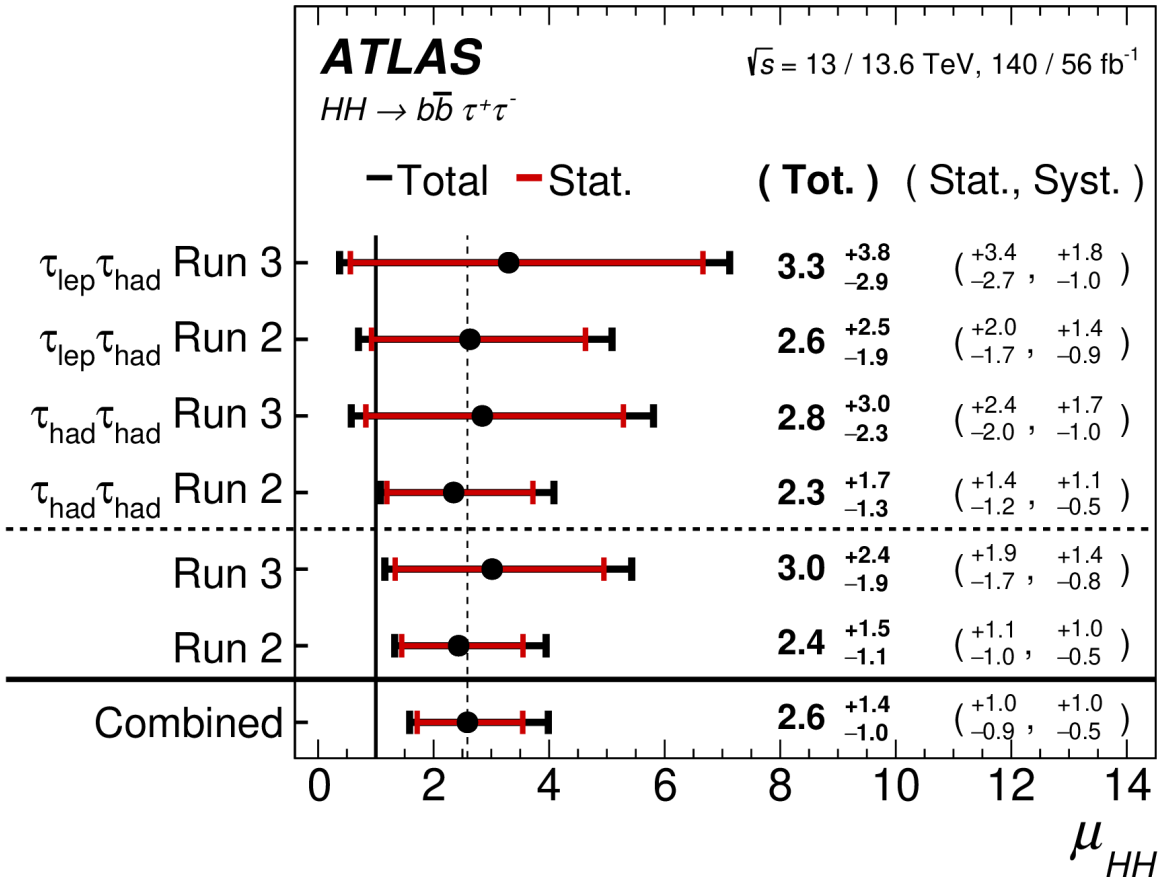


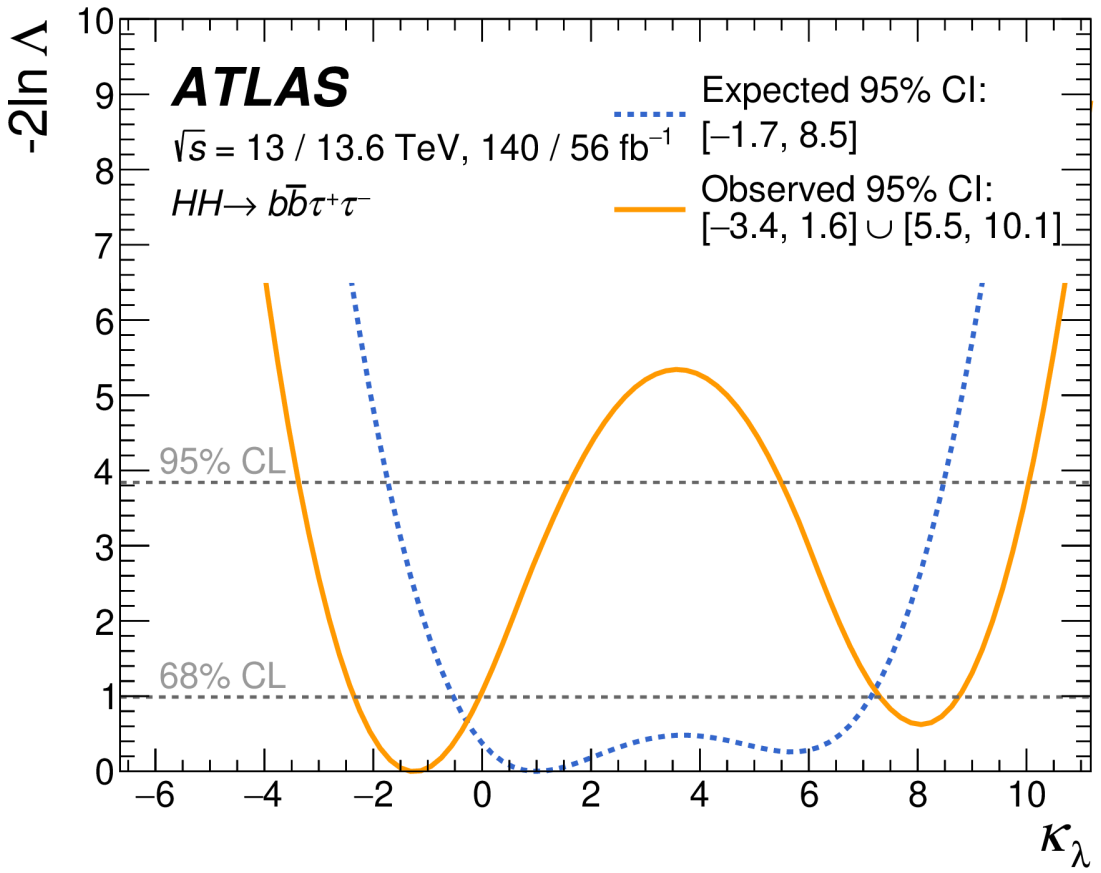

- Same final state and closely related analysis strategy
- Retrain the classifier for ZH and ZZ production
- ZH: 3.5σ observed (2.4σ expected)
- ZZ: 1.8σ observed (2.7σ expected)

**A useful test of reconstruction and background modeling**

# HH to bb̄ττ - results

arXiv:2607.26879




**65% gain in expected SM HH significance**

15–20% from the new classifier,

~10% from improved b-tagging

~15% from the additional Run 3 data

- Observed significance: 2.6σ (1.2σ exp)
- Compatible with the SM within 1.65σ
- 95% CL upper limit: 5.3 × SM
- Expected (background only): 2.4 × SM

# HH to $b\bar{b}\tau\tau$ - uncertainties

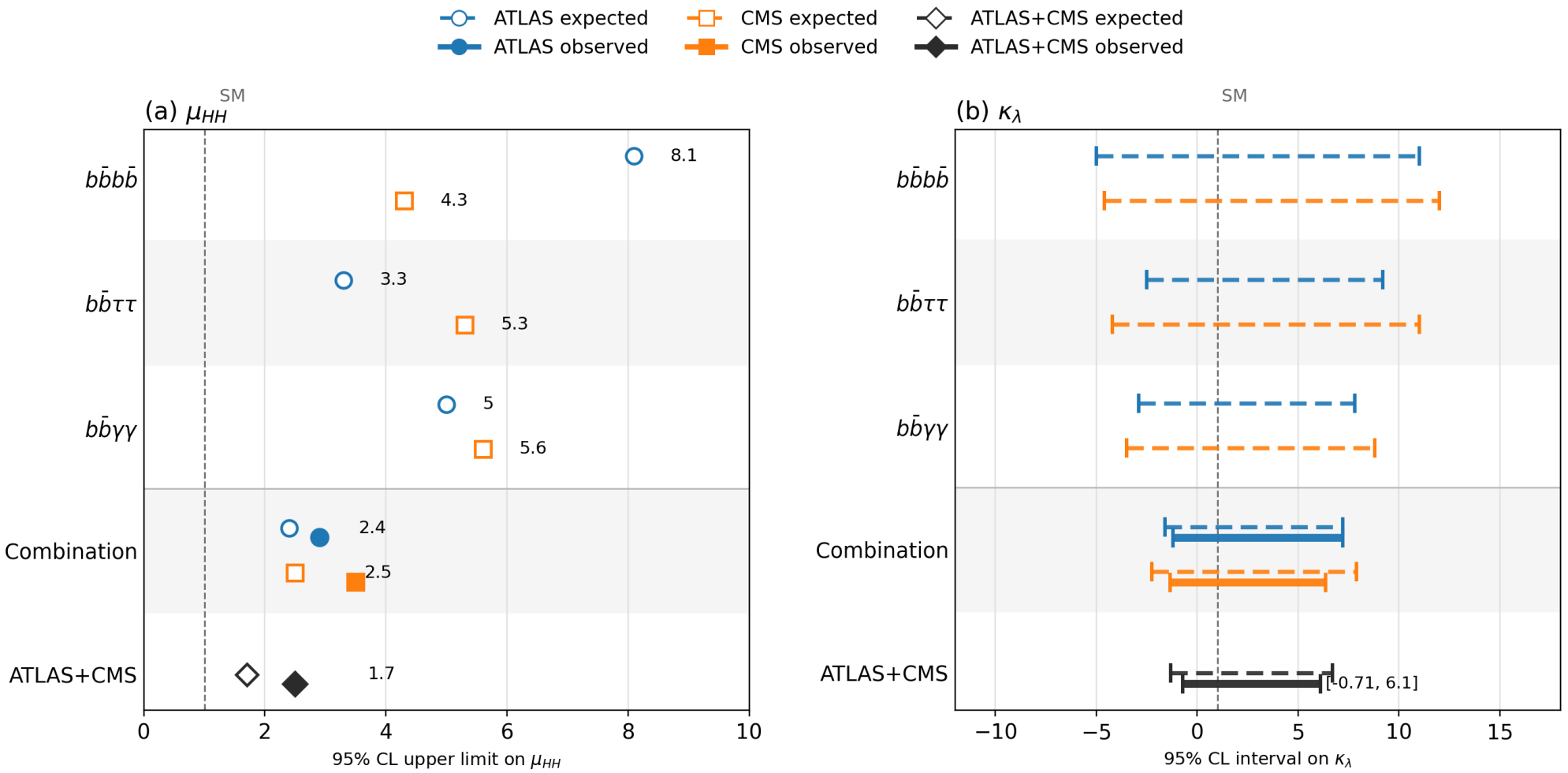
arXiv:2607.26879

| Source of uncertainty | $\sigma_{\mu_{HH}}$ |
|---|---|
| Total | 1.20 |
| Statistical | 0.91 |
| Systematic | 0.76 |
| Experimental uncertainties | 0.20 |
| Electron and muon | 0.01 |
| $\tau_{\text{had}}$ | 0.13 |
| $E_{\text{T}}^{\text{miss}}$ | 0.03 |
| Jet | 0.14 |
| Flavour tagging | 0.04 |
| Pile-up | 0.01 |
| Luminosity | 0.03 |
| Modelling uncertainties | 0.71 |
| Background template statistical | 0.21 |
| $HH$ | 0.54 |
| $ZH$ | 0.02 |
| $ZZ$ | <0.01 |
| Other SM Higgs | 0.25 |
| $Z$+jets | 0.07 |
| $tW$ | 0.21 |
| Top | 0.12 |
| jet $\rightarrow \tau_{\text{had}}$ fakes | 0.07 |
| Others | 0.01 |

- Still statistically limited
  - Experimental uncertainties are 3% of the total: jet and tau reconstruction
- Modeling are the dominant uncertainties, 35%:
  - Leading systematics: HH theory, photon energy calibration and single-Higgs + heavy flavor
  - Interference between $t\bar{t}$ & $tW$

# Run 2 combinations - the reference

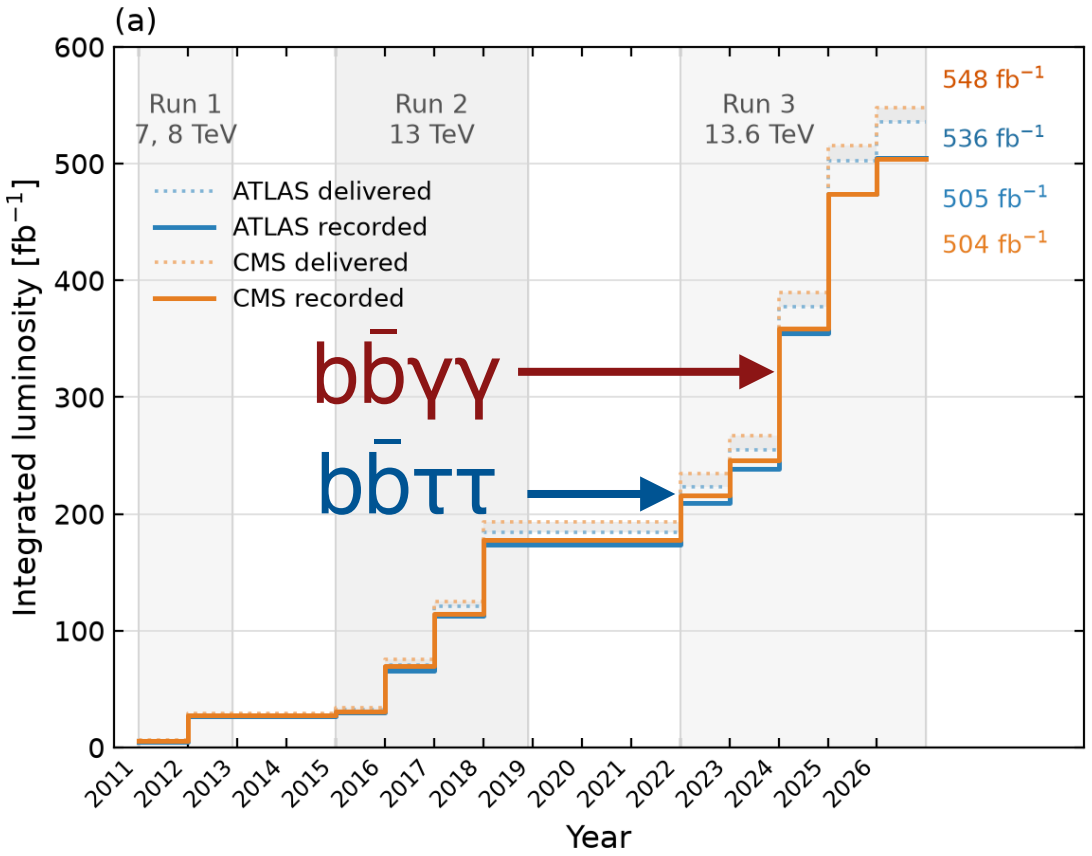
ATLAS+CMS PRL 137 (2026) 131803

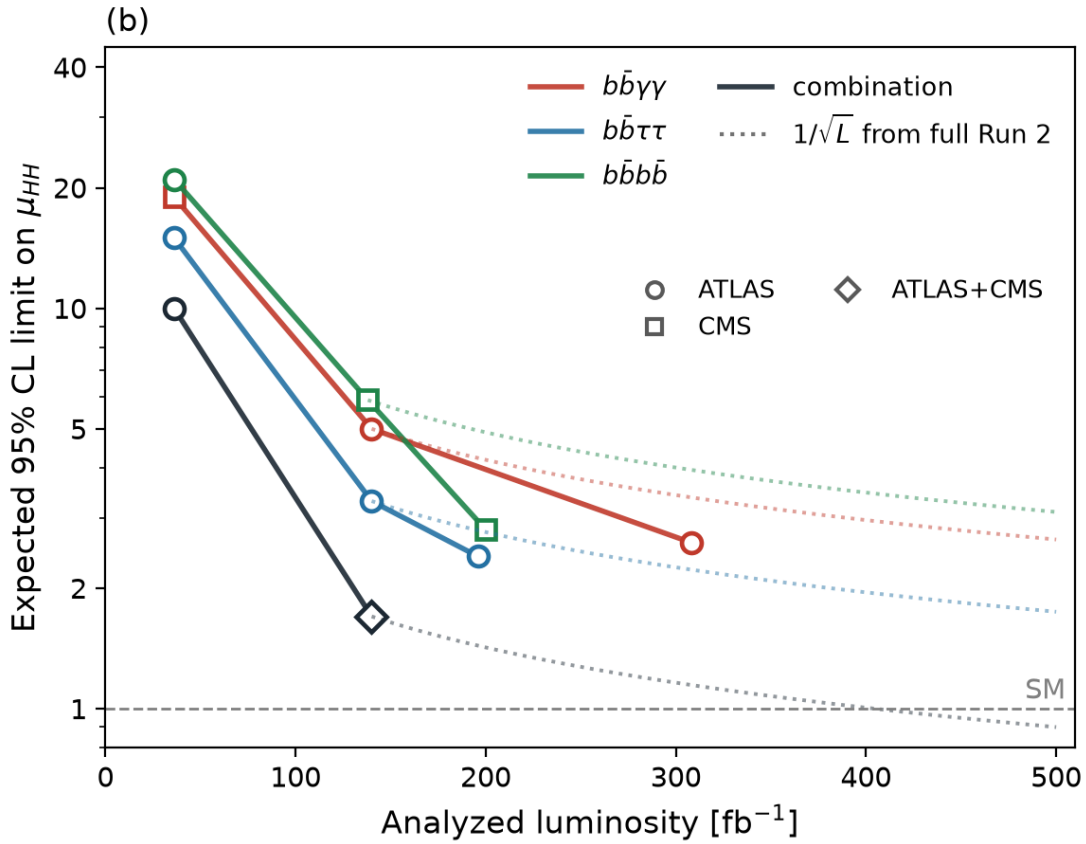



**ATLAS+CMS: expected limit 1.7 × SM, observed 2.5 × SM**

**Run 2 inputs only; the new Run 3 results are not included**

# Run 3 - beyond luminosity scaling




Published limits improve faster than the 1/√L reference

Much of the recorded Run 3 sample has yet to enter these analyses

# LHC → High Luminosity LHC

HL-LHC schedule

RUN 3

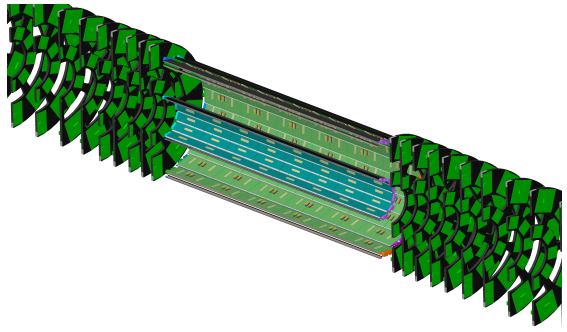
16M H

HL-LHC installation
ATLAS Upgrade

RUN 4/5

170M H
120K HH

... 2022 2023 2024 2025 2026 2027 2028 2029 2030 ... 2041

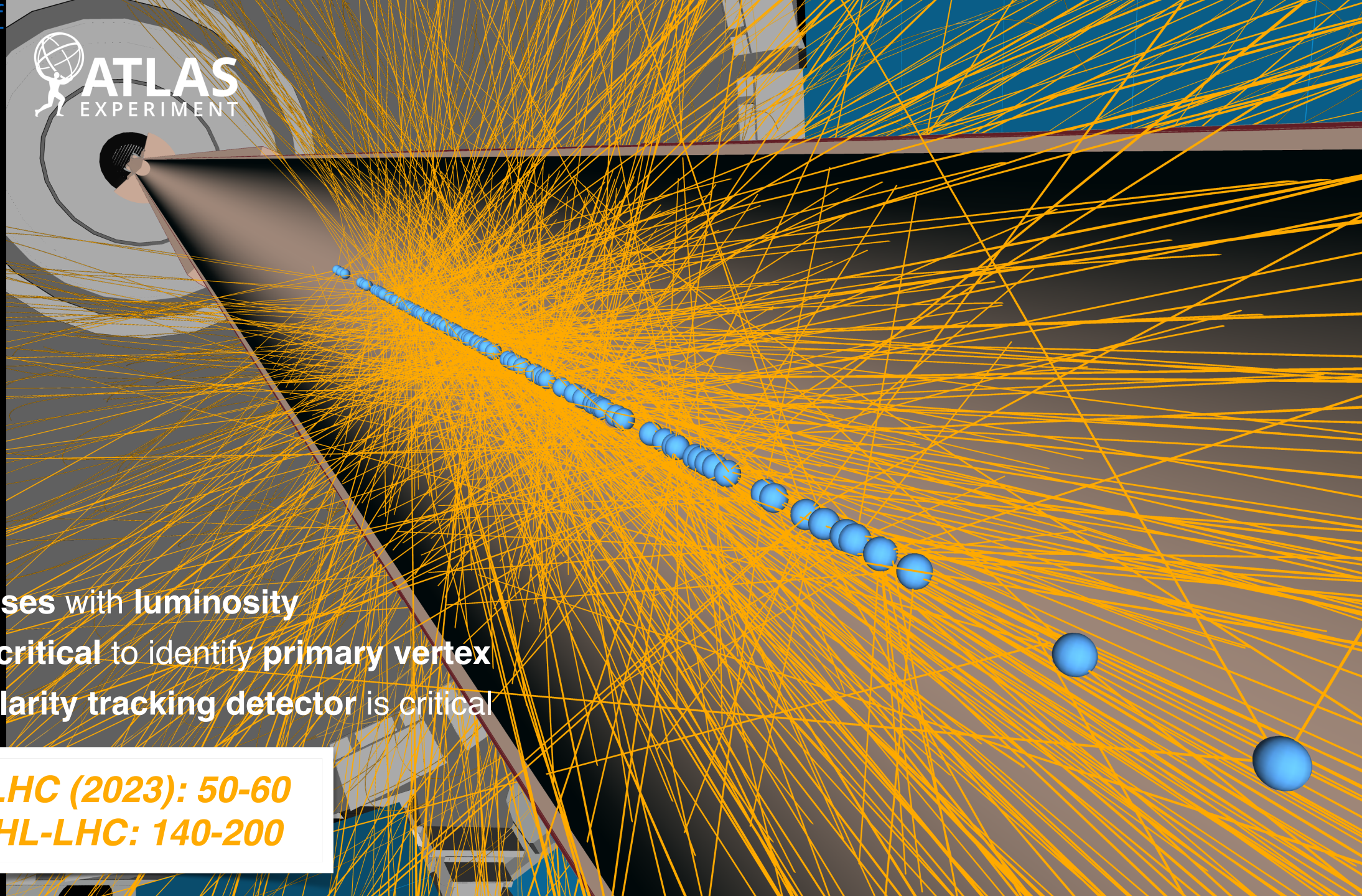


TODAY

**Phase-2 HL-LHC detector upgrades are being built**



ref




**Pileup increases** with **luminosity**

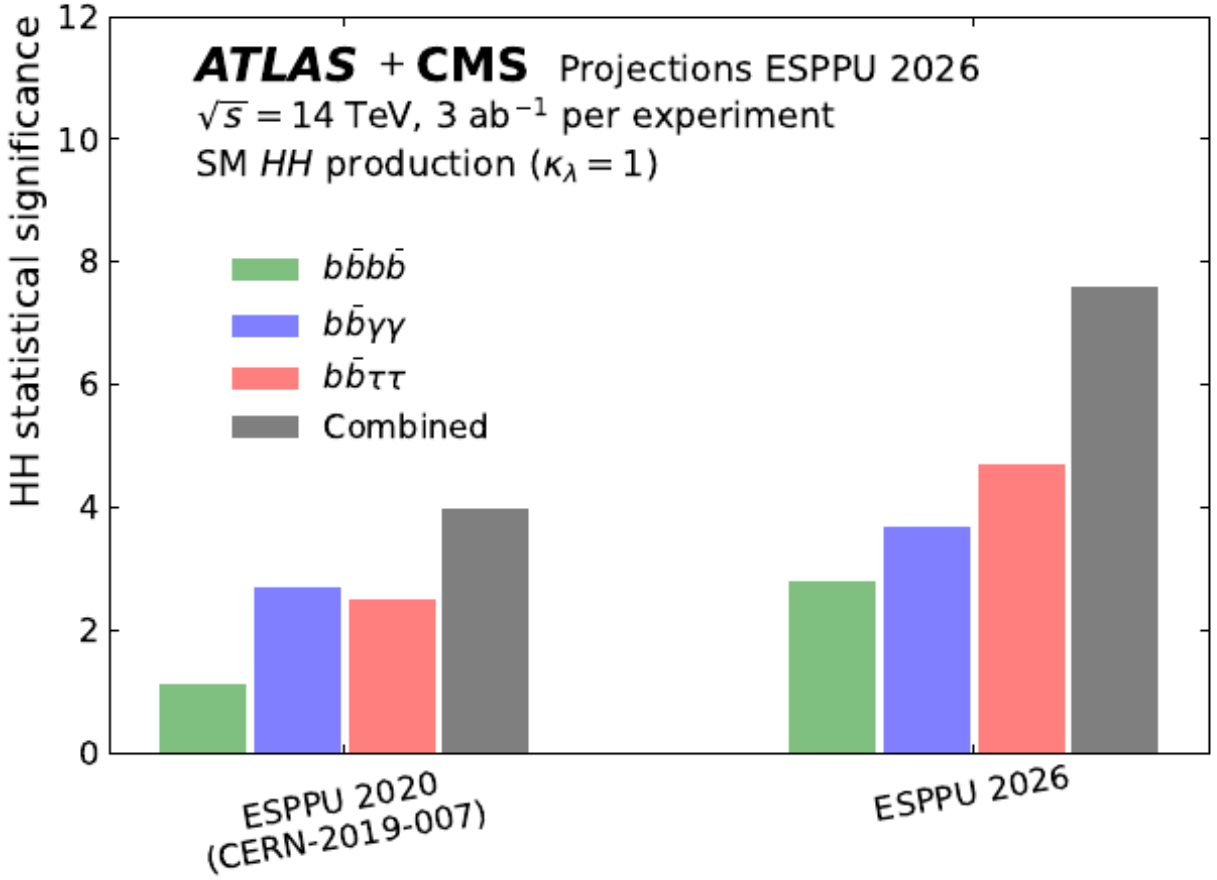
**z position is critical** to identify **primary vertex**

**High granularity tracking detector** is critical

***LHC (2023): 50-60***
***HL-LHC: 140-200***

# HL-LHC - how the projection changed

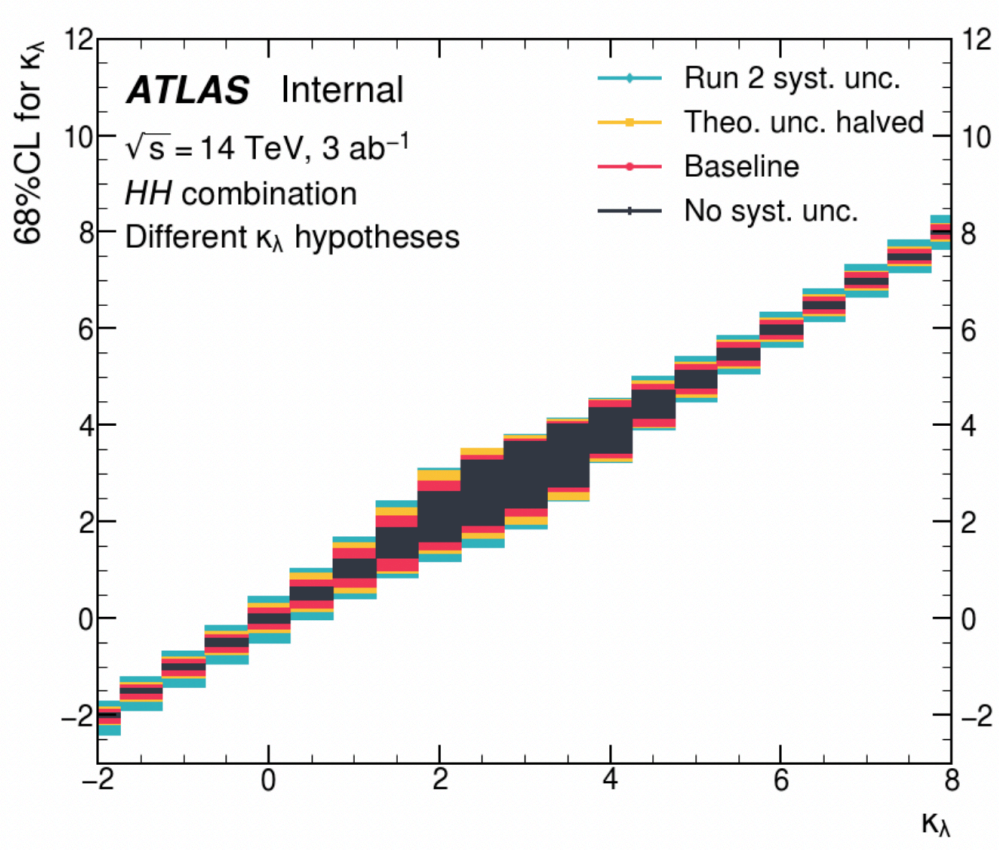
ESPPU 2025 HL-LHC

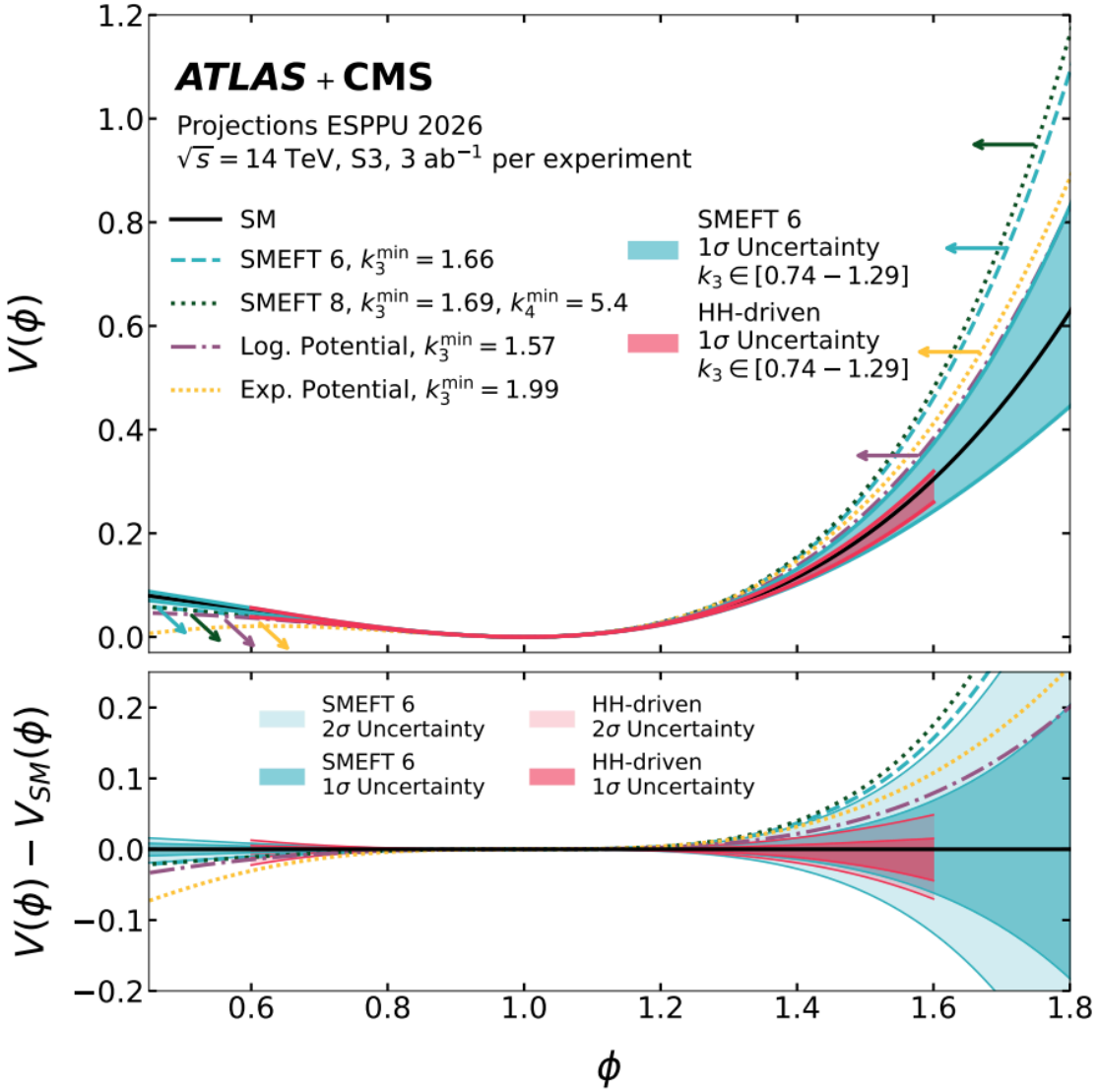



- 3 ab$^{-1}$ per experiment, 14 TeV
- Combined HH significance: about 4σ in ESPPU 2020 to 7.6σ in ESPPU 2026
- Improved analyses, with the largest relative gain in 4b
- Reduced systematic uncertainties and improved b/τ identification are part of the projection
- Halved theoretical uncertainties

# Higgs physics at the HL-LHC

ESPPU 2025 HL-LHC
ATL-COM-PHYS-2025-038

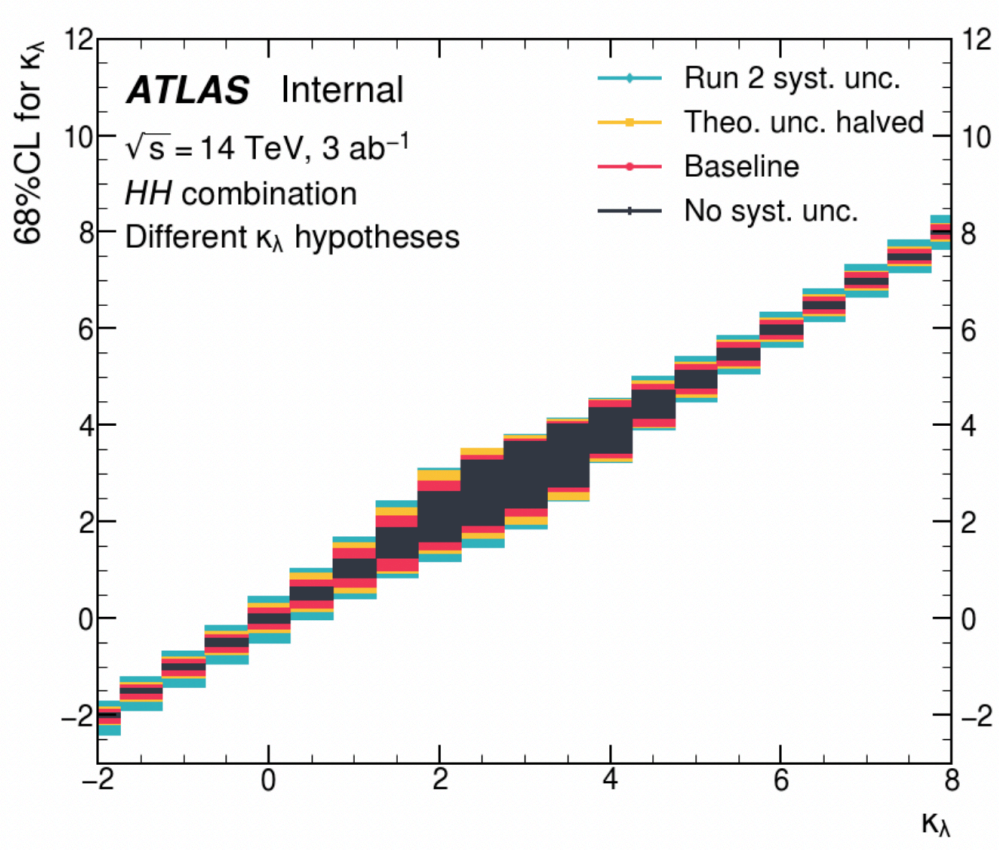


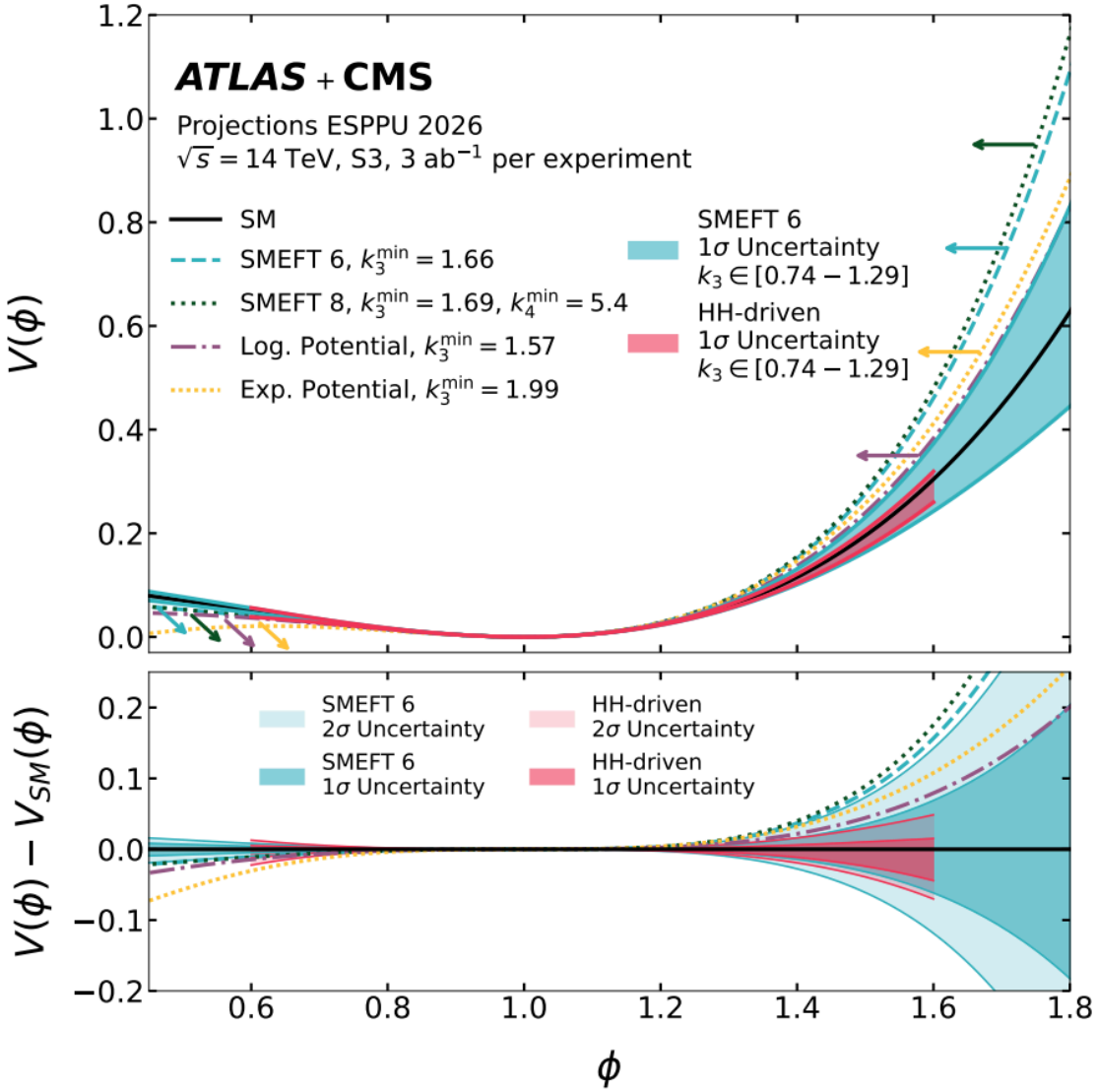




**Uncertainty on $\lambda_{SM}$ improved by 50% to 30%**
**2/ab → 3/ab + 20% on the signal significance**

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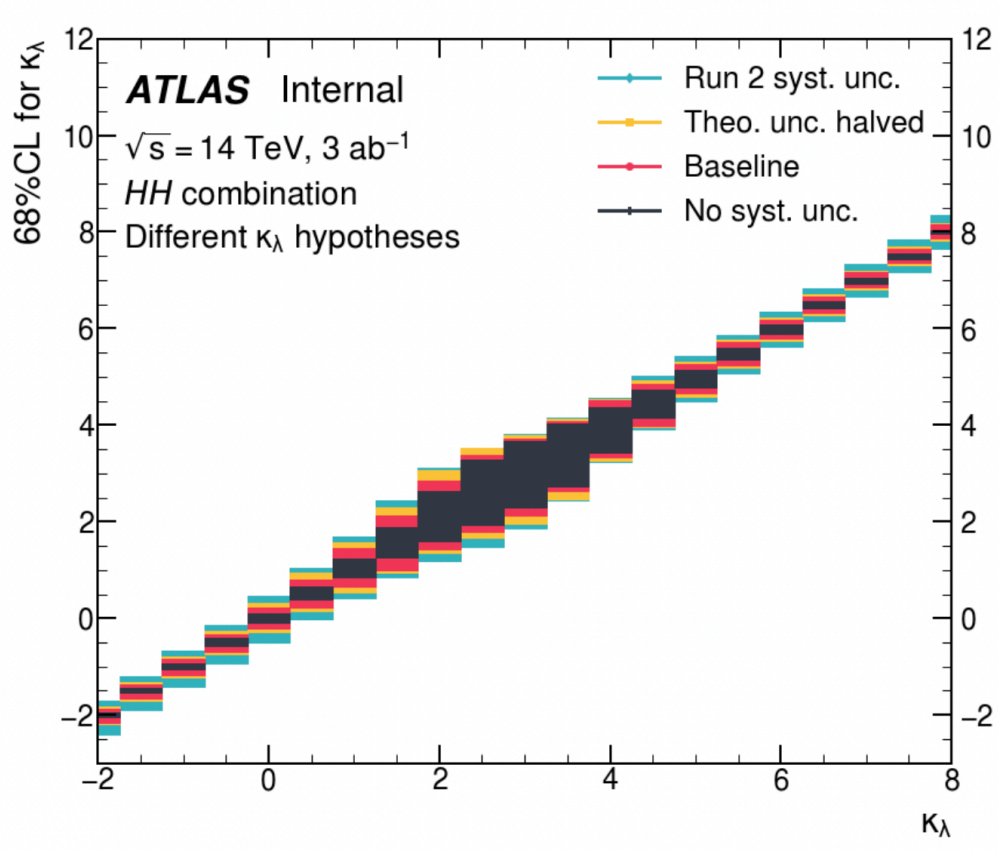


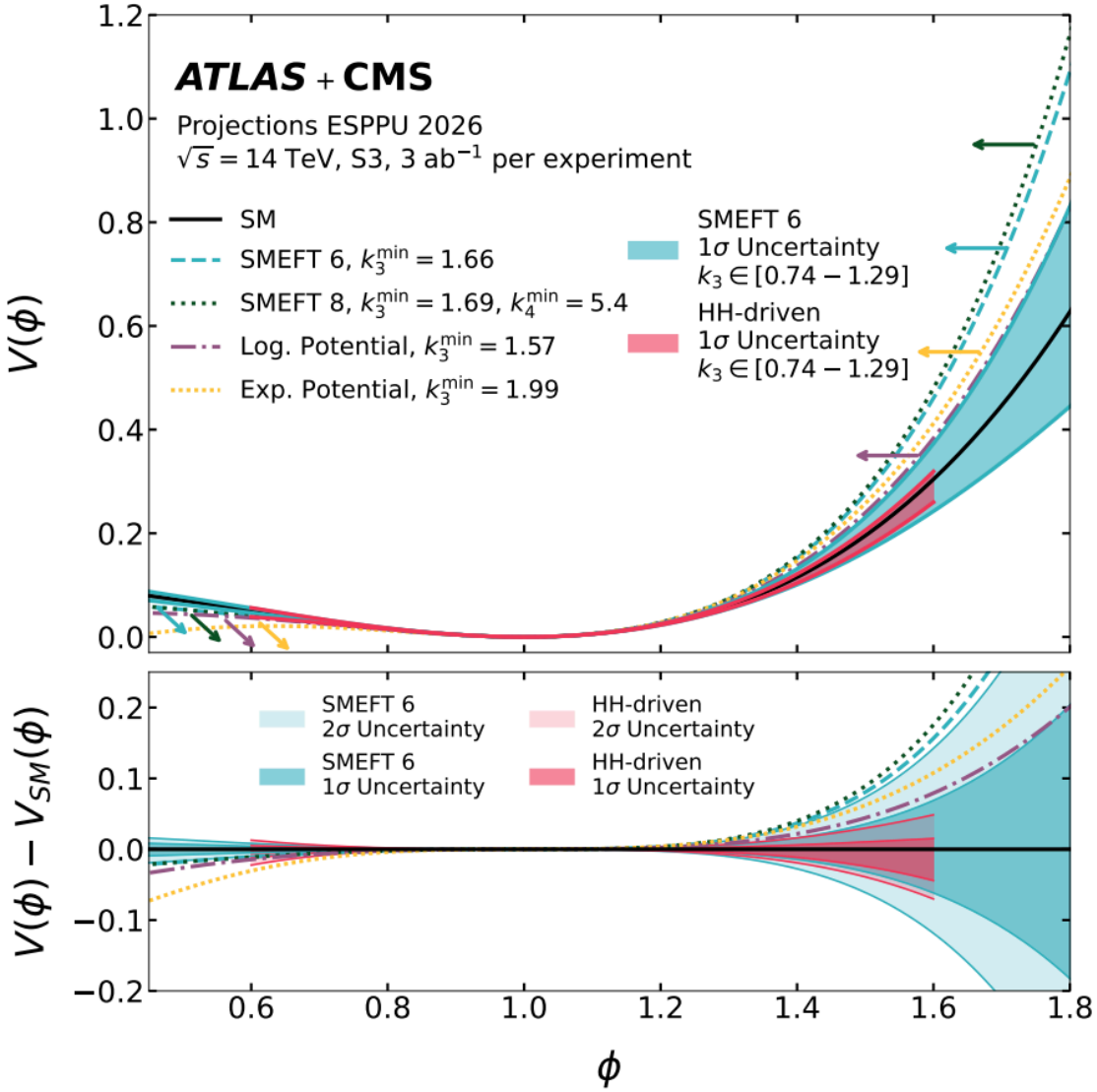




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ATL-COM-PHYS-2025-038




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# Perspectives

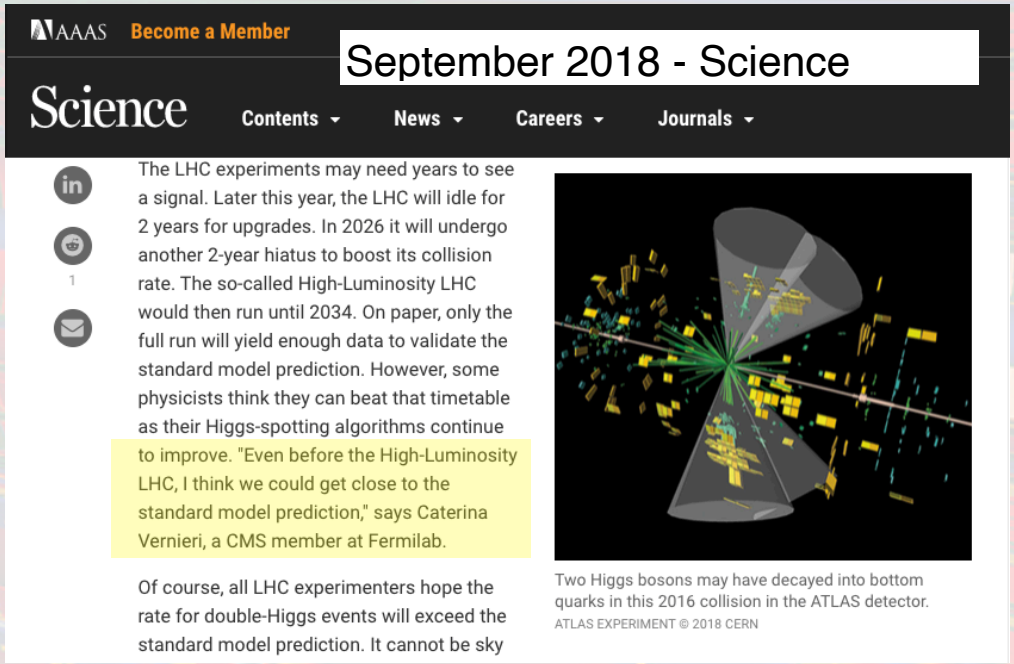
## Experiments at LHC are approaching SM sensitivity to non-resonant HH production

- Several final states investigated, more to exploit with more Run 3 data
  - More sophisticated analysis techniques and ML improvements from object reconstruction to analysis categorization
  - More to be learned on the self-coupling from differential $m_{HH}$
  - H+HH and EFT combined analyses for a more general interpretation
- Effective luminosity scales faster than adding more LHC data
  - Getting to SM sensitivity by Run 3 is a real possibility
- At HL-LHC more data will be available to test the self-coupling and probe rare (new?) processes
  - Challenging experimental environment for online selections and b-tagging
  - Improved tracker and new timing detectors should allow us to maintain or even yield to increased acceptance

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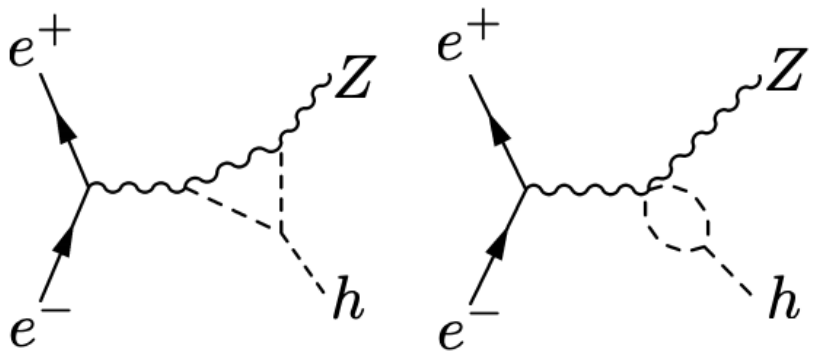
# Next?

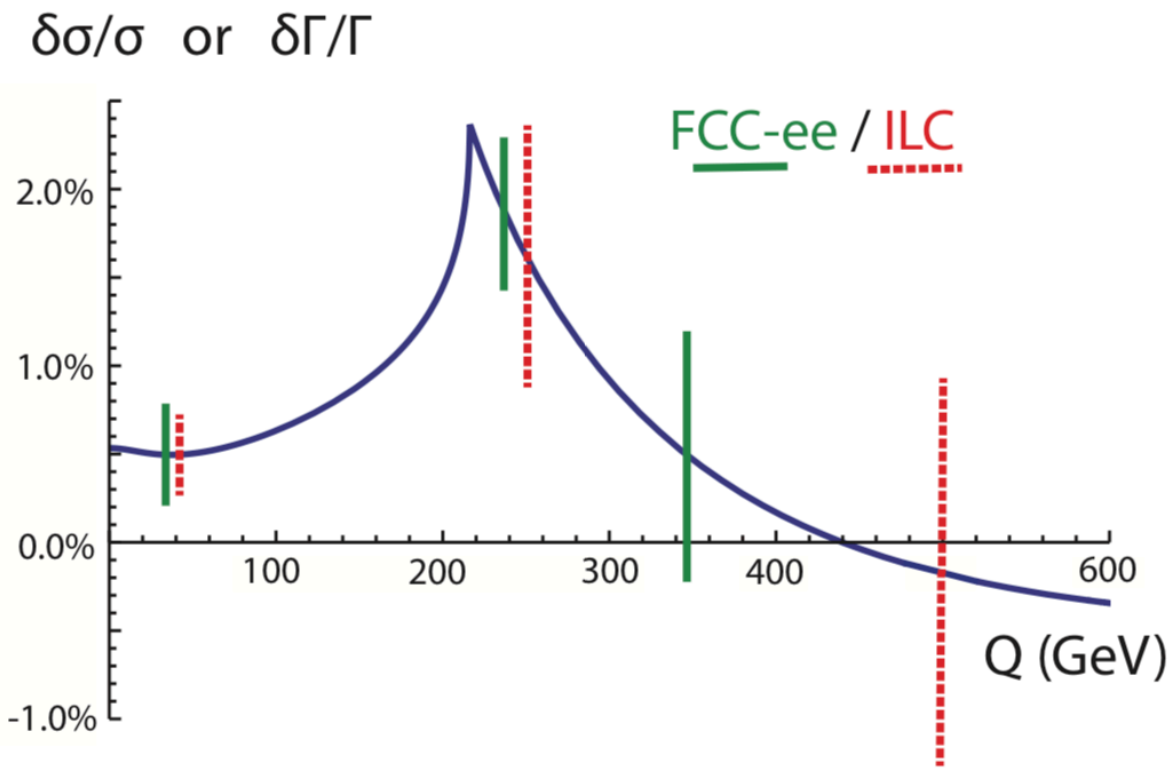
# Self-coupling at e+e- with single Higgs

arXiv:1312.3322
arXiv:1910.00012
ESPPU FCC -arXiv:2504.05974

- Relative enhancement of e+e−→ ZH and H→W+W− partial width
- Need multiple $Q^2$ to identify the effects due to the self-coupling
- ***(More) model dependent***
  - ***18%: HL-LHC+FCC365 (baseline)***

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$



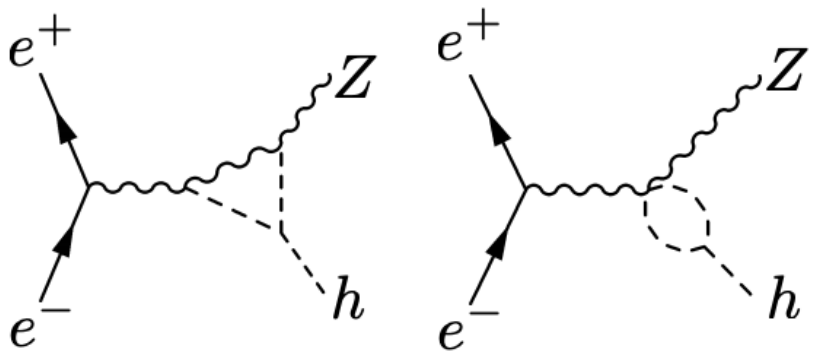

**New observables? Top-quark uncertainties? Which is the optimal energy scan?**

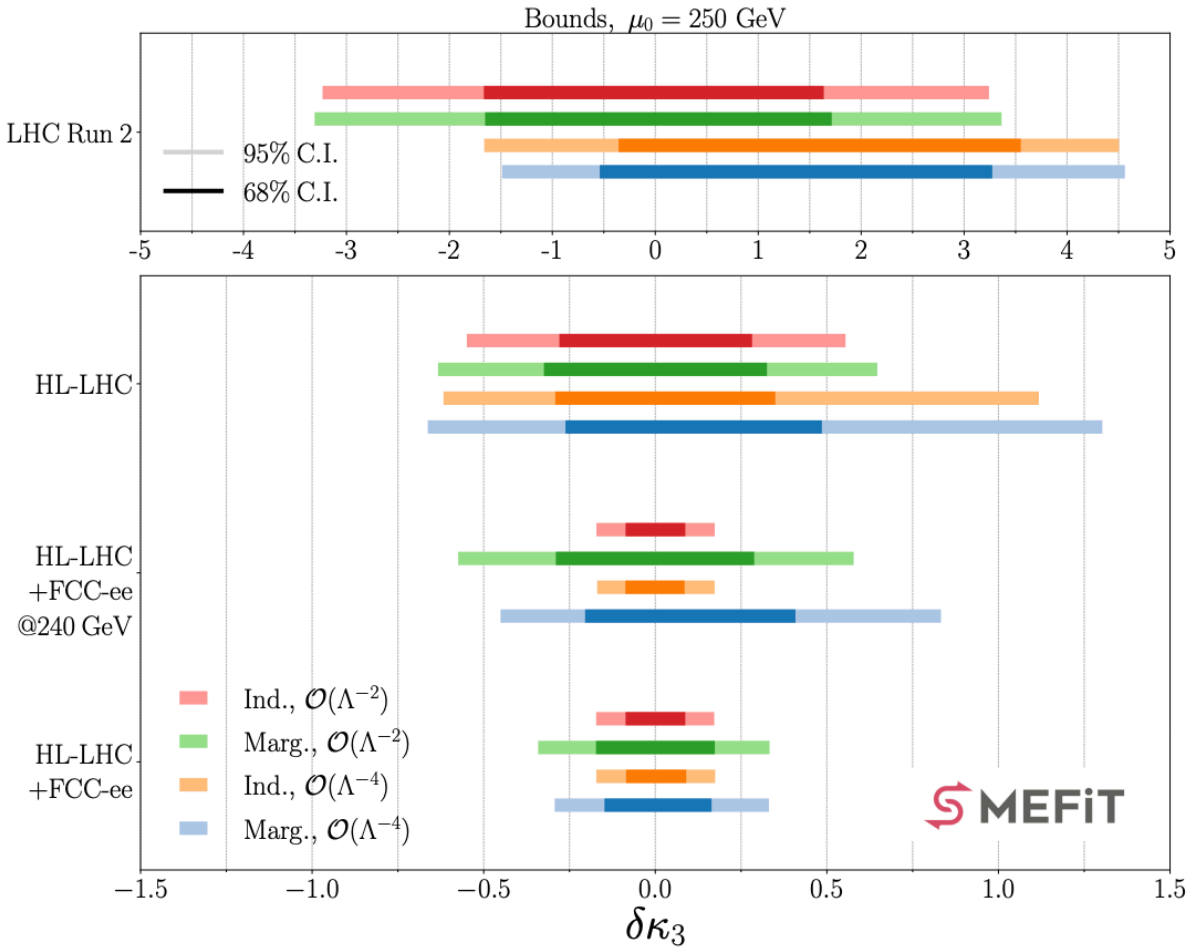
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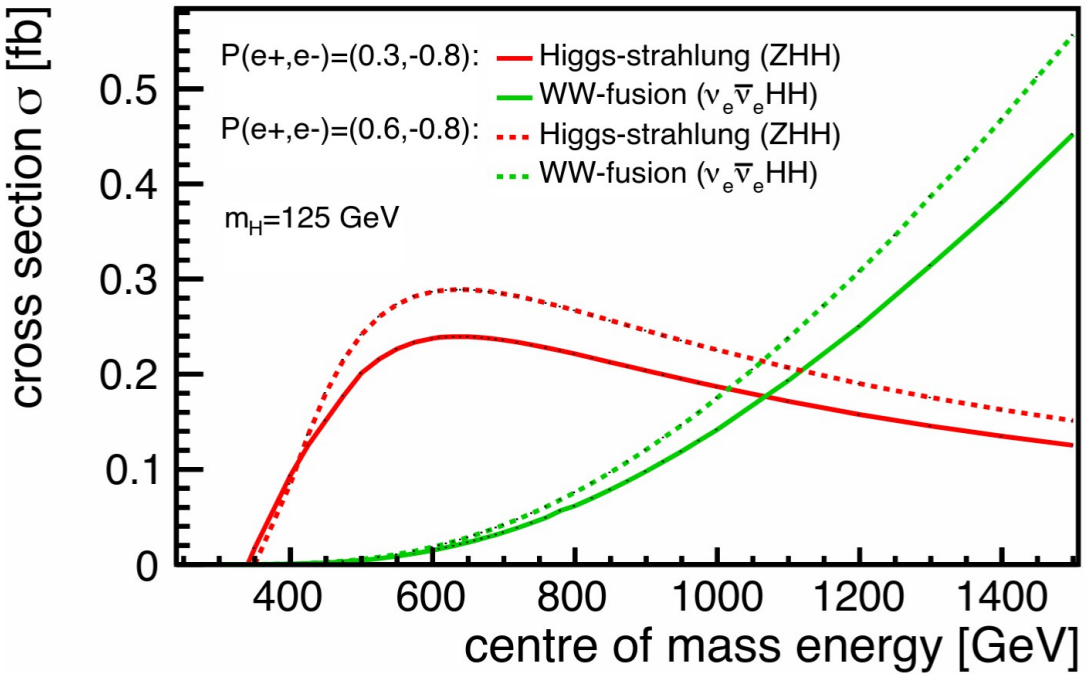



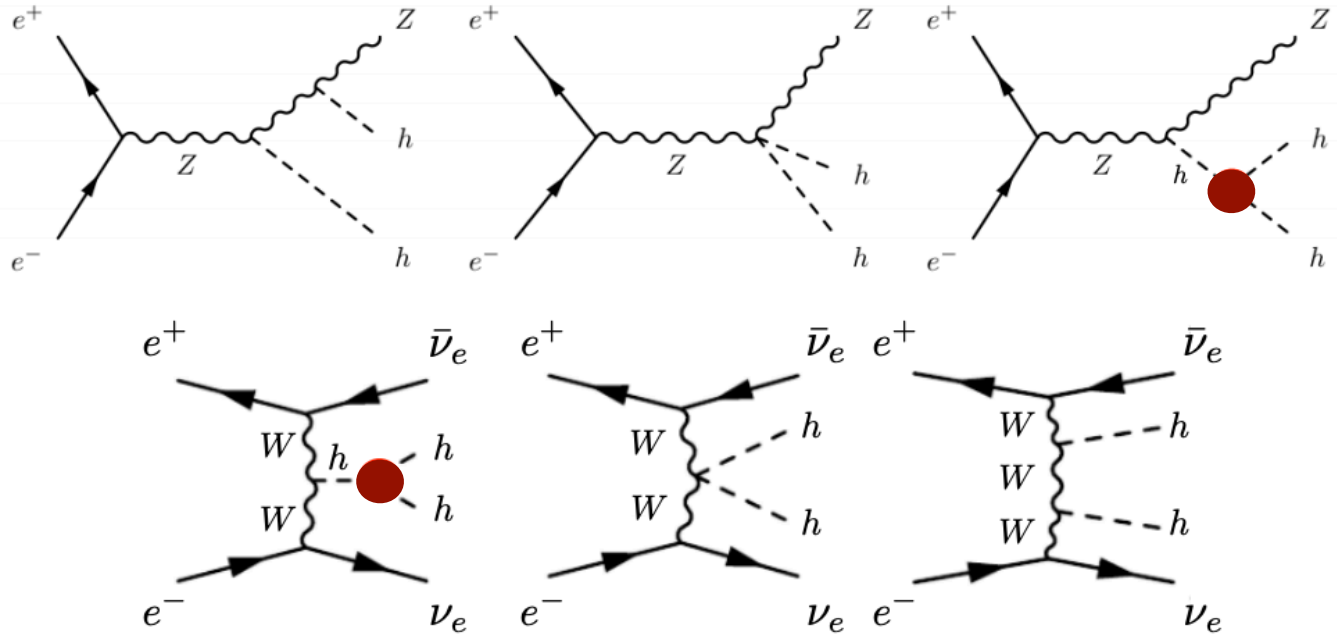

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# Self-coupling at $e^+e^-$ with double Higgs

Review in Physics (2020) 100045

ZHH and vvHH have similar P=(-80%,+30%) cross section at 1 TeV = 0.18 fb



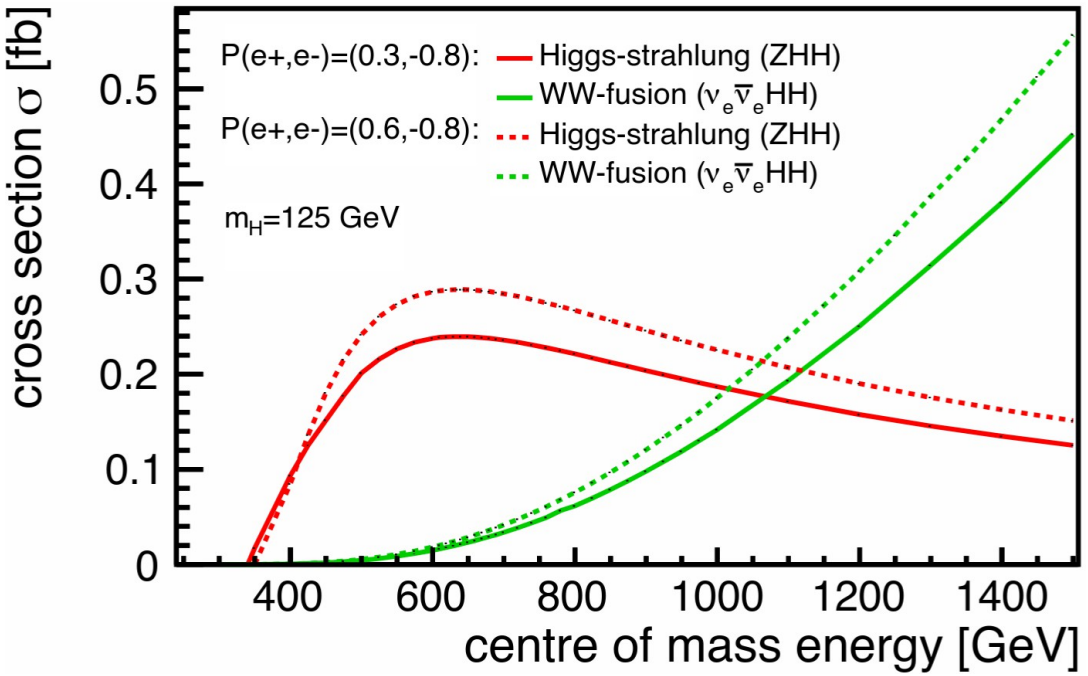



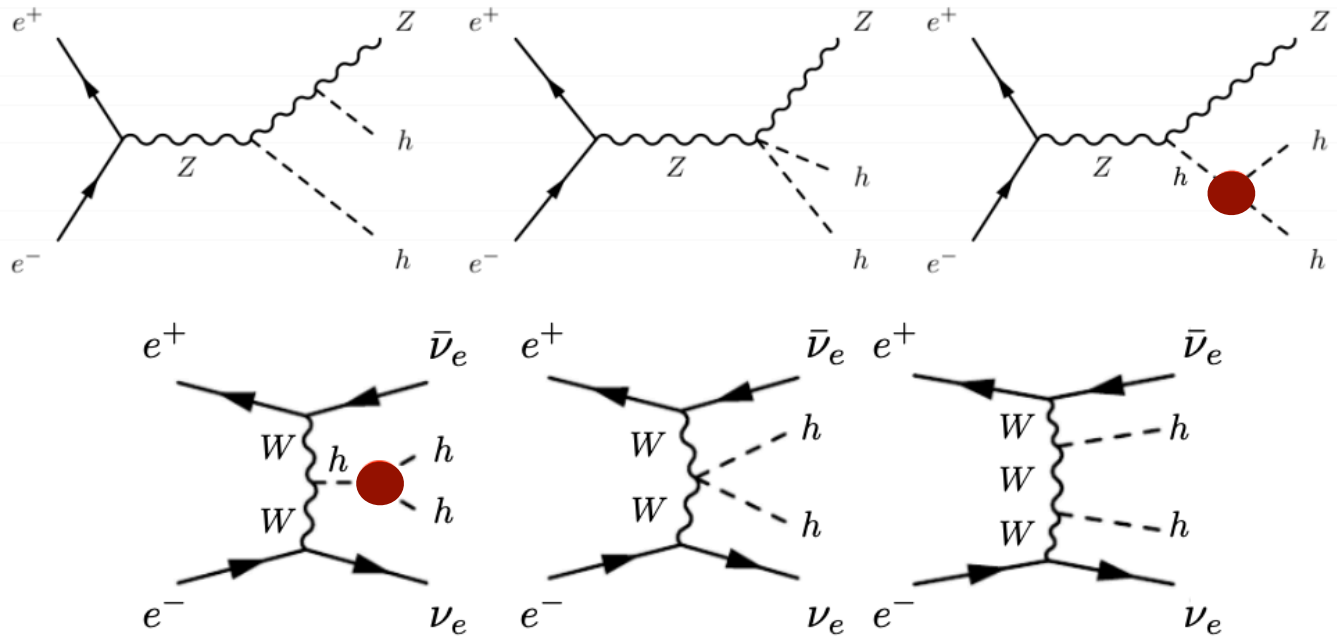

- The self-coupling can be probed at e⁺e⁻ through HH with ZHH ~500GeV and vvHH ≥1TeV
  - **HHvv** requires $e_L^- e_R^+$ , the use of polarized beams could increase the cross-section by a factor ~2
- For both ZHH and WBF processes there are diagrams involving the self-coupling in **constructive/deconstructive interference** with diagrams that do not contain this coupling.

# Self-coupling at $e^+e^-$ with double Higgs

Review in Physics (2020) 100045

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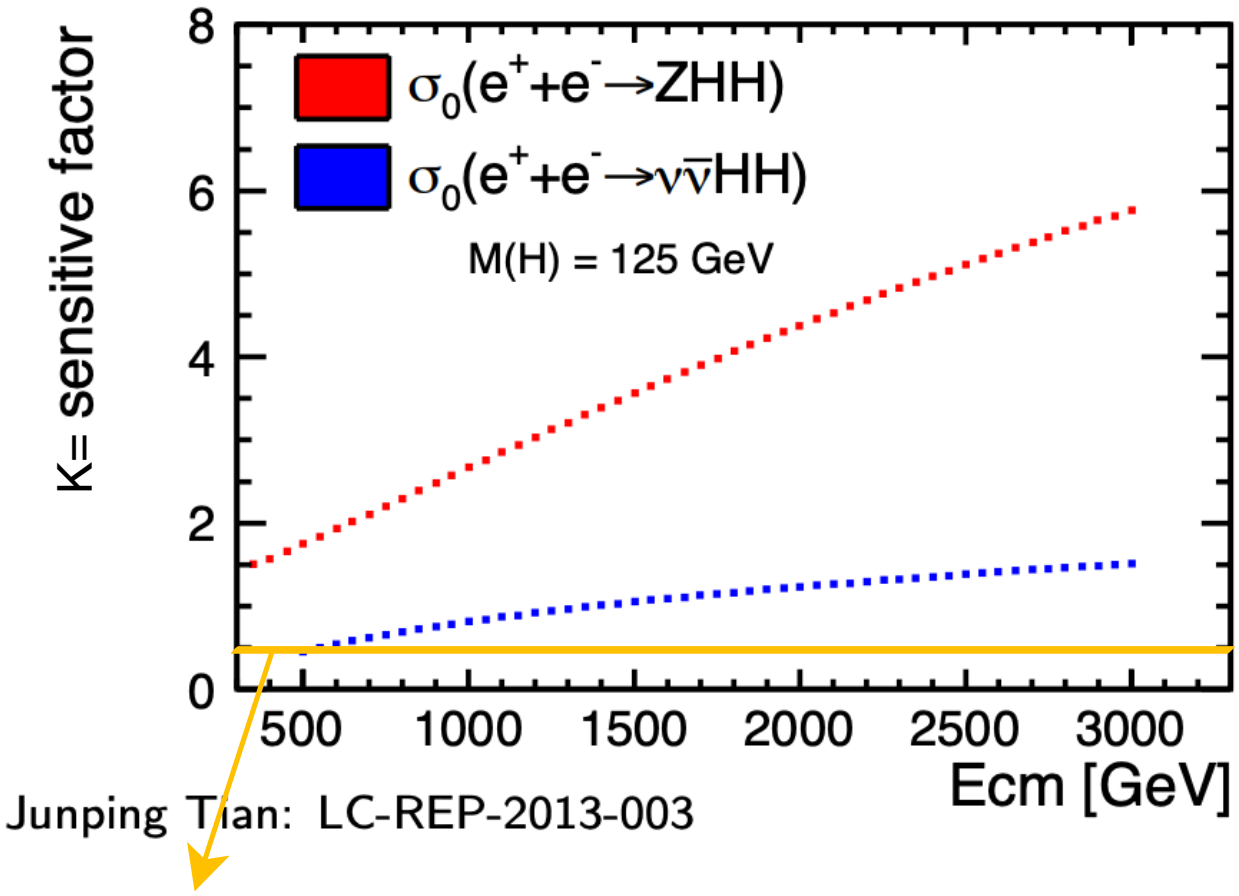




- Th… ~2
- Fo… constructive int…

**No matter what is the sign of the deviation of the Higgs self-coupling one process is always enhanced**

# Self-coupling at $e^+e^-$ with double Higgs

LC-REP-2013-003




**Sensitivity factor = 0.5 w/o additional diagrams**

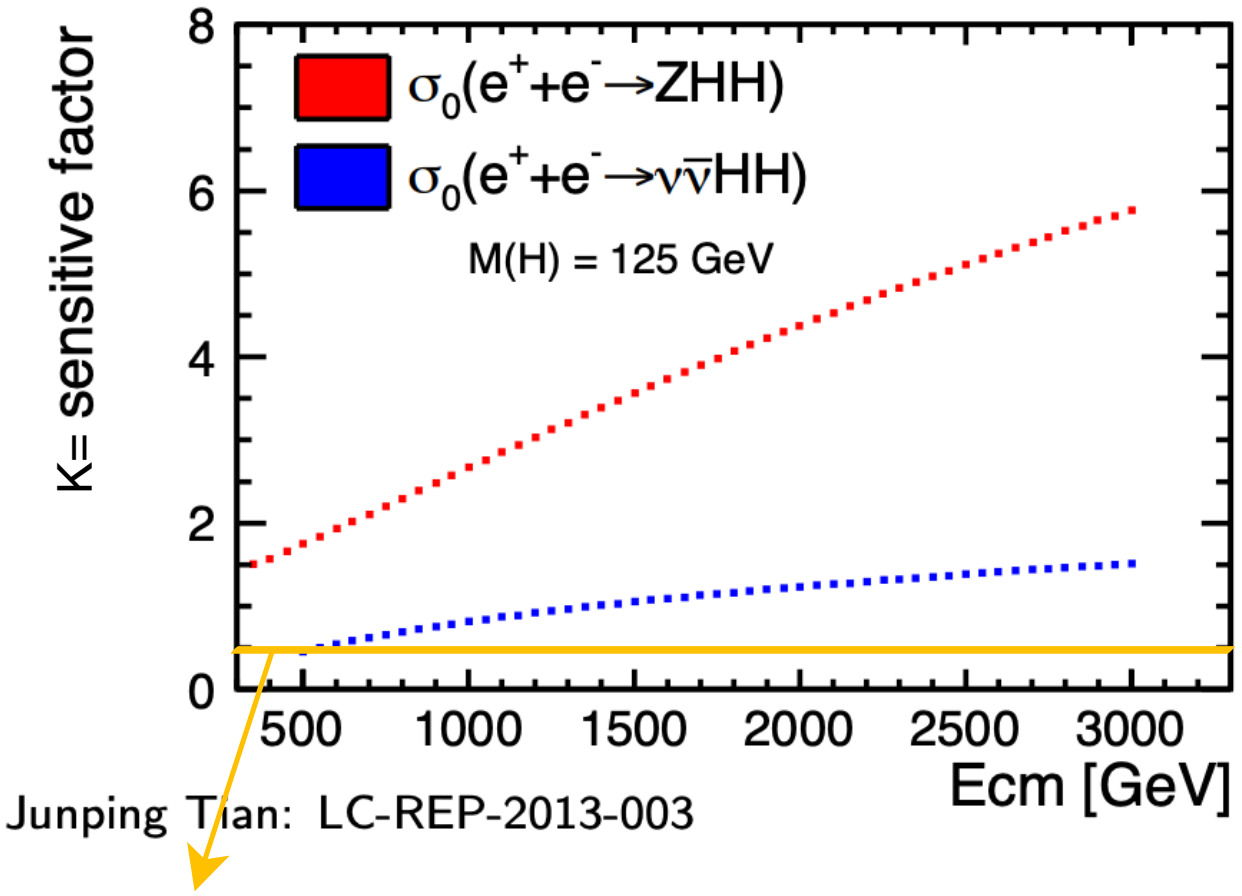
$$\sigma(\lambda) = a\lambda^2 + b\lambda + c$$

- **a** Higgs self-coupling diagram
- **c** irreducible diagrams
- **b** interference between them

$$\frac{\delta\lambda}{\lambda} = \mathrm{K} \cdot \frac{\delta\sigma}{\sigma}$$

# Self-coupling at $e^+e^-$ with double Higgs

LC-REP-2013-003




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$$\sigma(\lambda) = a\lambda^2 + b\lambda + c$$

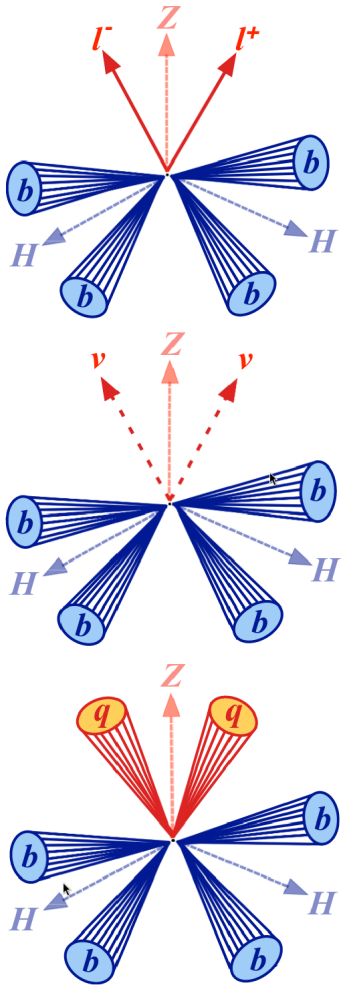
- **a** Higgs self-coupling diagram
- **c** irreducible diagrams
- **b** interference between them

Effect for $\delta\sigma/\sigma \sim 10\%$

| | **500 GeV ZHH** | **1 TeV WBF** |
|---|---|---|
| K | 1.64 | 0.76 |
| $\delta\lambda/\lambda$ | 16.4% | 7.6% |

# Updating 2014 ZHH Analysis

Thesis-2016-Durig



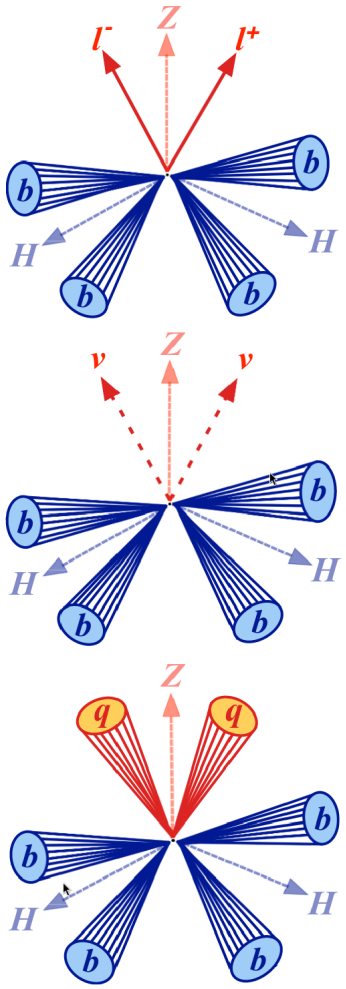

- Extensive projections for 4/ab ILC 500 based full Geant4 based simulations of the ILD concept (DBD ’13, IDR ’20)

- ***HH → 4b (Z → ee/μμ/νν/qq)***
  - inclusive approach i.e. HH → 4b + non-4b
  - specific 4f+6f+8f backgrounds
  - likelihood ratio
- ***HH → bbWW improves by 20%***

- ***Combined sensitivity :***
  - $\Delta\sigma^{ZHH}/\sigma^{ZHH}$= 16.8 %
  - $\Delta\lambda_{SM}/\lambda_{SM}$ = 26.6%

# Updating 2014 ZHH Analysis

Thesis-2016-Durig




- Extensive projections for 4/ab ILC 500 based full Geant4 based simulations of the ILD concept (DBD '13, IDR '20)

- ***HH → 4b (Z → ee/μμ/νν/qq)***
  - inclusive approach i.e. HH → 4b + non-4b
  - specific 4f+6f+8f backgrounds
  - likelihood ratio
- ***HH → bbWW improves by 20%***

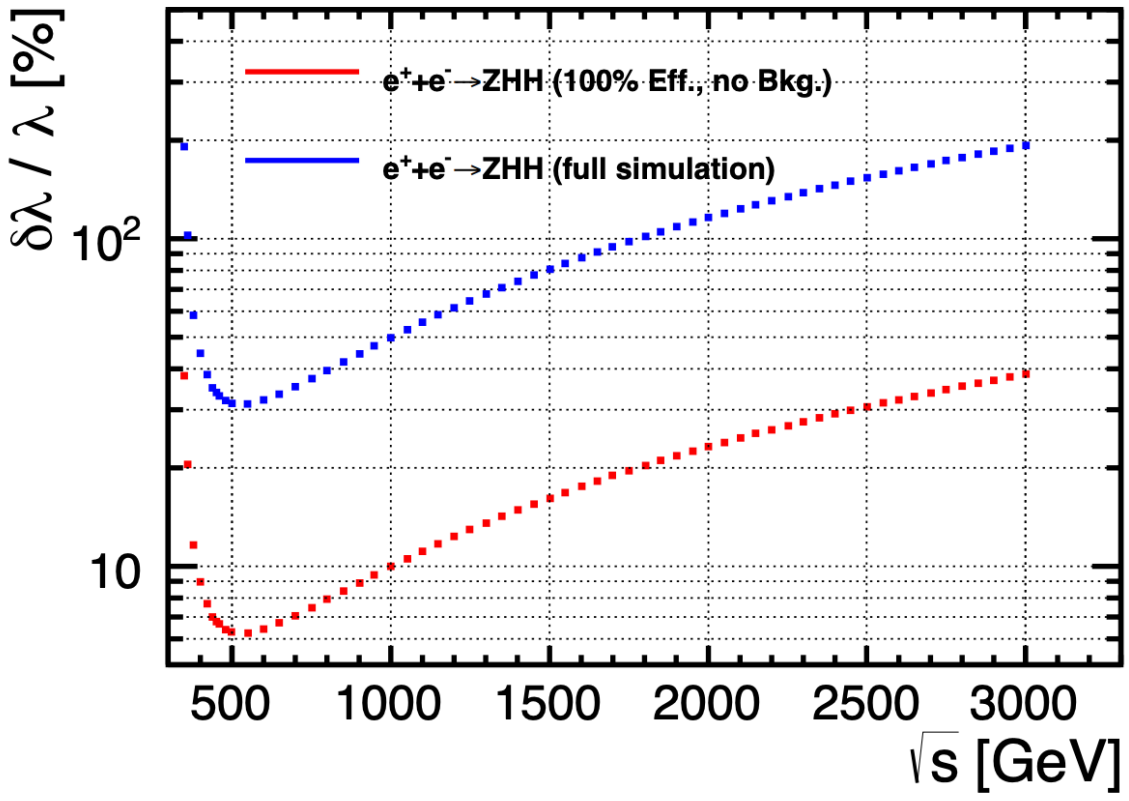
- ***Combined sensitivity :***
  - $\Delta\sigma^{ZHH}/\sigma^{ZHH}$= 16.8 %
  - $\Delta\lambda_{SM}/\lambda_{SM}$ = 26.6%

**same as latest HL-LHC projections…**
**But ML improvements not included yet**

# Towards improved ZHH projections

Thesis-2016-Durig

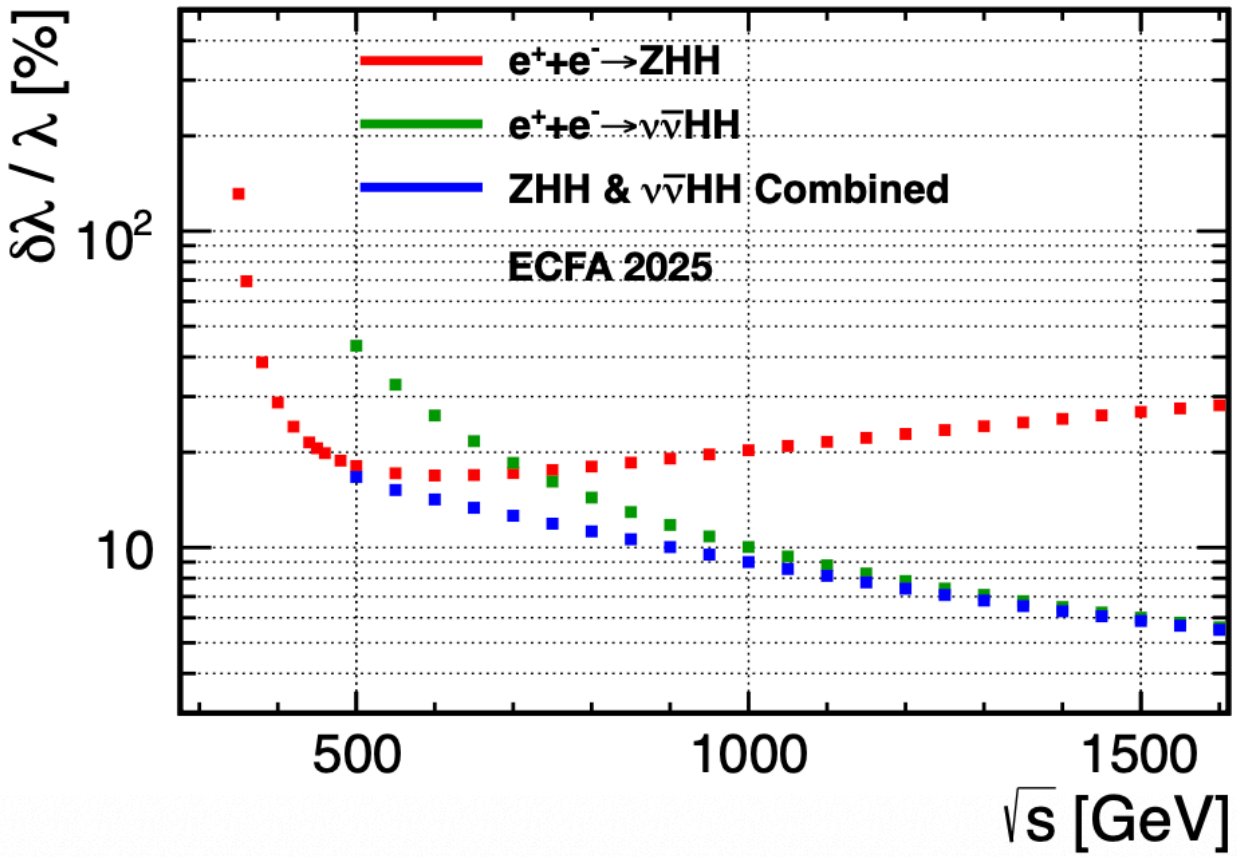
Evaluate dependency as a function of CM and further analysis improvements




- ✓**Z→ττ**: +8% improvement expected
- +10% with all **other HH channels** (+30% signal)
- ✓**Flavor tagging**: +30% improvement in 4b final state
- ✓Improved kinematic reconstruction for better ZZH/ZHH separation
  - ✓neutrino energy corrections for semi-leptonic b-decays
  - including matrix element ratios in selection
- better jet clustering: “perfect” jet clustering +40%
- better removal of $\gamma\gamma \rightarrow had$ +15%

# ECM dependency

ILD-note 2509.14148v1




**500 GeV → 550 GeV**

- increases $\sigma_{ZHH}$ by **16%**
- increases $\sigma_{WBF}$ by~ 2x

**L = 4/ab →8/ab & |P(e–,e+)| = (80%,30%) →(80%,60%)**

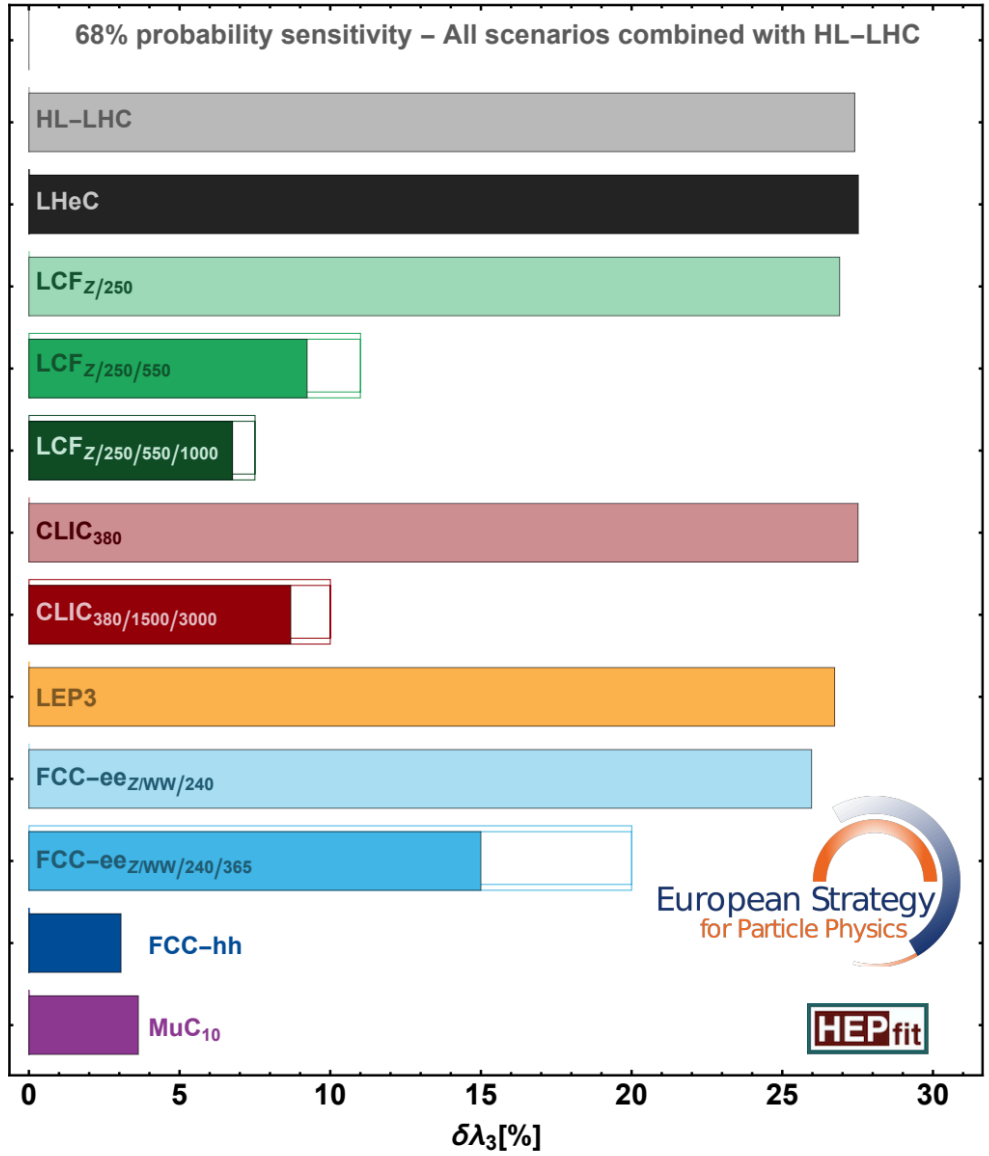
- P(e+) = 30%→60% **~ 10% higher luminosity**

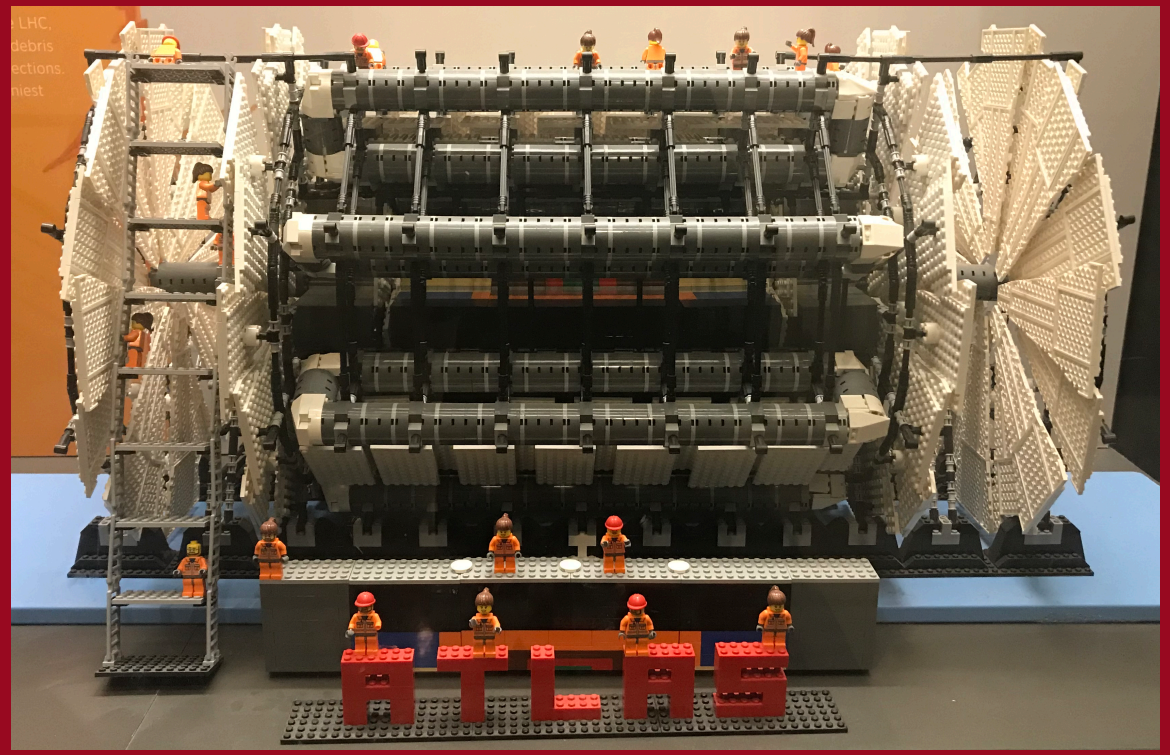
Further improvements with run at 1 TeV (5-10%)

Uncertainties of ~11% for 8/ab at 550 GeV could be achieved at LC from direct measurements.

- Collider physics is essential to explore the property of the Higgs Boson and EWSB
  - Higgs plays a central element for the **future colliders**
    - We want to expand our understanding of Higgs properties far beyond HL-LHC sensitivity reach
- ***Quantitative*** improvement and ***Qualitatively*** new information available to us to test physics beyond the ~~Higgs~~ SM
- **Know-how developed at LHC is key to really assess potential of future facilities and inform both machine and detector design**
  - Cost/sensitivity optimization

[ESPPU Physics Briefing Book]

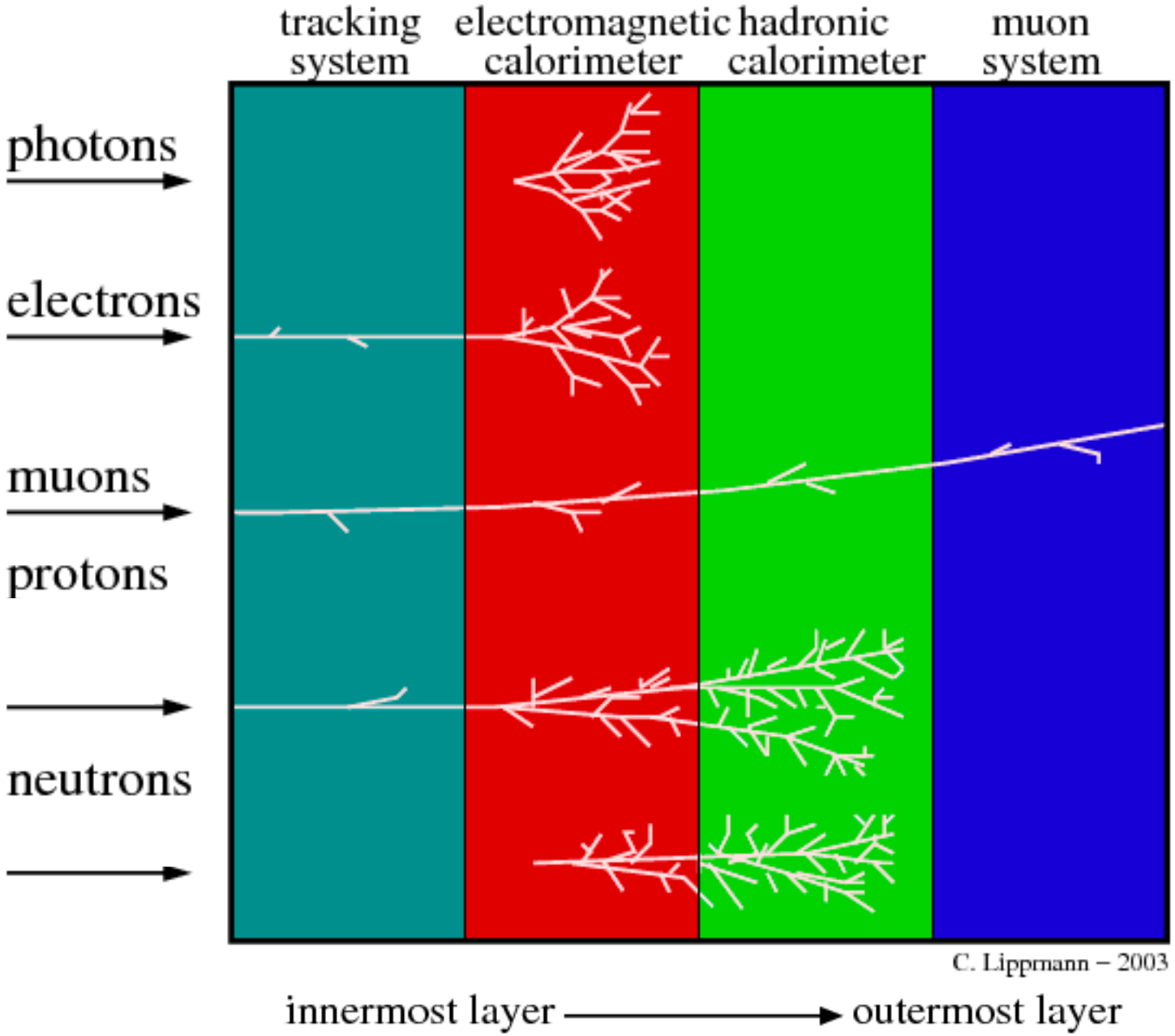







*thank you!*

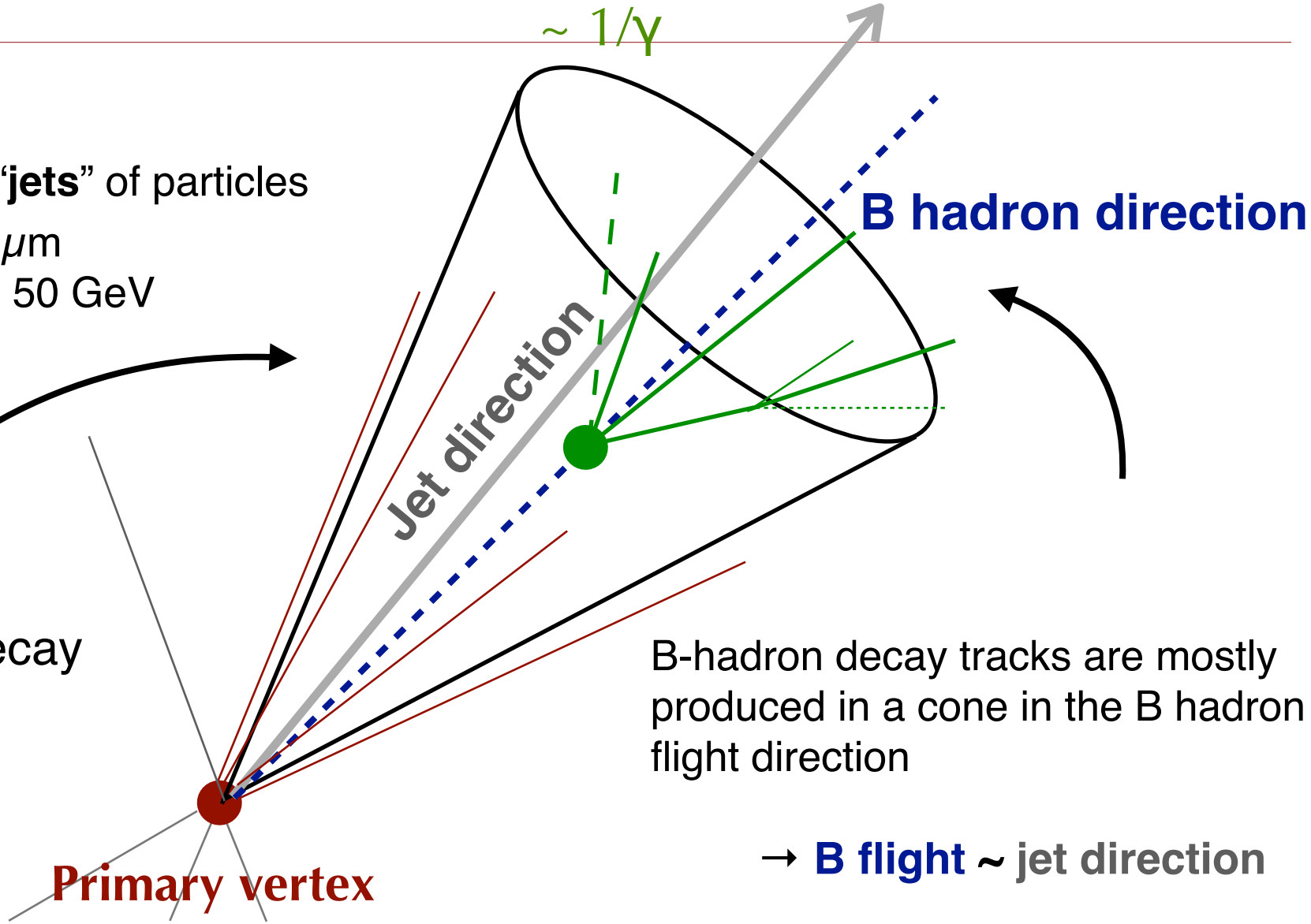
# From the detector to particle images



# b tagging

b quarks hadronize into "**jets**" of particles

- B hadron cτ~ 500 $\mu$m
  → βγcτ ~ 5mm @ 50 GeV




Reconstruct **secondary vertex** from B hadron decay

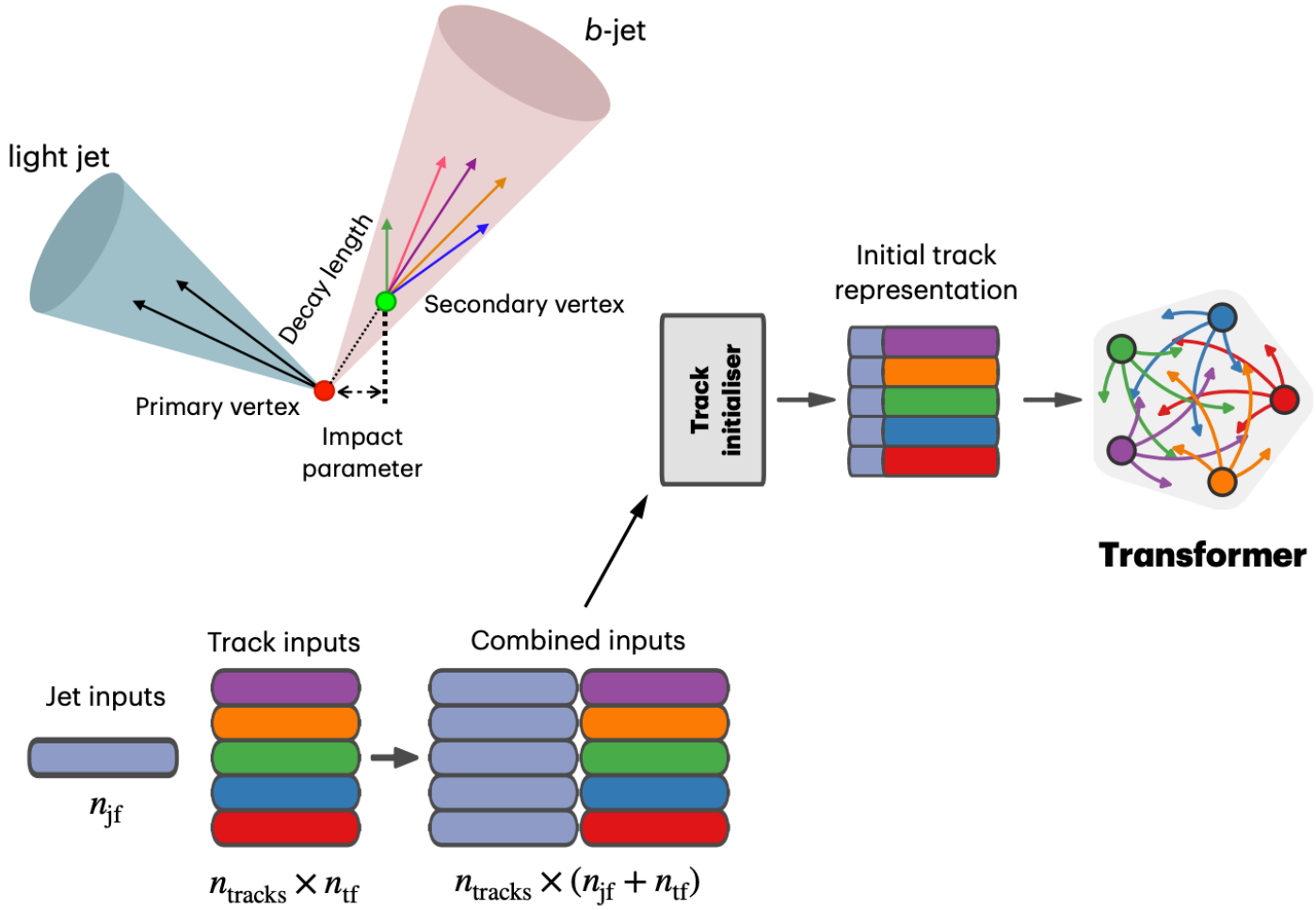
B-hadron decay tracks are mostly produced in a cone in the B hadron flight direction

→ **B flight ~ jet direction**

# Incredible progress in flavor tagging

ATLAS-FTAG-23-05
ATLAS-FTAG-23-01

## Low level algorithms replaced by complex models

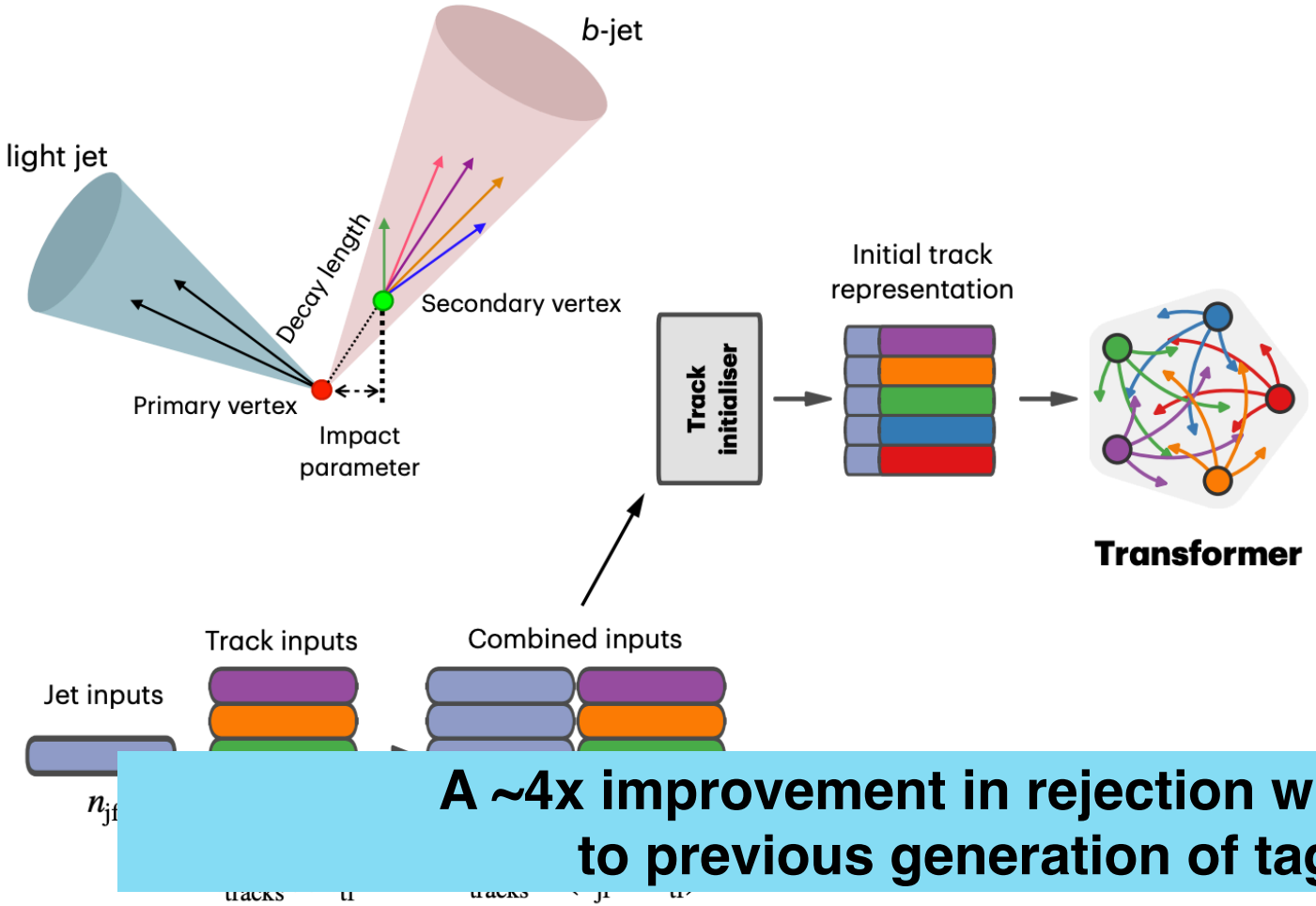



- In Run 3 ATLAS uses a single transformer with low-level input
- It directly takes tracks variables and jet kinematics as input
  - **looser track selection**
  - auxiliary tasks replace low-level taggers
  - can adapt better to other use-cases
    (c-jet, bb-jets)

# Incredible progress in flavor tagging

ATLAS-FTAG-23-05
ATLAS-FTAG-23-01

## Low level algorithms replaced by complex models



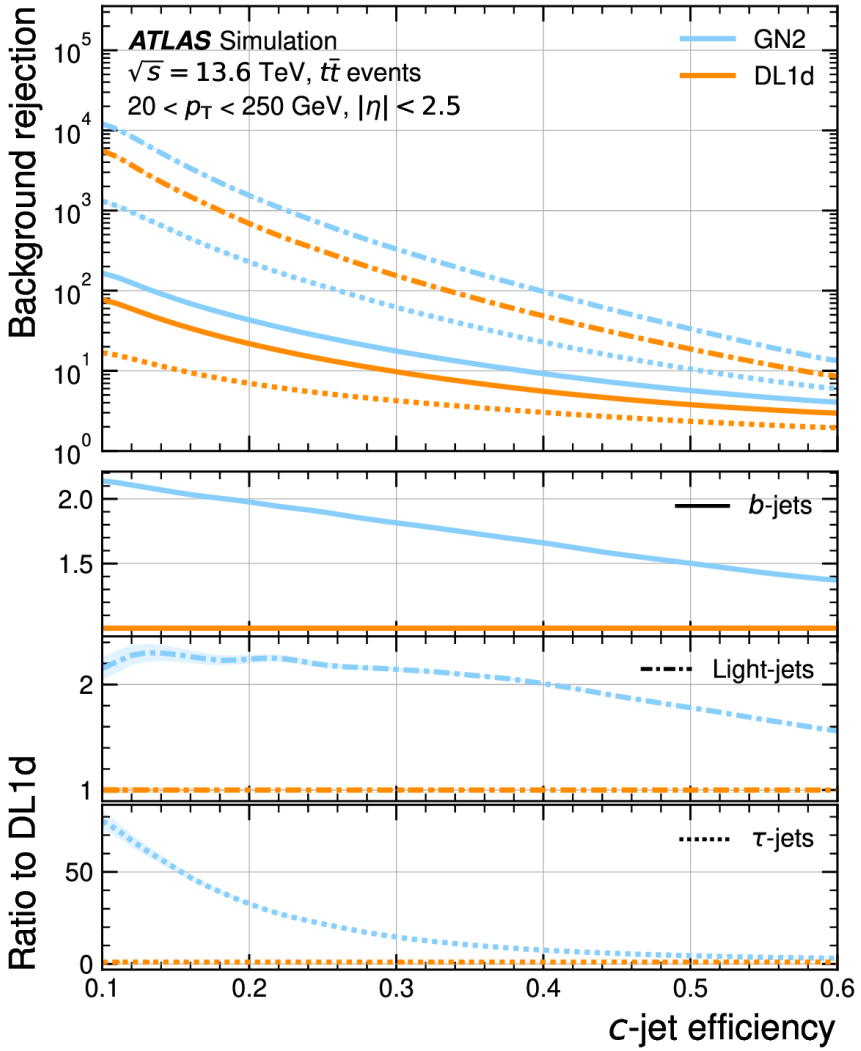

- In Run 3 ATLAS uses a single transformer with low-level input
- It directly takes tracks variables and jet kinematics as input
  - **looser track selection**
  - auxiliary tasks replace low-level taggers
  - can adapt better to other use-cases
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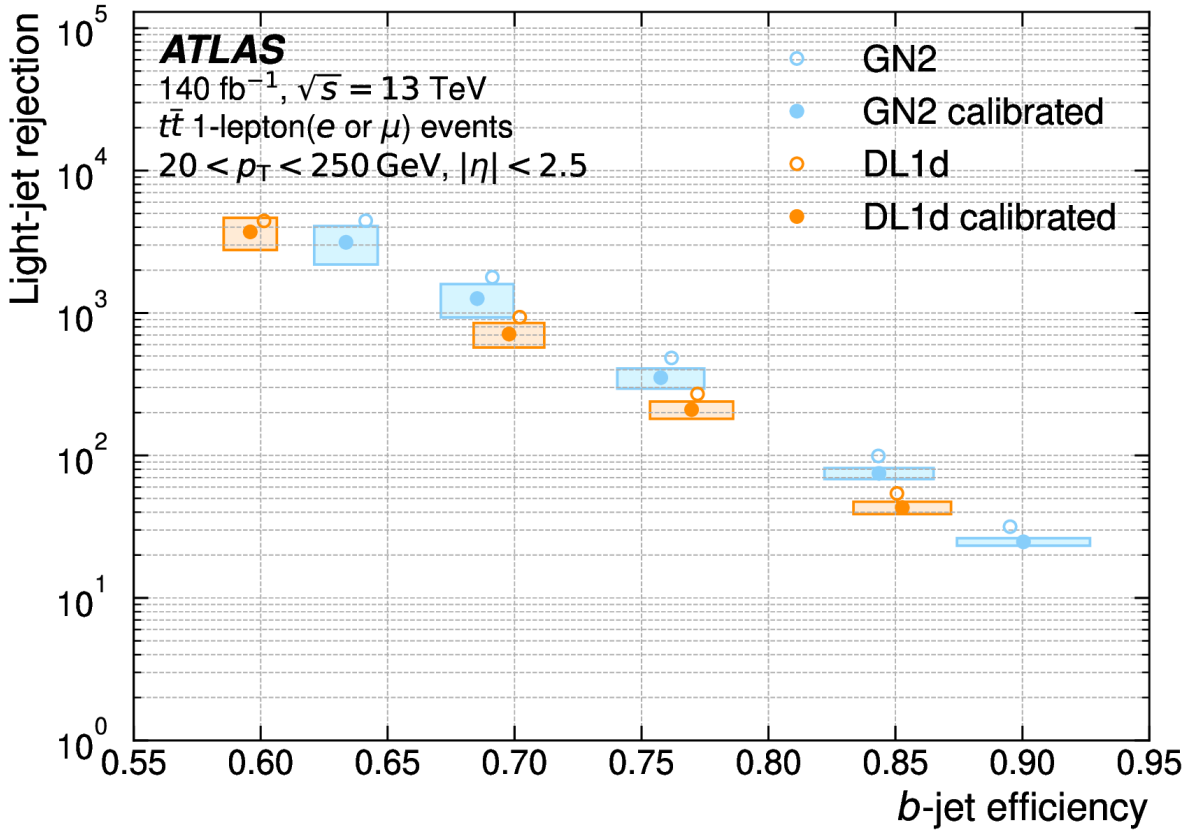
**A ~4x improvement in rejection with respect to previous generation of taggers**

# The ultimate b-tagging algorithm

ATLAS-FTAG-23-05

## Good agreement between data and simulation




- Excellent b-jets identification performance:
  85% efficiency at 1% q/g (20% c) mistag probability
- Good agreement between data and simulation

# Evolution of algorithms from Run 1 to Run 3

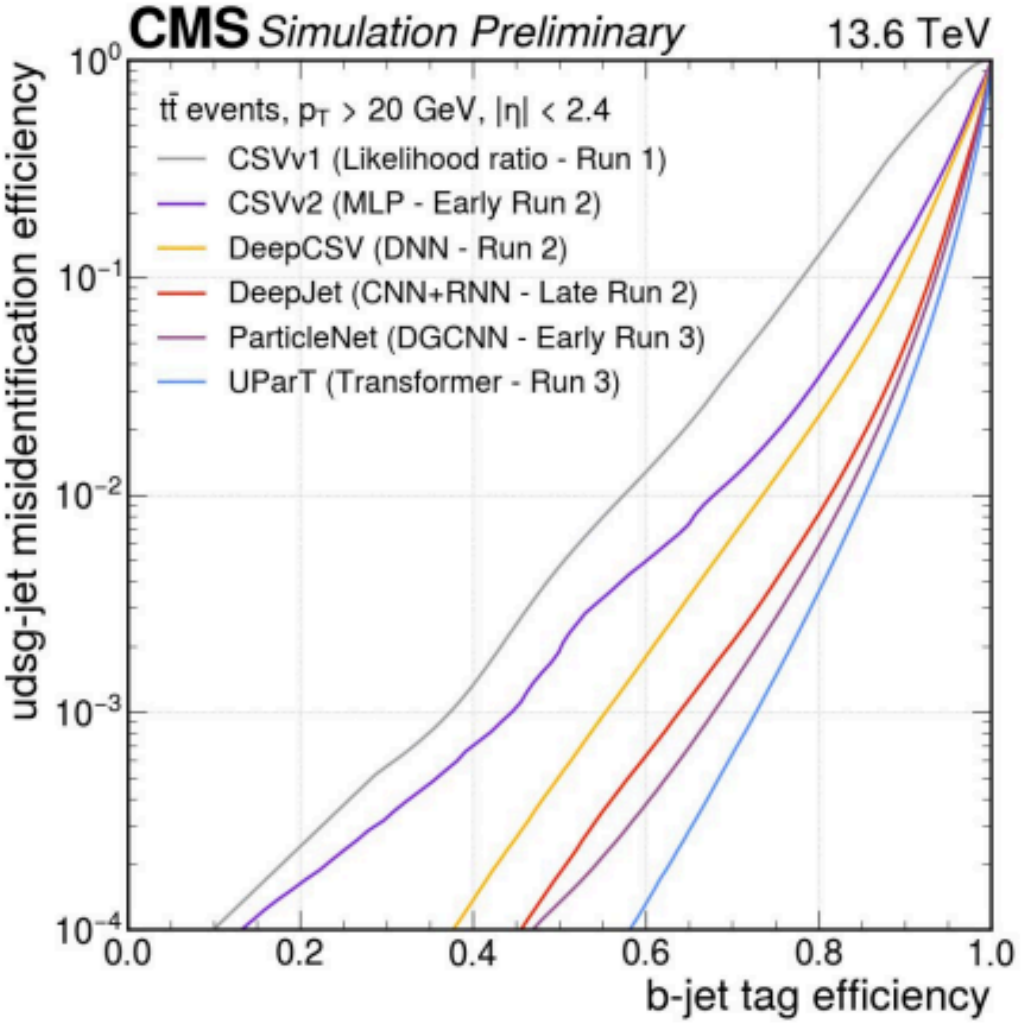



**Figure 11: Evolution of the b-tagging performance for identification algorithms used in CMS from Run 1 to Run 3 [4,5,6,7,18,19]. The increase in object performance follows the progression in machine learning. The underlying network architecture for each algorithm is given in the brackets, together with the era when the algorithm was first used in physics analyses. The figure shows the approximate performance and has to be considered illustrative.**

# Evolution of algorithms from Run 1 to Run 3

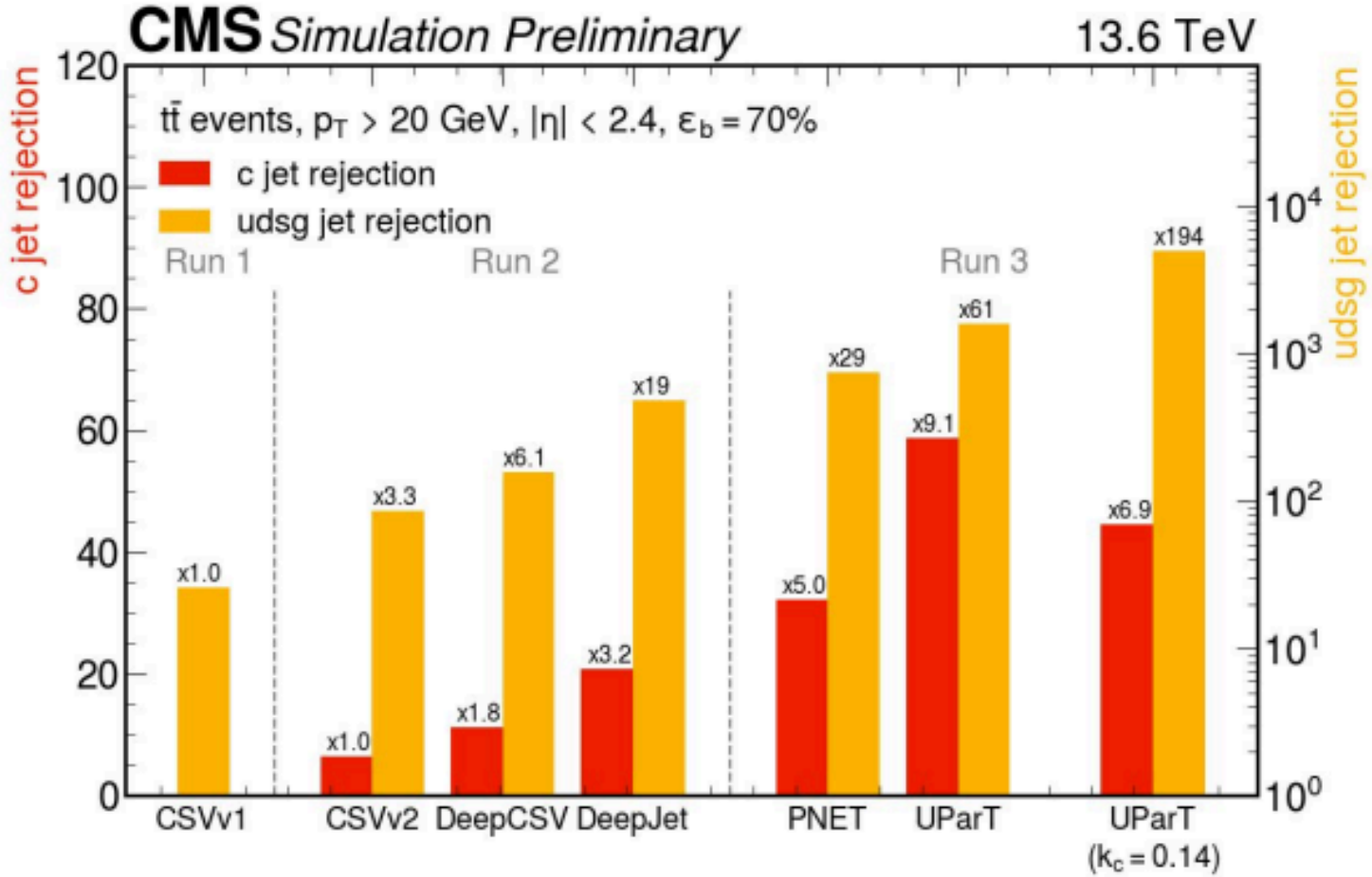



**Figure 13: Evolution of the light- (udsg, yellow bars) and c-jet (red bars) rejection for a fixed b-jet identification efficiency of 70% for taggers from Run 1 to Run 3. The BvsAll discriminator is used to derive all numbers but the last one, where the weighted BvsAll discriminator with a factor of $k_c$ = 0.14 is used, yielding a good trade-off between light- and c-jet rejection.**

# Theory predictions for HH

LHCHWG-2026-010
JHEP 06 (2026) 005

## ggF HH at 13.6 TeV

Normalization in current analyses

34.1 fb +6.5% / –23.2% total

NNLO (FTapprox): exact NLO with full $m_t$
+ mass-improved NNLO in the heavy-top limit
NLO + parton shower signal samples

## 2026 LHCHWG recommendation

33.62 fb +7.26% / –21.04% theory
±2.43% PDF + $\alpha_s$

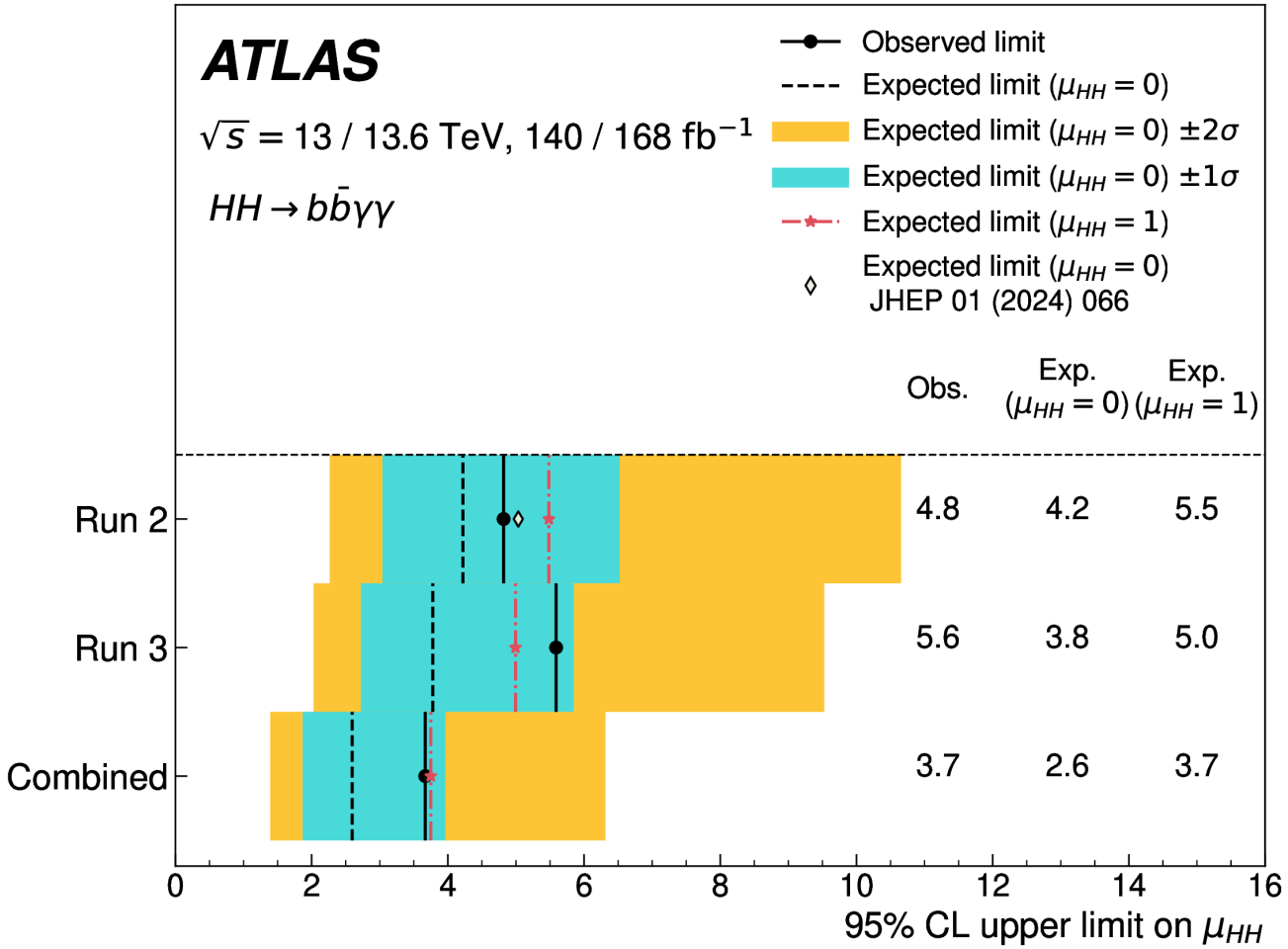
N³LO+N³LL QCD and NLO EW factors
on NNLO (FTapprox), with PDF4LHC21

Differential N³LO QCD in the heavy-top limit
+ exact NLO $m_t$ dependence
NNLO + parton shower with $m_t$ effects (GENEVA)

**The top-mass scheme remains the dominant ggF theory uncertainty**

# HH to bb̄γγ - Run 2 + Run 3

ATLAS PLB 876 (2026) 140280




- 140 fb$^{-1}$ at 13 TeV + 168 fb$^{-1}$ at 13.6 TeV

  $\mu_{HH}$ = 0.9 (+1.4 / −1.1)

- Statistical uncertainty: +1.3 / −1.0

  Systematic uncertainty: ±0.5

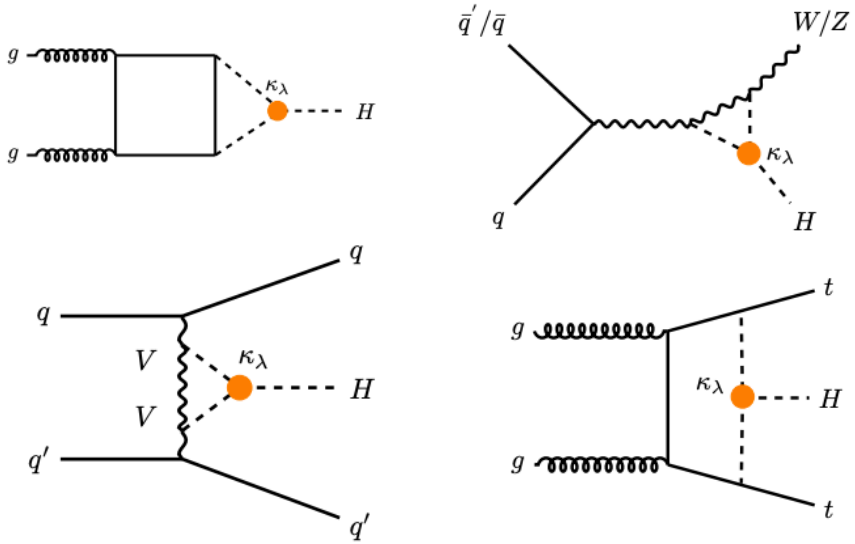
- Run 2 and Run 3 results are compatible

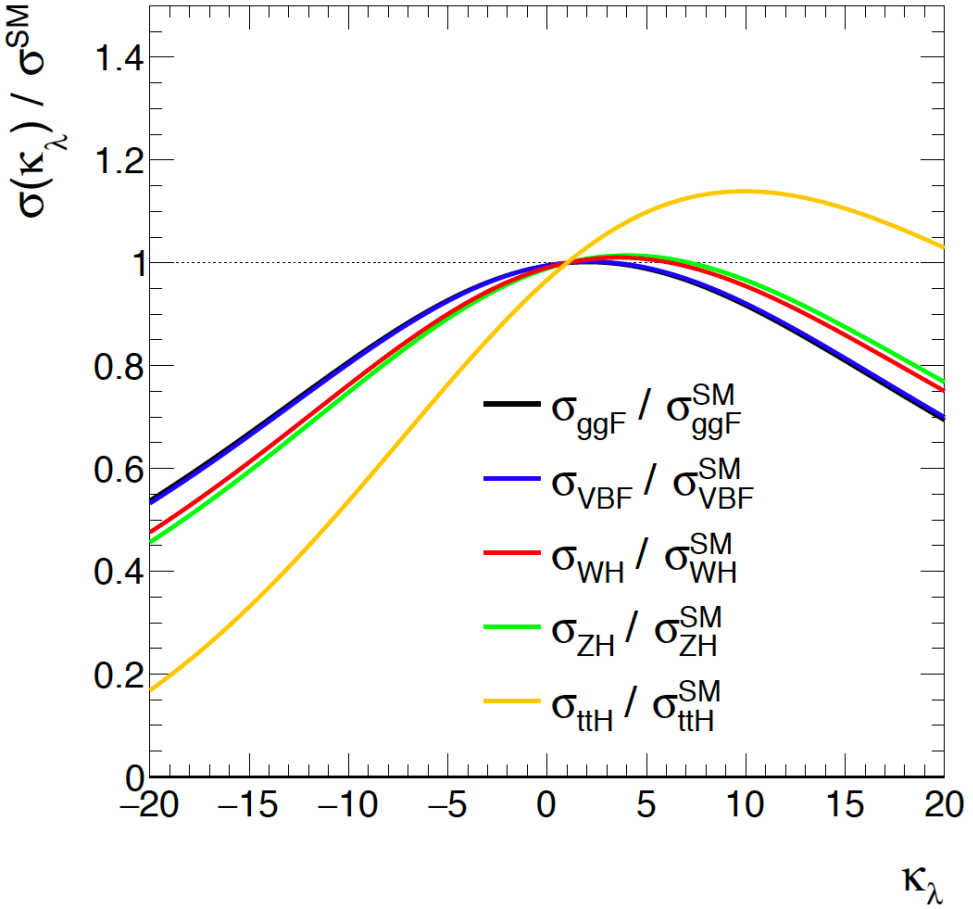
# Single Higgs to probe $\kappa_\lambda$

JHEP 12 (2016) 080,
Eur. Phys. J. C77 (2017) 887

Single Higgs processes are sensitive to λ via NLO EW $\kappa_\lambda$-dependent corrections to

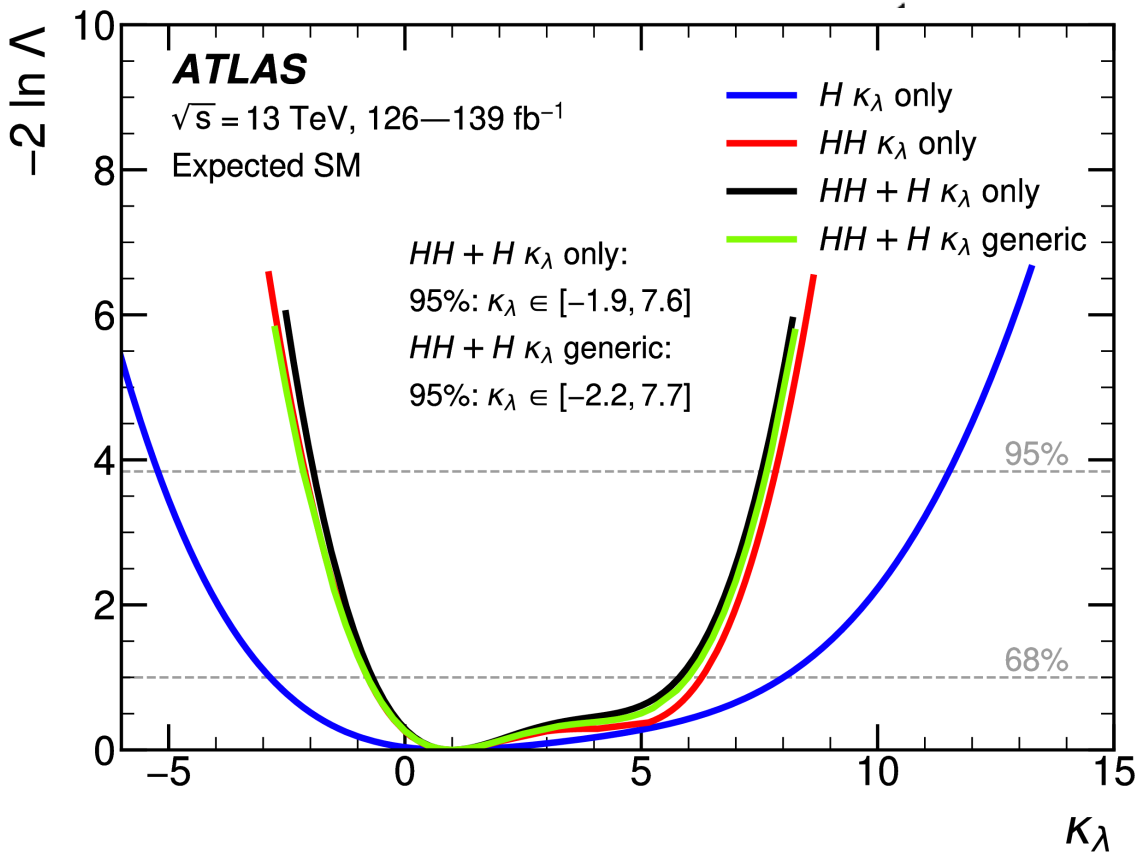
- cross-sections (**ttH, ggF, VH, VBF** )
- Higgs boson decay rates
- kinematic properties of the event (differential distributions)



# First double and single Higgs combination

ATLAS-Phys. Lett. B 843 (2023) 137745
CMS-Phys. Lett. B 861 (2025) 139210

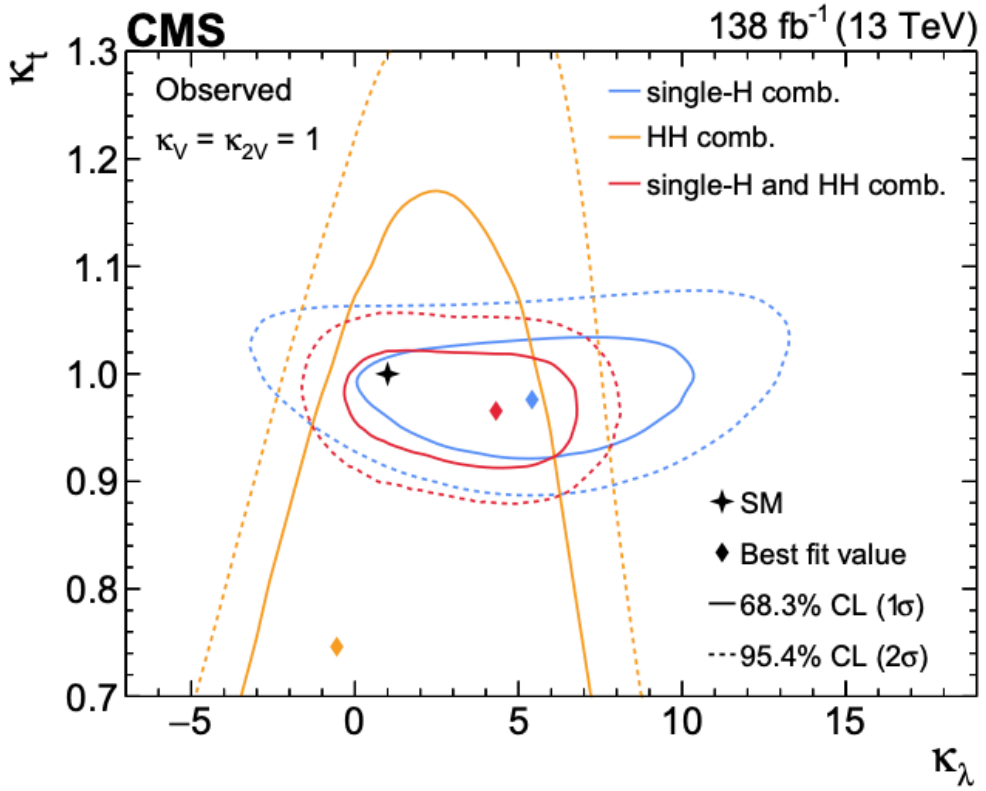



**First constraints** derived from 13 TeV
single H + double H measurements with 126-139/fb

| Combination assumption | Obs. 95% CL | Exp. 95% CL | Obs. value$^{+1\sigma}_{-1\sigma}$ |
|---|---|---|---|
| $HH$ combination | $-0.6 < \kappa_\lambda < 6.6$ | $-2.1 < \kappa_\lambda < 7.8$ | $\kappa_\lambda = 3.1^{+1.9}_{-2.0}$ |
| Single-$H$ combination | $-4.0 < \kappa_\lambda < 10.3$ | $-5.2 < \kappa_\lambda < 11.5$ | $\kappa_\lambda = 2.5^{+4.6}_{-3.9}$ |
| $HH$+$H$ combination | $-0.4 < \kappa_\lambda < 6.3$ | $-1.9 < \kappa_\lambda < 7.6$ | $\kappa_\lambda = 3.0^{+1.8}_{-1.9}$ |
| $HH$+$H$ combination, $\kappa_t$ floating | $-0.4 < \kappa_\lambda < 6.3$ | $-1.9 < \kappa_\lambda < 7.6$ | $\kappa_\lambda = 3.0^{+1.8}_{-1.9}$ |
| $HH$+$H$ combination, $\kappa_t$, $\kappa_V$, $\kappa_b$, $\kappa_\tau$ floating | $-1.4 < \kappa_\lambda < 6.1$ | $-2.2 < \kappa_\lambda < 7.7$ | $\kappa_\lambda = 2.3^{+2.1}_{-2.0}$ |

ATLAS-Phys. Lett. B 843 (2023) 137745
CMS-Phys. Lett. B 861 (2025) 139210

# First double and single Higgs combination



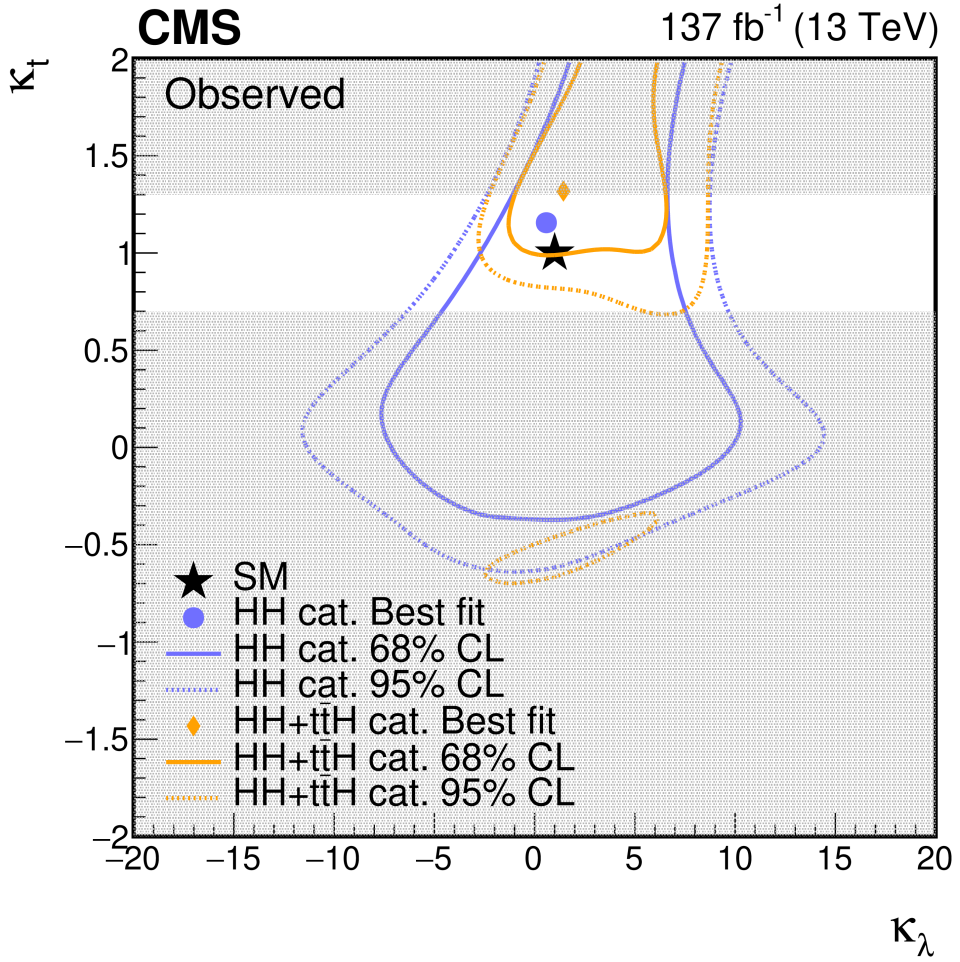

**First constraints** derived from 13 TeV single H + double H measurements with 126-139/fb

*They are compatible to those derived from HH direct searches but an EFT global analysis is needed to properly account for BSM contributions*

# More on the constrains from HH on $\kappa_\lambda$

CMS-JHEP 03 (2021) 257

**It is impossible to extract $\kappa_\lambda$ constraints from HH production without assumptions on $\kappa_t$**



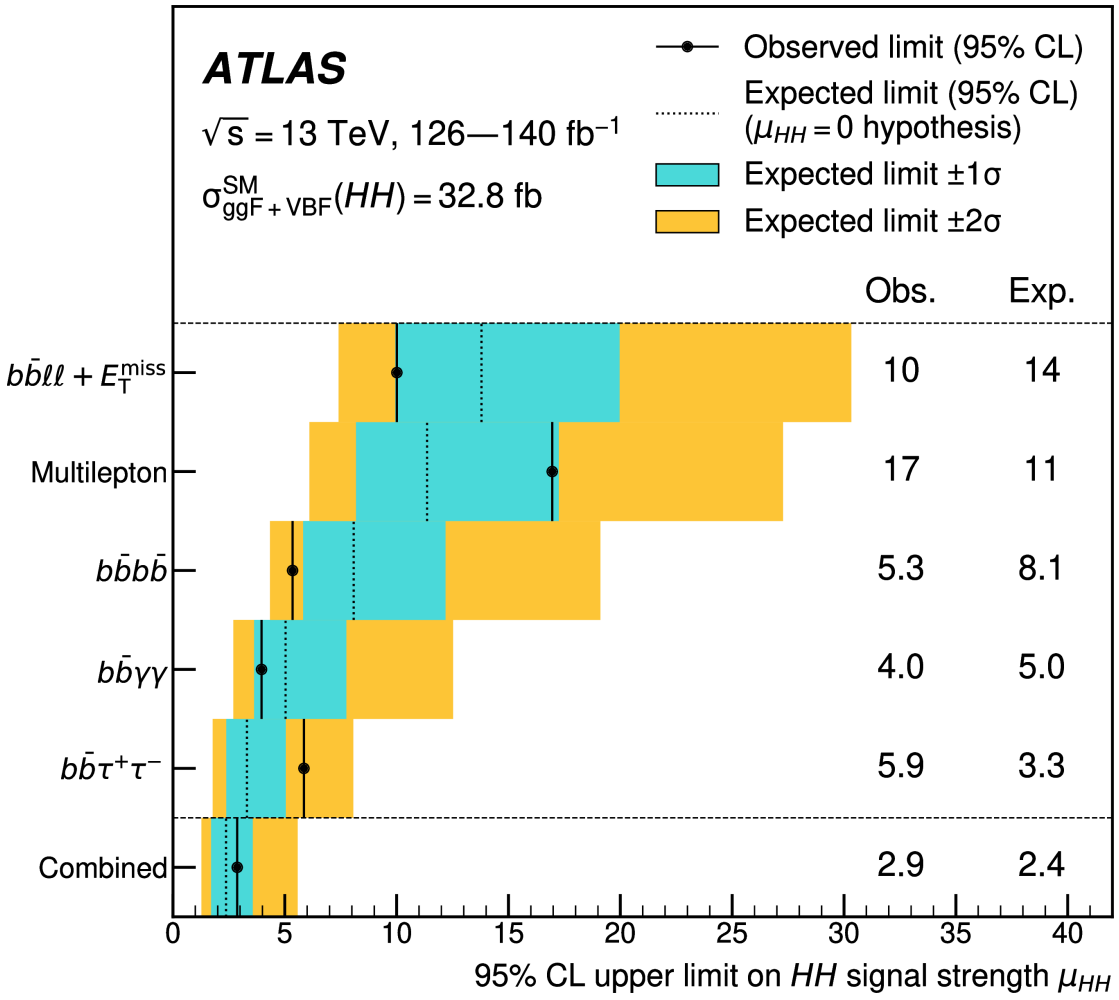

- A simultaneous likelihood scan for $\kappa_\lambda$ and $\kappa_t$ is performed to account for the modifications to
  - production HH and single Higgs cross sections
  - Br(H → $b\bar{b}$) and Br(H → γγ)
- Combination with ttH (lep. & had.) categories improves the constraints on $\kappa_t$

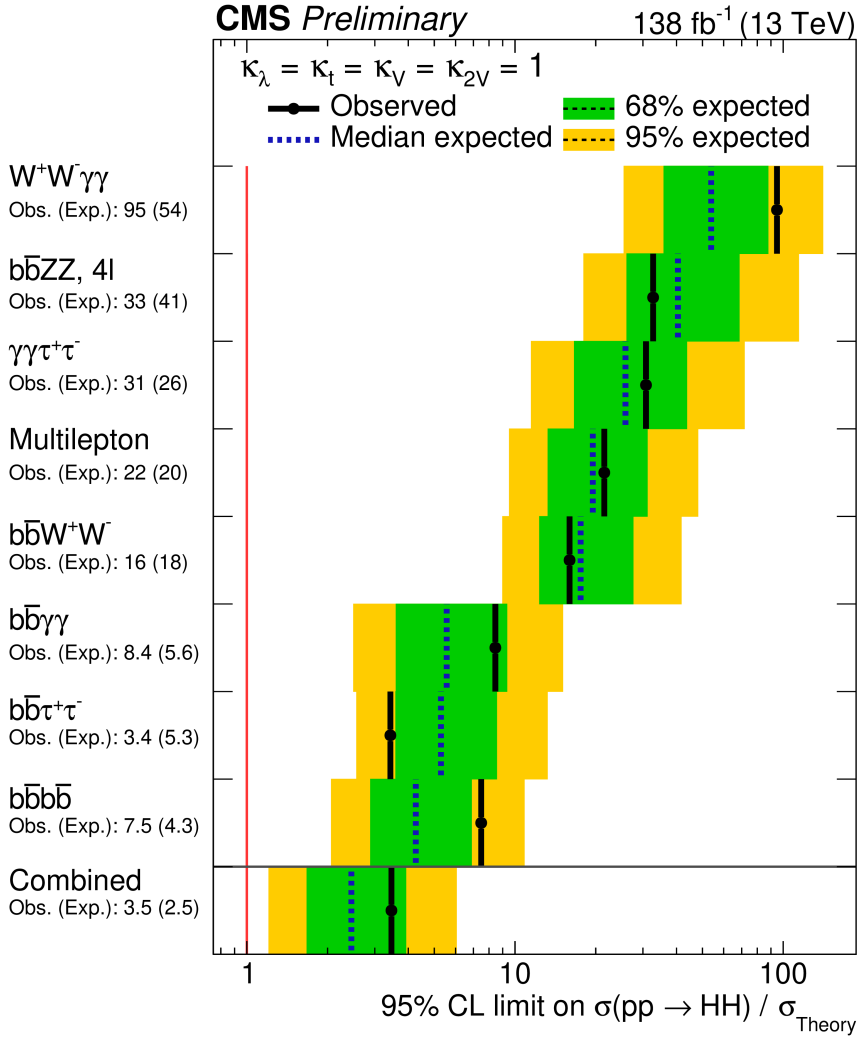
***A combination of single H and HH measurements would provide a more model independent determination of $\kappa_\lambda$***

ATLAS-Phys. Rev. Lett. 133 (2024) 101801
CMS-PAS-HIG-20-011

# Double Higgs Results

## Similar sensitivity from $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ to SM HH production

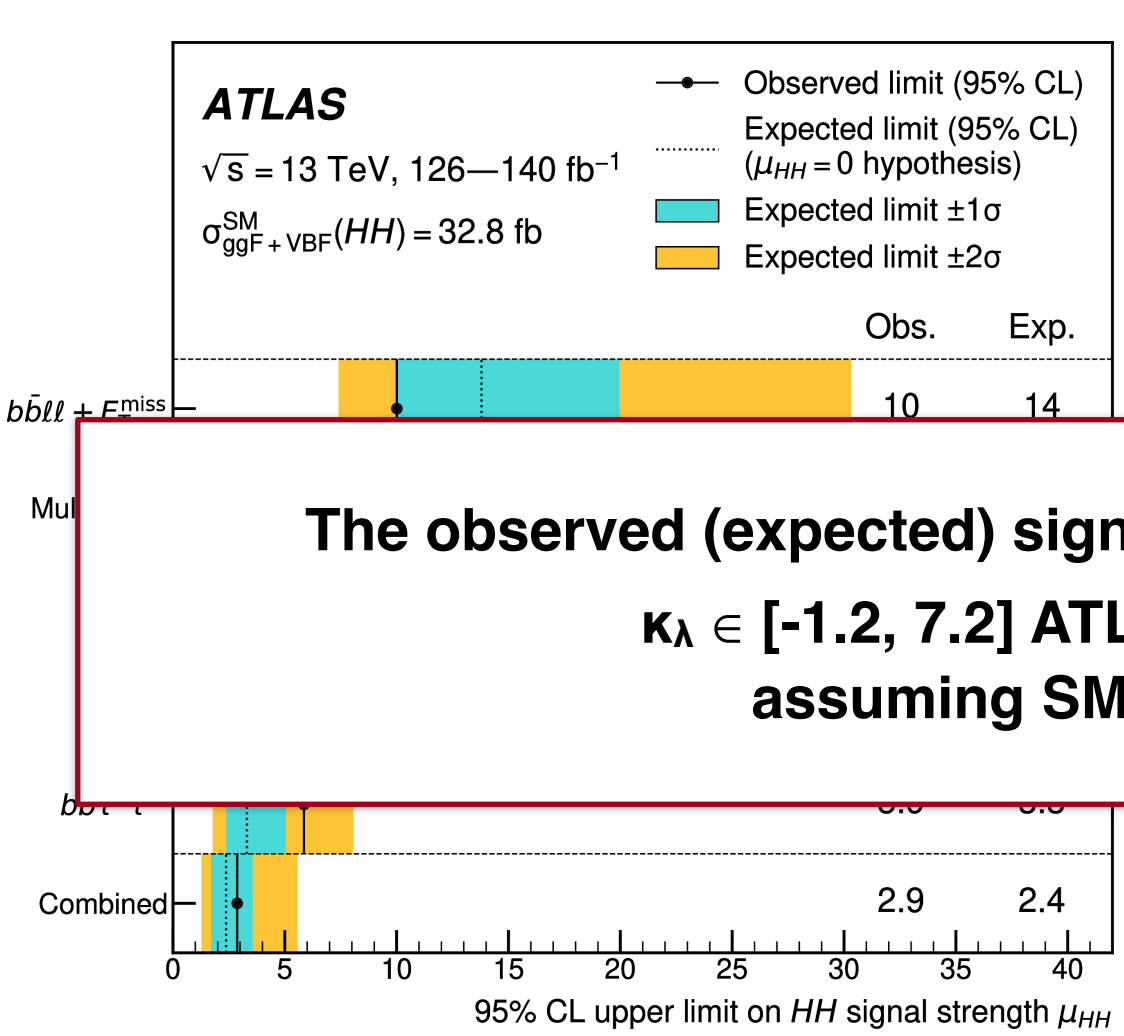


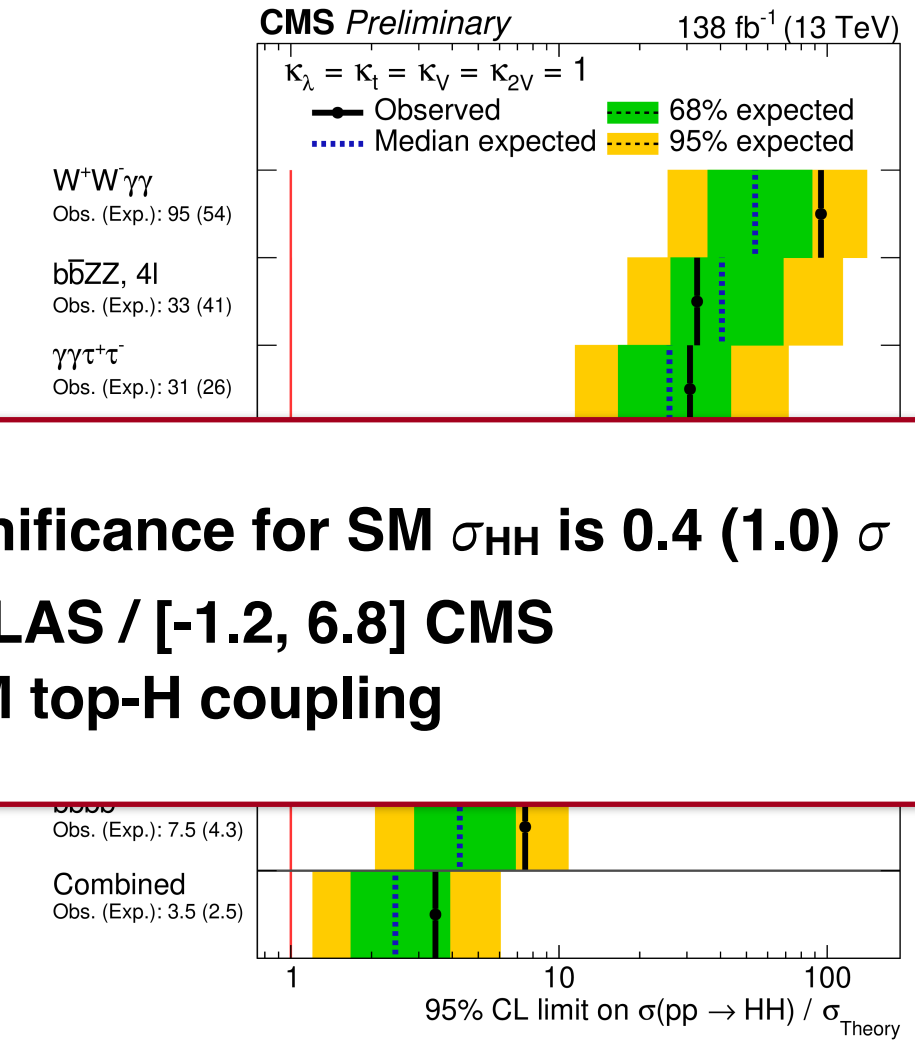



ATLAS-Phys. Rev. Lett. 133 (2024) 101801
CMS-PAS-HIG-20-011

# Double Higgs Results

## Similar sensitivity from $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ to SM HH production



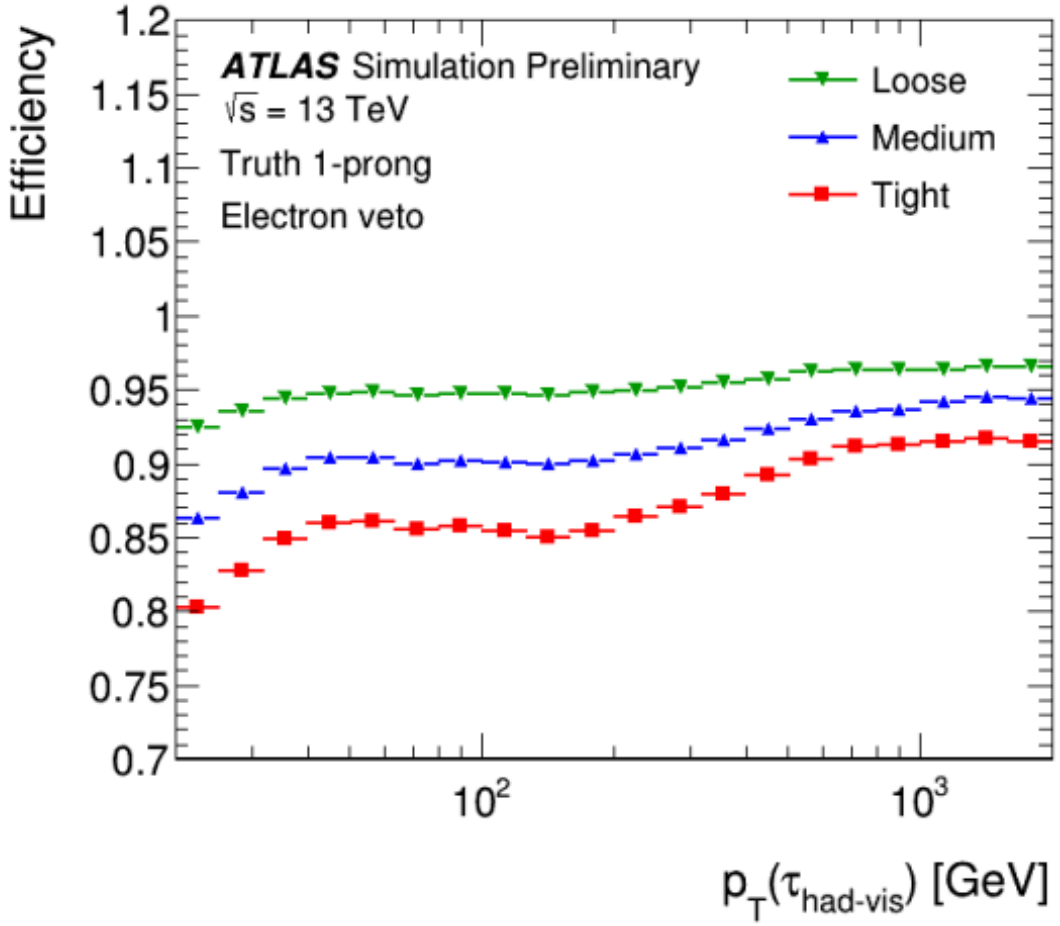




**The observed (expected) significance for SM $\sigma_{HH}$ is 0.4 (1.0) $\sigma$**

**$\kappa_\lambda \in$ [-1.2, 7.2] ATLAS / [-1.2, 6.8] CMS**
**assuming SM top-H coupling**

# HH to $b\bar{b}\tau\tau$ - τ reconstruction

ATLAS arXiv:2607.26879; ATL-PHYS-PUB-2022-044

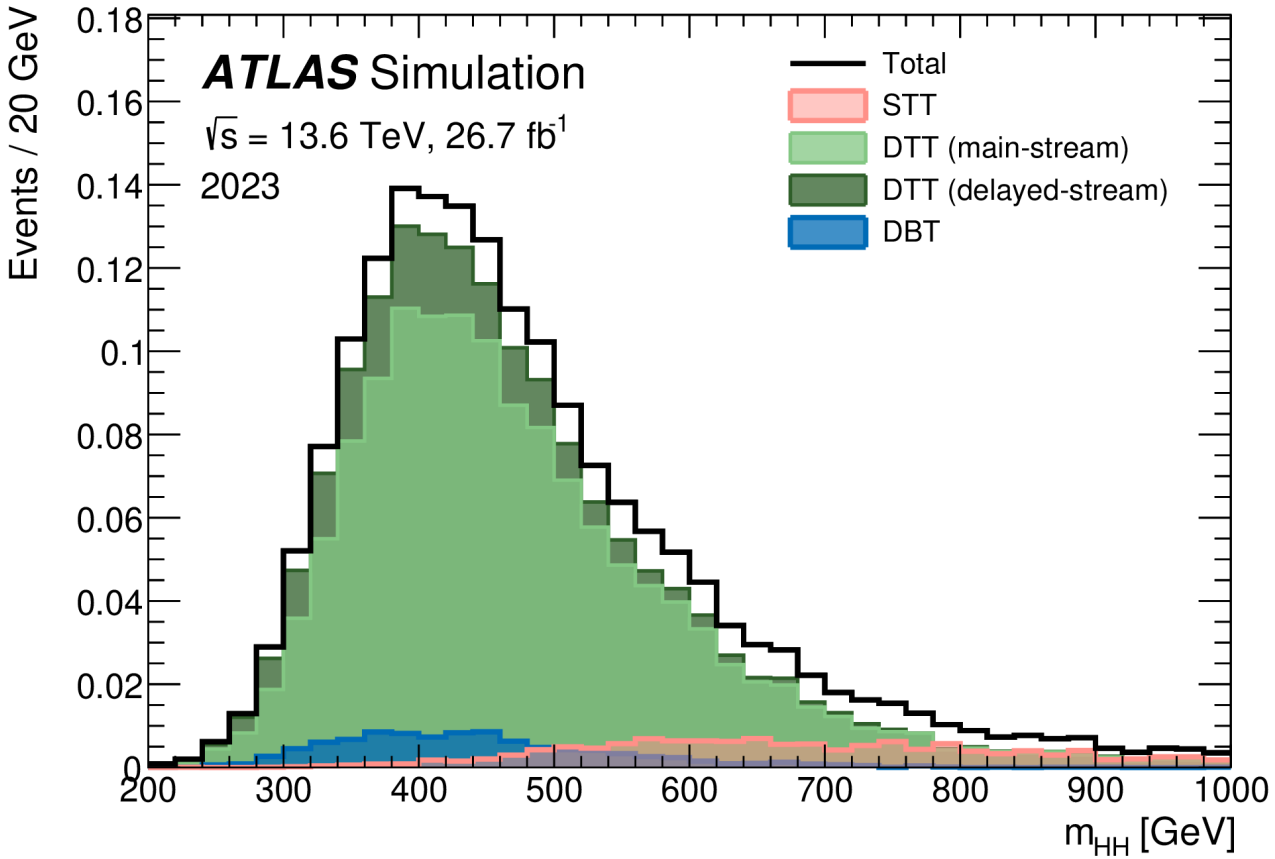


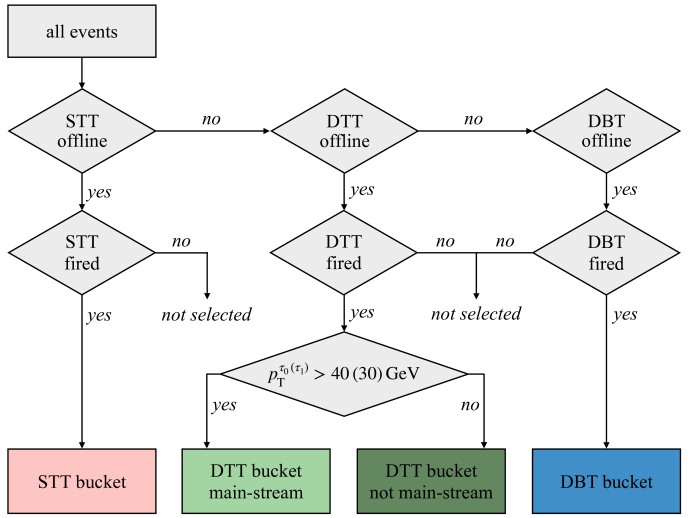

Electron-veto efficiency for one-prong τ candidates

- τhad identification uses charged tracks and calorimeter information
- Recurrent neural networks separate τhad from quark- and gluon-initiated jets
- Leptonic τ decays appear as an electron or muon plus neutrinos
- Fake-τ estimates and identification calibrations remain essential

# HH to $b\bar{b}\tau\tau$ - trigger acceptance

arXiv:2607.26879




**STT offline selection**

$p_T^{\tau_0} > 180$ GeV

(100 or 140 GeV in 2015 and parts of 2016)

**DTT offline selection**

| Nominal | Only DTT with 2 L1 jets fired |
|---|---|
| $p_T^{\tau_0} > 40$ GeV | $p_T^{\tau_0} > 40$ GeV |
| $p_T^{\tau_1} > 30$ GeV | $p_T^{\tau_1} > 30$ GeV |
| $p_T^{j_0} > 70$ GeV | $p_T^{j_0} > 50$ GeV |
| $p_T^{j_1} > 20$ GeV | $p_T^{j_1} > 50$ GeV |

$\Delta R_{\tau\tau} < 2.5$ (from 2017)

(2023 : $p_T^{\tau_0} > 35$ GeV, $p_T^{\tau_1} > 25$ GeV)

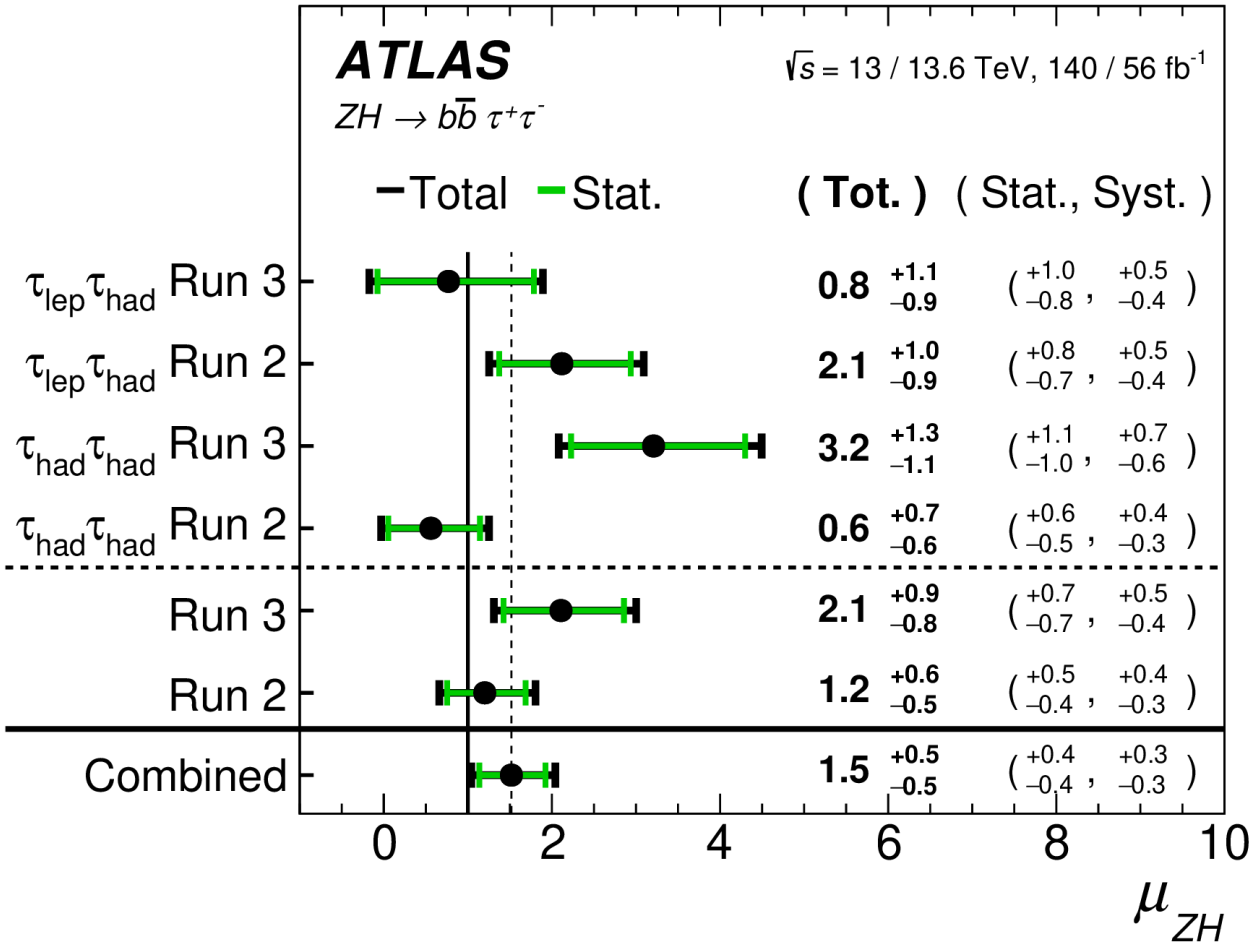
**DBT offline selection**

Ordered $\{p_T^{\tau_0}, p_T^{\tau_1}, p_T^{j_0}, p_T^{j_1}, \ldots, p_T^{j_N}\} > \{85, 60, 50, 25\}$ GeV

32% improvement in acceptance in Run 2

# Validating the $b\bar{b}\tau\tau$ analysis with ZH

arXiv:2607.26879

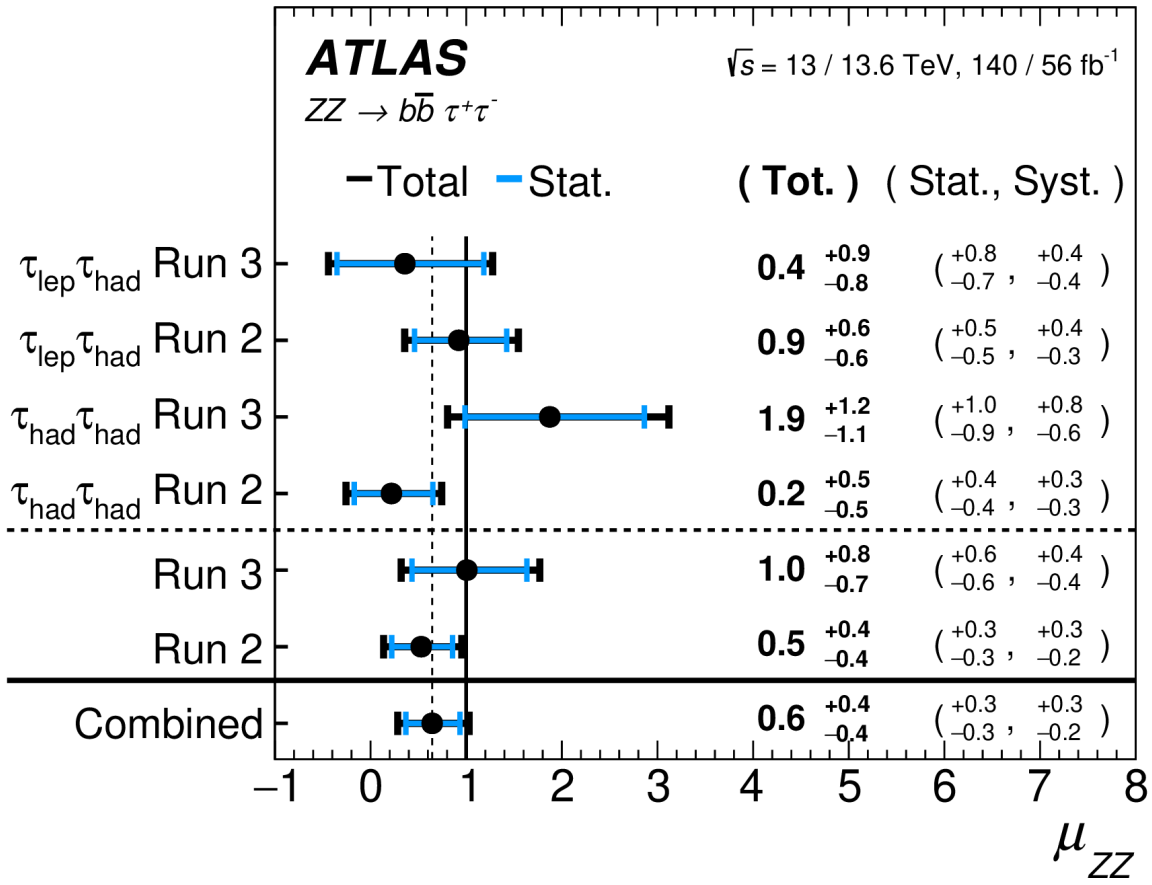



- Same final state and closely related analysis strategy
- Retrain the classifier for ZH and ZZ production
- ZH: 3.5σ observed (2.4σ expected)
- ZZ: 1.8σ observed (2.7σ expected)

**A useful test of reconstruction and background modeling**

# ZZ validation in $b\bar{b}\tau\tau$

ATLAS arXiv:2607.26879



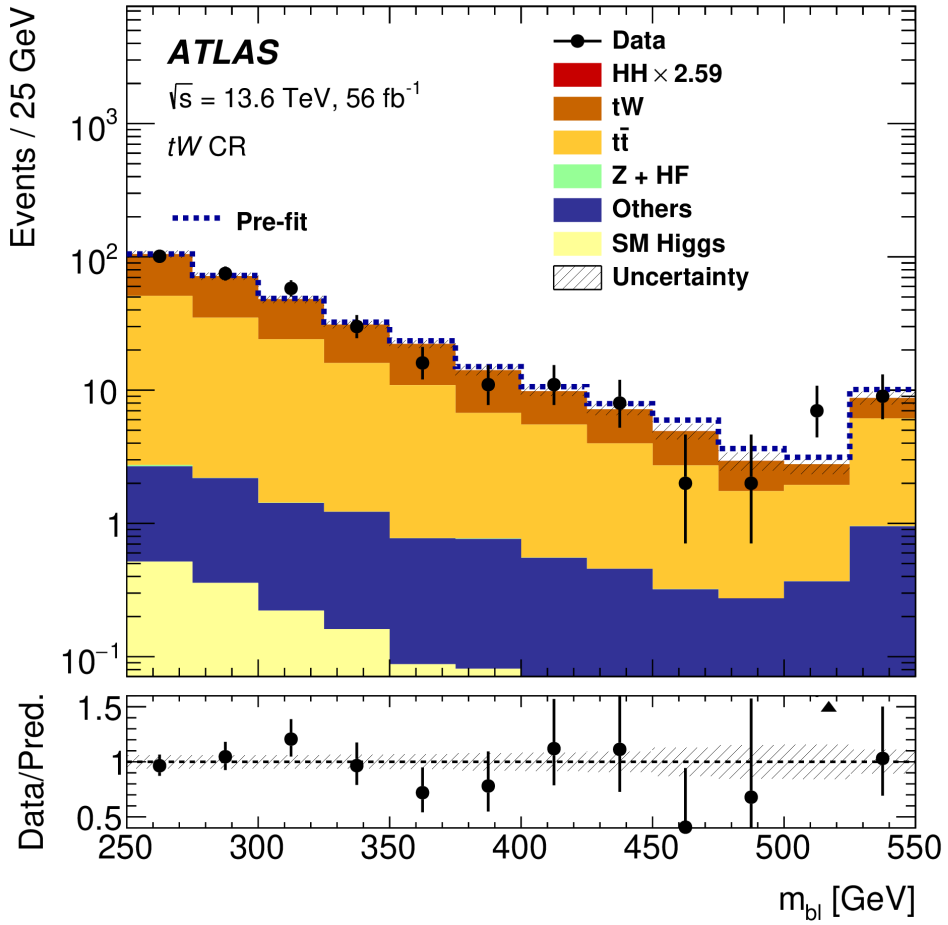

- Retrain the classifier to select ZZ
- Observed significance: 1.8σ

Expected significance: 2.7σ

- Separate run periods and τ channels give compatible results
- The selected data overlap with the HH and ZH fits

# HH to $b\bar{b}\tau\tau$ - tW and $t\bar{t}$ interference

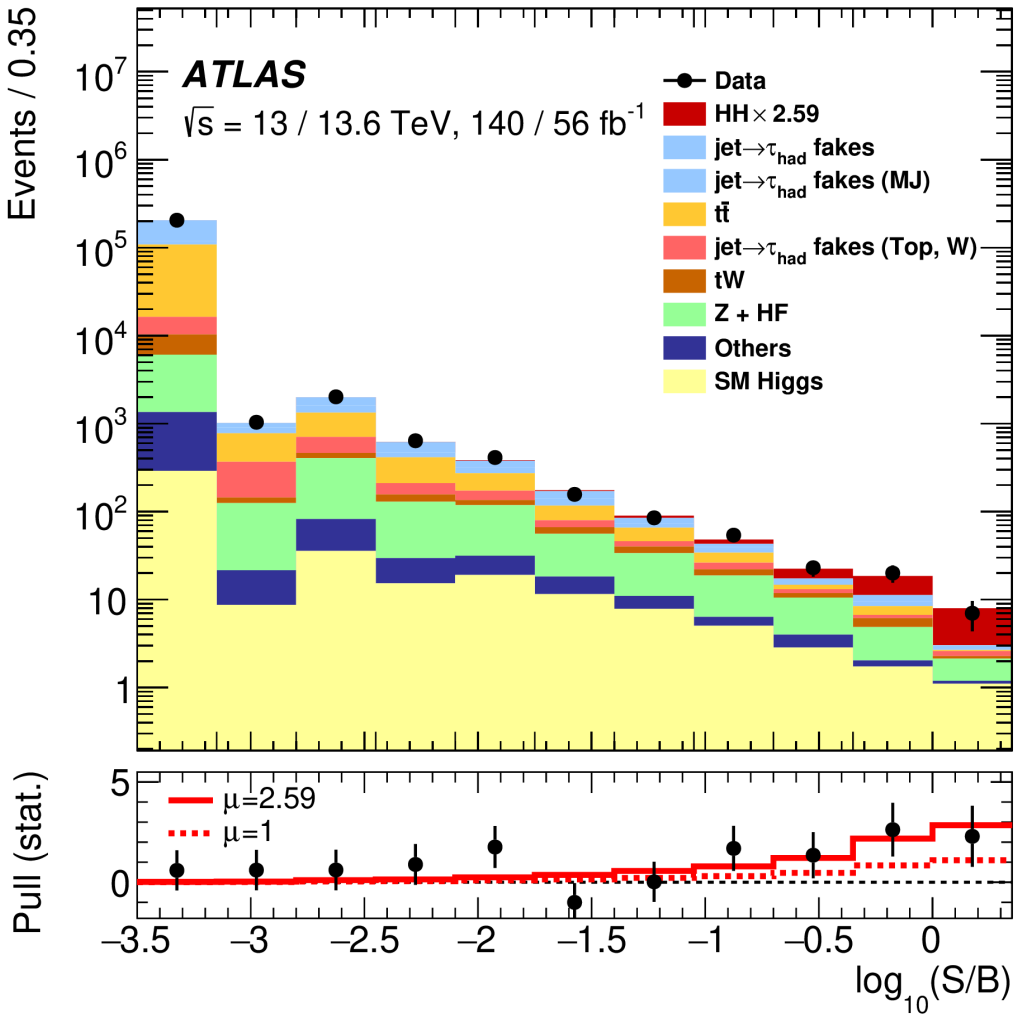
ATLAS arXiv:2607.26879

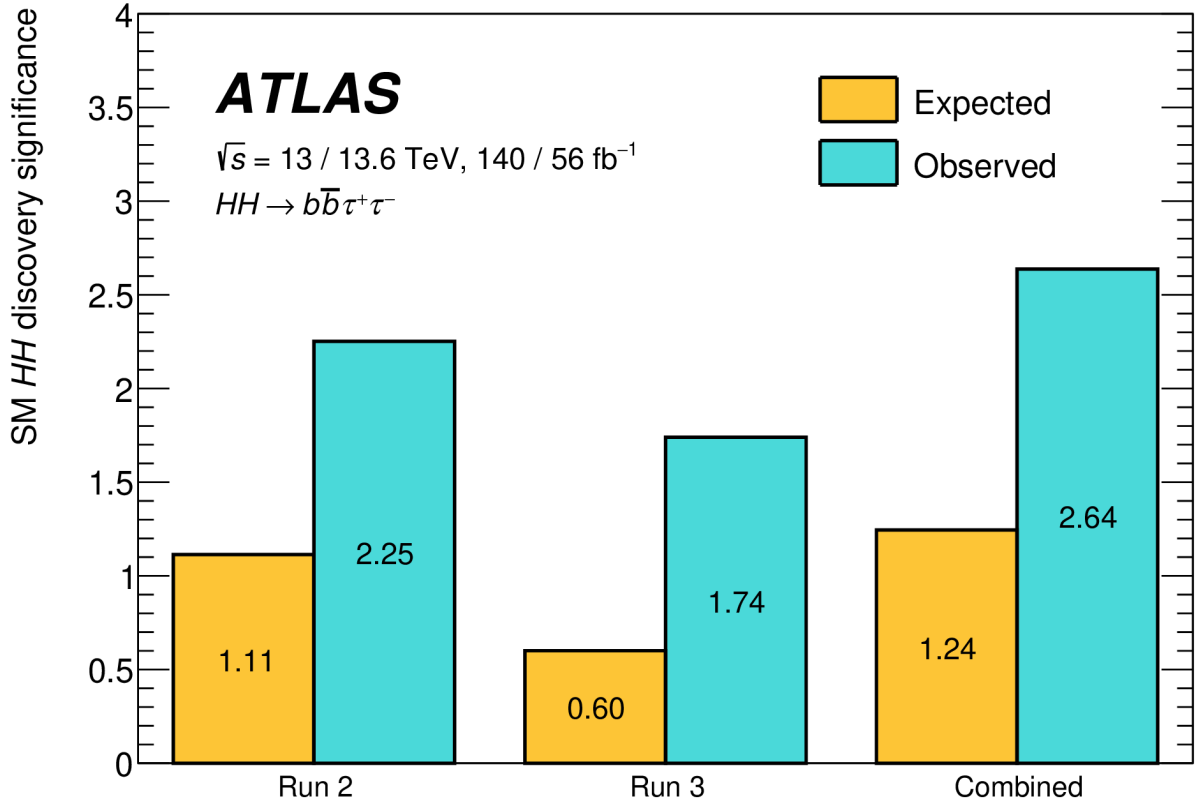



- tW is subdominant inclusively but important in the signal-like bins
- NLO tW and $t\bar{t}$ amplitudes overlap in the WbWb final state
- Diagram-removal and diagram-subtraction prescriptions probe the modelling difference
- A dedicated tW control region constrains its normalisation and the interference uncertainty

# HH to $b\bar{b}\tau\tau$ - final fit

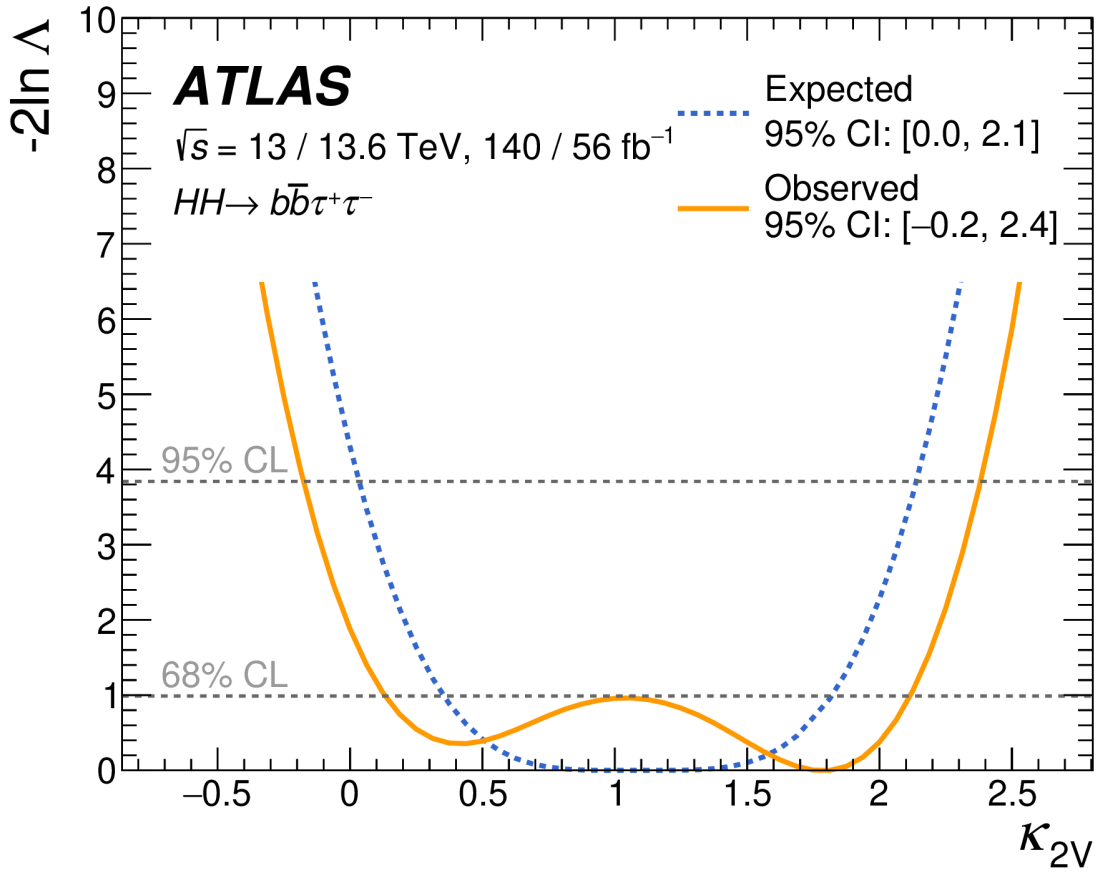
arXiv:2607.26879



# HH to $b\bar{b}\tau\tau$ - Constraints on κ2V

ATLAS arXiv:2607.26879



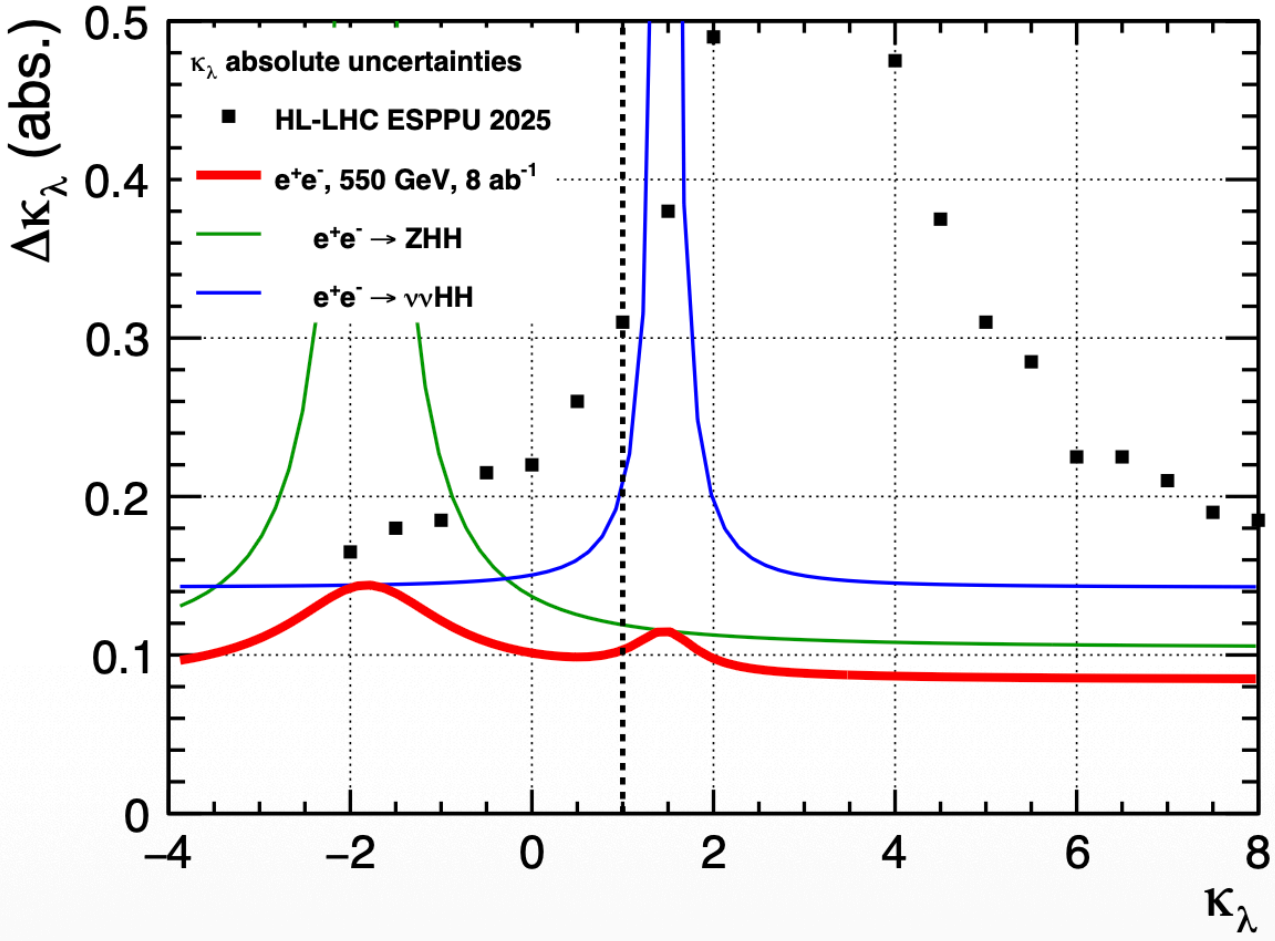

- The VBF category probes the VVHH interaction
- 95% CL observed: κ2V ∈ [–0.2, 2.4]
- 95% CL expected: [0.0, 2.1]
- κλ and the remaining couplings fixed to the SM

# Direct HH at a linear collider

Linear Collider Vision

ILD-note 2509.14148v1

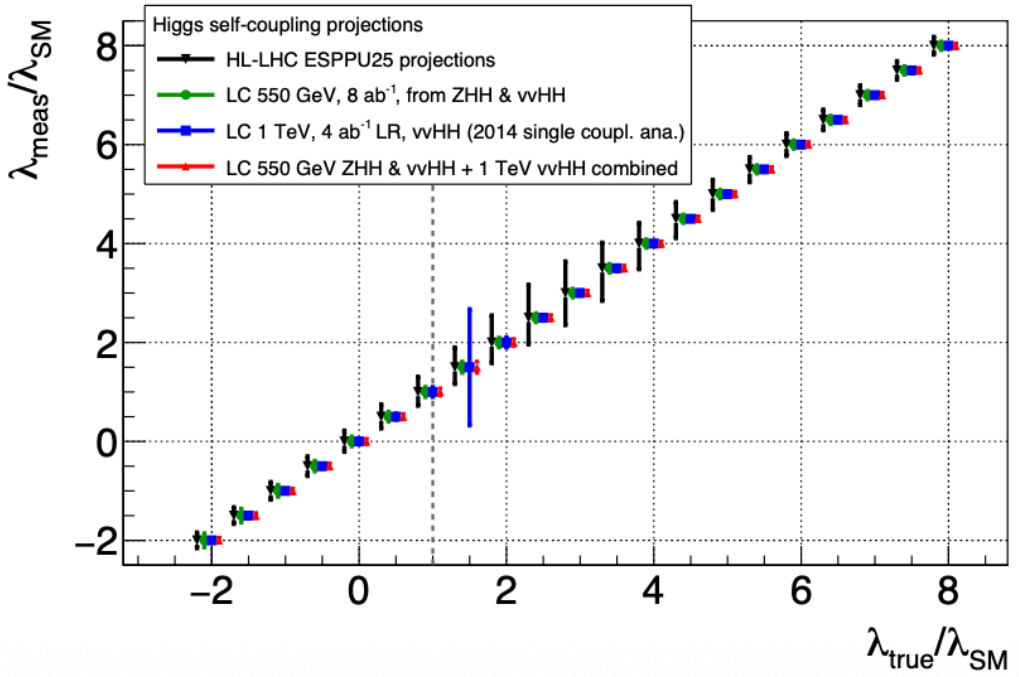
Uncertainties of ~11% for 8/ab at 550 GeV could be achieved at LC from direct measurements.




**L = 4/ab →8/ab & |P(e–,e+)| = (80%,30%) →(80%,60%)**

- P(e+) = 30%→60% **~ 10% higher luminosity**

Further improvements with run at 1 TeV (5-10%)




Sensitivity degrades at HL-LHC for $\kappa\lambda > 2$

# Next steps - even more sensitivity to squeeze

## Full update of analysis ongoing

- Include additional HH final states to increase overall sensitivity ~30% more signal
- Improve b-tagging performance by training with larger statistics.
- Develop ML-based jet clustering and color-singlet identification (à la CEPC) ~ 20-40% improvement
- Implement ML-based event selection (BDTs with modern multi-class)
- Include the Matrix Element Method (MEM)
  - Better ZHH/ZZH separation
- Exploit **kinematic information sensitive to λ**, in particular the $m_{HH}$ distribution
  - a simple $m_{HH}$-based weighting already improved sensitivity by ~6% in the current projections.

**Note**: For $e^+e^- \rightarrow ZHH$, a single-parameter λ extraction is effectively equivalent to a full dim-6 SMEFT interpretation

All other operators will be tightly constrained by independent measurements.

# 2014 analysis

| channel | decay mode | $S$ | $B$ | $S/\sqrt{S+B}$ |
|---|---|---|---|---|
| qqHH | 8j | 15 | 88 | 1.5 |
| qqHH | lν6j | 1.6 | 18 | 0.38 |
| llHH | 2l6j | 2.2 | 8.4 | 0.69 |
| llHH | 3lν4j | 1.0 | 2.6 | 0.55 |
| combined | | | | 1.9 |

| $P(e^-)$, $P(e^+)$ | channel | decay mode | S | B | $\sigma_m$ | $S/\sqrt{S+B}$ |
|---|---|---|---|---|---|---|
| −80%, +30% | eeHH | inclusive | 3.9 | 7.0 | 1.07 | 1.14 |
| | | HH → 4b | 2.6 | | | 0.84 |
| | μμHH | inclusive | 5.1 | 8.9 | 1.26 | 1.36 |
| | | HH → 4b | 2.8 | | | 0.82 |
| | ννHH | inclusive | 5.6 | 6.5 | 1.50 | 1.58 |
| | | HH → 4b | 5.5 | | | 1.56 |
| | bbHH | inclusive | 8.5 | 21.9 | 1.57 | 1.54 |
| | | HH → 4b | 8.0 | | | 1.46 |
| | qqHH | inclusive | 12.6 | 55.0 | 1.55 | 1.53 |
| | | HH → 4b | 10.9 | | | 1.34 |
| −80%, +30% | combined | inclusive | | | | 3.2 |
| | | HH → 4b | | | | 2.8 |
| +80%, −30% | eeHH | inclusive | 2.9 | 4.2 | 0.92 | 1.09 |
| | | HH → 4b | 1.9 | | | 0.77 |
| | μμHH | inclusive | 3.8 | 5.3 | 1.10 | 1.26 |
| | | HH → 4b | 2.0 | | | 0.74 |
| | ννHH | inclusive | 3.6 | 1.1 | 1.54 | 1.66 |
| | | HH → 4b | 3.5 | | | 1.63 |
| | bbHH | inclusive | 5.9 | 7.0 | 1.58 | 1.64 |
| | | HH → 4b | 5.6 | | | 1.58 |
| | qqHH | inclusive | 8.3 | 16.0 | 1.64 | 1.68 |
| | | HH → 4b | 7.8 | | | 1.60 |
| +80%, −30% | combined | inclusive | | | | 3.3 |
| | | HH → 4b | | | | 3.0 |
| combined | combined | inclusive | | | | 4.6 |
| | | HH → 4b | | | | 4.1 |

# 2025 analysis

| $P(e^-)$, $P(e^+)$ | channel | decay mode | S | B | $S/\sqrt{S+B}$ | $\delta\sigma/\sigma$[%] |
|---|---|---|---|---|---|---|
| −80%, +30% | eeHH | inclusive | 5.4 | 7.0 | 1.5 | 65 |
| | | $HH \to 4b$ | 3.8 | | 1.2 | 86 |
| | μμHH | inclusive | 6.9 | 8.9 | 1.7 | 58 |
| | | $HH \to 4b$ | 4.1 | | 1.1 | 88 |
| | ννHH (ZHH only) | inclusive | 6.1 | 6.5 | 1.8 | 55 |
| | | $HH \to 4b$ | 6.0 | | 1.7 | 60 |
| | bbHH | inclusive | 12.3 | 21.9 | 2.1 | 47 |
| | | $HH \to 4b$ | 11.7 | | 2.0 | 49 |
| | qqHH | inclusive | 18.0 | 55.0 | 2.1 | 47 |
| | | $HH \to 4b$ | 16.0 | | 1.9 | 53 |
| −80%, +30% | combined | inclusive | | | 4.2 | 24 |
| | | $HH \to 4b$ | | | 3.6 | 28 |
| +80%, −30% | eeHH | inclusive | 4.0 | 4.2 | 1.4 | 72 |
| | | $HH \to 4b$ | 2.8 | | 1.1 | 95 |
| | μμHH | inclusive | 5.1 | 5.3 | 1.6 | 63 |
| | | $HH \to 4b$ | 2.9 | | 1.0 | 98 |
| | ννHH | inclusive | 5.2 | | 2.1 | 48 |
| | | $HH \to 4b$ | 5.1 | | 2.1 | 49 |
| | bbHH | inclusive | 8.6 | 7.0 | 2.2 | 46 |
| | | $HH \to 4b$ | 8.2 | | 2.1 | 48 |
| | qqHH | inclusive | 12.0 | 16.0 | 2.3 | 44 |
| | | $HH \to 4b$ | 11.4 | | 2.2 | 46 |
| +80%, −30% | combined | inclusive | | | 4.3 | 23 |
| | | $HH \to 4b$ | | | 4.0 | 25 |
| combined | combined | inclusive | | | 6.0 | 16.6 |
| | | $HH \to 4b$ | | | 5.4 | 18.7 |

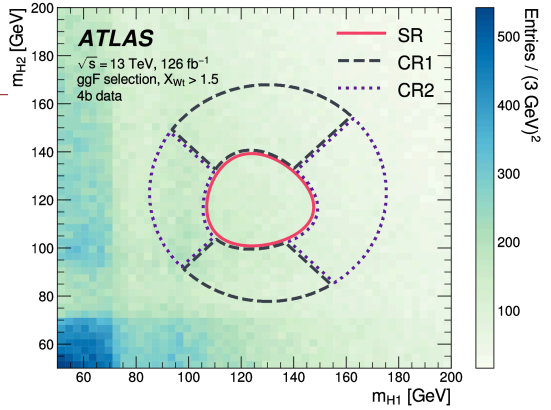
# HH to $b\bar{b}b\bar{b}$

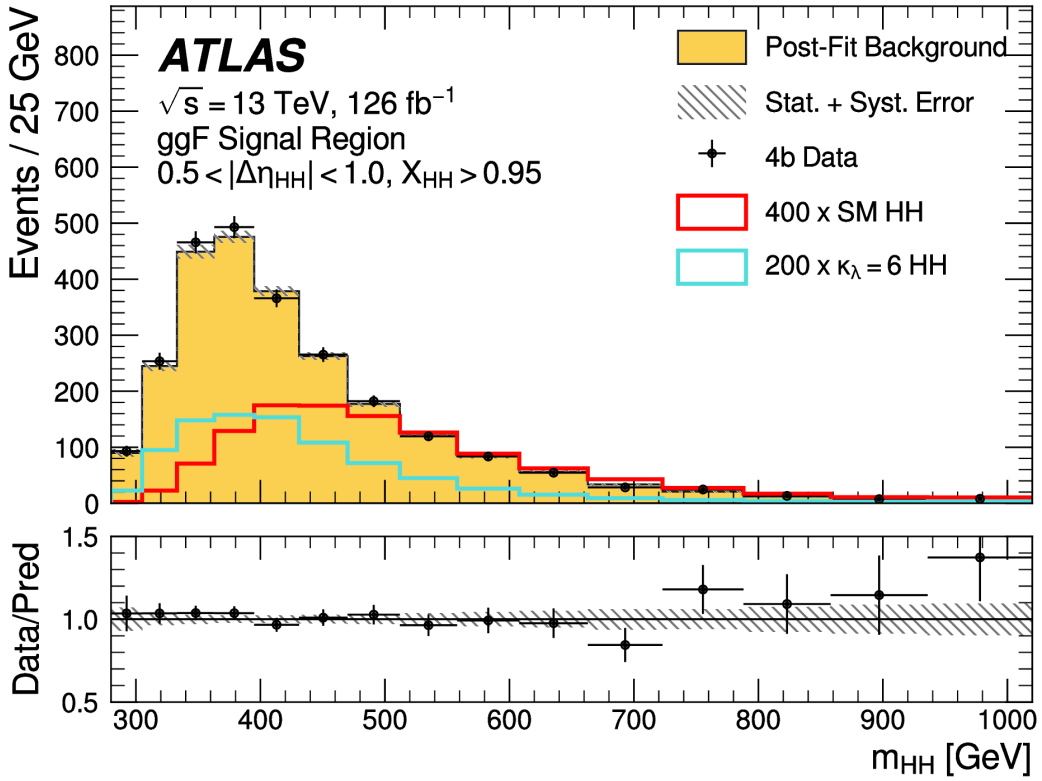
## Large background from QCD multi-jet processes

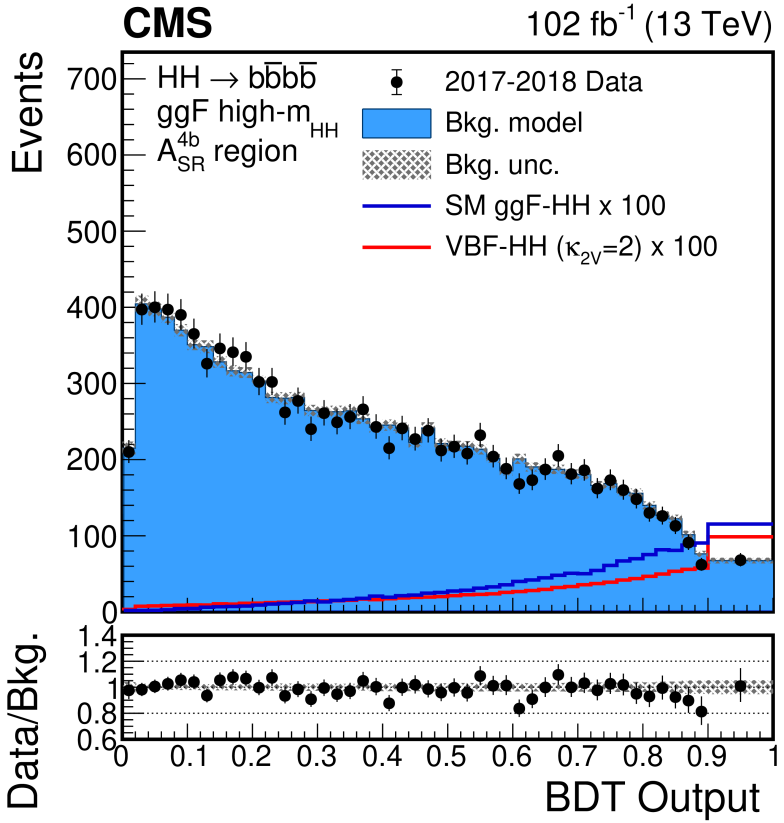
Online b-tagging requirements to suppress multi-jet background

Dedicated b-jet momentum corrections, to improve mass resolution (10–13%)

Data driven background modeling with multi-variate kinematic reweighing from control regions




ATLAS-Phys. Rev. D 108 (2023) 052003
CMS-Phys. Rev. Lett. 129 (2022) 081802

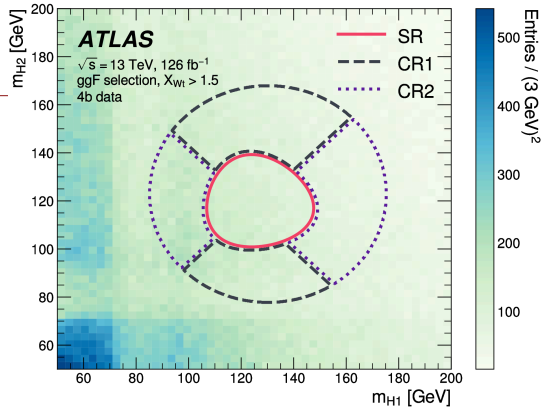
# HH to bb̄bb̄

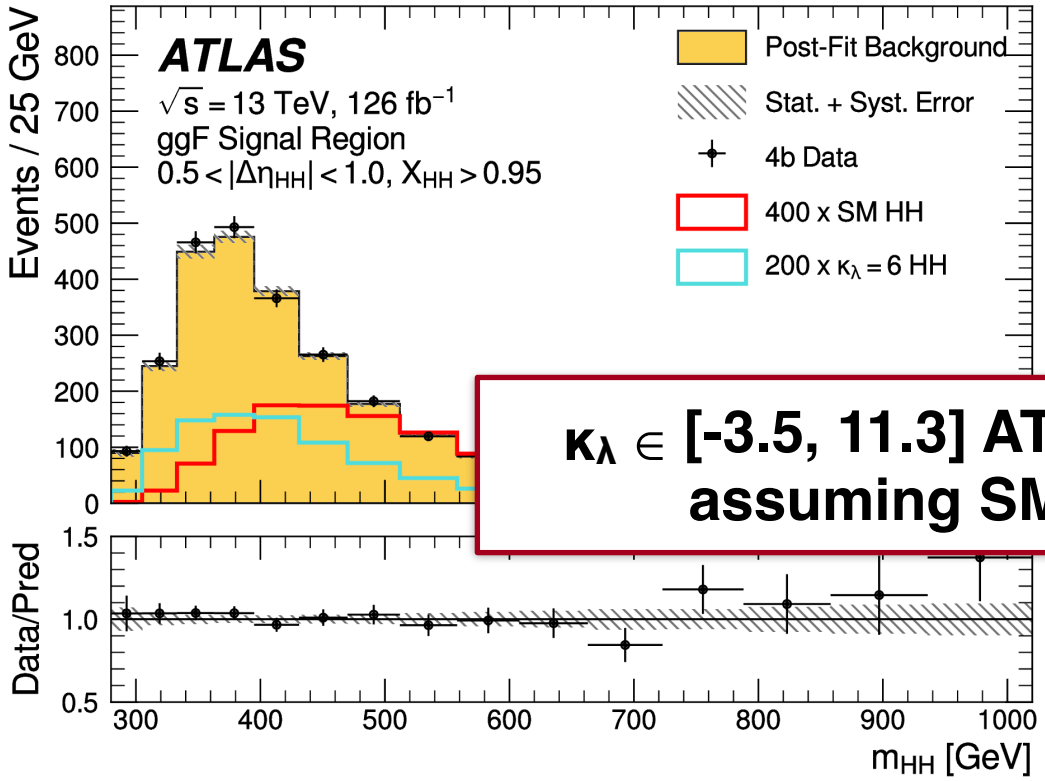
## Large background from QCD multi-jet processes

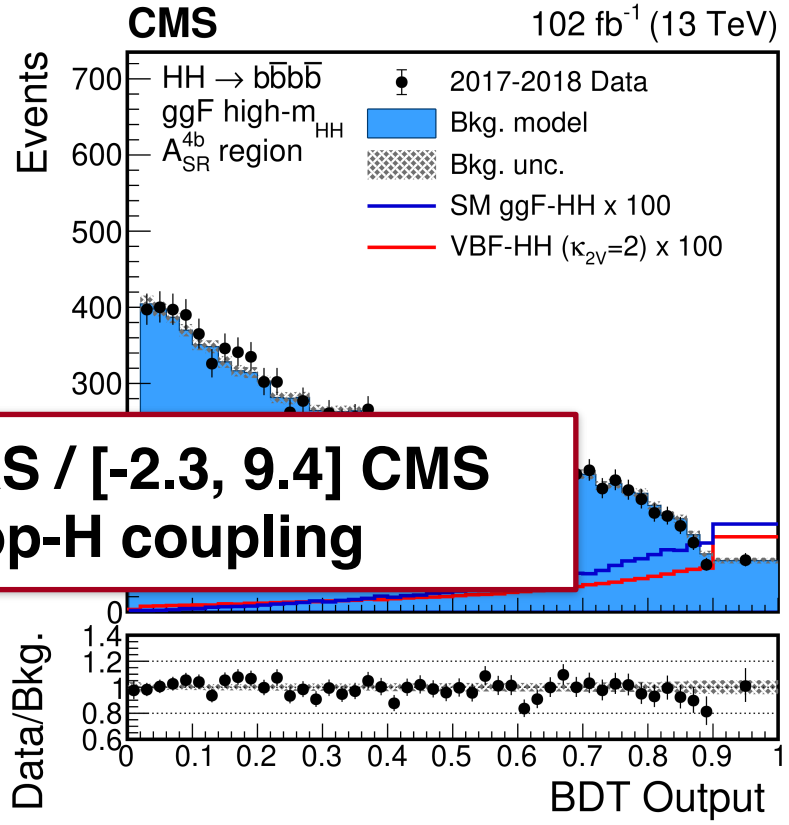
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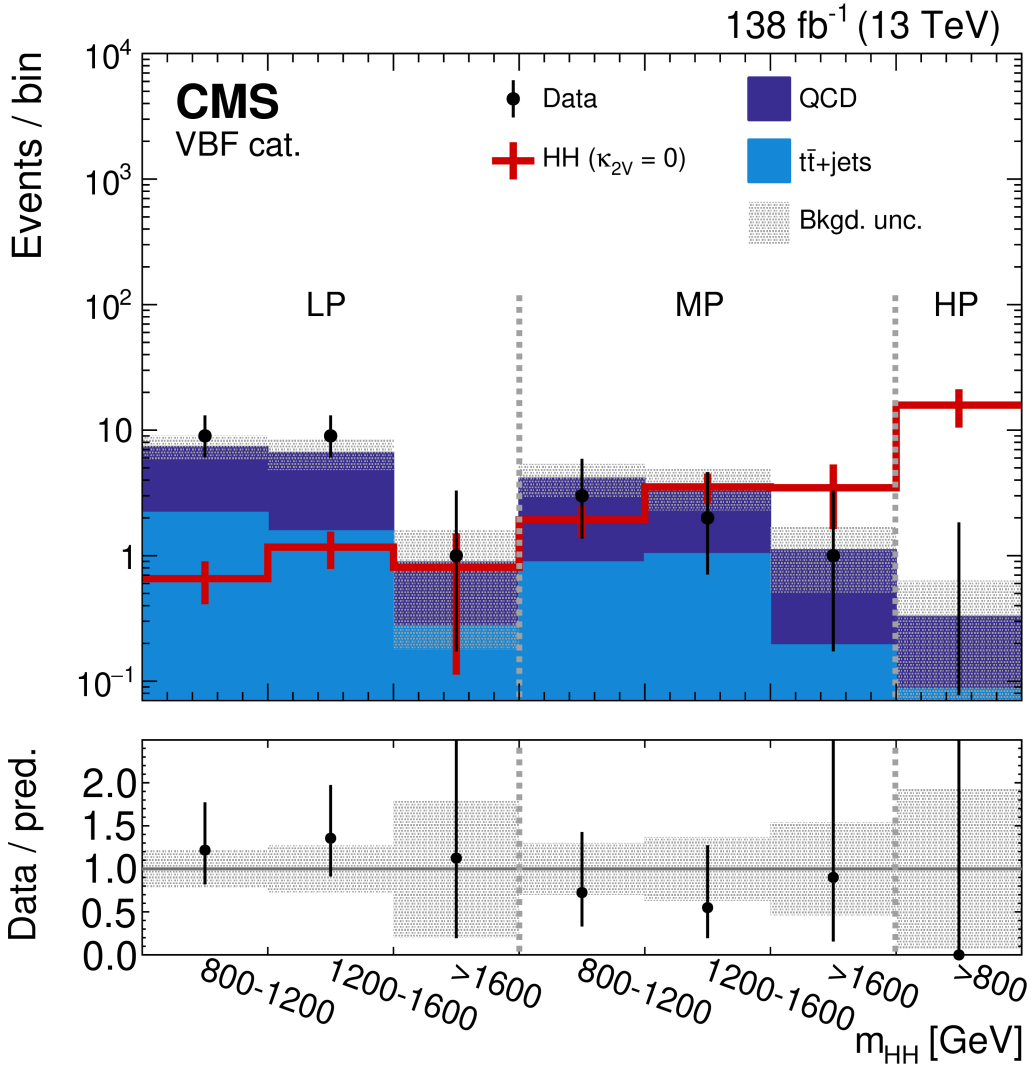




**$\kappa_\lambda \in$ [-3.5, 11.3] ATLAS / [-2.3, 9.4] CMS assuming SM top-H coupling**

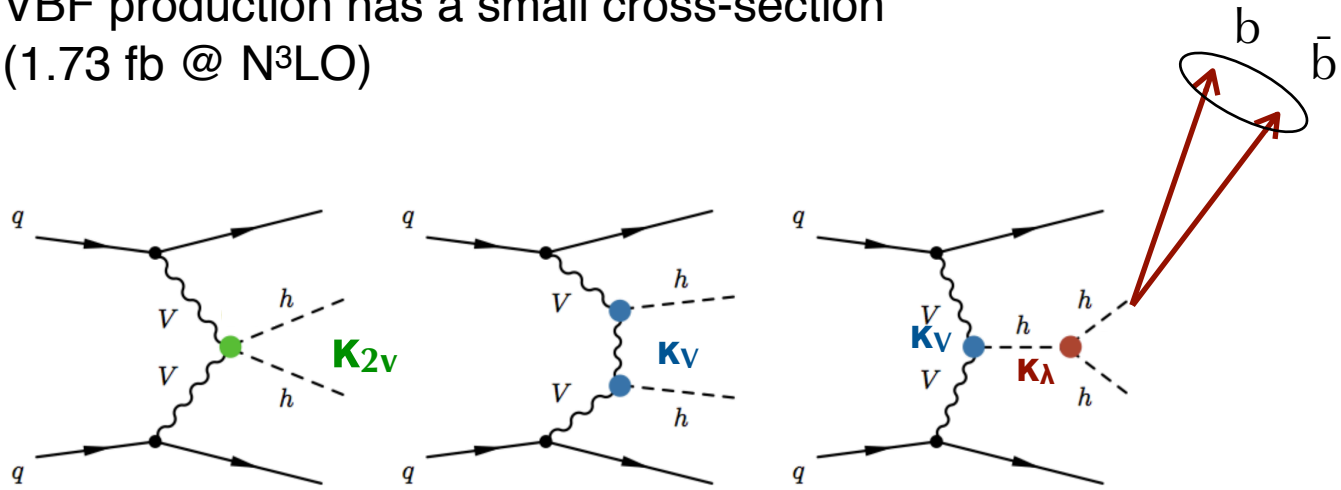
ATLAS-Phys. Rev. D 108 (2023) 052003
CMS-Phys. Rev. Lett. 129 (2022) 081802

ATLAS-Phys. Lett. B 858 (2024) 139007
CMS-ArXiv:2205.06667

# VBF production in $b\bar{b}b\bar{b}$



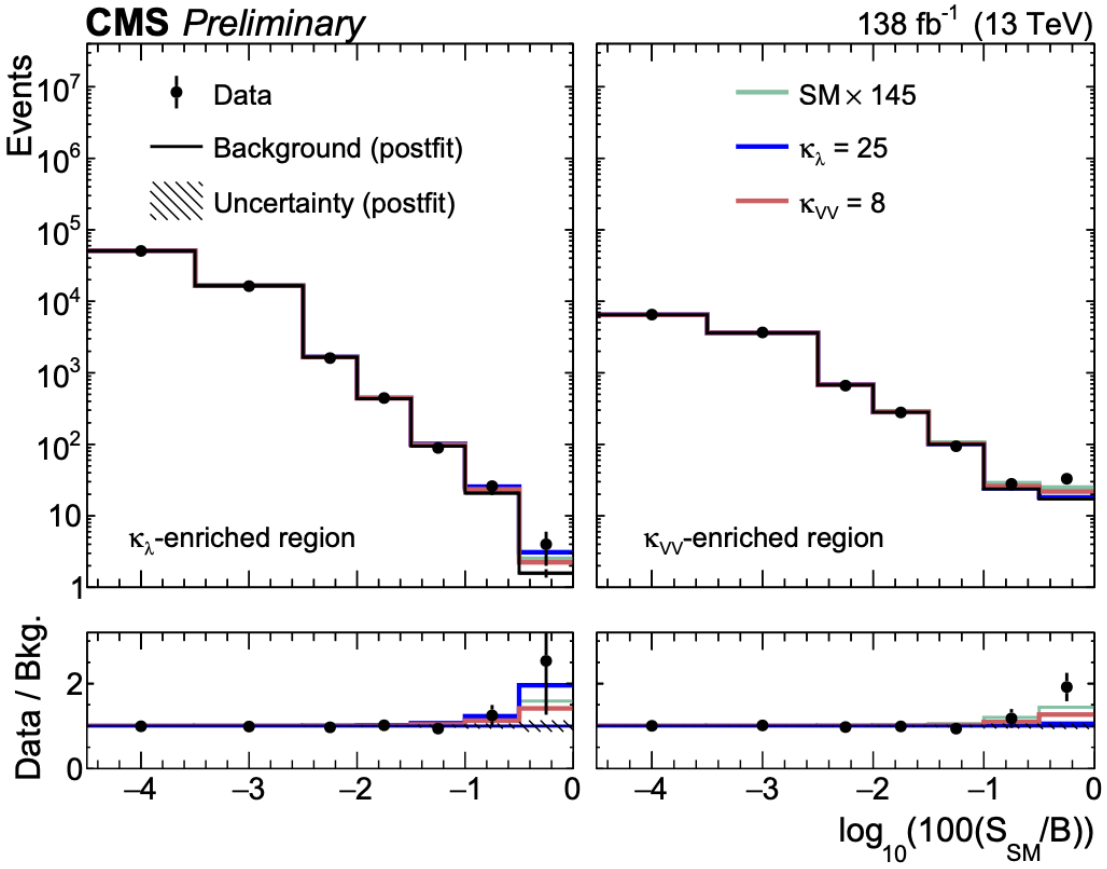

VBF production has a small cross-section
(1.73 fb @ N$^3$LO)




- New results from ATLAS & CMS for $b\bar{b}b\bar{b}$ which targets boosted Higgs bosons
  - It probes large deviations of $\kappa_V$ and $\kappa_{2V}$ from their SM predictions
    ⇒ Harder $m_{HH}$ spectrum ⇒ boosted Higgs bosons
- The observed limits $0.55/0.6 < \kappa_{2V} < 1.49/1.4$ at 95% CL
  ***x30 improvement wrt early Run 2 results***

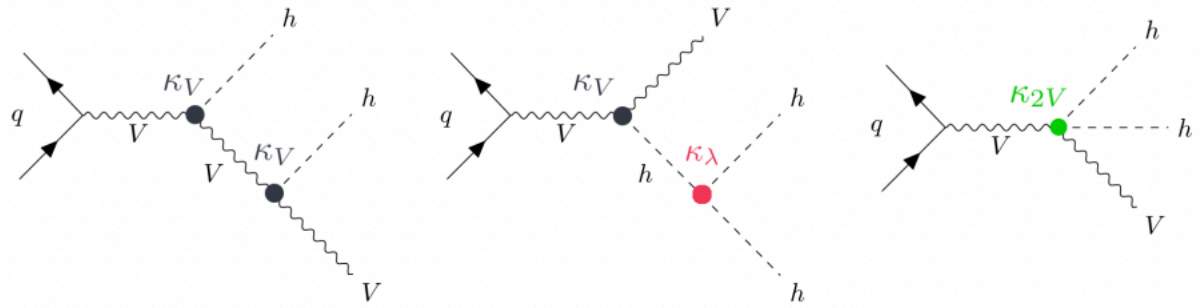
ATLAS-ArXiv:2210.054157
CMS-HIG-22-006

# VHH production




VHH production has a small cross-cross-section (0.86 fb @ NNLO)

- Dependencies on $\kappa_{2V}$ (VVHH), $\kappa_V$ and $\kappa_\lambda$




VHH production allows separation of WHH and ZHH

- Three leptonic channels (0L, 1L, 2L), one for each leptonic decay mode of the W and Z bosons
- HH in the $b\bar{b}b\bar{b}$ final state

- The observed (expected) limits constraint $\kappa_{2V}$ within $-8.6 < \kappa_{2V} < 10$ at 95% CL (ATLAS) and $-12.2 < \kappa_{2V} < 13.5$ at 95% CL (CMS)