Searching for DiHiggs

The $HH \rightarrow \bar{b}b\gamma\gamma$ analysis in ATLAS

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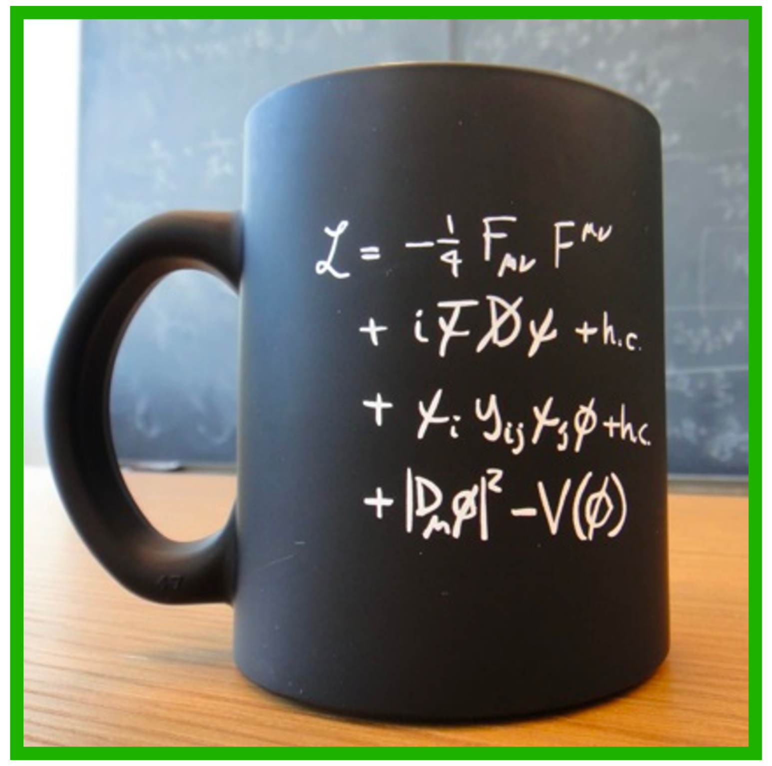
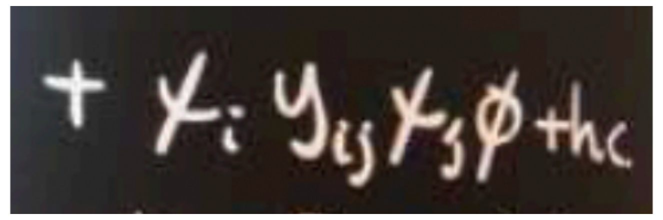
Preliminary results

1. Motivation

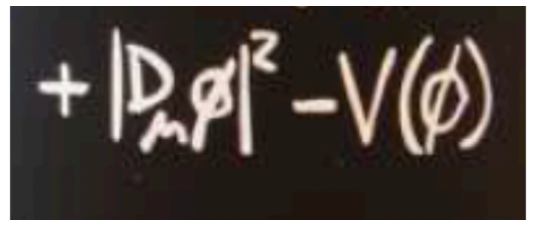
The Higgs Boson in the Standard Model

- The Standard Model (SM) thoroughly explored
- **Higgs sector** at the core
- Higgs discovery in 2012 at the LHC
- Remains a mystery





Fermion masses & mixing

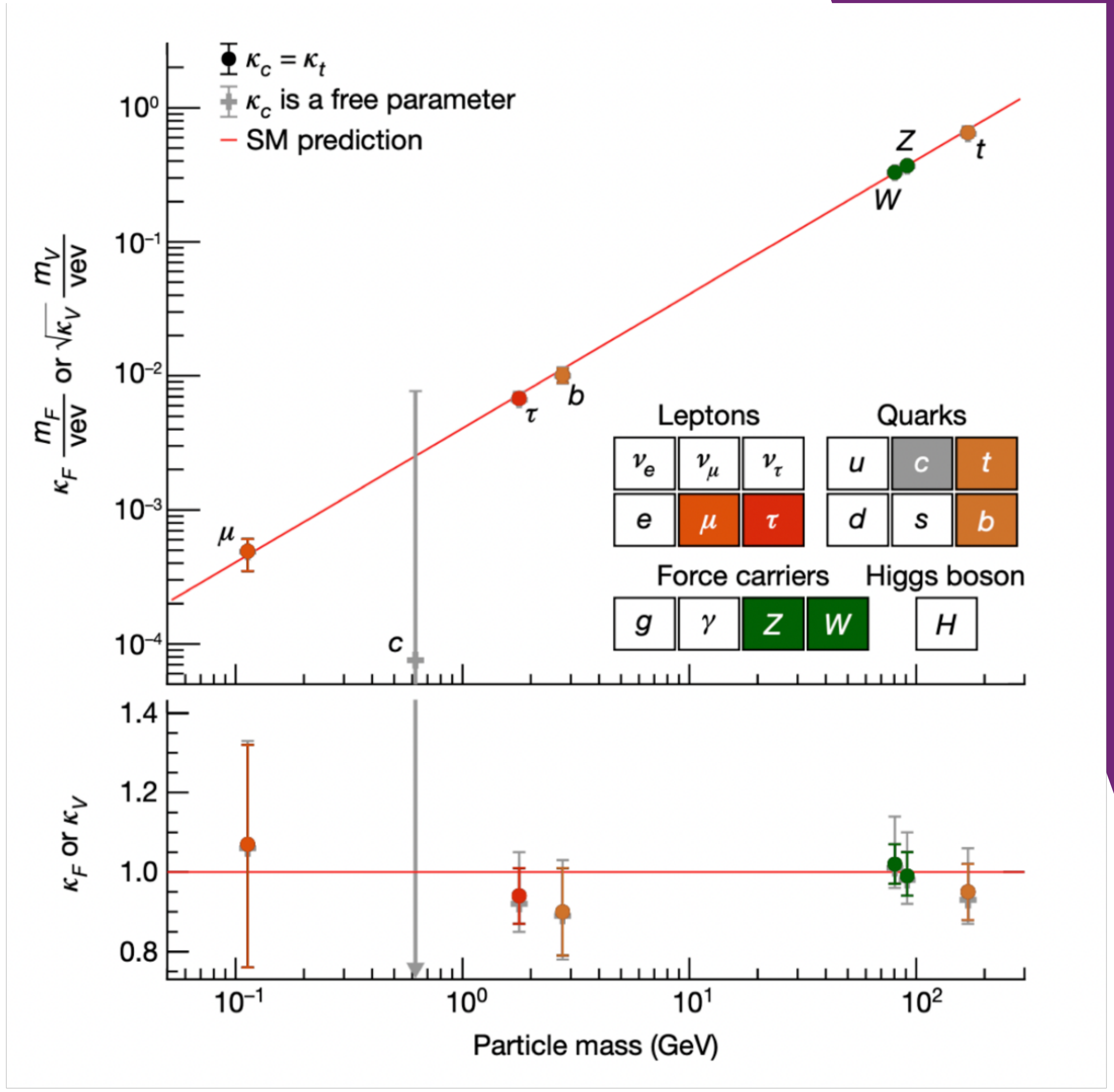


W,Z masses & Higgs potential

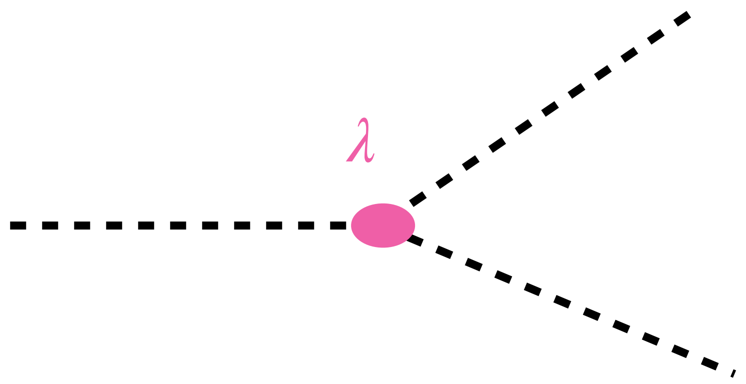
The Higgs Boson in the Standard Model

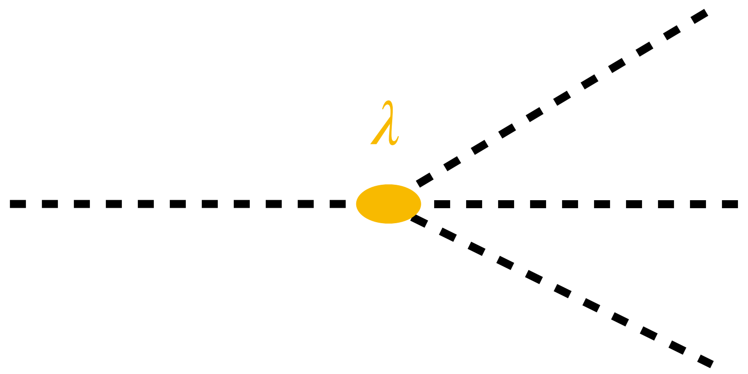
- SM predicts clear relationship between mass and coupling to Higgs

- What's missing? **The Higgs Boson self-coupling (λ)**



Nature 607, 52–59 (2022)





The Higgs Boson in the Standard Model

The Higgs potential $V(\phi)$ is closely linked to open questions in particle physics

- Hierarchy problem
- Baryonic asymmetry
- Dark matter

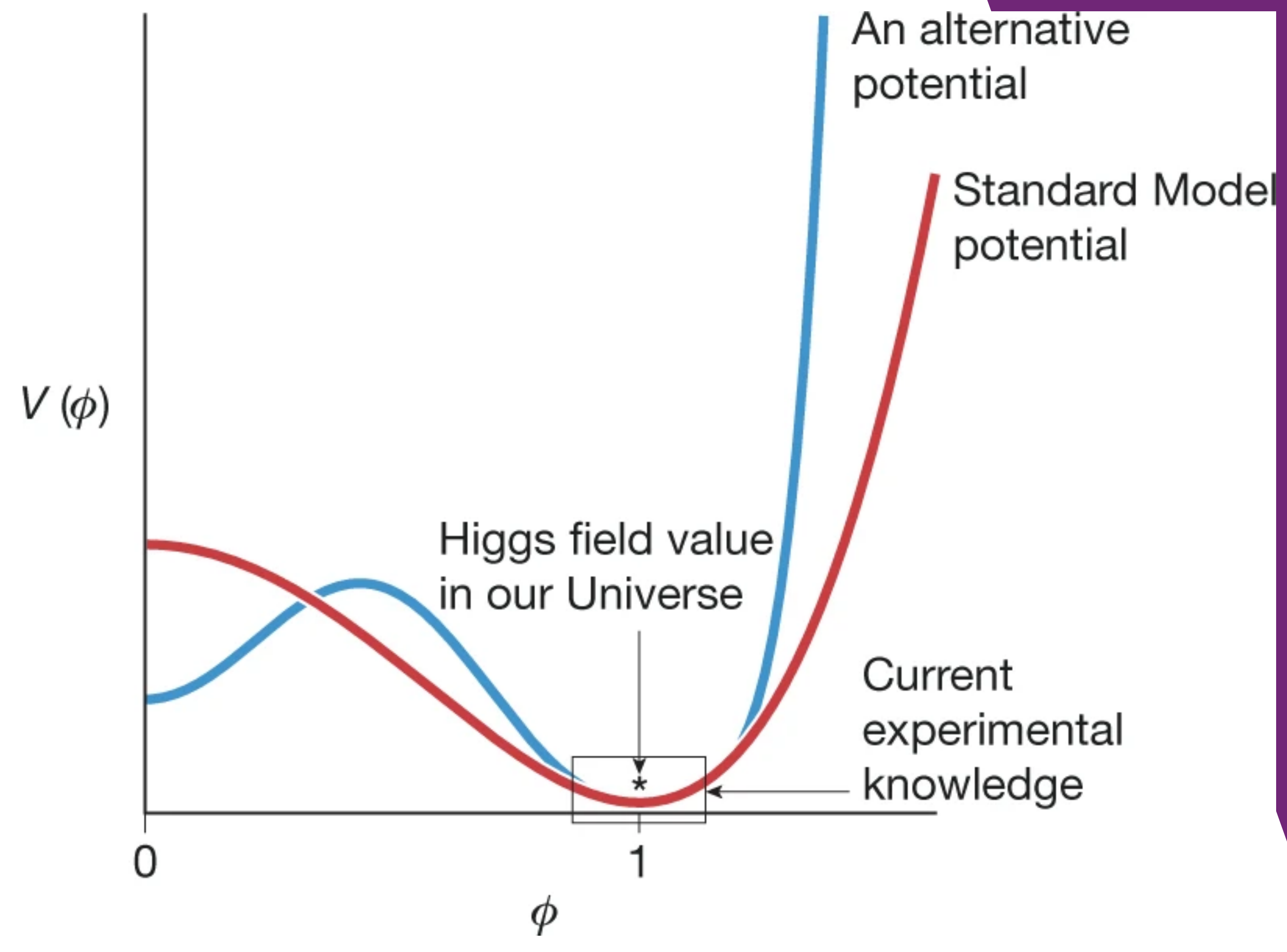
Possible theoretical solutions involve **non-SM** Higgs potential

The (SM) potential of the Higgs field can be written as

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \lambda H^4$$

Mass term   3 and 4 point interactions

λ_{SM}=0.13
λ_{true}=??



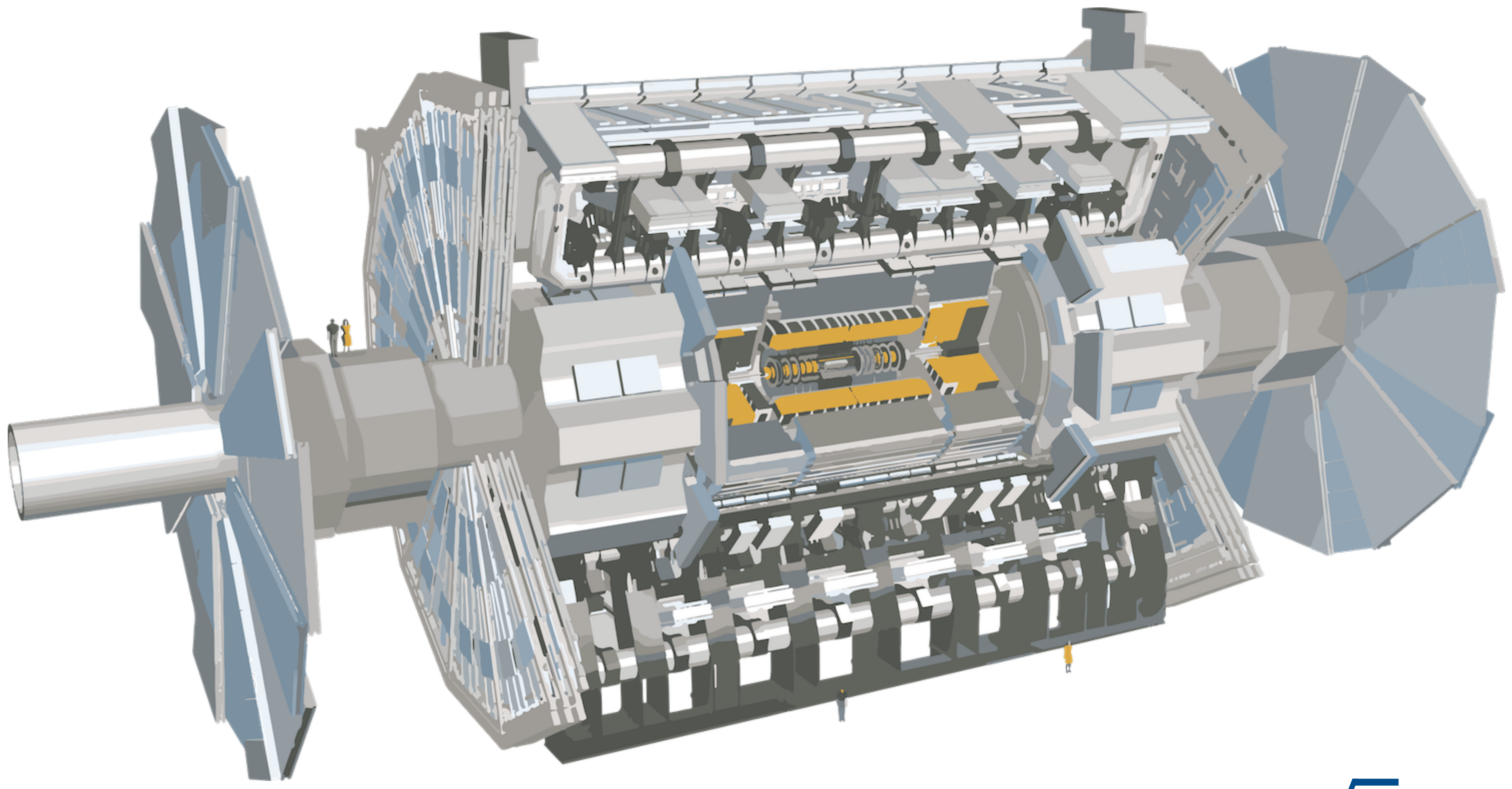
Nature 607, 41–47 (2022)

Measuring the Higgs self-interaction (λ) is crucial to understanding the Higgs potential

2. DiHiggs in ATLAS

The ATLAS experiment

Large general purpose detector on the LHC at CERN



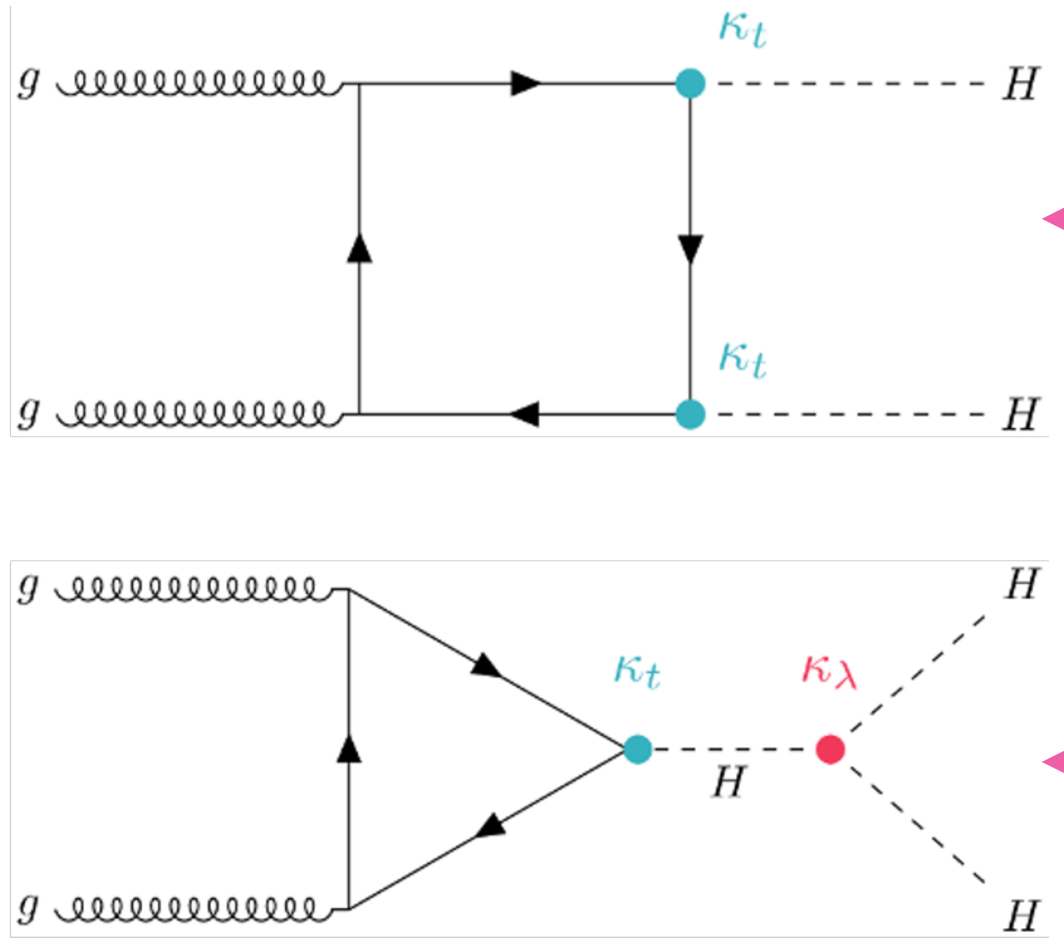
Bunches of protons are collided at $\sqrt{s} = 13.6\ TeV$

Produced 9 million Higgs bosons during Run 2 period

DiHiggs in ATLAS

The Higgs self-coupling λ can be probed in the ATLAS experiment for DiHiggs (HH) production

Primary HH **production modes**

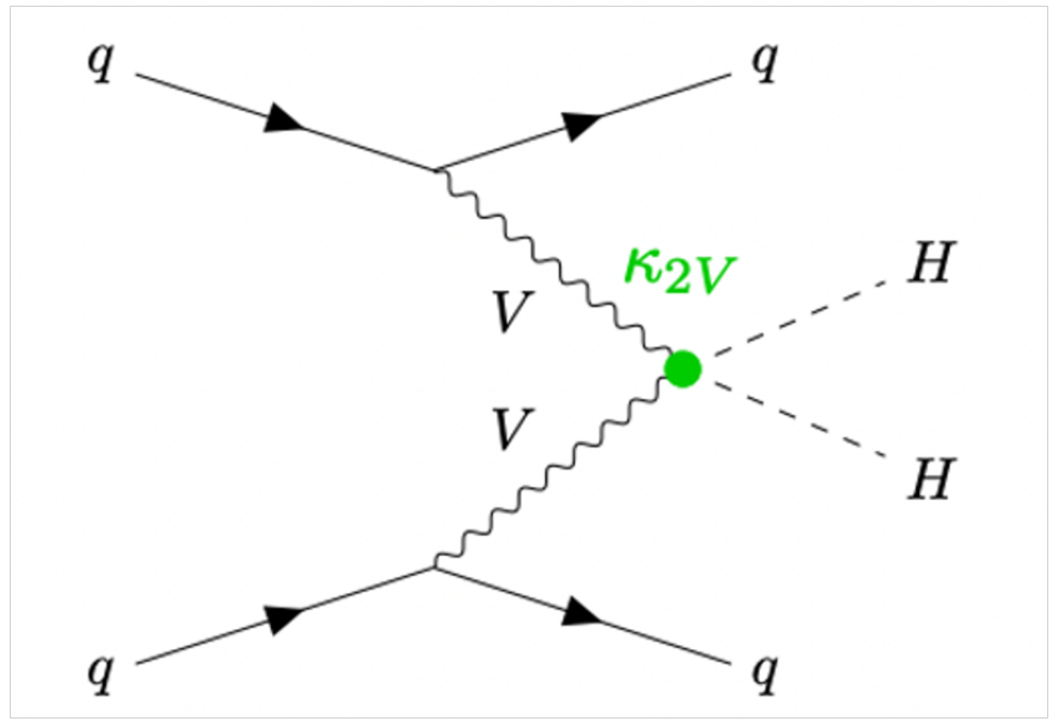


Gluon-gluon fusion (ggF)

ggF box diagram: not sensitive to self-coupling

ggF triangle diagram: sensitive to $\kappa_\lambda = \dfrac{\lambda}{\lambda_{SM}}$

Negative interference



Vector boson fusion (VBF)

DiHiggs in ATLAS

Primary DiHiggs **decay modes**

Clean signature →

↑ Large branching ratio

	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%

Golden channels:

$HH \rightarrow bbbb$, $HH \rightarrow b\bar{b}\tau\tau$

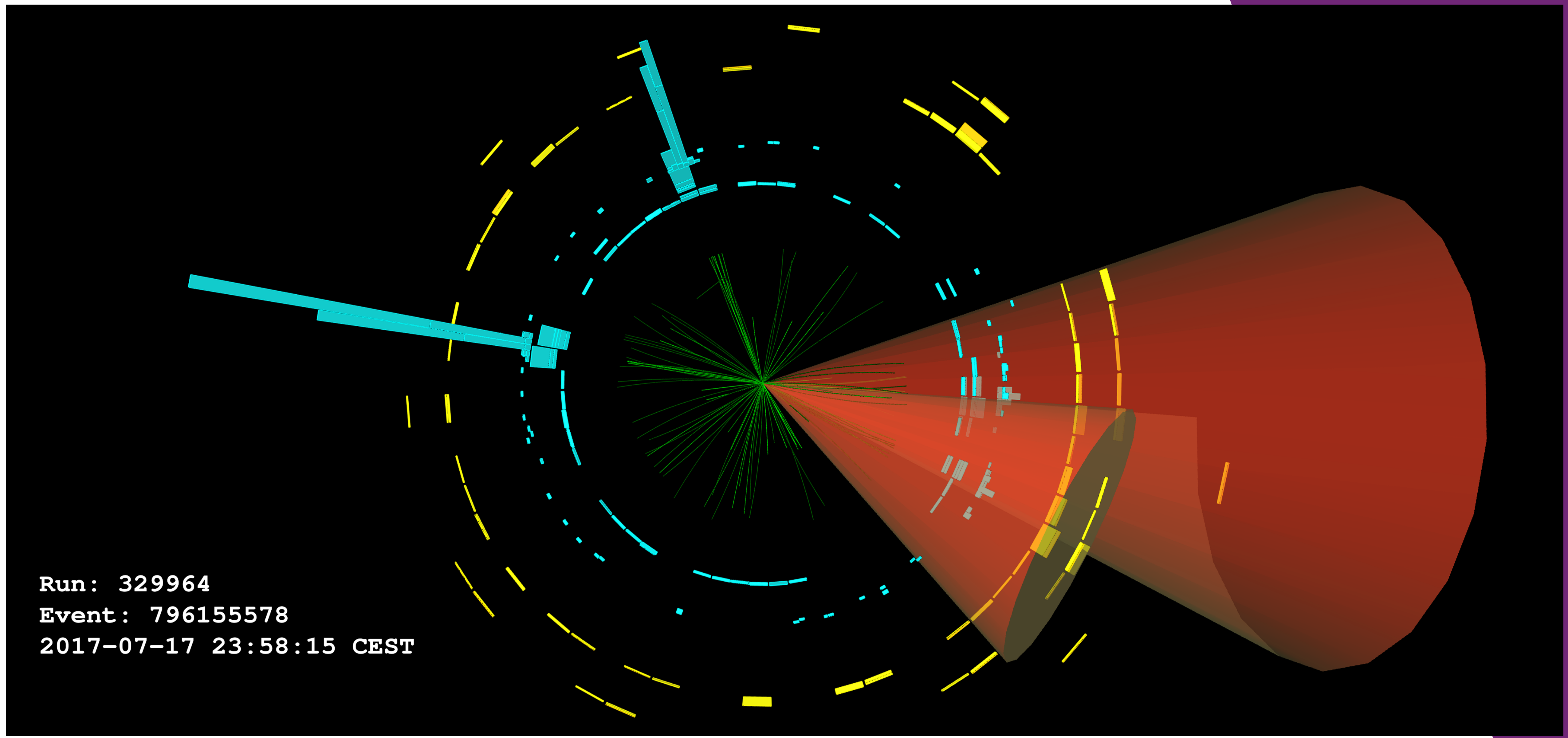
and $\underline{HH \rightarrow b\bar{b}\gamma\gamma}$

3. The $HH \to \bar{b}b\gamma\gamma$ Channel

The $HH \to \bar{b}b\gamma\gamma$ channel

Aims:

- Constrain the diHiggs production signal strength ($\mu_{HH} = \dfrac{S}{S_{SM}}$)
- Constrain κ_λ



Current analysis uses ATLAS full Run 2 and partial Run 3 data

Analysis strategy

Preselection

Narrow down the data

Categorisation

Split up the events

Modelling

Determine the shape of signal and background

Likelihood fit

Fit the data to extract signal strength

Preselection

How do we narrow down the data for $HH \rightarrow b\bar{b}\gamma\gamma$ events?

$H \rightarrow \gamma\gamma$ selection

- 2 energetic photons with combined mass around the Higgs mass

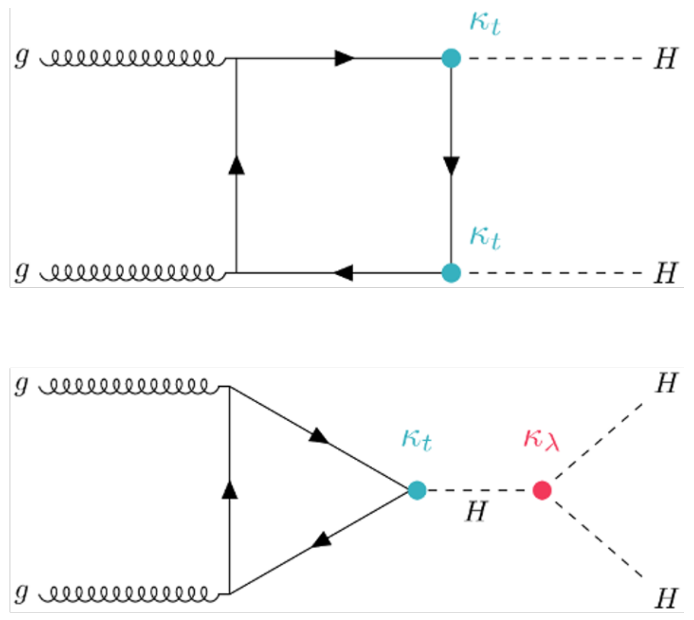
$H \rightarrow bb$ selection

- 2 b-jets passing the b-tagging working point
- Using brand new GNN-based b-tagger with 4x better background rejection wrt Run 2 legacy

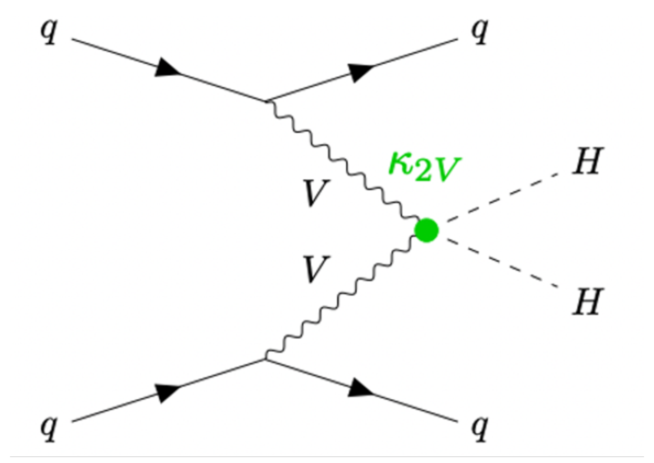
Preselection

What are we left with after pre-selection?

Signal



Gluon-gluon fusion (ggF)

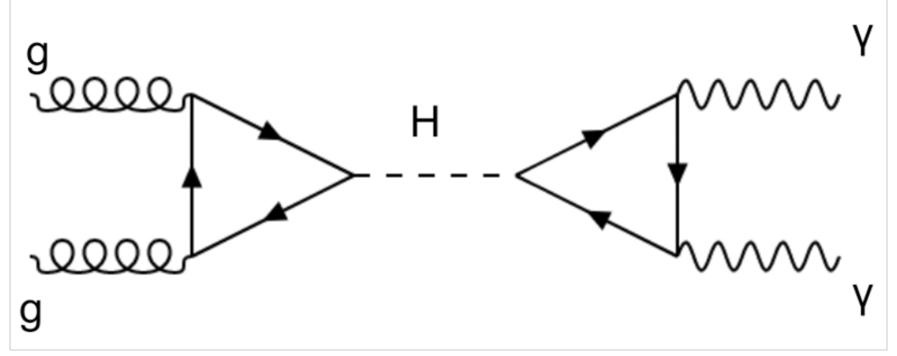


Vector boson fusion (VBF)

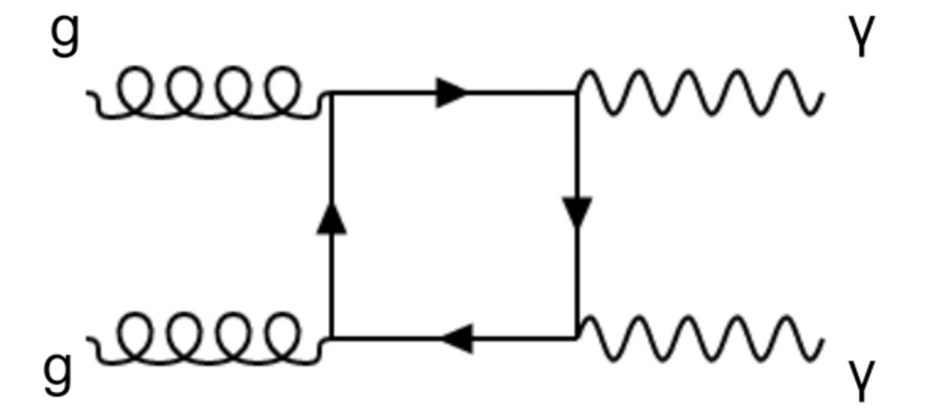
ggF and VBF

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

Background



Single Higgs/ resonant background ($H \to \gamma\gamma$)



Continuum background ($\gamma\gamma + jets$)

Event categorisation

In the Standard Model scenario, $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} = 1$

We want our search to be sensitive to SM as well as BSM scenarios

Define distinct analysis regions to be sensitive to both SM HH production and variations in κ_λ

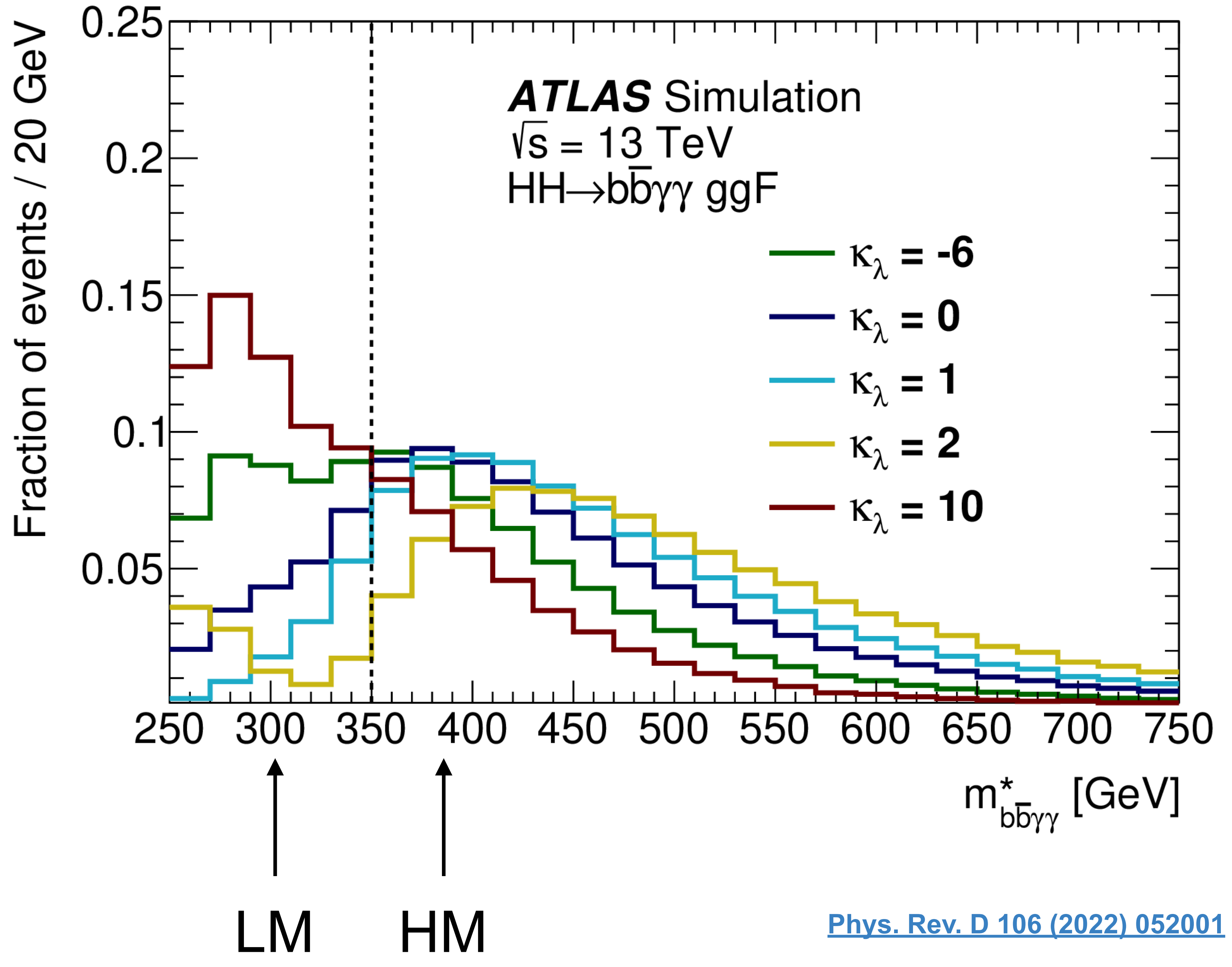
Event categorisation

- Use the invariant mass of the diHiggs final state ($m^*_{b\bar{b}\gamma\gamma}$) to define analysis regions
- **High-mass (HM)**: $m^*_{b\bar{b}\gamma\gamma} \geq 350\ GeV$

  Sensitive to SM-like κ_λ
- **Low-mass (LM)**: $m^*_{b\bar{b}\gamma\gamma} < 350\ GeV$

  Sensitive to BSM-like κ_λ

- Train boosted decision tree (BDT) in both
- **7 analysis categories** based on score



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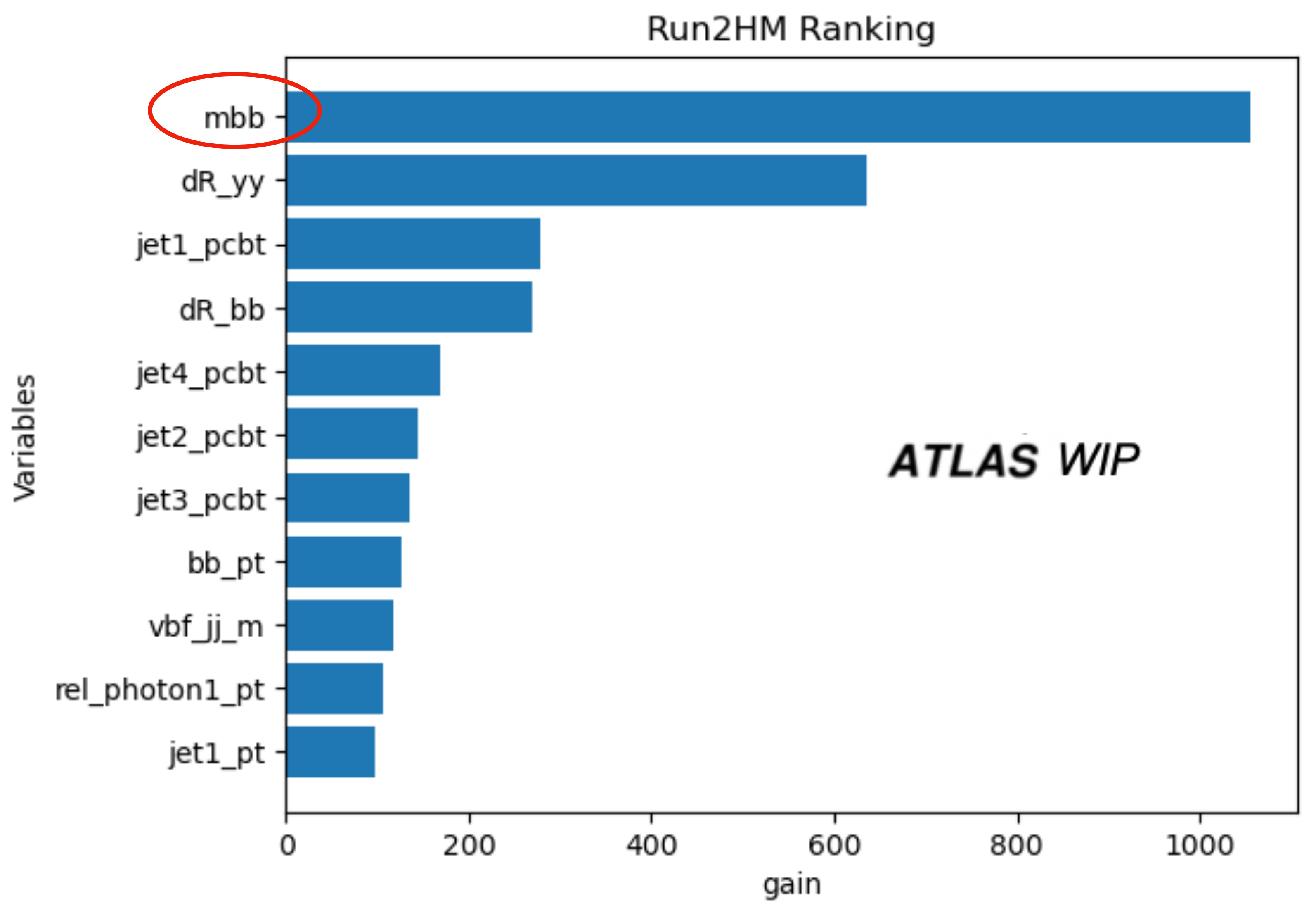
Kinematic Fit

- Invariant mass of the bb-system ($m_{b\bar{b}}$) found to be most important variable in BDT

- $m_{b\bar{b}}$ has bad resolution (~20%, compared to $m_{\gamma\gamma}$ ~1%)

- Improving the $m_{b\bar{b}}$ resolution can improve BDT performance



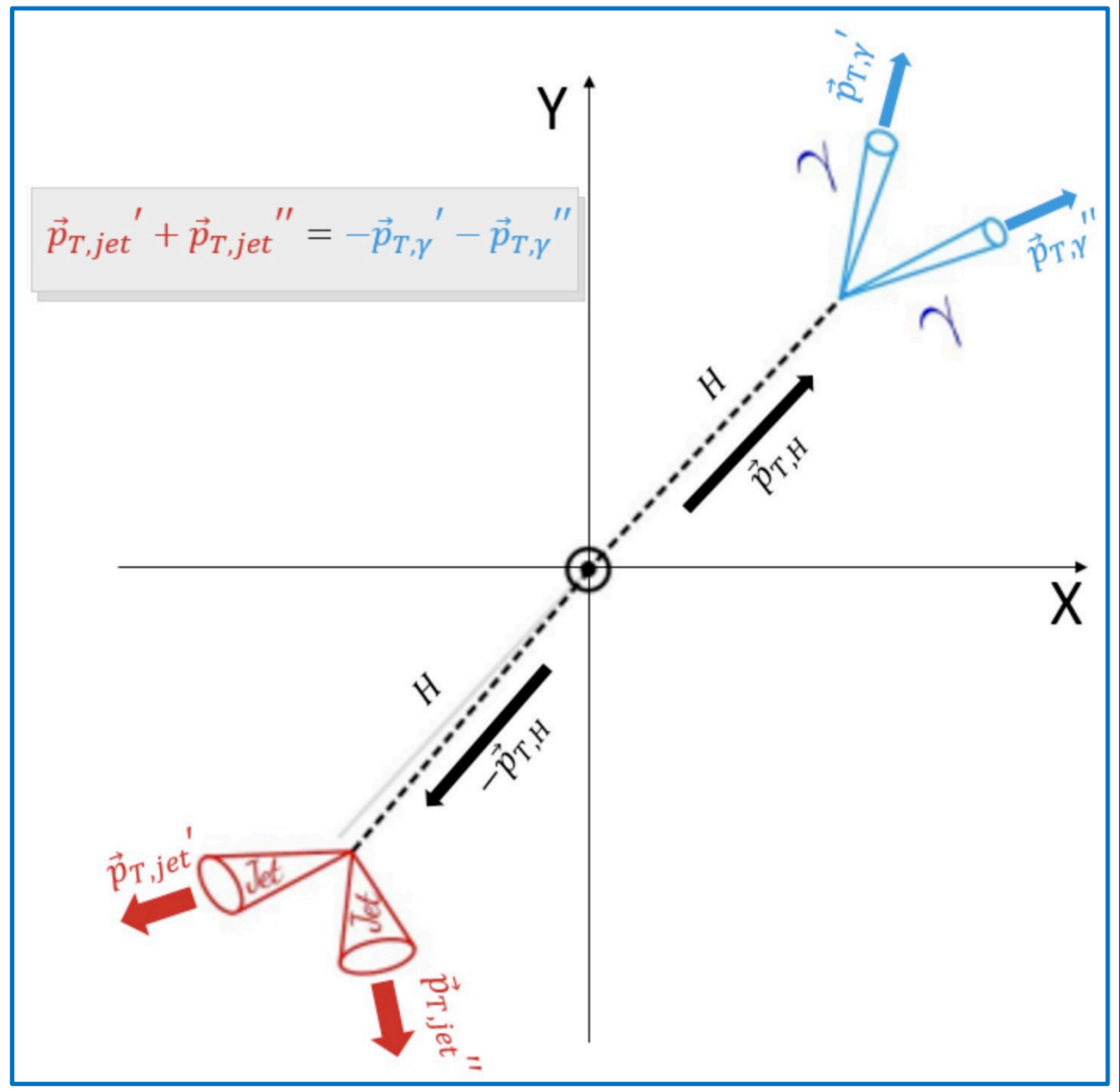
Kinematic Fit

- Exploit good $m_{\gamma\gamma}$ resolution, and use **momentum conservation**

- Fit a likelihood function per event

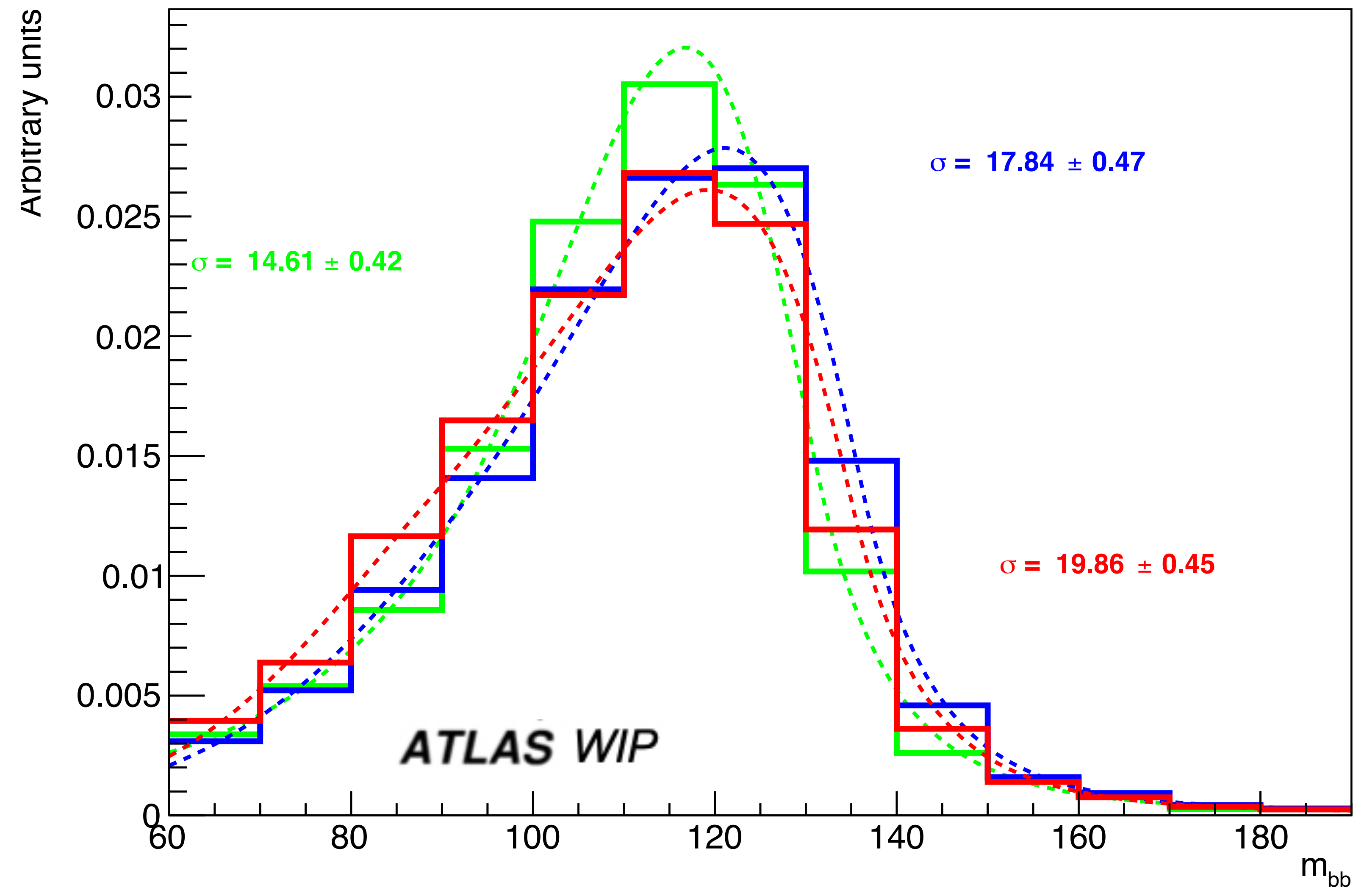
$$-2\,log(\mathcal{L}) = \sum_{j=jets}\left[-2\,log\left[f_E\left(\frac{E_{fit,j}-E_{Event,j}}{E_{fit,j}}\right)\right]-2\,log\left[f_{p_T}\left(\frac{pT_{fit,j}-pT_{Event,j}}{pT_{fit,j}}\right)\right]\right]+\sum_{j=photons}-2\,log\left[f_2\left(\frac{E_{fit,j}-E_{Event,j}}{E_{fit,j}}\right)\right]-2\,\lambda\,lo\,g[f_2(p_X^{HH})]-2\,\lambda\,log[f_2(p_Y^{HH})]$$

- $m_{b\bar{b}}$ reconstructed from Kinematic Fitted 4-momentum should have better resolution



Kinematic Fit

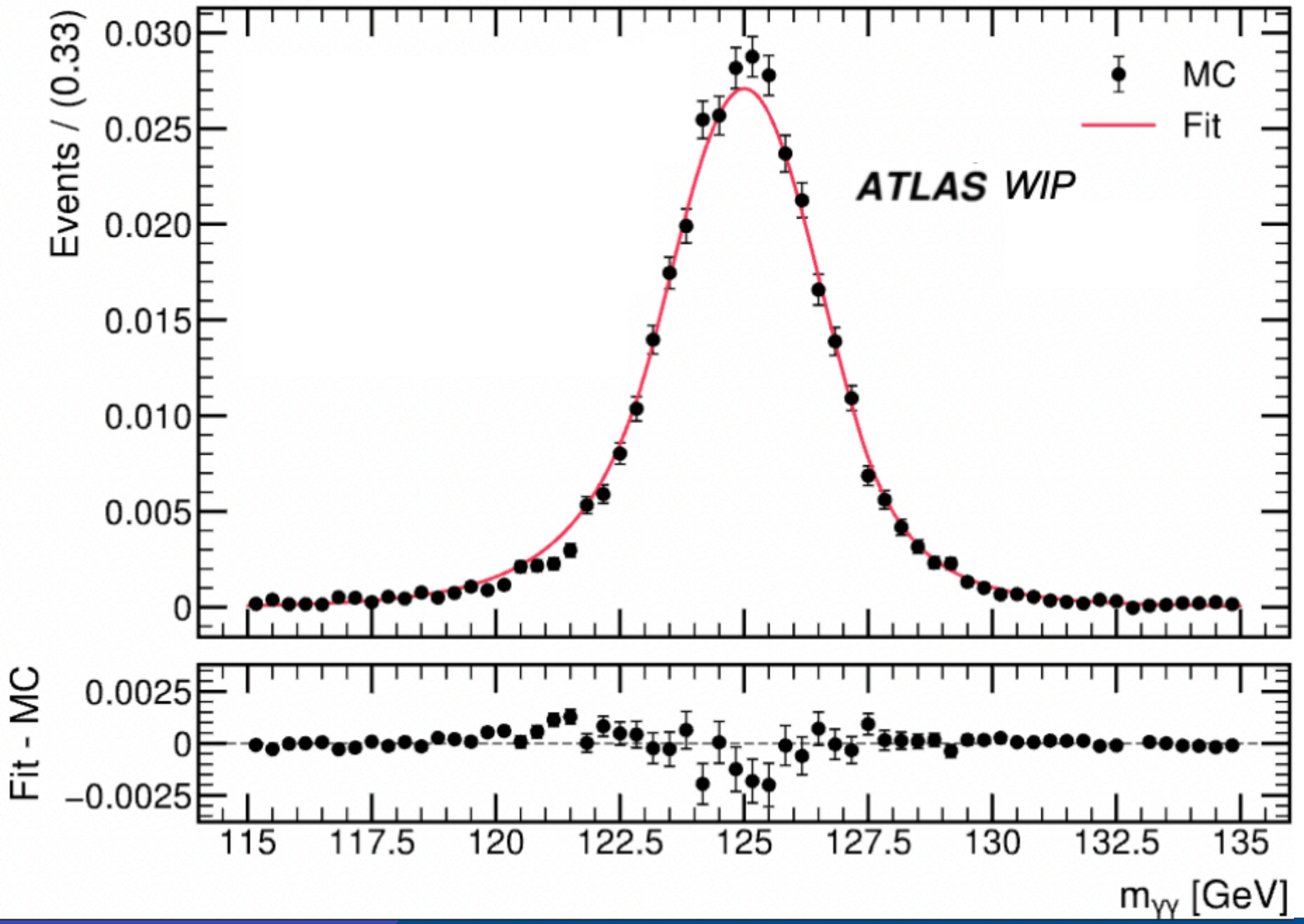
m_{bb} distribution with Kinematic Fit, BJetCalibration, and no correction

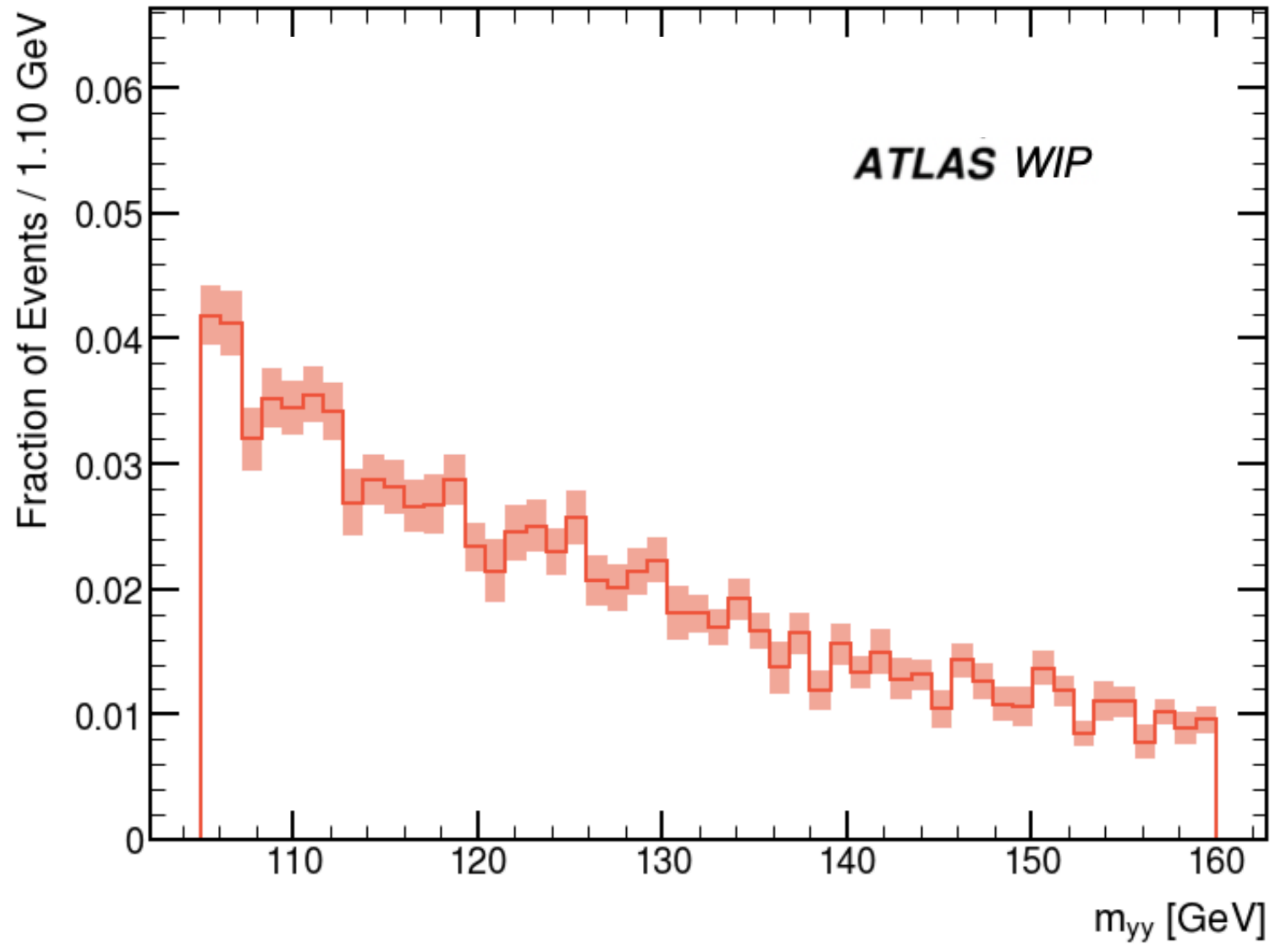


The Kinematic Fit improves the m_{bb} resolution by **26.9%** wrt no correction

Modelling and fit

Signal and background must be modelled in order to perform a likelihood fit to the diphoton mass distribution ($m_{\gamma\gamma}$)





4. Results

Disclaimers

- These results are preliminary and work in progress
- Expected limits based on stat-only likelihood fit
- Final analysis strategy not fixed - R&D for potential improvements ongoing

DiHiggs signal strength (μ_{HH}) expected upper limit and κ_λ constraints

We do not yet have the sensitivity to observe diHiggs or measure κ_λ, but we can set limits on both

Analysis	Expected upper limit	Significance
Run 2 legacy	4.86	0.54
Current Analysis	3.35	0.77

Current analysis improves ~31% over legacy in μ_{HH} sensitivity

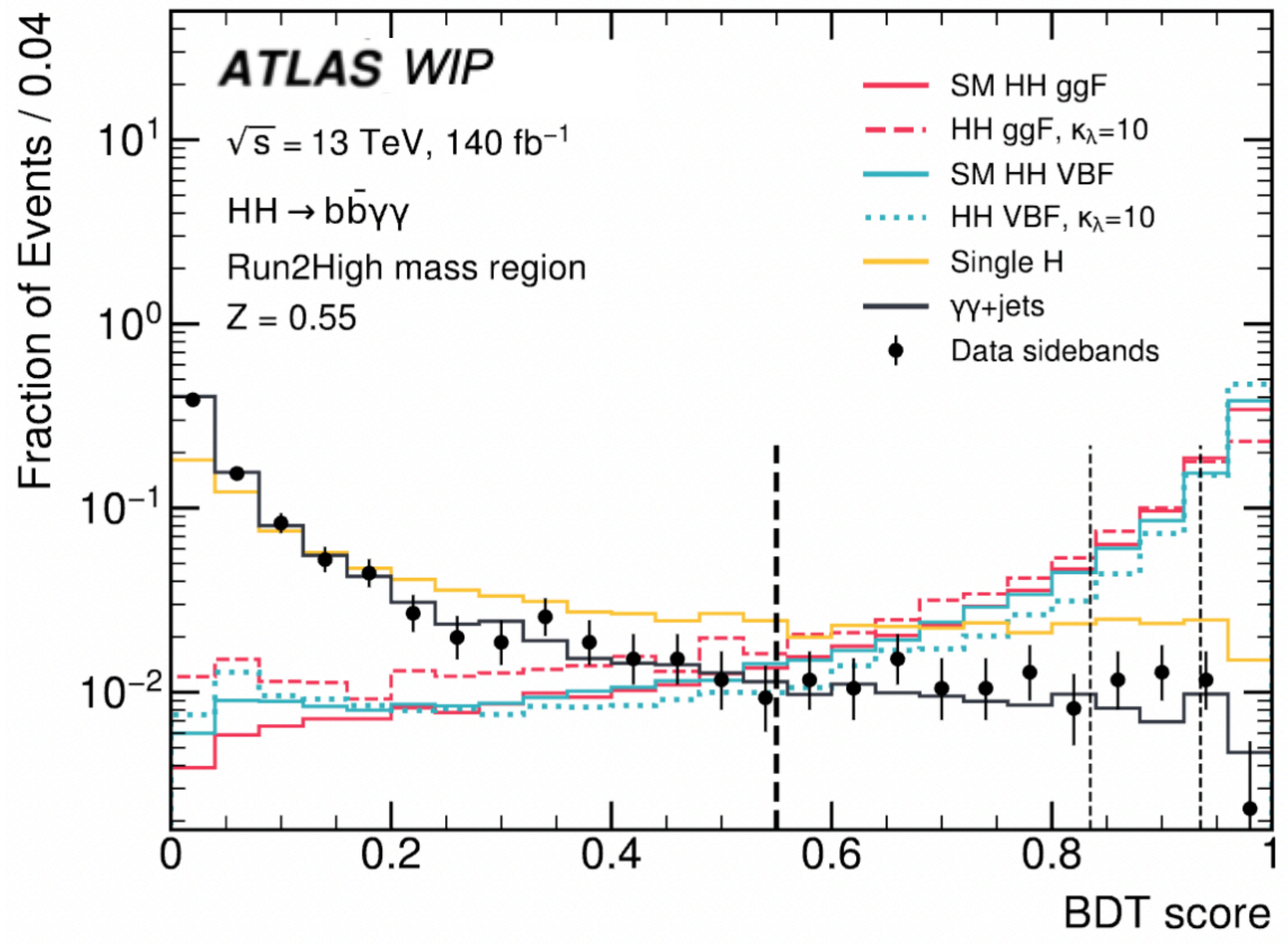
Legacy: $\kappa_\lambda \, \epsilon \, [-2.8, 7.8]$

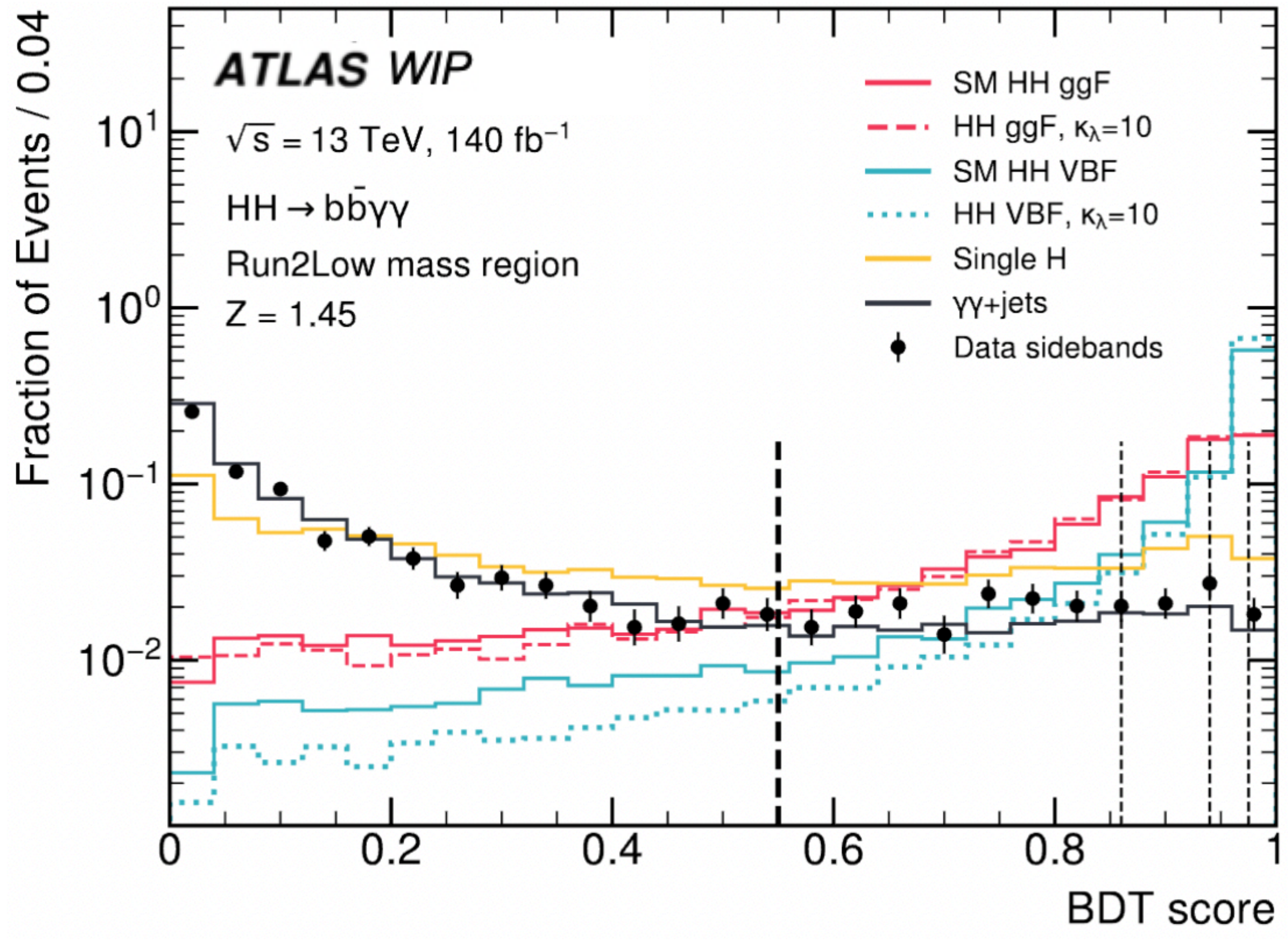
Current: $\kappa_\lambda \, \epsilon \, [-2.2, 7.3]$

Conclusion and outlook

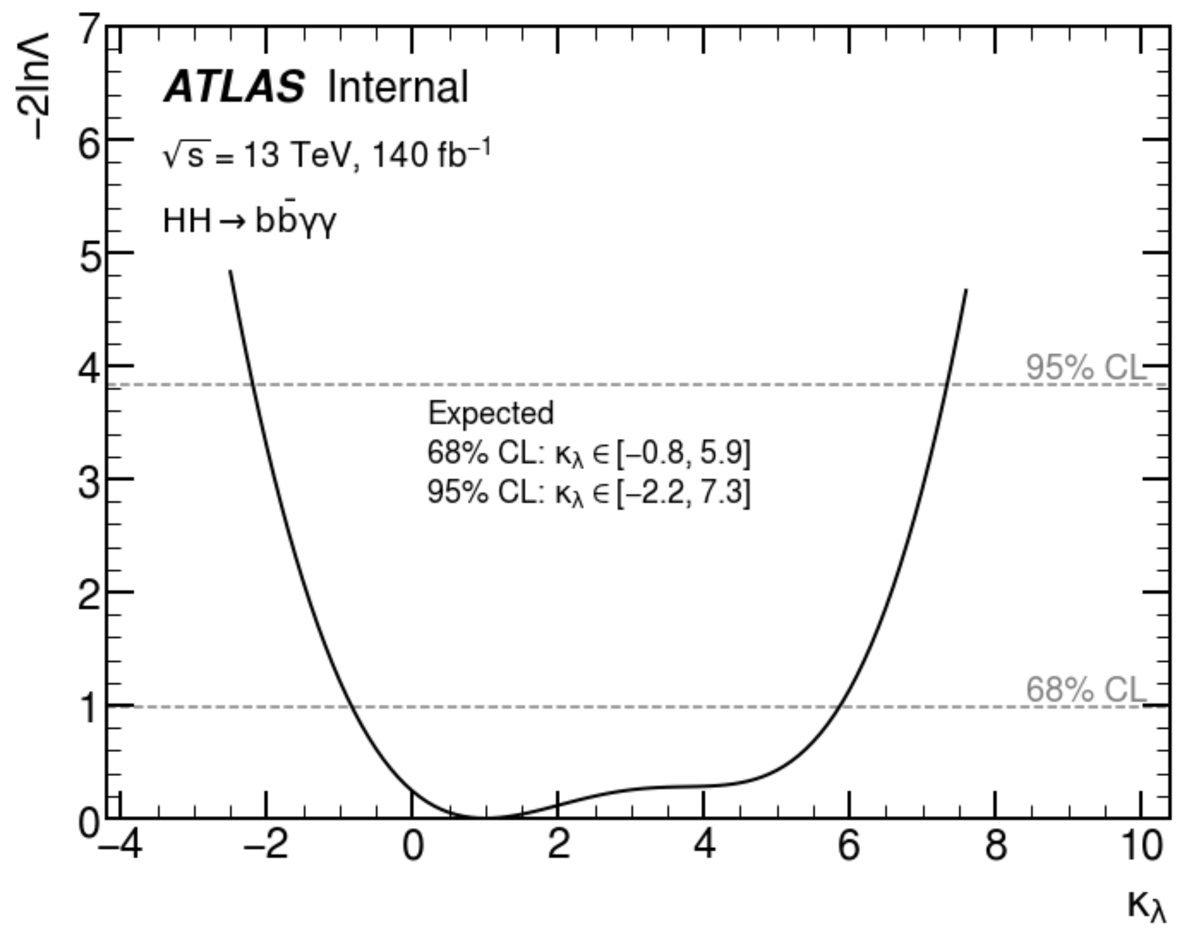
- $HH \to \bar{b}b\gamma\gamma$ analysis aims to constrain μ_{HH} and κ_λ
- First results are already show improvement over the Run 2 legacy analysis
- R&D will boost sensitivity even further
- Not so distant future: full Run 3 data and then HL-LHC bring us closer to observing diHiggs

Backup


ATLAS WIP
√s = 13 TeV, 140 fb⁻¹
HH → bb̄γγ
Run2High mass region
Z = 0.55
SM HH ggF
HH ggF, κλ=10
SM HH VBF
HH VBF, κλ=10
Single H
γγ+jets
Data sidebands
Fraction of Events / 0.04
BDT score


ATLAS WIP
√s = 13 TeV, 140 fb⁻¹
HH → bb̄γγ
Run2Low mass region
Z = 1.45
SM HH ggF
HH ggF, κλ=10
SM HH VBF
HH VBF, κλ=10
Single H
γγ+jets
Data sidebands
Fraction of Events / 0.04
BDT score

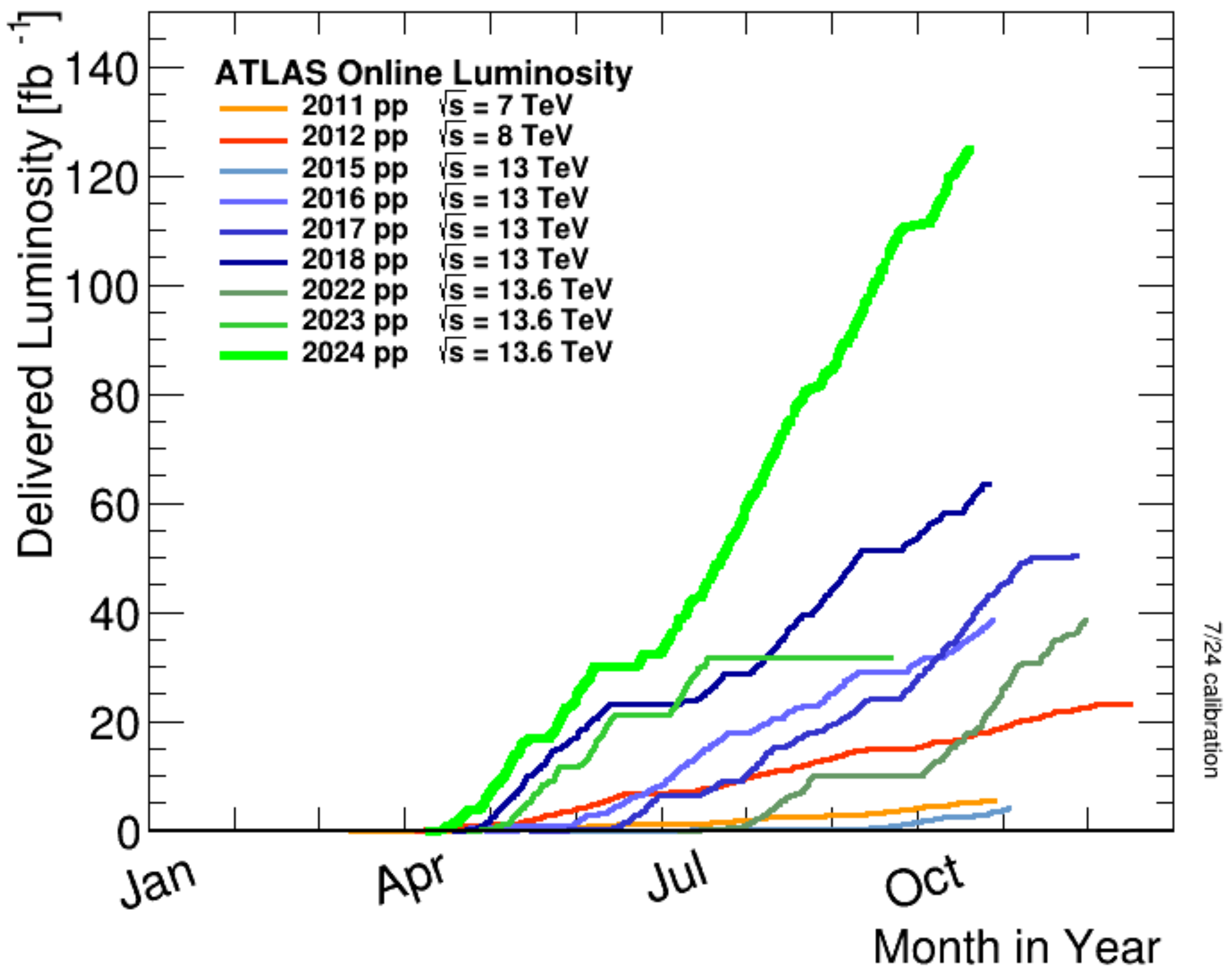
Backup



Expected limits @ 95% CL: $\kappa_\lambda \epsilon [-2.2, 7.3]$

Expected limits legacy analysis @ 95% CL: $\kappa_\lambda \epsilon [-2.8, 7.8]$

Backup



ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
2022 pp √s = 13.6 TeV
2023 pp √s = 13.6 TeV
2024 pp √s = 13.6 TeV
Delivered Luminosity [fb^{-1}]
0
20
40
60
80
100
120
140
Jan
Apr
Jul
Oct
Month in Year
7/24 calibration