

FJPPN project HEP_17

A path toward the discovery of the Higgs-pair production in ATLAS (ATLAS HH)

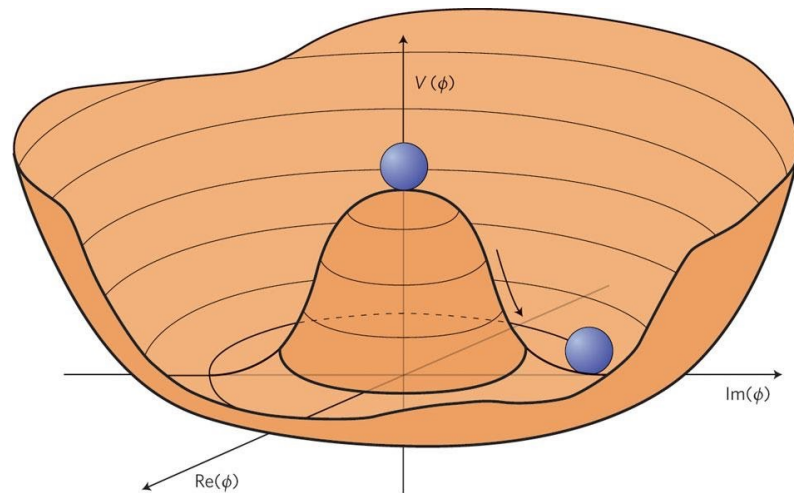


Yu Nakahama (KEK)
Tatsuya Masubuchi (Osaka)
Marco Delmastro (LAPP)



Nicolas Berger (LAPP)
Djamel Boumediene (LPC)
Louis D'Eramo (LPC)

*2025 Joint workshop of FKPPN and TYL/FJPPN
Nantes (France), 14/5/2025*

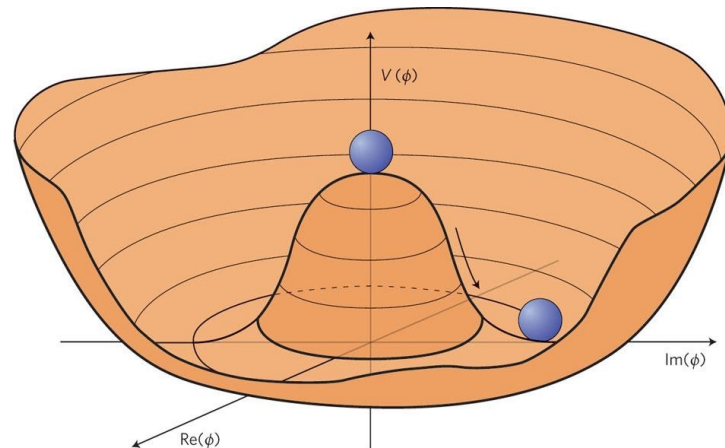


Why?

- In SM, Higgs boson self-coupling strength related to quartic term in energy potential of Higgs field, responsible for EW symmetry breaking...

✓ **Last missing piece of SM!**

- ✓ Understanding connect to multiple phenomena (e.g. nature of early universe phase transition, vacuum meta-stability, ...)

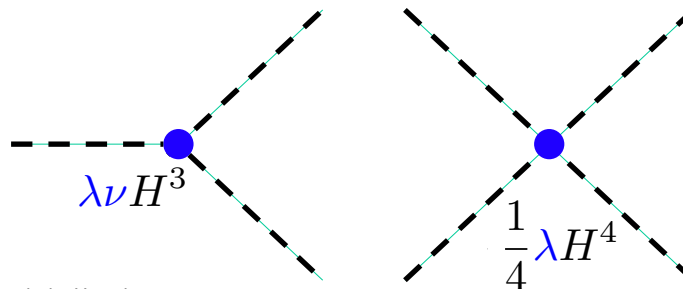


$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$V(\Phi) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda_\nu H^3 + \frac{1}{4} \lambda H^4$$

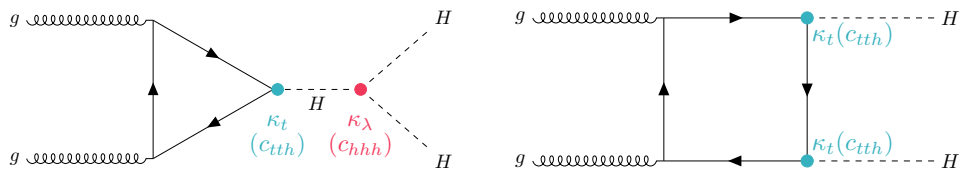
$$m_H = \sqrt{2}\mu = \sqrt{2\lambda\nu}$$

$$\nu = \frac{\mu}{\sqrt{\lambda}} = \frac{m_W}{g} = 246 \text{ GeV}$$

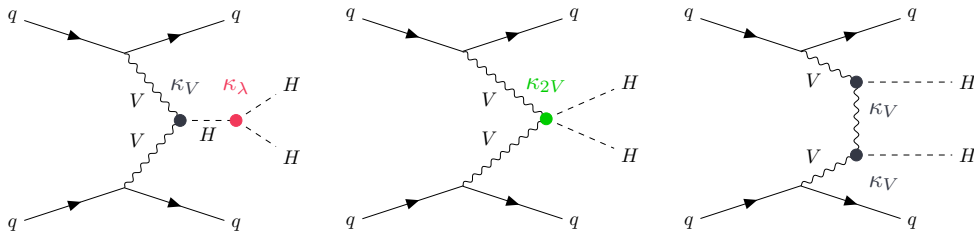


Measuring Higgs self coupling at LHC

Gluon fusion $\sigma_{\text{ggF}}(\text{pp} \rightarrow \text{HH}) = 31.05 \text{ fb @ 13 TeV}$



VBF $\sigma_{\text{VBF}}(\text{pp} \rightarrow \text{HH}) = 1.726 \text{ fb @ 13 TeV}$



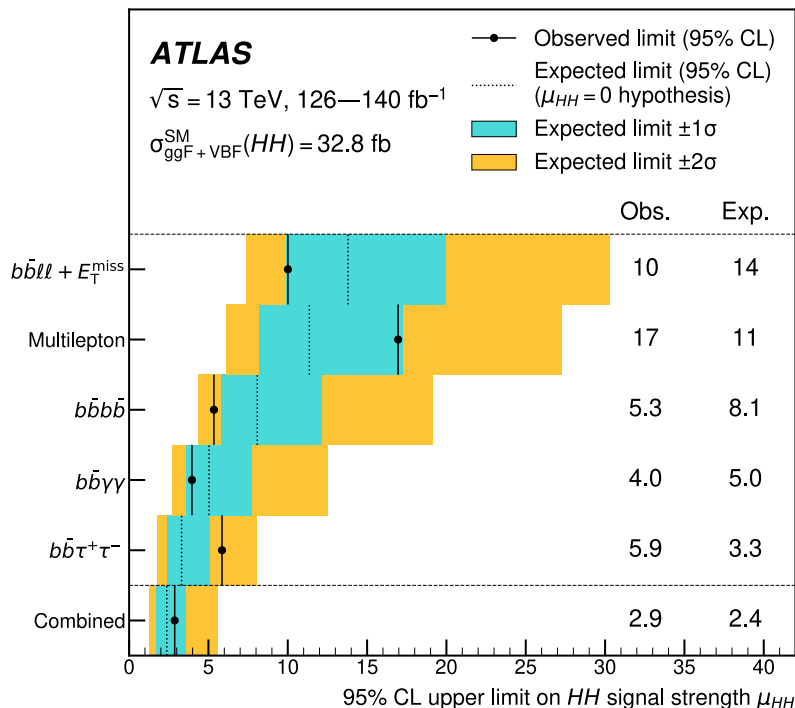
Many channels, different sensitivities...

	$b\bar{b}$	WW^*	$\tau^+\tau^-$	ZZ^*	$\gamma\gamma$
$b\bar{b}$	34%				
WW^*	25%	4.6%			
$\tau^+\tau^-$	7.3%	2.7%	0.39%		
ZZ^*	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

Current experimental limits on inclusive HH cross section

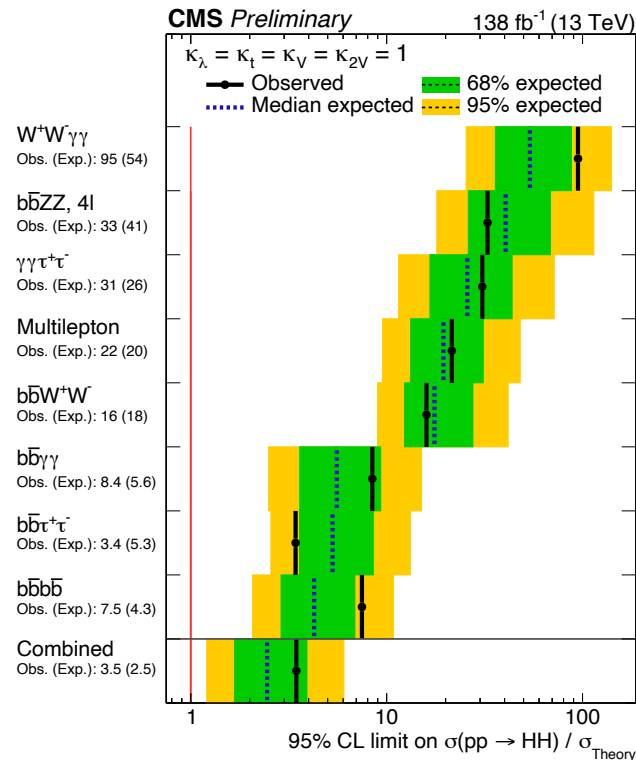
[Phys. Rev. Lett. 133 \(2024\) 101801](#)

[CMS PAS HIG-20-011](#)



ATLAS: **2.9** xSM (exp 2.4 xSM)

Limits calculated for assumption of no HH production ($\mu_{HH} = 0$)



CMS: **3.5** xSM (exp 2.5 xSM)

Run 2 “legacy” expected **significance of $\mu_{HH} \sim 1.0$ standard deviations** for each experiments

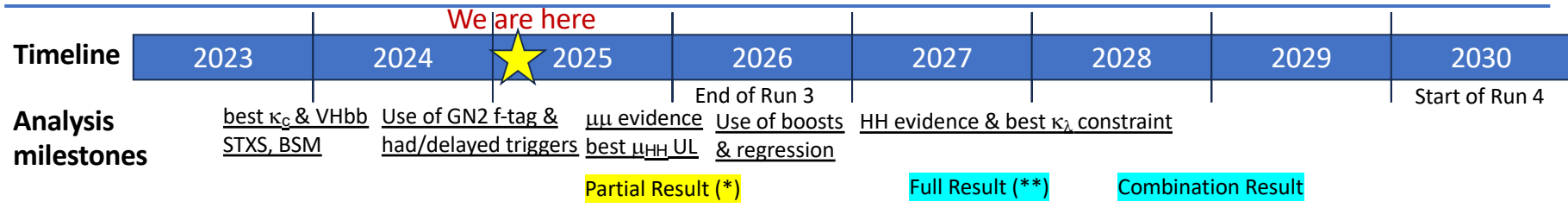
The TYL HEP_17 project



A **path** toward the **discovery** of the Higgs-pair production in ATLAS

- Launched in 2024
- Aiming to exploit the potentiality of the LHC Run 3
- Several younger collaborators (post-doc, PhD students)
 - ✓ Excellent opportunity for ECR training

Japan	France
Nakahama, Yu (KEK)	Marco Delmastro (LAPP)
Masubuchi, Tatsuya (Osaka University)	Nicolas Berger (LAPP)
Kugo Rina (Osaka University, PhD)	Zhibo Wu (LAPP, postdoc)
Kita Sayuka (Tsukuba University, PhD)	Oleksii Kurdysh (LAPP, postdoc)
Kazuki Kojima (KEK, postdoc)	Gianna Loeschcke Centeno (LAPP, postdoc)
<i>I postdoc at Osaka from October 2025</i>	<i>I PhD at LAPP from October 2025</i>
	Djamel Boumediene (LPC)
	Louis D'Eramo (LPC)
	Arthur Lafarge (LPC, PhD)



From the FJPPN 2024 proposal...

The aim of this project is to build up a new France-Japan collaboration toward the HH discovery and the measurement of the Higgs self-coupling, through a series of coherent ATLAS analyses with $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ final states with 400 fb^{-1} data in Run 2 and Run 3. The milestones are as follows:

- 2024: ramp-up and consolidate individual analyses; prepare harmonized analysis framework, study trigger usage, and, establish reconstructions of boosted or soft objects using novel machine learning;
- 2025: establish the methodology to measure the self-coupling constant, and make public results with a partial dataset;
- 2026: conclude the publications of individual analyses with the full dataset;
- 2027: combine the results of the ATLAS $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ analyses with the $b\bar{b}b\bar{b}$ one, and initiate the combination with corresponding results in CMS, to conclude on the Higgs self-coupling constraint at LHC Run 3.

First result this week!

Official ATLAS+CMS
Run 2 HH combination
ongoing...

A support from FJPPL (TYL) in 2024 is critical for timely ramp-up of two harmonized analyses with EM and Hadronic final states, discussing together in-person to settle analysis details. Marco and Louis will visit KEK to work with Yu, Tatsuya and several early-career colleagues in Japan, and Tatsuya and Yu will visit LAPP and LPC to work with Marco, Nicolas, Djamel, Louis and other experts.

First project workshop in
LAPP in February 2025

What have we already done? What do we plan to do?

- Network active in designing ATLAS di-Higgs measurements exploiting Run2 + partial Run 3 LHC data:
 - ✓ **HH→bbyy channel** (KEK, Tsukuba, LAPP), HH→bbbb (Osaka)
 - ✓ **HH→bbττ** (Tokyo)
 - ✓ Development of relevant improvement in the reconstruction and calibration of objects relevant to these analyses (i.e. b-jet tagging, photon identification)
- **2024 dedicated to ramp-up and consolidate individual analyses**, prepare harmonized analysis framework, study trigger usage, and establish reconstructions of boosted or soft objects
- **2025 will see the release of first results** (HH→bbyy Run 2 + partial Run 3 measurement +EFT interpretation, Run2 ATLAS + CMS diHiggs combination).

- **Specific goals for 2025**
 - ✓ **Improved Photon ID** development and calibration (Tsukuba + LAPP);
 - ✓ **b-tagging for GN3**, baseline for Run 3 (LAPP + Tokyo);
 - ✓ **EFT interpretation for HH→yybb**, to be possibly extended to bbbb and bbττ on a longer timescale using the same parameterization (LAPP);
 - ✓ General work on **combinations (H+HH)** and **global EFT interpretation** (LAPP + Osaka)
- **Request of TYL support:** 2 travels/stays to KEK and/or Osaka & 2 travels/stays to LAPP and/or LPC

In-person interactions

The screenshot shows a web browser displaying an Indico meeting page. The browser's address bar shows 'indico.in2p3.fr'. The page title is 'Meeting FJPPN 2024 project HEP_17'. The meeting is scheduled for 'Monday Feb 24, 2025, 11:00 AM → 5:00 PM Europe/Paris' and is organized by 'Marco Delmastro (LAPP)'. The meeting is set to 'Public' and the user 'M. Delmastro' is logged in. The agenda includes:

- 11:00 AM → 12:00 PM Introduction**
 - Application2024-AT...
 - 11:00 AM Japan**
 - Speaker: Yu Nakahama Higuchi (KEK)
 - LAPPMeeting24Feb...
 - 11:20 AM France**
 - Speaker: Marco Delmastro (LAPP)
 - Delmastro_2025-02-...
- 12:00 PM → 1:30 PM Lunch** (1h 30m)
- 1:30 PM → 4:00 PM Brainstorming on common interests and plan**
 - 1:30 PM Progress in the first year**
 - b-tagging calibration at LAPP
 - Speaker: Zhibo Wu (LAPP)
 - LAPPBtagCalib202...

Progress in the first year

b-tagging calibration at LAPP

Speaker: Zhibo Wu (LAPP)

LAPPBtagCalib202...

Boosted HH->bbbb+GN2X tagger

Speaker: Rina Kugo (Osaka University)

rkugo_20250224.pdf

HH->yybb EFT interpretation at LAPP

Speaker: Oleksii KURDYSH (LAPP)

slide_14_EFT_statu...

HH->bbyy

Speaker: Sayuka Kita (Tsukuba University)

FJPPN_SayukaKita...



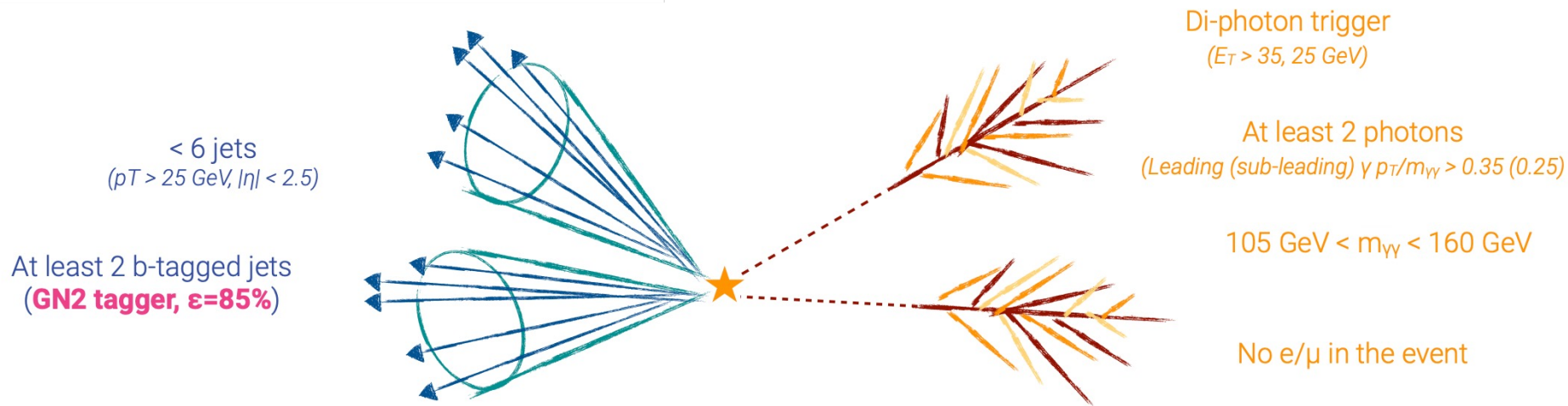
Fresh from the oven: Run 2 + partial Run 3 $HH \rightarrow b\bar{b}\gamma\gamma$

- First ATLAS result using 308 fb⁻¹ data!

ATLAS-CONF-2025-005

✓ 140 fb⁻¹ Run 2 data (2015—2018, 13 TeV)

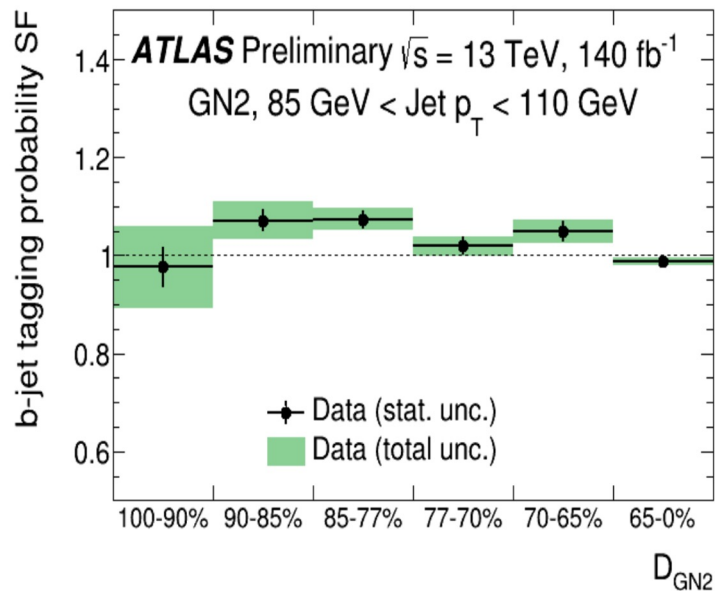
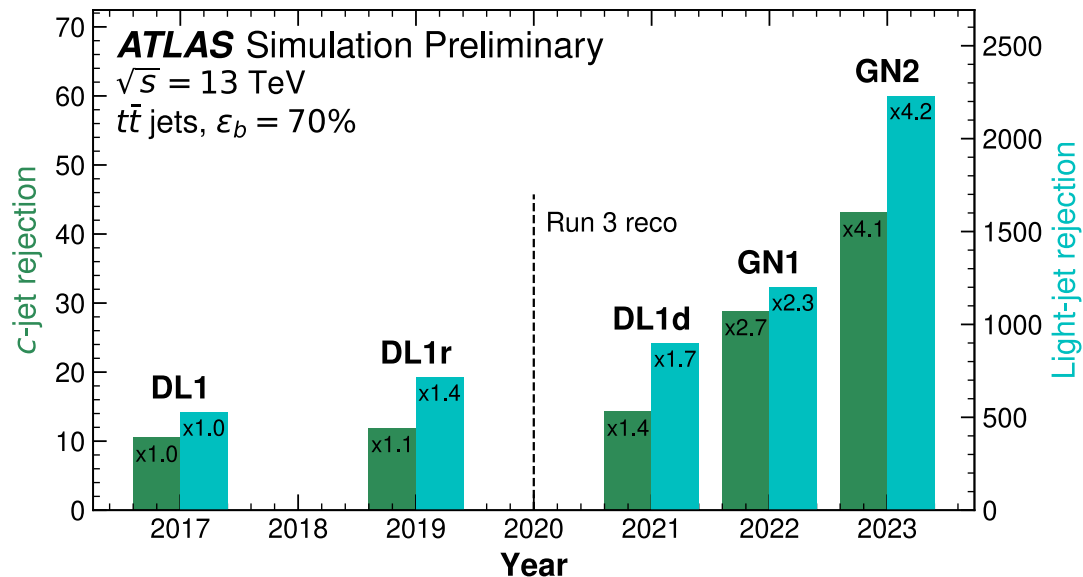
✓ 168 fb⁻¹ Run 3 data (2022—2024, 13.6 TeV)



Sketch courtesy of E. Brost

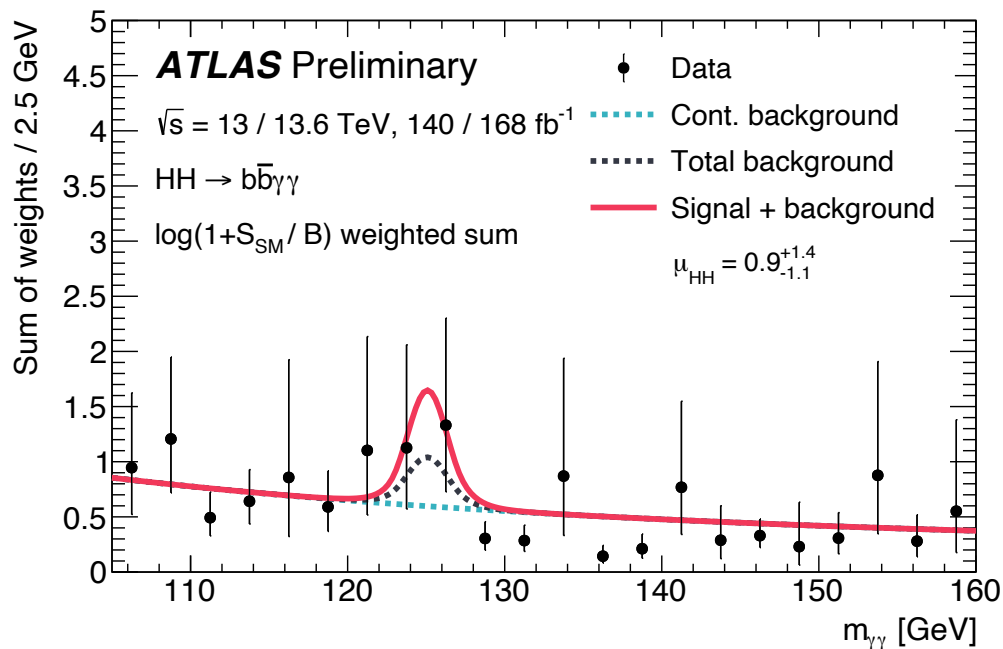
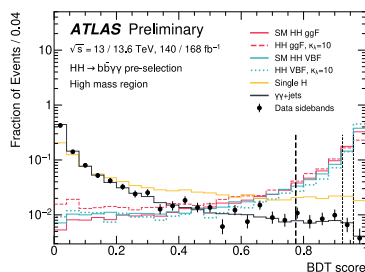
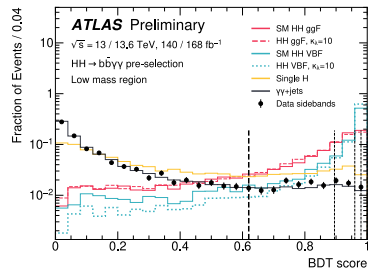
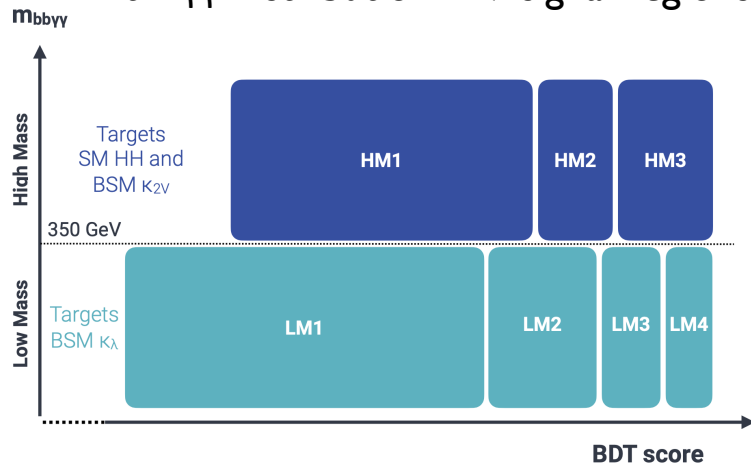
Run 2 + partial Run 3 HH→bb $\gamma\gamma$: new b-tagging

- Major improvements to b-tagging algorithms...
 - ✓ ... and a significant effort to calibrate them!



Run 2 + partial Run 3 HH→bbγγ: analysis overview

- Separate BDTs trained in low and high mass regions.
 - ✓ Input variables : kinematics of photons, b-jets, bb-system, missing ET, HT, 'single-topness'...
 - ✓ Fit m_{γγ} distribution in 7 signal regions based on BDT score



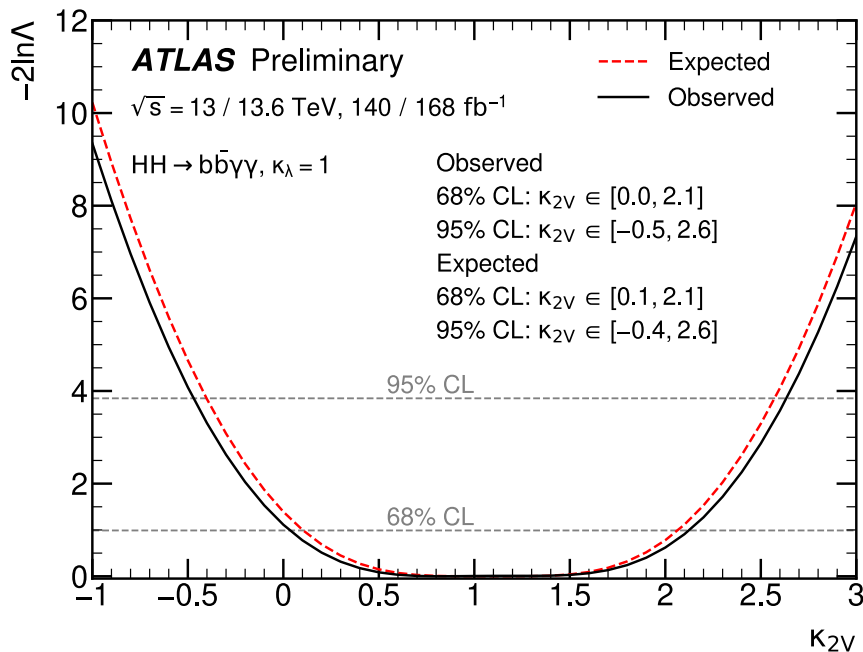
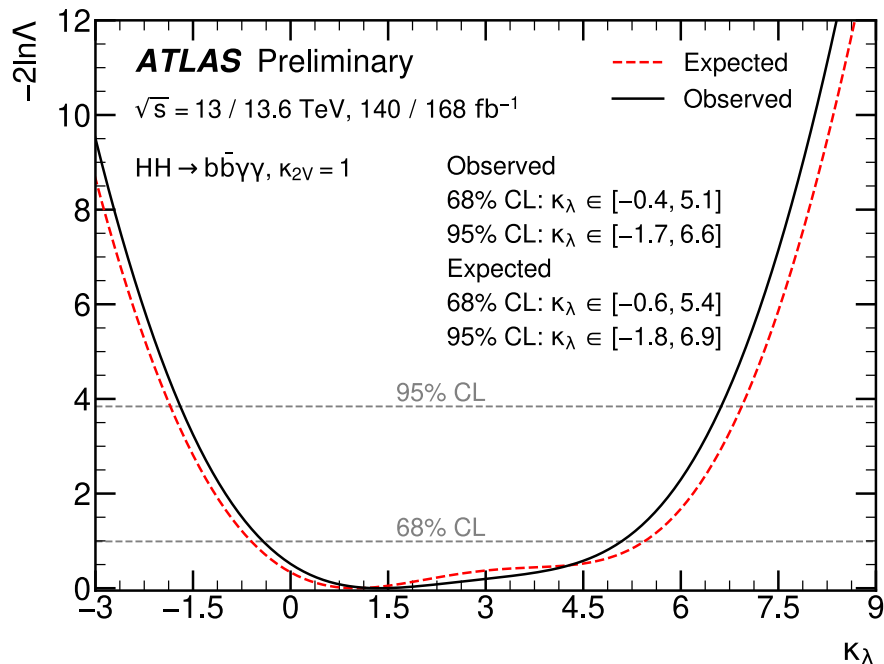
Run 2 + partial Run 3 HH→bbγγ: results!

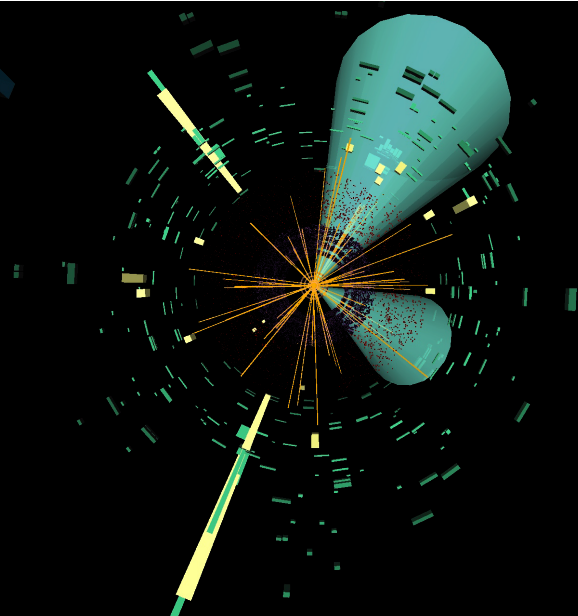
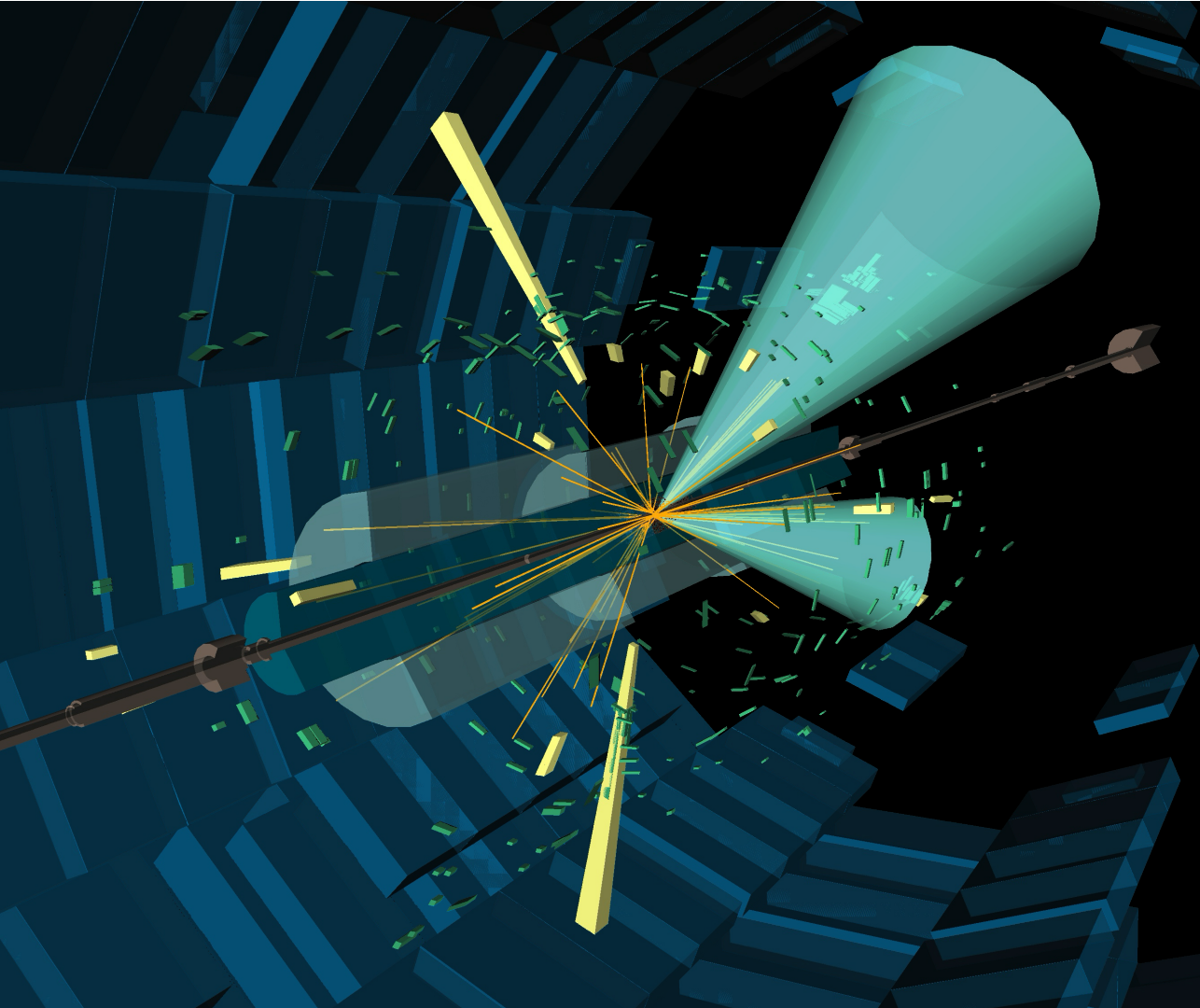
- Observed significance of SM HH: 0.8σ

✓ Expected significance: 1.0σ

- Observed signal strength: $\mu_{HH} = 0.9 + 1.4/-1.1$

✓ Expected upper limit on μ_{HH} (assuming $\mu_{HH} = 0$):
 $2.6 \times \text{SM}$





ATLAS
EXPERIMENT

Run: 456118

Event: 301264610

2023-07-08 06:59:42 CEST

Toward Full Run 3 HH→bbyy analysis: new Photon ID

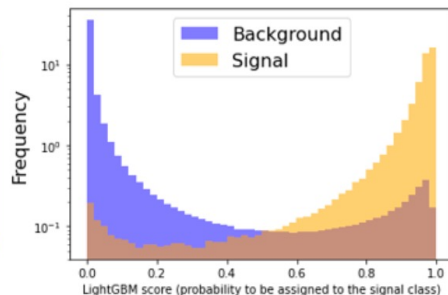
Objective: to investigate the possibility of improving the analysis sensitivity by introducing a **Boosted Decision Tree** (BDT) based Photon Identification algorithm.

Tested on the $HH \rightarrow \gamma\gamma\bar{b}b$ channel

- The BDT (from LightGBM package) was trained on **Pythia (direct) γj** and **Pythia (JFXX) jj MC samples**.

Used **mc16 Run2 Rel21** tuples provided by the Photon ID group for the BDT training

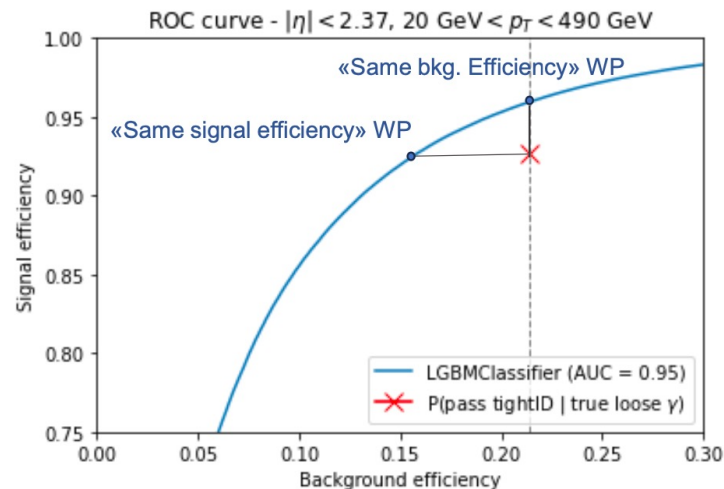
- signal** → the leading reco photon matched to *true* γ in Pythia γ -jet;
- background** → the leading reco photon matched to *true* background in Pythia JF.



Training variables:

- Photon kinematics:** η , p_T ;
 - Shower shapes:** R_η , R_ϕ , $\omega\eta_2$, frac_1 , $\omega\eta_1$, ωots_1 , R_{had} , R_{had_1} , E_{ratio} , ΔE ;
 - Photon conversion:** convRadius , convType .
- Reweighting:** reweighting the η and p_T distribution of the Py γ -jet signal onto the Py JF background

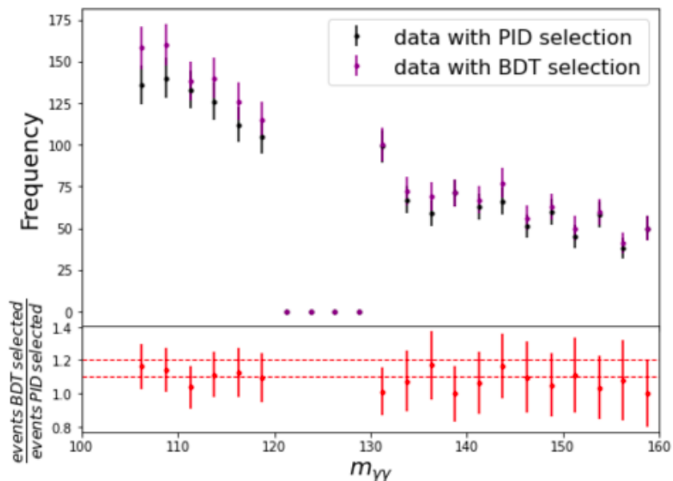
BDT does not have to learn from signal and background distributions of kinematic variables.



Toward Full Run 3 HH→bbyy analysis: new Photon ID

The **expected improvement** in SM signal yield with the new "Same bkg efficiency" w.r.t. the tight ID WP is **~ 6 – 8%**

An increase of data events in the sidebands considering the purities in data (majority of true γ in the sidebands).



	BDT-based photonID analysis	Nominal Legacy analysis
μ_{HH}	4.54	4.86

→ improvement of **~ 7% w.r.t. Legacy stat. only analysis!**

→ ~ 1.2% improvement on k_λ , no improvement found on k_{2V} .

- Add the photonID scores of both photons in the training
→ move away from the fixed WP and let the analysis BDT make good use of the ID scores.
- Re-optimize the categories on the new BDT to maximise the expected di-Higgs significance.

Conclusions

- FJPPN project HEP_17 “A path toward the discovery of the Higgs-pair production in ATLAS” well underway!
 - ✓ 2024 dedicated to ramp-up and consolidate individual analyses
 - ✓ First results published in 2025: $HH \rightarrow b\bar{b}\gamma\gamma$ Run 2 + partial Run 3 measurement!
 - ✓ More to come shortly ($HH \rightarrow b\bar{b}\gamma\gamma$ EFT interpretation, Run2 ATLAS+CMS diHiggs combination, ...)
- Network well connected both with analysis and performance work (e.g. b-tagging, photon identification), crucial to sensitive results!
- A significant part of the network is composed by ECR (post-docs, students), we want to reinforce their opportunity to collaborate (e.g. short stays in France and Japan)