# Improving the sensitivity of the trilinear Higgs boson self-coupling measurement in the $bb\tau\tau$ decay channel at the HL-LHC and FCC-hh

**Bastien Voirin**
Supervised by **Claude Charlot** at **LLR**

LLR Interns Seminar
June 2025

## The Higgs and the electroweak symmetry breaking

**Anderson-Brout-Englert-Guralnik-Hagen-Higgs-Kibble-'t Hooft mechanism** (1964)

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(4 degrees of freedom)

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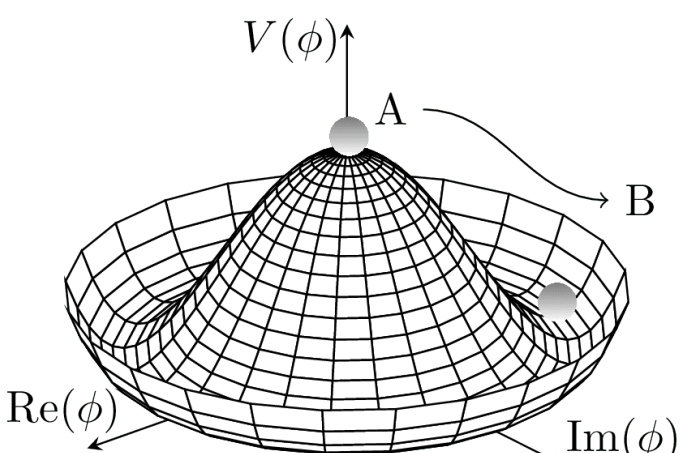

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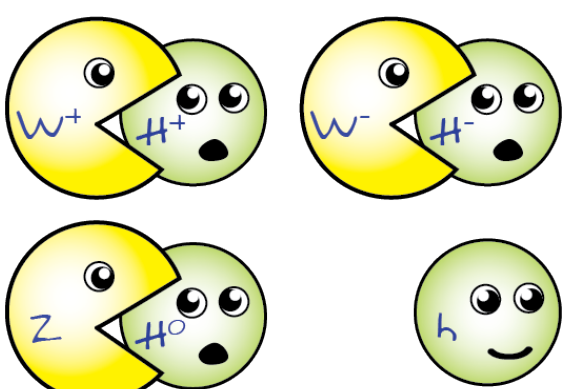


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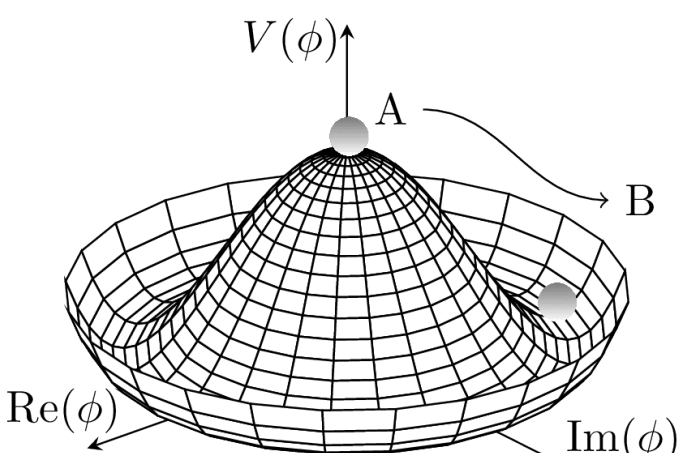

## Shape of the Higgs potential via Higgs boson pair production

- SM Higgs potential $V_{\mathrm{SM}}(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$ is **not the only possible shape**
- $\lambda = m_h^2/2v^2 \approx 0.129$ is **fully determined** by the
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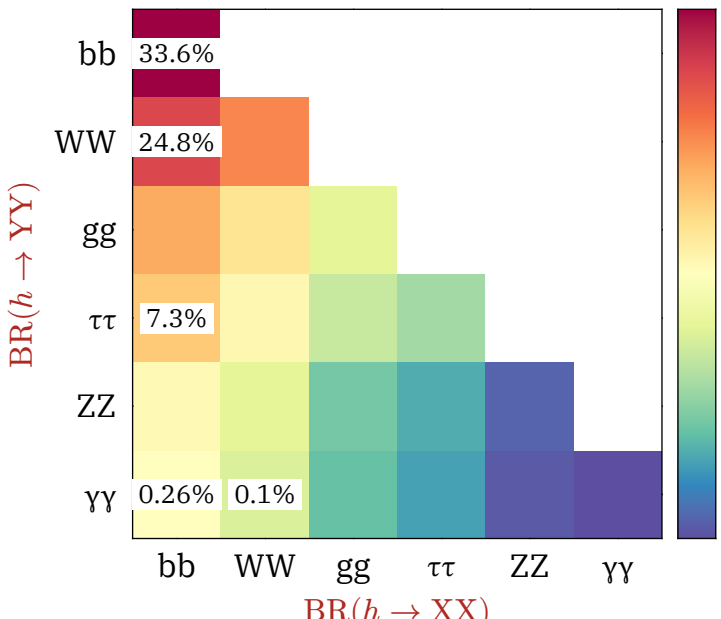
**Direct measurement** through the **rate of $\boldsymbol{hh}$ production** as some of them come from $\boldsymbol{h \to hh}$

## Status of Higgs boson pair production at CMS (https://arxiv.org/abs/2207.00043)




$h \to b\bar{b}$ has the largest branching ratio

$b\bar{b}\,b\bar{b}$, $b\bar{b}\,\tau\tau$, $b\bar{b}\,\gamma\gamma$, $b\bar{b}\,WW$, $b\bar{b}\,ZZ$, and multilepton $WWWW$, $WW\tau\tau$, $\tau\tau\tau\tau$

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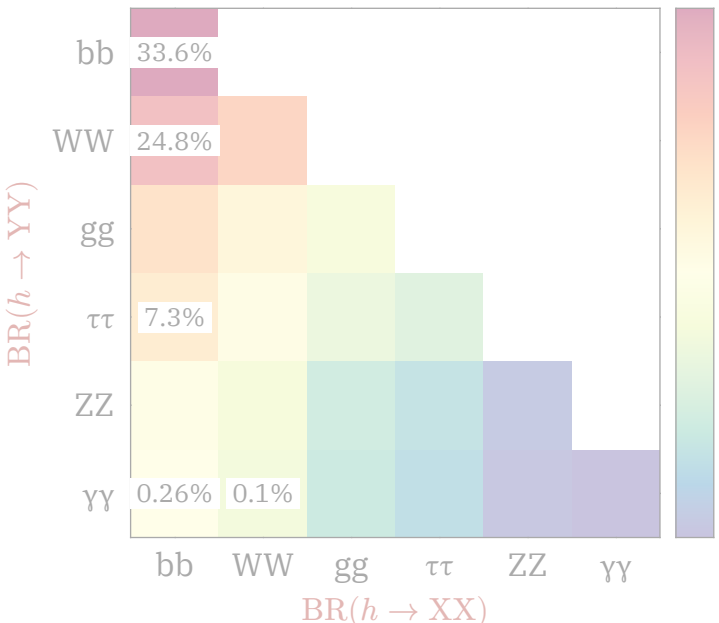


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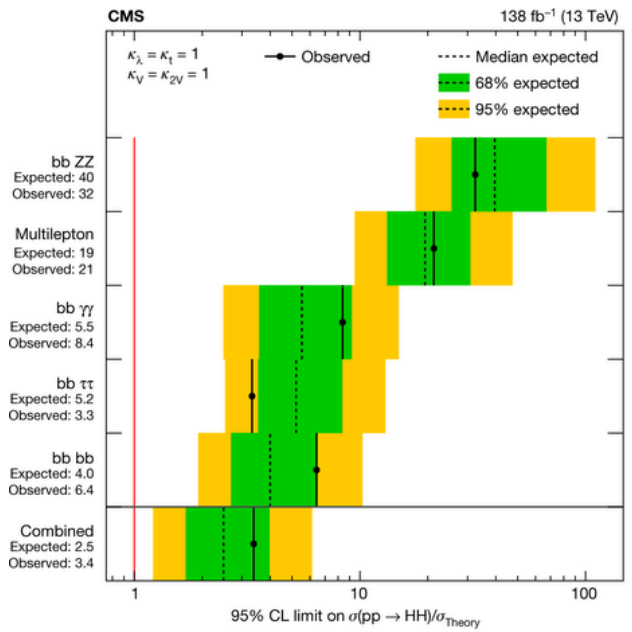
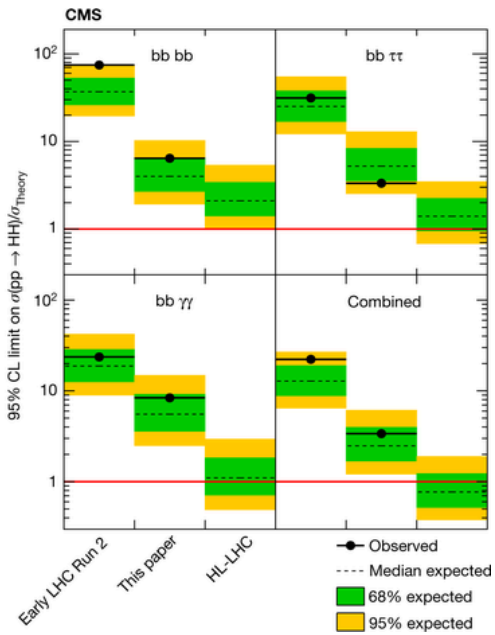


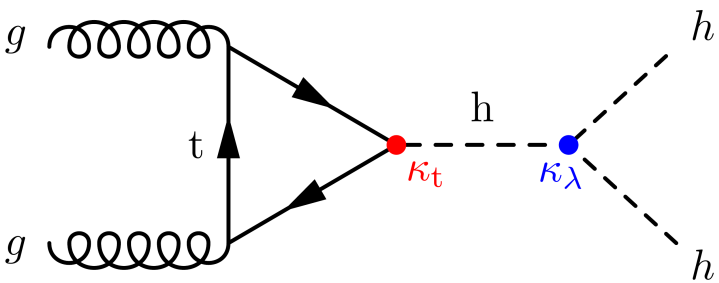




Full Run 2 data ($138\,\text{fb}^{-1}$) $\sigma_{pp\to hh}/\sigma^{\text{SM}}_{pp\to hh} \leqslant 3.4$ at 95% C.L.

HL-LHC ($3000\,\text{fb}^{-1}$) is expected to "establish the SM Higgs boson pair production with a significance of 4 s.d."

## Gluon-gluon fusion (ggF) Higgs boson pair ($hh$) production at the leading order

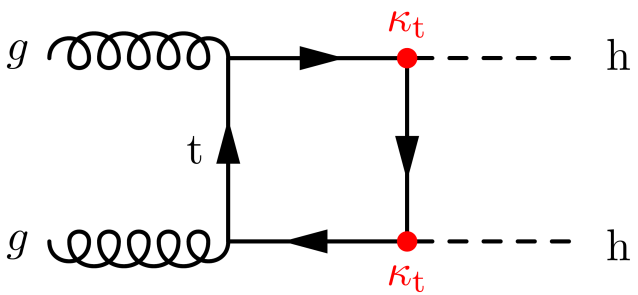
Dominant $hh$ production mode compared to vector boson fusion (VBF), WH/ZH (VH), ttH...




"Triangle" amplitude $\mathcal{A}_\triangle \propto \kappa_t \kappa_\lambda$

$$\kappa_t \equiv y_t / y_t^{\mathrm{SM}}$$

$$\kappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{\mathrm{SM}}$$

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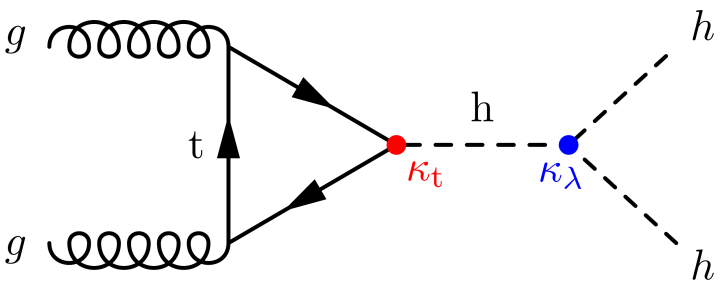


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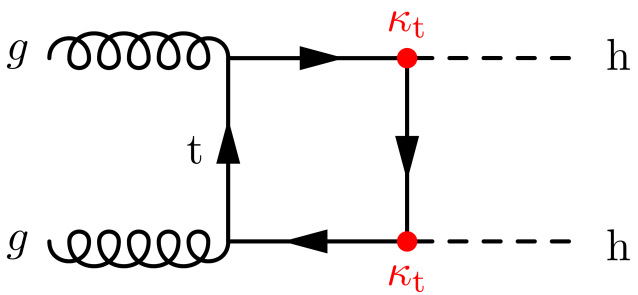


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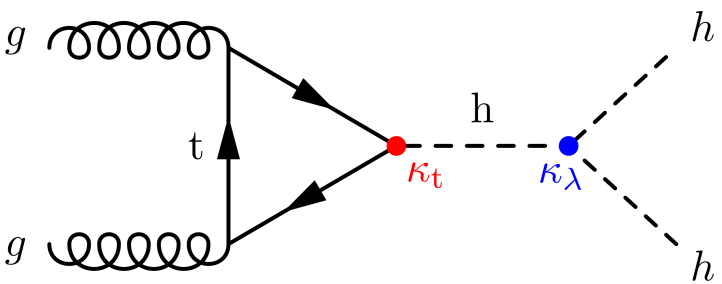


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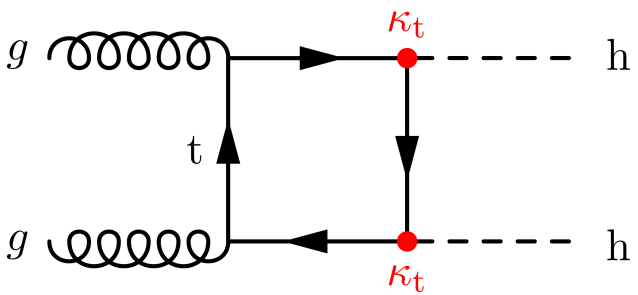


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**Exploit kinematic characteristics to purify the "triangle" contribution from the total $gg \to hh$ process so that the number of observed $gg \to hh$ events becomes more sensitive to $\lambda$**

## Sample production

- **MadGraph5_aMC@NLO** (Monte Carlo event generator) for the
  - $gg \to hh \to b\bar{b}\tau^-\tau^+$ total process (triangle + box + interference)
  - $gg \to h^* \to hh \to b\bar{b}\tau^-\tau^+$ triangle contribution
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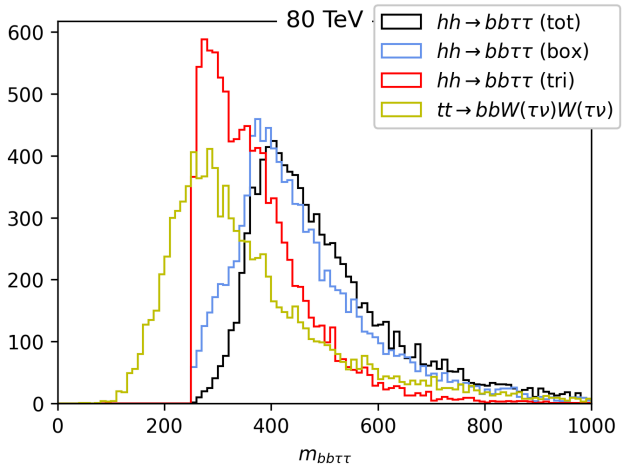
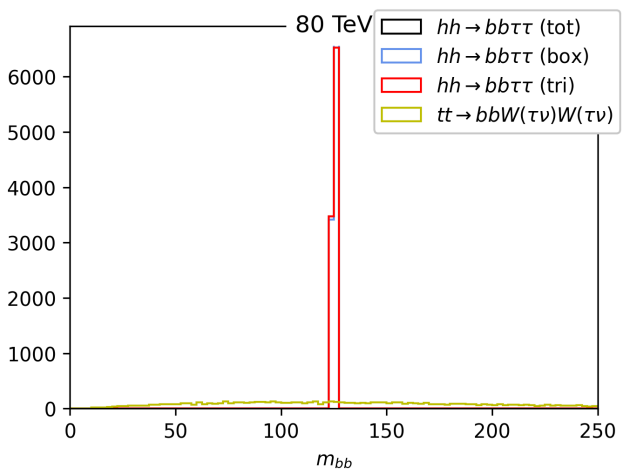
- **DelphesPythia** for the hadronization and fast parametric detector simulation

# Kinematics @ 80 TeV (FCC-hh)



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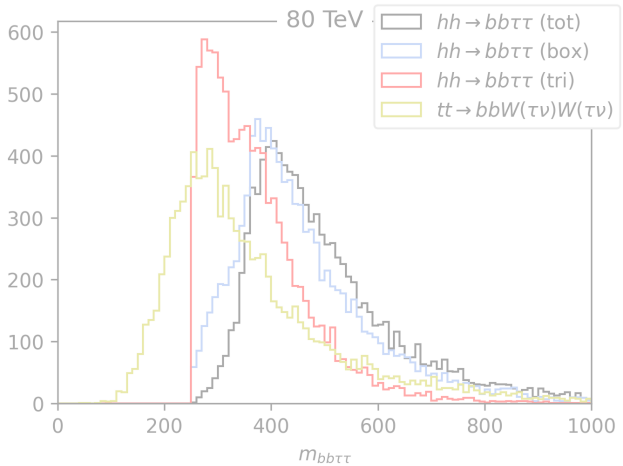


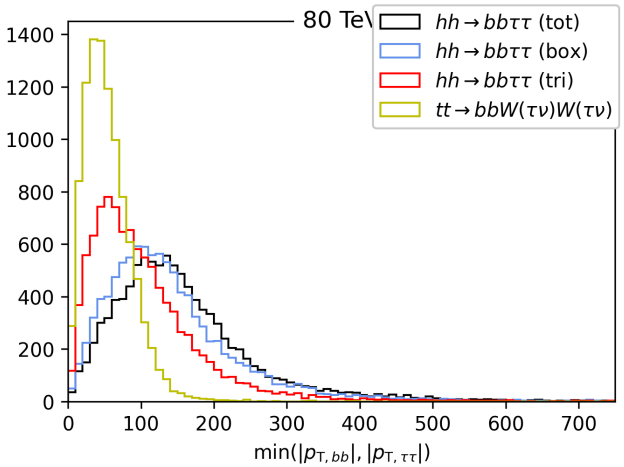


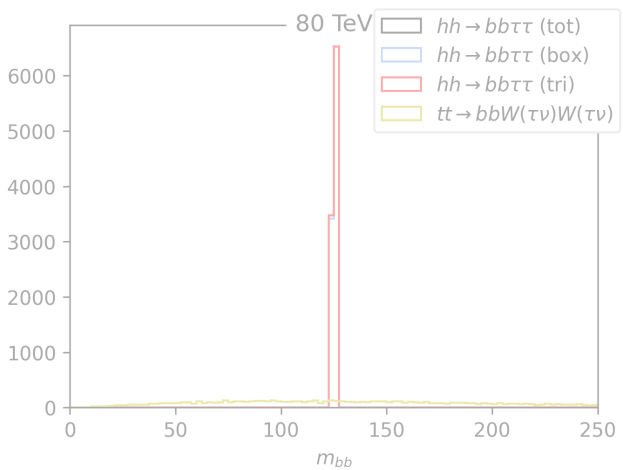


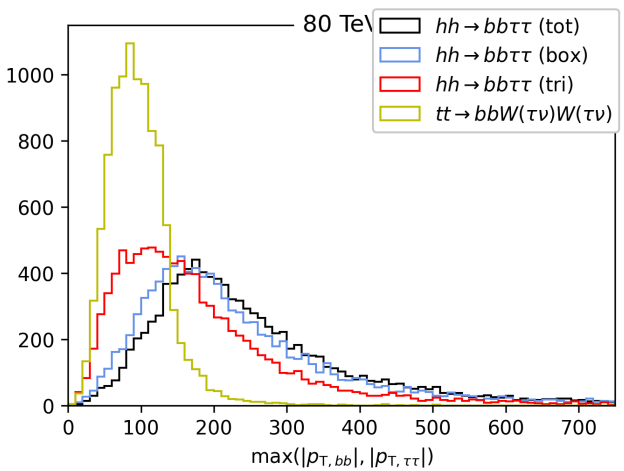

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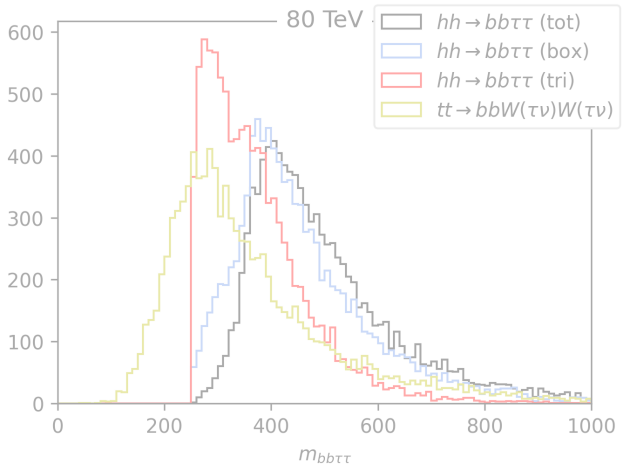


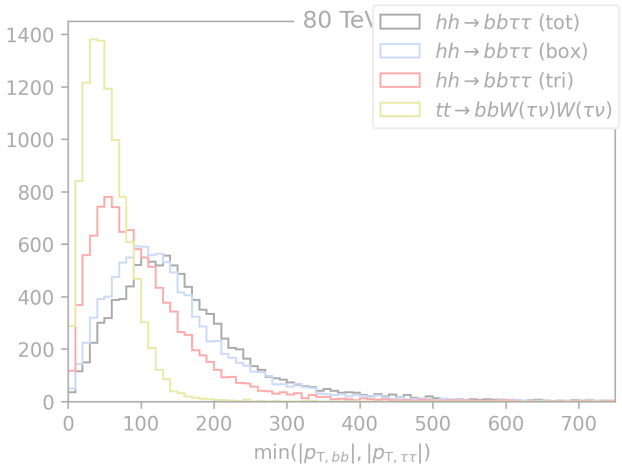


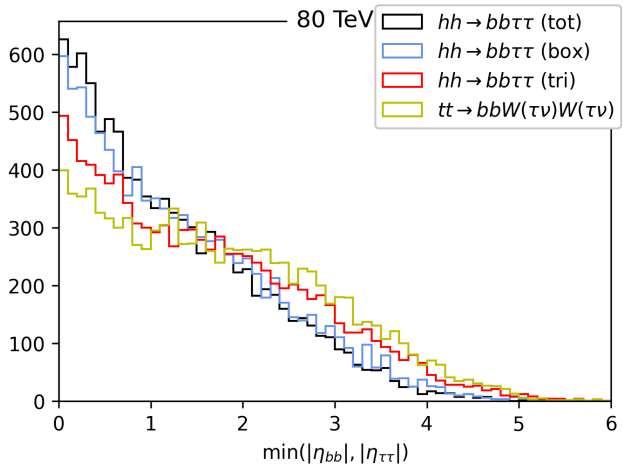


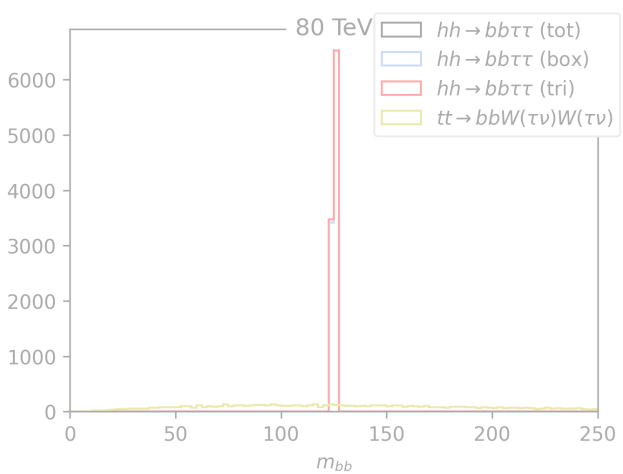


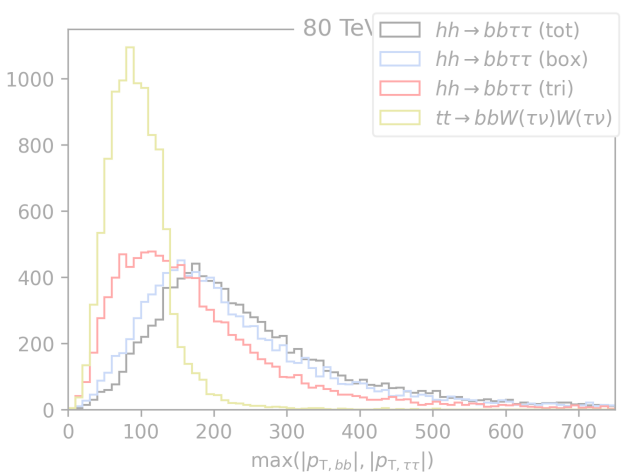


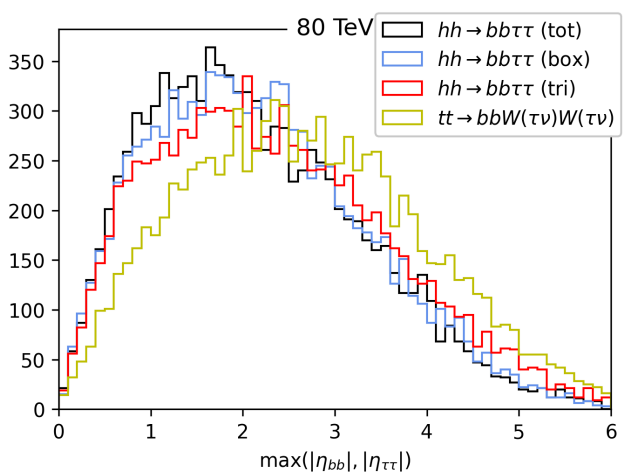

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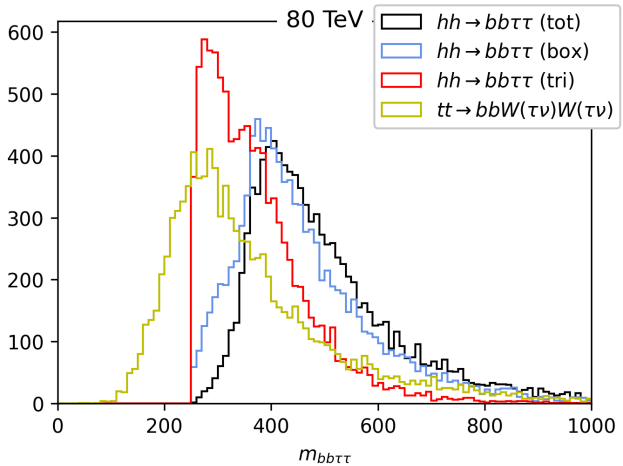
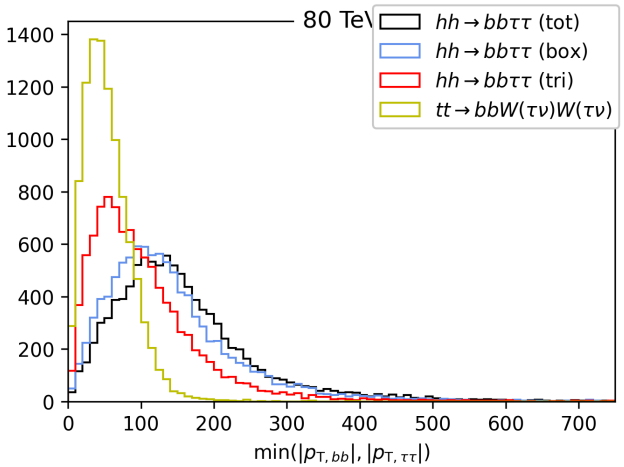
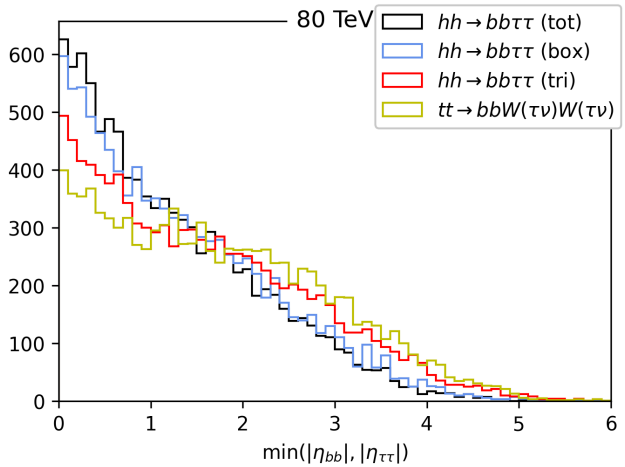
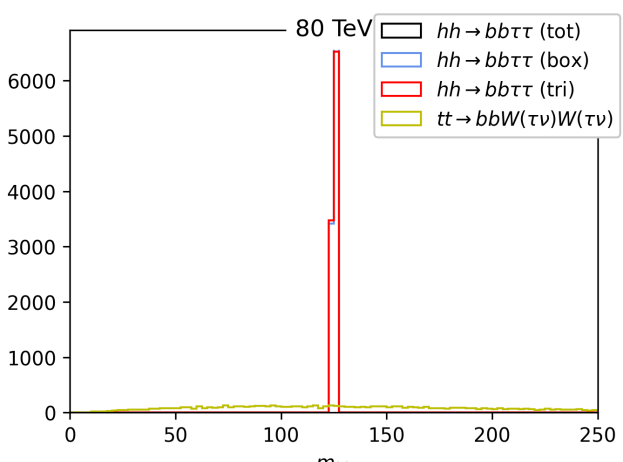
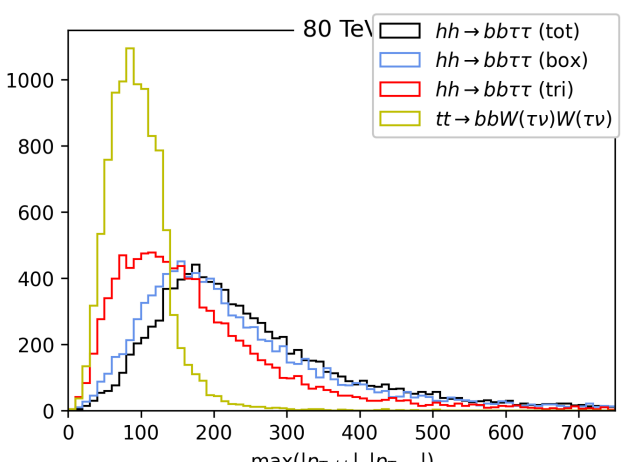
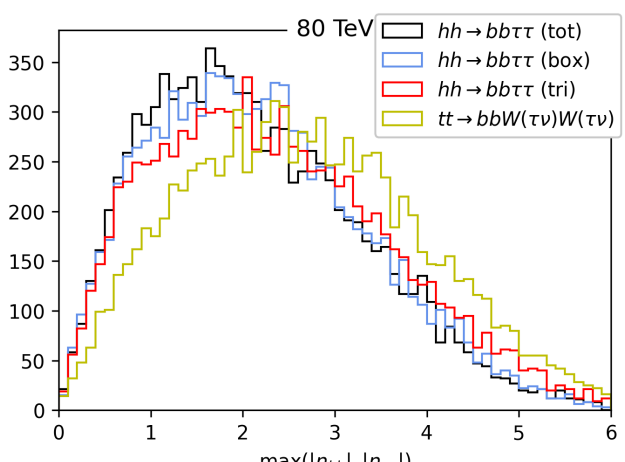


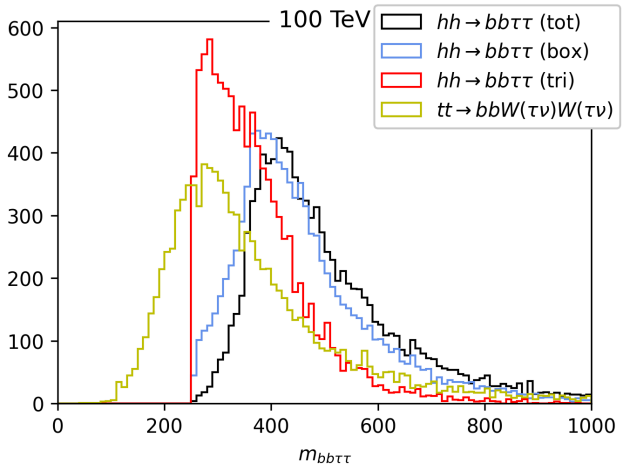



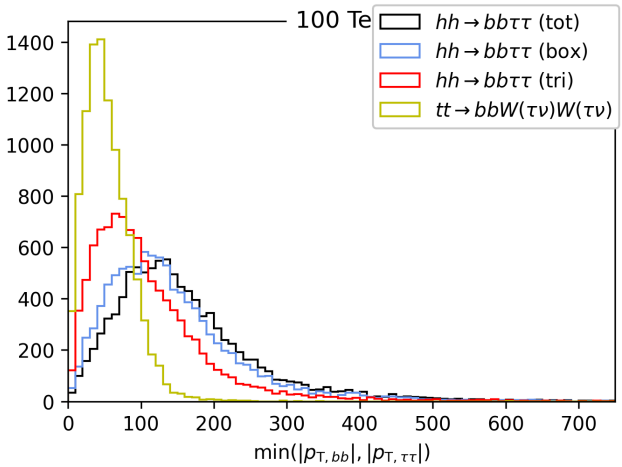



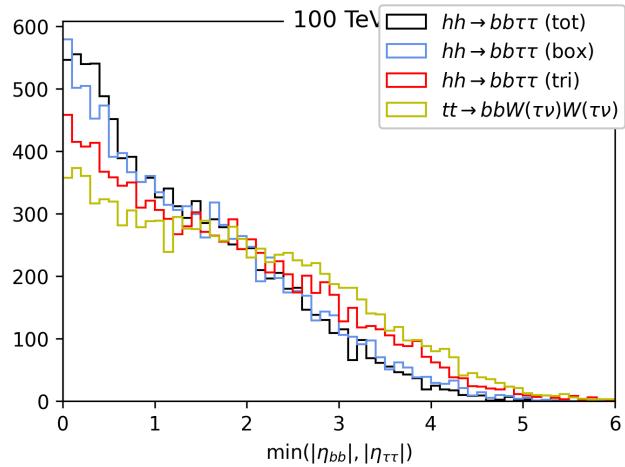



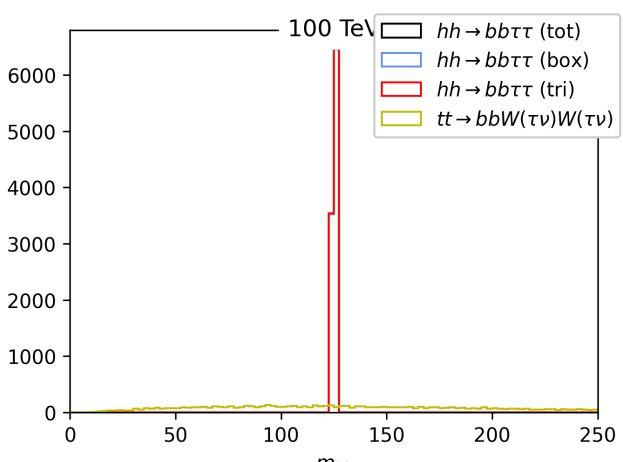



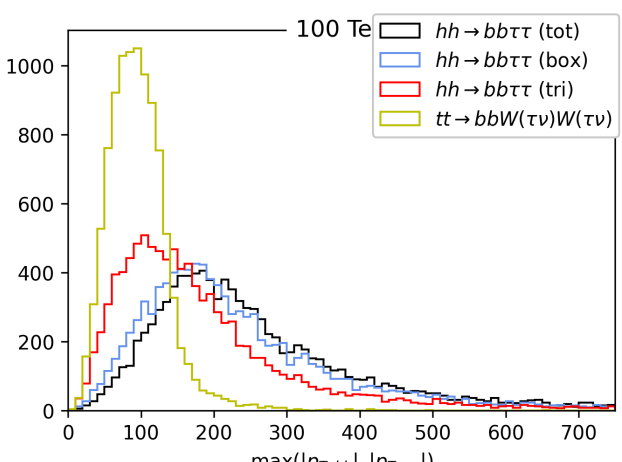
# Kinematics @ 100 TeV (FCC-hh)

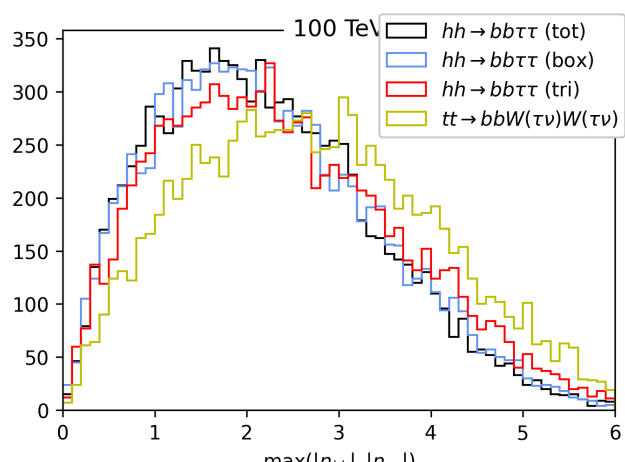


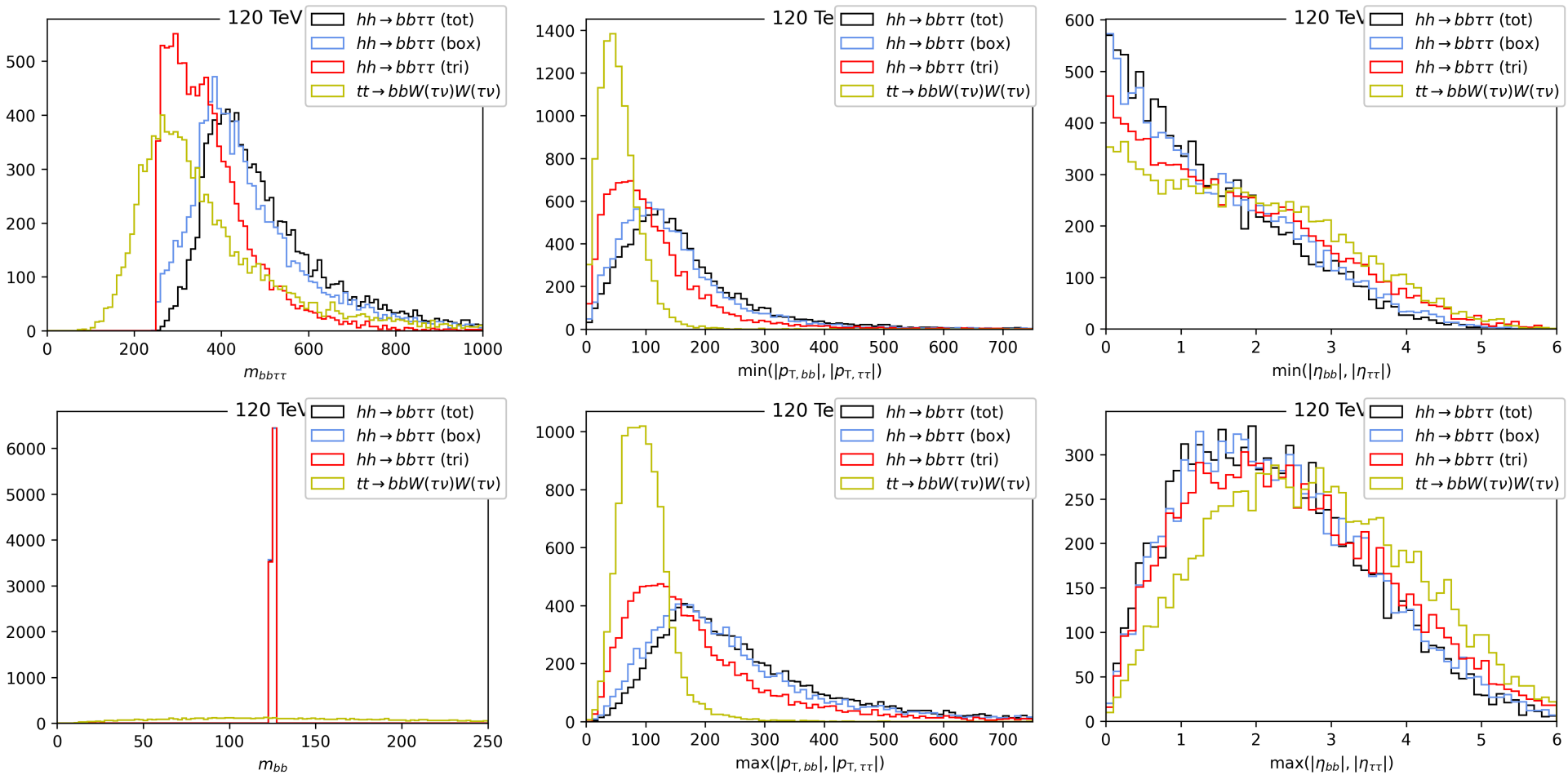



# Kinematics @ 120 TeV (FCC-hh)



## Work In Progress (until August 8)

- Preselection (2 $b$-tagged jets, 2 $\tau$ leptons, $\tau_{\text{had}}\tau_{\text{had}}$ or $\tau_{\text{had}}\tau_{\text{lep}}$, $p_{\text{T}}^{bb}$, $p_{\text{T}}^{\tau\tau}$, $\Delta R$...)
- Fit and scan of negative log-likehood $-2\Delta\ln(L)$ over $\kappa_\lambda$
- $hh$ vs. backgrounds discriminant
- $hh$ triangle vs. other contributions (box, interference) discriminant

# Testing the silicon readout electronics of the High-Granularity Calorimeter (HGCAL) endcaps for the CMS experiment at the HL-LHC

Bastien Voirin
Supervised by **Amina Zghiche** at **CERN**

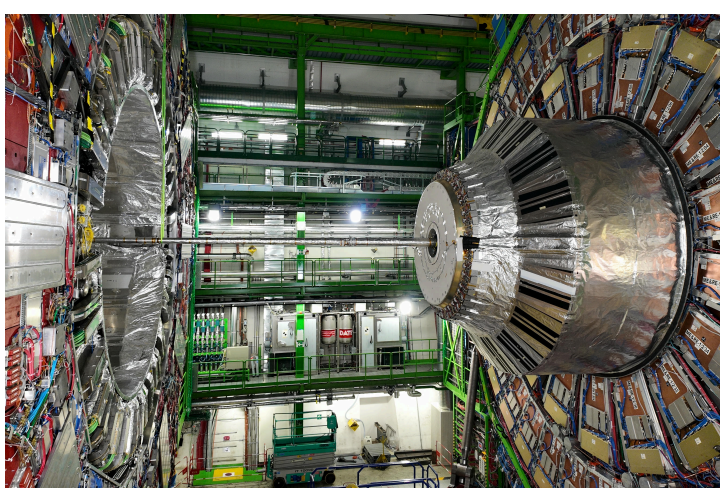
LLR Interns Seminar
June 2025

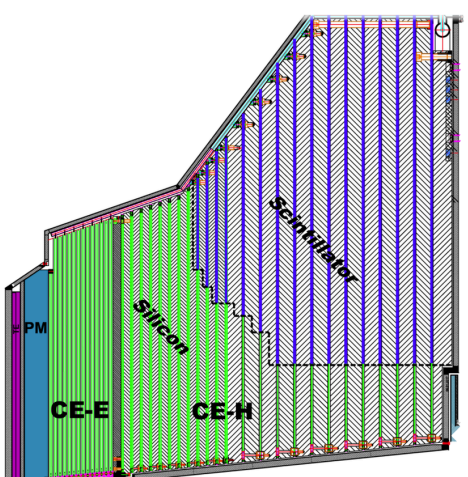
## The High-Granularity Calorimeter (HGCAL) endcaps for CMS at the HL-LHC

- **HL-LHC**, major upgrade of the LHC for the 2030s (way more data, finer $\eta$ and $\phi$ segmentation)

# The High-Granularity Calorimeter (HGCAL) endcaps for CMS at the HL-LHC

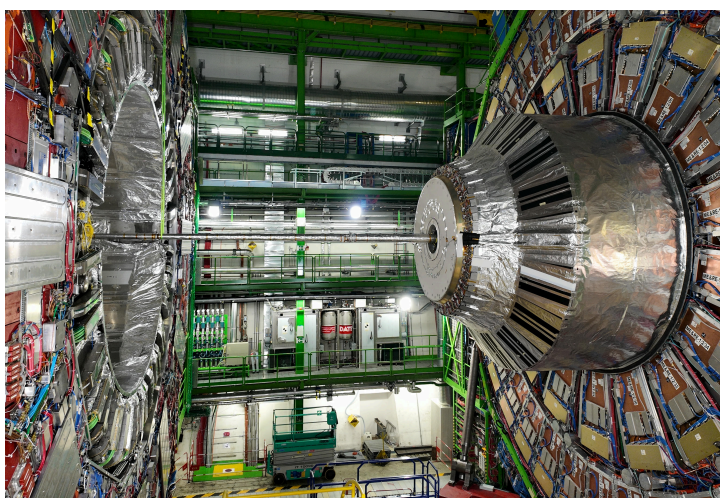
- **HL-LHC**, major upgrade of the LHC for the 2030s (way more data, finer $\eta$ and $\phi$ segmentation)
- **HGCAL**, state-of-the-art electromagnetic and hadronic sampling calorimeter to replace the current CMS endcaps (seen below)

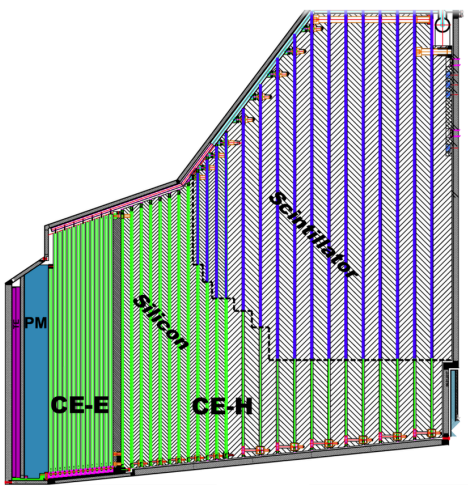




## The High-Granularity Calorimeter (HGCAL) endcaps for CMS at the HL-LHC

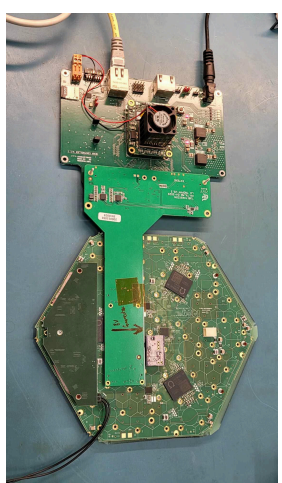
- **CE-E** (electromagnetic)
  Silicon sensors
- **CE-H** (hadronic)
  Silicon sensors (close to the interaction point) and plastic scintillators (far from the interaction point)





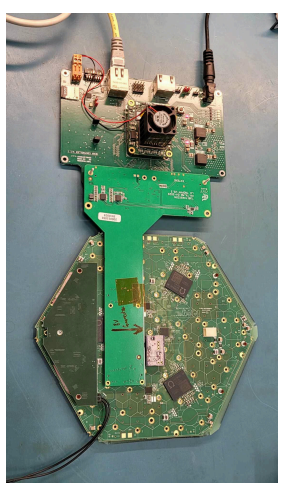
## HGCAL silicon readout electronics

- 27,000 hexaboards and modules to assemble and test
  - in numerous hexaboard assembly facilities
  - at the 6 module assembly centers (**USA**, **China**, **Taiwan**, **India**)

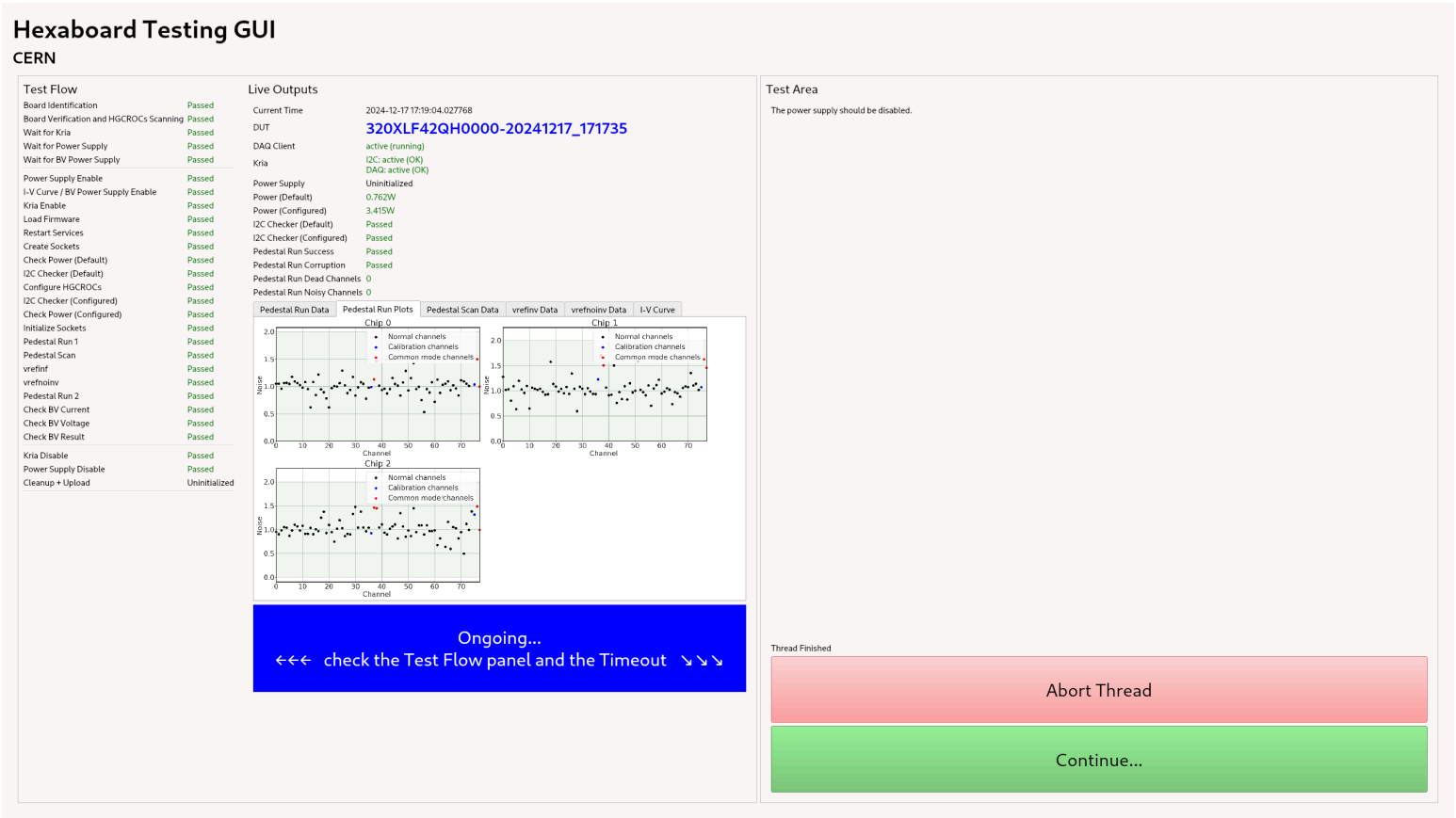


# HGCAL silicon readout electronics

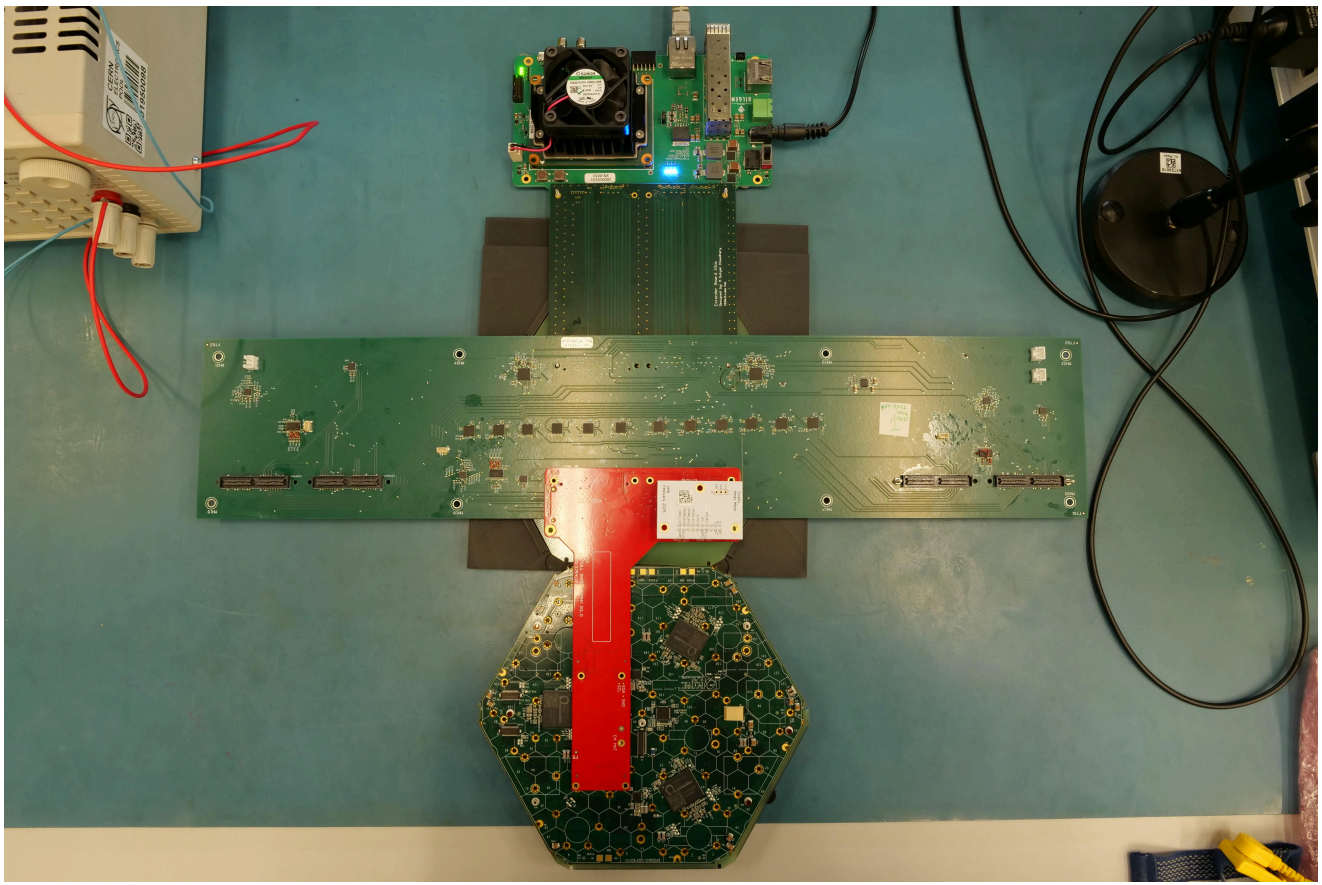
- 27,000 hexaboards and modules to assemble and test
  - in numerous hexaboard assembly facilities
  - at the 6 module assembly centers (**USA**, **China**, **Taiwan**, **India**)
  - at the 2 cassette assembly factories (**CERN** and **Fermilab**)



# Contribution 1/2 — development of the GUI from Alabama University



# Contribution 2/2 — module multiplexer board



# Testing the silicon readout electronics of [illegible] Calorimeter (HGCAL) endcaps for [illegible] y [illegible]-LHC

See Alper's presentation next Monday!

[illegible]na Zghiche at CERN

LLR Interns Seminar
June 2025

```
return;
```