Search for Higgs boson pair production in the $bb\tau\tau$ channel with the CMS experiment

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XXXV International school “Francesco Romano”
on Nuclear, Subnuclear and Astroparticle physics
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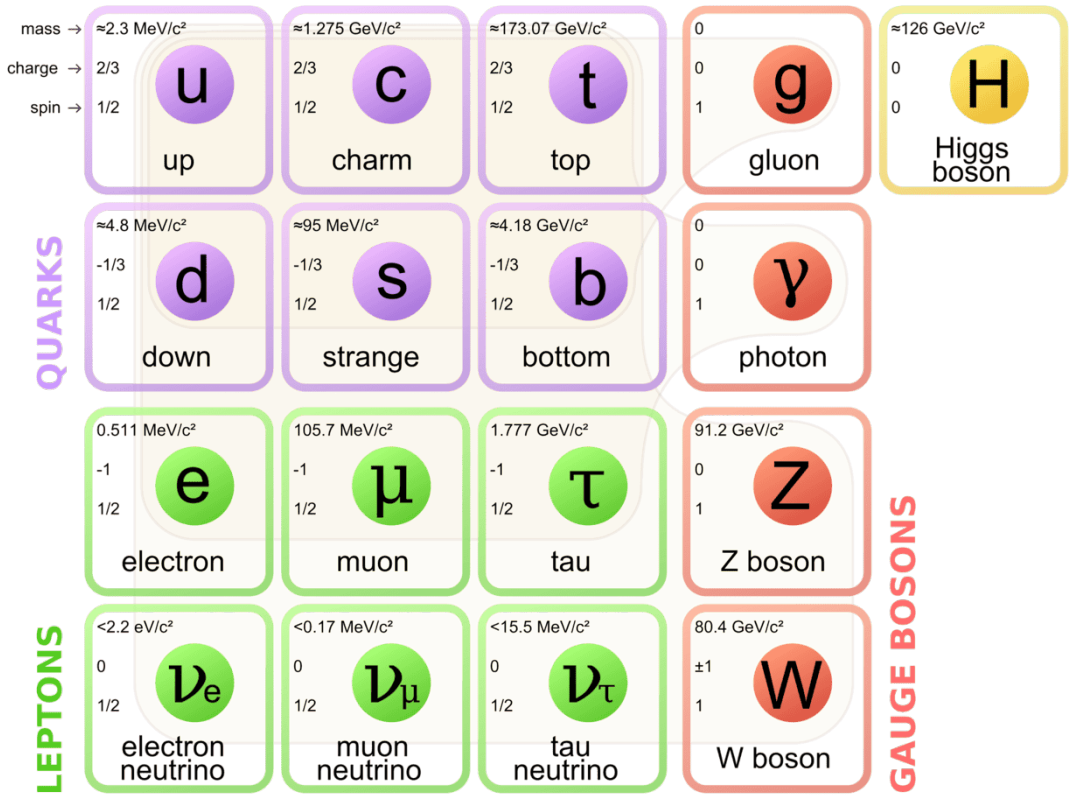
Overview

- The Higgs potential and the Higgs self-coupling
- The di-Higgs production @ LHC
- $\mathrm{HH} \rightarrow bb\tau\tau$: CMS analysis with Run-2 dataset and Run-3 perspectives
- My current work: derivation of scale factors for $b\bar{b}$ taggers
- Conclusions

The Higgs boson in the SM

1960's → Theorization of the **Brout-Englert-Higgs mechanism**
Spontaneous Symmetry Breaking (**SSB**) of the
$\mathbf{SU(2)_L \times U(1)_Y}$ symmetry
→ the **gauge bosons** acquire mass via their interaction with a new scalar field, the **Higgs field**
→ also the **fermions** acquire mass via their Yukawa interaction with the Higgs field

m_H → free parameter in the Standard Model



The Higgs boson discovery

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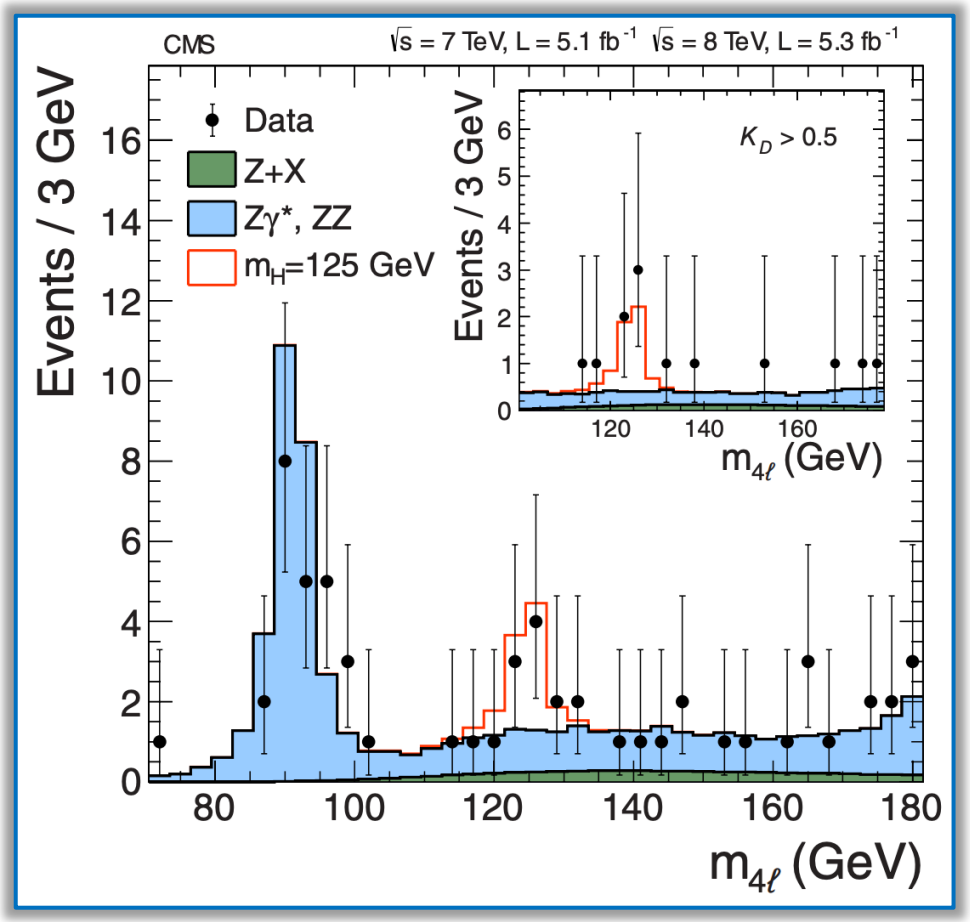
2012 → The **CMS** and the **ATLAS** experiments discovered the Higgs boson **@LHC**

$m_H \approx 125$ GeV → prediction of the **Higgs potential** according to the SM



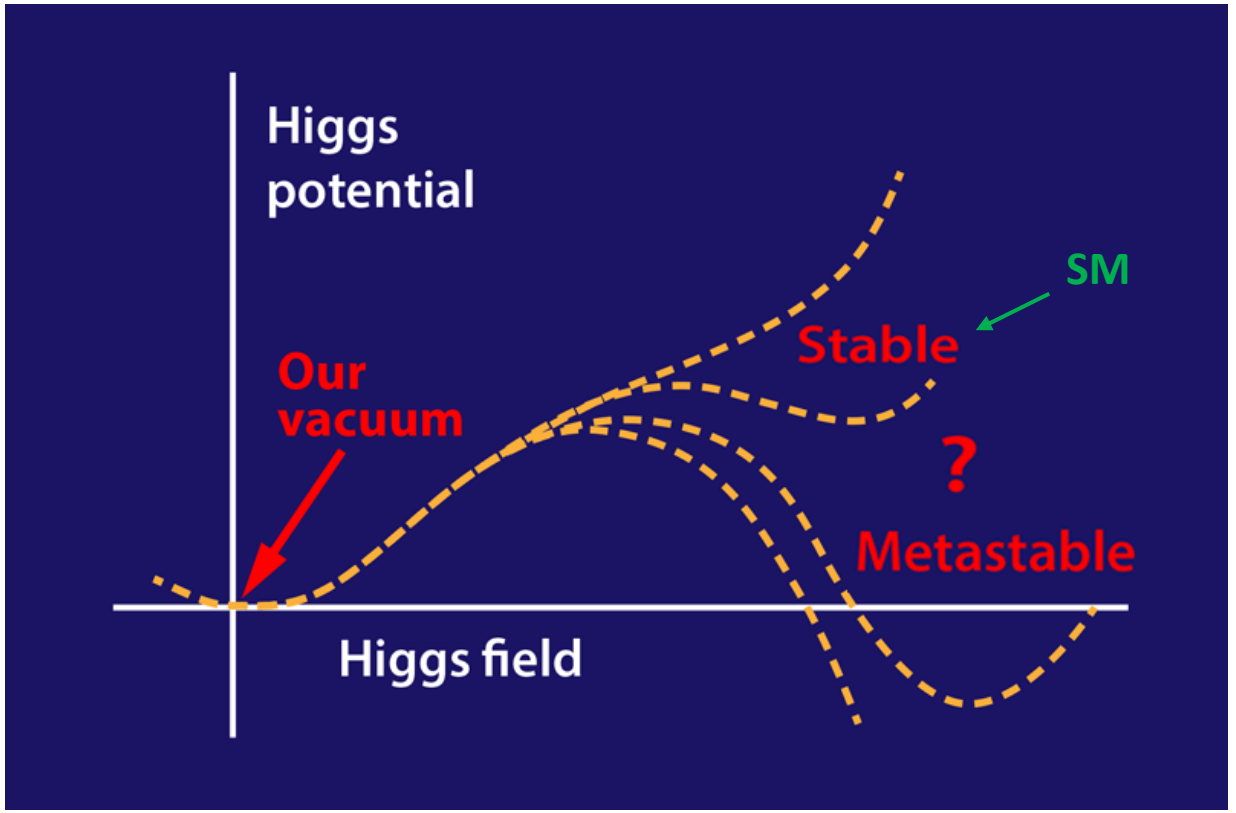
The Higgs potential in the SM

$$V(H) = \frac{1}{2!} m_H^2 h^2 + \frac{1}{3!} \lambda_{HHH} h^3 + \mathcal{O}(h^4)$$

- m_H: measured for the first time in **2012**
- λ_{HHH}: known from the **SM theory**

$$\lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2} \approx 0.13$$

λ_{HHH} directly accessible via **di-Higgs production** @LHC

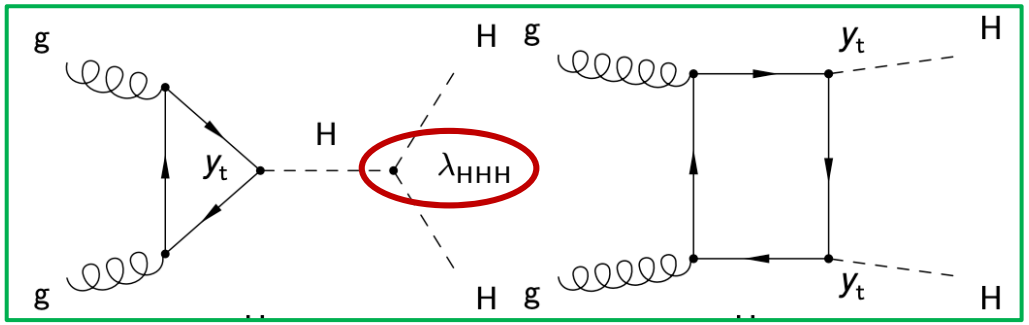


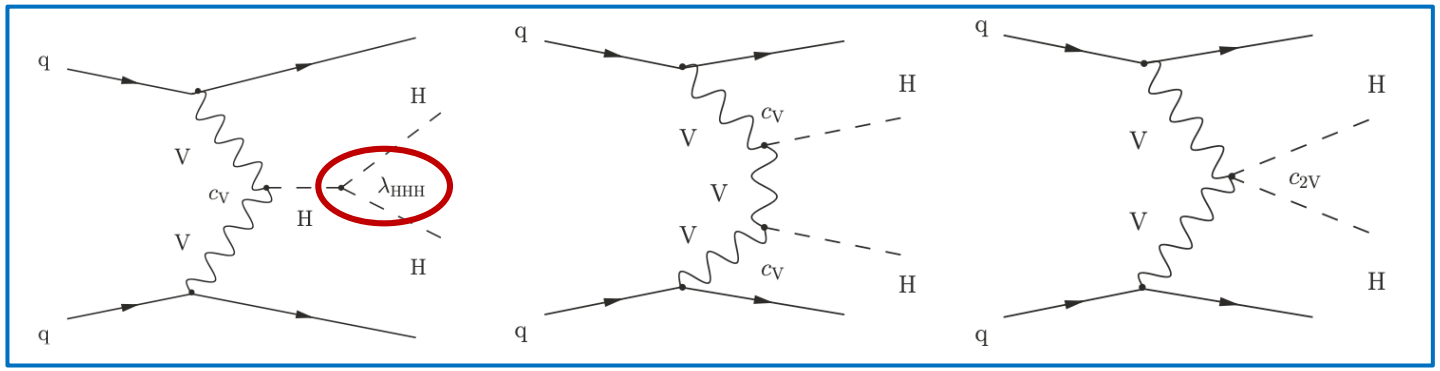
The di-Higgs production

Main **production modes**:

- gluon-gluon fusion (**ggF**)
- vector boson fusion (**VBF**)

$\sigma_{ggF} > \sigma_{VBF}$





Very **rare process**
$\rightarrow \sigma_{HH} \sim 10^{-3}\sigma_H$

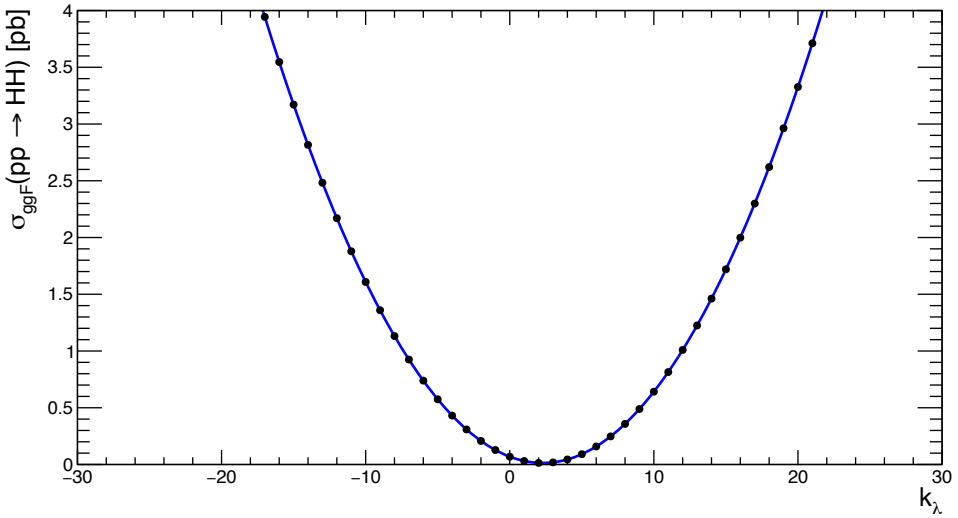
For ggF, the 2 diagrams interfere destructively

$\rightarrow$ Difficult observation, we need a **lot of statistics**

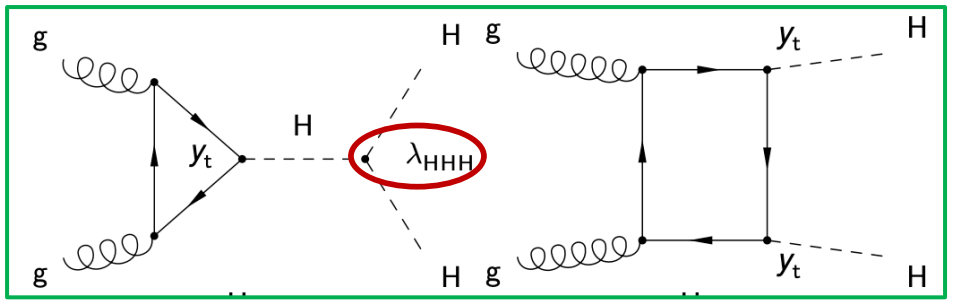
BSM effects

BSM effects incorporated in an **EFT** (effective field theory)
→ $\mathcal{L}_{\mathrm{EFT}}$ with **6-dim operators**

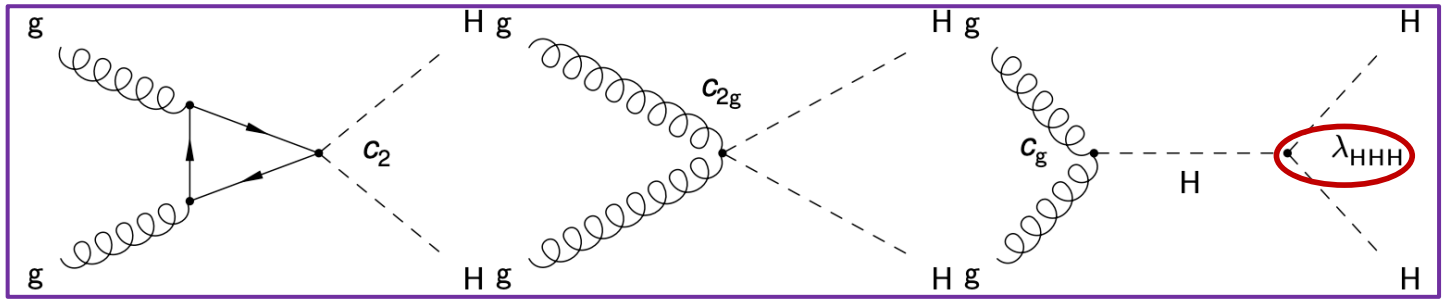
BSM can enhance σ_{HH}



SM



BSM

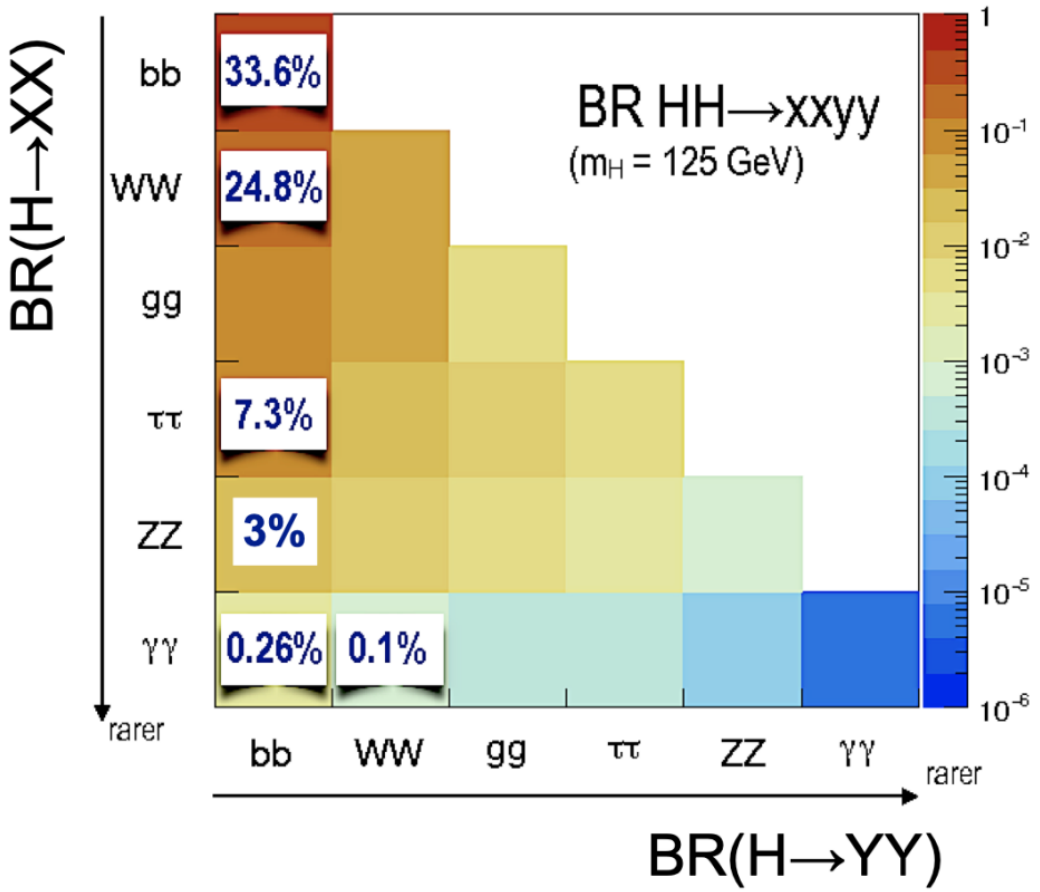


$$\sigma_{\mathrm{HH}} = 68.5624 - 48.3673 \times k_\lambda + 10.5635 \times k_\lambda^2$$

$$k_\lambda = {}^{\lambda_{\mathrm{HHH}}}/_{\lambda_{\mathrm{HHH}}^{\mathrm{SM}}}$$

Direct measurement of $\boldsymbol{\lambda_{\mathrm{HHH}}}$
→ measurement of $\boldsymbol{\sigma_{\mathrm{HH}}}$
→ **SM validation** or **BSM evidence**

The HH observation channels



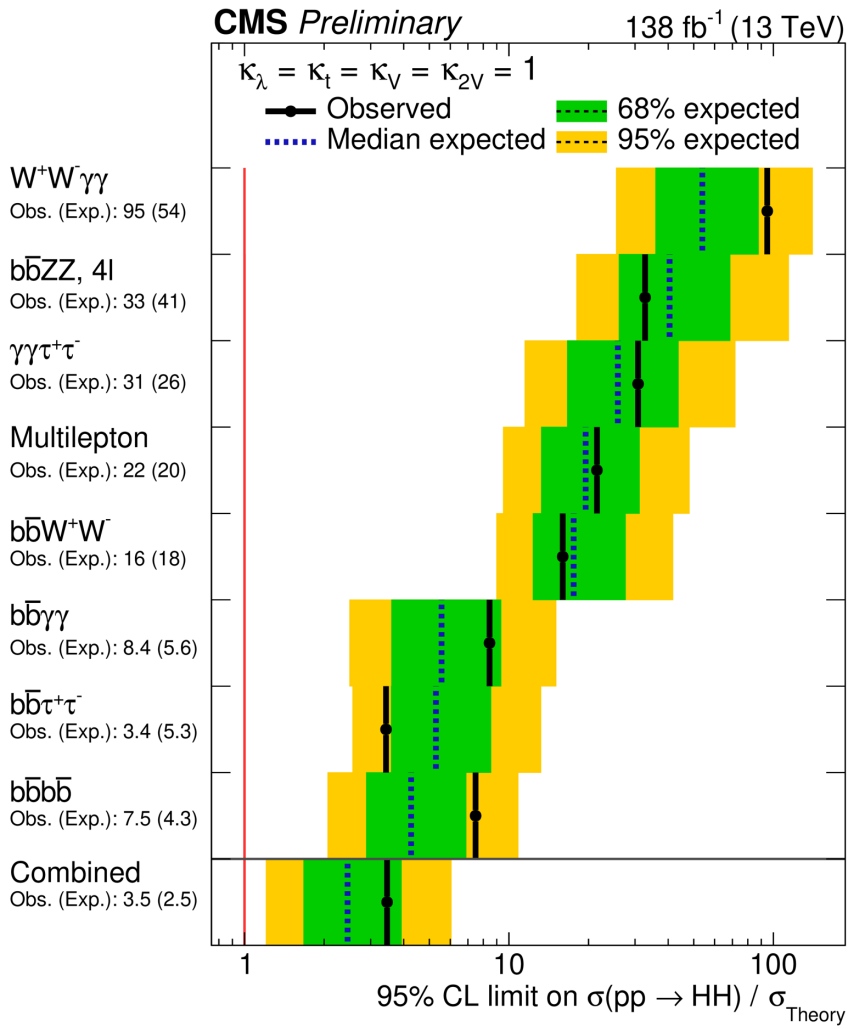
Rare process

→ best channels: **high BR** and **clean final state**

- $b\bar{b}b\bar{b}$ → the highest BR
- $b\bar{b}\tau\tau$ → quite high BR and leptonic decays
- $b\bar{b}\gamma\gamma$ → low BR but very clean final state

} CMS Run-3 analyses

CMS Run-2 limits



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} CMS Run-3 analyses

← CMS Run-2 results

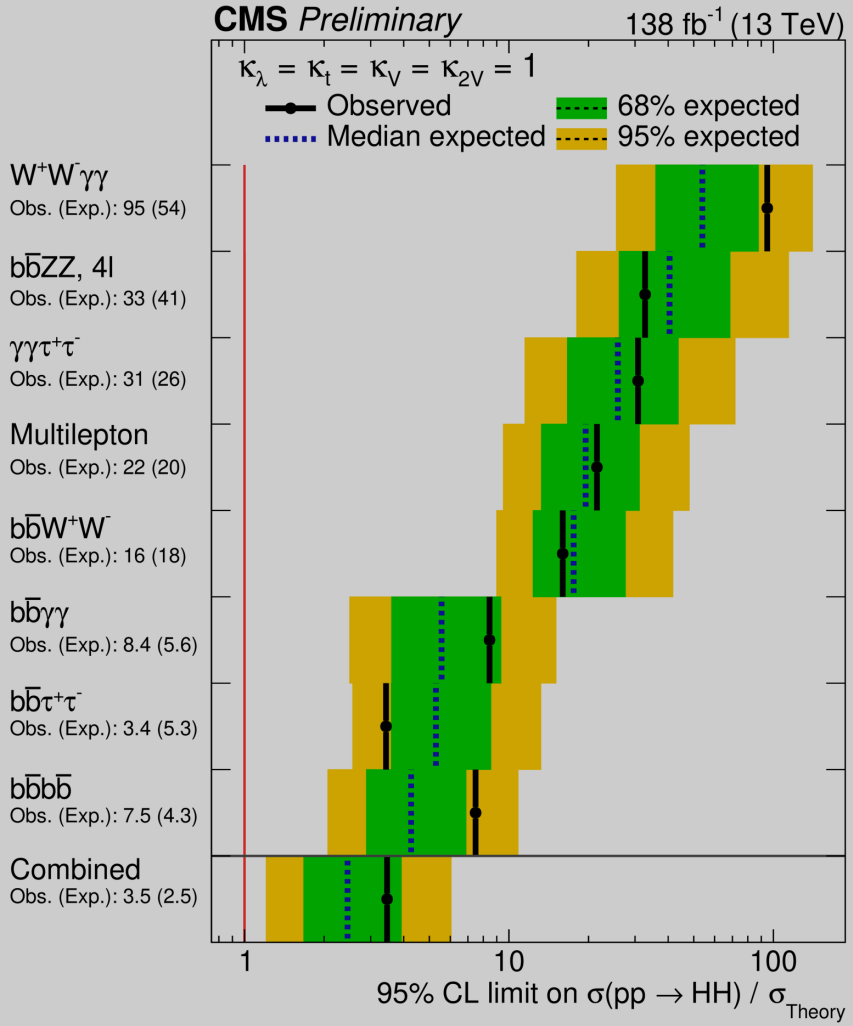
$\sigma_{\mathrm{obs}} \sim 3\sigma_{\mathrm{SM}}$

No evidence of HH production,
upper and lower limits

→ with **Run-3** we will approach the **SM prediction**

→ **HL-LHC direct observation** of HH production

CMS Run-2 limits



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No evidence of HH production, upper and lower limits

→ with Run-3 we will approach the SM prediction

$b\bar{b}\tau\tau$: good compromise between BR and clean final state

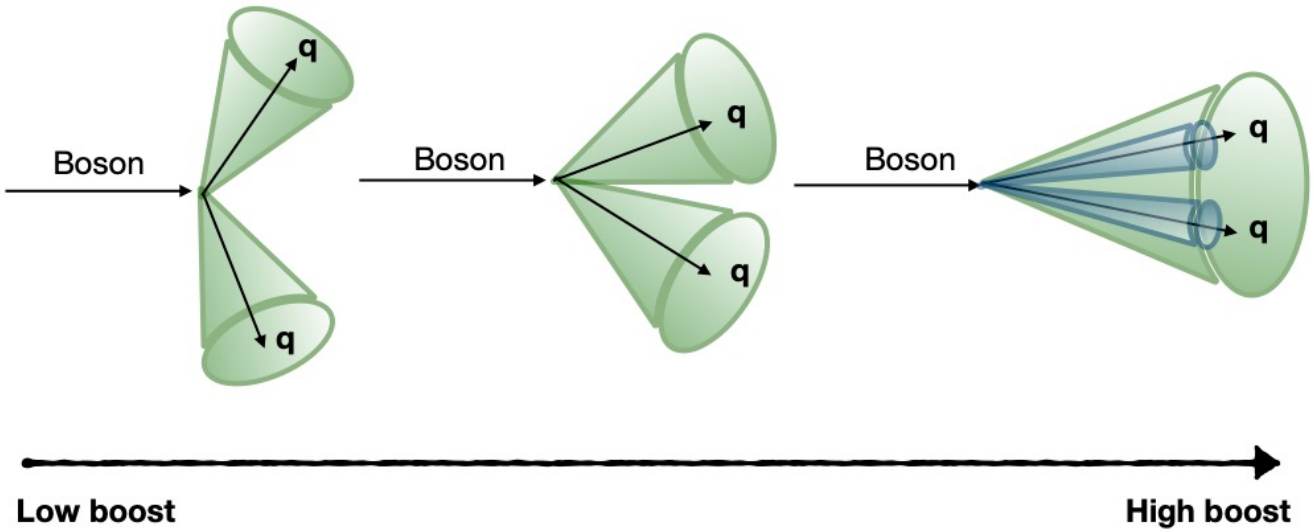
→ b-jets

→ hadronic and leptonic taus

Jets reconstruction

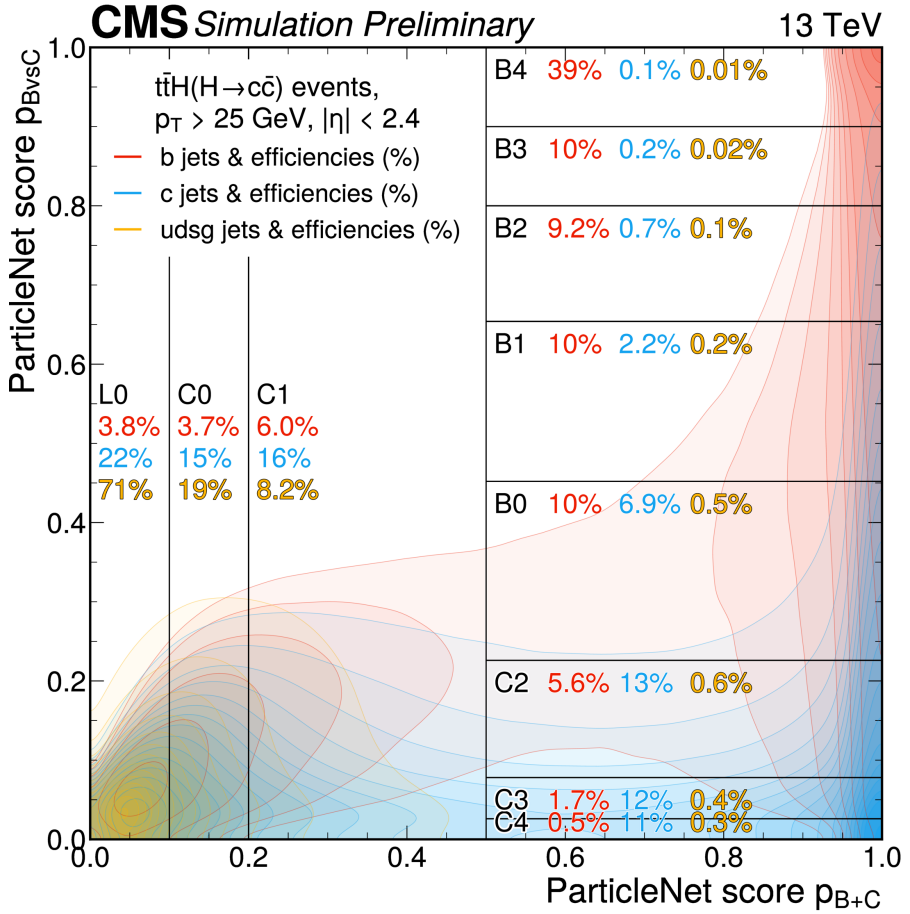
2 categories:

- **resolved** regime → clearly separable jets
- **boosted** regime → one "fat" jet containing two prong jets



b-tagging algorithms

- **Jets** are **produced frequently** in p-p collisions at the **LHC**
- Different particles produce different type of jets
- Many products to be reconstructed
  → **jet-tagging necessary!**



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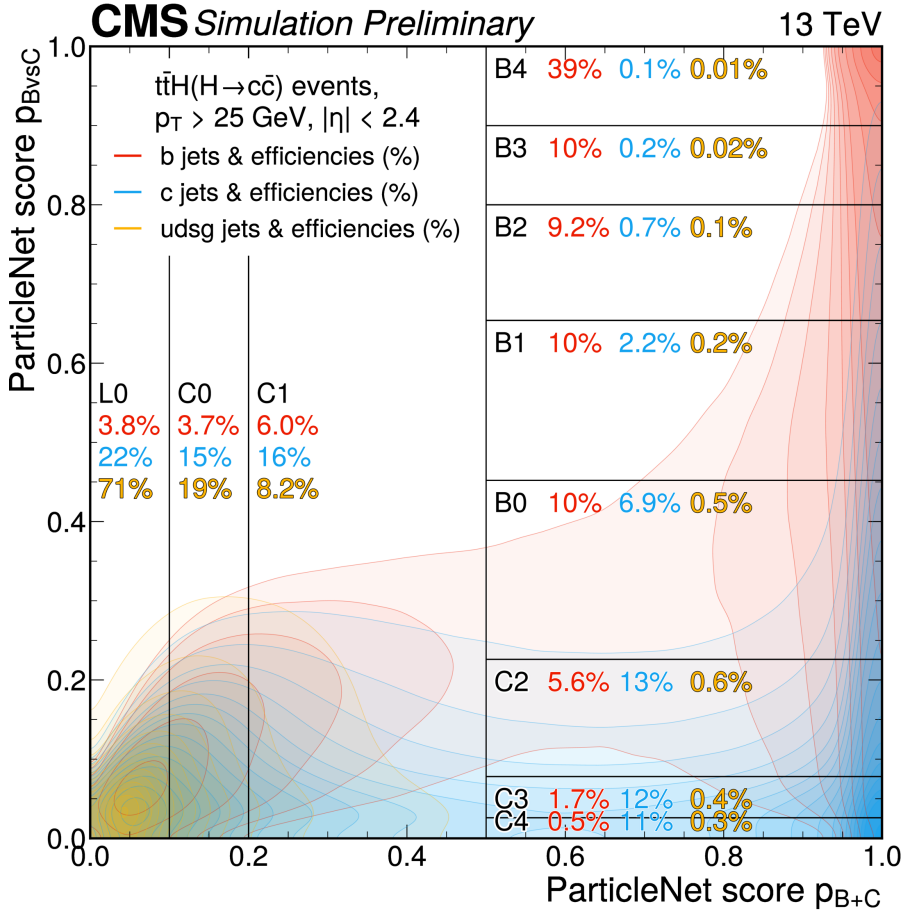


My current work on behalf of the CMS HH→bb$\tau\tau$ group:

Evaluation of **tagging efficiency** for $b\bar{b}$ **taggers**

→ improves the according of MC simulation and data

→ extraction of scale factors to apply to MC simulations

→ reduces **systematic uncertainties** and improves **results reliability**

Conclusions

- Measurement of λ_{HHH} crucial for characterizing the Higgs potentail shape
- CMS (and also ATLAS) Run-2 results → no evidence, $\sim 3\sigma_{\mathrm{SM}}$
- Run-3 perspectives → approaching SM prediction
- HL-LHC → direct observation of di-Higgs production

My work

- Complete the study on scale factors, fundamental effort for the final result
  → end of October
- Starting the Run-3 analysis on $\mathrm{HH} \rightarrow b\bar{b}\tau\tau$
  → **Goal**: full Run-3 study during my PhD (2022-2026 dataset)

Conclusions

- Measurement of $\boldsymbol{\lambda_{HHH}}$ **crucial** for characterizing the **Higgs potential** shape
- CMS (and also ATLAS) **Run-2 results** → **no evidence**, $\sim 3\sigma_{SM}$
- **Run-3 perspectives** → approaching **SM prediction**
- **HL-LHC** → **direct observation** of di-Higgs production

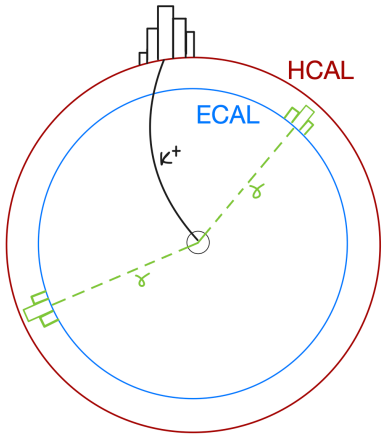
My work

- Complete the study on scale factors, fundamental effort for the final result → end of October
- **Analysis goal**: full Run-3 study during my PhD (2022-2026 dataset)

Thank you!

BACKUP

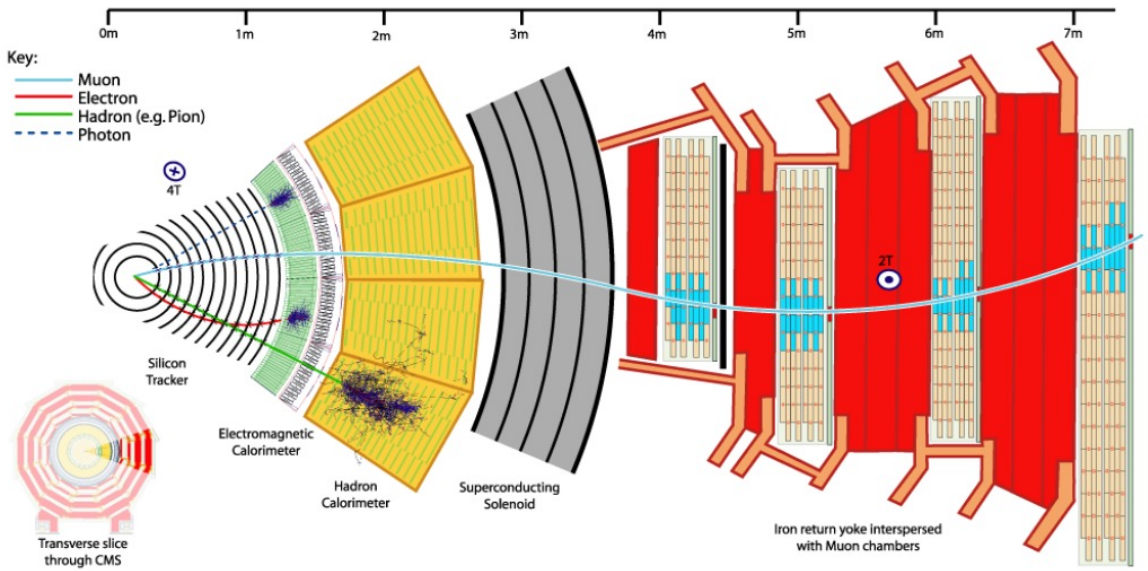
Objects reconstruction with CMS



Tracker

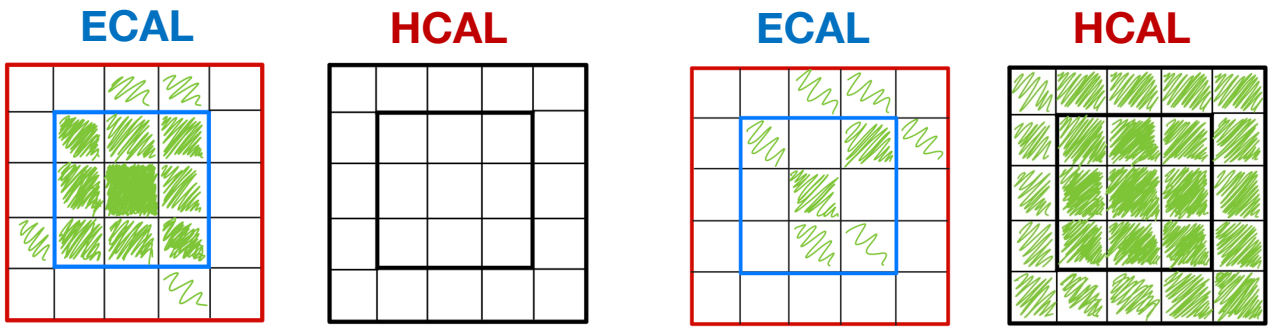
→ curvature of the charged particles

$$\mathbf{p = q \times B \times R}$$



Calorimeters

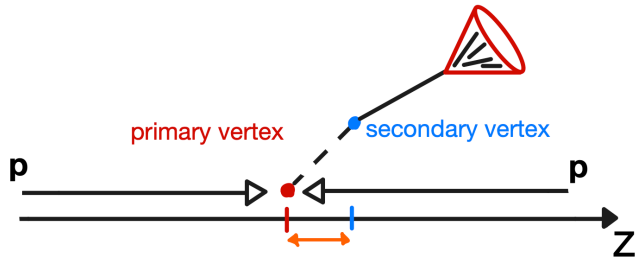
→ energy released by the particles



γ/e **hadrons/jets**

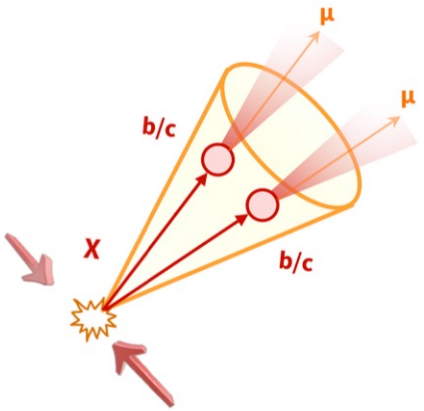
Primary and secondary vertex

→ τ, b, c, etc… travel different distances before decaying



μ-tagged method in a nutshell

❖ **Idea**
- 20% (10%) of jets originated from b (c) quarks contain an e/μ
- Select the $g \to b\bar{b}$ ($c\bar{c}$) QCD proxy requiring a **soft muon** inside the **AK8 jet ("fat" jet)** to enhance the $\mathrm{b\bar{b}}$ ($\mathrm{c\bar{c}}$) component



❖ **Signal-proxy similarity**
- Select two prong jets with an extra requirements on τ_{21}
- Vary the cut on τ_{21} to extract a systematic uncertainty for the SF

N-subjettiness ratio

$$\tau_{MN}^{\mathrm{h}} = \frac{\sum_{i\in\{\mathrm{had.}\}} p_{\mathrm{T},i} \min_{j=1}^{M}\{\Delta R_{i,\hat{n}_{M,j}}\}}{\sum_{i\in\{\mathrm{had.}\}} p_{\mathrm{T},i} \min_{j=1}^{N}\{\Delta R_{i,\hat{n}_{N,j}}\}}$$

$\tau_{21} \in [0,1]$
τ_{21} near 0 → 2 prong jets inside the AK8
τ_{21} near 1 → 1 prong jet inside the AK8

❖ **Pros**
- **Orthogonal** phase space
- Suitable for **calibration** of **taggers** not using the muon information