Higgs boson pair production in the bbττ final state @ CMS

From SM to EFT

Jona Motta (LLR, École Polytechnique)
jona.motta@polytechnique.edu

The Standard Model and the Higgs boson

- The Standard Model (SM) is an $SU(2)_L \otimes U(1)_Y \oplus SU(3)_C$ renormalizable gauge quantum field theory

- Brout-Englert-Higgs mechanism postulates the existence of an omnipervasive scalar field ⇒ Higgs bosons (H) are its excitations

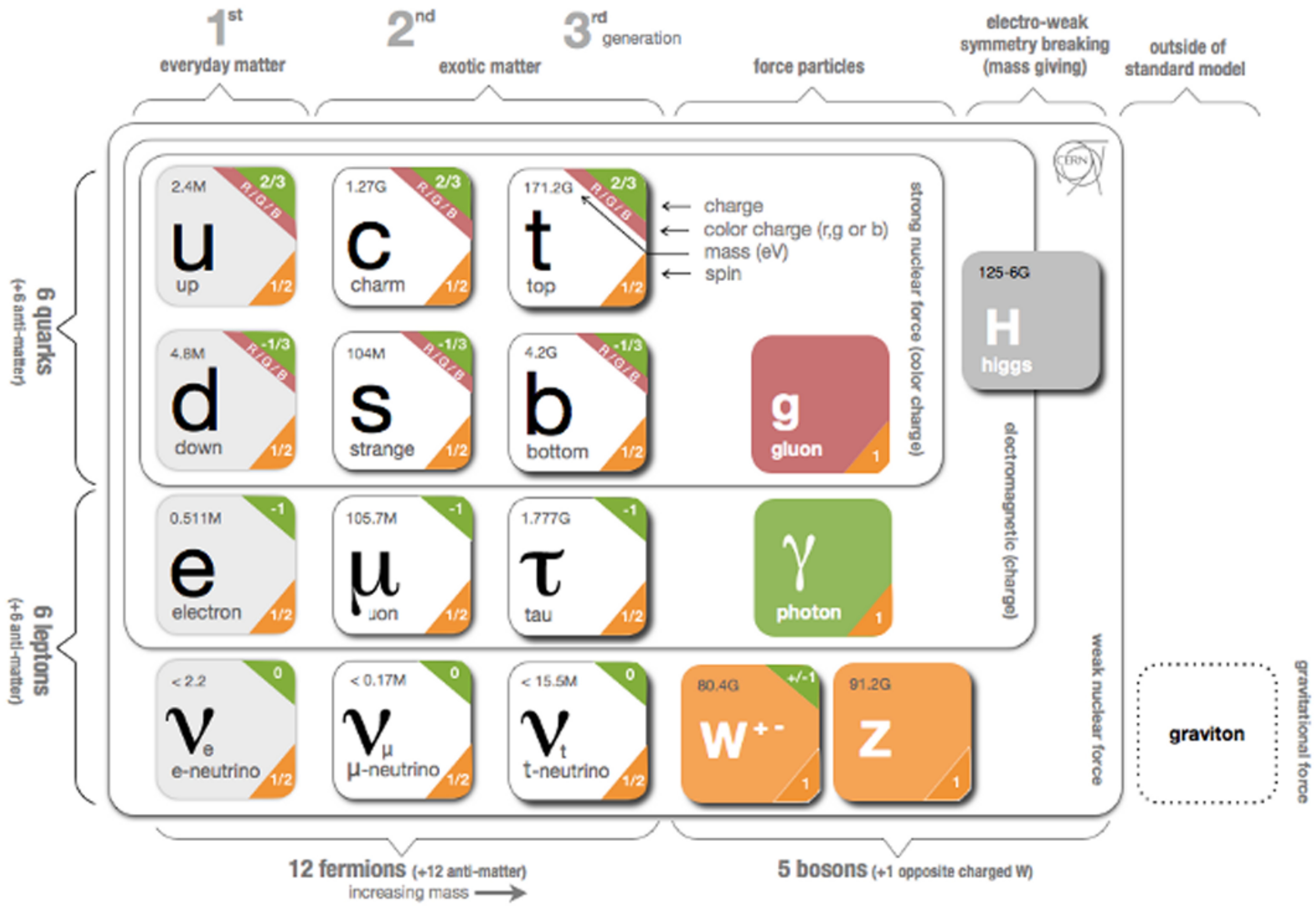
- The BEH mechanism induces the Electroweak Symmetry Breaking (EWSB) and gives mass to the particles of the SM

- H discovered in 2012 and $m_{\mathrm{H}} = 125.09 \pm 0.21(stat.) \pm 0.11(syst.)$ GeV (CMS + ATLAS combination at $\sqrt{s} =$ 7 and 8 TeV)

⇒ the full characterization of the H is of foremost importance for the understanding of EWSB and fathom the fabric of the Universe

⇒ the European Strategy for Particle Physics deems the study of the H and Higgs boson pairs (HH) as the most important topic for the next 50 years HEP studies

The Standard Model of Particle Physics



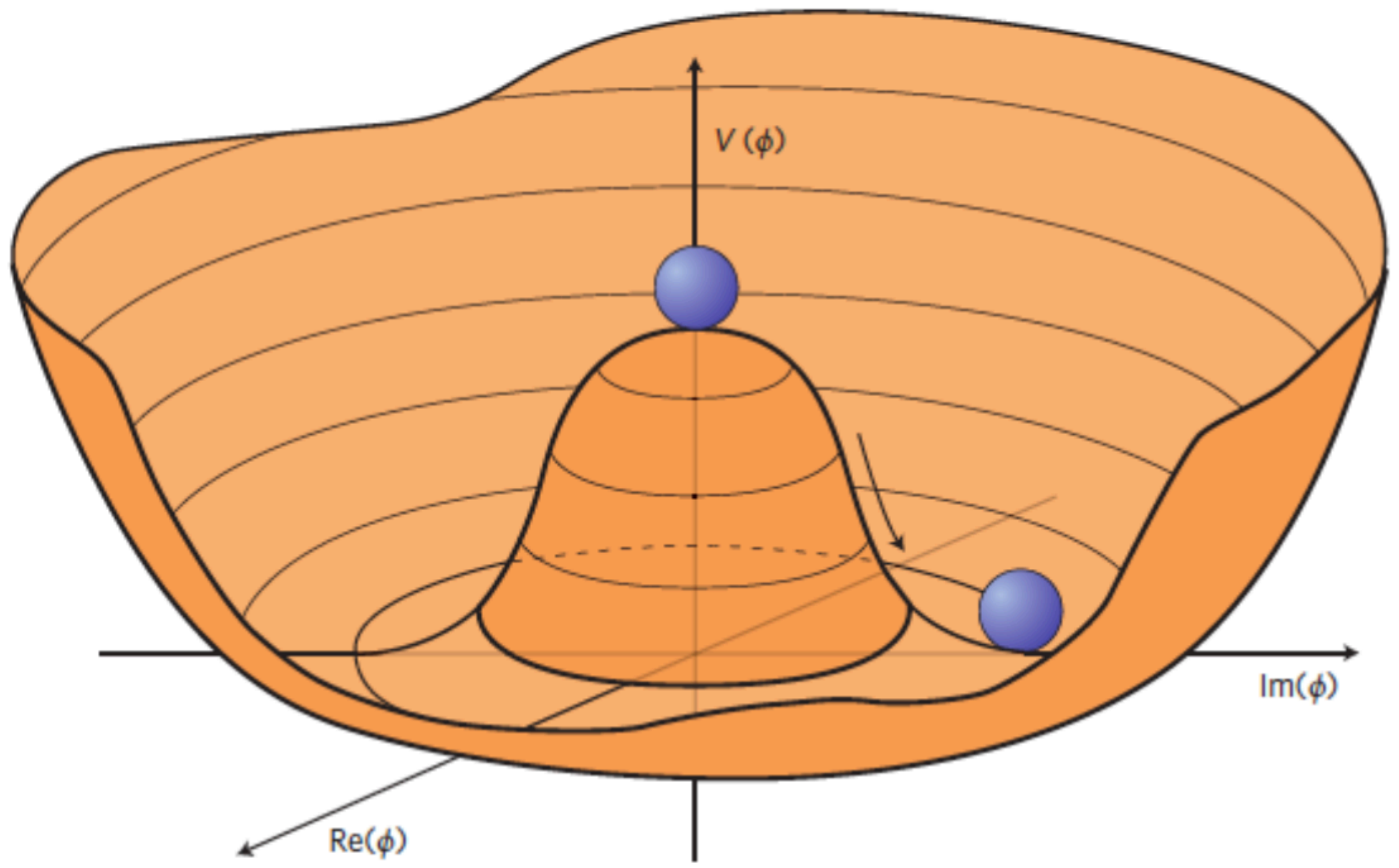
Higgs Boson pairs and Higgs potential

The Higgs potential can be written as:

$$V(\Phi) = \frac{1}{2}(2\mu)^2 + \frac{\mu^2}{v}H^3 + \frac{\mu^2}{4v}H^4$$
$$= \frac{1}{2}m_H^2 H^2 + \lambda_{HHH} v H^3 + \lambda_{HHHH} H^4$$

where:

$$\lambda_{HHH} = 4\lambda_{HHHH} = \frac{m_H^2}{v^2}$$



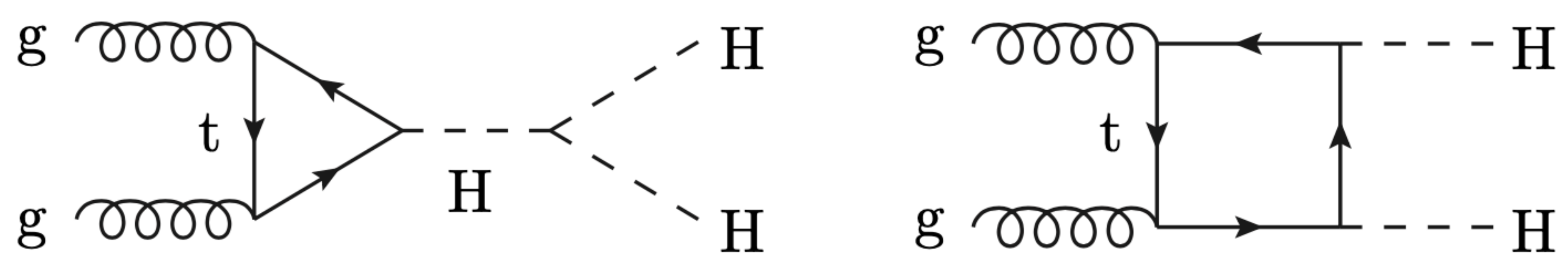
⇒ goal of today's physics is to put limits on λ_{HHH} (and in the future measure it)

⇒ goal of your work is to get a glimpse of this effort and to understand the EFT extensions associated

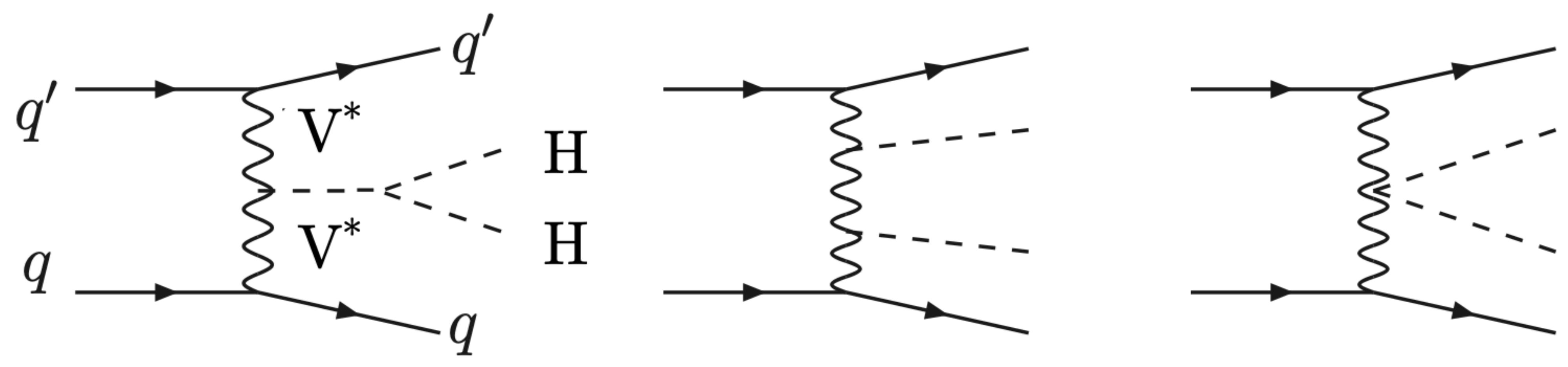
Channel of interest: Higgs boson pairs

- The channel of interest is the Higgs bosons pairs (HH) production

- The main contribution is gluon fusion (ggF) via a quark loop (mainly top): $\sigma_{ggF}^{NNLO}(13TeV) \approx 31$fb



- The second contribution is Vector Boson fusion (VBF): $\sigma_{VBF}^{N3LO}(13TeV) \approx 1.7$fb



What is an EFT?
The idea

The idea of an effective field theory dates back to the origin of modern physics itself: given the limited length scale at which we can probe a process, we can average over all the smaller scale interactions to get an approximate theory at the scale of interest

- i.e. if I am measuring with a ruler I do not care about atoms, but I do care if I am measuring with an electron microscope

- e.g. Fermi theory of β decays:

$n \rightarrow p + e + \bar{\nu}_e$ is studied as a pointlike interaction neglecting the presence of the W boson

(success of Fermi theory was because $m_W \approx 80$GeV, while early experiments were at energy $\lesssim 10$MeV)

What is an EFT?
The mathematical formulation

The basic idea behind the construction of an EFT is that of **dropping the assumption that the lagrangians must be renormalizable**. This approach opens the way to **interaction terms with arbitrary large mass dimensions** $\mathscr{D}$, which can be classified in order of $\mathscr{D}$ and **suppressed by powers of an arbitrary large mass scale** Λ

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{n=5}^{+\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)} =$$

$$= \mathscr{L}_{SM} + \sum_{i} \frac{c_i^{(5)}}{\Lambda} \mathscr{O}_i^{(5)} + \sum_{i} \frac{c_i^{(6)}}{\Lambda^2} \mathscr{O}_i^{(6)} + \dots$$

where $\mathscr{O}_i^{(\mathscr{D})}$ is a complete basis of SU(2) $\otimes$ U(1) $\oplus$ SU(3) invariant operators of dimension $\mathscr{D}$

What is an EFT?
For HH

In the case of HH, the smallest interesting operators are of dimension 6 and the Lagrangian reads:

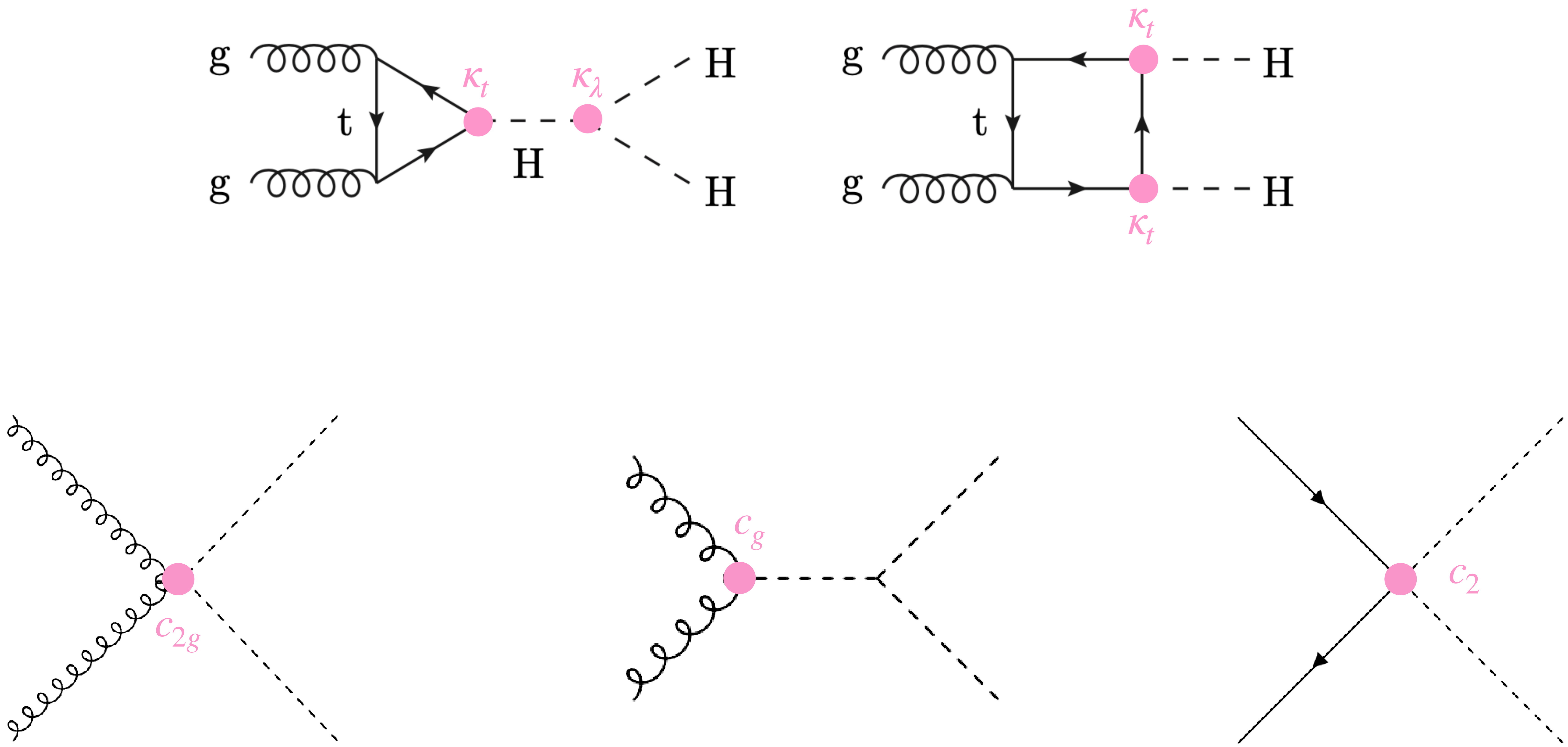
$$\mathcal{L}_{HH} = \frac{1}{2}\partial^\mu \mathcal{H} \partial_\mu \mathcal{H} - \frac{1}{2} m_{\mathrm{H}}^2 \mathcal{H}^2 + \kappa_\lambda \lambda_{HHH} v \mathcal{H}^3$$
$$- \frac{m_t}{v}\left(v + k_t \mathcal{H} + \frac{c_2}{v}\mathcal{H}^2\right)(\bar{t}_L t_R + t_R \bar{t}_L)$$
$$+ \frac{\alpha_s}{12\pi v}\left(c_g \mathcal{H} - \frac{c_{2g}}{2v}\mathcal{H}^2\right) G^A_{\mu\nu} G^{A,\mu\nu}$$

Where:

- $\kappa_\lambda = \dfrac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
- $\kappa_t = \dfrac{y_t}{y_t^{SM}}$

- c_2 = point interaction between two fermions and two H
- c_g = point interaction between two gluons and one H
- c_{2g} = point interaction between two gluons and two H

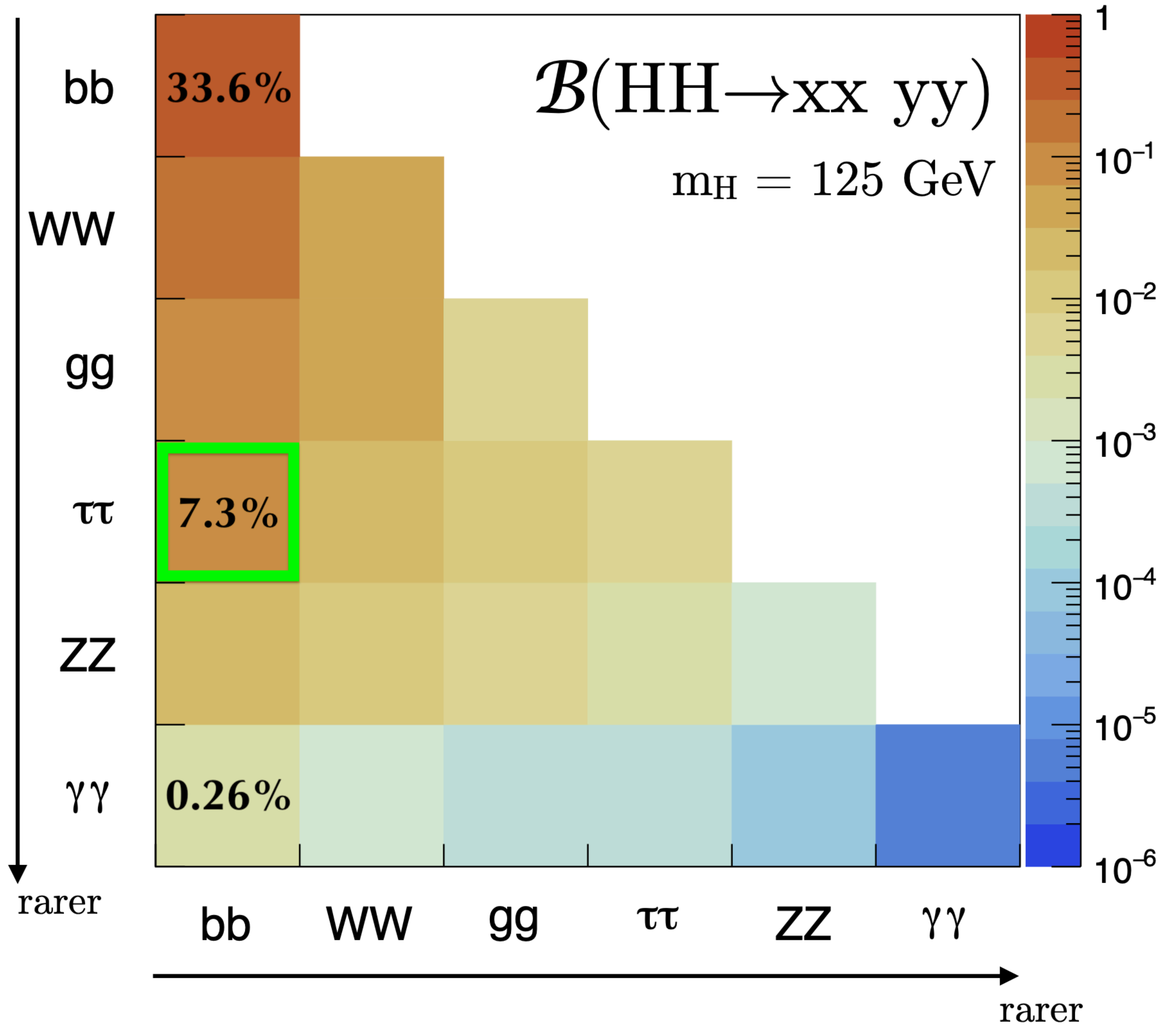
What is an EFT?
For HH



The bbττ channel

- The selected final state is $\mathrm{HH} \rightarrow bb\tau\tau$ which has $\mathscr{B}(\mathrm{HH} \rightarrow bb\tau\tau) = 7.3\,\%$

  - The bbττ final state gives a good compromise between the branching ratio $\mathscr{B}$ and the selection purity



- $\Rightarrow$ use the purity of the ττ channel to tag the event

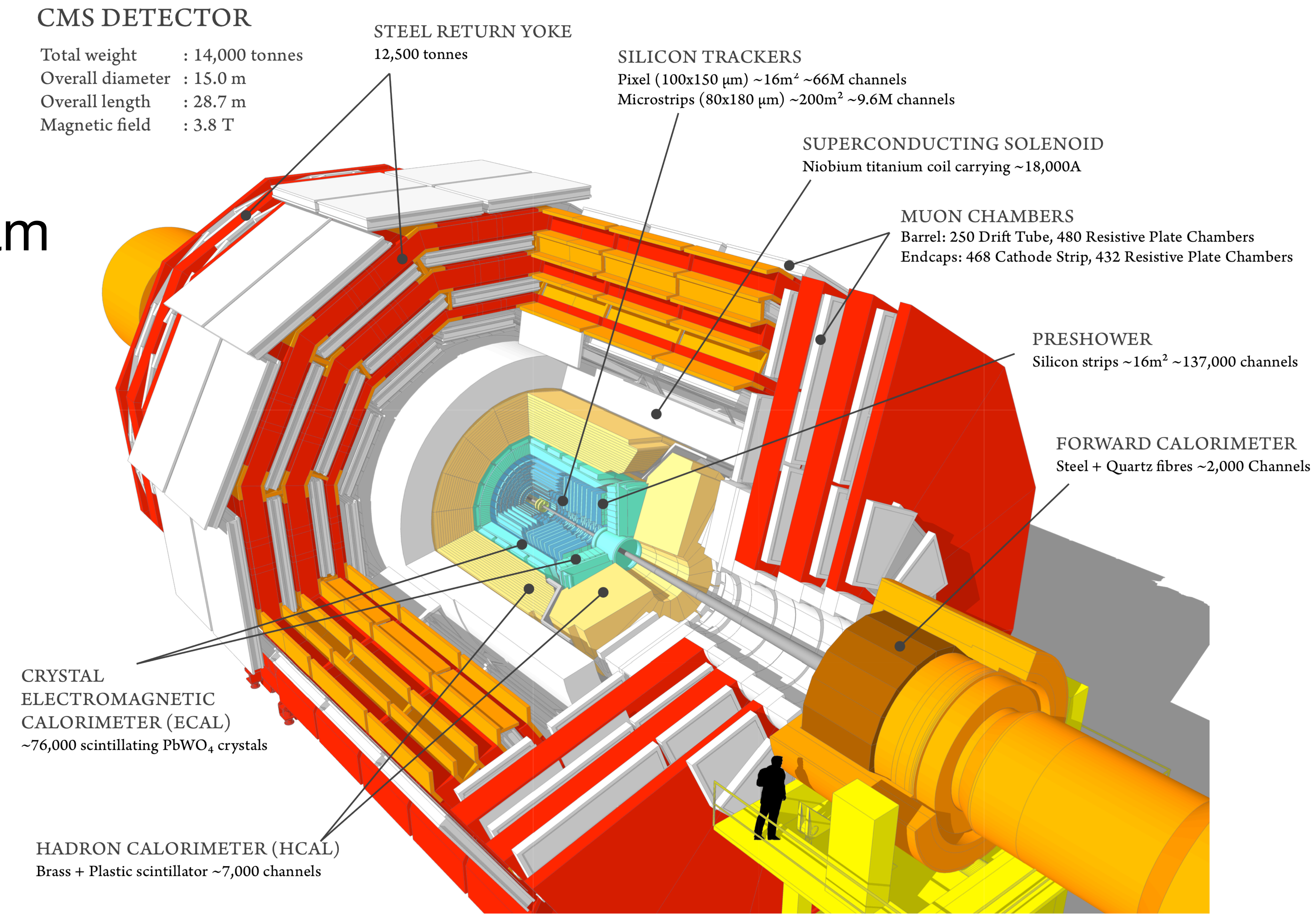
The CMS experiment

The Compact Muon Solenoid experimental apparatus:

- Multi-purpose apparatus (SM and BSM)
- Superconducting solenoid → 3.8T field parallel to the beam

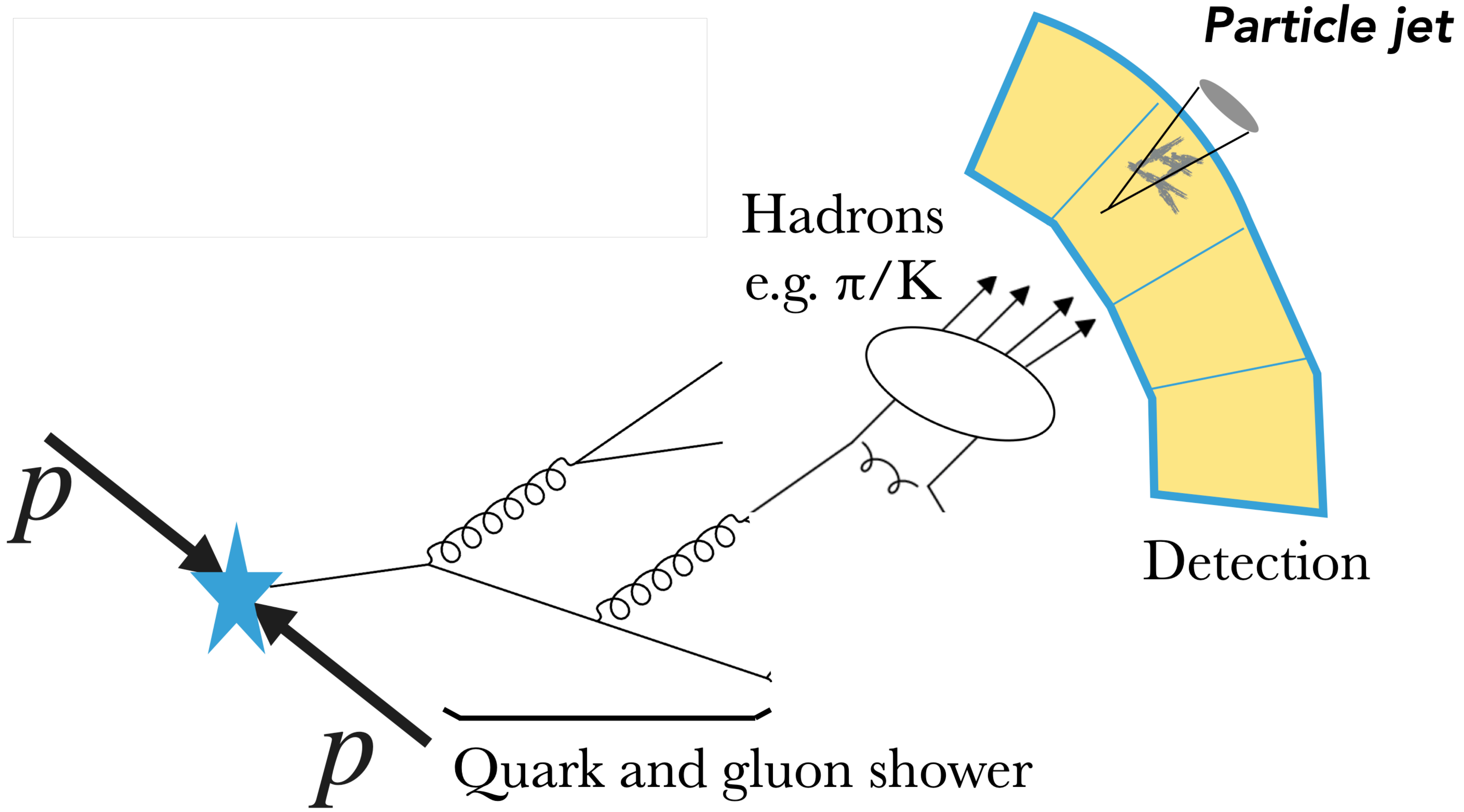
- Tracking and momentum measurements:
    - silicon tracker
    - μ-chambers

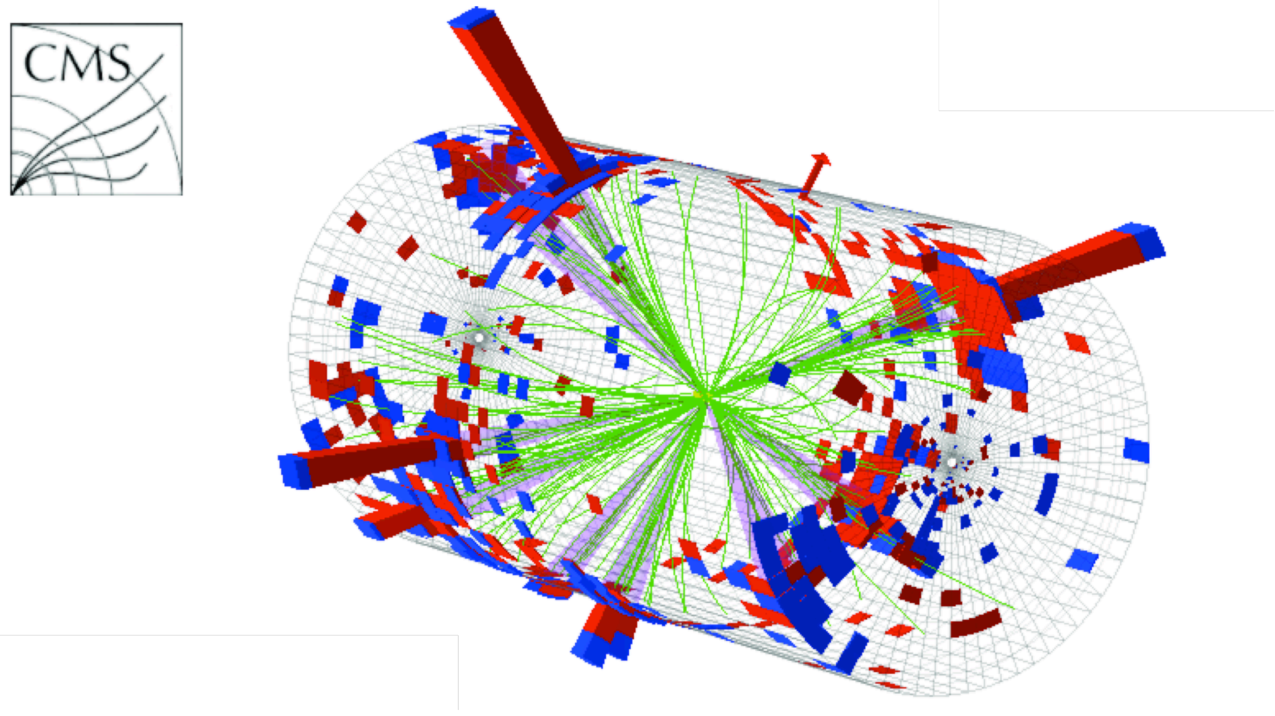
- Energy measurements:
    - ECAL
    - HCAL



Hadronic jets

Quarks and gluons give rise to the so-called jets, which are their typical signature in CMS ⇒ the b quarks in our work will always be reconstructed as so-called **b jets**





BUT quarks and gluons are not the only particles that give rise to jets!!

The tau lepton

- The heaviest lepton of the SM: a mass of about 1.7 GeV

- Lifetime of about $2.9 \cdot 10^{-13}$s → a τ with a momentum of 40 GeV flies on average 2 mm before decaying

≈ 1/3 of the decays
Covered by the standard e/μ algorithms

≈ 2/3 of the decays
τ_{h}, or sometimes just "τ"

- dedicated L1 and HLT triggers
- dedicated reconstruction algorithms
- dedicated analysis methods

Decay mode	Resonance	$\mathcal{B}$ (%)
Leptonic decays		35.2
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other		3.3

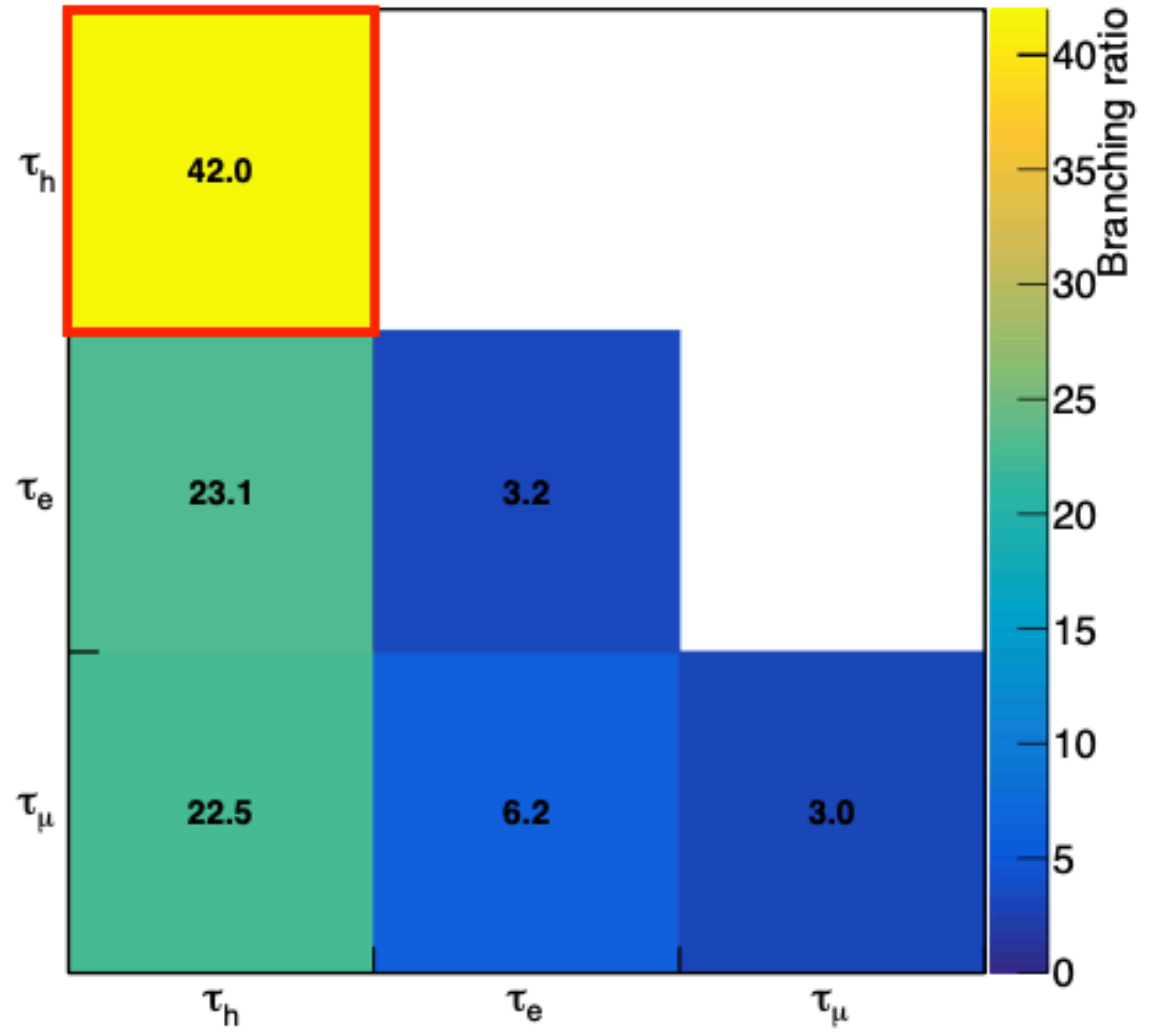
- The tau is the only lepton whose study needs hadronic signatures

H $\rightarrow \tau\tau$ categorization

- We categorize the H $\rightarrow \tau\tau$ channel depending on the decay mode of the τ

- You will use only the hadronic decay $\tau_h\tau_h$

  $\rightarrow$ only 42% of the total final states



What we will do

The main goal of the work you will do is to:

- **MAIN TASKS**
  - study the kinematic variables of the Higgs decay products and understand their behaviour
  - study the kinematic differences between the two production modes (ggF and VBF)
  - study the kinematic differences between the various EFT scenarios
- **SECONDARY TASKS**
  - study the selection criteria used in the analysis and to play around with them (understand efficiency and purity tradeoff)
  - study the definition of a signal region (and comparison of your ideas with the actual definition of the analysis)
- **OPTIONAL**
  - do a statistical study to obtain a measure of the compatibility of the data with the SM and the EFT scenarios

For next time

- Start reading the three documents you find here

    → they are the basics of tau and jets detection and identification

    (the support reference when you don't know the specific components of the CMS detector is CMS detector)

- Understand them as much as possible! When you are completely stuck just write me an email or on Skype and I will answer ASAP.

BACKUP

Event categorization

To maximise sensitivity we categorize the events depending on:

- $\tau\tau$ decay pair type
- presence of VBF jets candidates
- topology of b jets pair