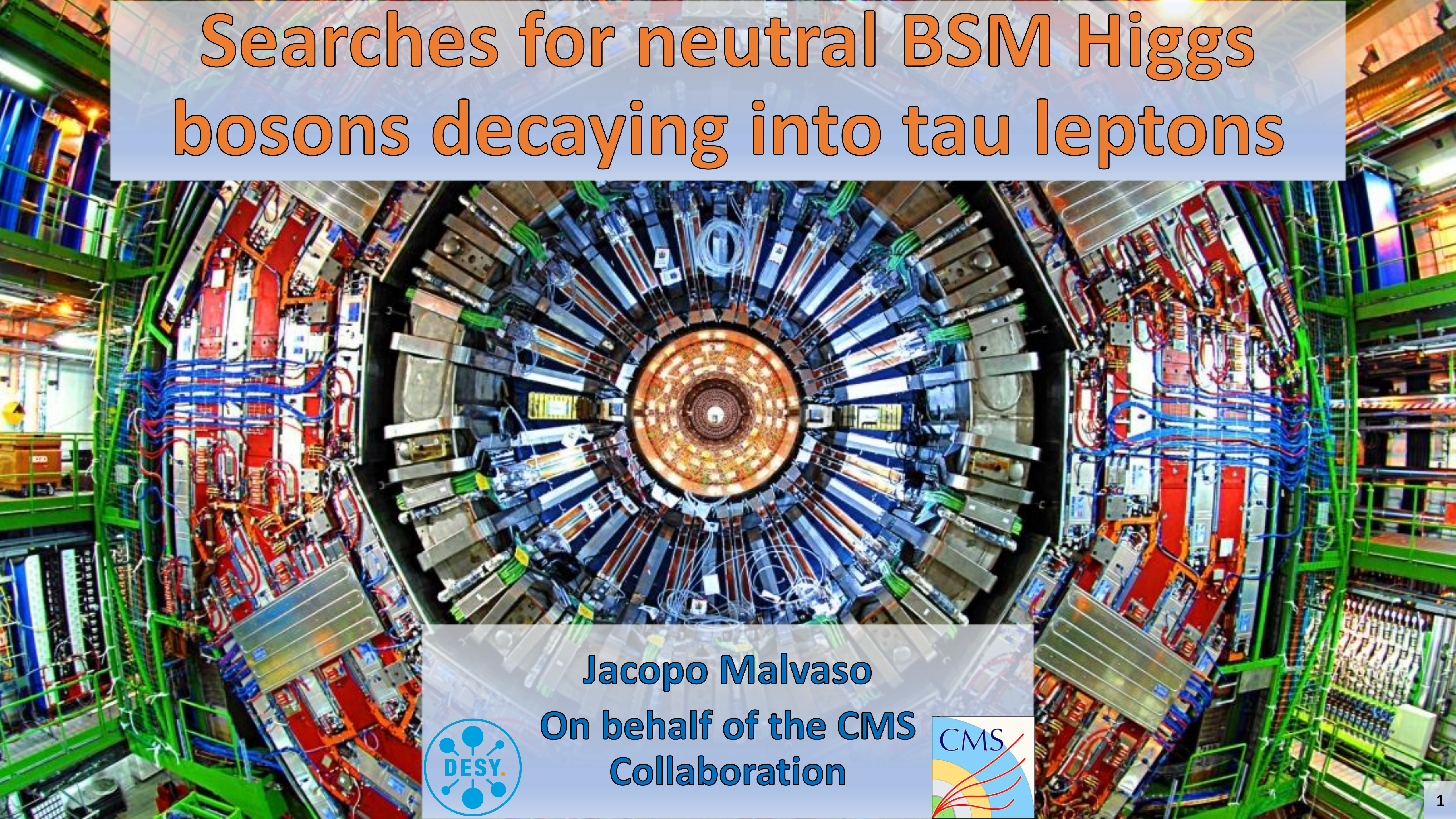
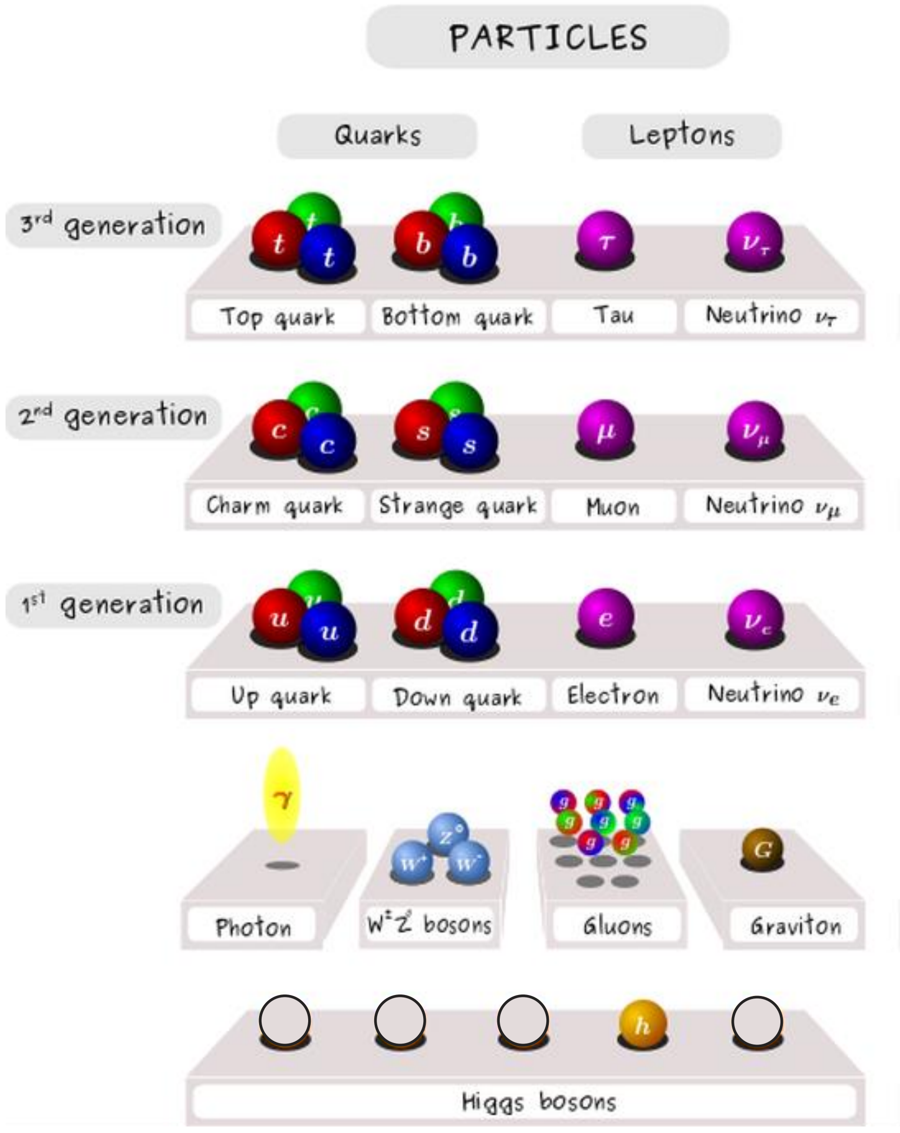
Searches for neutral BSM Higgs bosons decaying into tau leptons



Jacopo Malvaso

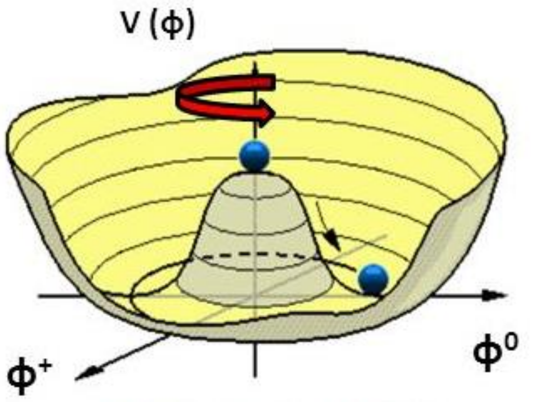
On behalf of the CMS Collaboration

The Standard Model (SM) and the Higgs sector



Thanks to Claire David for the very nice picture

The Higgs potential:



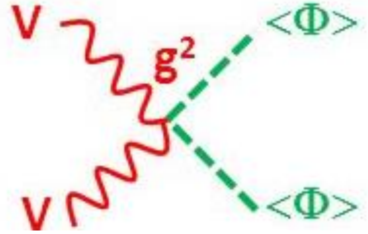
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

where $\Phi = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$ is an isospin SU(2) scalar doublet

Higgs Vacuum Expectation Value (VEV): $\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v\end{pmatrix}$

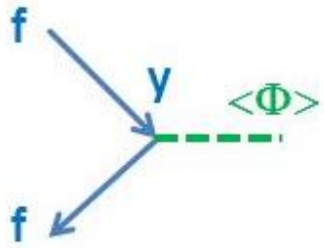
The physical states consist of only one neutral component h

Gauge boson mass



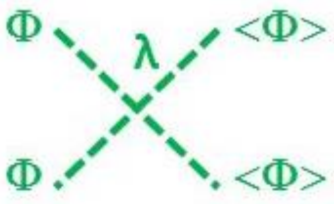
$m_V^2 = g^2 v^2$

Fermion mass



$m_f = yv$

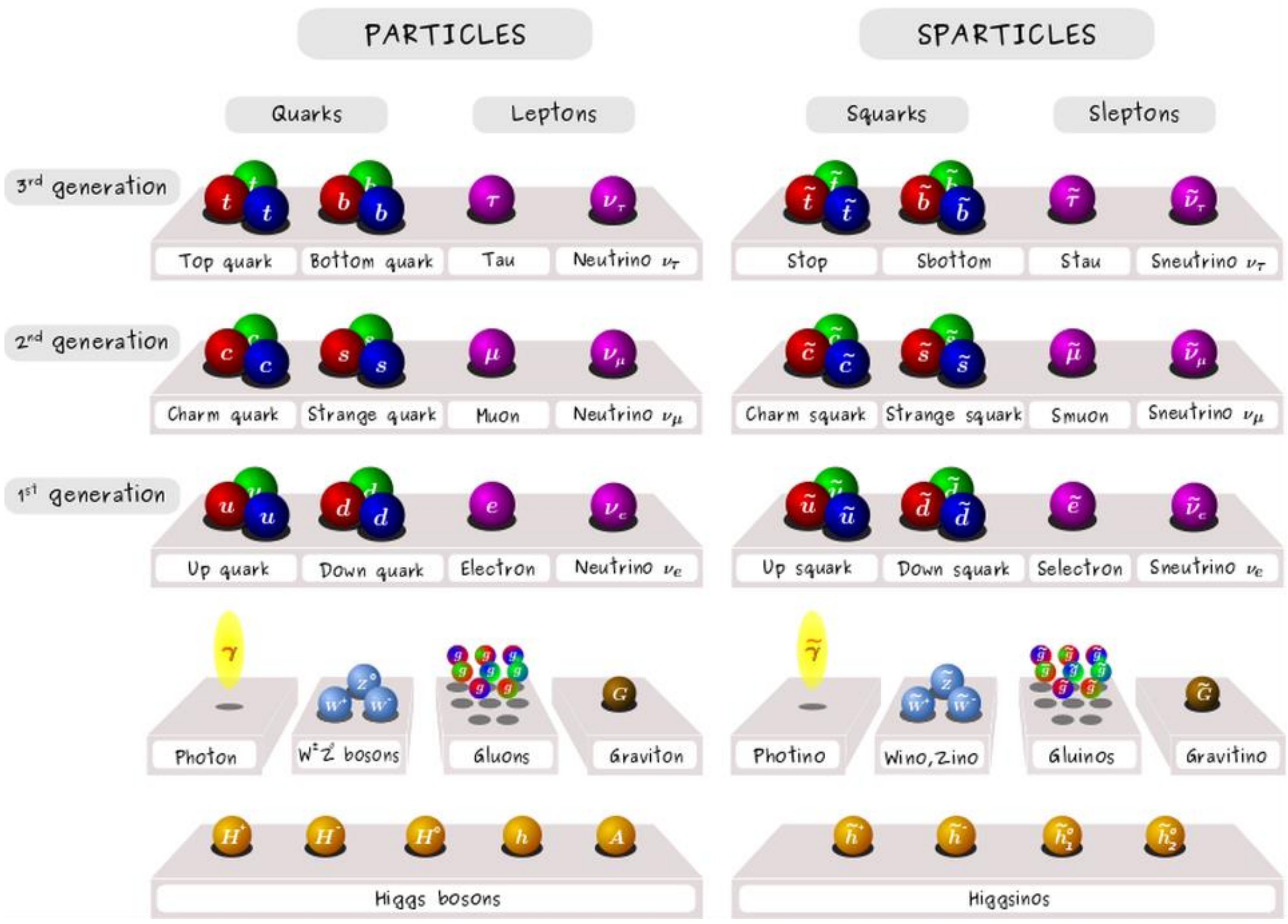
Higgs mass



$m_h = \lambda v^2$

All masses of particles are given by the Higgs VEV

Supersymmetry (SUSY)

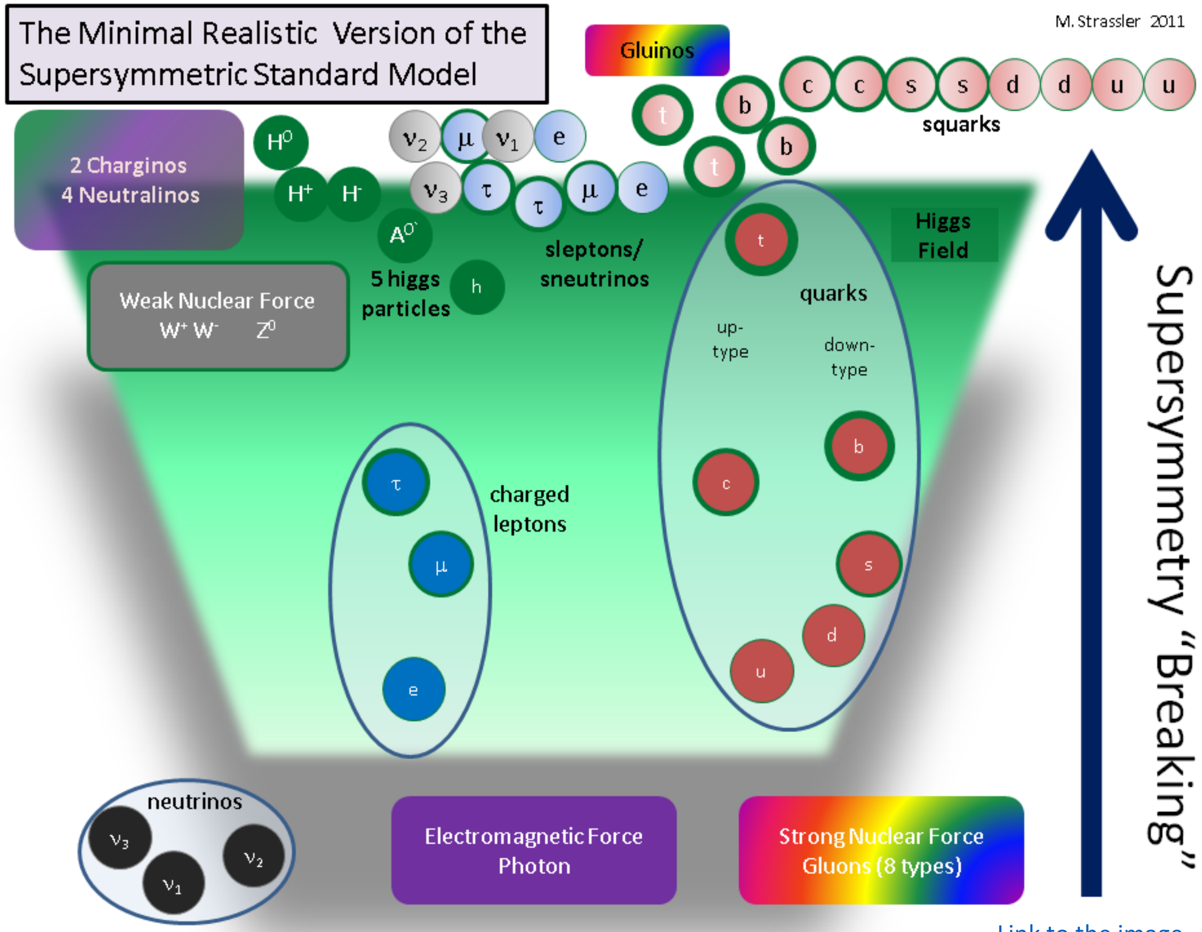


Thanks to Claire David for the very nice picture

- **Supersymmetry** is a theoretical framework in physics that suggests the existence of a **symmetry between** particles with integer spin (**bosons**) and particles with half-integer spin (**fermions**).
- It proposes that for every known particle, **there exists a partner particle with different spin properties**.
- Besides, **the Higgs sector grows larger** as new possible Higgs Bosons are theorized

The Minimal Supersymmetric extension to the SM

- The **Minimal Supersymmetric Standard Model** (**MSSM**) is an extension to the Standard Model that **realizes supersymmetry** considering only "**the minimum number of new particle states and interactions consistent with "Reality"**.
- There are **three principal motivations** for the MSSM over other theoretical extensions of the Standard Model, namely:
  - ➢ **Naturaless**
  - ➢ **Gauge coupling unification**
  - ➢ **Dark Matter candidate**
- **The MSSM** is the leading candidate for **a new theory to be discovered at** collider experiments such as the Tevatron or **the Large Hadron Collider (LHC).**



Link to the image

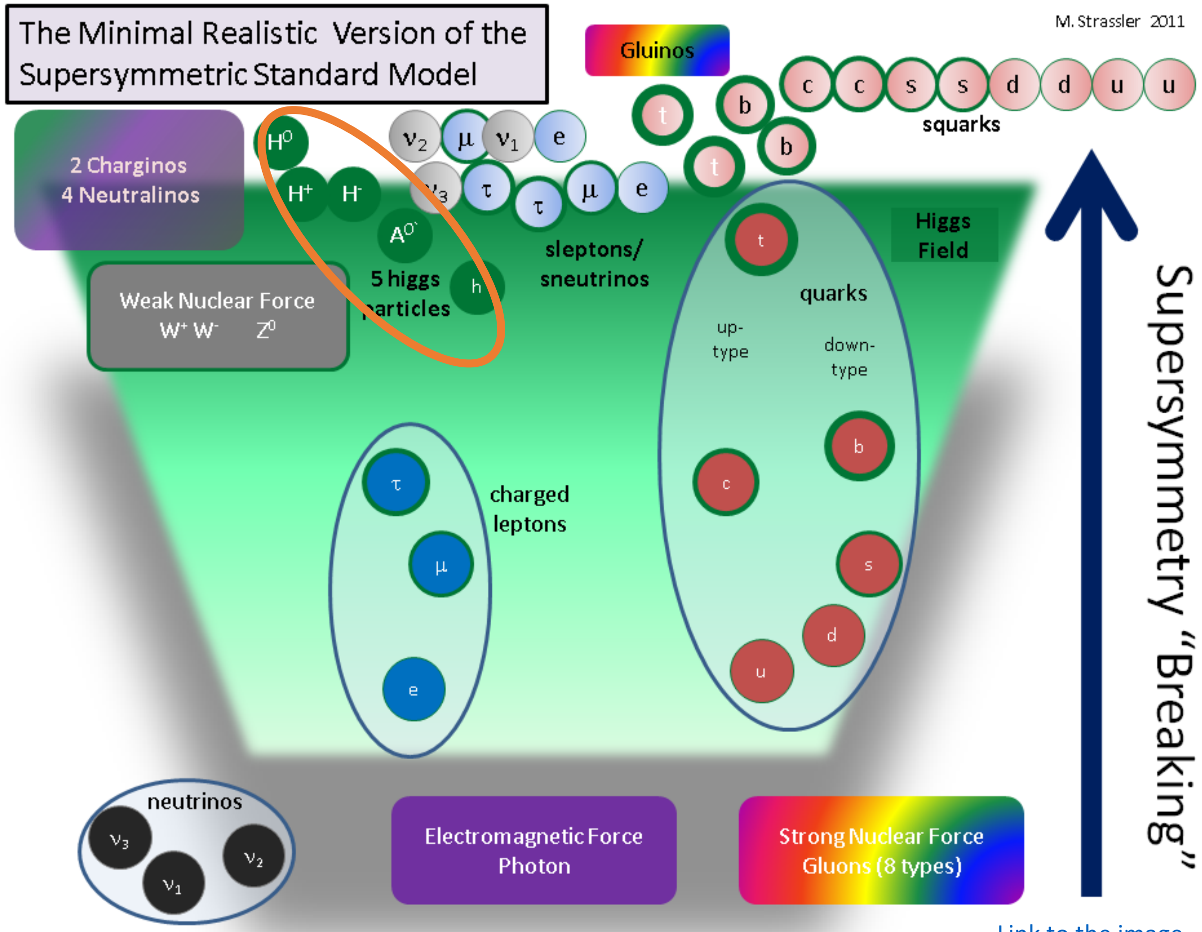
The Minimal Supersymmetric extension to the SM

- The **Minimal Supersymmetric Standard Model** (**MSSM**) is an extension to the Standard Model that **realizes supersymmetry** considering only "**the minimum number of new particle states and interactions consistent with "Reality"**.

- There are **three principal motivations** for the MSSM over other theoretical extensions of the Standard Model, namely:

  - **Naturaless**
  - **Gauge coupling unification**
  - **Dark Matter candidate**

- **The MSSM** is the leading candidate for **a new theory to be discovered at** collider experiments such as the Tevatron or **the Large Hadron Collider (LHC).**



Link to the image

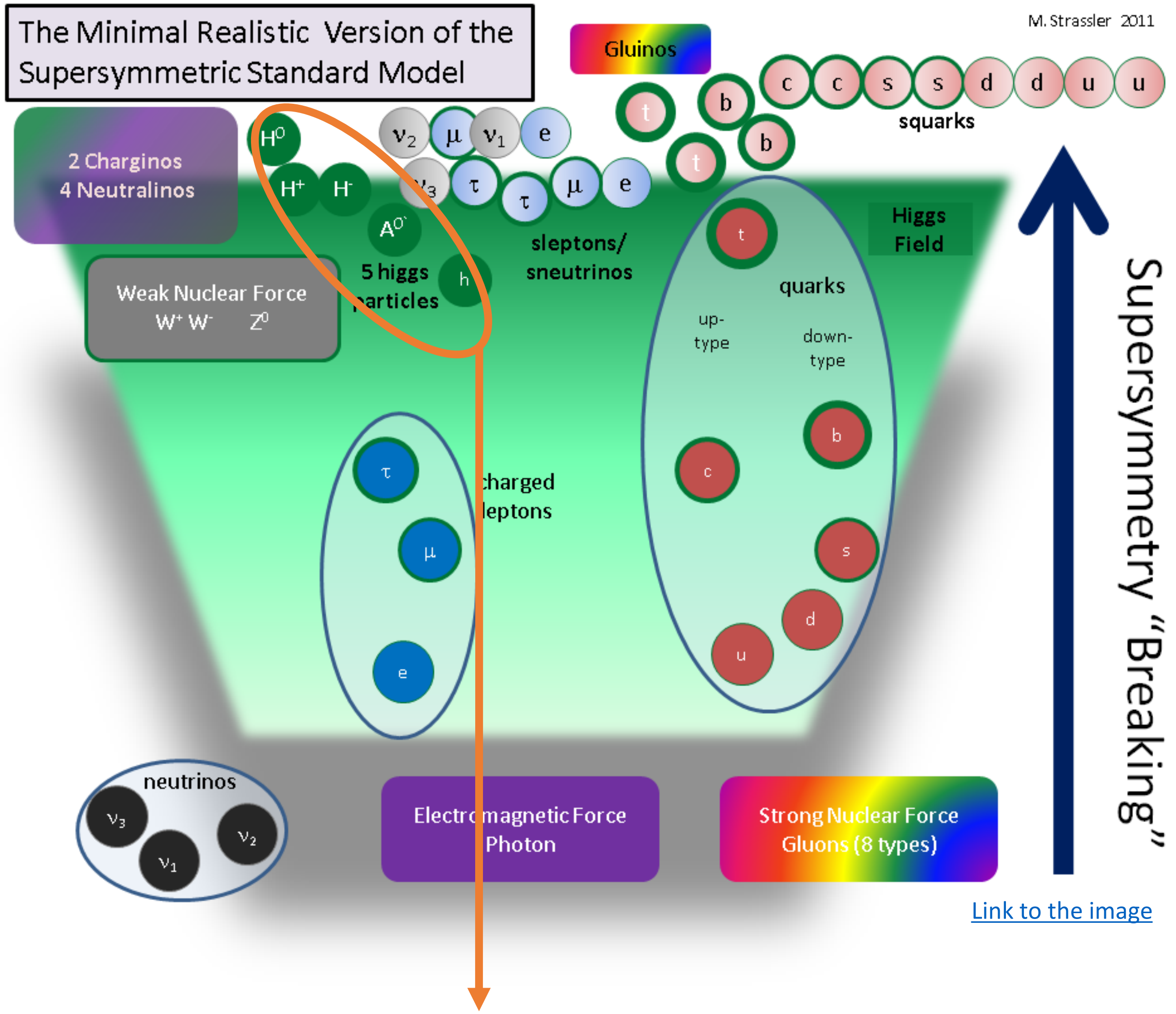
The Minimal Supersymmetric extension to the SM

- The **Minimal Supersymmetric Standard Model** (**MSSM**) is an extension to the Standard Model that **realizes supersymmetry** considering only "**the minimum number of new particle states and interactions consistent with "Reality"**.

- There are **three principal motivations** for the MSSM over other theoretical extensions of the Standard Model, namely:

    - **Naturaless**
    - **Gauge coupling unification**
    - **Dark Matter candidate**

- **The MSSM** is the leading candidate for **a new theory to be discovered at** collider experiments such as the Tevatron or **the Large Hadron Collider (LHC).**



Link to the image

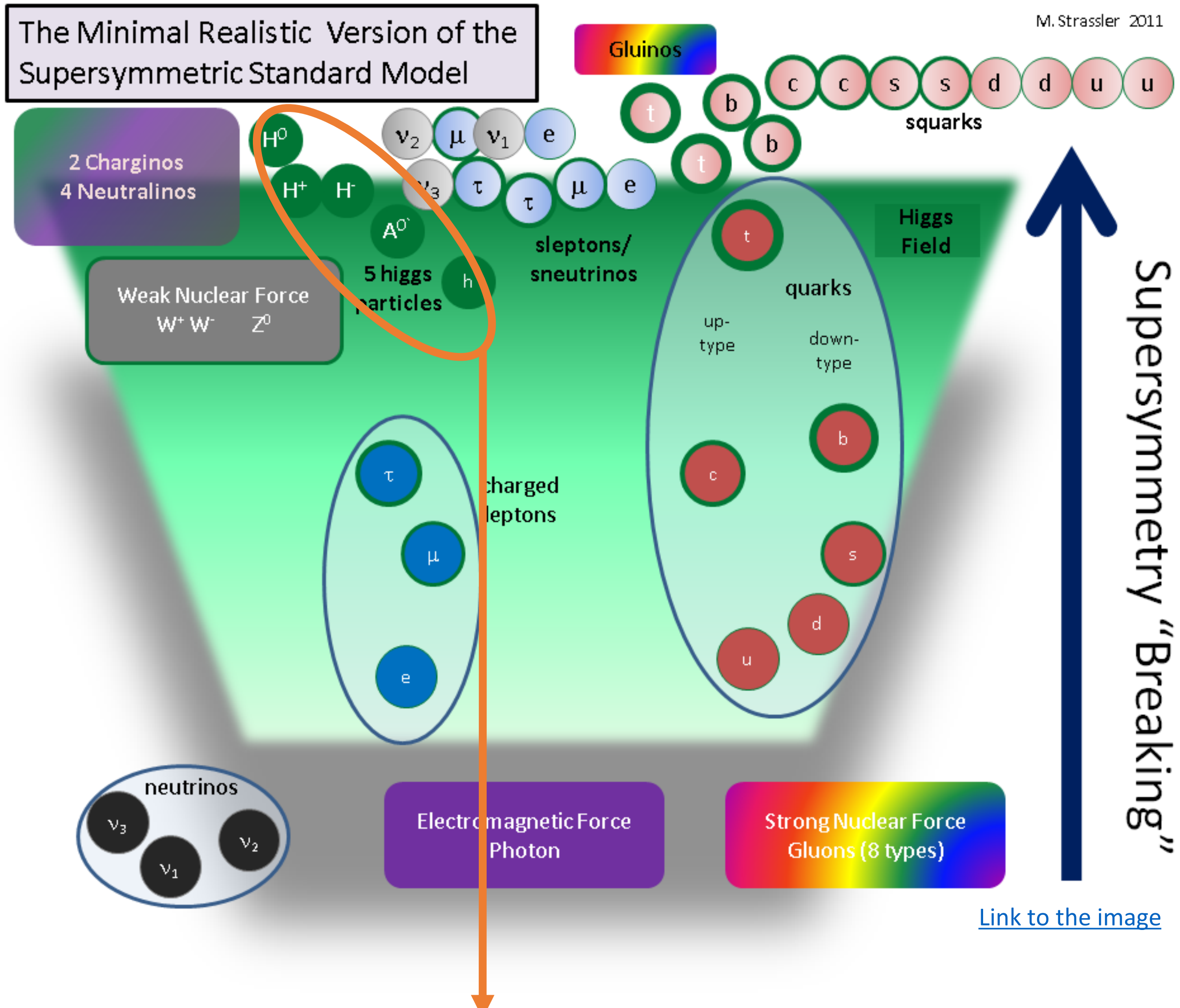
The Minimal Supersymmetric extension to the SM

- The **Minimal Supersymmetric Standard Model** (**MSSM**) is an extension to the Standard Model that **realizes supersymmetry** considering only "**the minimum number of new particle states and interactions consistent with "Reality"**.

- There are **three principal motivations** for the MSSM over other theoretical extensions of the Standard Model, namely:

    - ➢ **Naturaless**
    - ➢ **Gauge coupling unification**
    - ➢ **Dark Matter candidate**

- **The MSSM** is the leading candidate for **a new theory to be discovered at** collider experiments such as the Tevatron or **the Large Hadron Collider (LHC).**



Link to the image

The MSSM Higgs sector

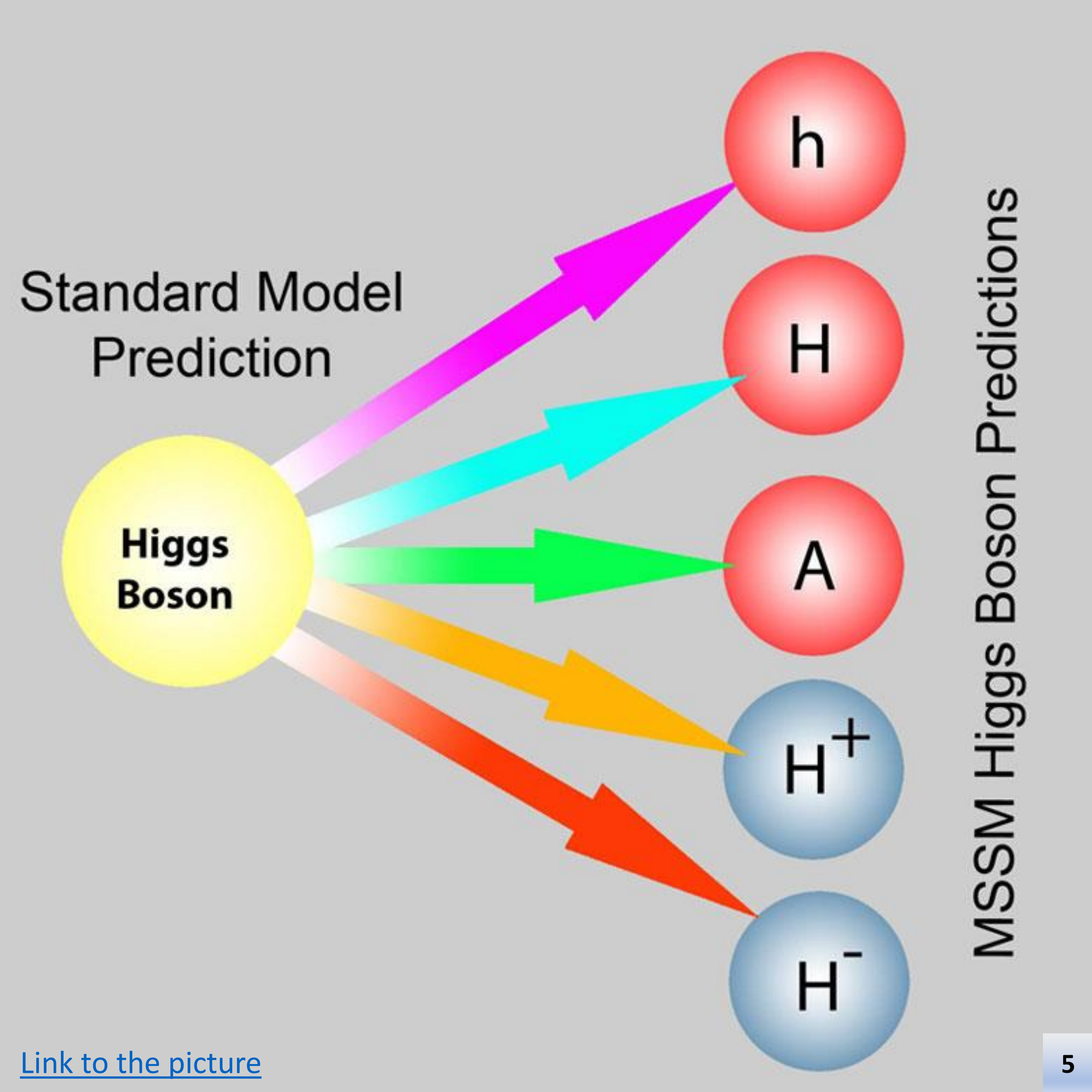
The MSSM Higgs sector

- **The Higgs sector** of the MSSM consists of **two Higgs doublets** that are indicated by $\boldsymbol{\Phi_1}$ **and** $\boldsymbol{\Phi_2}$, where Φ_1 couples to the up-type quarks, and Φ_2 couples to down-type quarks and leptons:

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

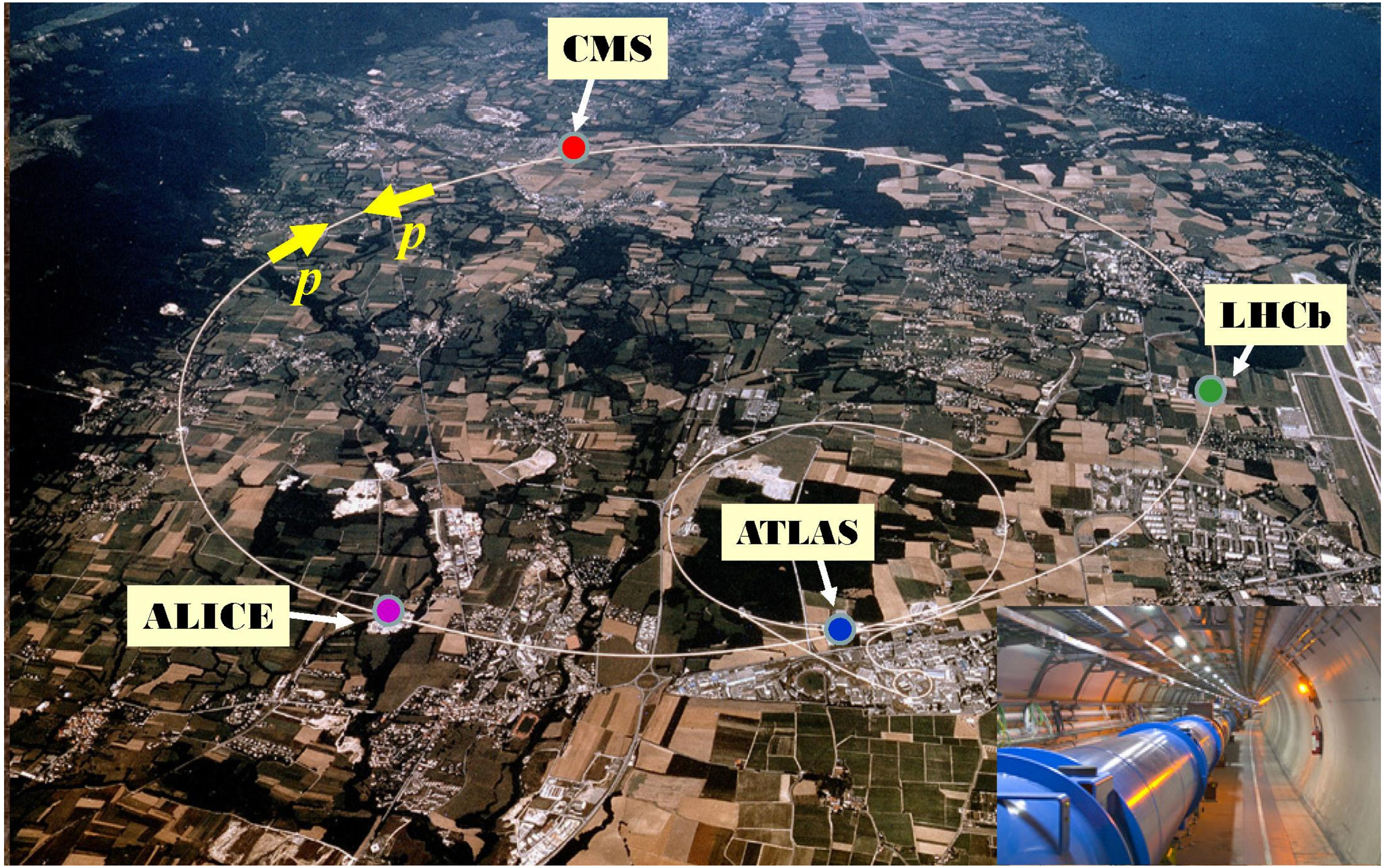
$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \nu_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \nu_2 \end{pmatrix}$$

- There are **5 physical states** called: h, H, A, H^+, H^-
- **At the tree level, the properties** of these particles **can be expressed in terms of:**
  - the known gauge boson masses
  - the mass of the **pseudoscalar** ($\boldsymbol{m_A}$)
  - the ratio of the VEVs of the two doublets **(tan**$\boldsymbol{\beta}$=$\boldsymbol{\frac{\nu_1}{\nu_2}}$**)**



Link to the picture

The Large Hadron Collider (LHC)



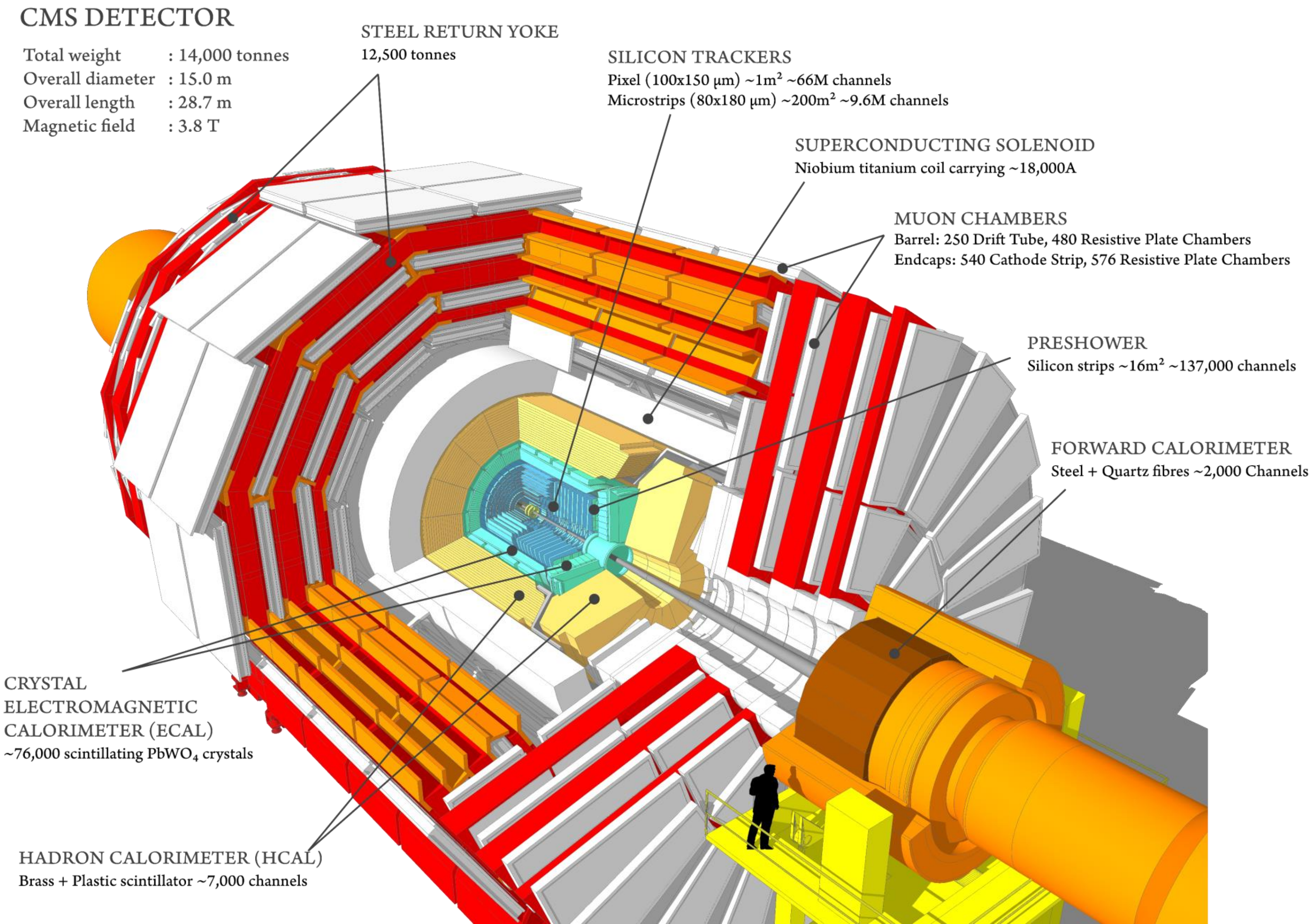
- **The Large Hadron Collider (LHC)** is the largest particle accelerator in the world, designed to **generate very high-energy collisions**

- **A fundamental characteristic**, directly linked to the machine's discovery power, is the "**integrated luminosity**" ($\mathcal{L}^{int}$), which links the **cross section** (σ) of a certain process to the **number of observed events** (N):

$$N = \sigma\mathcal{L}^{int}$$

- The accumulated integrated luminosity in Runs 1 and 2 was 196 fb^{-1}, and is expected to reach 300 fb^{-1} at the end of Run 3.

The Compact Muon Solenoid Experiment



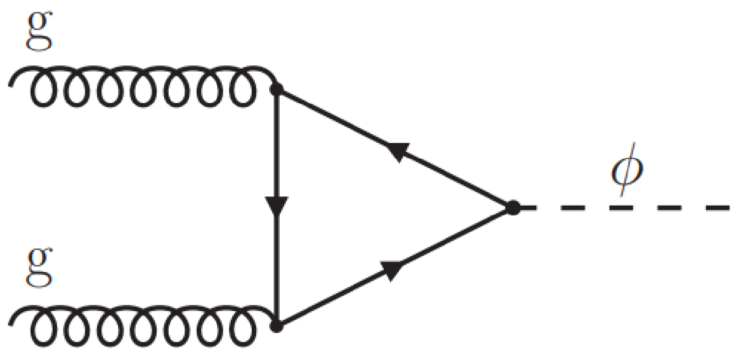
- **The Compact Muon Solenoid (CMS)** is a **cylindrically symmetric detector** made up of numerous coaxial sub-detectors and located **around one of the collision points of the LHC beams**
- **In 2012,** together with the ATLAS experiment, it made possible to claim the **discovery of the SM Higgs boson**

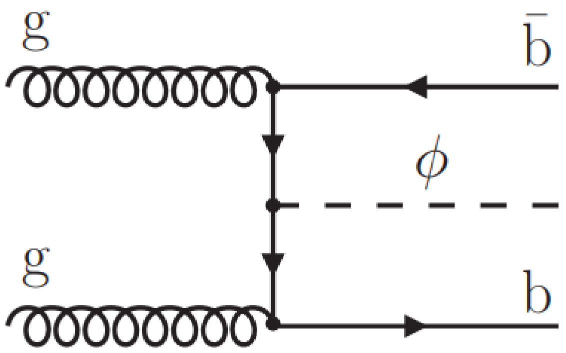
Search for additional Higgs bosons

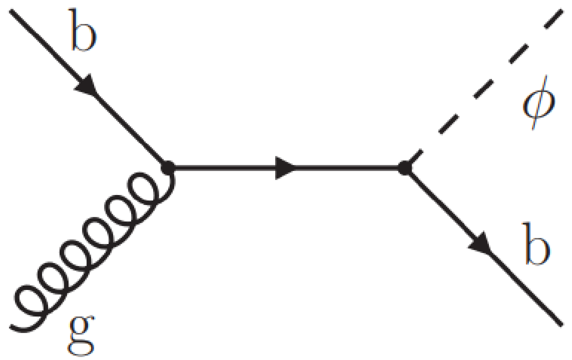
- **The CMS collaboration** has already published a paper (HIG-21-001) related to **search for signatures of physics beyond the SM in $\tau\tau$ final states** in proton-proton collisions at the CERN LHC

- **The data sample** used were collected with the CMS detector at a **centre-of-mass energy of $\sqrt{s}$= 13 TeV**, corresponding to an **integrated luminosity of 138 fb^{-1}**.

- **The first search**, which is meant to be as model independent as possible**, targets the production of a single narrow spin-0 resonance ϕ $(= h, H, A)$**, in addition to H(125), **via gluon fusion ($gg\phi$) or in association with b quarks ($bb\phi$**, not discussed today**) .**



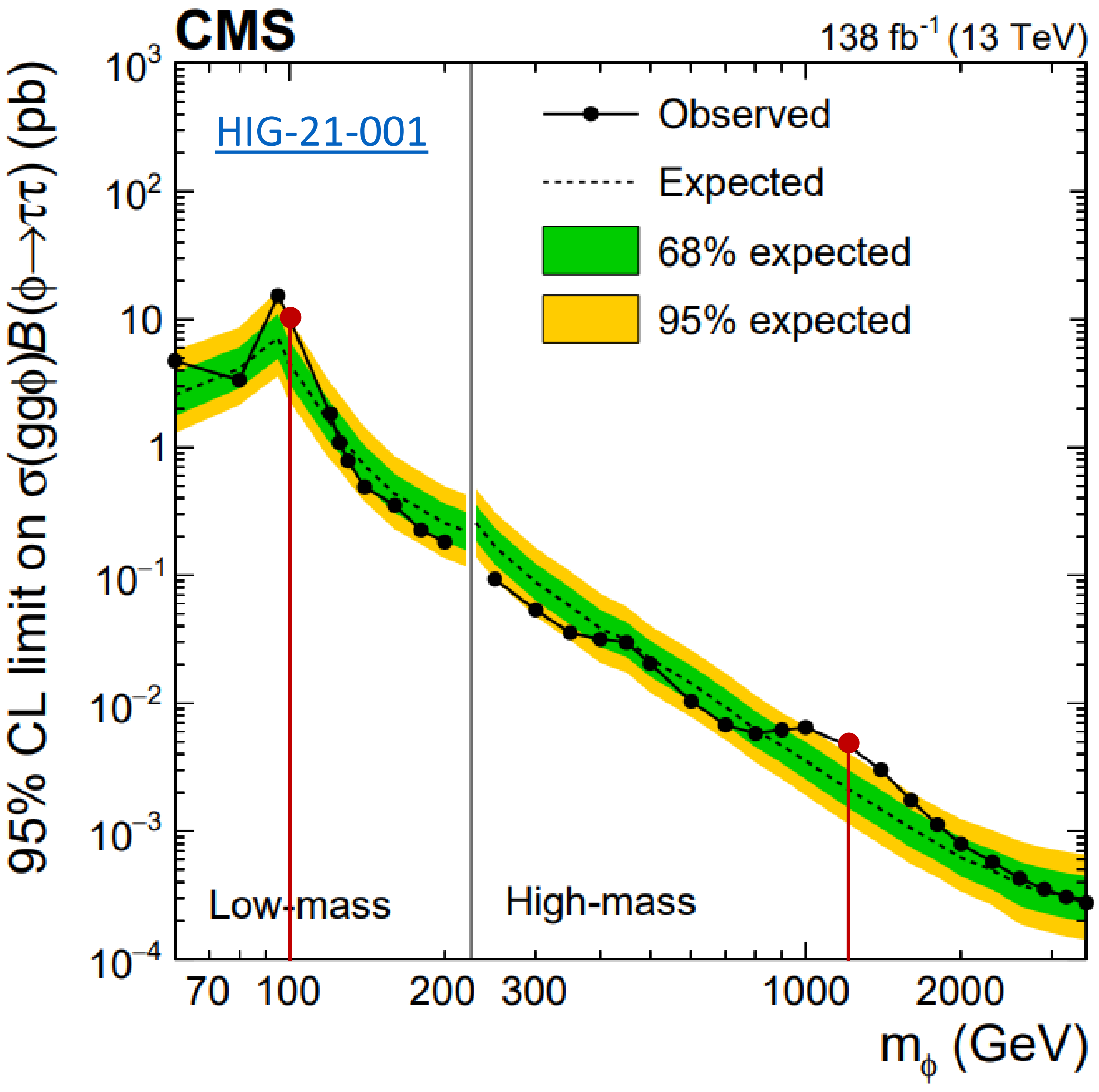




- **The second search** exploits selected **benchmark scenarios of the MSSM** that rely on the signal from three neutral Higgs bosons, one of which h **is associated with H(125).**

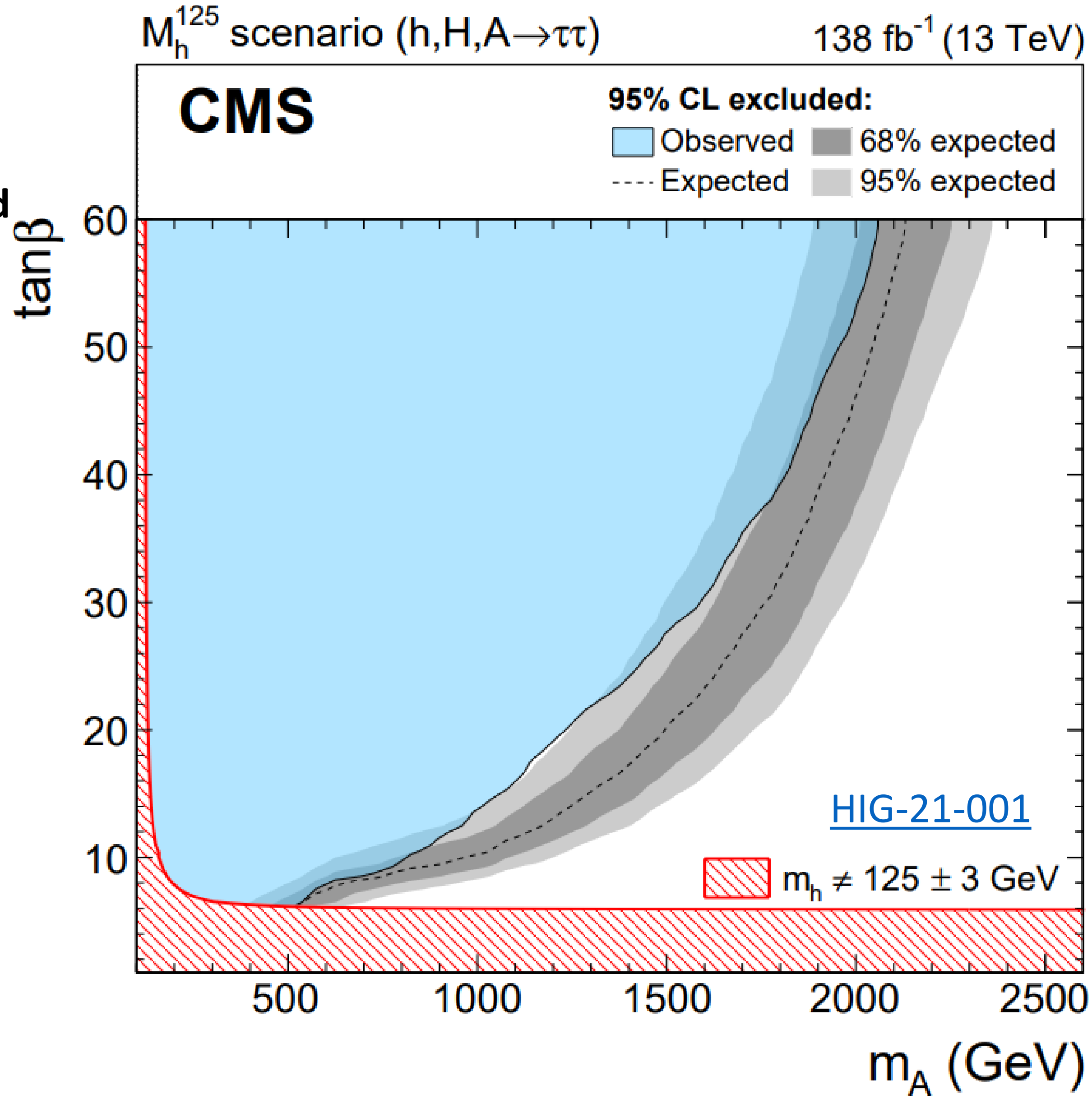
The Model Independent ϕ search

- This search targets **the production of a single resonance ϕ**, in addition to H(125), **via $gg\phi$**
- In the model, **H(125) is treated as background** assuming the production cross sections and branching fraction for the decay into τ leptons as expected from the SM.
- **Upper limits at 95% confidence level (CL) are set** on the products of the branching fraction for the decay into τ leptons and the cross sections to produce a resonance ϕ in addition to the observed Higgs boson**, ranging from O(10 pb) (at 60 GeV) to 0.3 fb (at 3.5 TeV)**.
- **The data reveal two excesses** for $gg\phi$ production with local p-values equivalent to **about three standard deviations at 0.1 and 1.2 TeV**.



The MSSM interpretation of the data

- **In the MSSM**, the signal constitutes a **multiresonance structure** with contributions from $\boldsymbol{h}$, $\boldsymbol{H}$ **and** $\boldsymbol{A}$ **bosons**.
- For the scenarios chosen for this paper, $\boldsymbol{h}$ **is associated with H(125)**
- Any MSSM prediction must match the observed properties of H(125).
- **To reflect the unknow effects** of higher order corrections, the $\boldsymbol{m_h}$ value is allowed to fluctuate $\pm$ **3 GeV around H(125)**
- **Additional Higgs bosons with masses below 350 GeV are excluded at 95% CL.**
- **The local excess** observed **at 1.2 TeV** causes the **deviation of the observed exclusion** from the expectation



Summary and outlooks

- In the paper (HIG-21-001) related to search for signatures of physics beyond the SM in $\tau\tau$ final states, the most recent results related to BSM Higgs boson searches with the CMS detector.

- We saw that data reveal two excesses for $gg\phi$ production with local p-values equivalent to about three standard deviations at 0.1 and 1.2 TeV.

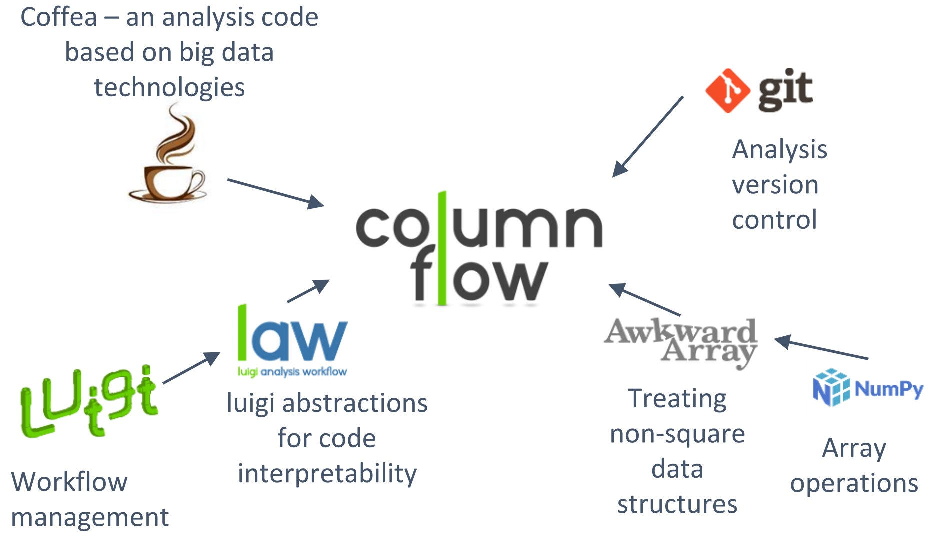
- The LHC has already delivered a portion of the data expected for RUN 3 which is still ongoing.

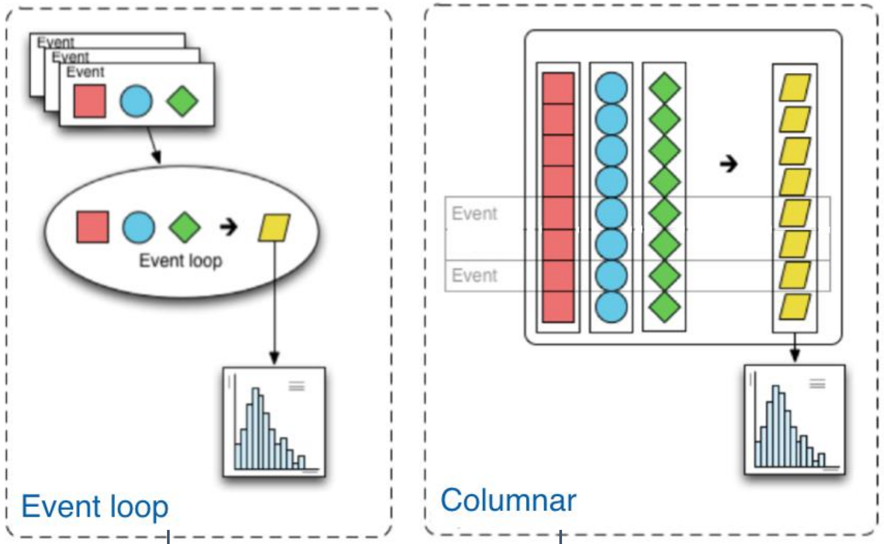
- The next objective will be to revisit the analysis already carried out by:

    - ➢ employing a columnar data analysis approach thanks to an under-development framework called **“columnflow”**

    - ➢ including the already existing RUN3 datasets and the yet-to-come ones

- This will help to clarify whether the excess are still present or not, and consequently gain a greater understanding of the BSM Higgs sector





- Explicit for loops
- Load all variables
- High Memory load

- Implicit loops
- Load variables needed
- Resource-Friendly Code


That's all Folks!
Thank you
For your attention!


BACK UP

Classification of Two-Higgs-doublet models

- Two-Higgs-doublet models can introduce FCNC which have not been observed so far.
- The Glashow-Weinberg condition, requiring that each group of fermions (up-type quarks, down-type quarks and charged leptons) couples exactly to one of the two doublets, is sufficient to avoid the prediction of FCNC currents.
- Depending on which type of fermions couples to which doublet, one can divide two-Higgs-doublet models into the following classes:

Type	Description	up-type quarks couple to	down-type quarks couple to	charged leptons couple to	remarks
Type I	Fermiophobic	Φ_2	Φ_2	Φ_2	charged fermions only couple to second doublet
Type II	MSSM-like	Φ_2	Φ_1	Φ_1	up- and down-type quarks couple to separate doublets
X	Lepton-specific	Φ_2	Φ_2	Φ_1	
Y	Flipped	Φ_2	Φ_1	Φ_2	
Type III		Φ_1, Φ_2	Φ_1, Φ_2	Φ_1, Φ_2	Flavor-changing neutral currents at tree level
Type FCNC-free		Φ_1, Φ_2	Φ_1, Φ_2	Φ_1, Φ_2	By finding a matrix pair which can be diagonalized simultaneously. [10]

By convention, Φ_2 is the doublet to which up-type quarks couple.

The statistical model

- The statistical model used to infer the signal from the data is defined by an extended binned likelihood of the form:

$$\mathcal{L}\left(\{k_i\},\{\mu_s\},\{\theta_j\}\right)=\prod_i \mathcal{P}\left(k_i|\sum_s \mu_s S_{si}(\{\theta_j\})+\sum_b B_{bi}(\{\theta_j\})\right)\prod_j \mathcal{C}(\tilde{\theta}_j|\theta_j).$$

where i labels the bins of the discriminating distributions of all categories, split by $\tau\tau$ final state and data-taking year.

- The function $P\left(k_i|\sum\mu_s S_{si}(\{\theta_i\})+\sum B_{bi}(\{\theta_j\})\right)$ corresponds to the Poisson probability to observe k_i events in bin i for a prediction of $\sum\mu_s S_{si}$ signal and $\sum B_{bi}$ background events.

- The parameters μ_s act as linear scaling parameters of the corresponding signal s.

- Systematic uncertainties are incorporated in the form of penalty terms for additional nuisance parameters $\{\theta_j\}$ in the likelihood, appearing as a product with predefined probability density functions $C(\widetilde{\theta}_j|\theta_j)$, where $\widetilde{\theta}_j$ corresponds to the nominal value for θ_j .

- The test statistic used for the inference of the signal is the profile likelihood ratio:

$$q_{\mu_s}=-2\ln\left(\frac{\mathcal{L}(\{k_i\}|\sum_s \mu_s S_{si}(\{\hat{\theta}_{j,\mu_s}\})+\sum_b B_{bi}(\{\hat{\theta}_{j,\mu_s}\}))}{\mathcal{L}(\{k_i\}|\sum_s \hat{\mu}_s S_{si}(\{\hat{\theta}_{j,\hat{\mu}_s}\})+\sum_b B_{bi}(\{\hat{\theta}_{j,\hat{\mu}_s}\}))}\right),\quad 0\leq\hat{\mu}_s\leq\mu_s$$

The Model independent ϕ search

Expected and observed 95% CL upper limits on the product of the cross sections and branching fraction into τ leptons bbϕ production in a mass range of 60 ≤ mϕ ≤ 3500 GeV, in addition to hobs.

The expected median of the exclusion limit in the absence of signal is shown by the dashed line.

The dark green and bright yellow bands indicate the 68 and 95% central intervals for the expected exclusion limit.

The black dots correspond to the observed limits.