



MINISTÈRE  
DE L'ENSEIGNEMENT SUPÉRIEUR,  
DE LA RECHERCHE  
ET DE L'INNOVATION



PHAST  
PHYSIQUE  
ET ASTROPHYSIQUE  
UNIVERSITÉ DE LYON



Lyon 1

# Recherche d'un boson de Higgs de haute masse se désintégrant en paire de taus dans l'expérience CMS au LHC

Soutenance de thèse de doctorat

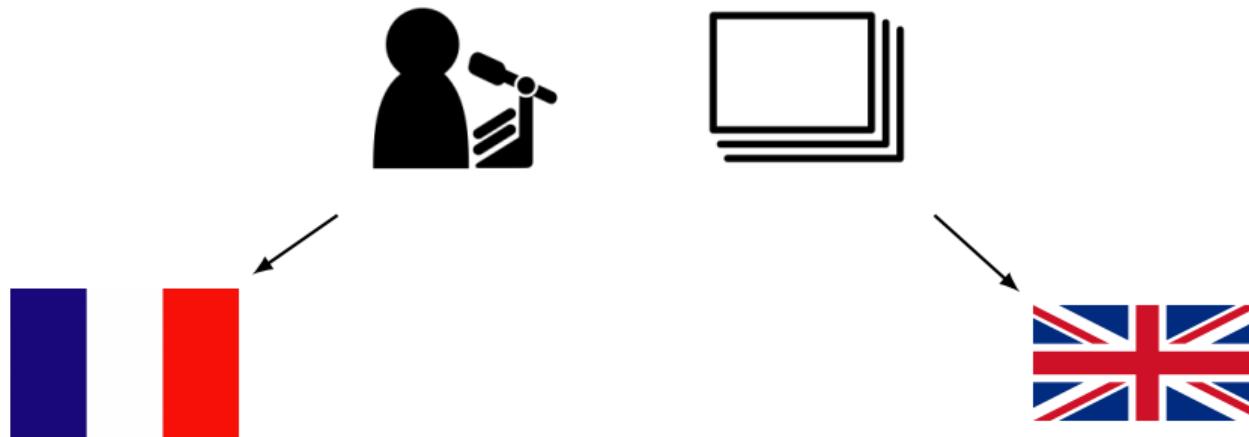
Lucas TORTEROTOT

Institut de Physique des deux Infinis – Lyon

XX xxxx 2021



# Lang(u)age





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RÉPUBLIQUE FRANÇAISE



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# Search for additional neutral Higgs bosons decaying to tau lepton pair in the CMS experiment at LHC

Ph.D. thesis defense

Lucas TORTEROTOT

Institut de Physique des deux Infinis – Lyon

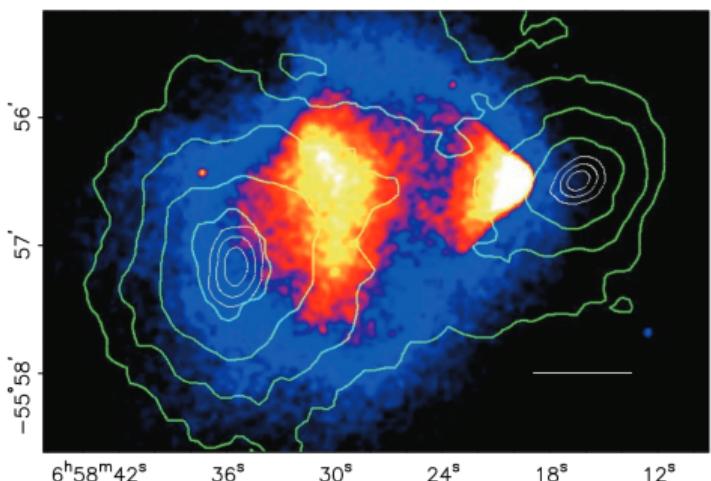
xxxx XX<sup>st/nd/rd/th</sup> 2021



## Why do we search for...?

### Current model status

- Robust and predictive (top quark,  $W$ ,  $Z$  and one Higgs boson...)
- still not good enough, unable to explain some observations such as:
  - ▶ dark matter →
  - ▶ matter vs antimatter asymmetry
  - ▶ ...
- Go beyond with a new model!
- Consequences of this new model? **Test it!**



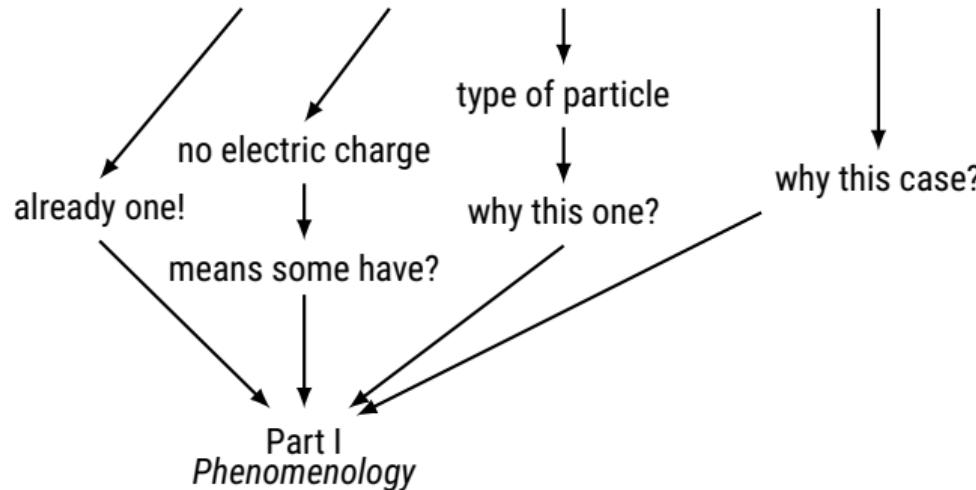
▷ D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

# Keywords in title

Search for **additional neutral Higgs bosons decaying to tau lepton pair** in the **CMS experiment** at **LHC**

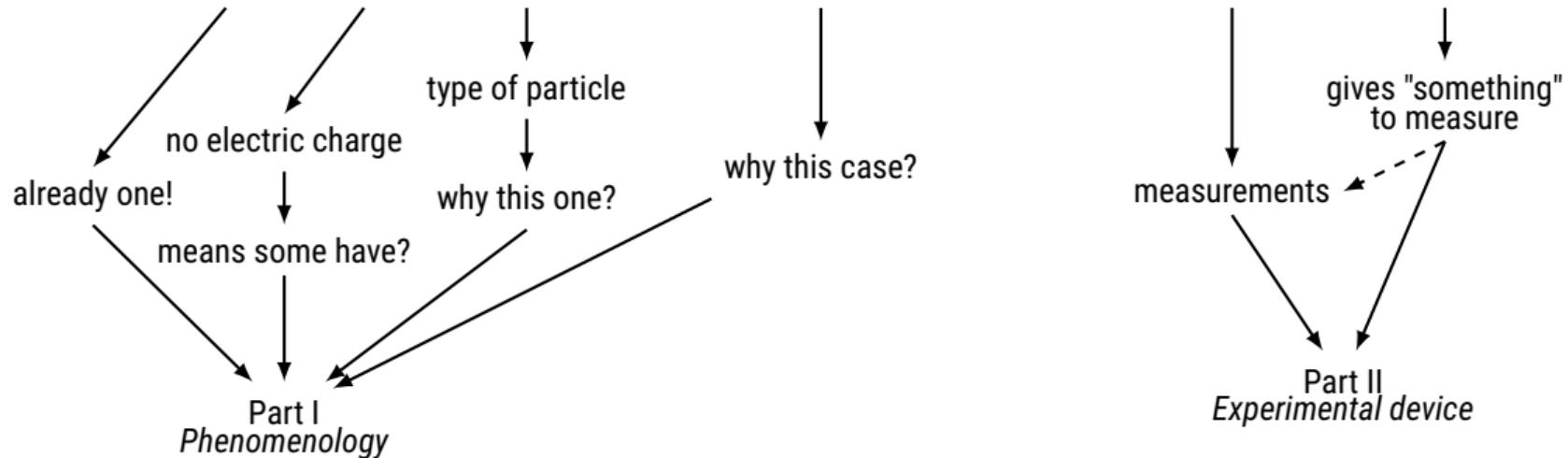
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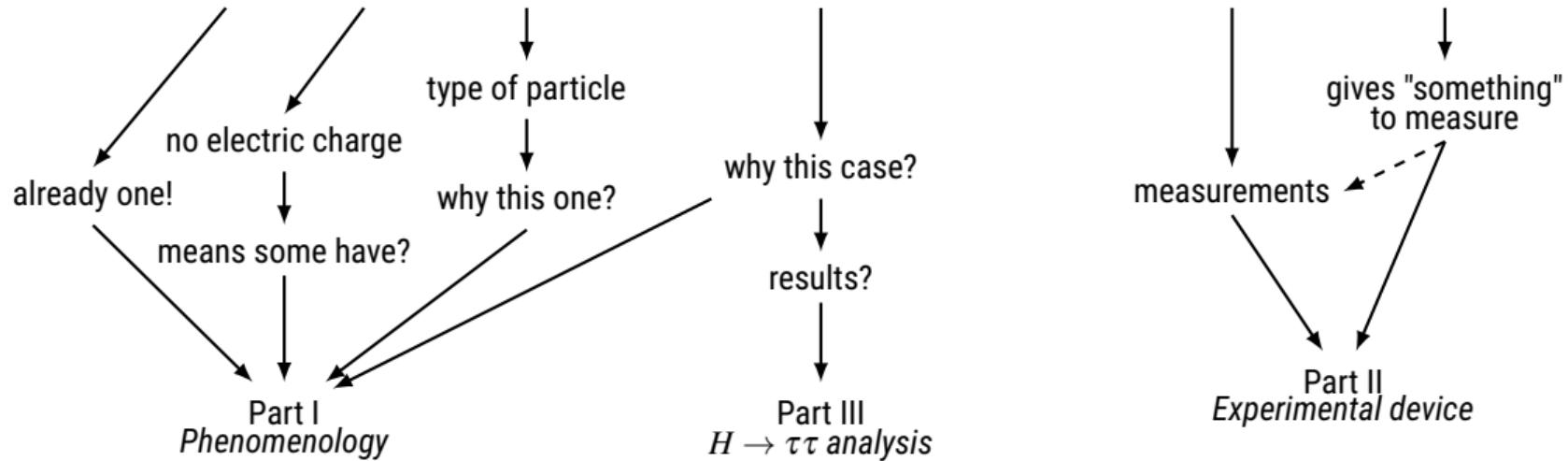
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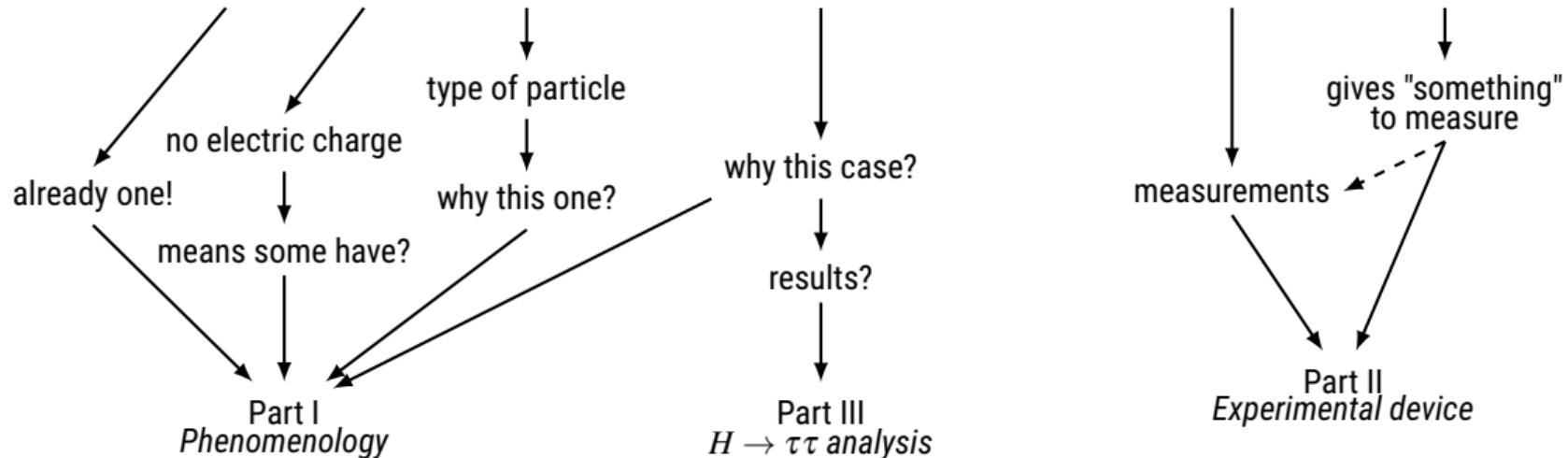
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# Keywords in title

Search for **additional neutral Higgs bosons decaying to tau lepton pair** in the **CMS experiment** at **LHC**



+ Part IV: Machine Learning use in the  $H \rightarrow \tau\tau$  analysis

## 1 Phenomenology

## 2 Experimental device

## 3 $H \rightarrow \tau\tau$ analysis

## 4 Machine Learning

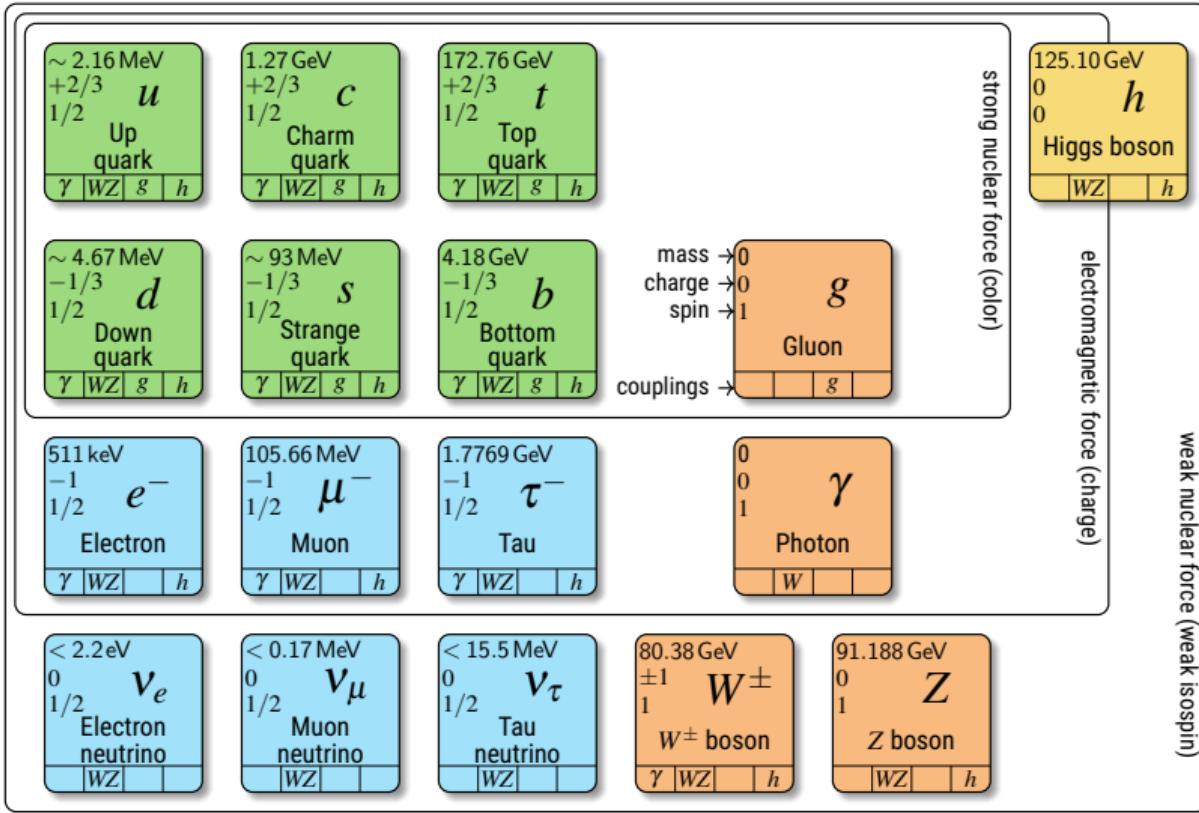
## 1 Phenomenology

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## 4 Machine Learning

# The Standard Model



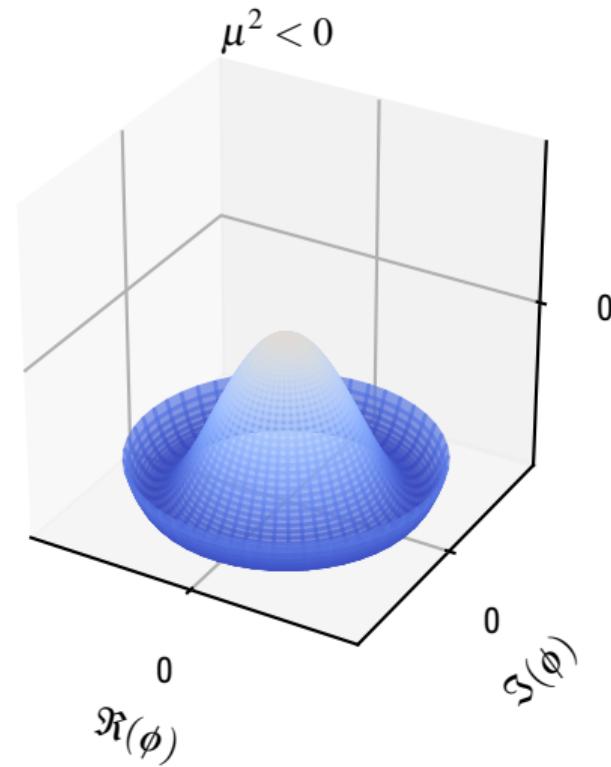
# Higgs boson in the Standard Model

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_3 + i\phi_4 \\ \phi_1 + i\phi_2 \end{pmatrix}$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad \lambda > 0$$

$$\langle \phi \rangle_0 = \frac{v}{\sqrt{2}} = \sqrt{\frac{-\mu^2}{2\lambda}} \neq 0$$

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

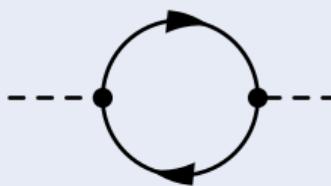


# The Standard Model and naturalness problem

► Higgs mass measured:  $m_h = 125.10 \pm 0.14 \text{ GeV}$

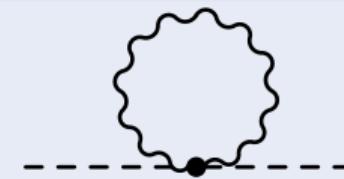
► Higgs mass derivation:  $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



$$-\frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim -(2 \text{ TeV})^2$$

vector bosons



$$+\frac{1}{16\pi^2} g^2 \Lambda^2 \sim +(0.7 \text{ TeV})^2$$

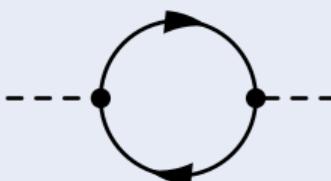
Higgs itself



$$+\frac{1}{16\pi^2} \lambda^2 \Lambda^2 \sim +(0.5 \text{ TeV})^2$$

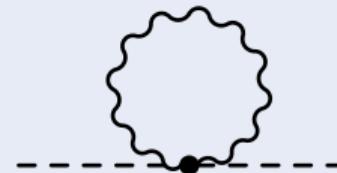
# Supersymmetry

top quark



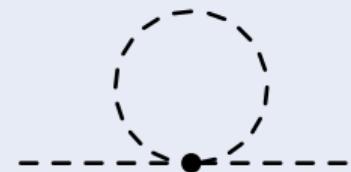
$$\sim -(2 \text{ TeV})^2$$

vector bosons



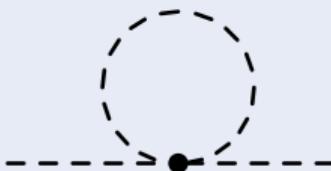
$$\sim +(0.7 \text{ TeV})^2$$

Higgs itself



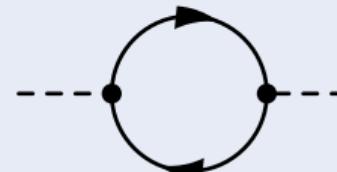
$$\sim +(0.5 \text{ TeV})^2$$

stop quark



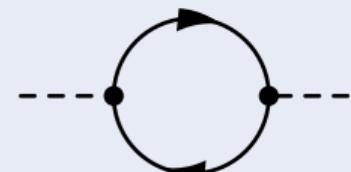
$$\sim +(2 \text{ TeV})^2$$

bosinos



$$\sim -(0.7 \text{ TeV})^2$$

Higgsinos



$$\sim -(0.5 \text{ TeV})^2$$

## 2 Higgs doublets models for supersymmetry

$$\begin{aligned} V(\phi_1, \phi_2) = & \lambda_1 \left( \phi_1^\dagger \phi_1 - \frac{1}{2} v_1^2 \right)^2 + \lambda_2 \left( \phi_2^\dagger \phi_2 - \frac{1}{2} v_2^2 \right)^2 \\ & + \lambda_3 \left[ \left( \phi_1^\dagger \phi_1 - \frac{1}{2} v_1^2 \right) + \left( \phi_2^\dagger \phi_2 - \frac{1}{2} v_2^2 \right) \right]^2 + \lambda_4 \left[ (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) - (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \right] \\ & + \lambda_5 \left[ \Re(\phi_1^\dagger \phi_2) - \frac{1}{2} v_1 v_2 \cos \xi \right]^2 + \lambda_6 \left[ \Im(\phi_1^\dagger \phi_2) - \frac{1}{2} v_1 v_2 \sin \xi \right]^2 \\ & + \lambda_7 \left[ \Re(\phi_1^\dagger \phi_2) - \frac{1}{2} v_1 v_2 \cos \xi \right] \left[ \Im(\phi_1^\dagger \phi_2) - \frac{1}{2} v_1 v_2 \sin \xi \right] \end{aligned}$$

## 2 Higgs doublets models for supersymmetry

$$\langle \phi_1 \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \phi_2 \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix}$$

$$\boxed{\tan \beta = \frac{\langle \phi_2 \rangle_0}{\langle \phi_1 \rangle_0} = \frac{v_2}{v_1}}$$

# Higgs bosons in the MSSM

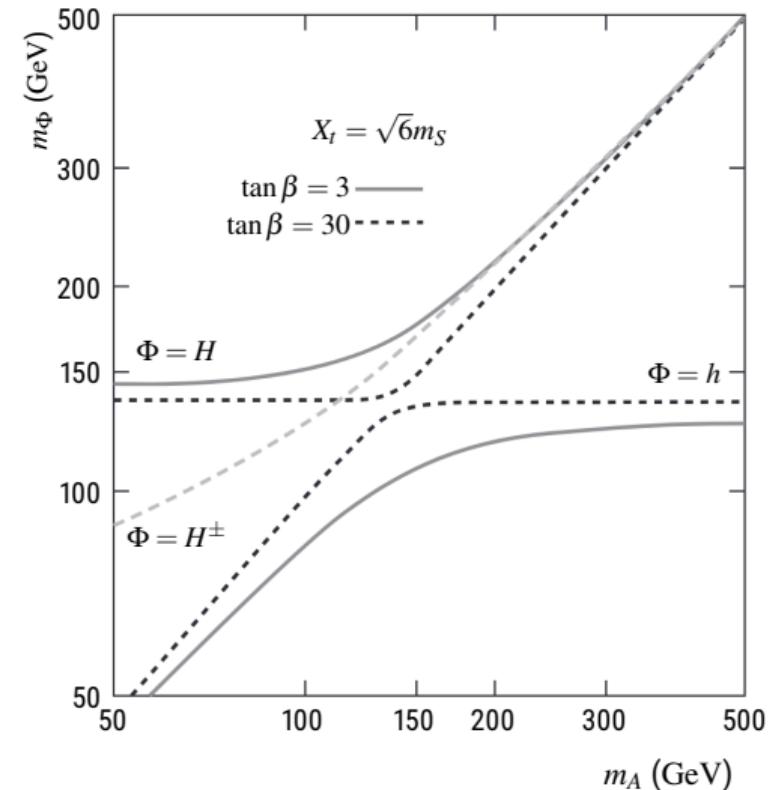
*Minimal Supersymmetric extension of Standard Model*

## 5 Higgs bosons

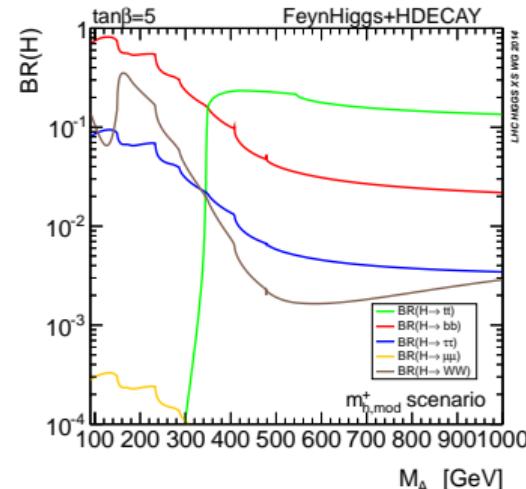
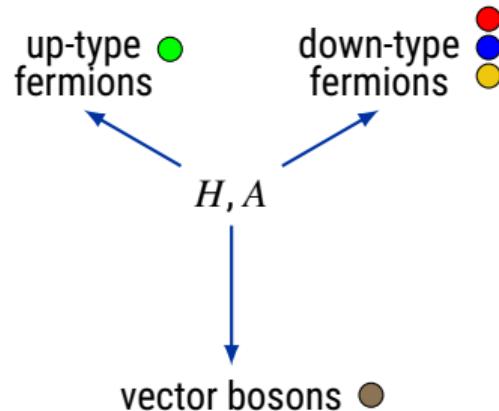
|               |       |            |
|---------------|-------|------------|
| light scalar  | $h$   | SM or MSSM |
| heavy scalar  | $H$   | MSSM or SM |
| pseudo-scalar | $A$   | MSSM       |
| + charged     | $H^+$ | MSSM       |
| - charged     | $H^-$ | MSSM       |

▷ **The CMS Collaboration.** "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13\text{ TeV}$ ". *Journal of High Energy Physics* **09.007** (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).

▷ **Y. Nagashima.** *Beyond the Standard Model of Elementary Particle Physics*. Weinheim: Wiley-VCH, June 2014. URL: <http://cds.cern.ch/record/1620277>.

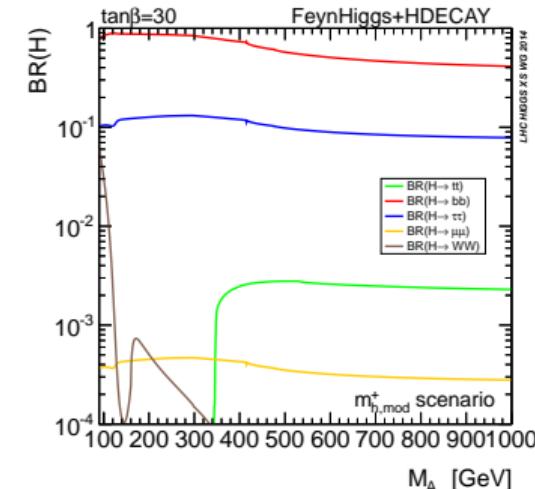
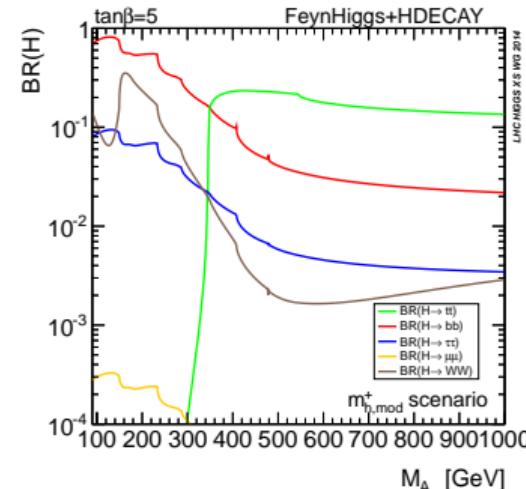
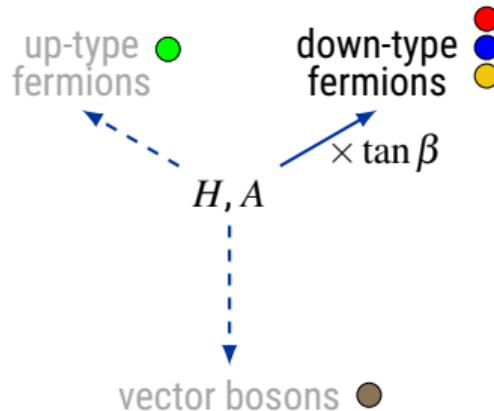


# $H \rightarrow \tau\tau?$

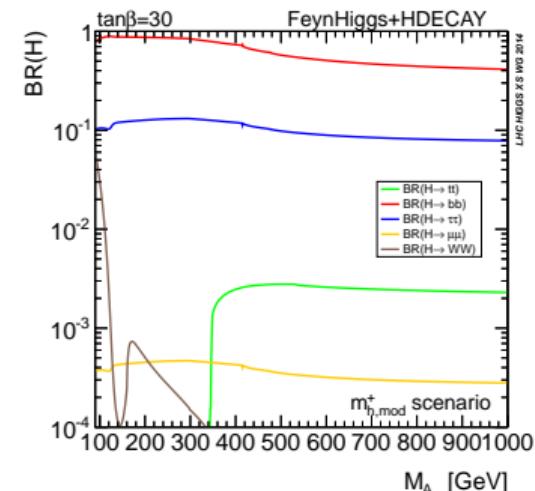
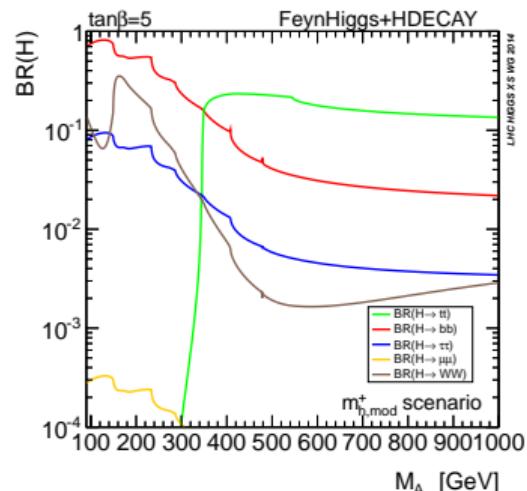
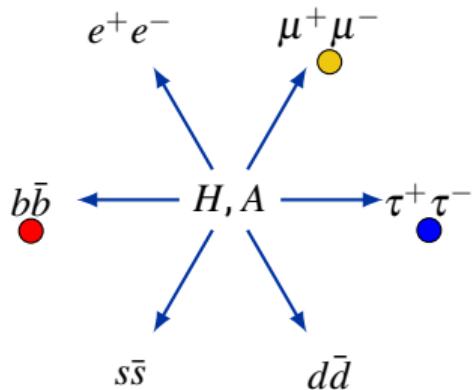


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections. 3. CERN Yellow Reports: Monographs*. Geneva: CERN, 2013. DOI: 10.5170/CERN-2013-004. URL: <https://cds.cern.ch/record/1559921>.

# $H \rightarrow \tau\tau?$ – enhanced and suppressed couplings

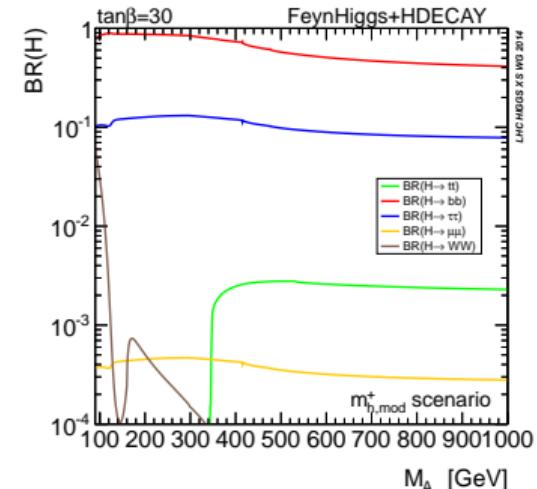
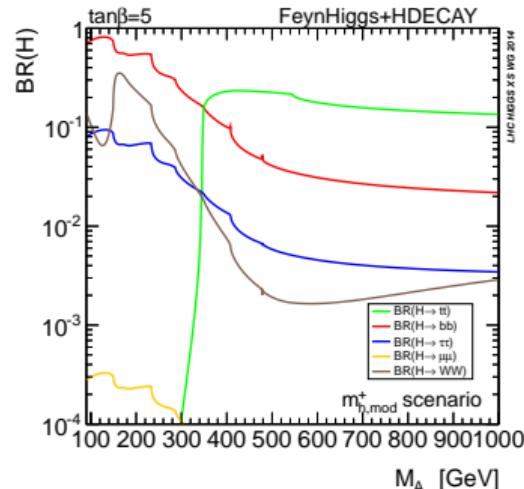
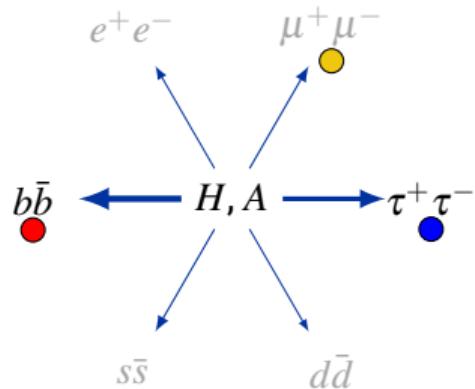


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections. 3. CERN Yellow Reports: Monographs*. Geneva: CERN, 2013. DOI: 10.5170/CERN-2013-004. URL: <https://cds.cern.ch/record/1559921>.

$H \rightarrow \tau\tau?$ 

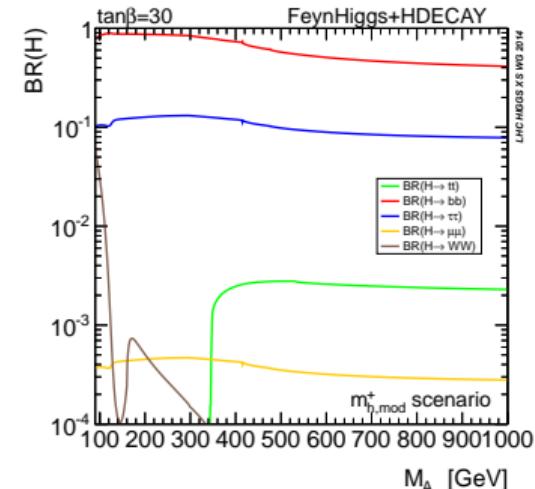
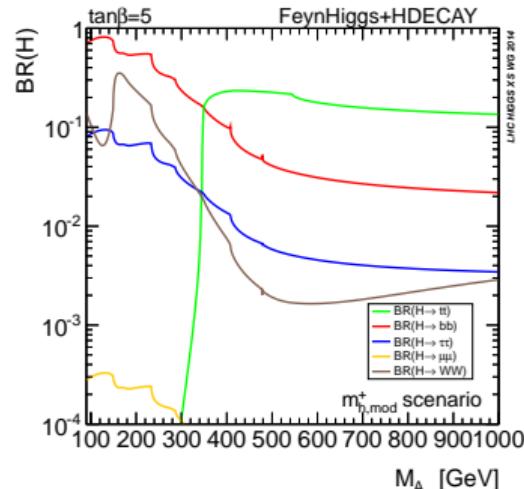
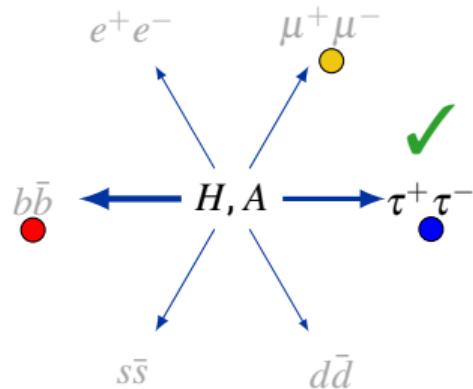
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections. 3. CERN Yellow Reports: Monographs*. Geneva: CERN, 2013. DOI: 10.5170/CERN-2013-004. URL: <https://cds.cern.ch/record/1559921>.

# $H \rightarrow \tau\tau?$ – Higgs couplings and particles masses



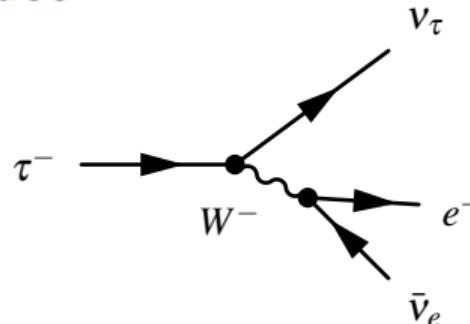
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections. 3. CERN Yellow Reports: Monographs*. Geneva: CERN, 2013. DOI: 10.5170/CERN-2013-004. URL: <https://cds.cern.ch/record/1559921>.

# $H \rightarrow \tau\tau?$ – avoid hadronic background

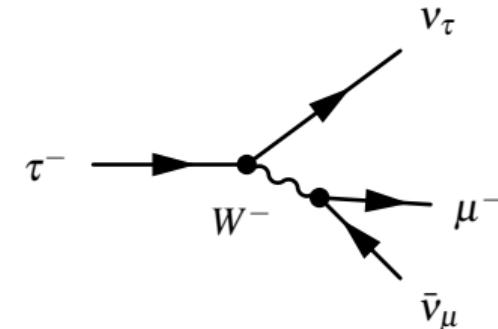
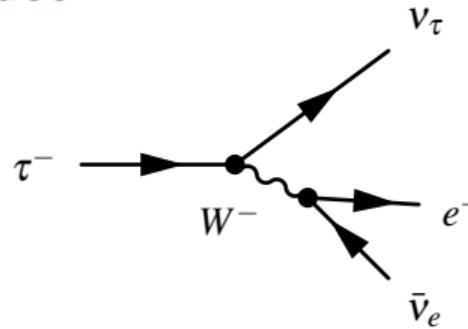


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections. 3. CERN Yellow Reports: Monographs*. Geneva: CERN, 2013. DOI: 10.5170/CERN-2013-004. URL: <https://cds.cern.ch/record/1559921>.

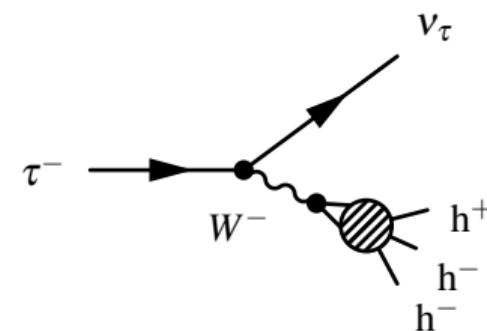
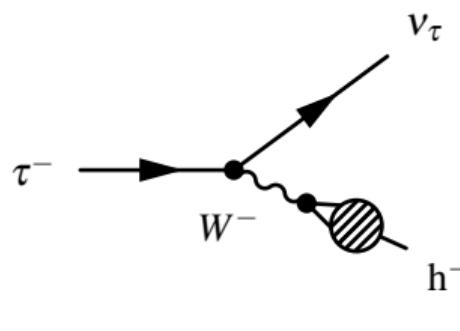
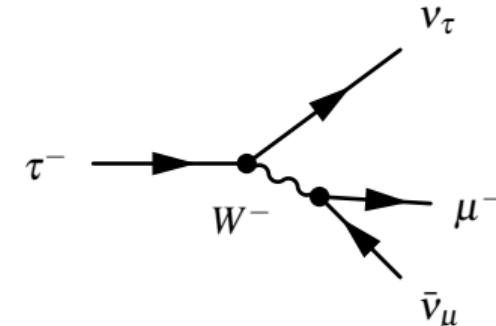
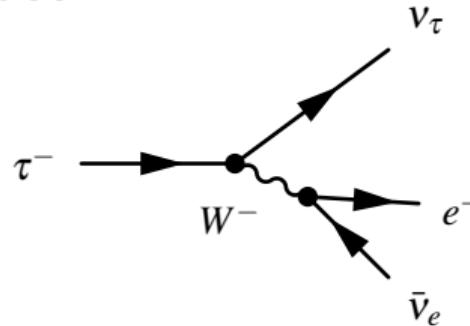
# $\tau$ decay modes



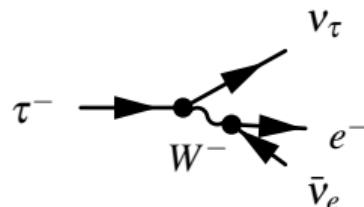
# $\tau$ decay modes



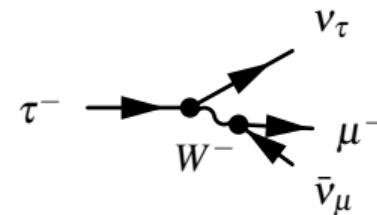
# $\tau$ decay modes



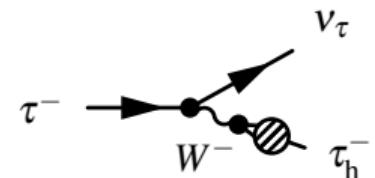
$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$



$$\tau \rightarrow e + \nu_e + \nu_\tau \Rightarrow e \\ 17.8\%$$

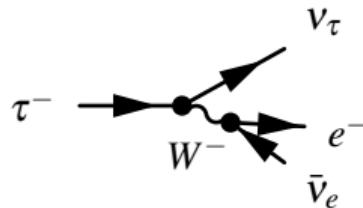


$$\tau \rightarrow \mu + \nu_\mu + \nu_\tau \Rightarrow \mu \\ 17.4\%$$

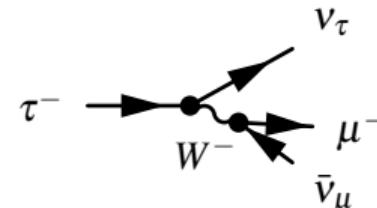


$$\tau \rightarrow \text{hadrons} + \nu_\tau \Rightarrow \tau_h \\ 64.8\%$$

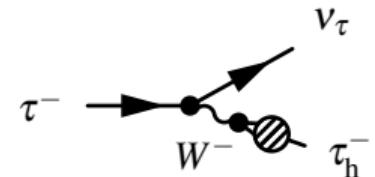
$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$



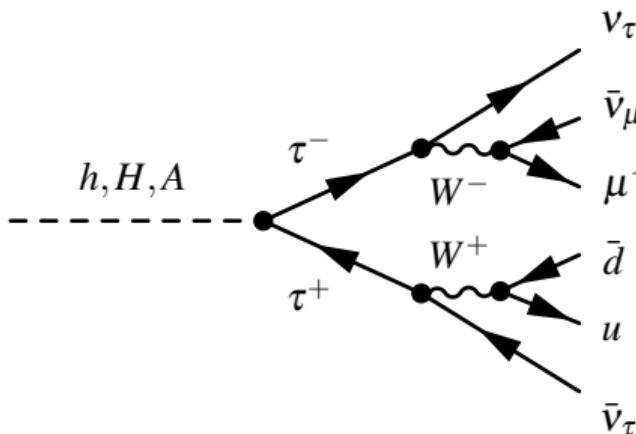
$$\tau \rightarrow e + \nu_e + \bar{\nu}_\tau \Rightarrow e \\ 17.8\%$$



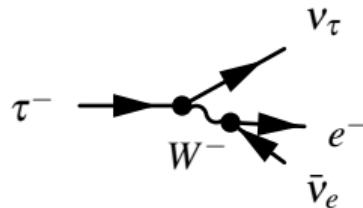
$$\tau \rightarrow \mu + \nu_\mu + \bar{\nu}_\tau \Rightarrow \mu \\ 17.4\%$$



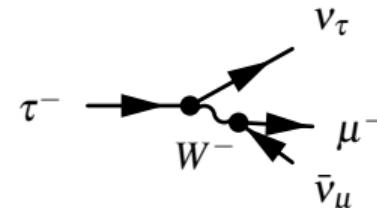
$$\tau \rightarrow \text{hadrons} + \nu_\tau \Rightarrow \tau_h \\ 64.8\%$$



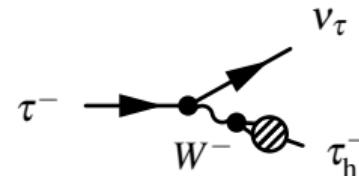
$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$



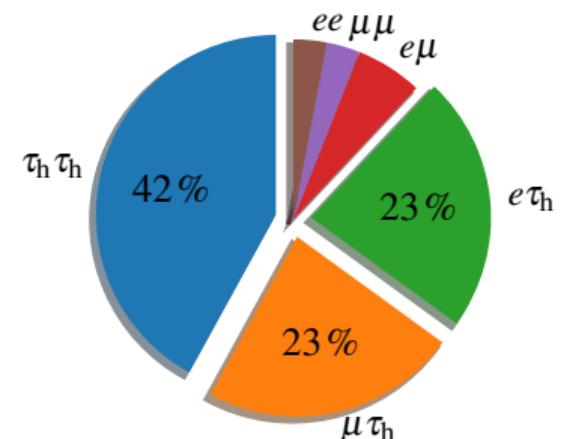
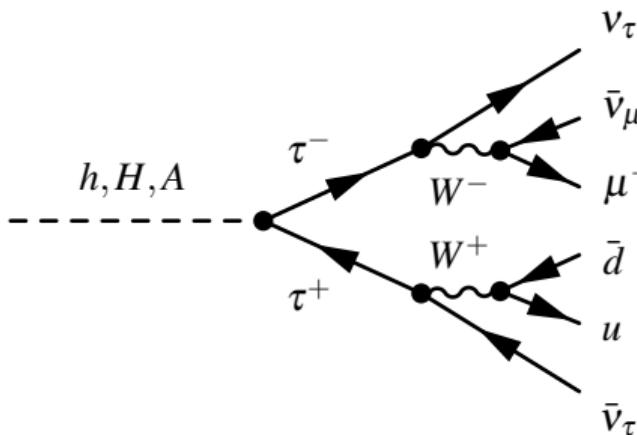
$$\tau \rightarrow e + \nu_e + \nu_\tau \Rightarrow e \\ 17.8\%$$



$$\tau \rightarrow \mu + \nu_\mu + \nu_\tau \Rightarrow \mu \\ 17.4\%$$



$$\tau \rightarrow \text{hadrons} + \nu_\tau \Rightarrow \tau_h \\ 64.8\%$$



## 1 Phenomenology

## 2 Experimental device

## 3 $H \rightarrow \tau\tau$ analysis

## 4 Machine Learning

# Principle

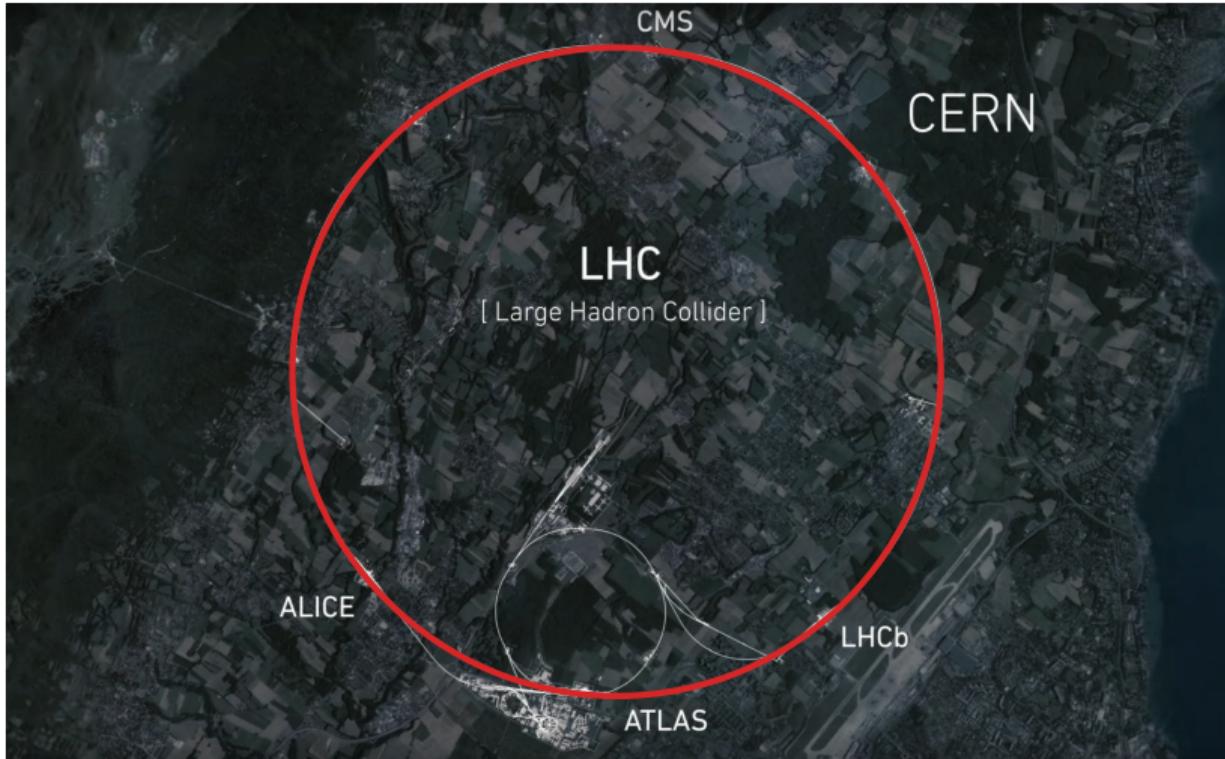
$$E = mc^2$$

mass (new particles) from the collision energy

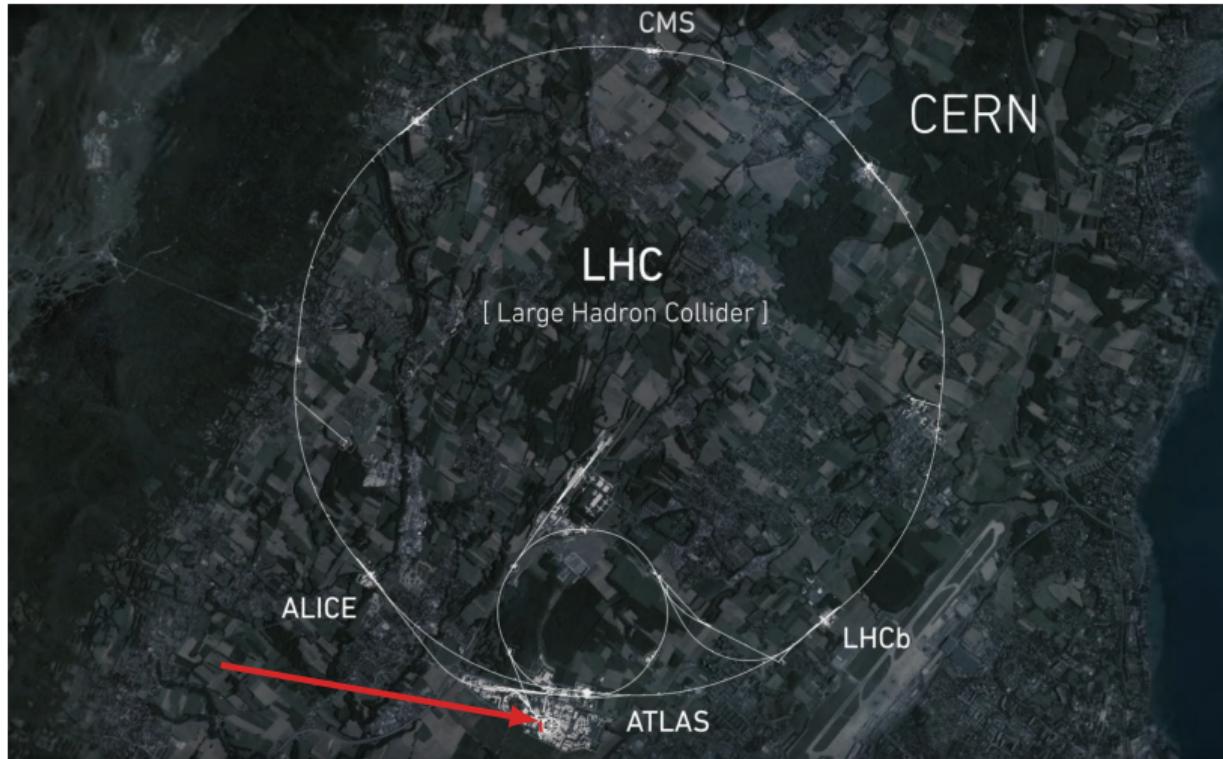
# CERN & LHC



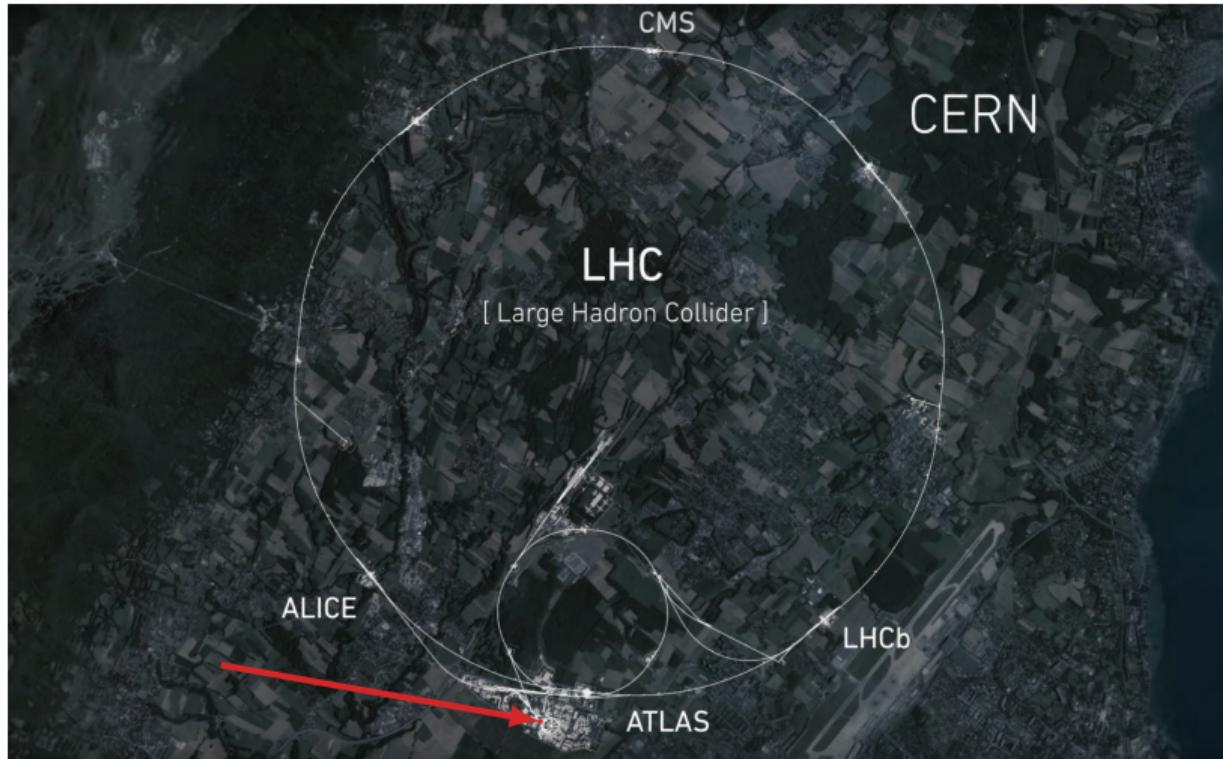
## LHC



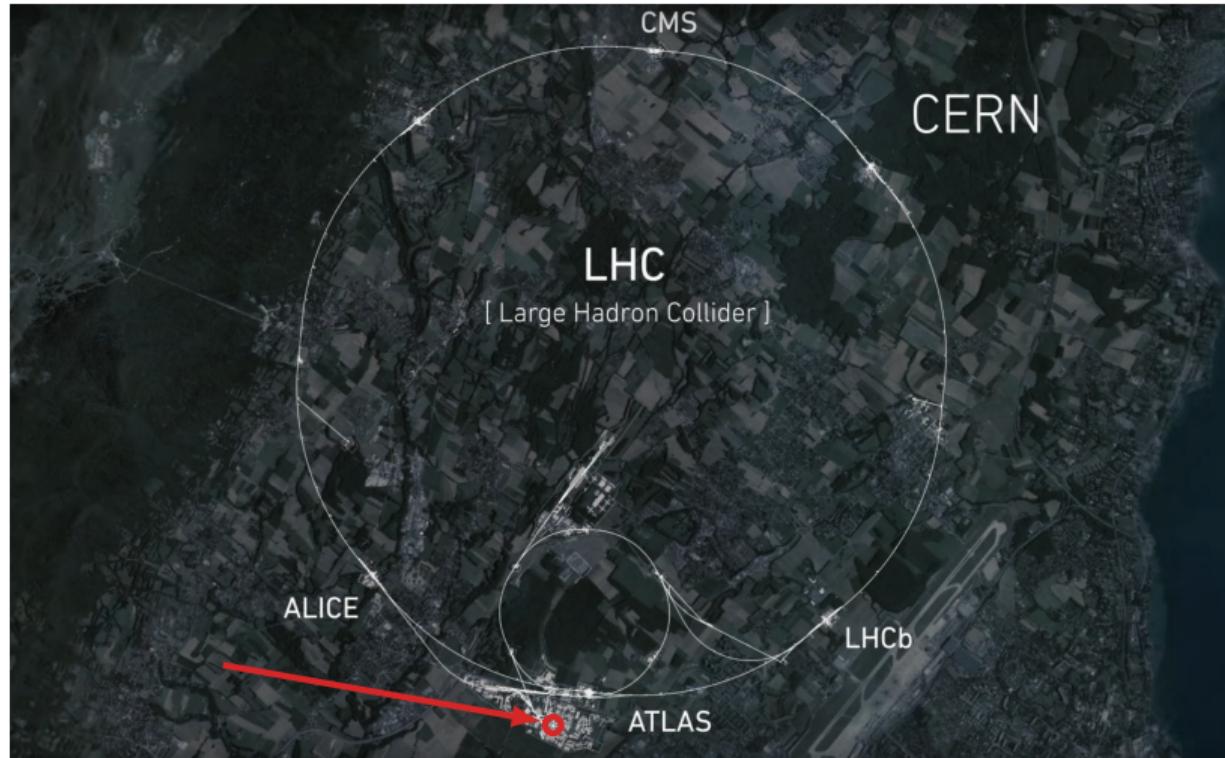
# LINAC2 (50MeV)



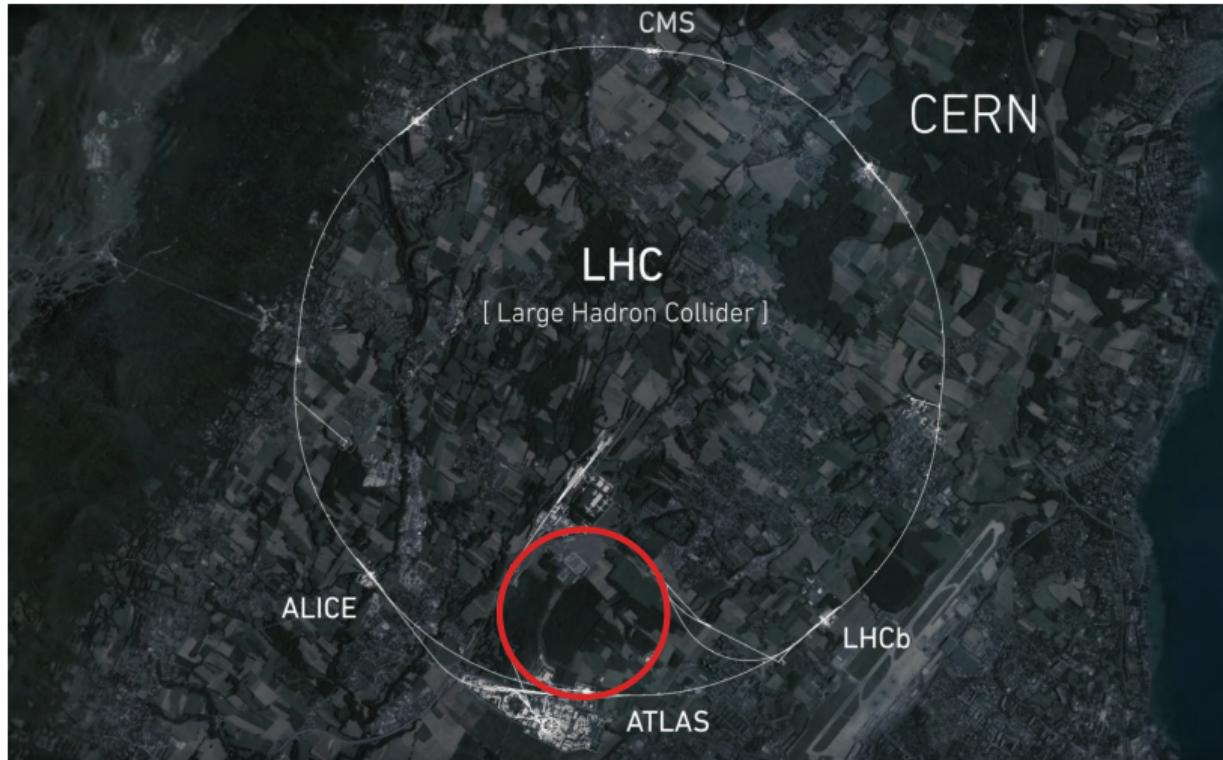
# Booster (1972, 157 m, 1.4 GeV)



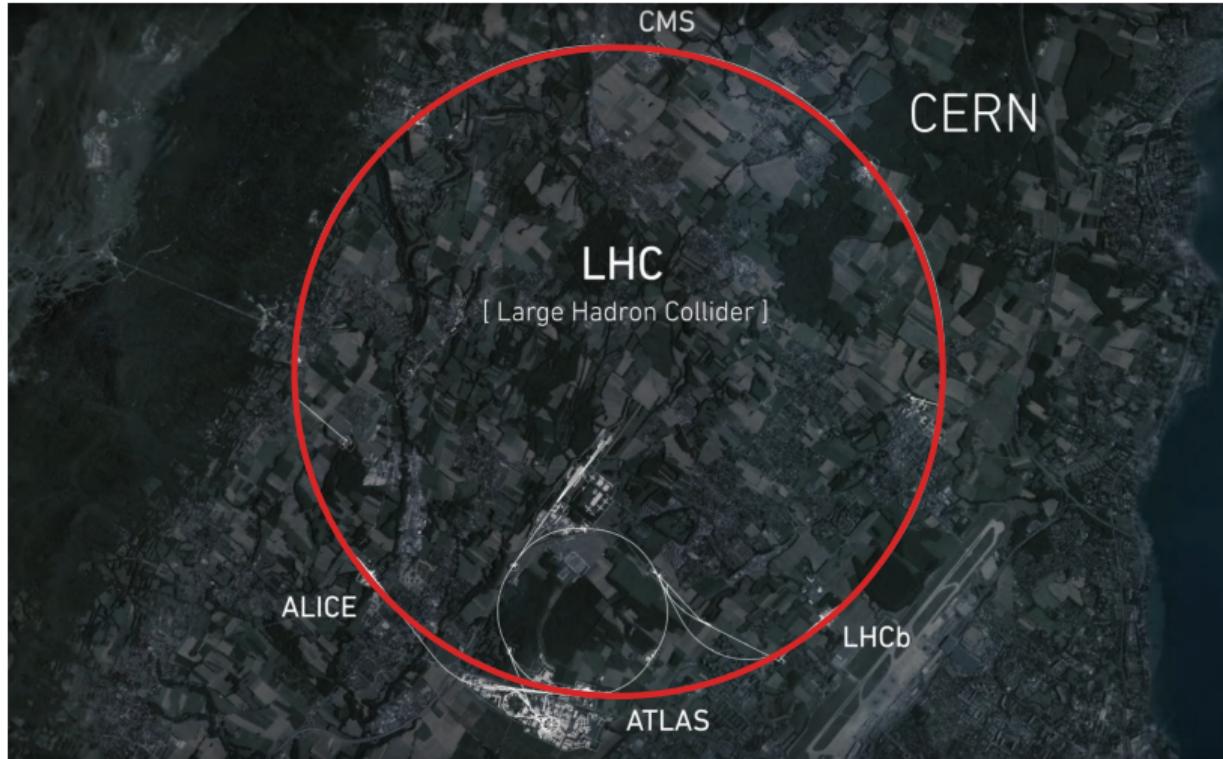
# PS (1959, 628 m, 25 GeV)

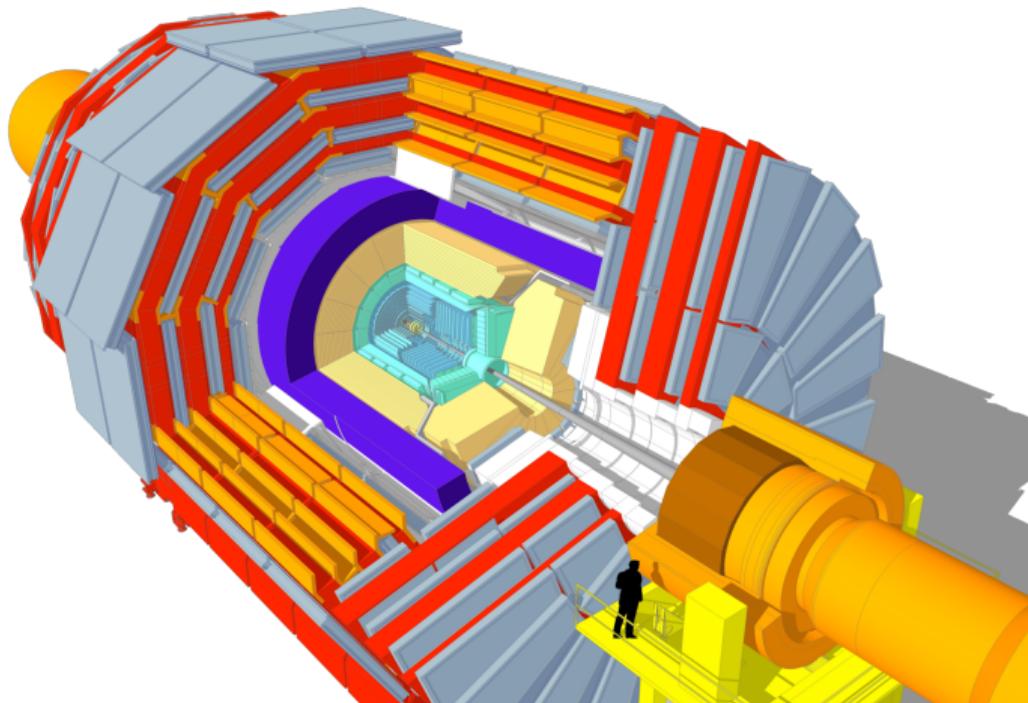


# SPS (1976, 7 km, 450 GeV)



# LHC (2008, 27 km, $2 \times 7 \text{ TeV}$ )

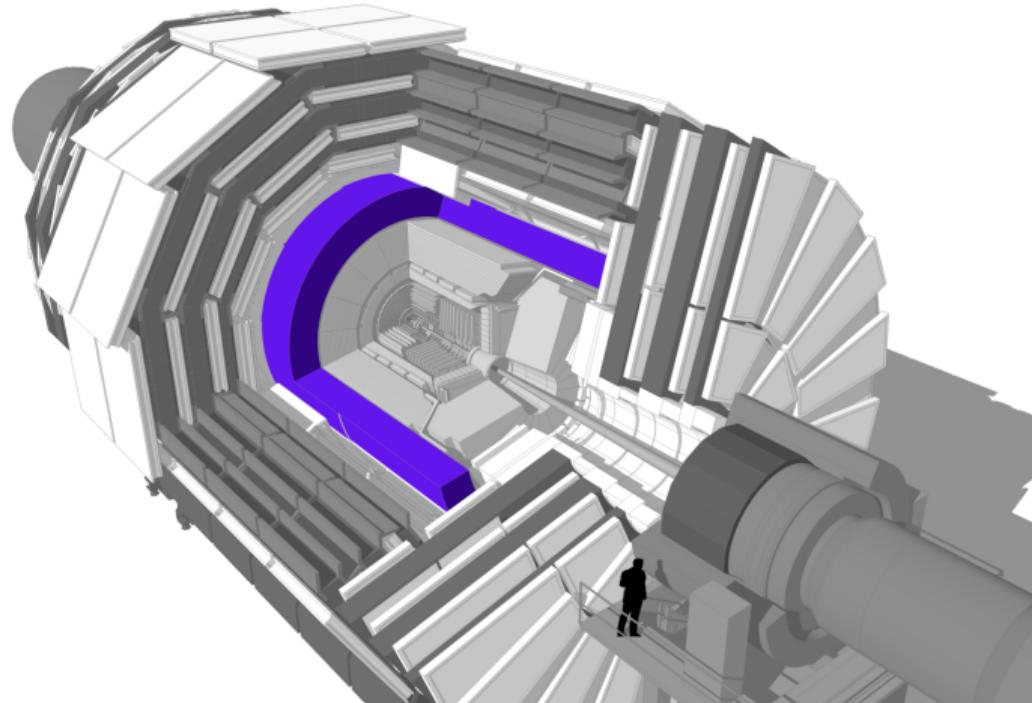




## CMS detector

- Mass:  $\sim 14,000\text{t}$
- Diameter: 15 m
- Length: 28.7 m

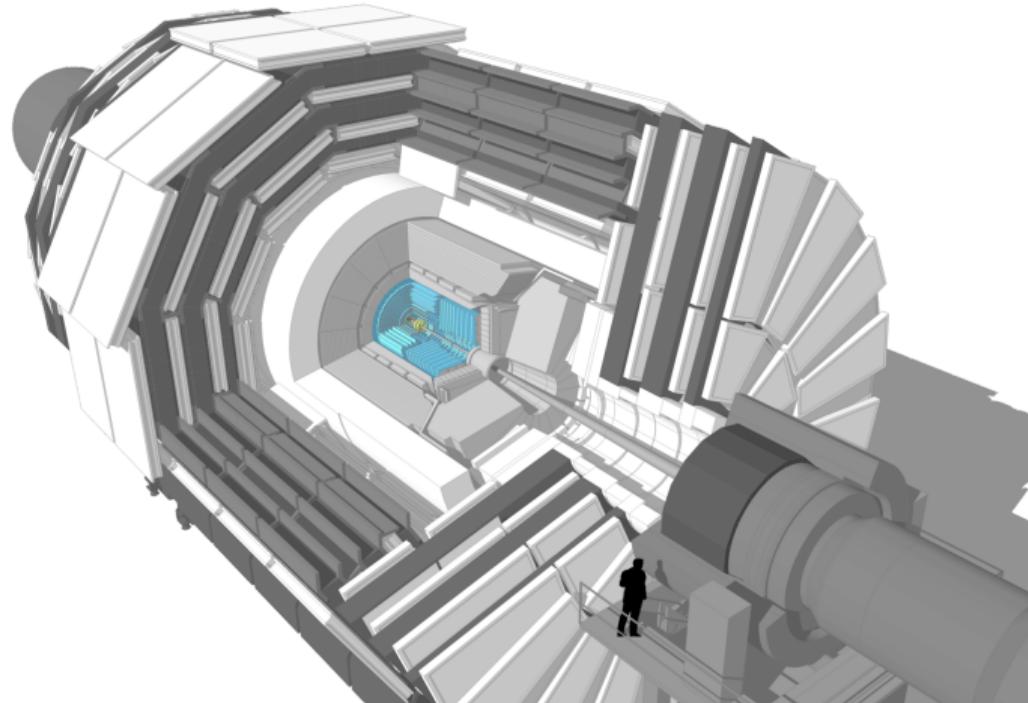
⇒ How to see the particles?



## Solenoid

- Niobium titanium coil
- Superconducting
- $\sim 18,000\text{ A}$
- 4 T in the inner volume

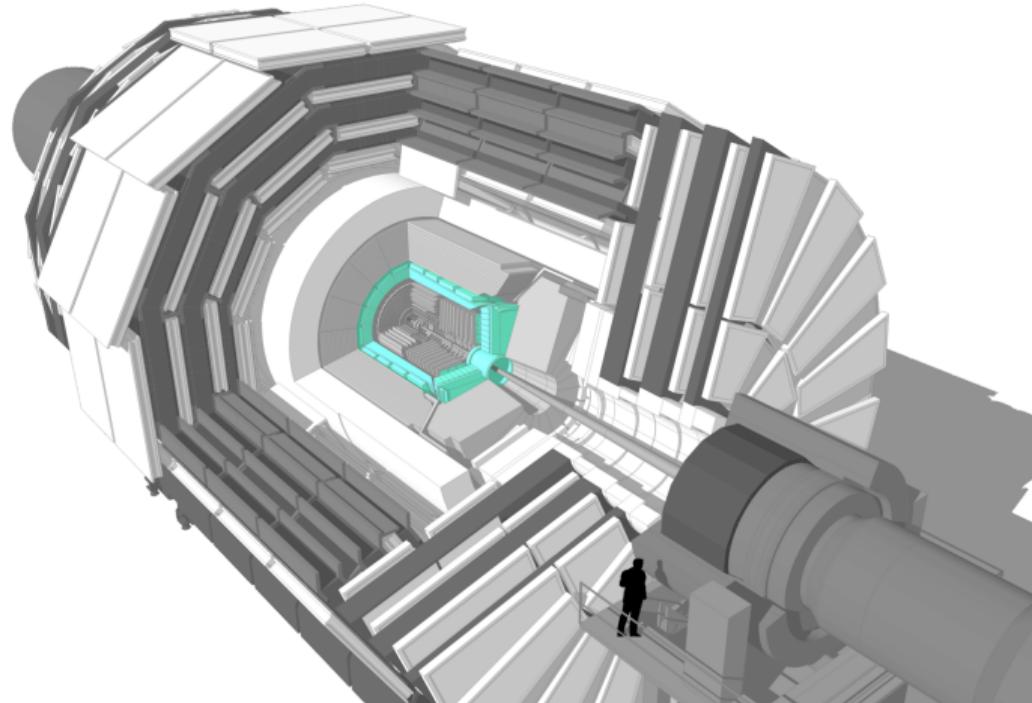
⇒ Bends charged particles trajectories  
in the transverse plane



## Tracker

- Made of Silicon
- Inner: pixels ( $100 \times 150 \mu\text{m}^2$ ,  $\sim 1.9 \text{ m}^2$ ,  $\sim 124 \text{ M}$  channels)
- Outer: microstrips ( $80 - 180 \mu\text{m}$ )  
 $\sim 200 \text{ m}^2 \sim 9.6 \text{ M}$  channels

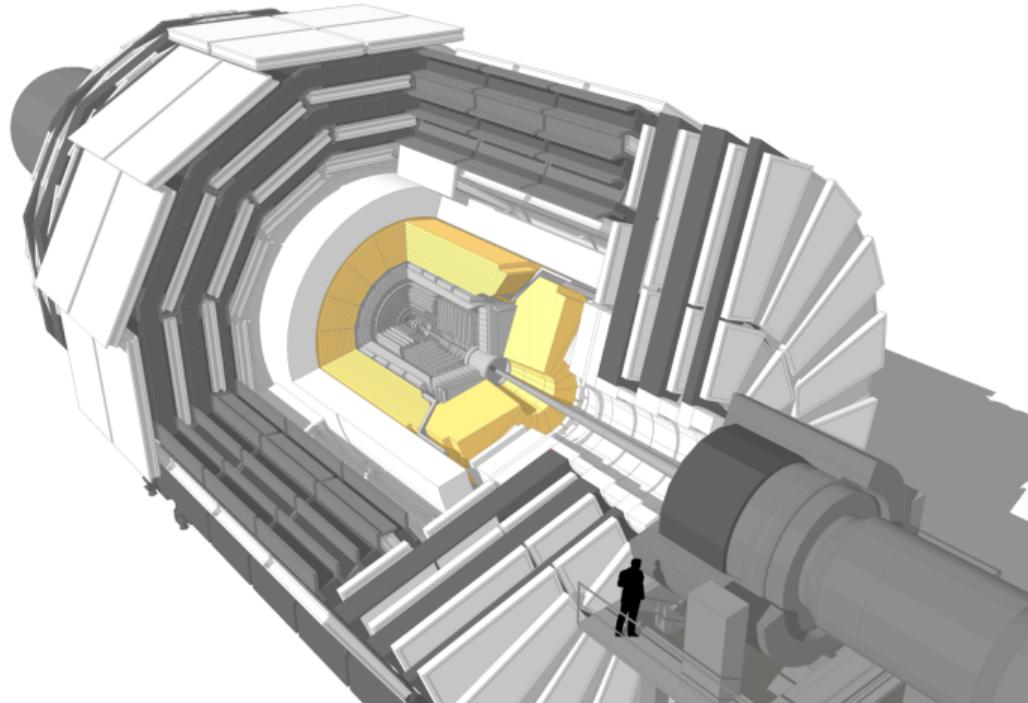
⇒ Charged particles leave hits when going through



## Electromagnetic CALorimeter

- $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

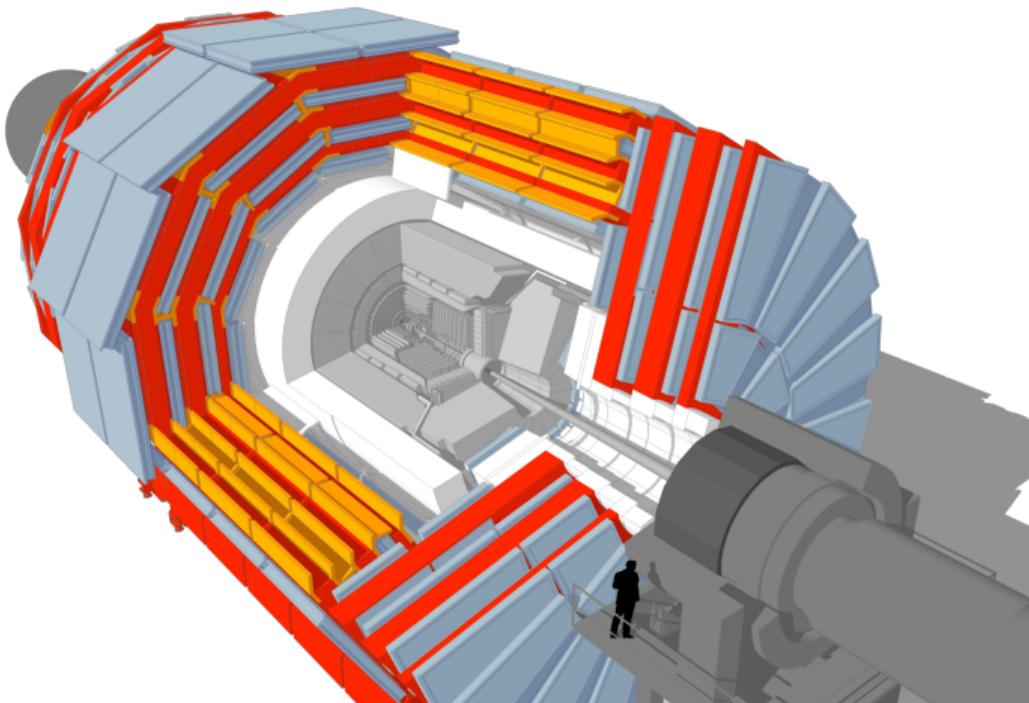
⇒ Electrons and photons are stopped,  
energy deposits



## Hadronic CALorimeter

- Brass + plastic scintillator,  
~ 7000 channels

⇒ Hadrons are stopped, energy deposits



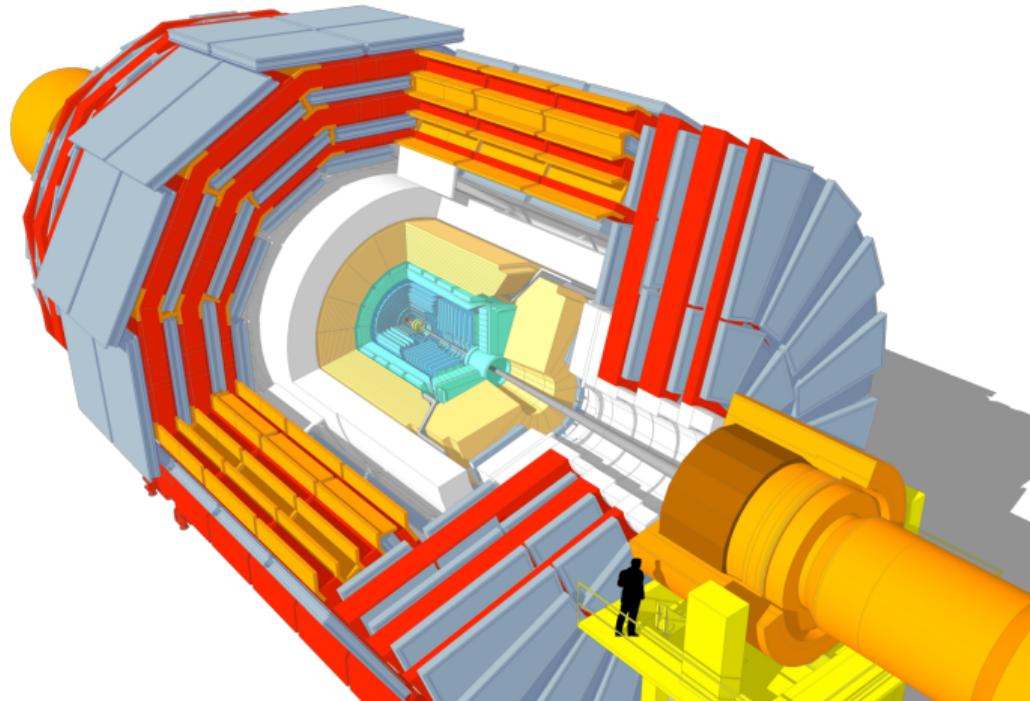
## Steel return yoke (red)

- Allows for 2 T magnetic field around the solenoid

## Muon chambers (blue-gray)

- Barrel: 250 drift tubes, 480 resistive plate chambers
- Endcaps: 540 cathode strips, 576 resistive plate chambers

⇒ Charged particles leave hits when going through (only muons do)

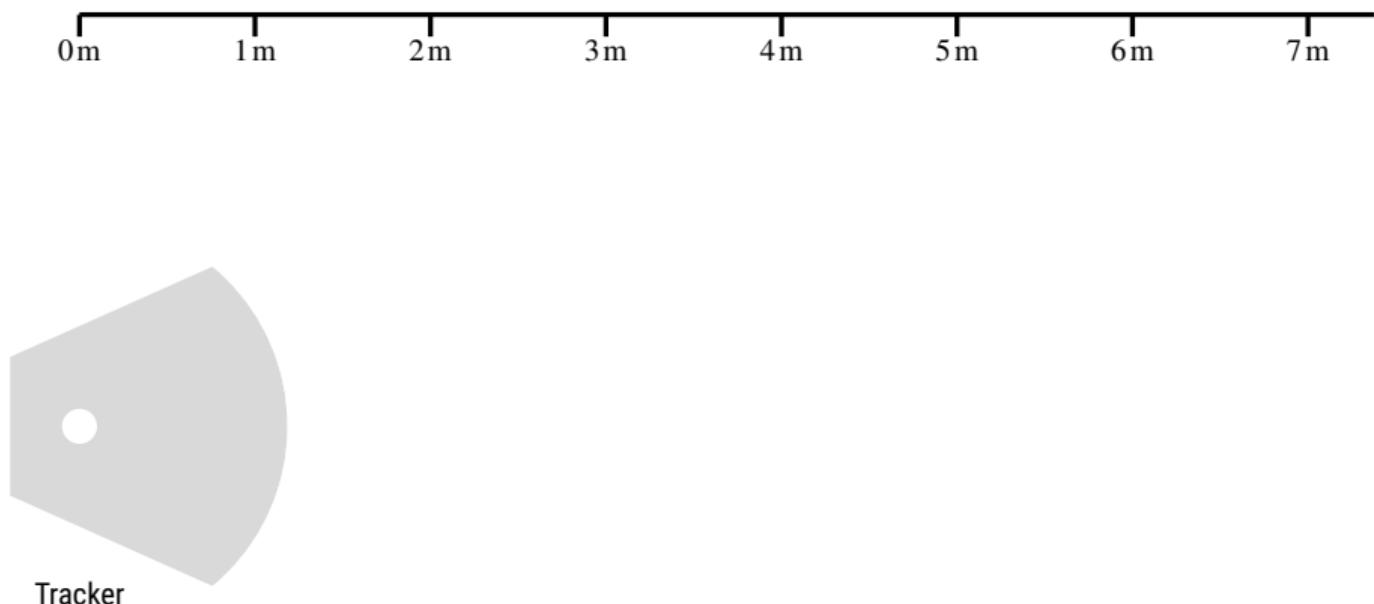


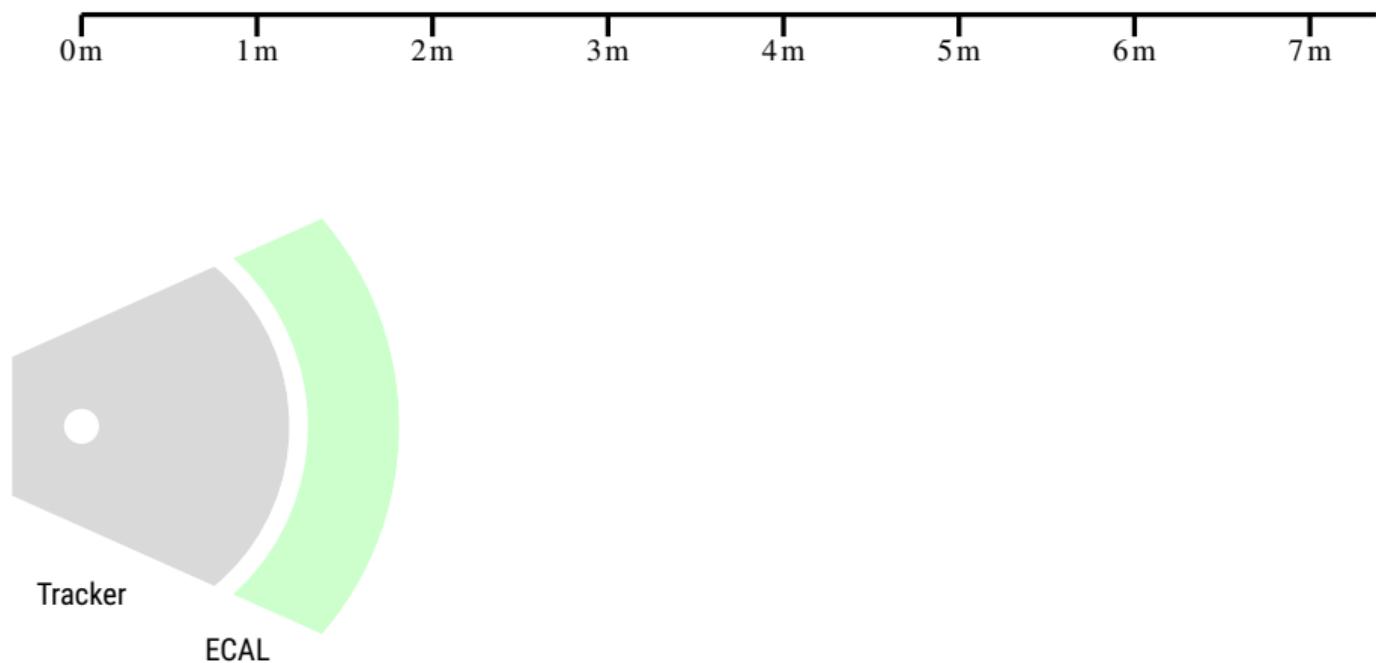
## Sensitive parts of CMS

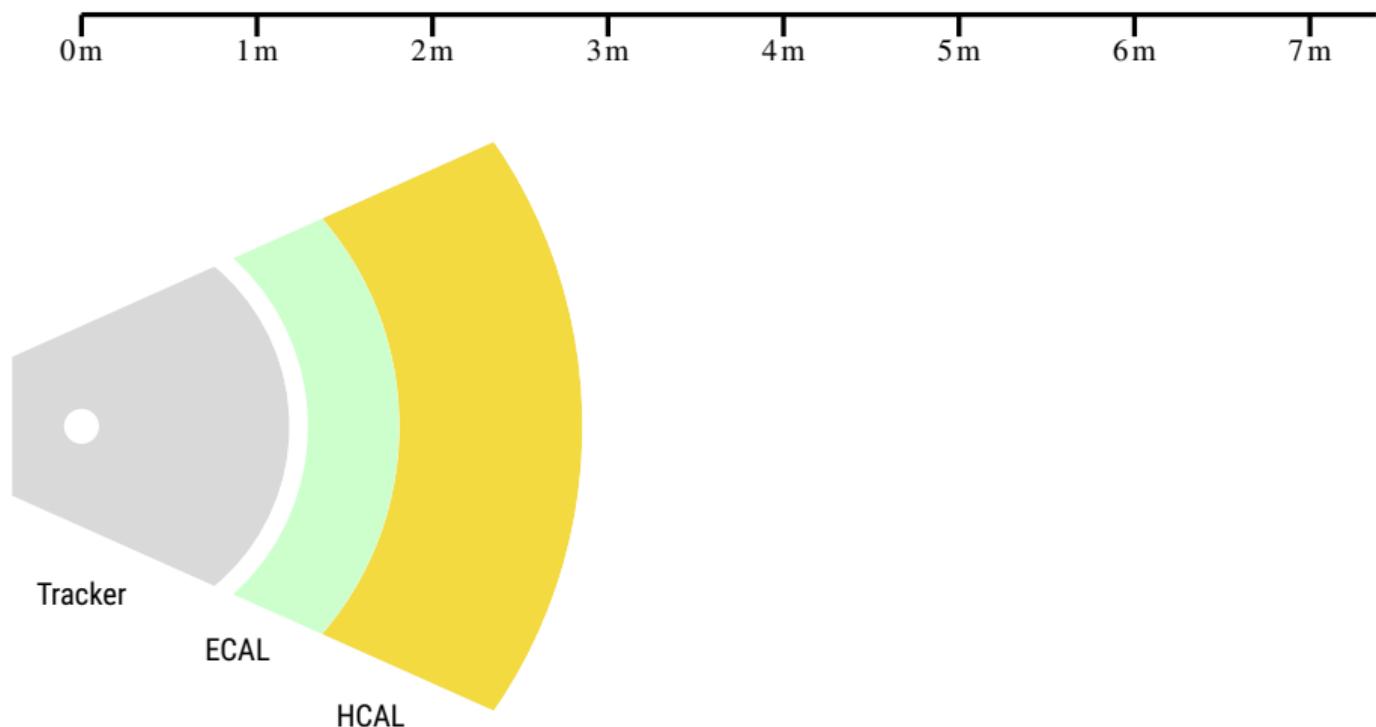
Combine sub-detectors signals to determine which particles were there!

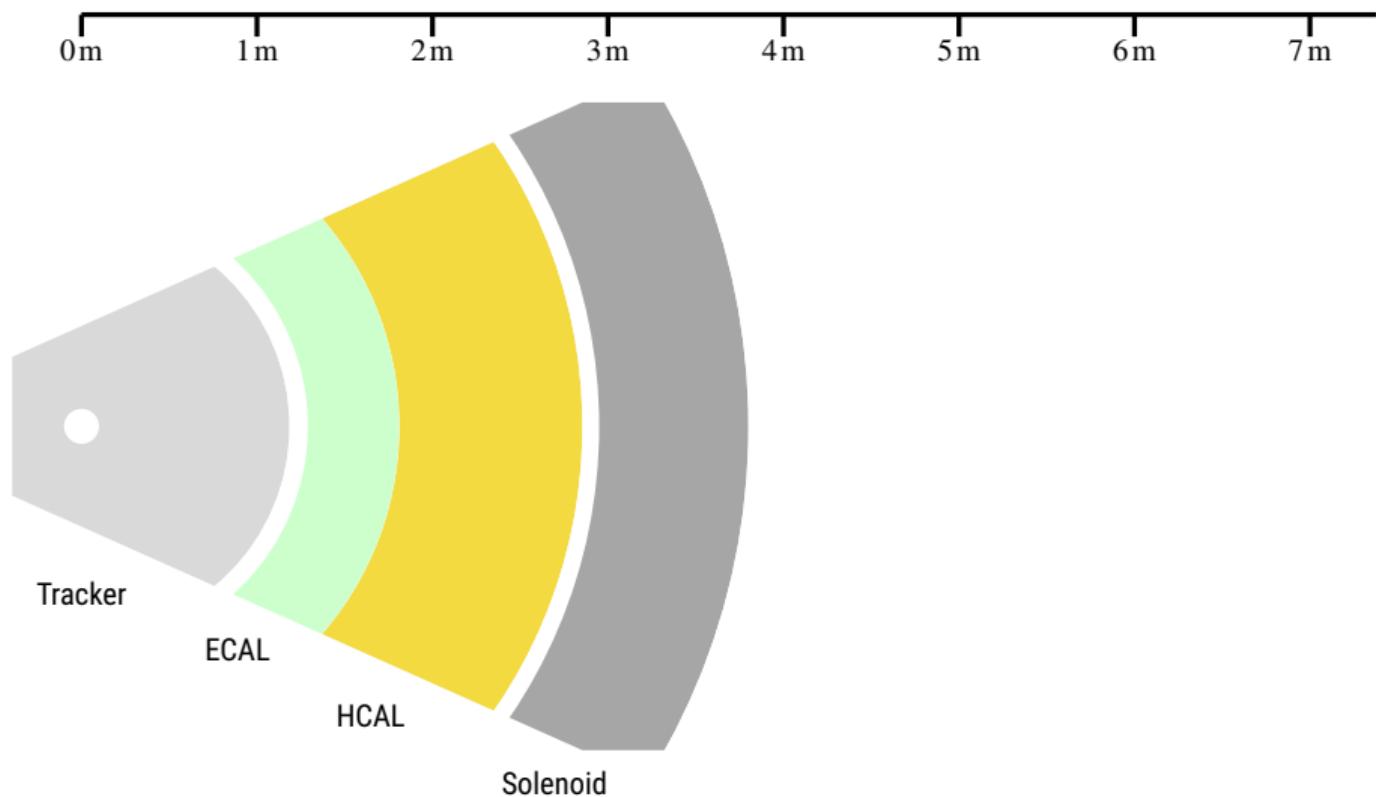


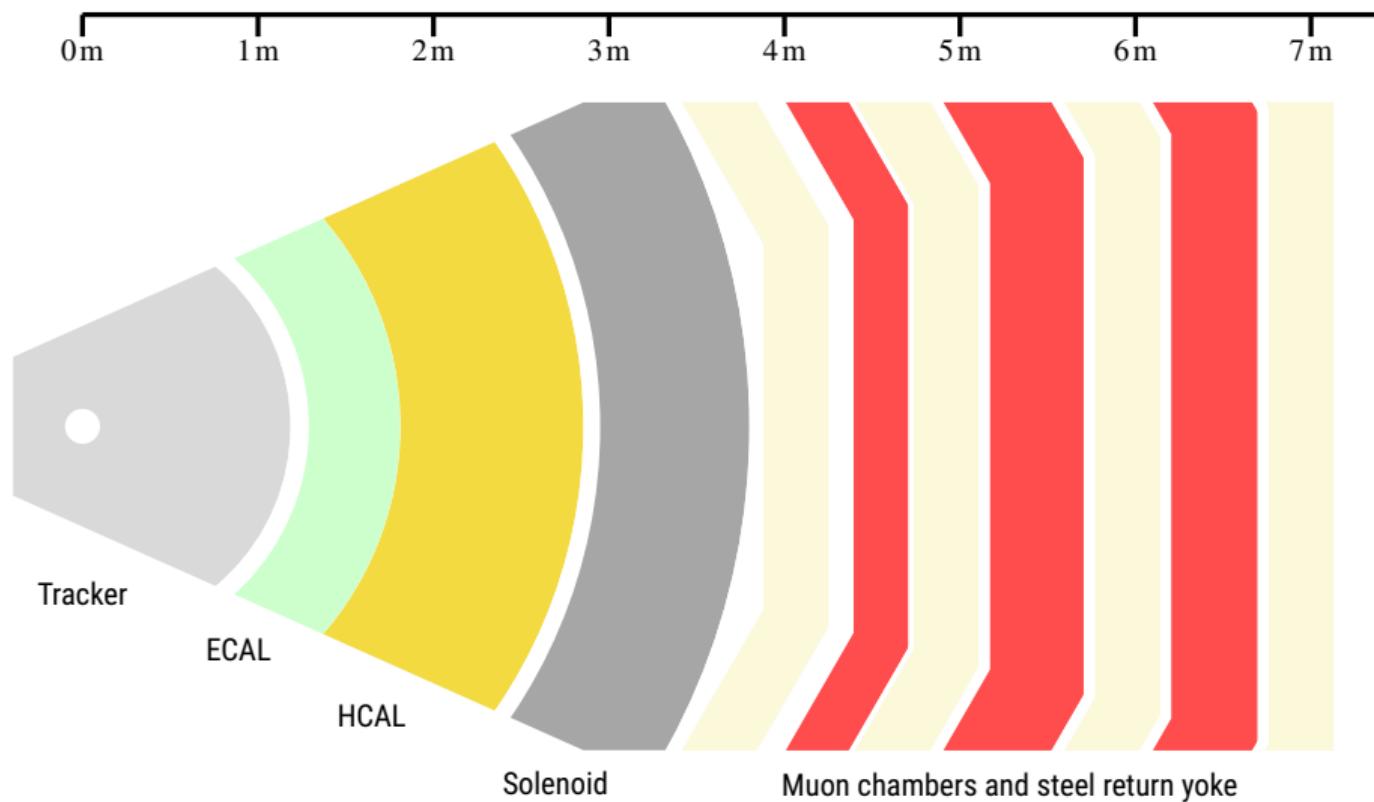


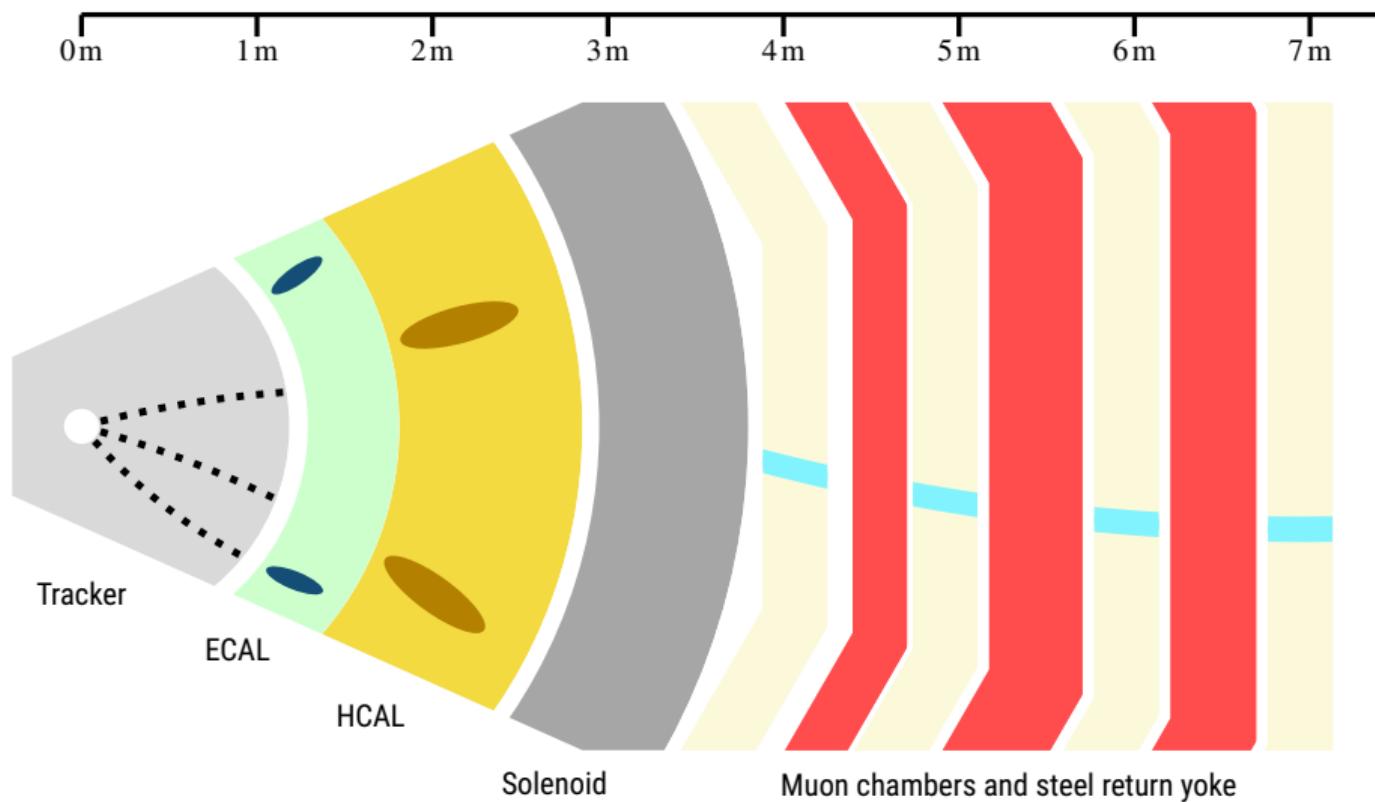


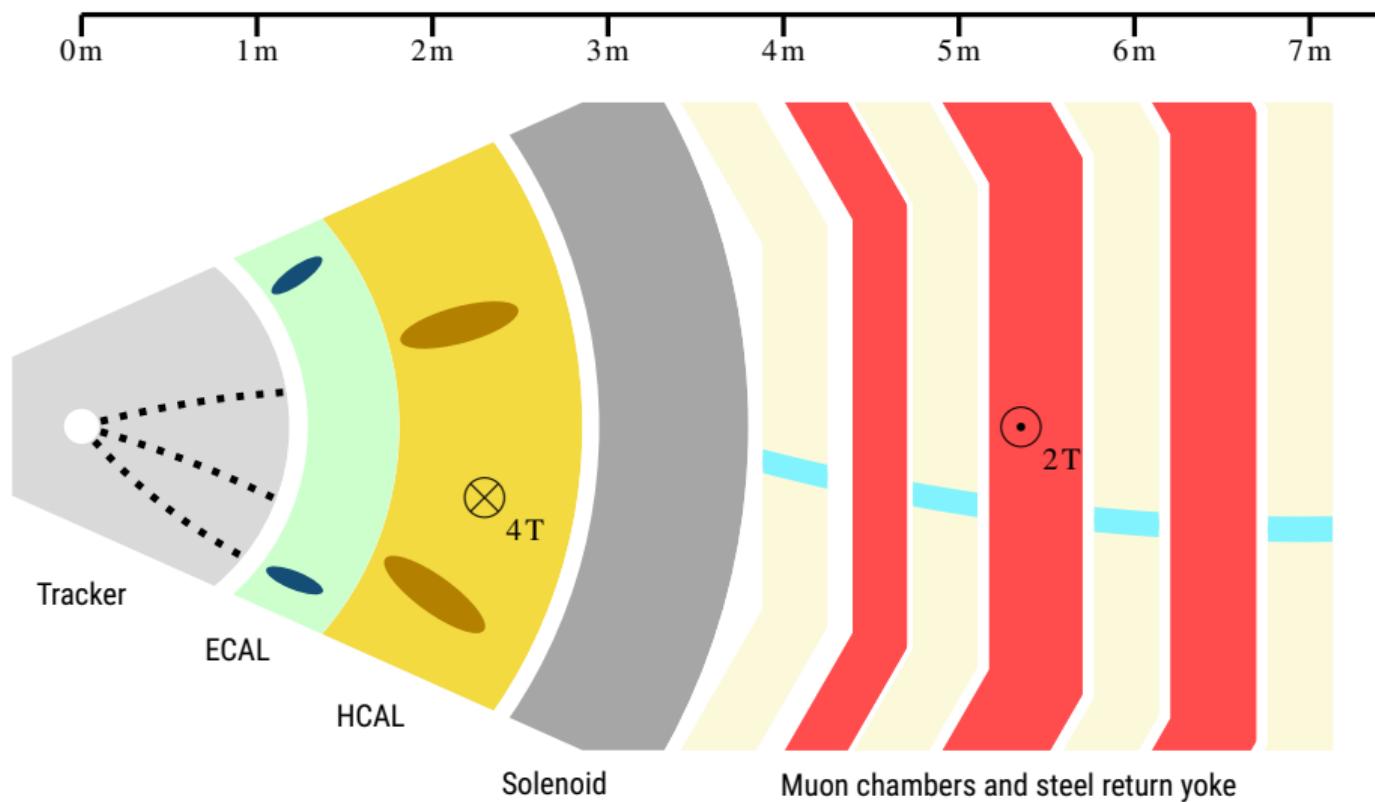


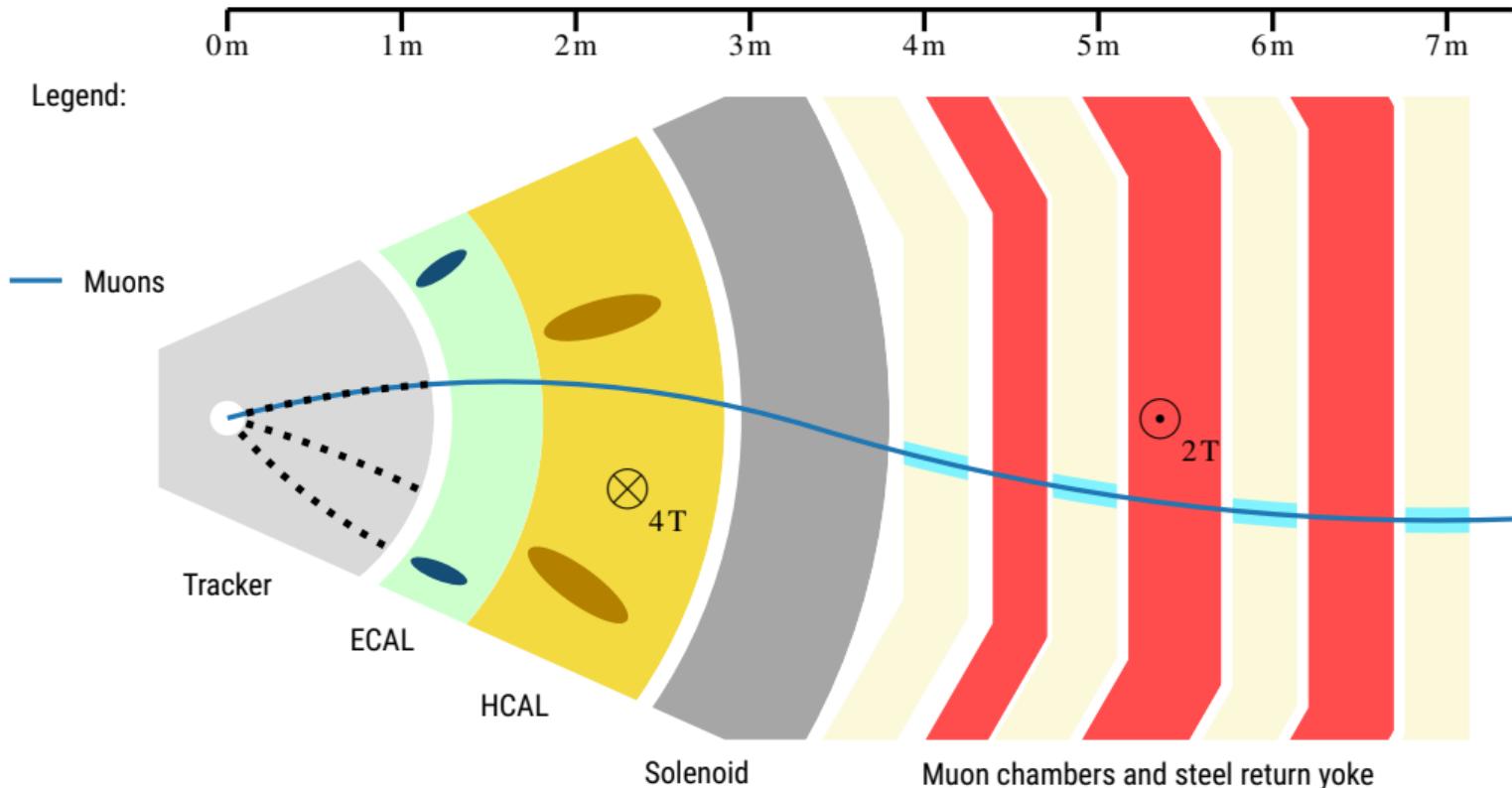






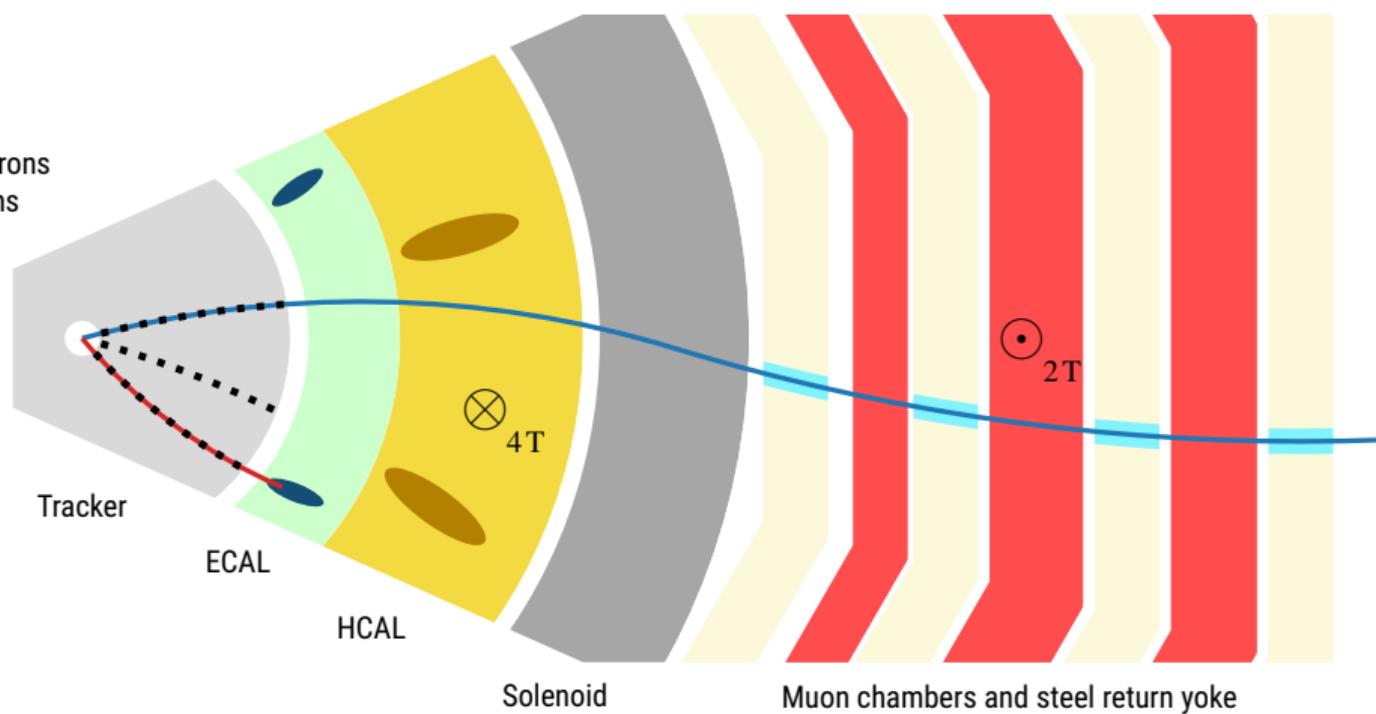


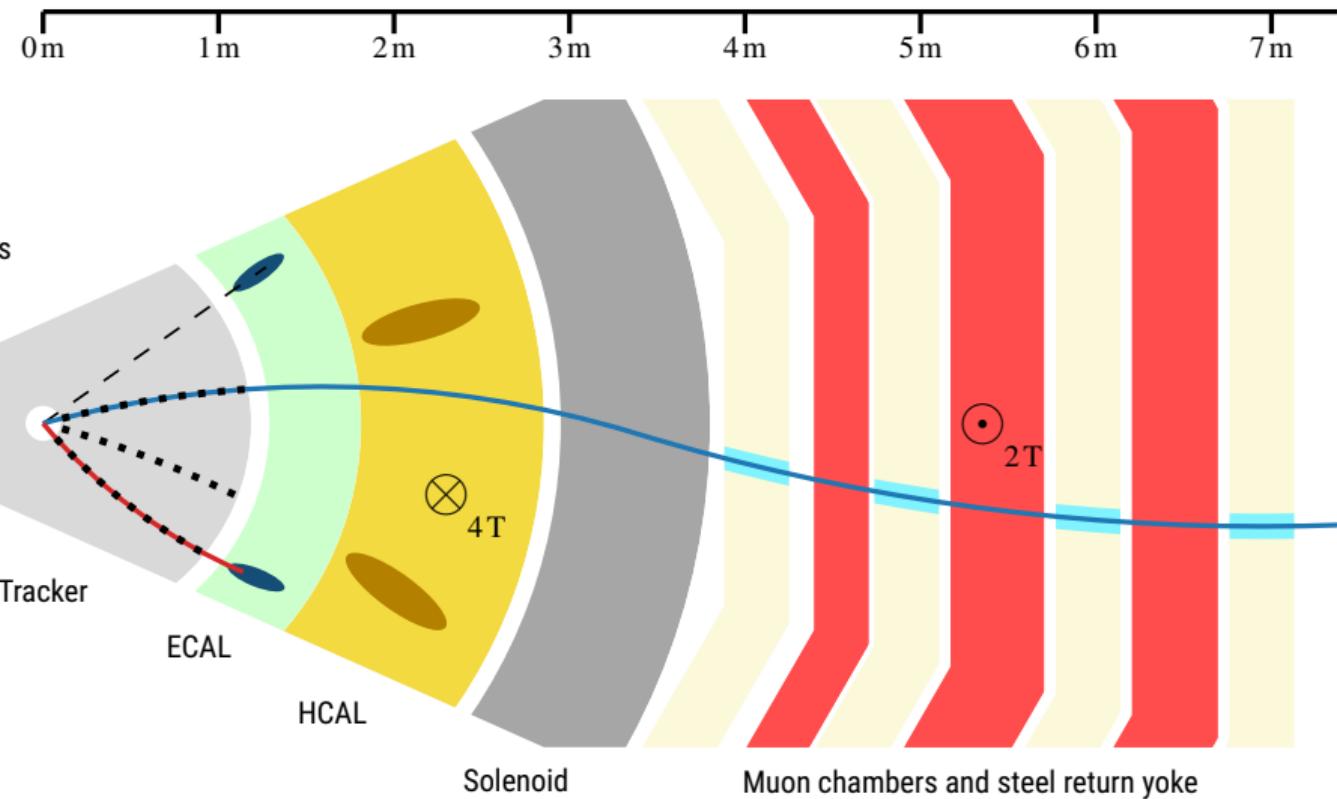


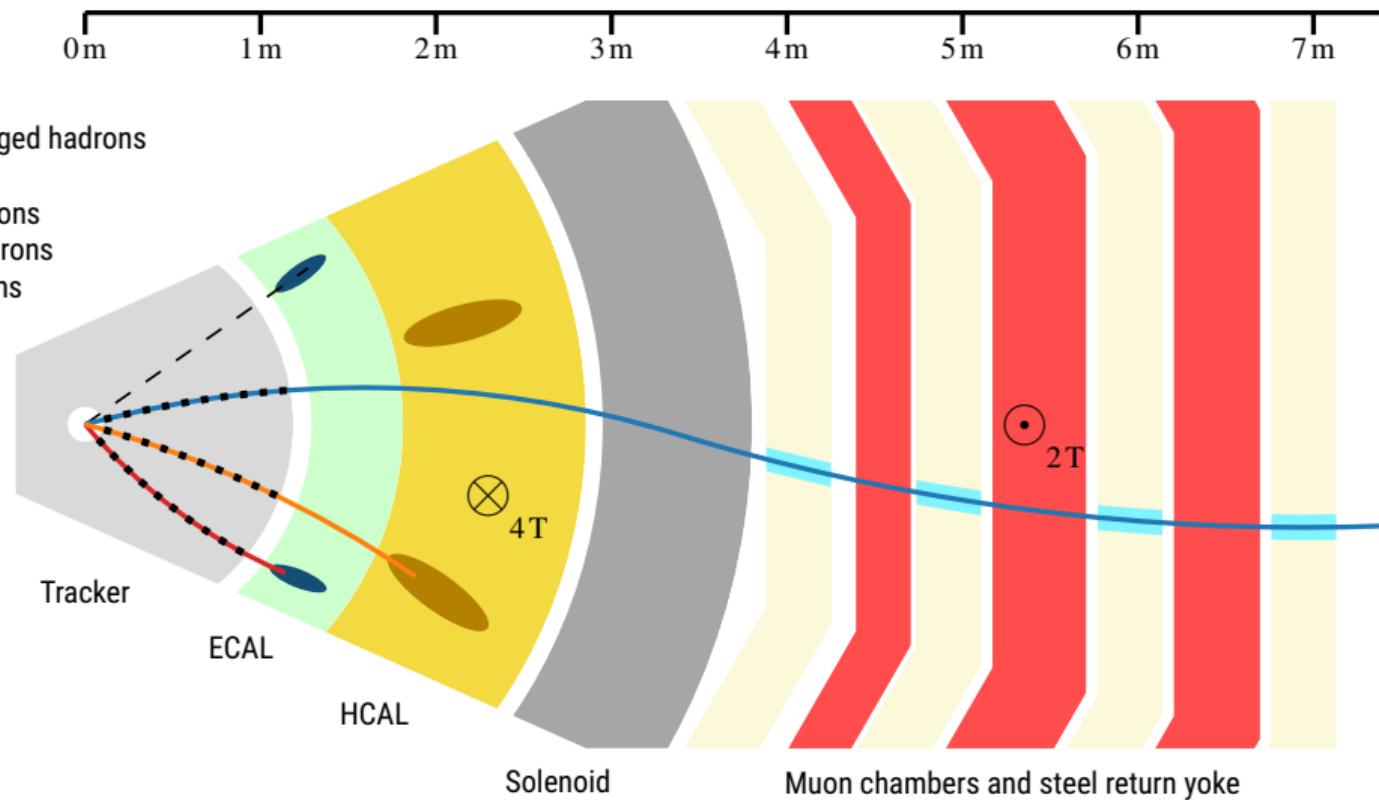


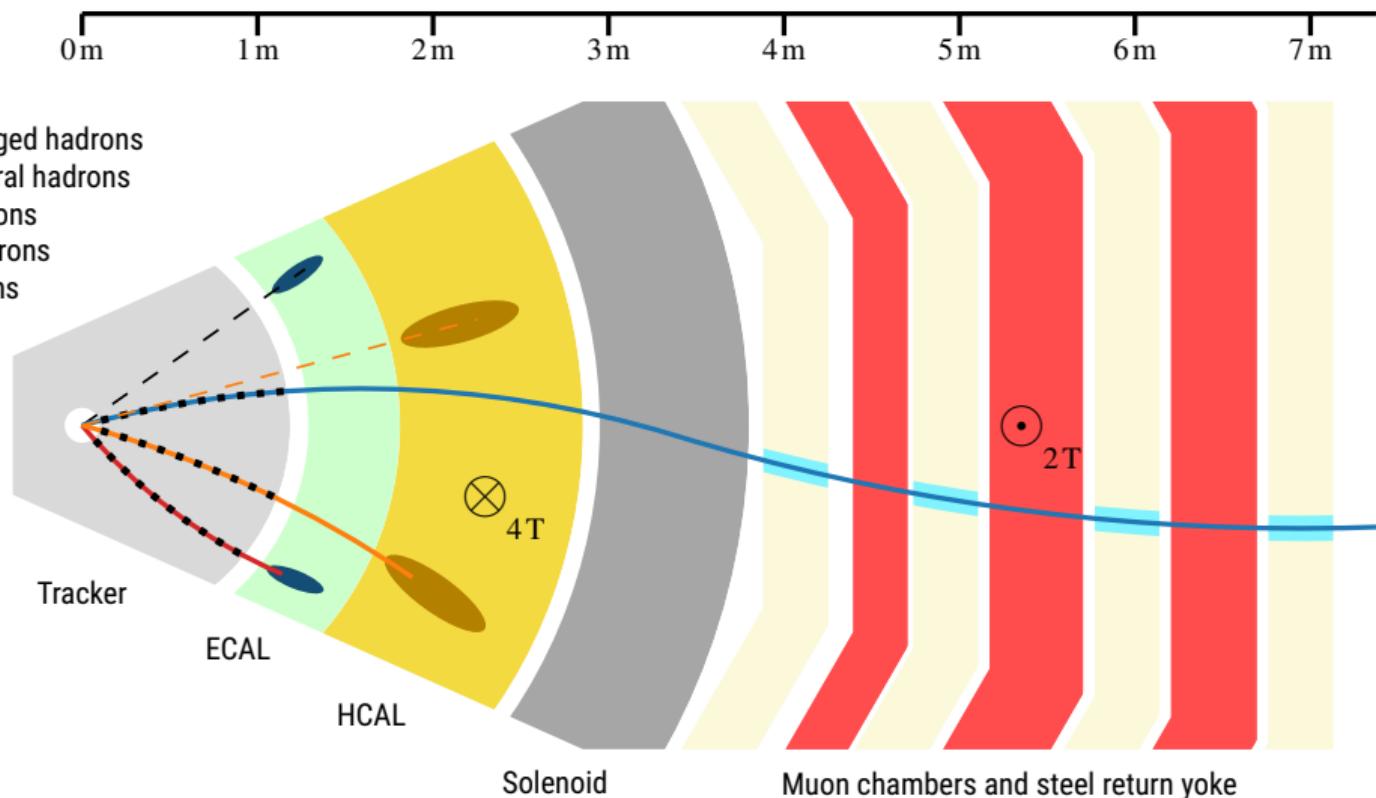
**Legend:**

- Electrons
- Muons



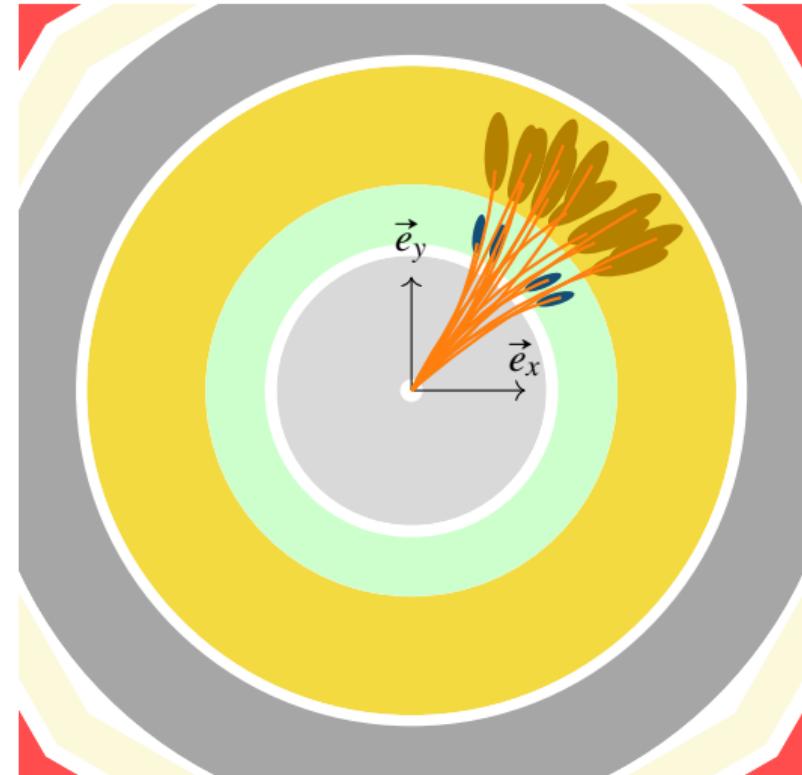
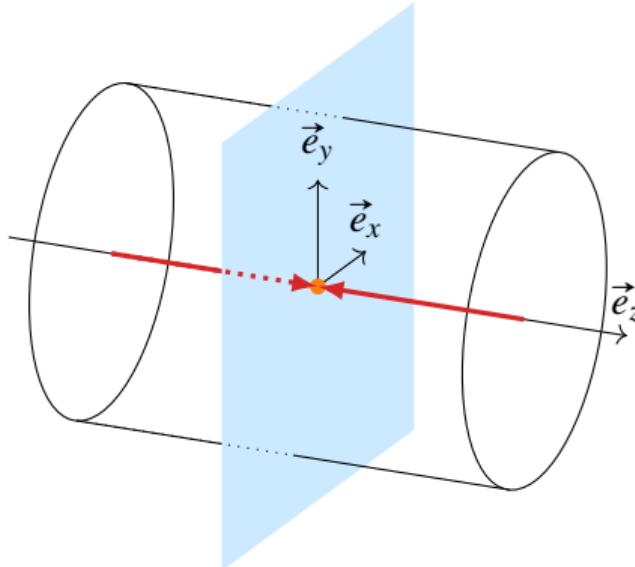






# Neutrinos and missing transverse energy (MET)

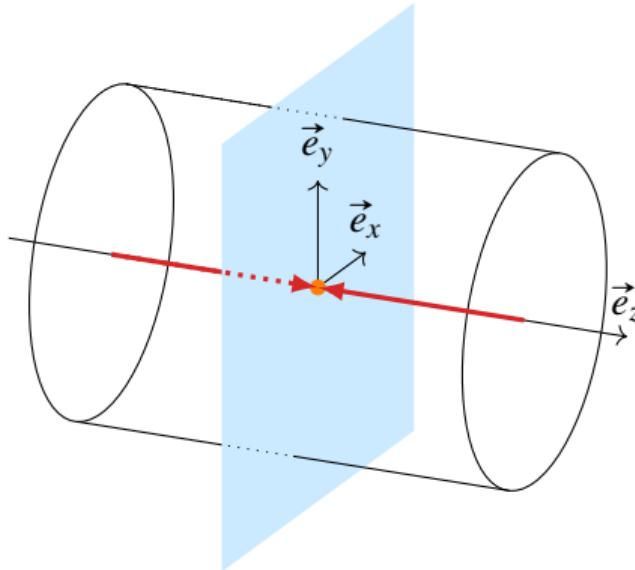
$(\vec{e}_x, \vec{e}_y)$  = transverse plane ( $\eta = 0$ )



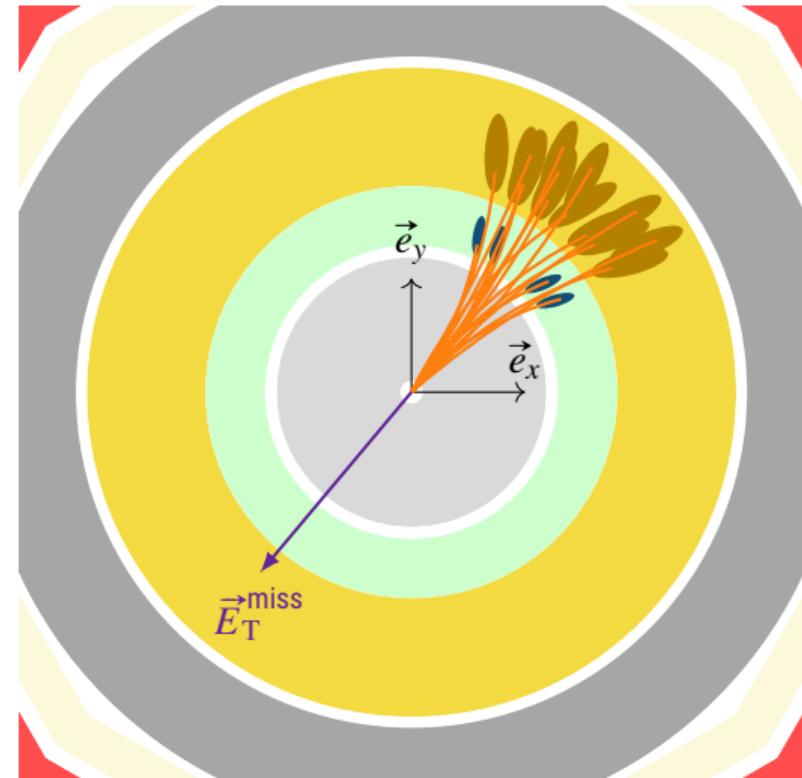
Conserved momentum:  $\sum_{\text{initial state}} \vec{p}_{\text{T}} = \sum_{\text{final state}} \vec{p}_{\text{T}} = \vec{0}$

# Neutrinos and missing transverse energy (MET)

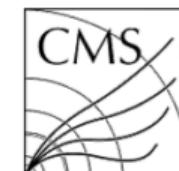
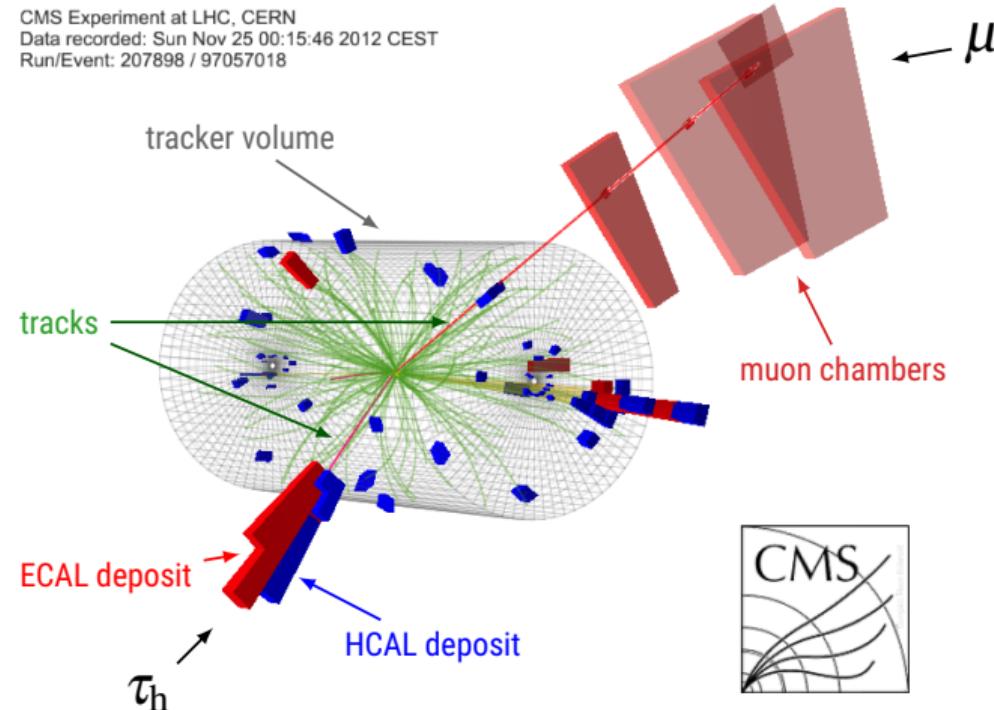
$(\vec{e}_x, \vec{e}_y)$  = transverse plane ( $\eta = 0$ )



$$\sum_{\text{final state}} \vec{p}_{\text{T}} = \vec{0} \Rightarrow \vec{E}_{\text{T}}^{\text{miss}} = - \sum_{\text{visible particles}} \vec{p}_{\text{T}}$$



# Event display: $h \rightarrow \tau\tau \rightarrow \mu\tau_h$ candidate from real data



## 1 Phenomenology

## 2 Experimental device

3  $H \rightarrow \tau\tau$  analysis

## 4 Machine Learning

# Using histograms

- ▶ Find a discriminating variable:
  - ▷ for uncorrelated  $\tau$  pairs, it's random
  - ▷ for  $\tau$  pairs coming from a particle (Higgs?), not random.
- ▶ For one  $\tau$  pair only, impossible to say!
- ▶ With many events, a difference may show up.

# The rabbit analogy

- ▶ What the theorists say:
  - ▷ There is a white rabbit that once lived in a casino.
  - ▷ The rabbit loved watching people playing dices.
  - ▷ He was happy when the result of dice was 4.
  - ▷ So when he sees a dice, he turns it so that the result is 4.
  - ▷ But this rabbit is very shy and nobody has seen him since the casino closure.
- ▶ The only way to know if he's here is to throw a dice and come back to see the result.
  - ▷ If the rabbit has been here, the dice will show a 4!

# The rabbit analogy

- ▶ Dice results: 4

# The rabbit analogy

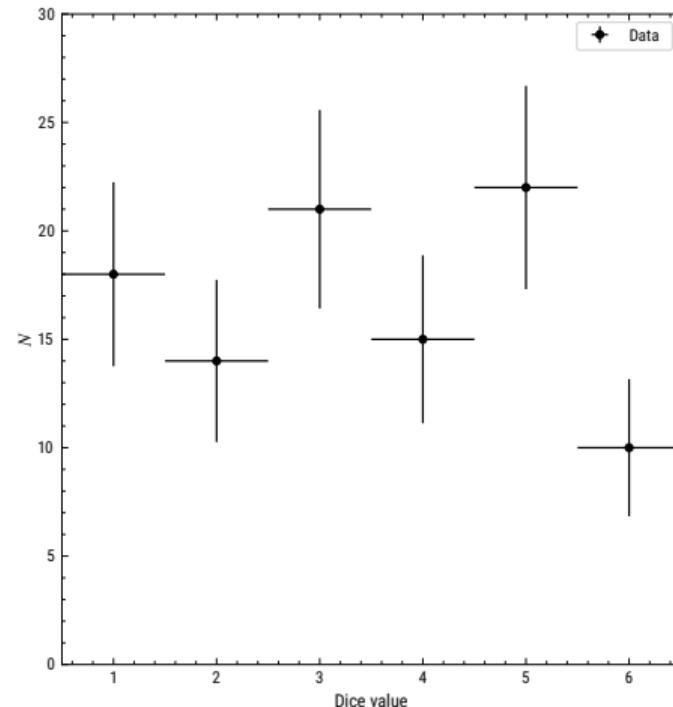
- ▶ Dice results: 4, 2

# The rabbit analogy

- ▶ Dice results: 4, 2, 4, 1, 3, 2, 5, 1, 1, 6...

# The rabbit analogy

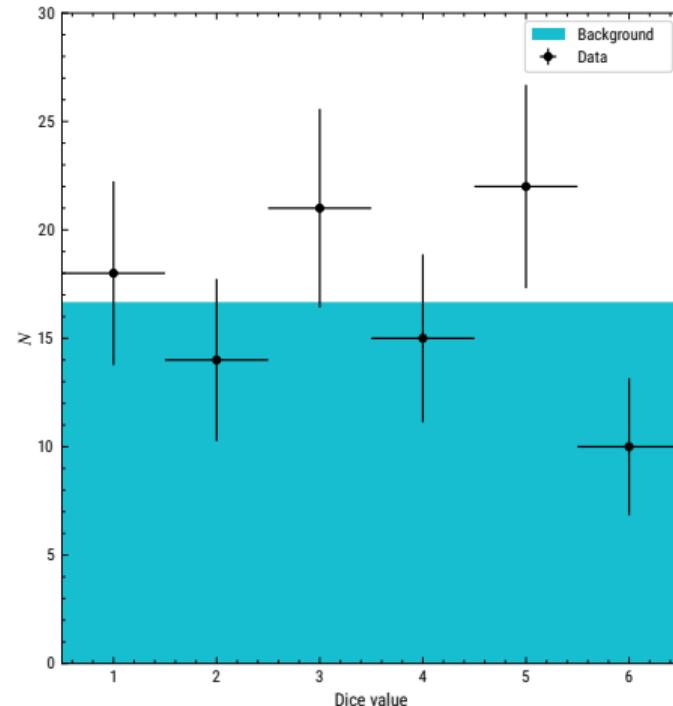
On 100 days →



Not really conclusive...

# The rabbit analogy

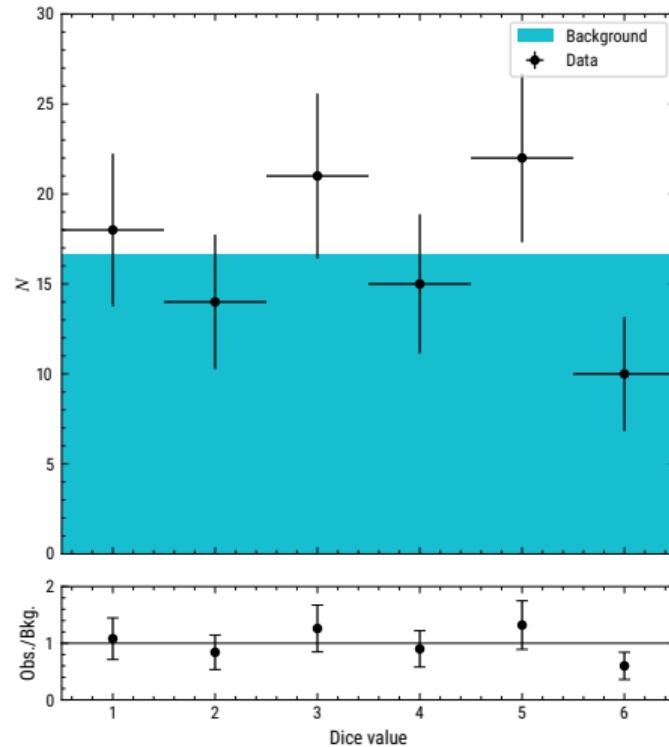
On 100 days →



Comparing with predictions!

# The rabbit analogy

On 100 days →

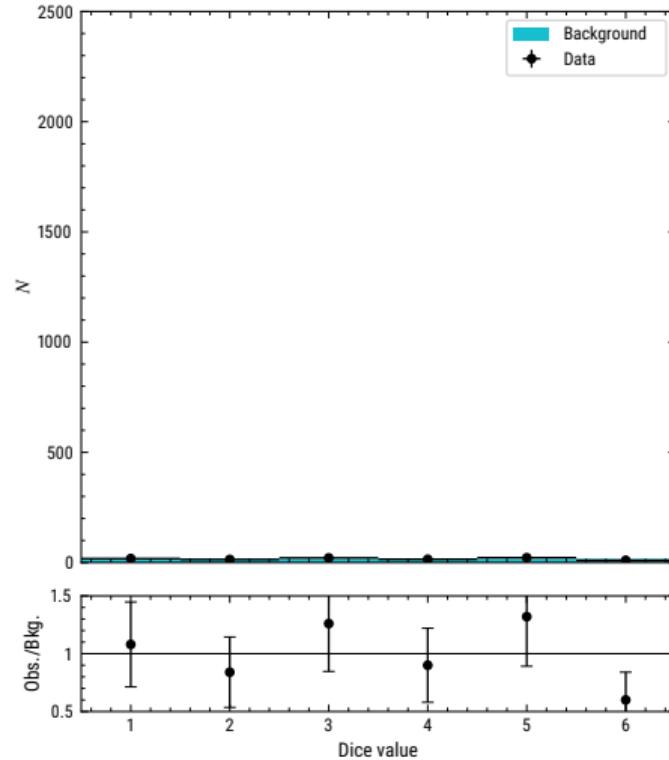


Also add ratio plot:  
observed / predictions

# The rabbit analogy

On 100 days →

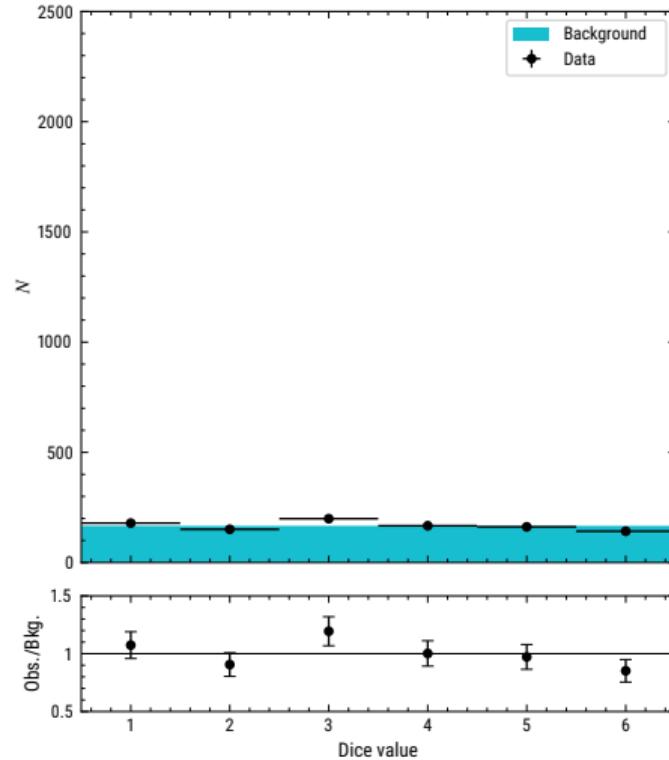
Fill up with more data!



# The rabbit analogy

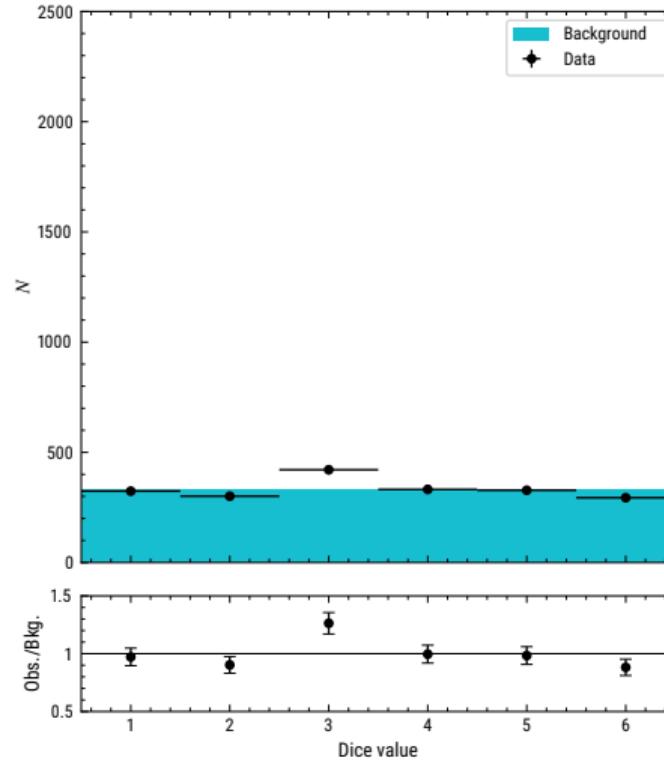
On 1000 days →

Fill up with more data!



# The rabbit analogy

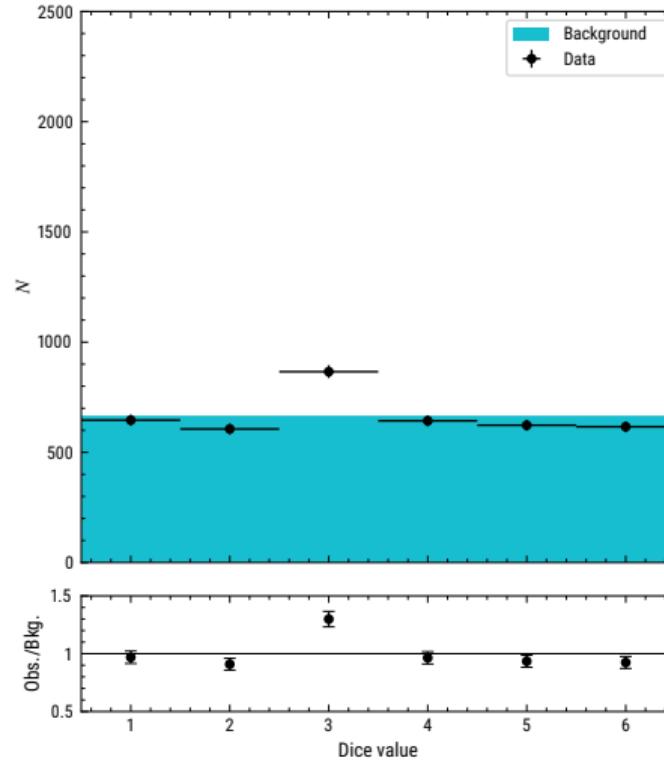
On 2000 days →



Fill up with more data!

# The rabbit analogy

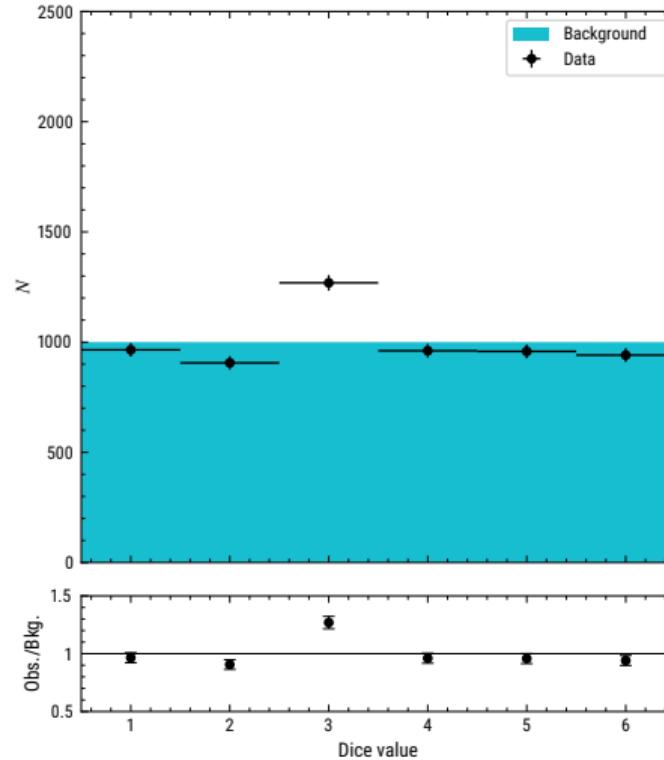
On 4000 days →



Fill up with more data!

# The rabbit analogy

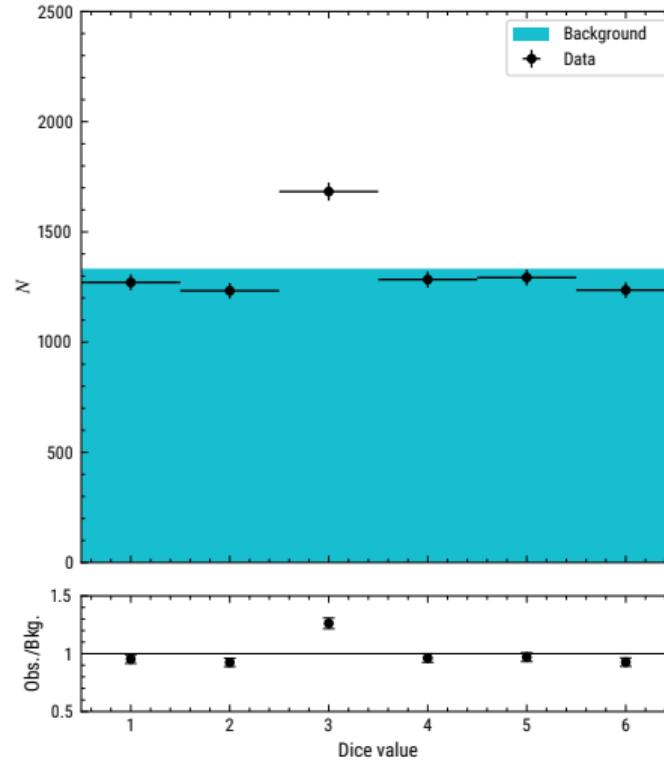
On 6000 days →



Fill up with more data!

# The rabbit analogy

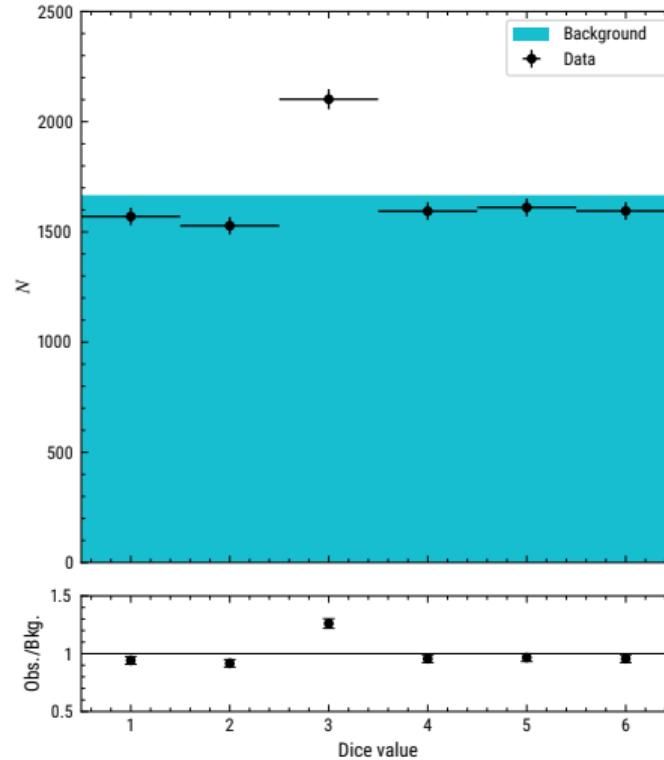
On 8000 days →



Fill up with more data!

# The rabbit analogy

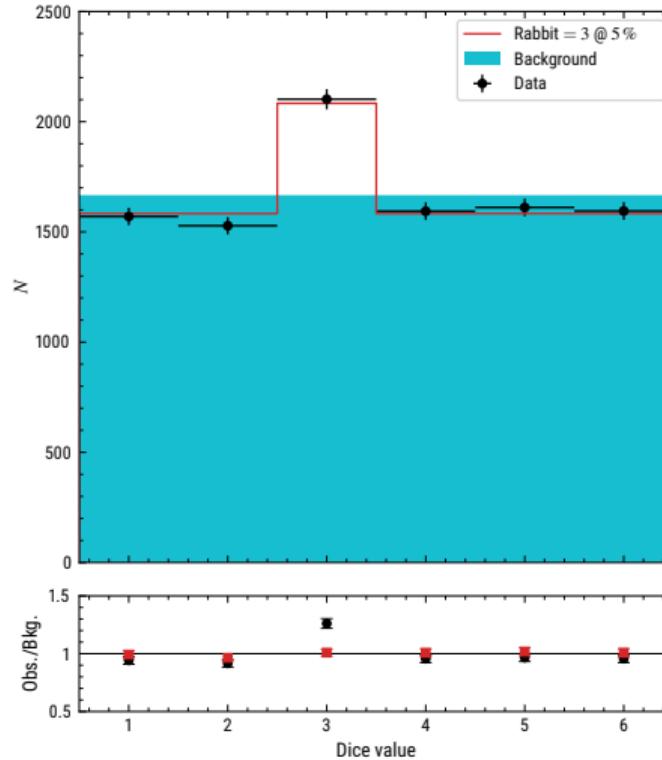
On 10,000 days →



Fill up with more data!

# The rabbit analogy

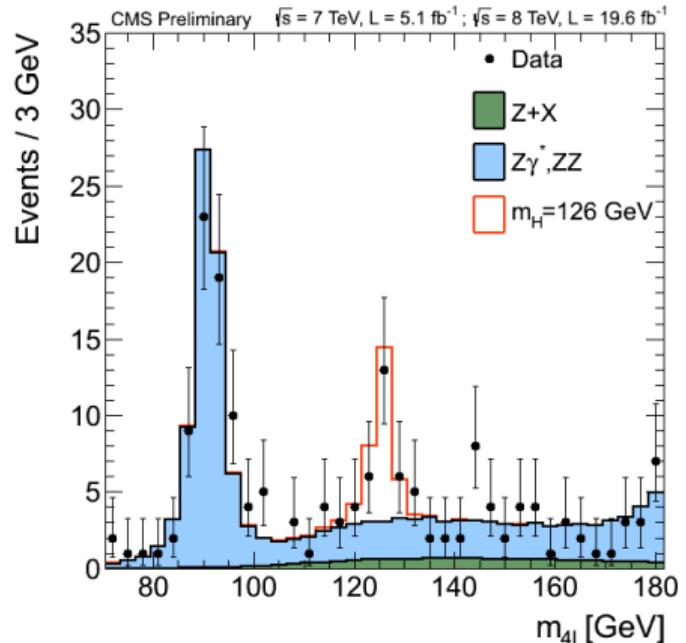
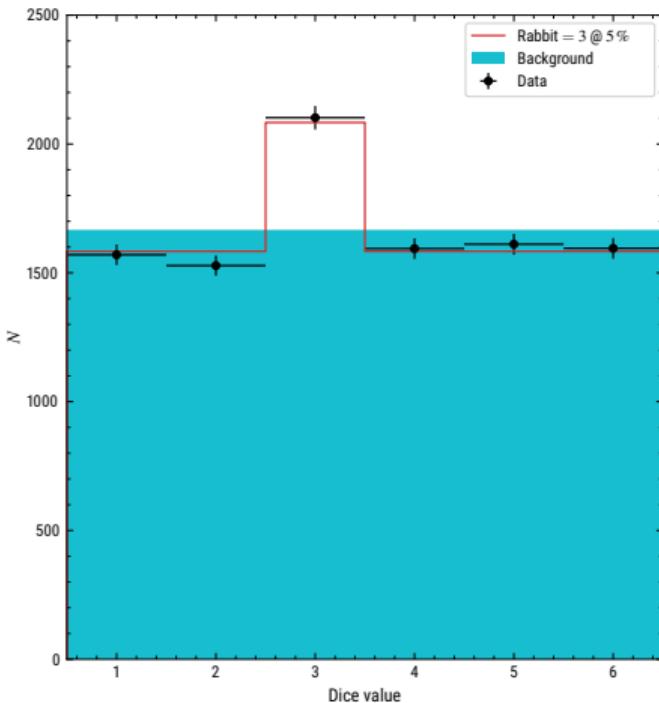
On 10,000 days →



In red, hypothesis of the rabbit with 3 as preferred result (instead of 4!), with a probability to show up of 5%.

# The rabbit analogy

| Search for              | the rabbit       | the Higgs                          |
|-------------------------|------------------|------------------------------------|
| Observed data           | dice values      | $pp$ collisions outgoing particles |
| Discriminating variable | dice value       | invariant or transverse mass       |
| Backgrounds predictions | random dice      | Standard Model processes           |
| Amount of data          | number of days   | luminosity                         |
| Signal probability      | rabbit's shyness | process cross-section              |



- ▷ The CMS Collaboration. "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC". *Physics Letters B* **716.1** (2012), pp. 30–61. DOI: 10.1016/j.physletb.2012.08.021. URL: <http://www.sciencedirect.com/science/article/pii/S0370269312008581>.
- ▷ The CMS Collaboration. Properties of the Higgs-like boson in the decay  $H \rightarrow ZZ \rightarrow 4\ell$  in  $pp$  collisions at  $\sqrt{s} = 7$  and  $8$  TeV. URL: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki>.

# Datasets

## Observed data (MiniAOD)

- $\tau_h\tau_h$

- ▶ /Tau/Run2016 [B-H]
- ▶ /Tau/Run2017 [B-F]
- ▶ /Tau/Run2018 [A-D]

- $e\mu$

- ▶ /MuonEG/Run2016 [B-H]
- ▶ /MuonEG/Run2017 [B-F]
- ▶ /MuonEG/Run2018 [A-D]

- $\mu\tau_h$

- ▶ /SingleMuon/Run2016 [B-H]
- ▶ /SingleMuon/Run2017 [B-F]
- ▶ /SingleMuon/Run2018 [A-D]

- $e\tau_h$

- ▶ /SingleElectron/Run2016 [B-H]
- ▶ /SingleElectron/Run2017 [B-F]
- ▶ /EGamma/Run2018 [A-D]

\*. More precisions on the exact datasets (date, version) in the manuscript!

# Datasets

## Simulated signals (MiniAODSIM)

### • SM Higgs signals

- ▶ /GluGluHToTauTau\_M125\_13TeV\_powheg\_pythia8
- ▶ /VBFHToTauTau\_M125\_13TeV\_powheg\_pythia8
- ▶ /WplusHToTauTau\_M125\_13TeV\_powheg\_pythia8
- ▶ /WminusHToTauTau\_M125\_13TeV\_powheg\_pythia8
- ▶ /ggZH\_HToTauTau\_ZToLL\_M125\_13TeV\_powheg\_pythia8
- ▶ /ggZH\_HToTauTau\_ZToNuNu\_M125\_13TeV\_powheg\_pythia8
- ▶ /ggZH\_HToTauTau\_ZToQQ\_M125\_13TeV\_powheg\_pythia8

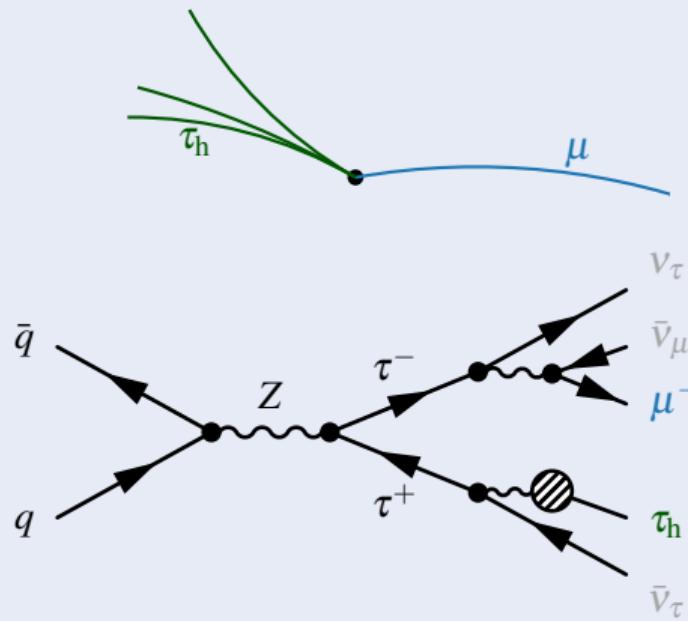
### • MSSM signals

- ▶ /SUSYGluGluToHToTauTau\_M-\*\_TuneCUETP8M1\_13TeV-pythia8
- ▶ /SUSYGluGluToBBHToTauTau\_M-\*\_TuneCUETP8M1\_13TeV-amcatnlo-pythia8

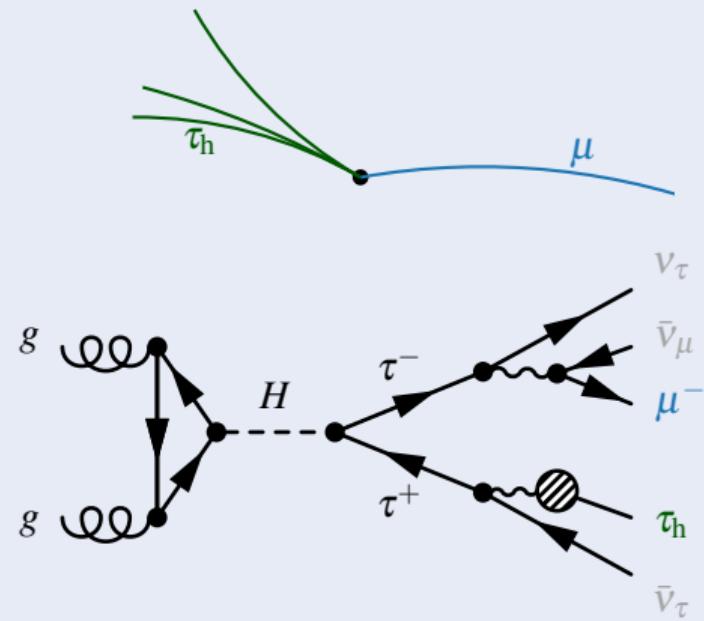
# Backgrounds?

# Backgrounds: Drell-Yan

Drell-Yan (especially  $Z \rightarrow \tau\tau$ )

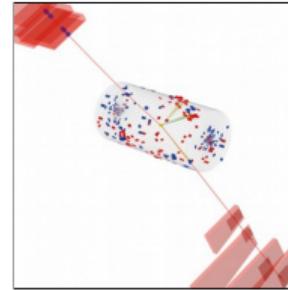


$H \rightarrow \tau\tau \rightarrow \mu\tau_h$



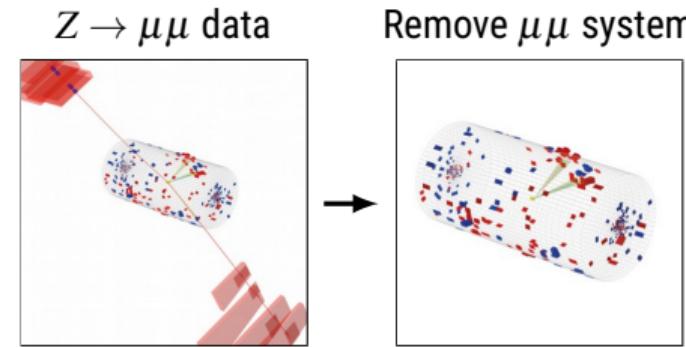
# Embedded events

$Z \rightarrow \mu\mu$  data



- ▷ The CMS Collaboration. "An embedding technique to determine  $\tau\tau$  backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

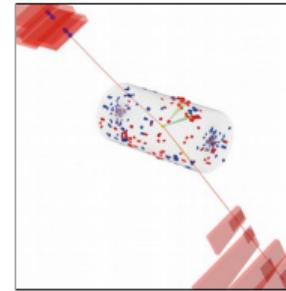
# Embedded events



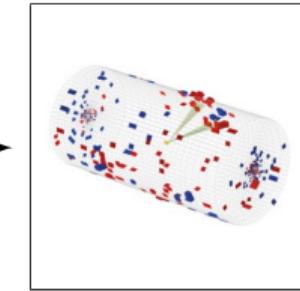
- ▷ The CMS Collaboration. "An embedding technique to determine  $\tau\tau$  backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

# Embedded events

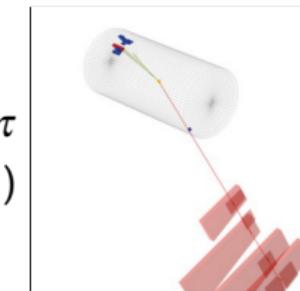
$Z \rightarrow \mu\mu$  data



Remove  $\mu\mu$  system

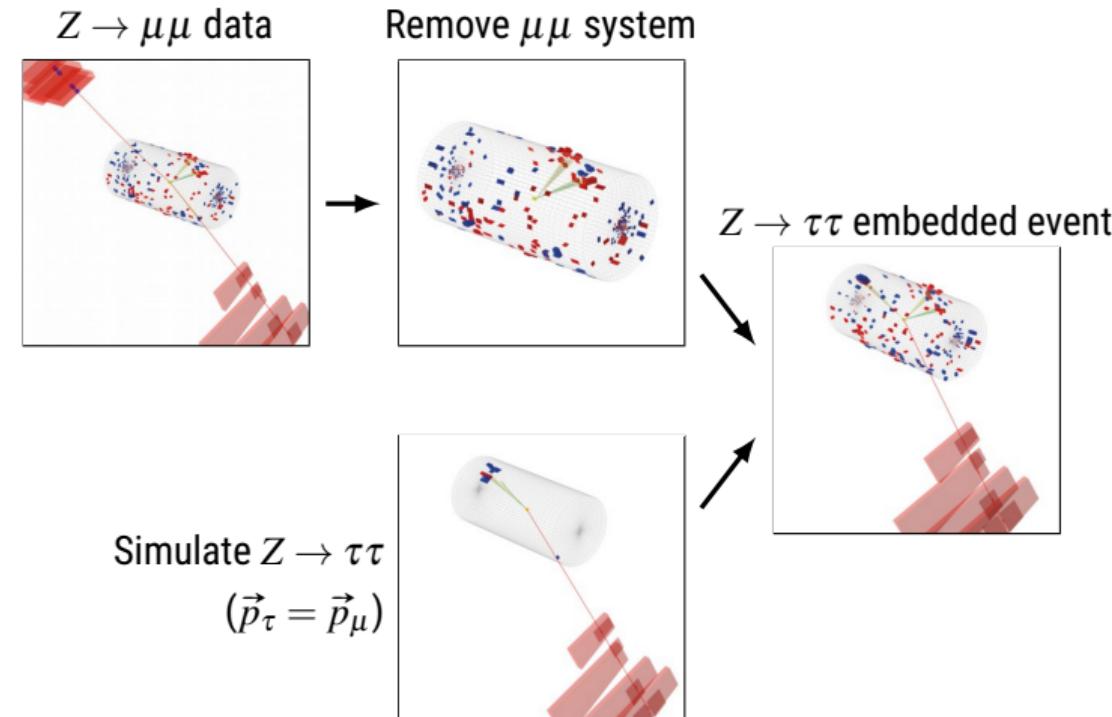


Simulate  $Z \rightarrow \tau\tau$   
 $(\vec{p}_\tau = \vec{p}_\mu)$

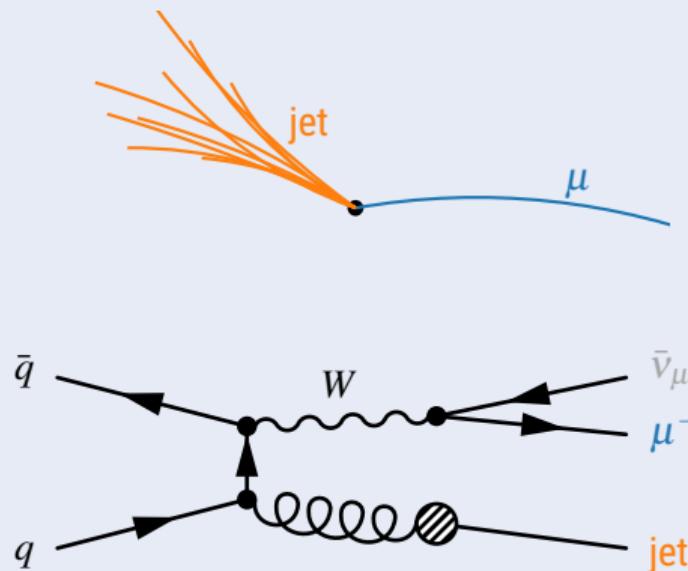
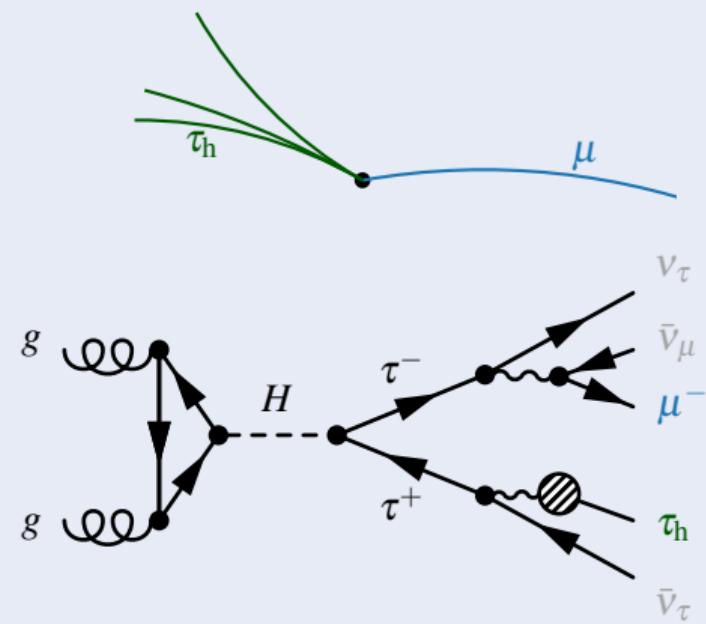


- ▷ The CMS Collaboration. "An embedding technique to determine  $\tau\tau$  backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

# Embedded events

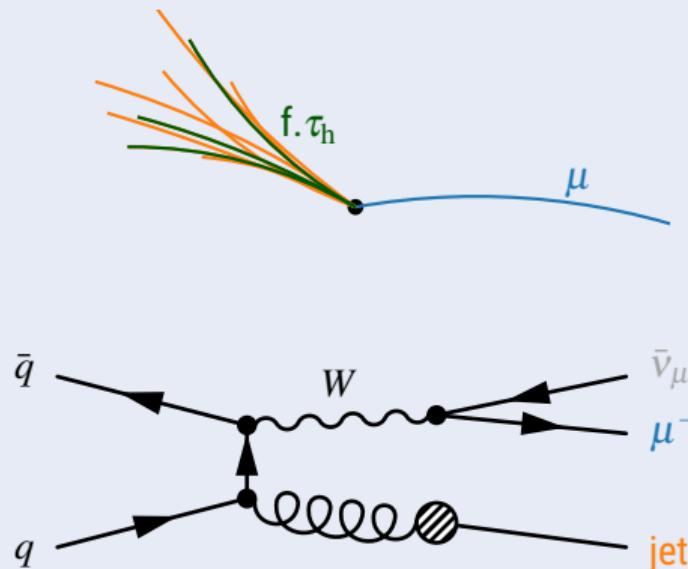


▷ The CMS Collaboration. "An embedding technique to determine  $\tau\tau$  backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

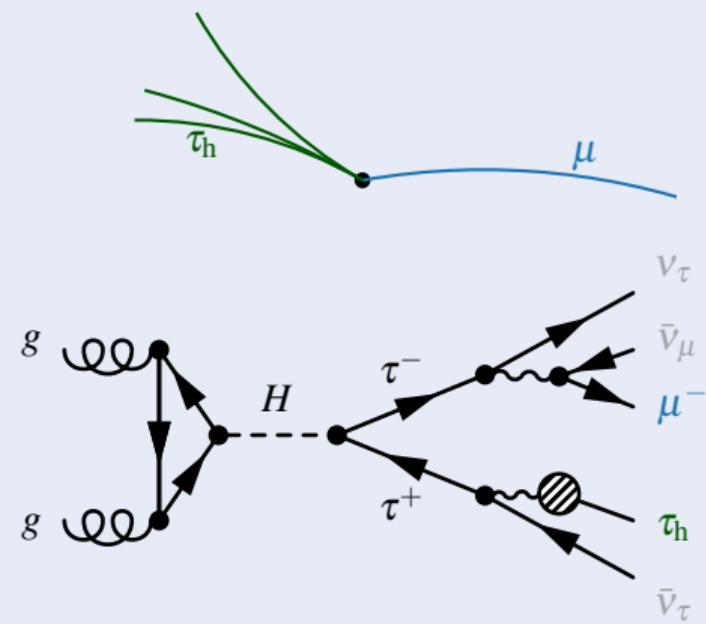
Backgrounds:  $W + \text{jets}$  $W + \text{jets}$  $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

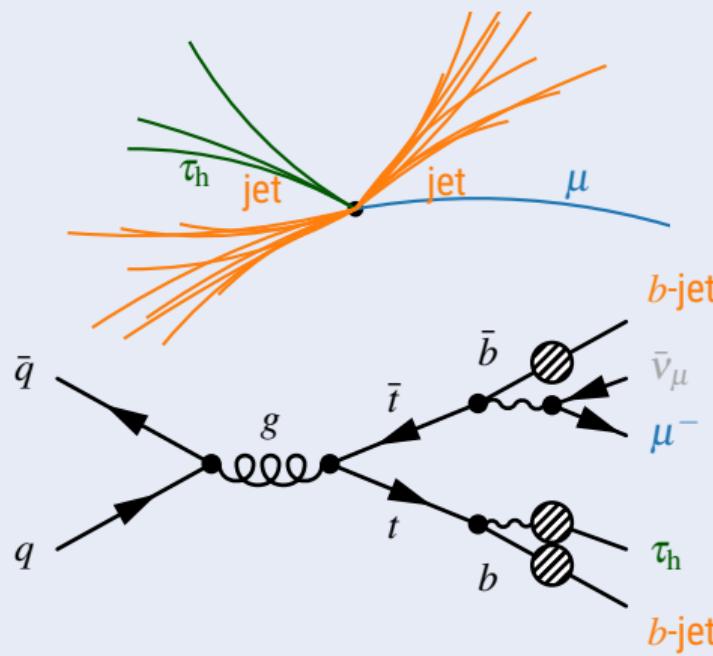
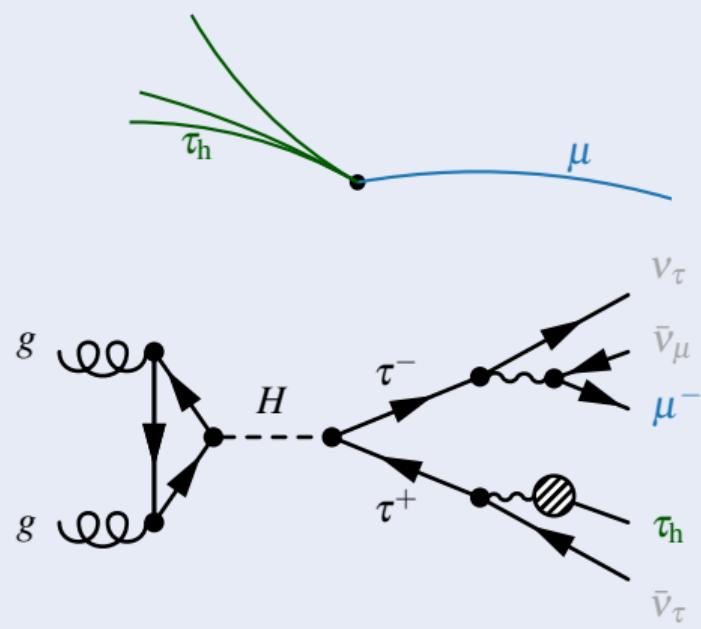
# Backgrounds: $W + \text{jets}$

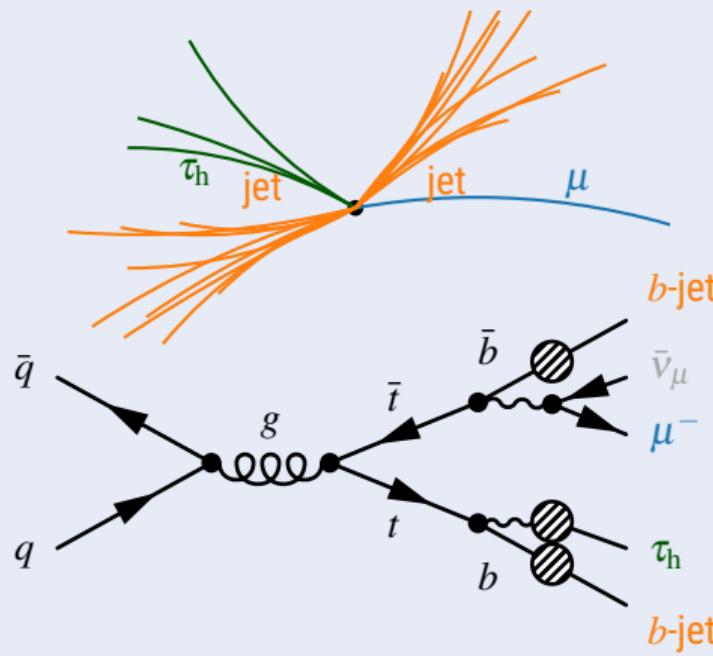
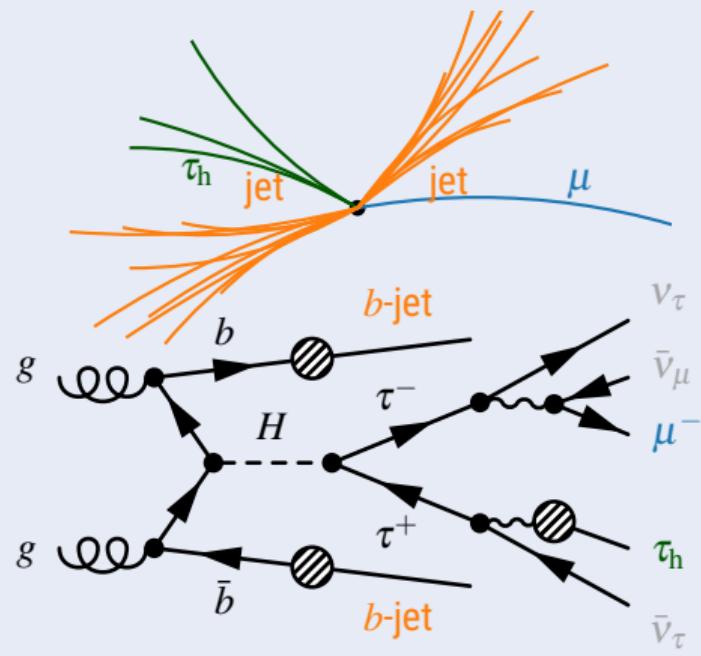
$W + \text{jets}$ , jet  $\rightarrow$  fake  $\tau_h$



$H \rightarrow \tau\tau \rightarrow \mu\tau_h$

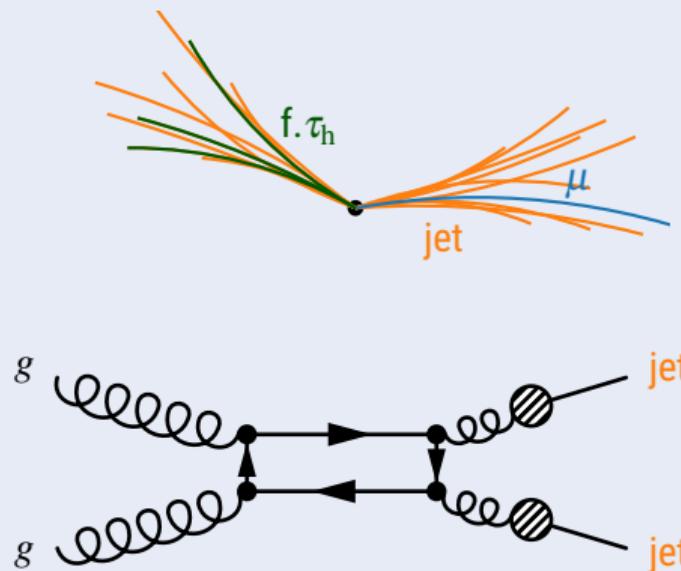


Backgrounds:  $t\bar{t}$  $t\bar{t}$  $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

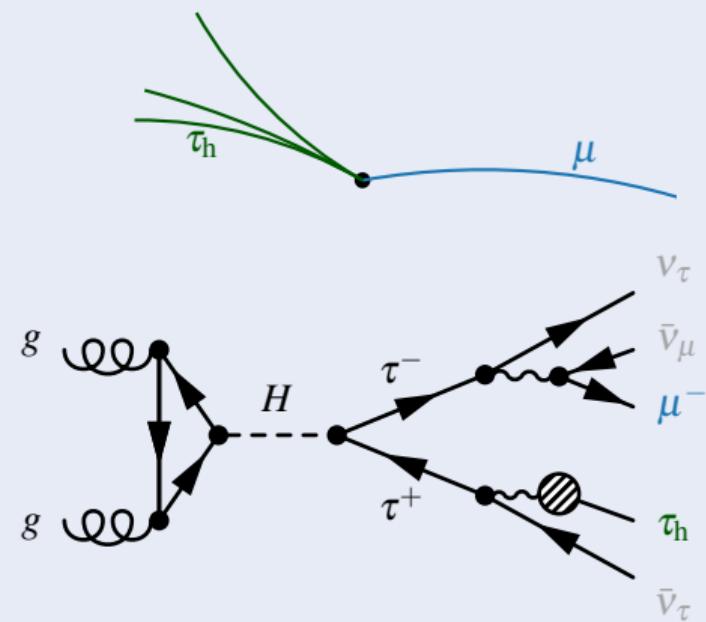
Backgrounds:  $t\bar{t}$  $t\bar{t}$  $H$  production with  $b$ -jets

# Backgrounds: QCD

QCD

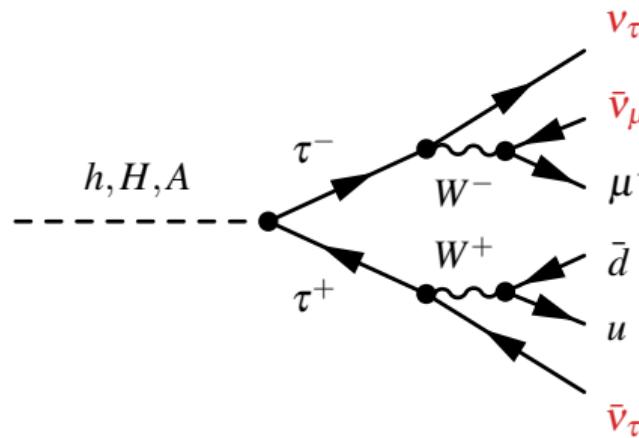


$H \rightarrow \tau\tau \rightarrow \mu\tau_h$



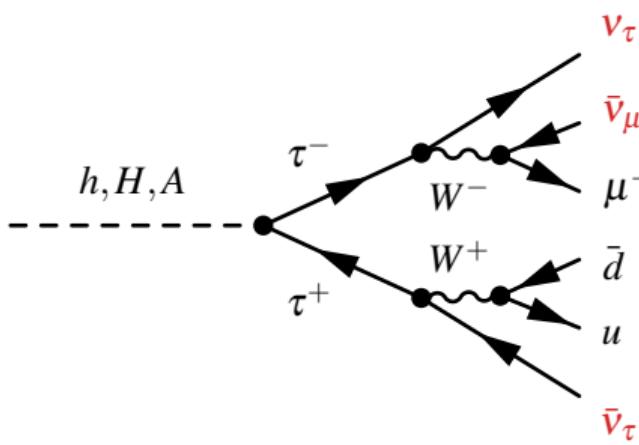
# Discriminant variable?

- ▶  $E_T^{\text{miss}}$  due to neutrinos.
- ▷ No invariant mass!

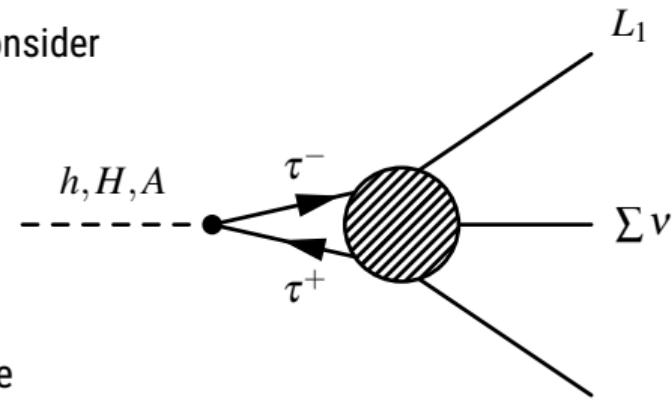


# Discriminant variable?

- ▶  $E_T^{\text{miss}}$  due to neutrinos.
- ▷ No invariant mass!



- ▶ Consider



where

- $L_1 = \mu;$
- $L_2 = u\bar{d} \rightarrow \tau_h;$
- $\sum \nu \simeq E_T^{\text{miss}};$

with respect to the left side.

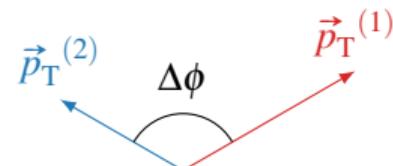
# Discriminant variable: $m_T^{\text{tot}}$

- ▶ For  $L_1, L_2$  and  $E_T^{\text{miss}}$  system,
  - ▷ in the transverse plane (use  $E_T^{\text{miss}}$ ),
  - ▷ for  $E_i \gg m_i$  (highly relativistic case),deriving the "invariant" mass would then lead to

the **total transverse mass**,  $m_T^{\text{tot}}$

$$m_T^{\text{tot}} = \sqrt{m_T^2(L_1, E_T^{\text{miss}}) + m_T^2(L_2, E_T^{\text{miss}}) + m_T^2(L_1, L_2)}$$

$$m_T(1,2) = \sqrt{2p_T^{(1)} p_T^{(2)} (1 - \cos \Delta\phi)}$$



# Signal region (SR) – 2017 $\mu\tau_h$ channel as example

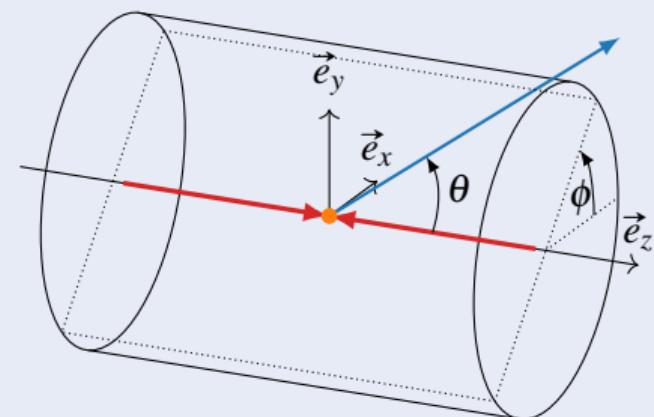
## $\mu$ and $\tau_h$ candidates

- $L_1 = \mu$

- $p_T > 21 \text{ GeV}$ ,  $|\eta| < 2.1$
- $d_z < 0.2 \text{ cm}$ ,  $d_{xy} < 0.045 \text{ cm}$
- relative isolation  $< 0.15$
- medium muon ID

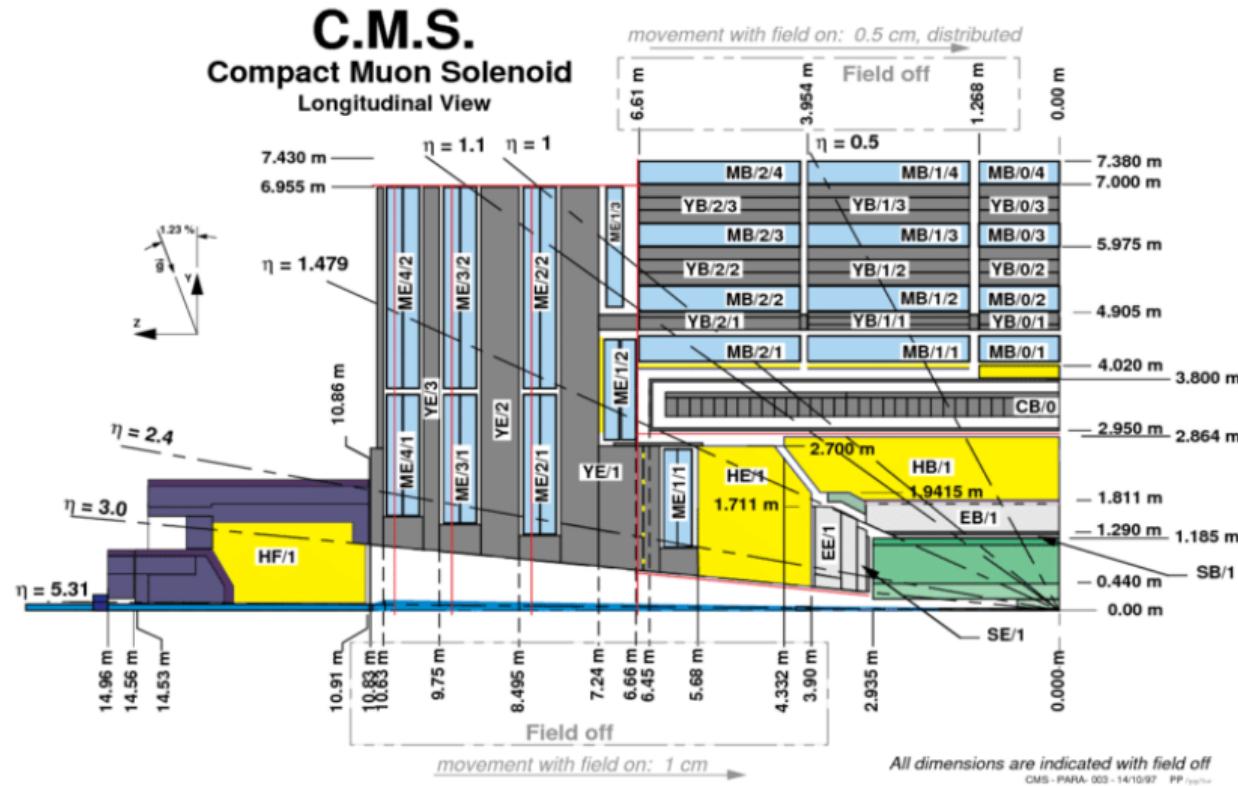
- $L_2 = \tau_h$

- $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.3$
- $d_z < 0.2 \text{ cm}$
- relative isolation  $< 0.15$
- NewDecayModeFinding (modes 5 to 9 vetoed)
- deepTau anti-electron (VVL WP)
- deepTau anti-muon (tight WP)
- deepTau vs jet (medium WP)

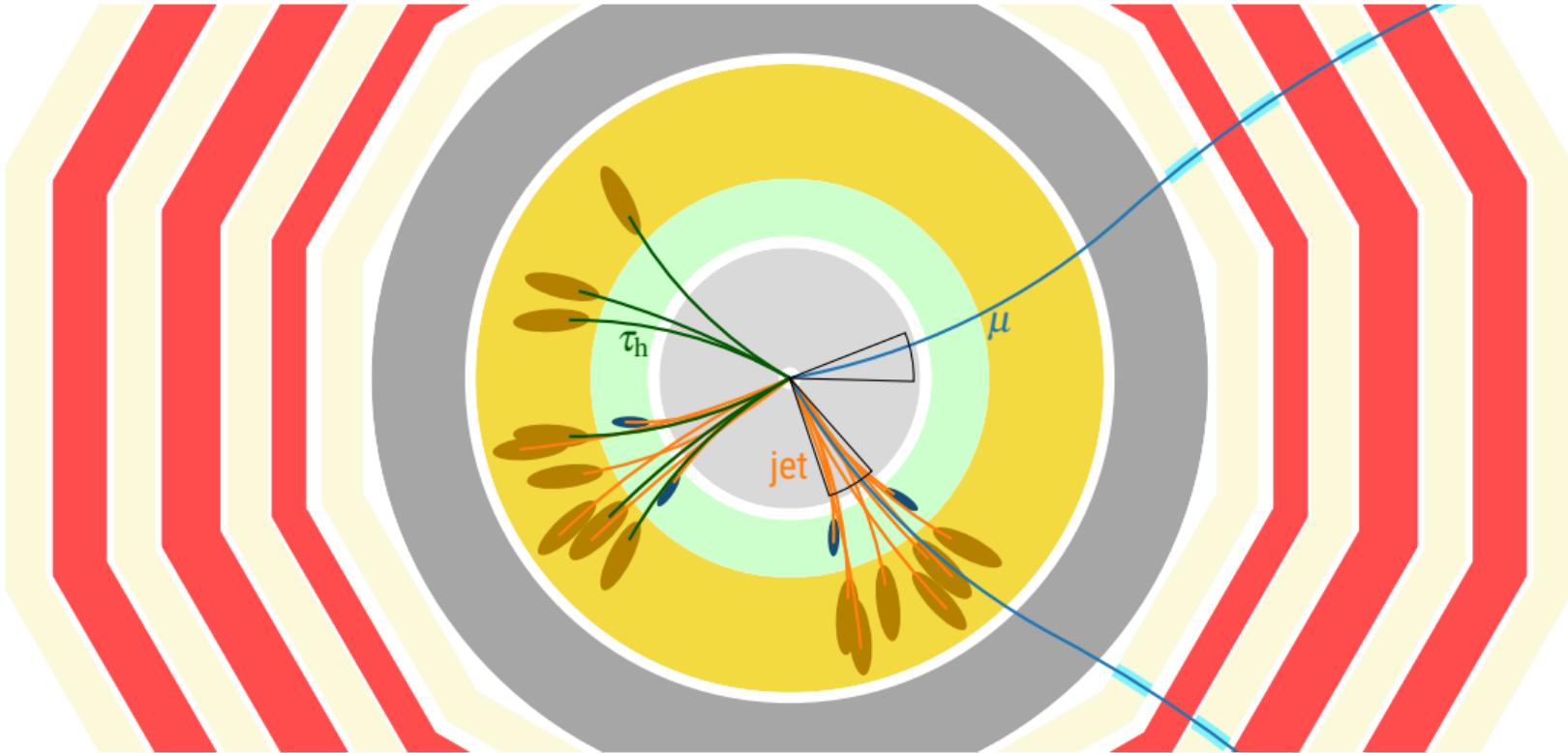


$$\eta = -\ln \tan \frac{\theta}{2}$$

# Values of $\eta$ and trajectories in CMS



## Particles isolation – qualitatively

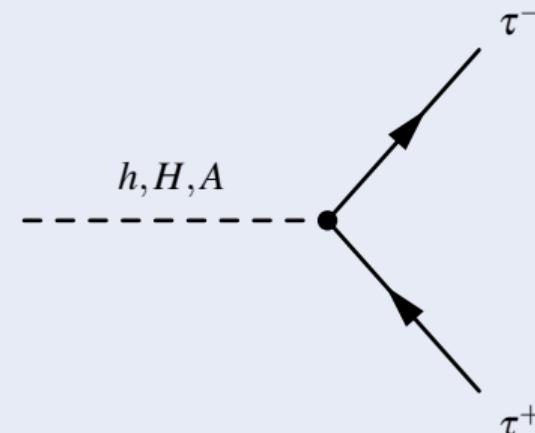


# Signal region (SR) – 2017 $\mu\tau_h$ channel as example

## Obtaining *dileptons* candidates

With all  $L_1$  and  $L_2$  passing selection,  
compose pairs ( $L_1L_2$ ) respecting:

- opposed electric charges:  
the initial Higgs is **neutral**.
- pair separation  $\Delta R > 0.5$ :  
avoid fake dileptons from jet particles.

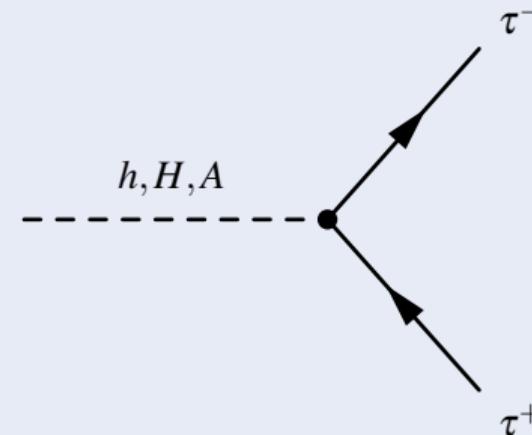


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avoid fake dileptons from jet particles.



## Selecting one dilepton

Choose by:

most isolated  $L_1$ ,

highest  $p_T^{L_1}$ ,

most isolated  $L_2$ ,

highest  $p_T^{L_2}$ .

# Signal region (SR) – 2017 $\mu\tau_h$ channel as example

## Extra leptons: reject events containing

- electron with  $p_T > 10\text{ GeV}$ ,  $|\eta| < 2.4$ , 90 % eff. WP of the electronID MVA, rel. iso  $< 0.3$
- second muon with  $p_T > 10\text{ GeV}$ ,  $|\eta| < 2.4$ , medium muonID, rel. iso  $< 0.3$
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# Signal region (SR) – 2017 $\mu\tau_h$ channel as example

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## Transverse mass

$$m_T^{(\ell)} < 70\text{ GeV}, \quad m_T^{(\ell)} = \sqrt{2p_T^{(\ell)} E_T^{\text{miss}} (1 - \cos \Delta\phi)}$$

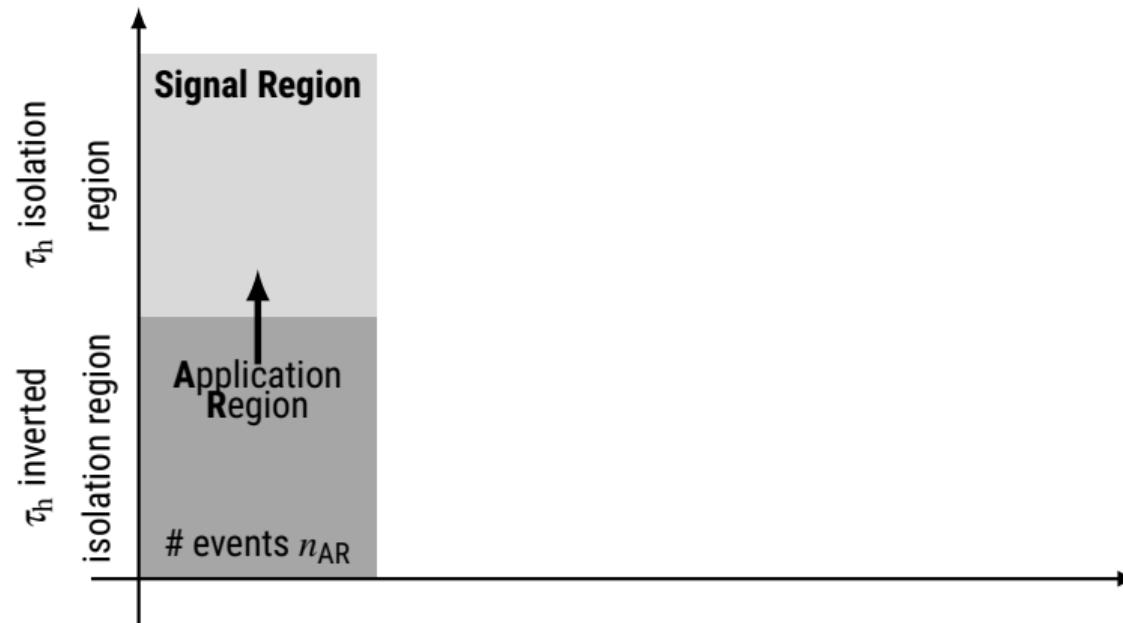
# The Fake Factor method

- ▶ How many events contain misidentified  $\tau_h$ ? (fake taus)

- 
- ▶ J. Andrejkovic et al. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with 2016 and 2017 data". *CMS analysis Note* (Oct. 2018).

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Estimation from simulated samples, same selection as in SR.

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Same as SR, except:

- transverse mass  $m_T^{(\ell)} > 70 \text{ GeV}$  ( $m_T^{(\ell)} < 70 \text{ GeV}$  in the SR);
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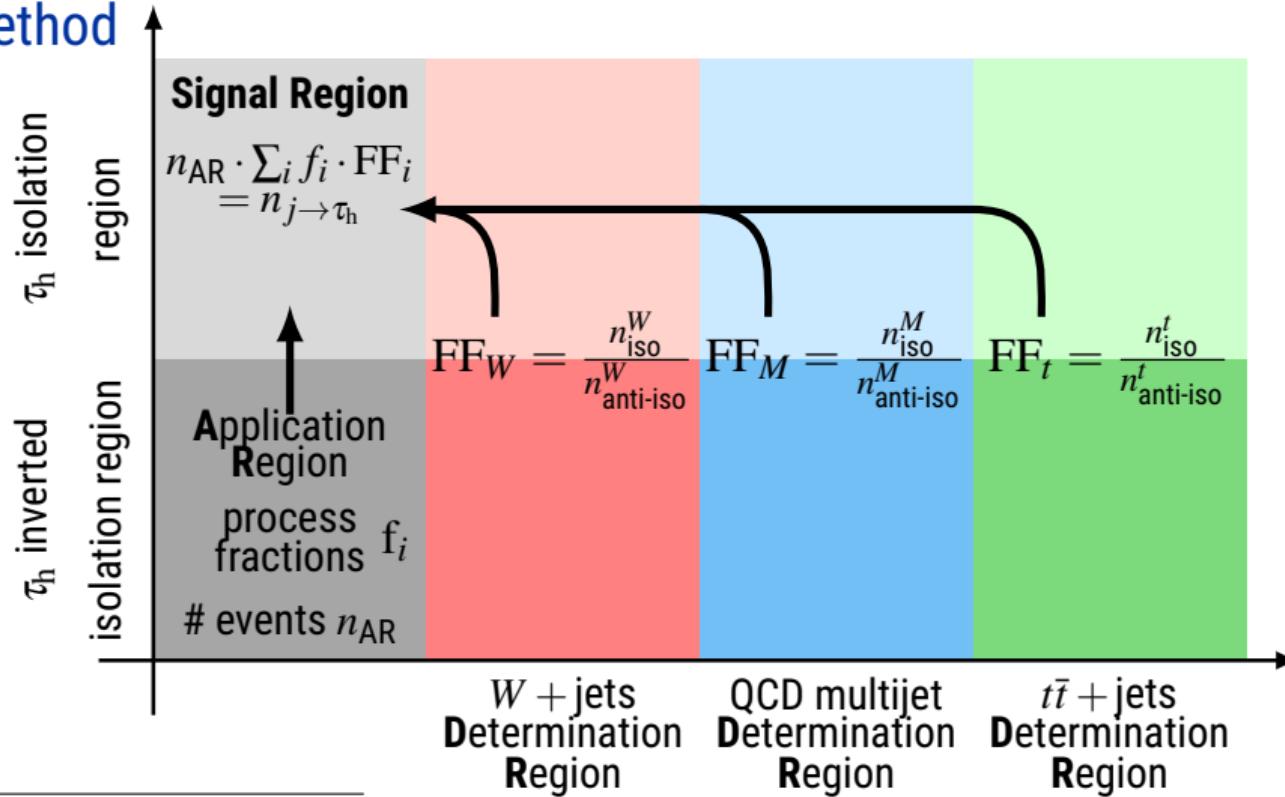
## QCD multijet

Same as SR, except:

- same signs for  $L_1$  and  $L_2$  electric charges (opposite signs in the SR).

▷ J. Andrejkovic et al. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with 2016 and 2017 data". *CMS analysis Note* (Oct. 2018).

# The FF method



▷ J. Andrejkovic et al. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with 2016 and 2017 data". *CMS analysis Note* (Oct. 2018).

# $m_T^{\text{tot}}$ distributions

# Exclusion limits

- 
- ▷ A. L. Read. "Modified frequentist analysis of search results (the  $CL_s$  method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. DOI: 10.5170/CERN-2000-005.81. URL: <http://cds.cern.ch/record/451614>.

# Model-dependant limits

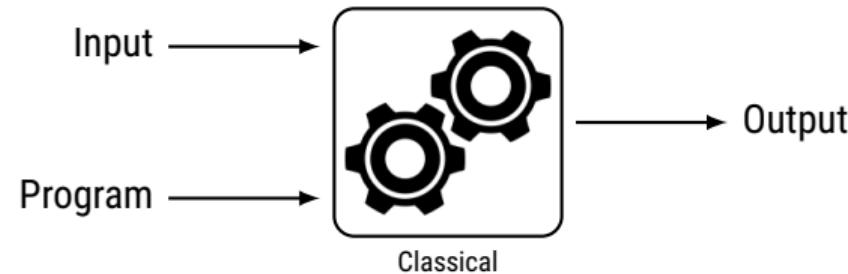
## 1 Phenomenology

## 2 Experimental device

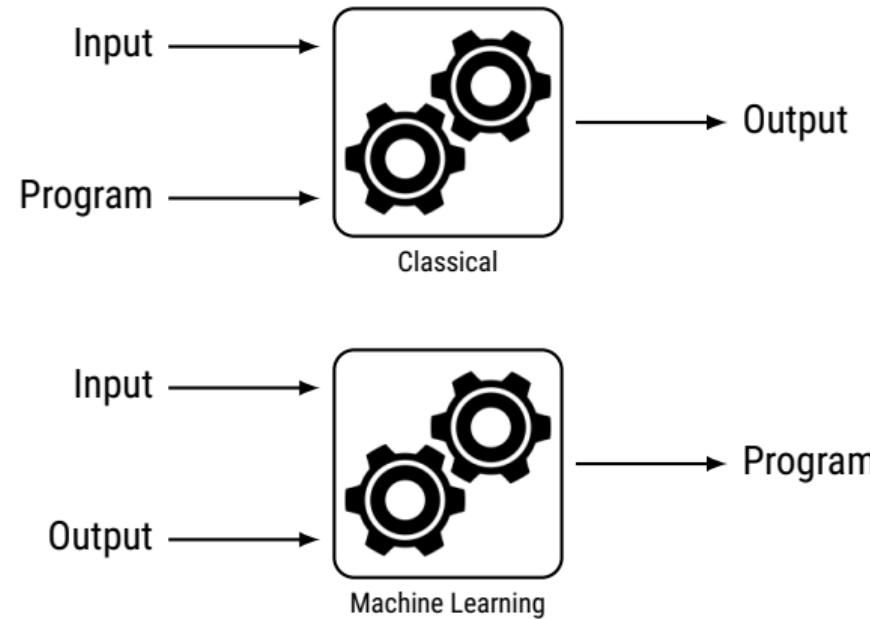
## 3 $H \rightarrow \tau\tau$ analysis

## 4 Machine Learning

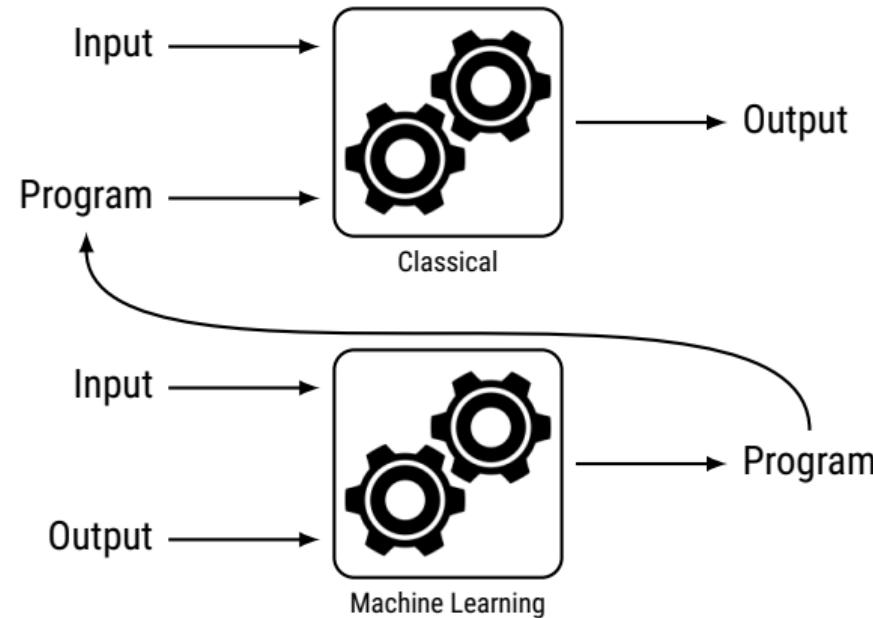
# What is *Machine Learning*? – A brief introduction



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- ▶ Categorical target ⇒ Classification  
e.g. cat or dog on the image



- ▶ C. Bernet. *The Data Frog – Image Recognition: Dogs vs Cats!* URL:  
<https://thedatafrog.com/en/articles/dogs-vs-cats/>.

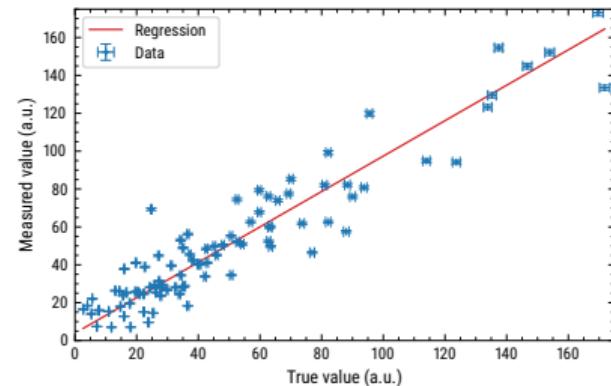
# What is *Machine Learning*? – A brief introduction

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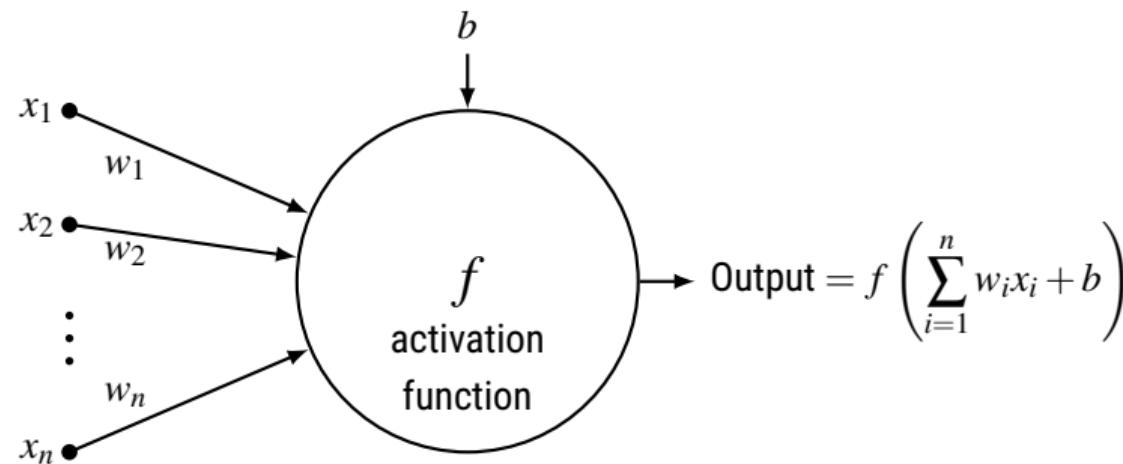
- ▶ Continuous target  $\Rightarrow$  Regression  
e.g. discriminating variable!  
Linear case:



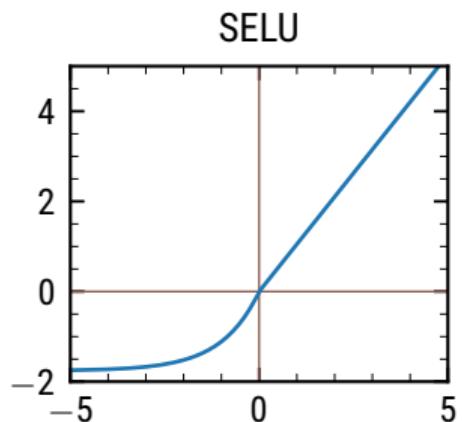
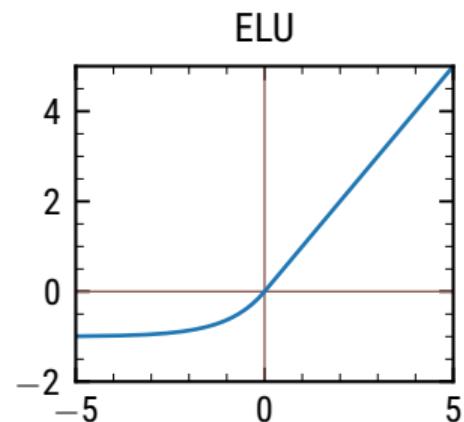
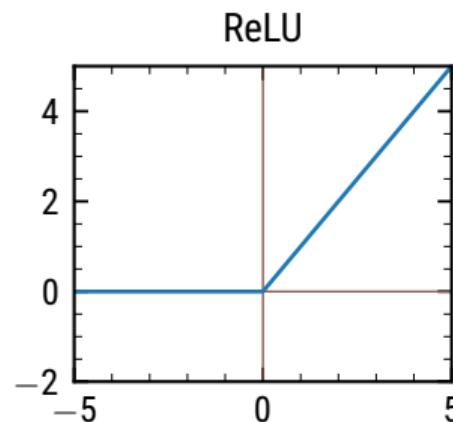
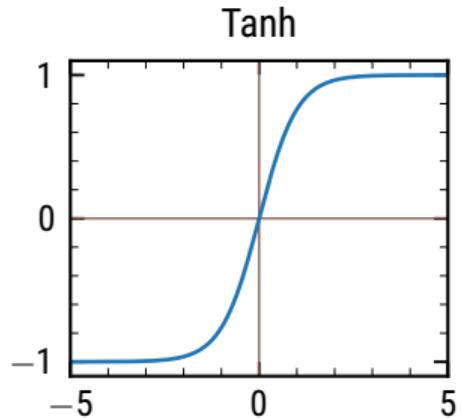
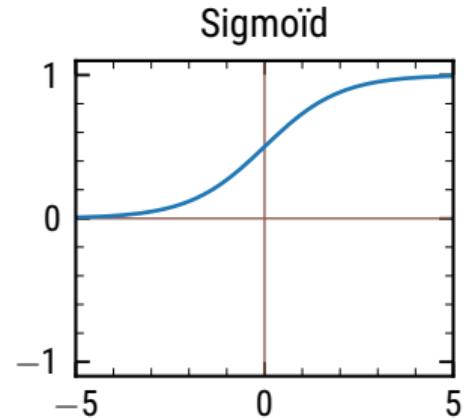
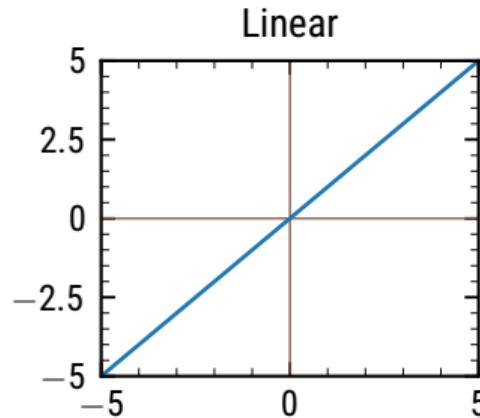
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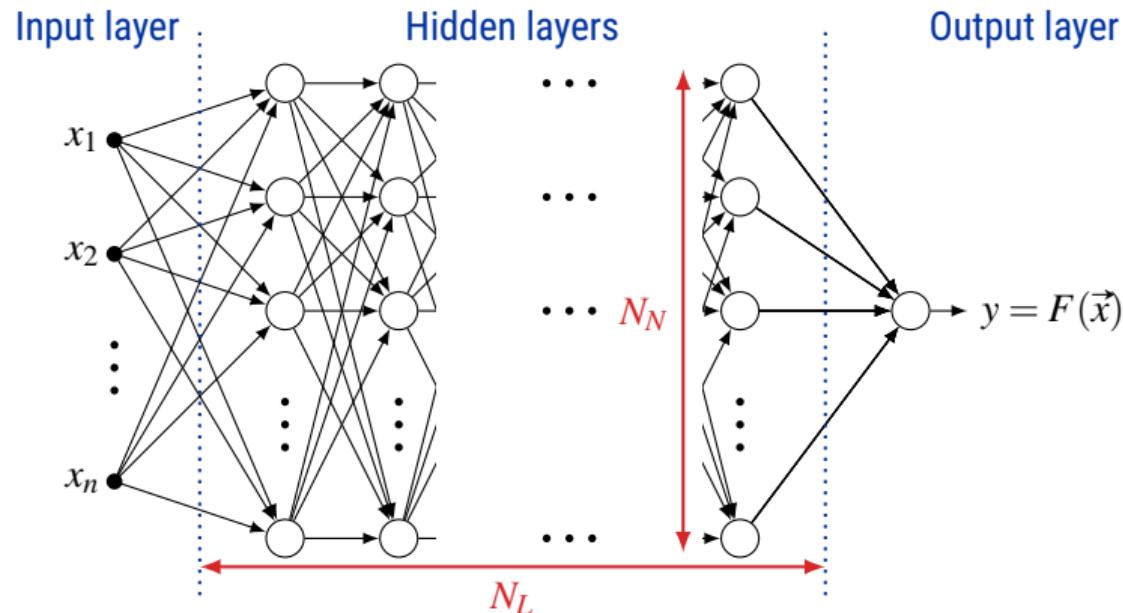
What if the target is not linear wrt. input?

# Neurons in ML



- ▶ Parameters:  $w_1, w_2, \dots, w_n, b$
- ▶ Equivalent to linear regression for  $f = \mathbb{1} : x \mapsto x$





e.g.  $N_L = 3$  and  $N_N = 1000$

# Grid search: hyperparameters

| Hyperparameter         | Values                             |
|------------------------|------------------------------------|
| Hidden layers          | from 2 to 5                        |
| Neurons per layers     | from 500 to 2000 (per sets of 100) |
| Loss function          | MAPE, MSE                          |
| Activation function    | ReLU, ELU, SELU                    |
| Optimizer              | Adam, Adadelta, SGD                |
| Weights initialisation | uniform, normal                    |

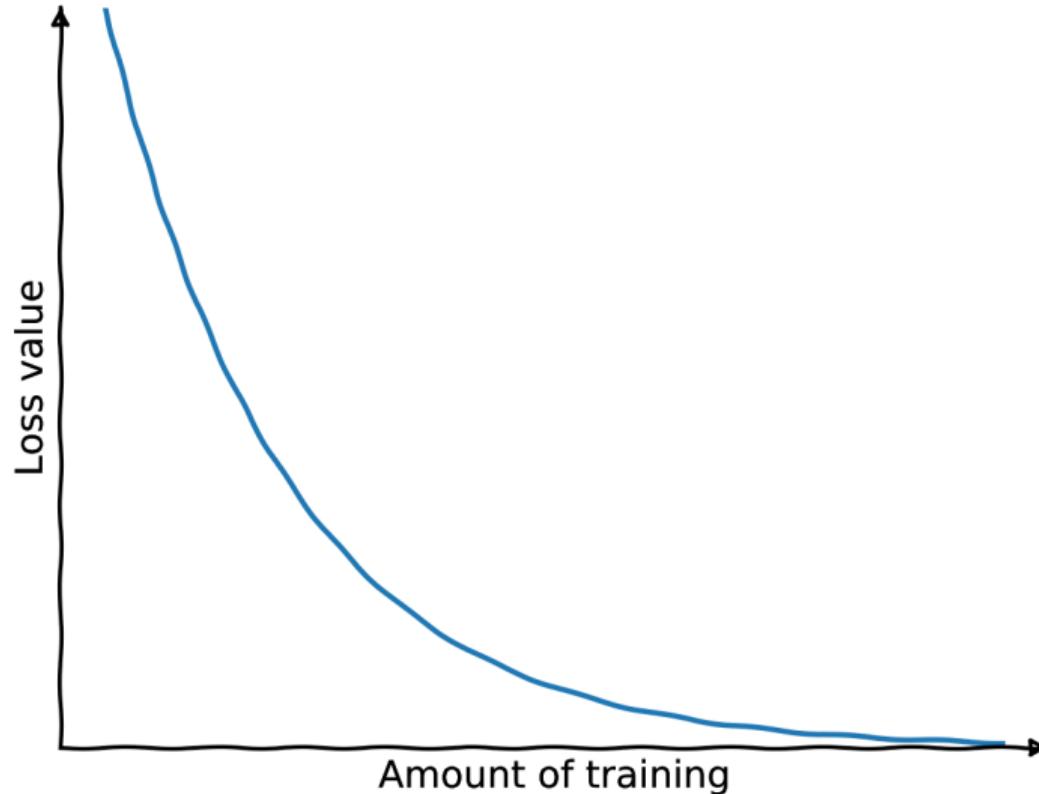
+ different sets of input variables

# How to train a neural network?

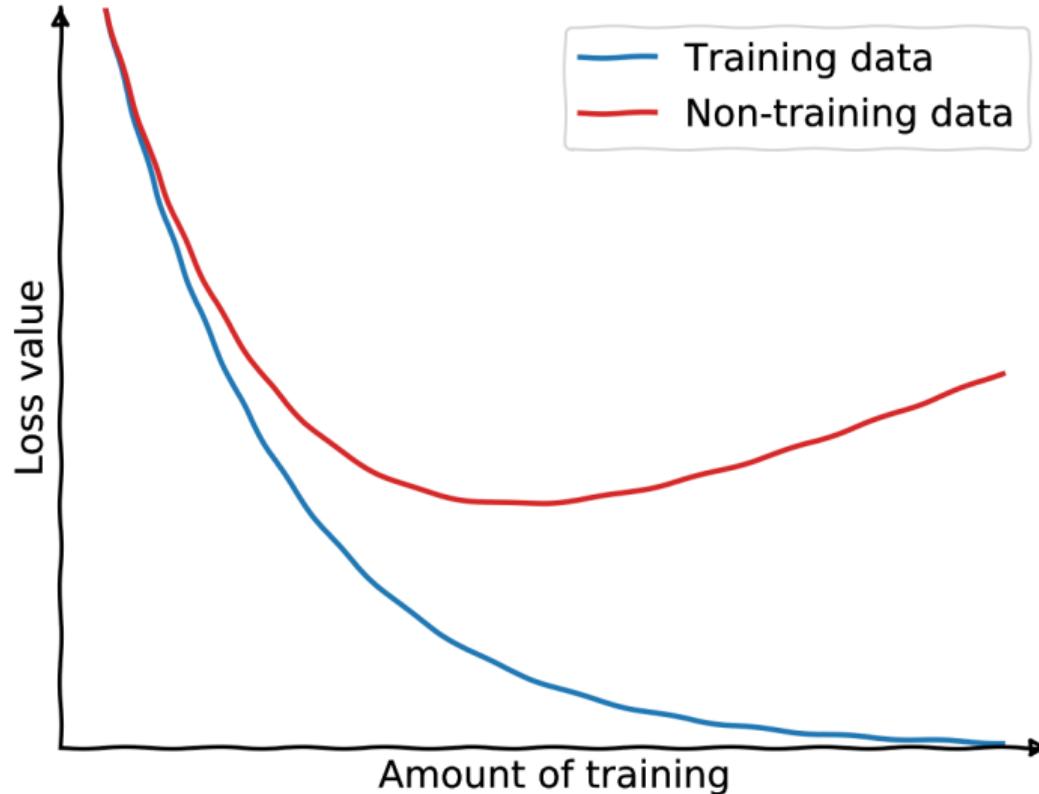
Train = optimize parameters  $(w_1, w_2, \dots, w_n, b)$  for each neuron.

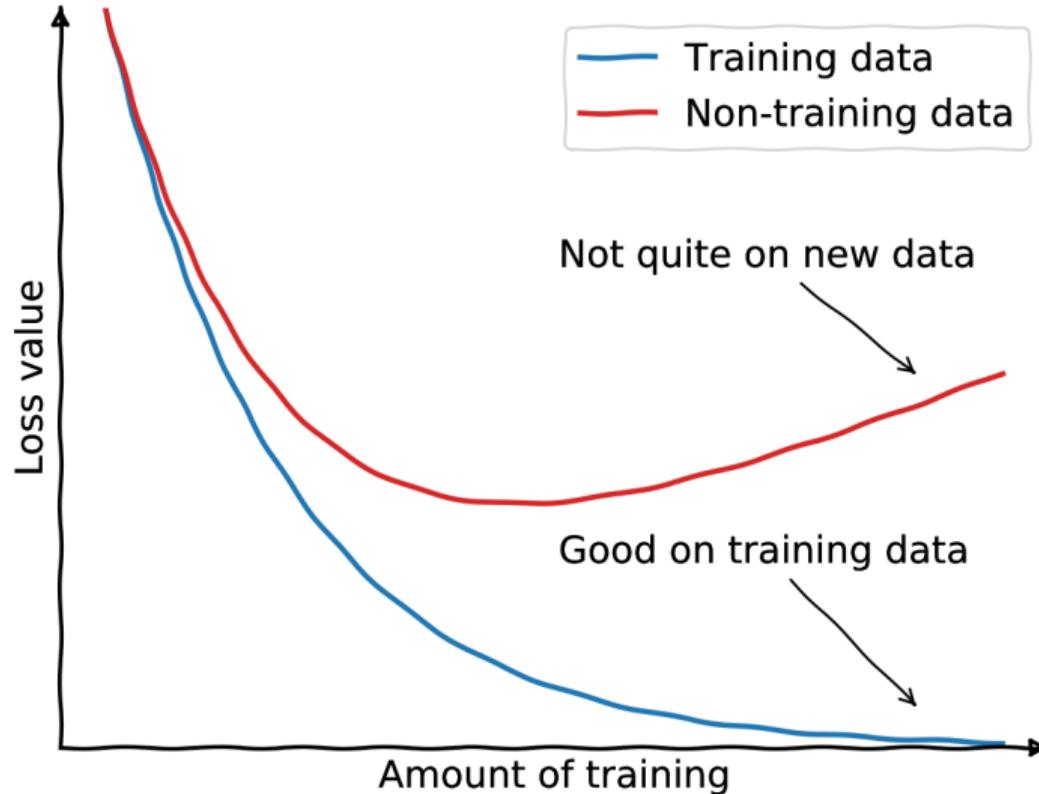
- ▶ Get a **training dataset** = examples of inputs  $\vec{x}_i$  with corresponding outputs  $y_i$
- ▶ Compare the model predictions  $F(\vec{x}_i)$  to the true values  $y_i$ 
  - ▷ Define a **loss function**  $L$  such that its minimum is reached when  $F(\vec{x}_i) = y_i$
  - ▷ Change the parameters a bit, aiming at minimizing  $L(F(\vec{x}_i), y_i)$
  - ▷ Repeat

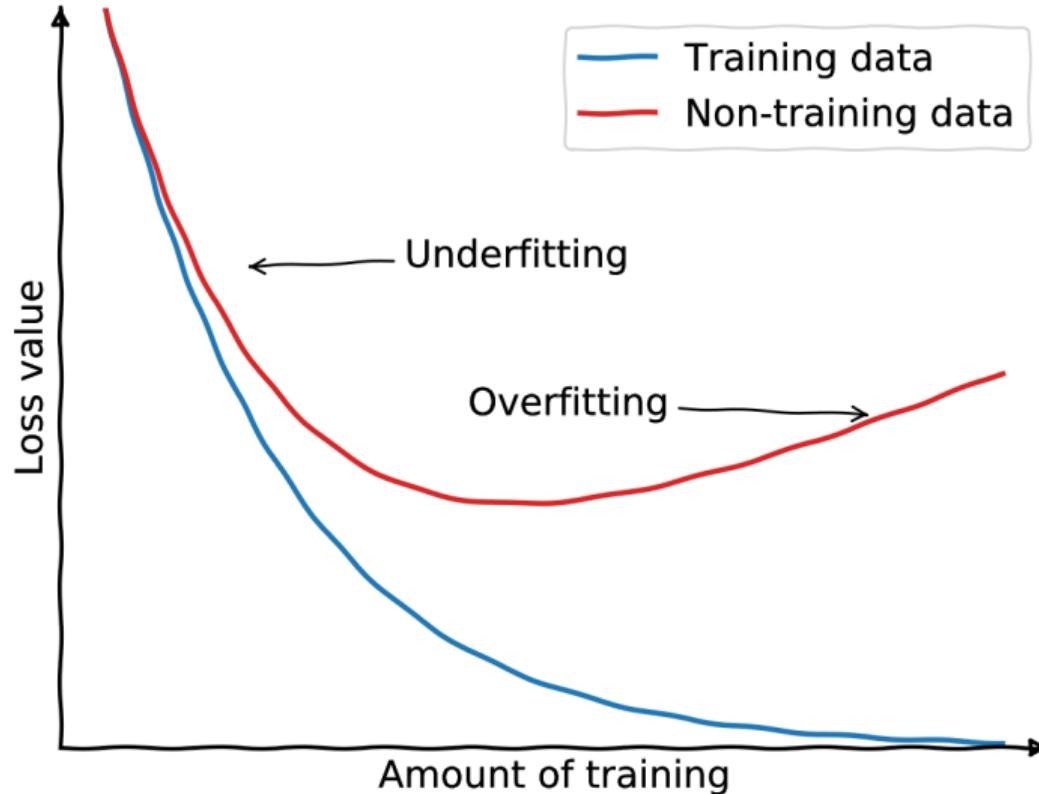
When to stop training?

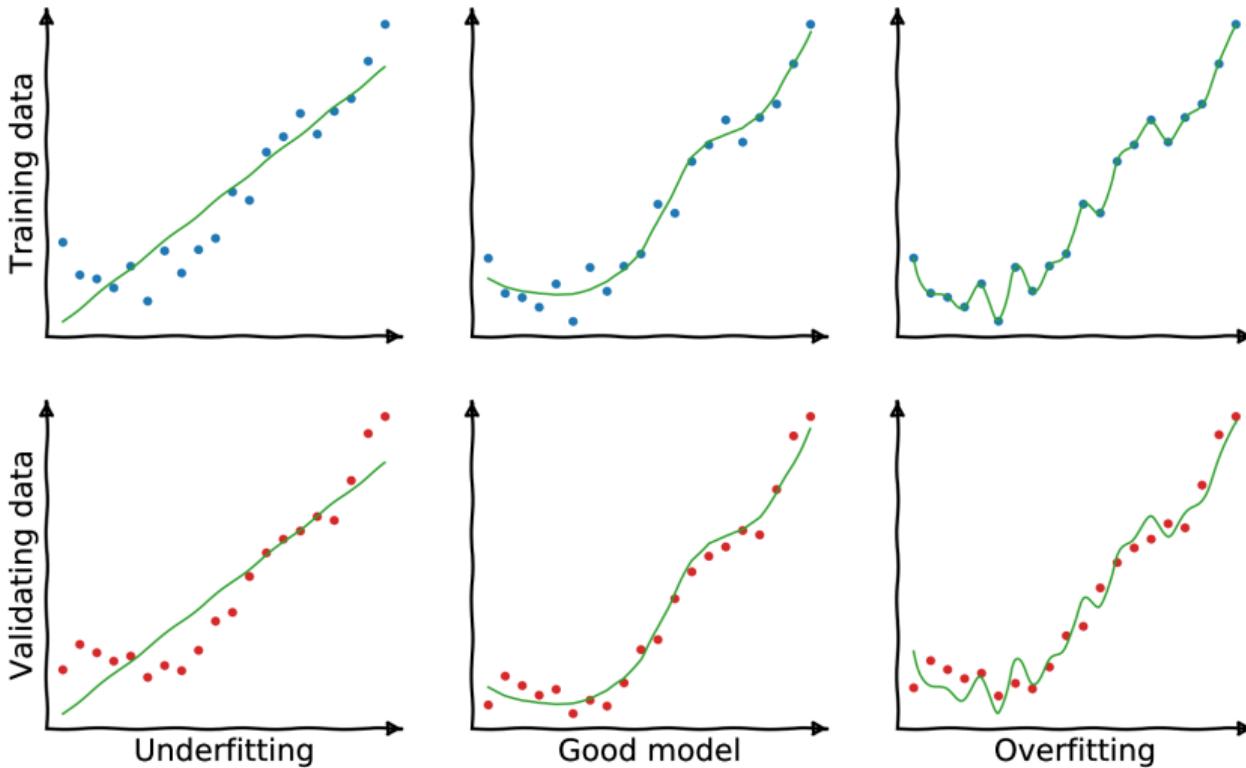


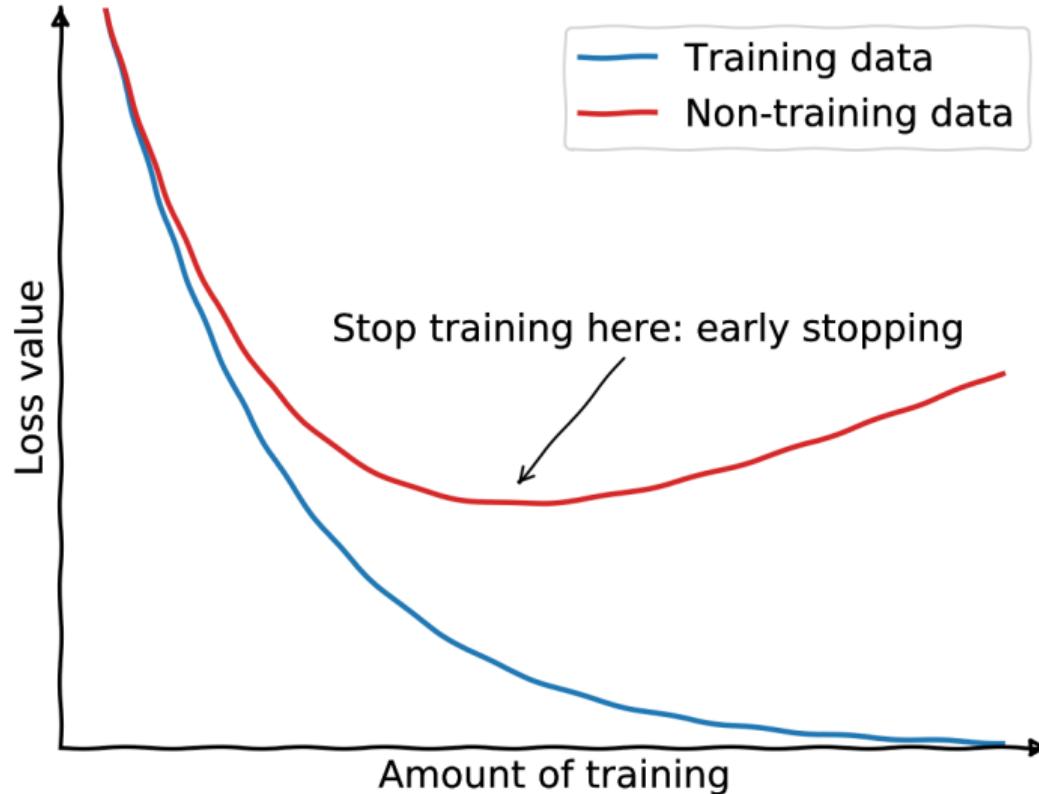


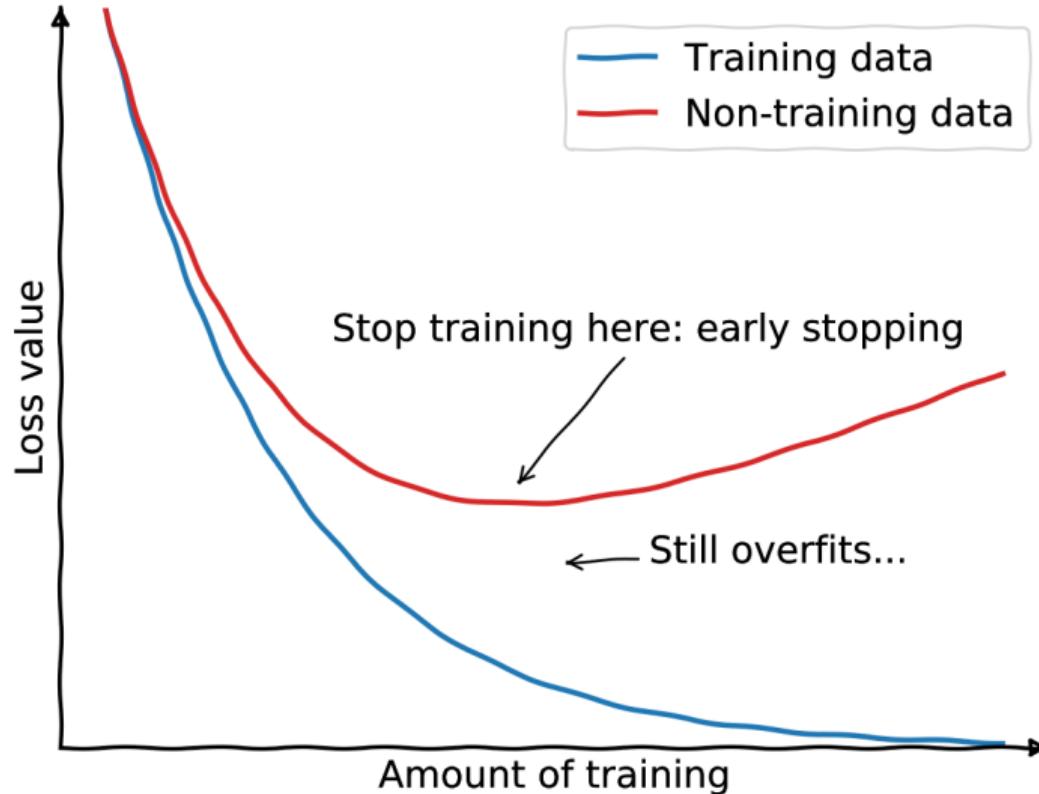


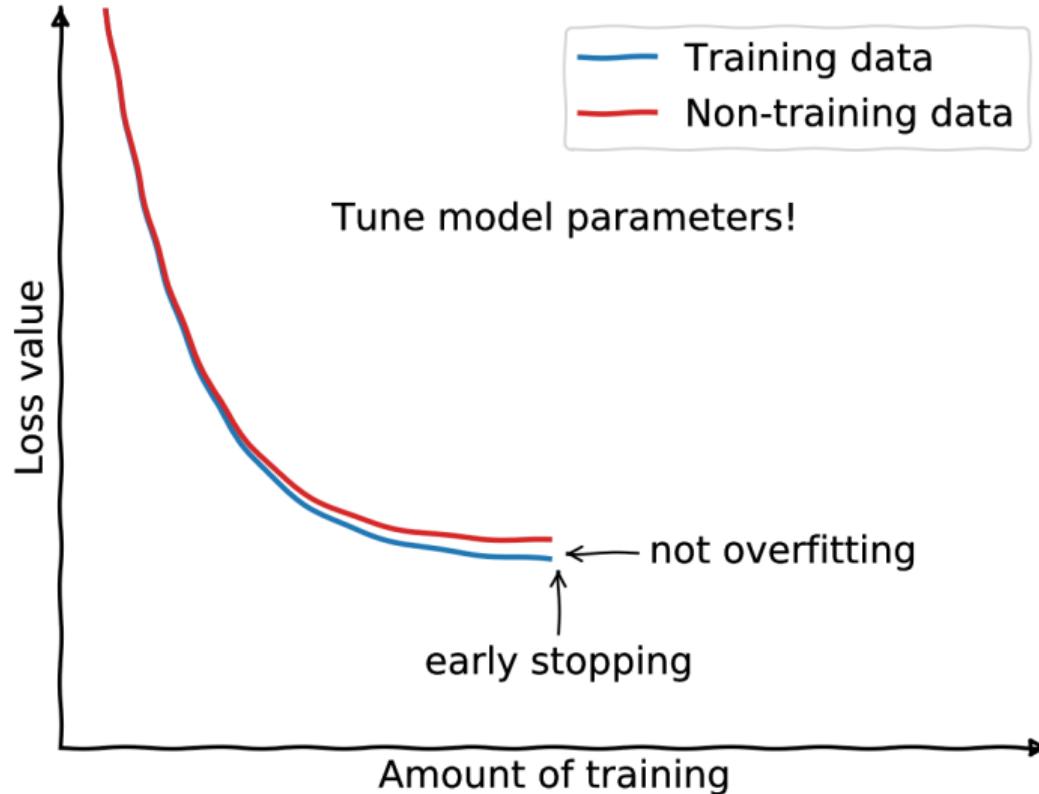








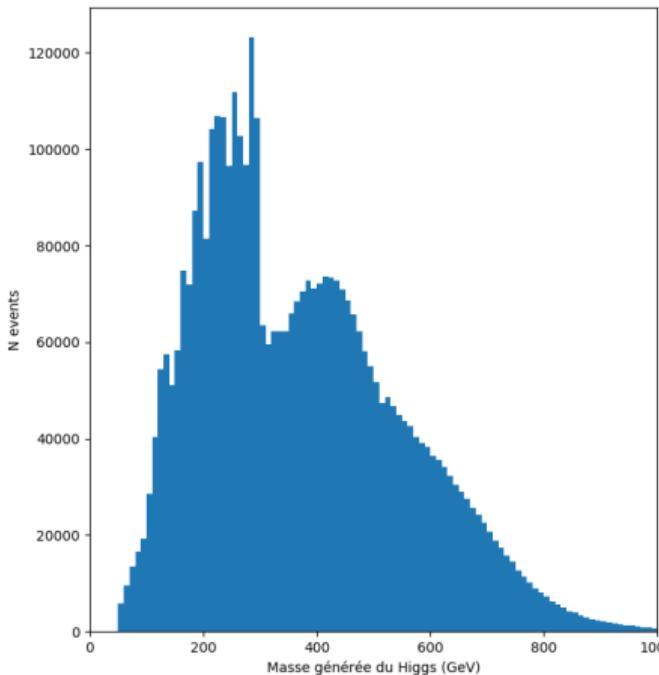




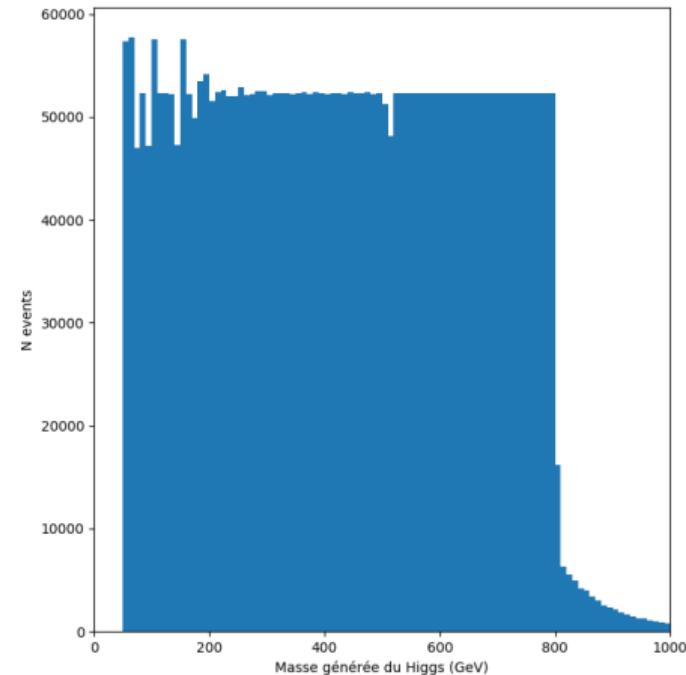
# Datasets

- ▶ We generated  $H \rightarrow \tau\tau$  with FastSim, only changing  $m_H \in [50, 800]$  GeV:
  - ▷ 60,000 events for  $m_H < 300$  GeV,
  - ▷ 20,000 events for  $300 \text{ GeV} \leq m_H < 500 \text{ GeV}$ ,
  - ▷ 10,000 events for  $m_H \geq 500 \text{ GeV}$ .
- ▶ Split into 3 subsamples:
  - ▷ 70 % for training,
  - ▷ 20 % for validation,
  - ▷ remaining 10 % for tests.

# Target: $m_H$

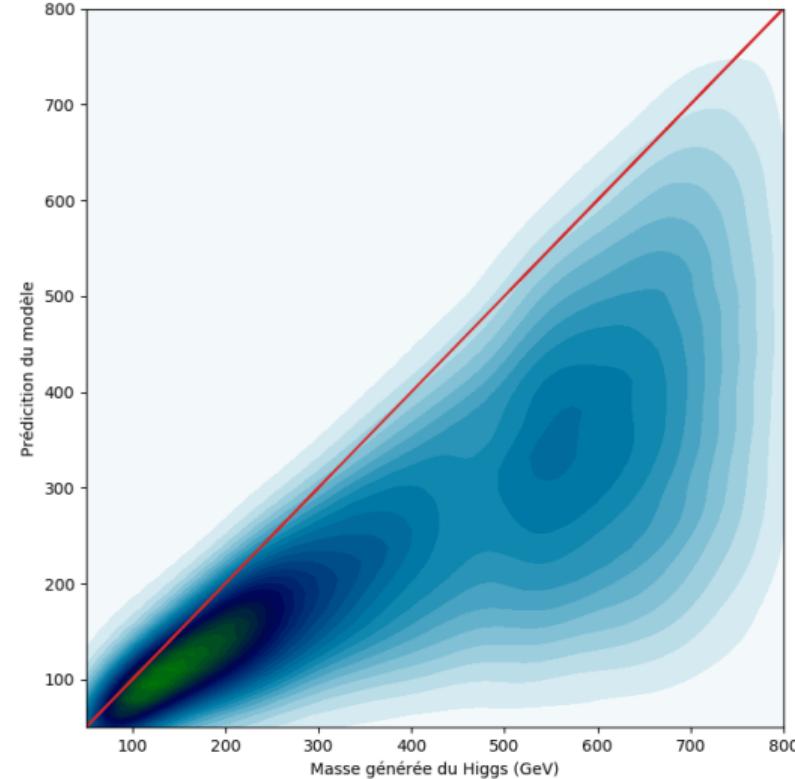


raw distribution



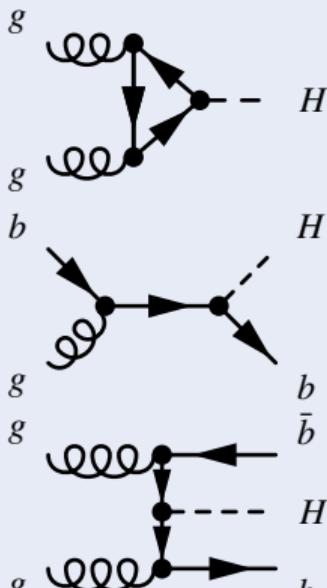
weighted distribution

# What if the model is $m_T^{\text{tot}}$ itself?



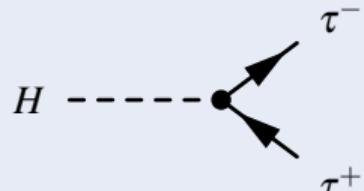
## What about input variables?

## Higgs production



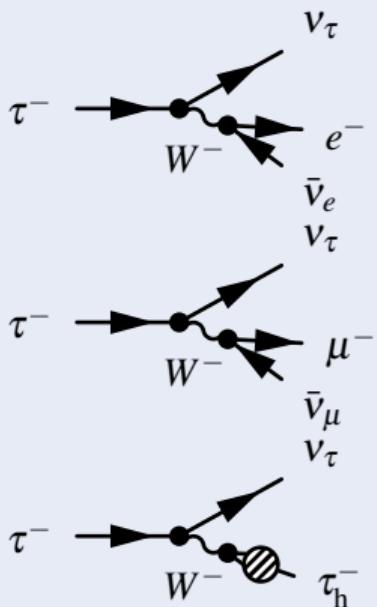
eventual jets

## $H \rightarrow \tau\tau$



2 taus

## $\tau$ decays



{1,2} neutrinos per tau  
+{ $e, \mu, \tau_h$ }

- ▶ ML models inputs are based on reconstructed variables (what is available in real data).

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- ▶  $H \rightarrow \tau\tau$  decays:
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  - ▷ MET to account for neutrinos  $\rightarrow E_T^{\text{miss}}, \phi^{\text{MET}}$ ;

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  - ▷ two leading jets  $\rightarrow p_T^{(j1,j2)}, \eta^{(j1,j2)}$  and  $\phi^{(j1,j2)}$ ;

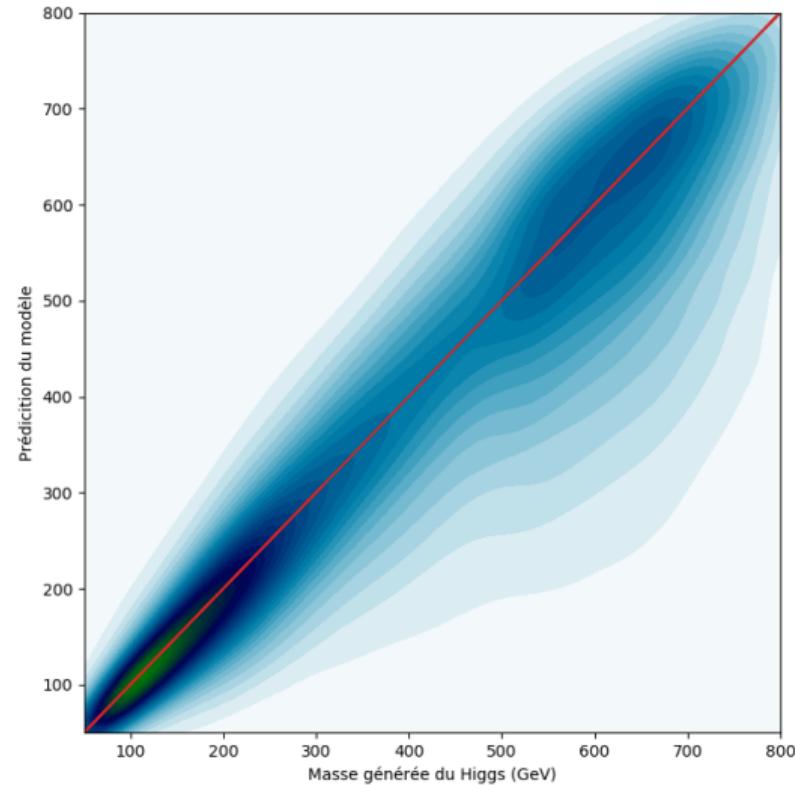
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- ▶ Higher level variables:
  - ▷ transverse masses  $m_T^1, m_T^2, m_T^{\tau\tau}$ ,
  - ▷ total transverse mass  $m_T^{\text{tot}}$ .

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  - ▷ total transverse mass  $m_T^{\text{tot}}$ .
- ▶ Additionnal variables:
  - ▷ MET covariance matrix;
  - ▷ remaining jets overall  $\vec{p} \rightarrow p_T^r, \eta^r$  and  $\phi^r$ ;
  - ▷ number of neutrinos ( $\tau_h \tau_h = 2, \ell \tau_h = 3, \ell \ell = 4$ );
  - ▷ number of PU vertices npvsGood.

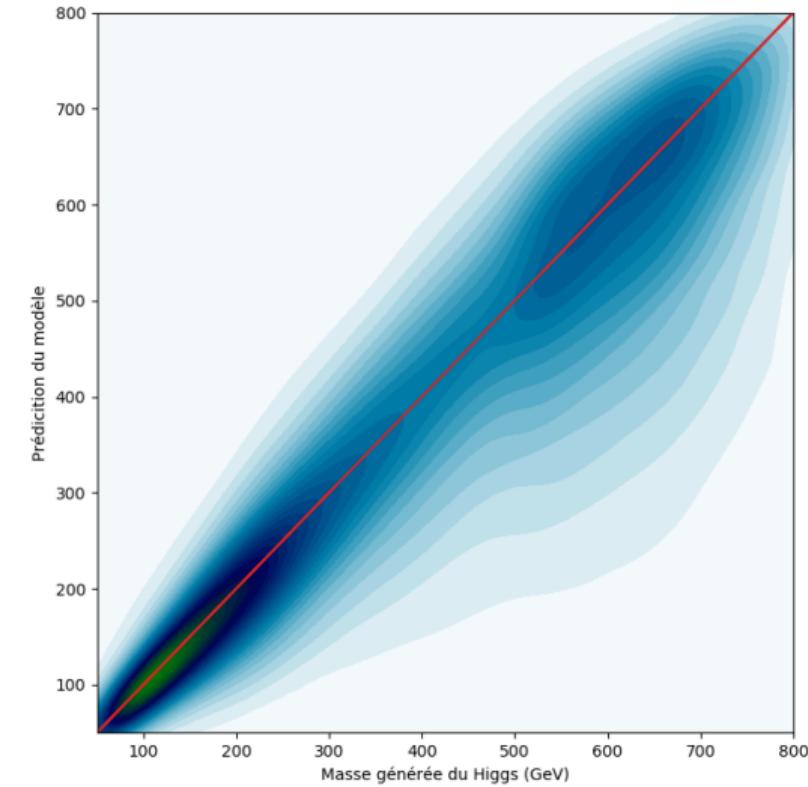
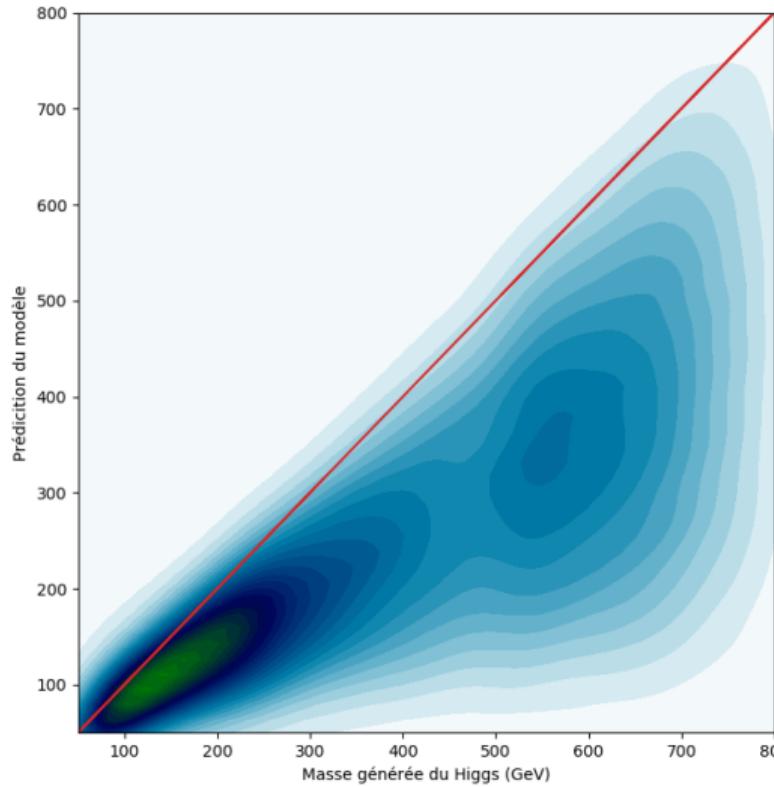
# Best model obtained

## Model properties

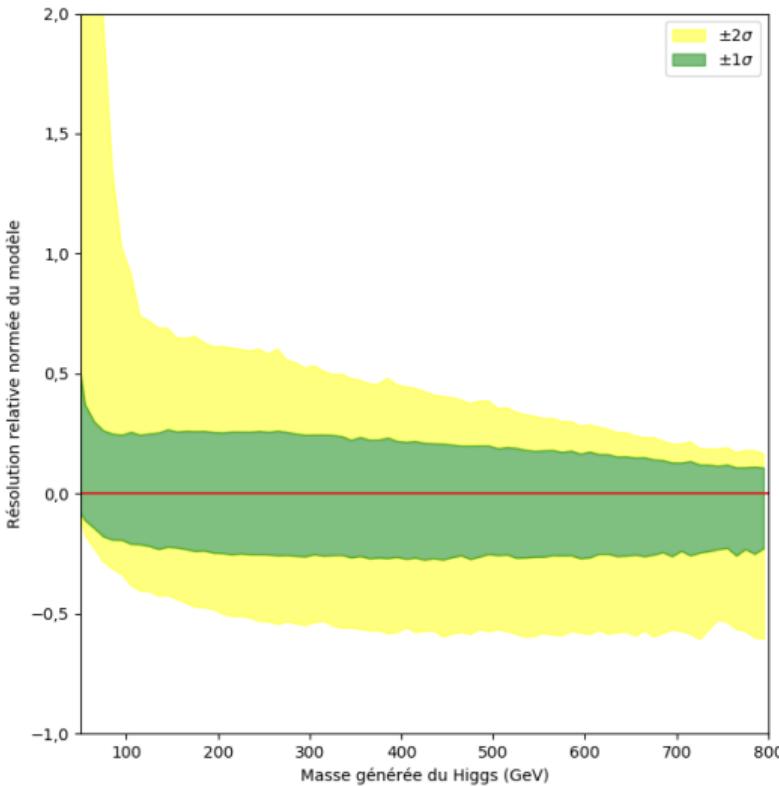
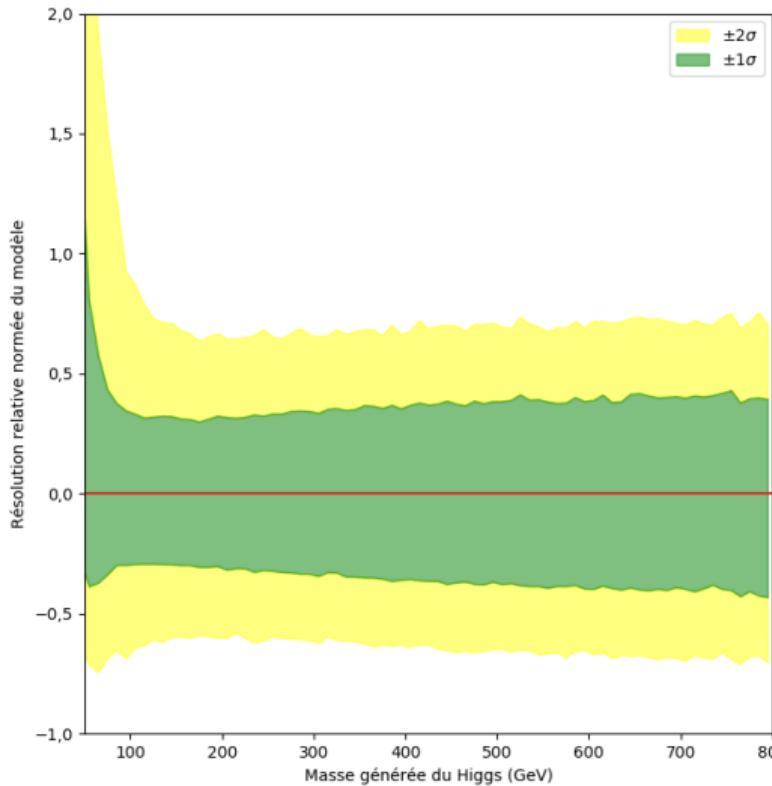
|                          |      |
|--------------------------|------|
| Activation function      | SELU |
| Loss function            | MAPE |
| Optimizer                | Adam |
| Hidden layers            | 3    |
| Neurons per hidden layer | 1000 |



## ► Compare with $m_T^{\text{tot}}$



► Compare with  $m_T^{\text{tot}}$ : relative resolutions, the thinner the better!



# Next step?

- ▶ Switch from  $m_T^{\text{tot}}$  to a ML-based output
- ▶ Improvement on exclusion limits?
- ▶ Computing on its way!

Thank you for your attention!