



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



# Recherche de bosons de Higgs supplémentaires de haute masse se désintégrant en paire de taus dans l'expérience CMS au LHC à l'aide du *machine learning*

## Soutenance de thèse de doctorat

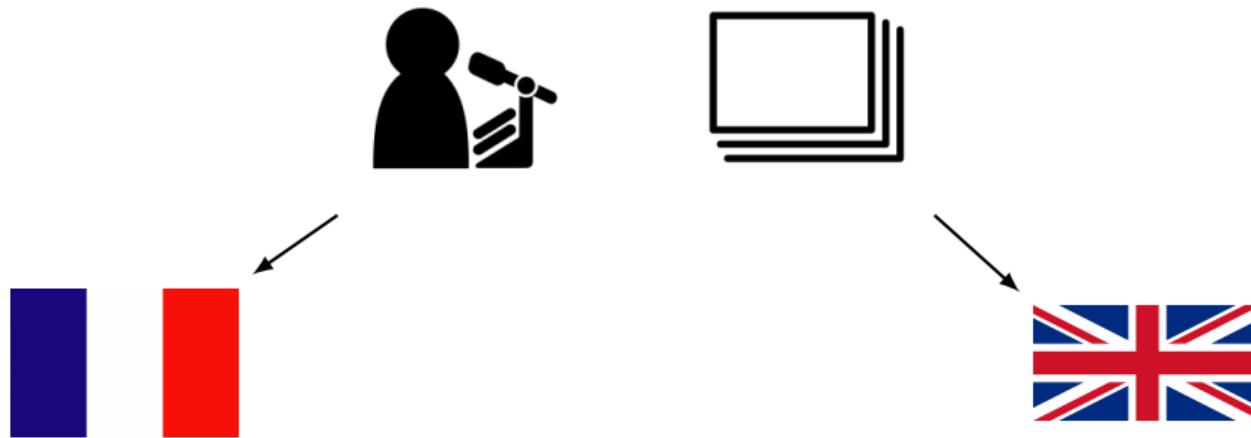
Lucas TORTEROTOT

Institut de Physique des deux Infinis – Lyon

8 juillet 2021



# Lang(u)age





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# Search for additional heavy Higgs bosons decaying to tau lepton pair in the CMS experiment at LHC with machine learning techniques

Ph.D. thesis defense

Lucas TORTEROTOT

Institut de Physique des deux Infinis – Lyon

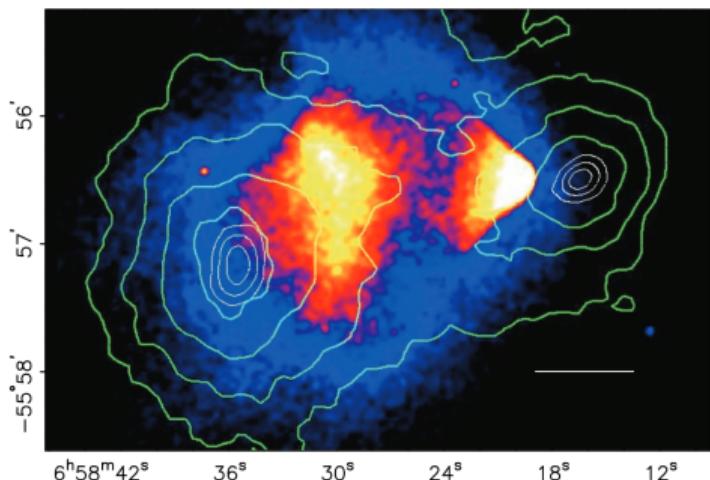
July 8, 2021



## Why do we search for...?

### Current standard 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
  - ▶ naturalness problem
  - ▶ ...
- Go beyond with a new model!
- Consequences of this new model? **Test it!**



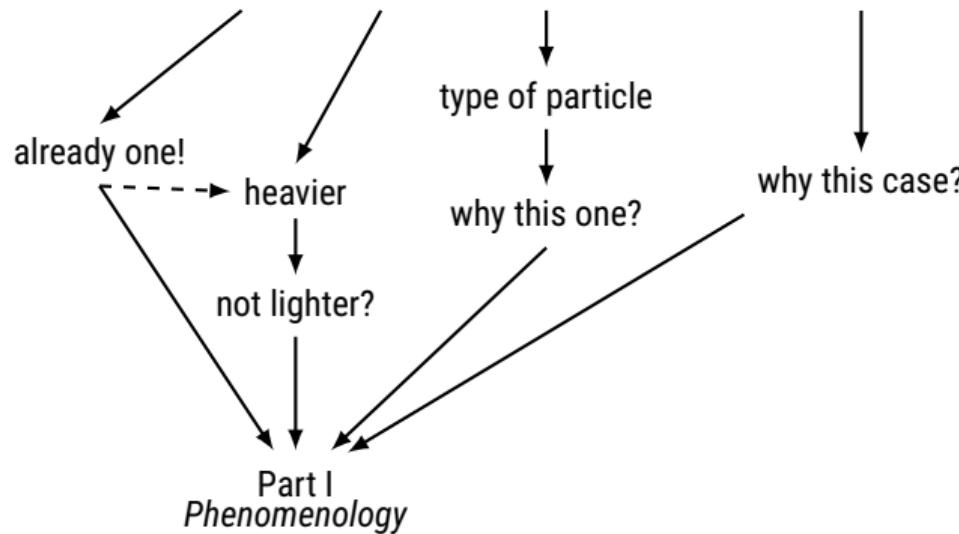
▷ D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

# Keywords in title

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

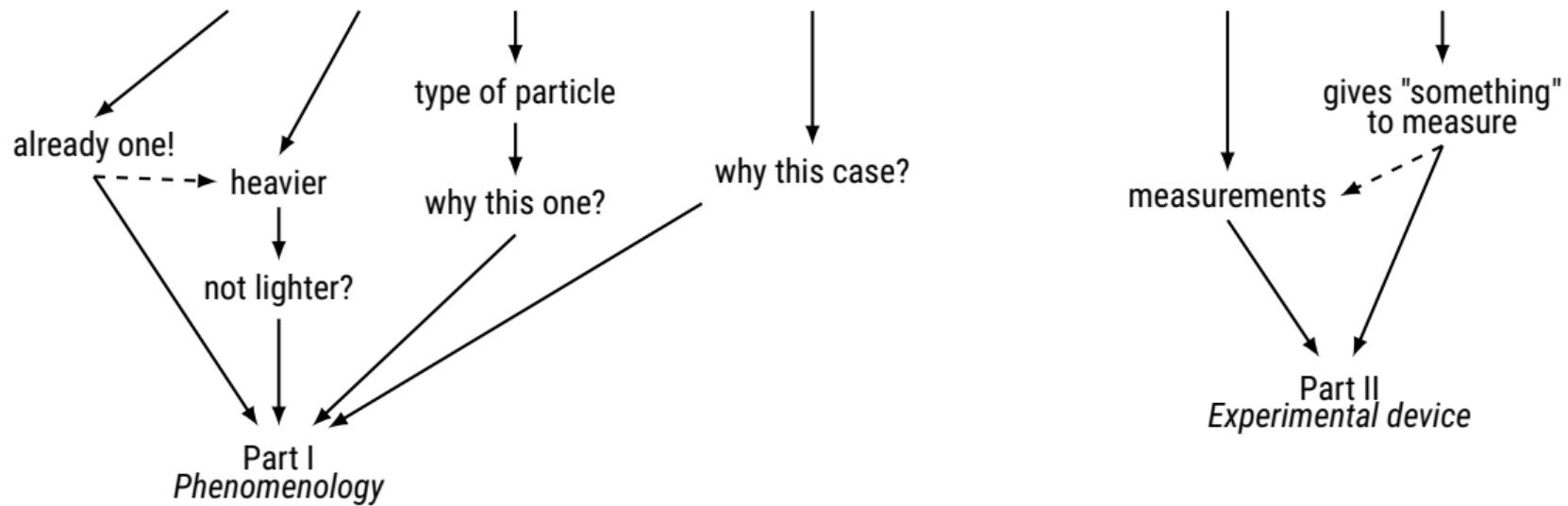
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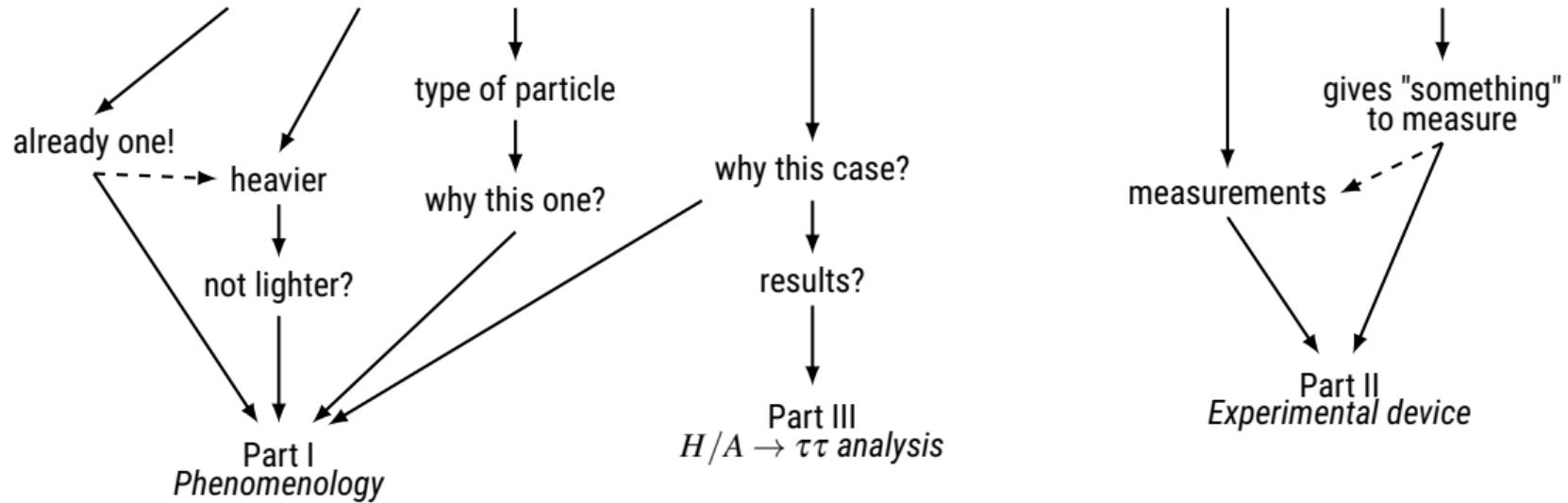
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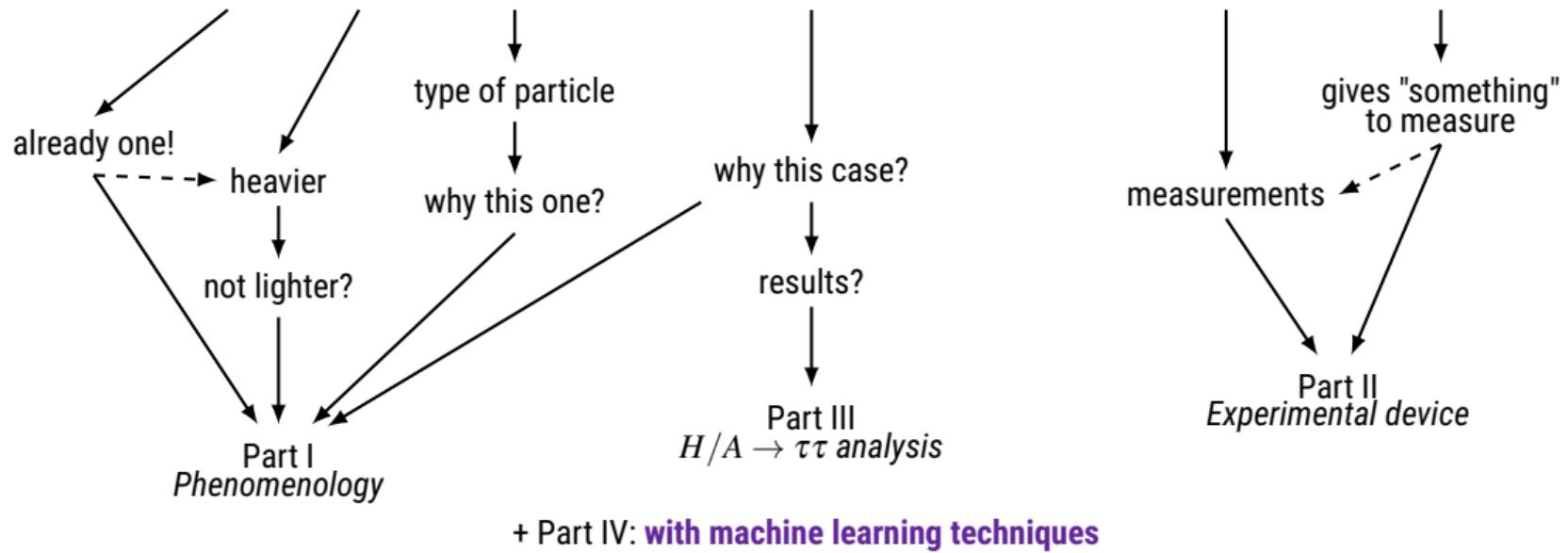
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## 1 Phenomenology

## 2 Experimental device

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

## 4 Machine learning

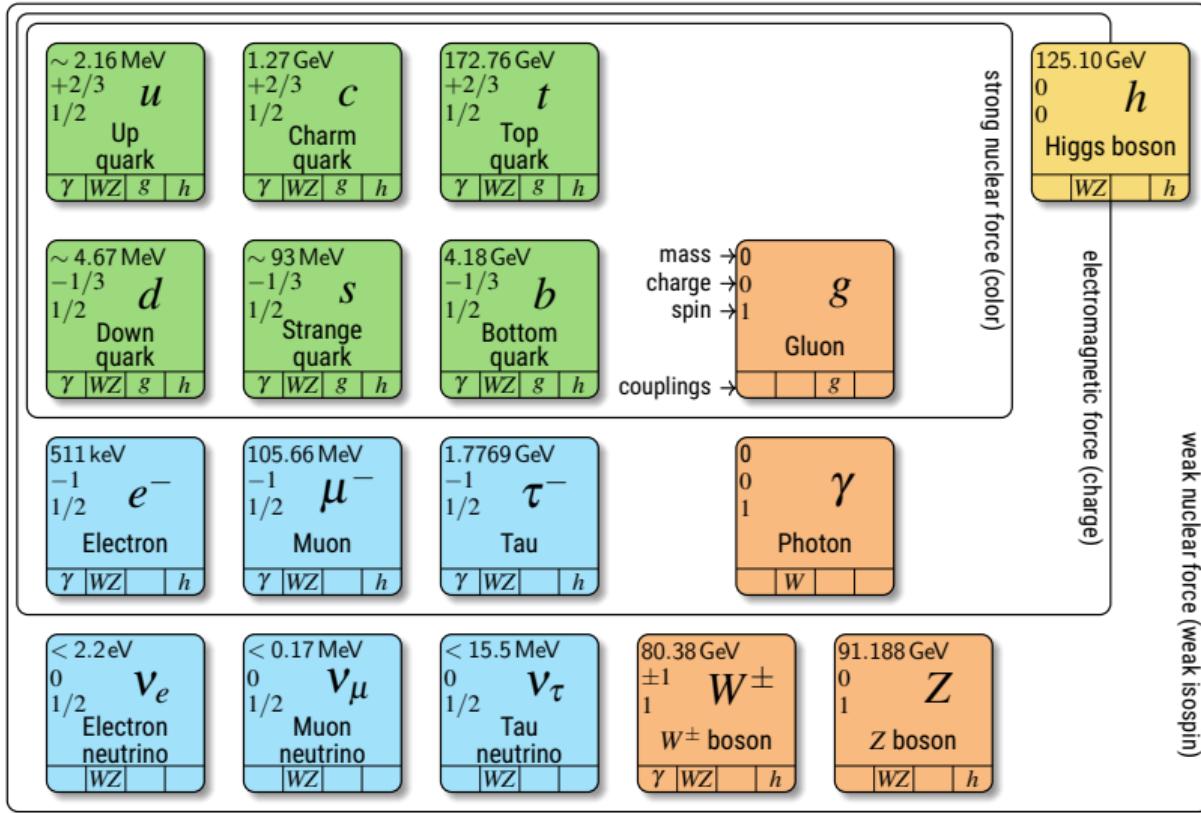
## 1 Phenomenology

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# The Standard Model



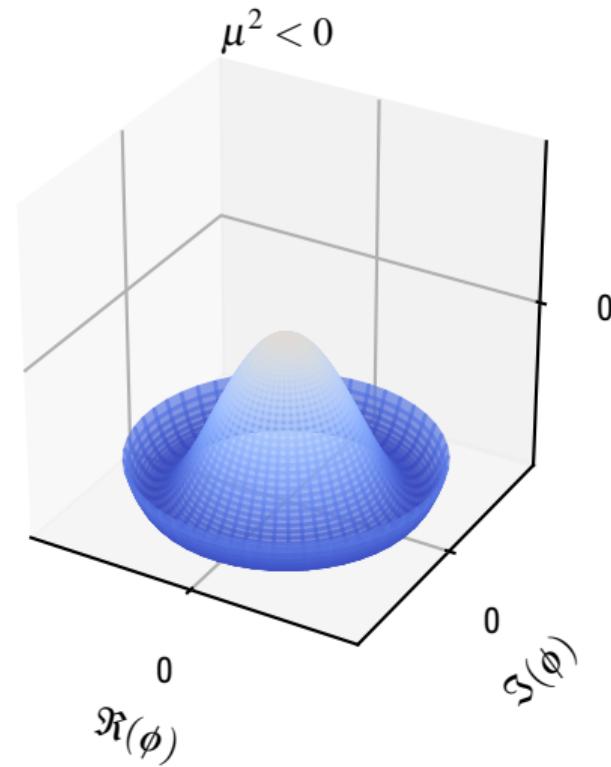
# Higgs boson in the Standard Model

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

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

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

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

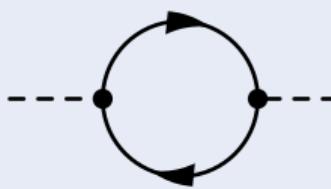


# The Standard Model and naturalness problem

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

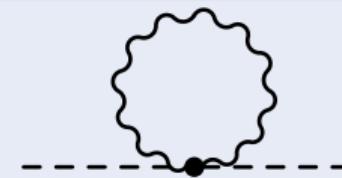
► Higgs mass derivation:  $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



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

vector bosons



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

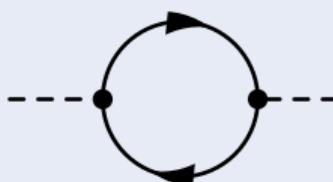
Higgs itself



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

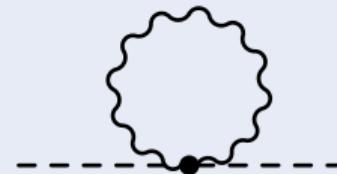
# Supersymmetry

top quark



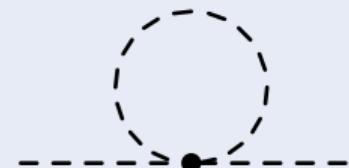
$$\sim -(2 \text{ TeV})^2$$

vector bosons



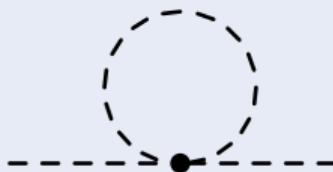
$$\sim +(0.7 \text{ TeV})^2$$

Higgs itself



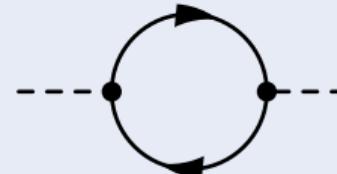
$$\sim +(0.5 \text{ TeV})^2$$

stop quark



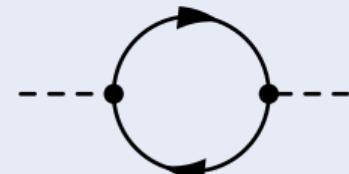
$$\sim +(2 \text{ TeV})^2$$

bosinos



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

Higgsinos



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

# 2 Higgs doublets models for supersymmetry

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

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

- ▷ J. F. Gunion et al. *The Higgs hunter's guide*. T. 80. Upton, NY: Brookhaven Nat. Lab., 1989. URL: <https://cds.cern.ch/record/425736>.

# Higgs bosons in the MSSM

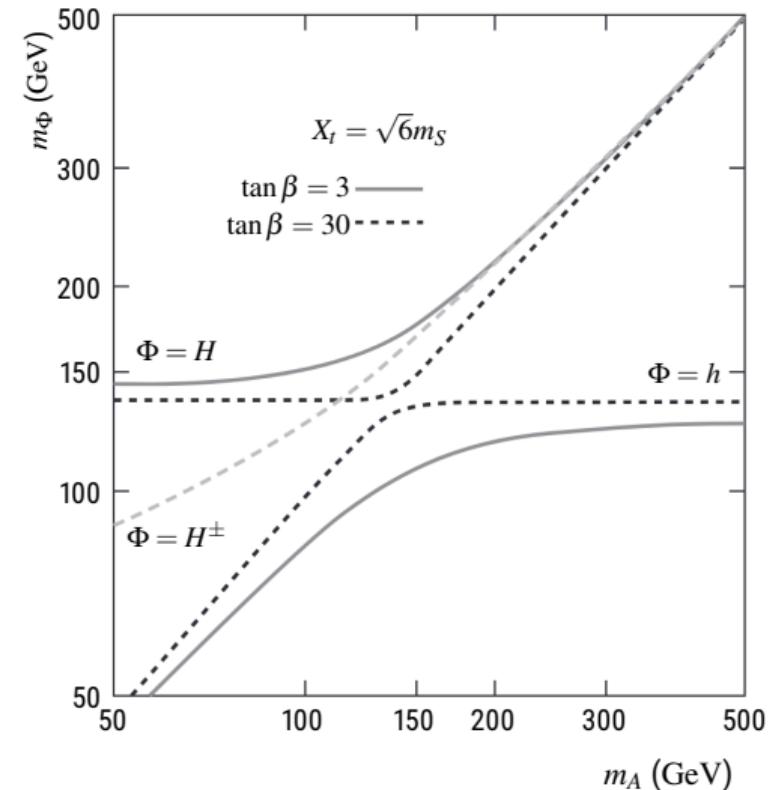
*Minimal Supersymmetric extension of Standard Model*

## 5 Higgs bosons

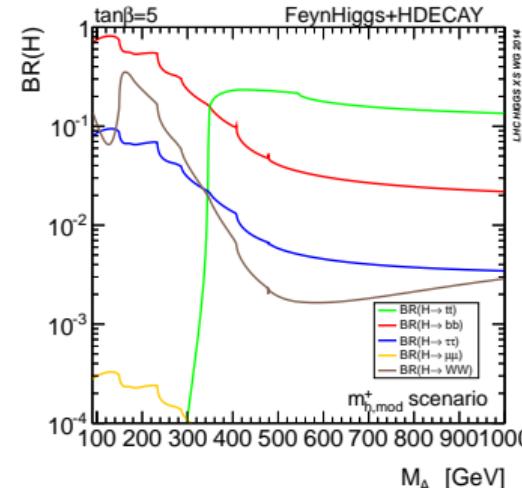
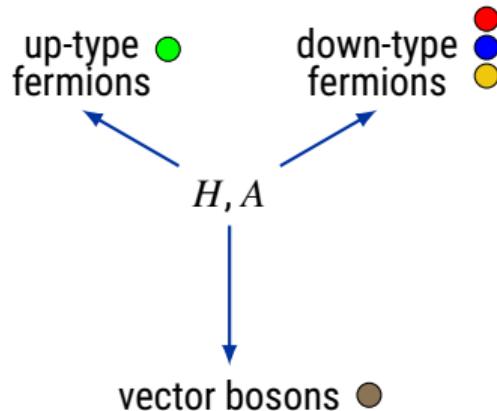
light scalar	$h$	SM or MSSM
heavy scalar	$H$	MSSM or SM
pseudo-scalar	$A$	MSSM
+ charged	$H^+$	MSSM
- charged	$H^-$	MSSM

▷ **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>.

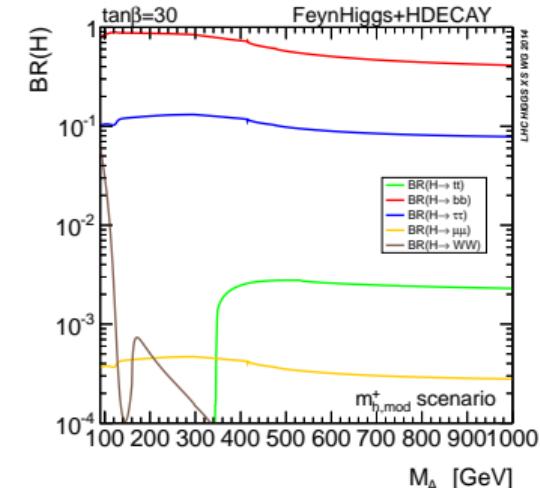
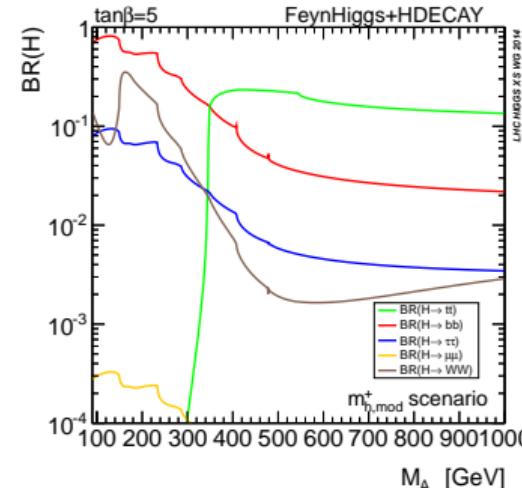
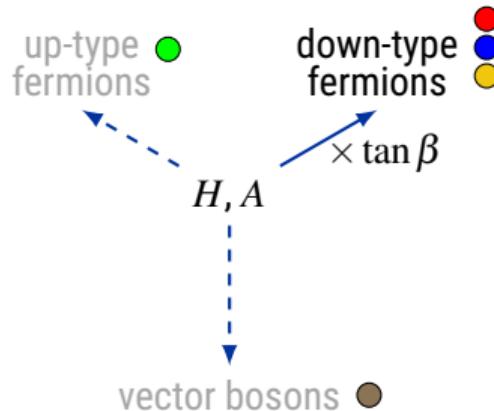


# $H/A \rightarrow \tau\tau?$

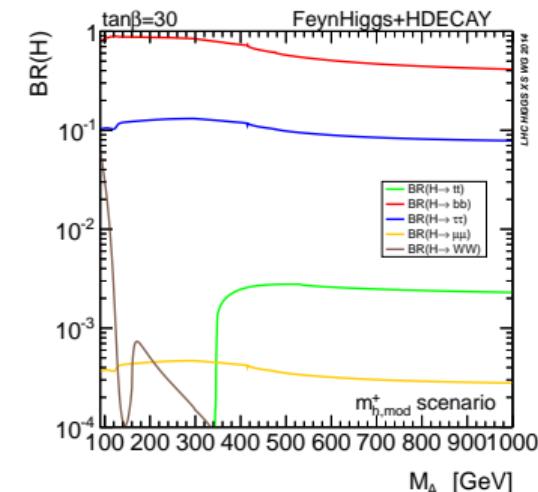
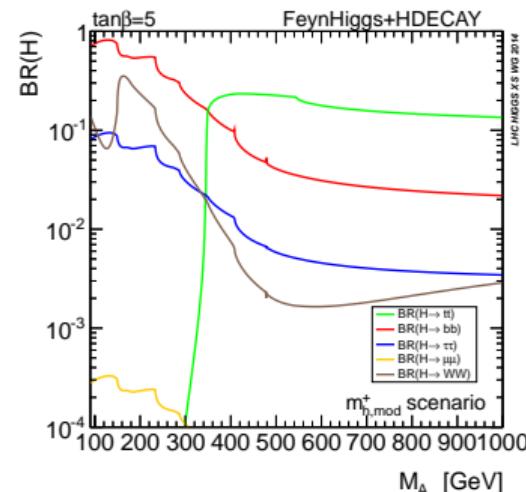
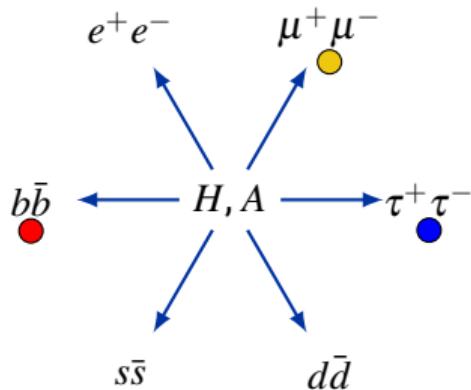


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook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

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

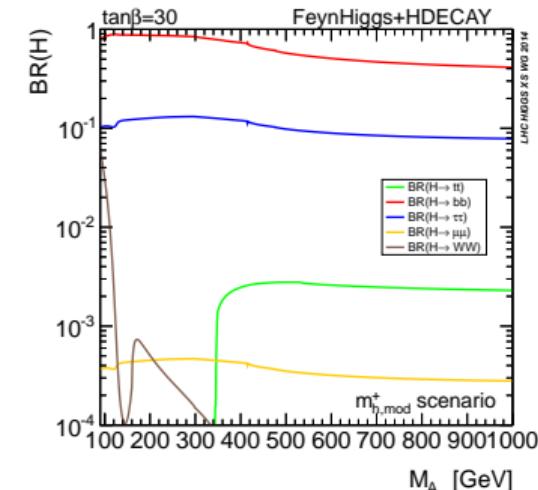
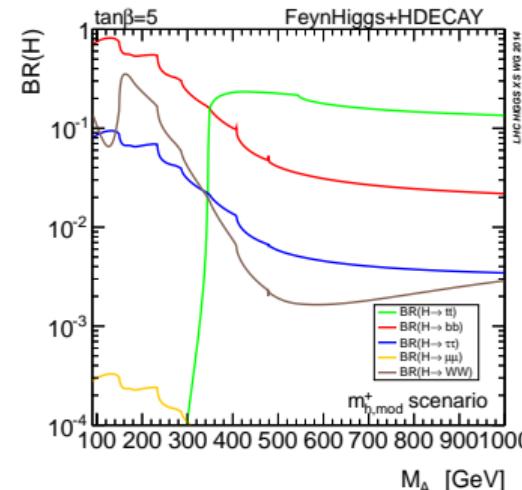
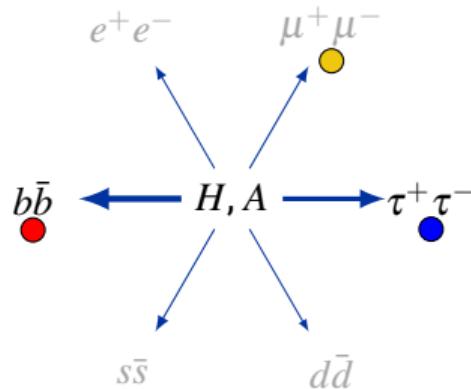


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook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

$H/A \rightarrow \tau\tau?$ 

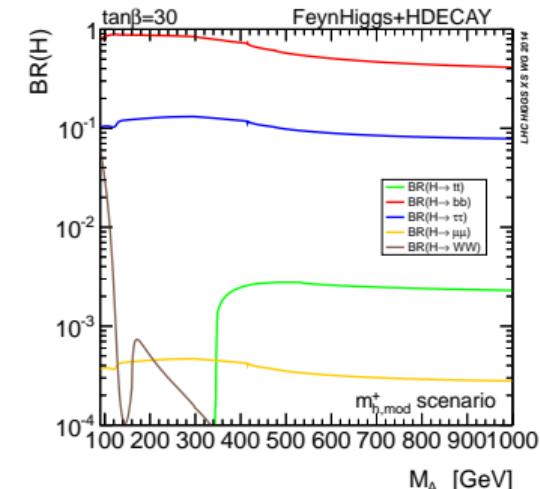
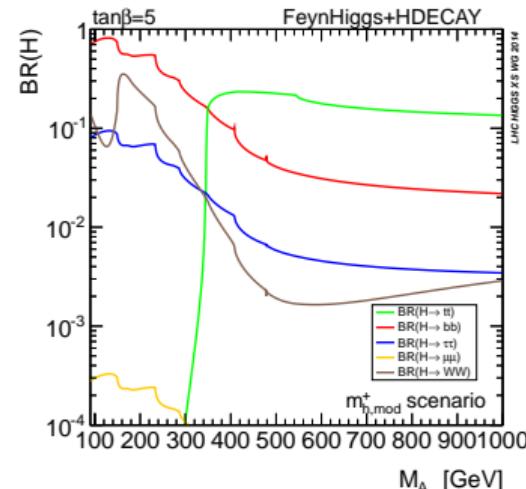
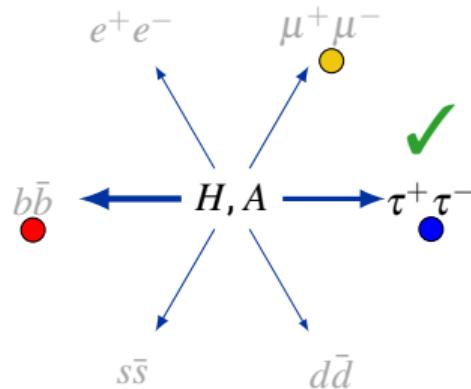
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook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

# $H/A \rightarrow \tau\tau?$ – Higgs couplings and particle masses



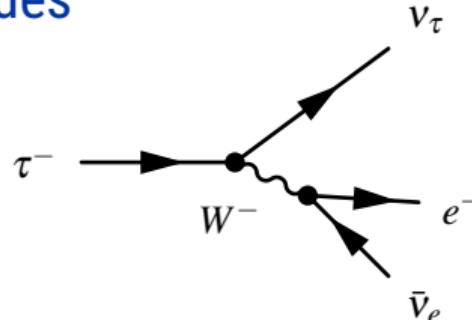
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook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

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

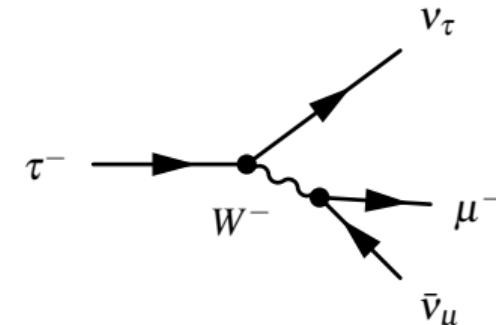
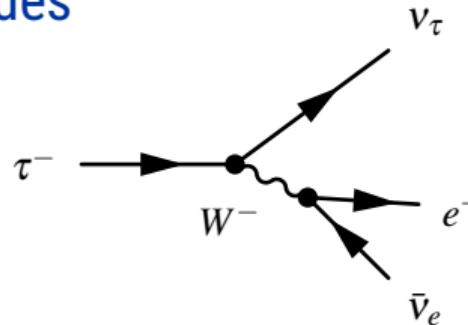


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in  $pp$  collisions at  $\sqrt{s} = 13$  TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).
- ▷ LHC Higgs Cross Section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

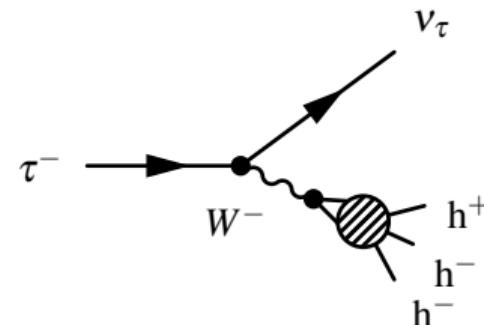
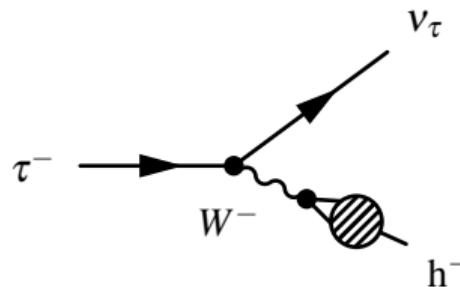
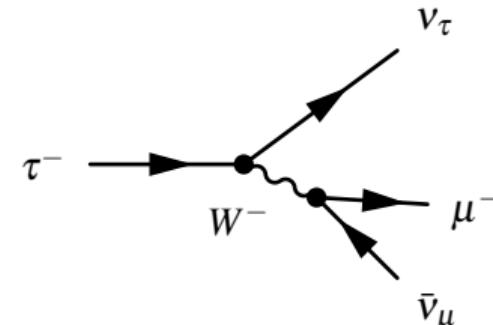
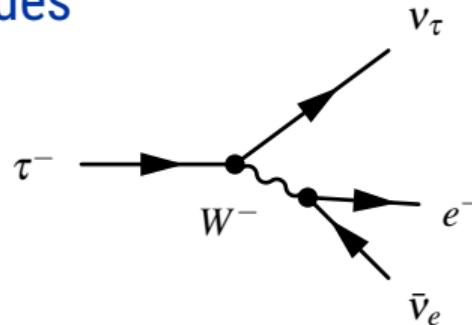
# $\tau$ decay modes

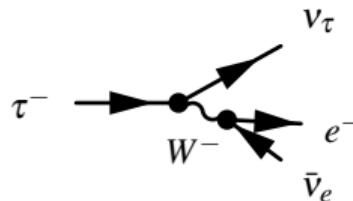
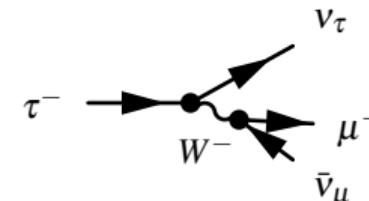
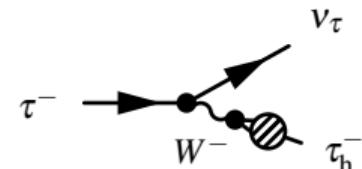


# $\tau$ decay modes



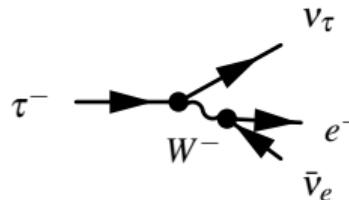
## $\tau$ decay modes



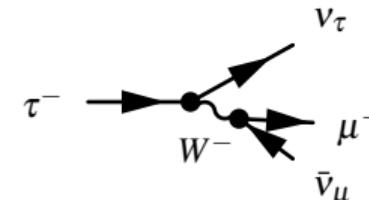
$H/A \rightarrow \tau\tau \rightarrow L_1 L_2$  $\tau \rightarrow e + v_e + \bar{v}_\tau \Rightarrow e$   
17.8 % $\tau \rightarrow \mu + v_\mu + \bar{v}_\tau \Rightarrow \mu$   
17.4 % $\tau \rightarrow \text{hadrons} + v_\tau \Rightarrow \tau_h$   
64.8 %

$$H/A \rightarrow \tau\tau \rightarrow L_1 L_2$$

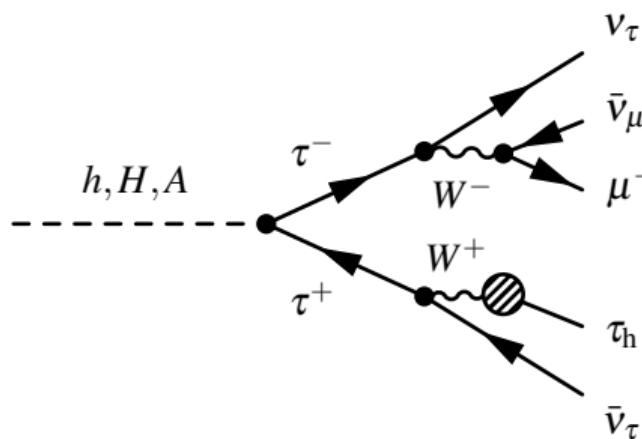
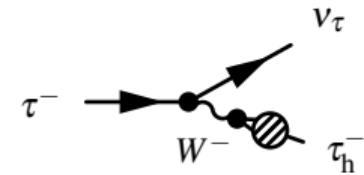
$$\tau \rightarrow e + v_e + \bar{v}_\tau \Rightarrow e \\ 17.8\%$$



$$\tau \rightarrow \mu + v_\mu + \bar{v}_\tau \Rightarrow \mu \\ 17.4\%$$



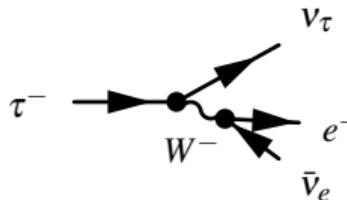
$$\tau \rightarrow \text{hadrons} + v_\tau \Rightarrow \tau_h \\ 64.8\%$$



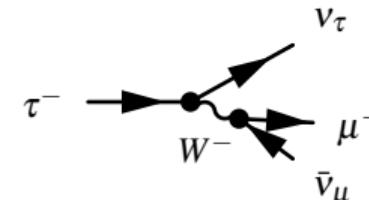
▷ Particle Data Group. "Review of Particle Physics". *Progress of Theoretical and Experimental Physics* 8 (Aug. 2020). DOI: 10.1093/ptep/ptaa104.

$$H/A \rightarrow \tau\tau \rightarrow L_1 L_2$$

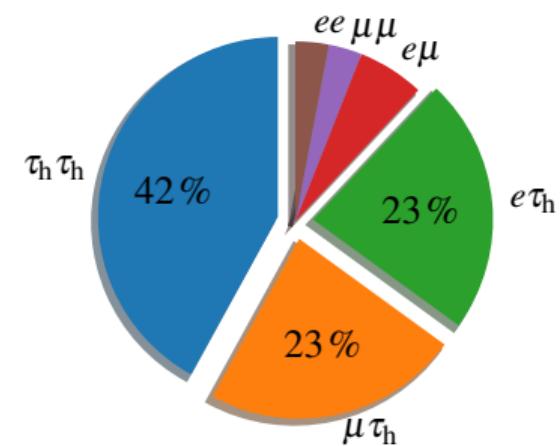
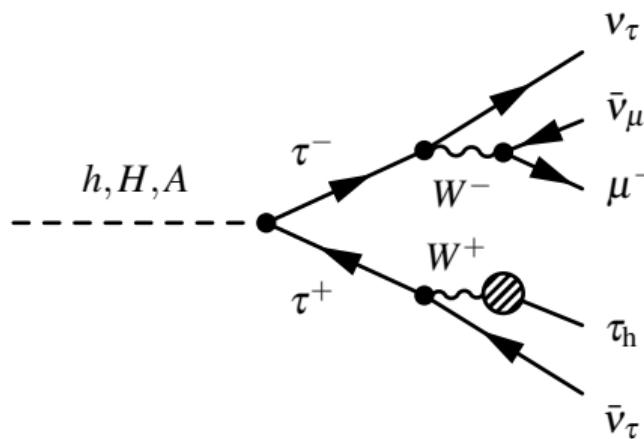
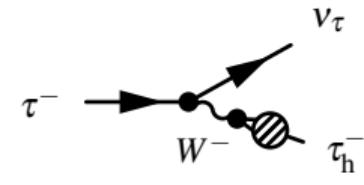
$$\tau \rightarrow e + v_e + \bar{v}_\tau \Rightarrow e \\ 17.8\%$$



$$\tau \rightarrow \mu + v_\mu + \bar{v}_\tau \Rightarrow \mu \\ 17.4\%$$



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



▷ Particle Data Group. "Review of Particle Physics". *Progress of Theoretical and Experimental Physics* 8 (Aug. 2020). DOI: 10.1093/ptep/ptaa104.

## 1 Phenomenology

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

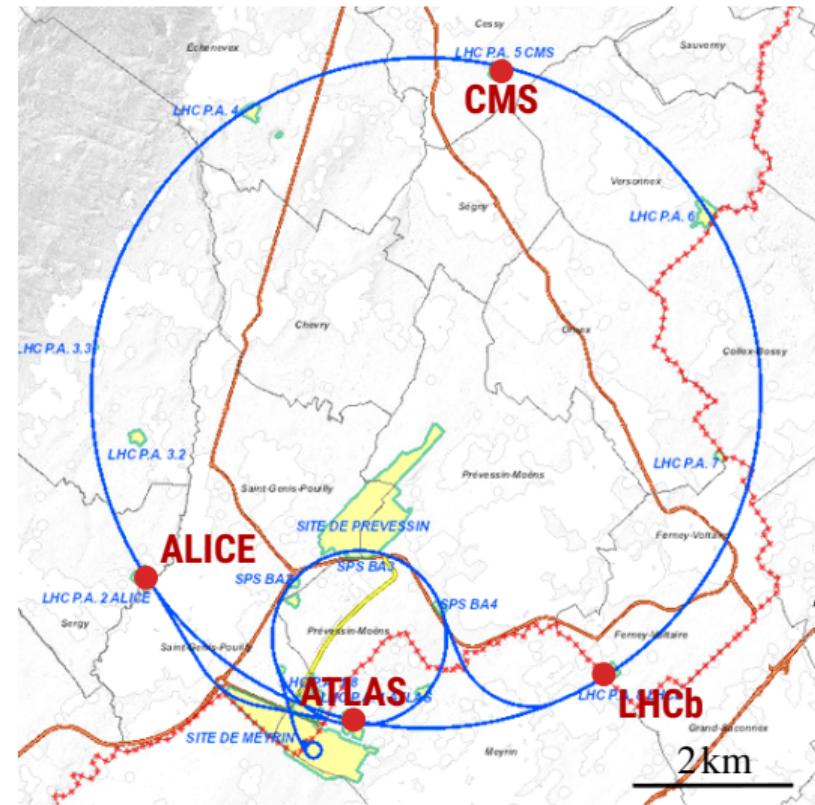
## 4 Machine learning

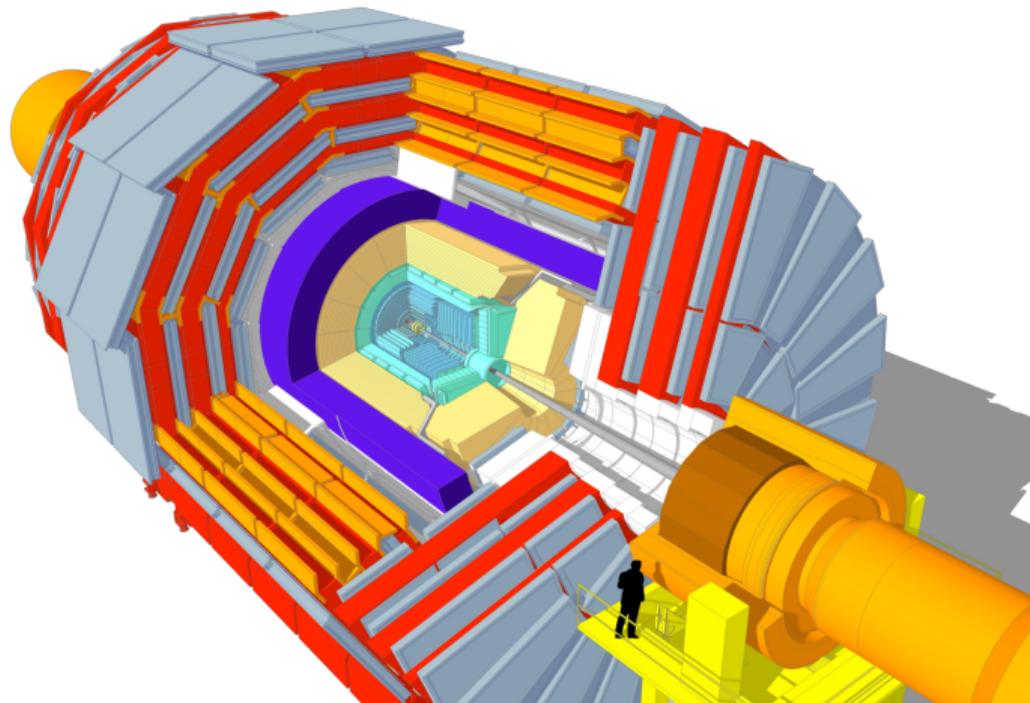
# Principle

$$E = mc^2$$

mass (new particles) from the collision energy

# CERN LHC

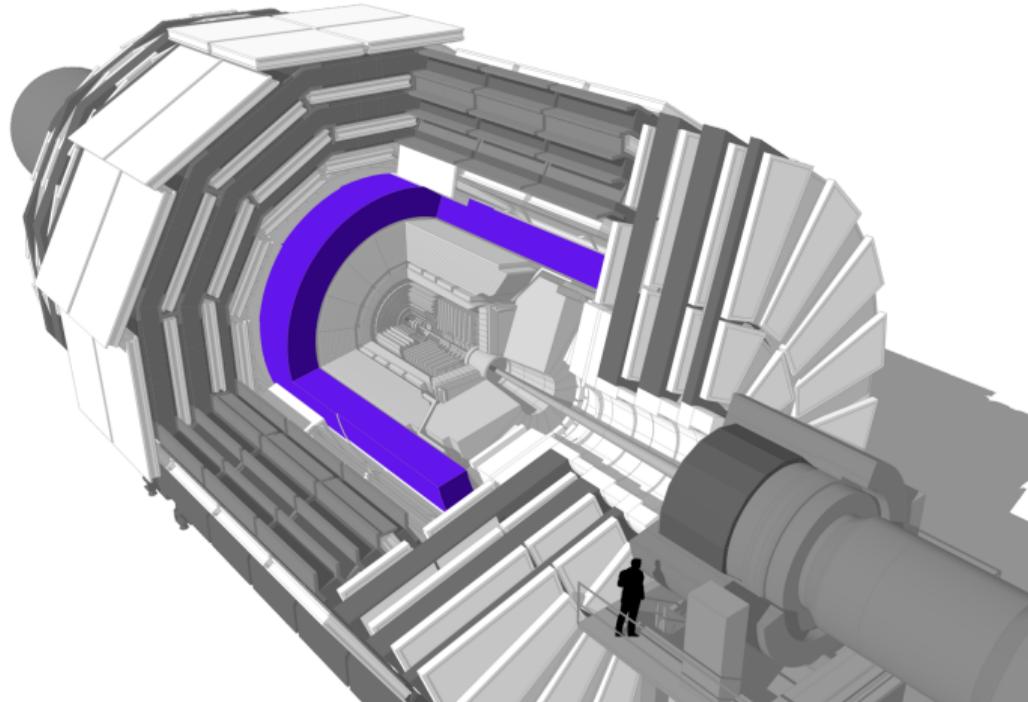




## CMS detector

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

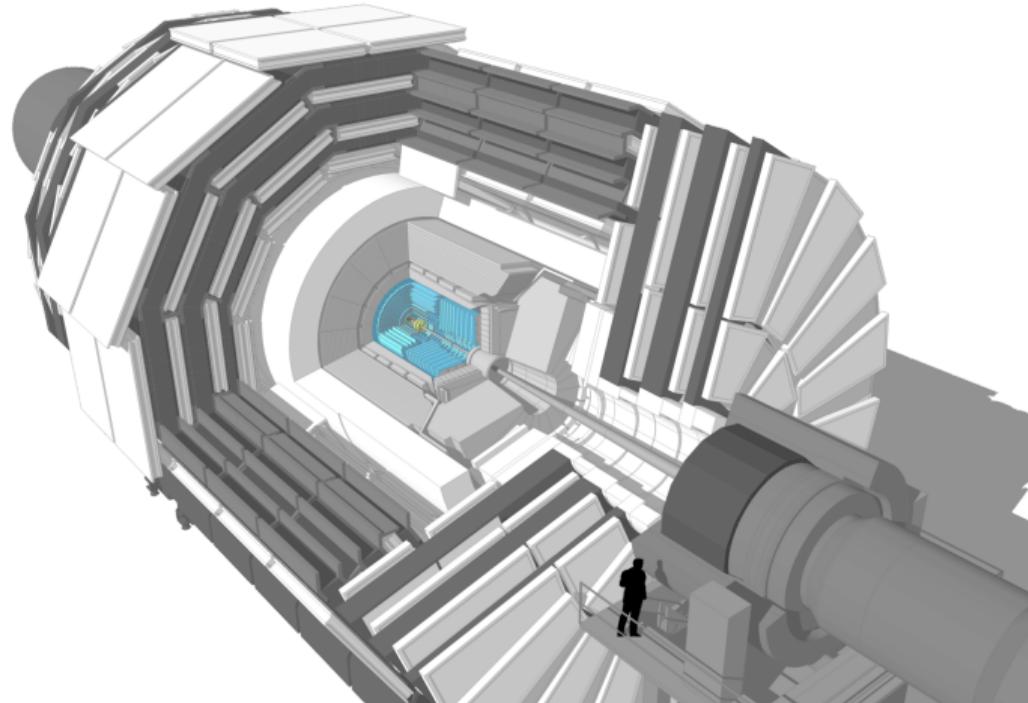
⇒ How to see the particles?



## Solenoid

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

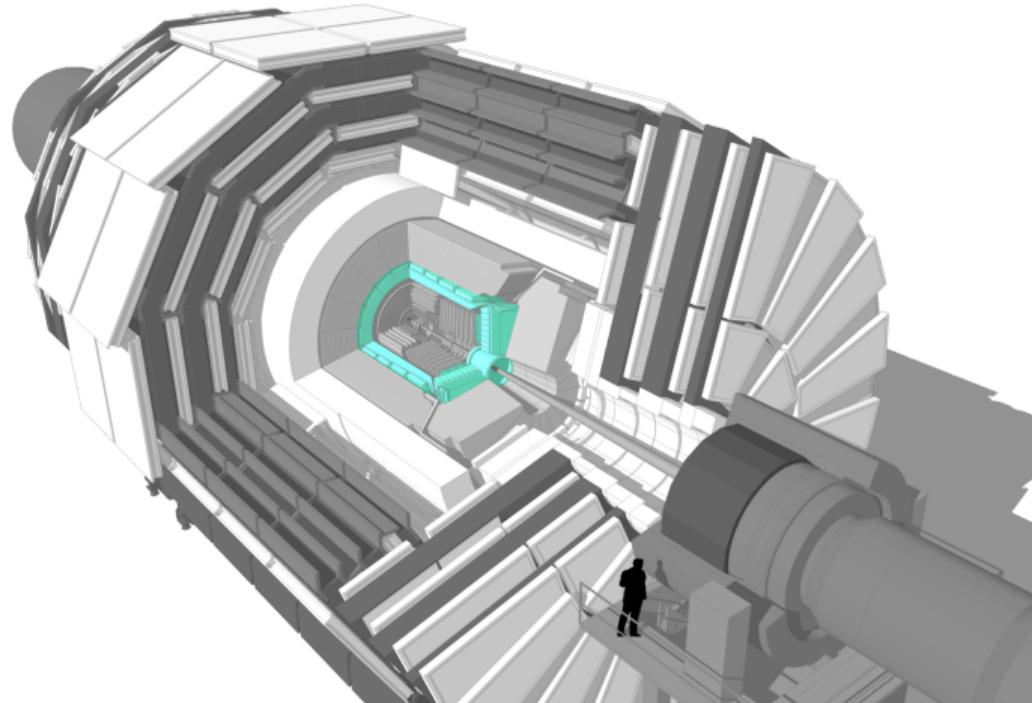
⇒ Bends charged particles trajectories  
in the transverse plane



## 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

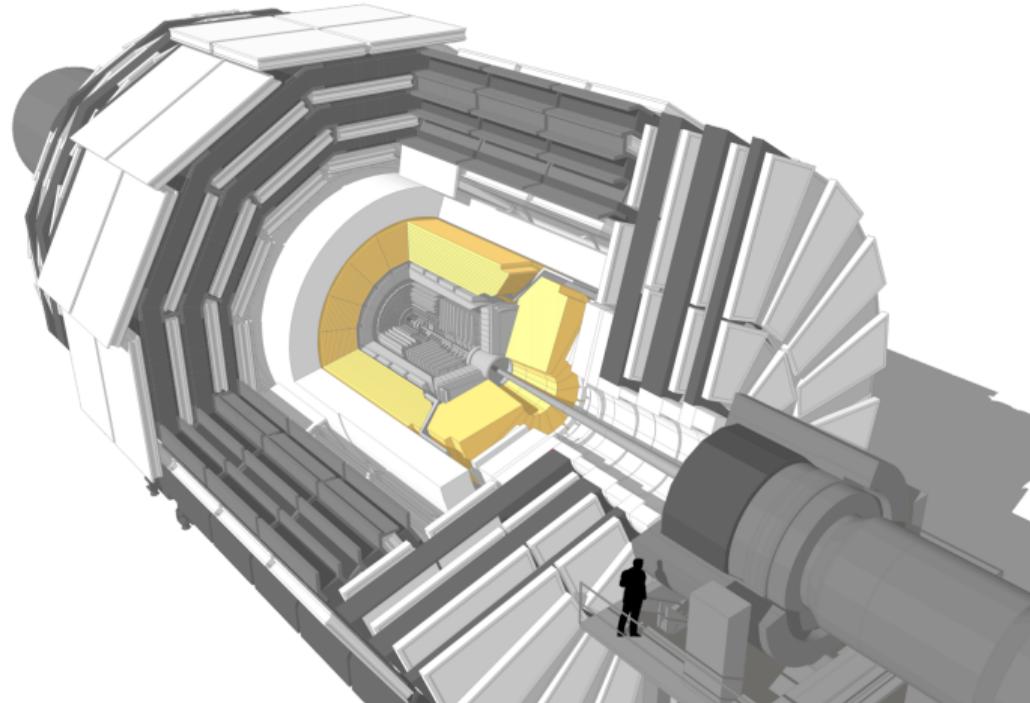
⇒ Charged particles leave hits when going through



## Electromagnetic CALorimeter

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

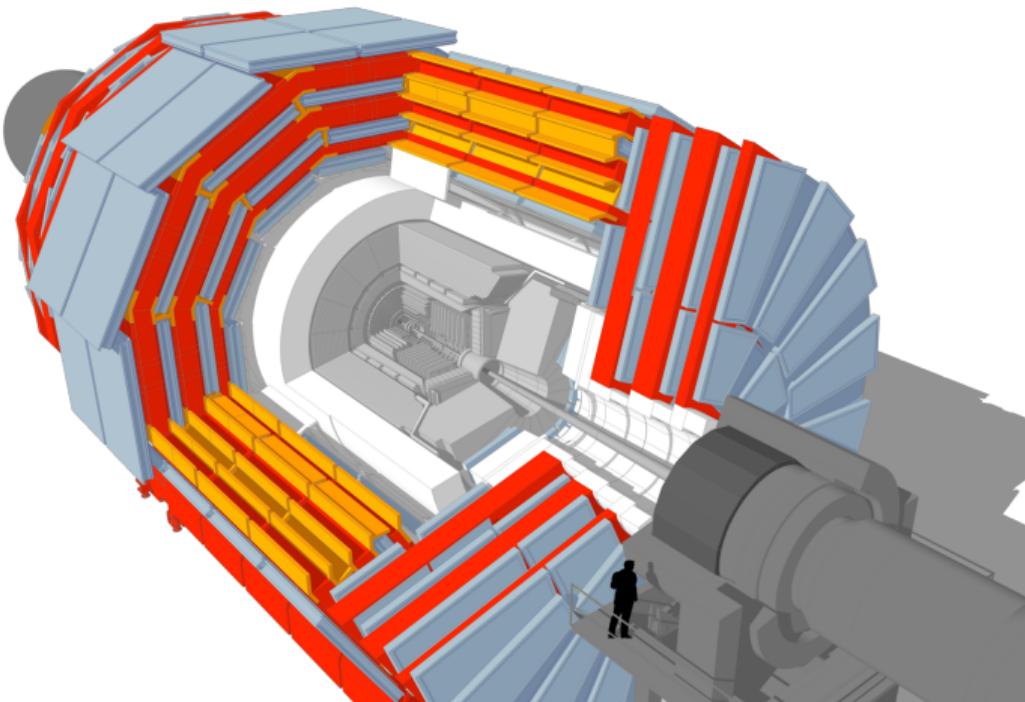
⇒ Electrons and photons are stopped,  
energy deposits



## Hadronic CALorimeter

- Brass + plastic scintillator,  
~ 7000 channels

⇒ Hadrons are stopped, energy deposits



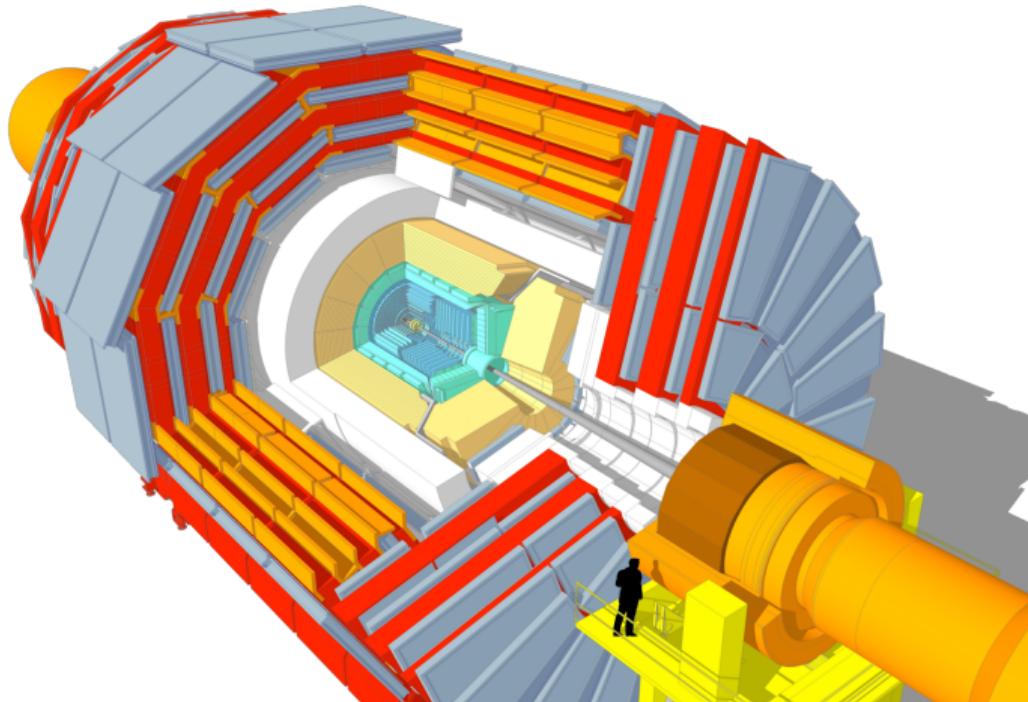
## Steel return yoke (red)

- 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)

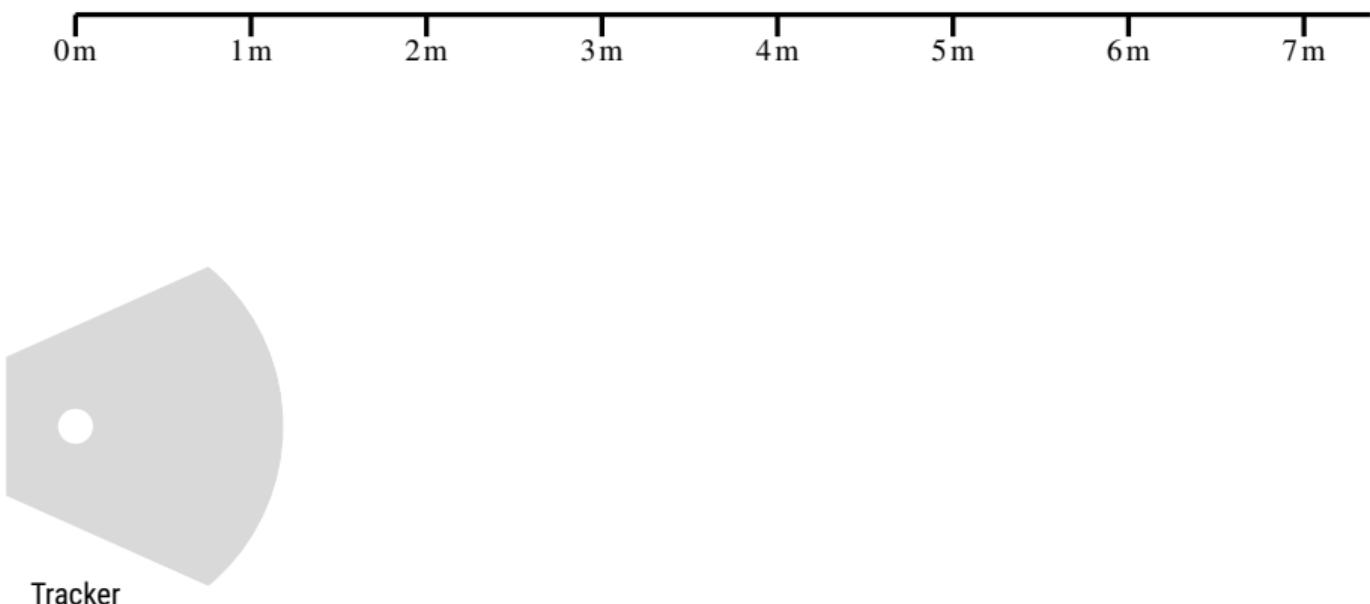


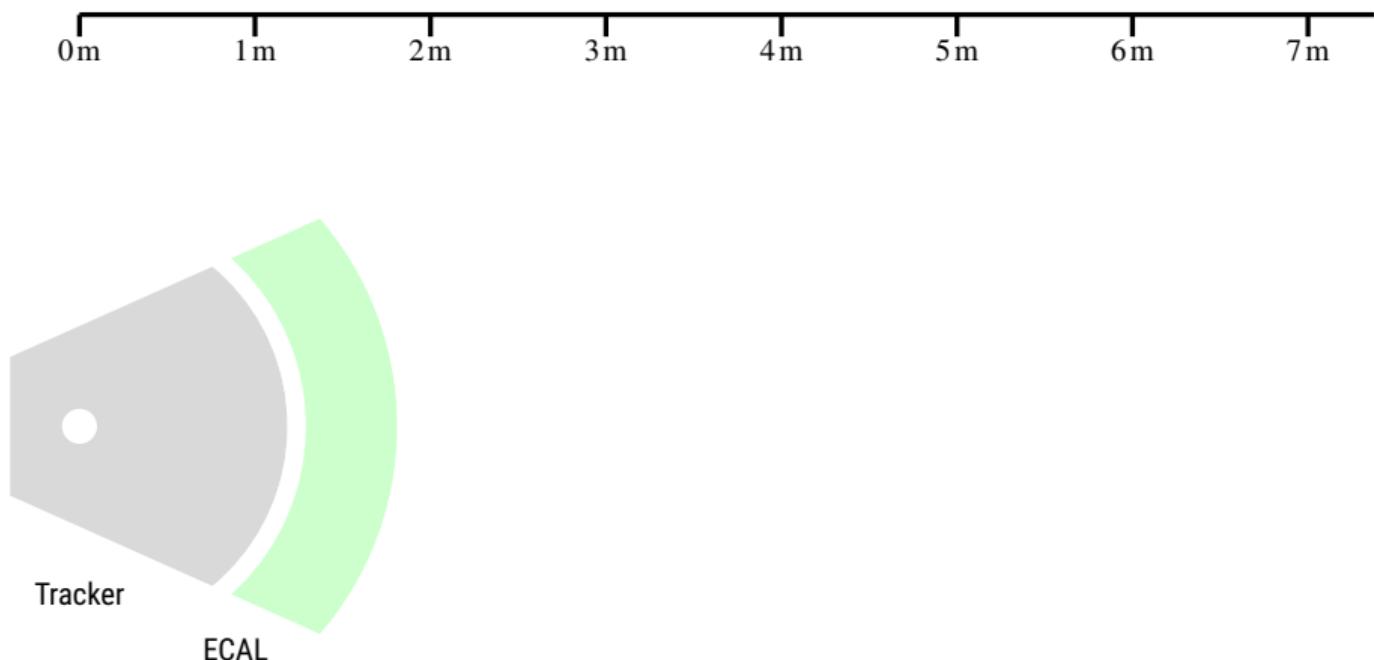
## Sensitive parts of CMS

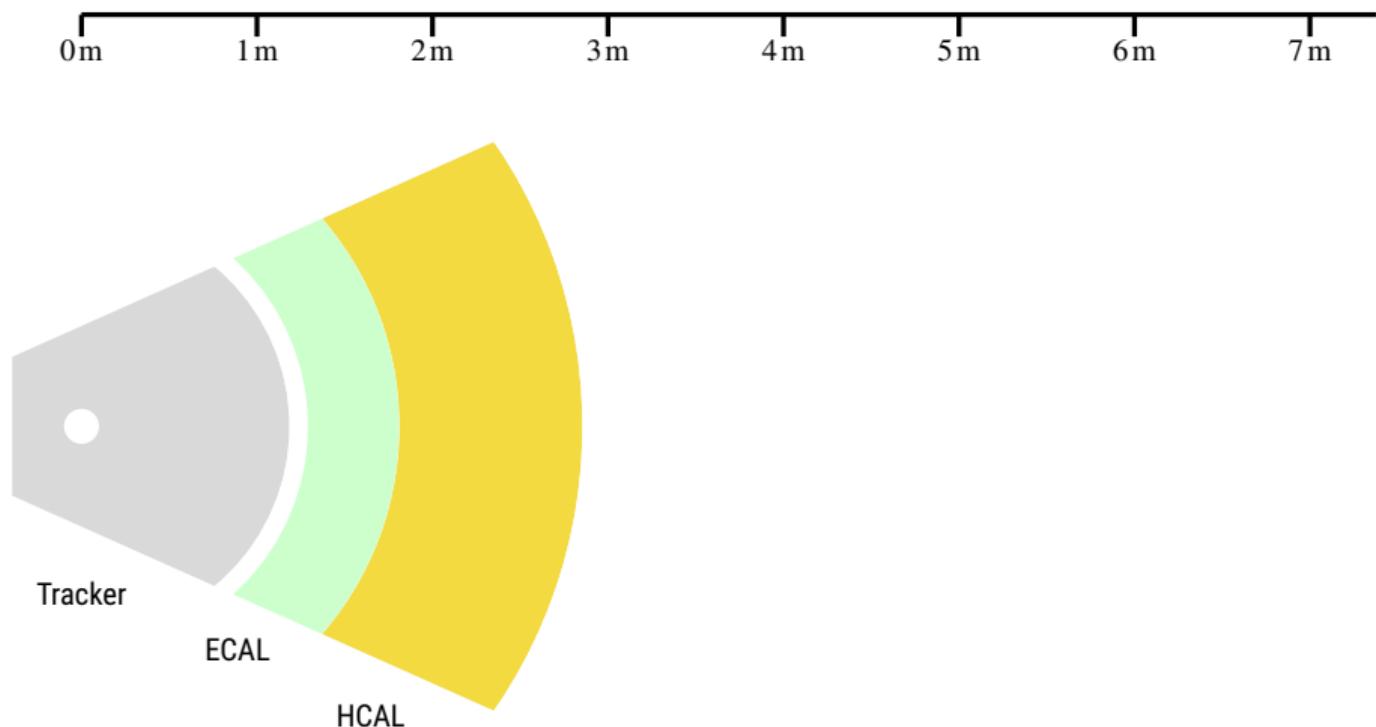
Combine sub-detectors signals to determine which particles were there!

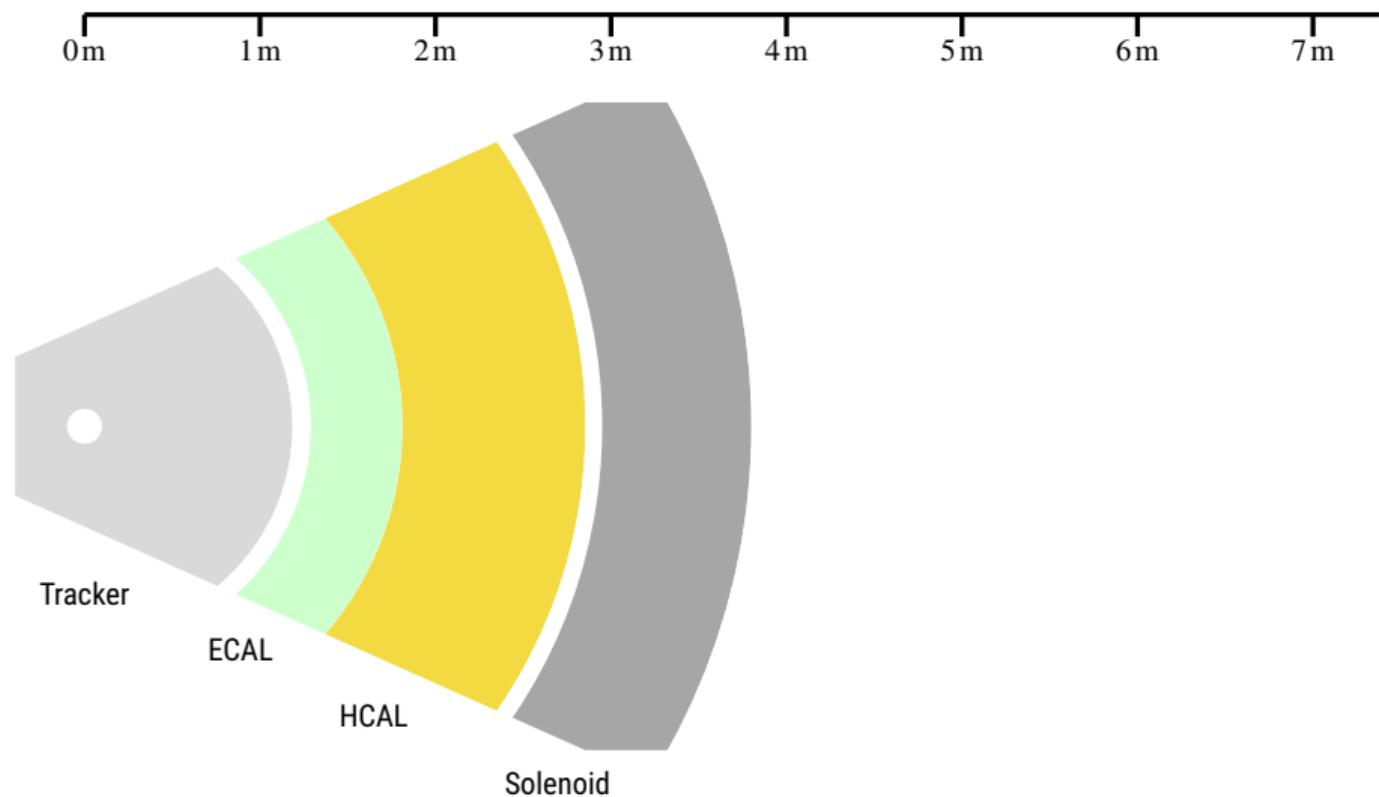


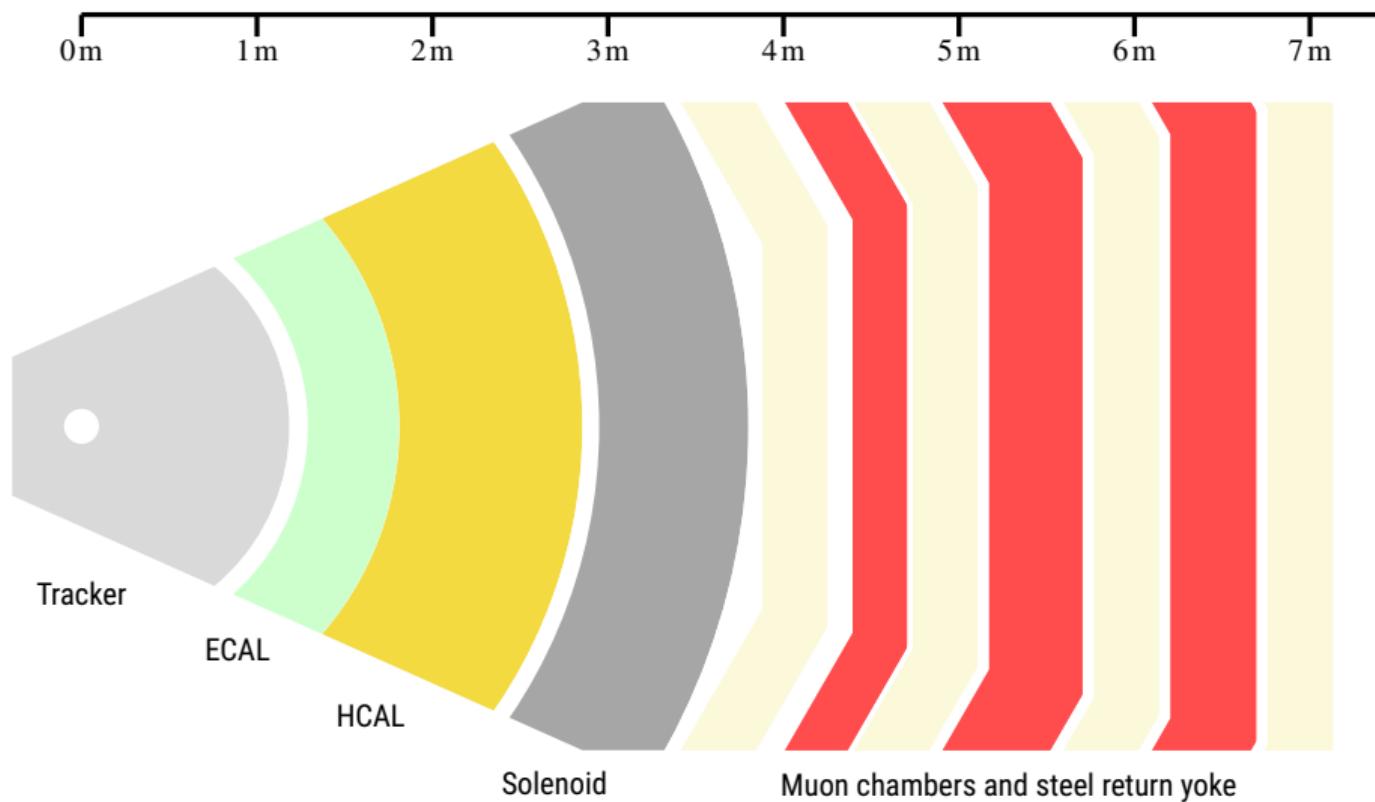


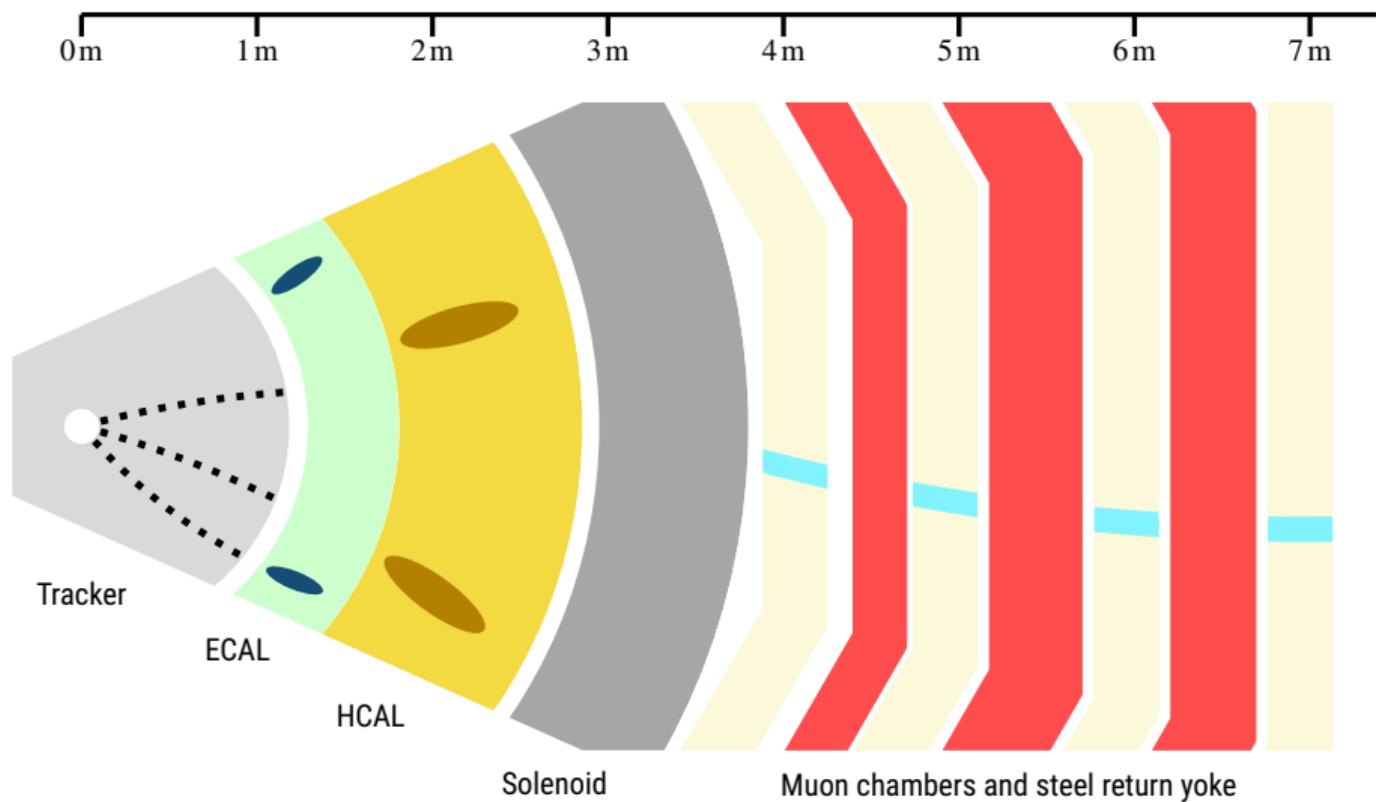


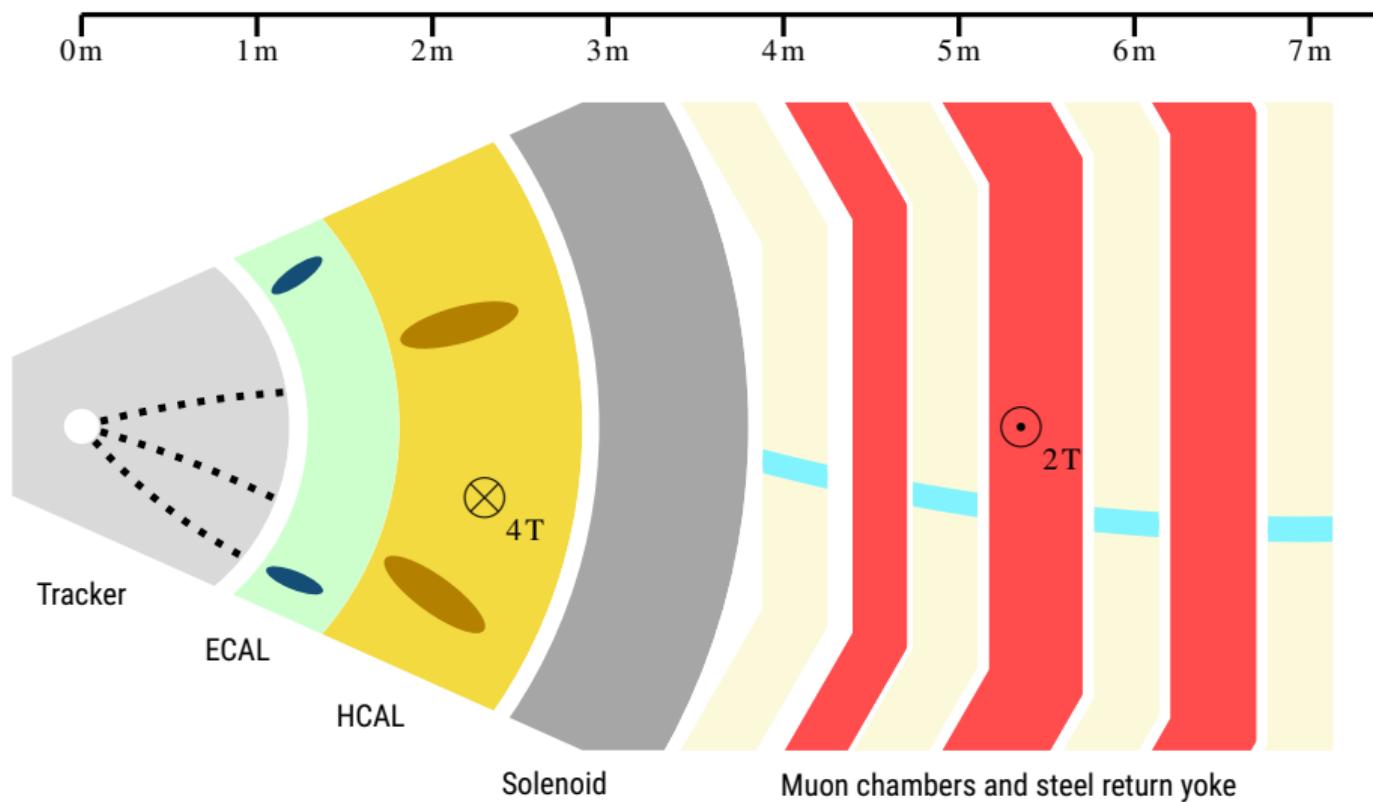


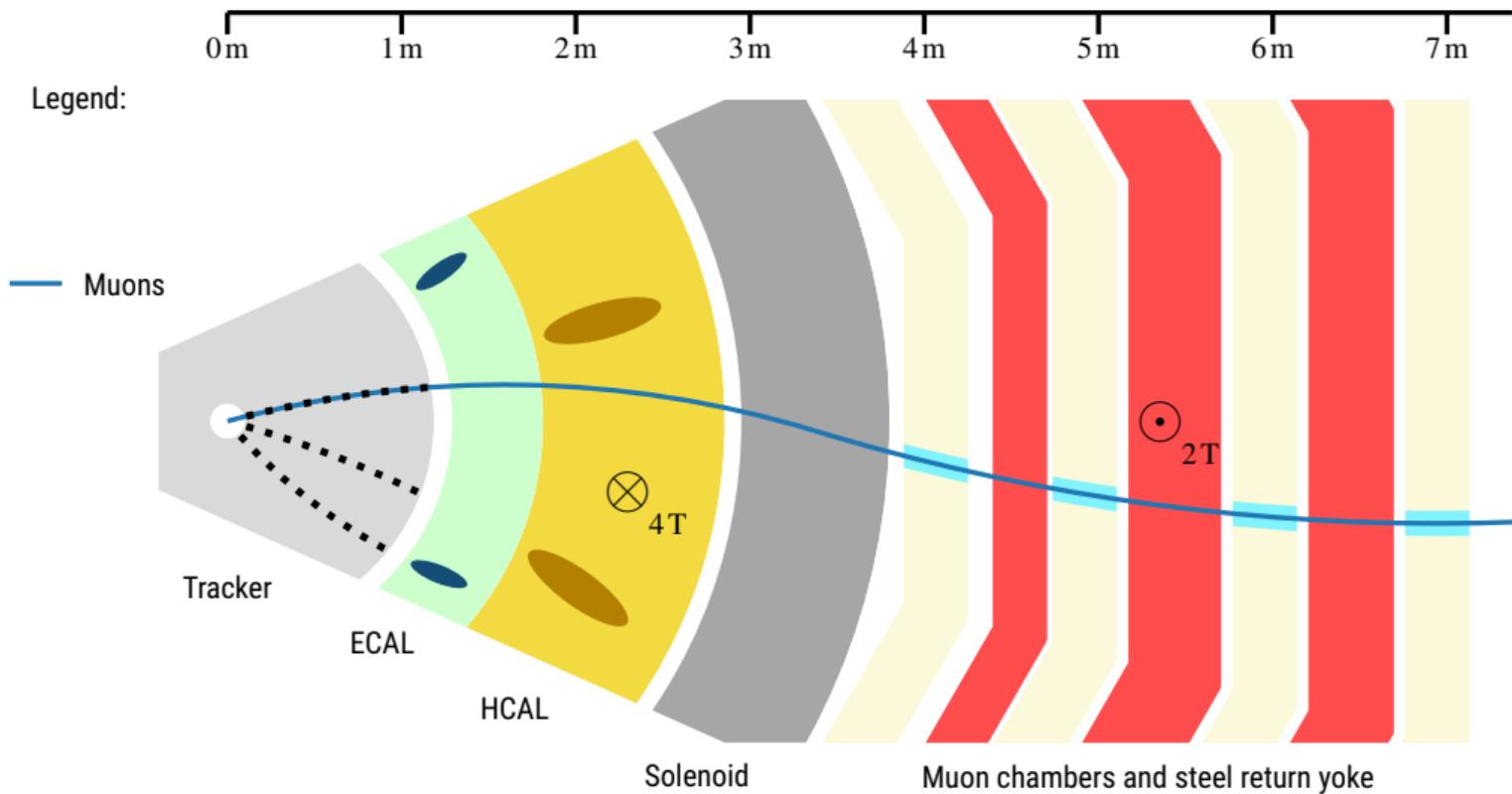






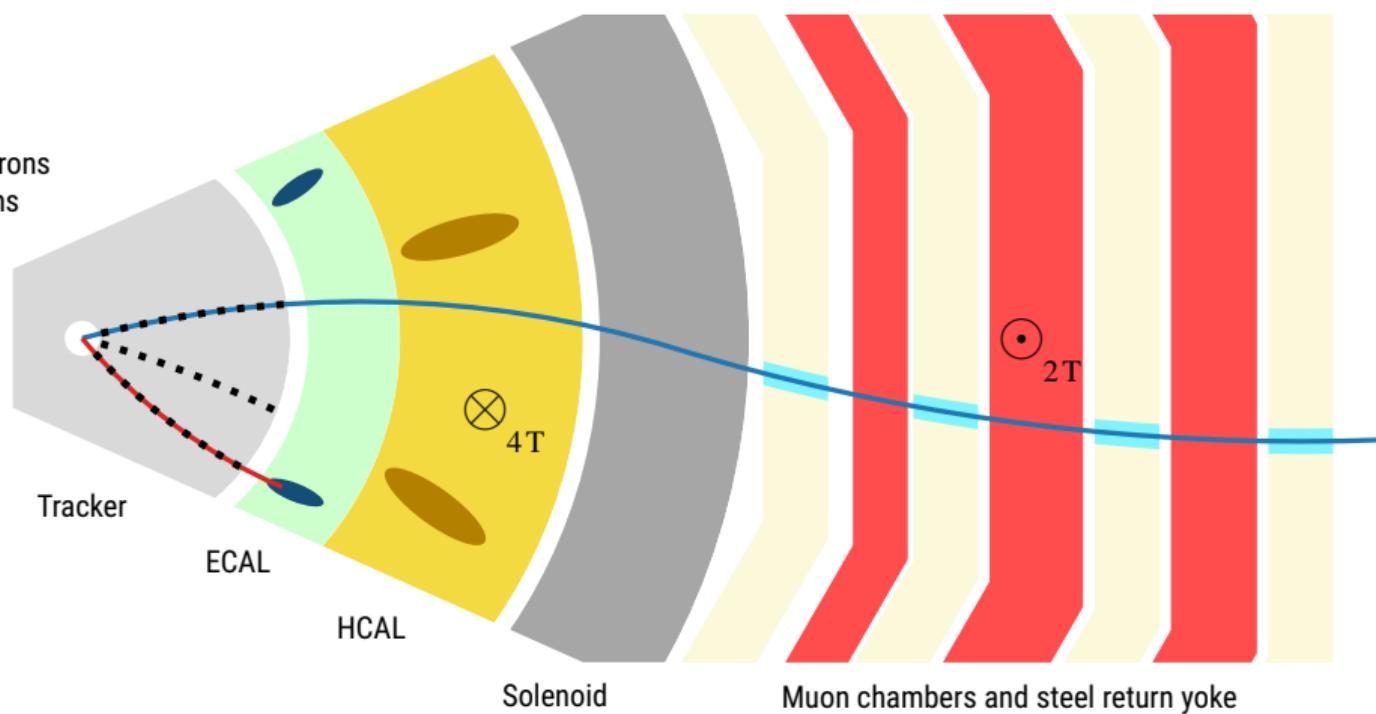


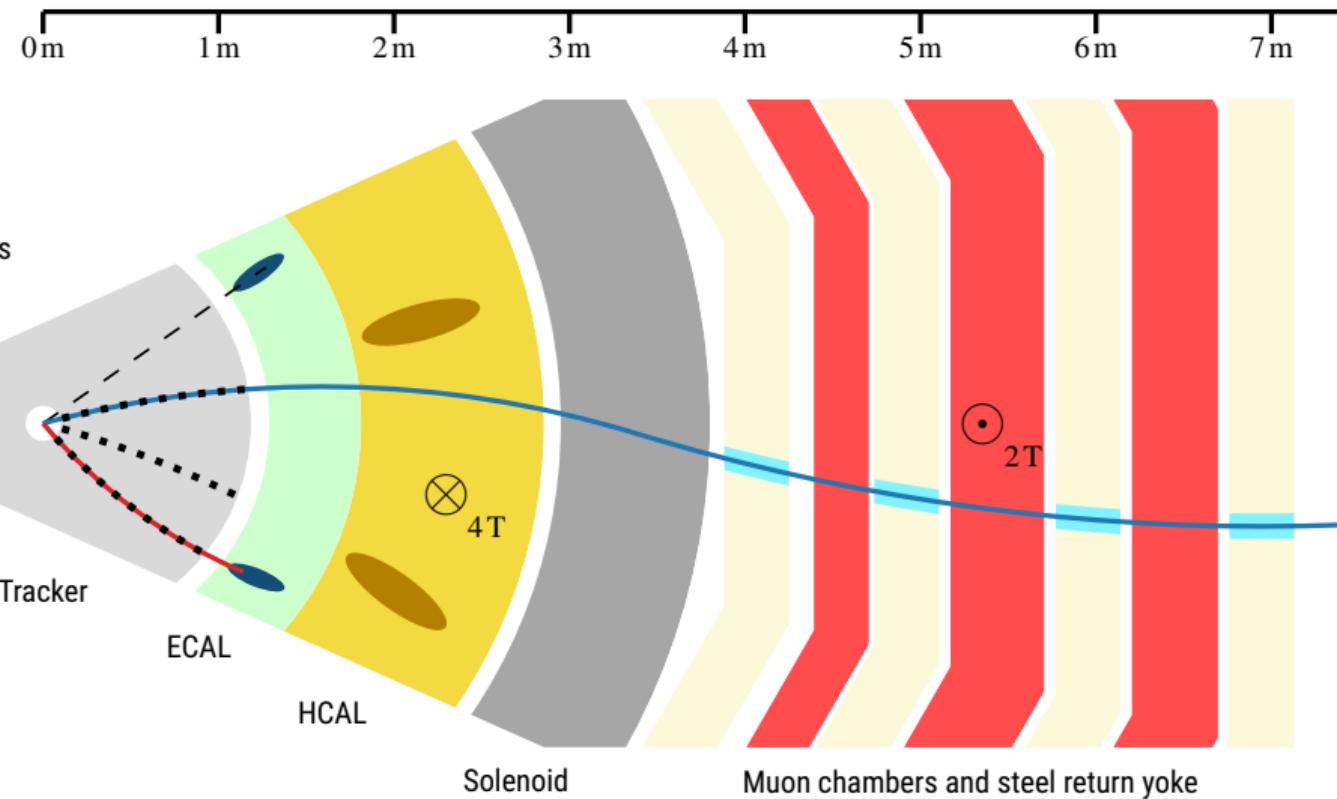


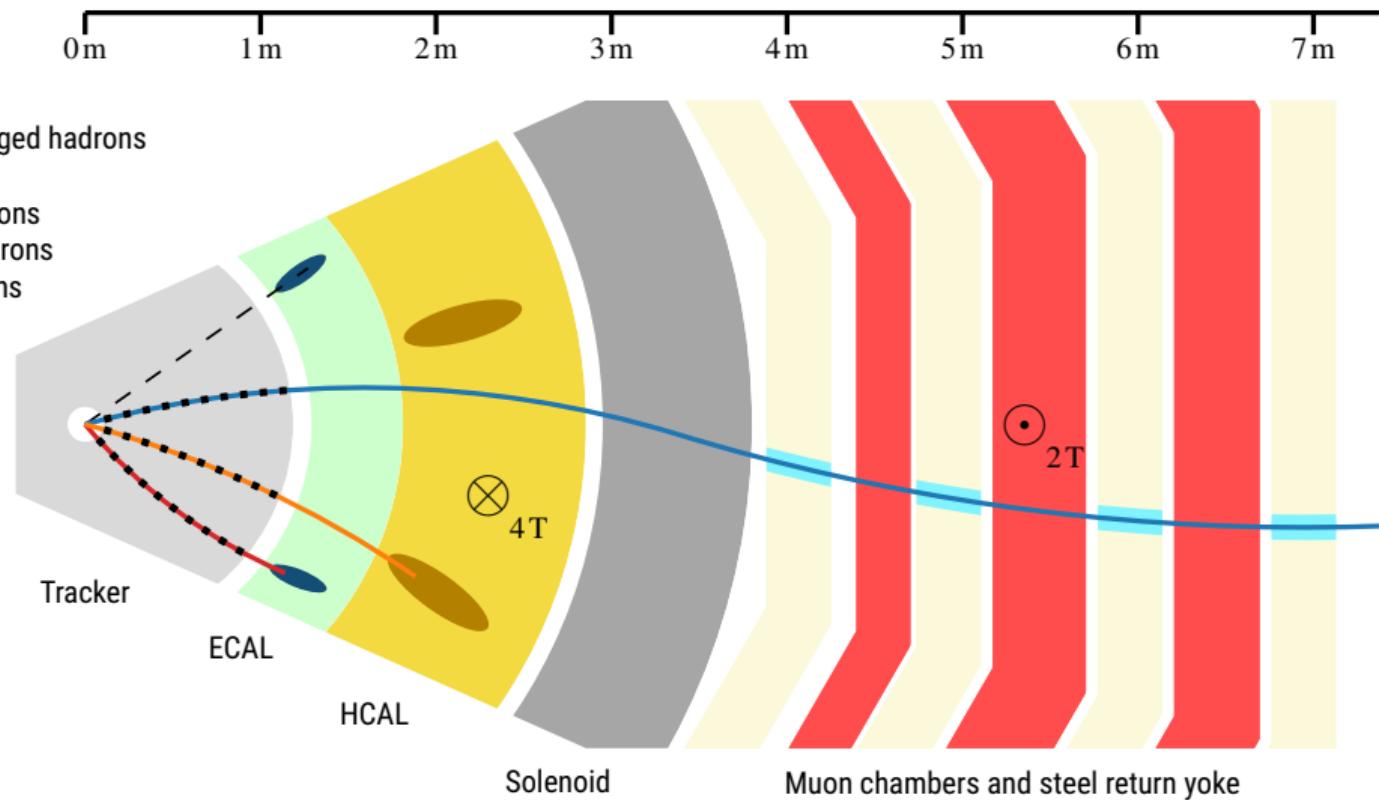


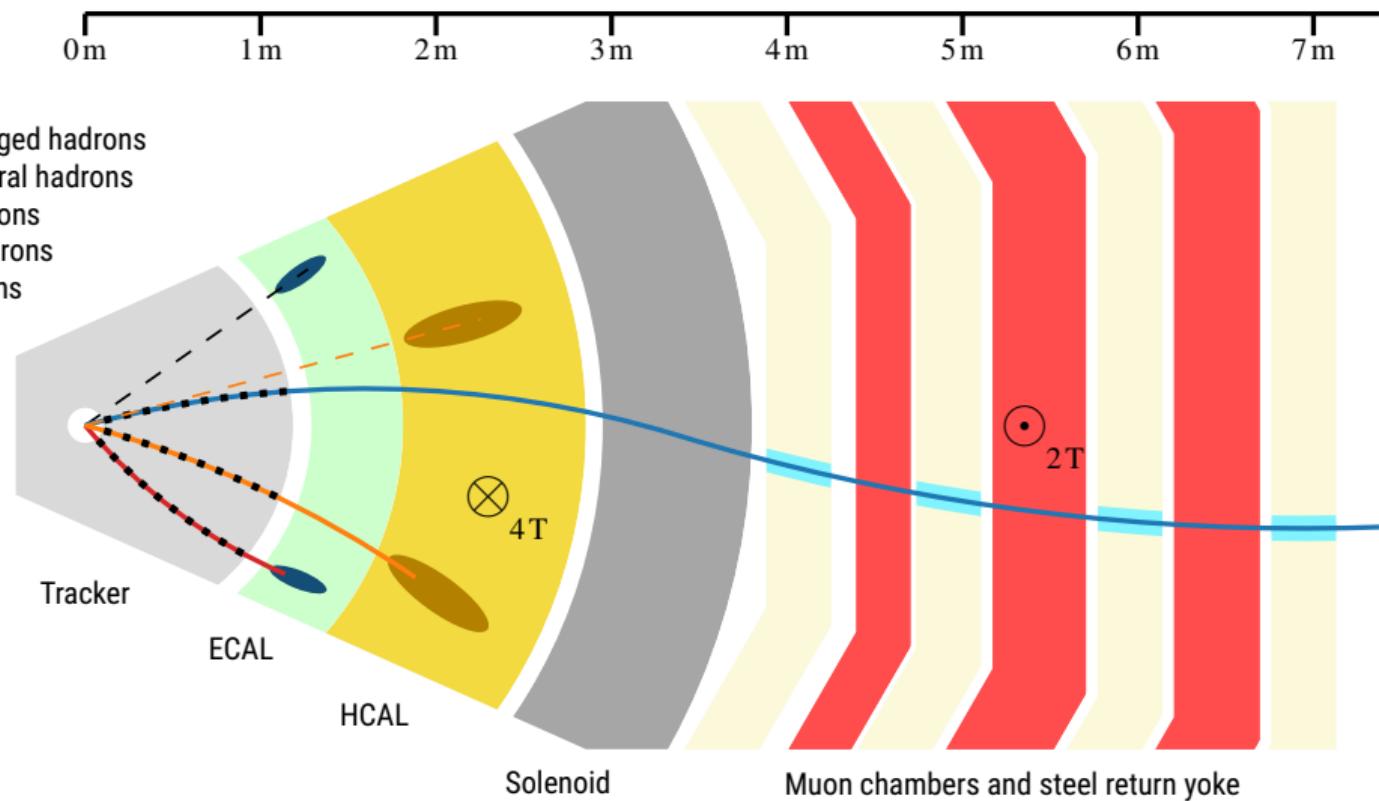
**Legend:**

- Electrons
- Muons



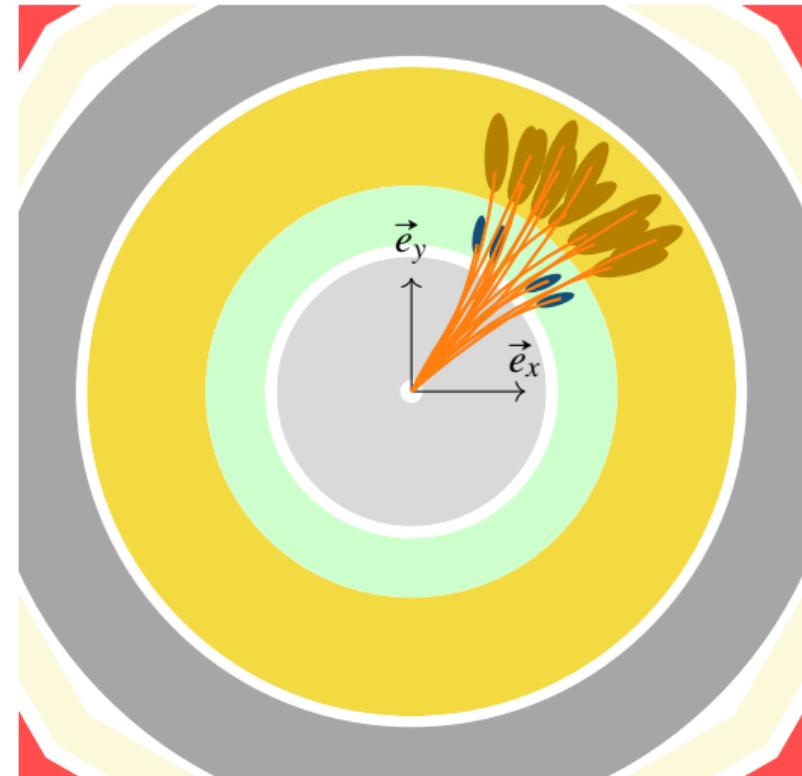
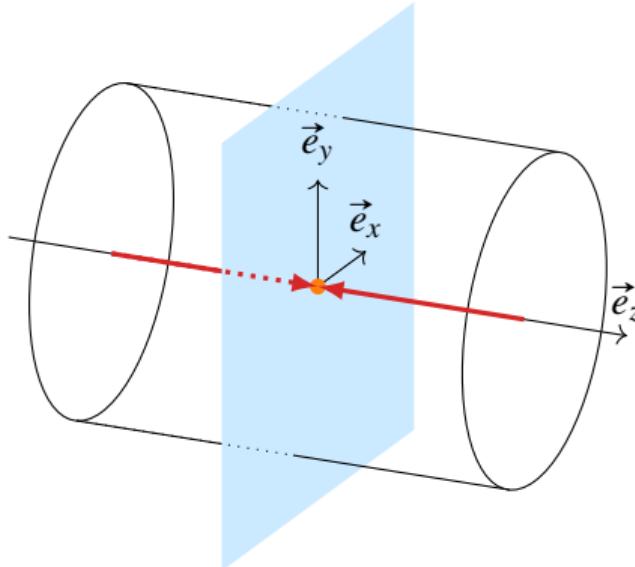






# Neutrinos and missing transverse energy (MET)

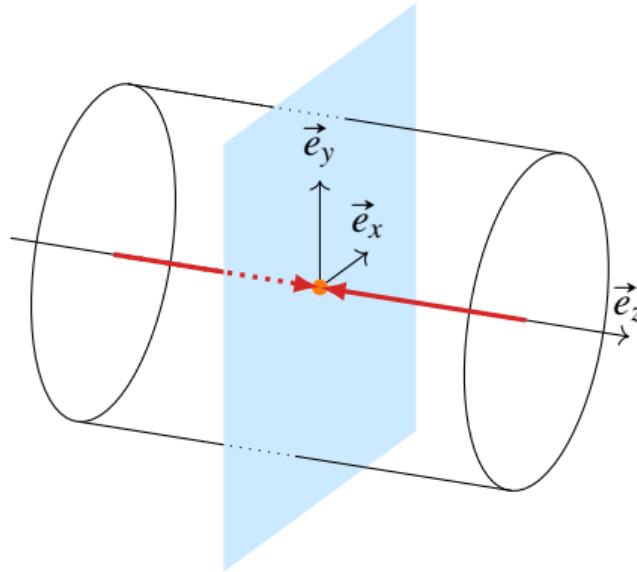
$(\vec{e}_x, \vec{e}_y)$  = transverse plane ( $\eta = 0$ )



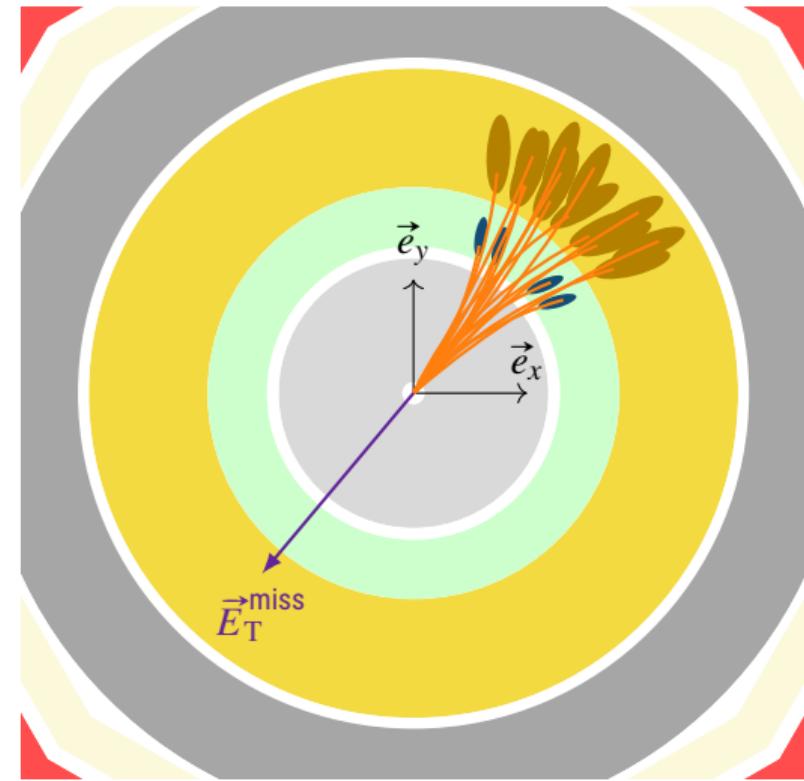
Conserved momentum:  $\sum_{\text{initial state}} \vec{p}_{\text{T}} = \sum_{\text{final state}} \vec{p}_{\text{T}} = \vec{0}$

# Neutrinos and missing transverse energy (MET)

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

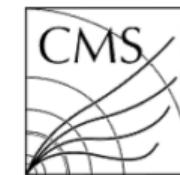
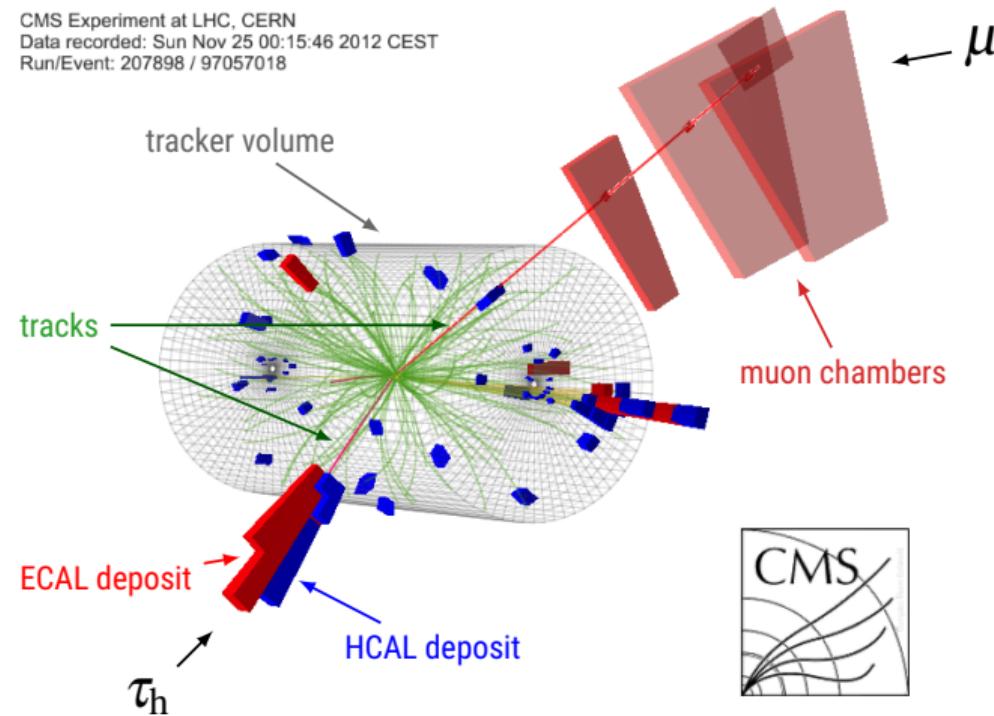


$$\sum_{\text{final state}} \vec{p}_{\text{T}} = \vec{0} \Rightarrow \vec{E}_{\text{T}}^{\text{miss}} = - \sum_{\text{visible particles}} \vec{p}_{\text{T}}$$



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

CMS Experiment at LHC, CERN  
Data recorded: Sun Nov 25 00:15:46 2012 CEST  
Run/Event: 207898 / 97057018



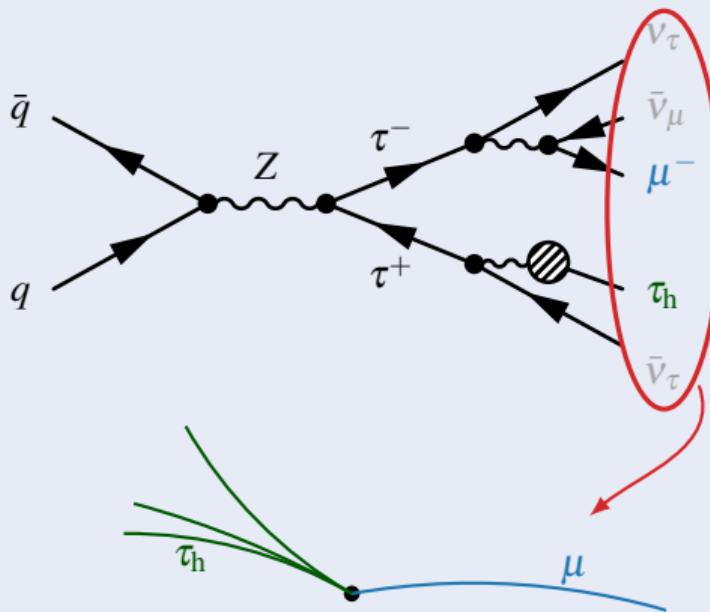
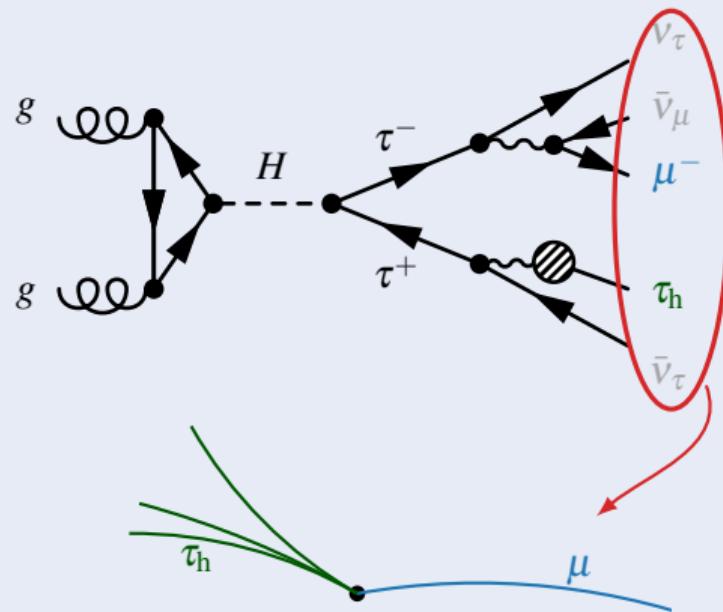
## 1 Phenomenology

## 2 Experimental device

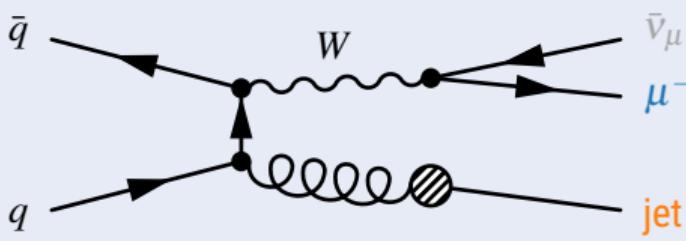
3  $H/A \rightarrow \tau\tau$  analysis

## 4 Machine learning

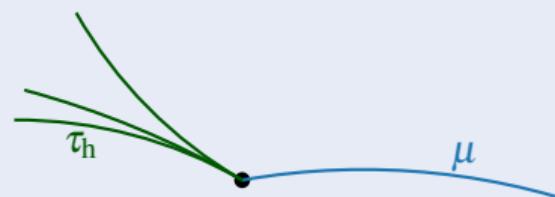
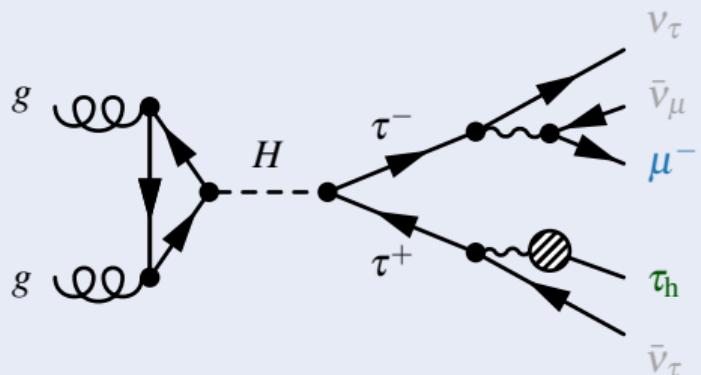
# Backgrounds?

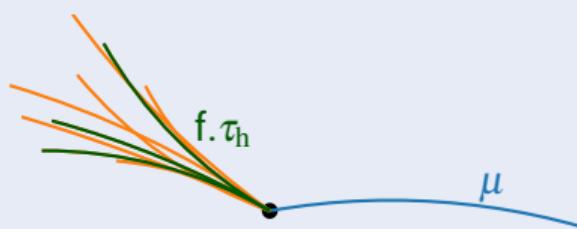
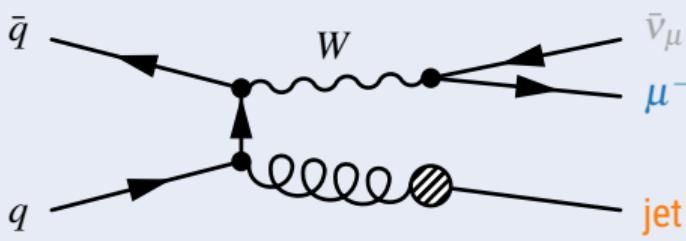
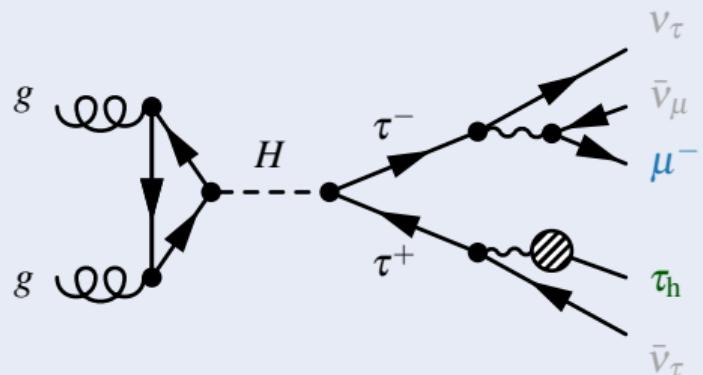
Drell-Yan (especially  $Z \rightarrow \tau\tau$ ) $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

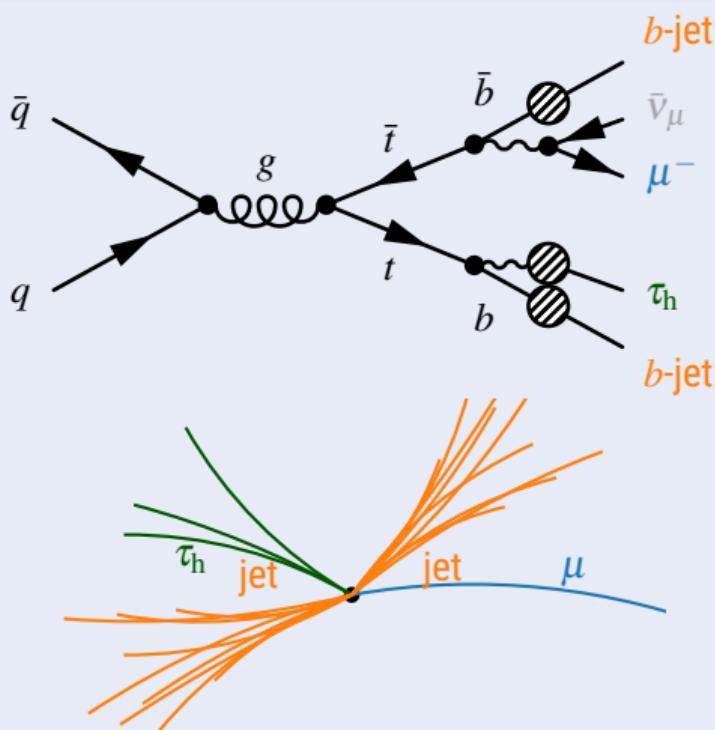
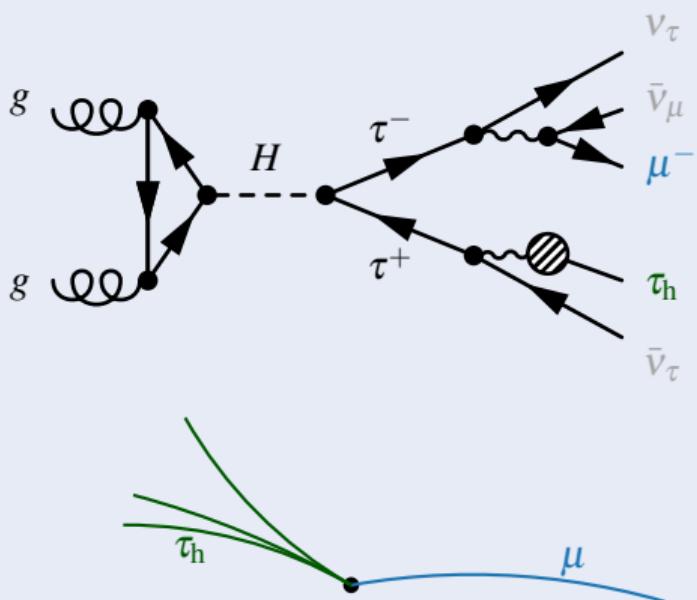
## $W + \text{jets}$

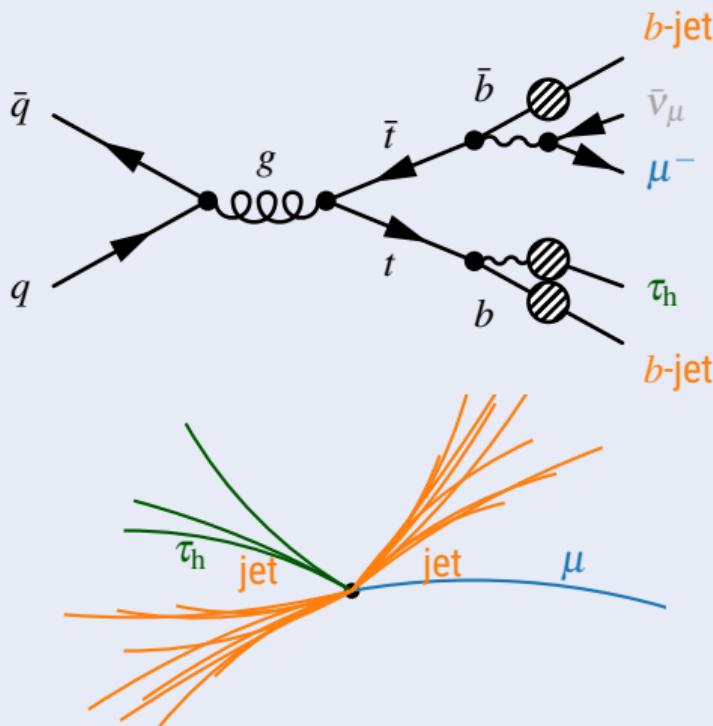


## $H \rightarrow \tau\tau \rightarrow \mu\tau_h$

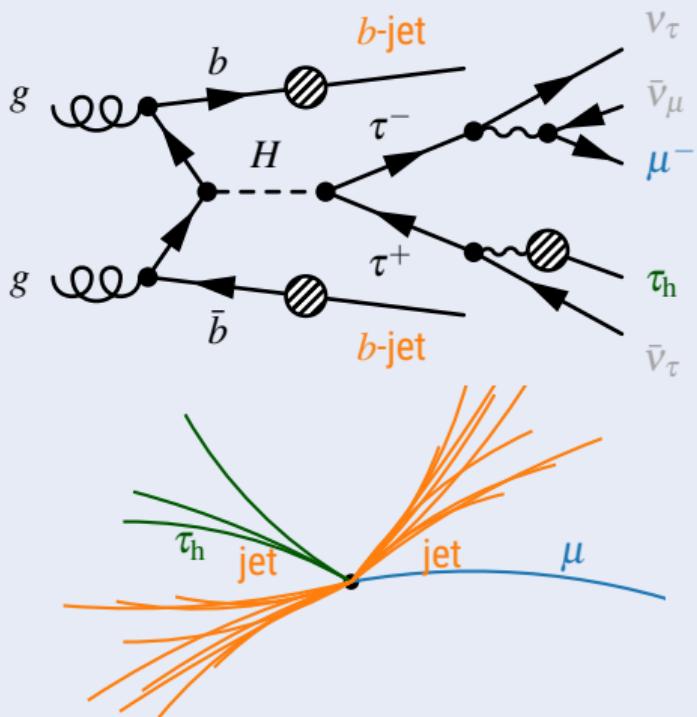


$W + \text{jets}, \text{jet} \rightarrow \text{fake } \tau_h$  $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

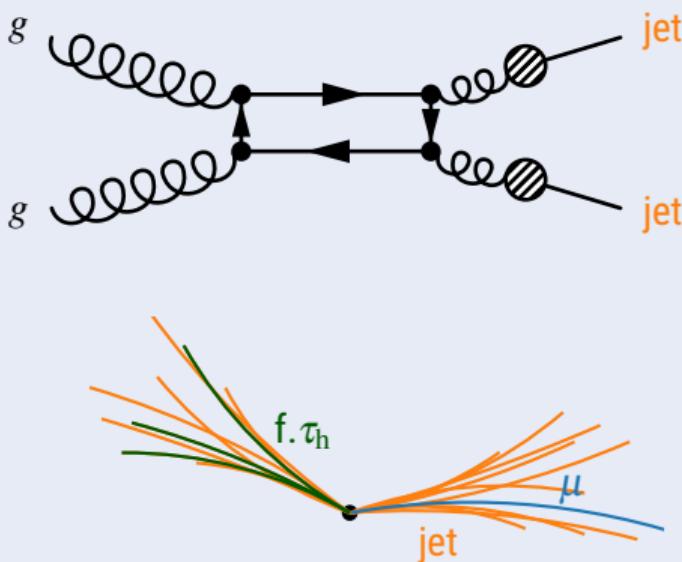
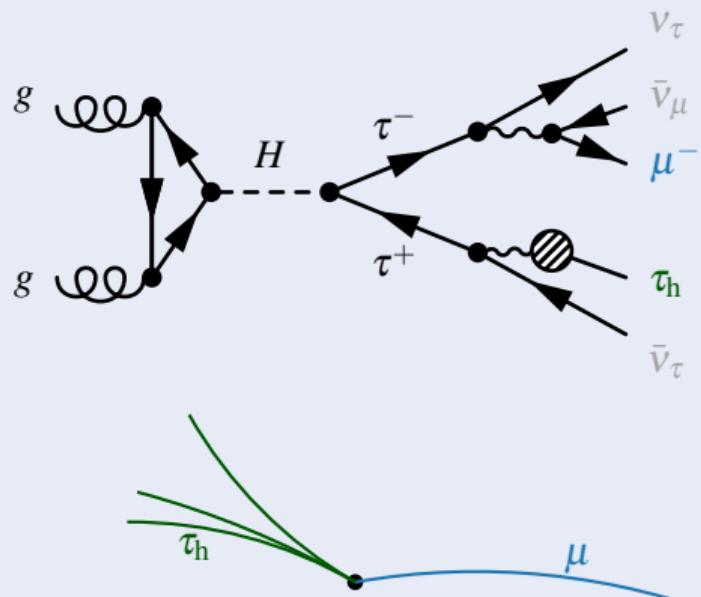
$t\bar{t}$  $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

$t\bar{t}$ 

## $H$ production with $b$ -jets

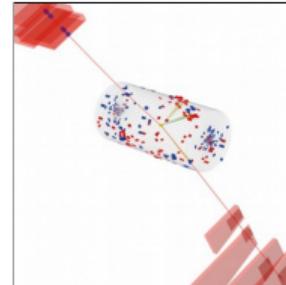


## QCD

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

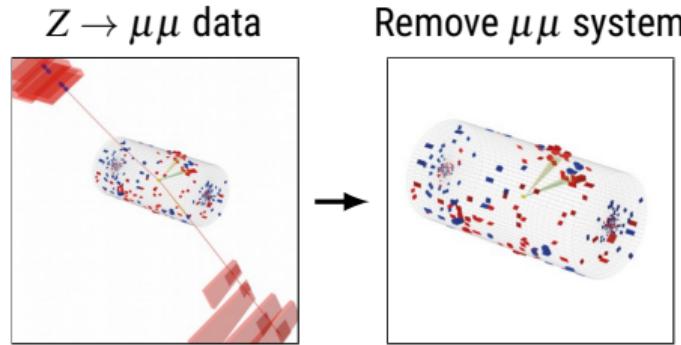
# Embedded events

$Z \rightarrow \mu\mu$  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).

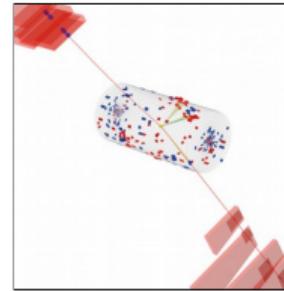
# Embedded events



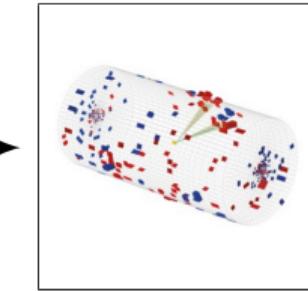
- ▷ The CMS Collaboration. "An embedding technique to determine  $\tau\tau$  backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

# Embedded events

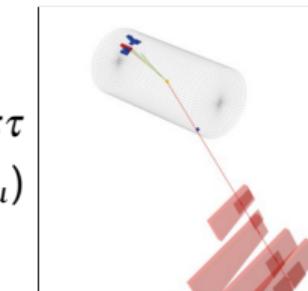
$Z \rightarrow \mu\mu$  data



Remove  $\mu\mu$  system

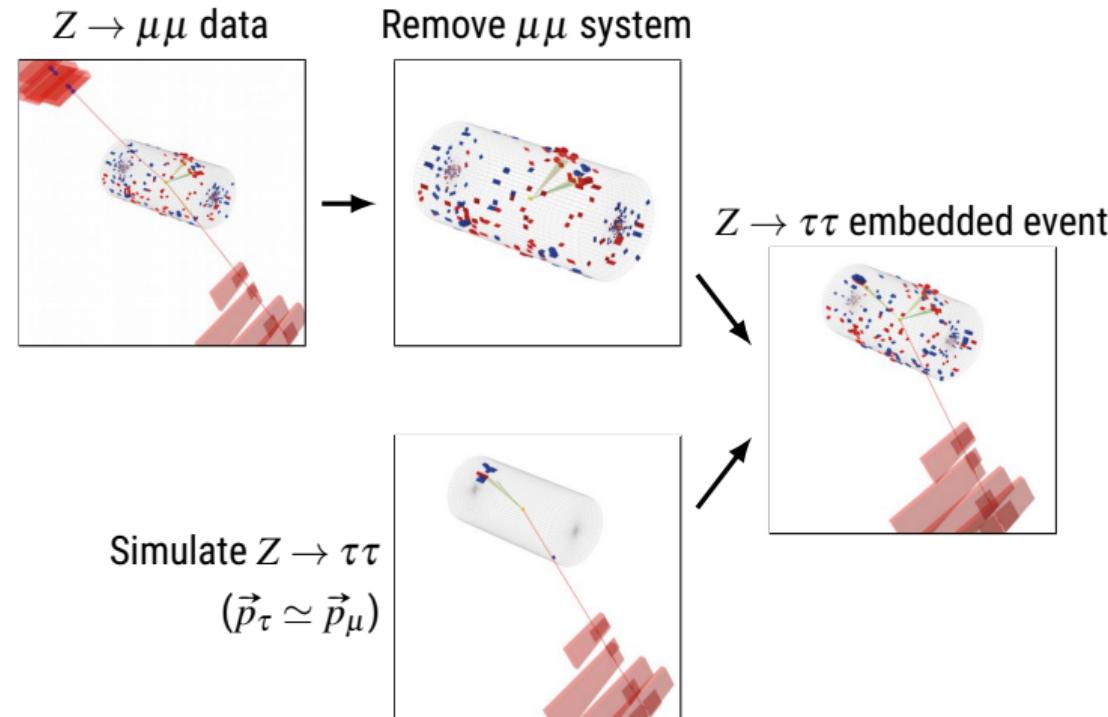


Simulate  $Z \rightarrow \tau\tau$   
 $(\vec{p}_\tau \simeq \vec{p}_\mu)$



- ▷ 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).

# The Fake Factor method

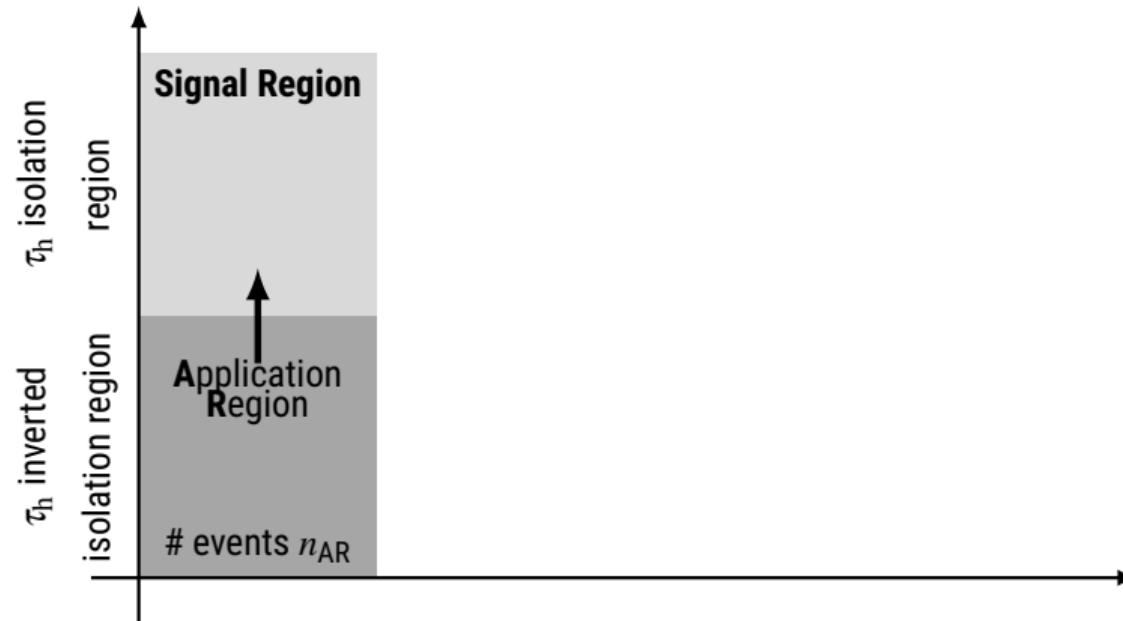
- ▶ How many events contain misidentified  $\tau_h$ ? (fake taus)

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► J. Andrejkovic & J. Bechtel. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with the full Run-II dataset". *CMS analysis Note* (June 2020). URL: [https://cms.cern.ch/iCMS/jsp/db\\_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170](https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170).

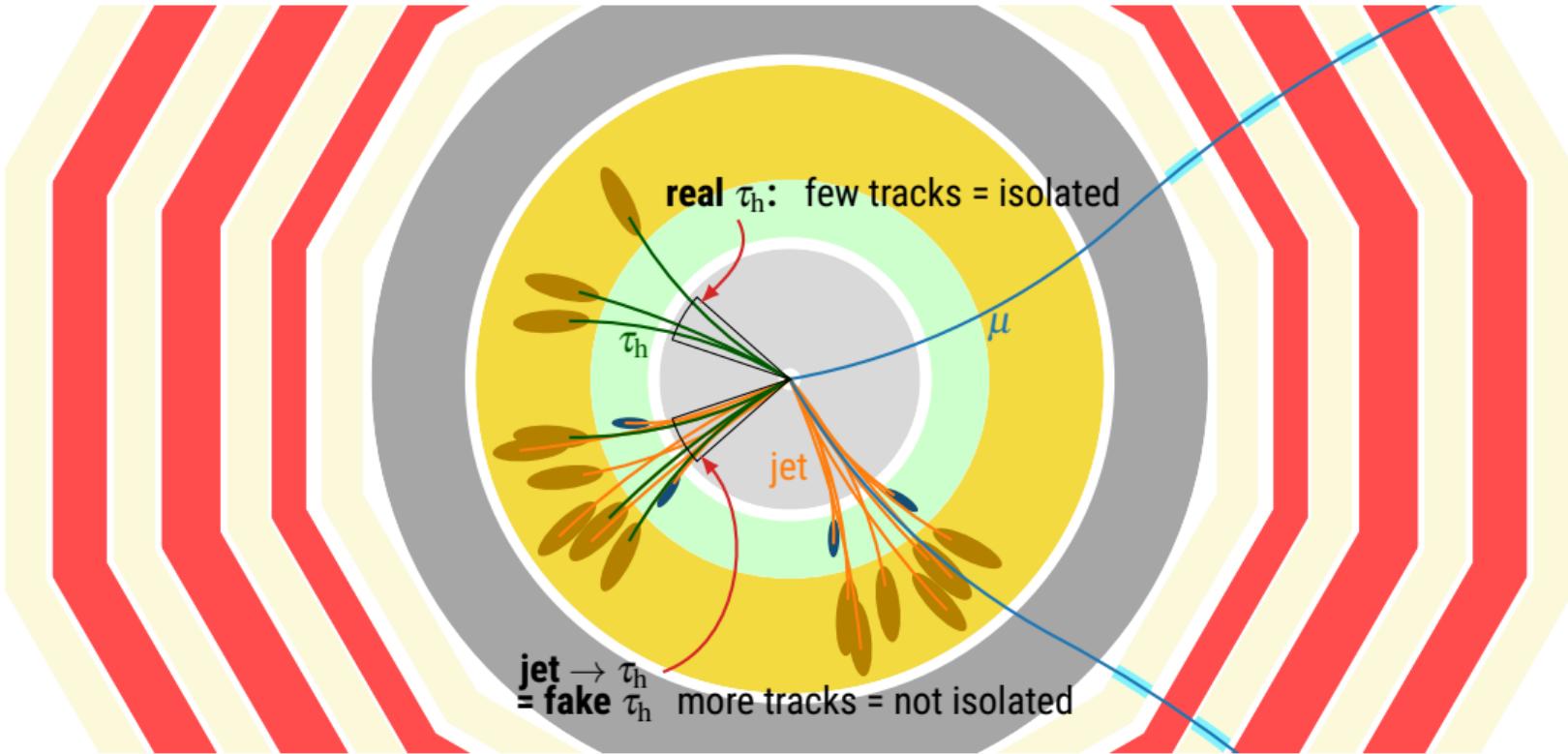
# The Fake Factor method

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- ▷ J. Andrejkovic & J. Bechtel. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with the full Run-II dataset". *CMS analysis Note* (June 2020). URL: [https://cms.cern.ch/iCMS/jsp/db\\_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170](https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170).

## Particles isolation – qualitatively



# The FF method: determination regions definitions

$t\bar{t}$

Estimation from simulated samples, same selection as in SR.

- 
- ▷ J. Andrejkovic & J. Bechtel. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with the full Run-II dataset". *CMS analysis Note* (June 2020). URL: [https://cms.cern.ch/iCMS/jsp/db\\_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170](https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170).

# The FF method: determination regions definitions

$t\bar{t}$

Estimation from simulated samples, same selection as in SR.

$W + \text{jets}$

Same as SR, except:

- transverse mass  $m_T^{(\ell)} > 70 \text{ GeV}$  ( $m_T^{(\ell)} < 70 \text{ GeV}$  in the SR);
- no  $b$ -jet (allowed in the SR).

▷ J. Andrejkovic & J. Bechtel. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with the full Run-II dataset". *CMS analysis Note* (June 2020). URL: [https://cms.cern.ch/iCMS/jsp/db\\_notes/noteInfo.jsp?cmsnoteid=CMS%5C%20AN-2019/170](https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C%20AN-2019/170).

# The FF method: determination regions definitions

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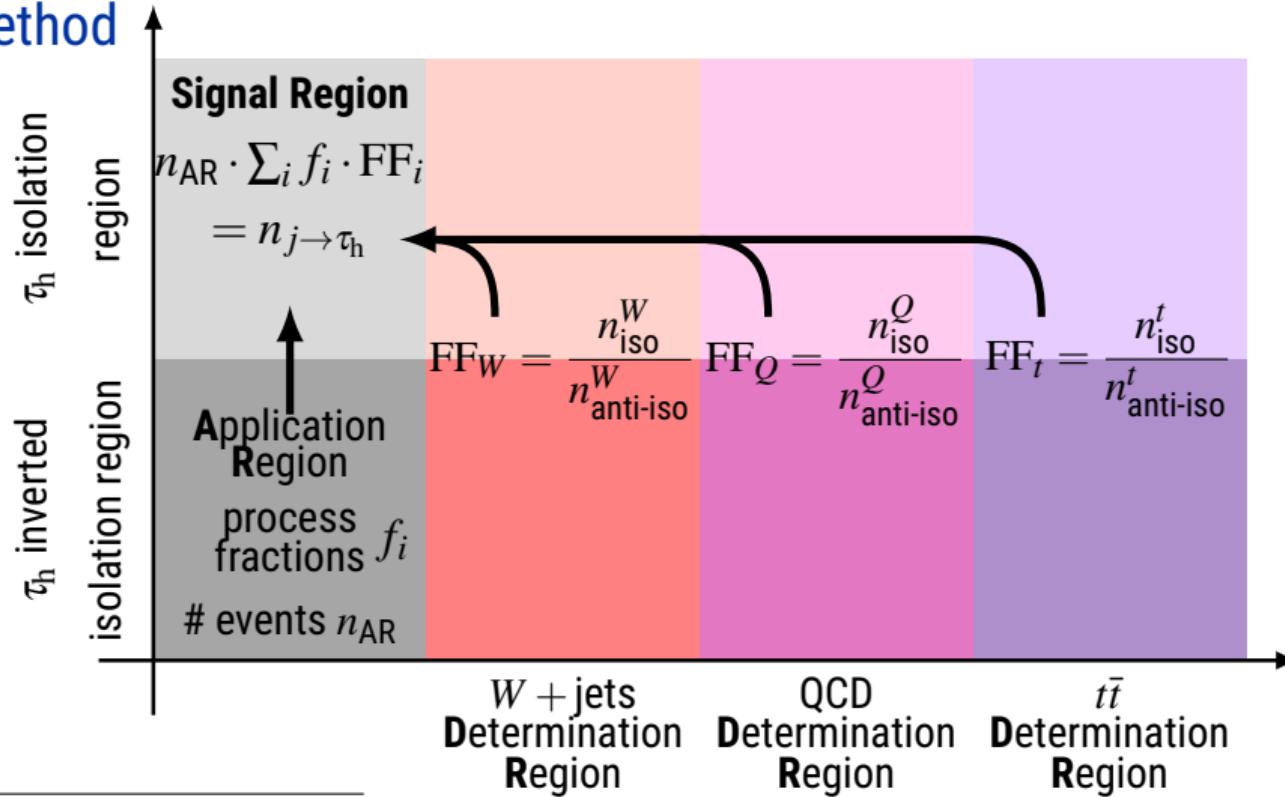
## QCD multijet

Same as SR, except:

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

▷ J. Andrejkovic & J. Bechtel. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with the full Run-II dataset". *CMS analysis Note* (June 2020). URL: [https://cms.cern.ch/iCMS/jsp/db\\_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170](https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170).

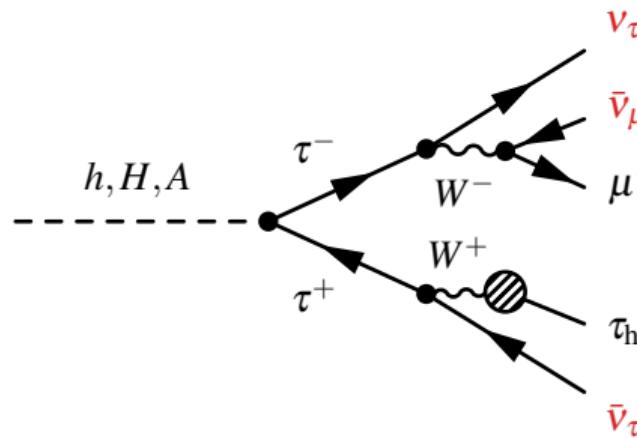
# The FF method



▷ J. Andrejkovic & J. Bechtel. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with the full Run-II dataset". *CMS analysis Note* (June 2020). URL: [https://cms.cern.ch/iCMS/jsp/db\\_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170](https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2019/170).

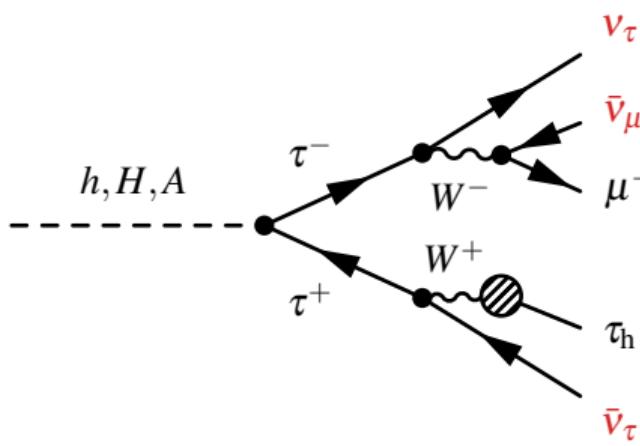
# Discriminant variable?

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

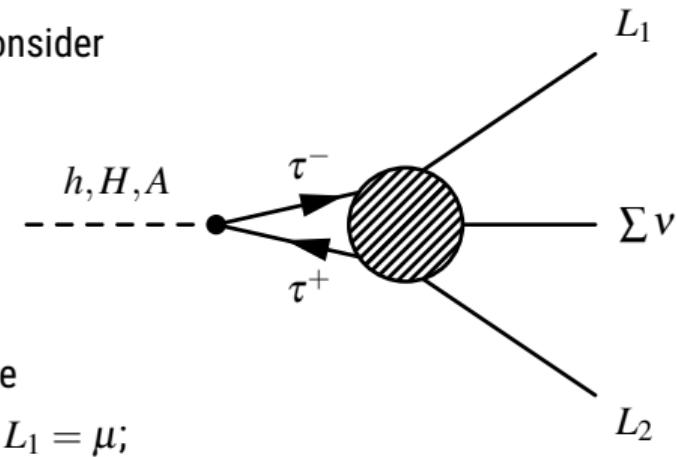


# Discriminant variable?

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



- ▶ Consider



where

- $L_1 = \mu;$
- $L_2 = \tau_h;$
- $\sum v \simeq E_T^{\text{miss}};$

with respect to the left side.

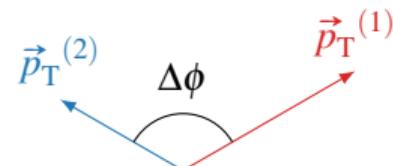
# Discriminant variable: $m_T^{\text{tot}}$

- ▶ 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**,  $m_T^{\text{tot}}$

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

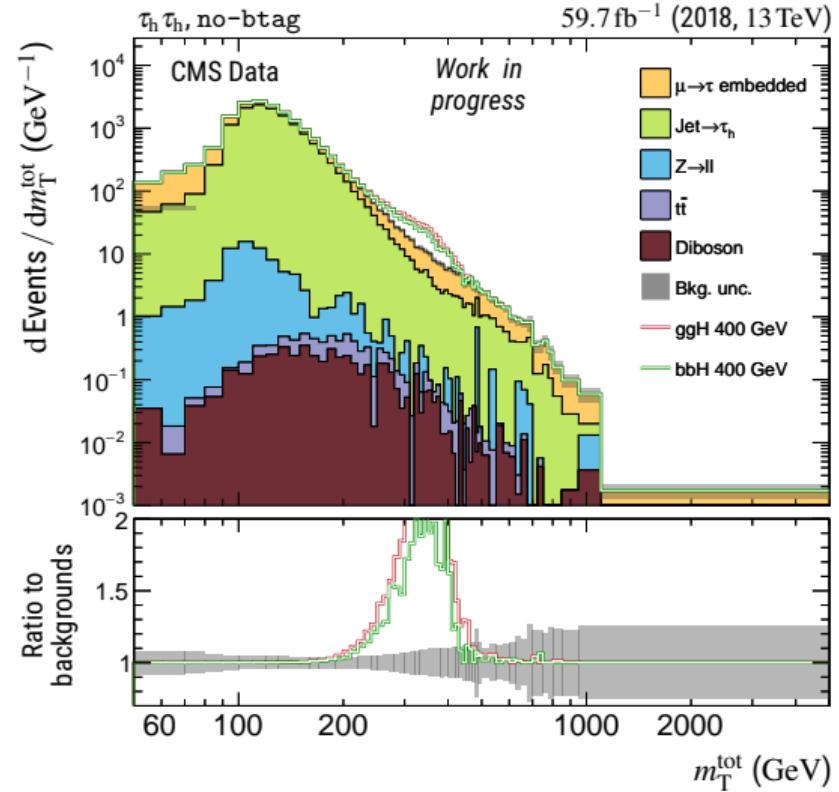
$$m_T(1,2) = \sqrt{2p_T^{(1)} p_T^{(2)} (1 - \cos \Delta\phi)}$$



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

## ► Backgrounds = SM expectations:

- ▷ DY  $Z \rightarrow \tau\tau$  and some  $t\bar{t}$  in  $\mu \rightarrow \tau$  embedded
- ▷ QCD,  $W + \text{jets}$  and some  $t\bar{t}$  in Jet  $\rightarrow \tau_h$
- ▷  $Z \rightarrow ee + Z \rightarrow \mu\mu$  in  $Z \rightarrow ll$
- ▷ Remaining  $t\bar{t}$  in  $t\bar{t}$
- ▷ Other small backgrounds in Diboson

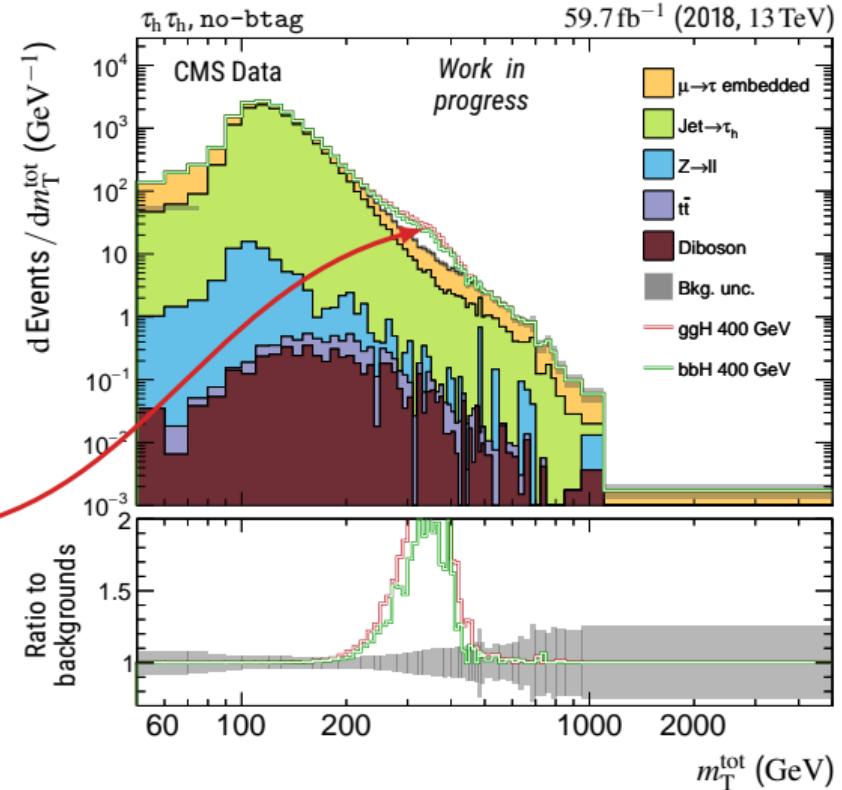


# $m_T^{\text{tot}}$ distributions

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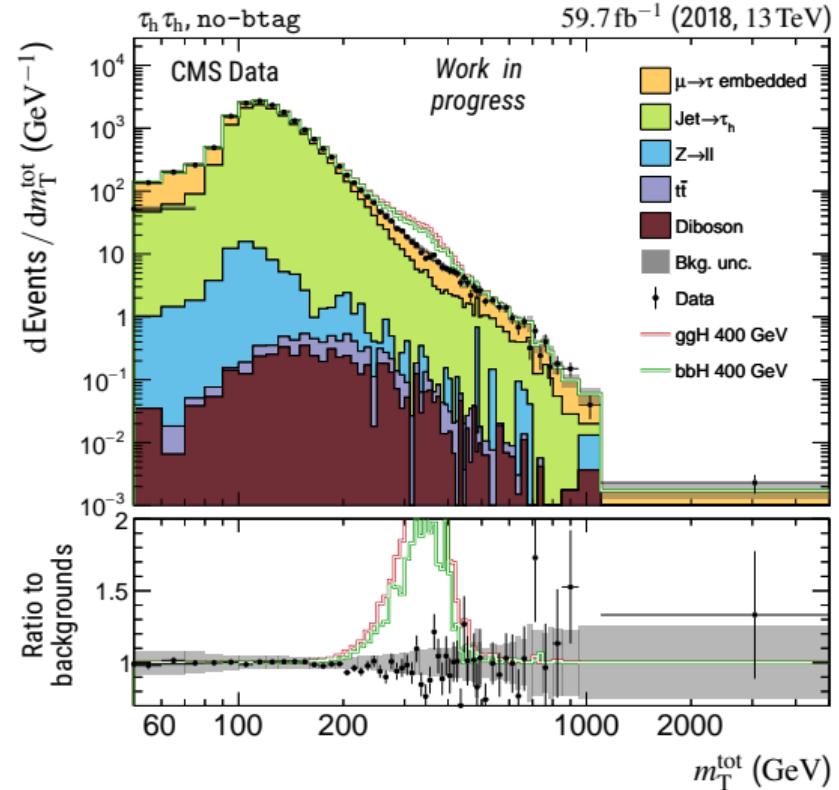
- ▷ DY  $Z \rightarrow \tau\tau$  and some  $t\bar{t}$  in  $\mu \rightarrow \tau$  embedded
- ▷ QCD,  $W + \text{jets}$  and some  $t\bar{t}$  in Jet  $\rightarrow \tau_h$
- ▷  $Z \rightarrow ee + Z \rightarrow \mu\mu$  in  $Z \rightarrow ll$
- ▷ Remaining  $t\bar{t}$  in  $t\bar{t}$
- ▷ Other small backgrounds in Diboson

►  $H$  at 400 GeV expected  $\sigma \times \mathcal{BR} = 1 \text{ pb}$  signal.



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

- ▶ Backgrounds = SM expectations:
  - ▷ DY  $Z \rightarrow \tau\tau$  and some  $t\bar{t}$  in  $\mu \rightarrow \tau$  embedded
  - ▷ QCD,  $W + \text{jets}$  and some  $t\bar{t}$  in Jet  $\rightarrow \tau_h$
  - ▷  $Z \rightarrow ee + Z \rightarrow \mu\mu$  in  $Z \rightarrow ll$
  - ▷ Remaining  $t\bar{t}$  in  $t\bar{t}$
  - ▷ Other small backgrounds in Diboson
- ▶  $H$  at 400 GeV expected  $\sigma \times \mathcal{BR} = 1 \text{ pb}$  signal.
- ▶ Compare to observed events (black dots).



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

## ► Background contributions:

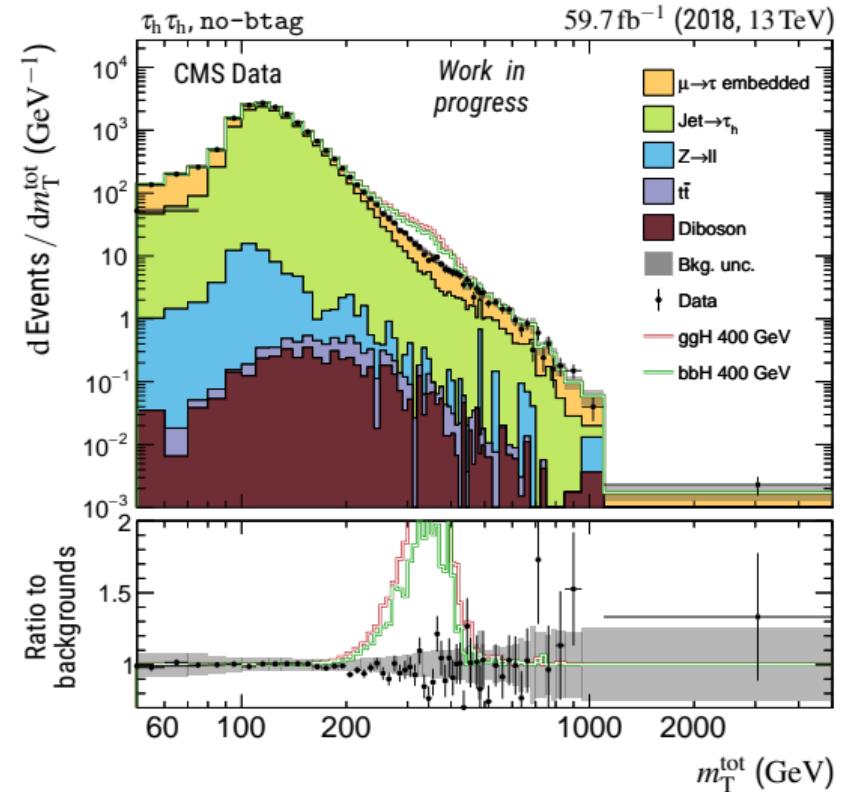
**Not just a plot!**

### ► Lot of hard work to obtain this: $\tau$ embedded

- ▷ simulated events
- ▷ QCD,  $W + \text{jets}$  and some  $t\bar{t}$  in Jet  $\rightarrow \tau_h$
- ▷ detector issues
- ▷  $Z \rightarrow ee + Z \rightarrow ll$
- ▷ uncertainties measured

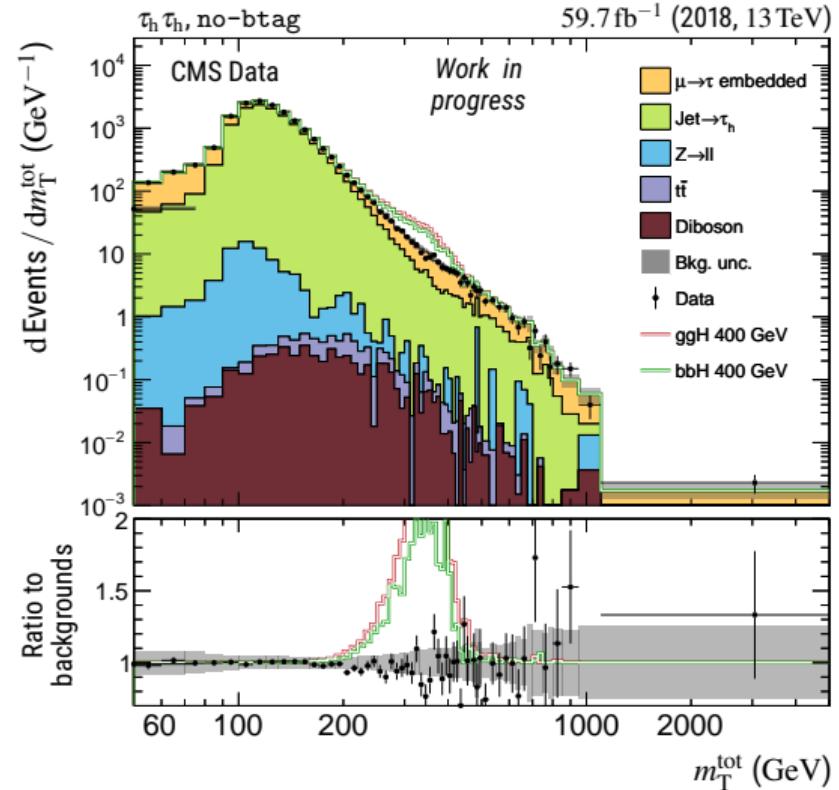
### ► Collaborative work:

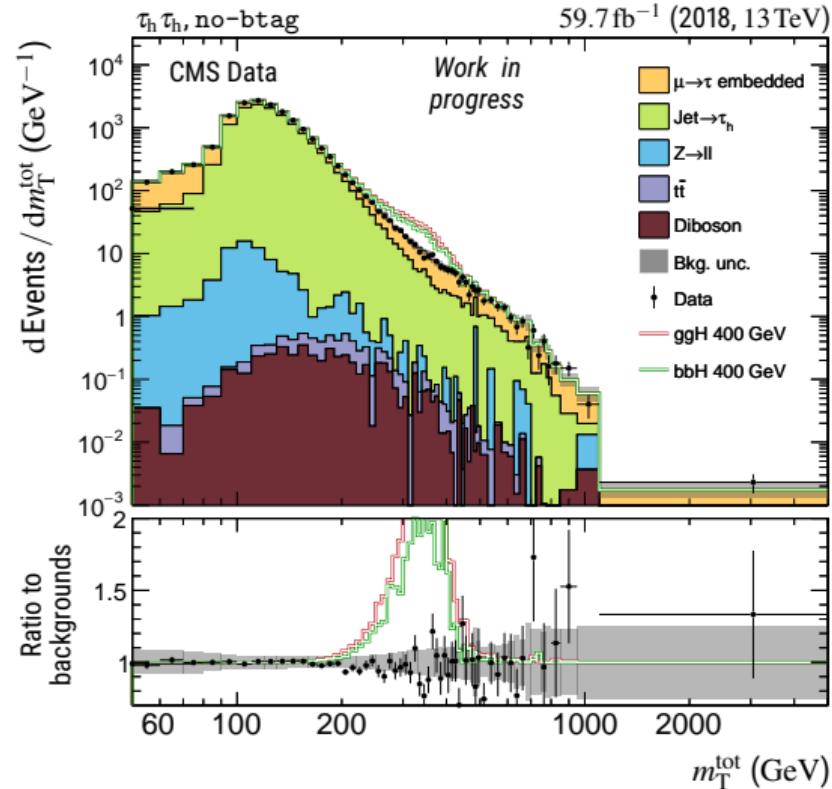
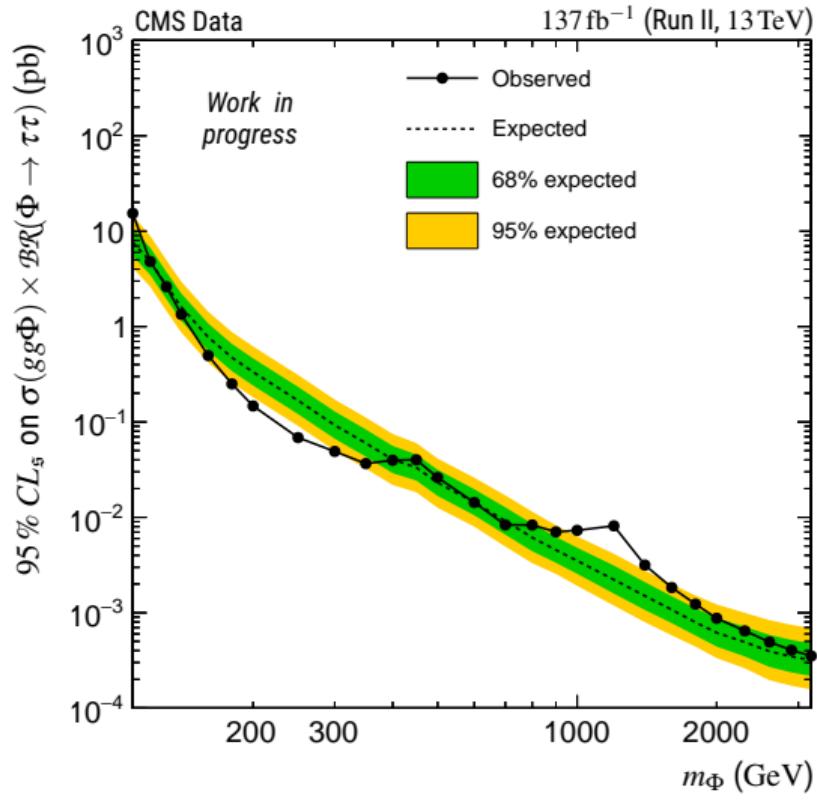
- ▷ Other collaboration
- ▷ Karlsruhe Institute of Technology (DE)
- ▷ Imperial College (UK)  $\mathcal{BR} = 1 \text{ pb}$  signal.
- ▷ COMPETE (DE) observed events (black dots).
- ▷ IP2I (FR)



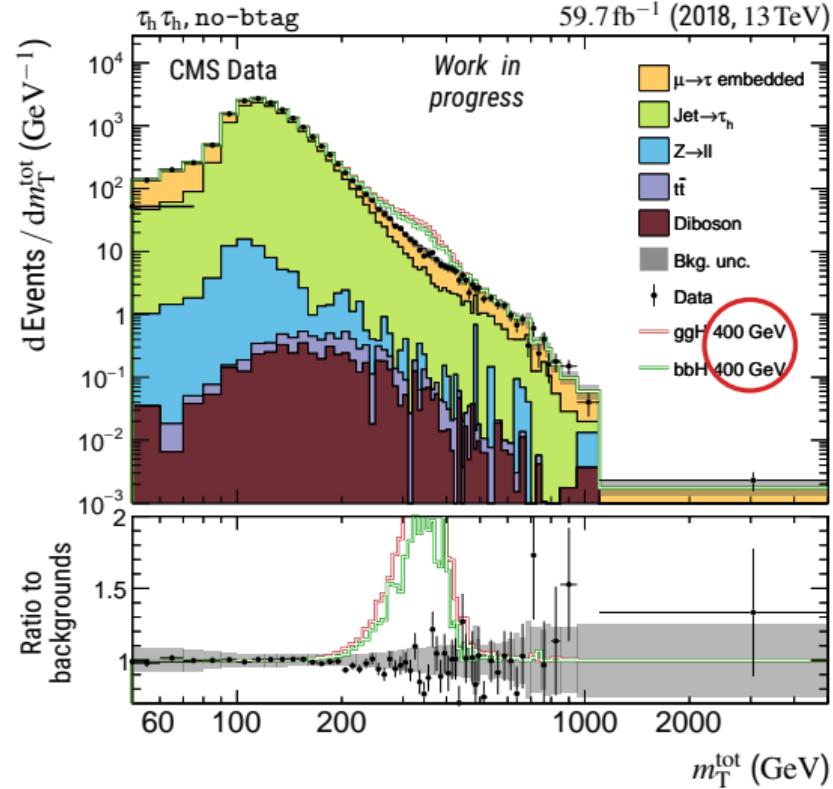
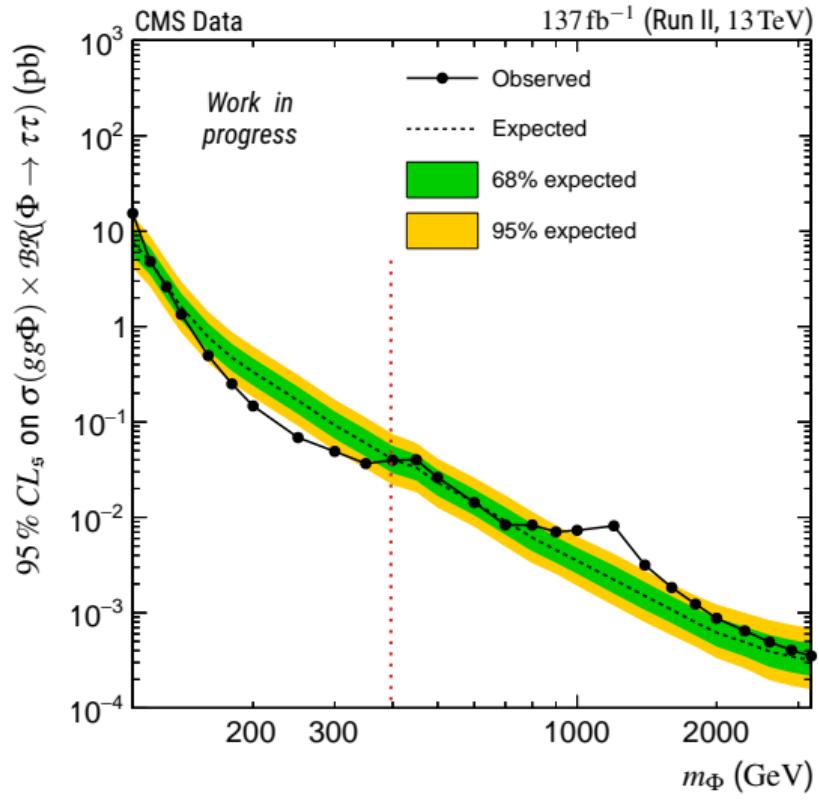
# $m_T^{\text{tot}}$ distributions

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  - ▷ DY  $Z \rightarrow \tau\tau$  and some  $t\bar{t}$  in  $\mu \rightarrow \tau$  embedded
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  - ▷  $Z \rightarrow ee + Z \rightarrow \mu\mu$  in  $Z \rightarrow ll$
  - ▷ Remaining  $t\bar{t}$  in  $t\bar{t}$
  - ▷ Other small backgrounds in Diboson
- ▶  $H$  at 400 GeV expected  $\sigma \times \mathcal{BR} = 1 \text{ pb}$  signal.
- ▶ Compare to observed events (black dots).
- ▶ Data/Bkg agreement  $\rightarrow$  **exclusion limits** on  $\sigma \times \mathcal{BR}$

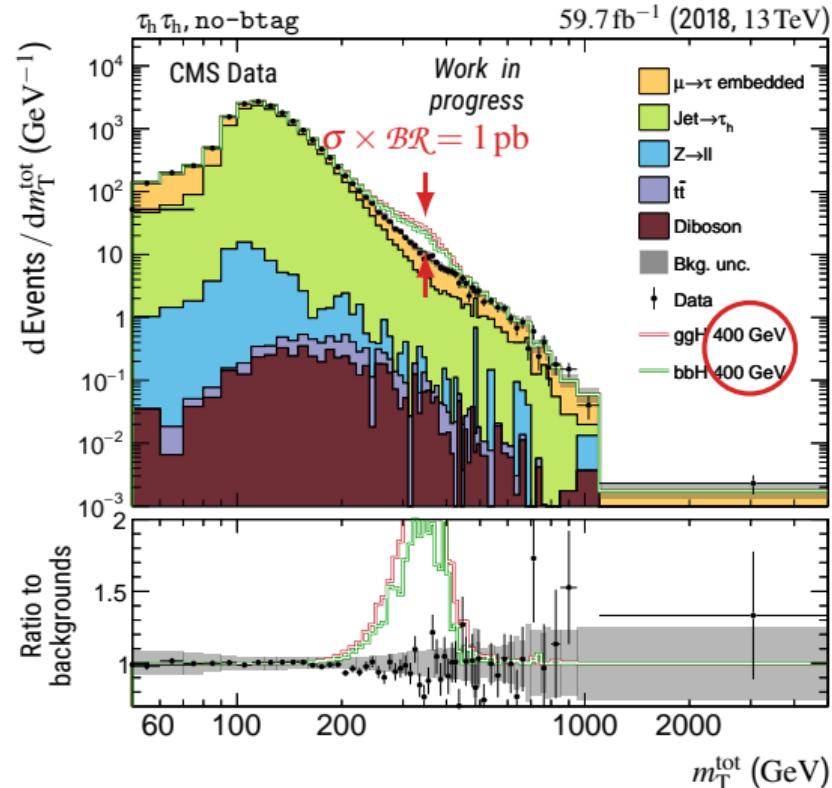
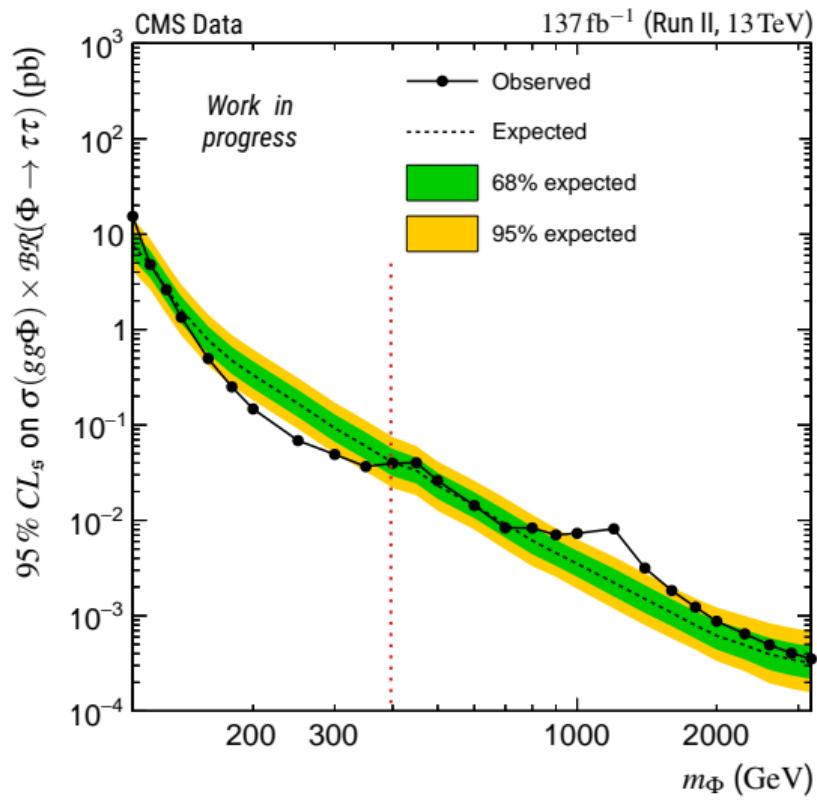




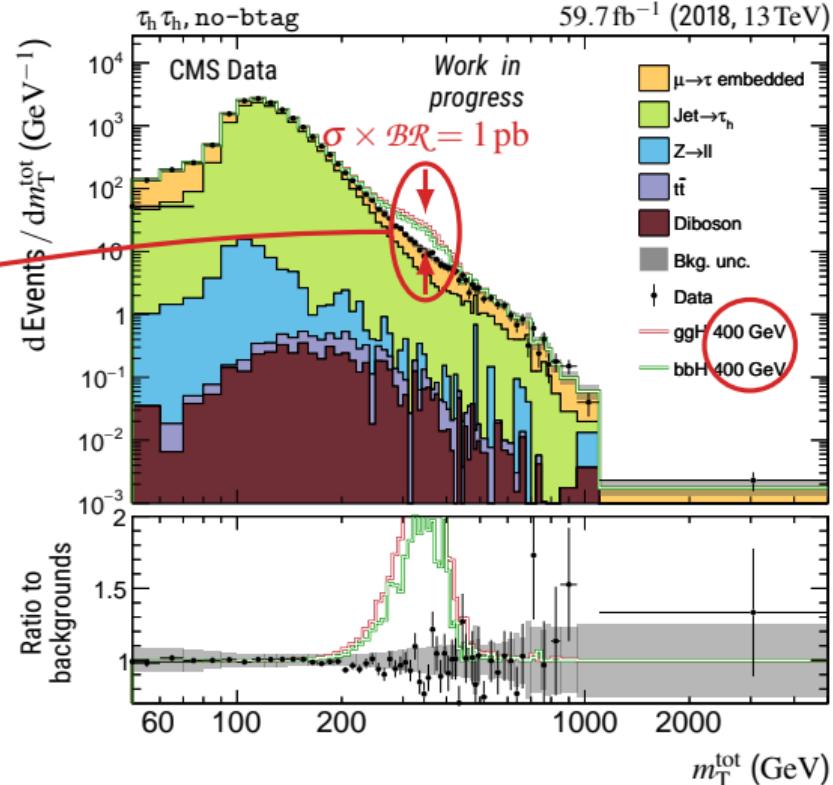
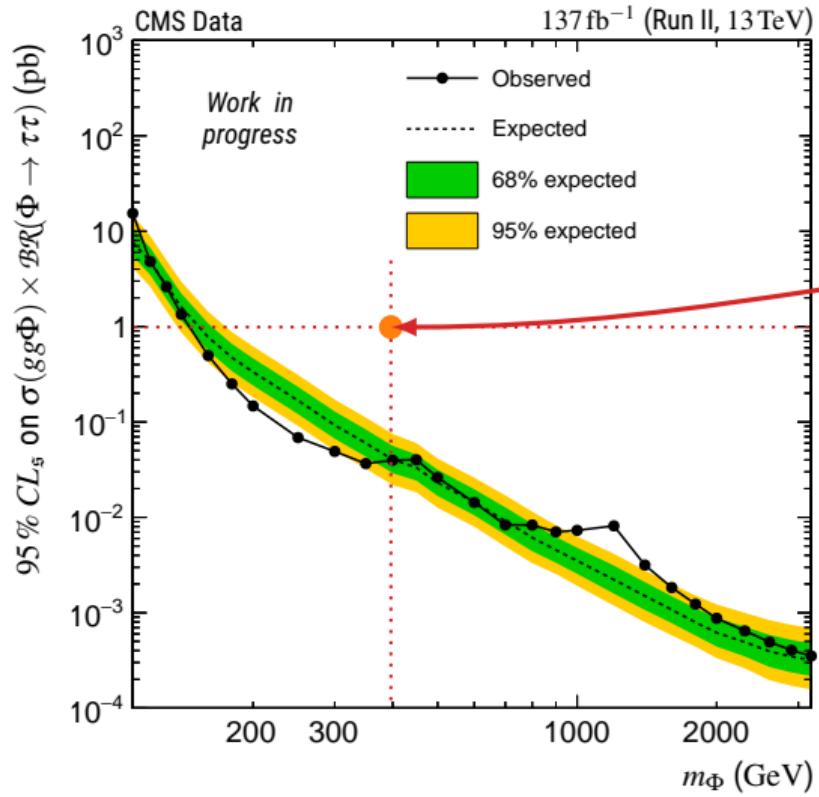
▷ A. L. Read. "Modified frequentist analysis of search results (the  $CL_s$  method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: <http://cds.cern.ch/record/451614>.



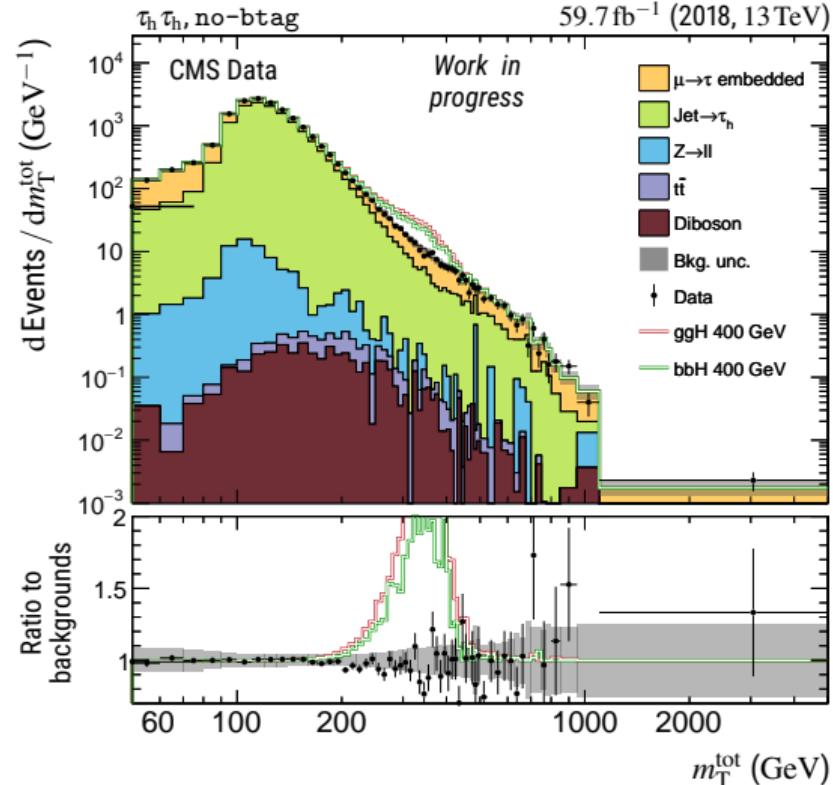
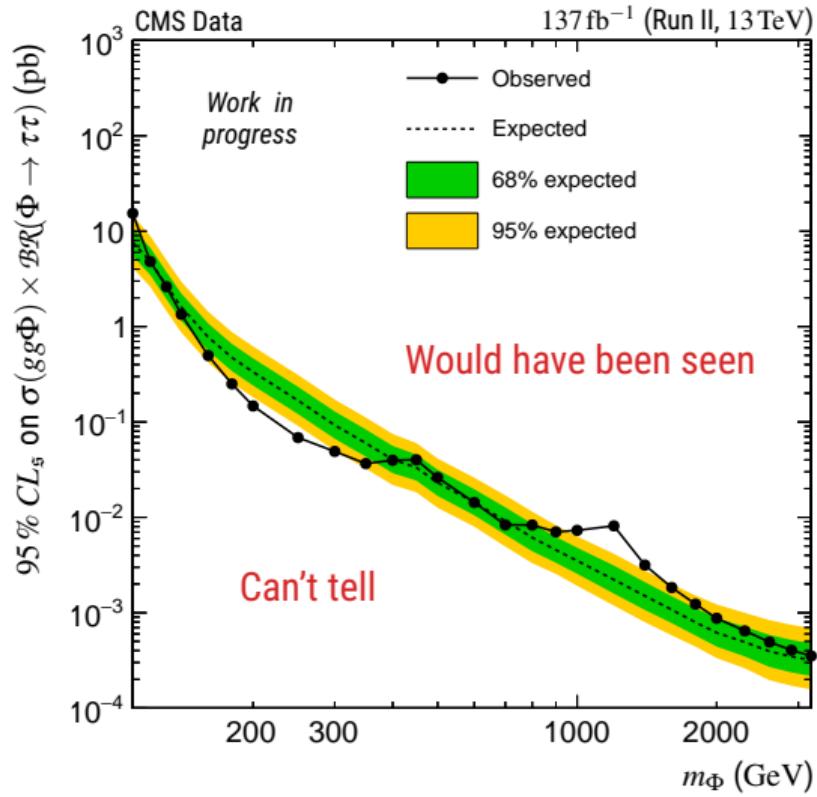
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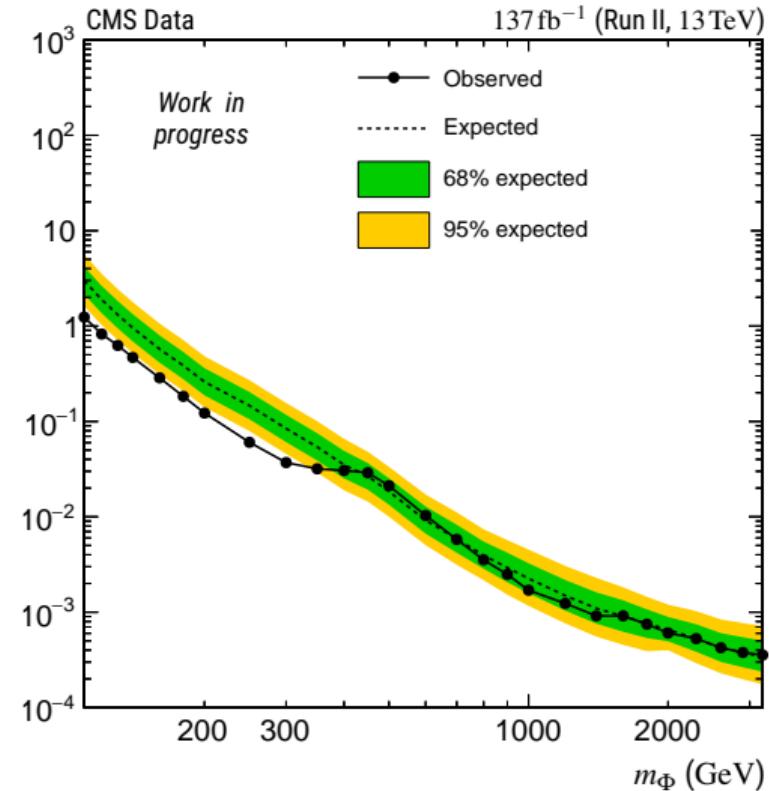
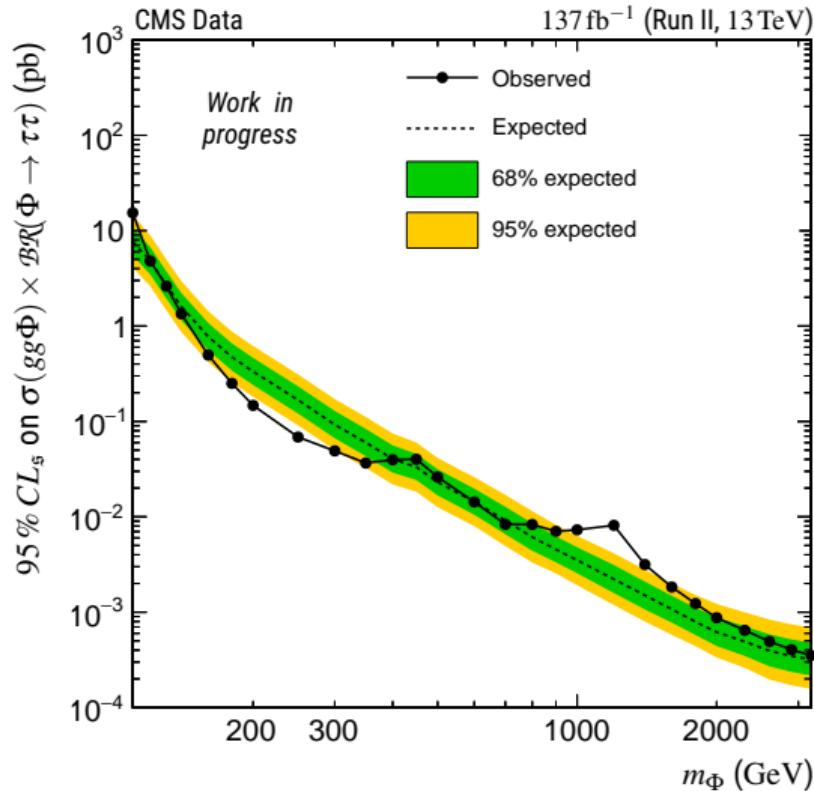
▷ A. L. Read. "Modified frequentist analysis of search results (the  $CL_s$  method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: <http://cds.cern.ch/record/451614>.



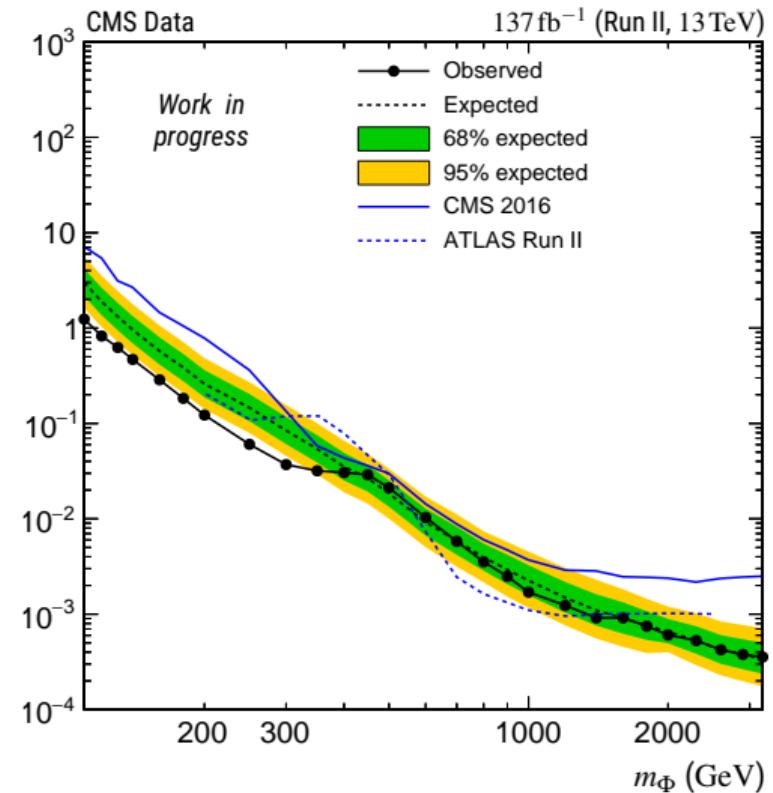
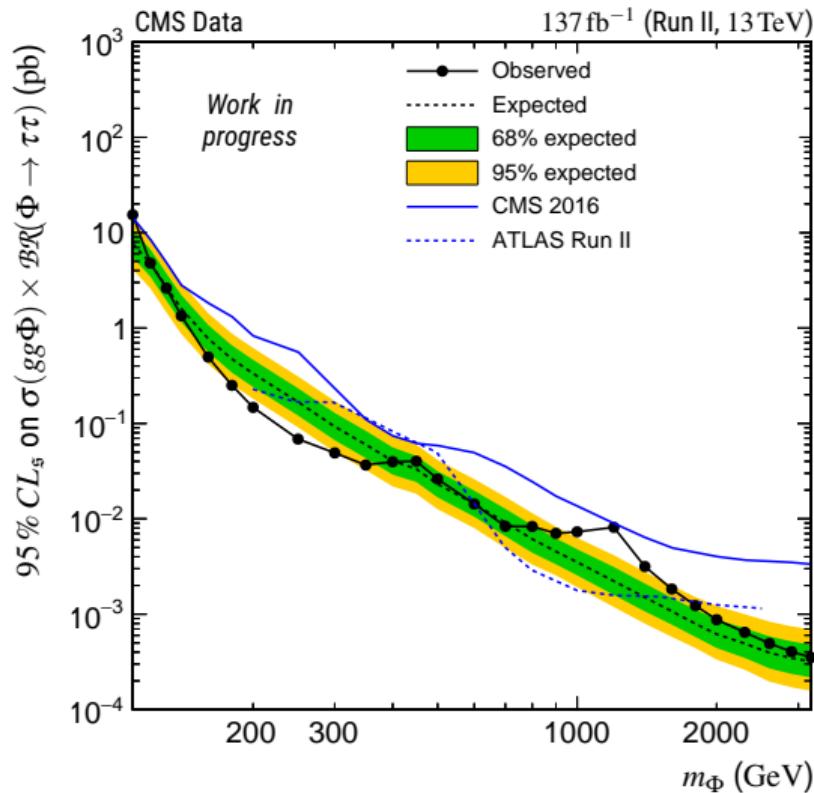
- ▷ A. L. Read. "Modified frequentist analysis of search results (the  $CL_s$  method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: <http://cds.cern.ch/record/451614>.



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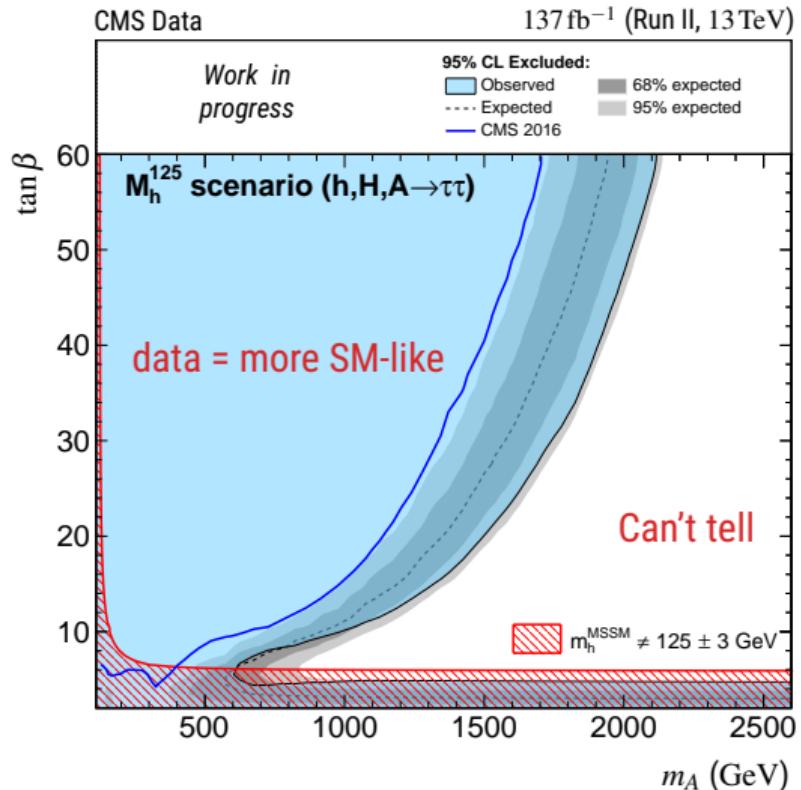


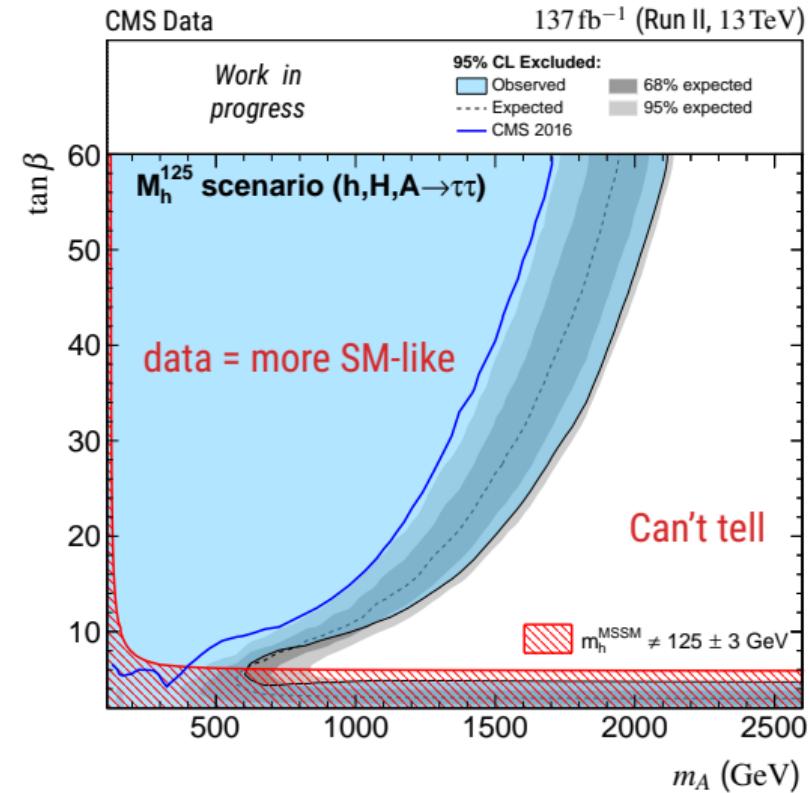
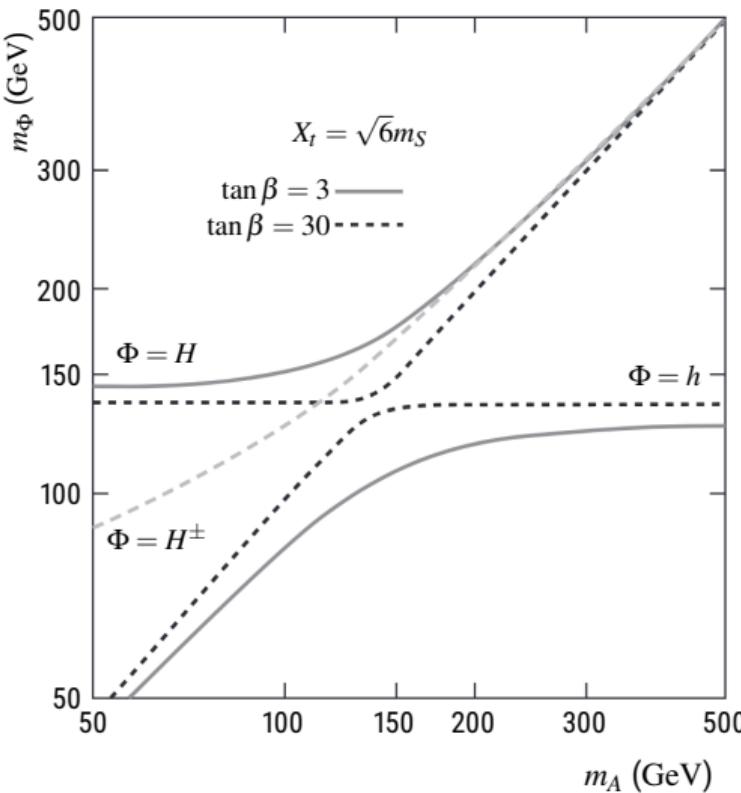
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- ▶ Model dependent limits:
  - ▷ Fix high-order MSSM parameter,
  - ▷ Explore  $(m_A, \tan \beta)$  plane,
  - ▷ Do data stick more to SM or MSSM?



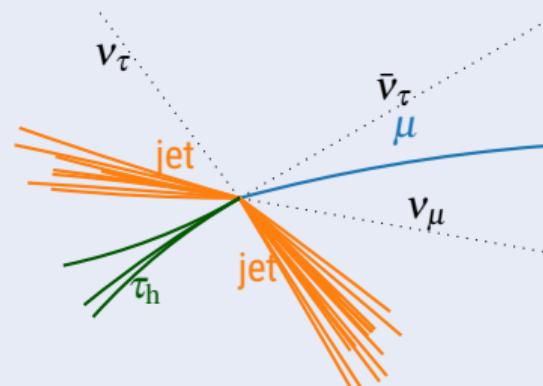


- ▶ Remember: invariant mass not fully available:
  - ▷ neutrinos in di- $\tau$  events.

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## What's here

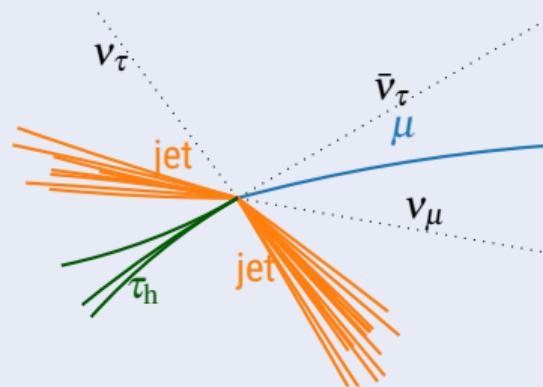
(e.g. VBF Higgs production + decay to  $\tau\tau, \mu\tau_h$  channel)



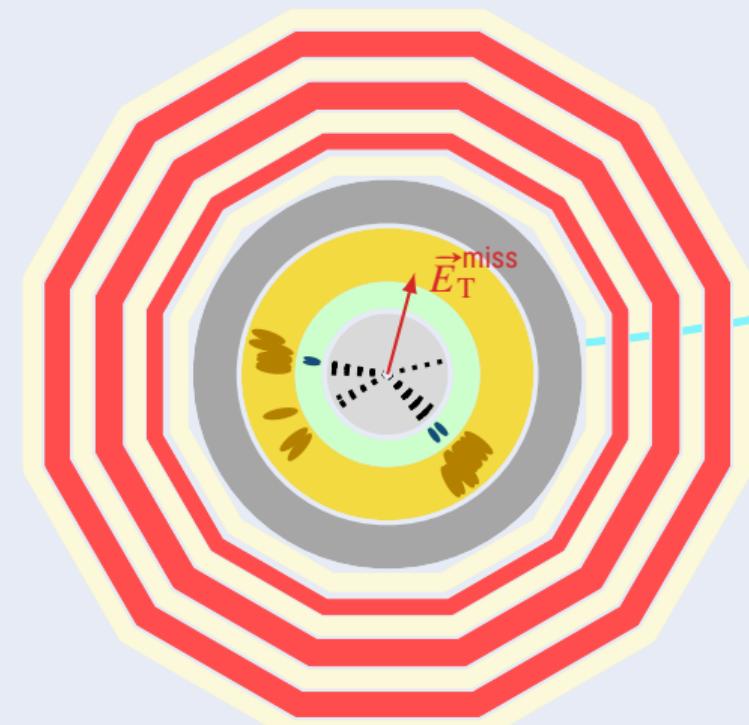
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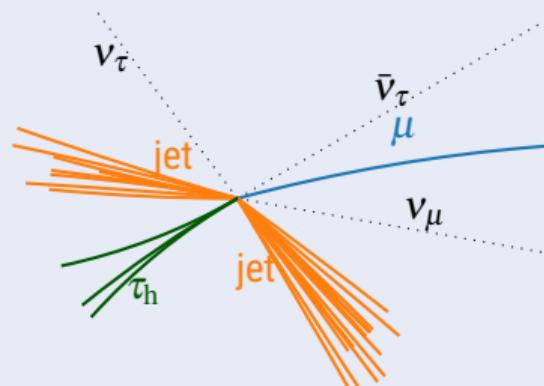
## What CMS sees



- ▶ Remember: invariant mass not fully available:
  - ▷ neutrinos in di- $\tau$  events.

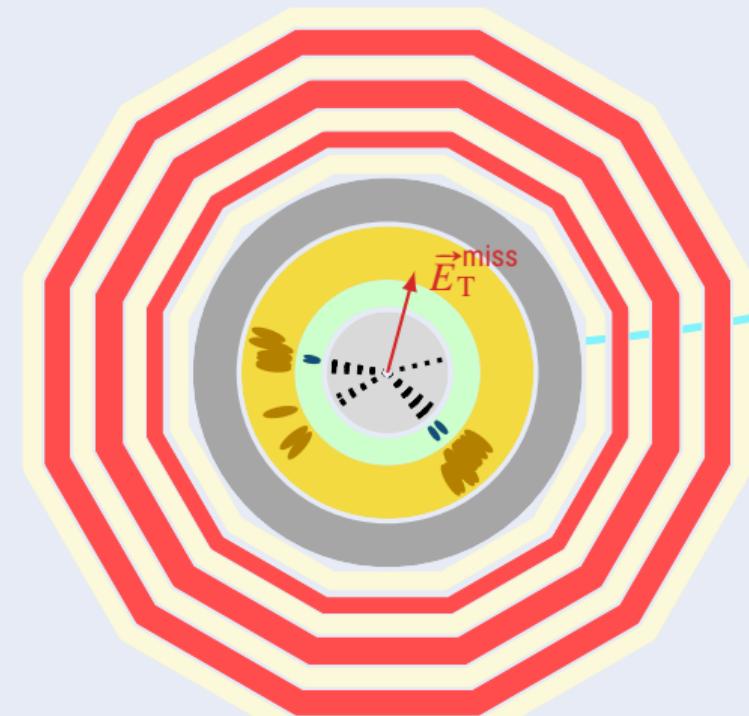
## What's here

(e.g. VBF Higgs production + decay to  $\tau\tau, \mu\tau_h$  channel)



- ▶ It would be great to have a di- $\tau$  mass estimator!
  - ▷ What about **machine learning?**

## What CMS sees



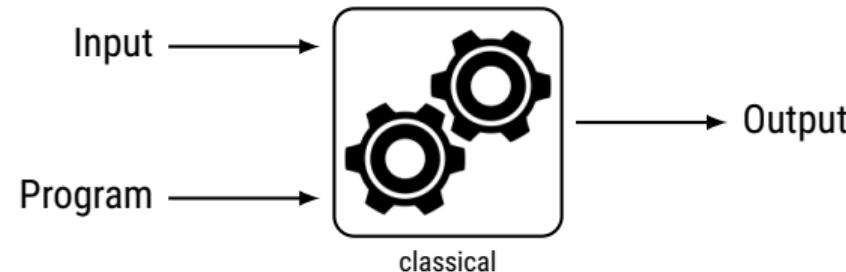
## 1 Phenomenology

## 2 Experimental device

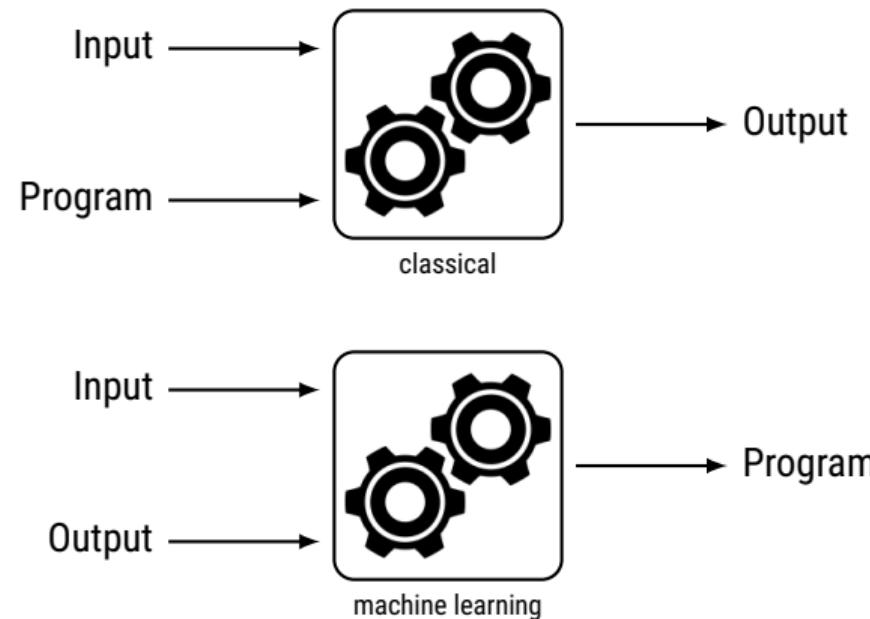
## 3 $H/A \rightarrow \tau\tau$ analysis

## 4 Machine learning

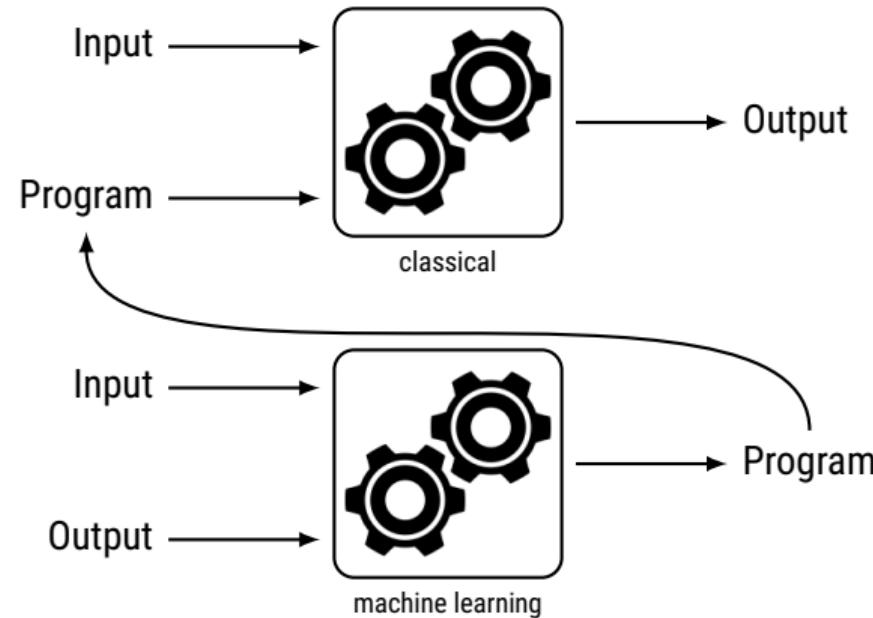
# What is *machine learning*? – A brief introduction



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**Aim:** find a function (program) mapping features (input) to a target (output)

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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/>.

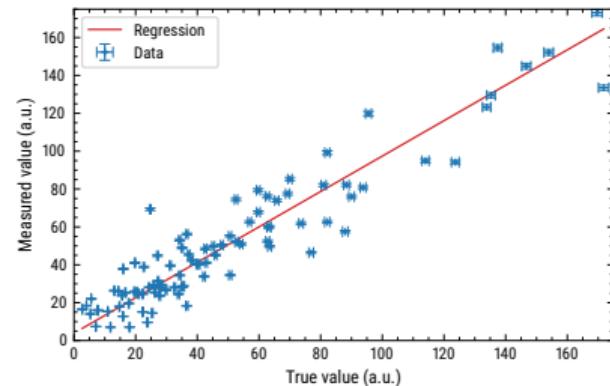
# What is *machine learning*? – A brief introduction

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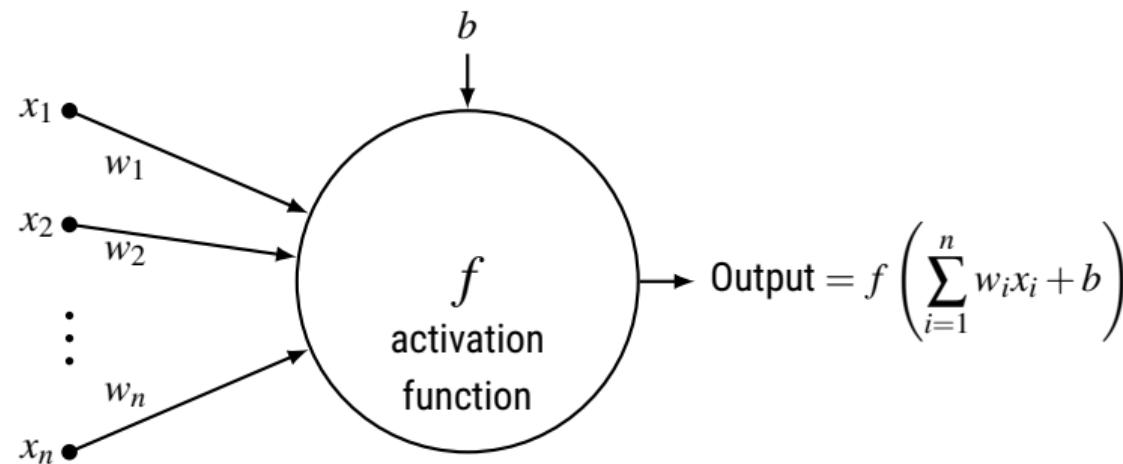
- ▶ Continuous target  $\Rightarrow$  Regression  
e.g. discriminating variable!  
Linear case:



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

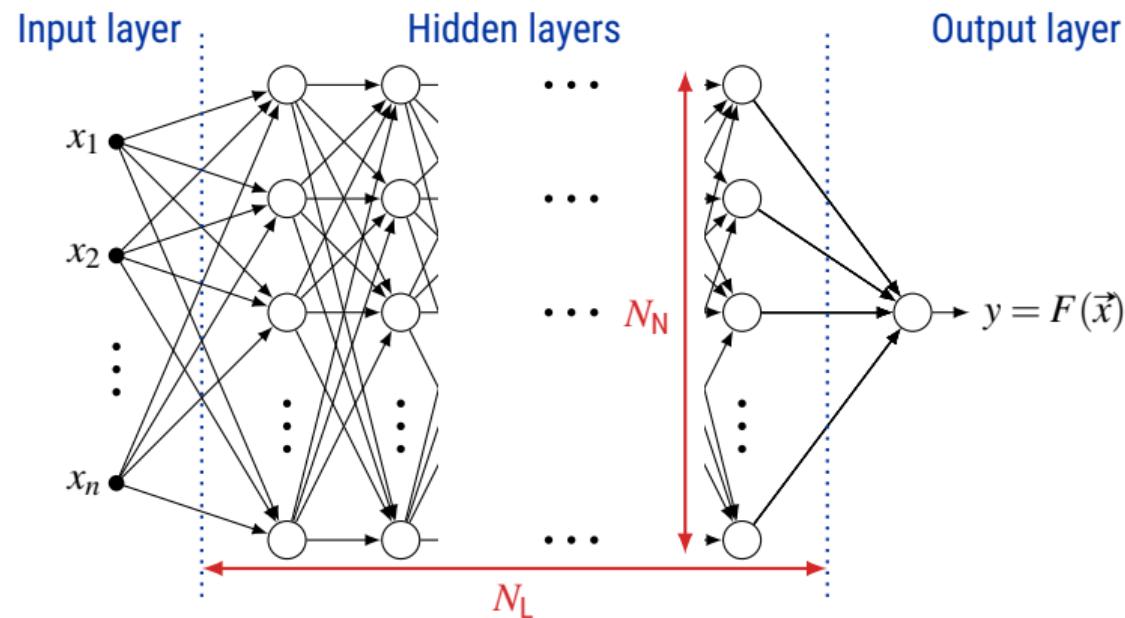
What if the target is not linear wrt. input?

# Neurons in ML



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

# (Deep) Neural Networks

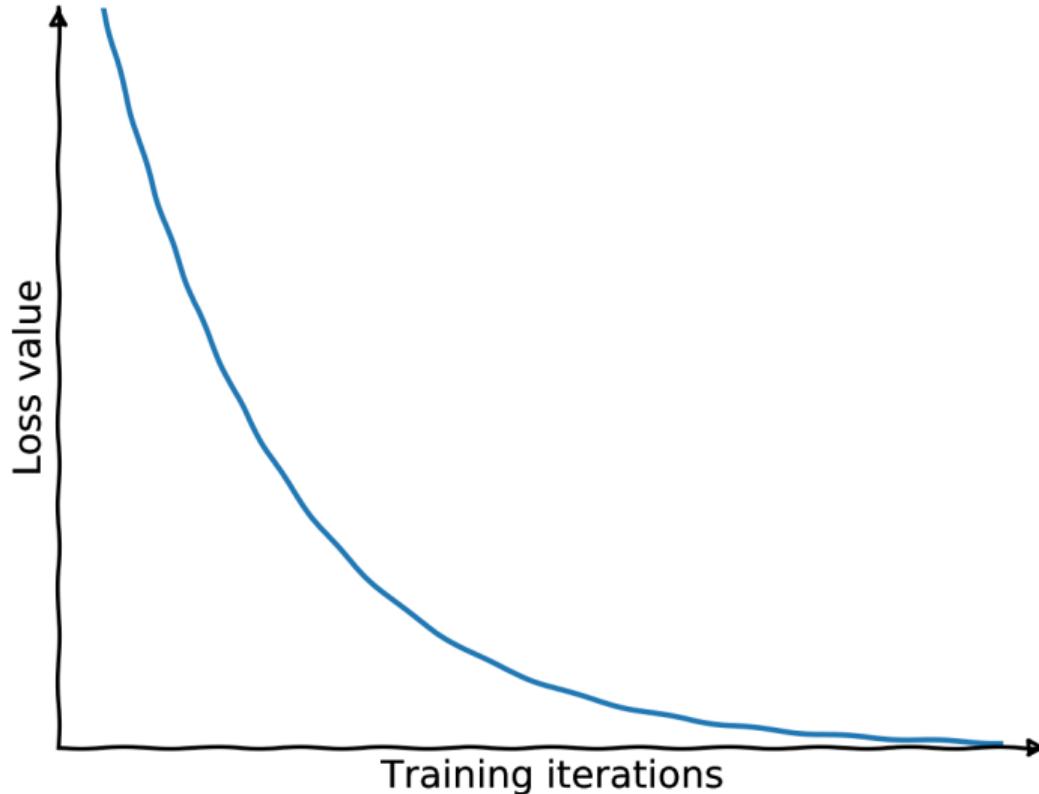


# How to train a neural network?

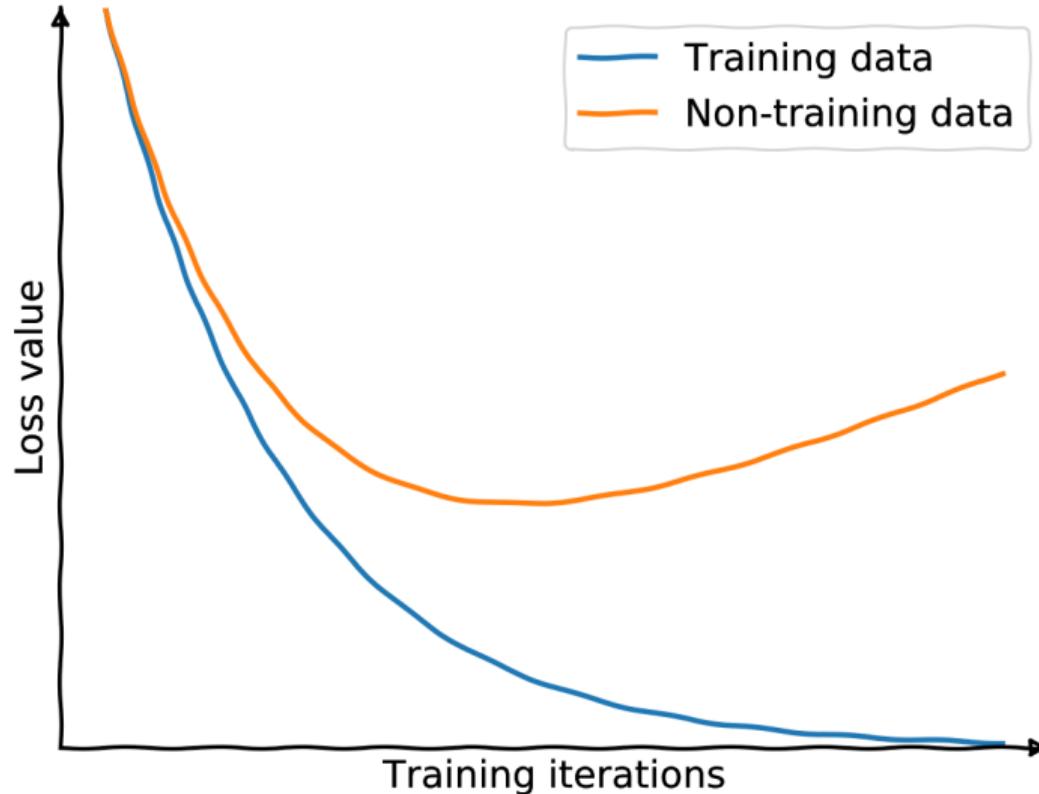
Train = optimize parameters  $(w_1, w_2, \dots, w_n, b)$  for each neuron.

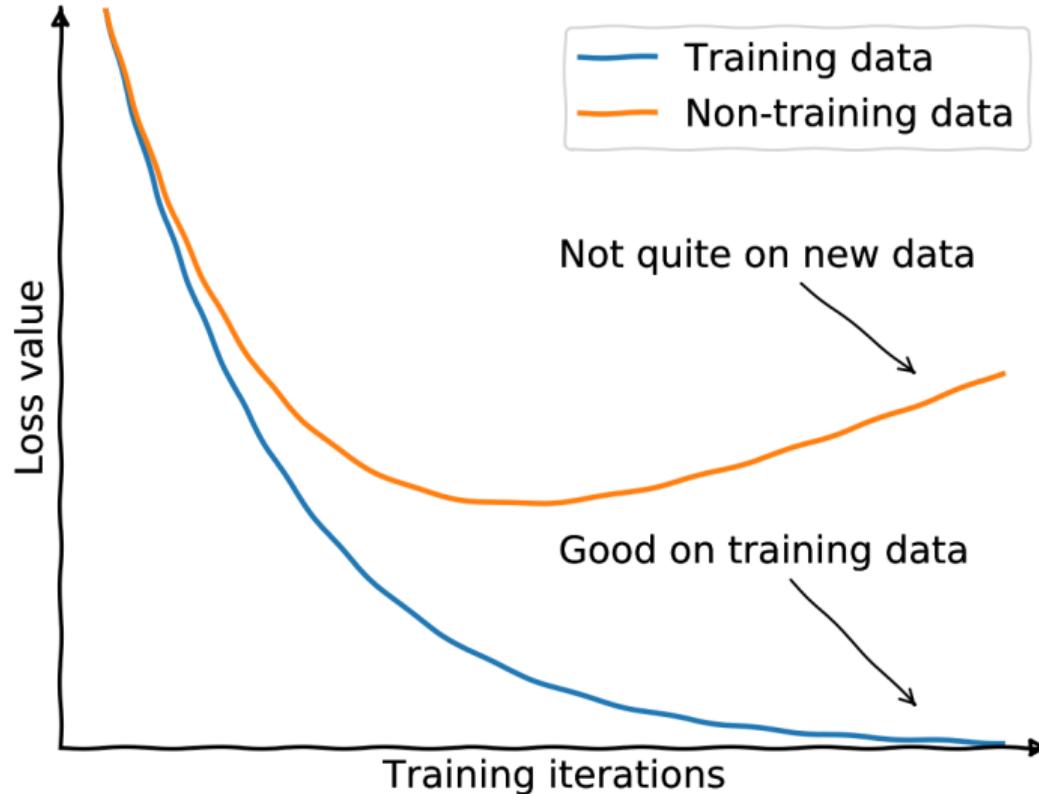
- ▶ Get a **training dataset** = examples of inputs  $\vec{x}_i$  with corresponding outputs  $y_i$
- ▶ Compare the model predictions  $F(\vec{x}_i)$  to the true values  $y_i$ 
  - ▷ Define a **loss function**  $\mathcal{L}$  such that its minimum is reached when  $F(\vec{x}_i) = y_i$
  - ▷ Change the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

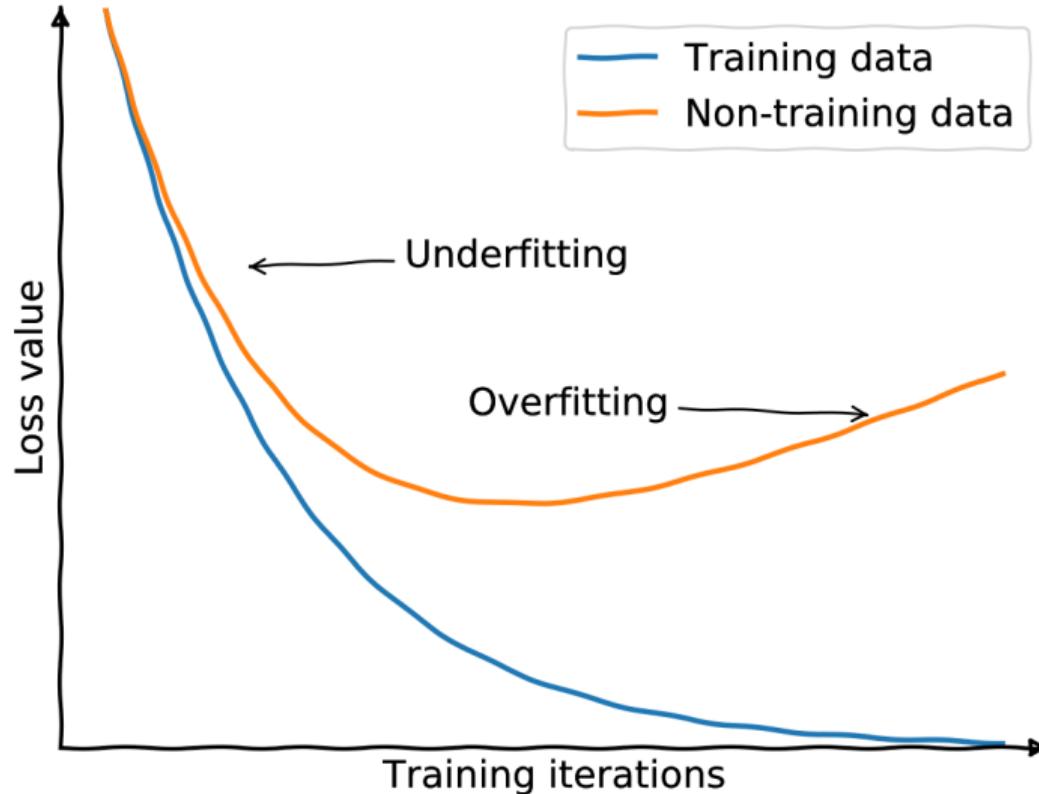
When to stop training?

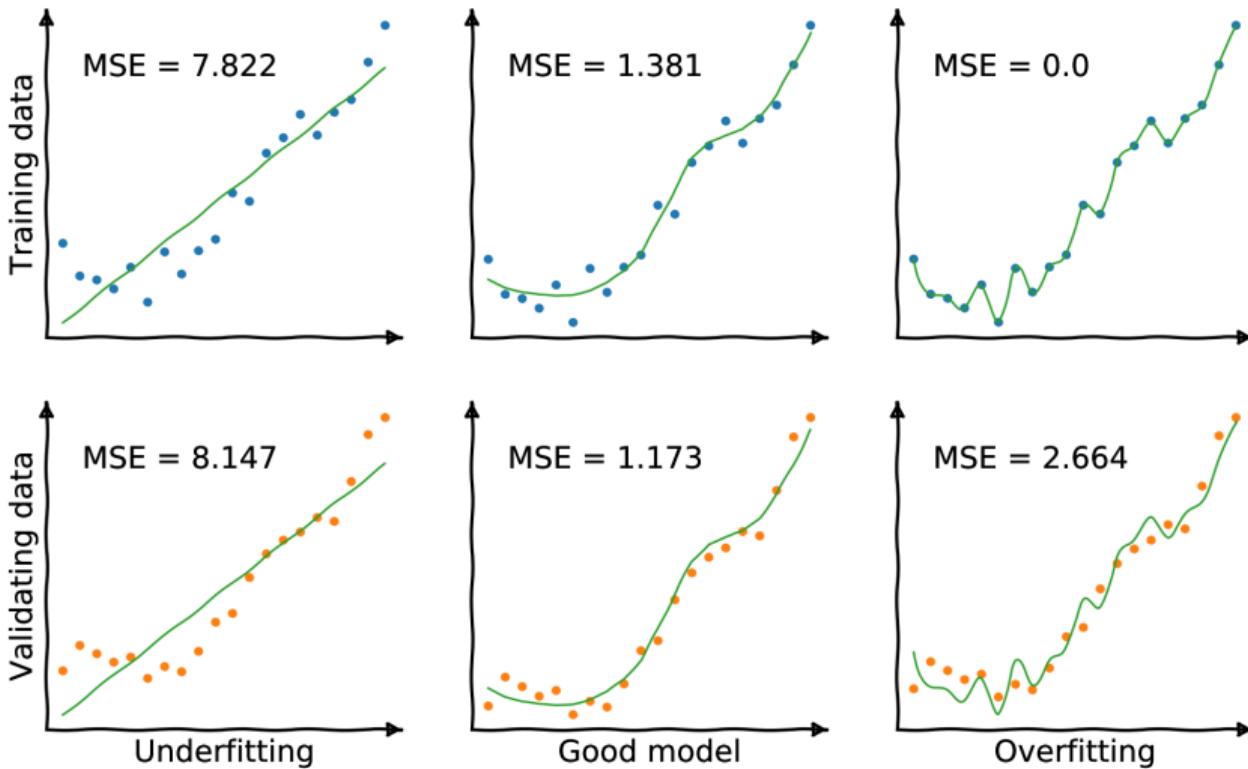


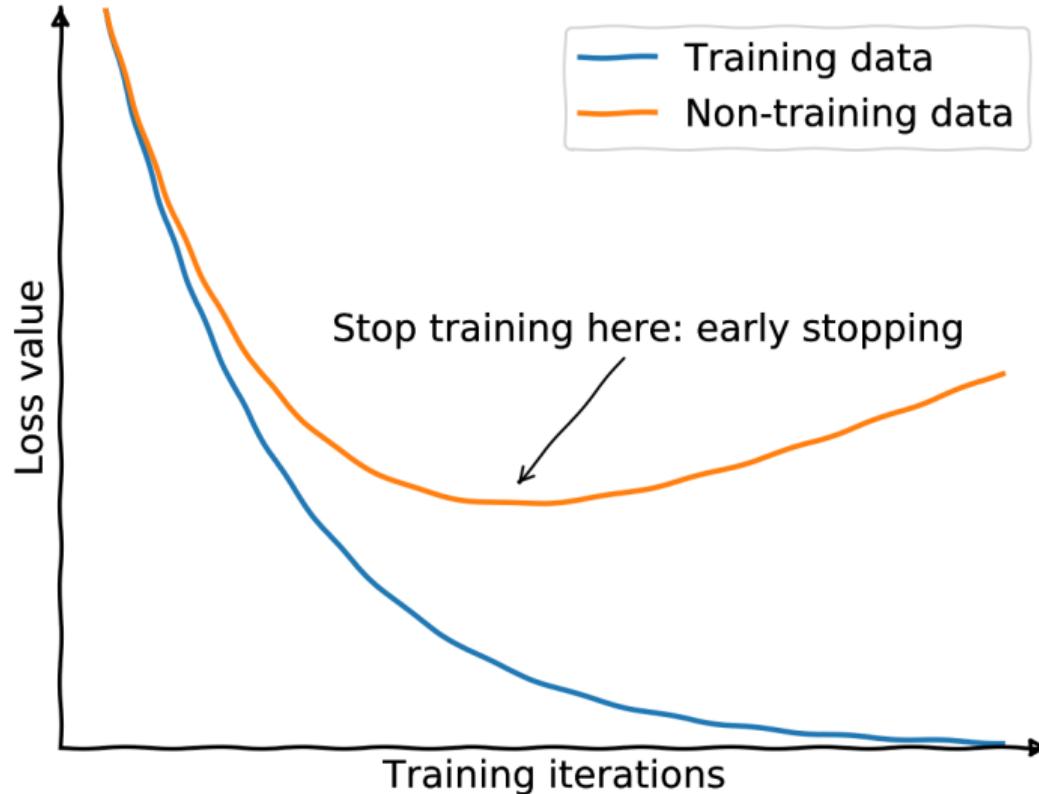


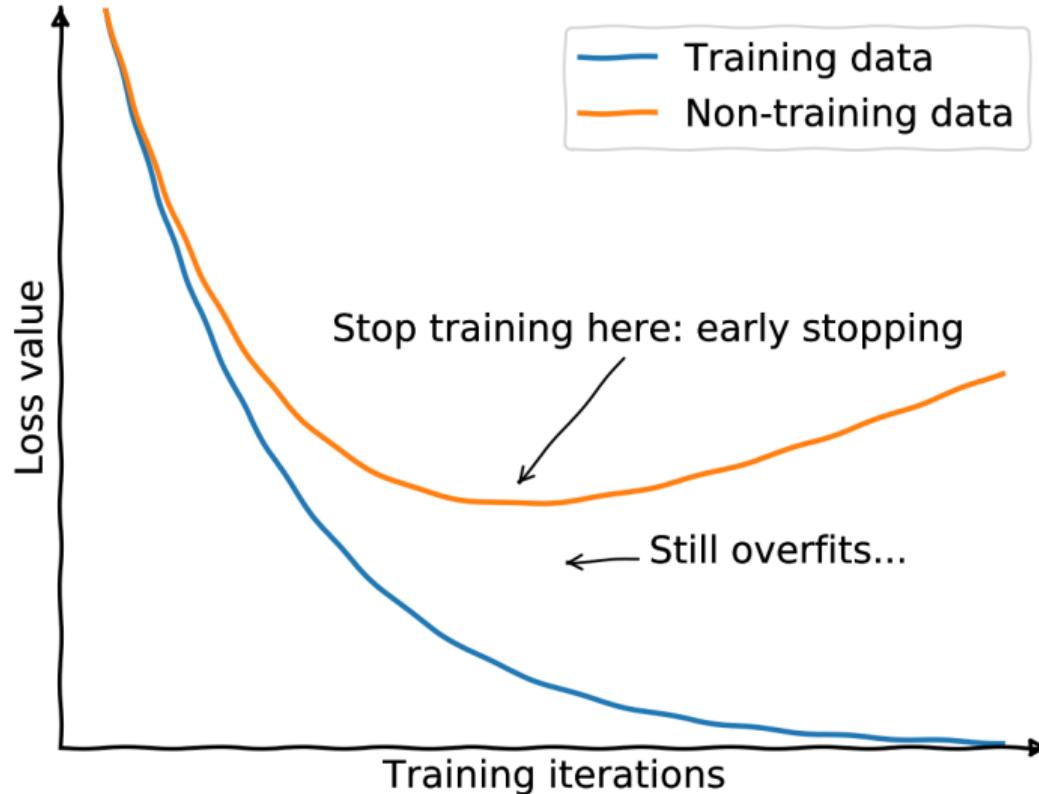


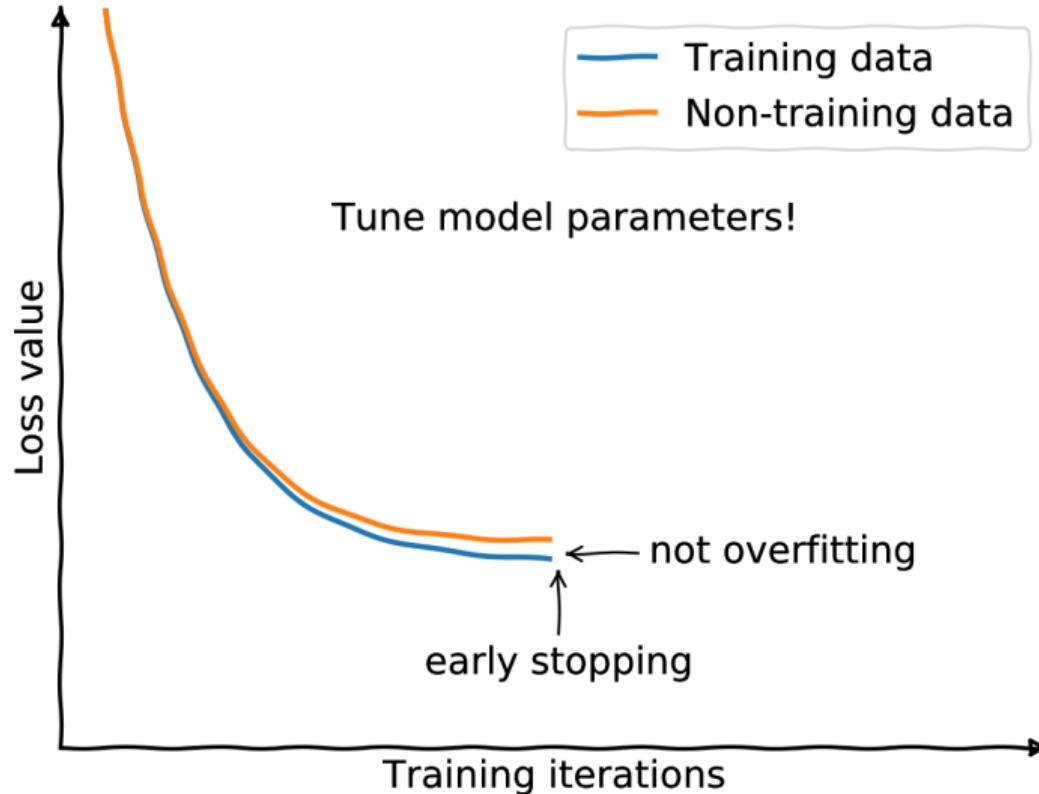




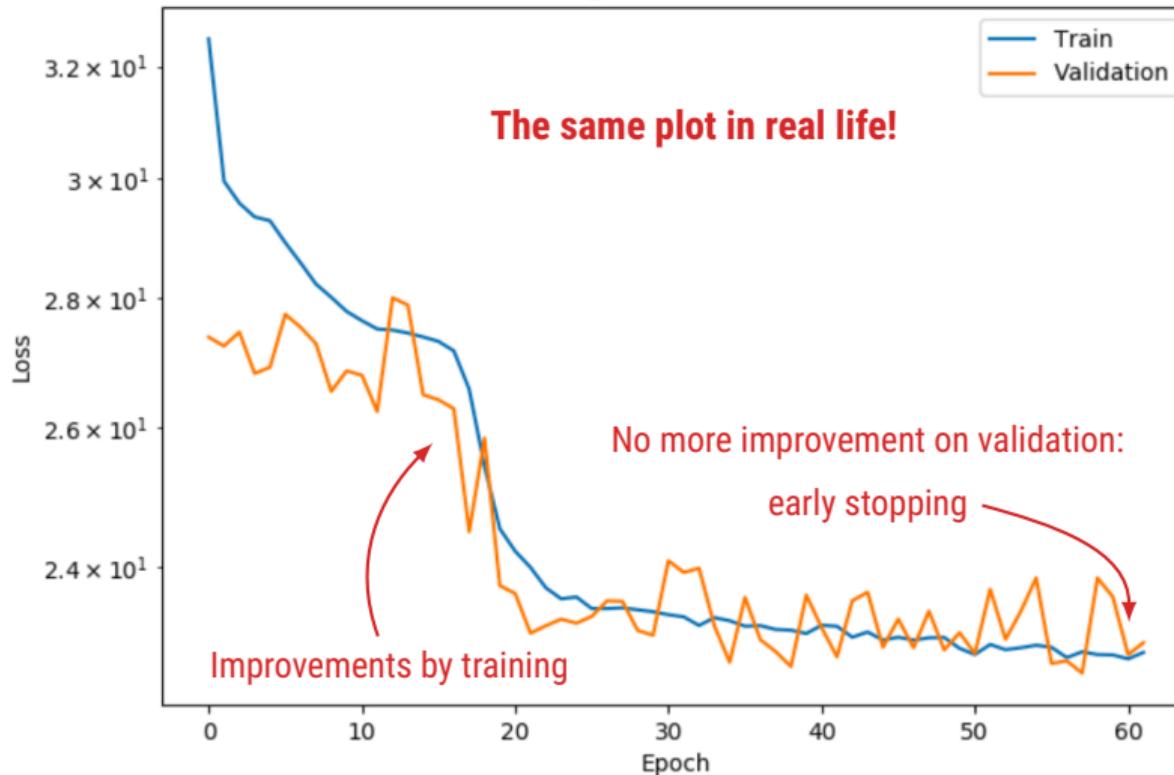








## Training vs Validation Loss



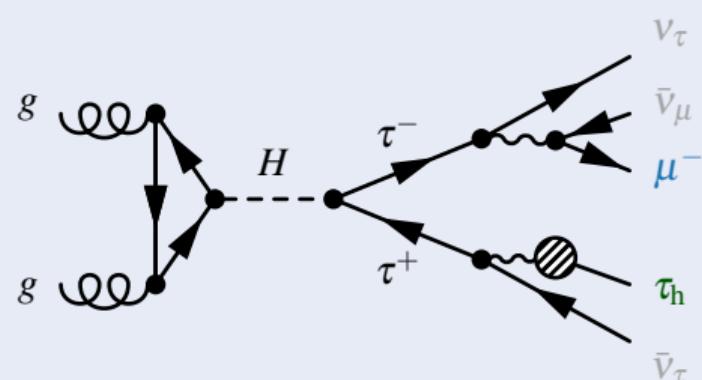
# Build a neural network: target and inputs?

► Model target: generated Higgs mass.

► Model inputs:

- ▷  $\tau_1$  (here =  $\mu^-$ ) and  $\tau_2$  (here =  $\tau_h$ )  $p_T, \eta, \phi$ ;
- ▷ PuppiMET  $p_T, \phi$ ;
- ▷ METcov xx, xy and yy;
- ▷ Number of neutrinos from reco tau decays;
- ▷  $m_T^{(1,MET)}, m_T^{(2,MET)}, m_T^{(1,2)}, m_T^{\text{tot}}$  (Puppi);
- ▷ jet 1, jet 2  $p_T, \eta, \phi$ ;
- ▷ Additionnal Hadronic Activity  $p_T, \eta, \phi, N_{\text{jets}}^{\text{AHA}}$ ;
- ▷ npvsGood  $\rightarrow$  how much PU.

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



$$m_T^{\text{tot}} = \sqrt{m_T^2(\tau_1, E_T^{\text{miss}}) + m_T^2(\tau_2, E_T^{\text{miss}}) + m_T^2(\tau_1, \tau_2)} , \quad m_T(1,2) = \sqrt{2 p_T^{(1)} p_T^{(2)} (1 - \cos \Delta\phi)}$$

# Build a neural network: hyperparameters?

- ▶ NN hyperparameters (and other tested values):
  - ▷ **Adam** optimizer (Adadelta, SGD),
  - ▷ Weight initialized with **Glorot uniform** (Glorot normal, normal, uniform),
  - ▷ Custom  $\mathcal{L}_{MA\sqrt{PE} \times b}$  loss ( $\mathcal{L}_{MAPE}$ ,  $\mathcal{L}_{MAE}$ ,  $\mathcal{L}_{MSE}$ ),
  - ▷ **Softplus** activation function (ReLU, ELU, SELU, Exponential),

$$\text{softplus}(x) = \ln(1 + e^x)$$

- ▷ 3 hidden layers (2 to 5),
- ▷ 1000 neurons per hidden layer (200 to 2000 per steps of 100).

# Datasets?

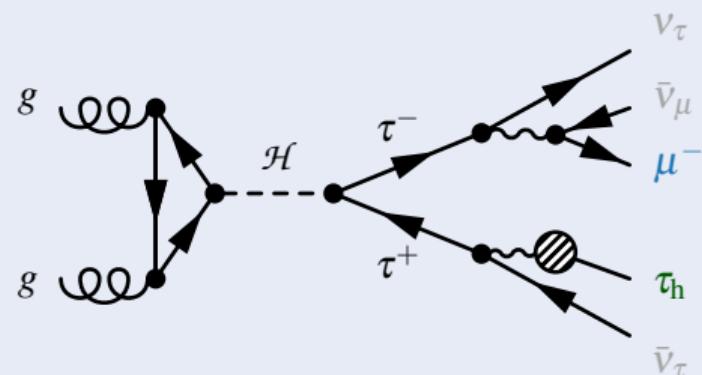
► Generate  $\mathcal{H} \rightarrow \tau\tau$  events:

- ▷  $\mathcal{H}$  is SM Higgs with a different mass,
- ▷  $\mathcal{H}$  produced by gluon fusion,
- ▷ set  $\mathcal{BR}(\mathcal{H} \rightarrow \tau\tau) = 1$  to avoid non di- $\tau$  events.

► All final states used simultaneously for training:

- ▷  $\tau_h\tau_h, \mu\tau_h, e\tau_h, \mu\mu, e\mu, ee$ .

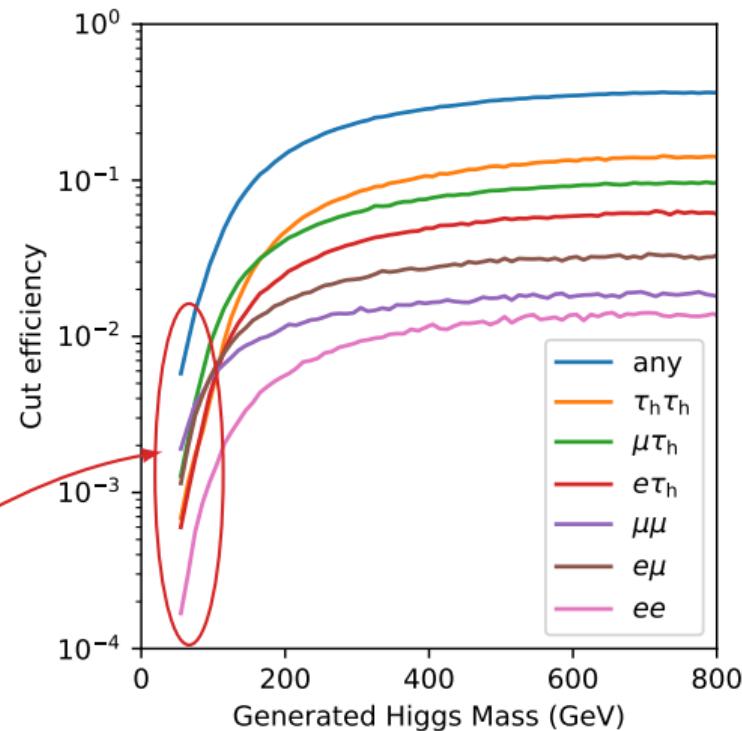
$$gg \rightarrow \mathcal{H} \rightarrow \tau\tau \rightarrow \mu\tau_h$$



# Datasets: low mass boundary

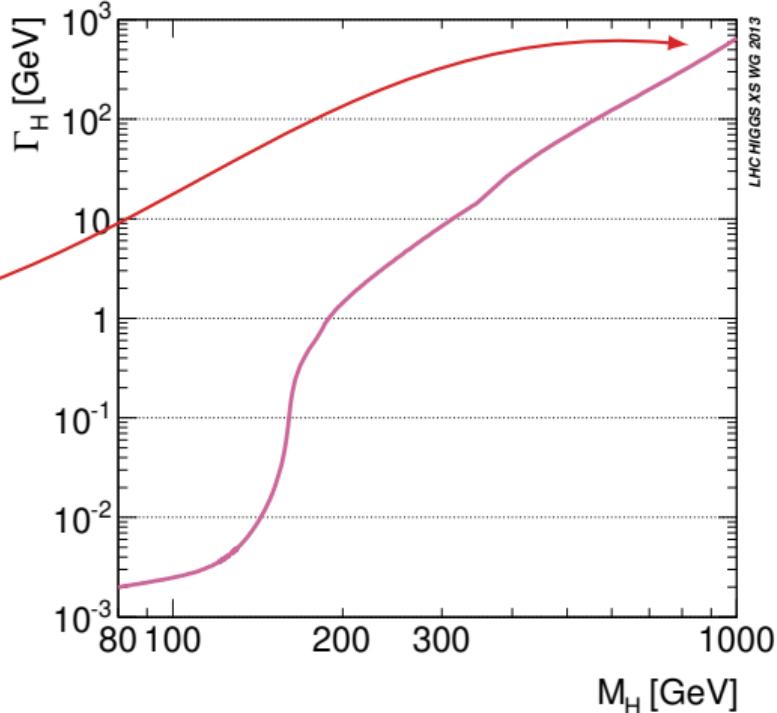
- ▶ Event selection:
  - ▷ Same as in the MSSM  $H/A \rightarrow \tau\tau$  analysis,
  - ▷ Add  $\mu\mu$  and  $ee$  channels.
- ▶ Events amount drops at low mass:
  - ▷ due to  $p_T$  cuts,
  - ▷ go down to 50 GeV for  $m_H$ .

Less than 1 % pass the selection



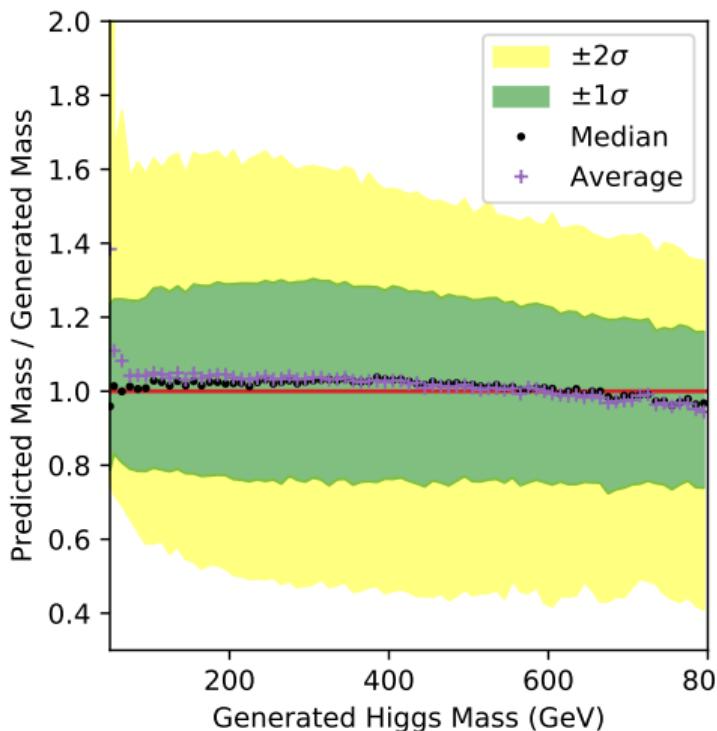
# Datasets: high mass boundary

- ▶ Higgs width  $\simeq$  Higgs mass around 1 TeV:
  - ▷ can't have coherent mass points,
  - ▷ go up to 800 GeV for  $m_H$ .



- ▶ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections*. 3. CERN Yellow Reports: Monographs. Geneva: CERN, 2013. URL: <https://cds.cern.ch/record/1559921>.

# Model's performances

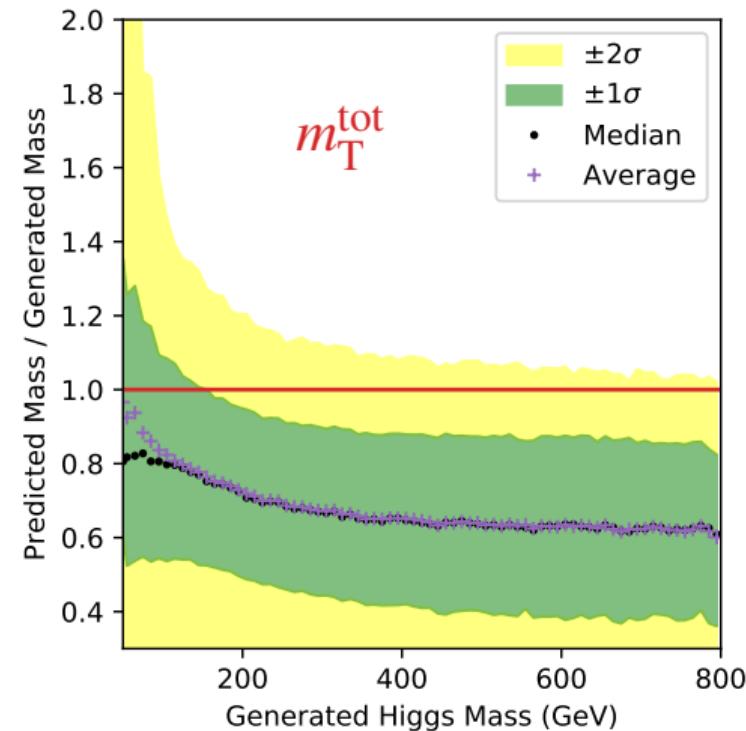
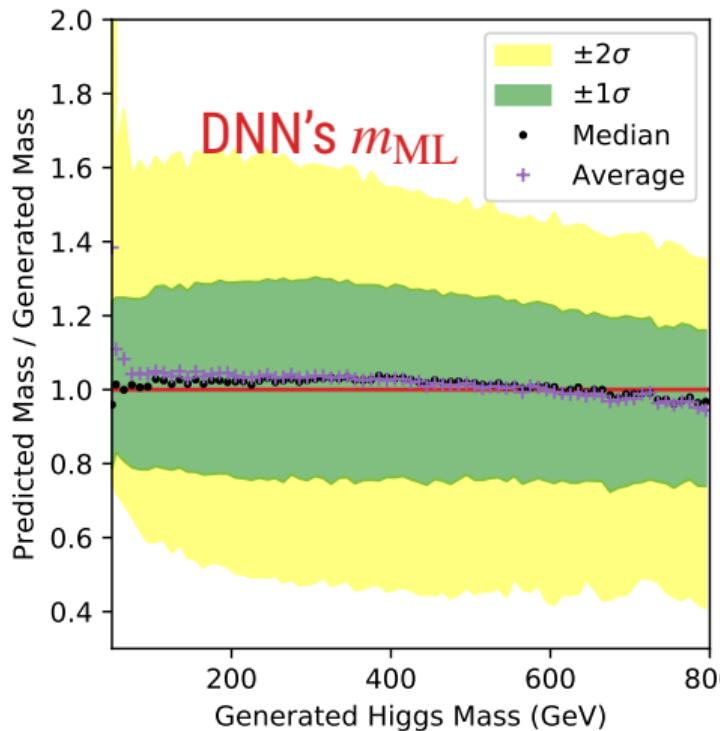


► Model's response:

$$r = \frac{\text{prediction}}{\text{true value}} = \frac{m_{\text{ML}}}{m_{\mathcal{H}}}$$

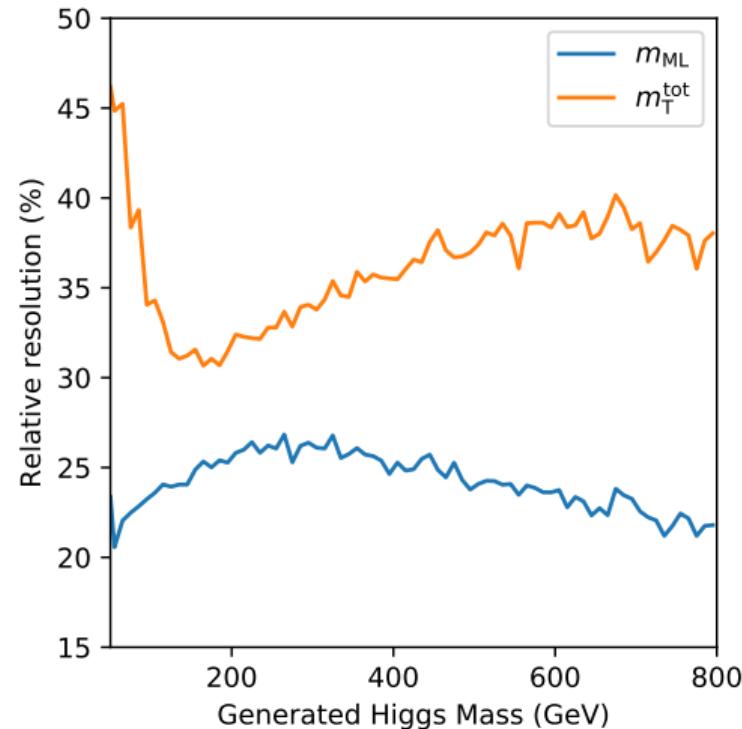
- ▷ Closer to 1 is better.
- ▷  $r = 1.00 \pm 0.05$  from 80 to 800 GeV
- ▷  $\mathcal{H}$  mass reconstruction achieved ✓

## DNN's $m_{\text{ML}}$ predictions vs $m_T^{\text{tot}}$

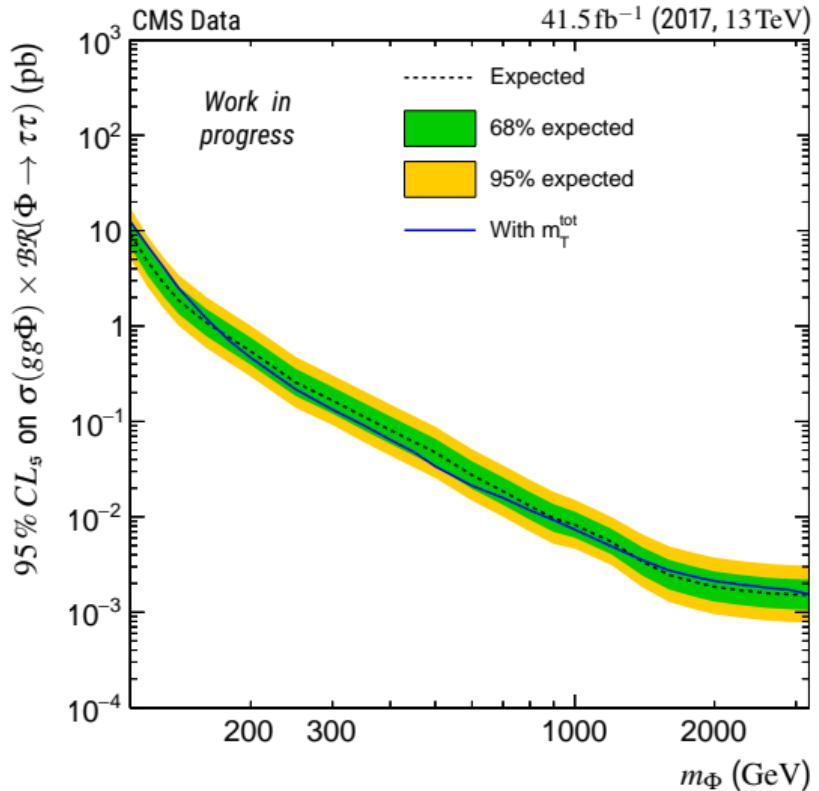


# Using the model to get a discriminating variable

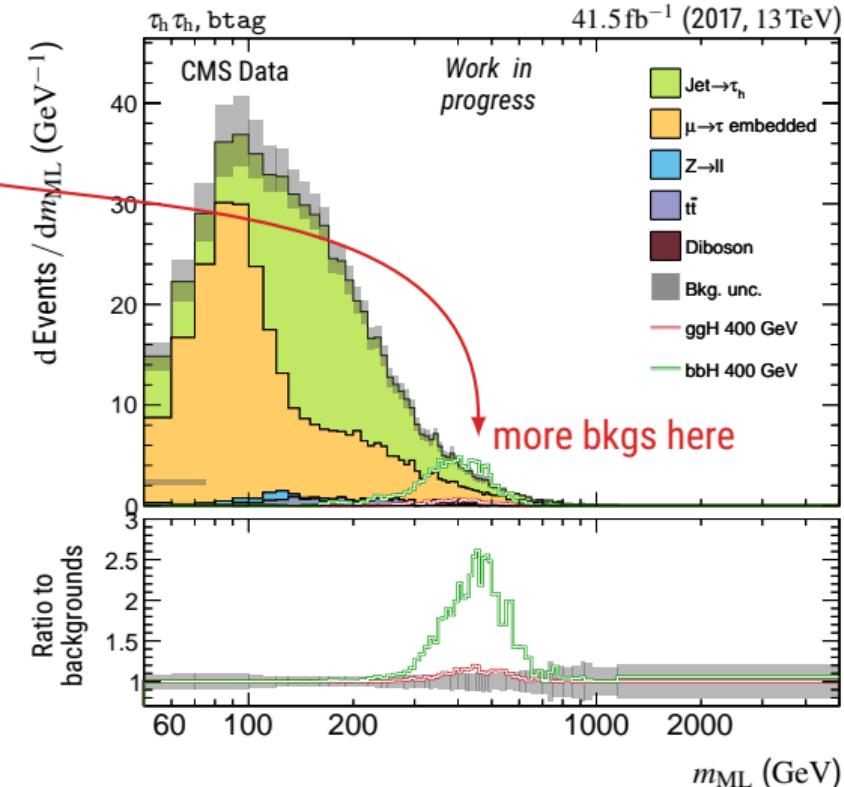
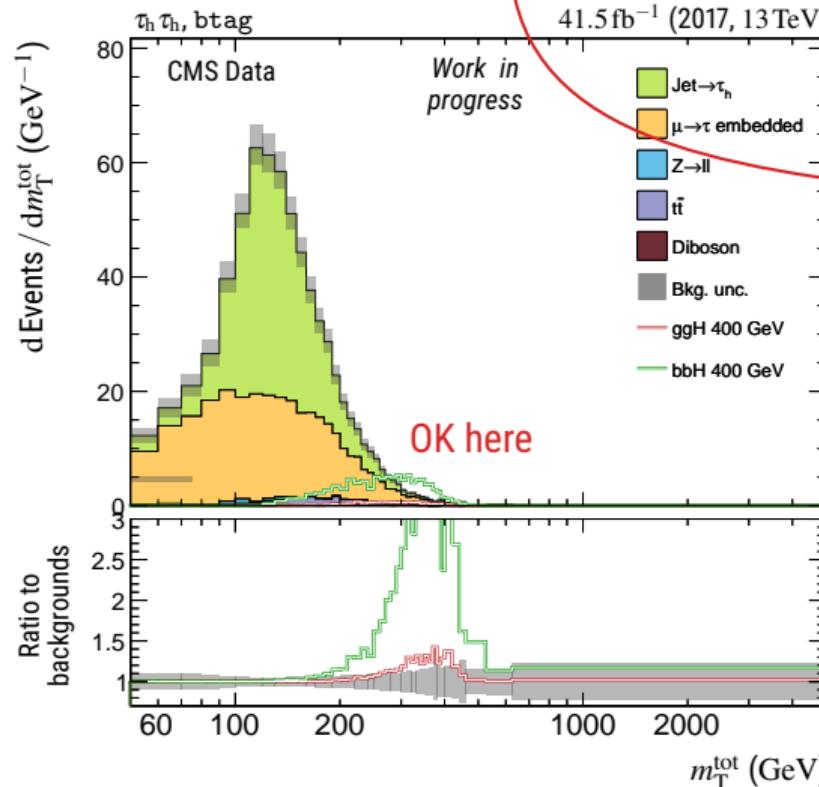
- ▶ In the  $H/A \rightarrow \tau\tau$  analysis, discriminating variable =  $m_T^{\text{tot}}$ .
- ▶  $m_T^{\text{tot}}$  is equal to the invariant mass assuming:
  - ▷ all neutrinos are a single particle with  $\vec{p}_T = \vec{E}_T^{\text{miss}}$ ,
  - ▷ all is going on in the transverse plane (any  $p_z = 0$ ).
- ▶ Our model has a better resolution on  $m_H$  than  $m_T^{\text{tot}}$ .



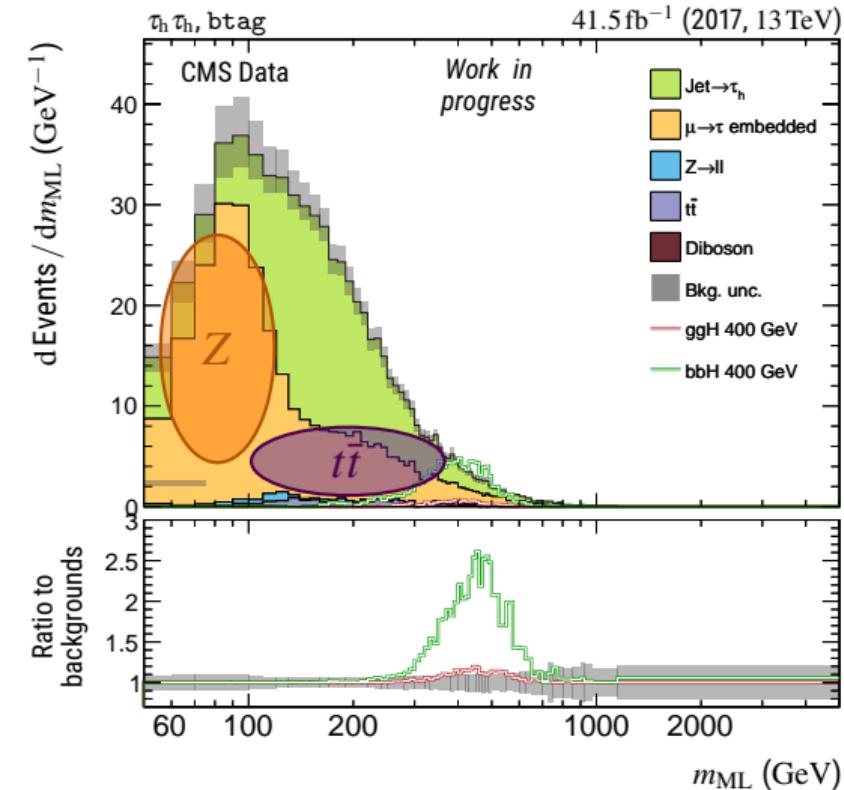
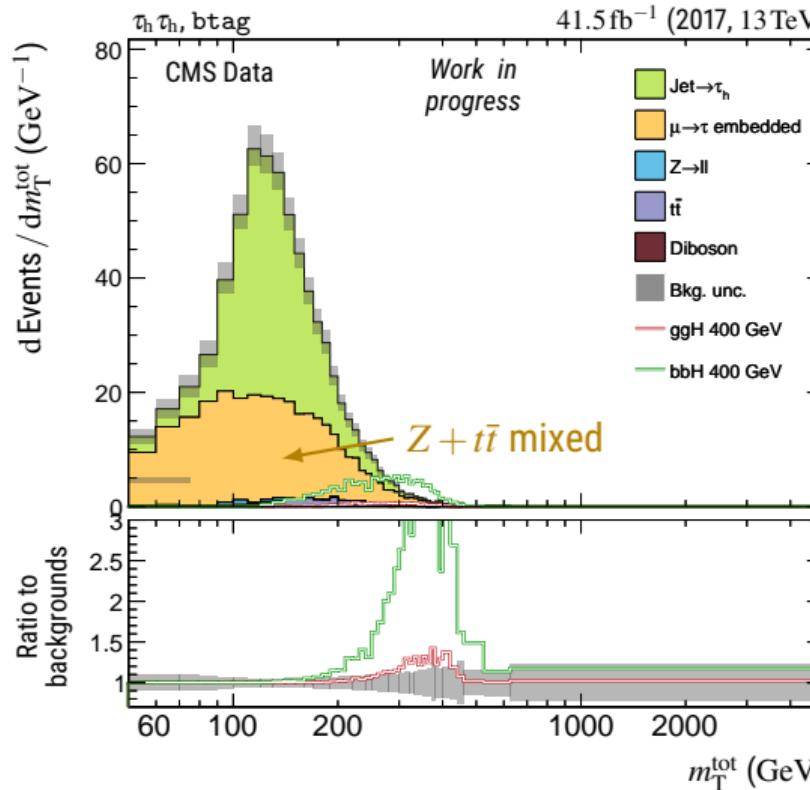
- ▶ Proceed to the search for massive Higgs boson  $\Phi$  with di- $\tau$  events on the 2017 era.
- ▶ Use  $m_{\text{ML}}$  as discriminating variable.
- ▶ Not really better than with  $m_T^{\text{tot}}$ ... Why?



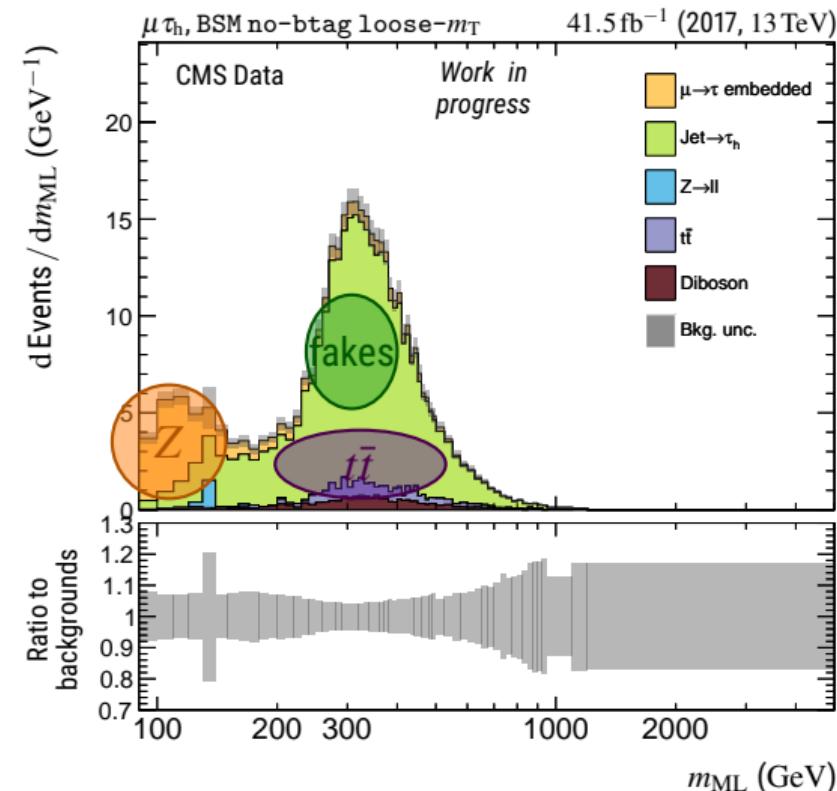
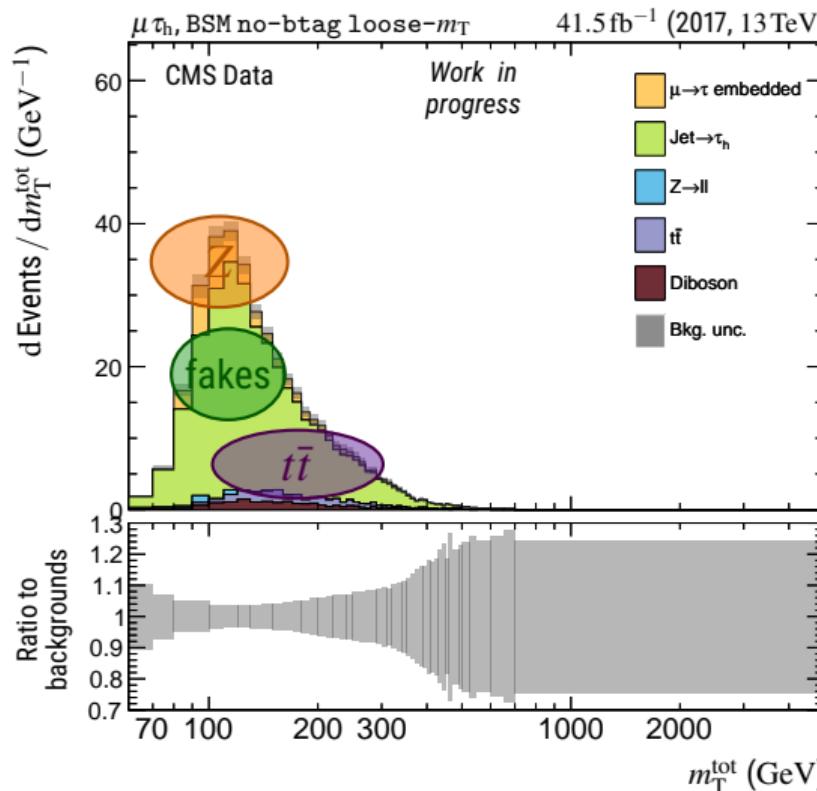
► Large fakes  $\tau_h$  high mass tails falling into the signal region  $\Rightarrow$  lowered signal to background ratio.



► BUT  $Z / t\bar{t}$  separation! See the two  $m_{ML}$  embedded components, not present with  $m_T^{\text{tot}}$ .

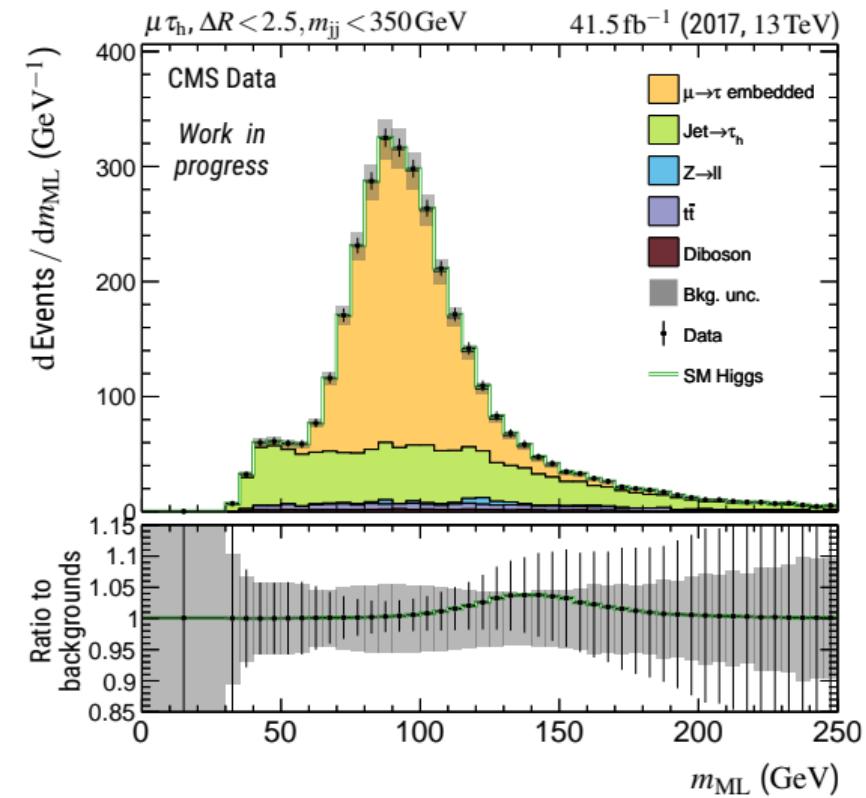
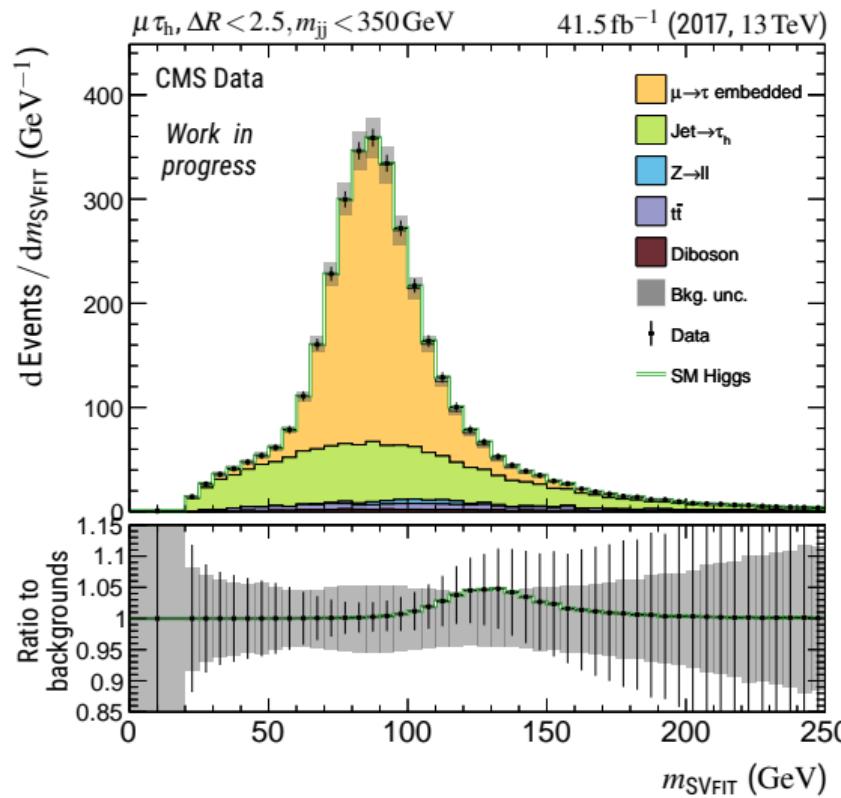


► Visible in other categories too. But here, the SVFit mass is above 250 GeV and our model sees a  $Z$  signal!

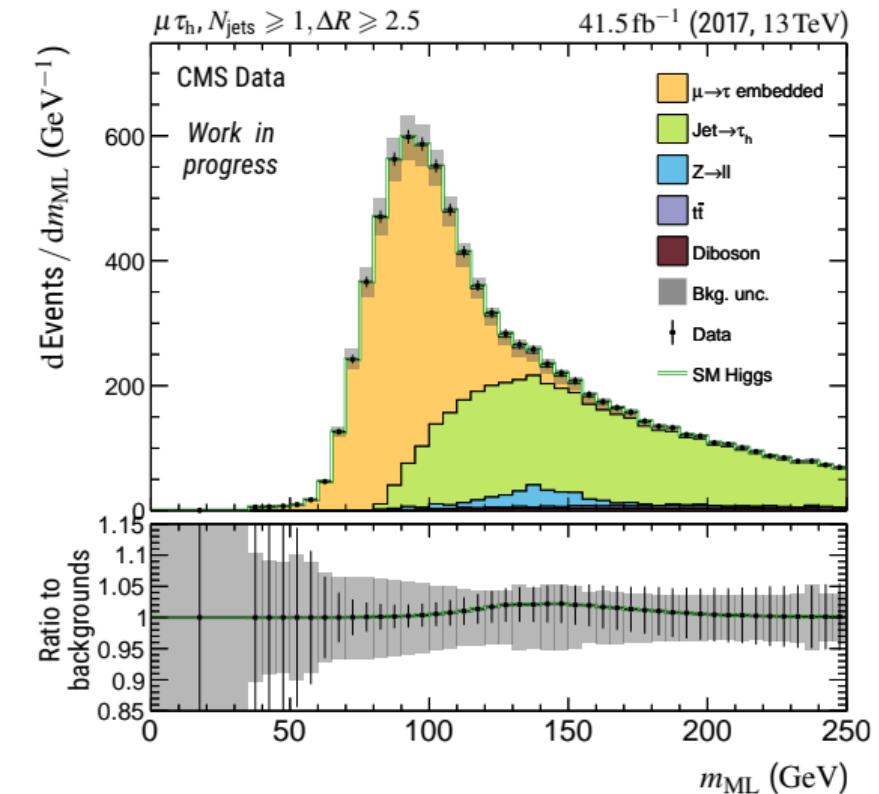
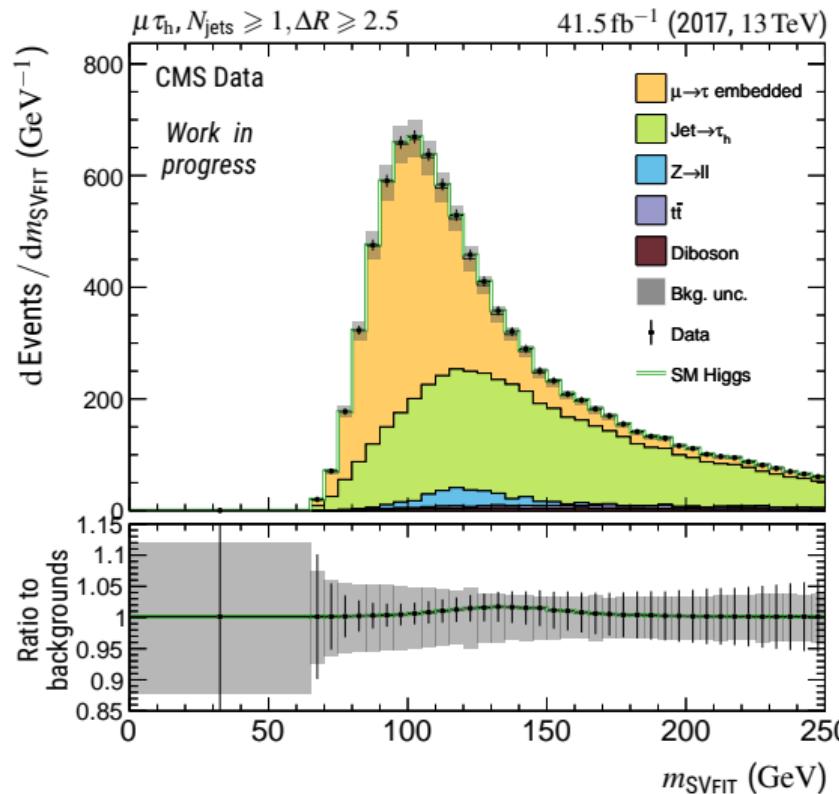


Let's compare the SVFit predictions  $m_{\text{SVFit}}$  to our model's ones  $m_{\text{ML}}$ .

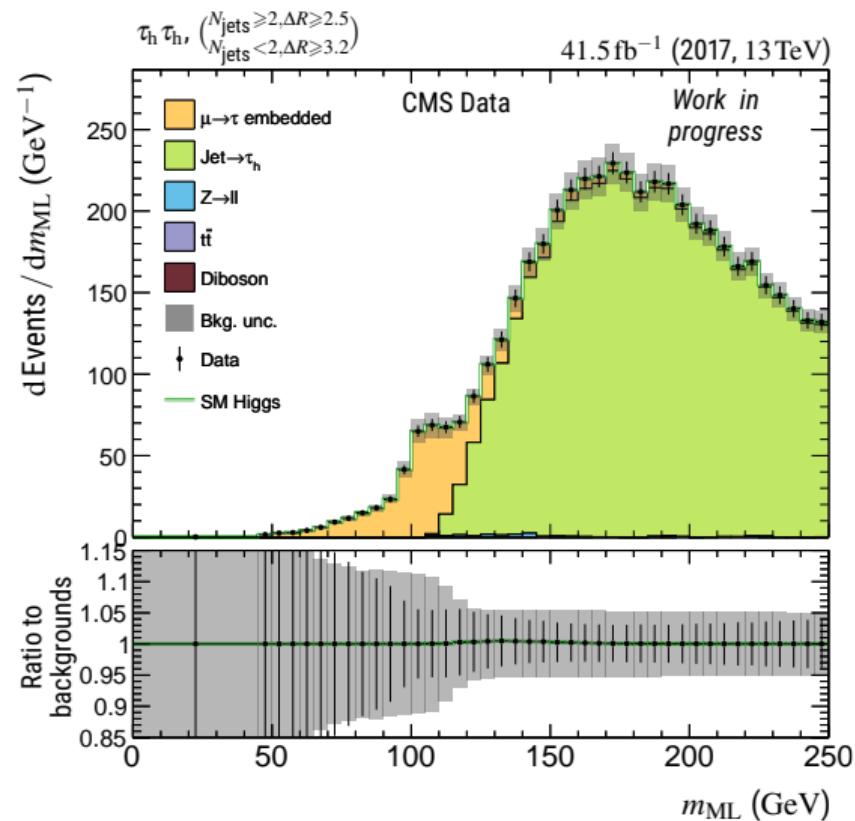
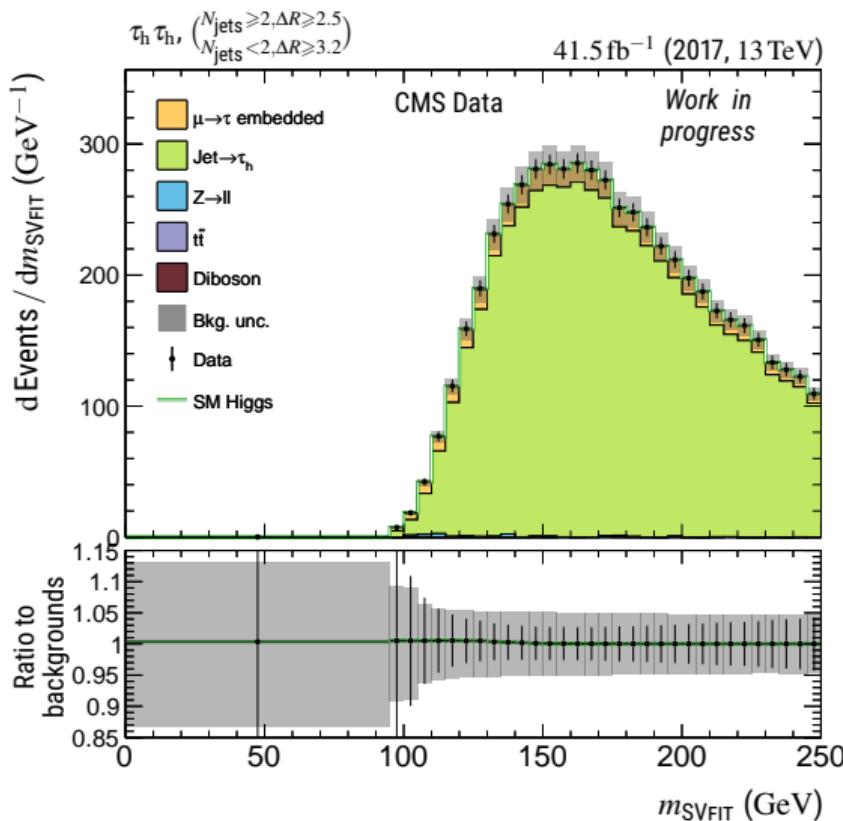
► Similar SM Higgs signal sensitivity, small (expected) overestimation from our model.



► Better DY estimations (peak at 100 GeV for  $m_{\text{SVFIT}}$ , 92 GeV for  $m_{\text{ML}}$ ) and fakes at higher masses!

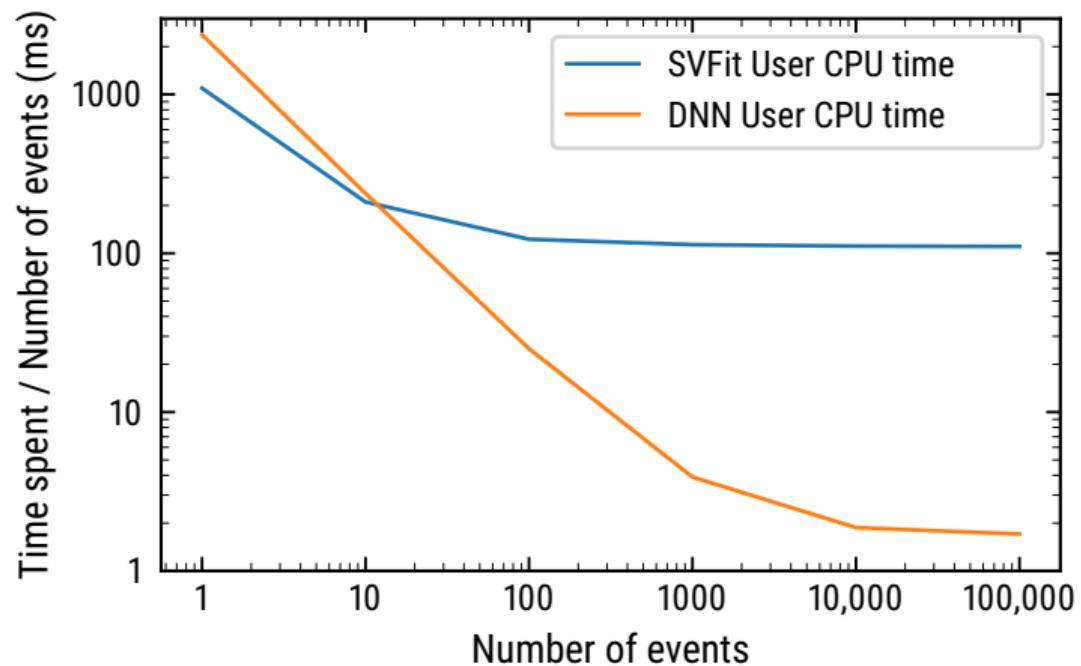


► Our model finds  $Z \rightarrow \tau\tau$  events when SVFIT does not!



- ▶ Computing time: DNN (Python) is  $\sim 60\times$  faster than SVFIT (C++)!

- ▶ SVFIT:
  - ▷ fit to find the best mass
  - ▷ for each event
- ▶ DNN:
  - ▷ fit done once (training)
  - ▷ apply the DNN formula



# Conclusion & prospects: $H/A \rightarrow \tau\tau$

TODO

# Conclusion & prospects: ML project

- ▶ Successful  $m_{\mathcal{H}}$  reconstruction in di- $\tau$  events.
  - ▷ Not only MSSM  $H/A \rightarrow \tau\tau$  but any  $X \rightarrow \tau\tau$  analysis could benefit.
- ▶  $m_{\text{ML}}$  vs  $m_{\text{T}}^{\text{tot}}$ :
  - ▷ A good mass estimator is not equivalent to a good discriminating variable.
  - ▷ Still, we already have the same performances at this point.
- ▶  $m_{\text{ML}}$  vs  $m_{\text{SVFIT}}$ :
  - ▷ Similar Higgs sensitivity for some event topologies.
  - ▷ Better  $Z$  estimation observed (the model has been trained on  $\mathcal{H} \rightarrow \tau\tau$  with various masses only).
  - ▷ Faster (about 60 times!).
  - ▷ Could be improved by updating the training datasets (other kinds of events).
  - ▷ Very promising as a SVFIT successor.

# Merci!

Thank you for your attention!