



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

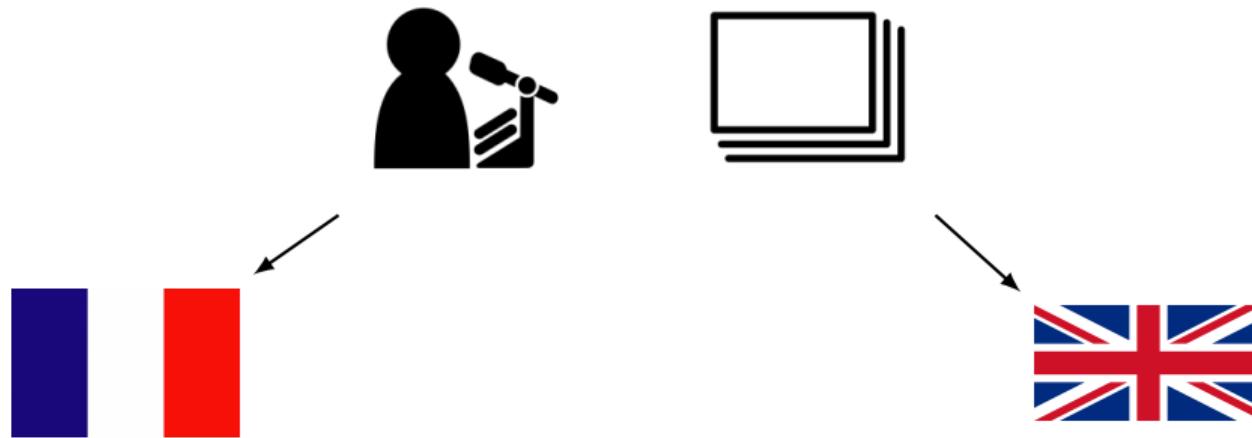
Lucas TORTEROTOT

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

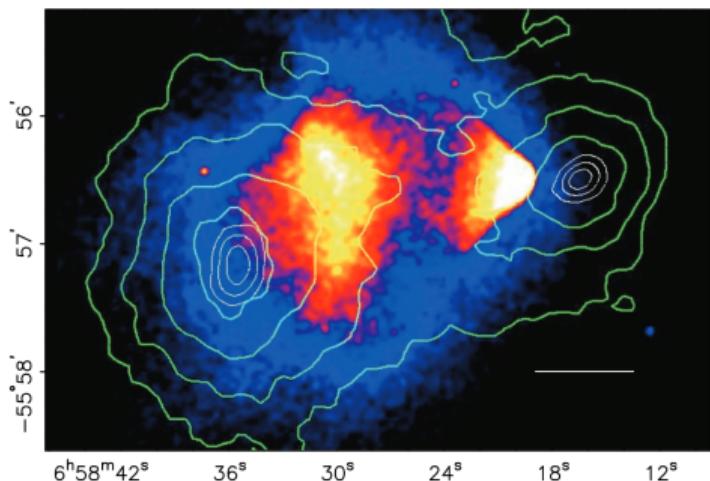
July 8, 2021



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!**



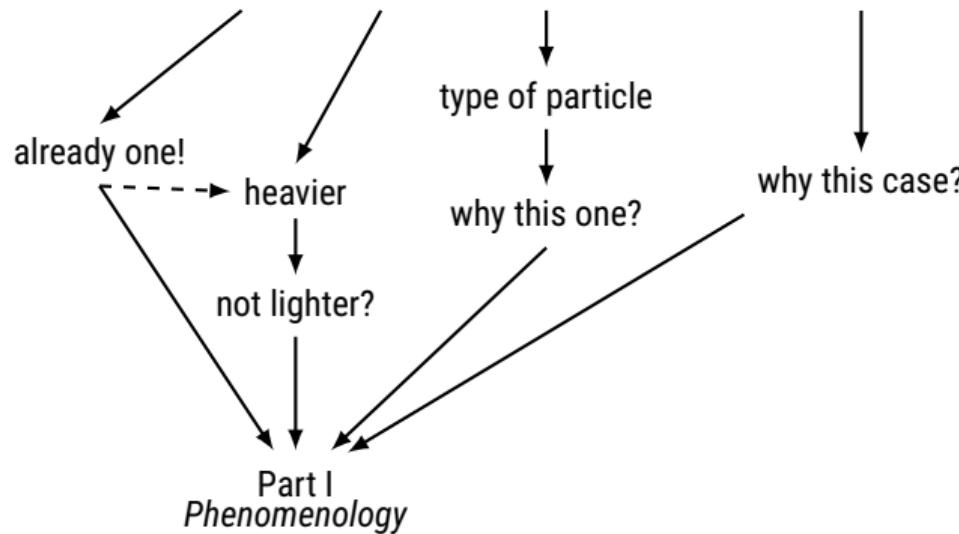
▷ D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

Keywords in title

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

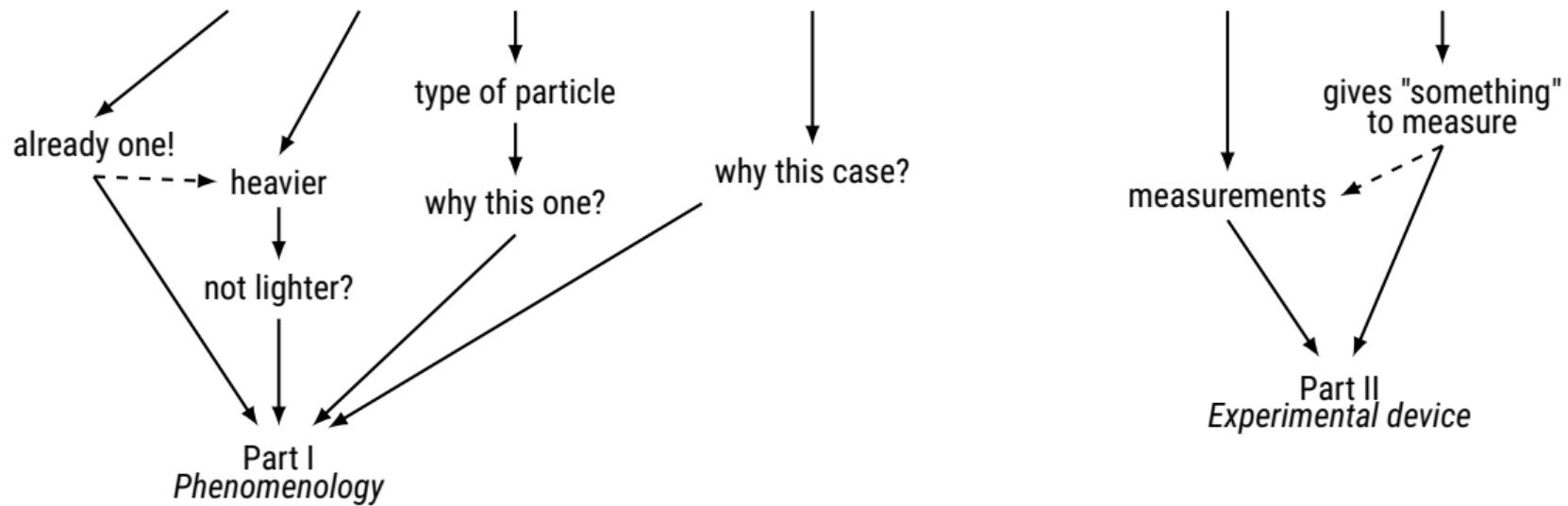
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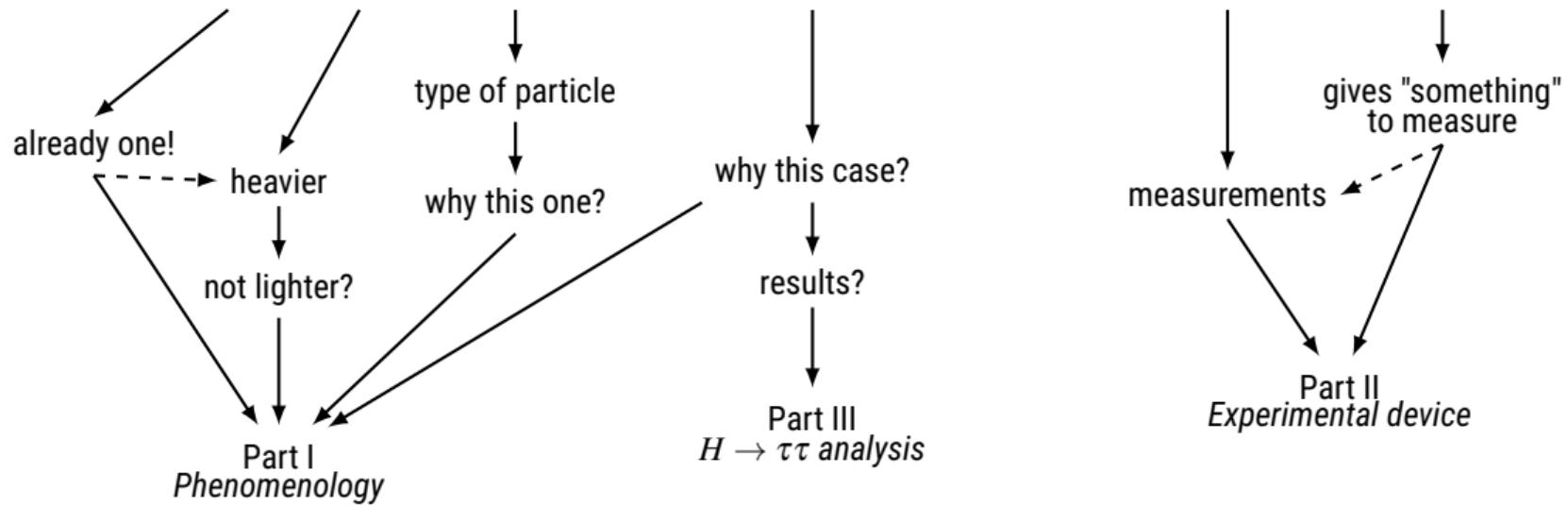
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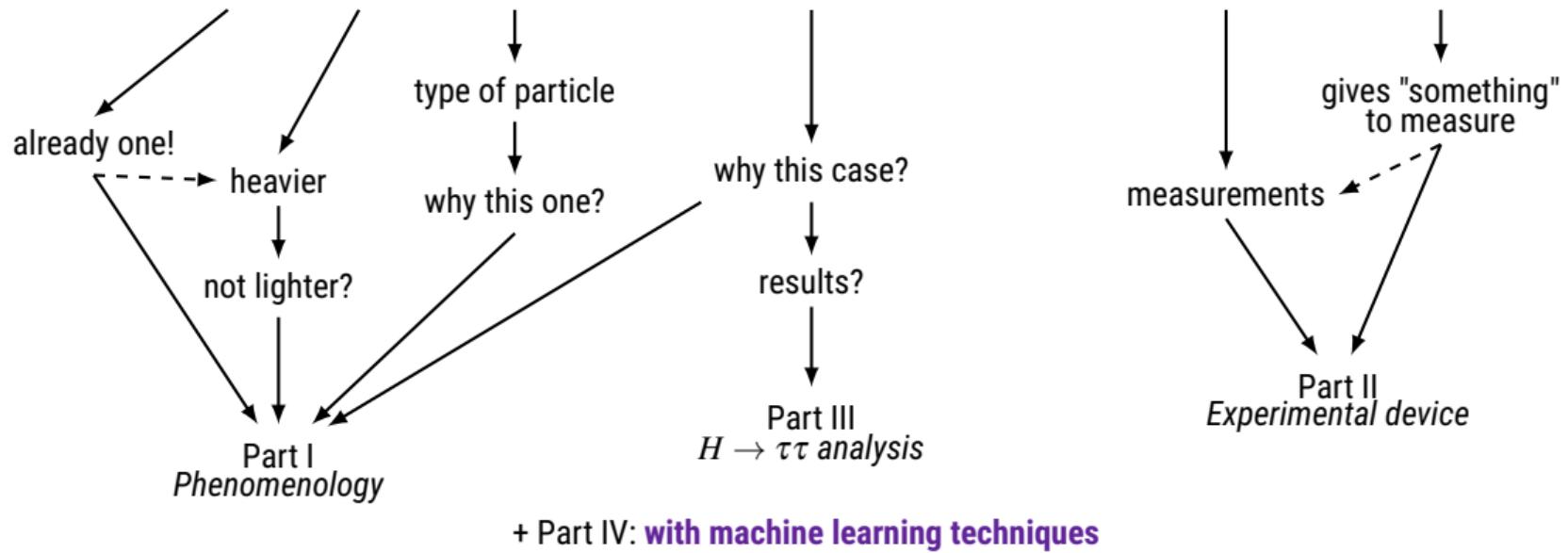
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Search for **additional heavy Higgs bosons decaying to tau lepton pair** in the **CMS experiment** at **LHC**



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1 Phenomenology

2 Experimental device

3 $H \rightarrow \tau\tau$ analysis

4 Machine learning

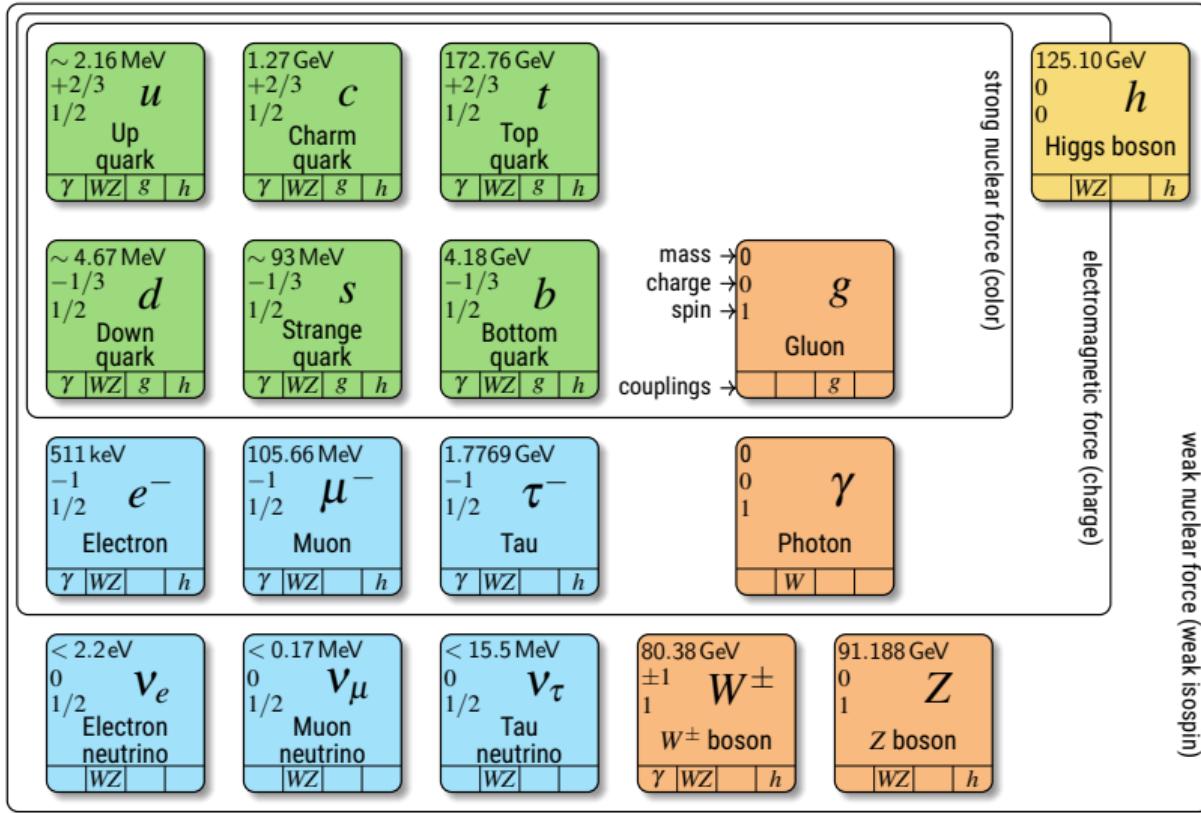
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The Standard Model



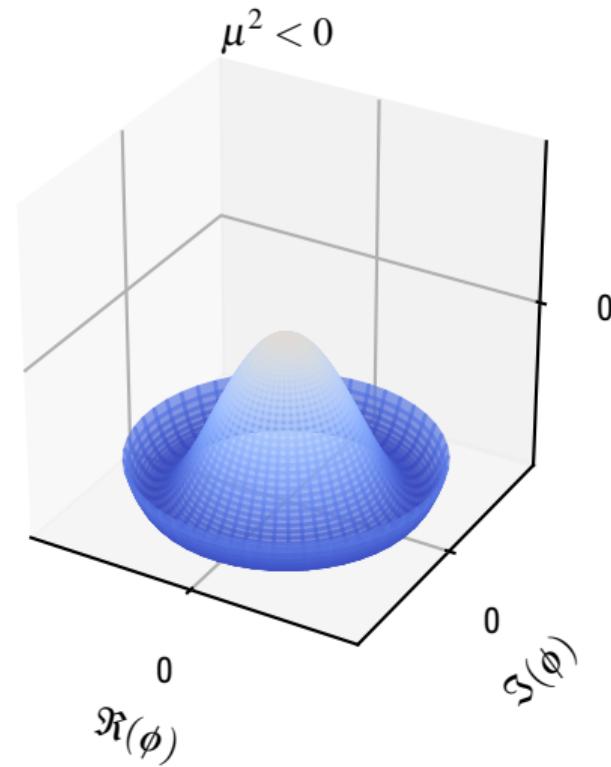
Higgs boson in the Standard Model

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

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

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

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

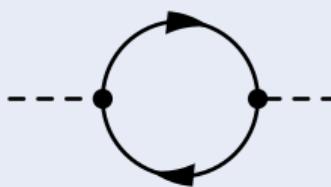


The Standard Model and naturalness problem

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

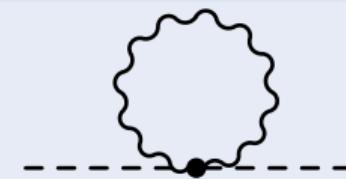
► Higgs mass derivation: $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



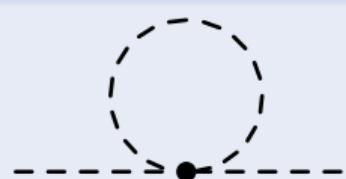
$$-\frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim -(2 \text{ TeV})^2$$

vector bosons



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

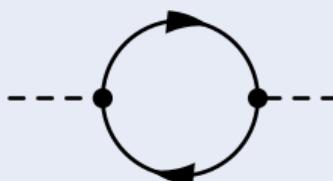
Higgs itself



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

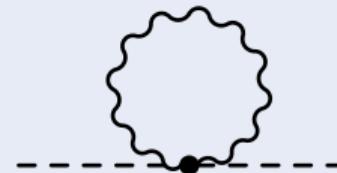
Supersymmetry

top quark



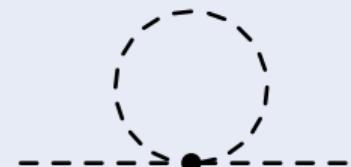
$$\sim -(2 \text{ TeV})^2$$

vector bosons



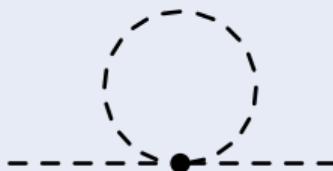
$$\sim +(0.7 \text{ TeV})^2$$

Higgs itself



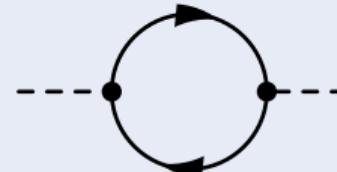
$$\sim +(0.5 \text{ TeV})^2$$

stop quark



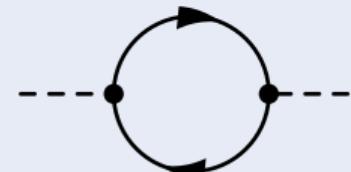
$$\sim +(2 \text{ TeV})^2$$

bosinos



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

Higgsinos



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

2 Higgs doublets models for supersymmetry

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

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

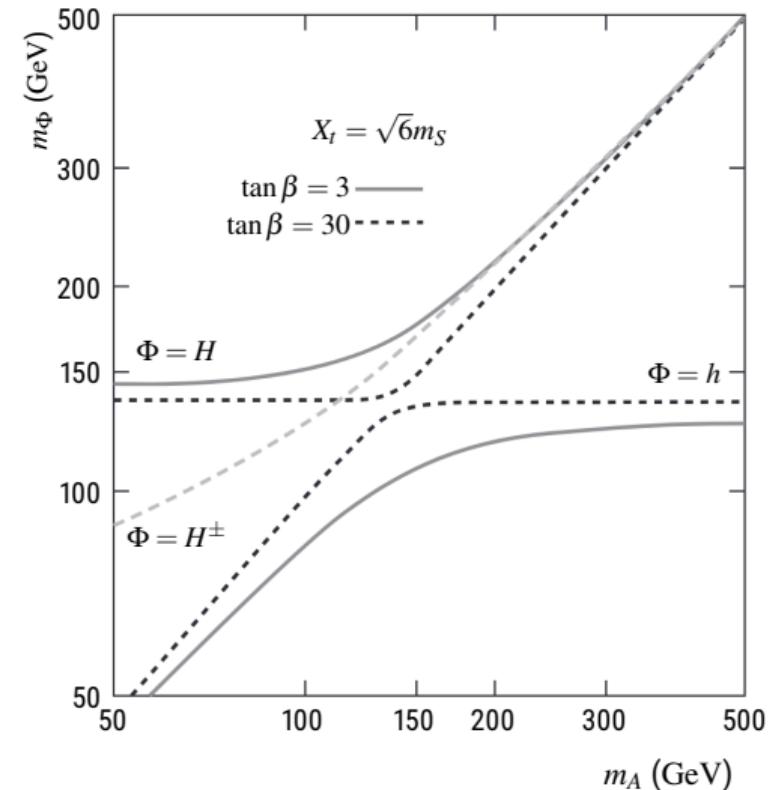
Minimal Supersymmetric extension of Standard Model

5 Higgs bosons

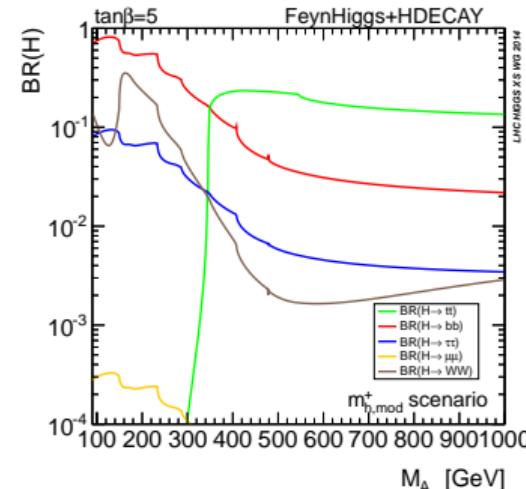
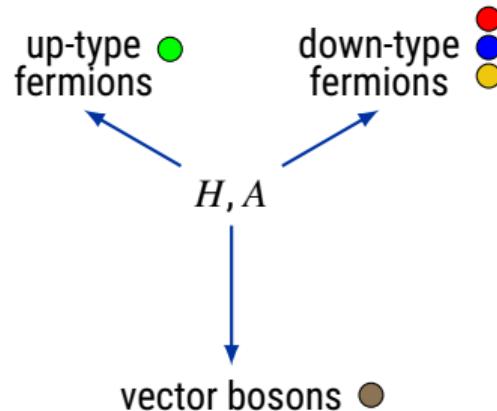
light scalar	h	SM or MSSM
heavy scalar	H	MSSM or SM
pseudo-scalar	A	MSSM
+ charged	H^+	MSSM
- charged	H^-	MSSM

▷ **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>.

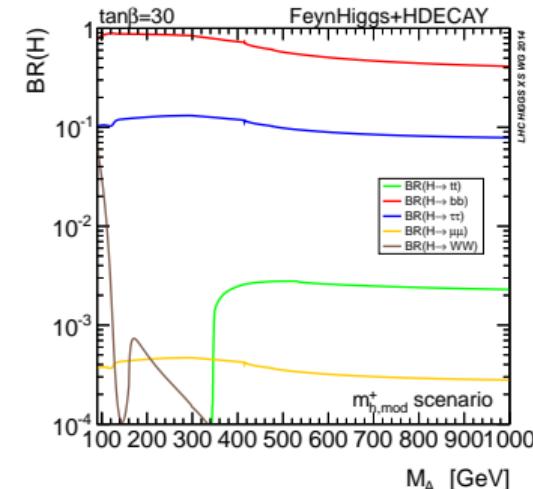
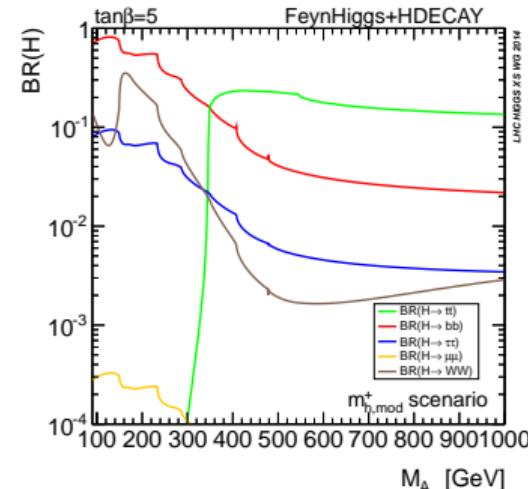
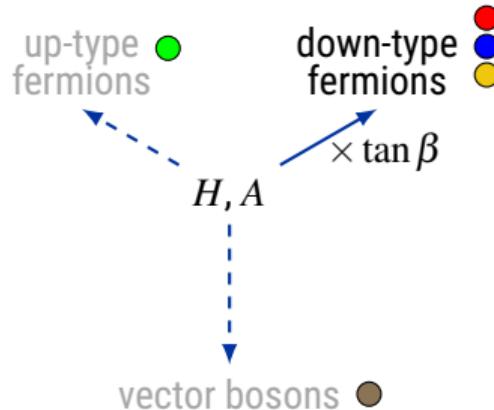


$H \rightarrow \tau\tau?$

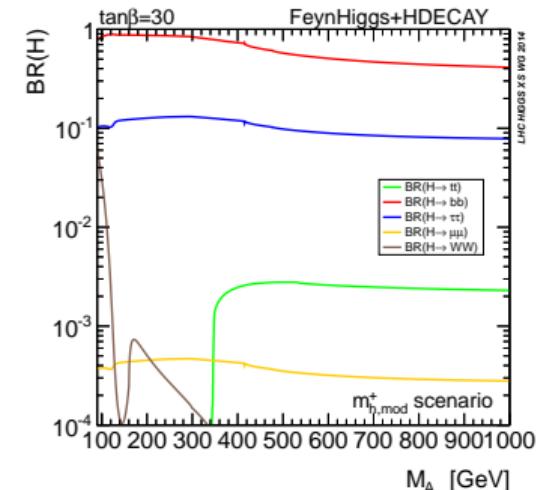
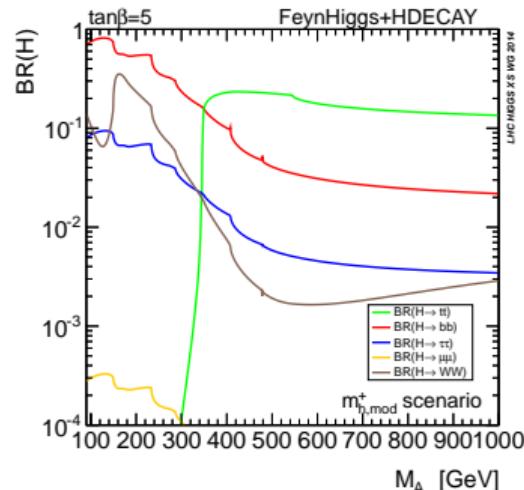
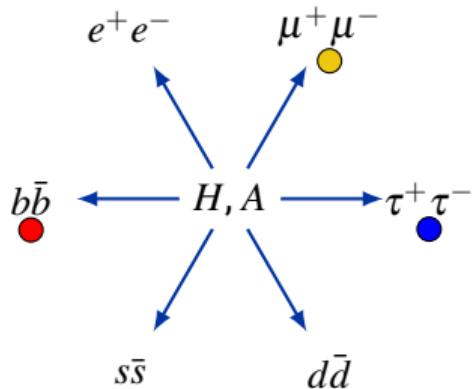


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook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

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

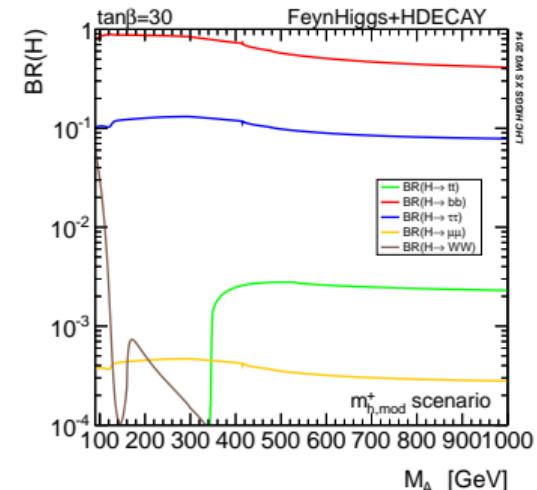
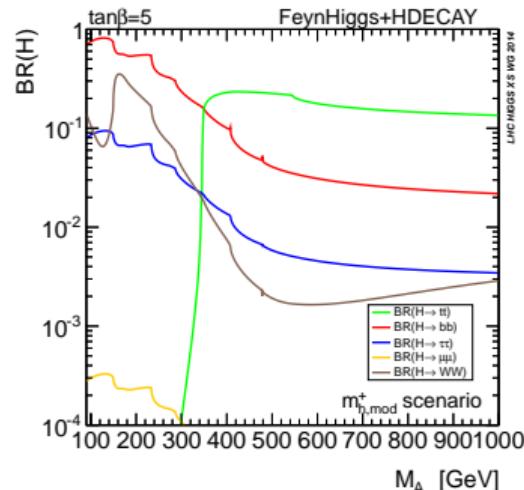
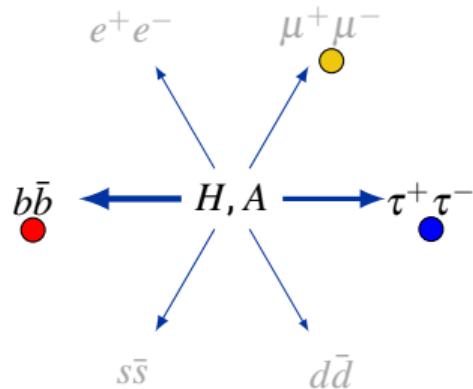


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook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

$H \rightarrow \tau\tau?$ 

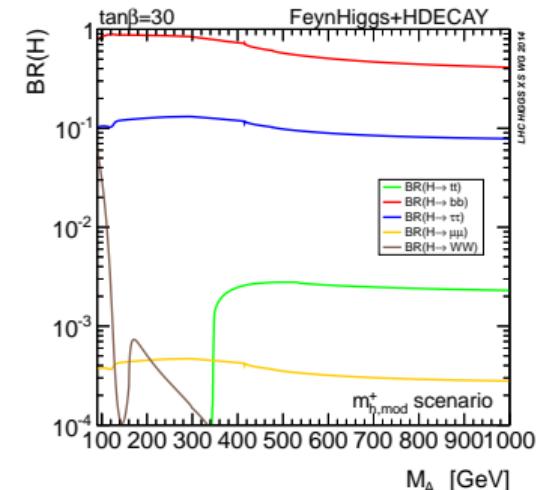
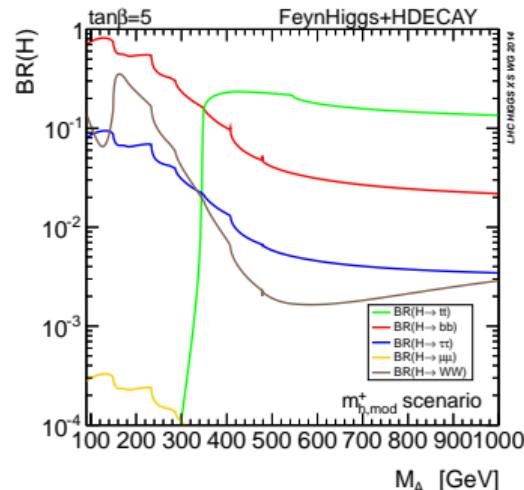
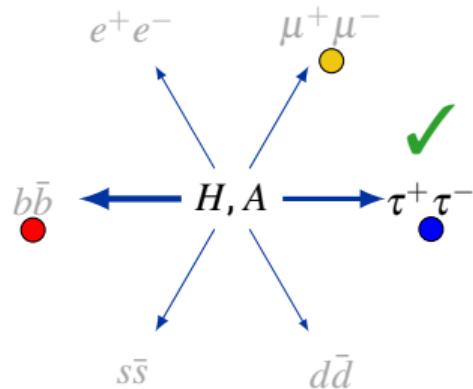
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ ". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).
- ▷ LHC Higgs Cross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

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



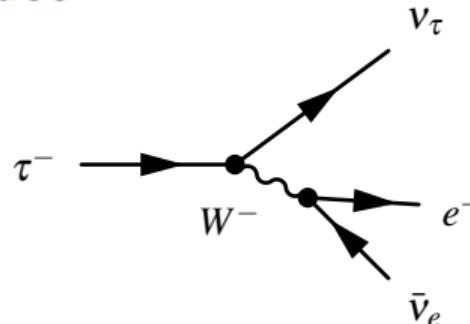
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).
- ▷ LHC Higgs Cross Section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

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

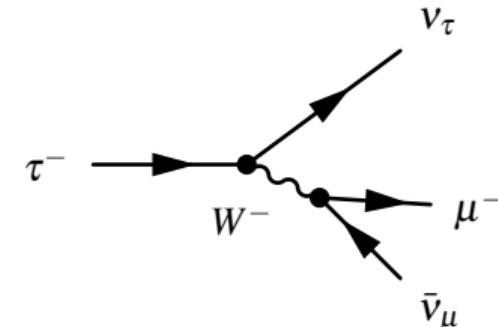
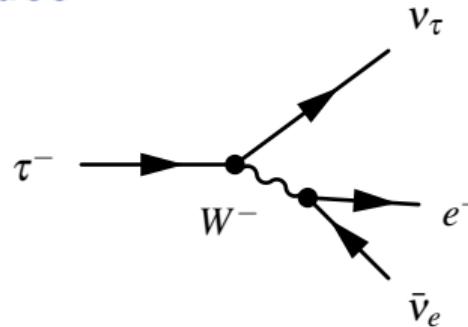


- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ ". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.
- ▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook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

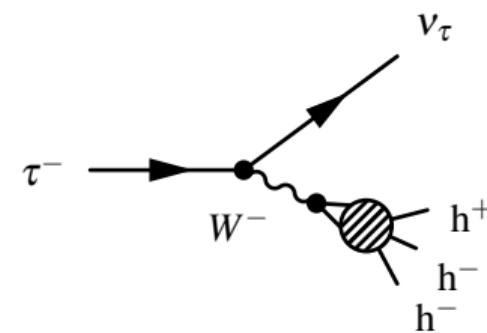
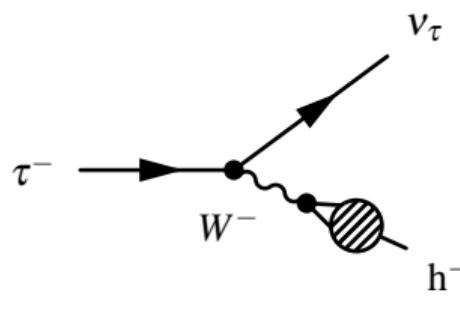
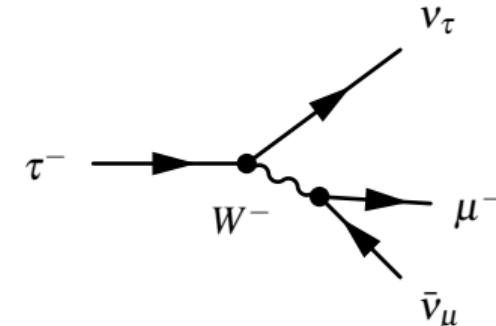
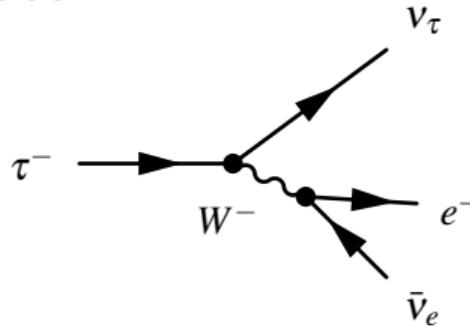
τ decay modes



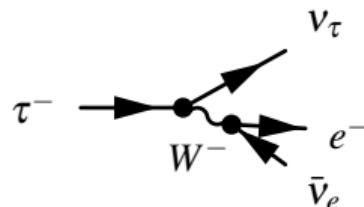
τ decay modes



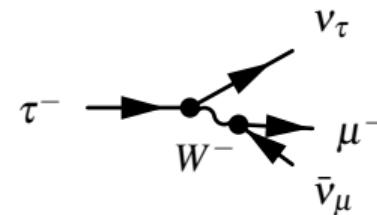
τ decay modes



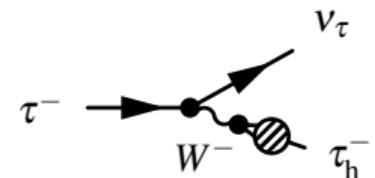
$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$



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

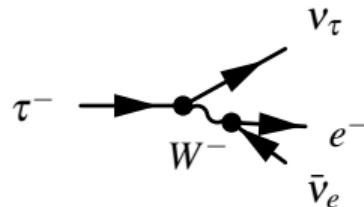


$$\tau \rightarrow \mu + \nu_\mu + \nu_\tau \Rightarrow \mu \\ 17.4\%$$

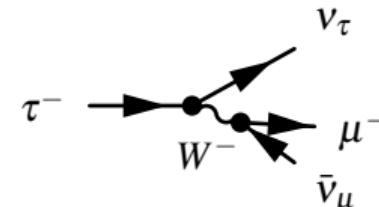


$$\tau \rightarrow \text{hadrons} + \nu_\tau \Rightarrow \tau_h \\ 64.8\%$$

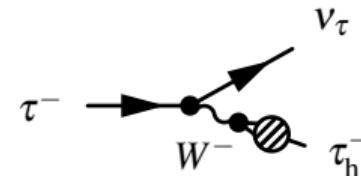
$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$



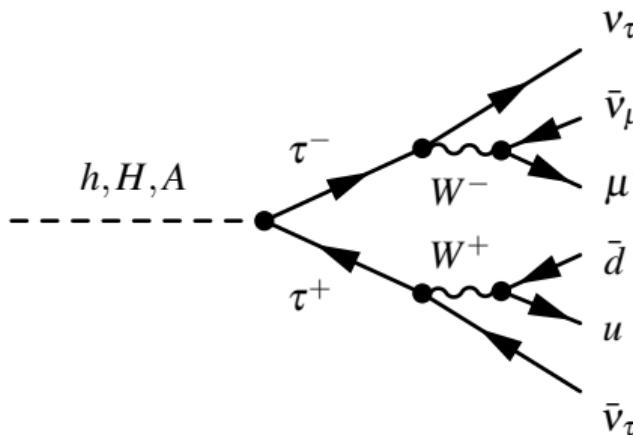
$$\tau \rightarrow e + \nu_e + \nu_\tau \Rightarrow e \\ 17.8\%$$



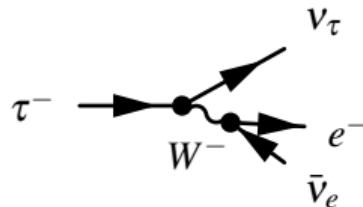
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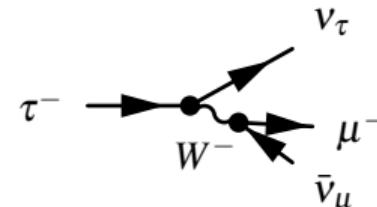
$$\tau \rightarrow \text{hadrons} + \nu_\tau \Rightarrow \tau_h \\ 64.8\%$$



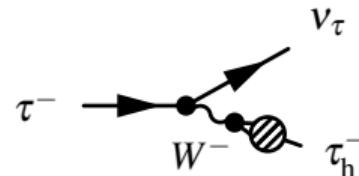
$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$



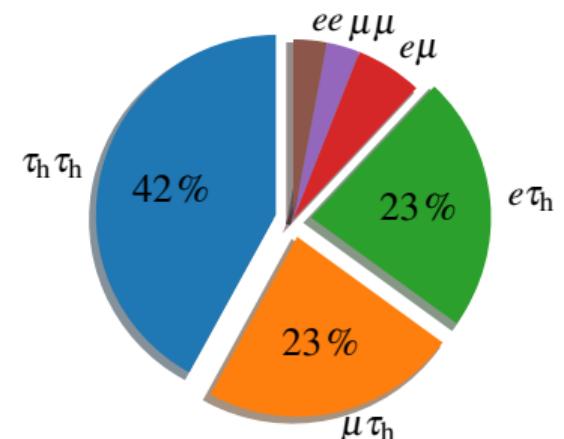
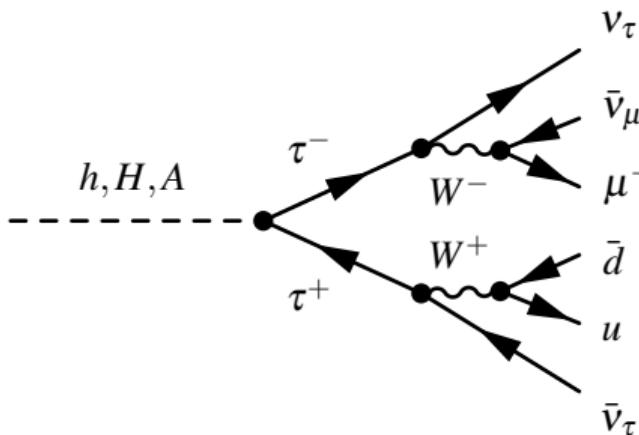
$$\tau \rightarrow e + \nu_e + \nu_\tau \Rightarrow e \\ 17.8\%$$



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



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



1 Phenomenology

2 Experimental device

3 $H \rightarrow \tau\tau$ analysis

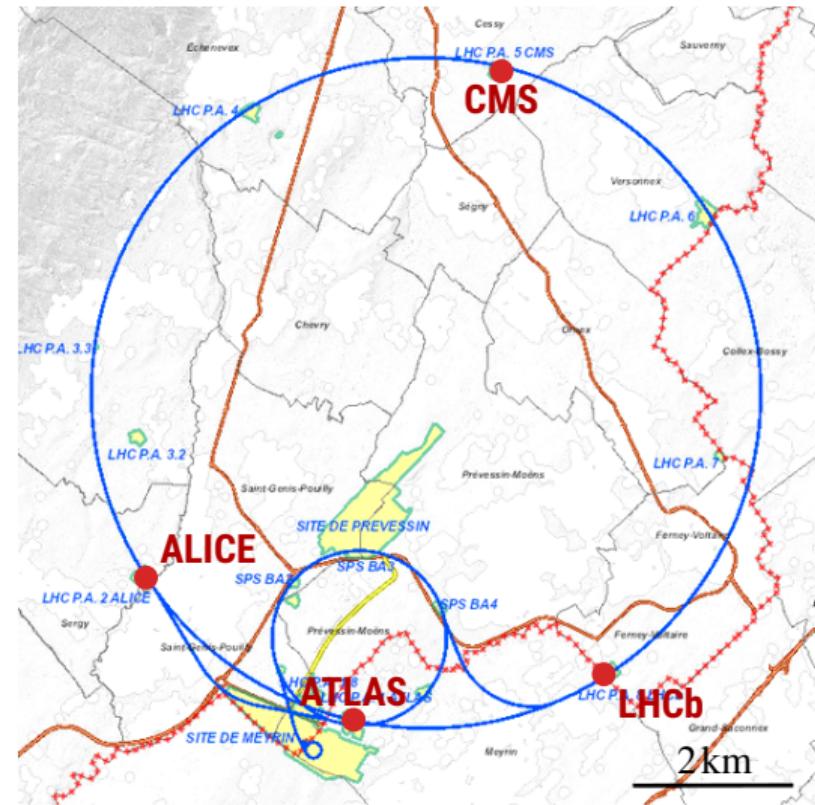
4 Machine learning

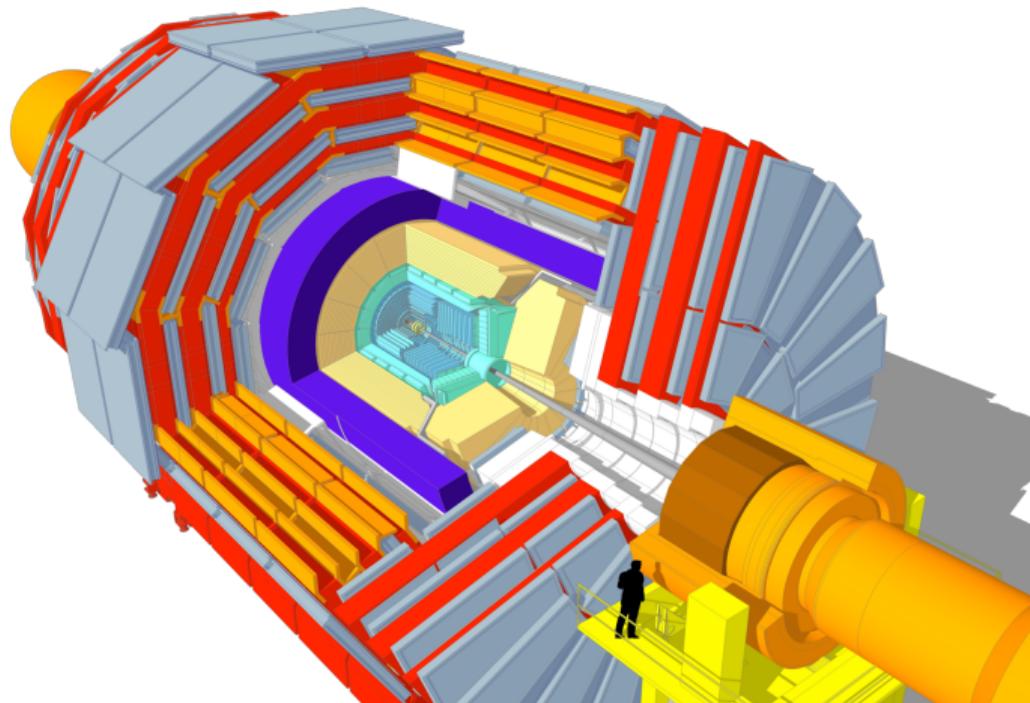
Principle

$$E = mc^2$$

mass (new particles) from the collision energy

CERN LHC

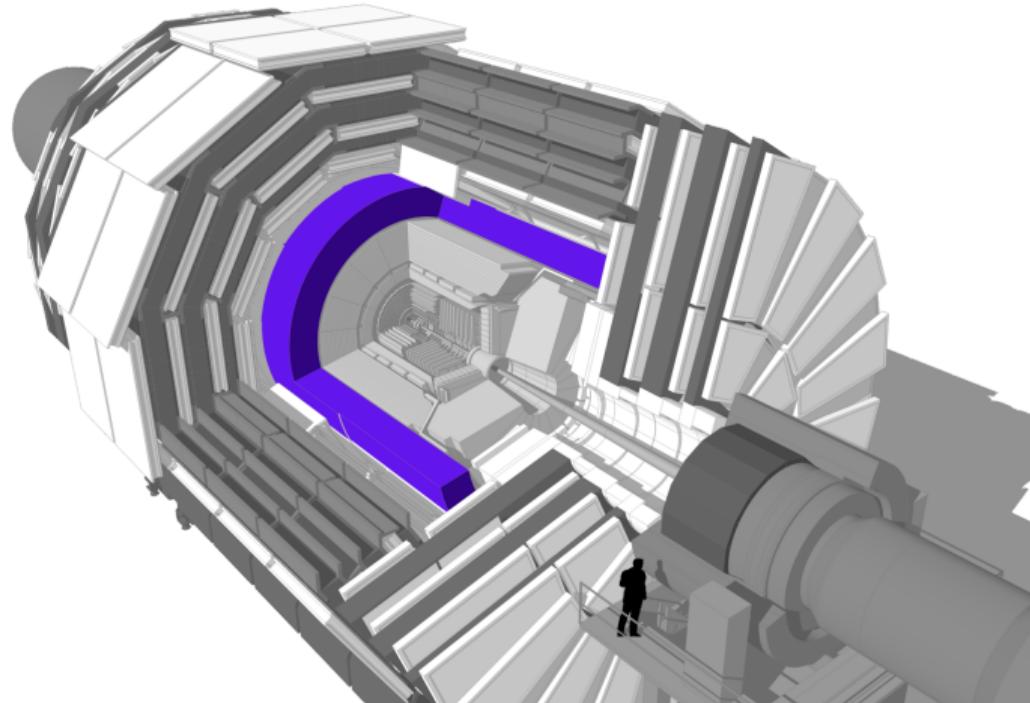




CMS detector

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

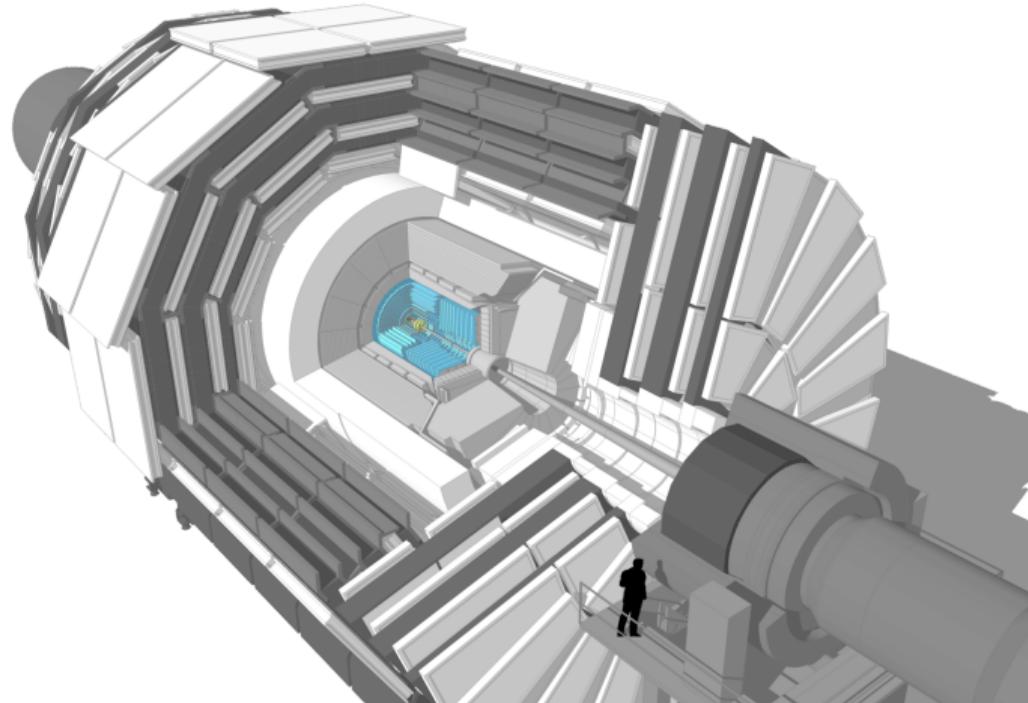
⇒ How to see the particles?



Solenoid

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

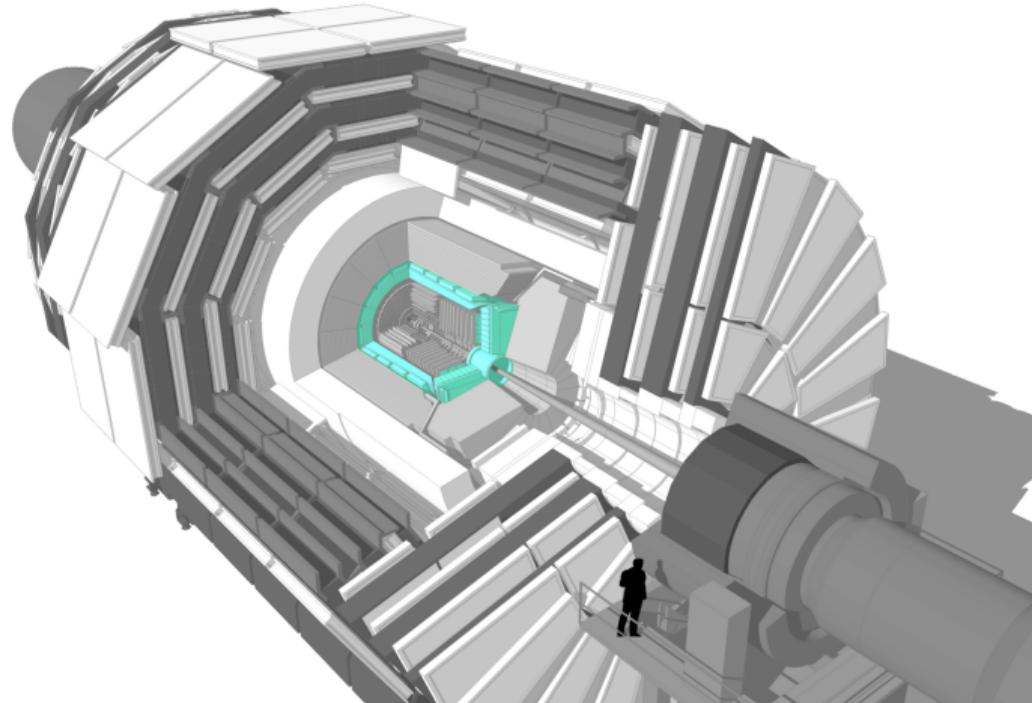
⇒ Bends charged particles trajectories
in the transverse plane



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

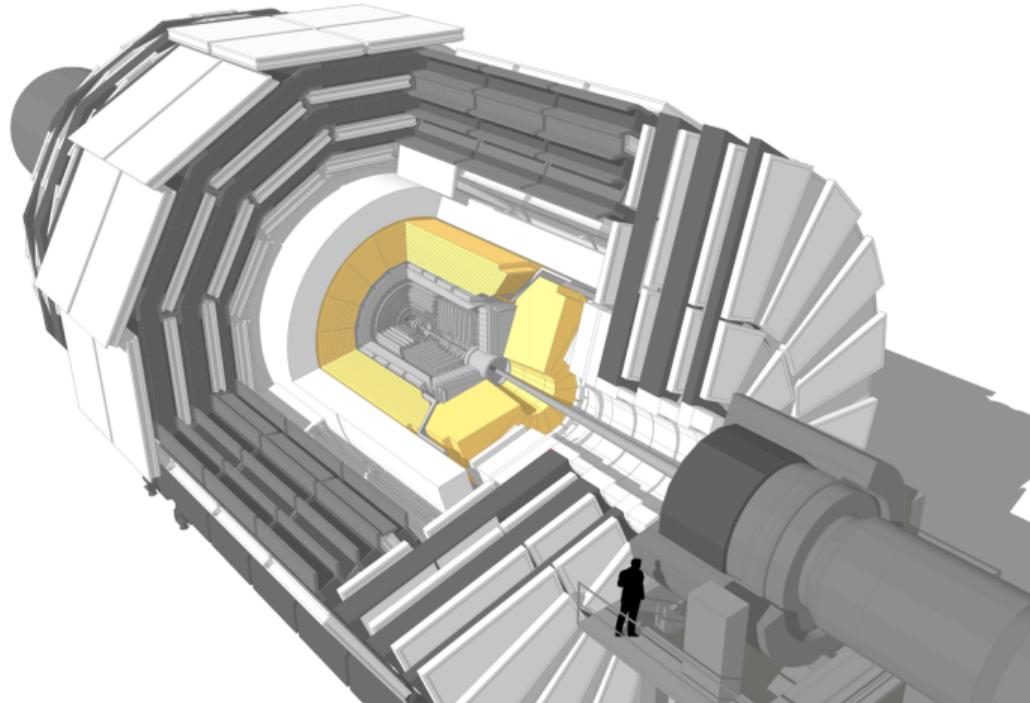
⇒ Charged particles leave hits when going through



Electromagnetic CALorimeter

- $\sim 76,000$ scintillating PbWO_4 crystals

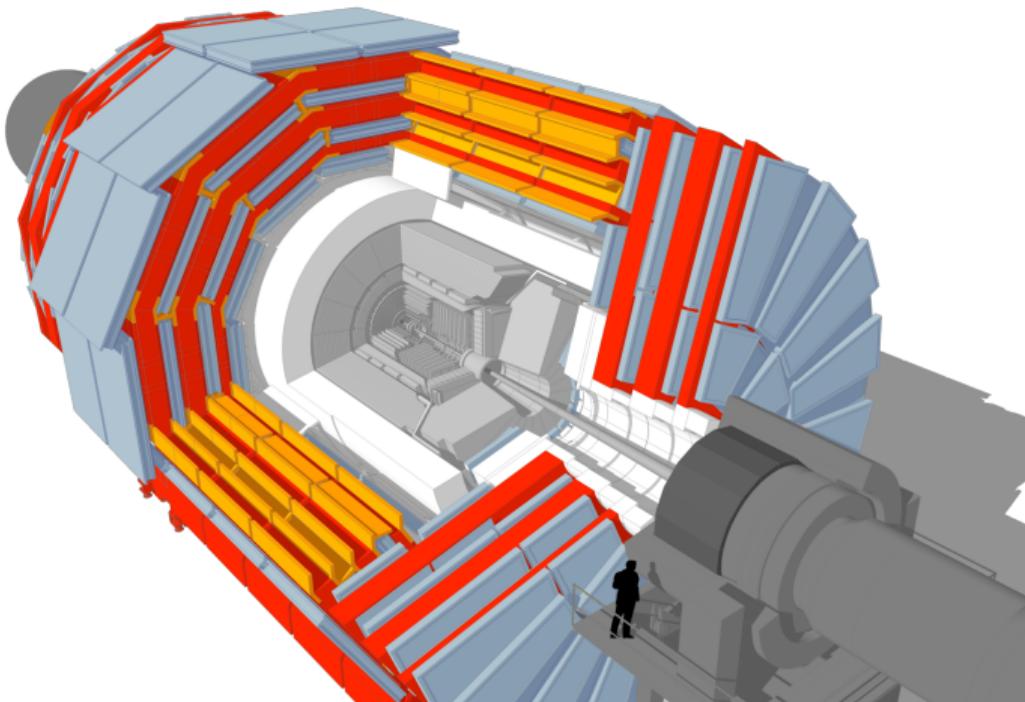
⇒ Electrons and photons are stopped,
energy deposits



Hadronic CALorimeter

- Brass + plastic scintillator,
~ 7000 channels

⇒ Hadrons are stopped, energy deposits



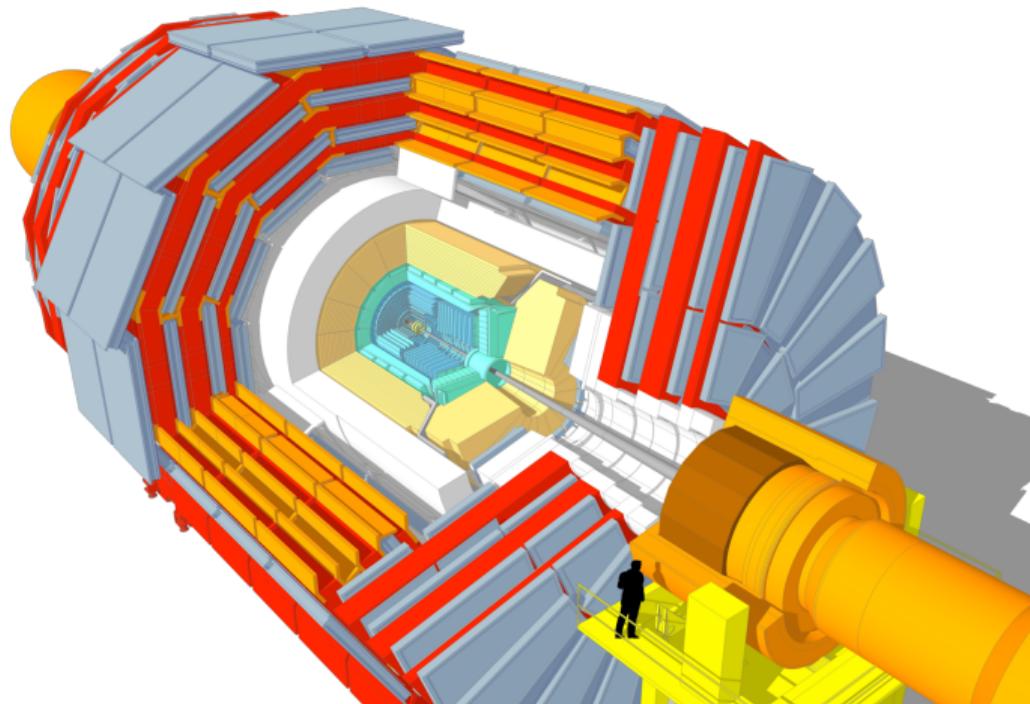
Steel return yoke (red)

- 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

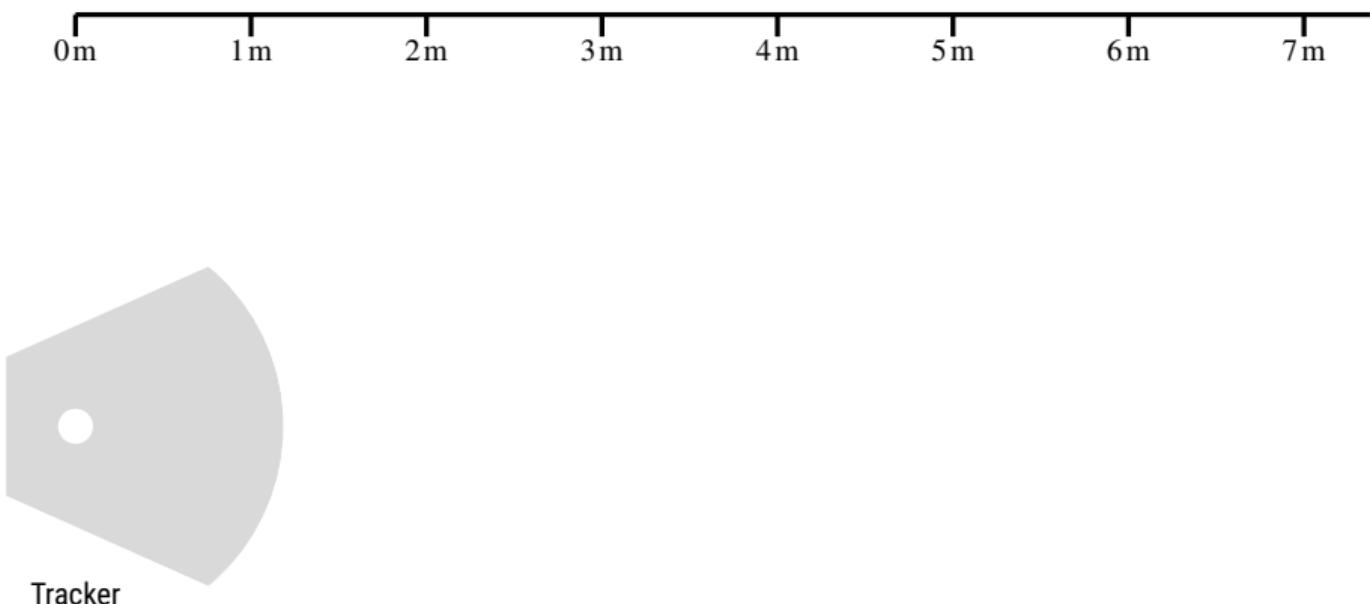
⇒ Charged particles leave hits when going through (only muons do)

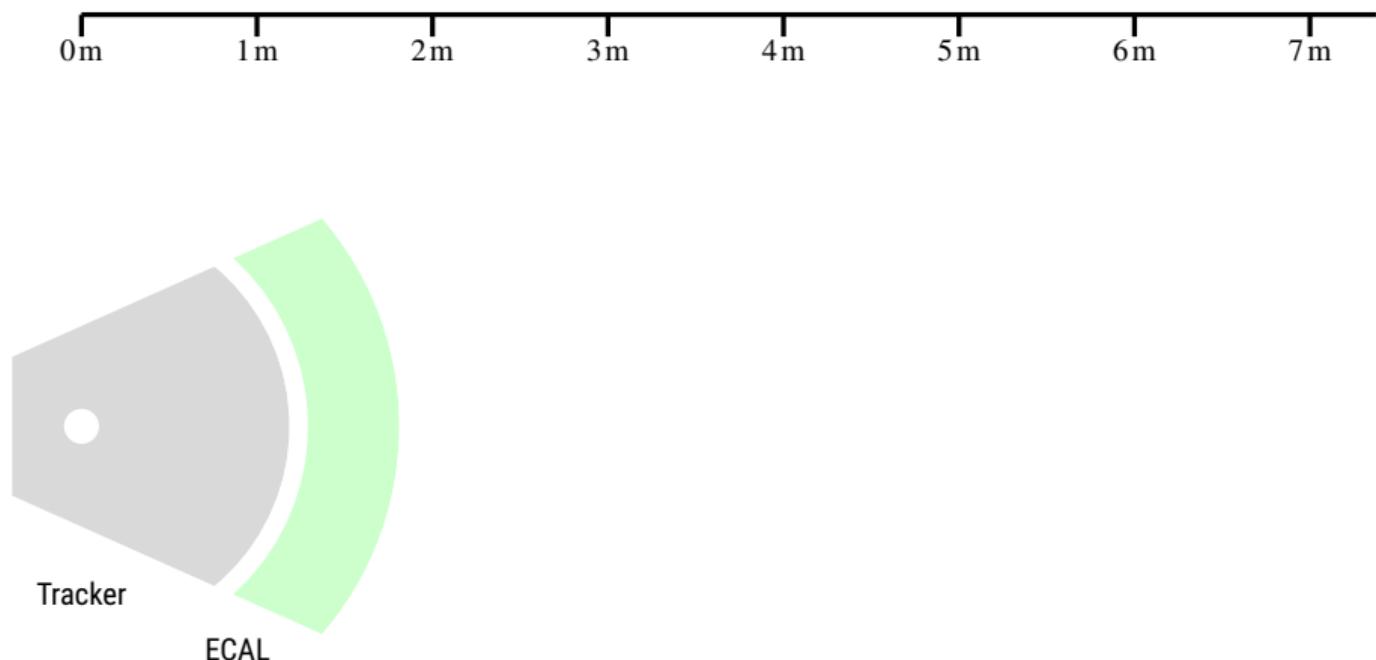


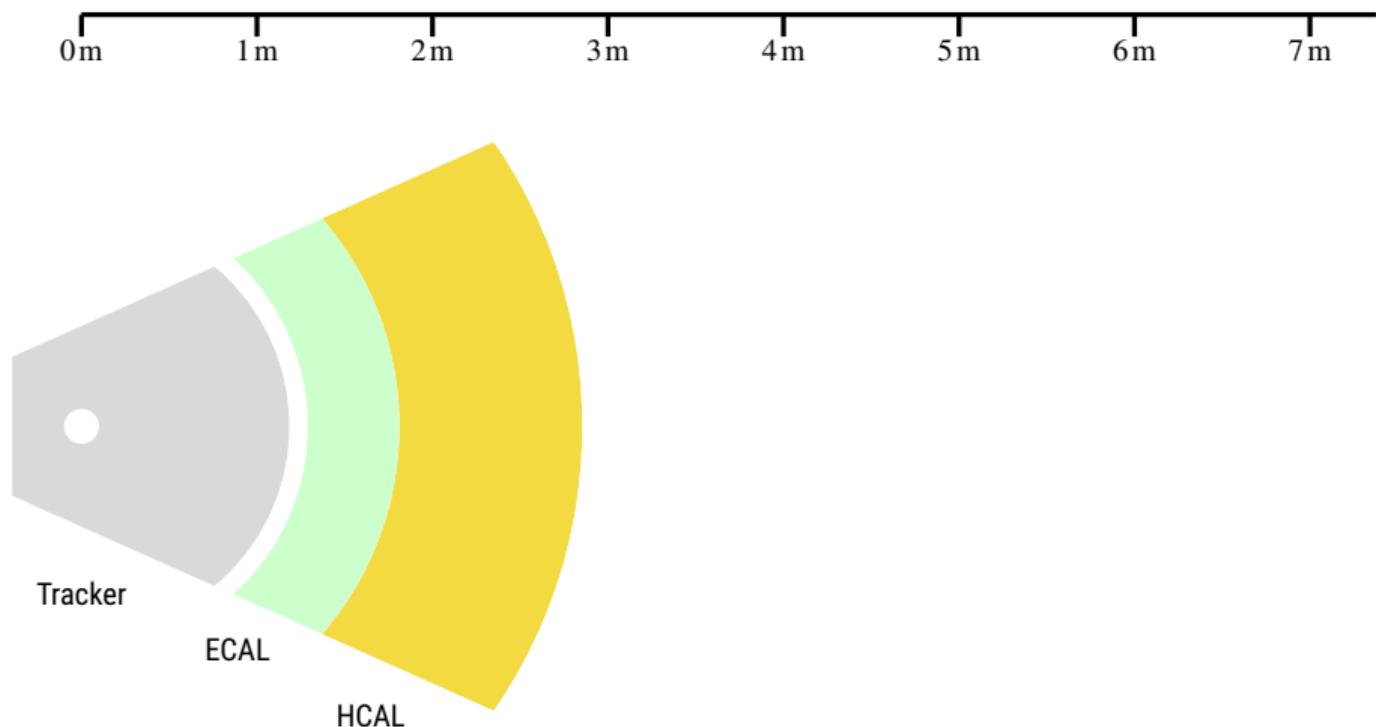
Sensitive parts of CMS

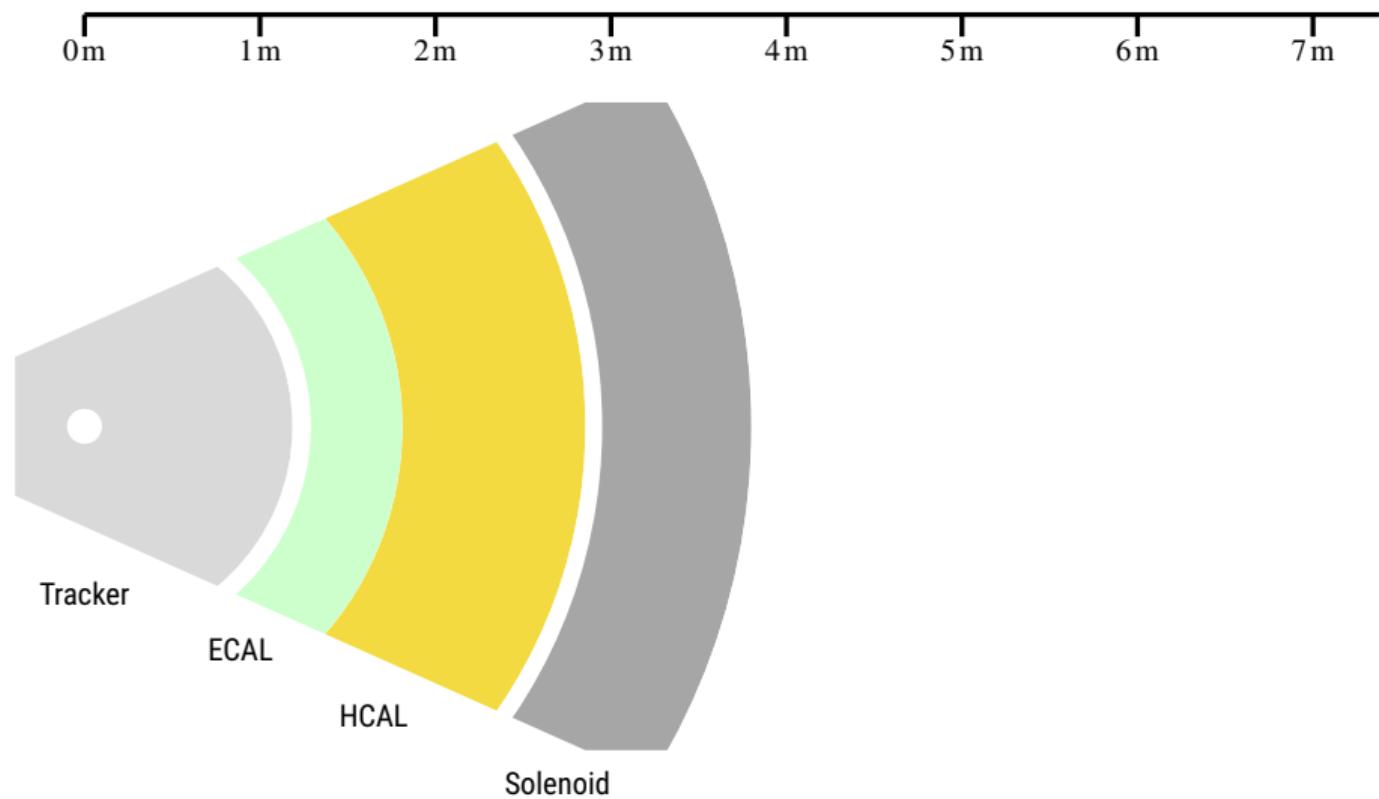
Combine sub-detectors signals to determine which particles were there!

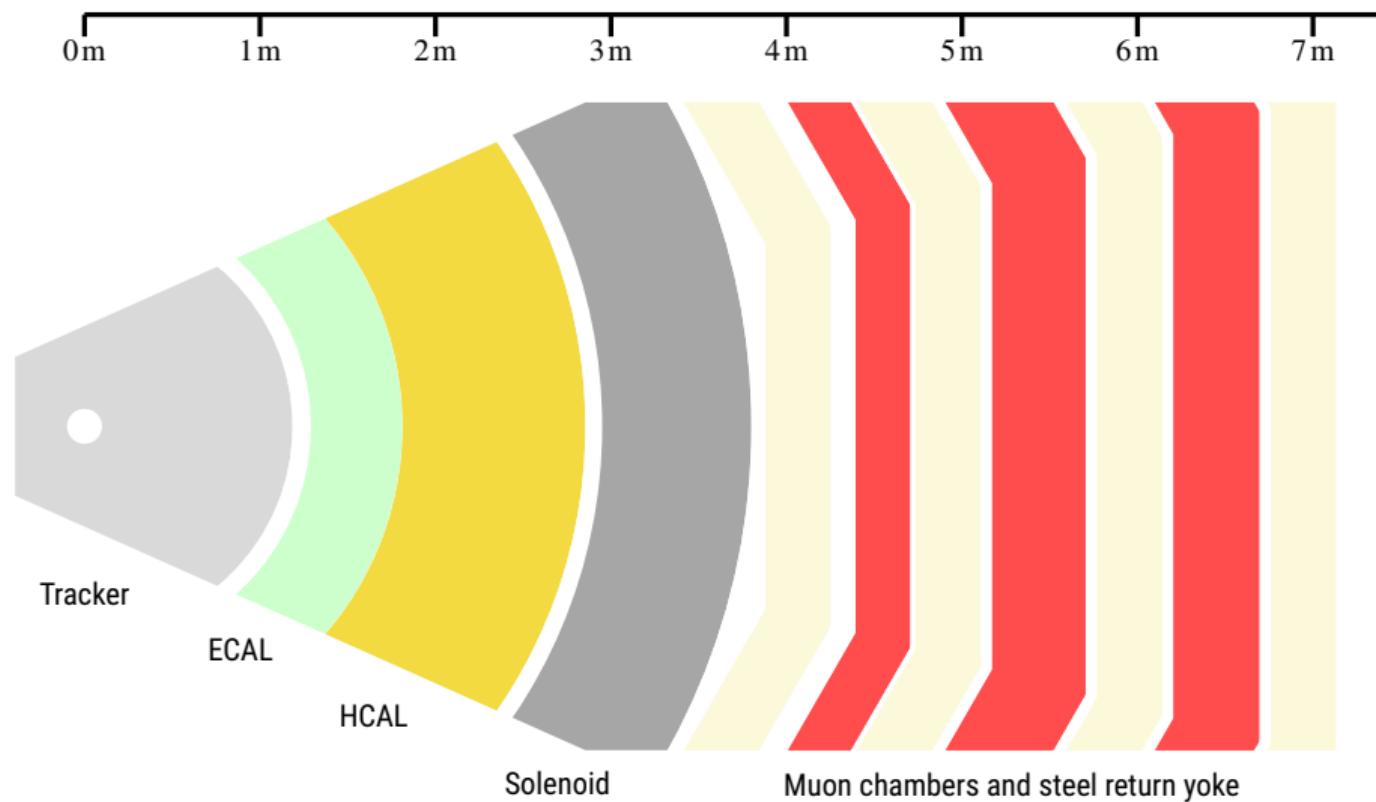


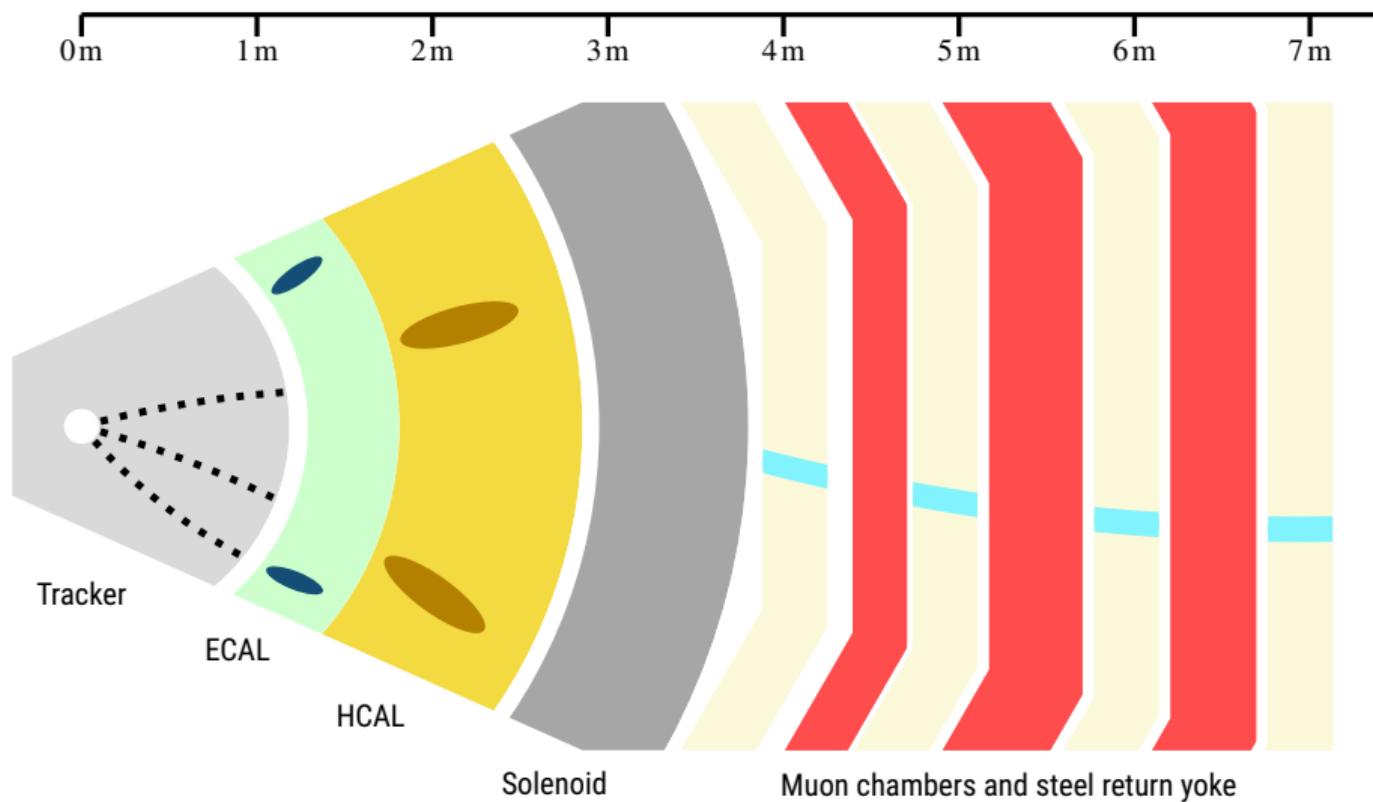


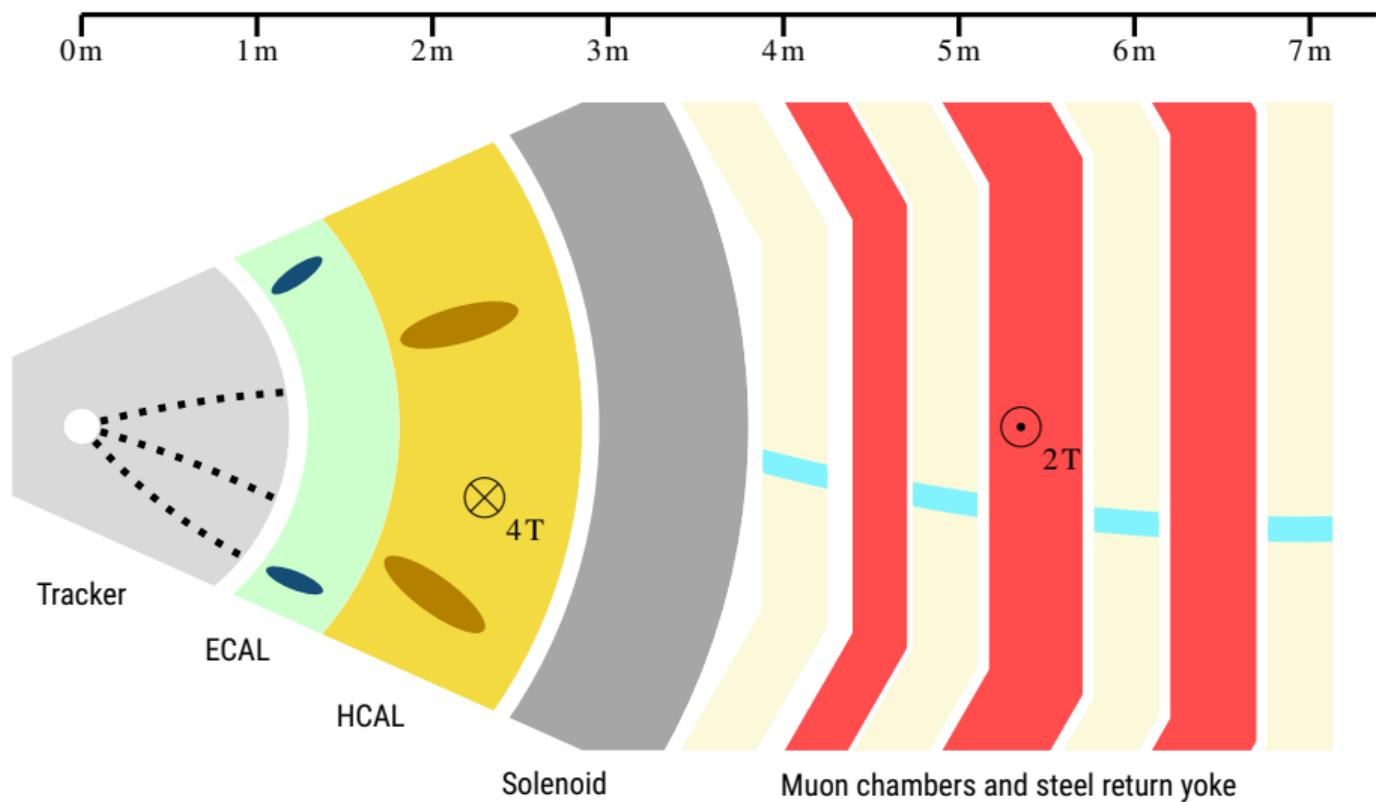


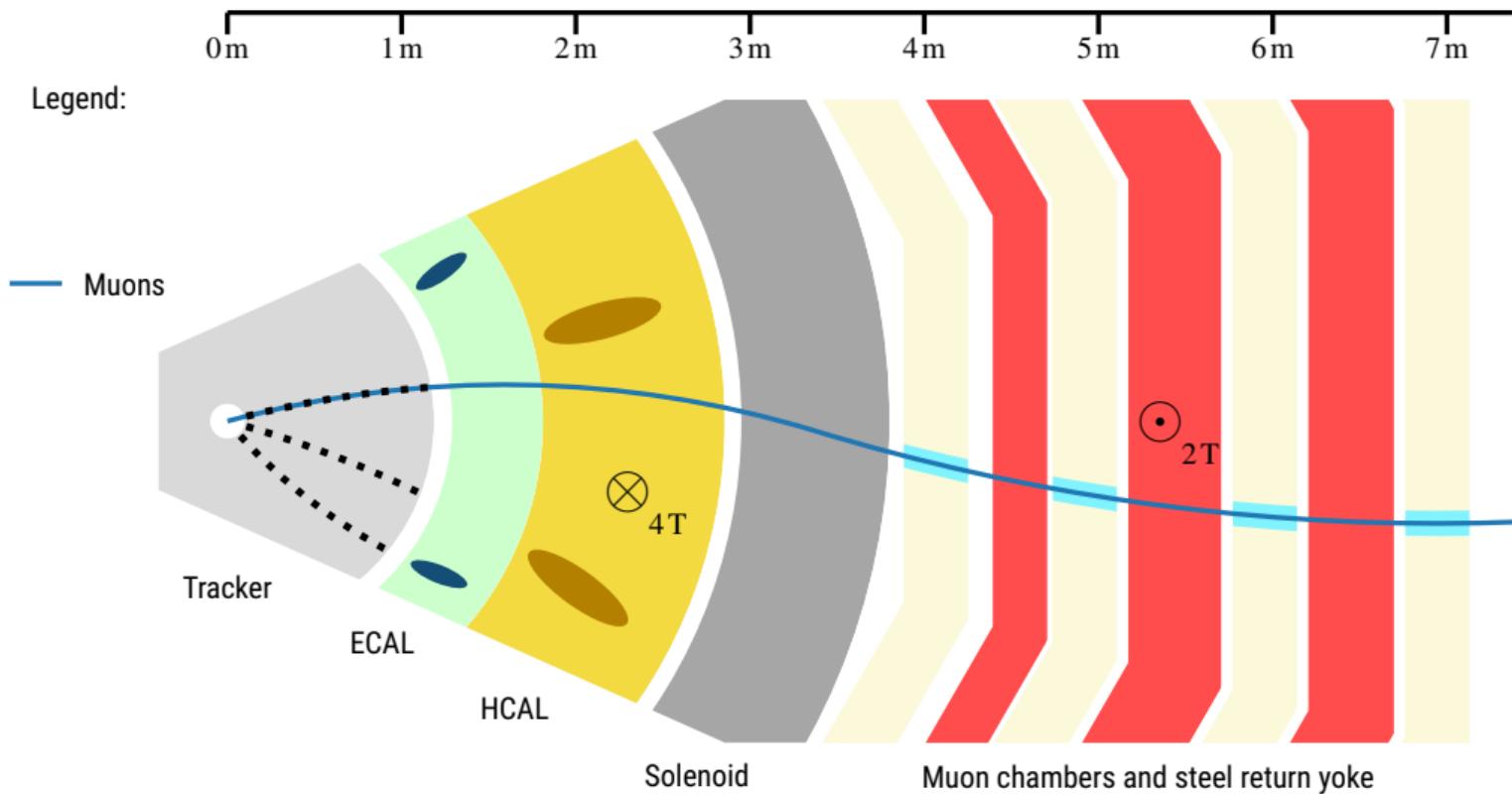






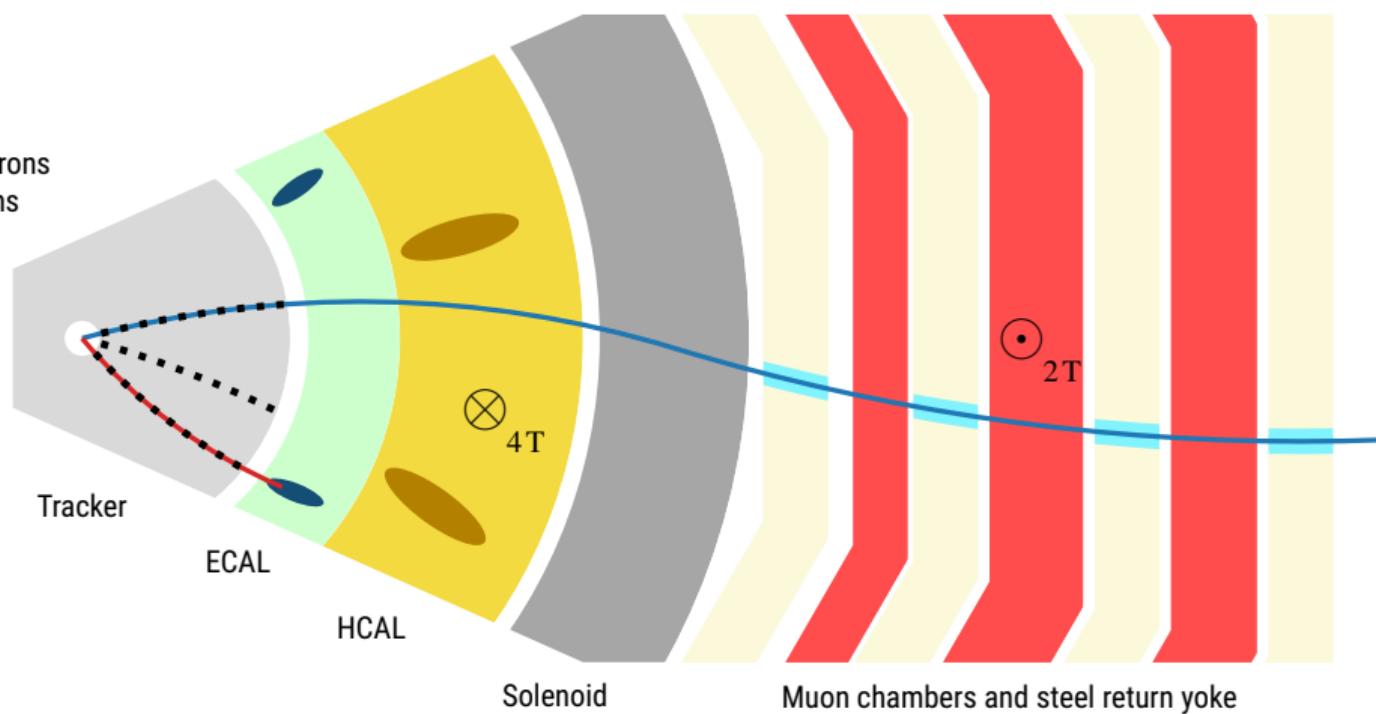


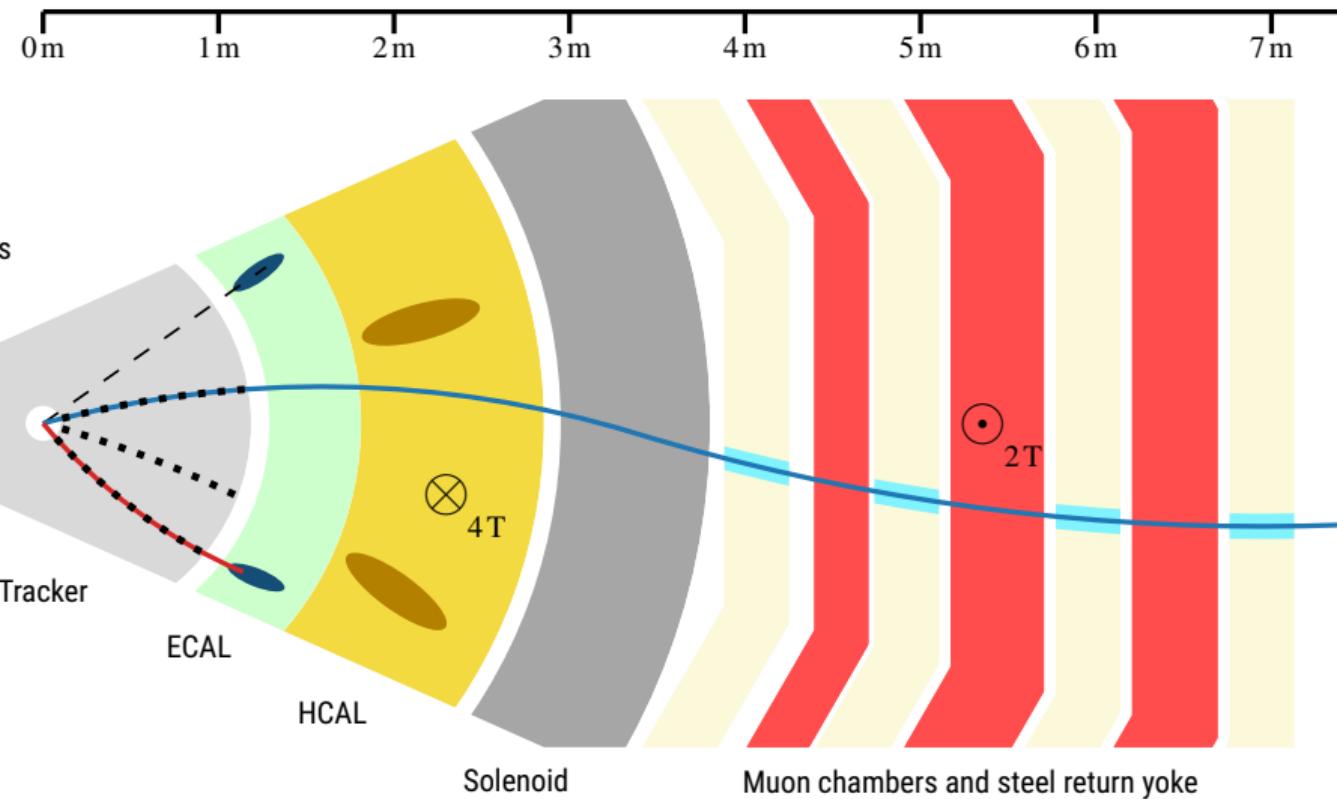


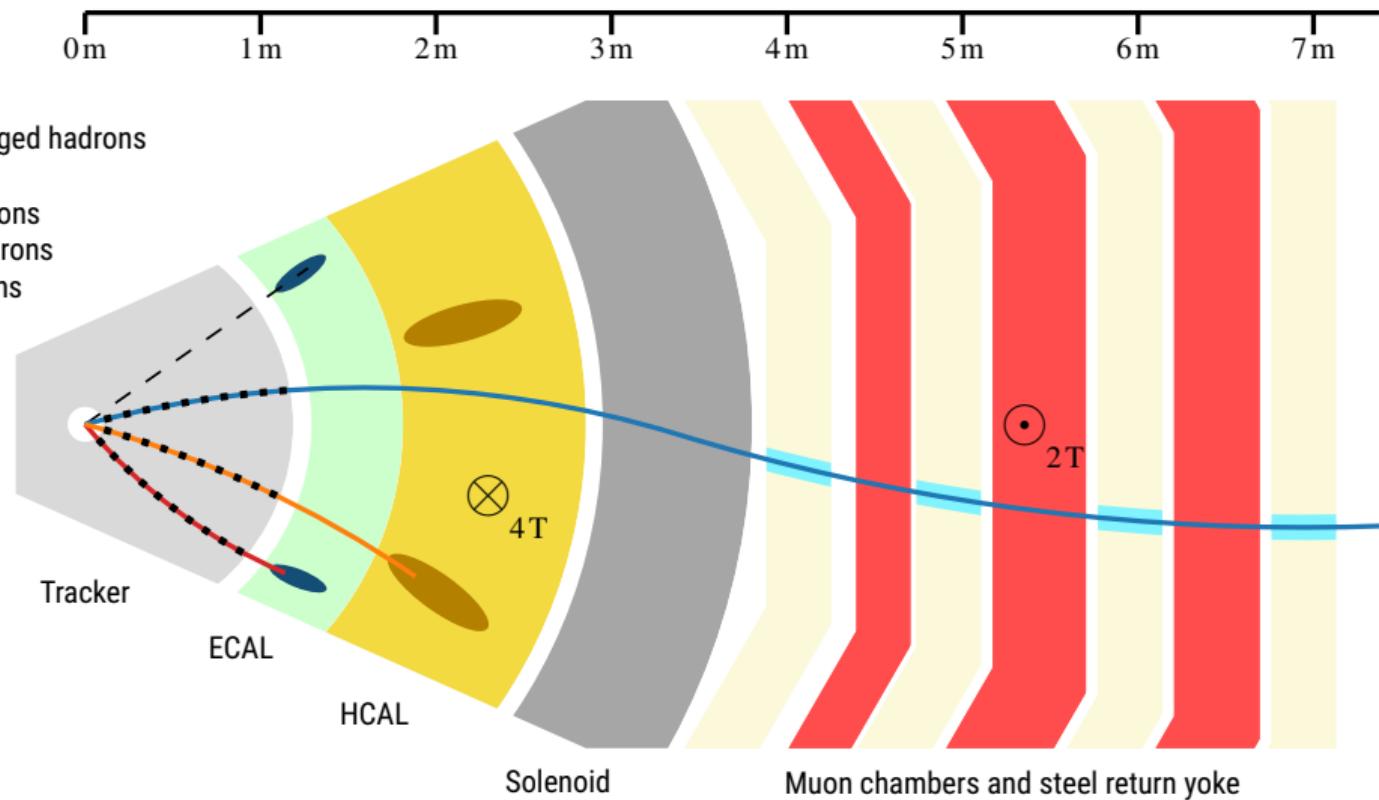


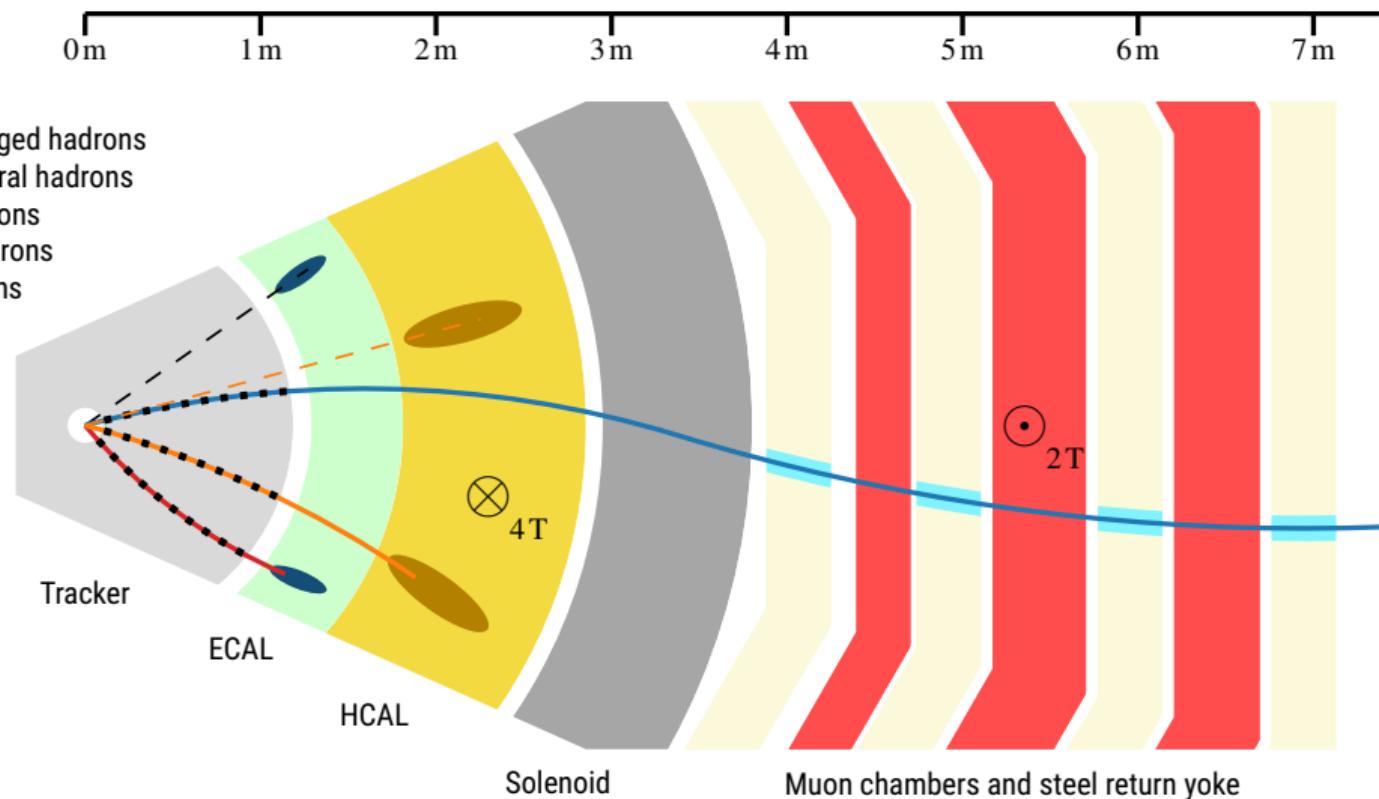
**Legend:**

- Electrons
- Muons



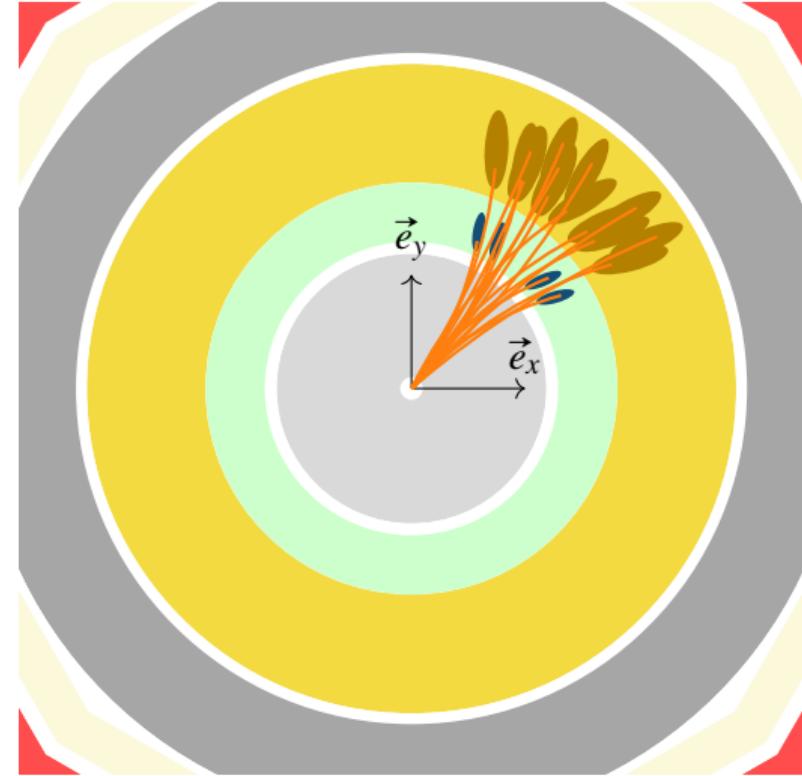
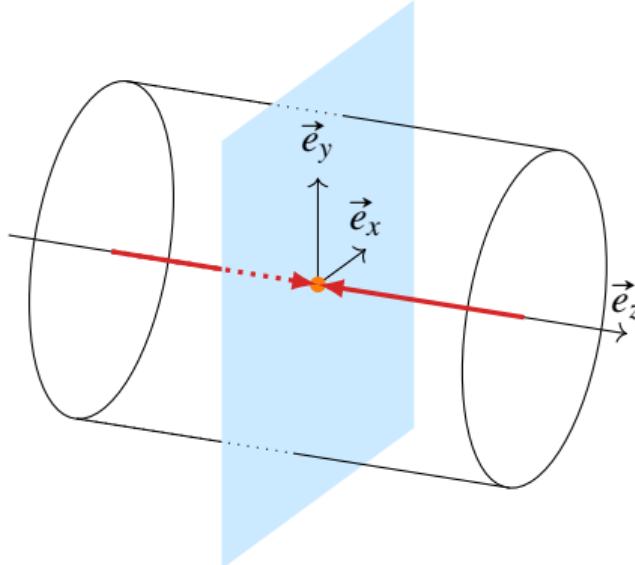






Neutrinos and missing transverse energy (MET)

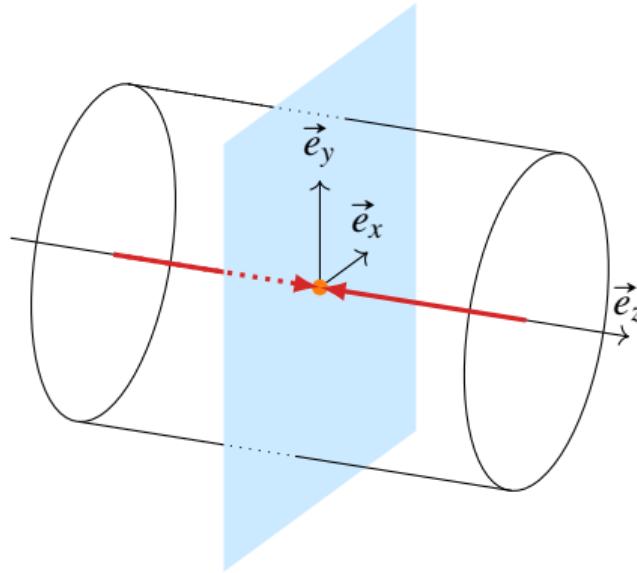
(\vec{e}_x, \vec{e}_y) = transverse plane ($\eta = 0$)



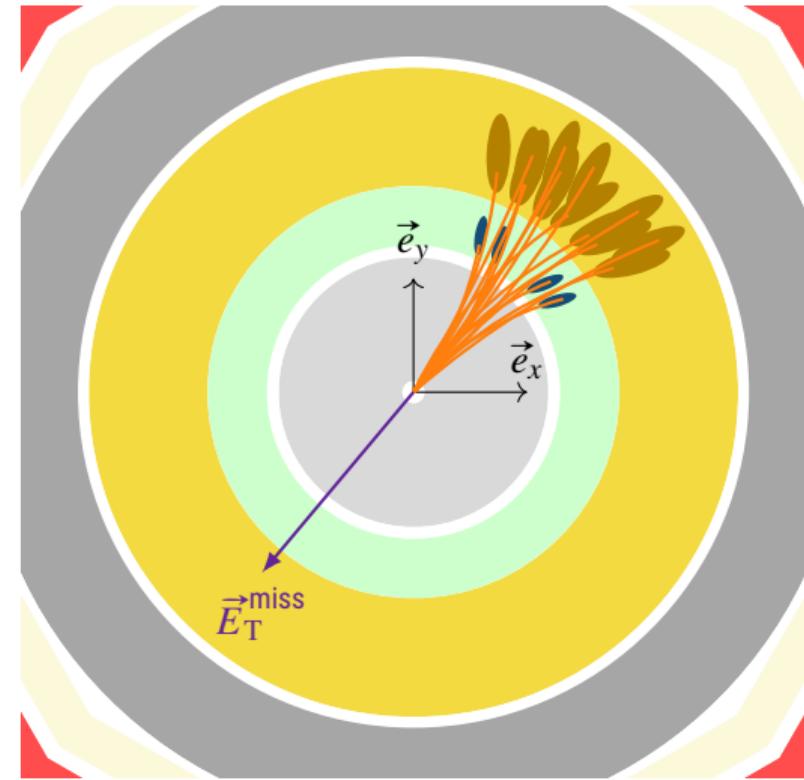
Conserved momentum: $\sum_{\text{initial state}} \vec{p}_{\text{T}} = \sum_{\text{final state}} \vec{p}_{\text{T}} = \vec{0}$

Neutrinos and missing transverse energy (MET)

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

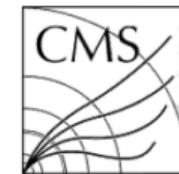
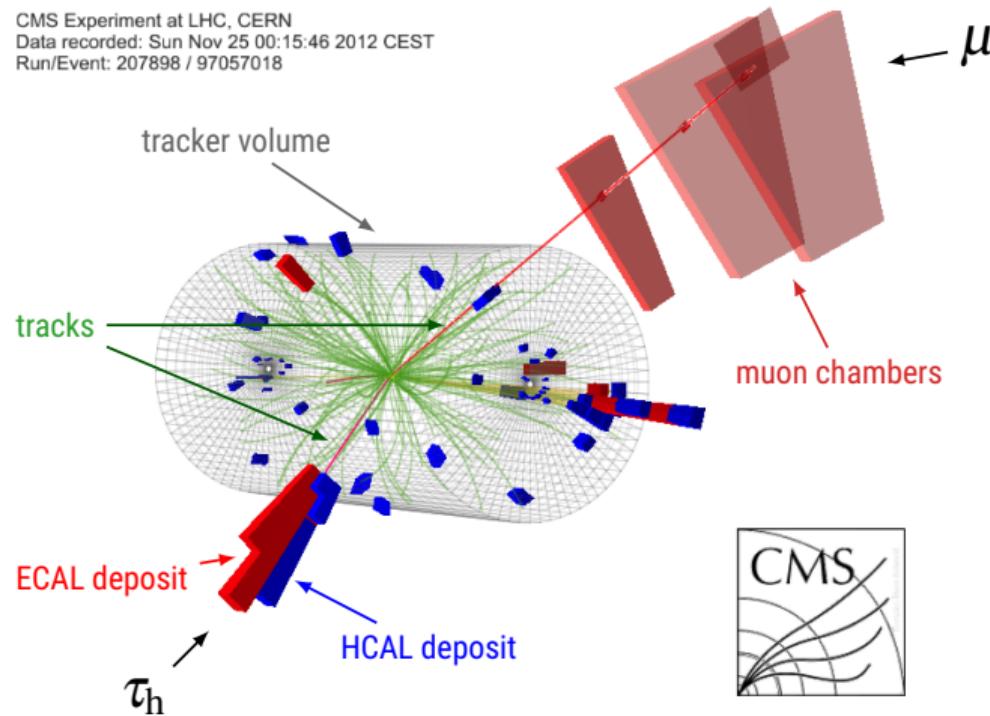


$$\sum_{\text{final state}} \vec{p}_T = \vec{0} \Rightarrow \vec{E}_T^{\text{miss}} = - \sum_{\text{visible particles}} \vec{p}_T$$



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



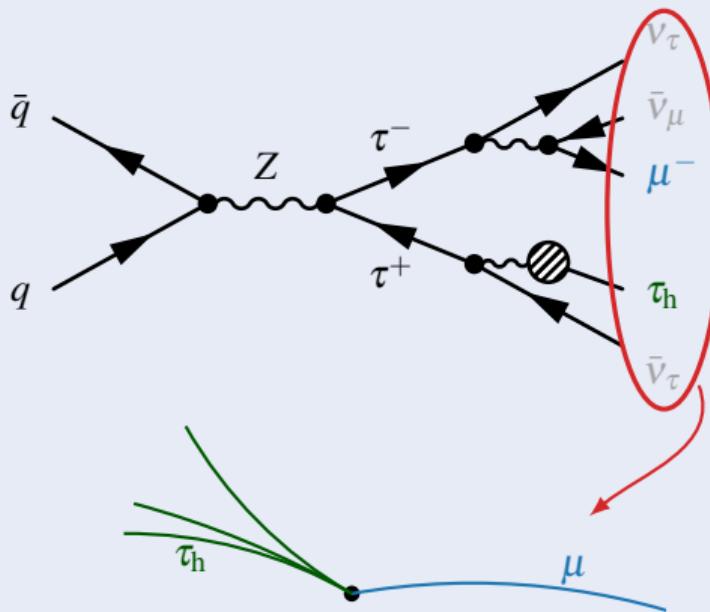
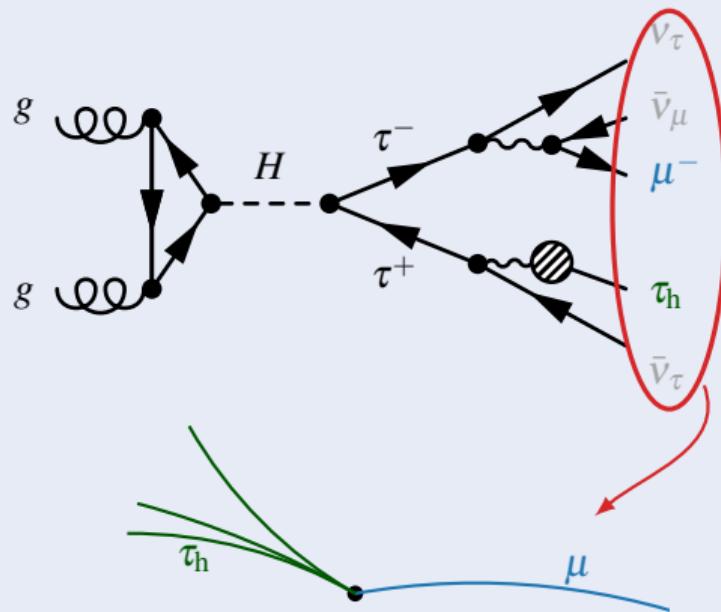
1 Phenomenology

2 Experimental device

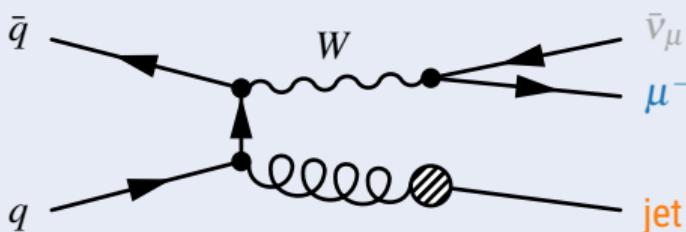
3 $H \rightarrow \tau\tau$ analysis

4 Machine learning

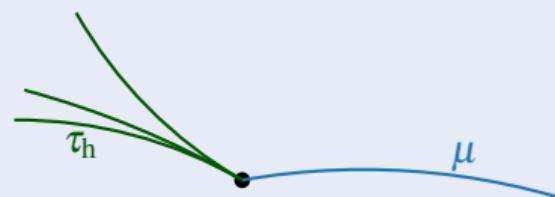
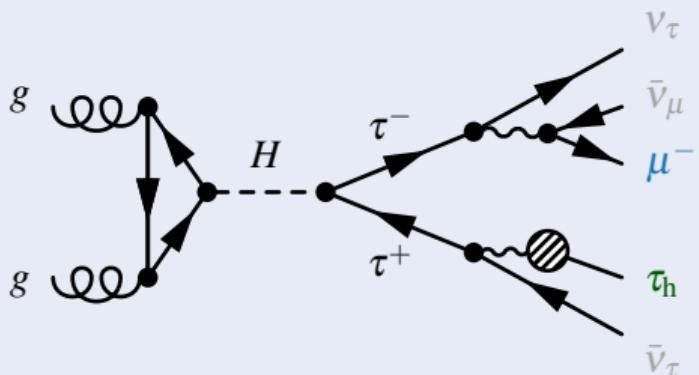
Backgrounds?

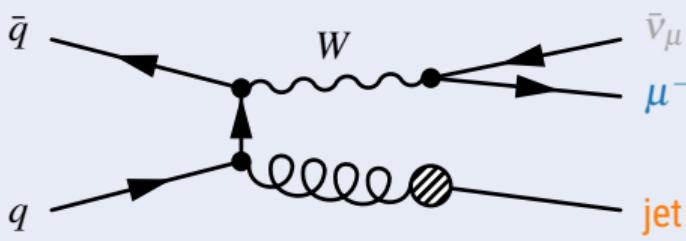
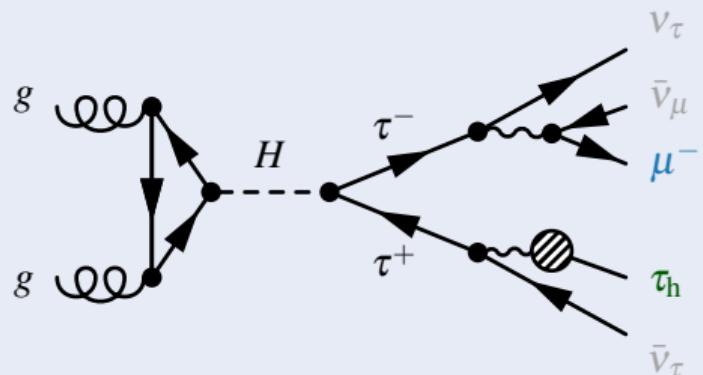
Drell-Yan (especially $Z \rightarrow \tau\tau$) $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

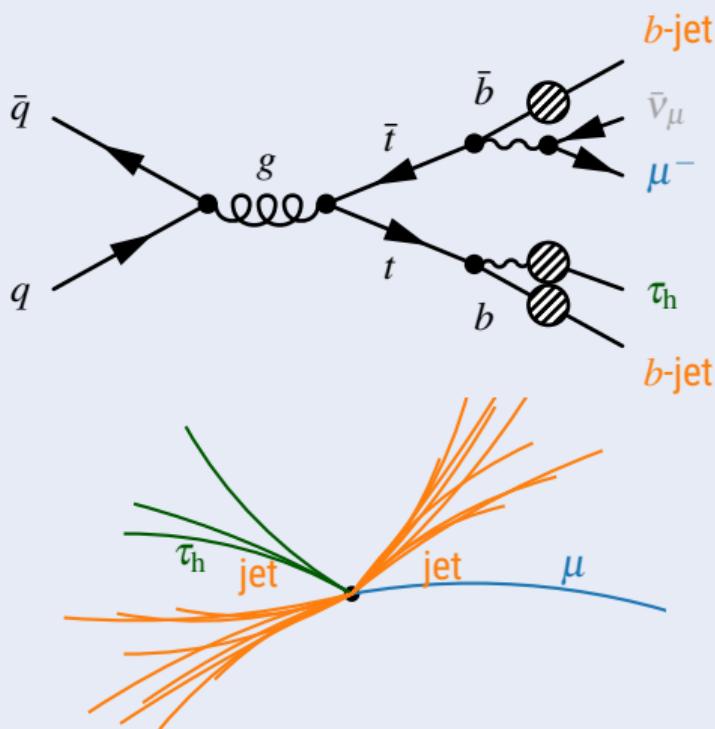
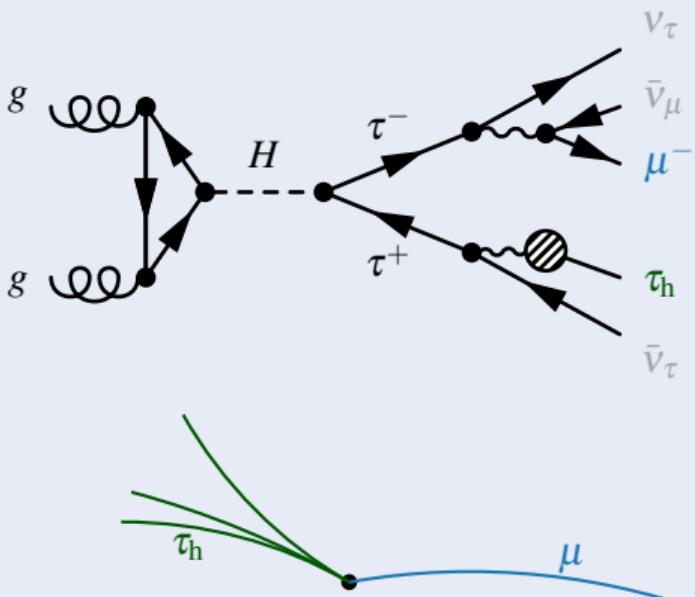
$W + \text{jets}$

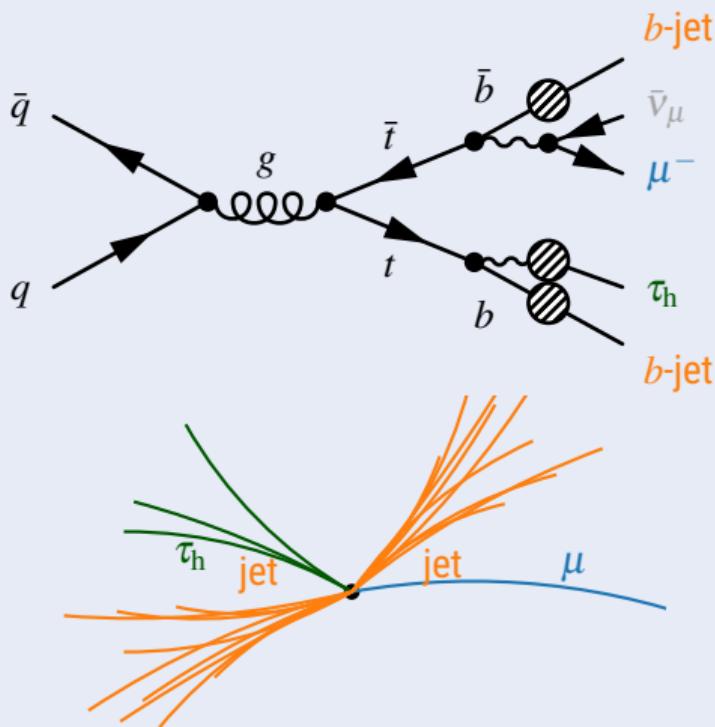


$H \rightarrow \tau\tau \rightarrow \mu\tau_h$

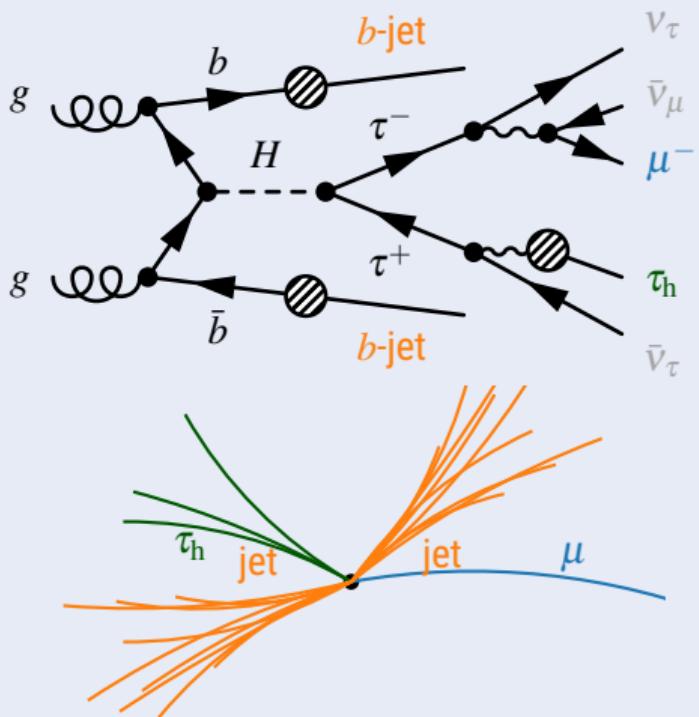


$W + \text{jets}, \text{jet} \rightarrow \text{fake } \tau_h$  $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

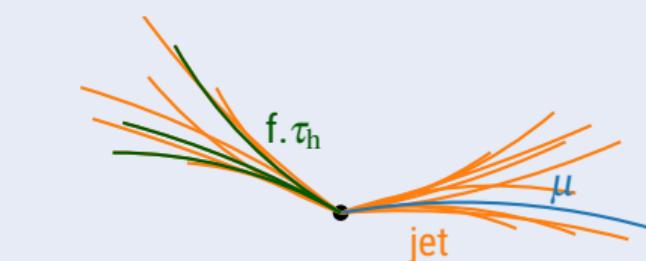
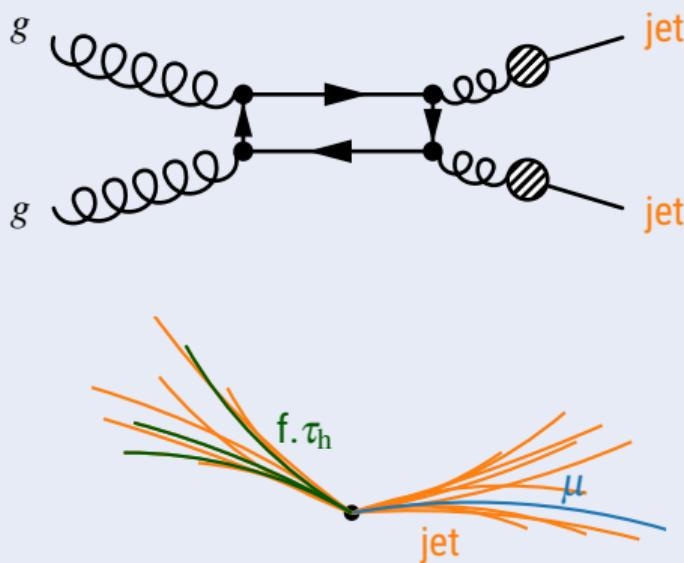
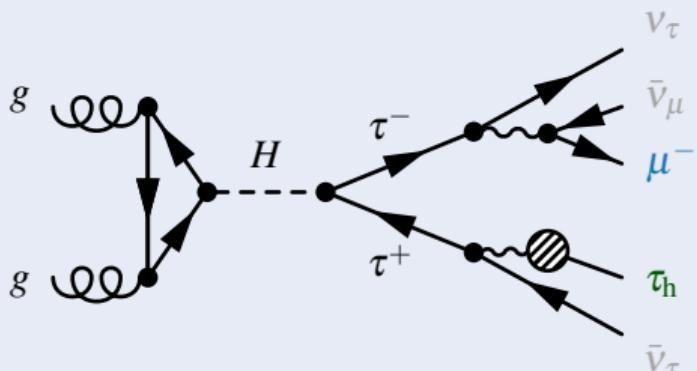
$t\bar{t}$  $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

$t\bar{t}$ 

H production with b -jets

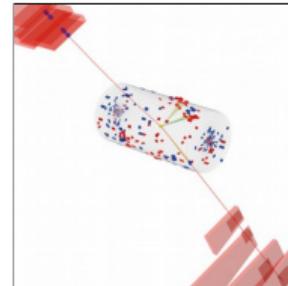


QCD

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

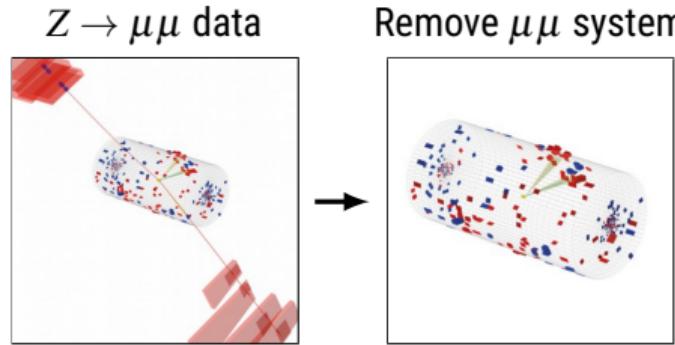
Embedded events

$Z \rightarrow \mu\mu$ data



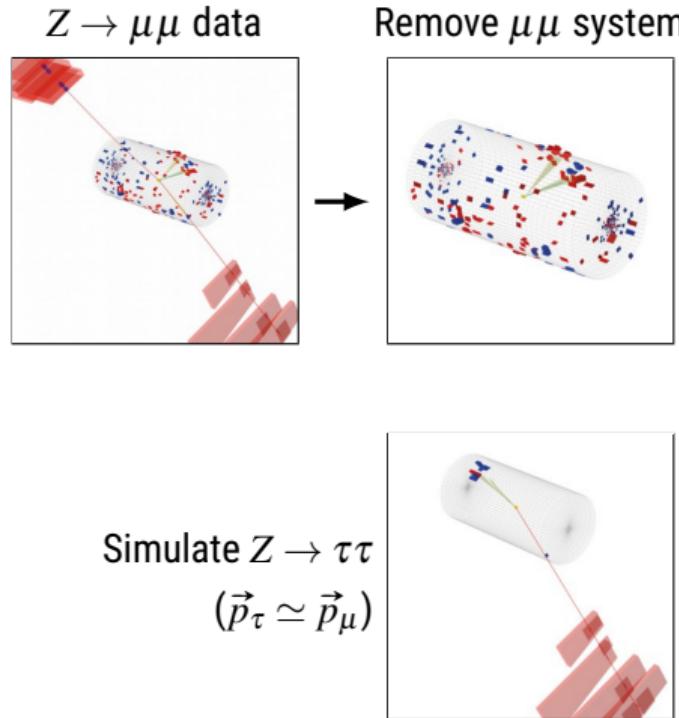
- ▷ The CMS Collaboration. "An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

Embedded events



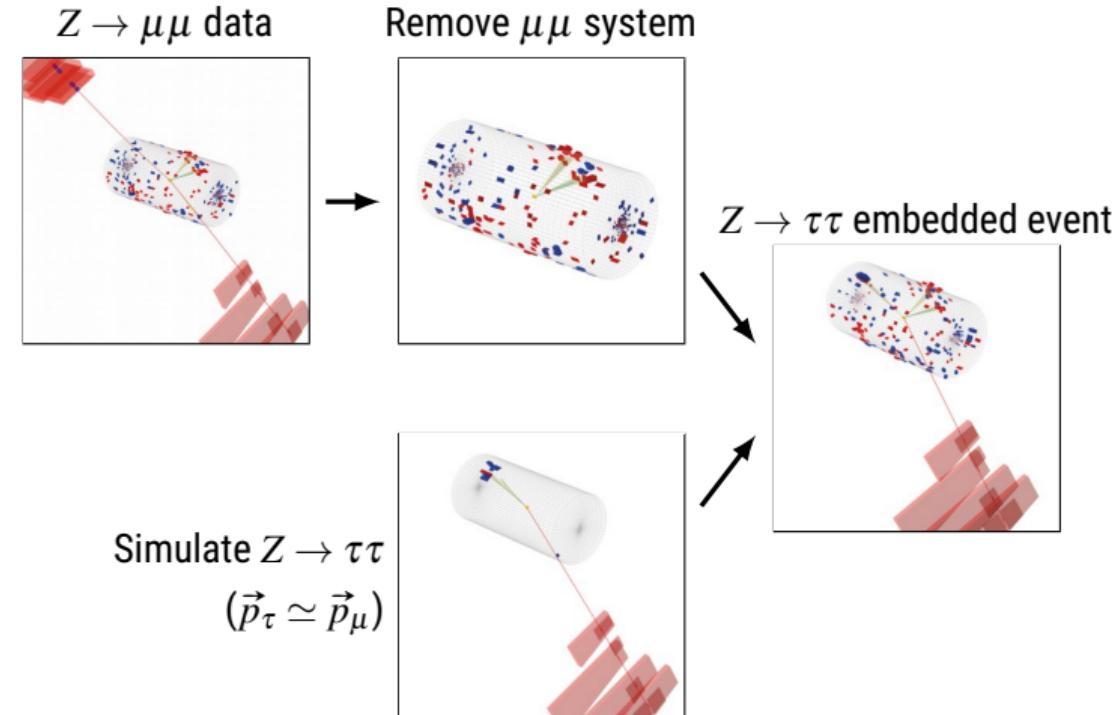
- ▷ The CMS Collaboration. "An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

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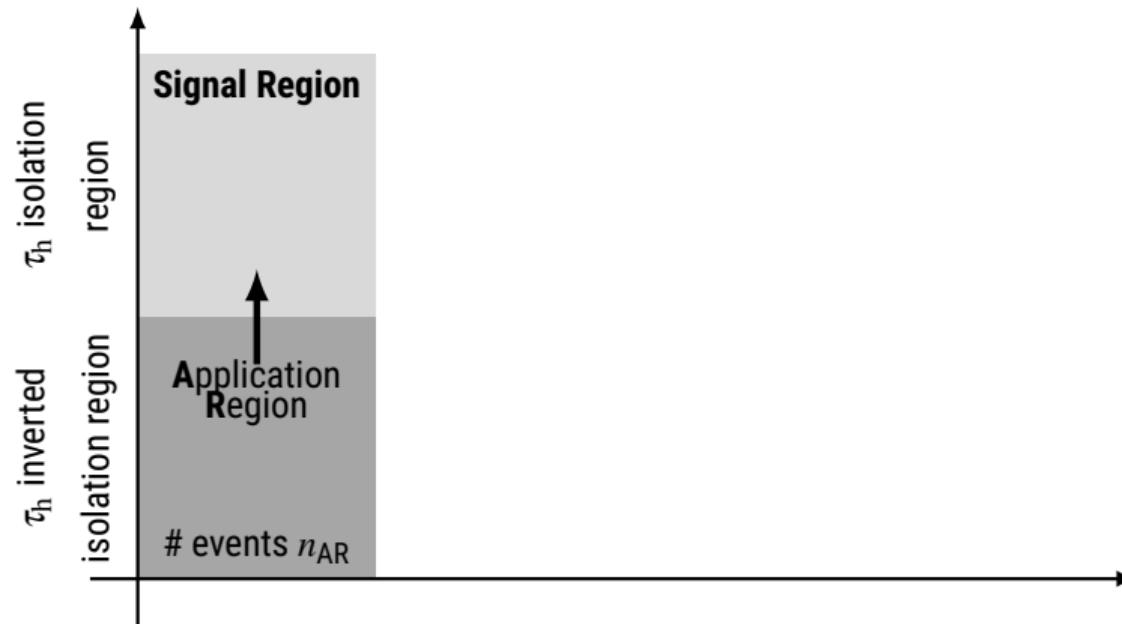
The Fake Factor method

- ▶ How many events contain misidentified τ_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). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C20AN-2018/257.

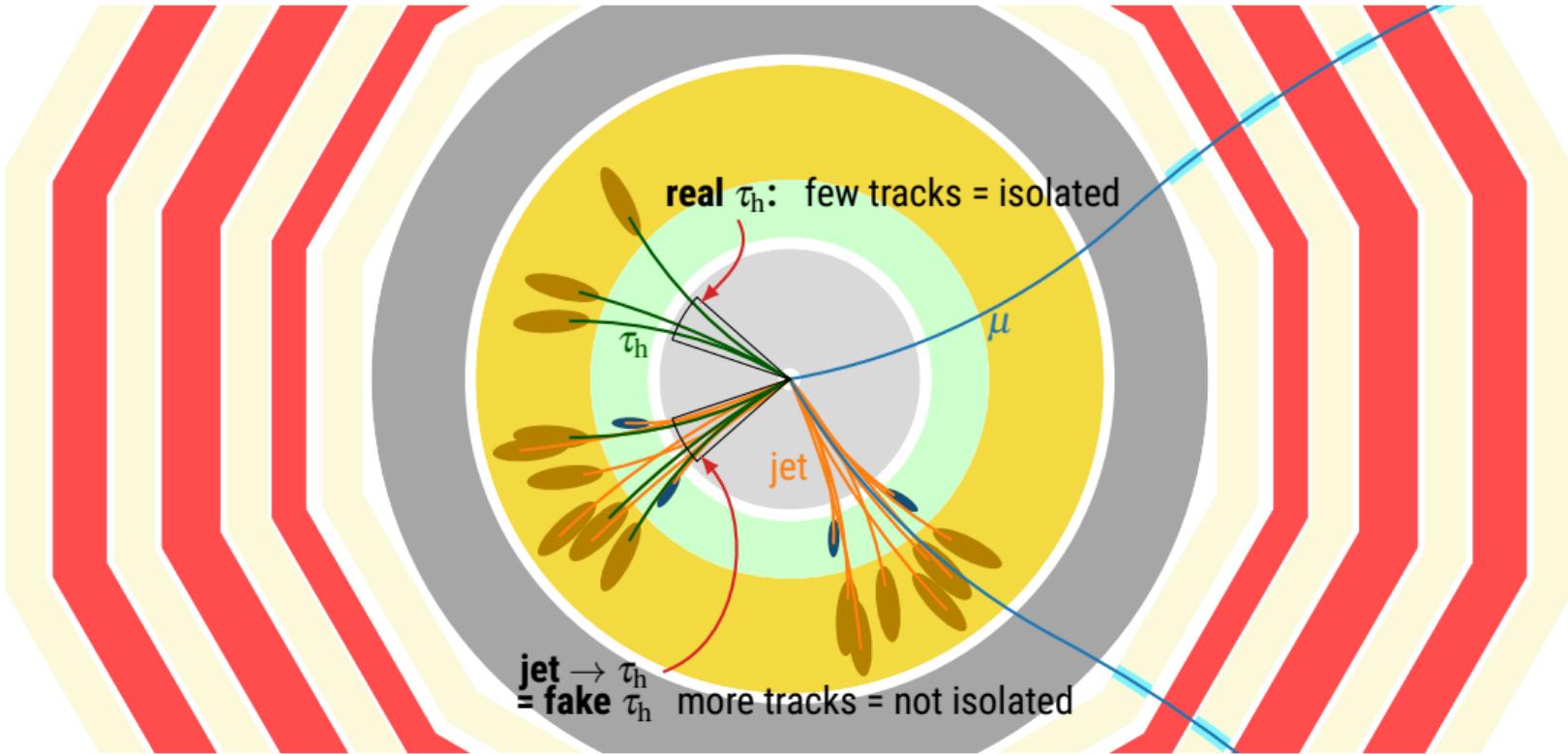
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Particles isolation – qualitatively



The FF method: determination regions definitions

$t\bar{t}$

Estimation from simulated samples, same selection as in 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). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C20AN-2018/257.

The FF method: determination regions definitions

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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 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). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C20AN-2018/257.

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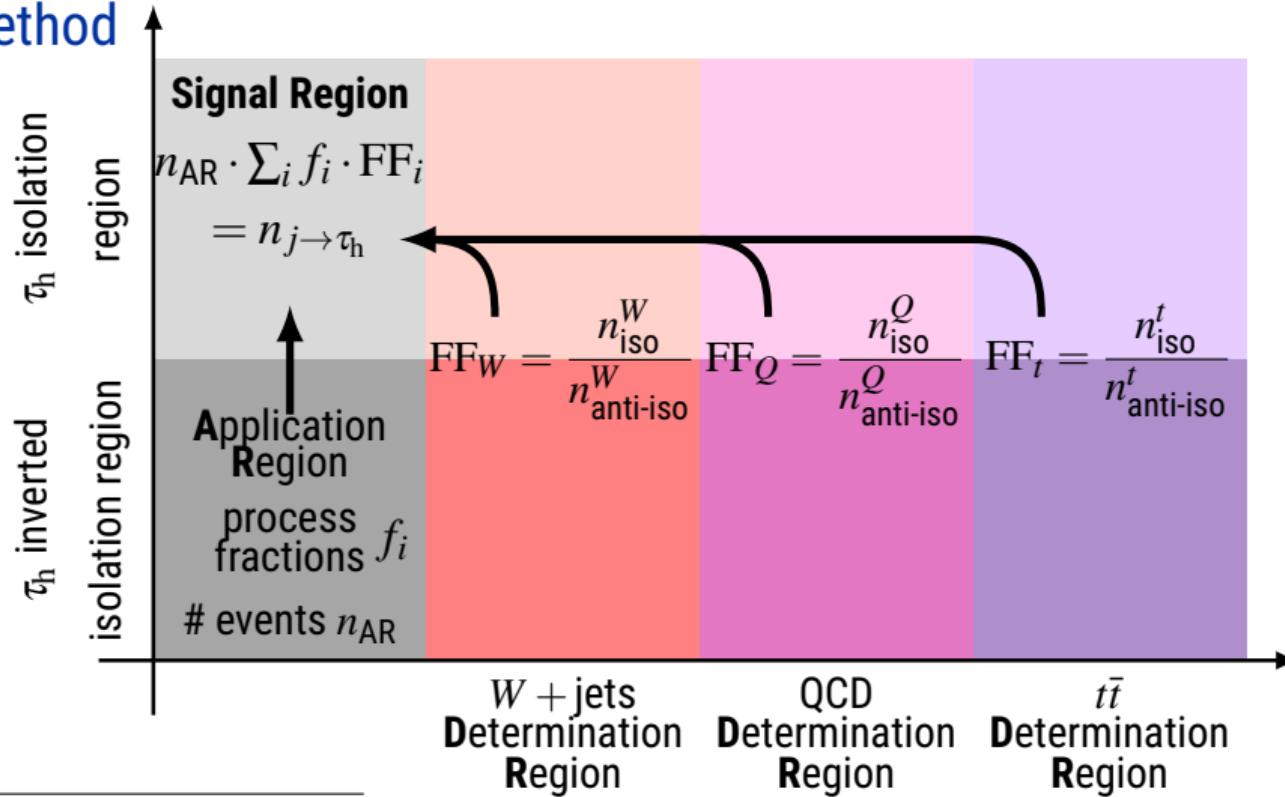
QCD multijet

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). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C20AN-2018/257.

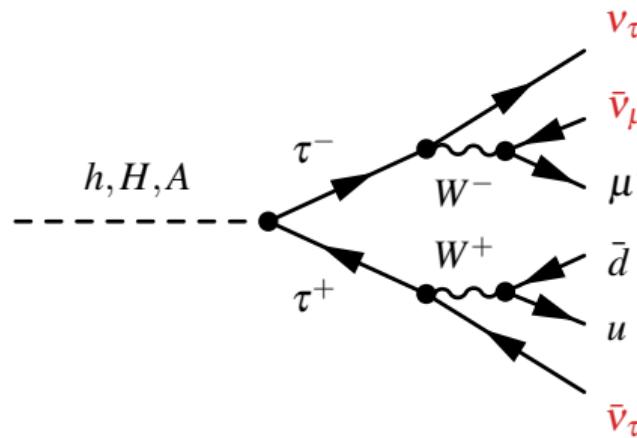
The FF method



▷ 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). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C20AN-2018/257.

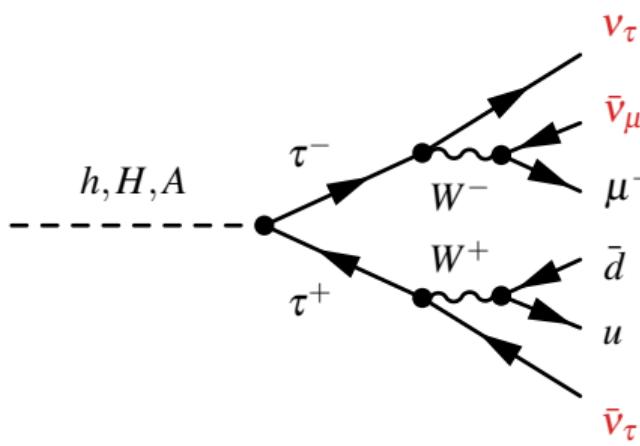
Discriminant variable?

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

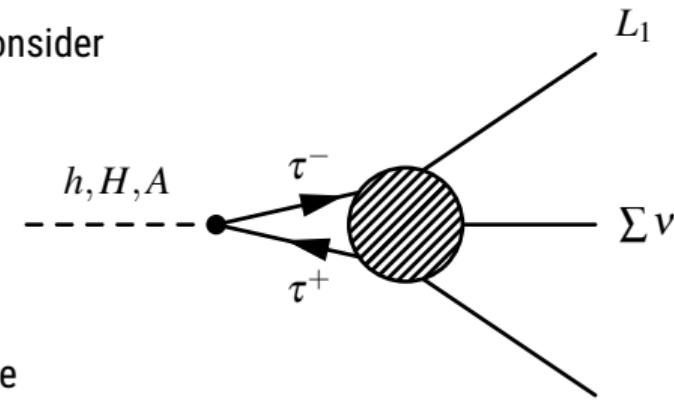


Discriminant variable?

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



- ▶ Consider



where

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

with respect to the left side.

Discriminant variable: m_T^{tot}

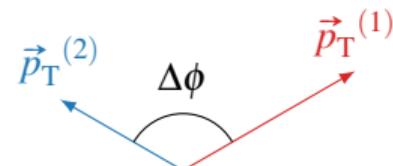
- ▶ For L_1, L_2 and E_T^{miss} system,
 - ▷ in the transverse plane (use E_T^{miss}),
 - ▷ for $E_i \gg m_i$ (highly relativistic case),

deriving the "invariant" mass would then lead to

the **total transverse mass**, m_T^{tot}

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

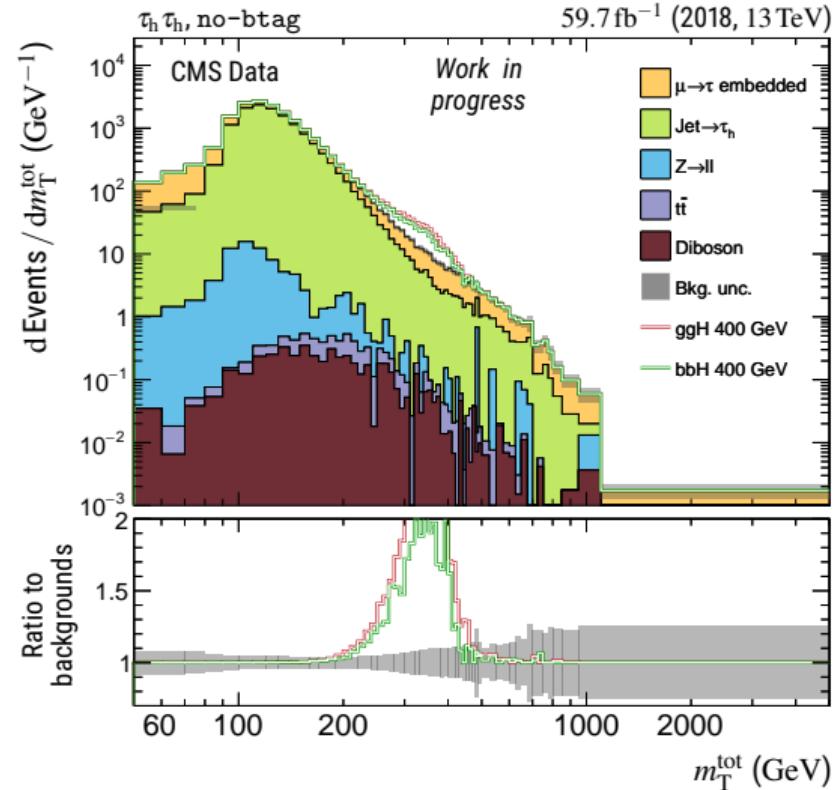
$$m_T(1,2) = \sqrt{2p_T^{(1)} p_T^{(2)} (1 - \cos \Delta\phi)}$$



m_T^{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

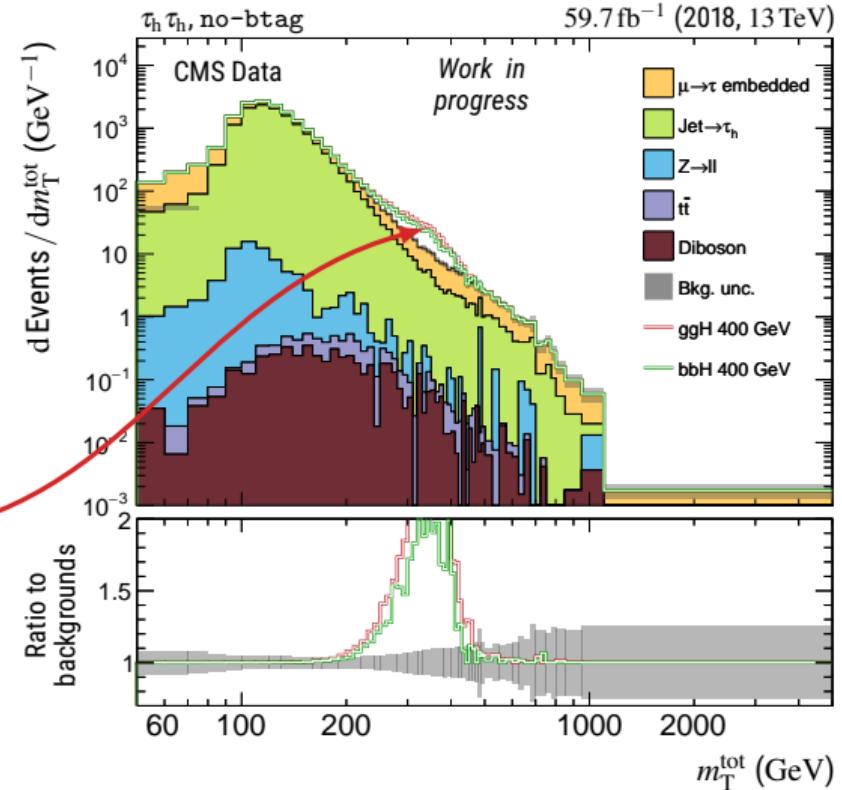


m_T^{tot} distributions

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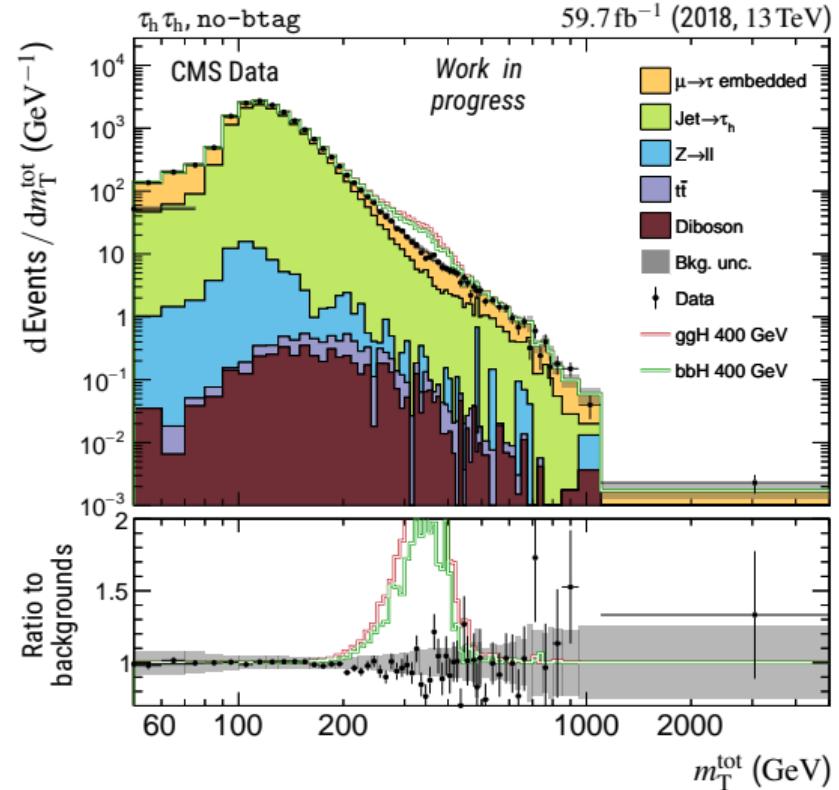
- ▷ DY $Z \rightarrow \tau\tau$ and some $t\bar{t}$ in $\mu \rightarrow \tau$ embedded
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- ▷ Remaining $t\bar{t}$ in $t\bar{t}$
- ▷ Other small backgrounds in Diboson

► MSSM H with $m = 400$ GeV expected signal.



m_T^{tot} distributions

- ▶ Backgrounds = SM expectations:
 - ▷ 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
- ▶ MSSM H with $m = 400 \text{ GeV}$ expected signal.
- ▶ Compare to observed events (black dots).



m_T^{tot} distributions

► Background contributions:

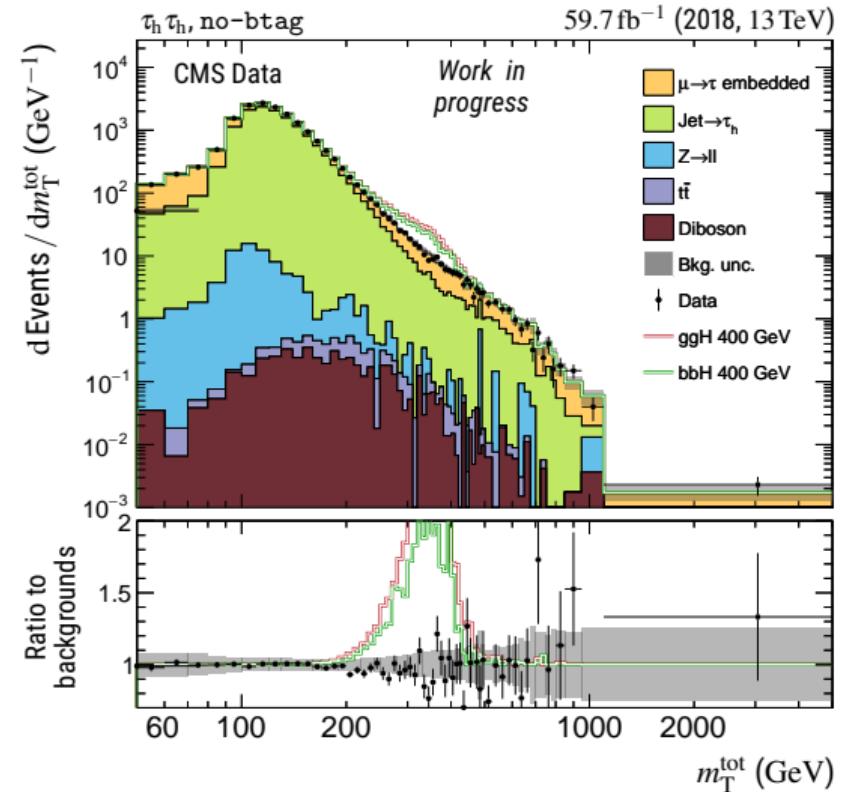
Not just a plot!

► Lot of hard work to obtain this: τ 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

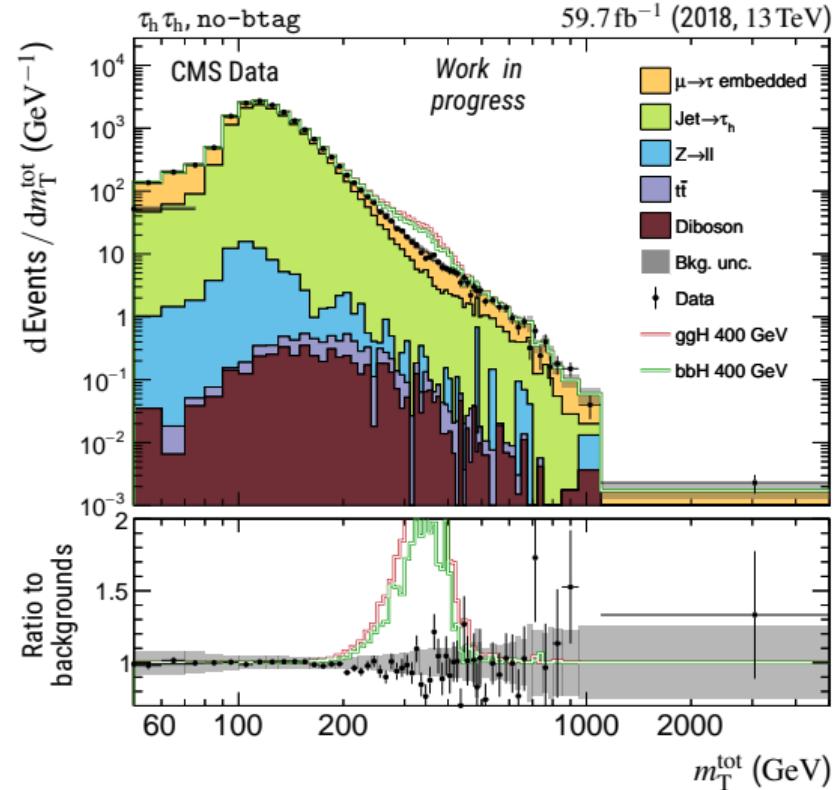
► Collaborative work:

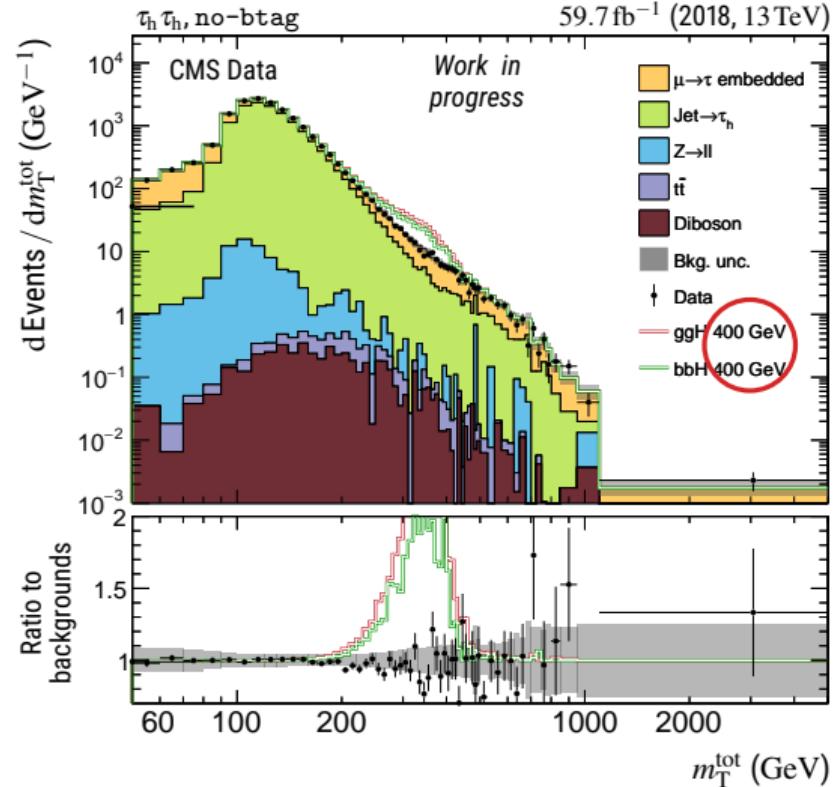
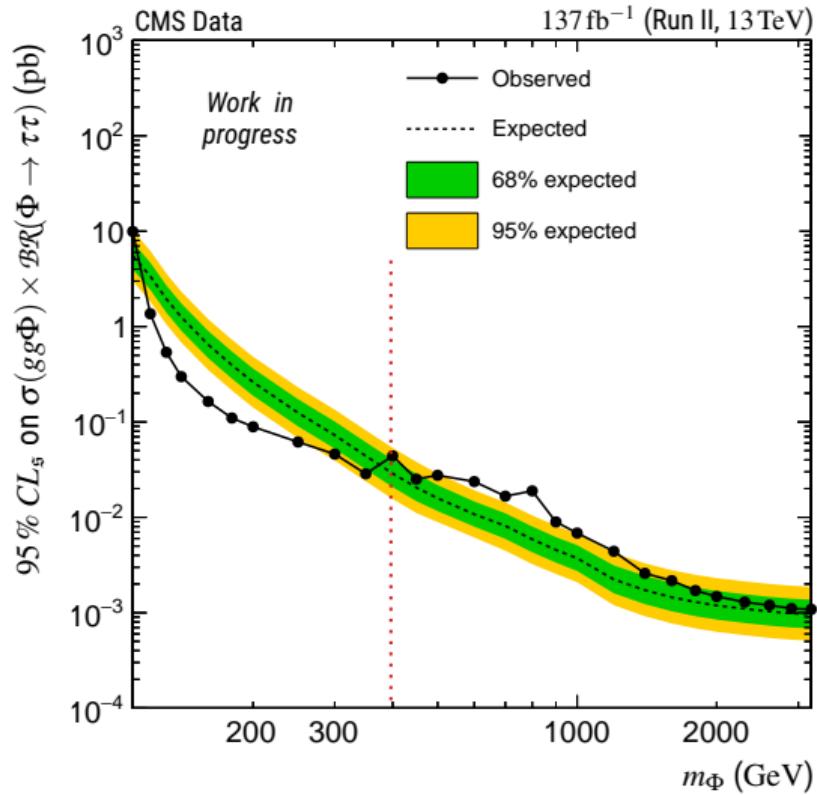
- ▷ Other collaboration
- ▷ Karlsruhe Institute of Technology (DE)
- ▷ Imperial College (UK) expected signal.
- ▷ DESY (DE) observed events (black dots).
- ▷ IP2I (FR)



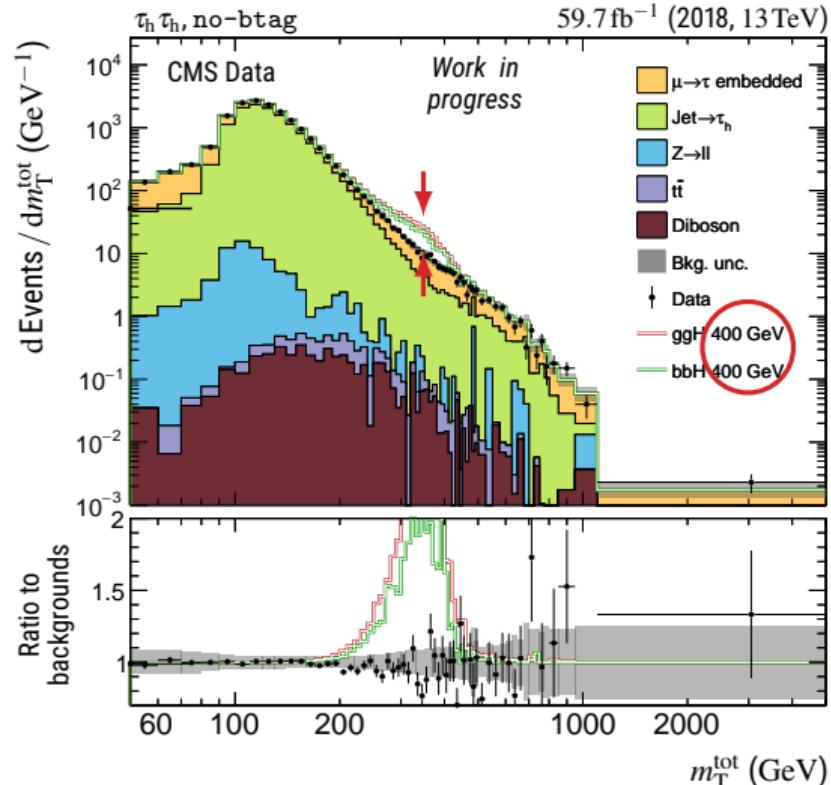
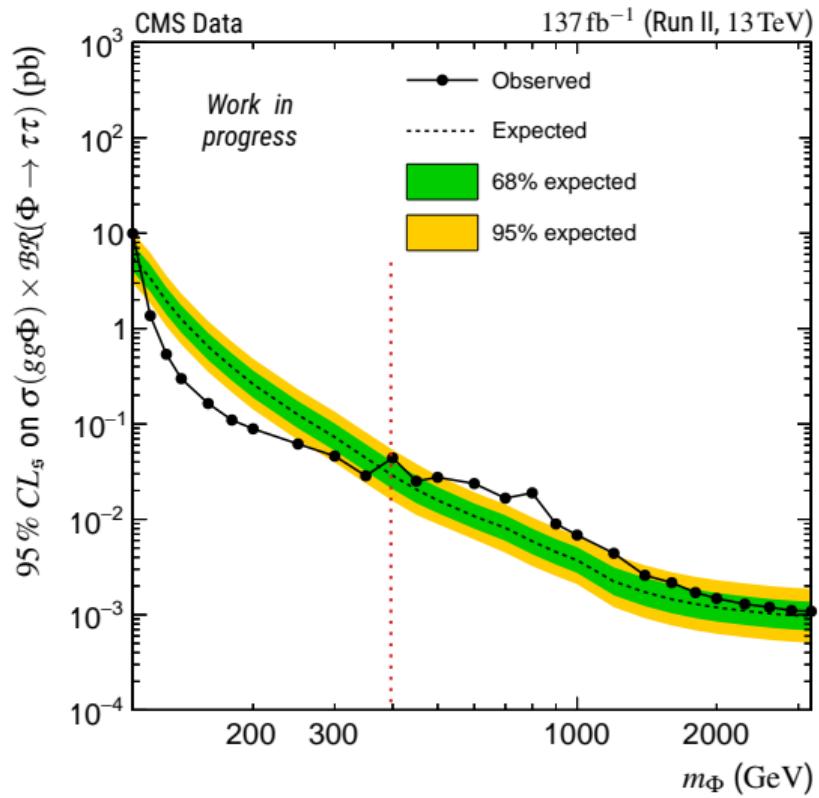
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 - ▷ Other small backgrounds in Diboson
- ▶ MSSM H with $m = 400 \text{ GeV}$ expected signal.
- ▶ Compare to observed events (black dots).
- ▶ Data/Bkg agreement \rightarrow **exclusion limits**.

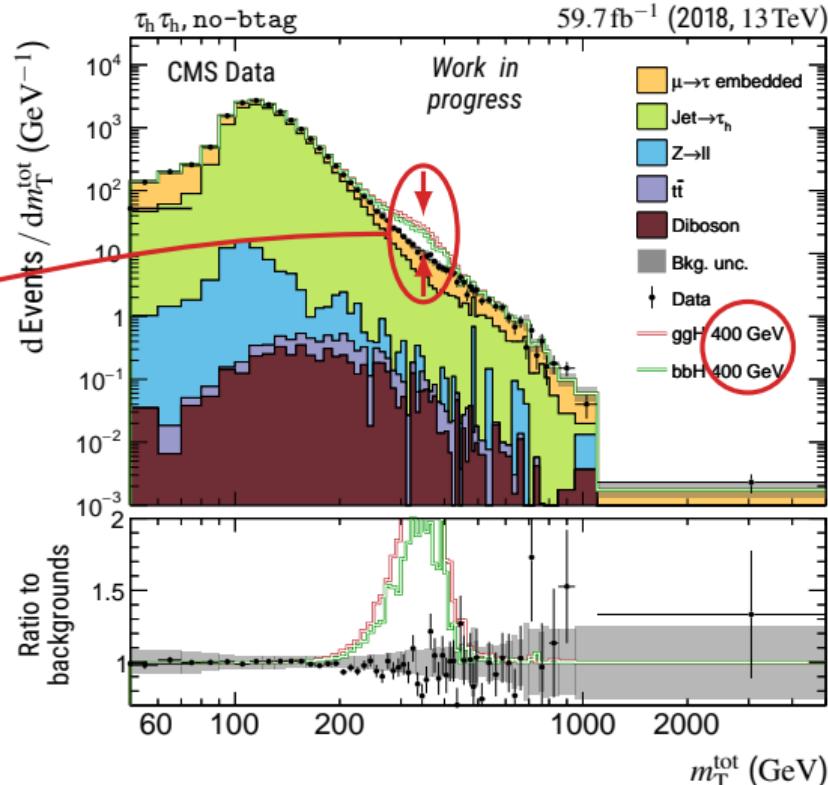
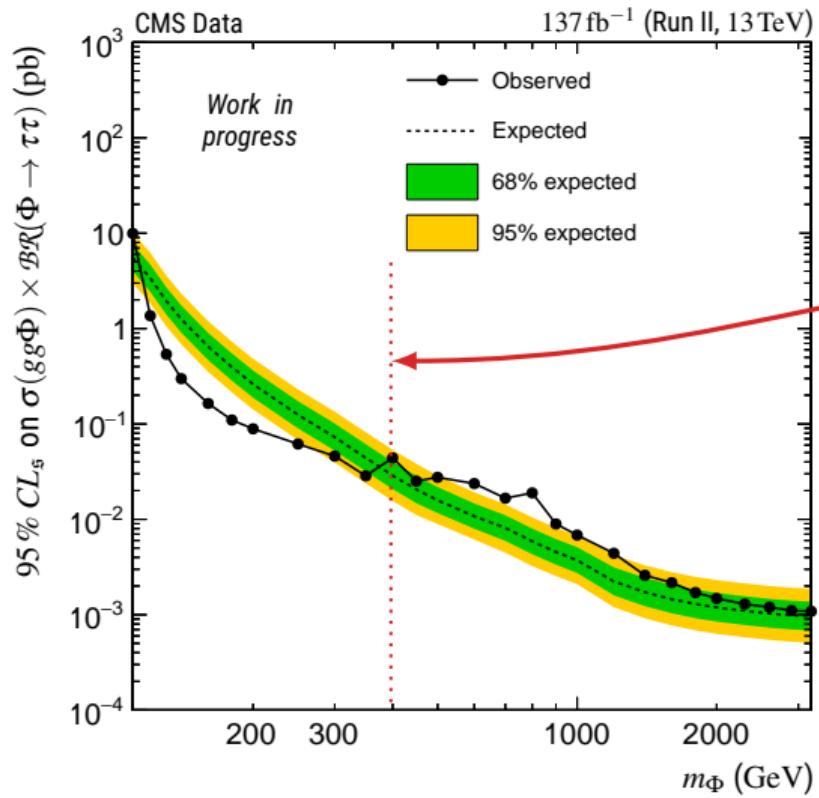




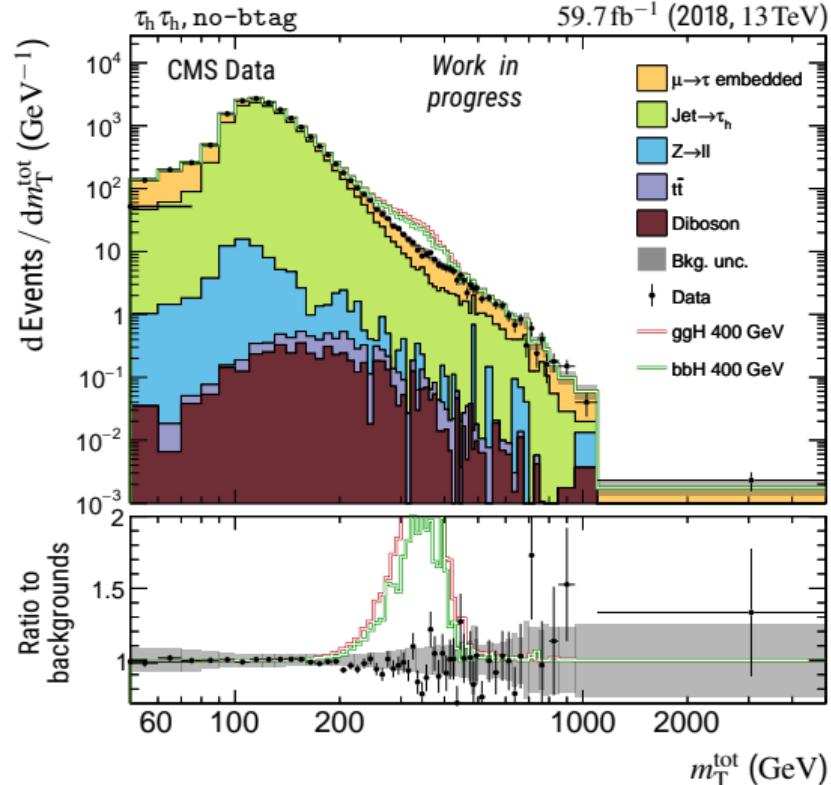
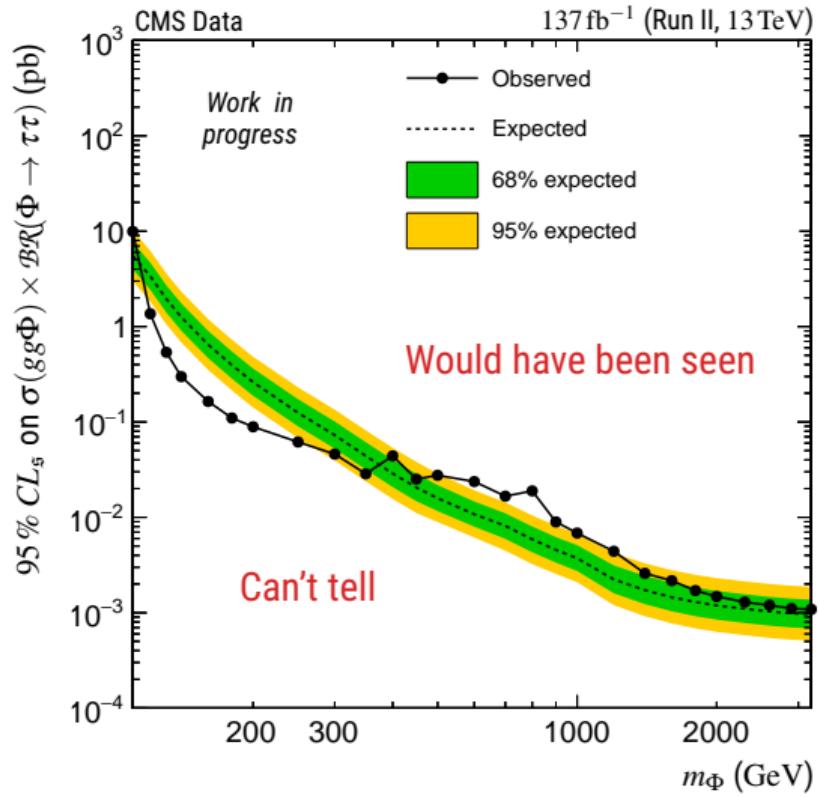
▷ A. L. Read. "Modified frequentist analysis of search results (the CL_s method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: <http://cds.cern.ch/record/451614>.



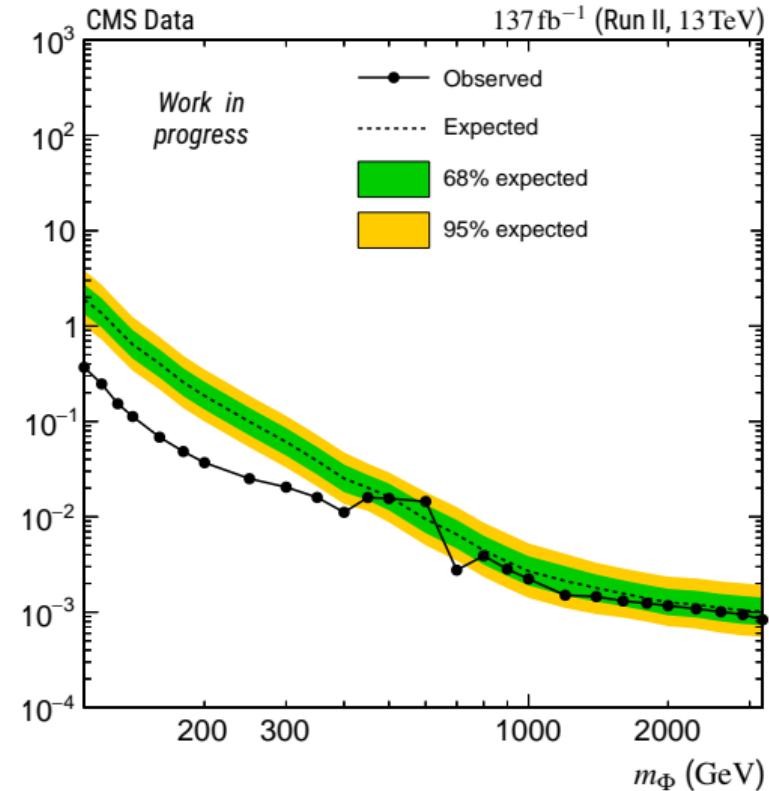
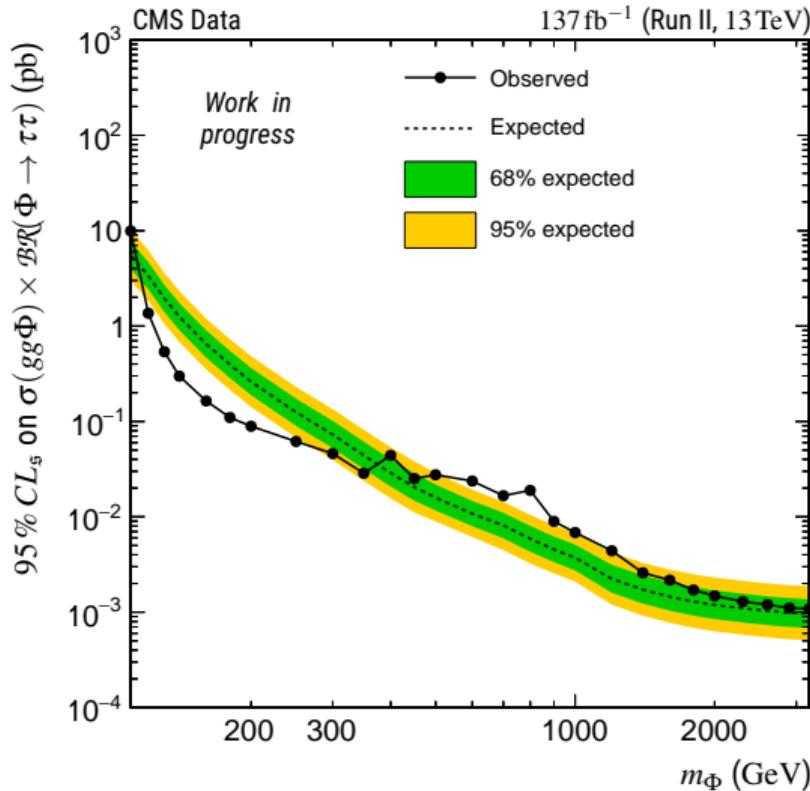
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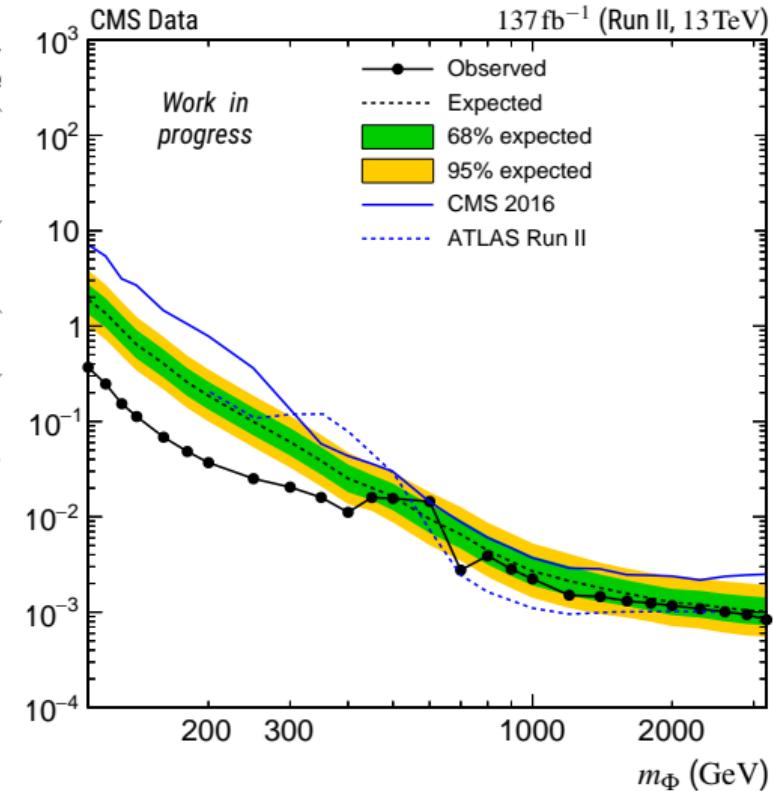
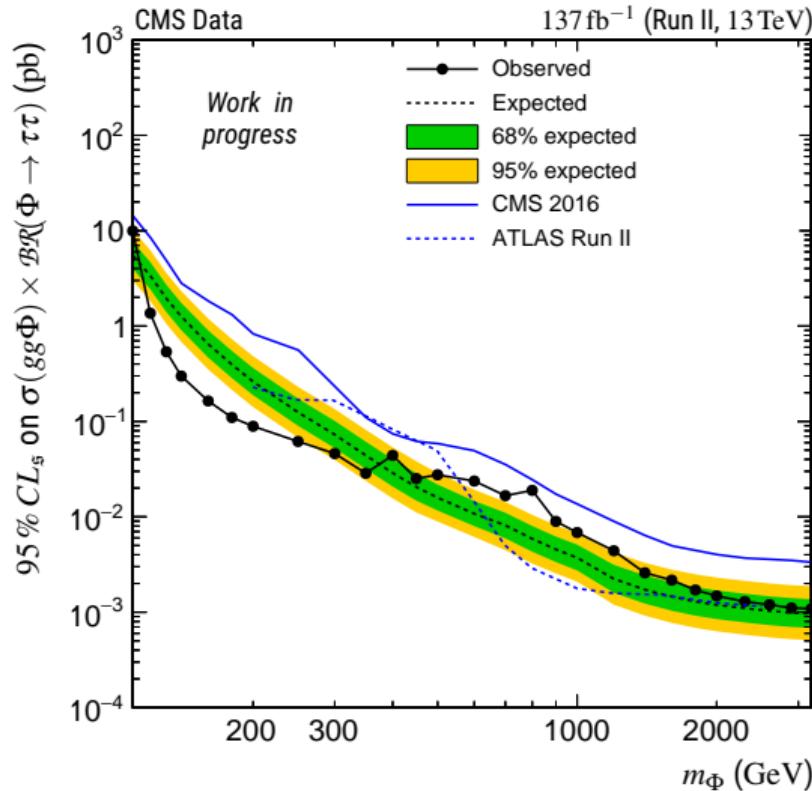
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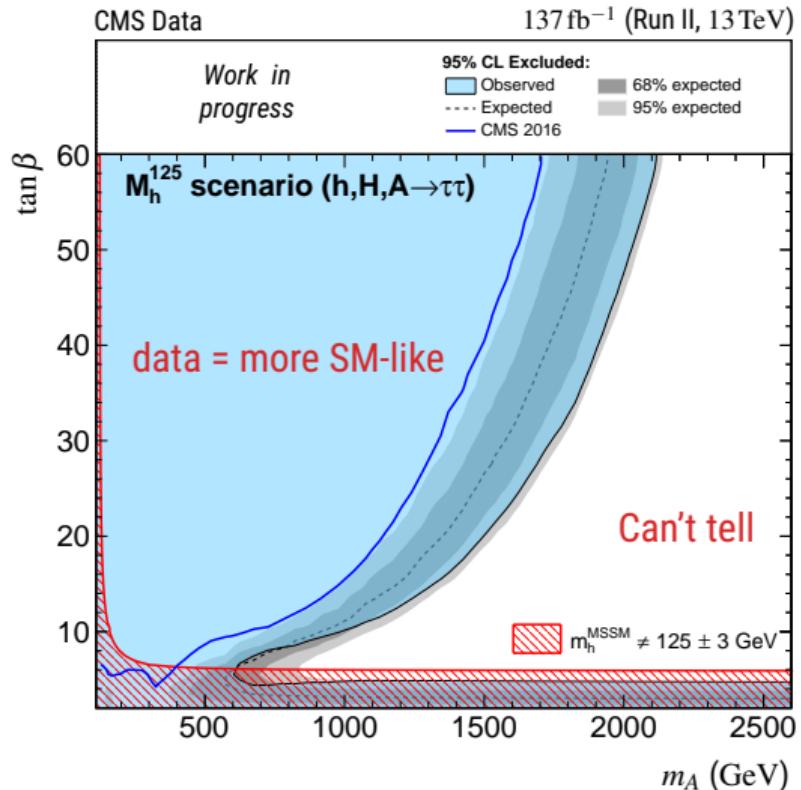


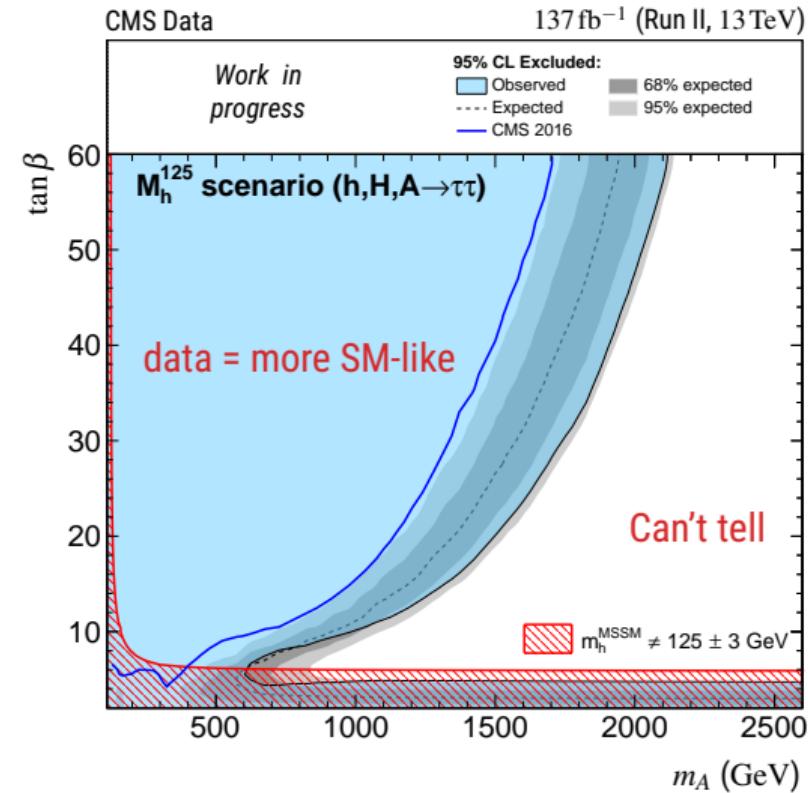
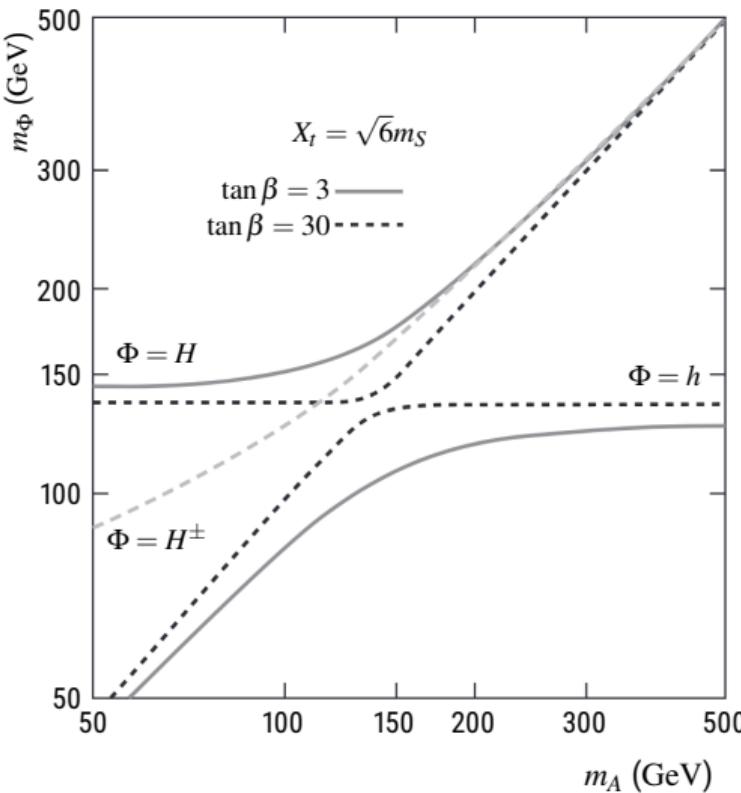
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- ▶ Model dependent limits:
 - ▷ Fix high-order MSSM parameter,
 - ▷ Explore $(m_A, \tan \beta)$ plane,
 - ▷ Do data stick more to SM or MSSM?



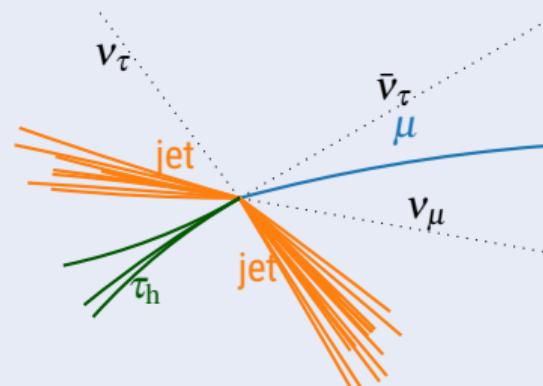


- ▶ Remember: invariant mass not fully available:
 - ▷ neutrinos in di- τ events.

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What's here

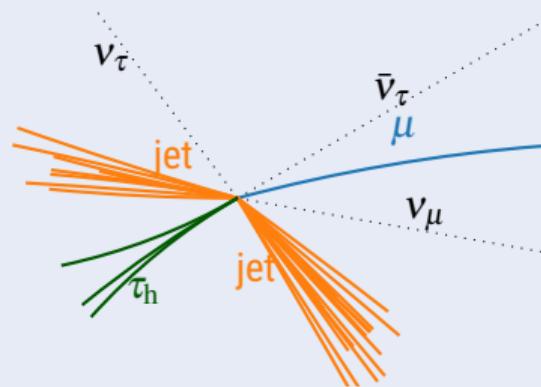
(e.g. VBF Higgs production + decay to $\tau\tau, \mu\tau_h$ channel)



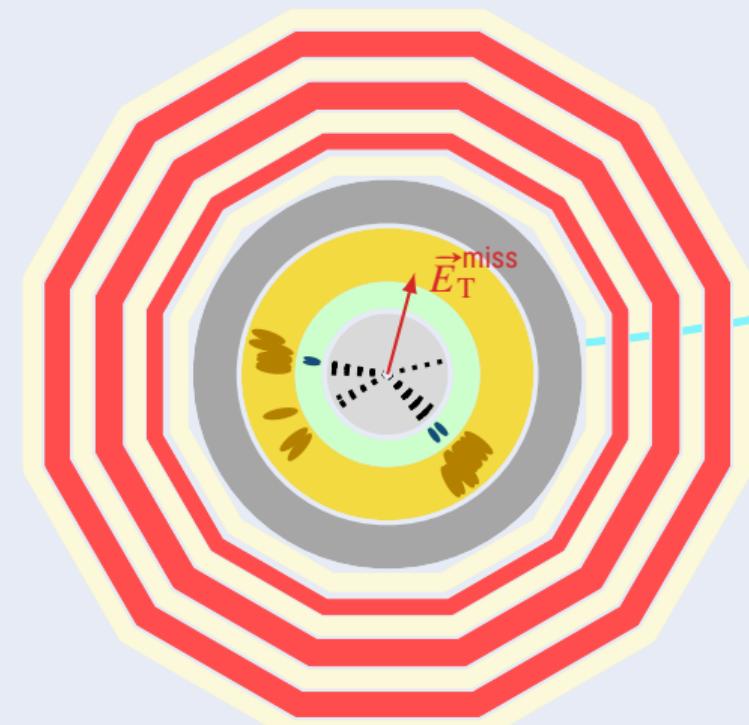
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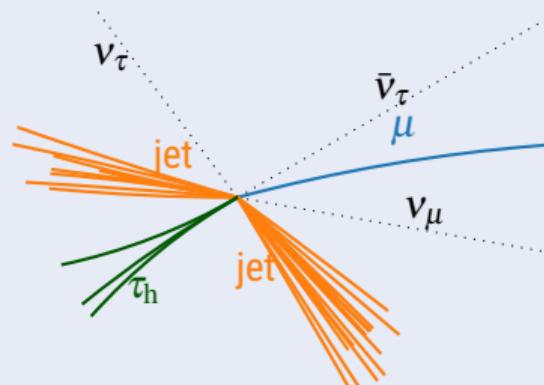
What CMS sees



- ▶ Remember: invariant mass not fully available:
 - ▷ neutrinos in di- τ events.

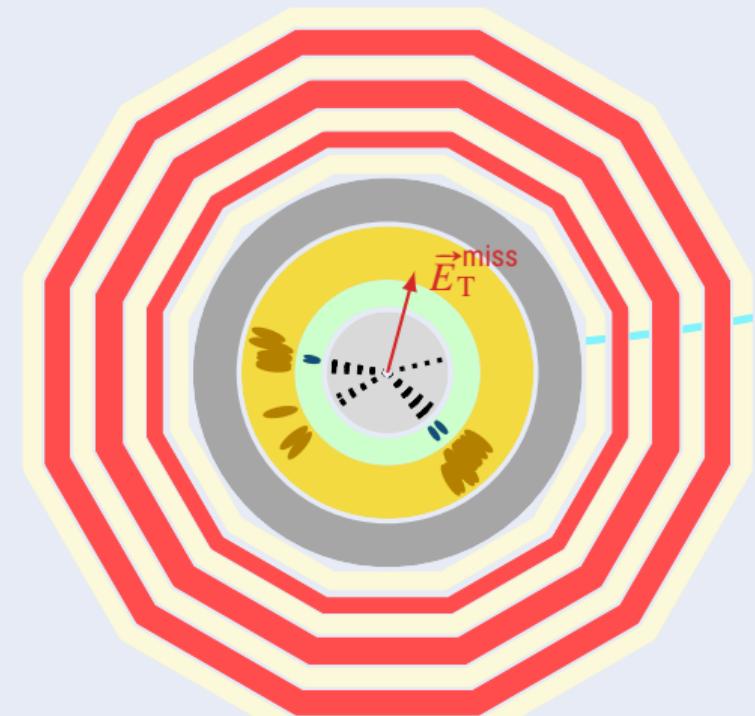
What's here

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



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

What CMS sees



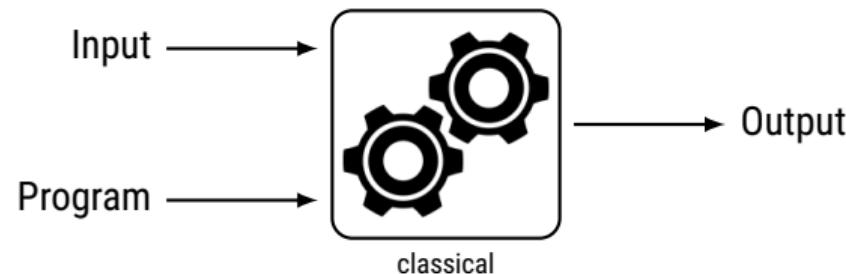
1 Phenomenology

2 Experimental device

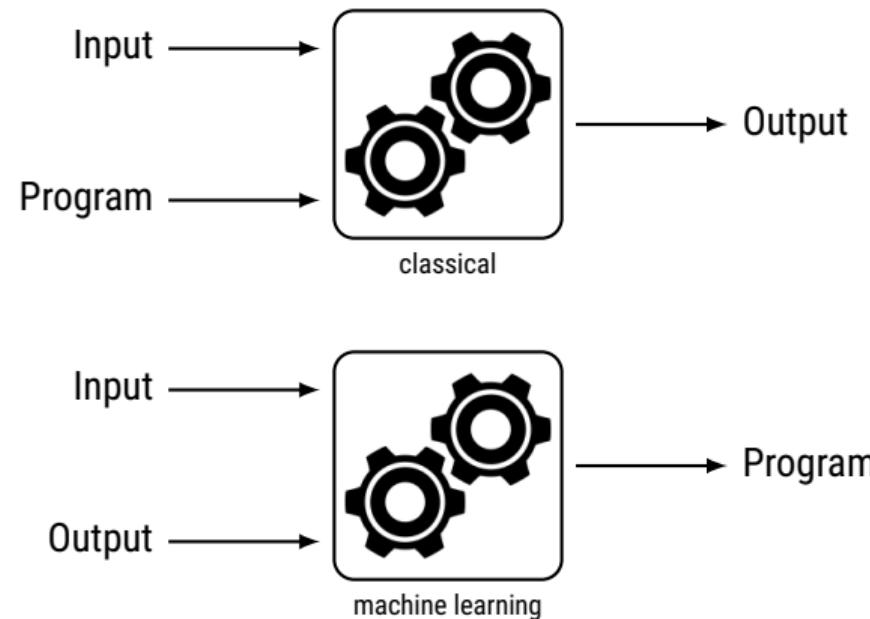
3 $H \rightarrow \tau\tau$ analysis

4 Machine learning

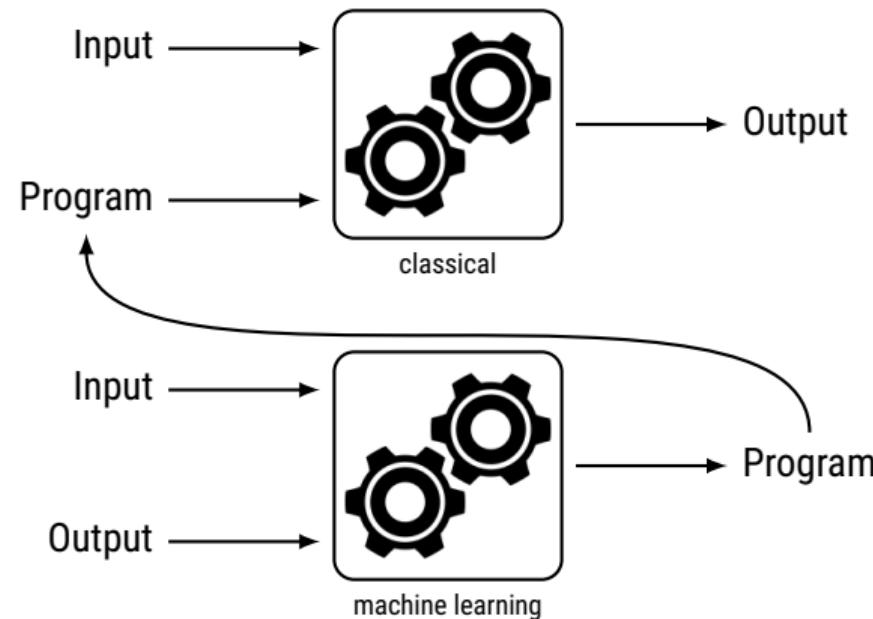
What is *machine learning*? – A brief introduction



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What is *machine learning*? – A brief introduction

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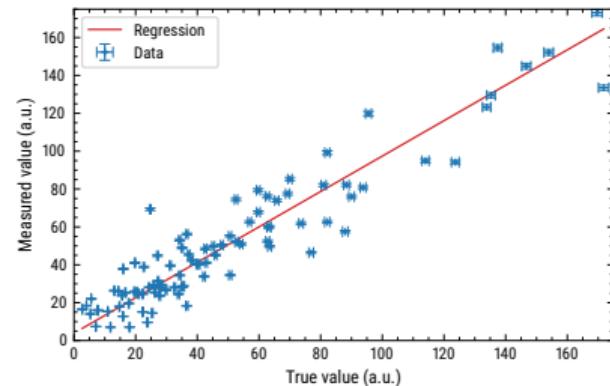
What is *machine learning*? – A brief introduction

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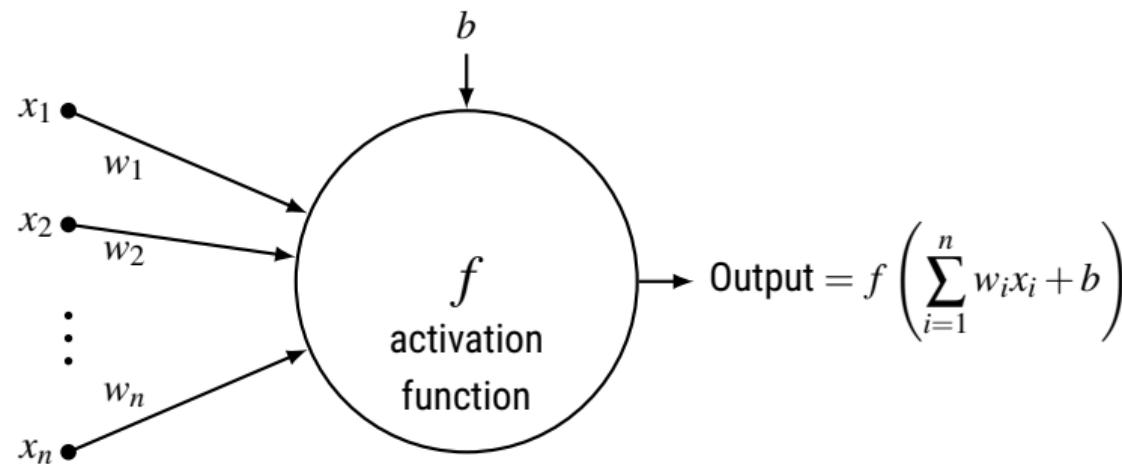
- ▶ Continuous target \Rightarrow Regression
e.g. discriminating variable!
Linear case:



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

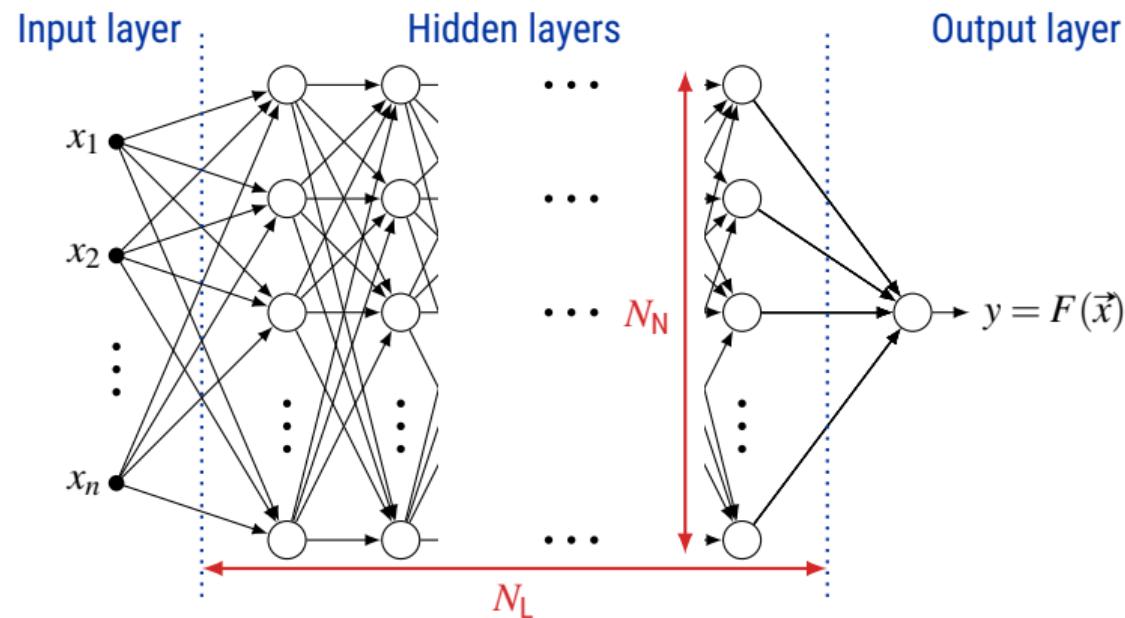
What if the target is not linear wrt. input?

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

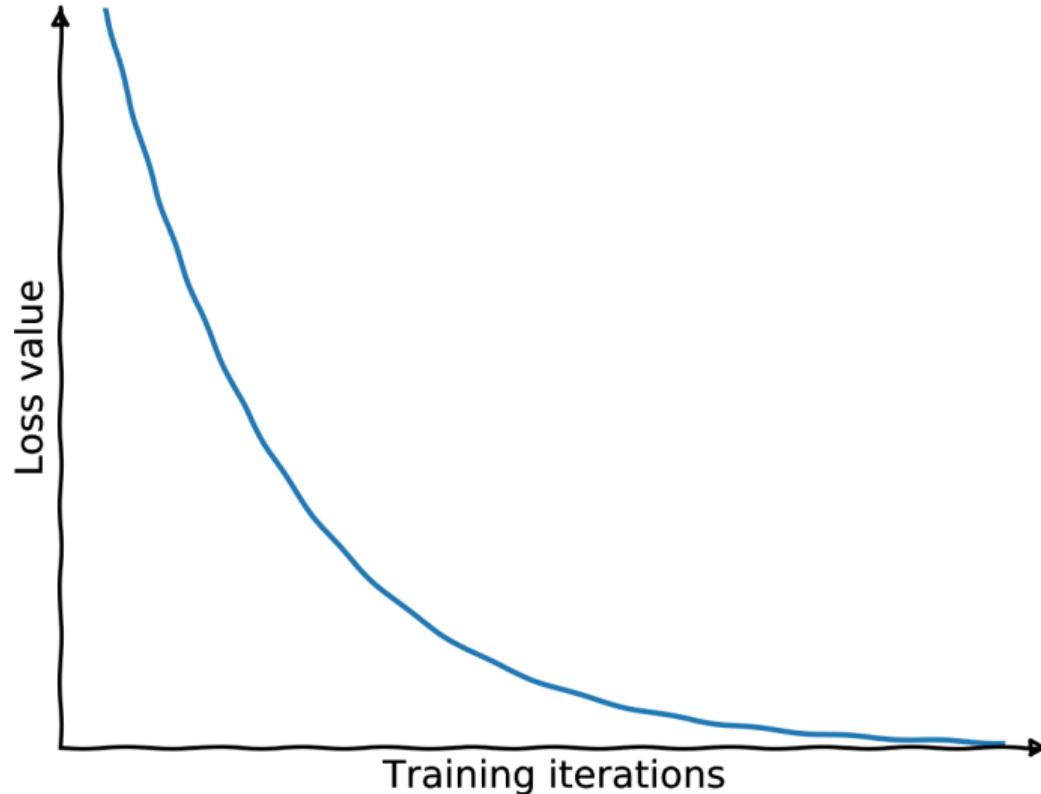


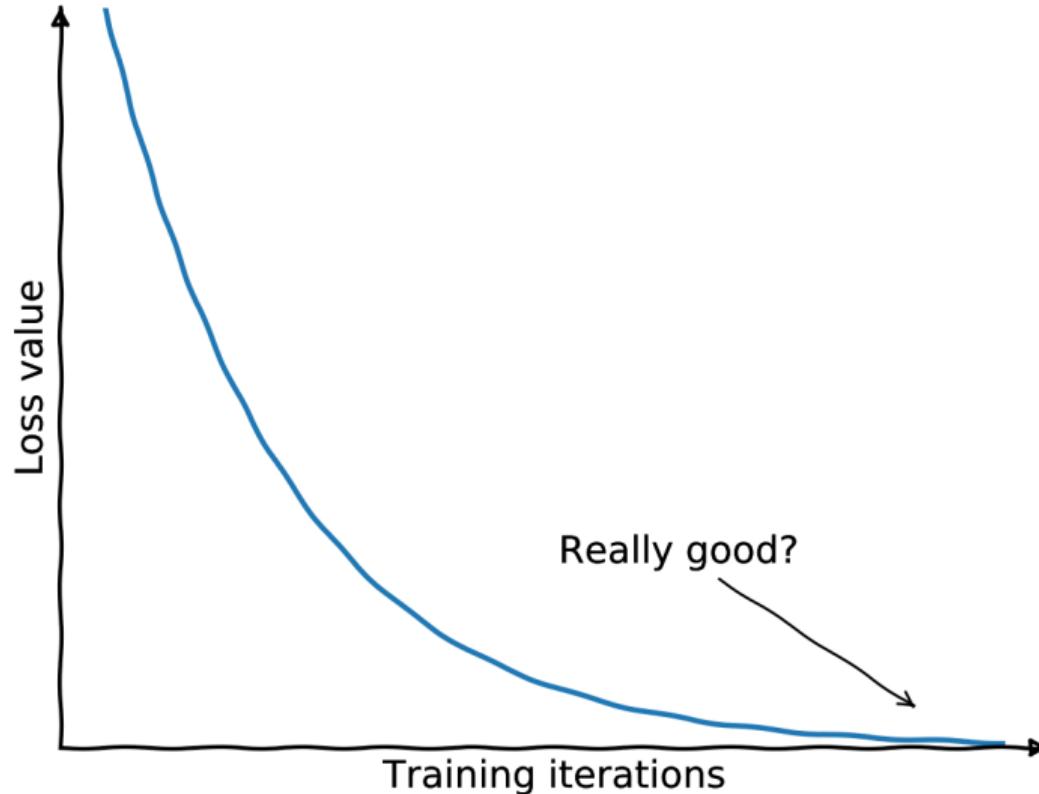
How to train a neural network?

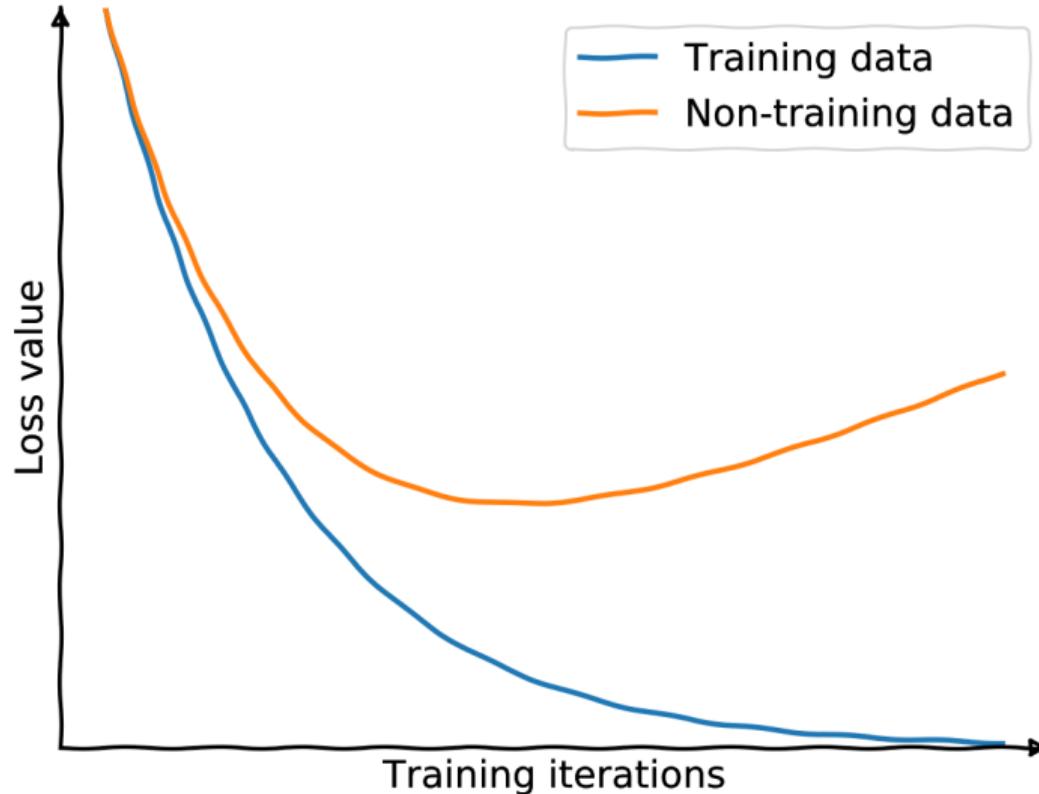
Train = optimize parameters $(w_1, w_2, \dots, w_n, b)$ for each neuron.

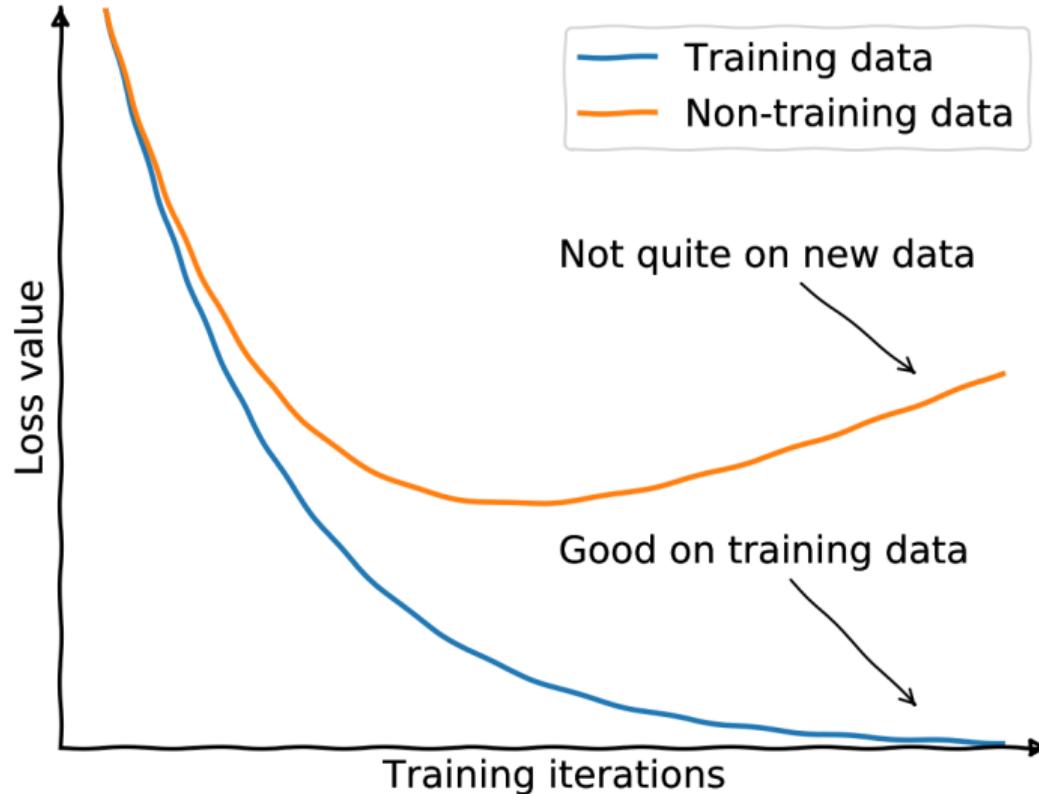
- ▶ Get a **training dataset** = examples of inputs \vec{x}_i with corresponding outputs y_i
- ▶ Compare the model predictions $F(\vec{x}_i)$ to the true values y_i
 - ▷ Define a **loss function** \mathcal{L} such that its minimum is reached when $F(\vec{x}_i) = y_i$
 - ▷ Change the parameters a bit,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

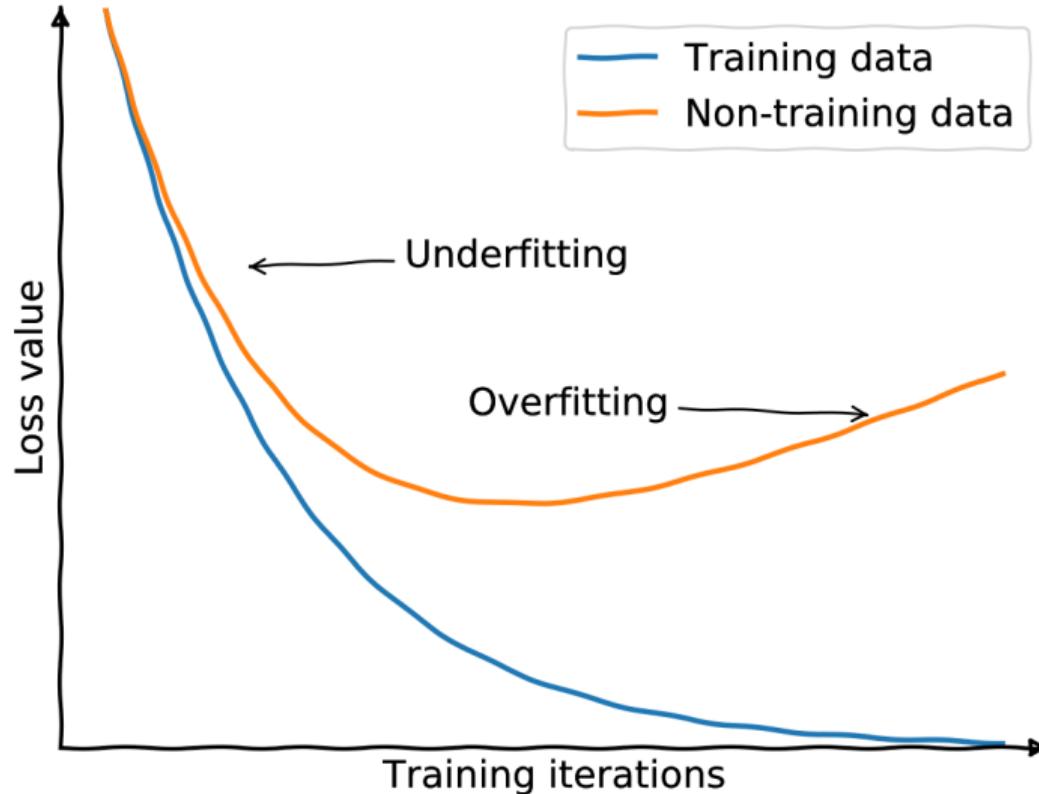
When to stop training?

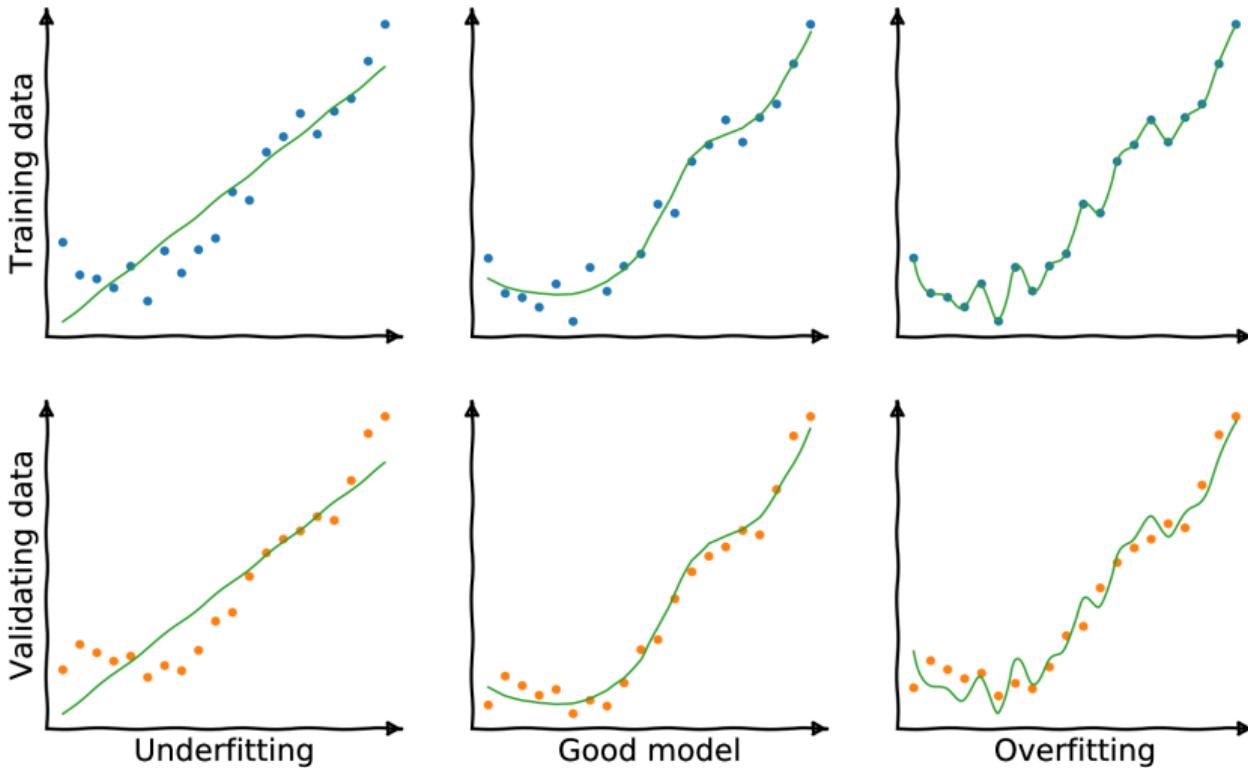


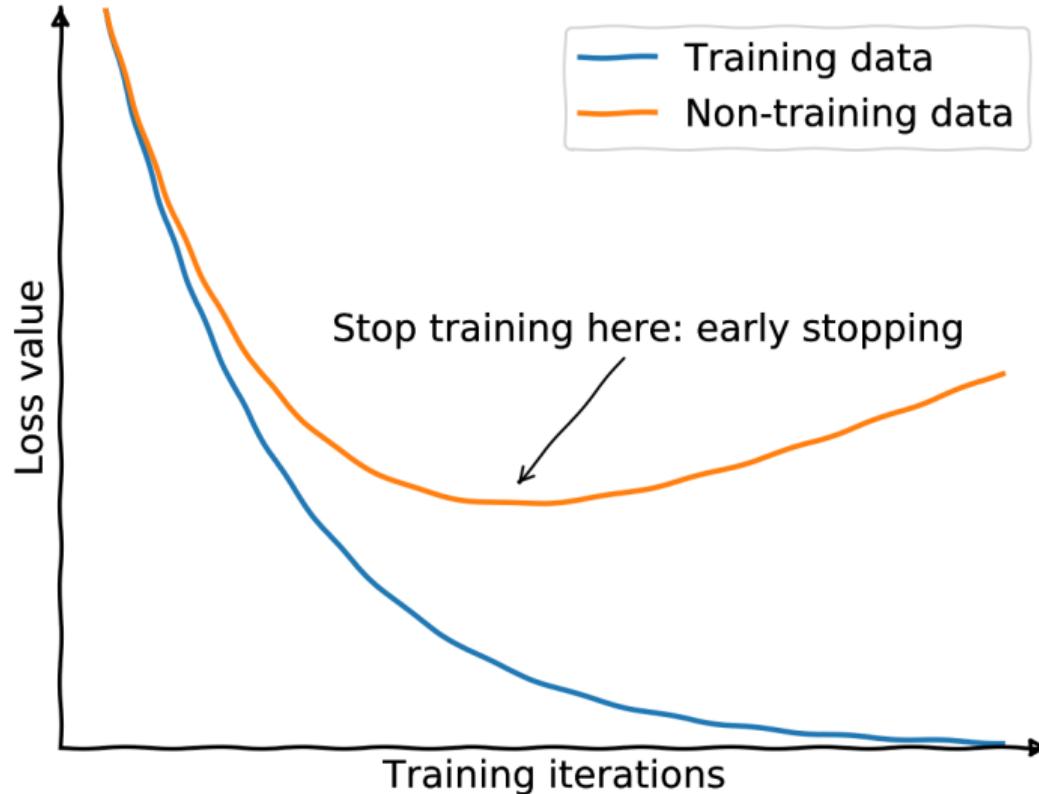


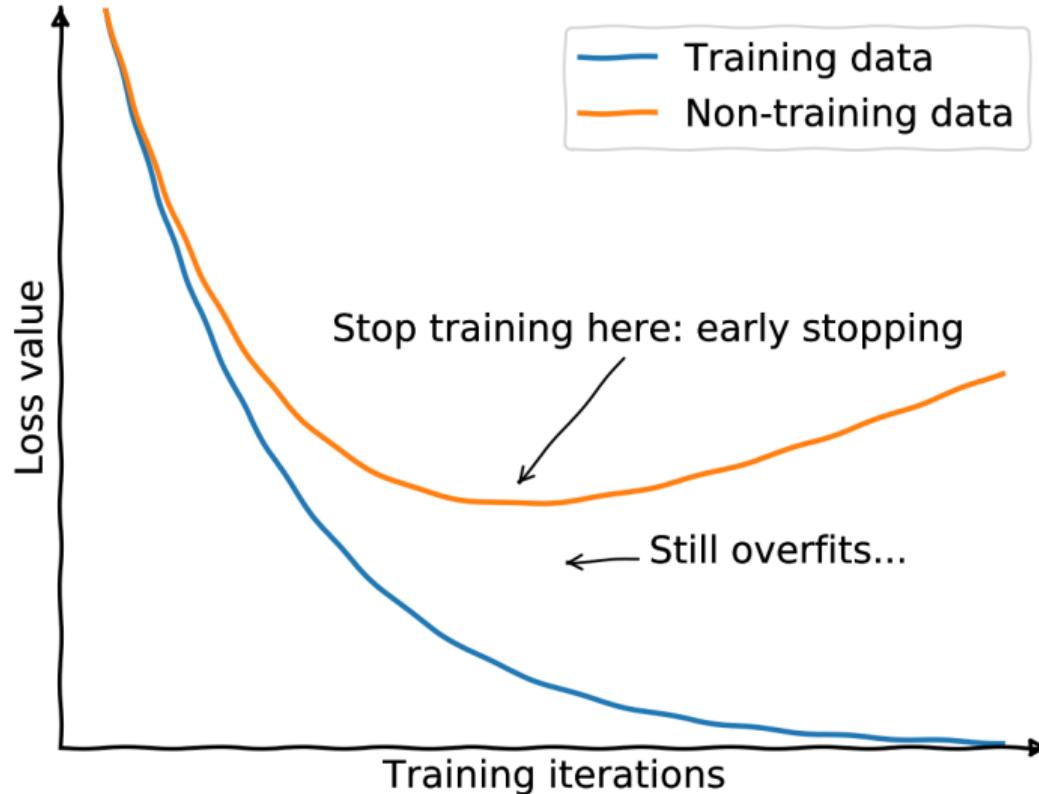


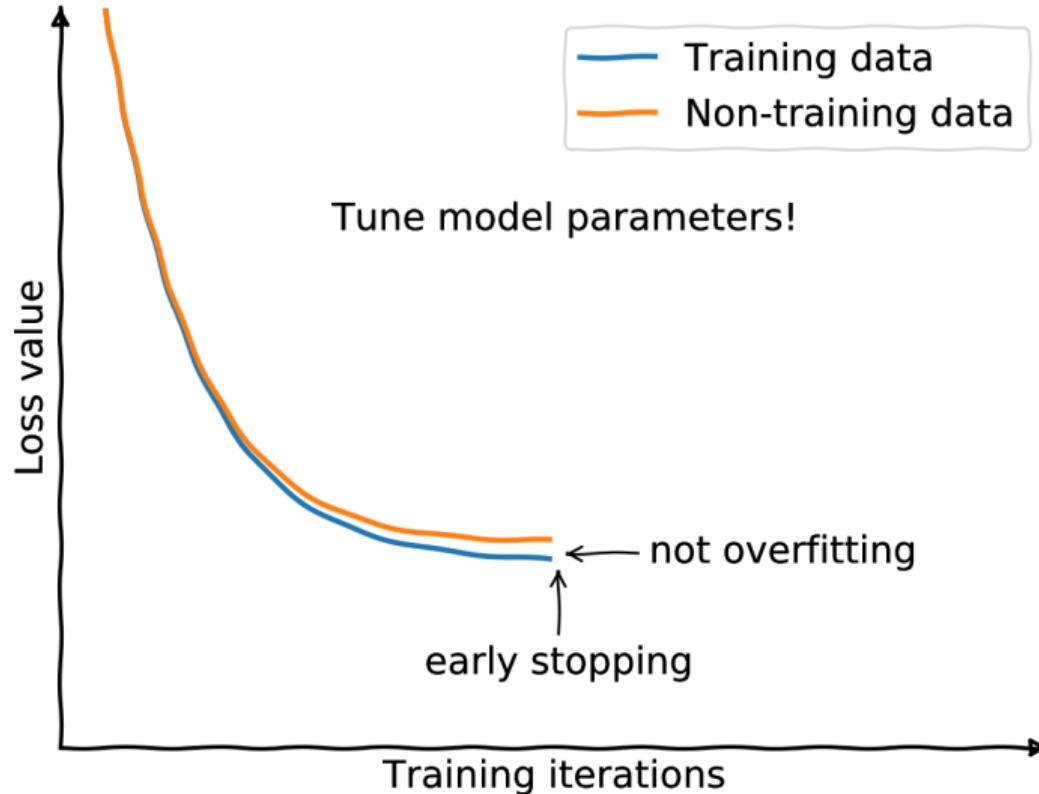




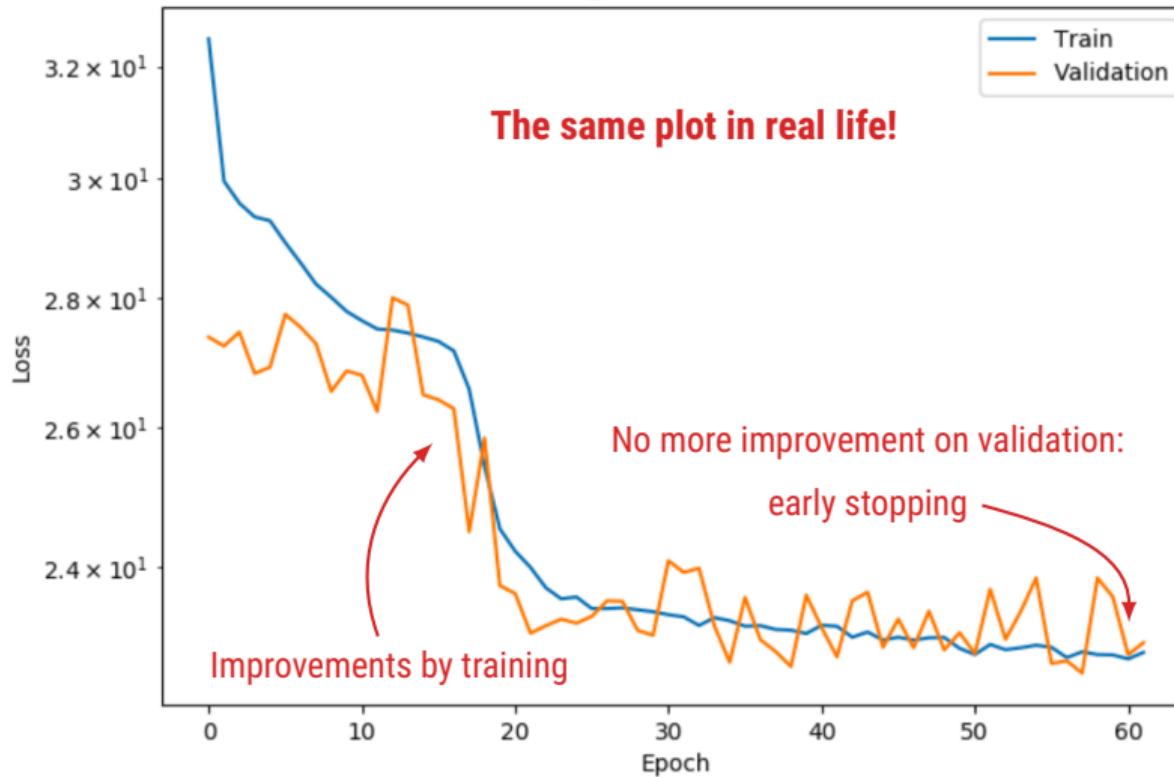








Training vs Validation Loss



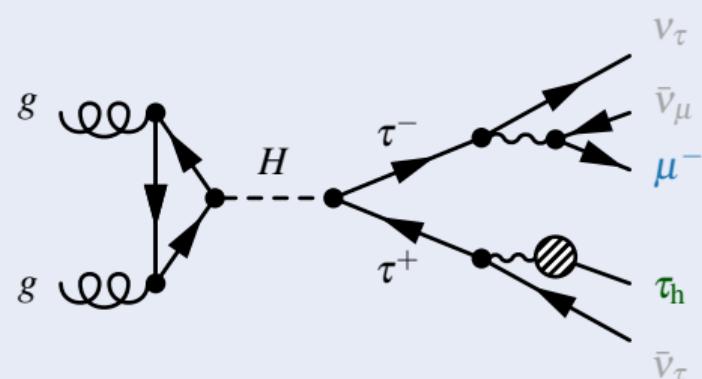
Build a neural network: target and inputs?

► Model target: generated Higgs mass.

► Model inputs:

- ▷ τ_1 (here = μ^-) and τ_2 (here = τ_h) p_T, η, ϕ ;
- ▷ PuppiMET p_T, ϕ ;
- ▷ 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, η, ϕ ;
- ▷ 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?

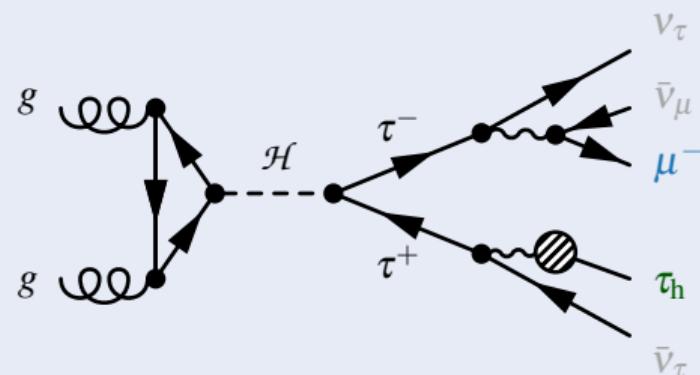
► Generate $\mathcal{H} \rightarrow \tau\tau$ events:

- ▷ \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- τ events.

► All final states used simultaneously for training:

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

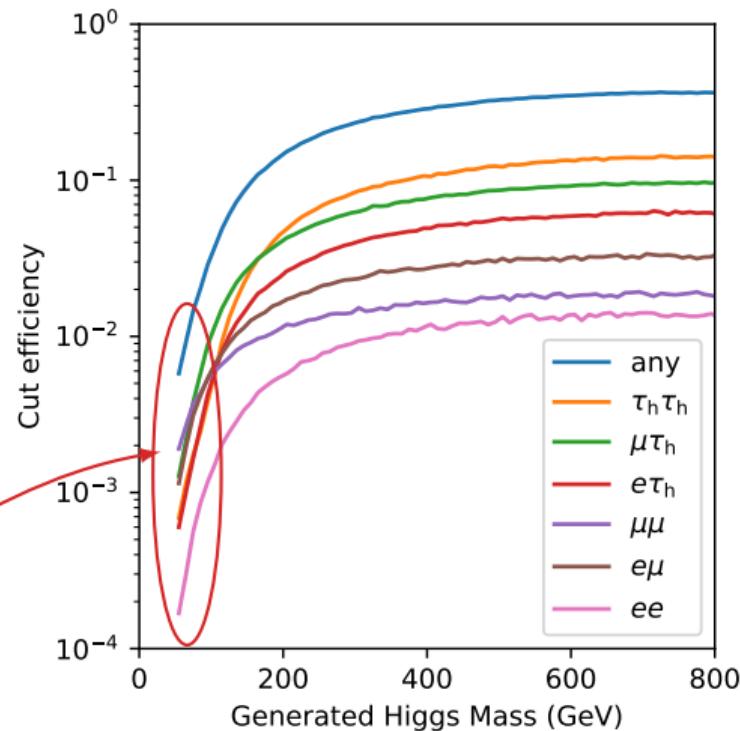
$$gg \rightarrow \mathcal{H} \rightarrow \tau\tau \rightarrow \mu\tau_h$$



Datasets: low mass boundary

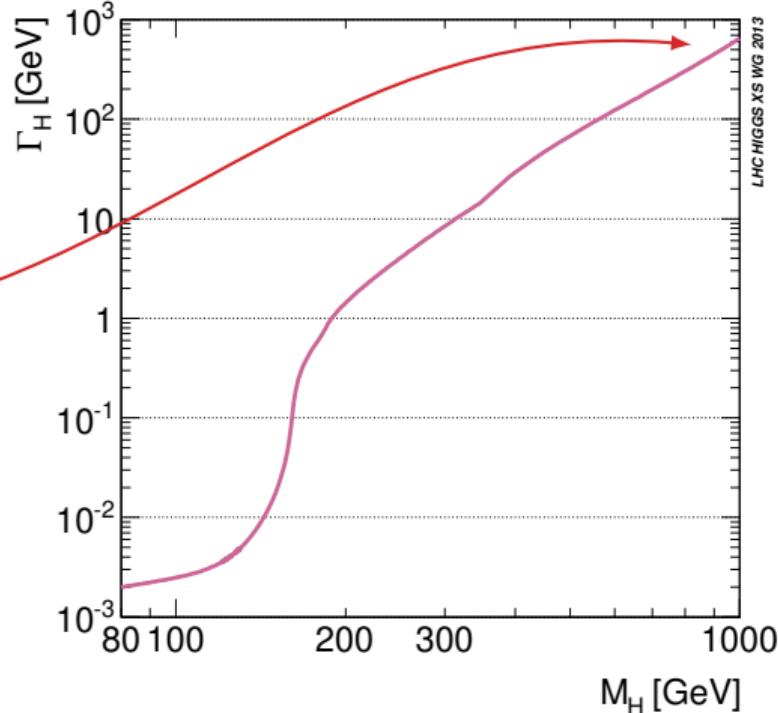
- ▶ Event selection:
 - ▷ Same as in the MSSM $H/A \rightarrow \tau\tau$ analysis,
 - ▷ Add $\mu\mu$ and ee channels.
- ▶ Events amount drops at low mass:
 - ▷ due to p_T cuts,
 - ▷ go down to 50 GeV for m_H .

Less than 1 % pass the selection



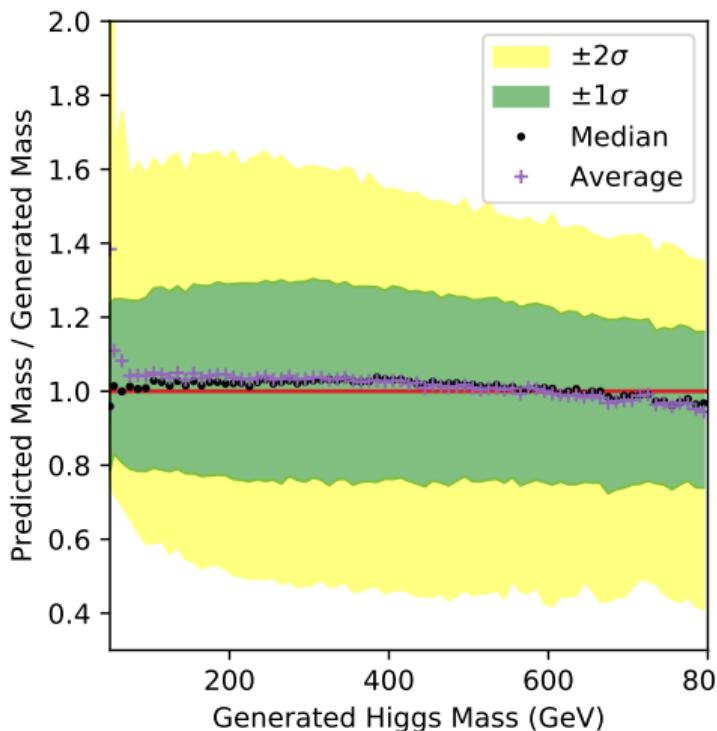
Datasets: high mass boundary

- ▶ 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

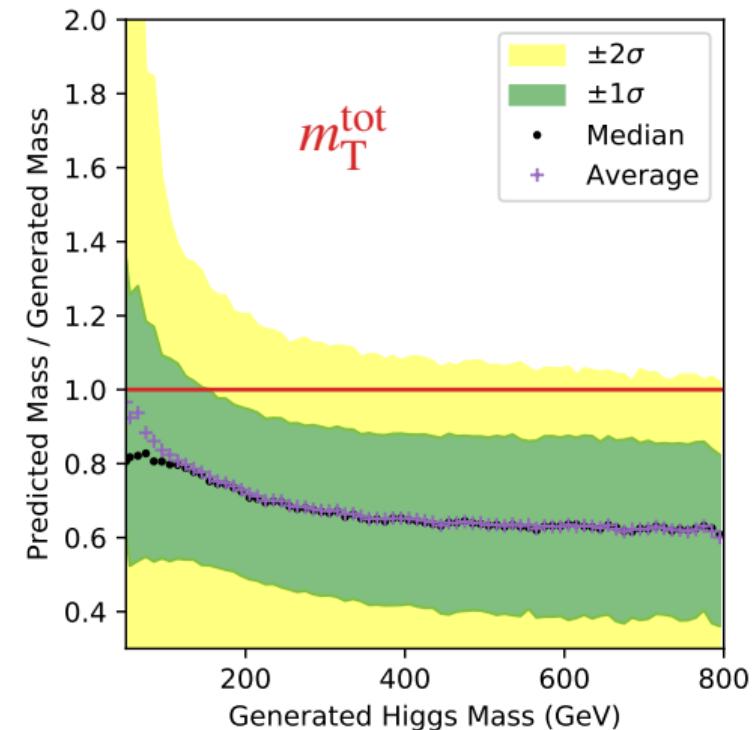
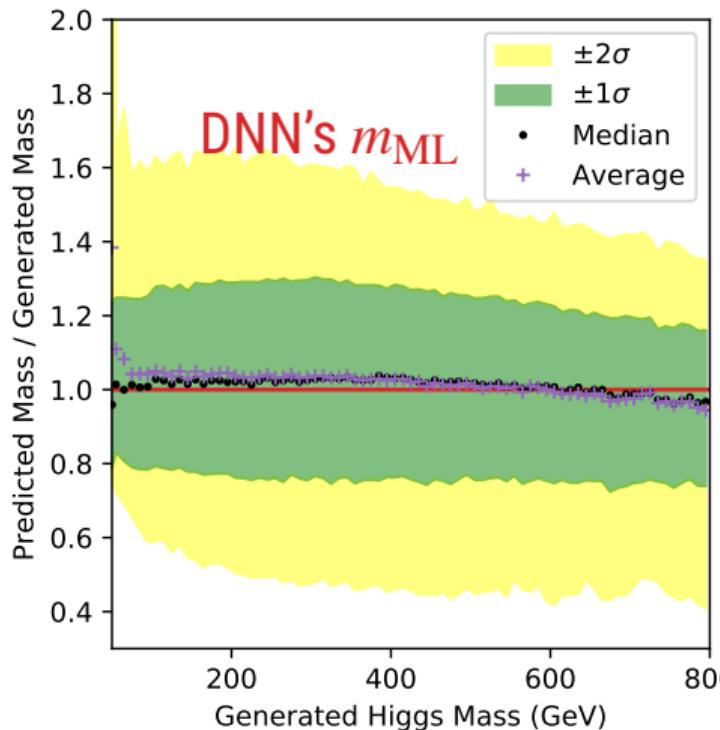


► Model's response:

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

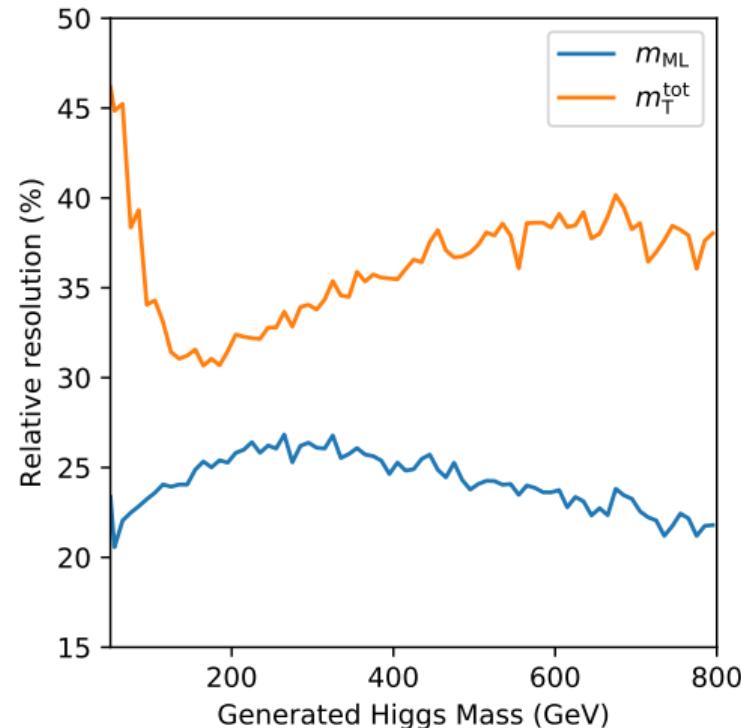
- ▷ Closer to 1 is better.
- ▷ $r = 1.00 \pm 0.05$ from 80 to 800 GeV
- ▷ \mathcal{H} mass reconstruction **achieved ✓**

DNN's m_{ML} predictions vs m_T^{tot}

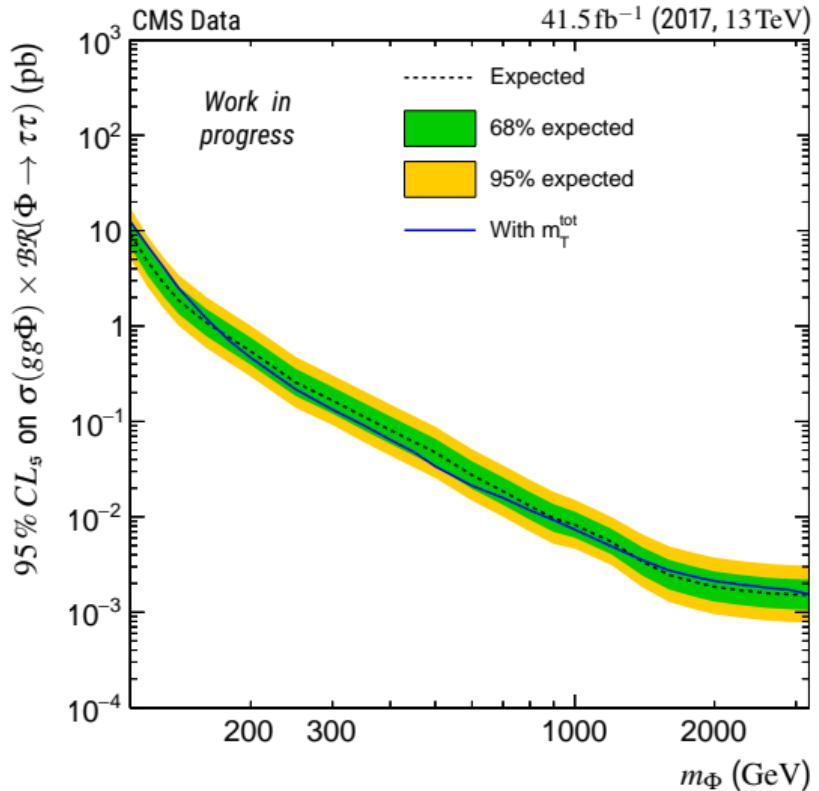


Using the model to get a discriminating variable

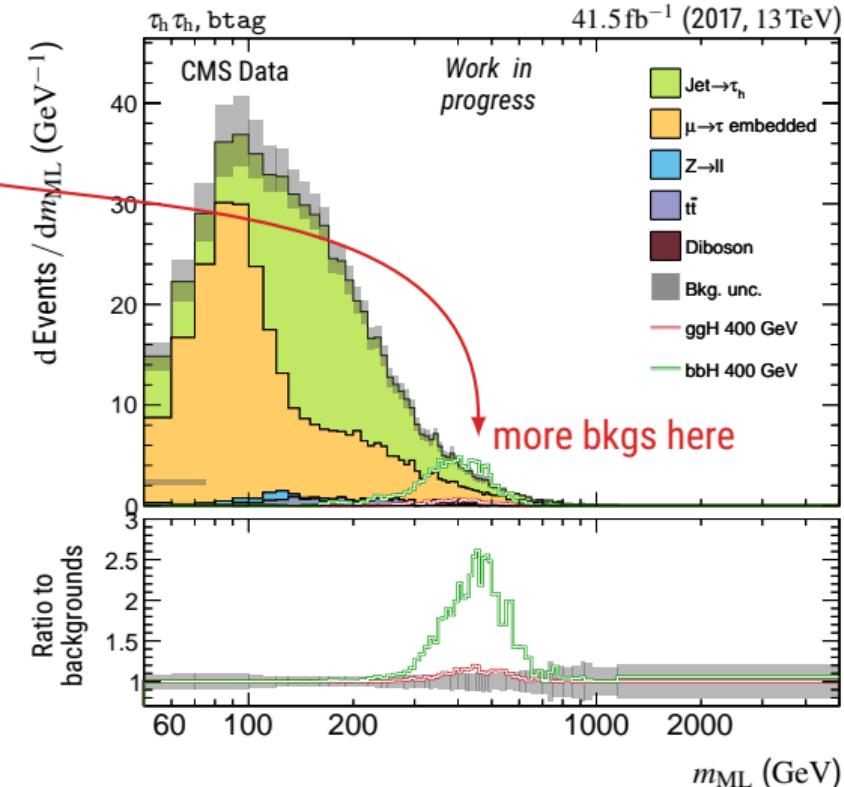
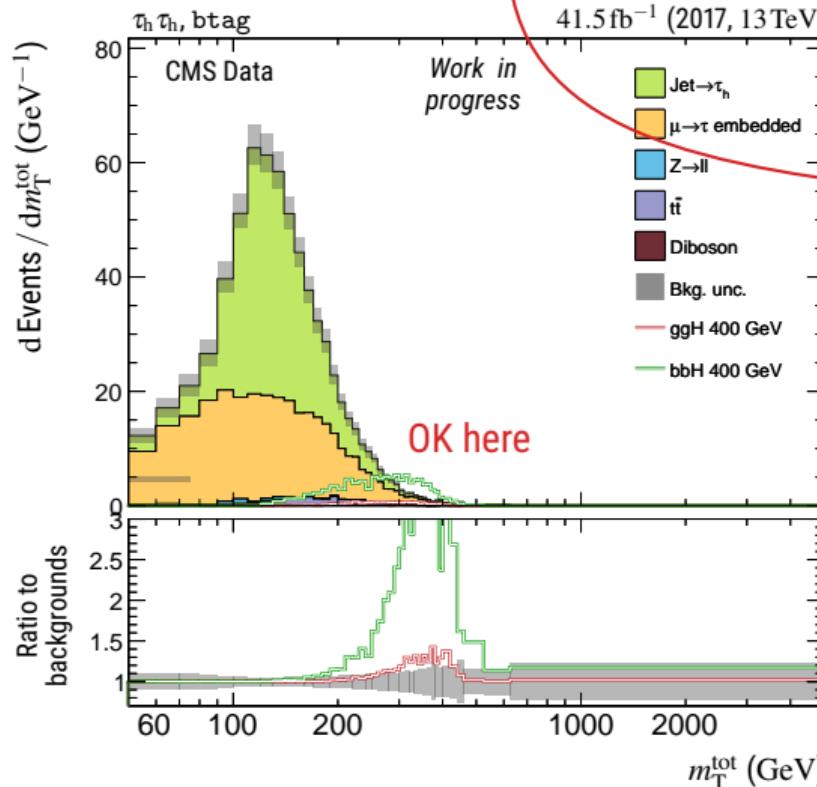
- ▶ In the $H/A \rightarrow \tau\tau$ analysis, discriminating variable = m_T^{tot} .
- ▶ m_T^{tot} is equal to the invariant mass assuming:
 - ▷ all neutrinos are a single particle with $\vec{p}_T = \vec{E}_T^{\text{miss}}$,
 - ▷ all is going on in the transverse plane (any $p_z = 0$).
- ▶ Our model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



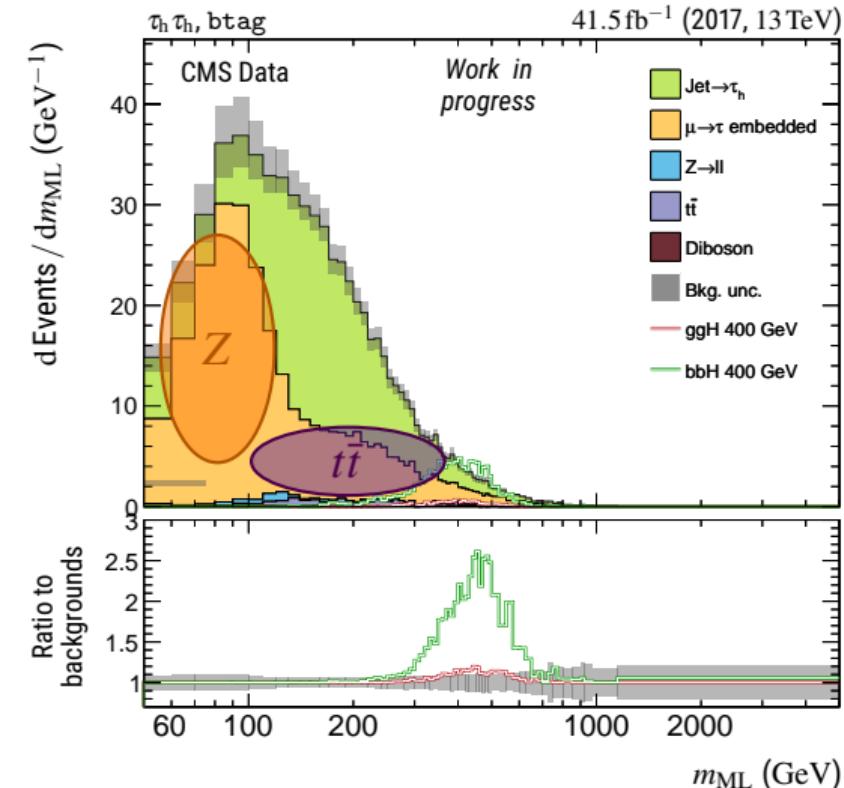
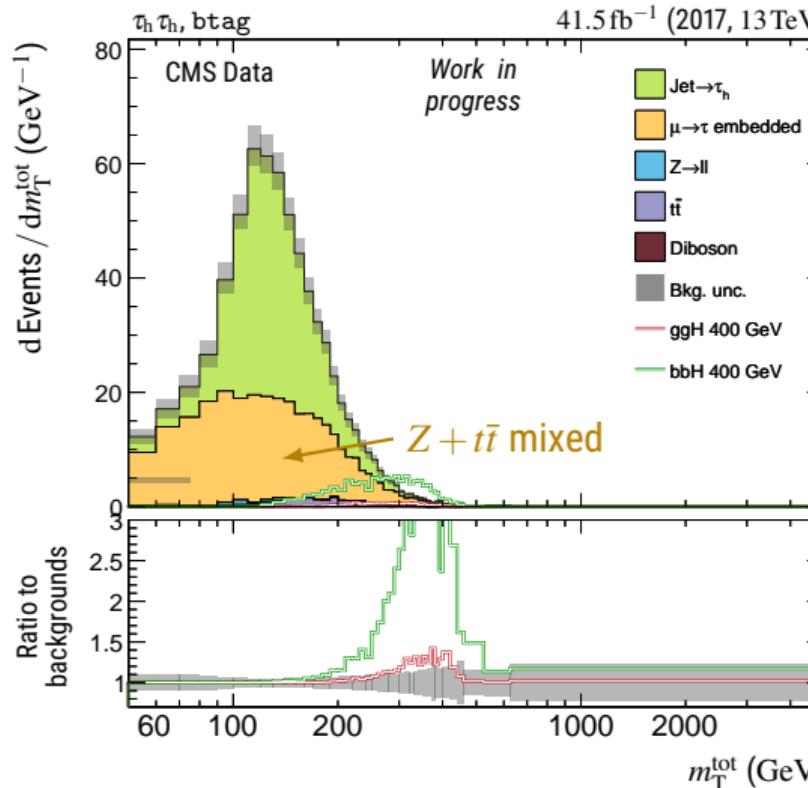
- ▶ Proceed to the search for massive Higgs boson Φ with di- τ events on the 2017 era.
- ▶ Use m_{ML} as discriminating variable.
- ▶ Not really better than with m_T^{tot} ... Why?



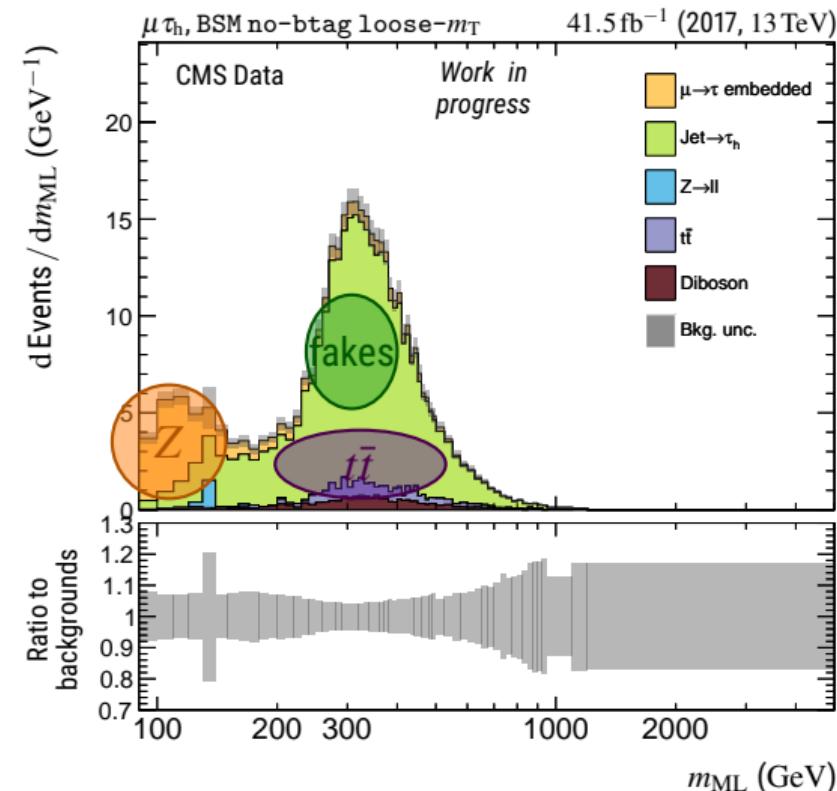
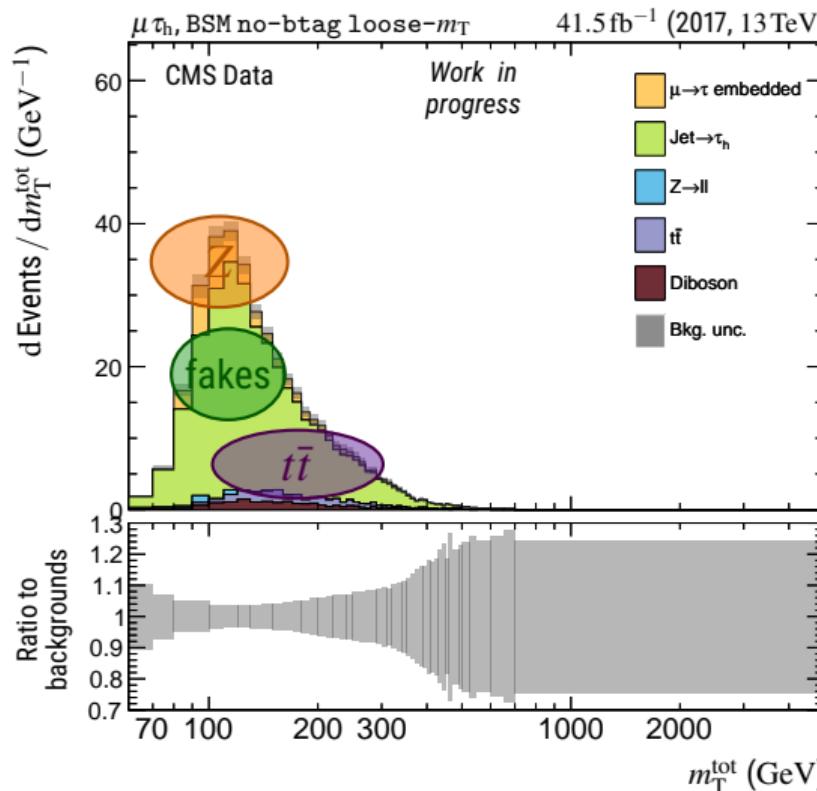
► Large fakes τ_h high mass tails falling into the signal region \Rightarrow lowered signal to background ratio.



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

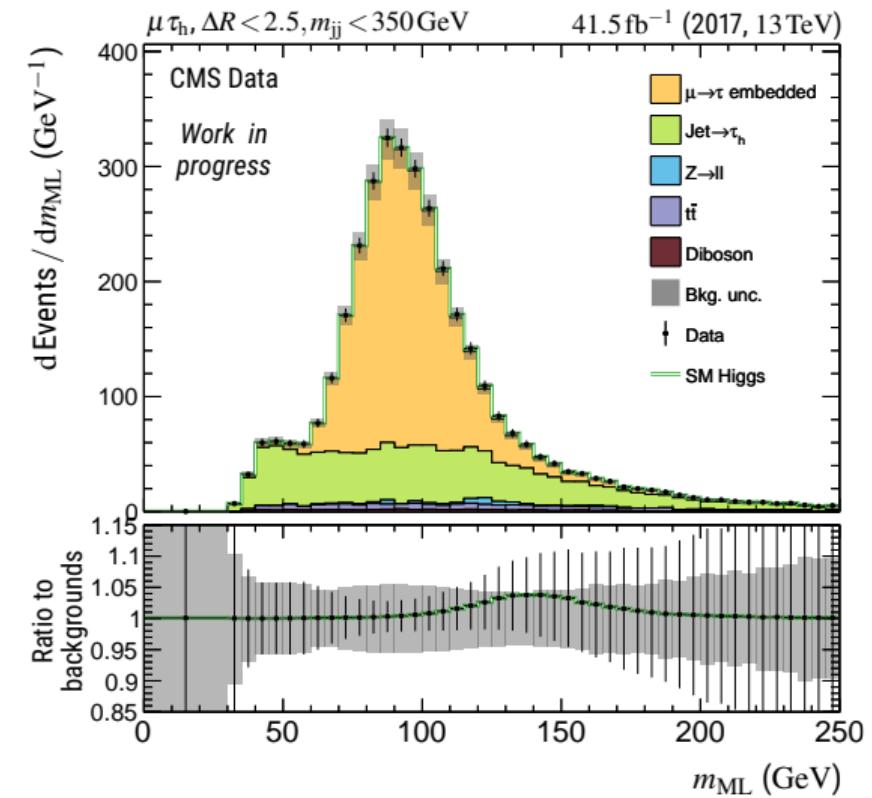
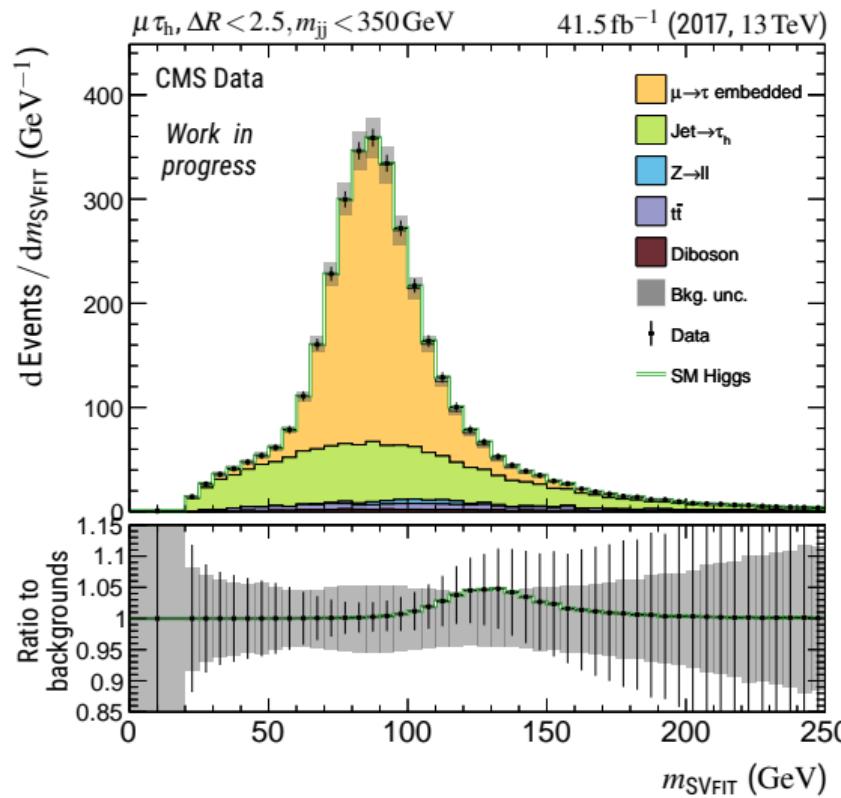


► Visible in other categories too. But here, the SVFIT mass is above 250 GeV and our model sees a Z signal!

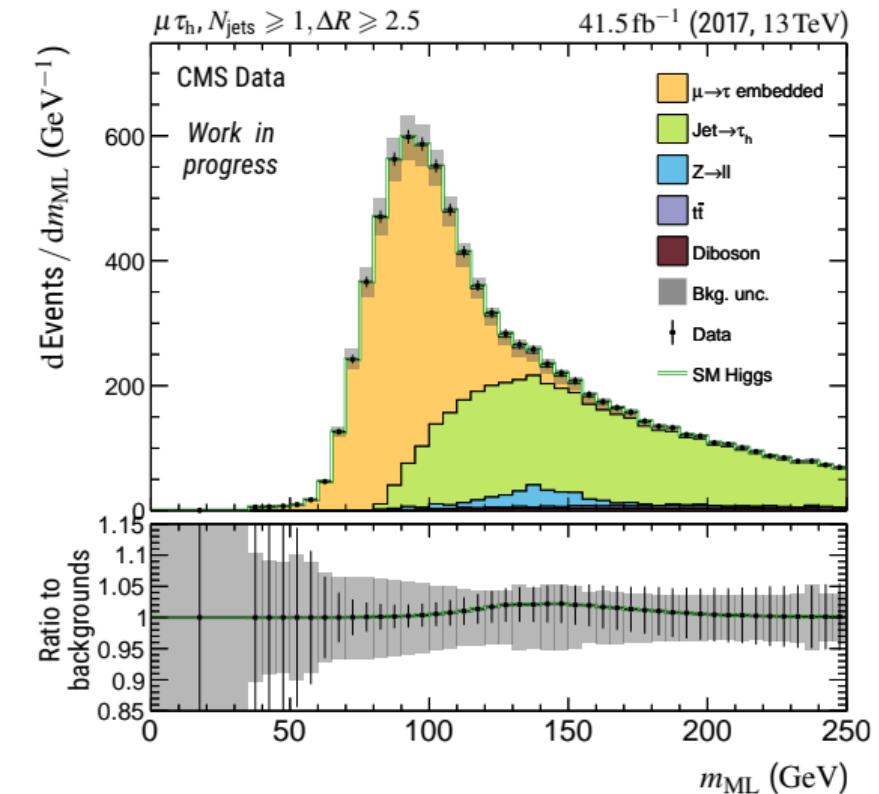
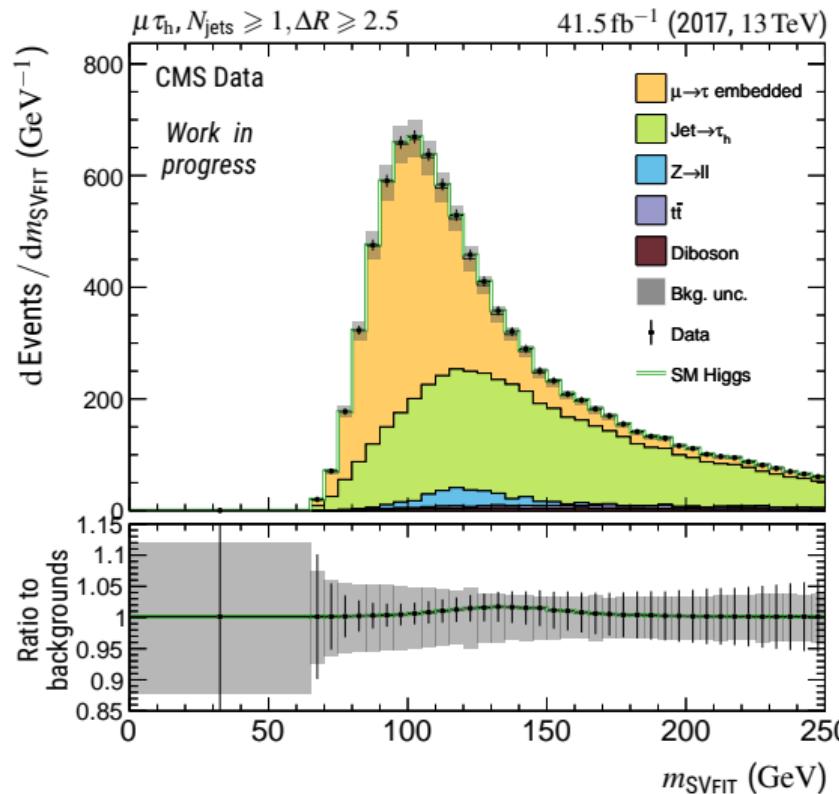


Let's compare the SVFit predictions m_{SVFit} to our model's ones m_{ML} .

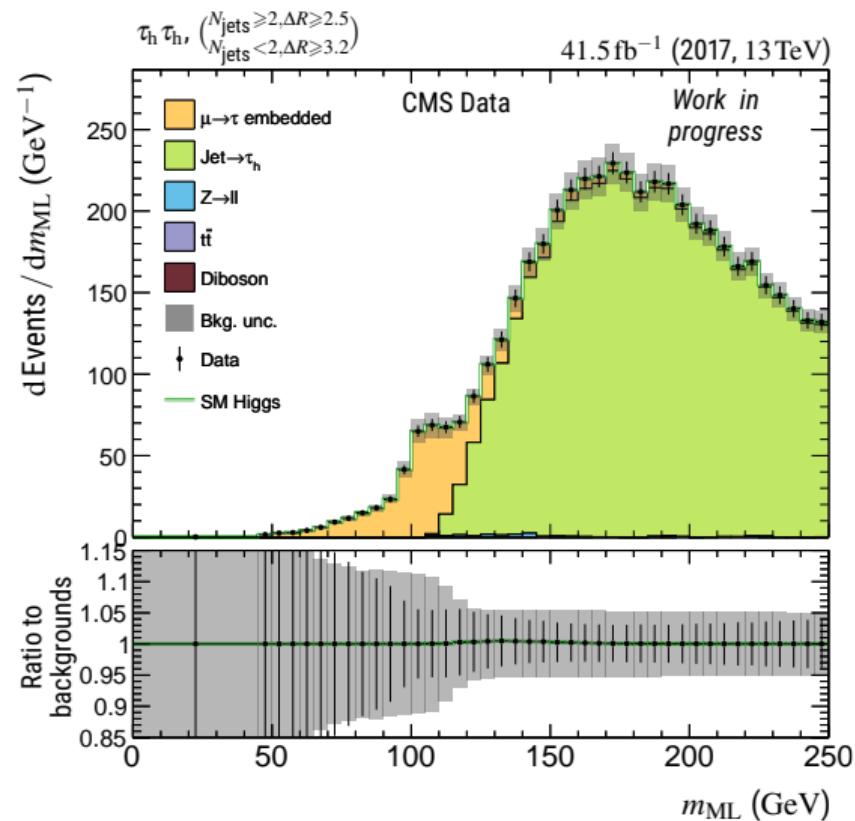
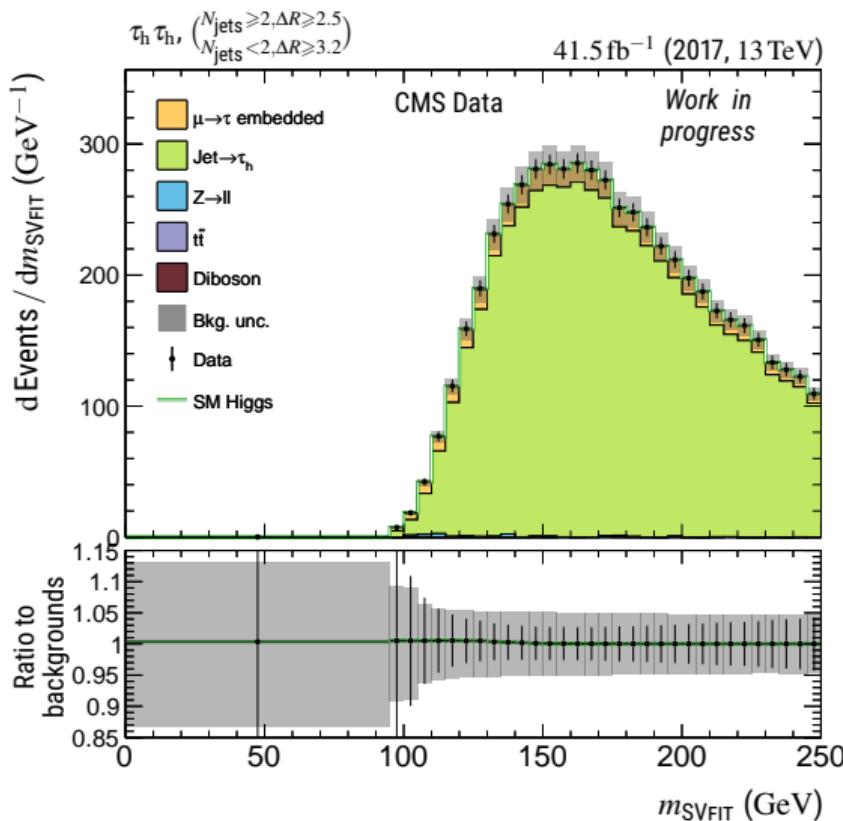
► Similar SM Higgs signal sensitivity, small (expected) overestimation from our model.



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

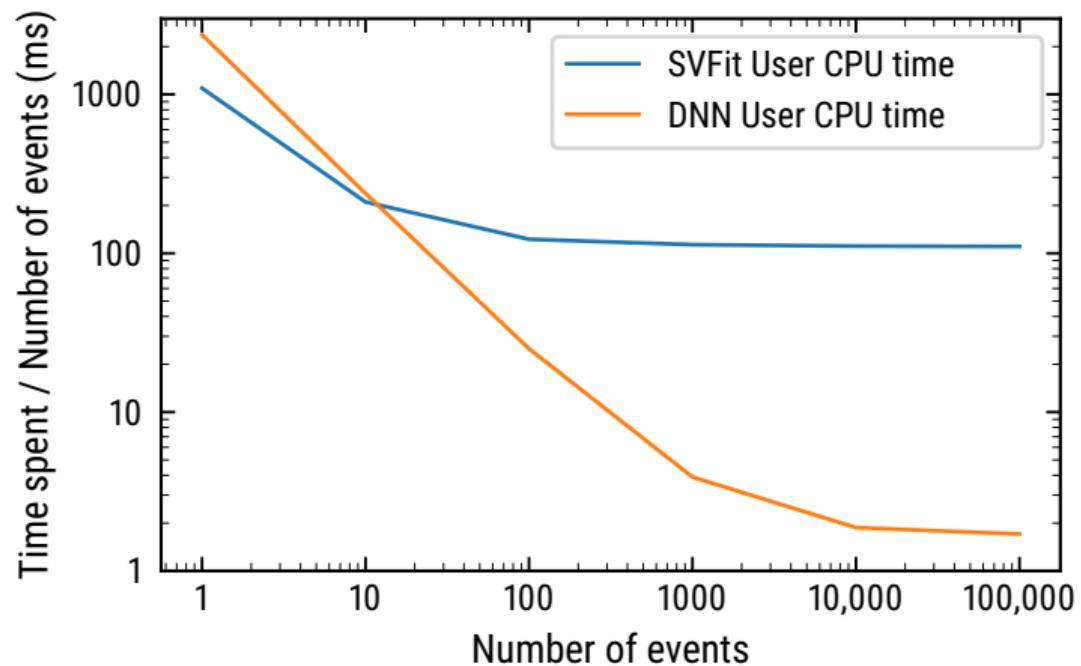


► Our model finds $Z \rightarrow \tau\tau$ events when SVFIT does not!



- ▶ 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- τ events.
 - ▷ Not only $H \rightarrow \tau\tau$ but any $X \rightarrow \tau\tau$ analysis could benefit.
- ▶ m_{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_{ML} vs m_{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!