Machine Learning et boson de Higgs

Fête de la Science 2021

Lucas Torterotot

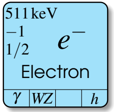
Lycée Raspail – Paris

11 octobre 2021

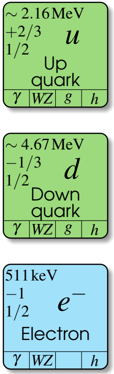
Particle physics?

$\Rightarrow$ study **elementary particles** and their **interactions**

The Standard Model



The Standard Model



proton = uud

neutron = udd

The Standard Model

$\sim 2.16\,\mathrm{MeV}$
$+2/3$ u
$1/2$
Up quark
γ | WZ | g | h

$\sim 4.67\,\mathrm{MeV}$
$-1/3$ d
$1/2$
Down quark
γ | WZ | g | h

$511\,\mathrm{keV}$
-1 e^-
$1/2$
Electron
γ | WZ | | h

$< 2.2\,\mathrm{eV}$
0 ν_e
$1/2$
Electron neutrino
| WZ | |

Beta decay: $n \to p + e^- + \nu_e$

actually $d \to u + e^- + \bar{\nu}_e$

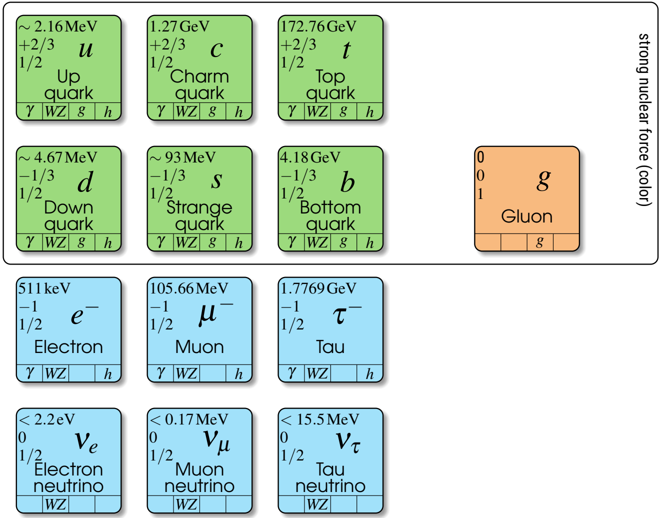
The Standard Model

$\sim 2.16\,\mathrm{MeV}$ $+2/3$ $1/2$ u Up quark γ WZ g h	$1.27\,\mathrm{GeV}$ $+2/3$ $1/2$ c Charm quark γ WZ g h
$\sim 4.67\,\mathrm{MeV}$ $-1/3$ $1/2$ d Down quark γ WZ g h	$\sim 93\,\mathrm{MeV}$ $-1/3$ $1/2$ s Strange quark γ WZ g h
$511\,\mathrm{keV}$ -1 $1/2$ e^- Electron γ WZ h	$105.66\,\mathrm{MeV}$ -1 $1/2$ μ^- Muon γ WZ h
$< 2.2\,\mathrm{eV}$ 0 $1/2$ ν_e Electron neutrino WZ	$< 0.17\,\mathrm{MeV}$ 0 $1/2$ ν_μ Muon neutrino WZ

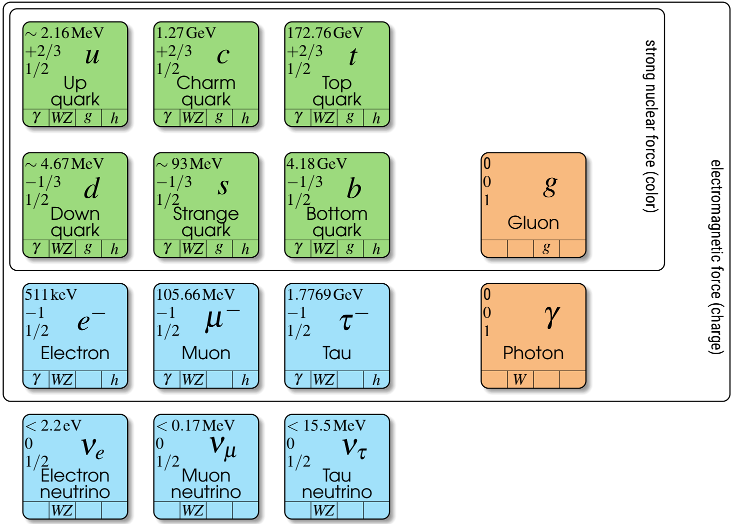
The Standard Model

$\sim 2.16\,\mathrm{MeV}$ $+2/3$ $1/2$ u Up quark γ WZ g h	$1.27\,\mathrm{GeV}$ $+2/3$ $1/2$ c Charm quark γ WZ g h	$172.76\,\mathrm{GeV}$ $+2/3$ $1/2$ t Top quark γ WZ g h
$\sim 4.67\,\mathrm{MeV}$ $-1/3$ $1/2$ d Down quark γ WZ g h	$\sim 93\,\mathrm{MeV}$ $-1/3$ $1/2$ s Strange quark γ WZ g h	$4.18\,\mathrm{GeV}$ $-1/3$ $1/2$ b Bottom quark γ WZ g h
$511\,\mathrm{keV}$ -1 $1/2$ e^- Electron γ WZ h	$105.66\,\mathrm{MeV}$ -1 $1/2$ μ^- Muon γ WZ h	$1.7769\,\mathrm{GeV}$ -1 $1/2$ τ^- Tau γ WZ h
$< 2.2\,\mathrm{eV}$ 0 $1/2$ ν_e Electron neutrino WZ	$< 0.17\,\mathrm{MeV}$ 0 $1/2$ ν_μ Muon neutrino WZ	$< 15.5\,\mathrm{MeV}$ 0 $1/2$ ν_τ Tau neutrino WZ

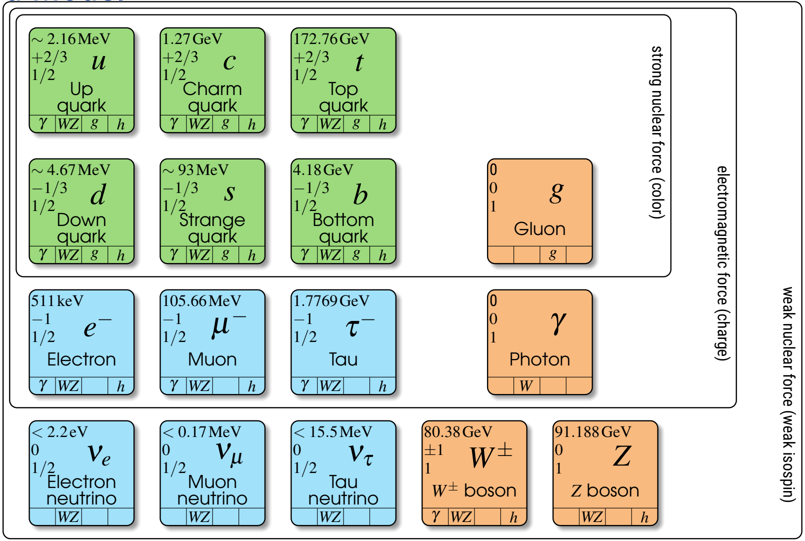
The Standard Model



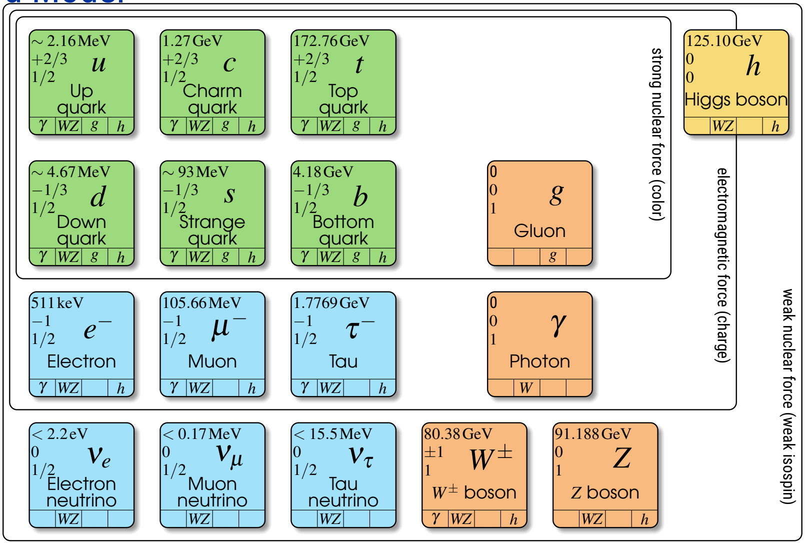
The Standard Model



The Standard Model



The Standard Model



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*

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

Why do we **search for** additional particles?

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!**

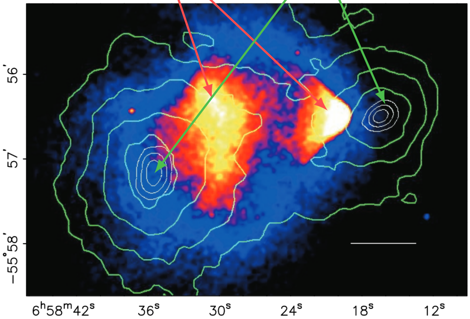
▷ D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

Why do we **search for** additional particles?

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 $\longrightarrow$
  - matter vs antimatter asymmetry
  - naturalness problem
  - ...
- Go beyond with a new model!
- Consequences of this new model? **Test it!**

Galaxies from: X rays gravitational lensing



Difference due to **dark matter**!

▷ 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**

Keywords in title

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

Part I
Phenomenology

Keywords in title

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

Part I
Phenomenology

Part II
Experimental device

Keywords in title

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

Part I
Phenomenology

Part II
Experimental device

Part III
$H/A \to \tau\tau$ *analysis*

Keywords in title

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

Part I
Phenomenology

Part II
Experimental device

Part III
$H/A \rightarrow \tau\tau$ *analysis*

+ Part IV: **with machine learning techniques**

1. Phenomenology
2. Experimental device
3. $H/A \to \tau\tau$ analysis
4. Machine learning

Higgs bosons in the MSSM

Minimal Supersymmetric extension of Standard Model

5 Higgs bosons

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

Main parameters: m_A and $\tan\beta$.

▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 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.

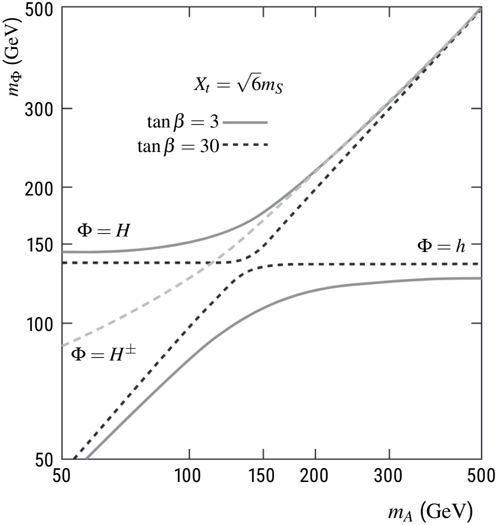
Higgs bosons in the MSSM

Minimal Supersymmetric extension of Standard Model

5 Higgs bosons

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

Main parameters: m_A and $\tan\beta$.



▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 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.

Higgs bosons in the MSSM

Minimal Supersymmetric extension of Standard Model

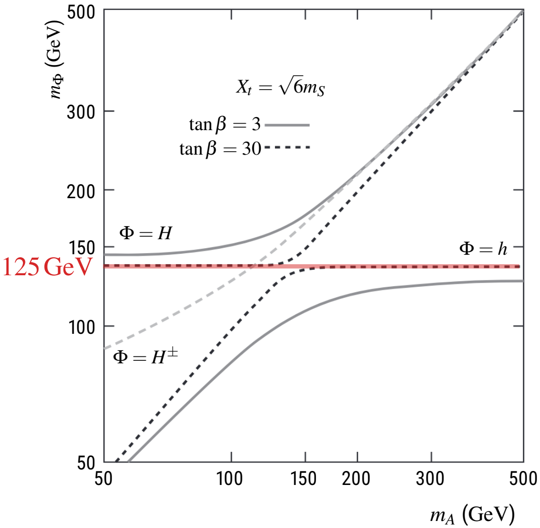
5 Higgs bosons

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

Main parameters: m_A and $\tan\beta$.

▷ The CMS Collaboration. “Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$”. *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 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.



Higgs bosons in the MSSM

Minimal Supersymmetric extension of Standard Model

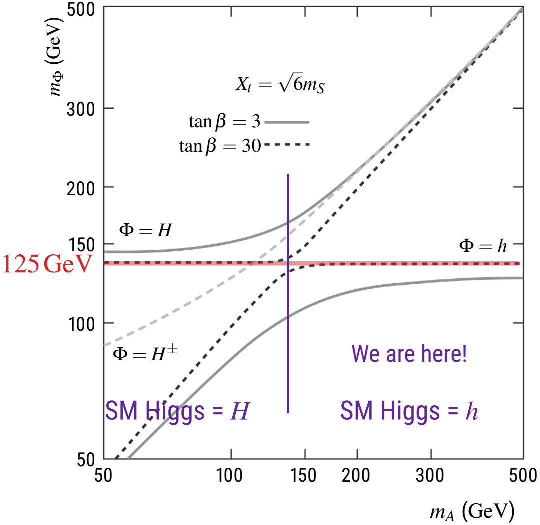
5 Higgs bosons

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

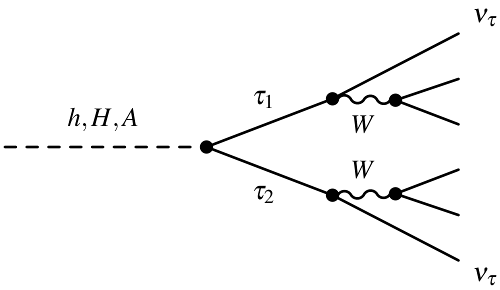
Main parameters: m_A and $\tan\beta$.

▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ 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.

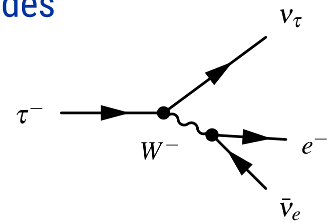
▷ Y. Nagashima. *Beyond the Standard Model of Elementary Particle Physics*. Weinheim: Wiley-VCH, June 2014. URL: http://cds.cern.ch/record/1620277.



$H/A \to \tau\tau$ decay channel

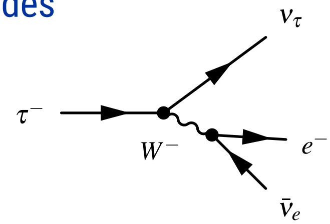


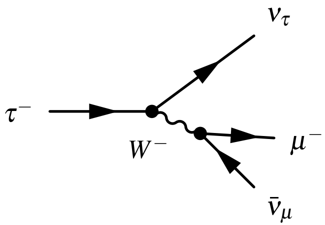
τ decay modes



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

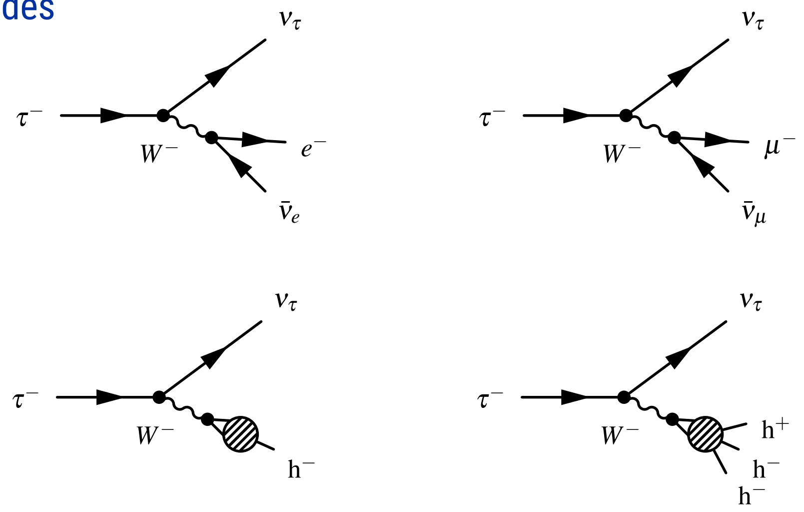
τ decay modes





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

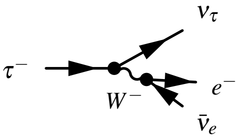
τ decay modes



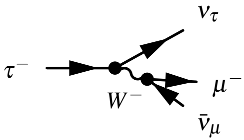
▷ Particle Data Group. "Review of Particle Physics". *Progress of Theoretical and Experimental Physics* **8** (Aug. 2020). DOI: 10.1093/ptep/ptaa104.

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

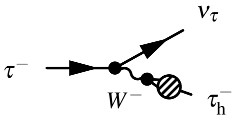
$\tau \to e + \nu_e + \nu_\tau \Rightarrow e$
17.8 %



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



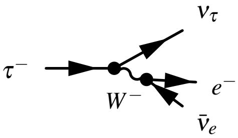
$\tau \to \text{hadrons} + \nu_\tau \Rightarrow \tau_h$
64.8 %



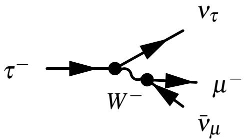
▷ Particle Data Group. “Review of Particle Physics”. *Progress of Theoretical and Experimental Physics* **8** (Aug. 2020). DOI: 10.1093/ptep/ptaa104.

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

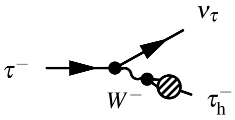
$\tau \to e + \nu_e + \nu_\tau \Rightarrow e$
$17.8\,\%$

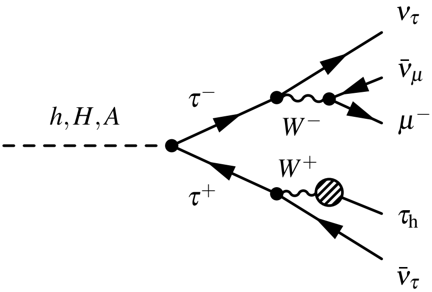


$\tau \to \mu + \nu_\mu + \nu_\tau \Rightarrow \mu$
$17.4\,\%$



$\tau \to \text{hadrons} + \nu_\tau \Rightarrow \tau_\mathrm{h}$
$64.8\,\%$

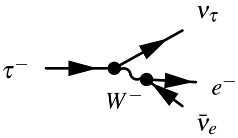




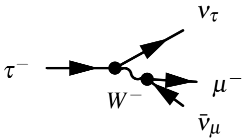
▷ Particle Data Group. “Review of Particle Physics”. *Progress of Theoretical and Experimental Physics* **8** (Aug. 2020). DOI: `10.1093/ptep/ptaa104`.

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

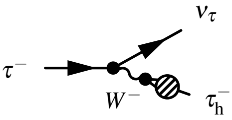
$\tau \to e + \nu_e + \nu_\tau \Rightarrow e$
$17.8\,\%$

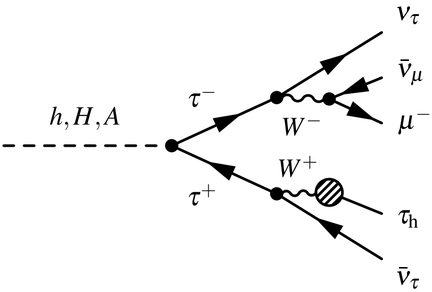


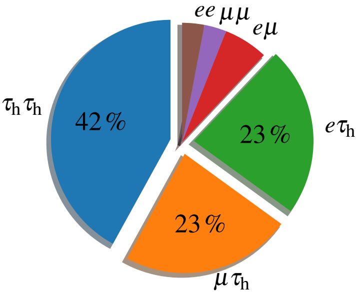
$\tau \to \mu + \nu_\mu + \nu_\tau \Rightarrow \mu$
$17.4\,\%$



$\tau \to \text{hadrons} + \nu_\tau \Rightarrow \tau_\text{h}$
$64.8\,\%$







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

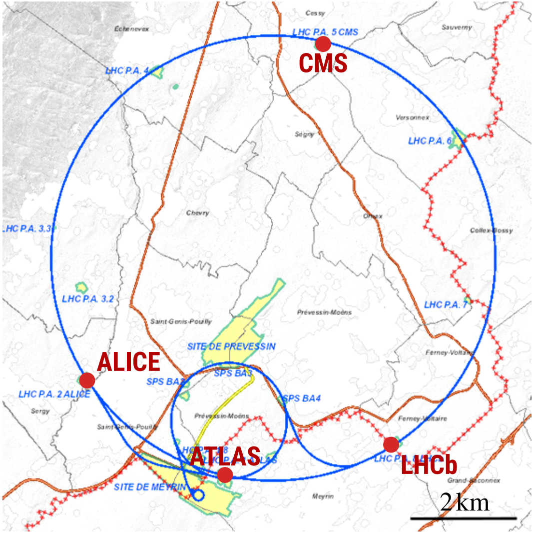
Principle

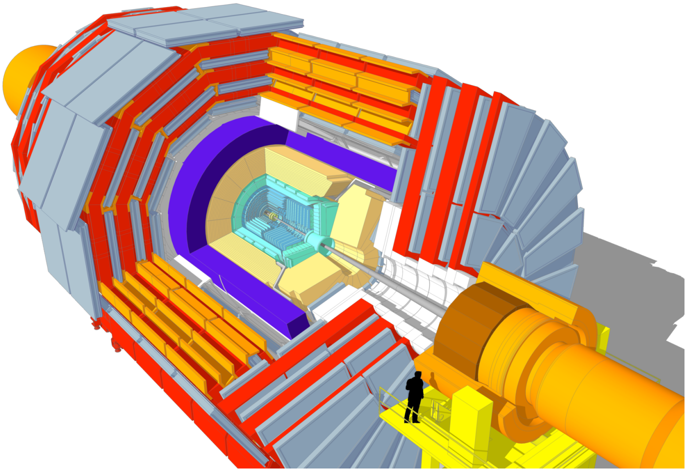
$$E = mc^2$$

mass (new particles) from the collision energy

CERN LHC


CERN
France
Switzerland
Germany
Italy
Belgium
Netherlands
Luxembourg
Liechtenstein
Paris
Lyon
Geneva

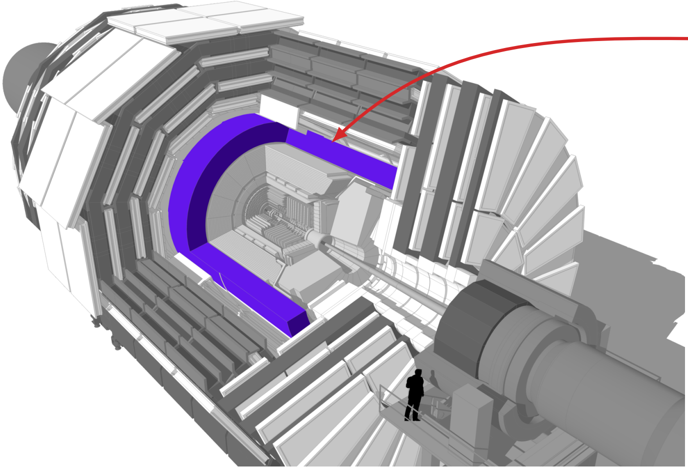

CMS
ALICE
ATLAS
LHCb
LHC P.A. 5 CMS
LHC P.A. 2 ALICE
LHC P.A. 4
LHC P.A. 6
LHC P.A. 7
LHC P.A. 3.2
SITE DE PREVESSIN
SITE DE MEYRIN
SPS BA4
2 km



CMS detector

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

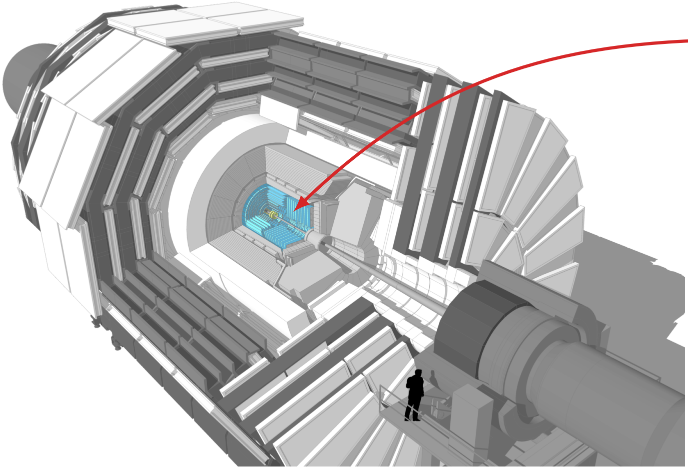
$\Rightarrow$ How to *see* the particles?



Solenoid

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

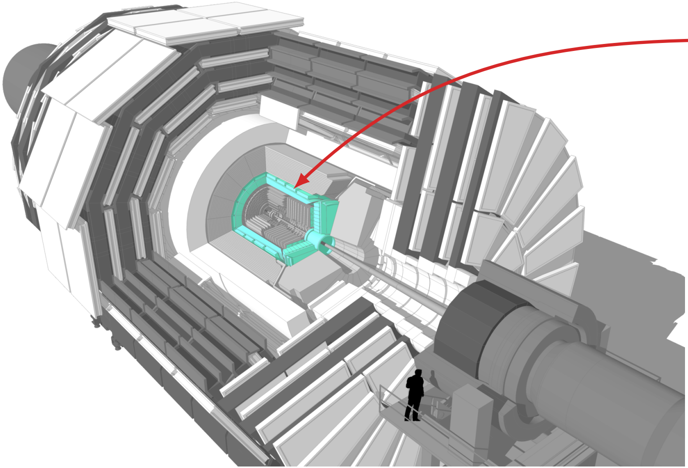
$\Rightarrow$ Bends charged particles trajectories in the transverse plane



Tracker

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

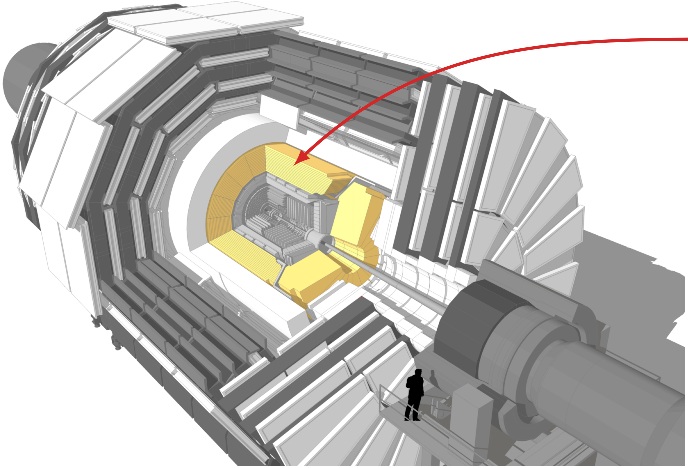
$\Rightarrow$ Charged particles leave hits when going through



Electromagnetic CALorimeter

- $\sim 76\,000$ scintillating $PbWO_4$ crystals

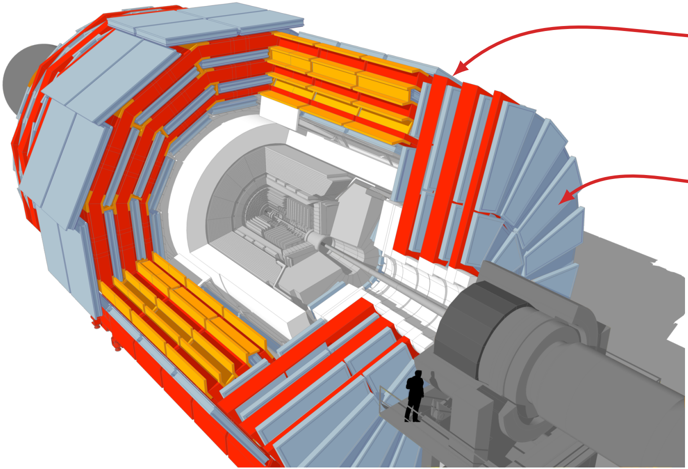
$\Rightarrow$ Electrons and photons are stopped, energy deposits



Hadronic CALorimeter

- Brass + plastic scintillator, ~ 7000 channels

$\Rightarrow$ Hadrons are stopped, energy deposits



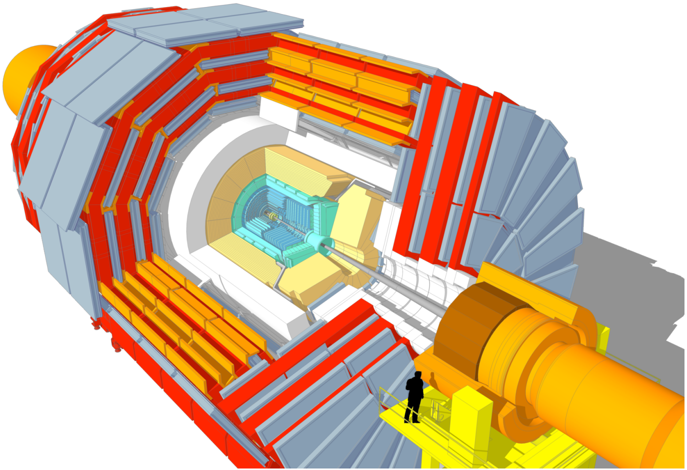
Steel return yoke (red)

- Allows for $2\,\mathrm{T}$ magnetic field around the solenoid

Muon chambers (blue-gray)

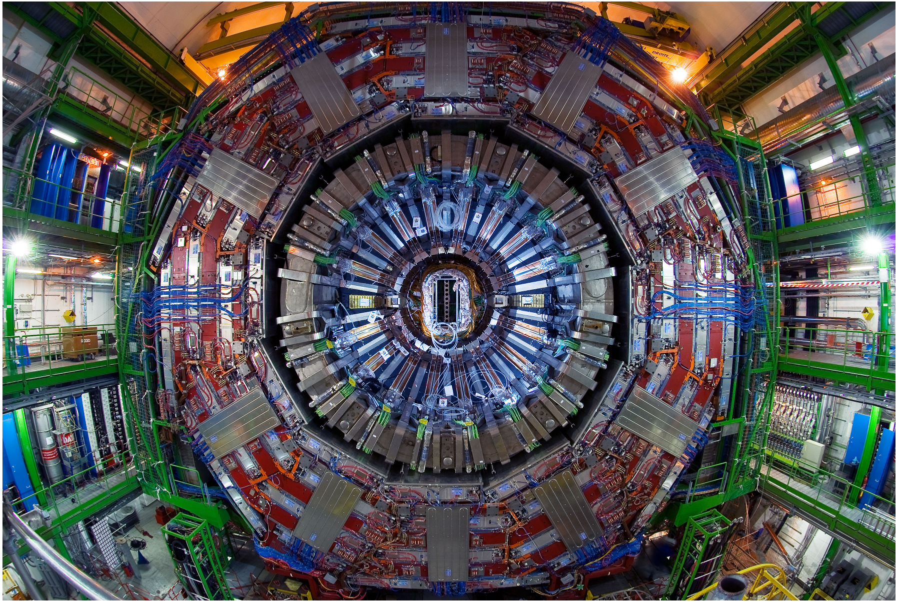
- Barrel: 250 drift tubes, 480 resistive plate chambers
- Endcaps: 540 cathode strips, 576 resistive plate chambers

$\Rightarrow$ Charged particles leave hits when going through (only muons do)

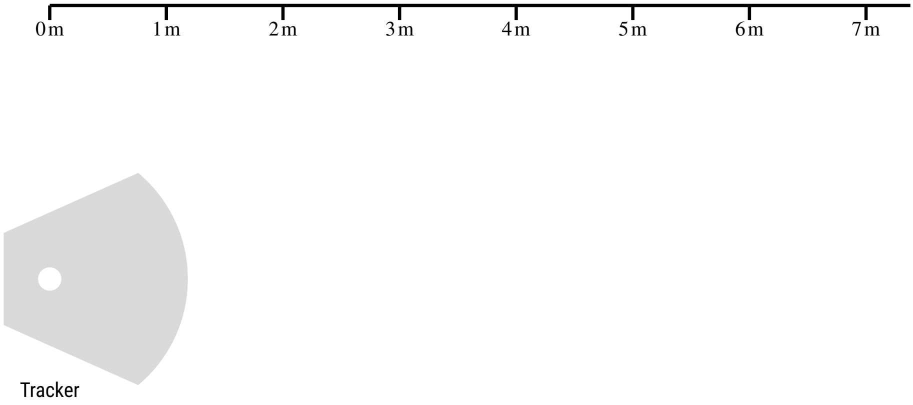


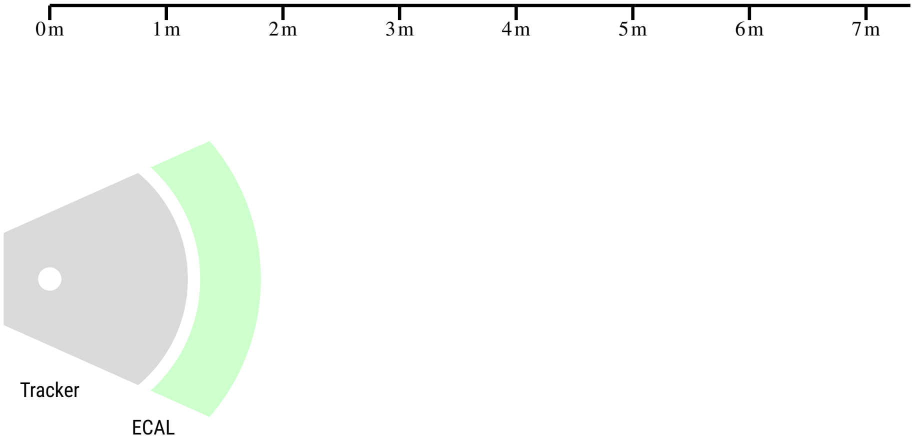
Sensitive parts of CMS

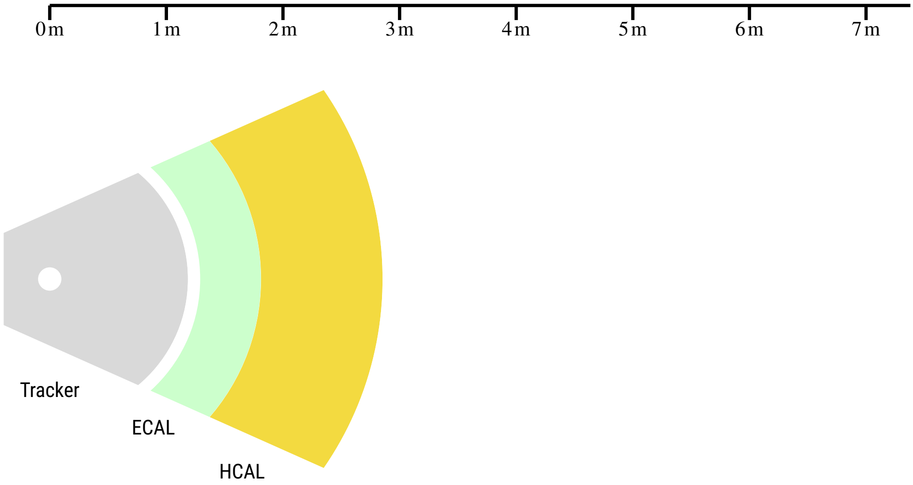
Combine sub-detectors signals to determine which particles were there!

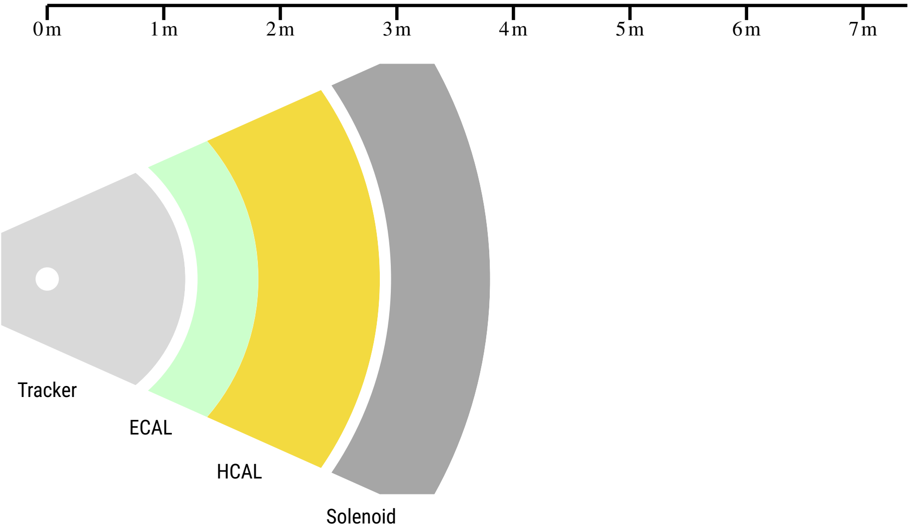


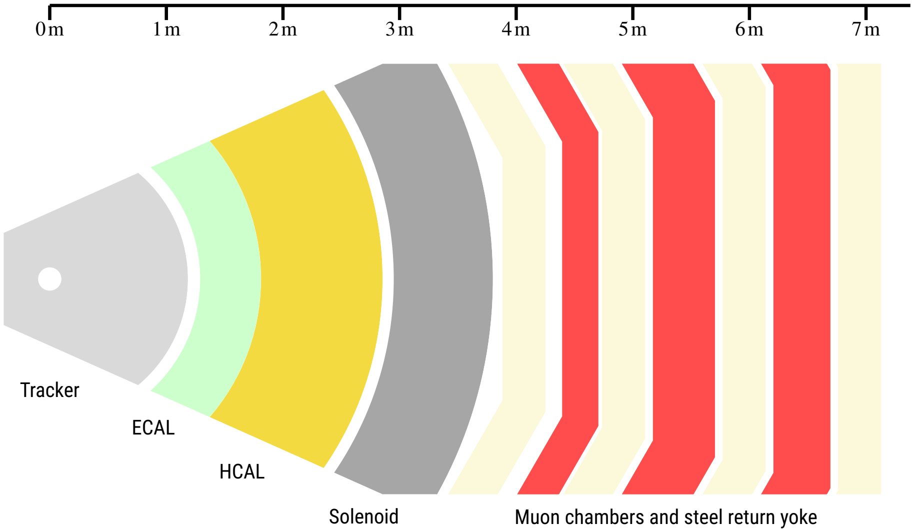

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m

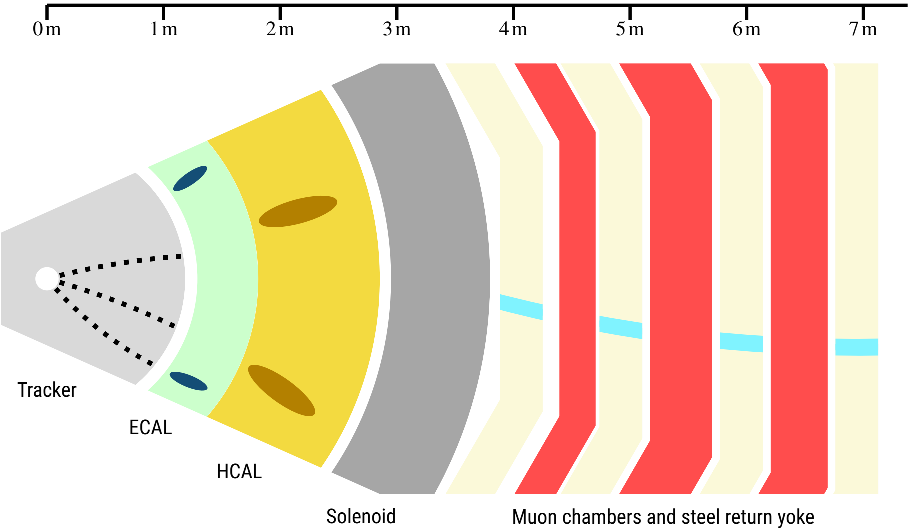

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker

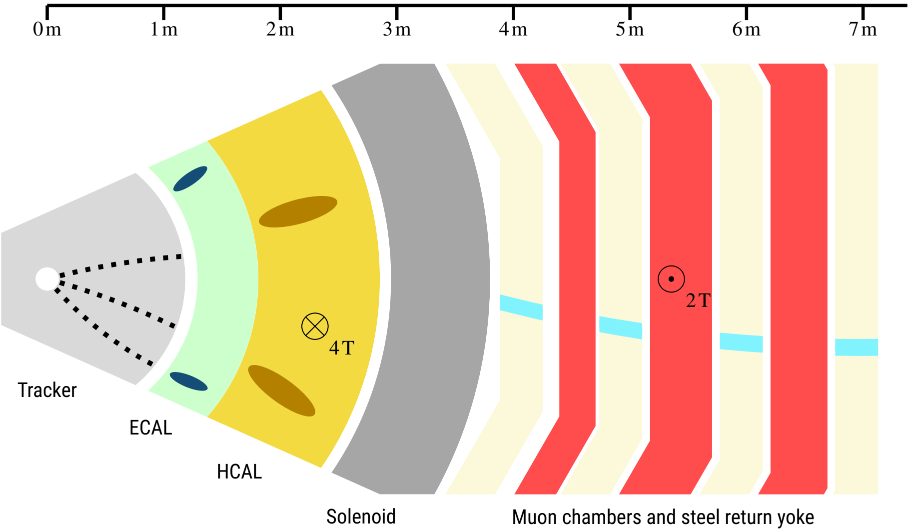

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL

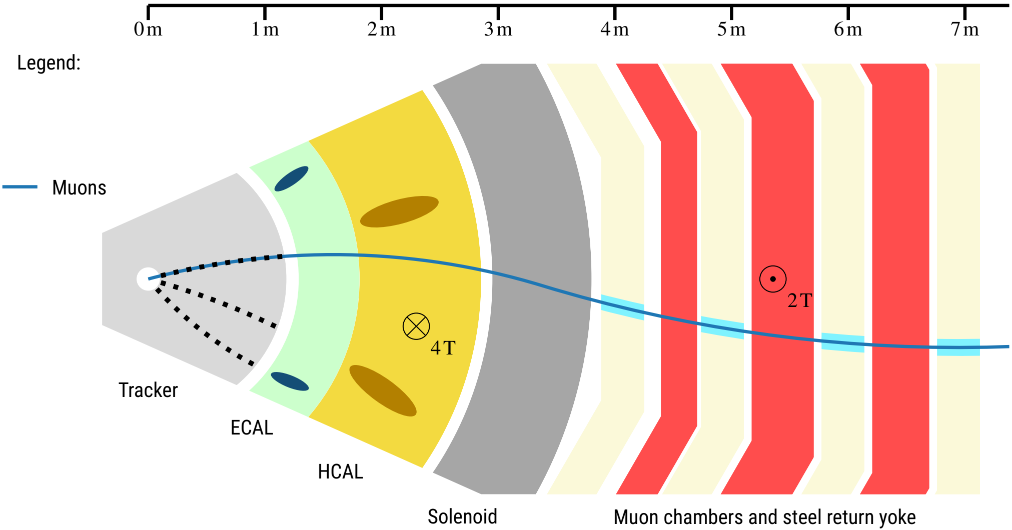

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL

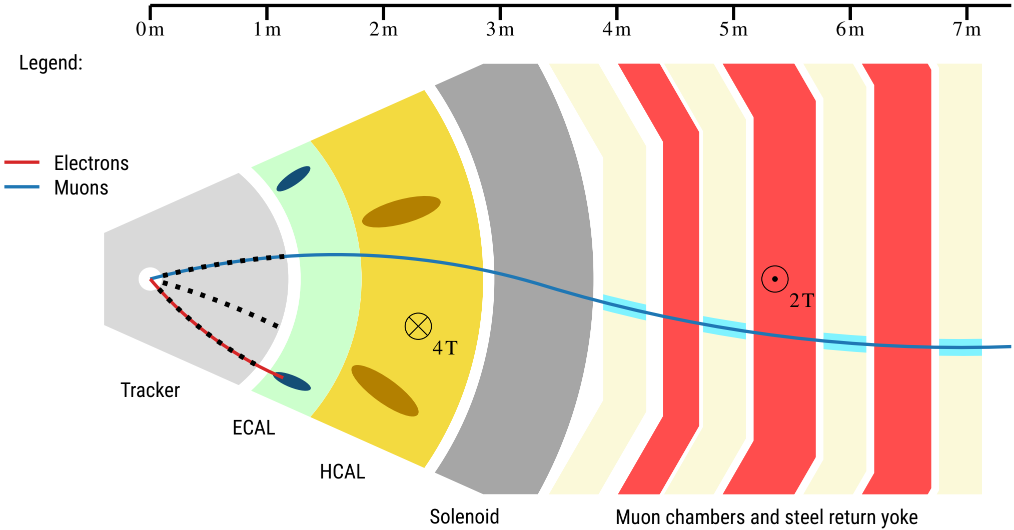

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid

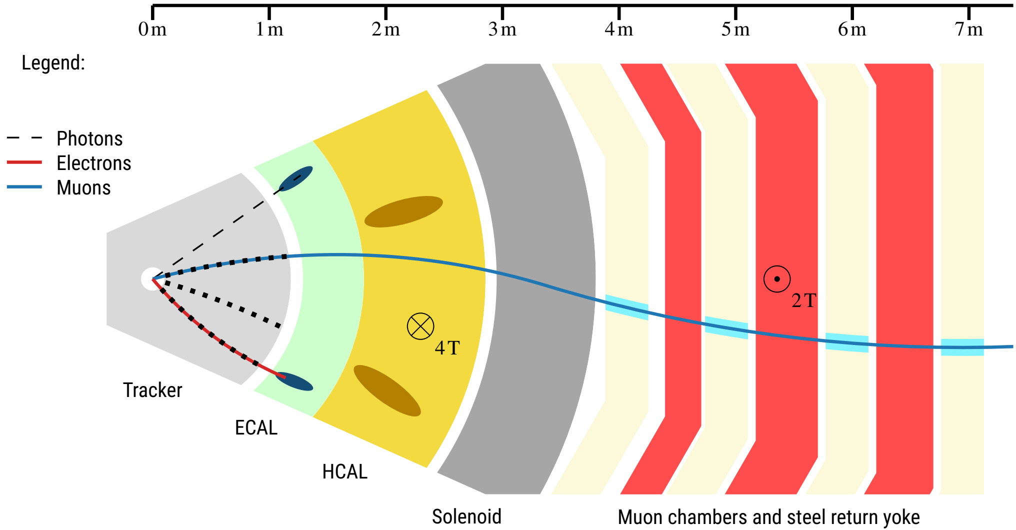

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

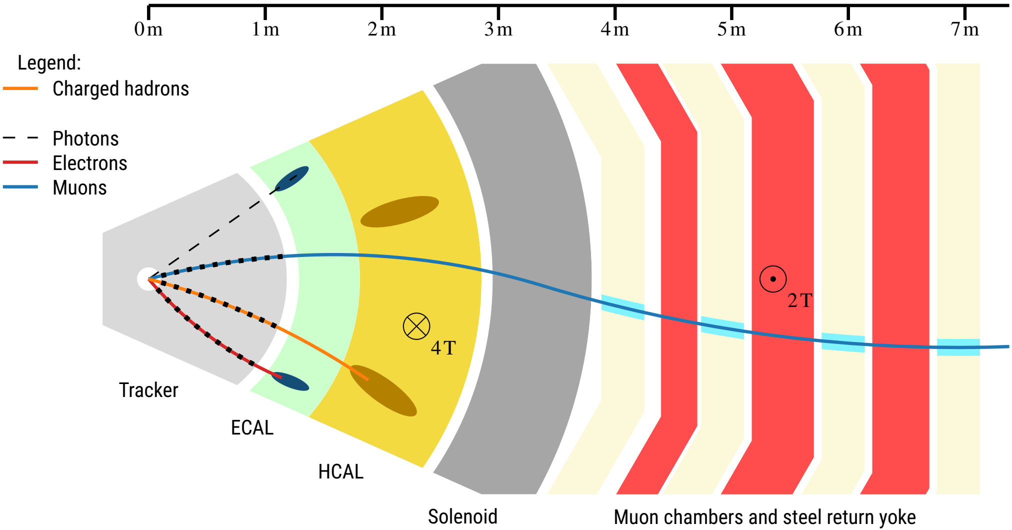

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

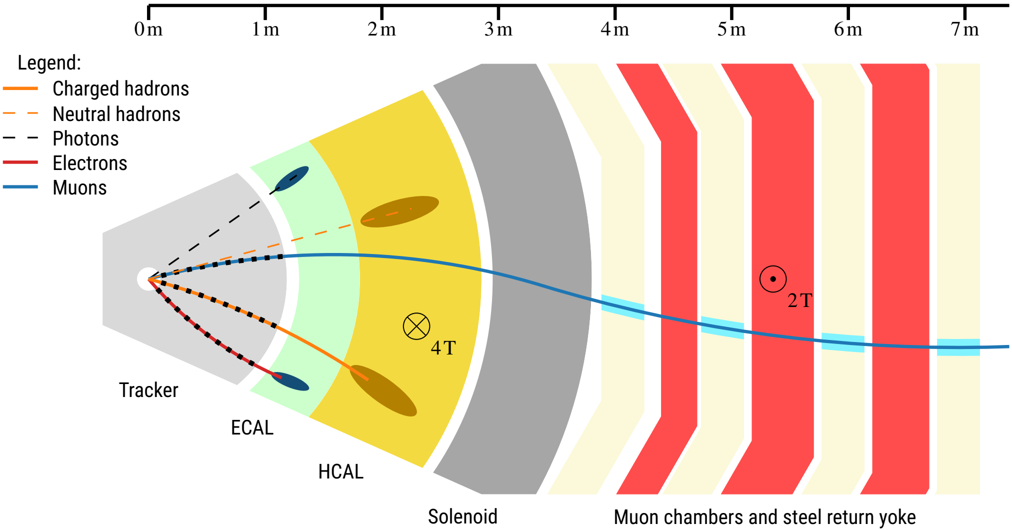

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

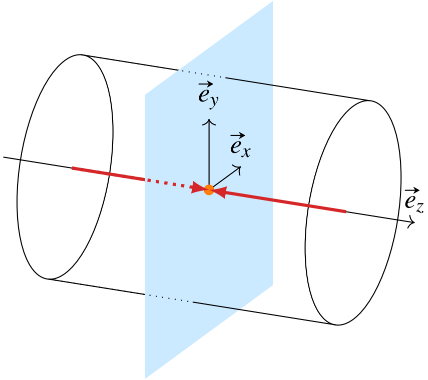

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

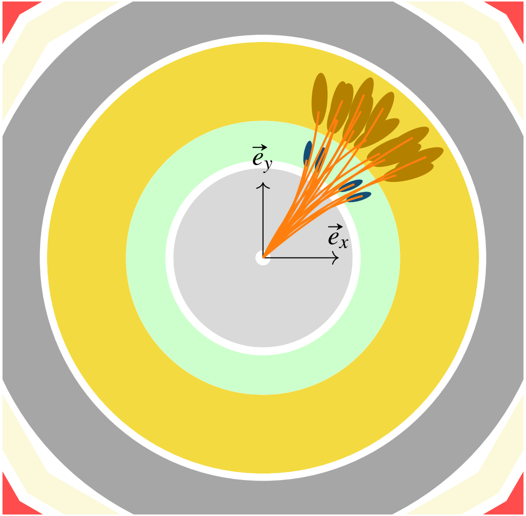

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Charged hadrons
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Charged hadrons
Neutral hadrons
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

Conserved momentum and neutrinos: missing transverse energy (MET)

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

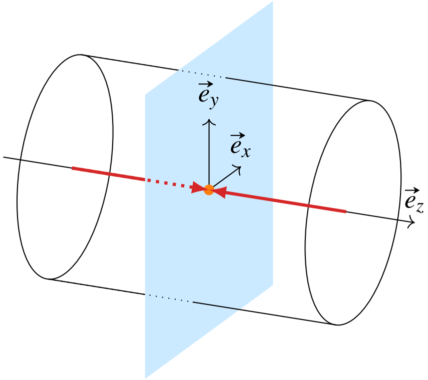


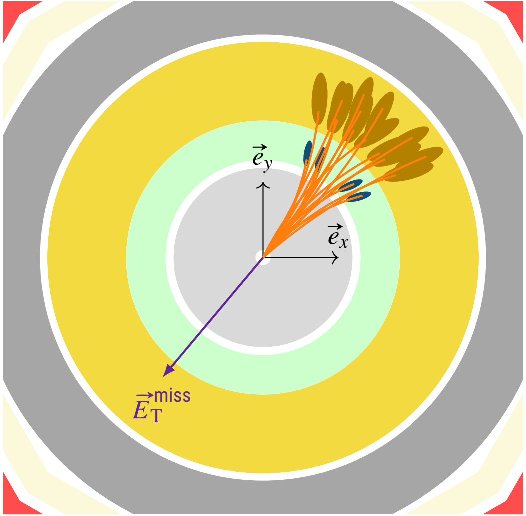


$$\sum_{\text{final state}} \vec{p}_{\mathrm{T}} = \sum_{\text{initial state}} \vec{p}_{\mathrm{T}} = \vec{0}$$

Conserved momentum and neutrinos: missing transverse energy (MET)

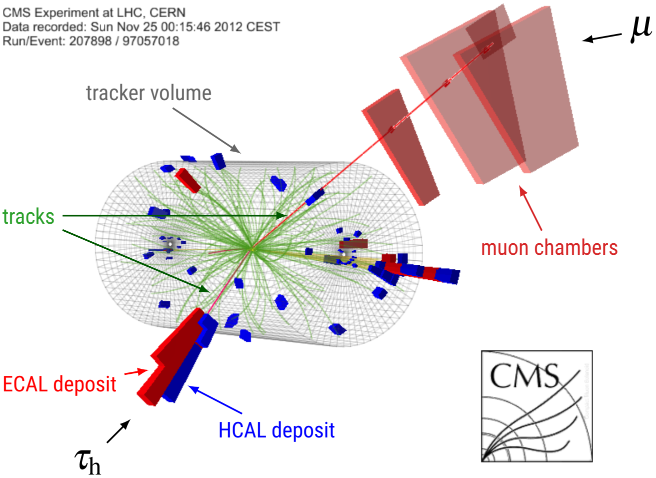
$(\vec{e}_x, \vec{e}_y)$ = transverse plane ($\eta = 0$)





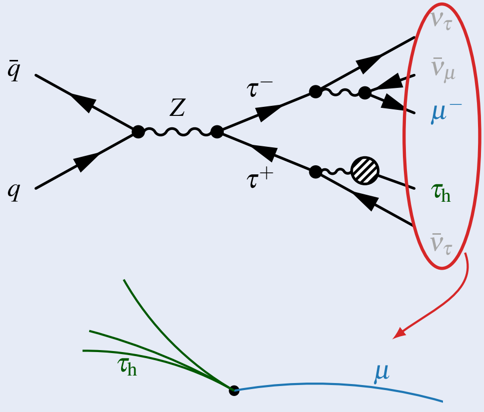
$$\sum_{\text{final state}} \vec{p}_{\mathrm{T}} = \sum_{\text{initial state}} \vec{p}_{\mathrm{T}} = \vec{0} \Rightarrow \boxed{\vec{E}_{\mathrm{T}}^{\text{miss}} = - \sum_{\text{visible particles}} \vec{p}_{\mathrm{T}}}$$

Event display: $h \to \tau\tau \to \mu\tau_{\mathrm{h}}$ candidate from real data

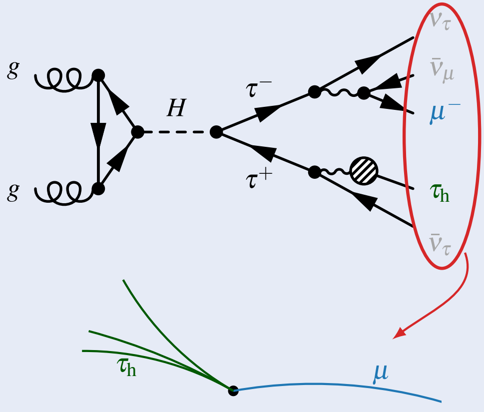


Background processes?

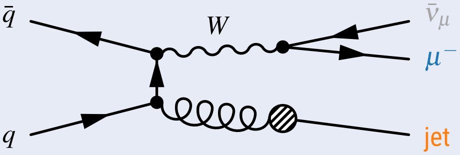
Drell-Yan background

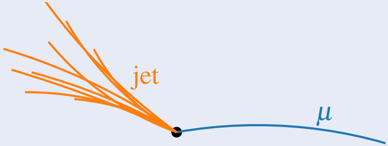


$H \to \tau\tau \to \mu\tau_h$ signal

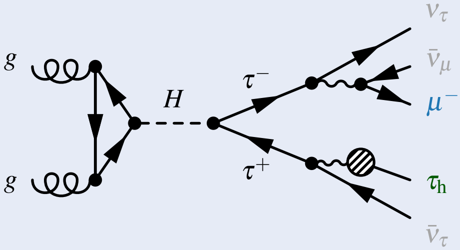


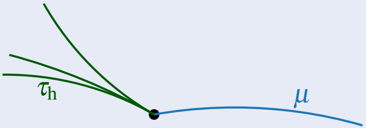
$W+$jets background



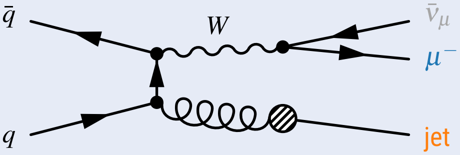


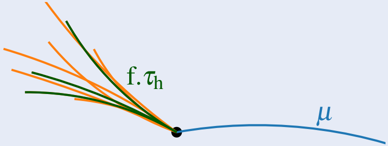
$H \to \tau\tau \to \mu\tau_h$ signal



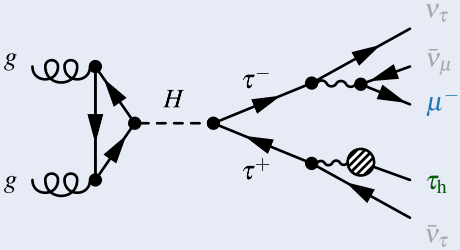


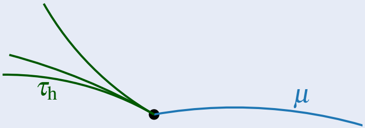
$W+$jets background, jet $\to$ fake τ_h



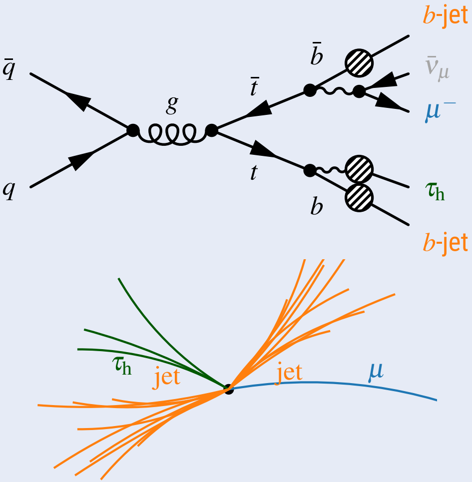


$H \to \tau\tau \to \mu\tau_\mathrm{h}$ signal

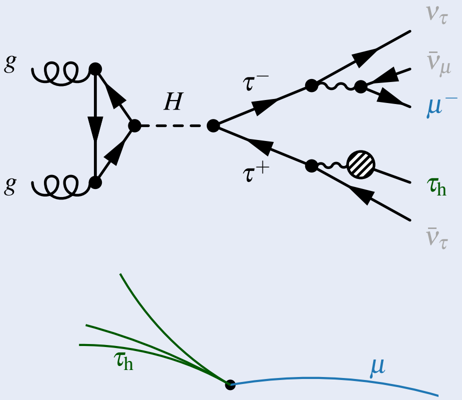




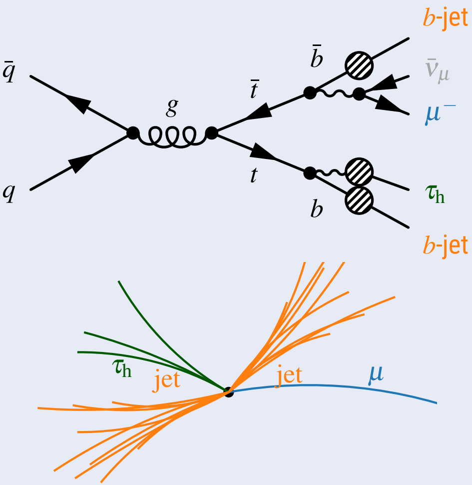
$t\bar{t}$ background



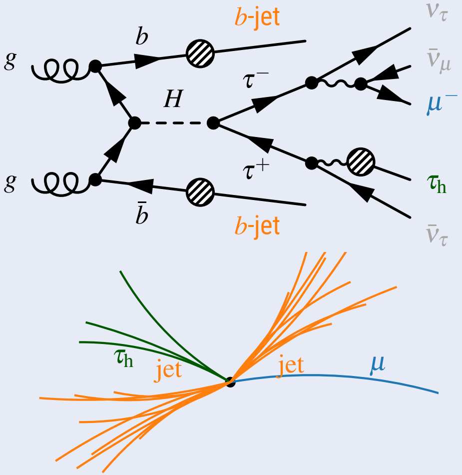
$H \to \tau\tau \to \mu\tau_h$ signal



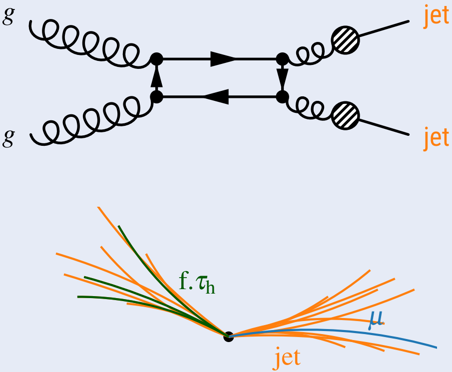
$t\bar{t}$ background



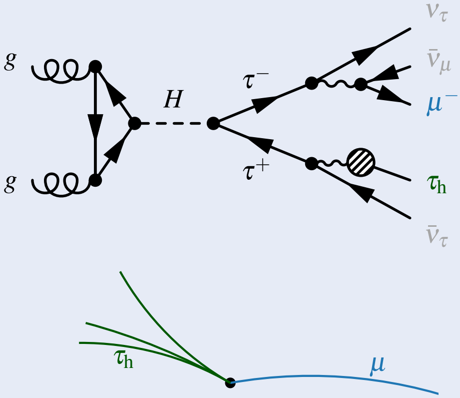
H production with b-jets



QCD background

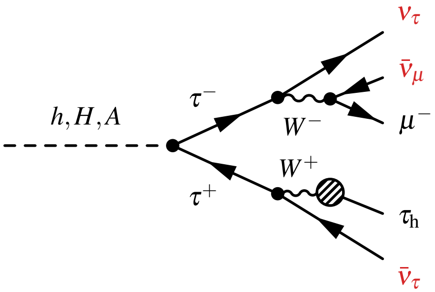


$H \to \tau\tau \to \mu\tau_h$ signal



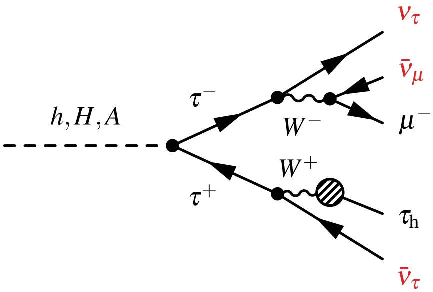
Discriminant variable?

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

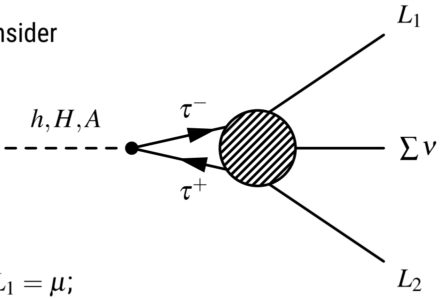


Discriminant variable?

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



- Consider



where

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

with respect to the left side.

Discriminant variable: $m_{\mathrm{T}}^{\mathrm{tot}}$

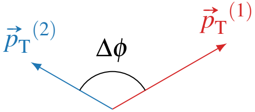
- For L_1, L_2 and $E_{\mathrm{T}}{}^{\text{miss}}$ system,
  - in the transverse plane (use $E_{\mathrm{T}}{}^{\text{miss}}$),
  - for $E_i \gg m_i$ (highly relativistic case),

deriving the "invariant" mass would then lead to

the **total transverse mass**, $m_{\mathrm{T}}^{\mathrm{tot}}$

$$\boxed{m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(L_1, E_{\mathrm{T}}{}^{\text{miss}}) + m_{\mathrm{T}}^2(L_2, E_{\mathrm{T}}{}^{\text{miss}}) + m_{\mathrm{T}}^2(L_1, L_2)}}$$

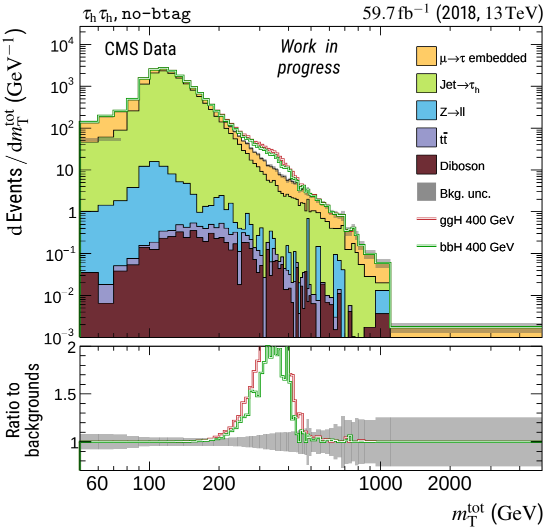
$$m_{\mathrm{T}}(1,2) = \sqrt{2 p_T^{(1)} p_T^{(2)} (1 - \cos\Delta\phi)}$$



Results obtained in this thesis?

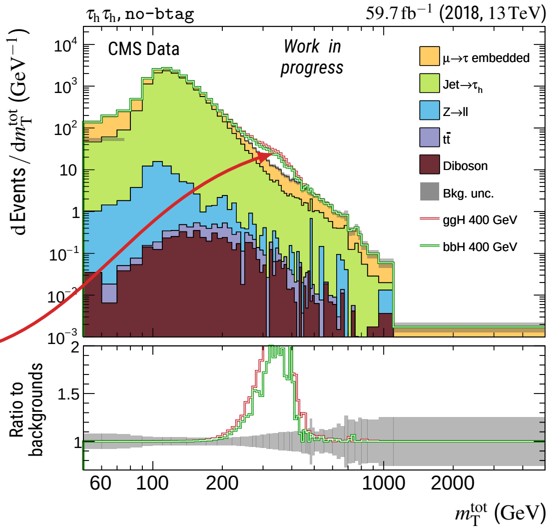
$m_{\mathrm{T}}^{\mathrm{tot}}$ distributions

- Backgrounds = SM expectations:
  - DY $Z \to \tau\tau$ and some $t\bar{t}$ in $\mu \to \tau$ embedded
  - QCD, $W+$jets and some $t\bar{t}$ in Jet $\to \tau_{\mathrm{h}}$
  - $Z \to ee$ + $Z \to \mu\mu$ in $Z \to \ell\ell$ ($\ell \to \tau_{\mathrm{h}}$)
  - Remaining $t\bar{t}$ in $t\bar{t}$
  - Other small backgrounds in Diboson



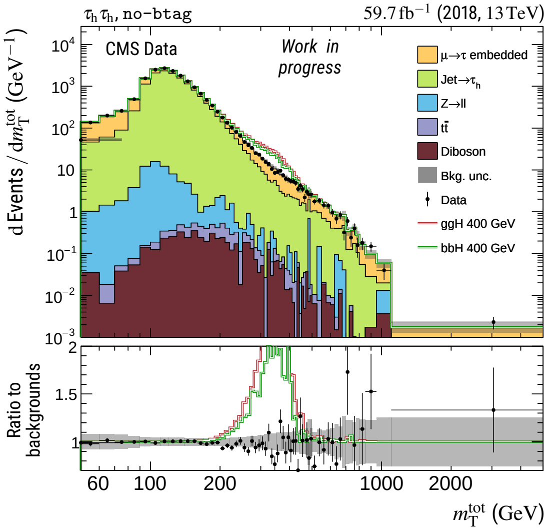
m_T^{tot} distributions

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



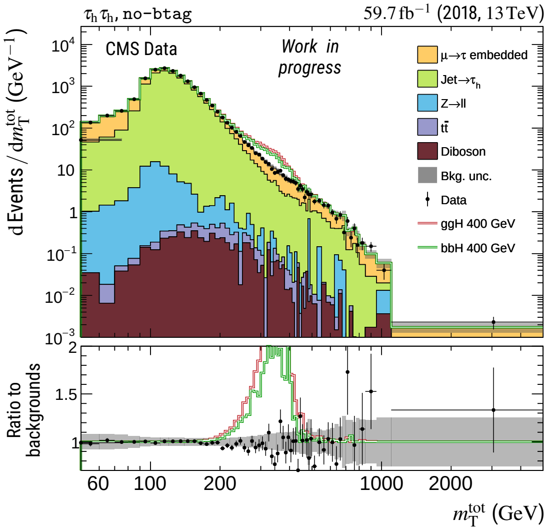
m_T^{tot} distributions

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



$m_{\mathrm{T}}^{\mathrm{tot}}$ distributions

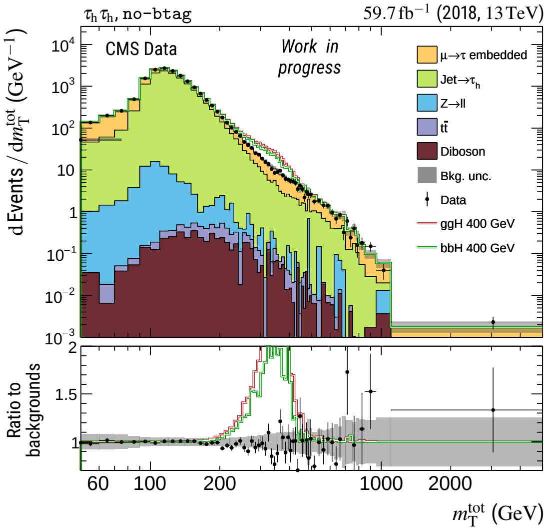
- Backgrounds = SM expectations:
  - DY $Z \to \tau\tau$ and some $t\bar{t}$ in $\mu \to \tau$ embedded
  - QCD, $W+$jets and some $t\bar{t}$ in Jet $\to \tau_{\mathrm{h}}$
  - $Z \to ee$ + $Z \to \mu\mu$ in $Z \to \ell\ell$ ($\ell \to \tau_{\mathrm{h}}$)
  - Remaining $t\bar{t}$ in $t\bar{t}$
  - Other small backgrounds in Diboson
- H at $400\,\mathrm{GeV}$ expected $\sigma \times \mathcal{BR} = 1\,\mathrm{pb}$ signal.
- Compare to observed events (black dots).
- Data/Bkg agreement → **exclusion limits** on $\sigma \times \mathcal{BR}$

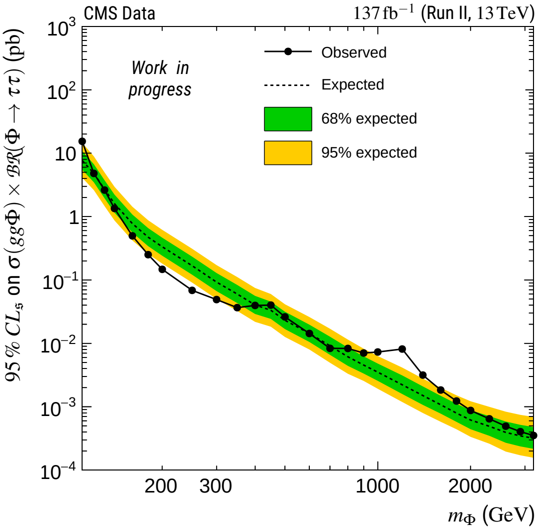


m_T^{tot} distributions

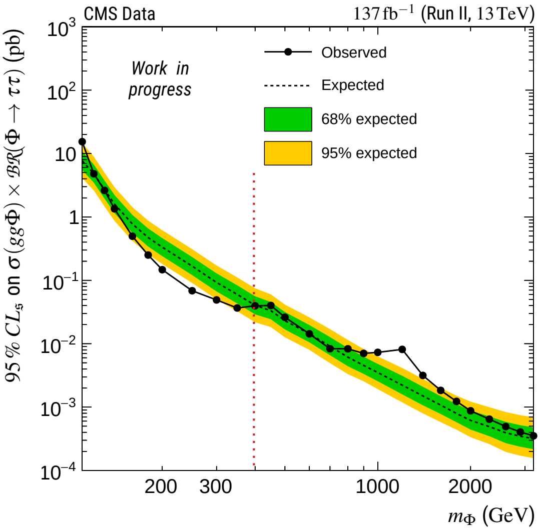
Not *just* a plot!

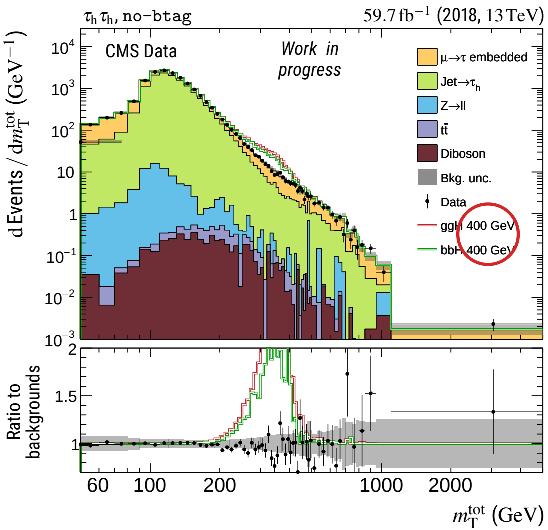
- **Lots** of hard work to obtain this:
  - simulated events
  - detector issues
  - uncertainties measured
- Collaborative work:
  - Karlsruhe Institute of Technology (DE)
  - Imperial College (UK)
  - DESY (DE)
  - HEPHY (AT)
  - IP2I (FR)



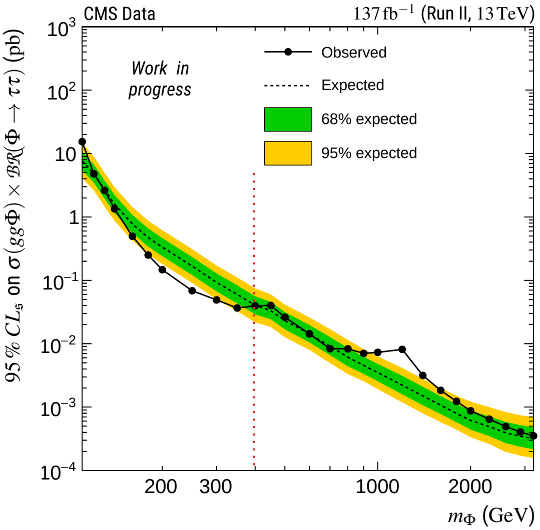


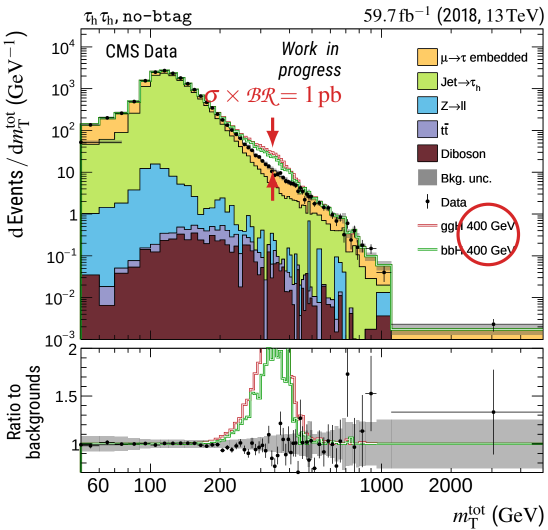
▷ A. L. Read. “Modified frequentist analysis of search results (the CL_s method)”. *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: http://cds.cern.ch/record/451614.



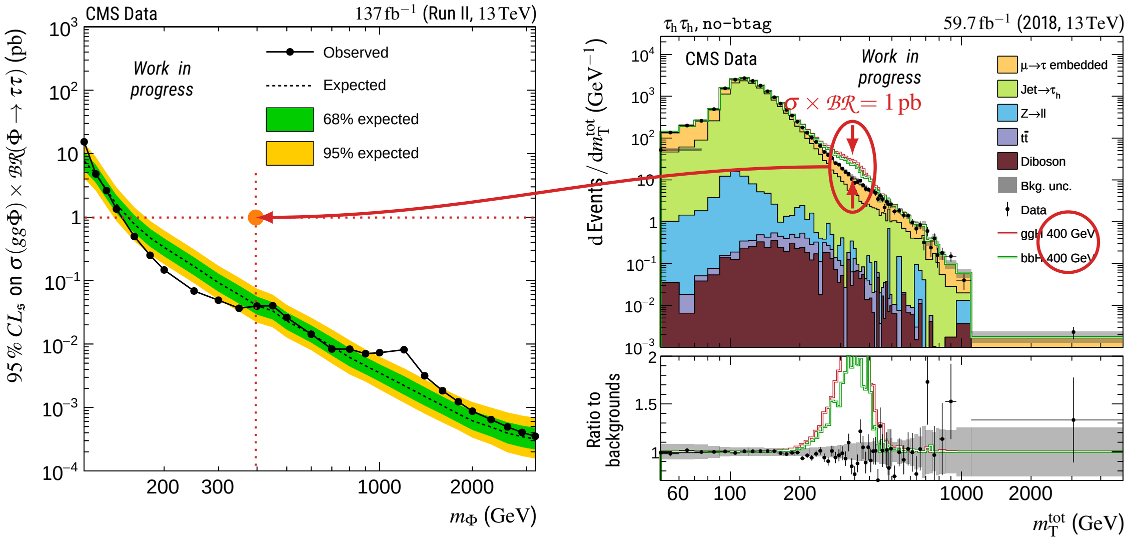


▷ A. L. Read. "Modified frequentist analysis of search results (the CL_s method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: http://cds.cern.ch/record/451614.

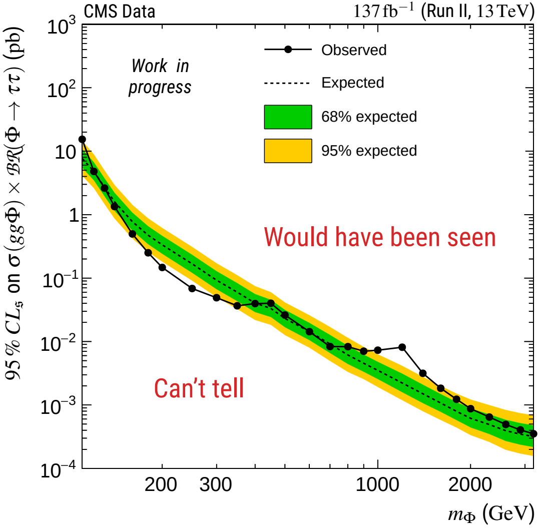


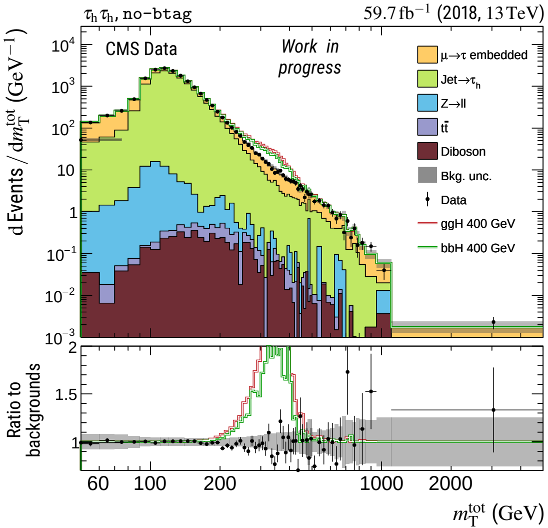


▷ A. L. Read. “Modified frequentist analysis of search results (the CL_s method)”. *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: http://cds.cern.ch/record/451614.



▷ 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.





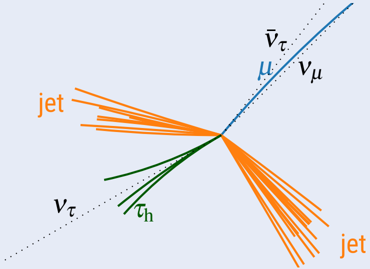
▷ A. L. Read. "Modified frequentist analysis of search results (the CL_s method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: `http://cds.cern.ch/record/451614`.

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

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

What's here

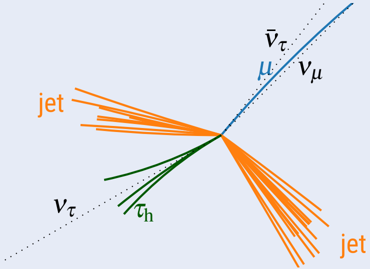
(e.g. VBF Higgs production + decay to $\tau\tau$, $\mu\tau_\mathrm{h}$ channel)



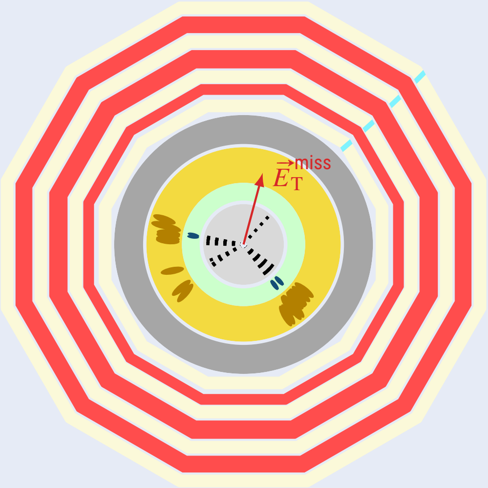
- Remember: invariant mass not fully available:
  - neutrinos in di-τ events.

What's here

(e.g. VBF Higgs production + decay to $\tau\tau$, $\mu\tau_{\mathrm{h}}$ channel)



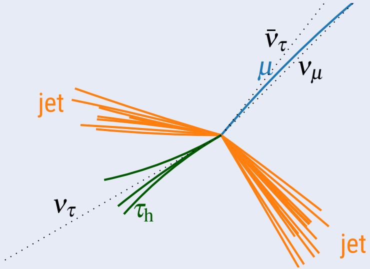
What CMS sees: no neutrinos but $E_{\mathrm{T}}^{\mathrm{miss}}$



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

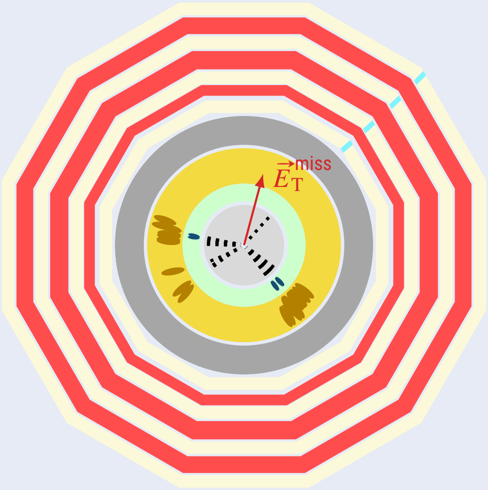
What's here

(e.g. VBF Higgs production + decay to $\tau\tau$, $\mu\tau_\mathrm{h}$ channel)

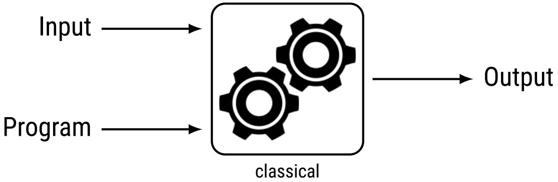


- It would be great to have a di-τ mass estimator!
  - What about ***machine learning***?

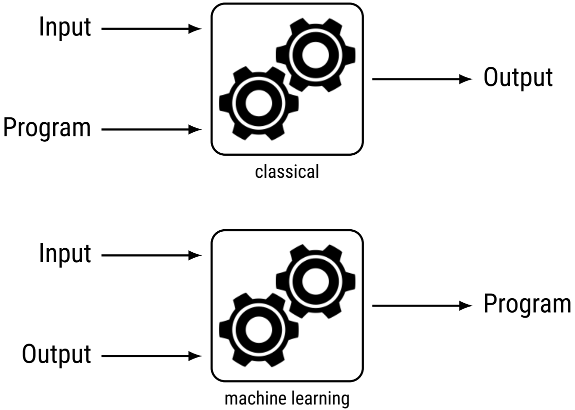
What CMS sees: no neutrinos but $E_\mathrm{T}{}^\mathrm{miss}$



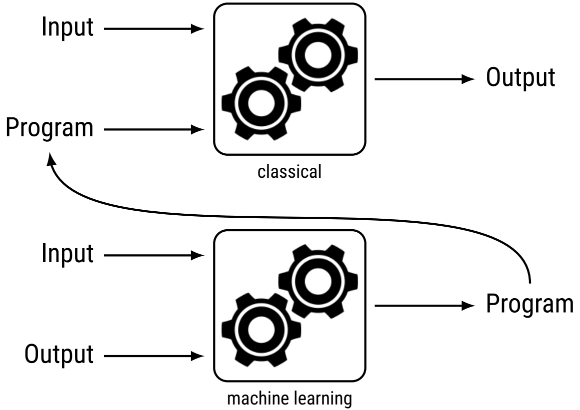
What is *machine learning*? – A brief introduction



What is *machine learning*? – A brief introduction



What is *machine learning*? – A brief introduction



What is *machine learning*? – A brief introduction

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

What is *machine learning*? – A brief introduction

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

- 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

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

- Categorical target ⇒ Classification

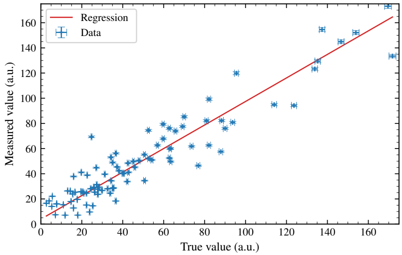
e.g. cat or dog on the image

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

- Continuous target ⇒ Regression

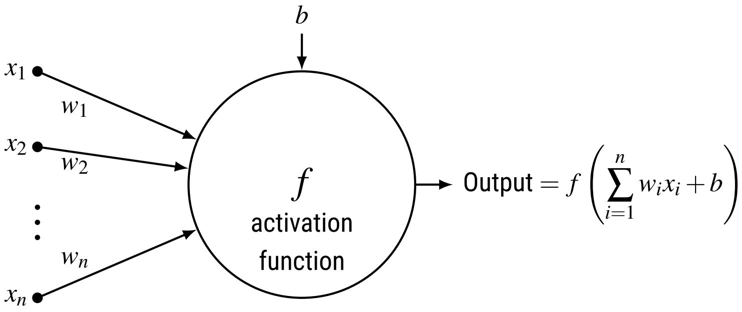
e.g. discriminating variable!

Linear case:



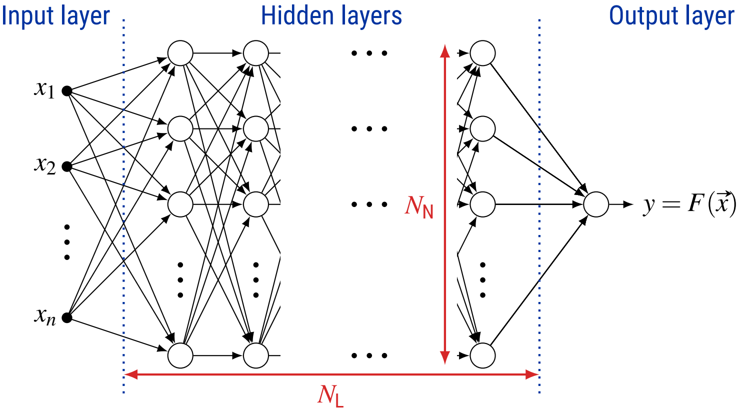
What if the target is not linear wrt. input?

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

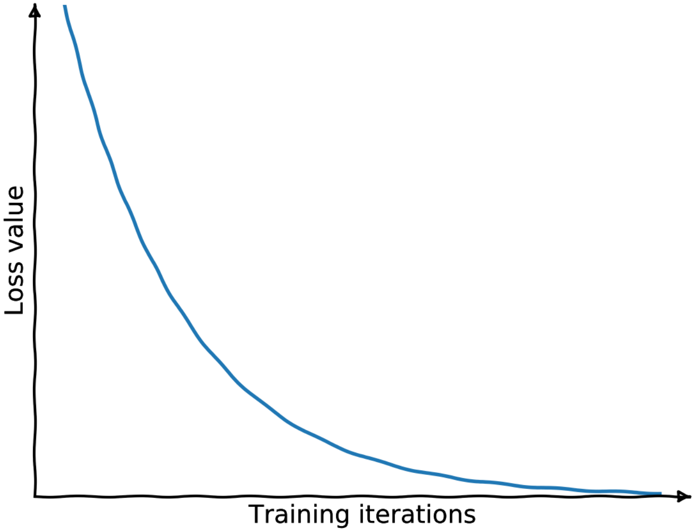


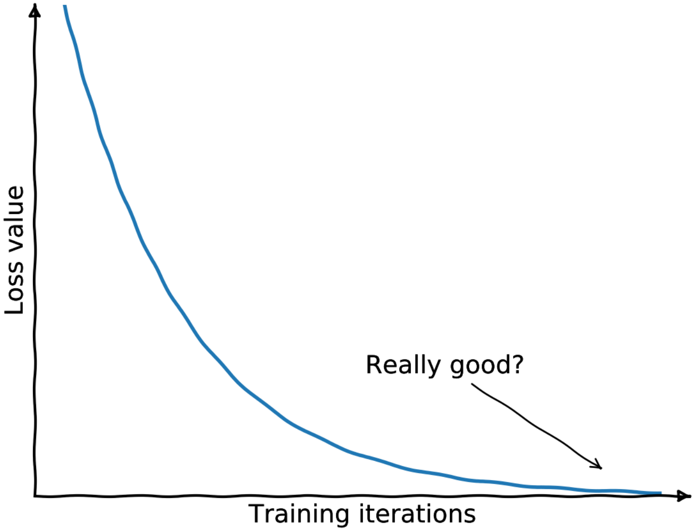
How to train a neural network?

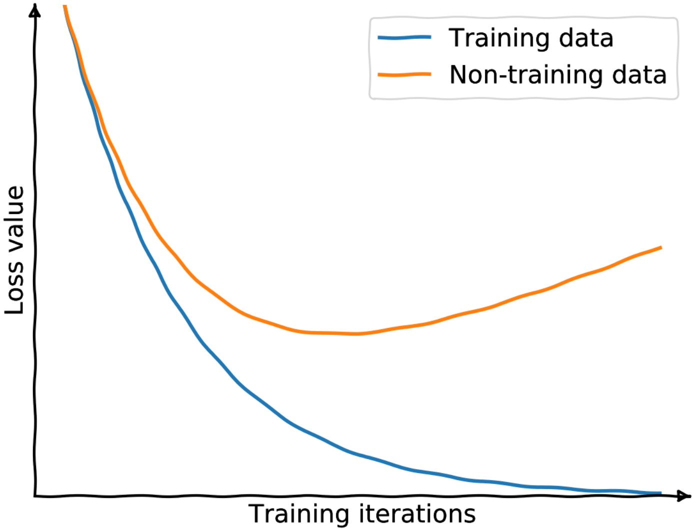
Train = optimize parameters $(w_1, w_2, \ldots, w_n, b)$ for each neuron.

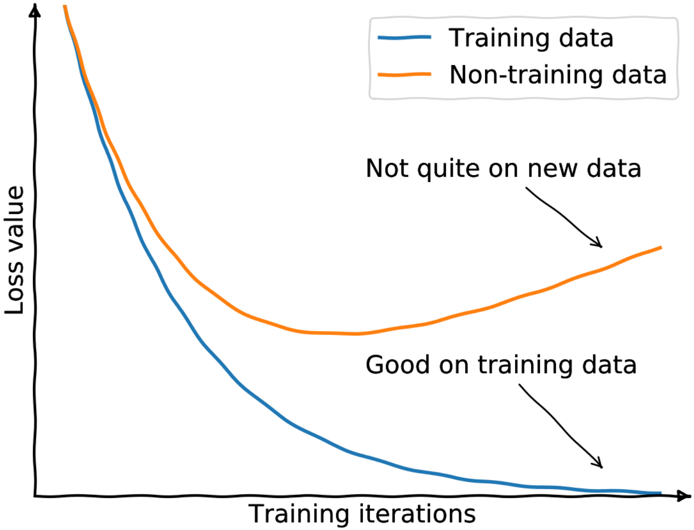
- Get a **training dataset** = examples of inputs $\vec{x}_i$ with corresponding outputs y_i
- Compare the model predictions $F(\vec{x}_i)$ to the true values y_i
  - Define a **loss function** $\mathfrak{L}$ such that its minimum is reached when $F(\vec{x}_i) = y_i$
  - Change the parameters a bit,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

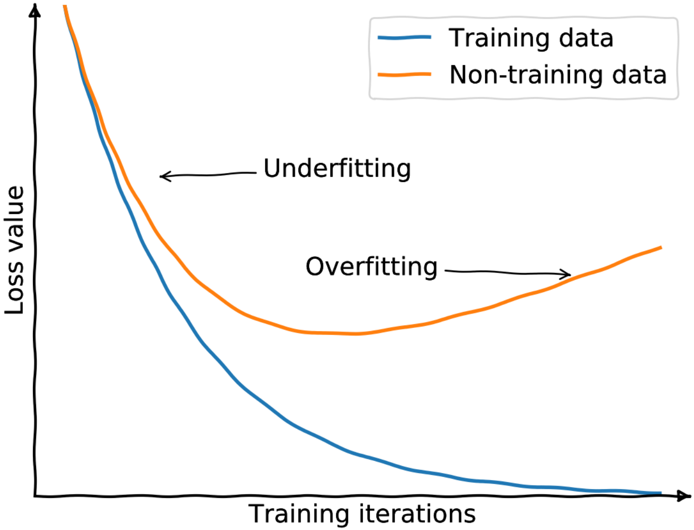
When to stop training?

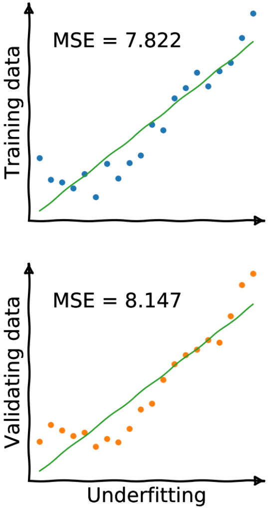

Loss value
Training iterations

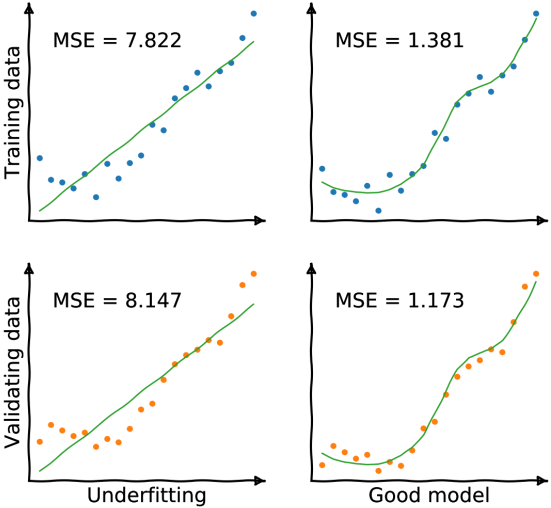

Loss value
Really good?
Training iterations

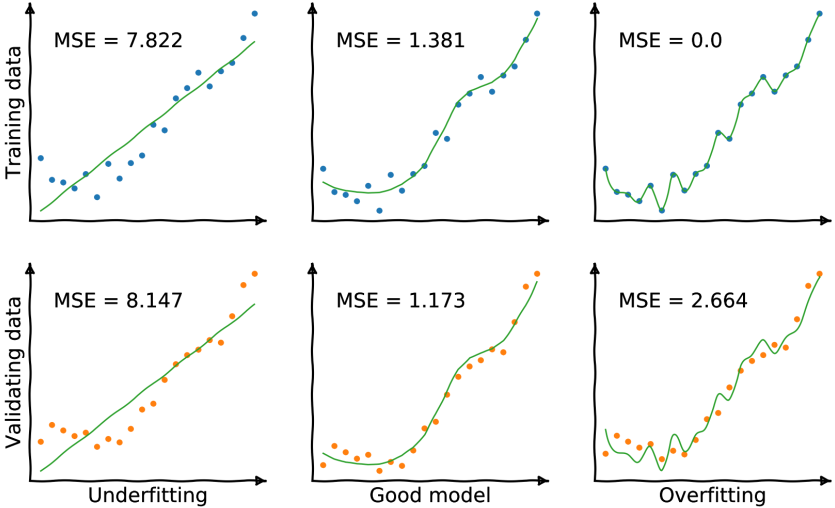

Training data
Non-training data
Loss value
Training iterations

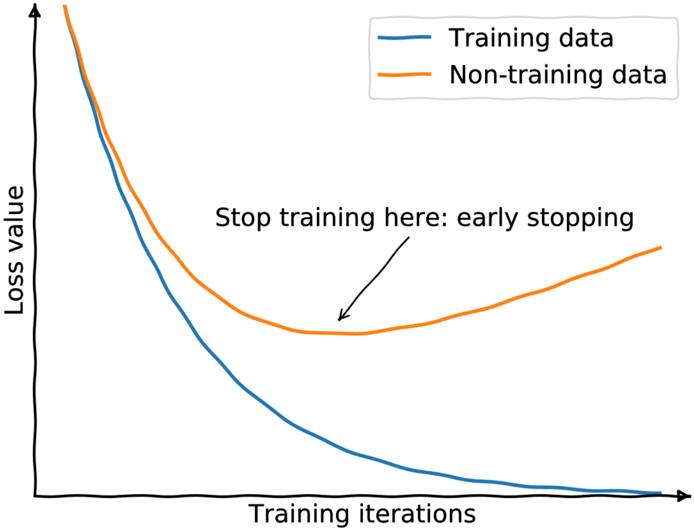

Training data
Non-training data
Loss value
Training iterations
Not quite on new data
Good on training data

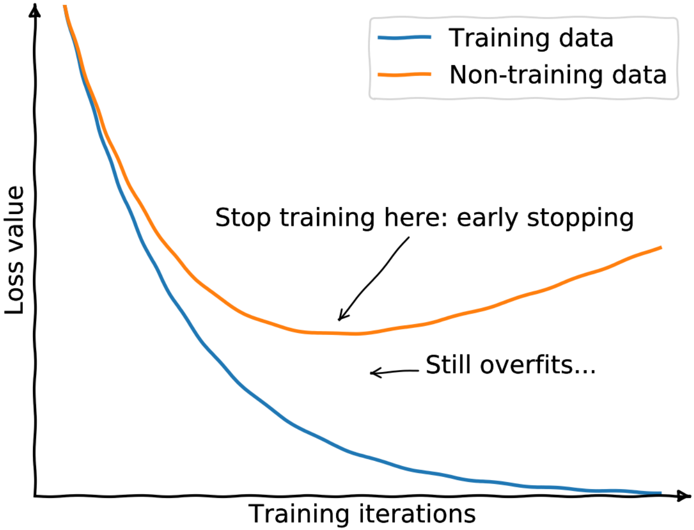

Training data
Non-training data
Underfitting
Overfitting
Loss value
Training iterations

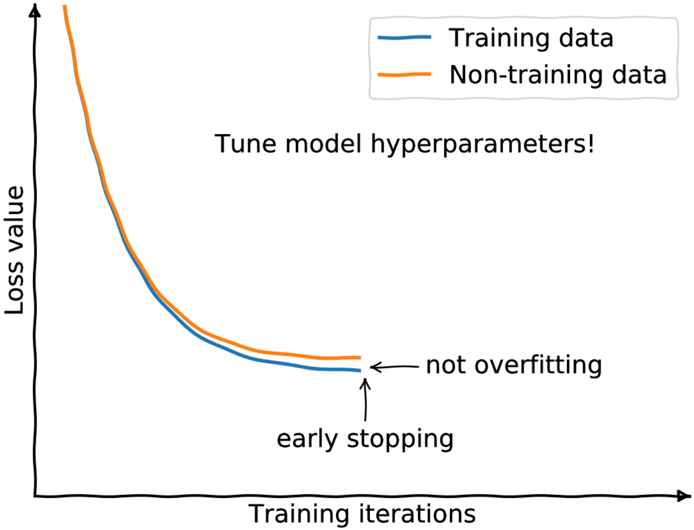

MSE = 7.822
Training data
MSE = 8.147
Validating data
Underfitting


MSE = 7.822
MSE = 1.381
Training data
MSE = 8.147
MSE = 1.173
Validating data
Underfitting
Good model

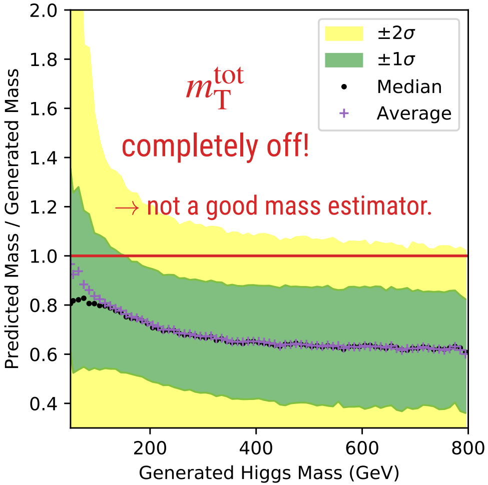

Training data
Validating data
MSE = 7.822
MSE = 1.381
MSE = 0.0
MSE = 8.147
MSE = 1.173
MSE = 2.664
Underfitting
Good model
Overfitting


Training data
Non-training data
Stop training here: early stopping
Loss value
Training iterations


Training data
Non-training data
Stop training here: early stopping
Still overfits...
Loss value
Training iterations


Training data
Non-training data
Tune model hyperparameters!
not overfitting
early stopping
Loss value
Training iterations

DNN's m_{ML} predictions *vs* $m_{\mathrm{T}}^{\mathrm{tot}}$

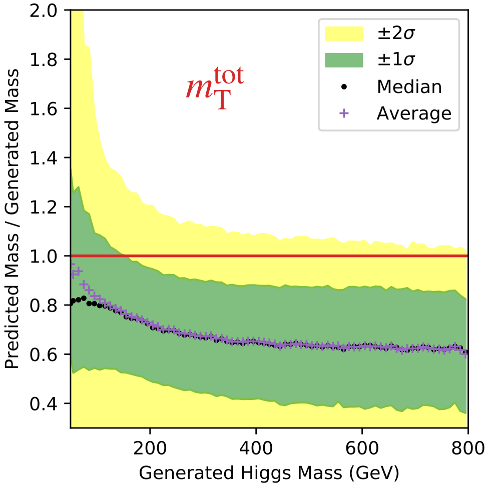


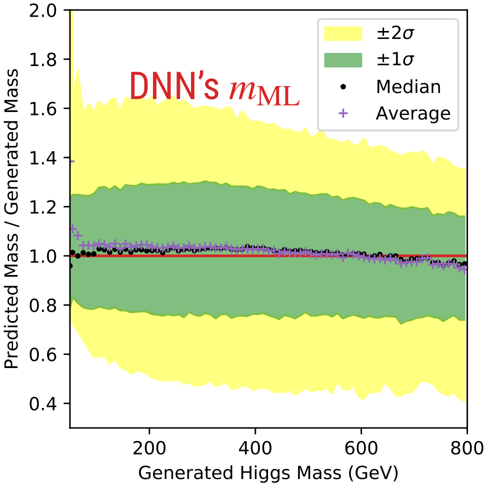
- Model's response:

$$r = \frac{\text{prediction}}{\text{true value}} = \frac{m_{\mathrm{ML}}}{m_{\mathcal{H}}} \text{ or } \frac{m_{\mathrm{T}}^{\mathrm{tot}}}{m_{\mathcal{H}}}$$

- Closer to 1 is better for black dots.

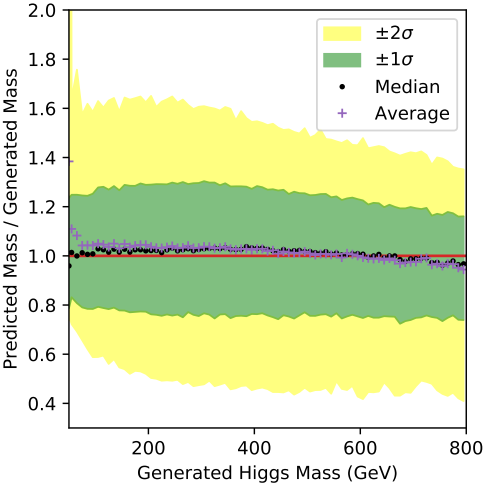
DNN's m_{ML} predictions *vs* $m_{\mathrm{T}}^{\mathrm{tot}}$





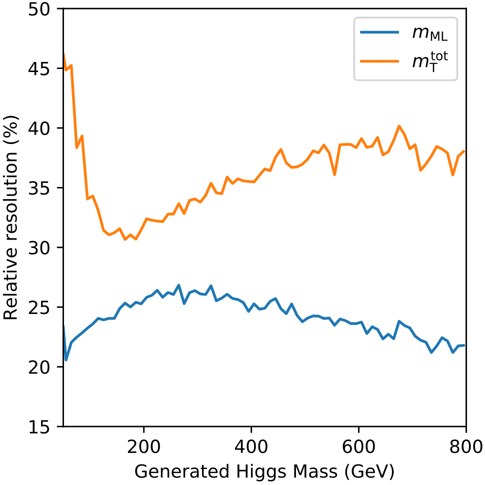
DNN's m_{ML} predictions *vs* $m_{\text{T}}^{\text{tot}}$

- $r = 1.00 \pm 0.05$ from 80 to $800\,\text{GeV}$
- $\mathcal{H}$ mass reconstruction **achieved** ✓

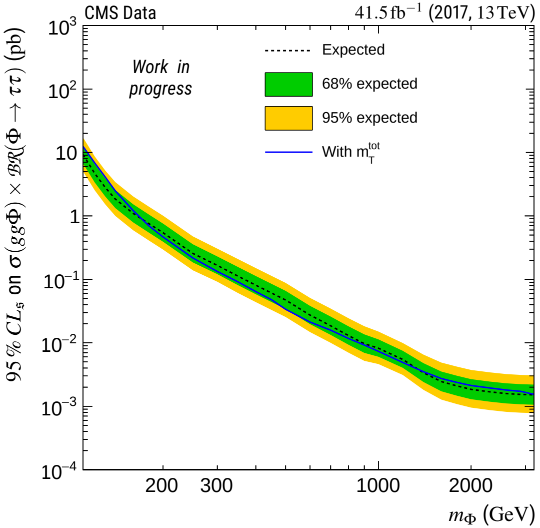


Using the model to get a discriminating variable

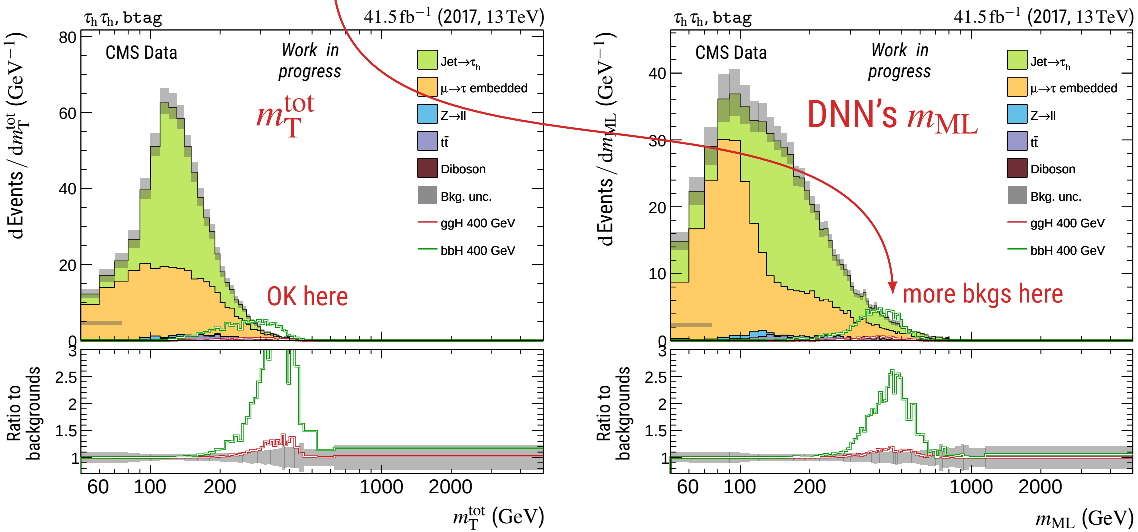
- In the $H/A \to \tau\tau$ analysis, discriminating variable $= m_\mathrm{T}^\mathrm{tot}$.
- $m_\mathrm{T}^\mathrm{tot}$ is equal to the invariant mass assuming:
  - all neutrinos are a single particle with $\vec{p}_\mathrm{T} = \vec{E}_\mathrm{T}^\mathrm{miss}$,
  - all is going on in the transverse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



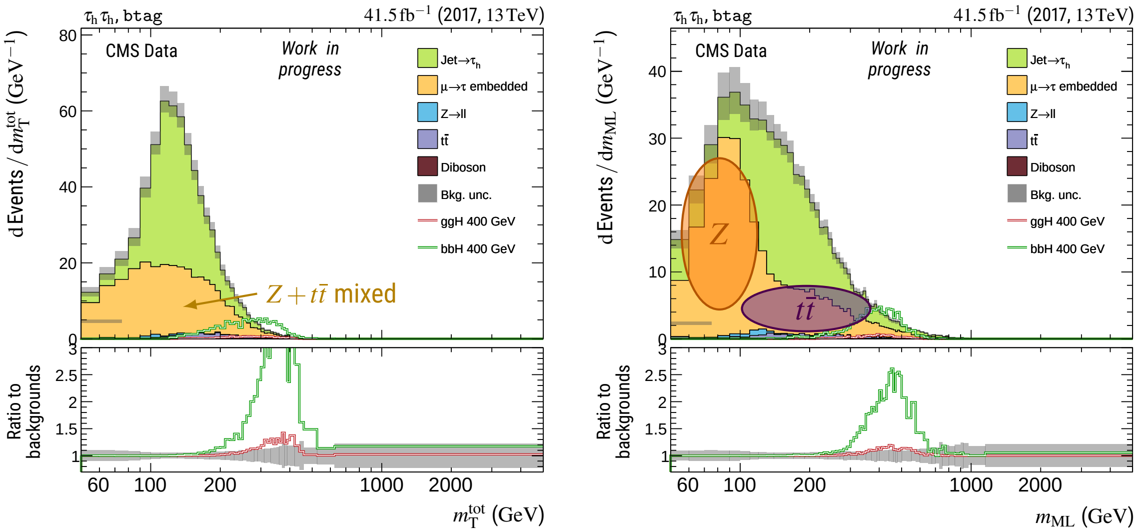
- Proceed to the search for massive Higgs boson Φ with di-τ events on the 2017 era.
- Use m_{ML} as discriminating variable.
- Not really better than with $m_{\mathrm{T}}^{\mathrm{tot}}$... Why?



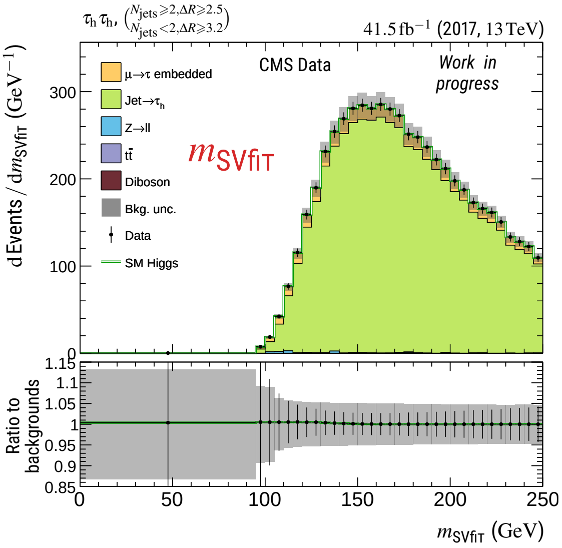
▶ Large fakes τ_h high mass tails falling into the signal region ⇒ lowered signal to background ratio.

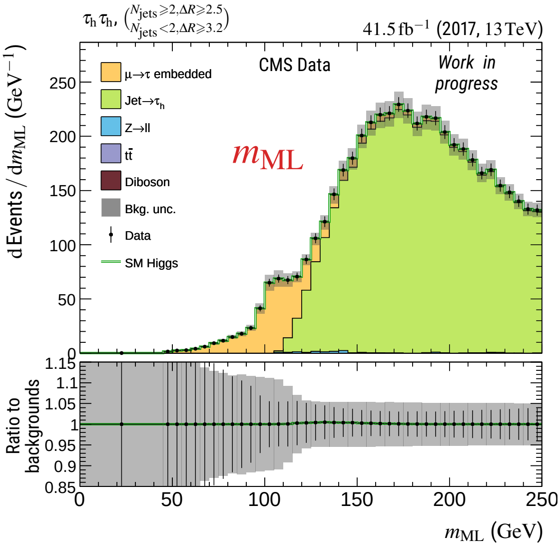


- **BUT** Z / $t\bar{t}$ separation! See the two m_{ML} embedded components, not present with $m_{\mathrm{T}}^{\mathrm{tot}}$.



▶ Our model finds $Z \to \tau\tau$ events when SVfiT does not!





What to conclude from this thesis?

Conclusion & prospects: $H/A \to \tau\tau$

- MSSM $H/A \to \tau\tau$ analysis on full Run II:
  - 4 final states: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$ and $e\mu$,
  - Model independent exclusion limits on $\sigma \times \mathcal{BR}$,
  - Model dependent exclusion contours in the $(m_A, \tan\beta)$ plane.
- CMS paper HIG-21-001 on its way for publication:
  - Leading-edge until Run III corresponding results!
- No evidence for MSSM.

Conclusion & prospects: ML project

- Successful $m_{\mathcal{H}}$ reconstruction in di-τ events.
  - Not only MSSM $H/A \to \tau\tau$ but any $X \to \tau\tau$ analysis could benefit from this project.
- m_{ML} vs $m_{\mathrm{T}}^{\mathrm{tot}}$:
  - A good mass estimator is not always 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 $\mathcal{H} \to \tau\tau$ with various masses only).
  - Could be improved by updating the training datasets (other kinds of events).
  - Faster (about 60 times!).
- Very promising as a di-τ mass predictor (SVfit successor?).

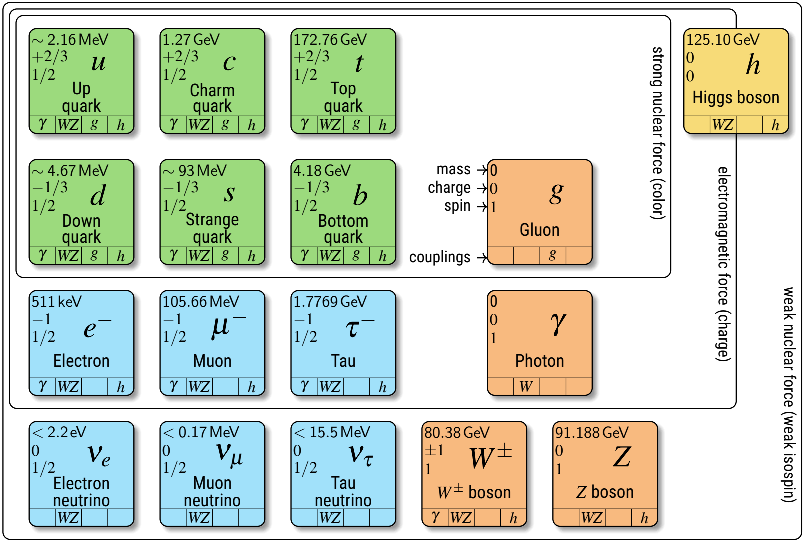
Conclusion & prospects: ML & particle physics

- Introduced a method to estimate a mass from the (partial) final state ;
- Other applications:
  - b-tagging (DeepCSV),
  - τ_{h} identification (DeepTau),
  - event classification.

Merci pour votre attention !

- Phenomenology:
  - SM, SUSY, 2HDM, $\tan\beta$ slide 45
  - Why $H/A \to \tau\tau$? slide 50
  - How histograms unveil particles slide 52
- MSSM $H/A \to \tau\tau$:
  - Embedded samples slide 59
  - Fake factors slide 60
  - Triggers in the $\tau_h\tau_h$ channel slide 64
  - Fake factors for subleading τ_h slide 65
  - CP violation in the Higgs sector slide 66
- Machine Learning:
  - Custom loss function for the DNN slide 68
  - Training mass range high boundary slide 71

The Standard Model



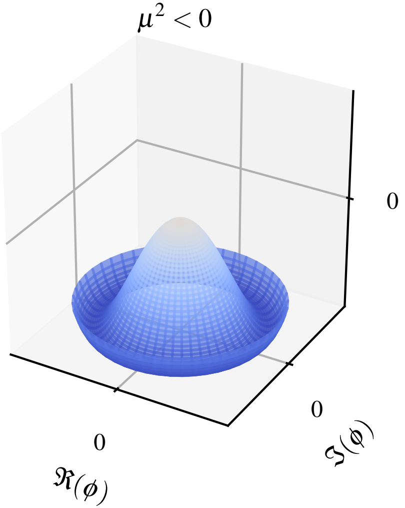
Higgs boson in the Standard Model

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

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

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

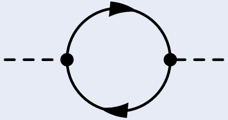
$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



The Standard Model and naturalness problem

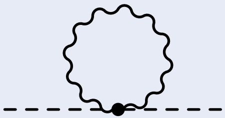
- Higgs mass measured: $m_h = 125.10 \pm 0.14\,\mathrm{GeV}$
- Higgs mass derivation: $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



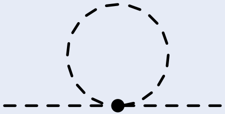
$$-\frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim -(2\,\mathrm{TeV})^2$$

vector bosons



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

Higgs itself

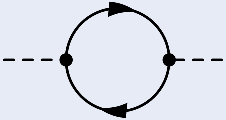


$$+\frac{1}{16\pi^2} \lambda^2 \Lambda^2 \sim +(0.5\,\mathrm{TeV})^2$$

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

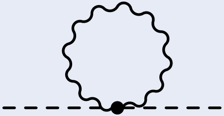
Supersymmetry

top quark



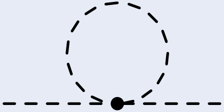
$\sim -(2\,\mathrm{TeV})^2$

vector bosons



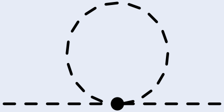
$\sim +(0.7\,\mathrm{TeV})^2$

Higgs itself



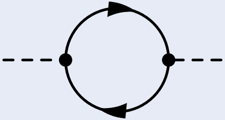
$\sim +(0.5\,\mathrm{TeV})^2$

stop quark



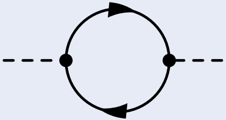
$\sim +(2\,\mathrm{TeV})^2$

bosinos



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

Higgsinos



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

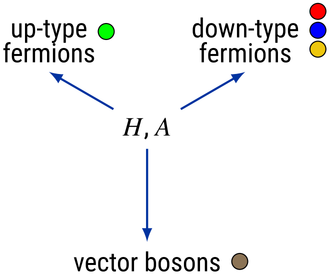
2 Higgs doublets models for supersymmetry

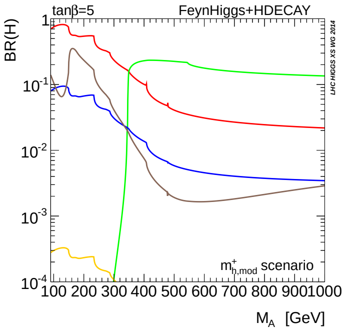
$$\langle\phi_1\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \quad \langle\phi_2\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2 \mathrm{e}^{\mathrm{i}\xi}\end{pmatrix}$$

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

▷ 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`.

Why $H/A \to \tau\tau$?

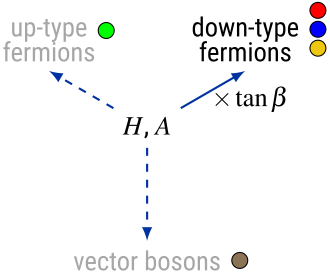


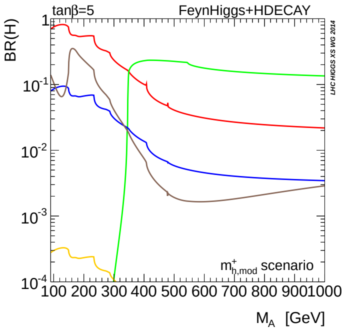


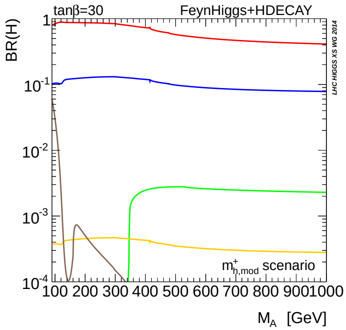
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

▷ 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.

Why $H/A \to \tau\tau$? – enhanced and suppressed couplings



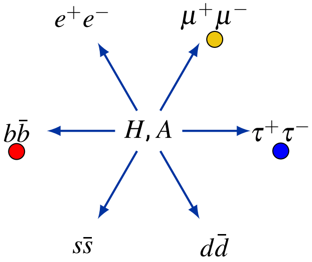


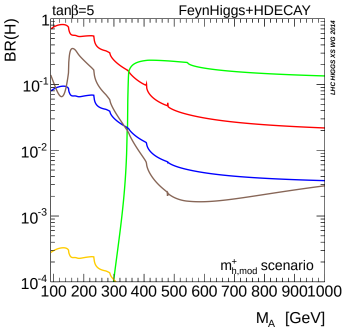


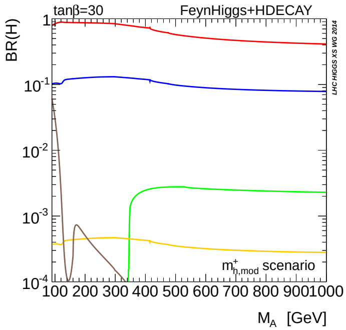
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: `10.1007/JHEP09(2018)007`.

▷ 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`.

Why $H/A \to \tau\tau$?



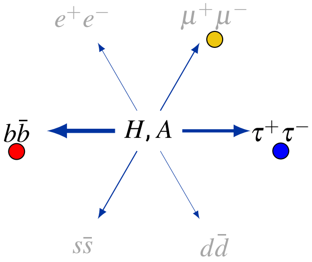


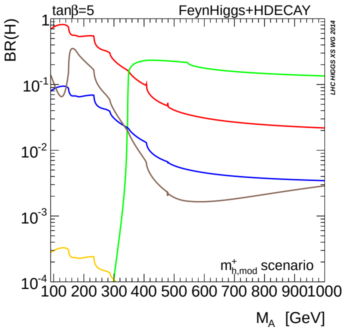


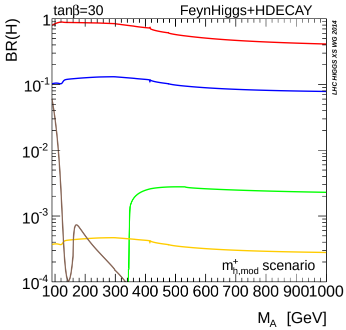
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

▷ 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.

Why $H/A \to \tau\tau$? – Higgs couplings and particules masses



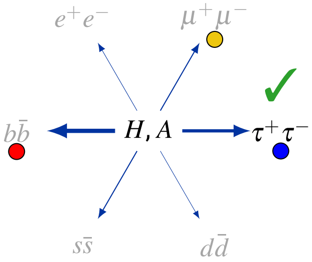


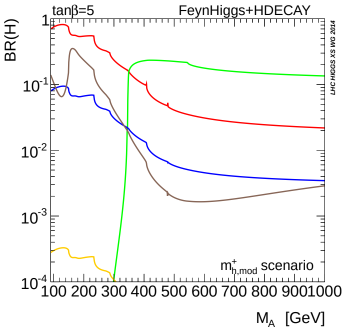


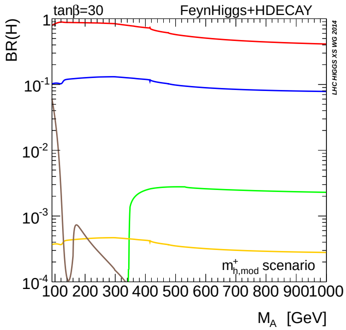
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

▷ 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.

Why $H/A \to \tau\tau$? – avoid hadronic background







▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *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.

Using histograms

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

The rabbit analogy

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

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

- Dice results: 4

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

- Dice results: 4, 2

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

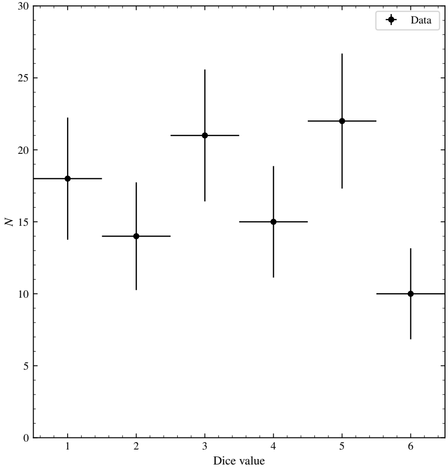
The rabbit analogy

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

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 100 days $\longrightarrow$

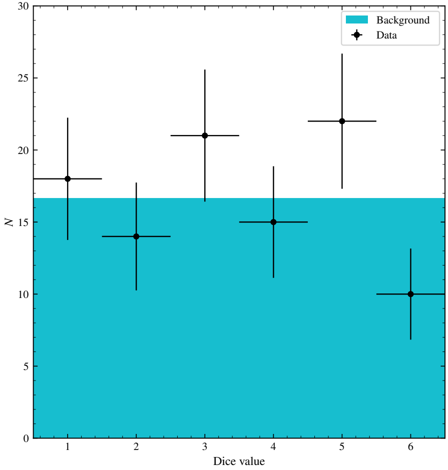


Not really conclusive...

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 100 days $\rightarrow$

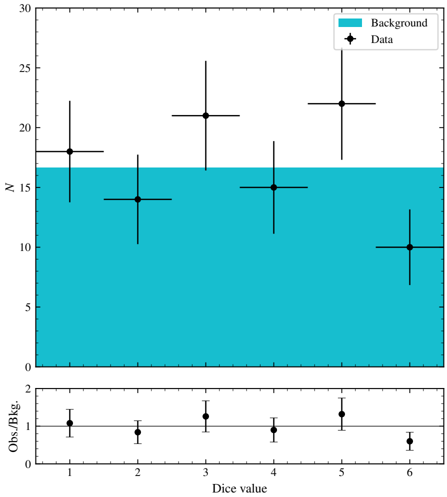


Comparing with predictions!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 100 days →

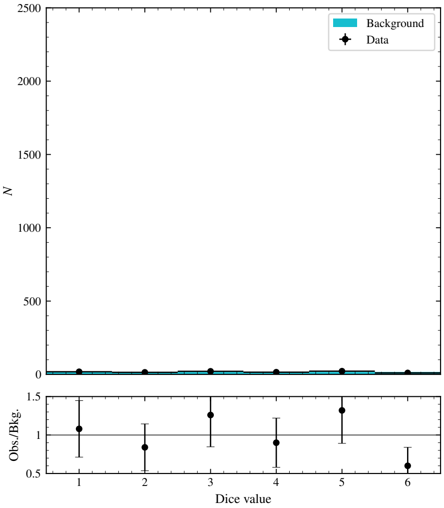


Also add ratio plot: observed / predictions

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 100 days →

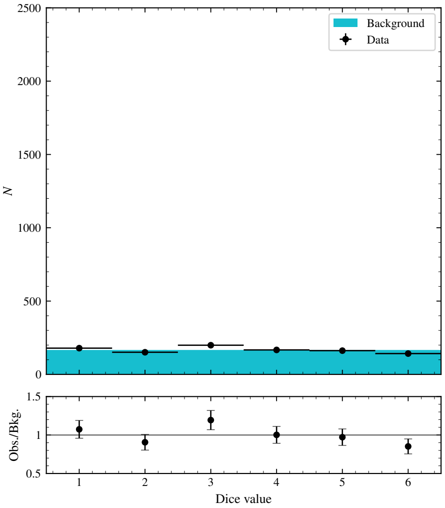


Fill up with more data!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 1000 days $\longrightarrow$

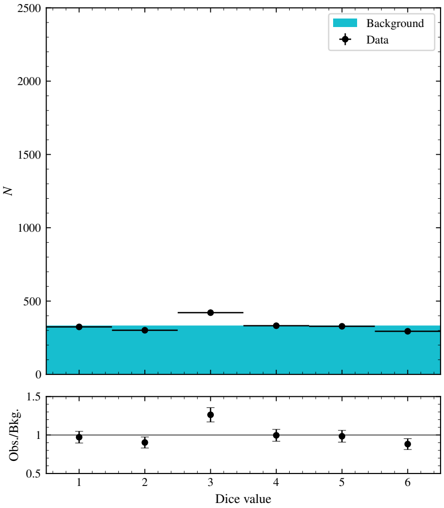


Fill up with more data!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 2000 days $\rightarrow$

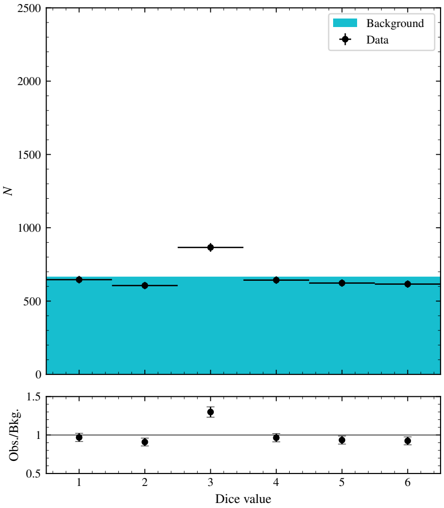


Fill up with more data!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 4000 days $\rightarrow$

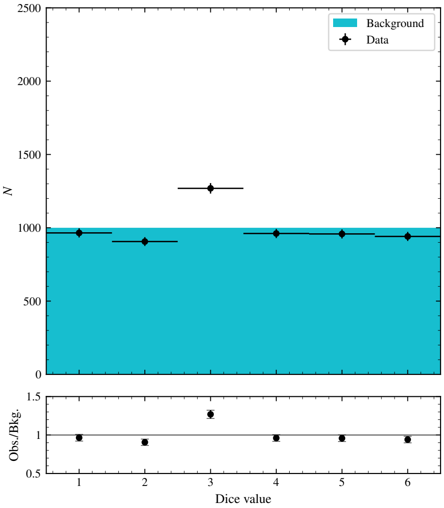


Fill up with more data!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 6000 days $\longrightarrow$

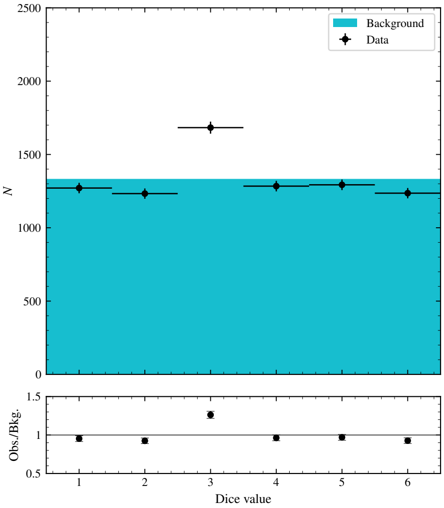


Fill up with more data!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 8000 days →

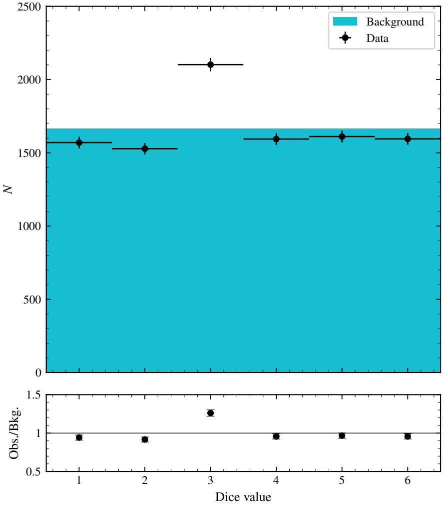


Fill up with more data!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 10 000 days →

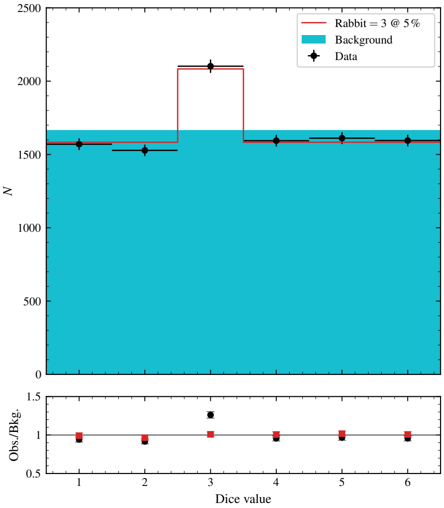


Fill up with more data!

▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

The rabbit analogy

On 10 000 days $\rightarrow$

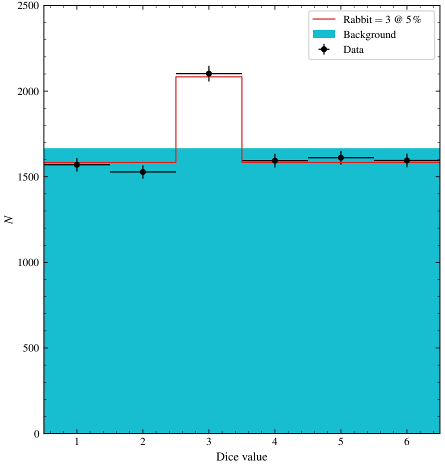


In red, hypothesis of the rabbit with 3 as preferred result (instead of 4!), with a probability to show up of $5\,\%$.

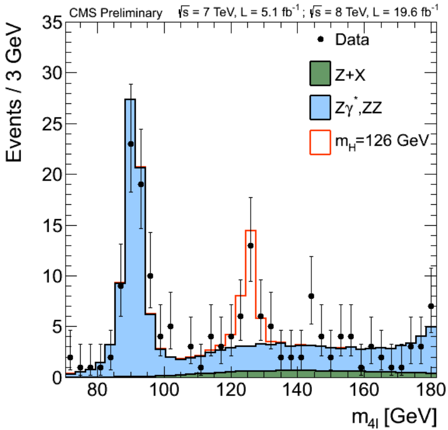
▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: `https://www.youtube.com/watch?v=8-WFBGCvv-w`.

The rabbit analogy

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



$\rightsquigarrow$

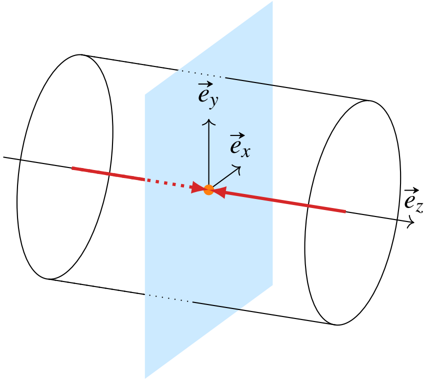


▷ The CMS Collaboration. "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC". *Physics Letters* **B716**.1 (2012), pp. 30–61. DOI: 10.1016/j.physletb.2012.08.021.

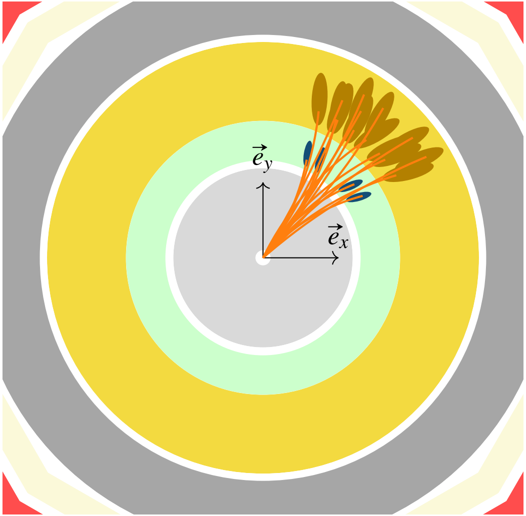
▷ The CMS Collaboration. *Properties of the Higgs-like boson in the decay $H \to ZZ \to 4\ell$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV.* URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki.

Conserved momentum and neutrinos: missing transverse energy (MET)

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

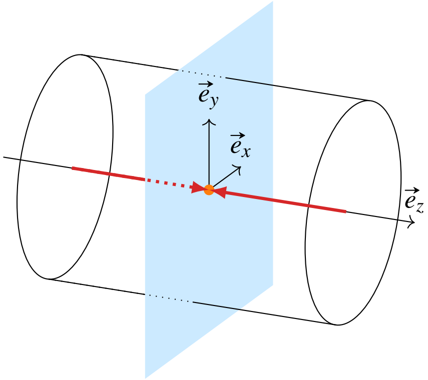


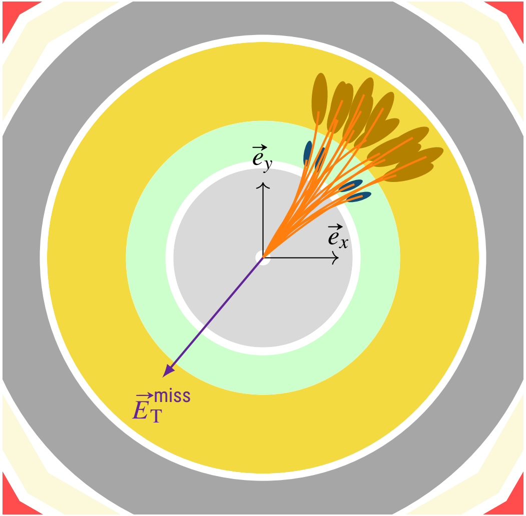
$$\sum_{\text{final state}} \vec{p}_{\mathrm{T}} = \sum_{\text{initial state}} \vec{p}_{\mathrm{T}} = \vec{0}$$



Conserved momentum and neutrinos: missing transverse energy (MET)

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

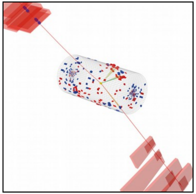




$$\sum_{\text{final state}} \vec{p}_\mathrm{T} = \sum_{\text{initial state}} \vec{p}_\mathrm{T} = \vec{0} \Rightarrow \boxed{\vec{E}_\mathrm{T}^\text{miss} = - \sum_{\text{visible particles}} \vec{p}_\mathrm{T}}$$

Embedded events & genuine τ leptons

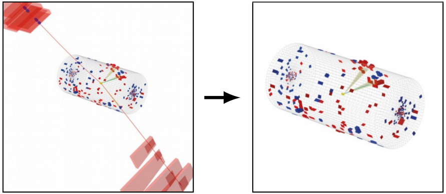
$Z \rightarrow \mu\mu$ data



▷ 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.

Embedded events & genuine τ leptons

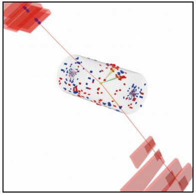
$Z \rightarrow \mu\mu$ data Remove $\mu\mu$ system



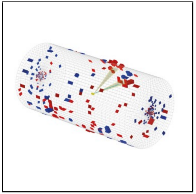
▷ The CMS Collaboration. “An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data”. *Journal of Instrumentation* **14**.06 (June 2019). DOI: 10.1088/1748-0221/14/06/p06032.

Embedded events & genuine τ leptons

$Z \to \mu\mu$ data

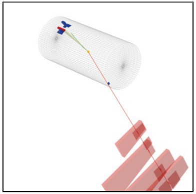


Remove $\mu\mu$ system



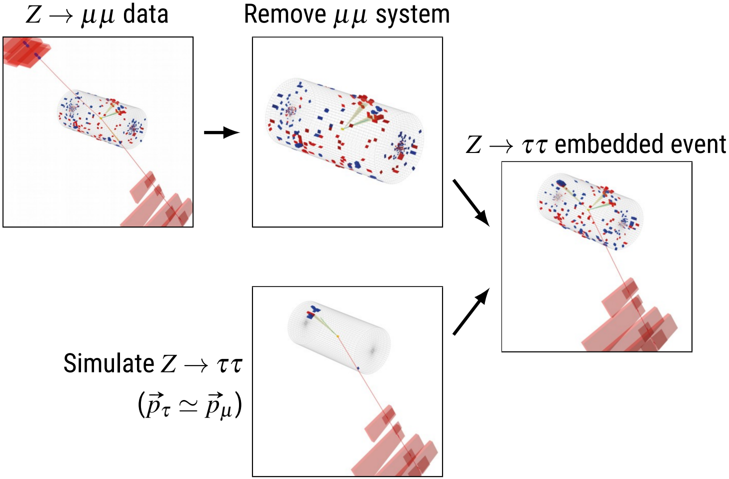
Simulate $Z \to \tau\tau$

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



▷ 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.

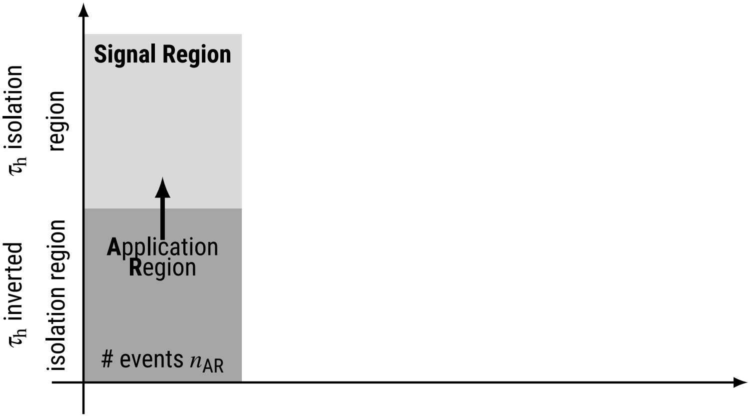
Embedded events & genuine τ leptons



▷ 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.

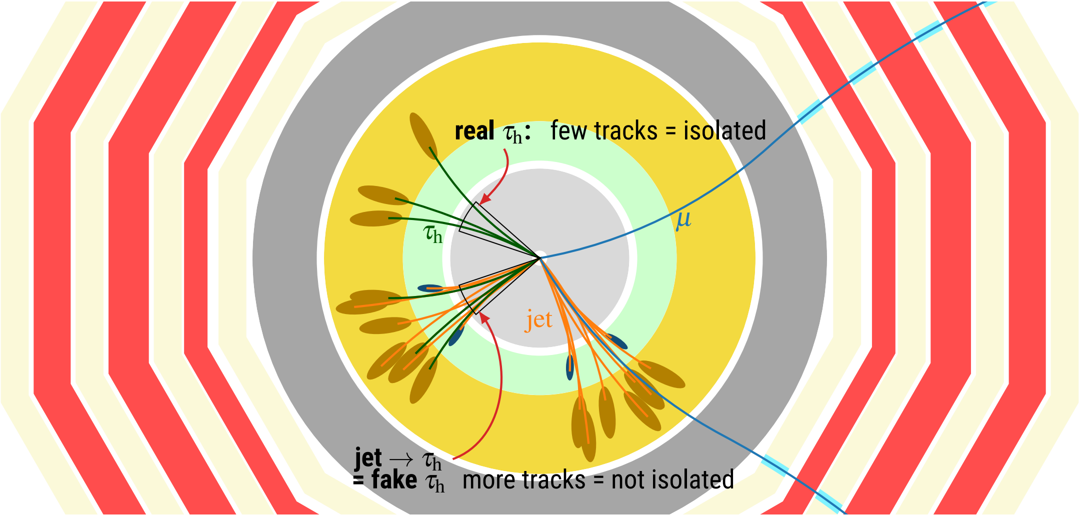
The Fake Factor method & jets faking τ_h

- How many events contain misidentified τ_h (fake taus) in the Signal Region (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.

Particles isolation – qualitatively



The Fake Factor method: determination regions definitions

QCD multijet ($\tau_h\tau_h$, $\mu\tau_h$ and $e\tau_h$ channels)

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%5C%20AN-2019/170.

The Fake Factor method: determination regions definitions

QCD multijet ($\tau_h\tau_h$, $\mu\tau_h$ and $e\tau_h$ channels)

Same as SR, except:

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

$W+$jets ($\mu\tau_h$ and $e\tau_h$ channels)

Same as SR, except:

- transverse mass $m_T^{(\ell)} > 70\,\mathrm{GeV}$ ($m_T^{(\ell)} < 70\,\mathrm{GeV}$ 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.

The Fake Factor method: determination regions definitions

QCD multijet ($\tau_h\tau_h$, $\mu\tau_h$ and $e\tau_h$ channels)

Same as SR, except:

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

$W+$jets ($\mu\tau_h$ and $e\tau_h$ channels)

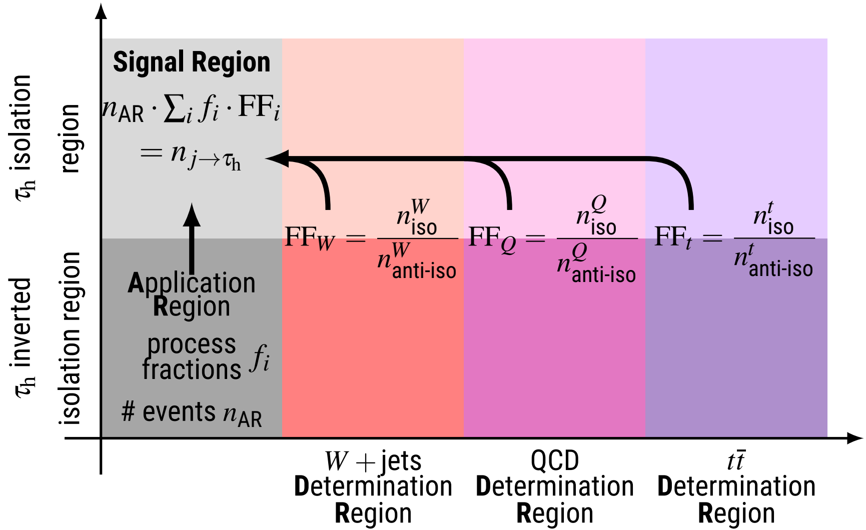
Same as SR, except:

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

$t\bar{t}$ ($\mu\tau_h$ and $e\tau_h$ channels)

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%5C%20AN-2019/170`.

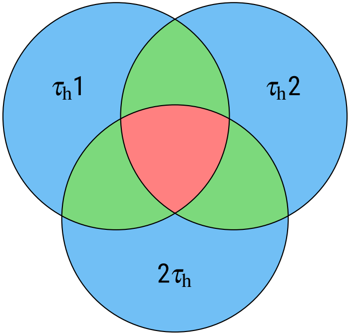


▷ J. Andrejkovic & J. Bechtel. “Data-driven background estimation of fake-tau backgrounds in di-tau final states with the full Run-II dataset”. *CMS analysis Note* (June 2020). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C%20AN-2019/170.

Triggers in the $\tau_h\tau_h$ channel

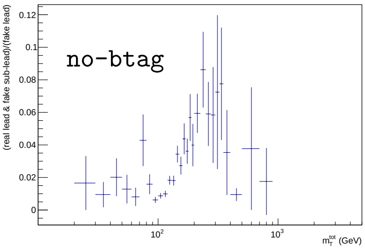
- In the manuscript: page 118, formula (4.5)

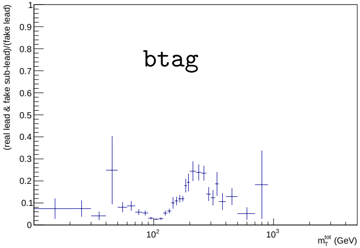
$$
\begin{aligned}
\varepsilon = {} & \varepsilon(2\tau_h) + \varepsilon(\tau_h 1) + \varepsilon(\tau_h 2) \\
& - \varepsilon(2\tau_h + \tau_h 1) - \varepsilon(2\tau_h + \tau_h 1) - \varepsilon(\tau_h 1 + \tau_h 2) \\
& + \varepsilon(2\tau_h + \tau_h 1 + \tau_h 2)
\end{aligned}
$$



Fake factors for subleading τ_h

- The $\tau_h\tau_h$ fake factors are measured for the leading τ_h candidate only.
  - The subleading one can be either a genuine or fake τ_h.
- At this point, underestimation of events in which only the subleading τ_h is a fake.
  - Adding these back using MC.
- Small fraction of fakes $< 10\,\%$ in `no-btag`, $< 30\,\%$ in `btag` (due to $t\bar{t}$):





▷ J. Andrejkovic et al. "BSM $H \to \tau\tau$ analysis on full Run 2 CMS data at $\sqrt{s} = 13\,\mathrm{TeV}$". *CMS analysis Note* (2021). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C%20AN-2020/218.

CP violation in the Higgs sector

$$\mathcal{L}_{\text{Yukawa}} = -\frac{m\sqrt{2}}{v}\left(\cos(\varphi)\bar{\psi}\Phi\psi + \sin(\varphi)\bar{\psi}i\gamma^5\Phi\psi\right)$$

- No violation case:

Mix. angle φ	State	J^{CP}	Type	Example
0	CP-even	0^{++}	Scalar	SM Higgs, MSSM h and H
$\pi/2$	CP-odd	0^{+-}	Pseudo-scalar	MSSM A

- What if $\varphi \notin \{0, \pi/2\}$?
  - Mass eigenstates $\neq$ CP eigenstates $\Rightarrow$ mixing!

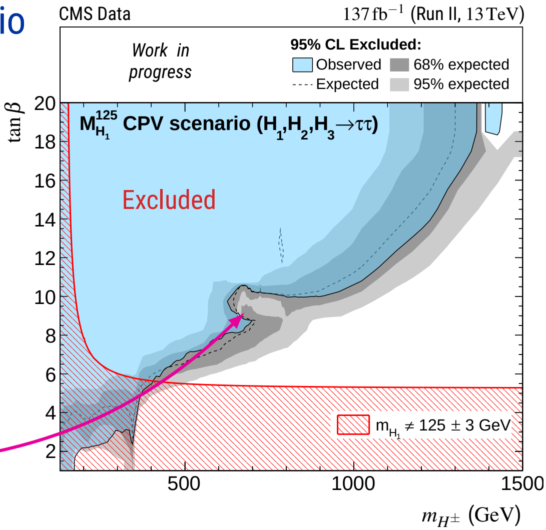
CP eigenstates: h, H, A
Mass eigenstates: H_1, H_2, H_3

CP violation and the $M_{H_1}^{125}(CPV)$ scenario

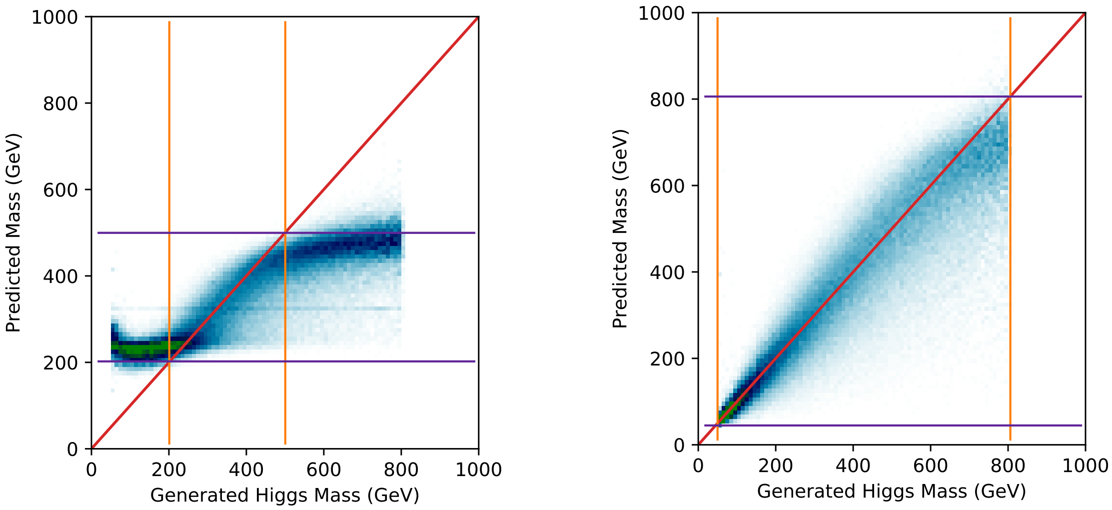
- Fixed higher-order MSSM parameter, in particular the trilinear Higgs-stop coupling constant:

$$|A_t| = \mu \cot\beta + 2.8\,\mathrm{TeV}, \quad \phi_{A_t} = \frac{2\pi}{15}$$

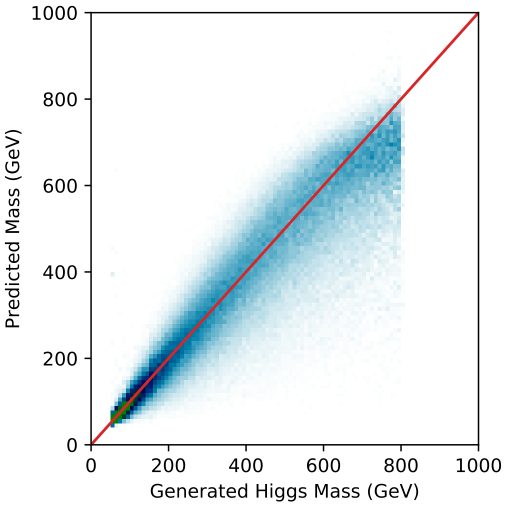
- m_A is replaced by $m_{H^\pm}$ as first-order parameter.
- H_1 should be the observed Higgs, interpreted now as the SM Higgs.
- H_2 and H_3 are additionnal wrt. the SM.
  - Interferences lowering sensitivity!

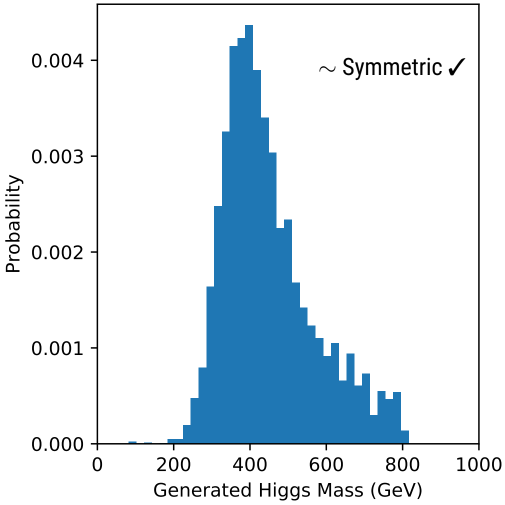


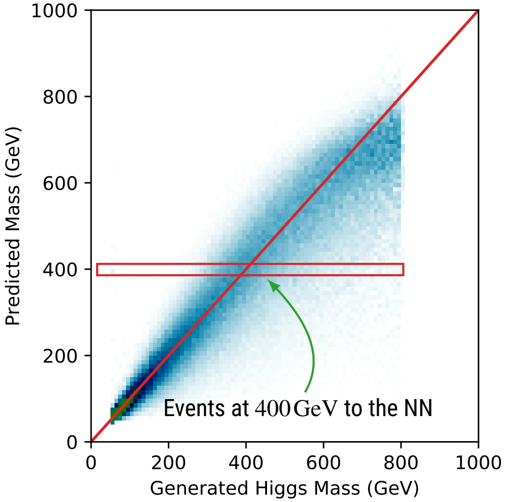
▷ E. Bagnaschi et al. "MSSM Higgs boson searches at the LHC: benchmark scenarios for Run 2 and beyond". *The European Physical Journal* **C79**.7 (July 2019). DOI: 10.1140/epjc/s10052-019-7114-8.

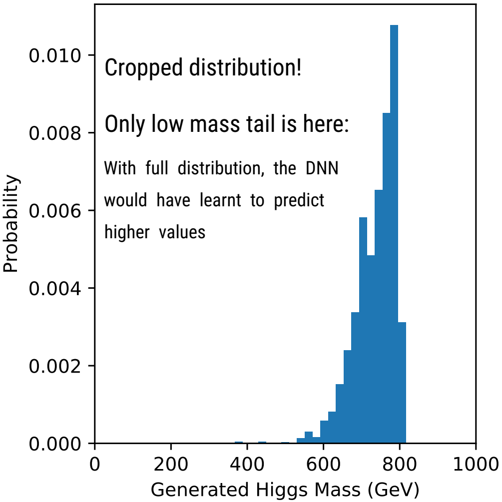

Predicted Mass (GeV)
Generated Higgs Mass (GeV)
0
200
400
600
800
1000
Predicted Mass (GeV)
Generated Higgs Mass (GeV)
0
200
400
600
800
1000

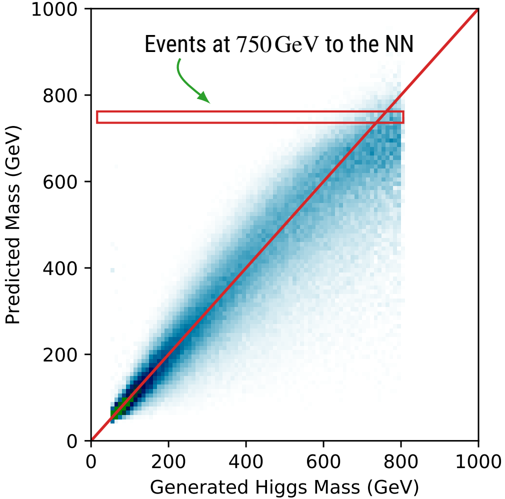
- How to cope with the boundaries?
  - Bias to be balanced,
  - Extend the mass range?
    - Would be nice!
    - Not always feasible...
- Every horizontal slice is one predicted value:
  - "Same family" of events to the NN.

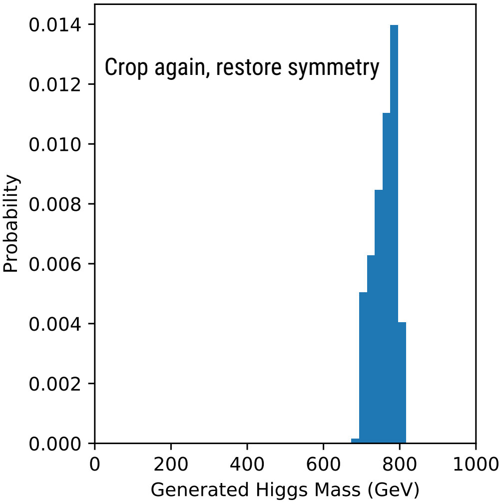


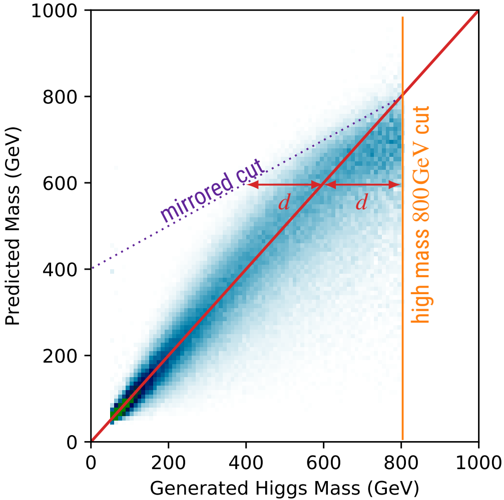

∼ Symmetric ✓
Probability
0.000
0.001
0.002
0.003
0.004
0
200
400
600
800
1000
Generated Higgs Mass (GeV)


Predicted Mass (GeV)
0
200
400
600
800
1000
Events at 400 GeV to the NN
Generated Higgs Mass (GeV)


Cropped distribution!
Only low mass tail is here:
With full distribution, the DNN would have learnt to predict higher values
Probability
0.000
0.002
0.004
0.006
0.008
0.010
0
200
400
600
800
1000
Generated Higgs Mass (GeV)

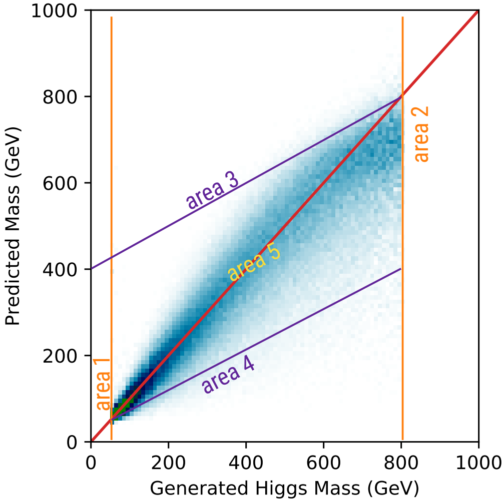

Events at 750 GeV to the NN
Predicted Mass (GeV)
0
200
400
600
800
1000
Generated Higgs Mass (GeV)


Crop again, restore symmetry
Probability
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
200
400
600
800
1000
Generated Higgs Mass (GeV)


Predicted Mass (GeV)
1000
800
600
400
200
0
mirrored cut
d
d
high mass 800 GeV cut
0
200
400
600
800
1000
Generated Higgs Mass (GeV)

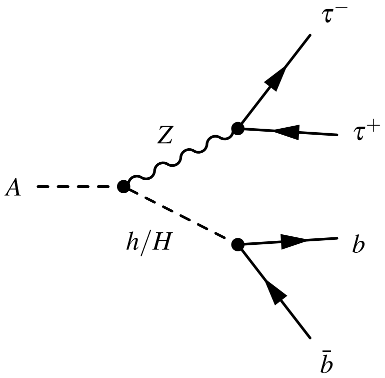
$$\mathfrak{L}_{\mathrm{MA\sqrt{PE}\times b}}(y_{\mathrm{true}}, y_{\mathrm{pred}}) = \mathfrak{L}_{\mathrm{MA\sqrt{PE}}}(y_{\mathrm{true}}, y_{\mathrm{pred}}) \times \begin{cases} 0 & \text{if } (y_{\mathrm{true}}, y_{\mathrm{pred}}) \in \text{area 3} \\ 0.1 & \text{if } (y_{\mathrm{true}}, y_{\mathrm{pred}}) \in \text{area 4} \\ 1 & \text{else} \end{cases}$$

$$\begin{aligned} \mathfrak{L}_{\mathrm{MA\sqrt{PE}}}(y_{\mathrm{true}}, y_{\mathrm{pred}}) &= \mathfrak{L}_{\mathrm{MAPE}}(y_{\mathrm{true}}, y_{\mathrm{pred}}) \times \sqrt{y_{\mathrm{true}}} \\ &= \left| \frac{y_{\mathrm{pred}} - y_{\mathrm{true}}}{y_{\mathrm{true}}} \right| \times \sqrt{y_{\mathrm{true}}} \\ \Leftrightarrow \mathfrak{L}_{\mathrm{MA\sqrt{PE}}}(y_{\mathrm{true}}, y_{\mathrm{pred}}) &= \left| \frac{y_{\mathrm{pred}} - y_{\mathrm{true}}}{\sqrt{y_{\mathrm{true}}}} \right| . \end{aligned}$$



Training mass range high boundary

- We used $\mathcal{H} \to \tau\tau$ events:
  - $\mathcal{H}$ is SM Higgs (pdg ID 25) with a different mass,
  - $\mathcal{H}$ produced by gluon fusion,
  - set $\mathcal{BR}(\mathcal{H} \to \tau\tau) = 1$ to avoid non di-τ events.
- SM particles well known (wrt. BSM particles).
- We produced samples with BSM particles too, **but**:
  - theoritical uncertainties (unknown particles !),
  - for a same mass point, τ kinematics do not match with $\mathcal{H}$ samples !
  - couplings effect ?



What to predict here?