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*

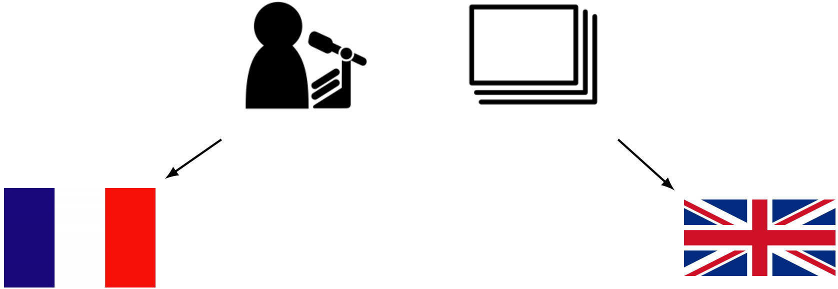
Soutenance de thèse de doctorat

Lucas TORTEROTOT

Institut de Physique des deux Infinis – Lyon

XX xxxx 2021

Lang(u)age



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

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

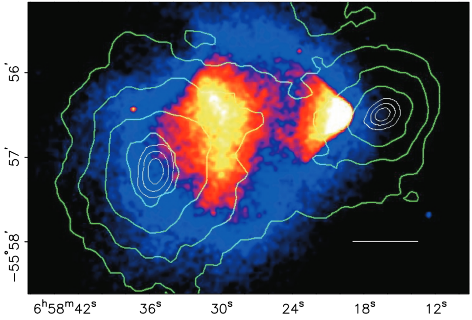
Institut de Physique des deux Infinis – Lyon

xxxx XXst/nd/rd/th 2021

Why do we **search for...**?

Current model status

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



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

Keywords in title

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

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

already one!

heavier

not lighter?

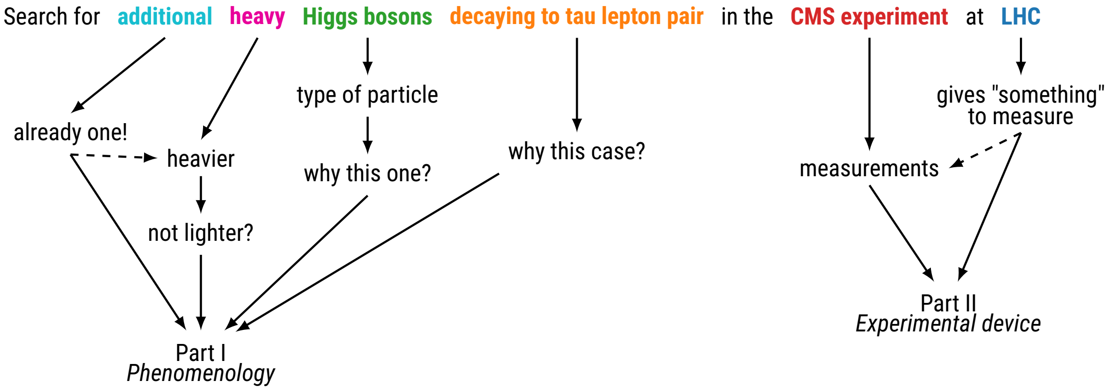
type of particle

why this one?

why this case?

Part I
Phenomenology

Keywords in title



Keywords in title

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

already one!

heavier

not lighter?

type of particle

why this one?

why this case?

results?

measurements

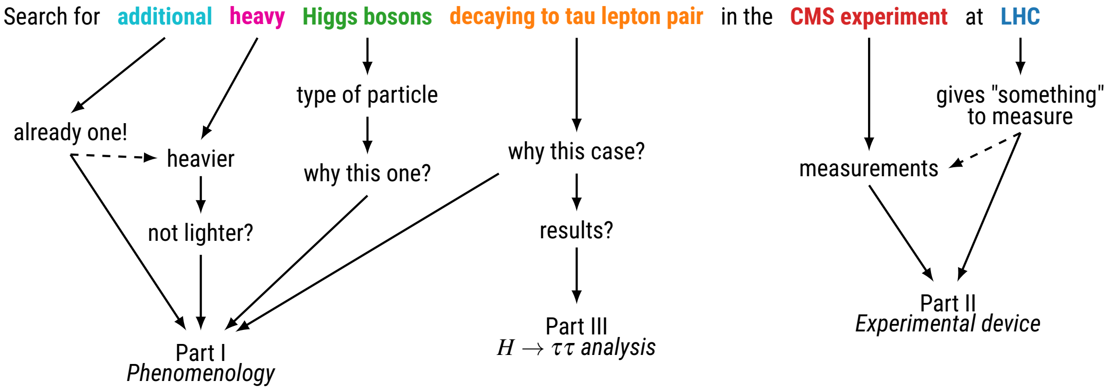
gives "something" to measure

Part I
Phenomenology

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

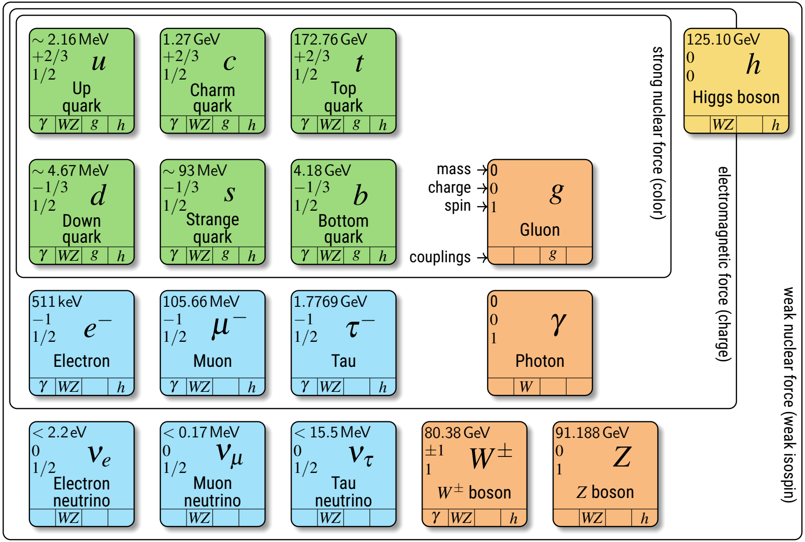
Part II
Experimental device

Keywords in title



+ Part IV: **with Machine Learning techniques**

The Standard Model



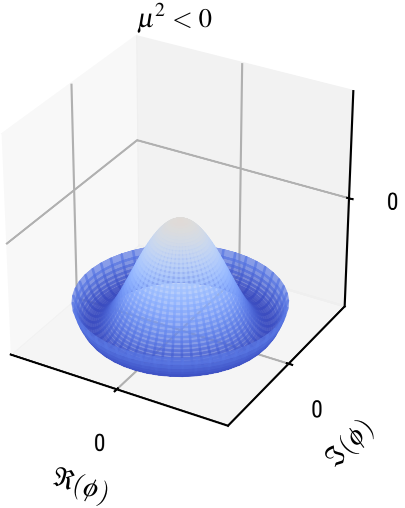
Higgs boson in the Standard Model

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

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

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

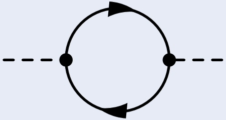
$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



The Standard Model and naturalness problem

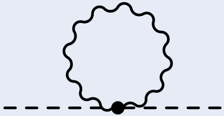
- Higgs mass measured: $m_h = 125.10 \pm 0.14\,\mathrm{GeV}$
- Higgs mass derivation: $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



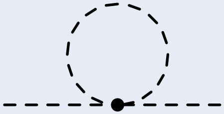
$$-\frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim -(2\,\mathrm{TeV})^2$$

vector bosons



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

Higgs itself

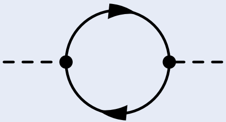


$$+\frac{1}{16\pi^2} \lambda^2 \Lambda^2 \sim +(0.5\,\mathrm{TeV})^2$$

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

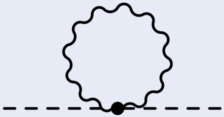
Supersymmetry

top quark



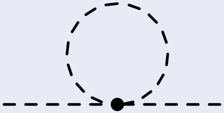
$\sim -(2\,\mathrm{TeV})^2$

vector bosons



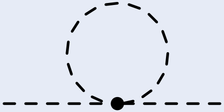
$\sim +(0.7\,\mathrm{TeV})^2$

Higgs itself



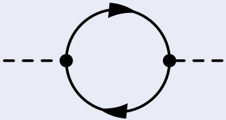
$\sim +(0.5\,\mathrm{TeV})^2$

stop quark



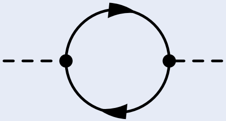
$\sim +(2\,\mathrm{TeV})^2$

bosinos



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

Higgsinos



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

2 Higgs doublets models for supersymmetry

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

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

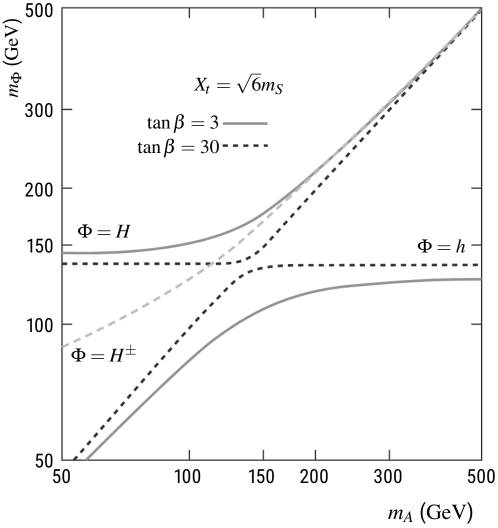
Minimal Supersymmetric extension of Standard Model

5 Higgs bosons

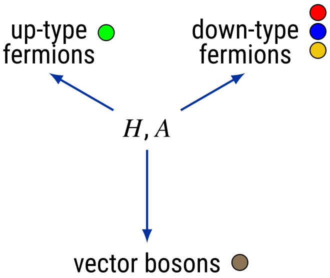
light scalar	h	SM or MSSM
heavy scalar	H	MSSM or SM
pseudo-scalar	A	MSSM
$+$ charged	H^+	MSSM
$-$ charged	H^-	MSSM

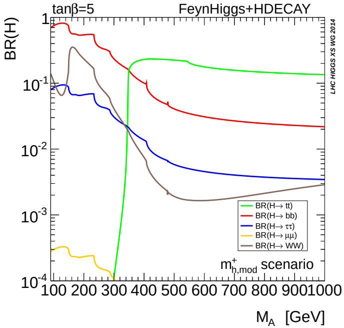
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

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



$H \to \tau\tau$?

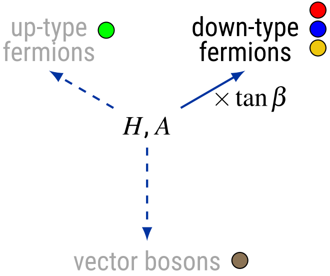


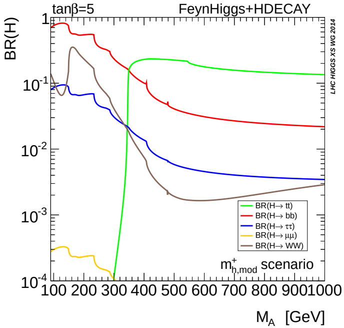


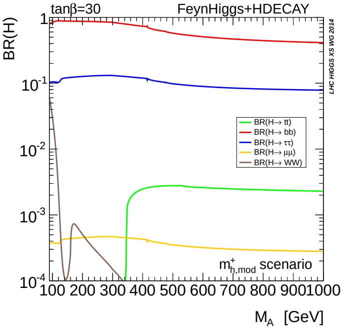
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: `10.1007/JHEP09(2018)007`.

▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections*. **3**. CERN Yellow Reports: Monographs. Geneva: CERN, 2013. DOI: `10.5170/CERN-2013-004`. URL: `https://cds.cern.ch/record/1559921`.

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



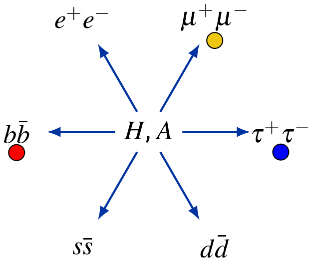


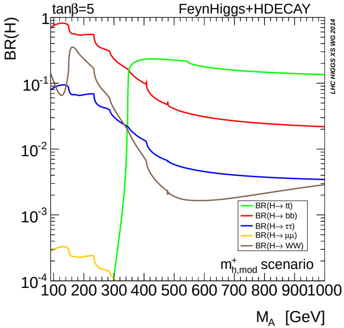


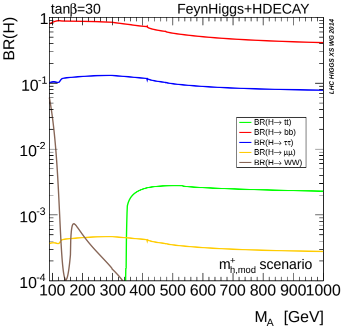
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

▷ LHC Higgs Cross Section Working Group. "Higgs Properties". *Handbook of LHC Higgs Cross Sections*. **3**. CERN Yellow Reports: Monographs. Geneva: CERN, 2013. DOI: 10.5170/CERN-2013-004. URL: https://cds.cern.ch/record/1559921.

$H \to \tau\tau$?



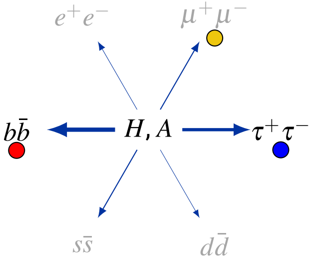


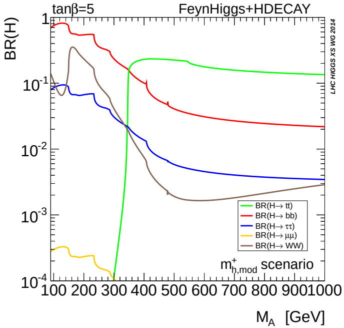


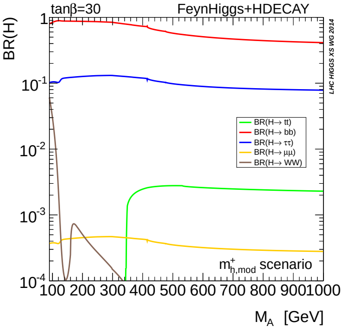
▷ The CMS Collaboration. “Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$”. *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

▷ LHC Higgs Cross Section Working Group. “Higgs Properties”. *Handbook of LHC Higgs Cross Sections*. **3**. CERN Yellow Reports: Monographs. Geneva: CERN, 2013. DOI: 10.5170/CERN-2013-004. URL: https://cds.cern.ch/record/1559921.

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







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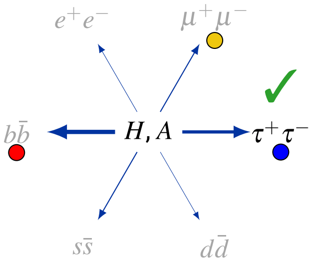
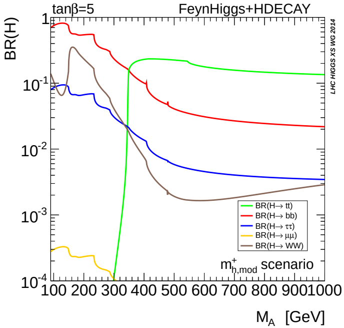
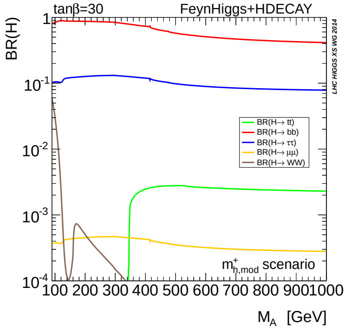
$H \to \tau\tau$? – avoid hadronic background







▷ 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.

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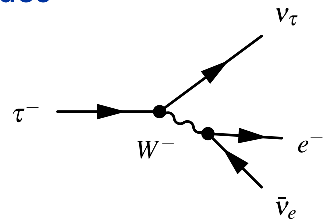
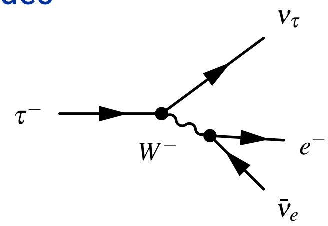
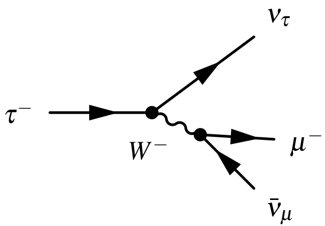
τ decay modes

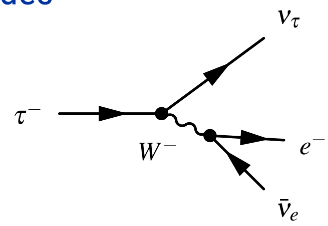


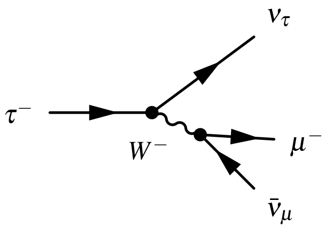
τ decay modes

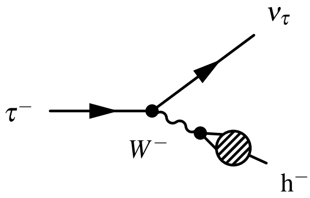


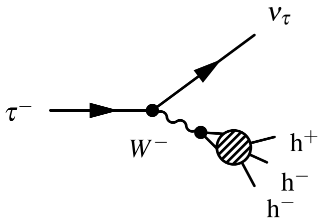


τ decay modes

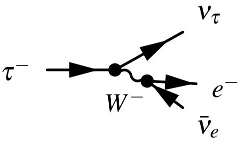






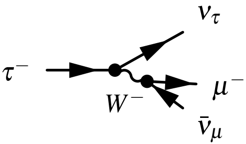


$H \to \tau\tau \to L_1 L_2$



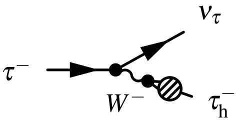
$$\tau \to e + \nu_e + \nu_\tau \Rightarrow e$$

17.8 %



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

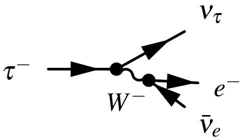
17.4 %



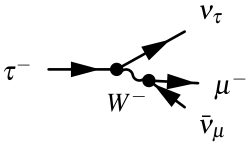
$$\tau \to \text{hadrons} + \nu_\tau \Rightarrow \tau_h$$

64.8 %

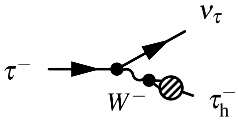
$H \to \tau\tau \to L_1 L_2$



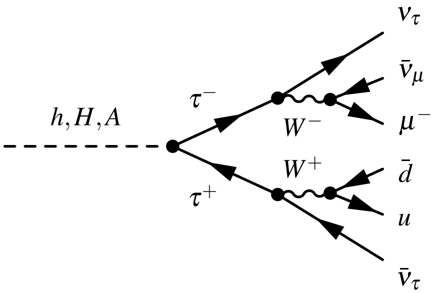
$\tau \to e + \nu_e + \nu_\tau \Rightarrow e$
17.8 %



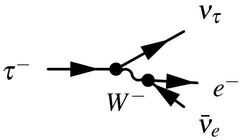
$\tau \to \mu + \nu_\mu + \nu_\tau \Rightarrow \mu$
17.4 %



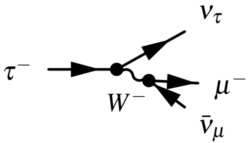
$\tau \to \text{hadrons} + \nu_\tau \Rightarrow \tau_h$
64.8 %



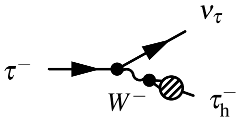
$H \to \tau\tau \to L_1 L_2$



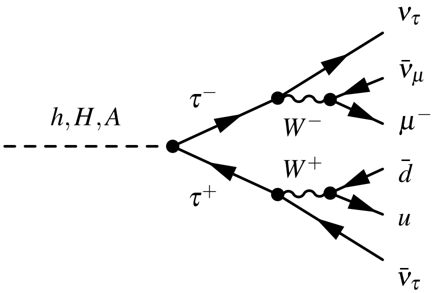
$$\tau \to e + \nu_e + \nu_\tau \Rightarrow e$$
17.8 %

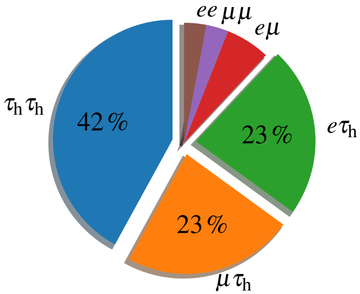


$$\tau \to \mu + \nu_\mu + \nu_\tau \Rightarrow \mu$$
17.4 %



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





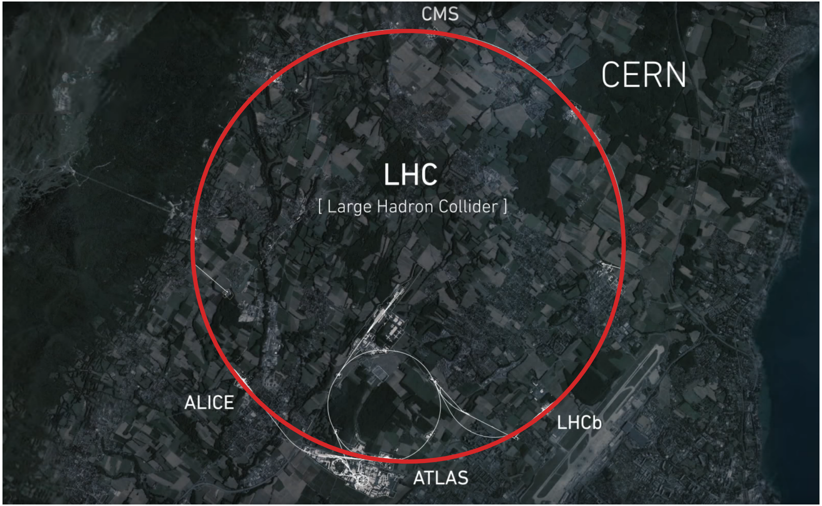
Principle

$$E = mc^2$$

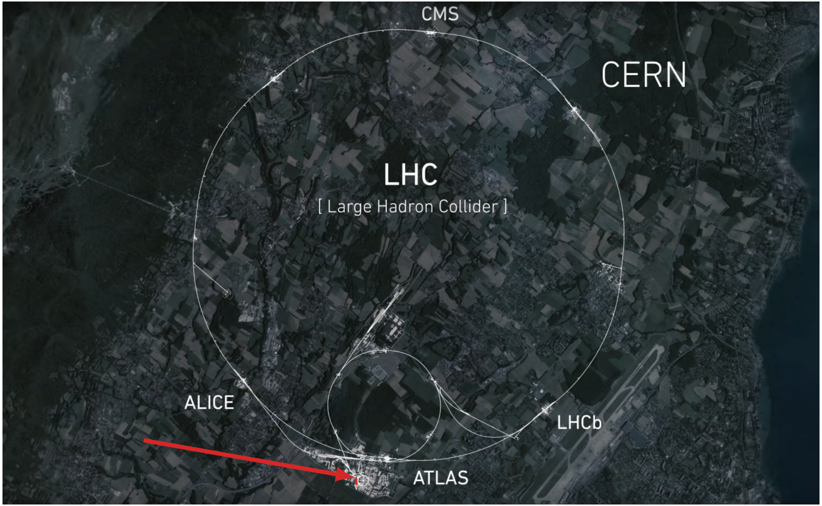
mass (new particles) from the collision energy

CERN & LHC

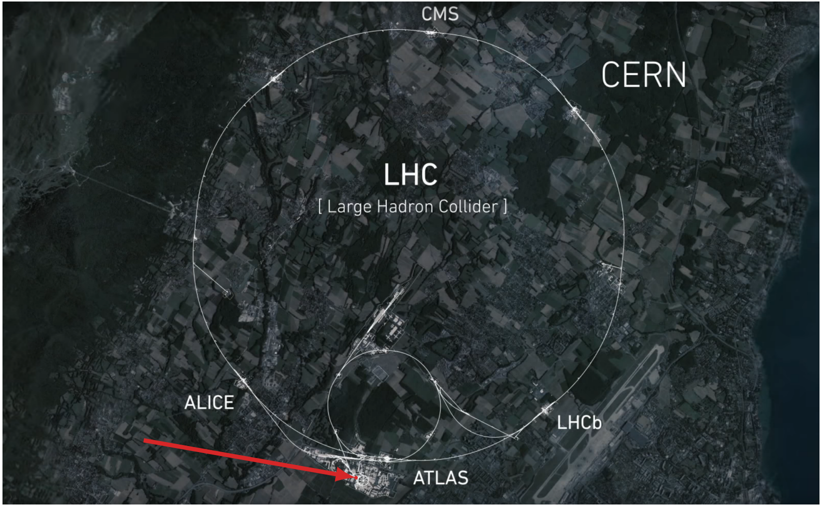
LHC



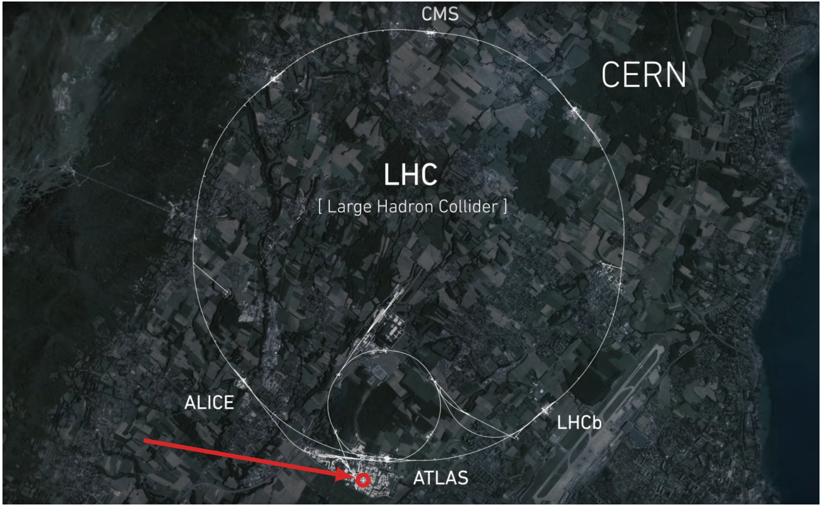
LINAC2 (50 MeV)



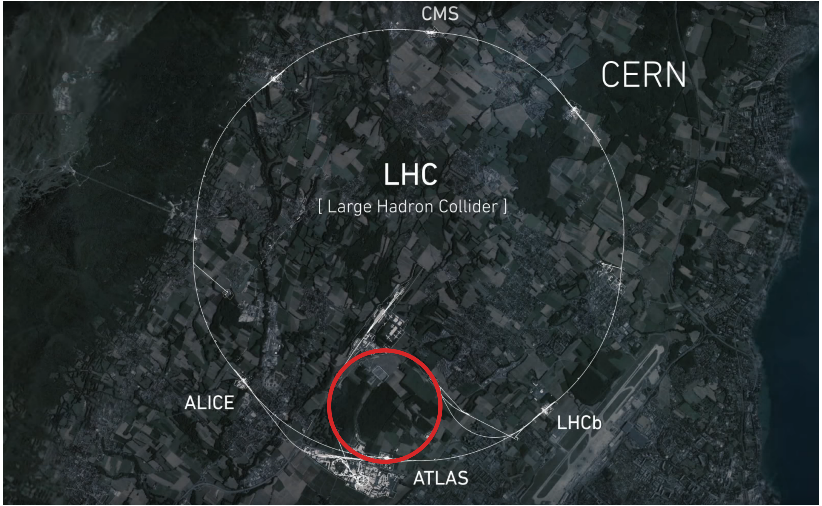
Booster (1972, $157\,\mathrm{m}$, $1.4\,\mathrm{GeV}$)



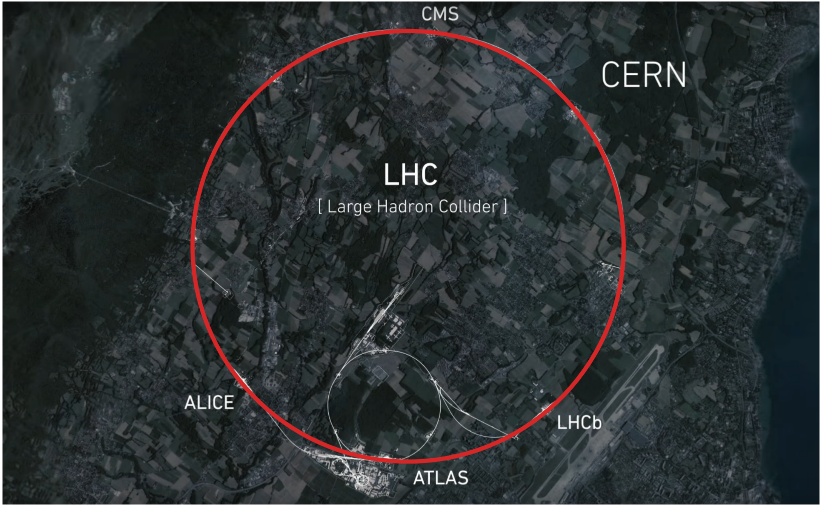
PS (1959, 628 m, 25 GeV)

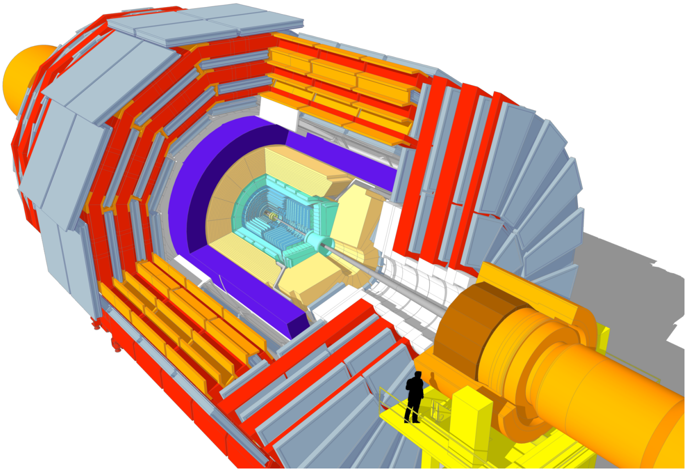


SPS (1976, 7 km, 450 GeV)



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

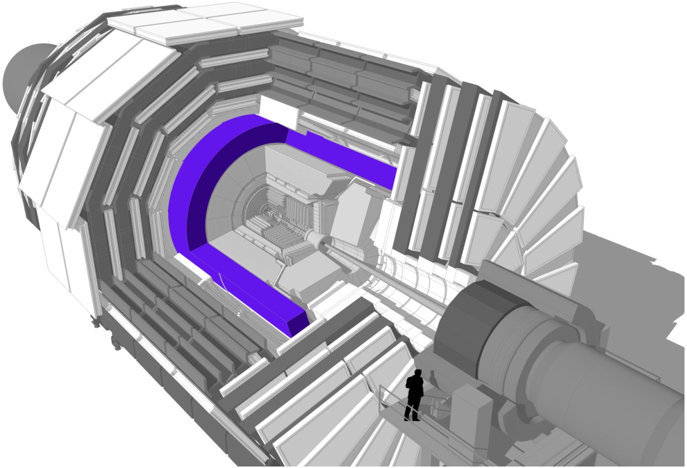




CMS detector

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

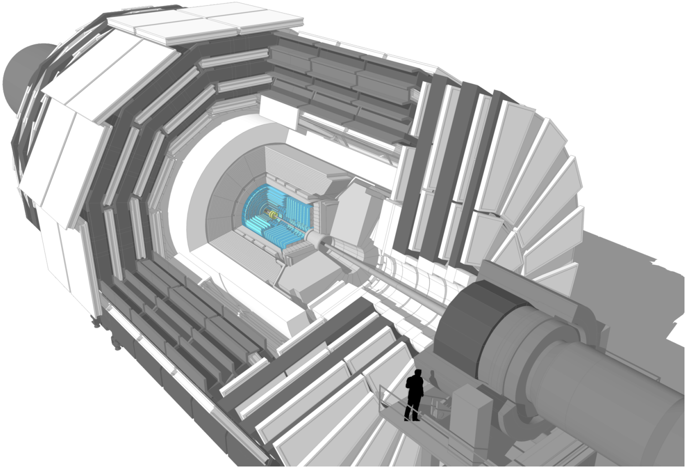
$\Rightarrow$ How to *see* the particles?



Solenoid

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

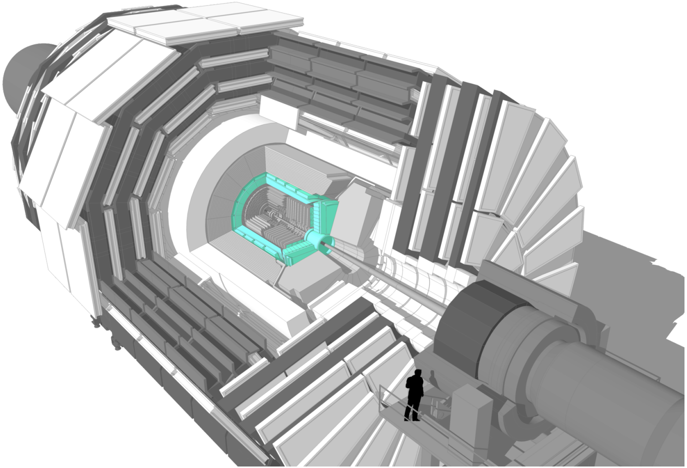
$\Rightarrow$ Bends charged particles trajectories in the transverse plane



Tracker

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

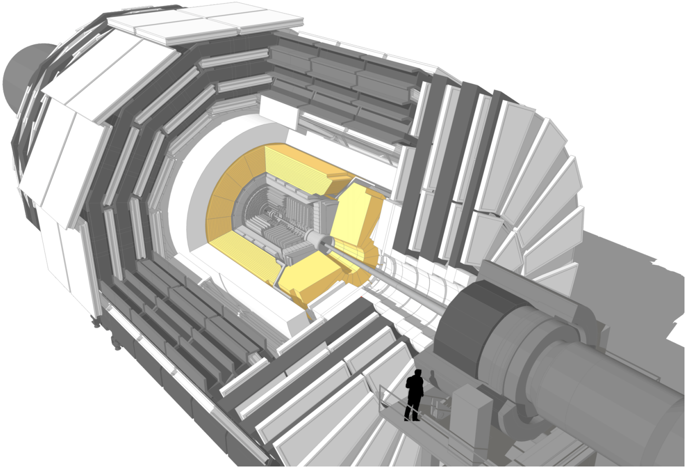
$\Rightarrow$ Charged particles leave hits when going through



Electromagnetic CALorimeter

- $\sim 76{,}000$ scintillating $\mathrm{PbWO_4}$ crystals

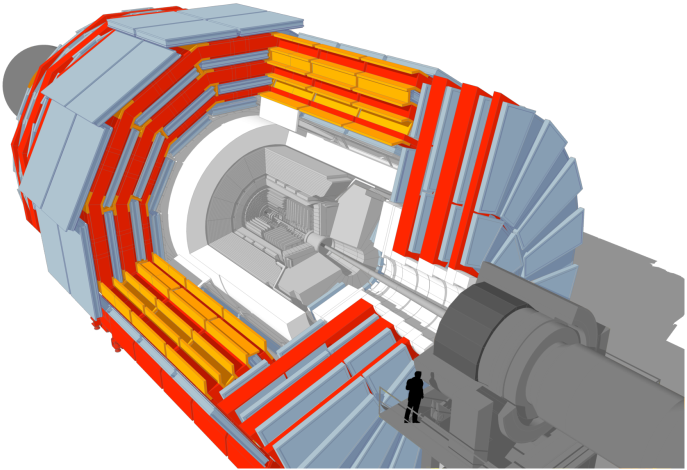
$\Rightarrow$ Electrons and photons are stopped, energy deposits



Hadronic CALorimeter

- Brass + plastic scintillator, ~ 7000 channels

$\Rightarrow$ Hadrons are stopped, energy deposits



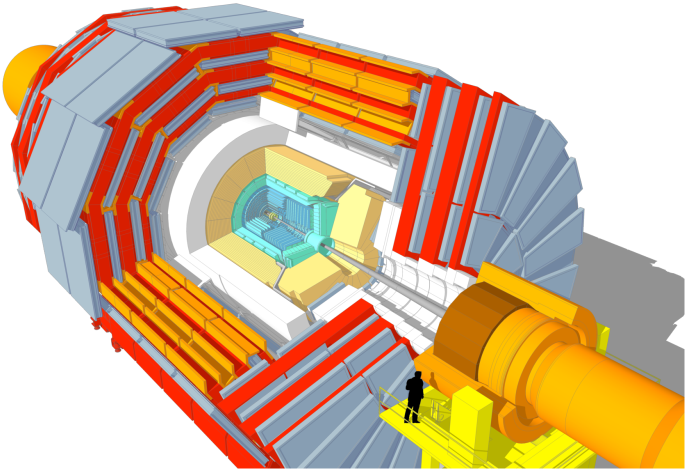
Steel return yoke (red)

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

Muon chambers (blue-gray)

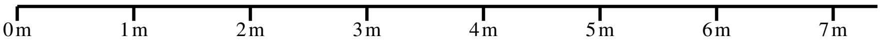
- Barrel: 250 drift tubes, 480 resistive plate chambers
- Endcaps: 540 cathode strips, 576 resistive plate chambers

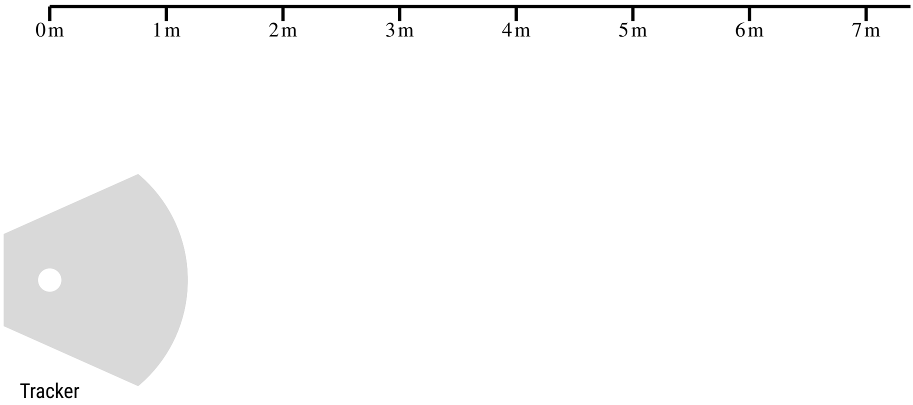
$\Rightarrow$ Charged particles leave hits when going through (only muons do)

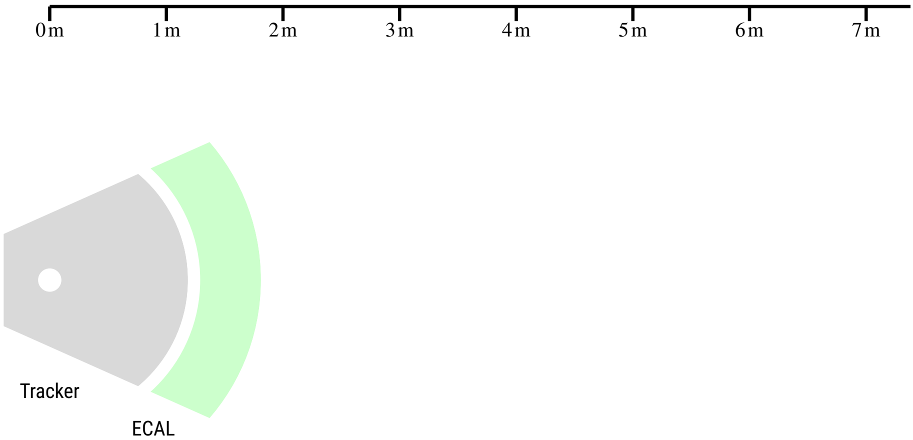


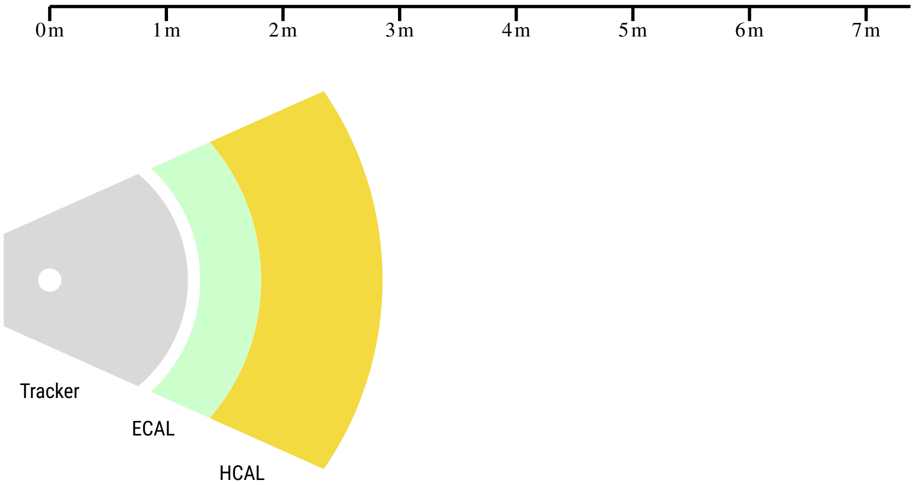
Sensitive parts of CMS

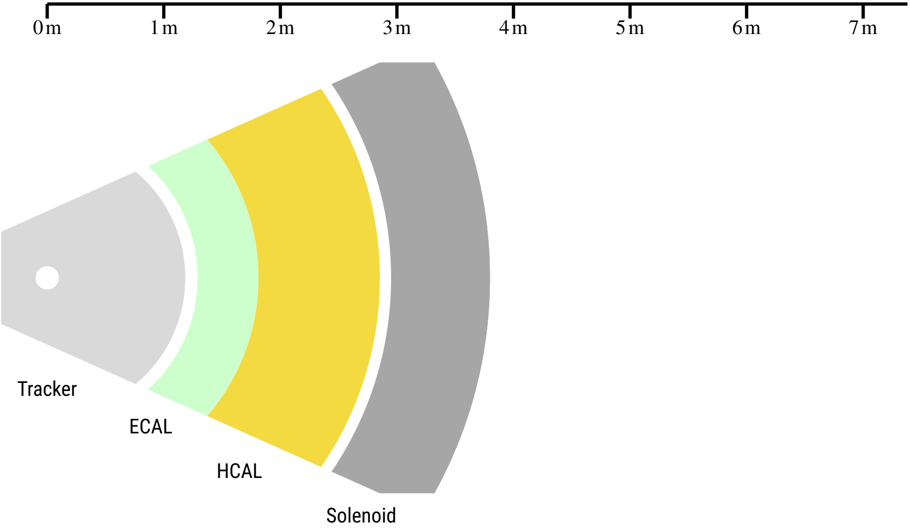
Combine sub-detectors signals to determine which particles were there!

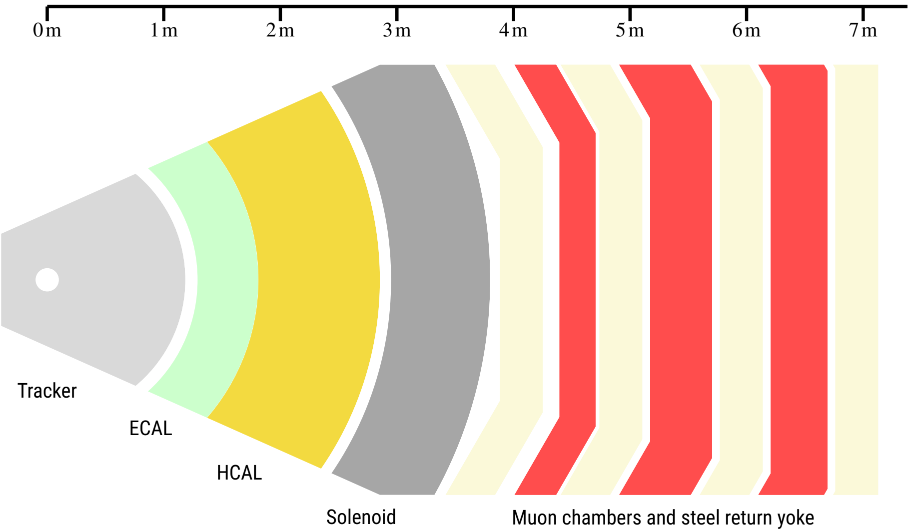

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m

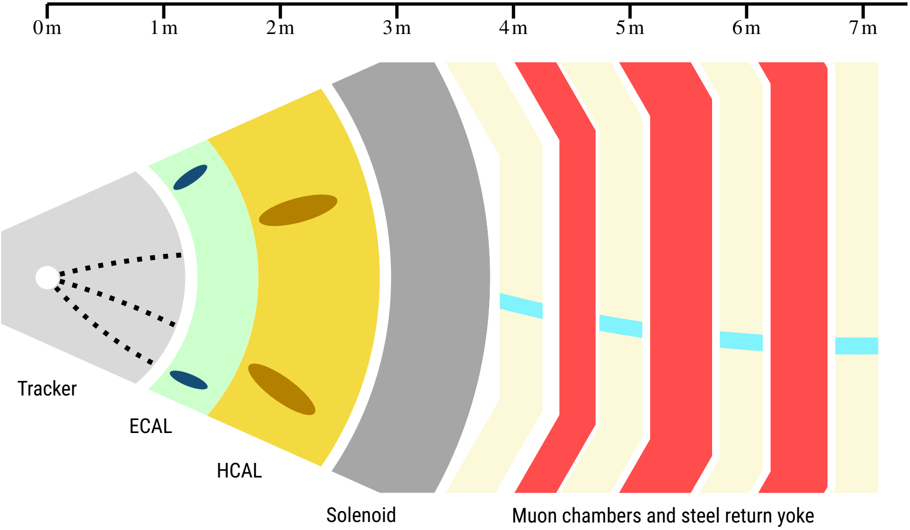

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker


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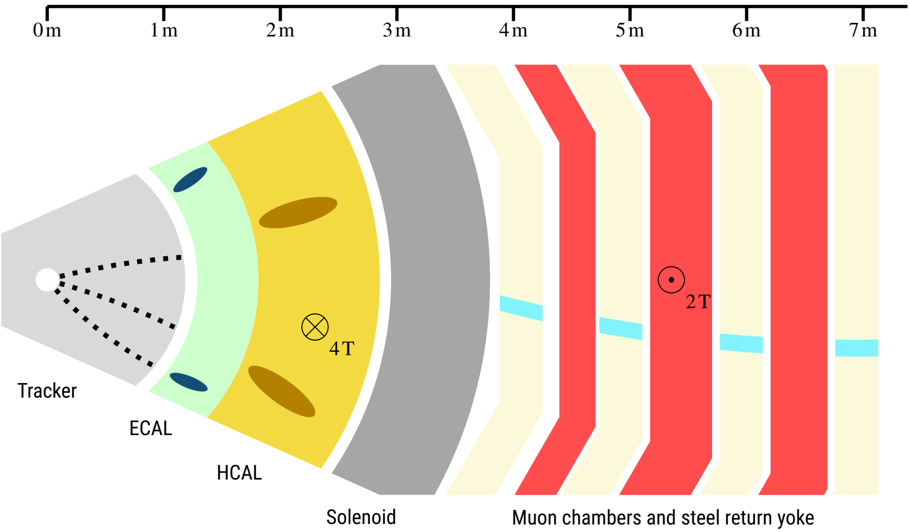
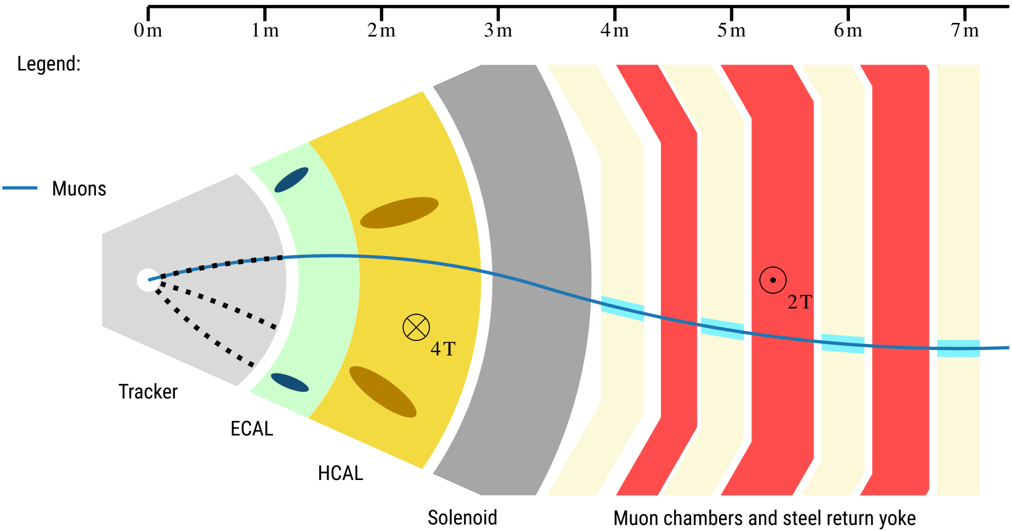
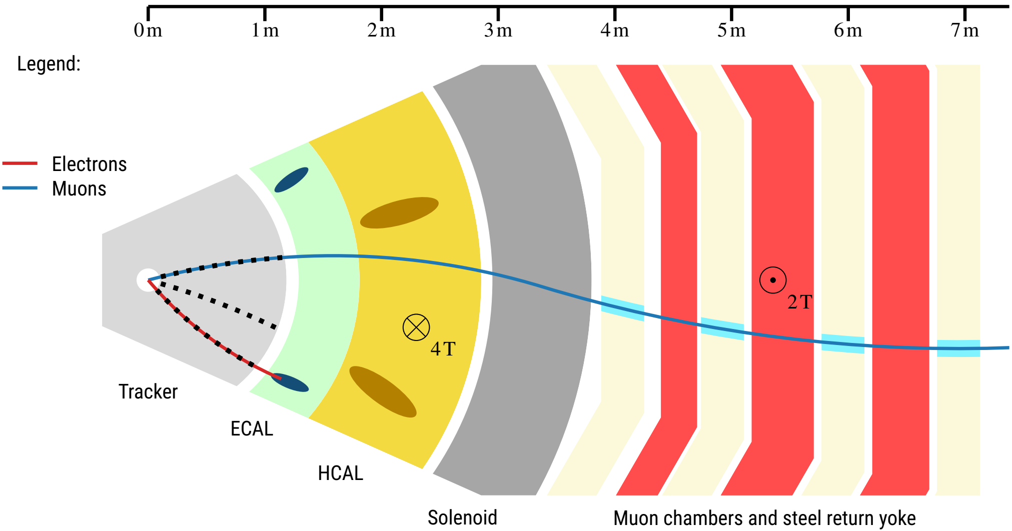
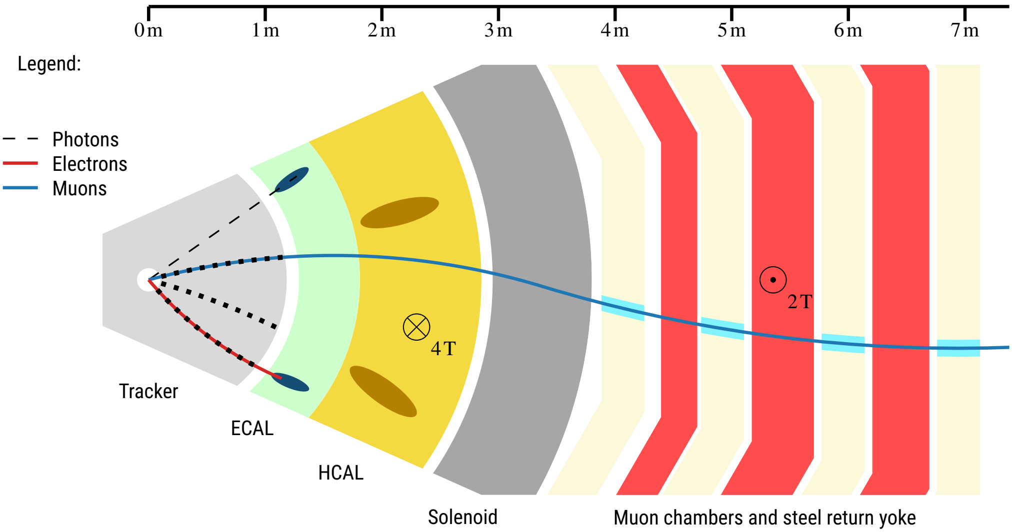
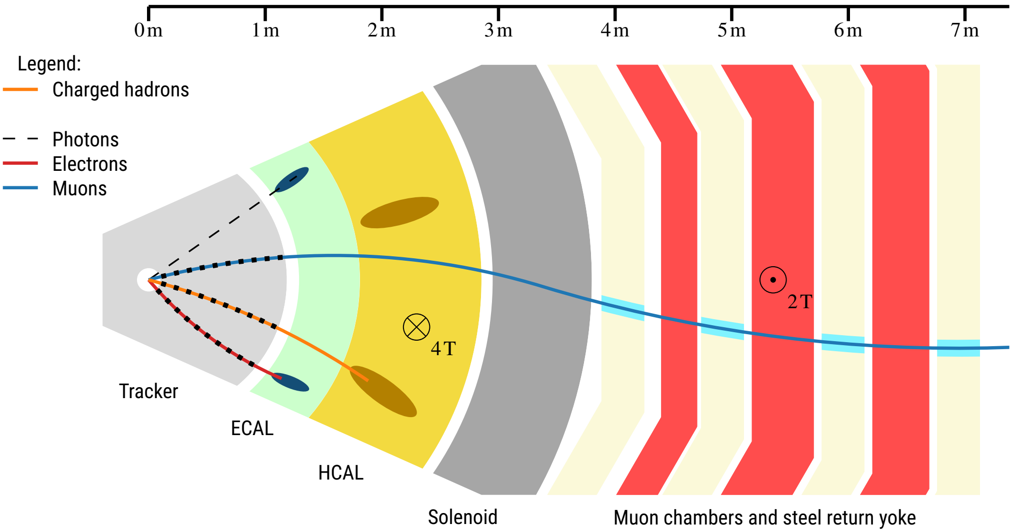
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

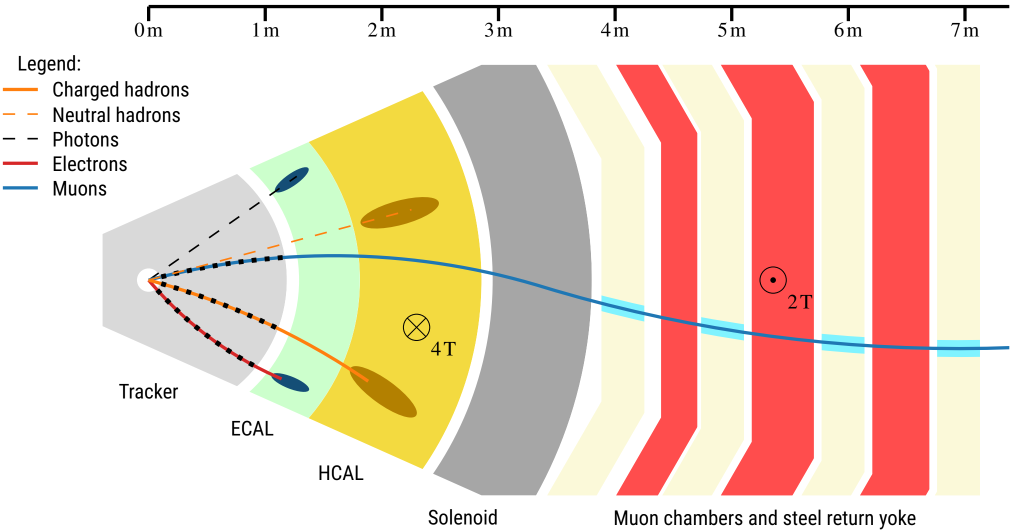

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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

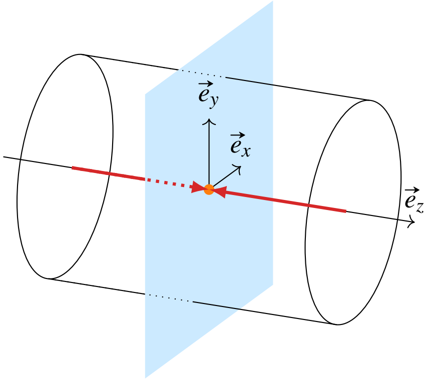

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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

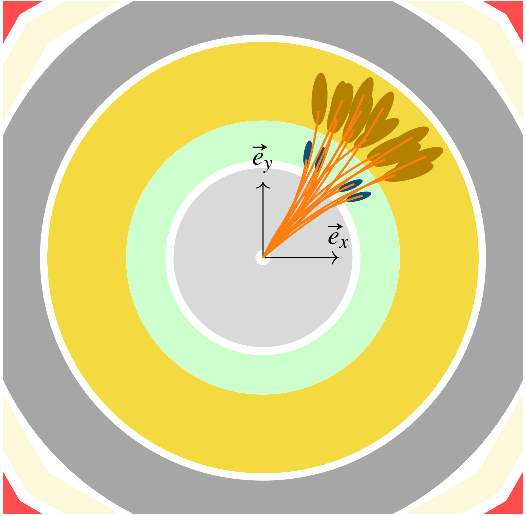

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Charged hadrons
Neutral hadrons
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

Neutrinos and missing transverse energy (MET)

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

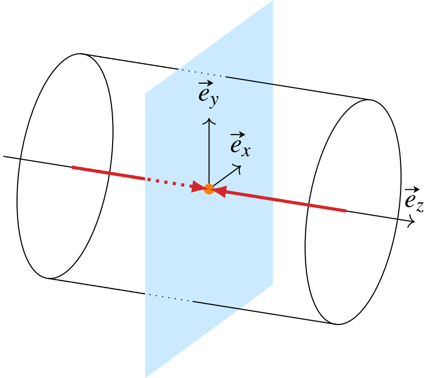


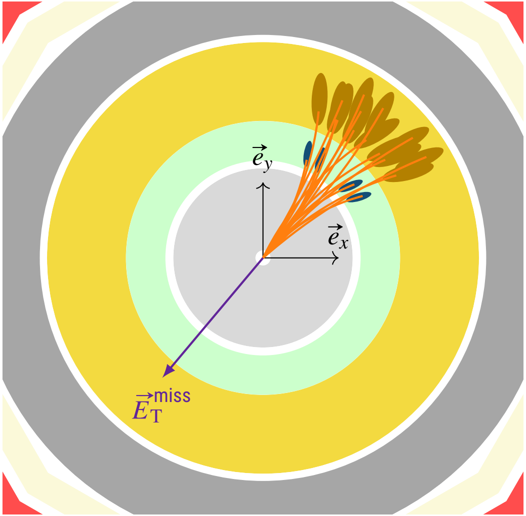
Conserved momentum: $\sum_{\text{initial state}} \vec{p}_\mathrm{T} = \sum_{\text{final state}} \vec{p}_\mathrm{T} = \vec{0}$



Neutrinos and missing transverse energy (MET)

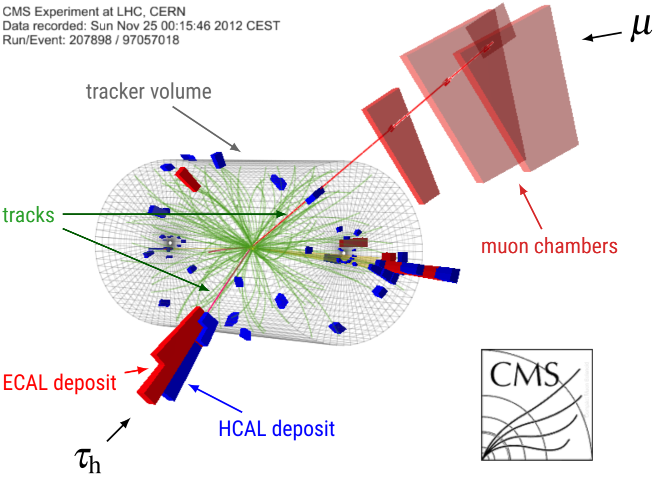
$(\vec{e}_x, \vec{e}_y)$ = transverse plane ($\eta = 0$)





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

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



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.

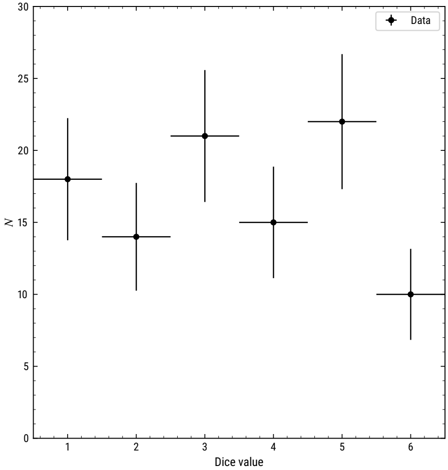
The rabbit analogy

- 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 $\longrightarrow$

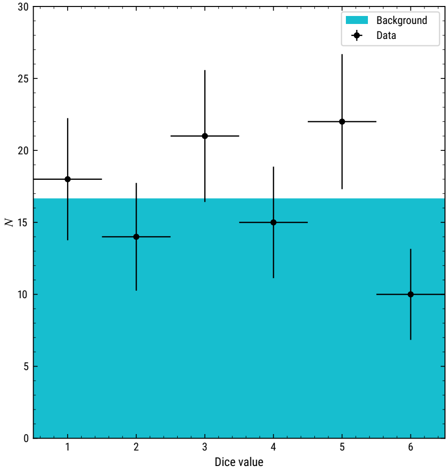


Not really conclusive...

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

The rabbit analogy

On 100 days $\longrightarrow$

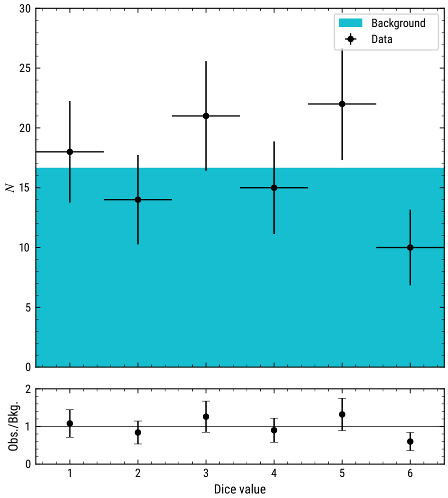


Comparing with predictions!

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

The rabbit analogy

On 100 days $\longrightarrow$

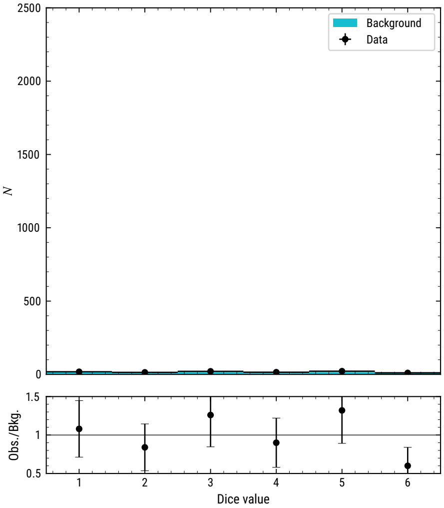


Also add ratio plot: observed / predictions

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

The rabbit analogy

On 100 days $\longrightarrow$

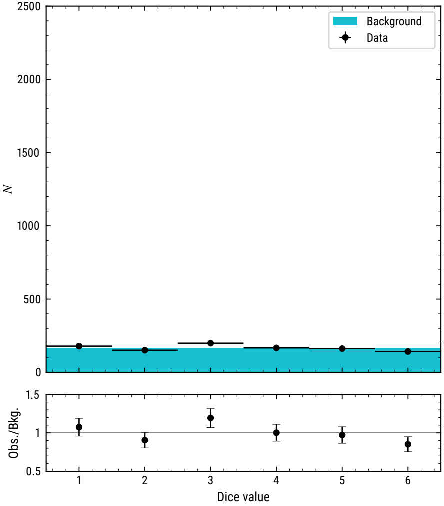


Fill up with more data!

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

The rabbit analogy

On 1000 days $\longrightarrow$

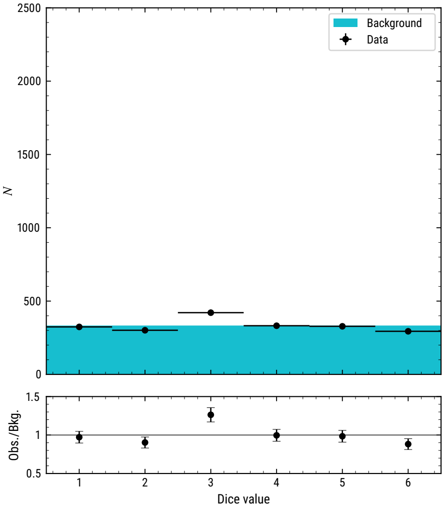


Fill up with more data!

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

The rabbit analogy

On 2000 days $\longrightarrow$

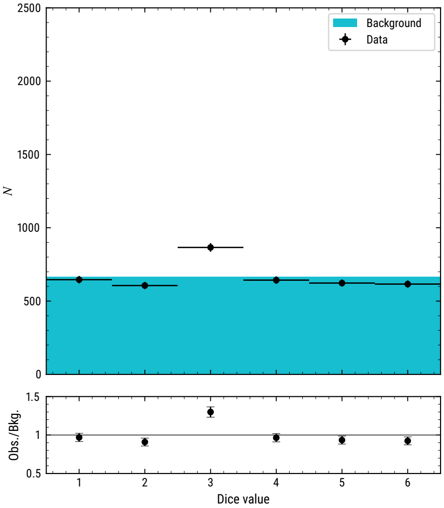


Fill up with more data!

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

The rabbit analogy

On 4000 days $\longrightarrow$

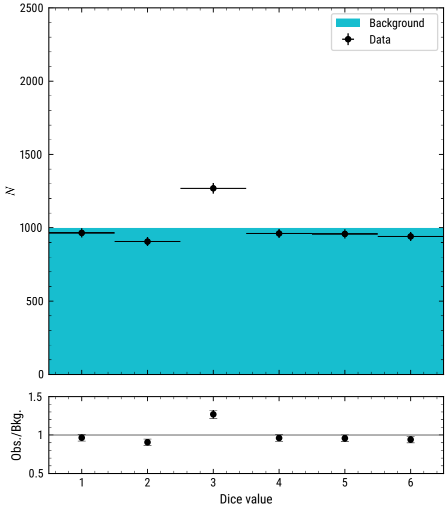


Fill up with more data!

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

The rabbit analogy

On 6000 days $\longrightarrow$

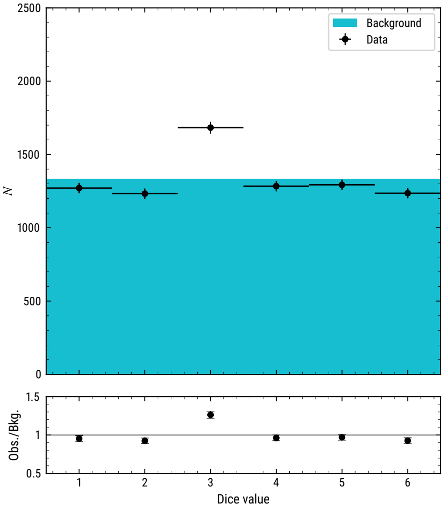


Fill up with more data!

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

The rabbit analogy

On 8000 days $\longrightarrow$

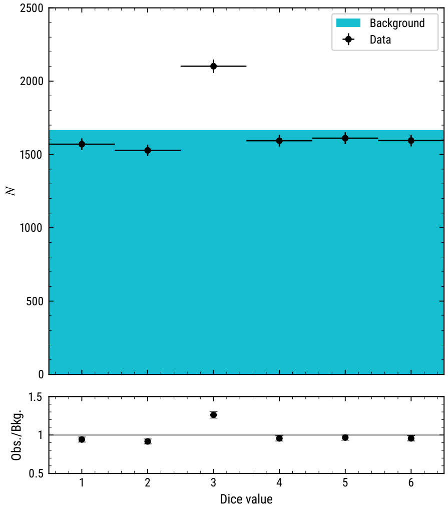


Fill up with more data!

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

The rabbit analogy

On 10,000 days $\longrightarrow$

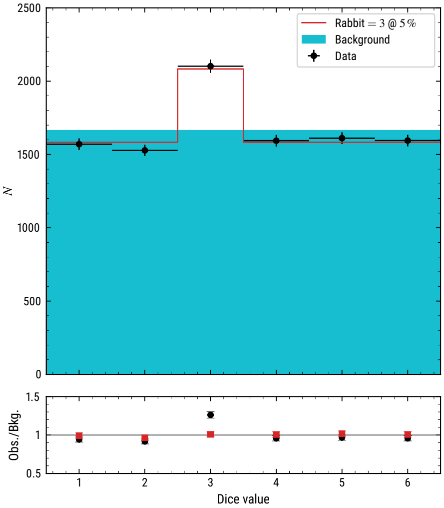


Fill up with more data!

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

The rabbit analogy

On 10,000 days $\longrightarrow$

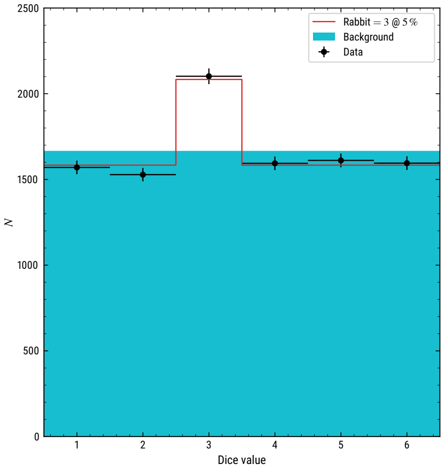


In red, hypothesis of the rabbit with 3 as preferred result (instead of 4!), with a probability to show up of $5\,\%$.

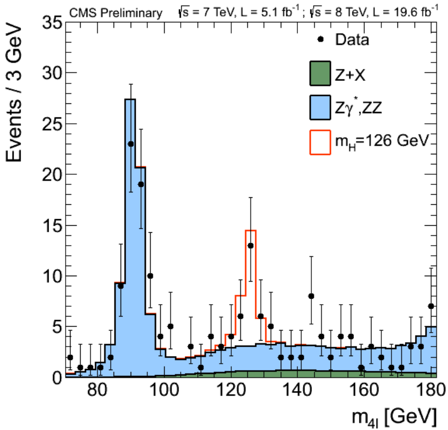
▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: https://www.youtube.com/watch?v=8-WFBGCvv-w.

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. URL: http://www.sciencedirect.com/science/article/pii/S0370269312008581.

▷ 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 $8\,\mathrm{TeV}$.* URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki.

Datasets

Observed data (MiniAOD)

- $\tau_h\tau_h$
  - /Tau/Run2016[B-H]
  - /Tau/Run2017[B-F]
  - /Tau/Run2018[A-D]
- $e\mu$
  - /MuonEG/Run2016[B-H]
  - /MuonEG/Run2017[B-F]
  - /MuonEG/Run2018[A-D]
- $\mu\tau_h$
  - /SingleMuon/Run2016[B-H]
  - /SingleMuon/Run2017[B-F]
  - /SingleMuon/Run2018[A-D]
- $e\tau_h$
  - /SingleElectron/Run2016[B-H]
  - /SingleElectron/Run2017[B-F]
  - /EGamma/Run2018[A-D]

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

Datasets

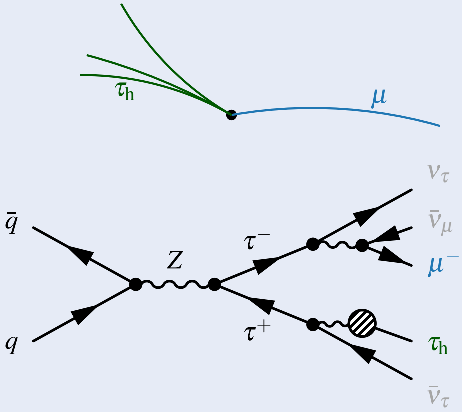
Simulated signals (MiniAODSIM)

- SM Higgs signals
  - /GluGluHToTauTau_M125_13TeV_powheg_pythia8
  - /VBFHToTauTau_M125_13TeV_powheg_pythia8
  - /WplusHToTauTau_M125_13TeV_powheg_pythia8
  - /WminusHToTauTau_M125_13TeV_powheg_pythia8
  - /ggZH_HToTauTau_ZToLL_M125_13TeV_powheg_pythia8
  - /ggZH_HToTauTau_ZToNuNu_M125_13TeV_powheg_pythia8
  - /ggZH_HToTauTau_ZToQQ_M125_13TeV_powheg_pythia8
- MSSM signals
  - /SUSYGluGluToHToTauTau_M-*_TuneCUETP8M1_13TeV-pythia8
  - /SUSYGluGluToBBHToTauTau_M-*_TuneCUETP8M1_13TeV-amcatnlo-pythia8

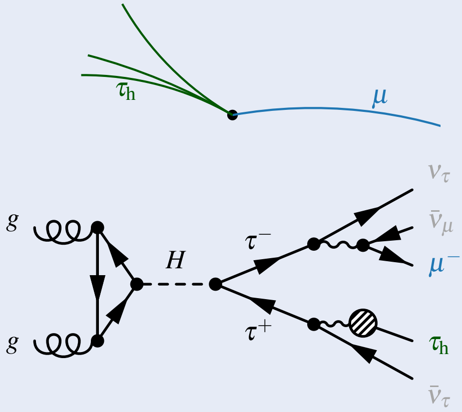
Backgrounds?

Backgrounds: Drell-Yan

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

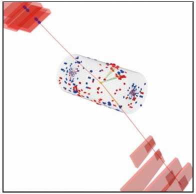


$H \to \tau\tau \to \mu\tau_h$



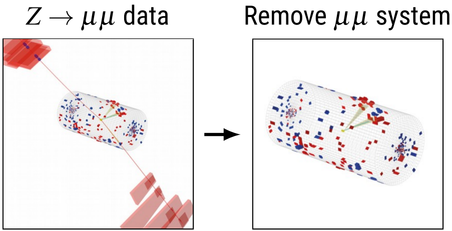
Embedded events

$Z \to \mu\mu$ 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



▷ 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

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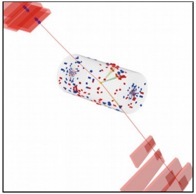
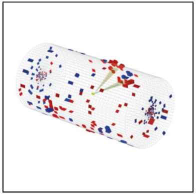
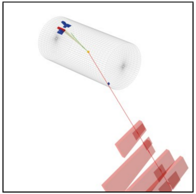


Remove $\mu\mu$ system



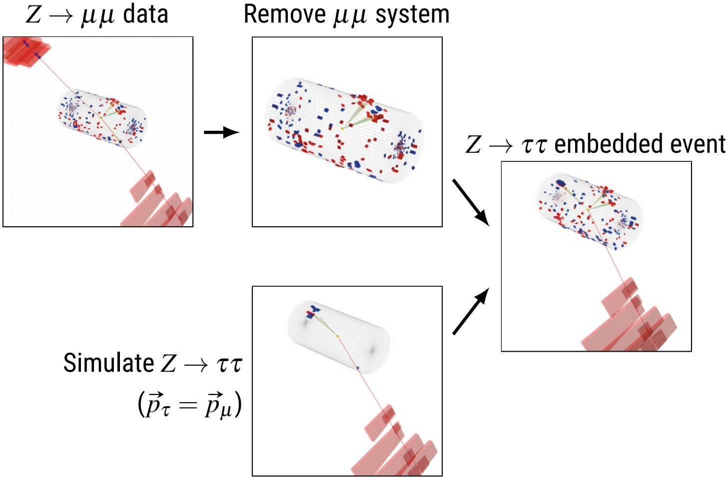
Simulate $Z \to \tau\tau$

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



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

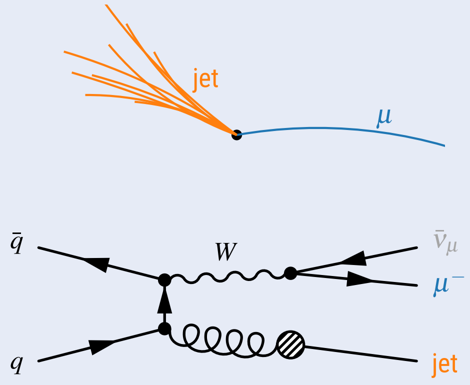
Embedded events



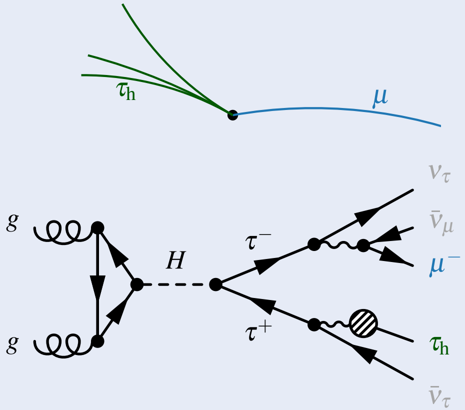
▷ The CMS Collaboration. “An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data”. *Journal of Instrumentation* **14**.06 (June 2019). DOI: 10.1088/1748-0221/14/06/p06032.

Backgrounds: $W +$ jets

$W +$ jets

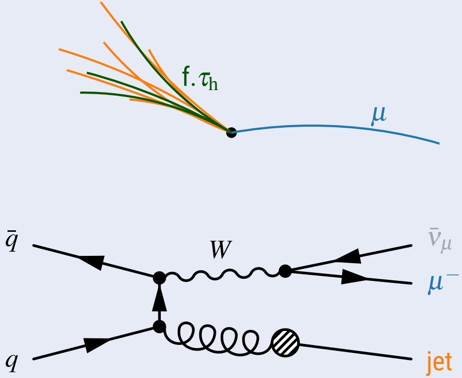


$H \to \tau\tau \to \mu\tau_h$

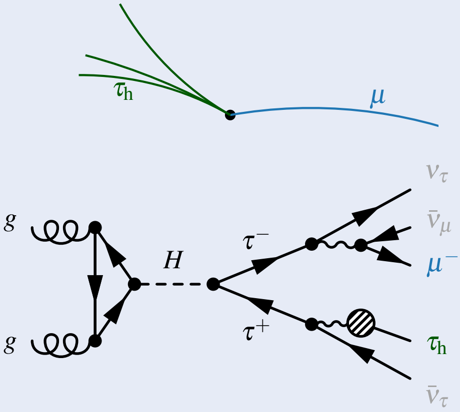


Backgrounds: $W+$jets

$W+$jets, jet $\to$ fake τ_h

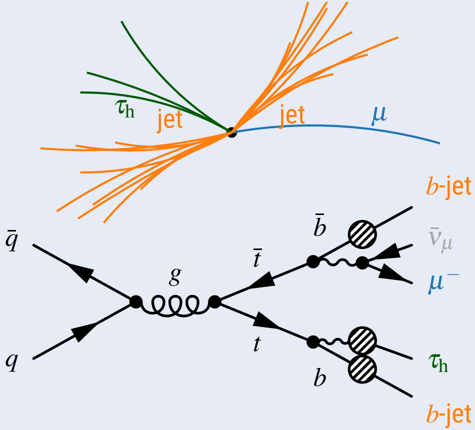


$H \to \tau\tau \to \mu\tau_\mathrm{h}$

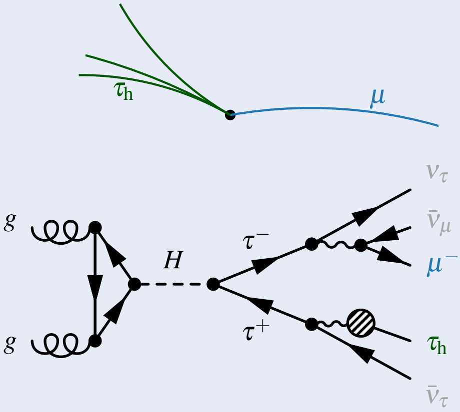


Backgrounds: $t\bar{t}$

$t\bar{t}$

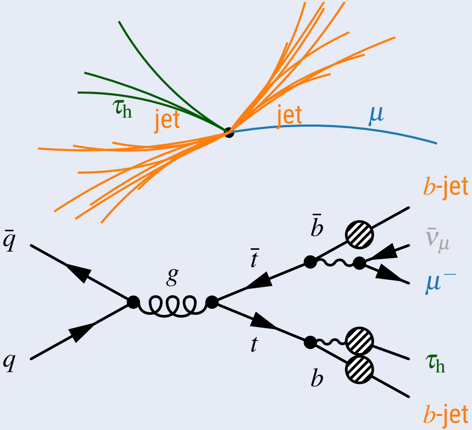


$H \to \tau\tau \to \mu\tau_h$

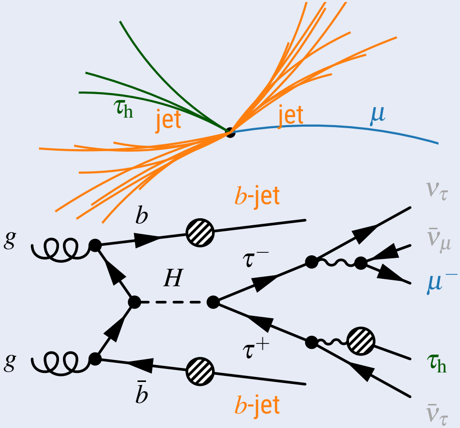


Backgrounds: $t\bar{t}$

$t\bar{t}$

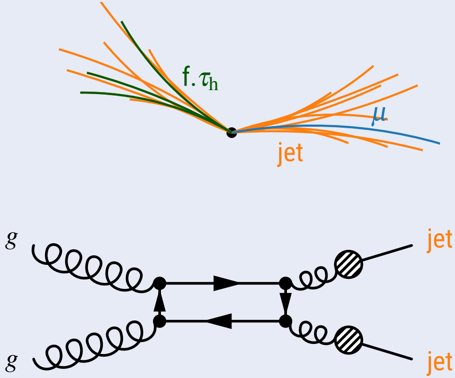


H production with b-jets

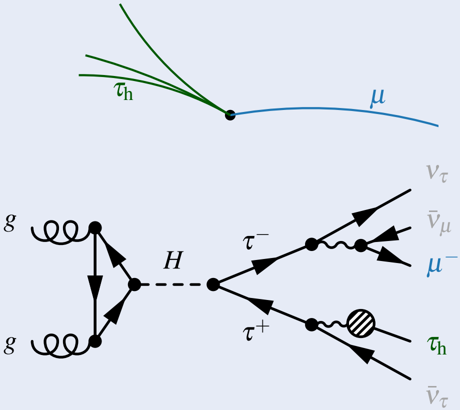


Backgrounds: QCD

QCD

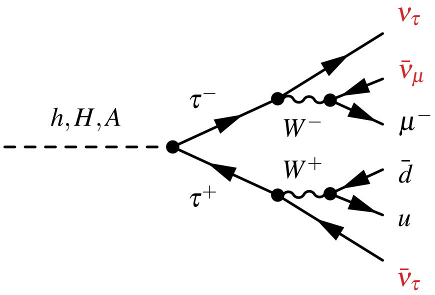


$H \to \tau\tau \to \mu\tau_h$



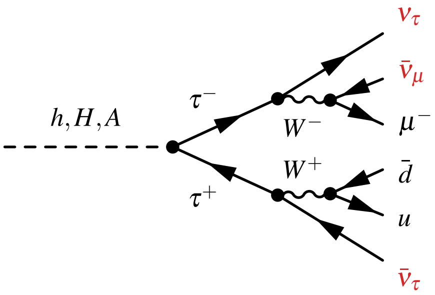
Discriminant variable?

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

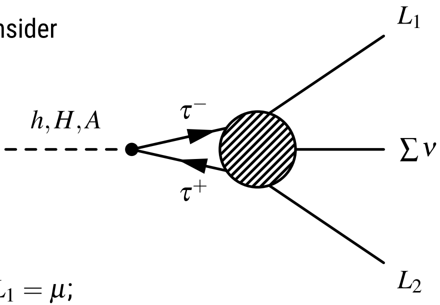


Discriminant variable?

- $E_{\mathrm{T}}^{\text{miss}}$ due to neutrinos.
  - No invariant mass!



- Consider



where

- $L_1 = \mu$;
- $L_2 = u\bar{d} \to \tau_{\mathrm{h}}$;
- $\sum \nu \simeq E_{\mathrm{T}}^{\text{miss}}$;

with respect to the left side.

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

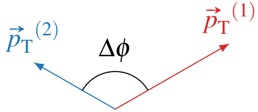
- For L_1, L_2 and $E_{\mathrm{T}}{}^{\text{miss}}$ system,
  - in the transverse plane (use $E_{\mathrm{T}}{}^{\text{miss}}$),
  - for $E_i \gg m_i$ (highly relativistic case),

deriving the "invariant" mass would then lead to

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

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

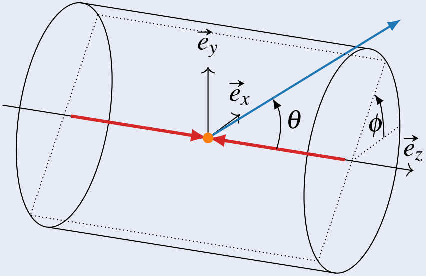
$$m_{\mathrm{T}}(1,2) = \sqrt{2 p_T^{(1)} p_T^{(2)} (1 - \cos\Delta\phi)}$$



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

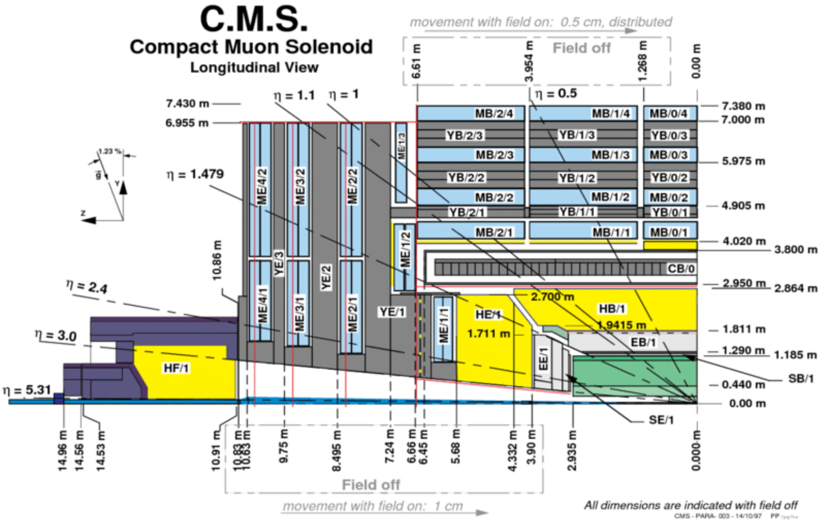
μ and τ_h candidates

- $L_1 = \mu$
  - $p_T > 21\,\mathrm{GeV}$, $|\eta| < 2.1$
  - $d_z < 0.2\,\mathrm{cm}$, $d_{xy} < 0.045\,\mathrm{cm}$
  - relative isolation < 0.15
  - medium `muonID`
- $L_2 = \tau_h$
  - $p_T > 30\,\mathrm{GeV}$, $|\eta| < 2.3$
  - $d_z < 0.2\,\mathrm{cm}$
  - relative isolation < 0.15
  - NewDecayModeFinding (modes 5 to 9 vetoed)
  - deepTau anti-electron (VVL WP)
  - deepTau anti-muon (tight WP)
  - deepTau vs jet (medium WP)

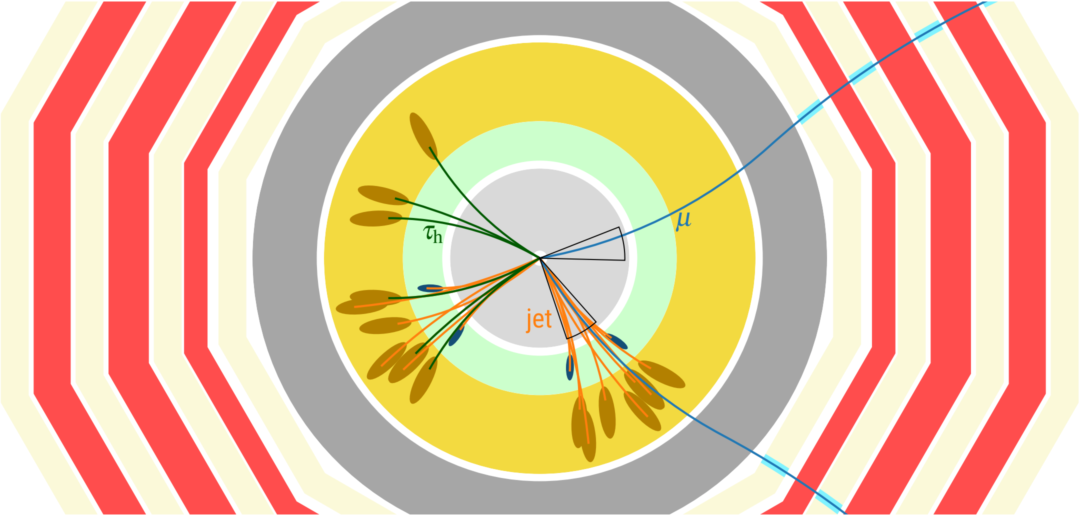


$$\eta = -\ln\tan\frac{\theta}{2}$$

Values of η and trajectories in CMS



Particles isolation – qualitatively

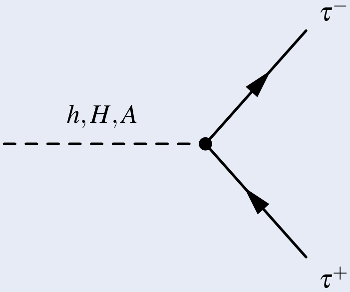


Signal region (SR) – 2017 $\mu\tau_h$ channel as example

Obtaining *dileptons* candidates

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

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



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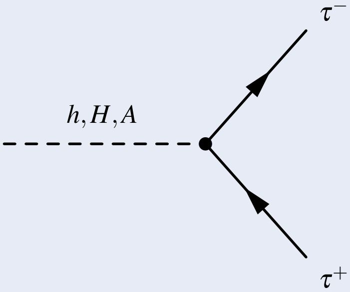

Selecting one dilepton

Choose by:

most isolated L_1, highest $p_T^{L_1}$, most isolated L_2, highest $p_T^{L_2}$.

Signal region (SR) – 2017 $\mu\tau_{\mathrm{h}}$ channel as example

Extra leptons: reject events containing

- electron with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $|\eta| < 2.4$, $90\,\%$ eff. WP of the `electronID` MVA, rel. iso < 0.3
- second muon with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $|\eta| < 2.4$, medium `muonID`, rel. iso < 0.3
- opposite-charge muon pair ($\mu\mu$ channel overlapping)

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

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Transverse mass

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

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).

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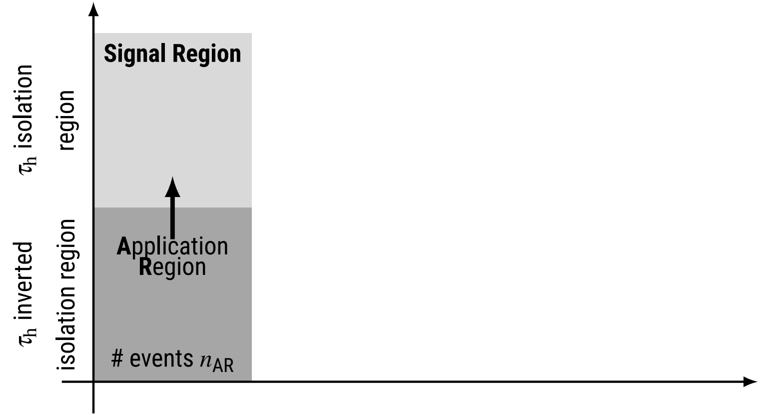

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The FF method: determination regions definitions

$t\bar{t}$ + jets

Estimation from simulated samples, same selection as in SR.

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The FF method: determination regions definitions

$t\bar{t}$ + jets

Estimation from simulated samples, same selection as in SR.

W + jets

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).

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The FF method: determination regions definitions

$t\bar{t} + \text{jets}$

Estimation from simulated samples, same selection as in SR.

$W + \text{jets}$

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).

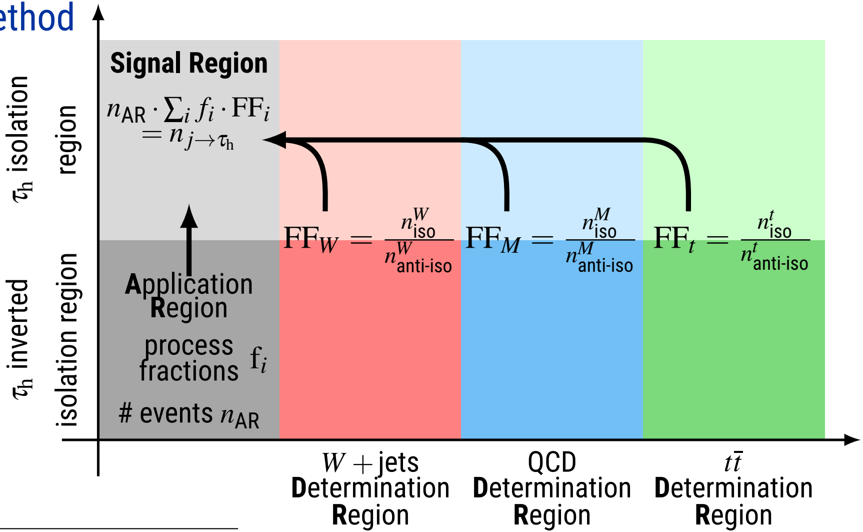
QCD multijet

Same as SR, except:

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

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

The FF method



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

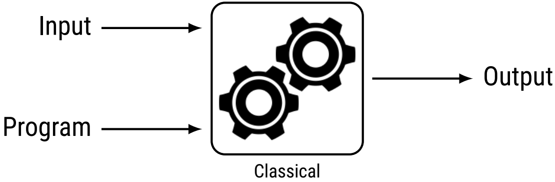
$m_{\mathrm{T}}^{\mathrm{tot}}$ distributions

Exclusion limits

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

Model-dependant limits

What is *Machine Learning*? – A brief introduction



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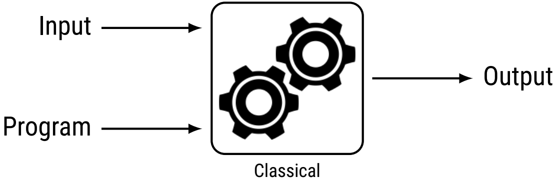

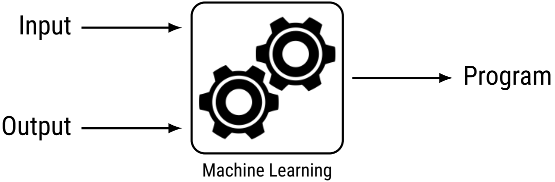

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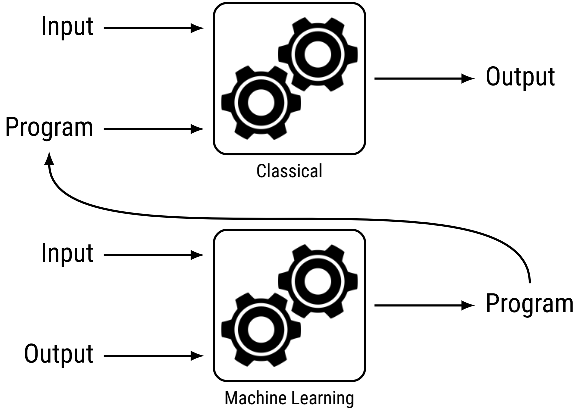

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Aim: find a function (program) mapping features (input) to a target (output)

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- Categorical target ⇒ Classification

e.g. cat or dog on the image

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

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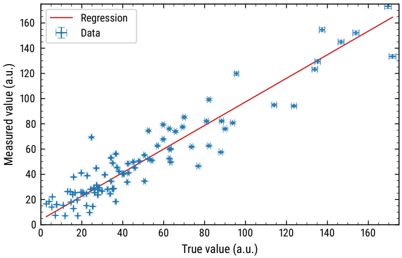
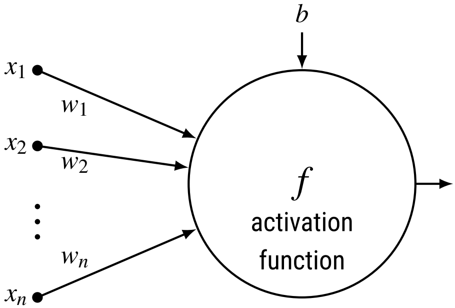
- Continuous target ⇒ Regression
e.g. discriminating variable!
Linear case:



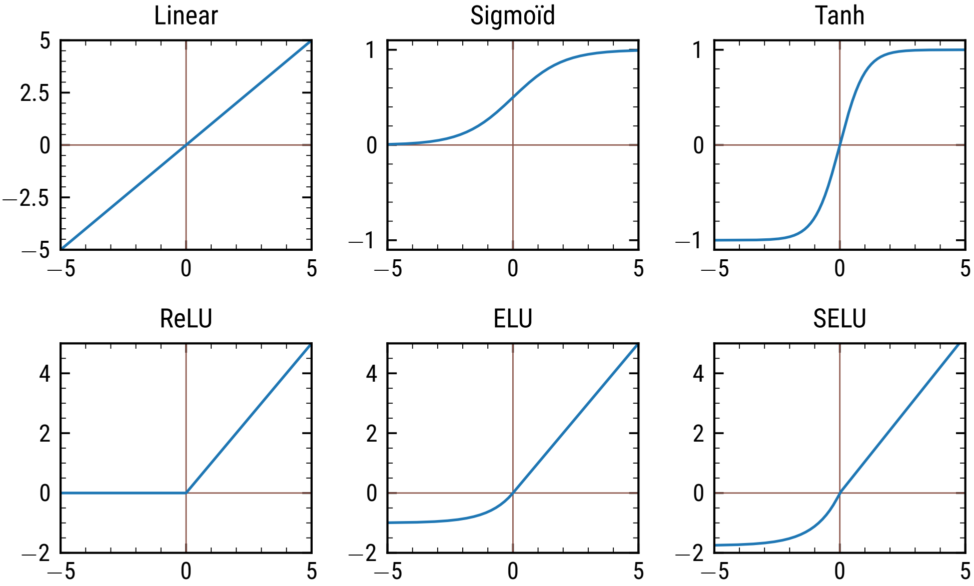
What if the target is not linear wrt. input?

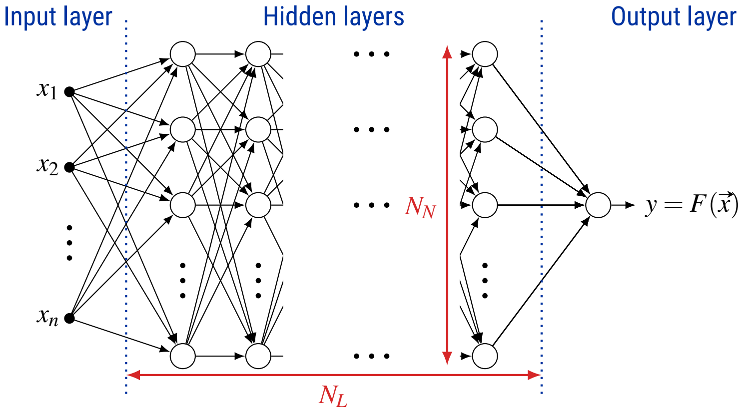
Neurons in ML



$$\text{Output} = f\left(\sum_{i=1}^{n} w_i x_i + b\right)$$

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


Linear
Sigmoïd
Tanh
ReLU
ELU
SELU



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

Grid search: hyperparameters

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

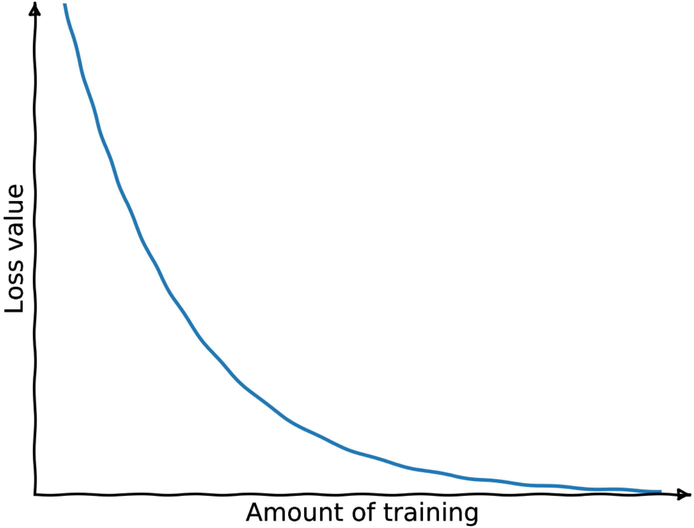
+ different sets of input variables

How to train a neural network?

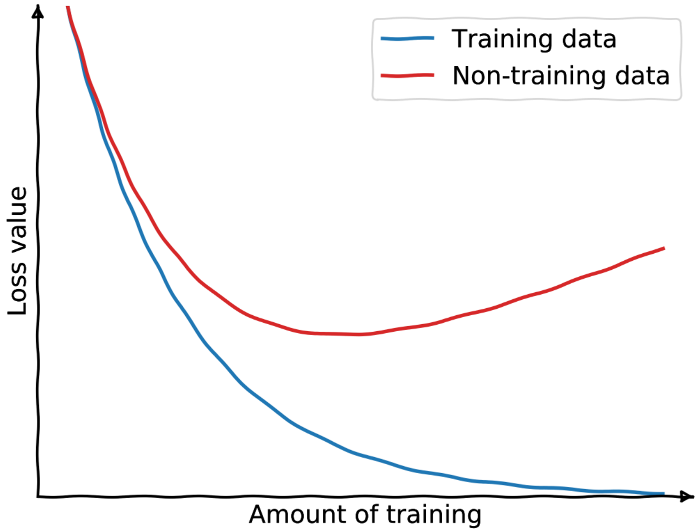
Train = optimize parameters $(w_1, w_2, \dots, w_n, b)$ for each neuron.

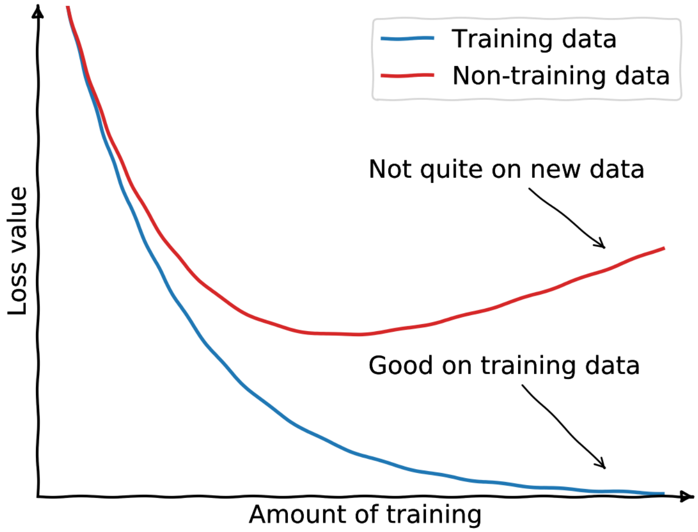
- Get a **training dataset** = examples of inputs $\vec{x}_i$ with corresponding outputs y_i
- Compare the model predictions $F(\vec{x}_i)$ to the true values y_i
  - Define a **loss function** L such that its minimum is reached when $F(\vec{x}_i) = y_i$
  - Change the parameters a bit, aiming at minimizing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

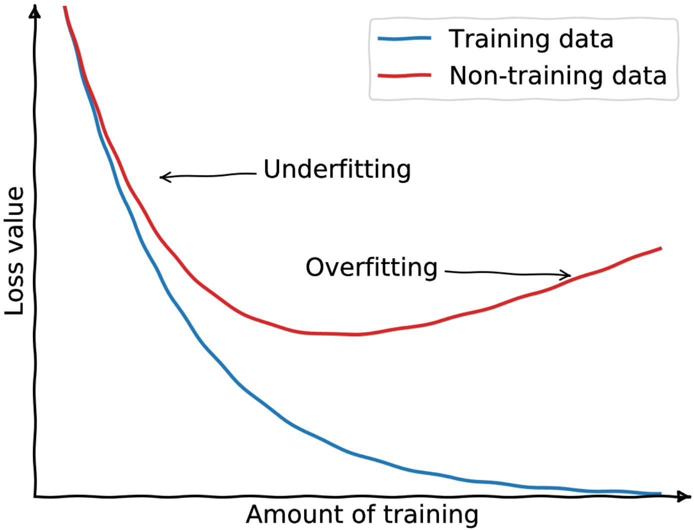
When to stop training?

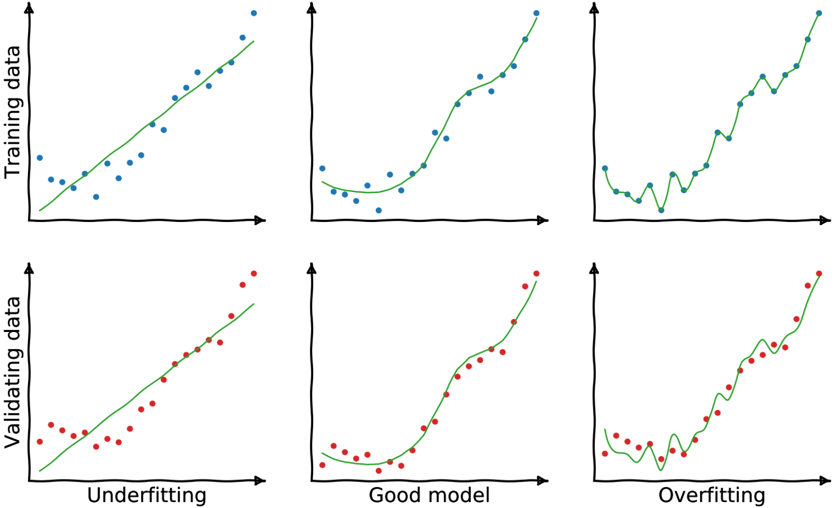

Loss value
Amount of training

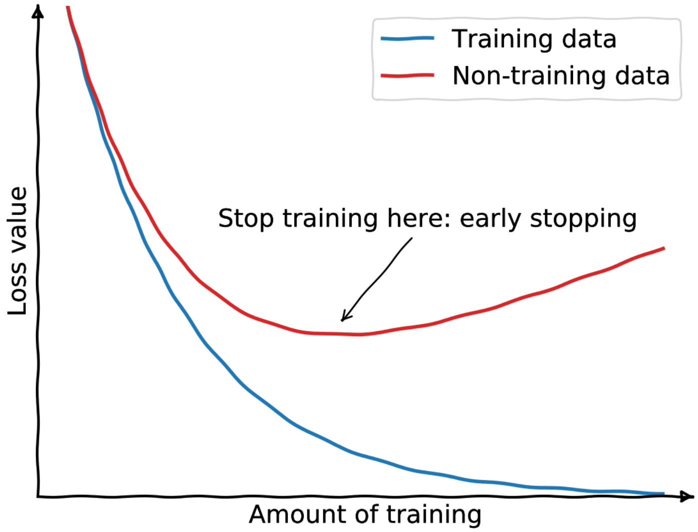

Loss value
Really good?
Amount of training

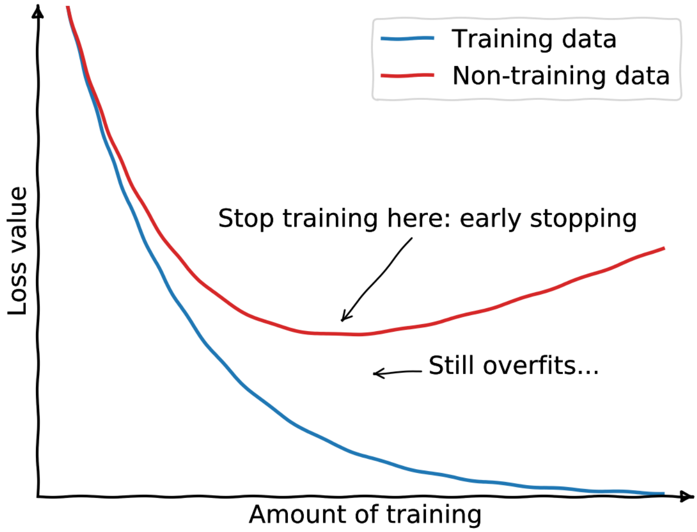

Training data
Non-training data
Loss value
Amount of training

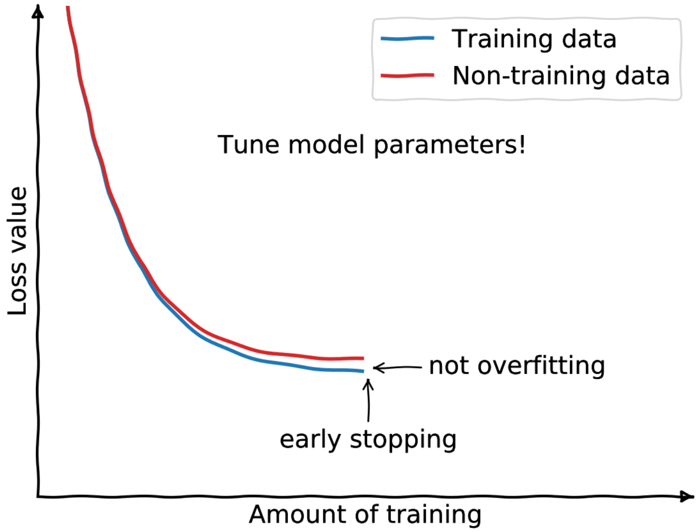

Training data
Non-training data
Not quite on new data
Good on training data
Loss value
Amount of training


Training data
Non-training data
Underfitting
Overfitting
Loss value
Amount of training


Training data
Validating data
Underfitting
Good model
Overfitting


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


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

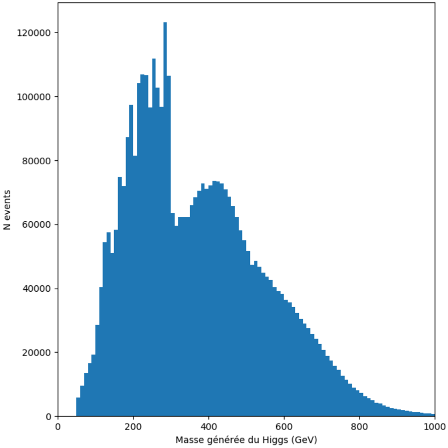

Training data
Non-training data
Tune model parameters!
not overfitting
early stopping
Loss value
Amount of training

P. Bärtschi et al. “Reconstruction of τ lepton pair invariant mass using an artificial neural network”. *Nuclear Instruments and Methods in Physics Research* **A929** (2019), pp. 29–33. DOI: 10.1016/j.nima.2019.03.029. URL: http://www.sciencedirect.com/science/article/pii/S0168900219303377

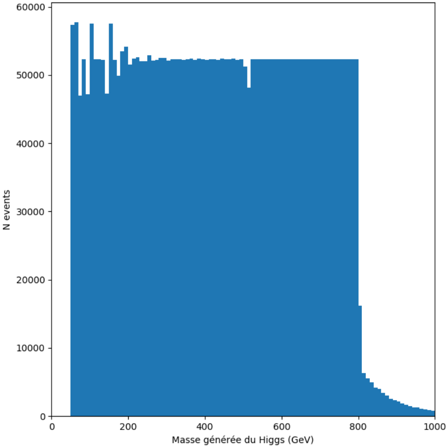
Datasets

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

Target: m_H

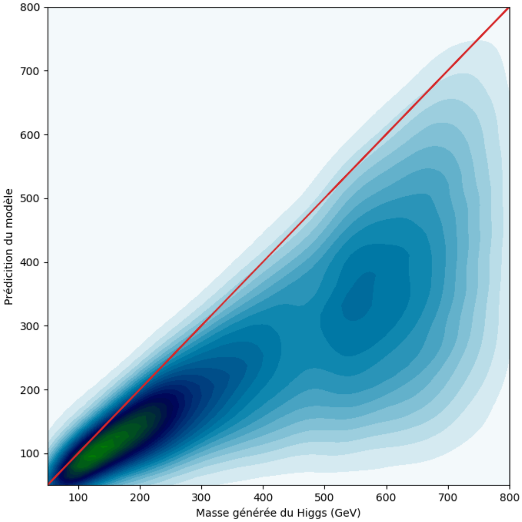


raw distribution



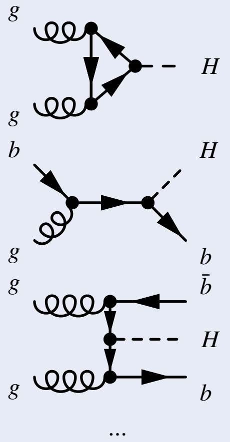
weighted distribution

What if the model is $m_{\mathrm{T}}^{\mathrm{tot}}$ itself?



What about input variables?

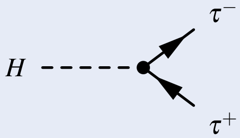
Higgs production



eventual jets

$\times$

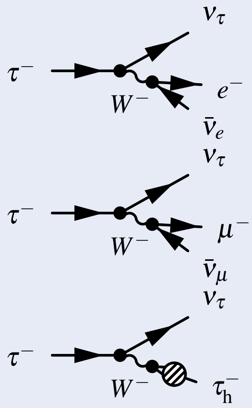
$H \to \tau\tau$



2 taus

$\times$

τ decays



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

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

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- $H \to \tau\tau$ decays:
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  - MET to account for neutrinos $\to {E_\mathrm{T}}^{\text{miss}}$, ϕ^{MET};

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  - MET to account for neutrinos $\to E_\mathrm{T}^{\text{miss}}$, ϕ^{MET};
- Higgs production:
  - two leading jets $\to p_\mathrm{T}^{(j1,j2)}$, $\eta^{(j1,j2)}$ and $\phi^{(j1,j2)}$;

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- Higher level variables:
  - transverse masses m_{T}^{1}, m_{T}^{2}, $m_{\mathrm{T}}^{\tau\tau}$,
  - total transverse mass $m_{\mathrm{T}}^{\text{tot}}$.

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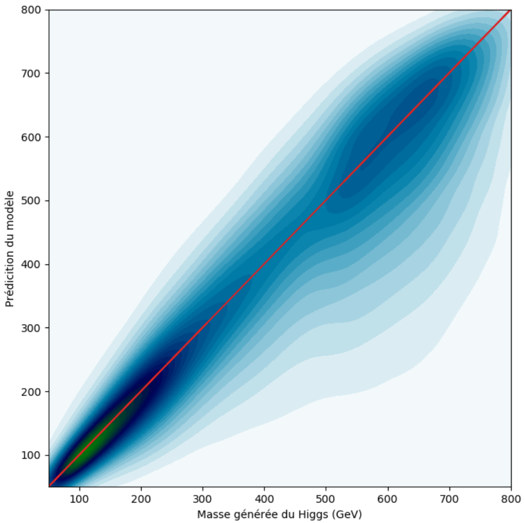
- Higher level variables:
  - transverse masses m_T^1, m_T^2, $m_\mathrm{T}^{\tau\tau}$,
  - total transverse mass $m_\mathrm{T}^{\text{tot}}$.
- Additionnal variables:
  - MET covariance matrix;
  - remaining jets overall $\vec{p} \to {p_\mathrm{T}}^r$, η^r and ϕ^r;
  - number of neutrinos ($\tau_\mathrm{h}\tau_\mathrm{h} = 2$, $\ell\tau_\mathrm{h} = 3$, $\ell\ell = 4$);
  - number of PU vertices `npvsGood`.

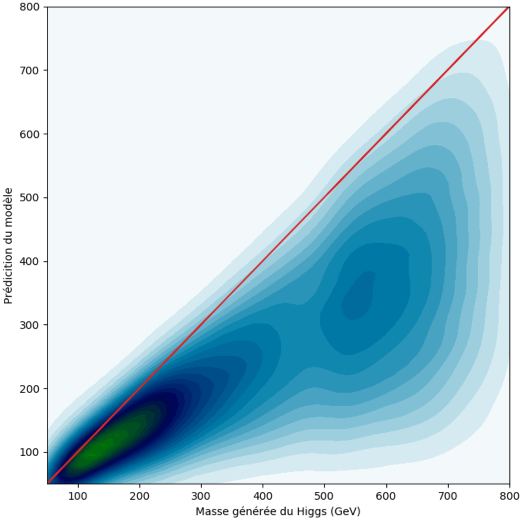
Best model obtained

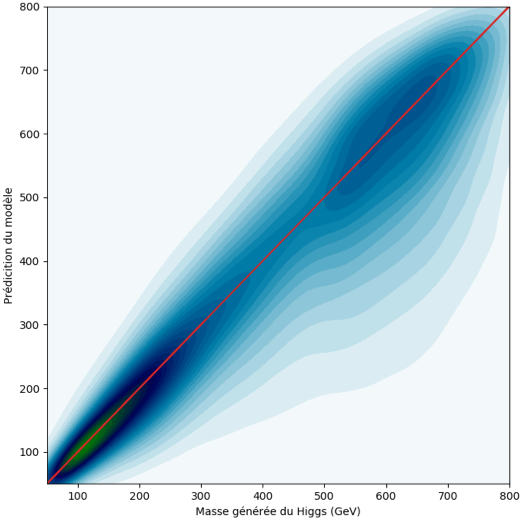
Model properties

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

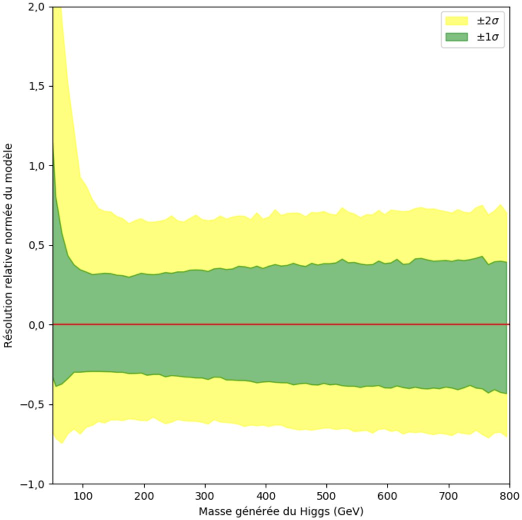


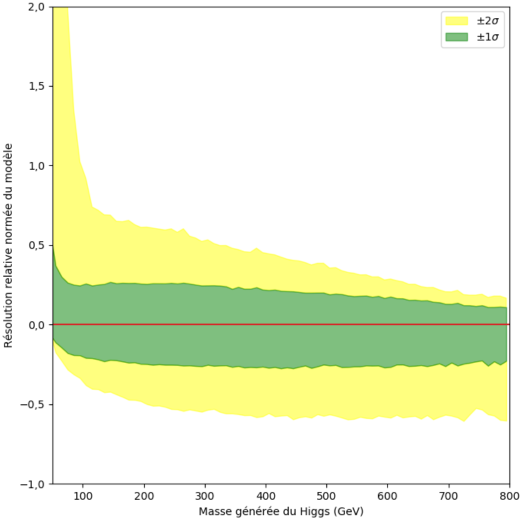
▶ Compare with m_T^{tot}





- Compare with $m_{\mathrm{T}}^{\mathrm{tot}}$: relative resolutions, the thinner the better!





Next step?

- Switch from $m_{\mathrm{T}}^{\mathrm{tot}}$ to a ML-based output
- Improvement on exclusion limits?
- Computing on its way!

Thank you for your attention!