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, under the direction of Colin BERNET

Institut de Physique des deux Infinis – Lyon

July 8, 2021

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

Current standard model status

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

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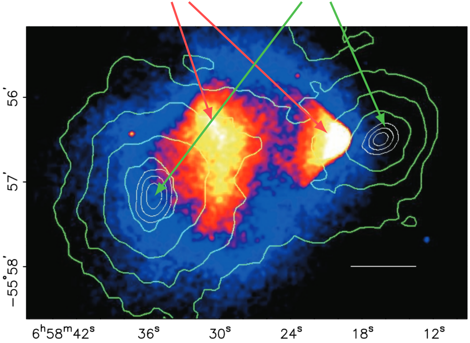
Galaxies from: X rays gravitational lensing



Difference due to **dark matter**!

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Keywords in title

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

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Part I
Phenomenology

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Experimental device

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

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+ 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 $\tan\beta$.

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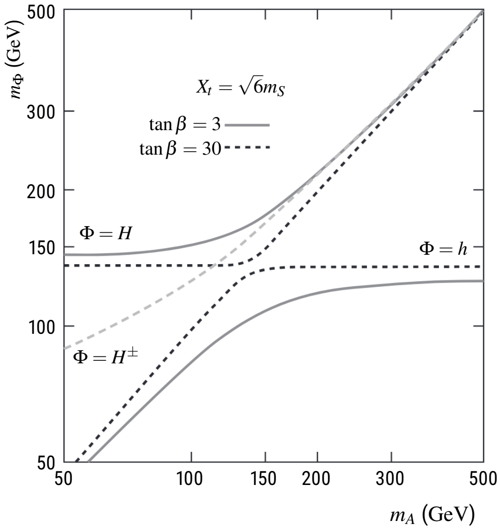

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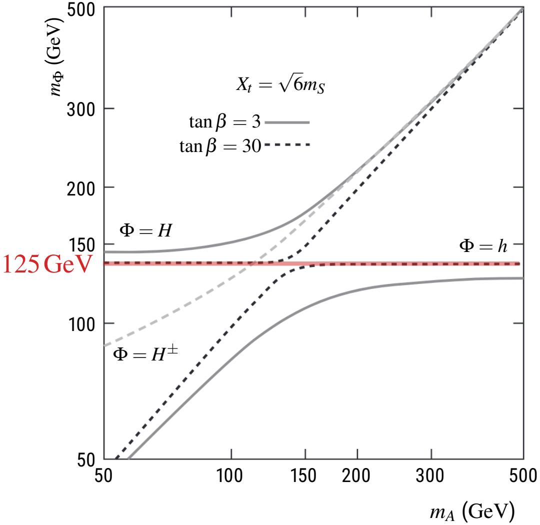

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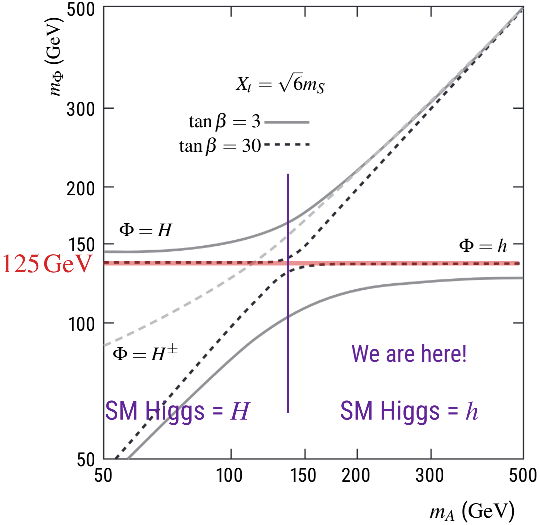
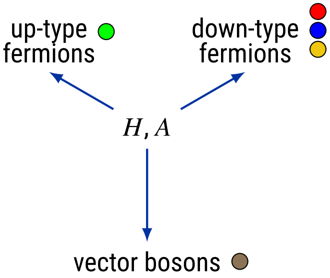
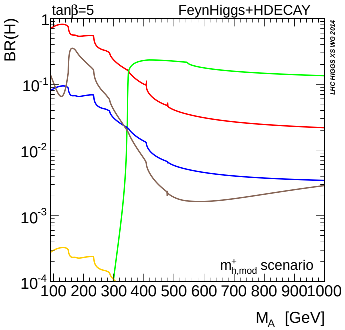


$H/A \to \tau\tau$?





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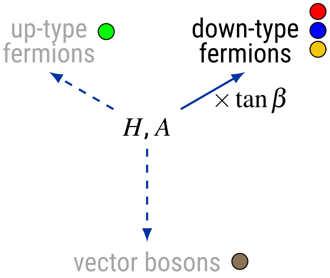
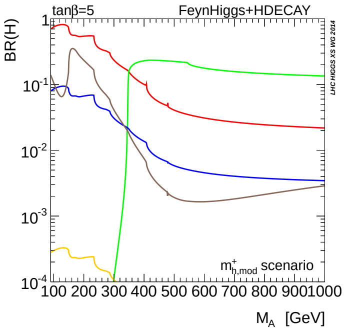
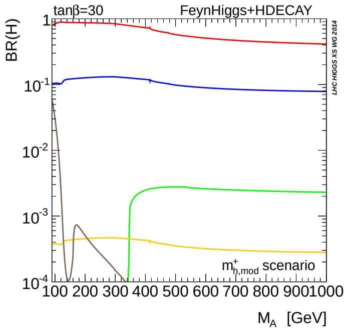
$H/A \to \tau\tau$? – enhanced and suppressed couplings







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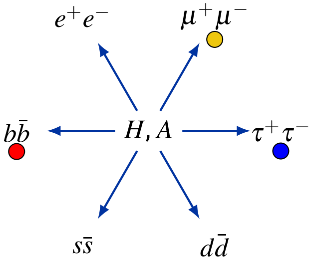

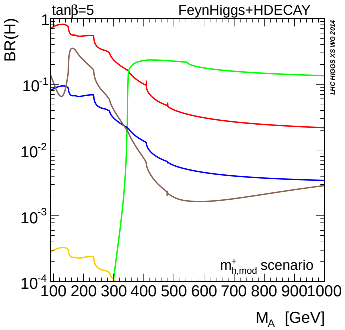

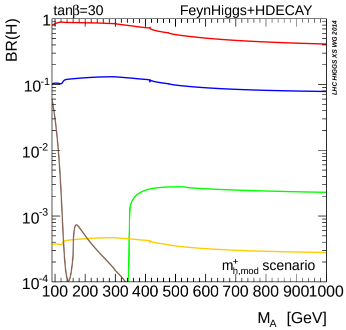

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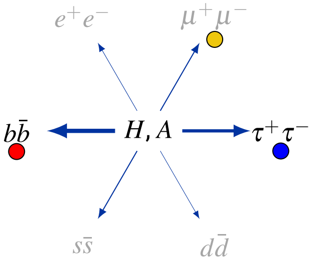
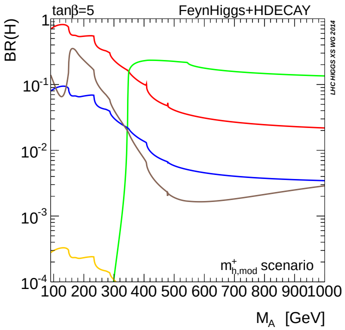
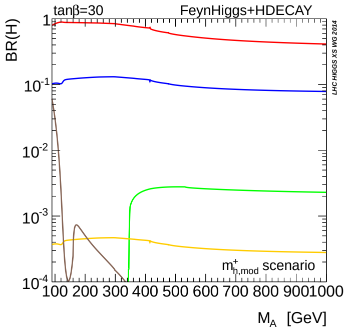
$H/A \to \tau\tau$? – Higgs couplings and particules masses







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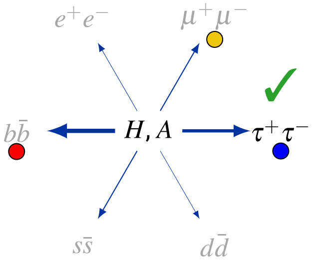
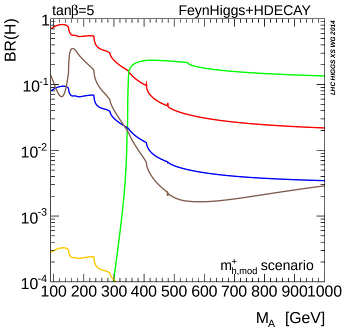
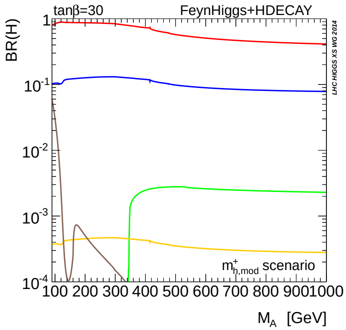
$H/A \to \tau\tau$? – avoid hadronic background







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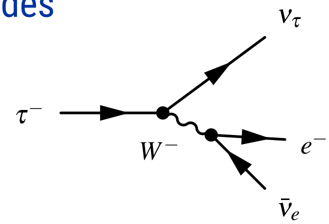
τ decay modes



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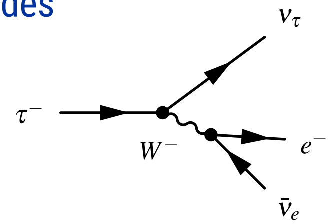

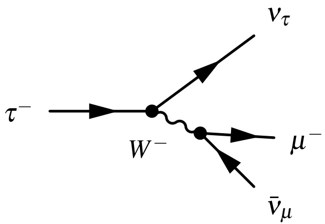

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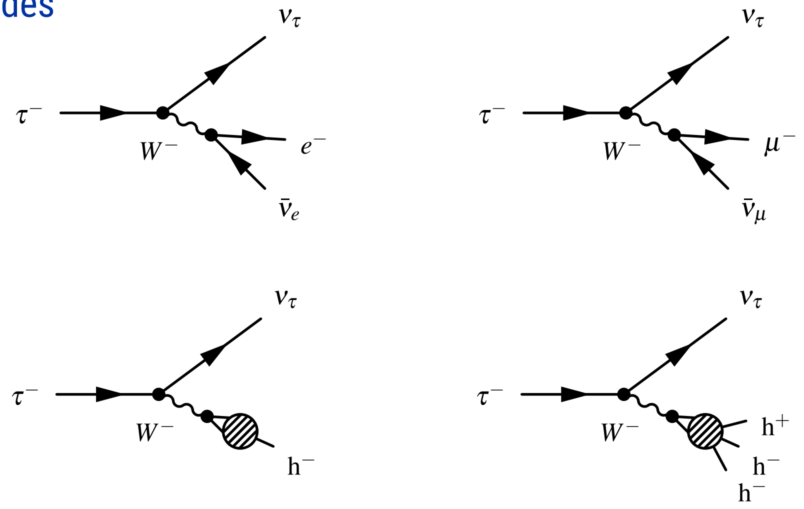

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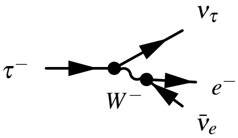
$H/A \to \tau\tau \to L_1 L_2$

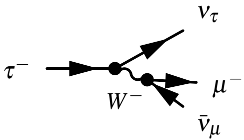
$\tau \to e + \nu_e + \nu_\tau \Rightarrow e$

17.8 %



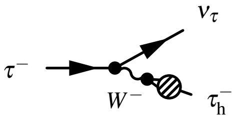
$\tau \to \mu + \nu_\mu + \nu_\tau \Rightarrow \mu$

17.4 %



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

64.8 %



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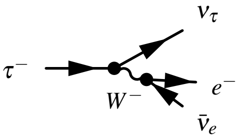

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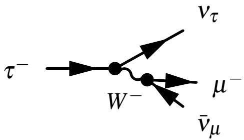

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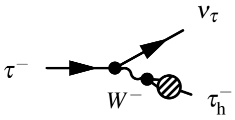

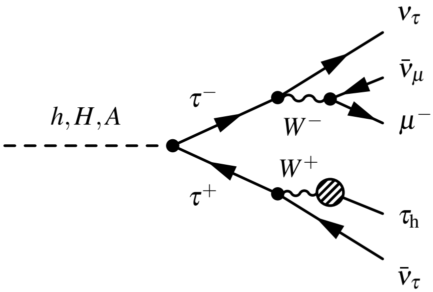

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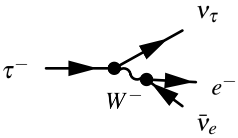

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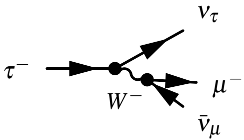

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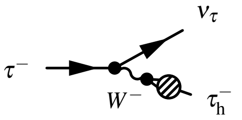

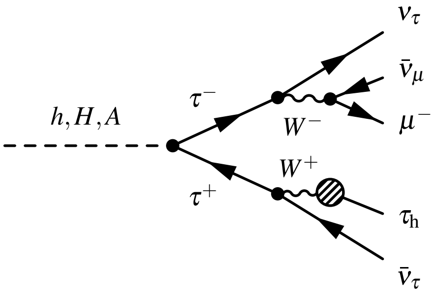

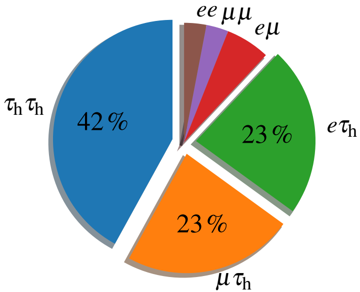

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1 Phenomenology

2 Experimental device

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

4 Machine learning

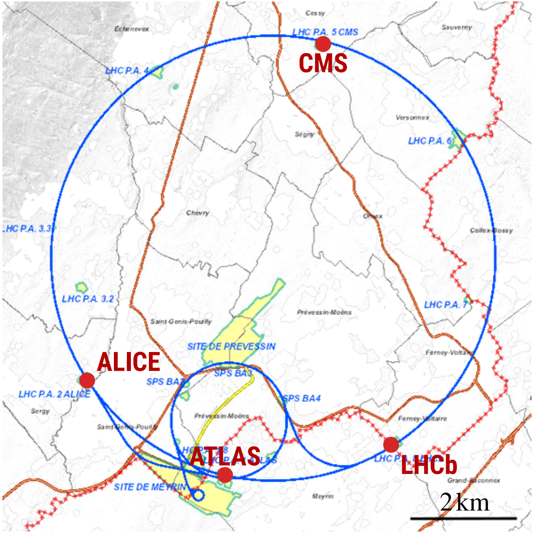
Principle

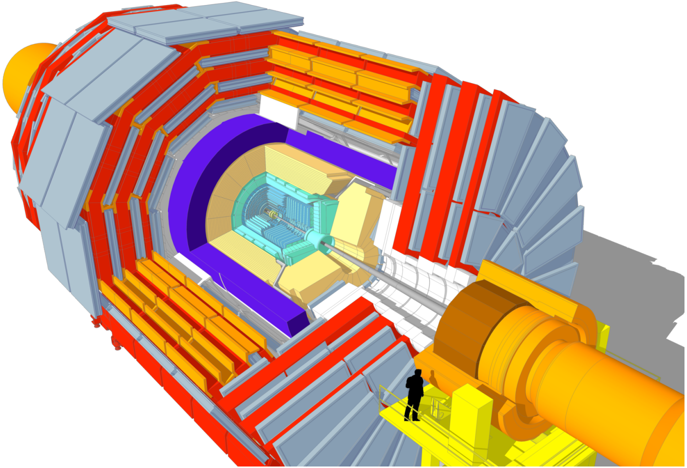
$$E = mc^2$$

mass (new particles) from the collision energy

CERN LHC


Londres
Bristol
Cardiff
Brighton
Southampton
Plymouth
Manche (mer)
Guernesey
Jersey
Brest
Rennes
Nantes
Tours
Paris
Anvers
Bruxelles
Lille
Belgique
Luxembourg
Dortmund
Cologne
Allemagne
Leipzig
Francfort-sur-le-Main
Mannheim
Nuremberg
Stuttgart
Strasbourg
Augsbourg
Munich
Salzbourg
Zurich
Liechtenstein
Suisse
France
CERN
Lyon
La Rochelle
Limoges
Clermont-Ferrand
Grenoble
Turin
Milan
Vérone
Venise
Padoue
Golfe de Gascogne
Bordeaux
Gênes
Bologne
Toulouse
Montpellier
Monaco
Marseille
Cannes
Pise
Saint-Marin
Florence
Italie
Santander
Saint-Sébastien
Bilbao
Vitoria-Gasteiz
Andorre

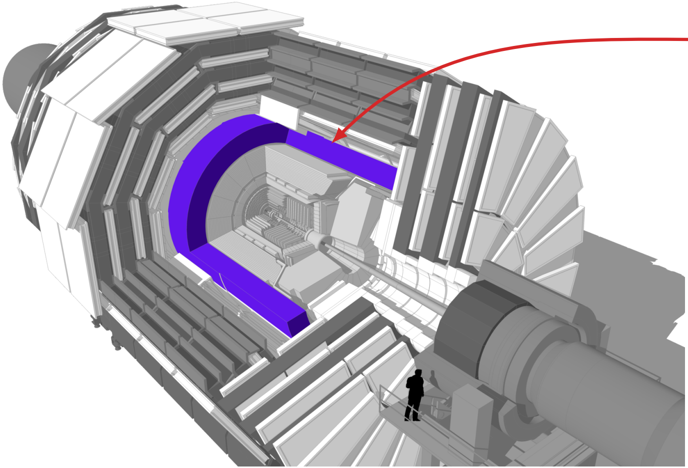

LHC P.A. 5 CMS
CMS
LHC P.A. 4
LHC P.A. 6
LHC P.A. 3.3
LHC P.A. 3.2
LHC P.A. 7
SITE DE PREVESSIN
ALICE
SPS BA3
SPS BA4
LHC P.A. 2 ALICE
ATLAS
LHCb
SITE DE MEYRIN
Cessy
Echenevex
Sauverny
Ségny
Versonnex
Chevry
Ornex
Collex-Bossy
Saint-Genis-Pouilly
Prévessin-Moëns
Ferney-Voltaire
Sergy
Meyrin
Grand-Saconnex
2 km



CMS detector

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

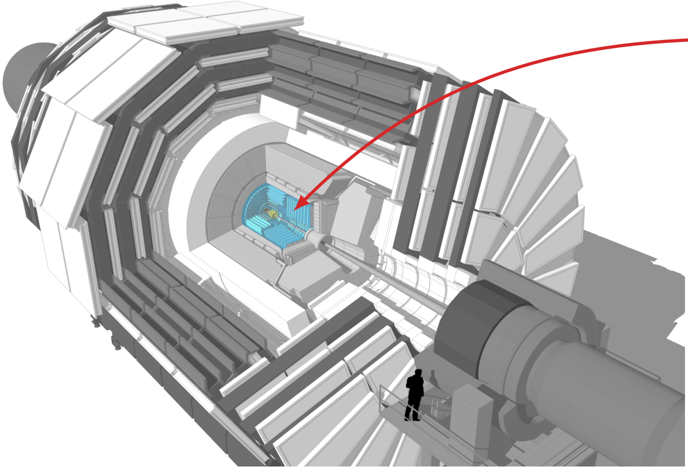
$\Rightarrow$ How to *see* the particles?



Solenoid

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

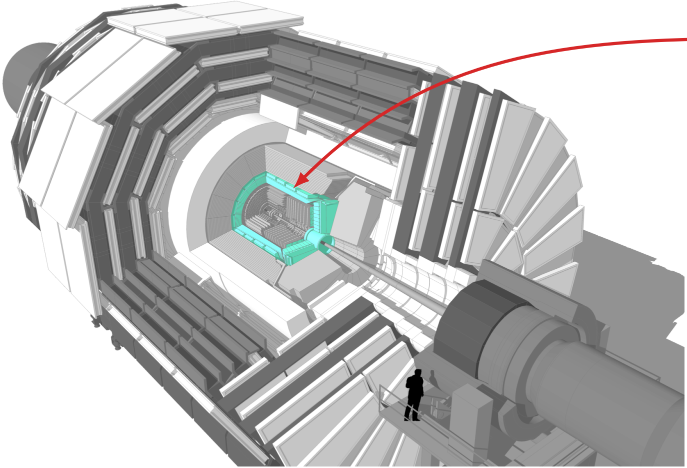
$\Rightarrow$ Bends charged particles trajectories in the transverse plane



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

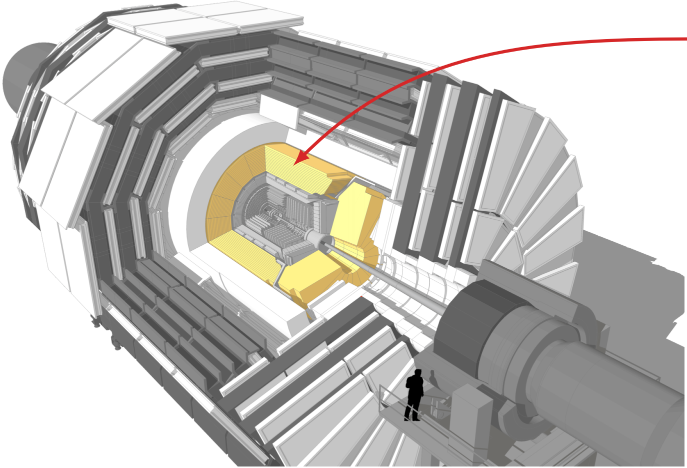
$\Rightarrow$ Charged particles leave hits when going through



Electromagnetic CALorimeter

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

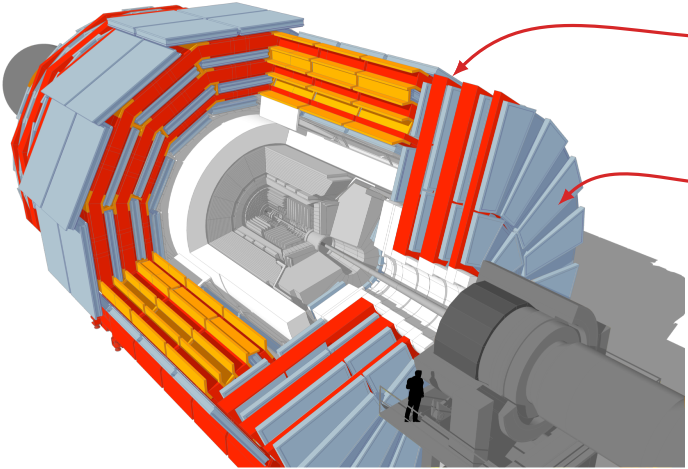
$\Rightarrow$ Electrons and photons are stopped, energy deposits



Hadronic CALorimeter

- Brass + plastic scintillator, ~ 7000 channels

$\Rightarrow$ Hadrons are stopped, energy deposits



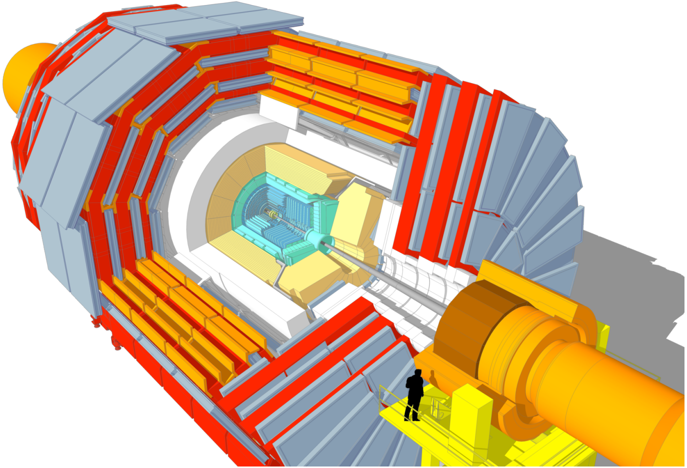
Steel return yoke (red)

- 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

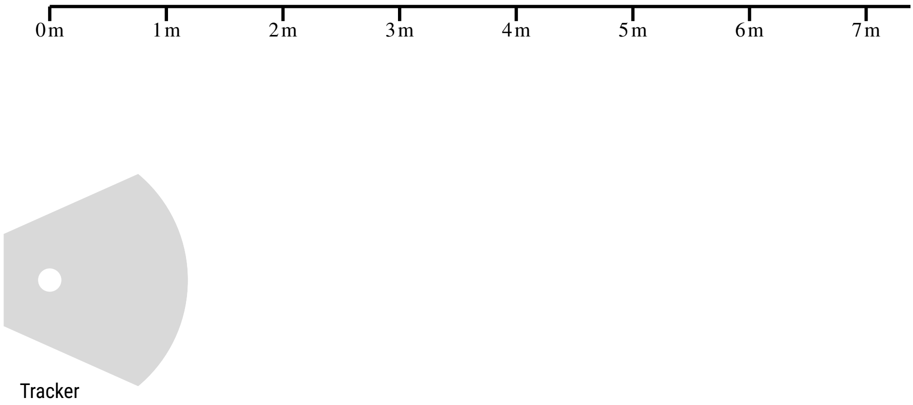
$\Rightarrow$ Charged particles leave hits when going through (only muons do)

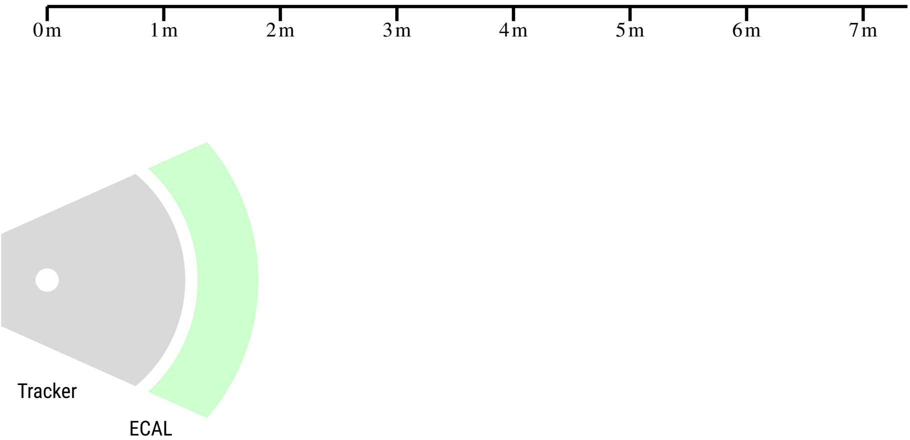


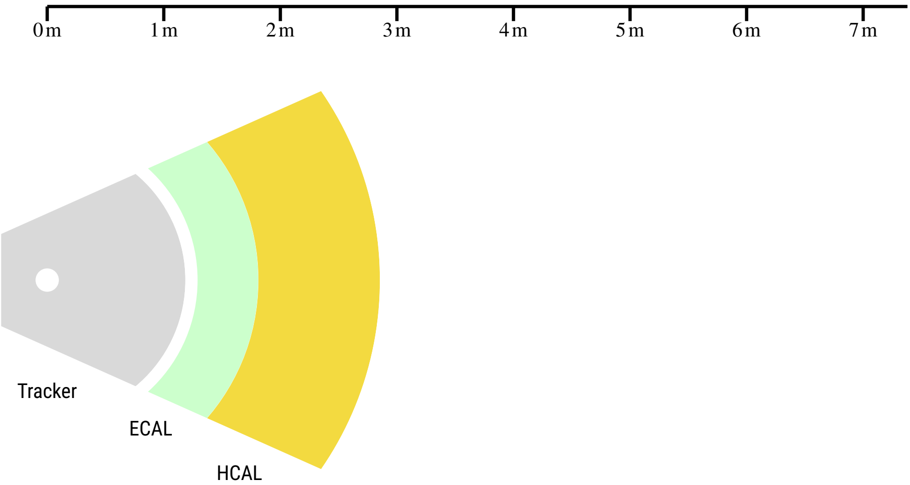
Sensitive parts of CMS

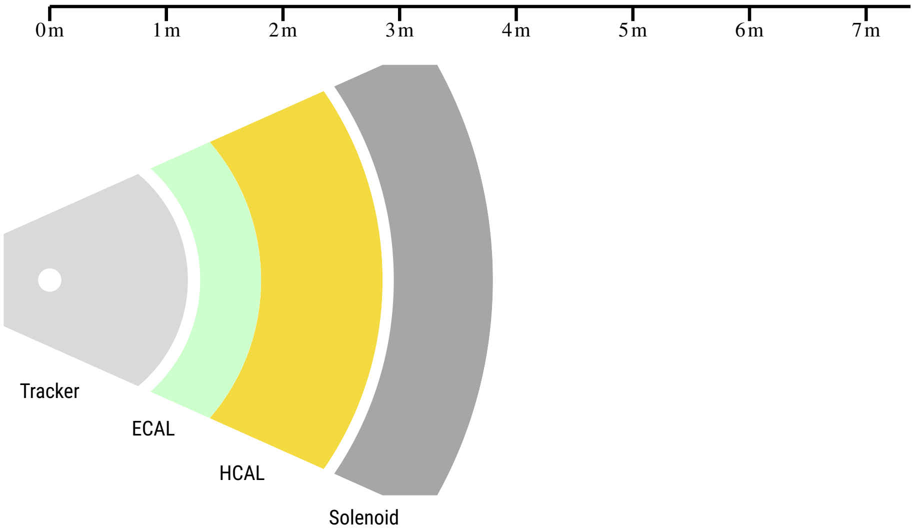
Combine sub-detectors signals to determine which particles were there!


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
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3 m
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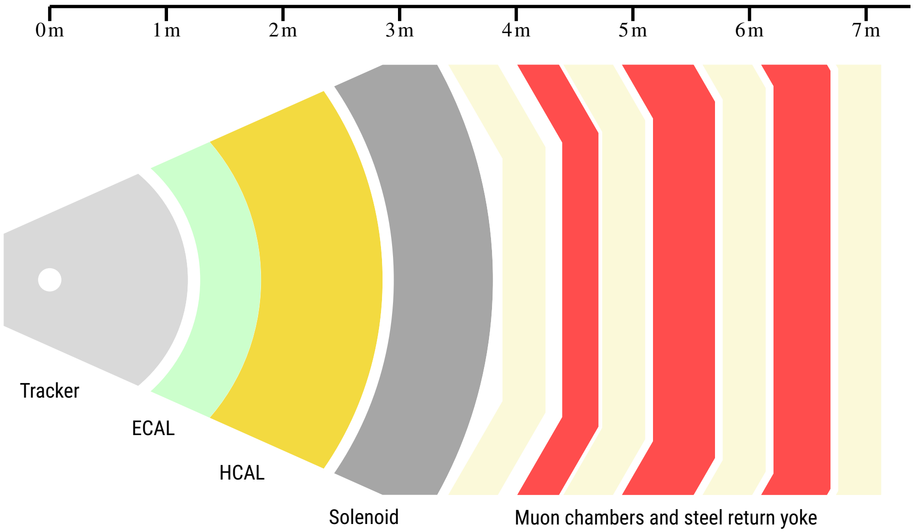
Tracker
ECAL
HCAL
Solenoid


0 m
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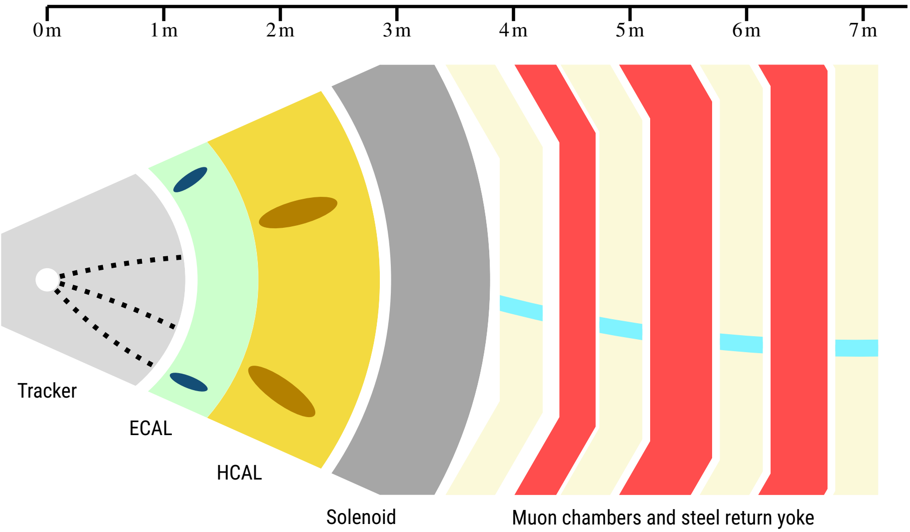
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


0 m
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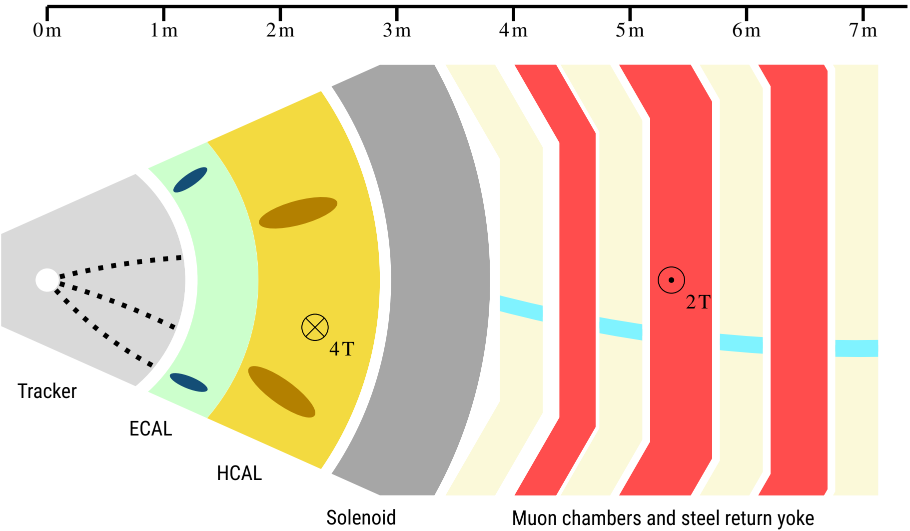
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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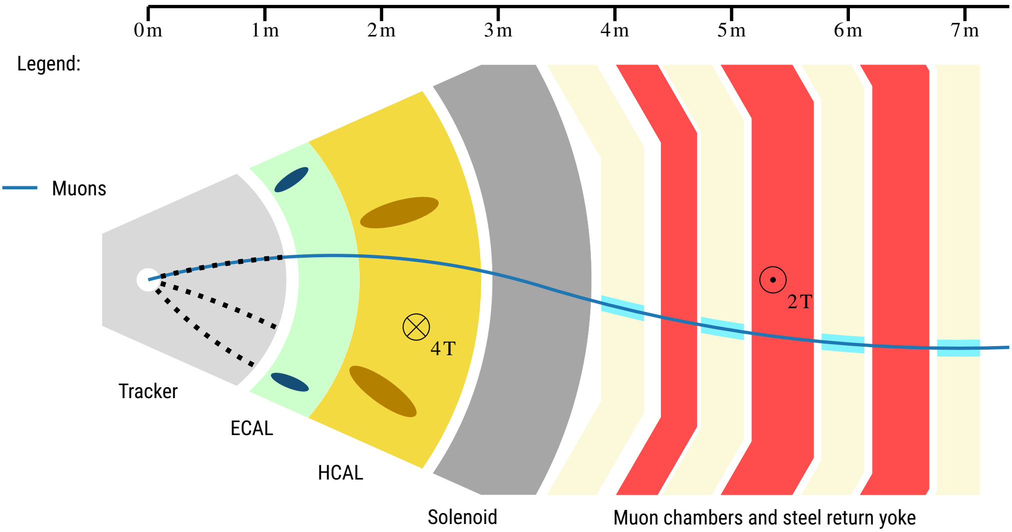
3 m
4 m
5 m
6 m
7 m
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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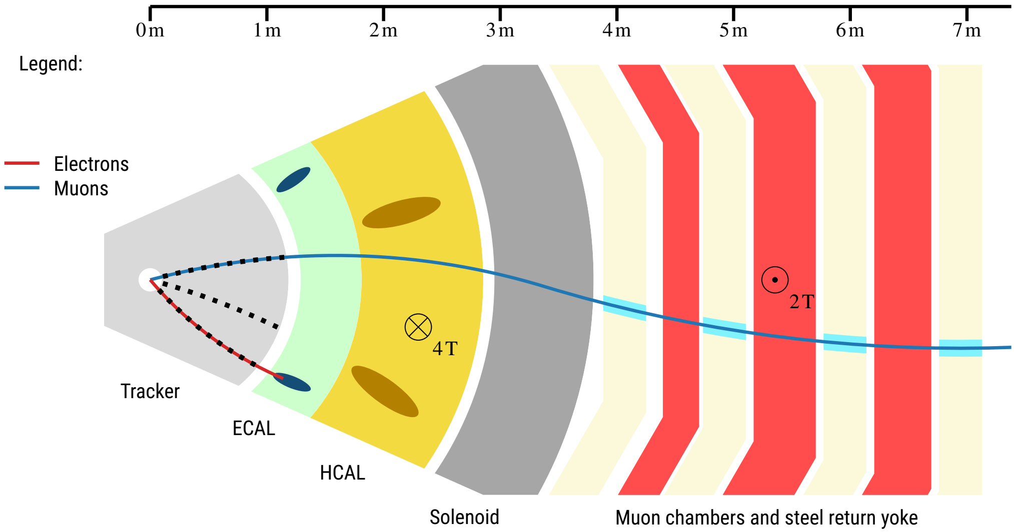
7 m
Legend:
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


0 m
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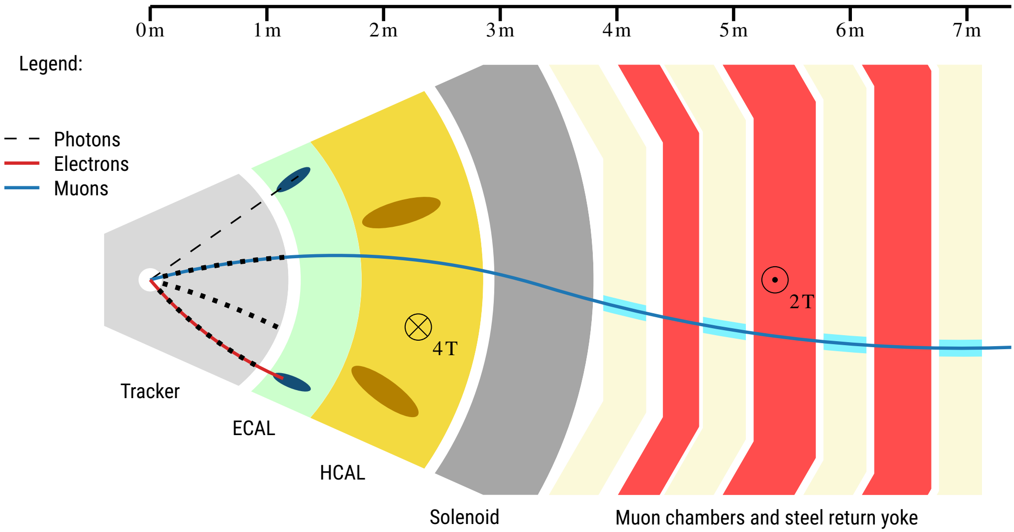
Legend:
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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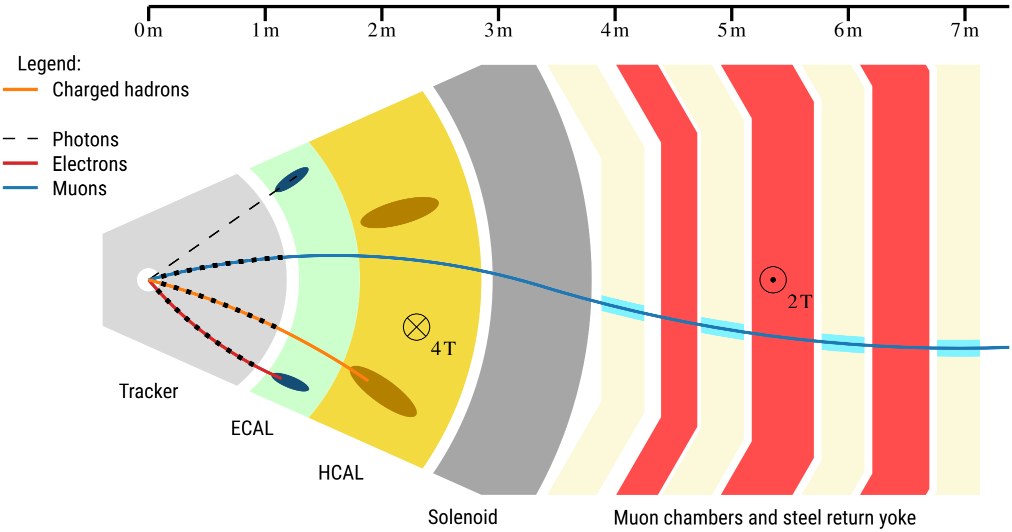
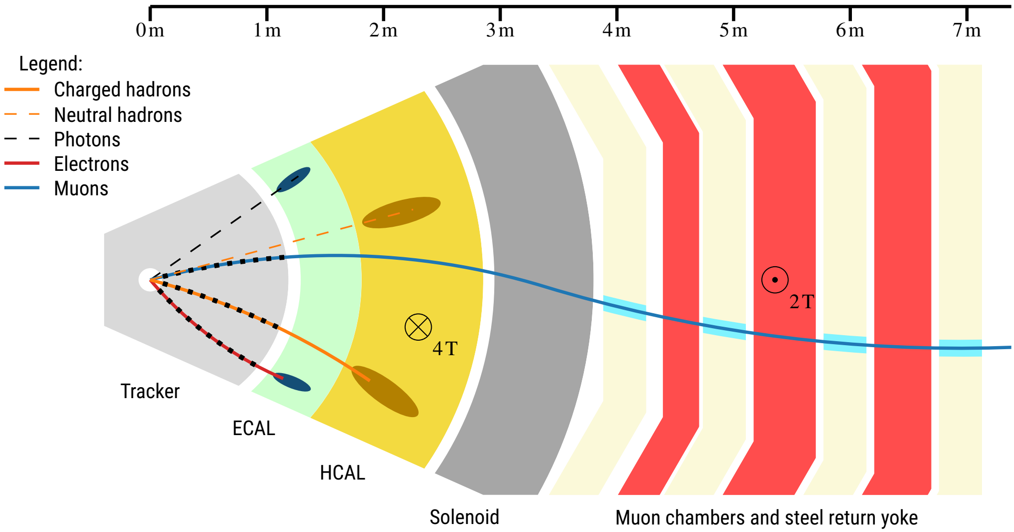
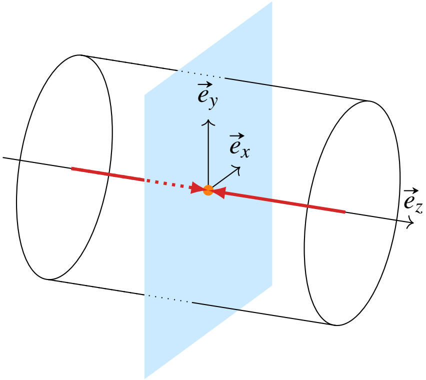
Legend:
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

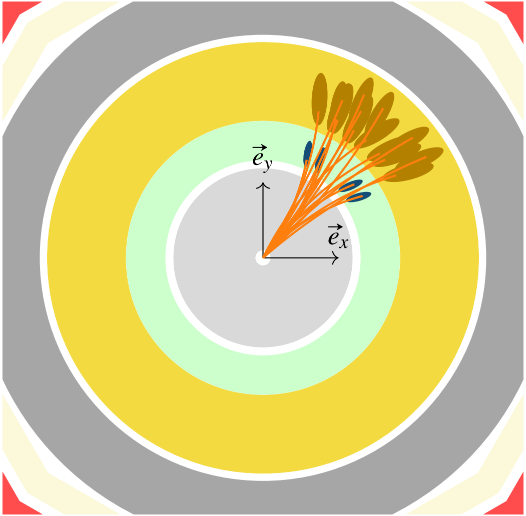

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Charged hadrons
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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 ($\eta = 0$)

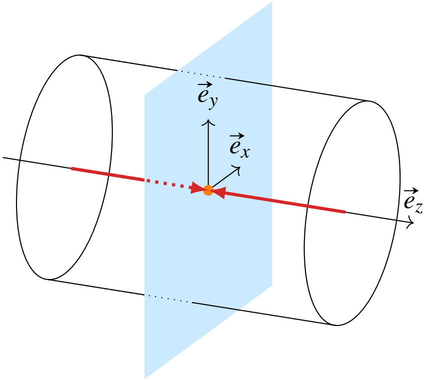




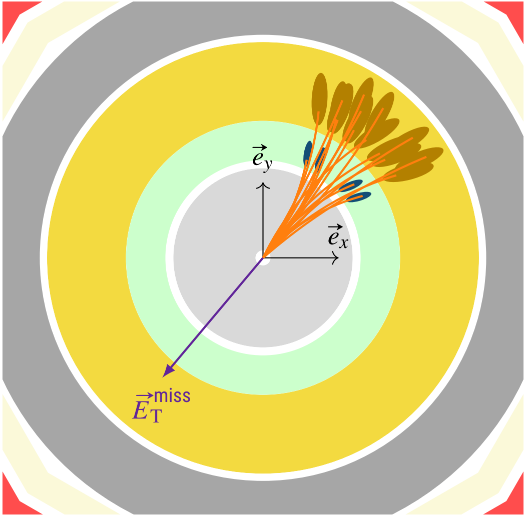
$$\sum_{\text{final state}} \vec{p}_{\mathrm{T}} = \sum_{\text{initial state}} \vec{p}_{\mathrm{T}} = \vec{0}$$

Conserved momentum and neutrinos: missing transverse energy (MET)

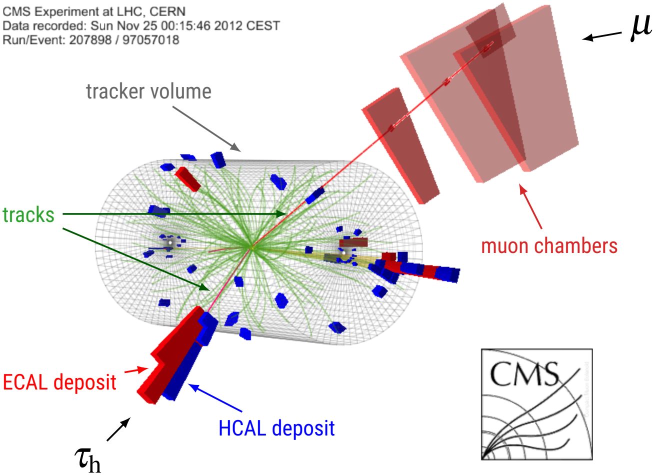
$(\vec{e}_x, \vec{e}_y)$ = transverse plane $(\eta = 0)$



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



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



1 Phenomenology

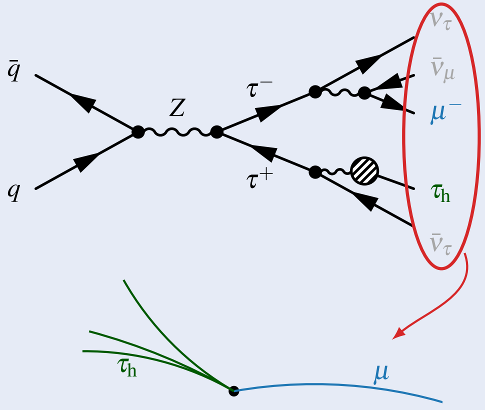
2 Experimental device

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

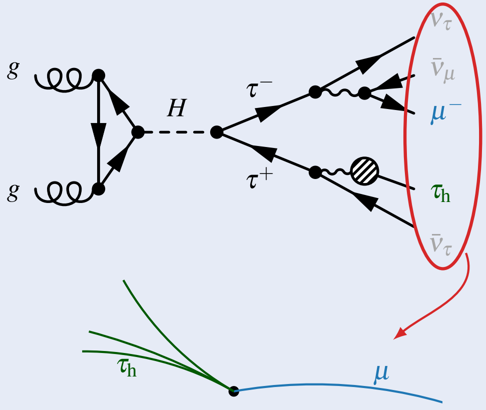
4 Machine learning

Backgrounds?

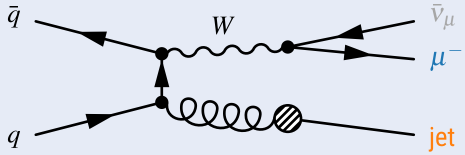
Drell-Yan background

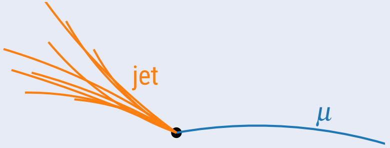


$H \to \tau\tau \to \mu\tau_h$ signal

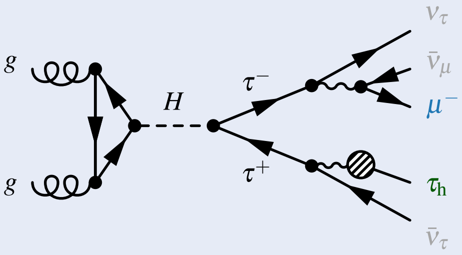


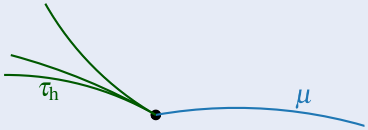
$W+$jets background



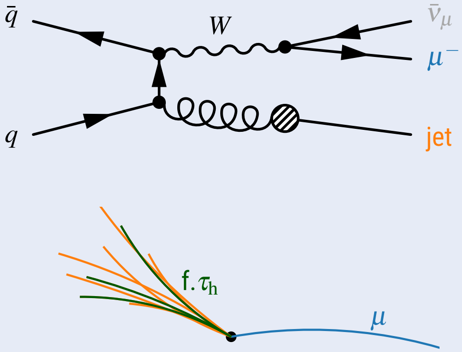


$H \to \tau\tau \to \mu\tau_\mathrm{h}$ signal

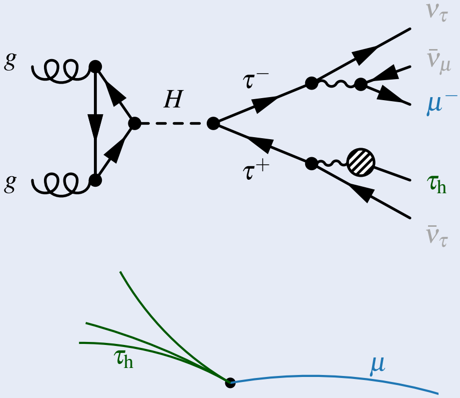




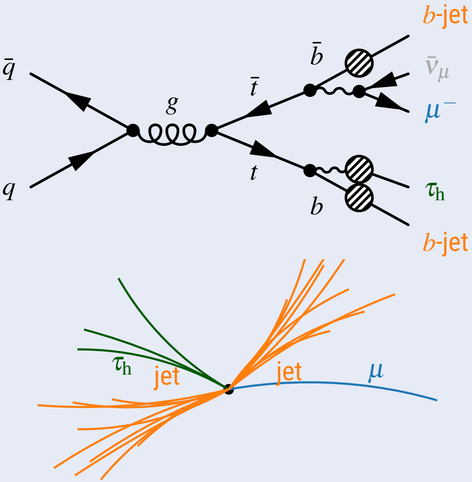
$W + $ jets background, jet $\to$ fake τ_h



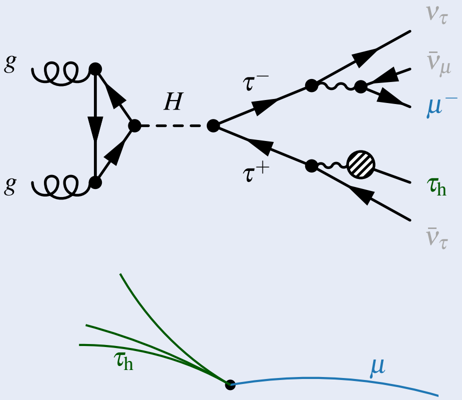
$H \to \tau\tau \to \mu\tau_h$ signal



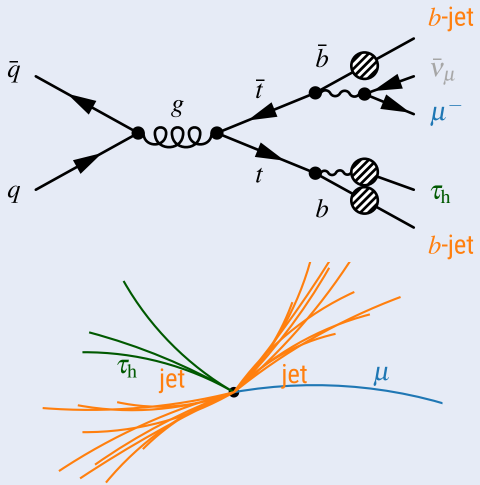
$t\bar{t}$ background



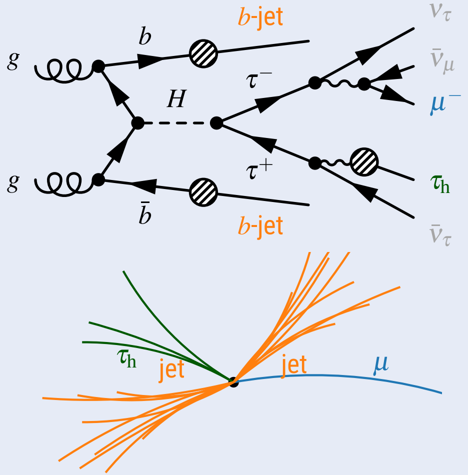
$H \to \tau\tau \to \mu\tau_h$ signal



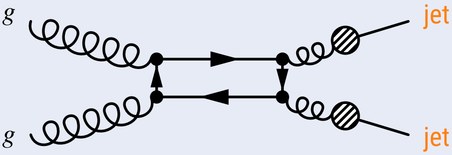
$t\bar{t}$ background

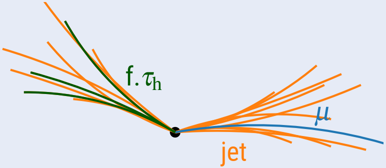


H production with b-jets

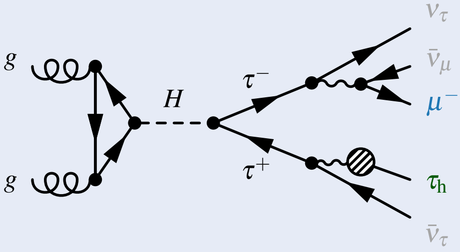


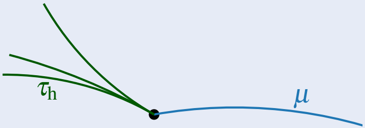
QCD background





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





Backgrounds modelling?

Pure simulation (Monte-Carlo)

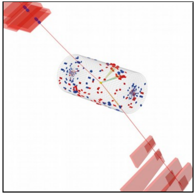
- Generate and simulate processes.
- Available for all *except QCD*.

Data-driven techniques

- Better observation - background agreement.
- In some case, lower uncertainties.

Embedded events & genuine τ leptons

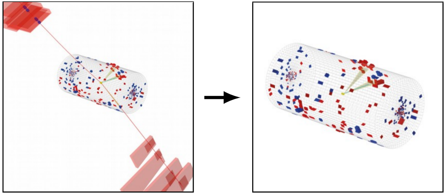
$Z \to \mu\mu$ data



▷ 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 & genuine τ leptons

$Z \to \mu\mu$ data Remove $\mu\mu$ system



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Embedded events & genuine τ leptons

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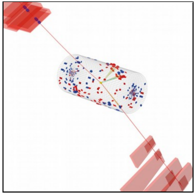
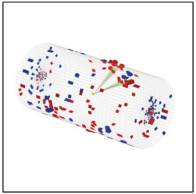
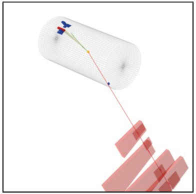


Remove $\mu\mu$ system



Simulate $Z \to \tau\tau$

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



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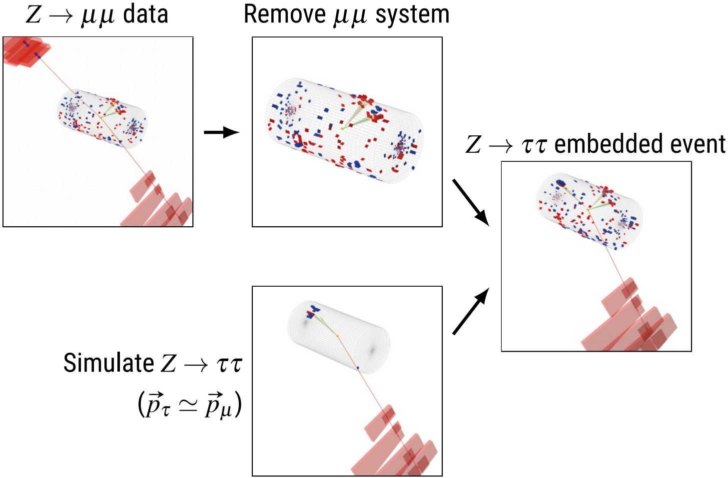
Embedded events & genuine τ leptons



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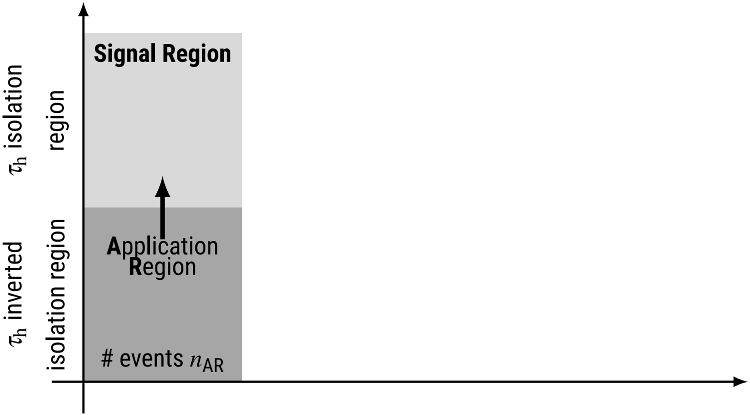
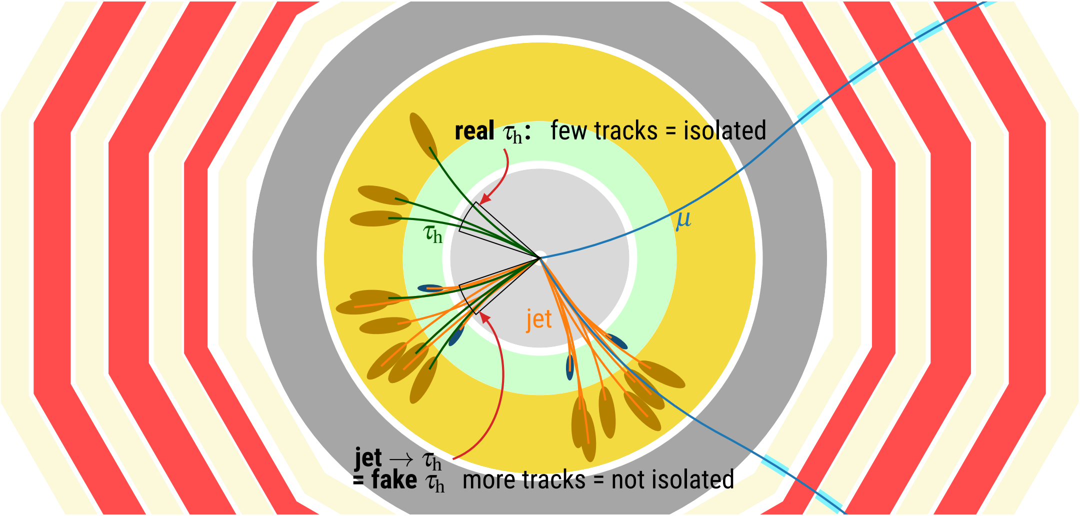
The Fake Factor method & jets faking τ_h

- 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 FF 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`.

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$W+$jets ($\mu\tau_{\mathrm{h}}$ and $e\tau_{\mathrm{h}}$ 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).

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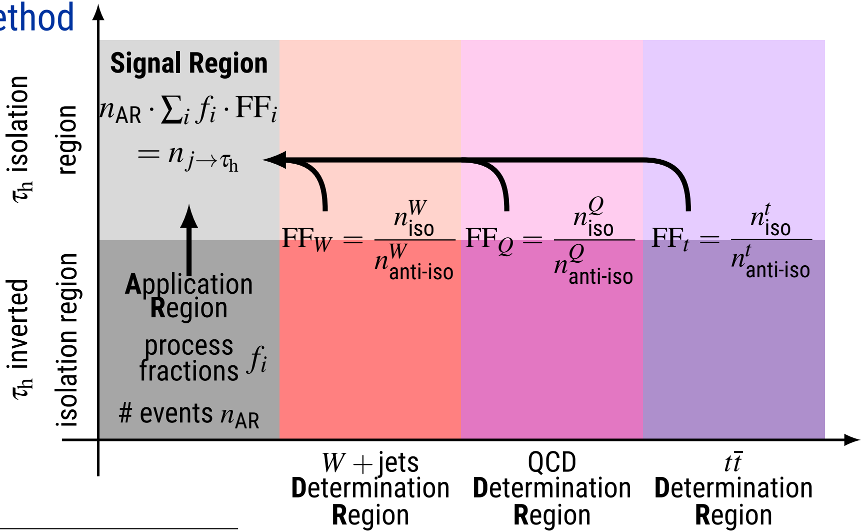
- no b-jet (allowed in the SR).

$t\bar{t}$ ($\mu\tau_h$ 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.

The FF method



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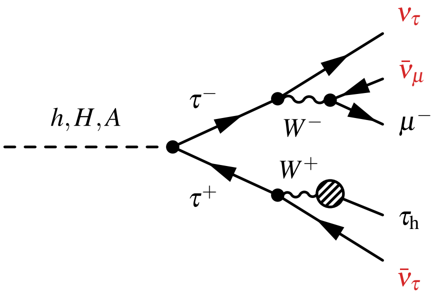
Discriminant variable?

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



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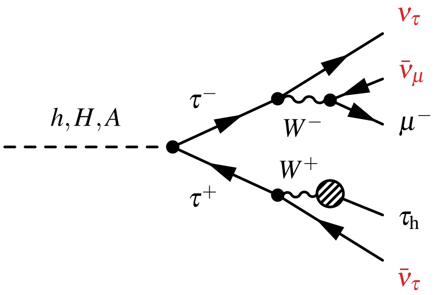
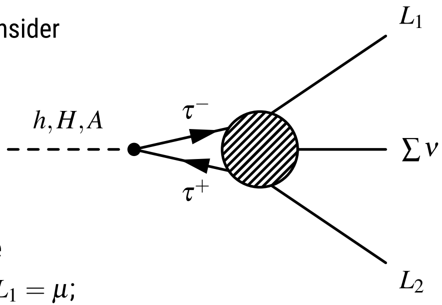


- Consider



where

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

with respect to the left side.

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

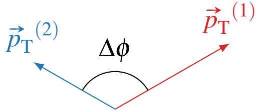
- For L_1, L_2 and $E_{\mathrm{T}}^{\text{miss}}$ system,
  - in the transverse plane (use $E_{\mathrm{T}}^{\text{miss}}$),
  - for $E_i \gg m_i$ (highly relativistic case),

deriving the "invariant" mass would then lead to

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

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

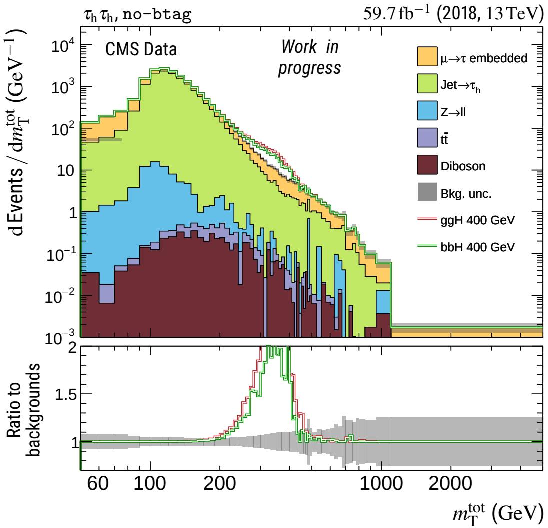
$$m_{\mathrm{T}}(1,2) = \sqrt{2 p_T^{(1)} p_T^{(2)} (1 - \cos\Delta\phi)}$$



Results obtained in this thesis?

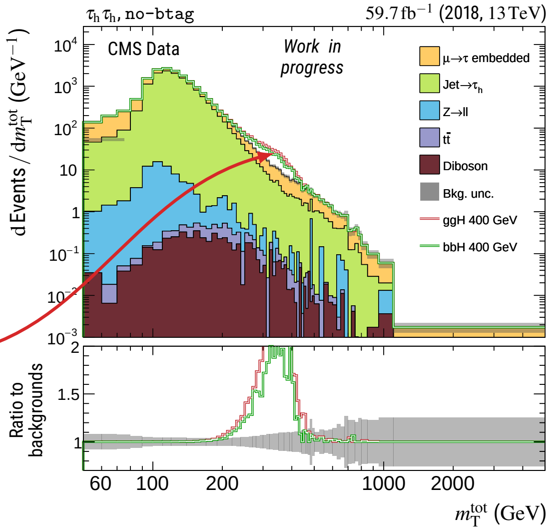
$m_{\mathrm{T}}^{\mathrm{tot}}$ distributions

- 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 $Z \to \ell\ell$
  - 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 $Z \to \ell\ell$
  - 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.



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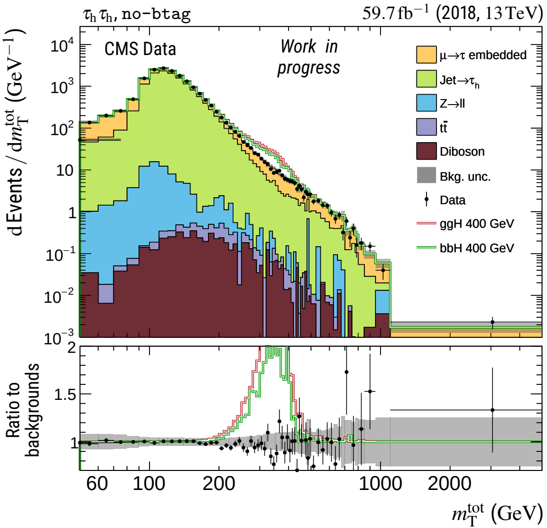
- Compare to observed events (black dots).



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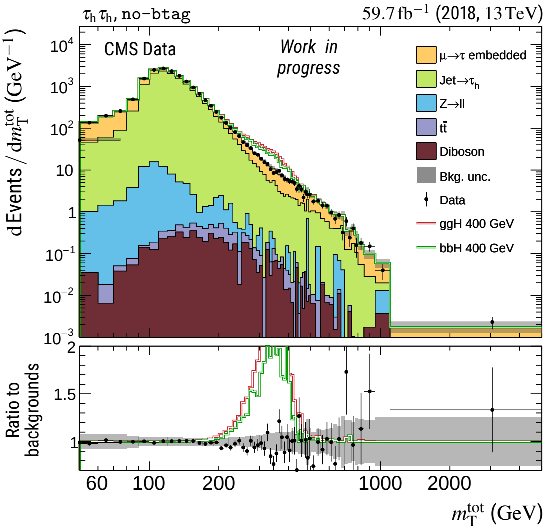
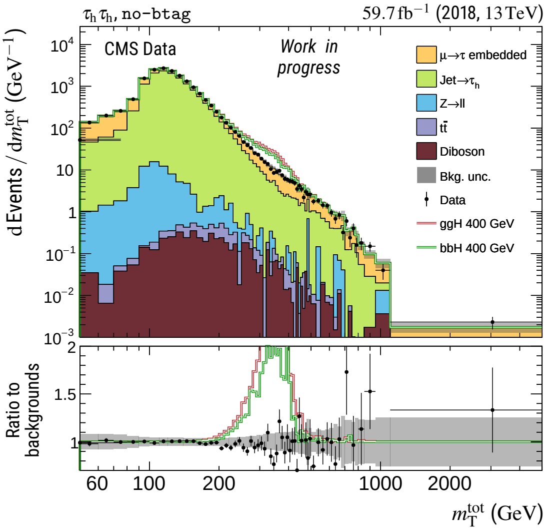
  - Other small backgrounds in Diboson
- H at $400\,\text{GeV}$ expected $\sigma \times \mathcal{BR} = 1\,\text{pb}$ signal.
- Compare to observed events (black dots).
- Data/Bkg agreement $\to$ **exclusion limits** on $\sigma \times \mathcal{BR}$

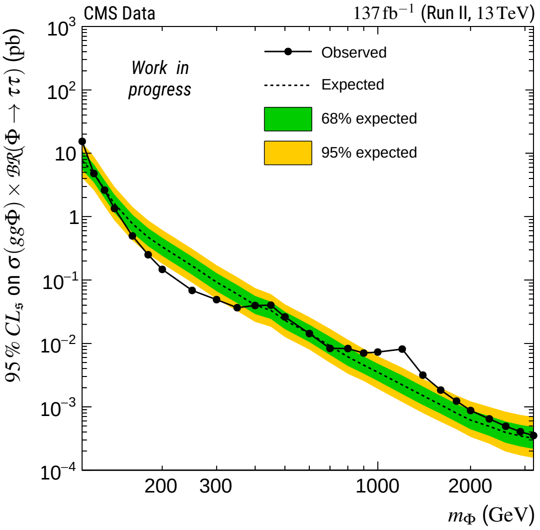


$m_{\mathrm{T}}^{\mathrm{tot}}$ distributions

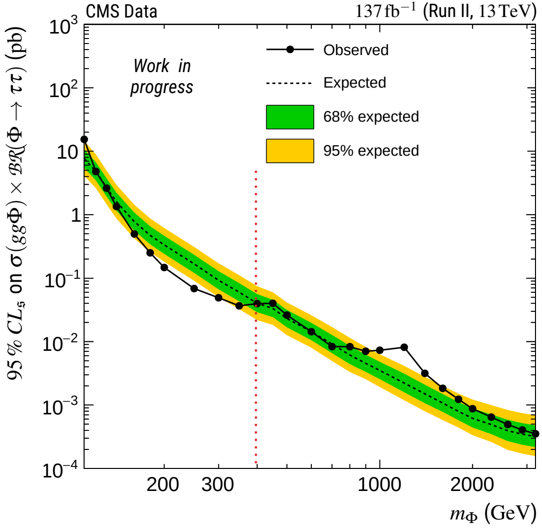
Not *just* a plot!

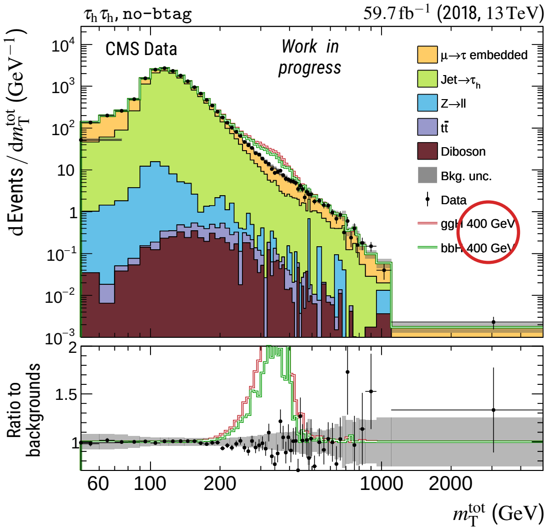
- Lot of hard work to obtain this:
  - simulated events
  - detector issues
  - uncertainties measured
- Collaborative work:
  - Karlsruhe Institute of Technology (DE)
  - Imperial College (UK)
  - DESY (DE)
  - HEPHY (AT)
  - IP2I (FR)





▷ 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.





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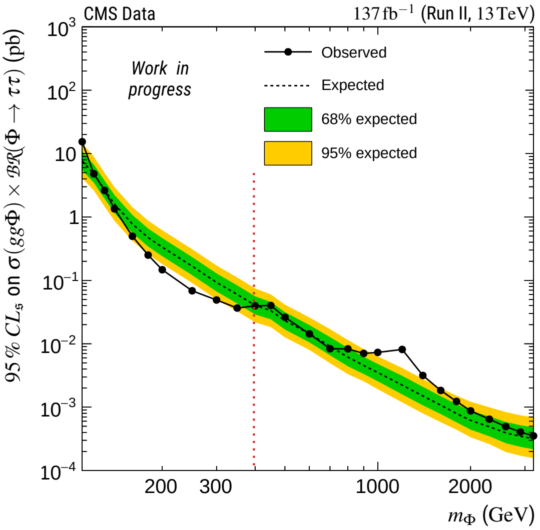

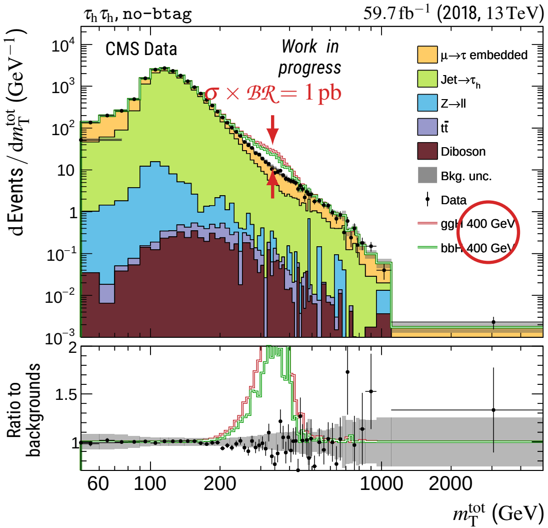

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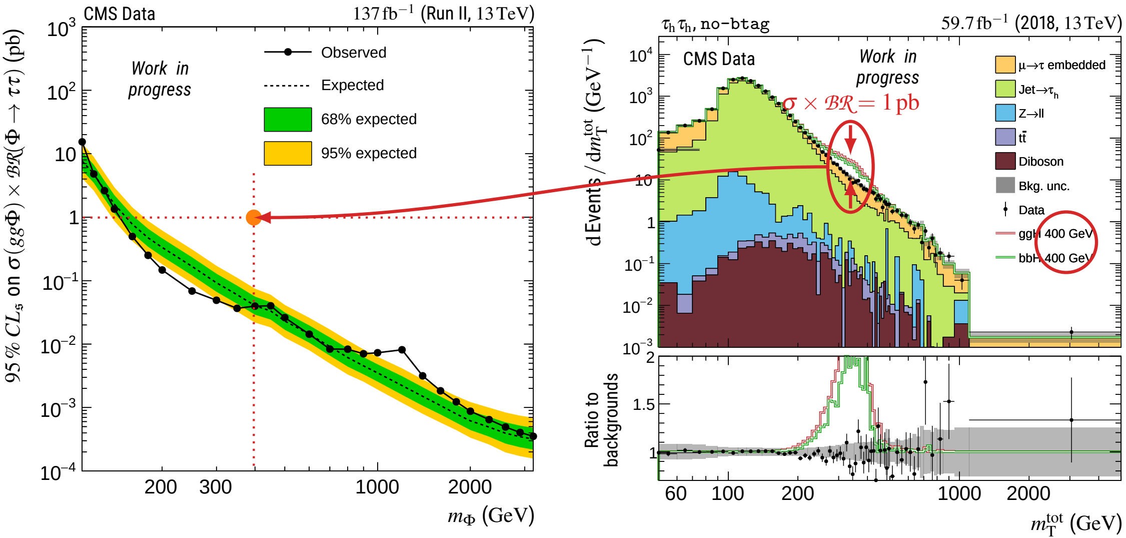
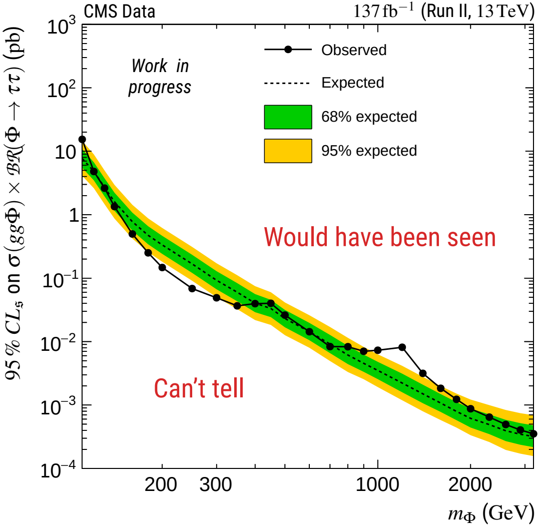
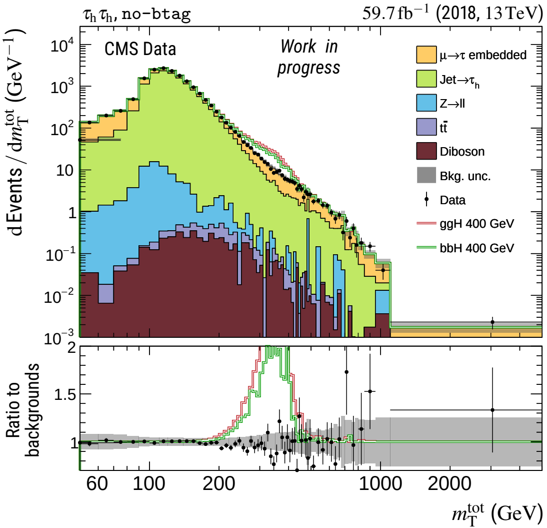


▷ A. L. Read. "Modified frequentist analysis of search results (the CL_s method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: http://cds.cern.ch/record/451614.





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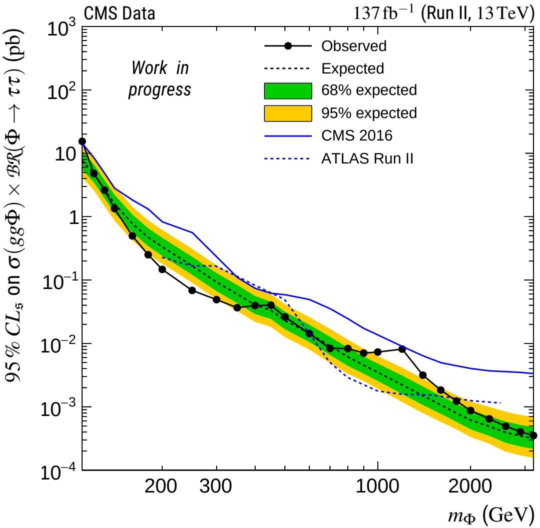
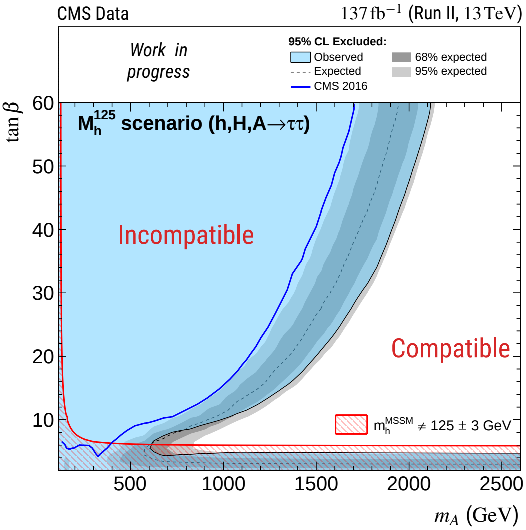
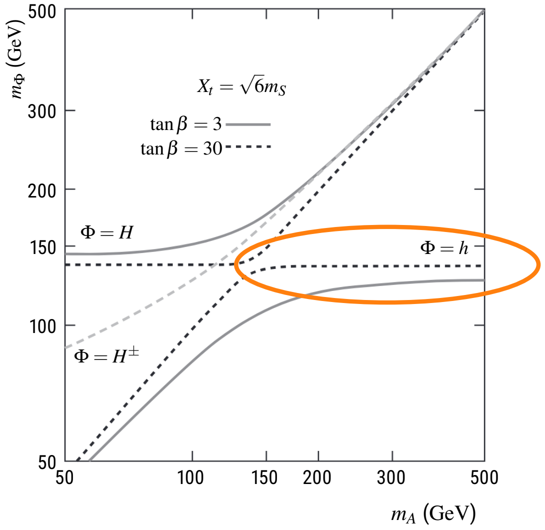


- **CMS 2016:**
  - The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: `10.1007/JHEP09(2018)007`.
- **ATLAS Run II:**
  - The ATLAS Collaboration. "Search for Heavy Higgs Bosons Decaying into Two Tau Leptons with the ATLAS Detector Using pp Collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Physical Review Letters* **125** (5 July 2020), p. 051801. DOI: `10.1103/PhysRevLett.125.051801`.

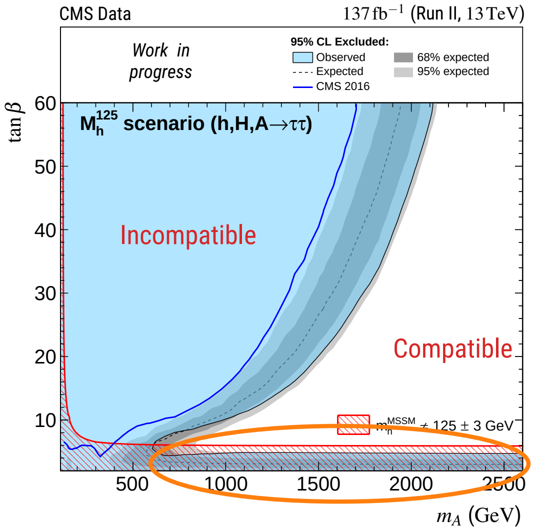
▷ A. L. Read. "Modified frequentist analysis of search results (the CL_s method)". *Workshop on confidence limits, CERN, Geneva, Switzerland, 17-18 Jan 2000: Proceedings*. CERN-OPEN-2000-205. May 2000. URL: `http://cds.cern.ch/record/451614`.

- Model dependent limits:
  - Fix high-order MSSM parameter,
  - Explore $(m_A, \tan\beta)$ plane,
  - Is MSSM compatible with data? Look for:
    - additional signal from H and A
    - compatibility with the already discovered h





$X_t = \sqrt{6} m_S$
$\tan\beta = 3$
$\tan\beta = 30$
$\Phi = H$
$\Phi = h$
$\Phi = H^{\pm}$
m_Φ (GeV)
m_A (GeV)



CMS Data
$137\,\mathrm{fb}^{-1}$ (Run II, 13 TeV)
Work in progress
95% CL Excluded:
Observed
Expected
CMS 2016
68% expected
95% expected
M_h^{125} scenario ($h,H,A\to\tau\tau$)
Incompatible
Compatible
$m_h^{MSSM} \neq 125 \pm 3$ GeV
$\tan\beta$
m_A (GeV)

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

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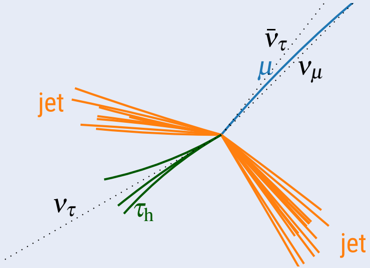
  - neutrinos in di-τ events.

What's here

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



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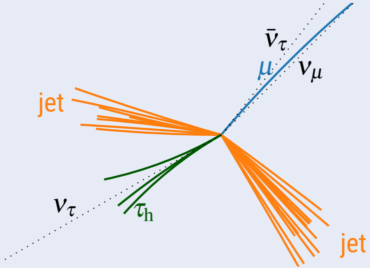
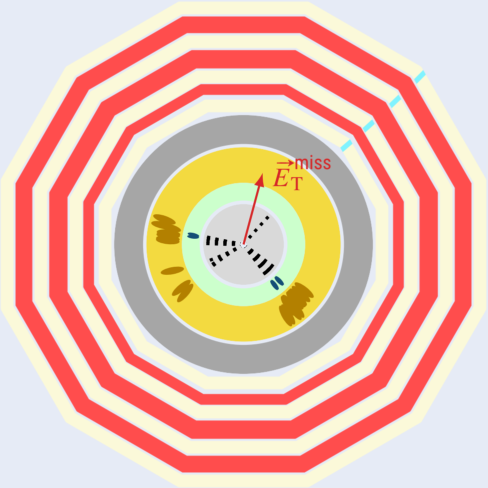


What CMS sees: no neutrinos but $E_{\mathrm{T}}^{\mathrm{miss}}$



- Remember: invariant mass not fully available:
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What's here

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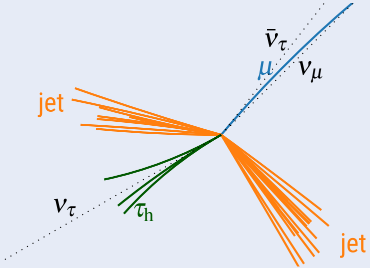
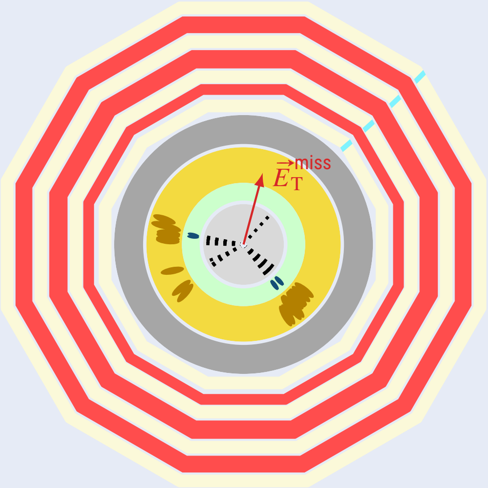


- It would be great to have a di-τ mass estimator!
  - What about ***machine learning***?

What CMS sees: no neutrinos but E_T^{miss}



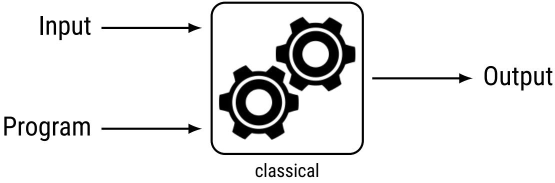
1 Phenomenology

2 Experimental device

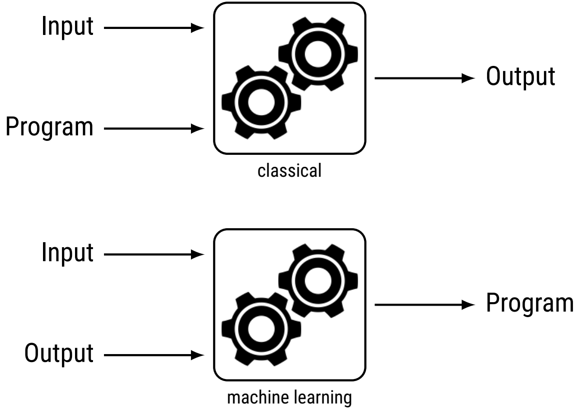
3 $H/A \to \tau\tau$ analysis

4 Machine learning

What is *machine learning*? – A brief introduction



What is *machine learning*? – A brief introduction



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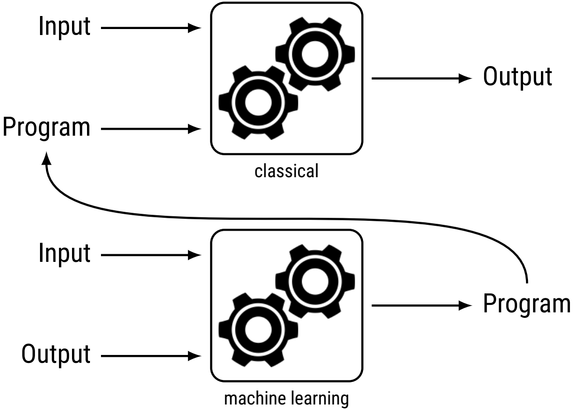

What is *machine learning*? – A brief introduction

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

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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)

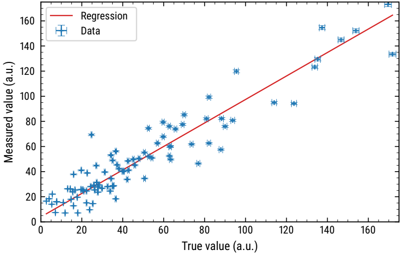
- Categorical target ⇒ Classification

e.g. cat or dog on the image

- Continuous target ⇒ Regression

e.g. discriminating variable!

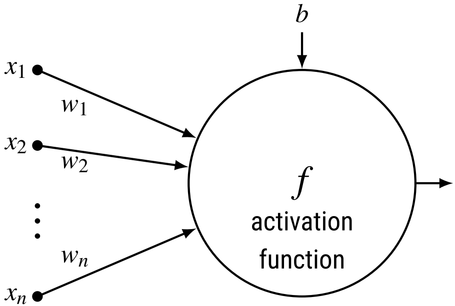
Linear case:



What if the target is not linear wrt. input?

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

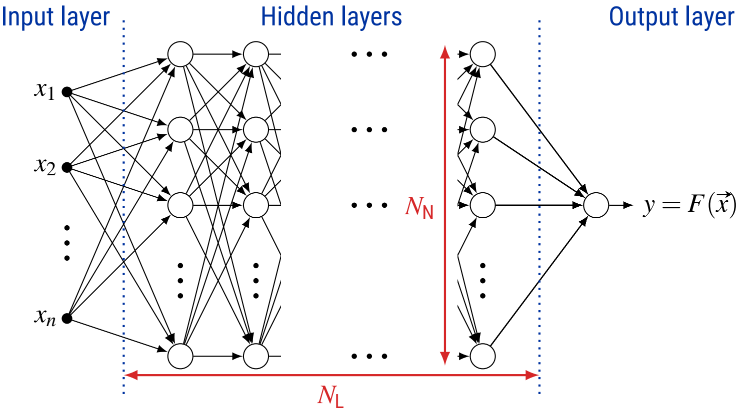
Neurons in ML



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

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

(Deep) Neural Networks

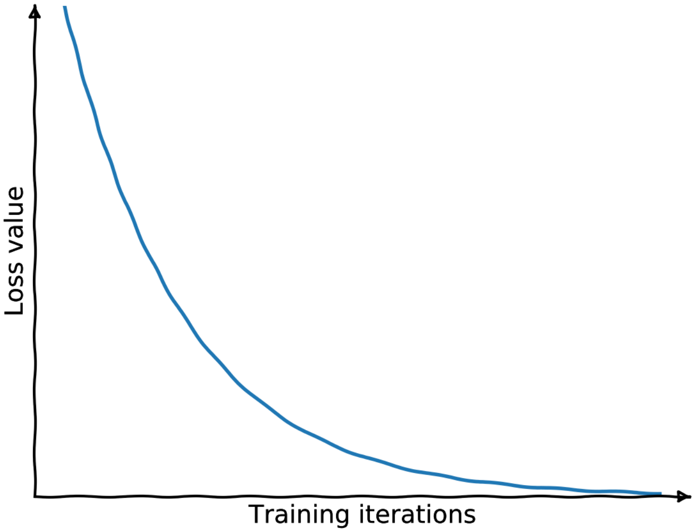


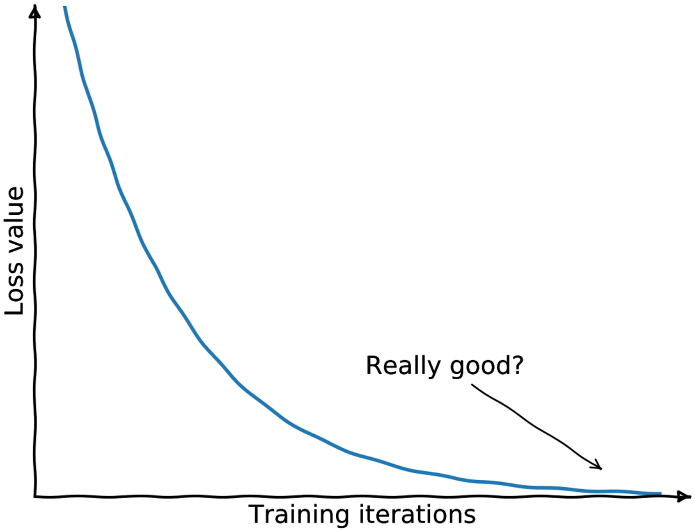
How to train a neural network?

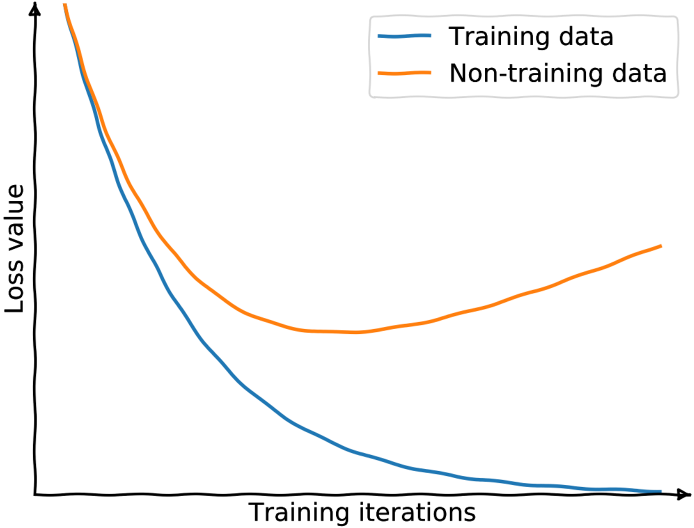
Train = optimize parameters $(w_1, w_2, \ldots, w_n, b)$ for each neuron.

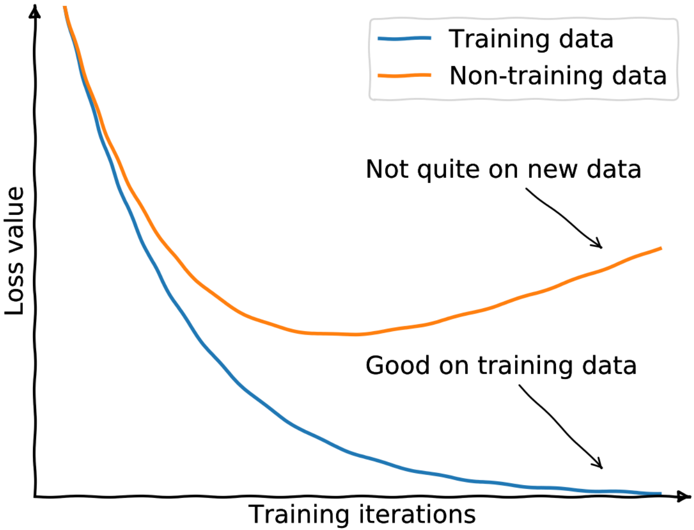
- Get a **training dataset** = examples of inputs $\vec{x}_i$ with corresponding outputs y_i
- Compare the model predictions $F(\vec{x}_i)$ to the true values y_i
  - Define a **loss function** $\mathfrak{L}$ such that its minimum is reached when $F(\vec{x}_i) = y_i$
  - Change the parameters a bit,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

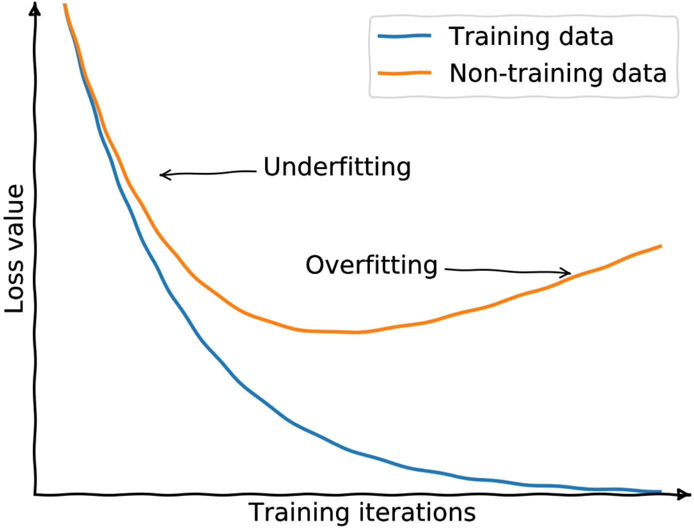
When to stop training?

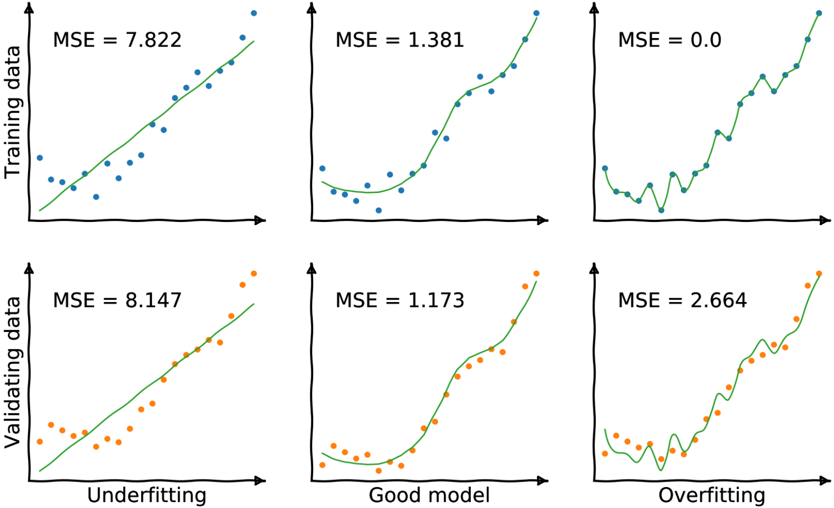

Loss value
Training iterations

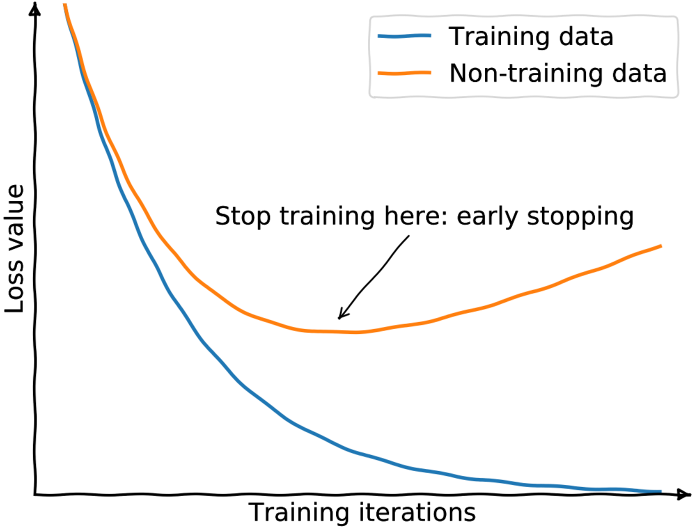

Loss value
Really good?
Training iterations

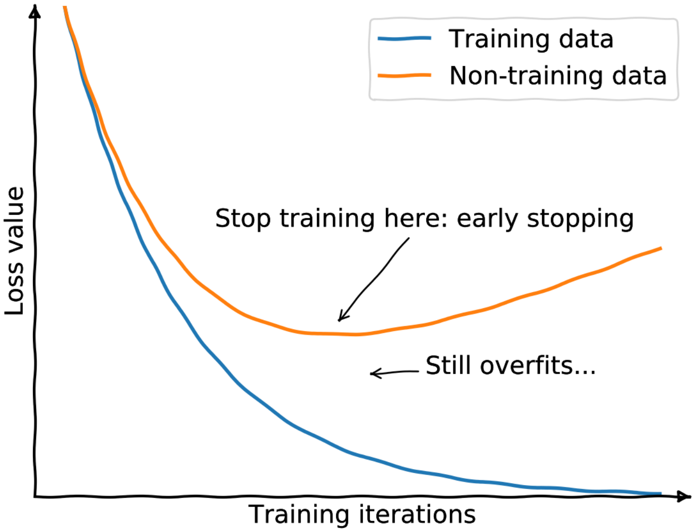

Training data
Non-training data
Loss value
Training iterations

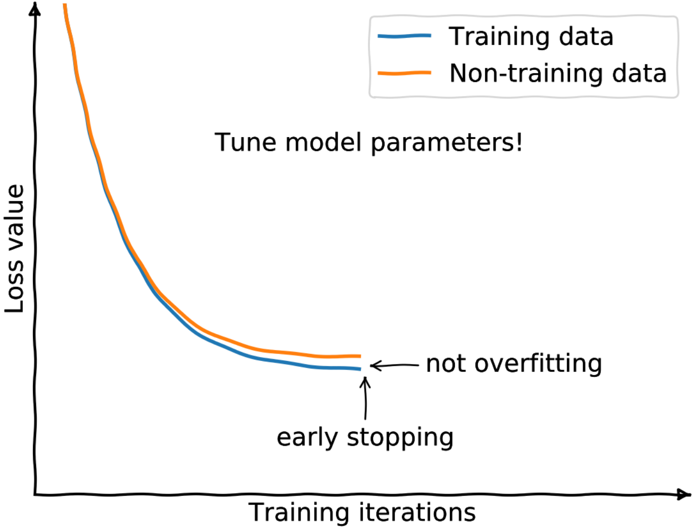

Training data
Non-training data
Not quite on new data
Good on training data
Loss value
Training iterations

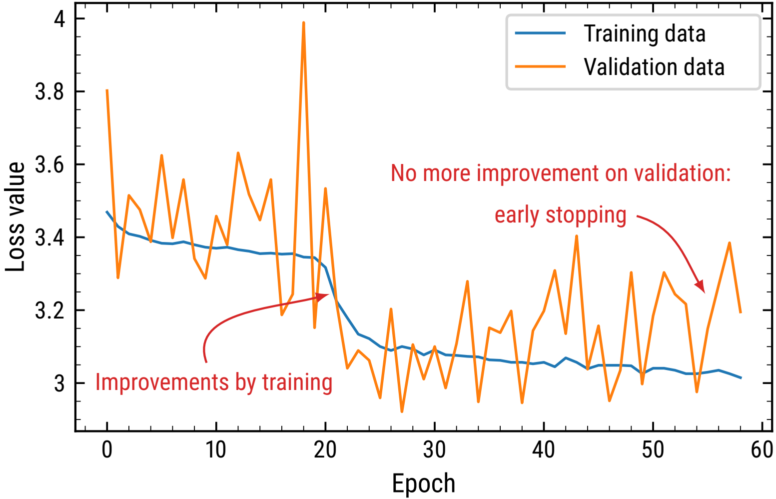

Training data
Non-training data
Underfitting
Overfitting
Loss value
Training iterations


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


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


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

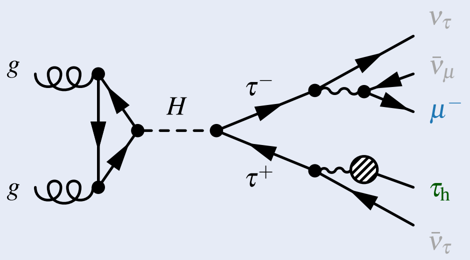

Training data
Non-training data
Tune model parameters!
Loss value
not overfitting
early stopping
Training iterations


Training data
Validation data
No more improvement on validation:
early stopping
Improvements by training
Loss value
Epoch
4
3.8
3.6
3.4
3.2
3
0
10
20
30
40
50
60

Build a neural network: target and inputs?

- Model target: generated Higgs mass.
- Model inputs:
  - τ_1 (here = μ^-) and τ_2 (here = τ_h) p_T, η, ϕ;
  - PuppiMET p_T, ϕ;
  - METcov xx, xy and yy;
  - Number of neutrinos from *reco* tau decays;
  - $m_\mathrm{T}^{(1,MET)}$, $m_\mathrm{T}^{(2,MET)}$, $m_\mathrm{T}^{(1,2)}$, $m_\mathrm{T}^{\mathrm{tot}}$ (Puppi);
  - jet 1, jet 2 p_T, η, ϕ;
  - Additionnal Hadronic Activity $p_\mathrm{T}, \eta, \phi, N_{\mathrm{jets}}^{\mathrm{AHA}}$;
  - `npvsGood` $\rightarrow$ how much PU.

$gg \rightarrow H \rightarrow \tau\tau \rightarrow \mu\tau_\mathrm{h}$



$$\boxed{m_\mathrm{T}^{\mathrm{tot}} = \sqrt{m_\mathrm{T}^2(\tau_1, E_\mathrm{T}^{\mathrm{miss}}) + m_\mathrm{T}^2(\tau_2, E_\mathrm{T}^{\mathrm{miss}}) + m_\mathrm{T}^2(\tau_1, \tau_2)}}, \quad m_\mathrm{T}(1,2) = \sqrt{2 p_T^{(1)} p_T^{(2)} (1 - \cos\Delta\phi)}$$

Build a neural network: hyperparameters?

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

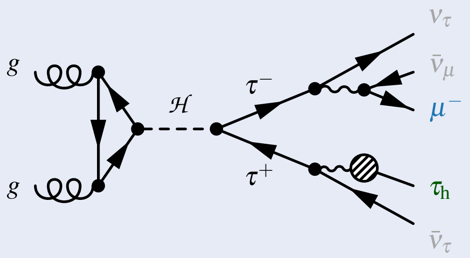
$$\mathit{softplus}(x) = \ln(1 + e^{x})$$

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

Datasets?

- Generate $\mathcal{H} \to \tau\tau$ events:
  - $\mathcal{H}$ is SM Higgs 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.
- All final states used simultaneously for training:
  - $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $\mu\mu$, $e\mu$, ee.

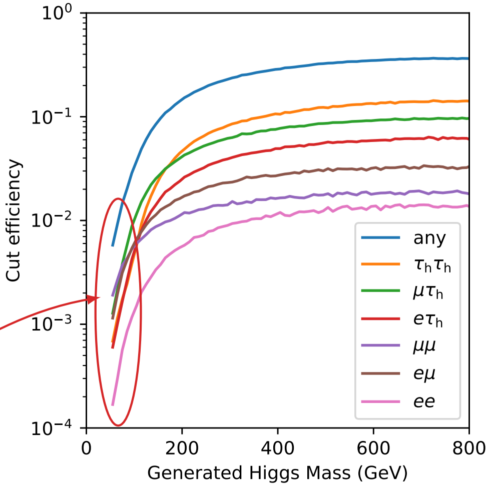
$gg \to \mathcal{H} \to \tau\tau \to \mu\tau_h$



Datasets: low mass boundary

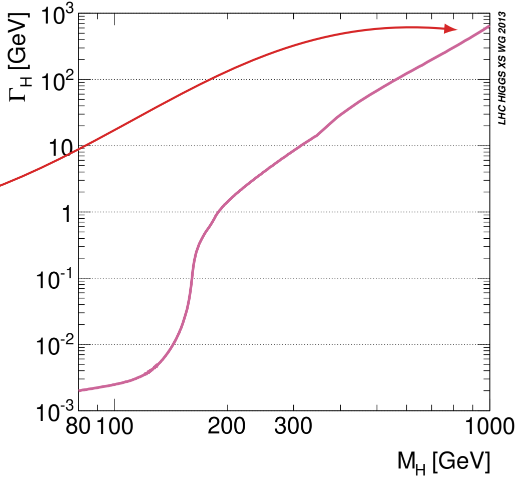
- Event selection:
  - Same as in the MSSM $H/A \to \tau\tau$ analysis,
  - Add $\mu\mu$ and ee channels.
- Events amount drops at low mass:
  - due to p_{T} cuts,
  - go down to $50\,\mathrm{GeV}$ for $m_{\mathcal{H}}$.

Less than $1\,\%$ pass the selection



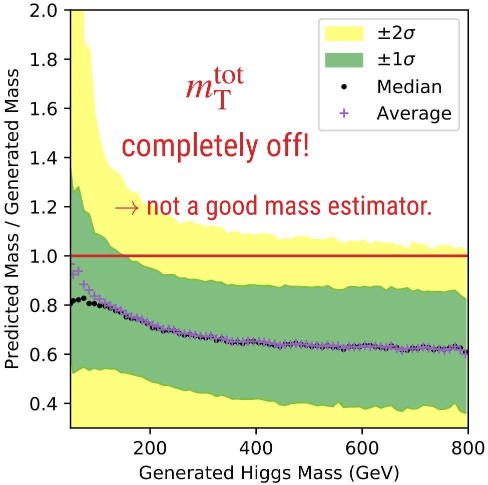
Datasets: high mass boundary

- Higgs width $\simeq$ Higgs mass around $1\,\mathrm{TeV}$:
  - can't have coherent mass points,
  - go up to $800\,\mathrm{GeV}$ for $m_{\mathcal{H}}$.



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

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

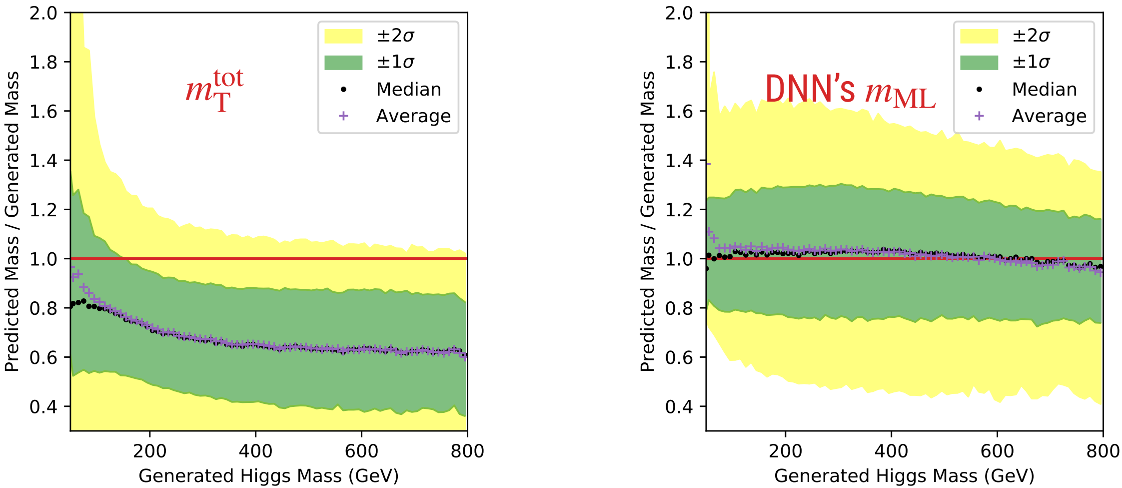


- Model's response:

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

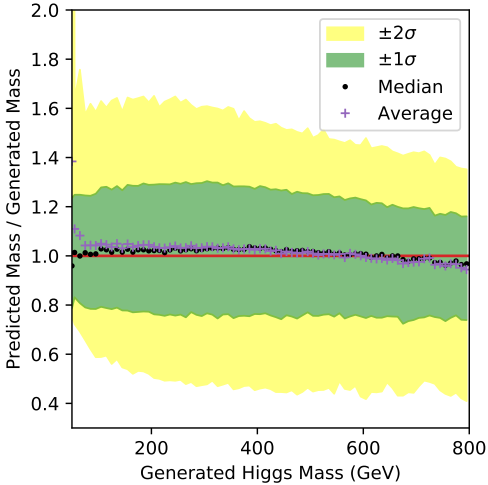
- Closer to 1 is better for black dots.

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



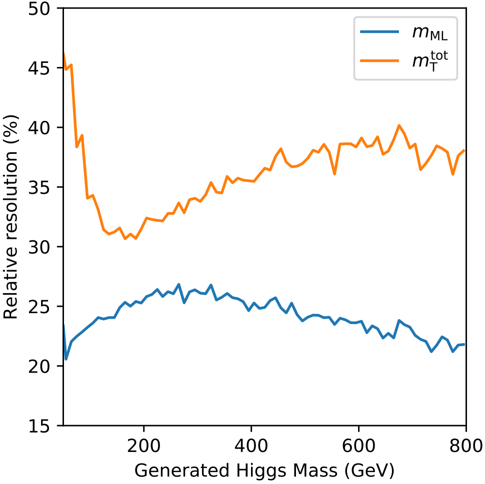
DNN's m_{ML} predictions *vs* $m_{\mathrm{T}}^{\mathrm{tot}}$

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

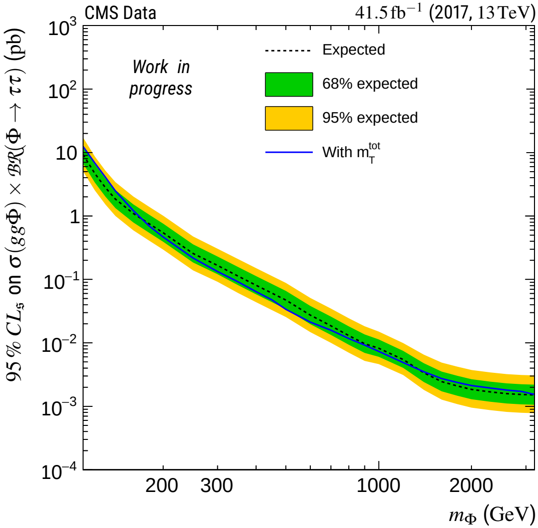


Using the model to get a discriminating variable

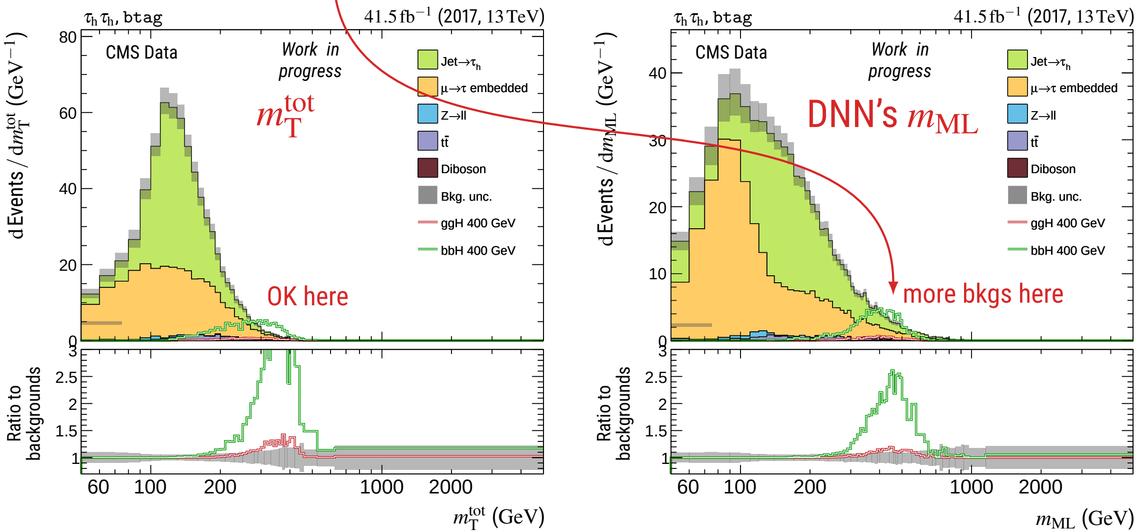
- In the $H/A \to \tau\tau$ analysis, discriminating variable $= m_{\mathrm{T}}^{\mathrm{tot}}$.
- $m_{\mathrm{T}}^{\mathrm{tot}}$ is equal to the invariant mass assuming:
  - all neutrinos are a single particle with $\vec{p}_{\mathrm{T}} = \vec{E}_{\mathrm{T}}^{\text{miss}}$,
  - all is going on in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



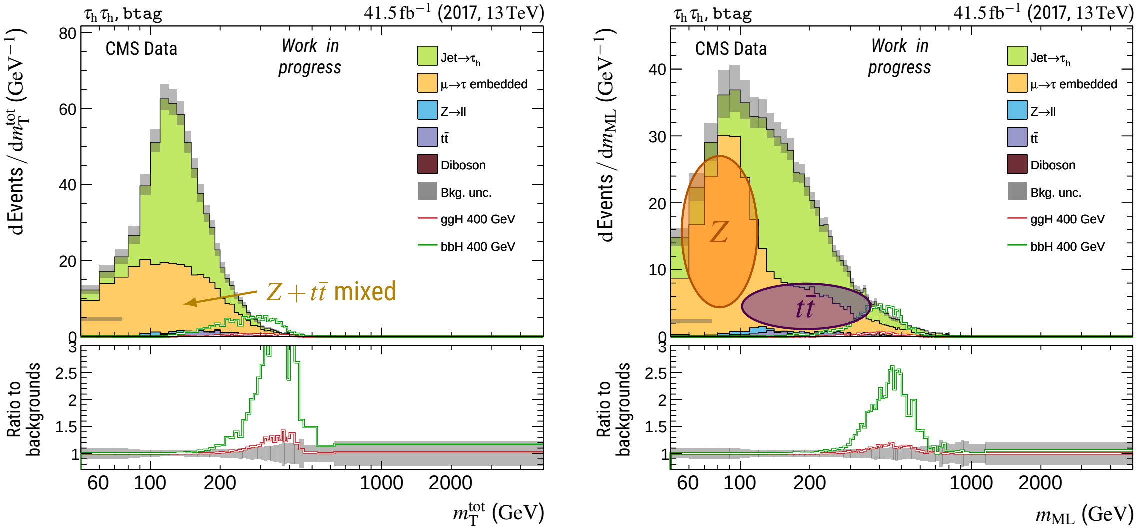
- Proceed to the search for massive Higgs boson Φ with di-τ events on the 2017 era.
- Use m_{ML} as discriminating variable.
- Not really better than with $m_{\mathrm{T}}^{\mathrm{tot}}$... Why?



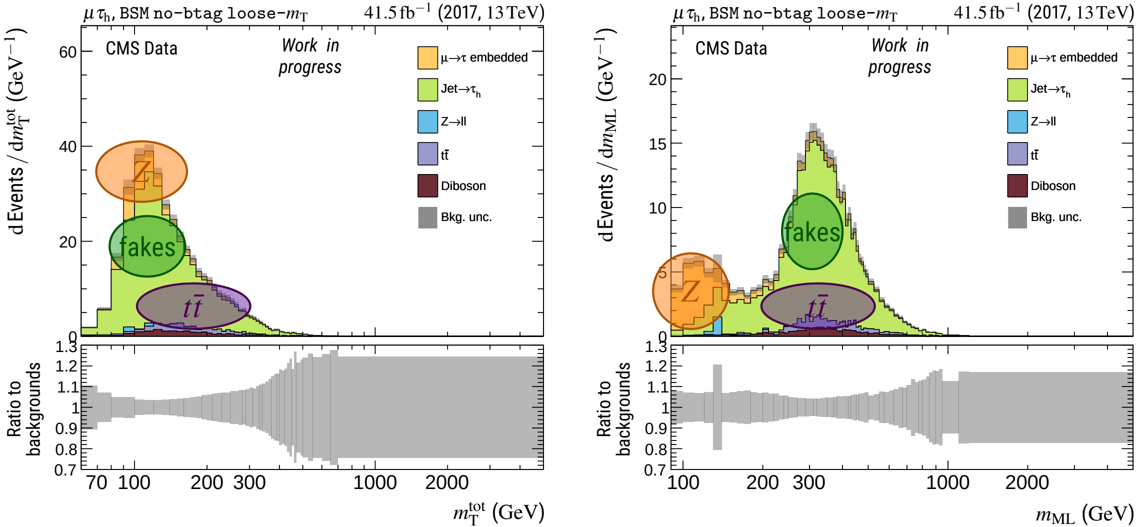
- Large fakes τ_h high mass tails falling into the signal region $\Rightarrow$ lowered signal to background ratio.



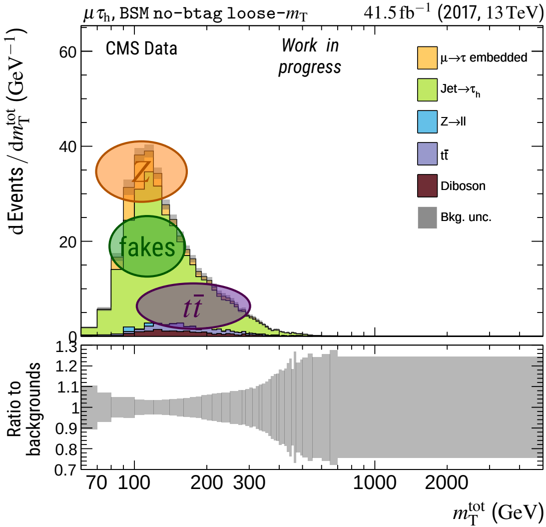
▶ **BUT** Z / $t\bar{t}$ separation! See the two m_{ML} embedded components, not present with $m_{\mathrm{T}}^{\mathrm{tot}}$.

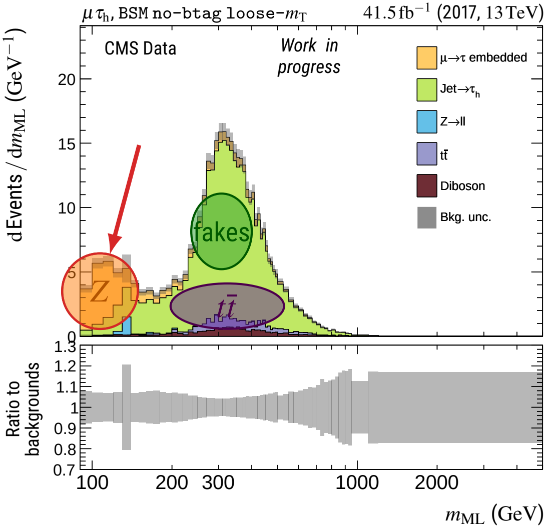


▶ Visible in other categories too. But here, the SVFIT mass is above $250\,\mathrm{GeV}$ and our model sees a Z signal!

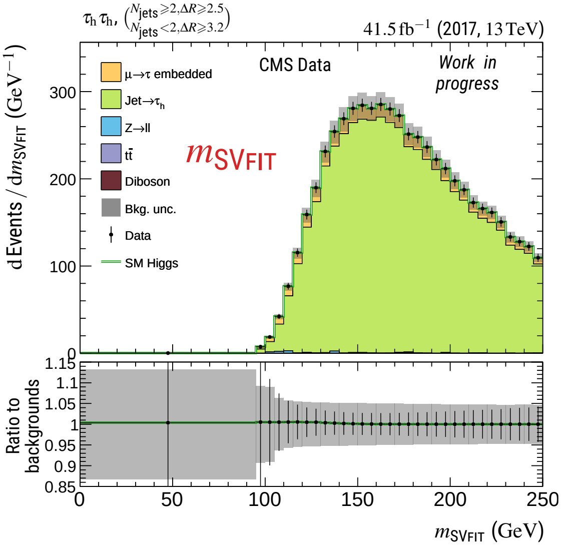


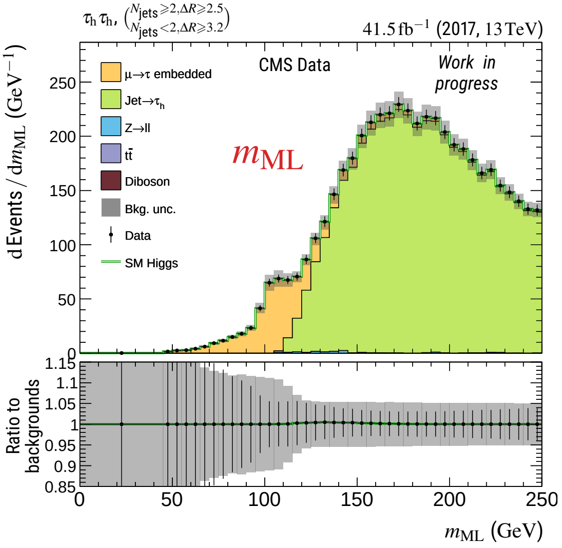
▶ Visible in other categories too. But here, the SVFIT mass is above $250\,\mathrm{GeV}$ and our model sees a Z signal!





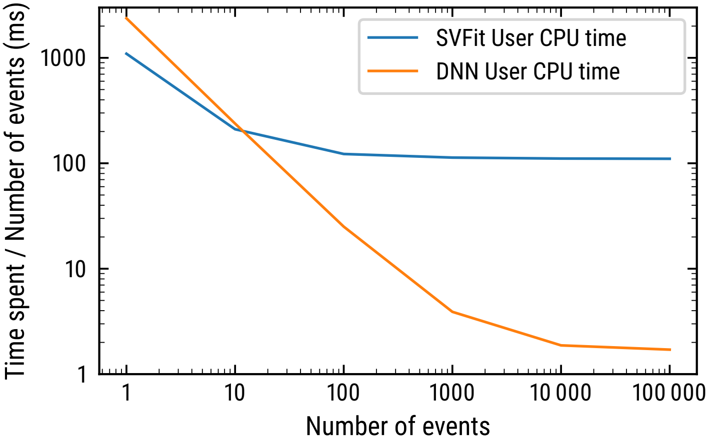
- Our model finds $Z \to \tau\tau$ events when SVFIT does not!





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

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



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

Merci !

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

- Colin
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- Felix

- Daniel
- David
- Georges

- Aleksei
- Mareike

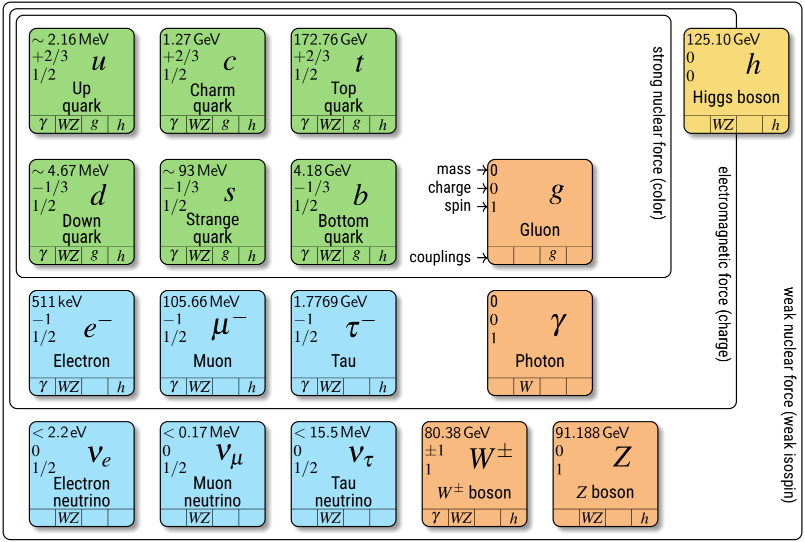
- Janik
- Suman

CERN Cantina cheatsheet

German word	French word	Say it like
Bohnen	haricots	ariko
Karotten	carottes	karot
Spinat	épinards	epinar
Lauch	poireaux	poaro
Zucchini	courgettes	kurjett
Reis	riz	ri
Nudeln	pâtes	pat
Grieß	semoule	semul
Pommes	frites	frit
Äpfel	pommes	pom
mehr	plus	plüss
bitte	s'il vous plaît	sil vu plä
danke	merci	mersi

- Phenomenology:
  - SM, SUSY, 2HDM, $\tan\beta$ slide 53
  - How histograms unveil particles slide 58
- JERC with $\gamma +$ jets events:
  - Jet energy calibration slide 64
  - Jet energy resolution slide 72
- MSSM $H/A \to \tau\tau$:
  - Triggers in the $\tau_h\tau_h$ channel slide 73
  - Fake factors for subleading τ_h slide 74
- Machine Learning:
  - Custom loss function for the DNN slide 75

The Standard Model



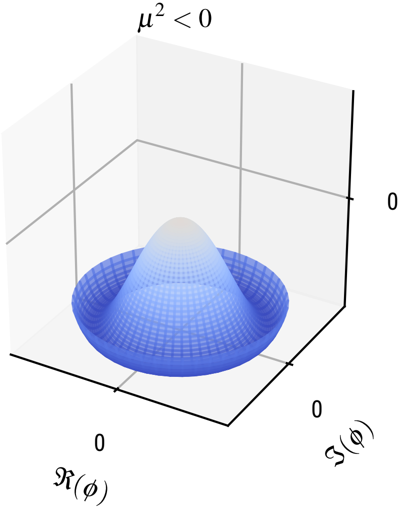
Higgs boson in the Standard Model

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

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

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

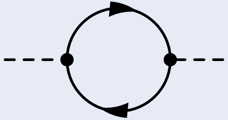
$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



The Standard Model and naturalness problem

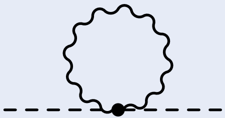
- Higgs mass measured: $m_h = 125.10 \pm 0.14\,\mathrm{GeV}$
- Higgs mass derivation: $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \ldots$

top quark



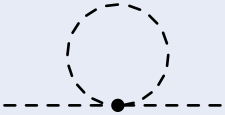
$$-\frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim -(2\,\mathrm{TeV})^2$$

vector bosons



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

Higgs itself

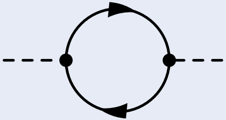


$$+\frac{1}{16\pi^2} \lambda^2 \Lambda^2 \sim +(0.5\,\mathrm{TeV})^2$$

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

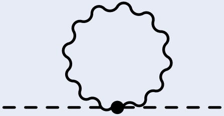
Supersymmetry

top quark



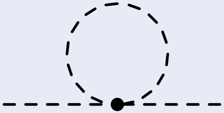
$\sim -(2\,\mathrm{TeV})^2$

vector bosons



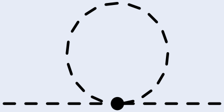
$\sim +(0.7\,\mathrm{TeV})^2$

Higgs itself



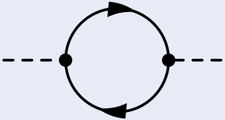
$\sim +(0.5\,\mathrm{TeV})^2$

stop quark



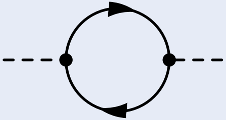
$\sim +(2\,\mathrm{TeV})^2$

bosinos



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

Higgsinos



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

2 Higgs doublets models for supersymmetry

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

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

▷ 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`.

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.

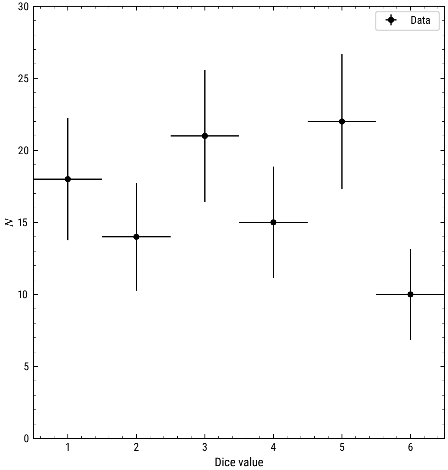
The rabbit analogy

- 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 $\longrightarrow$

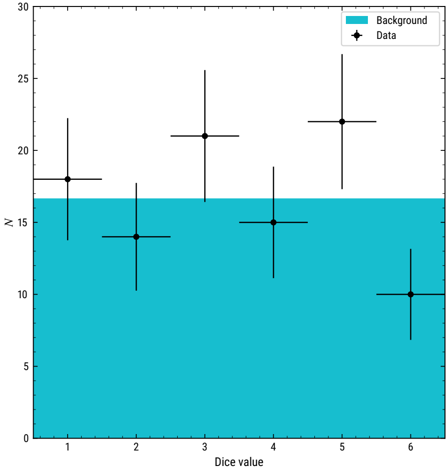


Not really conclusive...

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

The rabbit analogy

On 100 days $\longrightarrow$

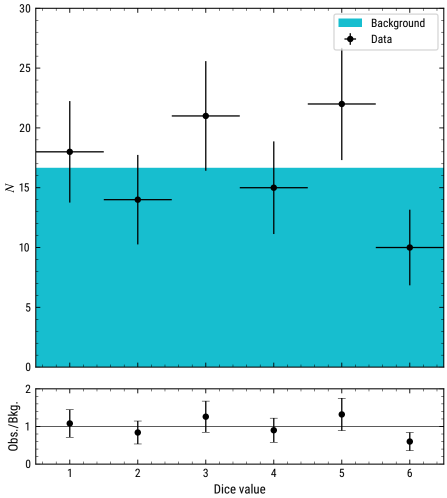


Comparing with predictions!

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

The rabbit analogy

On 100 days →

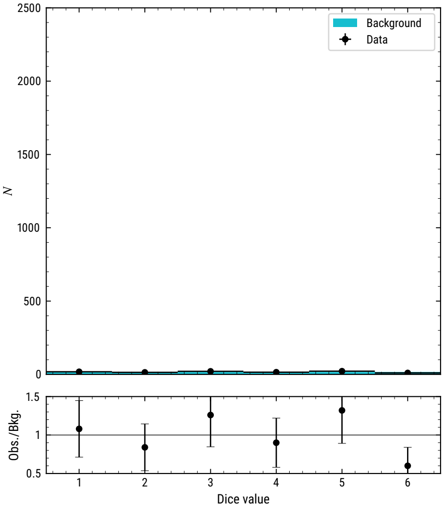


Also add ratio plot: observed / predictions

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

The rabbit analogy

On 100 days →

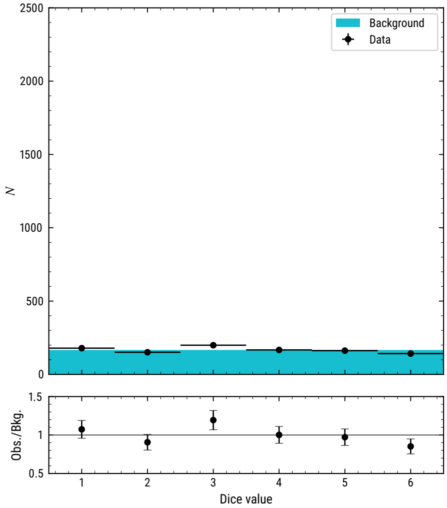


Fill up with more data!

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

The rabbit analogy

On 1000 days $\longrightarrow$

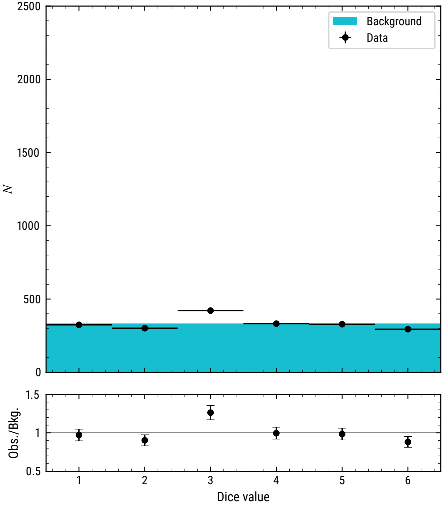


Fill up with more data!

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

The rabbit analogy

On 2000 days →

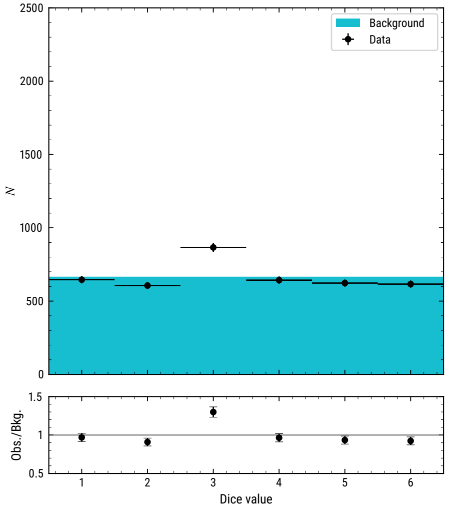


Fill up with more data!

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

The rabbit analogy

On 4000 days →

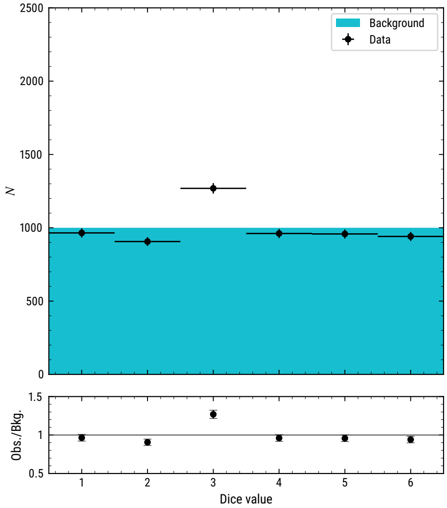


Fill up with more data!

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

The rabbit analogy

On 6000 days →

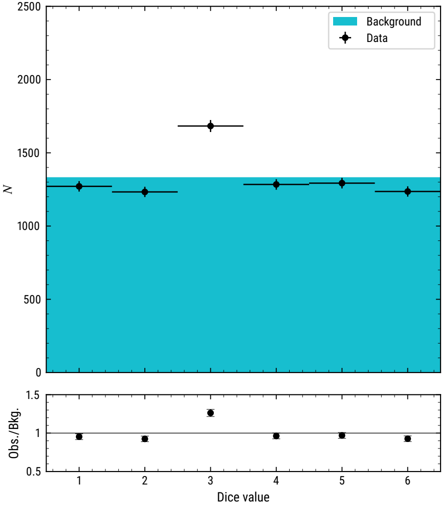


Fill up with more data!

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

The rabbit analogy

On 8000 days $\longrightarrow$

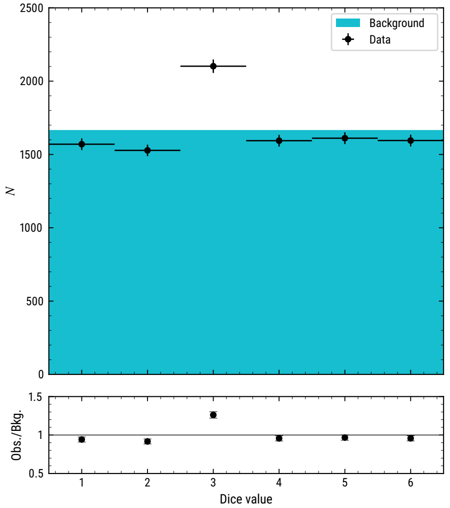


Fill up with more data!

▷ 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 →

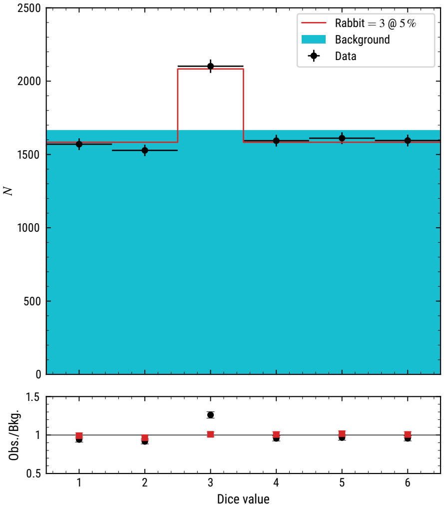


Fill up with more data!

▷ 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 $\rightarrow$

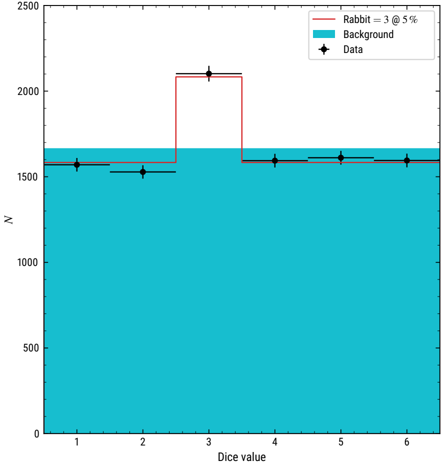


In red, hypothesis of the rabbit with 3 as preferred result (instead of 4!), with a probability to show up of $5\,\%$.

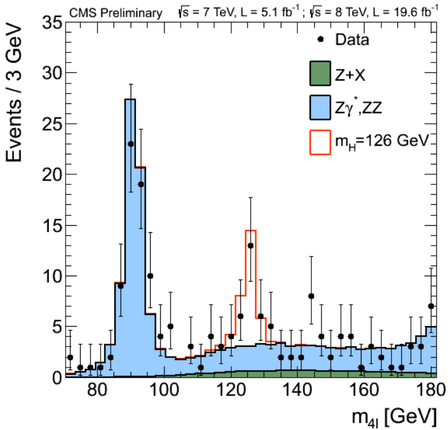
▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: `https://www.youtube.com/watch?v=8-WFBGCvv-w`.

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

- Levels of knowledge

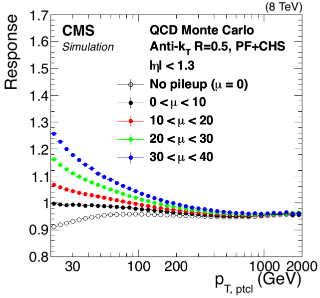
particle	(ptcl)
reconstructed	(reco)
corrected	(corr)

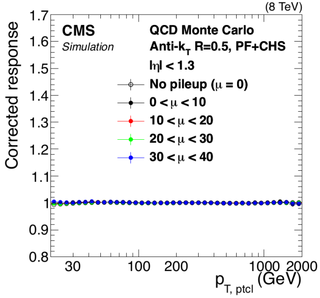
- Jet response

$$R = \frac{p_\mathrm{T}}{p_{\mathrm{T}\,\mathsf{ptcl}}}$$

Reconstructed Jets

Calibrated Jets



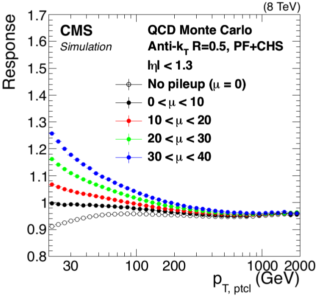


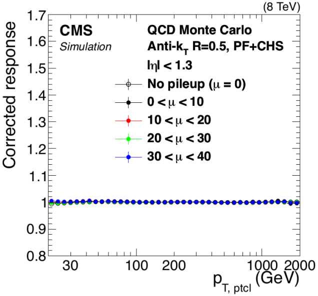
Applied to data

Reconstructed Jets

Calibrated Jets

Applied to simulation





Applied to data

Reconstructed Jets

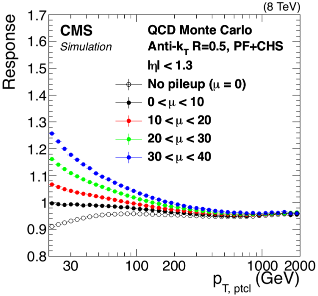
Pileup

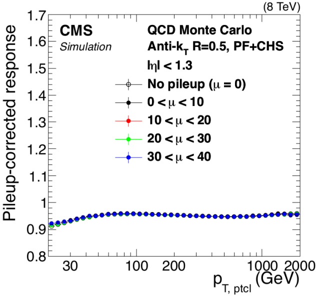
MC+RC

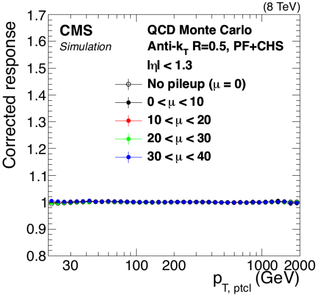
MC

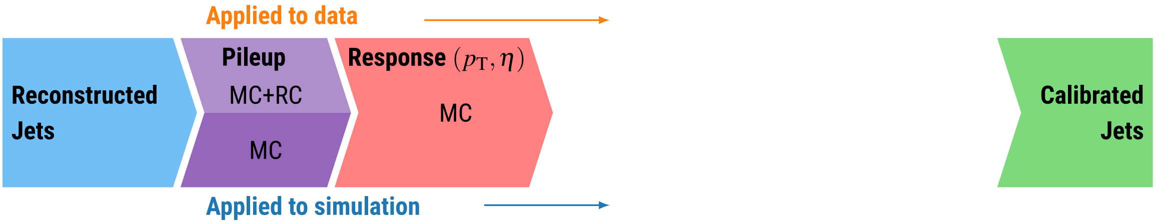
Calibrated Jets

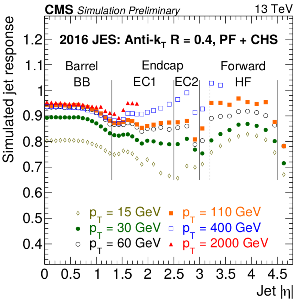
Applied to simulation

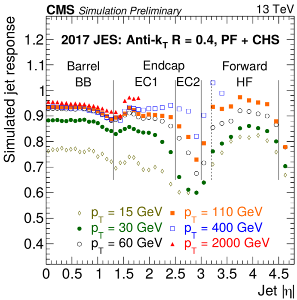







Applied to data
Reconstructed Jets
Pileup
MC+RC
MC
Response (p_T, η)
MC
Calibrated Jets
Applied to simulation


CMS Simulation Preliminary
13 TeV
2016 JES: Anti-k$_T$ R = 0.4, PF + CHS
Barrel
BB
Endcap
EC1
EC2
Forward
HF
p_T = 15 GeV
p_T = 30 GeV
p_T = 60 GeV
p_T = 110 GeV
p_T = 400 GeV
p_T = 2000 GeV
Simulated jet response
Jet |η|


CMS Simulation Preliminary
13 TeV
2017 JES: Anti-k$_T$ R = 0.4, PF + CHS
Barrel
BB
Endcap
EC1
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HF
p_T = 15 GeV
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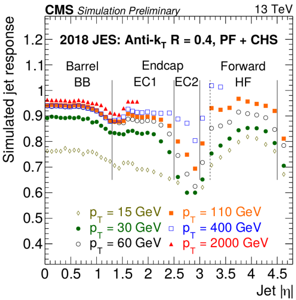
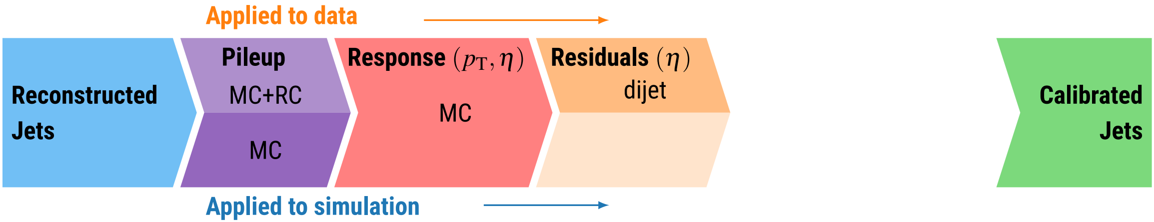
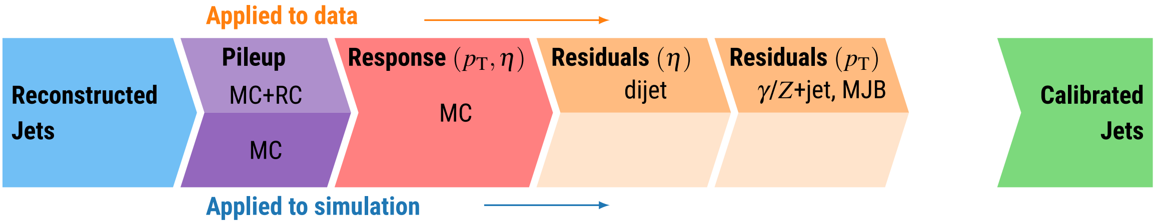
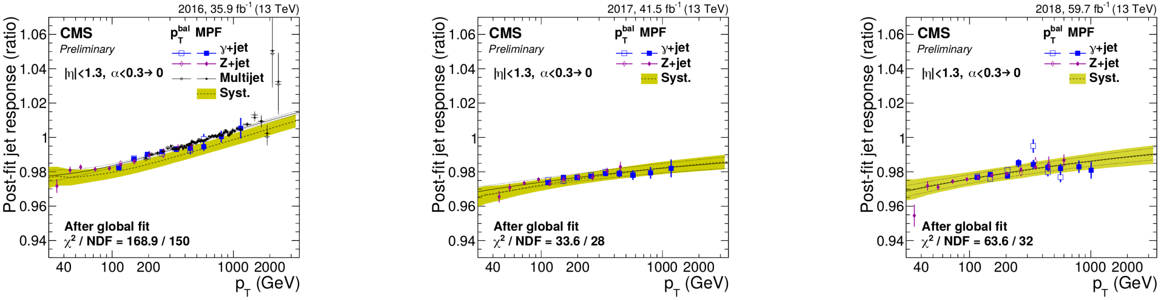
p_T = 60 GeV
p_T = 110 GeV
p_T = 400 GeV
p_T = 2000 GeV
Simulated jet response
Jet |η|


CMS Simulation Preliminary
13 TeV
2018 JES: Anti-k$_T$ R = 0.4, PF + CHS
Barrel
BB
Endcap
EC1
EC2
Forward
HF
p_T = 15 GeV
p_T = 30 GeV
p_T = 60 GeV
p_T = 110 GeV
p_T = 400 GeV
p_T = 2000 GeV
Simulated jet response
Jet |η|


Applied to data
Reconstructed Jets
Pileup
MC+RC
MC
Response (p_{T}, η)
MC
Residuals (η)
dijet
Calibrated Jets
Applied to simulation

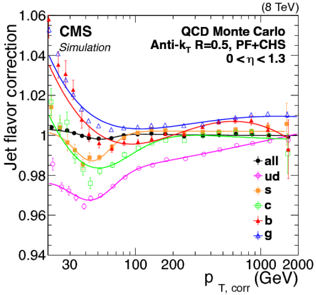

Applied to data
Reconstructed Jets
Pileup
MC+RC
MC
Response (p_T, η)
MC
Residuals (η)
dijet
Residuals (p_T)
γ/Z+jet, MJB
Calibrated Jets
Applied to simulation

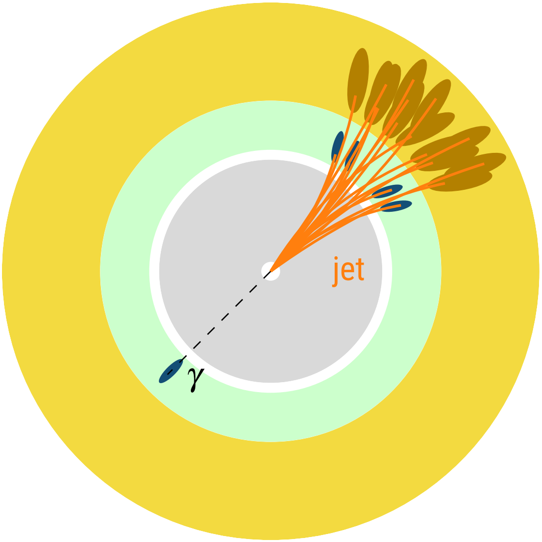

2016, 35.9 fb^{-1} (13 TeV)
CMS
Preliminary
$|\eta|<1.3$, $\alpha<0.3\rightarrow 0$
p_T^{bal} MPF
γ+jet
Z+jet
Multijet
Syst.
After global fit
χ^2 / NDF = 168.9 / 150
Post-fit jet jet response (ratio)
p_T (GeV)
2017, 41.5 fb^{-1} (13 TeV)
CMS
Preliminary
$|\eta|<1.3$, $\alpha<0.3\rightarrow 0$
p_T^{bal} MPF
γ+jet
Z+jet
Syst.
After global fit
χ^2 / NDF = 33.6 / 28
2018, 59.7 fb^{-1} (13 TeV)
CMS
Preliminary
$|\eta|<1.3$, $\alpha<0.3\rightarrow 0$
p_T^{bal} MPF
γ+jet
Z+jet
Syst.
After global fit
χ^2 / NDF = 63.6 / 32

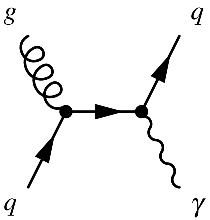
Applied to data →

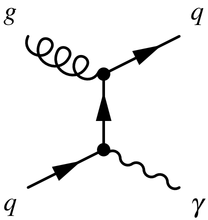
Reconstructed Jets	**Pileup** MC+RC / MC	**Response** (p_T, η) MC	**Residuals** (η) dijet	**Residuals** (p_T) γ/Z+jet, MJB	**Flavor** MC	**Calibrated Jets**

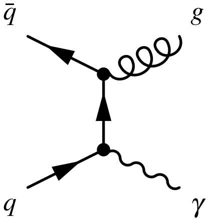
Applied to simulation →

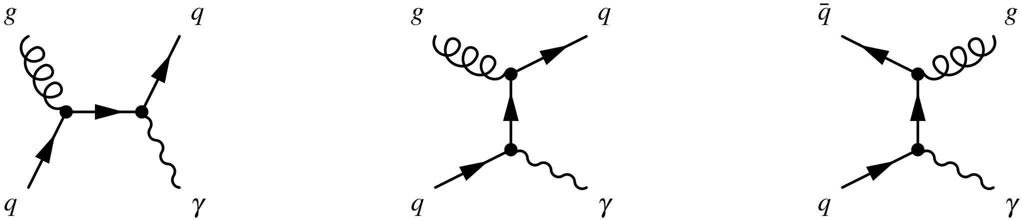



jet
γ

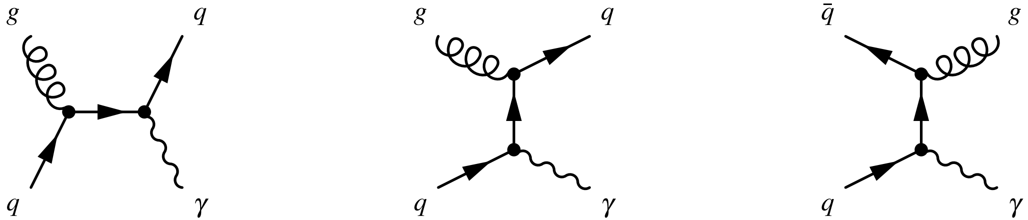

g
q
q
γ


g
q
q
γ


$\bar{q}$
g
q
γ

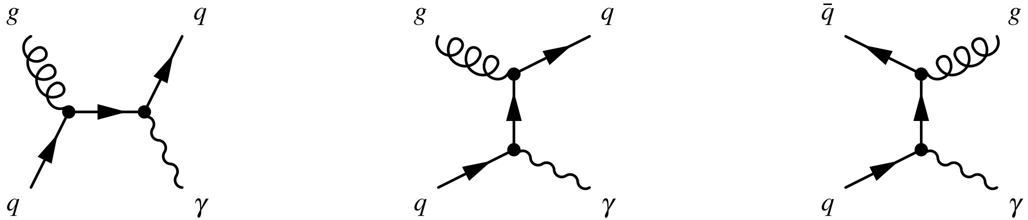


$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}} = \vec{0} \Rightarrow p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} = p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}$$



$$\vec{p}_{\mathrm{T}\,\mathrm{ptcl}}^{\,\gamma} + \vec{p}_{\mathrm{T}\,\mathrm{ptcl}}^{\,\mathrm{jet}} = \vec{0} \Rightarrow p_{\mathrm{T}\,\mathrm{ptcl}}^{\,\gamma} = p_{\mathrm{T}\,\mathrm{ptcl}}^{\,\mathrm{jet}}$$

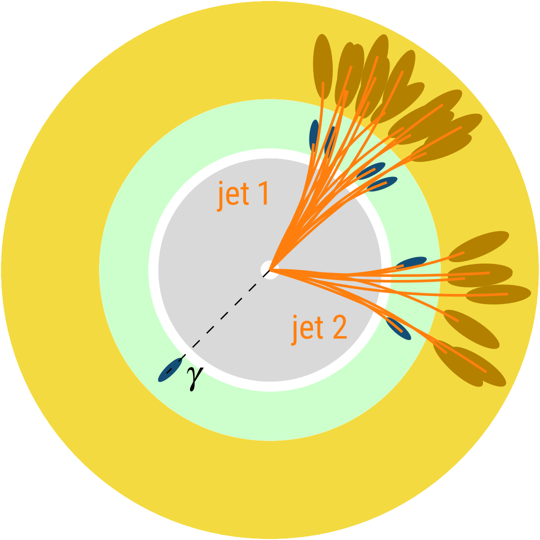
$$R = \frac{p_{\mathrm{T}\,\mathrm{reco}}^{\,\mathrm{jet}}}{p_{\mathrm{T}\,\mathrm{ptcl}}^{\,\mathrm{jet}}} = \frac{p_{\mathrm{T}\,\mathrm{reco}}^{\,\mathrm{jet}}}{p_{\mathrm{T}\,\mathrm{ptcl}}^{\,\gamma}} \simeq \frac{p_{\mathrm{T}\,\mathrm{reco}}^{\,\mathrm{jet}}}{p_{\mathrm{T}\,\mathrm{reco}}^{\,\gamma}}$$

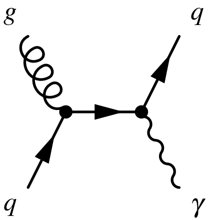


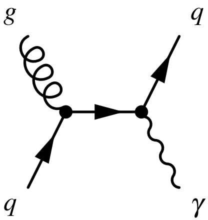
$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\text{jet}}_{\text{ptcl}} = \vec{0} \Rightarrow p_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}} = p_{\mathrm{T}}{}^{\text{jet}}_{\text{ptcl}}$$

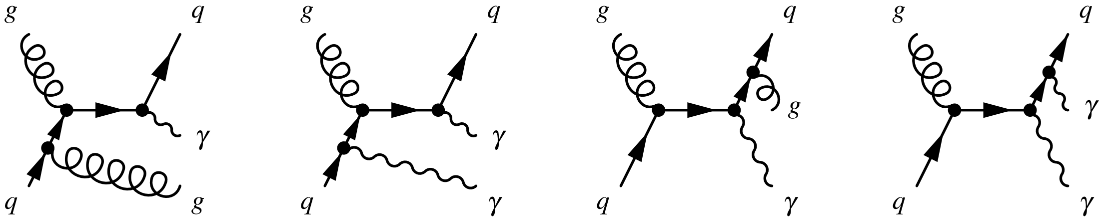
$$R = \frac{p_{\mathrm{T}}{}^{\text{jet}}_{\text{reco}}}{p_{\mathrm{T}}{}^{\text{jet}}_{\text{ptcl}}} = \frac{p_{\mathrm{T}}{}^{\text{jet}}_{\text{reco}}}{p_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}}} \simeq \frac{p_{\mathrm{T}}{}^{\text{jet}}_{\text{reco}}}{p_{\mathrm{T}}{}^{\gamma}_{\text{reco}}}$$

$$R_{bal} = \frac{p_{\mathrm{T}}{}^{\text{jet}}_{\text{reco}}}{p_{\mathrm{T}}{}^{\gamma}}$$


jet 1
jet 2
γ


g
q
q
γ


g
q
q
γ


g
q
γ
q
g
g
q
γ
q
γ
g
q
g
q
γ
g
q
γ
q
γ

$$R_{bal} = \frac{p_{\mathrm{T}}{}^{\text{jet 1}}_{\text{reco}}}{p_{\mathrm{T}}{}^{\gamma}}$$

$$\alpha = \frac{p_{\mathrm{T}}{}^{\text{jet 2}}_{\text{reco}}}{p_{\mathrm{T}}{}^{\gamma}}$$

$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\text{recoil}}_{\text{ptcl}} = \vec{0}$$

$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\text{recoil}}_{\text{ptcl}} = \vec{0}$$

$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\text{reco}} + \underbrace{R_{MPF}\,\vec{p}_{\mathrm{T}}{}^{\text{recoil}}_{\text{ptcl}}}_{\vec{p}_{\mathrm{T}}{}^{\text{recoil}}_{\text{reco}}} = -\vec{E}_{\mathrm{T}}^{\text{miss}} \Rightarrow \boxed{R_{MPF} = 1 + \frac{\vec{p}_{\mathrm{T}}{}^{\gamma} \cdot \vec{E}_{\mathrm{T}}^{\text{miss}}}{|\vec{p}_{\mathrm{T}}{}^{\gamma}|^2}}$$

Jet Energy Resolution

- Remember R_{bal} definition,

$$R_{bal} = \frac{p_{\mathrm{T}\,\mathrm{reco}}^{1^{\mathrm{st}}\mathrm{jet}}}{p_{\mathrm{T}\,\mathrm{reco}}^{\gamma}}$$

Jet Energy Resolution

- Remember R_{bal} definition,

$$R_{bal} = \frac{p_{\mathrm{T}\,\text{reco}}^{\,1^{\text{st}}\text{jet}}}{p_{\mathrm{T}\,\text{reco}}^{\,\gamma}}$$

Then

$$R_{bal} = \underbrace{\frac{p_{\mathrm{T}\,\text{reco}}^{\,1^{\text{st}}\text{jet}}}{p_{\mathrm{T}\,\text{ptcl}}^{\,1^{\text{st}}\text{jet}}}}_{\sigma_{\text{jet}}=\text{JER}} \times \underbrace{\frac{p_{\mathrm{T}\,\text{ptcl}}^{\,1^{\text{st}}\text{jet}}}{p_{\mathrm{T}\,\text{ptcl}}^{\,\gamma}}}_{\text{PLI}} \times \underbrace{\frac{p_{\mathrm{T}\,\text{ptcl}}^{\,\gamma}}{p_{\mathrm{T}\,\text{reco}}^{\,\gamma}}}_{\sigma_{\gamma}\equiv 1}$$

- PLI: Particle Level Imbalance (pile-up, radiations, neutrinos...), $\rightarrow 0$ when $\alpha \rightarrow 0$.

Jet Energy Resolution

- Remember R_{bal} definition,

$$R_{bal} = \frac{p_{\mathrm{T}\,\mathrm{reco}}^{1^{\mathrm{st}}\mathrm{jet}}}{p_{\mathrm{T}\,\mathrm{reco}}^{\gamma}}$$

Then

$$R_{bal} = \underbrace{\frac{p_{\mathrm{T}\,\mathrm{reco}}^{1^{\mathrm{st}}\mathrm{jet}}}{p_{\mathrm{T}\,\mathrm{ptcl}}^{1^{\mathrm{st}}\mathrm{jet}}}}_{\sigma_{\mathrm{jet}}=\mathrm{JER}} \times \underbrace{\frac{p_{\mathrm{T}\,\mathrm{ptcl}}^{1^{\mathrm{st}}\mathrm{jet}}}{p_{\mathrm{T}\,\mathrm{ptcl}}^{\gamma}}}_{\mathrm{PLI}} \times \underbrace{\frac{p_{\mathrm{T}\,\mathrm{ptcl}}^{\gamma}}{p_{\mathrm{T}\,\mathrm{reco}}^{\gamma}}}_{\sigma_{\gamma}\equiv 1}$$

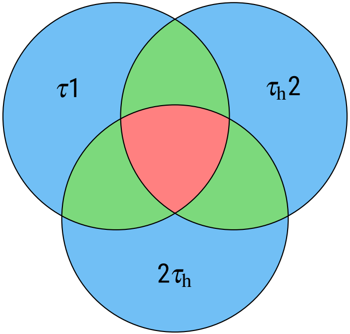
- PLI: Particle Level Imbalance (pile-up, radiations, neutrinos...), $\to 0$ when $\alpha \to 0$.

$$\boxed{\mathrm{JER} = \sigma_{\mathrm{jet}} = \sqrt{\sigma_{R_{bal}}^2 - \sigma_{\mathrm{PLI}}^2}}$$

Triggers in the $\tau_h \tau_h$ channel

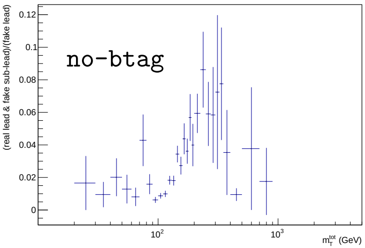
- In the manuscript: page 118, formula (4.5)

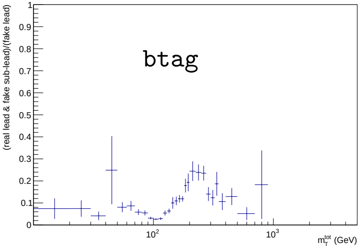
$$\begin{aligned}\varepsilon = {} & \varepsilon(2\tau_h) + \varepsilon(\tau_h 1) + \varepsilon(\tau_h 2) \\ & - \varepsilon(2\tau_h + \tau_h 1) - \varepsilon(2\tau_h + \tau_h 1) - \varepsilon(\tau_h 1 + \tau_h 2) \\ & + \varepsilon(2\tau_h + \tau_h 1 + \tau_h 2)\end{aligned}$$



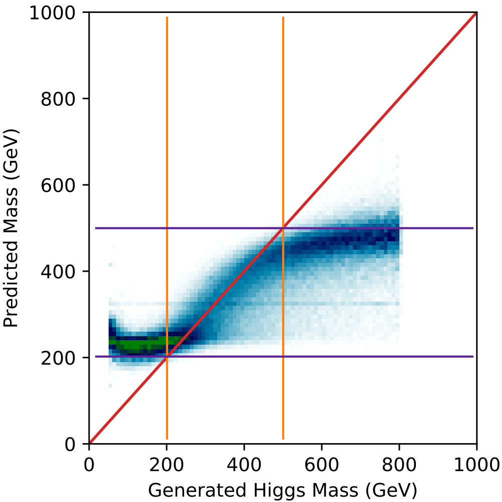
Fake factors for subleading τ_h

- 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 $t\bar{t}$):

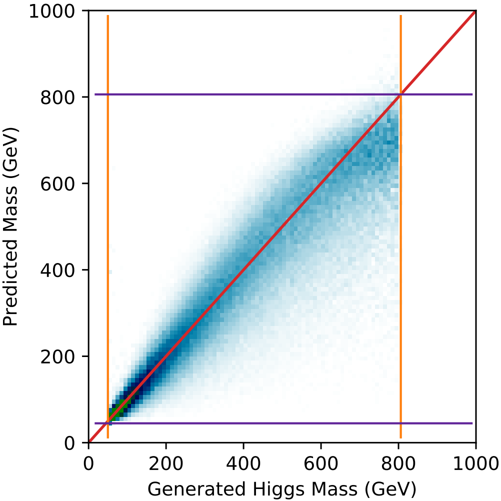




▷ J. Andrejkovic et al. "BSM $H \to \tau\tau$ analysis on full Run 2 CMS data at $\sqrt{s} = 13\,\text{TeV}$". *CMS analysis Note* (2021). URL: https://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%5C%20AN-2020/218.

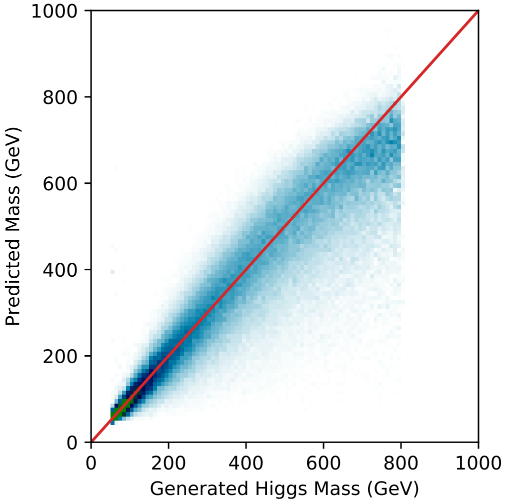


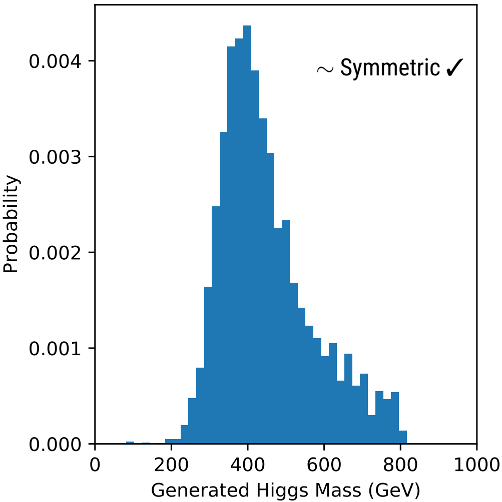
1000
800
600
400
200
0
0
200
400
600
800
1000
Predicted Mass (GeV)
Generated Higgs Mass (GeV)

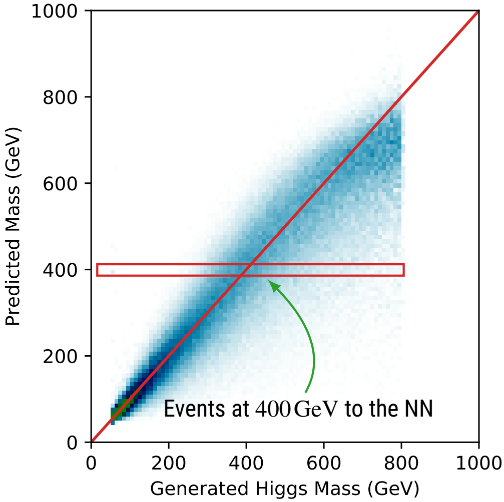


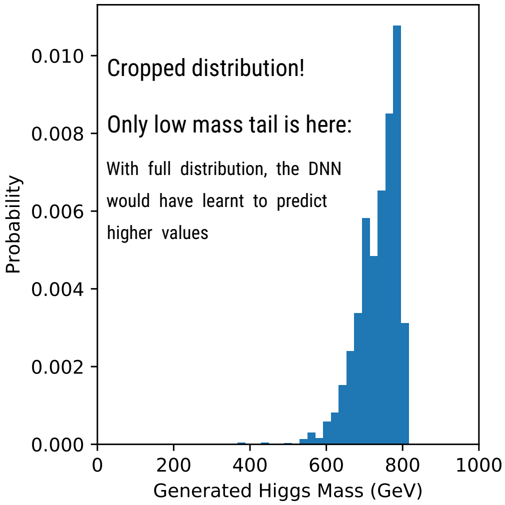
1000
800
600
400
200
0
0
200
400
600
800
1000
Predicted Mass (GeV)
Generated Higgs Mass (GeV)

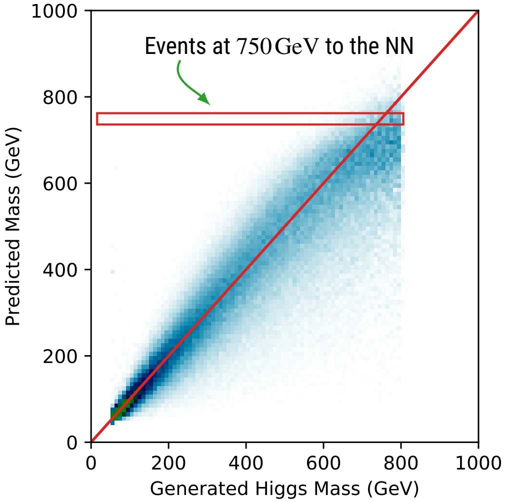
- How to cope with the boundaries?
  - Bias to be balanced,
  - Extend the mass range?
    - Would be nice!
    - Not always feasible...
- Every horizontal slice is one predicted value:
  - "Same family" of events to the NN.

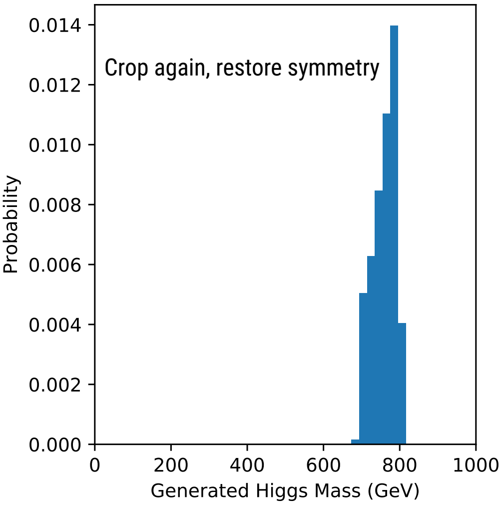


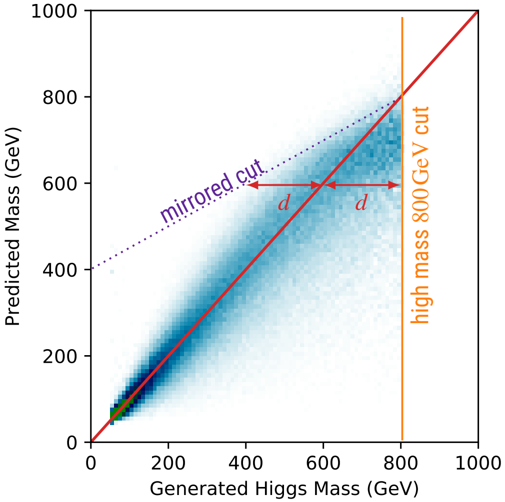

~ Symmetric ✓
Probability
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
Generated Higgs Mass (GeV)


Predicted Mass (GeV)
1000
800
600
400
200
0
Events at $400\,\mathrm{GeV}$ to the NN
0
200
400
600
800
1000
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
0.010
0.008
0.006
0.004
0.002
0.000
0 200 400 600 800 1000
Generated Higgs Mass (GeV)


Events at $750\,\mathrm{GeV}$ to the NN
Predicted Mass (GeV)
1000
800
600
400
200
0
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)

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

$$\mathfrak{L}_{\mathrm{MA}\sqrt{\mathrm{PE}}}(y_{\text{true}}, y_{\text{pred}}) = \mathfrak{L}_{\mathrm{MAPE}}(y_{\text{true}}, y_{\text{pred}}) \times \sqrt{y_{\text{true}}} = \left| \frac{y_{\text{pred}} - y_{\text{true}}}{y_{\text{true}}} \right| \times \sqrt{y_{\text{true}}}$$

$$\Leftrightarrow \mathfrak{L}_{\mathrm{MA}\sqrt{\mathrm{PE}}}(y_{\text{true}}, y_{\text{pred}}) = \left| \frac{y_{\text{pred}} - y_{\text{true}}}{\sqrt{y_{\text{true}}}} \right| .$$