MINISTÈRE
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ÉCOLE DOCTORALE 52
PHAST
PHYSIQUE ET ASTROPHYSIQUE
UNIVERSITÉ DE LYON

UNIVERSITÉ DE LYON
Lyon 1

Recherche d'un boson de Higgs de haute masse se désintégrant en paire de taus dans l'expérience CMS au LHC

Soutenance de thèse de doctorat

Lucas TORTEROTOT

Institut de Physique des deux Infinis – Lyon

XX xxxx 2021

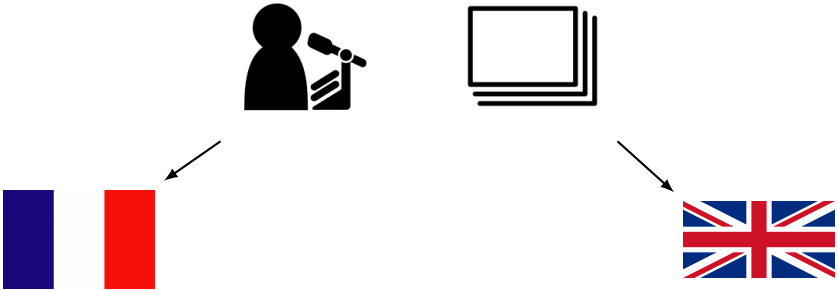
cnrs IN2P3 Les deux infinis

CERN

CMS

iP2I LES 2 INFINIS LYON

Lang(u)age



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Lyon 1

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

Ph.D. thesis defense

Lucas TORTEROTOT

Institut de Physique des deux Infinis – Lyon

xxxx XXst/nd/rd/th 2021

cnrs IN2P3 Les deux infinis

CERN

CMS

iP2I LES 2 INFINIS LYON

Keywords in title

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

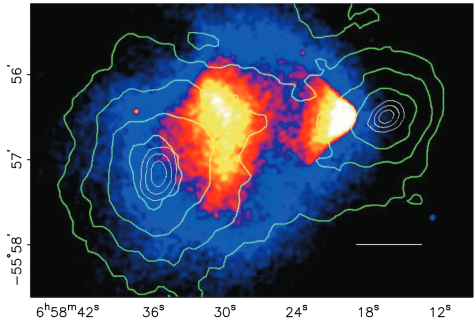
▷ D. Clowe et al. “A Direct Empirical Proof of the Existence of Dark Matter”. *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

Keywords in title

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

Current model status

- Robust and predictive (top quark, W, Z and Higgs bosons...)
- 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!**

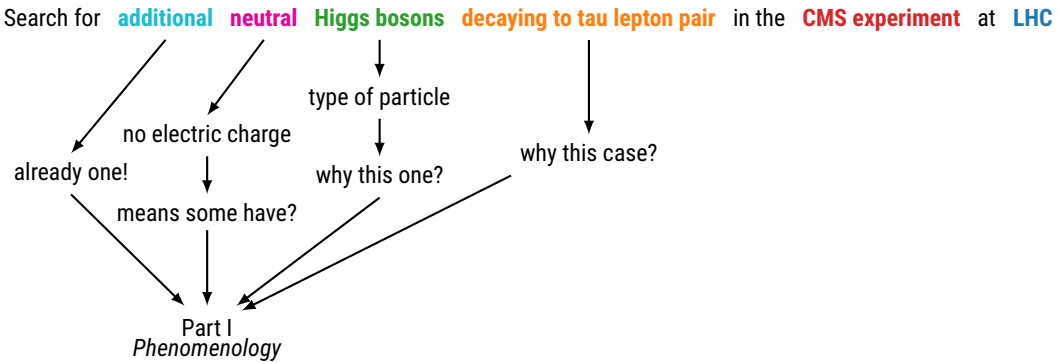


▷ D. Clowe et al. “A Direct Empirical Proof of the Existence of Dark Matter”. *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

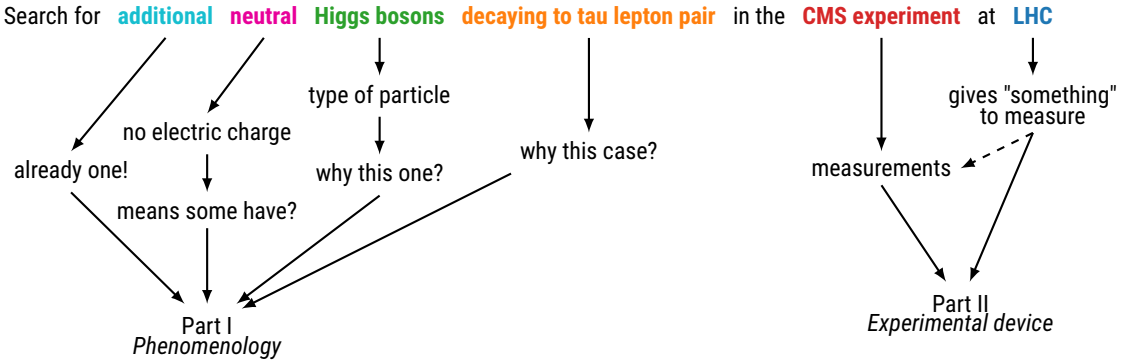
Keywords in title

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

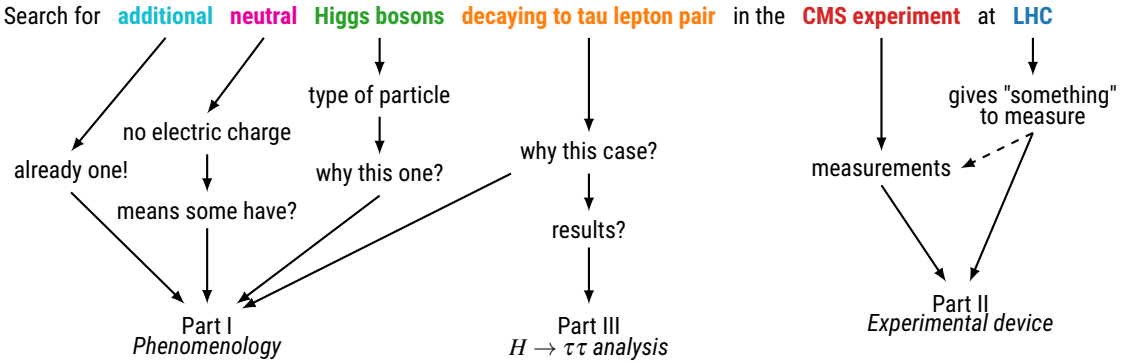
Keywords in title



Keywords in title



Keywords in title



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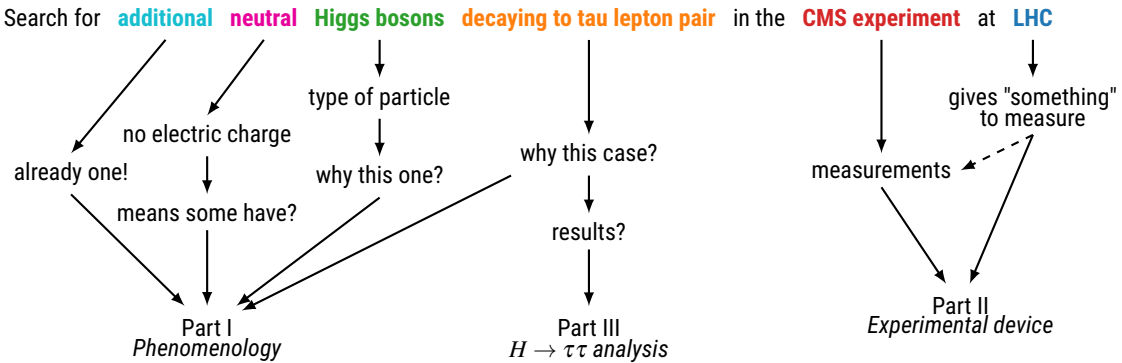
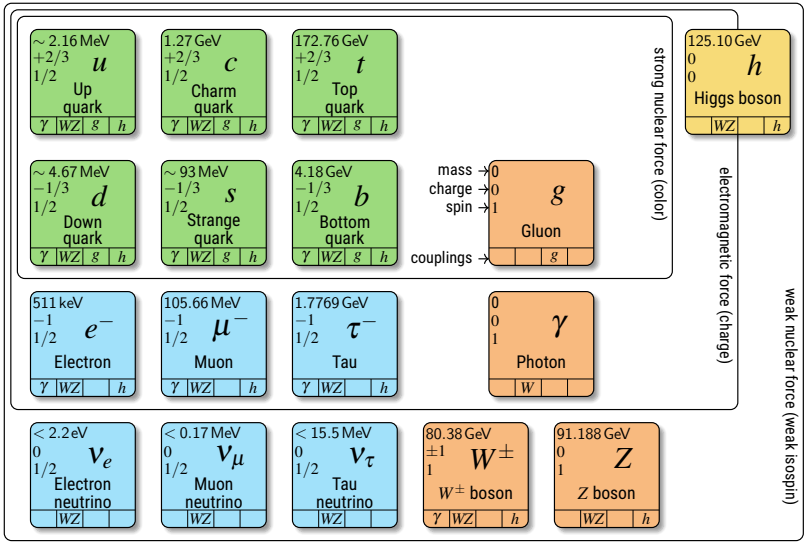


+ Part IV: *Machine Learning use in the* $H \to \tau\tau$ *analysis*

1. Phenomenology
2. Experimental device
   - Jet energy calibration
3. $H \to \tau\tau$ analysis
4. Machine Learning
   - Event topology
   - NN inputs
   - NN structure
   - NN training

The Standard Model



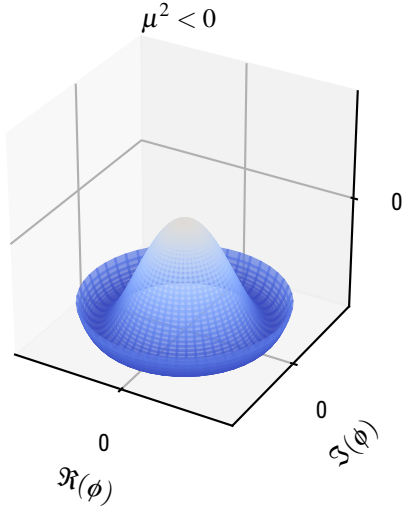
Higgs boson in the Standard Model

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

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

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

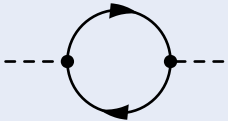
$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



The Standard Model and naturalness problem

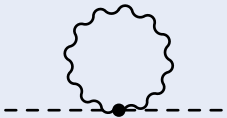
- Higgs mass measured: $m_h = 125.10 \pm 0.14\,\text{GeV}$
- Higgs mass derivation: $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



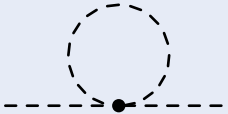
$$-\frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim -(2\,\text{TeV})^2$$

vector bosons



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

Higgs itself

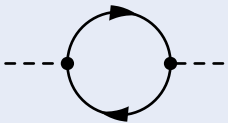


$$+\frac{1}{16\pi^2} \lambda^2 \Lambda^2 \sim +(0.5\,\text{TeV})^2$$

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

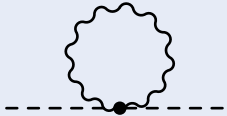
Supersymmetry

top quark



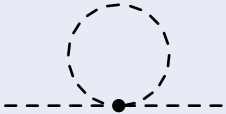
$\sim -(2\,\mathrm{TeV})^2$

vector bosons



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

Higgs itself

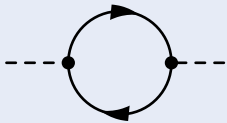


$\sim +(0.5\,\mathrm{TeV})^2$

stop quark

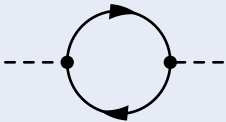
$\sim +(2\,\mathrm{TeV})^2$

bosinos



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

Higgsinos



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

2 Higgs doublets models for supersymmetry

$$
\begin{aligned}
V(\phi_1,\phi_2) = {} & \lambda_1\left(\phi_1^\dagger\phi_1 - \frac{1}{2}v_1^2\right)^2 + \lambda_2\left(\phi_2^\dagger\phi_2 - \frac{1}{2}v_2^2\right)^2 \\
& + \lambda_3\left[\left(\phi_1^\dagger\phi_1 - \frac{1}{2}v_1^2\right) + \left(\phi_2^\dagger\phi_2 - \frac{1}{2}v_2^2\right)\right]^2 + \lambda_4\left[(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) - (\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)\right] \\
& + \lambda_5\left[\Re\left(\phi_1^\dagger\phi_2\right) - \frac{1}{2}v_1v_2\cos\xi\right]^2 + \lambda_6\left[\Im\left(\phi_1^\dagger\phi_2\right) - \frac{1}{2}v_1v_2\sin\xi\right]^2 \\
& + \lambda_7\left[\Re\left(\phi_1^\dagger\phi_2\right) - \frac{1}{2}v_1v_2\cos\xi\right]\left[\Im\left(\phi_1^\dagger\phi_2\right) - \frac{1}{2}v_1v_2\sin\xi\right]
\end{aligned}
$$

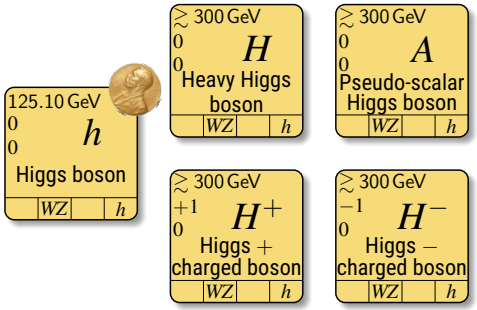
2 Higgs doublets models for supersymmetry

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

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

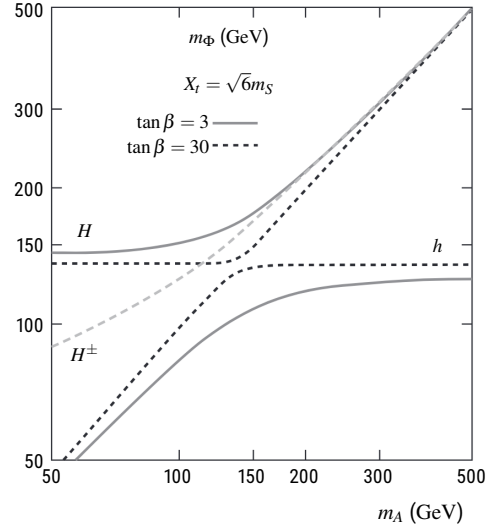
Higgs bosons in the MSSM

Minimal Supersymmetric extension of Standard Model



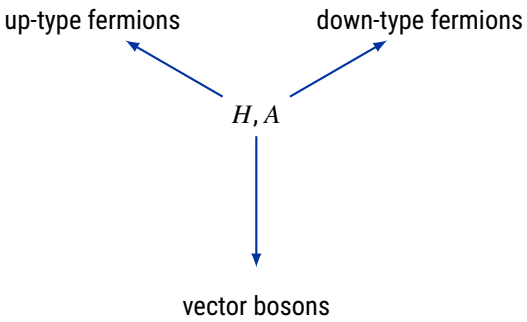
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

Higgs bosons in the MSSM



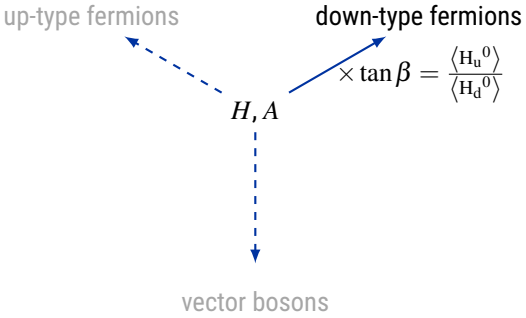
▷ Y. Nagashima. *Beyond the Standard Model of Elementary Particle Physics*. Weinheim: Wiley-VCH, June 2014. URL: http://cds.cern.ch/record/1620277

$H \to \tau\tau$?



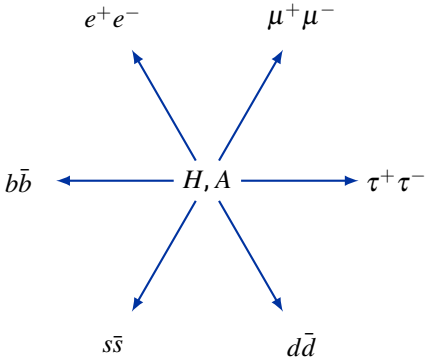
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

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



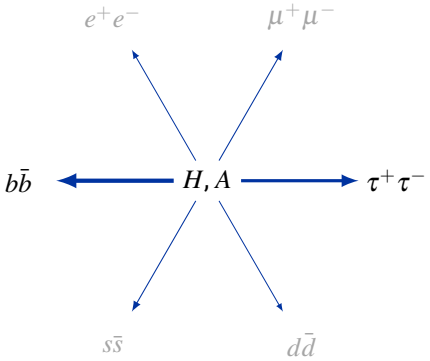
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

$H \to \tau\tau$?



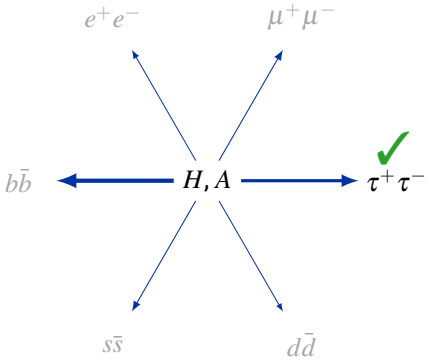
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

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



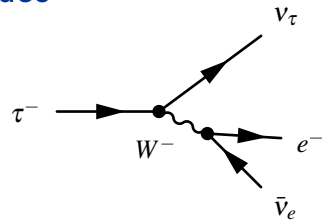
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

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

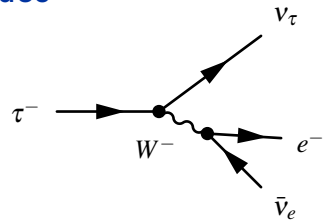


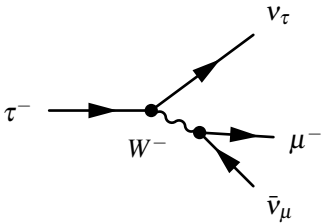
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

τ decay modes

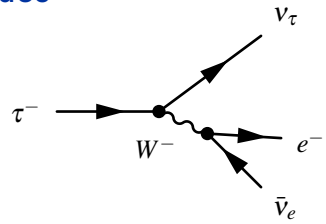


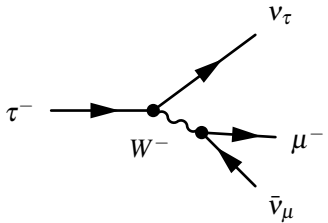
τ decay modes

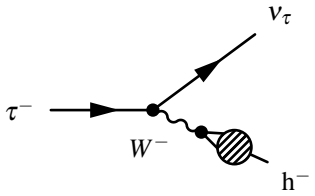


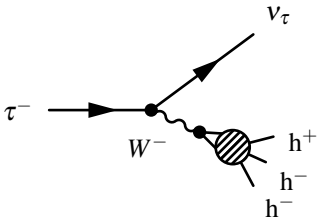


τ decay modes









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

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

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

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

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

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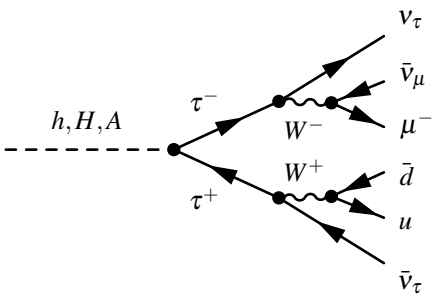

$H \to \tau\tau \to L_1 L_2$

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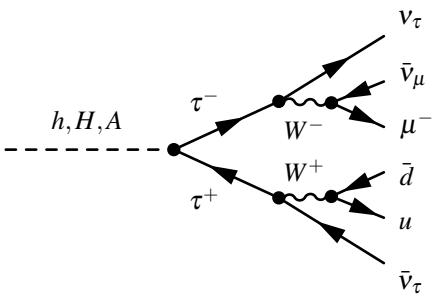
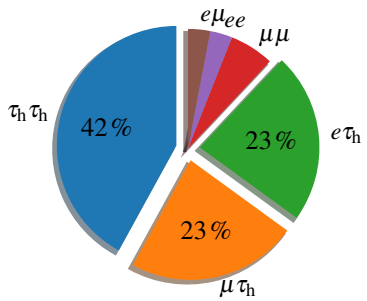




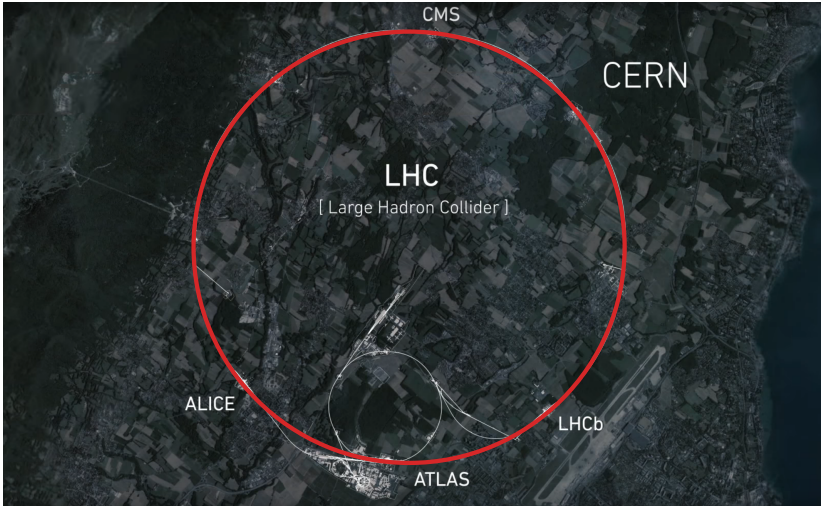
Principle

$$E = mc^2$$

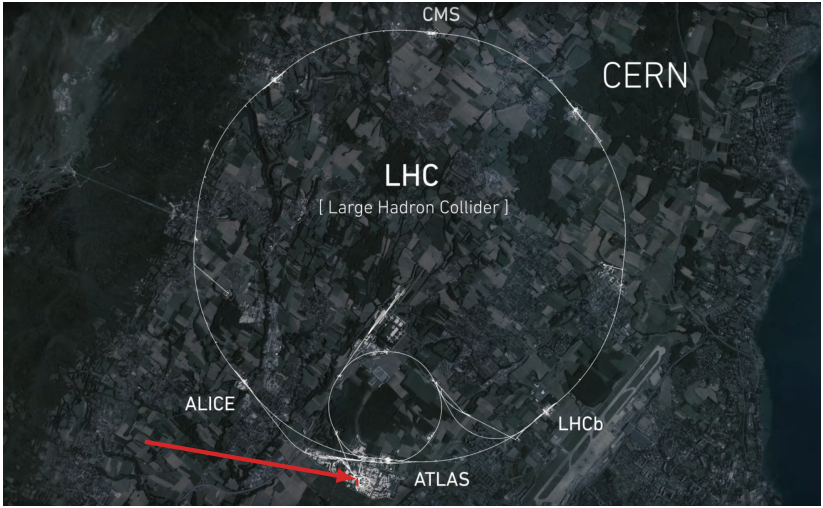
mass (new particles) from the collision energy

CERN & LHC

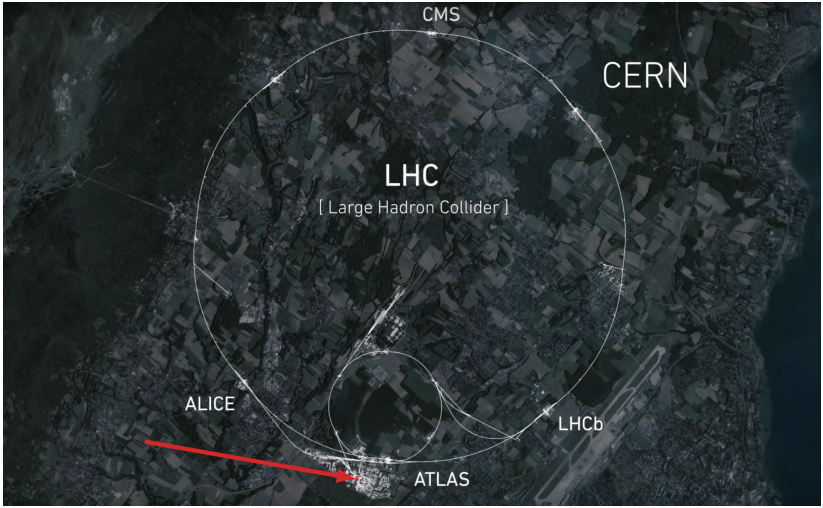
LHC



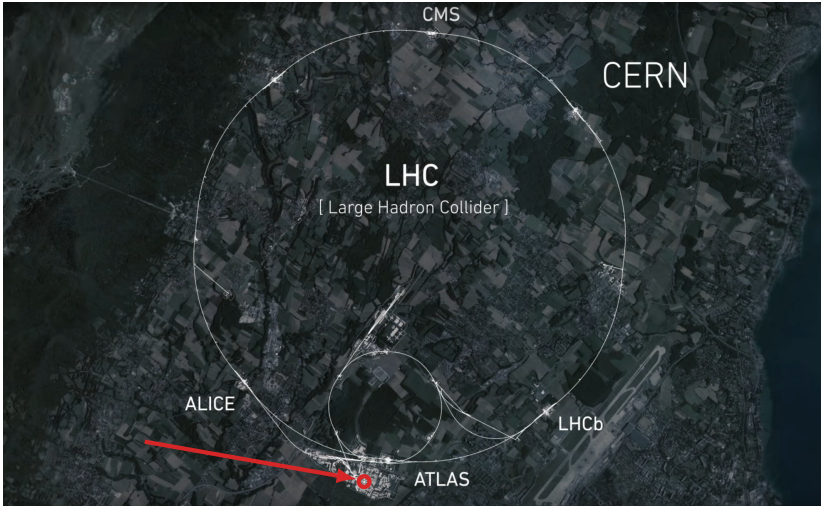
LINAC2 (50 MeV)



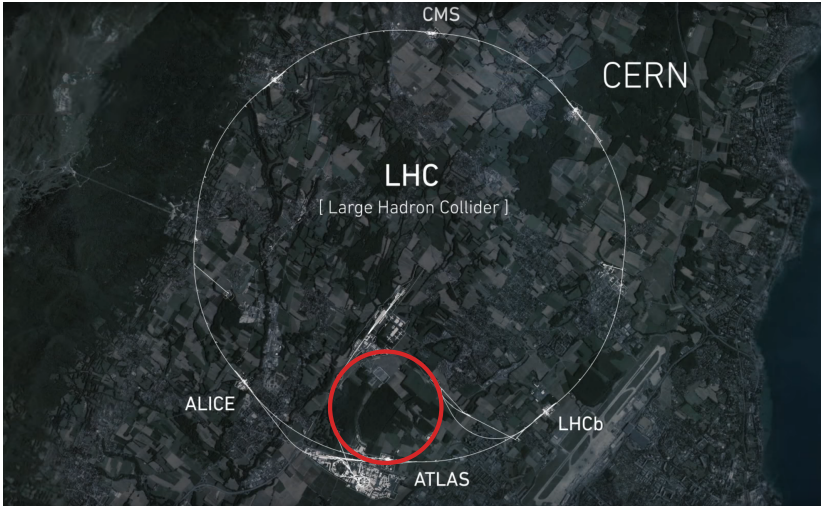
Booster (1972, 157 m, 1.4 GeV)



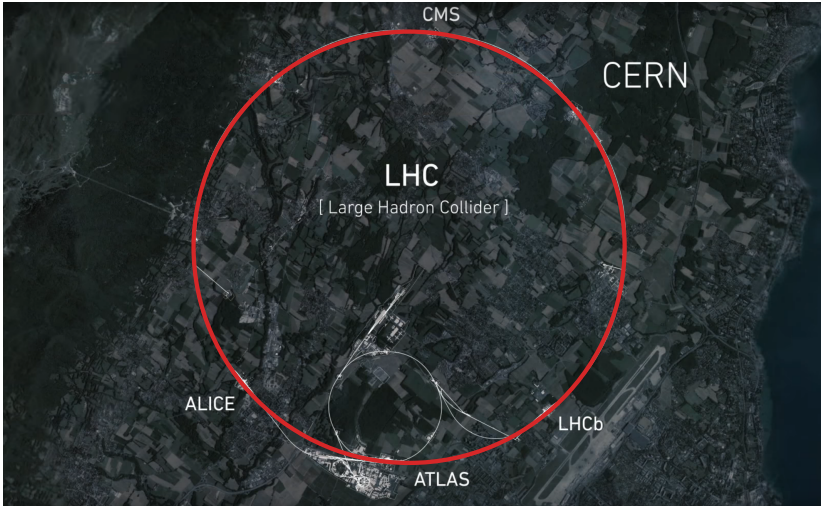
PS (1959, 628 m, 25 GeV)

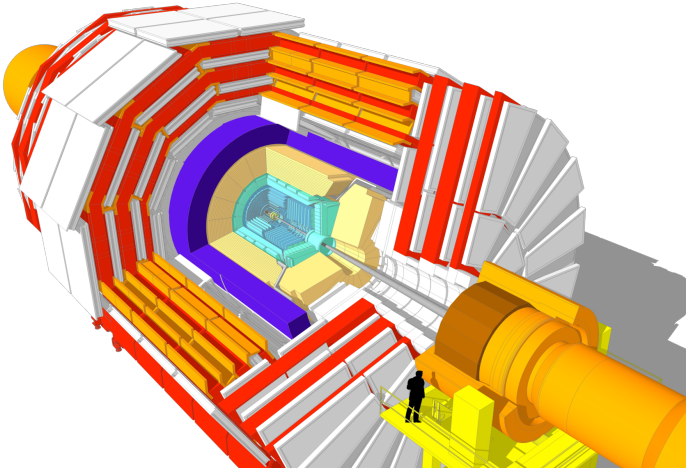


SPS (1976, 7 km, 450 GeV)



LHC (2008, 27 km, 2×7 TeV)

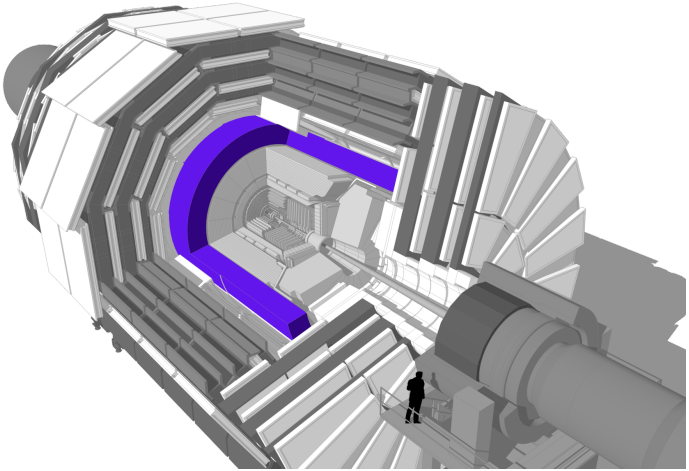




CMS detector

- Mass: $\sim 14{,}000\,\mathrm{t}$, $12{,}500$ only for red part
- Diameter: $15\,\mathrm{m}$
- Length: $28.7\,\mathrm{m}$

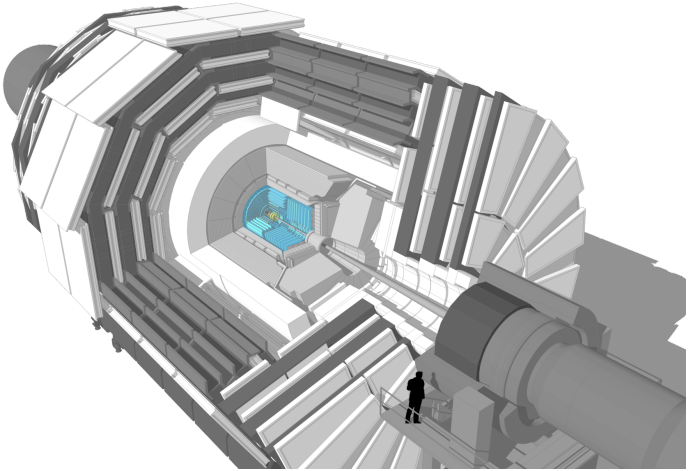
$\Rightarrow$ How to *see* the particles?



Solenoid

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

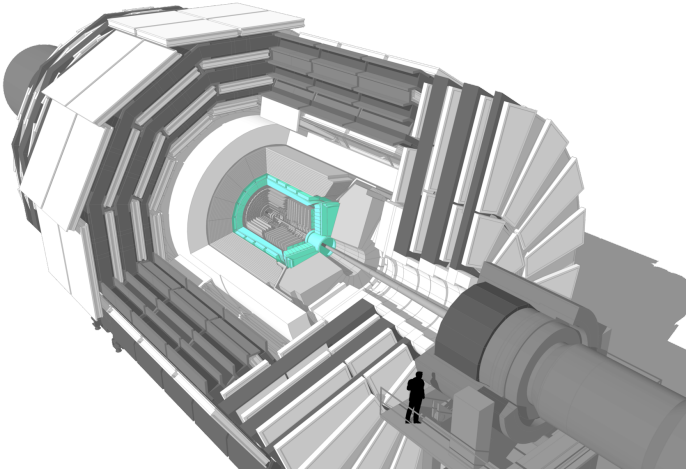
$\Rightarrow$ Bends charged particles trajectories in the transverse plane



Tracker

- 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

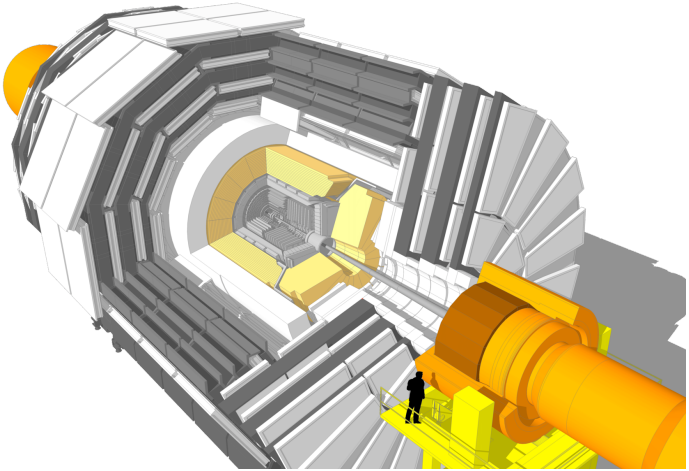
$\Rightarrow$ Charged particles leave hits when going through



Electromagnetic CALorimeter

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

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



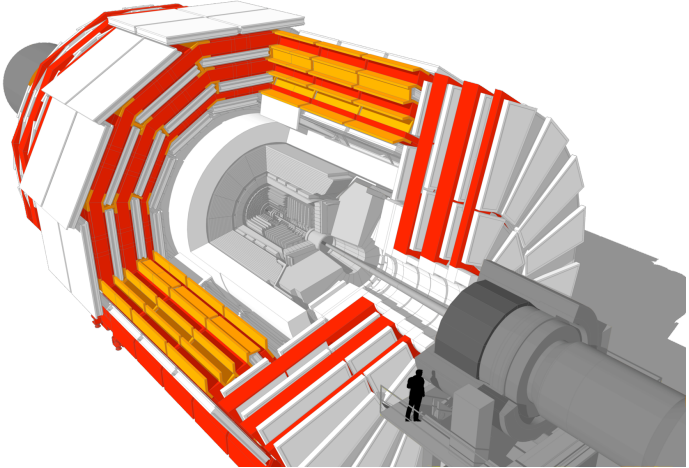
Hadronic CALorimeter (yellow)

- brass + plastic scintillator, ~ 7000 channels

Forward CALorimeter (orange)

- steel + quartz fibres, ~ 2000 channels

$\Rightarrow$ hadrons are stopped, energy deposits



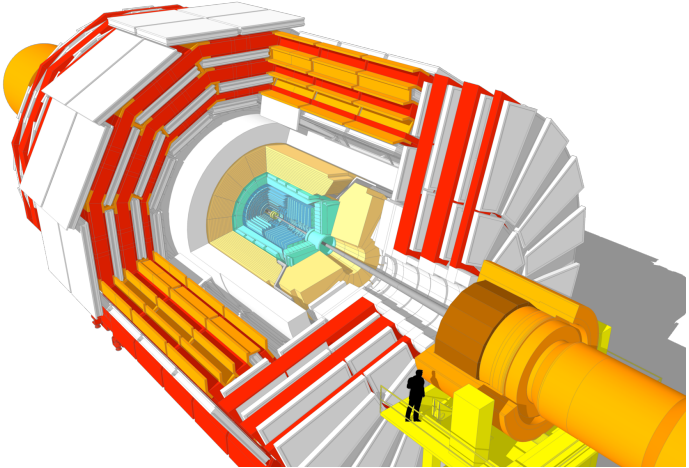
Steel return yoke (red)

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

Muon chambers (white)

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

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

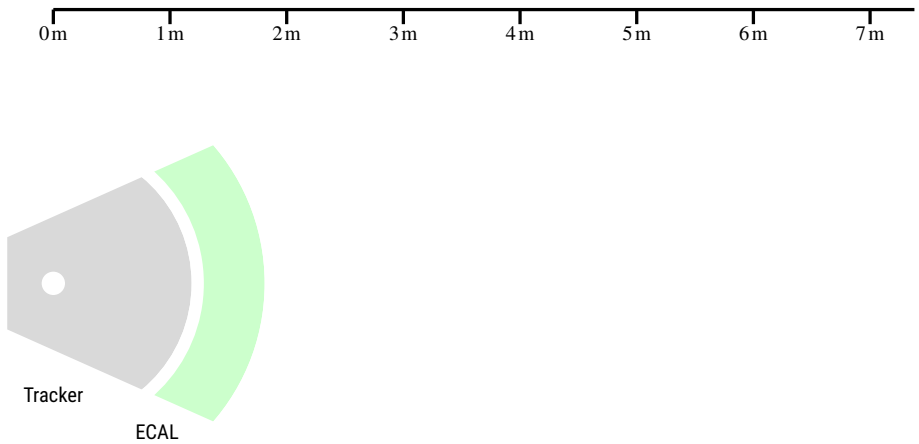


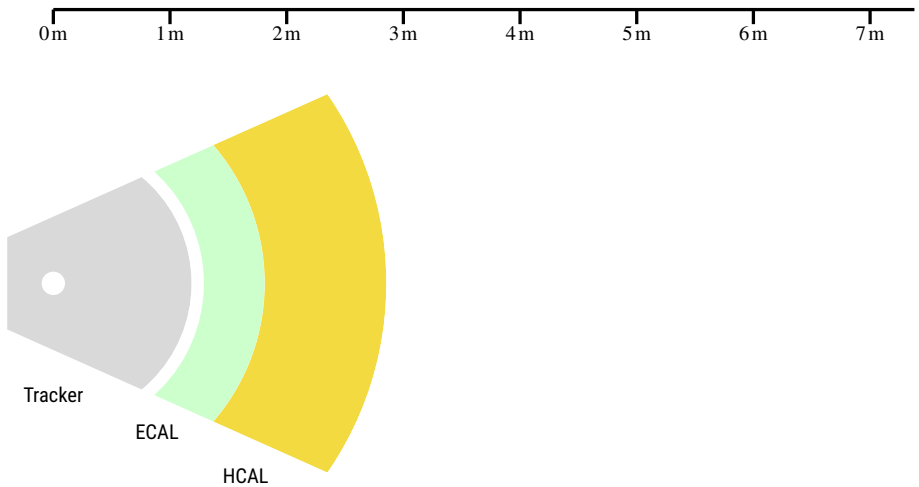
Sensitive parts of CMS

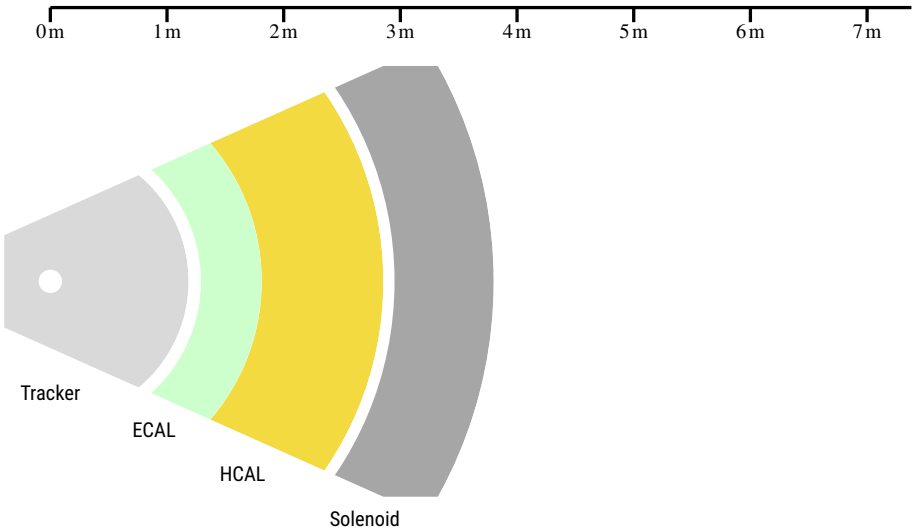
Combine sub-detectors signals to determine which particles were there!

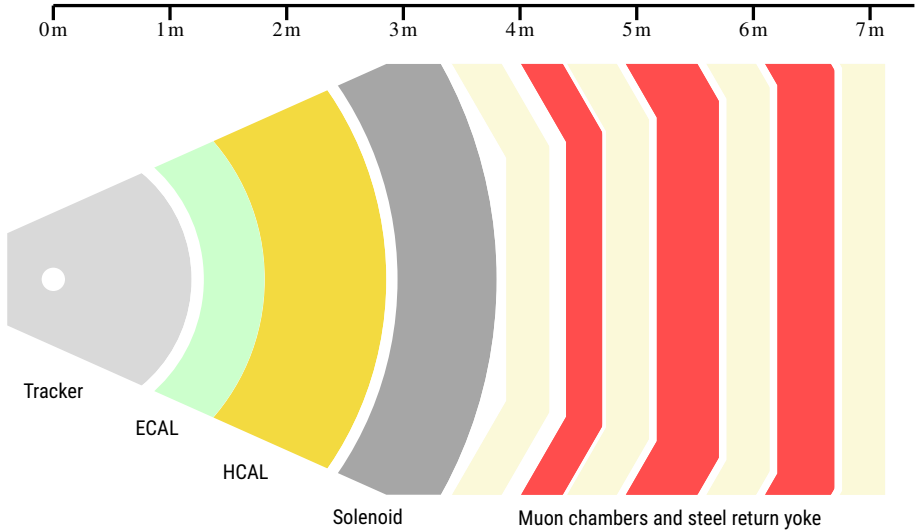

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m

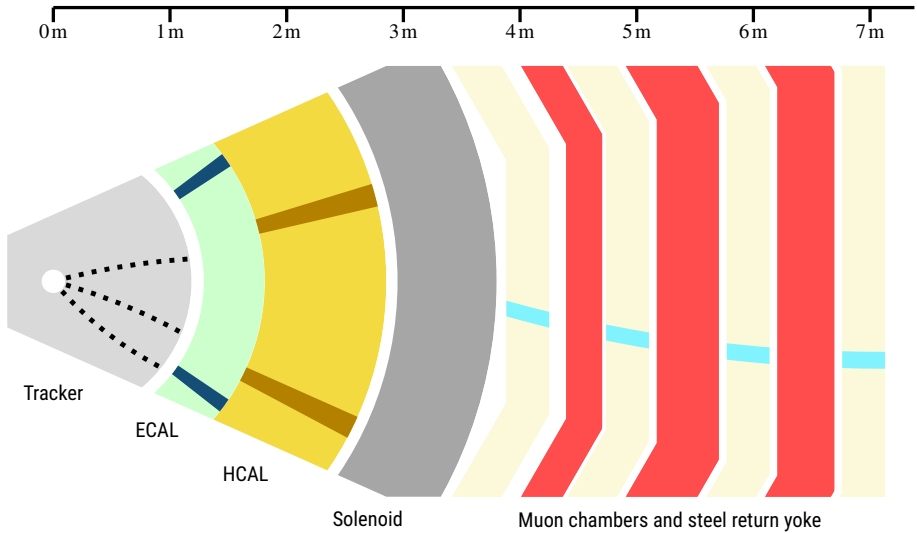
Tracker

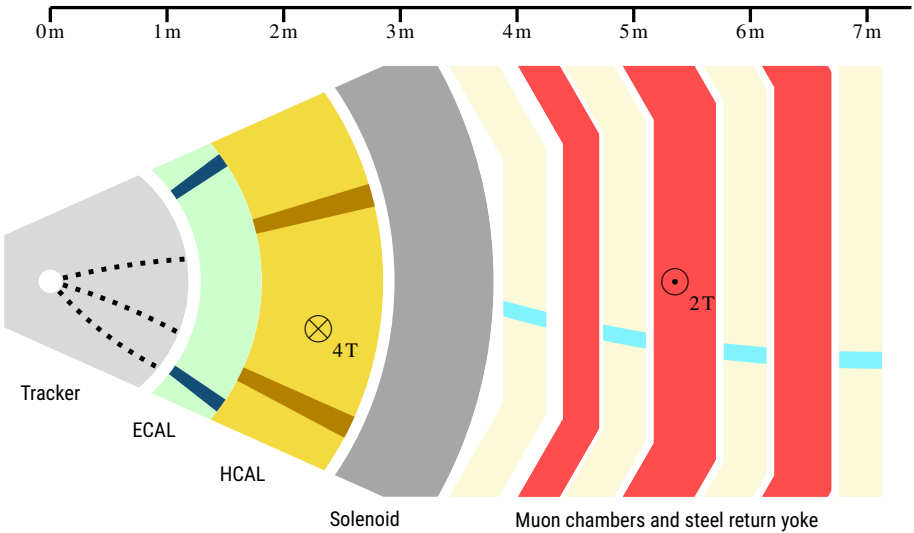

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL

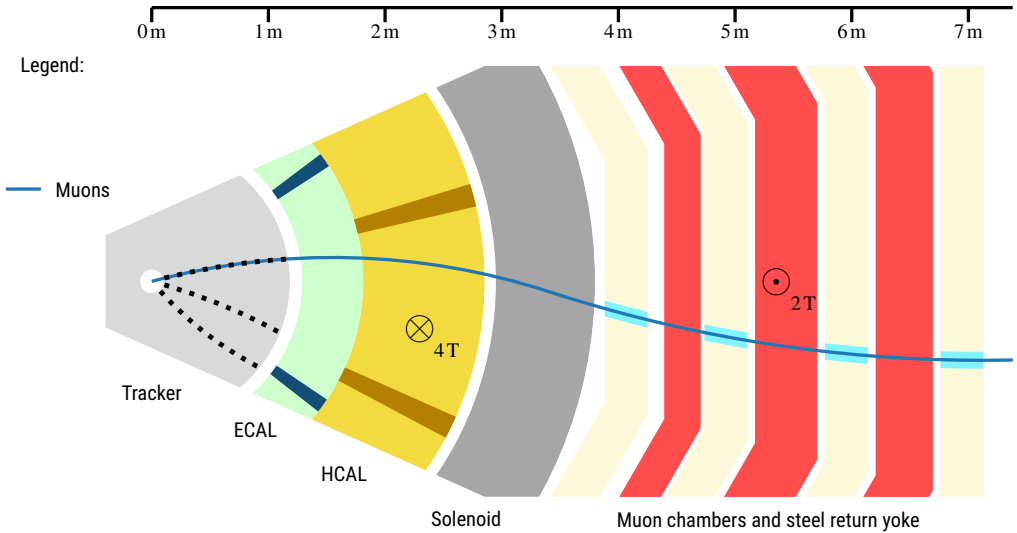

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL

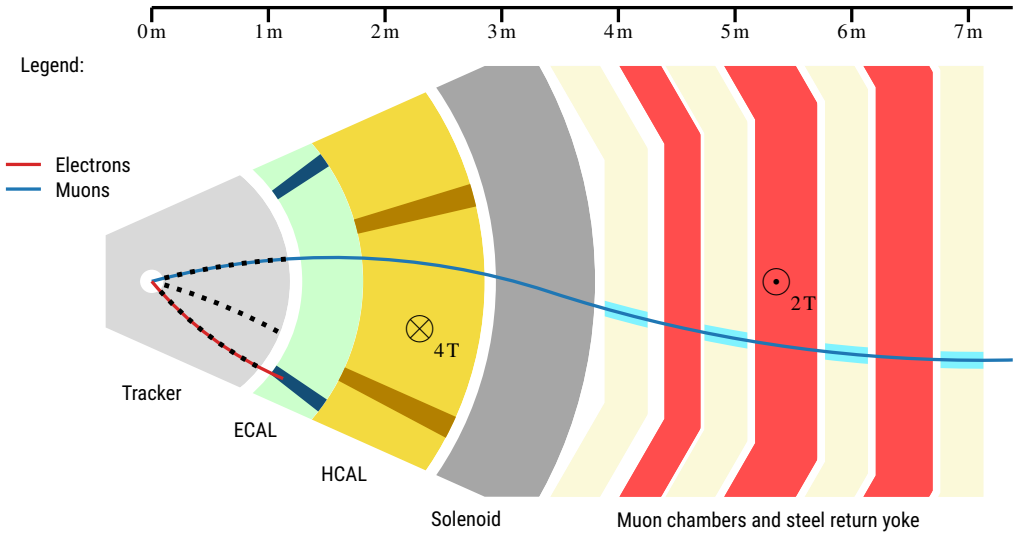

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid

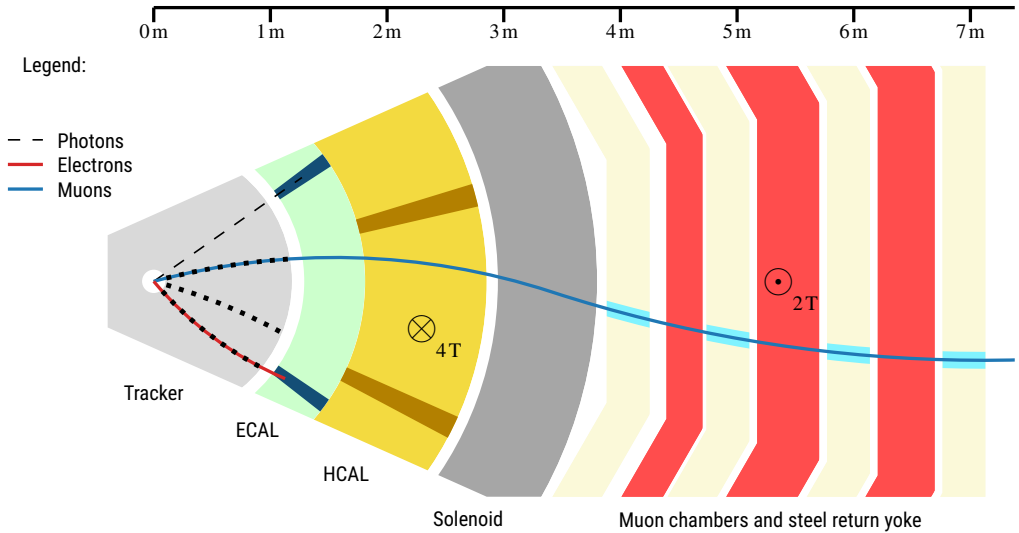

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

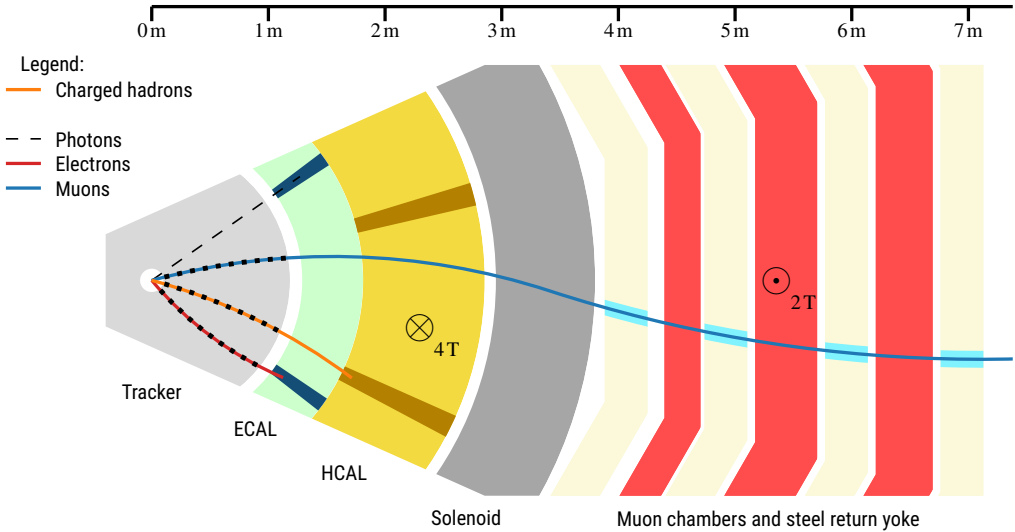

0m
1m
2m
3m
4m
5m
6m
7m
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

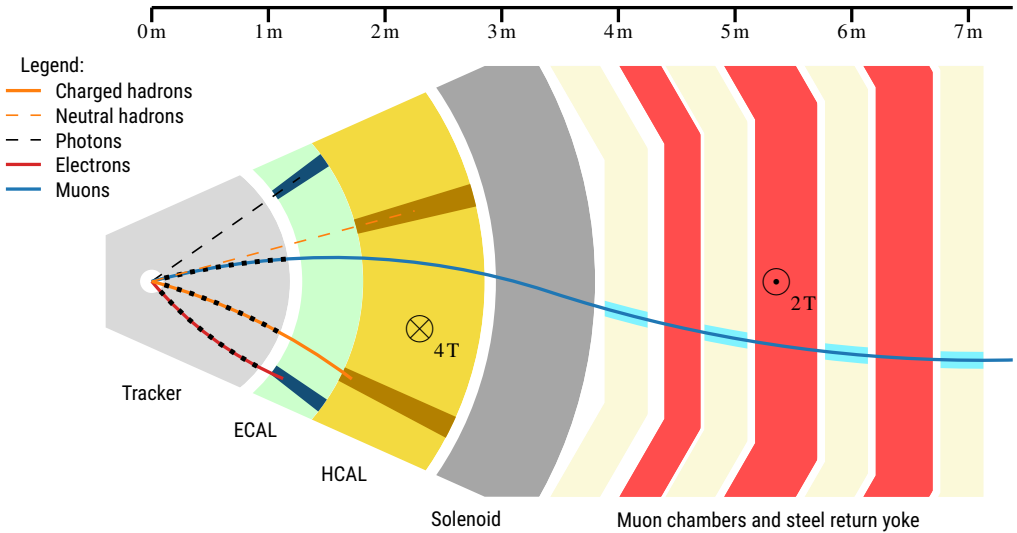

0m
1m
2m
3m
4m
5m
6m
7m
4T
2T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Muons
Tracker
ECAL
HCAL
4 T
2 T
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

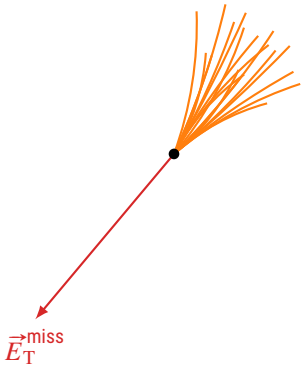

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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

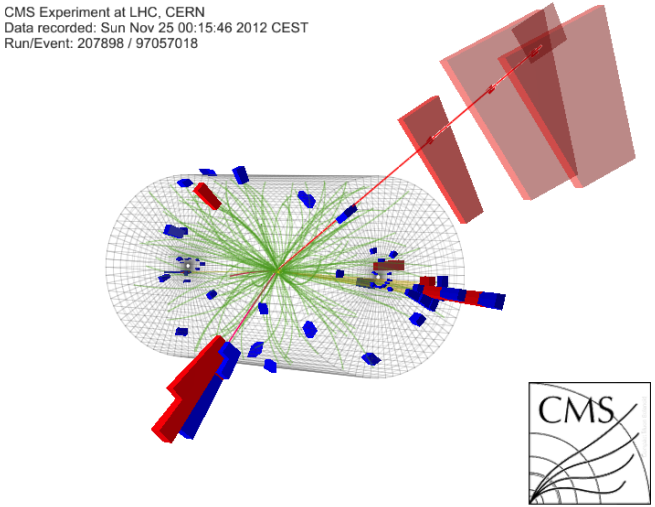

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Charged hadrons
Neutral hadrons
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

Neutrinos and missing transverse energy (MET)

Neutrinos and missing transverse energy (MET)



Event display: $h \to \tau\tau \to \mu\tau_h$ candidate



- Niveaux de connaissance

particule	(ptcl)
reconstruit	(reco)
corrigé	(corr)

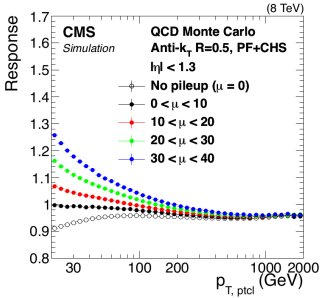
- Niveaux de connaissance

particule	(ptcl)
reconstruit	(reco)
corrigé	(corr)

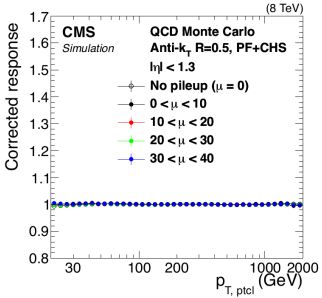
- Réponse d'un jet

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

Jets Reconstruits



Jets Calibrés

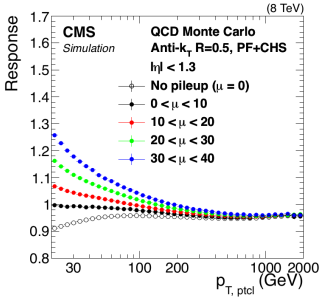


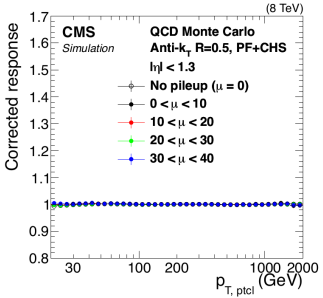
Appliqué aux données

Jets Reconstruits

Jets Calibrés

Appliqué aux simulations

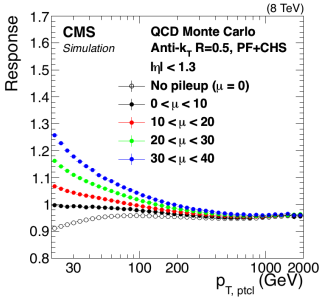


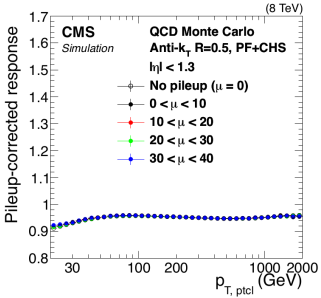


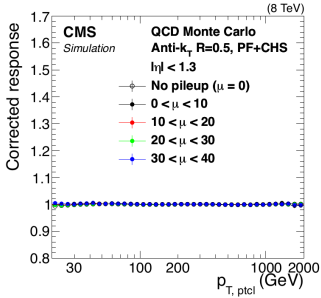
Appliqué aux données

Jets Reconstruits → Empilement (MC+RC / MC) → Jets Calibrés

Appliqué aux simulations



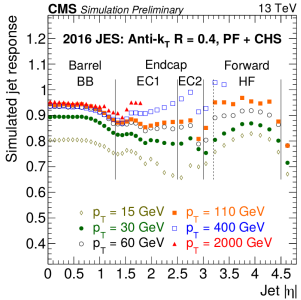


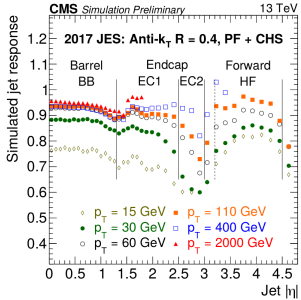


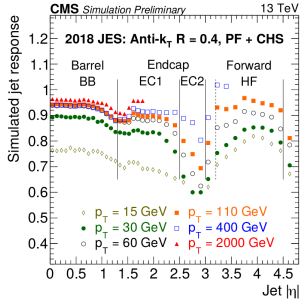
Appliqué aux données

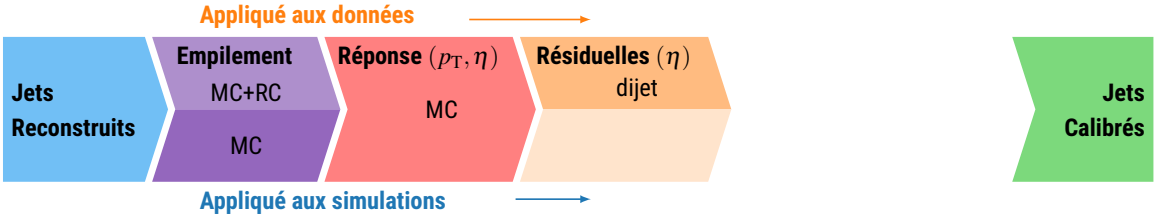
Jets Reconstruits → **Empilement** MC+RC / MC → **Réponse** (p_T, η) MC → **Jets Calibrés**

Appliqué aux simulations





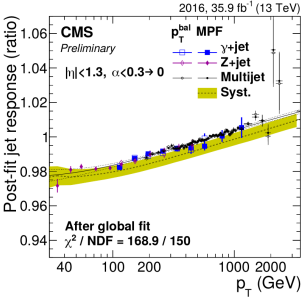


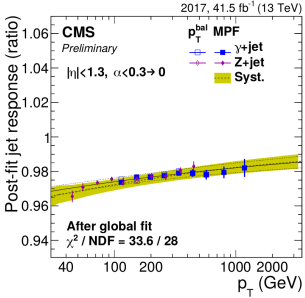

Appliqué aux données
Jets Reconstruits
Empilement
MC+RC
MC
Réponse (p_T, η)
MC
Résiduelles (η)
dijet
Jets Calibrés
Appliqué aux simulations

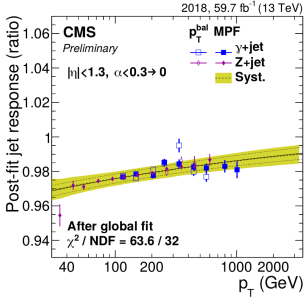
Appliqué aux données

Jets Reconstruits → Empilement (MC+RC / MC) → Réponse (p_T, η) (MC) → Résiduelles (η) (dijet) → Résiduelles (p_T) (γ/Z+jet, MJB) → Jets Calibrés

Appliqué aux simulations



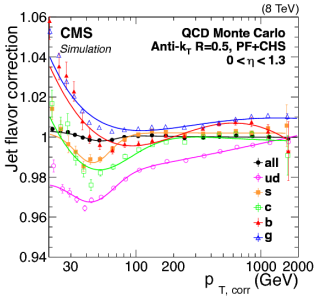


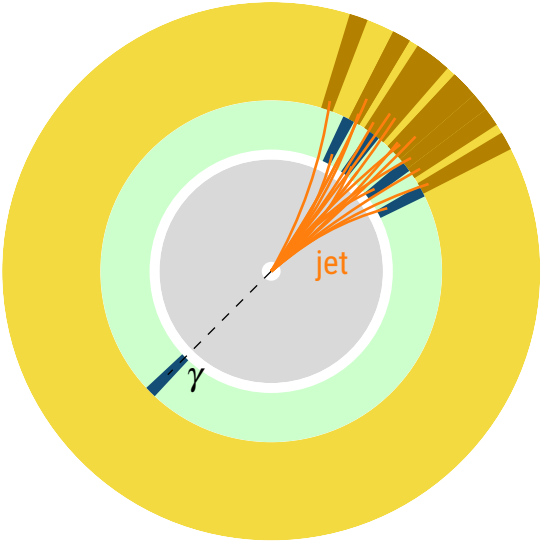


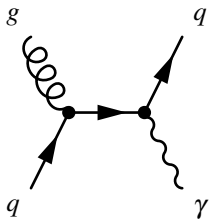
Appliqué aux données

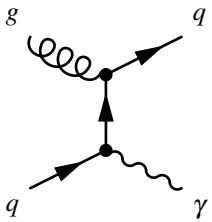
Jets Reconstruits	Empilement	Réponse (p_T, η)	Résiduelles (η)	Résiduelles (p_T)	Saveur	Jets Calibrés
	MC+RC	MC	dijet	γ/Z+jet, MJB	MC	
	MC					

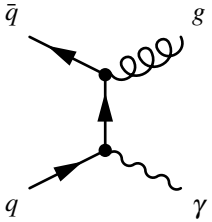
Appliqué aux simulations

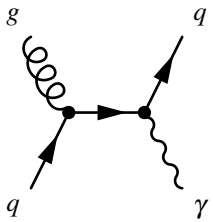


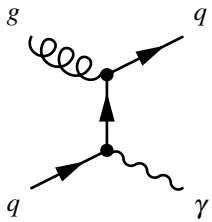

jet
γ

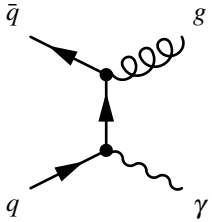

g
q
q
γ


g
q
q
γ

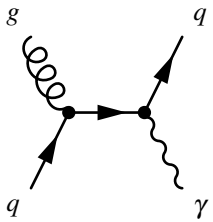

q̄
g
q
γ

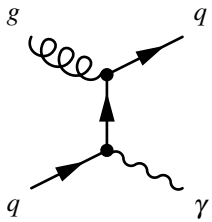


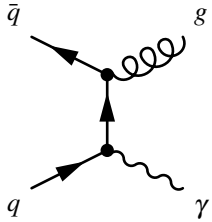




$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}} = \vec{0} \Rightarrow p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} = p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}$$

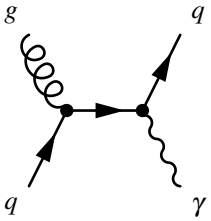


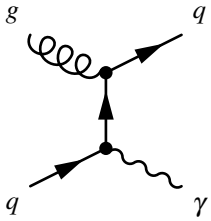


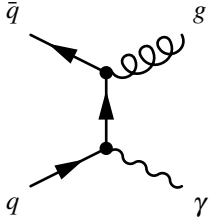


$$\vec{p}_{\mathrm{T}\,\mathrm{ptcl}}^{\,\gamma} + \vec{p}_{\mathrm{T}\,\mathrm{ptcl}}^{\,\mathrm{jet}} = \vec{0} \Rightarrow p_{\mathrm{T}\,\mathrm{ptcl}}^{\,\gamma} = p_{\mathrm{T}\,\mathrm{ptcl}}^{\,\mathrm{jet}}$$

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



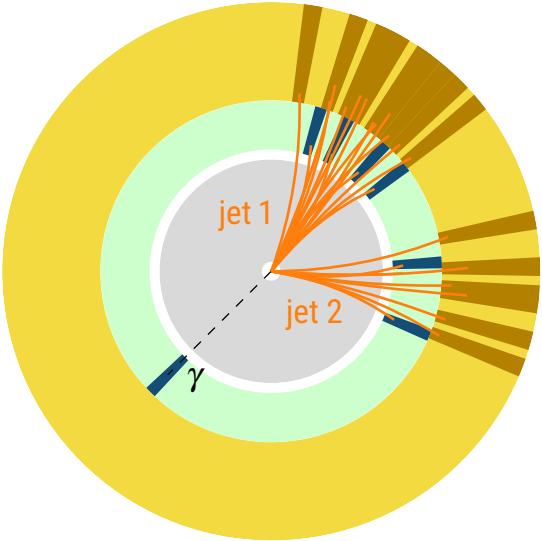


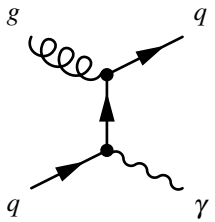


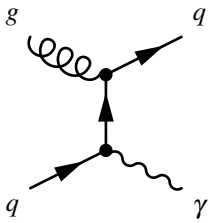
$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}} = \vec{0} \Rightarrow p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} = p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}$$

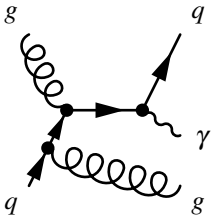
$$R = \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}} = \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}}} \simeq \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{reco}}}$$

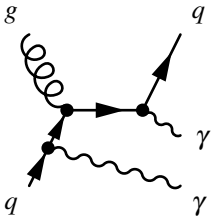
$$R_{bal} = \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\gamma}}$$

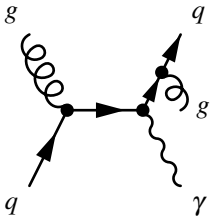

jet 1
jet 2
γ

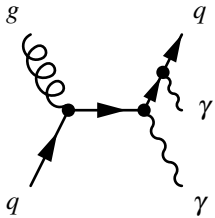

g
q
q
γ


g
q
q
γ


g
q
γ
q
g


g
q
γ
q
γ


g
q
g
q
γ


g
q
γ
q
γ

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

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

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

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

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

Jet Energy Resolution

- Remember R_{bal} definition,

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

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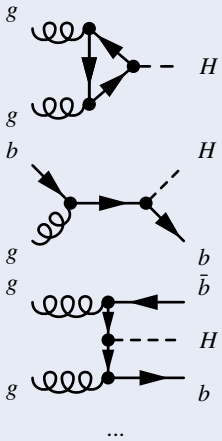
$$\boxed{\mathrm{JER} = \sigma_{\mathrm{jet}} = \sqrt{\sigma^2_{R_{bal}} - \sigma^2_{\mathrm{PLI}}}}$$

Higgs production



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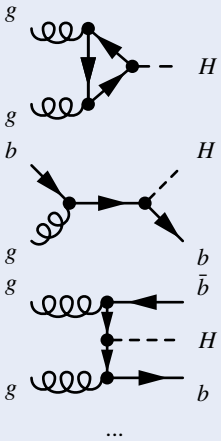
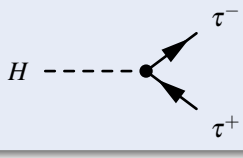
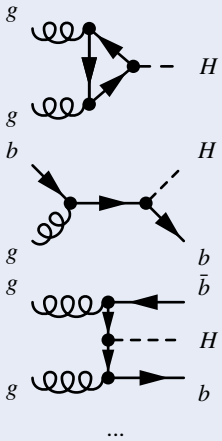


$\otimes$

$H \to \tau\tau$



Higgs production



⊗

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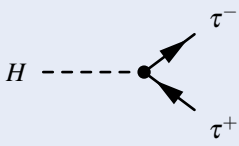
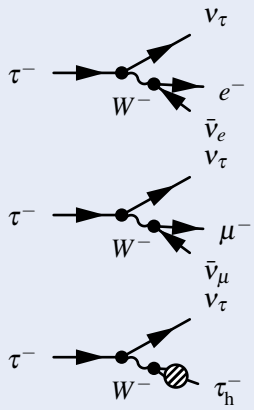
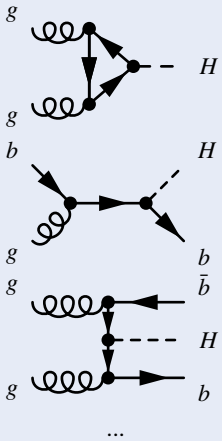


⊗

τ decays



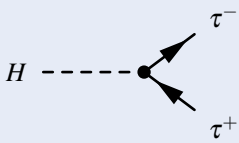
Higgs production



$\{0,1,2\}$ jets

$\otimes$

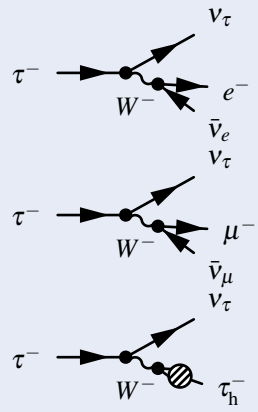
$H \to \tau\tau$



2 taus

$\otimes$

τ decays



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

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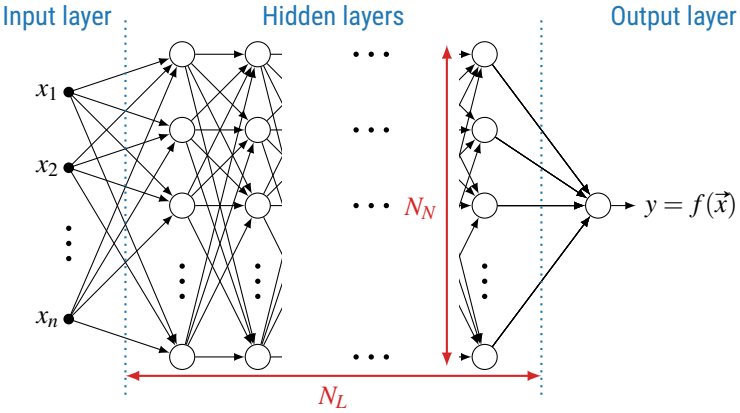
- 18 inputs.



$$N_L \in [\![2, 10]\!] \cup \{15\} \qquad N_N \in \{500, 1000, 1500, 2000\}$$

- The "bottleneck" variant:
  - Get a smoother reduction from $\sim$ 1k neurons in hidden layers to 1 neuron for the output layer.
  - Set a maximum value for N_N in the 3 last hidden layers: $[1000, 500, 100]$.

- Example: neurons per layers with settings $N_L = 4, N_N = 2000$ gives

Case	Hidden layers				Output layer
without bottleneck	2000	2000	2000	2000	1
with bottleneck	2000	1000	500	100	1

- Activation functions:
  - relu for hidden layers;
  - linear for output layer.

- GeV switched to TeV
- Target is m_H
- Get a flat target distribution for the training, validating and testing sub-samples.
- Train a NN for:
  - all channels at once;
  - each channel separately;
  - full-hadronic, semi-leptonic, full-leptonic channels (categorize per amount of neutrinos in the final state).

Thank you for your attention!