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

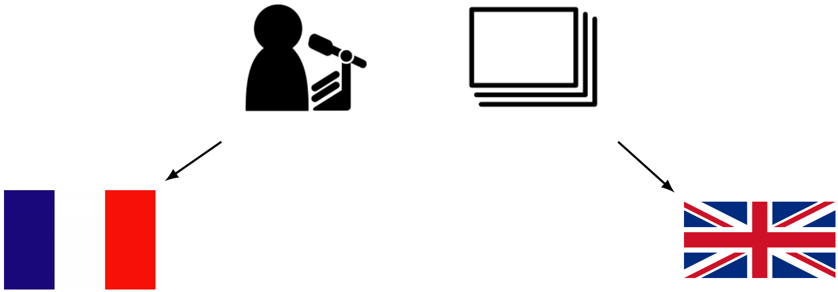
Soutenance de thèse de doctorat

Lucas Torterotot

Institut de Physique des deux Infinis – Lyon

XX xxxx 2021

Lang(u)age



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

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 XX$^{st/nd/rd/th}$ 2021

Keywords in title

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

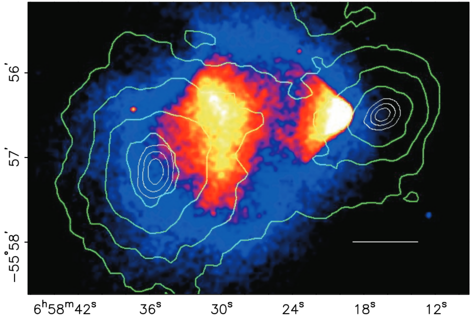
▷ D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

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!**



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

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

already one!

no electric charge

means some have?

type of particle

why this one?

why this case?

Part I
Phenomenology

Keywords in title

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

already one!

no electric charge

means some have?

type of particle

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why this case?

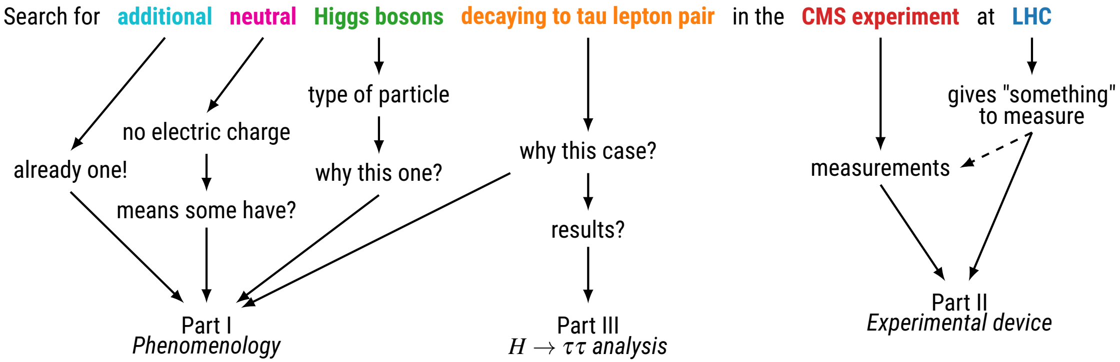
Part I
Phenomenology

measurements

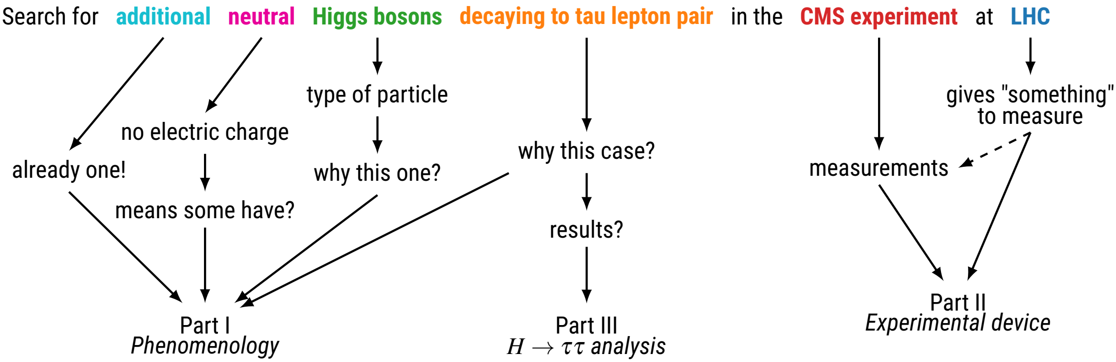
gives "something" to measure

Part II
Experimental device

Keywords in title



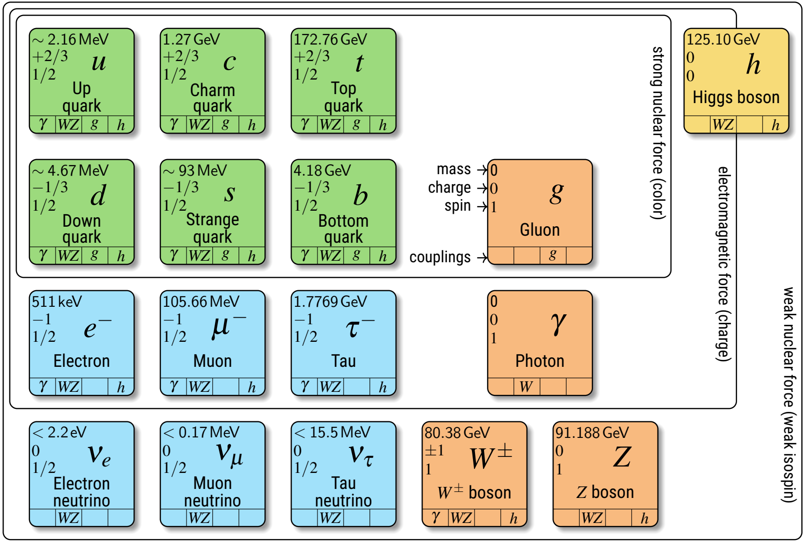
Keywords in title



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

1. Phenomenology
2. Experimental device
3. $H \rightarrow \tau\tau$ analysis
4. Machine Learning

The Standard Model



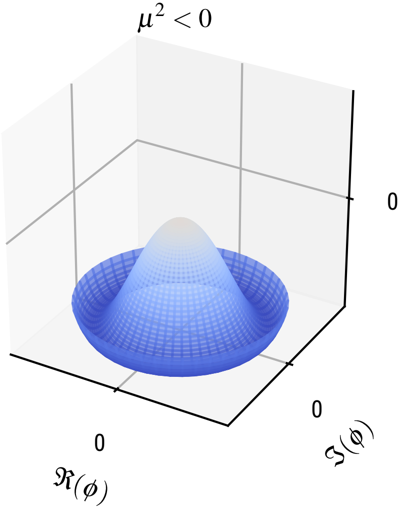
Higgs boson in the Standard Model

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

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

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

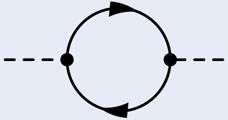
$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



The Standard Model and naturalness problem

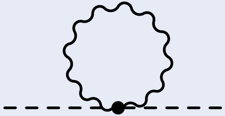
- Higgs mass measured: $m_h = 125.10 \pm 0.14\,\mathrm{GeV}$
- Higgs mass derivation: $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



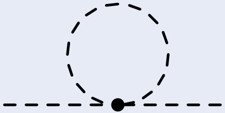
$$-\frac{3}{8\pi^2} y_t^2 \Lambda^2 \sim -(2\,\mathrm{TeV})^2$$

vector bosons



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

Higgs itself

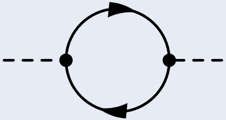


$$+\frac{1}{16\pi^2} \lambda^2 \Lambda^2 \sim +(0.5\,\mathrm{TeV})^2$$

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

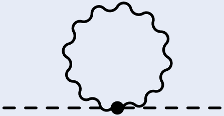
Supersymmetry

top quark



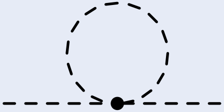
$\sim -(2\,\mathrm{TeV})^2$

vector bosons



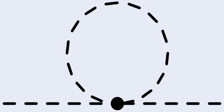
$\sim +(0.7\,\mathrm{TeV})^2$

Higgs itself



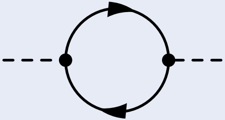
$\sim +(0.5\,\mathrm{TeV})^2$

stop quark



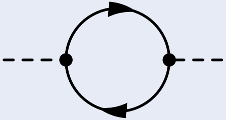
$\sim +(2\,\mathrm{TeV})^2$

bosinos



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

Higgsinos



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

2 Higgs doublets models for supersymmetry

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

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

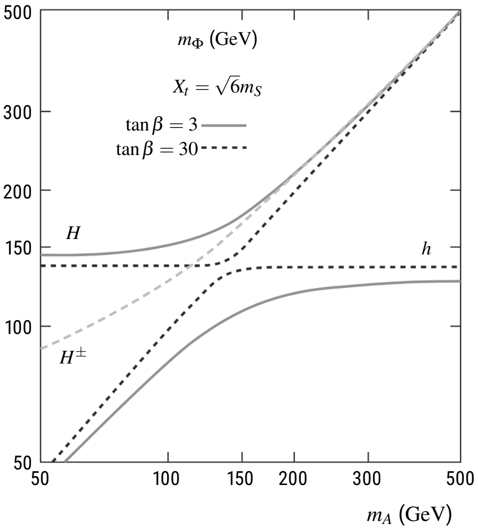
Minimal Supersymmetric extension of Standard Model

5 Higgs bosons

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

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

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



$H \to \tau\tau$?

up-type fermions

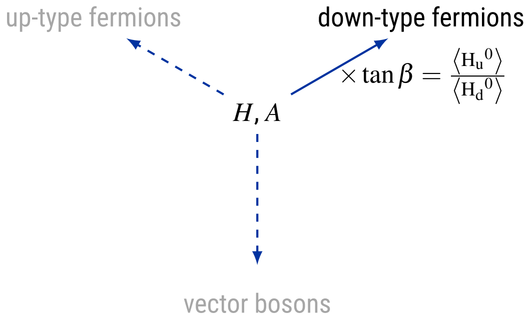
down-type fermions

H, A

vector bosons

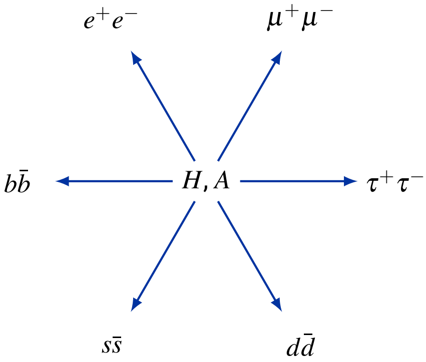
▷ The CMS Collaboration. “Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$”. *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

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



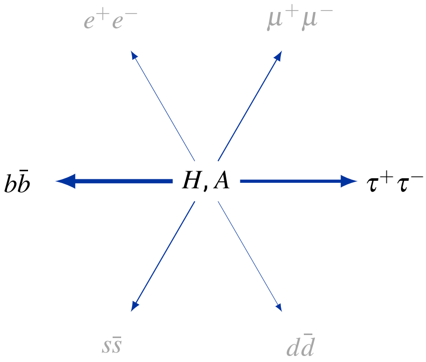
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

$H \to \tau\tau$?



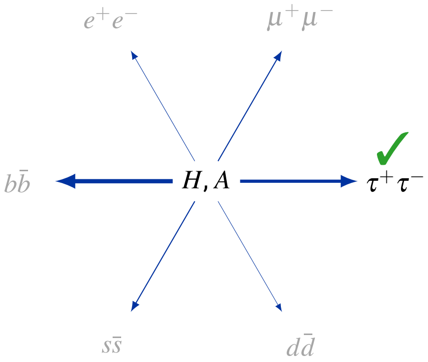
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\text{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

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



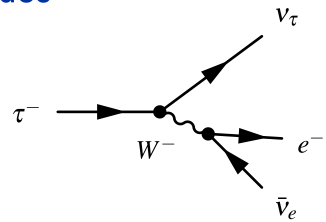
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: 10.1007/JHEP09(2018)007.

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

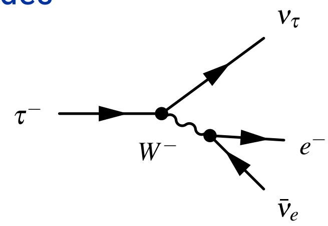


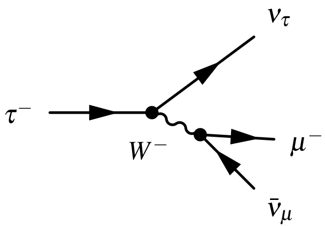
▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$". *Journal of High Energy Physics* **09**.007 (Sept. 2018). DOI: `10.1007/JHEP09(2018)007`.

τ decay modes

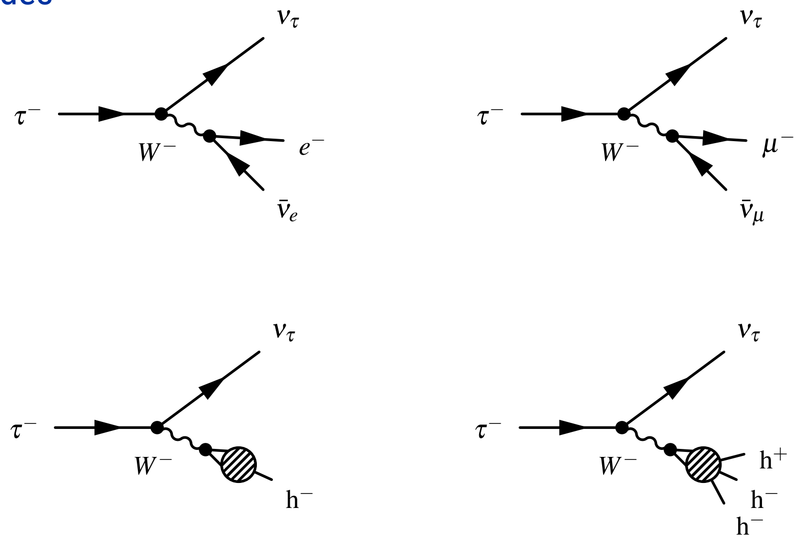


τ decay modes





τ decay modes



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

$\tau \to e + \nu_e \Rightarrow e$	$\tau \to \mu + \nu_\mu \Rightarrow \mu$	$\tau \to \text{hadrons} + \nu_\tau \Rightarrow \tau_\mathrm{h}$
$17.8\,\%$	$17.4\,\%$	$64.8\,\%$

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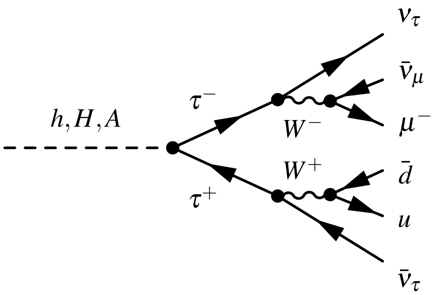

$H \to \tau\tau \to L_1 L_2$

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$17.8\,\%$

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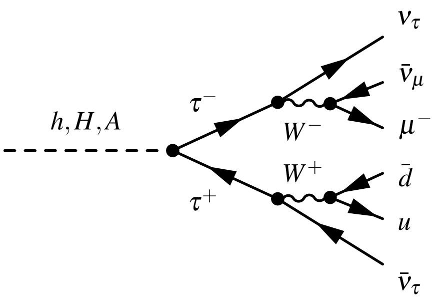
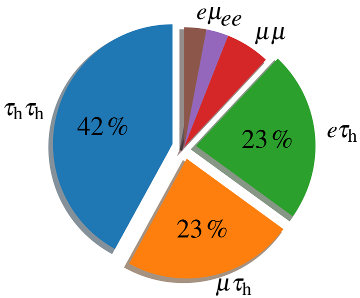
$17.4\,\%$

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





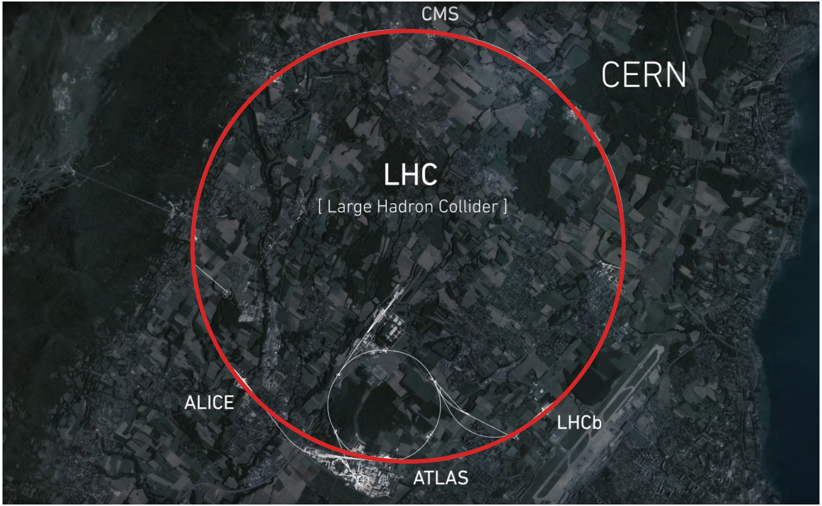
Principle

$$E = mc^2$$

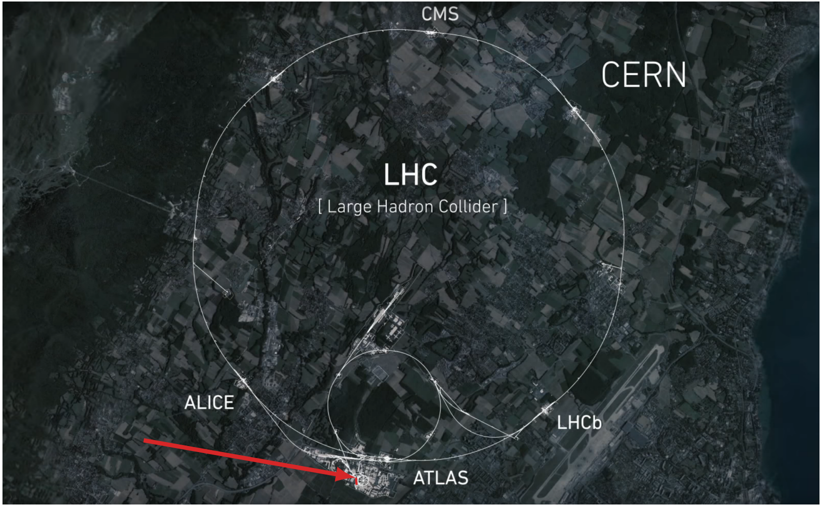
mass (new particles) from the collision energy

CERN & LHC

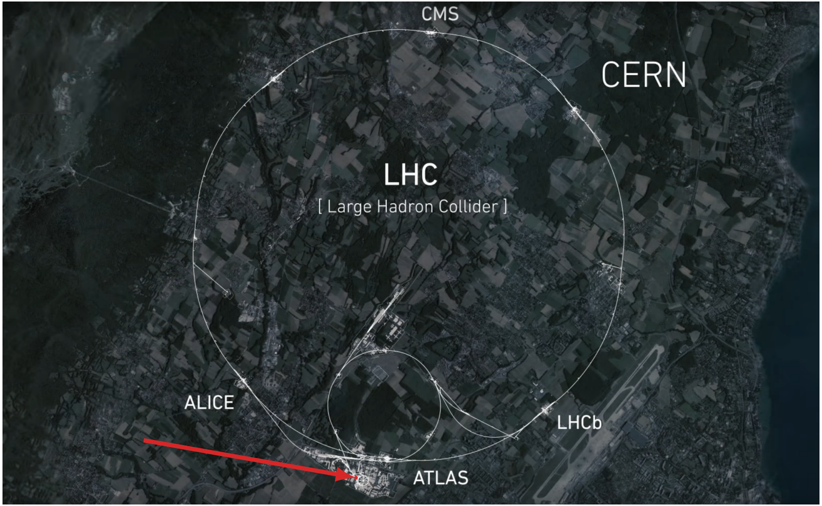
LHC



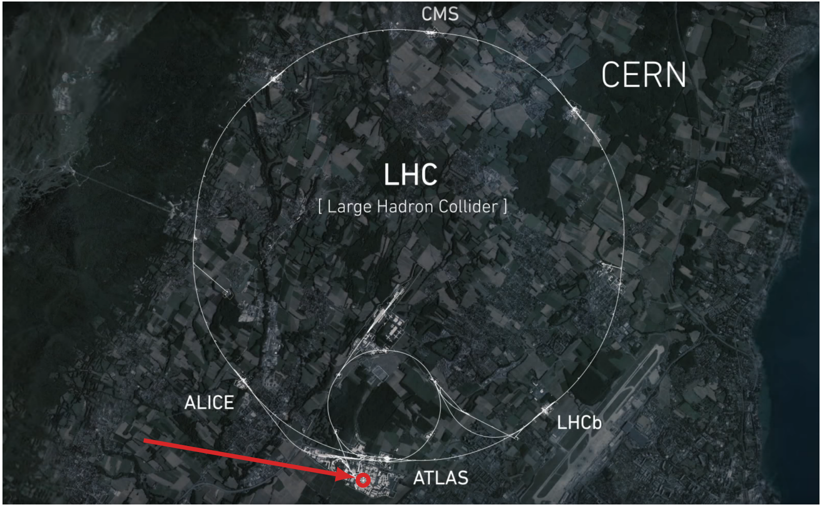
LINAC2 (50 MeV)



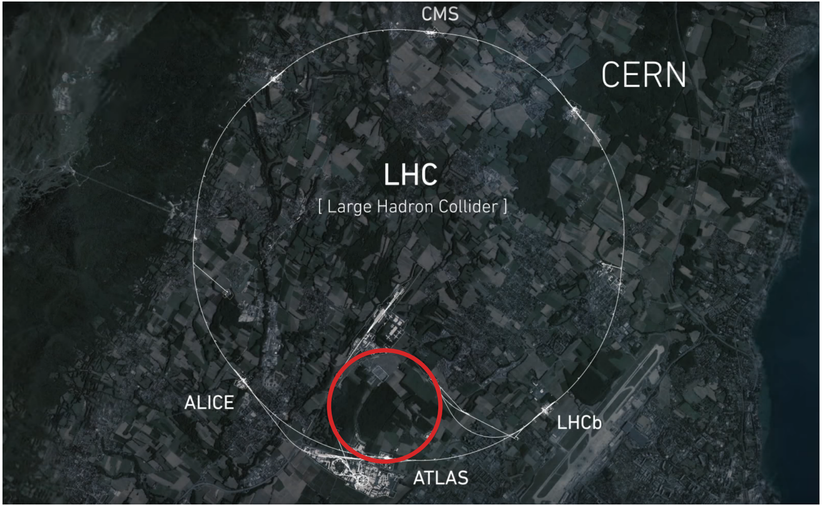
Booster (1972, 157 m, 1.4 GeV)



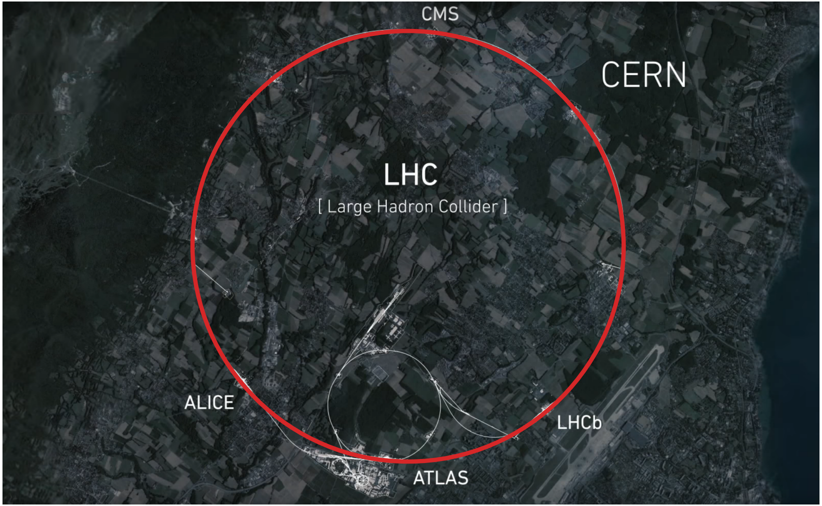
PS (1959, 628 m, 25 GeV)

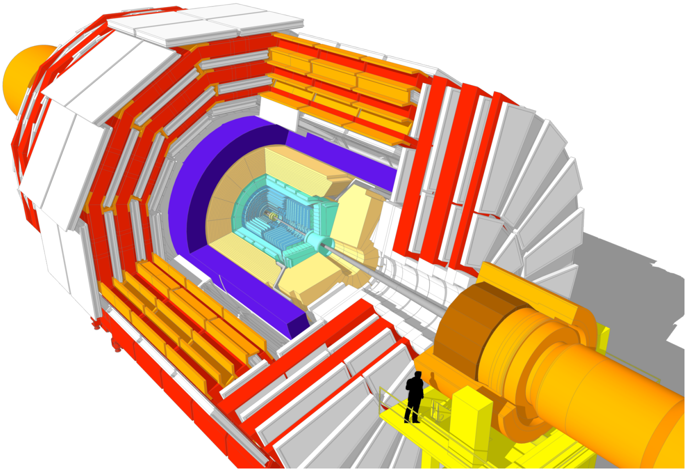


SPS (1976, 7 km, 450 GeV)



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

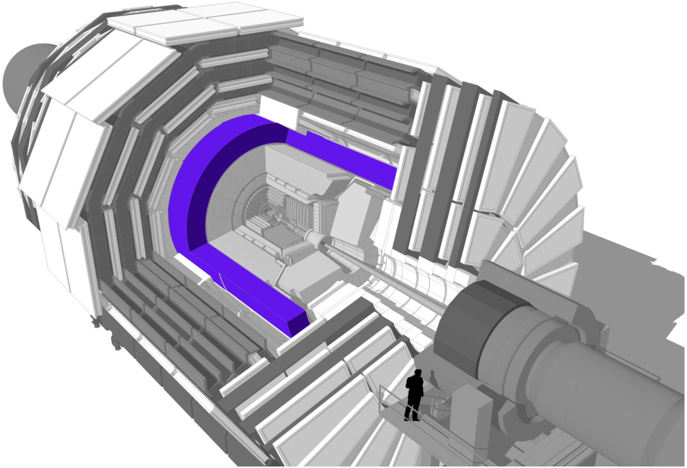




CMS detector

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

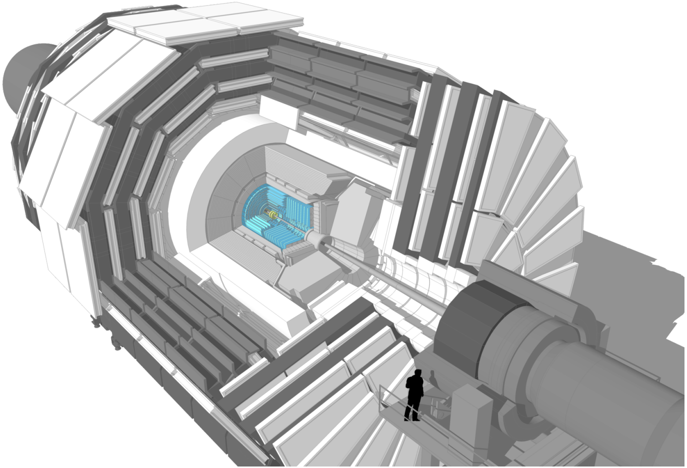
$\Rightarrow$ How to *see* the particles?



Solenoid

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

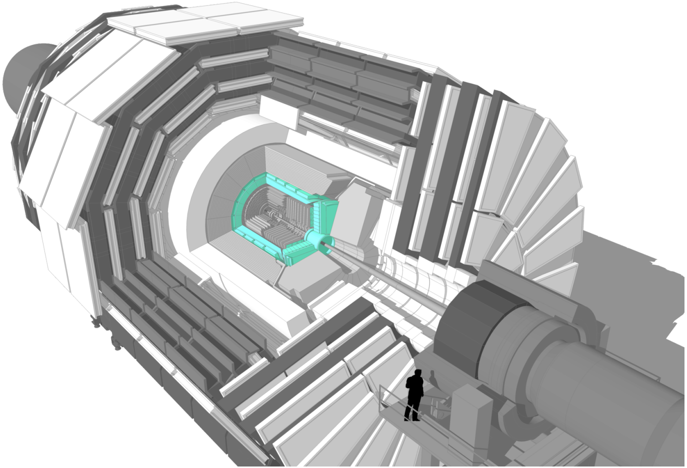
$\Rightarrow$ Bends charged particles trajectories in the transverse plane



Tracker

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

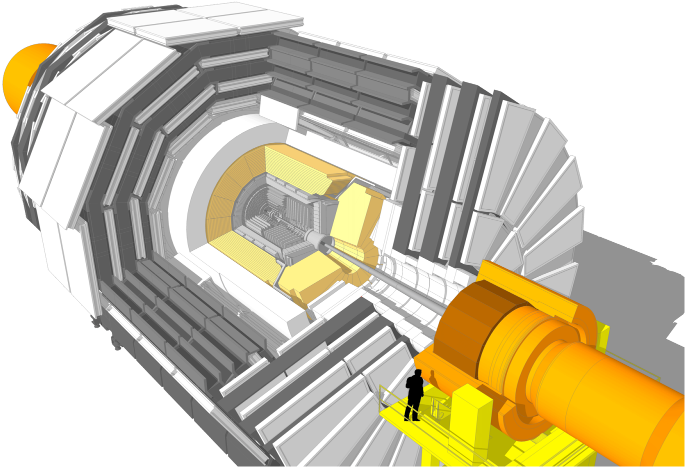
$\Rightarrow$ Charged particles leave hits when going through



Electromagnetic CALorimeter

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

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



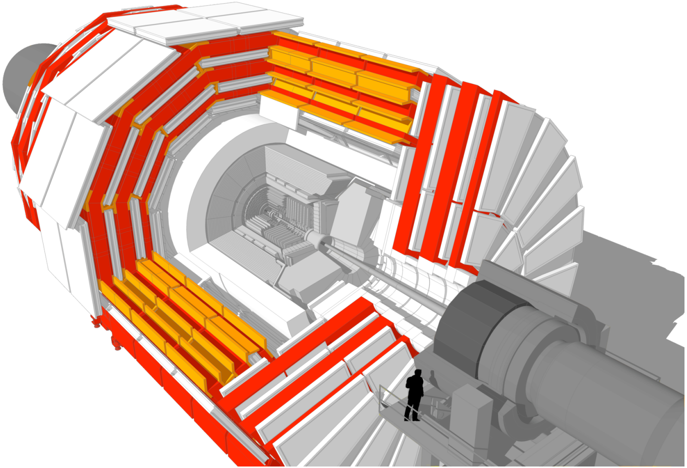
Hadronic CALorimeter (yellow)

- brass + plastic scintillator, ~ 7000 channels

Forward CALorimeter (orange)

- steel + quartz fibres, ~ 2000 channels

$\Rightarrow$ hadrons are stopped, energy deposits



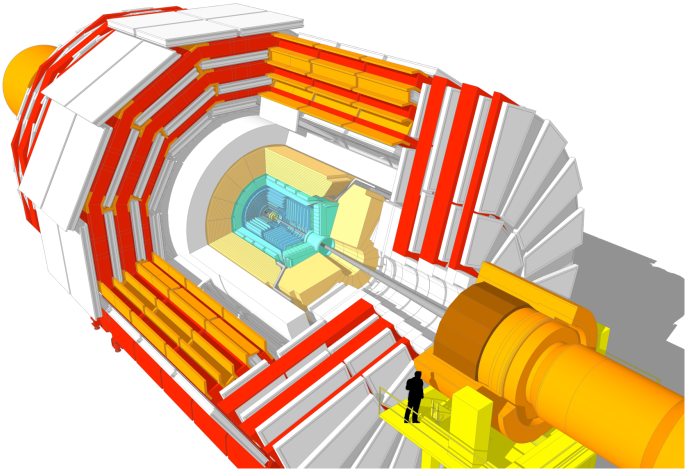
Steel return yoke (red)

- 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

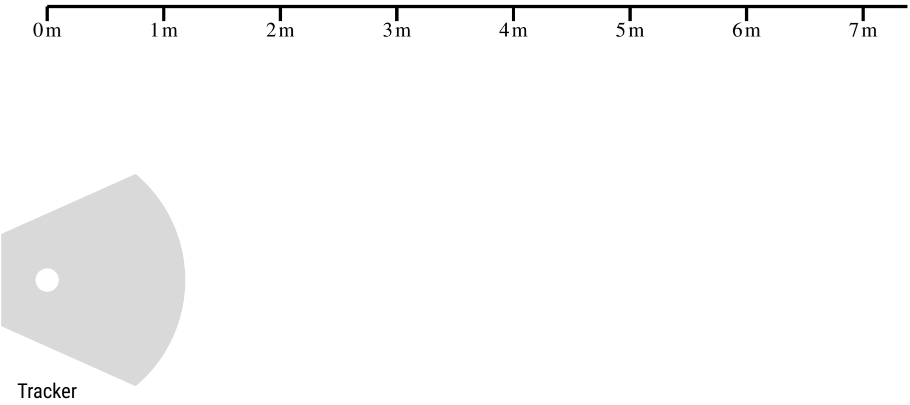
$\Rightarrow$ charged particles leave hits when going through (only muons do)

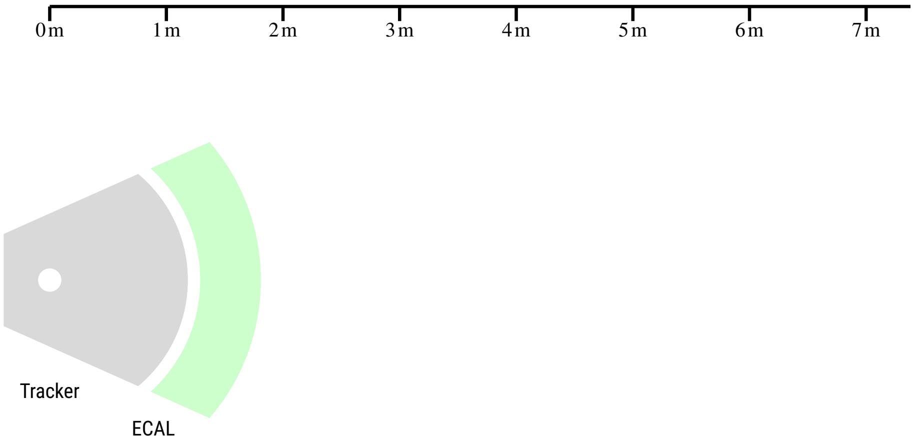


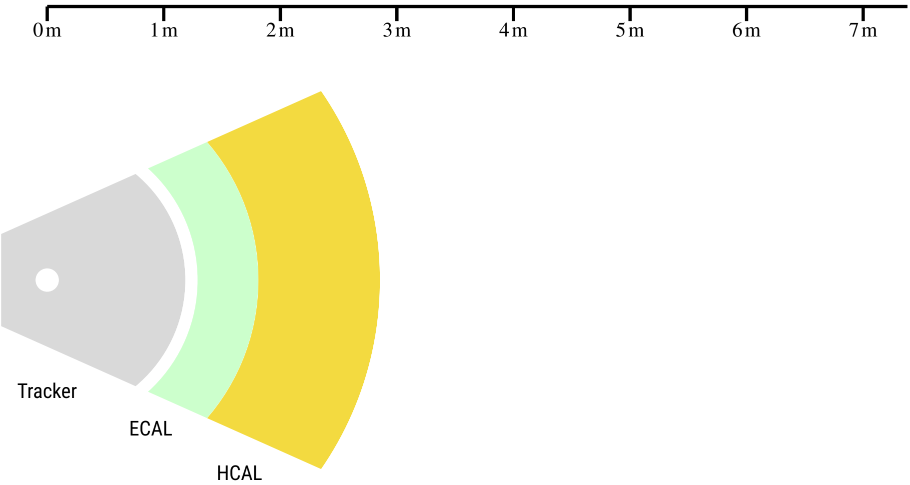
Sensitive parts of CMS

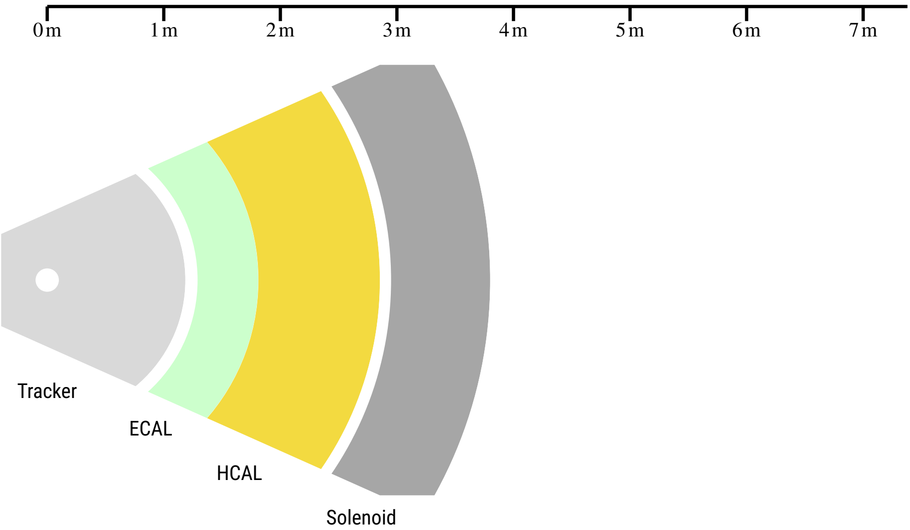
Combine sub-detectors signals to determine which particles were there!

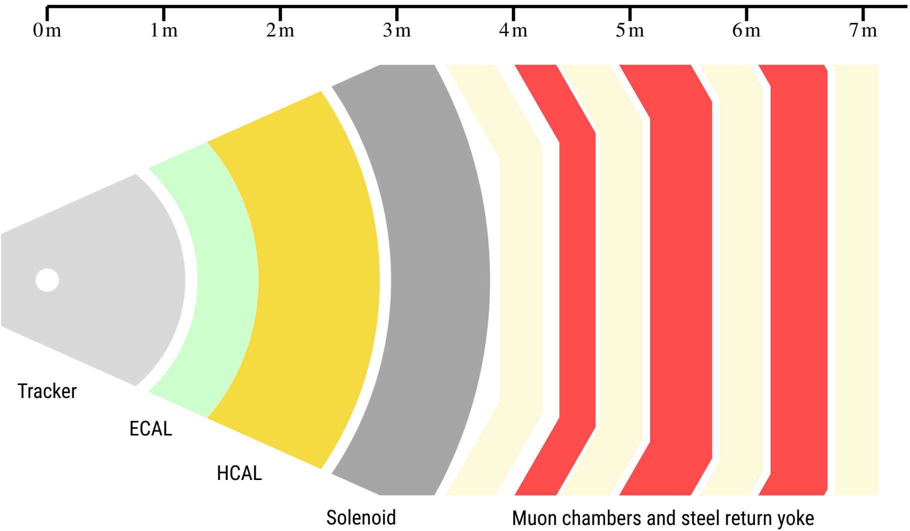

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m

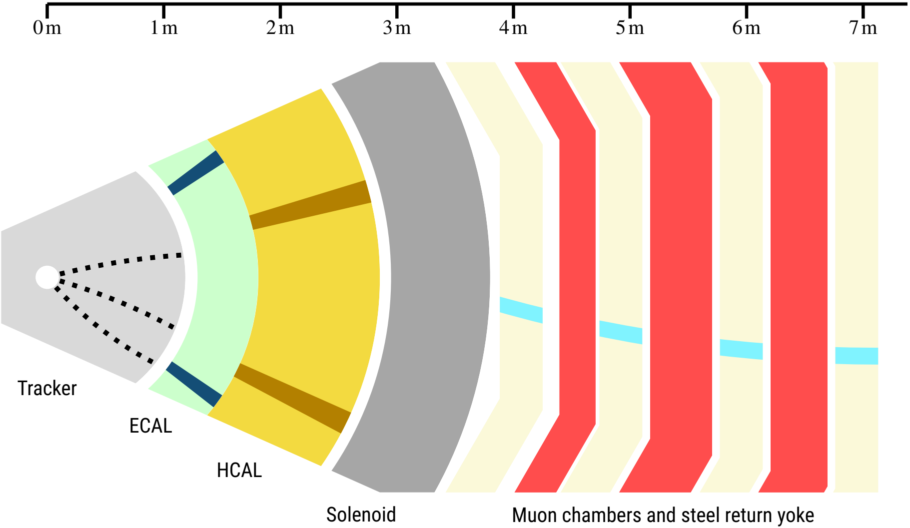

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker

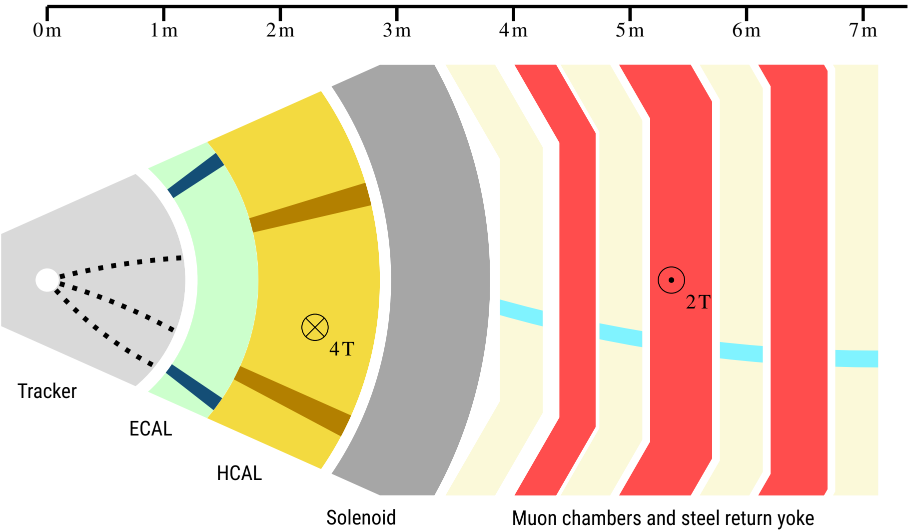

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL

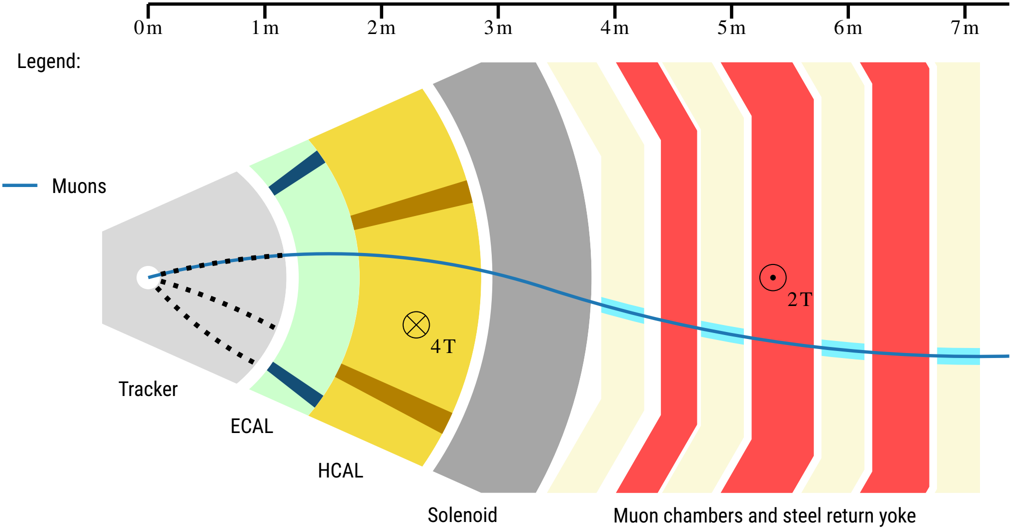

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL


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

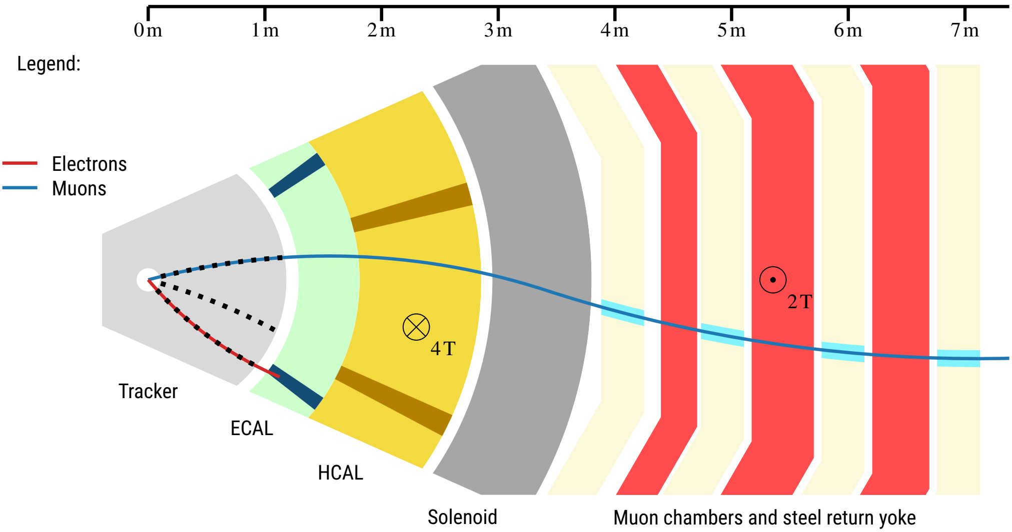

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

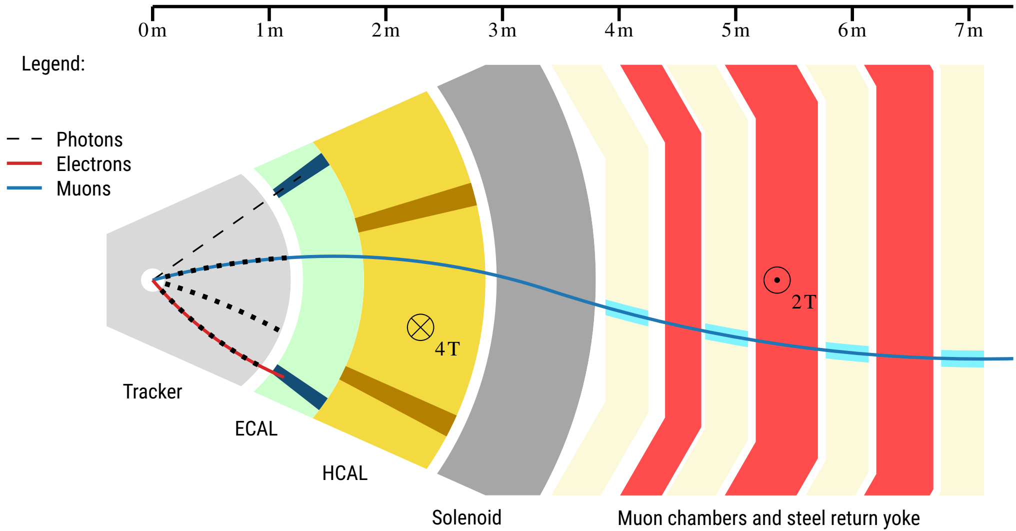

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke

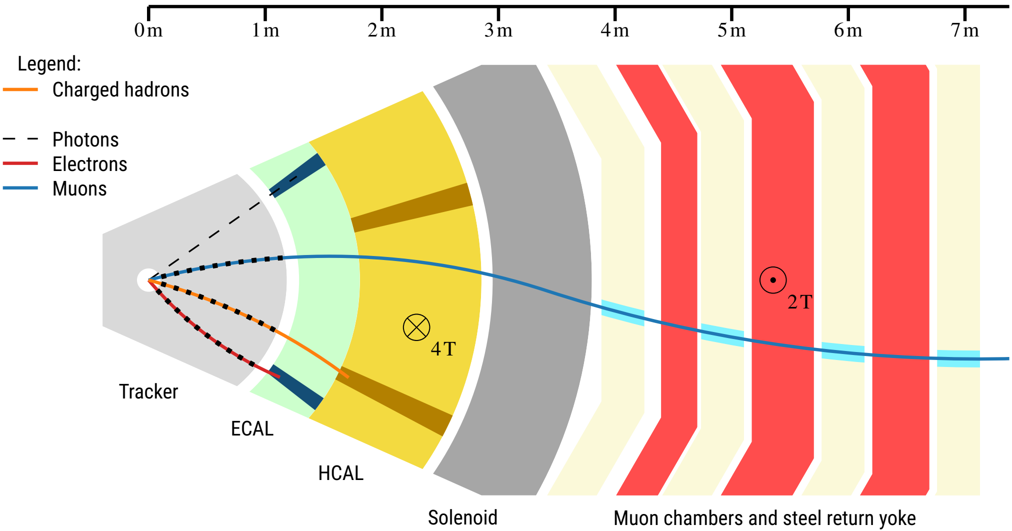

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke



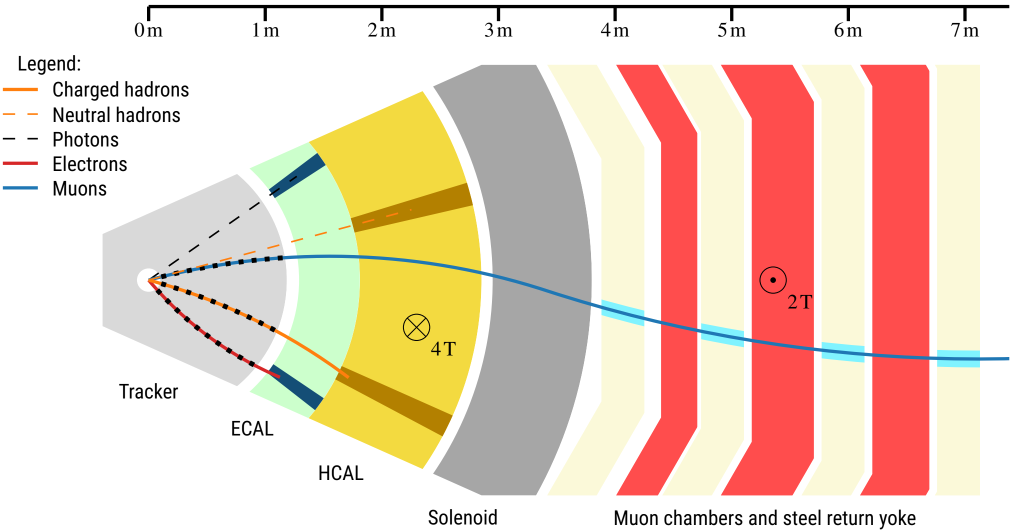
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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

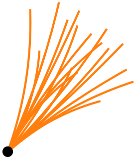

0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke



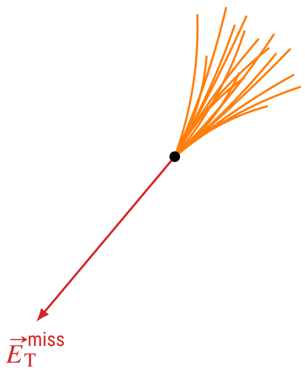
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Legend:
Charged hadrons
Photons
Electrons
Muons
4 T
2 T
Tracker
ECAL
HCAL
Solenoid
Muon chambers and steel return yoke


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

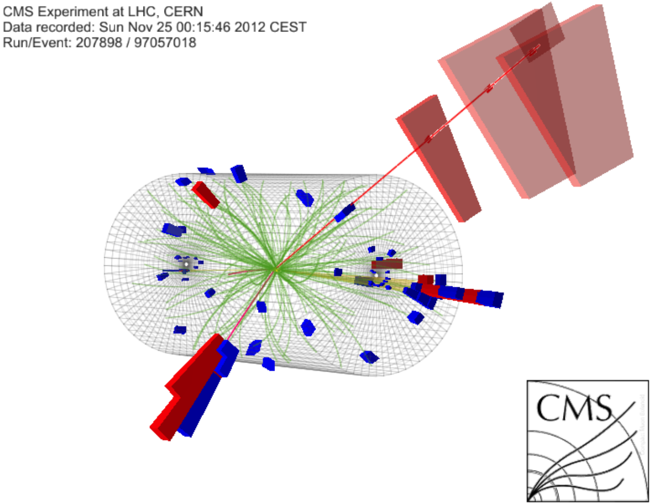
Neutrinos and missing transverse energy (MET)



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

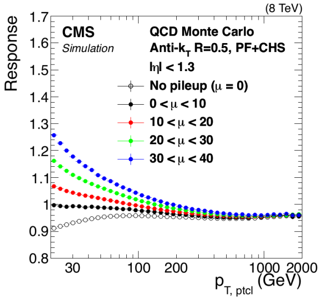
particule	(ptcl)
reconstruit	(reco)
corrigé	(corr)

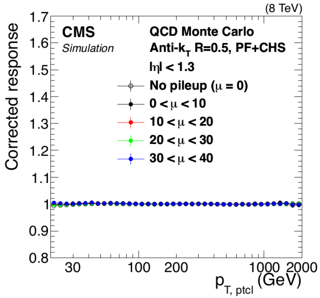
- Réponse d'un jet

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

Jets Reconstruits

Jets Calibrés



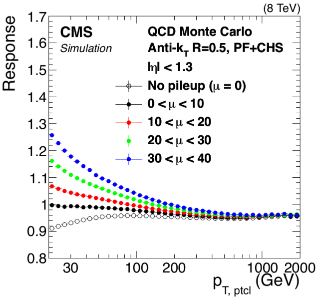


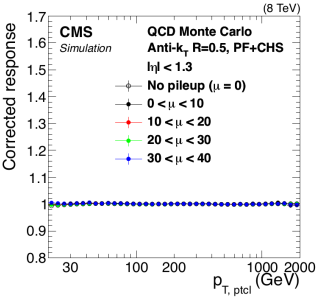
Appliqué aux données →

Jets Reconstruits

Jets Calibrés

Appliqué aux simulations →





Appliqué aux données

Jets Reconstruits

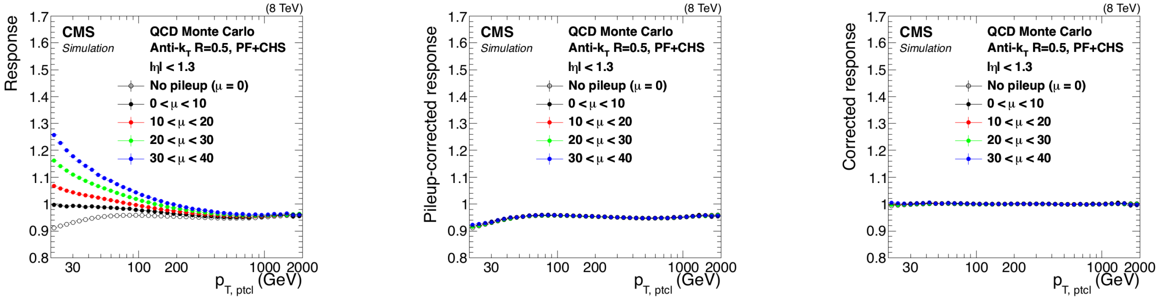
Empilement

MC+RC

MC

Jets Calibrés

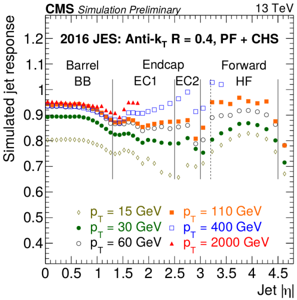
Appliqué aux simulations

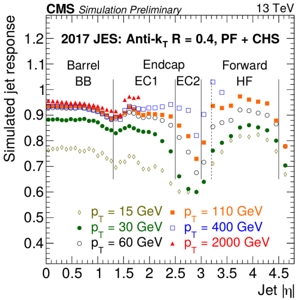


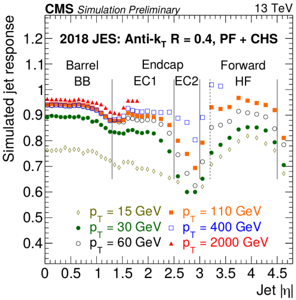
Appliqué aux données →

Jets Reconstruits → **Empilement** MC+RC / MC → **Réponse** (p_{T},η) MC → **Jets Calibrés**

Appliqué aux simulations →







Appliqué aux données

Jets Reconstruits

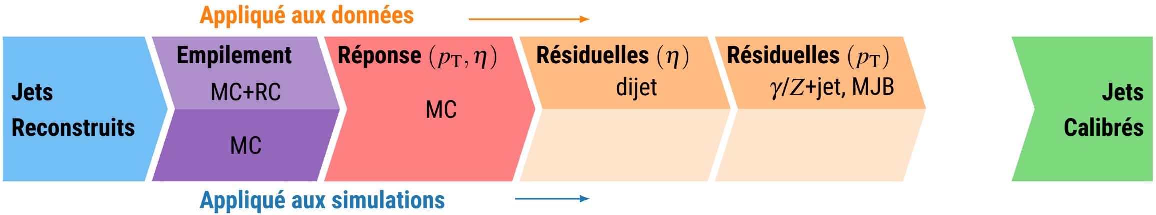
Empilement
MC+RC
MC

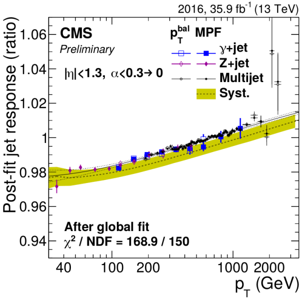
Réponse (p_{T}, η)
MC

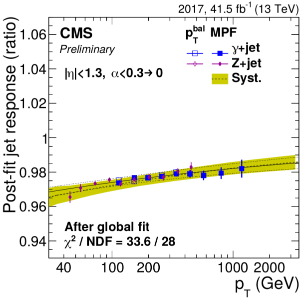
Résiduelles (η)
dijet

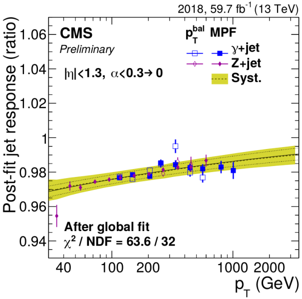
Jets Calibrés

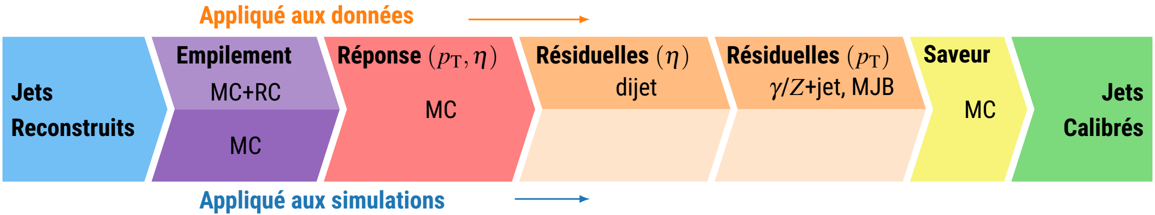
Appliqué aux simulations

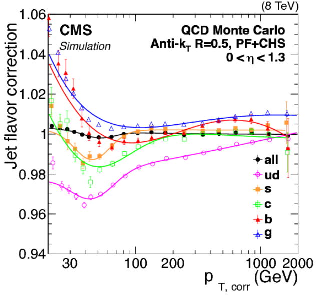

Appliqué aux données
Jets Reconstruits
Empilement
MC+RC
MC
Réponse (p_T, η)
MC
Résiduelles (η)
dijet
Résiduelles (p_T)
γ/Z+jet, MJB
Jets Calibrés
Appliqué aux simulations

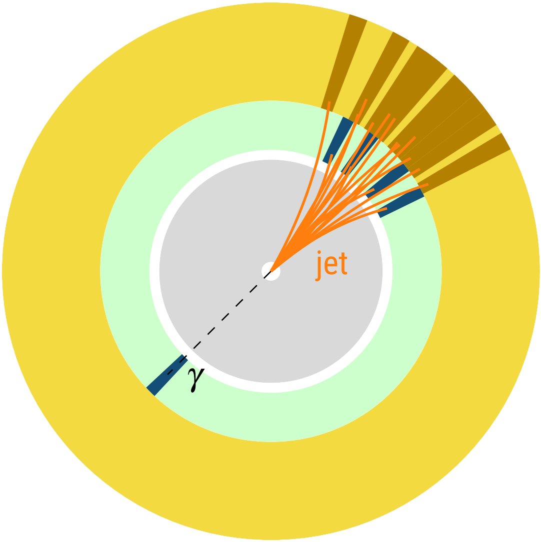

2016, 35.9 fb-1 (13 TeV)
CMS
Preliminary
|η|<1.3, α<0.3→ 0
pTbal MPF
γ+jet
Z+jet
Multijet
Syst.
After global fit
χ2 / NDF = 168.9 / 150
Post-fit jet response (ratio)
pT (GeV)

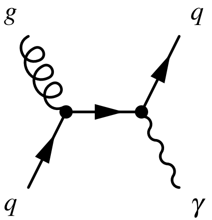

2017, 41.5 fb-1 (13 TeV)
CMS
Preliminary
|η|<1.3, α<0.3→ 0
pTbal MPF
γ+jet
Z+jet
Syst.
After global fit
χ2 / NDF = 33.6 / 28
Post-fit jet response (ratio)
pT (GeV)

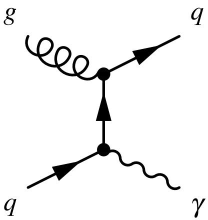

2018, 59.7 fb-1 (13 TeV)
CMS
Preliminary
|η|<1.3, α<0.3→ 0
pTbal MPF
γ+jet
Z+jet
Syst.
After global fit
χ2 / NDF = 63.6 / 32
Post-fit jet response (ratio)
pT (GeV)

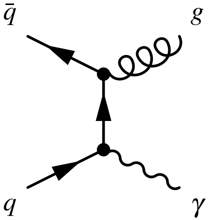

Appliqué aux données
Jets Reconstruits
Empilement
MC+RC
MC
Réponse (p_T, η)
MC
Résiduelles (η)
dijet
Résiduelles (p_T)
γ/Z+jet, MJB
Saveur
MC
Jets Calibrés
Appliqué aux simulations

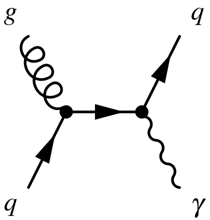

(8 TeV)
CMS
Simulation
QCD Monte Carlo
Anti-k$_T$ R=0.5, PF+CHS
0 < η < 1.3
Jet flavor correction
all
ud
s
c
b
g
$p_{T, corr}$ (GeV)

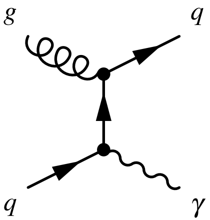

jet
γ

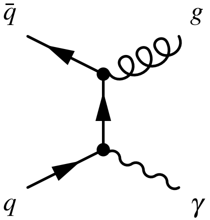

g
q
q
γ


g
q
q
γ

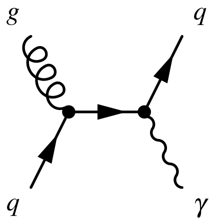

$\bar{q}$
g
q
γ

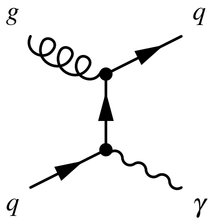


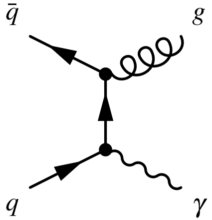




$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}} = \vec{0} \Rightarrow p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} = p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}$$

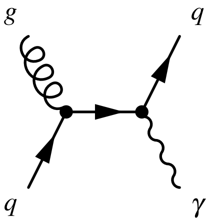


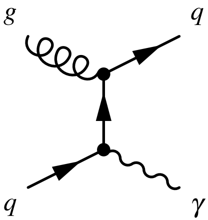


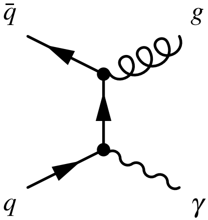


$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\text{jet}}_{\text{ptcl}} = \vec{0} \Rightarrow p_{\mathrm{T}}{}^{\gamma}_{\text{ptcl}} = p_{\mathrm{T}}{}^{\text{jet}}_{\text{ptcl}}$$

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



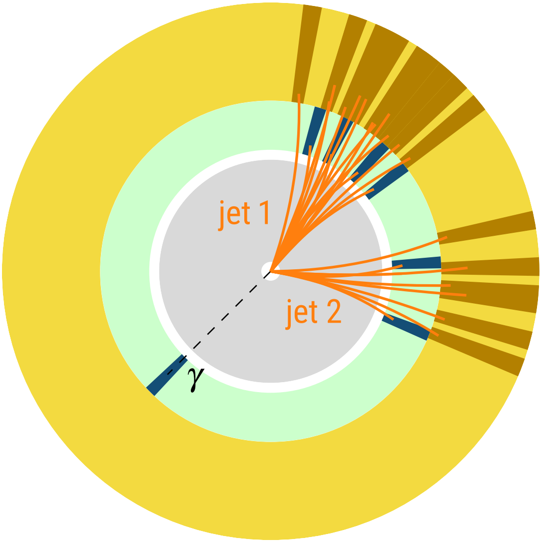


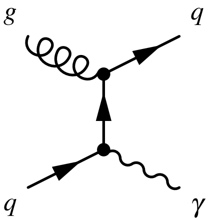


$$\vec{p}_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} + \vec{p}_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}} = \vec{0} \Rightarrow p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}} = p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}$$

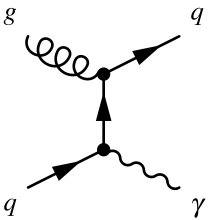
$$R = \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{ptcl}}} = \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{ptcl}}} \simeq \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\gamma}_{\mathrm{reco}}}$$

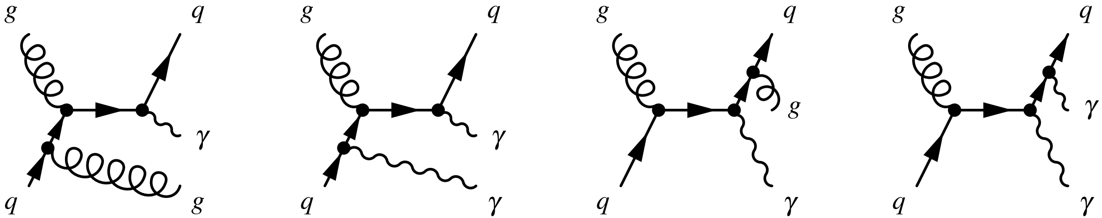
$$R_{bal} = \frac{p_{\mathrm{T}}{}^{\mathrm{jet}}_{\mathrm{reco}}}{p_{\mathrm{T}}{}^{\gamma}}$$


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

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

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

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

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

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

Jet Energy Resolution

- Remember R_{bal} definition,

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

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...), $\to 0$ when $\alpha \to 0$.

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...), $\to 0$ when $\alpha \to 0$.

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

Using histograms

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

The rabbit analogy

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

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

The rabbit analogy

- Dice results: 4

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

The rabbit analogy

- Dice results: 4, 2

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

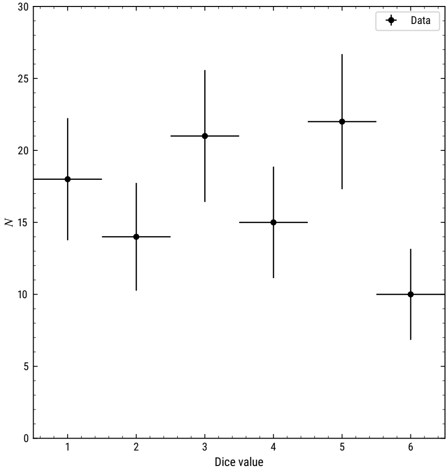
The rabbit analogy

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

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

The rabbit analogy

On 100 days $\longrightarrow$

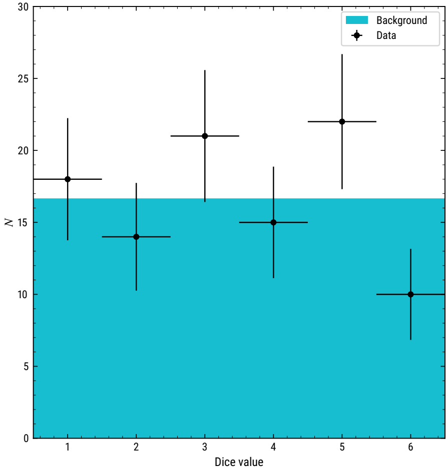


Not really conclusive...

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

The rabbit analogy

On 100 days $\longrightarrow$

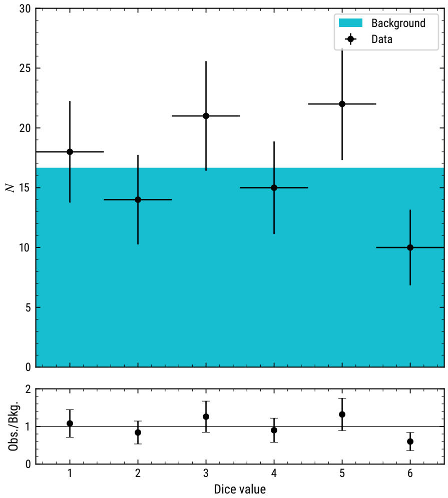


Comparing with predictions!

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

The rabbit analogy

On 100 days $\longrightarrow$

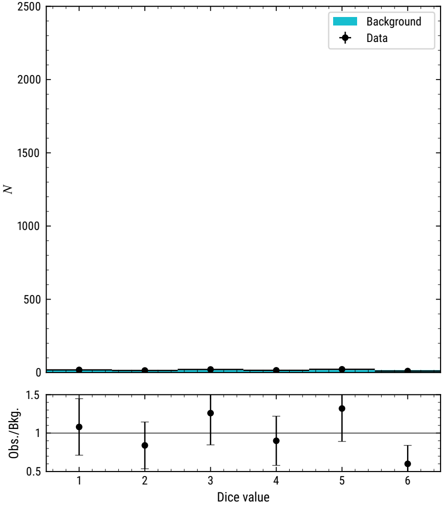


Also add ratio plot:
observed / predictions

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

The rabbit analogy

On 100 days $\longrightarrow$

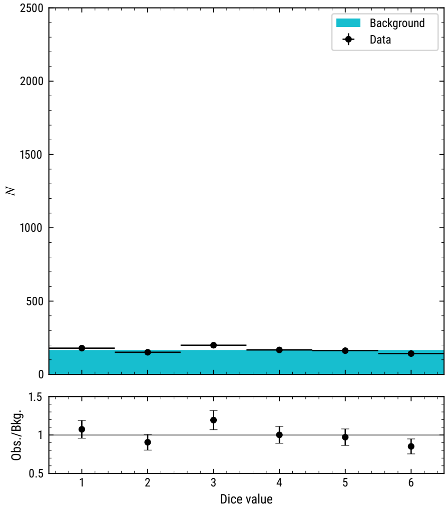


Fill up with more data!

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

The rabbit analogy

On 1000 days $\longrightarrow$

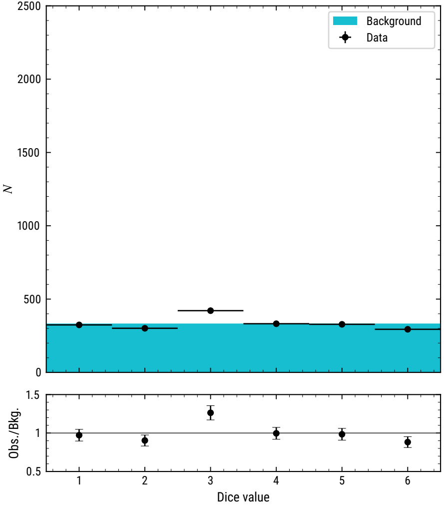


Fill up with more data!

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

The rabbit analogy

On 2000 days $\longrightarrow$

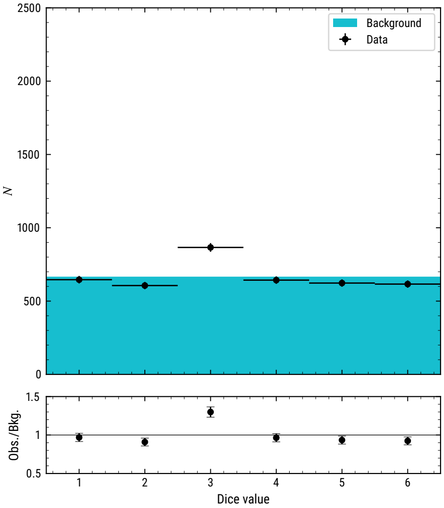


Fill up with more data!

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

The rabbit analogy

On 4000 days $\longrightarrow$

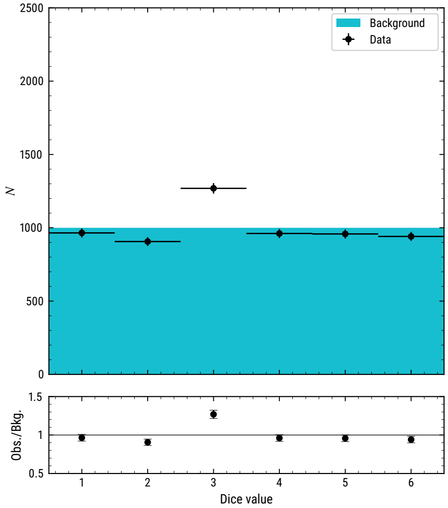


Fill up with more data!

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

The rabbit analogy

On 6000 days $\longrightarrow$

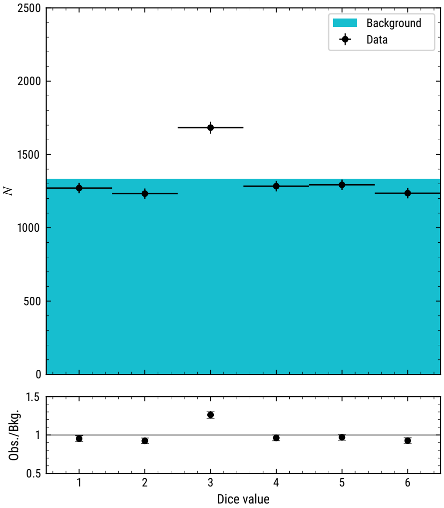


Fill up with more data!

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

The rabbit analogy

On 8000 days $\to$

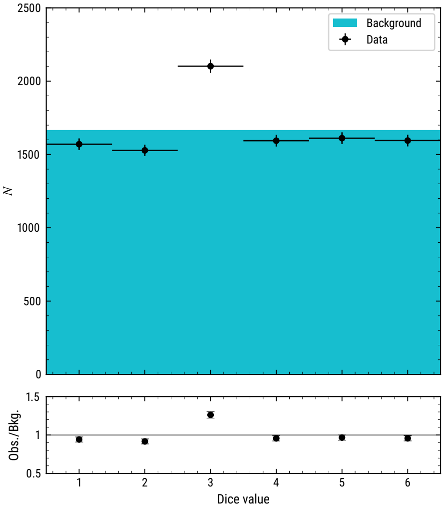


Fill up with more data!

- 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 $\to$

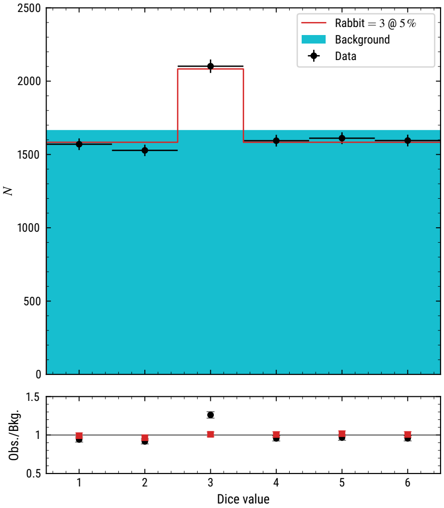


Fill up with more data!

▷ 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 $\rightarrow$

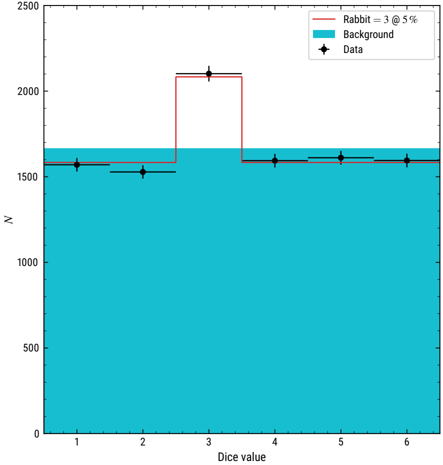


In red, hypothesis of the rabbit with 3 as preferred result (instead of 4!), with a probability to show up of $5\,\%$.

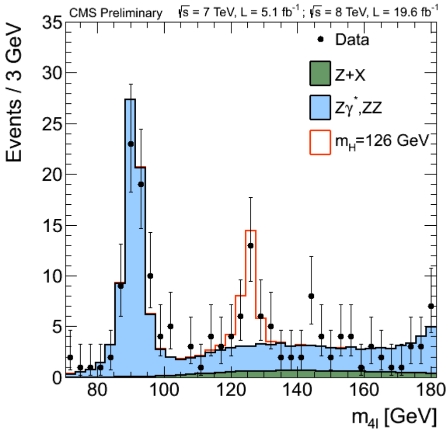
▷ CERN. *The Higgs Discovery Explained – Ep. 3/3*. URL: `https://www.youtube.com/watch?v=8-WFBGCvv-w`.

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



$\rightsquigarrow$

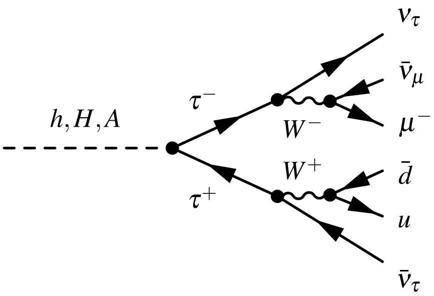


▷ The CMS Collaboration. "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC". *Physics Letters* **B716**.1 (2012), pp. 30–61. DOI: 10.1016/j.physletb.2012.08.021. URL: https://www.sciencedirect.com/science/article/pii/S0370269312008581.

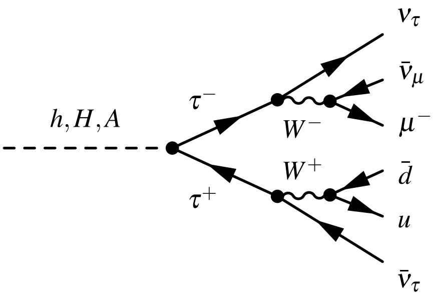
▷ The CMS Collaboration. *Properties of the Higgs-like boson in the decay $H \to ZZ \to 4\ell$ in pp collisions at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$*. URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki.

Discriminant variable?

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



Discriminant variable?



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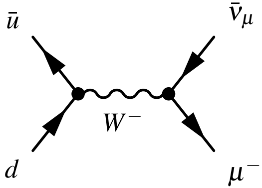
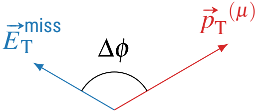


- For muon and $E_{\mathrm{T}}{}^{\text{miss}}$,

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

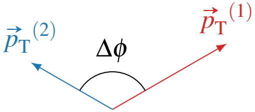


Discriminant variable: $m_{\mathrm{T}}^{\mathrm{tot}}$

- For L_1, L_2 and $E_{\mathrm{T}}{}^{\text{miss}}$ system,

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

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



Datasets

Observed data (MiniAOD)

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

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

Datasets

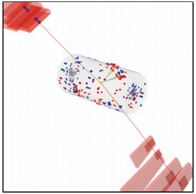
Simulated signals (MiniAODSIM)

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

Backgrounds?

Embedded events

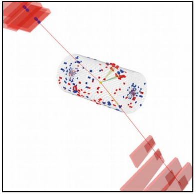
$Z \to \mu\mu$ data



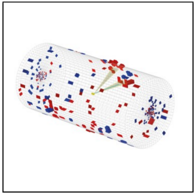
▷ The CMS Collaboration. "An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: 10.1088/1748-0221/14/06/p06032.

Embedded events

$Z \to \mu\mu$ data



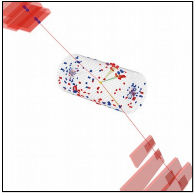
Remove $\mu\mu$ system



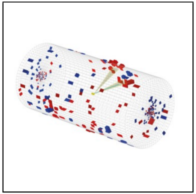
▷ The CMS Collaboration. “An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data”. *Journal of Instrumentation* **14**.06 (June 2019). DOI: 10.1088/1748-0221/14/06/p06032.

Embedded events

$Z \to \mu\mu$ data

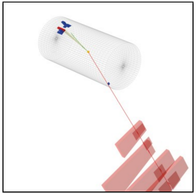


Remove $\mu\mu$ system



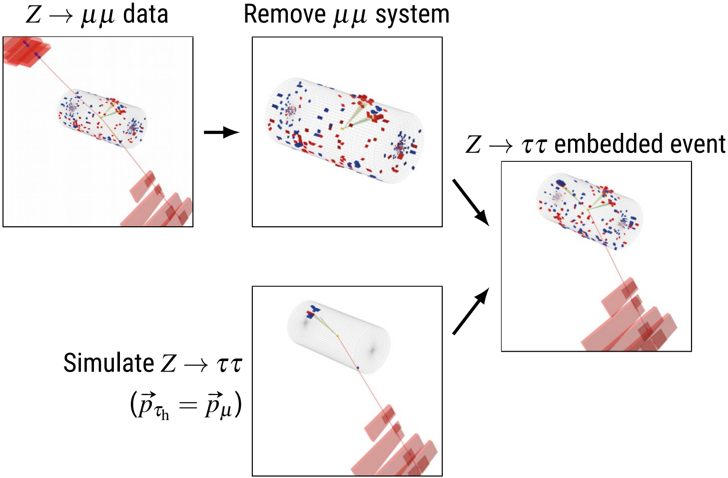
Simulate $Z \to \tau\tau$

$(\vec{p}_{\tau_{\mathrm{h}}} = \vec{p}_{\mu})$



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

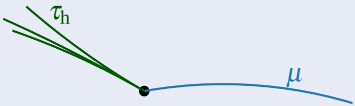
Embedded events



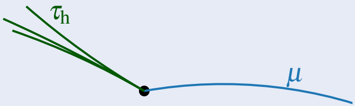
▷ The CMS Collaboration. "An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: 10.1088/1748-0221/14/06/p06032.

Backgrounds: Drell-Yan

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



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

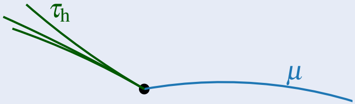


- `/EmbeddingRun2016B/MuTauFinalState` & others years and channels
- `/DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8` ...

Backgrounds: $W+$jets

$W+$jets

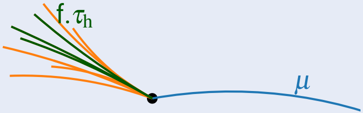
$H \to \tau\tau \to \mu\tau_h$



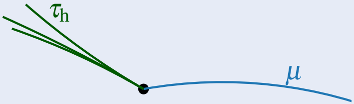
- /W[1-4]JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8
- /WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8 ...

Backgrounds: $W+$jets

$W+$jets, jet $\to$ fake τ_h



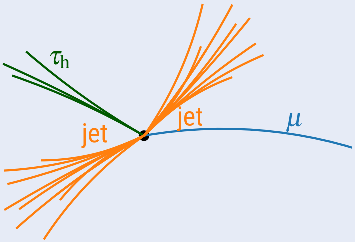
$H \to \tau\tau \to \mu\tau_h$



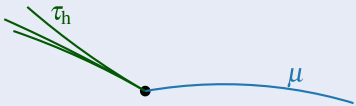
- `/W[1-4]JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8`
- `/WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8` ...

Backgrounds: $t\bar{t}$

$t\bar{t}$



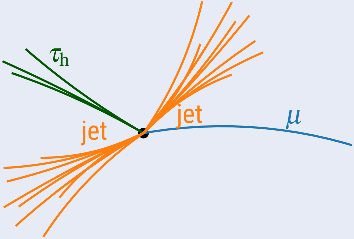
$H \to \tau\tau \to \mu\tau_h$



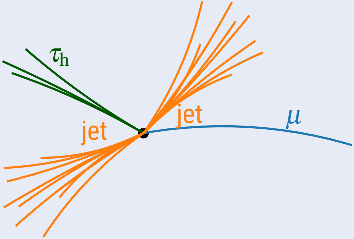
- /TTToHadronic_TuneCP5_13TeV-powheg-pythia8
- /TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8 ...

Backgrounds: $t\bar{t}$

$t\bar{t}$



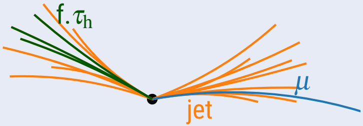
H production with b-jets



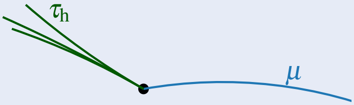
- /TTToHadronic_TuneCP5_13TeV-powheg-pythia8
- /TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8 ...

Backgrounds: QCD

QCD



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

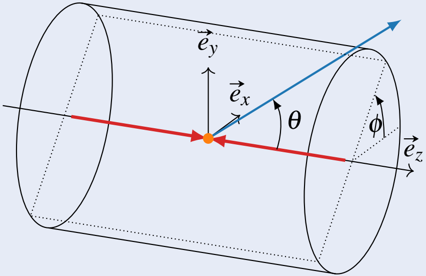


Comes from fake τ_hs
$\Rightarrow$ estimation based on different regions, see later

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

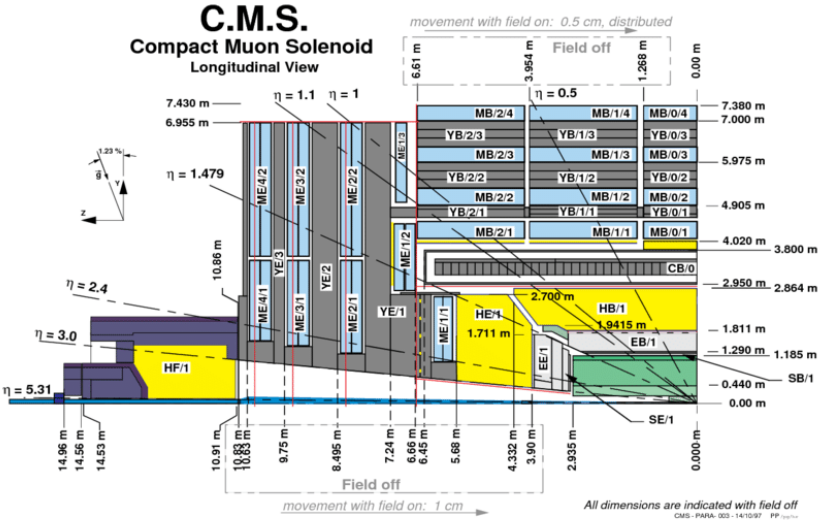
μ and τ_h candidates

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

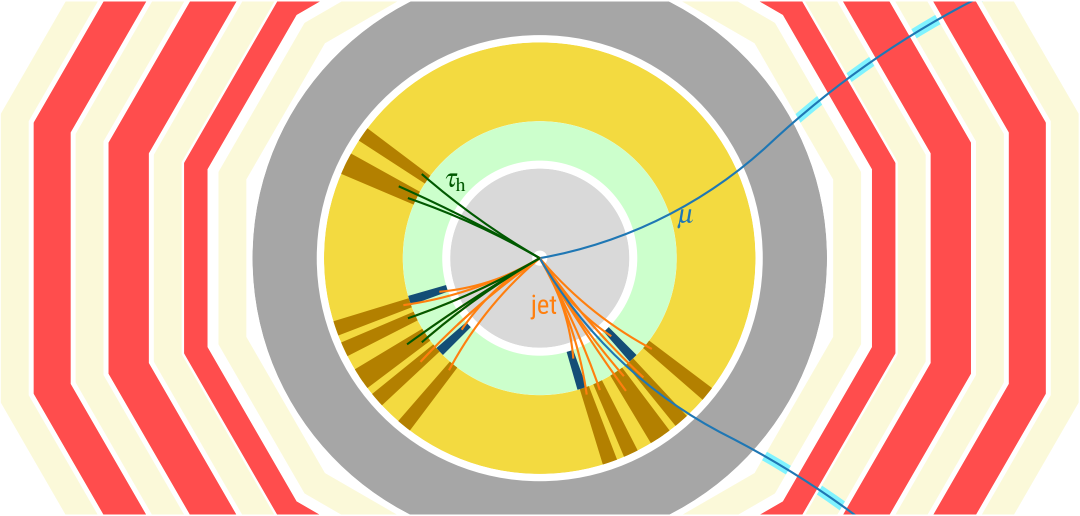


$$\eta = -\ln \tan \frac{\theta}{2}$$

Values of η and trajectories in CMS



Particles isolation – qualitatively

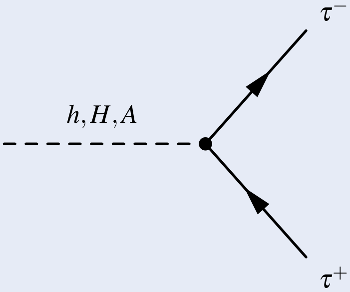


Signal region (SR) – 2017 $\mu\tau_\mathrm{h}$ channel as example

Obtaining *dileptons* candidates

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

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



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

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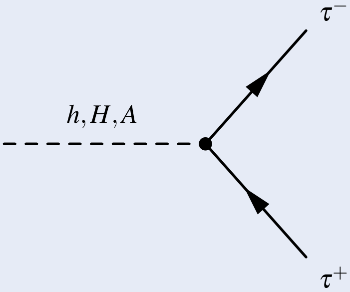

Selecting one dilepton

Choose by:

most isolated L_1, highest ${p_\mathrm{T}}^{L_1}$, most isolated L_2, highest ${p_\mathrm{T}}^{L_2}$.

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

Extra leptons: reject events containing

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

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

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- opposite-charge muon pair ($\mu\mu$ channel overlapping)

Transverse mass

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

The Fake Factor method

- How many events contain misidentified τ_h? (fake taus)

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

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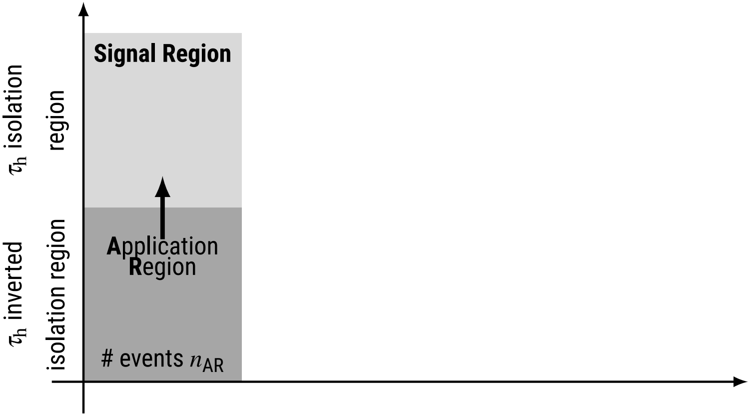


▷ J. Andrejkovic et al. "Data-driven background estimation of fake-tau backgrounds in di-tau final states with 2016 and 2017 data". *CMS analysis Note* (Oct. 2018).

The FF method: determination regions definitions

$t\bar{t}$ + jets

Estimation from simulated samples, same selection as in SR.

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

The FF method: determination regions definitions

$t\bar{t}$ + jets

Estimation from simulated samples, same selection as in SR.

W + jets

Same as SR, except:

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

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

The FF method: determination regions definitions

$t\bar{t}$ + jets

Estimation from simulated samples, same selection as in SR.

W + jets

Same as SR, except:

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

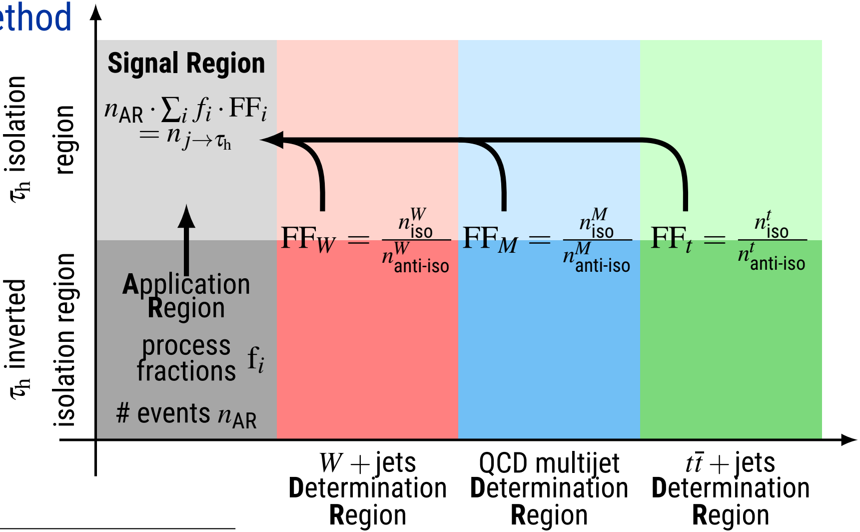
QCD multijet

Same as SR, except:

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

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

The FF method



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

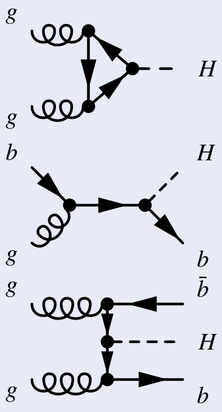
$m_{\mathrm{T}}^{\mathrm{tot}}$ distributions

Exclusion limits

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

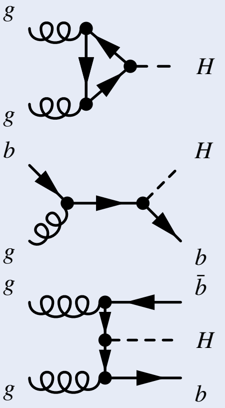
Model-dependant limits

Higgs production



...

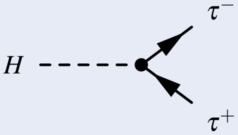
Higgs production



...

$\otimes$

$H \to \tau\tau$



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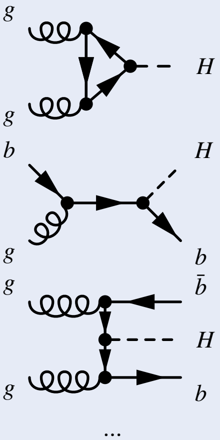

$\otimes$

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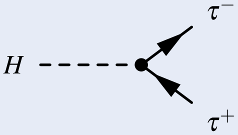
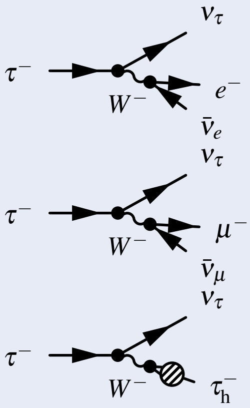
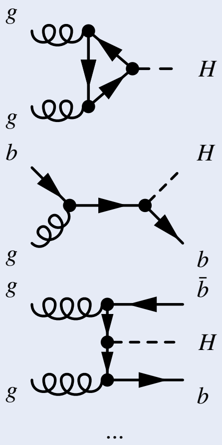


$\otimes$

τ decays

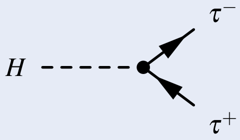


Higgs production



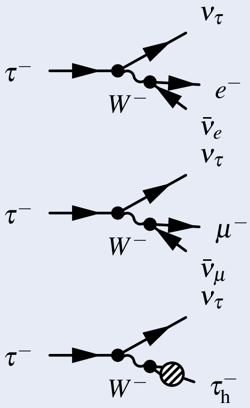
eventual jets

$H \to \tau\tau$



2 taus

τ decays



$\{1,2\}$ neutrinos per tau $+\{e,\mu,\tau_{\mathrm{h}}\}$

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

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  - two leading jets $\to$ ${p_{\mathrm{T}}}^{(j1,j2)}$, $\eta^{(j1,j2)}$ and $\phi^{(j1,j2)}$;

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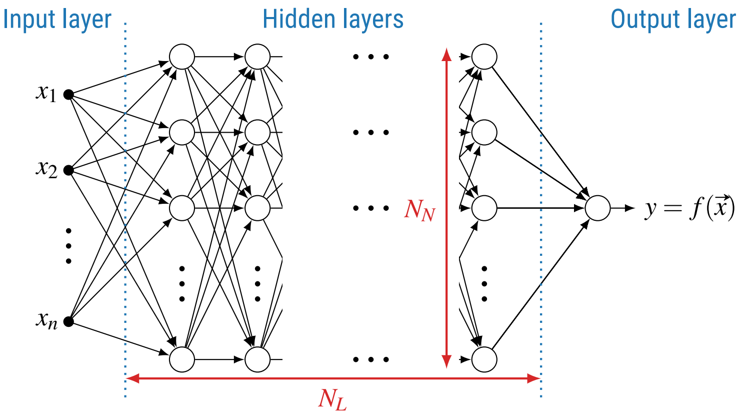
  - transverse masses m_{T}^{1}, m_{T}^{2}, $m_{\mathrm{T}}^{\tau\tau}$,
  - total transverse mass $m_{\mathrm{T}}^{\text{tot}}$.
- Additionnal variables:
  - MET covariance matrix;
  - remaining jets overall $\vec{p} \to {p_{\mathrm{T}}}^{r}$, η^{r} and ϕ^{r};
  - number of neutrinos ($\tau_{\mathrm{h}}\tau_{\mathrm{h}}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



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

- 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!