



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



PHAST
PHYSIQUE
ET ASTROPHYSIQUE
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

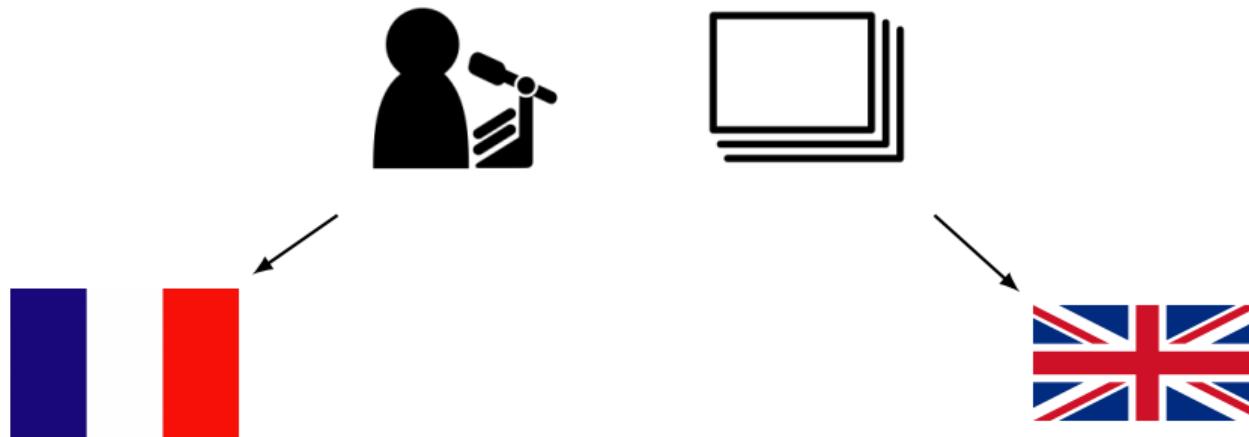
Lucas TORTEROTOT

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XX xxxx 2021



Lang(u)age





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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...?**

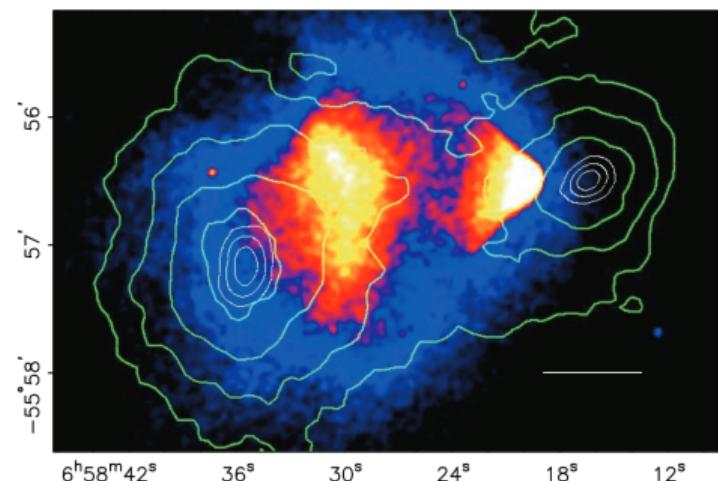
- ▷ D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

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 →
 - ▶ matter vs antimatter asymmetry
 - ▶ ...
- Go beyond with a new model!
- Consequences of this new model? **Test it!**



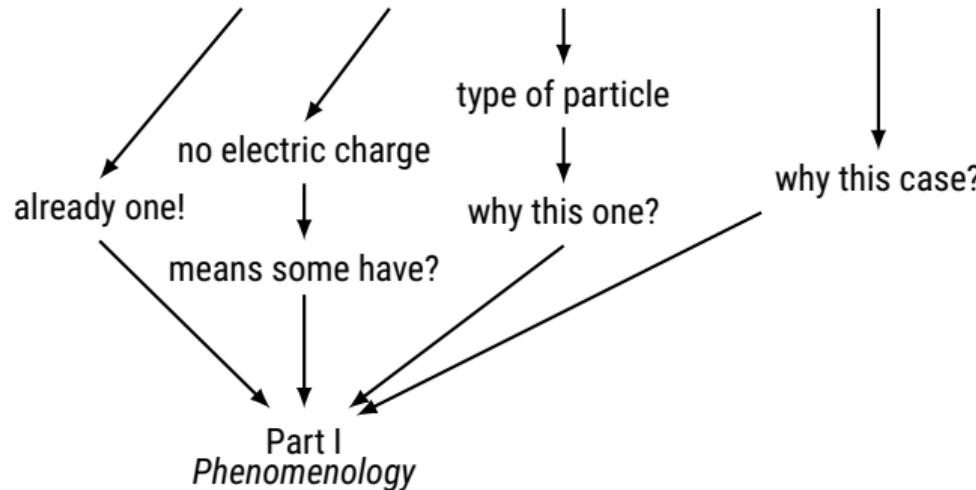
▷ D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark Matter". *Astrophysical Journal* **648**.2 (Aug. 2006). DOI: 10.1086/508162.

Keywords in title

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

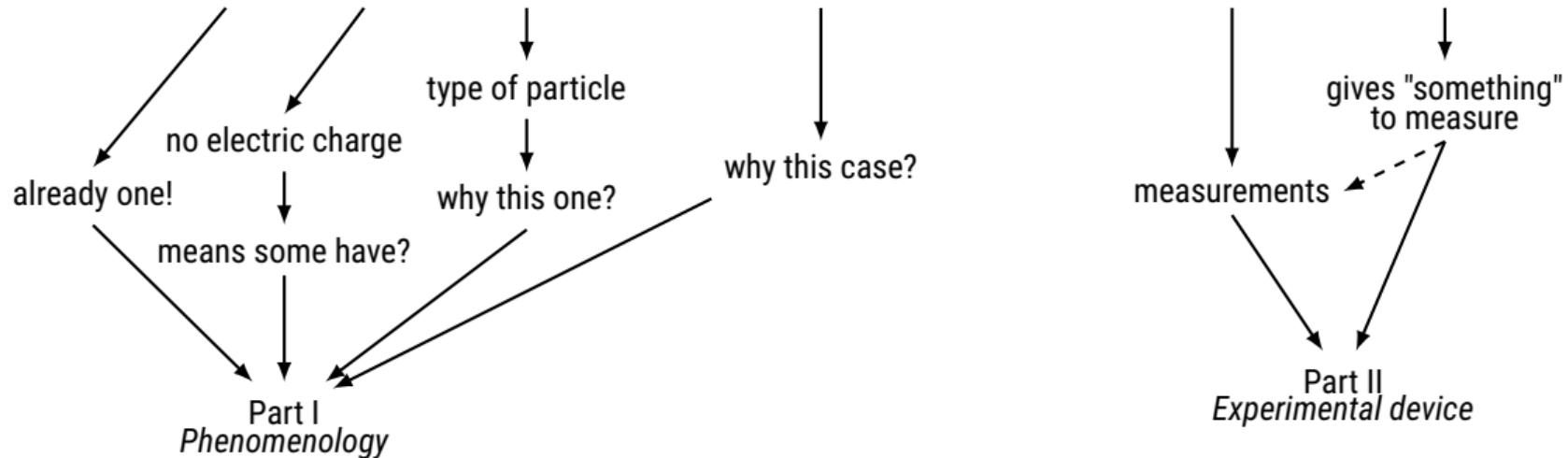
Keywords in title

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



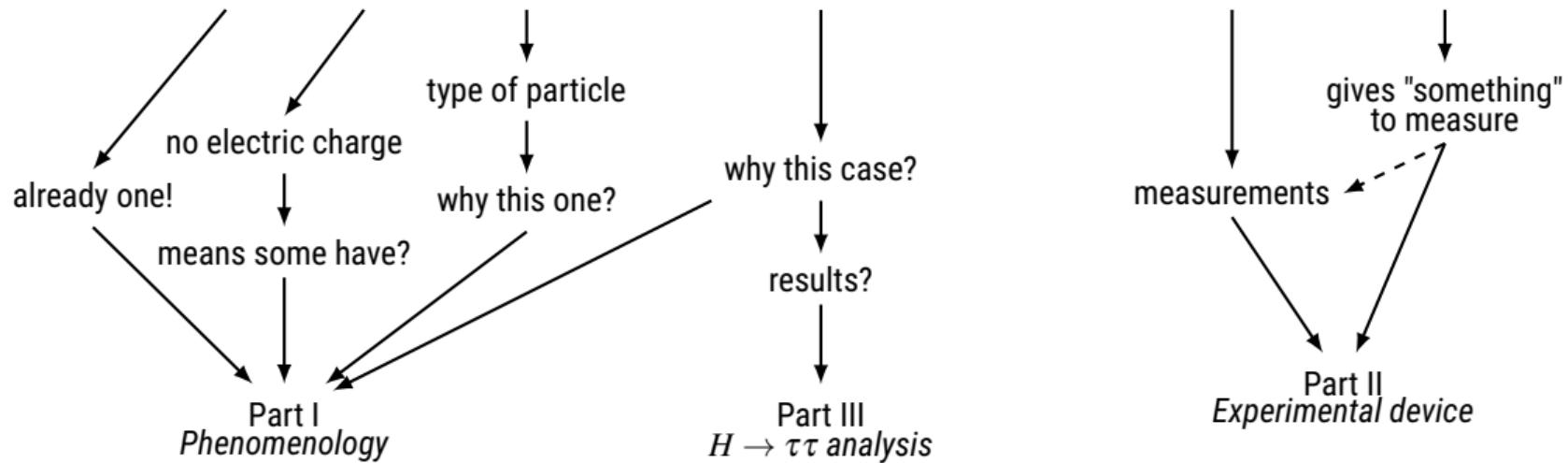
Keywords in title

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



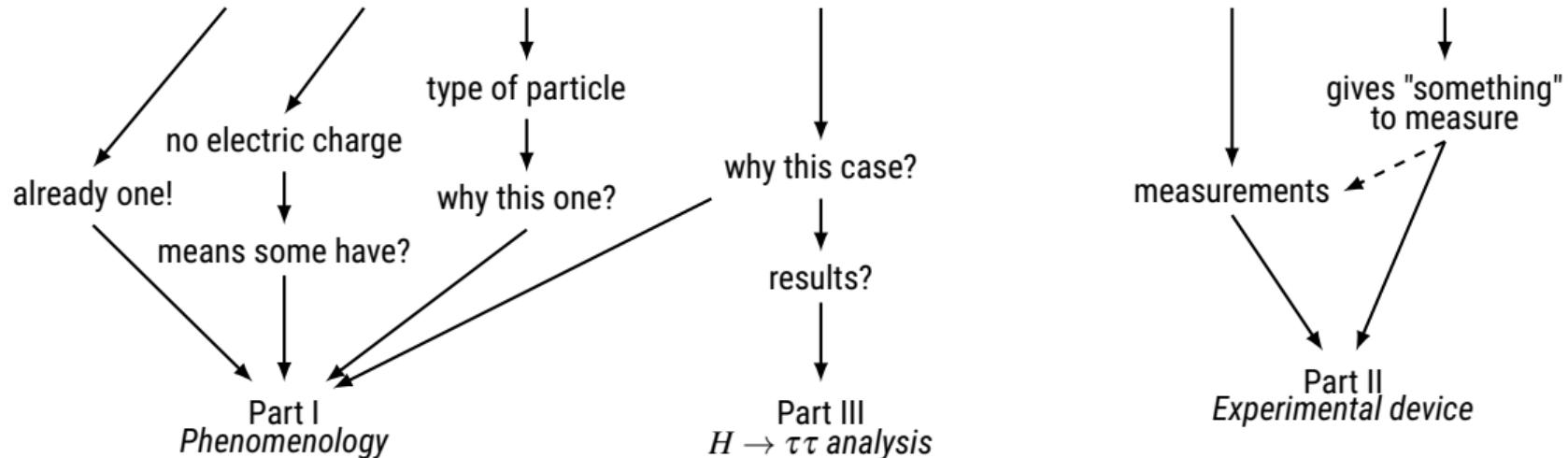
Keywords in title

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



Keywords in title

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



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

1 Phenomenology

2 Experimental device

3 $H \rightarrow \tau\tau$ analysis

4 Machine Learning

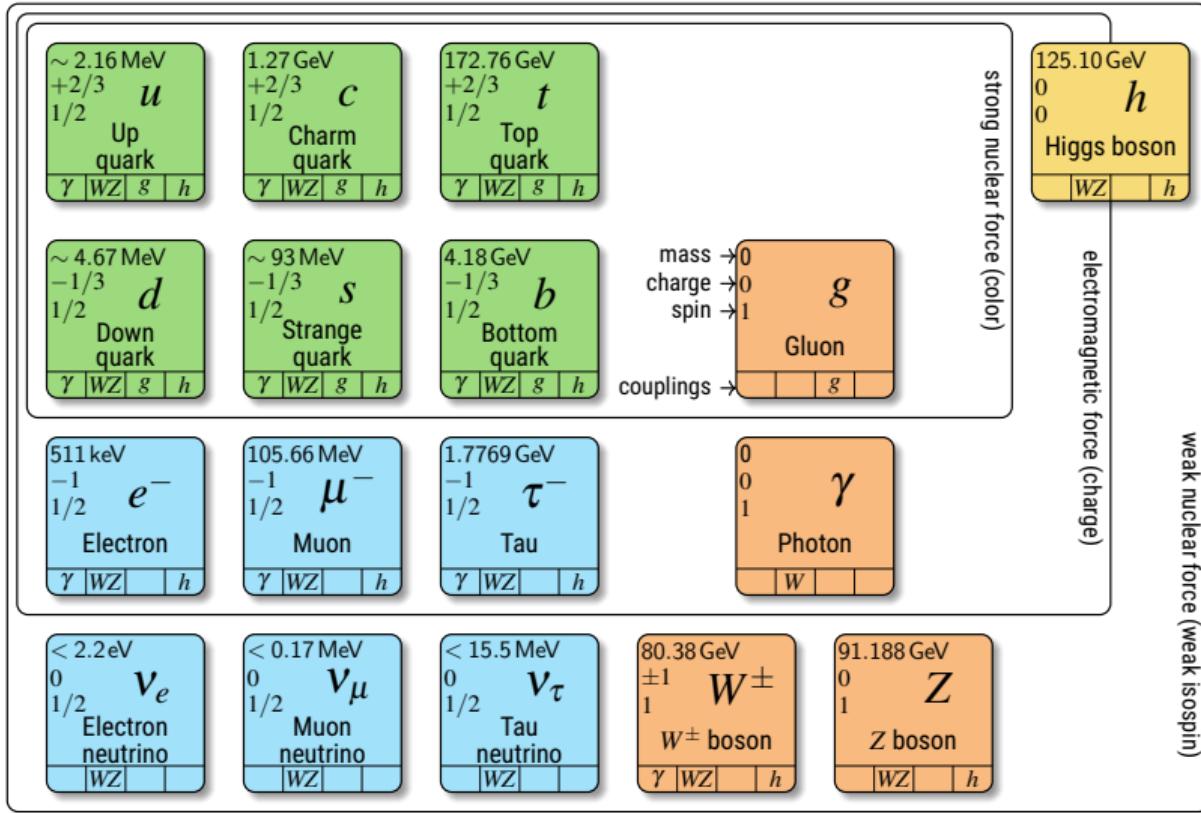
1 Phenomenology

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4 Machine Learning

The Standard Model



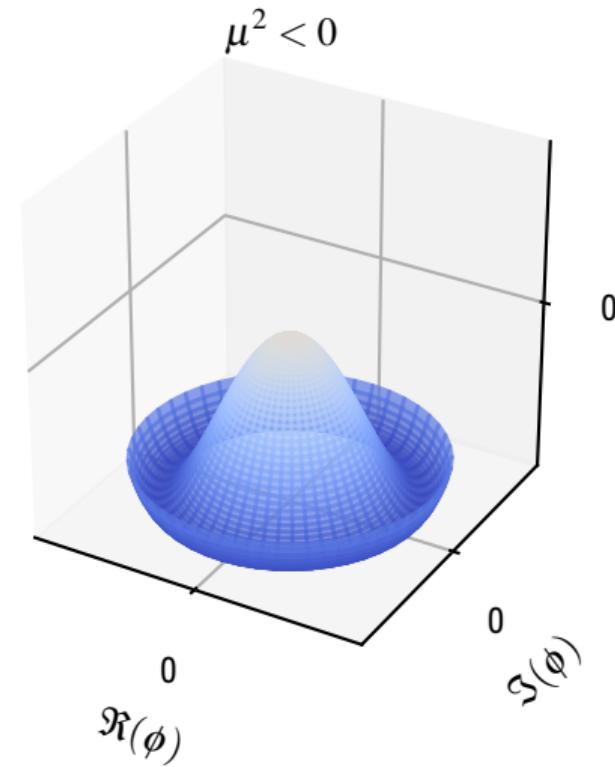
Higgs boson in the Standard Model

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

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

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

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

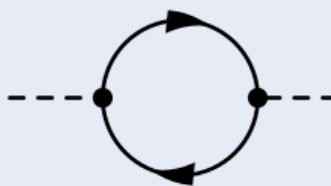


The Standard Model and naturalness problem

► Higgs mass measured: $m_h = 125.10 \pm 0.14 \text{ GeV}$

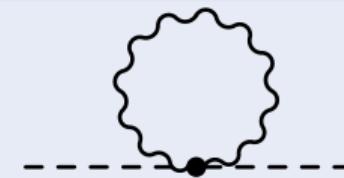
► Higgs mass derivation: $m_h^2 = m_{h0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \dots$

top quark



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

vector bosons



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

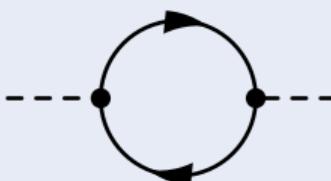
Higgs itself



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

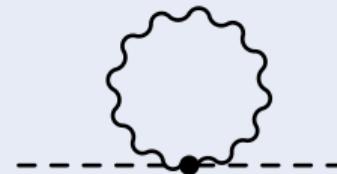
Supersymmetry

top quark



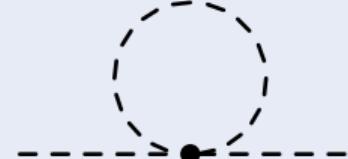
$$\sim -(2 \text{ TeV})^2$$

vector bosons



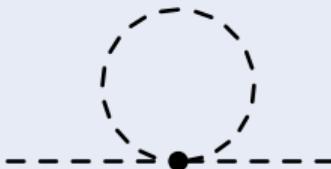
$$\sim +(0.7 \text{ TeV})^2$$

Higgs itself



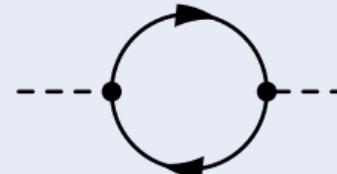
$$\sim +(0.5 \text{ TeV})^2$$

stop quark



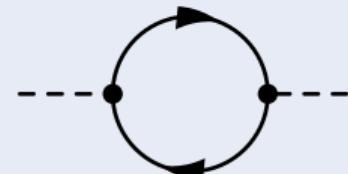
$$\sim +(2 \text{ TeV})^2$$

bosinos



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

Higgsinos



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

2 Higgs doublets models for supersymmetry

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

2 Higgs doublets models for supersymmetry

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

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

Higgs bosons in the MSSM

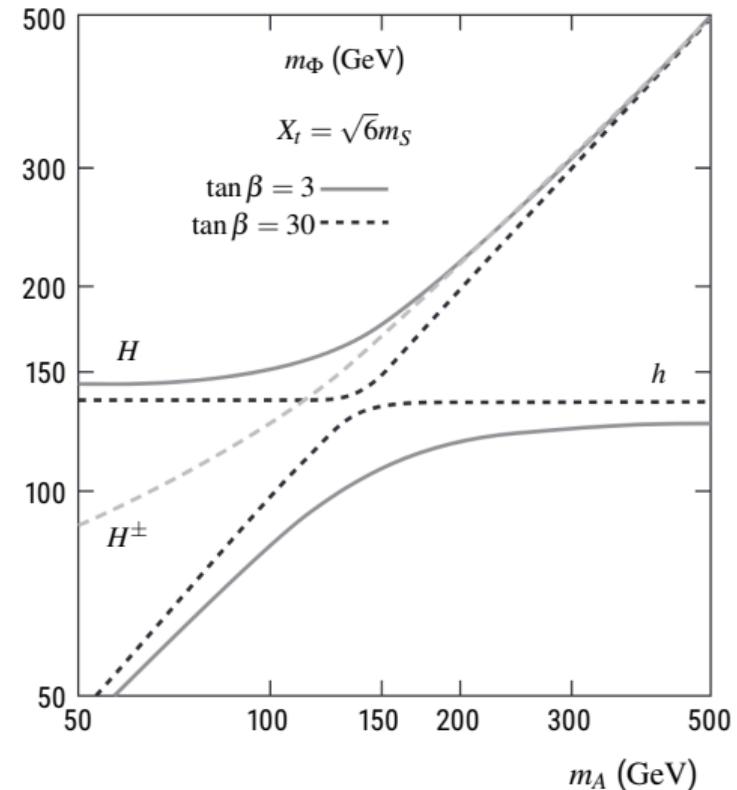
Minimal Supersymmetric extension of Standard Model

5 Higgs bosons

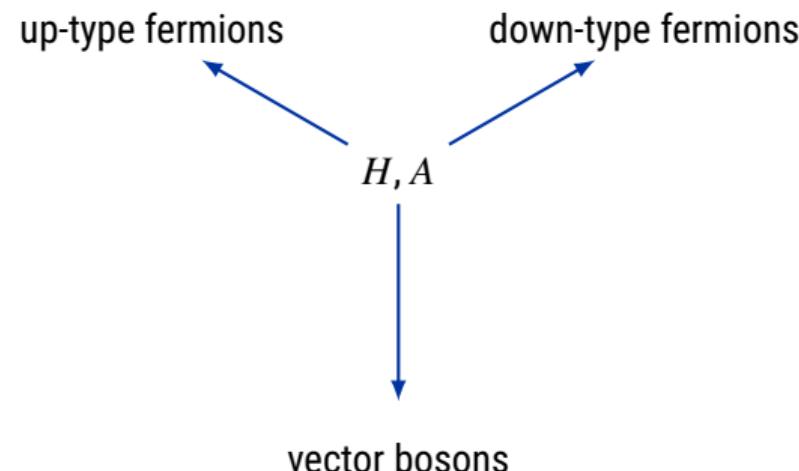
light scalar	h	SM or MSSM
heavy scalar	H	MSSM or SM
pseudo-scalar	A	MSSM
+ charged	H^+	MSSM
- charged	H^-	MSSM

► The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13\text{ TeV}$ ". *Journal of High Energy Physics* **09.007** (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/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>.

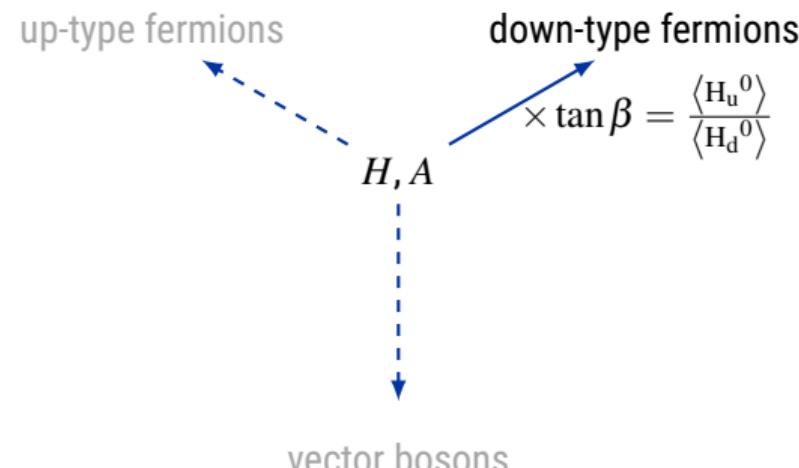


$H \rightarrow \tau\tau?$



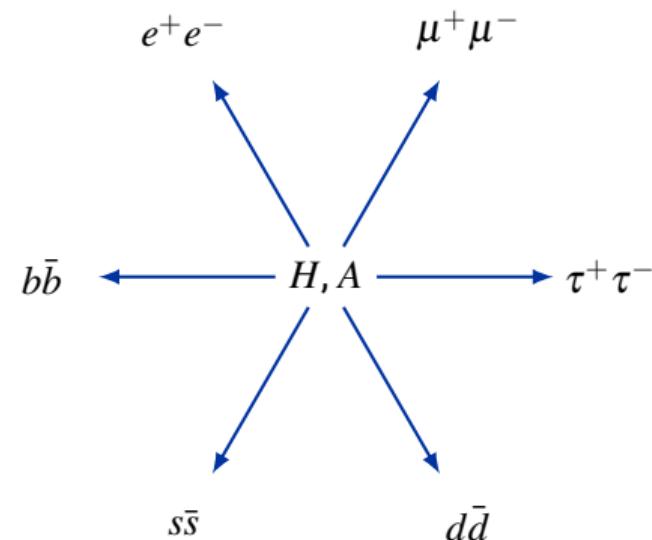
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).

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



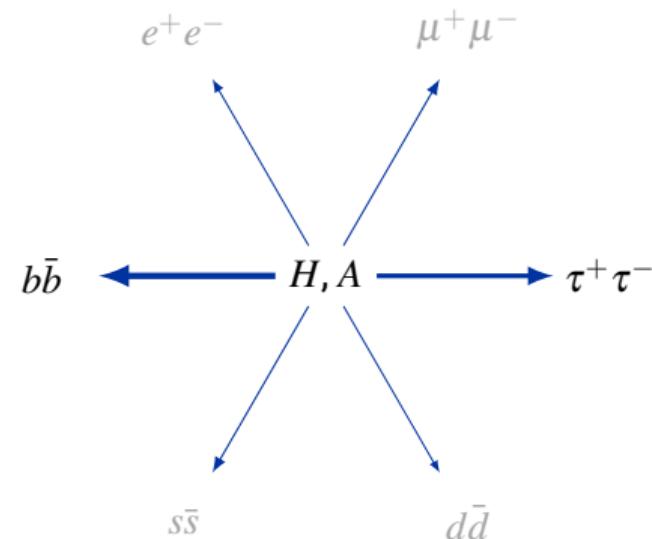
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).

$H \rightarrow \tau\tau?$



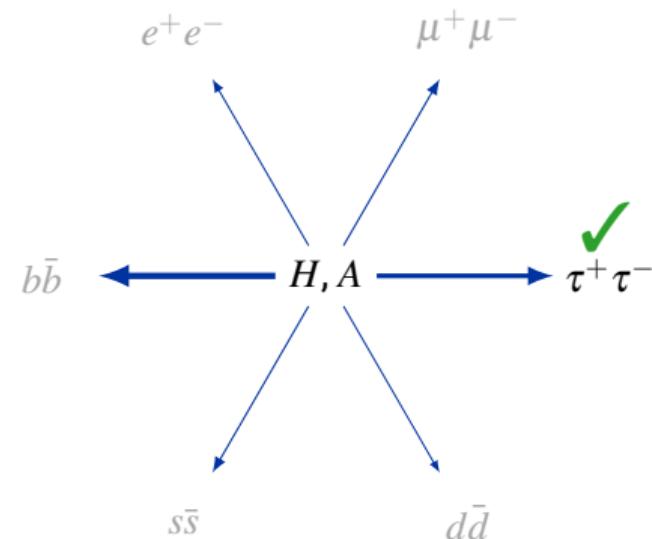
- The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).

$H \rightarrow \tau\tau?$ – Higgs couplings and particles masses



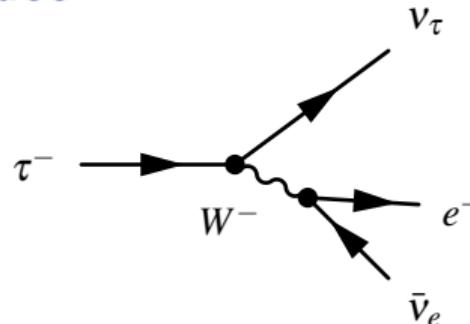
- ▷ The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).

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

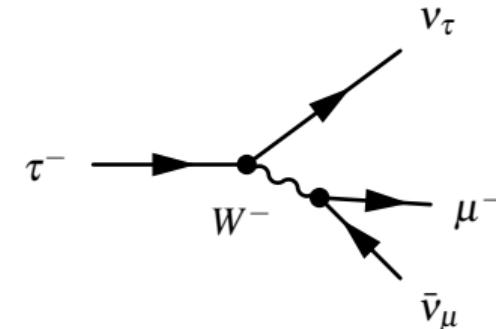
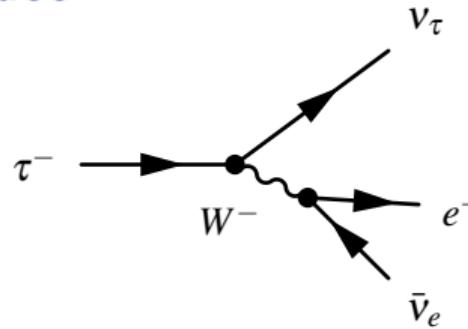


► The CMS Collaboration. "Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV". *Journal of High Energy Physics* 09.007 (Sept. 2018). DOI: [10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007).

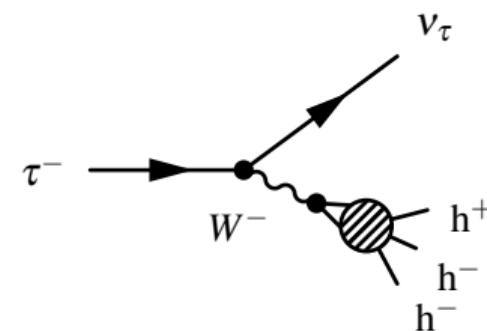
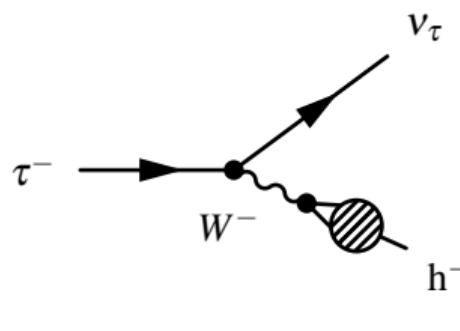
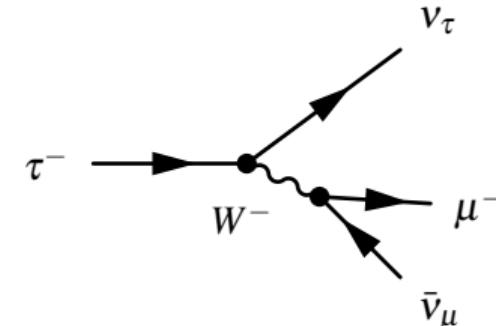
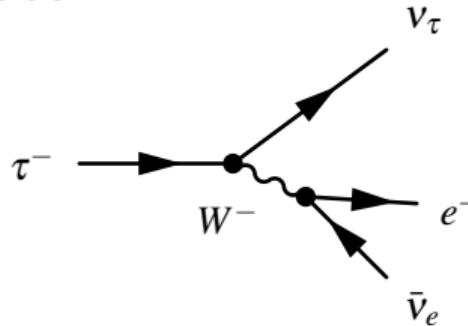
τ decay modes



τ decay modes



τ decay modes



$H \rightarrow \tau\tau \rightarrow L_1 L_2$

$$\tau \rightarrow e + \nu_e \Rightarrow e$$

17.8 %

$$\tau \rightarrow \mu + \nu_\mu \Rightarrow \mu$$

17.4 %

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

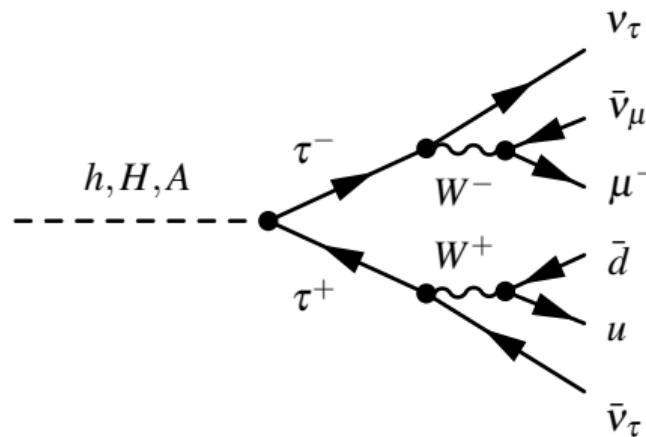
64.8 %

$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$

$$\begin{aligned}\tau &\rightarrow e + \nu_e \Rightarrow e \\ &17.8\%\end{aligned}$$

$$\begin{aligned}\tau &\rightarrow \mu + \nu_\mu \Rightarrow \mu \\ &17.4\%\end{aligned}$$

$$\begin{aligned}\tau &\rightarrow \text{hadrons} + \nu_\tau \Rightarrow \tau_h \\ &64.8\%\end{aligned}$$

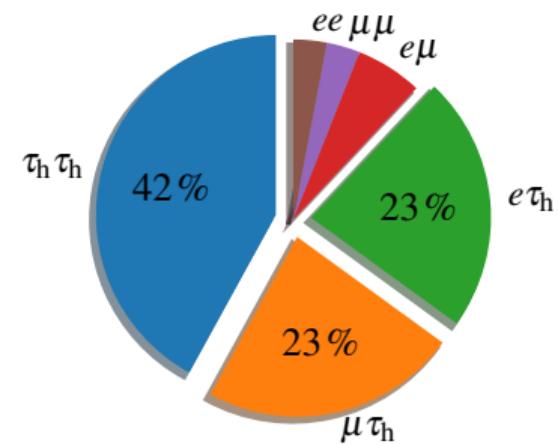
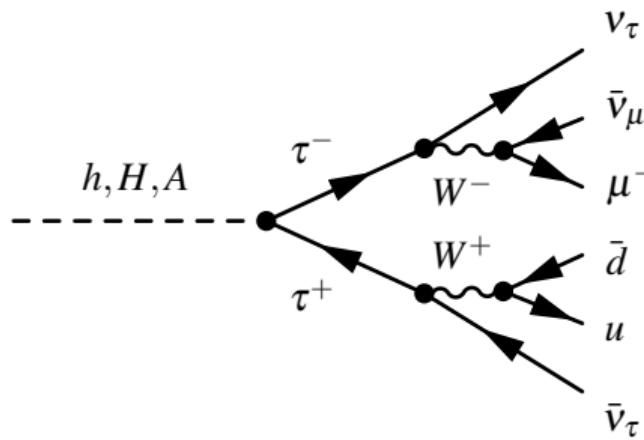


$$H \rightarrow \tau\tau \rightarrow L_1 L_2$$

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

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

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



1 Phenomenology

2 Experimental device

3 $H \rightarrow \tau\tau$ analysis

4 Machine Learning

Principle

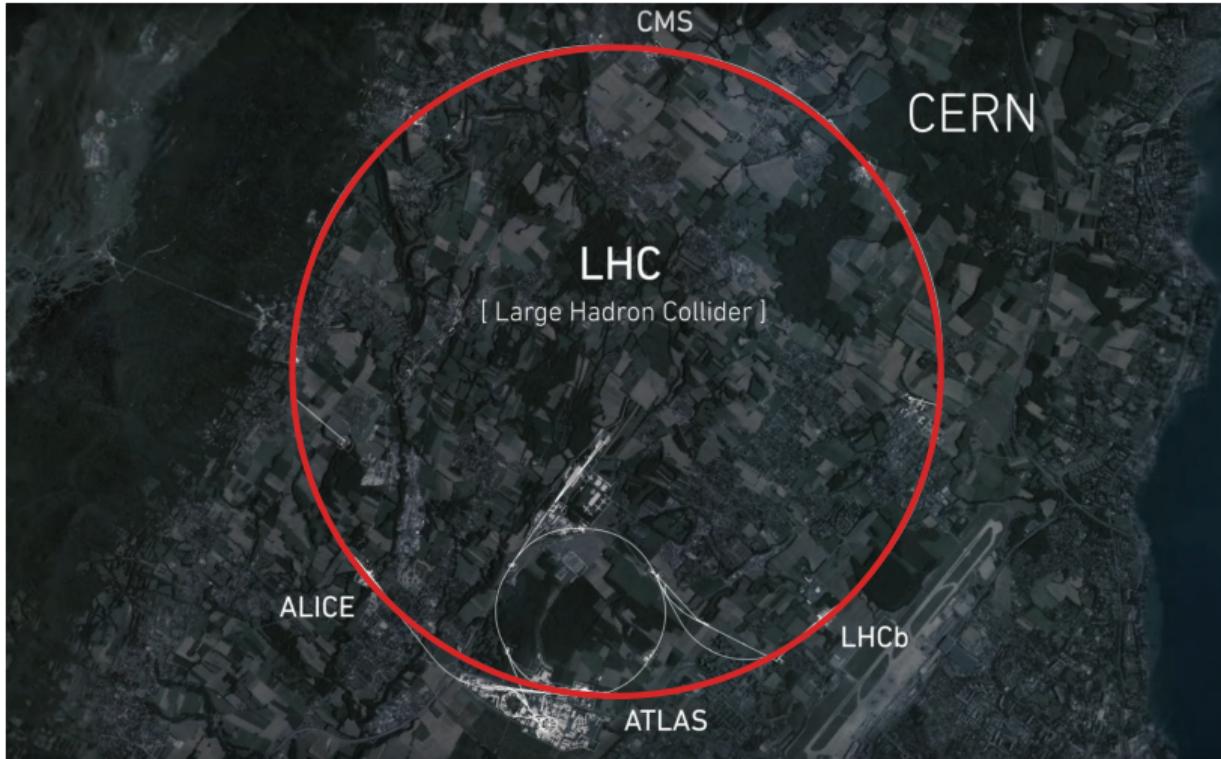
$$E = mc^2$$

mass (new particles) from the collision energy

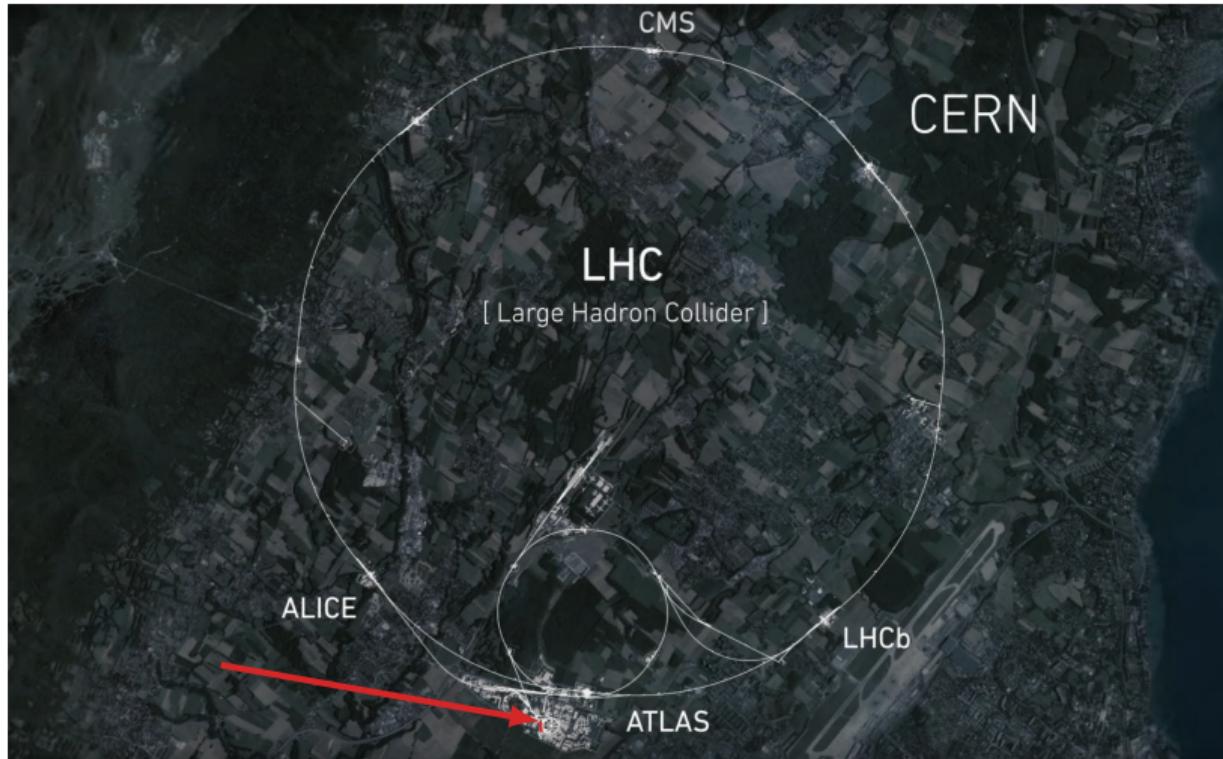
CERN & LHC



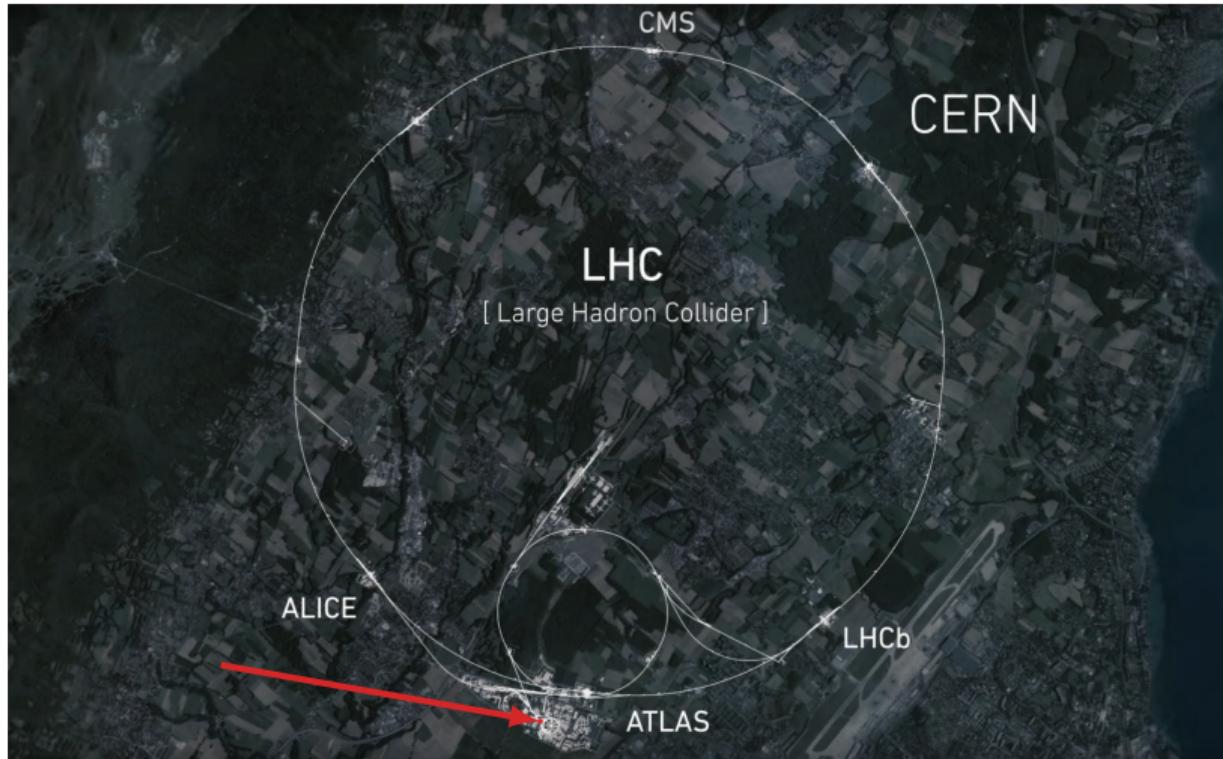
LHC



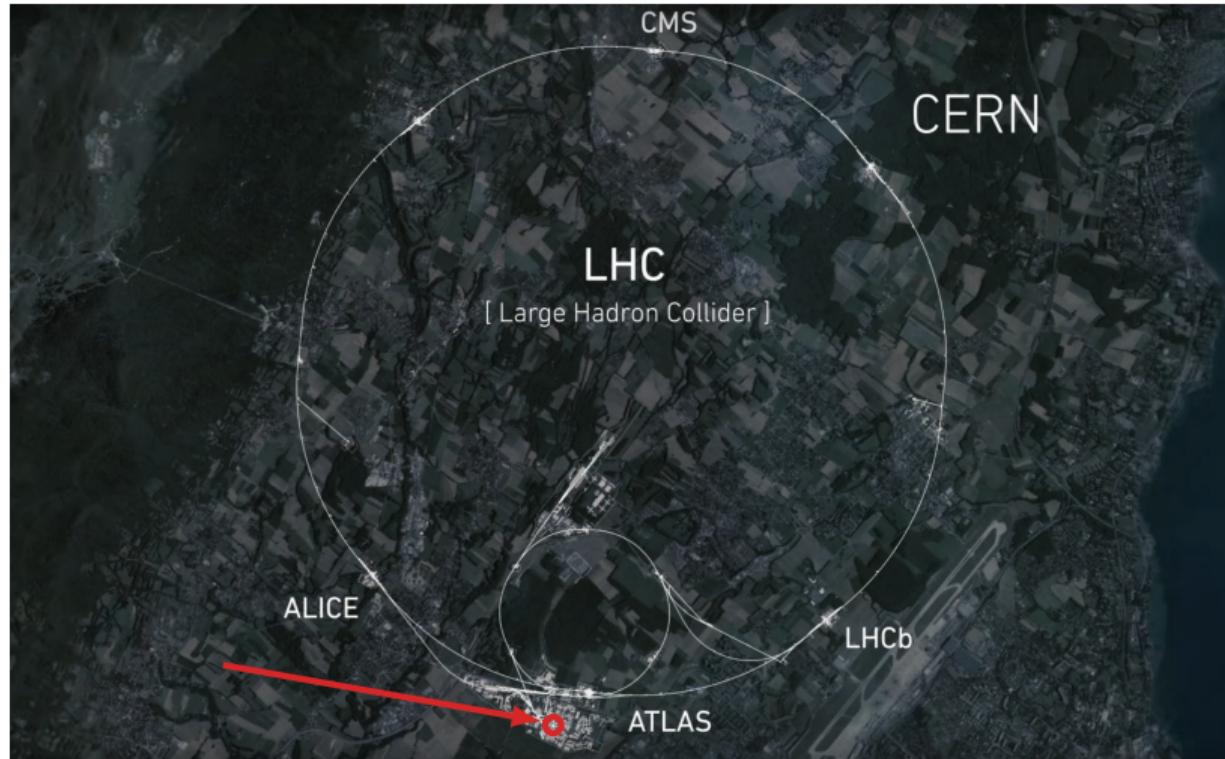
LINAC2 (50MeV)



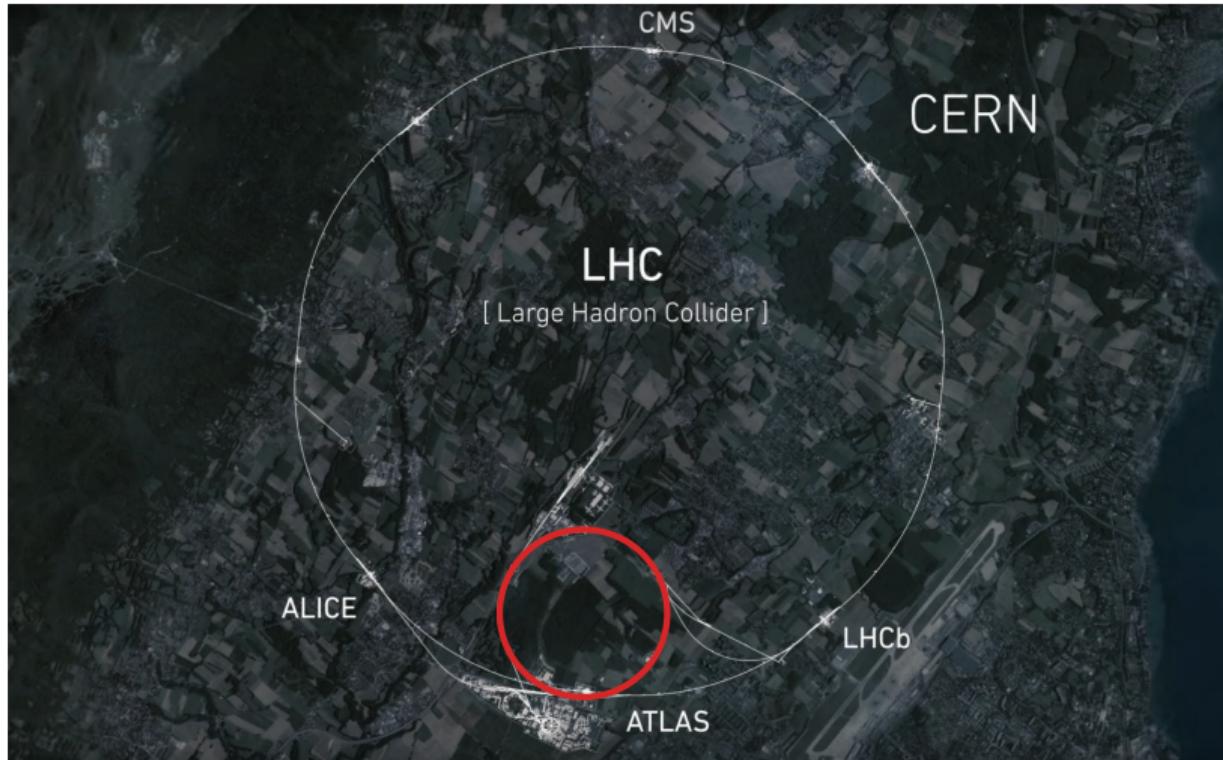
Booster (1972, 157 m, 1.4 GeV)



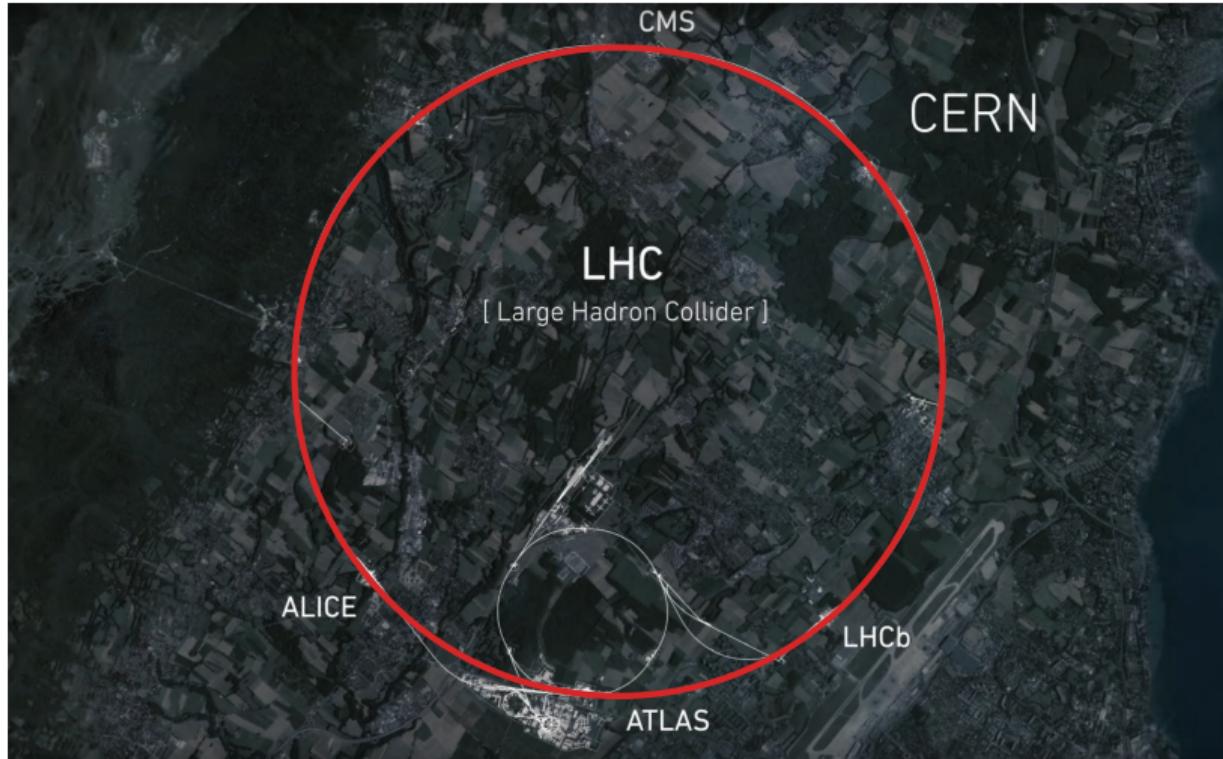
PS (1959, 628 m, 25 GeV)

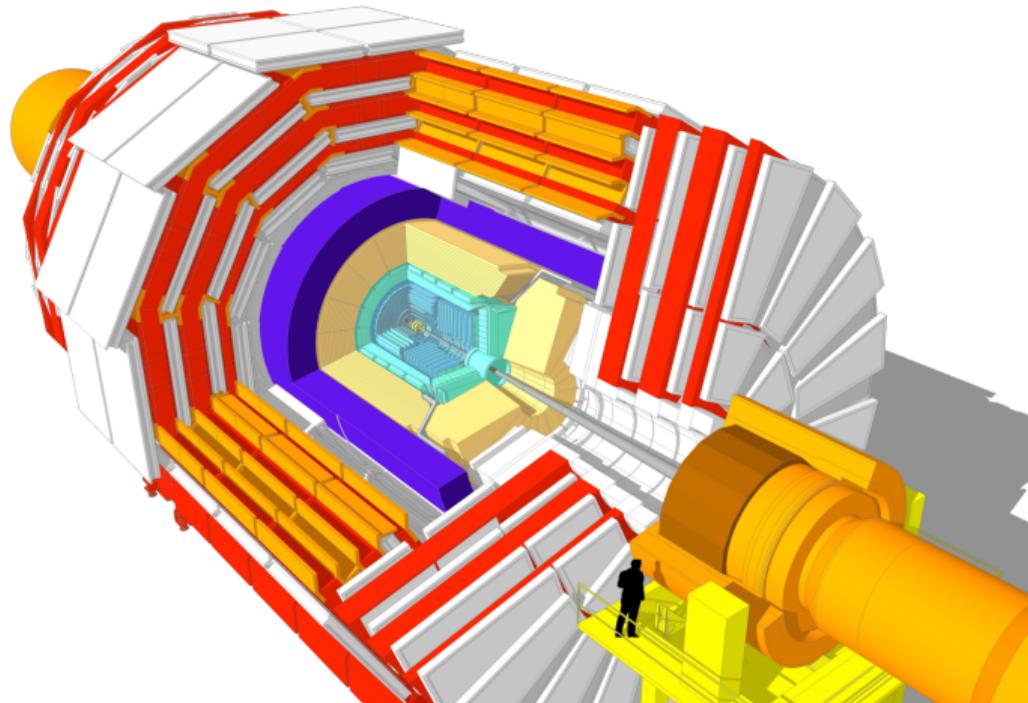


SPS (1976, 7 km, 450 GeV)



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

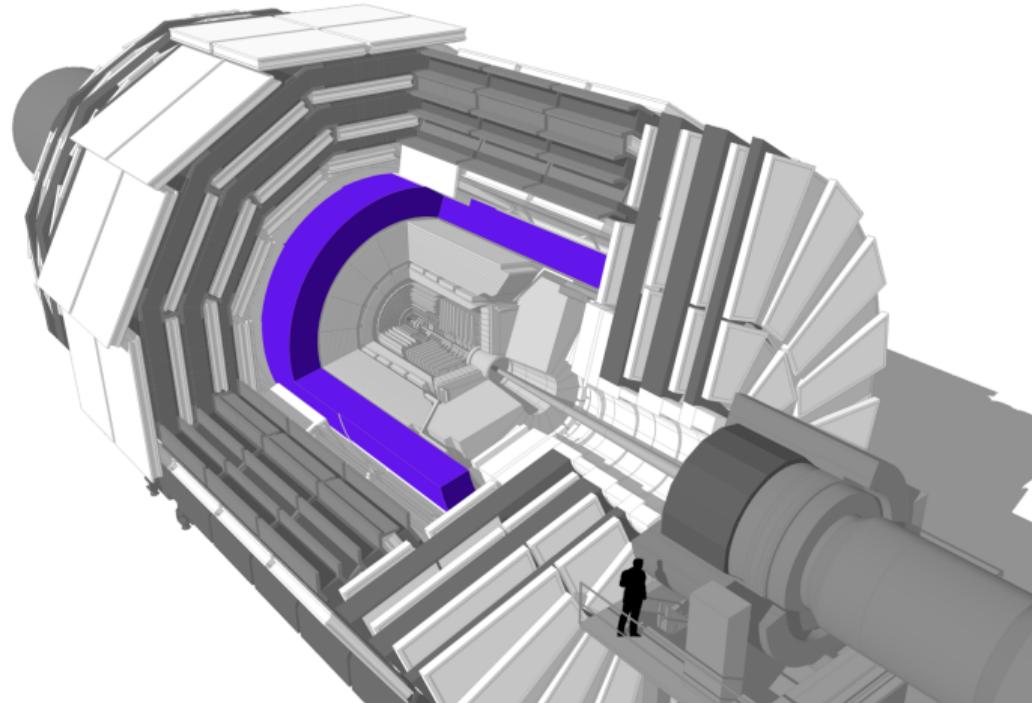




CMS detector

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

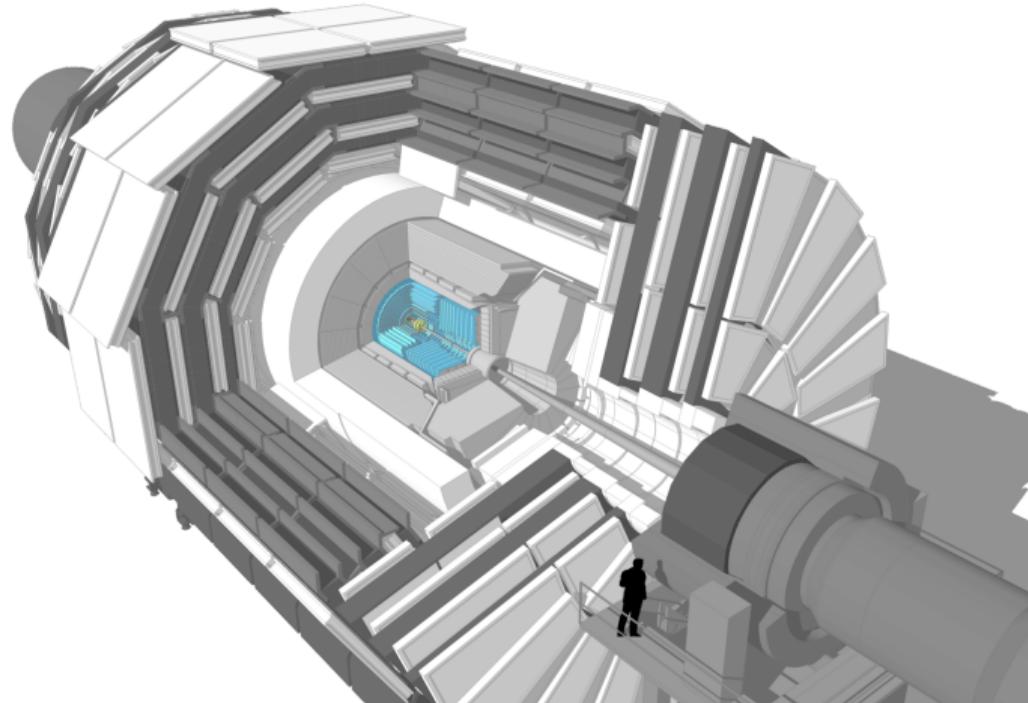
⇒ How to see the particles?



Solenoid

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

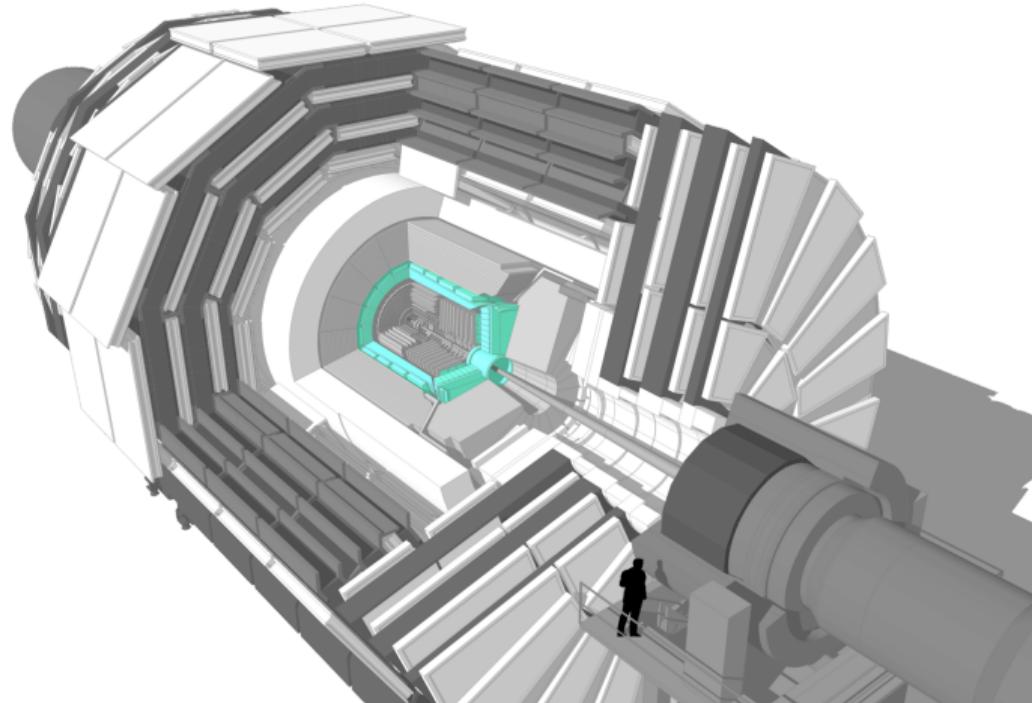
⇒ Bends charged particles trajectories
in the transverse plane



Tracker

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

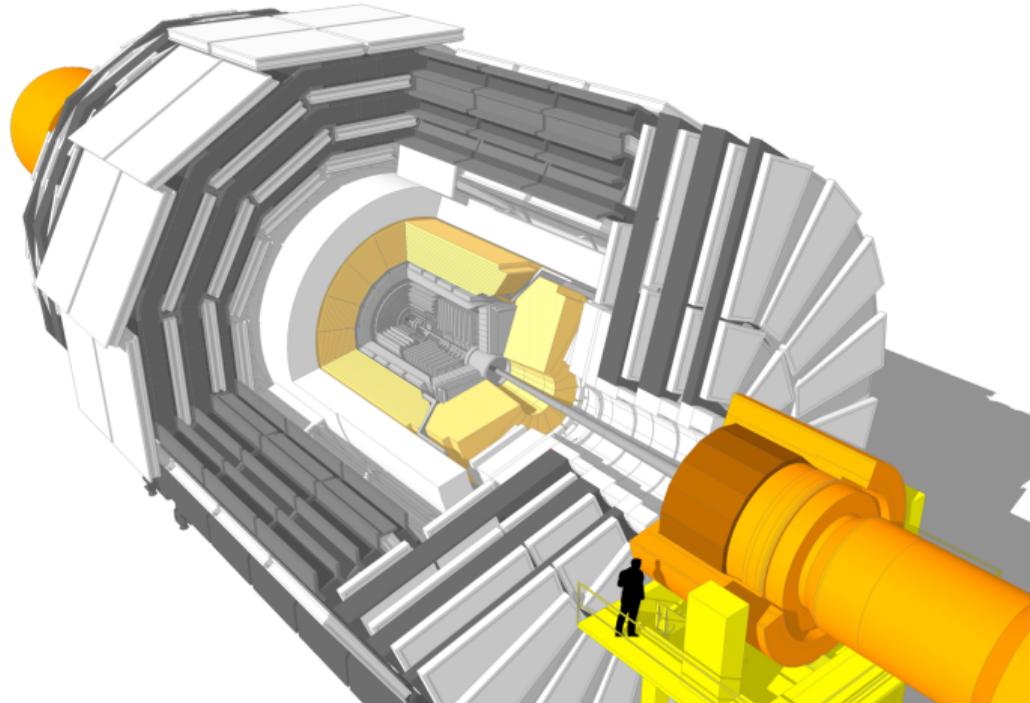
⇒ Charged particles leave hits when going through



Electromagnetic CALorimeter

- $\sim 76,000$ scintillating PbWO_4 crystals

⇒ electrons and photons are stopped,
energy deposits



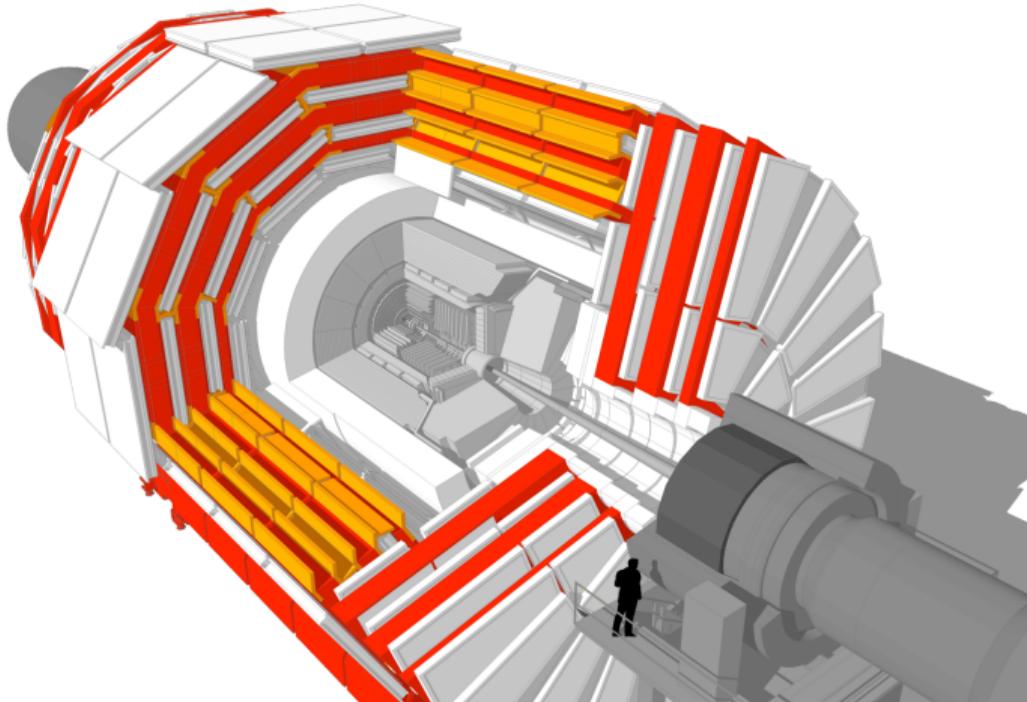
Hadronic CALorimeter (yellow)

- brass + plastic scintillator,
 ~ 7000 channels

Forward CALorimeter (orange)

- steel + quartz fibres, ~ 2000 channels

⇒ hadrons are stopped, energy deposits



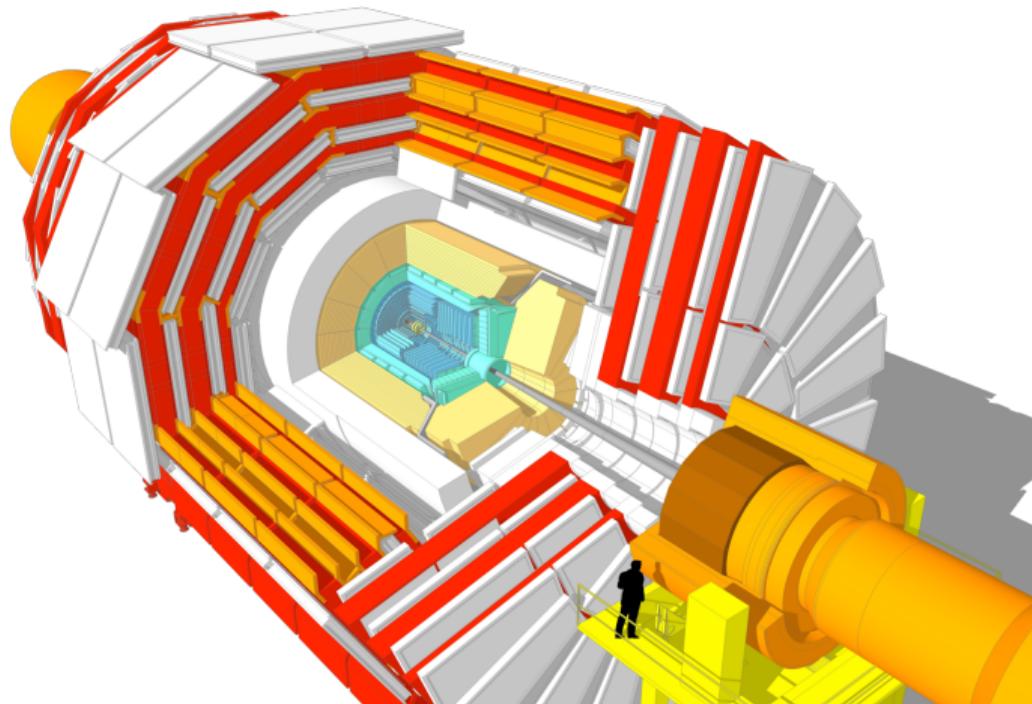
Steel return yoke (red)

- allows for 2 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

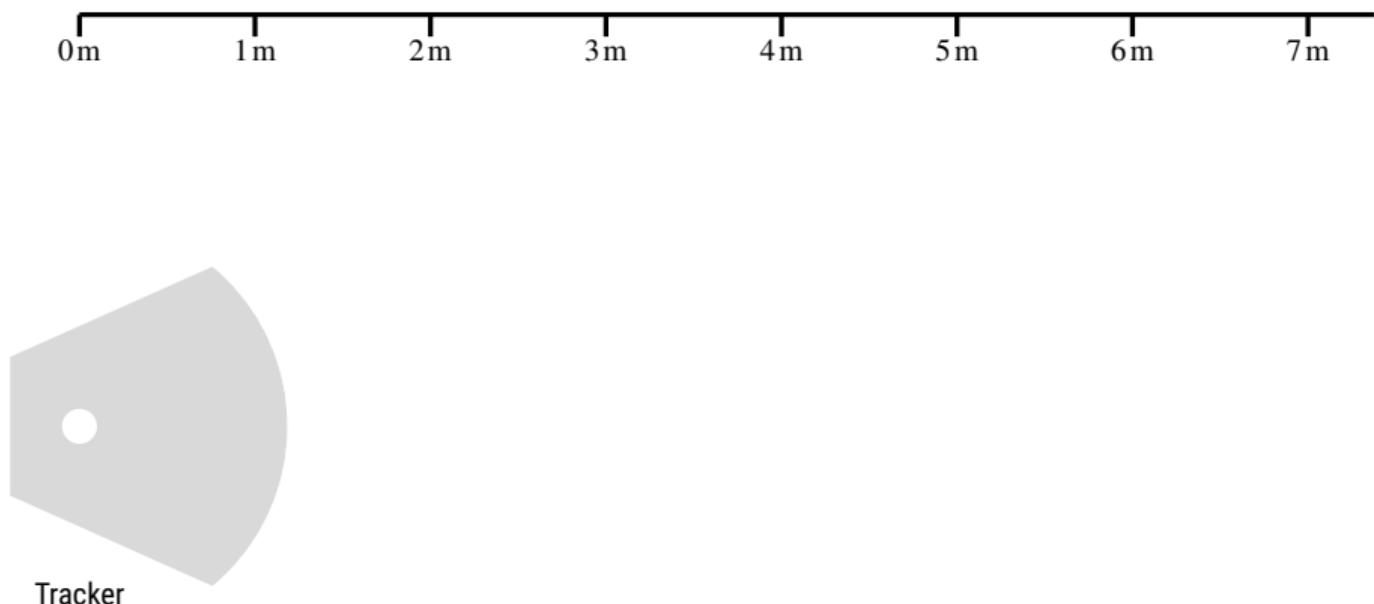
⇒ charged particles leave hits when going through (only muons do)

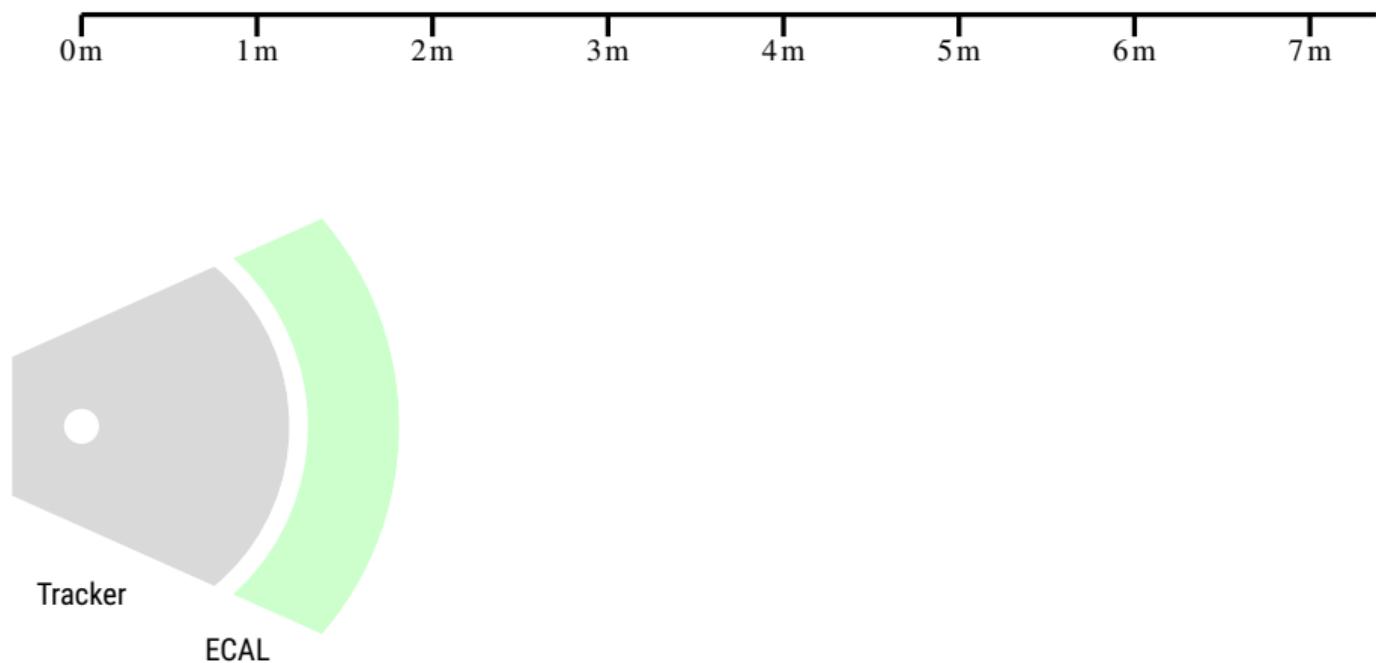


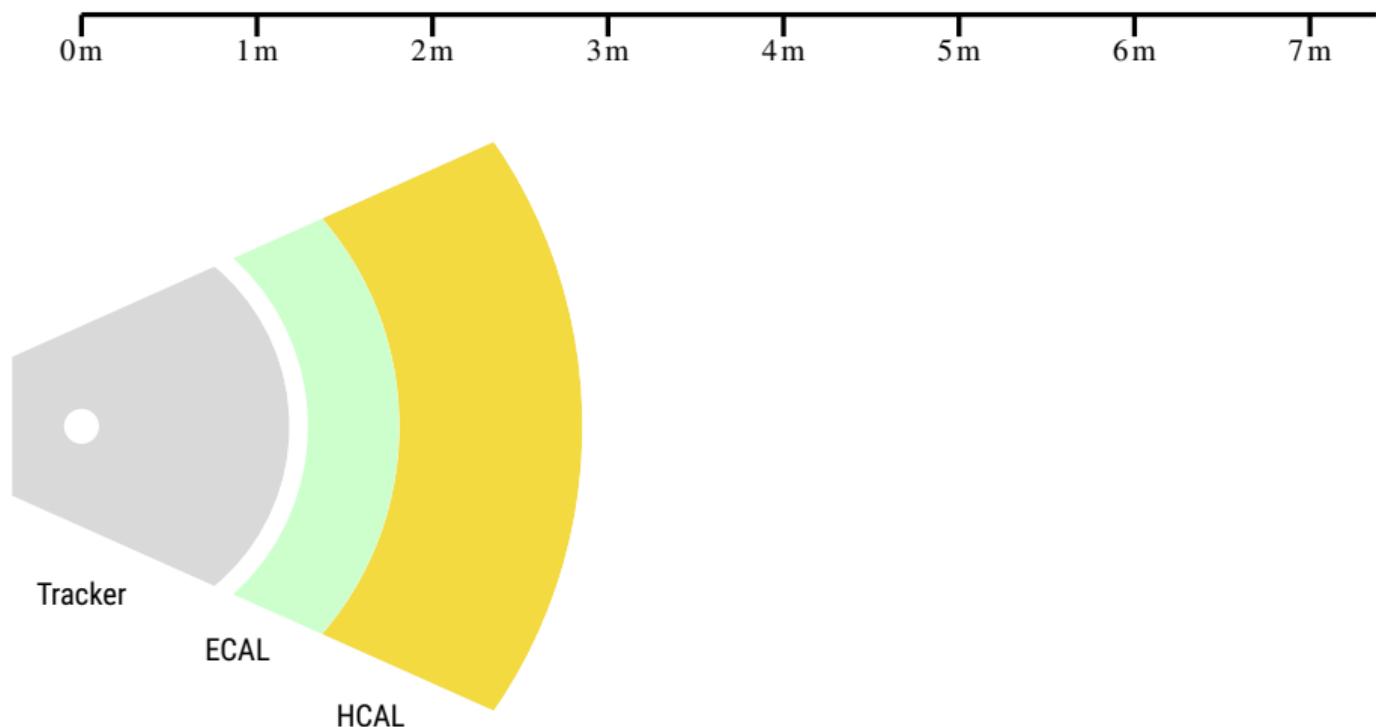
Sensitive parts of CMS

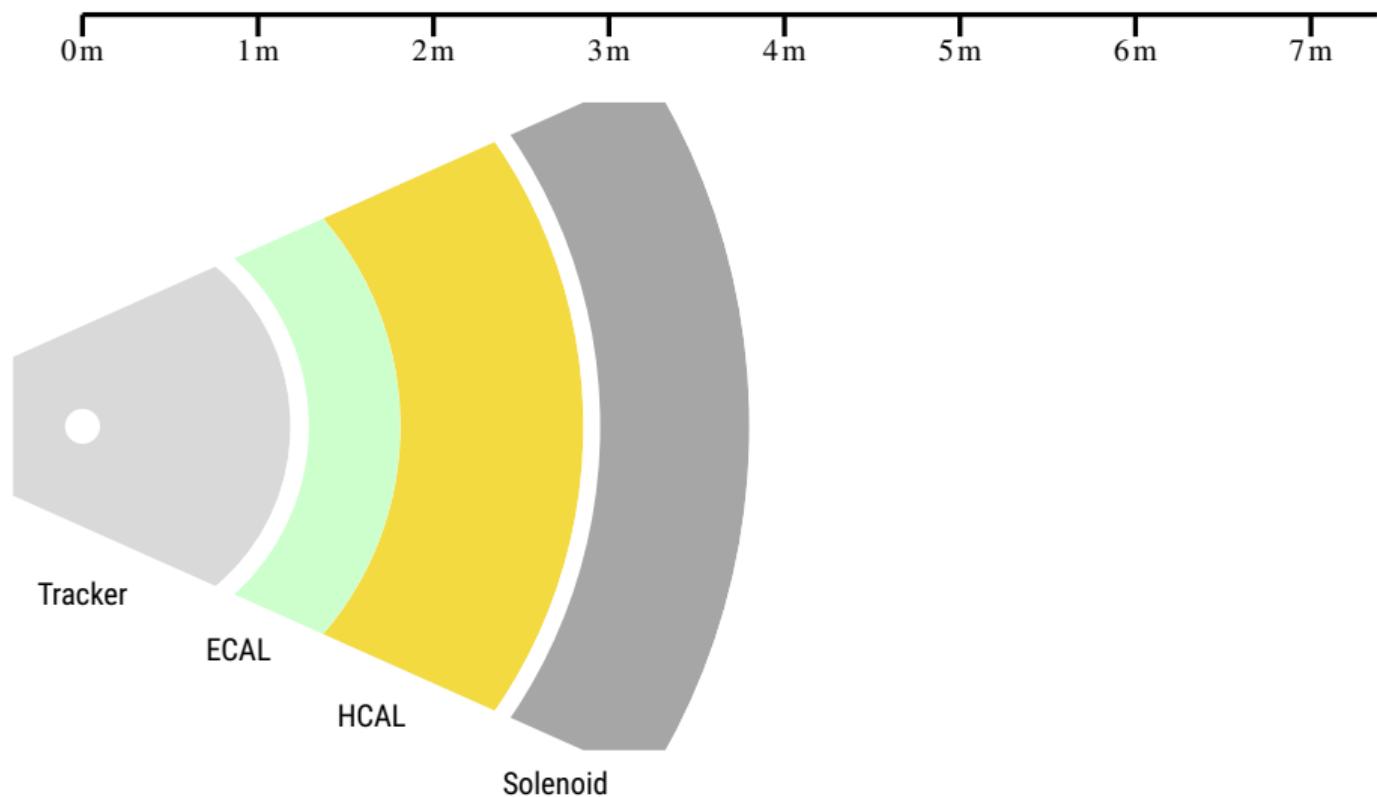
Combine sub-detectors signals to determine which particles were there!

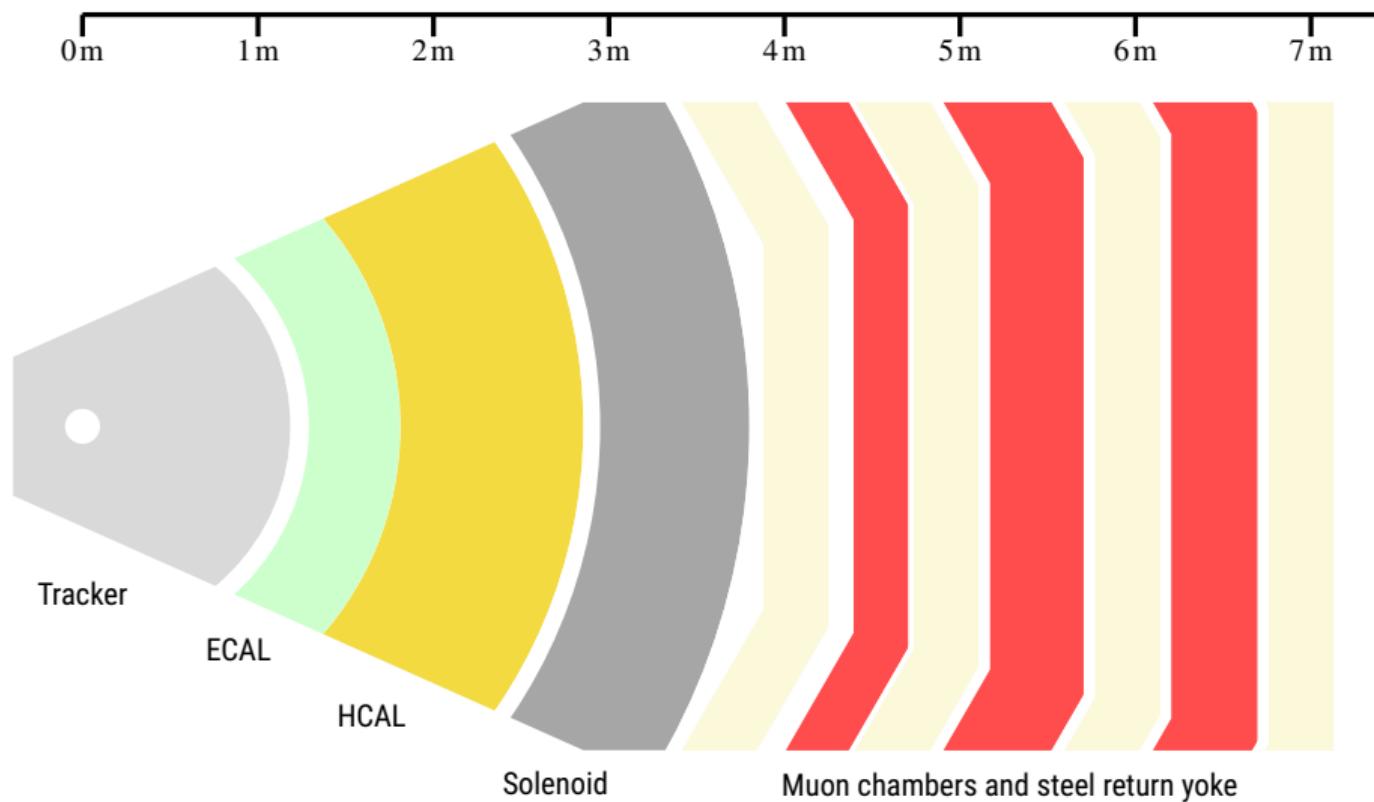


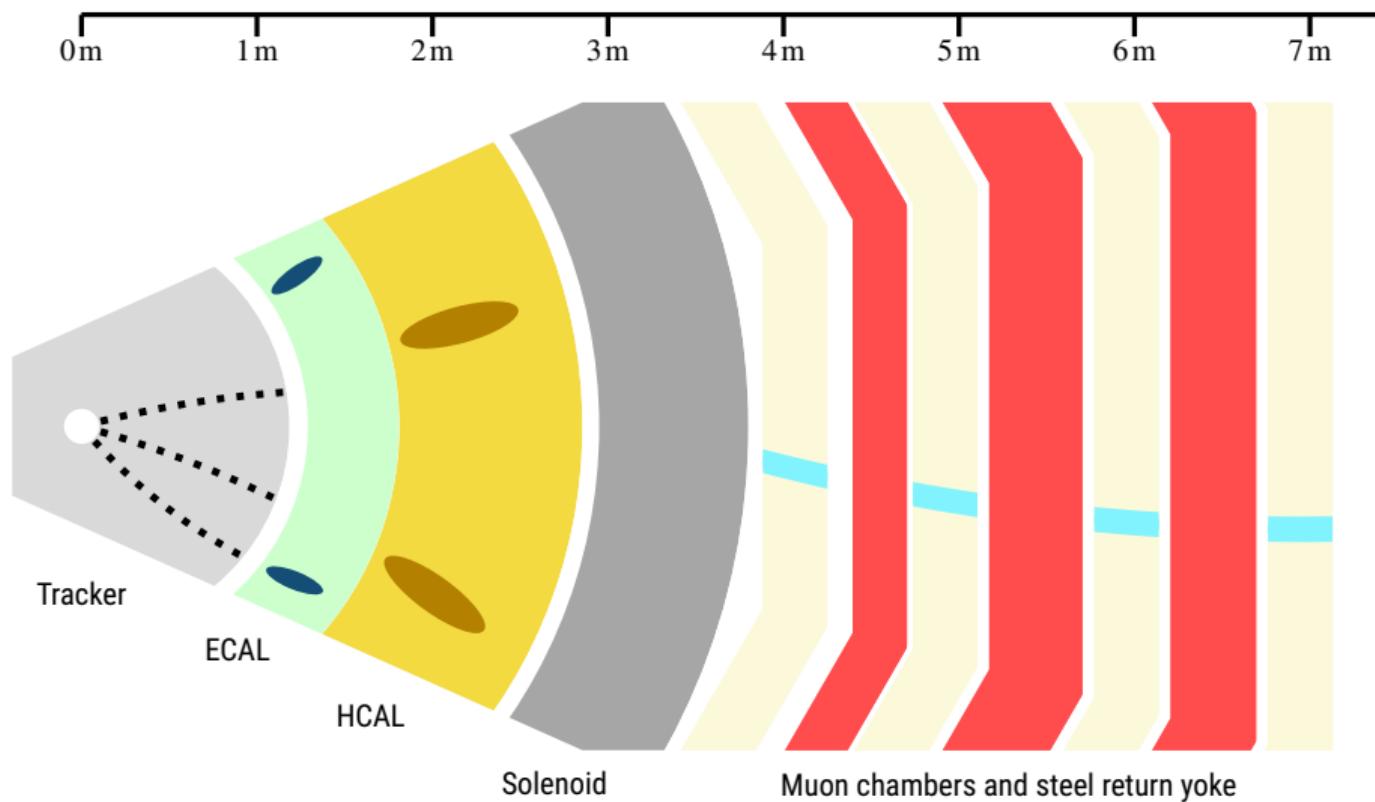


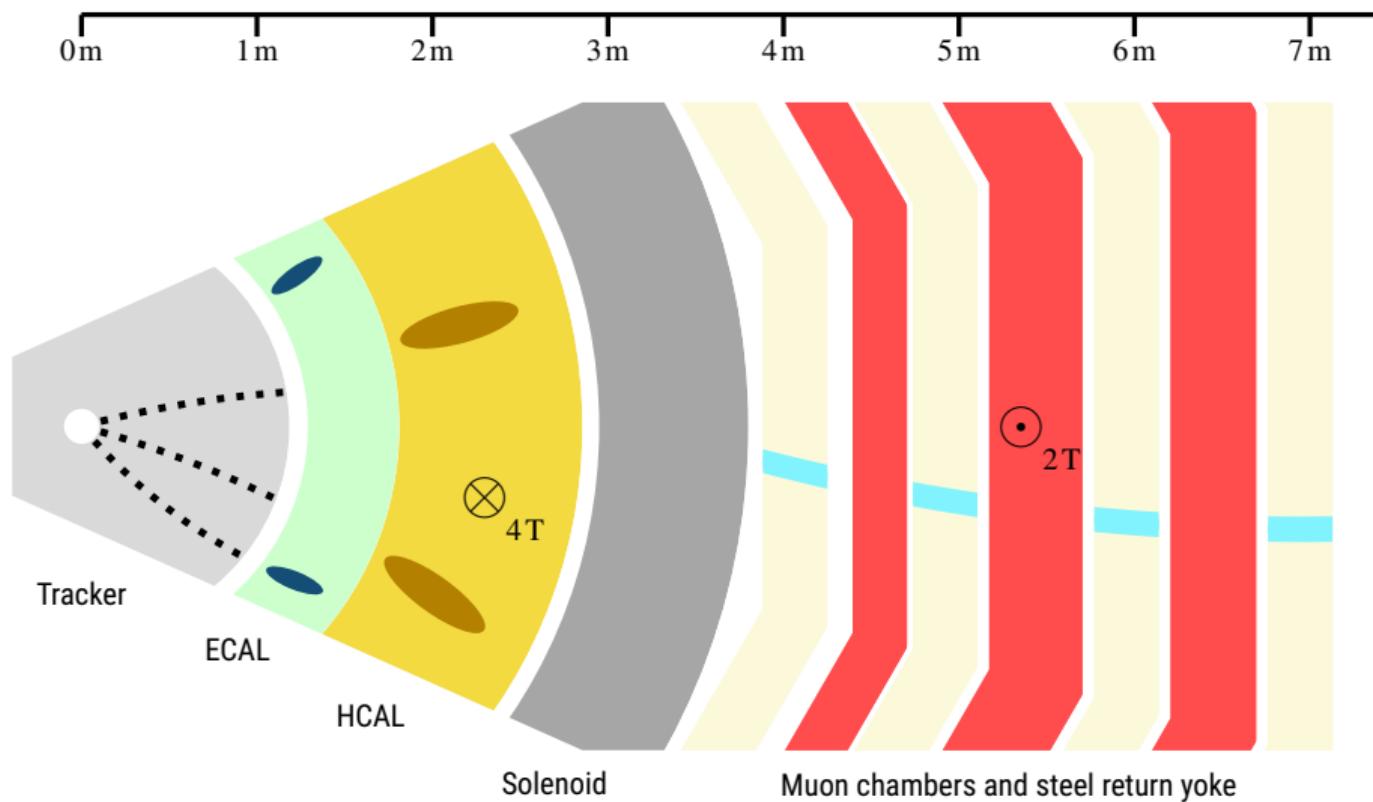


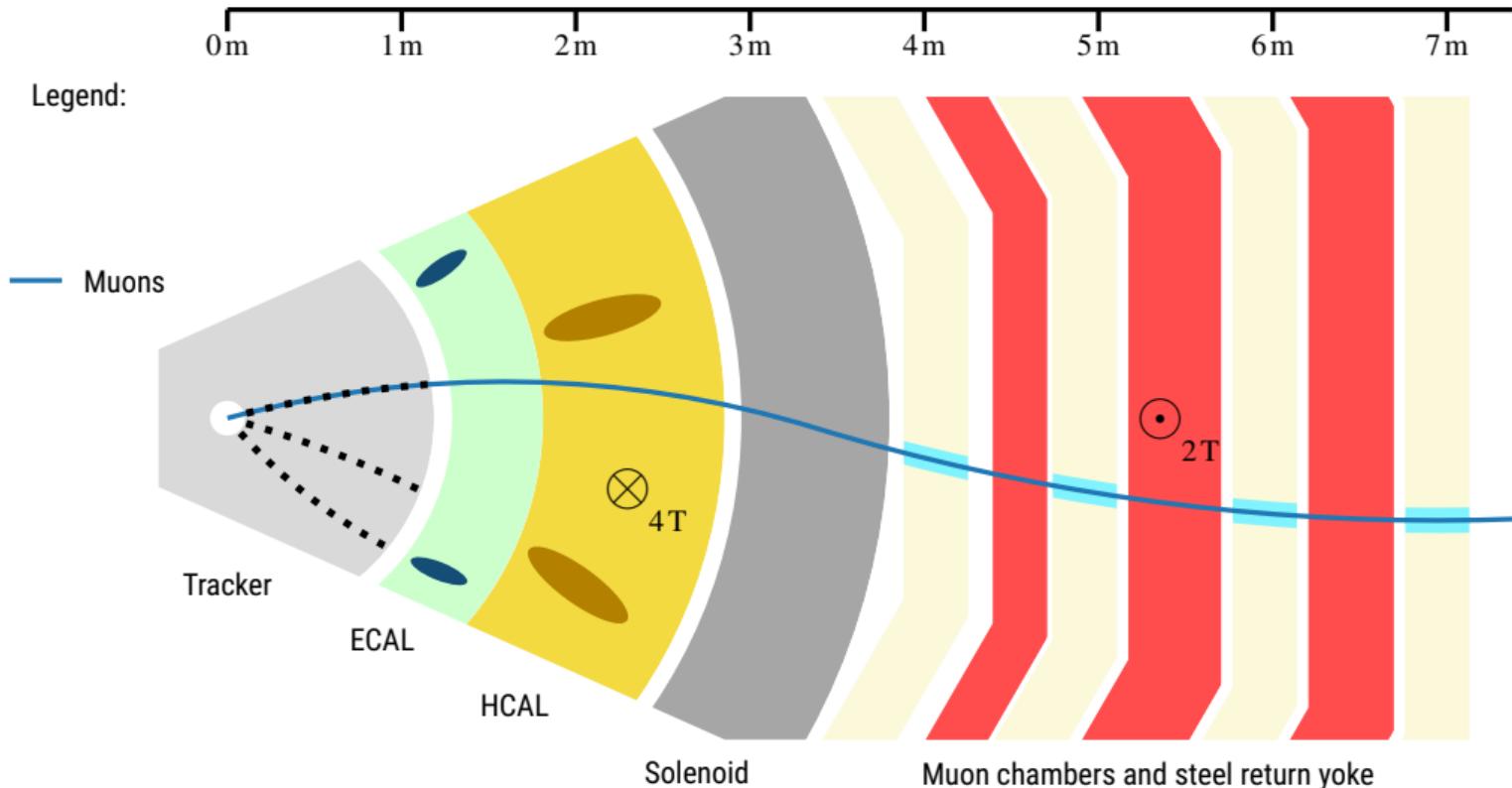






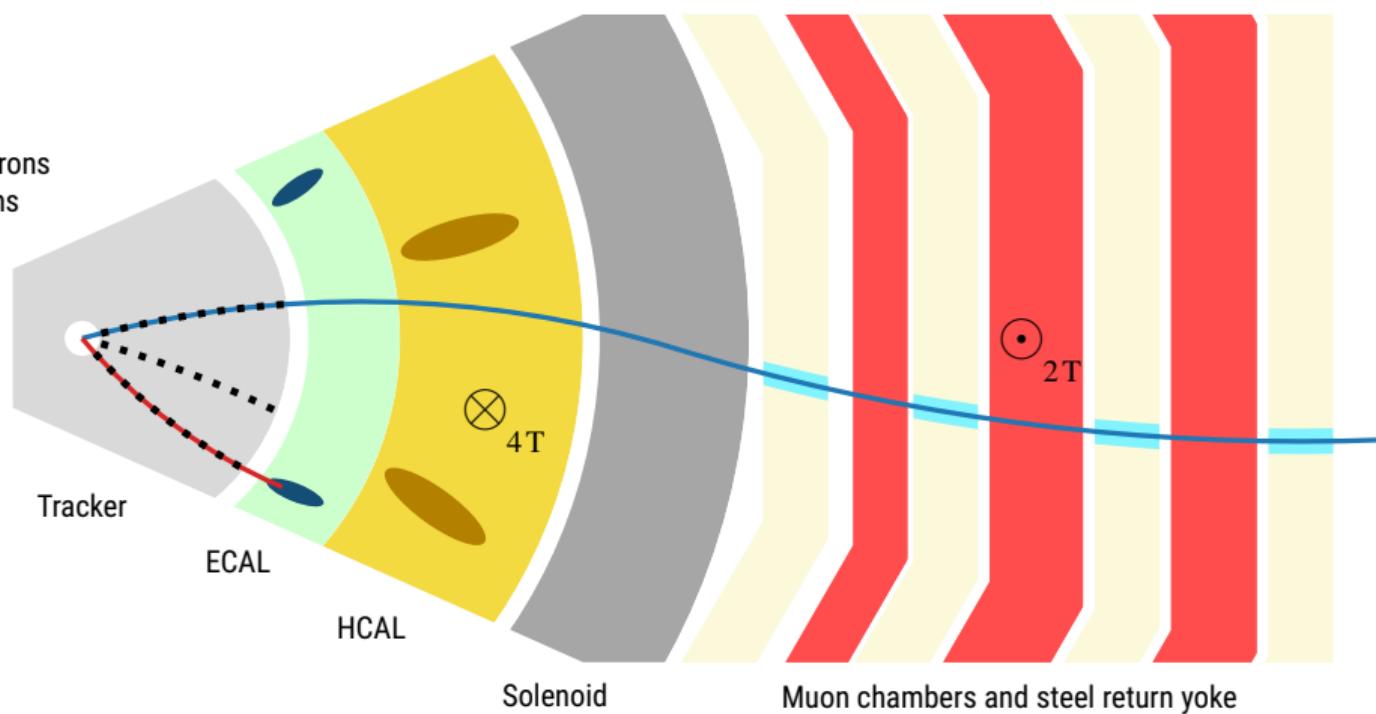


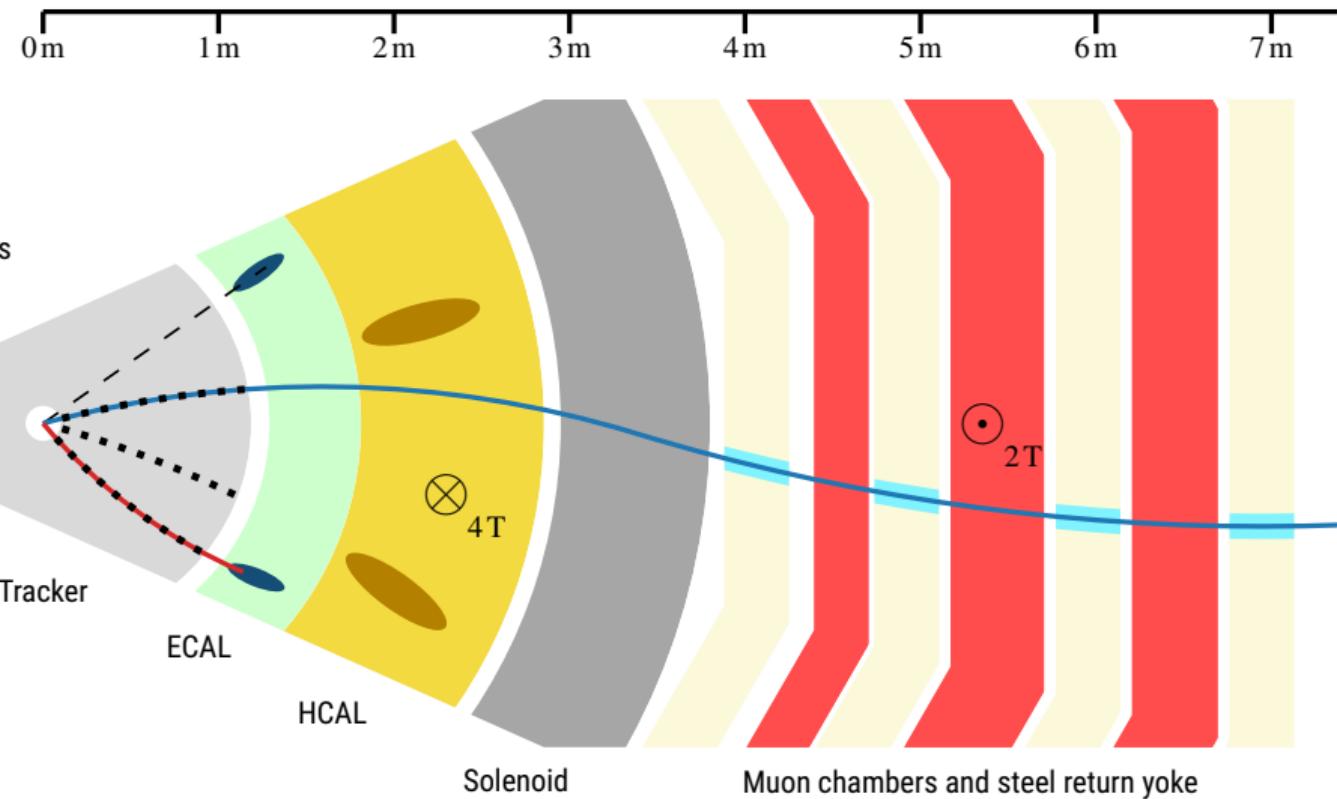


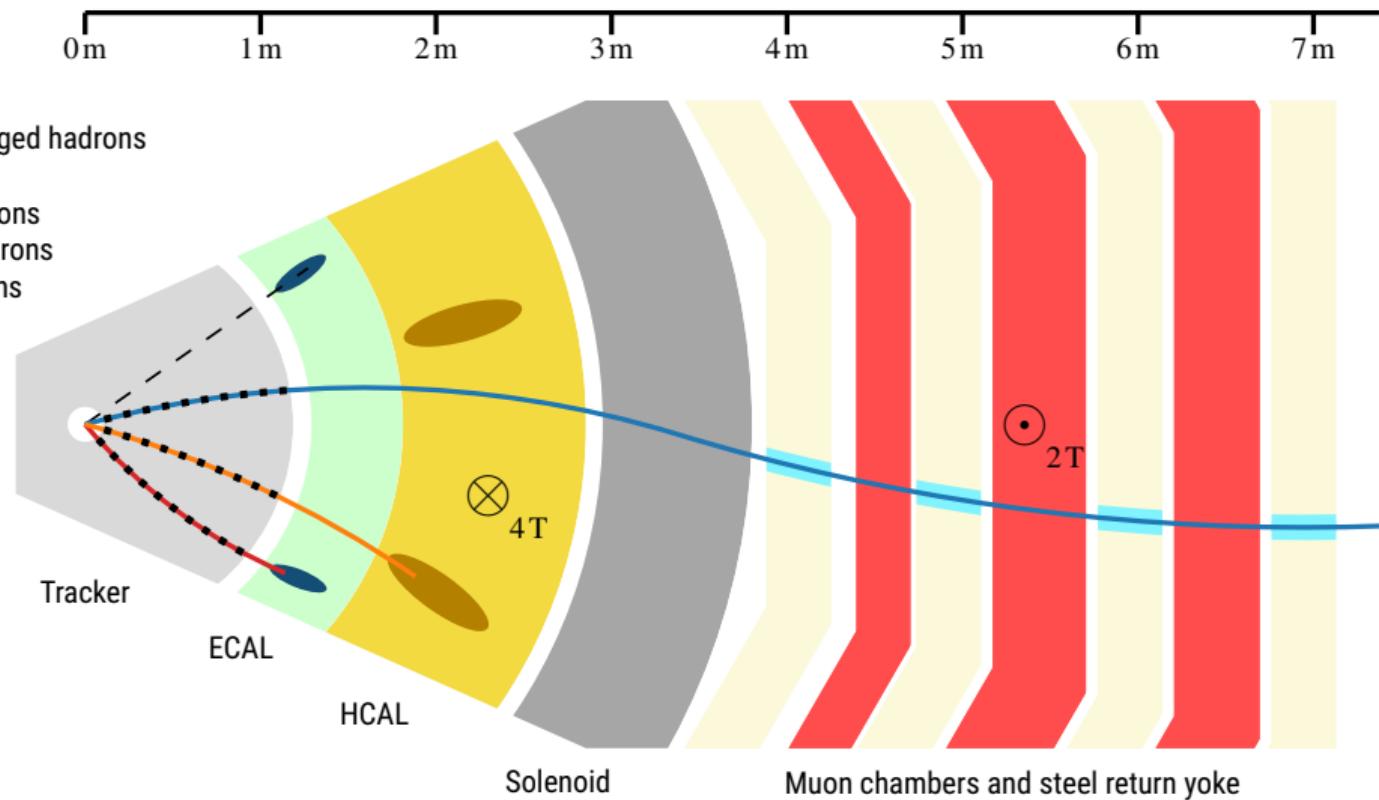


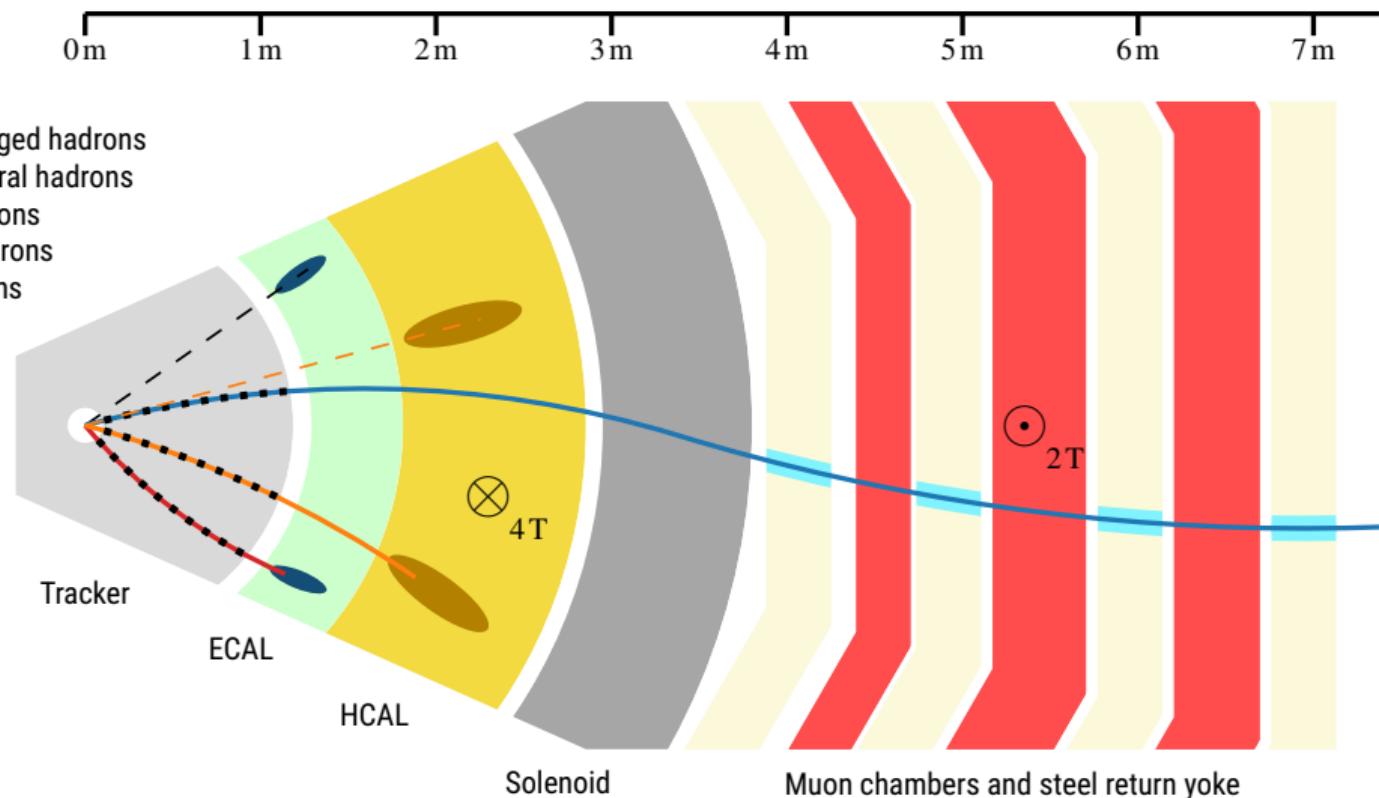
**Legend:**

- Electrons
- Muons





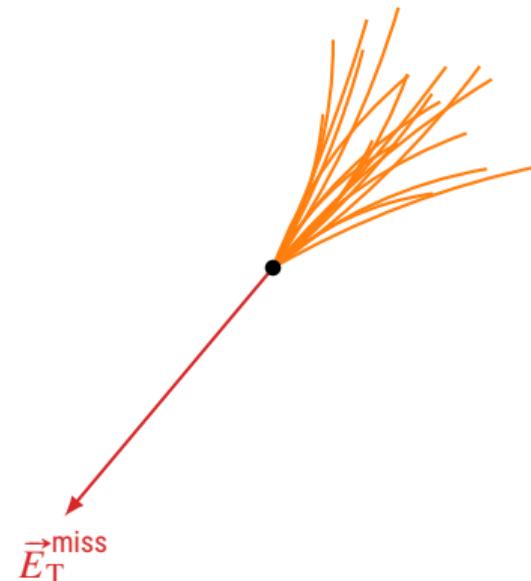




Neutrinos and missing transverse energy (MET)

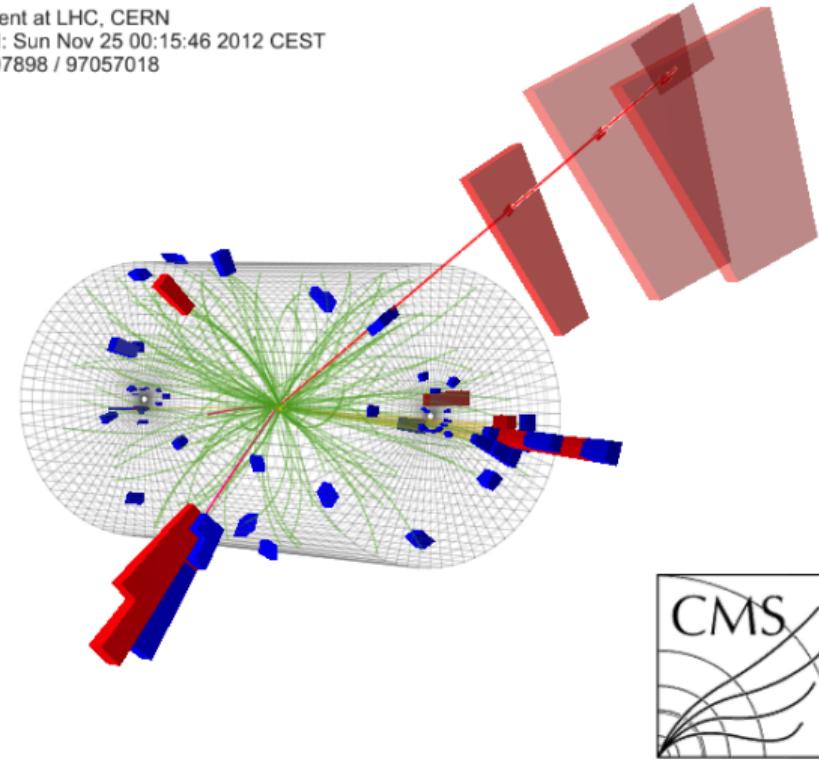


Neutrinos and missing transverse energy (MET)



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

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018



► Niveaux de connaissance

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

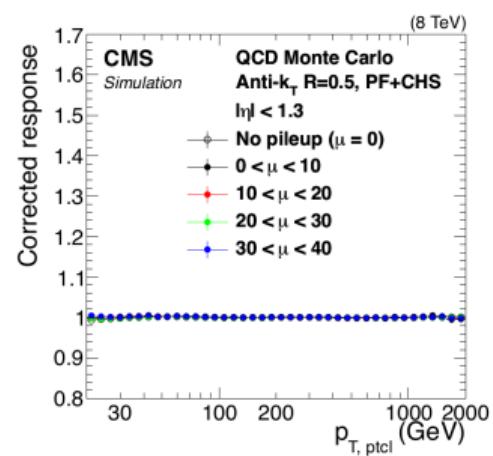
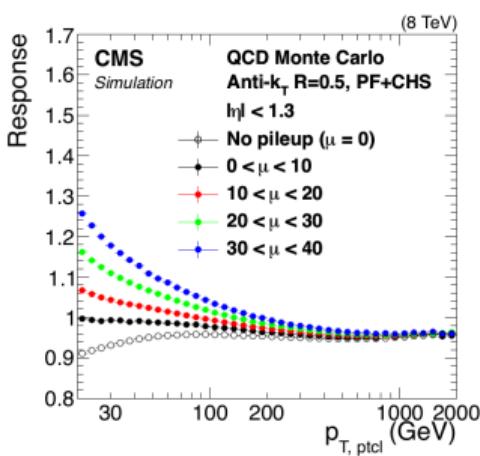
▶ Niveaux de connaissance

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

▶ Réponse d'un jet

$$R = \frac{p_T}{p_{T\text{ptcl}}}$$

Jets Reconstructs

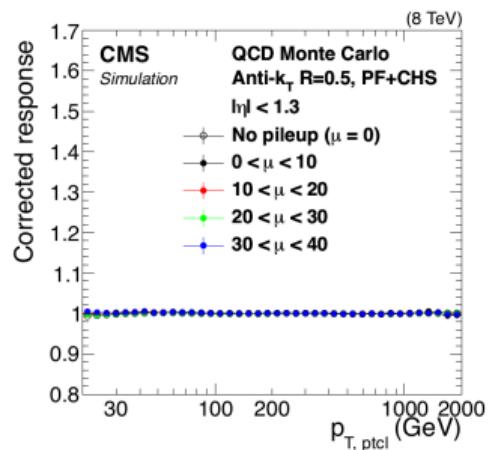
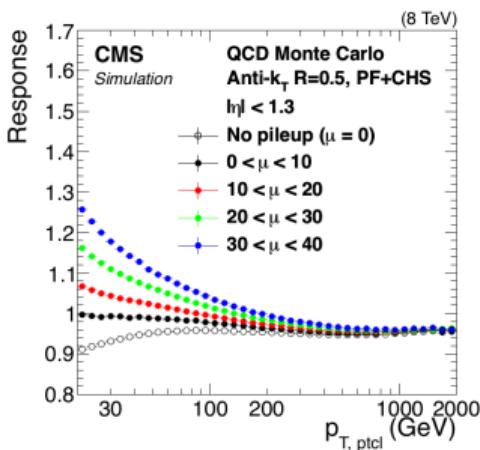


Appliqué aux données

Jets
Reconstitués

Jets
Calibrés

Appliqué aux simulations

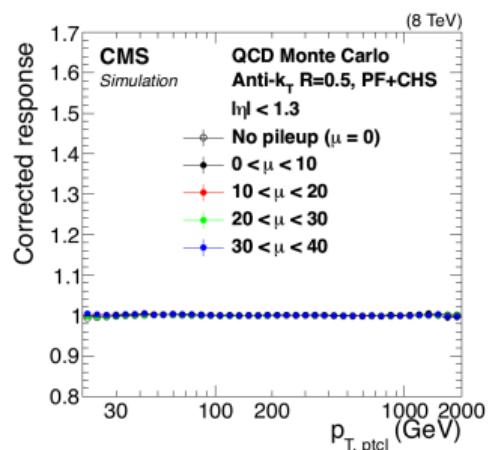
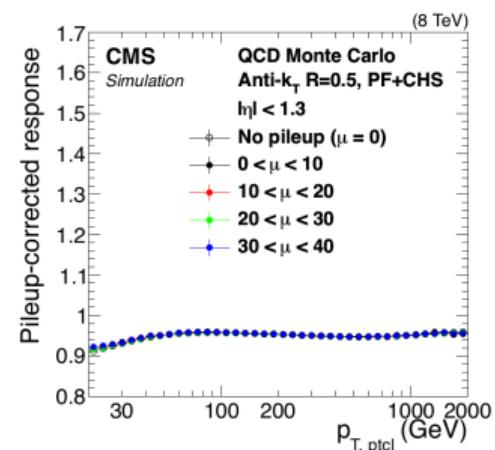
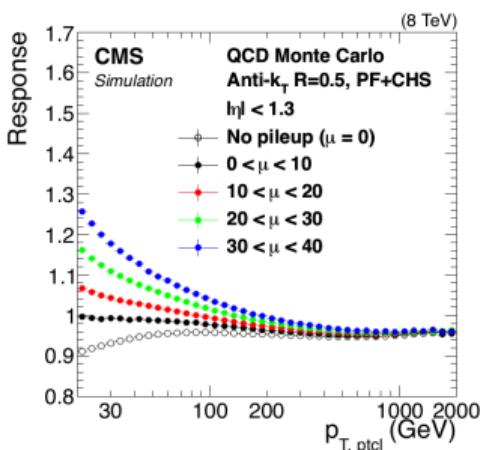


Appliqué aux données

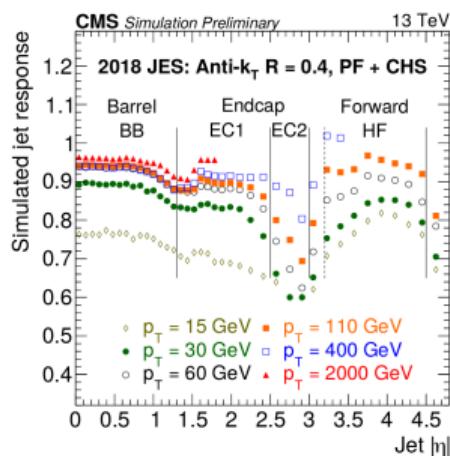
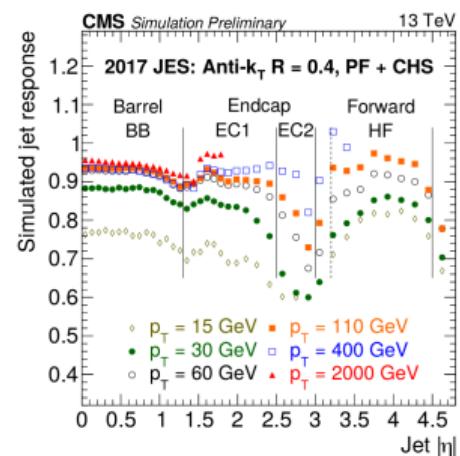
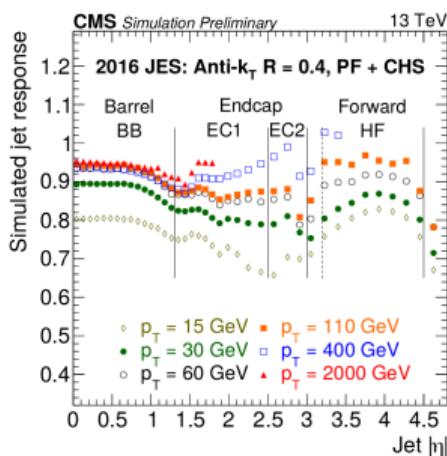
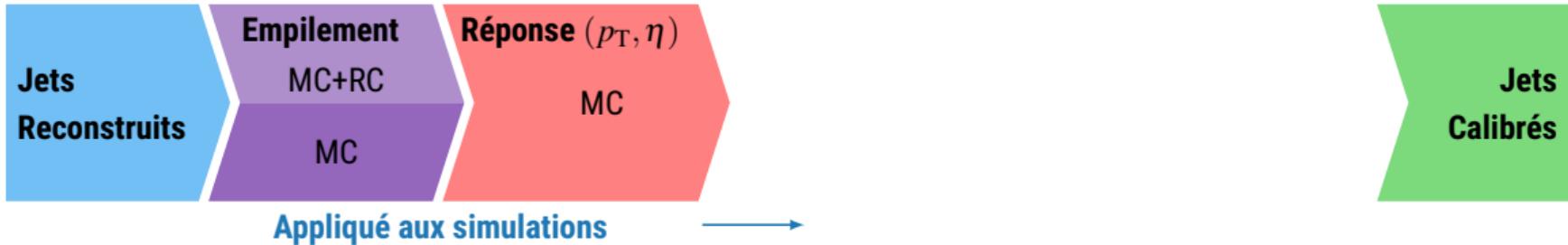


Jets
Calibrés

Appliqué aux simulations



Appliqué aux données



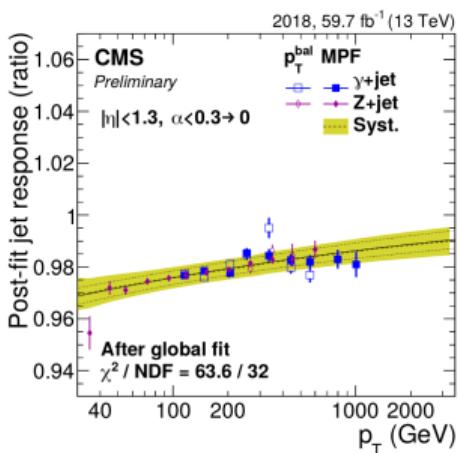
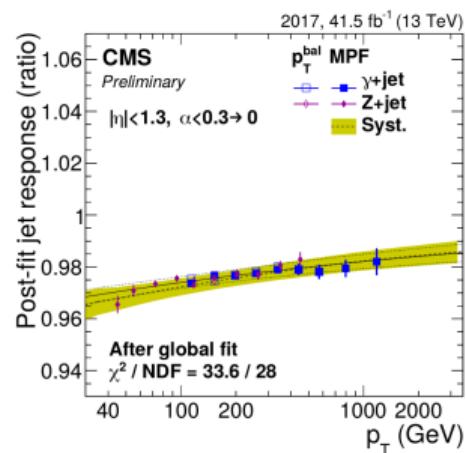
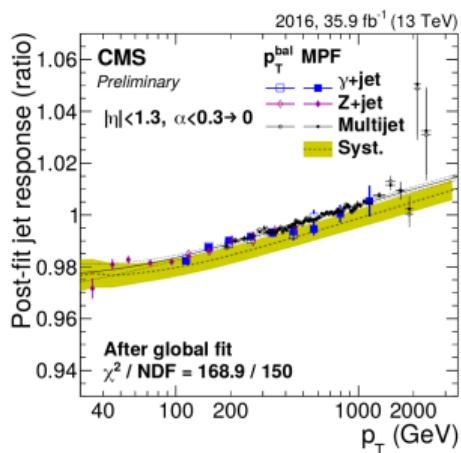
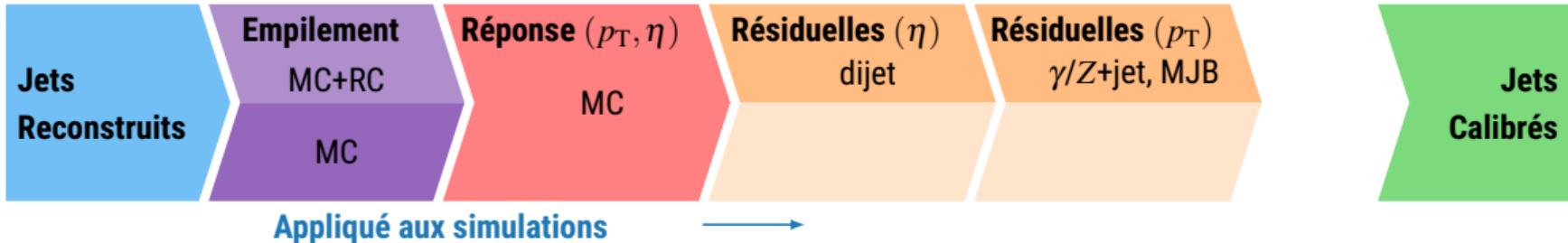
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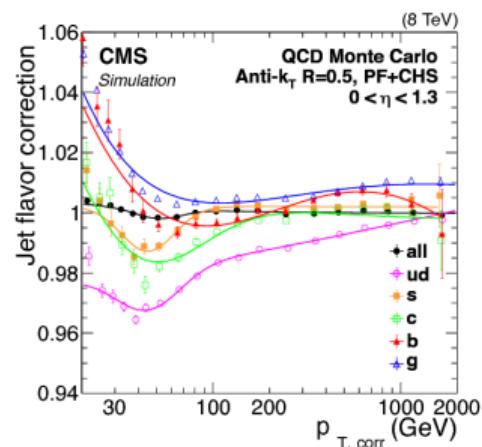
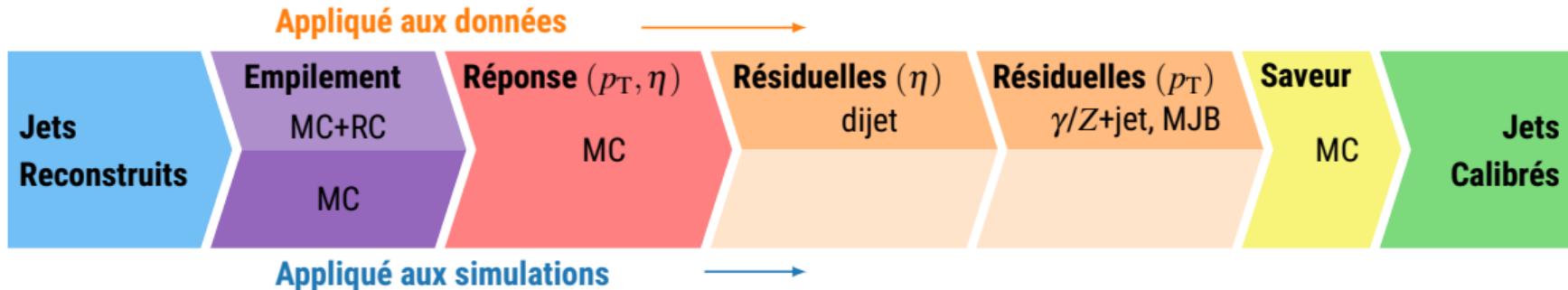


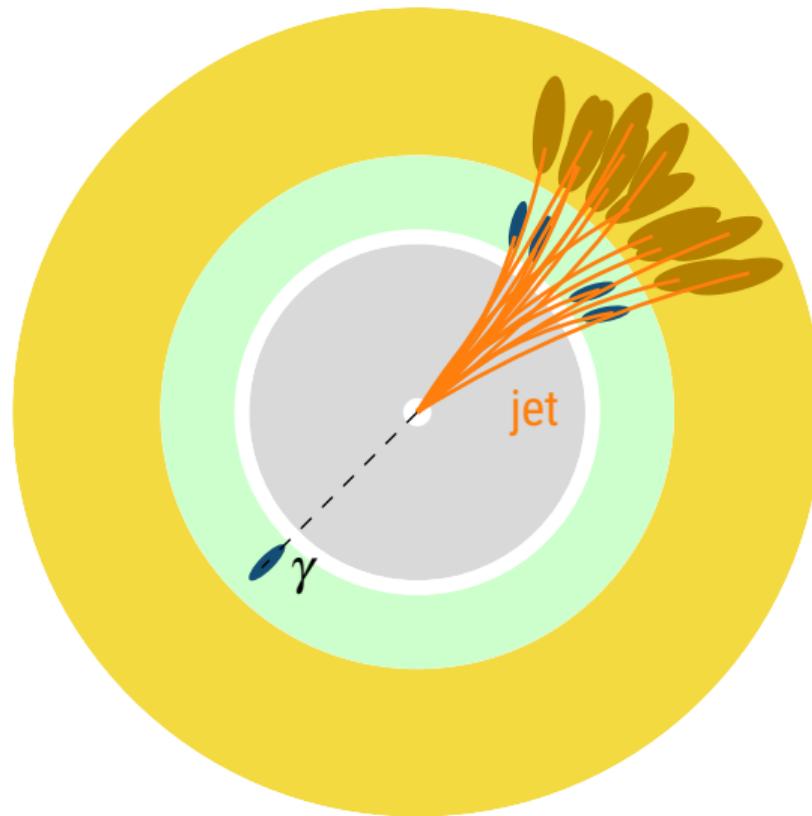
Appliqué aux simulations

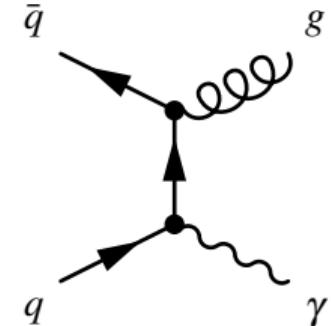
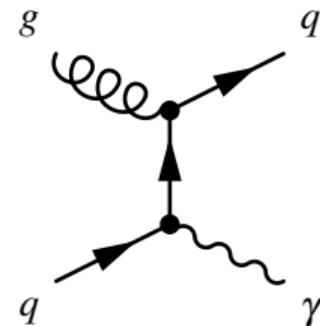
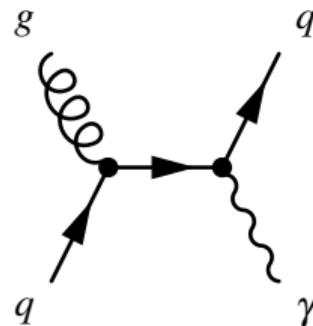


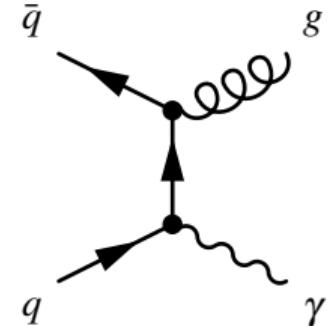
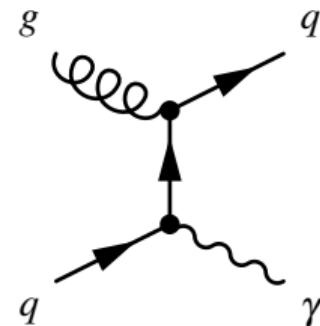
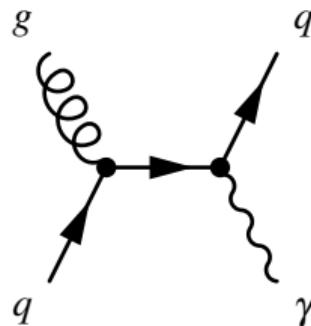
Appliqué aux données



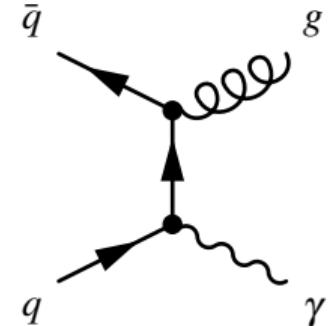
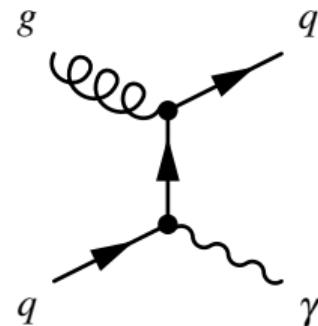
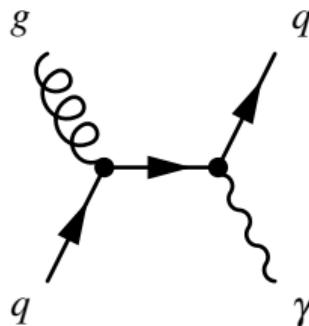






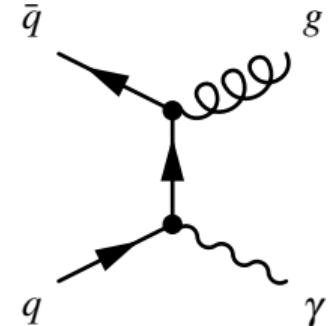
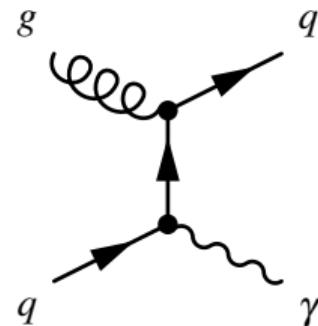
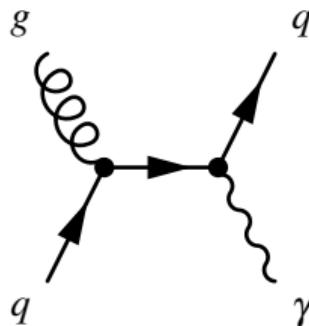


$$\vec{p}_{T \text{ ptcl}}^{\gamma} + \vec{p}_{T \text{ ptcl}}^{\text{jet}} = \vec{0} \Rightarrow p_{T \text{ ptcl}}^{\gamma} = p_{T \text{ ptcl}}^{\text{jet}}$$



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

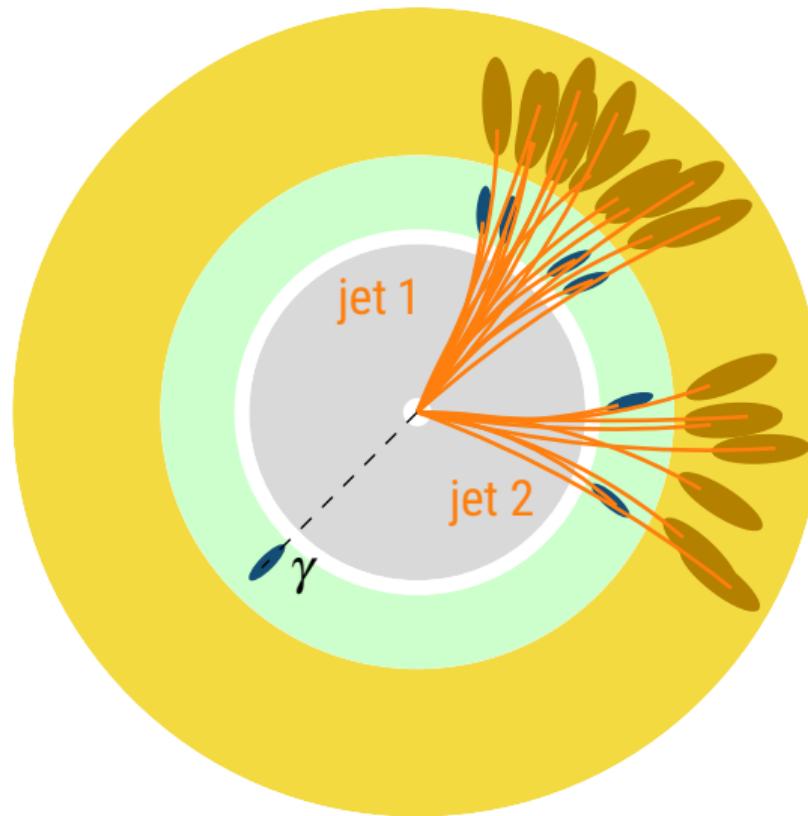
$$R = \frac{p_{\text{T ptcl}}^{\text{jet}}}{p_{\text{T ptcl}}^{\gamma}} = \frac{p_{\text{T ptcl}}^{\text{jet}}}{p_{\text{T ptcl}}^{\gamma}} \simeq \frac{p_{\text{T ptcl}}^{\text{jet}}}{p_{\text{T ptcl}}^{\gamma}}$$

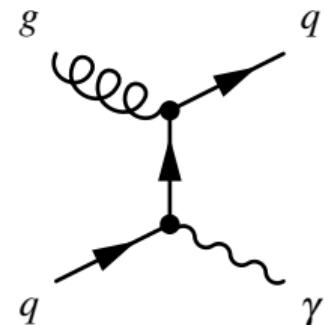


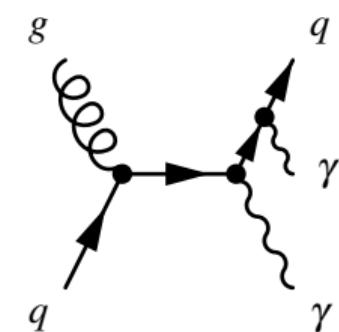
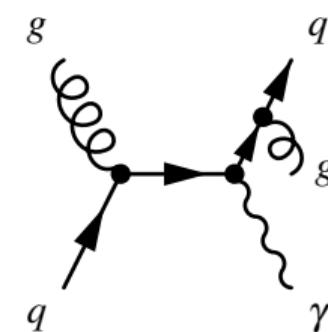
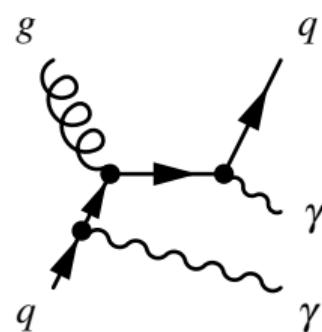
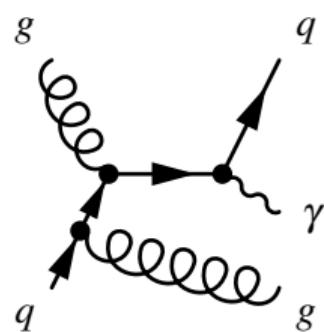
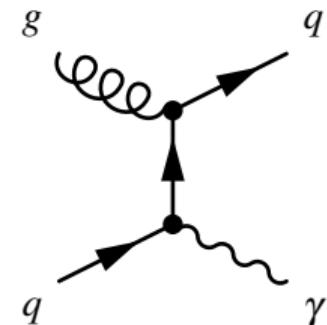
$$\vec{p}_{T \text{ ptcl}}^\gamma + \vec{p}_{T \text{ ptcl}}^{\text{jet}} = \vec{0} \Rightarrow p_{T \text{ ptcl}}^\gamma = p_{T \text{ ptcl}}^{\text{jet}}$$

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

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







$$R_{bal} = \frac{p_T^{\text{jet 1}}}{p_T^\gamma}$$

$$\alpha = \frac{p_T^{\text{jet 2}}}{p_T^\gamma}$$

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

$$\vec{p}_T^\gamma + \vec{p}_T^{\text{recul}} = \vec{0}$$

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

Jet Energy Resolution

- ▶ Remember R_{bal} definition,

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

Jet Energy Resolution

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

Then

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

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

Jet Energy Resolution

- ▶ Remember R_{bal} definition,

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

Then

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

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

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

1 Phenomenology

2 Experimental device

3 $H \rightarrow \tau\tau$ analysis

4 Machine Learning

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!

The rabbit analogy

- ▶ Dice results: 4

The rabbit analogy

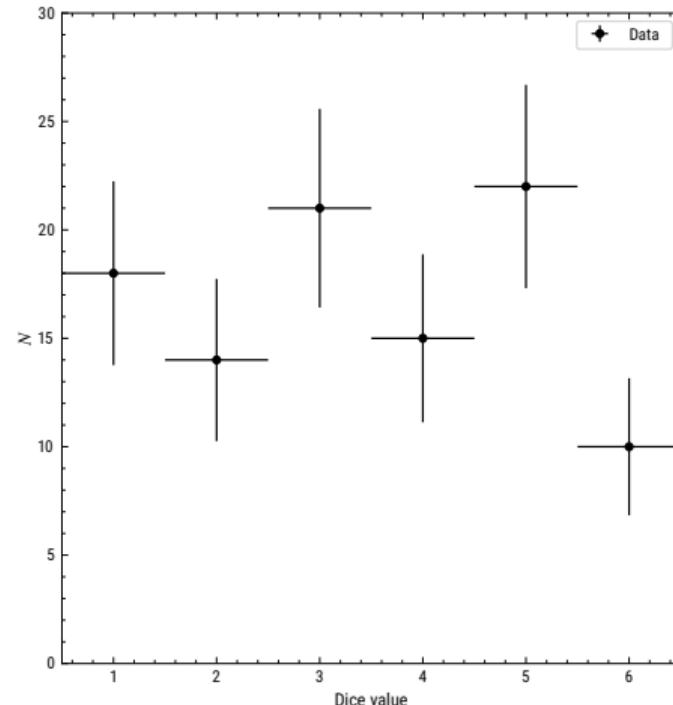
- ▶ Dice results: 4, 2

The rabbit analogy

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

The rabbit analogy

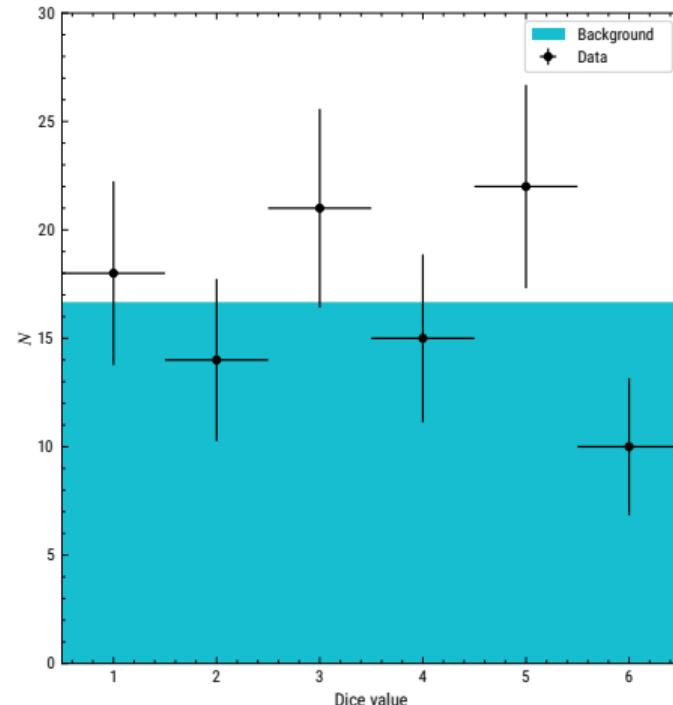
On 100 days →



Not really conclusive...

The rabbit analogy

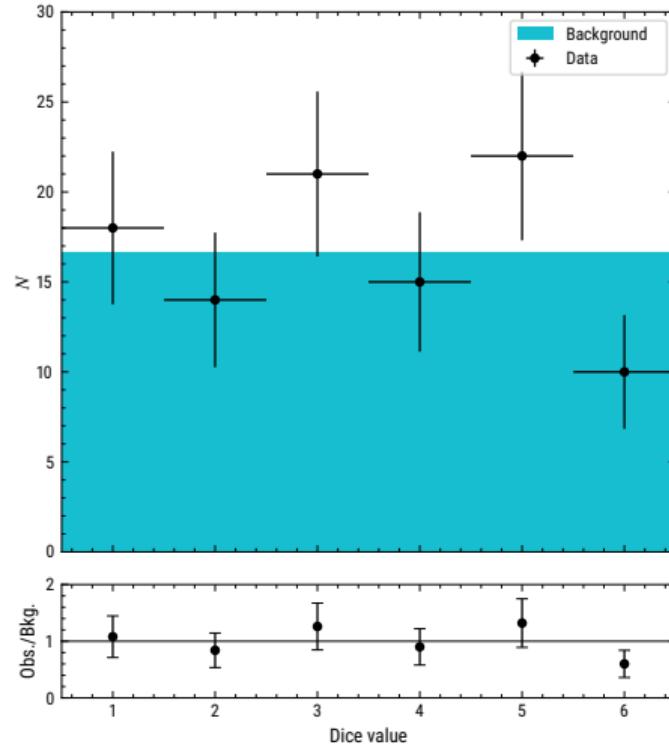
On 100 days →



Comparing with predictions!

The rabbit analogy

On 100 days →

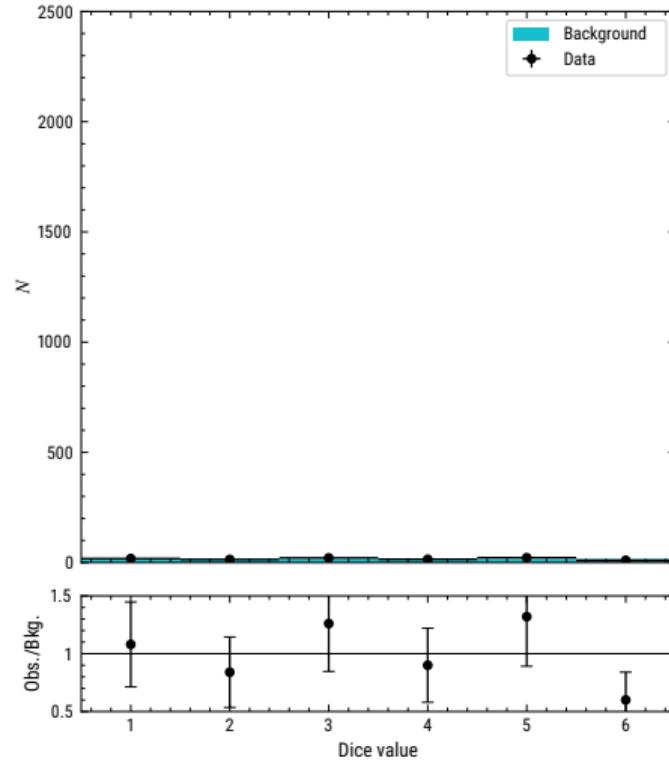


Also add ratio plot:
observed / predictions

The rabbit analogy

On 100 days →

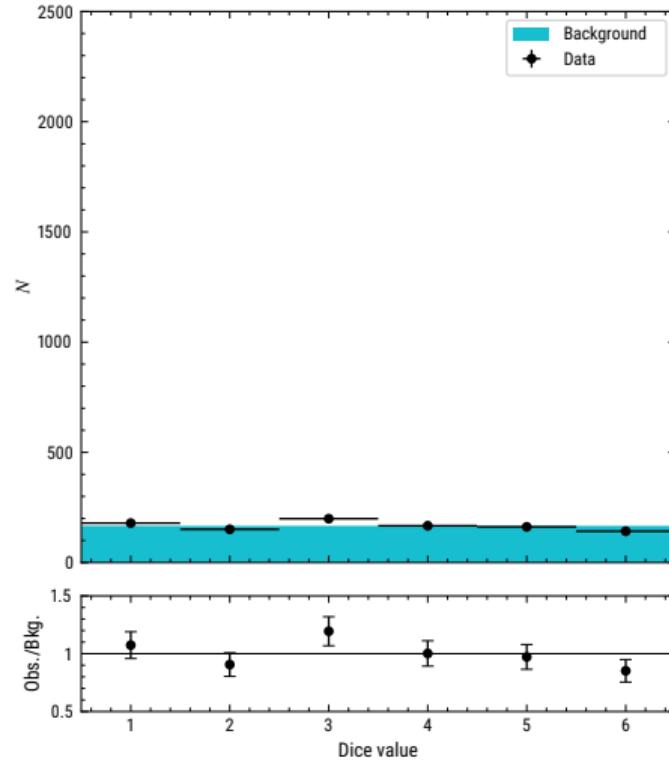
Fill up with more data!



The rabbit analogy

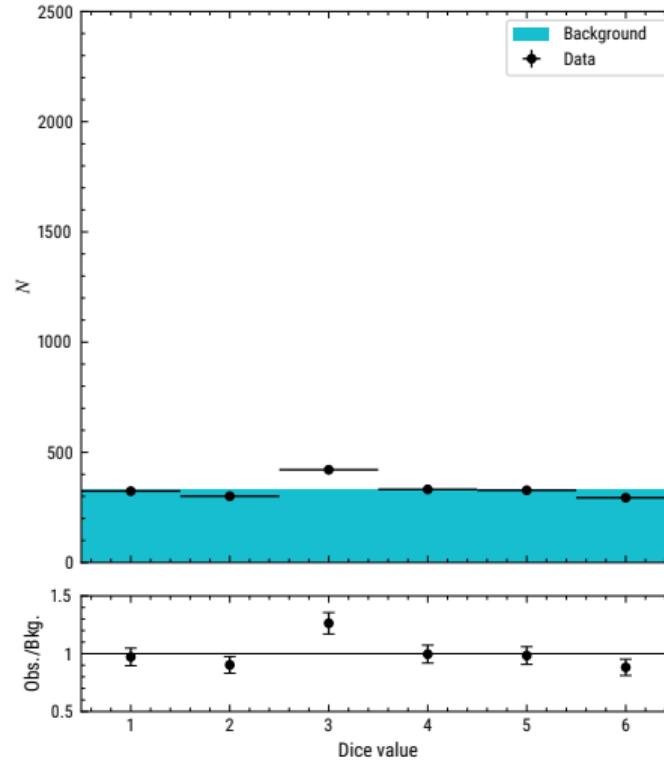
On 1000 days →

Fill up with more data!



The rabbit analogy

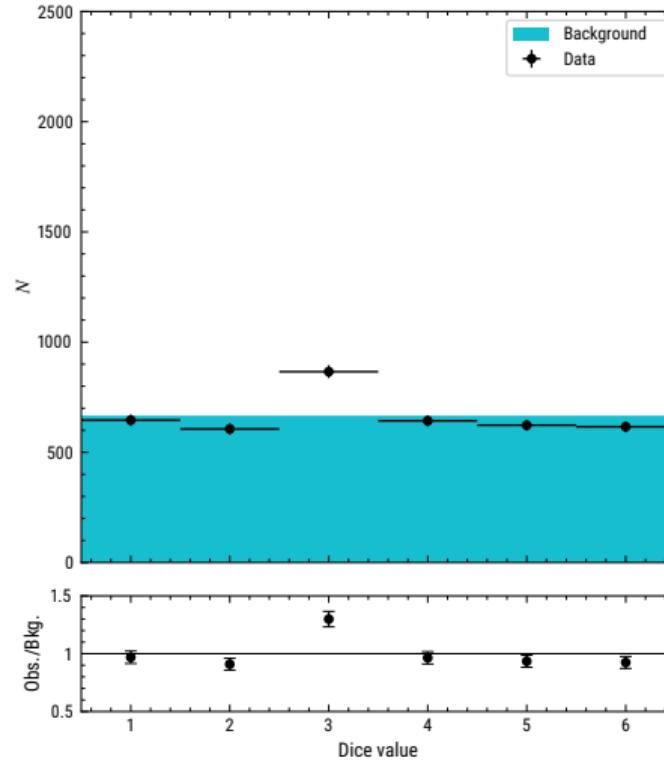
On 2000 days →



Fill up with more data!

The rabbit analogy

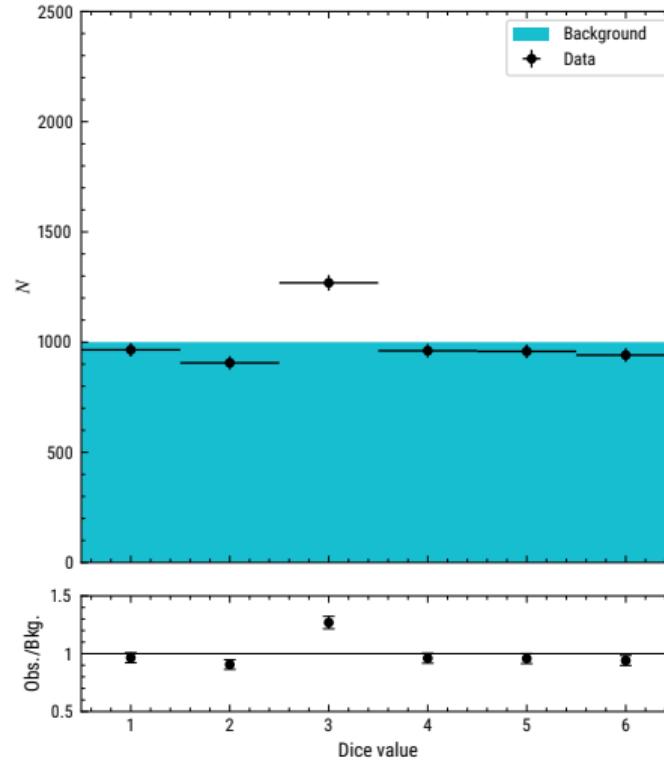
On 4000 days →



Fill up with more data!

The rabbit analogy

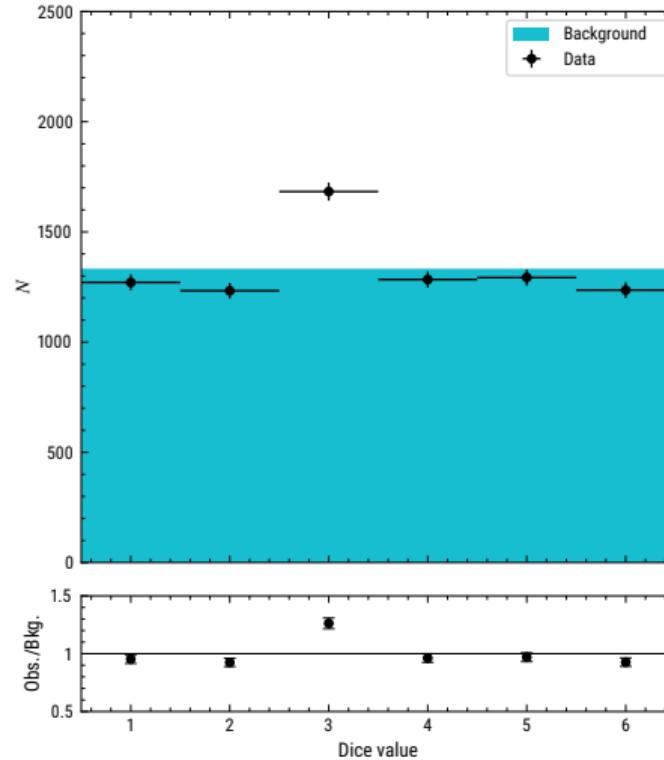
On 6000 days →



Fill up with more data!

The rabbit analogy

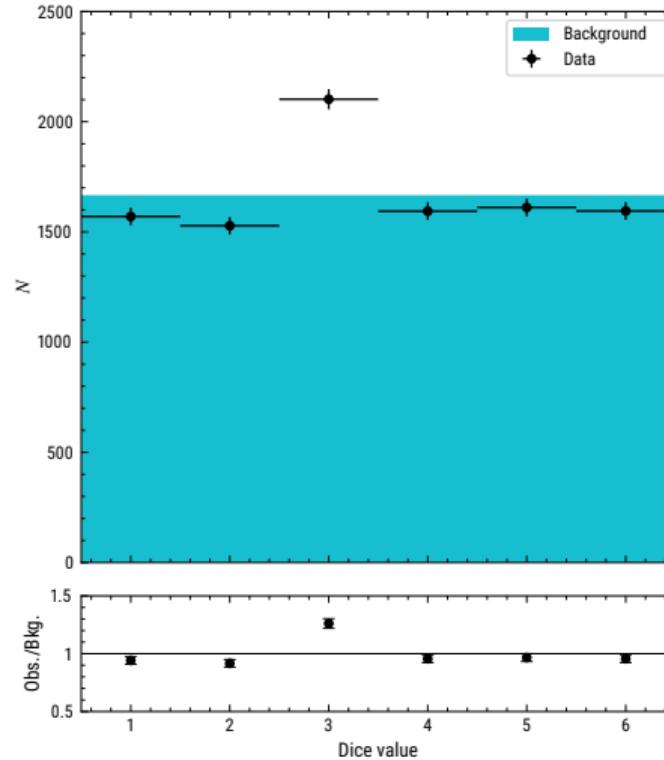
On 8000 days →



Fill up with more data!

The rabbit analogy

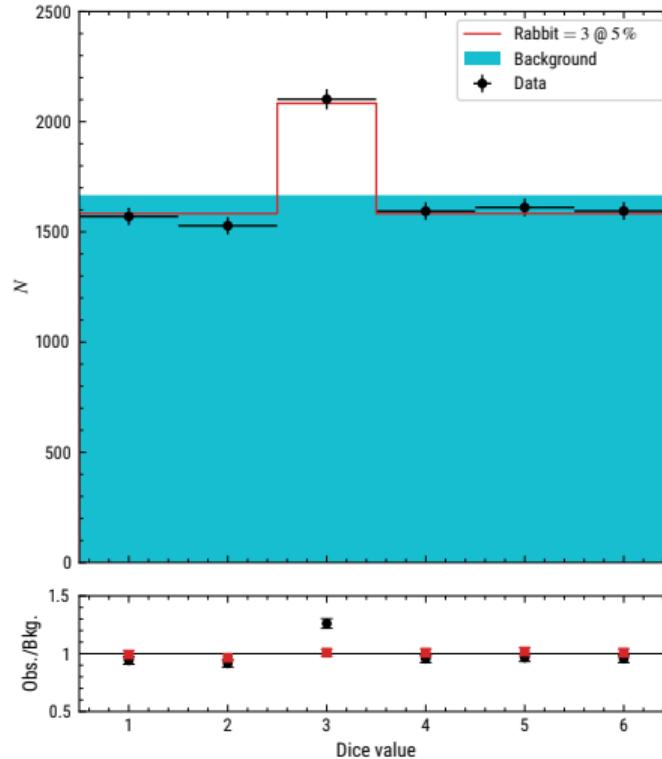
On 10,000 days →



Fill up with more data!

The rabbit analogy

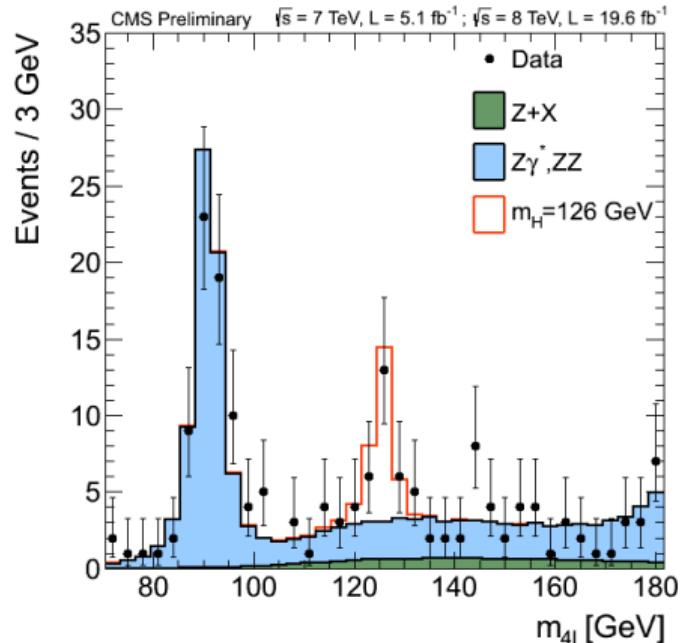
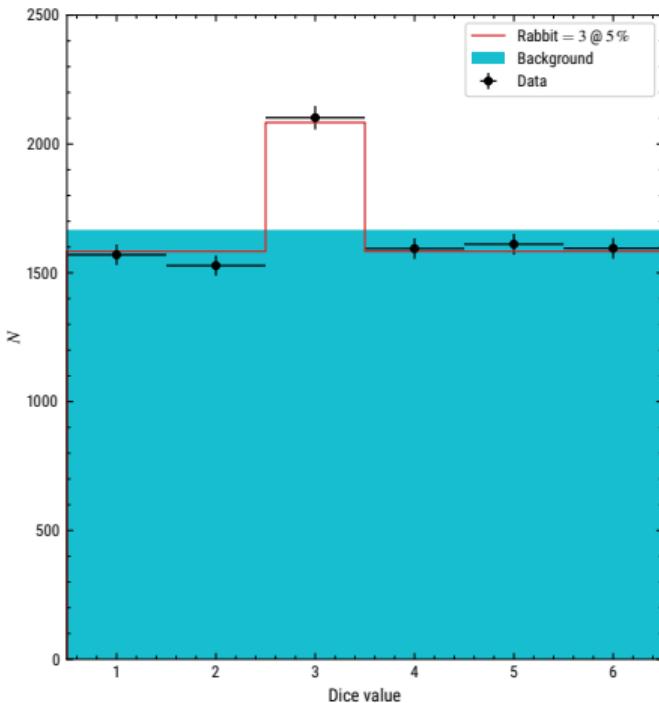
On 10,000 days →



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

The rabbit analogy

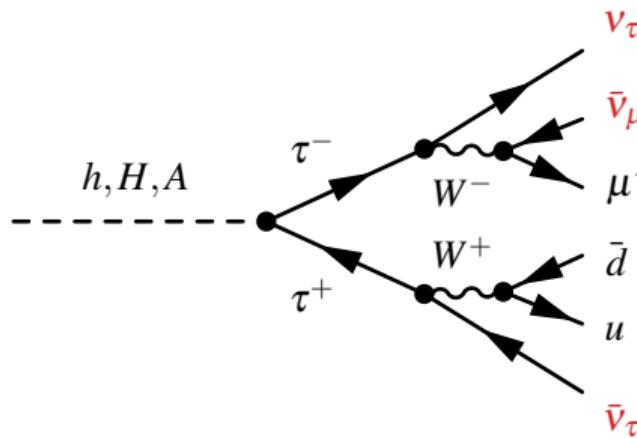
Search for	the rabbit	the Higgs
Observed data	dice values	pp collisions outgoing particles
Discriminating variable	dice value	invariant or transverse mass
Backgrounds predictions	random dice	Standard Model processes
Amount of data	number of days	luminosity
Signal probability	rabbit's shyness	process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



- ▷ The CMS Collaboration. "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC". *Physics Letters B* **716.1** (2012), pp. 30–61. DOI: 10.1016/j.physletb.2012.08.021. URL: <http://www.sciencedirect.com/science/article/pii/S0370269312008581>.
- ▷ The CMS Collaboration. Properties of the Higgs-like boson in the decay $H \rightarrow ZZ \rightarrow 4\ell$ in pp collisions at $\sqrt{s} = 7$ and 8 TeV. URL: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki>.

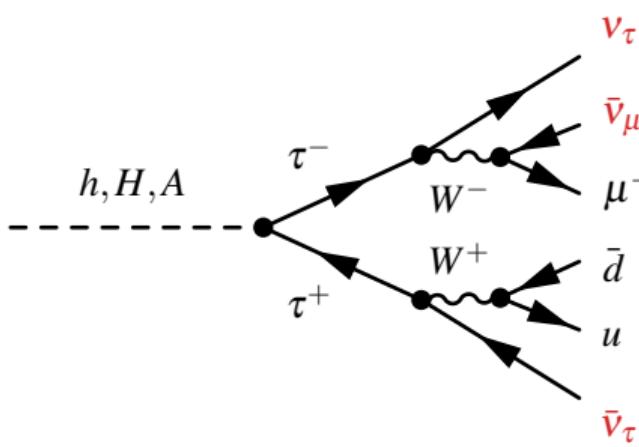
Discriminant variable?

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

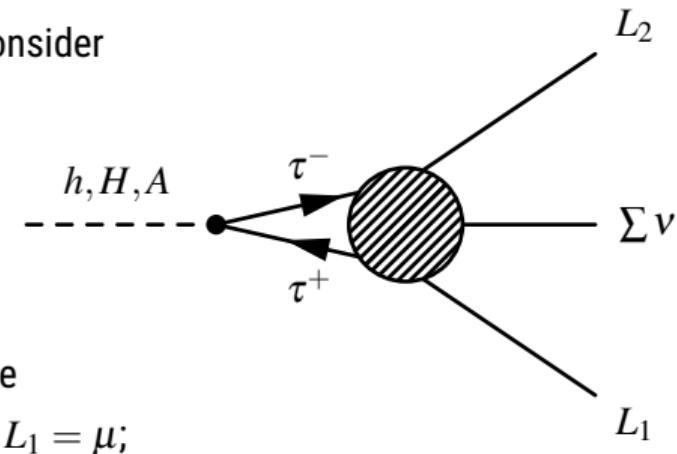


Discriminant variable?

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



- ▶ Consider



where

- $L_1 = \mu$;
- $L_2 = u\bar{d} \rightarrow \tau_h$;
- $\Sigma \nu \simeq E_T^{\text{miss}}$;

with respect to the left side.

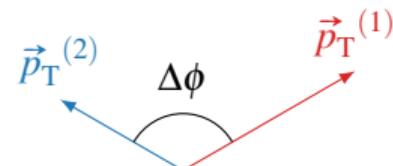
Discriminant variable: m_T^{tot}

- ▶ For L_1, L_2 and E_T^{miss} system,
 - ▷ in the transverse plane (use E_T^{miss}),
 - ▷ for $E_i \gg m_i$ (highly relativistic case),deriving the "invariant" mass would then lead to

the **total transverse mass**, m_T^{tot}

$$m_T^{\text{tot}} = \sqrt{m_T^2(L_1, E_T^{\text{miss}}) + m_T^2(L_2, E_T^{\text{miss}}) + m_T^2(L_1, L_2)}$$

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



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

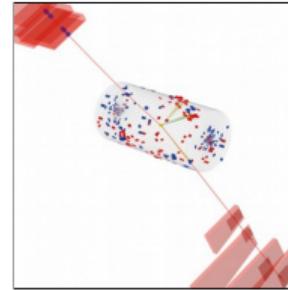
• MSSM signals

- ▶ /SUSYGluGluToHToTauTau_M-*_TuneCUETP8M1_13TeV-pythia8
- ▶ /SUSYGluGluToBBHToTauTau_M-*_TuneCUETP8M1_13TeV-amcatnlo-pythia8

Backgrounds?

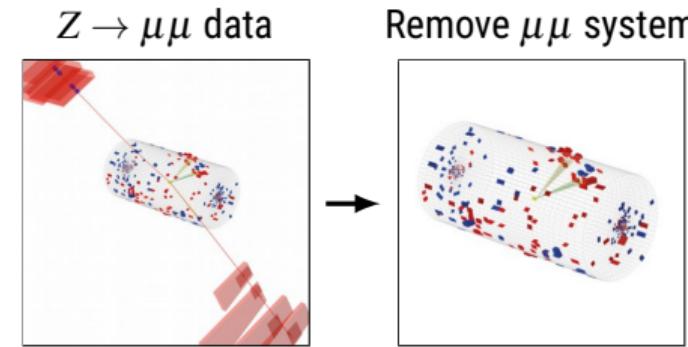
Embedded events

$Z \rightarrow \mu\mu$ data



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

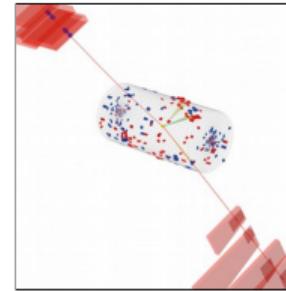
Embedded events



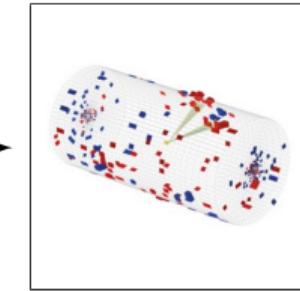
- ▷ The CMS Collaboration. "An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data". *Journal of Instrumentation* **14**.06 (June 2019). DOI: [10.1088/1748-0221/14/06/p06032](https://doi.org/10.1088/1748-0221/14/06/p06032).

Embedded events

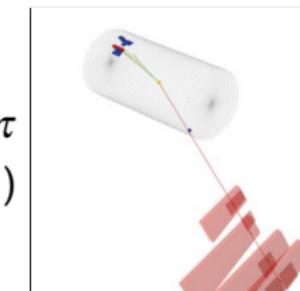
$Z \rightarrow \mu\mu$ data



Remove $\mu\mu$ system

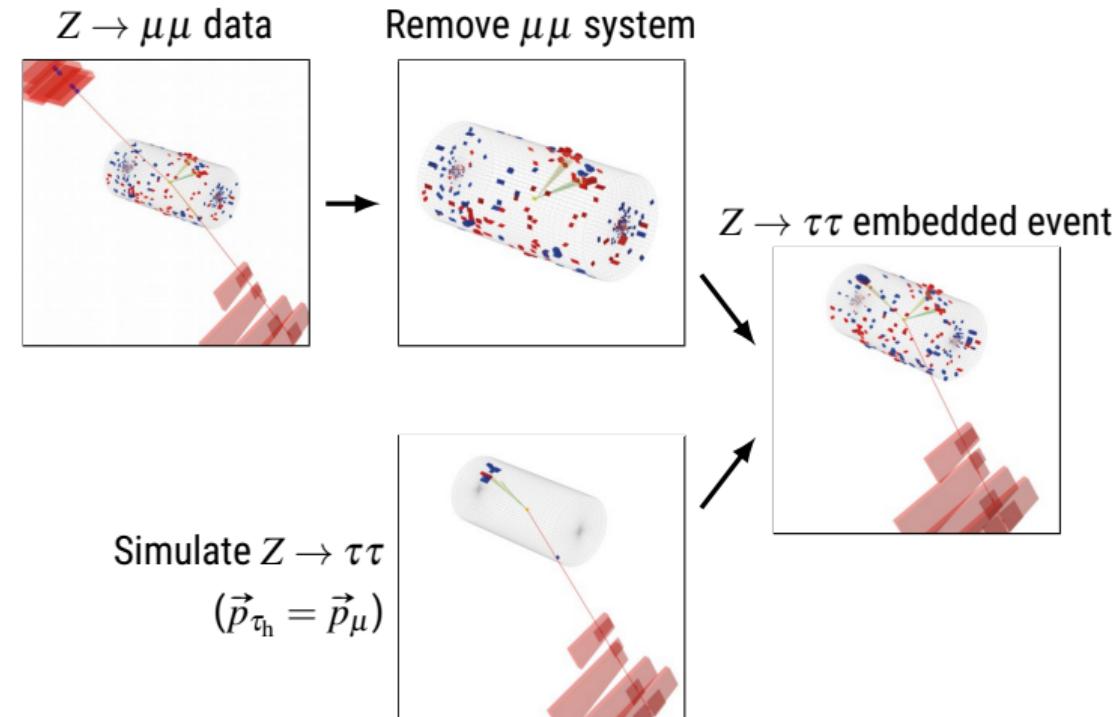


Simulate $Z \rightarrow \tau\tau$
 $(\vec{p}_{\tau_h} = \vec{p}_\mu)$



- ▷ 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](https://doi.org/10.1088/1748-0221/14/06/p06032).

Embedded events



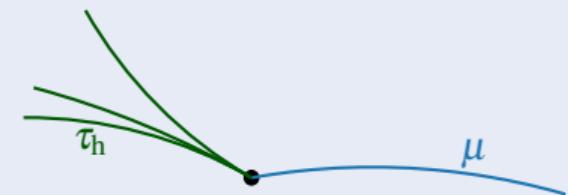
▷ The CMS Collaboration. "An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data". *Journal of Instrumentation* 14.06 (June 2019). DOI: 10.1088/1748-0221/14/06/p06032.

Backgrounds: Drell-Yan

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



$H \rightarrow \tau\tau \rightarrow \mu\tau_h$



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

Backgrounds: $W + \text{jets}$

$W + \text{jets}$



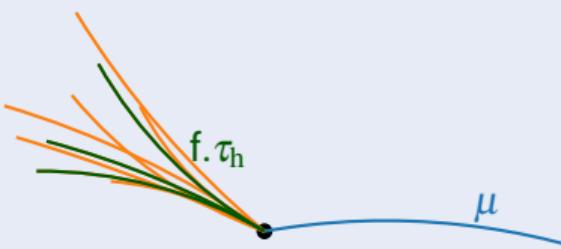
$H \rightarrow \tau\tau \rightarrow \mu\tau_h$



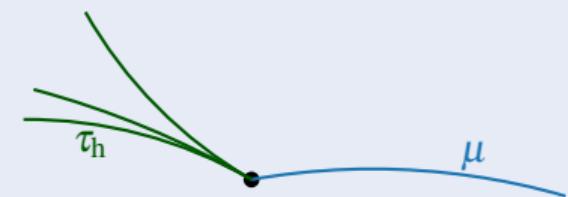
- /W[1-4]JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8
- /WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8 ...

Backgrounds: $W + \text{jets}$

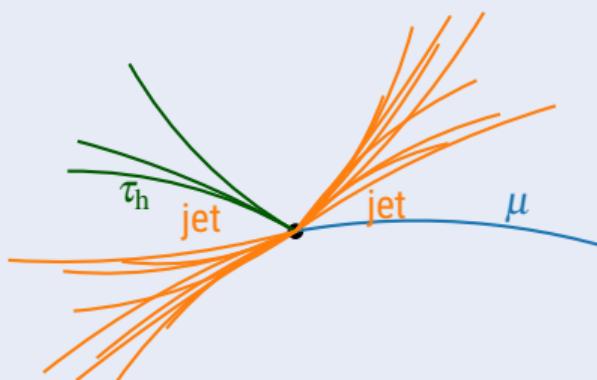
$W + \text{jets}, \text{jet} \rightarrow \text{fake } \tau_h$



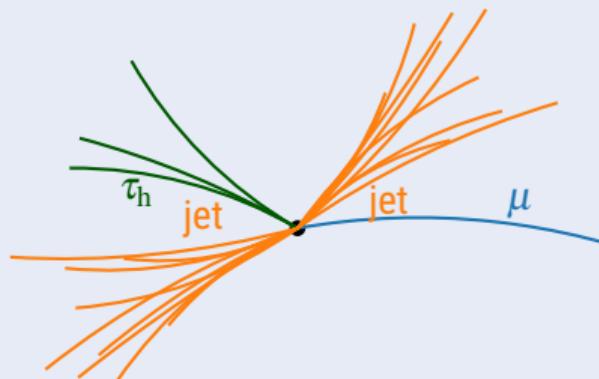
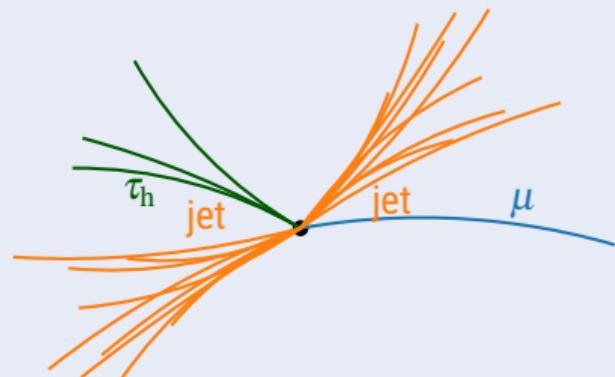
$H \rightarrow \tau\tau \rightarrow \mu\tau_h$



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

Backgrounds: $t\bar{t}$ $t\bar{t}$  $H \rightarrow \tau\tau \rightarrow \mu\tau_h$ 

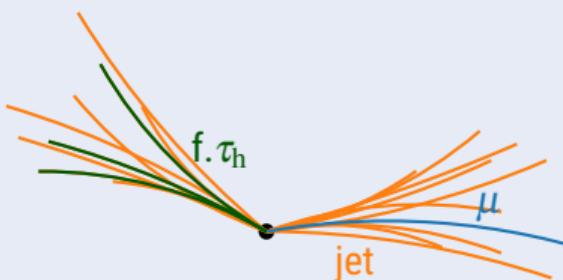
- /TTToHadronic_TuneCP5_13TeV-powheg-pythia8
- /TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8 ...

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



$H \rightarrow \tau\tau \rightarrow \mu\tau_h$



Comes from fake τ_h s
⇒ estimation based on different regions, see later

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

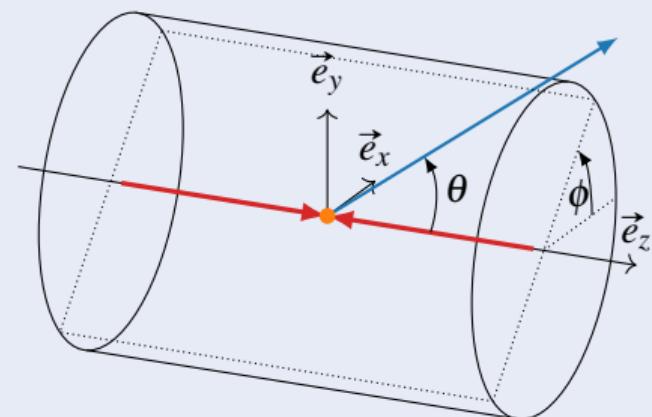
μ and τ_h candidates

- $L_1 = \mu$

- $p_T > 21 \text{ GeV}$, $|\eta| < 2.1$
- $d_z < 0.2 \text{ cm}$, $d_{xy} < 0.045 \text{ cm}$
- relative isolation < 0.15
- medium muon ID

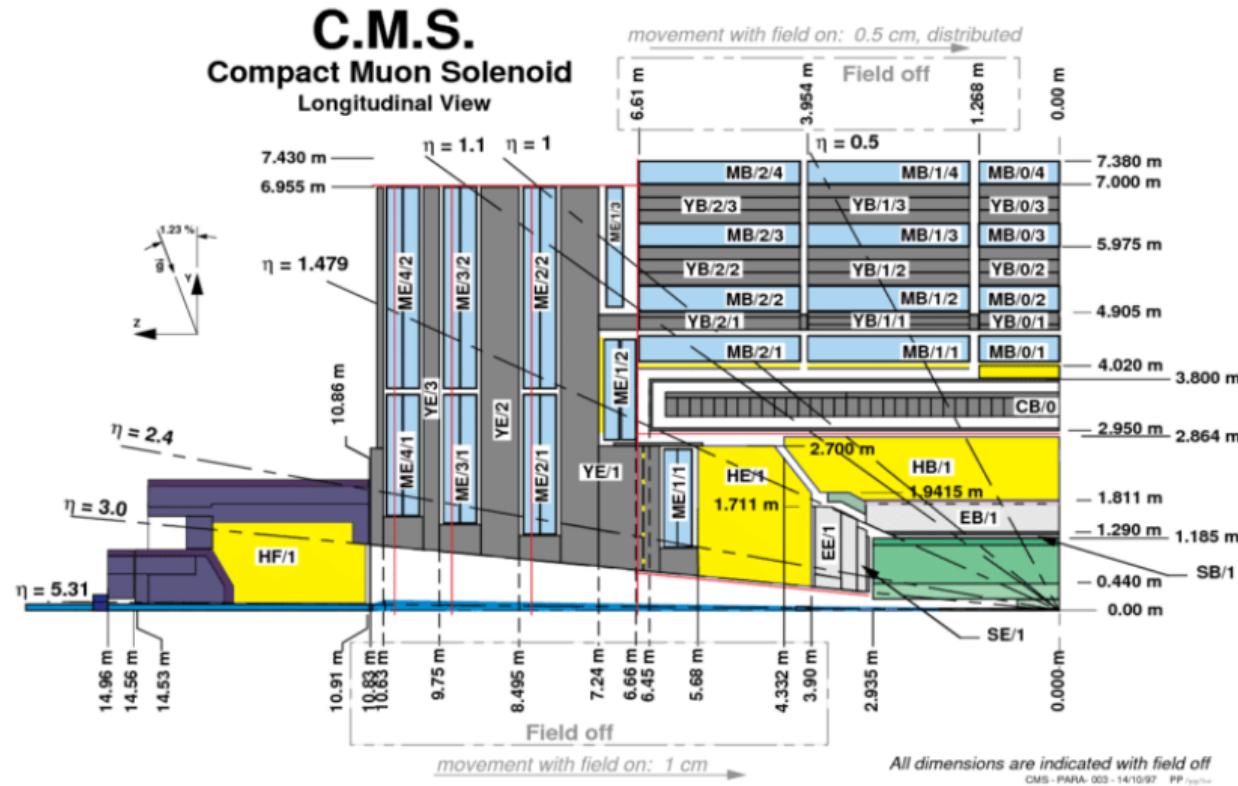
- $L_2 = \tau_h$

- $p_T > 30 \text{ GeV}$, $|\eta| < 2.3$
- $d_z < 0.2 \text{ cm}$
- relative isolation < 0.15
- NewDecayModeFinding (modes 5 to 9 vetoed)
- deepTau anti-electron (VVL WP)
- deepTau anti-muon (tight WP)
- deepTau vs jet (medium WP)

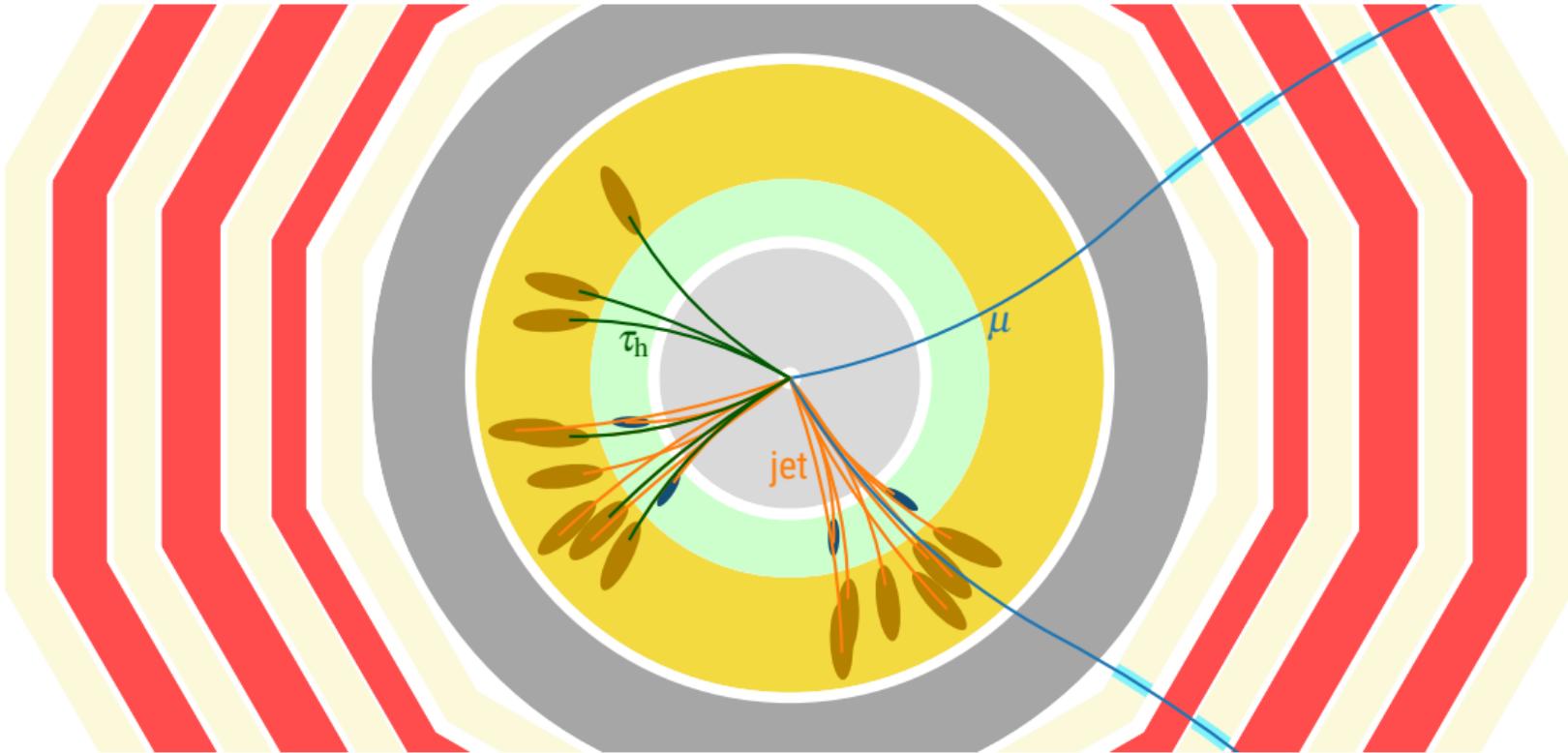


$$\eta = -\ln \tan \frac{\theta}{2}$$

Values of η and trajectories in CMS



Particles isolation – qualitatively

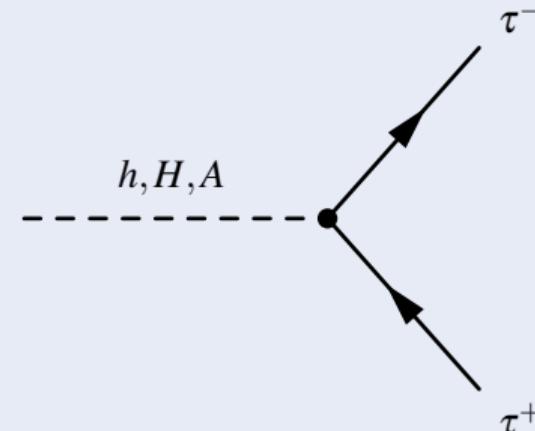


Signal region (SR) – 2017 $\mu\tau_h$ channel as example

Obtaining *dileptons* candidates

With all L_1 and L_2 passing selection,
compose pairs (L_1L_2) respecting:

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

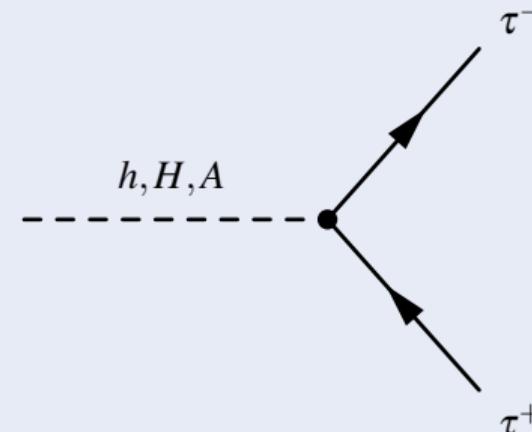


Signal region (SR) – 2017 $\mu\tau_h$ channel as example

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Selecting one dilepton

Choose by:

most isolated L_1 ,

highest $p_T^{L_1}$,

most isolated L_2 ,

highest $p_T^{L_2}$.

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

Extra leptons: reject events containing

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

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

Extra leptons: reject events containing

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Transverse mass

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

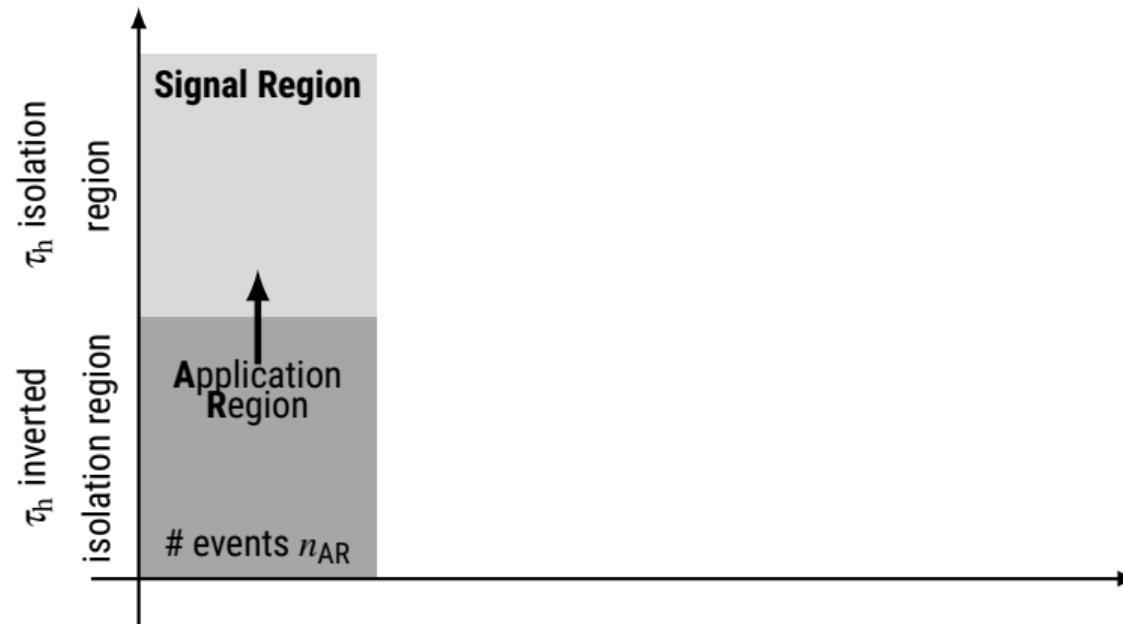
The Fake Factor method

- ▶ 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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The FF method: determination regions definitions

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

Estimation from simulated samples, same selection as in SR.

-
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The FF method: determination regions definitions

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$W + \text{jets}$

Same as SR, except:

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

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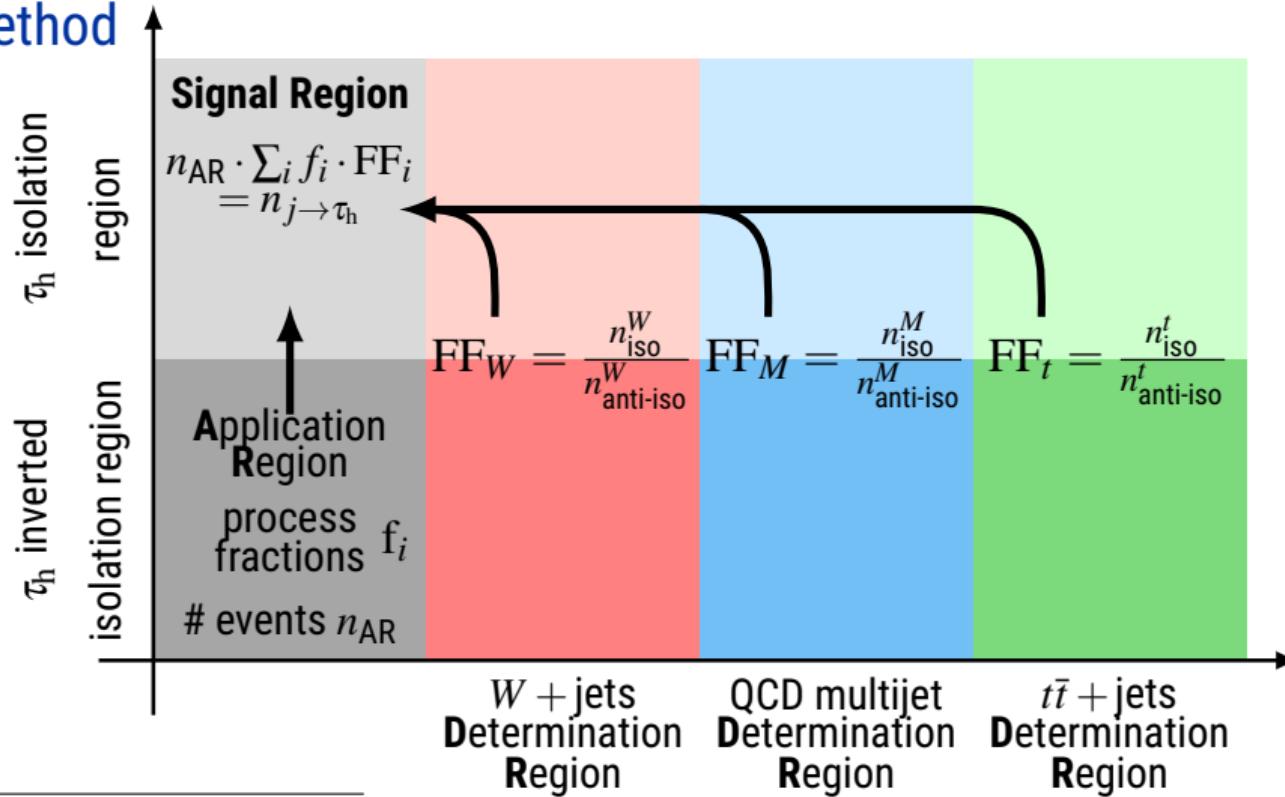
QCD multijet

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



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m_T^{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

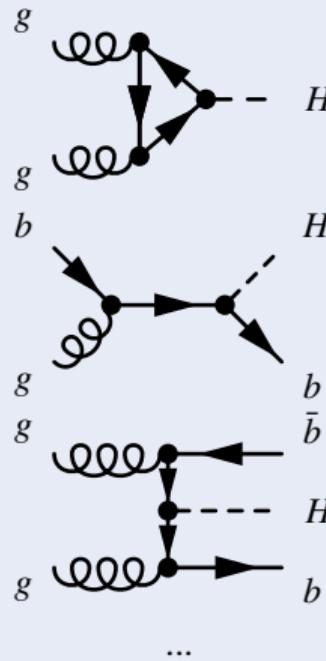
1 Phenomenology

2 Experimental device

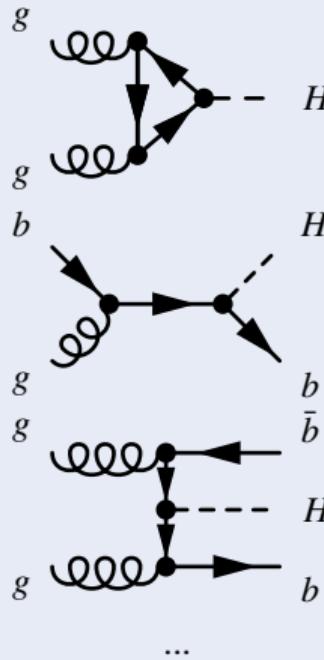
3 $H \rightarrow \tau\tau$ analysis

4 Machine Learning

Higgs production

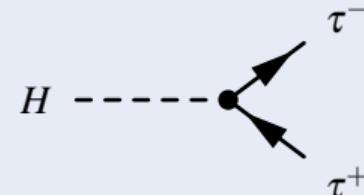


Higgs production

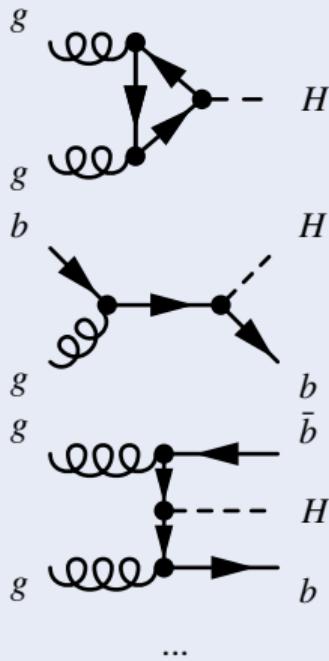


$H \rightarrow \tau\tau$

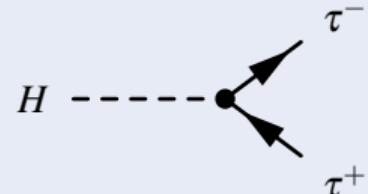
\otimes



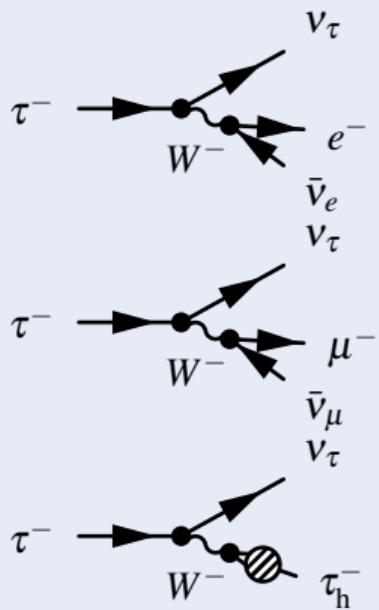
Higgs production



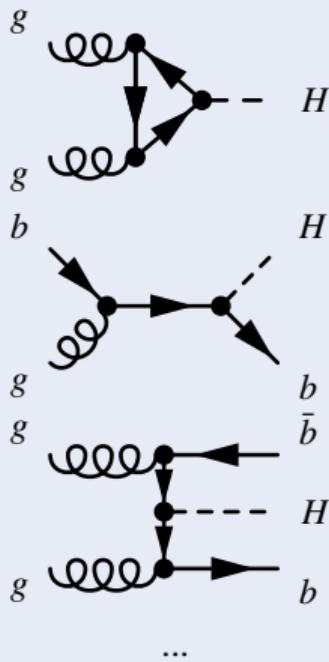
$H \rightarrow \tau\tau$



τ decays

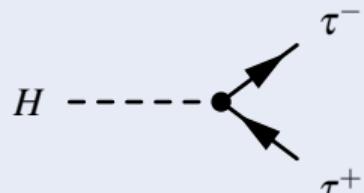


Higgs production



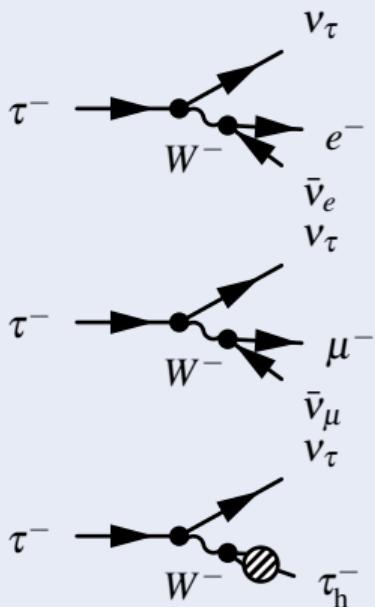
eventual jets

$H \rightarrow \tau\tau$



2 taus

τ decays



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

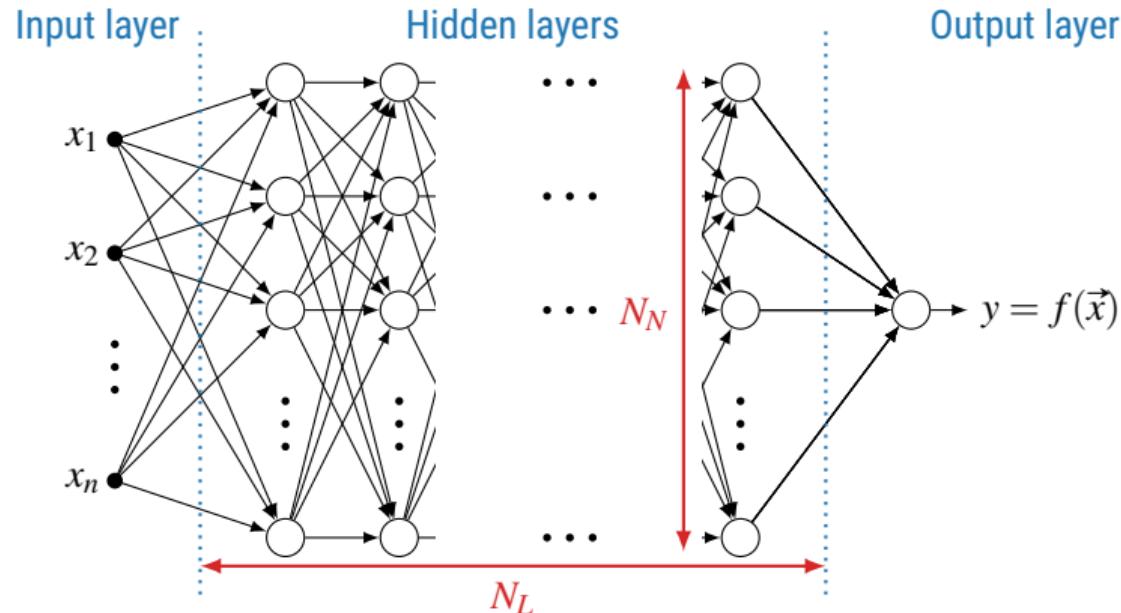
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 - ▷ visible decay products $\rightarrow p_T^{(1,2)}, \eta^{(1,2)}$ and $\phi^{(1,2)}$,
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- ▶ Higher level variables:
 - ▷ transverse masses $m_T^1, m_T^2, m_T^{\tau\tau}$,
 - ▷ total transverse mass m_T^{tot} .
- ▶ Additionnal variables:
 - ▷ MET covariance matrix;
 - ▷ remaining jets overall $\vec{p} \rightarrow p_T^r, \eta^r$ and ϕ^r ;
 - ▷ number of neutrinos ($\tau_h \tau_h = 2, \ell \tau_h = 3, \ell \ell = 4$);
 - ▷ number of PU vertices `npvsGood`;



$$N_L \in [2, 10] \cup \{15\}$$

$$N_N \in \{500, 1000, 1500, 2000\}$$

► 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!