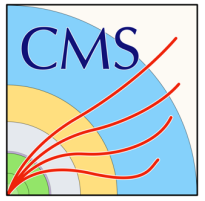


SAPIENZA
UNIVERSITÀ DI ROMA

HH production at the CMS experiment: High-Lumi is the way!

Speaker: Marco Del Vecchio

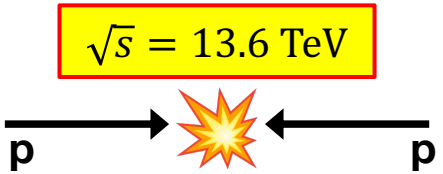
INFN@Young, 26 Marzo 2025

The Large Hadron Collider

The **leading accelerator** In the world!

Protons are accelerated at **99.999999% speed of light** at a **centre of mass energy** of **13.6 TeV**

One collision every **25 ns**.



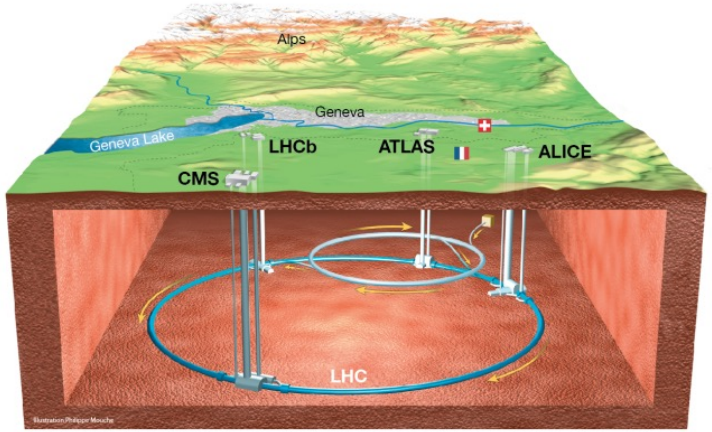
Between France and Switzerland (near **Geneva**)

27 km long!

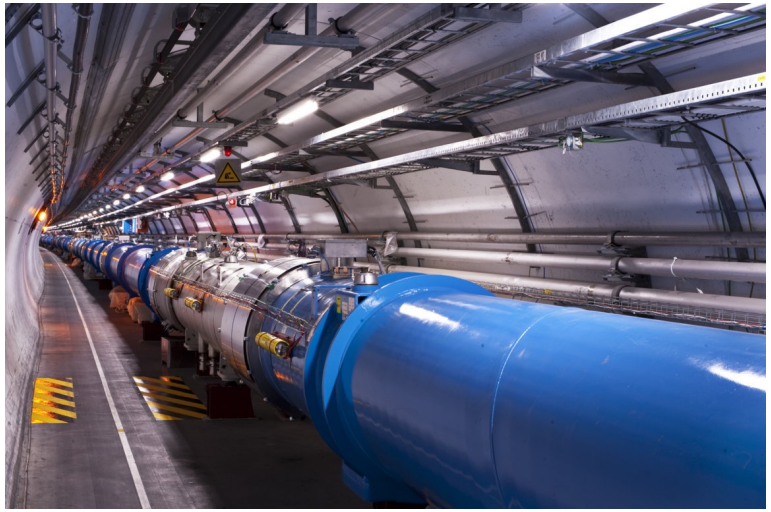
4 major experiments

- **ATLAS**
- **CMS**
- **ALICE**
- **LHCb**

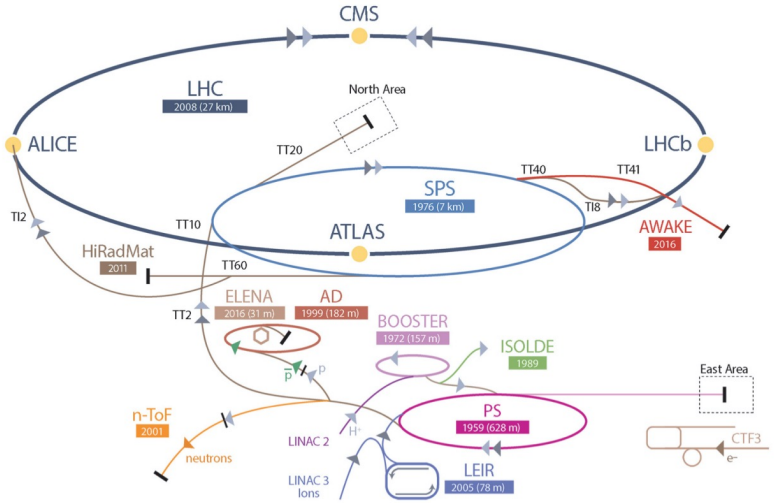
The Large Hadron Collider



~ **100 meters** underground

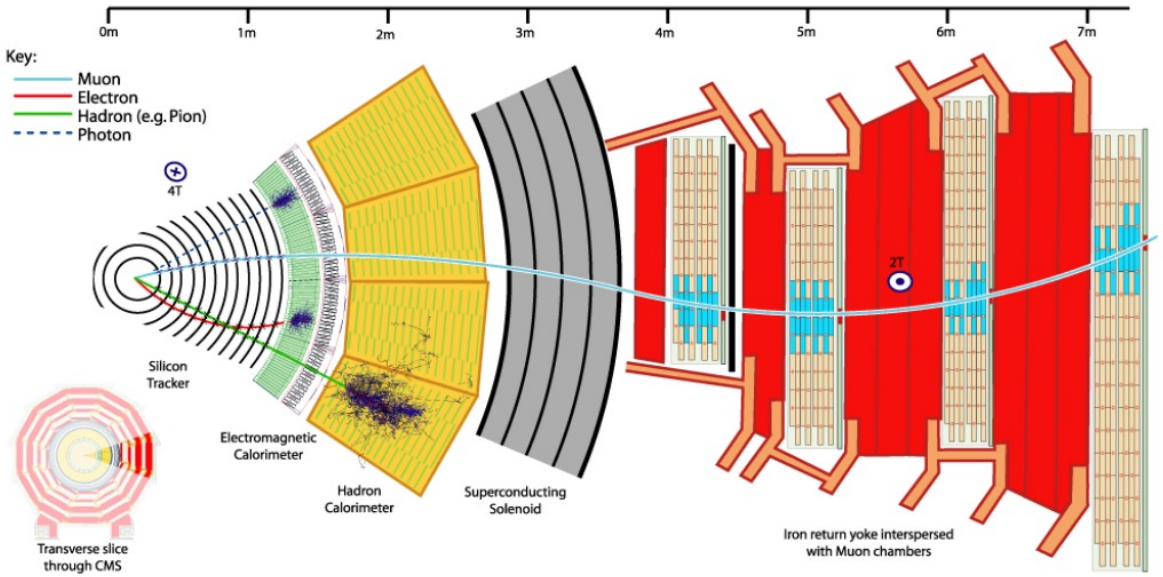


- **Acceleration** provides via **electric field** (**RF cavities**)
- **Bending** via **magnets**



Various **steps of acceleration** before be injected in the main tunnel

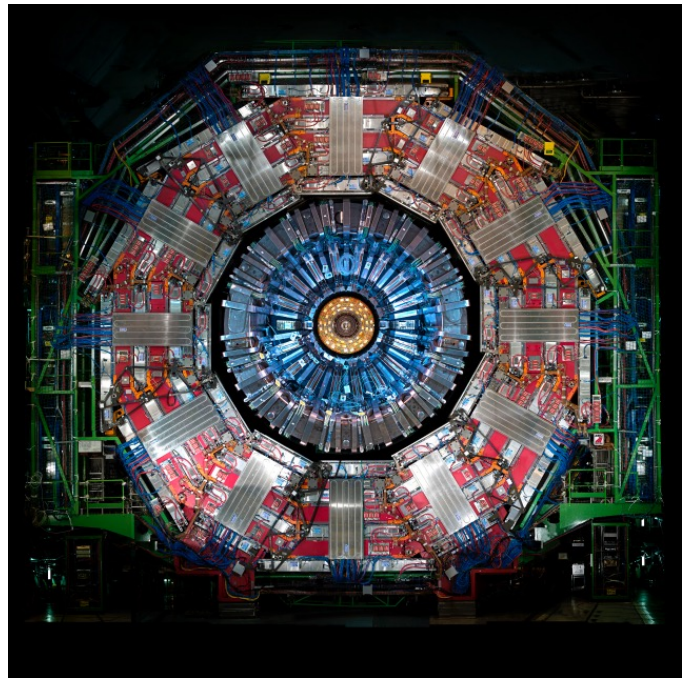
The CMS experiment



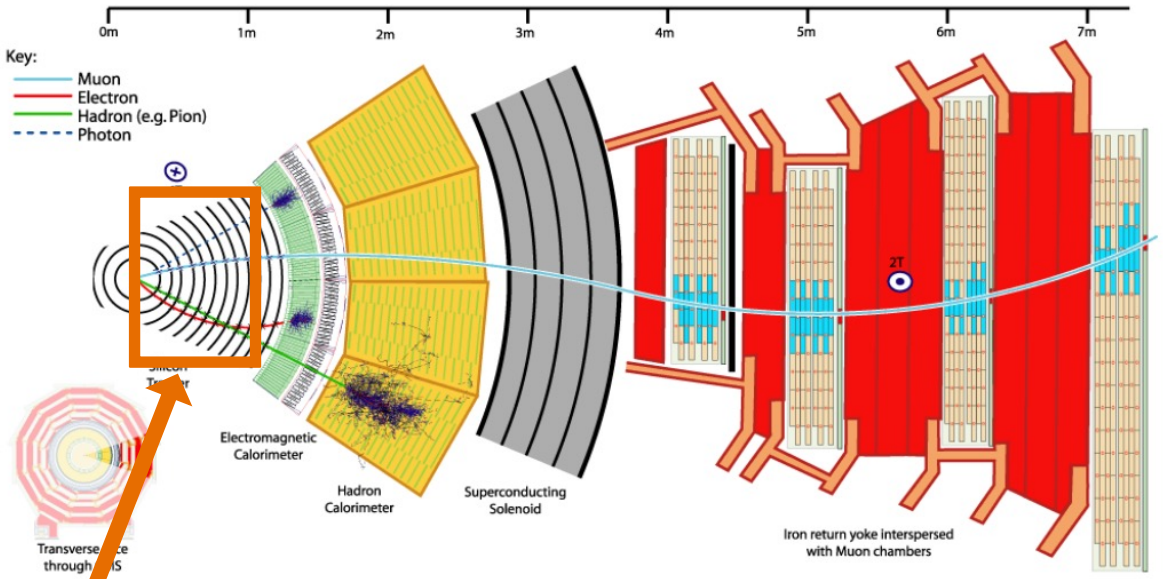
Compact **M**uon **S**olenoid

General purpose experiment

- Inner tracker
- Electromagnetic calorimeter
- Hadron calorimeter
- Superconducting solenoid
- Muon chambers



The CMS experiment



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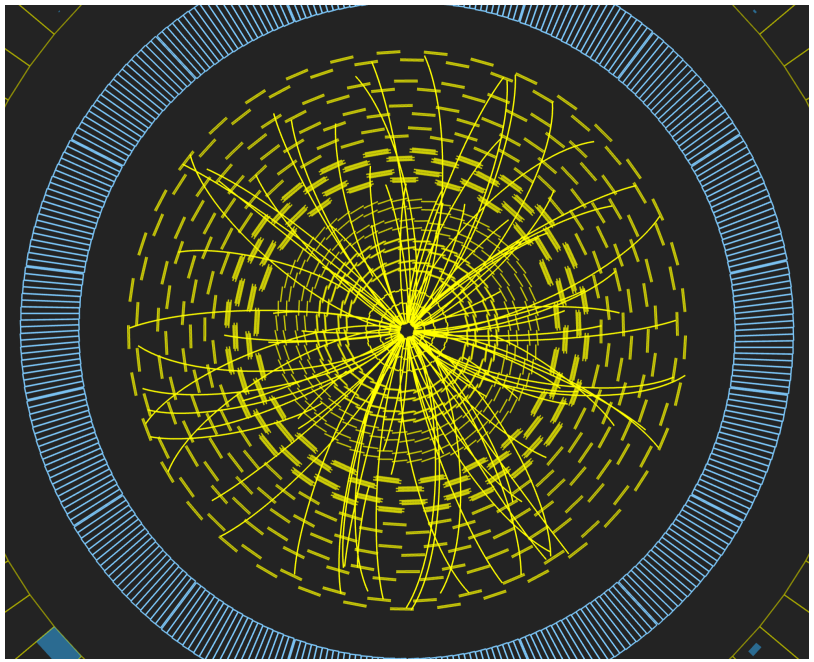

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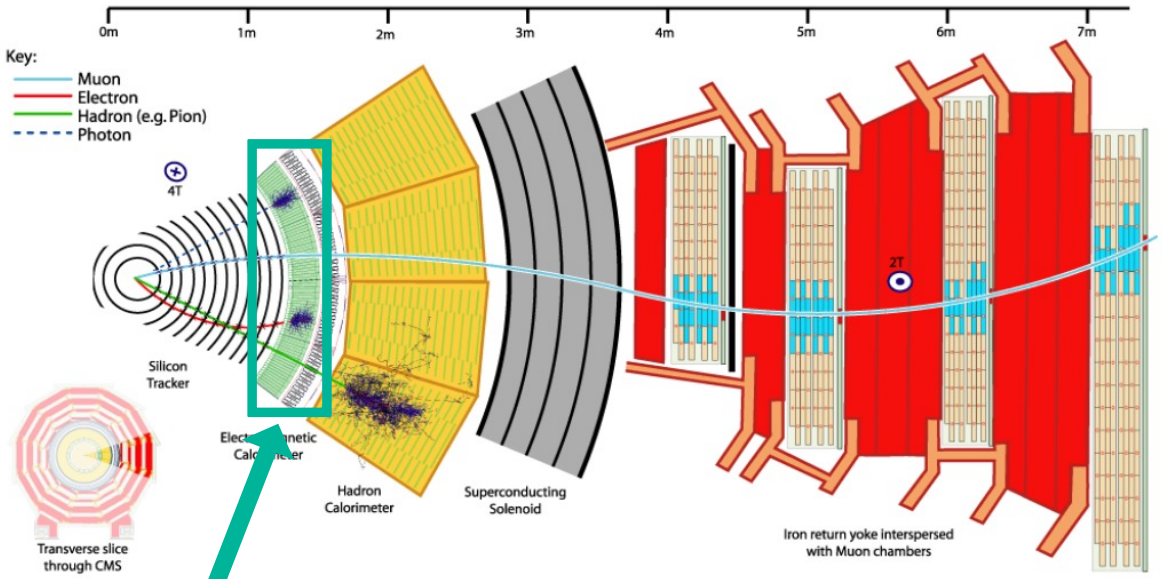

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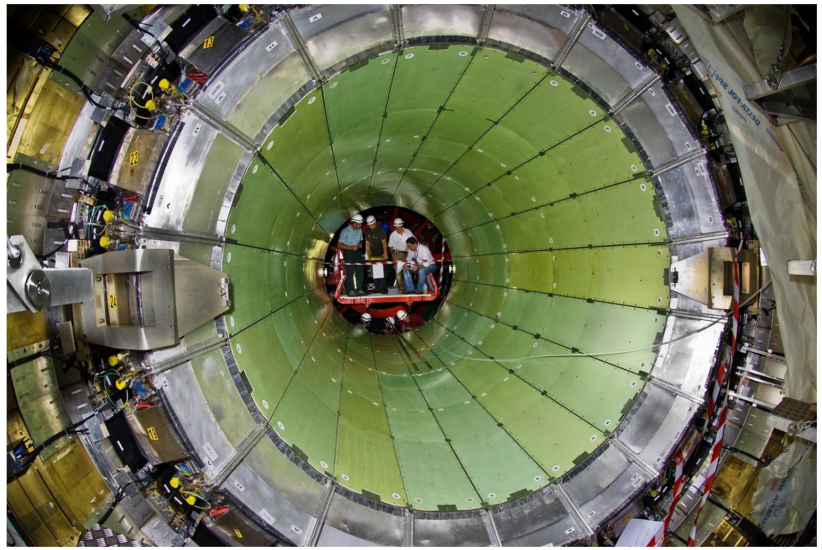

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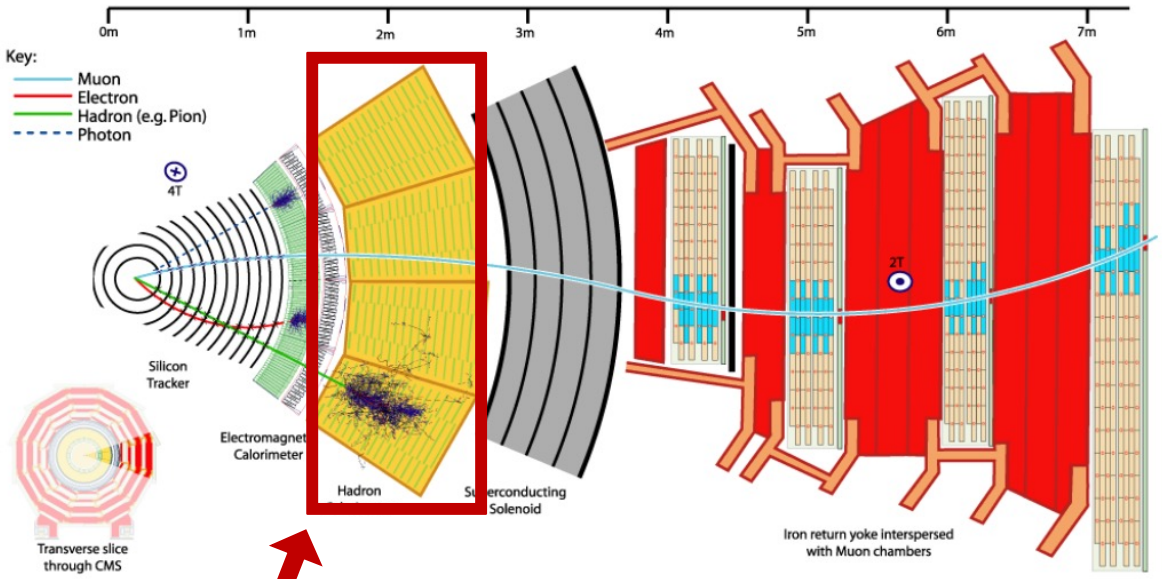

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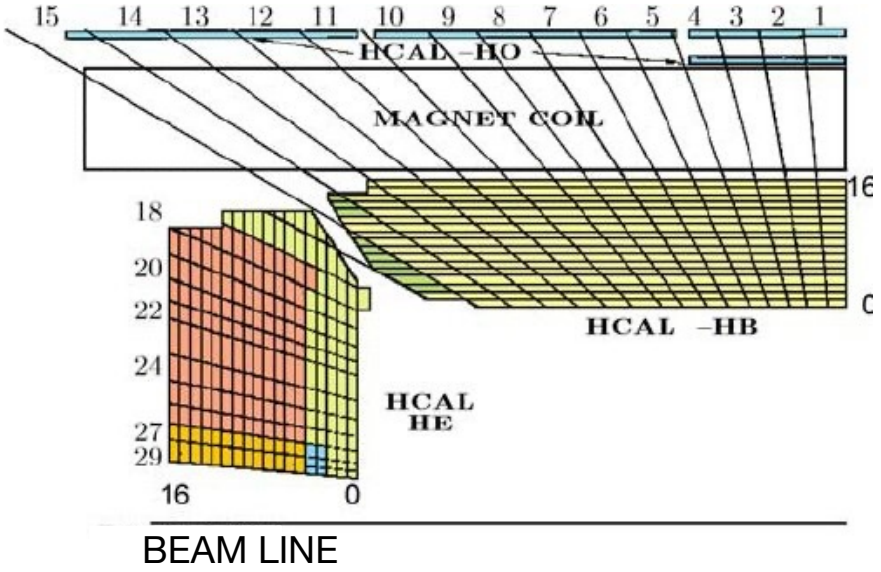

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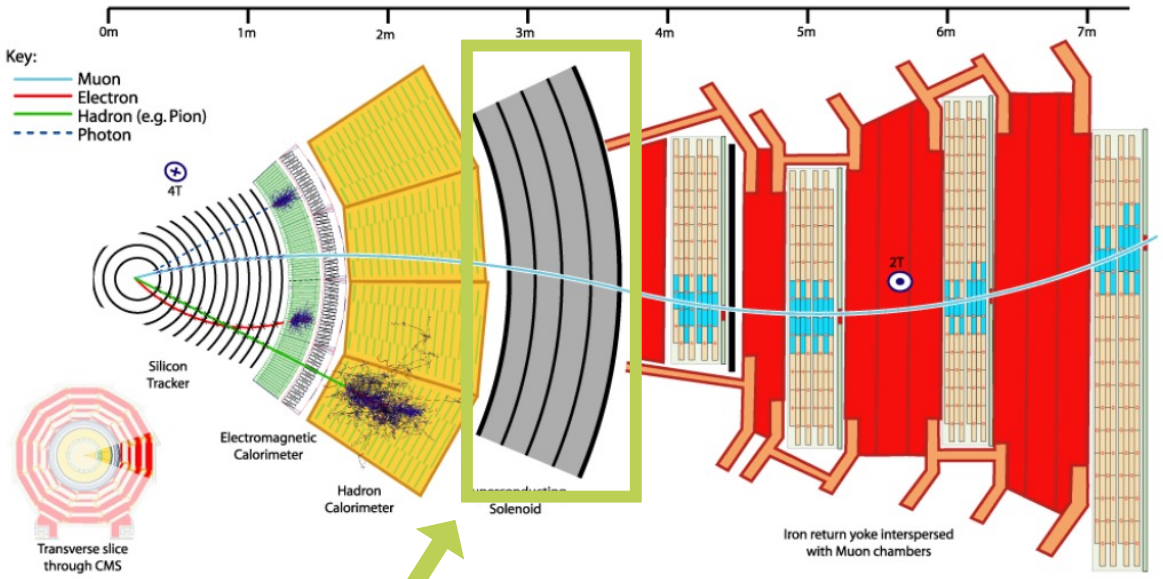

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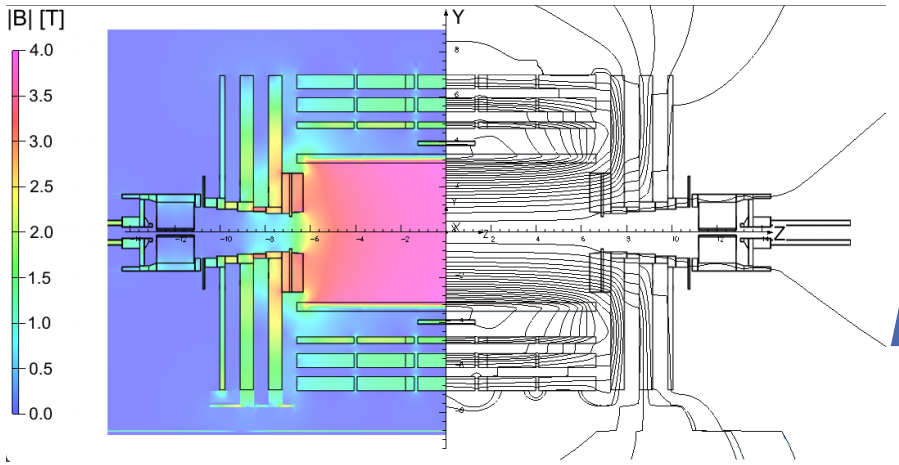

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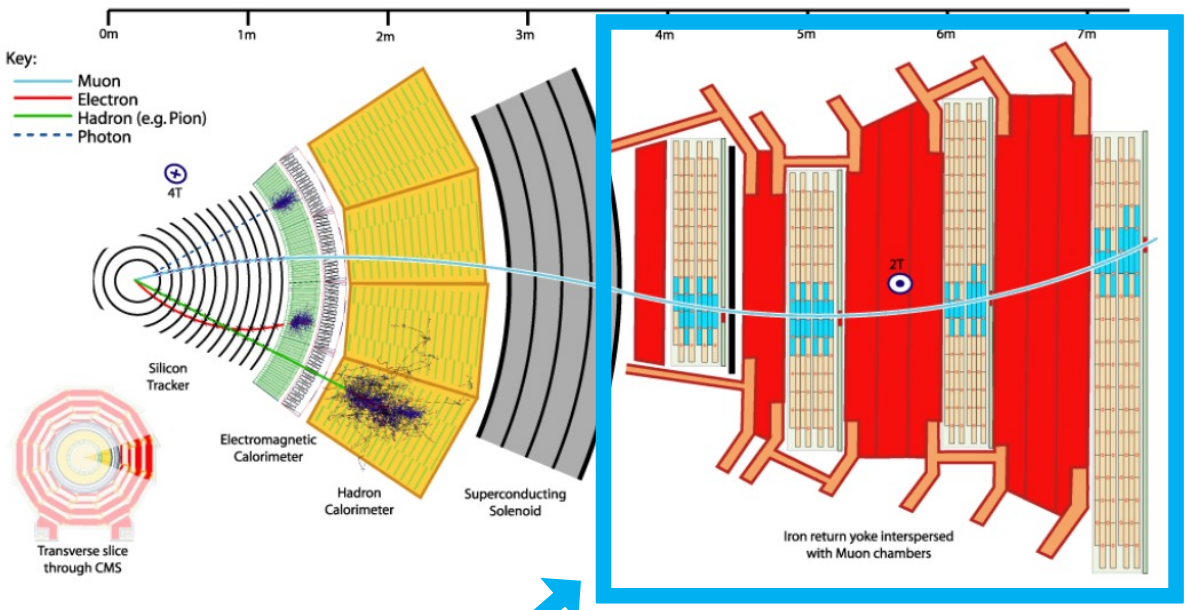

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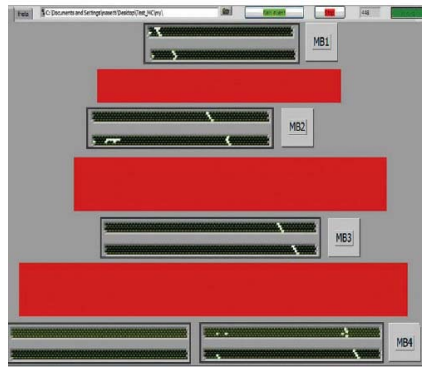


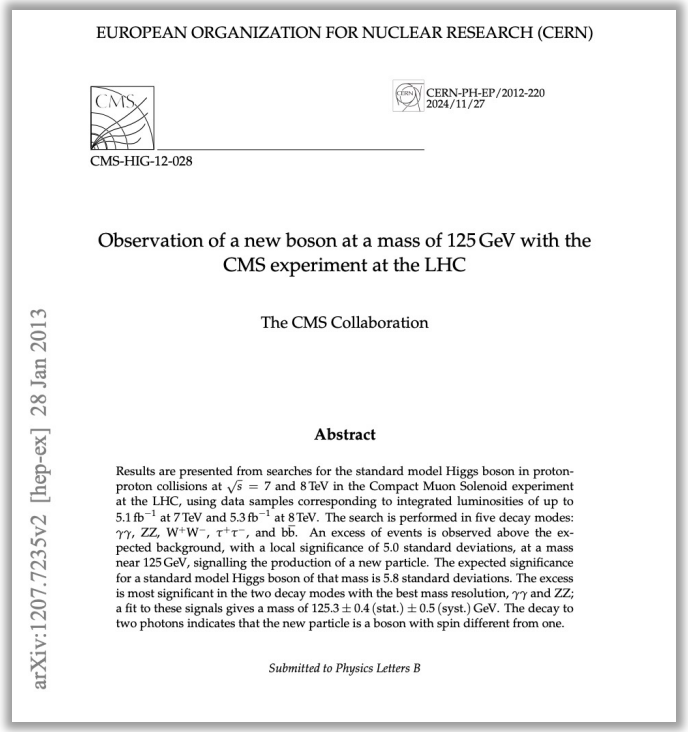
Goal of the experiment

LHC → improve our knowledge on **particle physics**

- Validation of the Standard Model (**SM**)
- **Beyond SM** physics

2009 Start of the experimental activity of the LHC

First important achievement
↓
Higgs discovery (2012)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2012-220
2024/11/27

CMS-HIG-12-028

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration

Abstract

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Submitted to Physics Letters B

arXiv:1207.7235v2 [hep-ex] 28 Jan 2013

The Higgs mechanism

The Higgs mechanism

1964

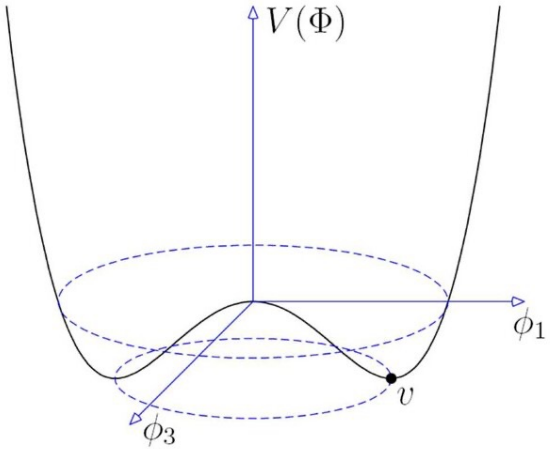
Timeline

Higgs mechanism formulation

$\phi \rightarrow$ new complex scalar field associated with a new particle

$$\mathrm{SU}(3) \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1) \xrightarrow{\mathrm{SSB}} \mathrm{SU}(3) \otimes \mathrm{U}(1)_{\mathrm{EM}}$$

Vacuum expectation value → $v = 246$ GeV



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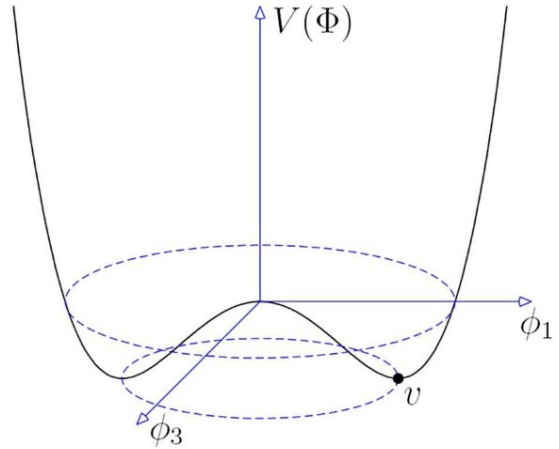
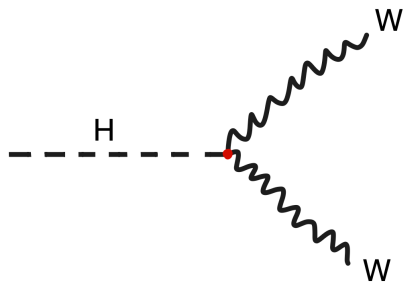
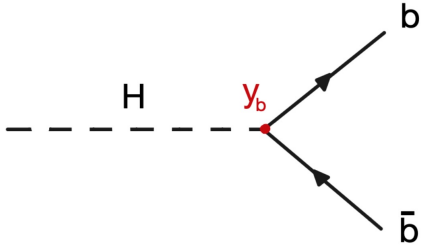


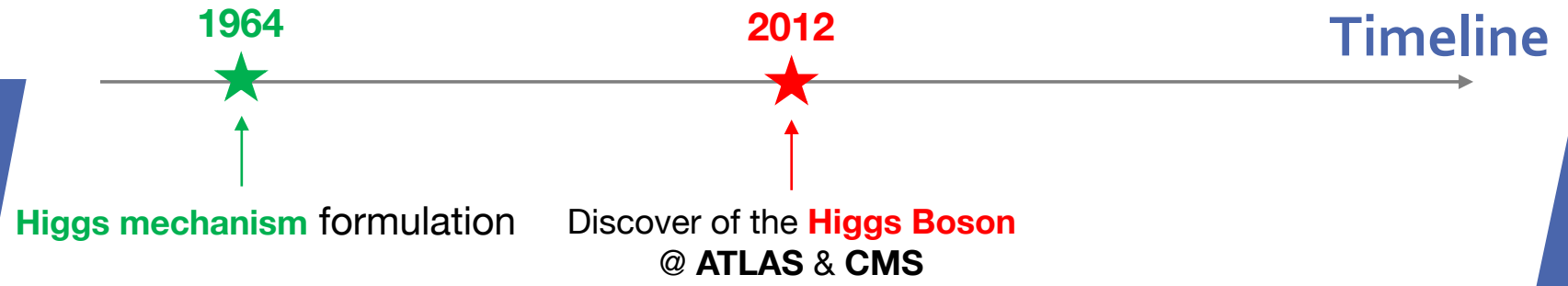
During **SSB**, vector bosons $\mathbf{W}^{\pm}$ and $\mathbf{Z}$ acquire mass, while γ remains massless



In addition, **interactions** between the **Higgs field** and **fermions** give **mass** to them



Higgs boson discovery

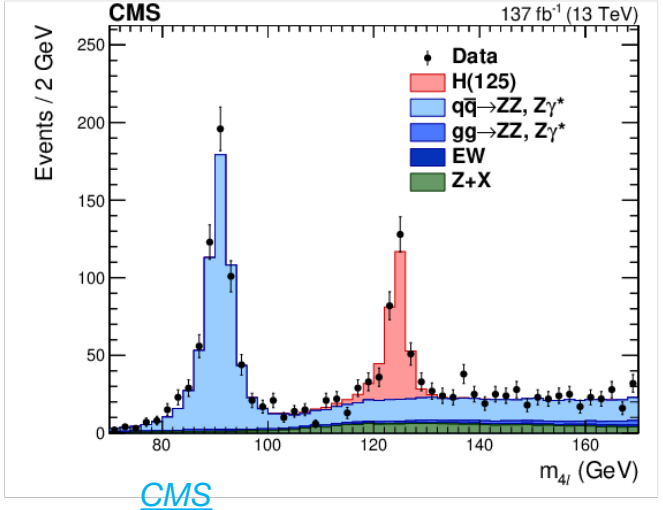


Higgs boson discovery

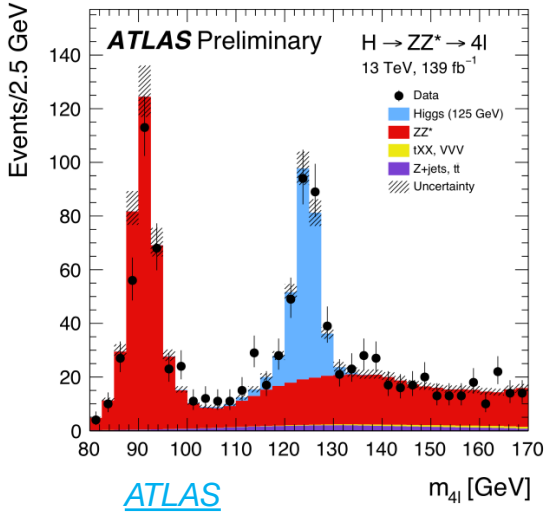
Timeline

1964 — **Higgs mechanism** formulation

2012 — Discover of the **Higgs Boson** @ **ATLAS** & **CMS**



CMS



ATLAS

Higgs boson discovery

Timeline

1964 — **Higgs mechanism** formulation

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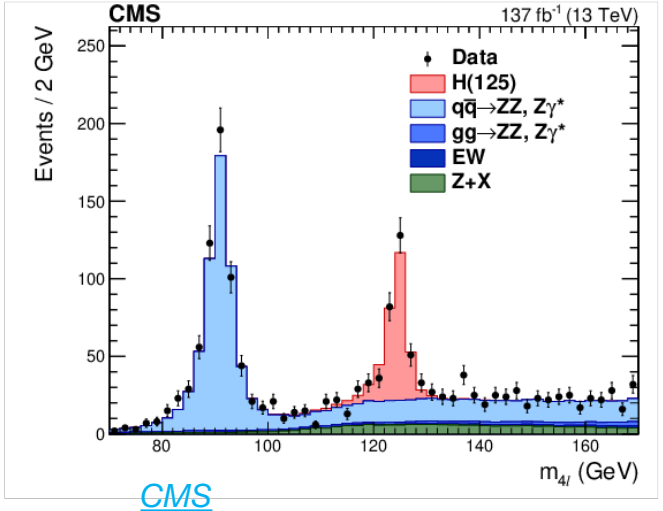
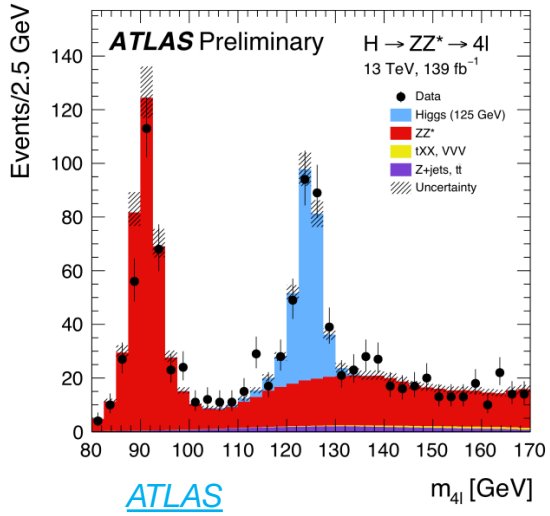


[CMS]



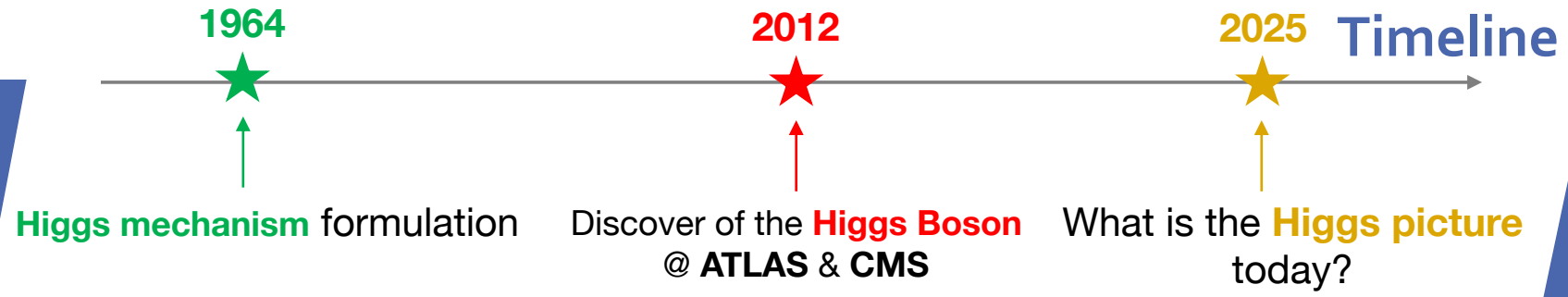
[ATLAS]

- Electric charge: **Q** = 0
- Spin: **S** = 0
- Parity: **P** = +1
- C-parity: **C** = +1
- Width: $\Gamma = 2.9^{+2.3}_{-1.7}$ MeV
- Mass: **M** = 125.08 ± 0.12 GeV

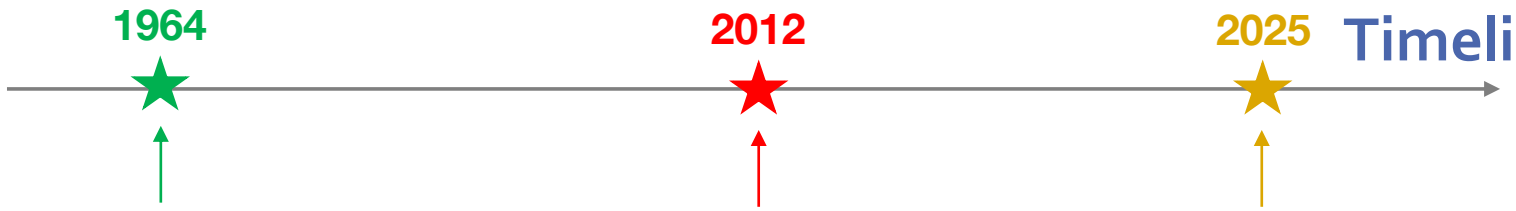
Finally found 😀 ...

… but it's only the start 😟

Nowadays…


1964
2012
2025
Timeline
Higgs mechanism formulation
Discover of the Higgs Boson
@ ATLAS & CMS
What is the Higgs picture
today?

Nowadays…

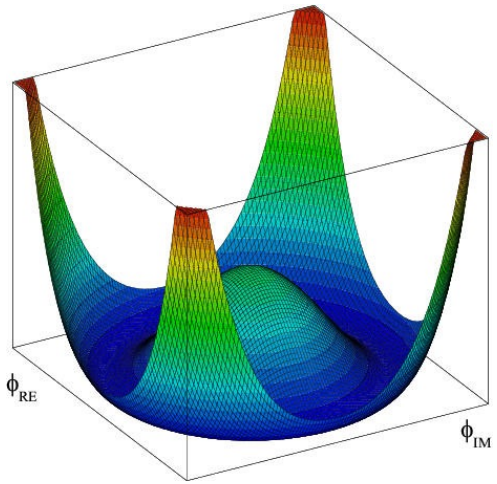


Higgs potential

$$V(H) = V_0 + \frac{1}{2!} m_H^2 h^2 + \frac{1}{3!} \lambda_{HHH} h^3 + \mathcal{O}(h^4)$$

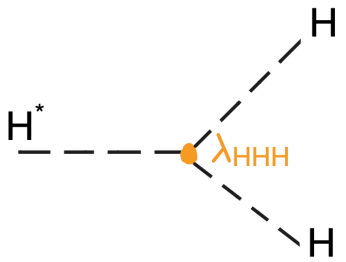
Mass **directly** measured

Higgs trilinear self-coupling



$$\lambda_{HHH} = \frac{m_H^2}{2v^2} \approx 0.13$$

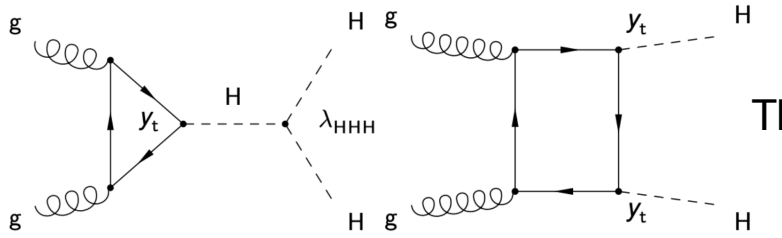
from the **SM theory**



The **experimental proof** is taking much time → **Why?**

Double Higgs production

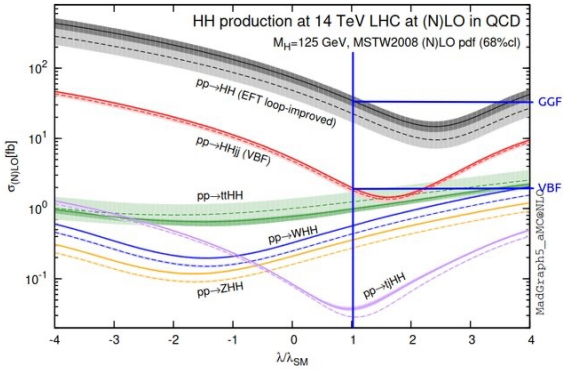
- **Dominant production mechanism** at the LHC is the **gluon-gluon fusion** (**ggF**)



The two diagrams interact **destructively**

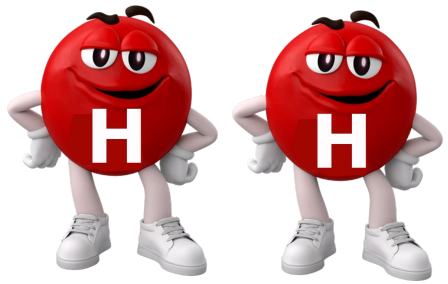
- Other productions are **VBF** (vector boson fusion) and **VHH** (double Higgs production in association with a vector boson)

  Cross section very low with respect to ggF



- **Rare process** at the LHC energy $\sigma_{HH} \sim 10^{-3}\sigma_H$

- **Good validation exam** for the Standard Model or evidence of BSM physics

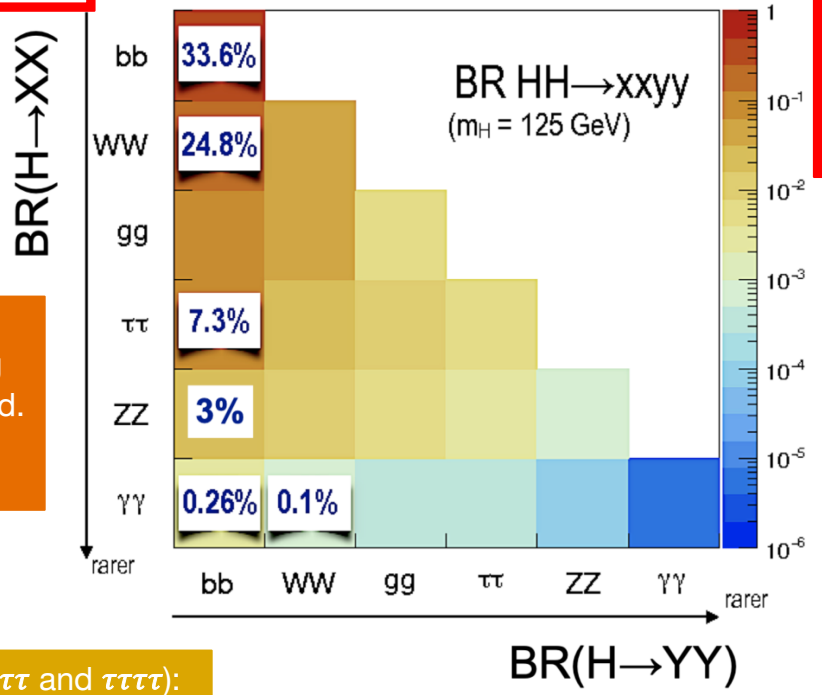


HH decays

bbbb:
the highest branching fraction, large multijet background

bb$\tau\tau$:
relatively large branching fraction, cleaner final state

bb$\gamma\gamma$:
very small branching fraction, clean signal extraction due to the narrow $H \to \gamma\gamma$ mass peak



bbWW(bbVV):
second largest branching fraction, large background. Final states with at least one lepton cleaner

WW$\gamma\gamma$:
clean $\gamma\gamma$ peak, leptonic final states of jets

Multilepton(WW*WW*, WW$^*\tau\tau$ and $\tau\tau\tau\tau$):
many different signatures, clean leptonic final states, no b-tagging needed

$\tau\tau\gamma\gamma$:
best of $\tau\tau$ and $\gamma\gamma$. Small BR

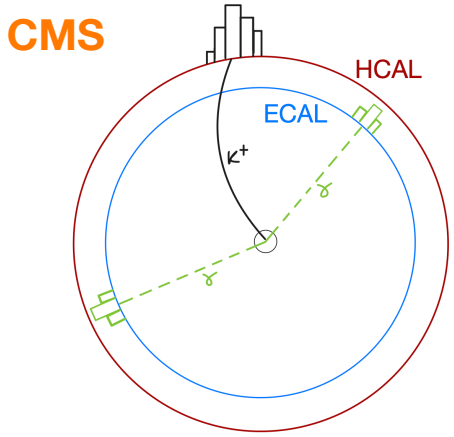
$$\mathbf{BR} = \frac{\Gamma(\mathrm{H} \to \mathrm{X})}{\Gamma_{\mathrm{H}}^{\mathrm{total}}}$$

Most sensitive channels:

- **bbbb**
- **bb$\tau\tau$**
- **bb$\gamma\gamma$**

Reconstruction in CMS

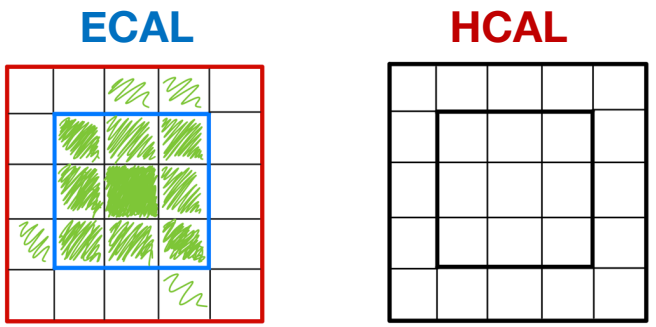
Reconstruction of the physics objects via the **tracker** and **calorimeters**



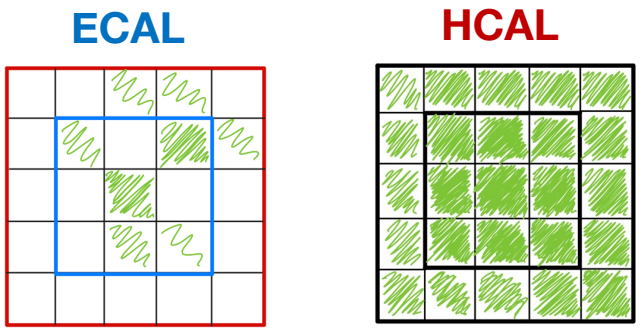
Tracker
→ curvature of the charged particles

$$p = q \times B \times R$$

Calorimeters
→ energy released by the particles

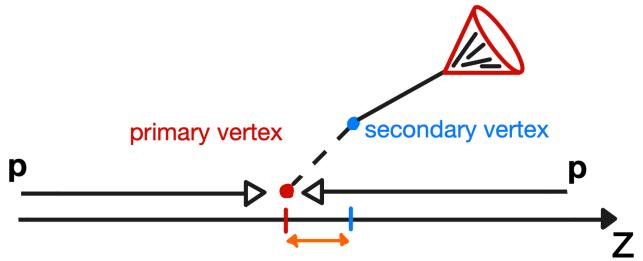


γ/e



hadrons/jets

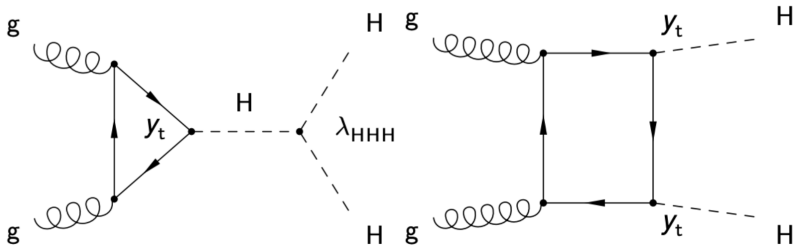
Primary and secondary vertex
→ τ, b, c and others travel different distances before decaying



HH cross section with BSM

The importance of the **HH production** observation lies on the study of BSM effects

→ very sensitive to these contributions

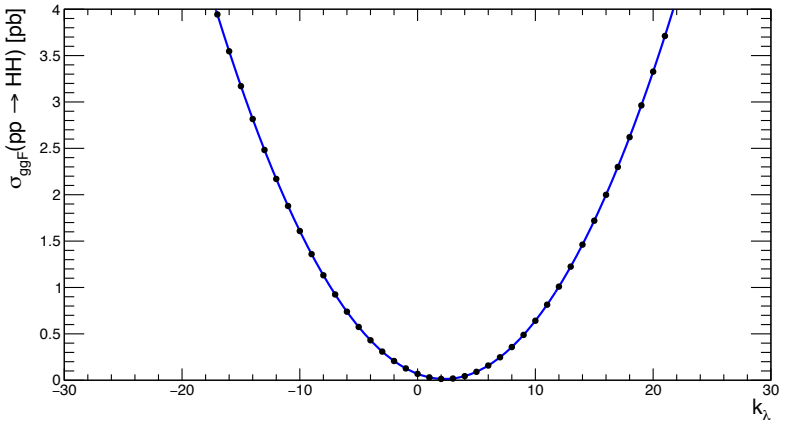


$$k_\lambda = {}^{\lambda_{HHH}}/_{\lambda^{SM}_{HHH}}$$

EFT lagrangian with dim-6 operators (only the **ggF** production):

$$\mathcal{L}_{HH} = k_\lambda \lambda^{SM}_{HHH} v H^3 - \frac{m_t}{v}(k_t H + \frac{c_2}{v}H^2)(\bar{t}_L t_R + h.c.) + \frac{1}{4}\frac{\alpha_S}{3\pi v}(c_g H - \frac{c_{2g}}{2v}H^2)\mathcal{G}^{\mu\nu}\mathcal{G}_{\mu\nu}$$

$$\sigma_{HH} = 68.5624 - 48.3673 \times k_\lambda + 10.5635 \times k_\lambda^2$$

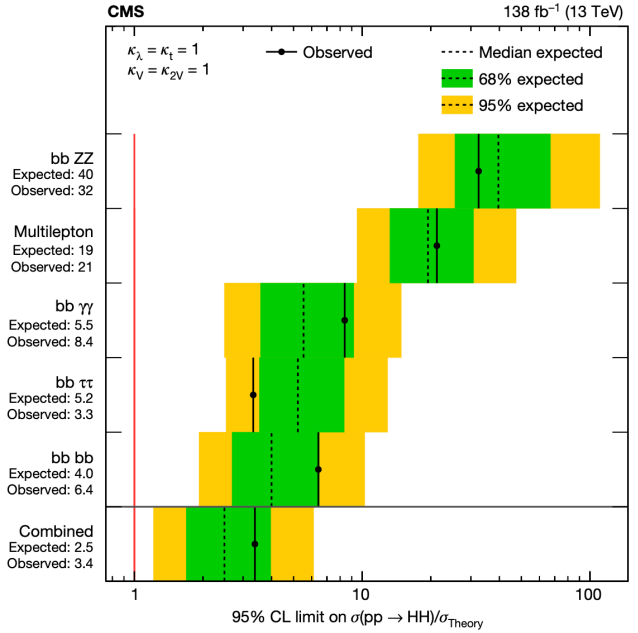


Analysis status

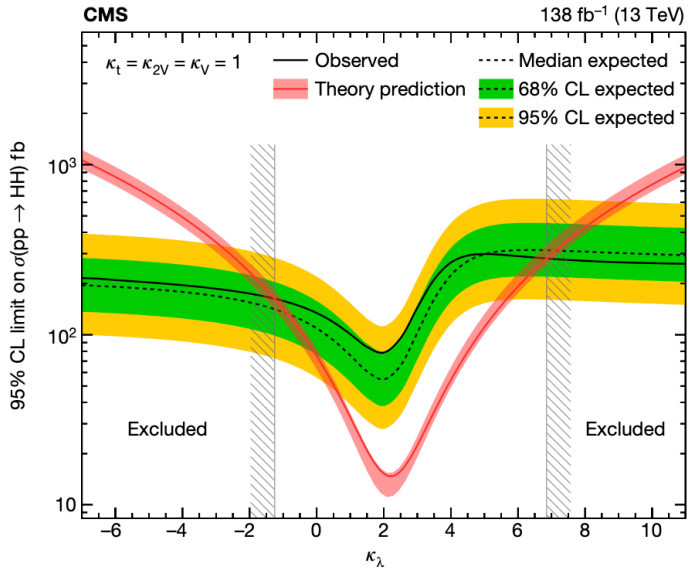
Run2 (2015-2018, **L = 138 fb^{-1}**) results

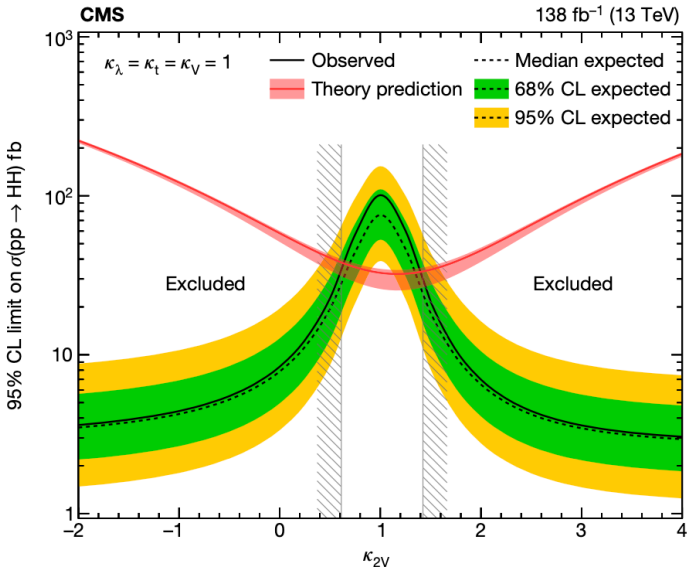
Current limits (with Run2 dataset):

- $-1.24 < \boldsymbol{k_\lambda} < 6.49$
- $0.67 < \boldsymbol{k_{2V}} < 1.38$



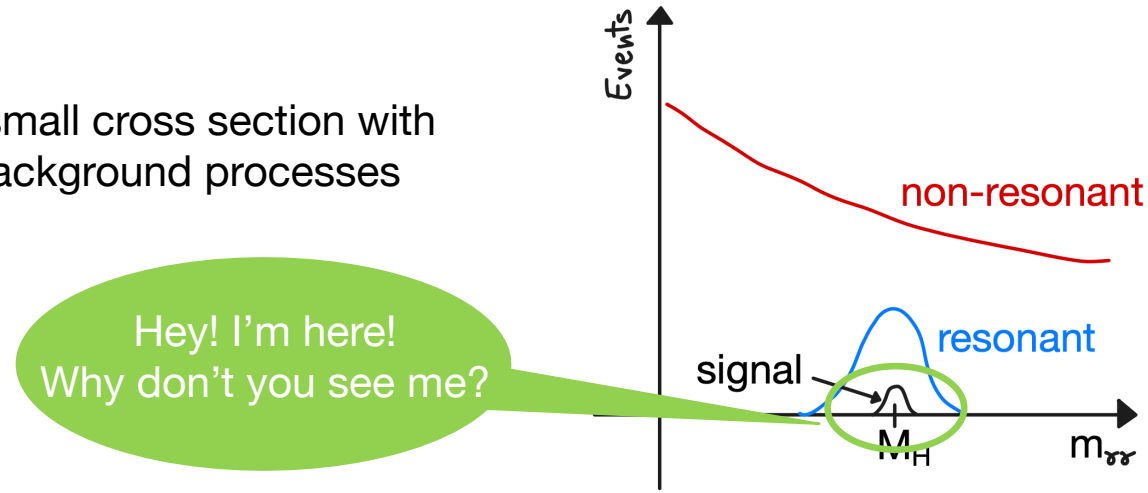
Nature vol. 607, 60-68 (2022)



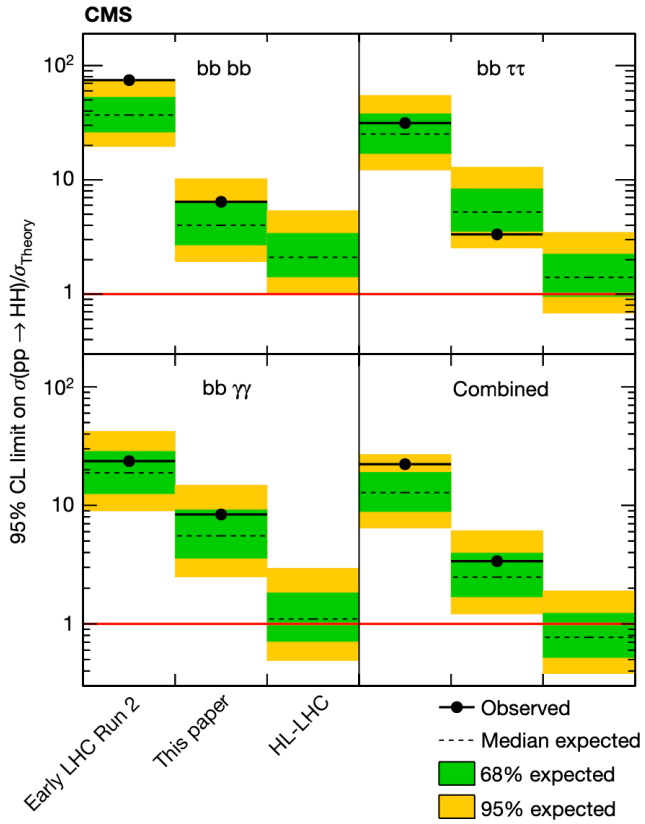


It's a matter of size… …of the dataset!

Main challenge: small cross section with respect to other background processes



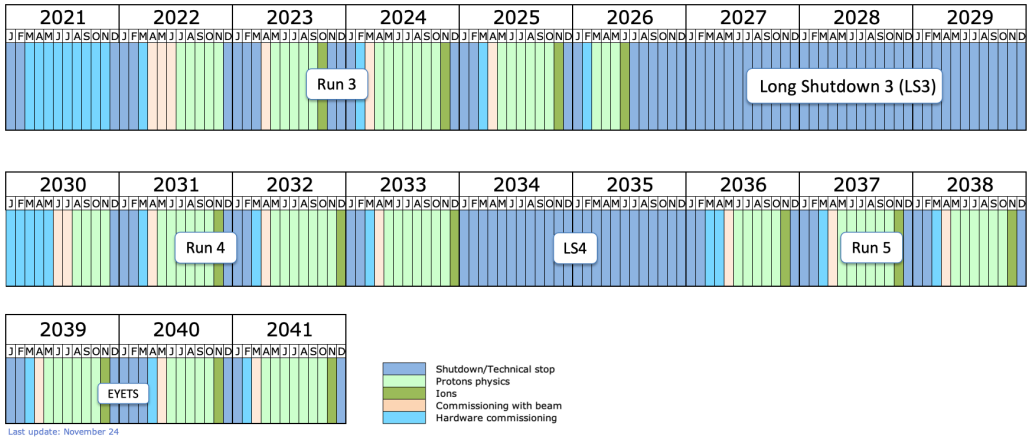
Nature vol. 607, 60-68 (2022)



Solution?
More data → **HL-LHC**

High-Lumi LHC upgrade

Time period:
from 2026 (LS3) to 2040s



LHC Run3 (2022-2026)
Levelled luminosity → $L_{\text{levelled}} = 2.2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
PU = 64

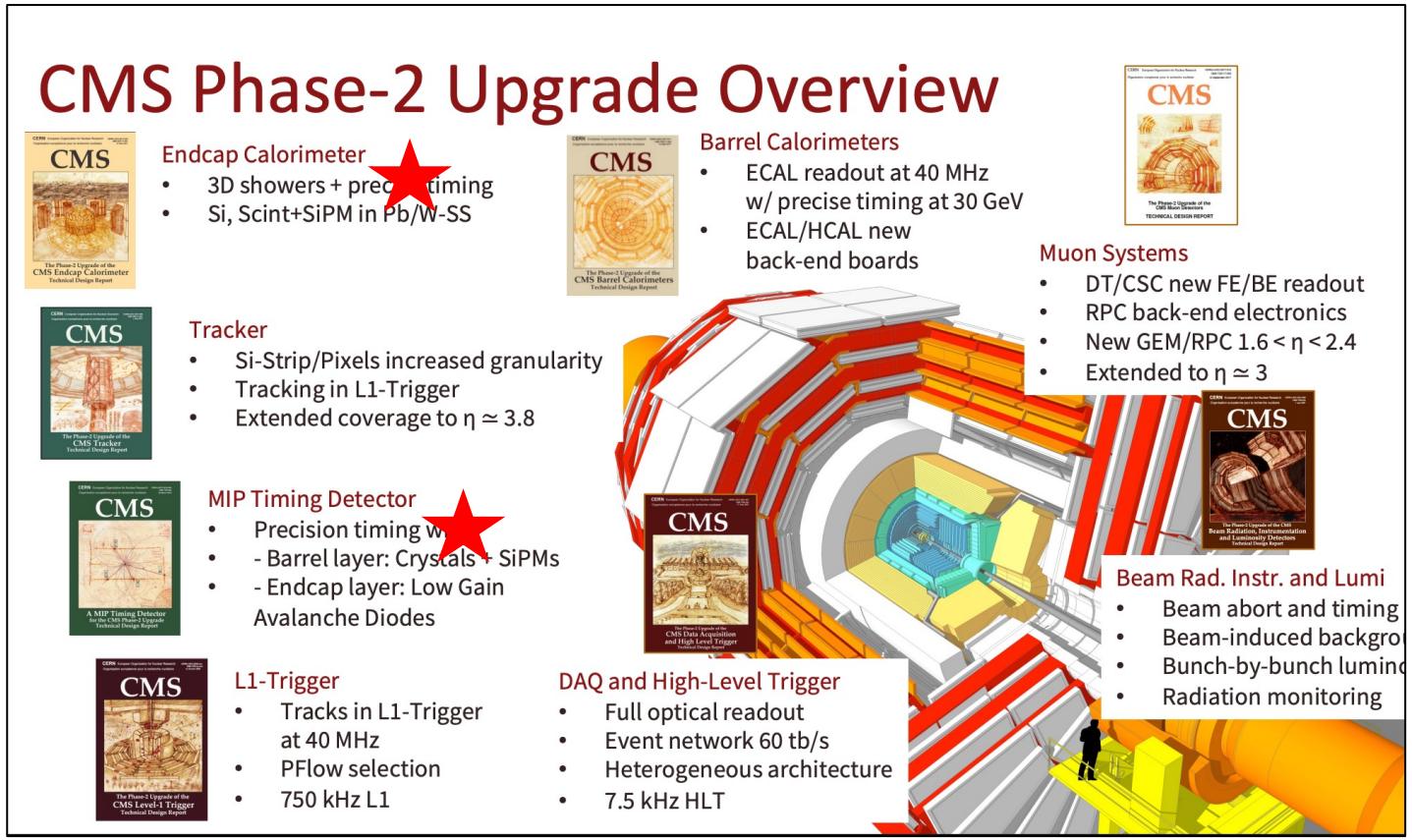
HL-LHC
Levelled luminosity → $L_{\text{levelled}} = 5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
PU = 140 ÷ 200

Aim: increase the number of data without loosing performance

Upgrade of the LHC machine itself and of the main experiments!

CMS upgrade

The upgrade will include all the sub-detectors

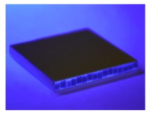


The new Mip Timing Detector

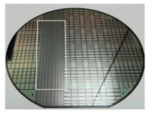
Two different technologies to cope with different radiation levels:

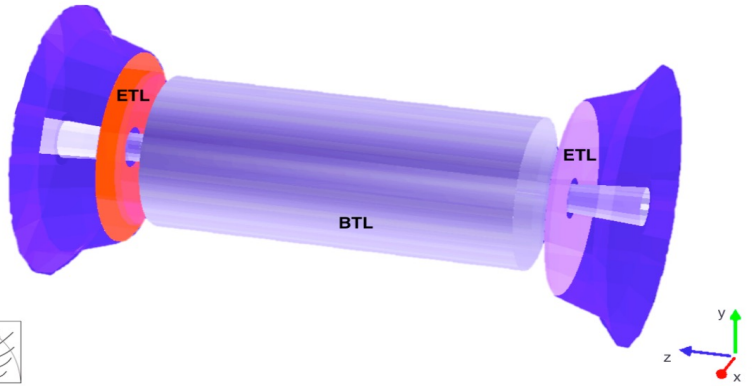
- **Barrel** ($|\eta| < 1.45$) → **LYSO** cristals + **SiPM**
- **Endcap** ($1.5 < |\eta| < 3$) → Low Gain Avalanche Detectors (**LGAD**)

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



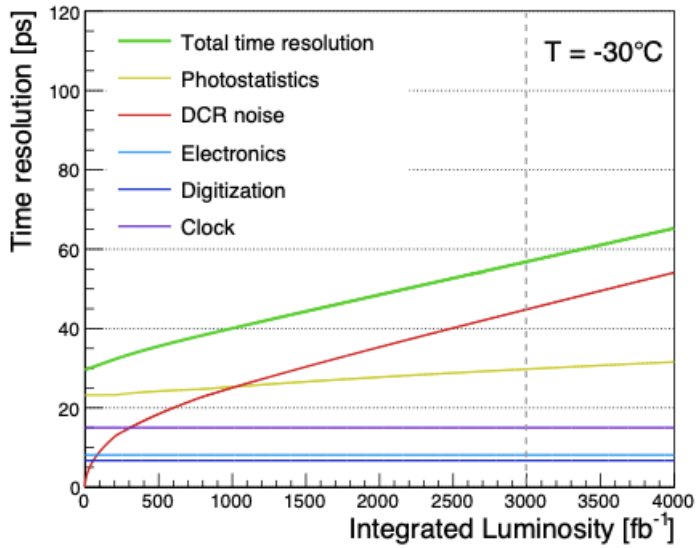
ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200$ mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2





[CMS Technical Design Report]

- Timing resolution of **30÷60 ps**



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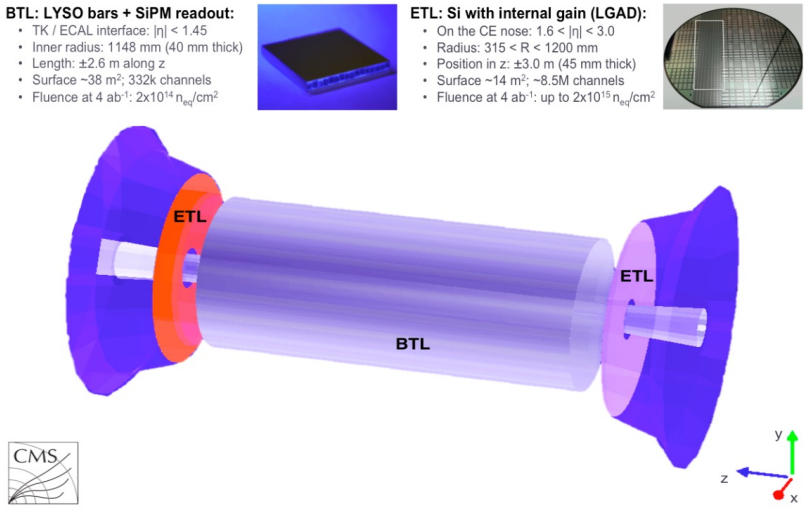
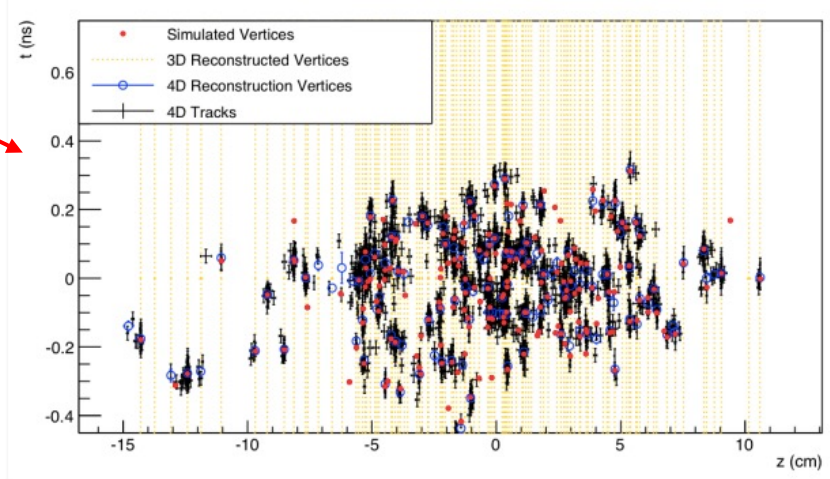


CMS Technical Design Report

- Timing resolution of 30÷60 ps
- **4D vertex reconstruction**



The new Mip Timing Detector

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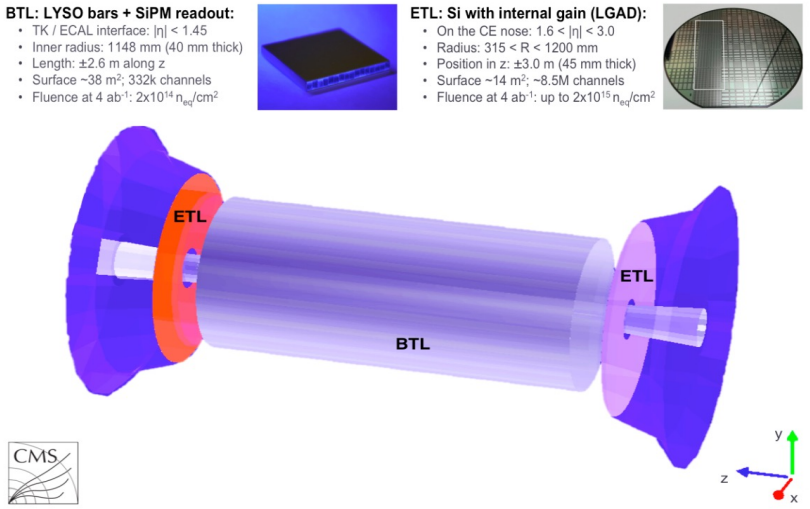
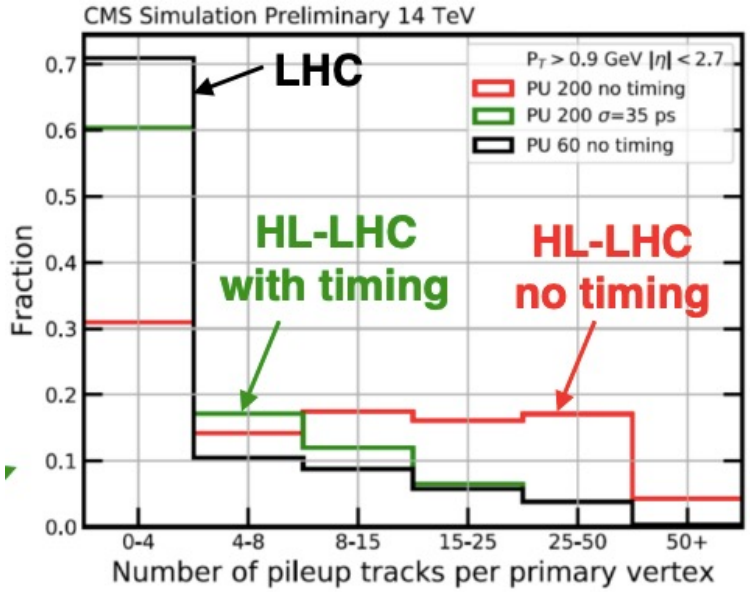


[CMS Technical Design Report]

- Timing resolution of 30÷60 ps
- 4D vertex reconstruction
- **Suppress pileup** tracks



The new Mip Timing Detector

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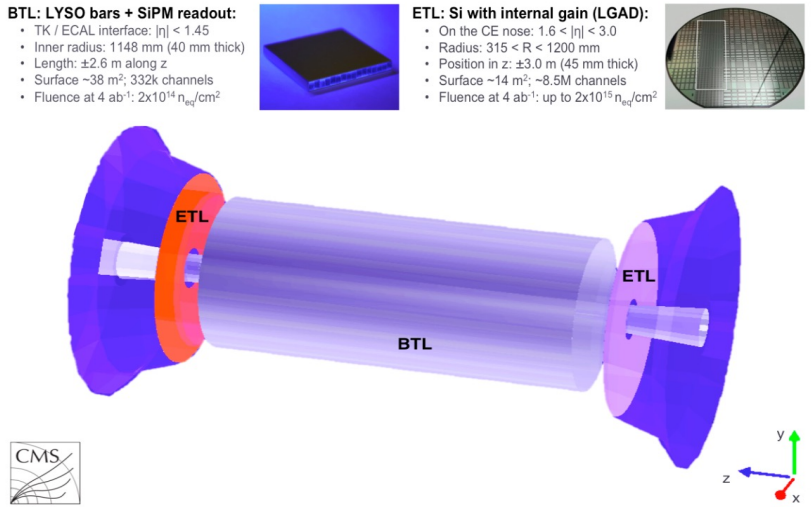
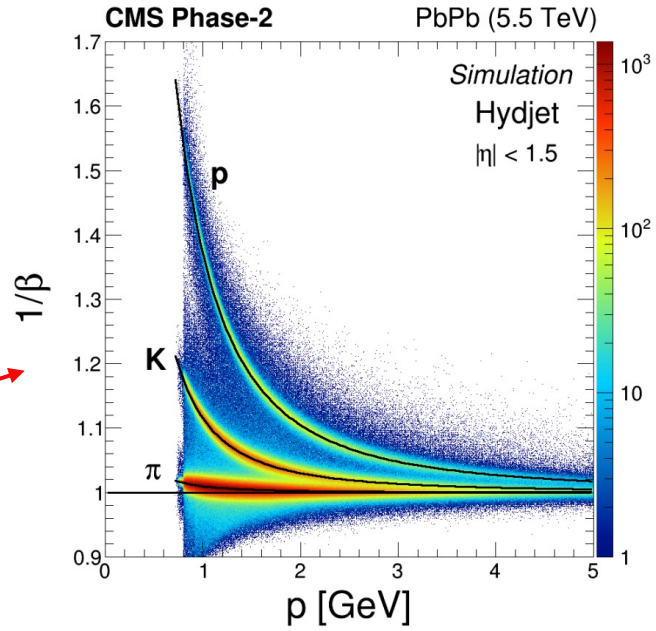


[CMS Technical Design Report]

- Timing resolution of 30÷60 ps
- 4D vertex reconstruction
- Suppress pileup tracks
- **Particle Identification**

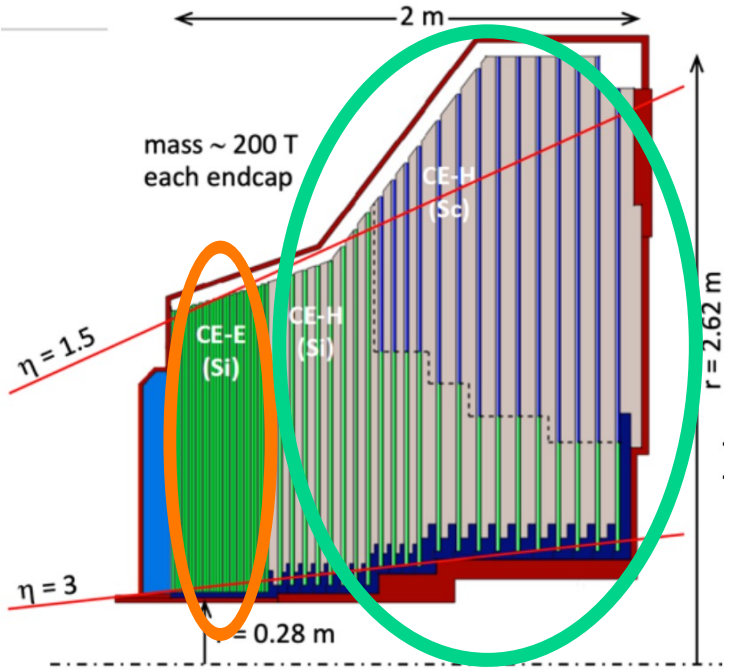


High Granularity Calorimeter

CMS Endcap calorimeter will be replaced with the new **HGCAL**

Very **dense sampling calorimeter**

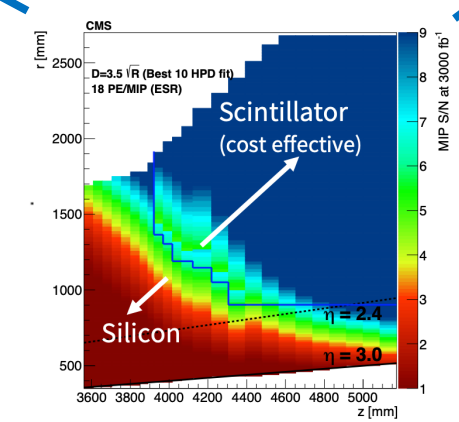
Clusterization and **timing** improvement



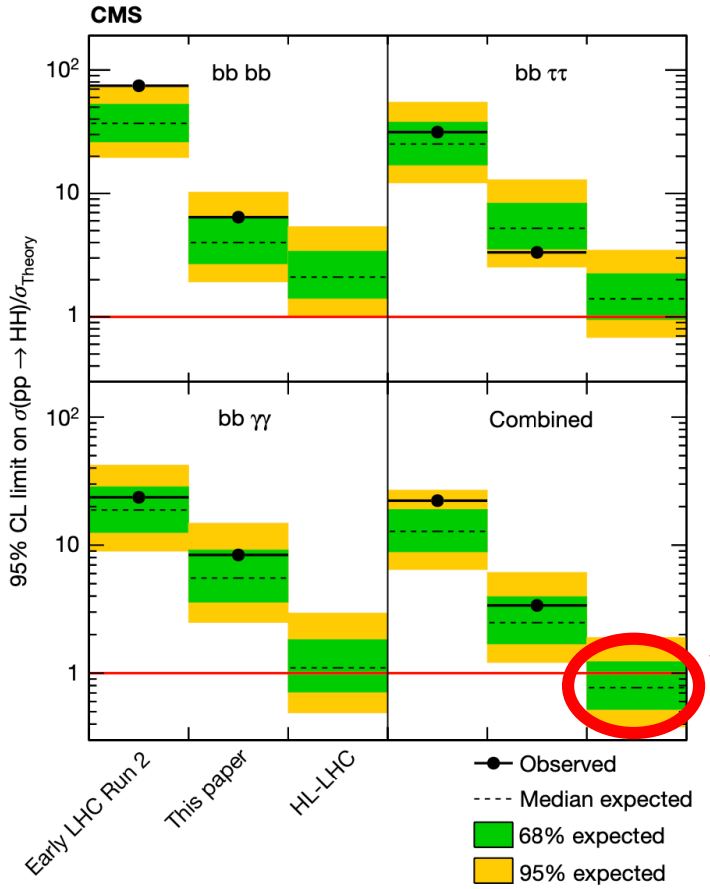
Electromagnetic calorimeter (**CE-E**)

Hadronic calorimeter (**CE-H**)

Mix of **silicon absorbers** and **scintillator detectors**



HH production @ HL-LHC



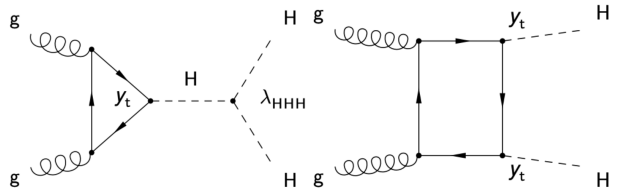
Predictions of HL-LHC luminosity
→ $\mathbf{L \sim 3000 \div 4000\ fb^{-1}}$

Sensitive to SM double Higgs production!

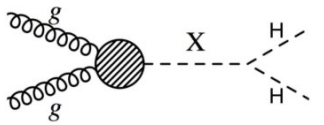
The HL-LHC will probably be the time of HH production observation

SM-like?

BSM contributions?



Resonant production?



Conclusions

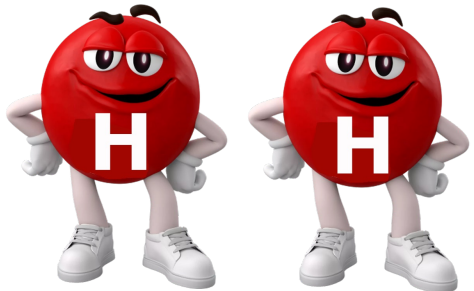
- The **Higgs boson pair production** is one of the guiding analysis nowadays
  → Higgs potential still not well understood, starting from $\boldsymbol{\lambda_{HHH}}$
  → sensitive to **BSM contributions**

- Most **sensitive channels** (decaying BR and reconstruction efficiency):
  - $\boldsymbol{bbbb}$
  - $\boldsymbol{bb\tau\tau}$
  - $\boldsymbol{bb\gamma\gamma}$

  → new channels studied: $\boldsymbol{bbWW}$ and $\boldsymbol{\gamma\gamma\tau\tau}$

- Waiting for the full Run3 data taking, there is **no evidence today** of HH production
  → only **upper and lower limits** on parameters
  → predictions exclude to see it with full Run3 data, but who knows…

- The turning point will be **High-Luminosity LHC** (according to predictions)
  → expected to **see the HH production evidence**
  → possibility to validate more the SM theory or to go beyond it



Backup

Sketch of the LHC upgrade

Triplet magnets → experienced big radiation damage
⟹ need to replace with radiaion hard system

- larger aperture
- new magnets technology

RF cavities improved to be more precise and compact

Increased of **vacuum**, **cryogenics** and **machine protection** demand

New concepts for **collimation**

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⟹ need to replace with radi
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Available here:
https://doi.org/10.1142/13487

Increased of **vacuum**, **cryogenics**

New concepts for **collimation**