Based on arxiv.org/pdf/2009.14009

Search for dark photons in Higgs production via vector boson fusion in pp colisions at $\sqrt{s}=13\,TeV$

A measurement by the CMS collaboration

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TÉCNICO LISBOA

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Outline

I) Standard Model and the LHC

1) The Standard Model
2) Higgs boson
3) Large Hadron Collider
4) CMS experiment

II) Search for a dark photon in Higgs production via VBF

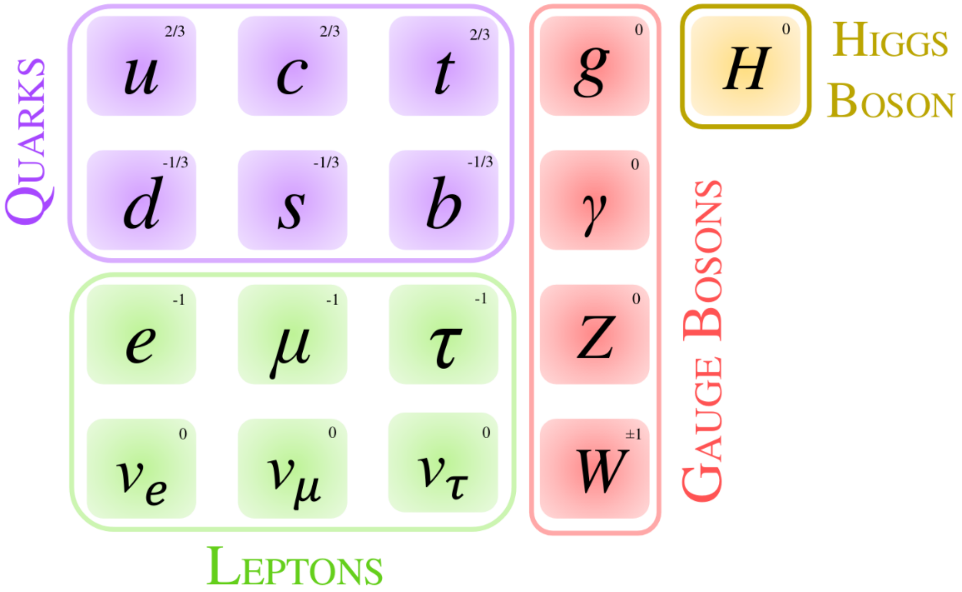
1) Dark photons
2) Vector Boson Fusion
3) Data samples
4) Event reconstruction & selection
5) Background estimation & signal extraction
6) Efficiencies and Systematic Uncertainties
7) Results
8) Summary

Standard Model and the Large Hadron Collider

The Standard Model (SM)

SM is the most successful theory describing the strong, weak and eletromagnetic forces

Governed by four classes of particles: leptons, quarks, gauge bosons and the **Higgs**



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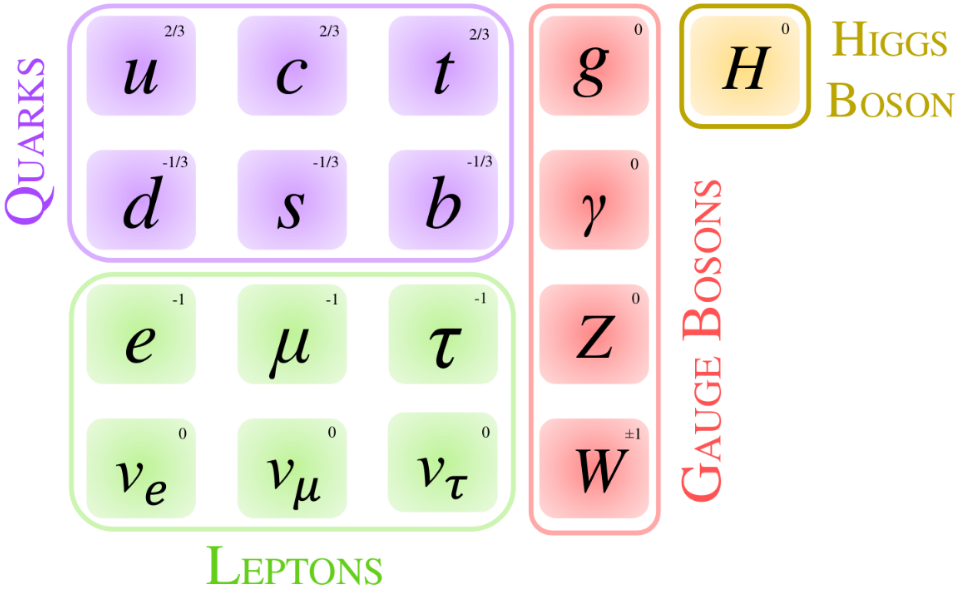

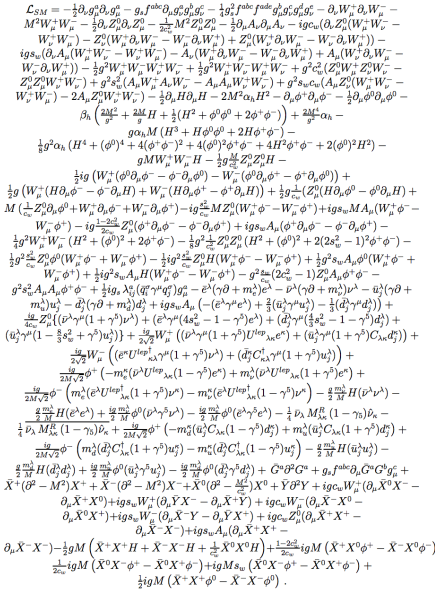

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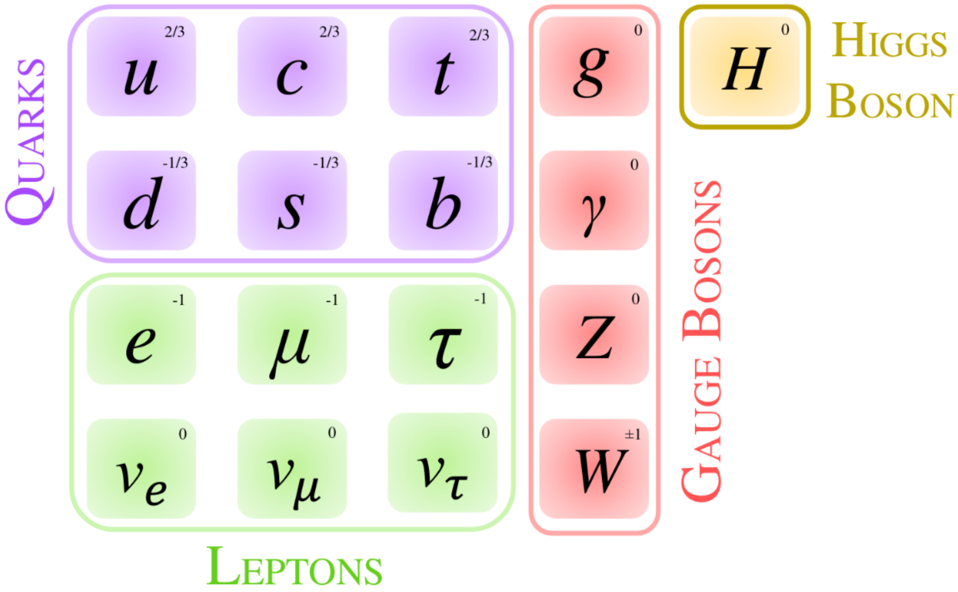


$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\psi}\not{D}\psi + h.c. \\ &+ \bar{\psi}_i y_{ij}\psi_j\phi + h.c. \\ &+ |D_\mu\phi|^2 - V(\phi)\end{aligned}$$

Higgs Boson

Higgs boson is the result of a ***spontaneous symmetry breaking*** (SSB) in the vacuum expectation value of an SU(2) scalar field, breaking the original SU(2)xU(1)$_y$ symmetry into U(1)$_{em}$

SSB of the scalar sector directly generates **mass terms** for **electroweak (EW) gauge bosons**

$$D_\mu \phi D^\mu \phi \rightarrow \; ... + \frac{gv}{2} W^{+\mu} W^-_\mu + \frac{gv}{2\cos\theta_W} Z^\mu Z_\mu$$

+ interactions H/WZ

For **quarks** and **leptons**, mass is generated by transformations of the Yukawa sector after SSB

$$\bar{\psi}_i y_{ij} \phi \psi_j \rightarrow ... + \bar{\psi} M \psi$$

+ interactions H/psi

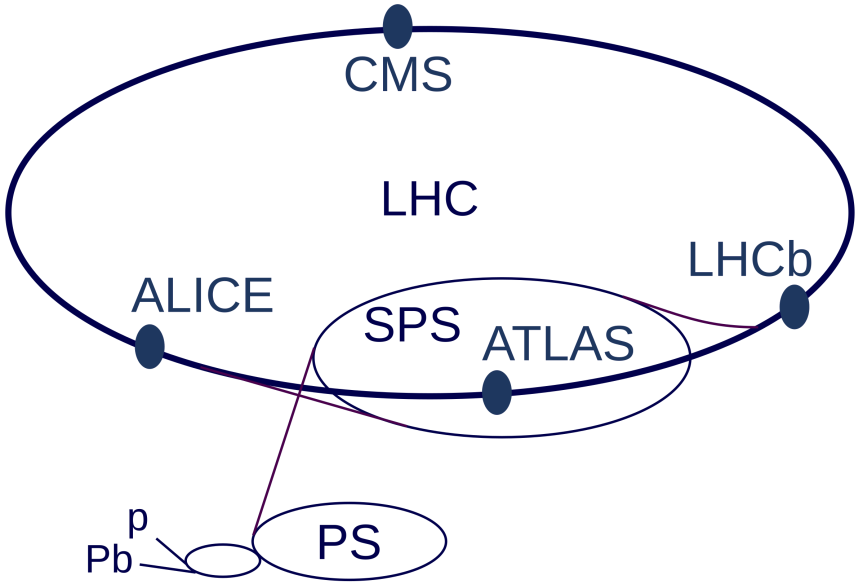
ⓘ The Higgs boson was discovered in 2012 at the **LHC**, in proton-proton collisions, marking one of the greatest triumphs of the SM!

The Large Ion Collider (LHC)

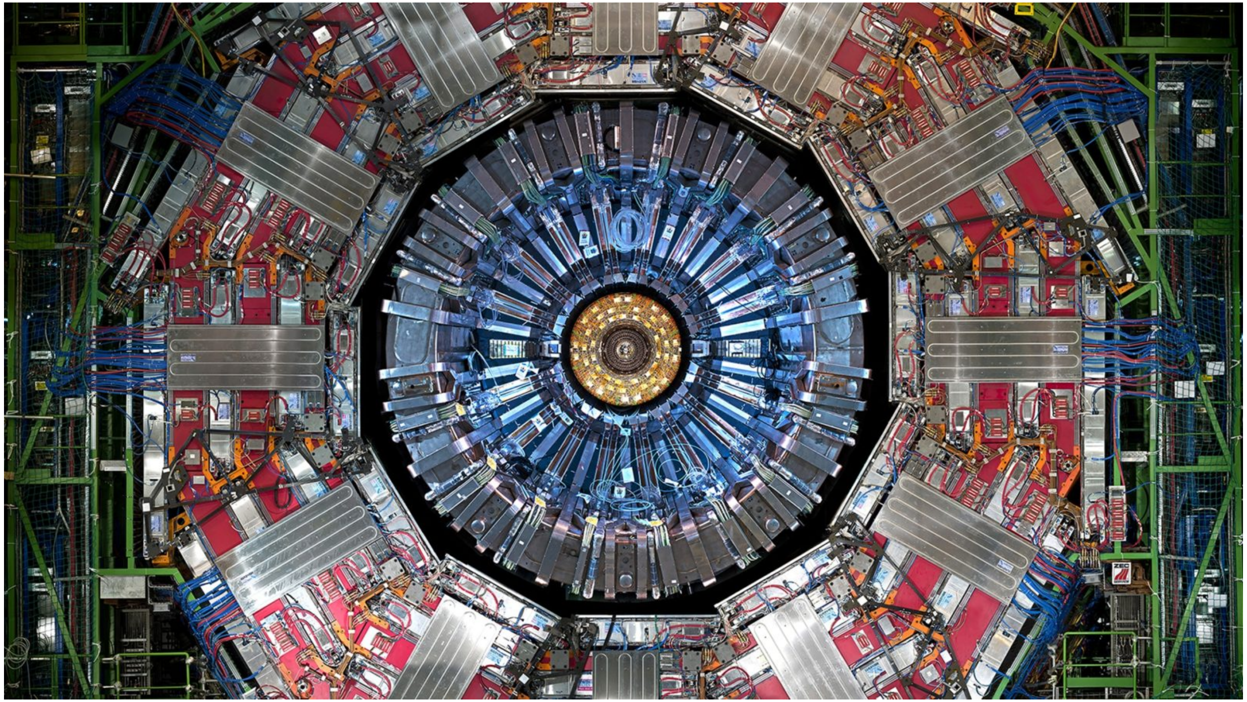
The LHC is the largest particle collider in the world, with ~27km of perimeter

It is composed of **four** detector sites, each corresponding to an experiment:

- **ALICE** (A Large Ion Collider Experiment)
- **ATLAS**
- **CMS** (Compact Muon Solenoid)
- **LHCb** (LHC beauty)



The CMS experiment



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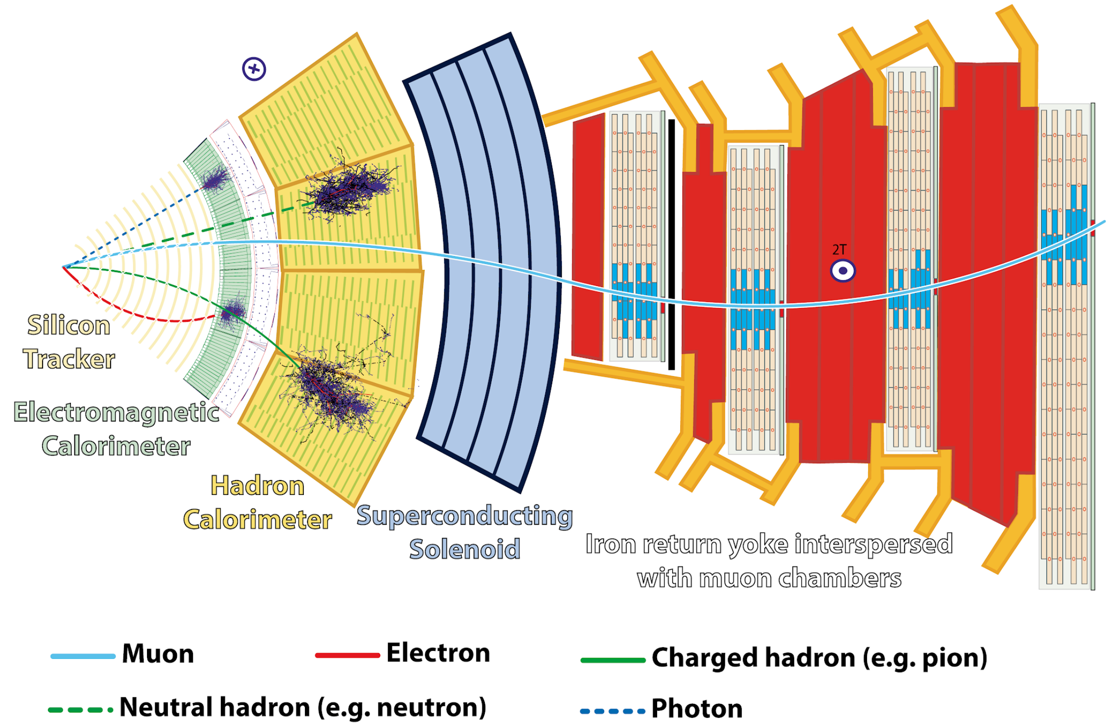


Search for a Dark Photon in Higgs production via VBF

Dark photons

The SM is still **incomplete:** does not explain gravity, neutrino masses, **dark matter/energy**

BSM (Beyond the SM) extension: introduction of a hidden/dark sector

$$\mathcal{L}_{\mathrm{BSM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{dark}}$$

In some BSM models, the Higgs decays into a photon and an undetected particle, the **dark photon**

$$\mathrm{H} \to \gamma\gamma_{\mathrm{D}}$$

Vector Boson Fusion

Two vector bosons fuse in a Higgs

Higgs decay products + two jets in the final state

Resulting jets exhibit **large separation in rapidity** and **large dijet mass**

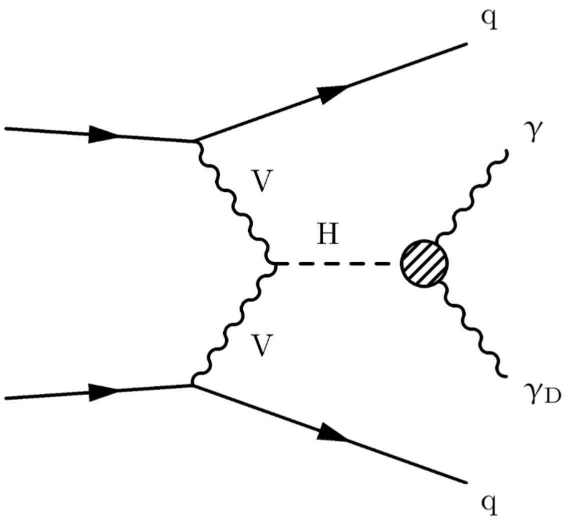
<u>Expected main backgrounds:</u>

→ W(eν) + jets

→ Z + γ

→ W + γ

→ γ + jets



Search for: events with γ+jets and significant missing transverse momentum

Data samples

Experimental data was collected in separate LHC running periods during 2016-2018 (run 2)

→ corrections and calibrations must reflect the different conditionsof the LHC and the CMS detector in each period

integrated luminosities, different triggers, ...

Monte Carlo (MC) simulations data models signal and background, acting as a baseline

Event reconstruction: Particle Flow

Jets

Electrons & Muons

Photons

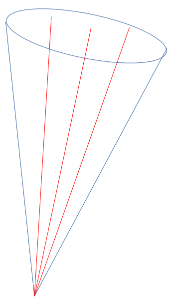
Event reconstruction: Particle Flow

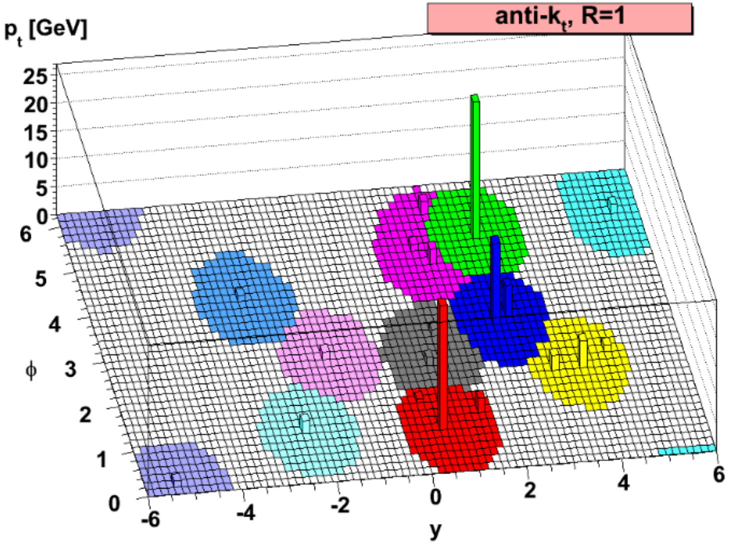
Jets | Electrons & Muons | Photons

Anti-kT clustering algorithm
(IRC safe, regular cone base)

Jet radius R = 0.4
pT > 30 GeV
|η| < 4.7

$$\vec{p}_T^{\,miss} = -\sum \vec{p}_T$$





Event reconstruction: Particle Flow

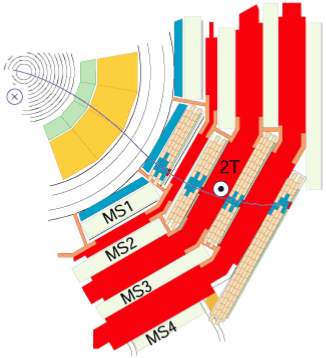
Jets | **Electrons & Muons** | Photons

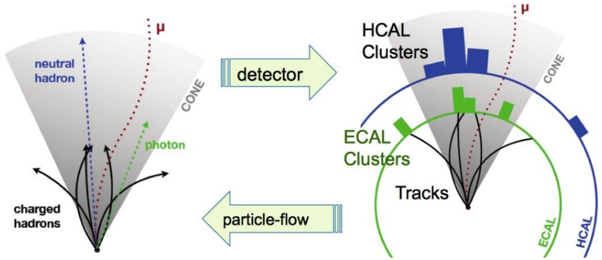
Muons: Global, use **tracks** with cluster of energy in the ECAL and/or muon chaimber

pT > 10 GeV
|η| < 2.4

Electrons: Tracks in the ECAL

pT > 10 GeV
|η| < 2.5





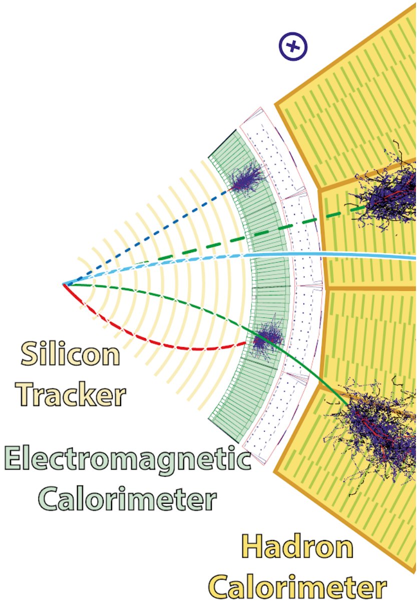
Event reconstruction: Particle Flow

Jets | Electrons & Muons | **Photons**

Energy deposits in the ECAL

pT > 80 GeV
$|\eta| < 1.47$ (barrel)
Isolated

Veto algorithm applies to reject electrons misclassified as phtons



Event selection

Imposed: Signal region (SR) consistent with VBF topology, trigger compatiblity

Main criteria (VBF topology):

→ Minimum of 1 photon

→ Leading and subleading jets with pT > 50 GeV

→ 2-5 jets

→ Forward (leading jets), η < 0, with large separation η

→ pTmiss >~ 100 GeV, angle(pTmiss, jets) > 1.0 to reject bulk of gamma+jets backgrounds

Further details in backup slides...

Background estimations

Control regions (CR): background enriched region with similar kinematics to the SR but with selection criteria based on expected background

γ+jets

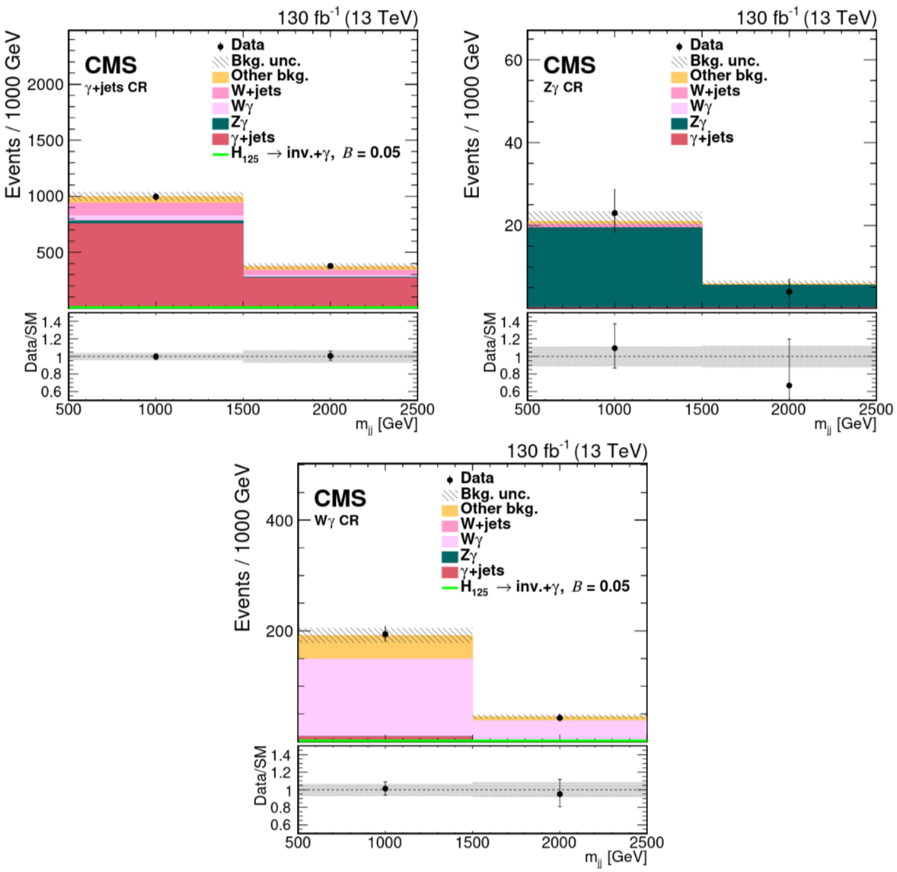
Small azimuthal angle between jets and pTmiss

Z + γ

Two muons + gamma

W+γ

Muon + photon



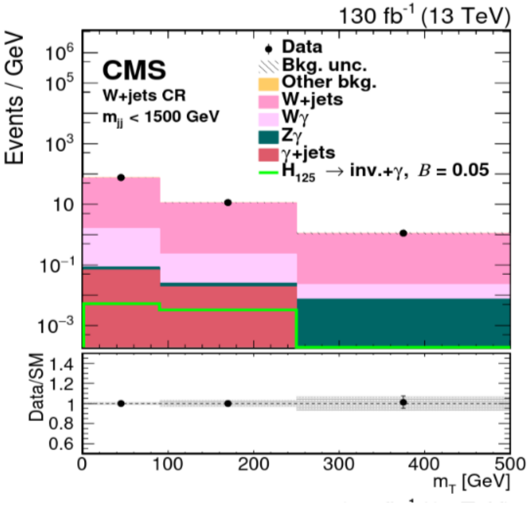
Background estimations

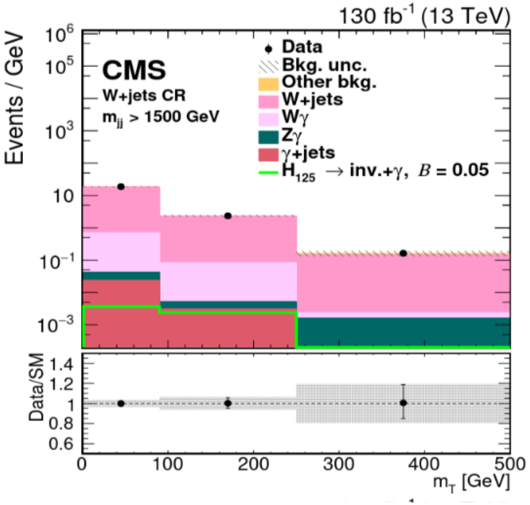
W+jets

Selection of electrons, no photons
(joint fit with signal)

Other backgrounds (nonprompt photons, mismeasured photons, rare processes...)

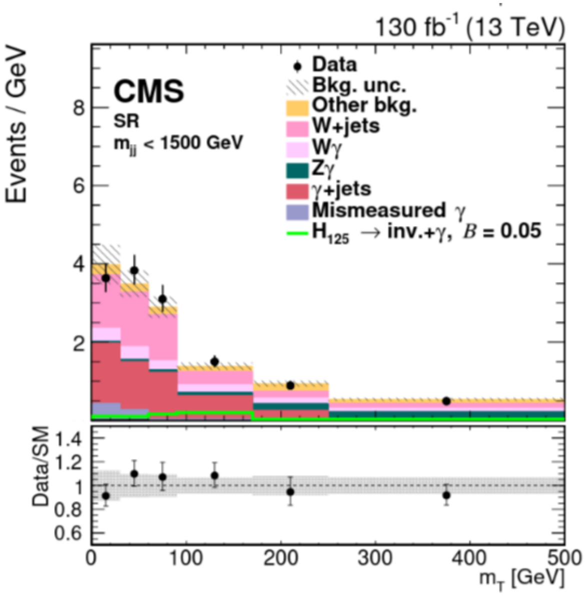
Mainly simulation-based

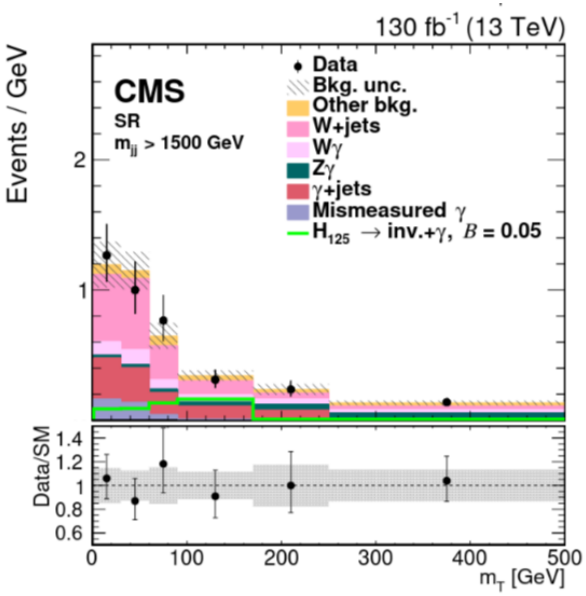




Signal extraction

Simultaneous maximum-likelihood fit to data in both SR and CR for W+jets





Efficiencies and systematic uncertainties

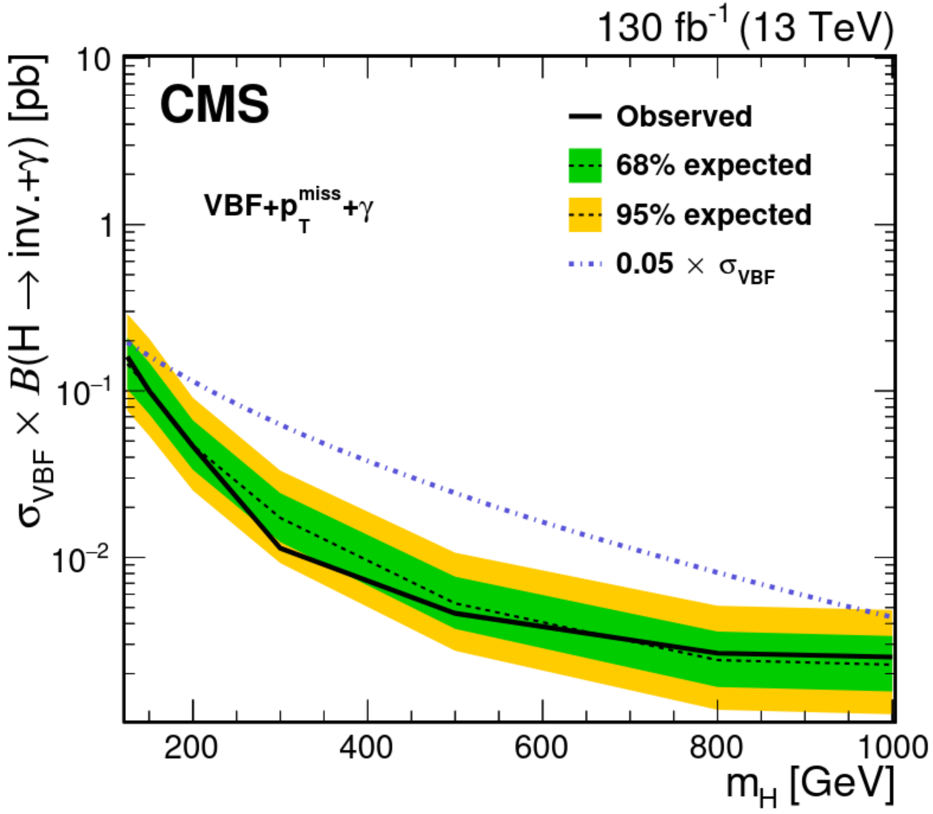
Source of uncertainty	Impact for scenario with signal (fb)	Impact for scenario without signal (fb)
Integrated luminosity	3.3	0.6
Lepton and trigger measurements	17	7.7
Jet energy scale and resolution	24	19
Pileup	9.7	8.5
Background normalization	25	18
Theory	6.0	3.0
Simulation sample size	36	36
Total systematic uncertainty	54	46
Statistical uncertainty	58	48
Total uncertainty	79	66

Did we find a dark photon?

No excess found in the process branching ration with respect to the SM expectation

↓

<u>Lack of evidence for the existance of a dark photon from this analysis</u>



Thank you for your attention!

Data-taking year	2016	2017/2018	
Trigger	VBF+γ	Single-photon	$p_{\mathrm{T}}^{\mathrm{miss}}$
Number of photons		$\geq$1 photon	
p_{T}^{γ}	$>$80 GeV	$>$230 GeV	$>$80 GeV
Number of leptons		0	
$p_{\mathrm{T}}^{\mathrm{j}_1}$, $p_{\mathrm{T}}^{\mathrm{j}_2}$		$>$50 GeV	
$p_{\mathrm{T}}^{\mathrm{miss}}$	$>$100 GeV	$>$140 GeV	$>$140 GeV
Jet counting		2–5	
m_{jj}		$>$500 GeV	
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$		$>$3.0	
$\eta_{\mathrm{j}_1}\eta_{\mathrm{j}_2}$		$<$0	
$\Delta\phi_{\mathrm{jet},\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}$		$>$1.0 radians	
z_{γ}^{*}		$<$0.6	
$p_{\mathrm{T}}^{\mathrm{tot}}$		$<$150 GeV	